The SPHEREx All-Sky Infrared Spectral Survey: Science Overview

Spectro-Photometer for the History of the Universe, Epoch of Reionization, and Ices Explorer

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http://spherex.caltech.edu

SPHEREx Team

SPHEREX DESIGNED TO ADDRESS THE MOST IMPORTANT QUESTIONS IN ASTROPHYSICS

- How did the Universe begin?
  - ➡ Probe the physics of the young inflationary Universe through the 3D spatial distribution of galaxies
- How did Galaxies begin?
  - ➡ Study the cosmic history of light production through near-infrared background fluctuations
- What are the Conditions for Life Outside the Solar System?
  - ➡ Survey the Milky Way for water ices and other biogenic molecules

SPHEREx probes the origin of the Universe, galaxies, and life

We will do so by constructing the first all-sky near-infrared spectral survey

SPHEREX: AN ALL-SKY SPECTRAL SURVEY

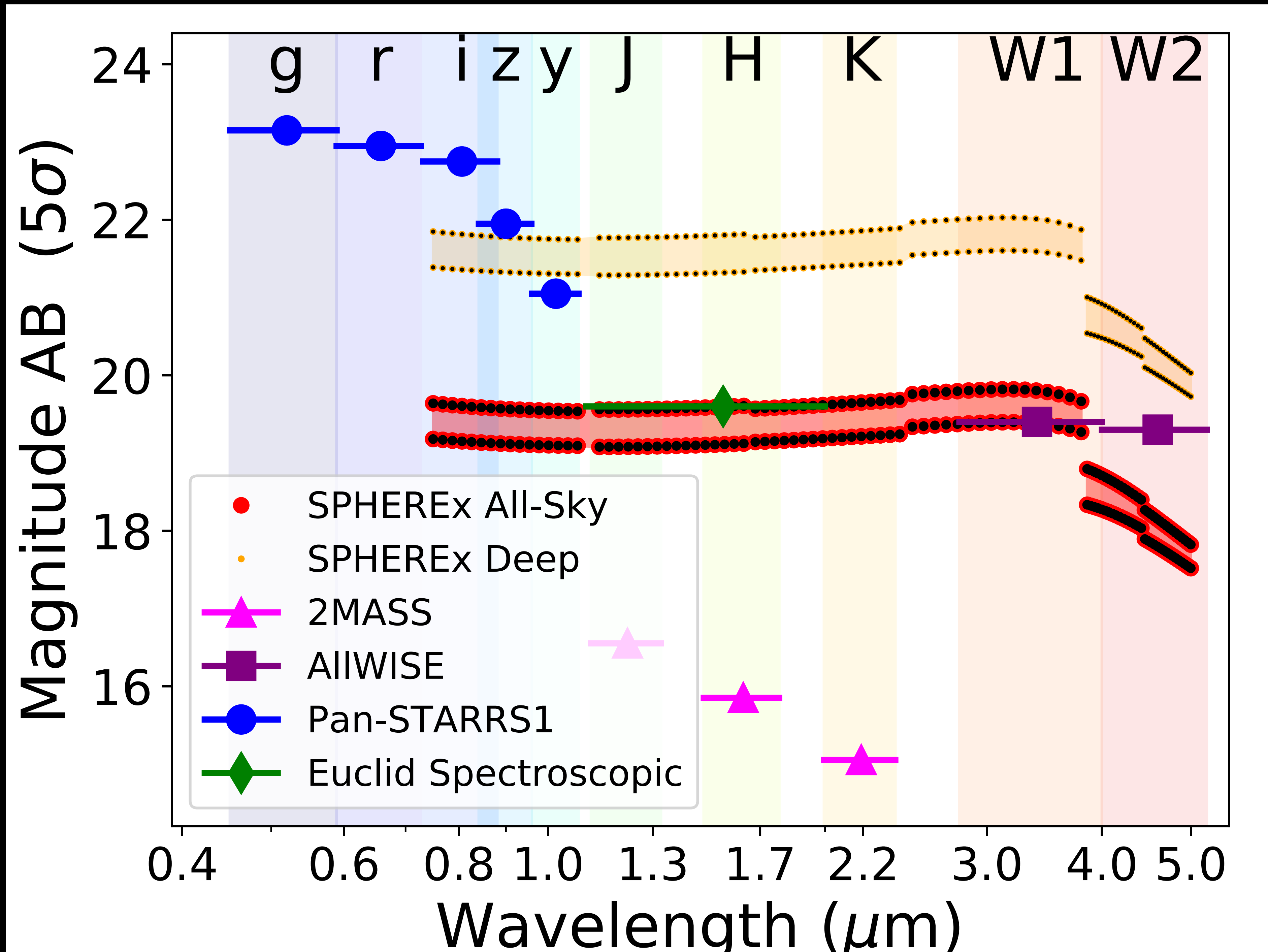
SPHEREx Dataset:

- For every 6.2” pixel over the entire sky:

  ➡ R=35-41 spectra spanning 0.75 μm < λ < 3.82 μm
  ➡ R=110-130 spectra spanning 3.82 μm < λ < 5.0 μm

- ≃ all-sky survey with 102 fine photometric bands

SPHEREX SURVEY DEPTH



Deep survey

All-sky survey

Plot generated in 2018 but actual performances in the lab consistent

SPHEREX SCIENCE TEAM

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ca. March 2023

& strong and experienced engineering team @ JPL and Ball Aerospace

Image Credit: Illustris TNG

SPHEREX TEAM

ca. November 2023

Marveling at the Heavens with SPHEREx

Camille Flamarion 1888

SPHEREX PROVIDES A RICH ALL-SKY SPECTRAL ARCHIVE

Galaxies

Detected
> 1 billion

Med. Accuracy z's
> 100 million

High Accuracy z's
10 million

Clusters
25,000

Stars

Main Seq. Spectra
> 100 million

Dust-forming
10,000

Brown Dwarfs
> 400

Cataclysms
> 1,000

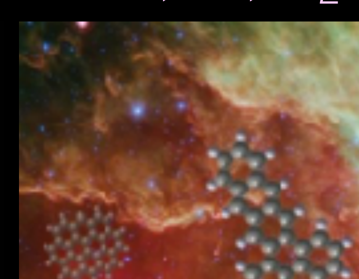
Other

Quasars
> 1 million

Quasars z >7
3 – 300?

Asteroid Spectra
10,000

Galactic Line Maps
PAH, HI, H_2



- ➡ All-Sky surveys demonstrated high scientific returns with lasting data legacy used across astronomy (COBE, IRAS, GALEX, WMAP, Planck, WISE)
- ➡ Many exciting discoveries will come from the community

OD++16,18

AGGRESSIVE DATA RELEASE PLAN
"CONVEYOR BELT MODEL"

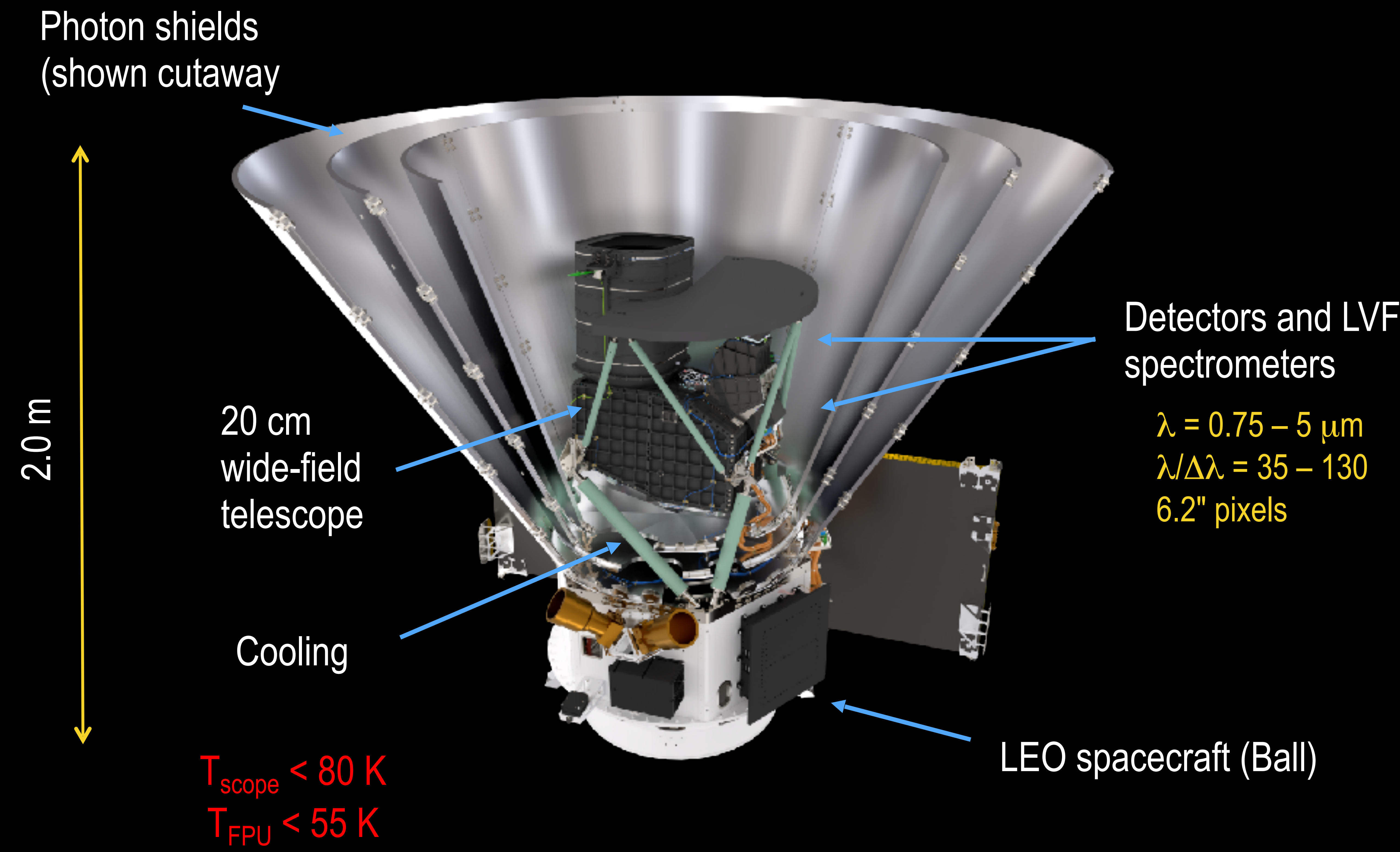
- L : Launch no later than April 2025
- L+1 : End of commissioning
- L+2n: Within 2 months of collection, for 24 months
  - ➡ Release spectral images data (L2 product)
- L+6n : Every 6 months, we complete a full sky survey
  - ➡ Release full-sky products (L2 and data cubes) within 6 months of survey completion
- L+12n: Every 12 months, complete two full sky surveys
  - ➡ Release source catalogs within 2 months of 3d survey data release
- L+24 : End of nominal mission + 1yr of analysis
  - ➡ Release L4 (science) catalogs (galaxy, ices, maps, legacy catalogs)

- Archive hosted by IRSA at IPAC/Caltech (http://irsa.ipac.caltech.edu)
  - ➡ Will also host tools to do on the fly mosaic, forced photometry on a catalog, time variable sources photometry, etc.

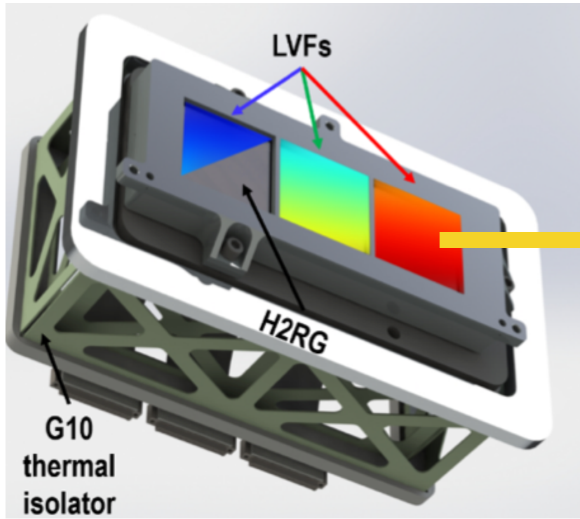
SPHEREX: THE YEARS AHEAD

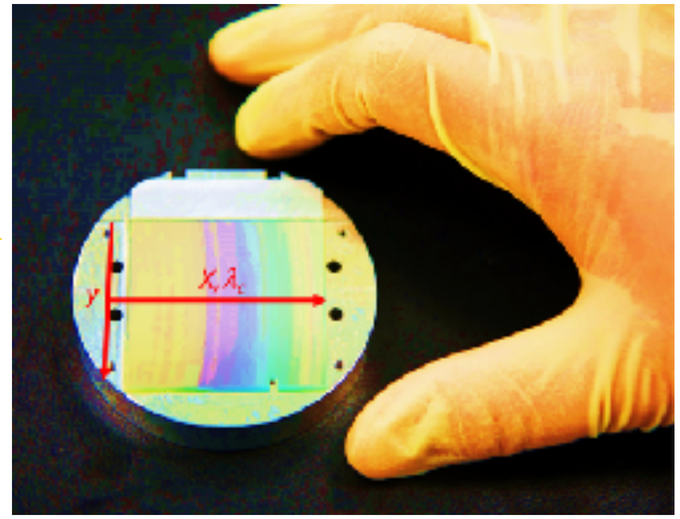
- 08/18-09/18: Phase A
  - ➡ Concept Study
- 02/19: Selection
- 05/19-12/20: Phase B
  - ➡ Preliminary functional design, final trade studies, pipeline development planning, etc.
- 01/21-01/24: Phase C
  - ➡ Final design, fabrication, system assembly
- 02/24-04/25: Phase D
  - ➡ Assemble, integrate, test, and launch using SpaceX F9 @ Vanderberg, AFB
- 02/25-04/27: Phase E
  - ➡ Operate for 2 years
- 05/27-05/28: Phase F
  - ➡ Final analysis

