Large-Scale Structure Observations

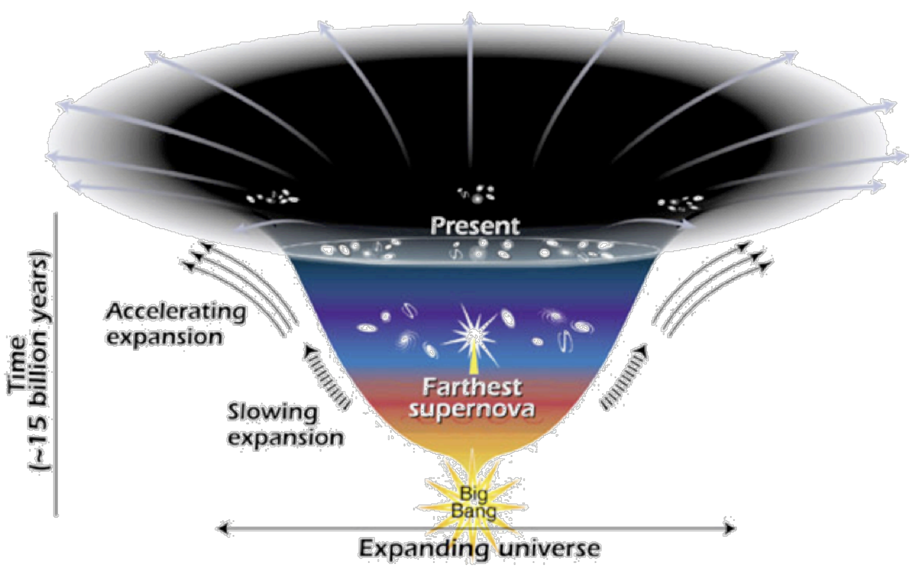
Lecture 1

Will Percival

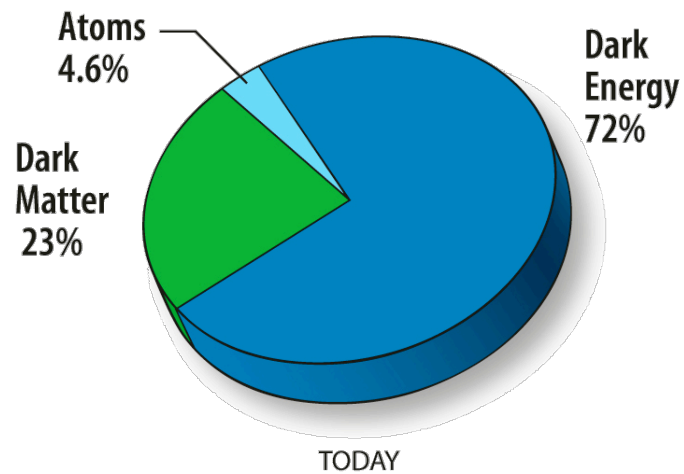
The standard “model” for cosmology

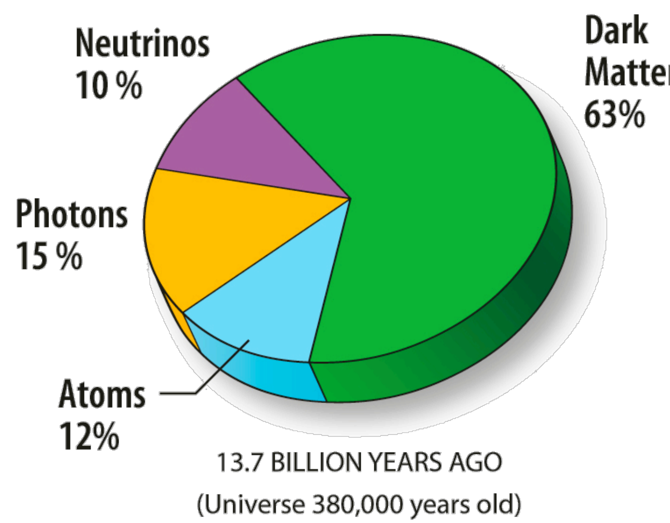
$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

$$\frac{H^2}{H_0^2} = \Omega_M a^{-3} + (1 - \Omega_M)$$



NASA/A. Riess





The problem of Λ

ΛCDM fits all (believable?) current data well
It's the simplest (mathematical) model available
But … we cannot explain Λ with physics

- why so small?

$$\rho_\Lambda|_{\rm obs} = \frac{\Lambda}{8\pi G} \sim (10^{-3}\,{\rm eV})^4$$

$$\rho_\Lambda|_{\rm theory} \sim (M_{\rm new\ physics})^4 \sim (1\,{\rm TeV})^4 >> \rho_\Lambda|_{\rm obs}$$

- why so fine tuned?

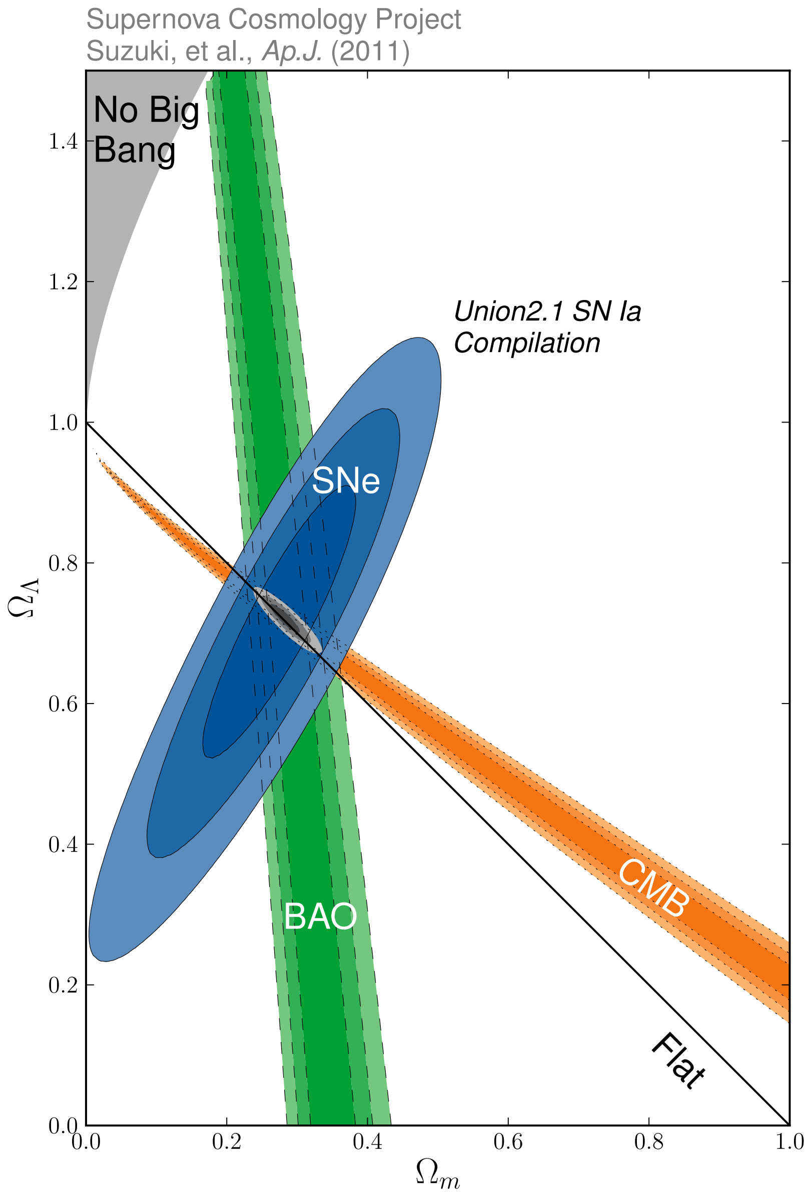
$$\rho_\Lambda \lesssim \rho_m \ : \ \text{crucial for structure formation}$$

$$\text{but } \rho_\Lambda \propto a^0 \text{ while } \rho_m \propto a^{-3}$$

Many alternative explanations

- anthropic arguments?
- modify gravity on large-scales or at low densities?
- more general scalar field model?
- link with Dark Matter?
- back-reaction from structure growth?

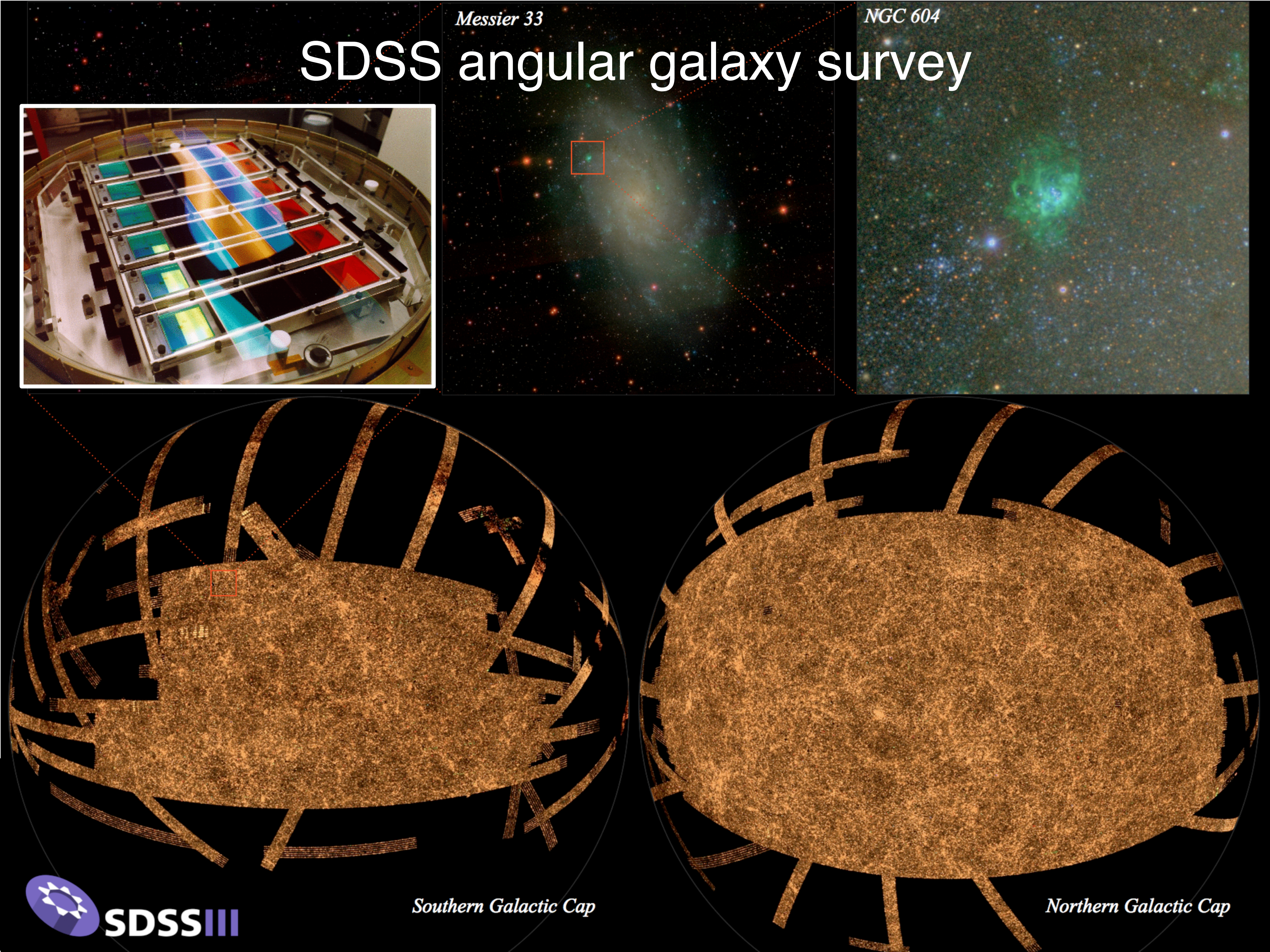
How did we get here?



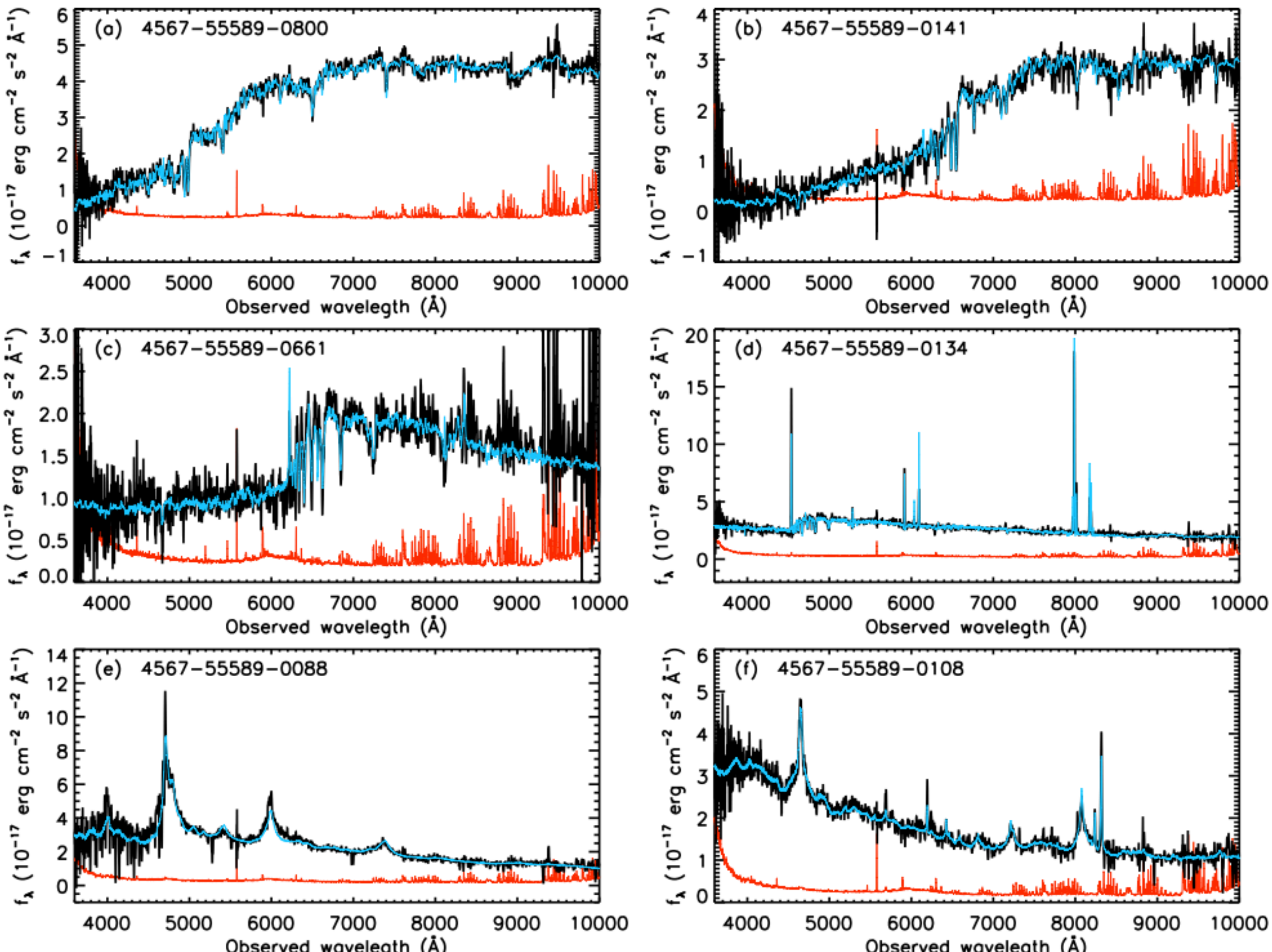
Goal of lecture: The galaxy survey "pillar"

Galaxy surveys

SDSS angular galaxy survey



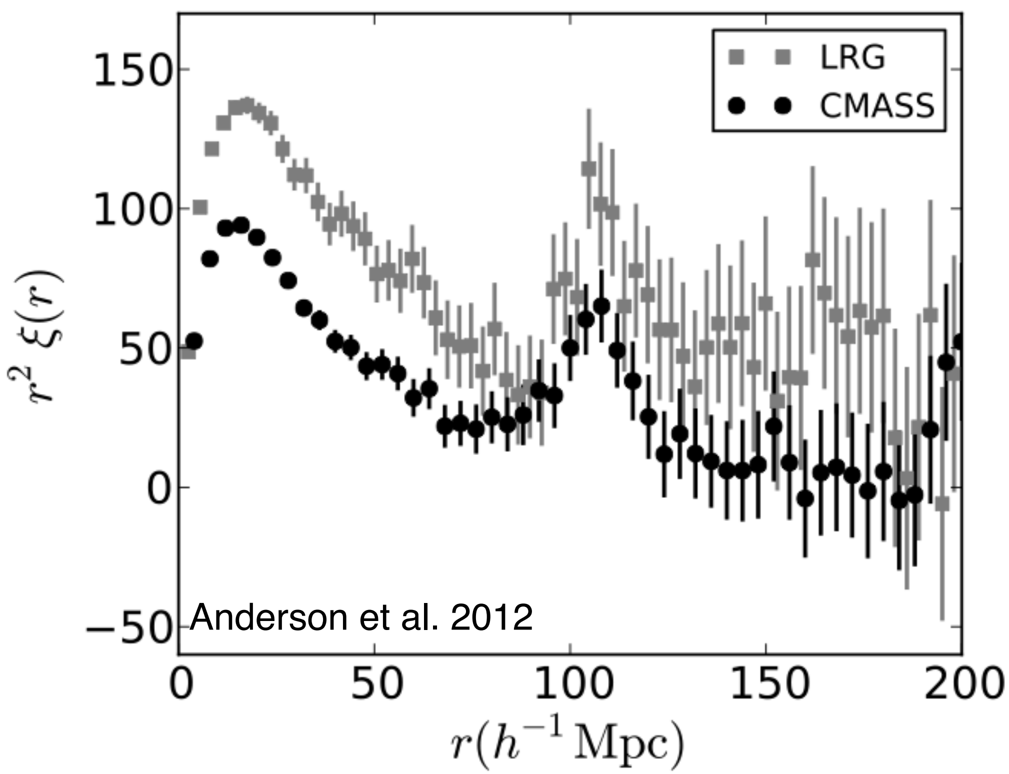
Spectra gives recession velocities and redshifts



Bolton et al. 2012

Galaxy survey "history"

1986	CfA	3500
1996	LCRS	23000
2003	2dFGRS	250000
2005	SDSS-I/II	800000
2012	SDSS-III	1500000



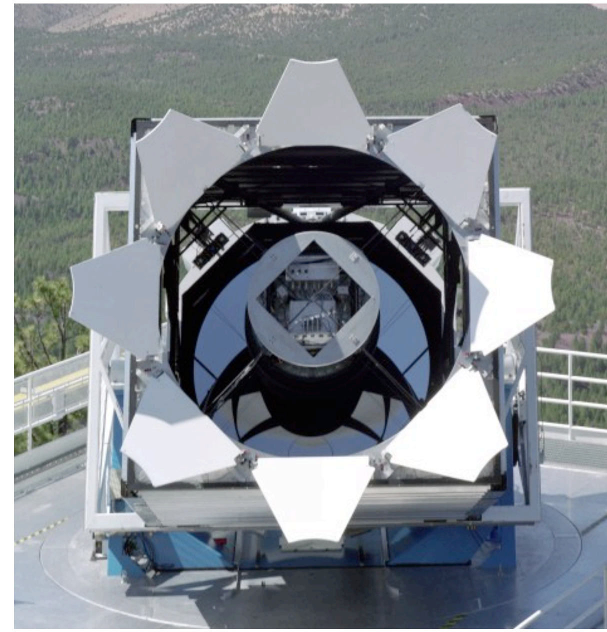
Fractional error in the amplitude of the fluctuation spectrum

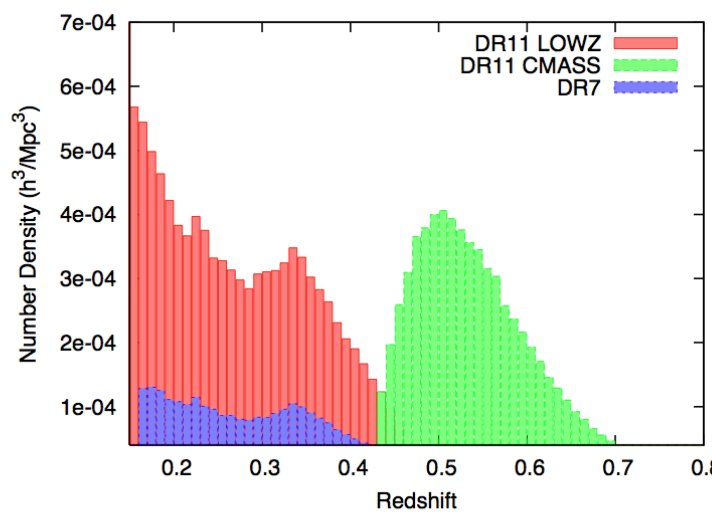
1970	x100
1990	x2
1995	±0.4
1998	±0.2
1999	±0.1
2002	±0.05
2003	±0.03
2009	±0.01
2012	±0.002

