Cosmology with Spectroscopic Surveys

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The simplified plan

Why clustering for cosmology ?

From photons to spectra

From spectra to clustering

From clustering to cosmology

Why clustering for cosmology ?

Which fundamental questions in Physics we would like to answer ?

Why clustering for cosmology ?

Dark energy

Alternate theories of gravity

Inflation

Neutrino masses

Dark matter

Clustering informs us about all these questions

Latest constraints

Dark energy

Alternate theories of gravity

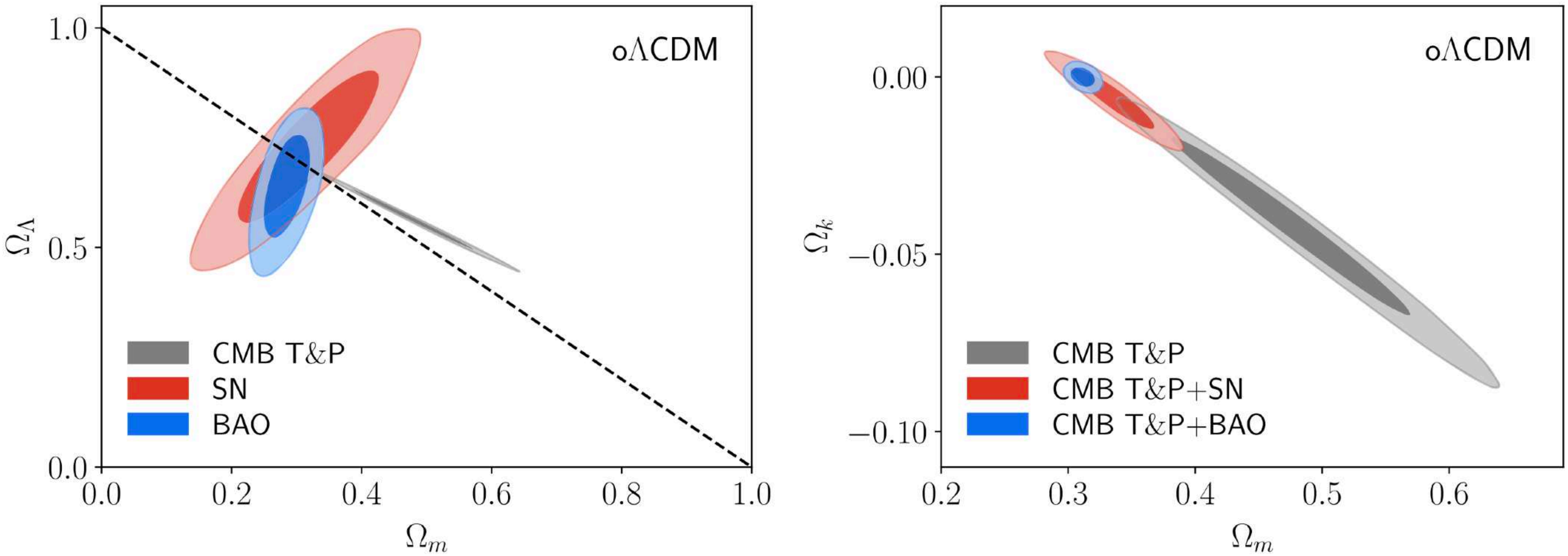
Inflation

Neutrino masses

Latest constraints

Dark energy Alternate theories of gravity Inflation Neutrino masses

Cosmological constant and curvature

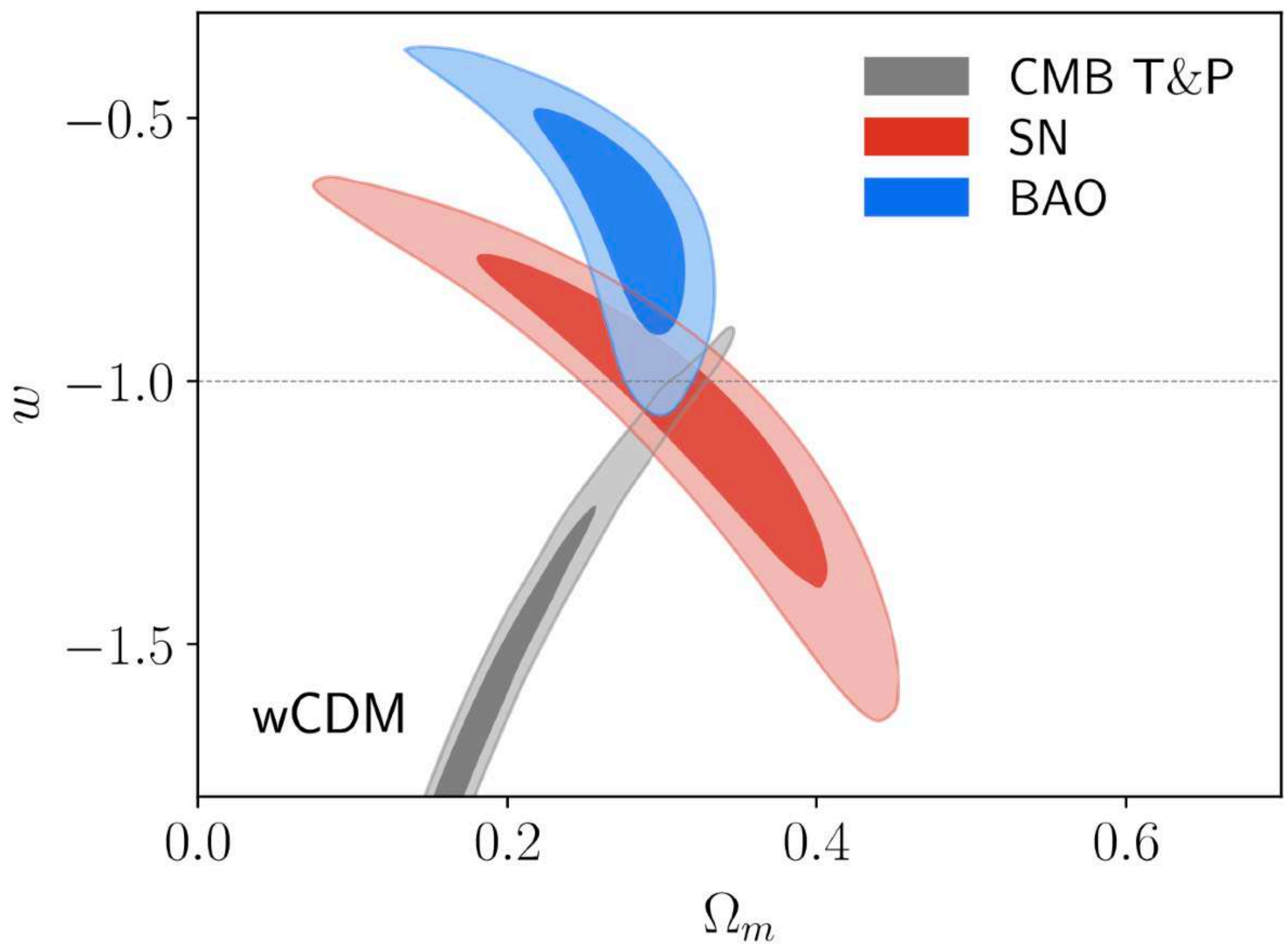


eBOSS Collaboration 2021

Latest constraints

Dark energy Alternate theories of gravity Inflation Neutrino masses

Equation of state of dark energy

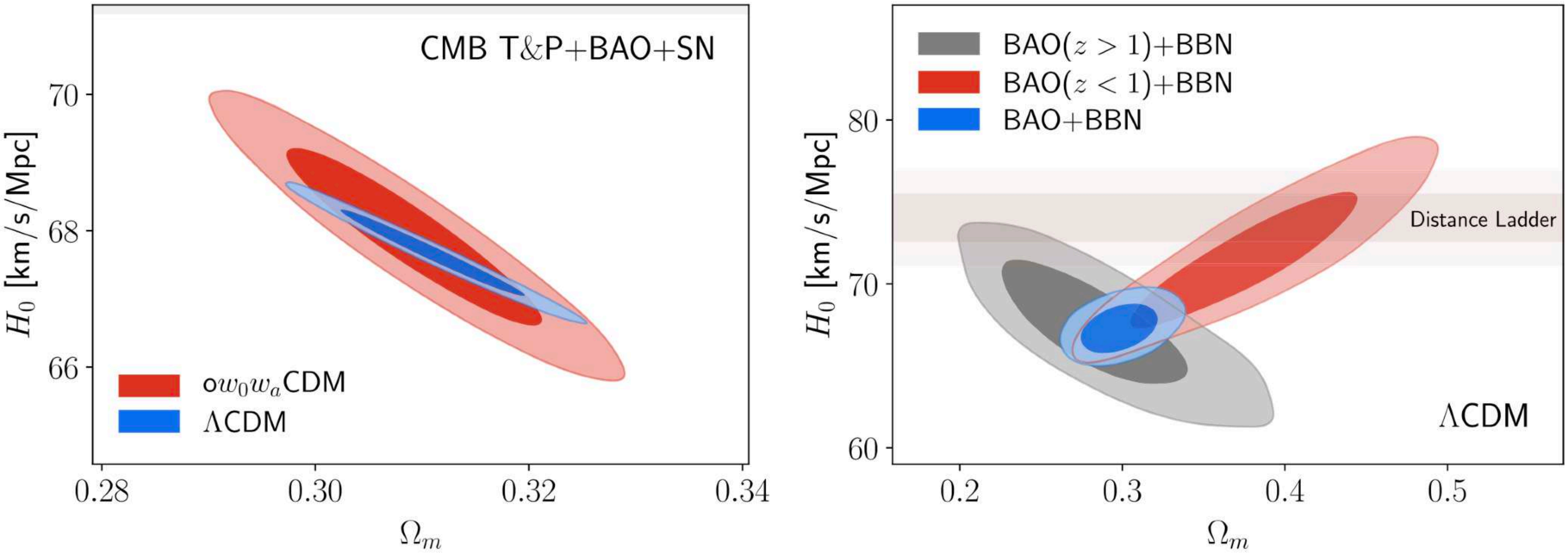


eBOSS Collaboration 2021

Latest constraints

Dark energy Alternate theories of gravity Inflation Neutrino masses

Hubble constant

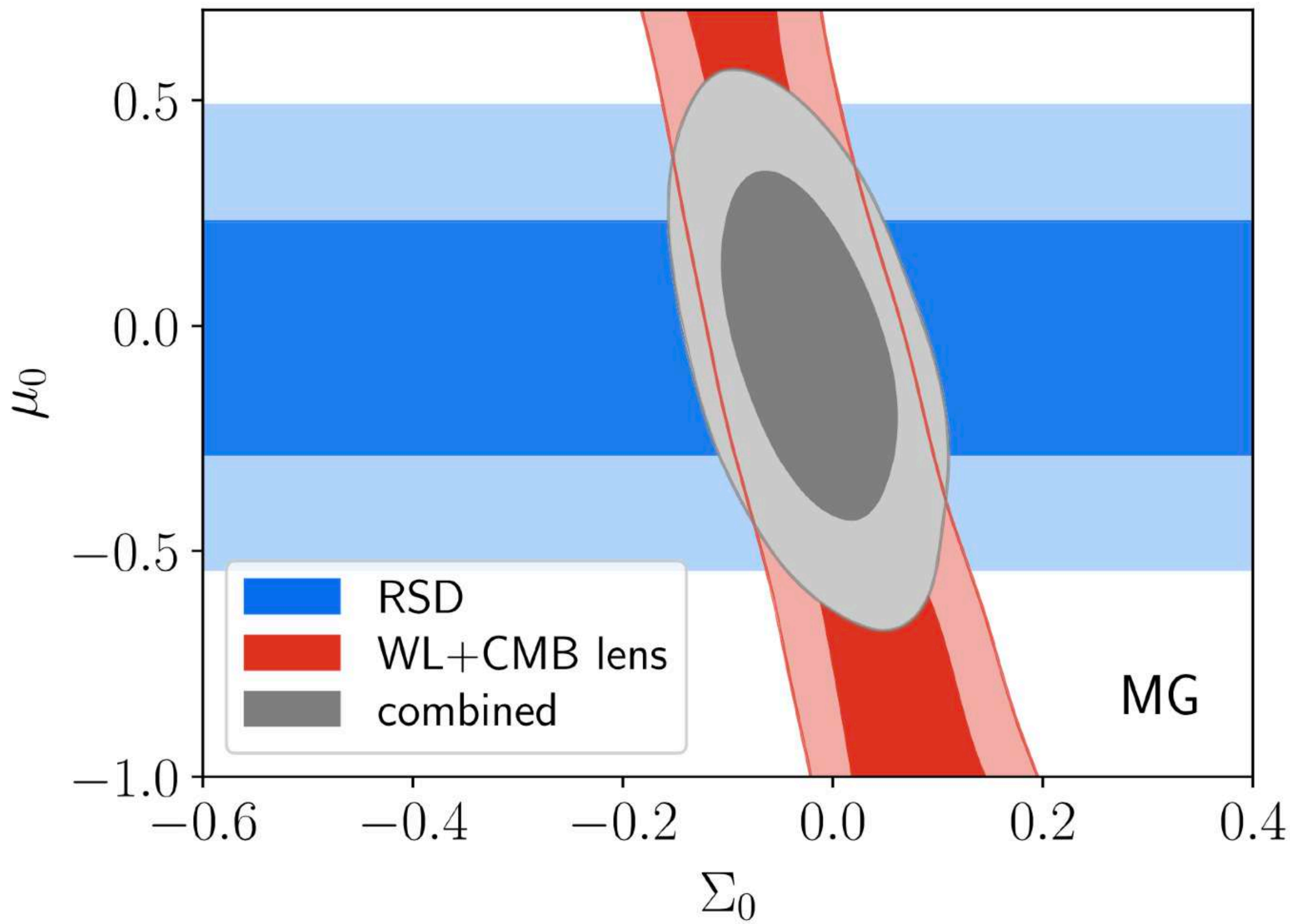


eBOSS Collaboration 2021

Latest constraints

Dark energy | **Alternate theories of gravity** | Inflation | Neutrino masses

Perturbations to GR

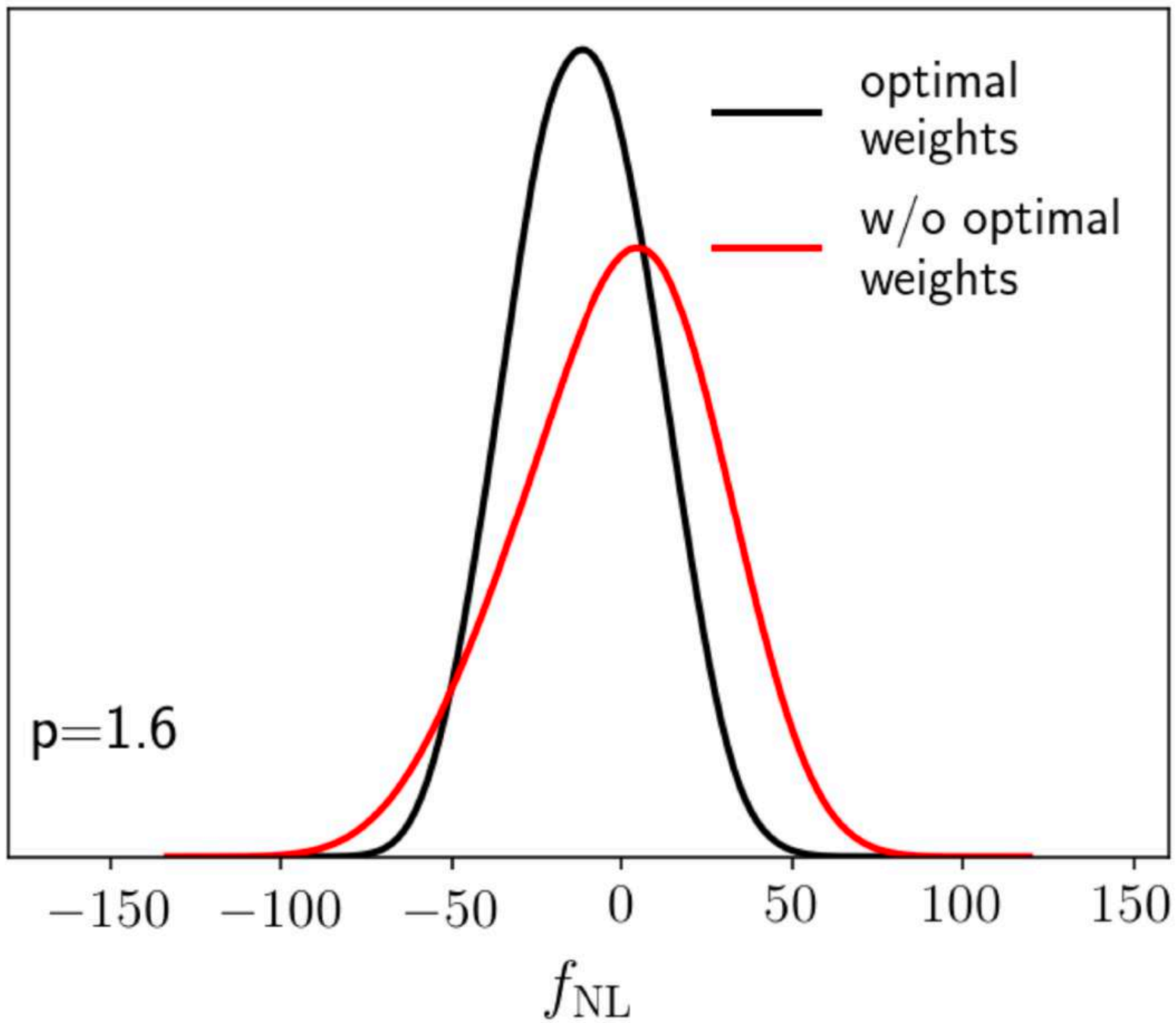


eBOSS Collaboration 2021

Latest constraints

Dark energy Alternate theories of gravity **Inflation** Neutrino masses

Non-Gaussianities



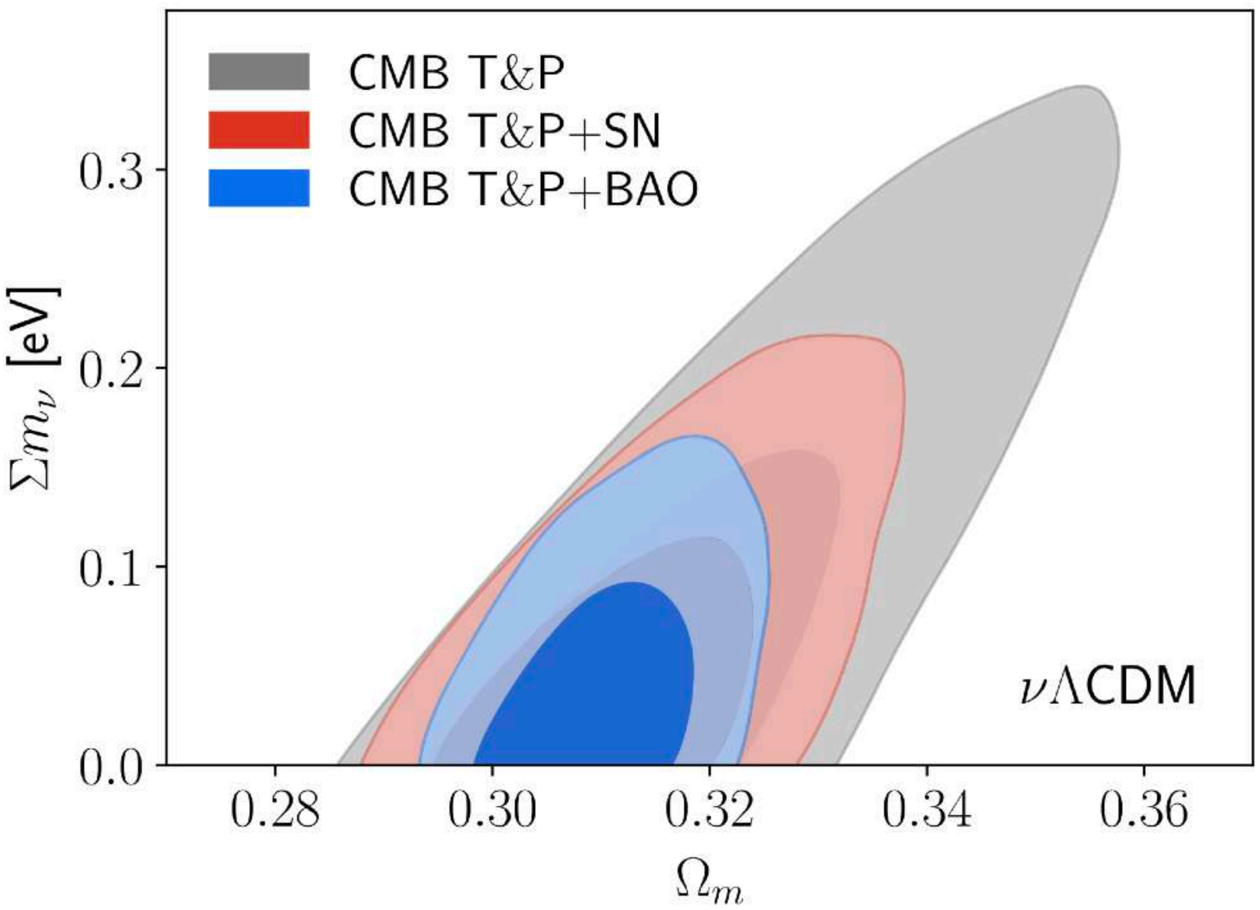
Mueller et al. 2022

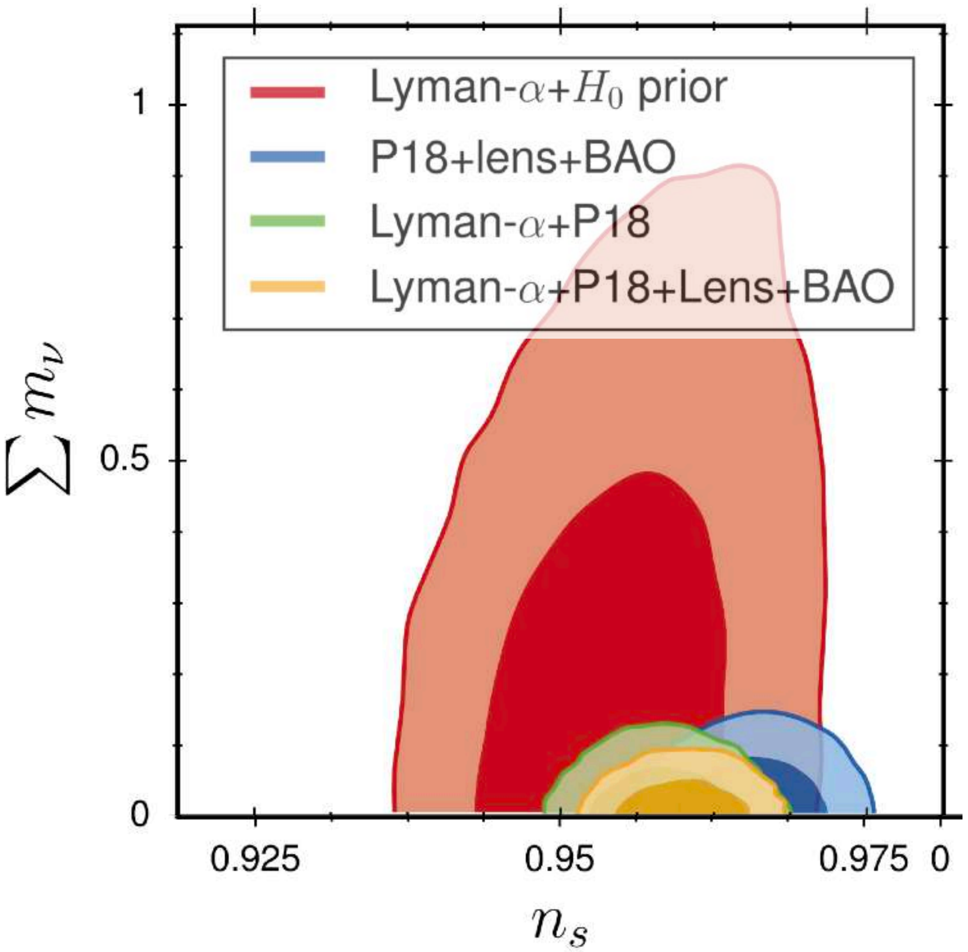
Latest constraints

Dark energy Alternate theories of gravity Inflation **Neutrino masses**

From background expansion

From clustering of Lyman-α forests





eBOSS Collaboration 2021

Palanque-Delabrouille et al 2020

Why clustering for cosmology ?

Dark energy

Alternate theories of gravity

Inflation

Neutrino masses

Dark matter

Clustering informs us about all these questions

The whole plan

The whole plan

γ_n ➡ $\left(\theta_i, \phi_i, z_i\right)$

$\left(\theta_i, \phi_i, z_i, \{f_j\}\right)$

The whole plan

$\gamma_n \Rightarrow$

$$\left(\theta_i, \phi_i, z_i\right)$$

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From photons to spectra

Obtain **redshifts** for **galaxies and quasars**

+

Measure **fluxes** in the **Lyman-α forests** of quasars

The whole plan

$$\gamma_n \Rightarrow \begin{matrix} (\theta_i, \phi_i, z_i) \\ \left(\theta_i, \phi_i, z_i, \{f_j\}\right) \end{matrix} \Rightarrow \begin{matrix} \delta_g(\vec{x}) \\ \delta_{\mathrm{Ly}\alpha}(\vec{x}) \end{matrix} \Rightarrow \langle \delta\delta' \rangle$$

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From spectra to clustering

Compute contrast of

galaxy, quasar densities or **Lyman-α fluxes**

+

Compute 2-point statistics

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From clustering to cosmology

Fit models for BAO, RSD (observables)
+
Fit for dark energy or alternative gravity models

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From photons to spectra

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Compute contrast of

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Compute 2-point statistics

From clustering to cosmology

Fit models for BAO, RSD (observables)

+

Fit for dark energy or alternative gravity models

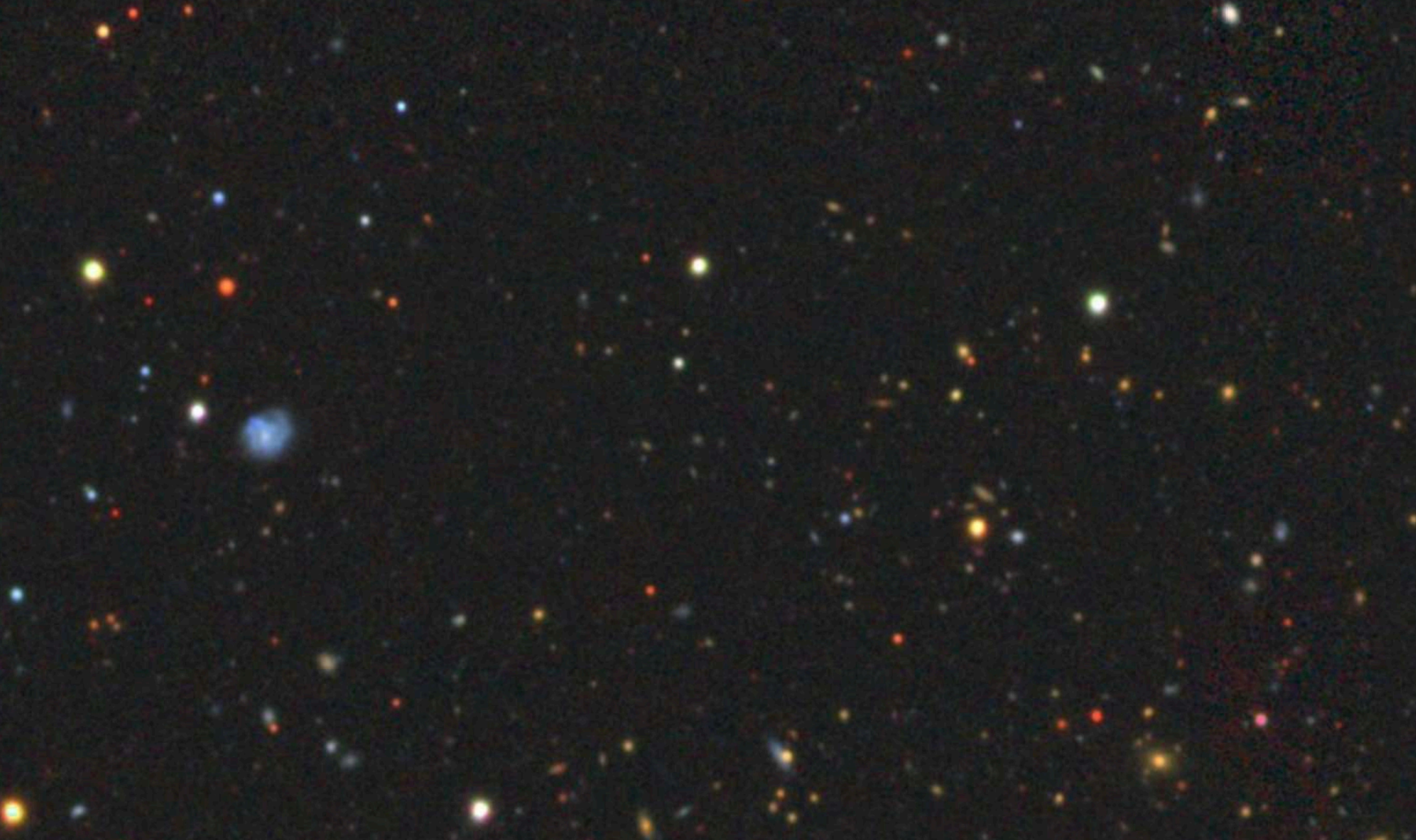
Each step is equally important for cosmology

From photons to spectra and redshifts

$$\gamma_n \rightarrow \begin{matrix} (\theta_i, \phi_i, z_i) \\ \left(\theta_i, \phi_i, z_i, \{f_j\}\right) \end{matrix}$$

A small portion of our sky

as seen by Legacy Survey

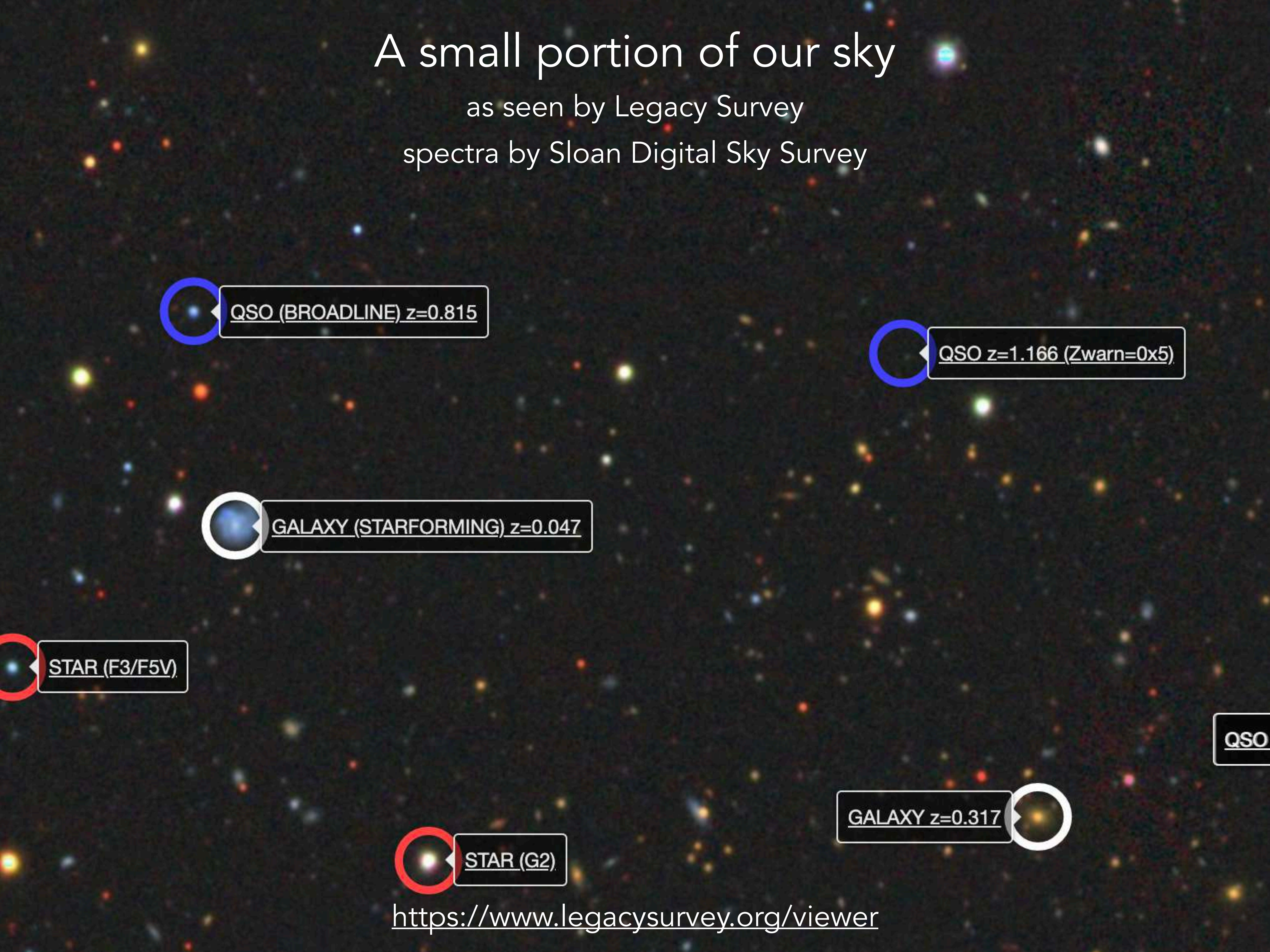


https://www.legacysurvey.org/viewer

A small portion of our sky

as seen by Legacy Survey

spectra by Sloan Digital Sky Survey



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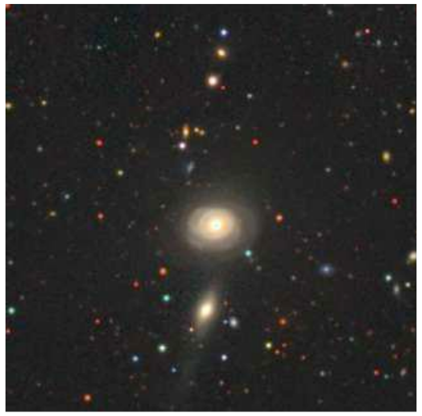
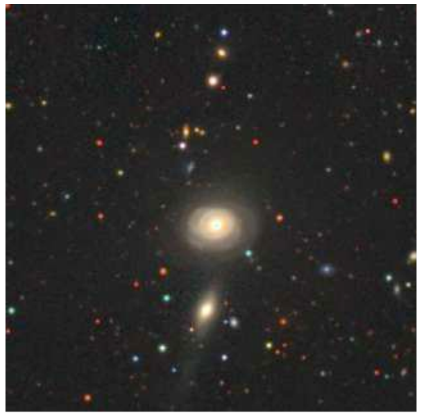
Methods of observing

Photometry



Spectroscopy



Methods of observing

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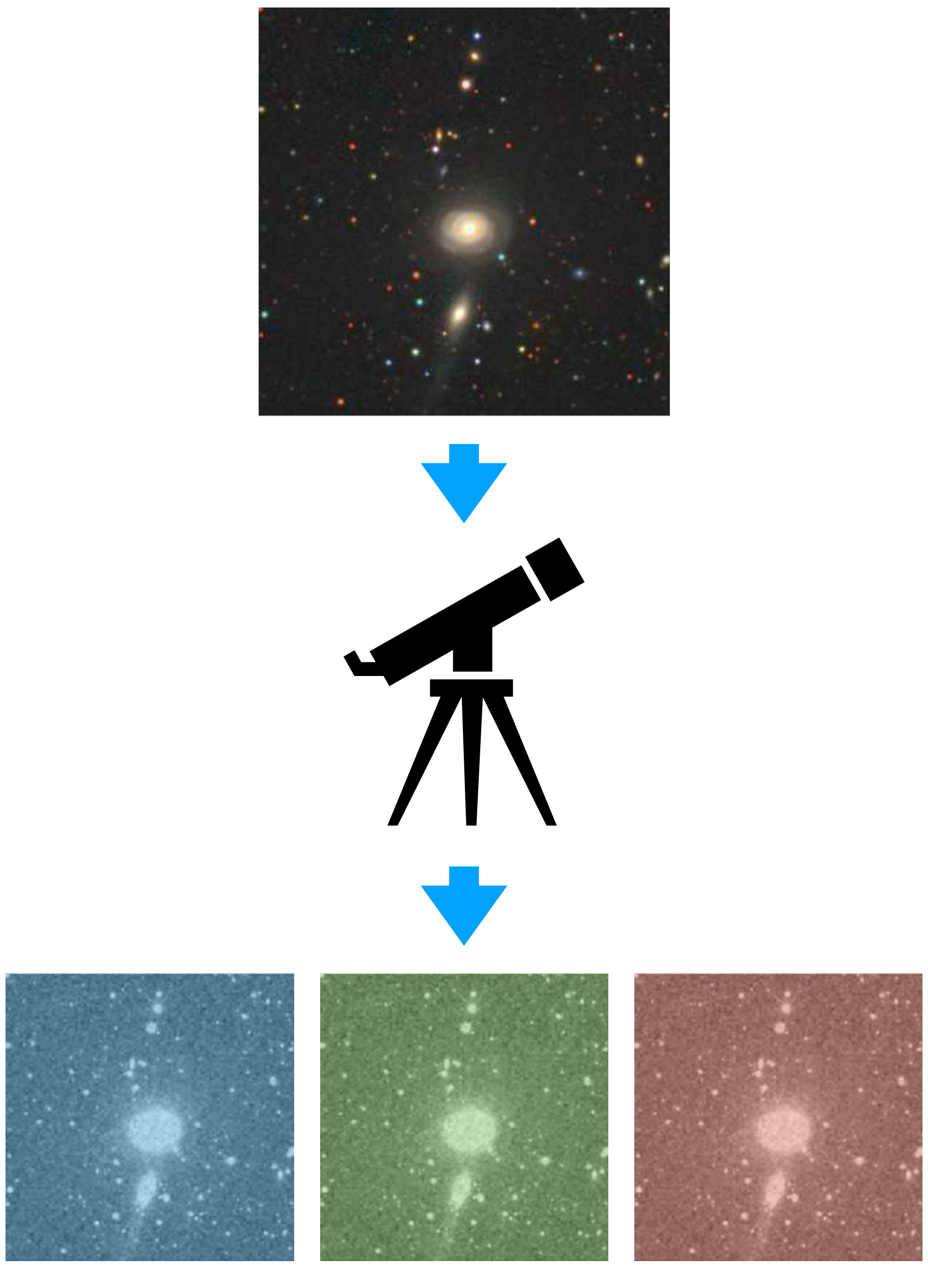

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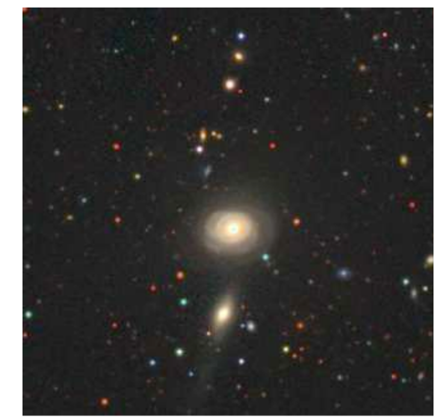

Methods of observing

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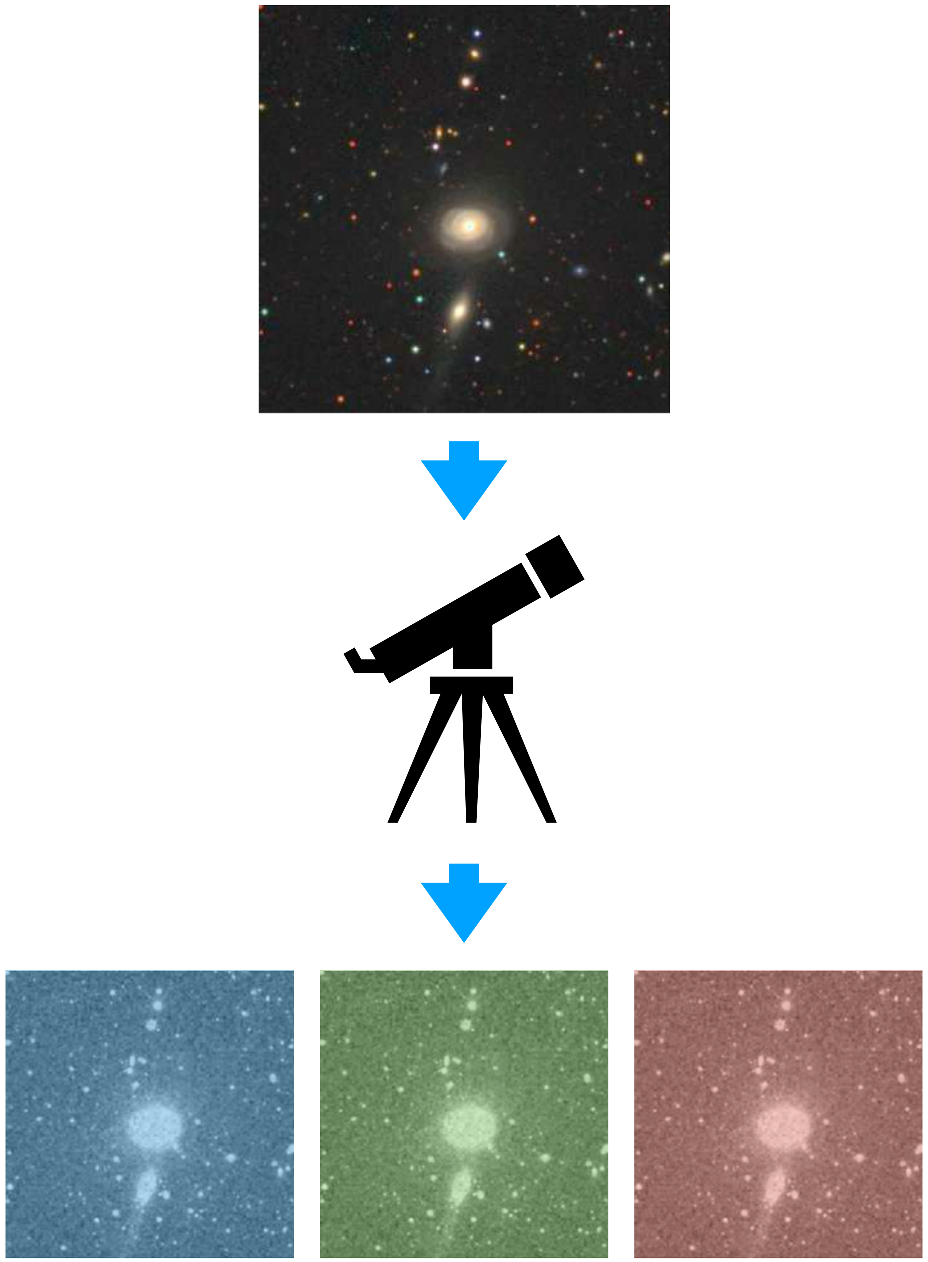
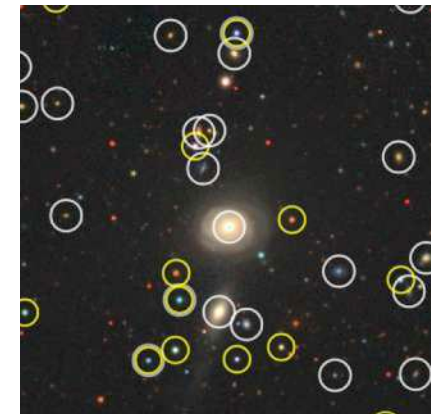


Spectroscopy



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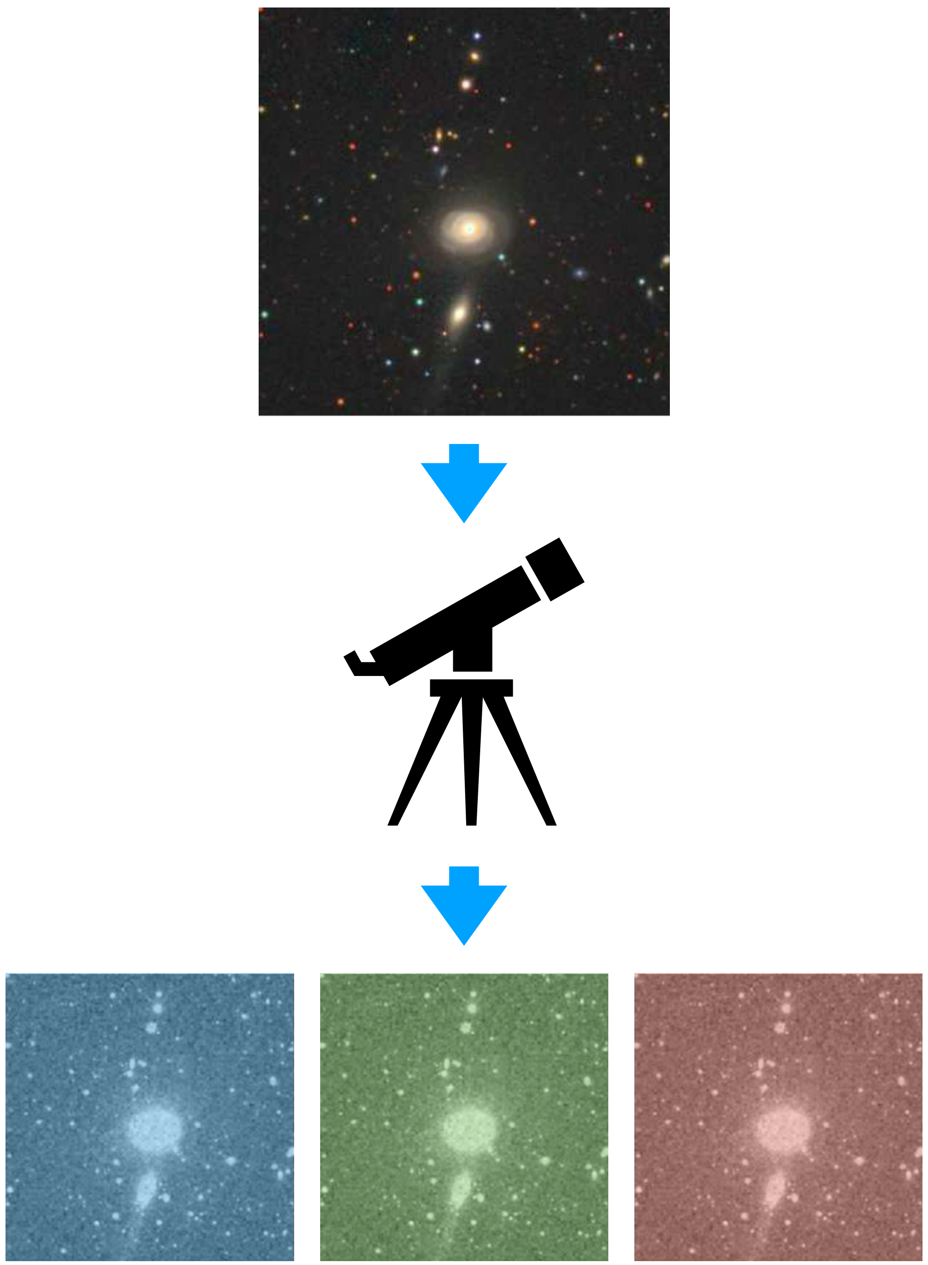

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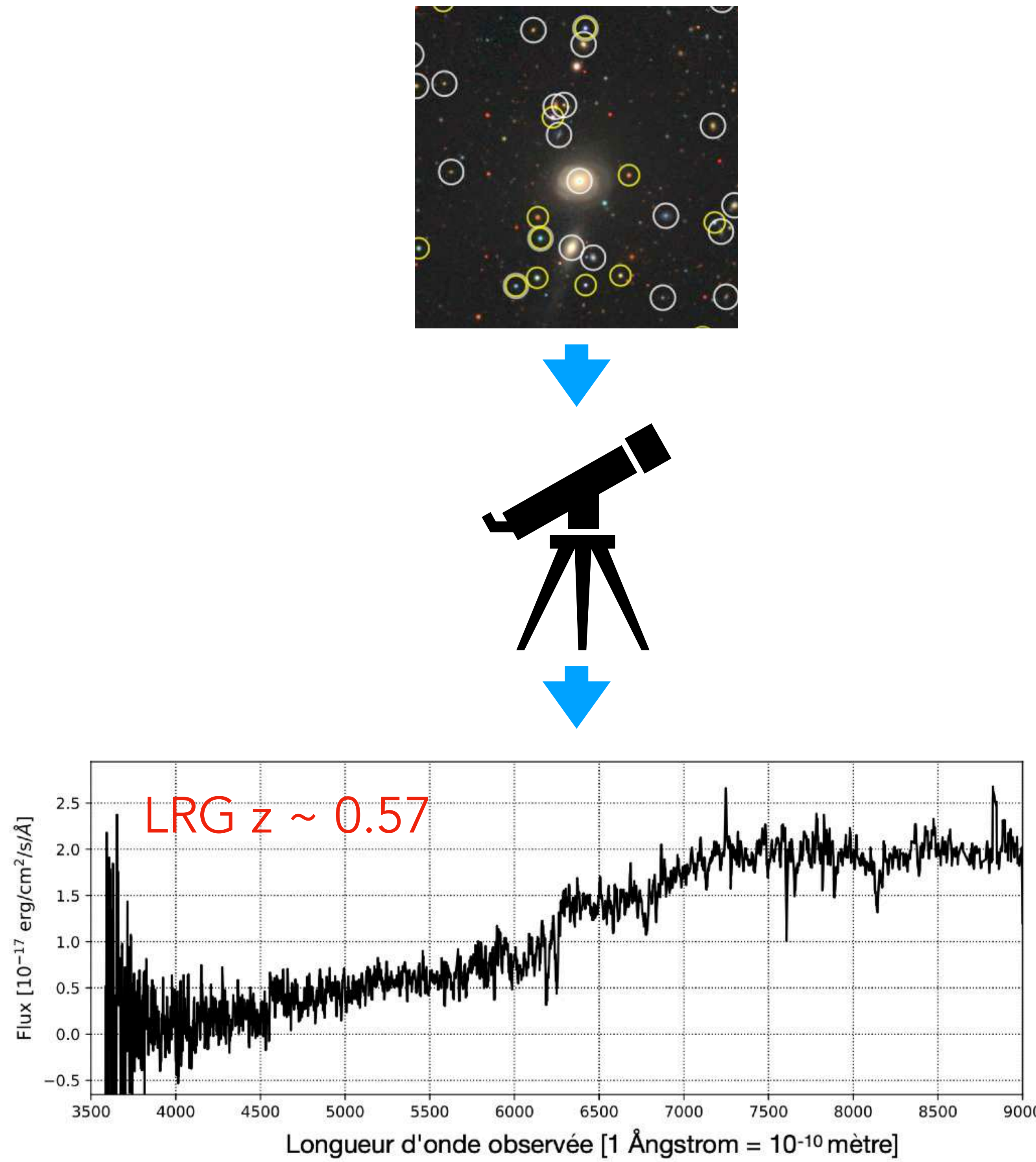
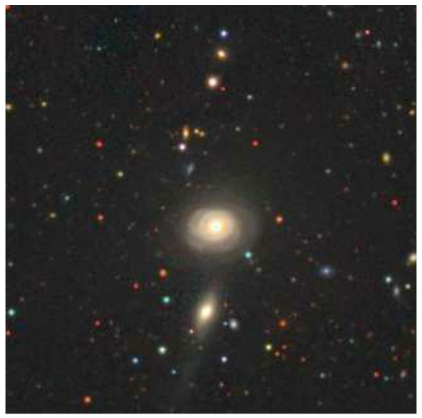
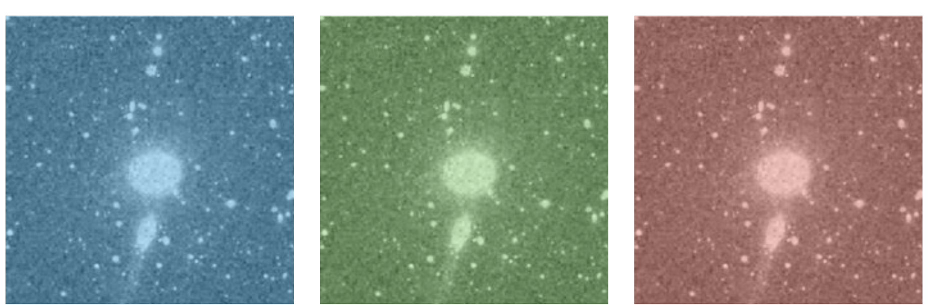


Methods of observing

Photometry





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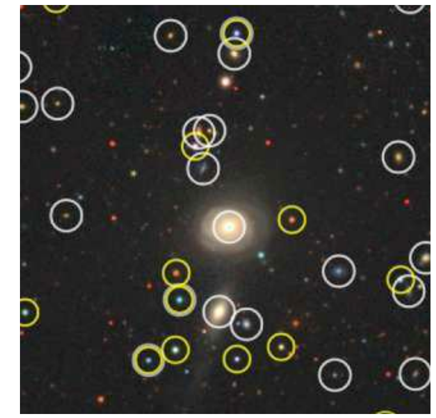
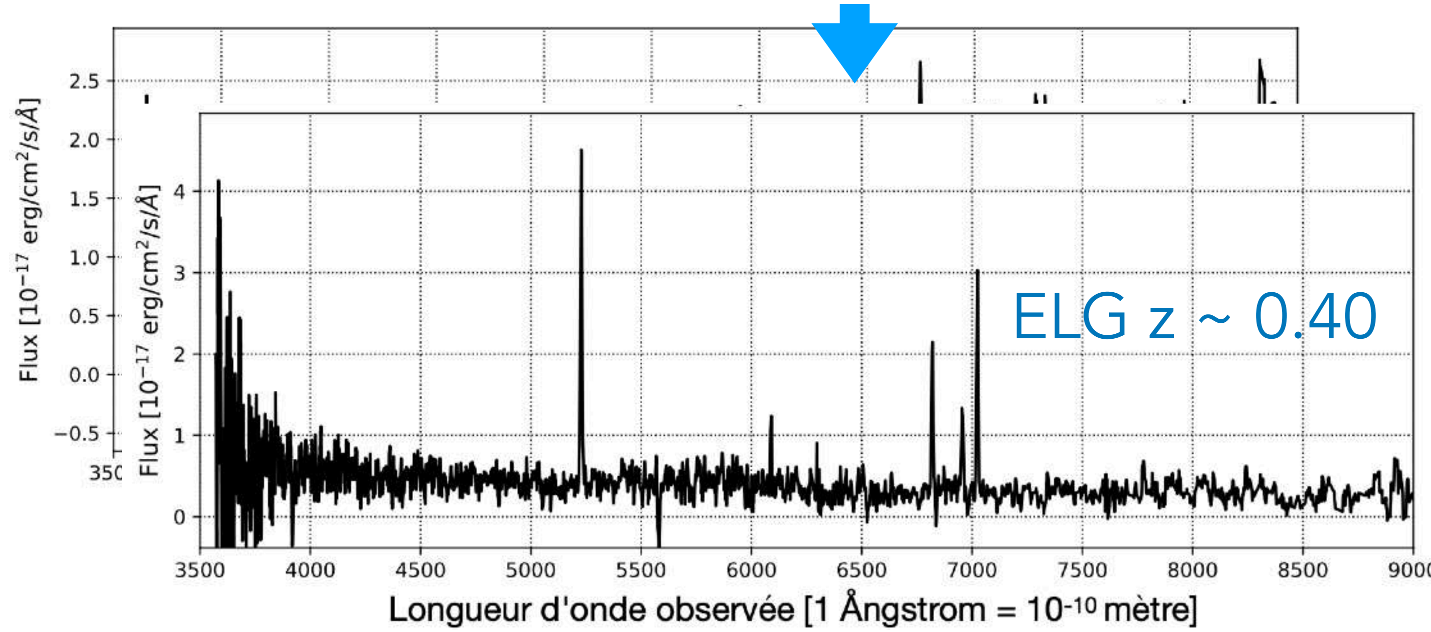
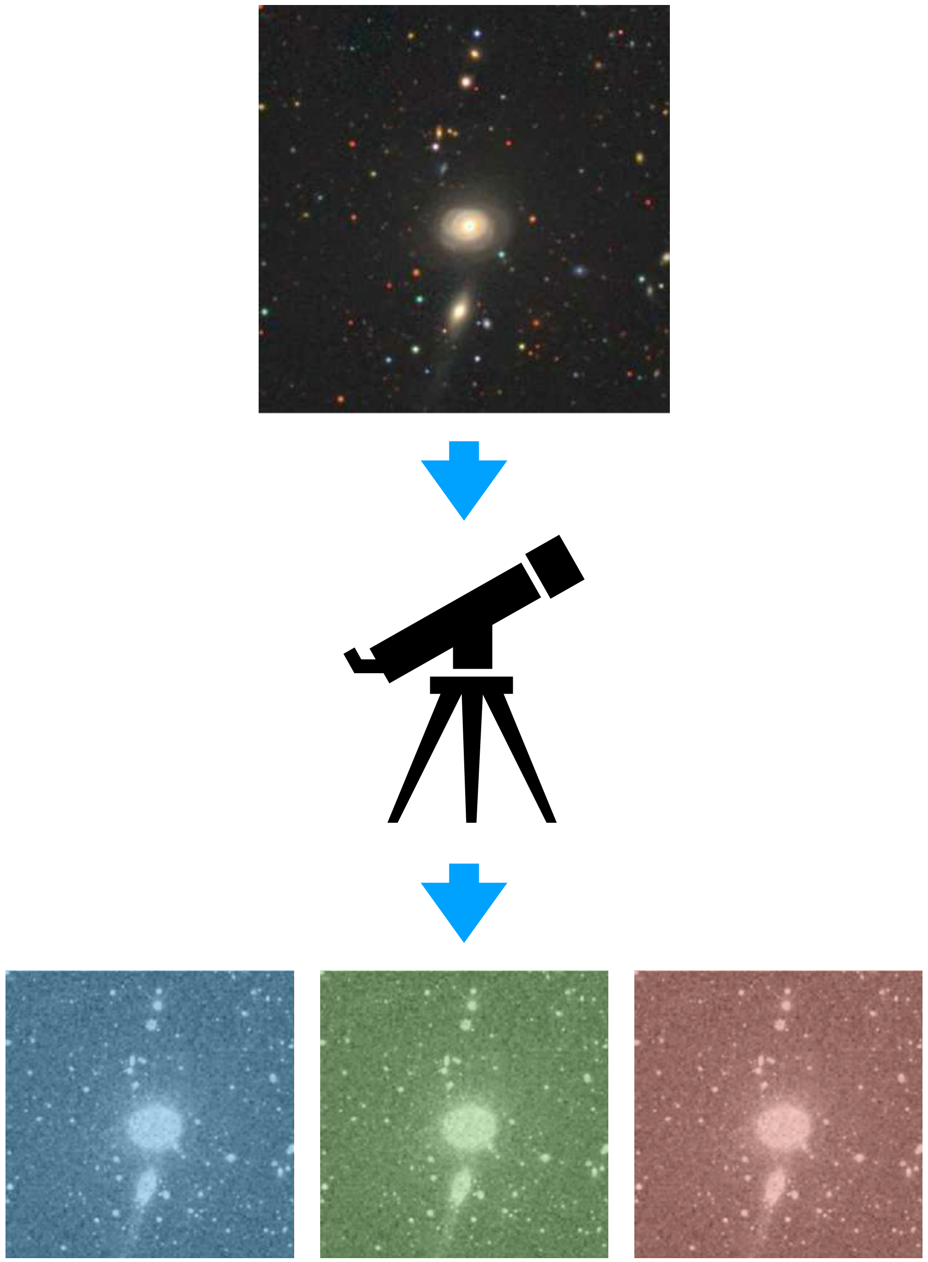




Methods of observing

Photometry



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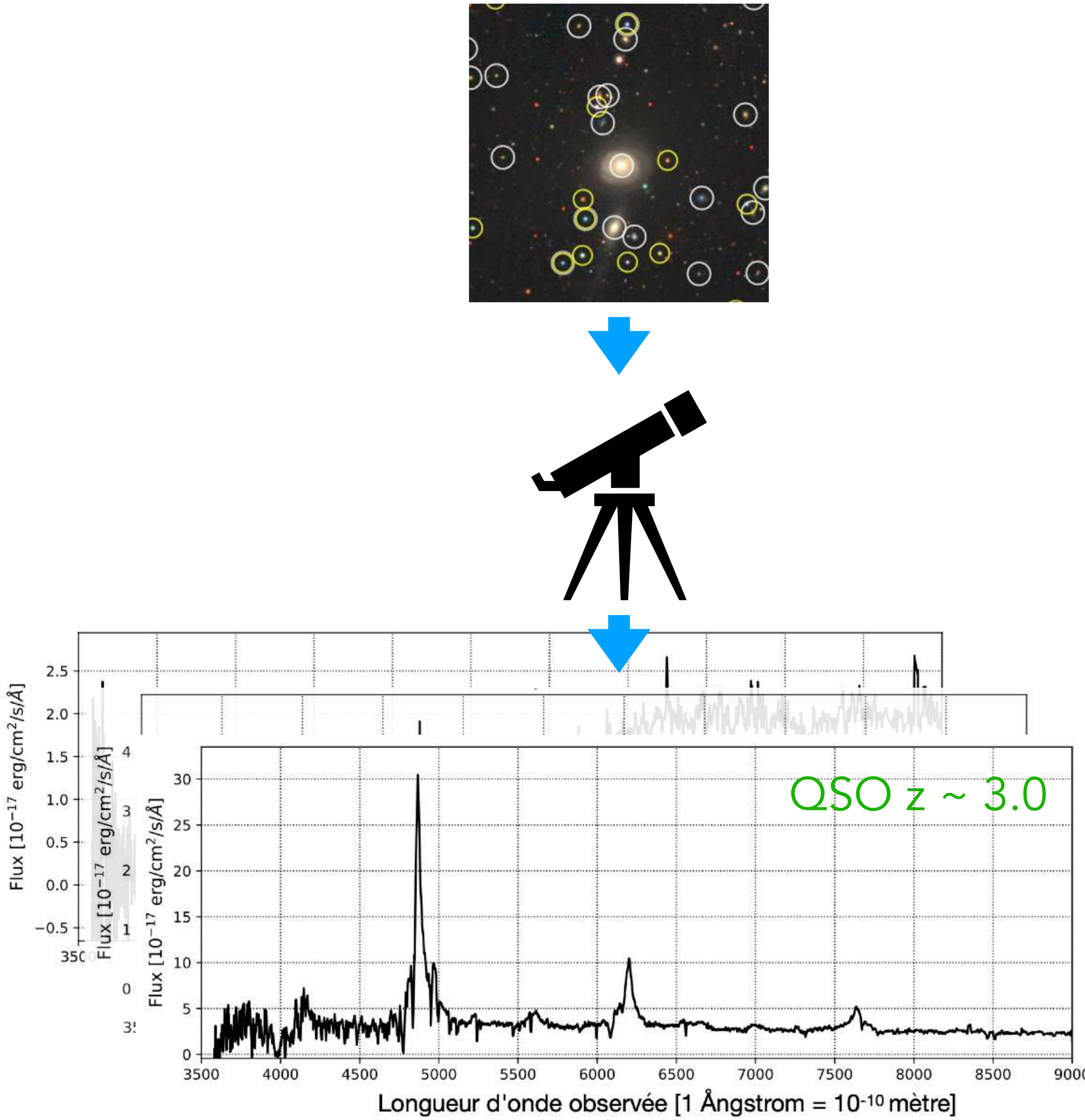

Methods of observing

Photometry

Spectroscopy

Main differences ?

Implications for cosmology ?

Discuss !

Methods of observing

Photometry

- angular information → (θ_i, ϕ_i)
- integrated fluxes over few bands
- rough spectral information
- higher signal-to-noise
- many more detected objects
- no prior selection required
- ... ?

Spectroscopy

- 1D flux information → f_j
- precise radial information → z_i
- higher spectral resolution
- lower signal-to-noise
- requires long exposure times
- requires prior selection of targets (if not slitless)
- fewer objects measured
- .... ?

Methods of observing

Photometry

- angular information → (θ_i, ϕ_i)
- integrated fluxes over few bands
- rough spectral information
- higher signal-to-noise
- many more detected objects
- no prior selection required
- ... ?

Less selection effects (SNIa)
Great for galaxy shapes (WL)
Cluster characterisation and counts
...

Spectroscopy

- 1D flux information → f_j
- precise radial information → z_i
- higher spectral resolution
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- requires long exposure times
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- fewer objects measured
- .... ?

Better redshifts for clustering (BAO, RSD)
Better physical characterisation of galaxies/stars

How to make a spectroscopic survey?

boldface for the slit-less case

How to make a spectroscopic survey?

boldface for the slit-less case

1 - make a photometric survey

2 - decide the sky coverage for spectroscopy

3 - select targets using magnitudes and colors

4 - define observing strategy for spectroscopy

5 - test and validate

a - instruments

b - data reduction pipeline

c - target selection

6 - measure redshifts

7 - analyse data

8 - publish results

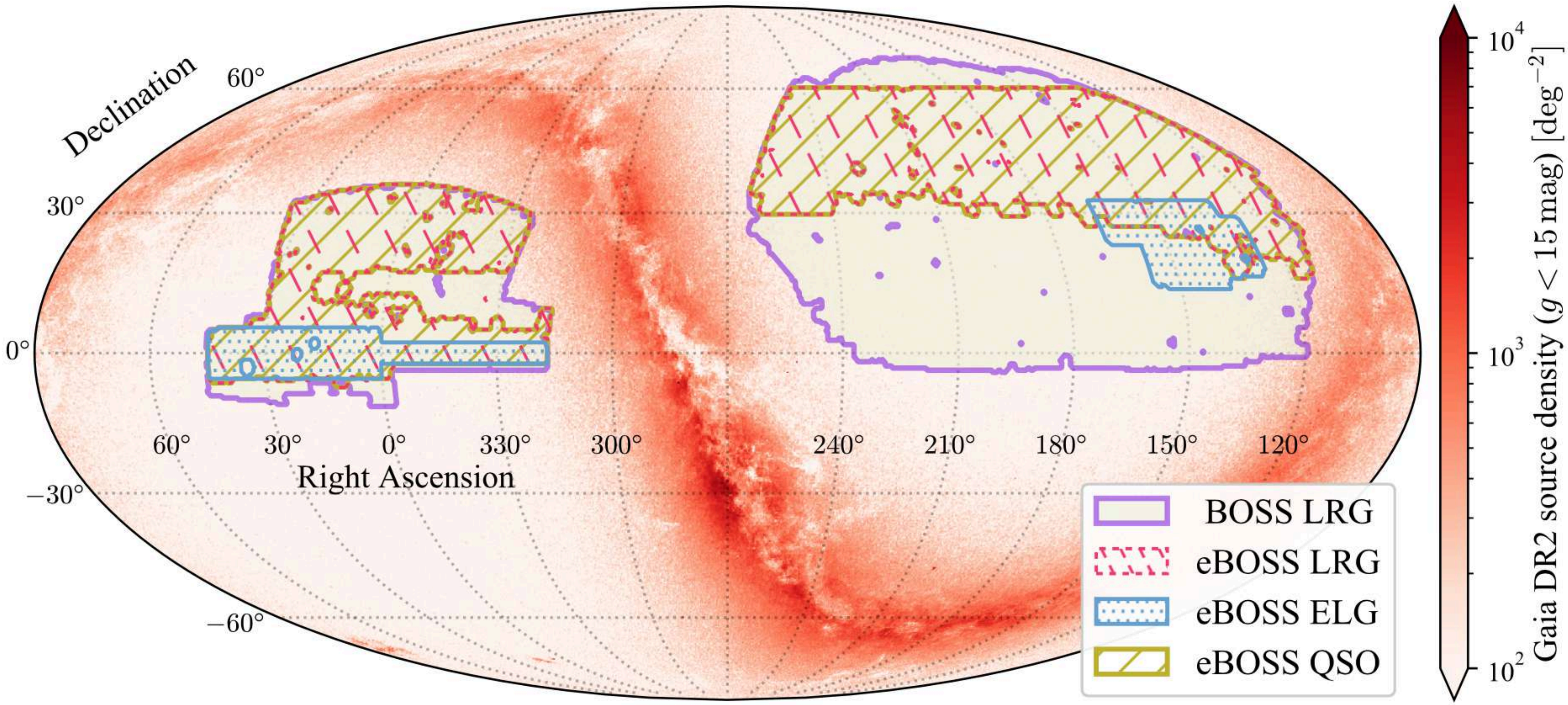
9 - ...

10 - profit !

From photons to spectra

2 - Sky coverage

BOSS and eBOSS surveys



BOSS overview - Dawson et al. 2013

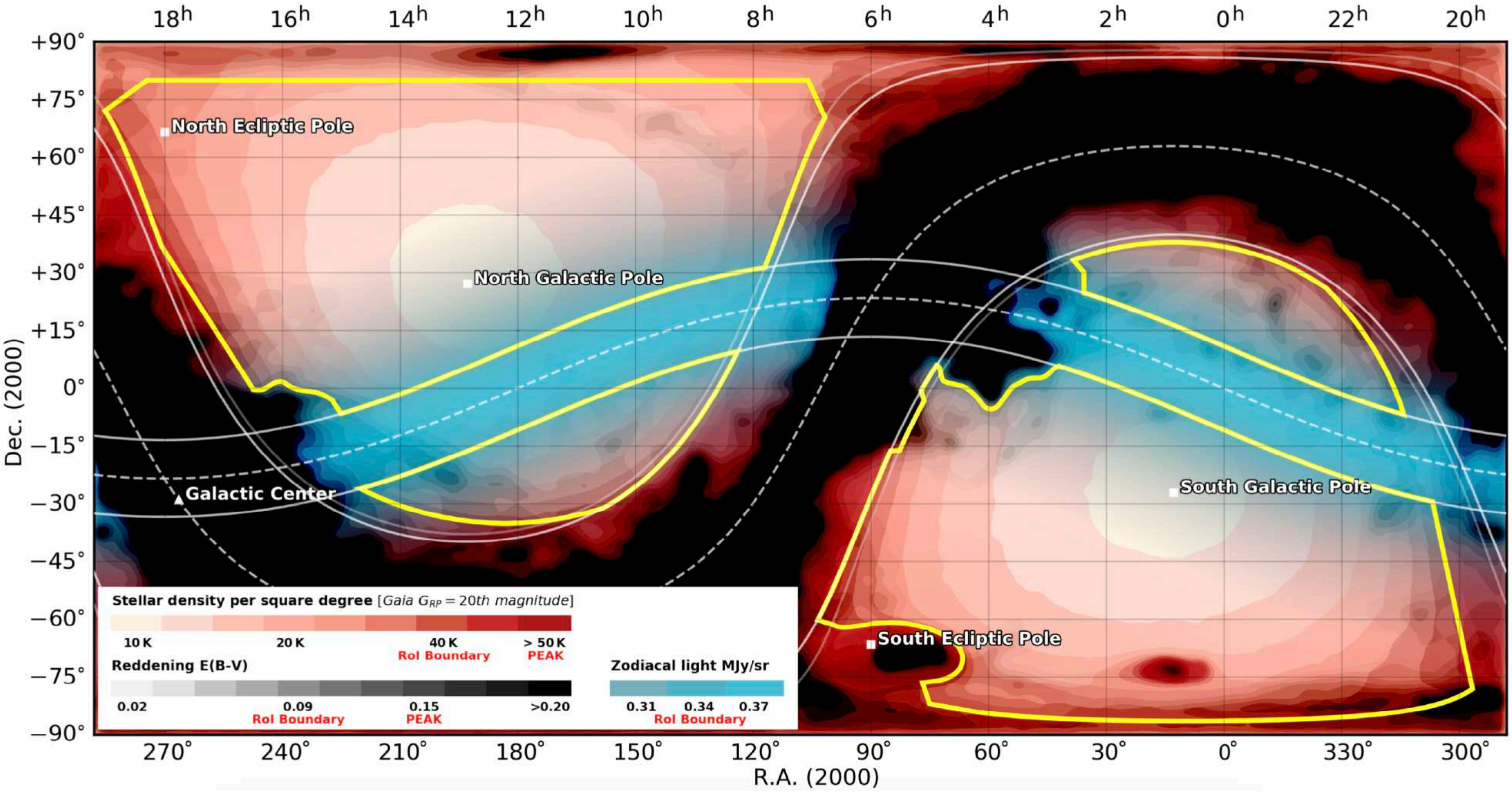
eBOSS overview - Dawson et al. 2016

Plot from Zhao et al. 2021

From photons to spectra

2 - Sky coverage

Euclid Wide Survey

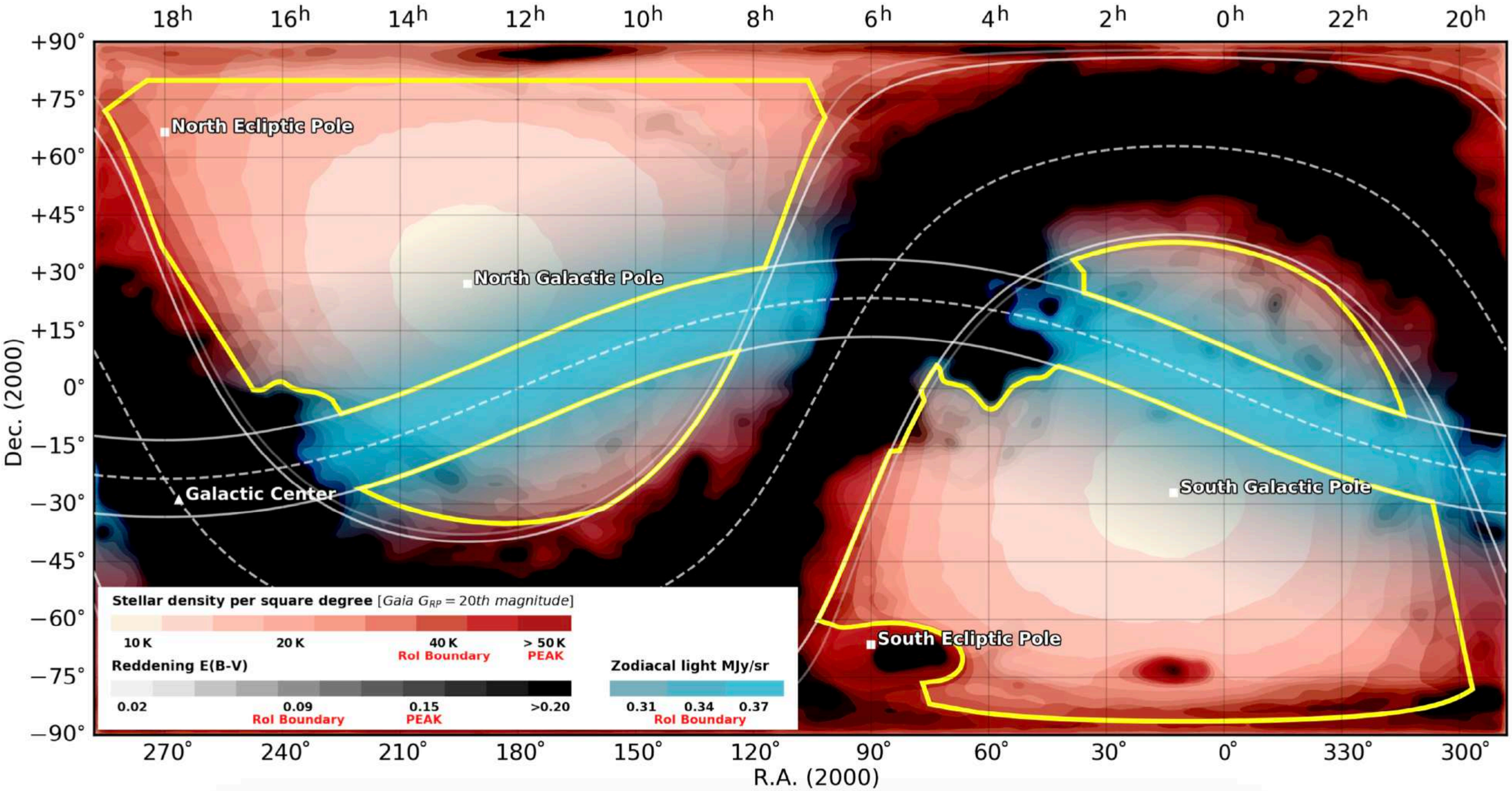


Euclid Preparation I - Euclid Collaboration 2022

From photons to spectra

2 - Sky coverage

Euclid Wide Survey



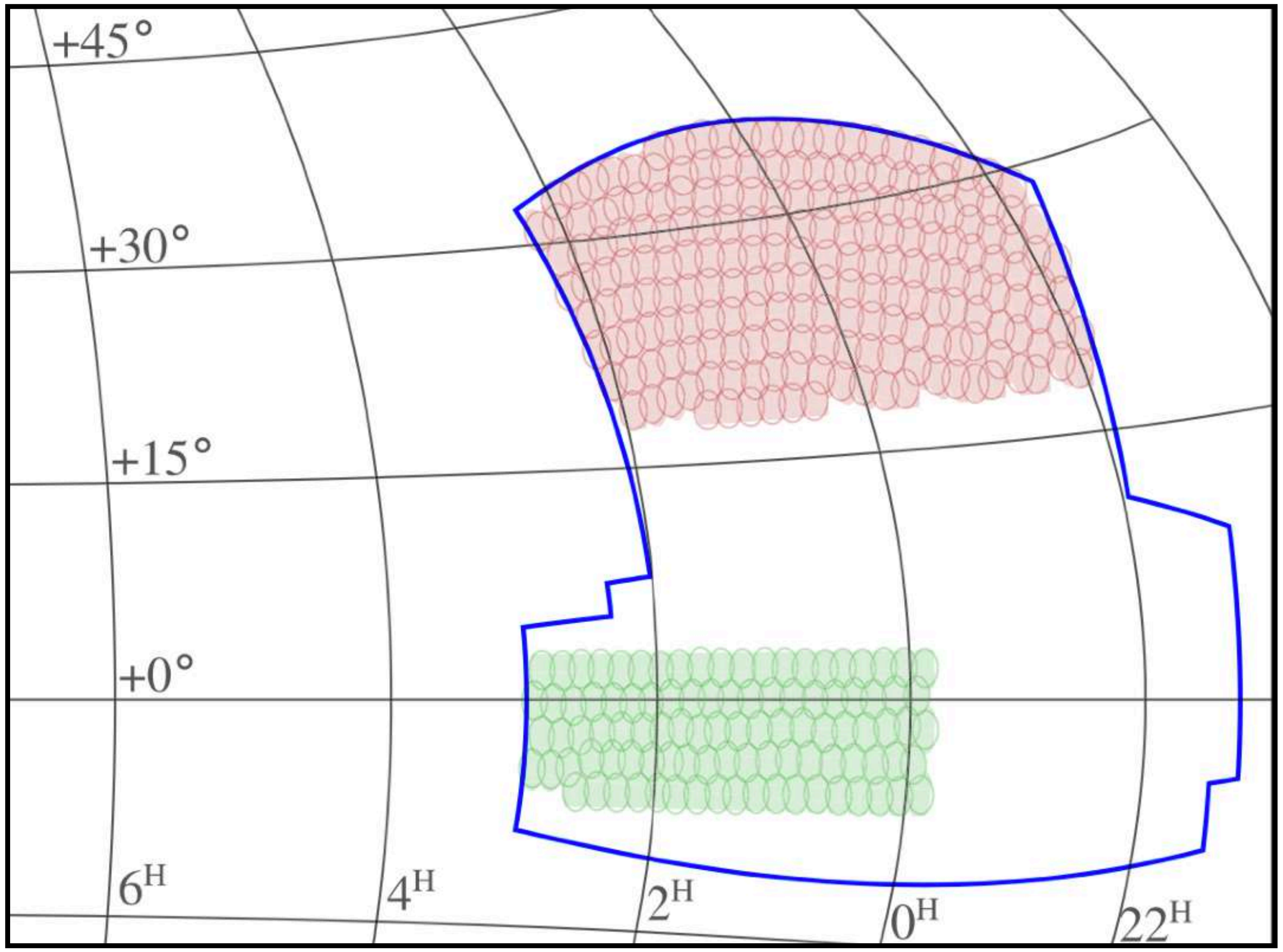
Euclid Preparation I - Euclid Collaboration 2022

The sky coverage defines the selection/window function of the survey
Important for clustering !

From photons to spectra

4 - Observing strategy

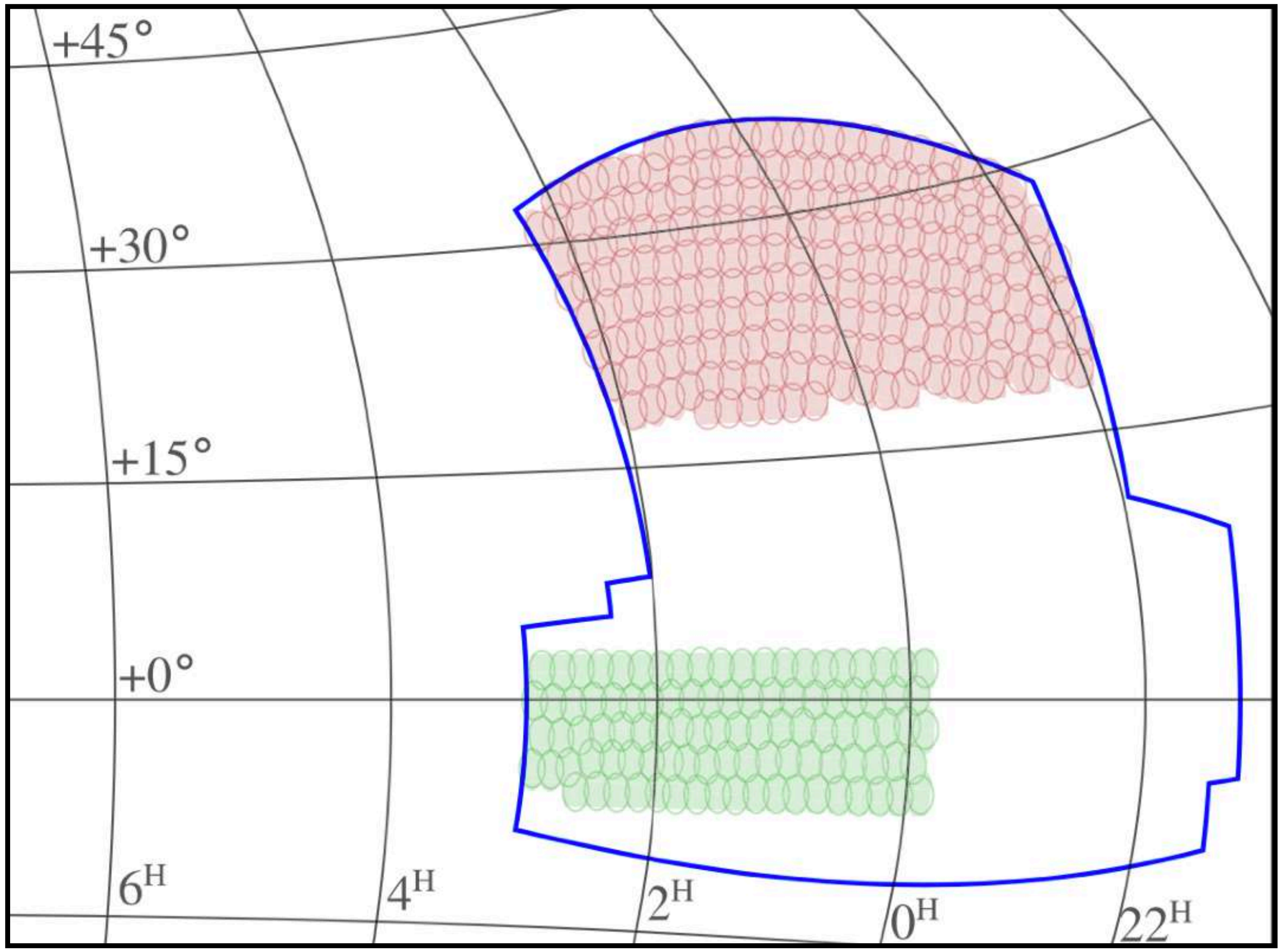
eBOSS tiling



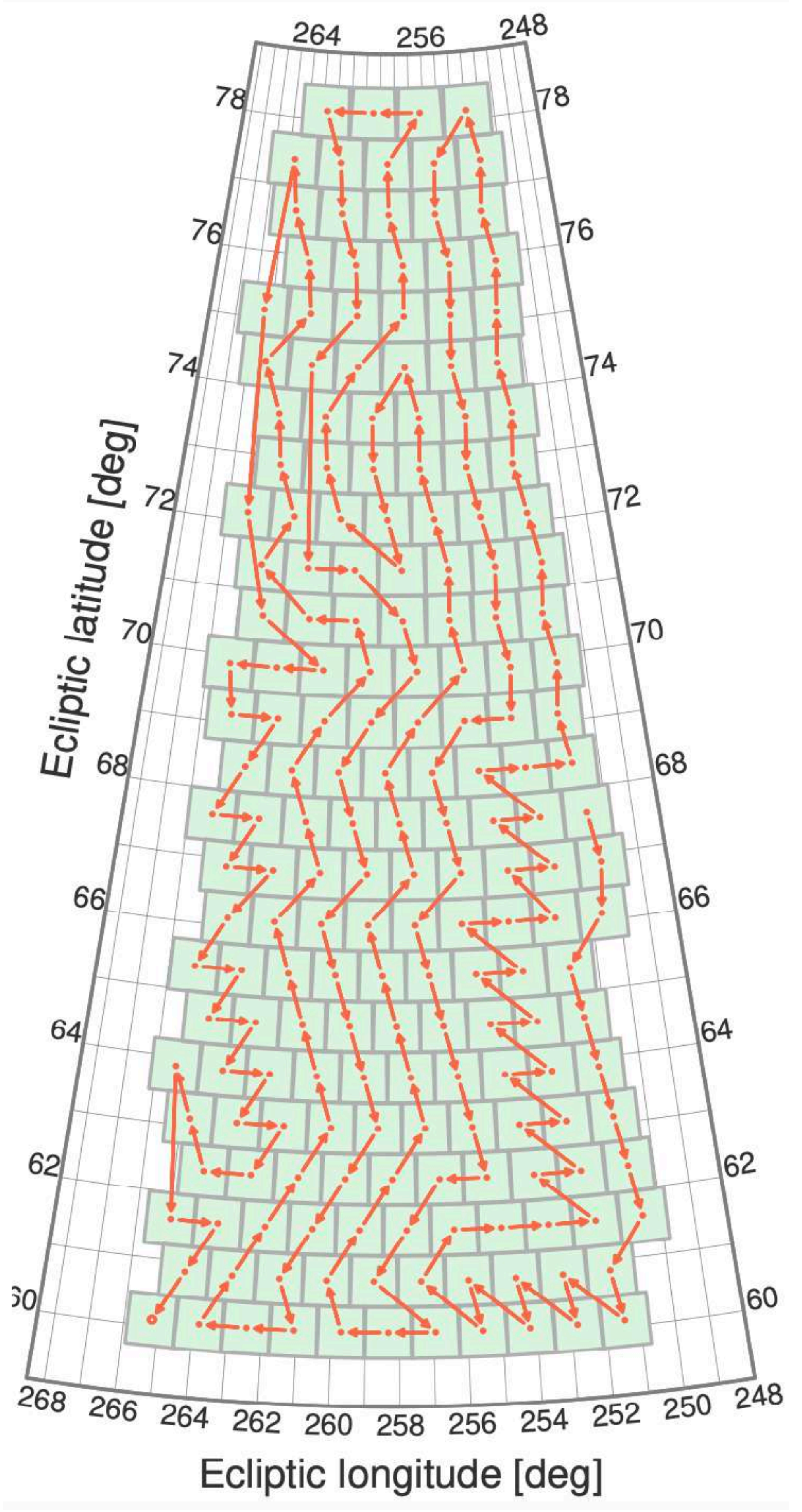
From photons to spectra

4 - Observing strategy

eBOSS tiling



Euclid scan strategy



From photons to spectra

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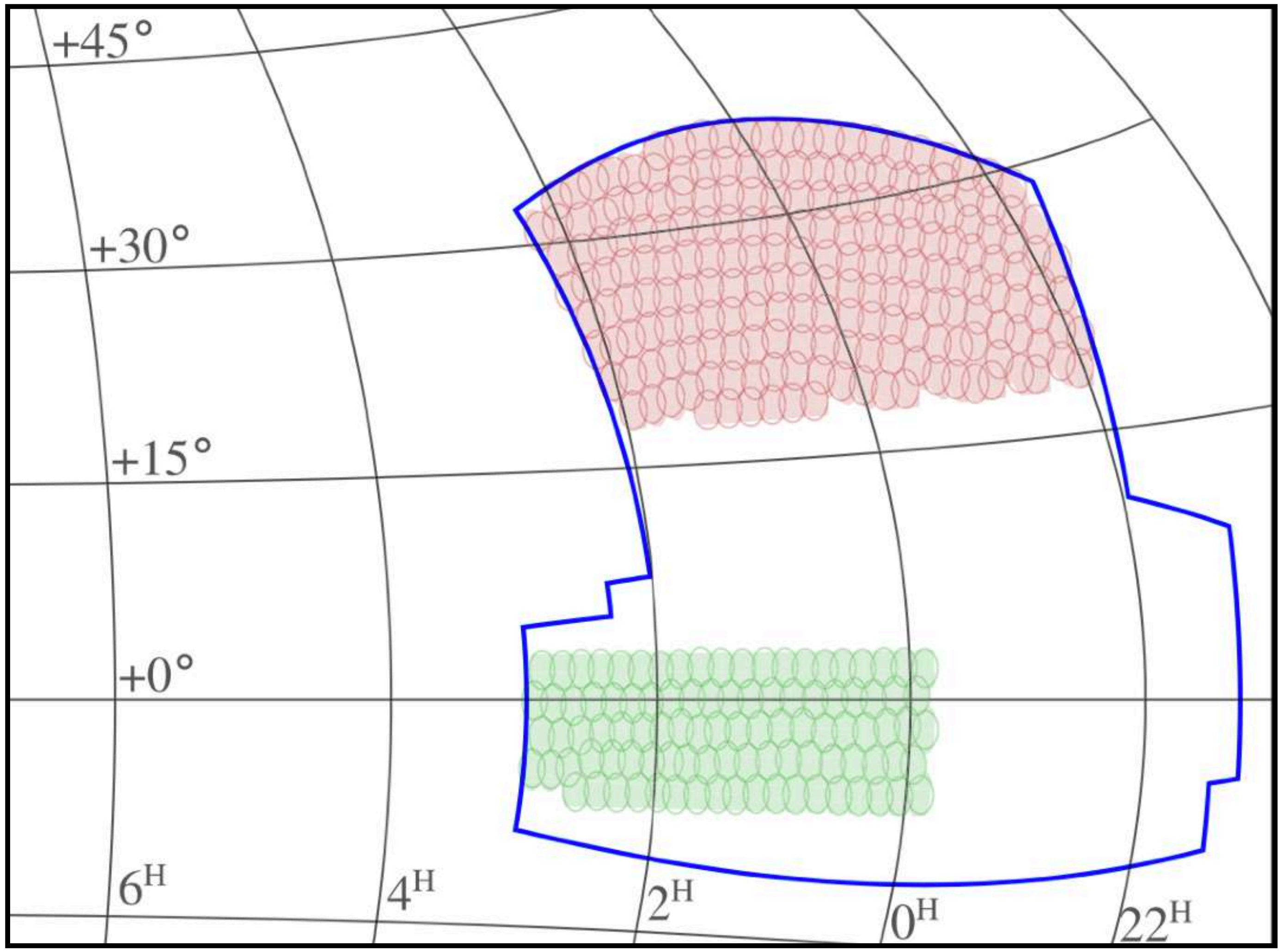
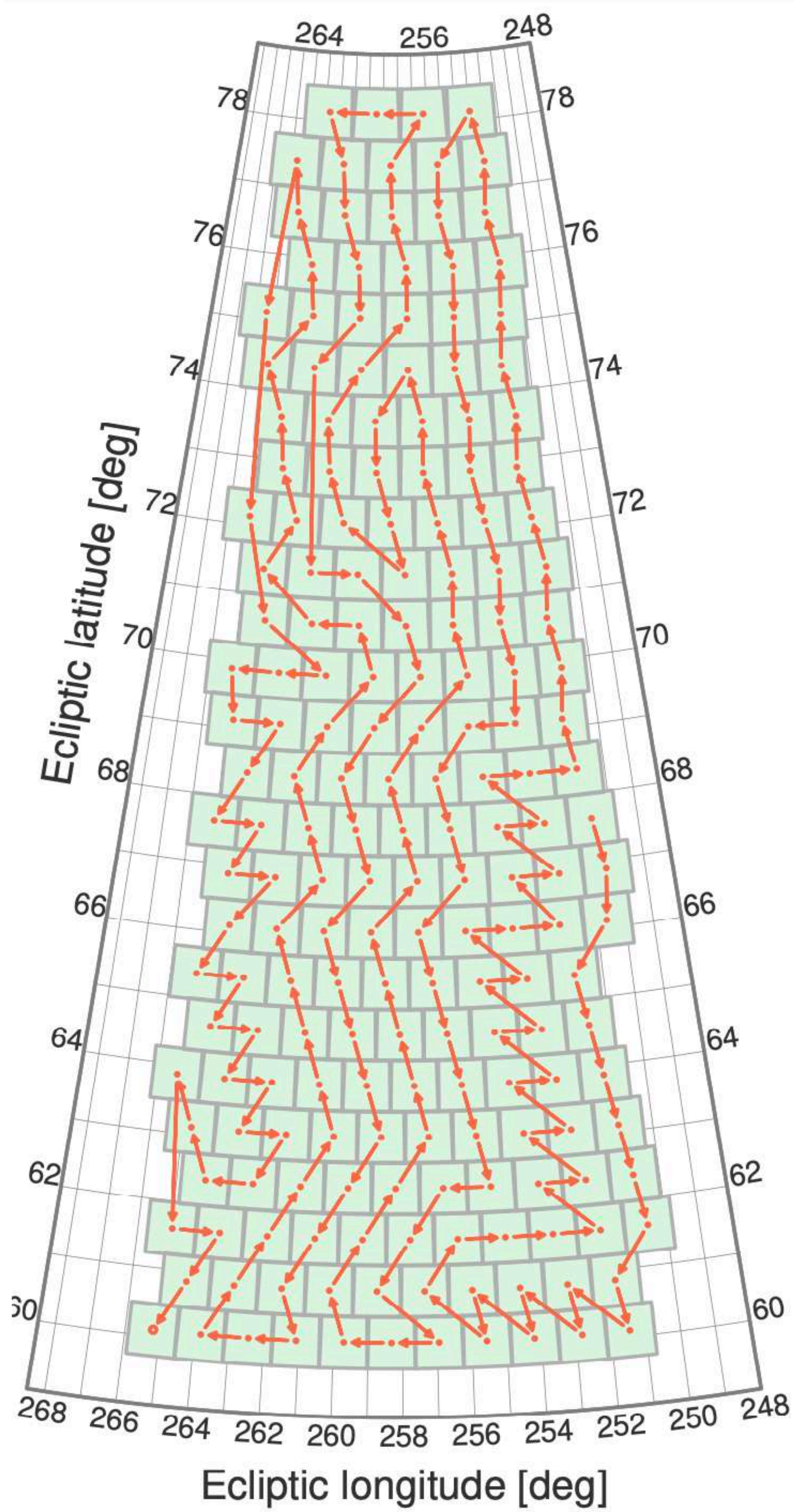


Scanning strategy depends on :

- time of the year, time of the day
- moon brightness
- weather
- location of telescope
- etc...

Euclid scan strategy



From photons to spectra

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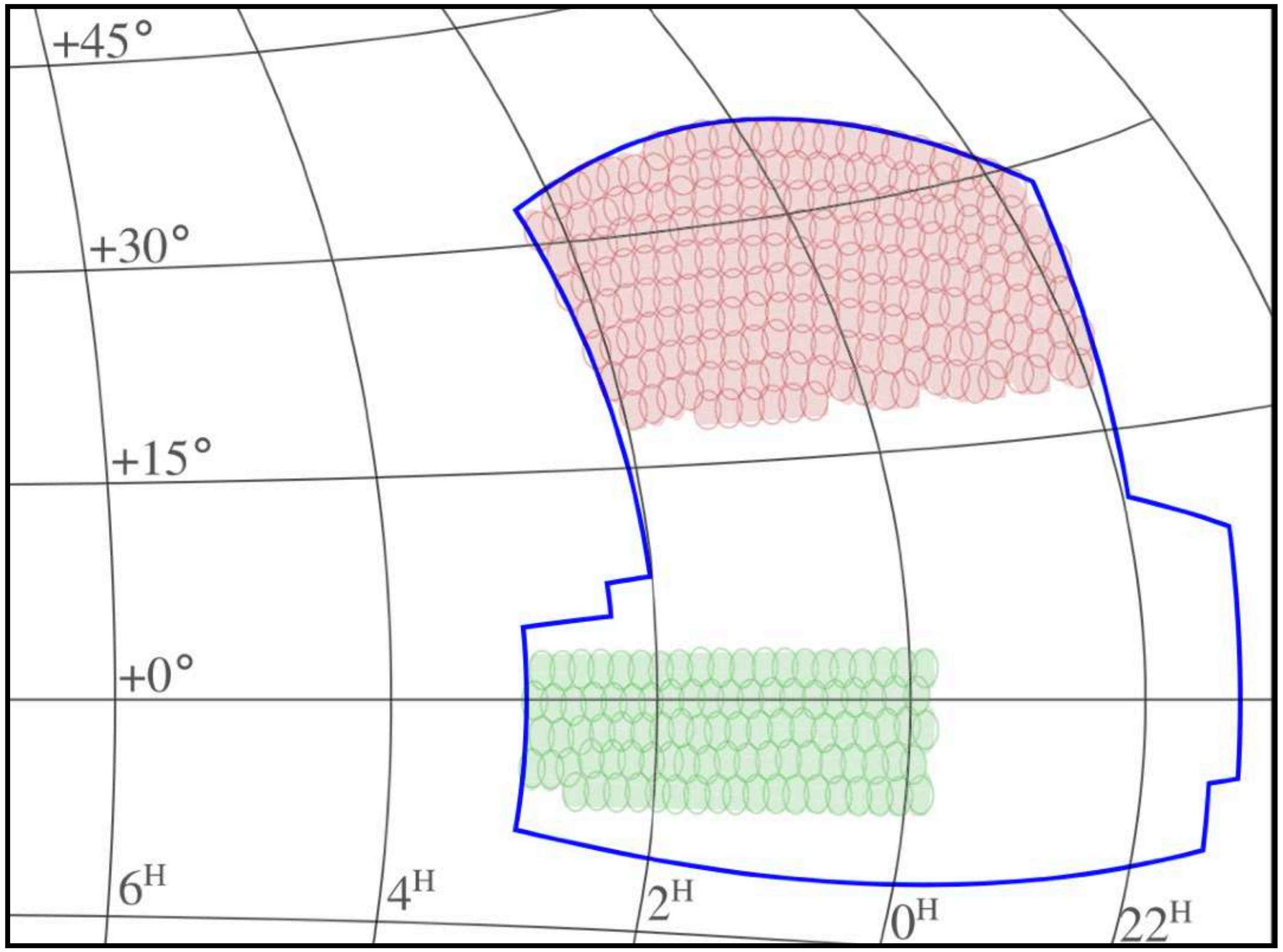

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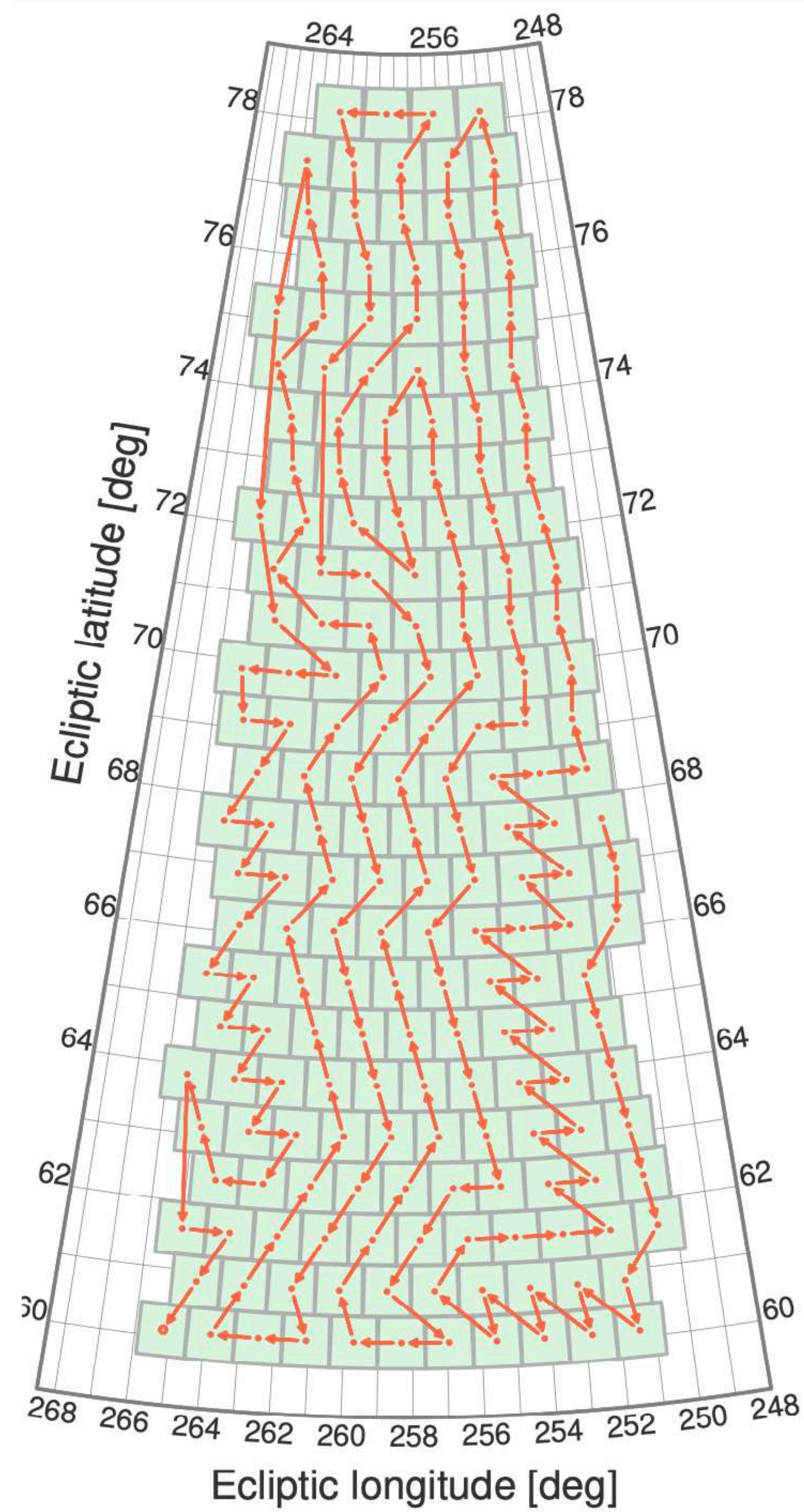

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Strategy directly impacts cosmological constraints

From photons to spectra

5b - Spectroscopic data reduction

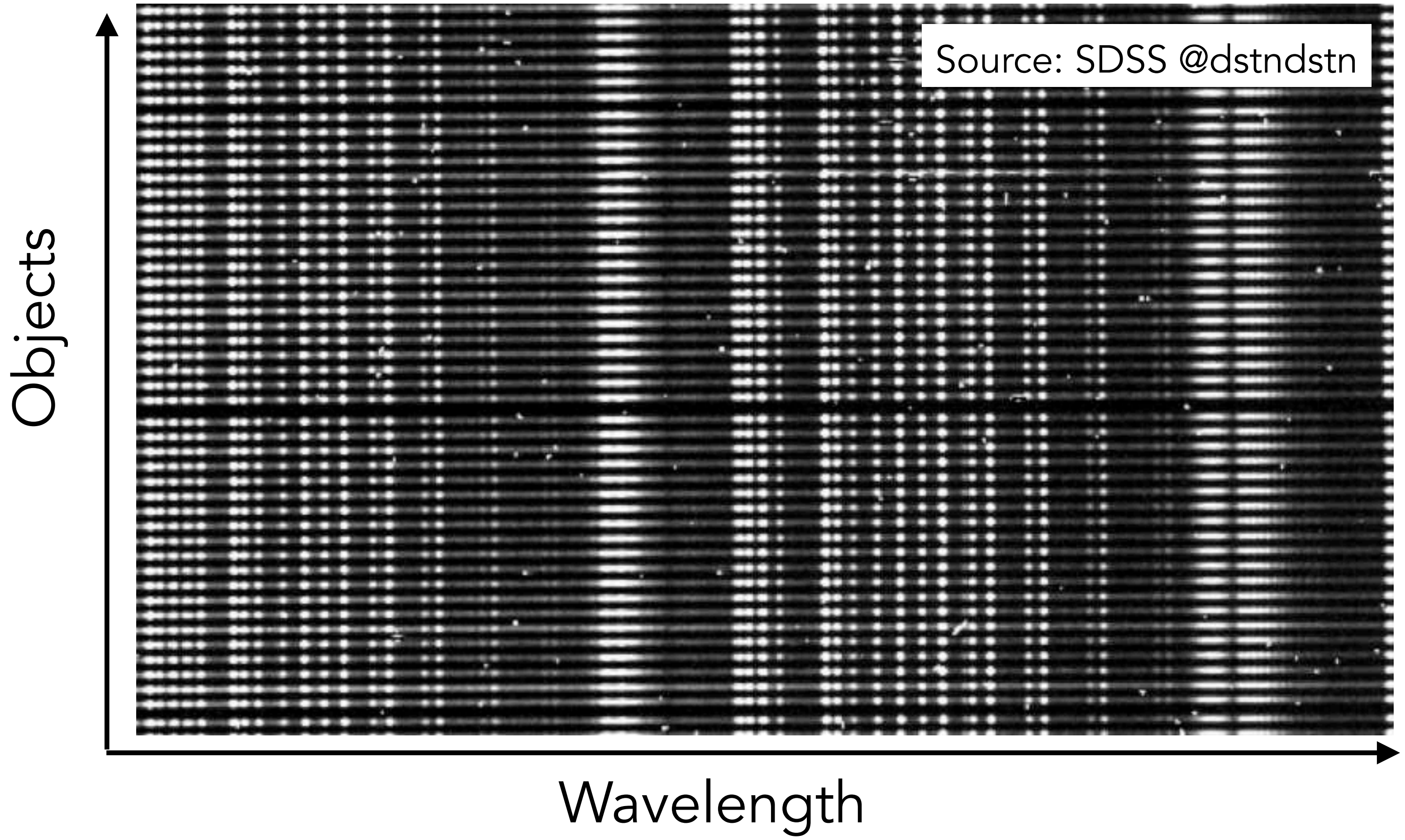
Raw image

From photons to spectra

5b - Spectroscopic data reduction

Raw image

Multi-object fiber based case (SDSS or DESI-like)



From photons to spectra

5b - Spectroscopic data reduction

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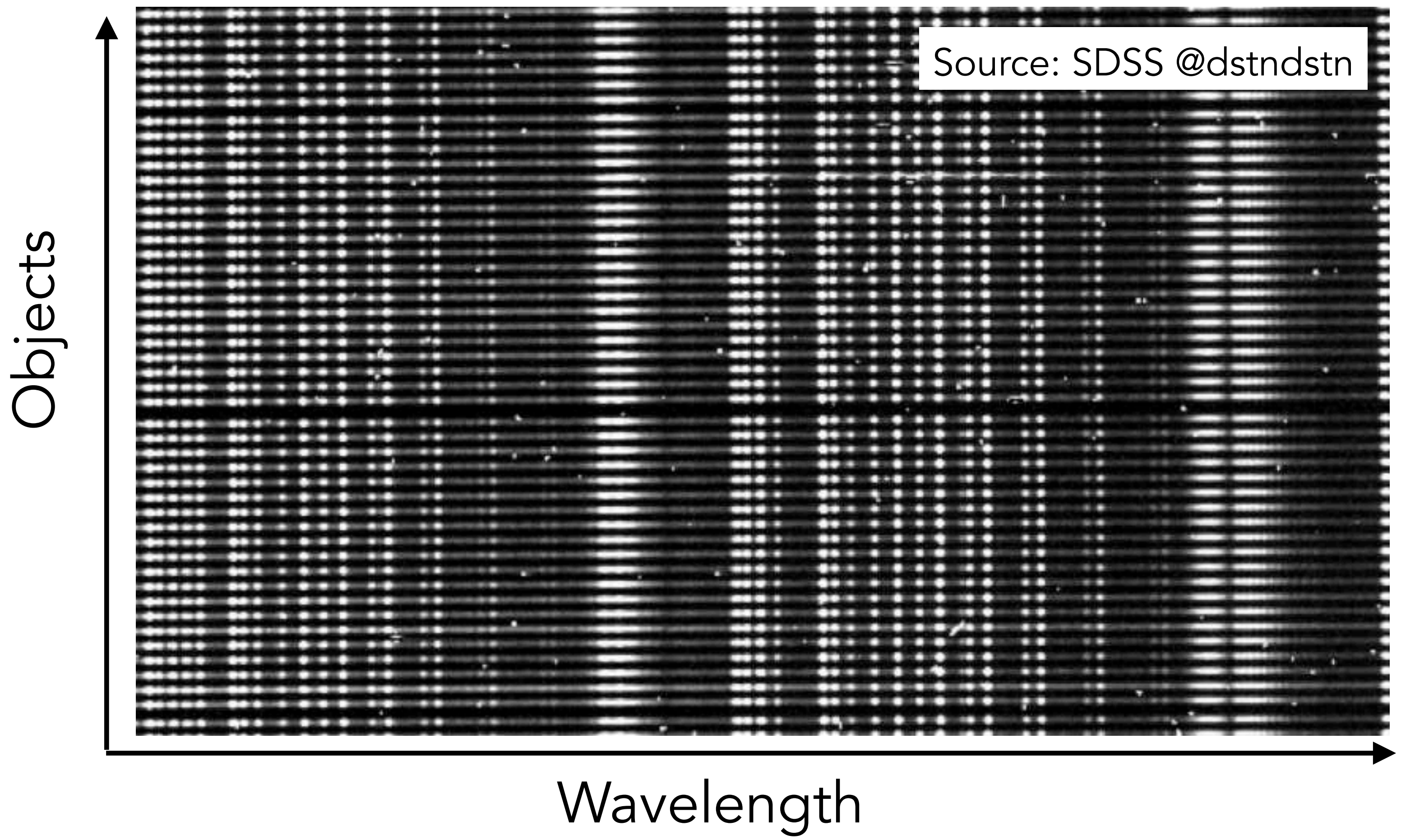
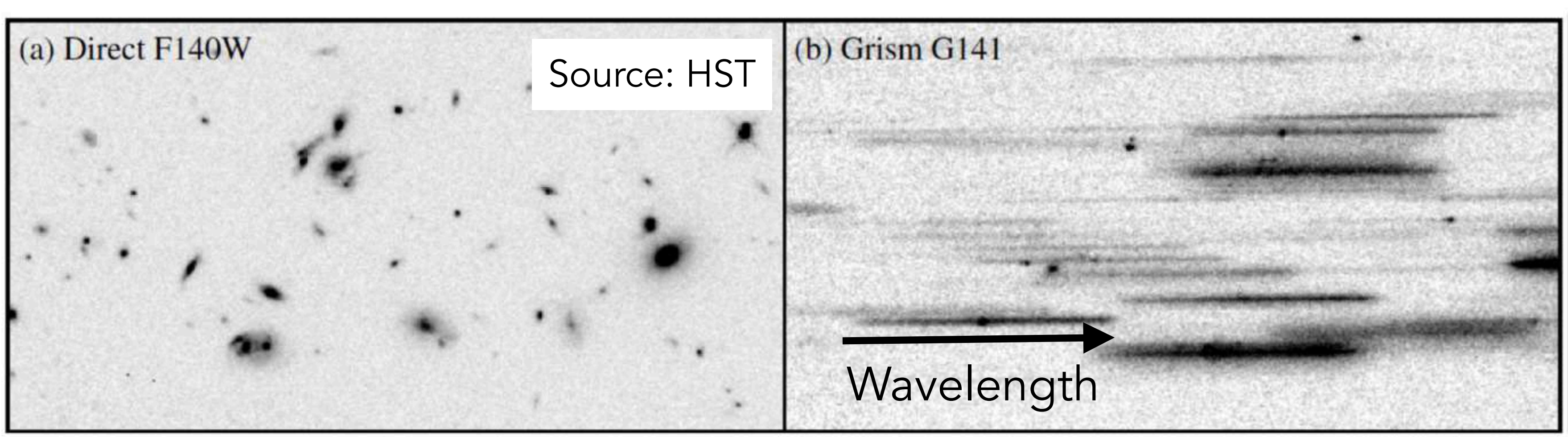


Slitless case (Euclid-like)



From photons to spectra

5b - Spectroscopic data reduction

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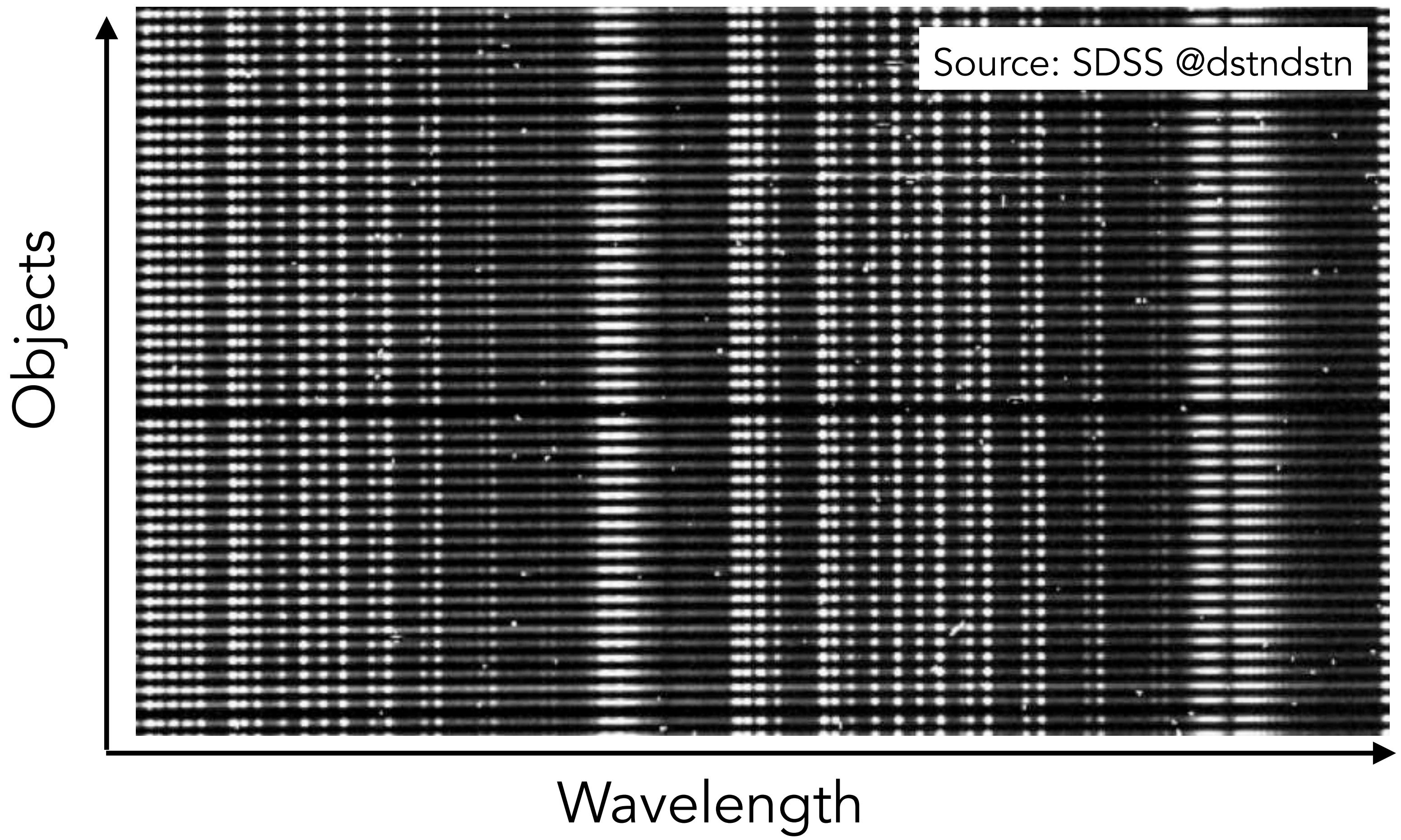

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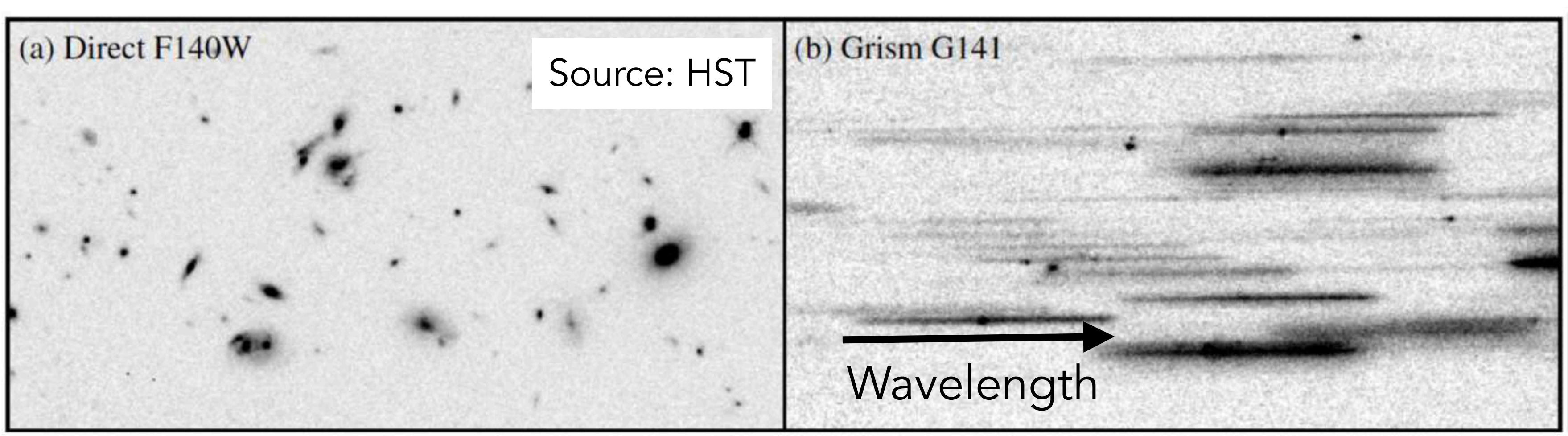

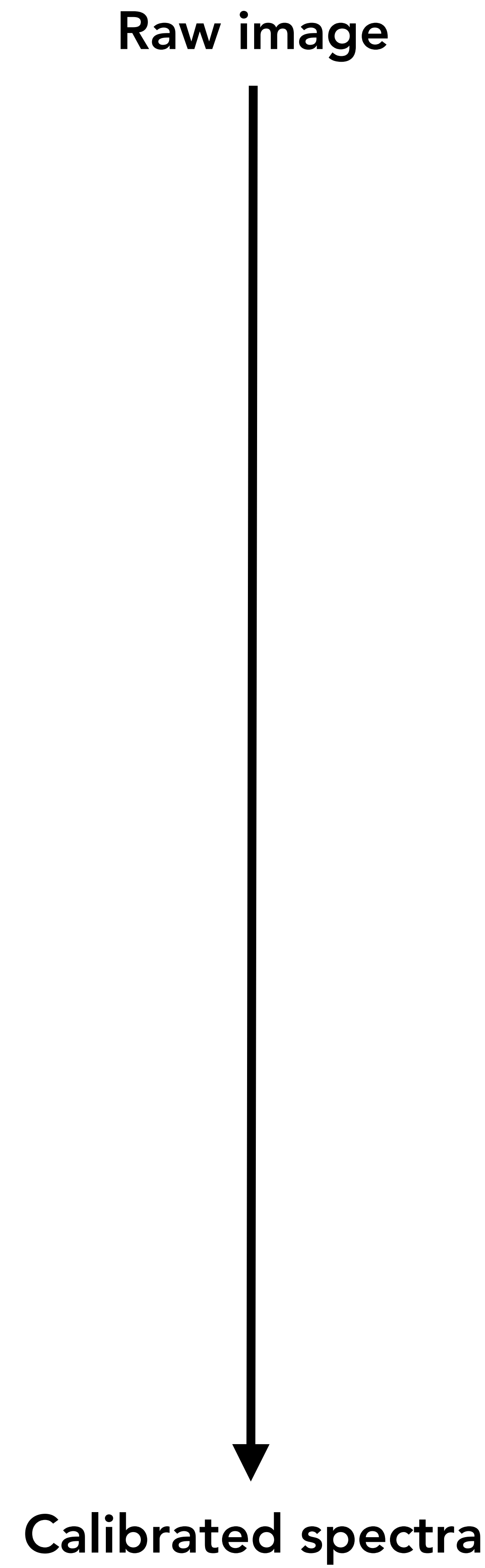

From photons to spectra

5b - Spectroscopic data reduction

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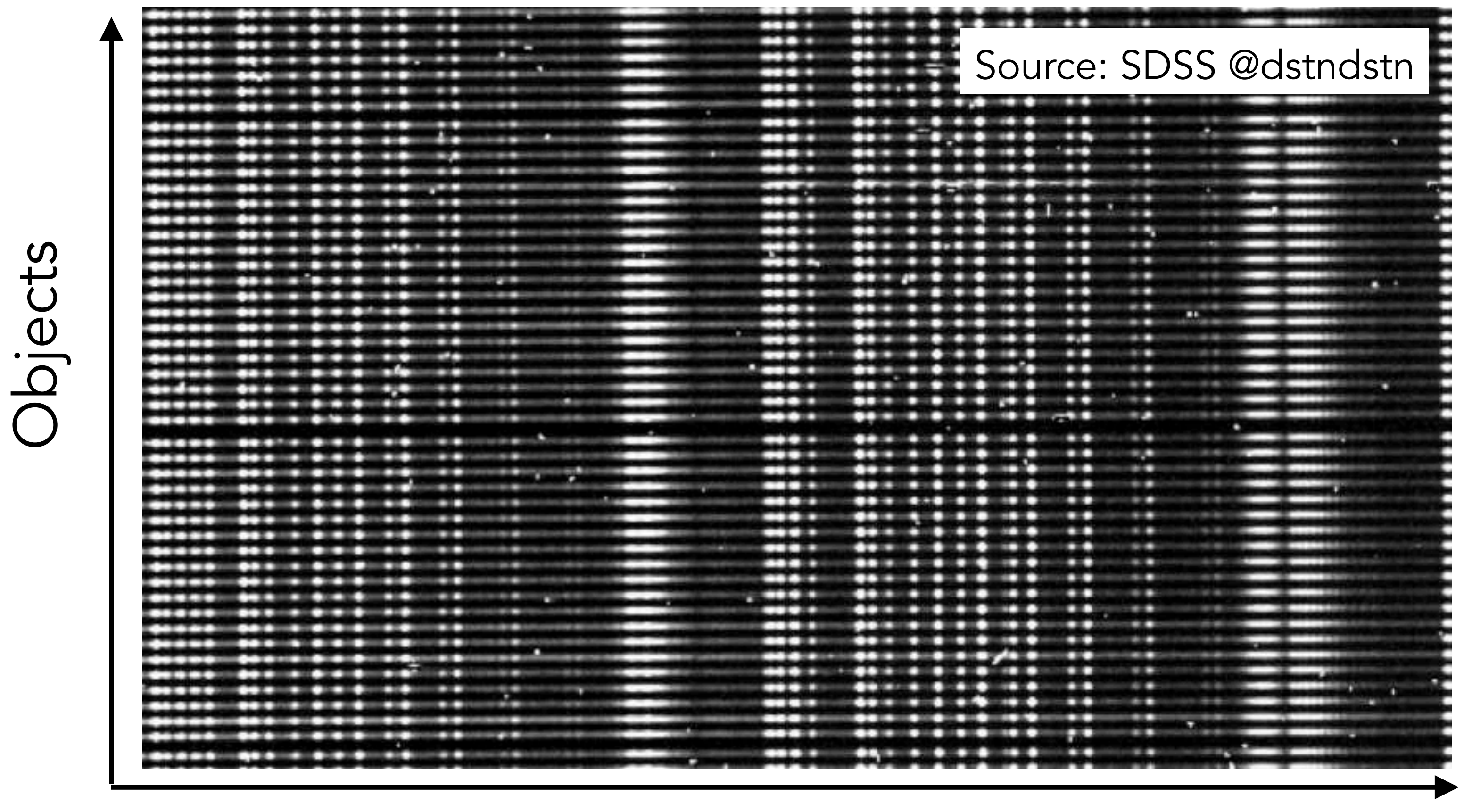

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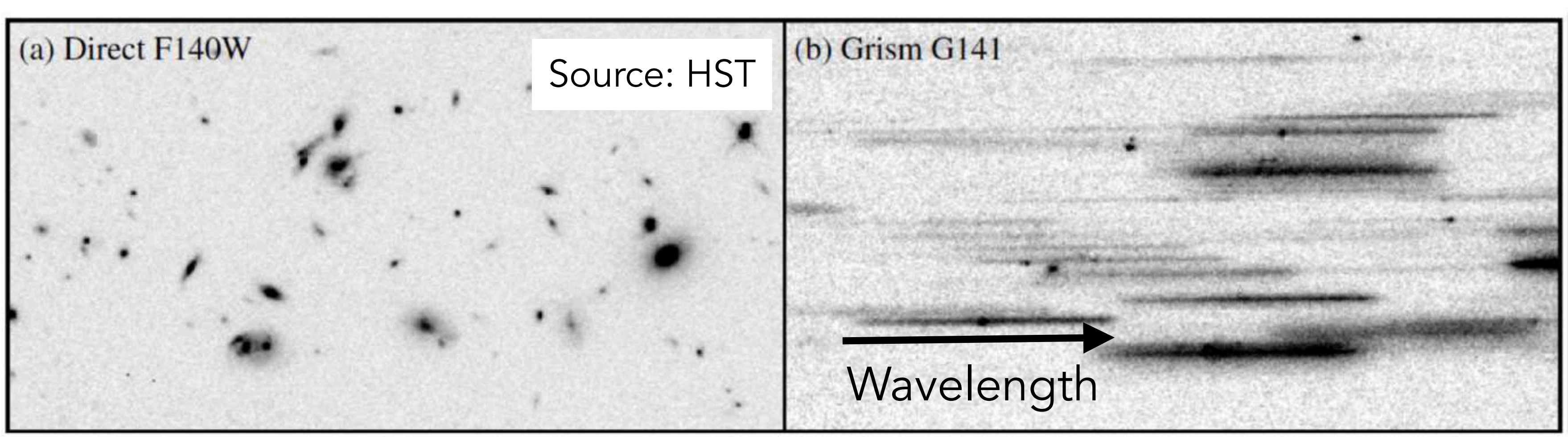