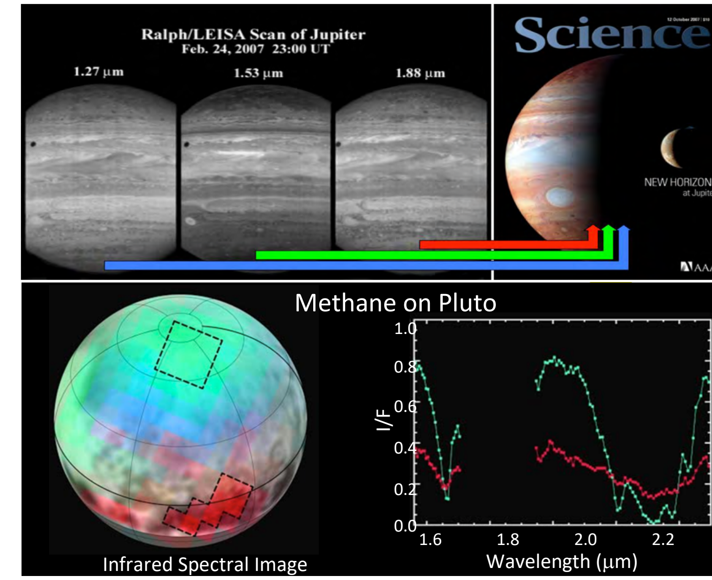
SPHERE^{x} IN A NUTSHELL



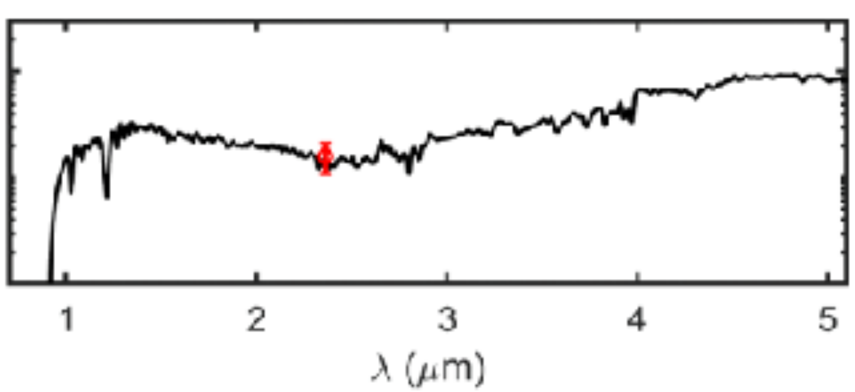
High-Throughput Linearly Variable Filters Spectroscopy

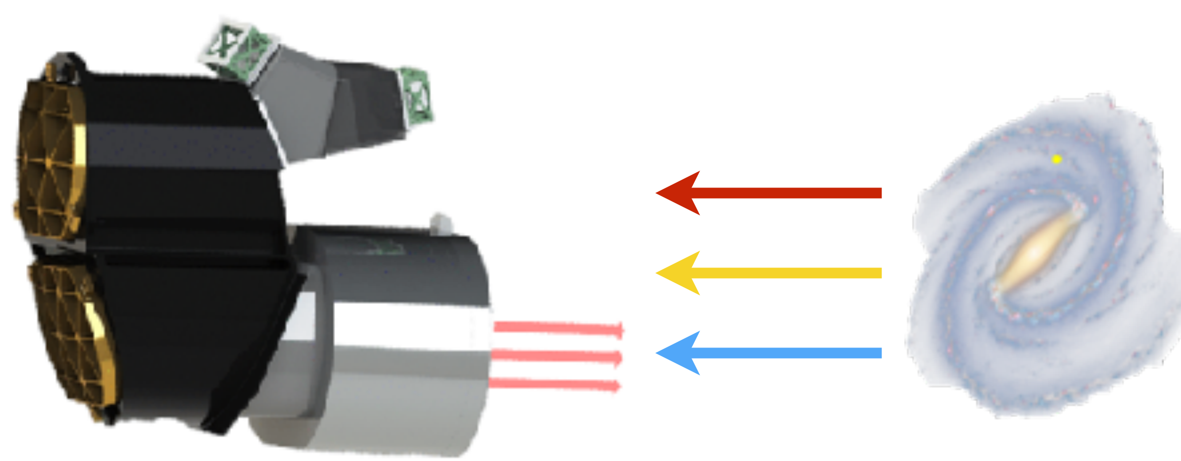






LVF used on ISOCAM, HST-WPC2, New Horizons LEISA, OSIRIS-REx





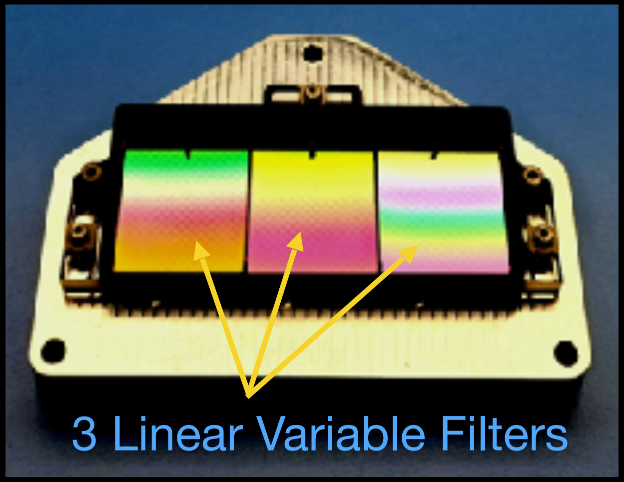
Spectra obtained by stepping sources over the FOV in multiple images: <u>no moving parts</u>

FAST PACE ASSEMBLY AT CALTECH, BALL, AND JPL

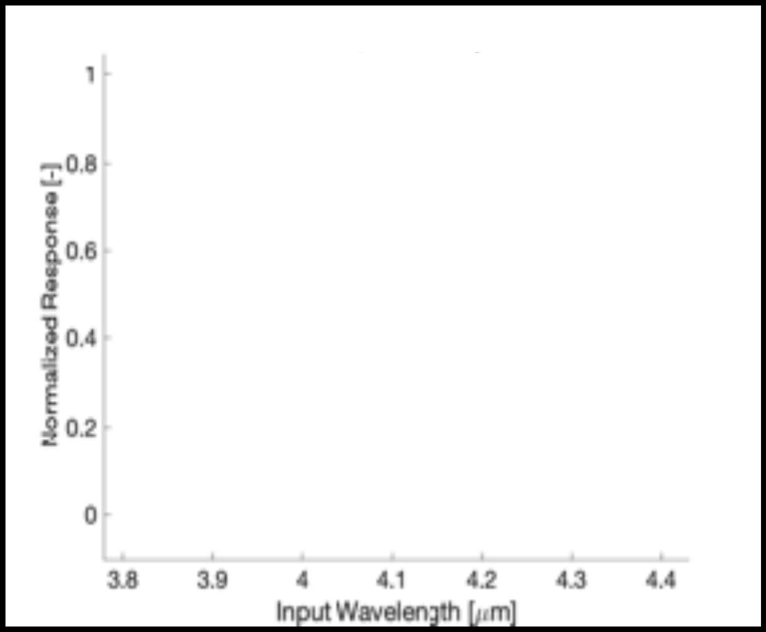
https://www.jpl.nasa.gov/news/test-chamber-for-nasas-new-cosmic-mapmaker-makes-dramatic-entrance

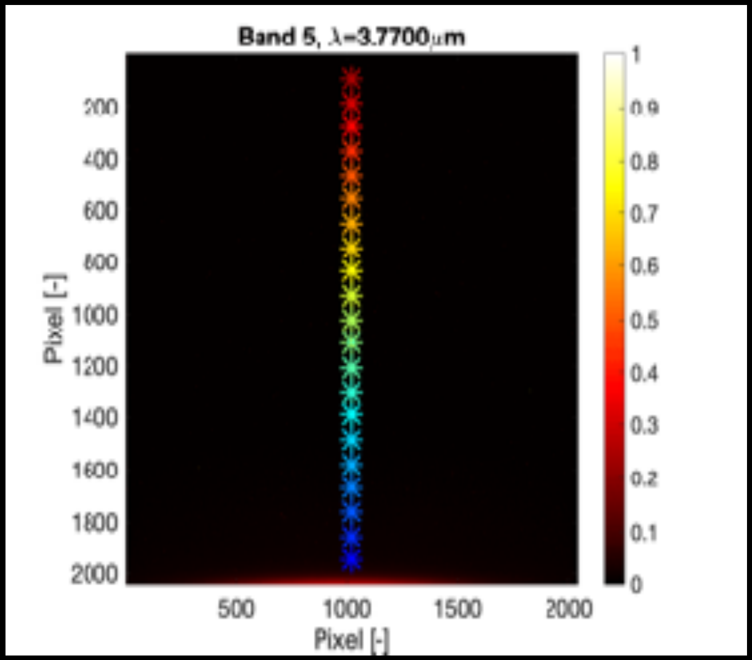
FOCAL PLANES TESTED – SPECTRAL RESPONSE

3 H2RG arrays



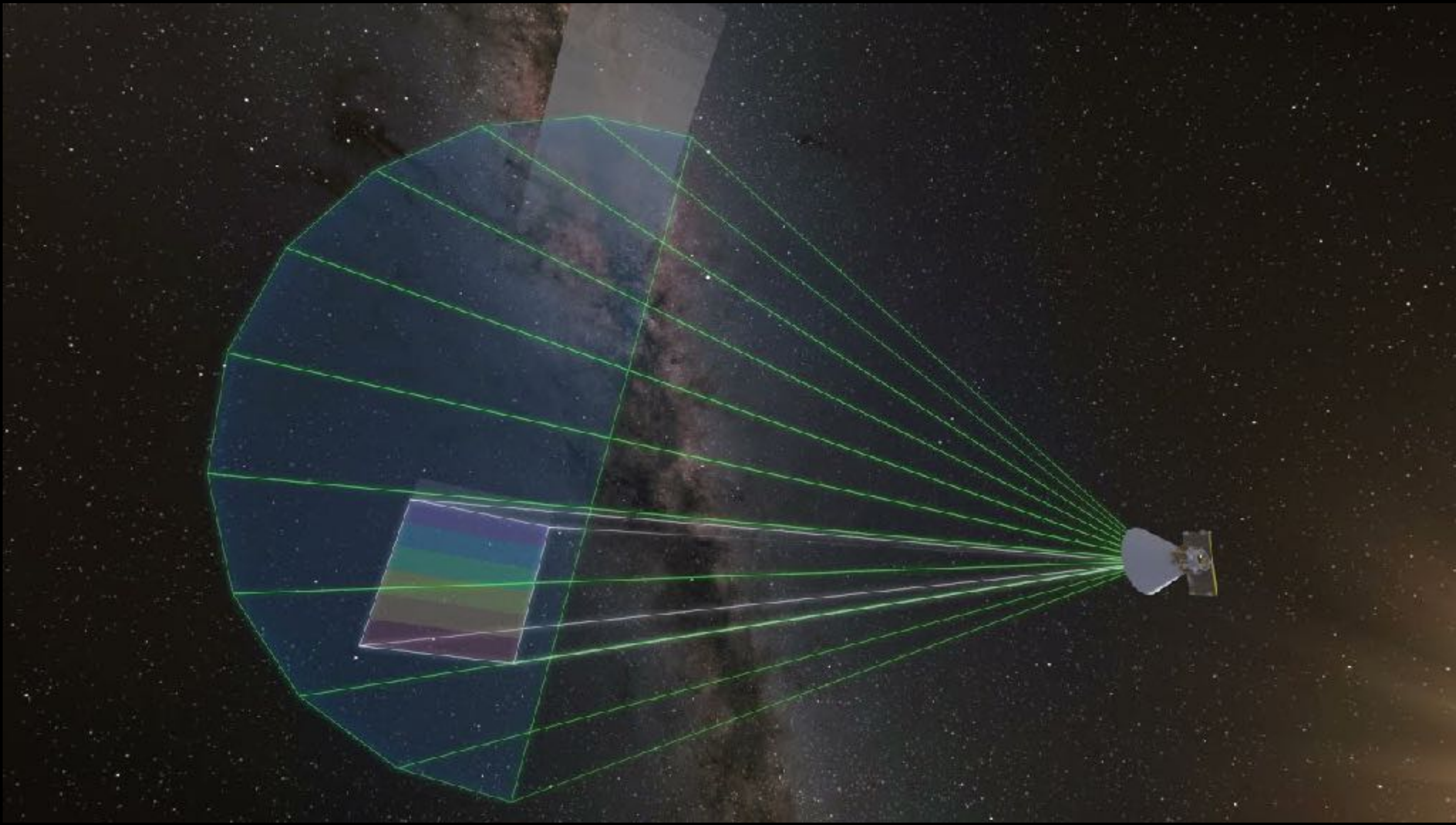
Measured Spectral Response



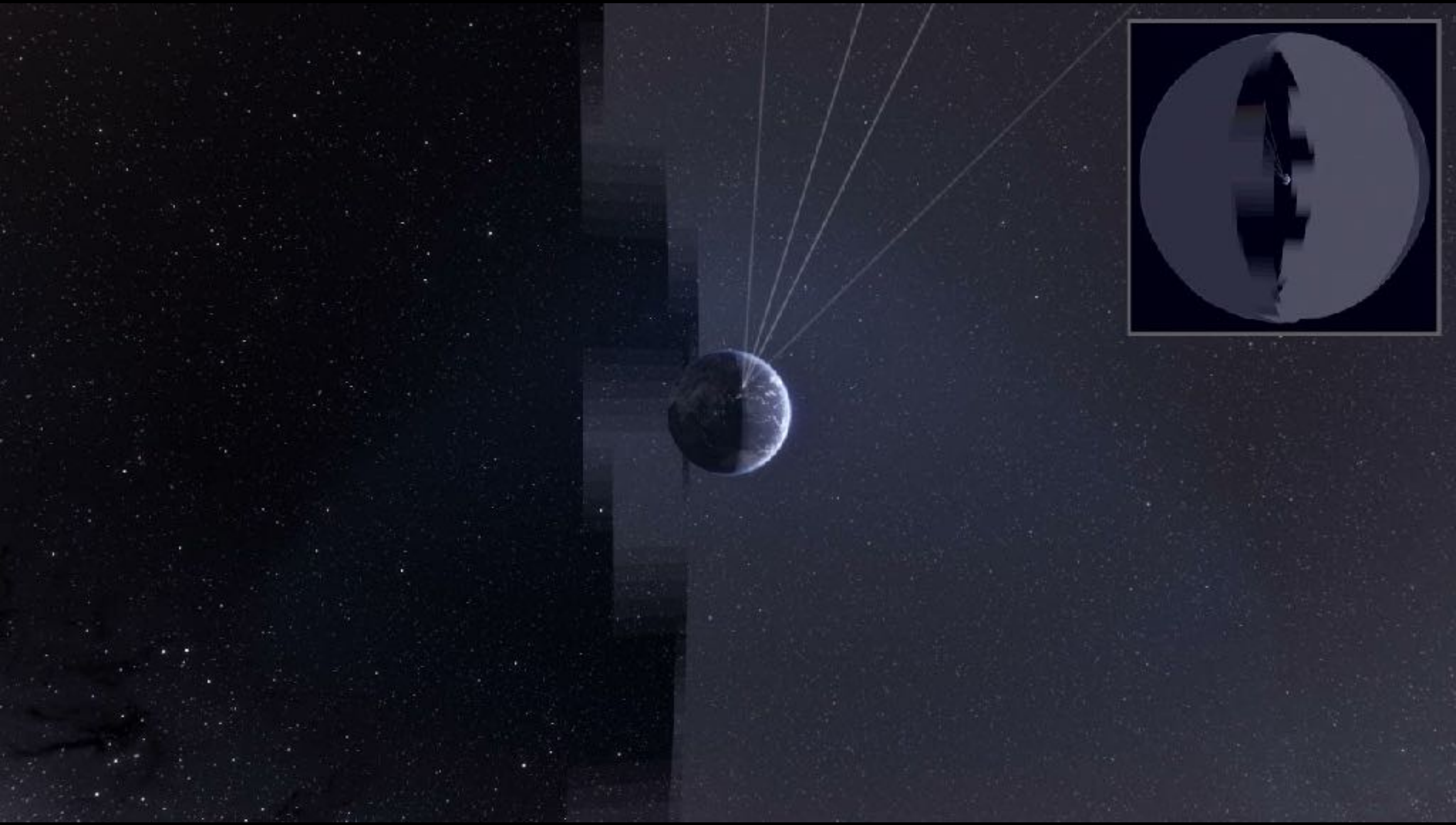


All 6 LVF/H2RG pairs have passed environmental and optical/dark performance testing