Baryon Oscillation Spectroscopic Survey

SDSS III

- Duration: Fall 2009 - Summer 2014
- Telescope: 2.5m Sloan
- Upgrade to SDSS-II spectrograph
  - 1000 smaller fibers
  - higher throughput
- Spectra:
  - $3600\,\mathring{A} < \lambda < 10{,}000\,\mathring{A}$ New spectrograph
  - $R = \lambda/\Delta\lambda = 1300 - 3000$
  - (S/N) at mag. limit
    - 22 per pix. (averaged over 7000-8500Å)
    - 10 per pix. (averaged over 4000-5500Å)
- Area: 10,000 deg2
- Targets:
  - **1.5×10^6 massive galaxies, $z < 0.7$, $i < 19.9$**
  - 1.5×10^5 quasars, $z>2.2$, $g<22.0$
  - 75,000 ancillary science targets, many categories





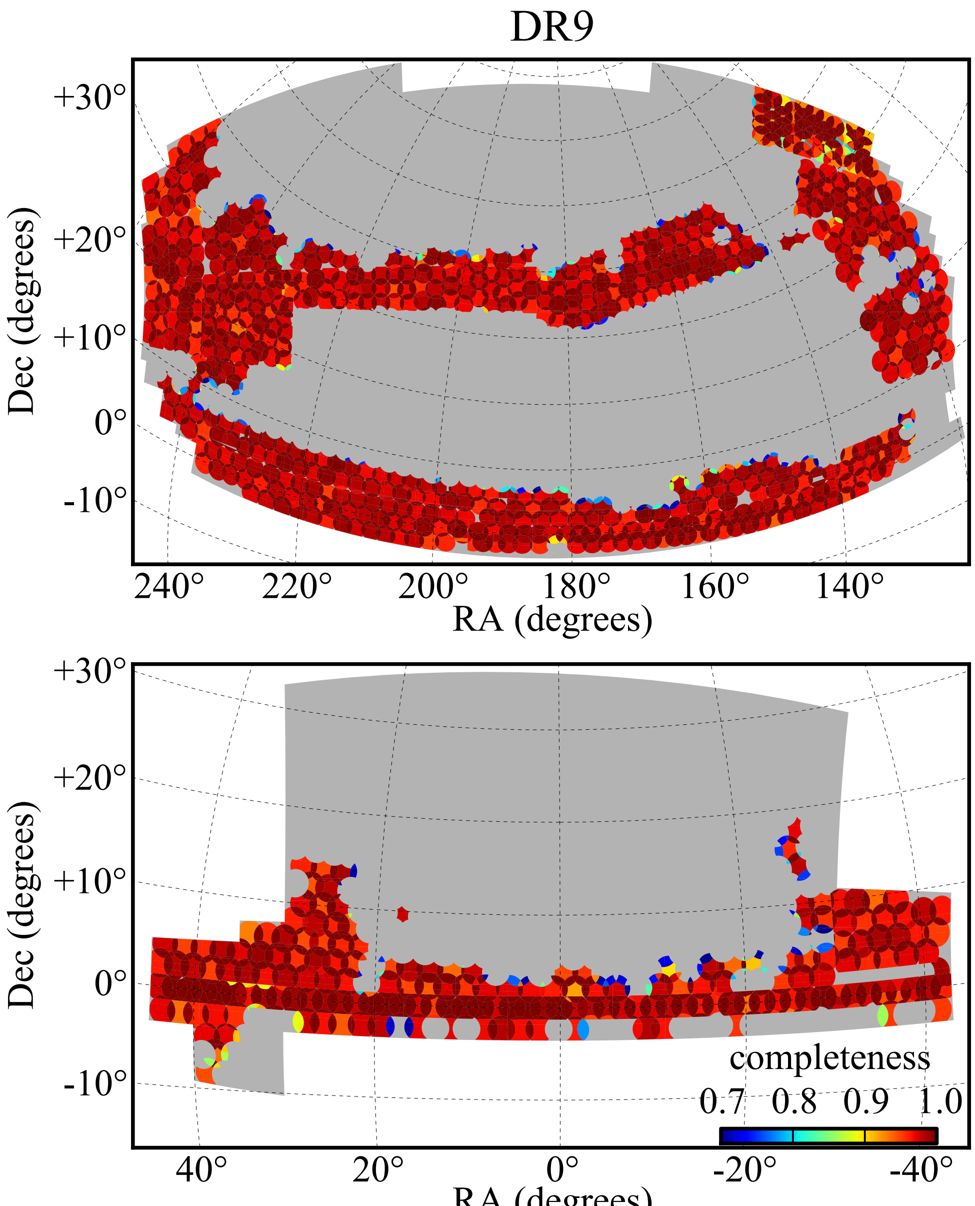
The Sloan Digital Sky Survey telescope

A collaborative effort … BOSS

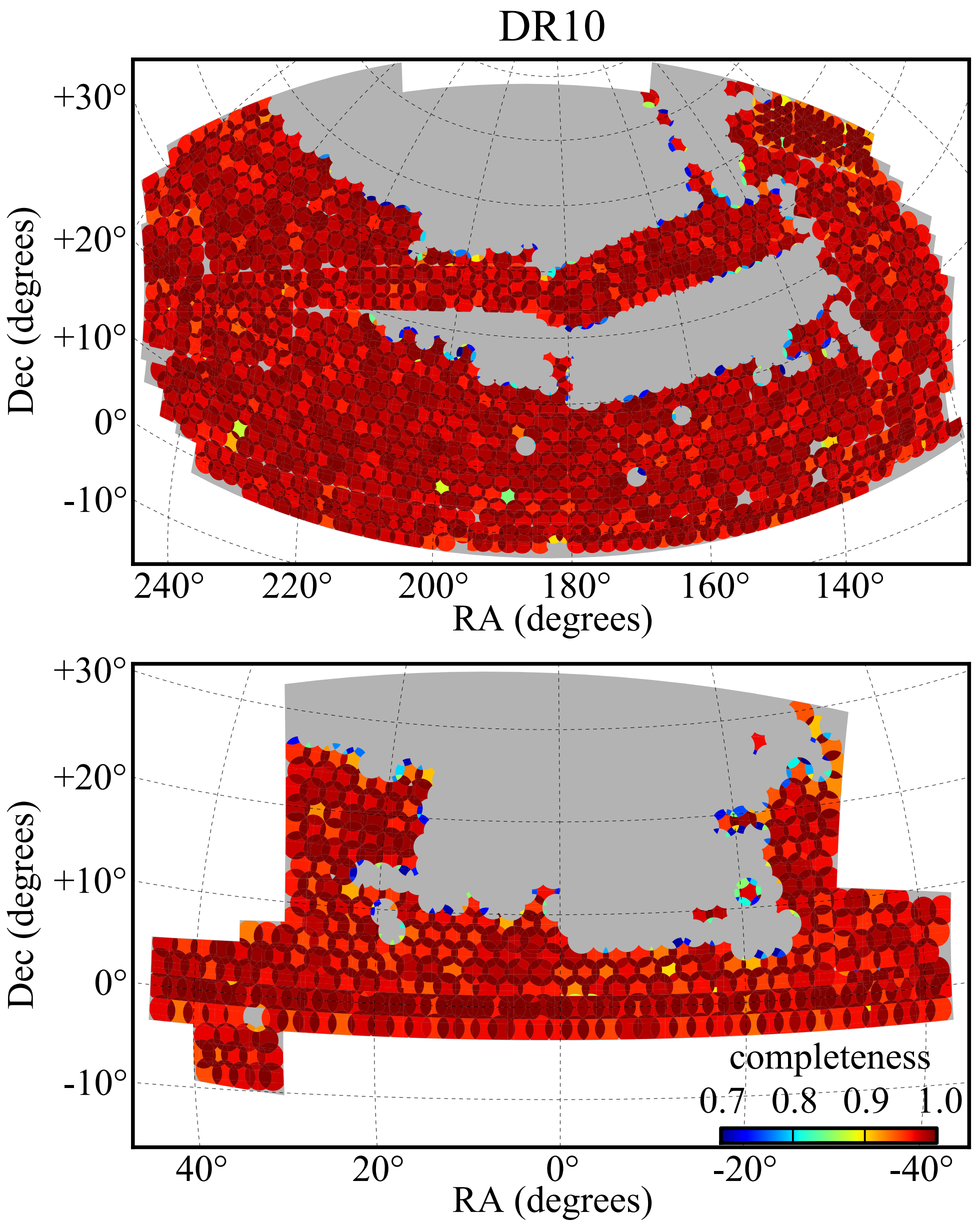
Lauren Anderson[1], Eric Aubourg[2], Stephen Bailey[3], Dmitry Bizyaev[4], Michael Blanton[5], Adam S. Bolton[6], J. Brinkmann[4], Joel R. Brownstein[6], Angela Burden[7], Antonio J. Cuesta[8], Luiz N. A. da Costa[9,10], Kyle S. Dawson[6], Roland de Putter[11,12], Daniel J. Eisenstein[13], James E. Gunn[14], Hong Guo[15], Jean-Christophe Hamilton[2], Paul Harding[15], Shirley Ho[3,14], Klaus Honscheid[16], Eyal Kazin[17], D. Kirkby[18], Jean-Paul Kneib[19], Antione Labatie[20], Craig Loomis[21], Robert H. Lupton[14], Elena Malanushenko[4], Viktor Malanushenko[4], Rachel Mandelbaum[14,21], Marc Manera[7], Claudia Maraston[7], Cameron K. McBride[13], Kushal T. Mehta[22], Olga Mena[11], Francesco Montesano[23], Demetri Muna[5], Robert C. Nichol[7], Sebastián E. Nuza[24], Matthew D. Olmstead[6], Daniel Oravetz[4], Nikhil Padmanabhan[8], Nathalie Palanque-Delabrouille[25], Kaike Pan[4], John Parejko[8], Isabelle Pâris[26], Will J. Percival[7], Patrick Petitjean[26], Francisco Prada[27,28,29], Beth Reid[3,30], Natalie A. Roe[3], Ashley J. Ross[7], Nicholas P. Ross[3], Lado Samushia[7,31], Ariel G. Sánchez[23], David J. Schlegel[*3], Donald P. Schneider[32,33], Claudia G. Scóccola[34,35], Hee-Jong Seo[36], Erin S. Sheldon[37], Audrey Simmons[4], Ramin A. Skibba[22], Michael A. Strauss[21], Molly E. C. Swanson[13], Daniel Thomas[7], Jeremy L. Tinker[5], Rita Tojeiro[7], Mariana Vargas Magaña[2], Licia Verde[38], Christian Wagner[12], David A. Wake[39], Benjamin A. Weaver[5], David H. Weinberg[40], Martin White[3,41,42], Xiaoying Xu[22], Christophe Yèche[25], Idit Zehavi[15], Gong-Bo Zhao[7,43]

Anderson et al. 2012; arXiv:1203.6565

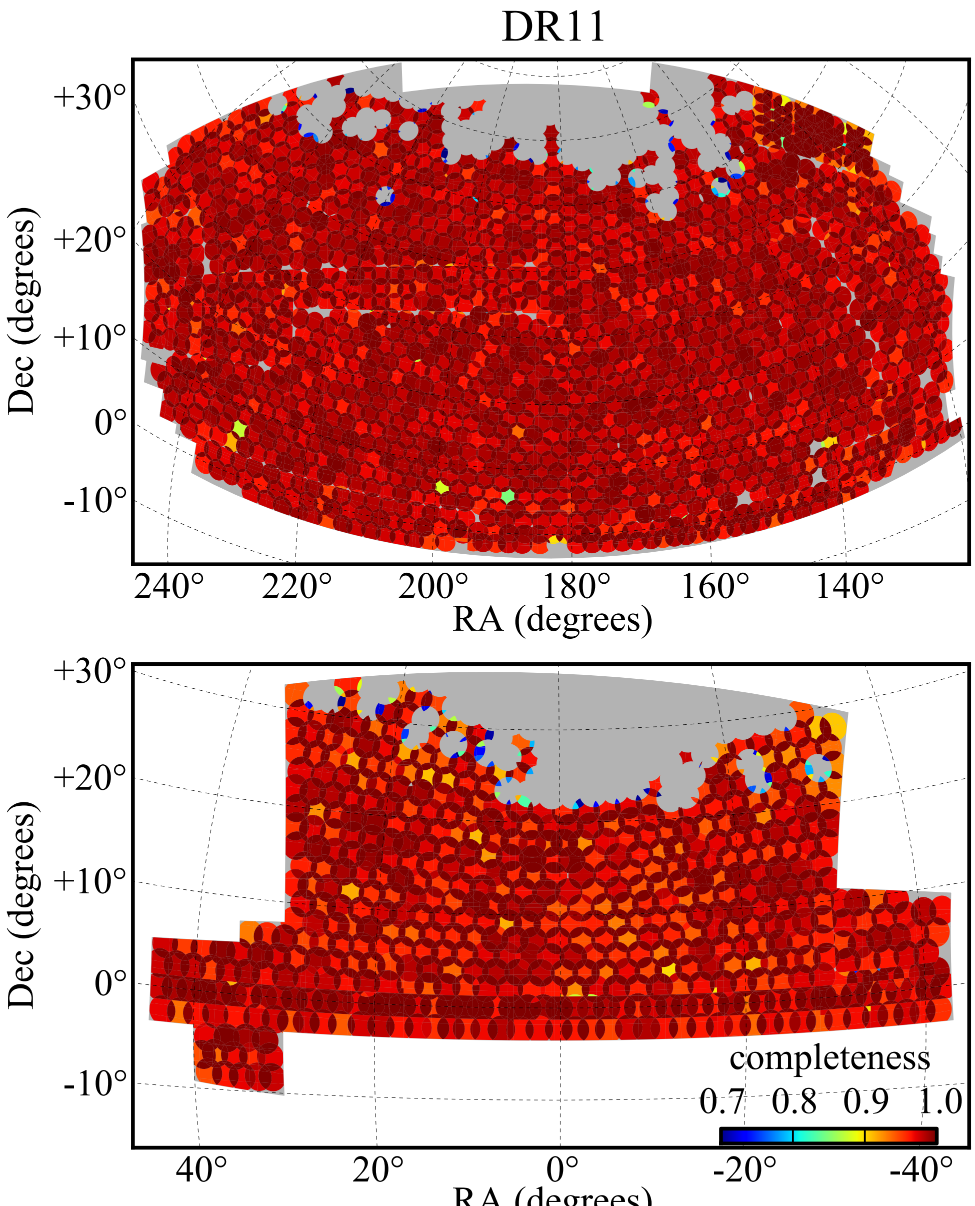
BOSS DR9 galaxies



BOSS DR10 galaxies



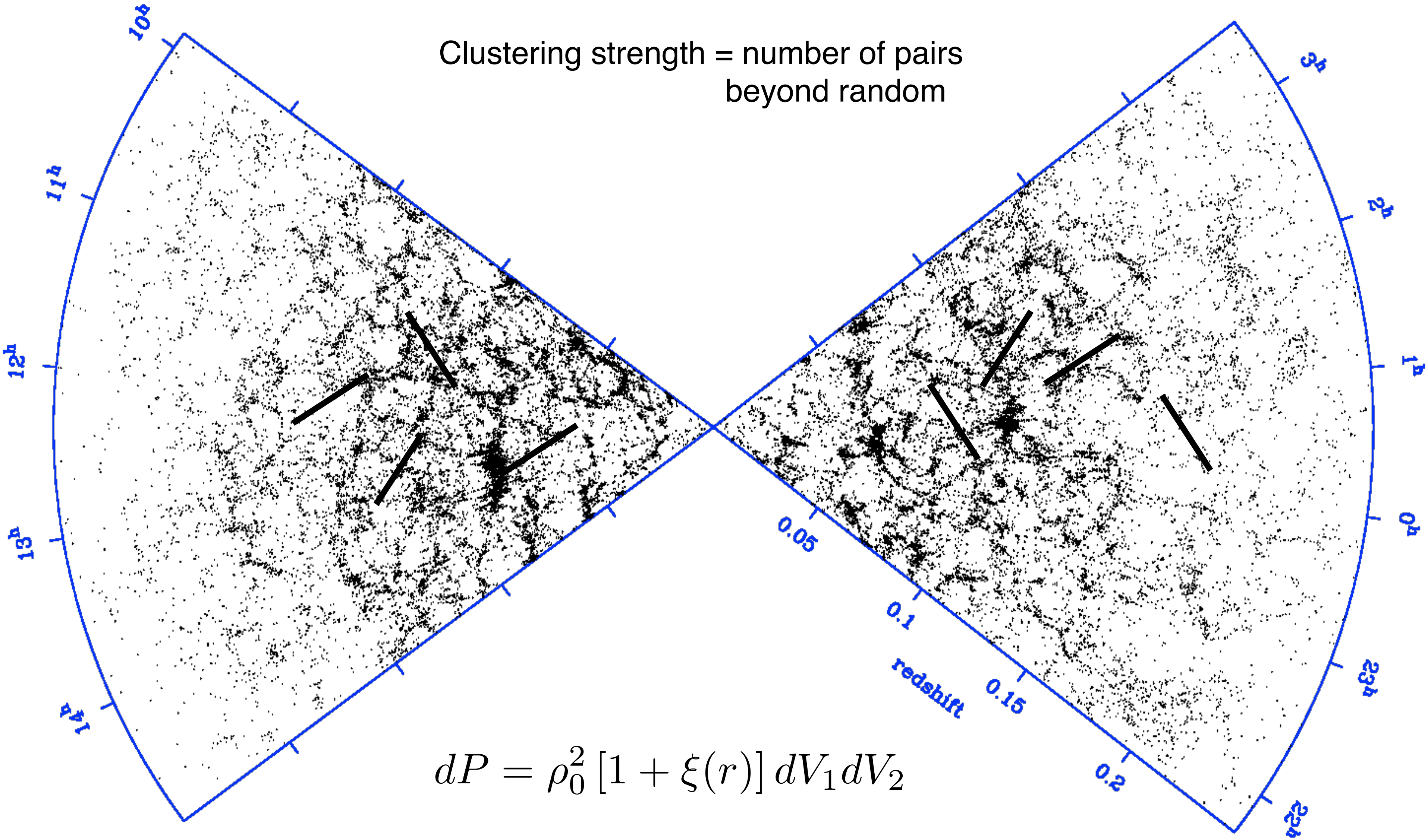
BOSS DR11 galaxies



Clustering

What does “clustering” mean?

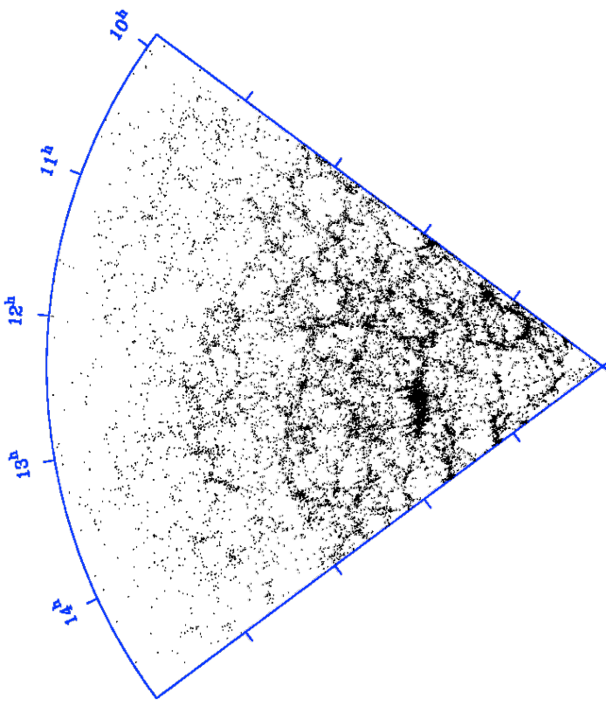
Clustering strength = number of pairs beyond random



$$dP = \rho_0^2 \left[1 + \xi(r)\right] dV_1 dV_2$$

2dFGRS

Over-density fields



"probability of seeing structure", can be recast in terms of the overdensity

$$\delta = \frac{\rho - \rho_0}{\rho_0}$$

The correlation function is simply the real-space 2-pt statistic of the field

$$\xi(r) = \langle \delta(\mathbf{x}) \delta(\mathbf{x} + \mathbf{r}) \rangle$$

Its Fourier analogue, the power spectrum is defined by

$$P(k) = \langle \delta(\mathbf{k}) \delta(\mathbf{k}) \rangle$$

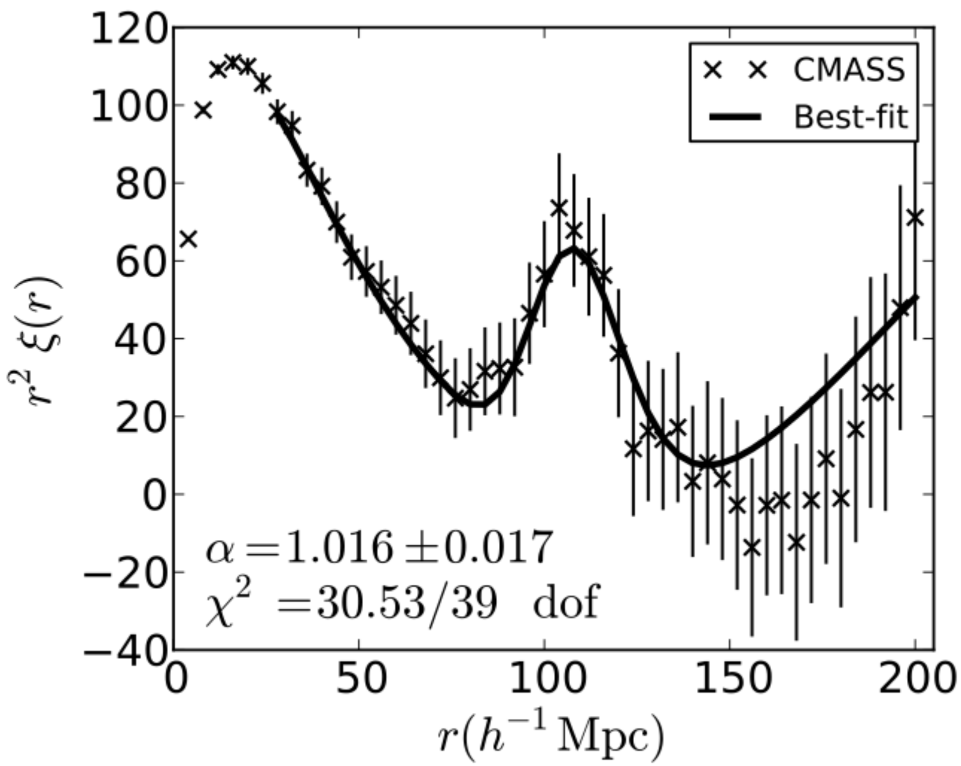
By analogy, one should think of "throwing down" Fourier modes rather than "sticks"