Raw image

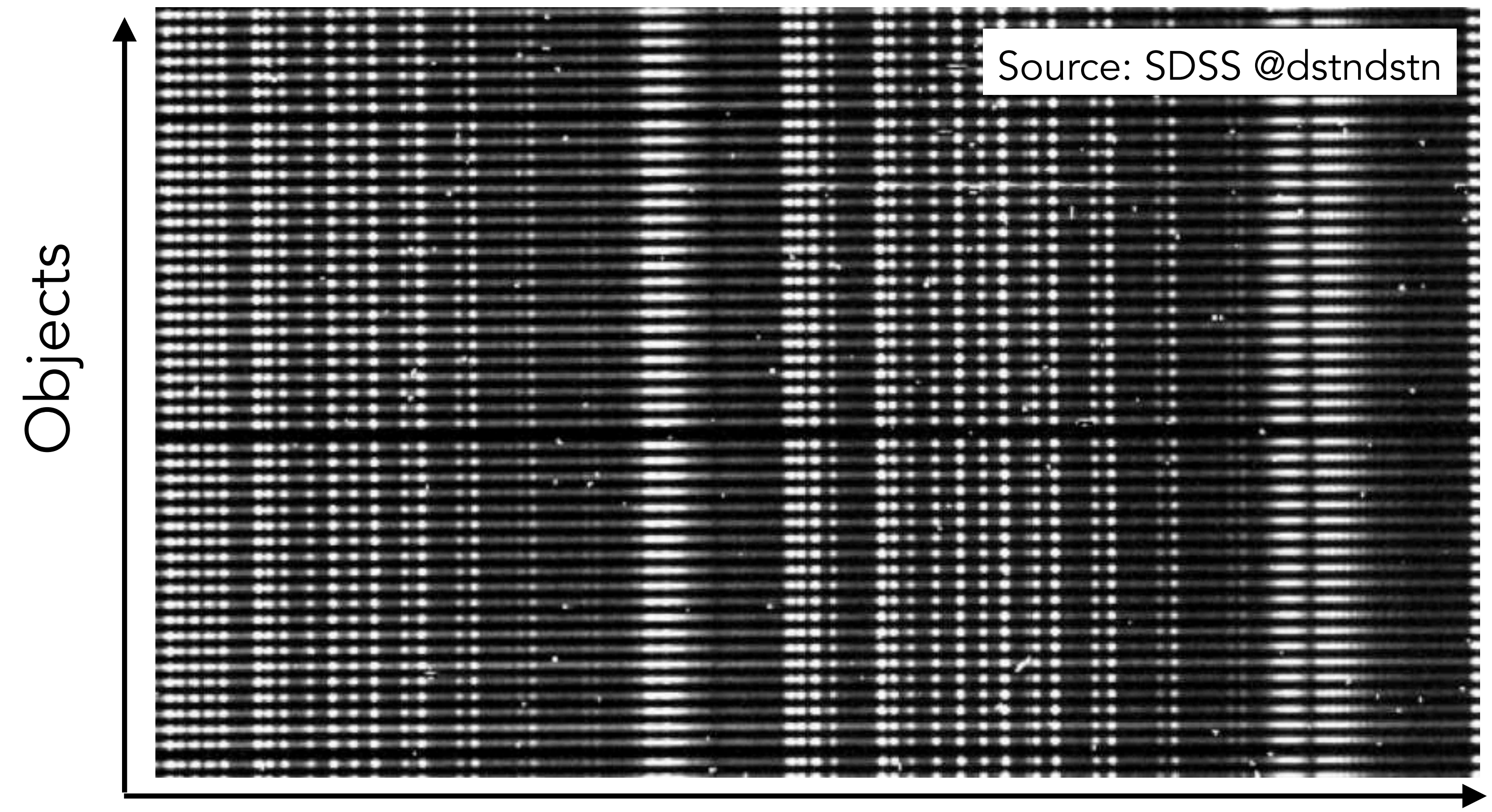
Extraction of counts from CCD
Clean cosmic rays

Calibrated spectra

From photons to spectra

5b - Spectroscopic data reduction

Multi-object fiber based case (SDSS or DESI-like)



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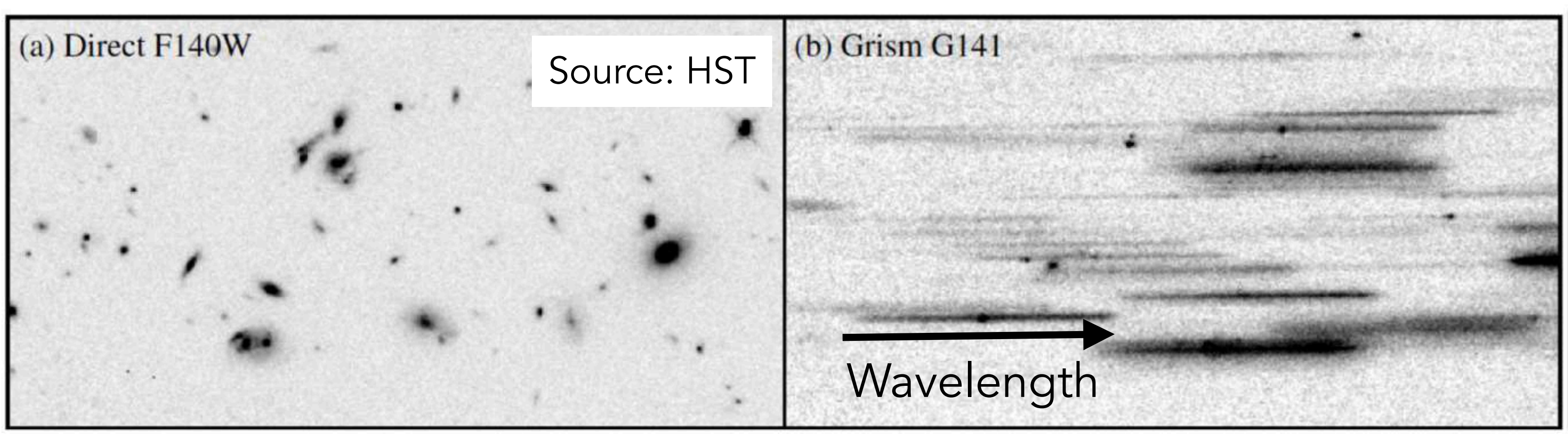

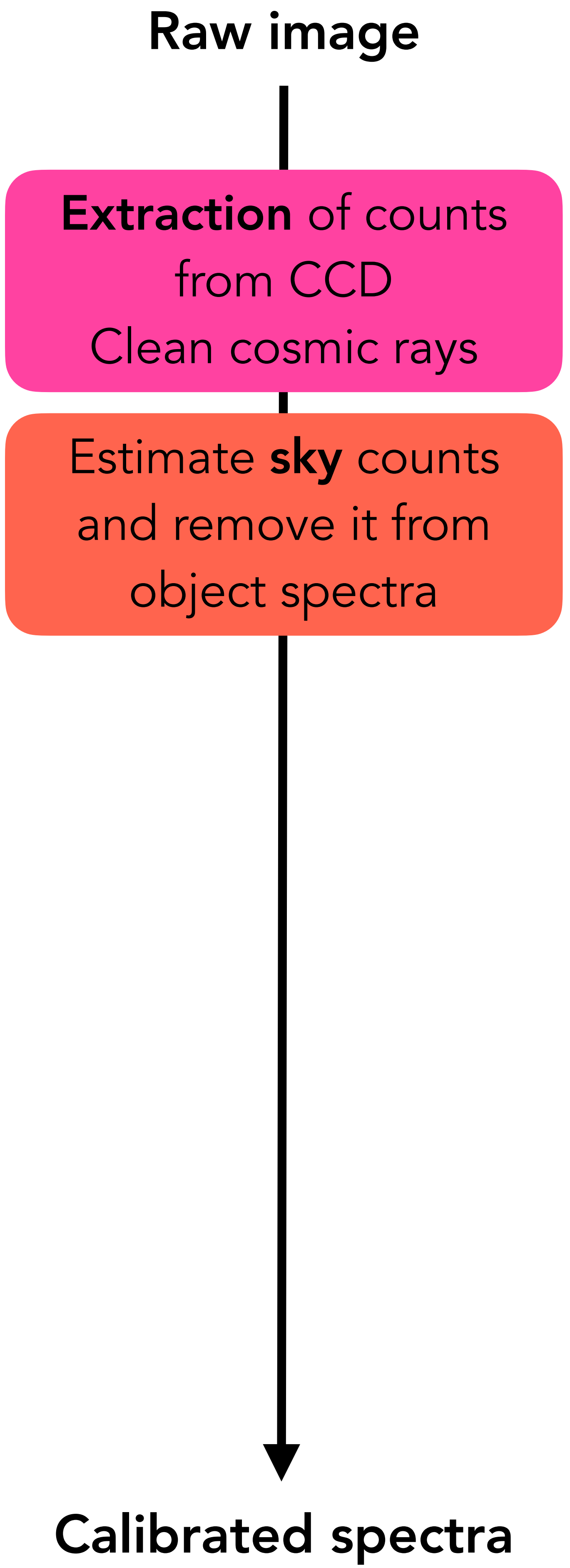

From photons to spectra

5b - Spectroscopic data reduction

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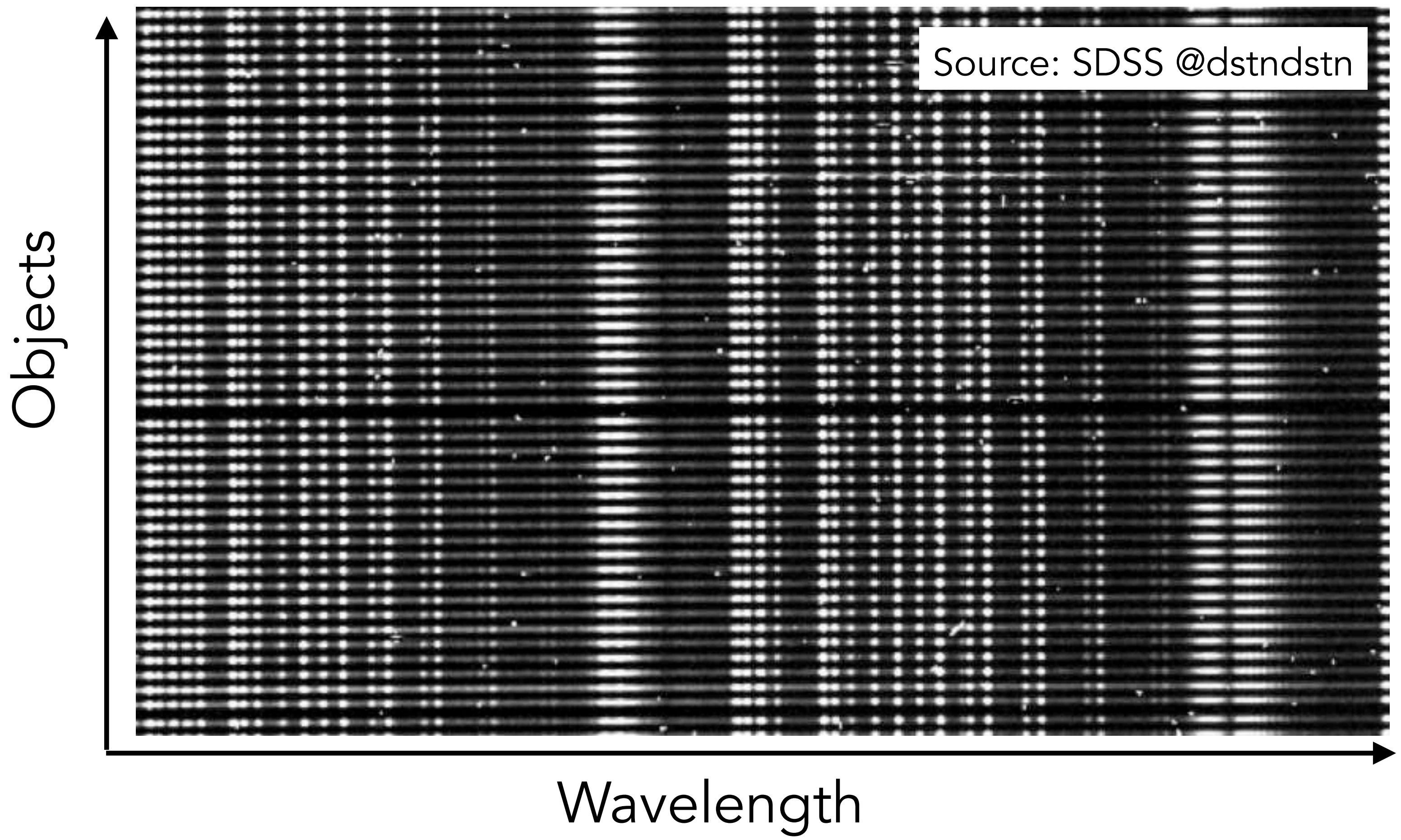

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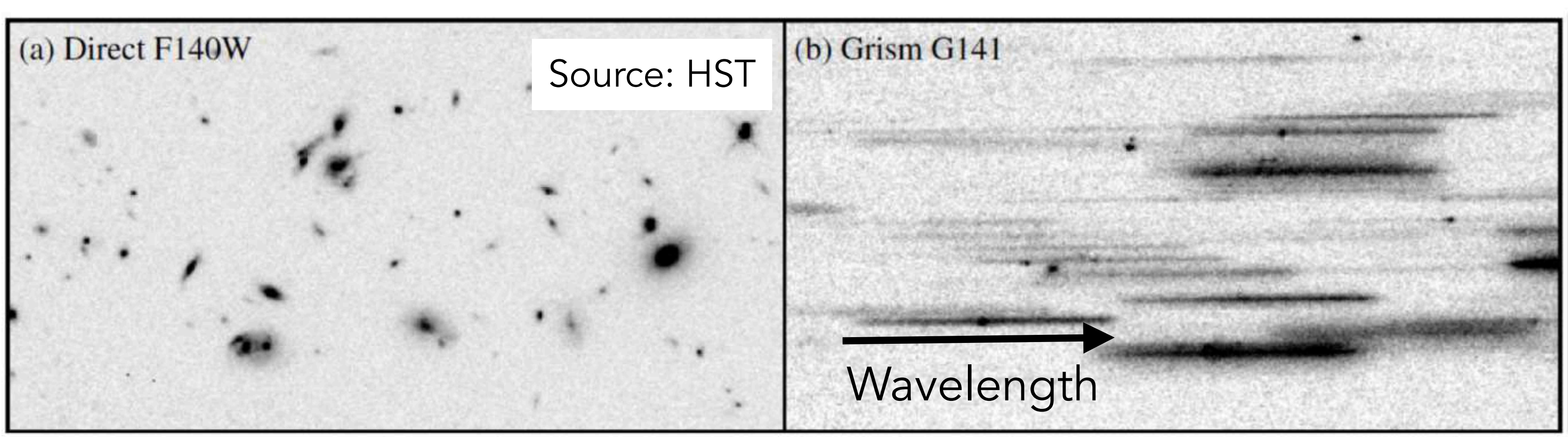


Raw image

Extraction of counts from CCD
Clean cosmic rays

Estimate **sky** counts and remove it from object spectra

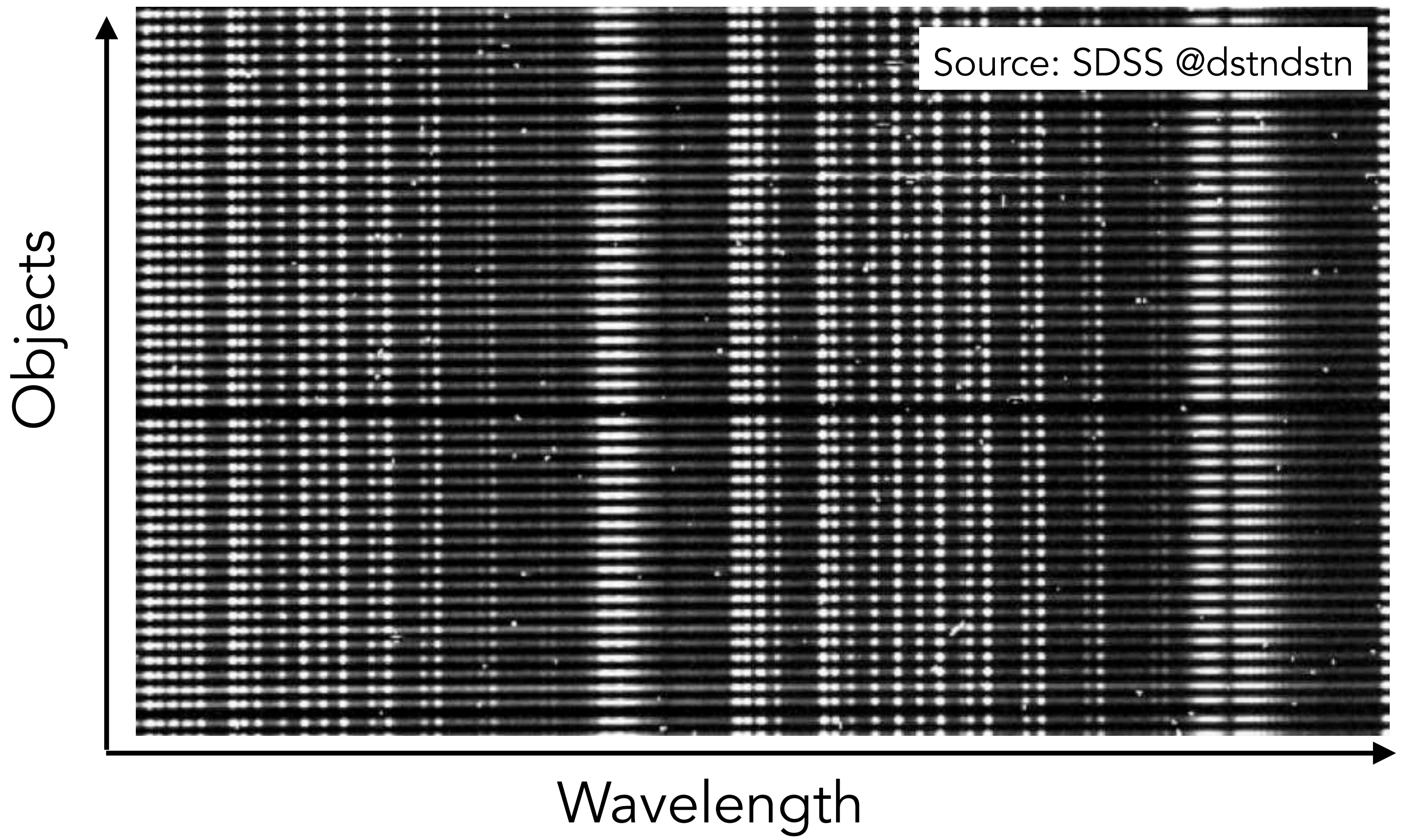
Calibrate **wavelengths** solution using arc lamps

Calibrated spectra

From photons to spectra

5b - Spectroscopic data reduction

Multi-object fiber based case (SDSS or DESI-like)



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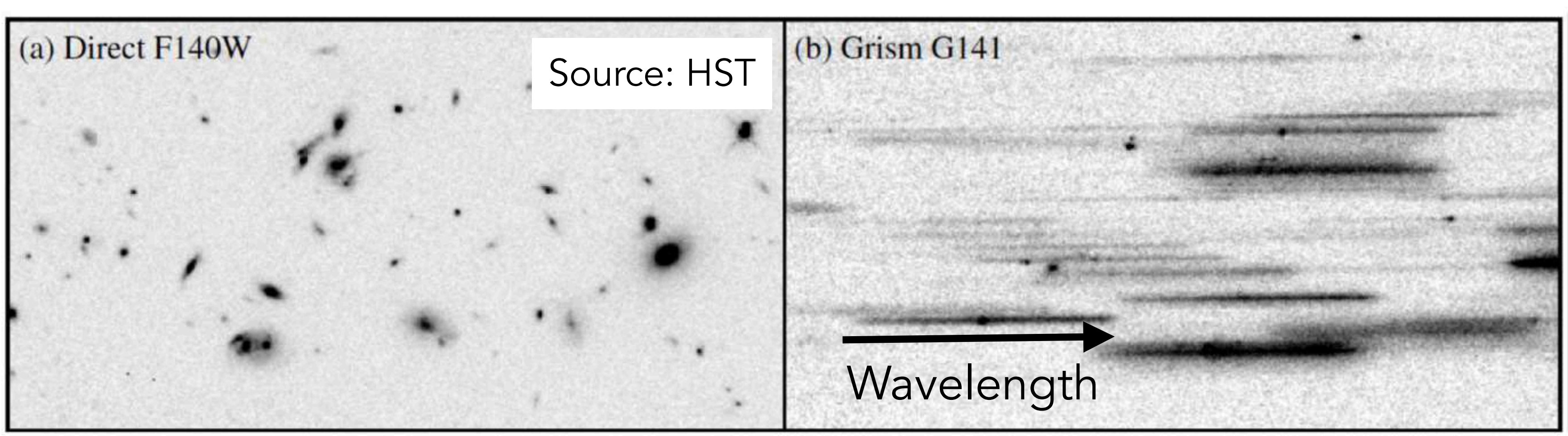


Raw image

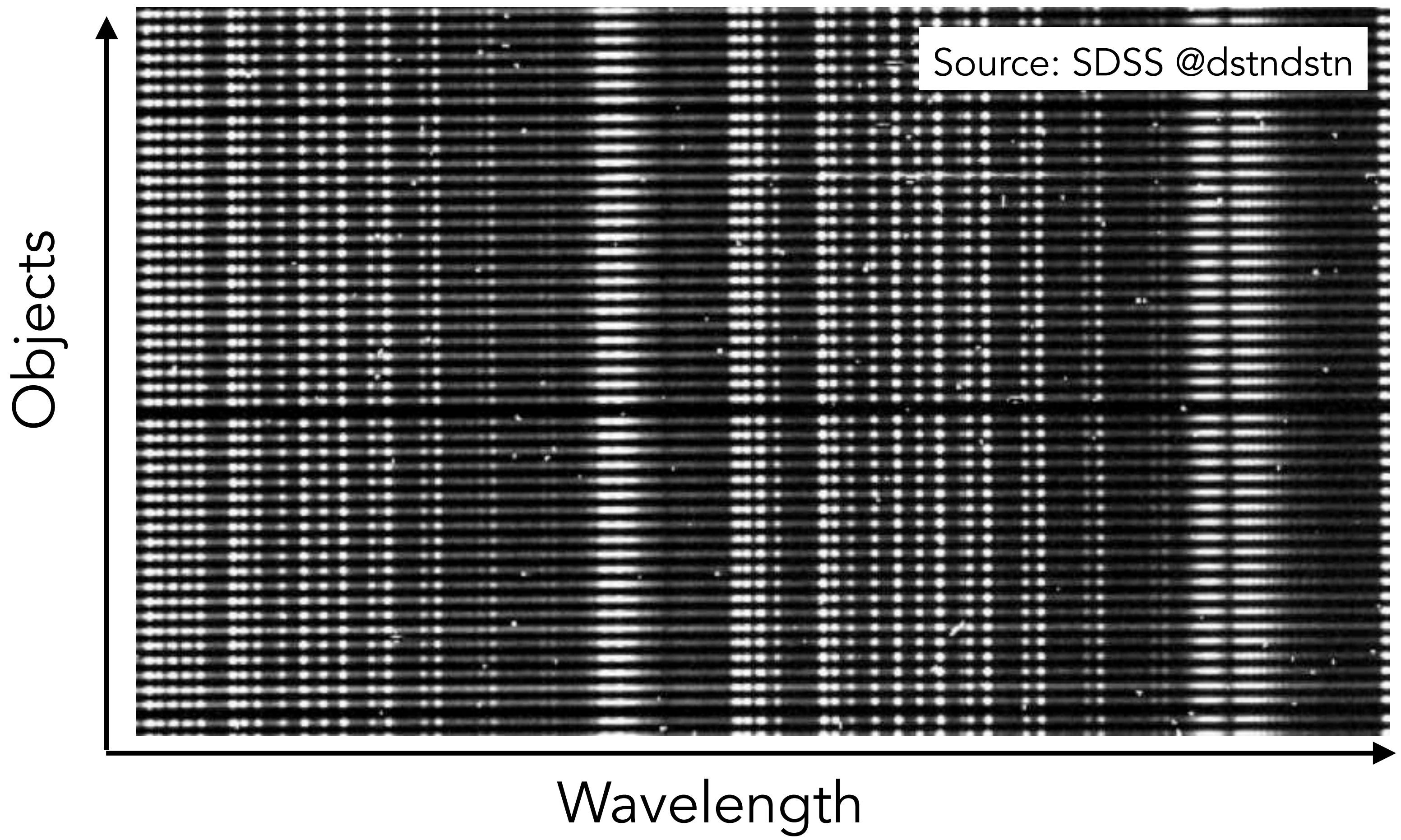
- **Extraction** of counts from CCD
  Clean cosmic rays
- Estimate **sky** counts and remove it from object spectra
- Calibrate **wavelengths** solution using arc lamps
- Convert counts into **physical flux** using standard stars

Calibrated spectra

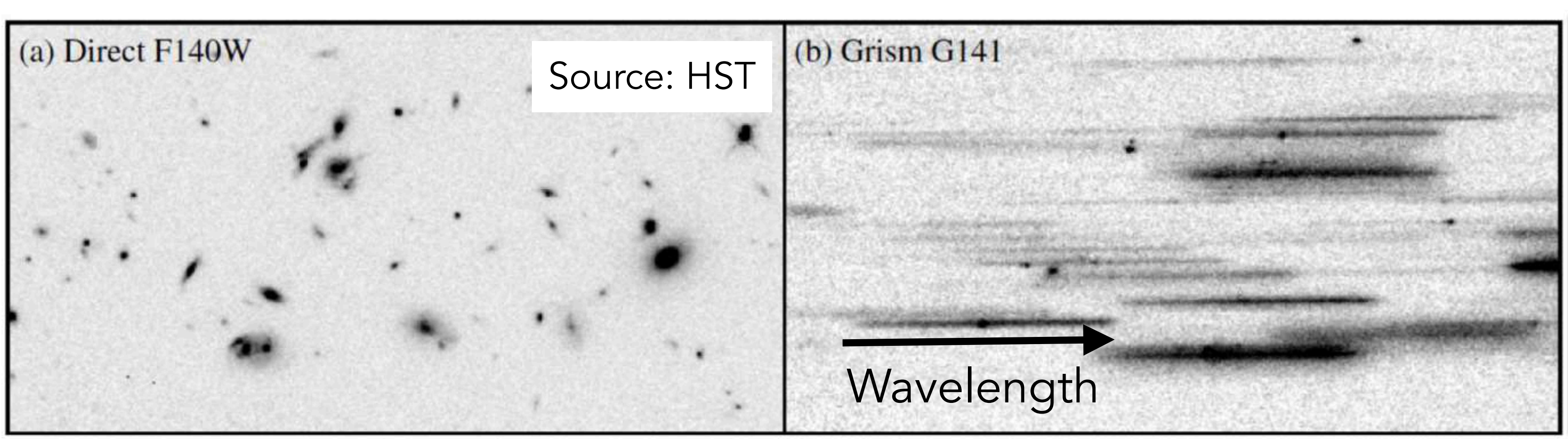
From photons to spectra

5b - Spectroscopic data reduction

Multi-object fiber based case (SDSS or DESI-like)



Slitless case (Euclid-like)



Raw image

↓

Extraction of counts from CCD
Clean cosmic rays

↓

Estimate **sky** counts and remove it from object spectra

↓

Calibrate **wavelengths** solution using arc lamps

↓

Convert counts into **physical flux** using standard stars

↓

Coadd exposures
Correct **distortions**

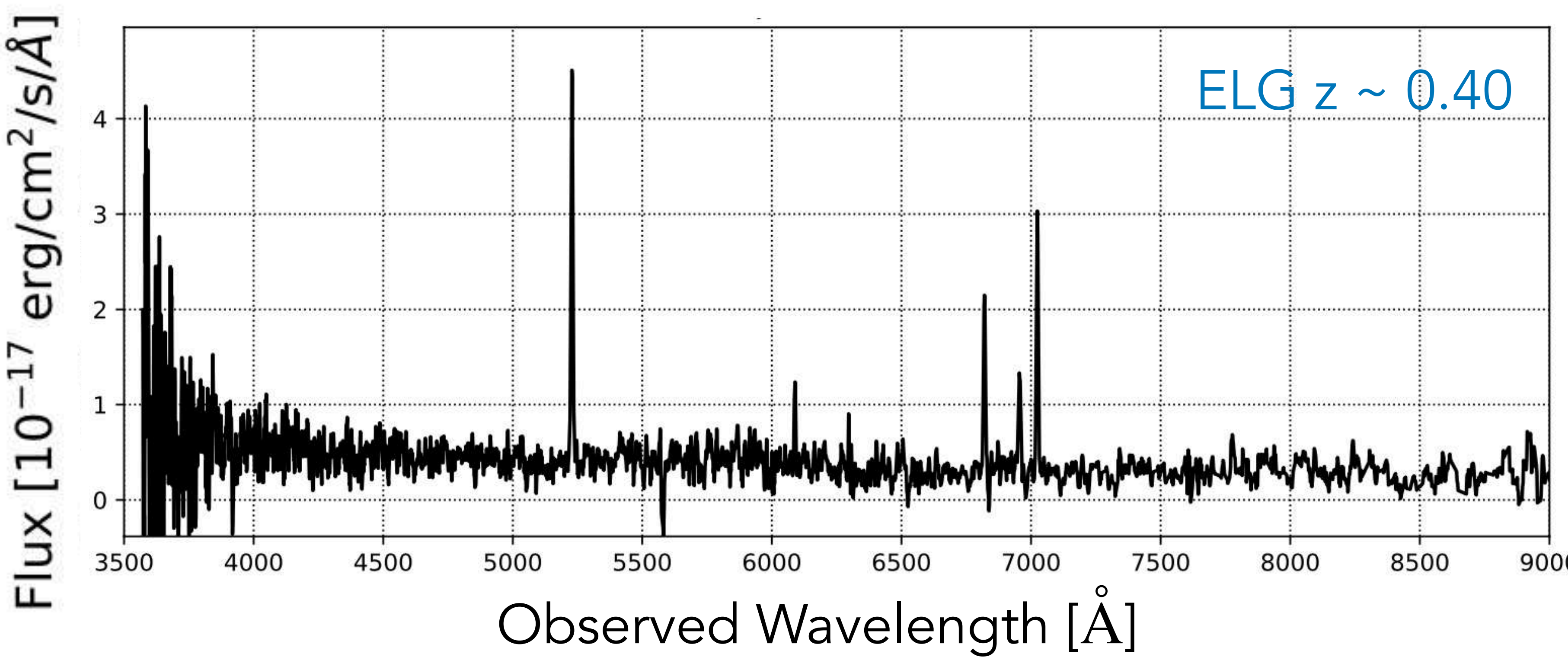
↓

Calibrated spectra

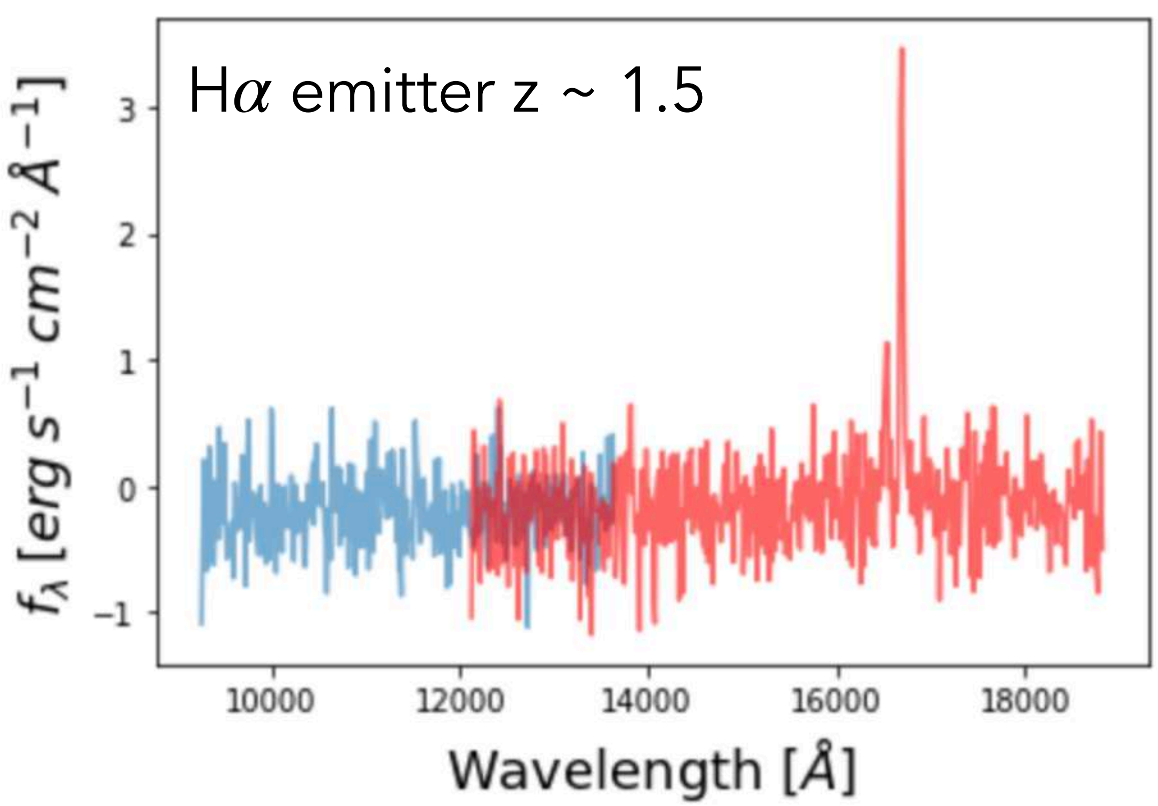
From photons to spectra

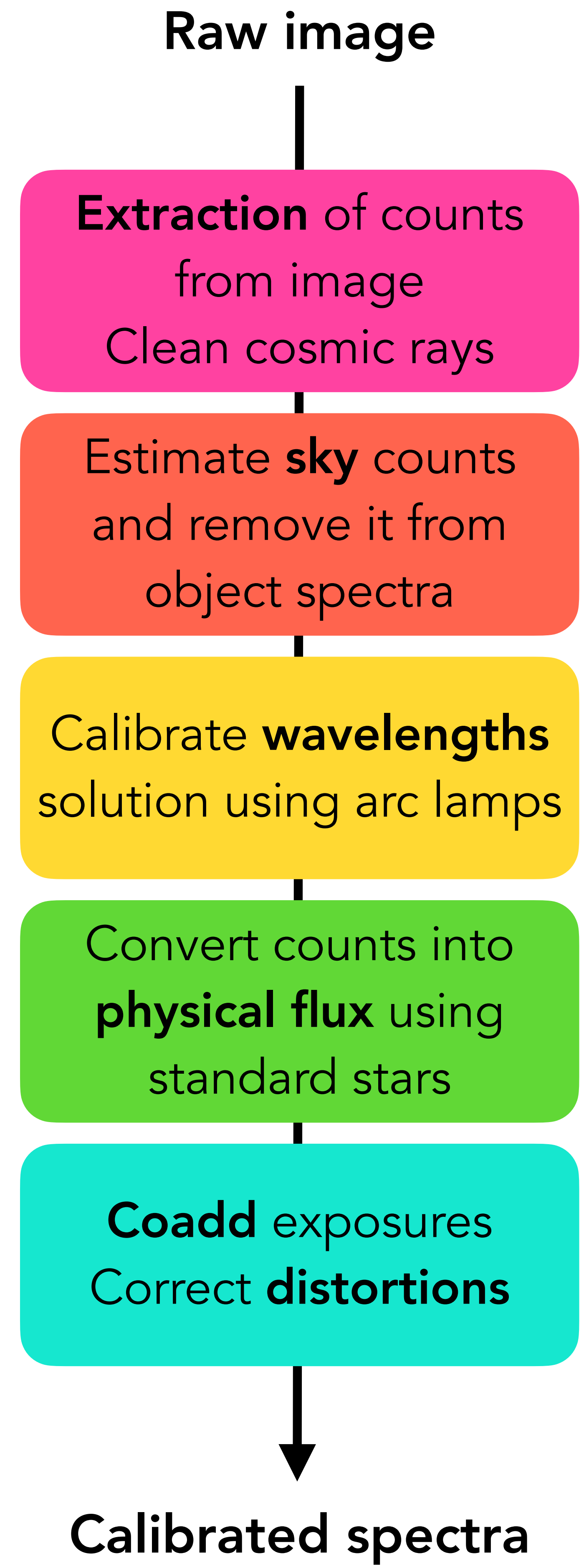
5b - Spectroscopic data reduction

Multi-object fiber based case (SDSS or DESI-like)



Slit-less case (Euclid-like)





From photons to spectra

6 - Measuring redshifts

From photons to spectra

6 - Measuring redshifts

Visual inspection

Fitting templates
(empirical or physical)

Machine learning

From photons to spectra

6 - Measuring redshifts

Visual inspection

Fitting templates
(empirical or physical)

Machine learning

Pros

Cons

From photons to spectra

6 - Measuring redshifts

Visual inspection

Fitting templates
(empirical or physical)

Machine learning

Pros

Identification of peculiar objects

Identification of problems in spectra

Robust when double checked

Required to start a survey

Cons

From photons to spectra

6 - Measuring redshifts

Visual inspection | Fitting templates (empirical or physical) | Machine learning

Pros

Identification of peculiar objects

Identification of problems in spectra

Robust when double checked

Required to start a survey

Cons

Slow

Small number of objects

Prone to human error or biases

Hard to define uncertainties

Visual inspection

Fitting templates (empirical or physical)

Machine learning

From photons to spectra

6 - Measuring redshifts

Visual inspection

Fitting templates (empirical or physical)

Machine learning

Physical templates : galaxy models from stellar populations

Empirical templates : Principal Component Analysis or equivalent

From photons to spectra

6 - Measuring redshifts

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Physical templates : galaxy models from stellar populations

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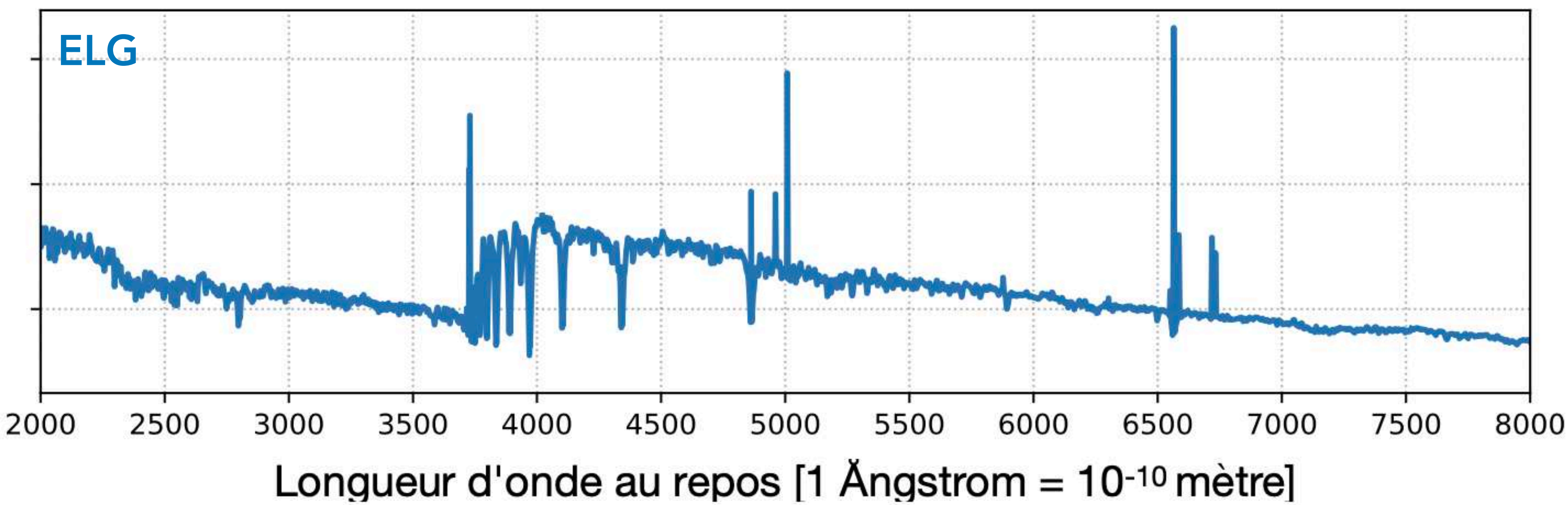

From photons to spectra

6 - Measuring redshifts

Visual inspection

Fitting templates (empirical or physical)

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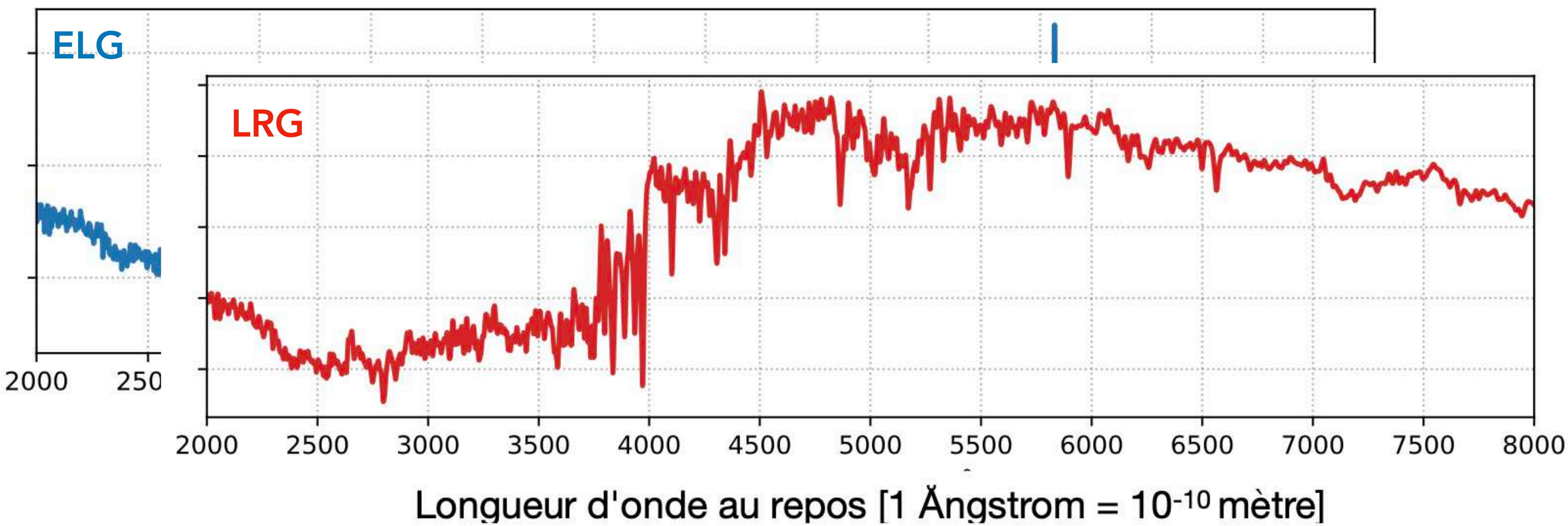
Physical templates : galaxy models from stellar populations

Empirical templates : Principal Component Analysis or equivalent



From photons to spectra

6 - Measuring redshifts

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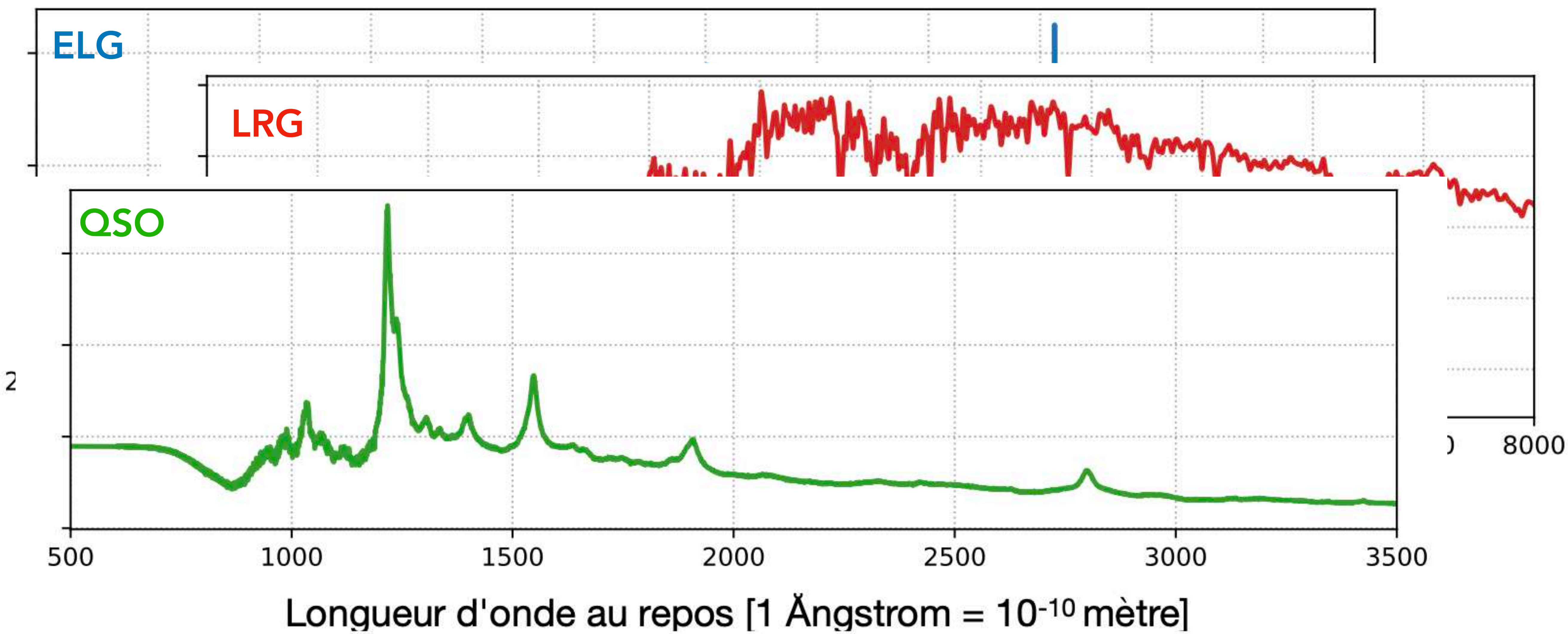


From photons to spectra

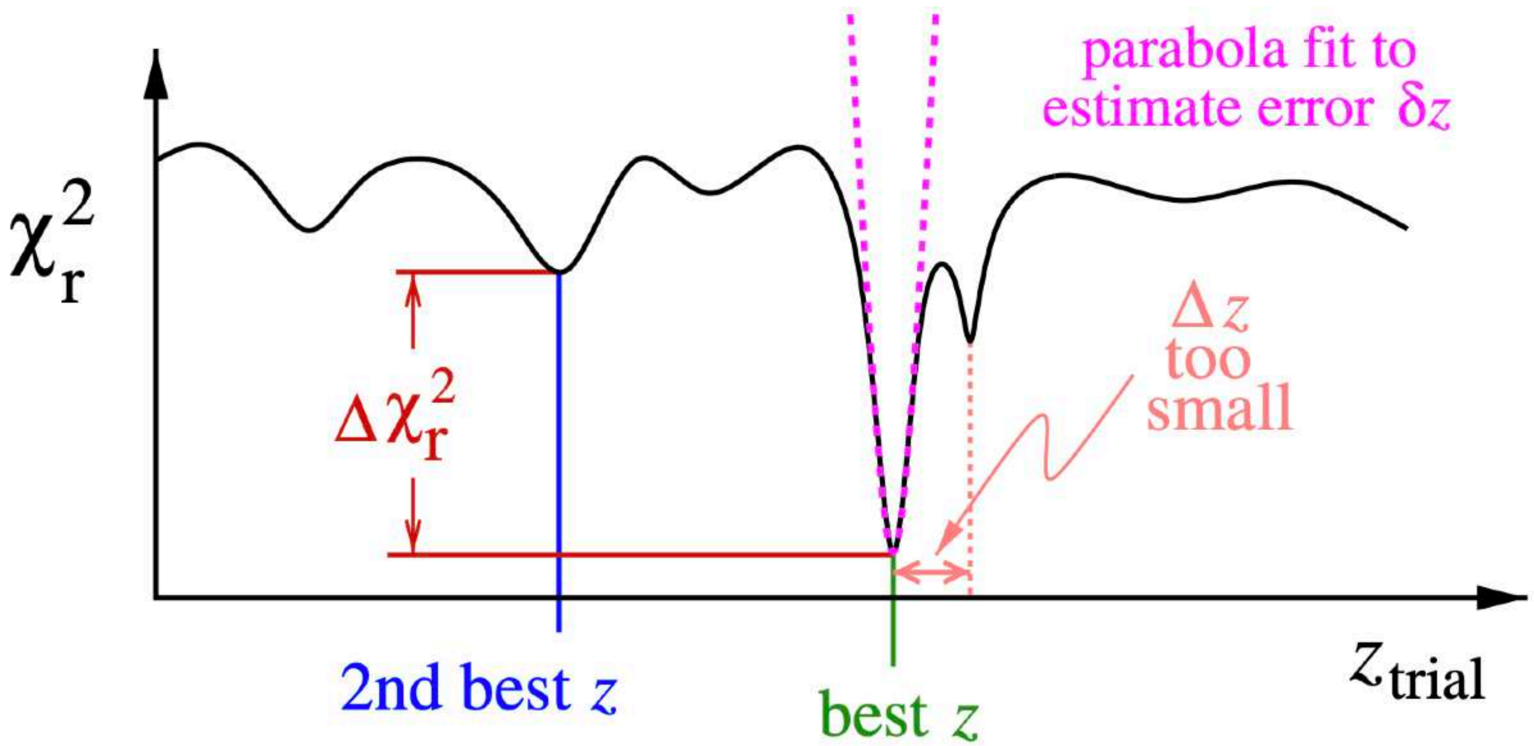
6 - Measuring redshifts

Visual inspection

Fitting templates (empirical or physical)

Machine learning

Shift templates and minimise χ^2 versus redshift



From photons to spectra

6 - Measuring redshifts

Visual inspection

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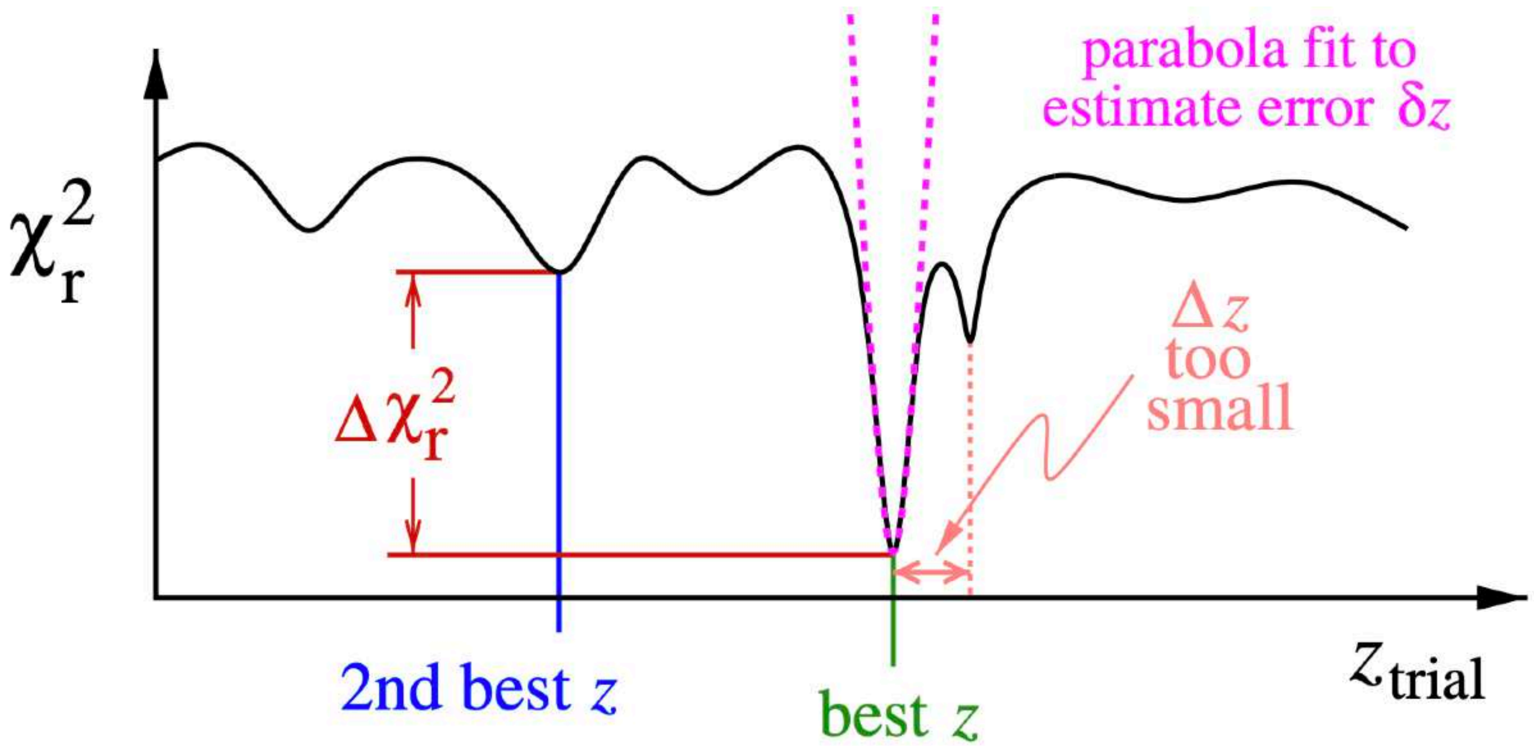

BOSS fitter - Bolton et al. 2012

eBOSS and DESI fitters - redrock

From photons to spectra

6 - Measuring redshifts

Visual inspection

Fitting templates (empirical or physical)

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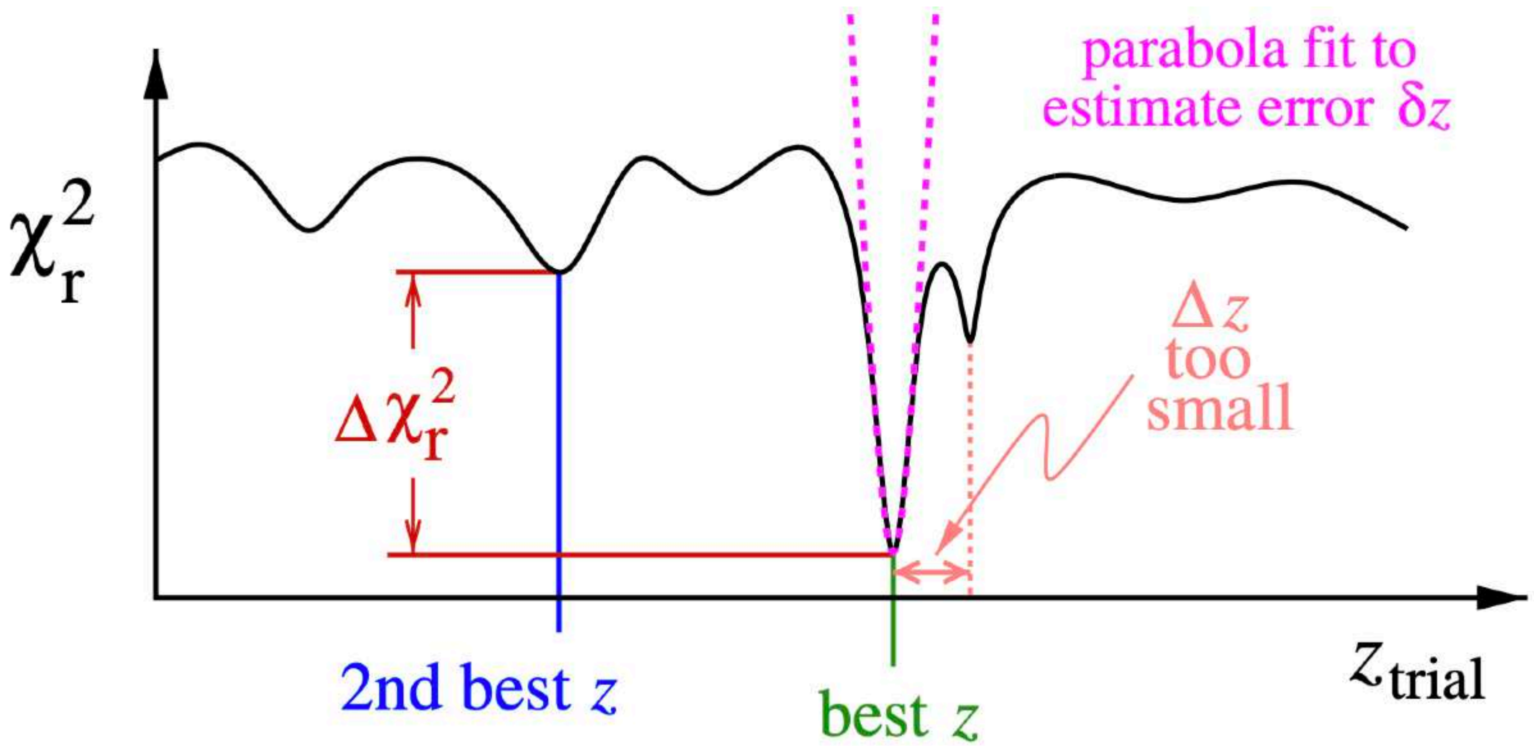


BOSS fitter - Bolton et al. 2012

eBOSS and DESI fitters - redrock

Pros

Fast and automated

Deterministic

Quantifiable uncertainties

Good on low S/N spectra

From photons to spectra

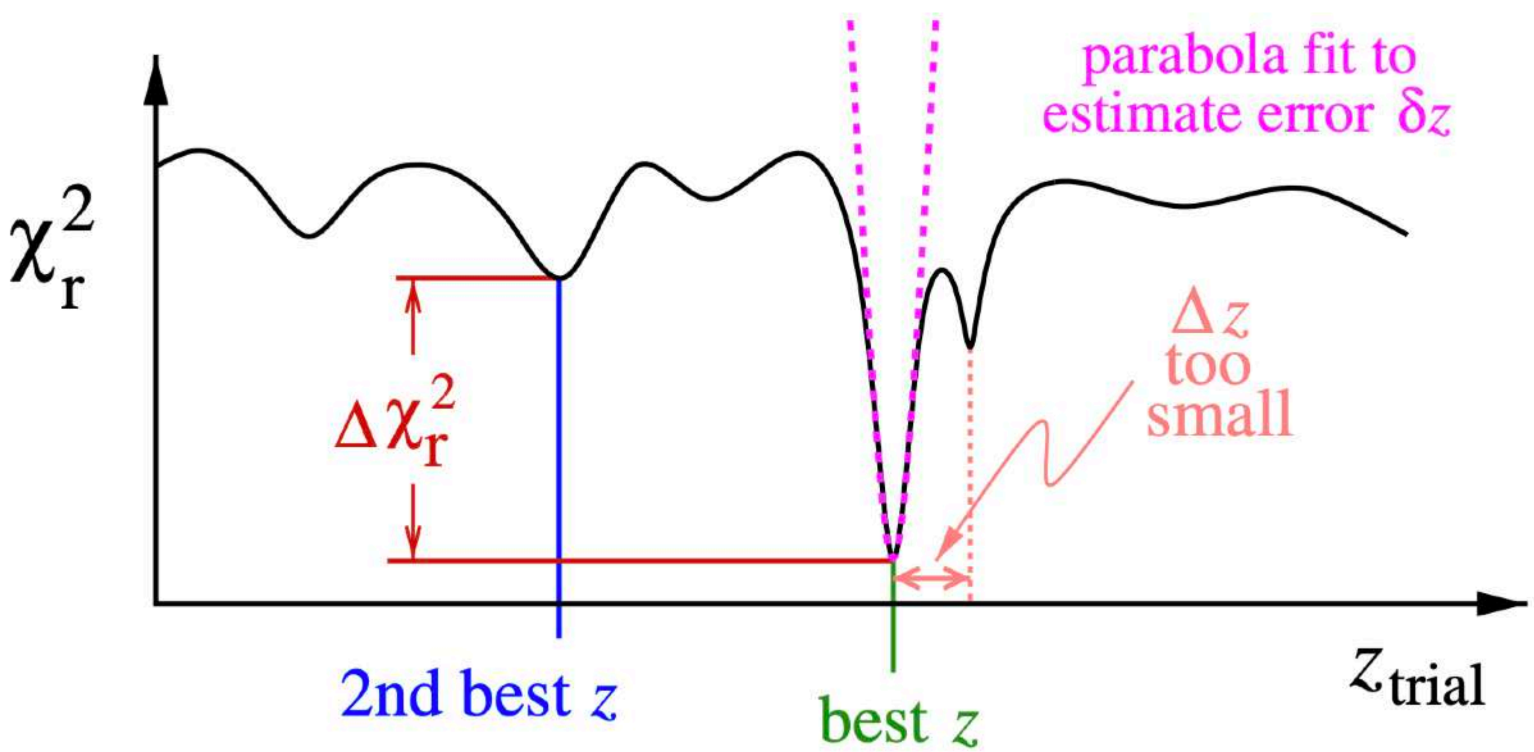
6 - Measuring redshifts

Visual inspection

Fitting templates (empirical or physical)

Machine learning

Shift templates and minimise χ^2 versus redshift



BOSS fitter - Bolton et al. 2012

eBOSS and DESI fitters - redrock

Pros

Fast and automated

Deterministic

Quantifiable uncertainties

Good on low S/N spectra

Cons

Results depend on templates

Fails on peculiar objects

From photons to spectra

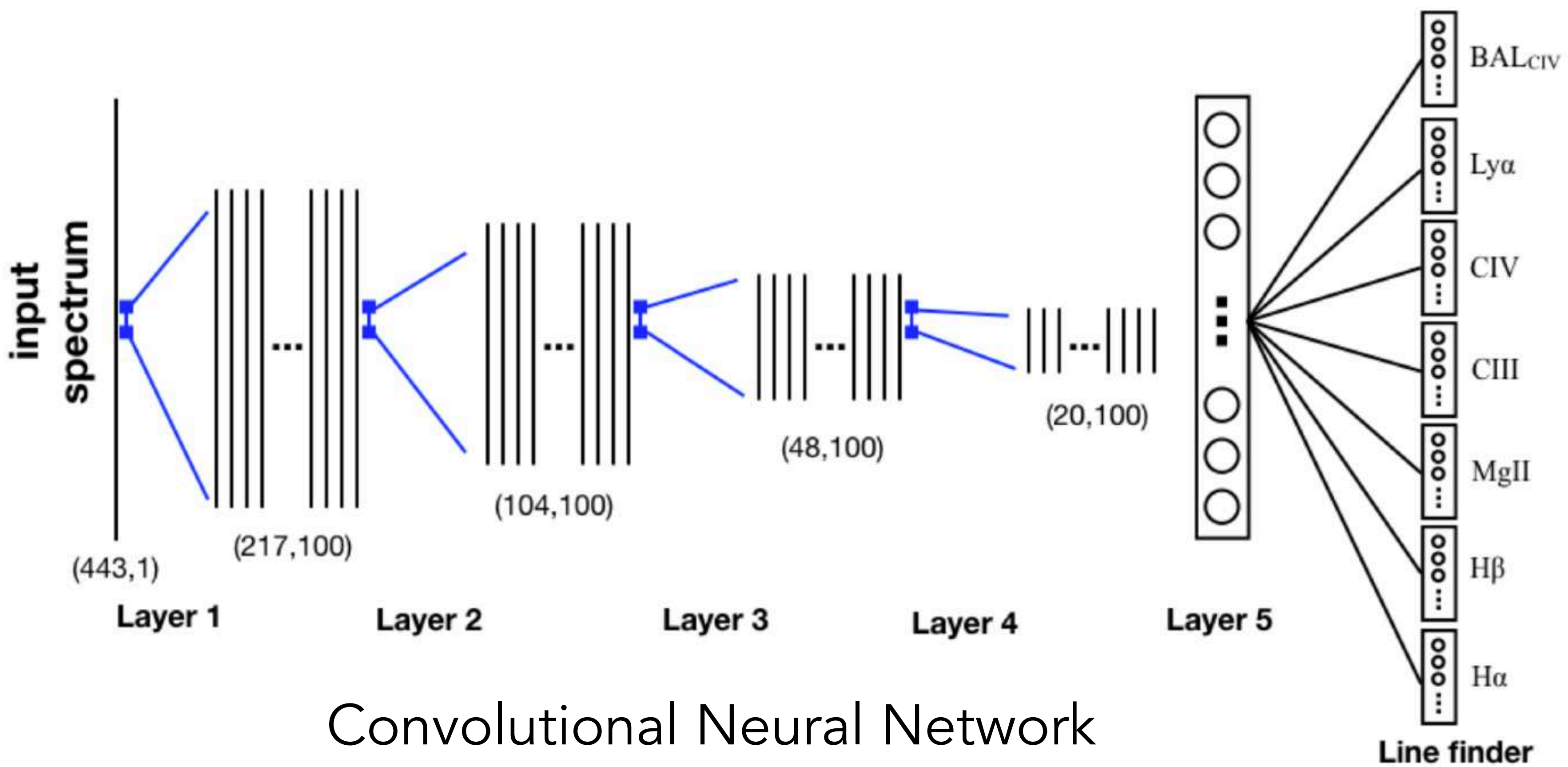
6 - Measuring redshifts

Visual inspection

Fitting templates
(empirical or physical)

Machine learning

Useful for quasars : no physical model !



Convolutional Neural Network

Busca & Balland 2018

From photons to spectra

6 - Measuring redshifts

Visual inspection

Fitting templates (empirical or physical)

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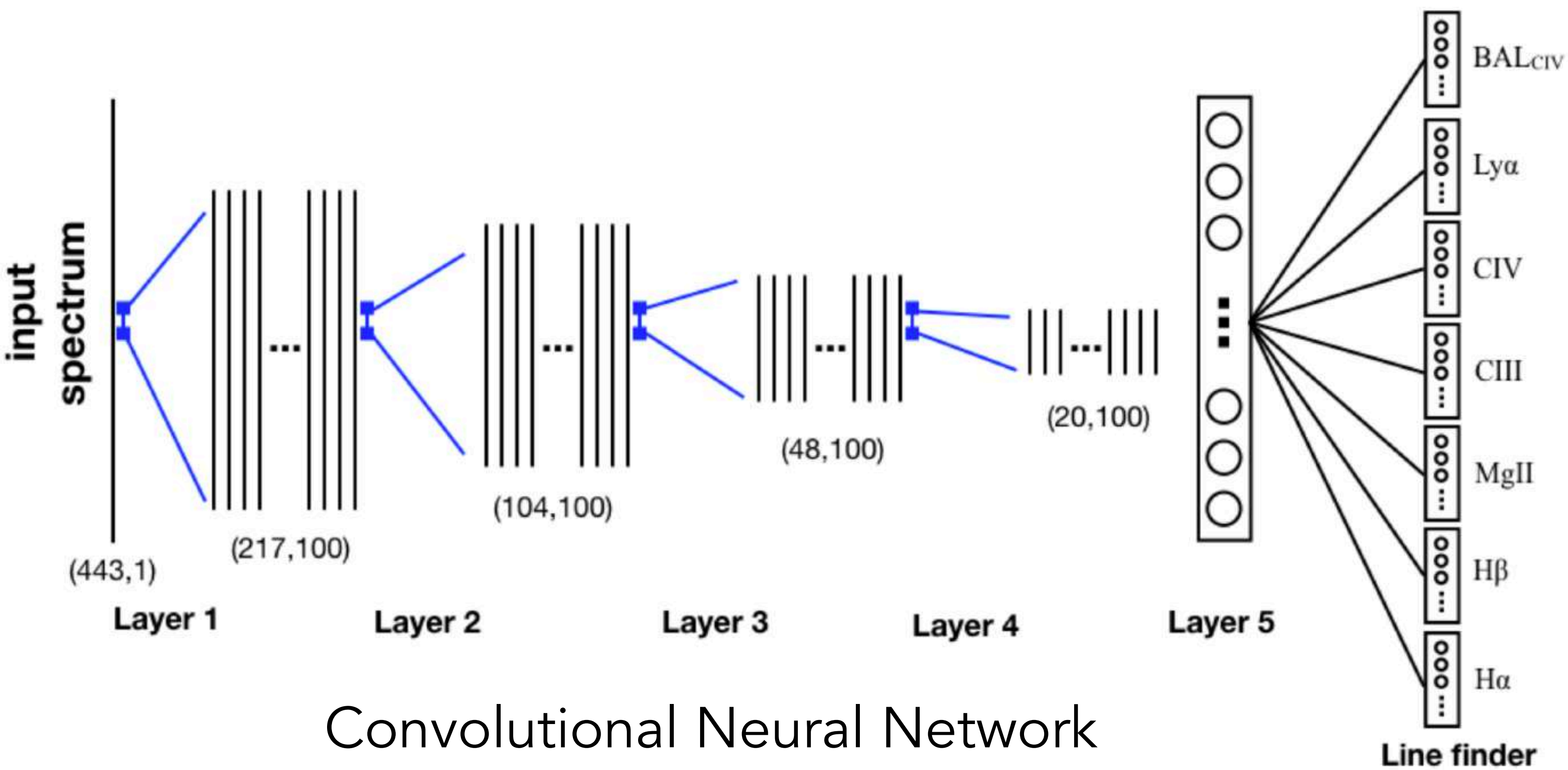
Useful for quasars : no physical model !



Convolutional Neural Network

Busca & Balland 2018

Pros

Fast and automated

Better than templates for quasars

From photons to spectra

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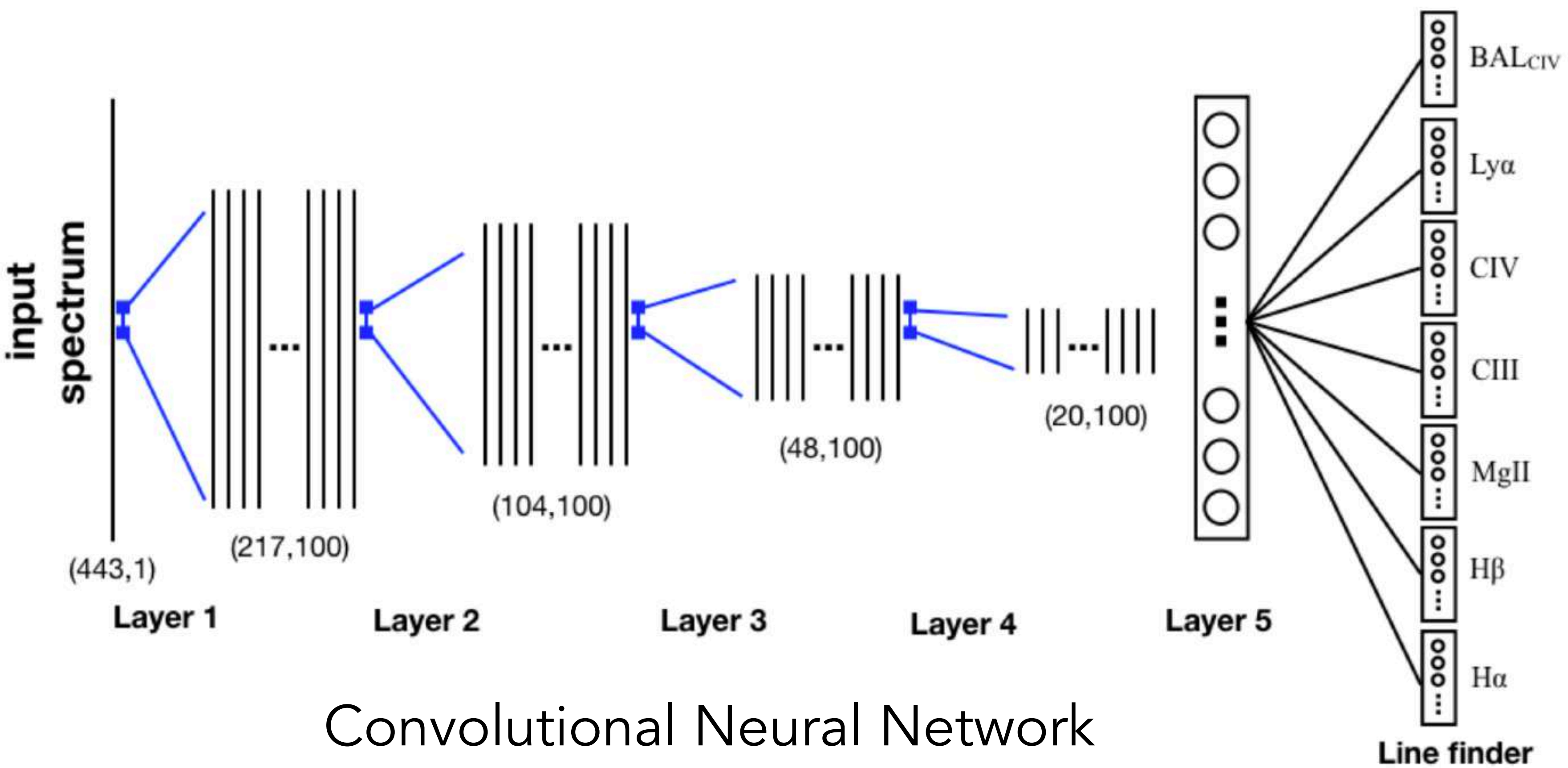

Convolutional Neural Network

Busca & Balland 2018

Pros

Fast and automated

Better than templates for quasars

Cons

Requires careful training

"Black-box"

Uncertainties not well defined

Fails on peculiar objects

From photons to spectra

6 - Measuring redshifts

Visual inspection	Fitting templates (empirical or physical)	Machine learning

All three methods have been used in eBOSS, are being used in DESI, and will most likely be used in Euclid and other surveys

From photons to spectra and redshifts

$$\gamma_n \rightarrow \begin{matrix}(\theta_i, \phi_i, z_i) \\ \left(\theta_i, \phi_i, z_i, \{f_j\}\right)\end{matrix} \rightarrow \begin{matrix}\delta_g(\vec{x}) \\ \delta_{\mathrm{Ly}\alpha}(\vec{x})\end{matrix} \rightarrow \langle \delta\delta' \rangle \rightarrow \Omega_i$$

Summary

Type of instrument and survey

Choice of sky coverage, target type and scan strategy

Quality of spectroscopic data reduction

Quality of spectral classification and redshift measurement

All directly impact cosmological constraints

From spectra to clustering

$$\gamma_n \rightarrow \begin{matrix} (\theta_i, \phi_i, z_i) \\ \left(\theta_i, \phi_i, z_i, \{f_j\}\right) \end{matrix} \rightarrow \begin{matrix} \delta_g(\vec{x}) \\ \delta_{\mathrm{Ly}\alpha}(\vec{x}) \end{matrix} \rightarrow \langle \delta \delta' \rangle \rightarrow \Omega_i$$

From spectra to clustering

$$\begin{matrix} \left(\theta_i, \phi_i, z_i\right) \\ \left(\theta_i, \phi_i, z_i, \{f_j\}\right) \end{matrix} \;\rightarrow\; \begin{matrix} \delta_g(\vec{x}) \\ \delta_{\mathrm{Ly}\alpha}(\vec{x}) \end{matrix} \;\rightarrow\; \langle \delta \delta' \rangle$$

From spectra to clustering

(θ_i, ϕ_i, z_i) → $\delta_g(\vec{x})$ → $\langle \delta\delta' \rangle$

$\left(\theta_i, \phi_i, z_i, \{f_j\}\right)$ → $\delta_{\mathrm{Ly}\alpha}(\vec{x})$

How to convert a list of (θ_i, ϕ_i, z_i) to $\delta_g(\vec{x})$?
Case of **galaxies and quasars**

How to convert a list of $\left(\theta_i, \phi_i, z_i, \{f_j\}\right)$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$?
Case of **Lyman-α forests**

How to compute 2-pt statistics $\langle \delta(\vec{x})\delta(\vec{x}') \rangle$ from $\delta(\vec{x})$?

How to compute covariance/error-matrix for $\langle \delta(\vec{x})\delta(\vec{x}') \rangle$?

BAO and RSD

BAO and Neutrino masses

How to convert a list of (θ_i, ϕ_i, z_i) to $\delta_g(\vec{x})$?

Case of **galaxies and quasars**

$$(\theta_i, \phi_i, z_i) \;\Rightarrow\; \delta_g(\vec{x}) \;\Rightarrow\; \langle \delta\delta' \rangle$$

How to convert a list of (θ_i, ϕ_i, z_i) to $\delta_g(\vec{x})$?

Case of **galaxies and quasars**

$$(\theta_i, \phi_i, z_i) \rightarrow \delta_g(\vec{x}) \rightarrow \langle \delta\delta' \rangle$$

Galaxy overdensity field: $$\delta_g(\vec{x}) = \frac{n_g(\vec{x})}{\bar{n}_g} - 1$$

How to convert a list of (θ_i, ϕ_i, z_i) to $\delta_g(\vec{x})$?

Case of **galaxies and quasars**

$$(\theta_i, \phi_i, z_i) \rightarrow \delta_g(\vec{x}) \rightarrow \langle \delta\delta' \rangle$$

Galaxy overdensity field:

$$\delta_g(\vec{x}) = \frac{n_g(\vec{x})}{\bar{n}_g} - 1$$

How to compute $n_g(\vec{x})$?

How to compute $\bar{n}_g \equiv \langle n(\vec{x}) \rangle$?

How to convert a list of $\left(\theta_i, \phi_i, z_i\right)$ to $\delta_g(\vec{x})$?

Case of **galaxies and quasars**

$$\left(\theta_i, \phi_i, z_i\right) \Rightarrow \delta_g(\vec{x}) \Rightarrow \langle \delta\delta' \rangle$$

Galaxy overdensity field:

$$\delta_g(\vec{x}) = \frac{n_g(\vec{x})}{\bar{n}_g} - 1$$

How to compute $n_g(\vec{x})$?

We only want cosmological fluctuations !

How to compute $\bar{n}_g \equiv \langle n(\vec{x}) \rangle$?

How to convert a list of (θ_i, ϕ_i, z_i) to $\delta_g(\vec{x})$?

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Galaxy overdensity field:

$$\delta_g(\vec{x}) = \frac{n_g(\vec{x})}{\bar{n}_g} - 1$$

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We only want cosmological fluctuations !

How to compute $\bar{n}_g \equiv \langle n(\vec{x}) \rangle$?

But...

- Survey area and masks
- Observational completeness
- Fake overdensities caused by photometry
- Collisions of fibers
- Spectra without redshifts

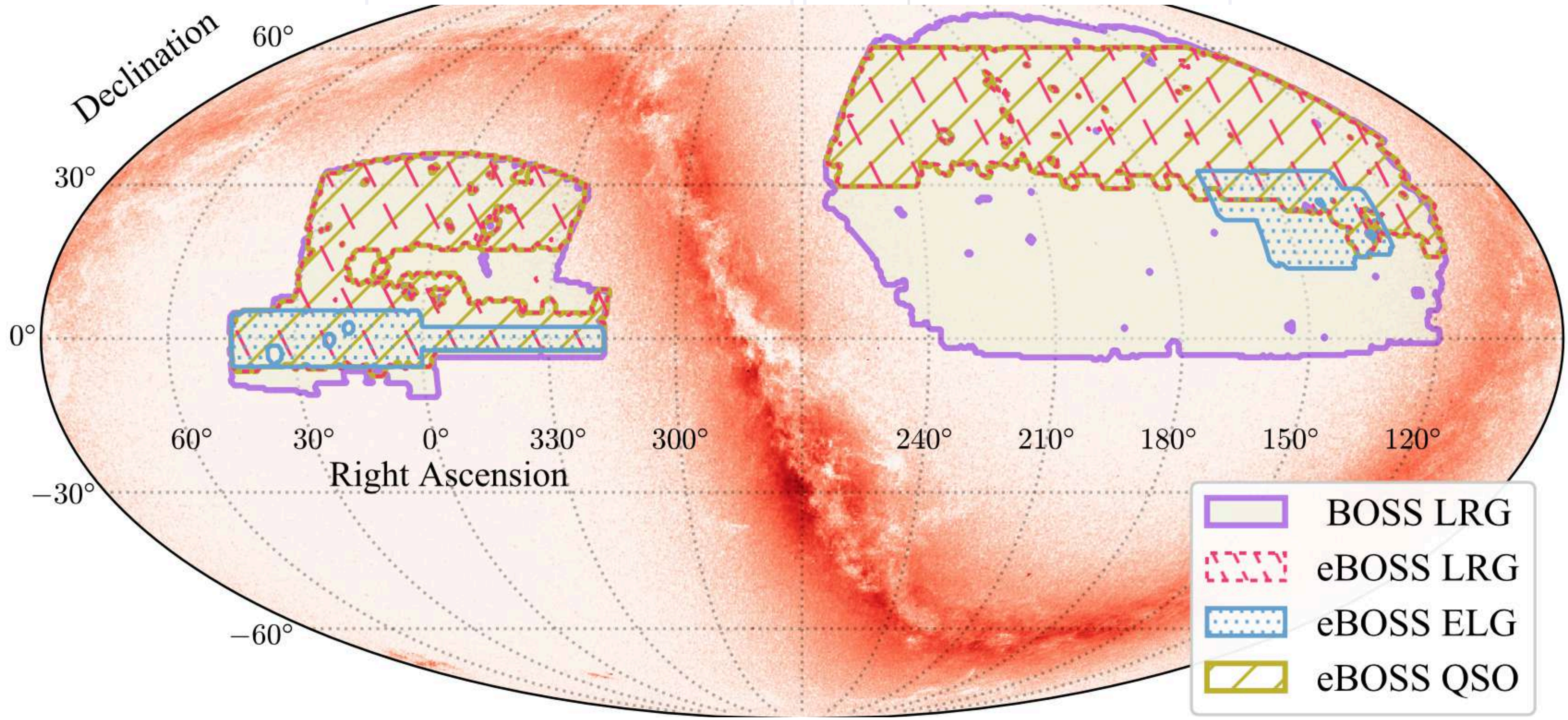
Survey area and masks

Observational completeness

Fake overdensities caused by photometry

Collisions

Spectra without



The sky area is described by a random (unclustered) set of points

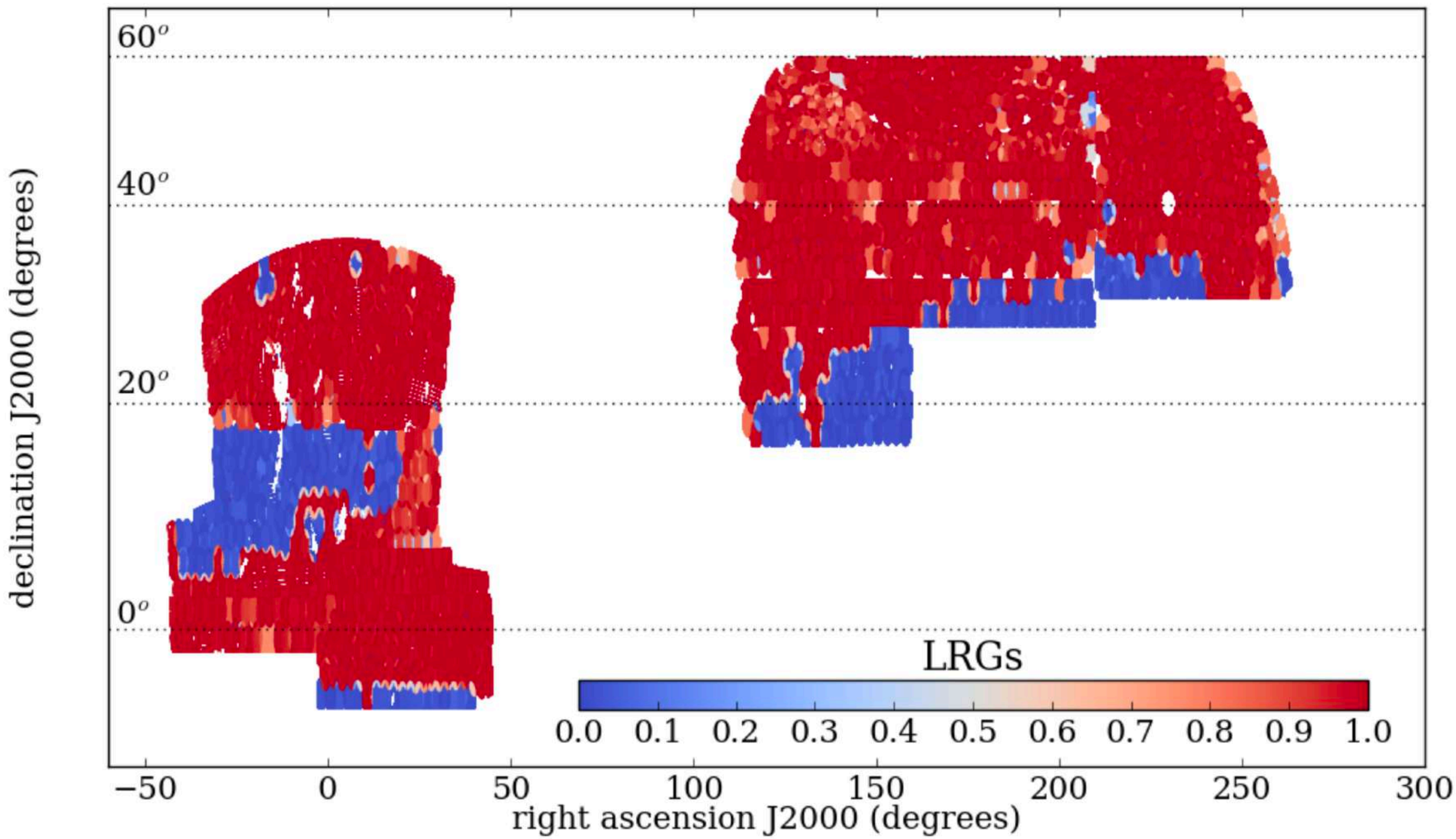
Not all targets receive a fiber = fiber completeness

Survey area and masks

Observational completeness

Fake overdensities caused by photometry

Not all targets receive a fiber = fiber completeness

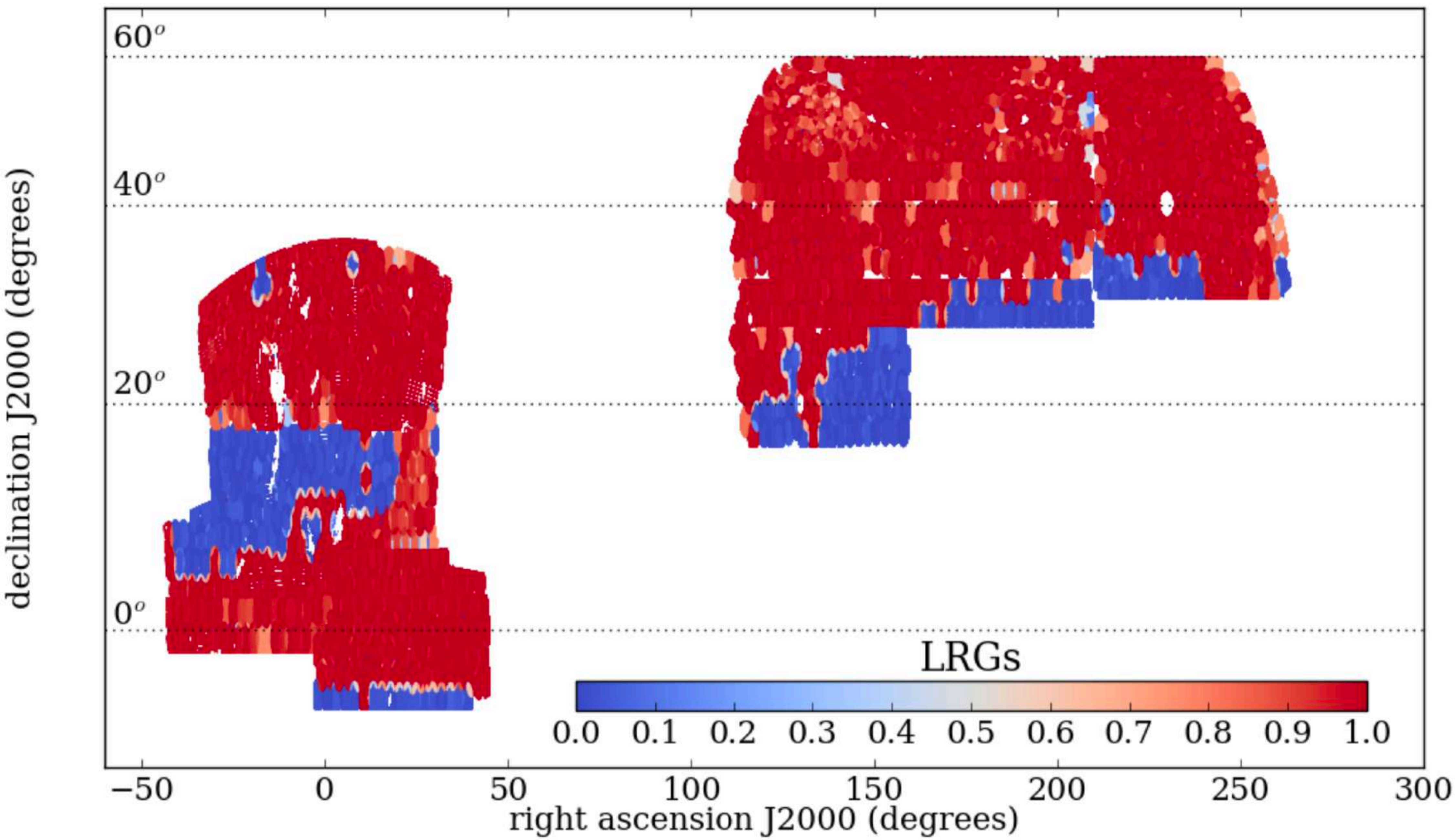


Survey area and masks

Observational completeness

Fake overdensities caused by photometry

Not all targets receive a fiber = fiber completeness



Randoms are subsampled or weighted by the fiber completeness

Ross, JB, et al. 2020

Survey area and masks

Observational completeness

Fake overdensities caused by photometry

Collisions of fibers

Spectra without redshifts

Survey area and masks

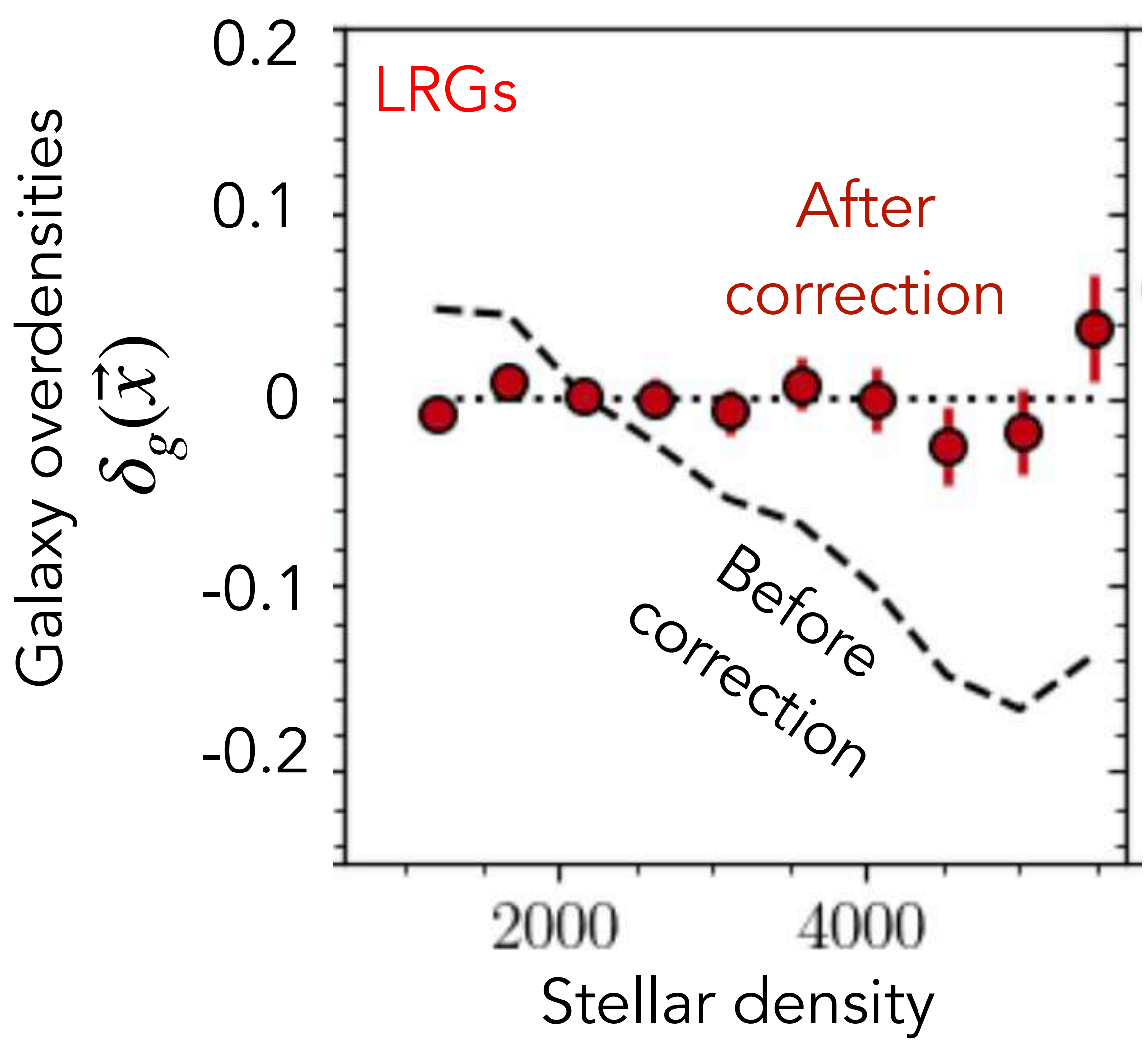
Observational completeness

Fake overdensities caused by photometry

Collisions of fibers

Spectra without redshifts

Spurious non-cosmological fluctuations



Ross, JB, et al. 2020

Survey area and masks

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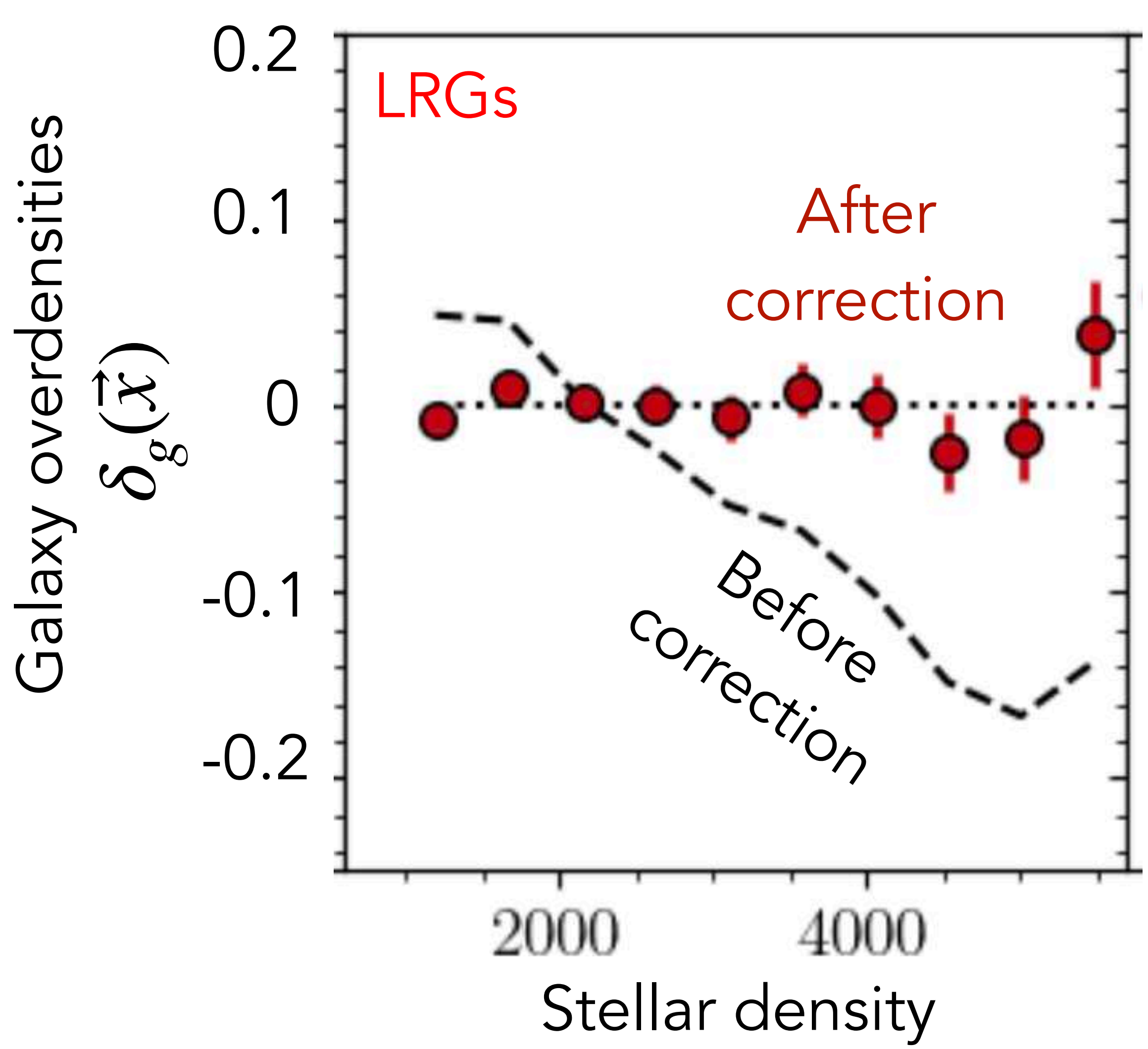
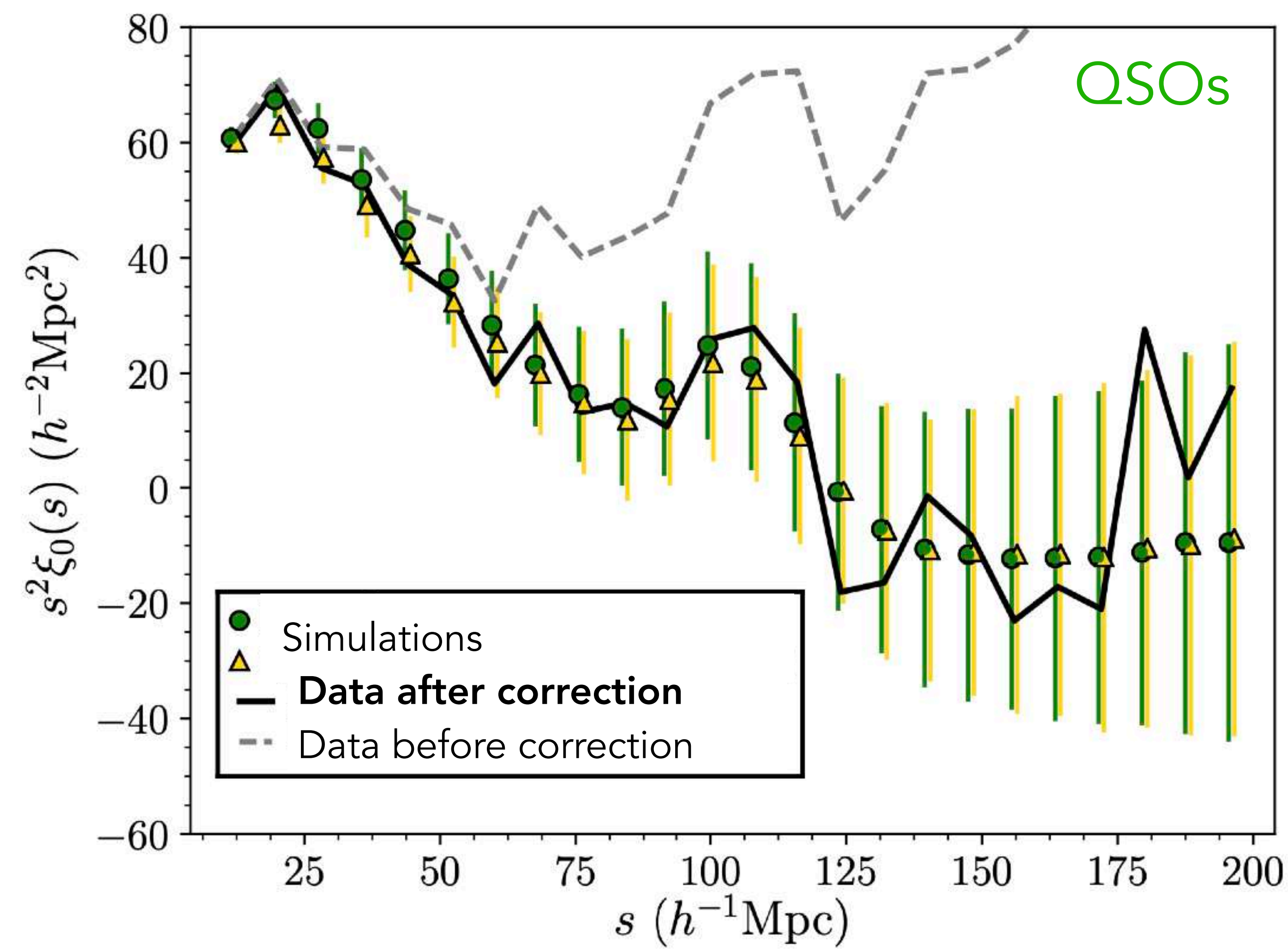


Ross, JB, et al. 2020

Effect on correlation function

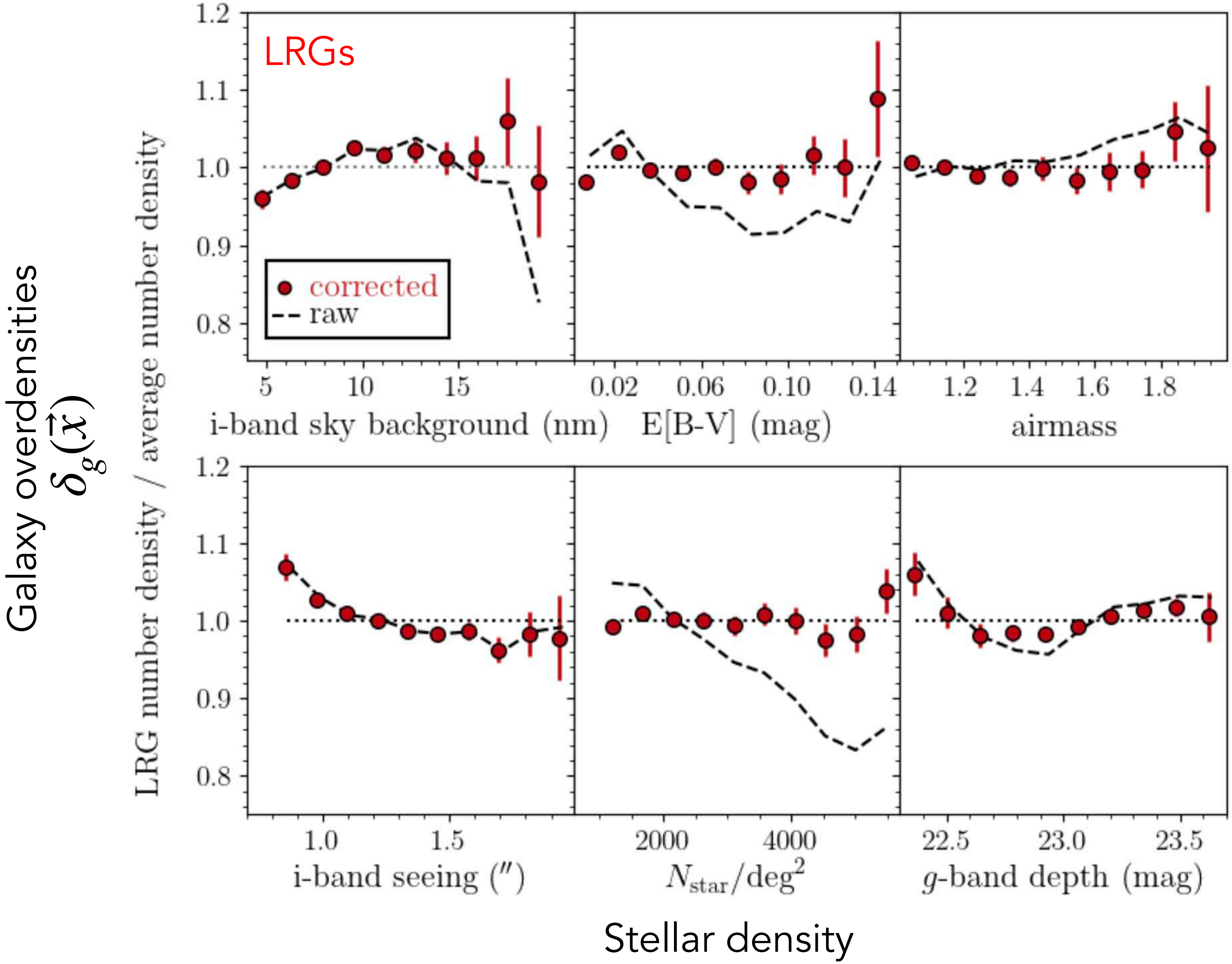


Ata et al. 2018

Survey area and masks

Observational completeness

Fake overdensities caused by photometry



Correction method 1: Simultaneous linear fit of trends

Survey area and masks

Observational completeness

Fake overdensities caused by photometry

Collisions of fibers

Spectra without redshifts

Correction method 1: Simultaneous linear fit of trends

Correction method 2 : Machine learning

Survey area and masks

Observational completeness

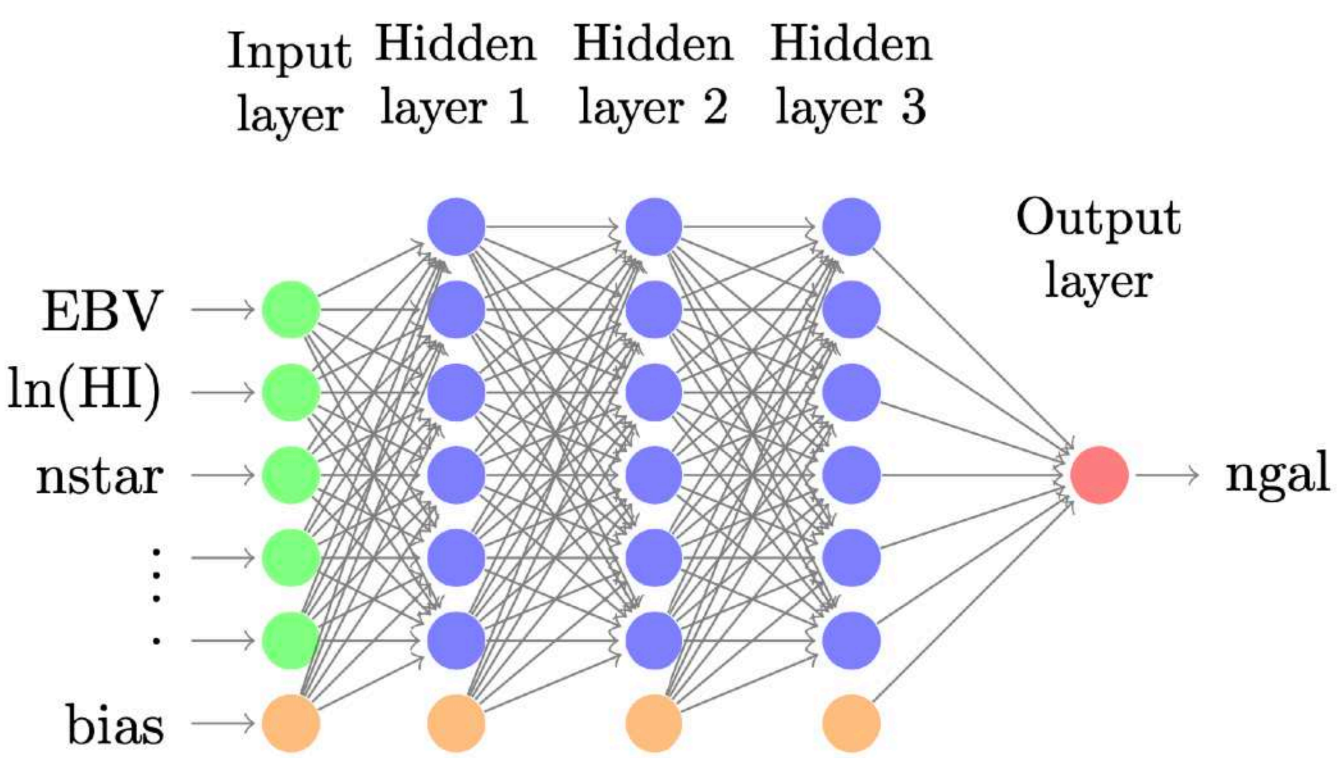
Fake overdensities caused by photometry

Collisions of fibers

Spectra without redshifts

Correction method 1: Simultaneous linear fit of trends

Correction method 2 : Machine learning



Rezaie et al. 2020

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Observational completeness

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Spectra without redshifts

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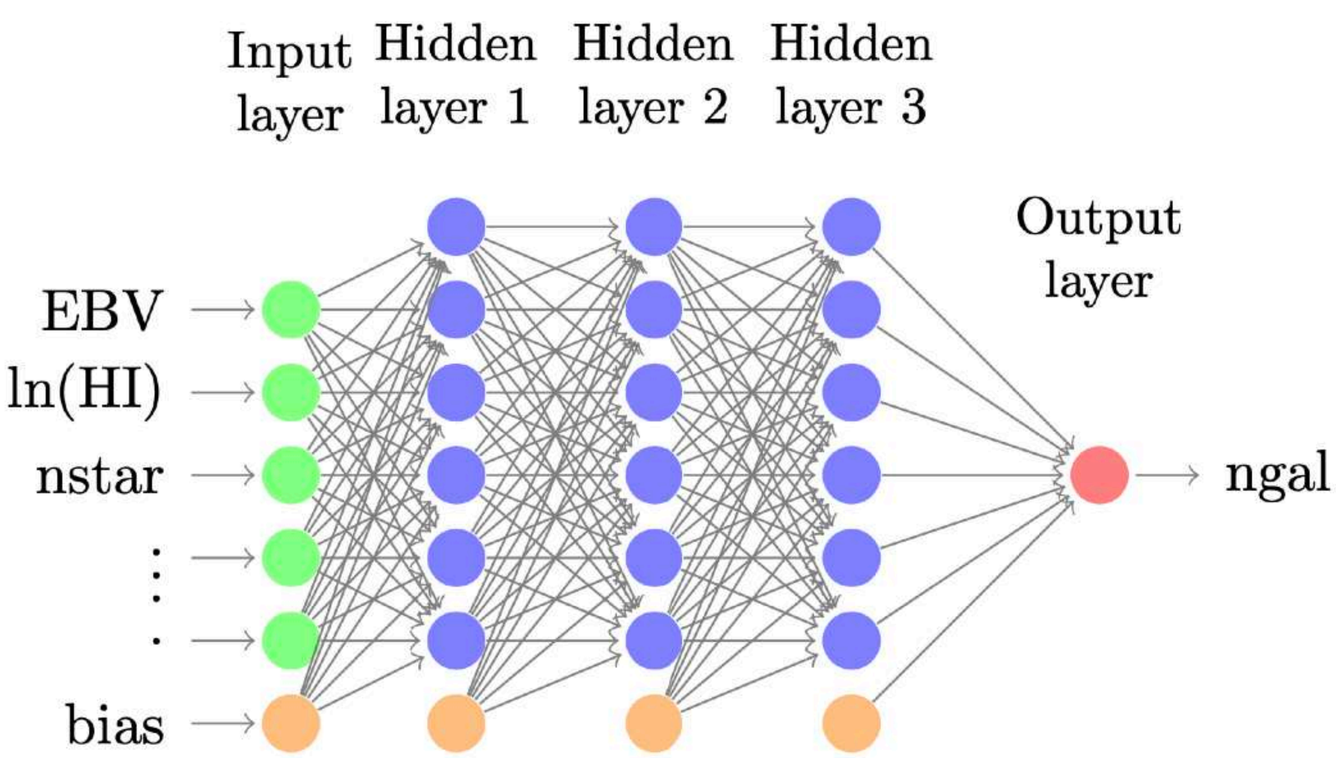
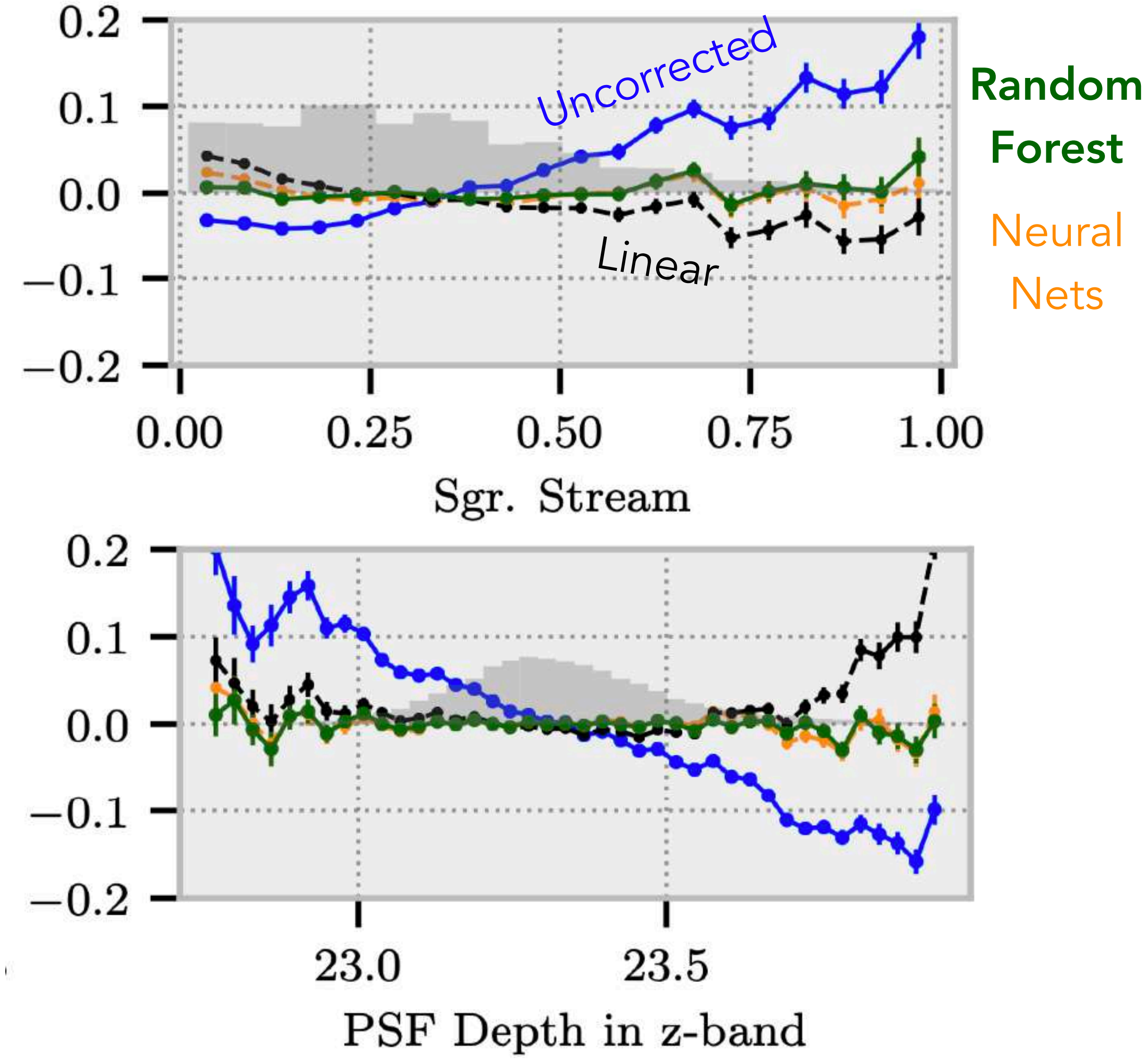


Rezaie et al. 2020



Chaussidon et al. 2021

Survey area and masks

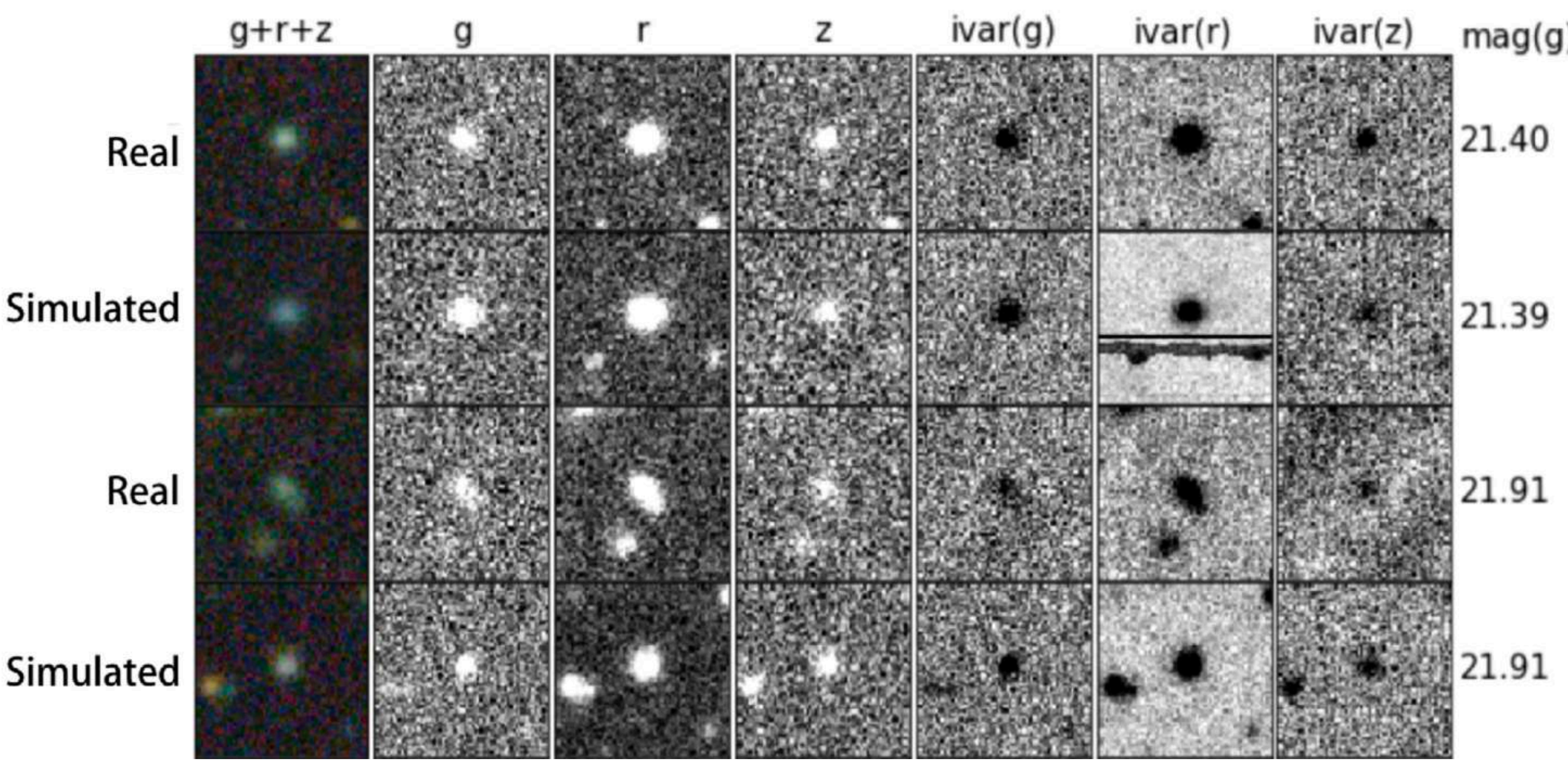
Observational completeness

Fake overdensities caused by photometry

Correction method 1: Simultaneous linear fit of trends

Correction method 2 : Machine learning

Correction method 3 : Simulate photometry



Spurious trends appear naturally !

Obiwan - Kong et al. 2020

Survey area and masks

Observational completeness

Fake overdensities caused by photometry

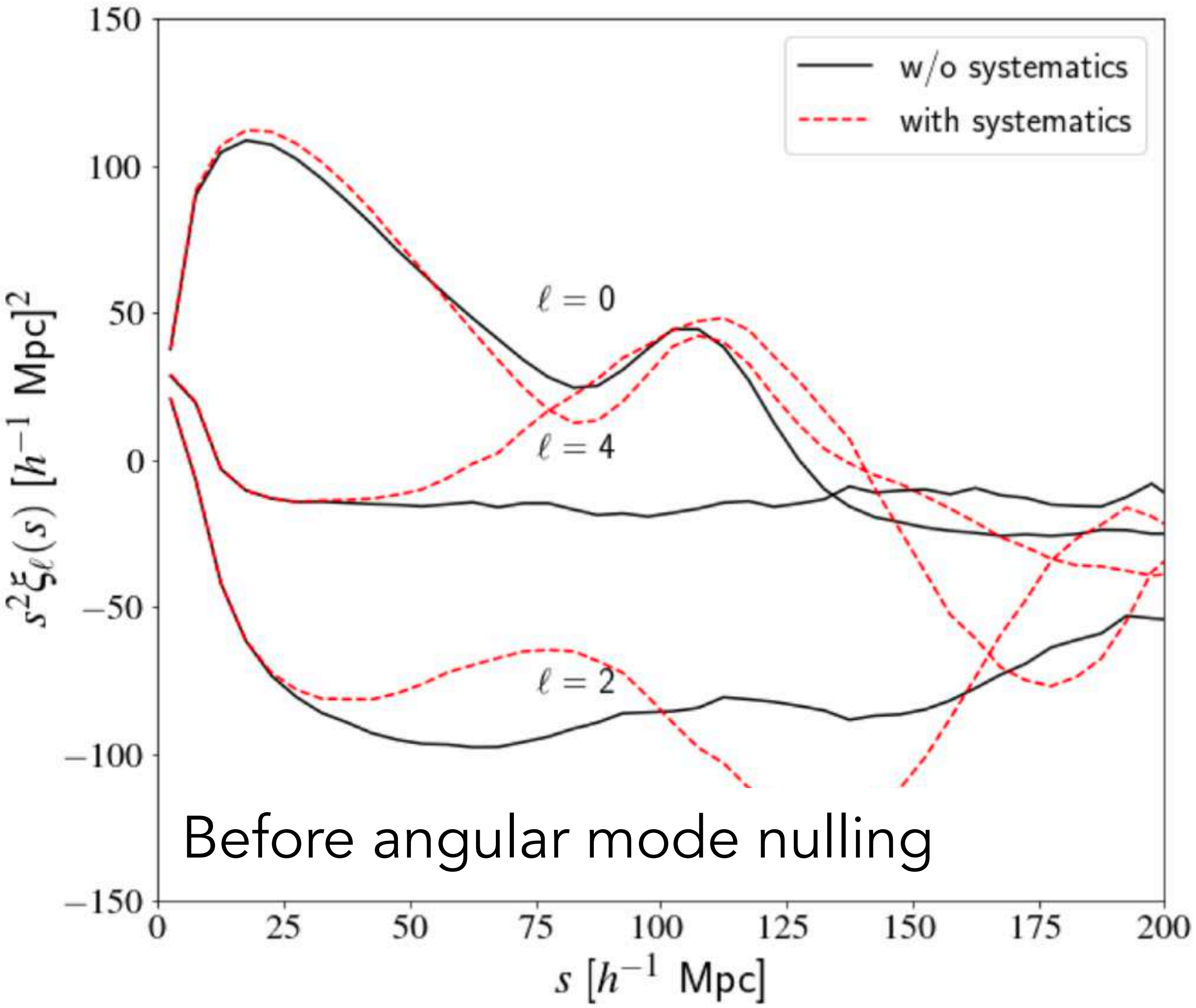
Correction method 1: Simultaneous linear fit of trends

Correction method 2 : Machine learning

Correction method 3 : Simulate photometry

Correction method 4 : Mode projection/nulling

Remove angular modes that are contaminated



Elsner et al. 2016; Paviot et al. 2021 and references therein

Survey area and masks

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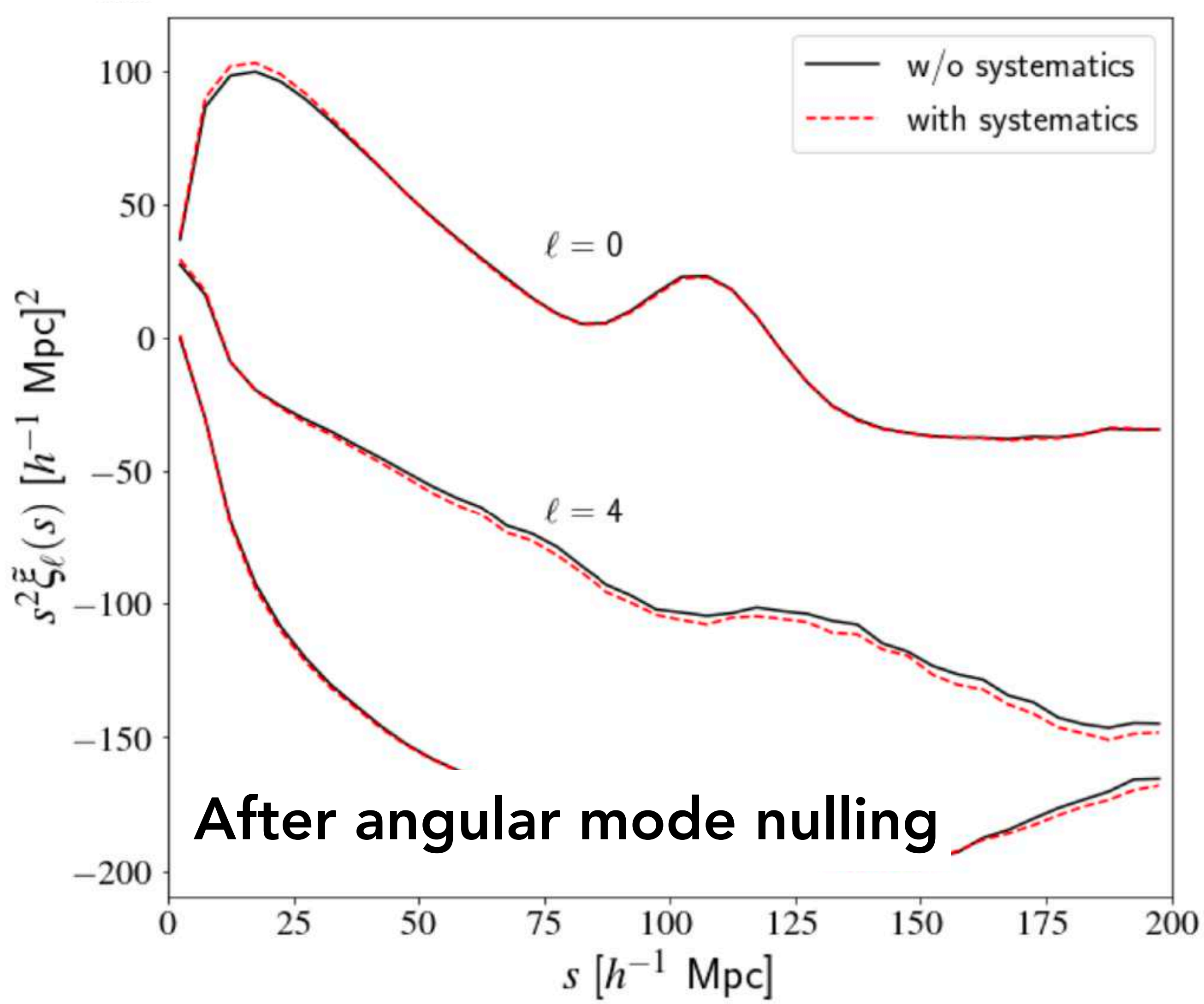

Survey area and masks

Observational completeness

Fake overdensities caused by photometry

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Spectra without redshifts

Survey area and masks

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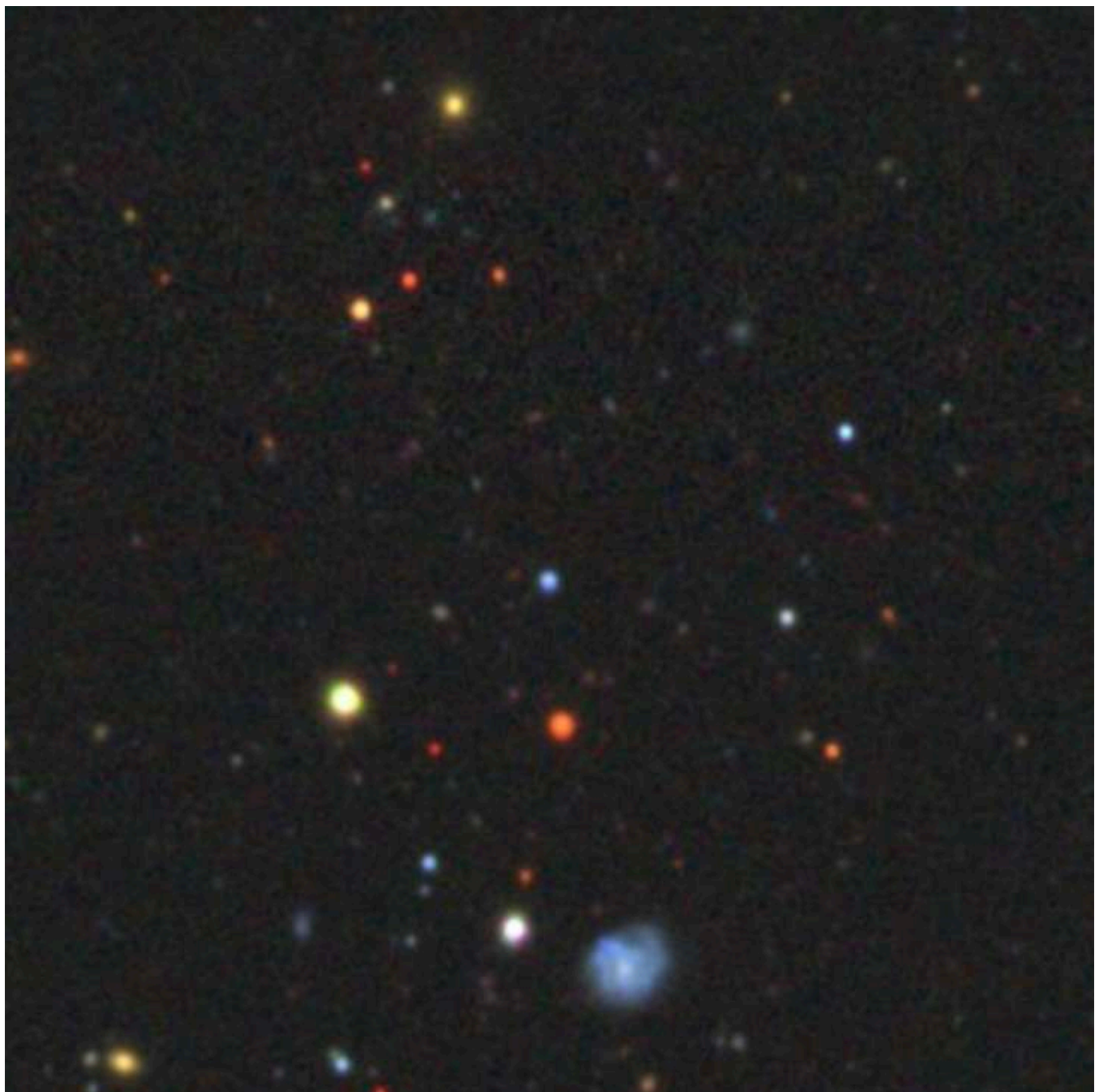


Missing pairs of galaxies due to physical size of optical fibers !