PRE-PROGRAMED SCANNING STRATEGY

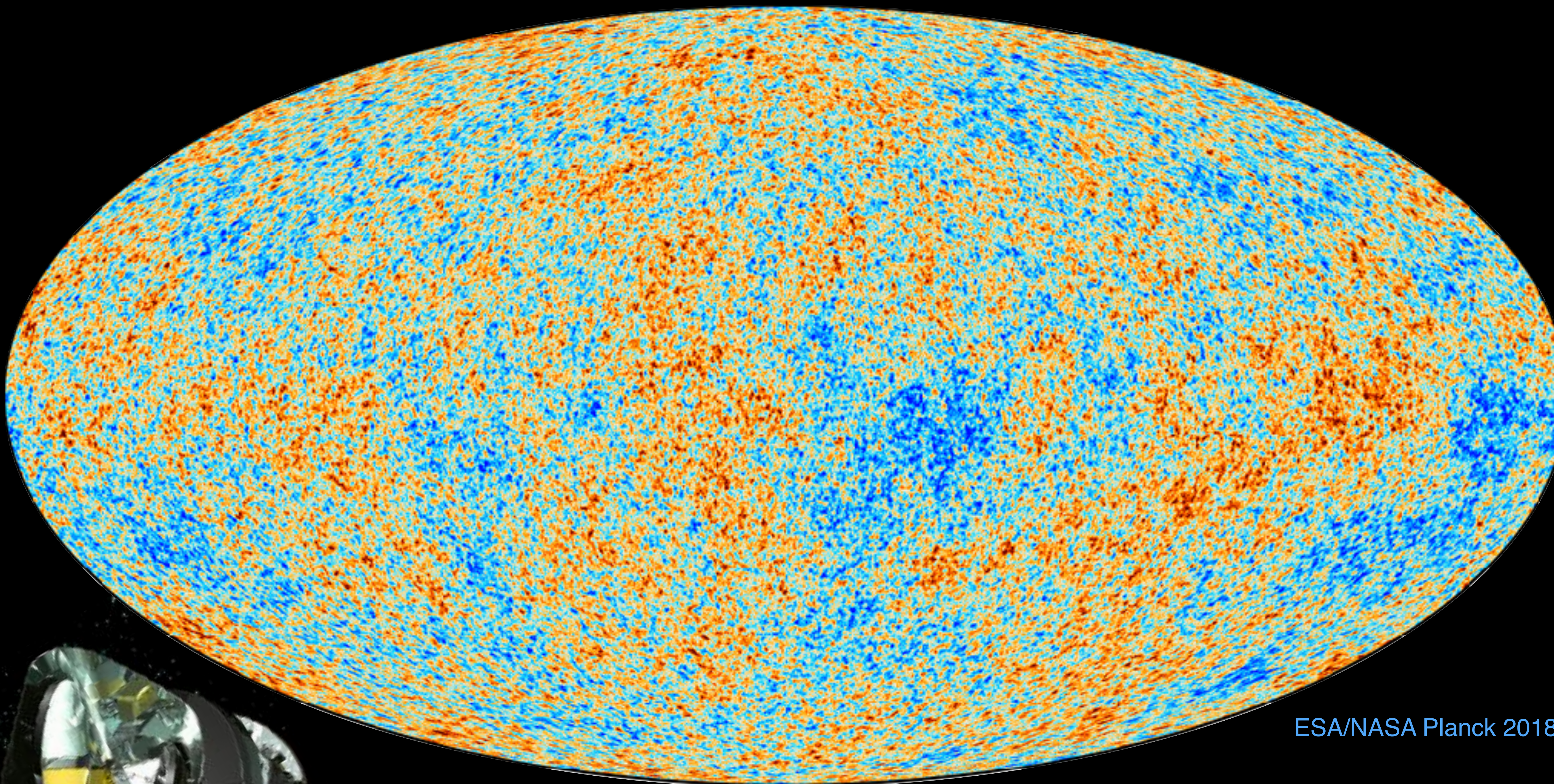


PRE-PROGRAMED SCANNING STRATEGY

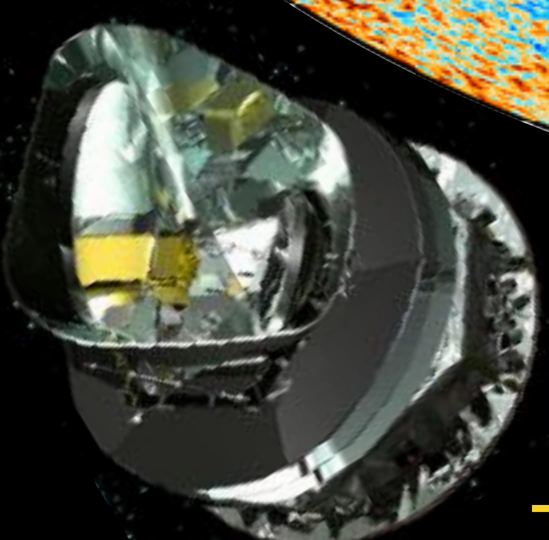


INFLATION INVESTIGATION

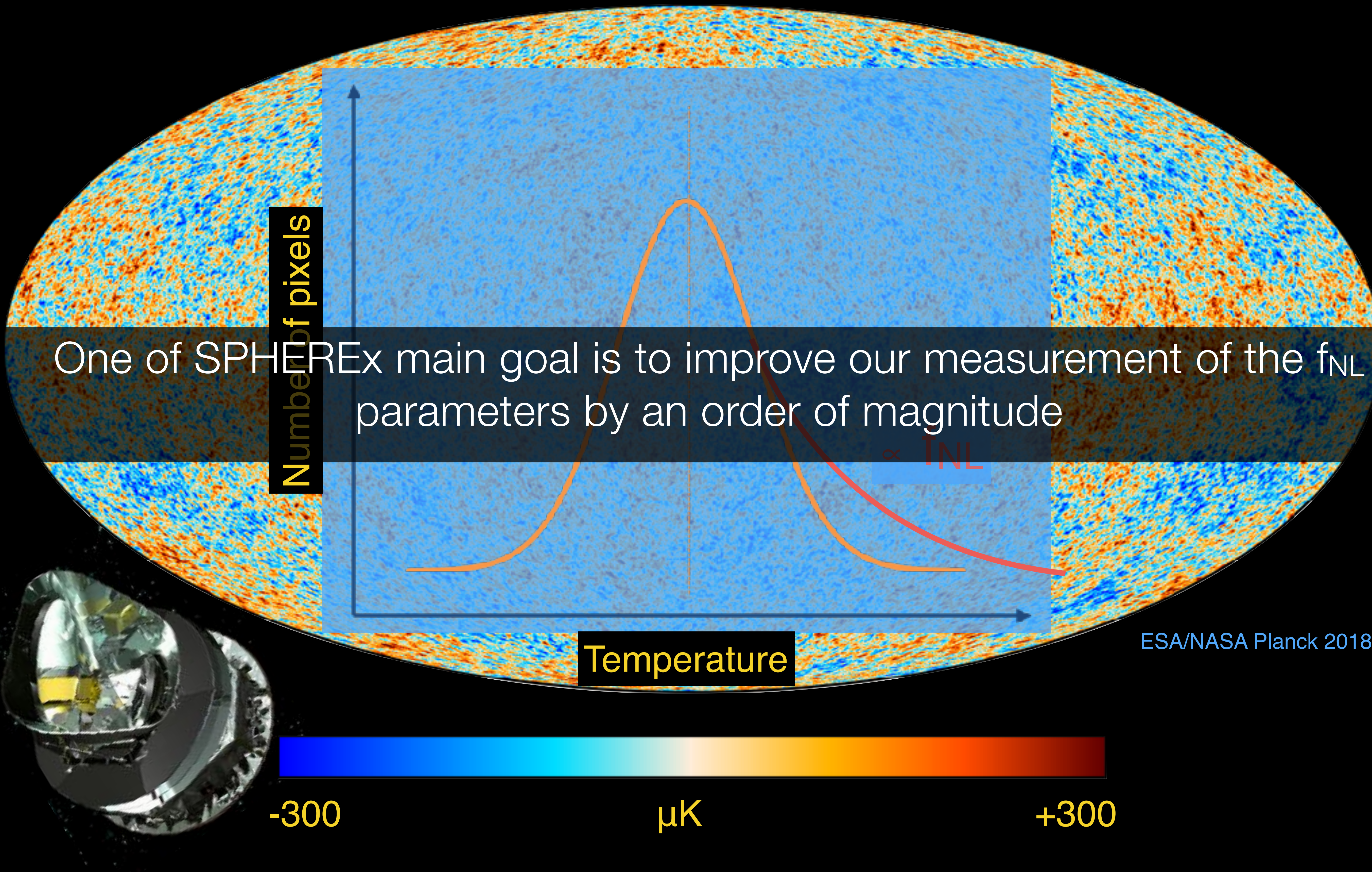
PLANCK MAP OF THE YOUNG UNIVERSE



ESA/NASA Planck 2018

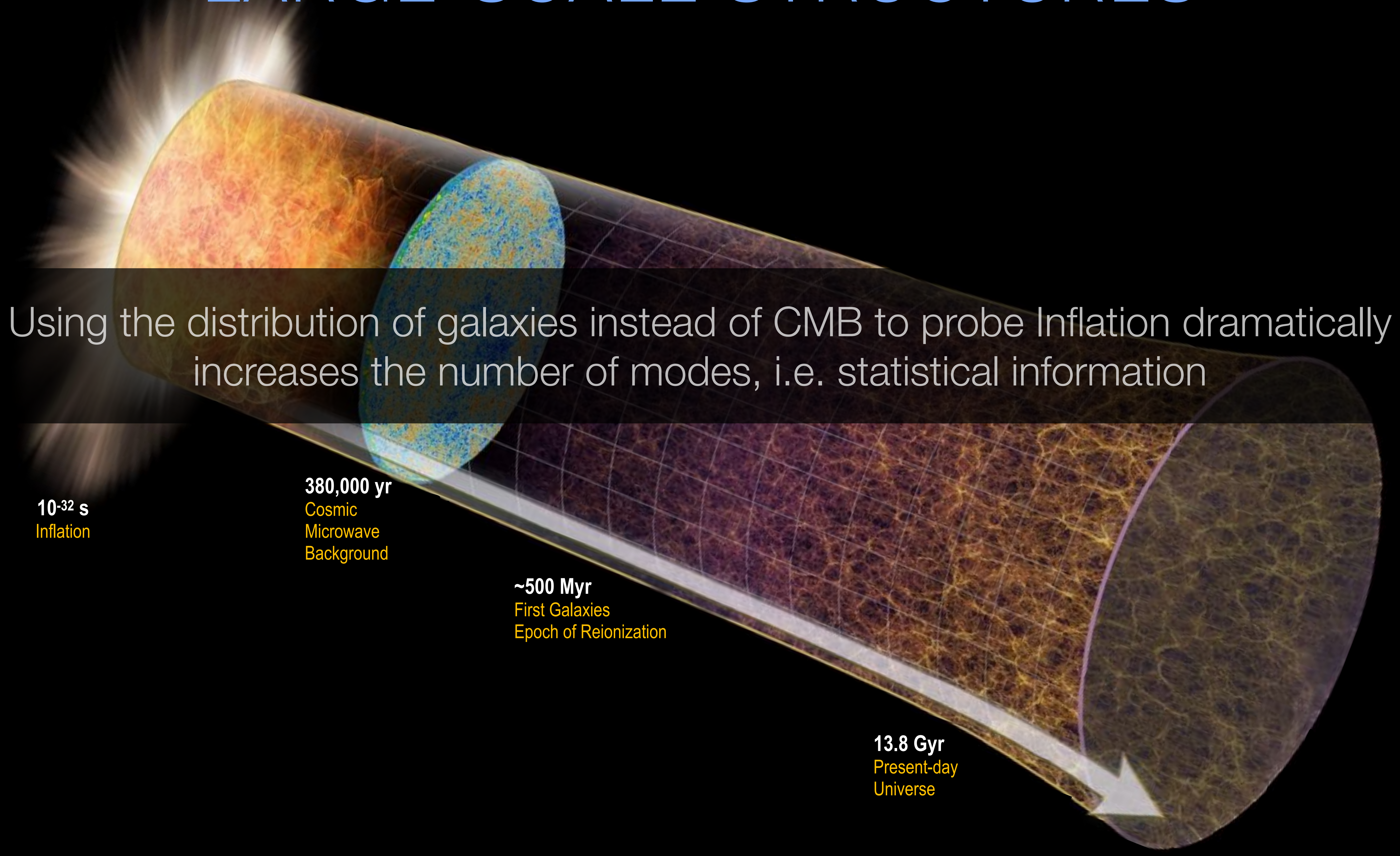


PLANCK MAP IS GAUSSIAN



One of SPHEREx main goal is to improve our measurement of the f_{NL} parameters by an order of magnitude