Real-space correlation function

$$\begin{aligned}\xi(\mathbf{x_1}, \mathbf{x_2}) &= \langle \delta(\mathbf{x_1}) \delta(\mathbf{x_2}) \rangle \\ &= \xi(\mathbf{x_1} - \mathbf{x_2}) \\ &= \xi(|\mathbf{x_1} - \mathbf{x_2}|)\end{aligned}$$

from statistical homogeneity

from statistical isotropy

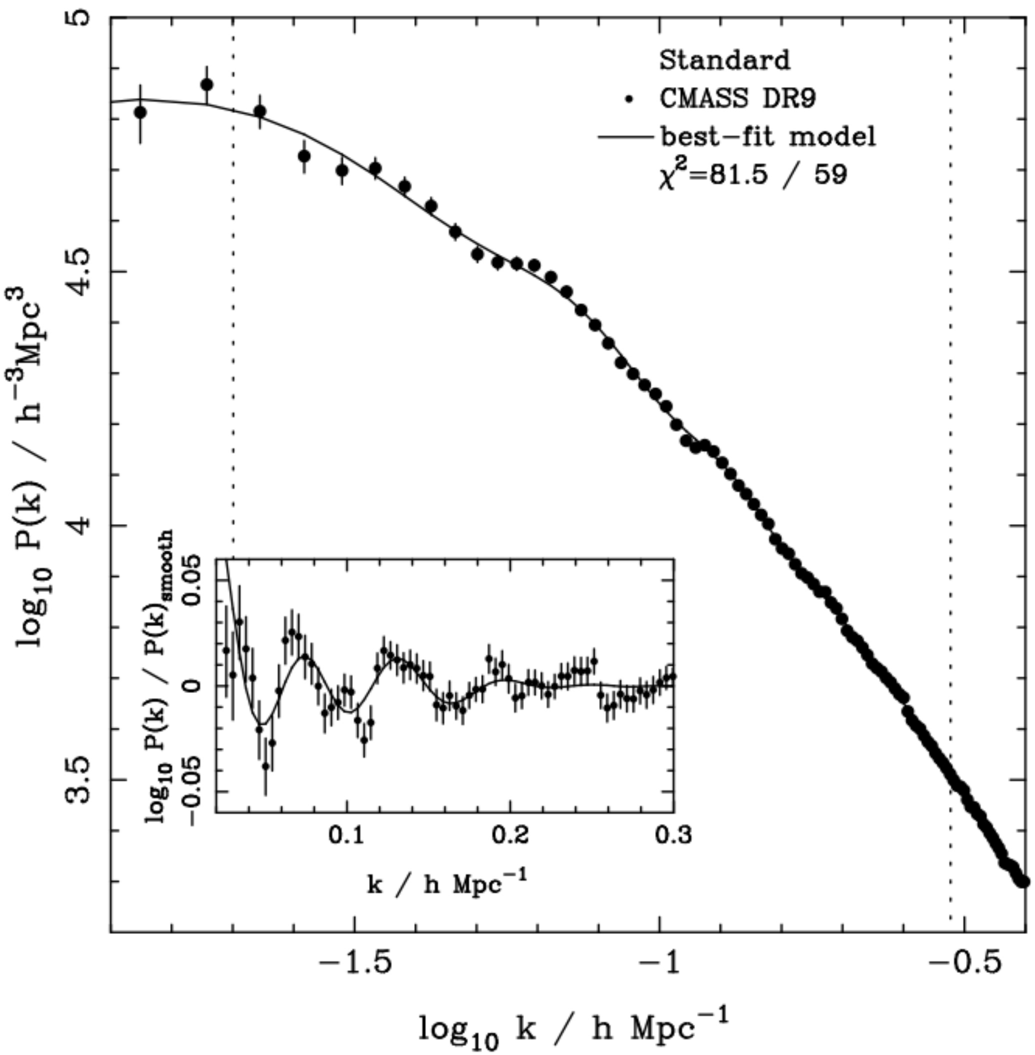


Power spectrum

$$\langle\delta(\mathbf{k_1})\delta(\mathbf{k_2})\rangle = (2\pi)^3\delta_D(\mathbf{k_1}-\mathbf{k_2})P(k_1)$$

from statistical homogeneity

from statistical isotropy

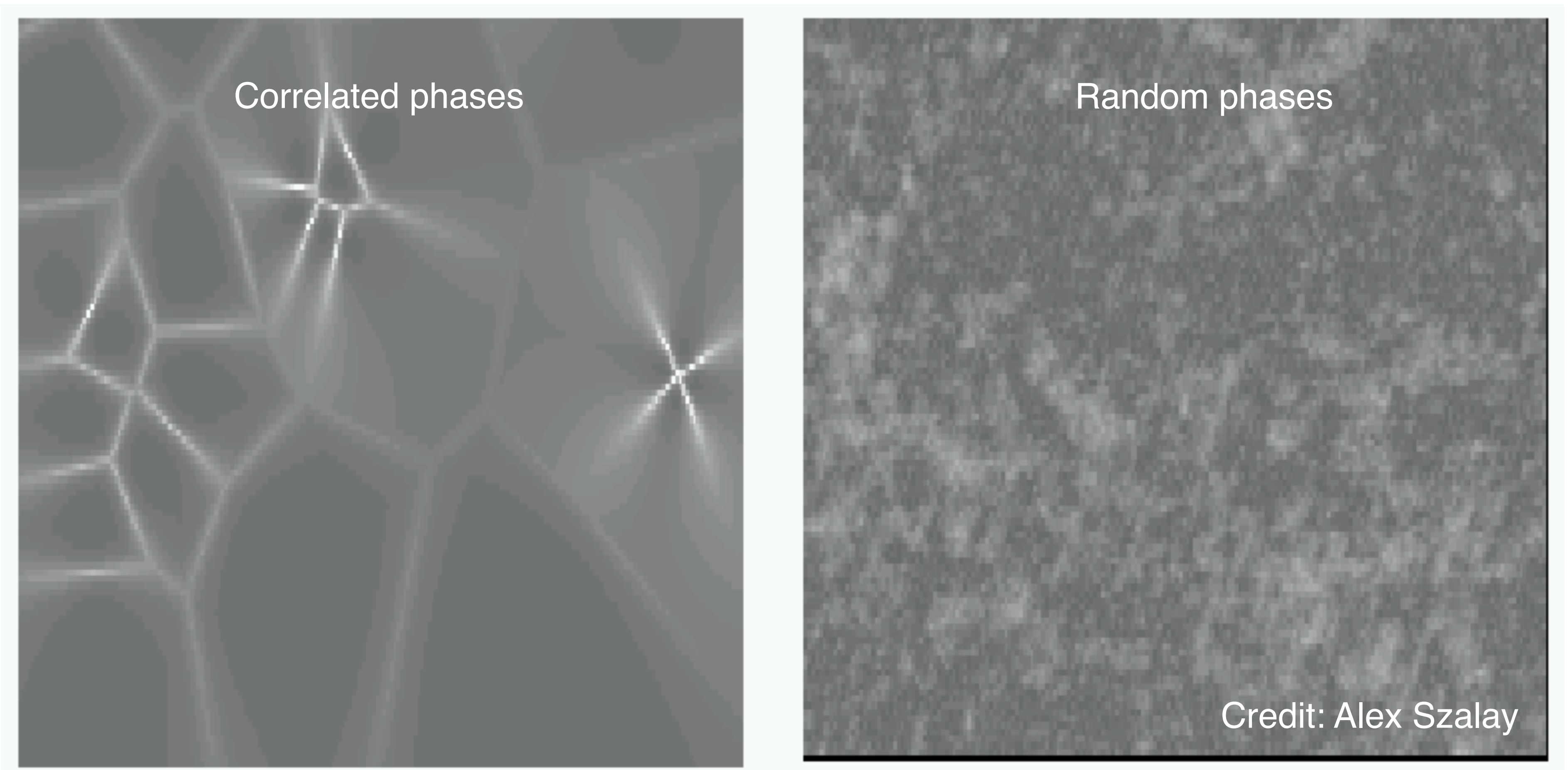


$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

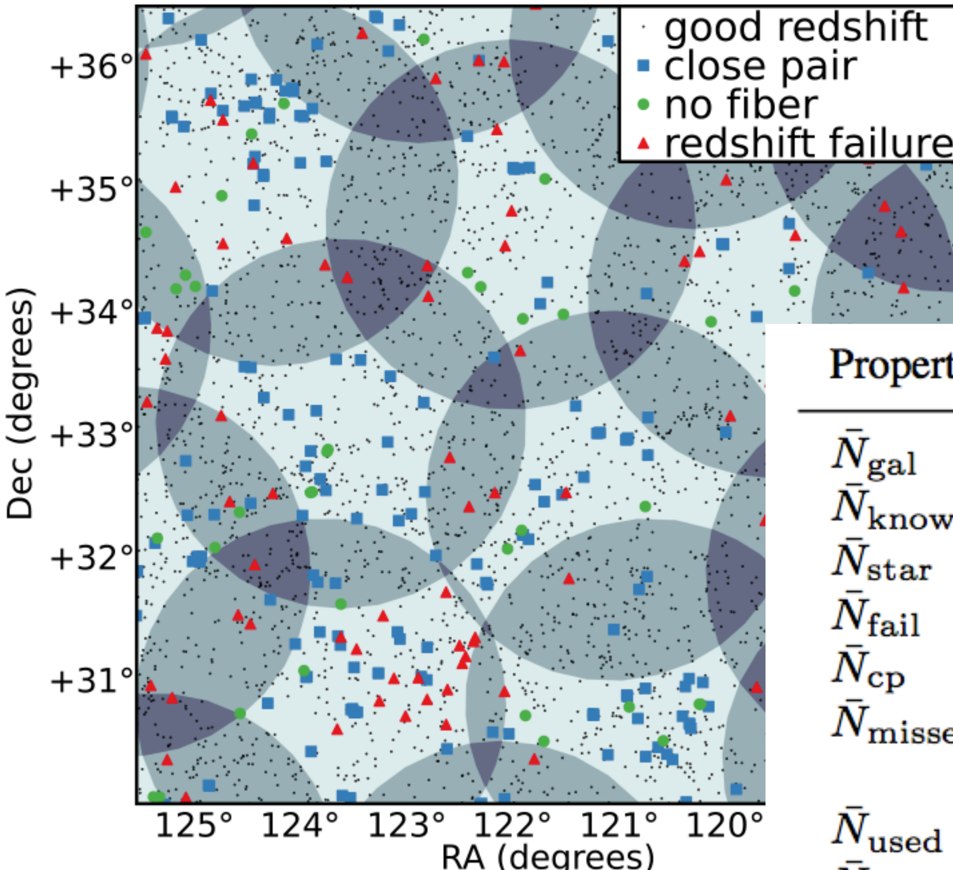
Power spectrum often written in dimensionless form

Statistically complete knowledge?

Gaussian random field: knowledge of either the correlation function or power spectrum is sufficient – they are statistically complete … but …

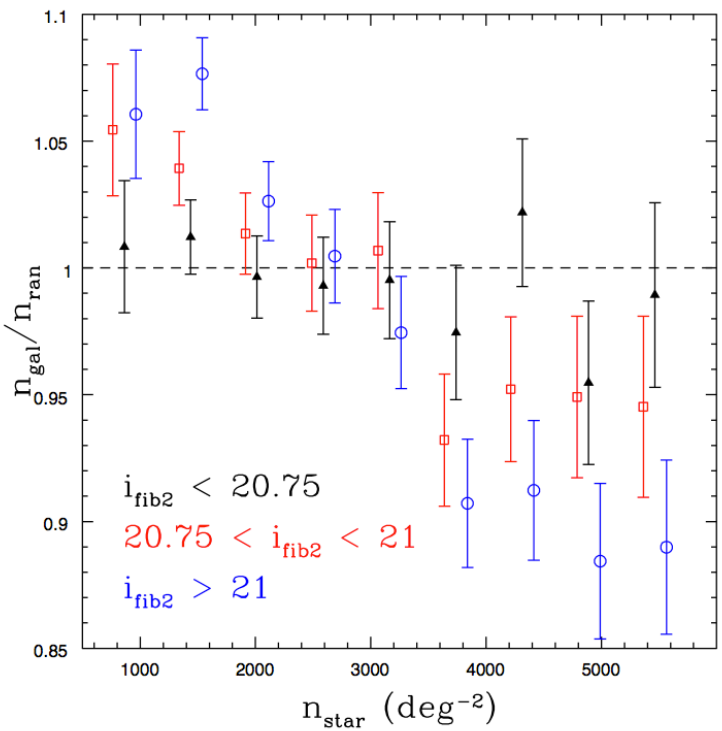


Modeling the angular galaxy mask

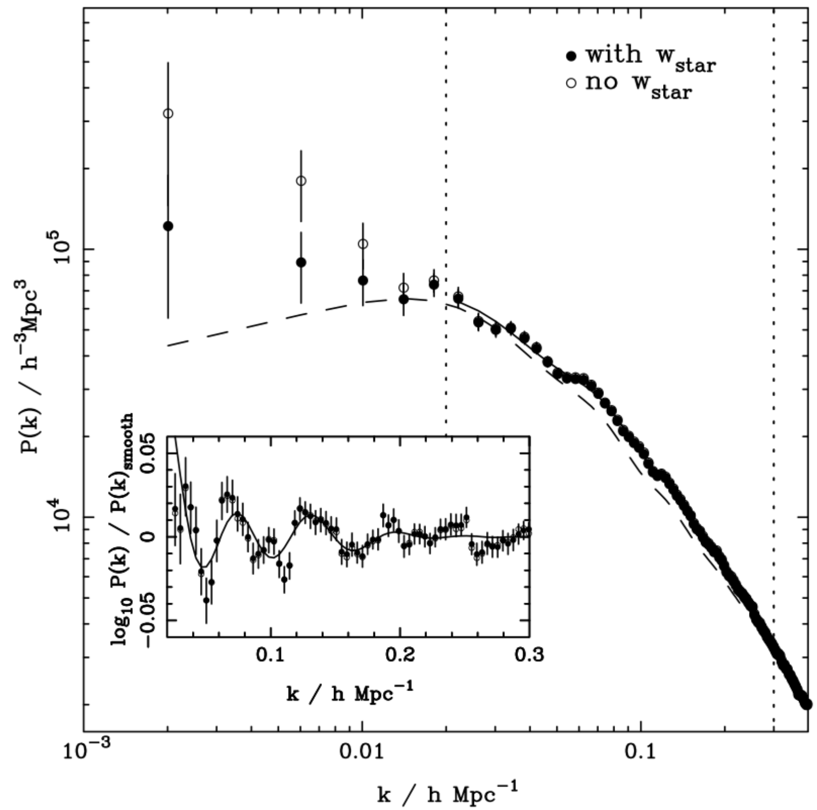


Property	NGC	SGC	total
$\bar{N}_{\rm gal}$	222 538	60 792	283 330
$\bar{N}_{\rm known}$	3766	1810	5576
$\bar{N}_{\rm star}$	7201	1771	8972
$\bar{N}_{\rm fail}$	3751	1122	4873
$\bar{N}_{\rm cp}$	14 116	3640	17 756
$\bar{N}_{\rm missed}$	4931	1911	6842
$\bar{N}_{\rm used}$	207 246	57 037	264 283
$\bar{N}_{\rm obs}$	233 490	63 685	297 175
$\bar{N}_{\rm targ}$	256 303	71 046	327 349
Total area / deg^2	2635	709	3344
Effective area / deg^2	2584	690	3275

Target density fluctuations

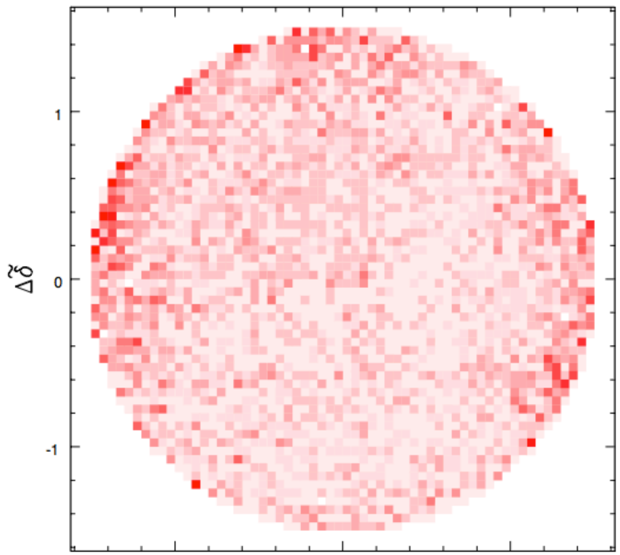


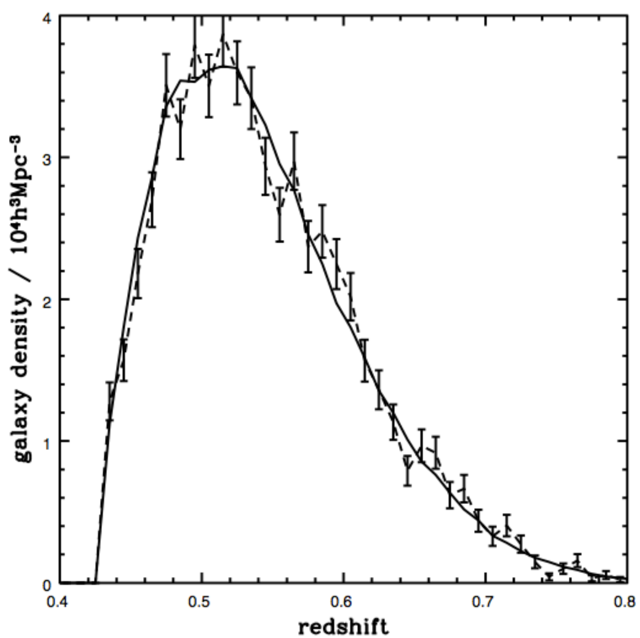
Target density correlates with stellar density and brightness
Corrected by weighting
See Ross et al. for more details



Ross et al. 2012; arXiv:1208.1491

Redshift failures & close pairs



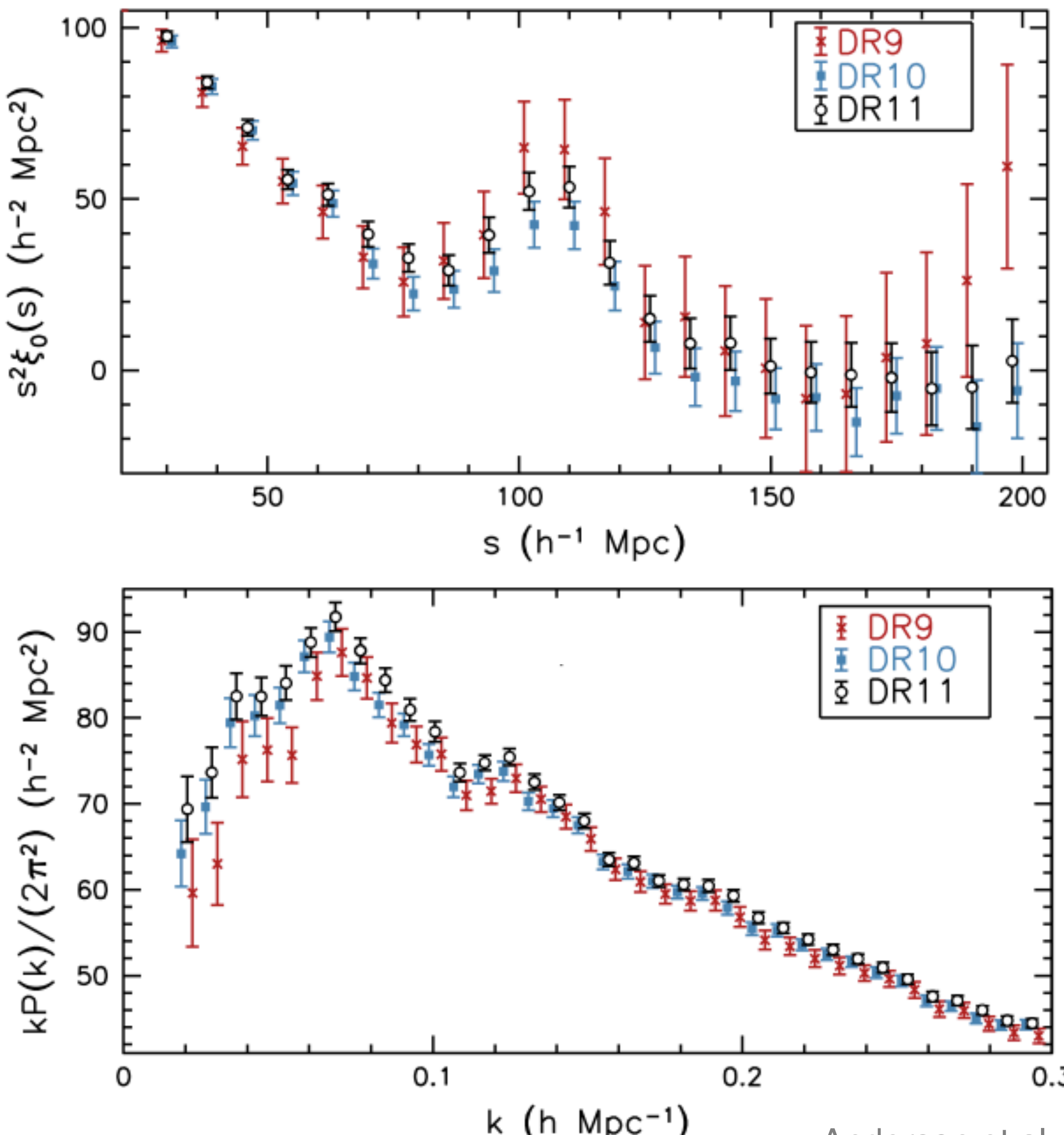


Spectra where we failed to get an accurate redshift are spatially correlated
Close pairs obviously correlated with density