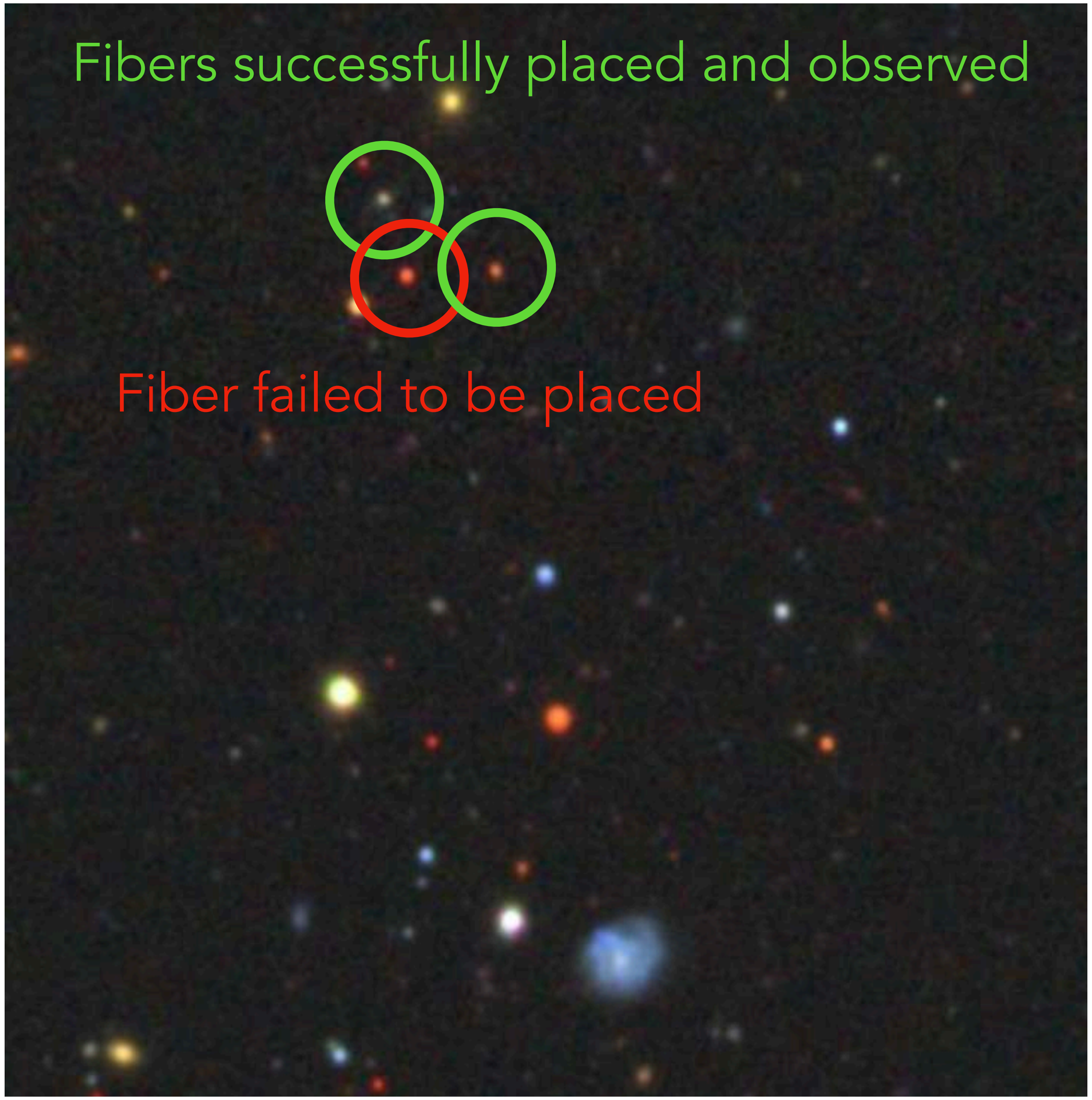
Survey area and masks

Observational completeness

Fake overdensities caused by photometry

Collisions of fibers

Spectra without redshifts



Missing pairs of galaxies due to physical size of optical fibers !

Survey area and masks

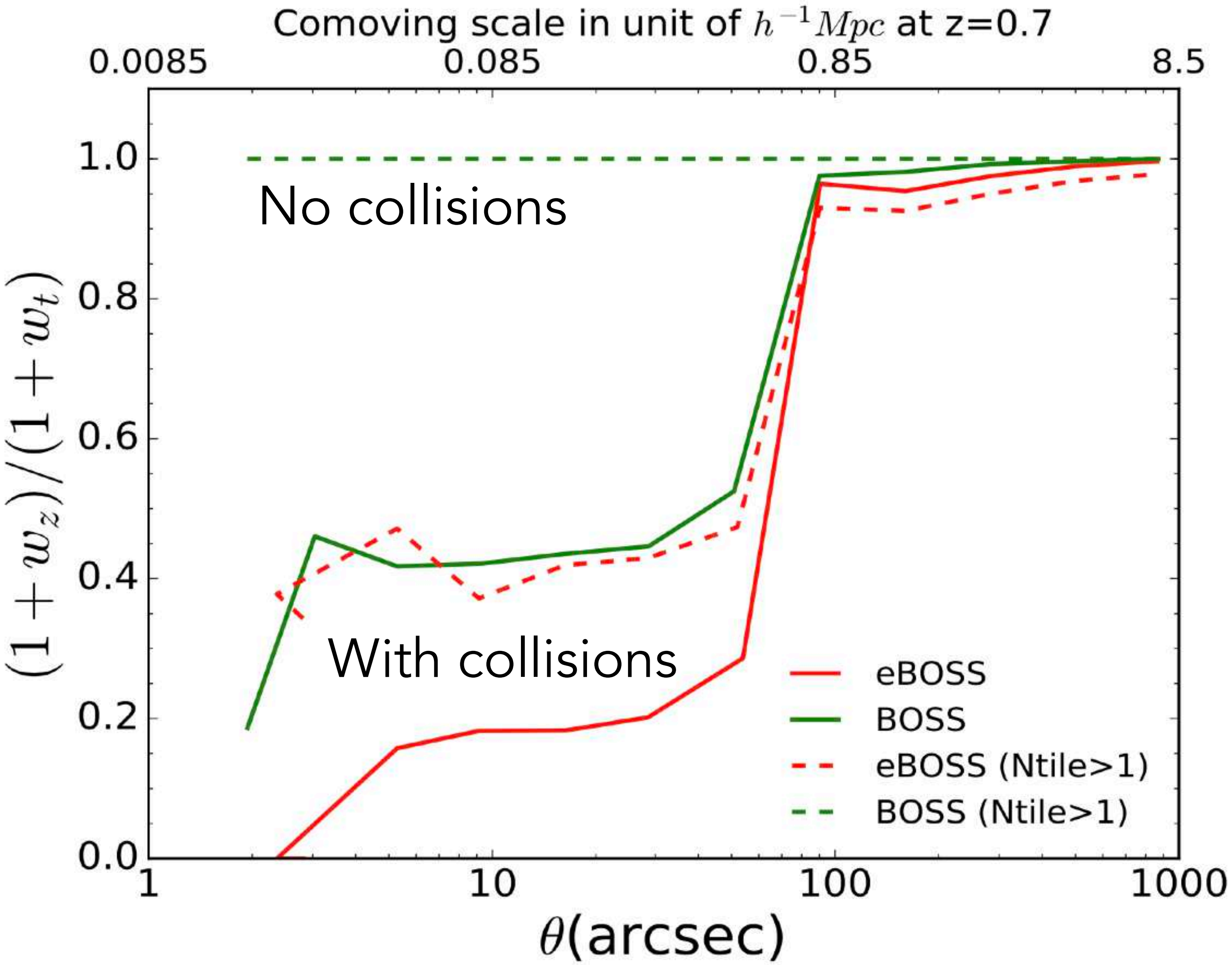
Observational completeness

Fake overdensities caused by photometry

Collisions of fibers

Spectra without redshifts

Impacts clustering on small angular separations



Zhai et al. 2017

Survey area and masks

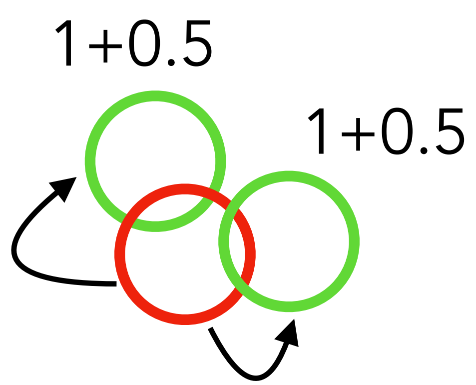
Observational completeness

Fake overdensities caused by photometry

Collisions of fibers

Spectra without redshifts

Correction method 1 : upweight nearest neighbours



Survey area and masks

Observational completeness

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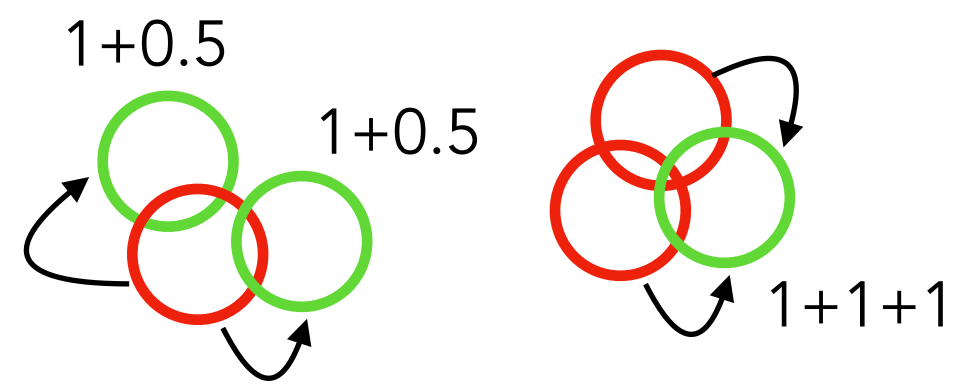

Survey area and masks

Observational completeness

Fake overdensities caused by photometry

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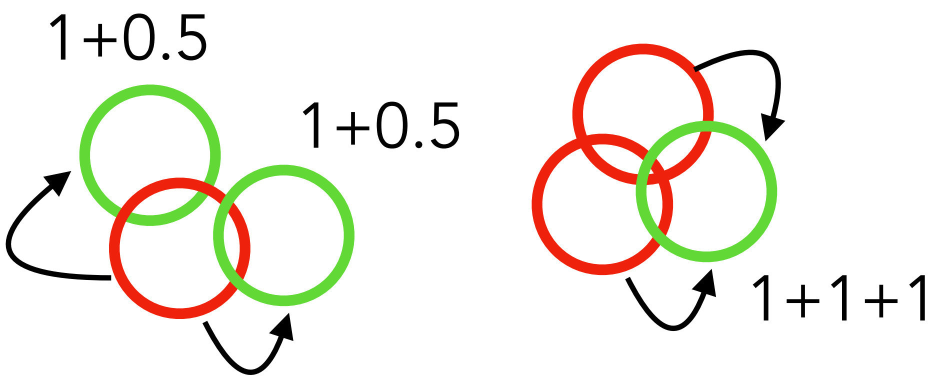
Spectra without redshifts

Correction method 1 : upweight nearest neighbours

Assumes missing galaxy is physically close angularly (ok) and radially (strong assumption!)



Survey area and masks

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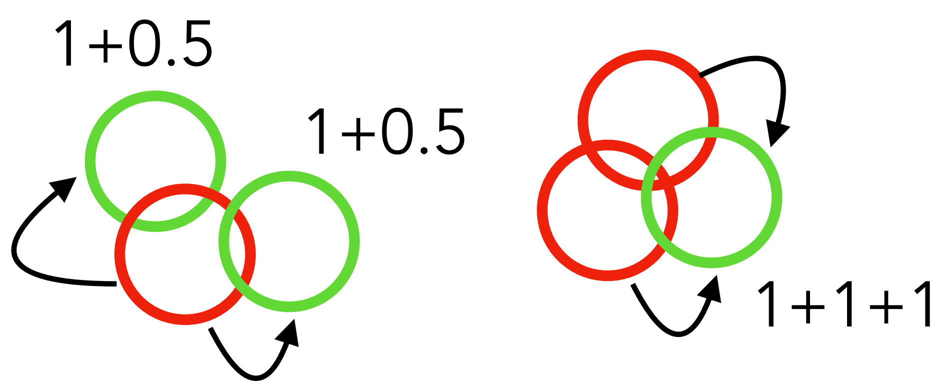

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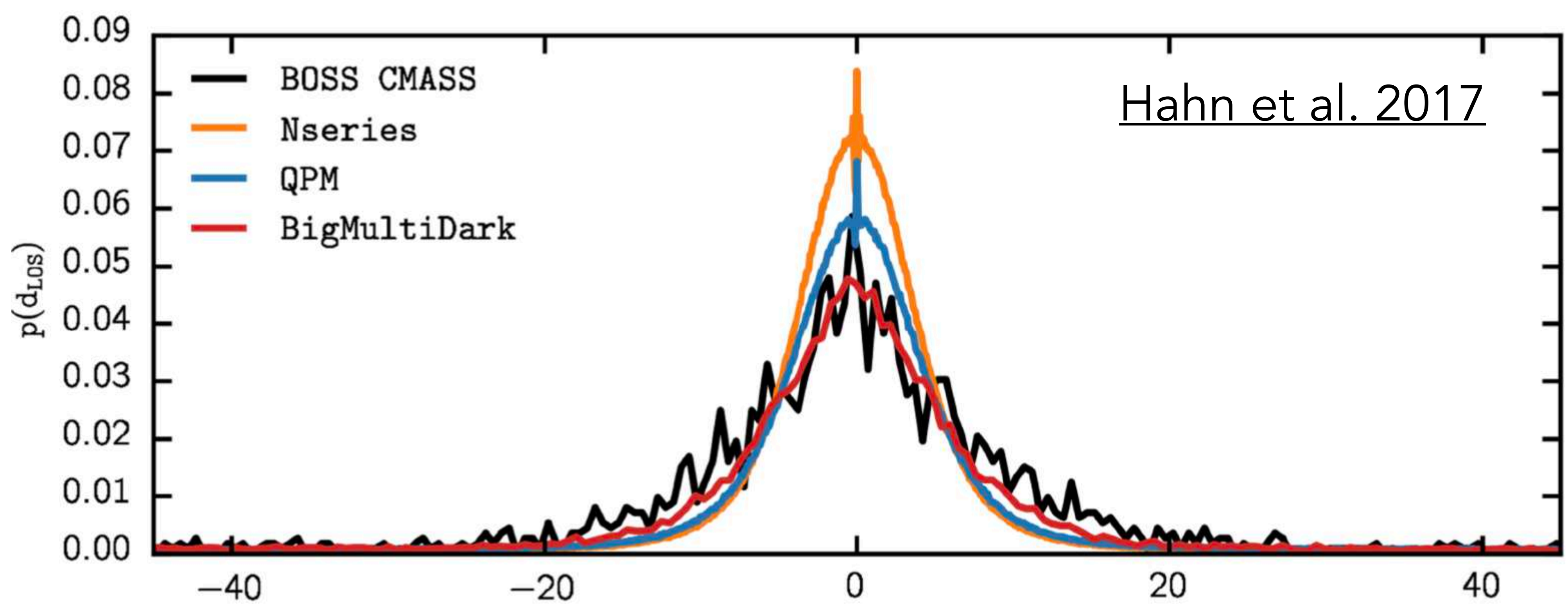

Radial distance between pairs [Mpc]

Collisions of fibers

Spectra without redshifts

Correction method 1 : upweight nearest neighbours

Correction method 2 : model "collisioned" clustering Hahn et al. 2017

$$\frac{1+\xi^{\rm coll}(\vec{r})}{1+\xi^{\rm true}(\vec{r})} \equiv 1 - f_s W_{\rm coll}(\vec{r})$$

and Fourier Transform to obtain model for $P^{\rm coll}(\vec{k})$

Collisions of fibers

Spectra without redshifts

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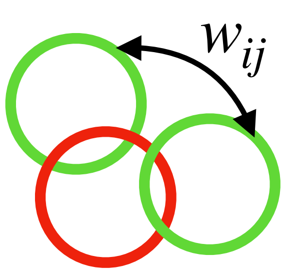
Correction method 3 : use pairwise weighting   Bianchi & Percival 2017



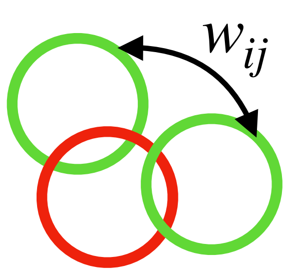
Each galaxy pair has a weight $w_{ij} \neq w_i w_j$
defined as the inverse probability of it being observed

Correction method 1 : upweight nearest neighbours

Correction method 2 : model "collisioned" clustering Hahn et al. 2017

$$\frac{1+\xi^{\mathrm{coll}}(\vec{r})}{1+\xi^{\mathrm{true}}(\vec{r})} \equiv 1 - f_s W_{\mathrm{coll}}(\vec{r})$$ and Fourier Transform to obtain model for $P^{\mathrm{coll}}(\vec{k})$

Correction method 3 : use pairwise weighting Bianchi & Percival 2017



Each galaxy pair has a weight $w_{ij} \neq w_i w_j$
defined as the inverse probability of it being observed

Requires running tiling algorithm several times to compute probabilities

Currently used in DESI

Collisions of fibers	Spectra without redshifts

Correction method 1 : upweight nearest neighbours

Correction method 2 : model "collisioned" clustering Hahn et al. 2017

$$\frac{1+\xi^{\rm coll}(\vec{r})}{1+\xi^{\rm true}(\vec{r})} \equiv 1 - f_s W_{\rm coll}(\vec{r})$$ and Fourier Transform to obtain model for $P^{\rm coll}(\vec{k})$

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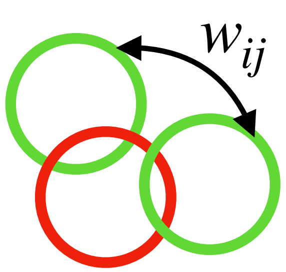

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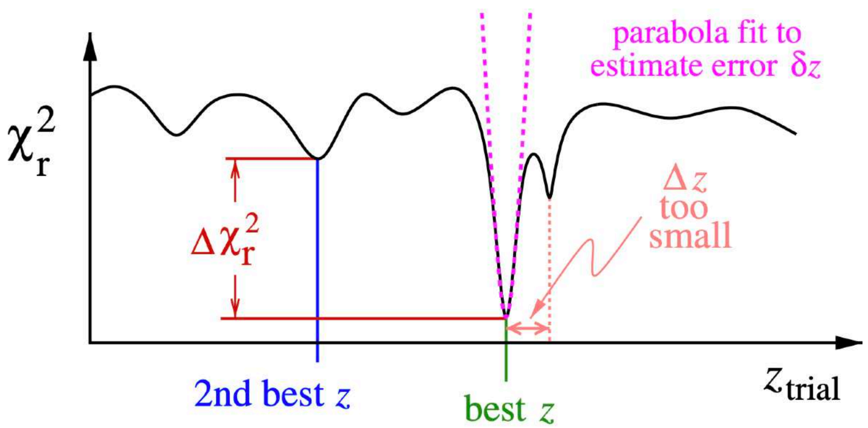
Currently used in DESI

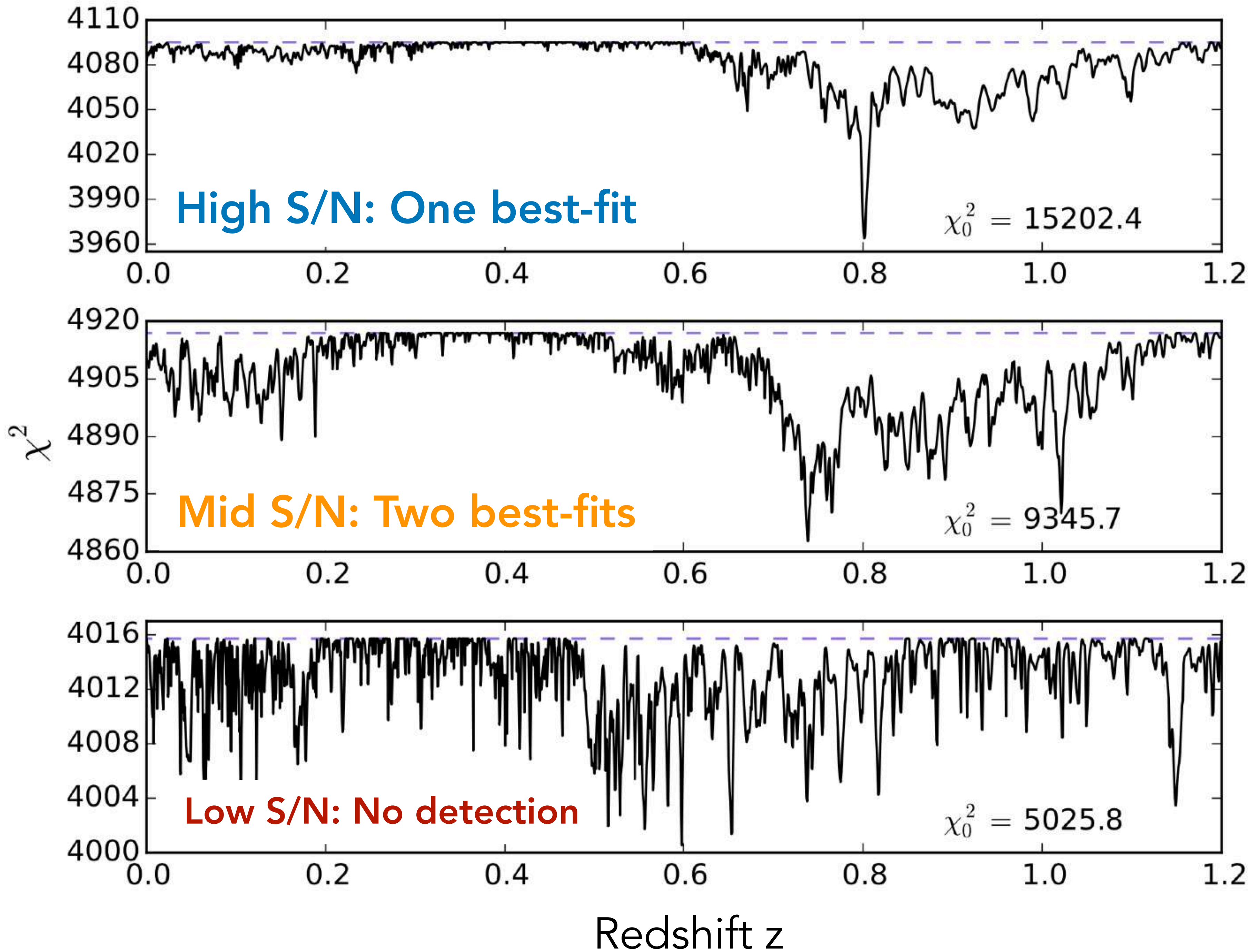
Is Euclid affected by "collisions" ? How to correct for them ?

Collisions of fibers

Spectra without redshifts

Some spectra have low S/N and do not yield a confident redshift





Collisions of fibers

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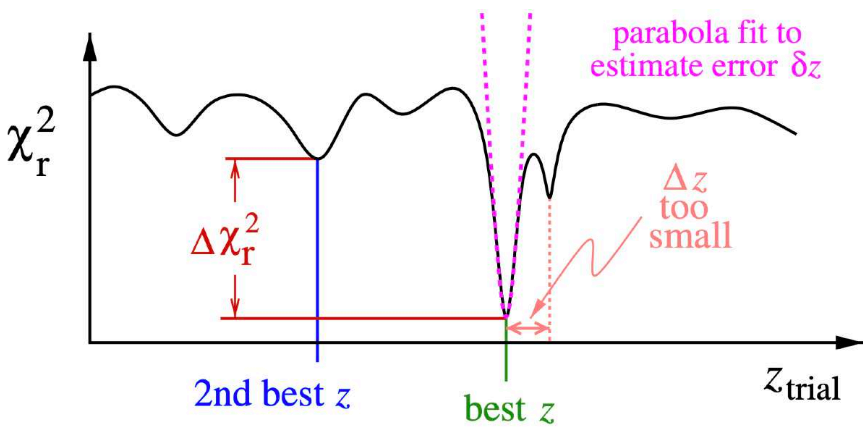
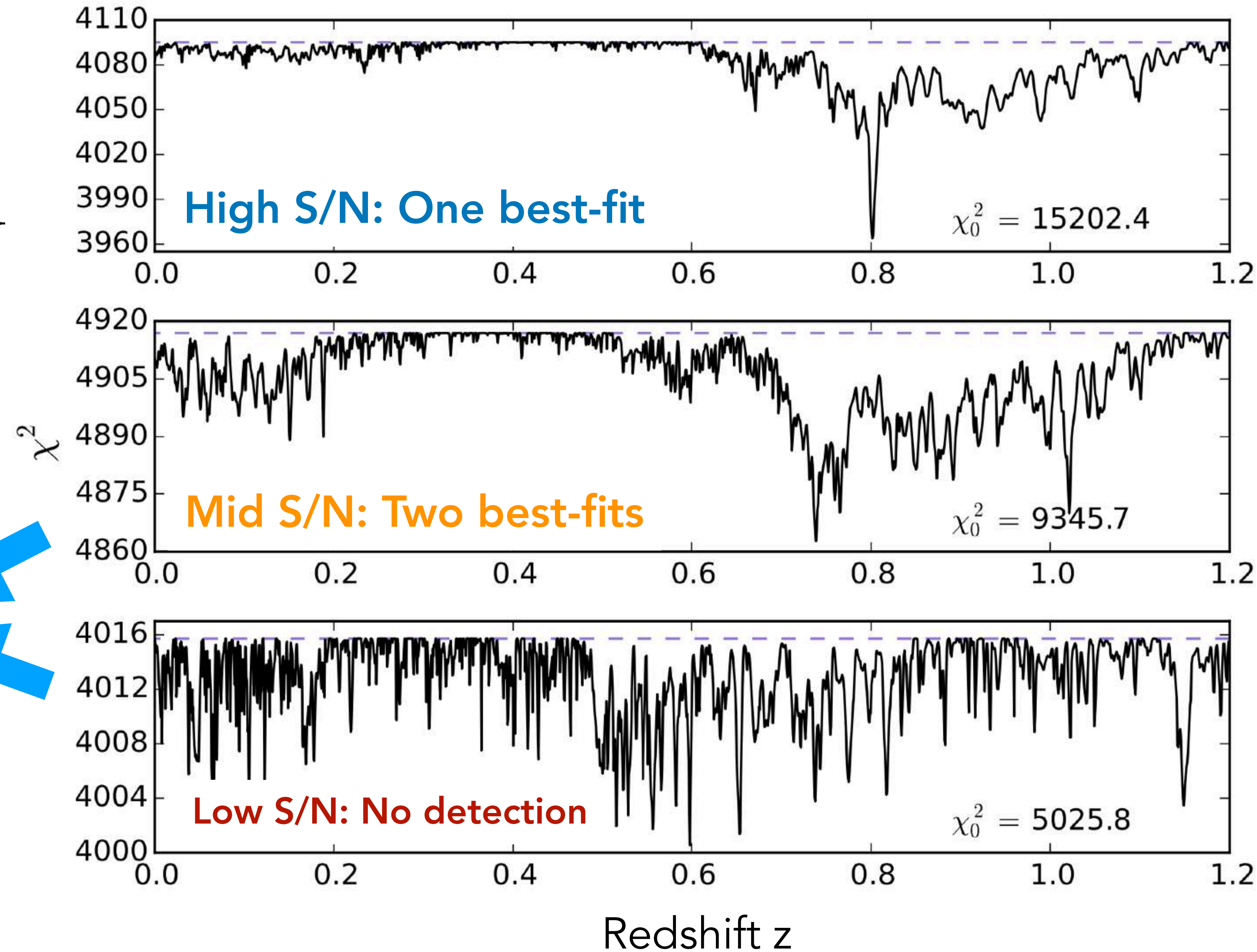


Redshift "failure"



Collisions
of fibers

Spectra without
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Collisions of fibers

Spectra without redshifts

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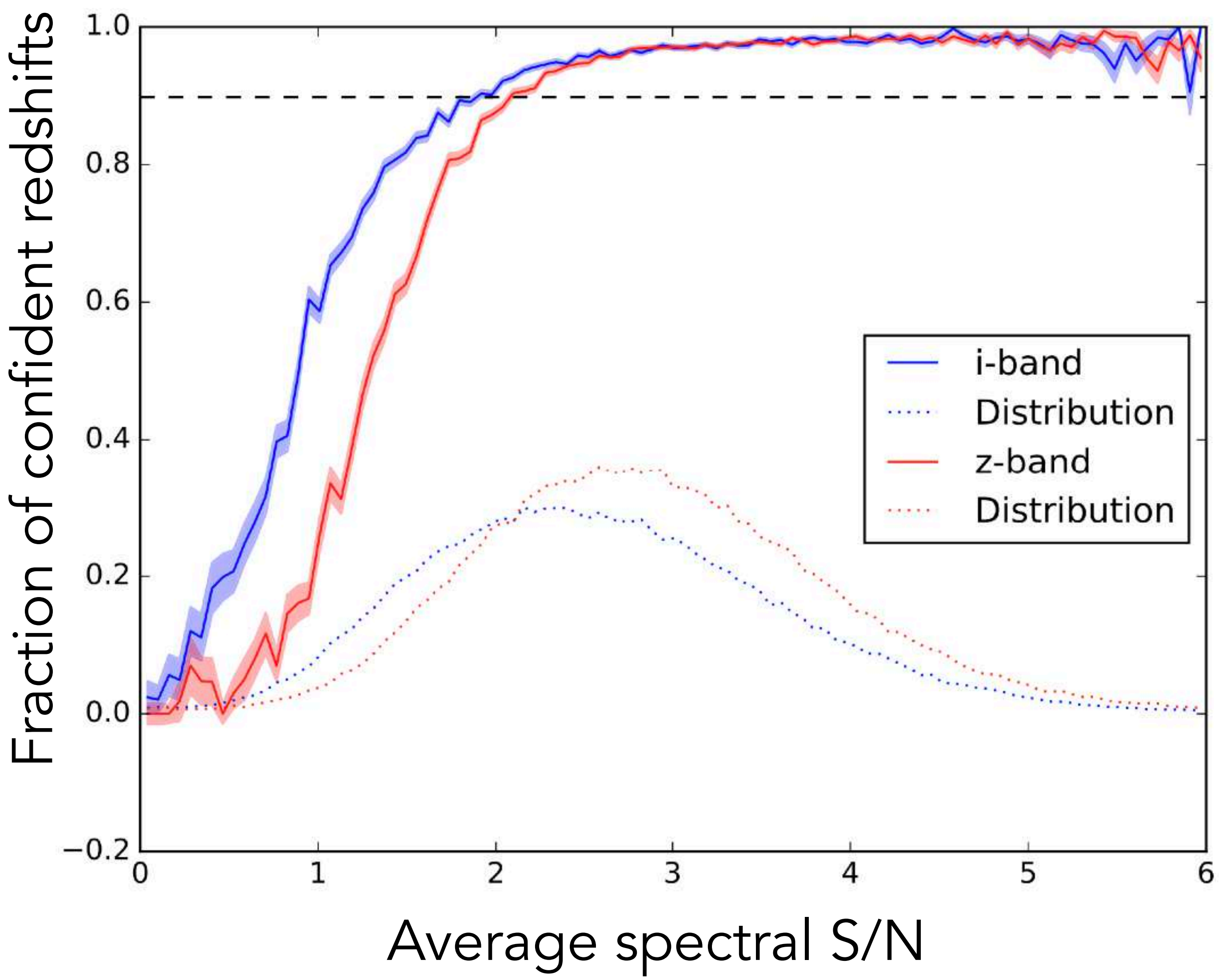

JB et al. 2018

Collisions of fibers

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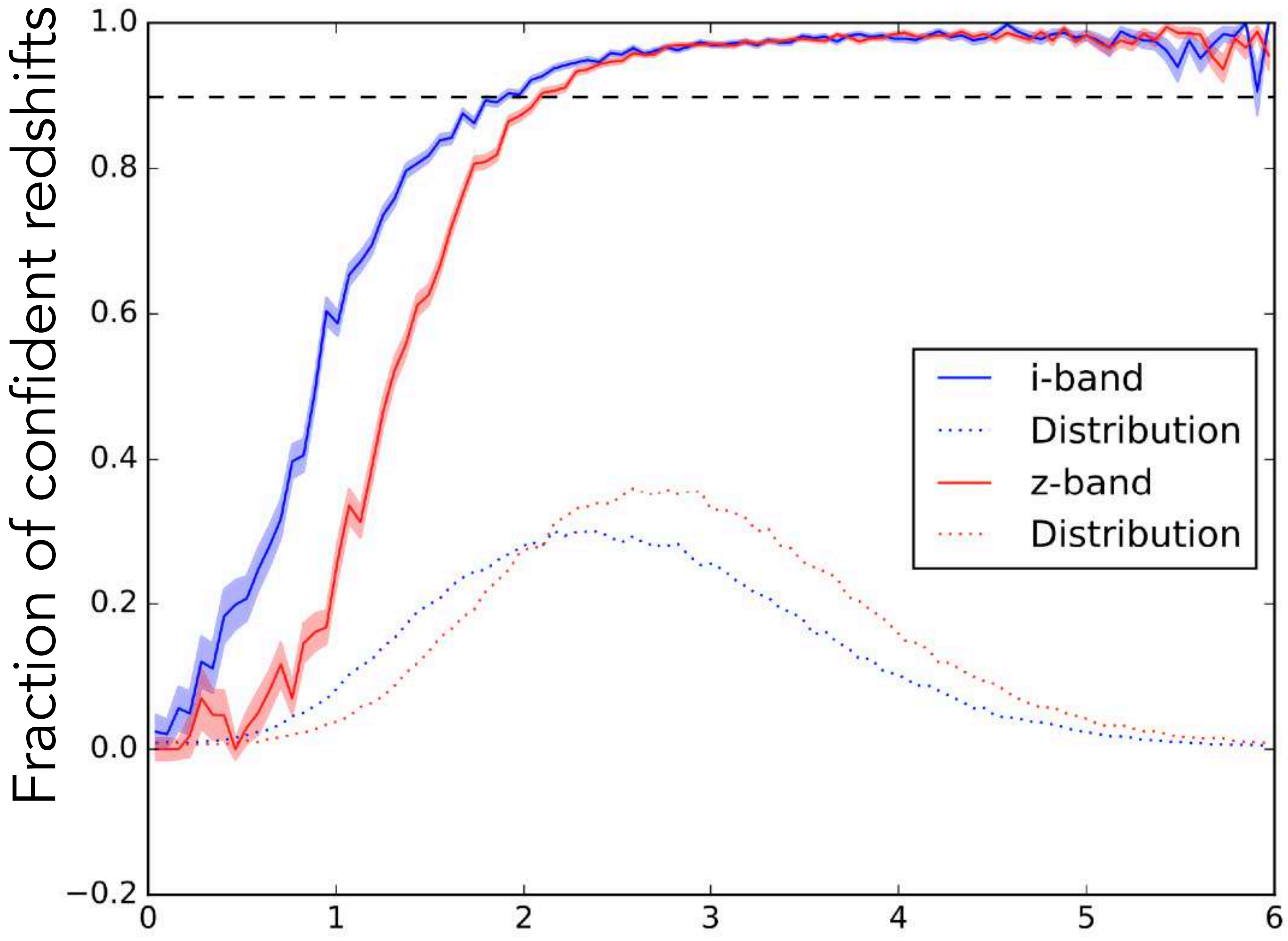
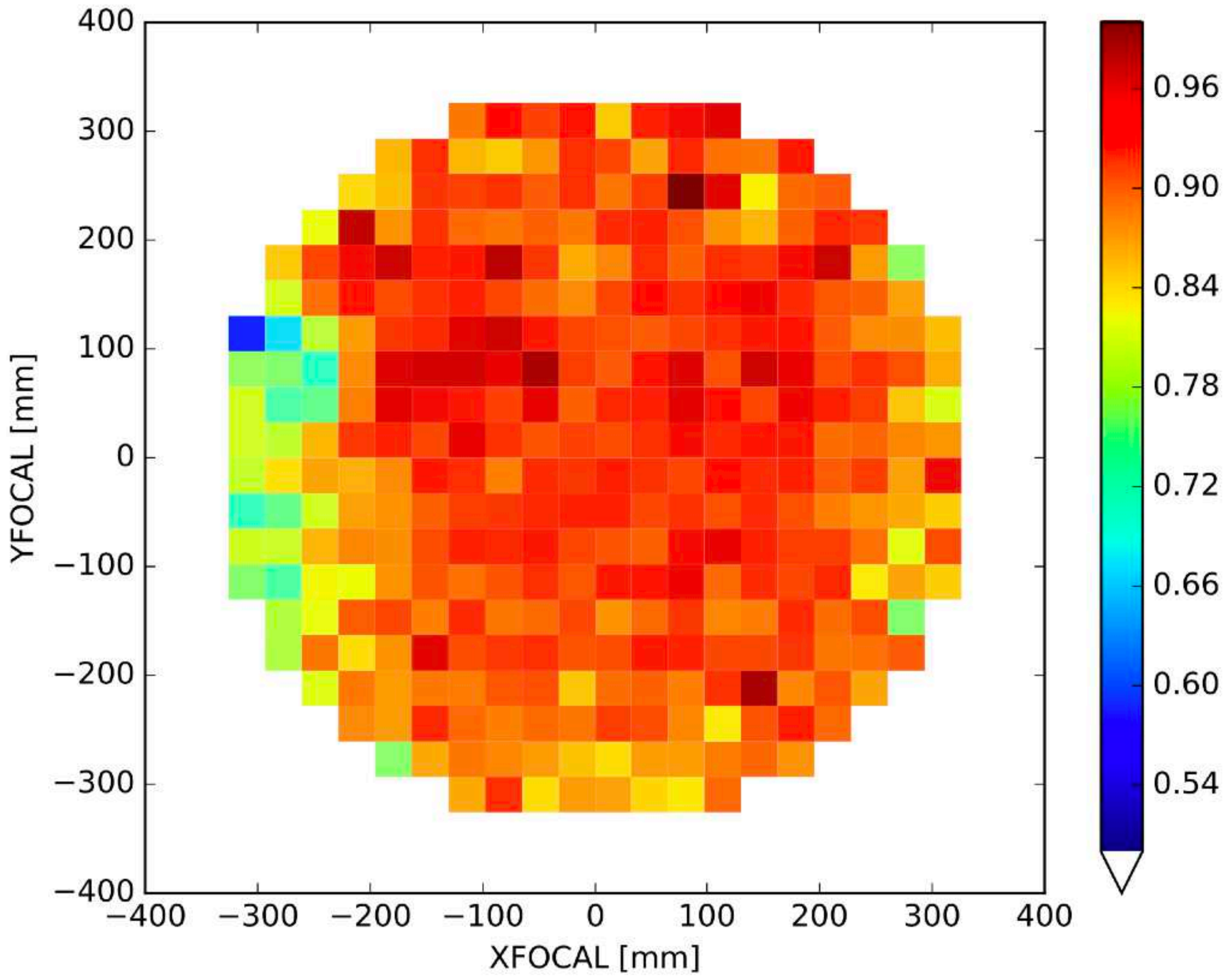


JB et al. 2018

Fraction of confident redshifts versus focal plane location



This pattern can bias clustering and are corrected using weights

How to convert a list of (θ_i, ϕ_i, z_i) to $\delta_g(\vec{x})$?

Case of **galaxies and quasars**

$$(\theta_i, \phi_i, z_i) \rightarrow \delta_g(\vec{x}) \rightarrow \langle \delta\delta' \rangle$$

Galaxy overdensity field:

$$\delta_g(\vec{x}) = \frac{n_g(\vec{x})}{\bar{n}_g} - 1$$

- Survey area and masks
- Observational completeness
- Fake overdensities caused by photometry
- Collisions of fibers
- Spectra without redshifts

Corrected using weights

Galaxies are weighted by $w_{\rm photo} w_{\rm coll} w_{\rm no-z}$

Randoms are weighted by $w_{\rm mask} w_{\rm comp}$

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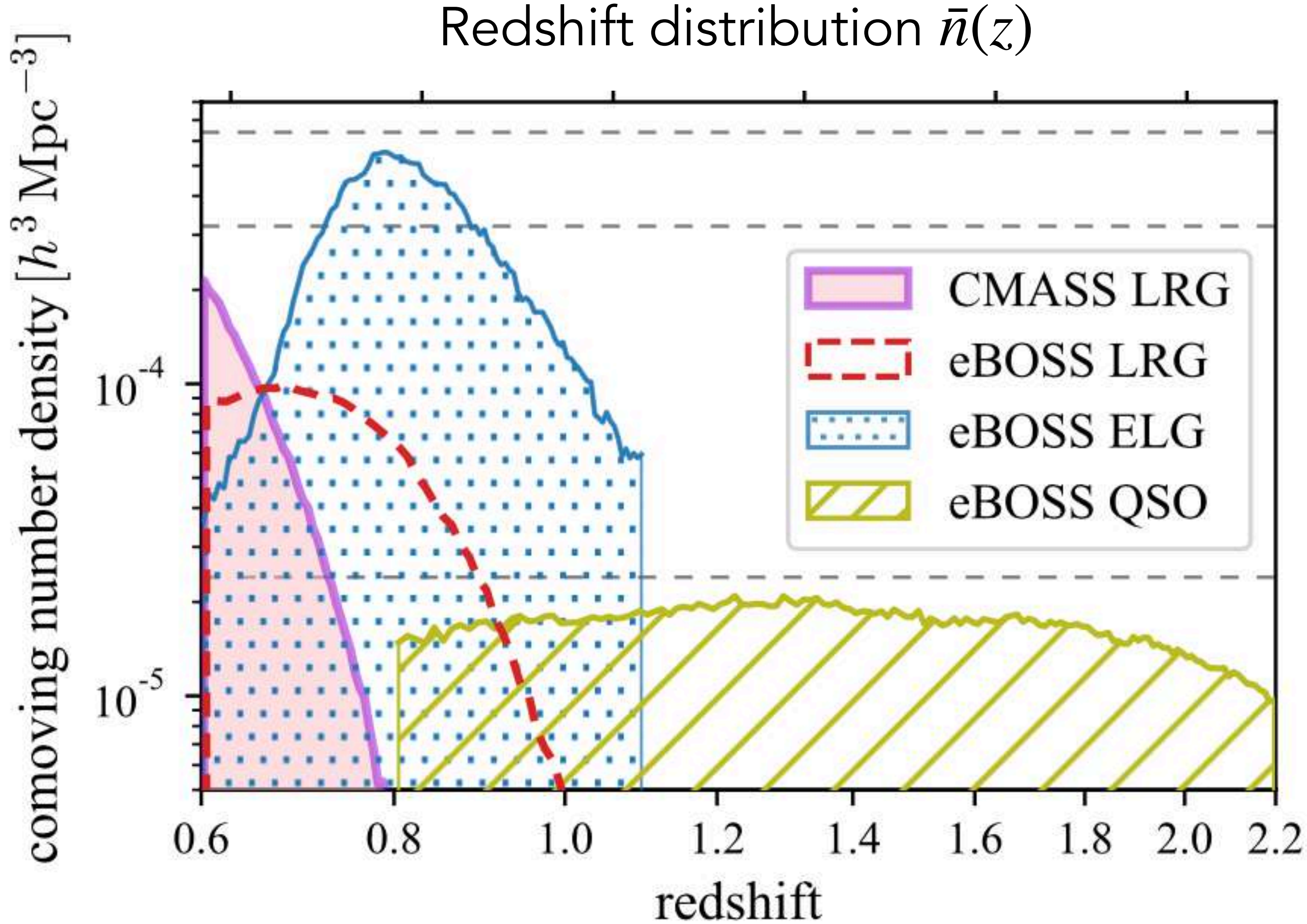
Redshift distribution $\bar{n}(z)$



Zhao et al. 2021

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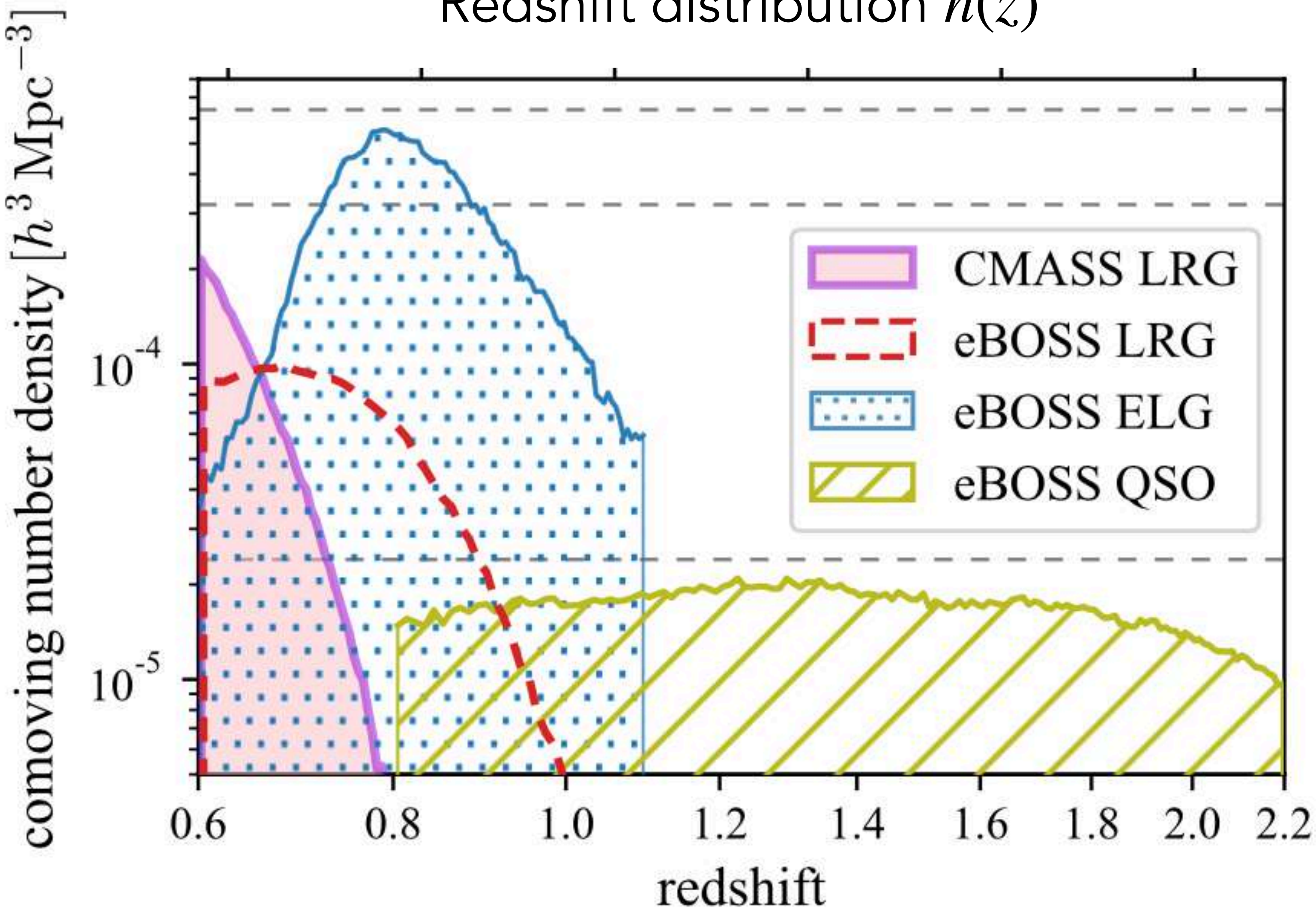

Zhao et al. 2021

Optimal weights for clustering:

FKP weights

Feldman, Kaiser & Peacock 1994

$$w_{\mathrm{FKP,i}} = \frac{1}{1 + \bar{n}(z_i)P(k_0)}$$

$P(k_0)$ is power spectrum at some scale of interest (usually $k_0 \sim 0.02\ h\mathrm{Mpc}^{-1}$)

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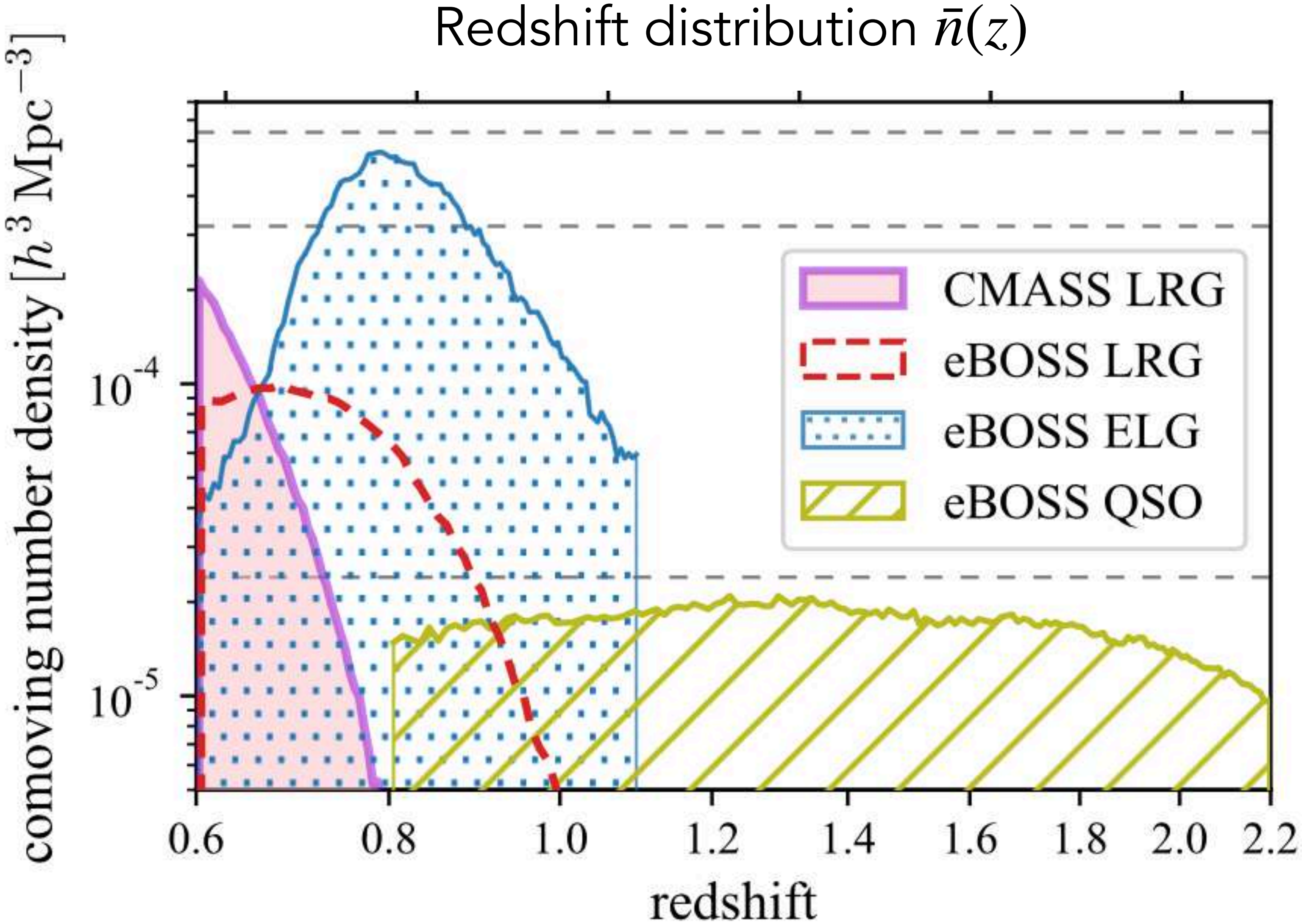

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➡ $\delta_g(\vec{x})$

From spectra to clustering

$\left(\theta_i, \phi_i, z_i\right) \rightarrow \delta_g(\vec{x}) \rightarrow \langle \delta\delta' \rangle$

How to convert a list of $\left(\theta_i, \phi_i, z_i\right)$ to $\delta_g(\vec{x})$?

Case of **galaxies and quasars**

How to convert a list of $\left(\theta_i, \phi_i, z_i, \{f_j\}\right)$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$?

Case of **Lyman-α forests**

How to compute 2-pt statistics $\langle \delta(\vec{x})\delta(\vec{x}') \rangle$ from $\delta(\vec{x})$?

How to compute covariance/error-matrix for $\langle \delta(\vec{x})\delta(\vec{x}') \rangle$?

BAO and RSD

BAO and Neutrino masses

How to compute 2-pt statistics $\langle \delta(\vec{x})\delta(\vec{x}')\rangle$ from $\delta(\vec{x})$?

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Power spectrum

$$(2\pi)^3 \delta_{\mathrm{D}}^3(\vec{k}-\vec{k}')P(\vec{k}) \equiv \left\langle \tilde{\delta}_g^*(\vec{k})\delta_g(\vec{k}') \right\rangle$$

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Configuration space | **Fourier space**

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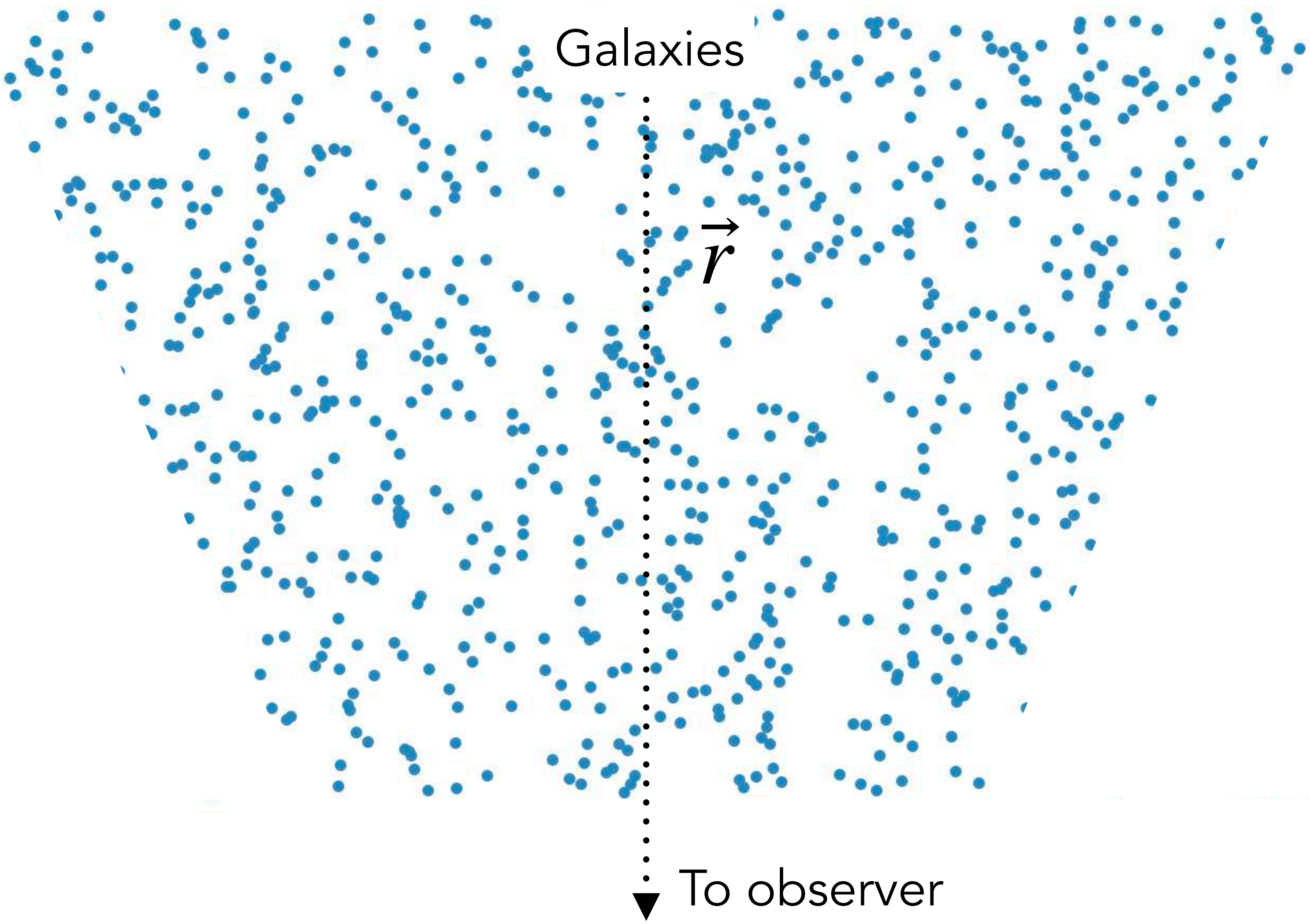

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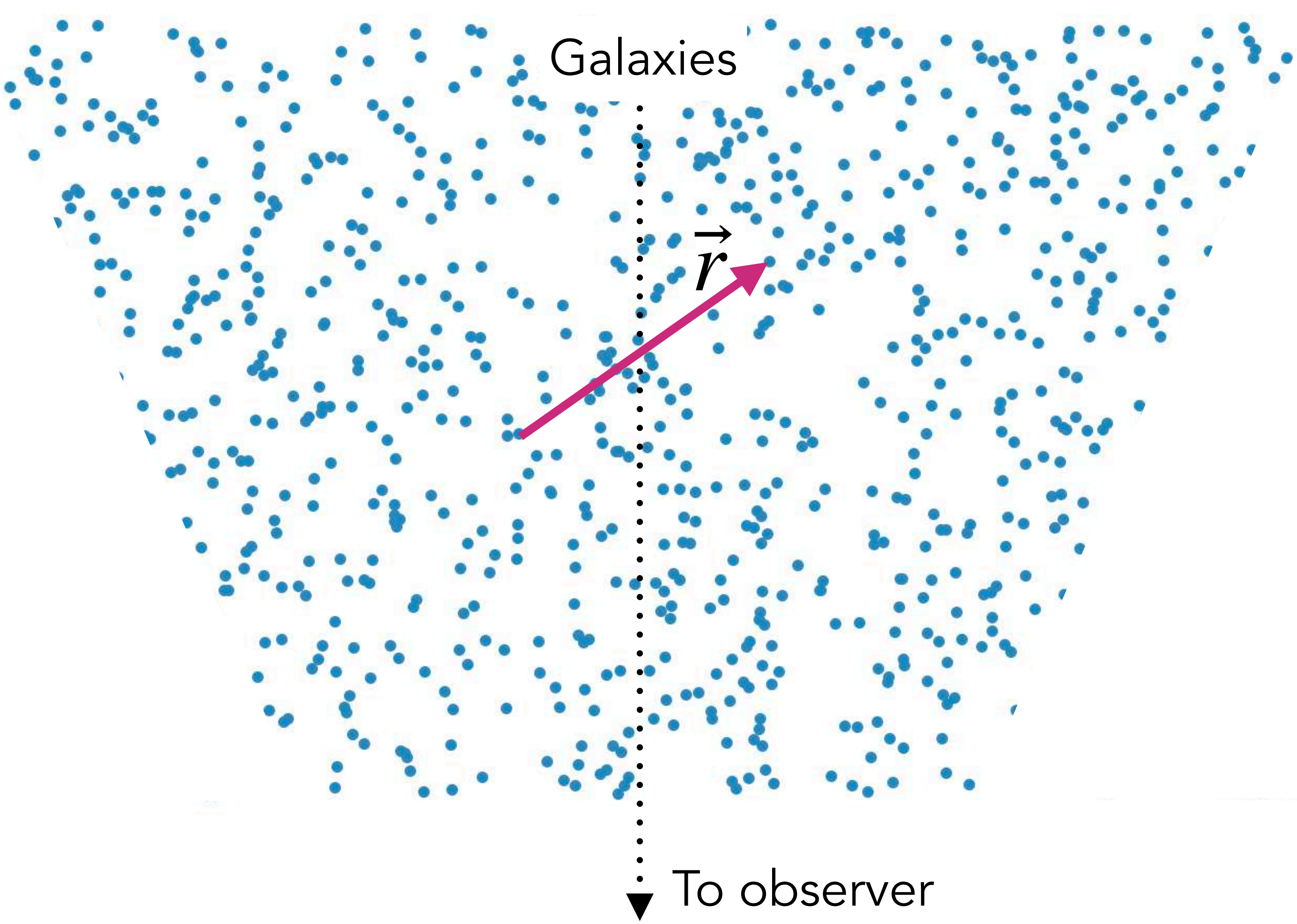

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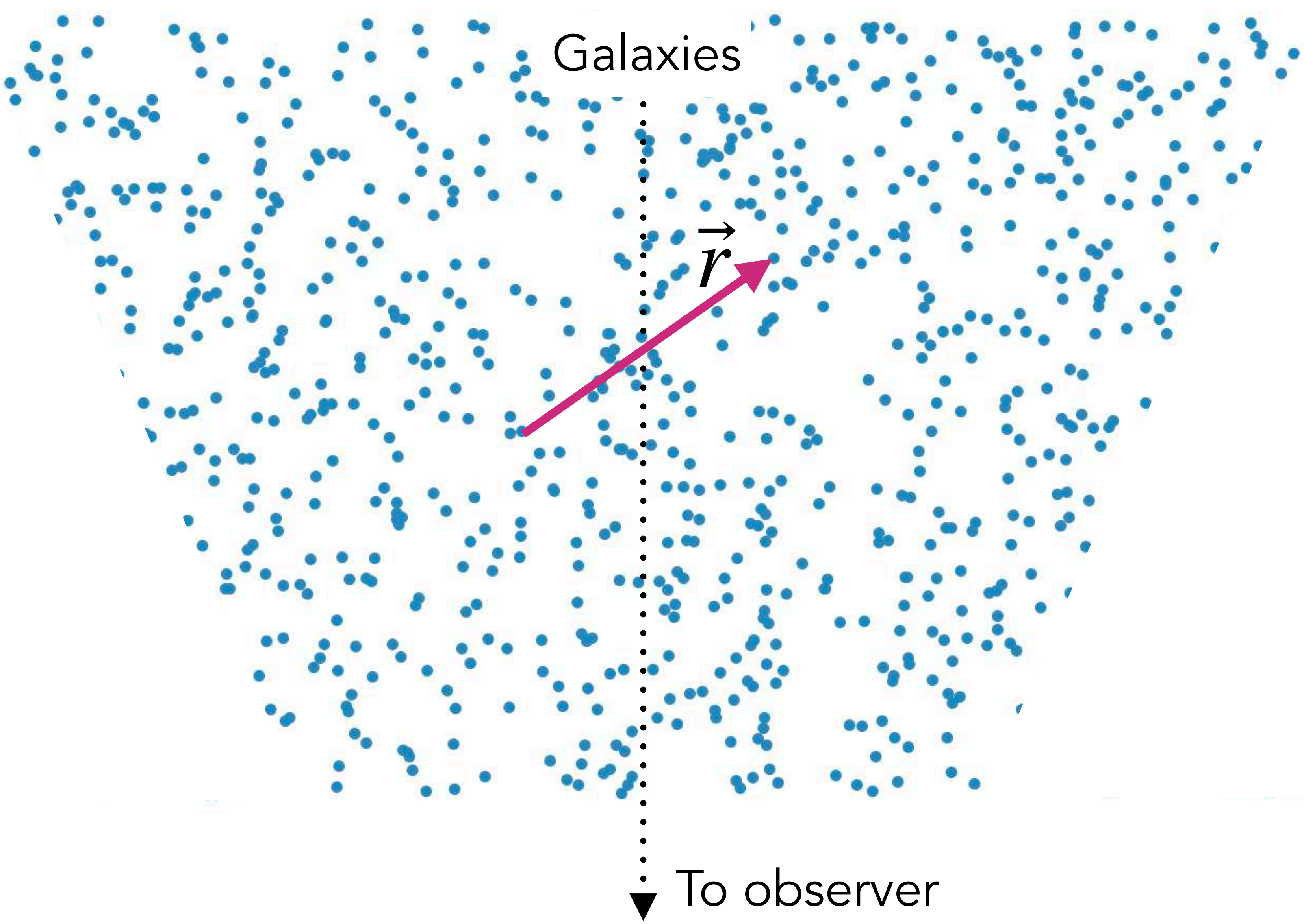

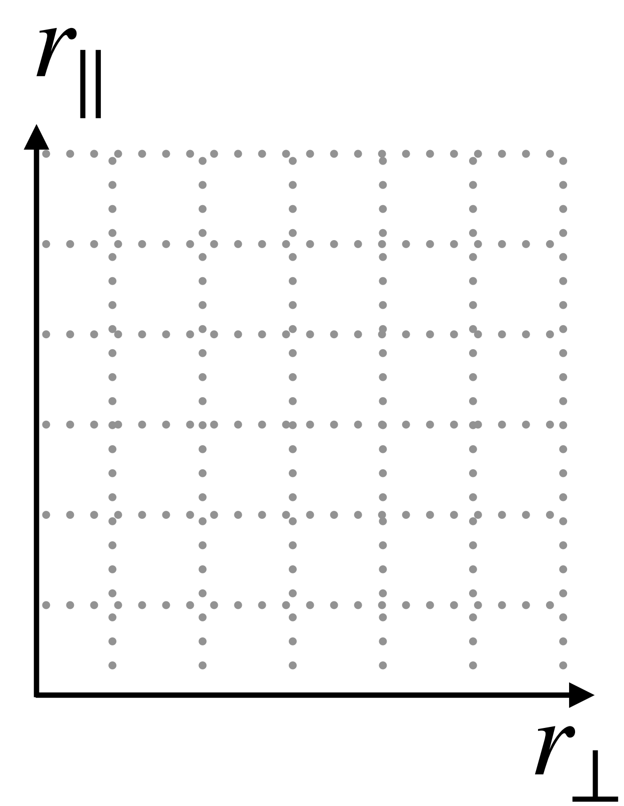

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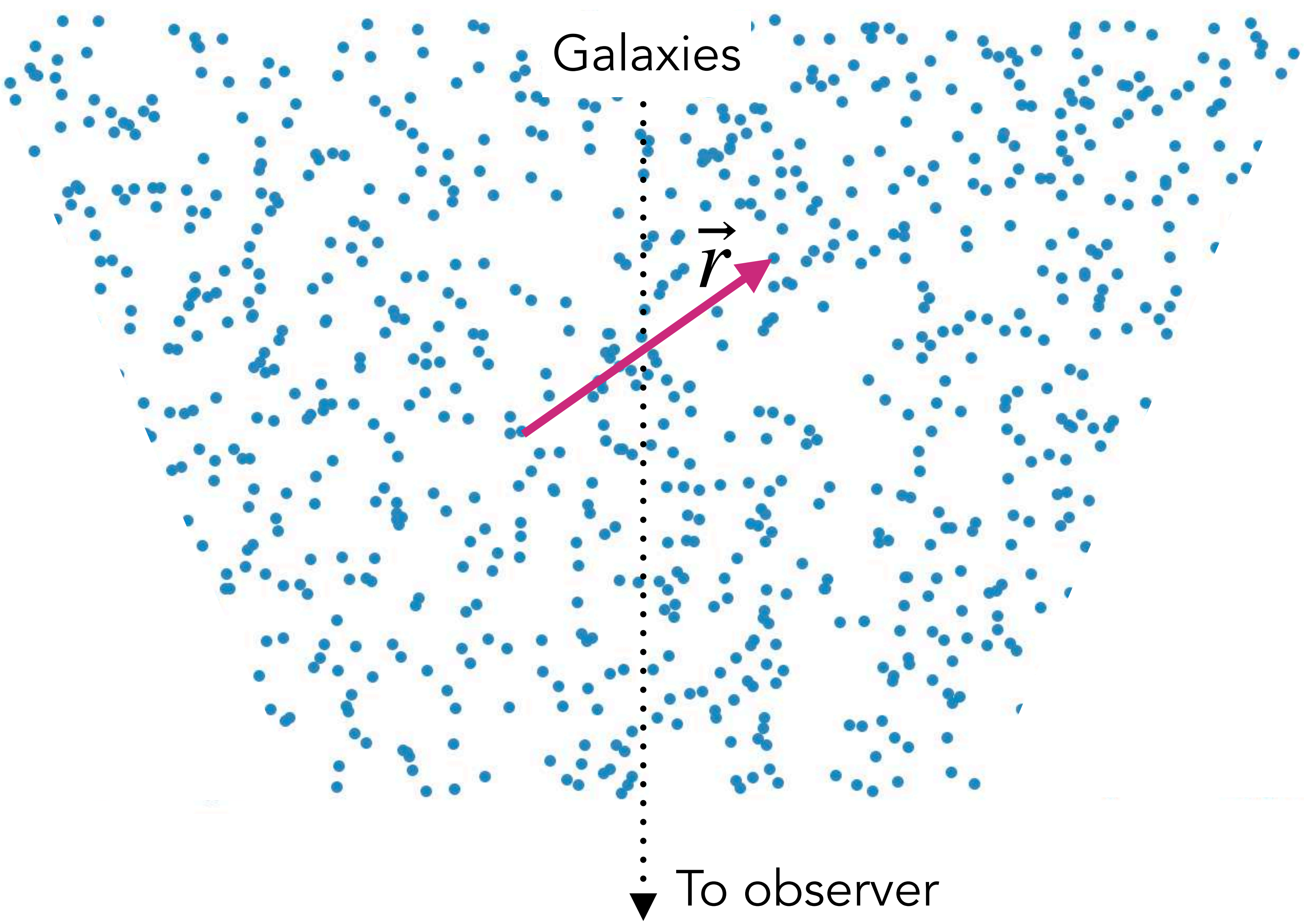

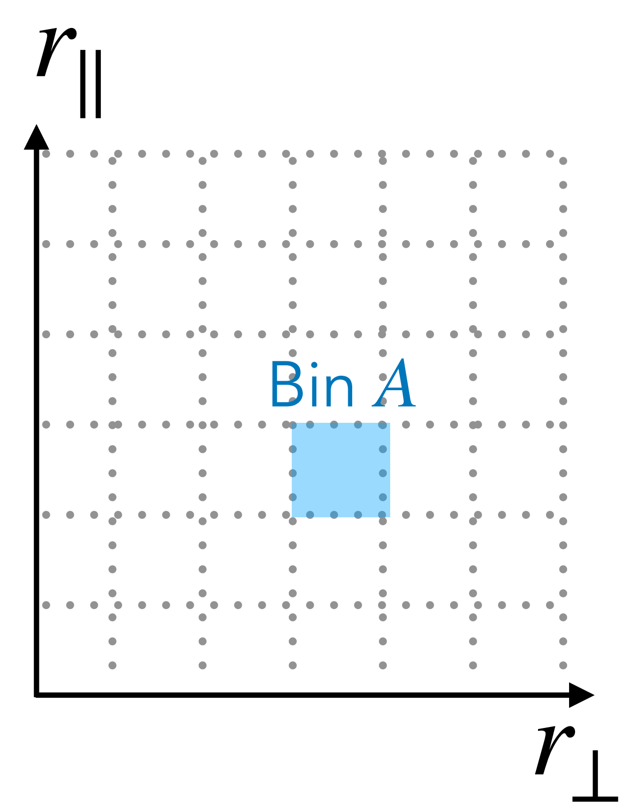

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Case of **galaxies and quasars**

Configuration space | **Fourier space**

Correlation function | Power spectrum

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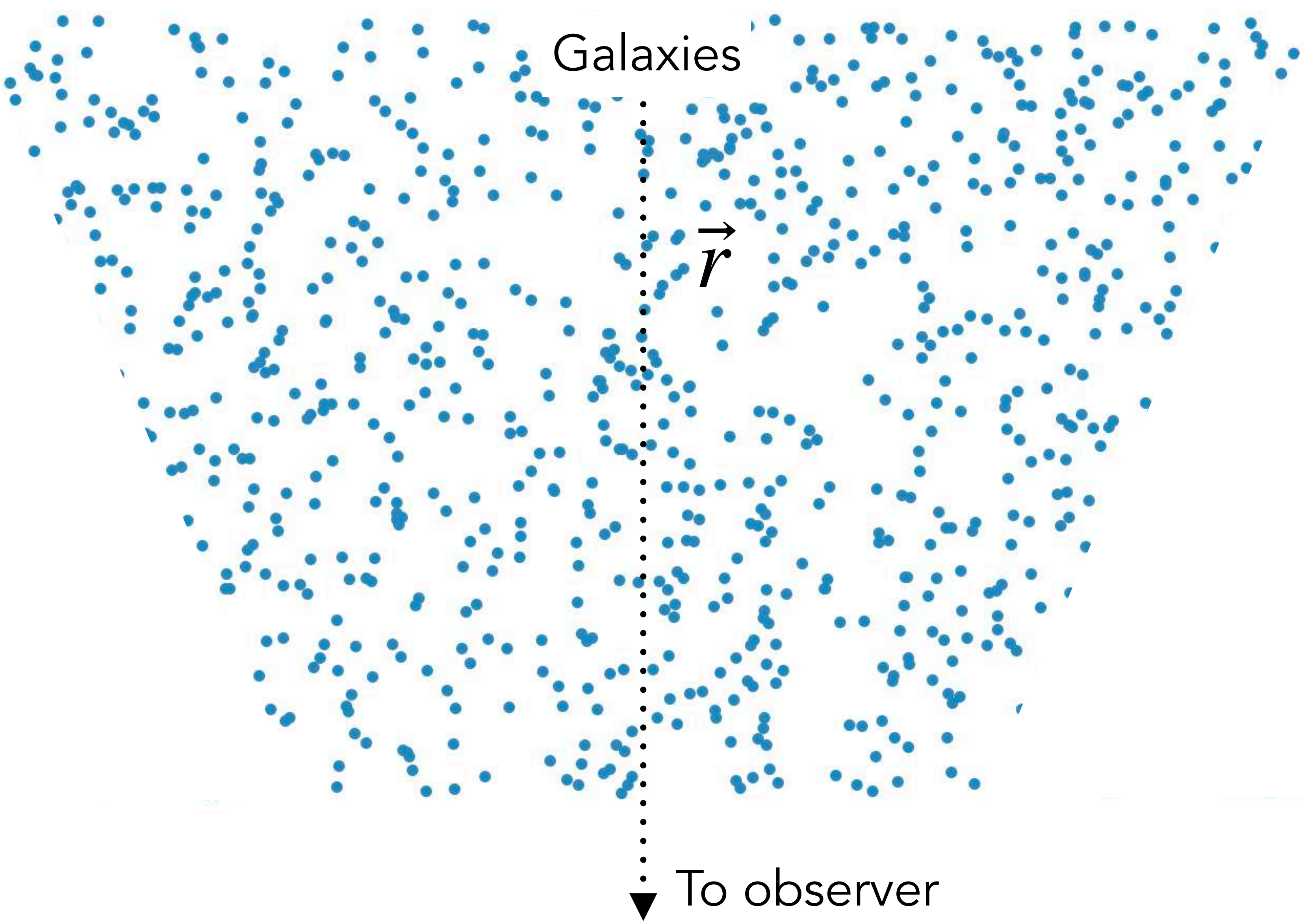

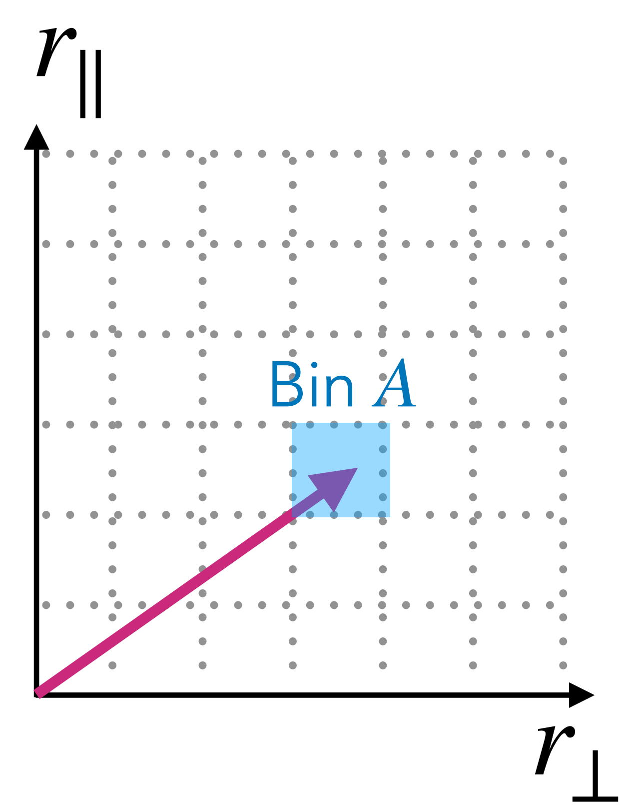

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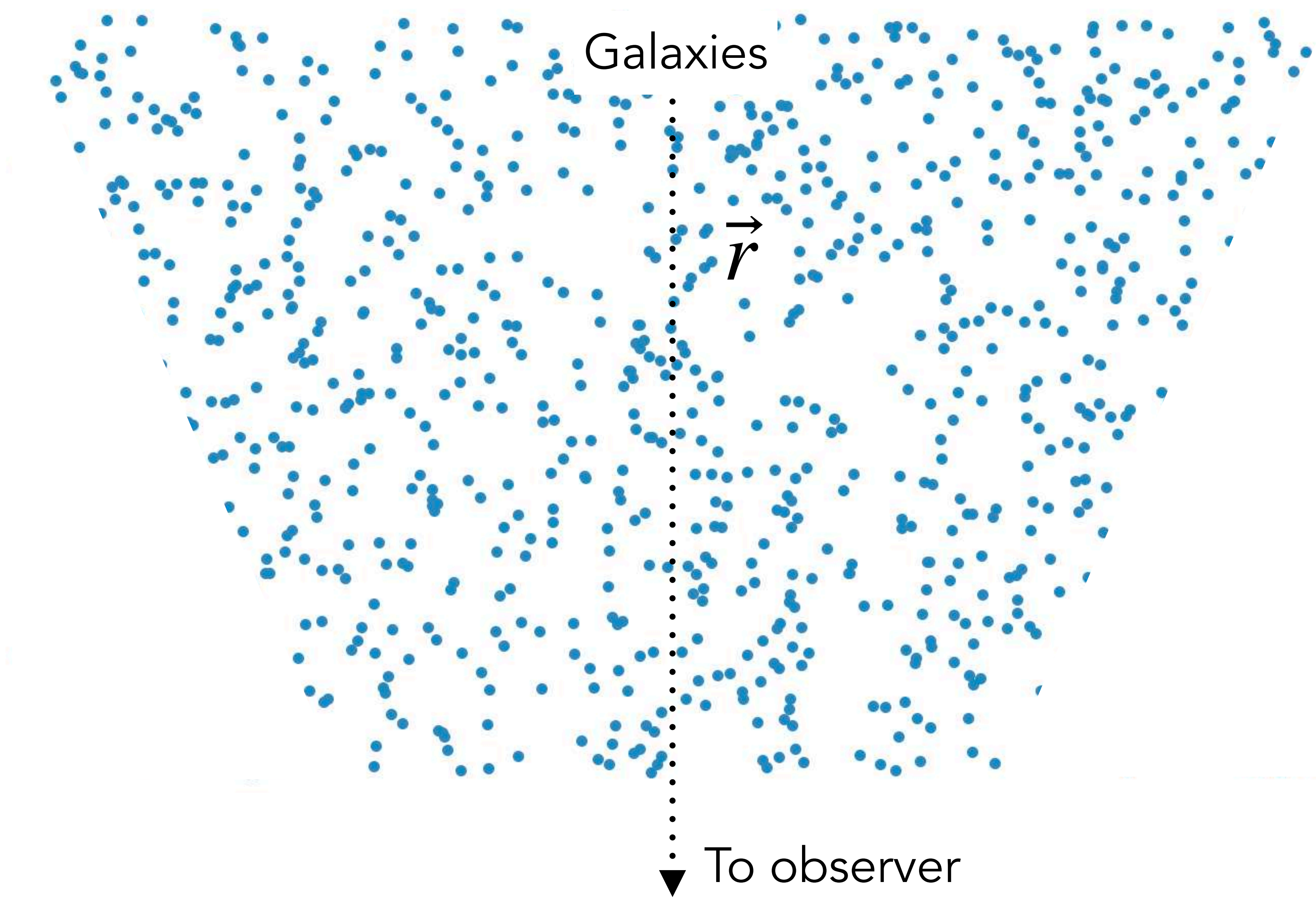

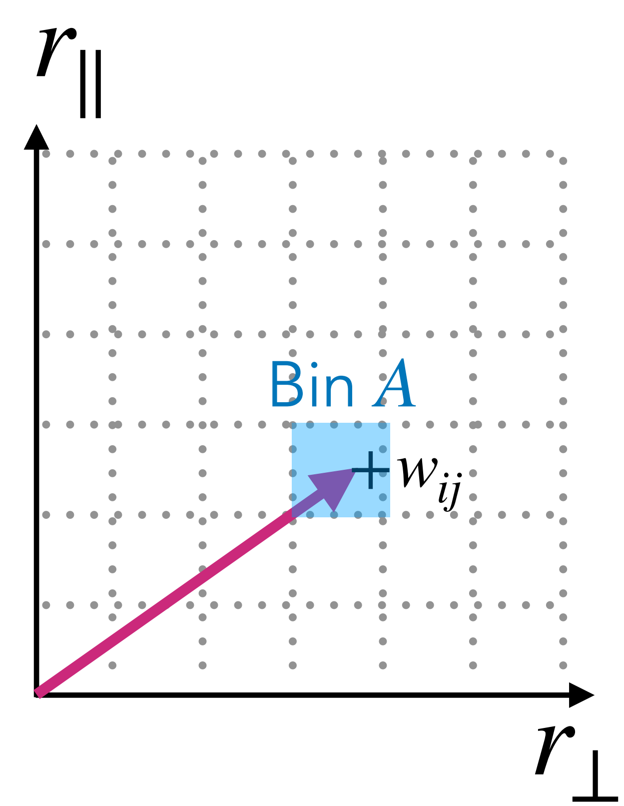

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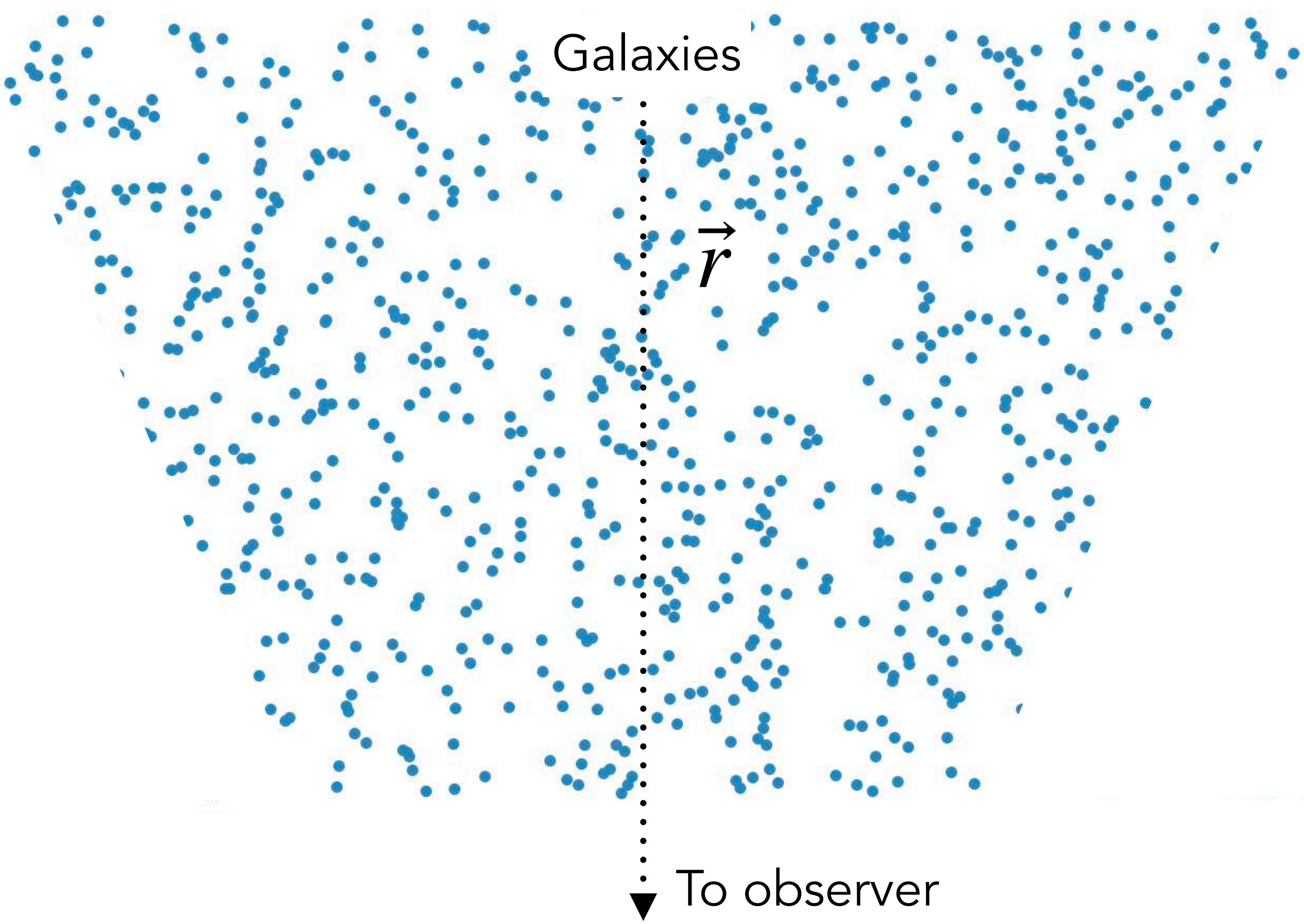
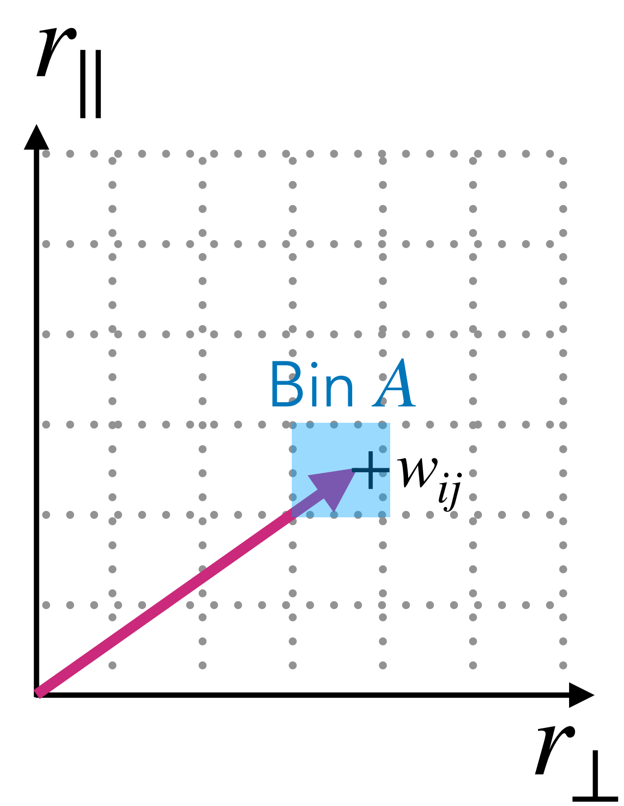
Case of **galaxies and quasars**

Configuration space	**Fourier space**
Correlation function	Power spectrum
$\xi(\vec{r}) \equiv \left\langle \delta_g(\vec{x})\delta_g(\vec{x}+\vec{r}) \right\rangle$	$(2\pi)^3 \delta_{\rm D}^3(\vec{k}-\vec{k}')P(\vec{k}) \equiv \left\langle \tilde{\delta}_g^*(\vec{k})\delta_g(\vec{k}') \right\rangle$





$$DD(\vec{r}_A) = \frac{1}{W_{DD}} \sum_{i,j \in A} w_{ij}$$

How to compute 2-pt statistics $\langle \delta(\vec{x})\delta(\vec{x}') \rangle$ from $\delta(\vec{x})$?

Case of **galaxies and quasars**

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Fourier space

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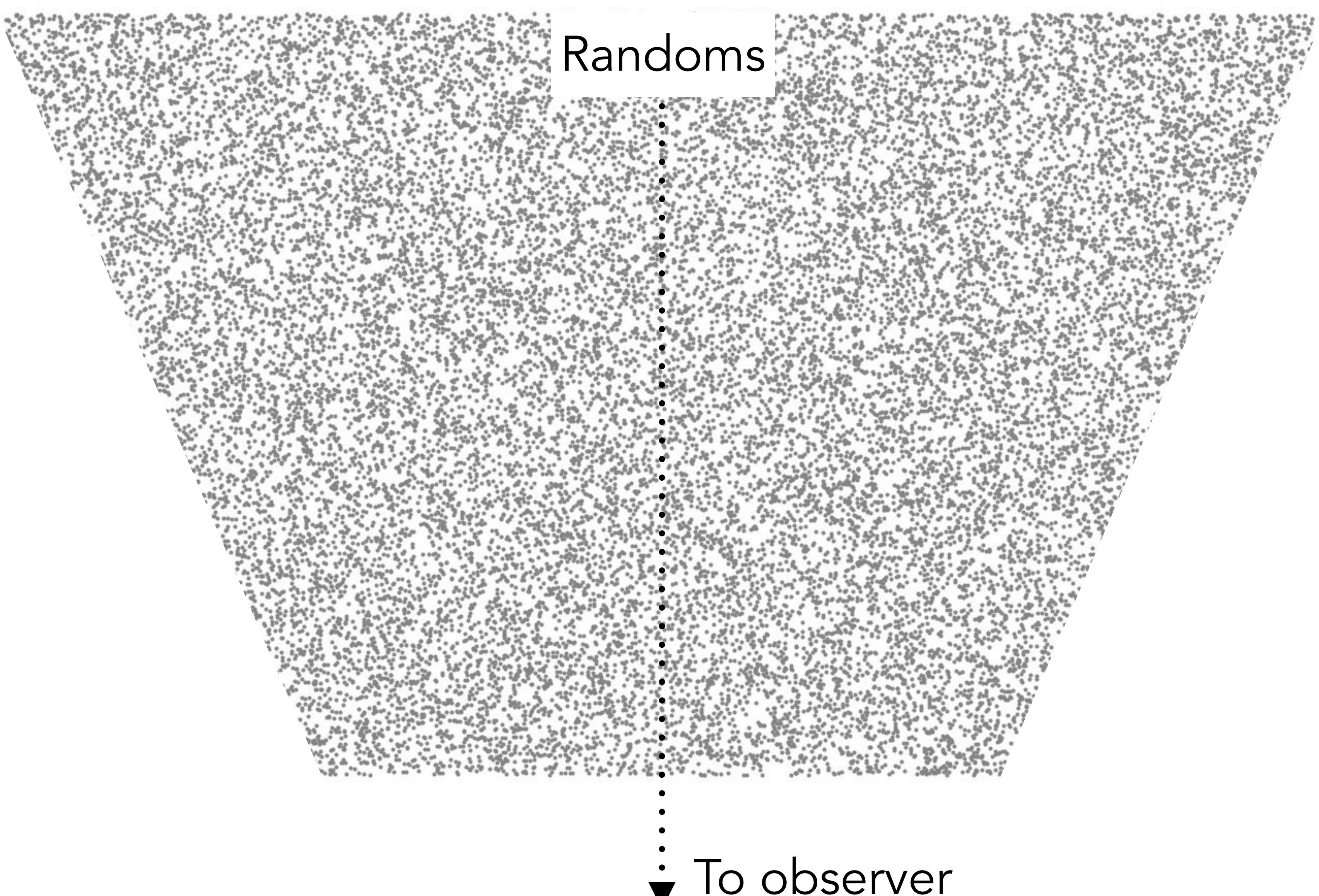

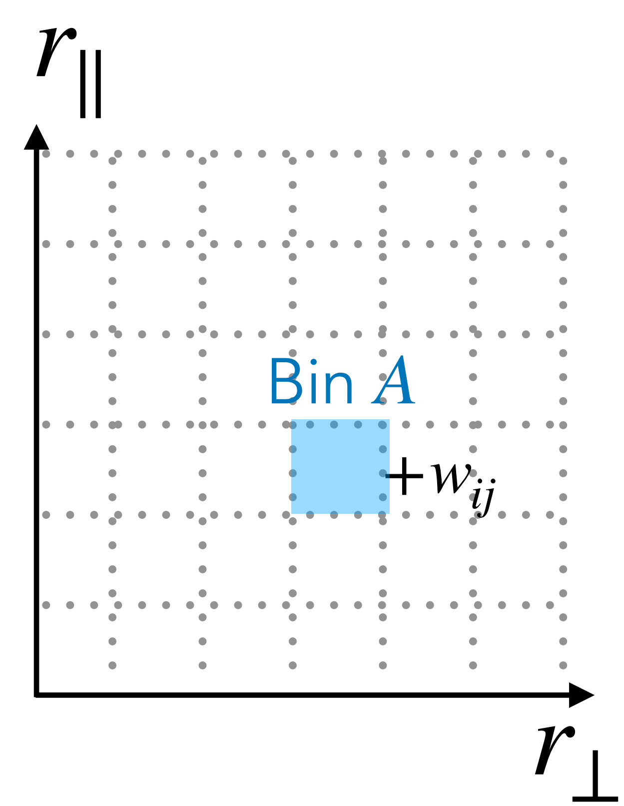

$$DD(\vec{r}_A) = \frac{1}{W_{DD}} \sum_{i,j \in A} w_{ij}$$

and similarly for DR and RR

How to compute 2-pt statistics $\langle \delta(\vec{x})\delta(\vec{x}\,')\rangle$ from $\delta(\vec{x})$?

Case of **galaxies and quasars**

Configuration space

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Fourier space

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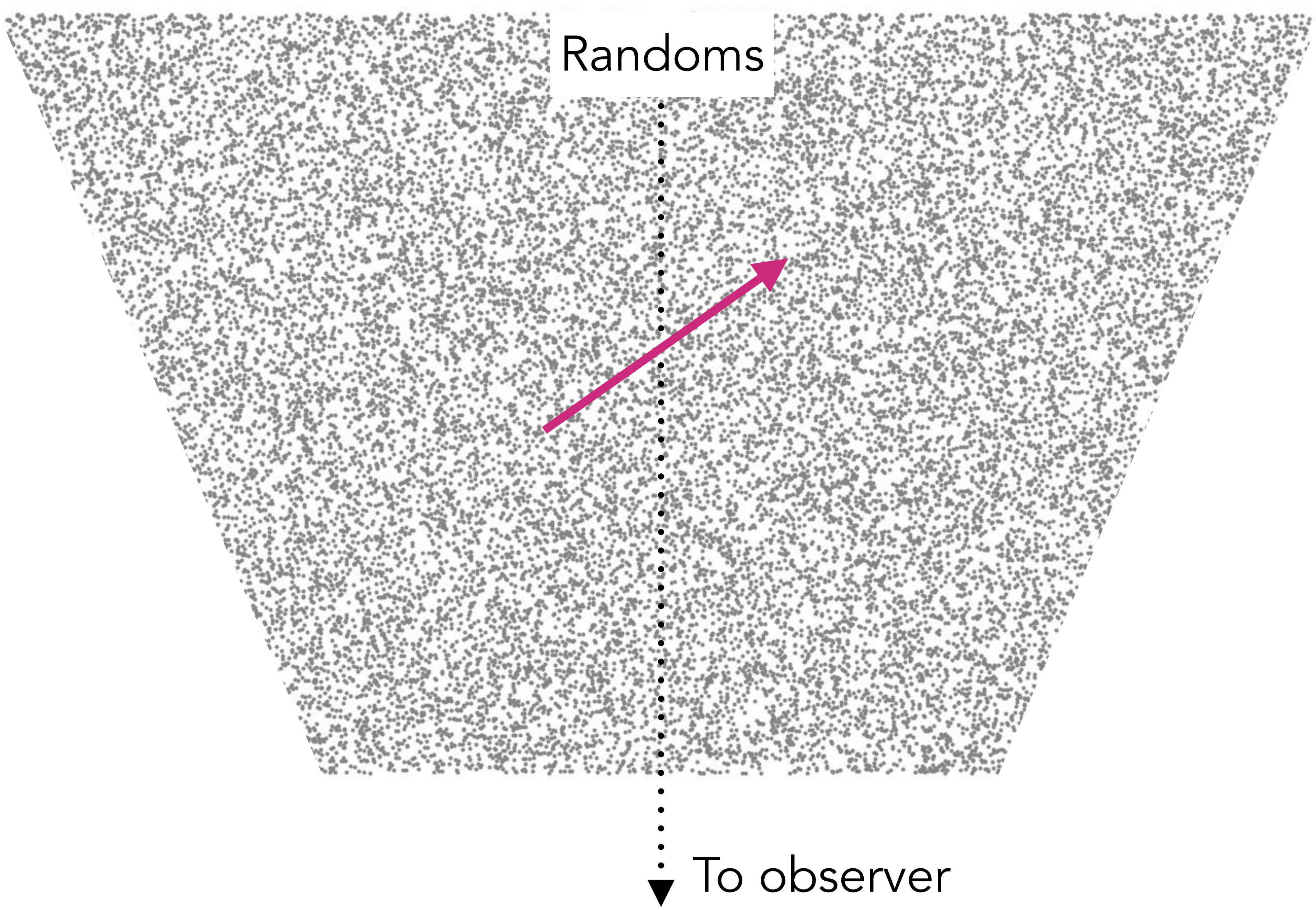

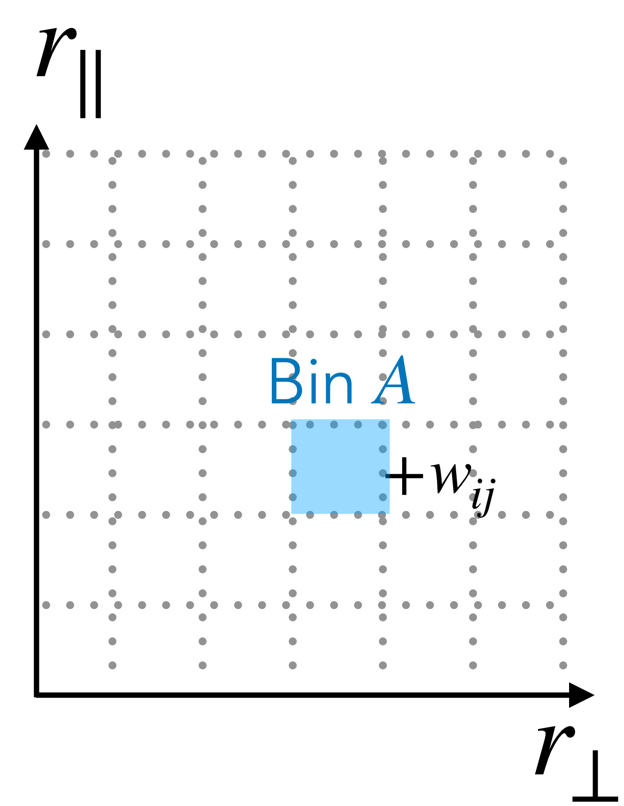

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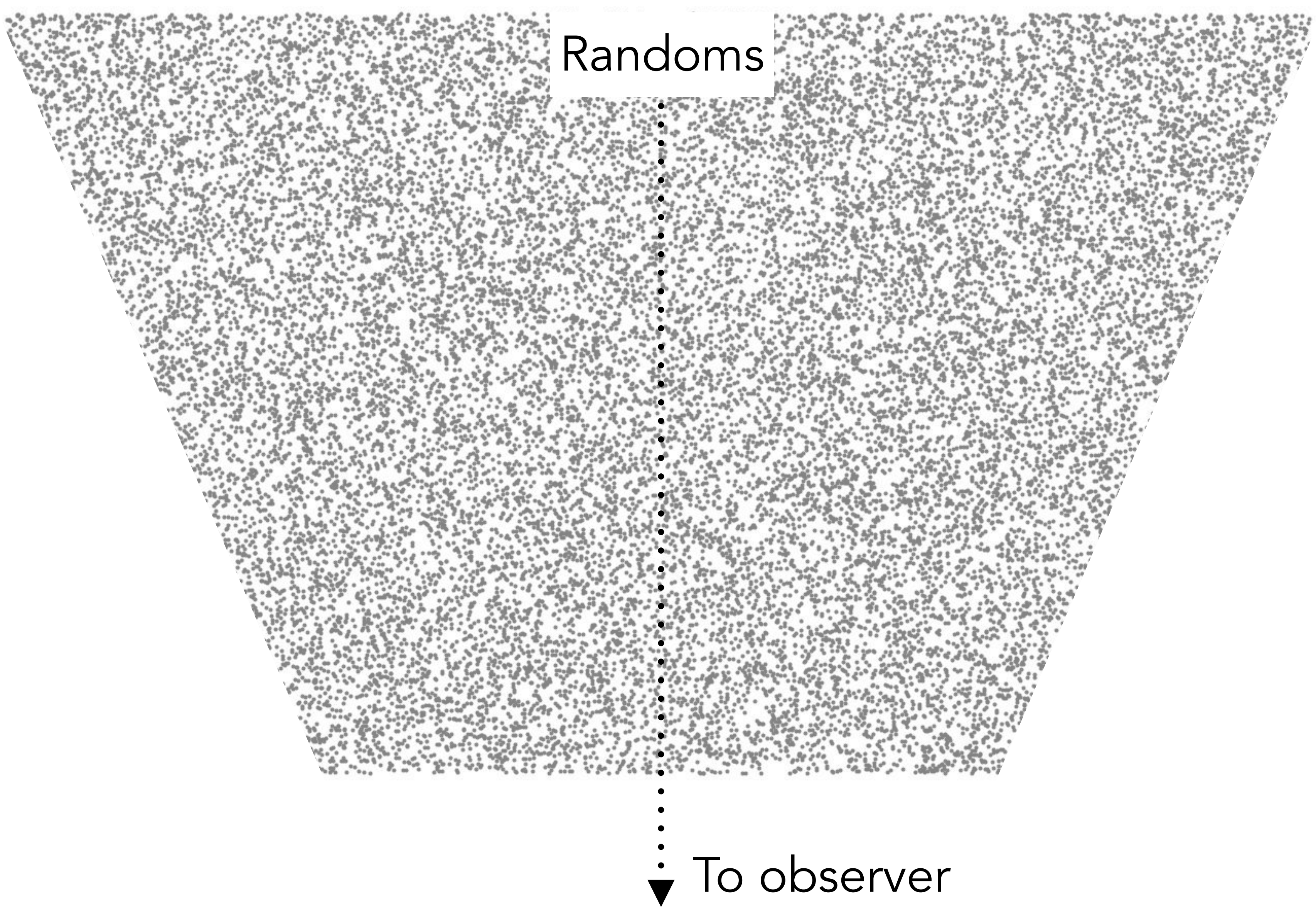

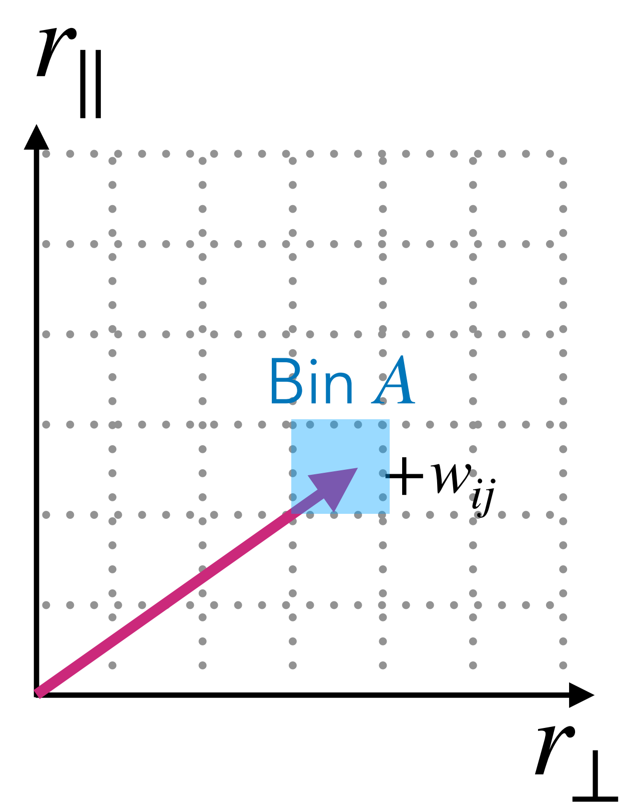

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Estimator

Landy & Szalay 1993

$$\hat{\xi}(\vec{r}_A) = \frac{DD(\vec{r}_A) - 2DR(\vec{r}_A)}{RR(\vec{r}_A)} + 1$$

Fourier space

Power spectrum

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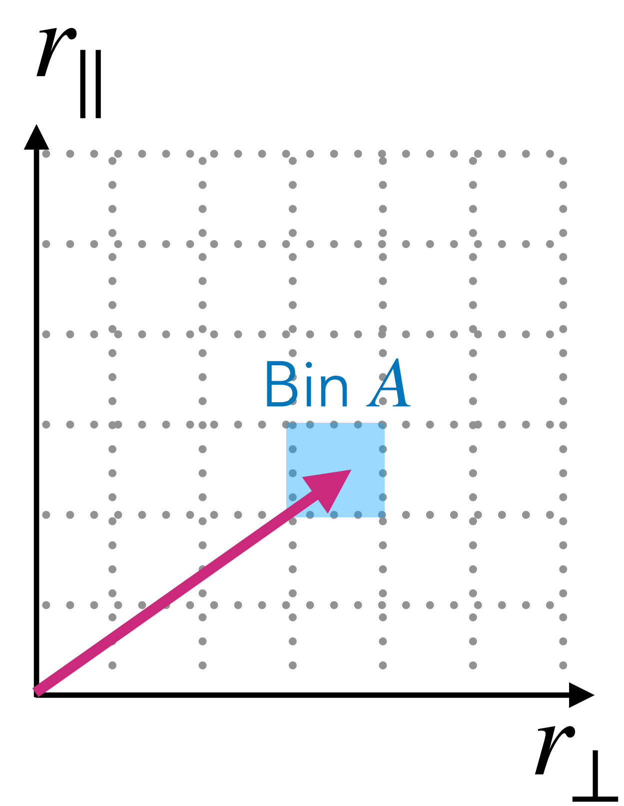

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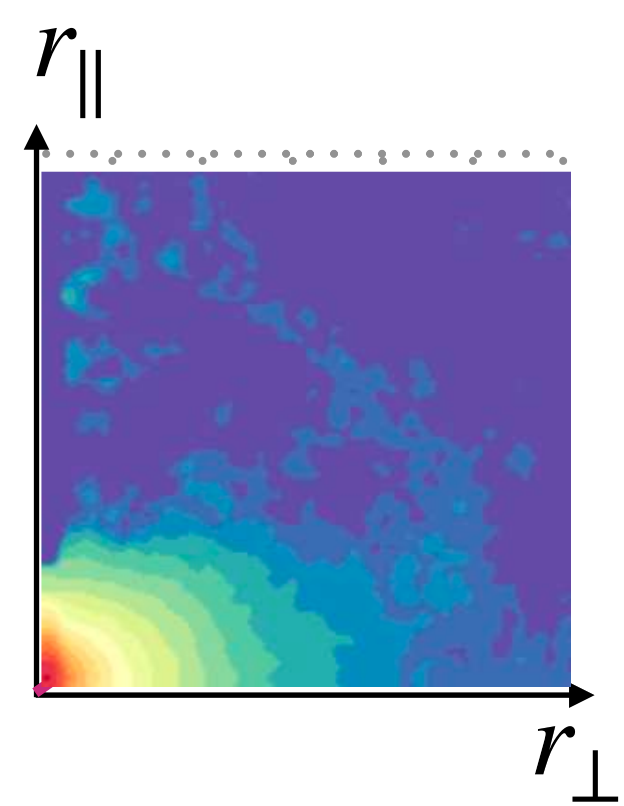

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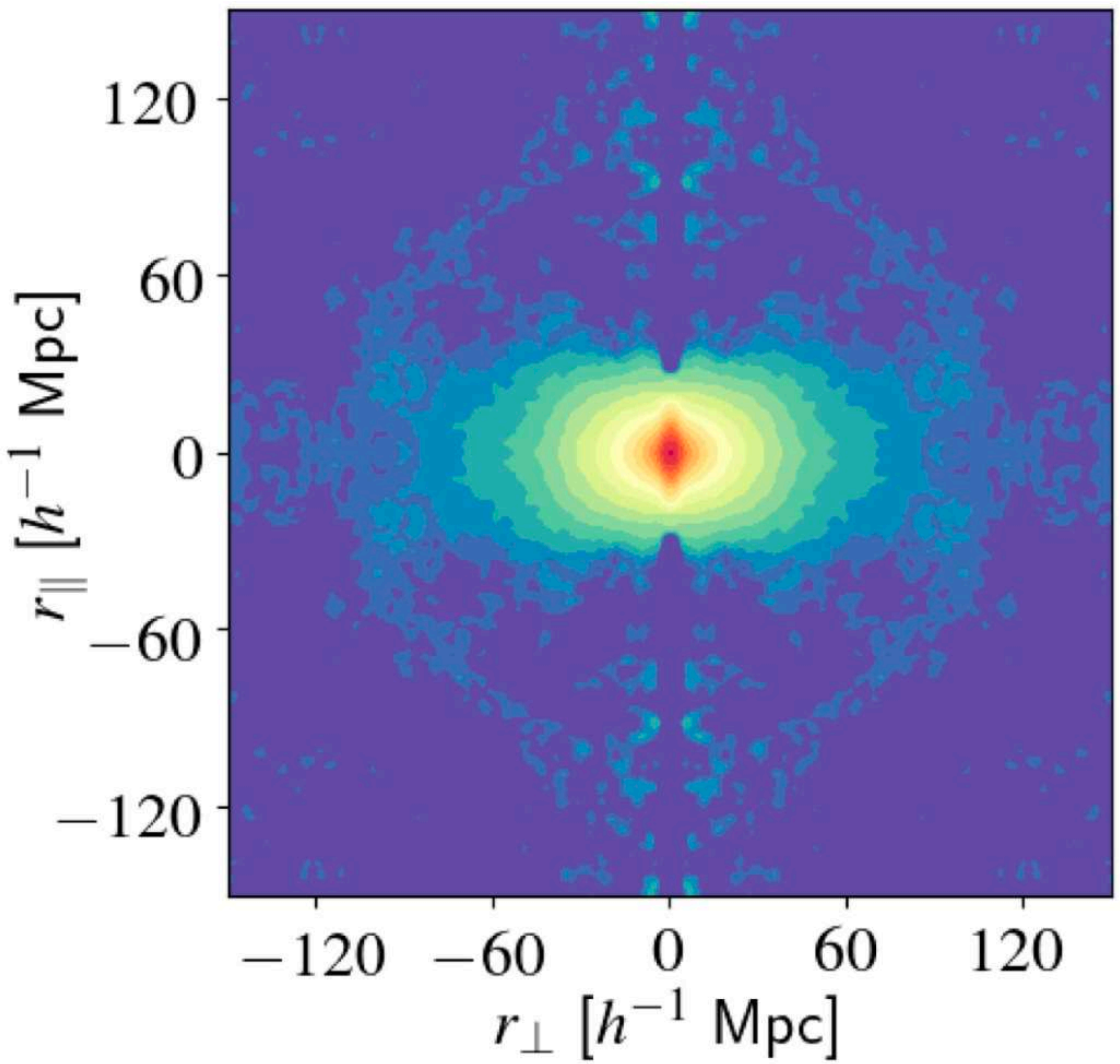
eBOSS LRG



JB et al. 2020

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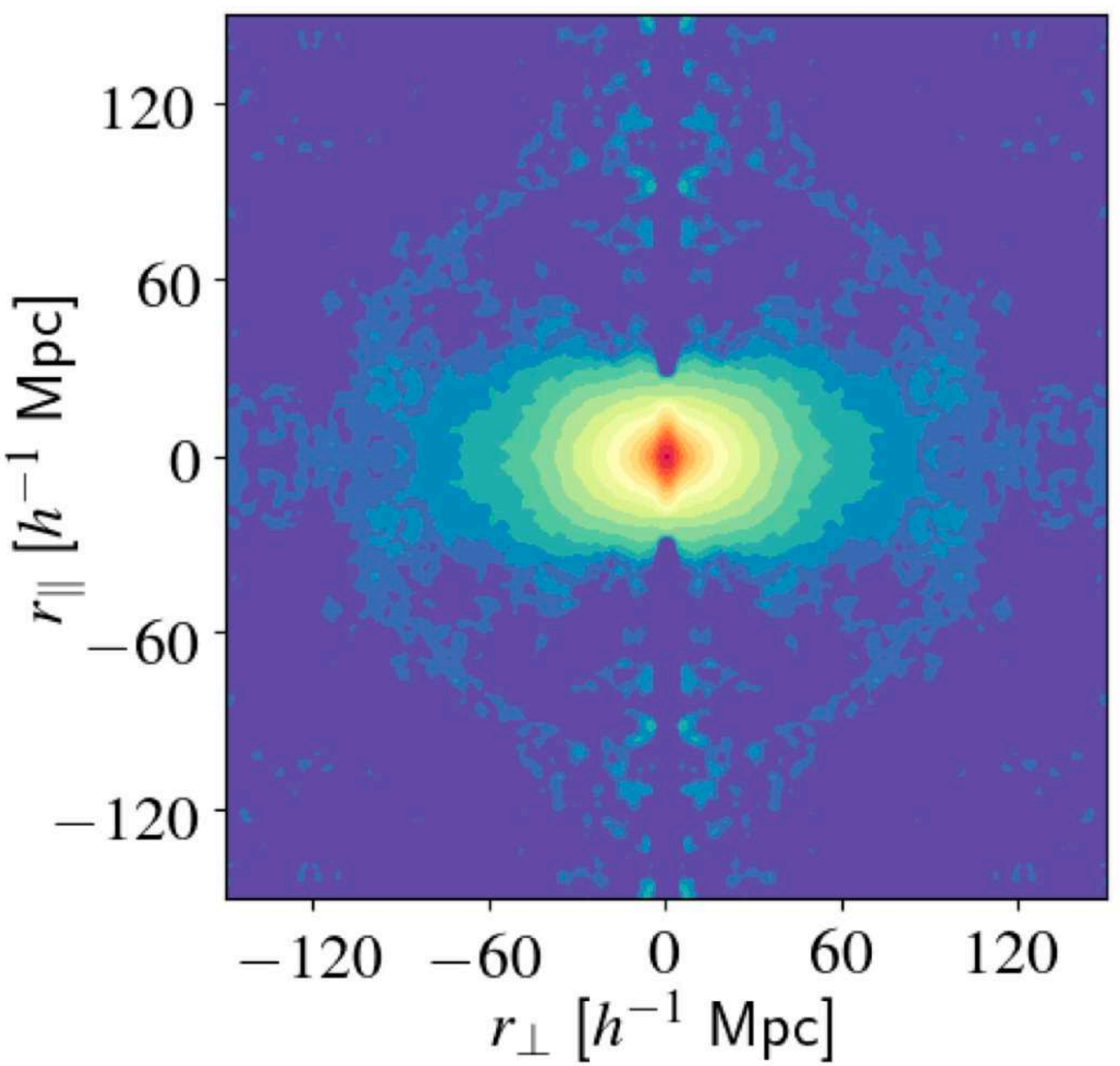
Compute multipoles

$$\hat{\xi}_\ell(r) = (2\ell+1)\sum_i \xi(r,\mu_i)L_\ell(\mu_i)\mathrm{d}\mu$$

where $\mu_i = \frac{r_\parallel}{r}$ and $L_\ell \equiv$ Legendre polynomials

eBOSS LRG



JB et al. 2020

How to compute 2-pt statistics $\langle \delta(\vec{x})\delta(\vec{x}') \rangle$ from $\delta(\vec{x})$?