PROBING INFLATION THROUGH GALAXY LARGE-SCALE STRUCTURES



CMB CONSTRAINTS ON PRIMORDIAL NON-GAUSSIANITY

- Measuring f_{NL} is a unique probe of inflation:
  - ➡ Probes interactions in the primordial Lagrangian
  - ➡ Distinguish between single field and multi-field inflation

$$\Phi = \Phi_G + f_{NL}^{loc}\ \Phi_G^2$$

- Current limit using Planck (T+P) bispectrum:
  - ➡ $f_{NL} = 0.8 \pm 5$ (68%)

- Future limits with a perfect CMB experiment (T+P, $l<3000$):
  - ➡ $f_{NL} \lesssim 2$ (68%)

Planck 2018. IX

PRIMORDIAL NON-GAUSSIANITY INTRODUCES MODE COUPLING

- Peak-background split insights:

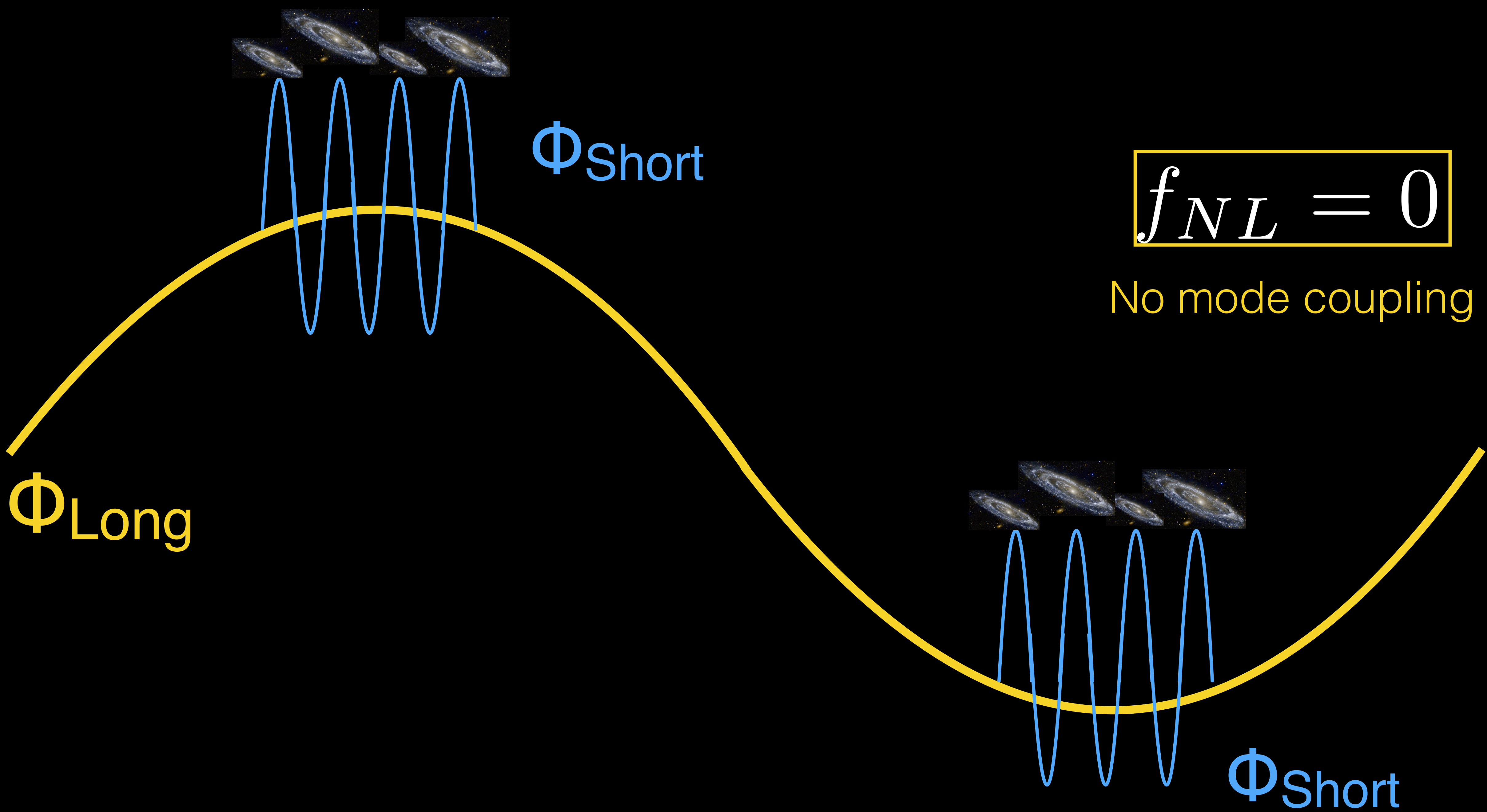
$$\Phi = \Phi_G + f_{NL}^{loc}\ \Phi_G^2$$

$$\Phi = \Phi_{Long} + \Phi_{Short}$$

$$\Phi = \Phi_{Long} + \boxed{f_{NL}^{loc}\ \Phi_{Long}\Phi_{Short}} + f_{NL}^{loc}\ \Phi_{Short}^2 + \ldots$$

Slosar++07, Desjacques++16

PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING



$$f_{NL} = 0$$

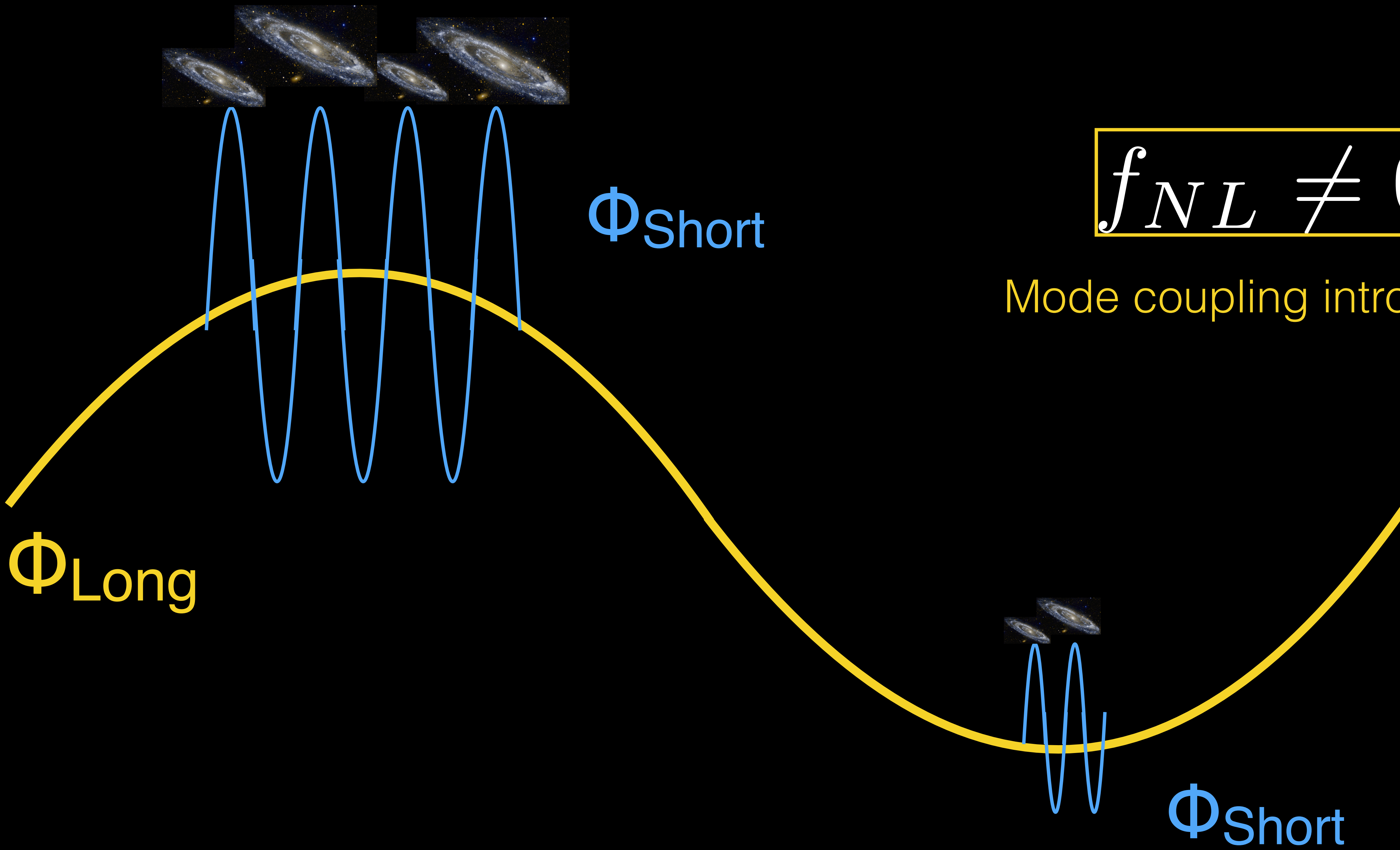
No mode coupling

$$\delta_{galaxy} = b\ \delta_{matter}$$

Galaxy bias (linear)

Slosar et al. 07

PRIMORDIAL NON-GAUSSIANITY AND GALAXY BIASING



$$f_{NL} \neq 0$$

Mode coupling introduced

$$\delta_{galaxy} = b\delta_{matter} + c f_{NL} \Phi_{Long} = (b + \Delta(b))\, \delta_{matter}$$

$$\Delta(b) \propto (b-1)\frac{f_{NL}}{k^2}$$

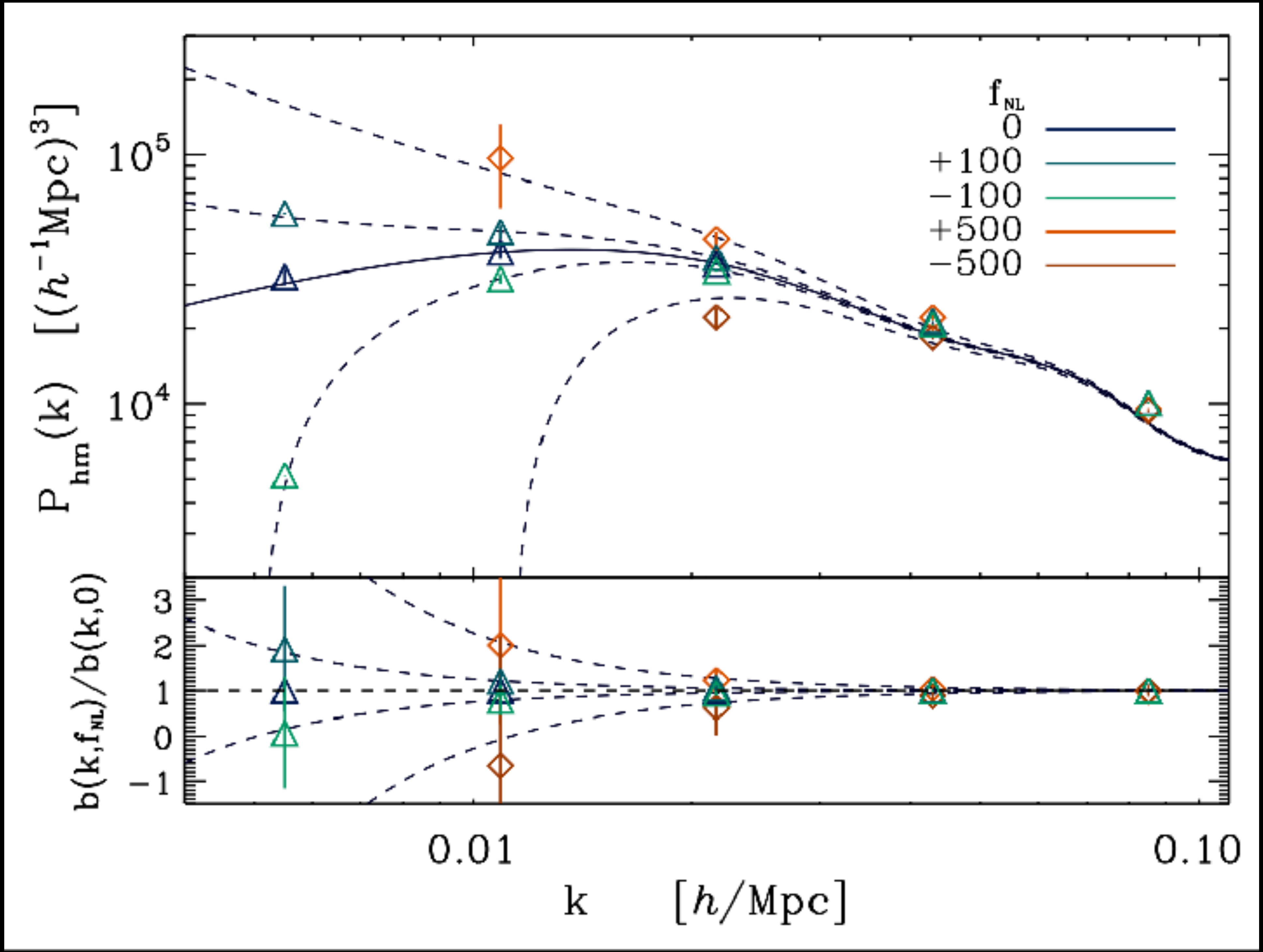
← Scale dependent galaxy bias (assuming universal bias rel.)