Correct both by upweighting the nearest target with good classification

Ross et al. 2012; arXiv:1208.1491

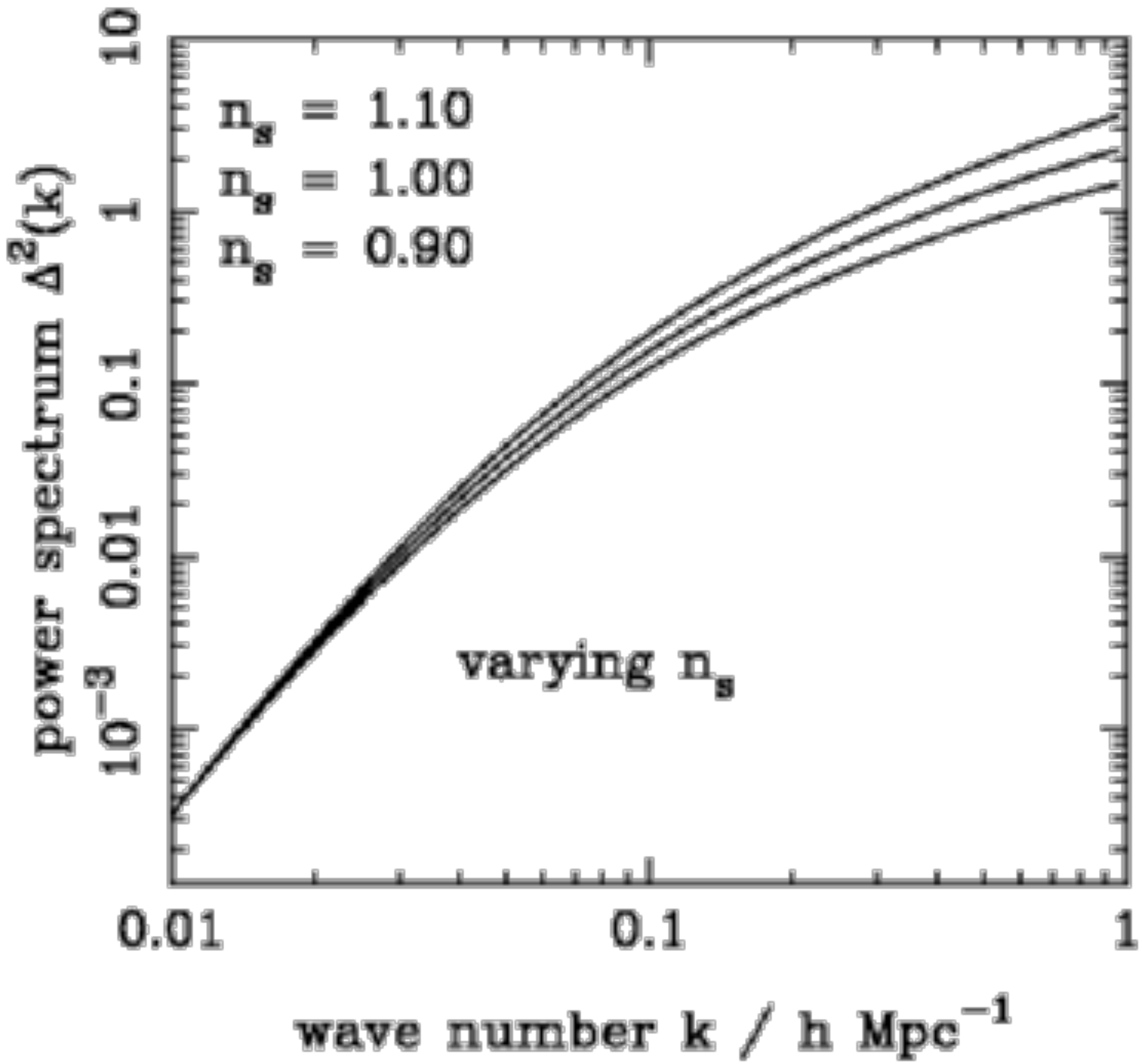
Measured 2-point functions



Anderson et al. 2013; arXiv:1312.4877

The matter power spectrum

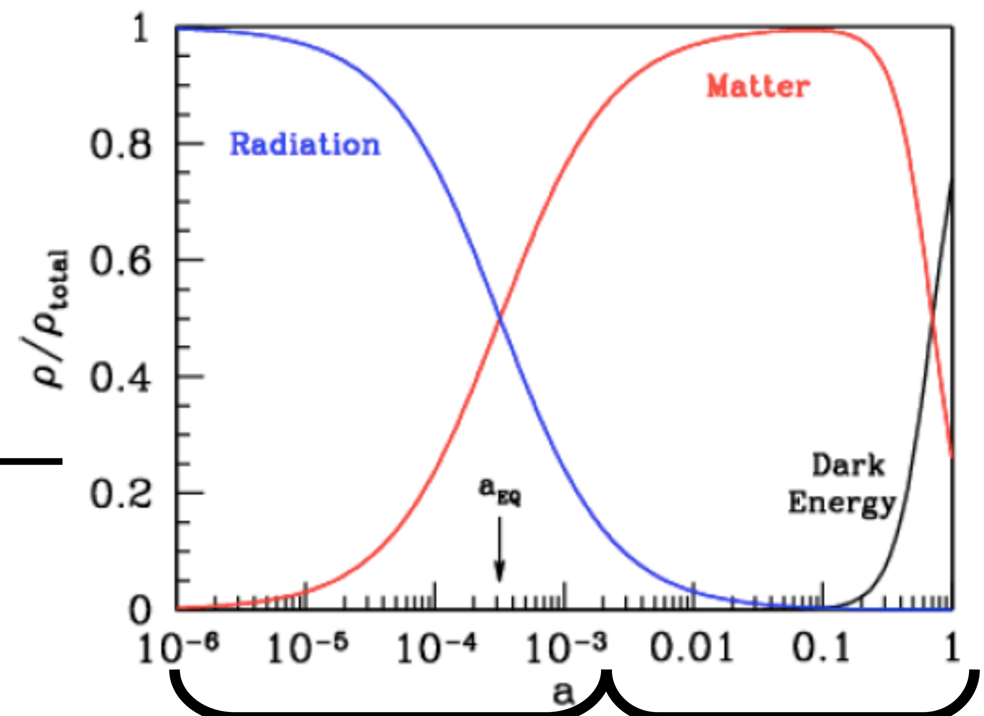
Matter P(k) depends on inflation



$$P(k) = k^n$$

$$(n \approx 1)$$

Evolution of the power spectrum after inflation



Inflation

Transfer function

Matter/DE domination

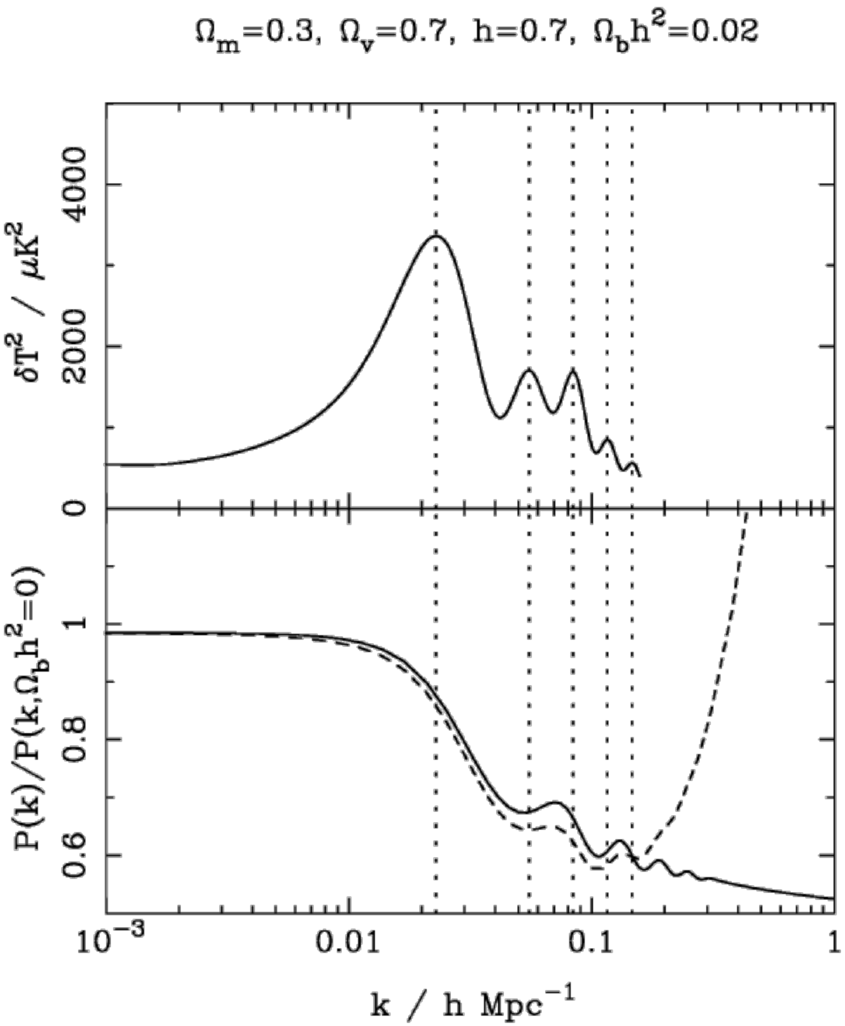
Non-linear

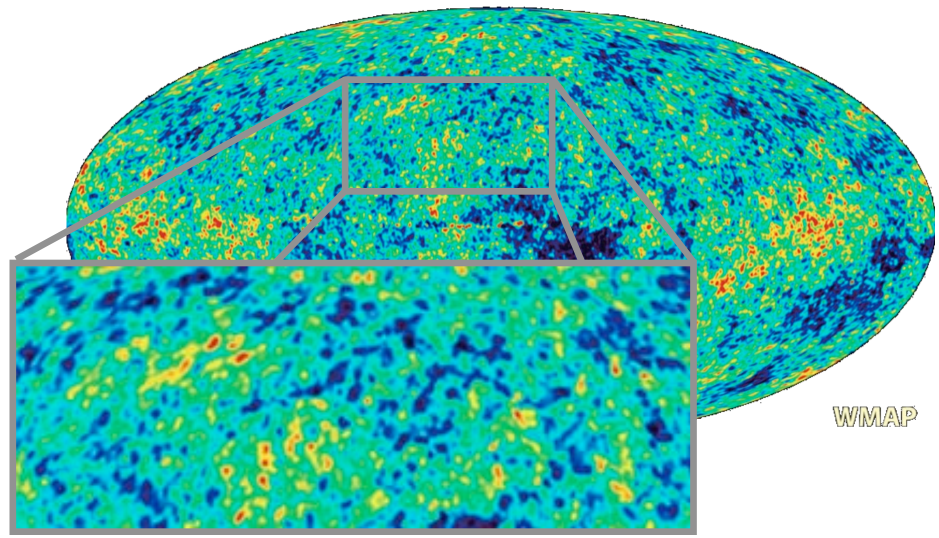
$$P_{\rm lin}(k) = k^n T^2(k) D^2(a)$$

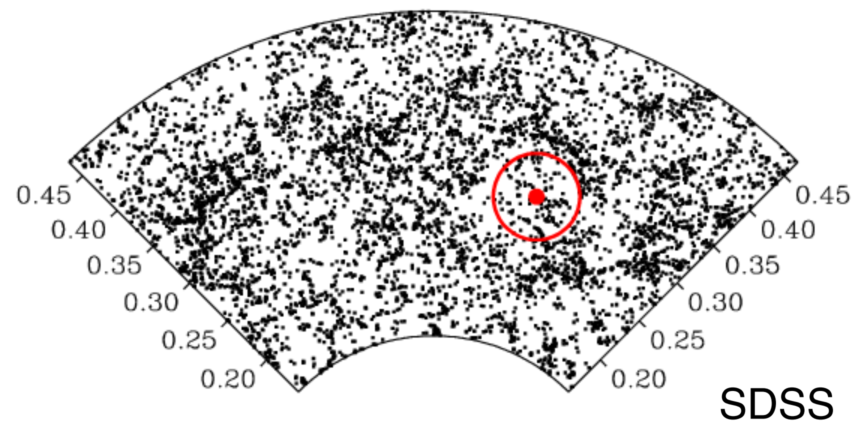
(comoving coordinates)

linear growth independent of scale

Comparison of CMB and LSS power spectra



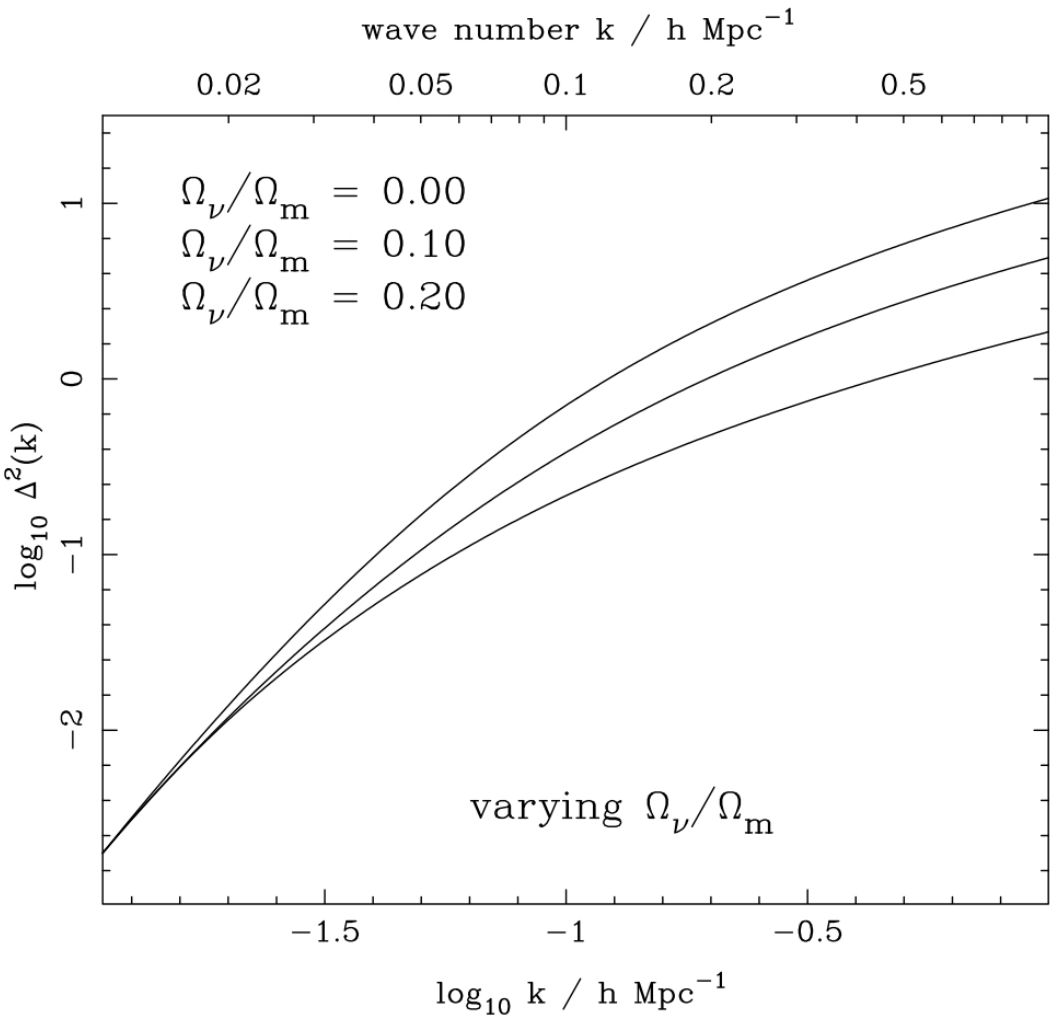




The transfer function - massive neutrinos

The effect of massive neutrinos

The existence of massive neutrinos can also introduce a suppression of T(k) on small scales relative to their Jeans length. Partly degenerate with the suppression caused by radiation epoch. Position depends on neutrino-mass equality scale.



Cosmological density -> neutrino mass

Standard model of particle physics links together photon and neutrino species densities

Based on current photon density (from CMB), we expect a cosmological neutrino background with a density 112 cm^{-2} per species

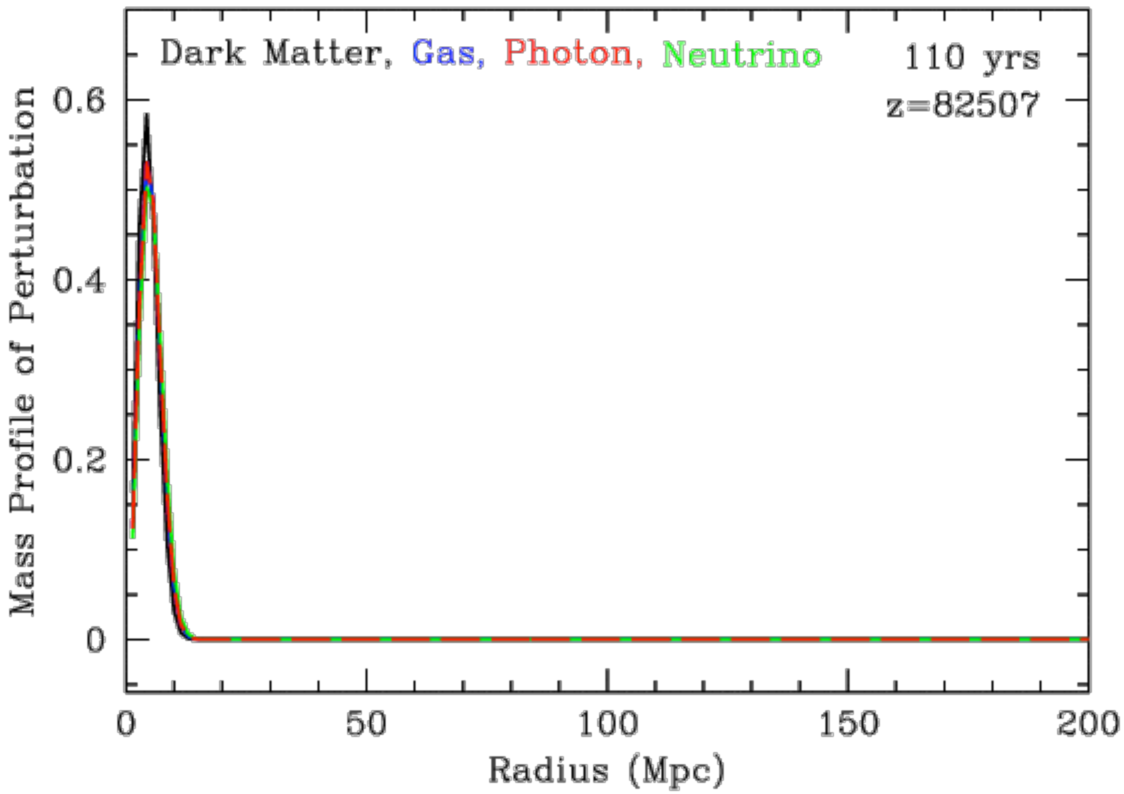
This leads to an expected cosmological density

$$f_\nu = \frac{\Omega_\nu}{\Omega_m} = \frac{\sum m_\nu}{93 \Omega_m h^2 \, \mathrm{eV}}$$

Thus a measurement of the cosmological density directly gives a measurement of the summed neutrino mass