Case of **galaxies and quasars**

Configuration space

Correlation function

$$\xi(\vec{r}) \equiv \left\langle \delta_g(\vec{x})\delta_g(\vec{x}+\vec{r}) \right\rangle$$

Estimator

Landy & Szalay 1993

$$\hat{\xi}(\vec{r}_A) = \frac{DD(\vec{r}_A) - 2DR(\vec{r}_A)}{RR(\vec{r}_A)} + 1$$

Compute multipoles

$$\hat{\xi}_\ell(r) = (2\ell+1)\sum_i \xi(r,\mu_i)L_\ell(\mu_i)\mathrm{d}\mu$$

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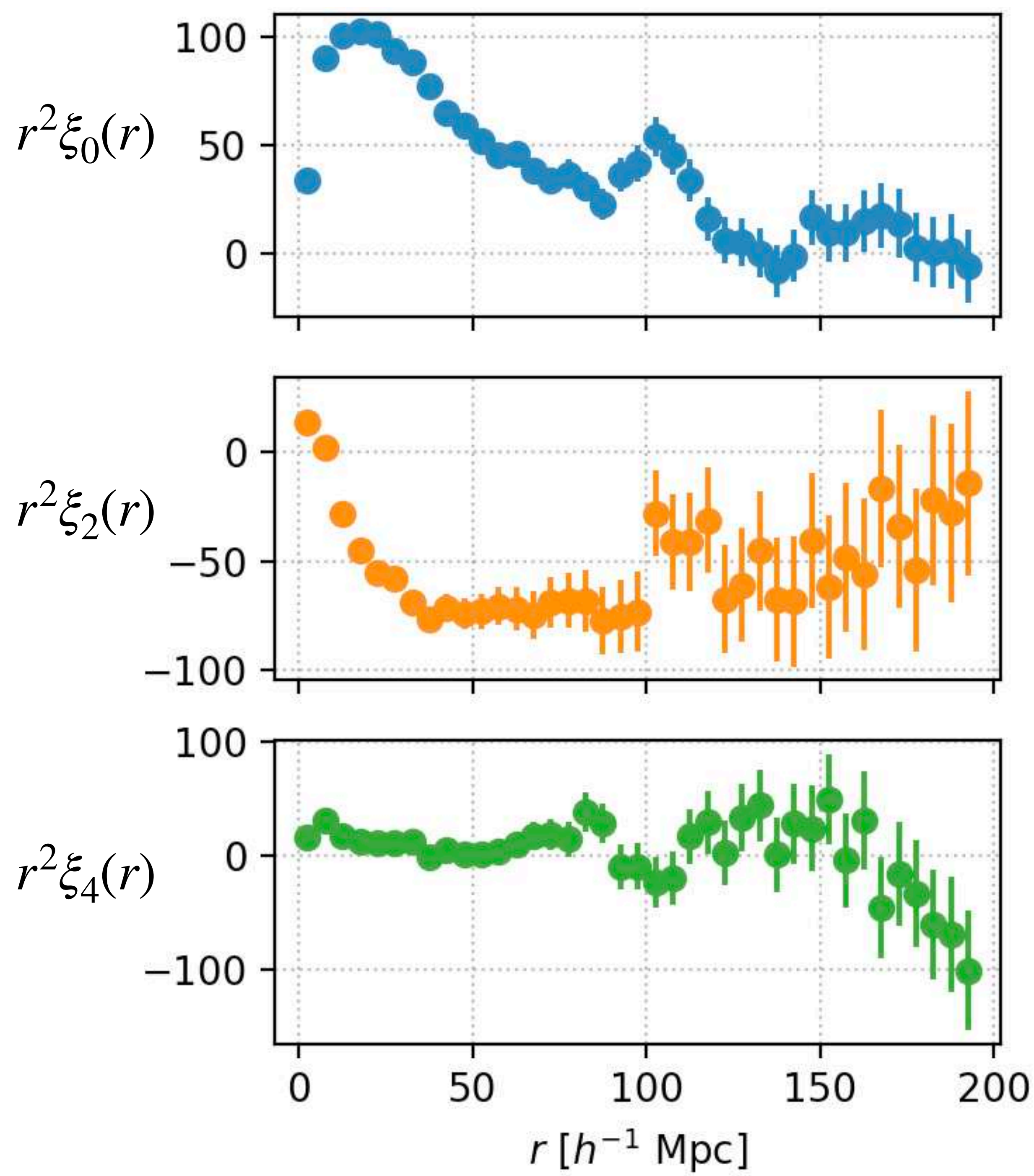

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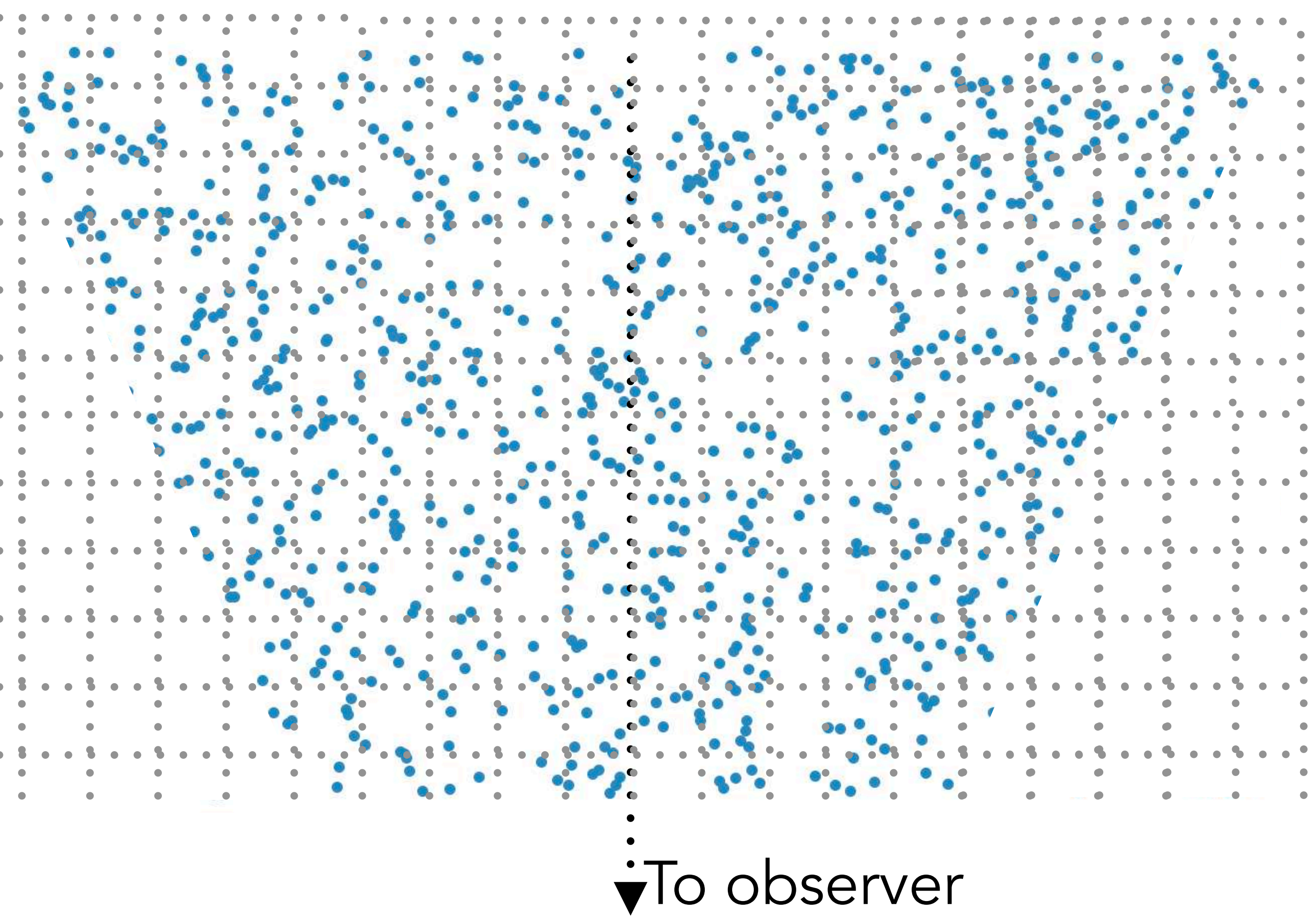

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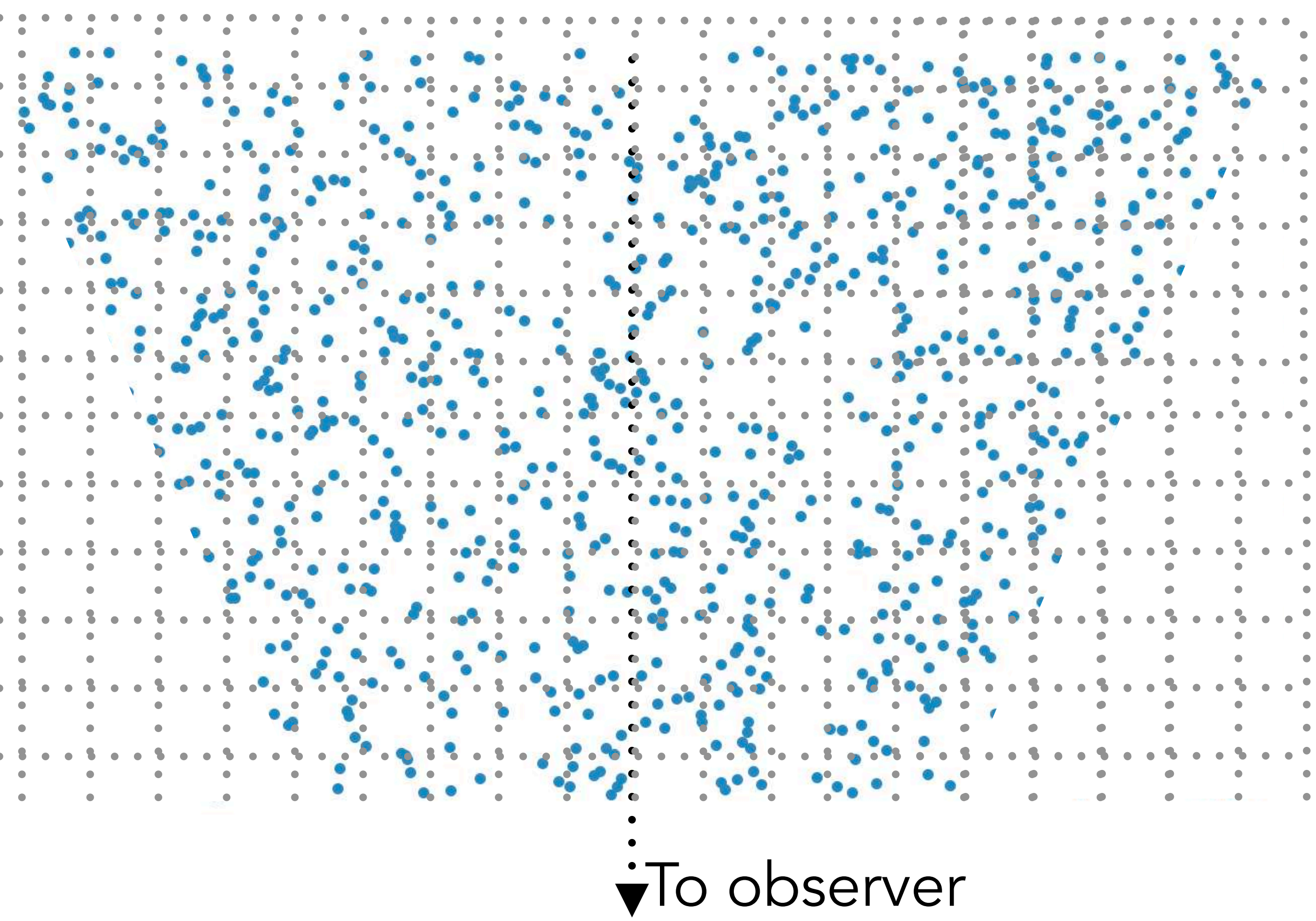

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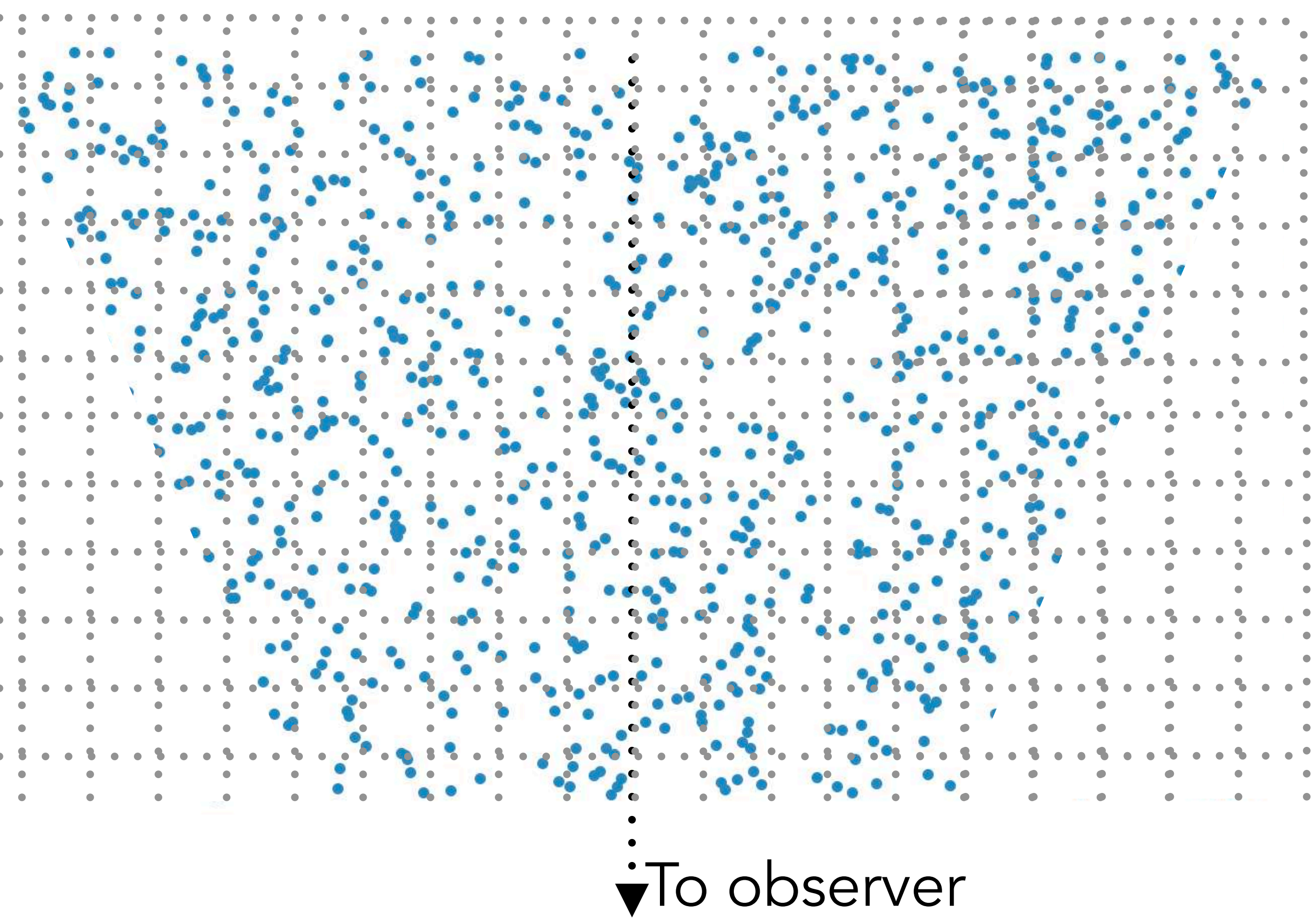

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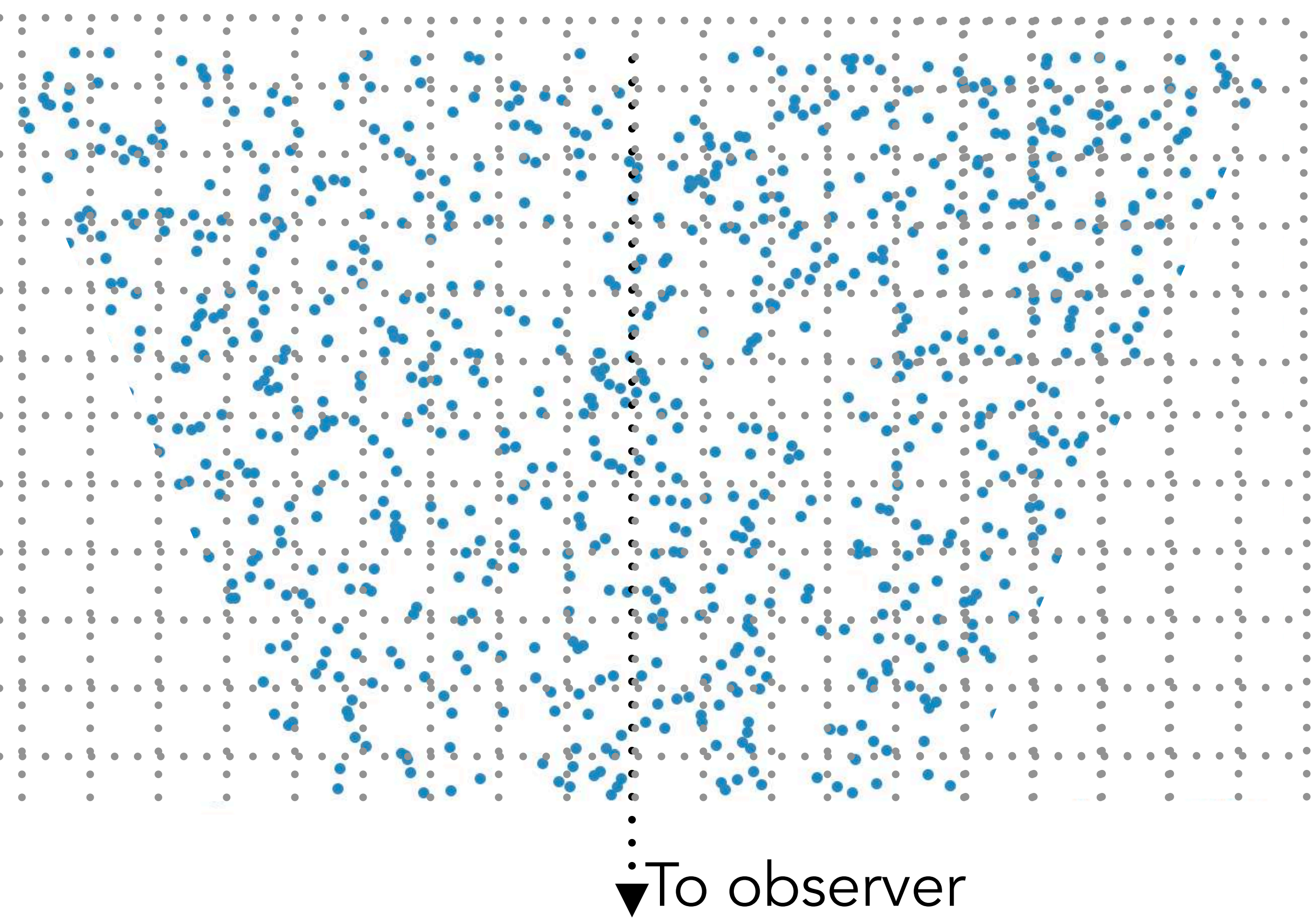

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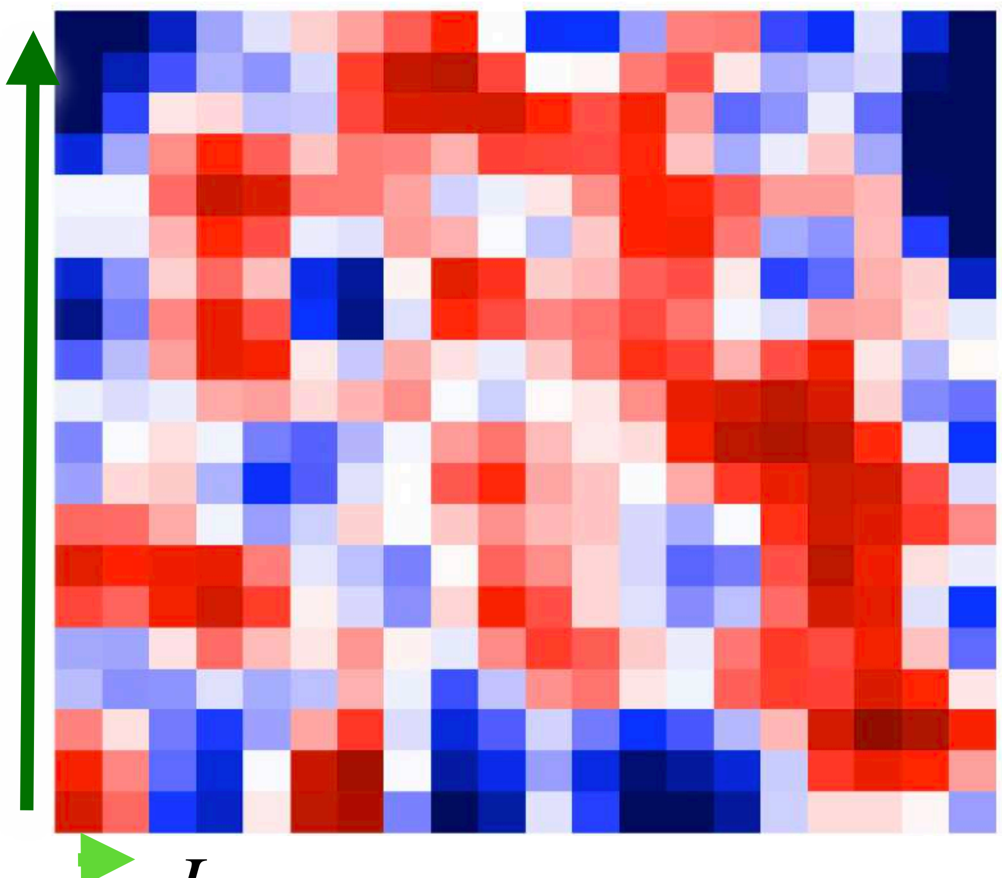
$\delta_g(\vec{x})$ on a mesh



L

$\Delta x = \frac{L}{N}$

The mesh properties (L, N) impact the scales probed

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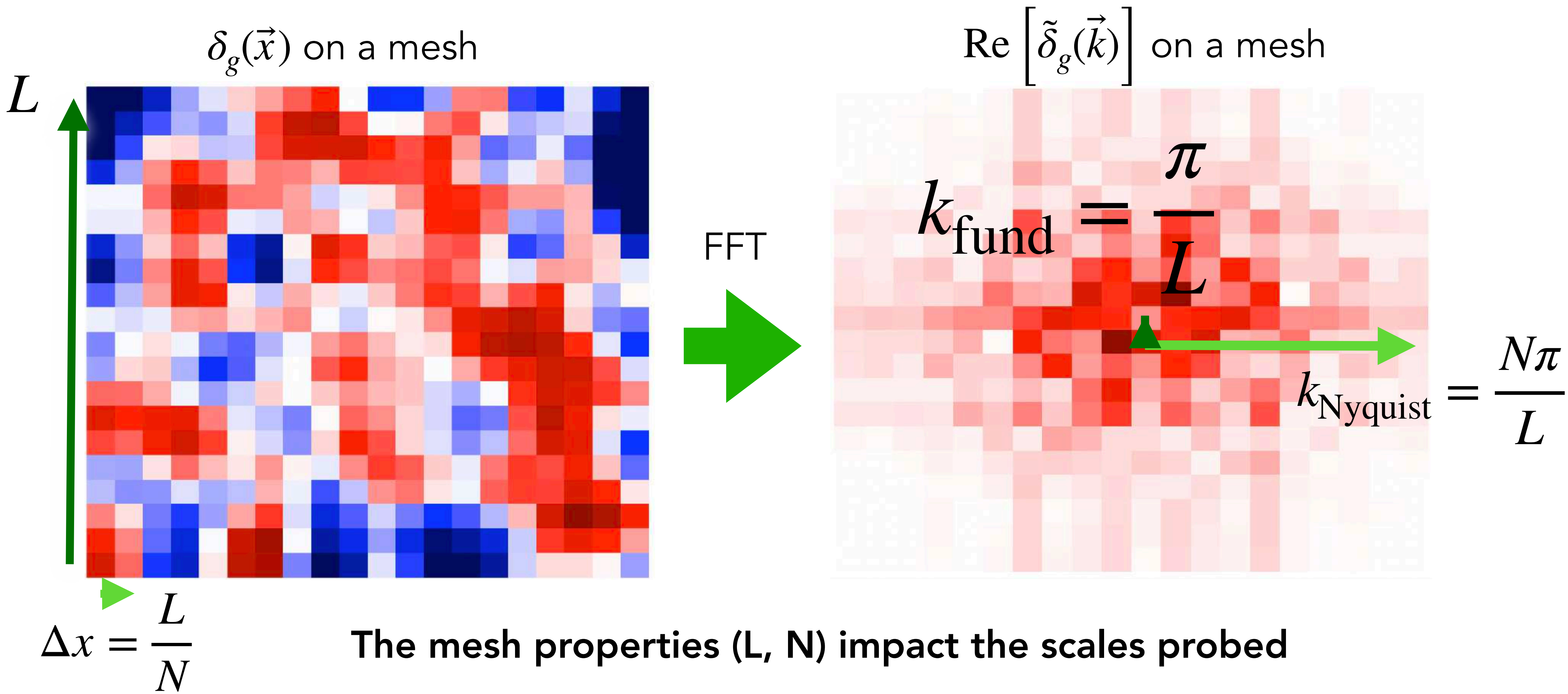

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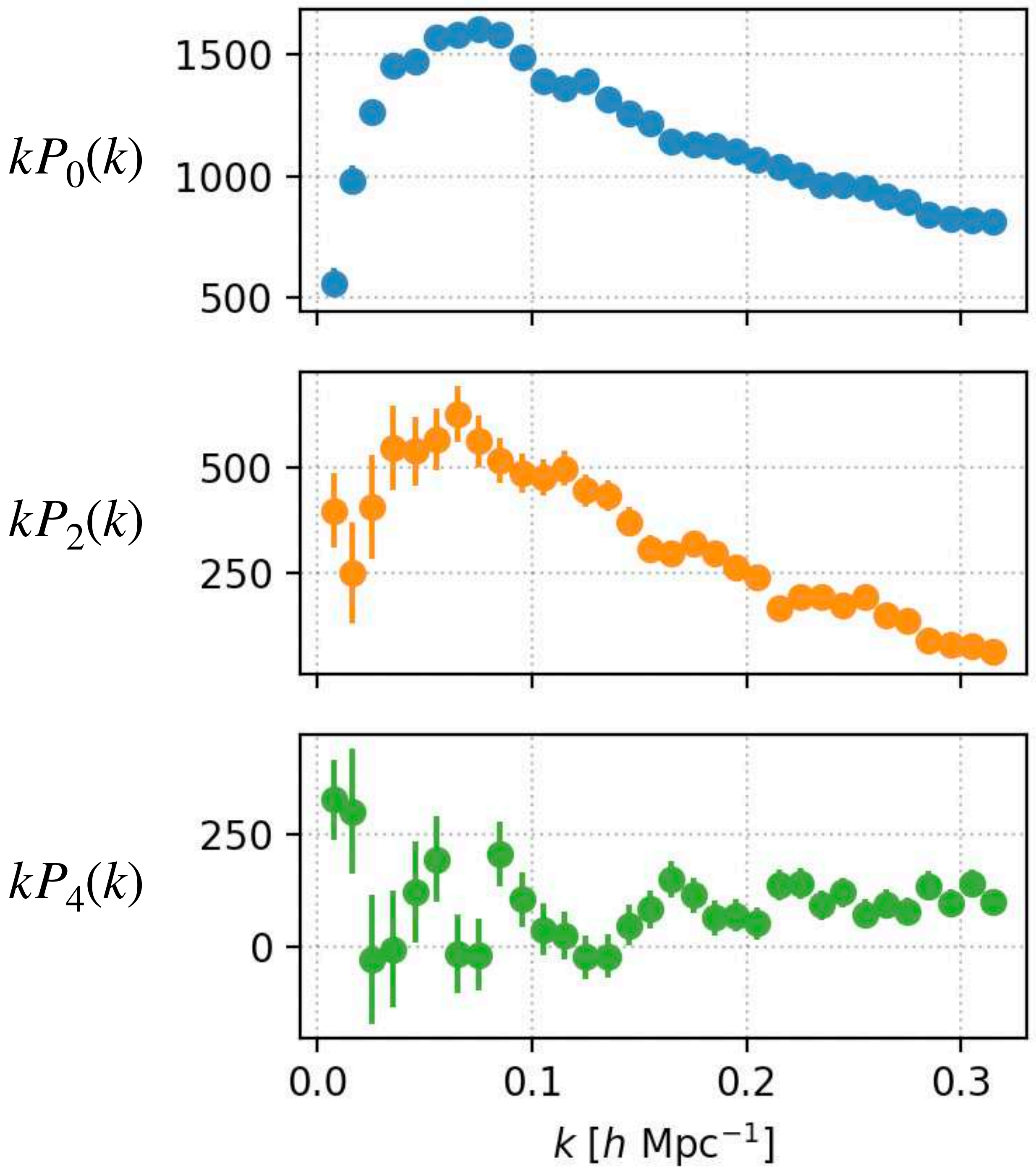
eBOSS LRG



Gil-Marín et al. 2020

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Codes

pycorr
by de Mattia et al.
based on Corrfunc

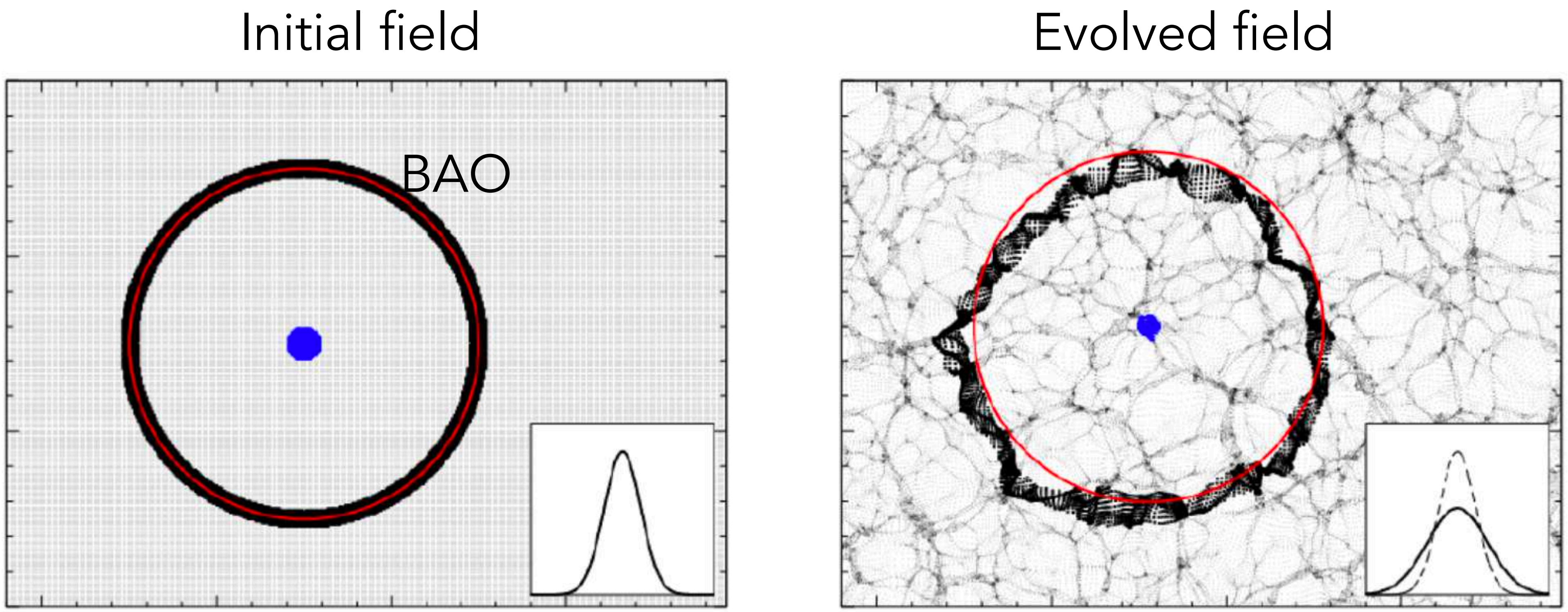
pypower
by de Mattia et al.
based on nbodykit

nbodykit
by Nick Hand & Yu Feng

... and many others!

Reconstruction for BAO

Removing bulk motions (~ 10 Mpc) that smear BAO peak



Padmanabhan et al. 2012 Code: pyrecon

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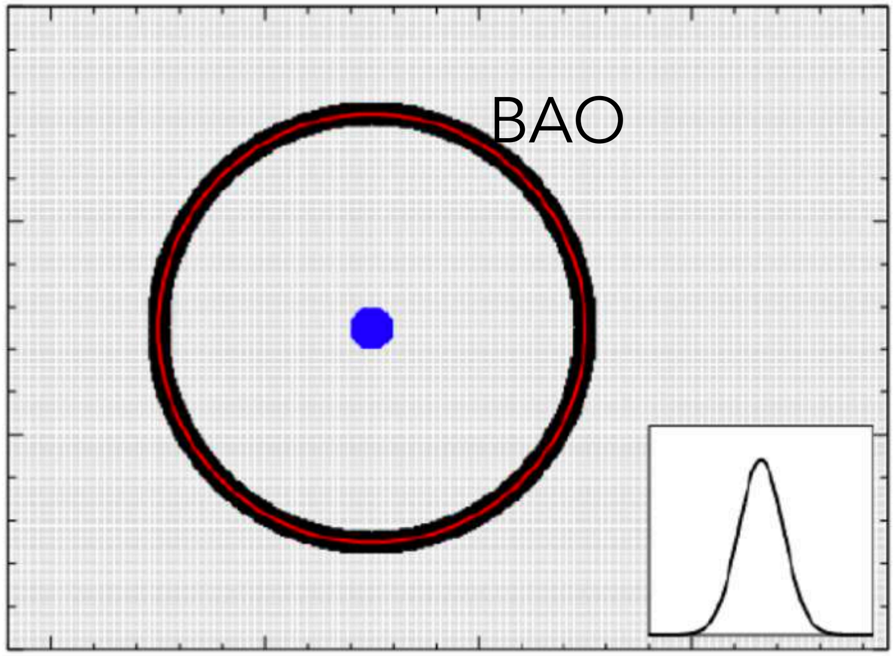
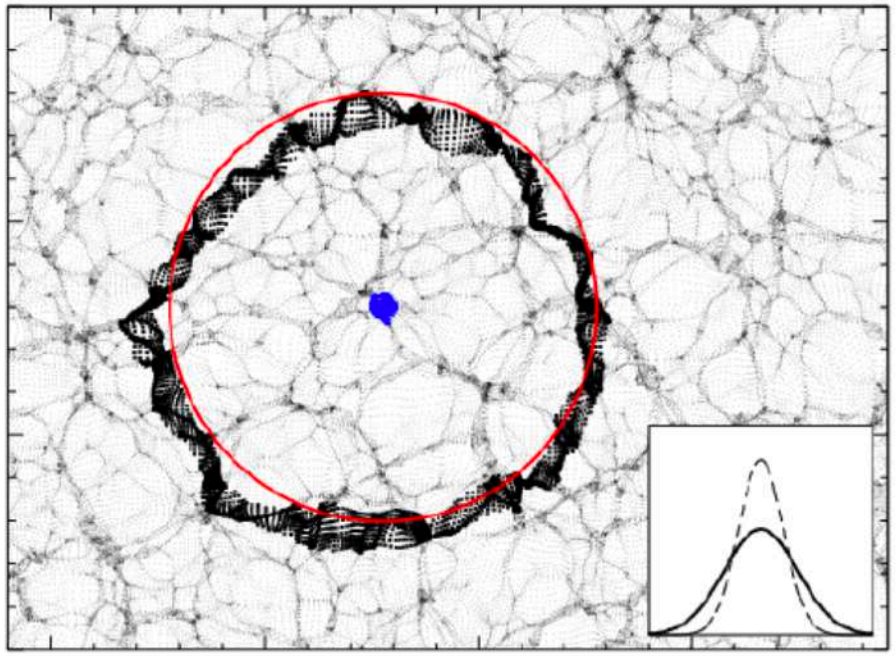
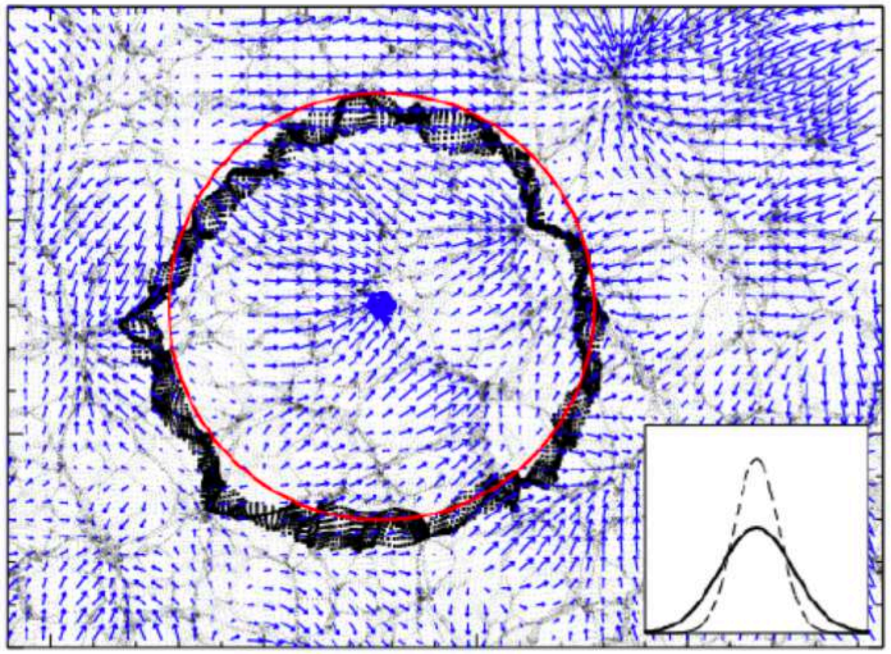


Evolved field



1st order Lagrangian
displacement field



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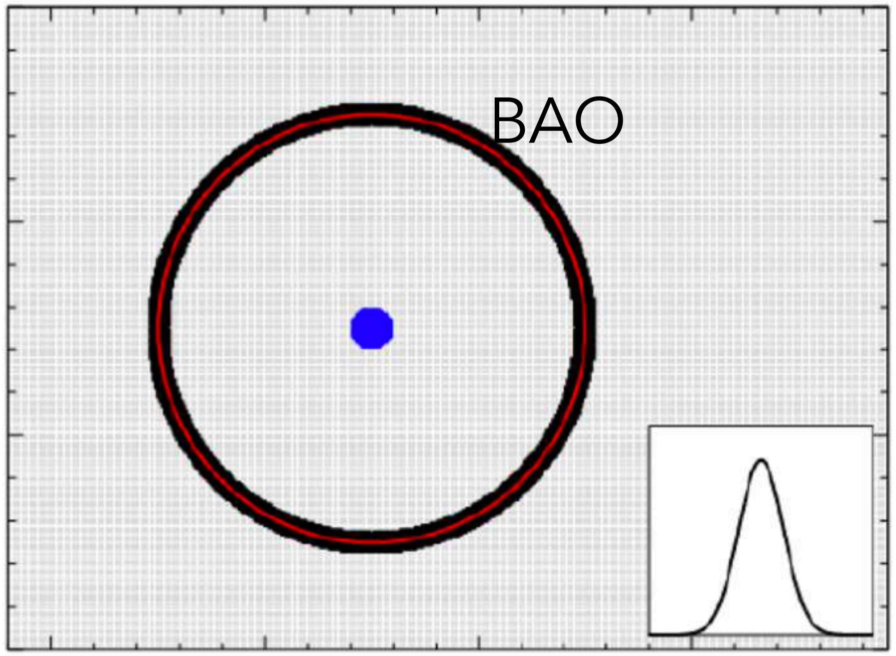

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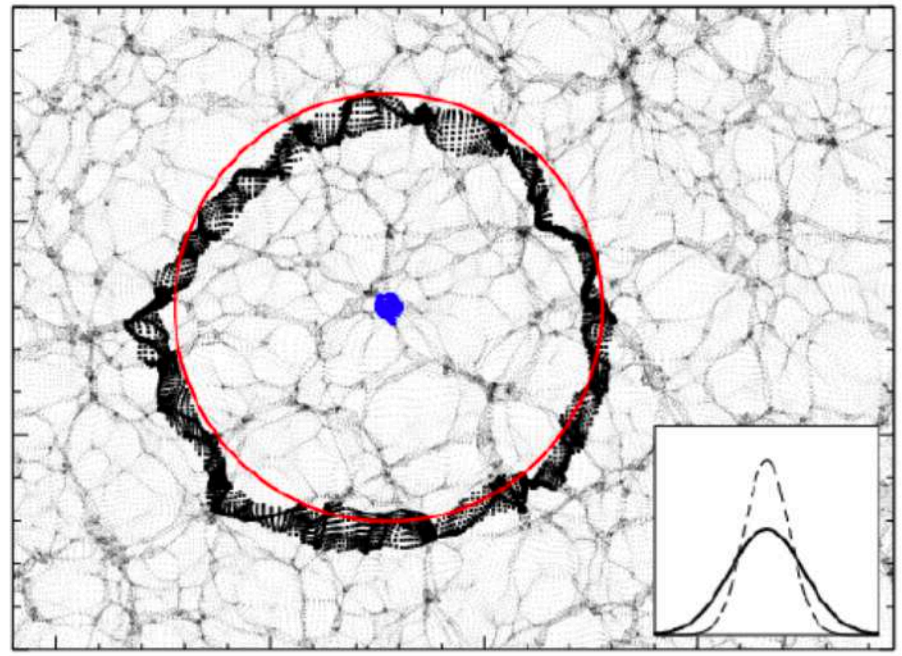

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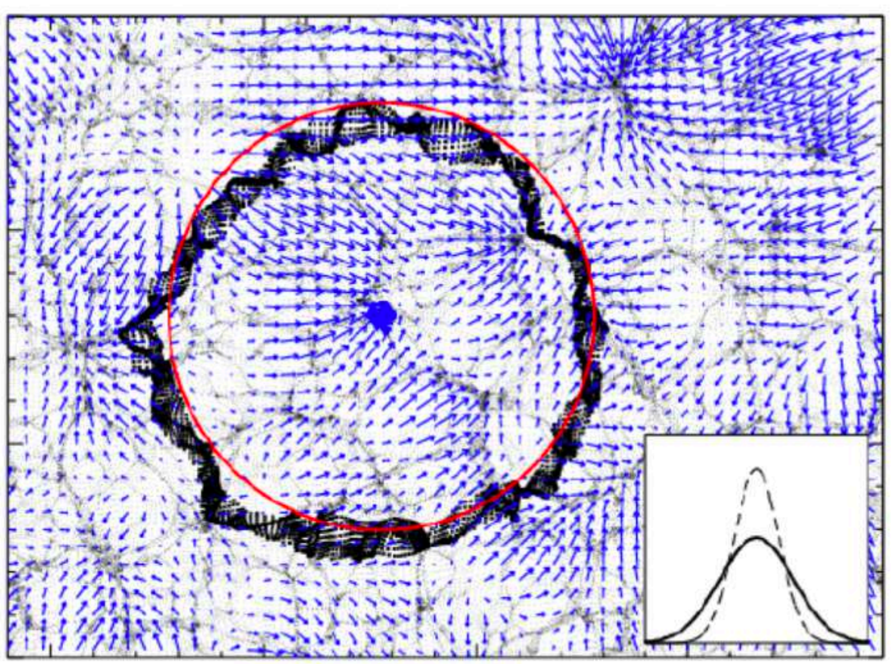

Lagrangian position

Eulerian position

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$$\vec{x}(\vec{q},t) = \vec{q} + \overrightarrow{\Psi}(\vec{q},t)$$

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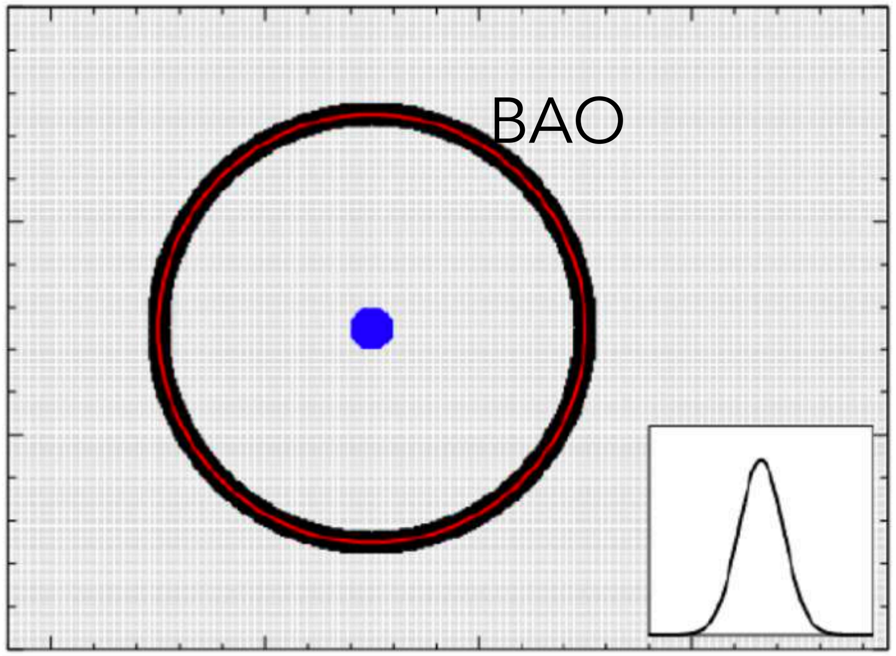

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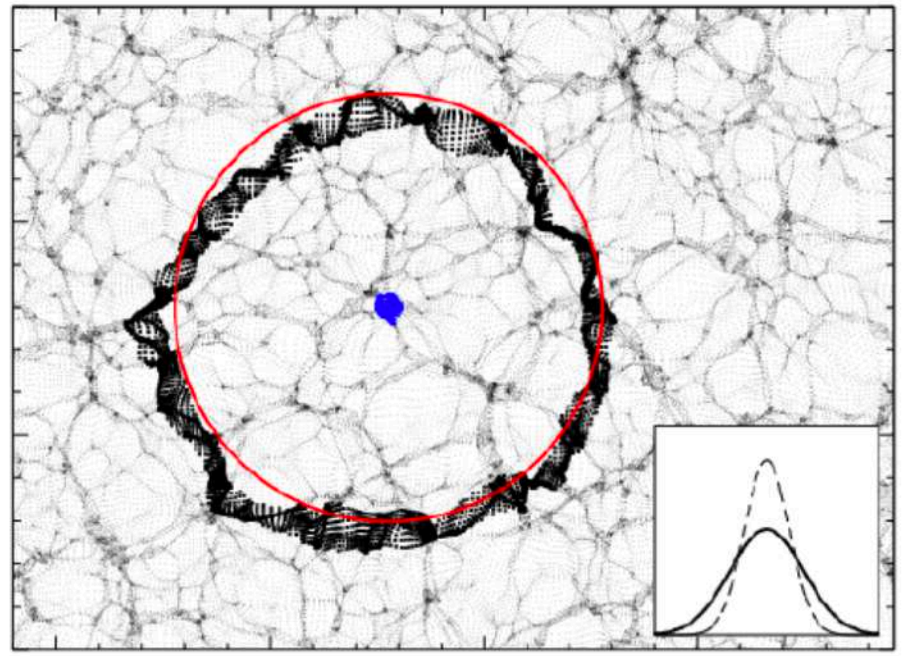

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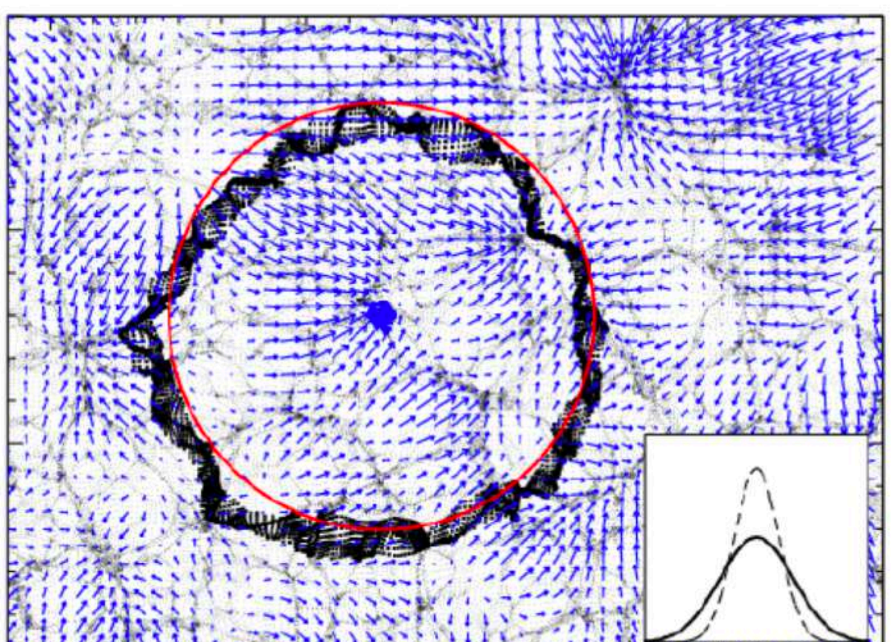

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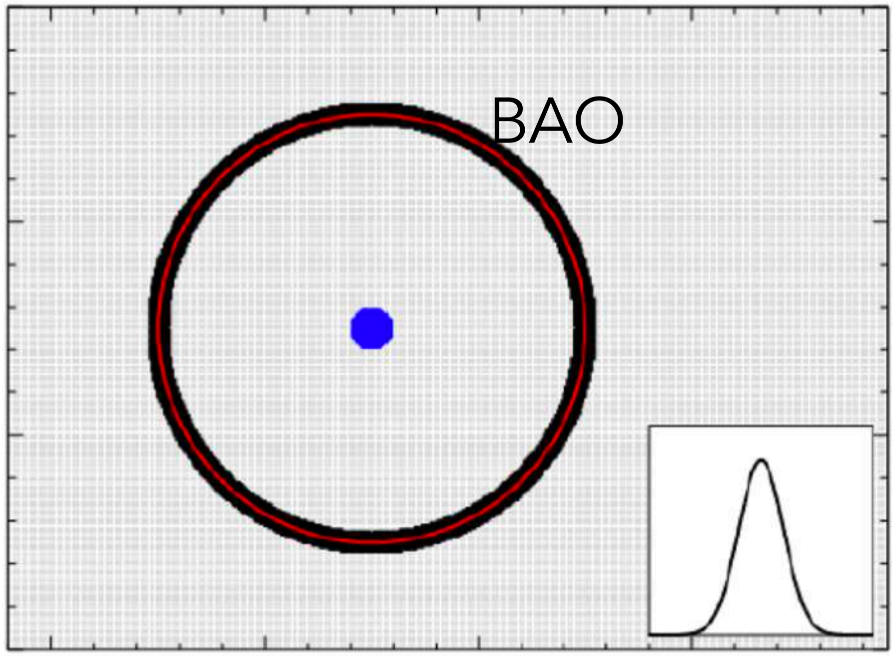

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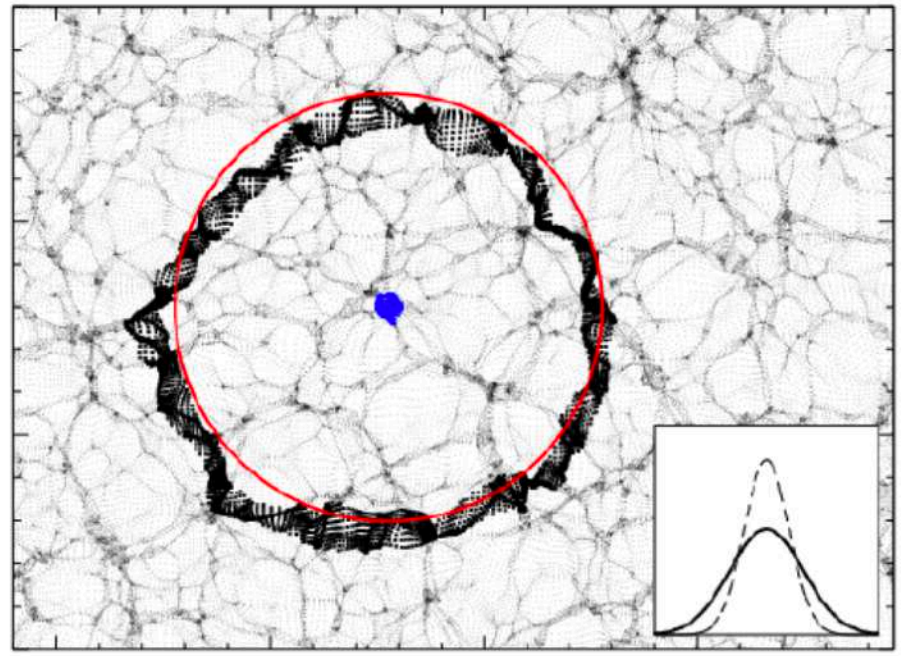

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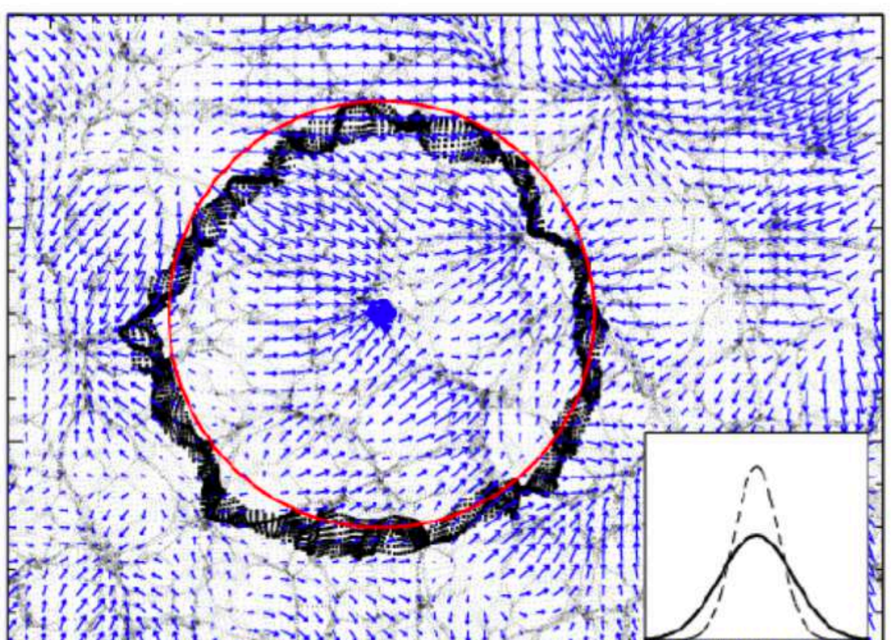

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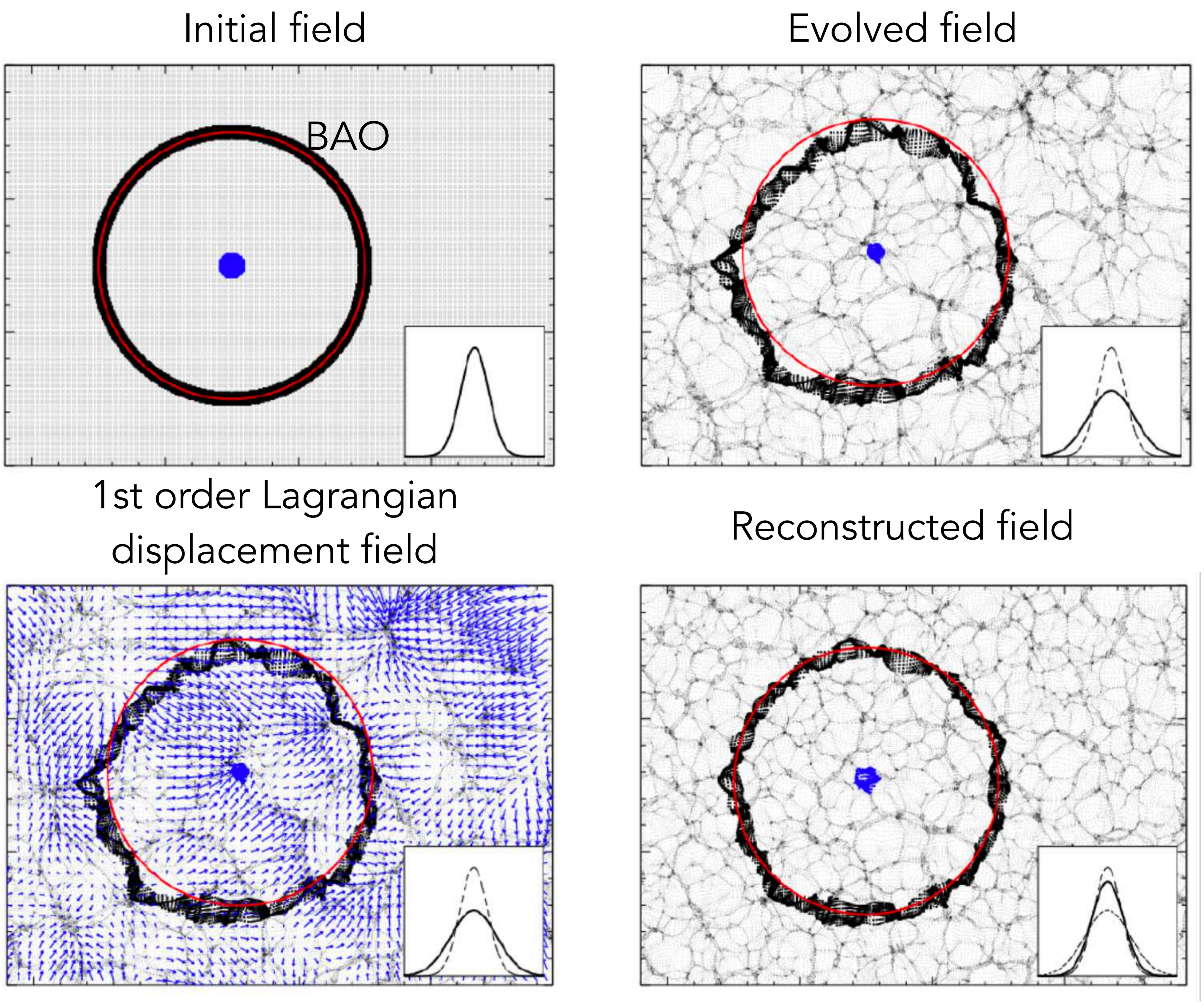

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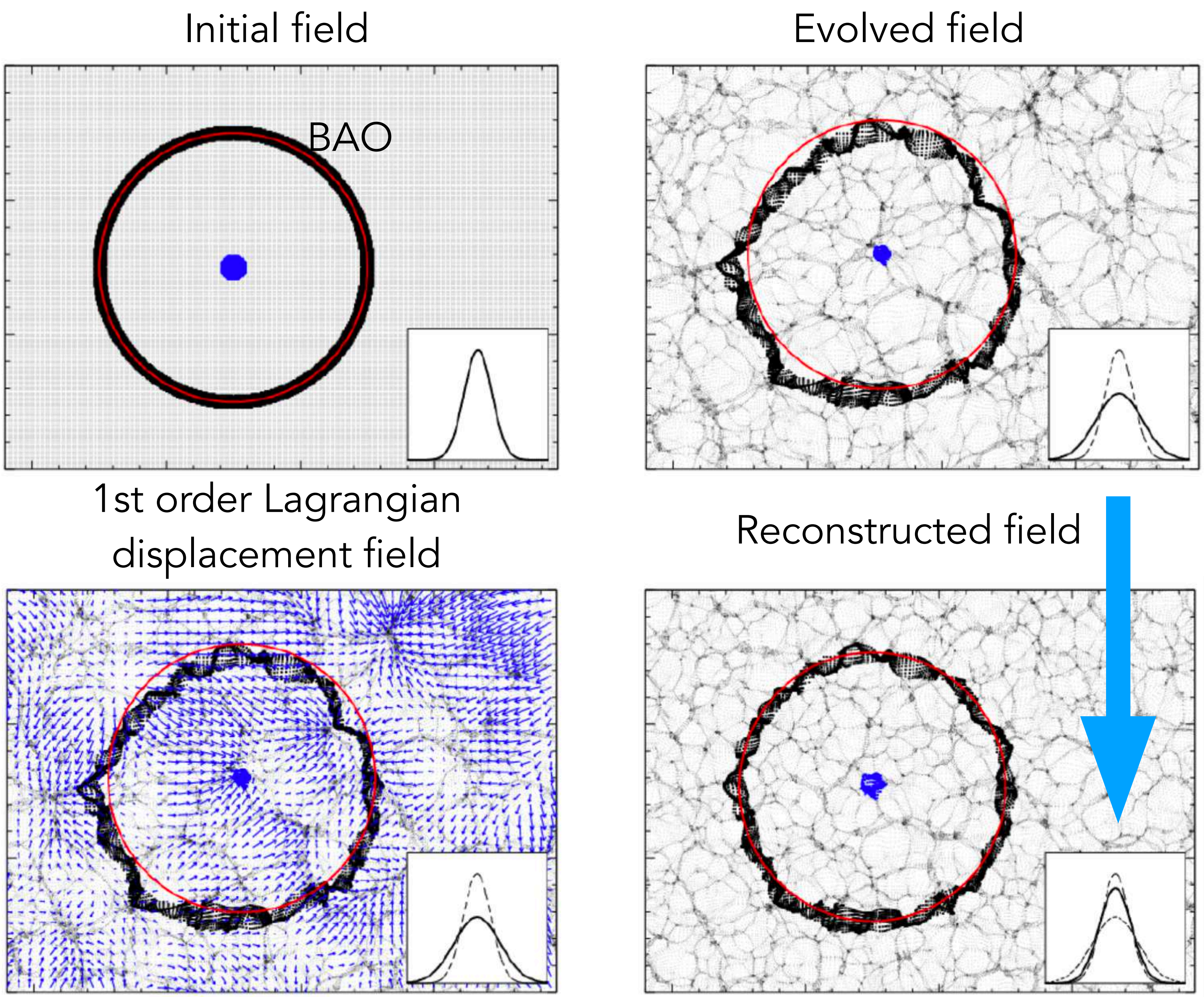
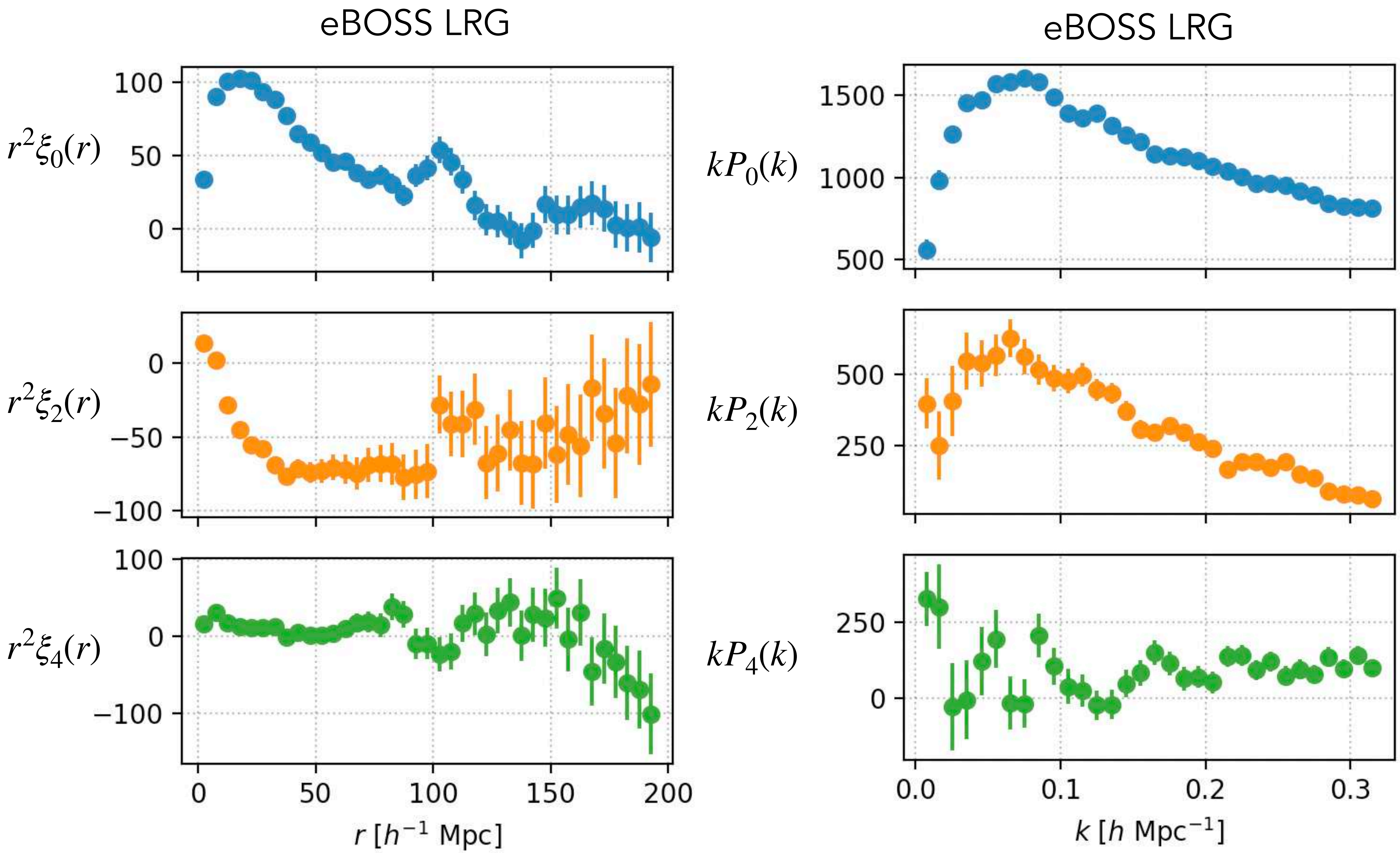


Improves BAO constraints up to factors of 2 !

Padmanabhan et al. 2012   Code: pyrecon

Reconstruction for BAO

Before reconstruction



JB et al. 2020

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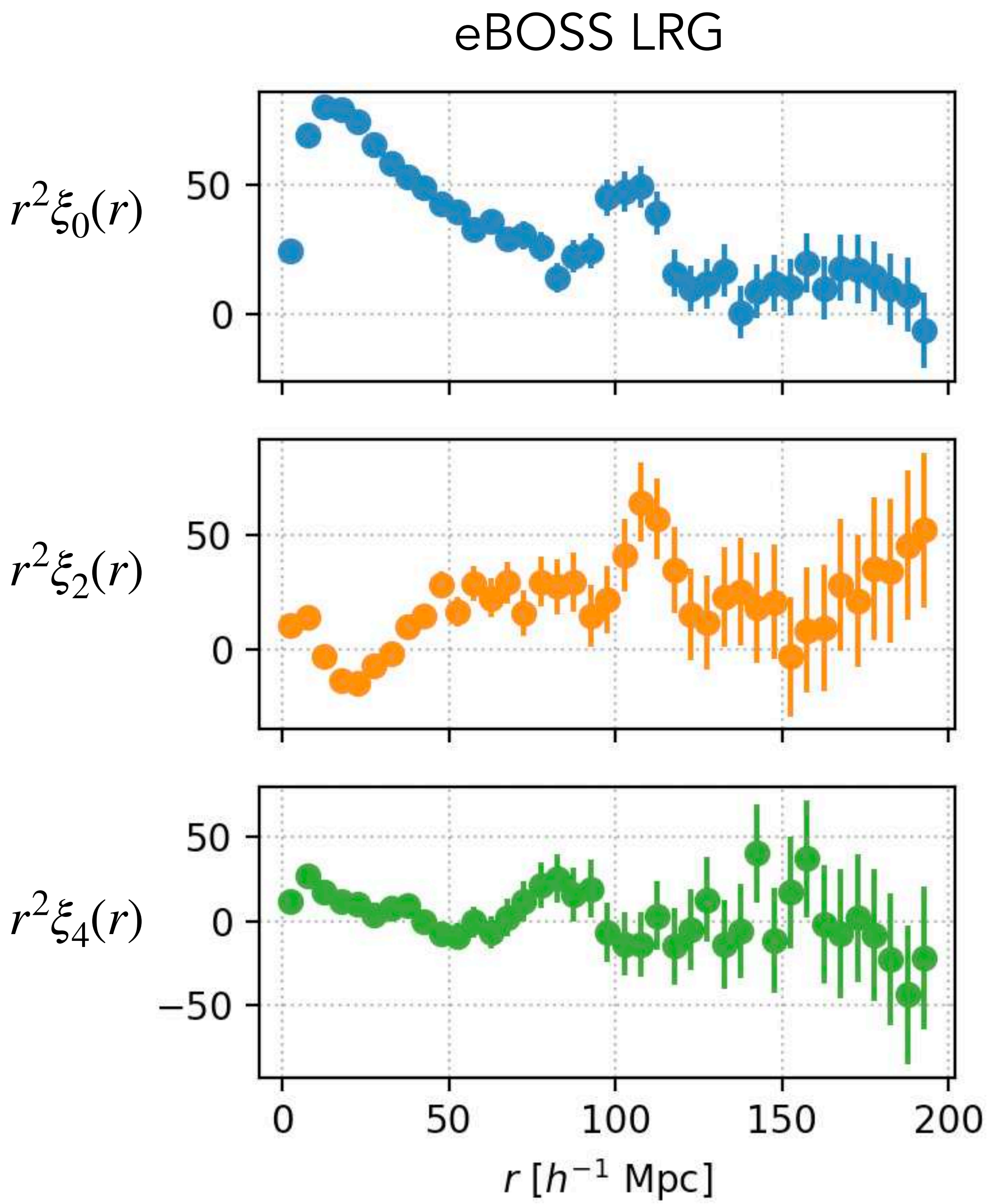

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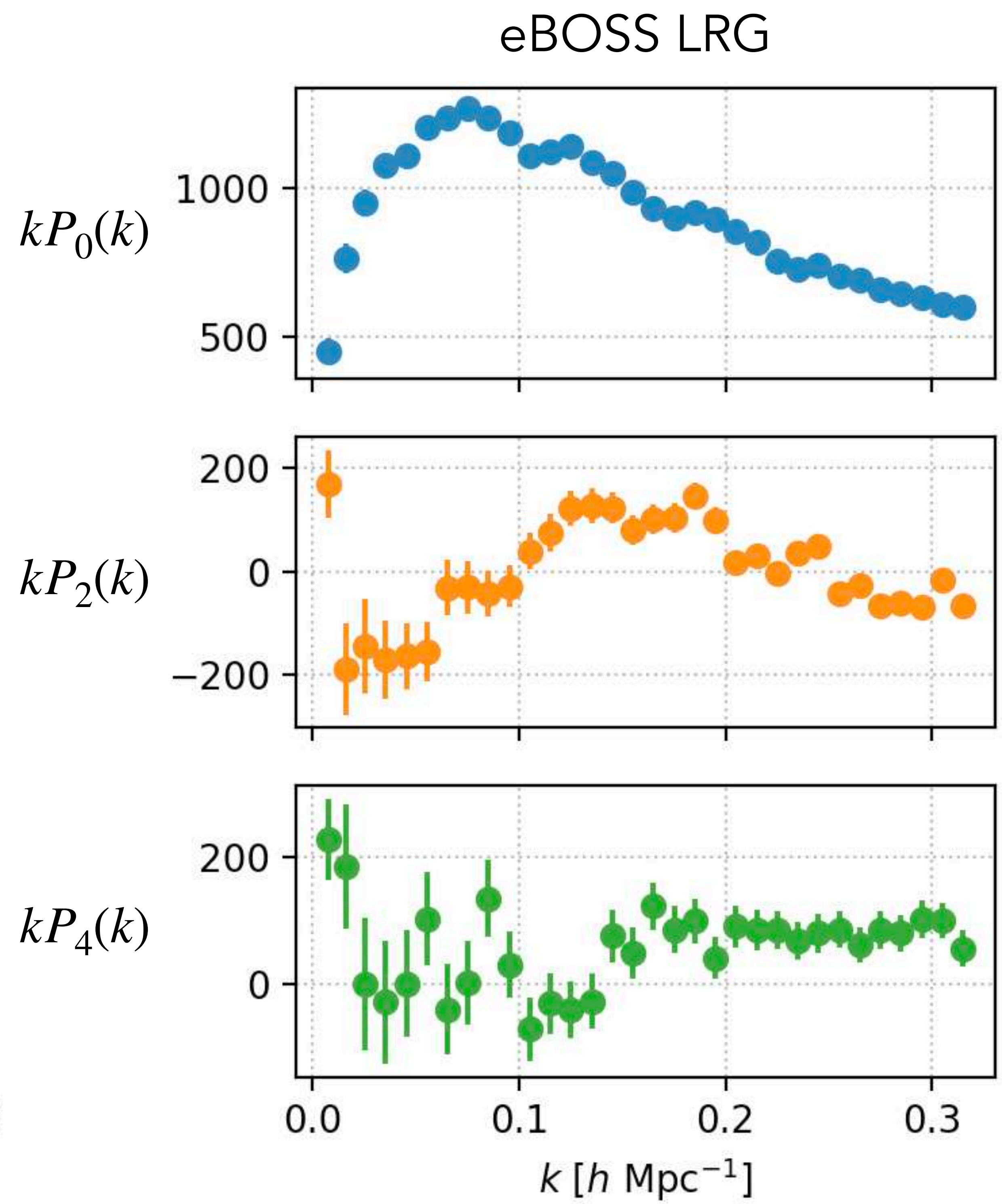

Gil-Marín et al. 2020

Cosmology with Spectroscopic Surveys

Julián Bautista
Aix Marseille Université - CPPM

Aix*Marseille université Socialement engagée

A*Midex Initiative d'excellence Aix-Marseille

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Summary until now

Main questions in cosmology

How to make a spectroscopic survey : getting redshifts

Defining the survey window function for galaxies $\delta_g(\vec{x})$

Two-point statistics : correlation function and power spectra

$$\gamma_n \Rightarrow \begin{matrix} (\theta_i, \phi_i, z_i) \\ (\theta_i, \phi_i, z_i, \{f_j\}) \end{matrix} \Rightarrow \begin{matrix} \delta_g(\vec{x}) \\ \delta_{\mathrm{Ly}\alpha}(\vec{x}) \end{matrix} \Rightarrow \langle \delta\delta' \rangle \Rightarrow \Omega_i$$

How to compute covariance/error-matrix for $\xi_\ell(r_i)$ or $P_\ell(k_i)$?

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Likelihood

$$\mathscr{L} = \frac{1}{(2\pi)^n \det(C)^{1/2}} \exp\left(-\frac{1}{2}[\vec{d} - \overrightarrow{m}(\vec{p})]^T C^{-1} [\vec{d} - \overrightarrow{m}(\vec{p})] \right)$$

Data vector

$$\vec{d} = \begin{bmatrix} \xi_0 \\ \xi_1 \\ \cdots \\ \xi_n \end{bmatrix}$$

Model

$$\overrightarrow{m}$$

Parameters

$$\vec{p}$$

Covariance matrix

$$C_{ij} = \langle \xi_i \xi_j \rangle$$

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$$C \rightarrow C(\vec{p})$$

Systematics?

Grieb et al 2016

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Data based
Bootstrap/Jacknife

More subsamples, less volume
Noisier

Mohammad & Percival 2022

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Monte-Carlo Mocks

CPU expensive

Realistic clustering?

How to compute covariance/error-matrix for $\langle \delta(\vec{x})\delta(\vec{x}') \rangle$?

Case of **galaxies and quasars**

Mocks = approximate simulations of clustering, realistic observational properties

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eBOSS EZmocks

Zhao et al. 2020

- Zel'dovich approximations to rapidly construct density field
- **1000** realisations of the survey
- includes redshift evolution
- includes observational effects
- includes cross-correlations between tracers

How to compute covariance/error-matrix for $\langle \delta(\vec{x})\delta(\vec{x}') \rangle$?

Case

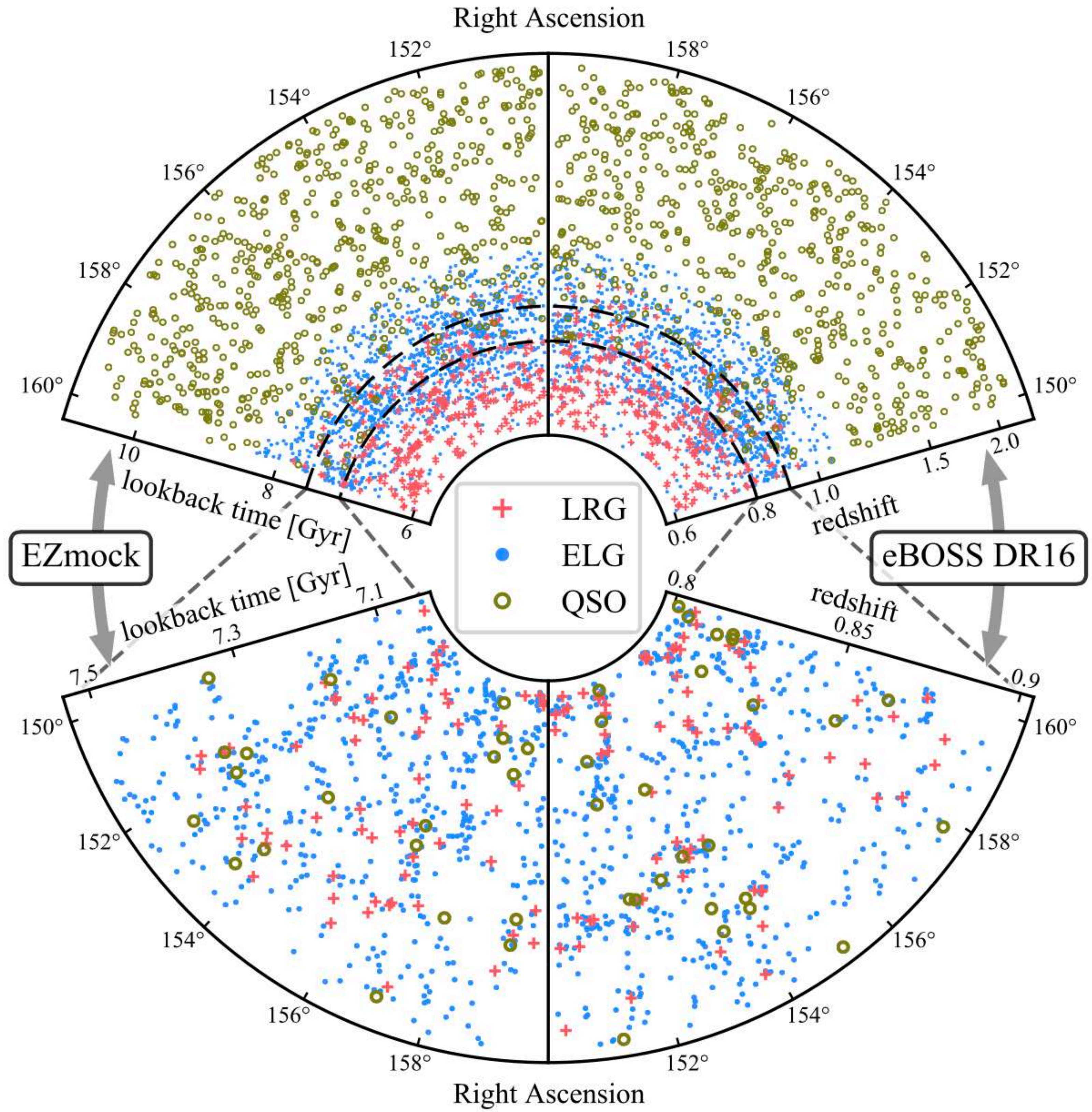
Mocks = approximate simulati

Covariance matrix is given by "

eBOSS EZmocks

Zhao et al. 2020

- Zel'dovich approximations to rapidly construct density field
- **1000** realisations of the survey
- includes redshift evolution
- includes observational effects
- includes cross-correlations between tracers

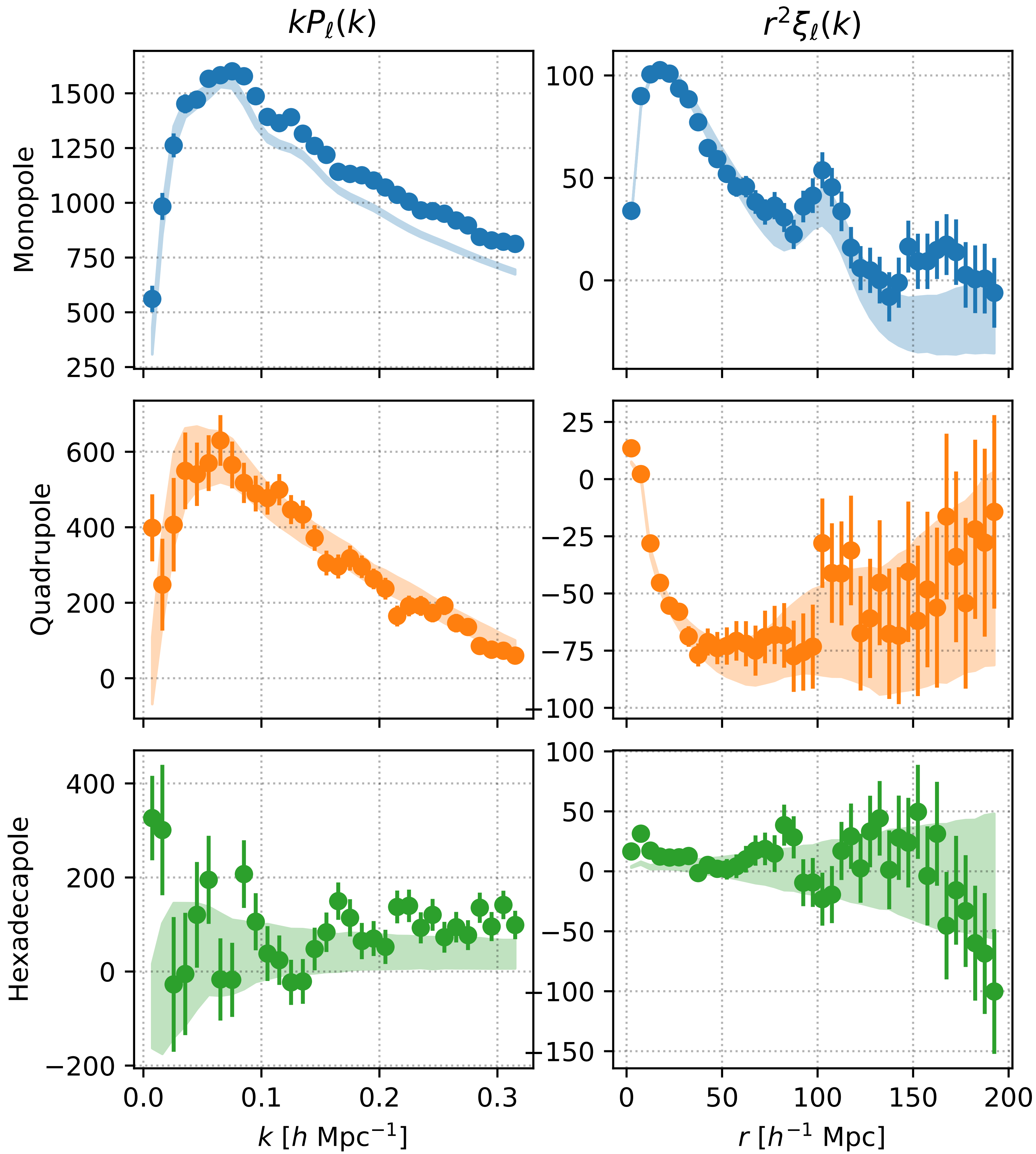


eBOSS EZmocks

Zhao et al. 2020

Points = data

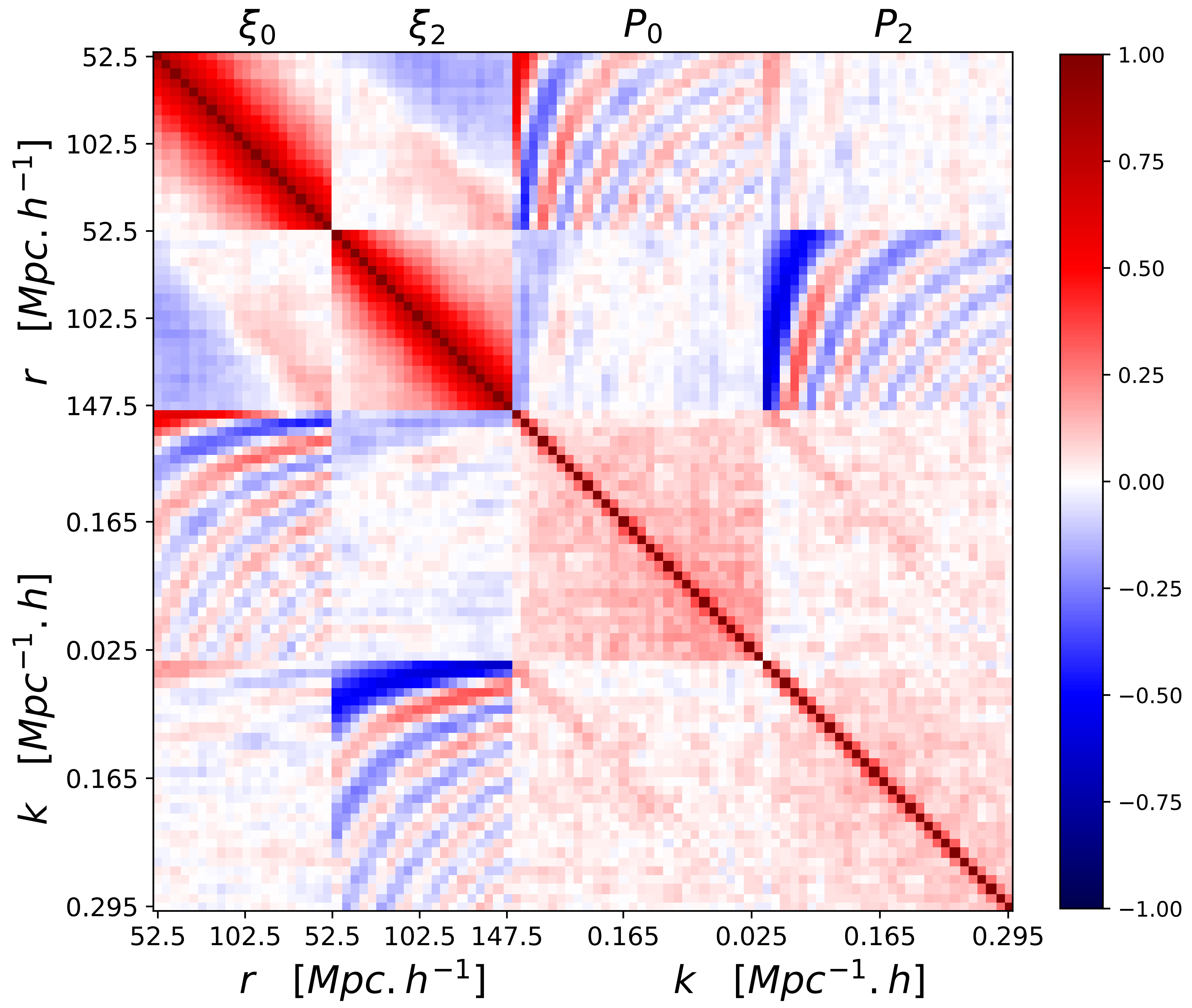
Shaded area = mocks



Covariance matrix is given by "scatter" over 1000 measurements of $\xi_\ell(r), P_\ell(k)$

eBOSS EZmock Covariance matrix

Dumerchat & JB 2022



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What next

Baryon acoustic oscillations (BAO)
Redshift-space distortions (RSD)
Models and simulations
Non-Gaussianities $f_{\rm NL}$

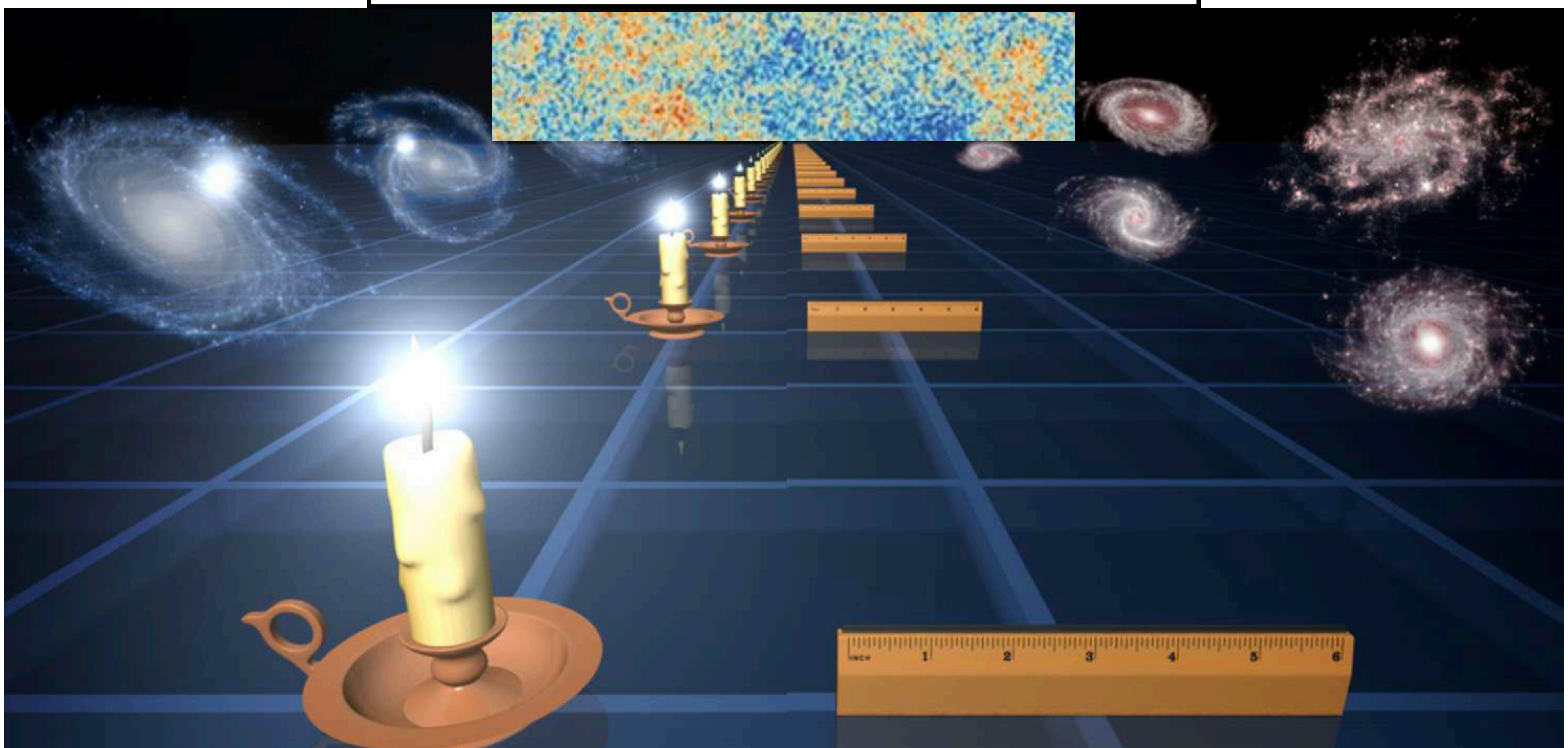
Converting quasar spectra to $\delta_{\rm Ly\alpha}(\vec{x})$
Clustering measurements
BAO analysis
Neutrino masses
Simulations

$$\gamma_n \rightarrow (\theta_i, \phi_i, z_i) \rightarrow \delta_g(\vec{x})$$

$$\left(\theta_i, \phi_i, z_i, \{f_j\}\right) \rightarrow \delta_{\rm Ly\alpha}(\vec{x}) \rightarrow \langle \delta\delta' \rangle \rightarrow \Omega_i$$

Baryon Acoustic Oscillations (BAO)

Cosmic microwave background (CMB)
z ~ 1100 or t ~ 380 000 years



Type-Ia Supernovae (SNIa) as standard candles	Baryon Acoustic Oscillations (BAO) as standard ruler
$0 < z < 1.5$	$0.1 < z < 2.5$
5 Gy < t < 13.8 Gy	3 Gy < t < 13 Gy

$$F = \frac{L_{\rm candle}}{4\pi D_L^2(z)} \qquad \Delta\theta = \frac{r_{\rm ruler}}{D_M(z)} \qquad \Delta z = \frac{r_{\rm ruler}}{D_H(z)}$$

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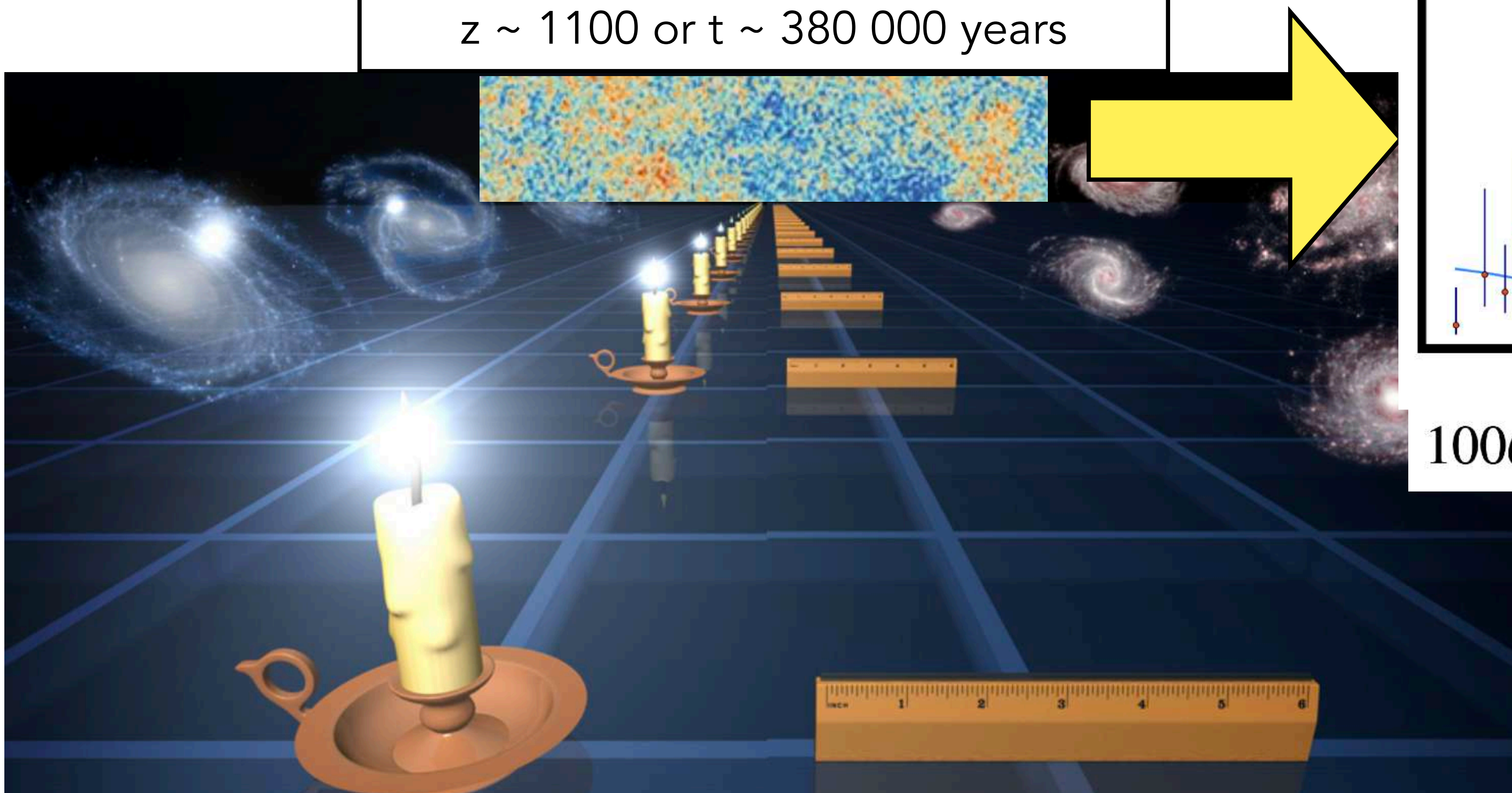

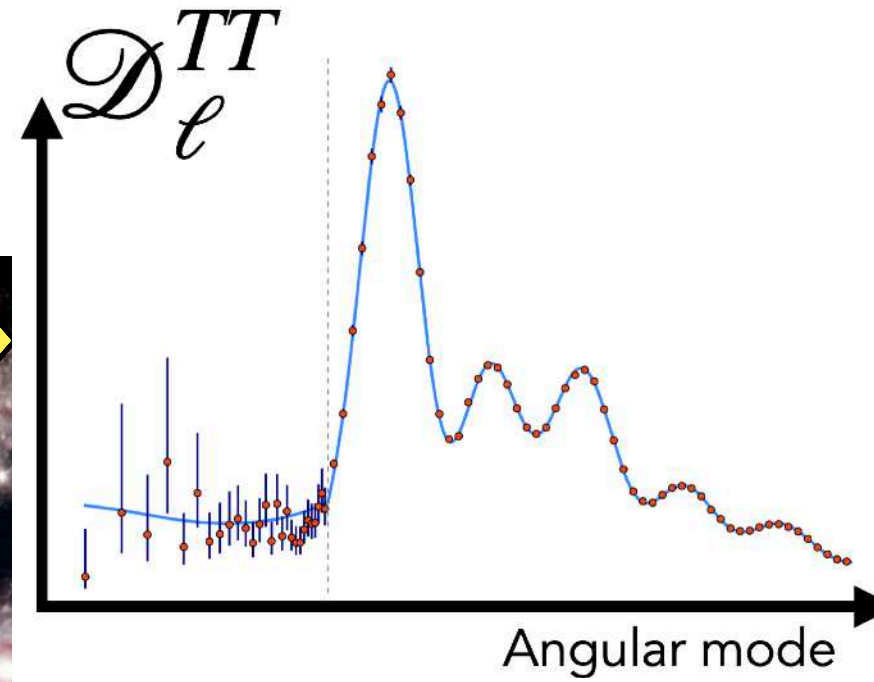

$$100\theta_* = 1.04109 \pm 0.00030$$

$$\theta_* \equiv r_* / D_\mathrm{M}$$

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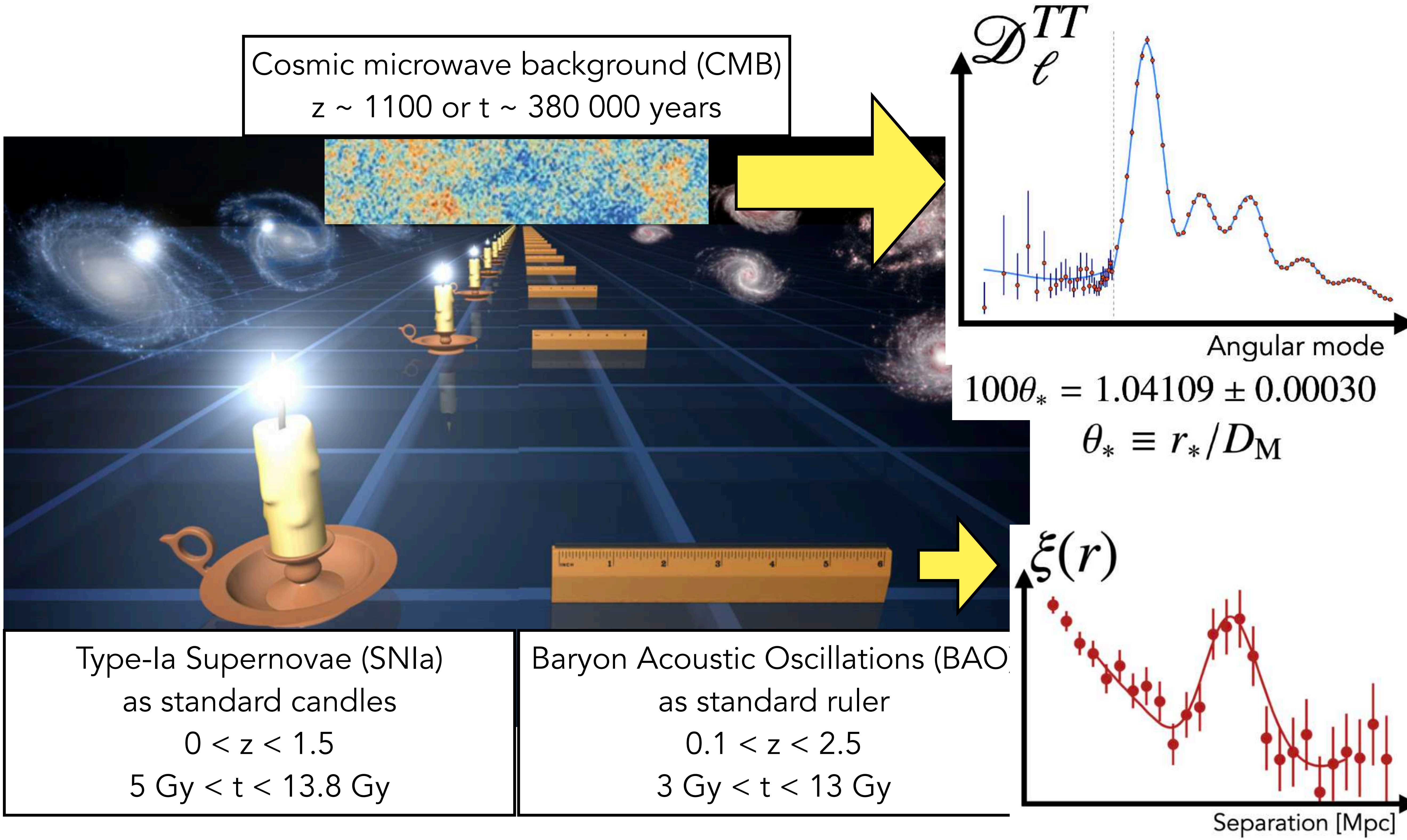

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$r_\mathrm{ruler} \sim 101 h^{-1}\mathrm{Mpc}$
(comoving)

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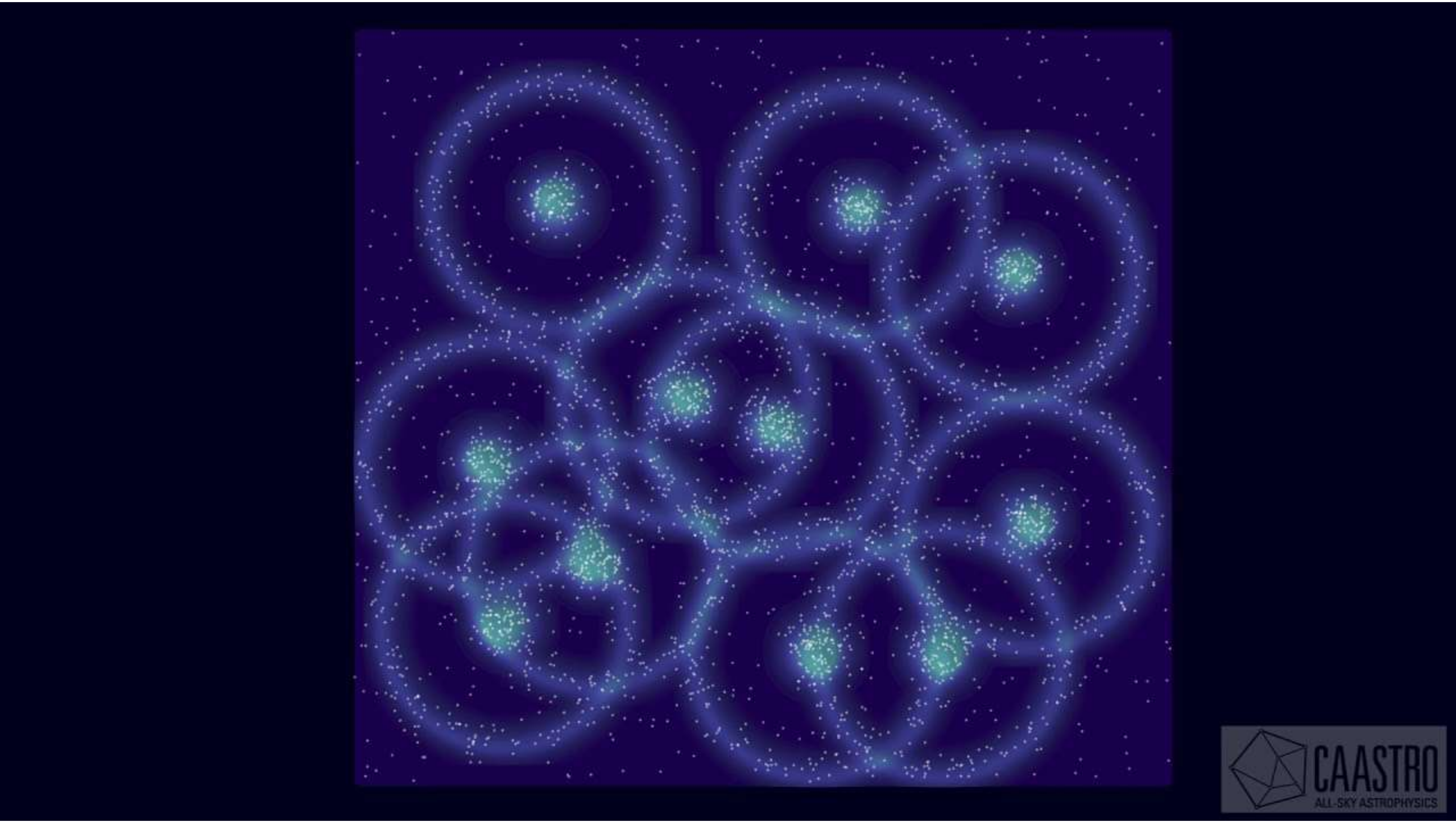

Link to video

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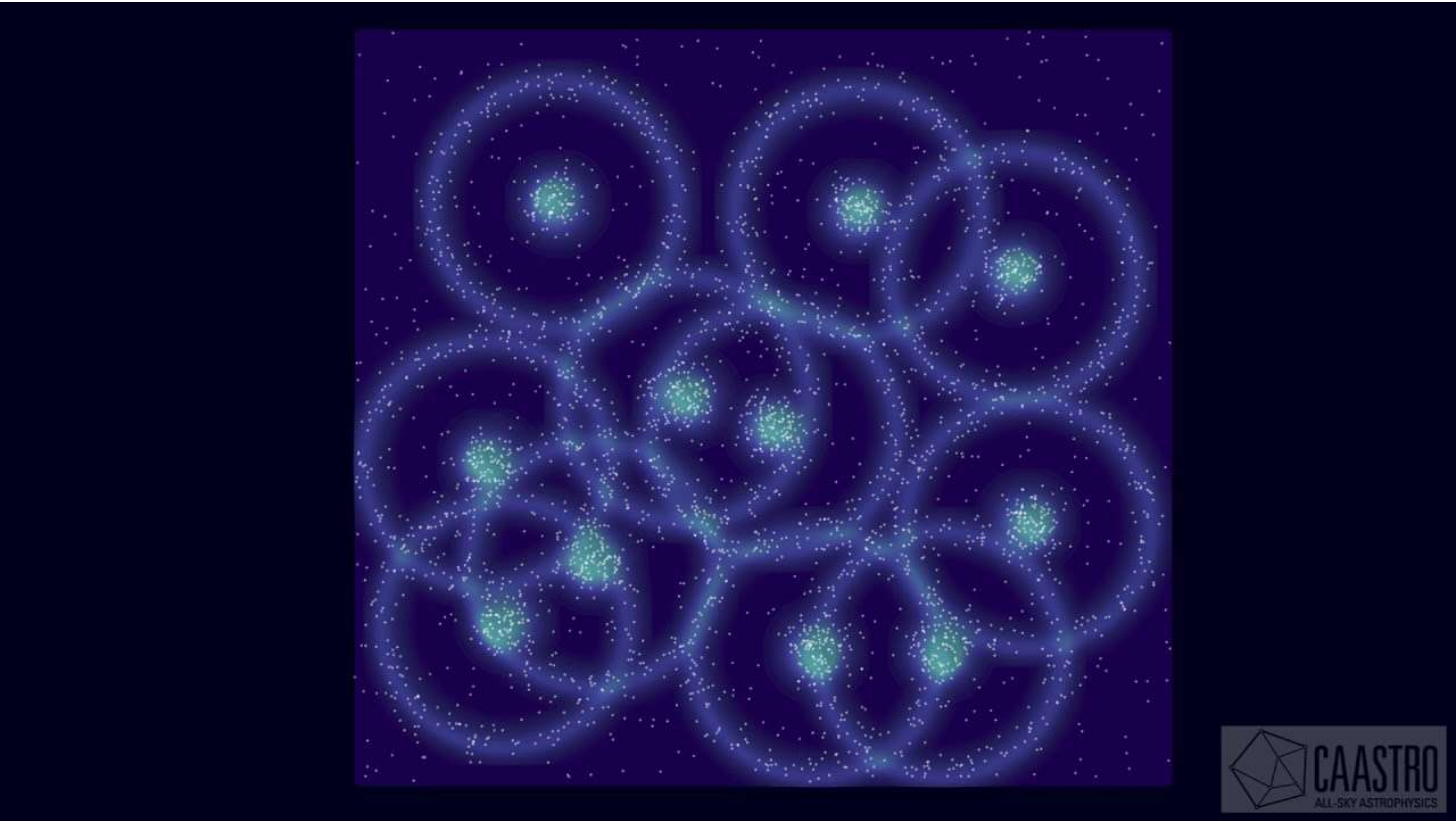

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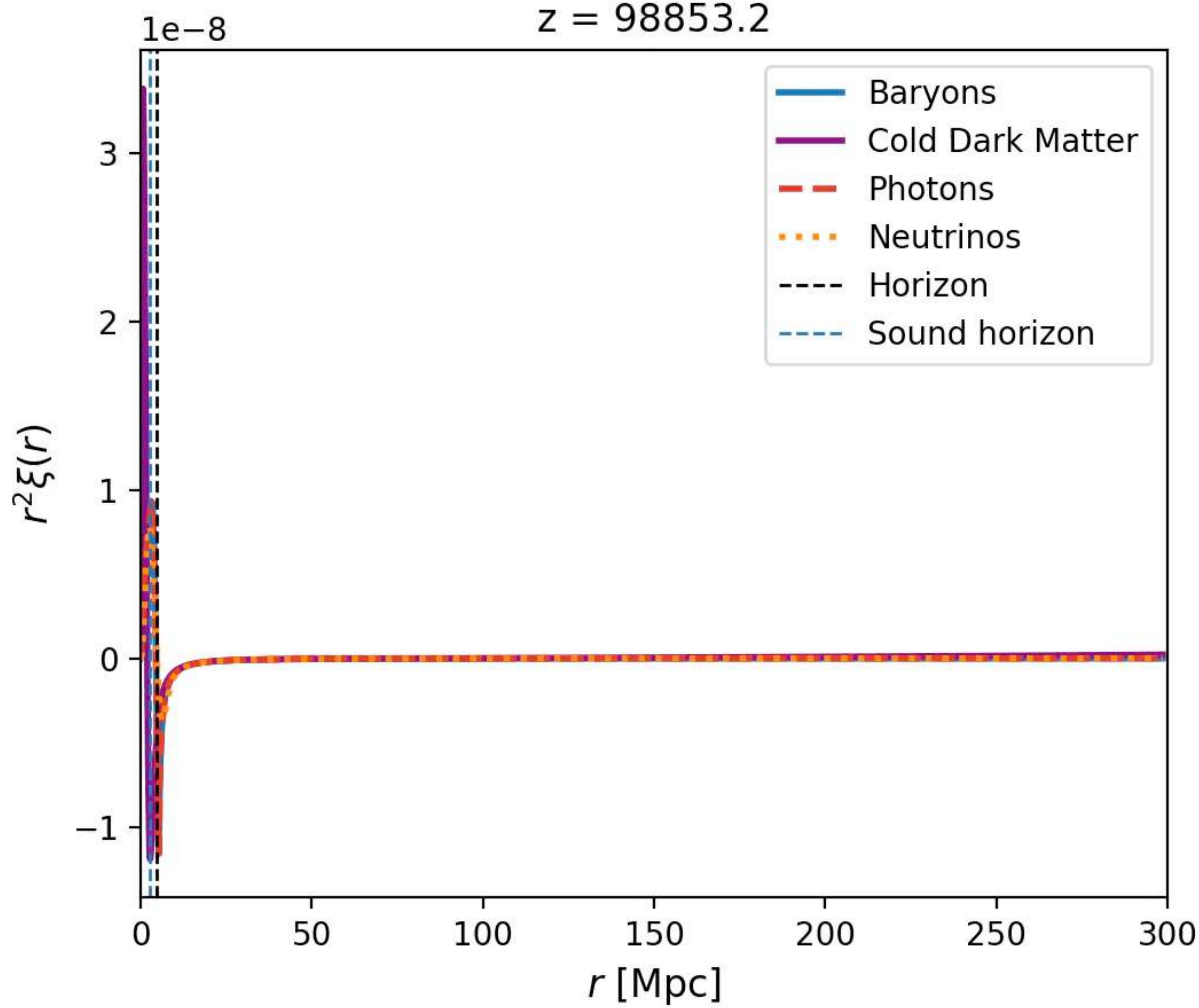
Baryon Acoustic Oscillations (BAO)

Well described by GR + Boltzmann

Configuration space



Link to code

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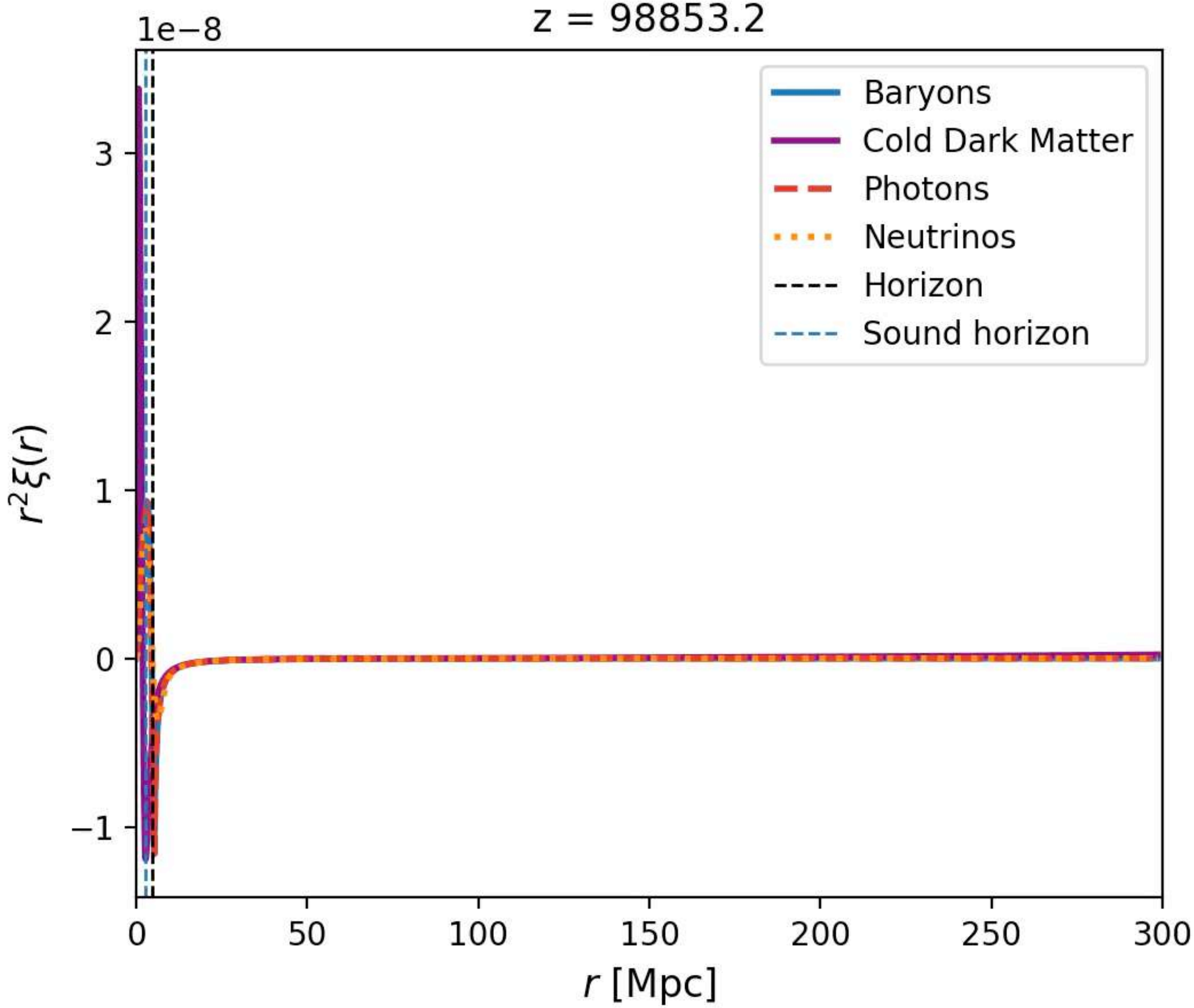

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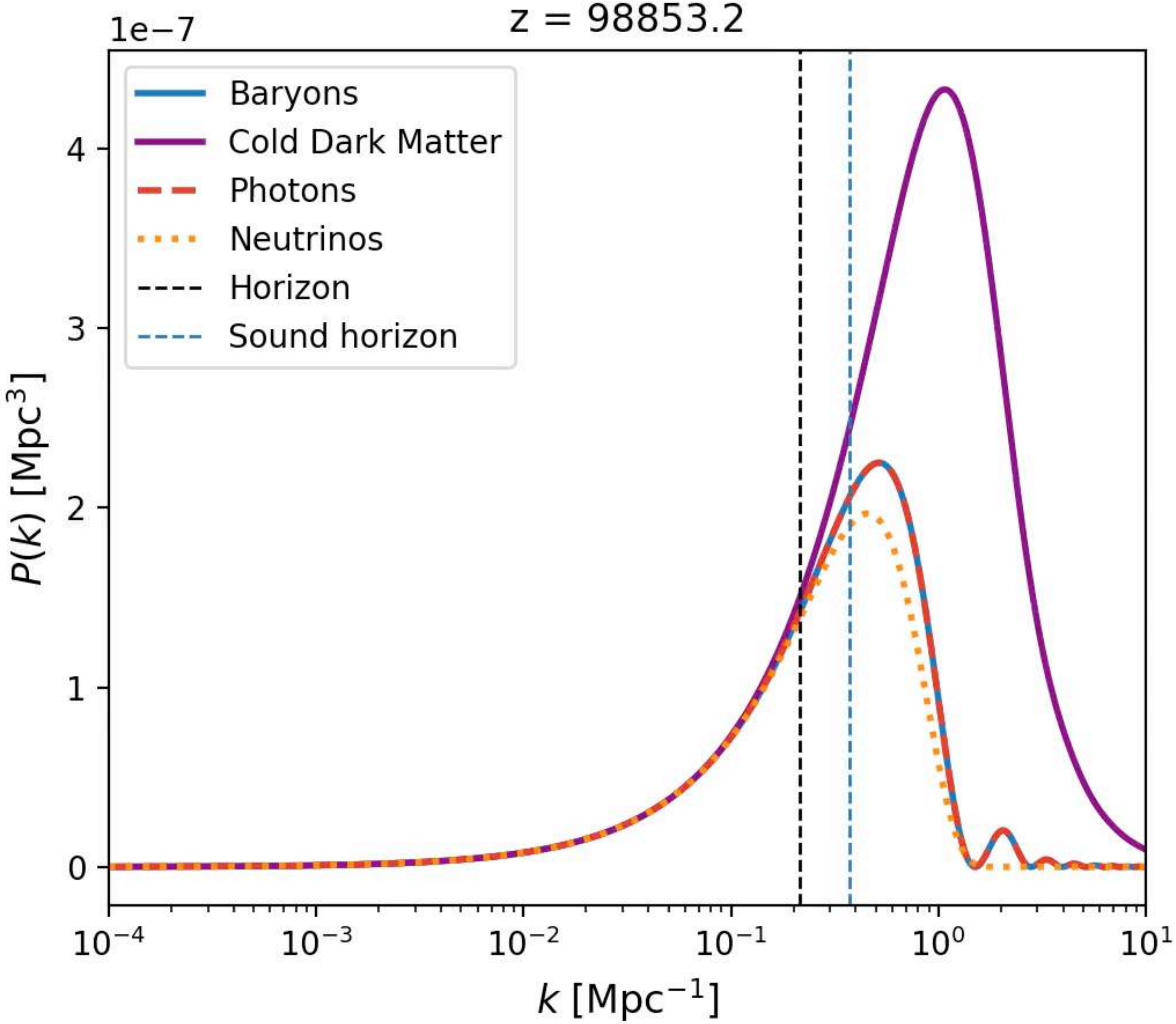

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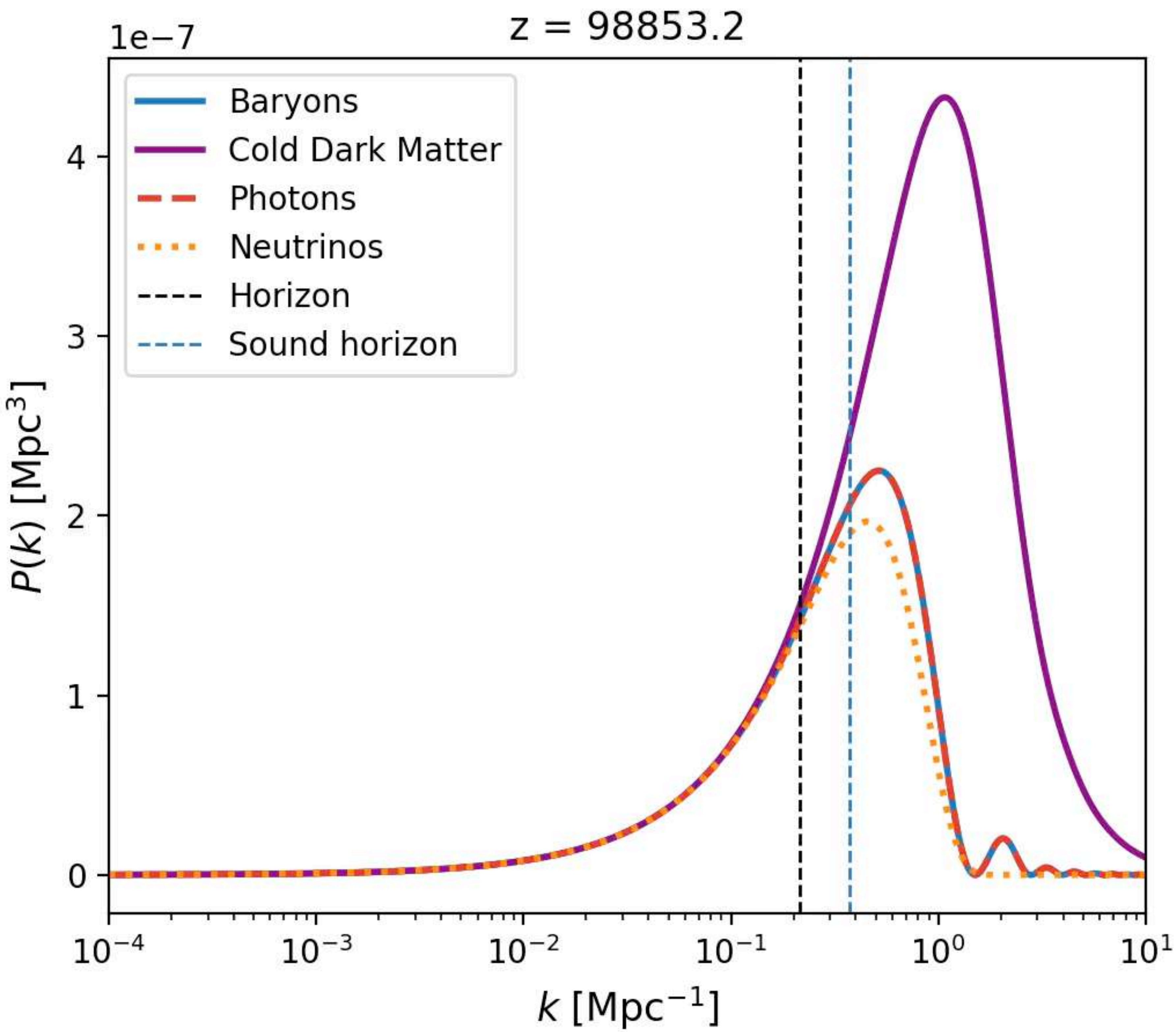

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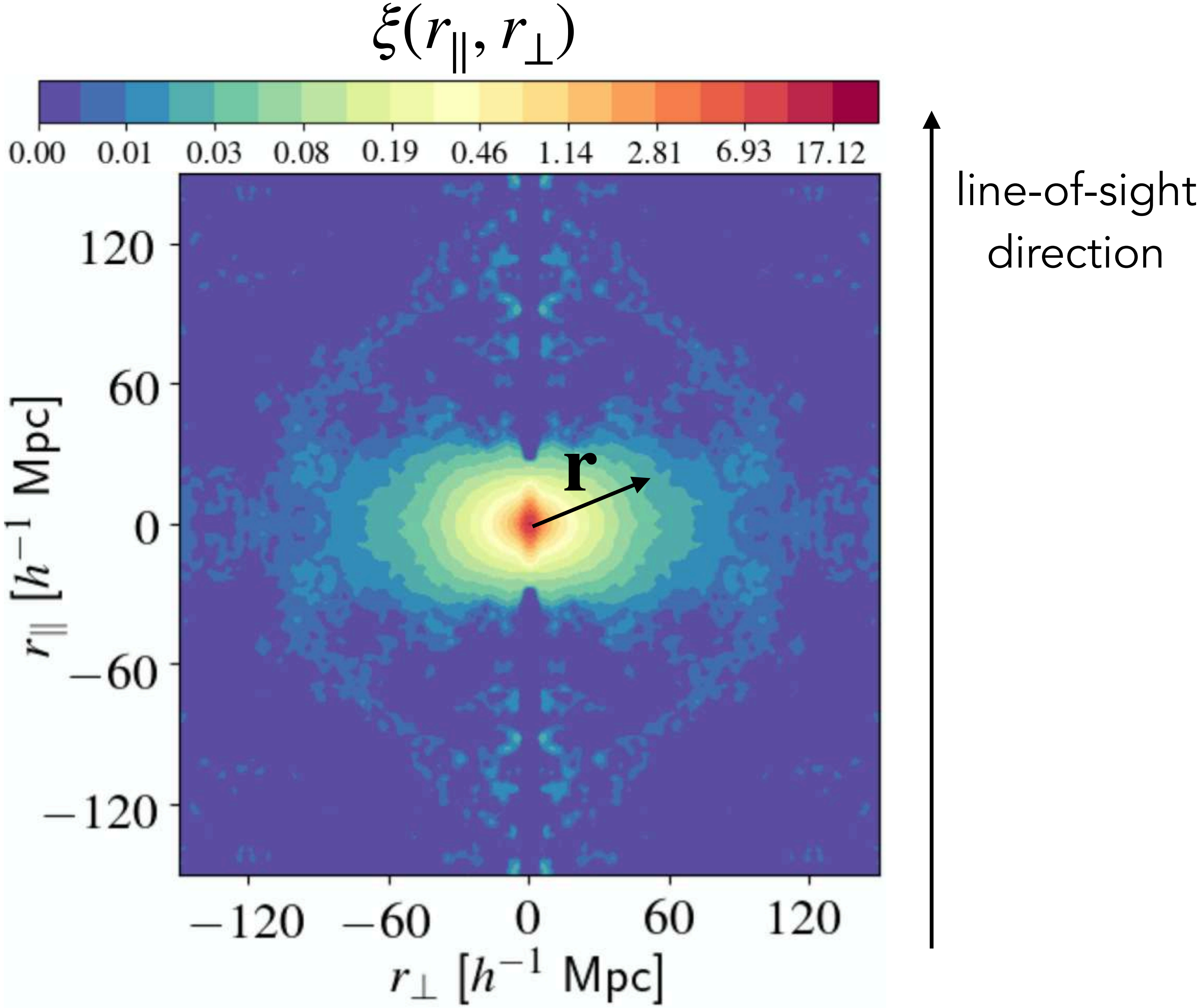

How to extract the BAO scale ?