PRIMORDIAL NON-GAUSSIANITY AND BIASING

$$b_{NG}^{loc}(q) \propto f_{NL}^{loc} \frac{1}{T(q)q^2}$$

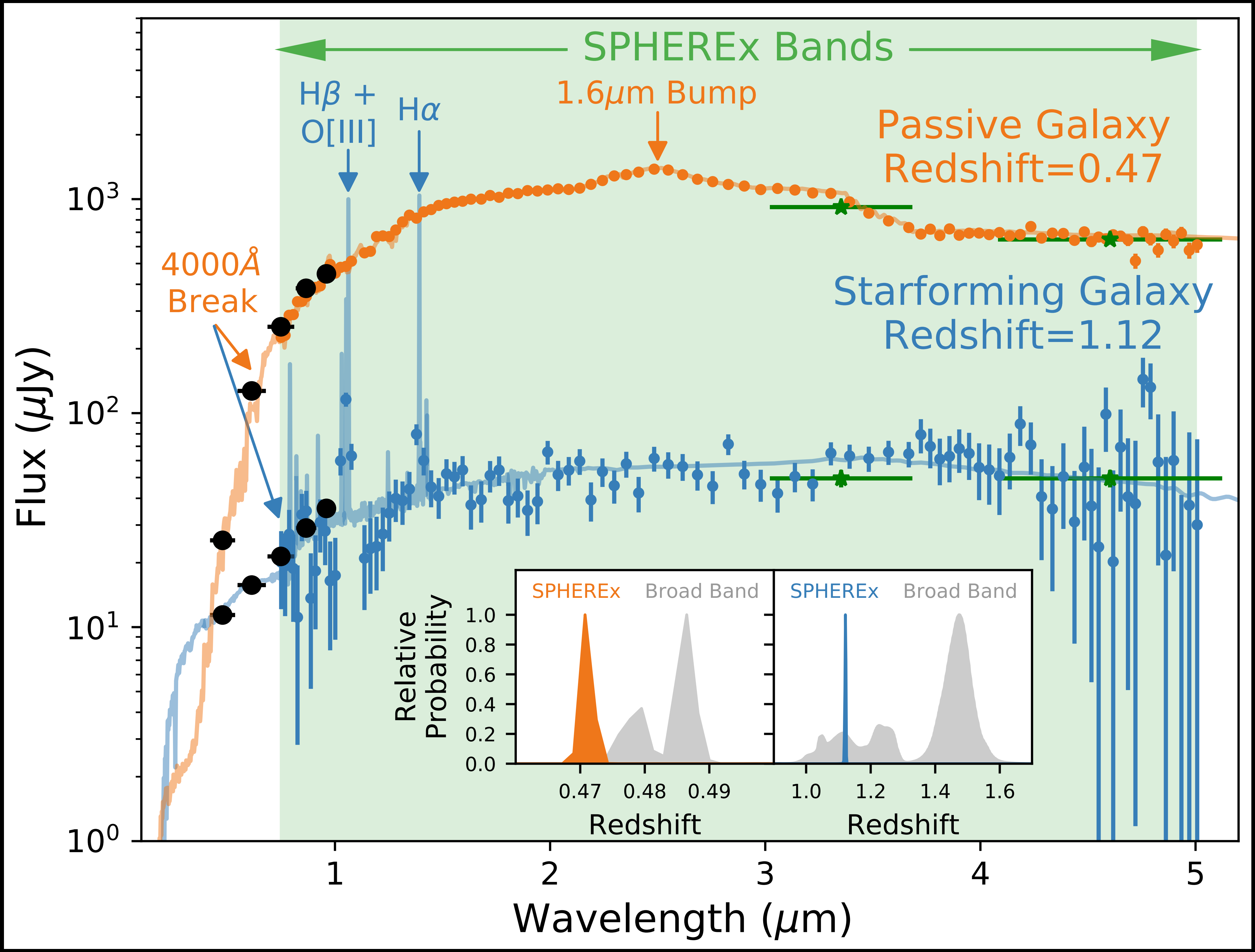
bias(k) $P_{mm}(k)$

bias(k)



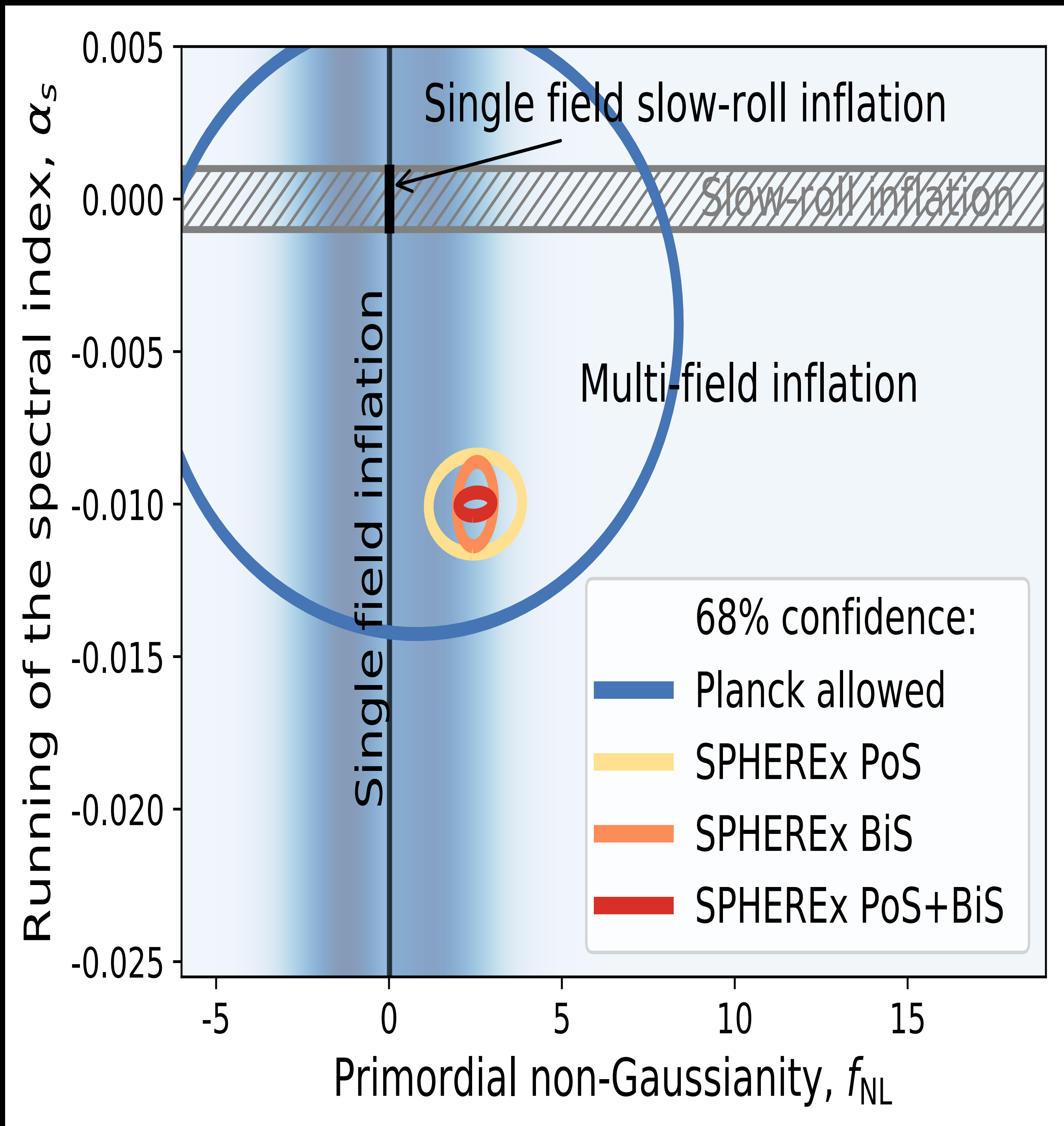
Dalal, OD, Huterer, Shirokov 07

BUILDING A 3-D GALAXY CATALOG WITH SPHEREX



Stickley++16

SPHEREX AND INFLATION



- SPHEREx produces a unique 3-D galaxy survey
  - ➡ Optimized for large scales to study inflation
  - ➡ Two ~independent tests of non-Gaussianity
- SPHEREx improves non-Gaussianity accuracy by a factor of ~10
  - ➡ Improves Δf_{NL} ~ 5 accuracy today to $\Delta f_{NL} < 0.5$
- Discriminates between models
  - ➡ Single-field inflation $f_{NL} << 1$
  - ➡ Multi-field inflation $f_{NL} \gtrsim 1$

WHAT WENT INTO THESE FORECASTS?

- Simulate exposures interpolating the ~166k 30 bands COSMOS sources at SPHEREx 102 frequency elements
- Forced photometry on PanSTARRS or Rubin “selected” sources
- Fit SED templates to measure redshifts
- Separate the sources into redshift accuracy bins→$n_{gal}(z,\sigma_z)$
- Assign a bias using either HOD or AM
- Multi-tracer power-spectrum and bispectrum with non-Gaussian photo-z errors to predict parameter constraints
- Fisher forecast with Gaussian covariance

- All this was done for our proposal (Stickley++16, Doré++14):
  - ➡ Now revisiting/reimplementing all into a production pipeline
  - ➡ Papers revisiting these steps to come in the coming months/years
  - ➡ Specs available at https://github.com/SPHEREx/Public-products

- This pipeline was run 100’s of time to explore trades, quantify the impact of design choices, quantify systematic effects by measuring directly in simulations $\delta\, n_{gal}(z,\sigma_z) / \delta$ *systematics* which leads to df_{NL}

SOME QUESTIONS FOR DISCUSSION

- (e)BOSS teams worked hard to get the large-scales right
  - ➡ But large scales were not a primary goal given the DE/BAO focus?
  - ➡ How far can we push if from the grounds, ie DESI, Rubin? What are the requirements?
  - ➡ How well will Euclid be able to calibrate on large scales (SPHEREx should help)?

- Ultimately the best and most robust constraints will come from joint survey analysis, which will increase statistical power and help mitigate systematics that do not correlate
  - ➡ But many systematics will correlate, sometimes in non obvious ways (extinction, star contamination, …), ground survey systematics
  - ➡ Are we ready for this?

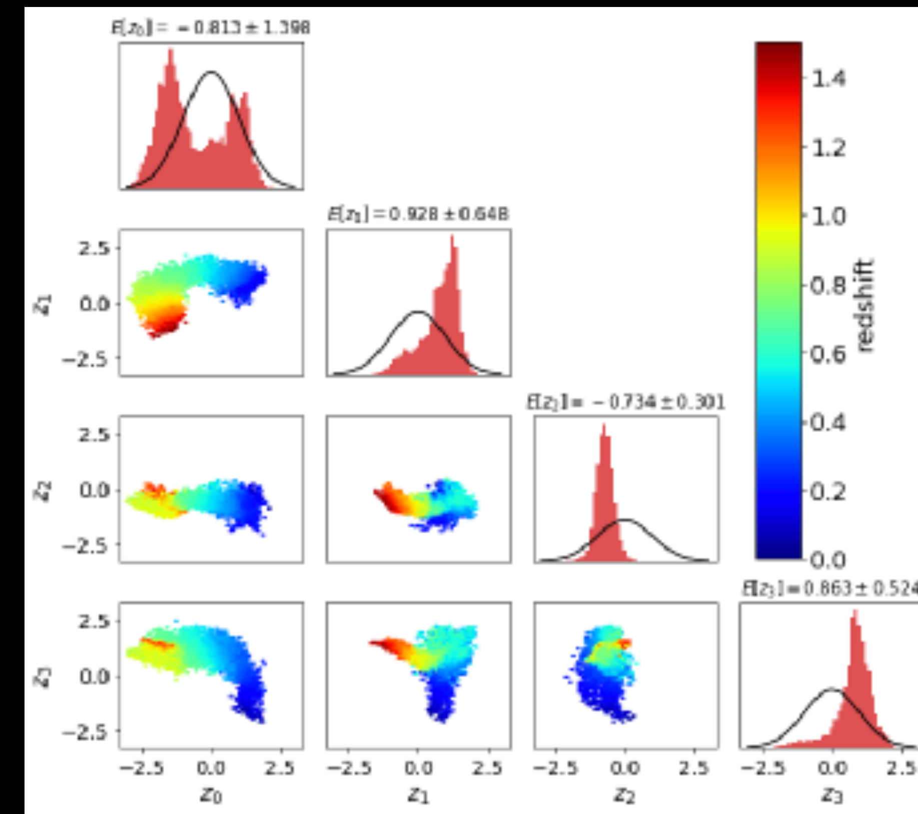
- CMB experiments will also help through CMB lensing and kSZ
  - ➡ Are we ready for this?

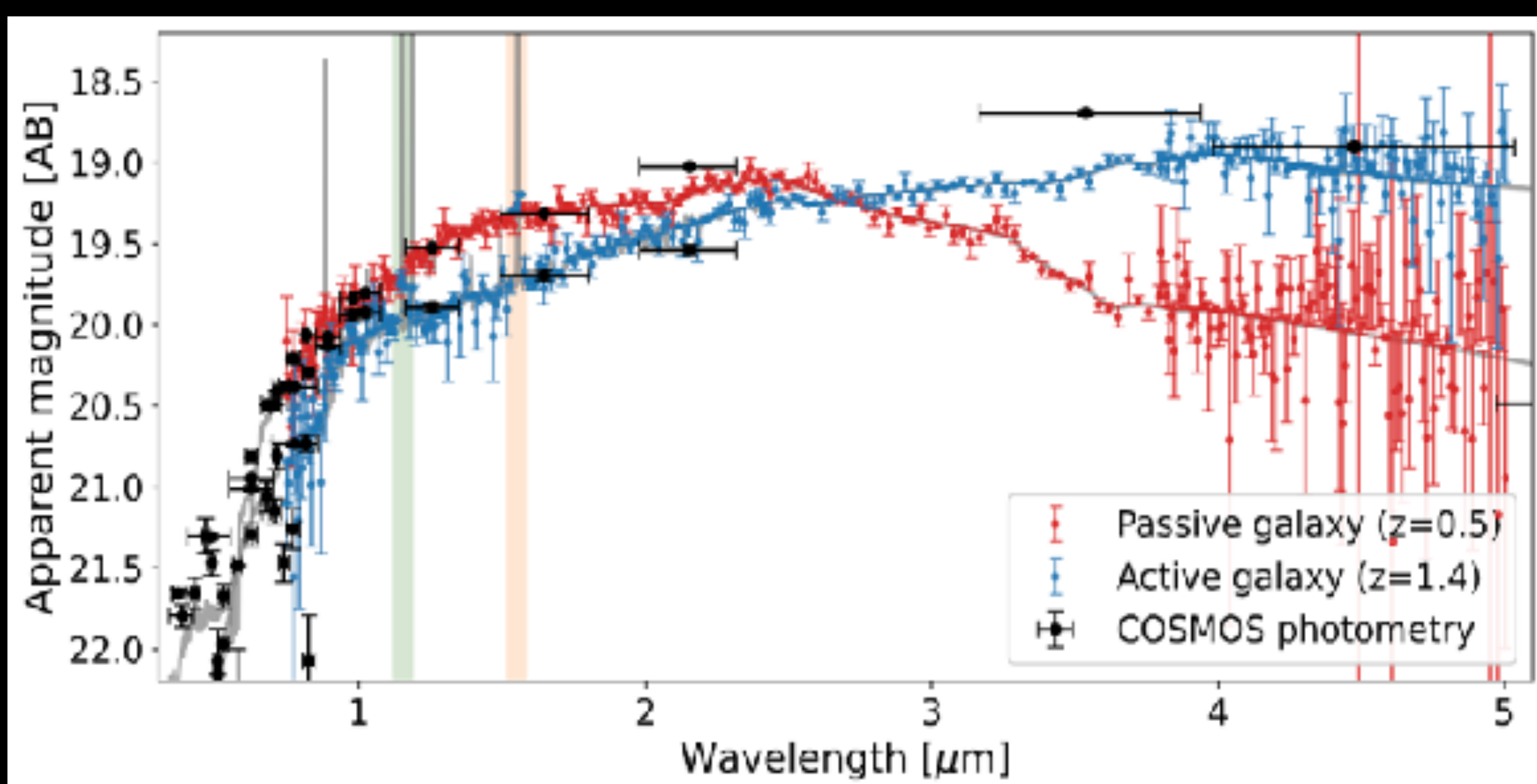
- Whatever happened during the inflation phase, SPHEREx should measure something looking like a non-zero f_{NL}, but coming from either *wide-angle effects* and/or *GR corrections (magnification, potential terms, doppler…)*
  - ➡ Do we computed these terms right? Not clear if proper modeling exist for SPHEREx yet. It would be great to have a standard validated community code.