The transfer function - Baryon Acoustic Oscillations

Configuration space description

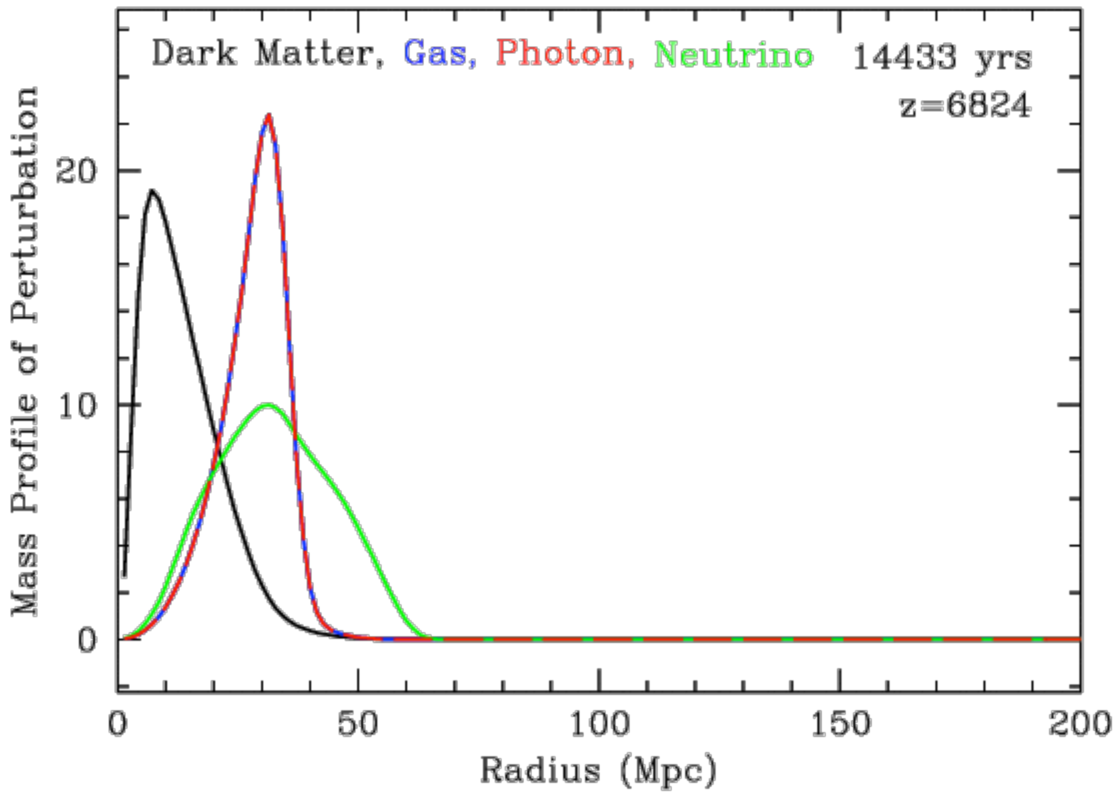


$\Omega_m h^2 = 0.147$, $\Omega_b h^2 = 0.024$

position-space description: Bashinsky & Bertschinger
astro-ph/0012153 & astro-ph/02022153

plots by Dan Eisenstein

Configuration space description



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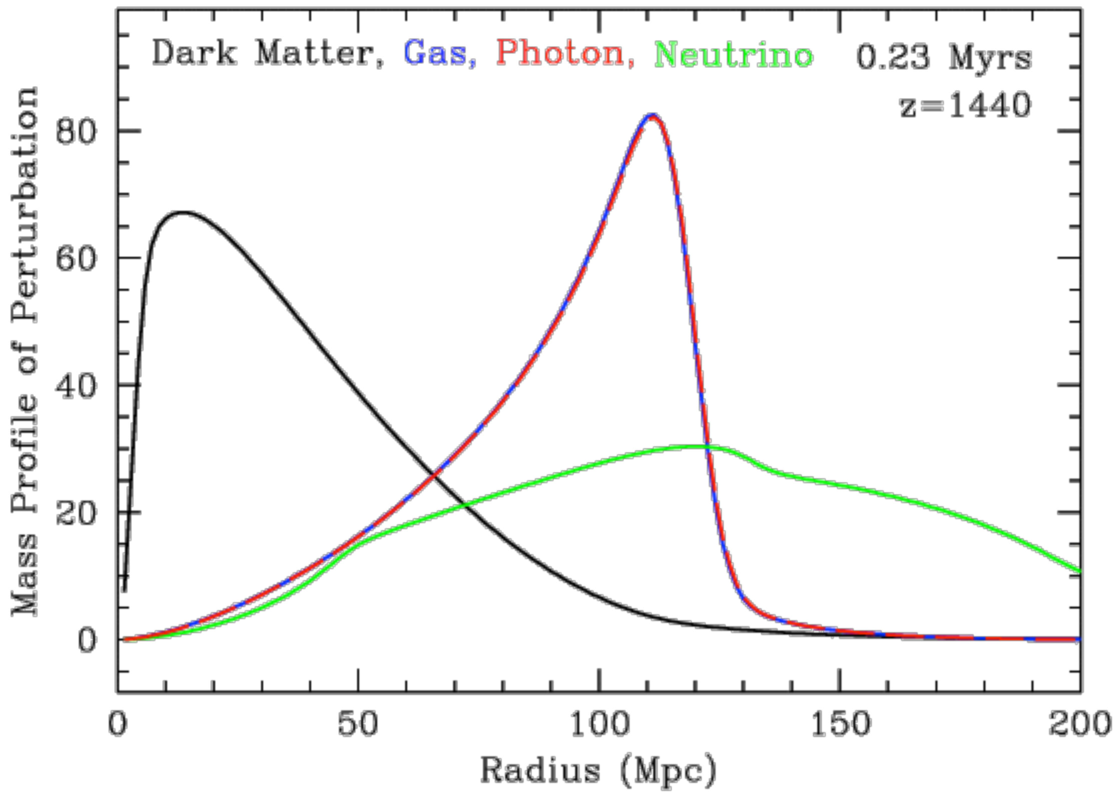

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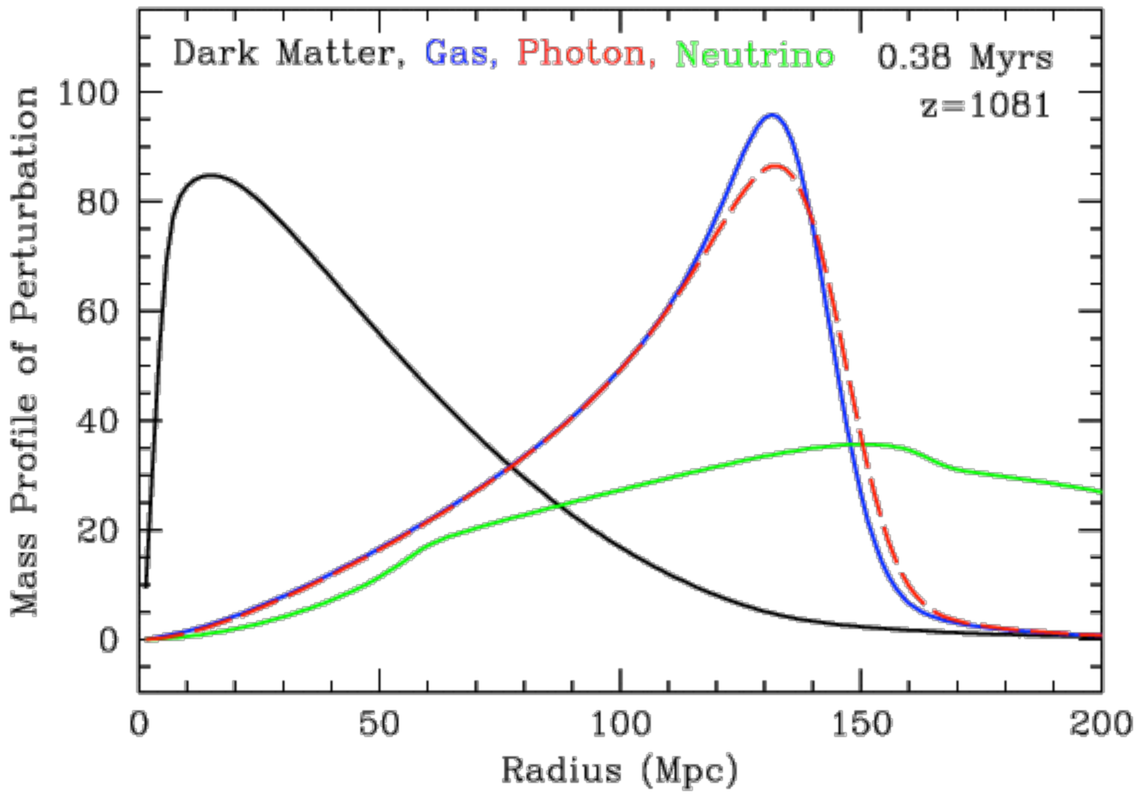

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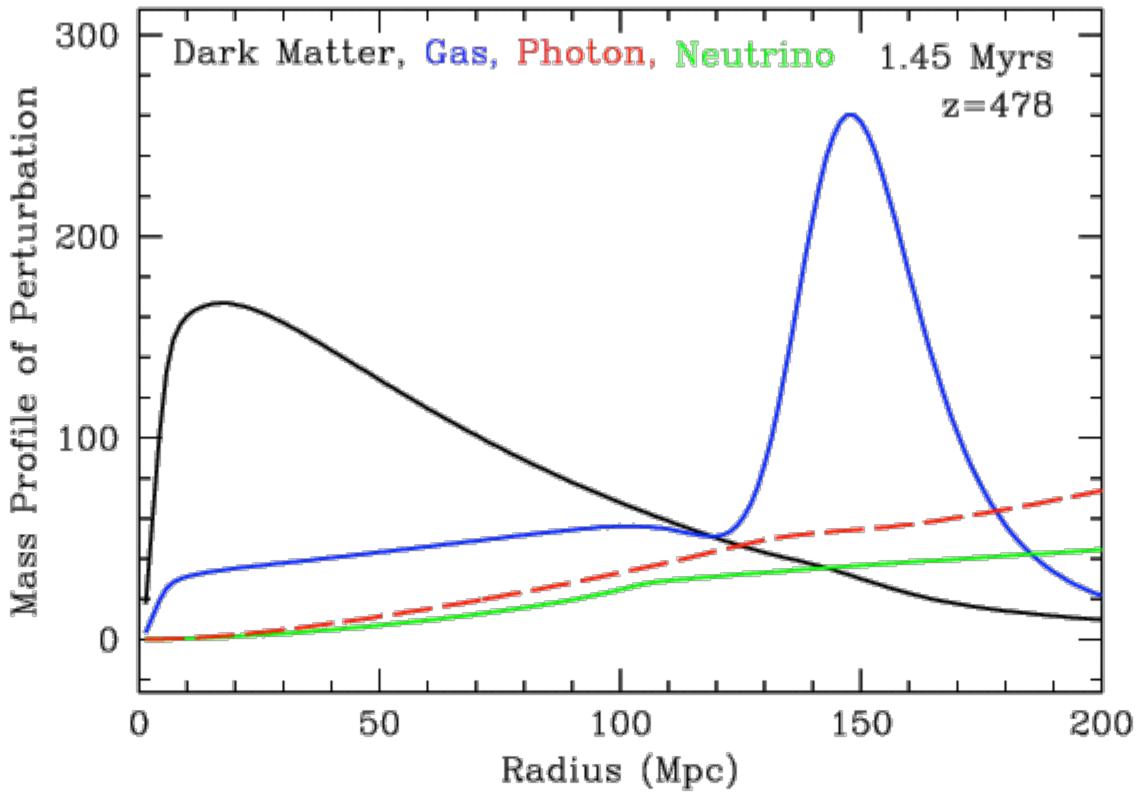

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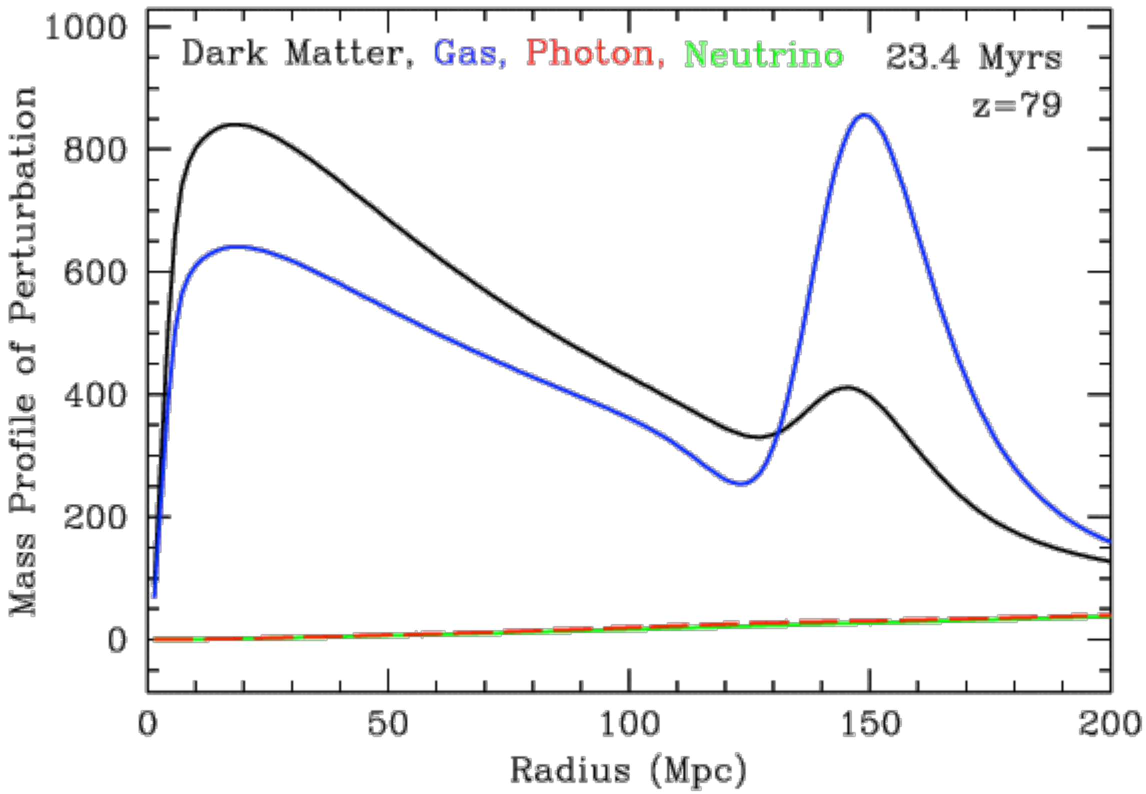

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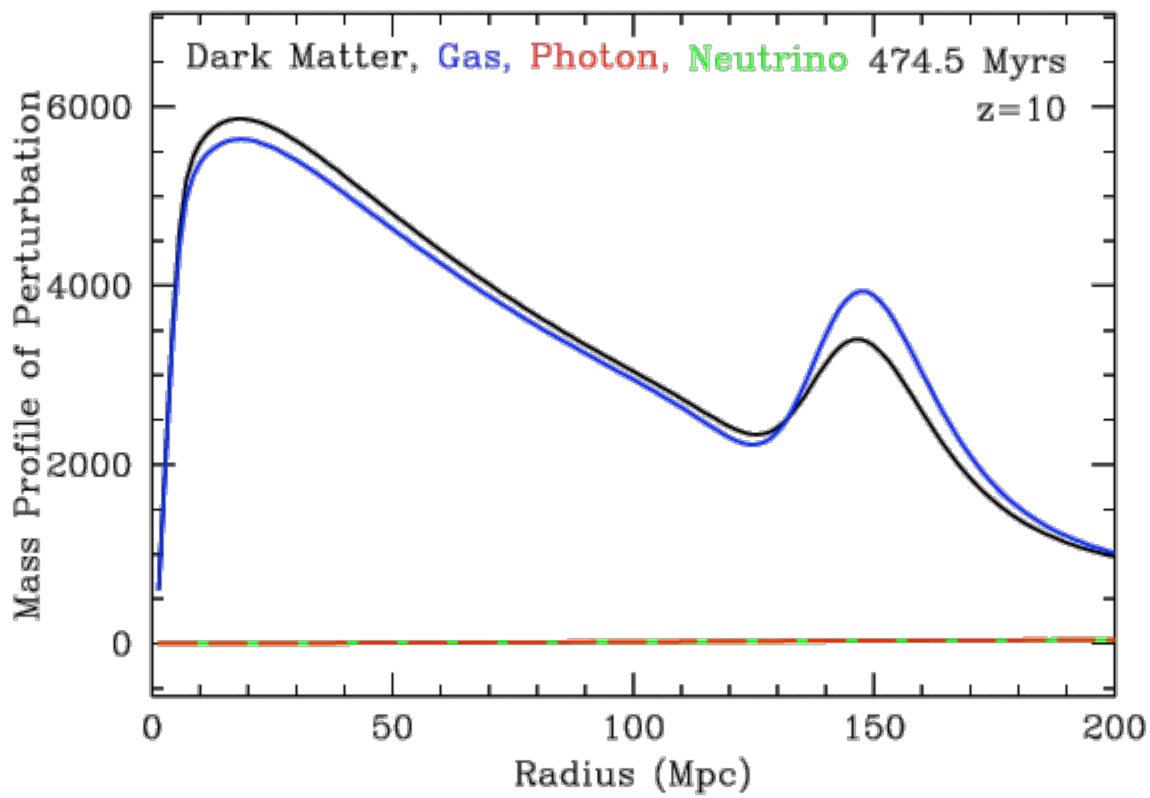

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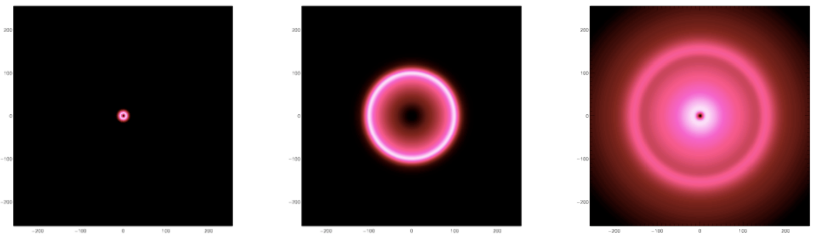
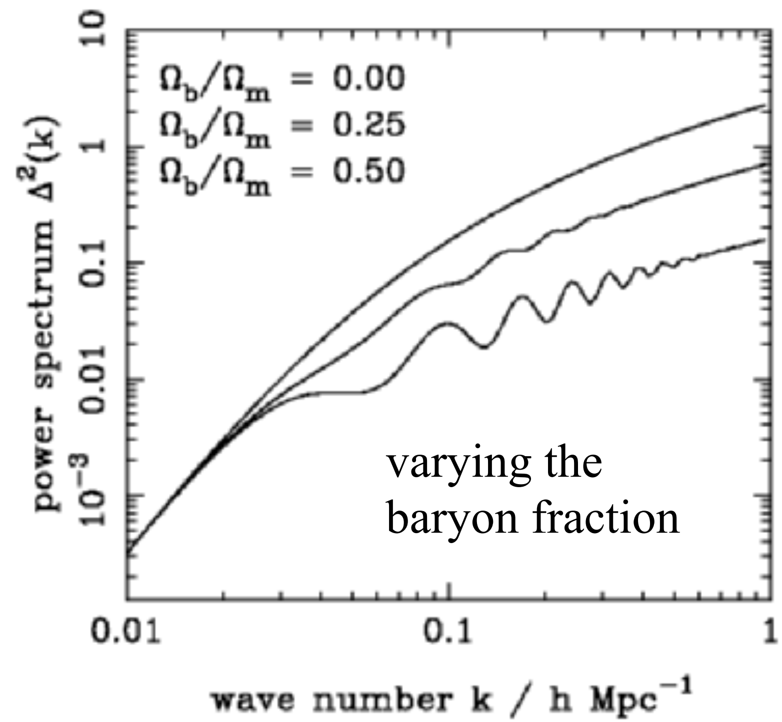
astro-ph/0012153 & astro-ph/02022153

plots by Dan Eisenstein

Baryon Acoustic Oscillations (BAO)



(images from Martin White)