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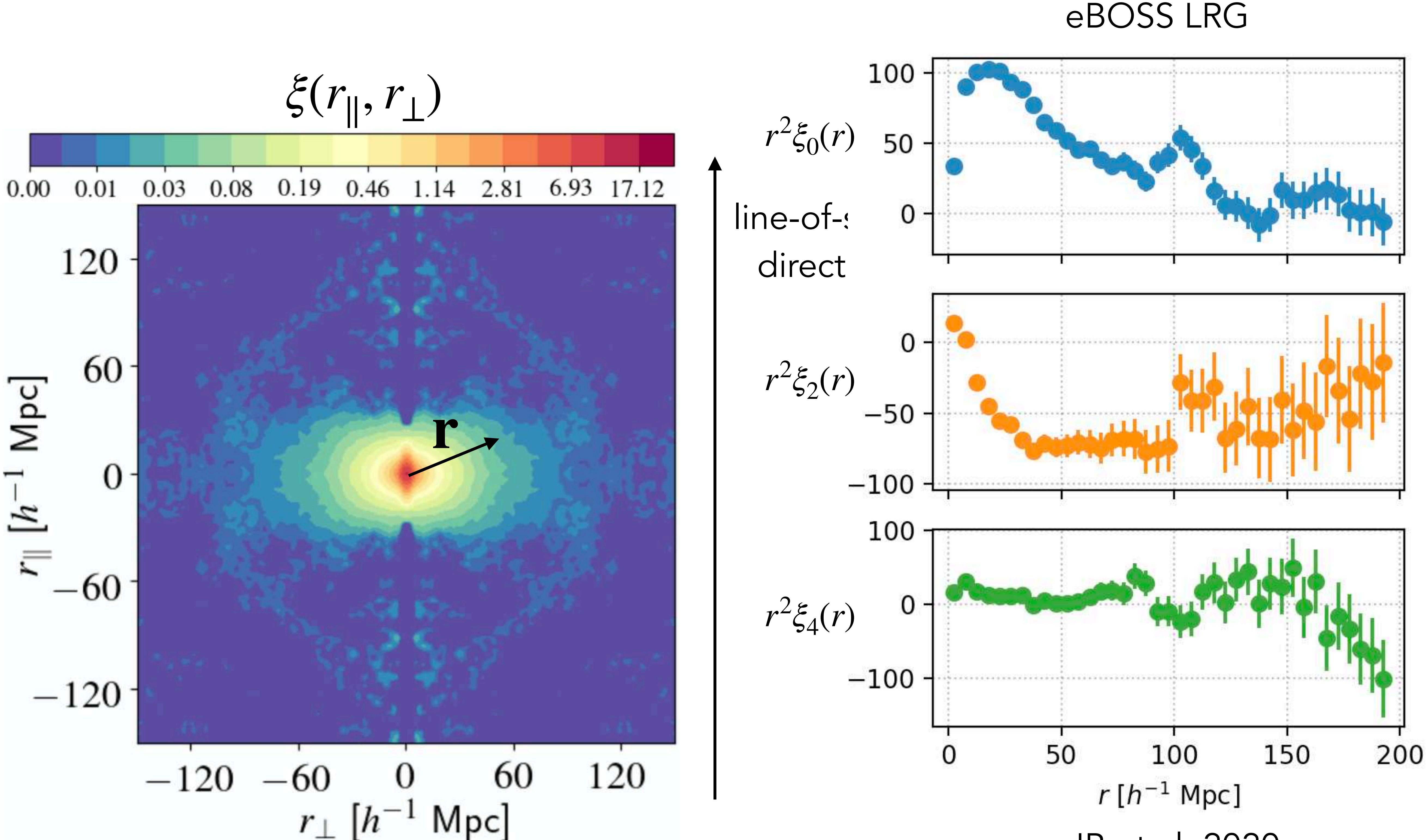

JB et al. 2020

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$$z_i \to \chi(z_i)$$

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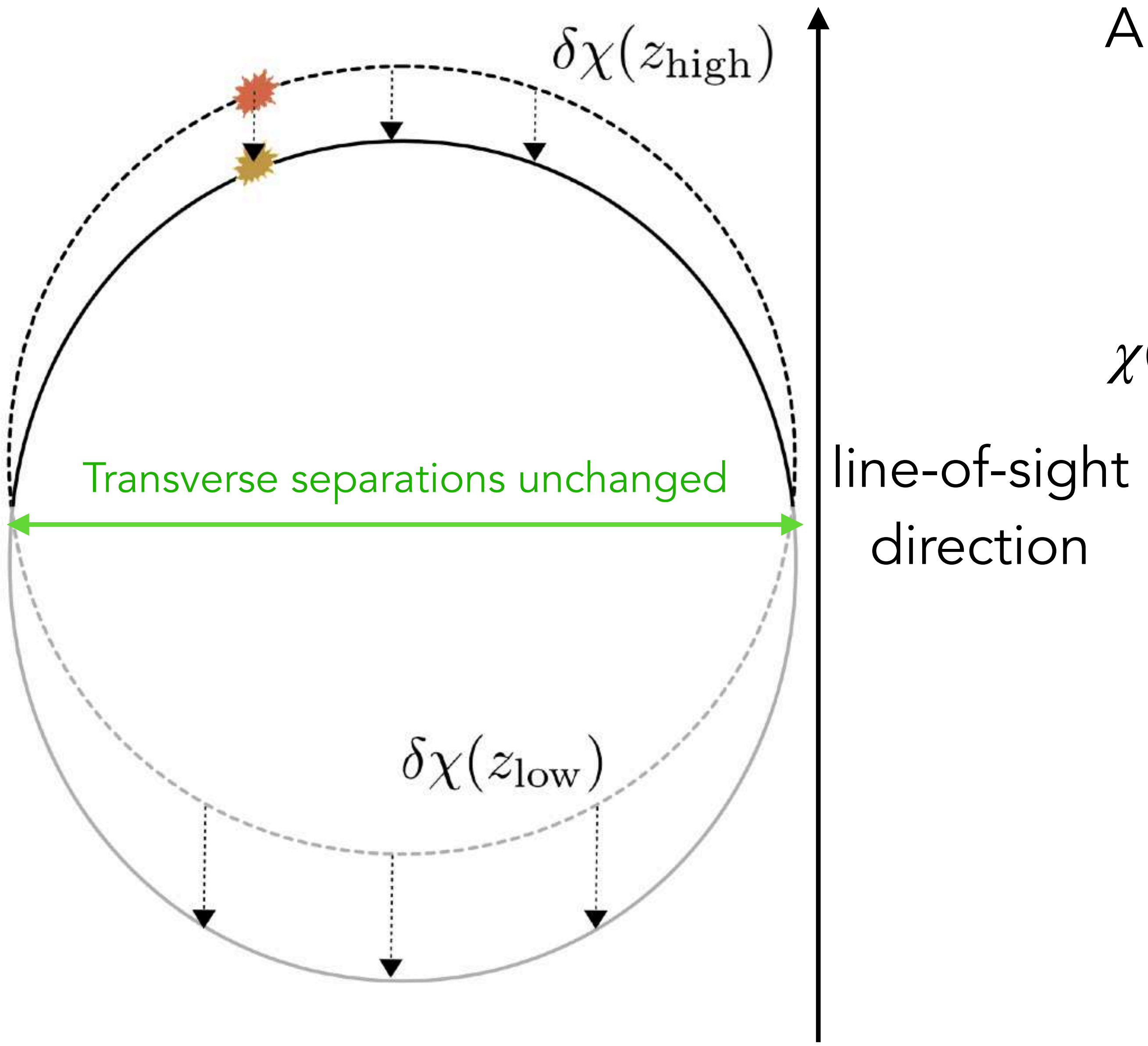

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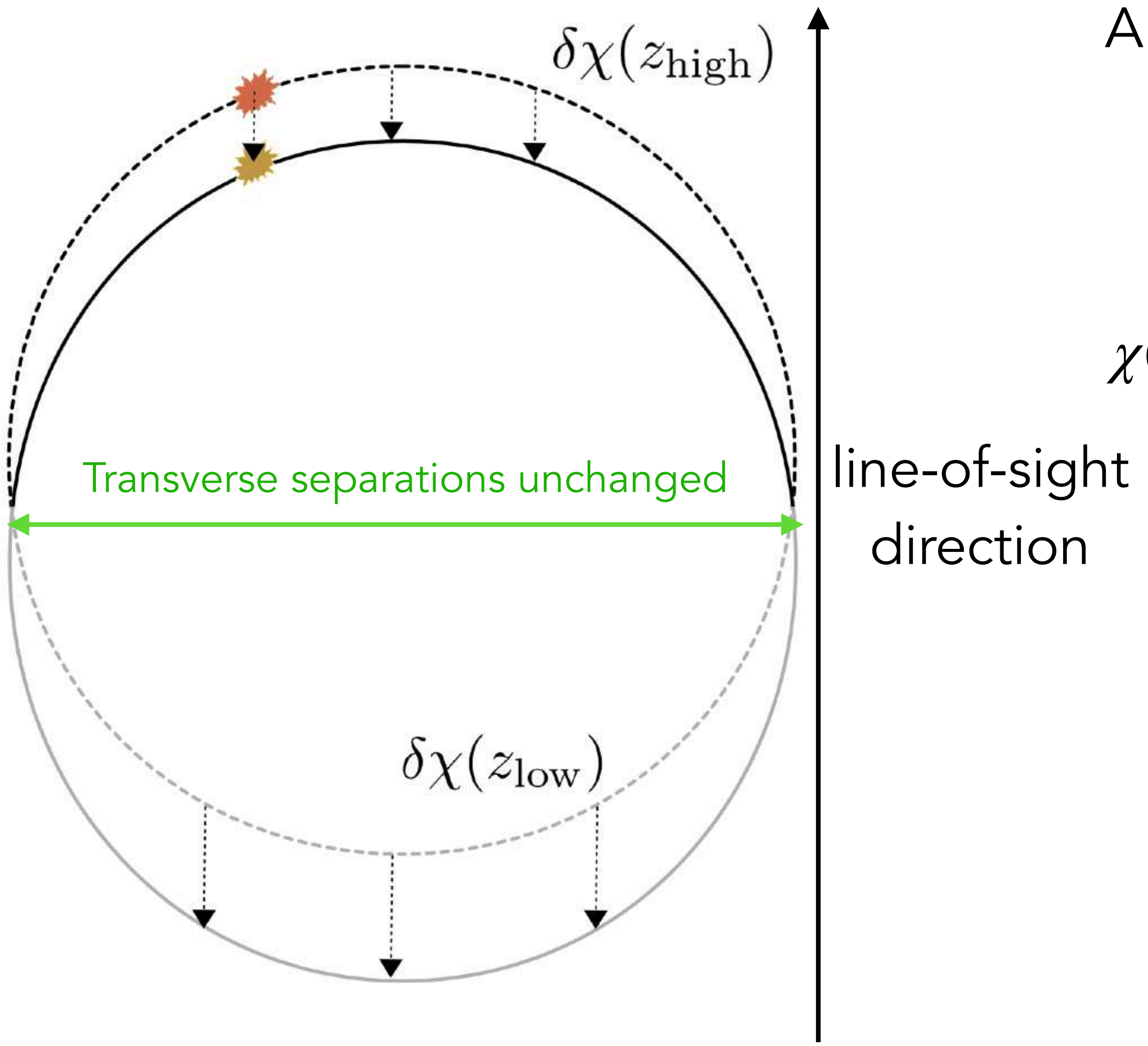

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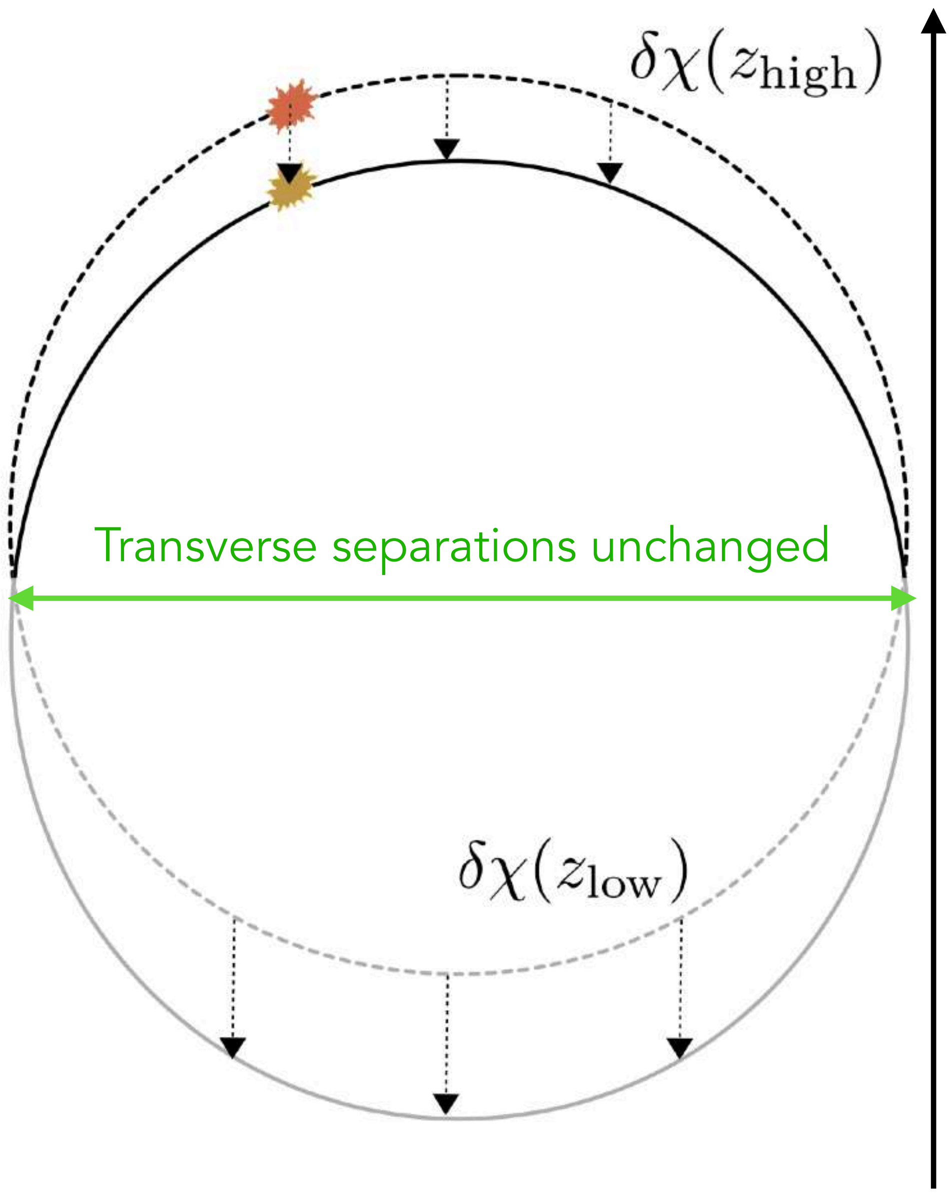

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Need to choose a "template" cosmology

e.g., $\Omega_m = 0.31,\ \Omega_k = 0,\ h = 0.67$

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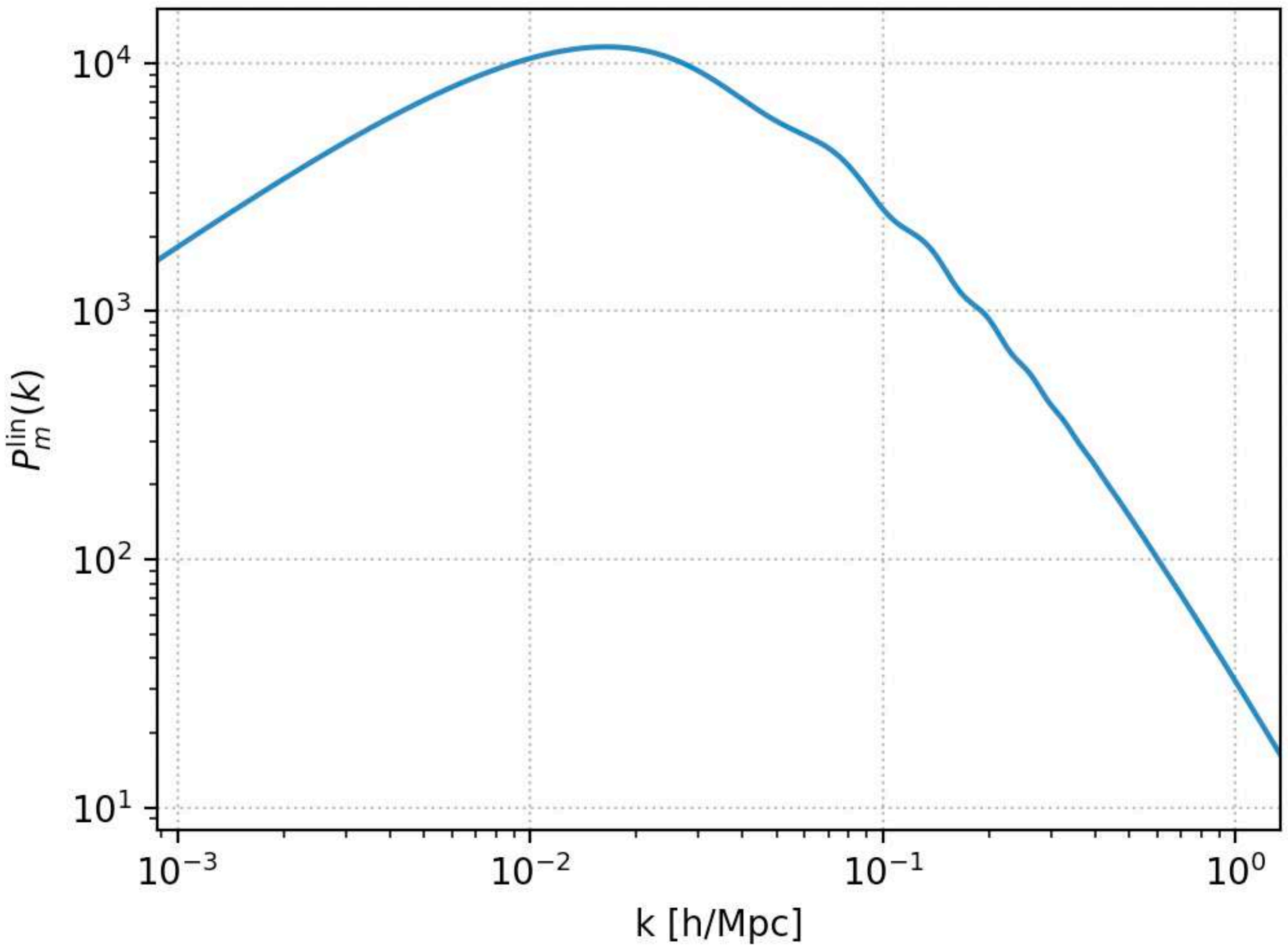

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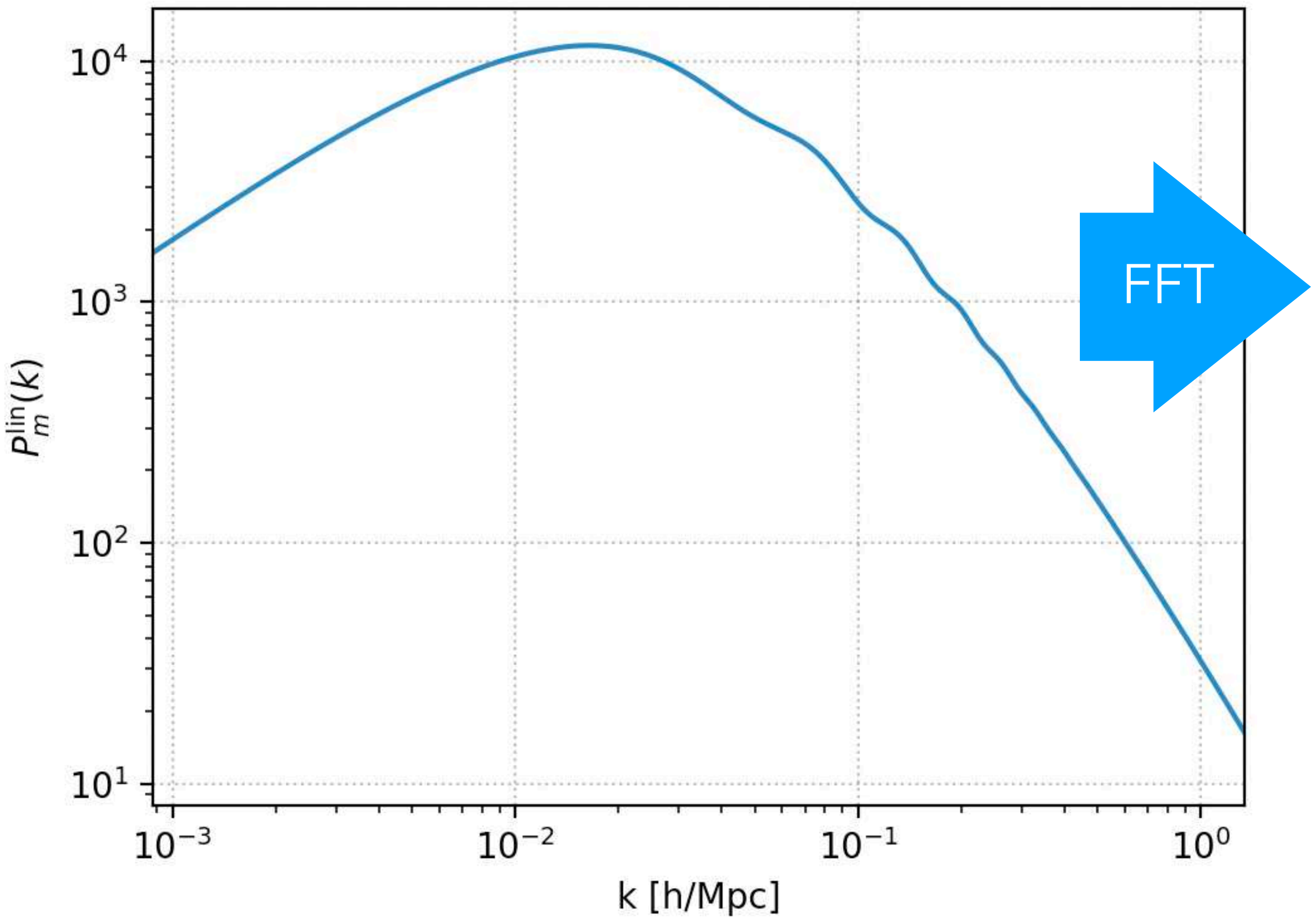

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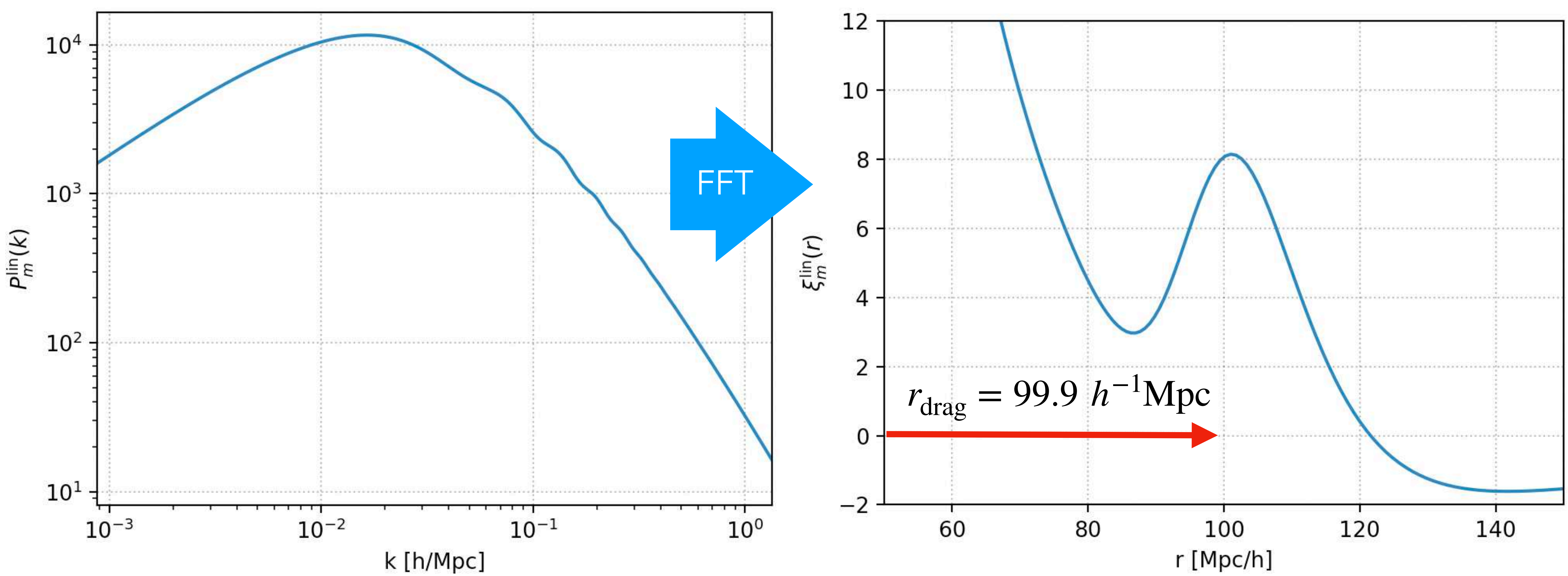

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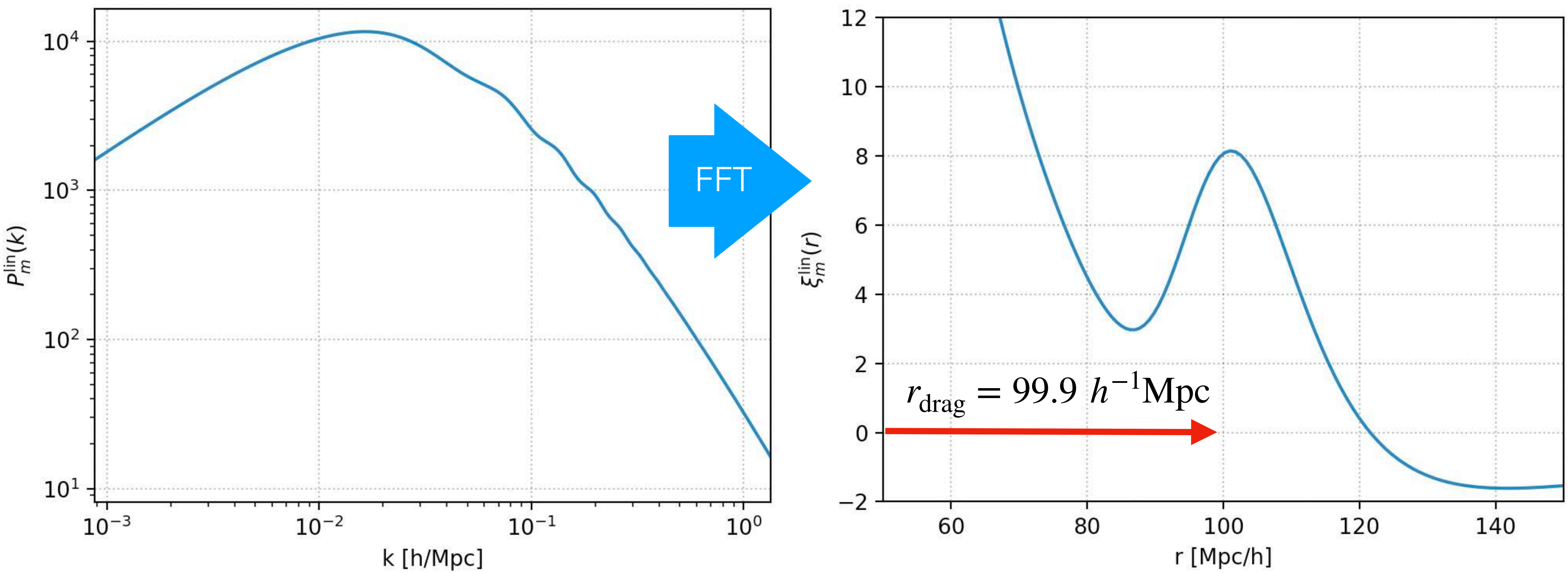

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We apply scaling to separations of model :

$$\xi(r_{\perp}, r_{\parallel}) \rightarrow \xi(\alpha_{\perp} r_{\perp}, \alpha_{\parallel} r_{\parallel})$$

Good approximation if $\Omega_i^{\mathrm{fid,template}} \sim \Omega_i^{\mathrm{true}}$!

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In practice

Linear redshift-space distortions: $P(\vec{k}) = (b + f\mu_k^2)^2 P_m^{\mathrm{lin}}(k)$ where $\mu_k = k_{\parallel}/k$

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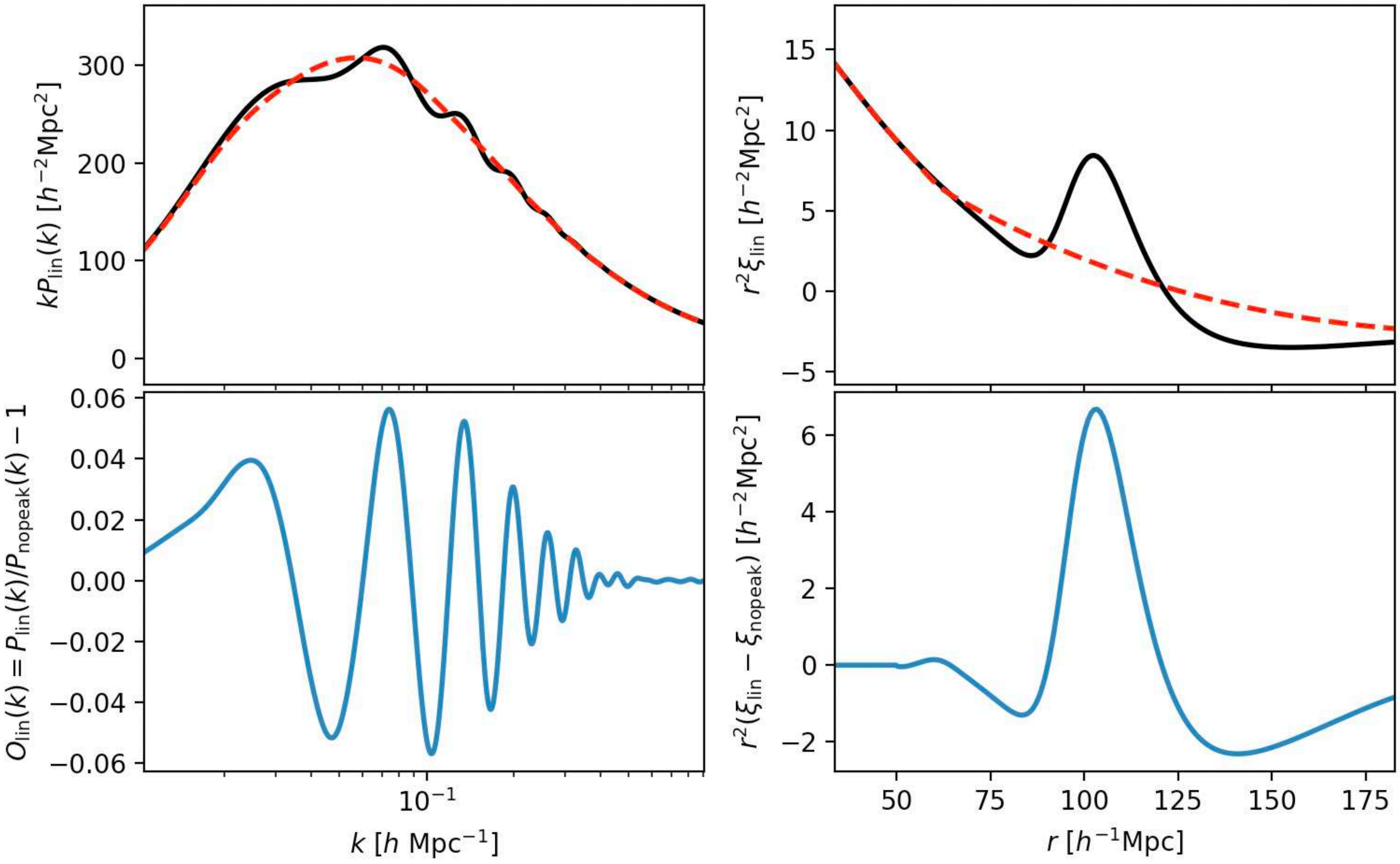

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Empirical smoothing of BAO peak (non-linearities): $O(k) \exp\left(-\frac{k^2 \Sigma_{\rm NL}^2(\mu_k)}{2}\right)$

$$\Sigma_{\rm NL}(\mu_k) = \Sigma_\parallel^2 \mu_k^2 + \Sigma_\perp^2 (1 - \mu_k^2)$$

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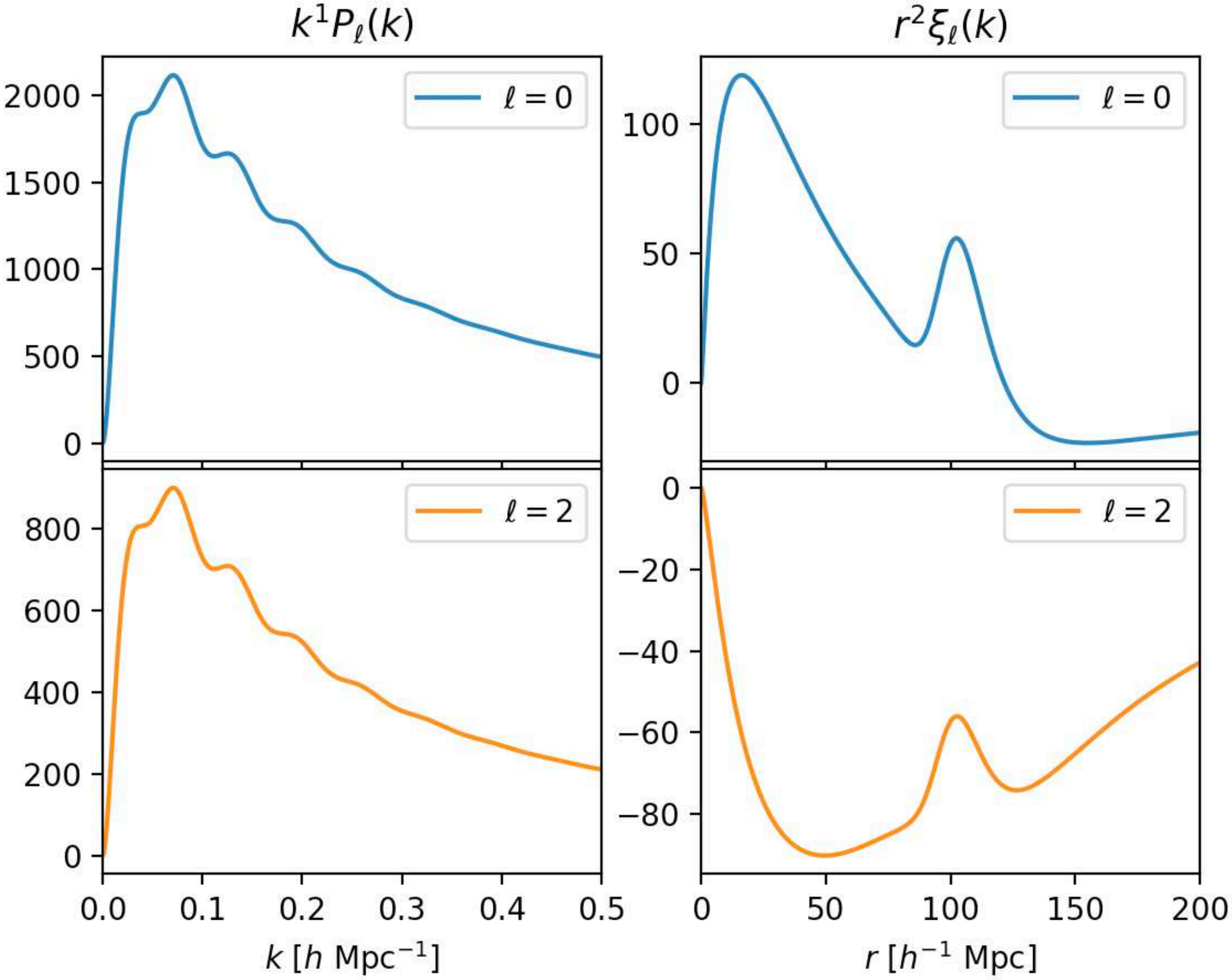

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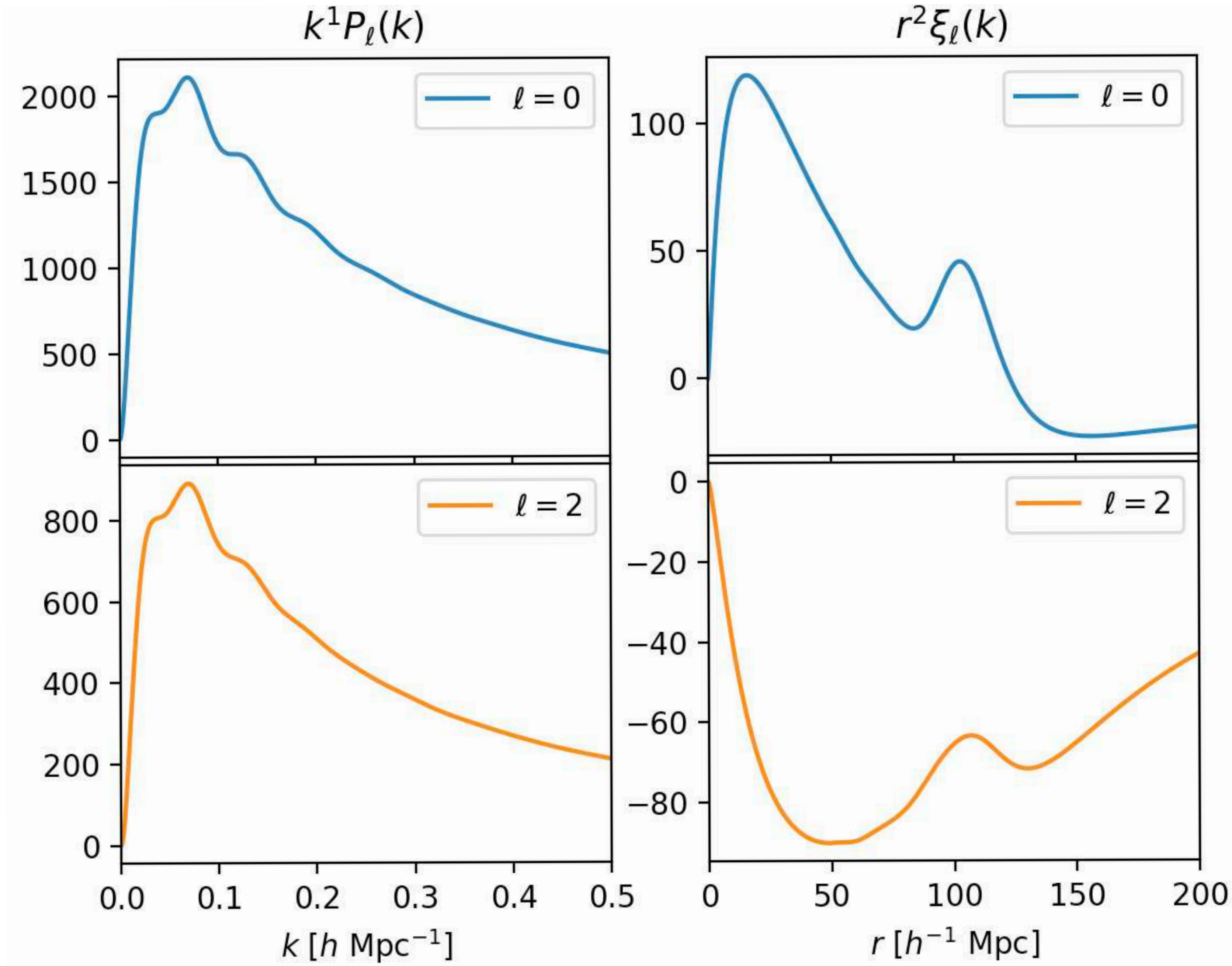
In practice



$u_k^2)P_m^{\mathrm{lin}}(k)$ where $\mu_k = k_\parallel / k$

$/P_{\mathrm{nopeak}}(k) - 1$

$$O(k)\exp\left(-\frac{k^2\Sigma_{\mathrm{NL}}^2(\mu_k)}{2}\right)$$

$$\Sigma_{\mathrm{NL}}(\mu_k) = \Sigma_\parallel^2 \mu_k^2 + \Sigma_\perp^2 (1 - \mu_k^2)$$

$\Sigma_\parallel = 7\ h^{-1}\mathrm{Mpc},\ \Sigma_\perp = 5\ h^{-1}\mathrm{Mpc}$

How to extract the BAO scale ?

In practice

Linear redshift-space distortions: $P(\vec{k}) = (b + f\mu_k^2)^2 P_m^{\rm lin}(k)$ where $\mu_k = k_\parallel / k$

Separate BAO peak from smooth part: $O(k) = P(k)/P_{\rm nopeak}(k) - 1$

Empirical smoothing of BAO peak (non-linearities): $O(k) \exp\left(-\frac{k^2 \Sigma_{\rm NL}^2(\mu_k)}{2}\right)$

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How to extract the BAO scale ?

In practice

Linear

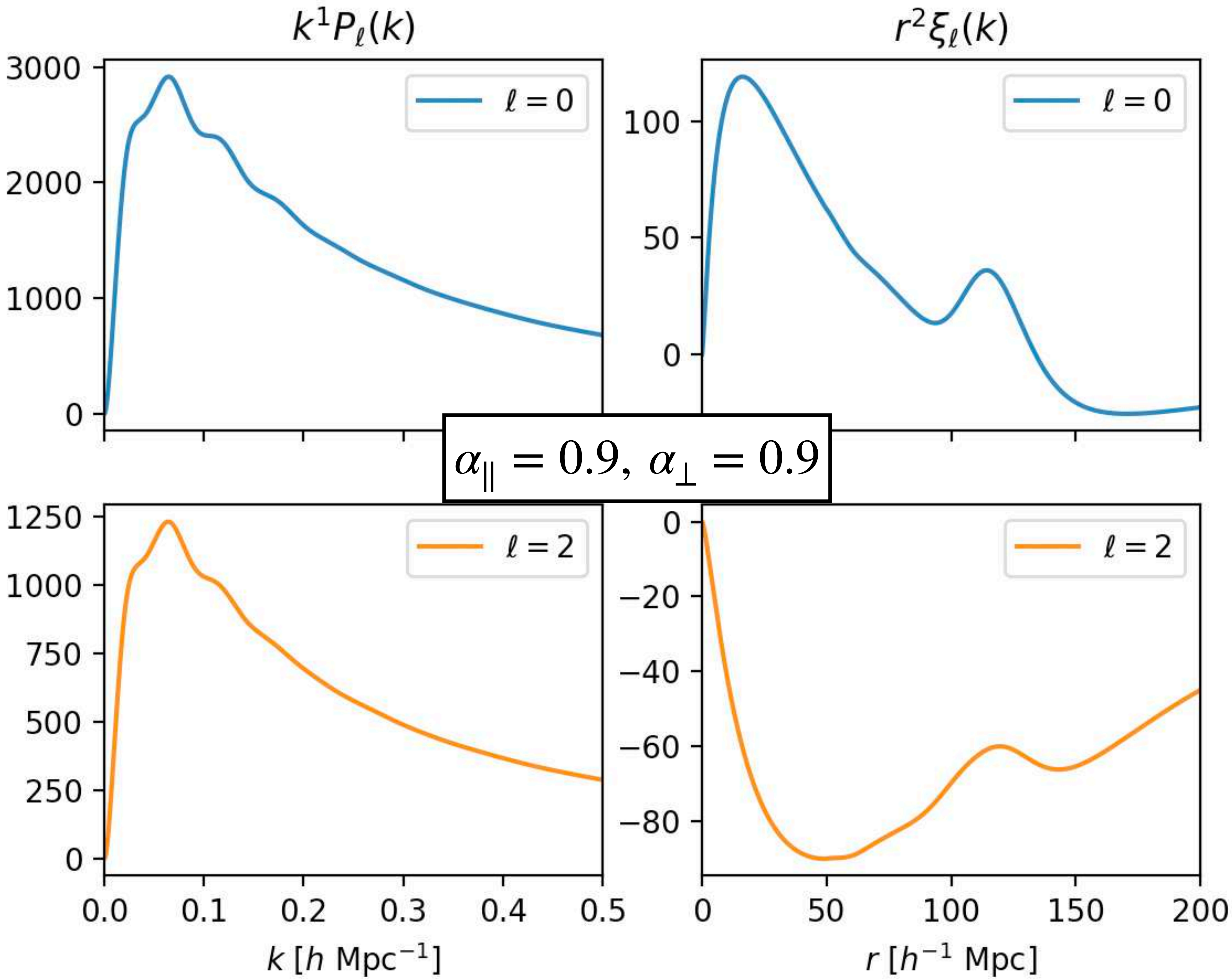
Separa

Empiri

Model

Power

$= k_{\parallel}/k$



$\mathrm{NL}(\mu_k)$ / 2

$+ \Sigma_{\perp}^2(1 - \mu_k^2)$

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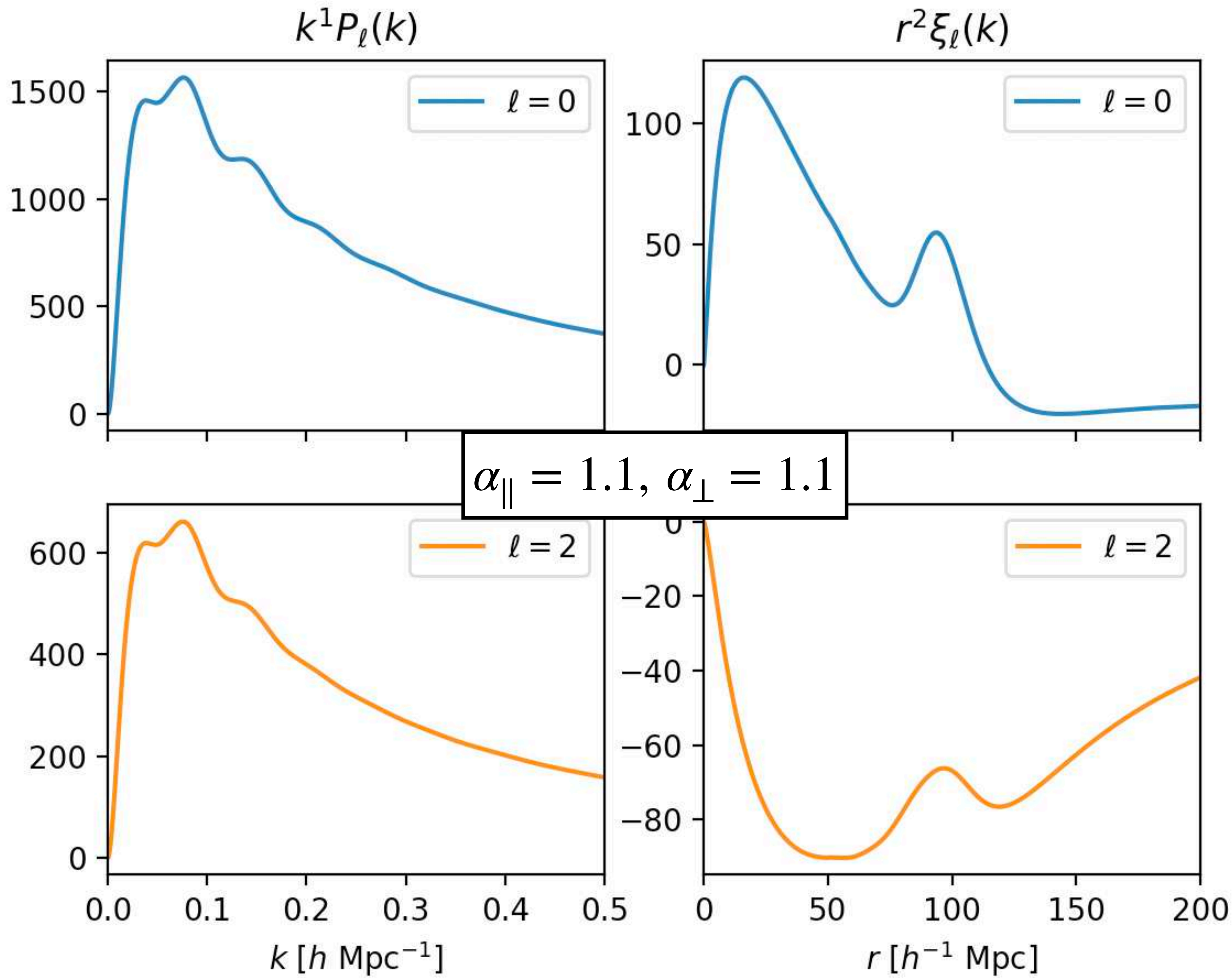

$= k_\parallel / k$

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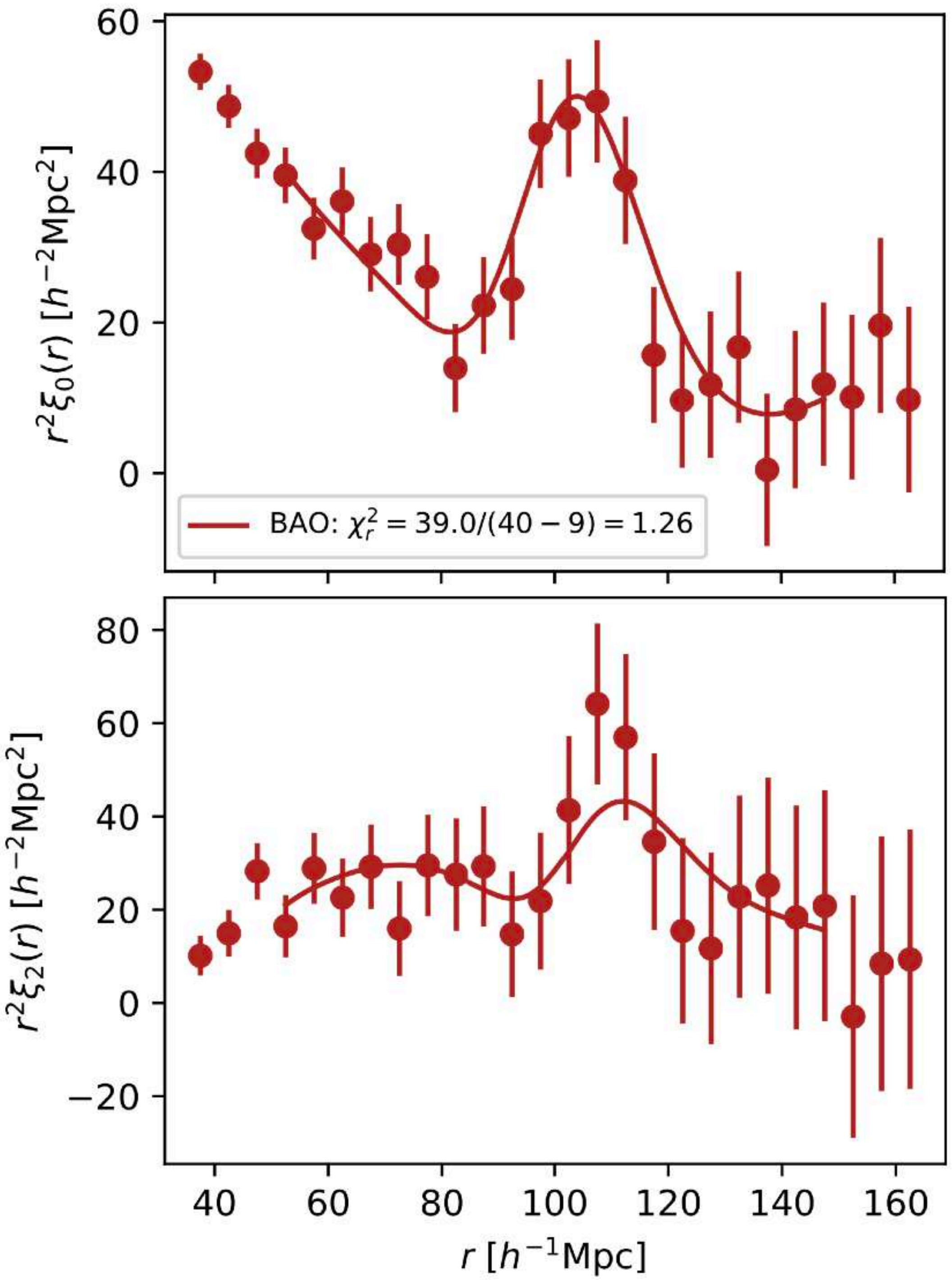
Results of BAO fits

eBOSS LRG reconstructed



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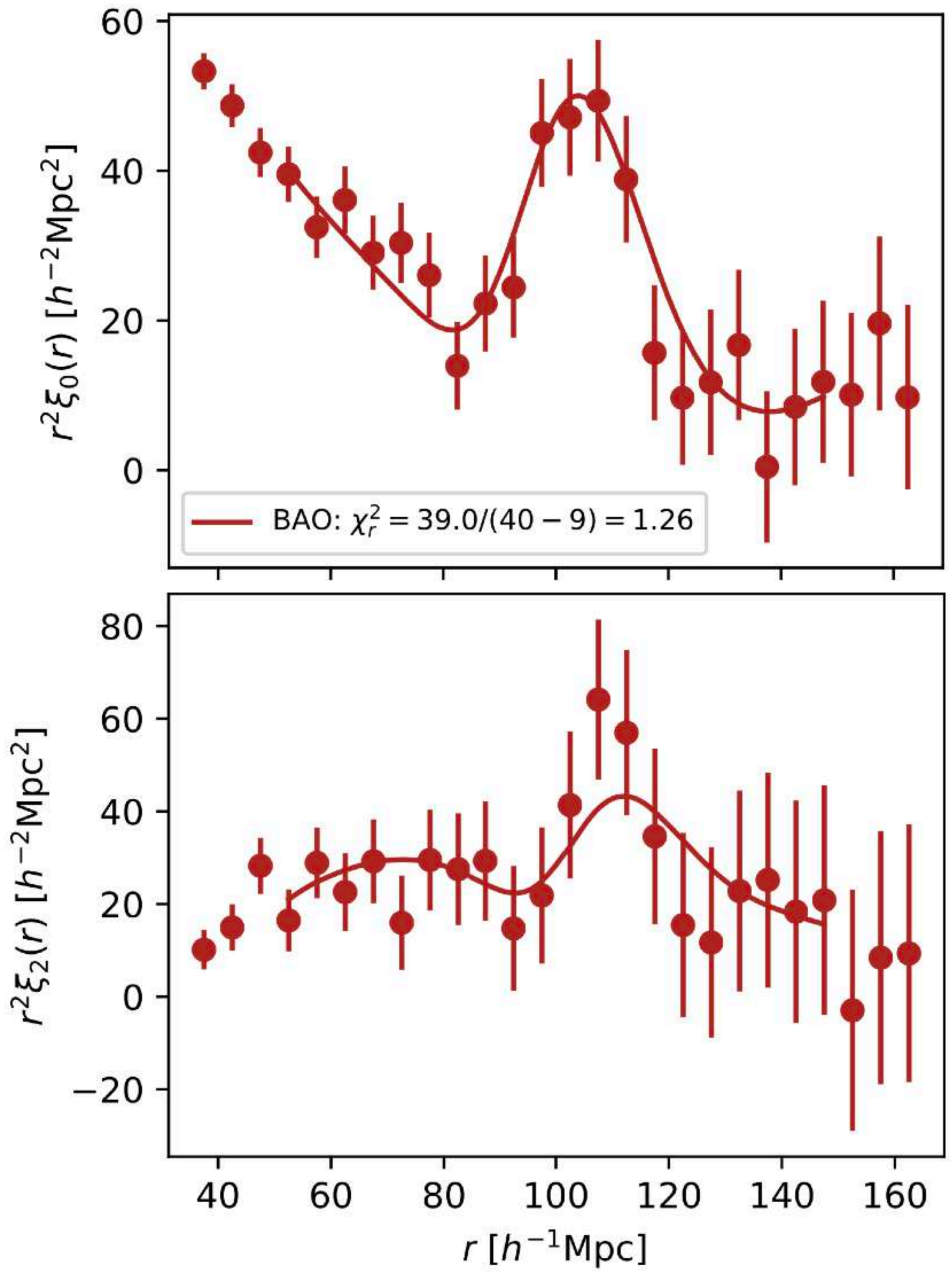
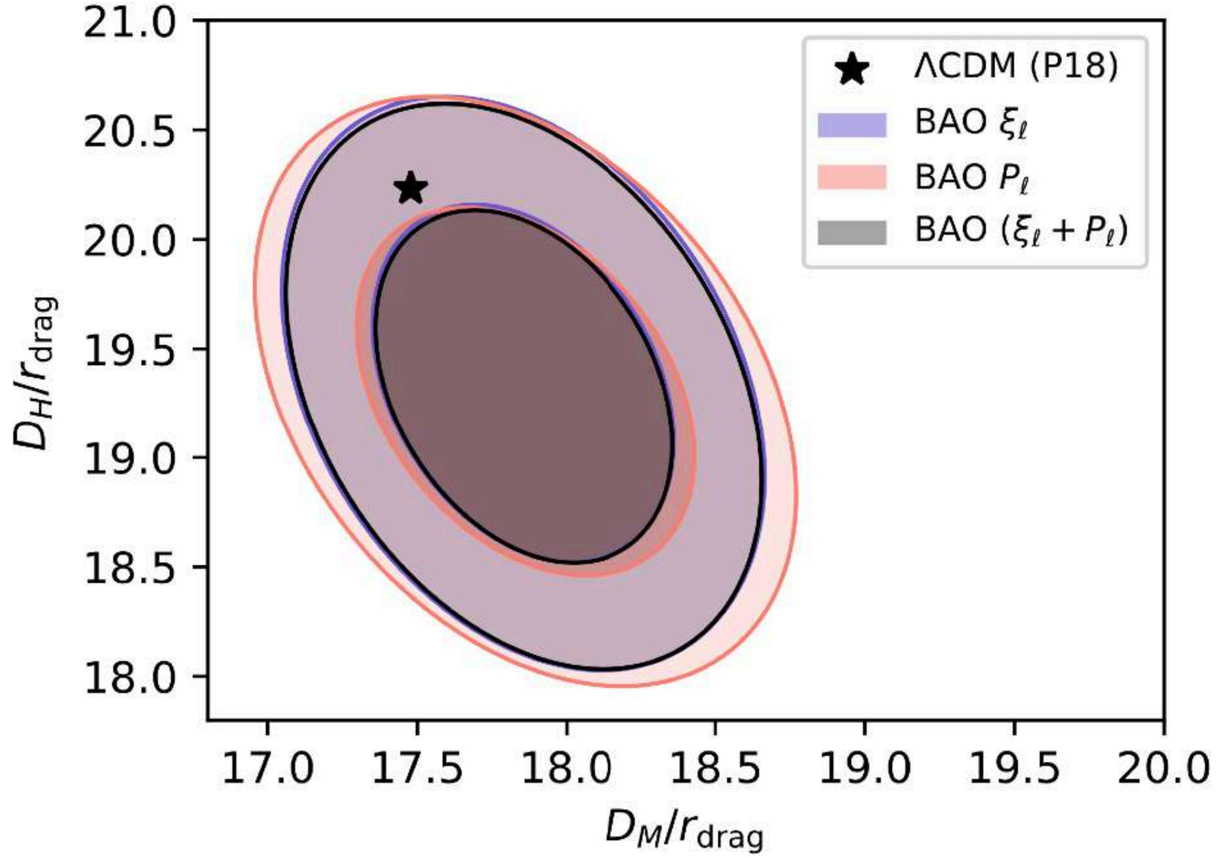


Convert alphas to ratios:

$$\frac{D_H(z)}{r_{\rm rdrag}} = \alpha_{\parallel} \frac{D_H^{\rm fid}(z)}{r_{\rm rdrag}^{\rm fid}}$$

$$\frac{D_M(z)}{r_{\rm rdrag}} = \alpha_{\perp} \frac{D_M^{\rm fid}(z)}{r_{\rm rdrag}^{\rm fid}}$$



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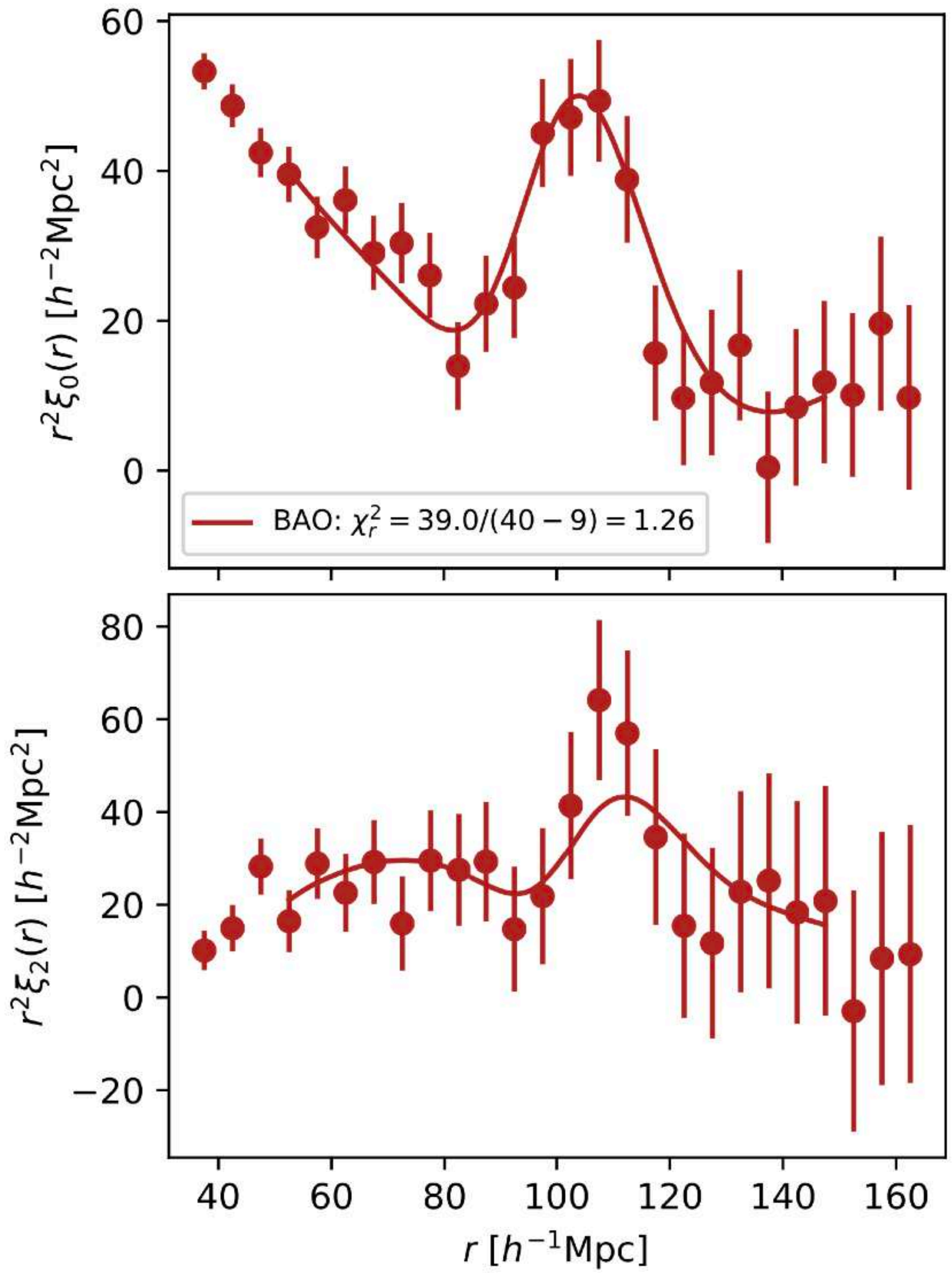

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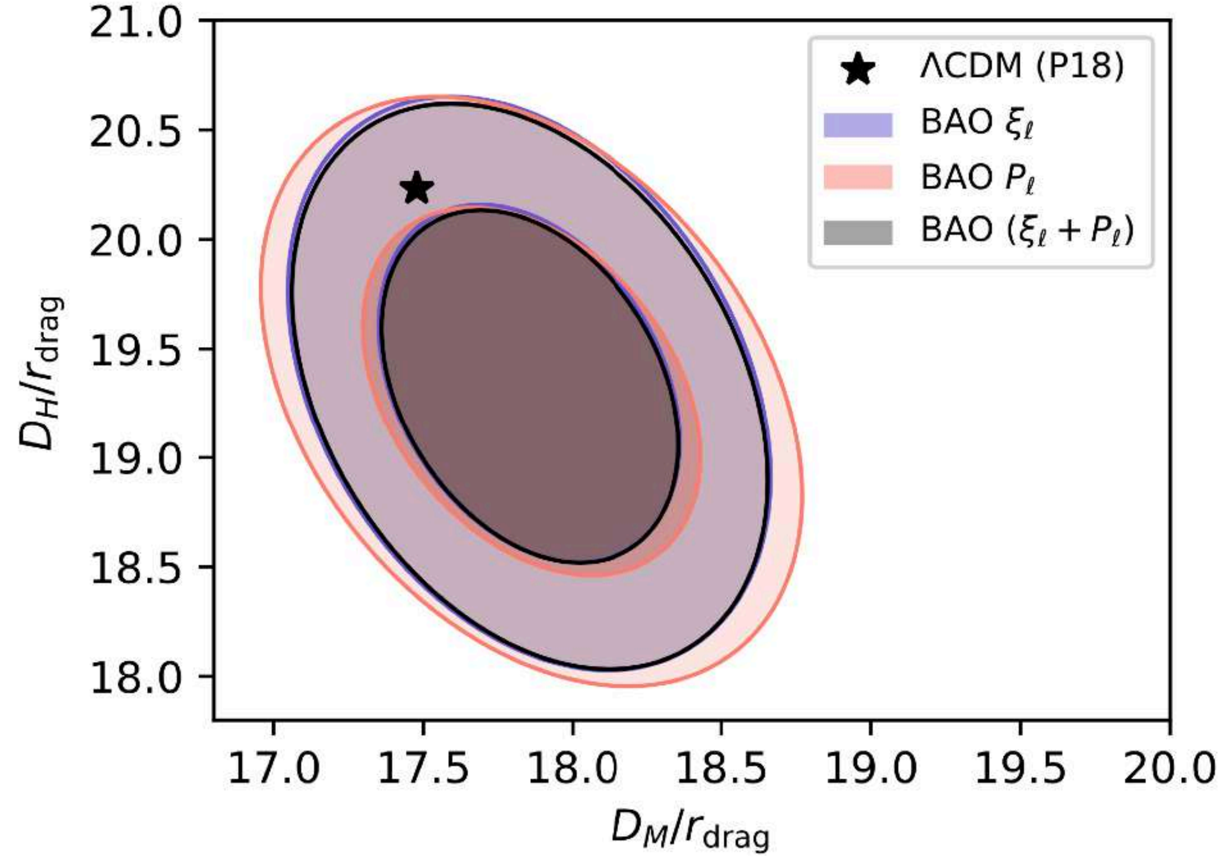
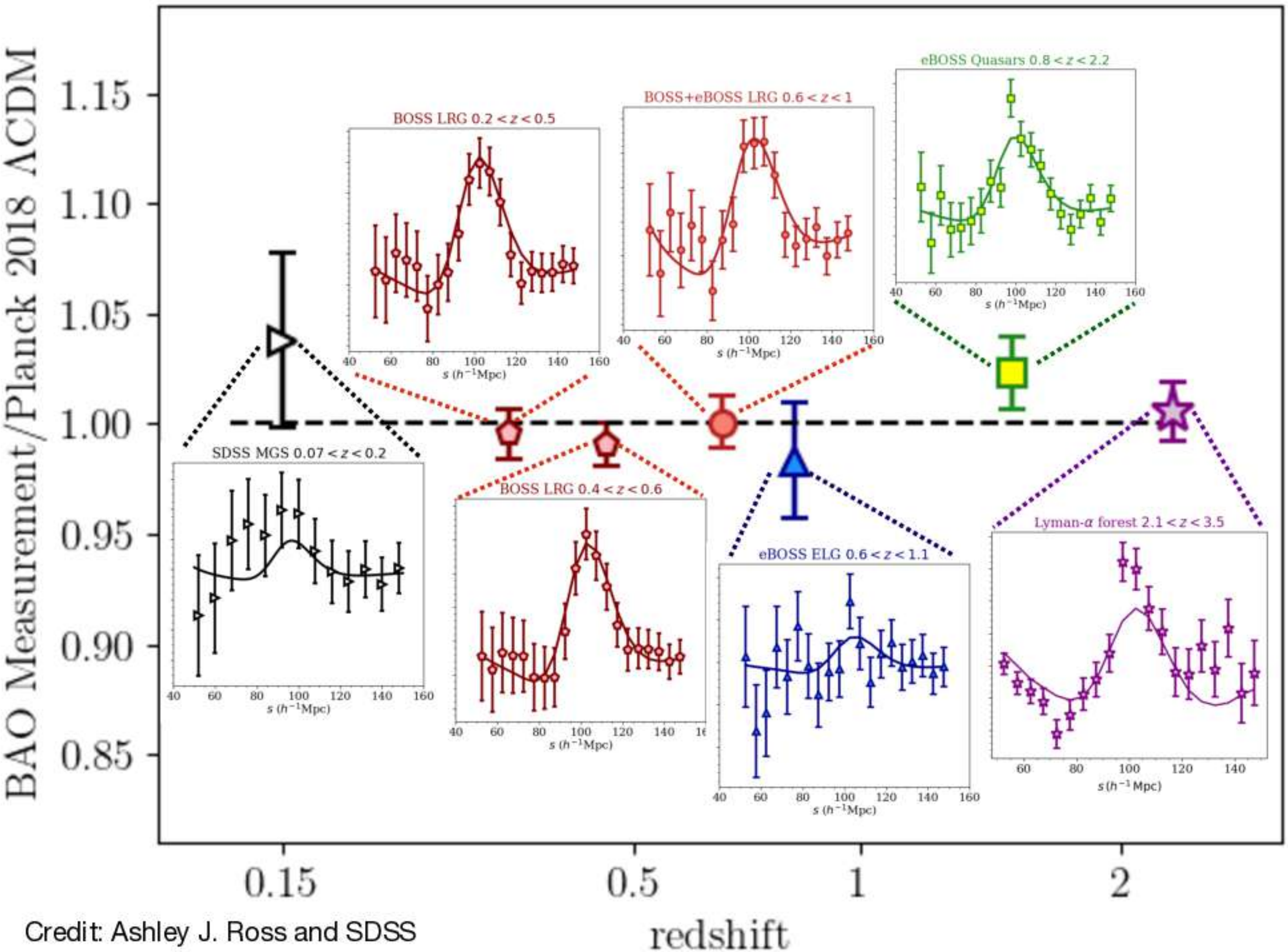


These constraints will be used to fit cosmological models

SDSS BAO Distance Ladder



Credit: Ashley J. Ross and SDSS

Redshift-space distortions (RSD)

We measure redshifts : peculiar velocities affect our distance inferences

Real space

Redshift space

Redshift-space distortions (RSD)

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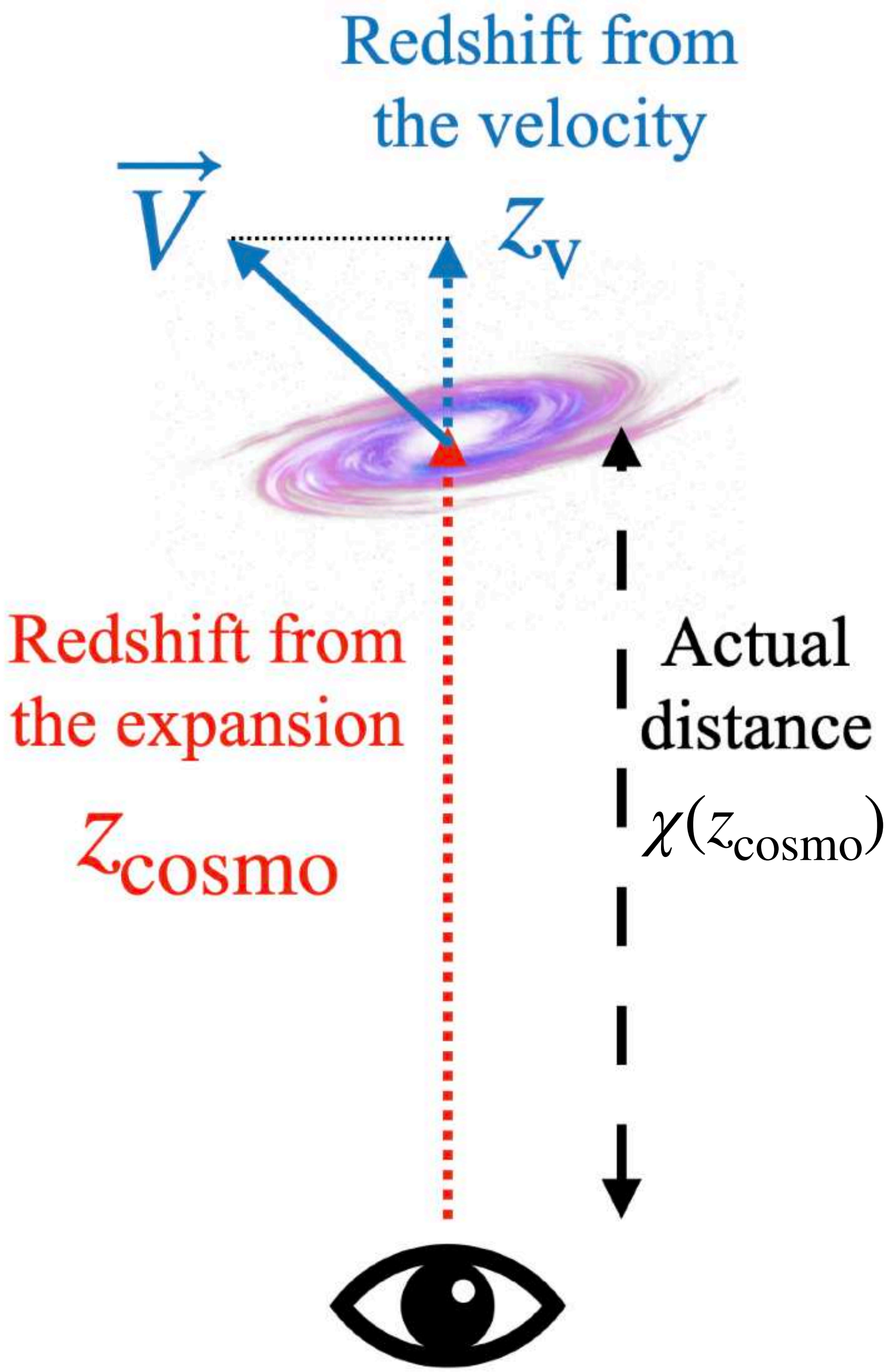

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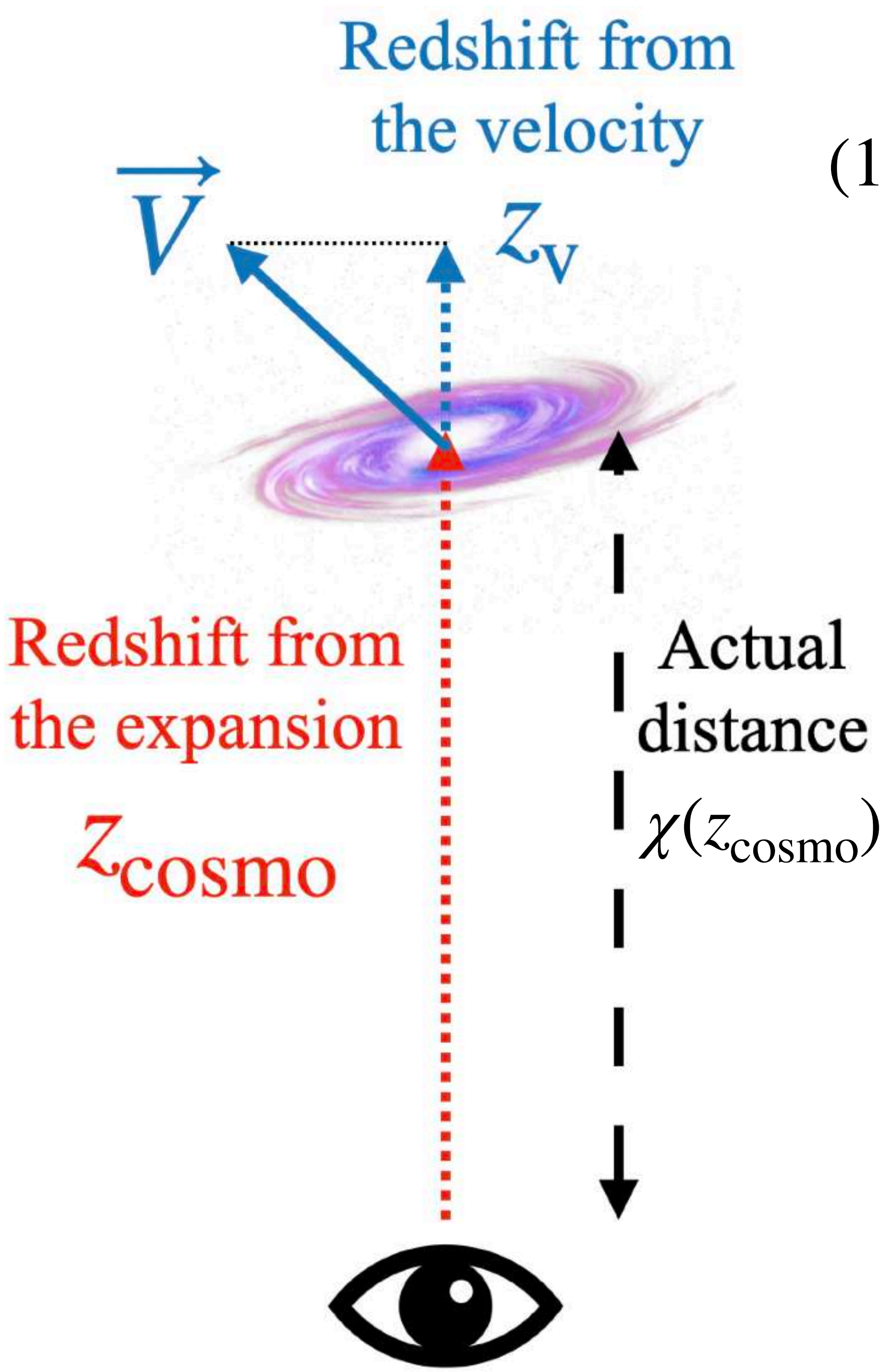

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$$(1 + z_{obs}) = (1 + z_{cosmo})(1 + z_v)$$

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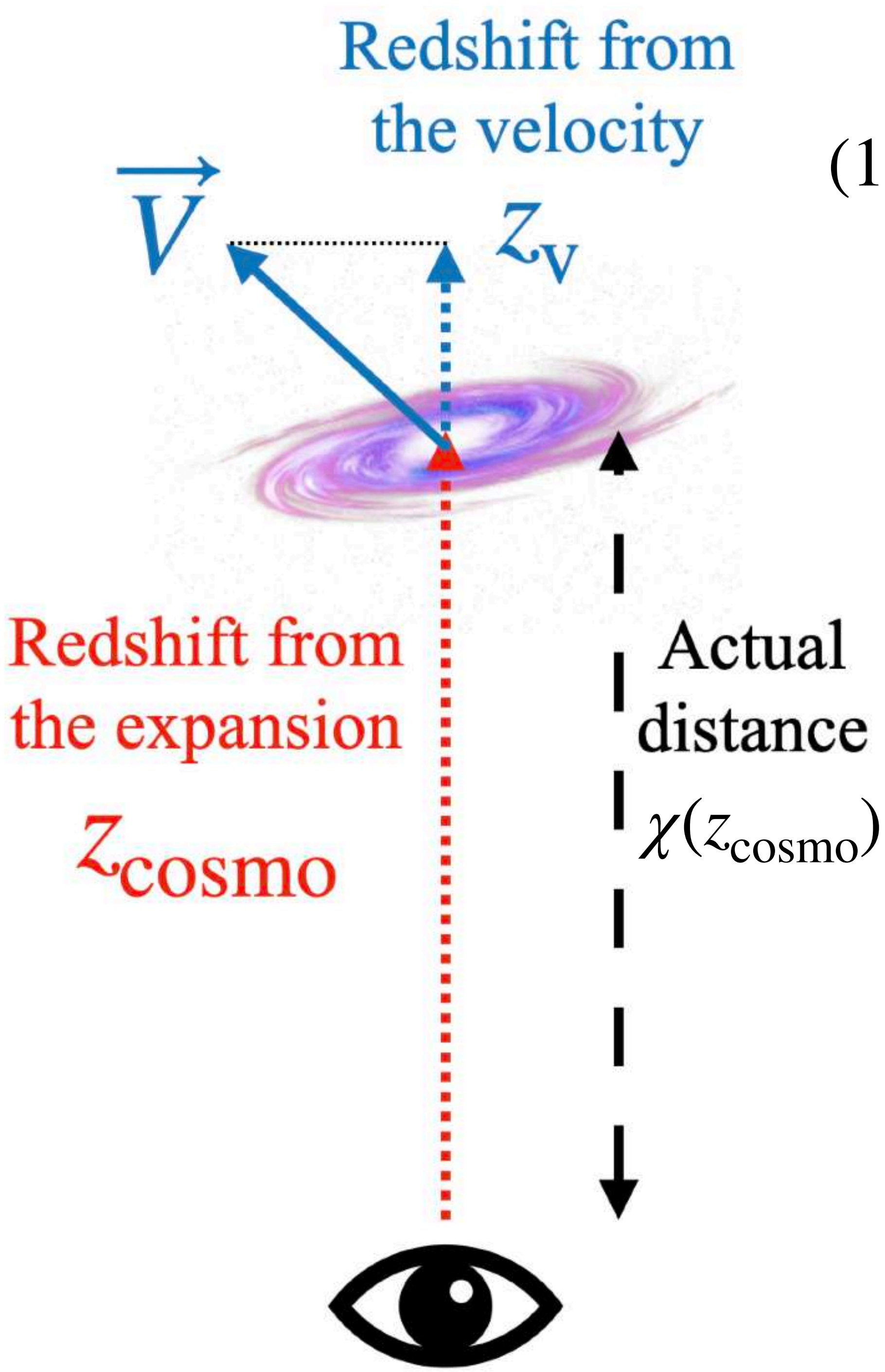

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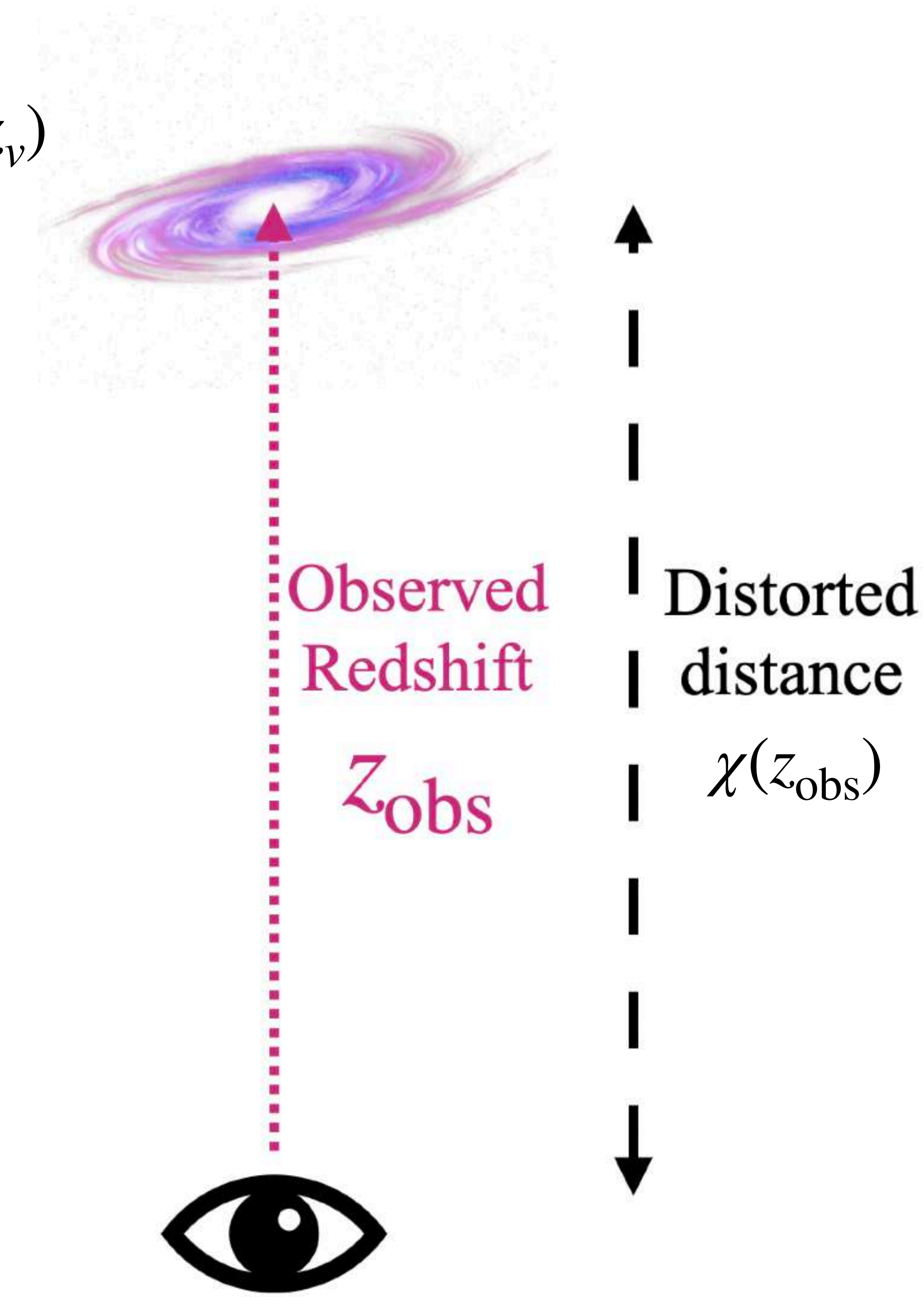


Redshift space

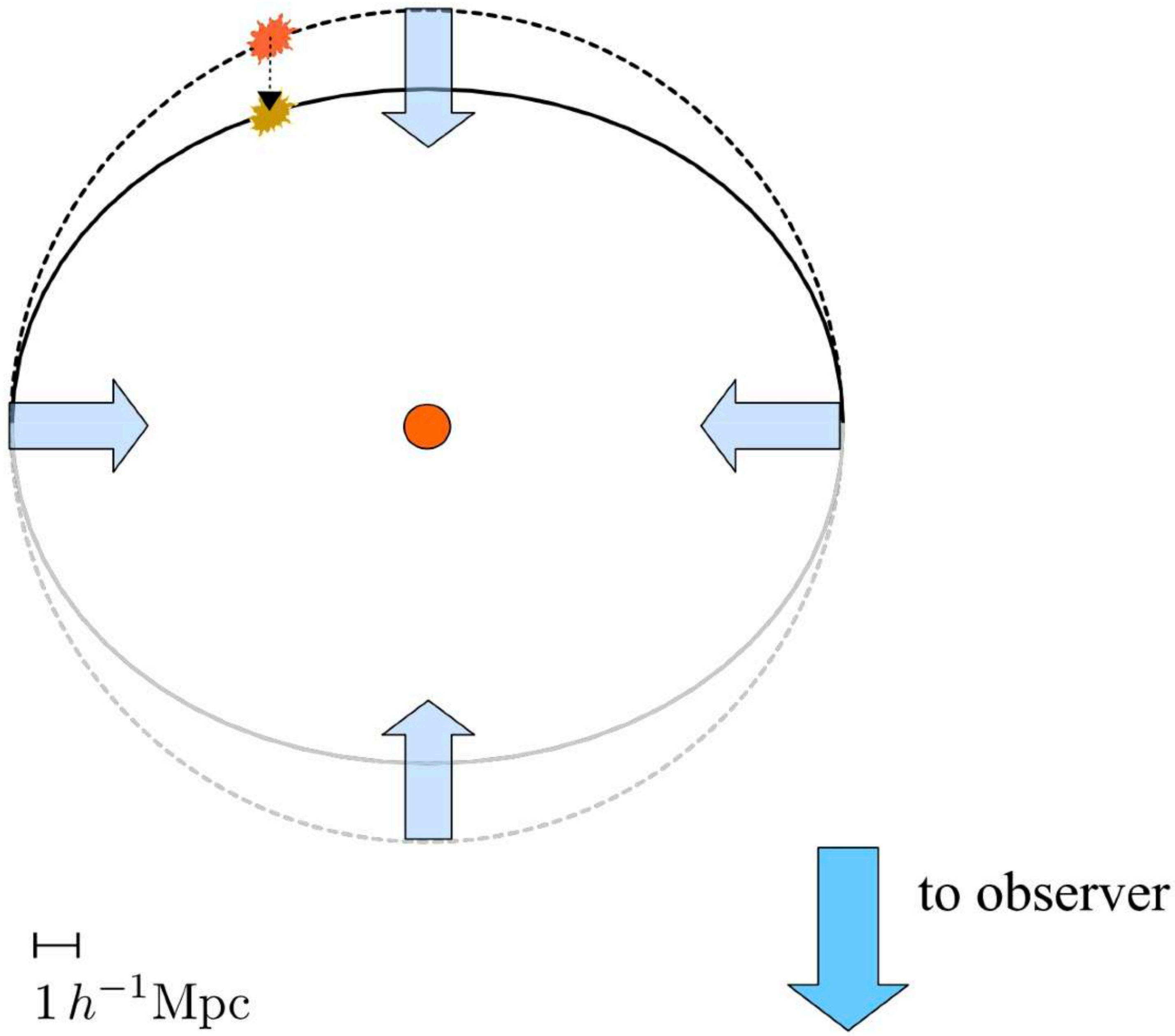
Redshift-space distortions (RSD)

Velocities on large separations

Linear RSD

Non-linear RSD

Fingers-of-God



From Dodelson & Schmidt 2020

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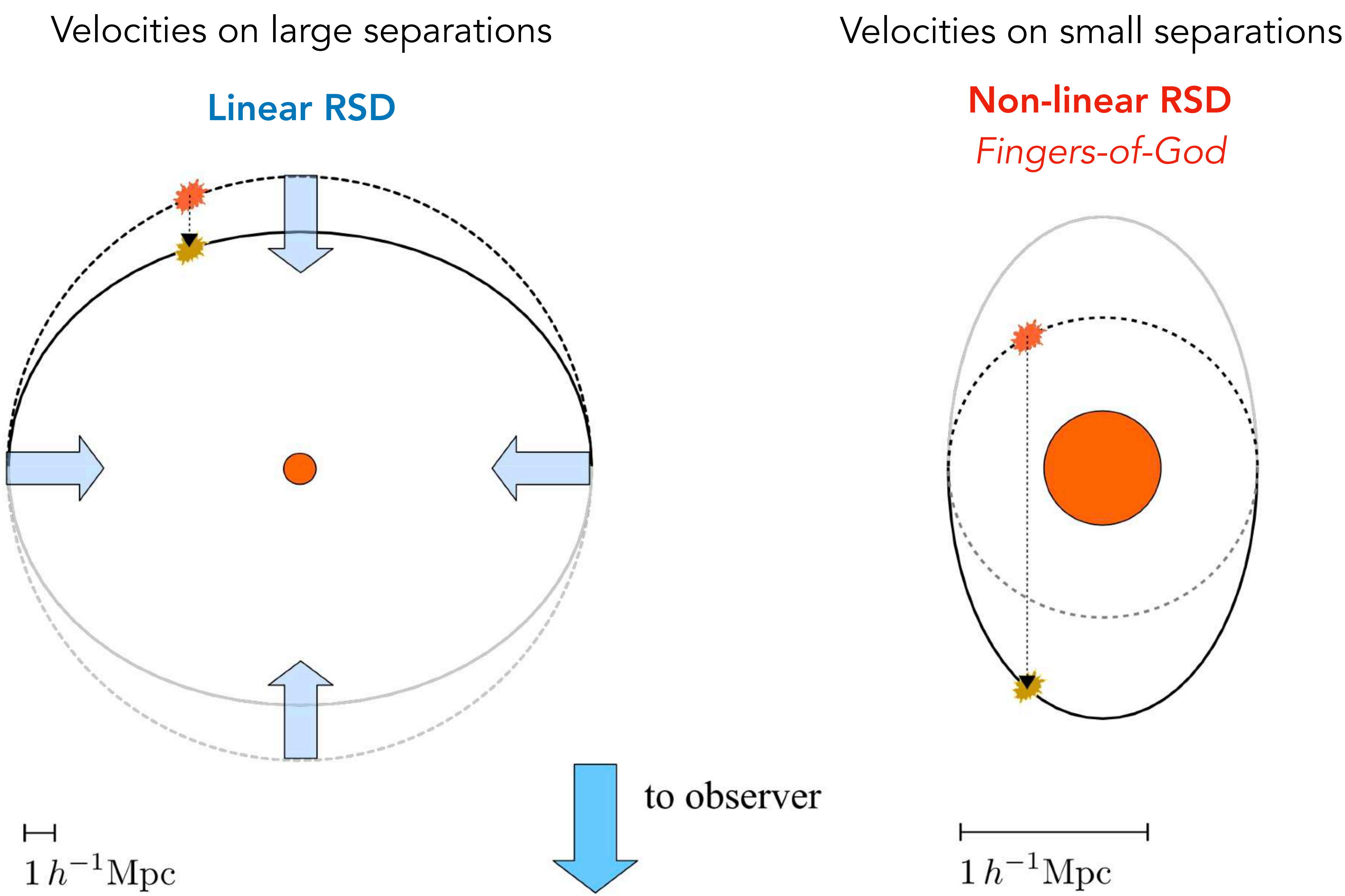

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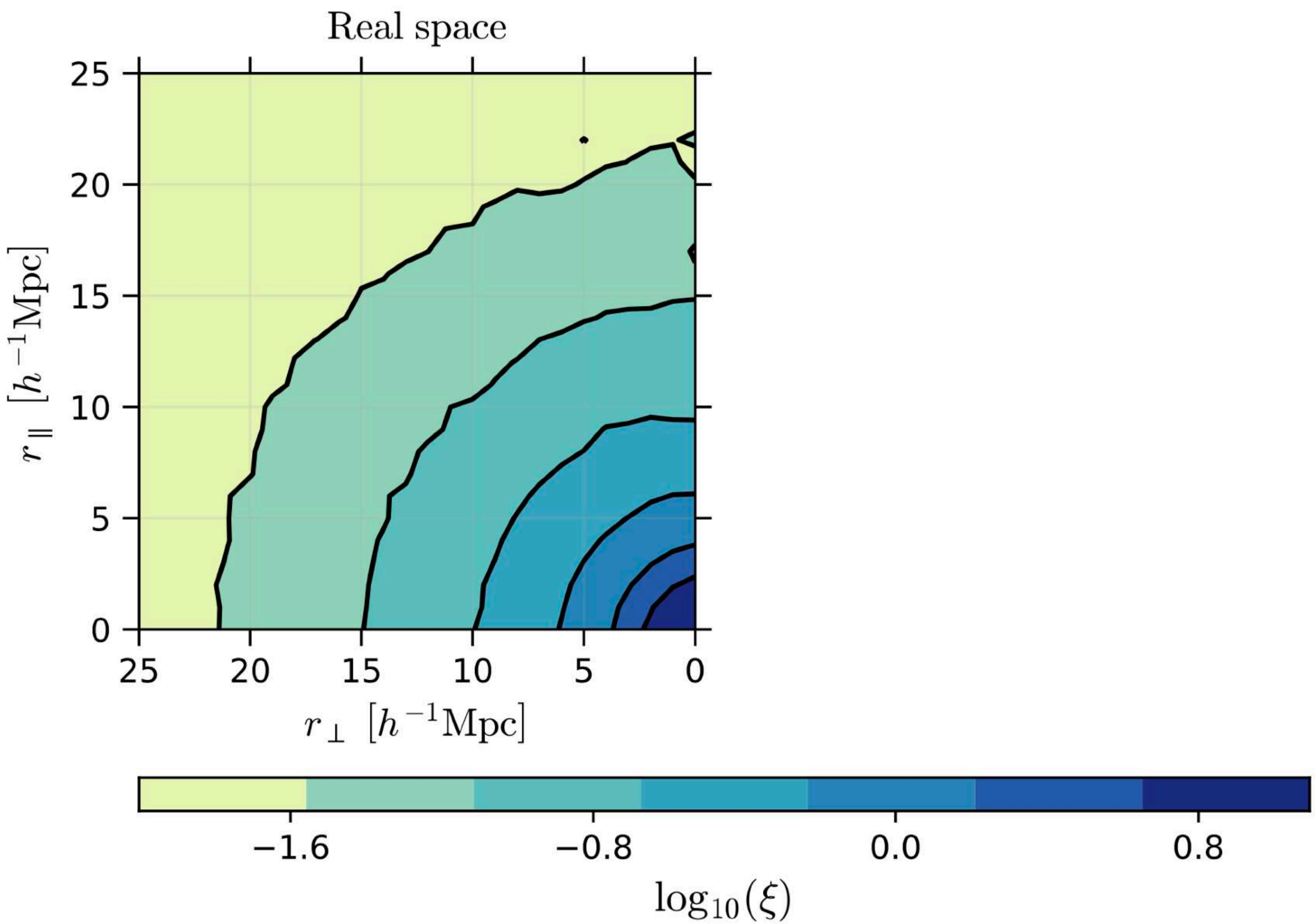

Simulation by Kuruvilla & Porciani 2018

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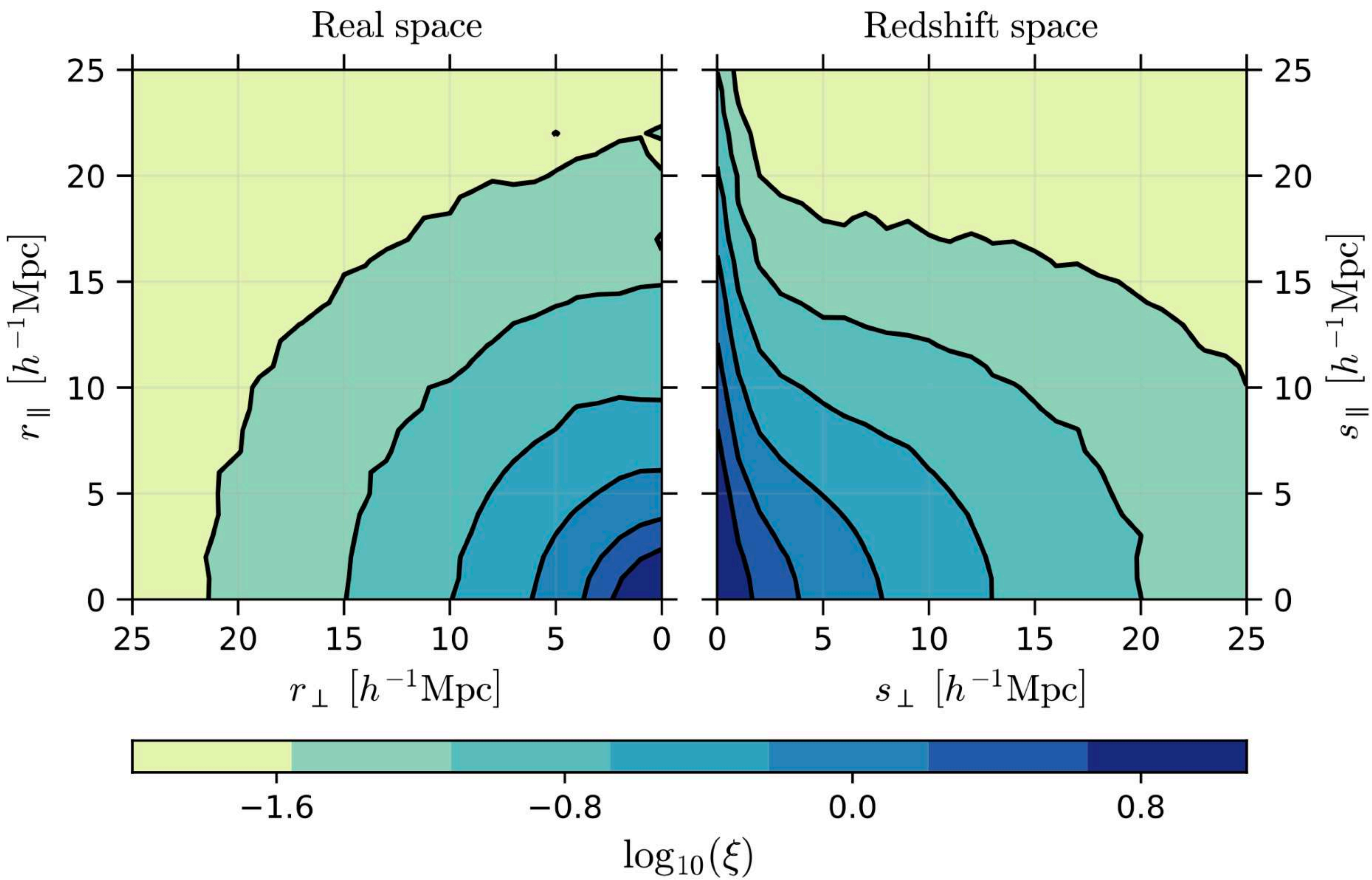

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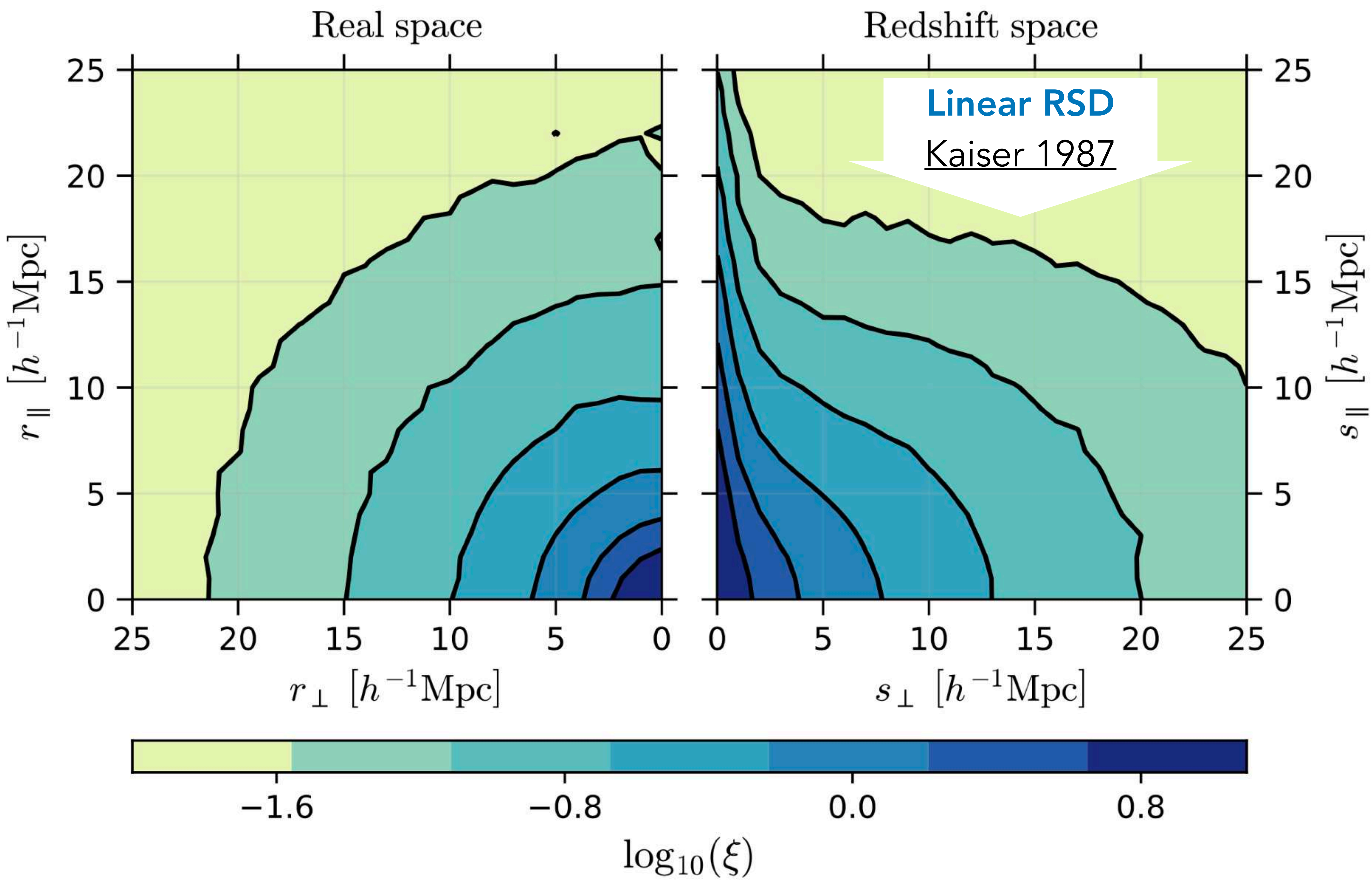

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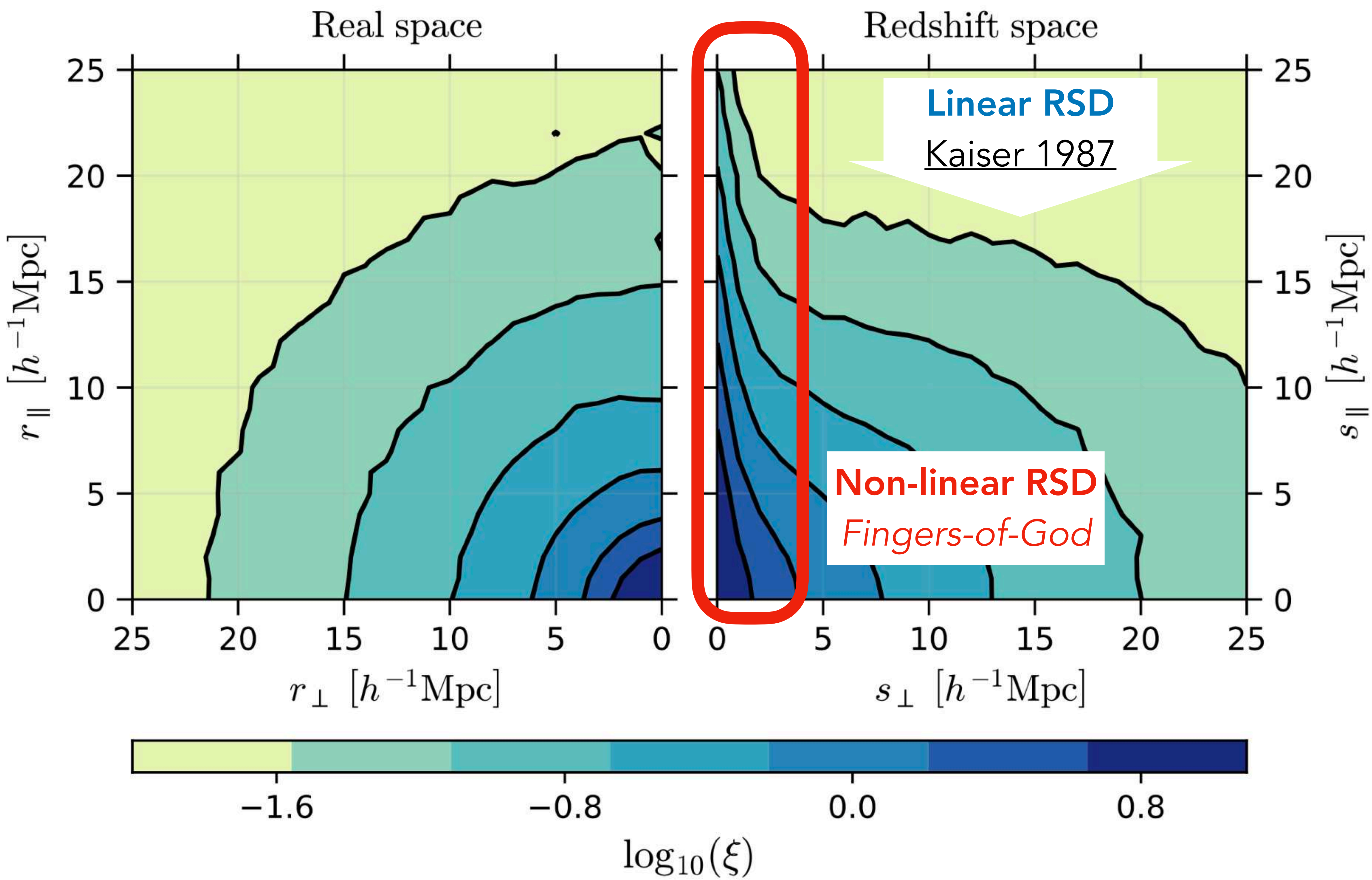

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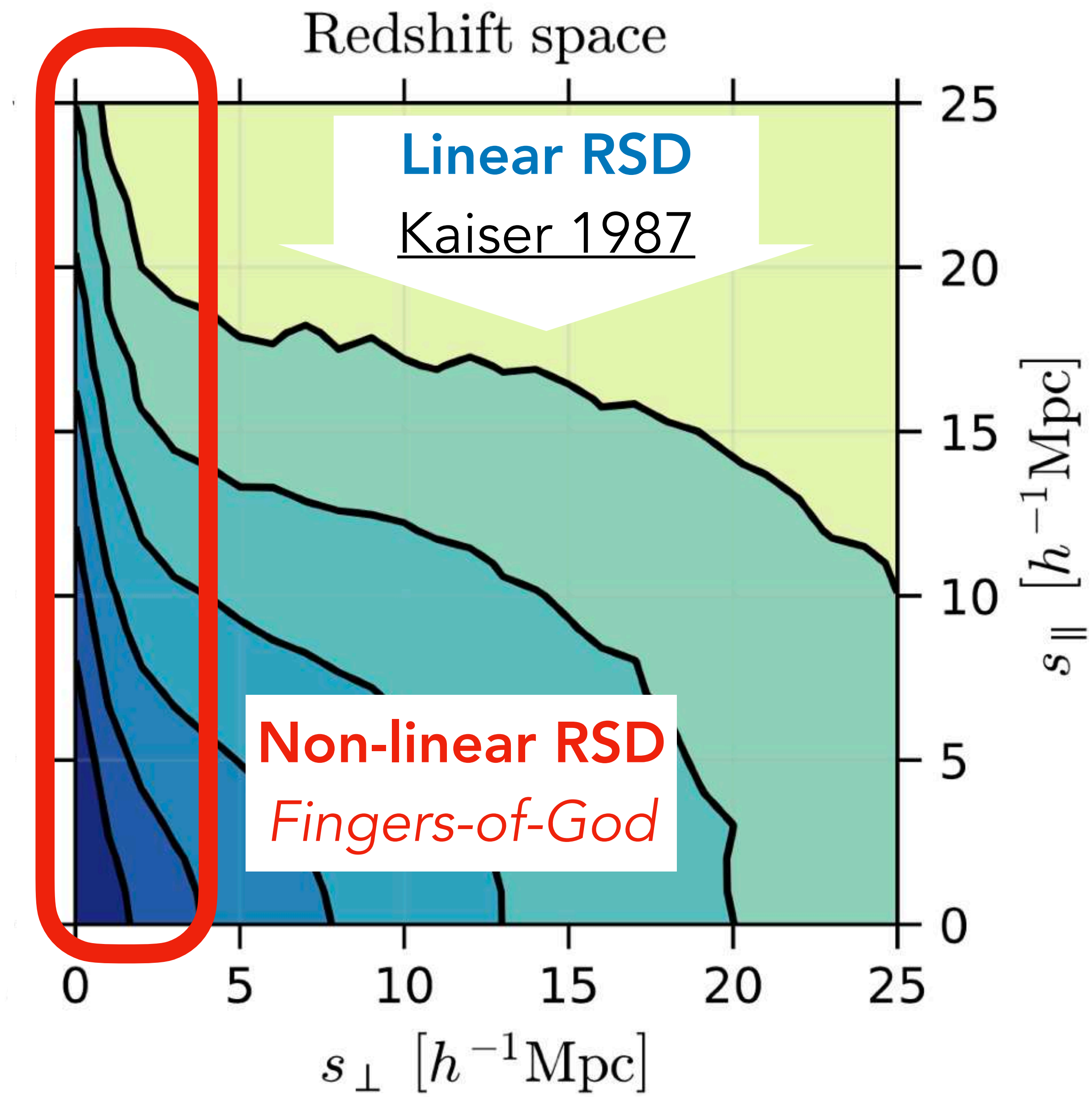

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Linear RSD
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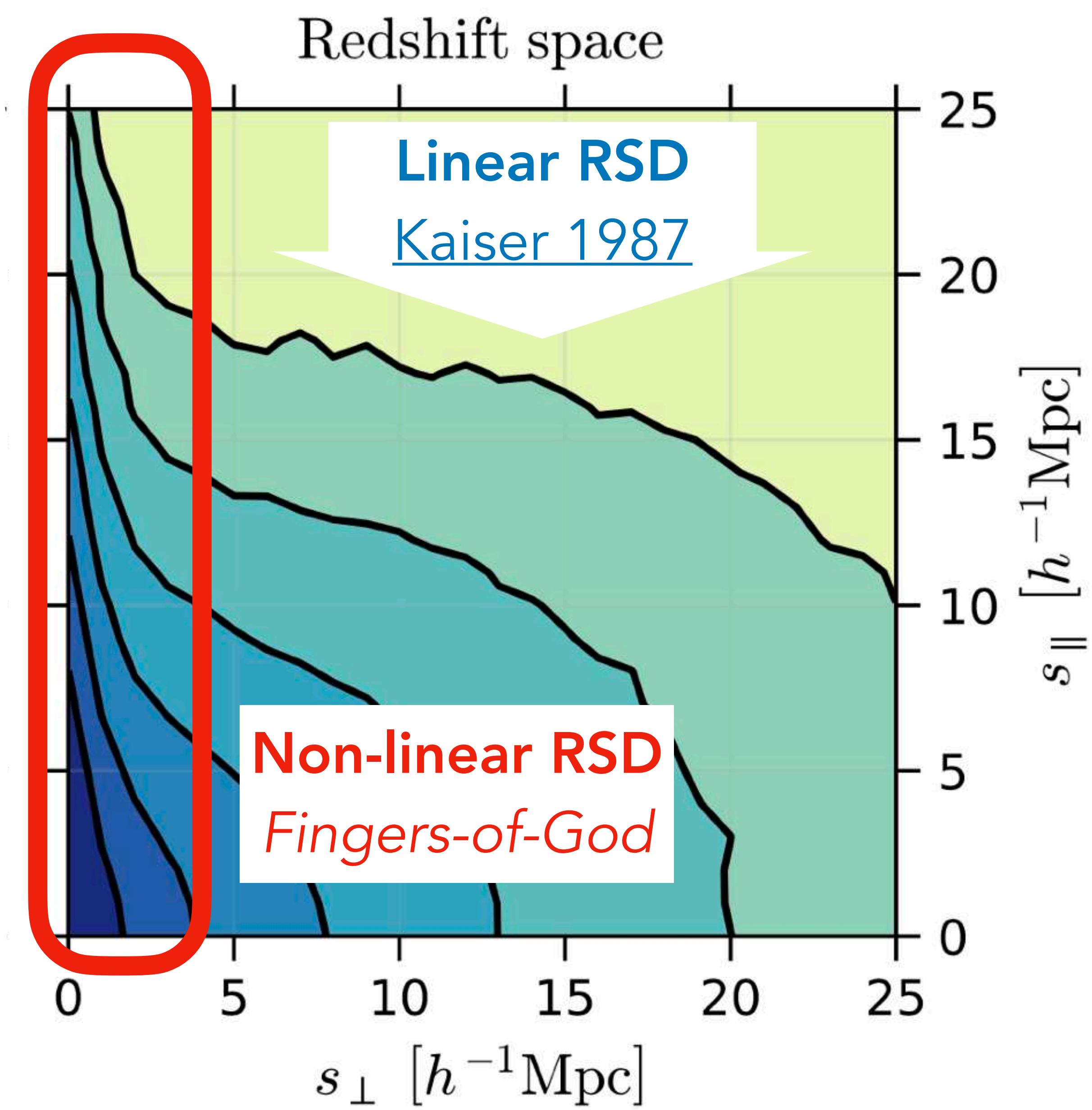

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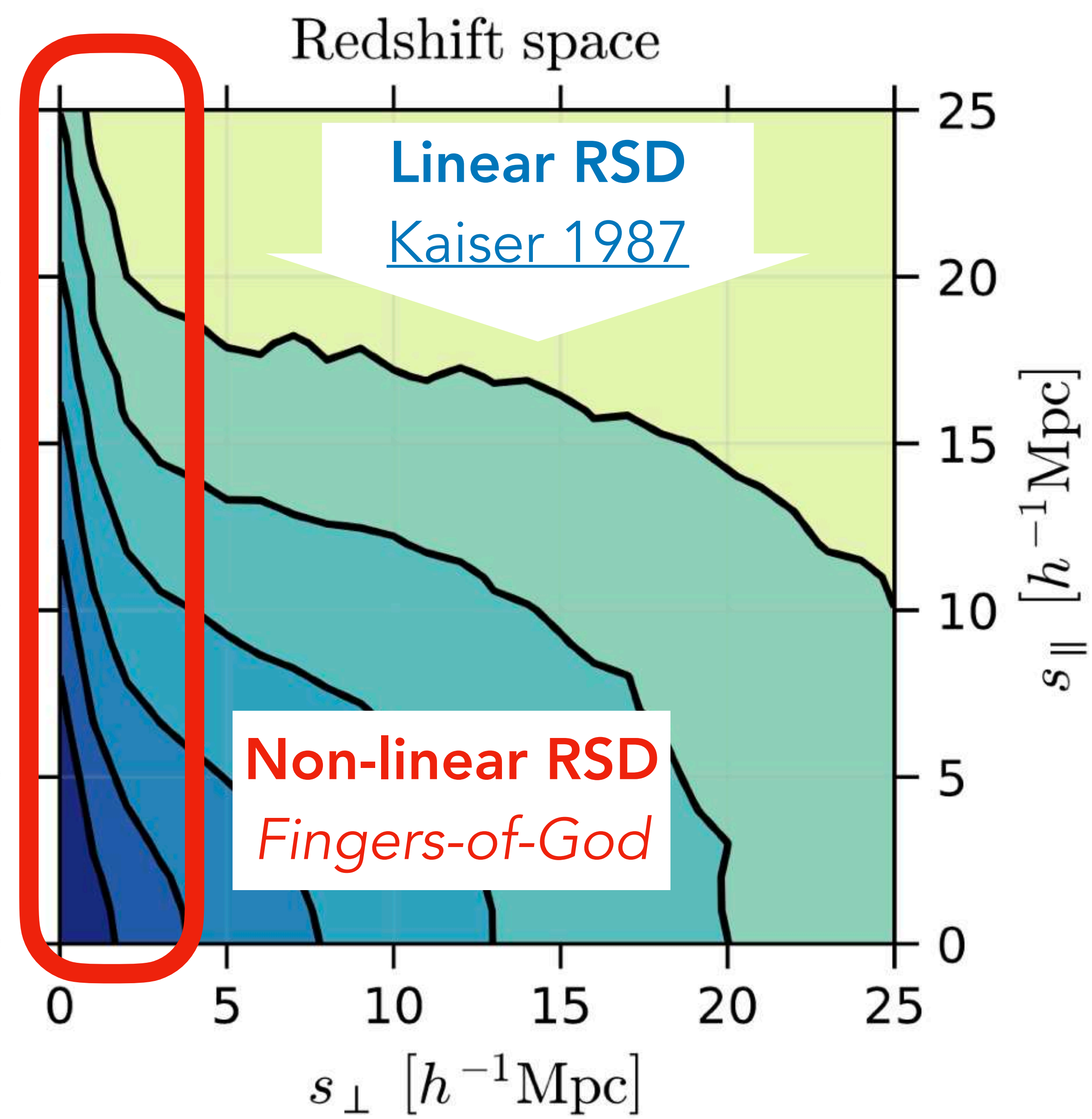

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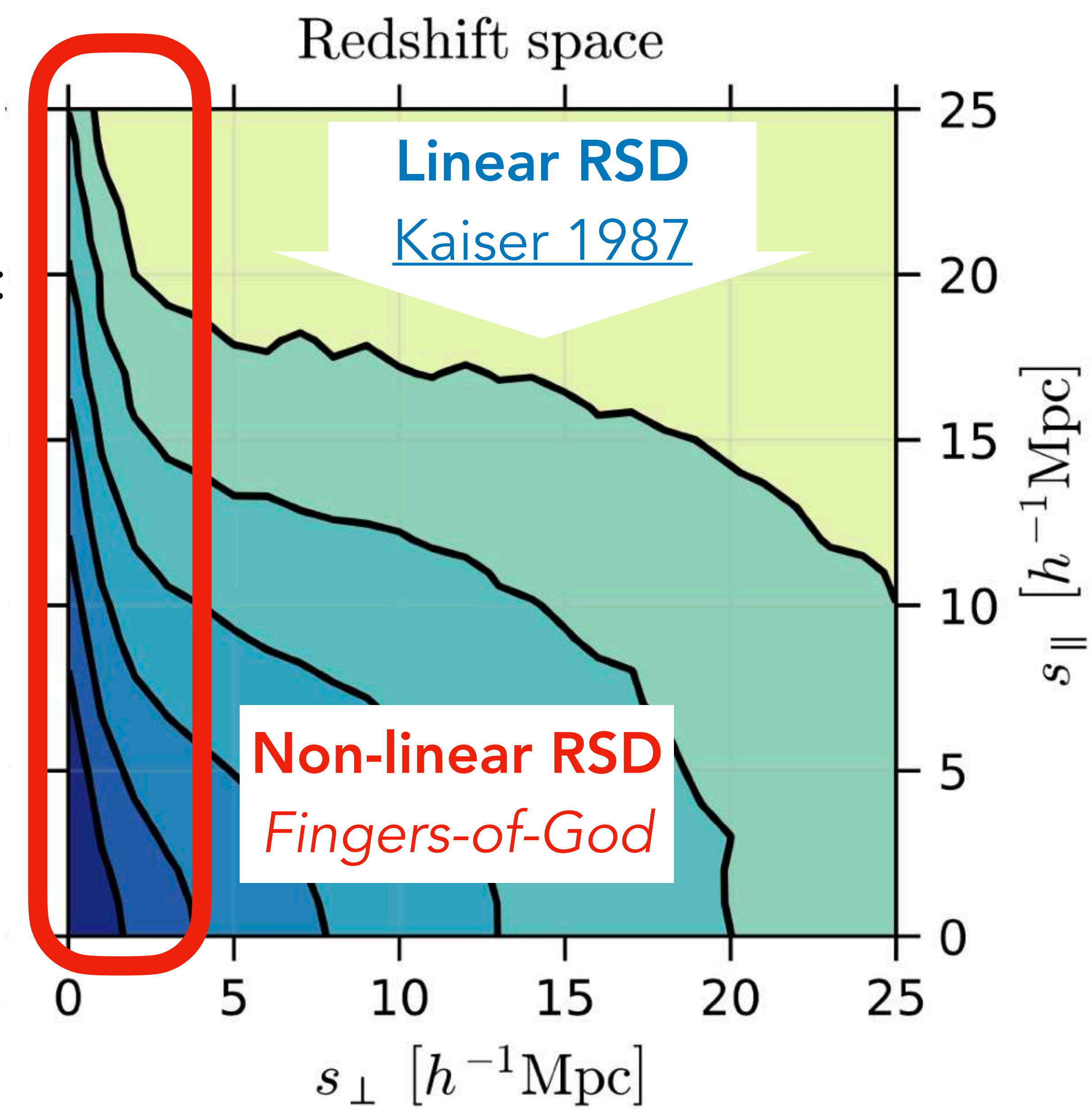

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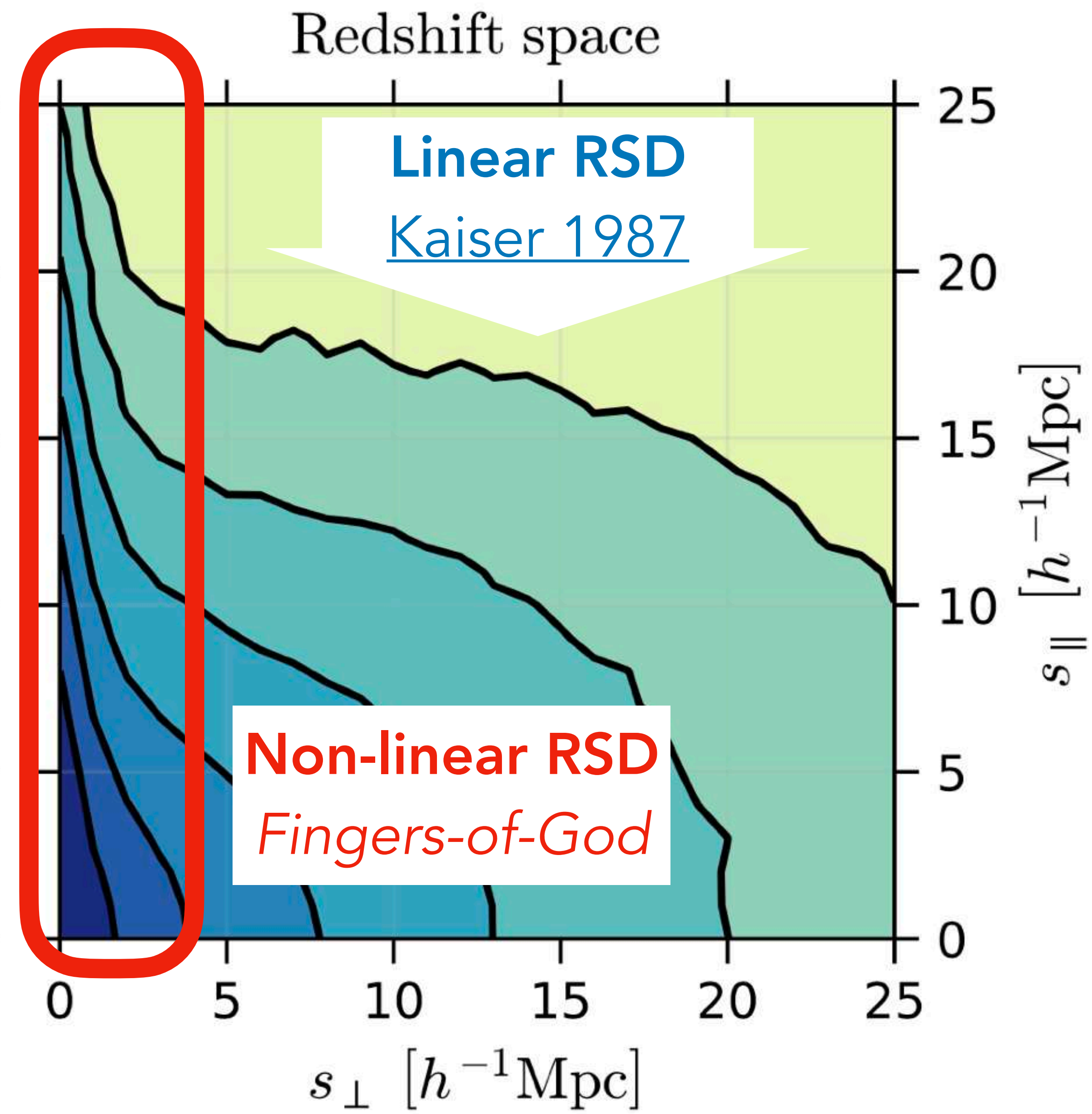

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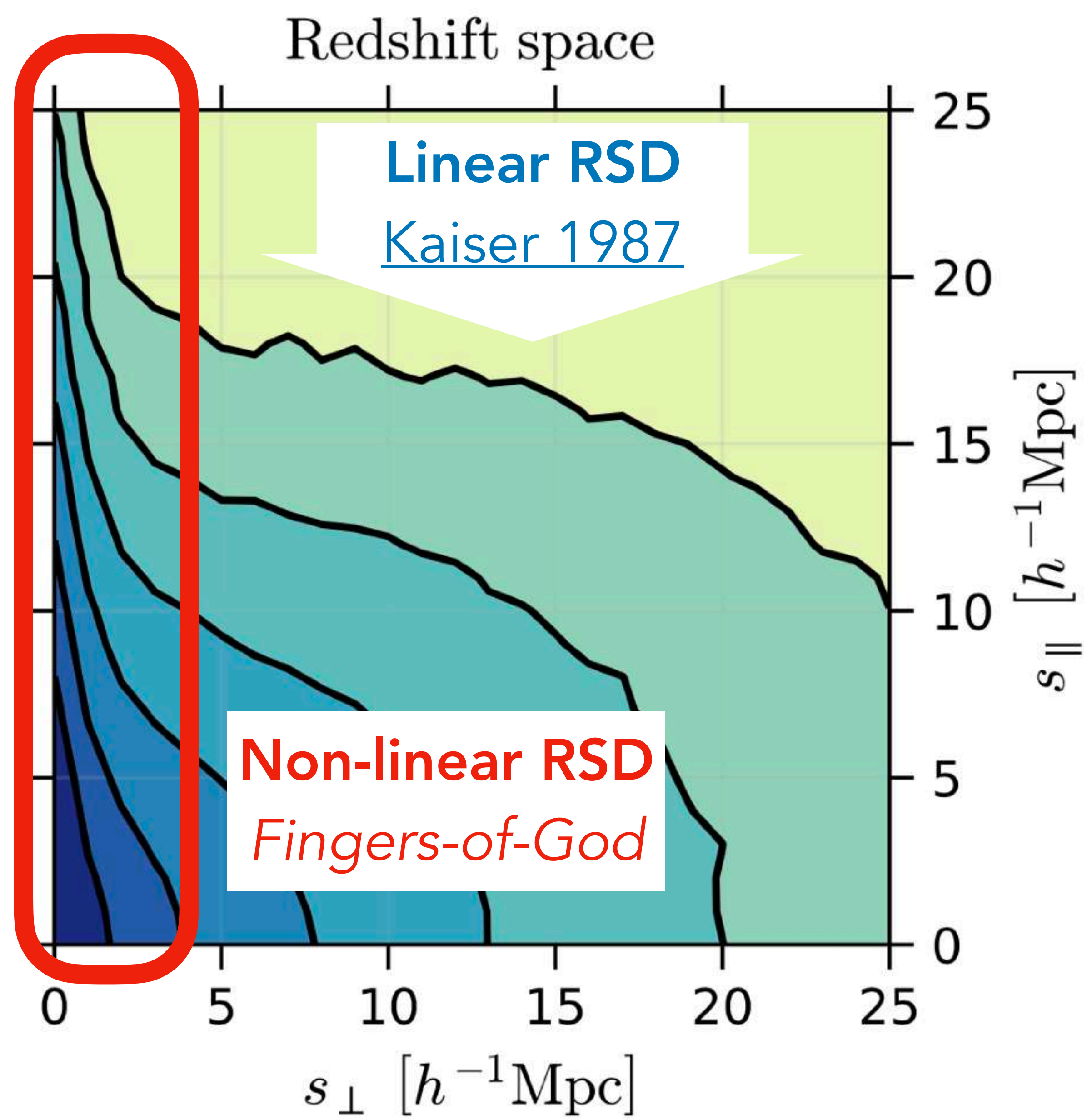

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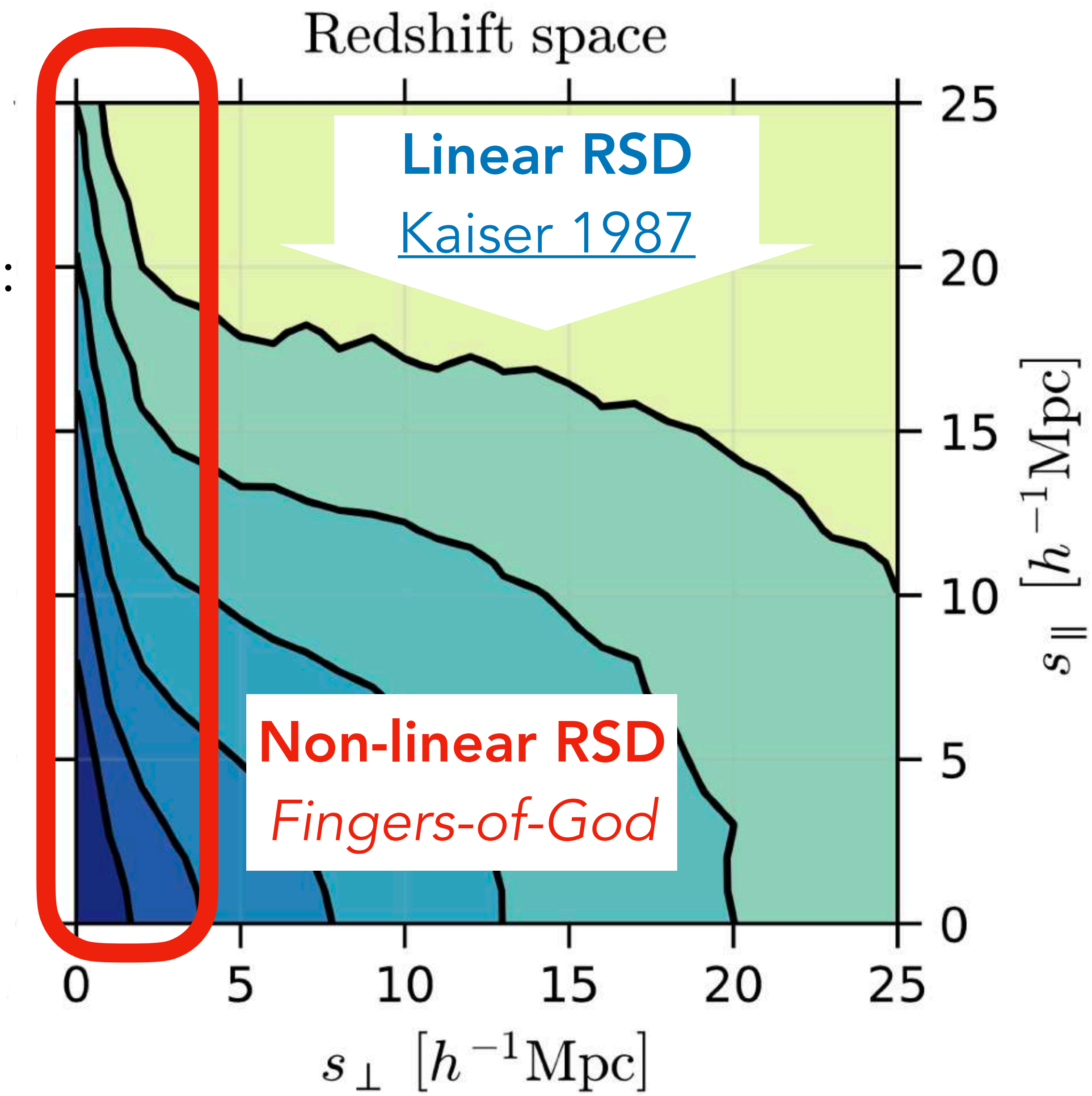

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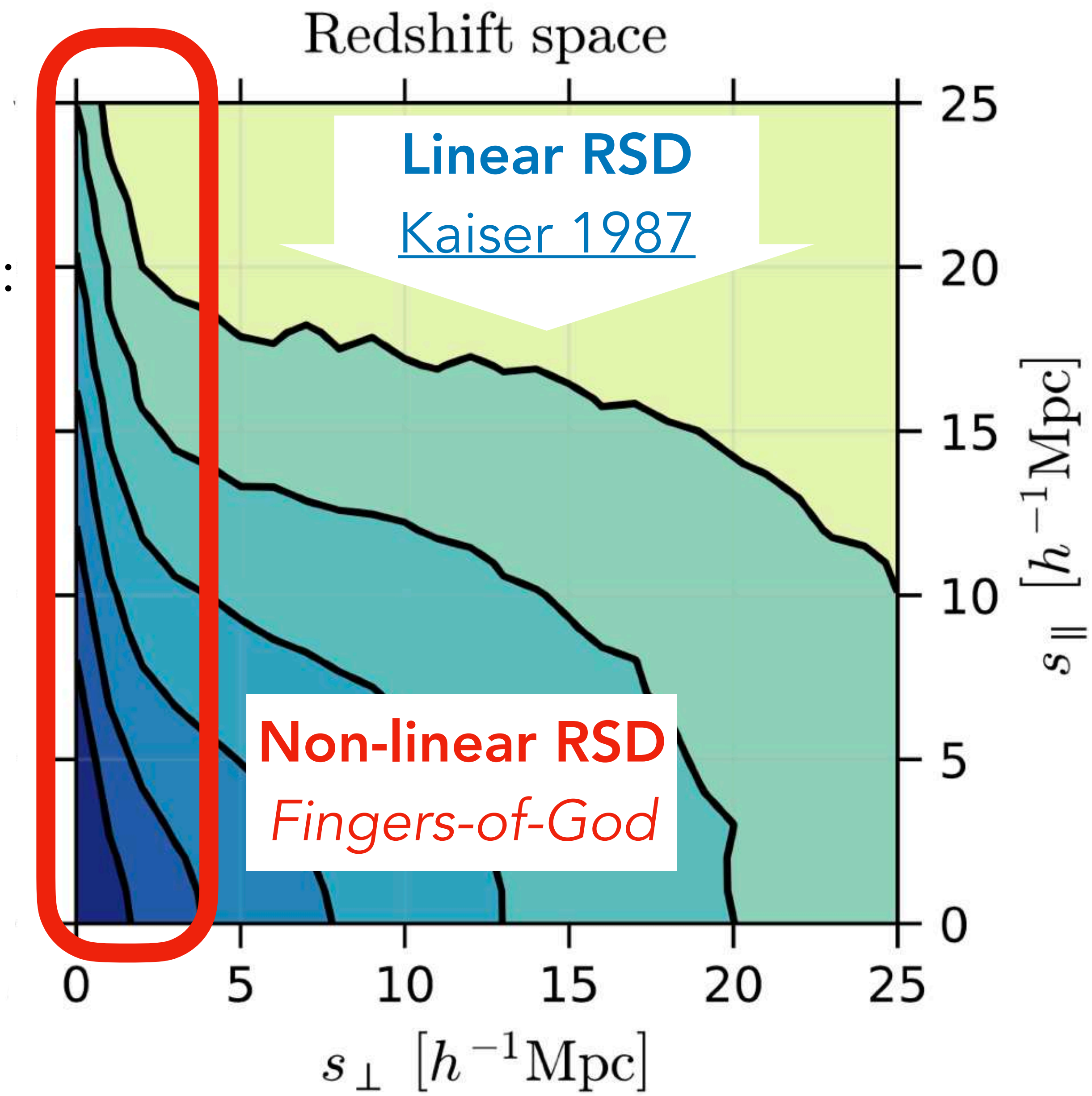

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Linear RSD model is basis for more advanced theoretical models

Redshift-space distortions (RSD)

What about σ_8 ?