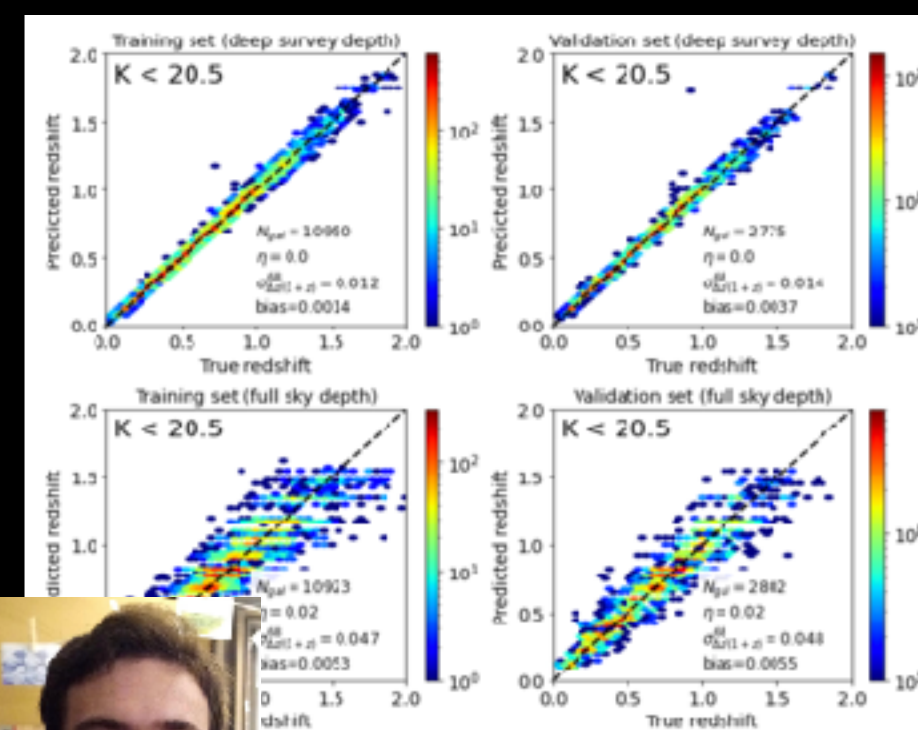
- Even if SPHEREx operates in a unique regime (all-sky and variable redshift accuracy), it seems very important to keep developing standard community analysis tools to help future joint analysis and comparison

SIMULATING/MEASURING REDSHIFTS WITH SPHEREX

- New template library based on fitting COSMOS 2020 multi-band photometry + emission lines from empirical scaling relations to generate synthetic SEDs
- Nonlinear dimensionality reduction with VAEs of mock SPHEREx spectra to four-dimensional latent space
  - ➡ Random forest model to predict redshifts from latent variables (+K-band magnitude)
  - ➡ Inferred variational posteriors yield reliable per-source photo-z uncertainties!



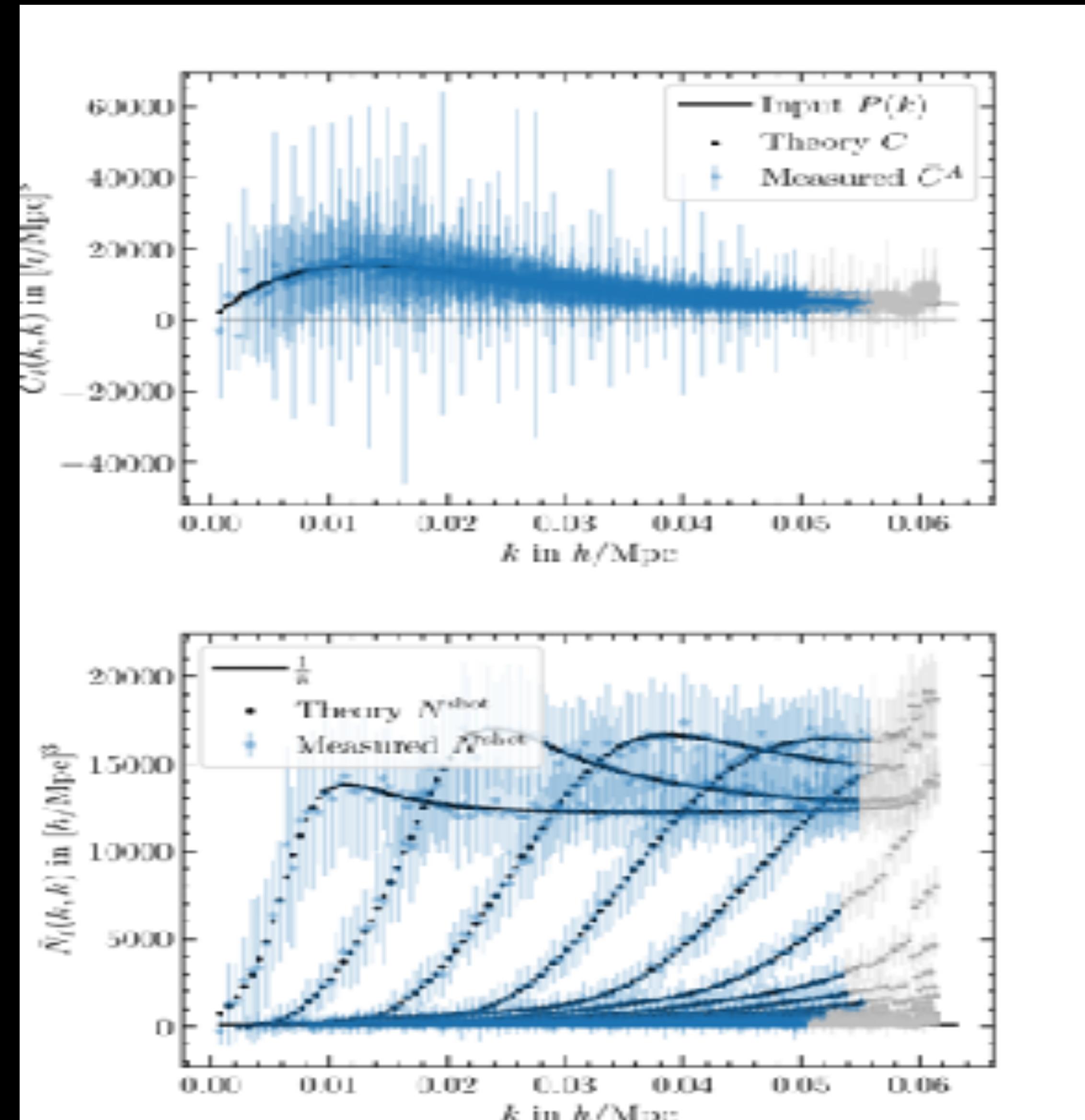




Fehder++22 *in prep.*

SFB POWER SPECTRUM ESTIMATOR: SUPERFAB

- SFB is ideal for large-scale clustering measurements:
  - ➡ Natural separation between angular and radial coordinates
  - ➡ Individual line of sights for each galaxy
  - ➡ Maximal information from RSD
  - ➡ All wide-angle effects
  - ➡ Redshift-evolution (e.g., growth of the non-linear power spectrum)
  - ➡ Nearly diagonal covariance matrix
- SuperFab is a ready to go estimator code, including an analytical approximation to the covariance matrix.
  - ➡ Application to data and likelihood in progress



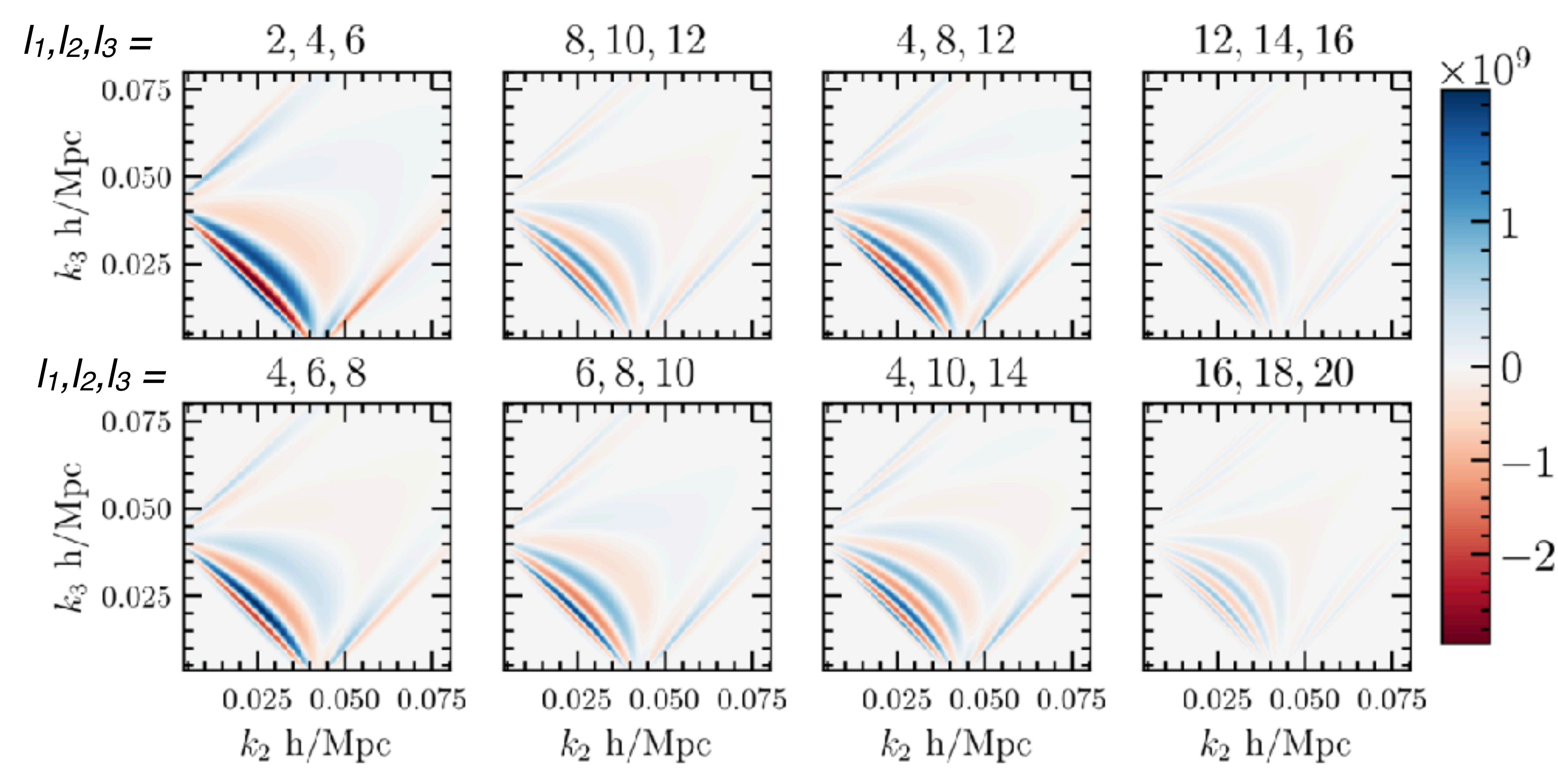
$$\delta(\boldsymbol{r}) = \int \mathrm{d}k \sum_{\ell m} \left[\sqrt{\frac{2}{\pi}}\, k\, j_\ell(kr)\, Y_{\ell m}(\hat{\boldsymbol{r}}) \right] \delta_{\ell m}(k)\,,$$

$$\delta_{\ell m}(k) = \int \mathrm{d}^3\boldsymbol{r} \left[\sqrt{\frac{2}{\pi}}\, k\, j_\ell(kr)\, Y^*_{\ell m}(\hat{\boldsymbol{r}}) \right] \delta(\boldsymbol{r})\,,$$