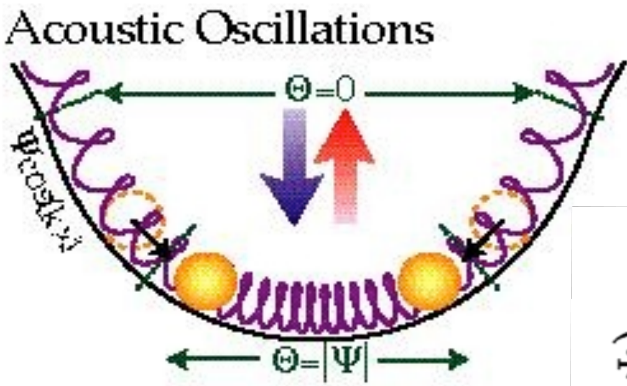
To first approximation, BAO wavelength is determined by the comoving sound horizon at recombination

$$k_{\rm bao} = 2\pi/s$$

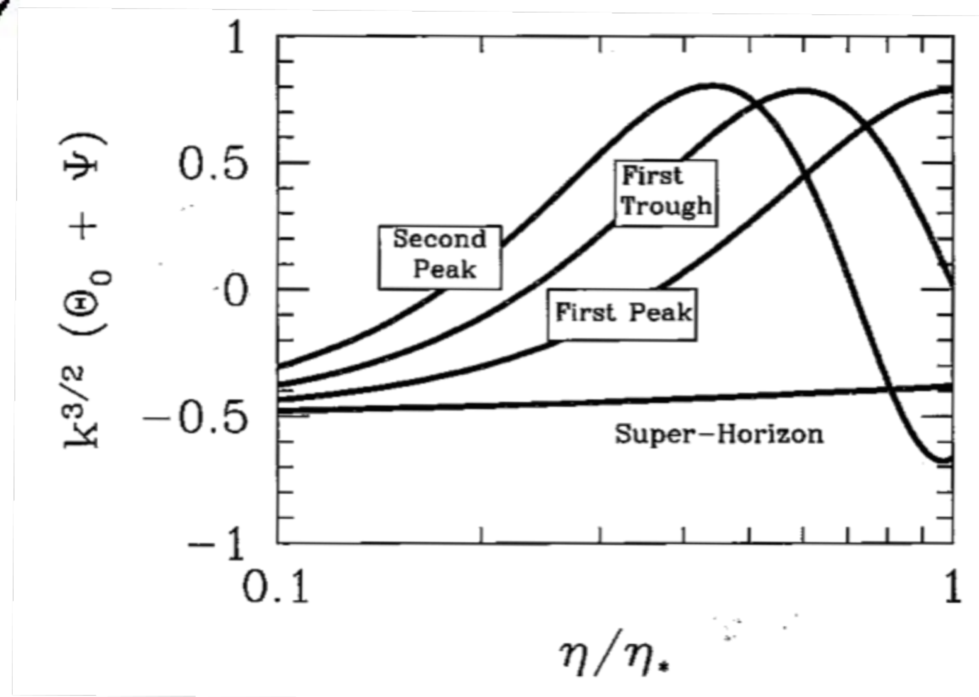
$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{\rm eq})^{1/2}}$$

comoving sound horizon ~110h^{-1}Mpc, BAO wavelength 0.06hMpc^{-1}

Acoustic Oscillations in the matter distribution

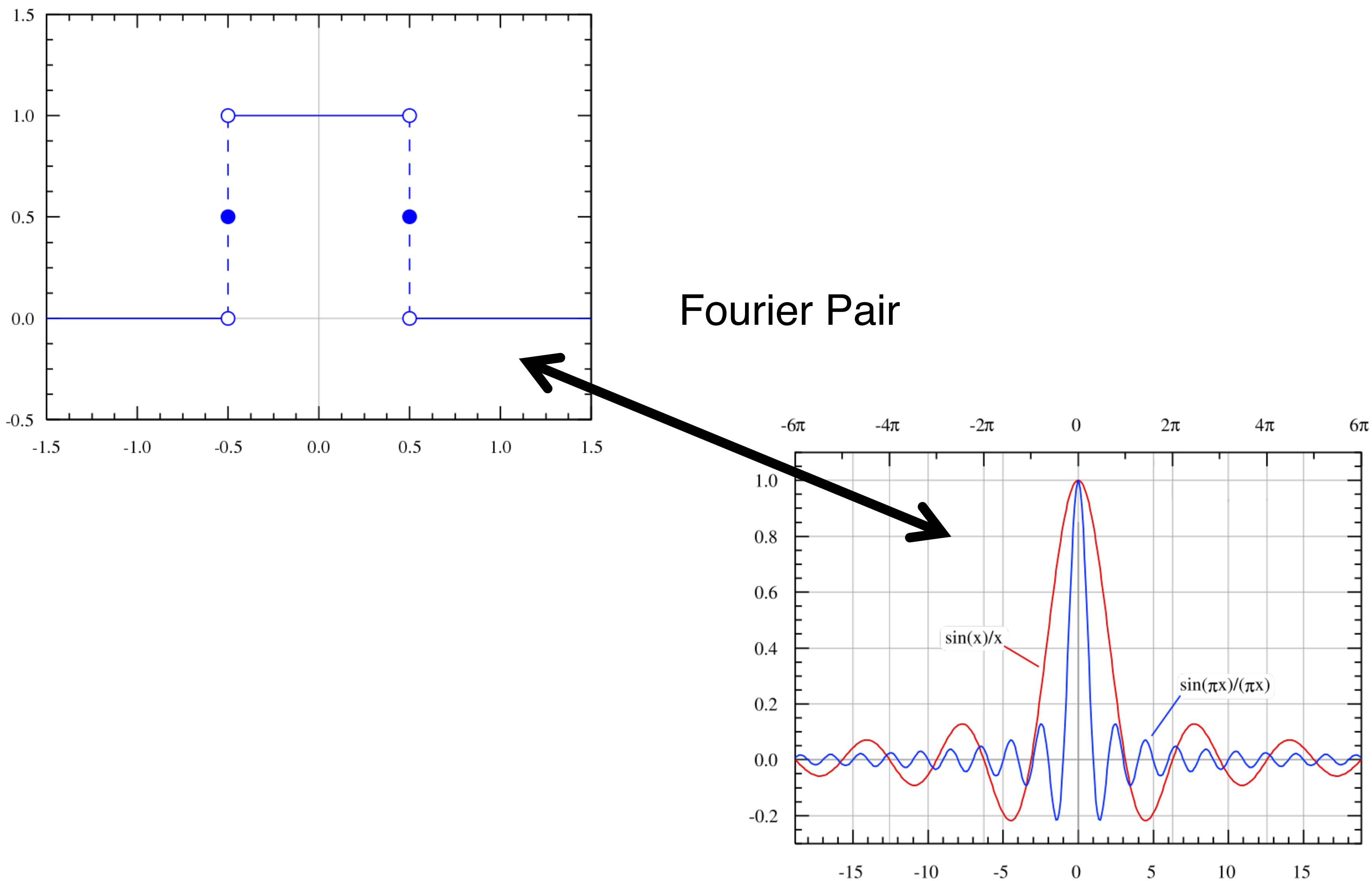


$$\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = F$$



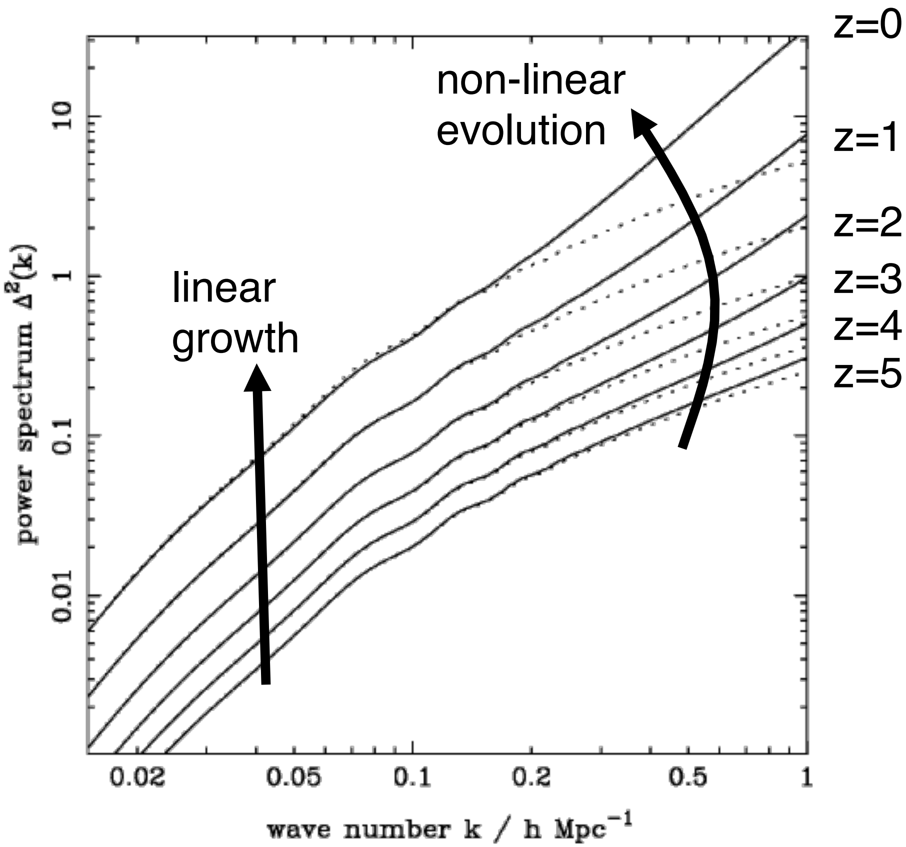
Dodelson “modern cosmology”

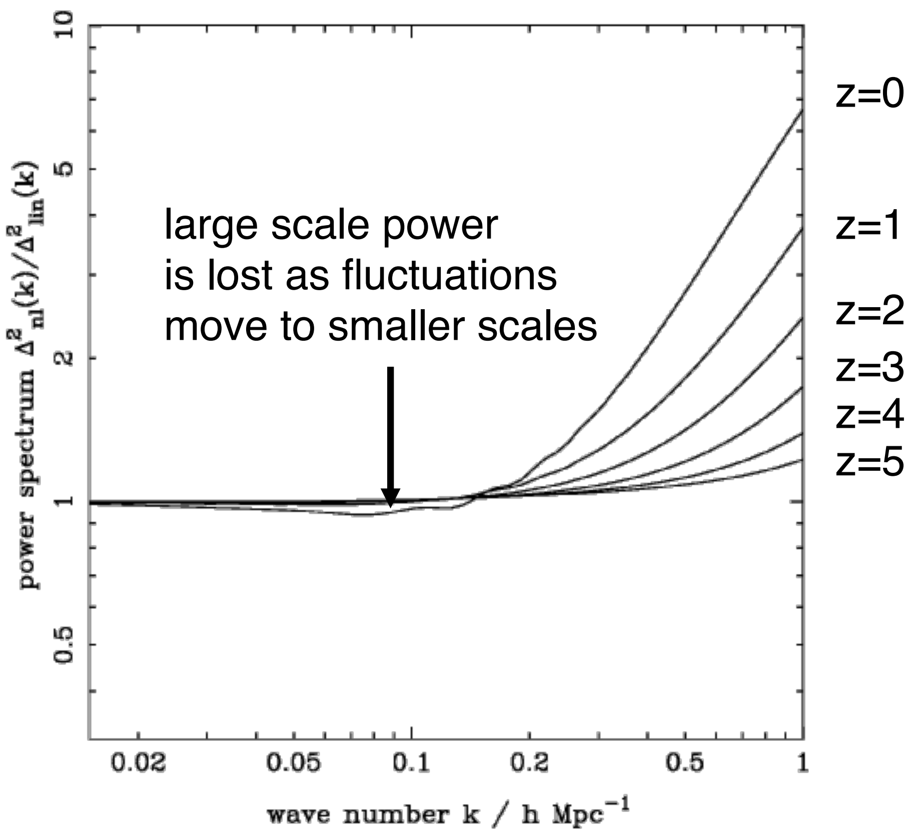
descriptions describe the same physics



Reconstruction of linear BAO

Linear vs Non-linear behaviour

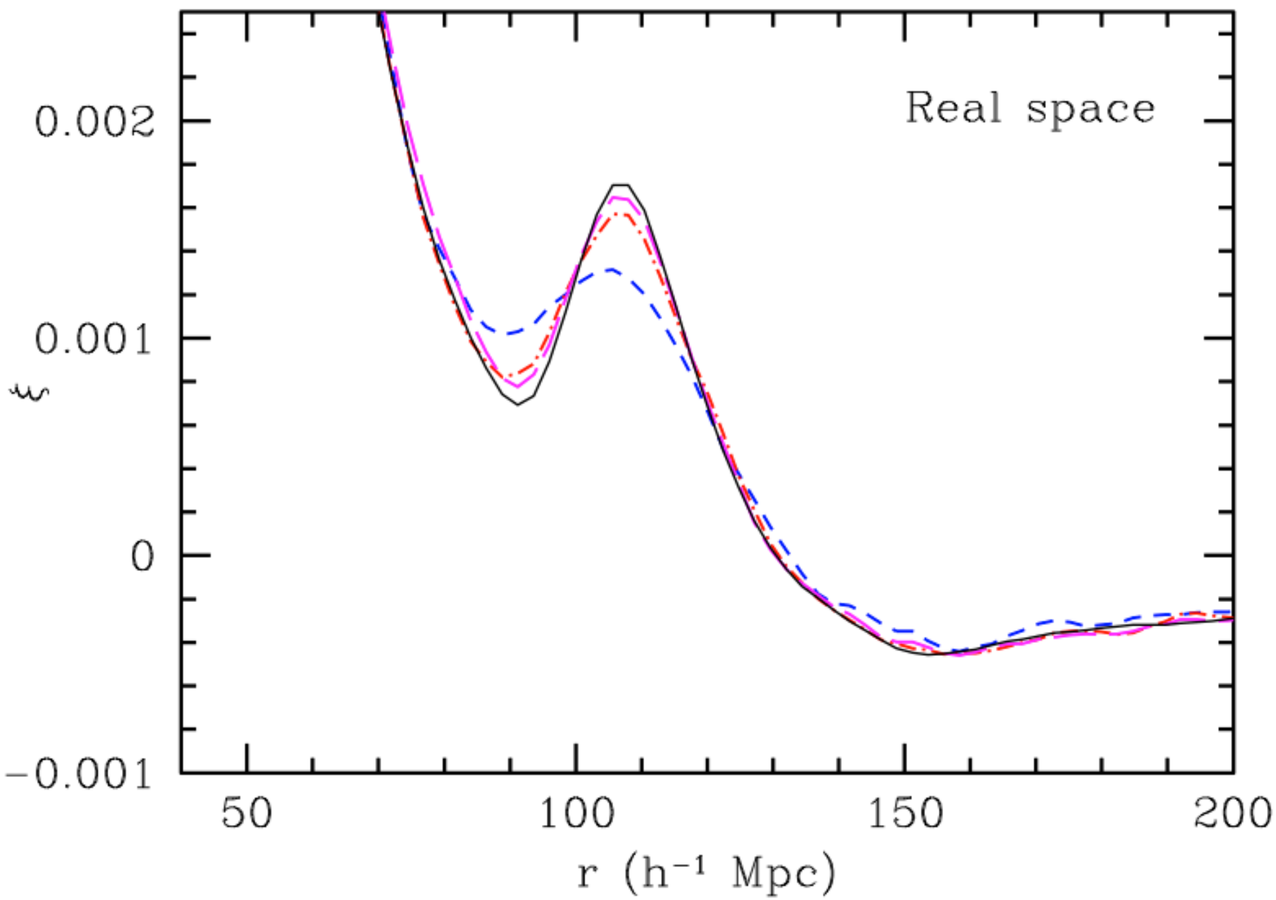




Cannot easily measure growth directly from galaxy surveys as degenerate with galaxy bias

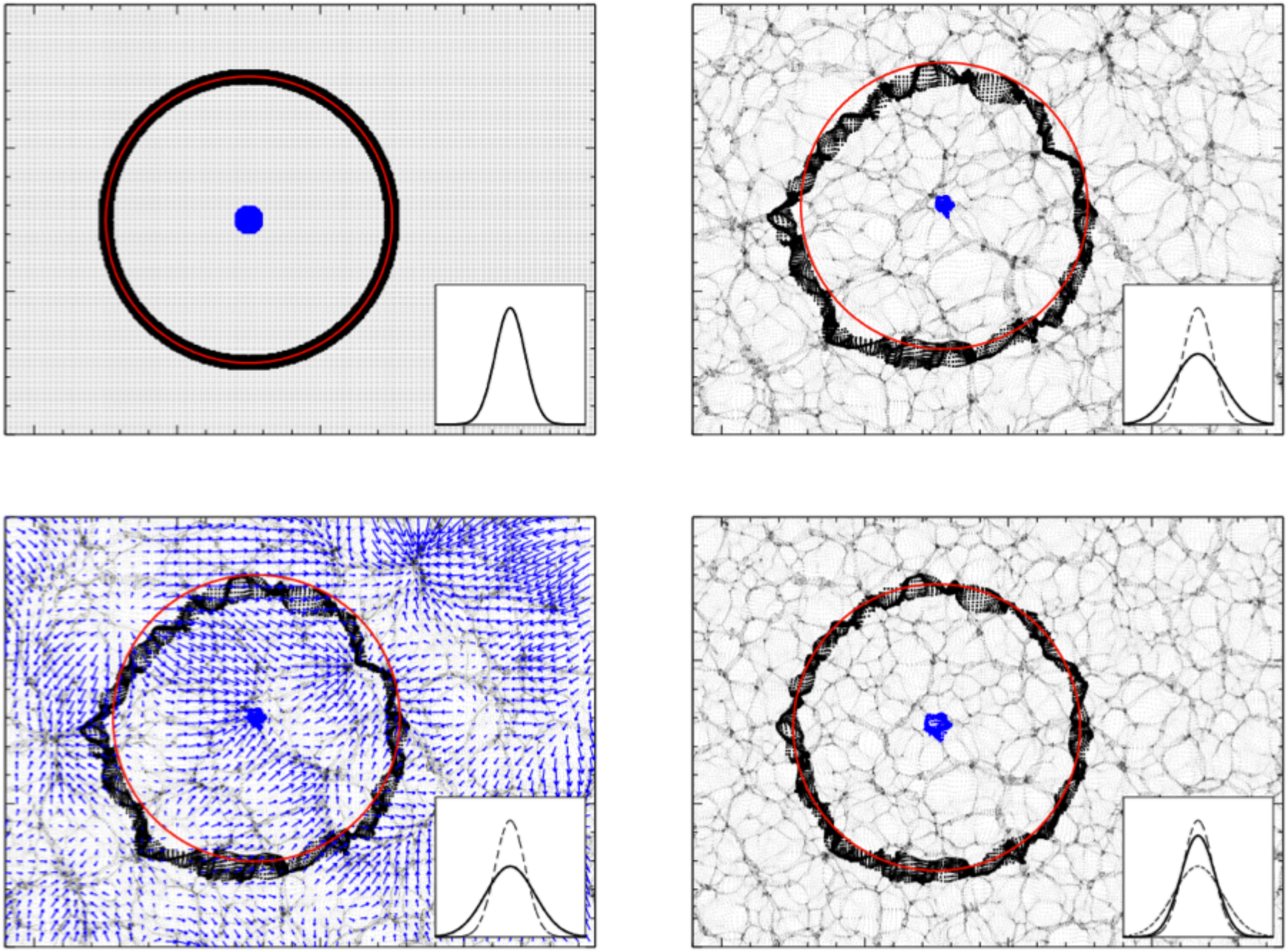
P(k) calculated from Smith et al. 2003, MNRAS, 341,1311 fitting formulae

Linear vs Non-linear behaviour



Eisenstein et al. 2006; arXiv:0604362

Non-linear movement on BAO scales



Padmanabhan et al. 2012; arXiv:1202.0090

A simple reconstruction algorithm

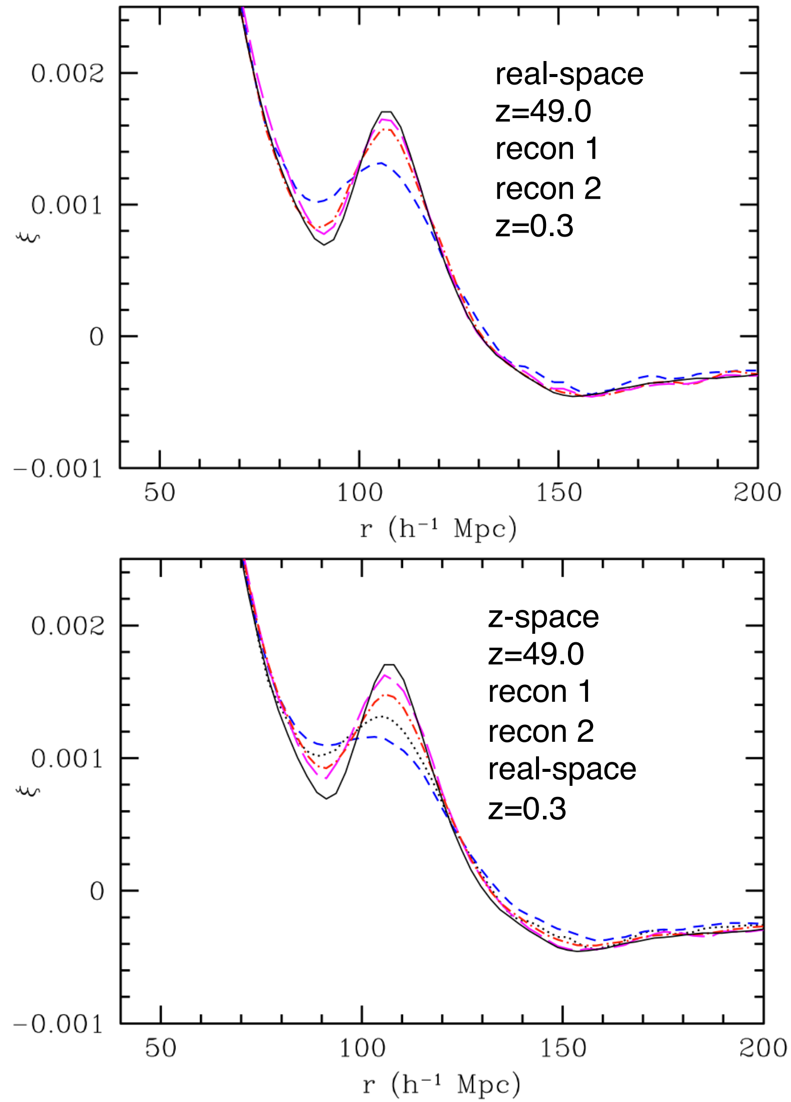
"Smoothing" dominated by large-scale flows