Redshift-space distortions (RSD)

What about σ_8 ?

Variance of top-hat smoothed linear matter density field on scales of 8 Mpc/h

$$\sigma_8^2(z) \equiv \frac{1}{2\pi^2} \int_0^\infty dk\ k^2 P_m^{\rm lin}(k, z) W_8^2(k)$$

Used to define amplitude of power spectrum instead of A_s (primordial amplitude)

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Anisotropic clustering is proportional to $f(z)\sigma_8(z)$

Redshift-space distortions (RSD)

Going beyond linear theory, few examples

Redshift-space distortions (RSD)

Going beyond linear theory, few examples

TNS (Taruya, Nishimishi & Saito 2010)
+ non-linear bias

$$P^s_{\rm g}(k,\mu) = D(k\mu\sigma_v)\big[P_{\rm gg}(k) + 2\mu^2 f P_{{\rm g}\theta} + \mu^4 f^2 P_{\theta\theta}(k) + C_A(k,\mu,f,b_1) + C_B(k,\mu,f,b_1)\big],$$

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Comoving Lagrangian Perturbation Theory + Gaussian streaming
Carlson et al. 2013, Reid & White 2011

$$1 + \xi_{\mathrm{X}}(r_\perp, r_\parallel) = \int \frac{1}{\sqrt{2\pi\left[\sigma_{12}^2(r) + \sigma_{\mathrm{FoG}}^2\right]}}[1 + \xi_{\mathrm{X}}(r)] \times \exp\left\{-\frac{[r_\parallel - y - \mu v_{12}(r)]^2}{2\left[\sigma_{12}^2(r) + \sigma_{\mathrm{FoG}}^2\right]}\right\} \mathrm{d}y,$$

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$$P_{\rm g}^{s}(k,\mu) = D(k\mu\sigma_v)\big[P_{\rm gg}(k) + 2\mu^2 f P_{{\rm g}\theta} + \mu^4 f^2 P_{\theta\theta}(k) + C_A(k,\mu,f,b_1) + C_B(k,\mu,f,b_1)\big],$$

Comoving Lagrangian Perturbation Theory + Gaussian streaming
Carlson et al. 2013, Reid & White 2011

$$1+\xi_X(r_\perp, r_\parallel) = \int \frac{1}{\sqrt{2\pi\left[\sigma_{12}^2(r)+\sigma_{\rm FoG}^2\right]}}[1+\xi_X(r)] \times \exp\left\{-\frac{[r_\parallel - y - \mu v_{12}(r)]^2}{2\left[\sigma_{12}^2(r)+\sigma_{\rm FoG}^2\right]}\right\} {\rm d}y,$$

- **effective field theory**: small scale sourced counterterm to regularize loop integrals (pybird, CLASS-PT, velocileptors...) ($k < 0.3\, h\,{\rm Mpc}^{-1}$)
- **hybrid PT/HOD models**, e.g. Hand et al. 2017 ($k < 0.4\, h\,{\rm Mpc}^{-1}$)

How to model galaxy clustering in general?

- Matter clustering
- Halo clustering
- Galaxy clustering
- Redshift-space
- Selection effects

How to model galaxy clustering in general?

Matter clustering

Halo clustering

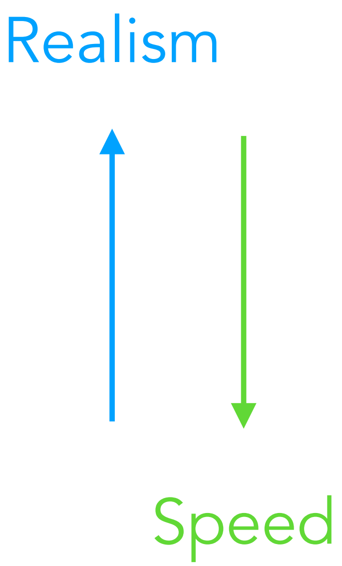
Galaxy clustering

Redshift-space

Selection effects

Approaches:

- n-body simulations
- hybrid : emulators, machine learning
- theoretical formulations



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Reviews on this topic

Large-scale structure of the Universe and cosmological perturbation theory
Bernardeau, Colombi, Gaztanaga, Scoccimarro 2002

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Any theoretical model is validated with n-body simulations

Redshift-space distortions (RSD)

In practice

We fit simultaneously for $(f\sigma_8,\ \alpha_{\parallel},\ \alpha_{\perp})$
+ bias and FoG terms

No power-laws, we want the *full-shape* information !

No reconstruction !

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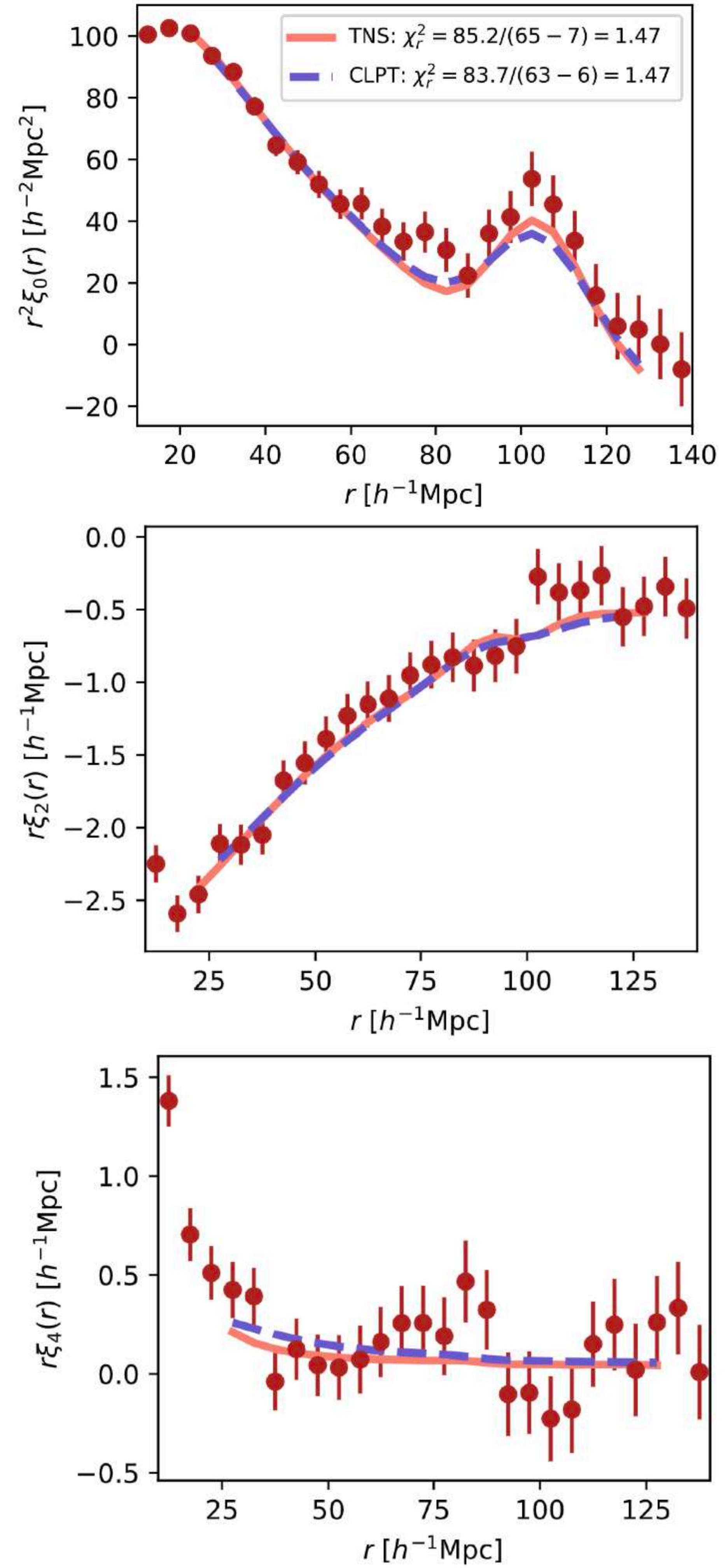
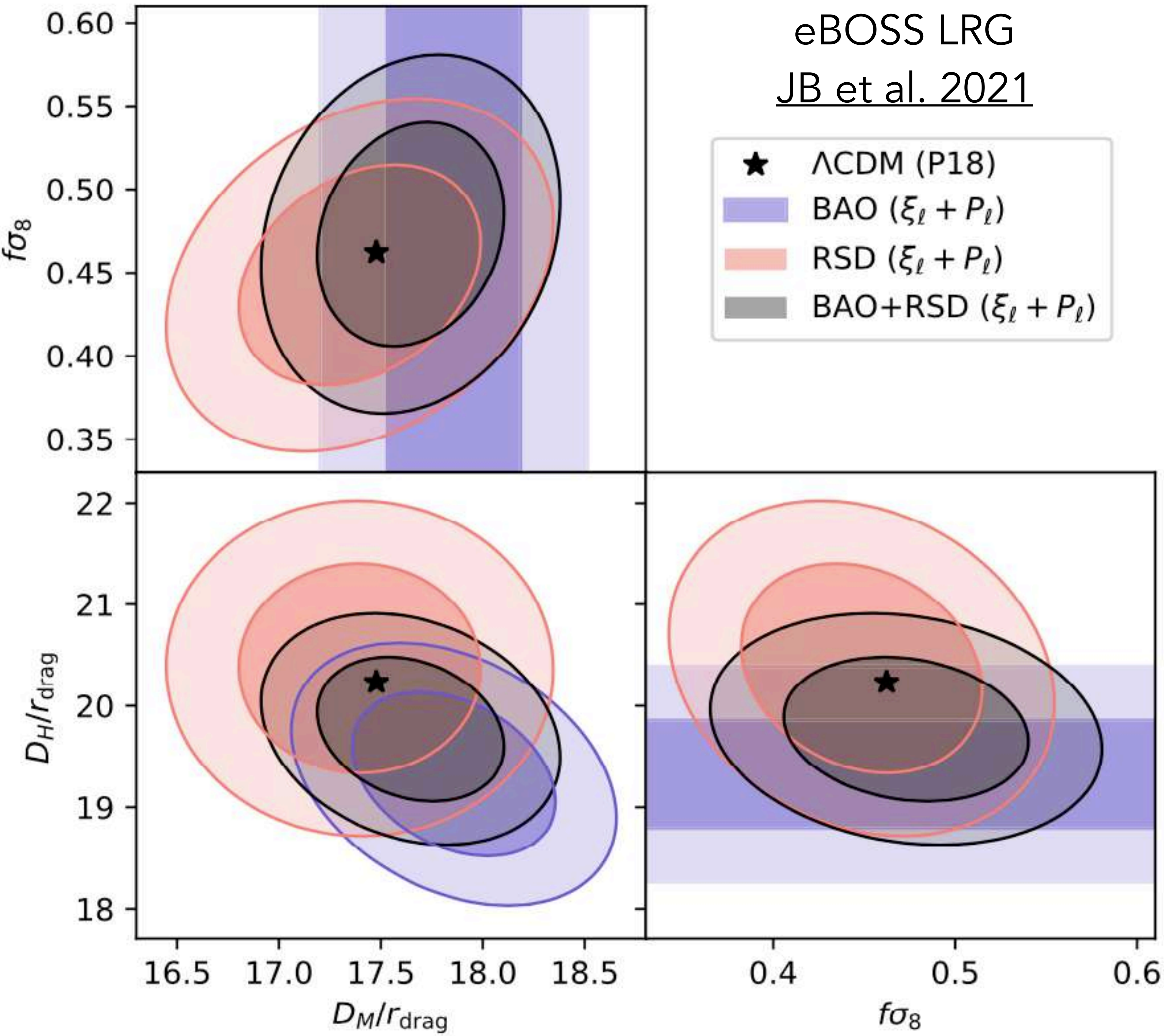
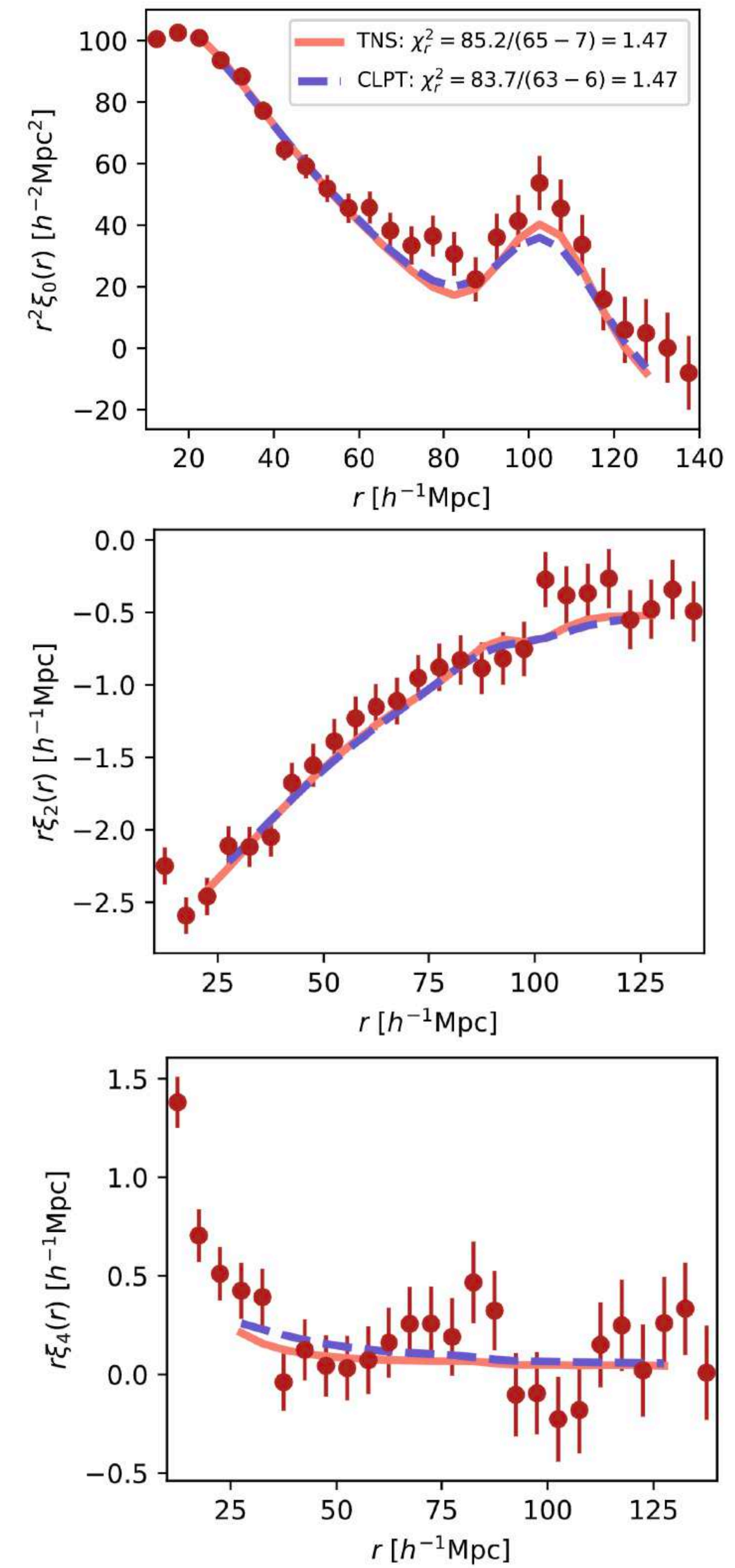


Redshift-space distortions (RSD)

eBOSS LRG

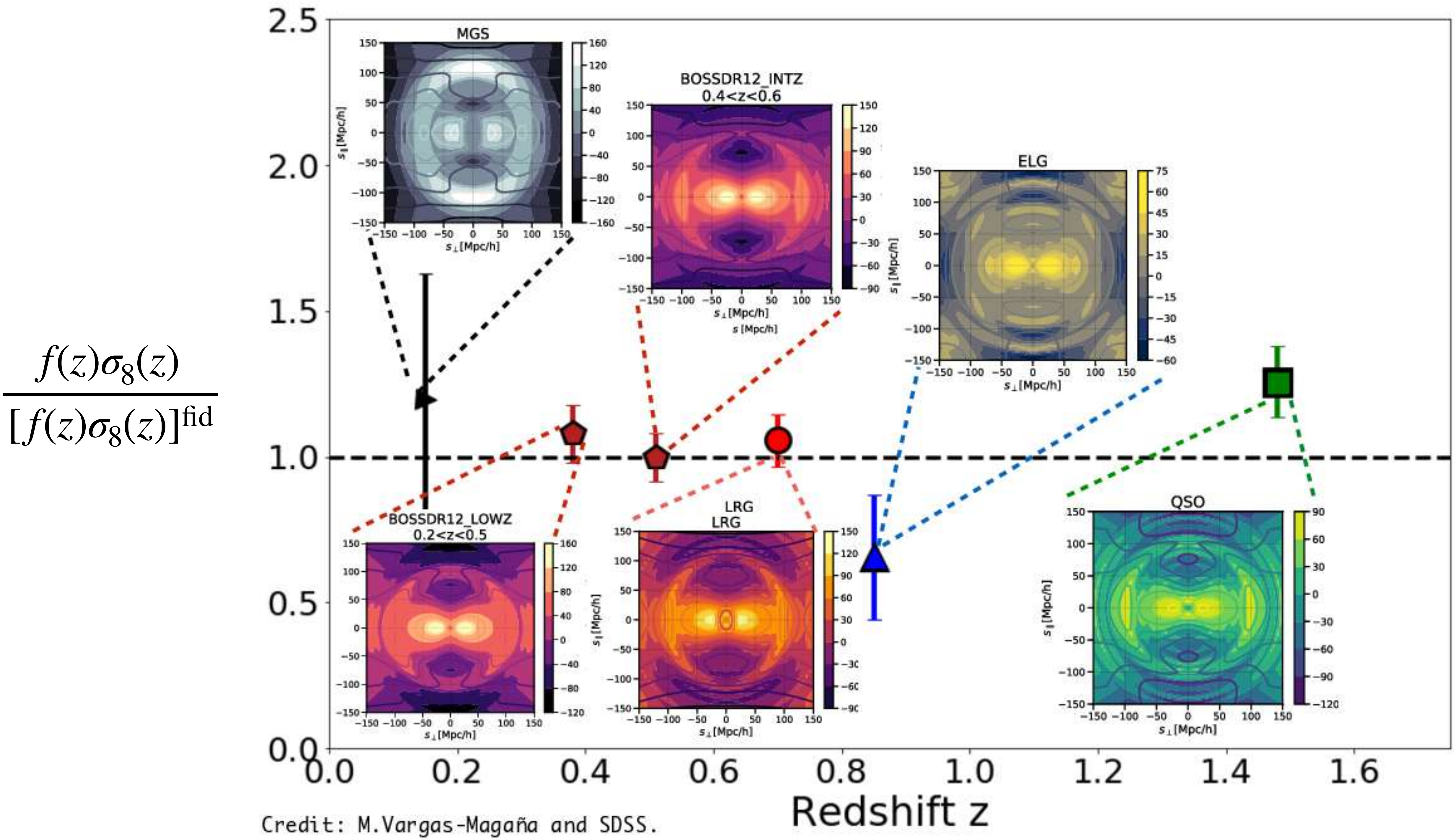
JB et al. 2021





Redshift-space distortions (RSD)

Measurements from SDSS II, III and IV



Used in constraining cosmological models

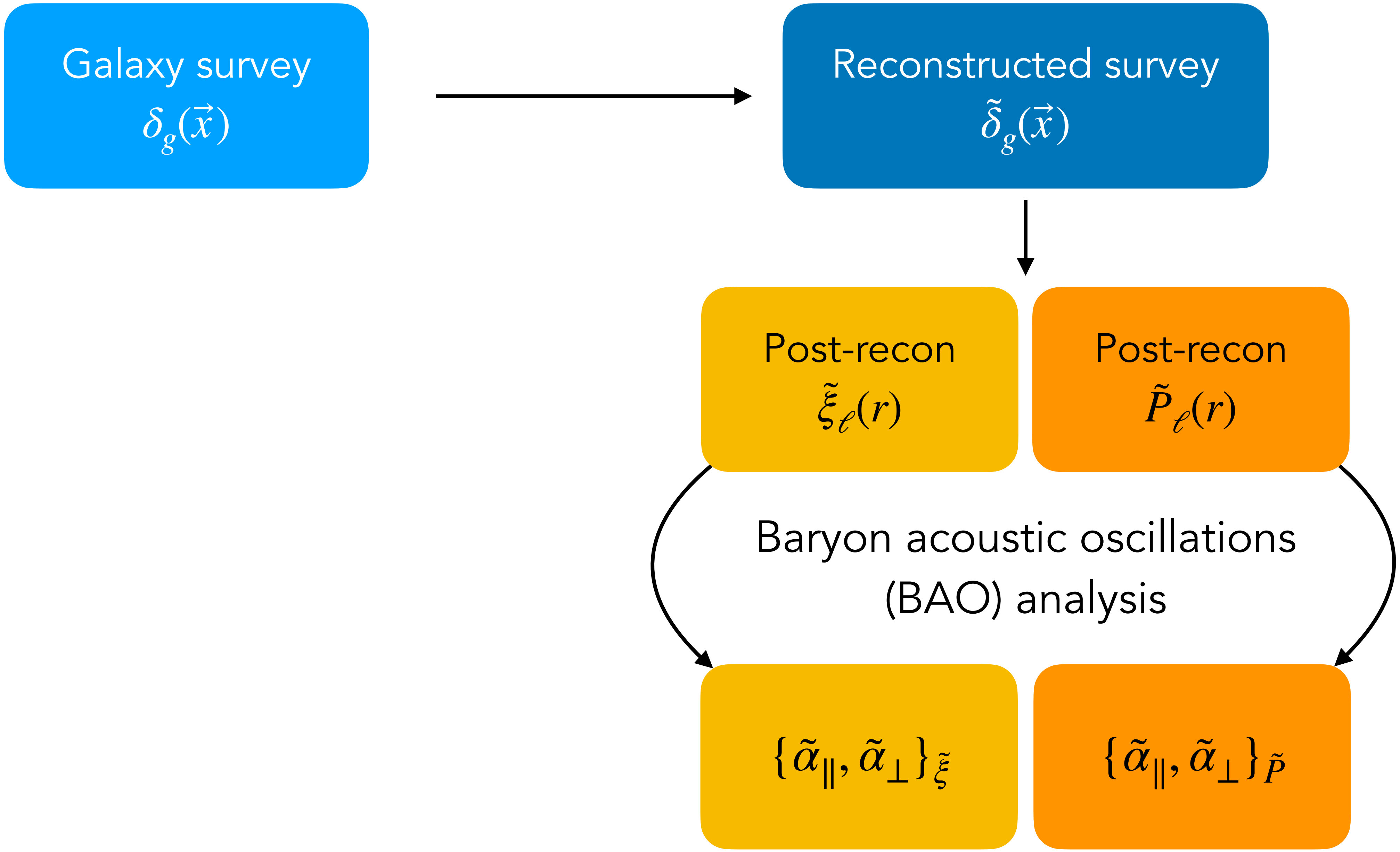
In a nutshell

	BAO	**RSD**
Goal	Standard ruler distances	Growth rate of structures
Information source	BAO peak position only	Full anisotropic shape of $\langle \delta\delta' \rangle$
Reconstruction	Yes	No
Parameters	$\left(\frac{D_H(z)}{r_{\rm drag}}, \frac{D_M(z)}{r_{\rm drag}}\right)_{\rm peak}$	$f(z)\sigma_8(z)$ and $\left(\frac{D_H(z)}{r_{\rm drag}}, \frac{D_M(z)}{r_{\rm drag}}\right)_{\rm shape}$
Model dependant	Less	More

In a nutshell

Galaxy survey
$\delta_g(\vec{x})$

In a nutshell



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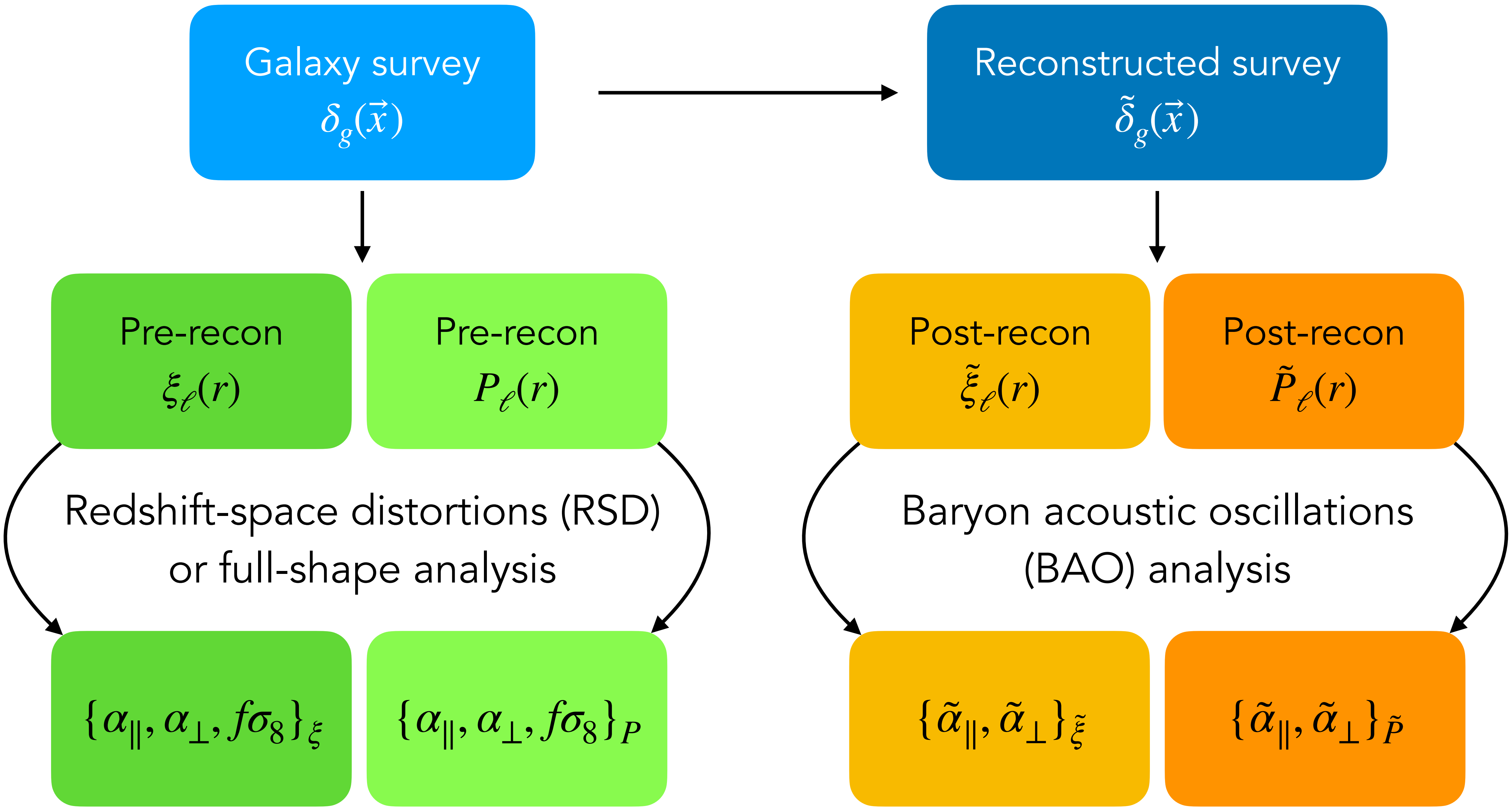

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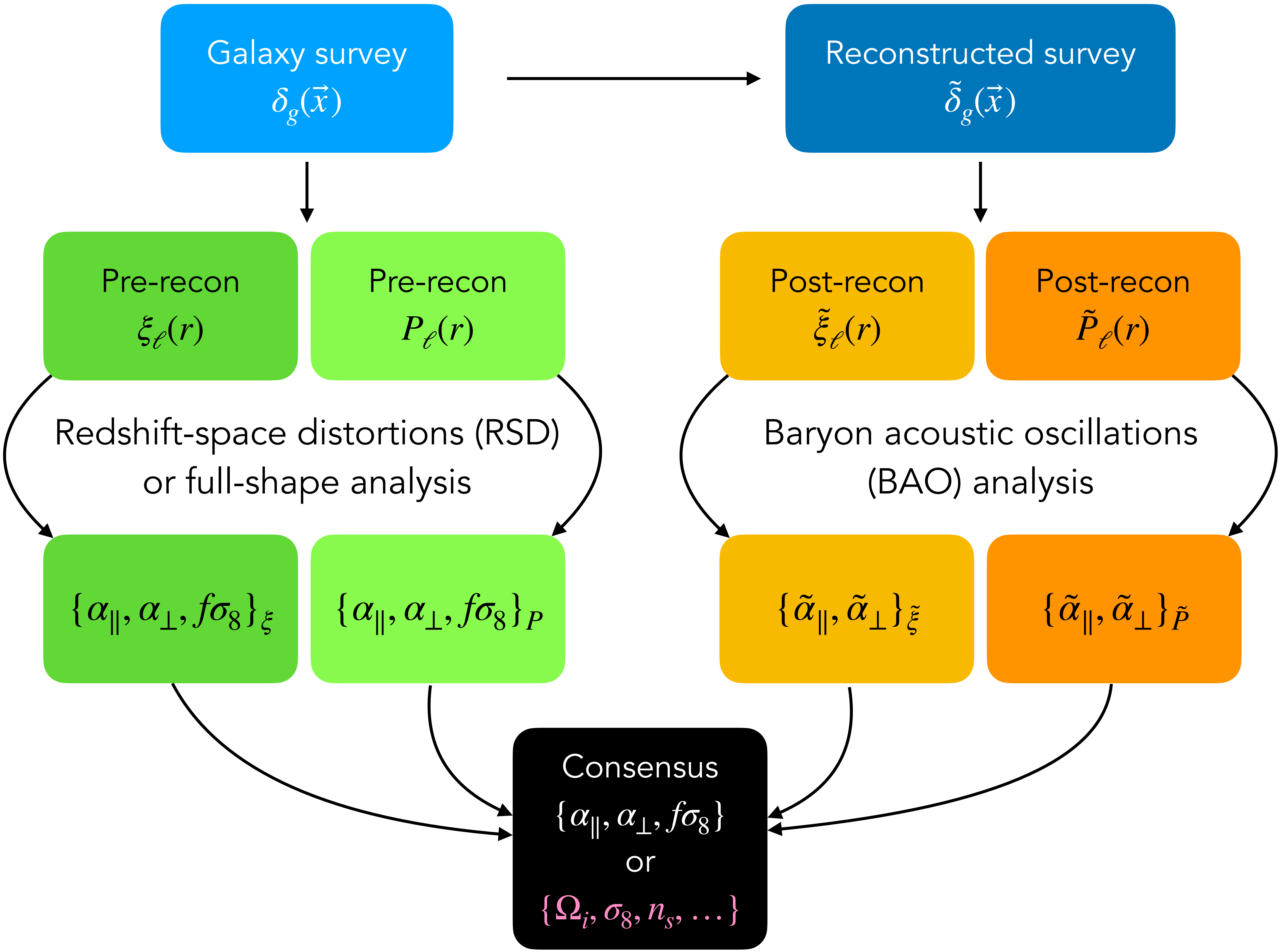

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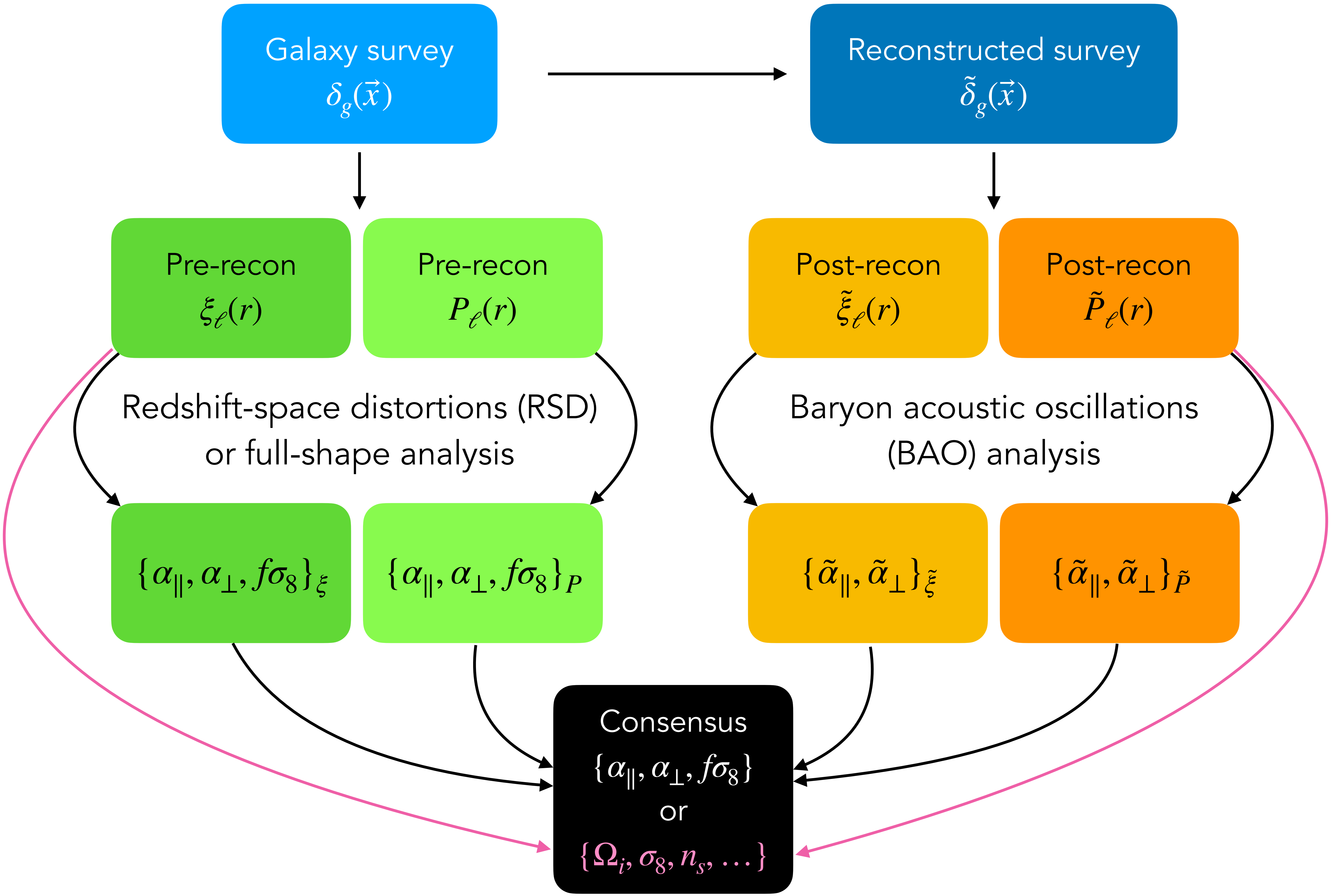

How to obtain consensus results ?

Combining Gaussian posteriors
(Sánchez et al. 2017)

$$\xi_\ell(r)$$
$$D_\xi = \{\alpha_\parallel, \alpha_\perp, f\sigma_8\}$$
C_ξ = 3 x 3 covariance

$$P_\ell(r)$$
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From mocks

$$C_{\rm tot} = \begin{pmatrix} C_\xi & C_{\xi,P} \\ C_{P,\xi} & C_P \end{pmatrix}$$

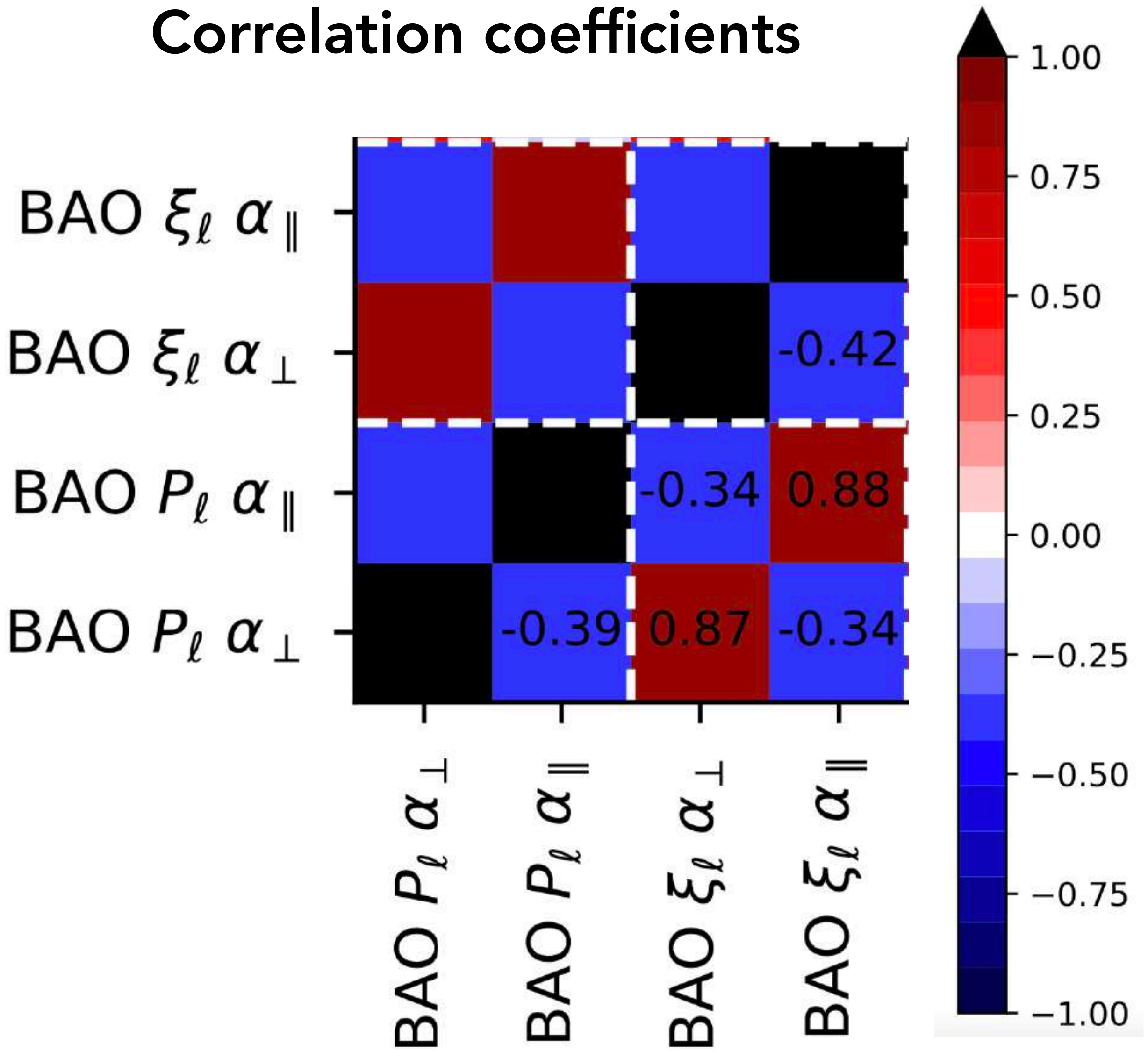
Consensus
$D = \{\alpha_\parallel, \alpha_\perp, f\sigma_8\}$
C = 3 x 3 covariance

- assumes Gaussian input posteriors
- yields Gaussian posteriors
- needs adjusting on $C_{\xi,P}$ for particular data realisation
- trickier to include systematic uncertainties

Obtaining consensus results

Application to eBOSS LRG sample

Correlation coefficients



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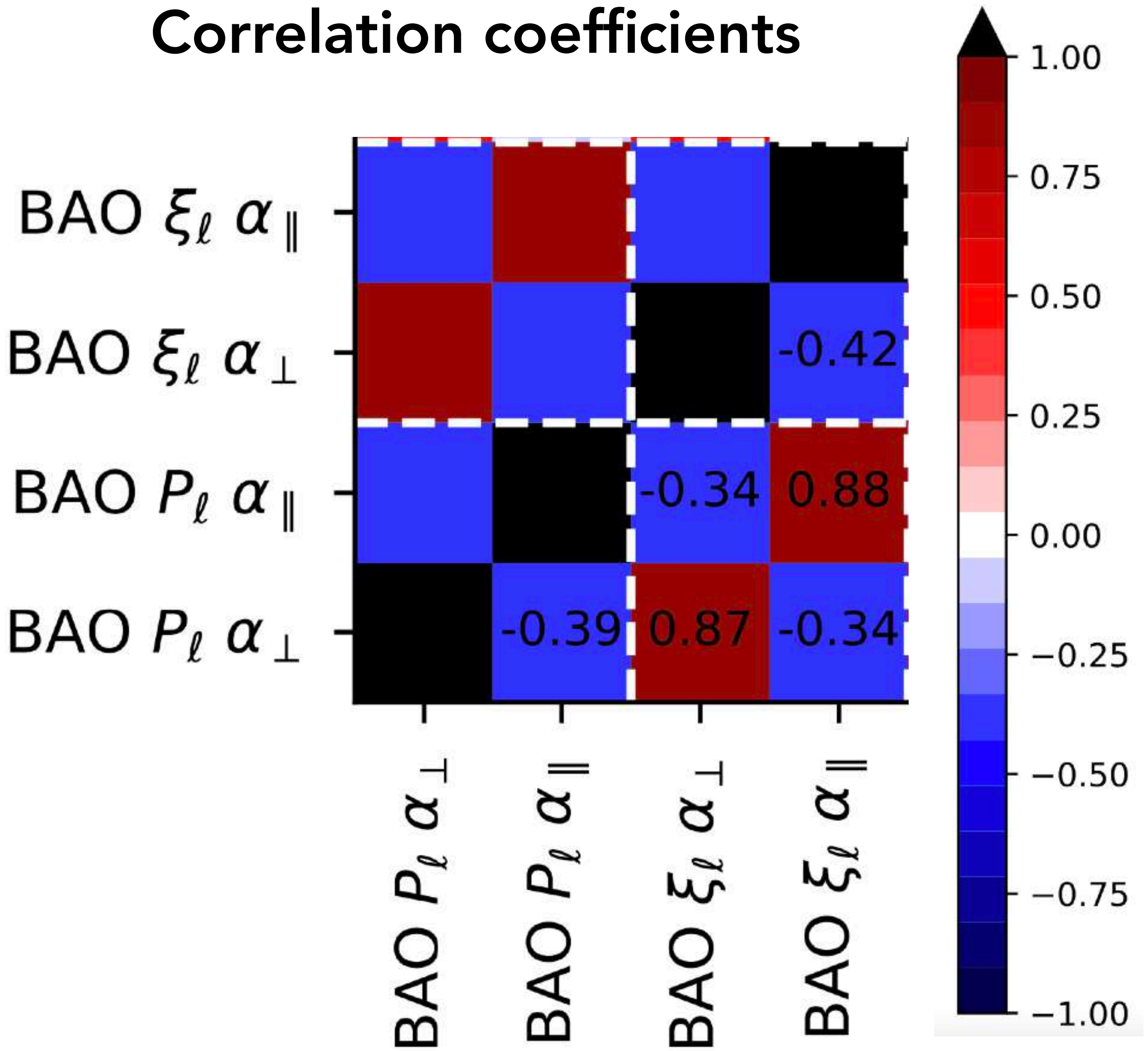
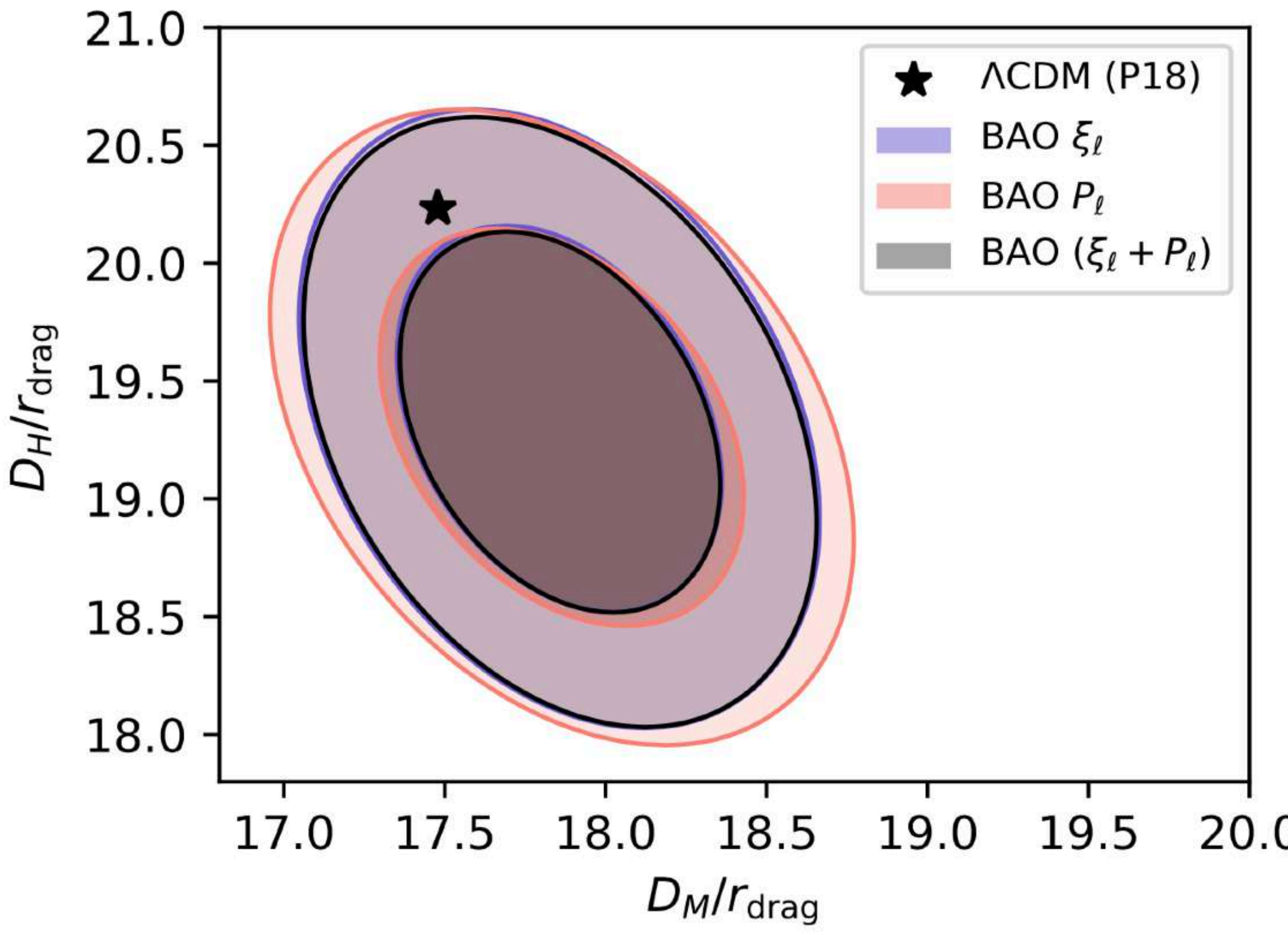


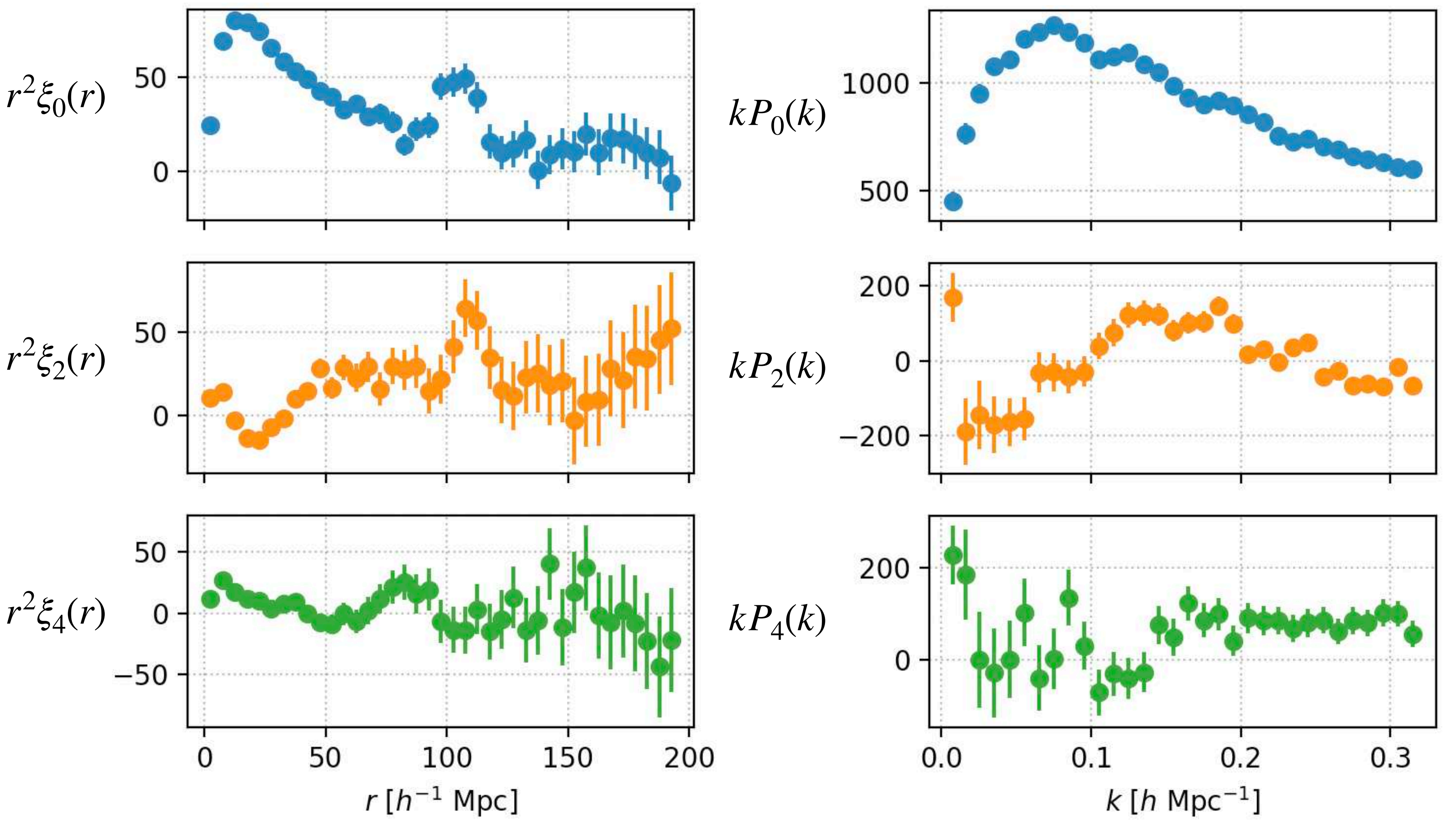


BAO results are really consistent between Fourier and Config

Alternative : joint fit of Fourier+Config

Dumerchat & JB 2022

- concatenate Fourier and Config data-vectors
- fit for same $\{\tilde{\alpha}_{\parallel}, \tilde{\alpha}_{\perp}\}$ on both, different nuisance parameters



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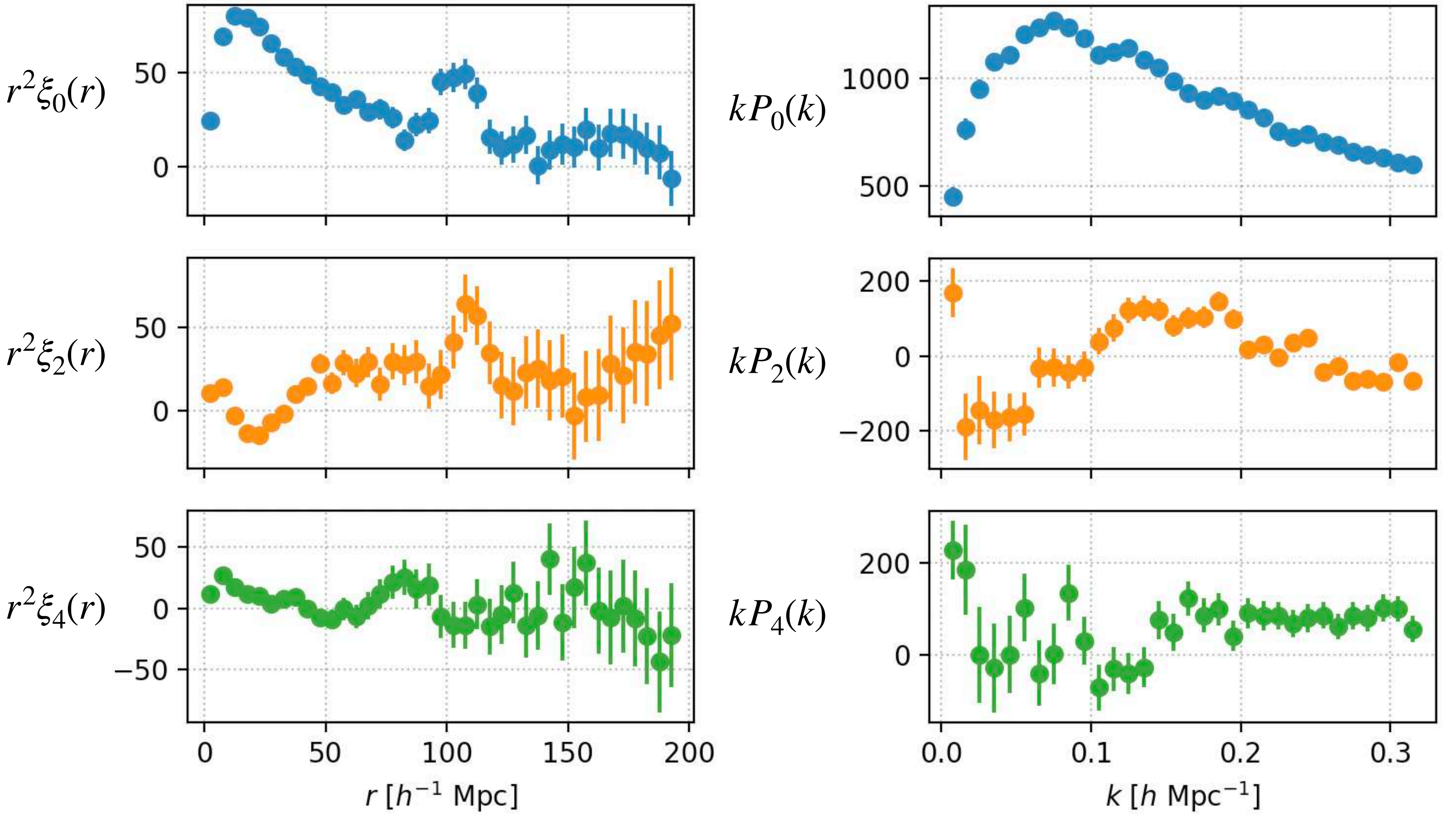


Pros:

- does not assume Gaussian posteriors
- simpler, no adjustments
- same model, just FFT'ed

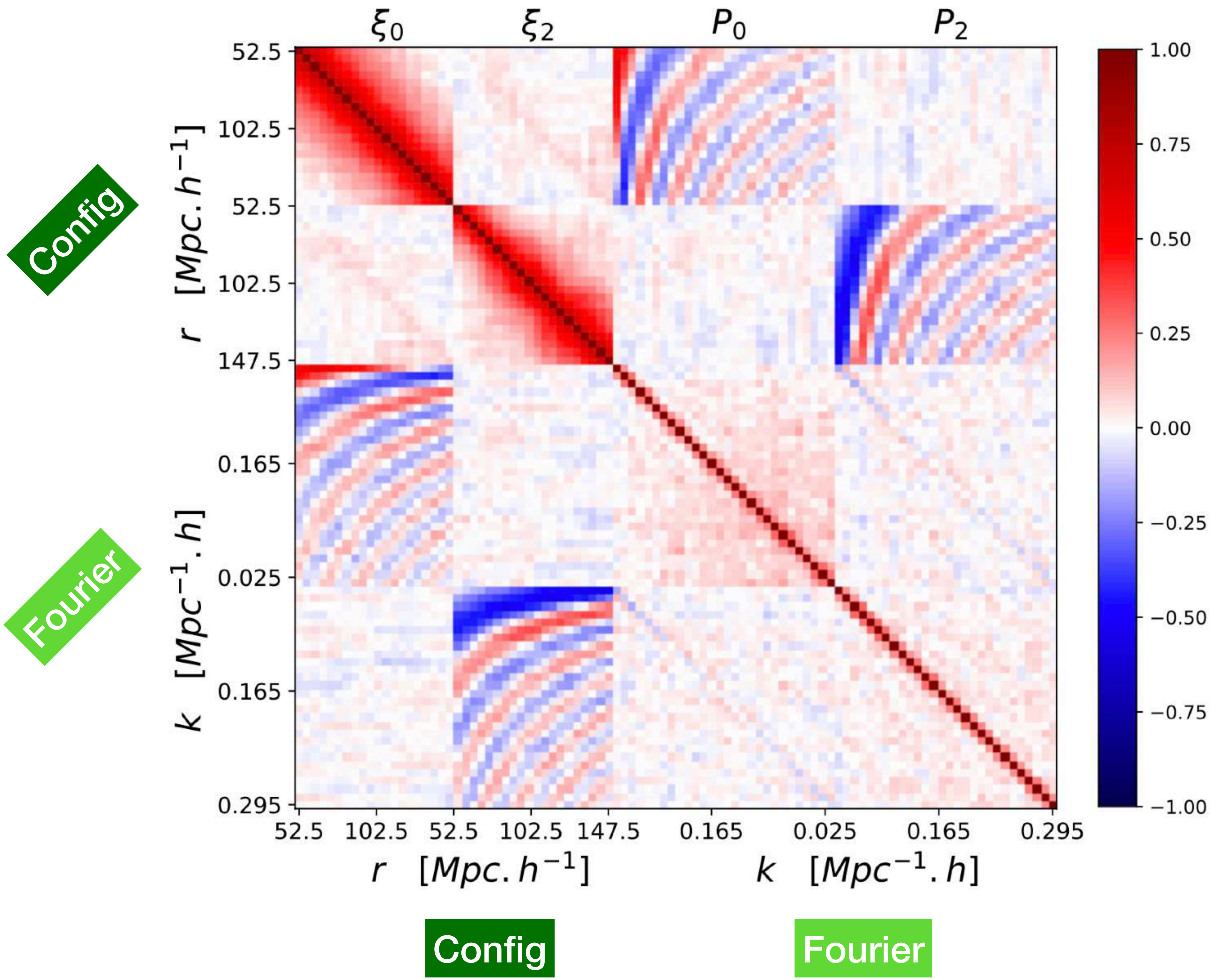
Cons:

- larger covariance matrix

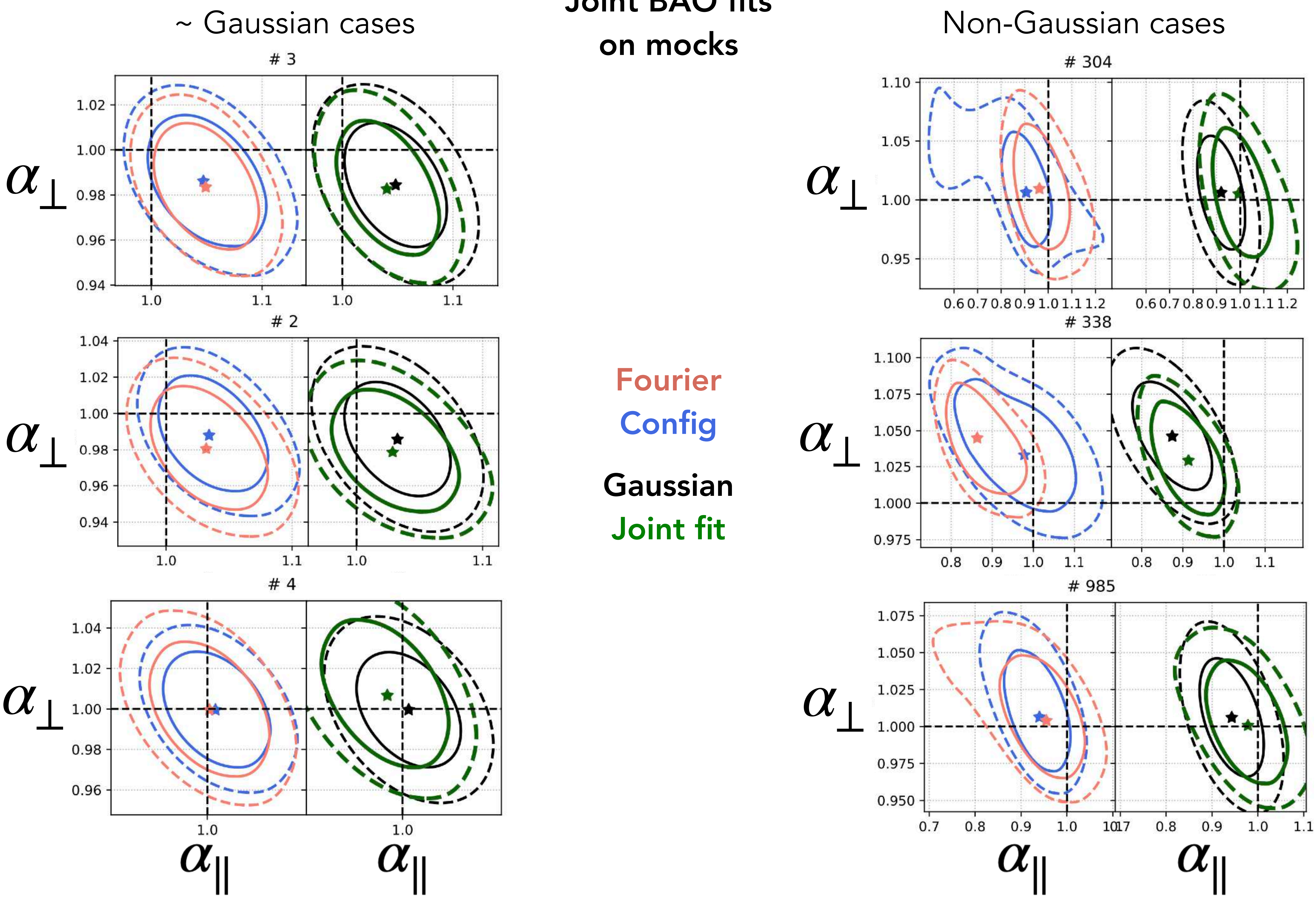
Alternative : joint fit of Fourier+Config

Dumerchat & JB 2022

Correlation matrix from 1000 mocks



Joint BAO fits on mocks



Joint fit is well-behaved, less biased statistically, with correct uncertainties

RSD fits

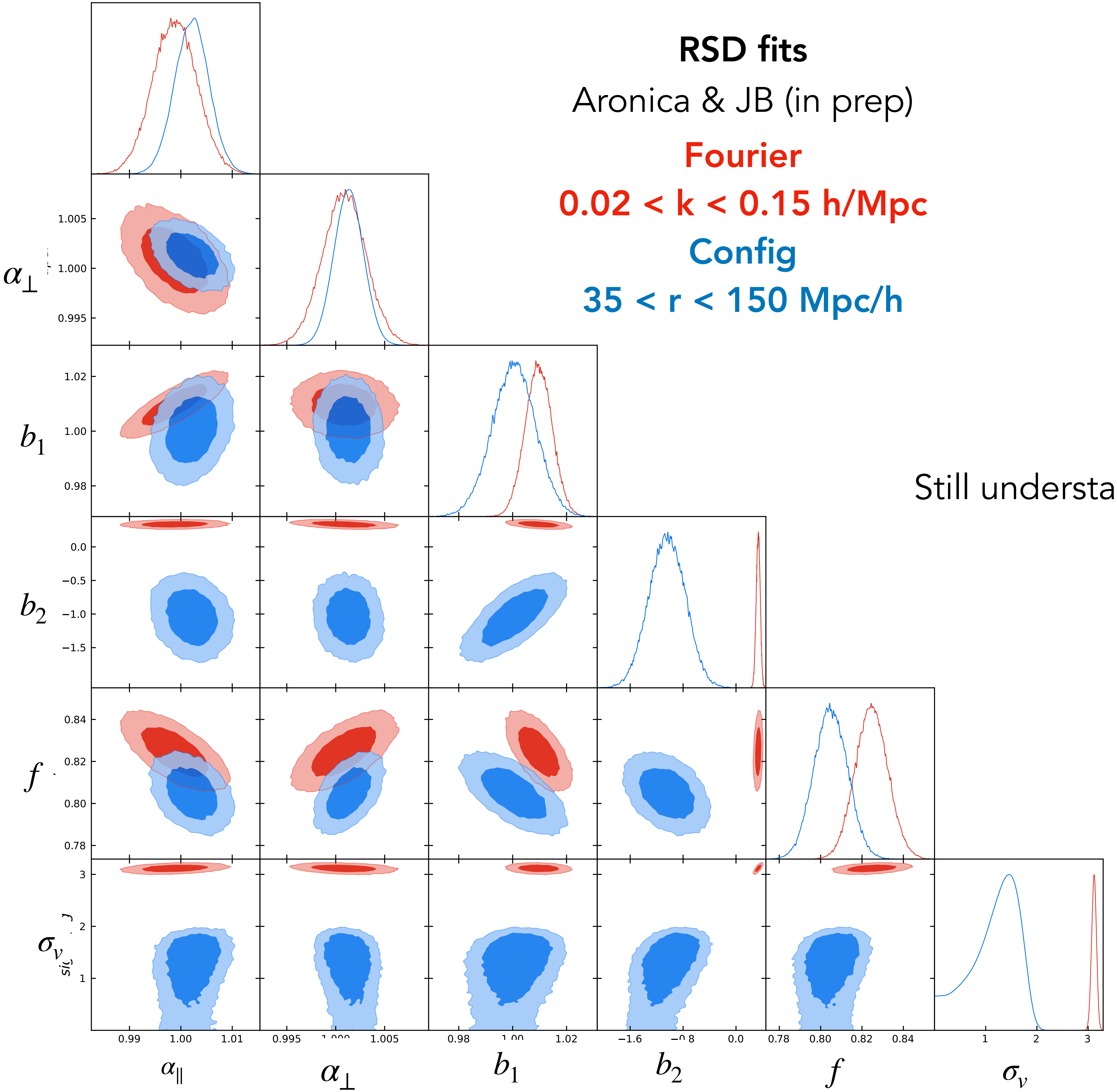
Aronica & JB (in prep)

Fourier

0.02 < k < 0.15 h/Mpc

Config

35 < r < 150 Mpc/h



Still understanding differences...

How to obtain consensus between BAO and RSD ?

Chen, Vlah & White 2022

Gil-Marín 2022

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Chen, Vlah & White 2022

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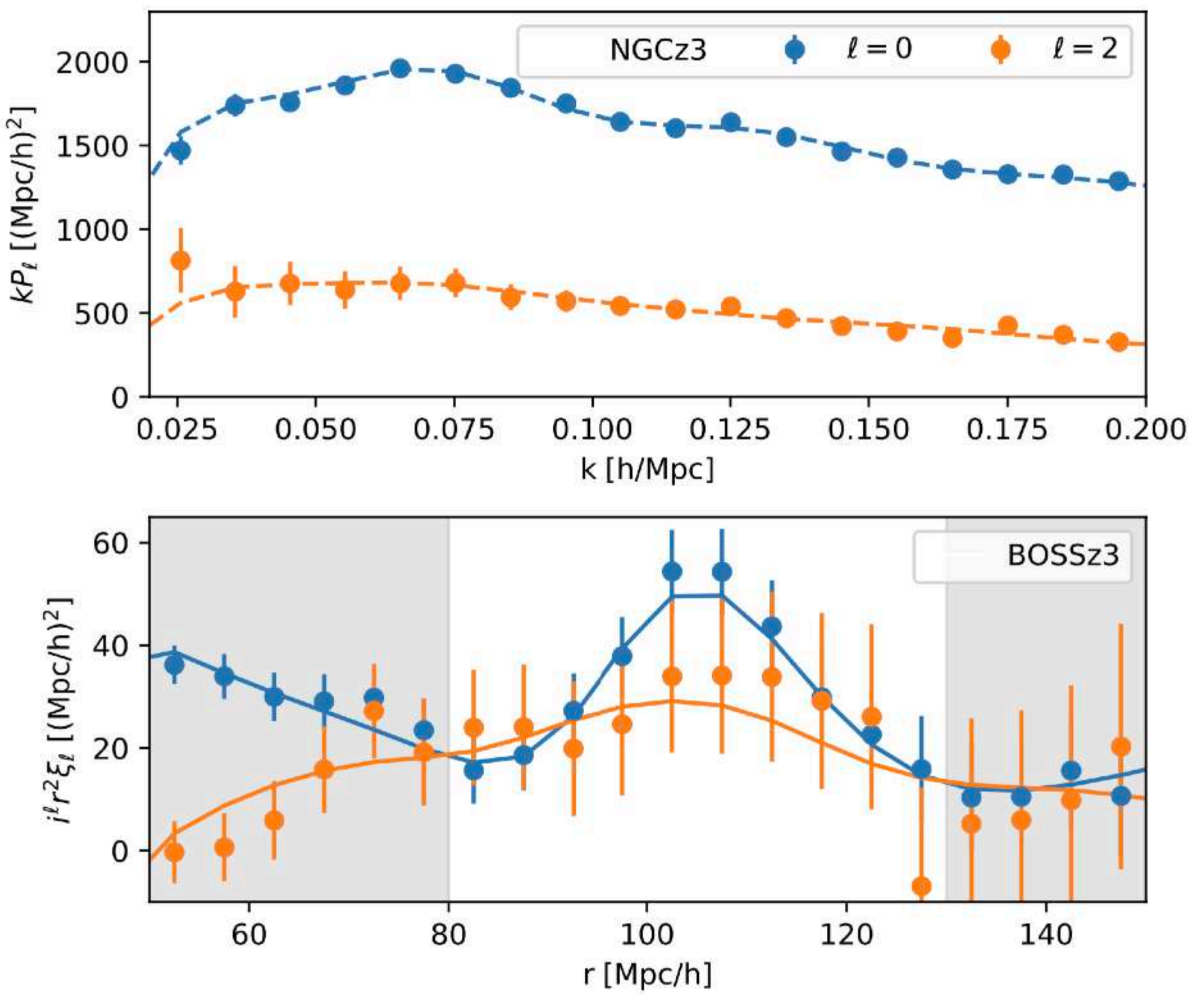
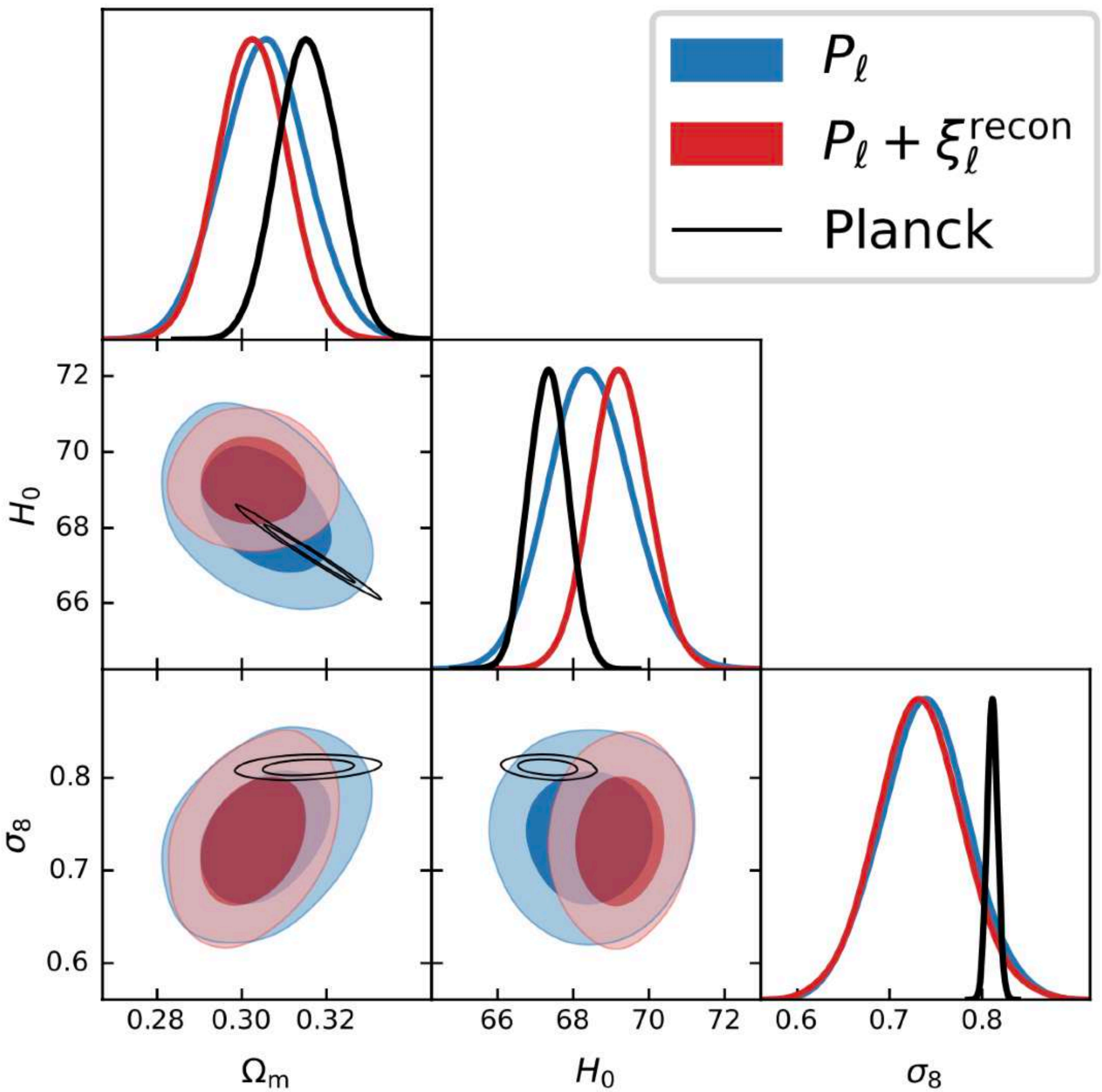
Pre-reconstruction power spectrum



Post-reconstruction correlation function



Fitting directly cosmological parameters with LPT predictions

How to obtain consensus between BAO and RSD ?

Chen, Vlah & White 2022

Gil-Marín 2022

Comparison of 3 methods:

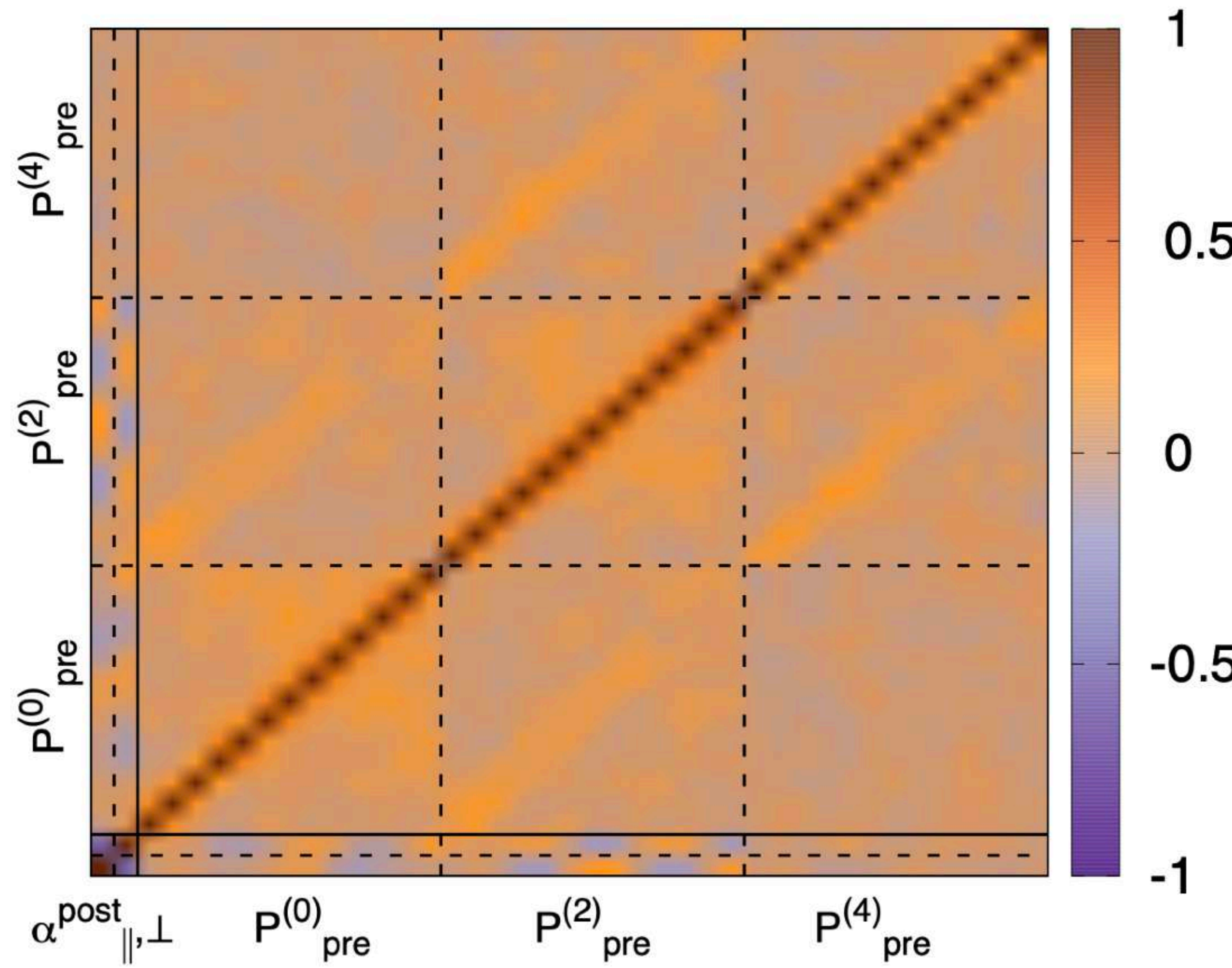
1. joint fit of pre+post-recon multipoles
2. combining alphas
3. hybrid approach

Fit for 4 variables

$$\{\alpha_{\|}, \alpha_{\perp}, f\sigma_8, m\}$$

Method 1 shows 5-10% smaller uncertainties and more robust results

Correlation matrix



Primordial Non-Gaussianities

Using very large-scale clustering of **quasars**

$f_{\mathrm{NL}} = 0$ corresponds to Gaussian initial conditions after inflation

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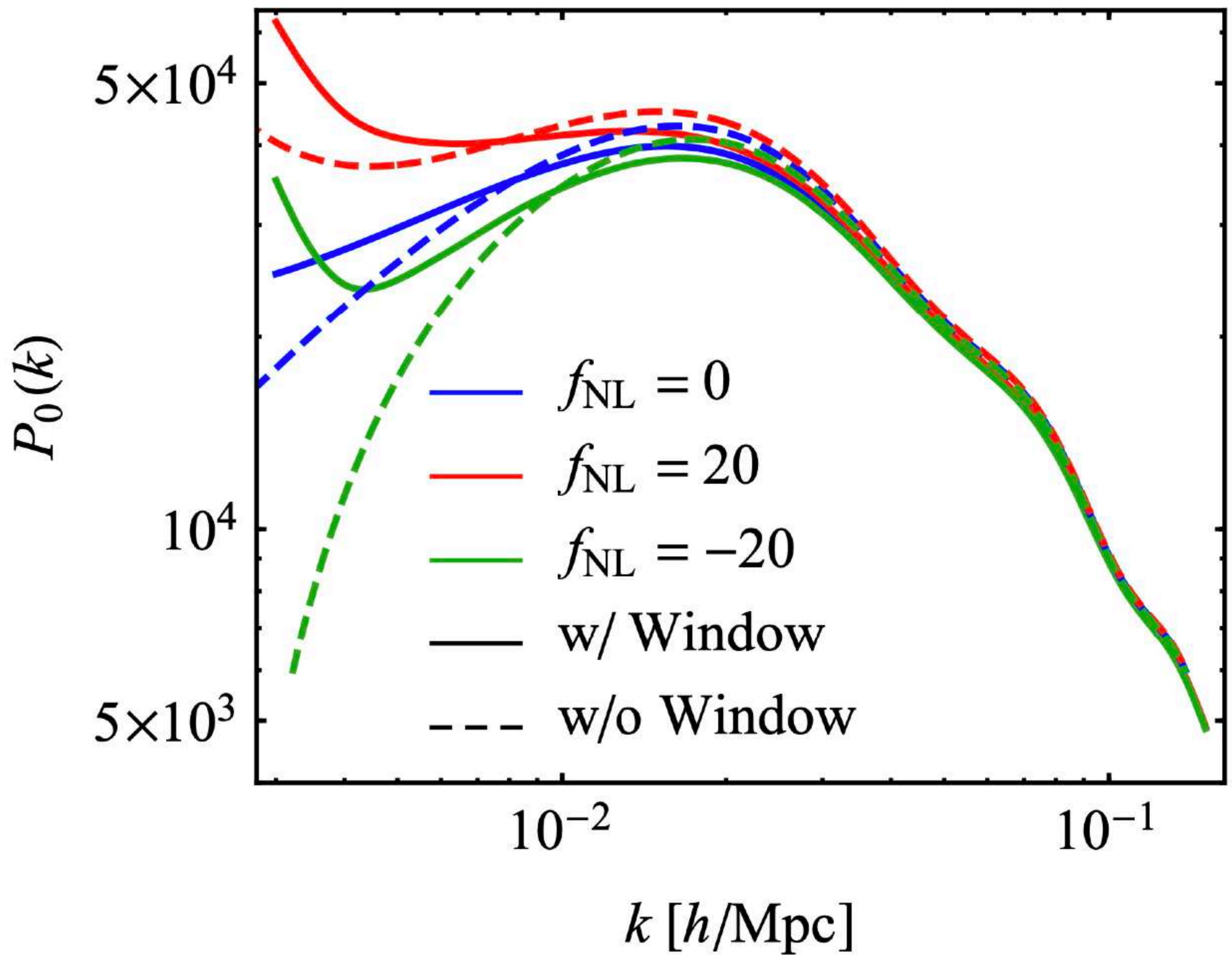

Castorina et al. 2019

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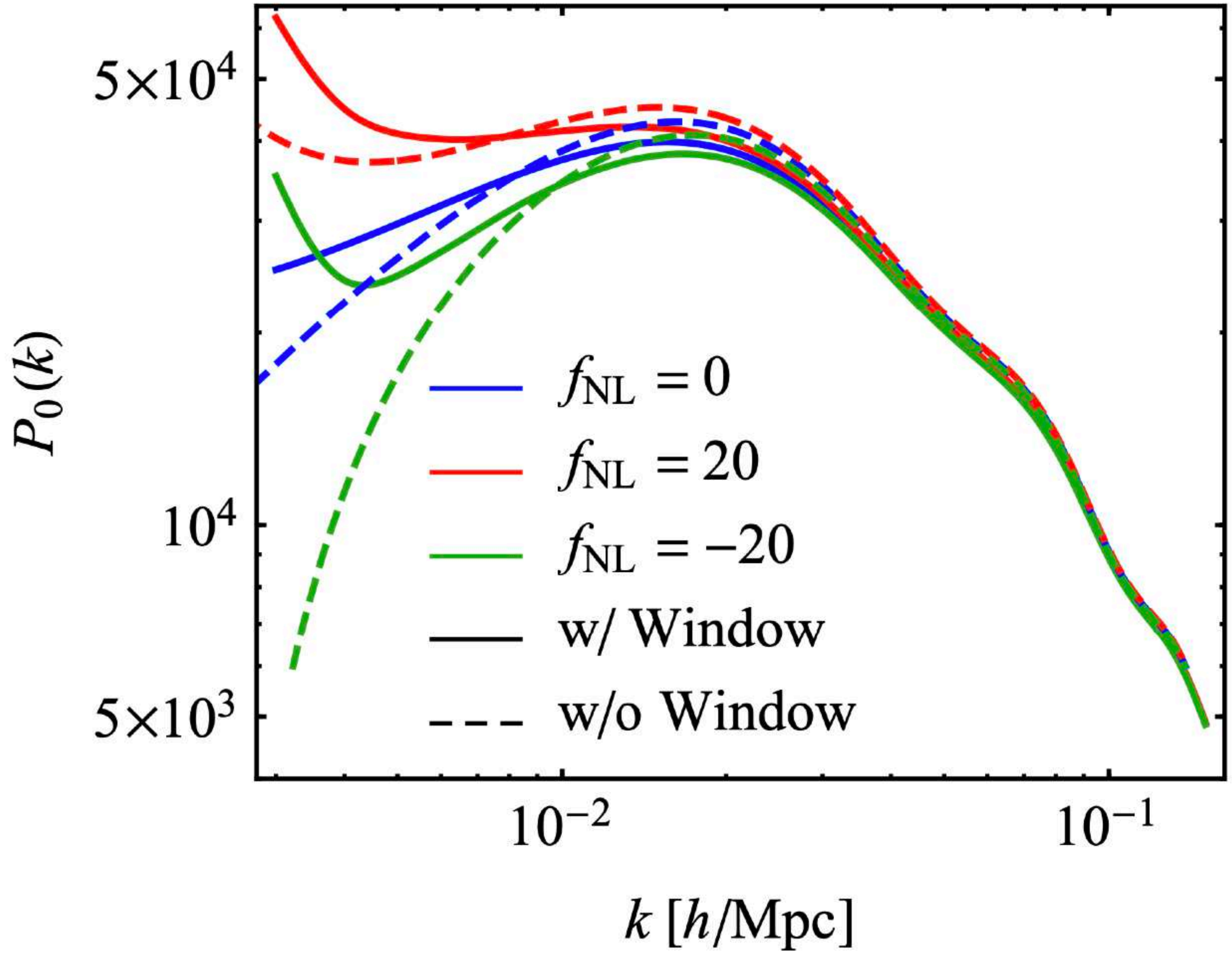


Castorina et al. 2019

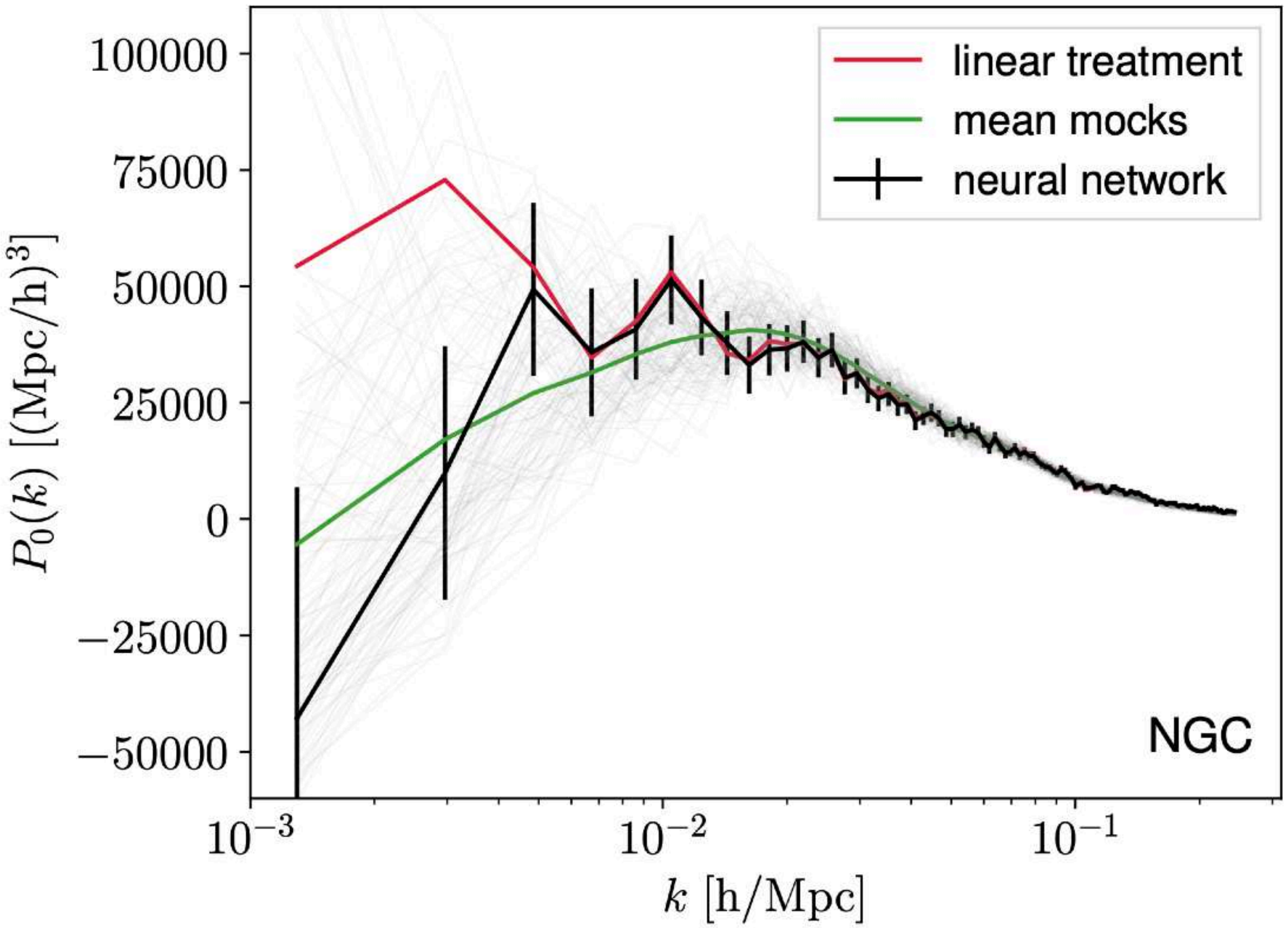
Large scales are the **most prone to systematic effects** : window, photometry, etc...

Primordial Non-Gaussianities

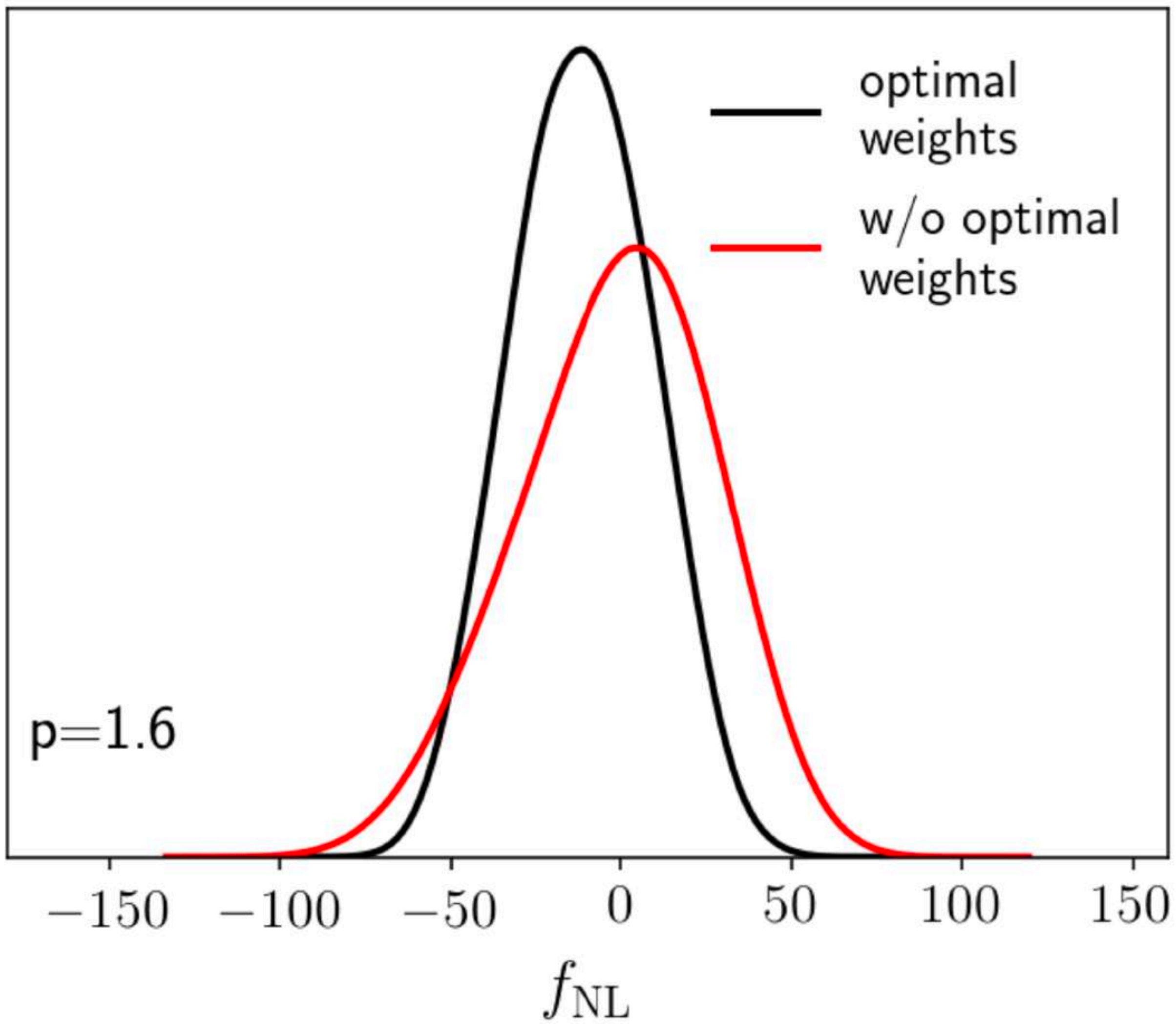
Using very large-scale clustering of **quasars**

Treatment of photometric systematics with neural networks

eBOSS QSOs



Constraints on $f_{\rm NL}$

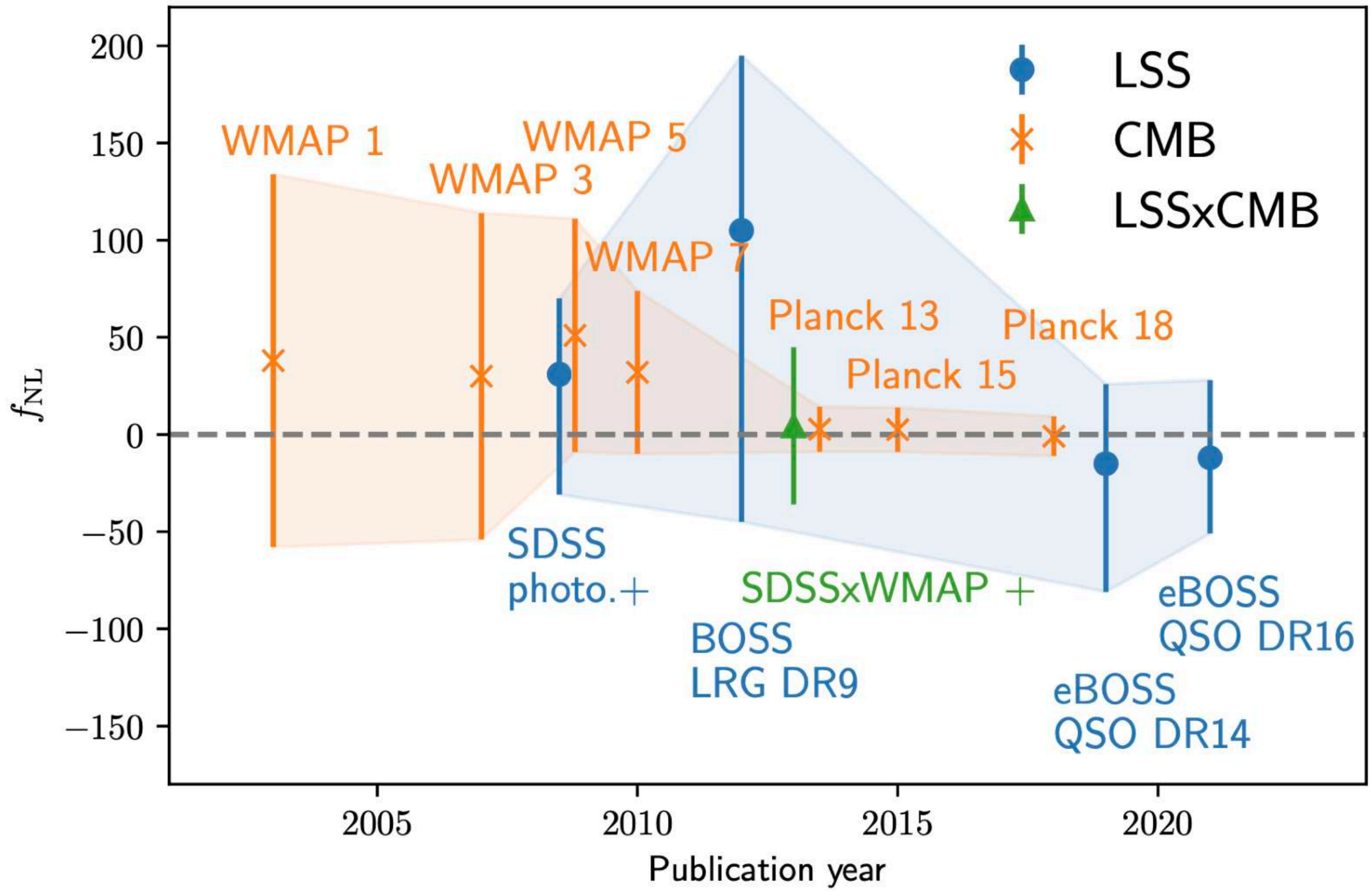


Mueller et al. 2022

No detection of departures from Gaussian initial conditions

Primordial Non-Gaussianities

Comparison between probes



Primordial Non-Gaussianities

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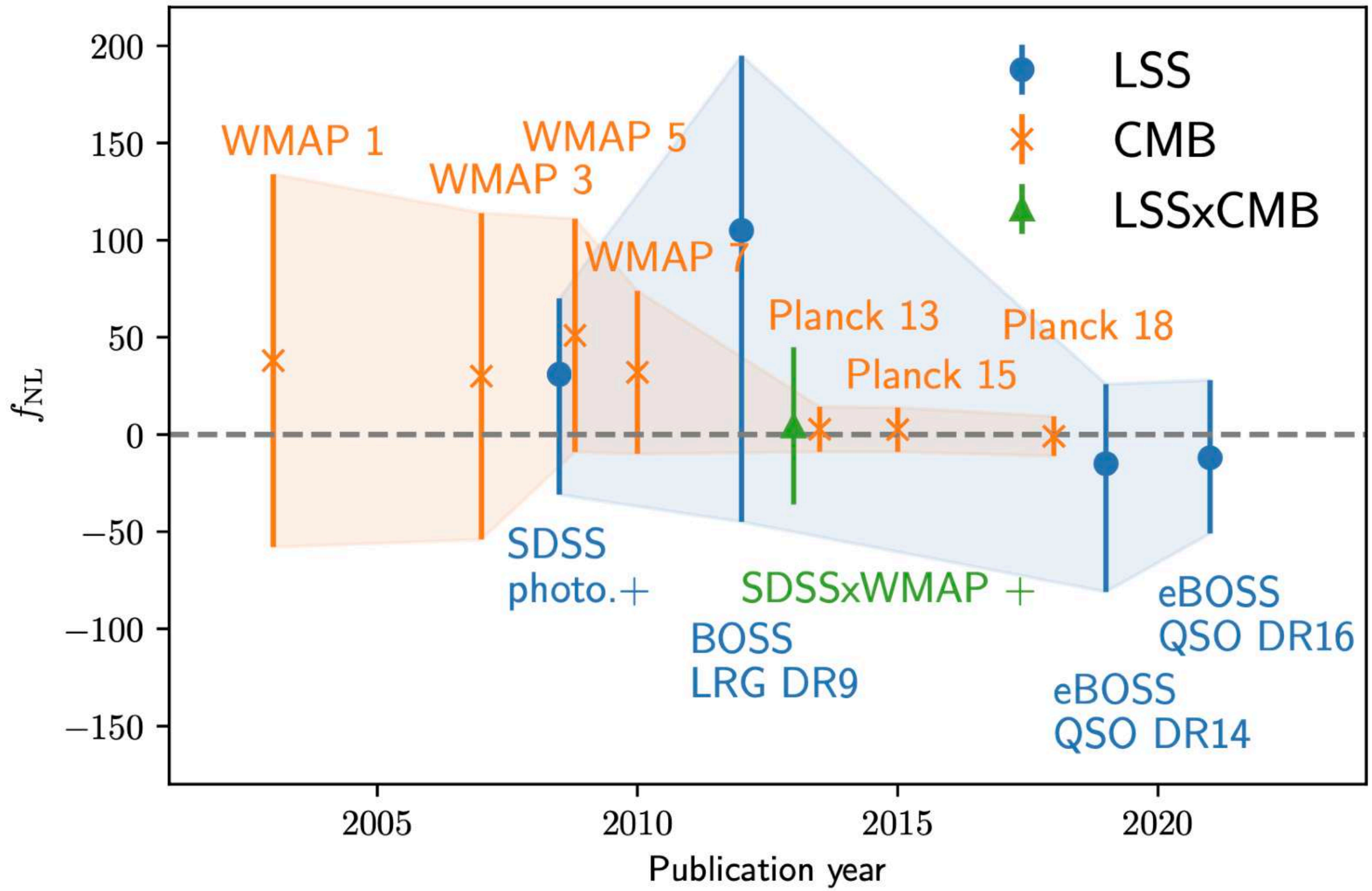

Forecast for future (DESI Collaboration 2016a)

$\sigma(f_{\rm NL}^{\rm local}) < 5.0$ (DESI)

$\sigma(f_{\rm NL}^{\rm local}) < 2.5$ (DESI + Planck)

How to convert a list of $\left(\theta_i, \phi_i, z_i, \{f_j\}\right)$ to $\delta_{\rm Ly\alpha}(\vec{x})$?