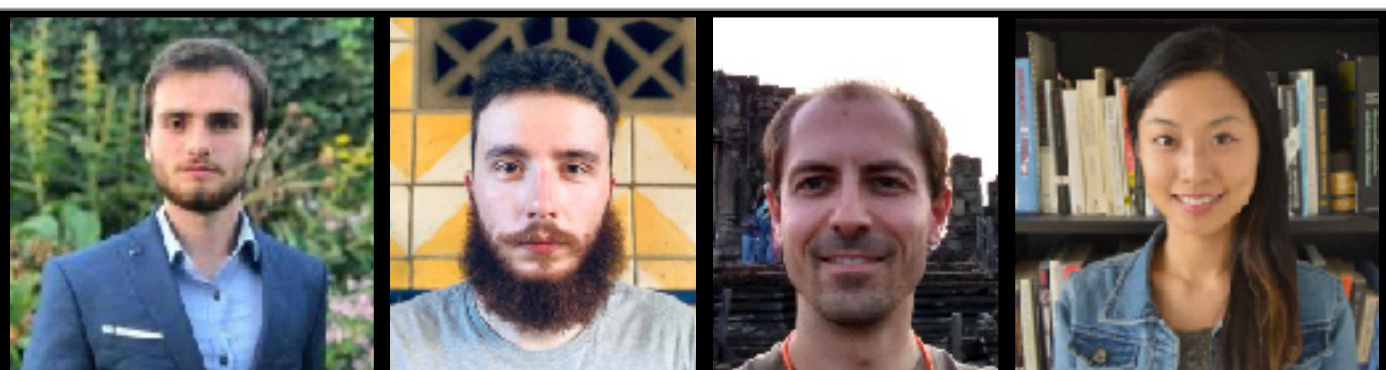
$$\left\langle \delta^{g,\mathrm{obs}}_{\ell m}(k)\, \delta^{g,\mathrm{obs},*}_{\ell' m'}(k') \right\rangle = \delta^K_{\ell\ell'}\, \delta^K_{mm'}\, C_\ell(k,k')$$

Gebhardt & Doré++21 a,b; Khek, Gebhardt & Doré, *in prep*
Julia code: SphericalFourierBesselDecompositions.jl

SFB BISPECTRUM



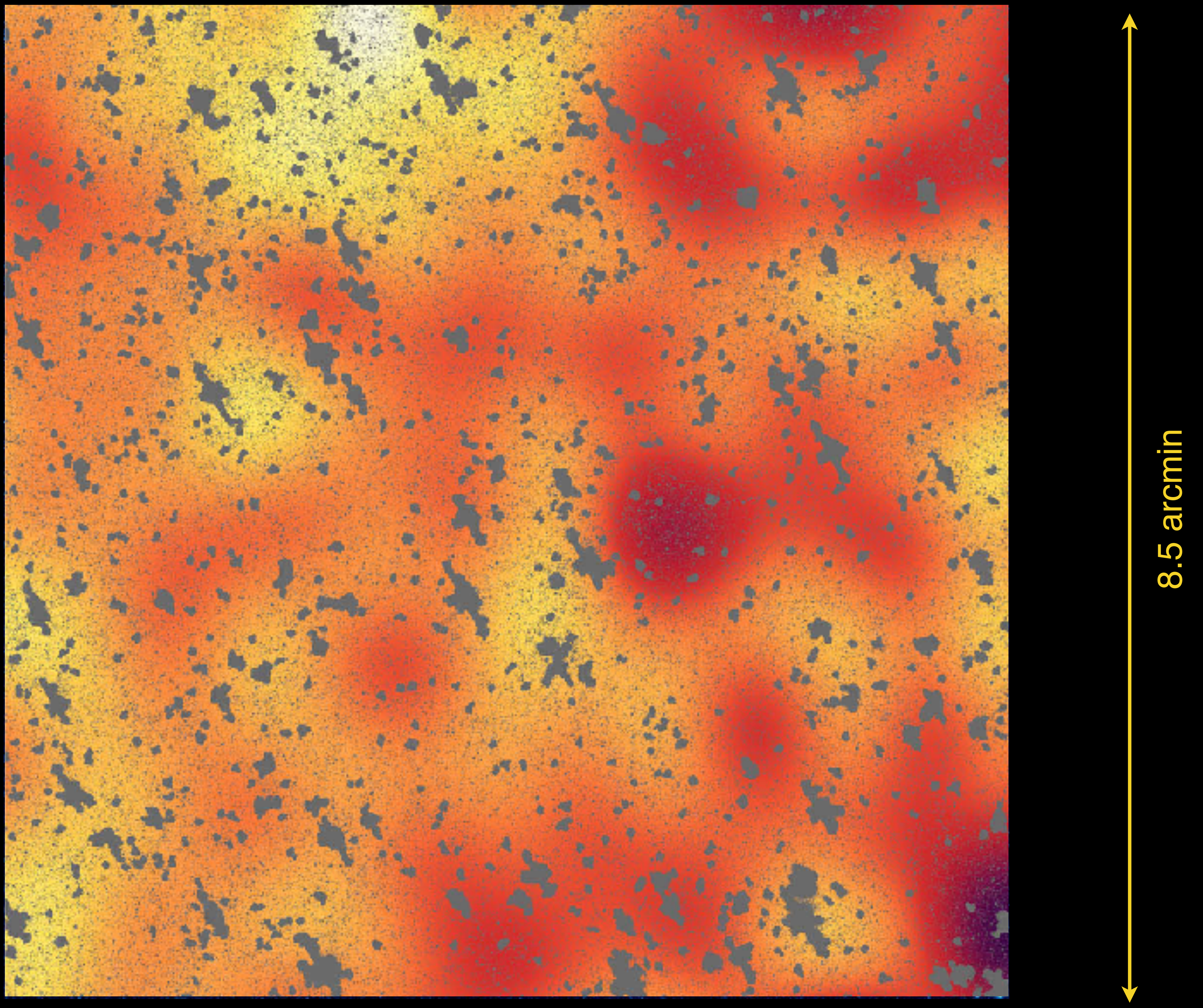
$k_1 = 4.18 \times 10^{-2}$ *h*/Mpc



Benabou, Testa, Gebhardt, Heinrich, Doré, *in prep*

EXTRA-GALACTIC BACKGROUND LIGHT INVESTIGATION

MAPPING EXTRA-GALACTIC BACKGROUND LIGHT



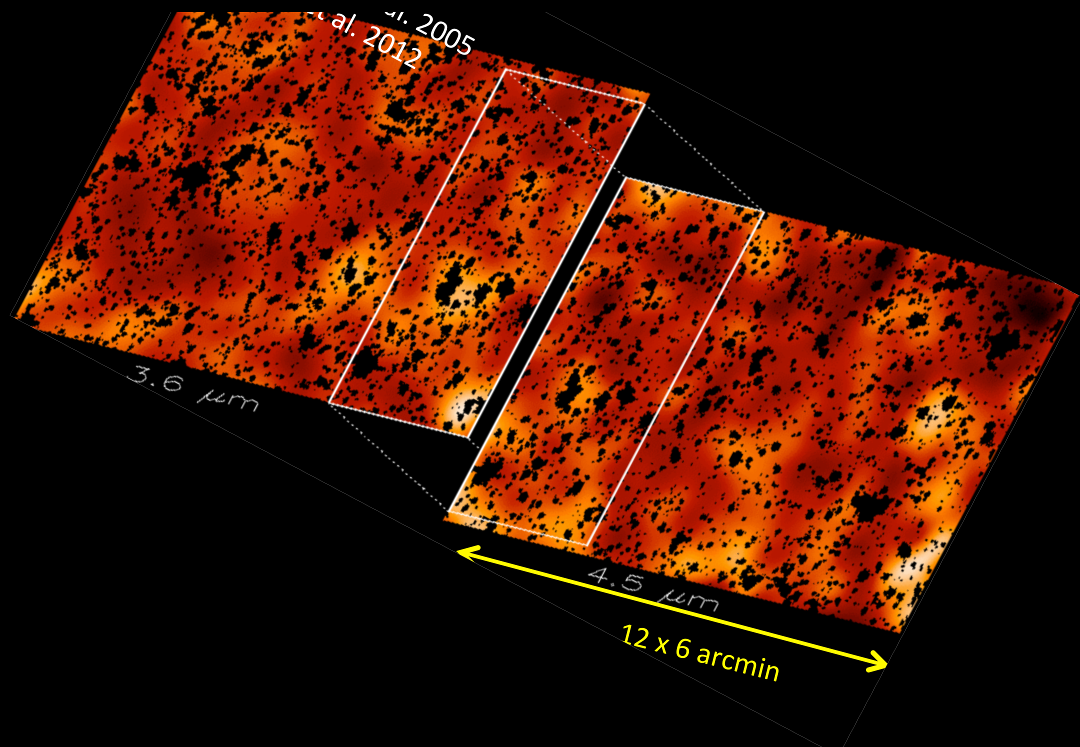
Spitzer @ 3.6 μm

Cooray++07

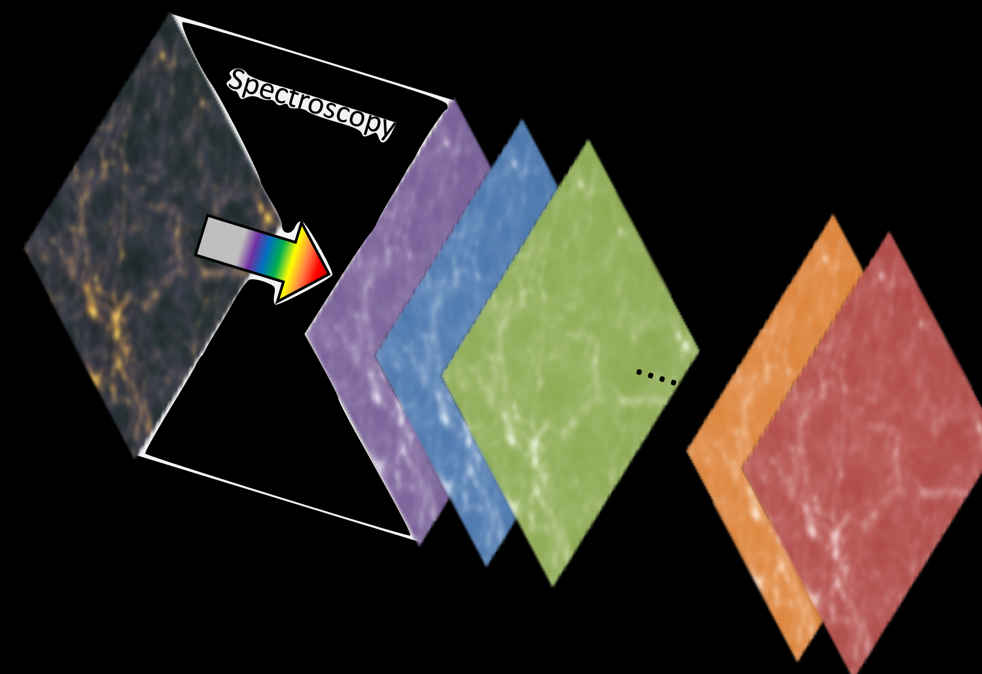
HOW DID GALAXIES BEGIN?

MEASURING THE SPECTRA OF THE INTEGRATED COSMIC LIGHT THROUGH NIR FLUCTUATIONS

Spitzer (but also DIRBE, Planck, Akari, or Herschel)
NIR in 2 bands and 72 sq. arcmin



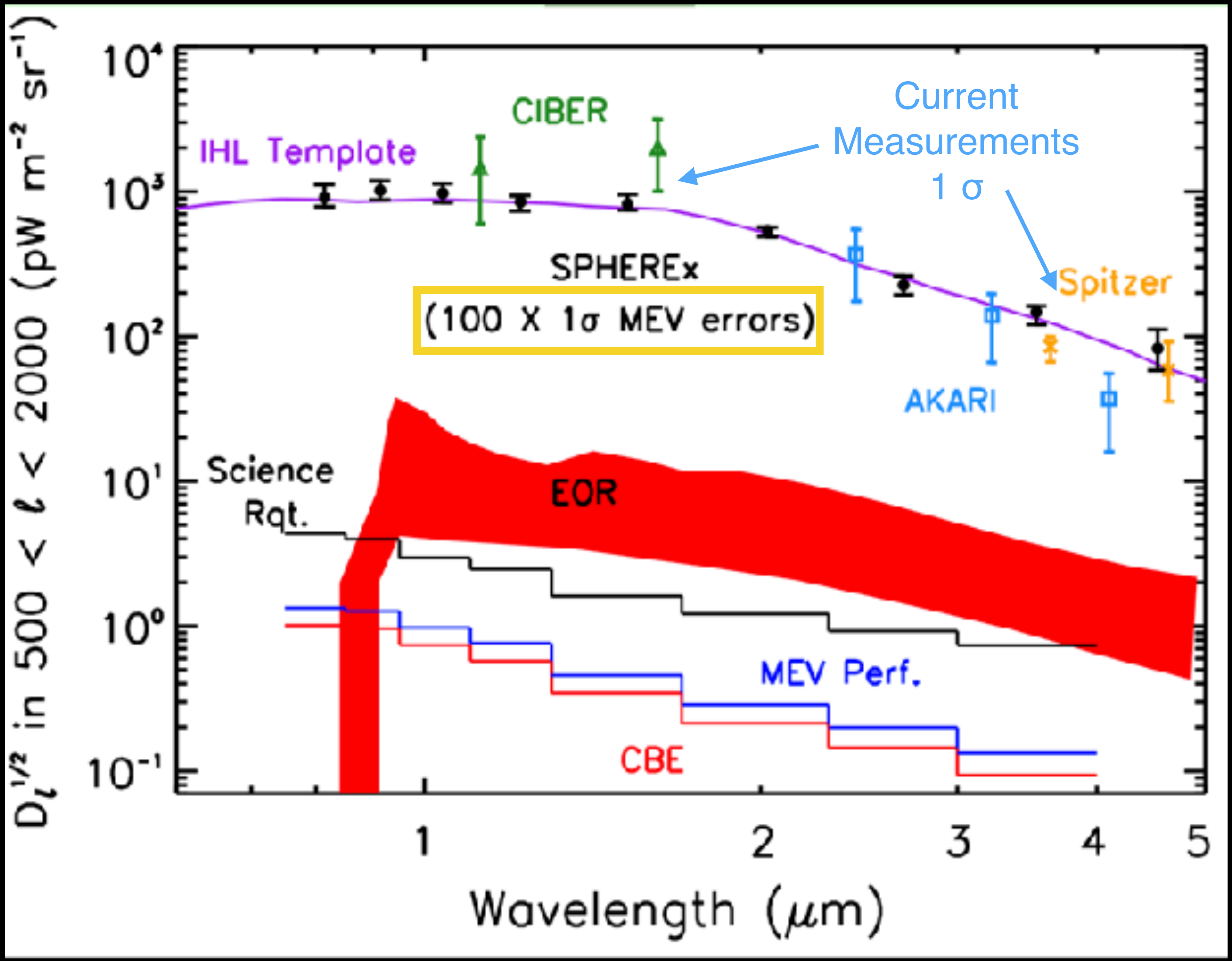
SPHEREx
Extends to 102 bands and 200 sq. deg.