Smooth field and move galaxies by predicted (linear) motion

Breaks coherence between large-scale and small-scale motion

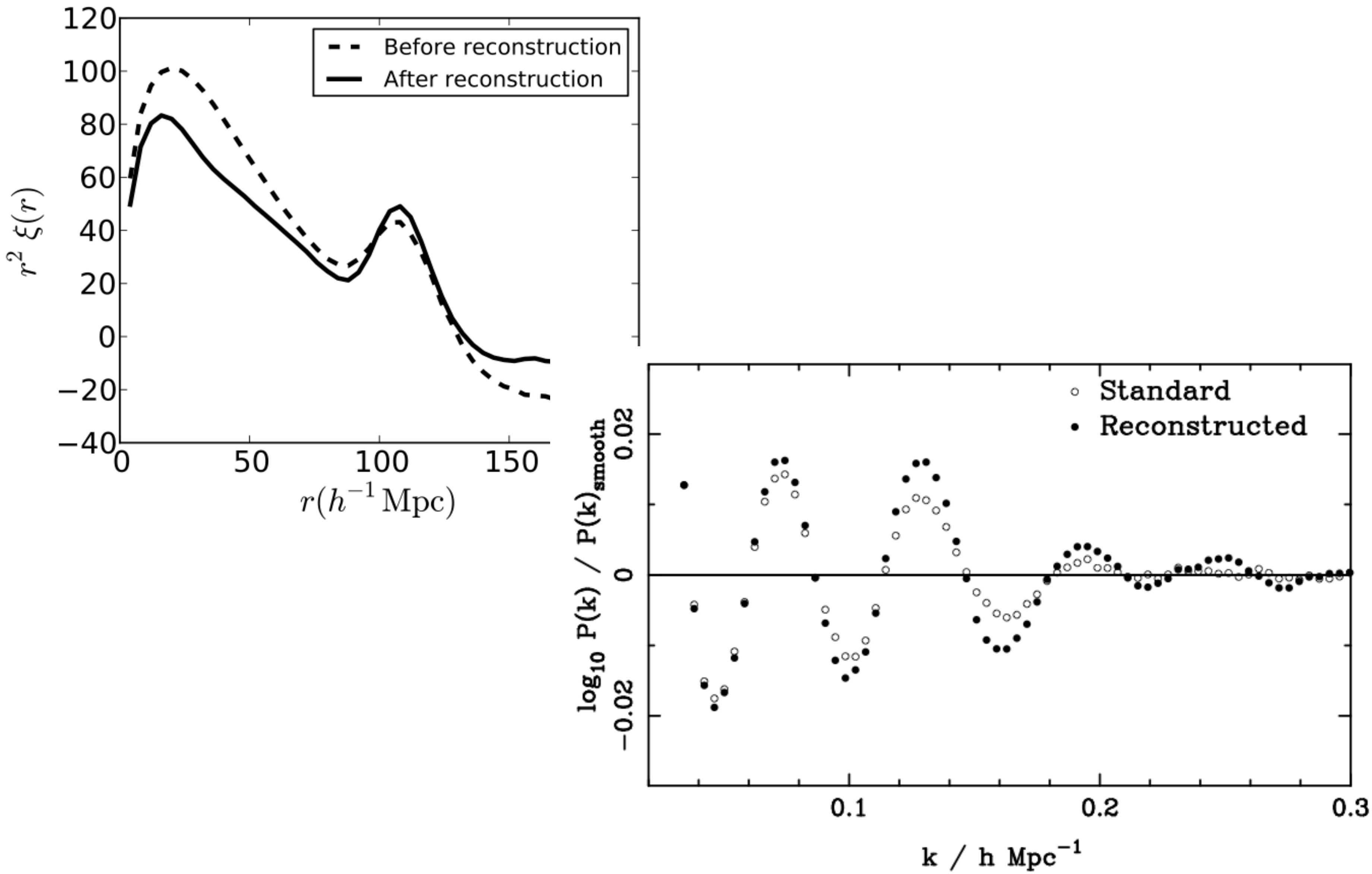
Does not recover the linear field, but does reduce the non-linear smoothing

See Padmanabhan et al. (2008; arXiv: 0812.2905) for a perturbation theory derivation of this



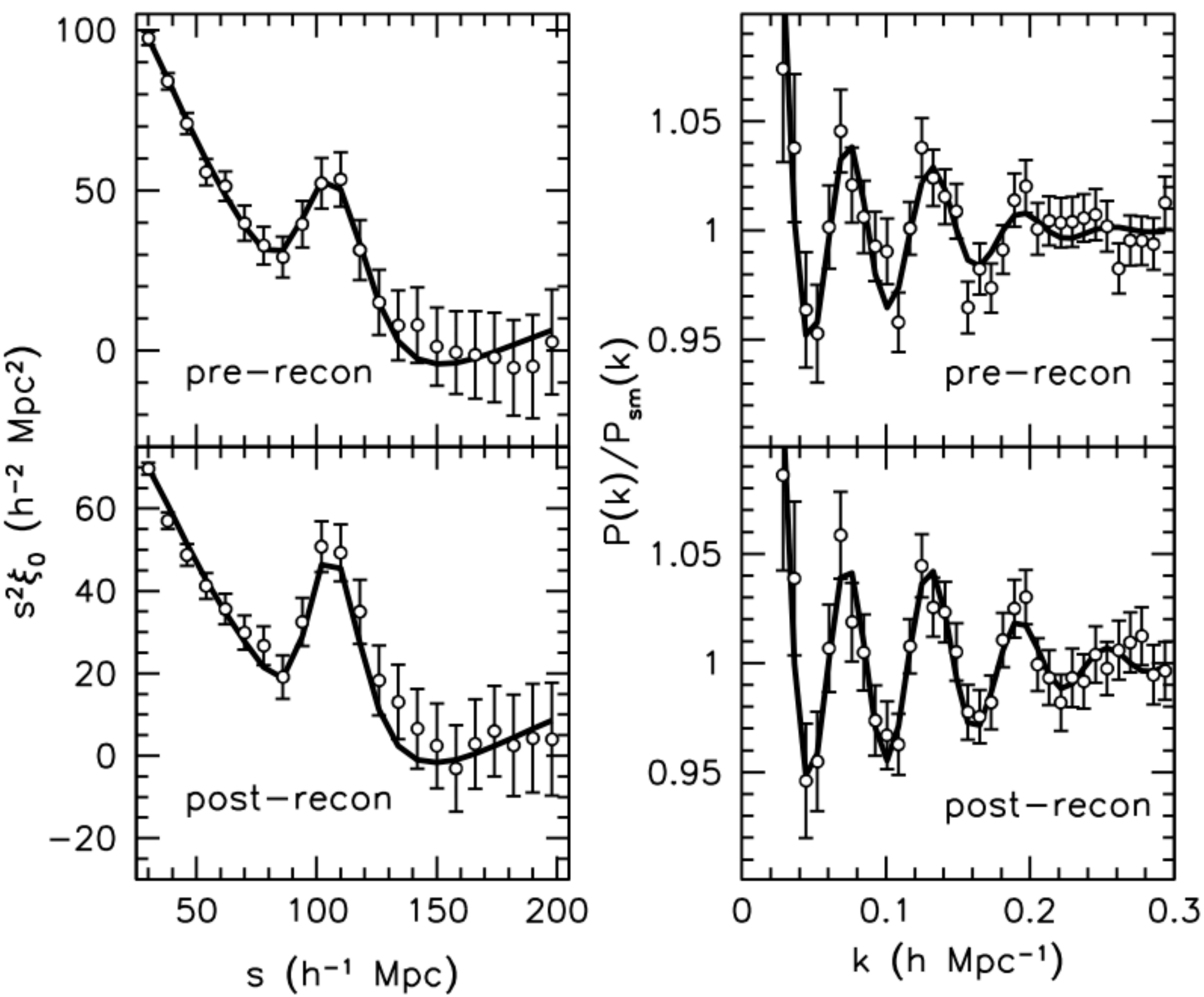
Eisenstein et al. 2006: arXiv:0604362

Reconstruction on SDSS-III mocks



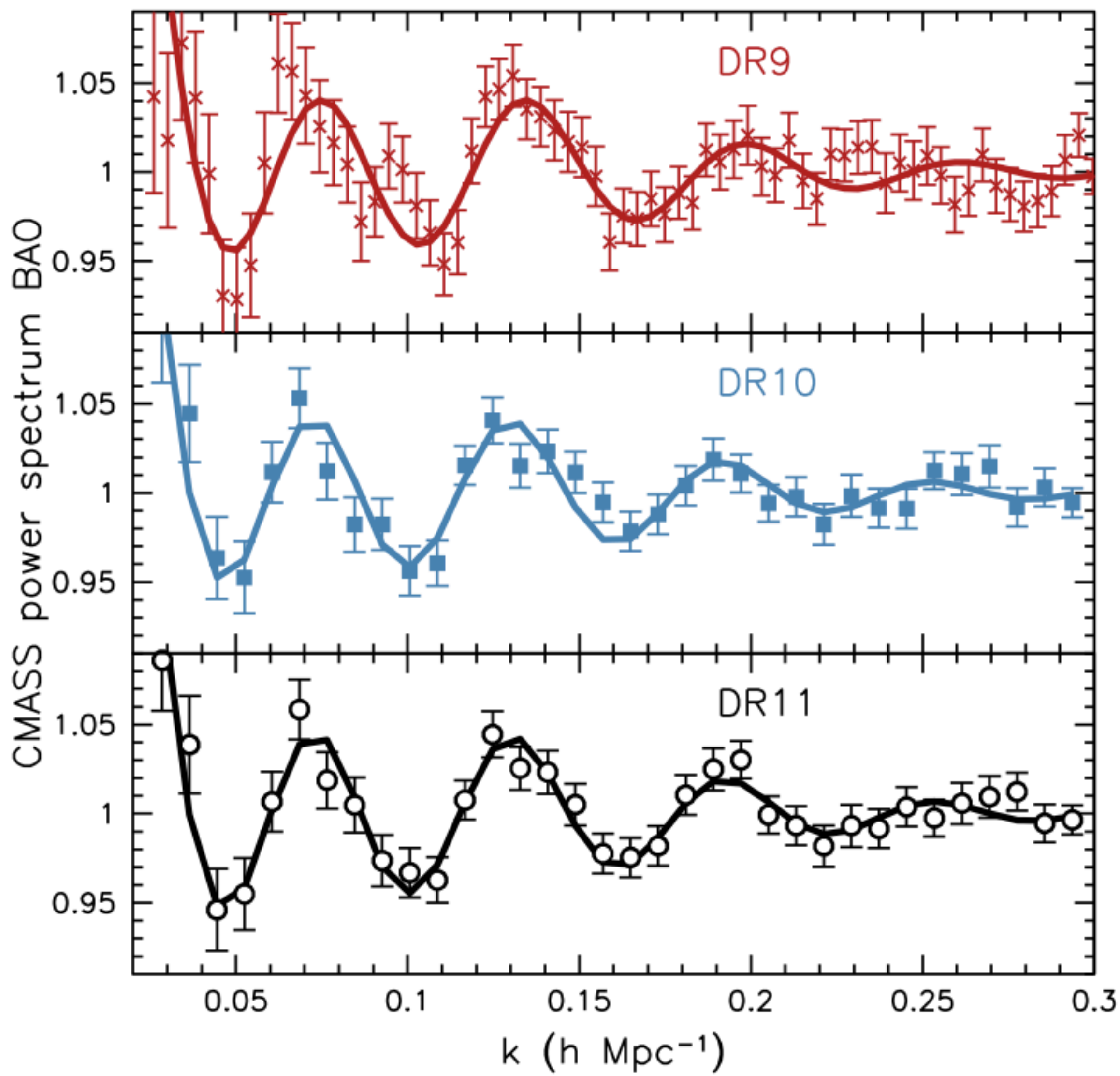
Anderson et al. 2012; arXiv:1203.6565

The improvement from reconstruction



Anderson et al. 2013; arXiv:1312.4877

The improvement DR9 - DR11



Anderson et al. 2013; arXiv:1312.4877

Galaxy clustering as a standard ruler

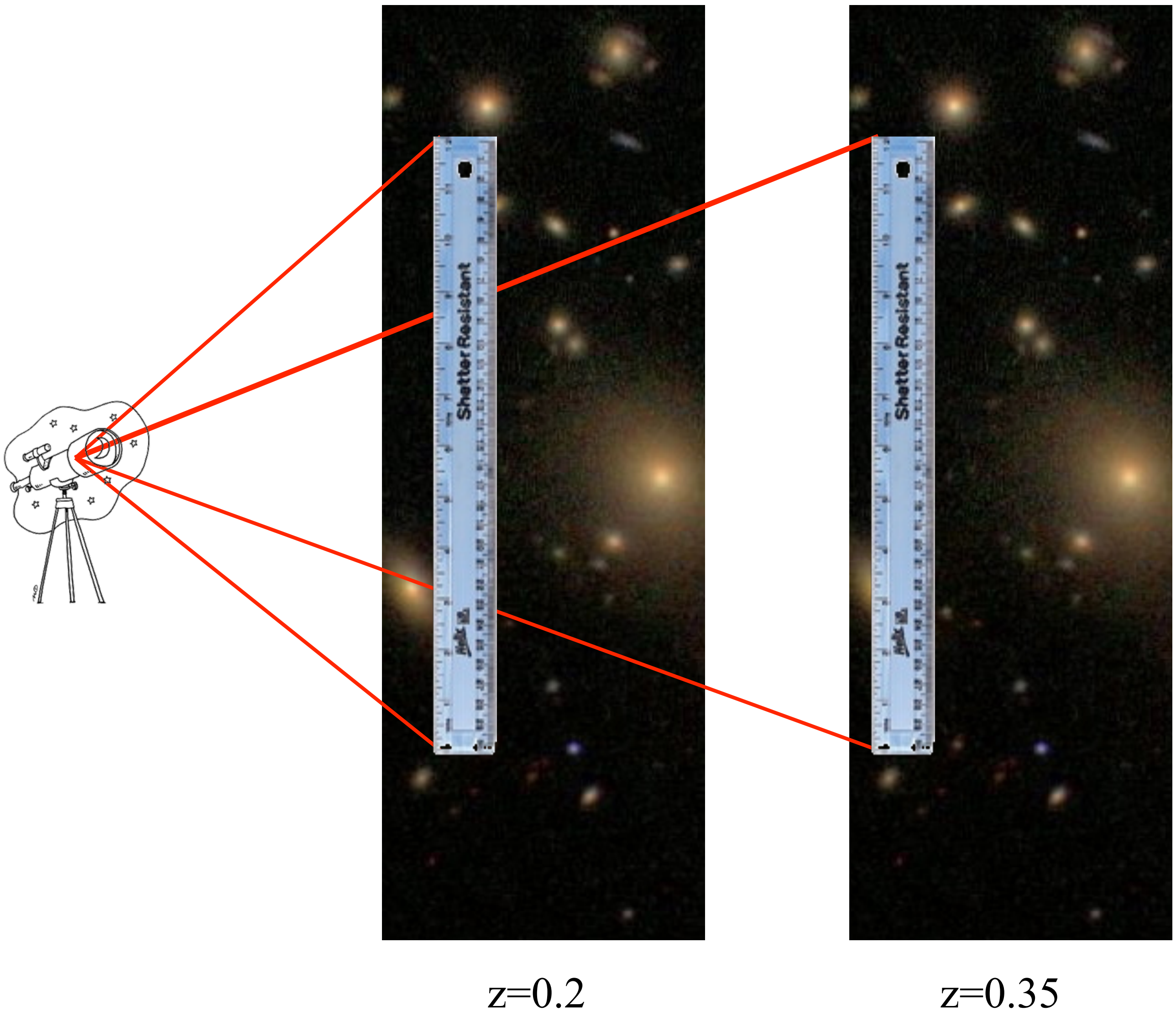
The evolution of the scale factor

If we observed the comoving power spectrum directly, we would not constrain evolution

However, we measure galaxy redshifts and angles and infer distances

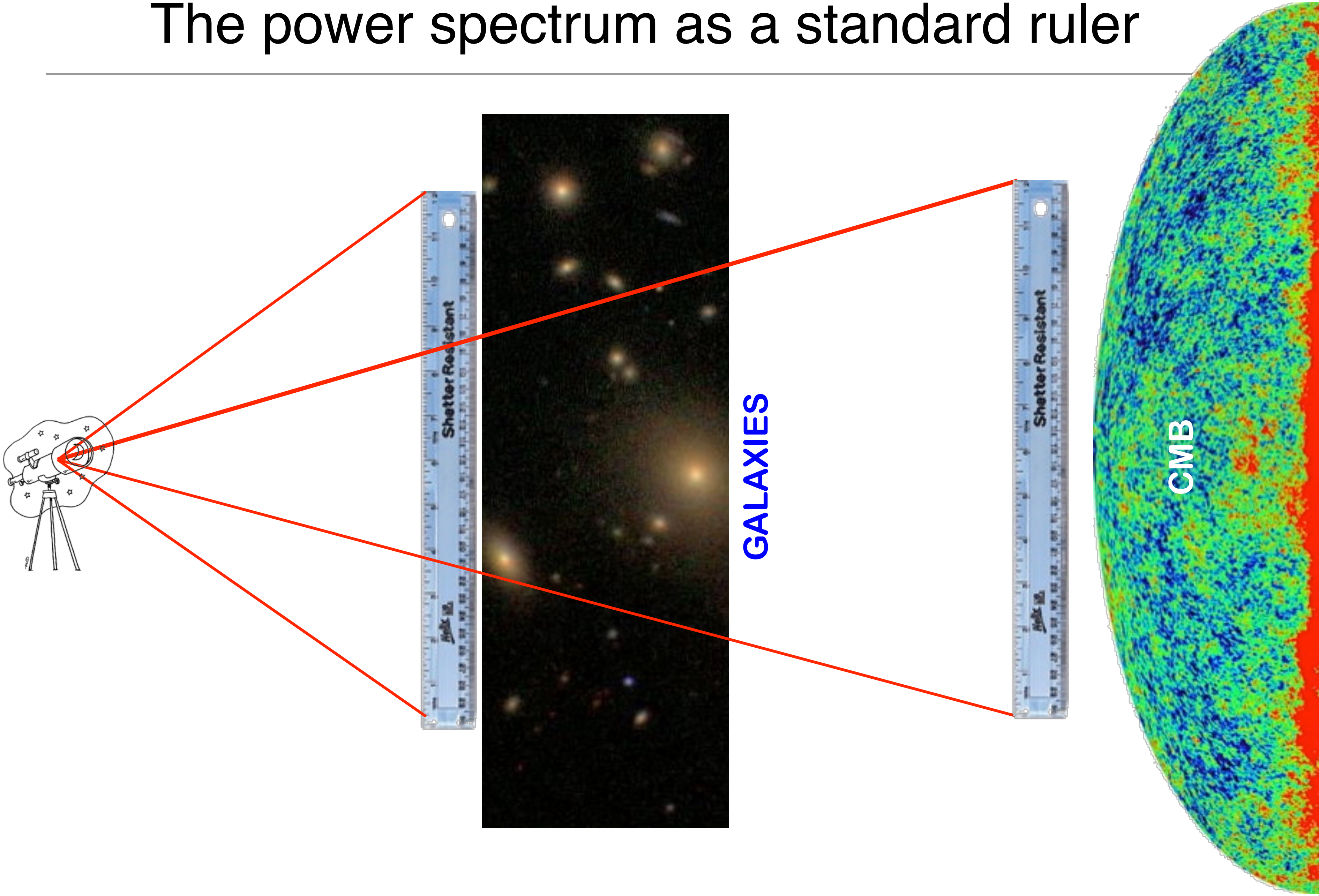
$$d_{\rm comov}(a) = \int_{t(a)}^{t_0} \frac{c\,dt'}{a(t')} = \int_a^1 \frac{c\,da'}{a'^2 H(a')}$$

The power spectrum as a standard ruler



CREDIT: WMAP & SDSS websites

The power spectrum as a standard ruler



CREDIT: WMAP & SDSS websites

BAO as a standard ruler

Changes in cosmological model alter measured BAO scale ($\Delta d_{\mathbf{comov}}$) by:

Radial direction $$\frac{c}{H(z)}\Delta z$$

(evolution of Universe)

Angular direction

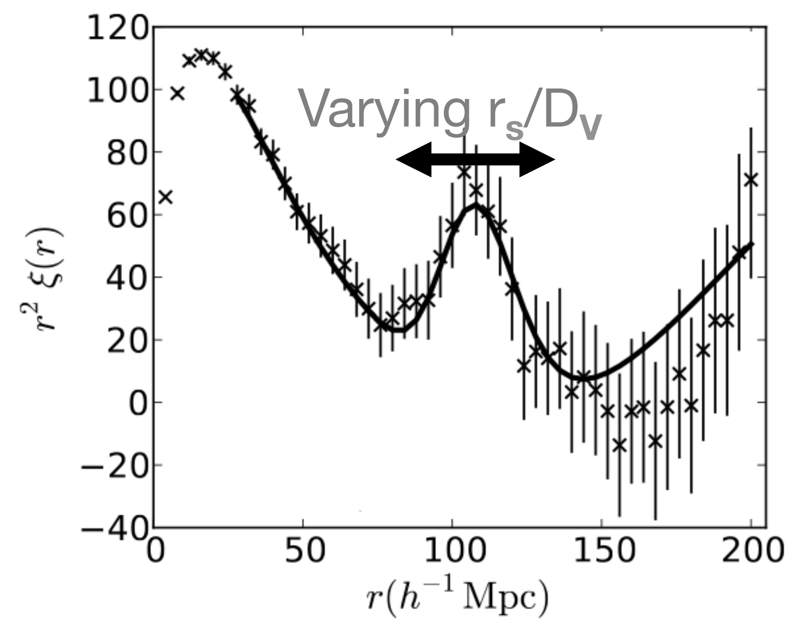
$$(1+z)D_A\Delta\theta$$

(line of sight)