Case of **Lyman-α forests**

$$\left(\theta_i, \phi_i, z_i, \{f_j\}\right) \rightarrow \delta_{\rm Ly\alpha}(\vec{x}) \rightarrow \langle \delta\delta' \rangle$$

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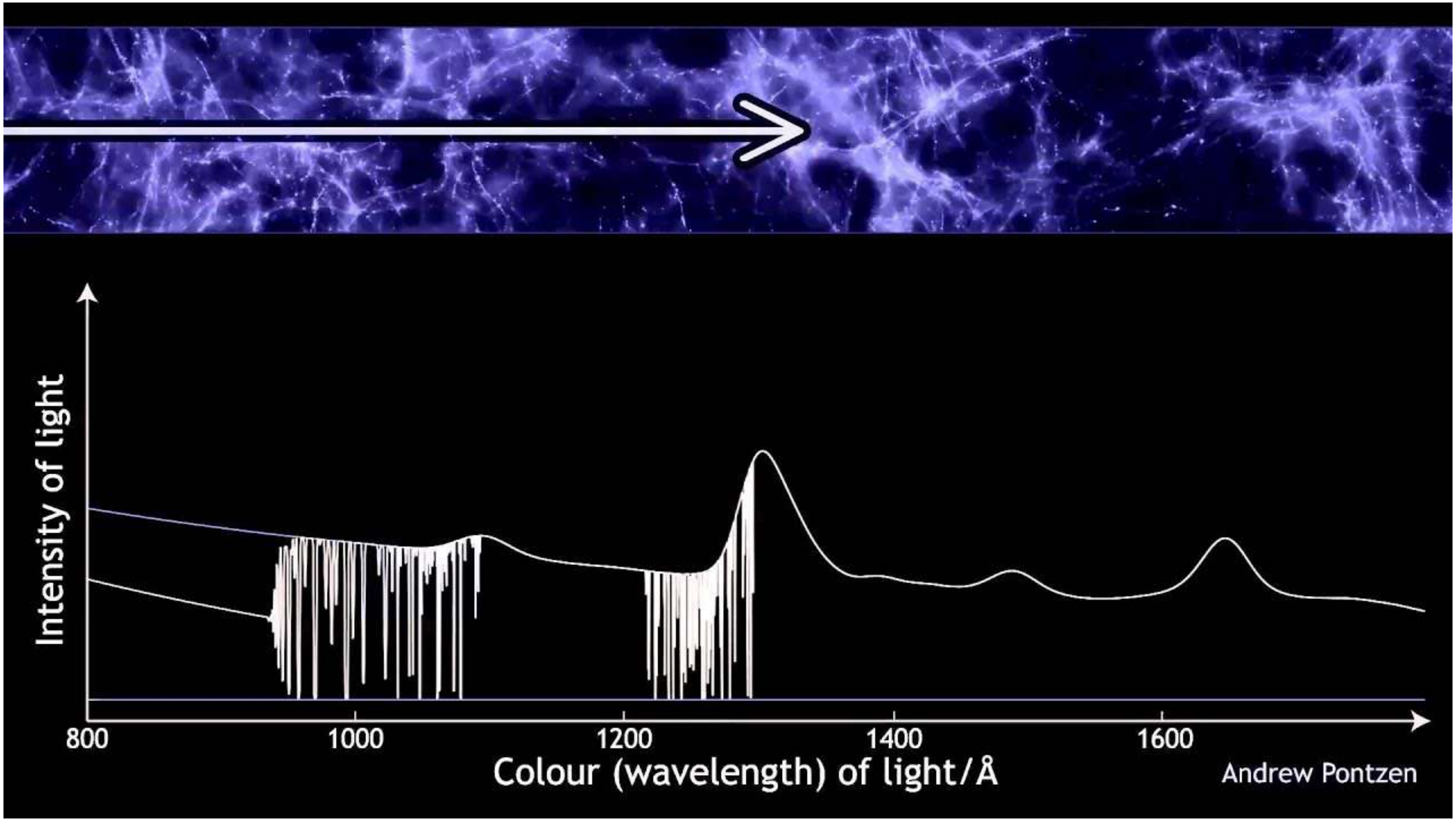
What is a Lyman-alpha forest ?



https://www.youtube.com/watch?v=6Bn7Ka0Tjjw

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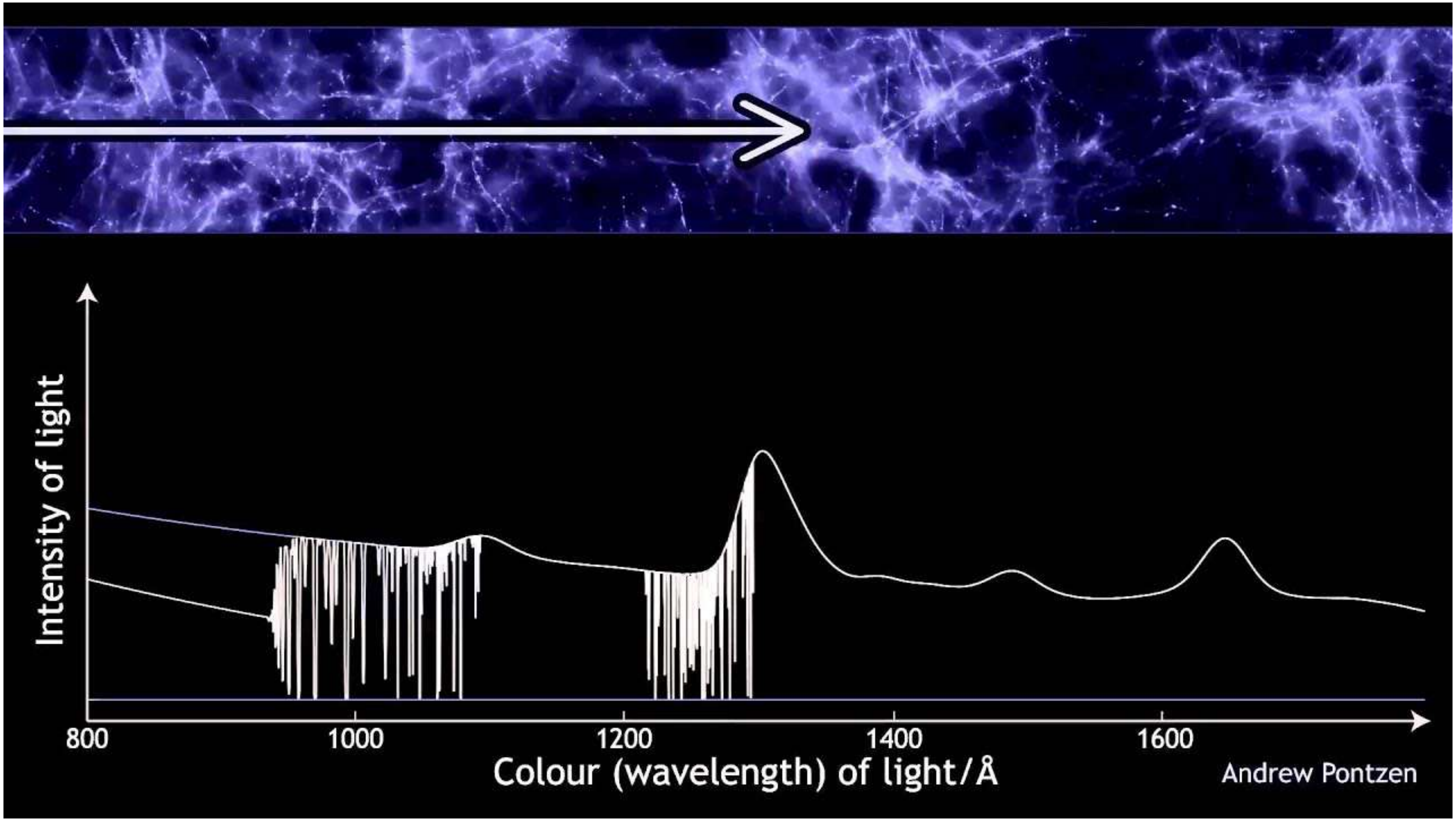
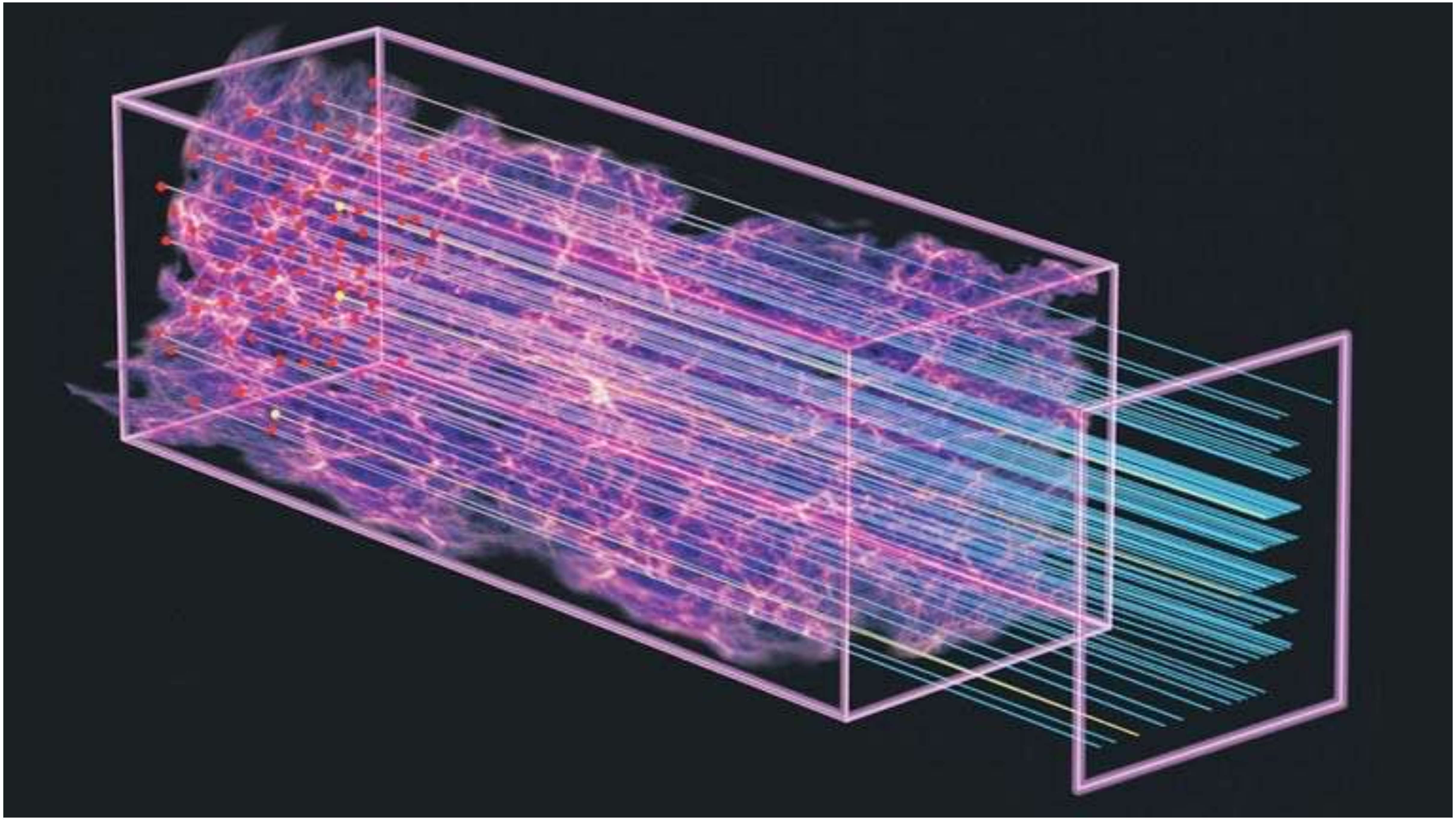


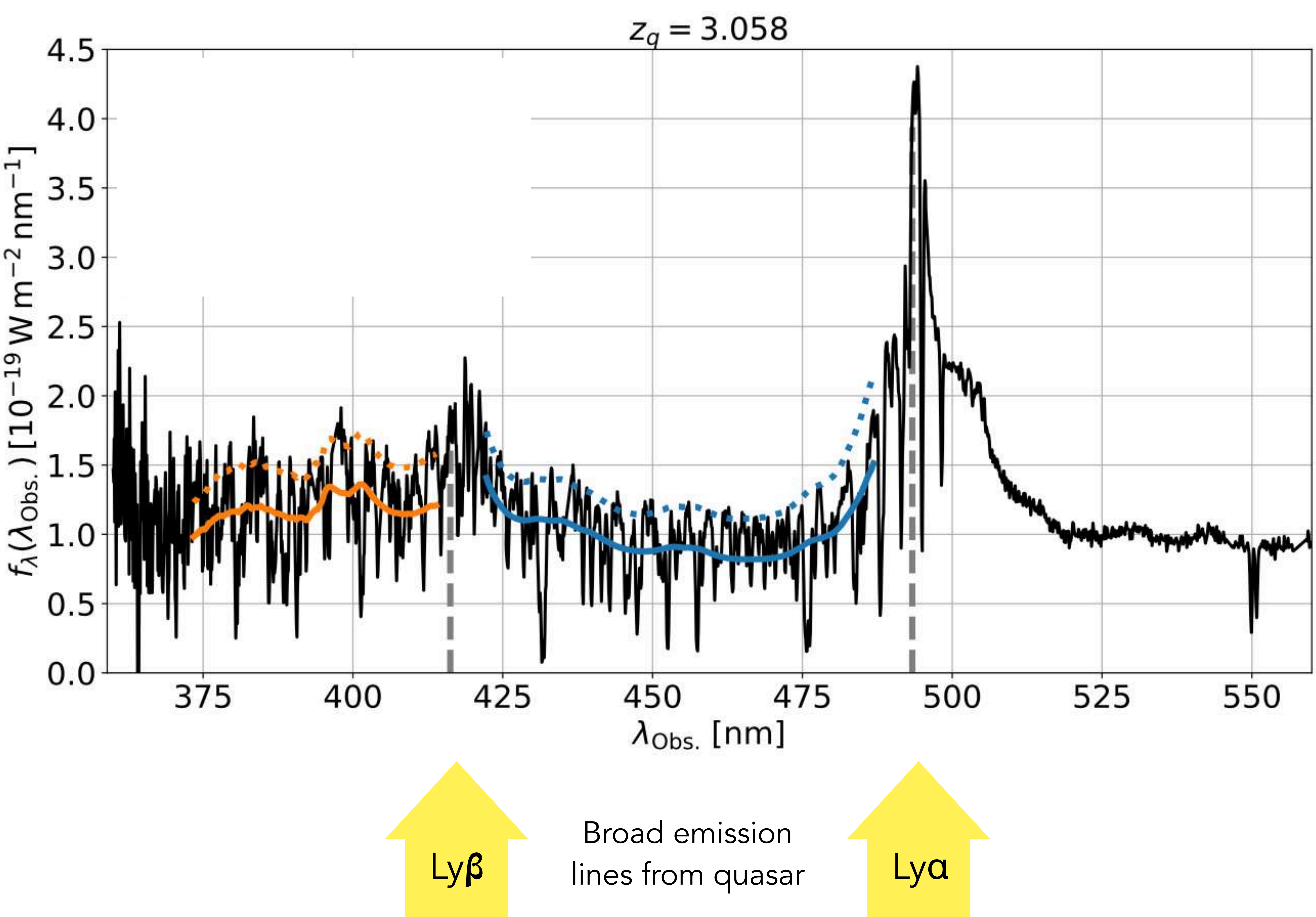
https://www.youtube.com/watch?v=6Bn7Ka0Tjjw

A survey of Lyman-alpha forests can map the neutral hydrogen fluctuations $\delta_{\mathrm{Ly}\alpha}(\vec{x})$

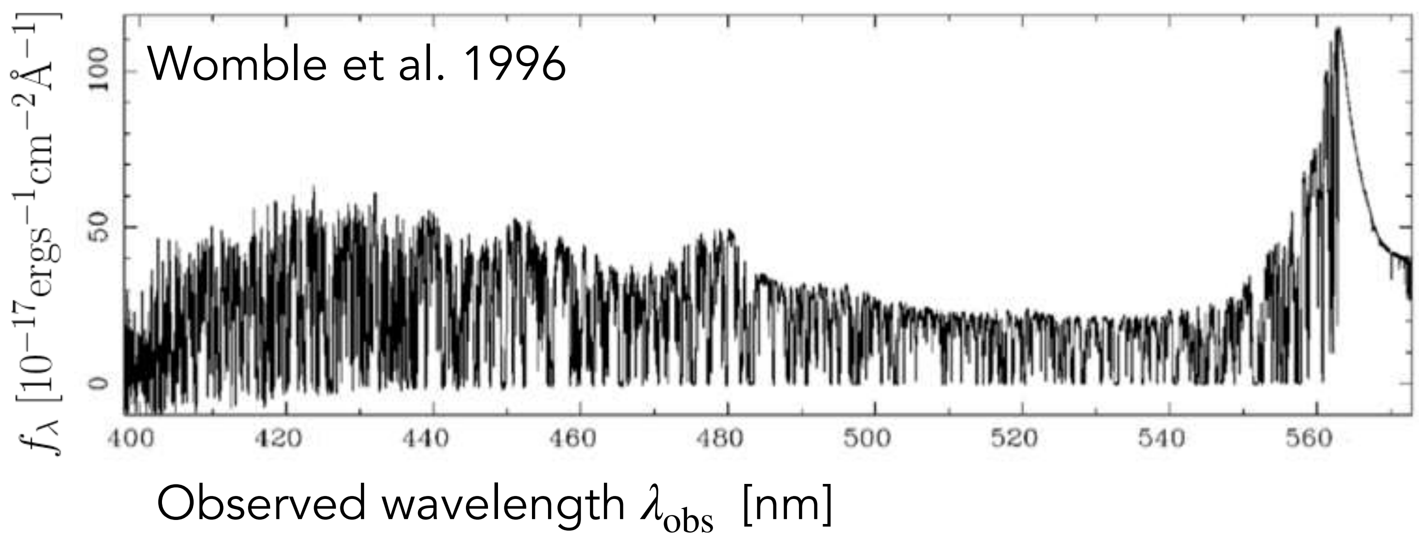


A Lyman-alpha forest

A high signal-to-noise ratio quasar spectrum from eBOSS

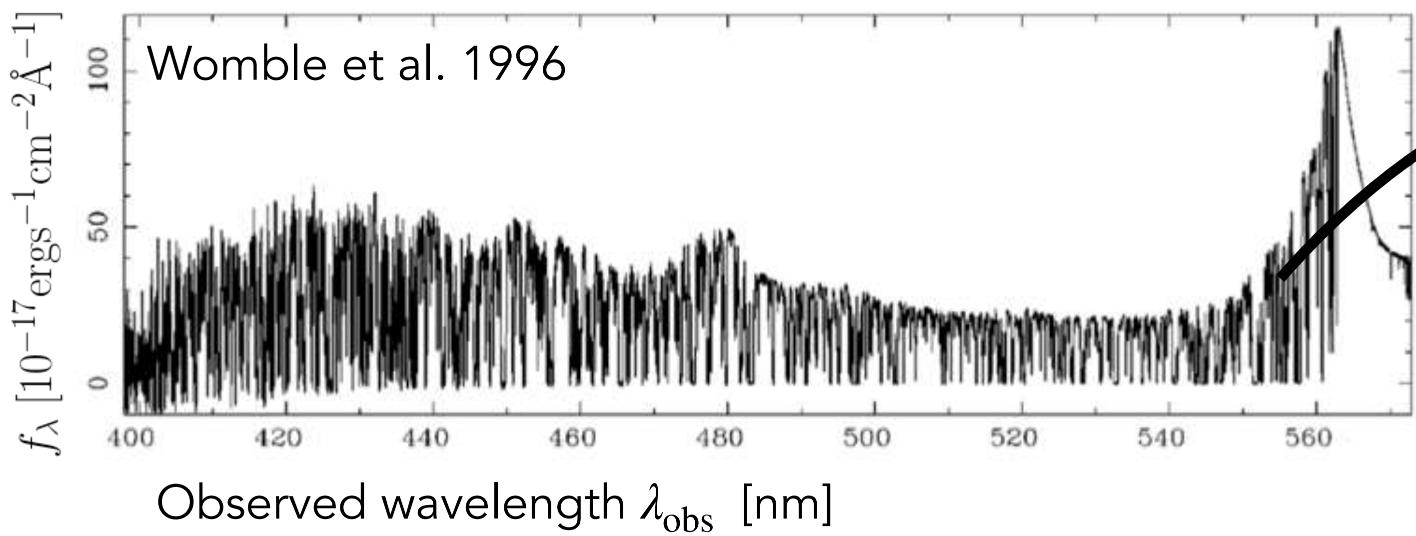


From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)} = \mathrm{e}^{-\tau(\lambda)}$$

From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



Flux

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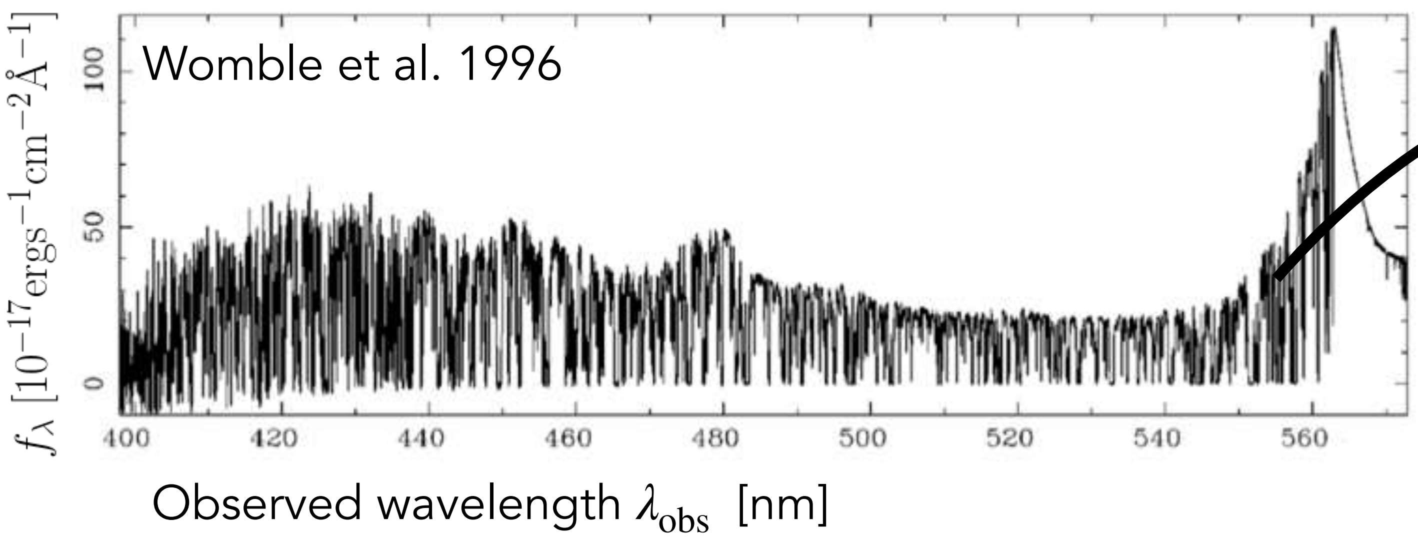
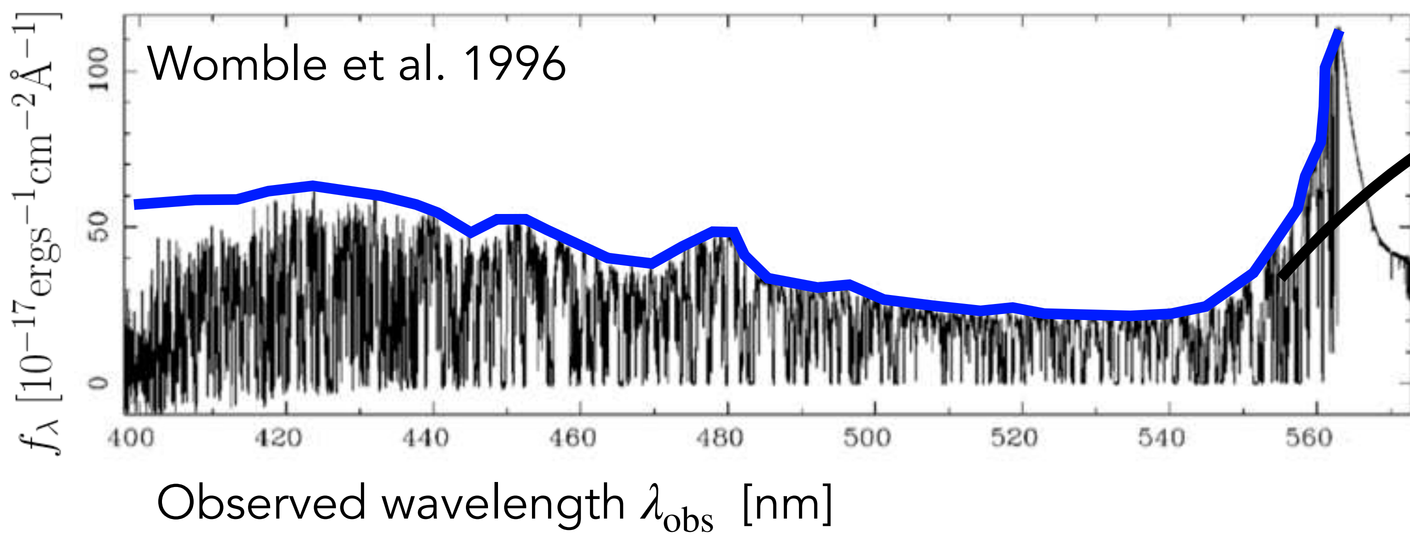


Flux

$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)} = \mathrm{e}^{-\tau(\lambda)}$$

Transmission

From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



Flux

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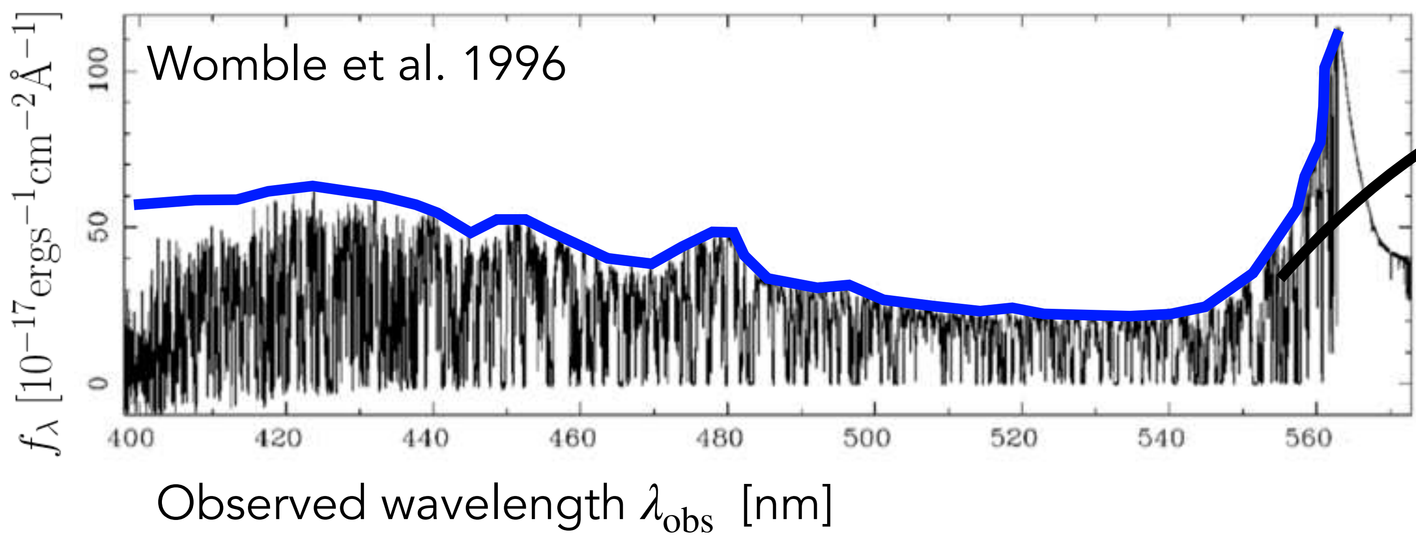
Transmission

Continuum

From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



Flux

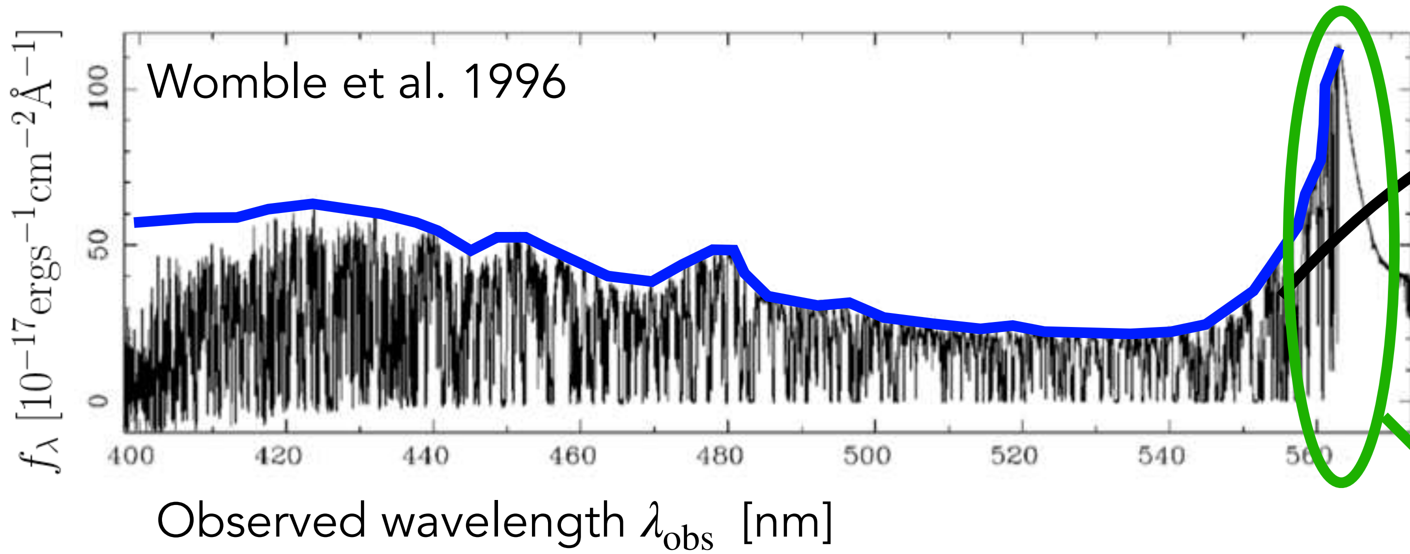
Optical Depth

$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)} = e^{-\tau(\lambda)}$$

Transmission

Continuum

From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



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Transmission

Continuum

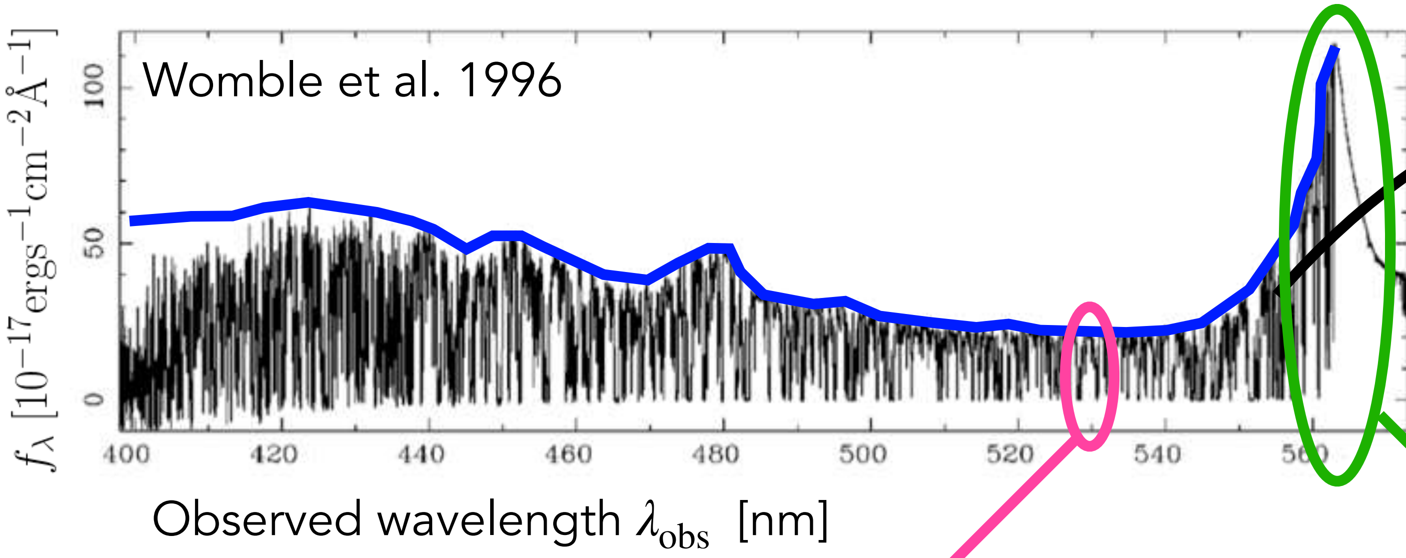
Lyman-alpha **emission** from quasar at :

$z_{QSO} = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{Ly}\alpha} - 1$

z_{QSO} = 5618 Å / 1216 Å - 1

z_{QSO} = 3.62

From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



Flux

Optical Depth

$$F(\lambda) = \frac{f(\lambda)}{C(\lambda)} = e^{-\tau(\lambda)}$$

Transmission

Continuum

Absorption from intergalactic medium at :

$z_{\mathrm{line}} = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{Ly}\alpha} - 1$

z_{line} = 5300 Å / 1216 Å -1

z_{line} = 3.36

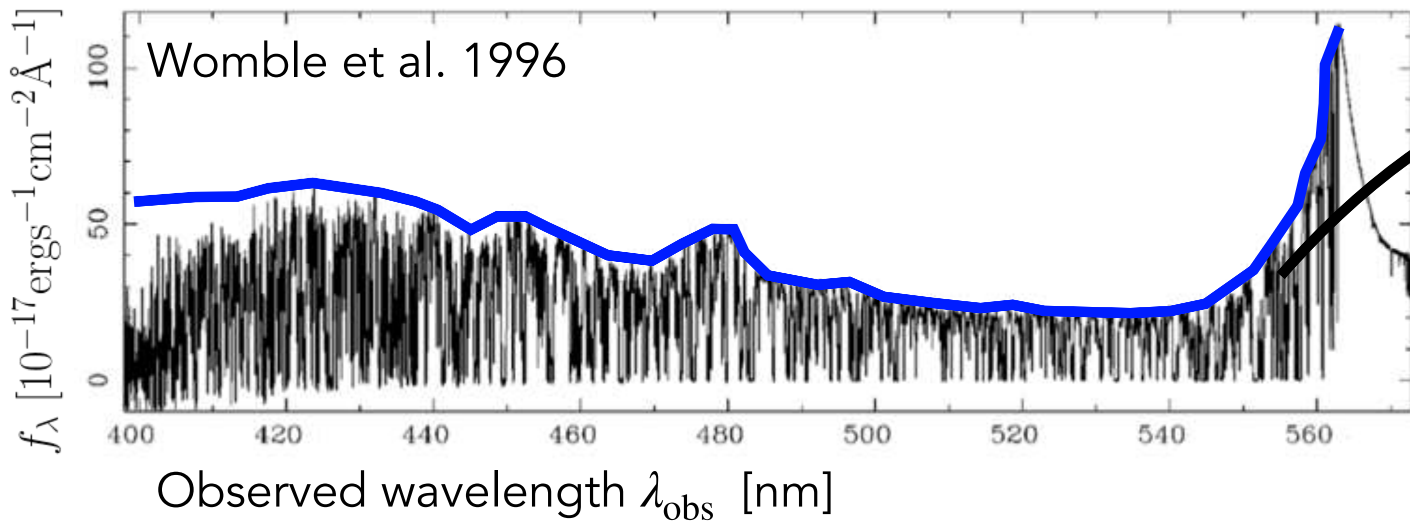
Lyman-alpha **emission** from quasar at :

$z_{\mathrm{QSO}} = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{Ly}\alpha} - 1$

z_{QSO} = 5618 Å / 1216 Å - 1

z_{QSO} = 3.62

From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



Flux

Optical Depth

$$F(\lambda_j) = \frac{f(\lambda_j)}{C(\lambda_j)} = e^{-\tau(\lambda_j)}$$

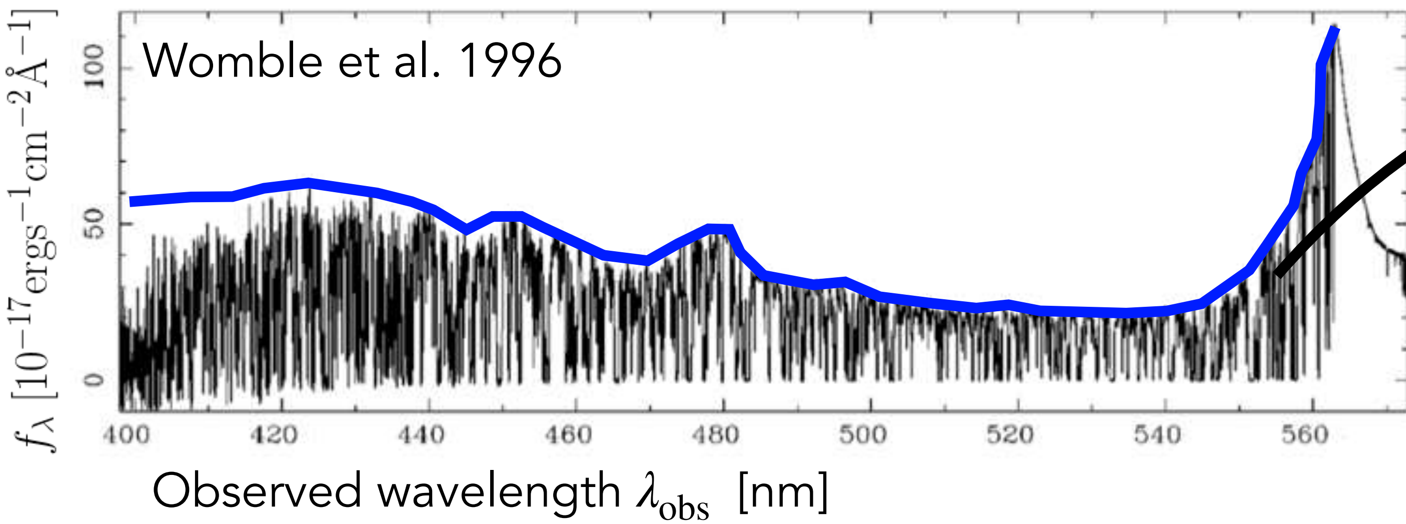
Transmission

Continuum

We want $\delta_F(\lambda) = \dfrac{F(\lambda)}{\langle F\rangle(\lambda)} - 1$

Just like for galaxies

From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



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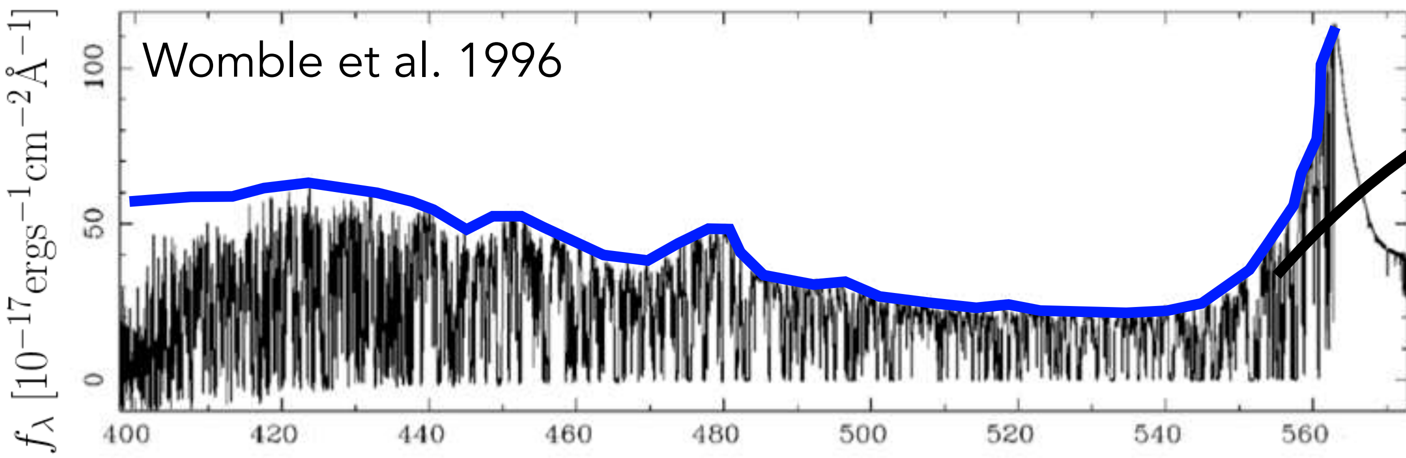
Transmission

Continuum

We want $\delta_F(\lambda) = \dfrac{F(\lambda)}{\langle F \rangle(\lambda)} - 1$

Just like for galaxies $\delta_g(\vec{x}) = \dfrac{n_g(\vec{x})}{\bar{n}_g} - 1$

From fluxes $\{f_j\}$ to $\delta_{\mathrm{Ly}\alpha}(\vec{x})$



Flux

Optical Depth

$$F(\lambda_j) = \frac{f(\lambda_j)}{C(\lambda_j)} = e^{-\tau(\lambda_j)}$$

Transmission

Continuum

We want $$\delta_F(\lambda) = \frac{F(\lambda)}{\langle F\rangle(\lambda)} - 1$$

Just like for galaxies $$\delta_g(\vec{x}) = \frac{n_g(\vec{x})}{\bar{n}_g} - 1$$

Methods to obtain $C(\lambda)$

- Use measurements of $\langle F\rangle(\lambda)$ from high-resolution spectra (Lee et al. 2012) or from **stacks** (Kamble et al. 2020)
- Build **PCA** templates for $C(\lambda_{\mathrm{rest}})$ from low-z high-res spectra (Suzuki et al. 2006)
- Use a **flux P.D.F.** from mocks (Busca et al. 2013)
- Give up and do the simplest thing for now (du Mas des Bourboux et al. 2020)

$$\hat{\delta}_F(\lambda) = \frac{f(\lambda)}{(a_q + b_q\lambda)\bar{C}(\lambda_{\mathrm{rest}})} - 1$$

where $\bar{C}(\lambda_{\mathrm{rest}})$ is a universal function

Weights of $\delta_{\mathrm{Ly}\alpha}(\vec{x})$

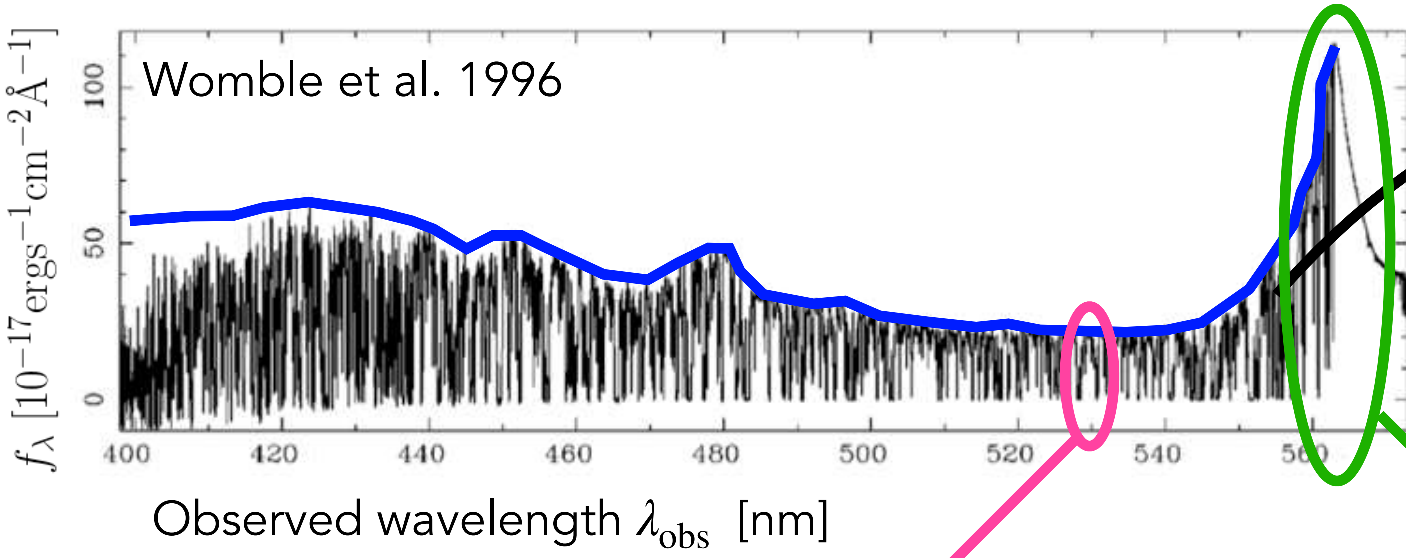
$$\hat{\delta}_F(\lambda) = \frac{f(\lambda)}{(a_q + b_q \log \lambda)\bar{C}(\lambda_{\mathrm{rest}})} - 1 \qquad w = 1/\sigma^2_{\delta_F}$$

Total variance of $\hat{\delta}_F$

$$\sigma^2_{\delta_F}(\lambda) = \sigma^2_{\mathrm{noise}}(\lambda) + \sigma^2_{\mathrm{LSS}}(\lambda) + \sigma^2_{\mathrm{cont}}(\lambda)$$

- $\sigma^2_{\mathrm{noise}}$ → From instrument and spectra
- σ^2_{LSS} → Analogous to σ_8 for galaxies
- σ^2_{cont} → Systematics?

A Lyman-alpha forest : some definitions



Flux

Optical Depth

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Transmission

Continuum

Absorption from IGM at :

$z_{\mathrm{line}} = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{Ly}\alpha} - 1$

z_{line} = 5300 Å / 1216 Å -1

z_{line} = 3.36

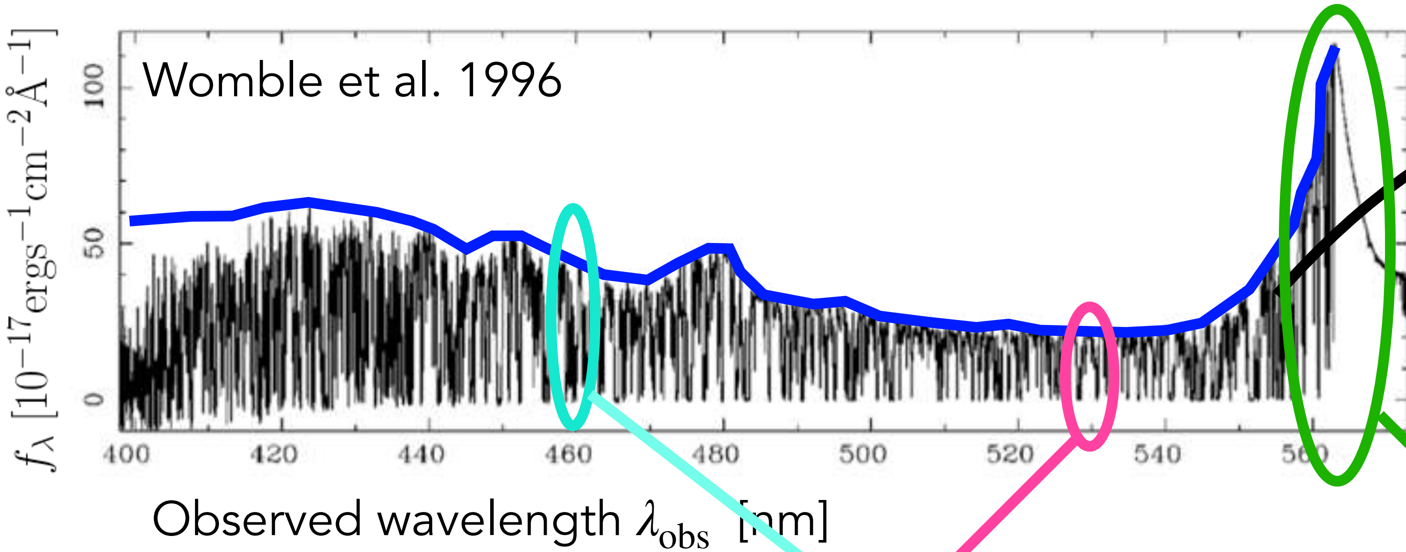
Lyman-α **emission** from quasar at :

$z_{\mathrm{QSO}} = \lambda_{\mathrm{obs}}/\lambda_{\mathrm{Ly}\alpha} - 1$

z_{QSO} = 5618 Å / 1216 Å - 1

z_{QSO} = 3.62

A Lyman-alpha forest : some definitions



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Lyman-α or Lyman-β **absorption** ?

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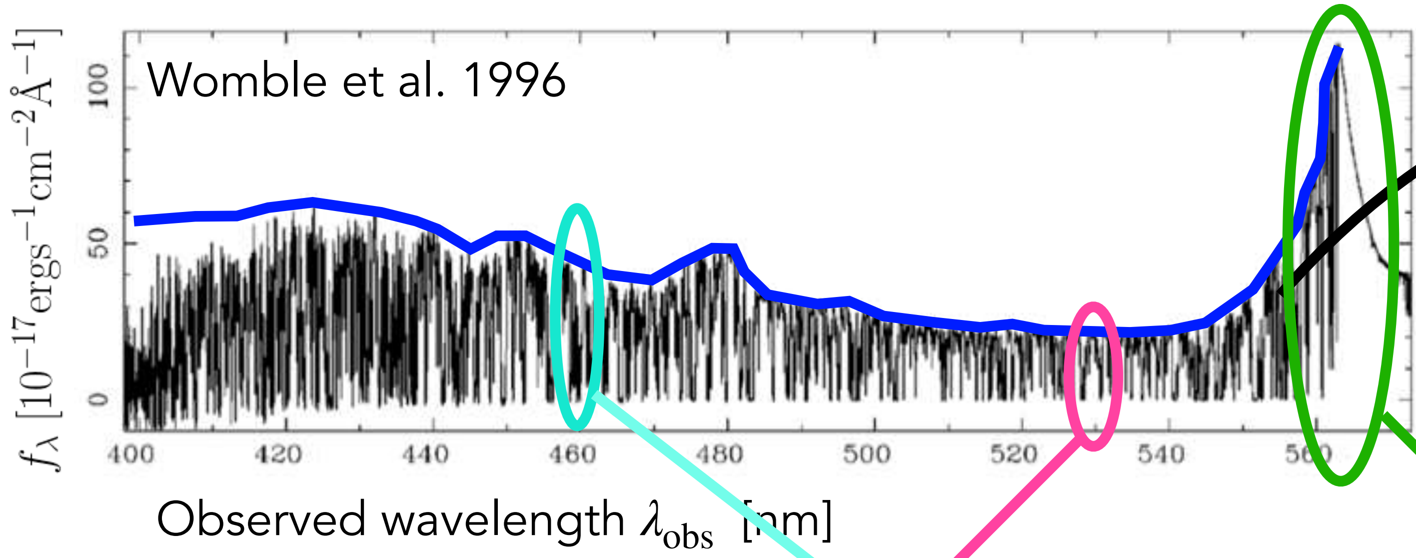

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$z_{line} = \lambda_{obs}/\lambda_{Ly\alpha}$ - 1

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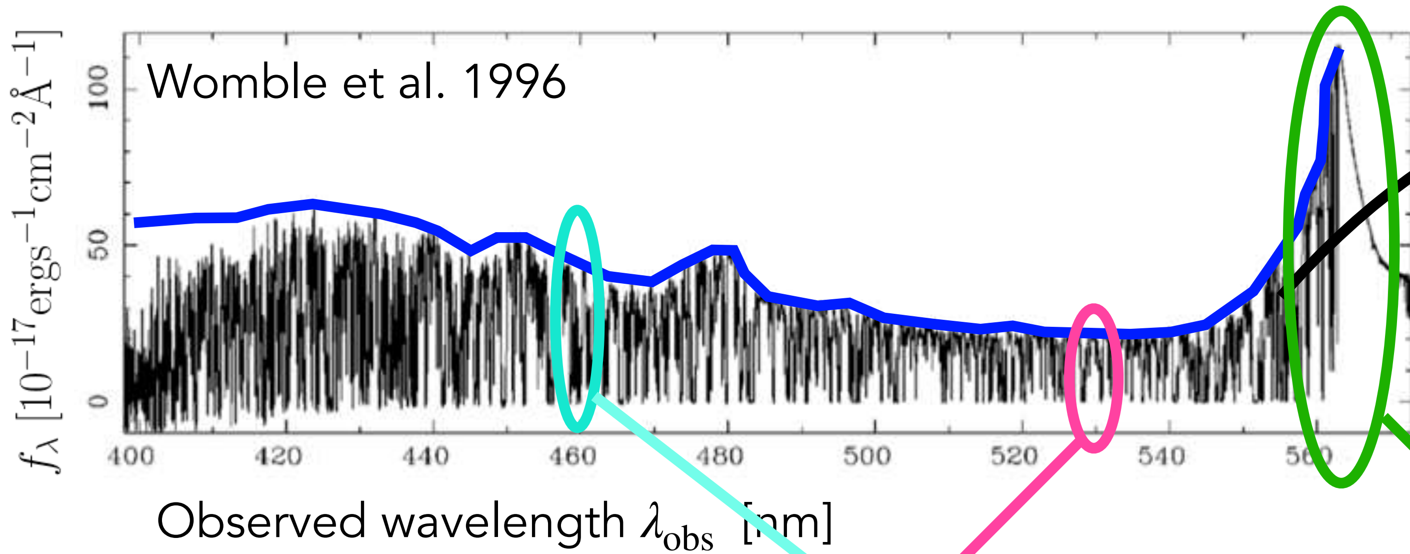
z_{line} = 2.78

A Lyman-alpha forest : some definitions



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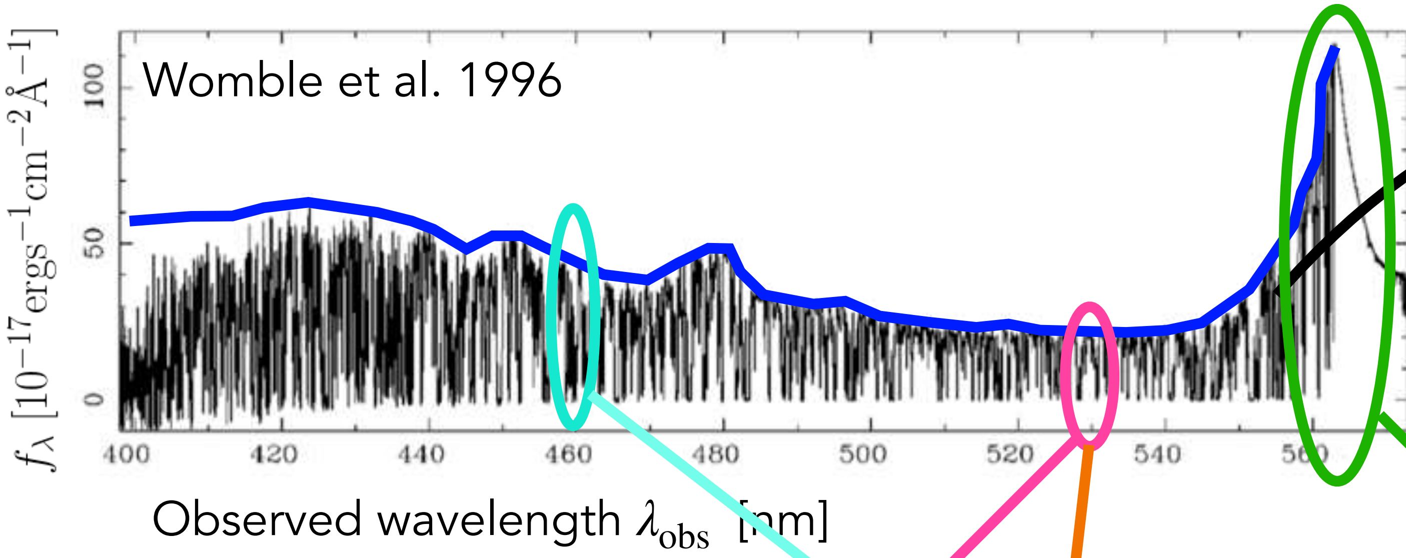
A Lyman-alpha forest : some definitions



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Lyman-α or **metal absorption (Si, C, N, etc)** ?

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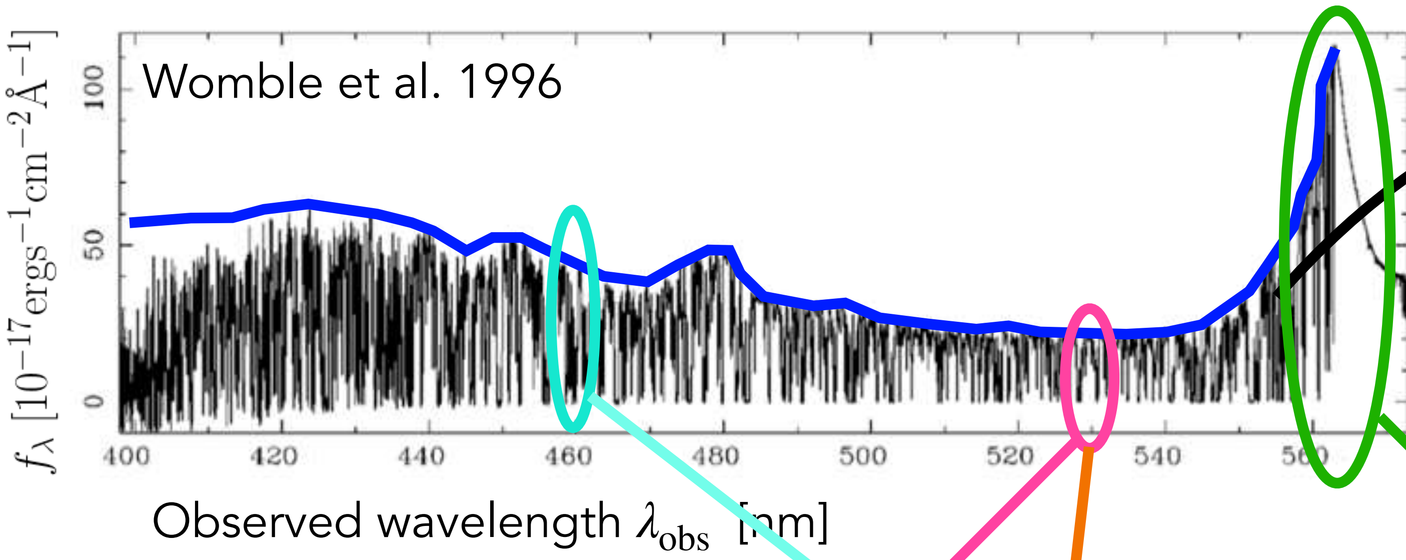

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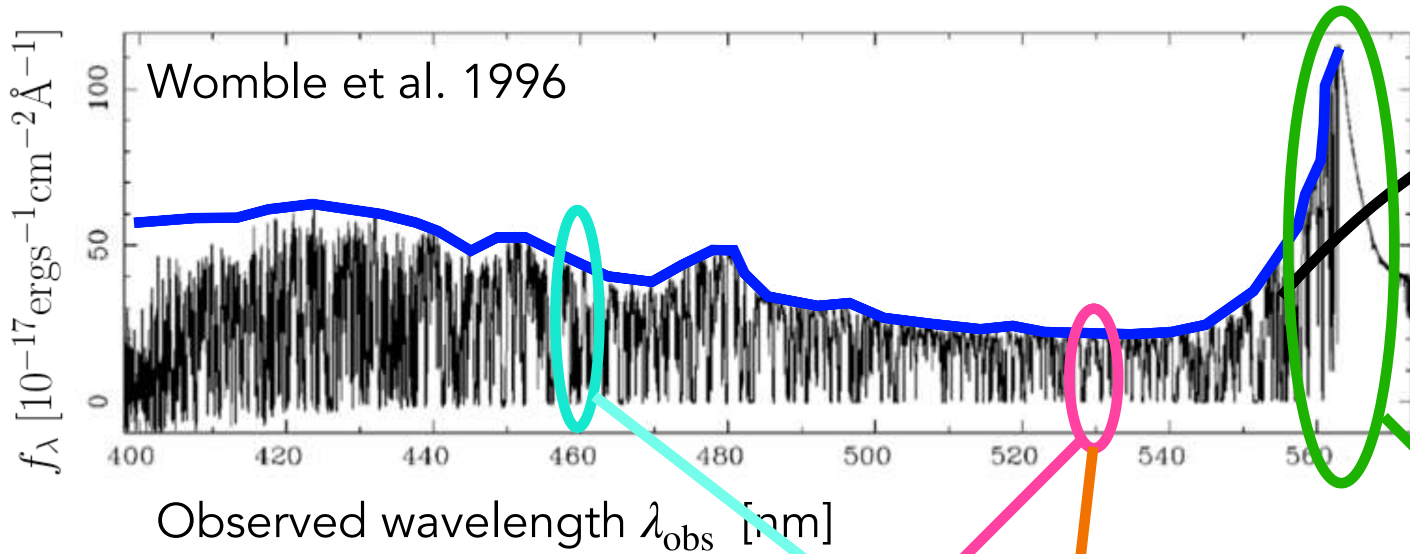
Lyman-α or **metal absorption (Si, C, N, etc)** ?

$z_{line} = \lambda_{obs}/\lambda_{SiIII}$ - 1

z_{line} = 5300 Å / 1207 Å -1

z_{line} = 3.39

A Lyman-alpha forest : some definitions



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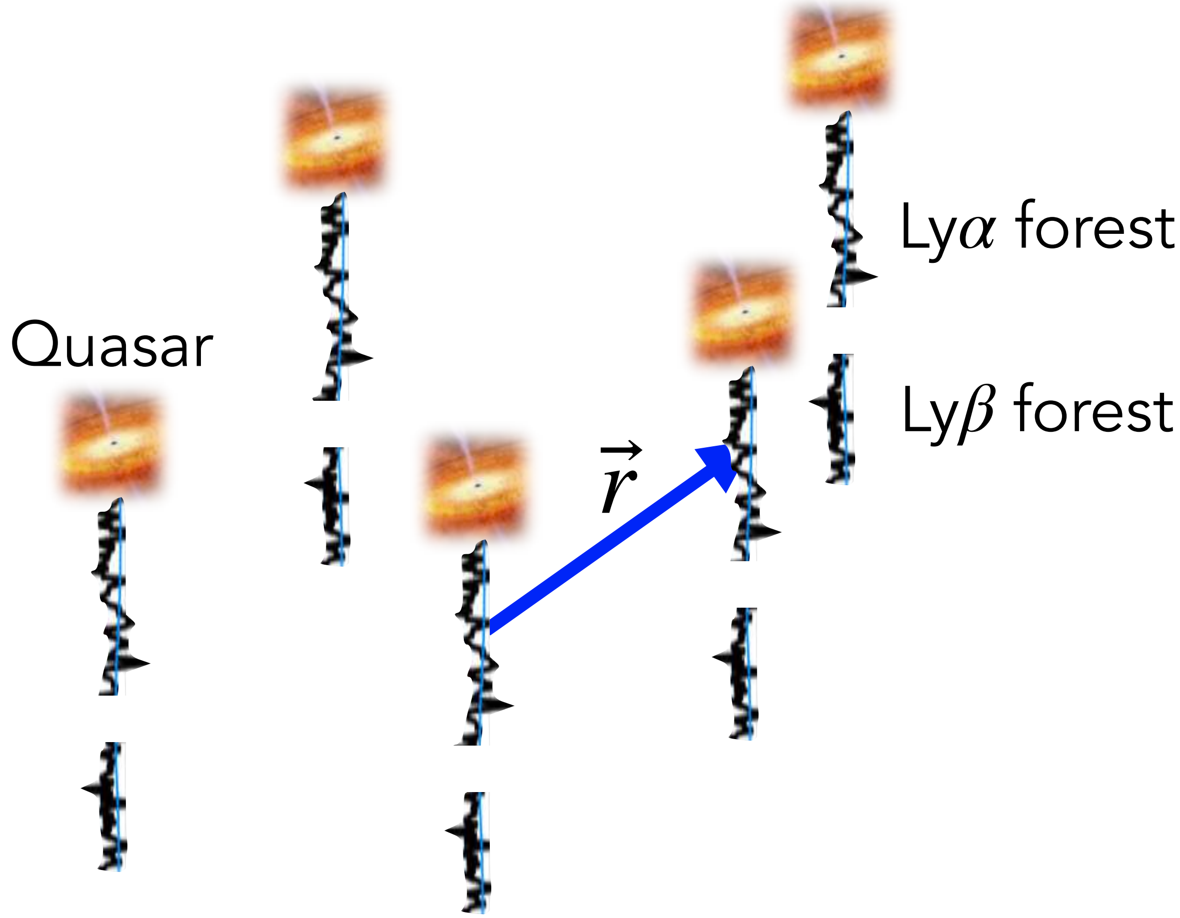
Lyβ or metal absorption is indistinguishable from Lyα !

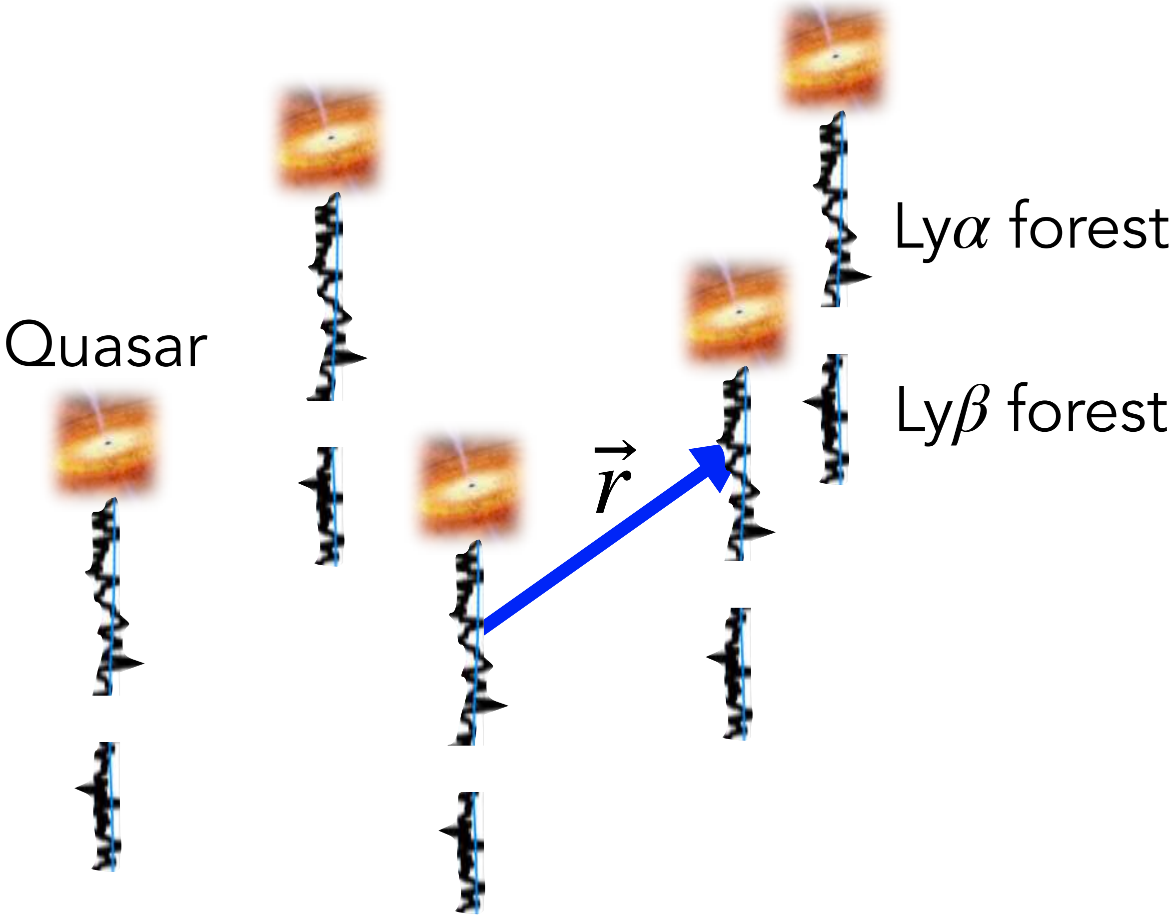
Correlation functions

Case of **Lyman-α forests**

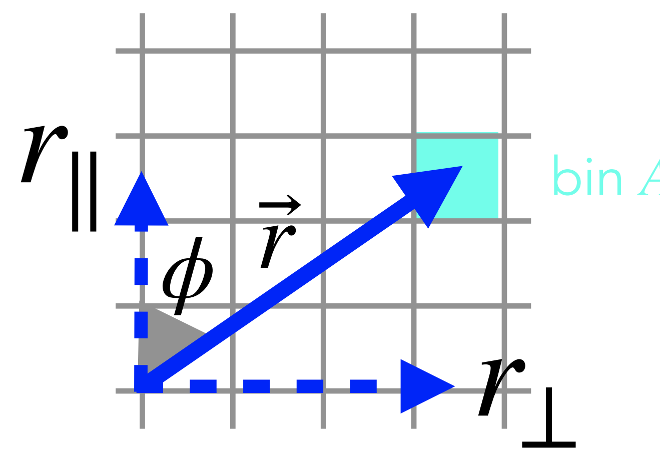


Correlation functions

Case of **Lyman-α forests**



$$\hat{\xi}(A) = \frac{\sum_{(i,j)\in A} w_i w_j \delta_i \delta_j}{\sum_{(i,j)\in A} w_i w_j}$$

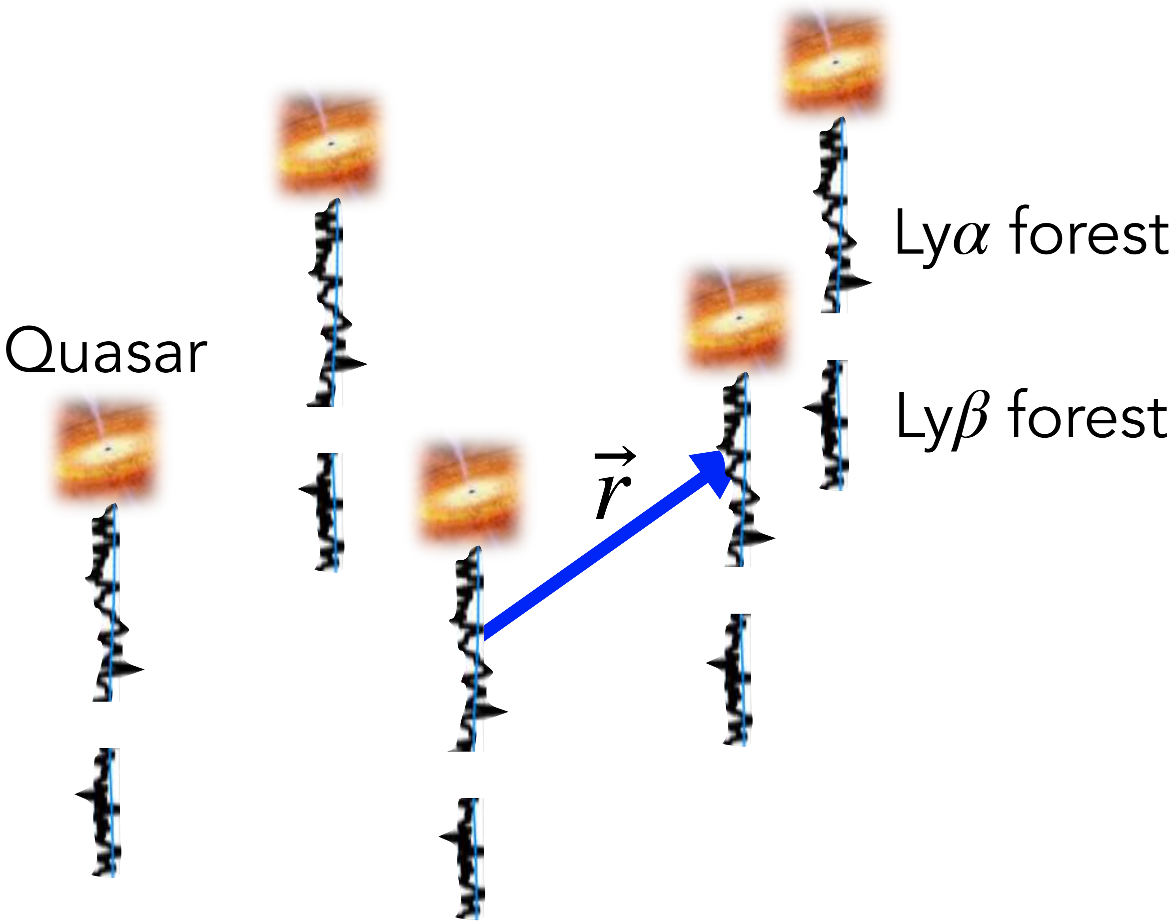


$$\mu = \frac{r_{\parallel}}{|\vec{r}\,|} = \cos\phi$$

"Intensity map" : no need for randoms!

Correlation functions

Case of **Lyman-α forests**



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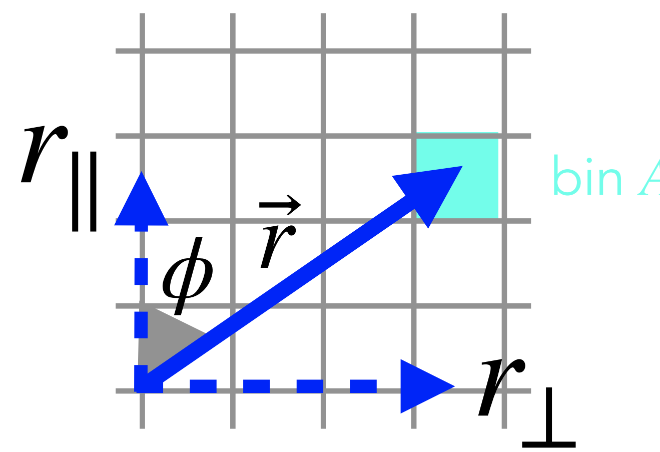

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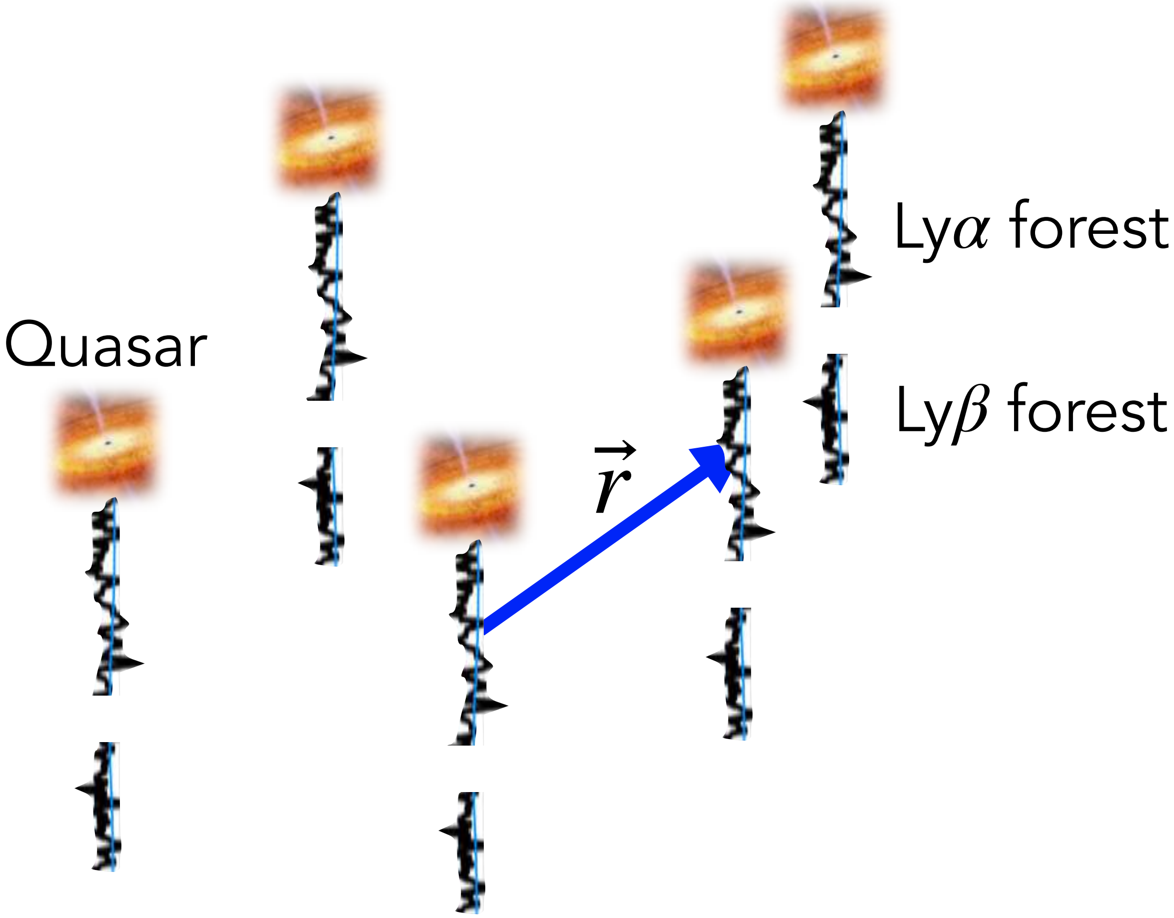
"Intensity map" : no need for randoms!

Tracers :

- Lyα (in Lyα forest)
- QSOs
- Lyα (in Lyβ forest)
- Lyβ (in Lyβ forest)
- metals (CIV, SiIV, MgII...)

Correlation functions

Case of **Lyman-α forests**



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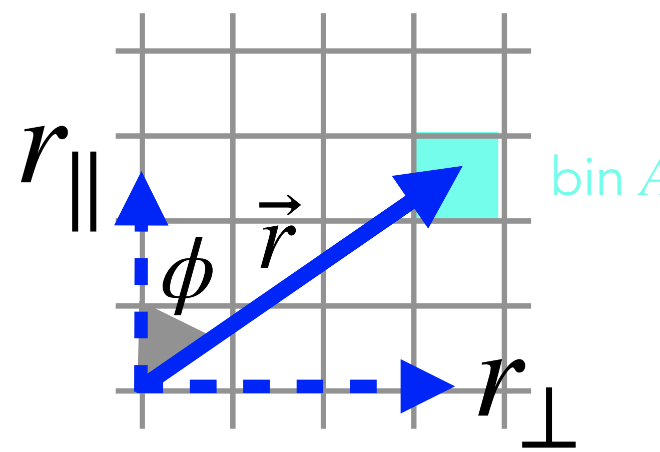

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- Lyα (in Lyα forest)
- QSOs
- Lyα (in Lyβ forest)
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- metals (CIV, SiIV, MgII...)

Auto and cross-correlations

Lyα (in Lyα forest) x Lyα (in Lyα forest)

Lyα (in Lyα forest) x QSOs

Lyα (in Lyβ forest) x Lyα (in Lyα forest)

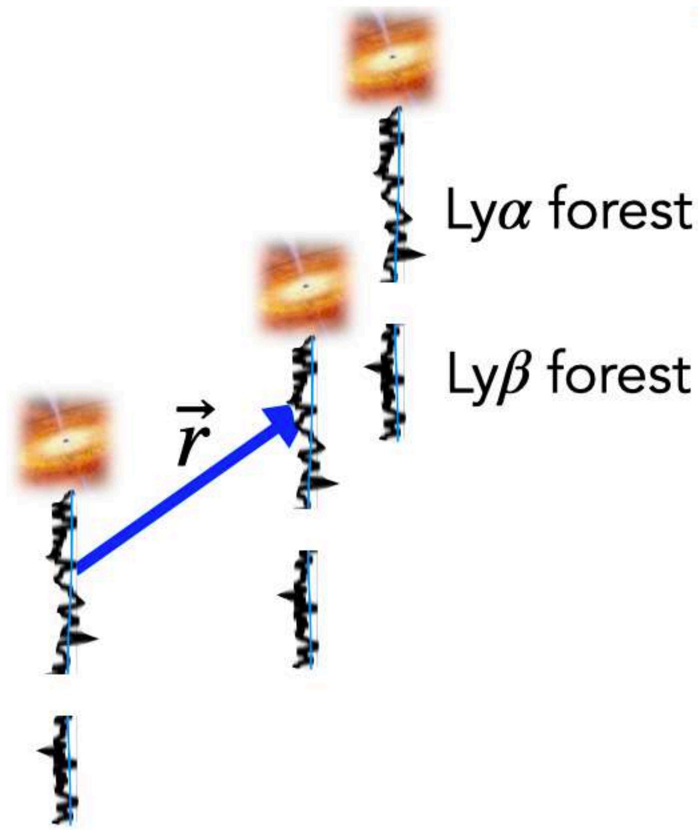
Lyα (in Lyβ forest) x QSOs

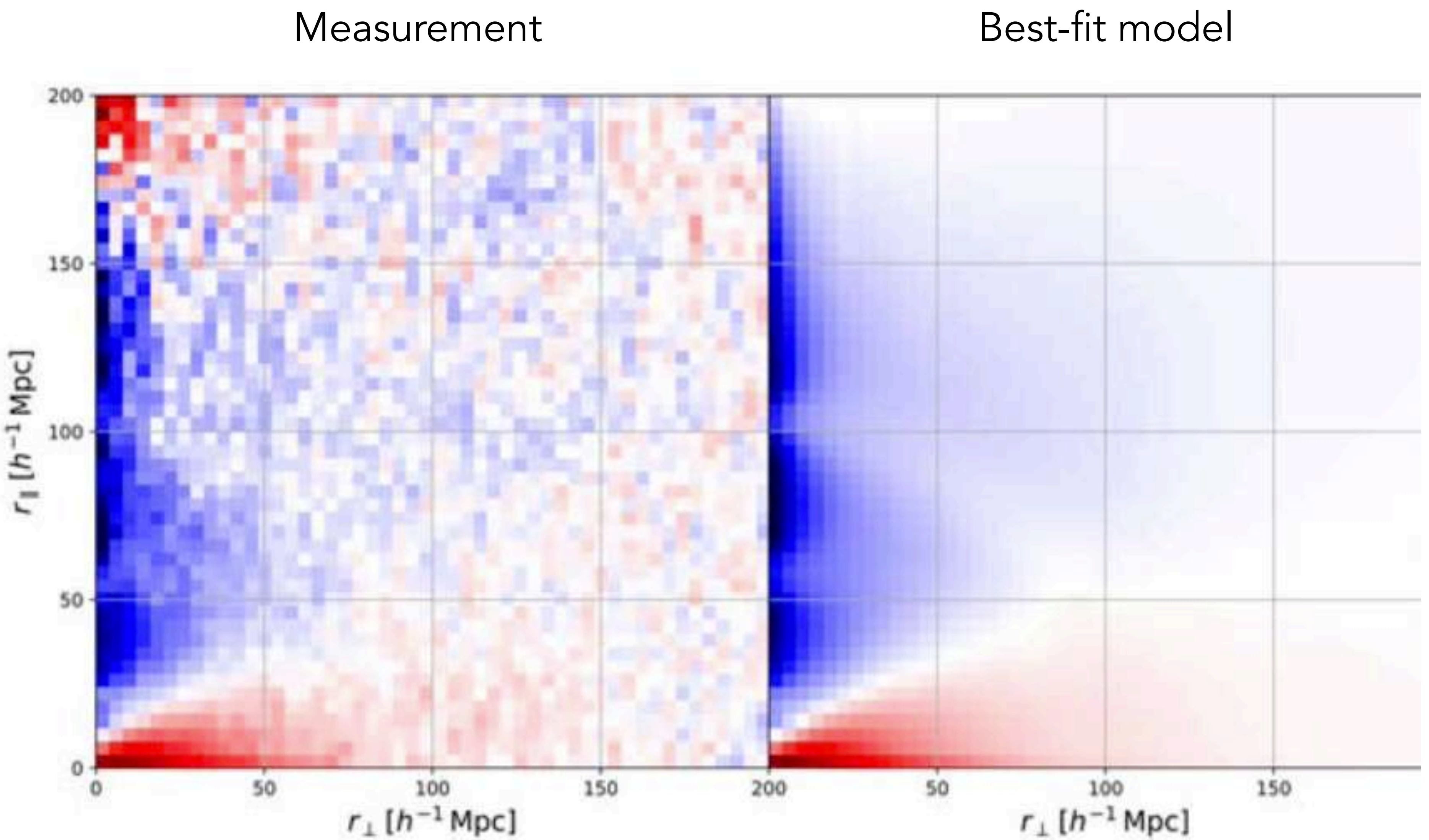
Others do not add much

Correlation functions

Auto-correlation of Lyα (in the Lyα forest)

$$\xi(\vec{r}_A) = \langle \delta_{\mathrm{Ly}\alpha}\delta_{\mathrm{Ly}\alpha} \rangle$$





eBOSS Lyα-forests

du Mas des Bourboux et al. 2020

Correlation functions

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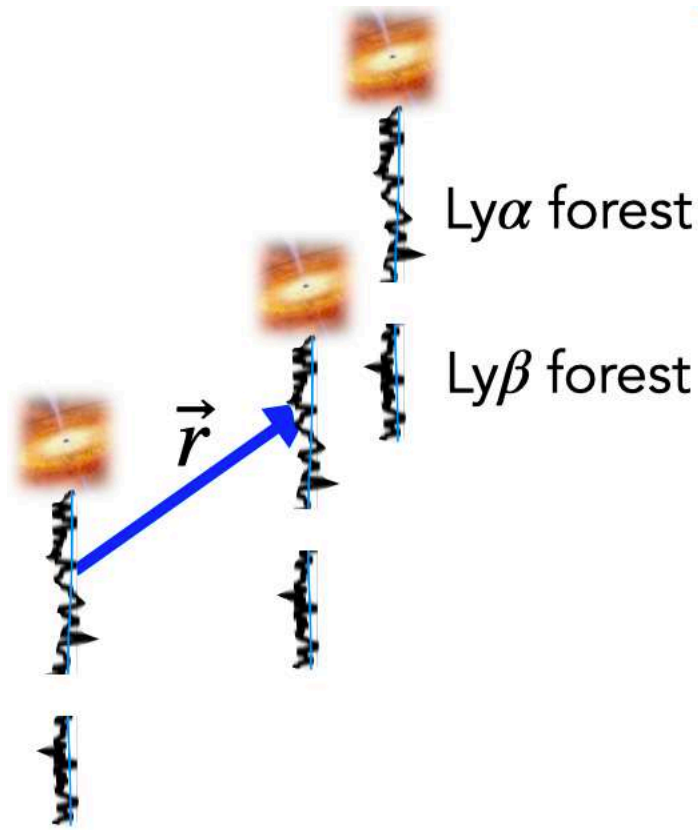

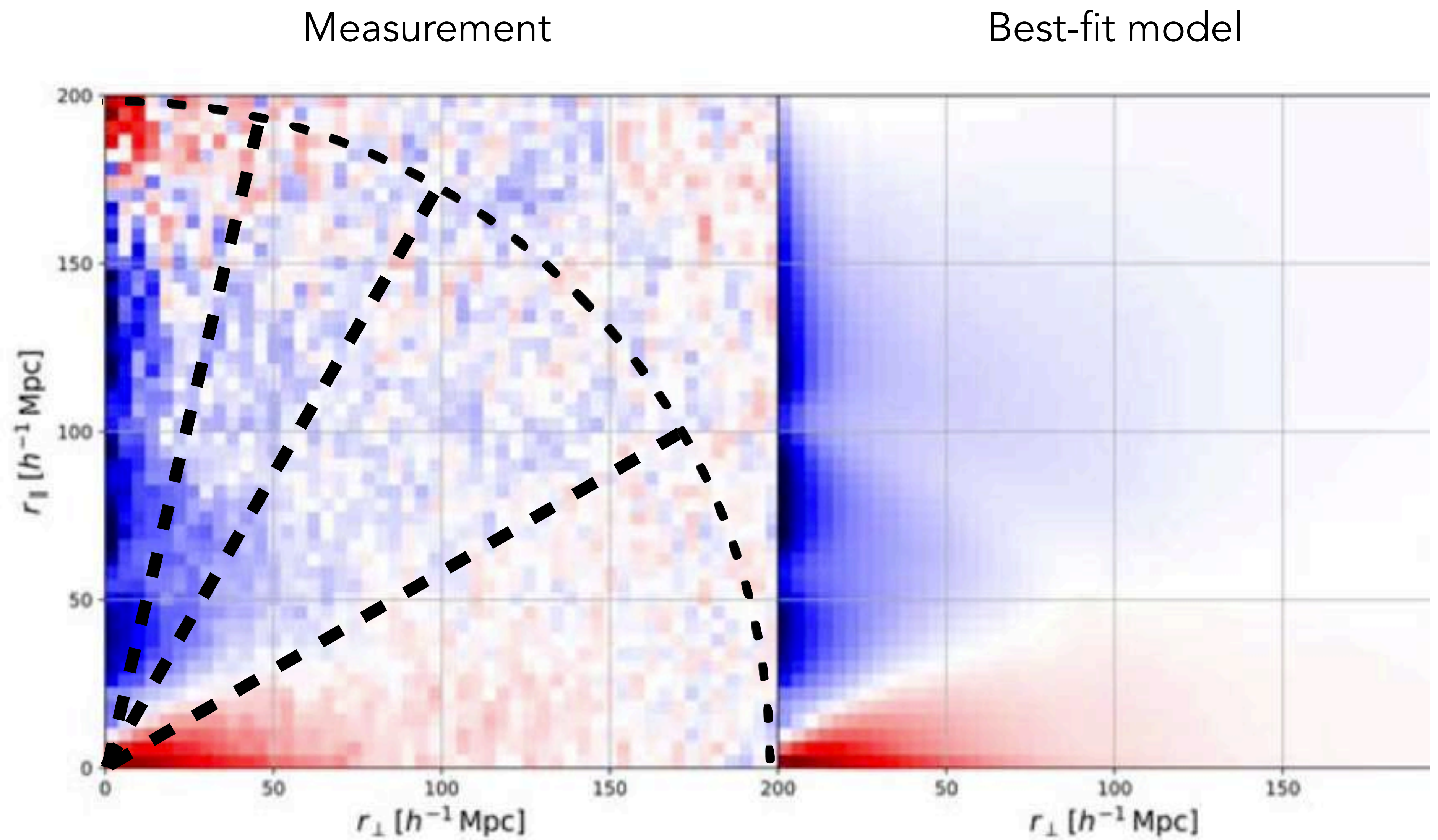

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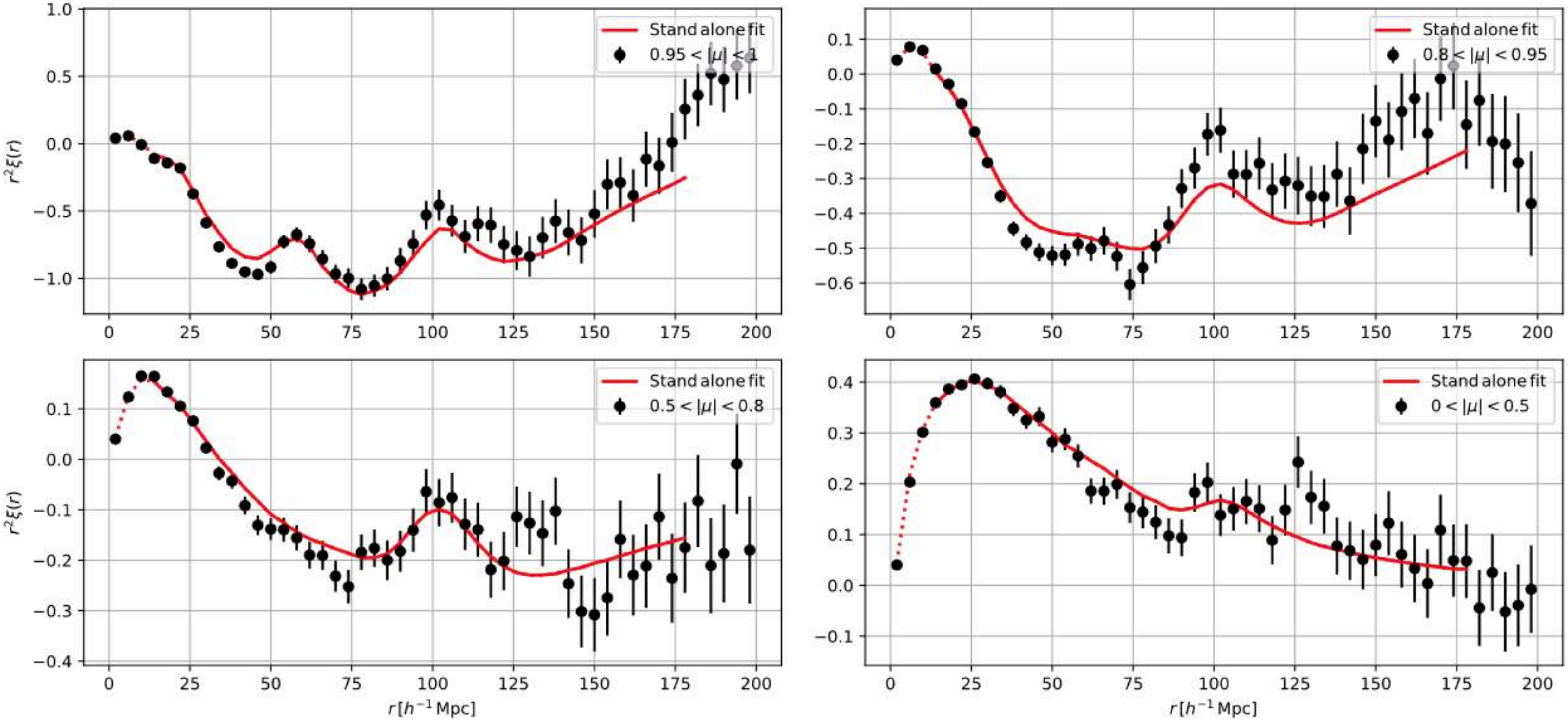
Radial wedge

Not-so-radial wedge



Not-so-transverse wedge

Transverse wedge

eBOSS Lyα-forests

<u>du Mas des Bourboux et al. 2020</u>

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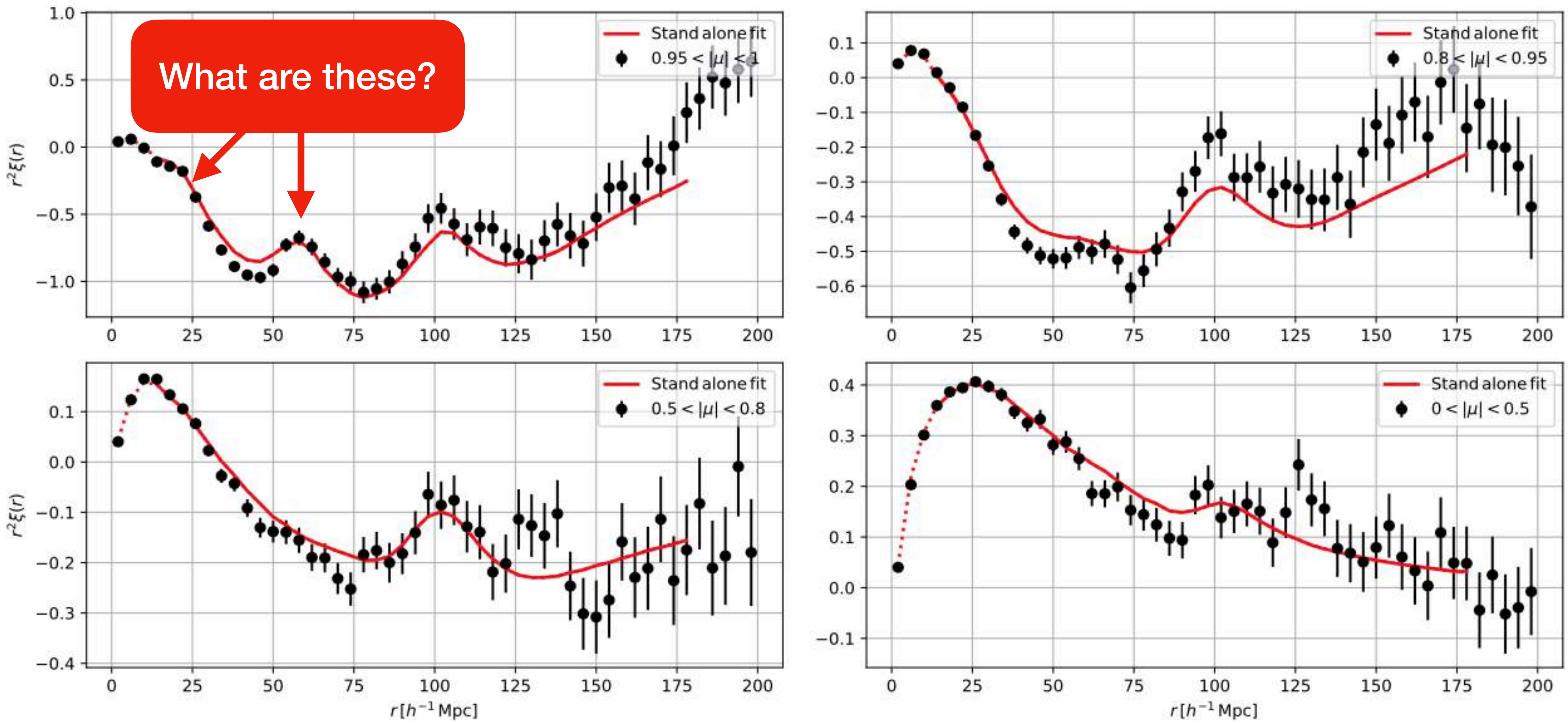

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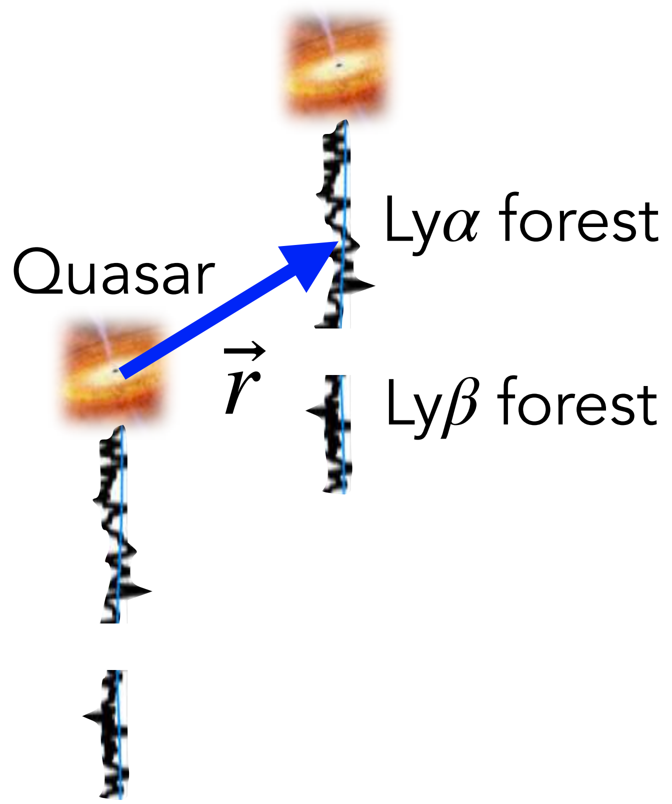
eBOSS Lyα-forests

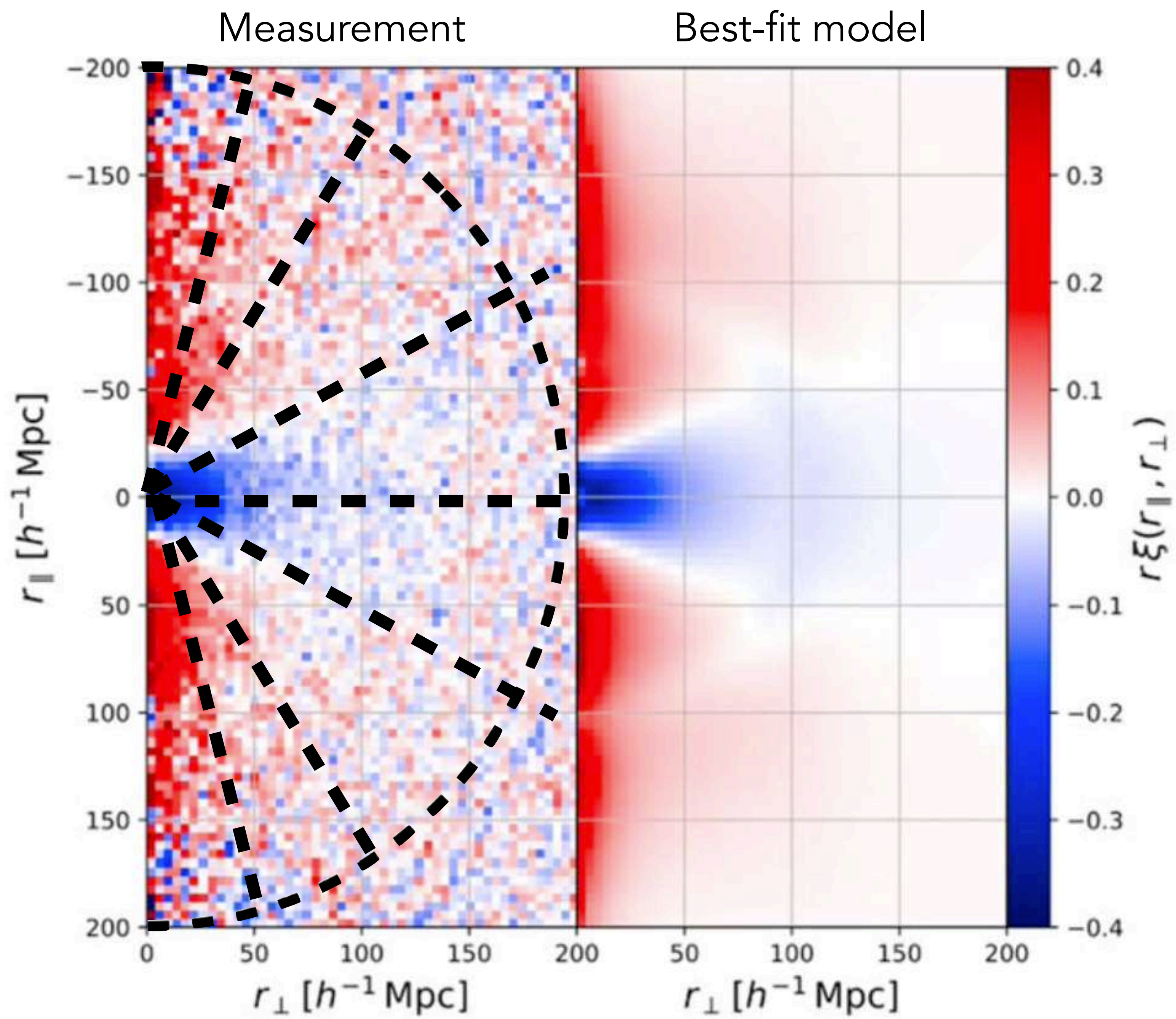
du Mas des Bourboux et al. 2020

Correlation functions

Cross-correlation of Lyα (in the Lyα forest) and QSOs

$$\xi(\vec{r}_A) = \langle \delta_{\mathrm{Ly}\alpha} \delta_{\mathrm{QSO}} \rangle$$





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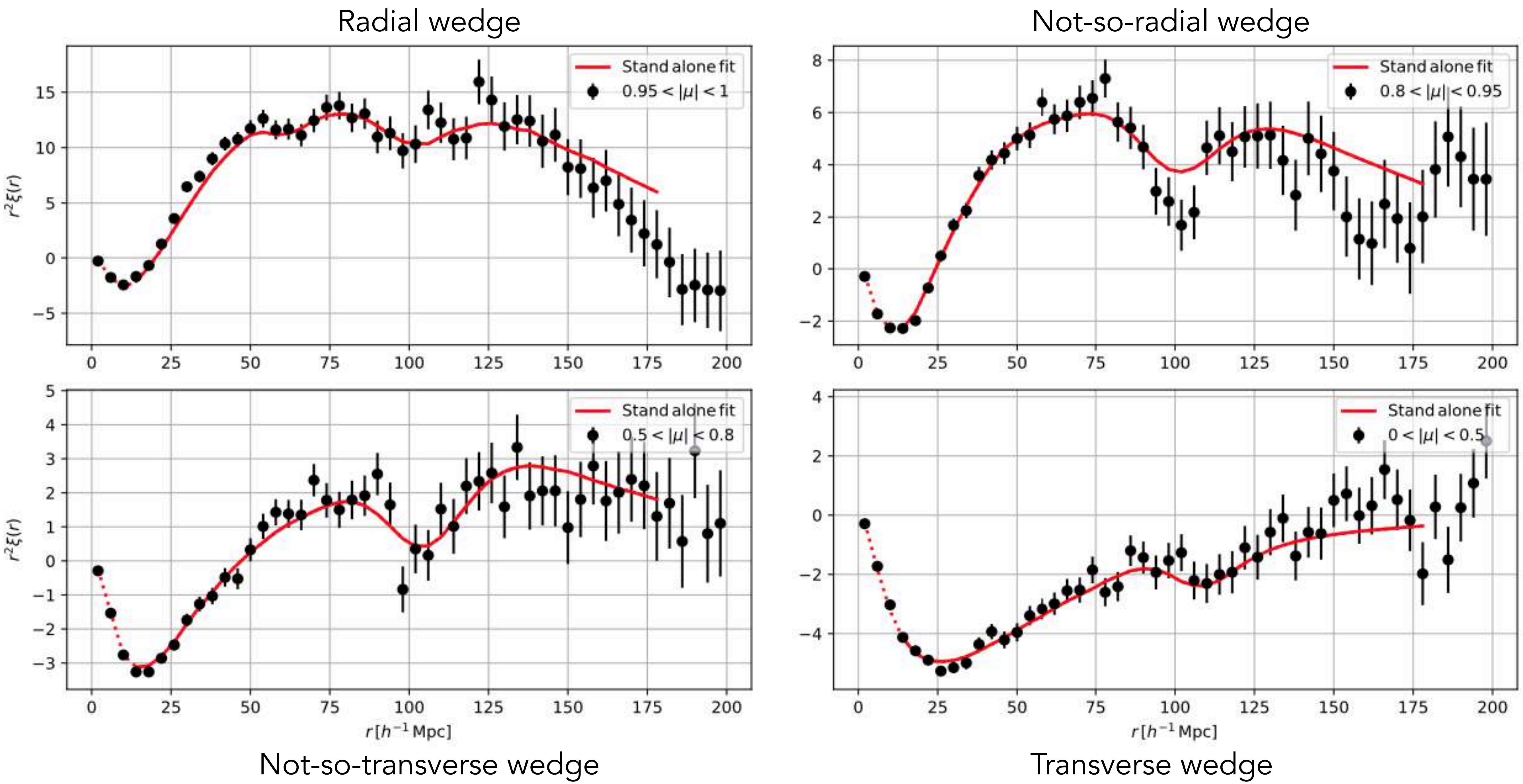

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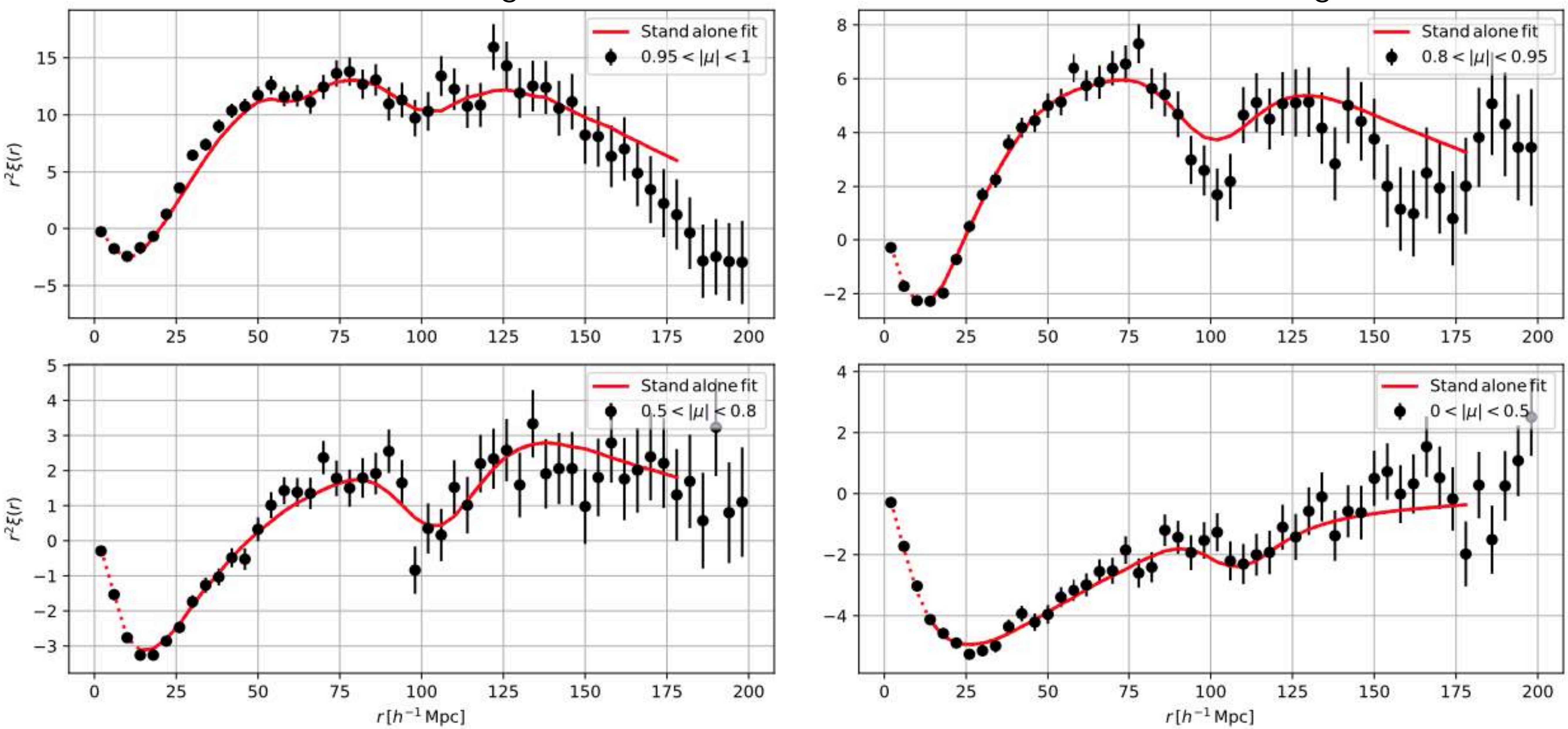

Not-so-transverse wedge

Transverse wedge

Have you noticed the **sign flip** compared to the auto-correlation ?

Covariance matrix

Case of **Lyman-α forests**

$$C_{AB} = \langle \xi_A \xi_B \rangle - \langle \xi_A \rangle \langle \xi_B \rangle$$

Subsamples or 4-pt with Wick Theorem

Covariance matrix

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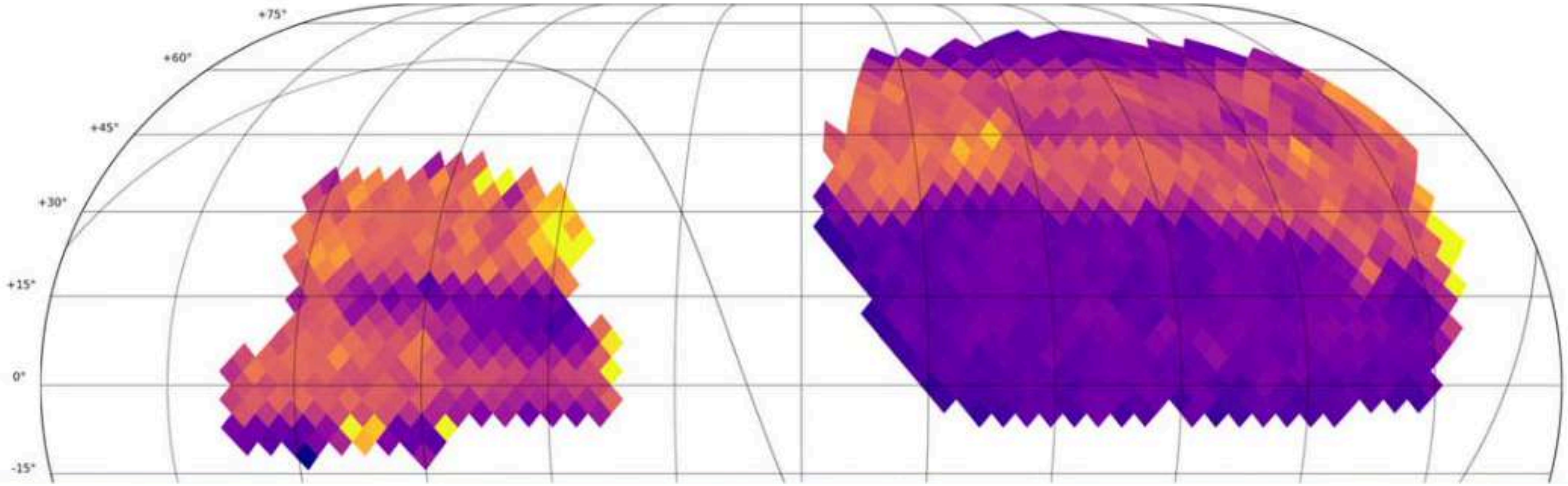
Subsamples or 4-pt with Wick Theorem

Divide the sky into N_s ~1000 sub regions



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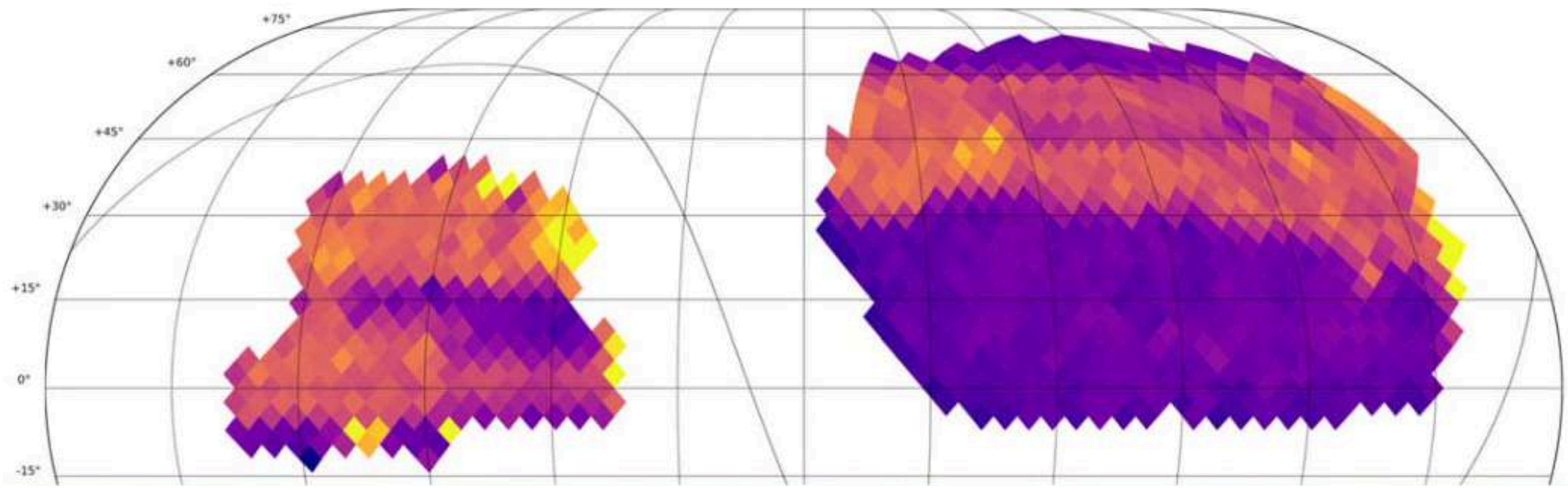

$$C_{AB} \approx \sum_{s}^{N_S} \xi_A^s \xi_B^s$$

Smoothing required for a positive definite matrix (since $N_{samples} < N_{bins}$) !

Covariance matrix

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Subsamples or **4-pt with Wick Theorem**

$$\langle \delta\delta\delta\delta \rangle \approx \sum \langle \delta\delta \rangle \langle \delta\delta \rangle$$

Covariance matrix

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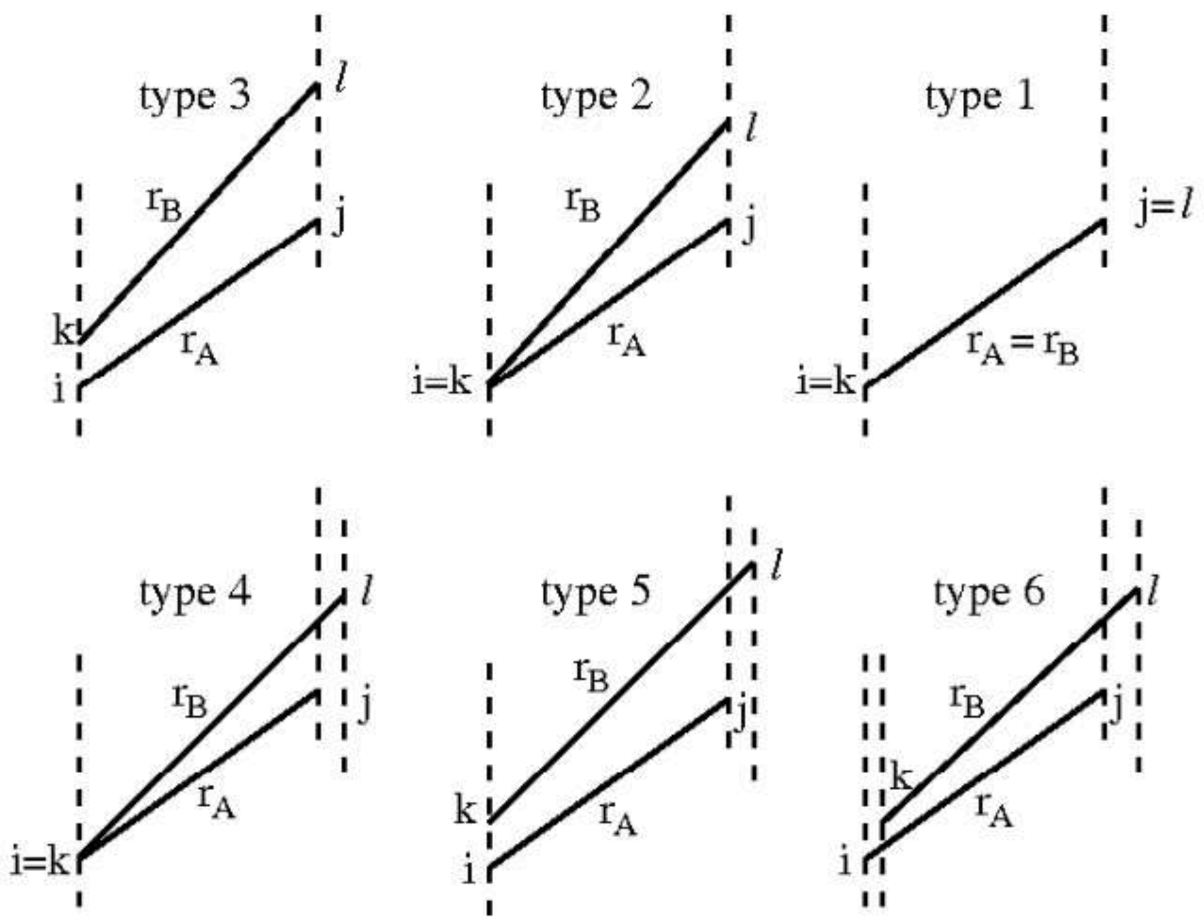
Configurations for auto correlation



Delubac et al. 2015

Covariance matrix

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$$C_{AB} = \langle \xi_A \xi_B \rangle - \langle \xi_A \rangle \langle \xi_B \rangle$$

Subsamples or **4-pt with Wick Theorem**

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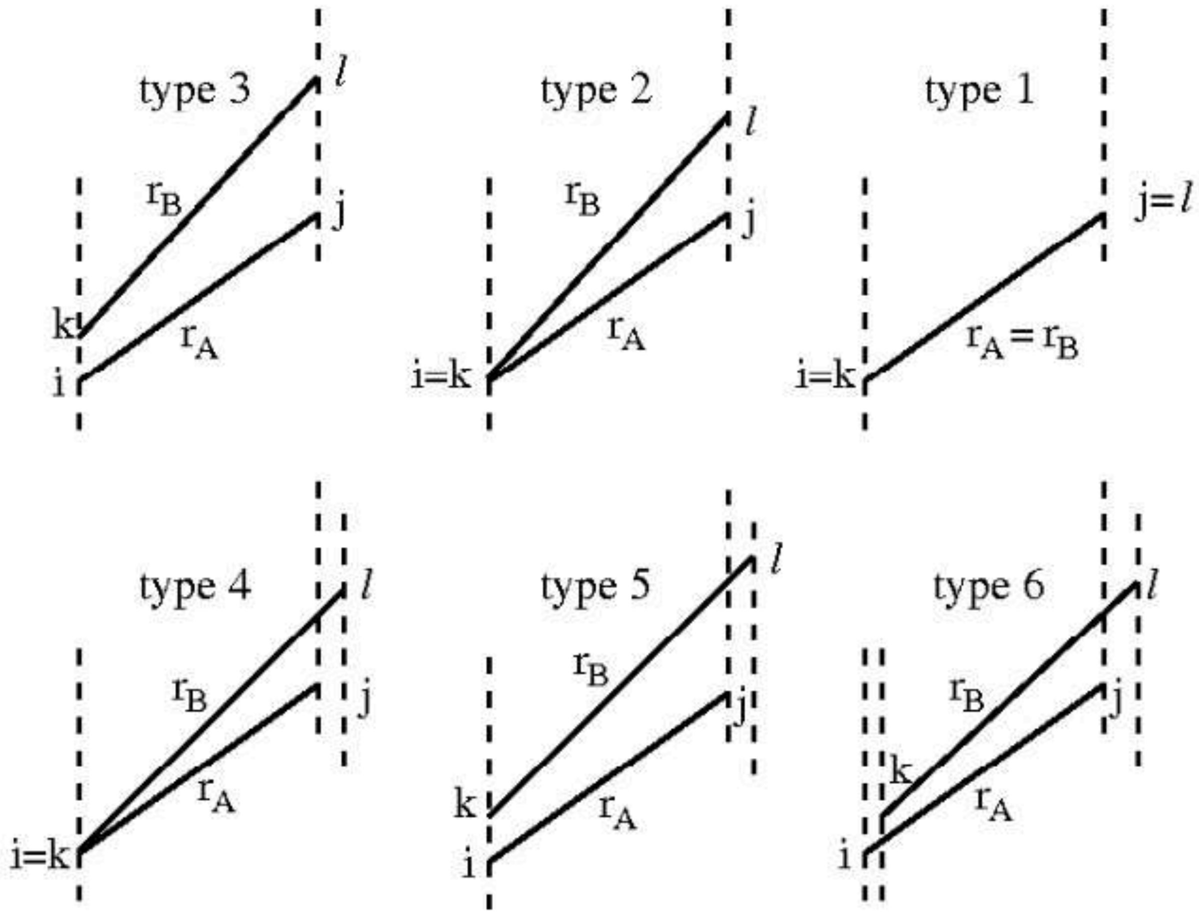
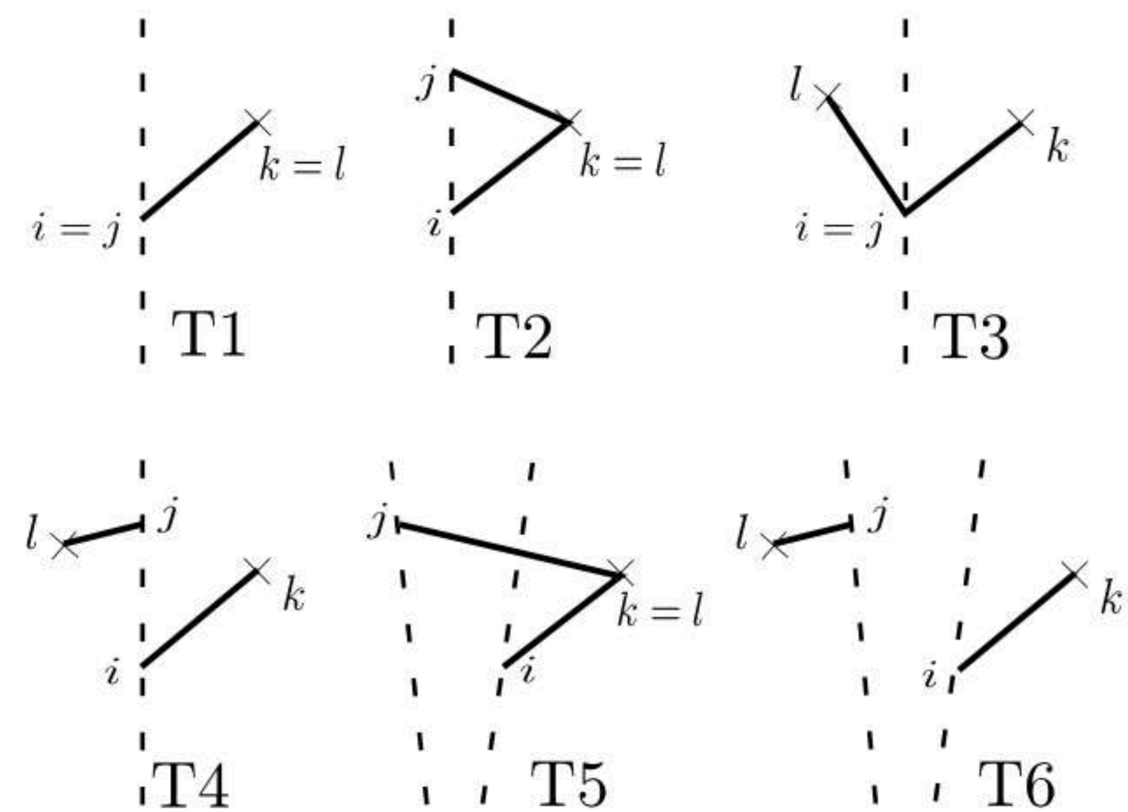
Configurations for auto correlation



Delubac et al. 2015

Configurations for cross correlation



du Mas des Bourboux et al. 2017

Covariance matrix

Case of **Lyman-α forests**

Why not use mocks, like in galaxy clustering ?

- Hard to reproduce signal in data + noise properties
- Costly to produce hundreds of realisations

Covariance matrix

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But we can **test our methods** using mocks self-consistently

Covariance matrix

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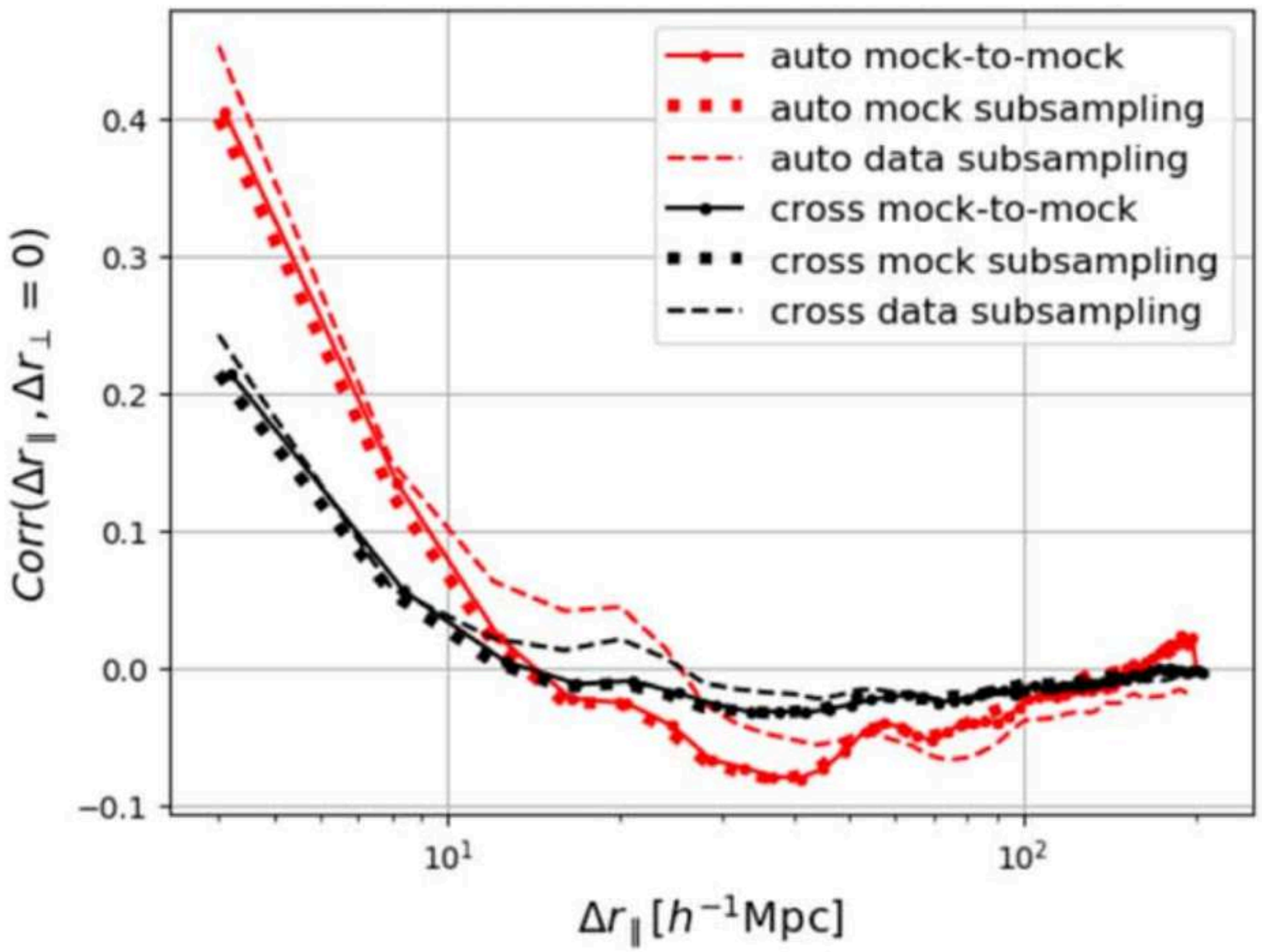
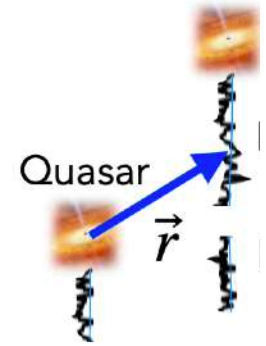
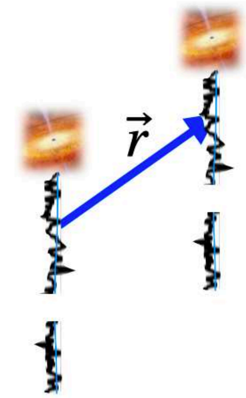


Subsamples ~ 4-pt with Wick Theorem ~ Mocks

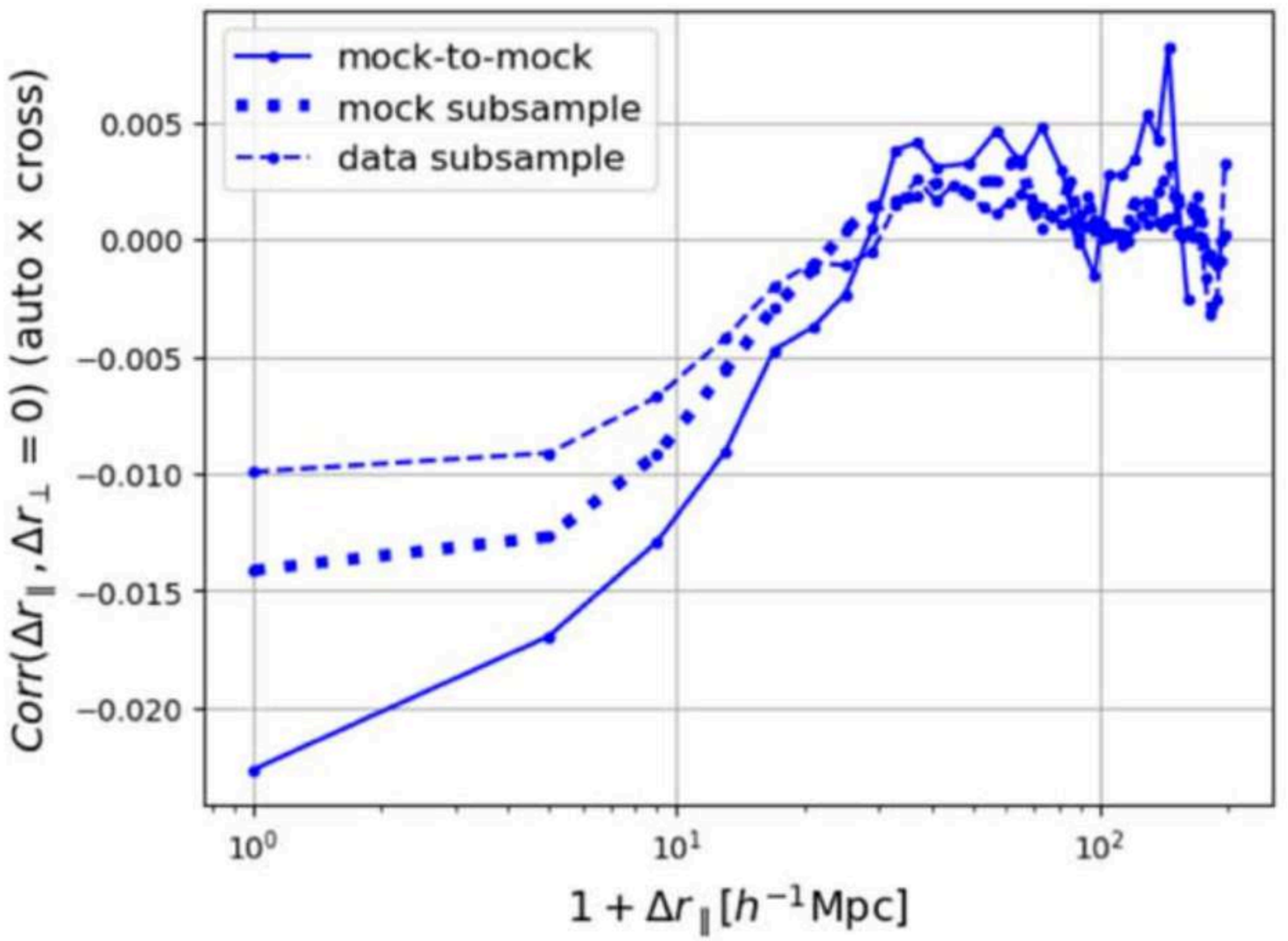
Are $\langle \delta_{\mathrm{Ly}\alpha} \delta_{\mathrm{QSO}} \rangle$ and $\langle \delta_{\mathrm{Ly}\alpha} \delta_{\mathrm{Ly}\alpha} \rangle$ correlated?





We can combine BAO constraints assuming they are independent

Are $\langle \delta_{\mathrm{Ly}\alpha} \delta_{\mathrm{QSO}} \rangle$ and $\langle \delta_{\mathrm{Ly}\alpha} \delta_{\mathrm{Ly}\alpha} \rangle$ correlated?



Covariance between $\langle \delta_{\mathrm{Ly}\alpha} \delta_{\mathrm{QSO}} \rangle$ and $\langle \delta_{\mathrm{Ly}\alpha} \delta_{\mathrm{Ly}\alpha} \rangle$ is less than 2% !

We can combine BAO constraints assuming they are independent

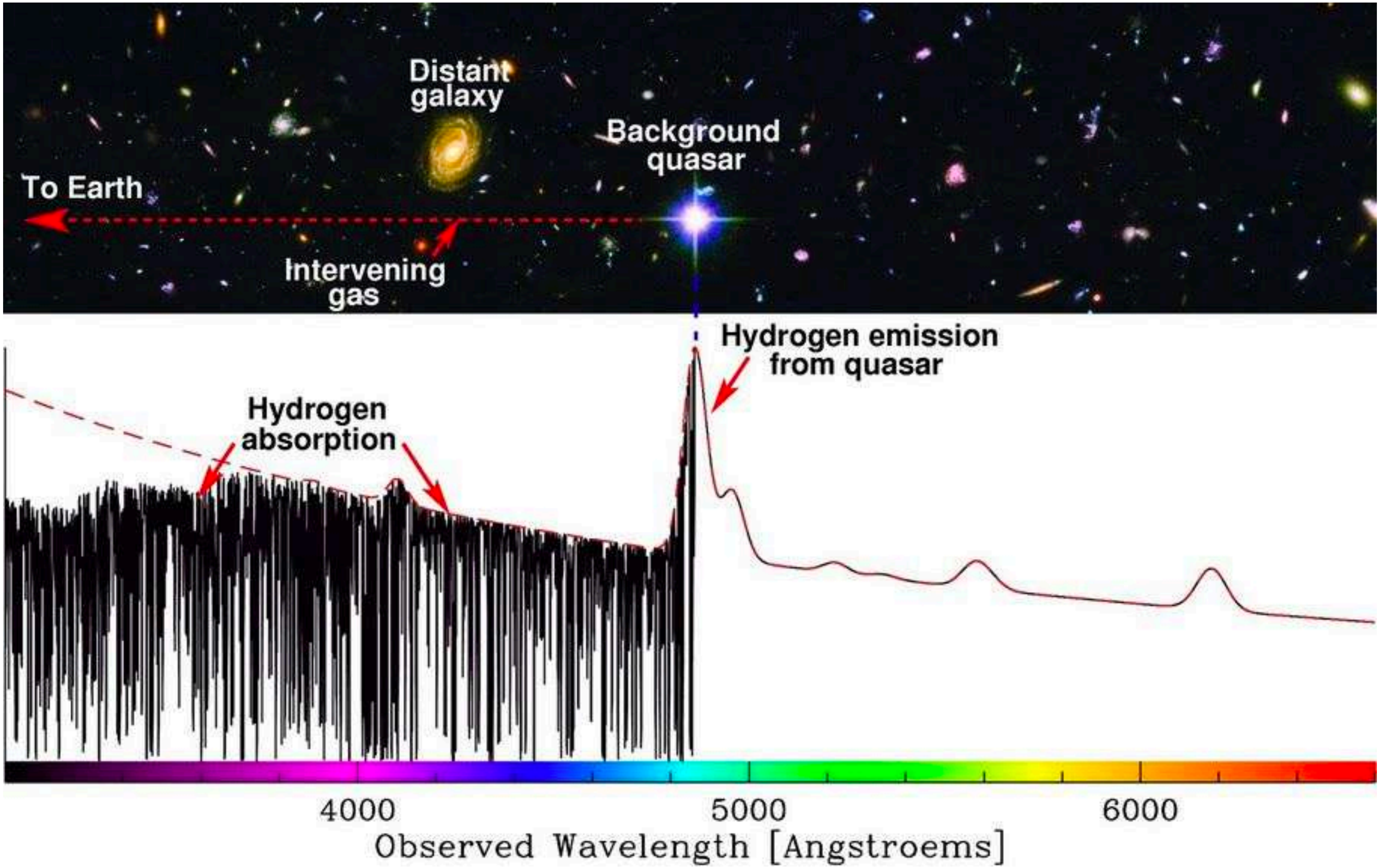
Contaminants and systematic effects

Case of **Lyman-α forests**

Astrophysical	Instrumental	Analysis
Damped Lyman-α	Biased extraction	
Broad Absorption Lines	Residuals from sky subtraction	Distortion by continuum fitting and mode-nulling
Metal absorption in the forest	Residuals from flux calibration with stars	

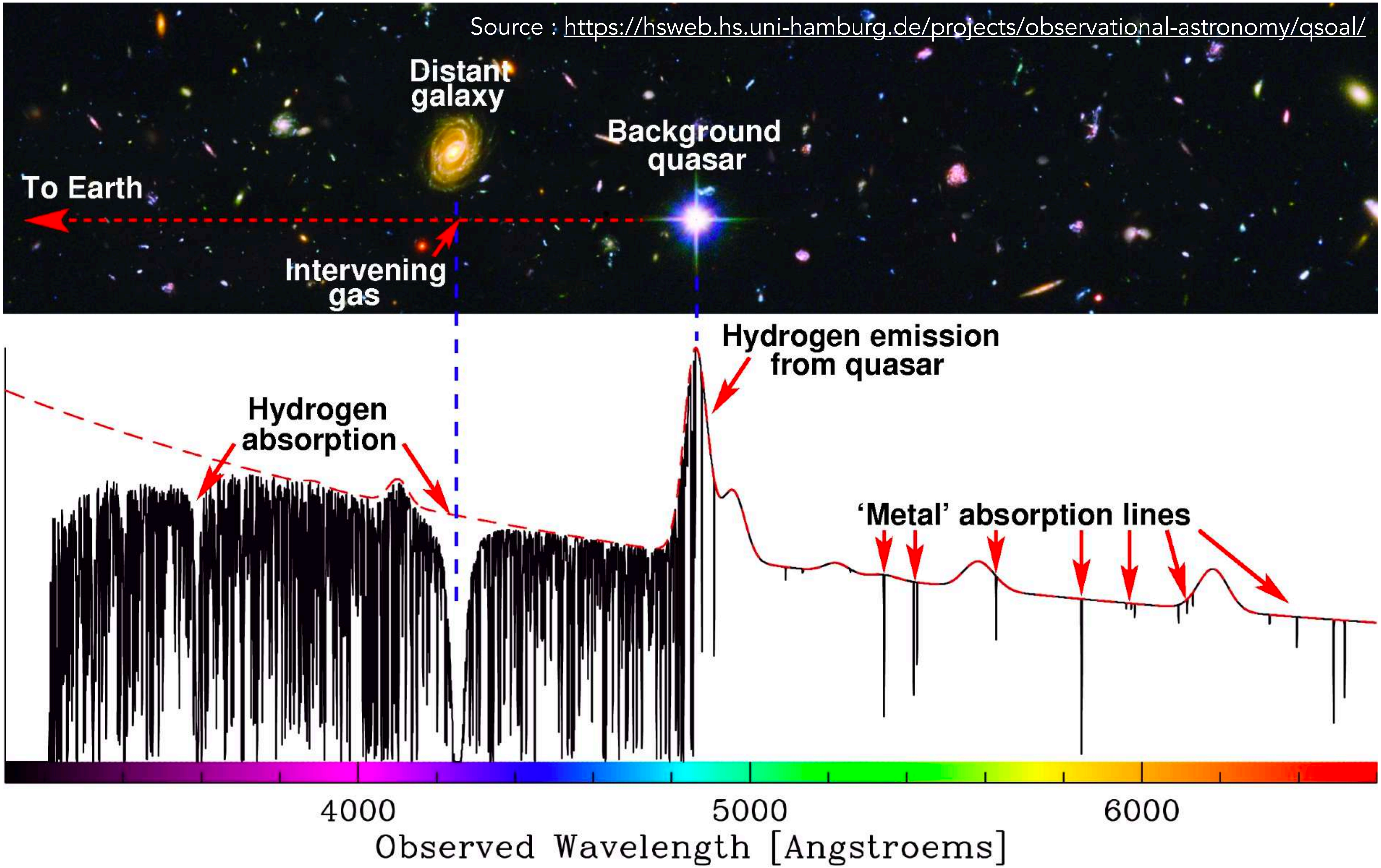
Damped Lyman-alpha

A optically thick patch of gas



Damped Lyman-alpha

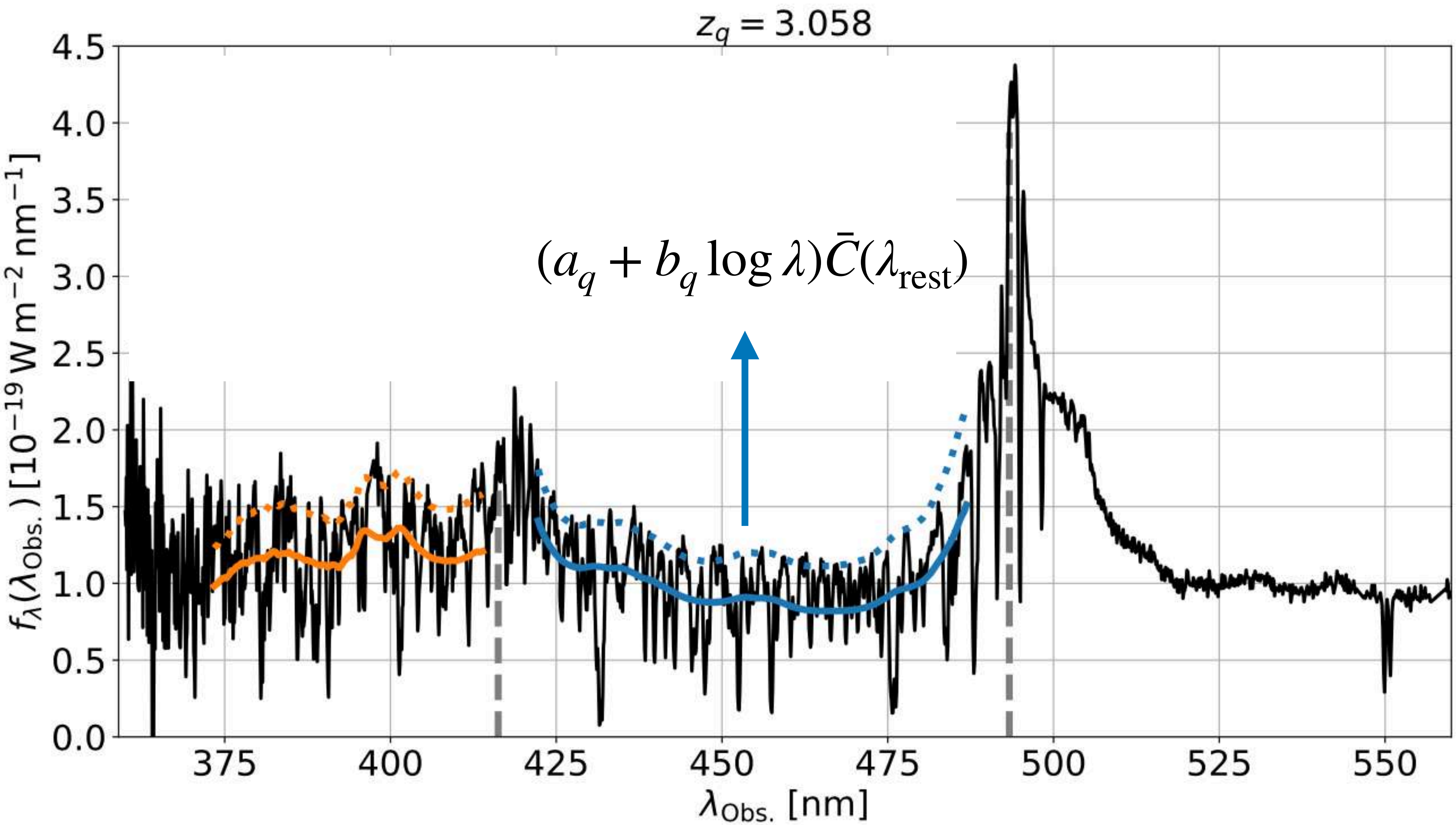
A optically thick patch of gas



Strong absorption in the forest is **masked** when fitting continuum

Distortions

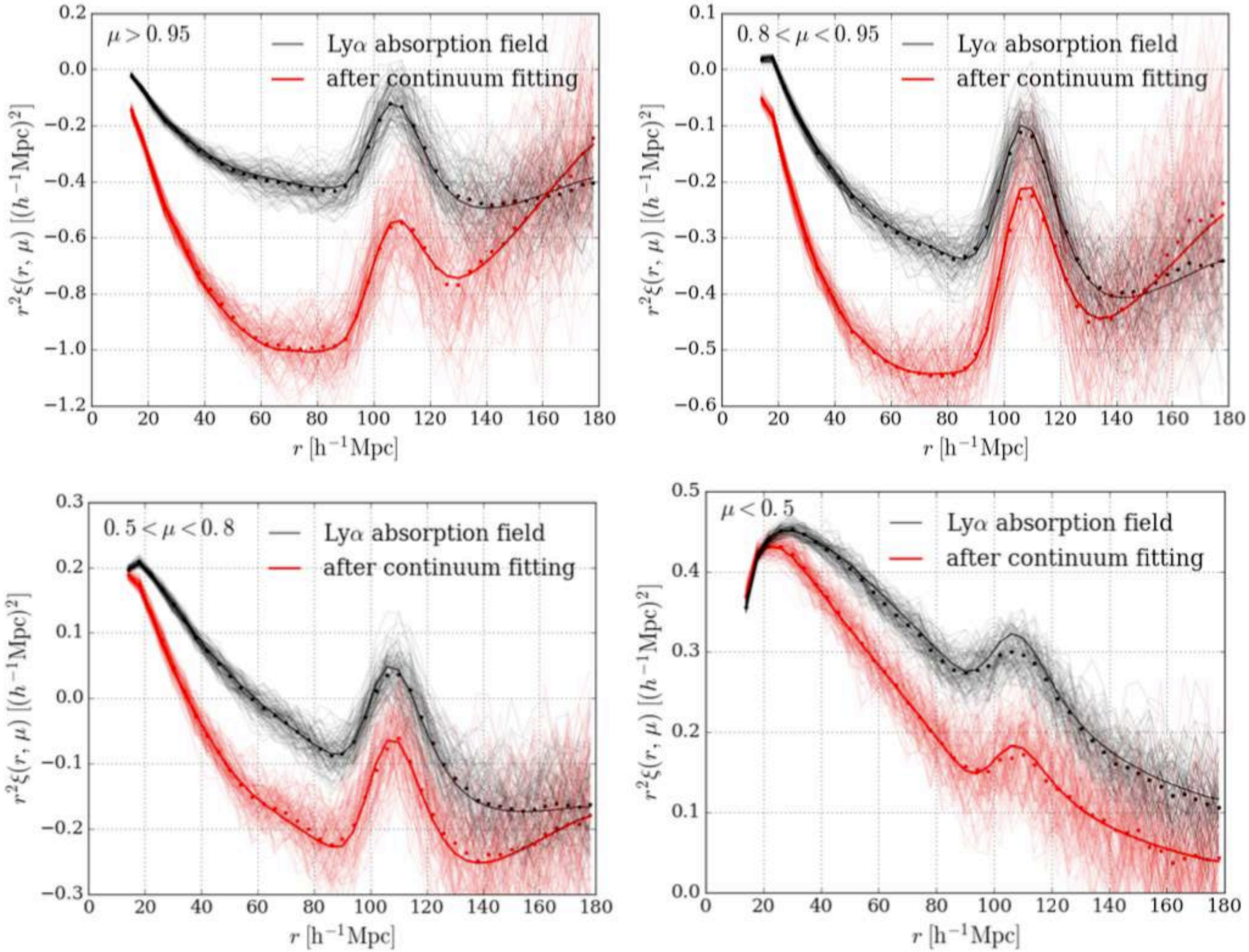
By fitting continuum using fluxes $\{f_j\}$ in a given forest
we introduce correlations between all $\delta_{\mathrm{Ly}\alpha,j}$ of that forest!