- SPHEREx observes every orbits ~2 x 100 sq. deg near the ecliptic poles
  ➡We can reliably map light fluctuations over these *deep fields*
- Fluctuations receive contributions from all galaxies (incl. the dwarf galaxies responsible for reionization), but also from stars from stripped galaxies, etc.
  ➡SPHEREx will measure the *spectra* of these fluctuations
  ➡These spectra allow the extraction of the emission from the first galaxies (Feng++19)

PROBING THE EPOCH OF REIONIZATION

Fluctuations in 9 broad continuum bands

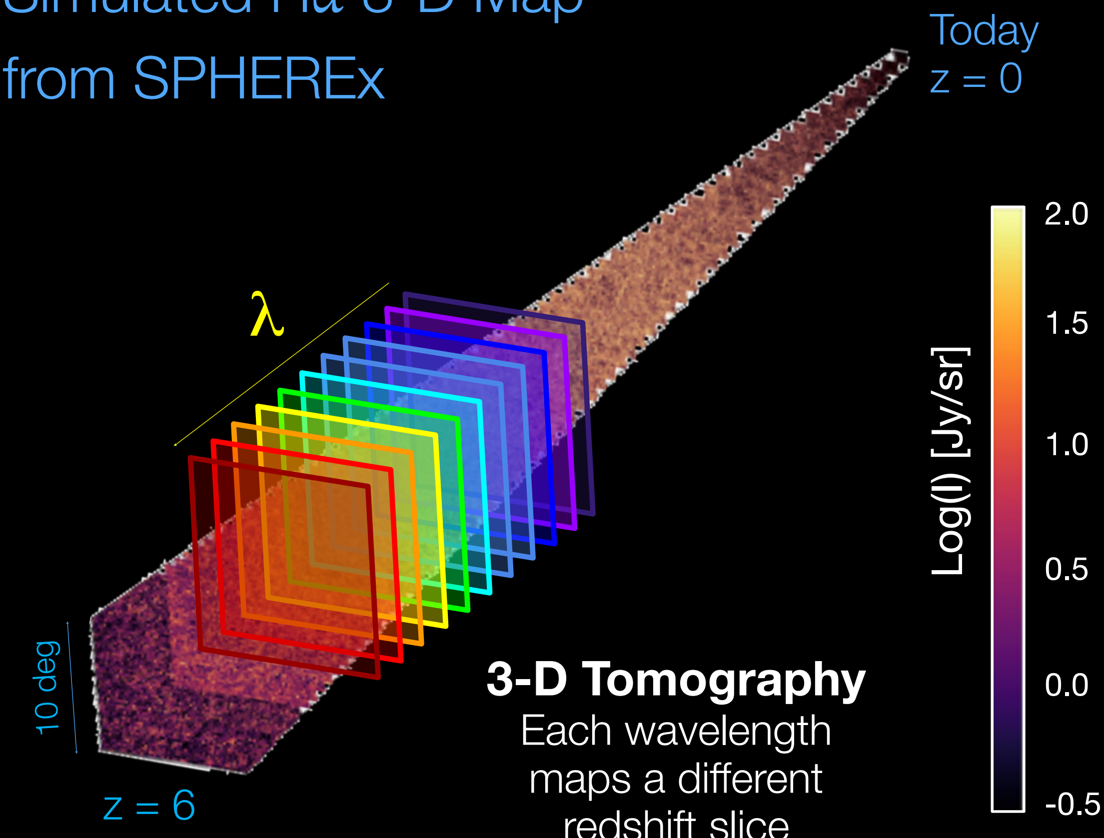


Can also extend to higher spectral resolution to do line intensity mapping

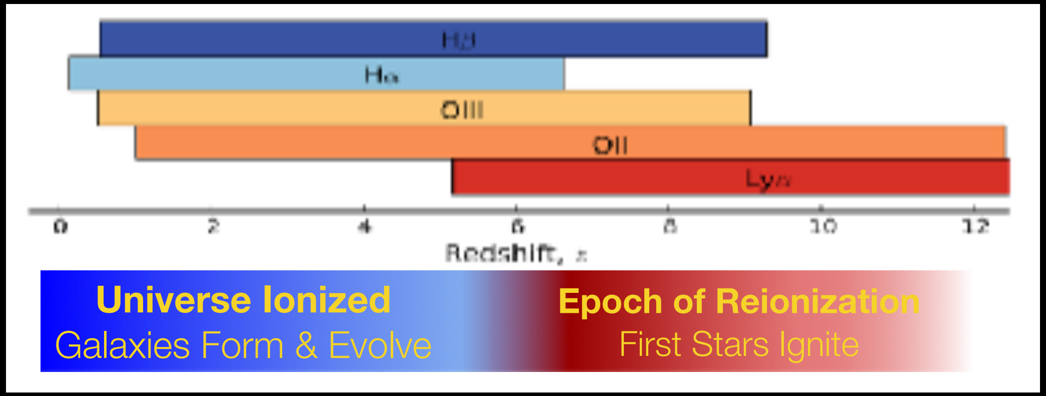
SPHEREX LINE INTENSITY MAPPING

- How Does Line Intensity Mapping Work?
  - ➡ Maps large scale-structure using the collective light from galaxies -- not from individual galaxy detections
  - ➡ Line emission uniquely gives the redshift
    - A powerful 3-D map of galaxy and star formation!
- What Does SPHEREx Provide?
  - ➡ The core SPHEREX program is 2-D and does not use line spectroscopy
  - ➡ However all of the deep field maps will be ready-built for spectroscopic analysis
  - ➡ Line emission maps can detect Hα, Hβ, OII and OIII lines with high SNR
  - ➡ Lyα line accessible at high redshifts $z > 5.2$
- Scientific Opportunity
  - ➡ Map the entire History of Galaxy and Star Formation in multiple lines (Hα, Hβ, OII and OIII)
  - ➡ Offer new insights on the Epoch of Reionization through Lyα and OIII
  - ➡ Provide unique measurements on the Geometry of the Universe at High Redshift ($z \sim 4$-5)

Simulated Hα 3-D Map from SPHEREx

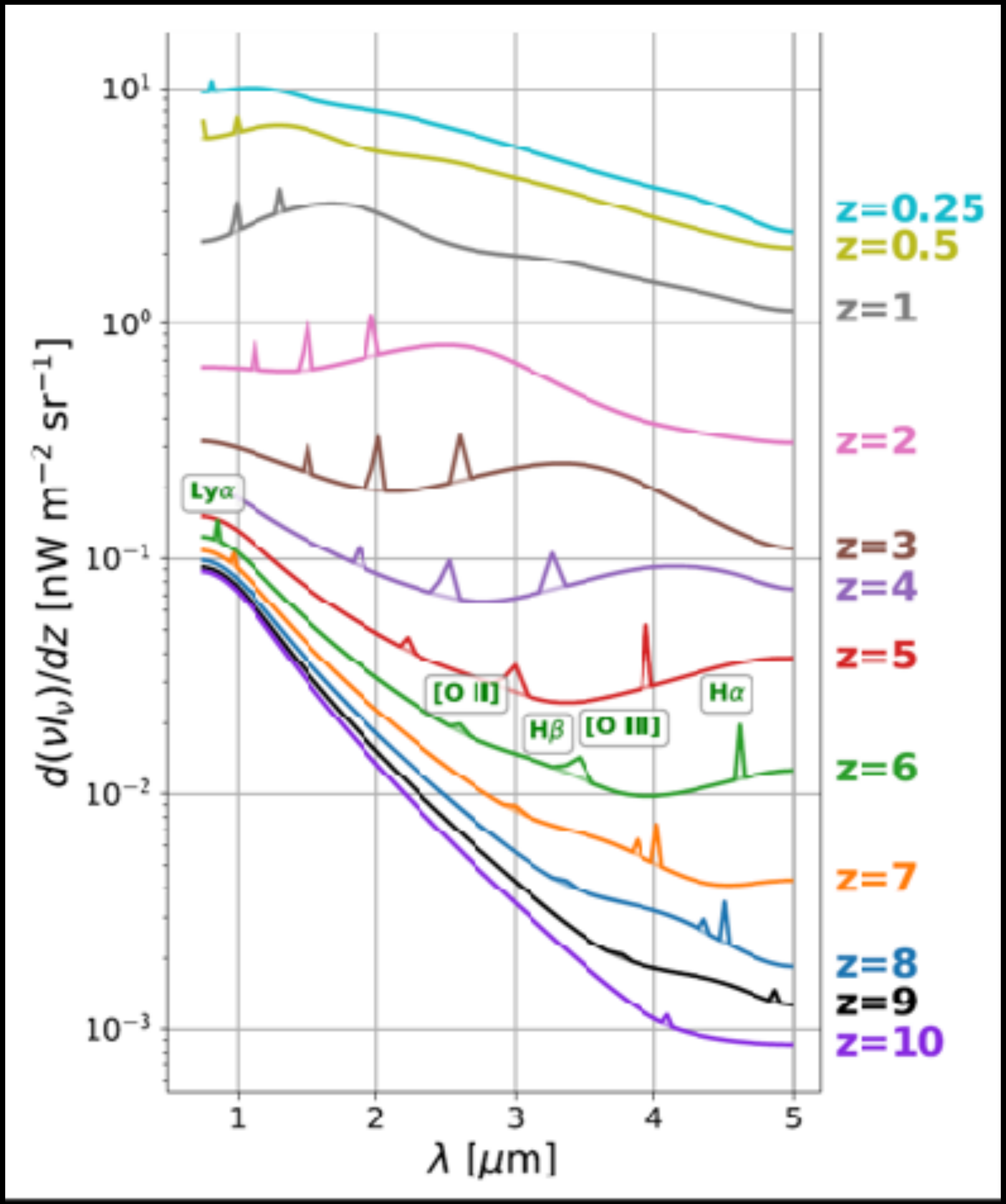


Emission Lines Observable by SPHEREx



LINE INTENSITY MAPPING AND CROSS-CORRELATIONS - I

Contribution of multiple redshift bins to the specific intensity as a function of wavelength



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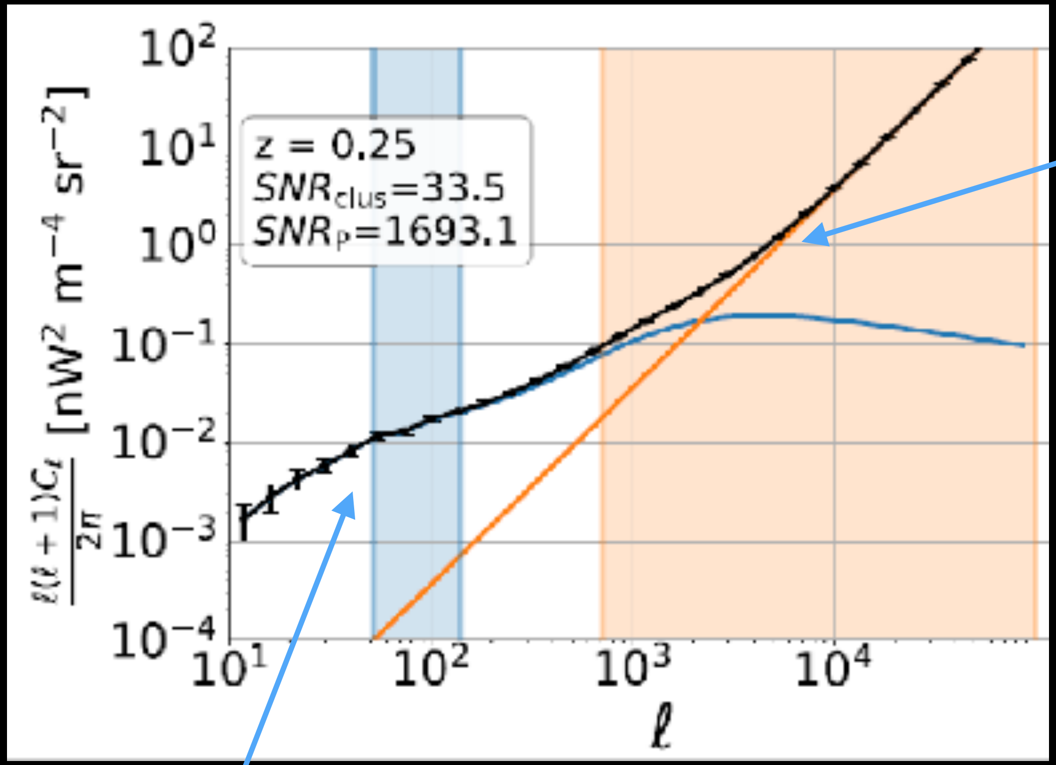
LINE INTENSITY MAPPING AND CROSS-CORRELATIONS - II

Simulated Cross-power Spectrum



Poisson regime

Linear clustering regime

Redshift	Δz slice	SNR per channel *	Galaxy Redshifts	Lines in range
0.25	0.1	50 – 65	SPHEREx	Hα
0.5	0.2	100 – 120	SPHEREx	Hα, OIII, Hβ
1	0.4	100 – 150	SPHEREx	Hα, OIII, Hβ
2	1	15 – 25	SPHEREx	Hα, OIII, Hβ, OII
3	1	6 – 9	DESI	Hα, OIII, Hβ, OII
4	1	15 – 30	Rubin LBG	Hα, OIII, Hβ, OII
5	1	5 – 20	Rubin LBG	Hα, OIII, Hβ, OII
6	1	3 – 10	Rubin LBG	Hα, OIII, Hβ, OII, Lyα
7	1	0.2 – 2	Roman LBG	OIII, Hβ, OII, Lyα

* SPHEREx has 102 channels

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SUMMARY

- SPHEREx will create the first all sky near-infrared spectroscopic survey:
  - ➡ A quickly released public dataset of lasting legacy
  - ➡ Many discoveries will come from the community
- SPHEREx offers a simple and very robust design and modus operandi:
  - ➡ Enables a high control of systematics thanks to multiple built-in redundancy, the CMB way
- SPHEREx will enable multiple and powerful studies:
  - ➡ Primordial non-Gaussianity to learn about Inflation
  - ➡ Extra-galactic background light from z=0 till the reionization era
  - ➡ Origin of water and biogenic ices in young stellar objects and proto-planetary systems
  - ➡ …
- SPHEREx has strong synergies with current and future observatories
  - ➡Rubin, DESI, JWST, Roman, Euclid, SDSS-V, TESS, e-ROSITA, SO, CMB-S4…
- A very exciting decade ahead!

FIN