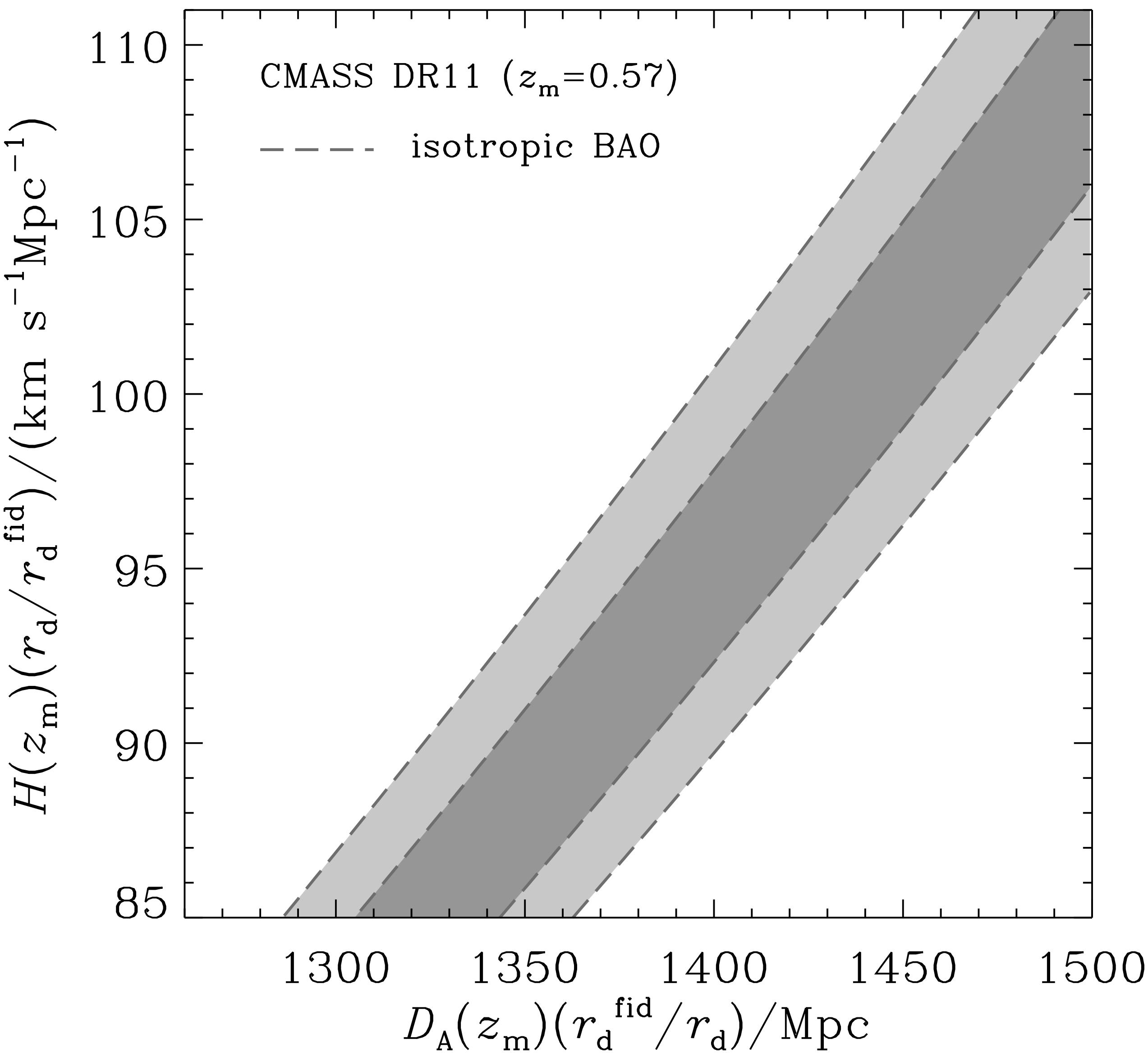
If we are considering radial and angular directions using randomly orientated galaxy pairs, we constrain (to 1st order)

$$D_V = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

BAO position (in a redshift slice) therefore constrains some multiple of $\frac{r_s}{D_V}$

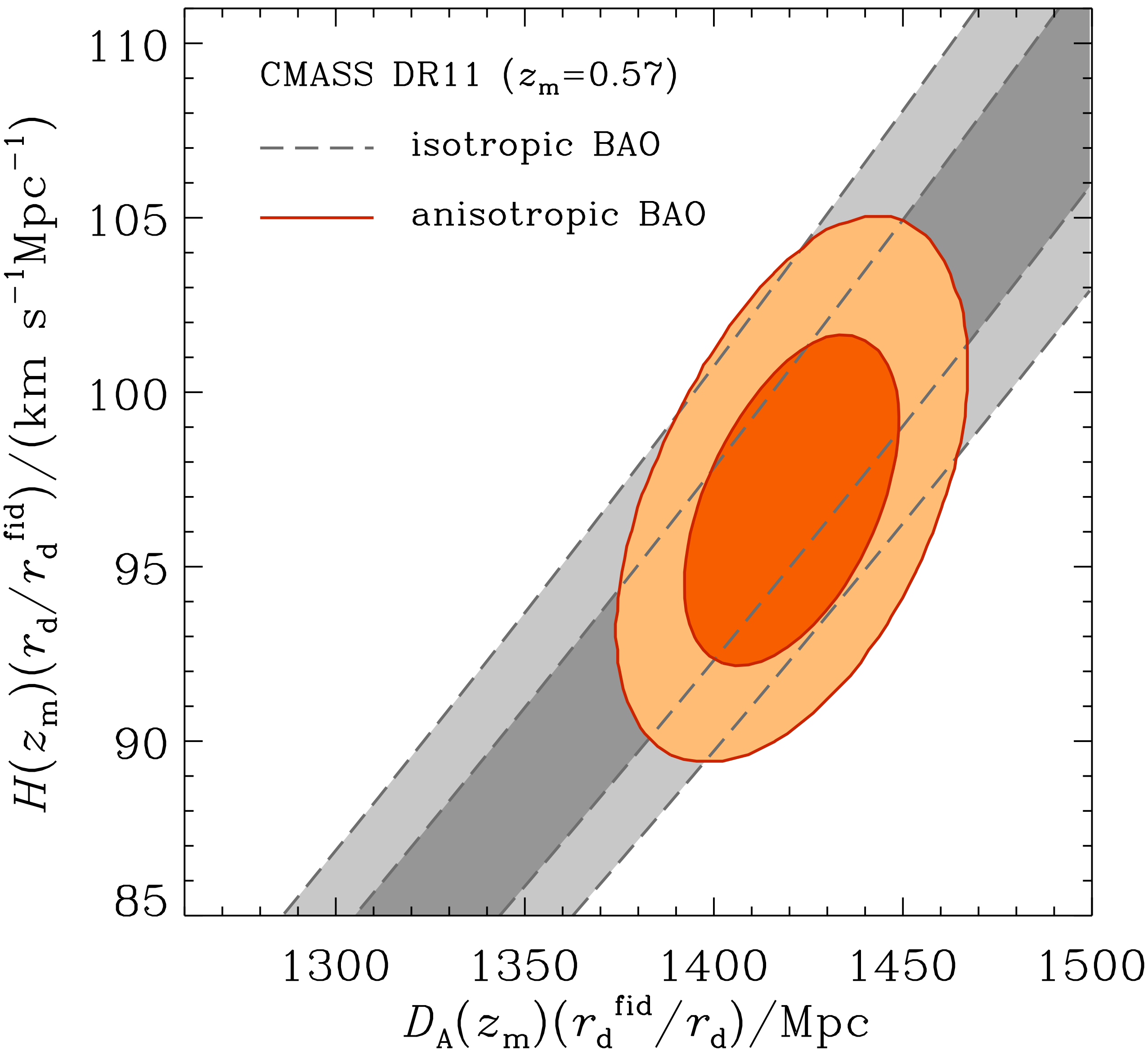


DR11 Measurements vs CMB



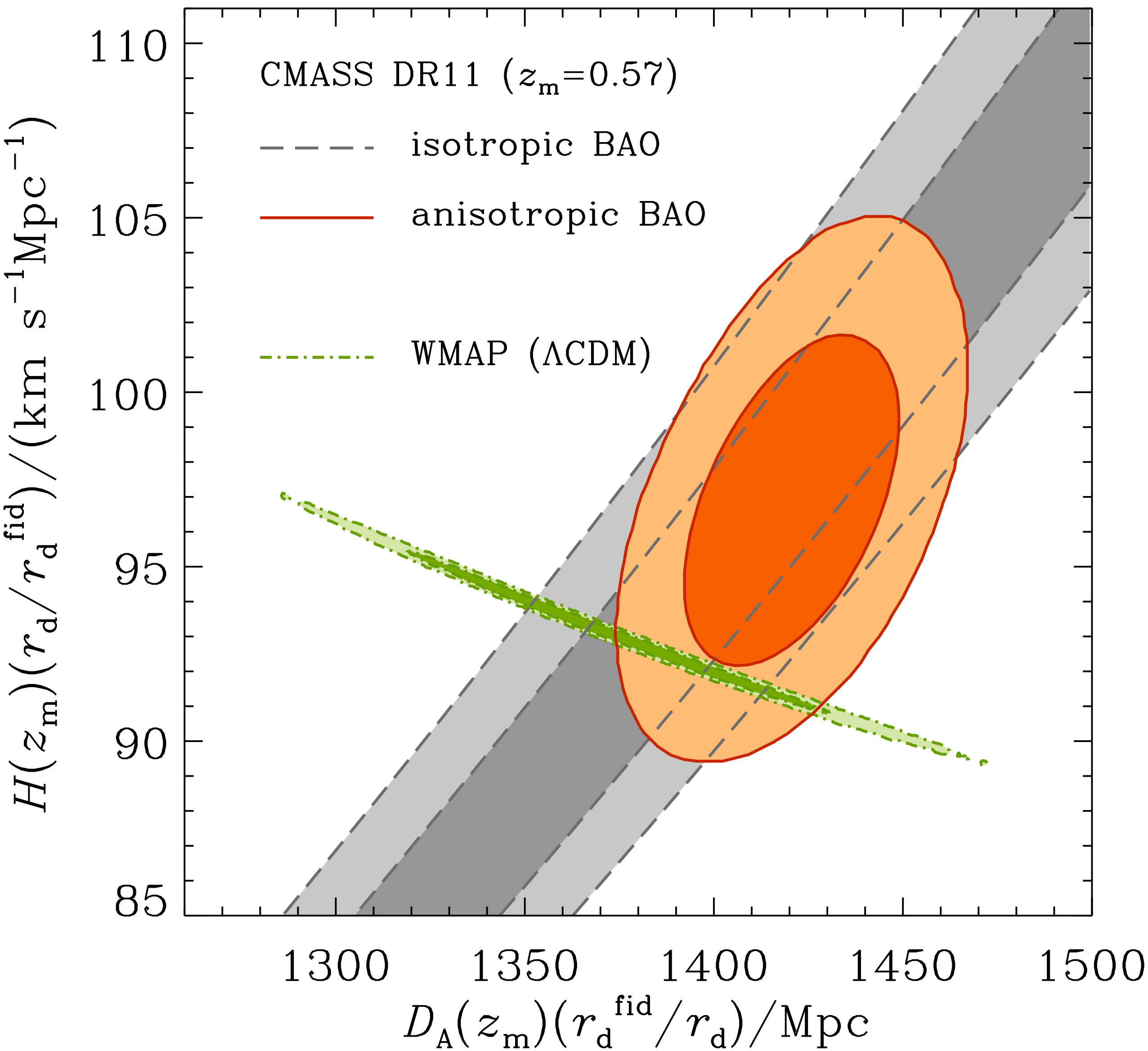
Anderson et al. 2013; arXiv:1312.4877

DR11 Measurements vs CMB



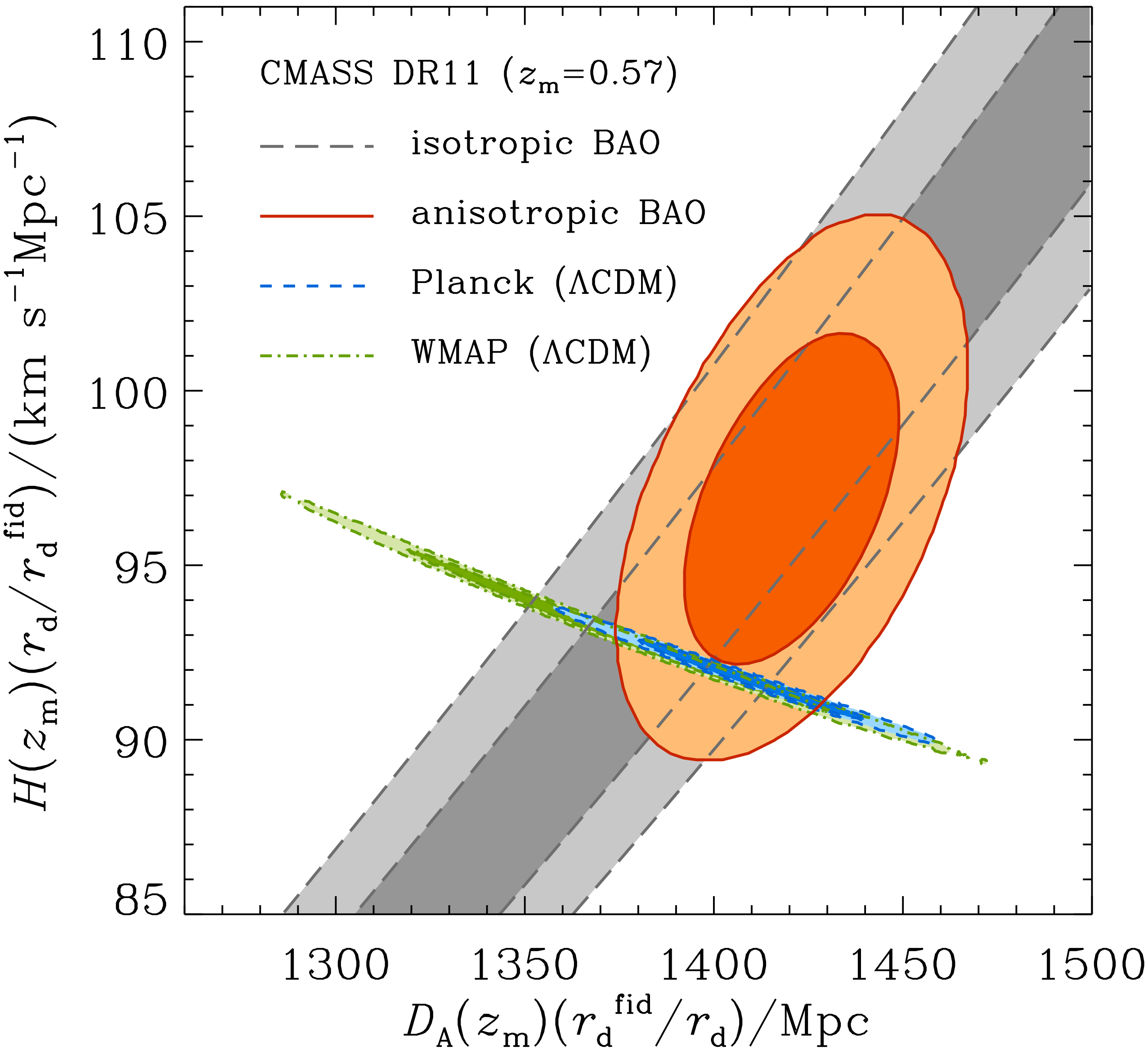
Anderson et al. 2013; arXiv:1312.4877

DR11 Measurements vs CMB



Anderson et al. 2013; arXiv:1312.4877

DR11 Measurements vs CMB



Anderson et al. 2013; arXiv:1312.4877

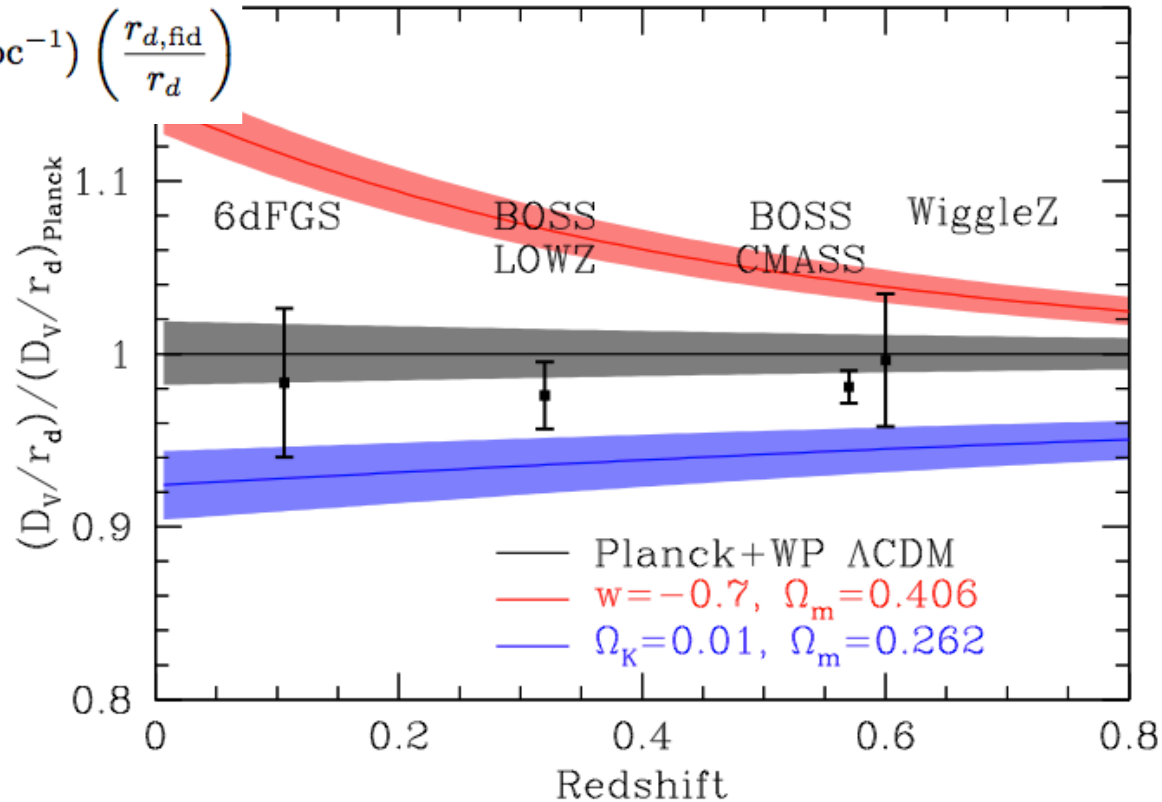
Results

$$D_V(0.57) = (2055 \pm 28\ \mathrm{Mpc})\left(\frac{r_d}{r_{d,\mathrm{fid}}}\right)$$

$$D_V(0.32) = (1275 \pm 36\ \mathrm{Mpc})\left(\frac{r_d}{r_{d,\mathrm{fid}}}\right),$$

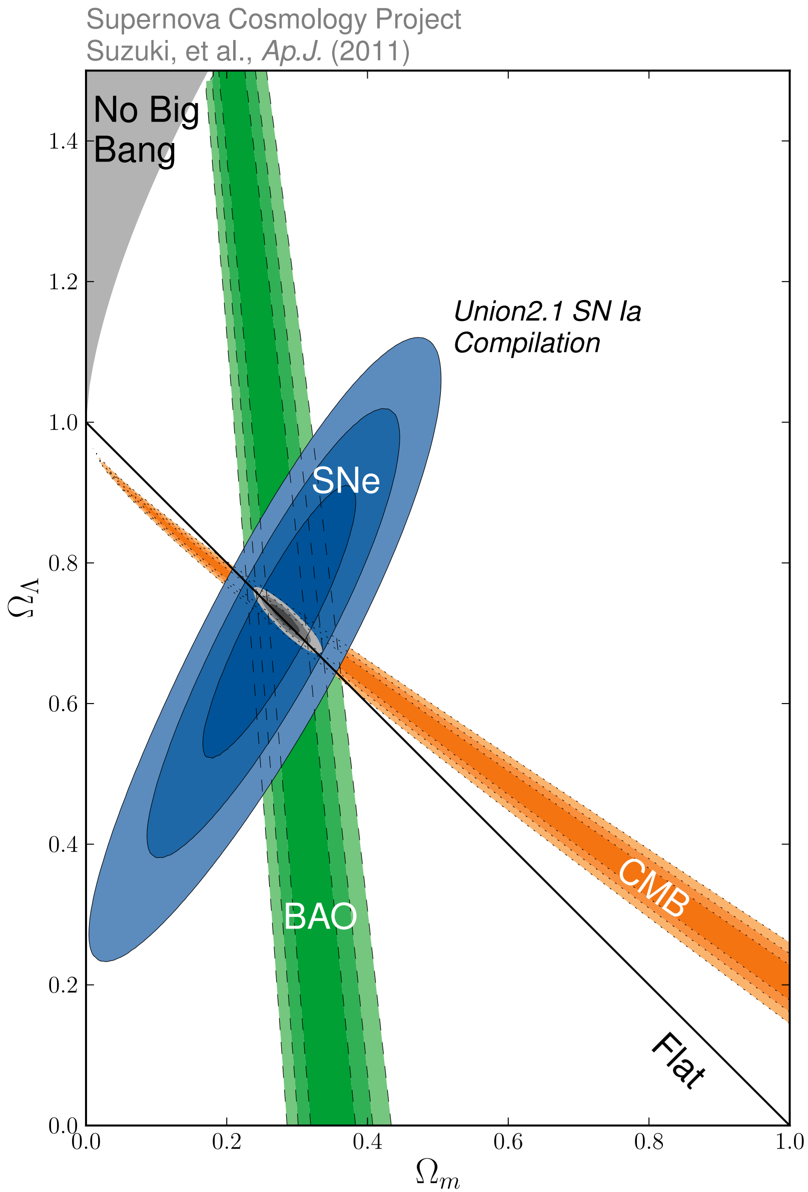
$$D_A(0.57) = (1386 \pm 26\ \mathrm{Mpc})\left(\frac{r_d}{r_{d,\mathrm{fid}}}\right),$$

$$H(0.57) = (94.1 \pm 4.7\ \mathrm{km\ s^{-1}\ Mpc^{-1}})\left(\frac{r_{d,\mathrm{fid}}}{r_d}\right)$$



Anderson et al. 2013; arXiv:1312.4877

Goal of this lecture



BAO tell us we live in a low matter density Universe