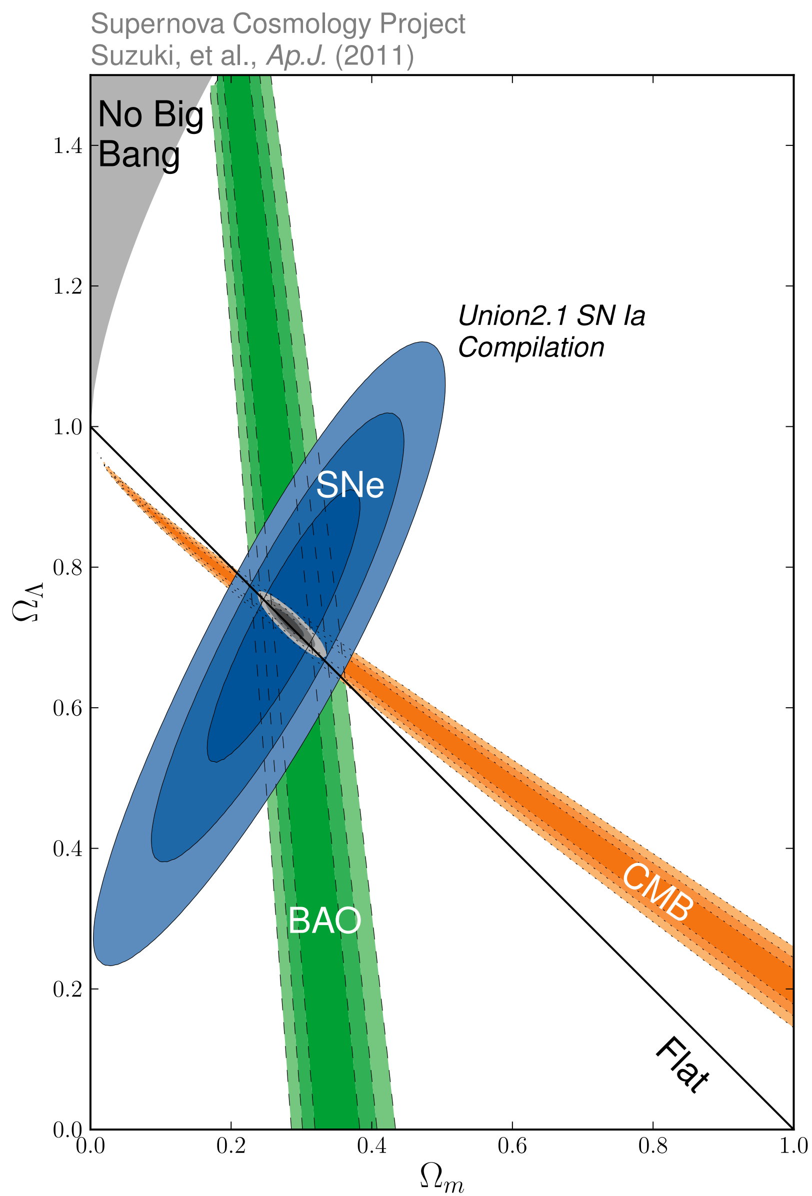
Cosmological surveys

Lecture 1

Will Percival

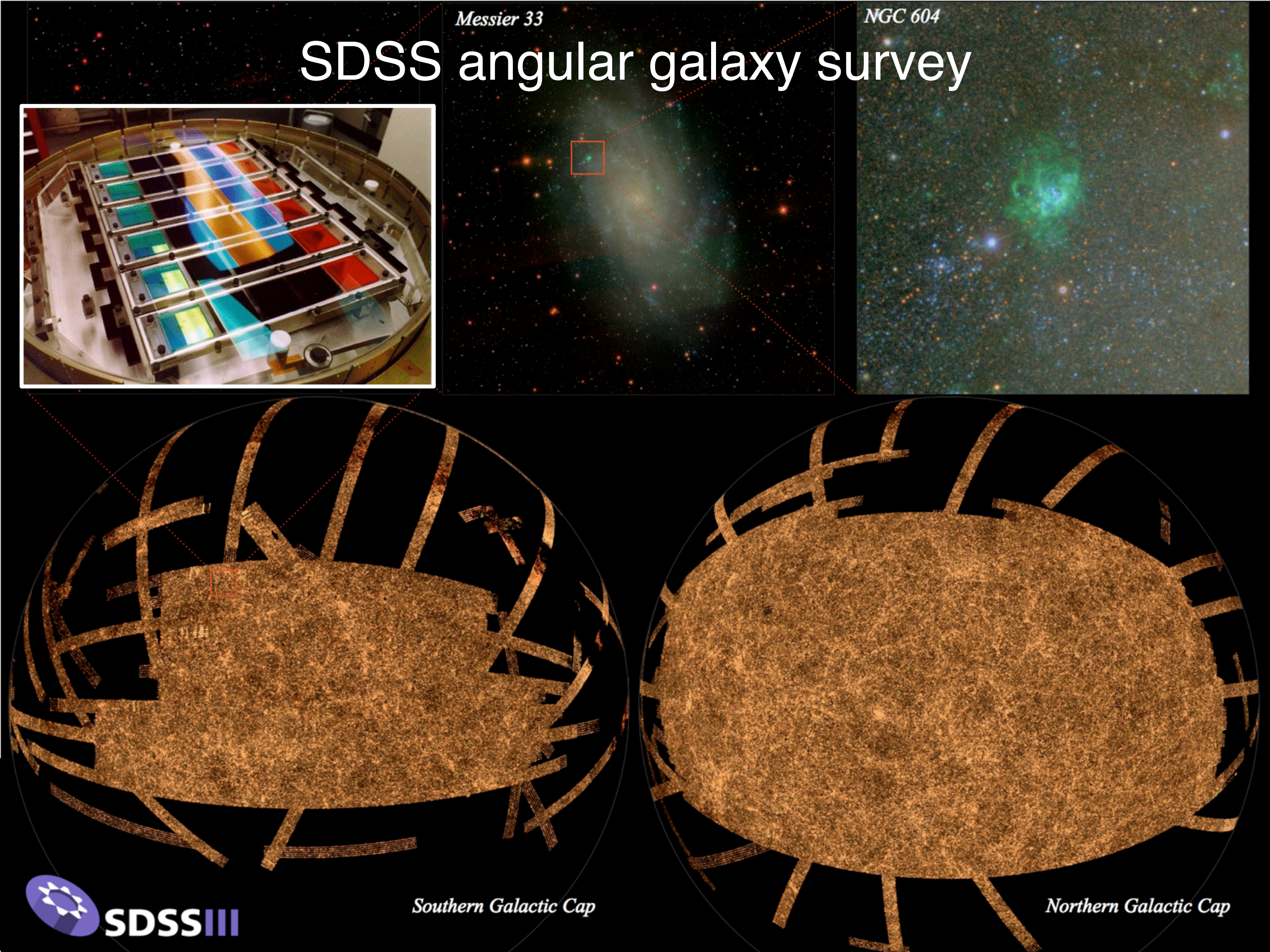
How did we get here?