Distortions

...creating an artificial **distortion** of the correlation function

Radial wedge | Not-so-radial wedge



Not-so-transverse wedge | Transverse wedge

JB et al. 2017

How to extract the BAO scale ?

Case of **Lyman-α forests**

Linear redshift-space distortions: $P(\vec{k}) = (b + f\mu_k^2)^2 P_m^{\rm lin}(k)$ where $\mu_k = k_{||}/k$

Separate BAO peak from smooth part: $O(k) = P(k)/P_{\rm nopeak}(k) - 1$

Empirical smoothing of BAO peak (non-linearities): $O(k)\exp\left(-\frac{k^2\Sigma_{\rm NL}^2(\mu_k)}{2}\right)$

$$\Sigma_{\rm NL}(\mu_k) = \Sigma_{||}^2\mu_k^2 + \Sigma_\perp^2(1-\mu_k^2)$$

Modelling of reconstruction and removal of RSD: $f\mu_k^2 \to f\mu^2\left(1 - e^{-k^2\Sigma_r^2/2}\right)$

Power-laws to marginalise shape information : $+\sum_{\ell,i=0} a_{\ell,i}k^i$

Scaling of separations:

$$k_{||} = k_{||}^{\rm fid}/\alpha_{||} \qquad k_\perp = k_\perp^{\rm fid}/\alpha_\perp$$

$$r_{||} = \alpha_{||}r_{||}^{\rm fid} \qquad r_\perp = \alpha_\perp r_\perp^{\rm fid}$$

Similar than for model for galaxies

Modelling the correlations

Case of **Lyman-α forests**

$$\hat{P}(\boldsymbol{k}) = b_i b_j (1 + \beta_i \mu_k^2)(1 + \beta_j \mu_k^2) P_{\mathrm{QL}}(\boldsymbol{k}) F_{\mathrm{NL}}(\boldsymbol{k}) G(\boldsymbol{k})$$

Modelling the correlations

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linear bias

linear RSD

Both account for damping tails from DLAs

Modelling the correlations

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Both account for damping tails from DLAs

$$P_{\mathrm{QL}}(\boldsymbol{k}, z) = P_{\mathrm{sm}}(k, z) + \exp\left[-\frac{k_{\parallel}^2 \Sigma_{\parallel}^2 + k_{\perp}^2 \Sigma_{\perp}^2}{2}\right] P_{\mathrm{peak}}(k, z)$$

Same as galaxy case

Modelling the correlations

Case of **Lyman-α forests**

$$\hat{P}(\boldsymbol{k}) = b_i b_j (1 + \beta_i \mu_k^2)(1 + \beta_j \mu_k^2) P_{\rm QL}(\boldsymbol{k}) F_{\rm NL}(\boldsymbol{k}) G(\boldsymbol{k})$$

linear bias

linear RSD

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Binning of correlations

$$P_{\rm QL}(\boldsymbol{k}, z) = P_{\rm sm}(k, z) + \exp\left[-\frac{k_\parallel^2 \Sigma_\parallel^2 + k_\perp^2 \Sigma_\perp^2}{2}\right] P_{\rm peak}(k, z)$$

Same as galaxy case

Modelling the correlations

Case of **Lyman-α forests**

Non-linear effects on small-scales

Arinyo-i-Prats et al. 2015

$$\hat{P}(\boldsymbol{k}) = b_i b_j (1 + \beta_i \mu_k^2)(1 + \beta_j \mu_k^2) P_{\mathrm{QL}}(\boldsymbol{k}) F_{\mathrm{NL}}(\boldsymbol{k}) G(\boldsymbol{k})$$

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Same as galaxy case

$\xi(\vec{r})$ is the Fourier transform of $P(\vec{k})$

Modelling the correlations

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Template auto: $$\xi^t = \xi^{\mathrm{Ly}\alpha \times \mathrm{Ly}\alpha} + \sum_m \xi^{\mathrm{Ly}\alpha \times m} + \sum_{m_1, m_2} \xi^{\mathrm{m_1} \times \mathrm{m_2}} + \xi^{\mathrm{sky}},$$

Template cross: $$\xi^t = \xi^{\mathrm{Ly}\alpha \times \mathrm{QSO}} + \sum_m \xi^{\mathrm{QSO} \times m} + \xi^{\mathrm{TP}}.$$

Modelling the correlations

Case of **Lyman-α forests**

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linear RSD

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Binning of correlations

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Modelling the correlations

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linear bias

linear RSD

Binning of correlations

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Same as galaxy case

Both account for damping tails from DLAs

$\xi(\vec{r})$ is the Fourier transform of $P(\vec{k})$

Cosmology

Template auto: $$\xi^t = \xi^{\rm Ly\alpha \times Ly\alpha} + \sum_m \xi^{{\rm Ly\alpha} \times m} + \sum_{m_1, m_2} \xi^{\rm m_1 \times m_2} + \xi^{\rm sky}$$

Template cross: $$\xi^t = \xi^{\rm Ly\alpha \times QSO} + \sum_m \xi^{{\rm QSO} \times m} + \xi^{\rm TP}$$

Modelling the correlations

Case of **Lyman-α forests**

$$\hat{P}(\boldsymbol{k}) = b_i b_j (1 + \beta_i \mu_k^2)(1 + \beta_j \mu_k^2) P_{\mathrm{QL}}(\boldsymbol{k}) F_{\mathrm{NL}}(\boldsymbol{k}) G(\boldsymbol{k})$$

- $b_i b_j$: linear bias
- $(1 + \beta_i \mu_k^2)(1 + \beta_j \mu_k^2)$: linear RSD
  - Both account for damping tails from DLAs
- $F_{\mathrm{NL}}(\boldsymbol{k})$: Non-linear effects on small-scales, Arinyo-i-Prats et al. 2015
- $G(\boldsymbol{k})$: Binning of correlations
- P_{QL}:

$$P_{\mathrm{QL}}(\boldsymbol{k}, z) = P_{\mathrm{sm}}(k, z) + \exp\left[-\frac{k_{\parallel}^2 \Sigma_{\parallel}^2 + k_{\perp}^2 \Sigma_{\perp}^2}{2}\right] P_{\mathrm{peak}}(k, z)$$

Same as galaxy case

$\xi(\vec{r})$ is the Fourier transform of $P(\vec{k})$

Cosmology: $\xi^{\mathrm{Ly}\alpha \times \mathrm{Ly}\alpha}$, $\xi^{\mathrm{Ly}\alpha \times \mathrm{QSO}}$

Metal contamination: $\sum_m \xi^{\mathrm{Ly}\alpha \times m}$, $\sum_{m_1, m_2} \xi^{\mathrm{m_1} \times \mathrm{m_2}}$, $\sum_m \xi^{\mathrm{QSO} \times m}$

Template auto: $$\xi^t = \xi^{\mathrm{Ly}\alpha \times \mathrm{Ly}\alpha} + \sum_m \xi^{\mathrm{Ly}\alpha \times m} + \sum_{m_1, m_2} \xi^{\mathrm{m_1} \times \mathrm{m_2}} + \xi^{\mathrm{sky}}$$

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Modelling the correlations

Case of **Lyman-α forests**

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Binning of correlations

linear bias

linear RSD

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Same as galaxy case

$\xi(\vec{r})$ is the Fourier transform of $P(\vec{k})$

Cosmology

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Contamination by sky-residuals

Modelling the correlations

Case of **Lyman-α forests**

Contamination by metals

Contamination by sky residuals

Modelling the correlations

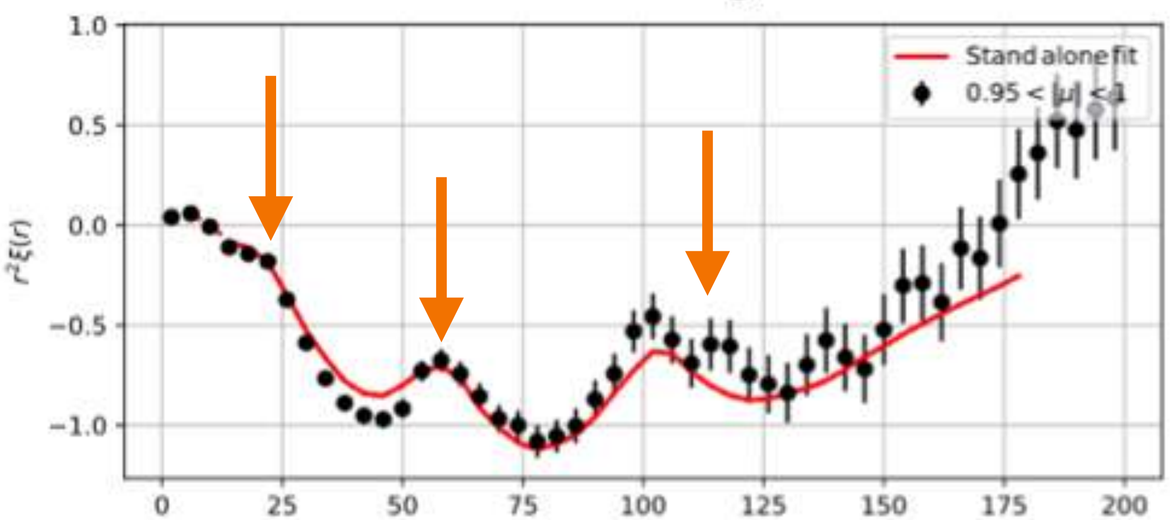
Case of **Lyman-α forests**

Contamination by metals

Linear transformation between
true correlation and shifted/confused correlation

$$\xi^{m-n}_{\text{mod}}(A) \rightarrow \sum_B M_{AB}\, \xi^{m-n}_{\text{mod}}(\tilde{r}_{\parallel}(B), \tilde{r}_{\perp}(B))$$

Radial wedge



Metal Line	λ_m (nm)	$r_{\parallel}$ (h^{-1} Mpc)
Si III	120.7	−21
Si IIa	119.0	−64
Si IIb	119.3	−56
Si IIc	126.0	+111

Contamination by sky residuals

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Case of **Lyman-α forests**

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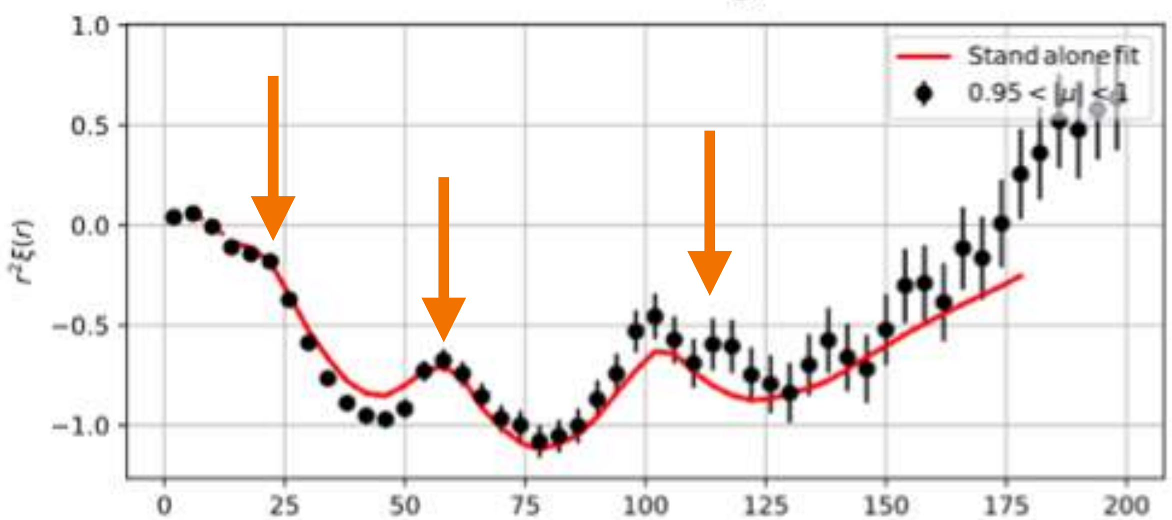

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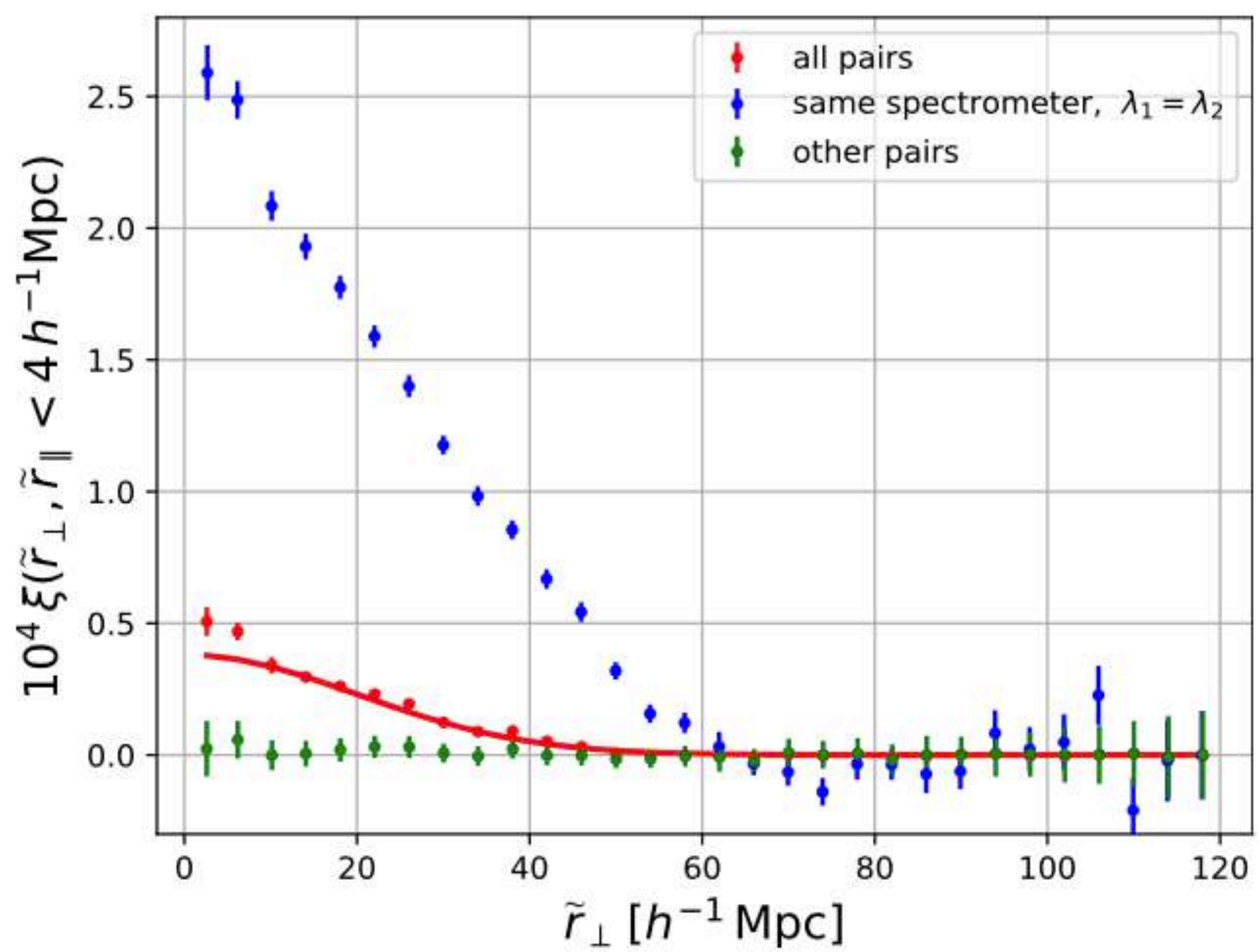
Contamination by sky residuals

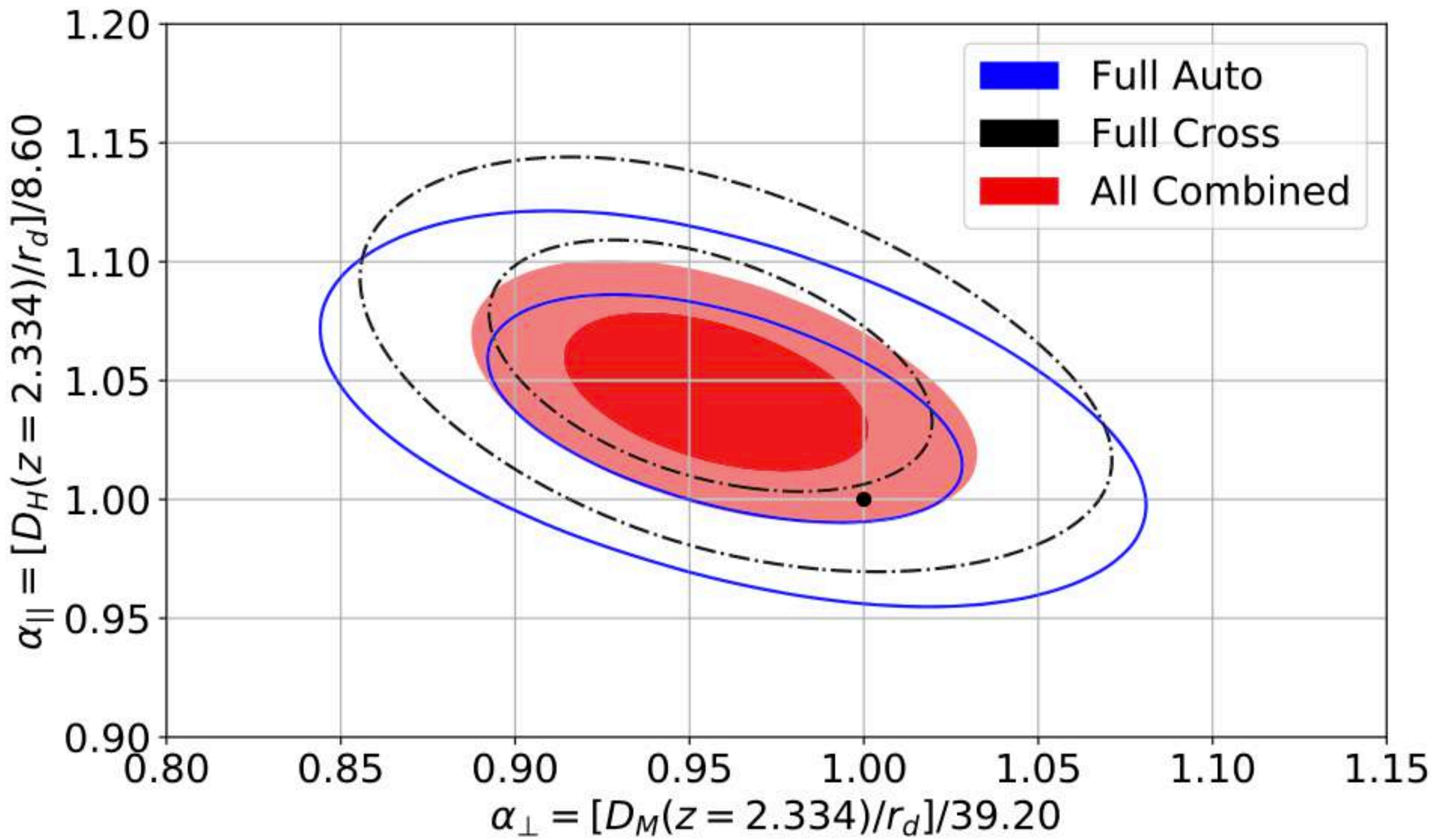


$$\xi^{\rm sky}(r_{\parallel}, r_{\perp}) = \begin{cases} \dfrac{A_{\rm sky}}{\sigma_{\rm sky}\sqrt{2\pi}} \exp\left(-\dfrac{1}{2}\left(\dfrac{r_{\perp}}{\sigma_{\rm sky}}\right)^2\right), & \text{if } r_{\parallel} = 0 \\ 0, & \text{if } r_{\parallel} \neq 0 \end{cases}$$

Constraints on BAO peak position

Case of **Lyman-α forests**

Radial BAO



Transverse BAO

Good agreement with prediction by Planck flat LCDM

Constraints on BAO peak position

Case of **Lyman-α forests**

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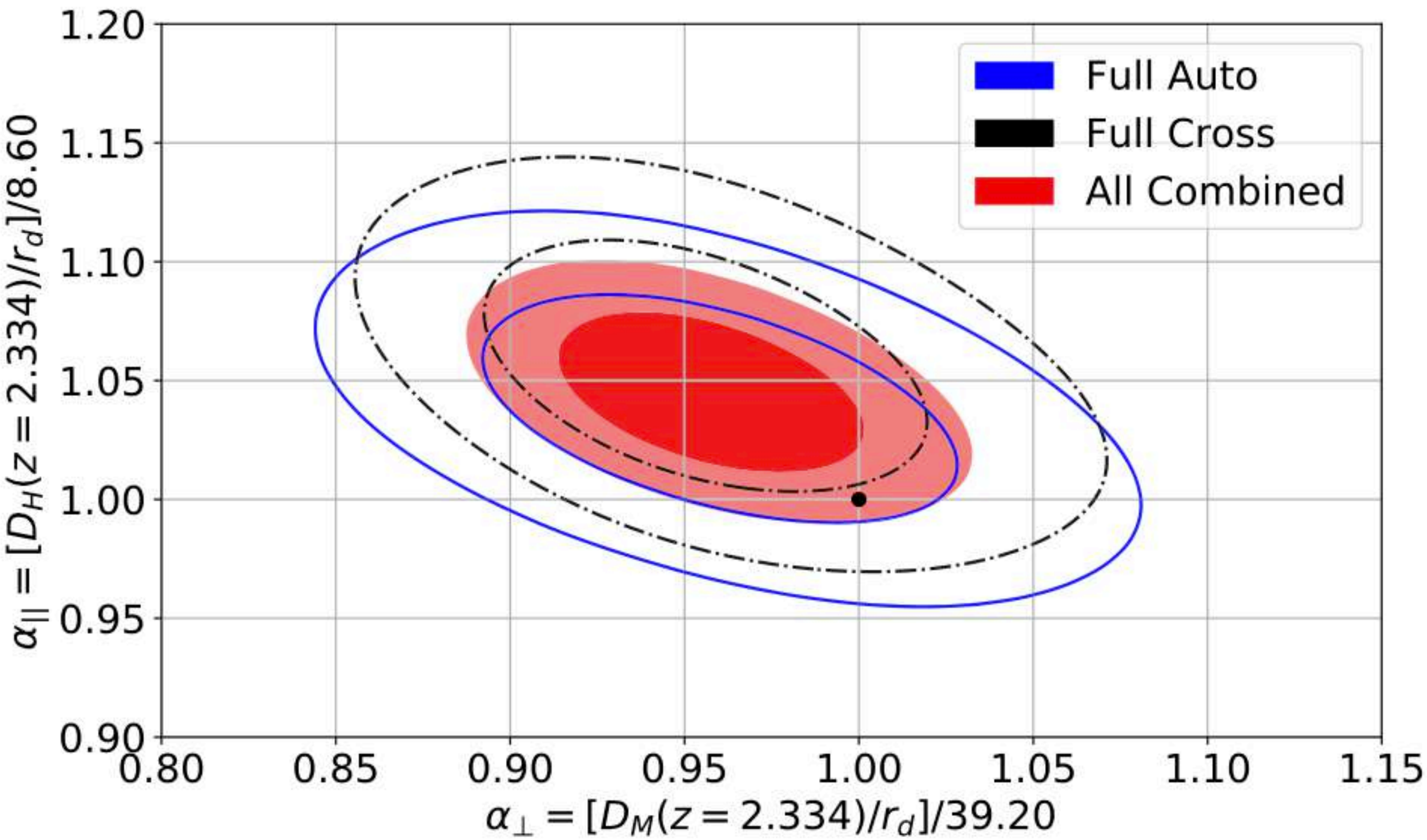


Transverse BAO

Good agreement with prediction by Planck flat LCDM

$$\begin{cases} D_H(z=2.334)/r_d = 8.99 \,{}^{+0.20}_{-0.19}\,{}^{+0.38}_{-0.38} \\ D_M(z=2.334)/r_d = 37.5 \,{}^{+1.2}_{-1.1}\,{}^{+2.5}_{-2.3} \\ \rho(D_H(z)/r_d,\, D_M(z)/r_d) = -0.45 \end{cases}$$

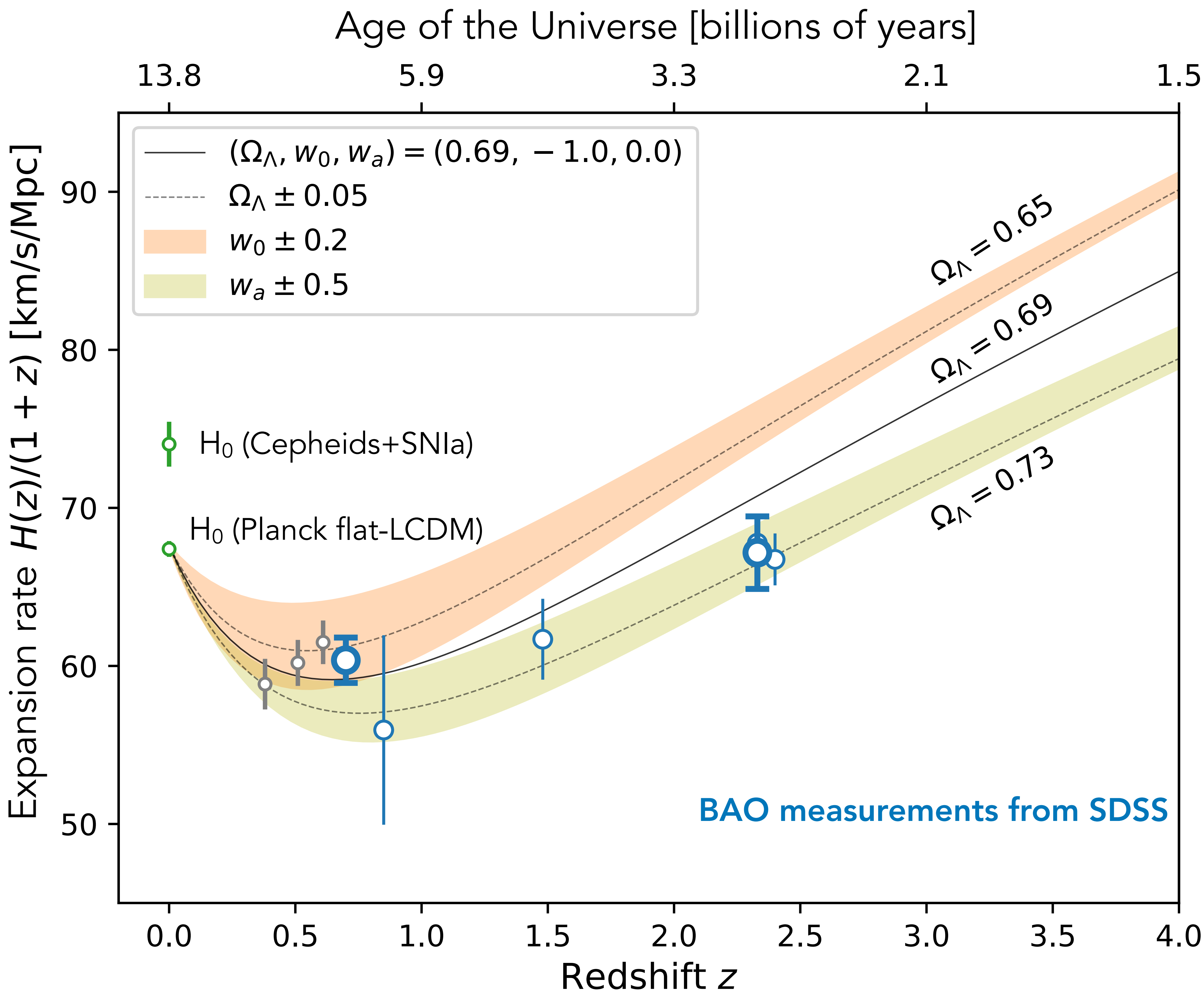
→ **2.2% precision**

→ **3.2% precision**

Robust against many analysis choices (at this precision)

Future with DESI Lyα forests

$\dot{a}(t)$



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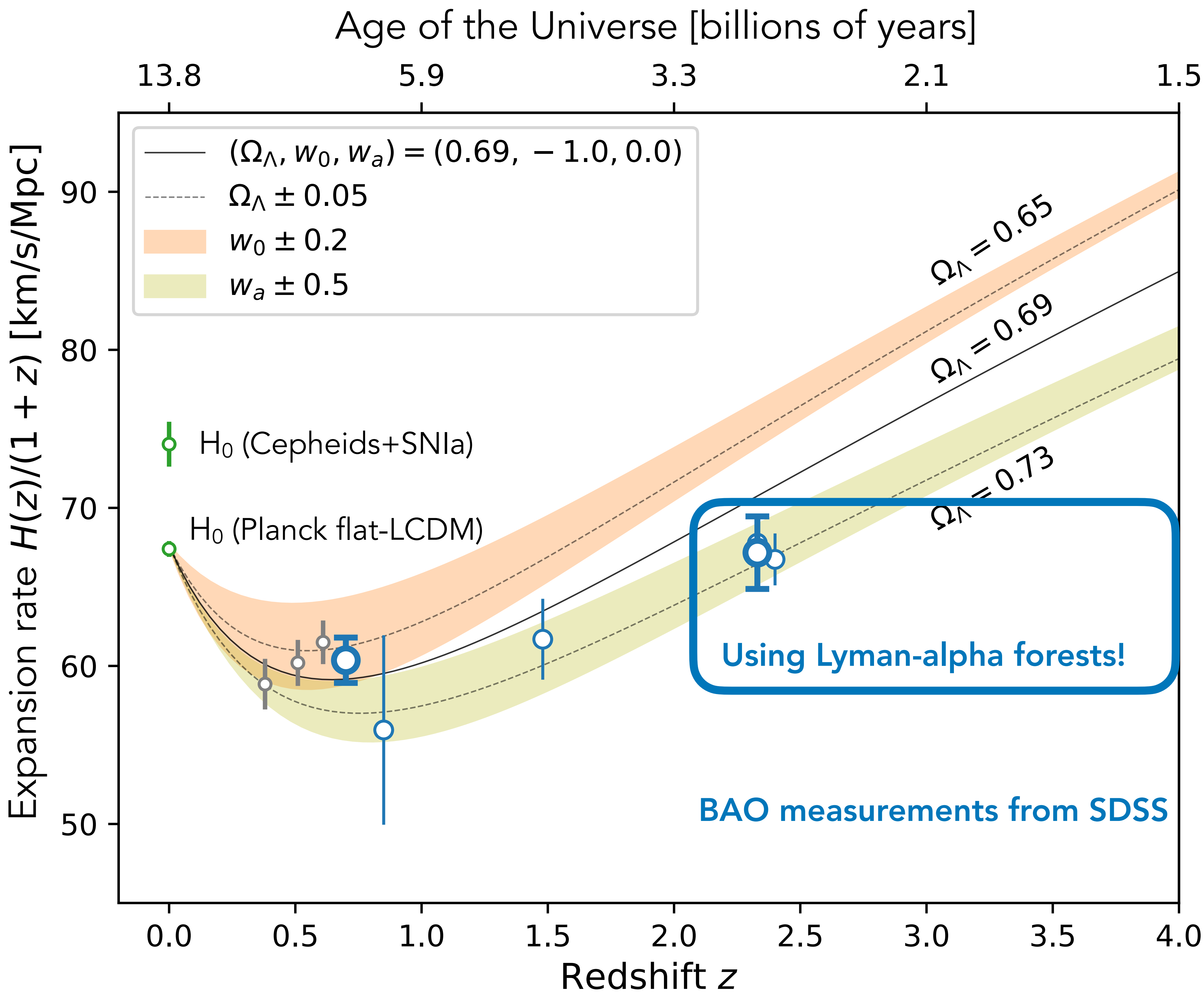

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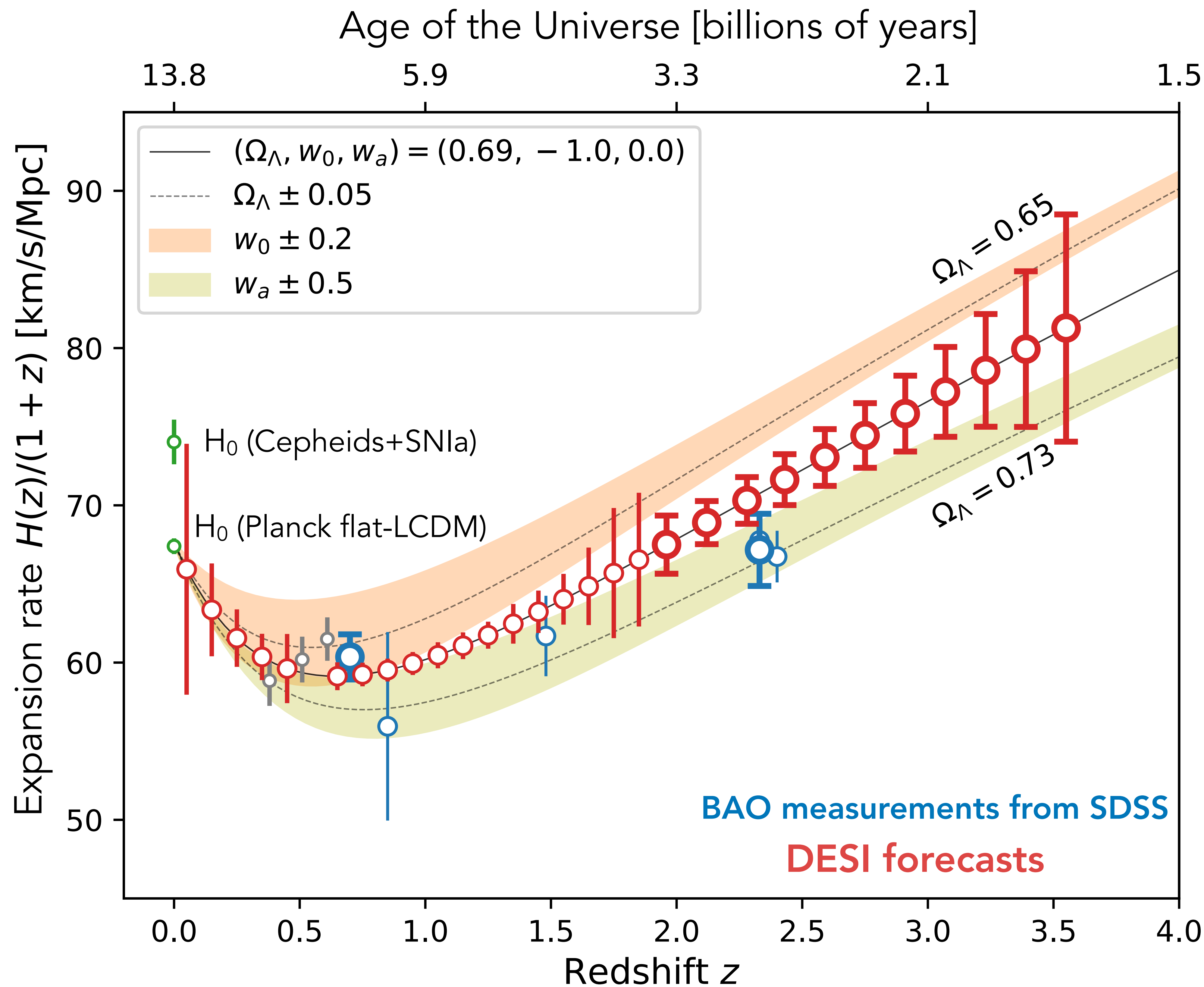

Future with DESI Lyα forests

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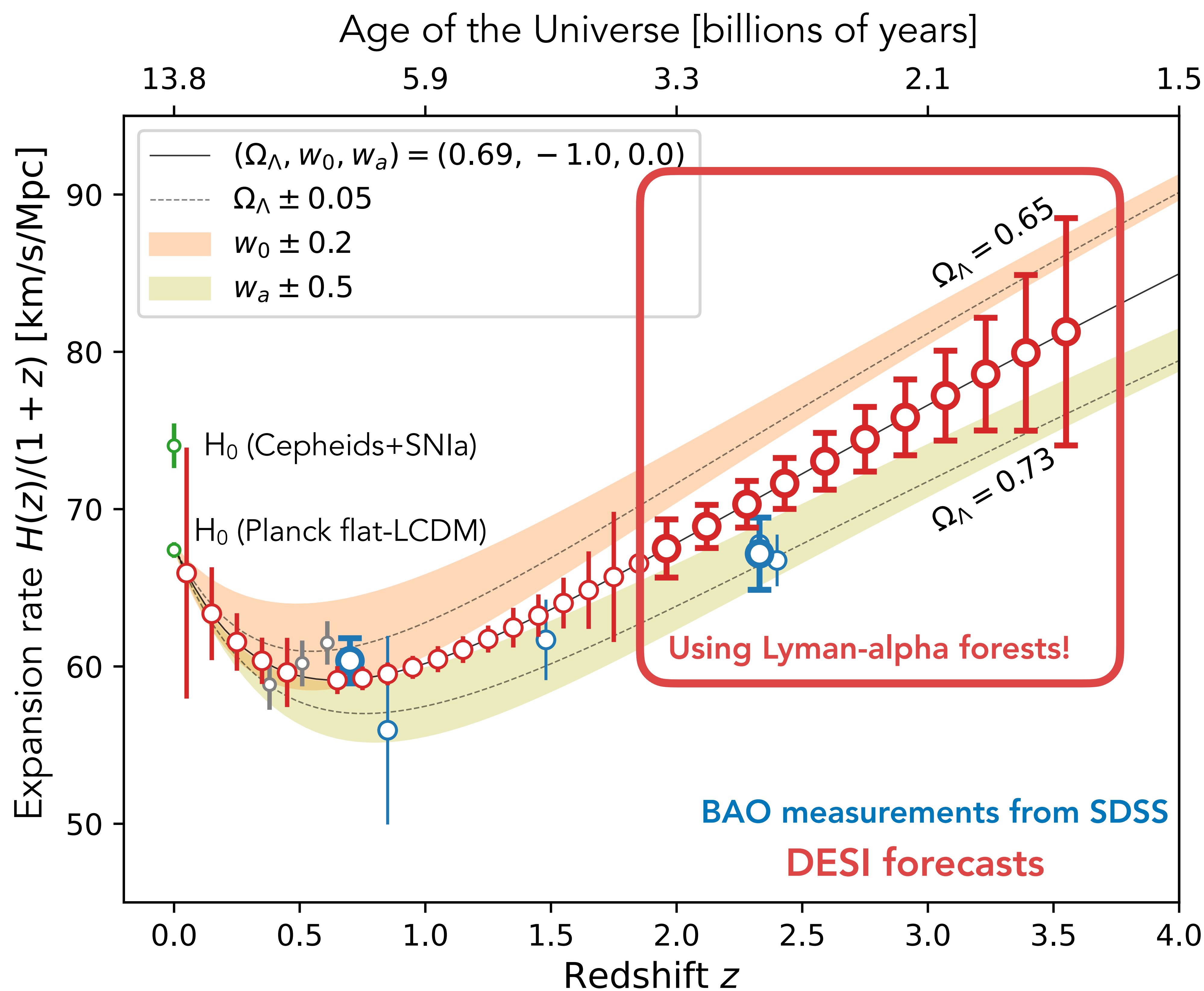
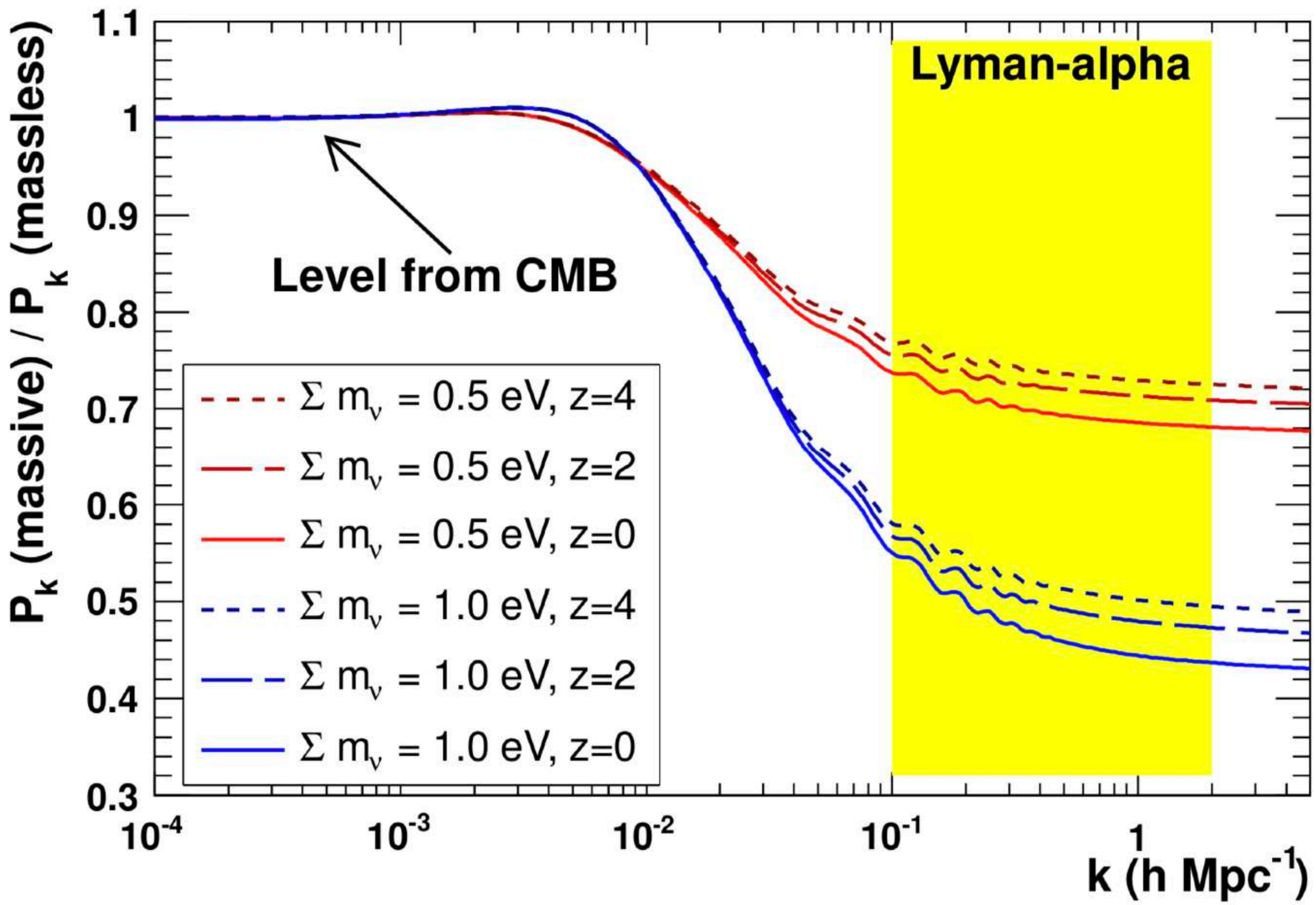


Neutrino masses with Lyα forests

Impact on linear matter power-spectrum

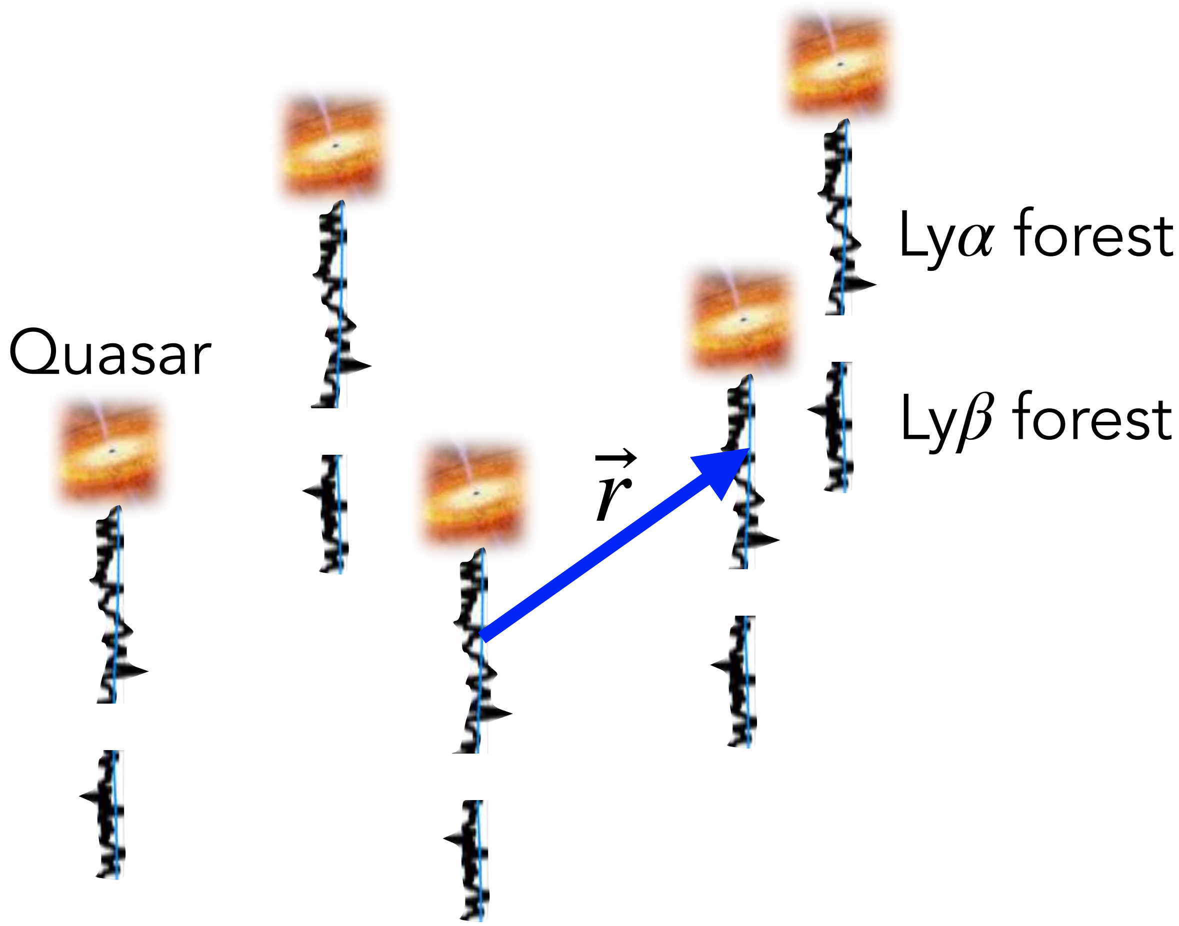
Palanque-Delabrouille et al. 2014



Current limits from ground oscillation experiments $\sum m_\nu < 0.06\ \mathrm{eV}$

One-dimensional power spectrum of Lyα forests

Instead of 3D correlations....



in Configuration space...

One-dimensional power spectrum of Lyα forests

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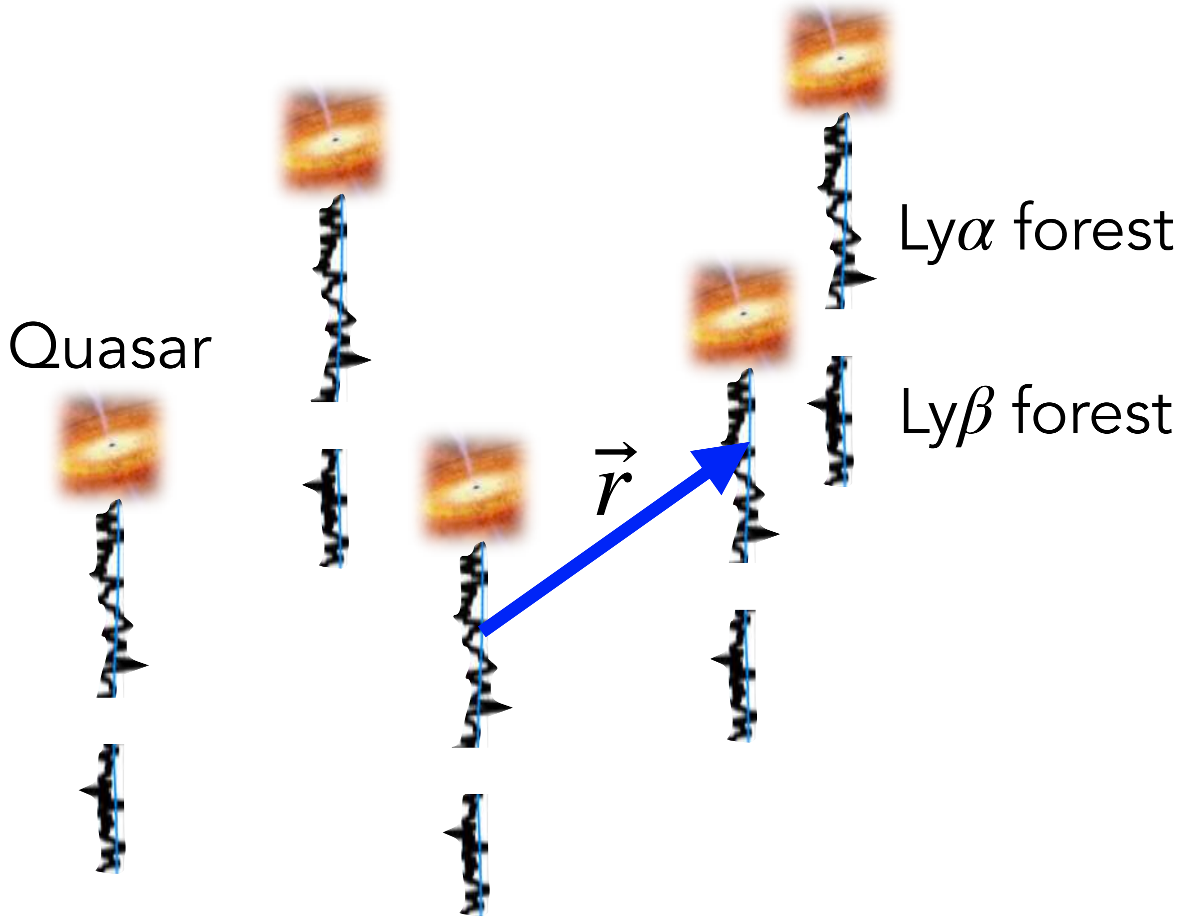
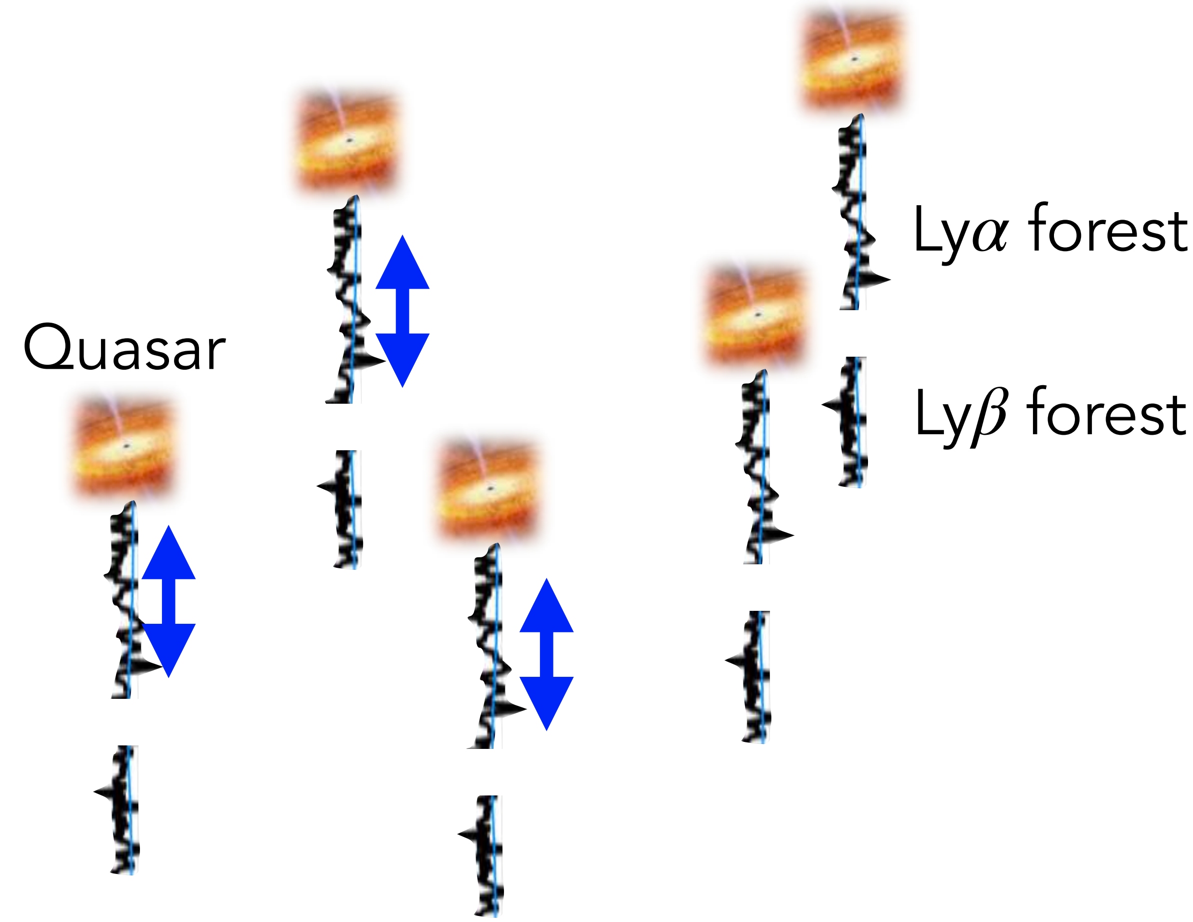


in Configuration space...

Line-of-sight clustering



in Fourier space!

One-dimensional power spectrum of Lyα forests

BOSS+eBOSS data: 43k forests

Chabanier et al. 2019

Start from fluctuations

$$\hat{\delta}_F(\lambda) = \frac{f(\lambda)}{(a_q + b_q \log\lambda)\bar{C}(\lambda_{\rm rest})} - 1$$

One-dimensional power spectrum of Lyα forests

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Start from fluctuations

$$\hat{\delta}_F(\lambda) = \frac{f(\lambda)}{(a_q + b_q \log \lambda)\bar{C}(\lambda_{\rm rest})} - 1$$

Compute raw power-spectrum along line-of-sights

$$P_{raw}(k) = < \left| \tilde{\delta}_F(k) \right|^2 >$$

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Noise subtraction and correct for spectral resolution
$$P_{raw}(k) = P_F(k) \cdot W^2(k) + P_{noise}(k)$$

One-dimensional power spectrum of Lyα forests

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Removing contaminations from uncorrelated metals

$$P_{raw}(k) = [P_{Ly\alpha}(k) + P_{correlated}(k) + P_{uncorrelated}(k)] \cdot W^2(k) + P_{noise}(k)$$

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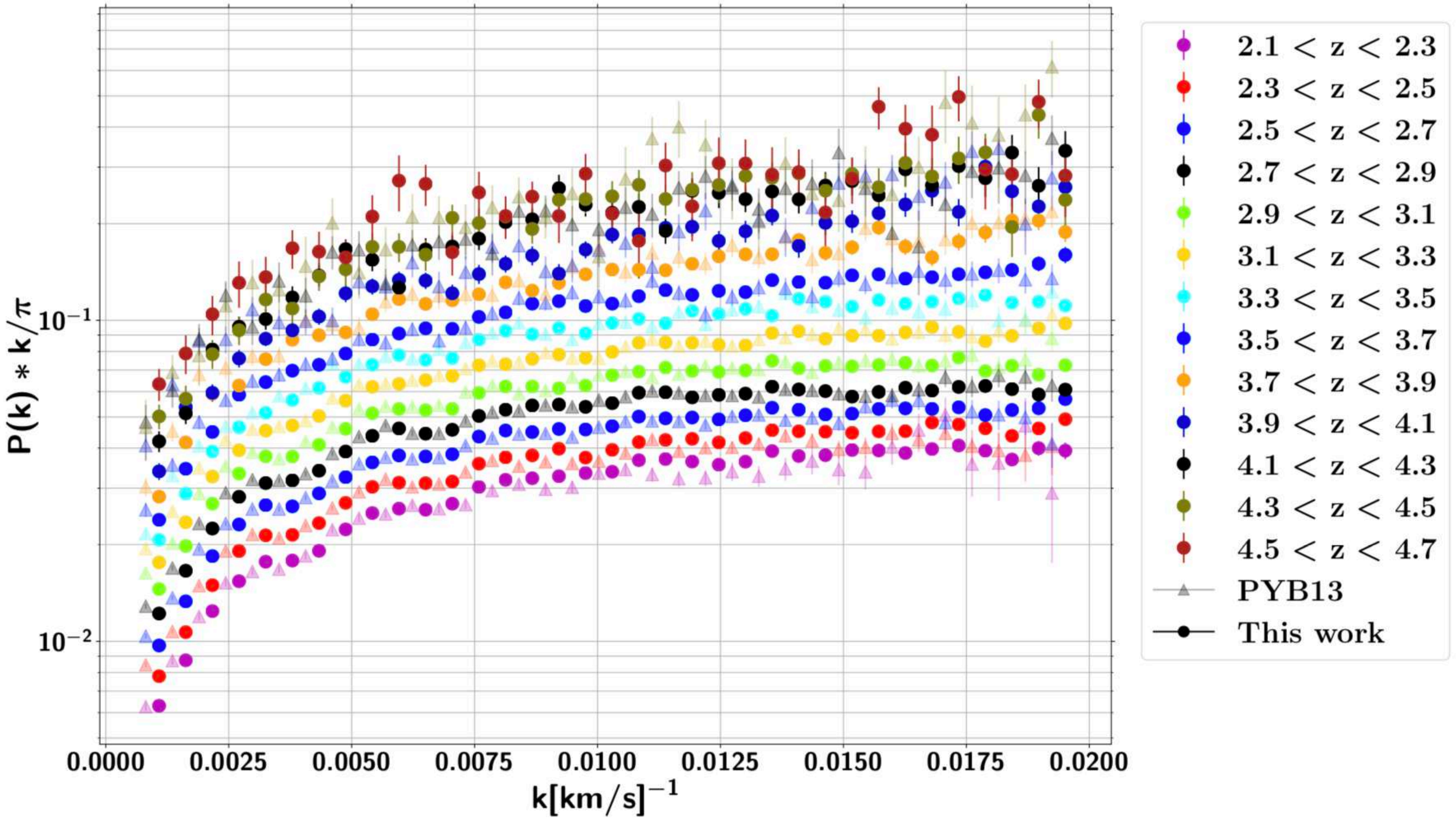
Final result

One-dimensional power spectrum of Lyα forests

BOSS+eBOSS data: 43k forests

Chabanier et al. 2019



Units: $\Delta v = c\dfrac{\Delta\lambda}{\lambda}$ [km/s] $k \equiv \dfrac{2\pi}{\Delta v}$ [s/km]

Pixel size: 69 km/s ~ 0.3 Mpc/h at z ~ 3

k^{max} ~ 0.09 [s/km]

One-dimensional power spectrum of Lyα forests

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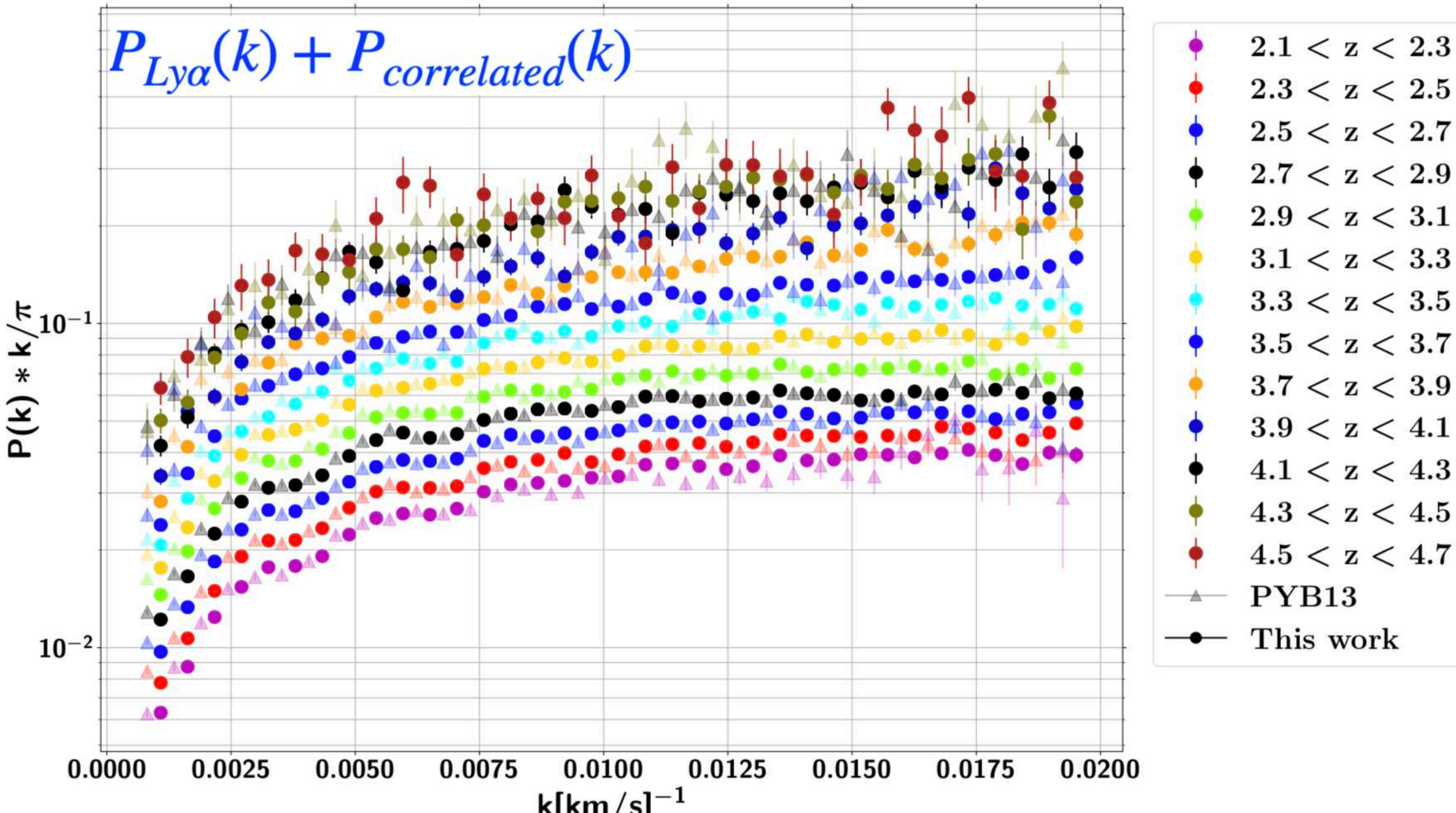
Chabanier et al. 2019



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Modelling the 1D power spectrum of Lyα forests

Suite of hydrodynamical n-body simulations

Borde et al. 2014, Rossi et al. 2014, Chabanier et al. 2019

Modelling the 1D power spectrum of Lyα forests

Suite of hydrodynamical n-body simulations

Borde et al. 2014, Rossi et al. 2014, Chabanier et al. 2019

Cosmology grid

Parameter	Value	
$\sigma_8(z=0)$	0.83	± 0.05
n_s	0.96	± 0.05
H_0 [km s^{-1} Mpc^{-1}]	67.5	± 5.0
Ω_m	0.31	± 0.05
Ω_b	0.044	
Ω_Λ	0.69	
$T_0(z=3)$[K]	15 000	± 7000
$\gamma(z=3)$	1.3	± 0.3
Starting redshift	30	

Modelling the 1D power spectrum of Lyα forests

Suite of hydrodynamical n-body simulations

Borde et al. 2014, Rossi et al. 2014, Chabanier et al. 2019

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Ω_Λ	0.69	
$T_0(z=3)$[K]	15 000	± 7000
$\gamma(z=3)$	1.3	± 0.3
Starting redshift	30	

G-astrophysics

Adiabatic cooling

Ultraviolet background ionization heating

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Modelling the 1D power spectrum of Lyα forests

Suite of hydrodynamical n-body simulations

Borde et al. 2014, Rossi et al. 2014, Chabanier et al. 2019

Cosmology grid

Parameter	Value	
$\sigma_8(z=0)$	0.83	±0.05
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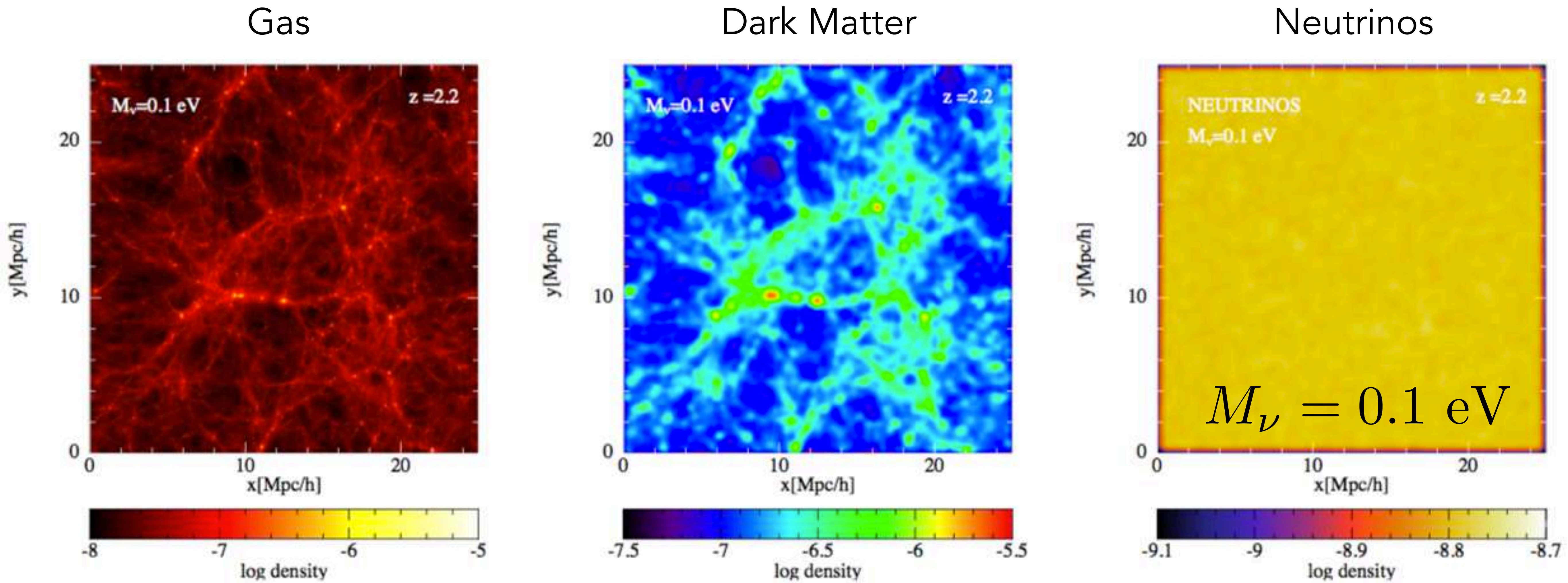
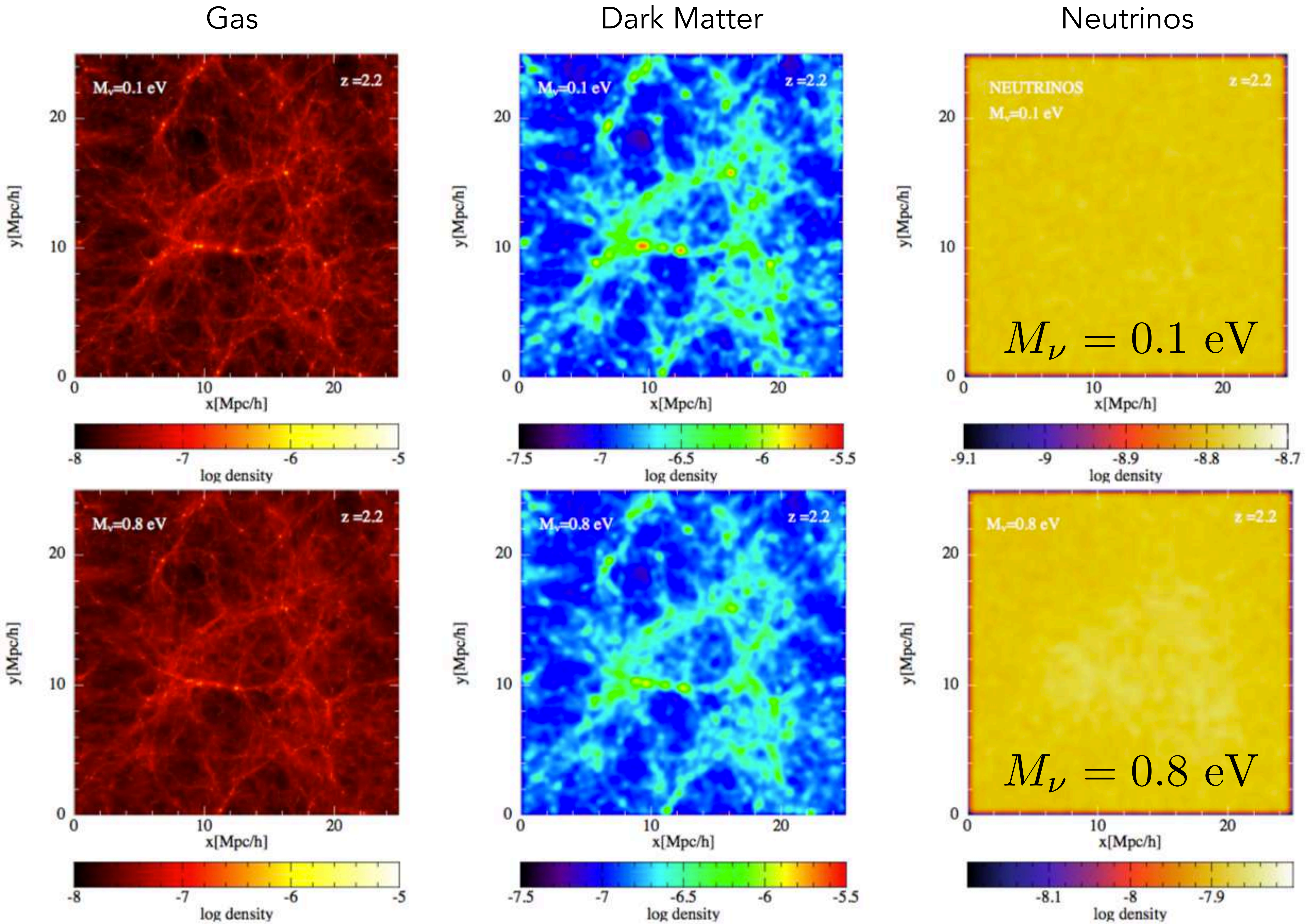
Model is interpolation/emulation of simulation results

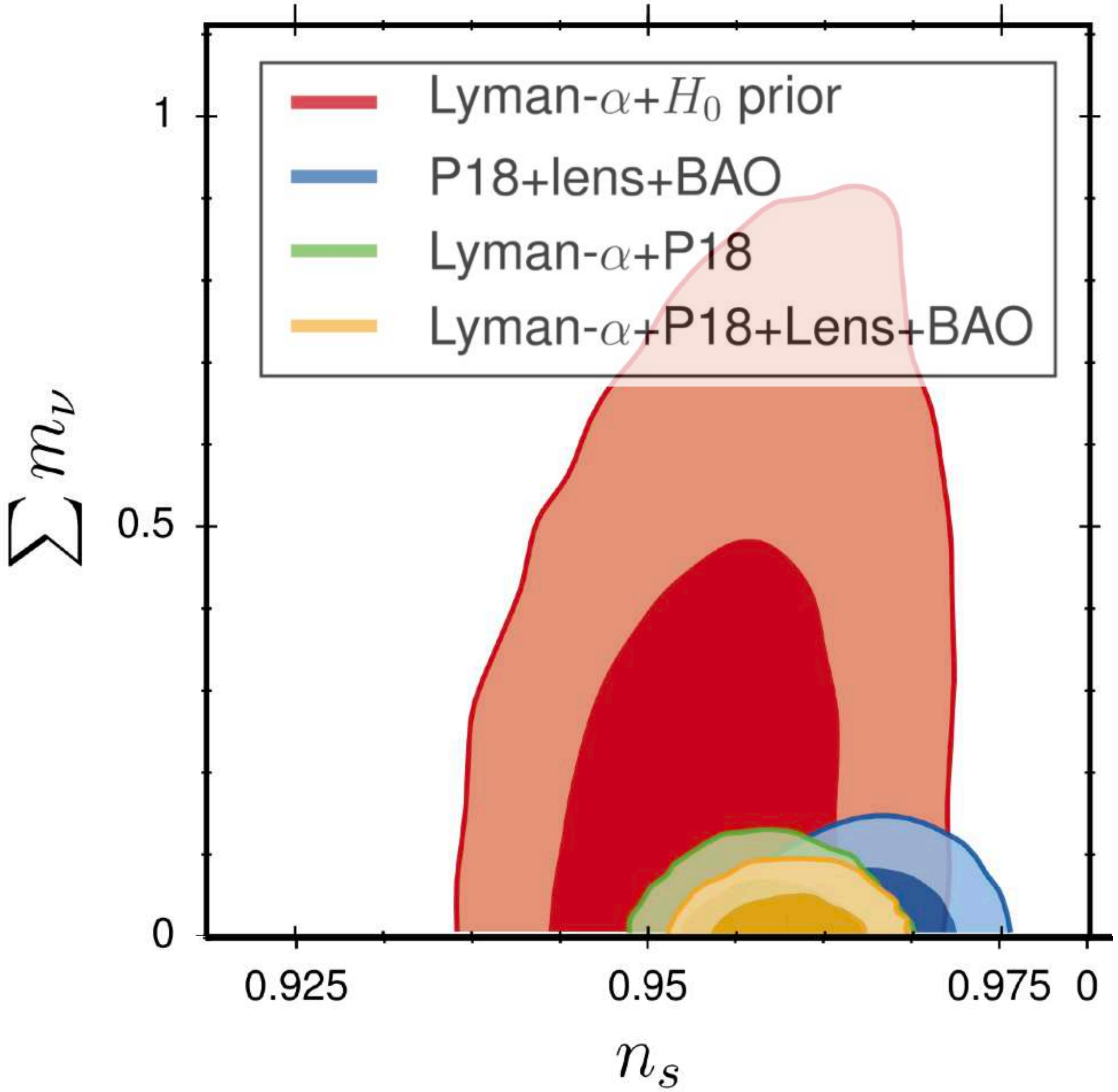


Rossi et al. 2014



Rossi et al. 2014

Constraints on neutrino mass from 1D power spectrum of Lyα forests



Palanque-Delabrouille et al 2020

$$\sum m_\nu < 0.11\text{eV}\ (95\%)$$

Forests + CMB T&P

$$\sum m_\nu < 0.09\text{eV}\ (95\%)$$

Forests + CMB T&P&Lens + BAO

In a nutshell

Case of **Lyman-α forests**

	3D	**1D**
Goal	BAO at high-redshift	Small-scale clustering
Space	Configuration	Fourier
Parameters	$\left(\frac{D_H(z)}{r_{\mathrm{drag}}}, \frac{D_M(z)}{r_{\mathrm{drag}}}\right)_{\mathrm{peak}}$	$M_\nu, A_s, n_s, \Omega_m h^2$
Model type	Analytical	Emulators from hydro-sims

From clustering to cosmology

$$\gamma_n \rightarrow \begin{matrix} (\theta_i, \phi_i, z_i) \\ \left(\theta_i, \phi_i, z_i, \{f_j\}\right) \end{matrix} \rightarrow \begin{matrix} \delta_g(\vec{x}) \\ \delta_{\mathrm{Ly}\alpha}(\vec{x}) \end{matrix} \rightarrow \langle \delta \delta' \rangle \rightarrow \Omega_i$$

From clustering to cosmology

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CMB

RSD

From clustering to cosmology

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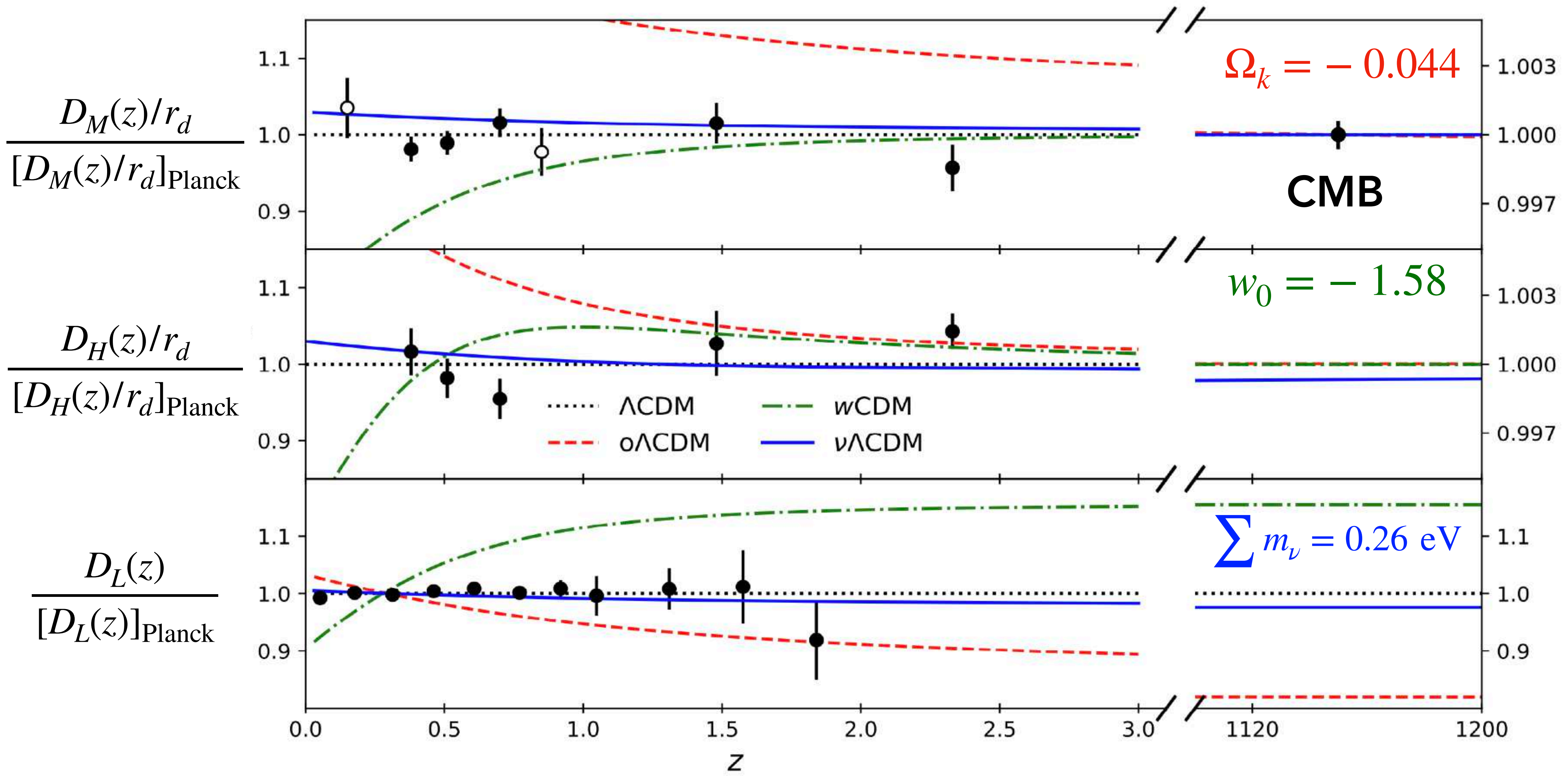
BAO



SNIa

RSD

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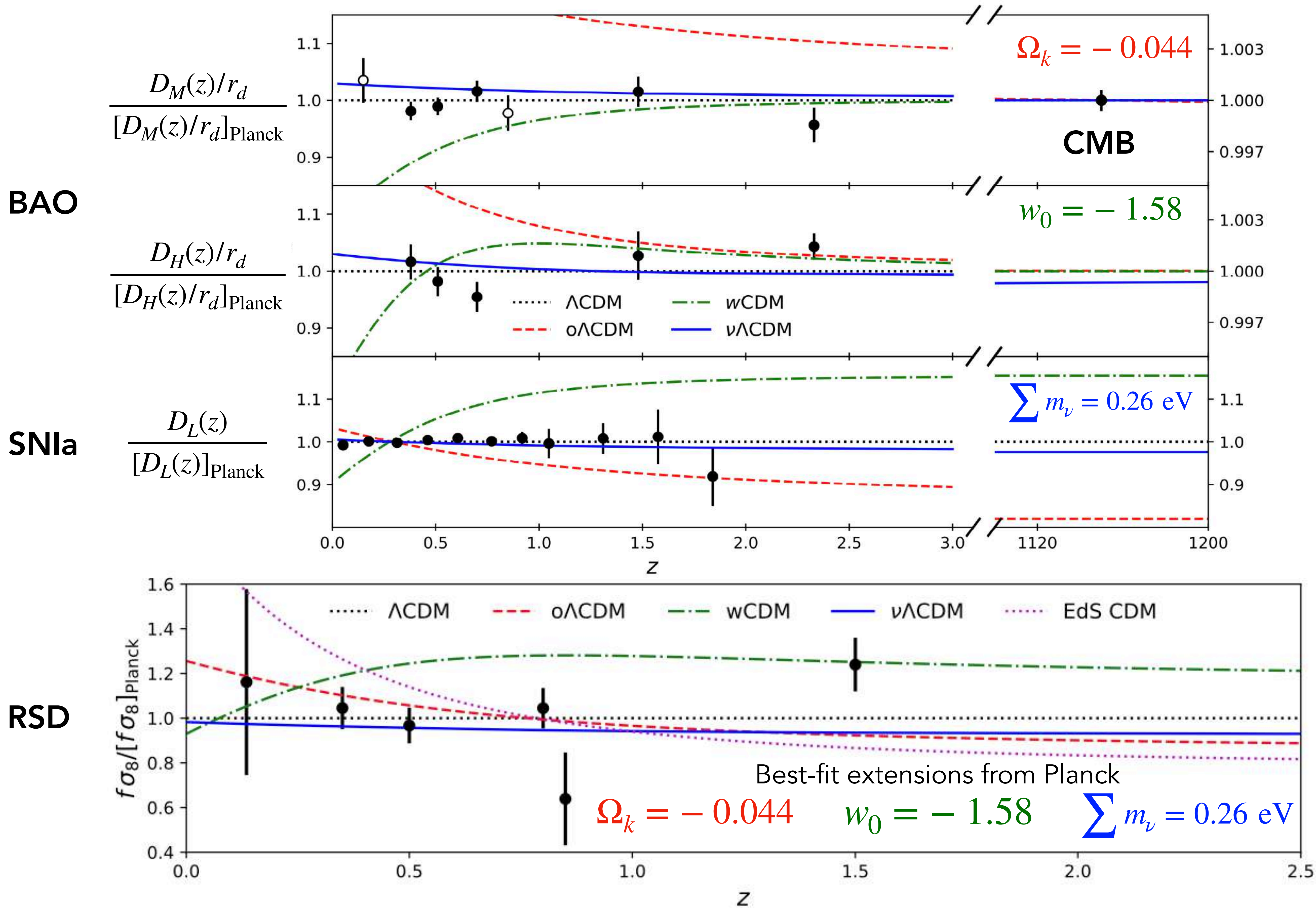

Baryon Acoustic Oscillations (BAO)

What does it measure ?

$$\Delta\theta(z) = \frac{r_{\rm ruler}}{D_M(z)}$$

$$\Delta z(z) = \frac{r_{\rm ruler}}{D_H(z)}$$

$$\Delta\theta(z) = \frac{r_{\rm ruler} H_0}{c \int_0^z {\rm d}z' \, [\Omega_m (1+z')^3 + \Omega_{\rm DE}(z')]^{-1/2}}$$

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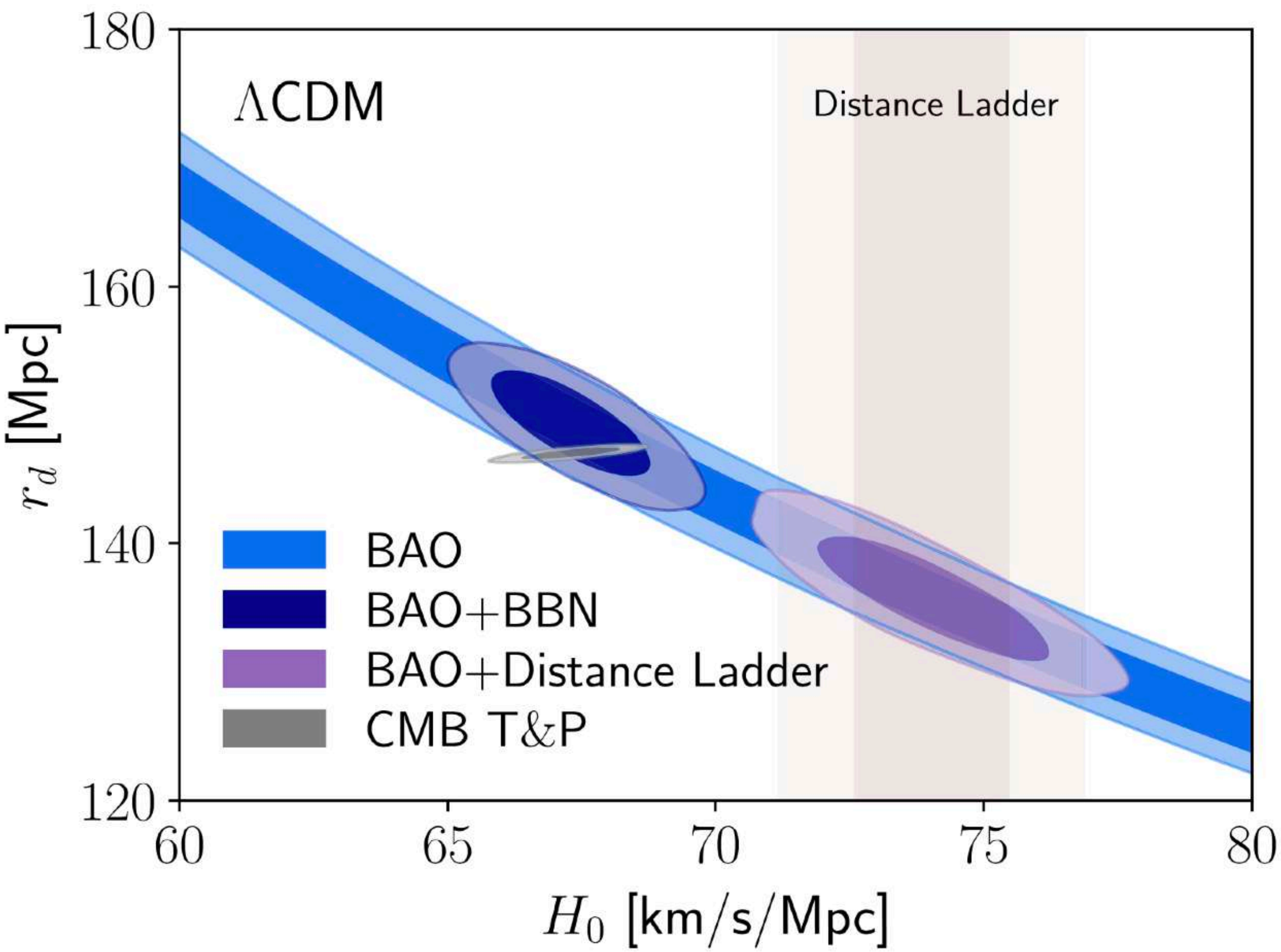

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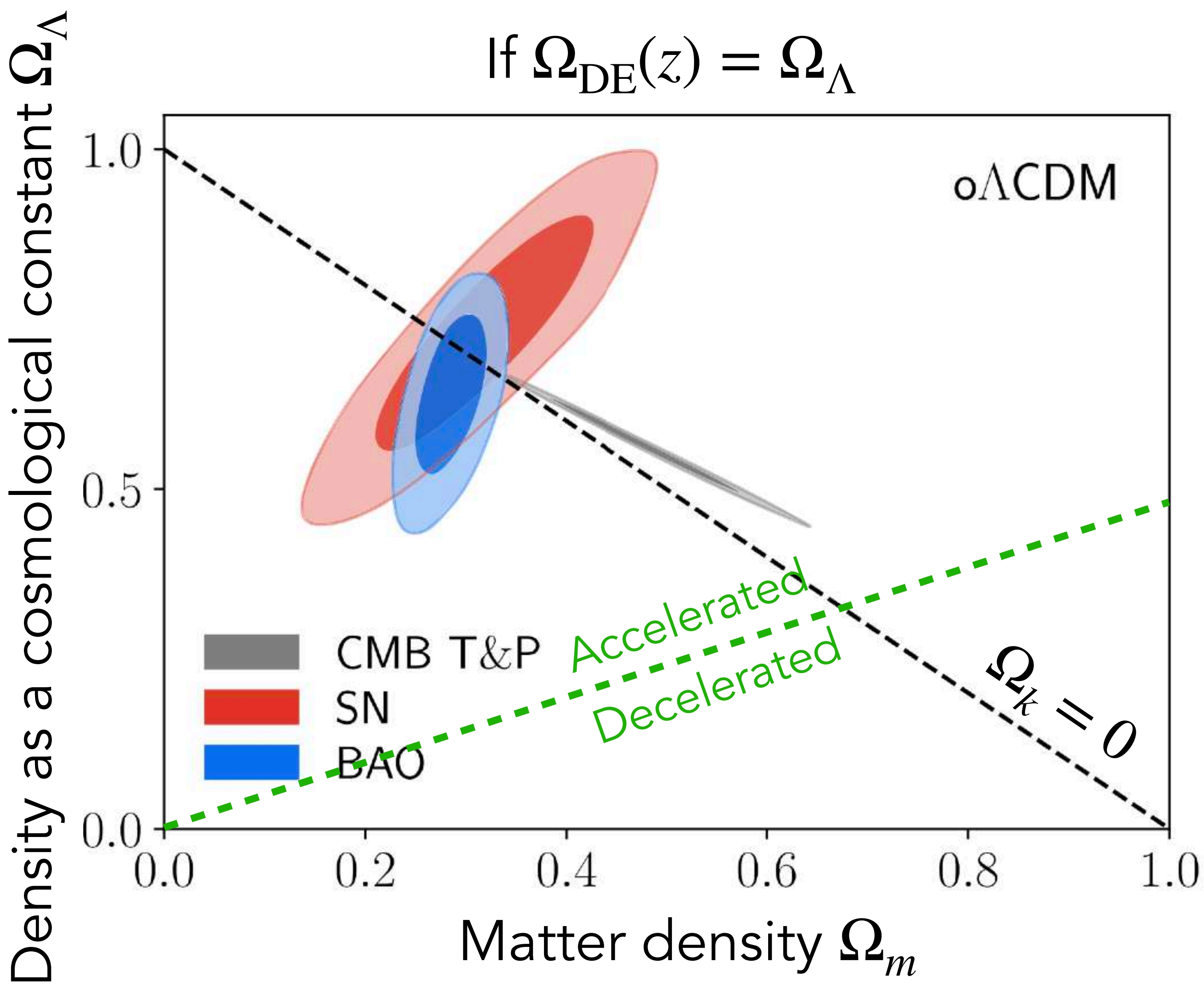
If $\Omega_{\rm DE}(z) = \Omega_\Lambda$



BAO as powerful as SNIa, and independently showing acceleration !

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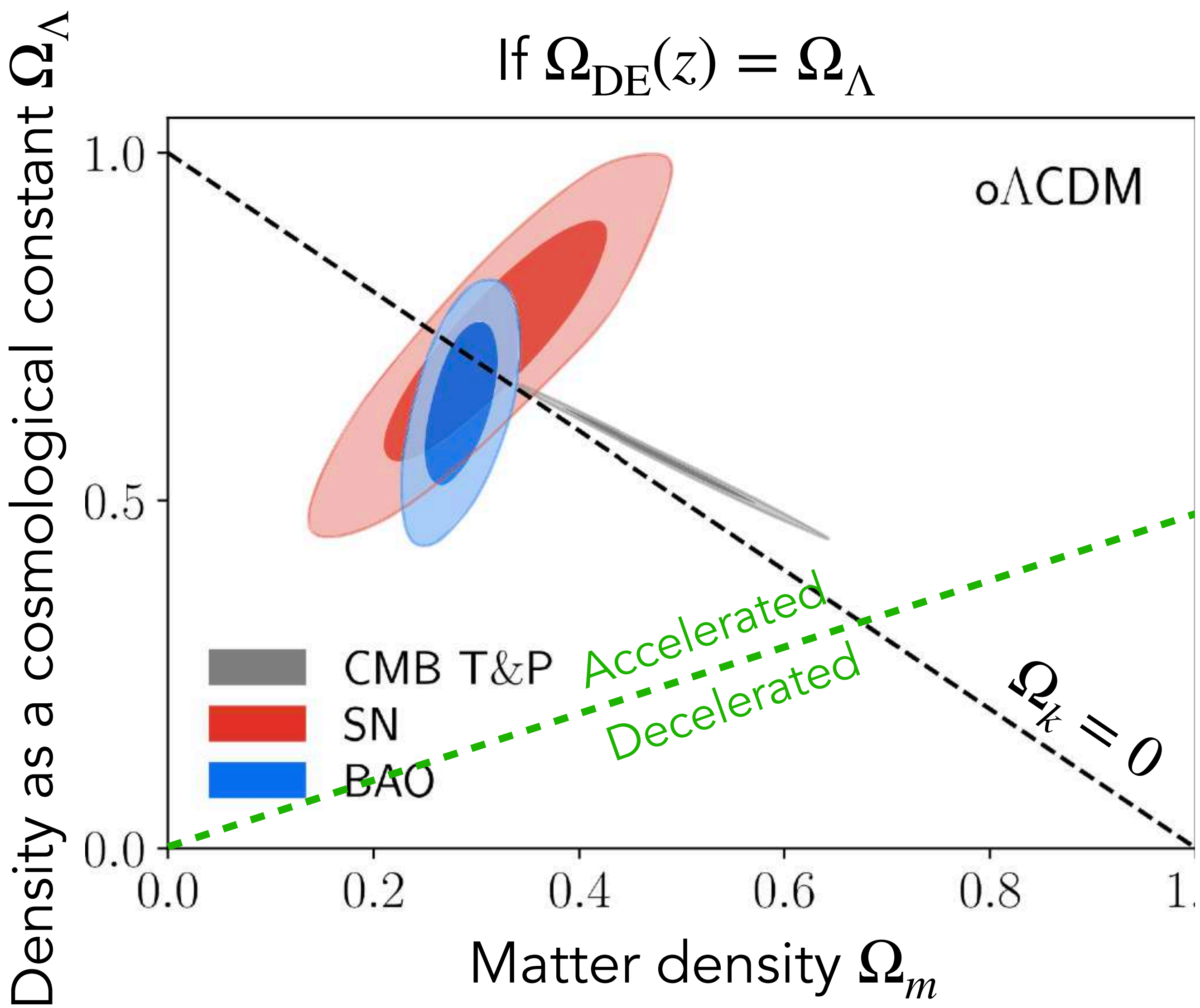

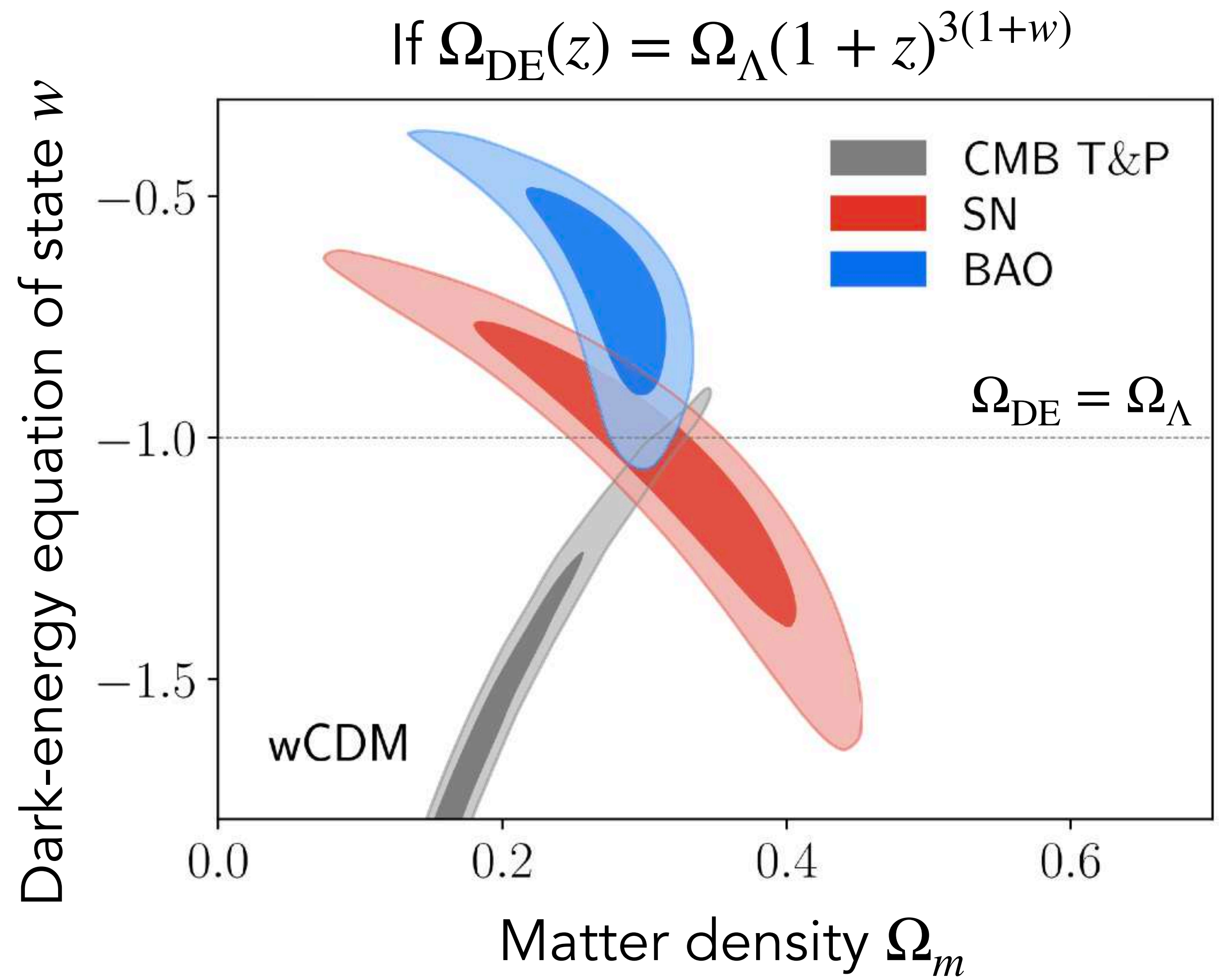

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Testing modified gravity

Redshift-space distortions (RSD) + Weak gravitational lensing (WL)

Scalar metric perturbations in the conformal Newtonian gauge :

$$ds^2 = a^2(\tau)[(1+2\Psi)d\tau^2 - (1-2\Phi)\delta_{ij}dx_i dx_j]$$

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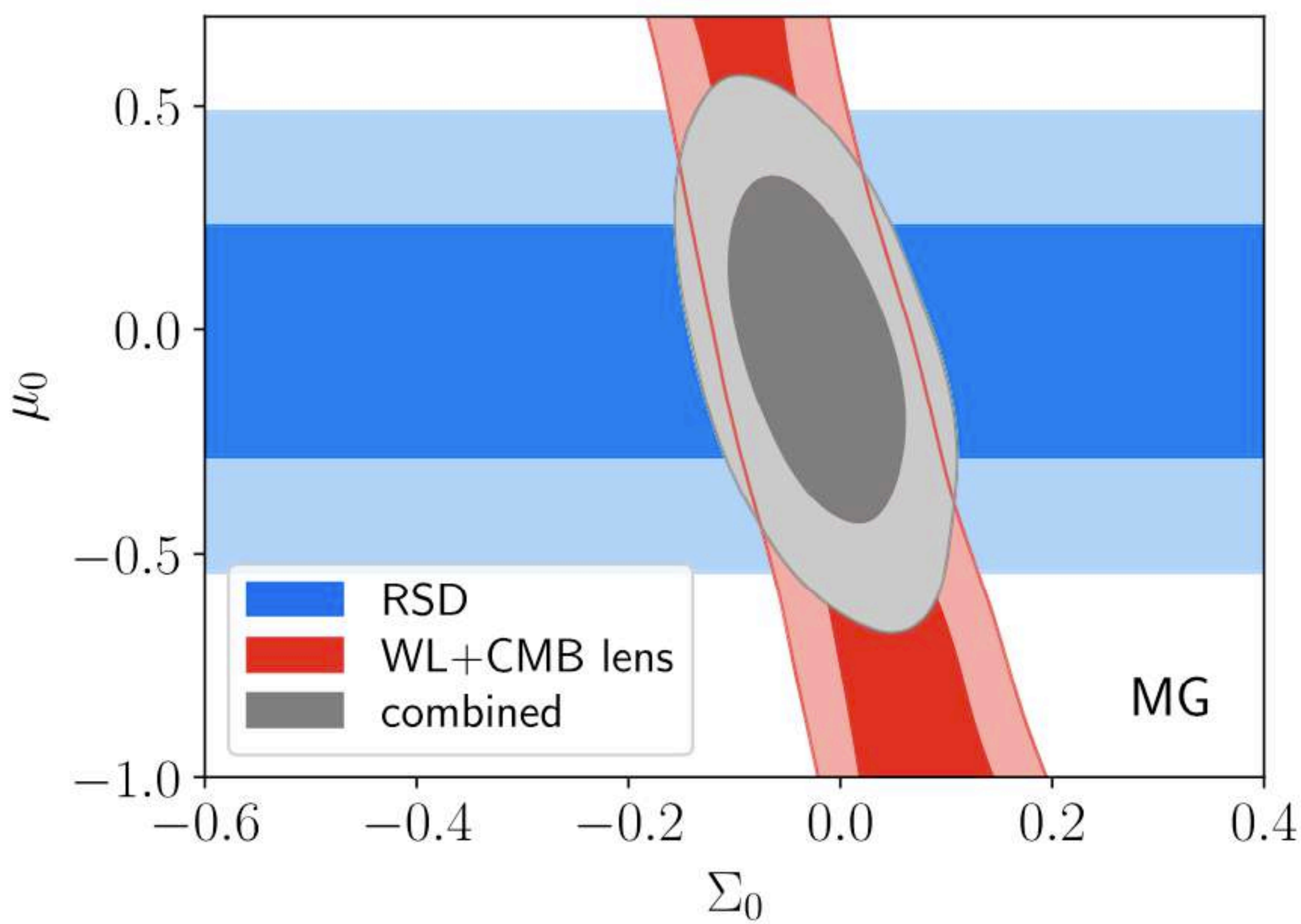

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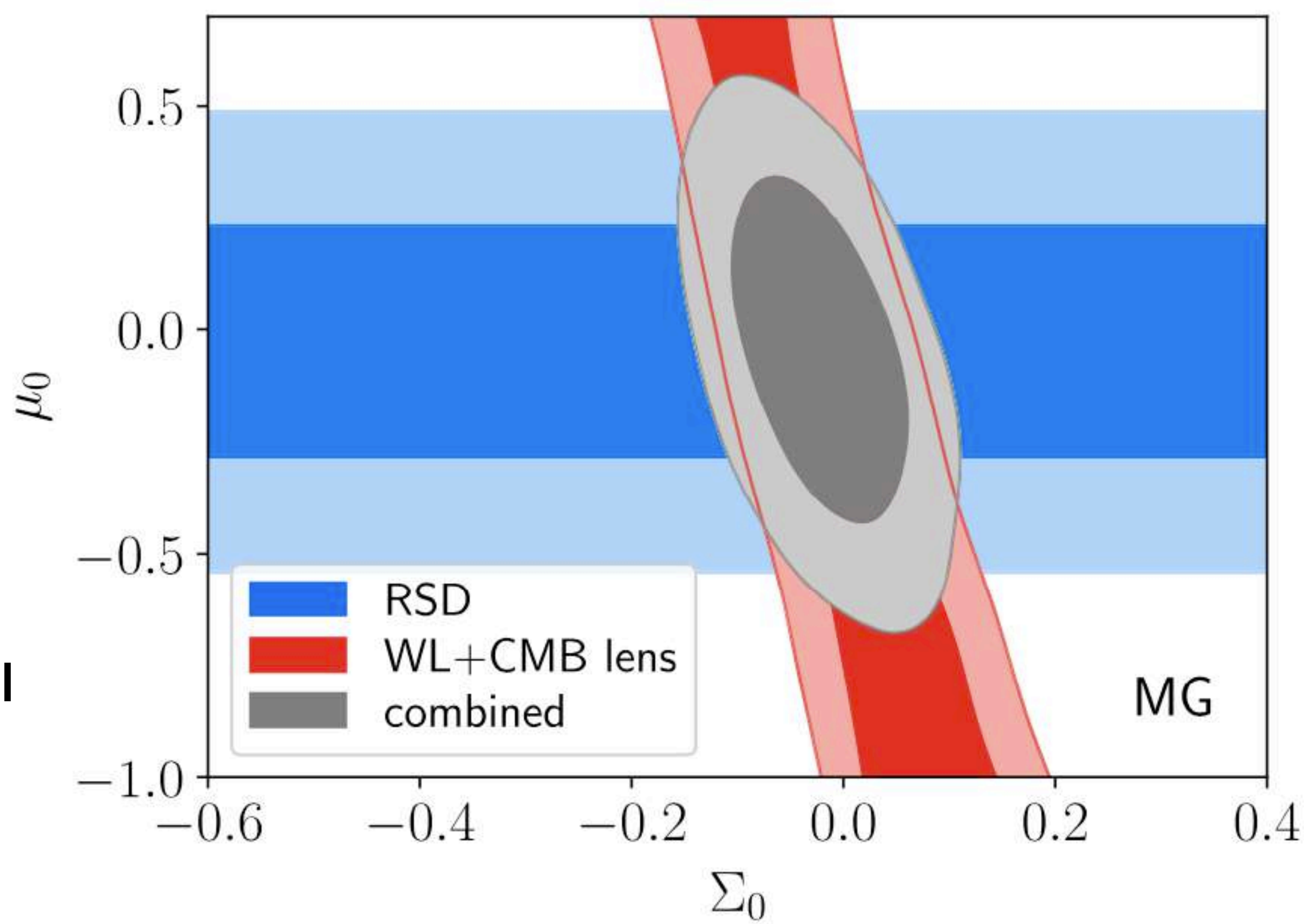
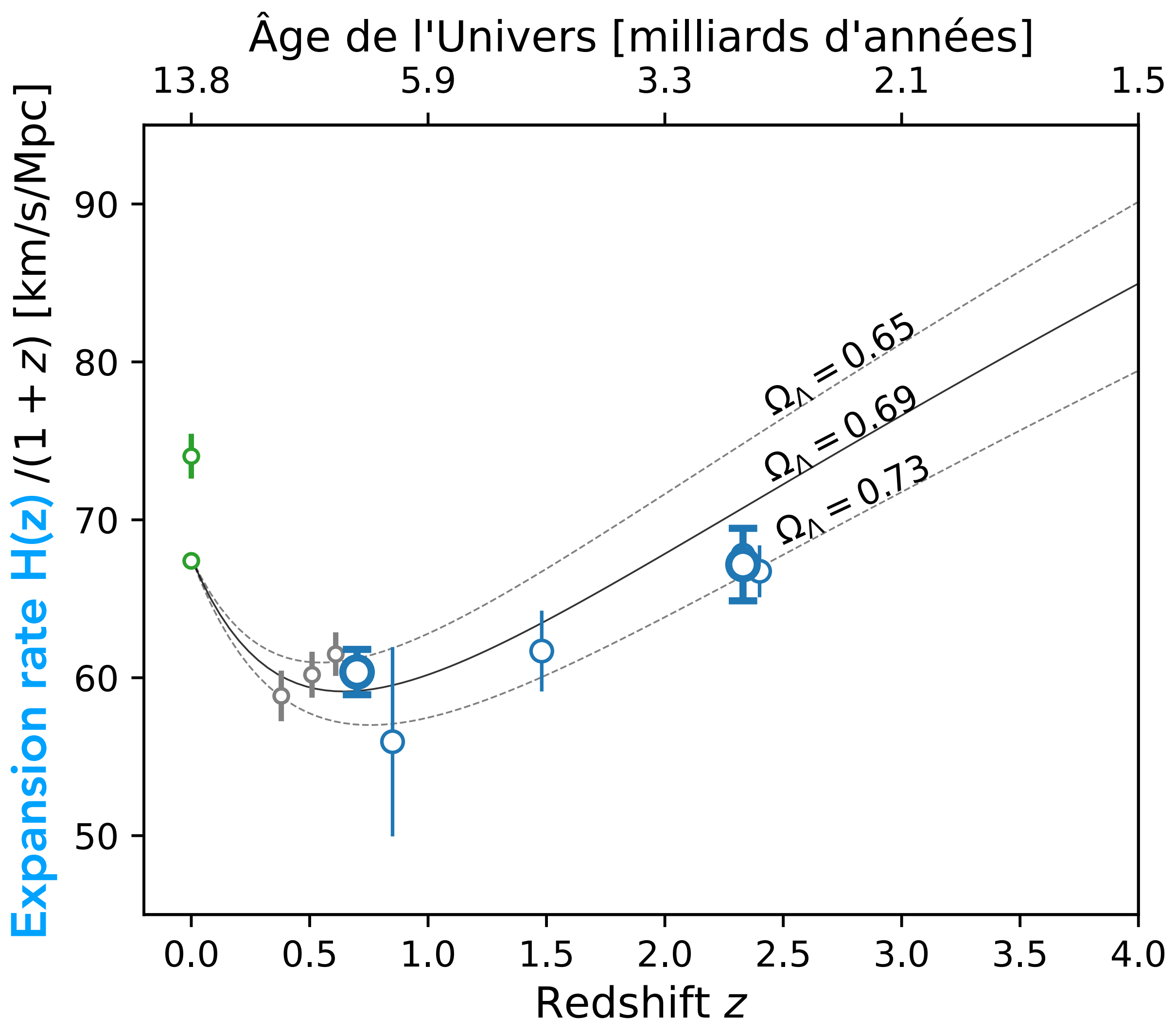


RSD and WL are both essential for testing GR !

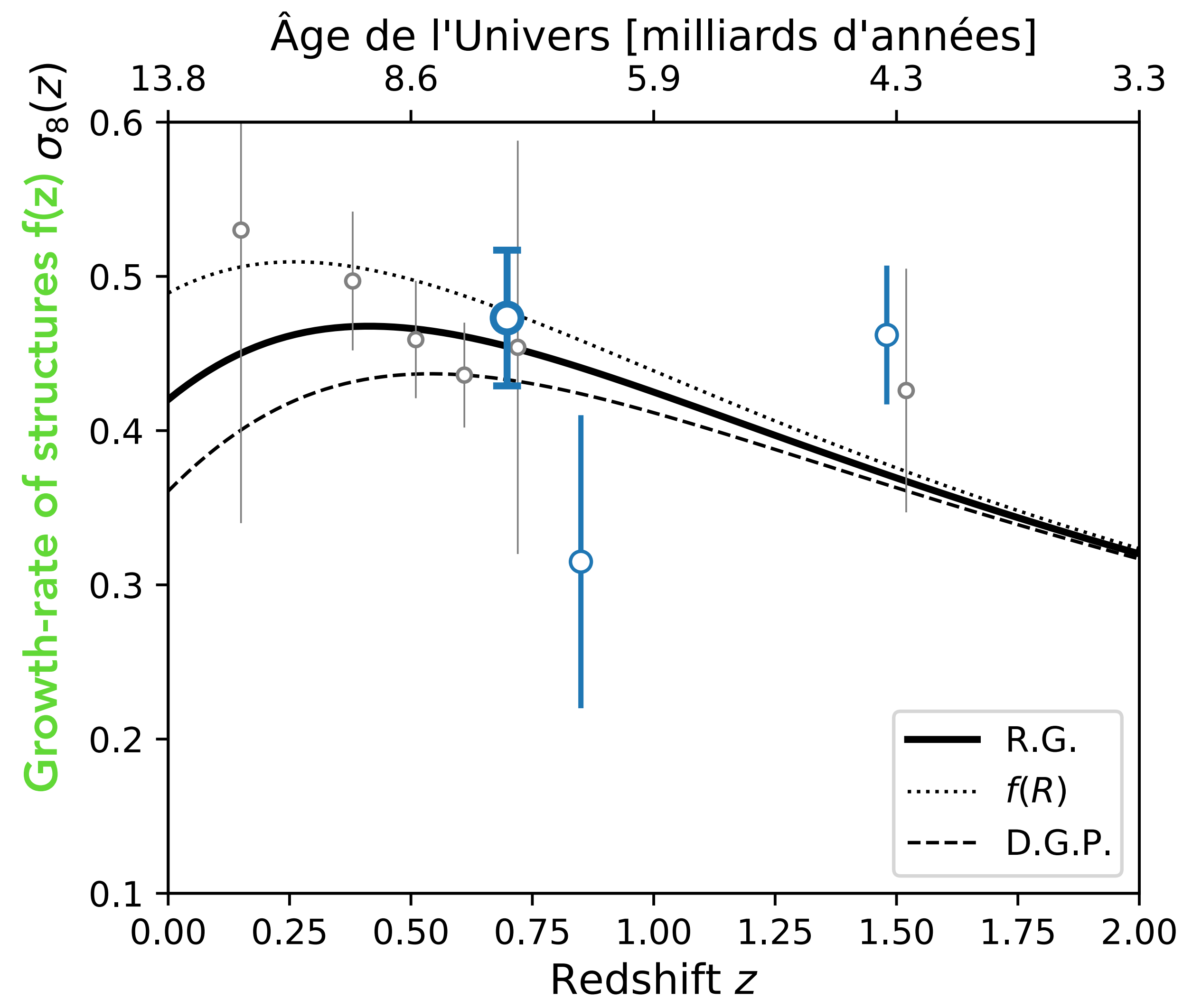
A hint of the future of observations

Future cosmological constraints

Expansion rate with BAO



Growth-rate of structures with RSD and peculiar velocities



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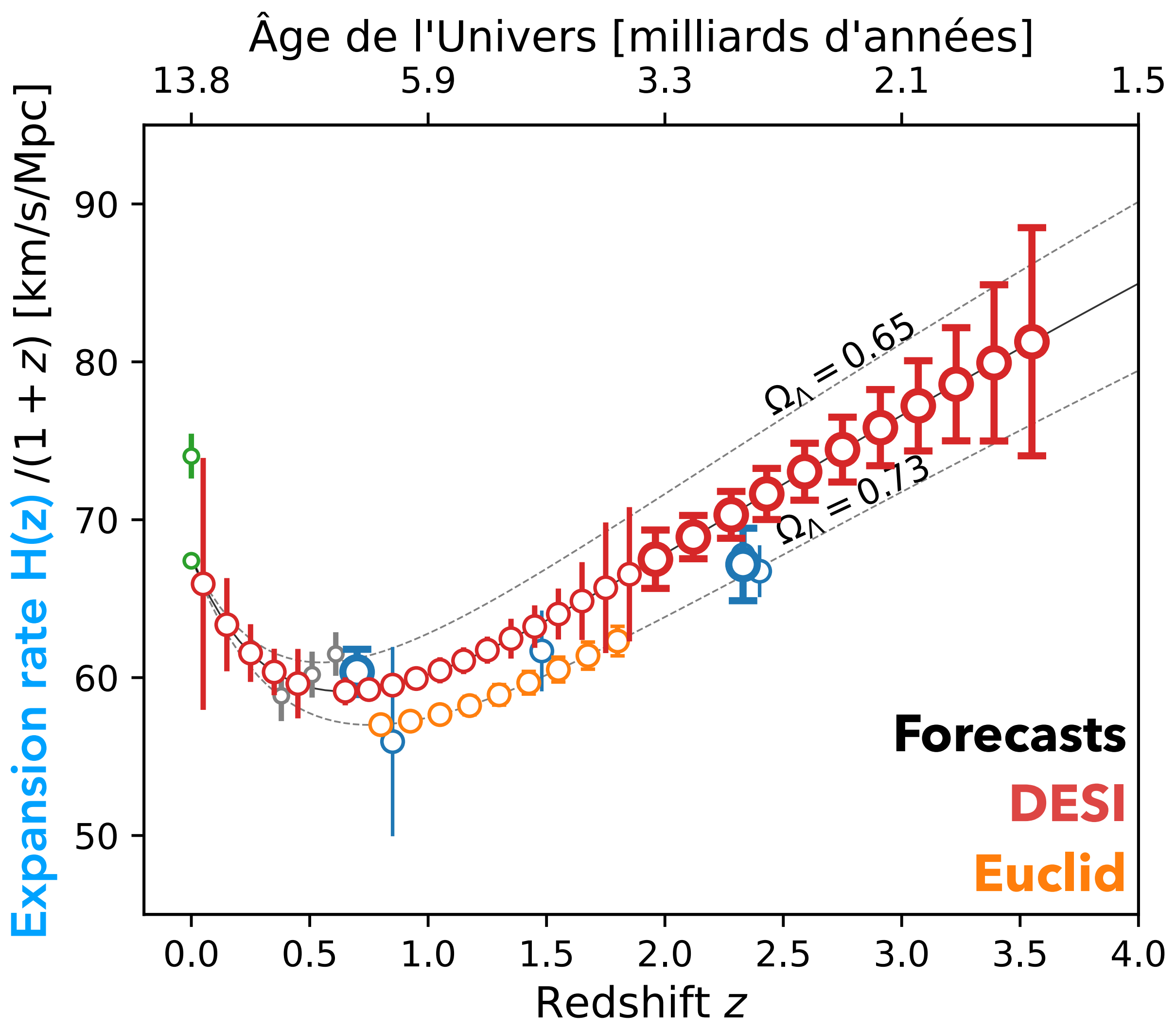

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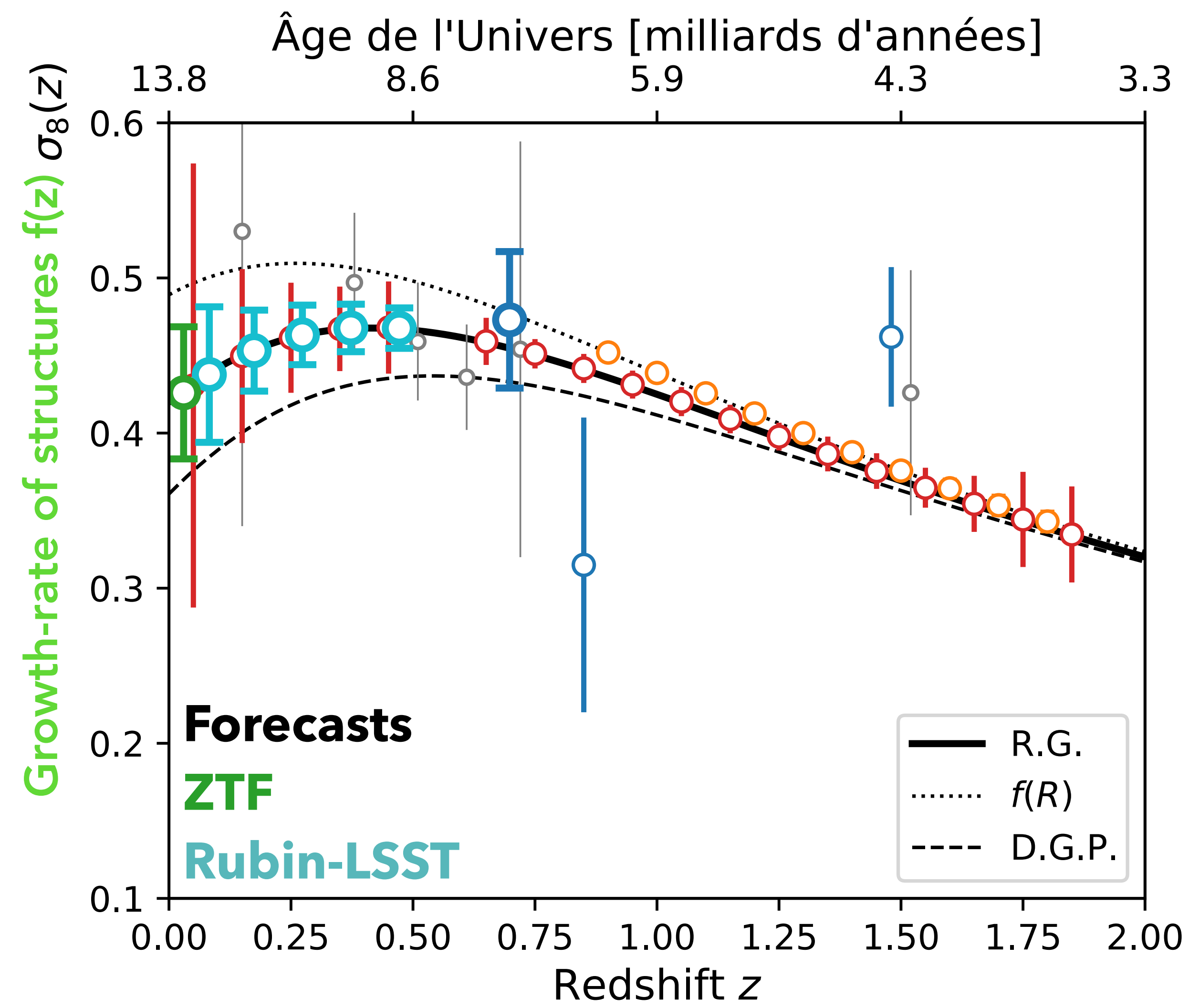

We hope we can learn more about cosmology !


Merci !