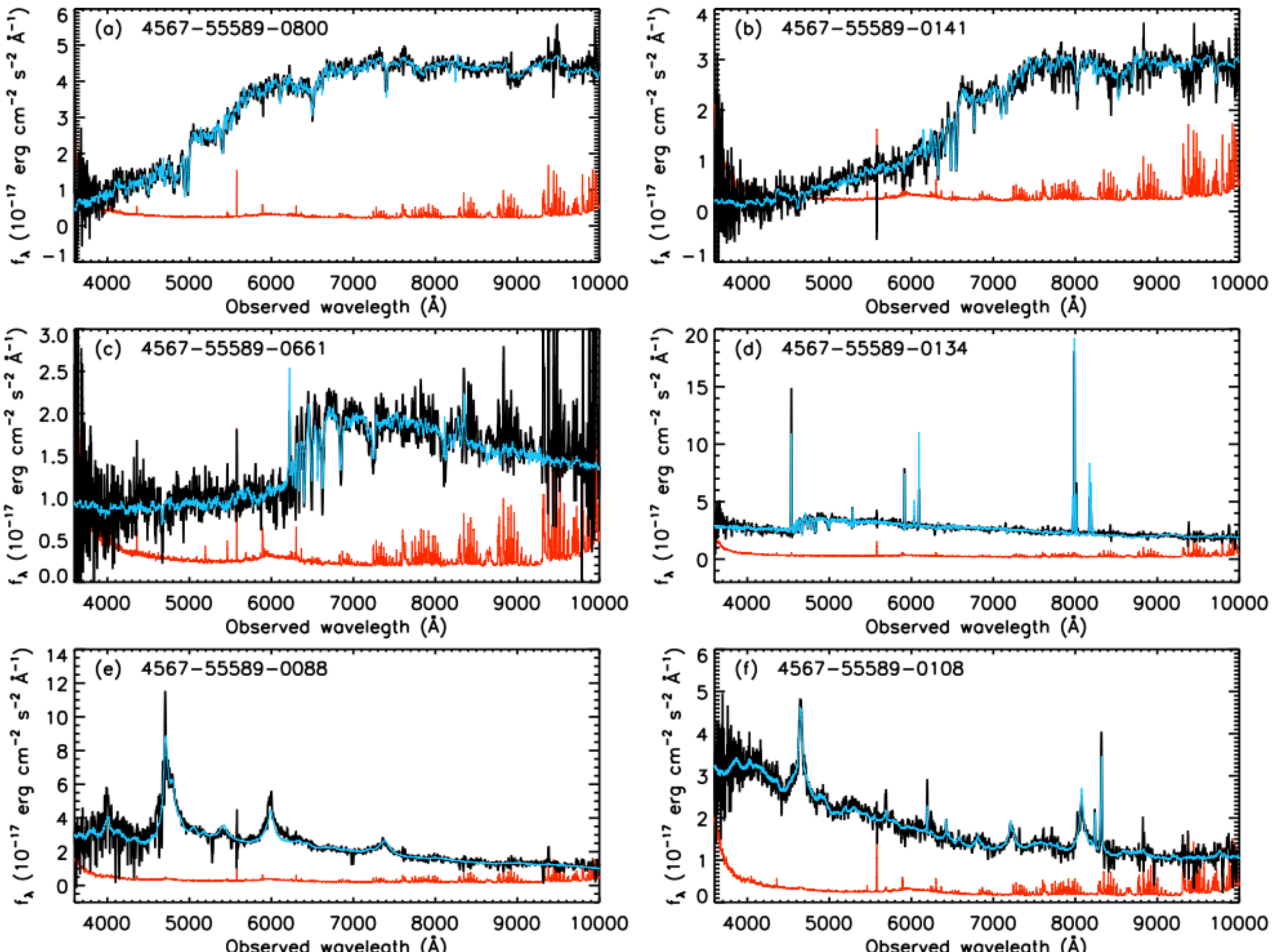
Goal of lecture: The galaxy survey "pillar"

Galaxy surveys

SDSS angular galaxy survey



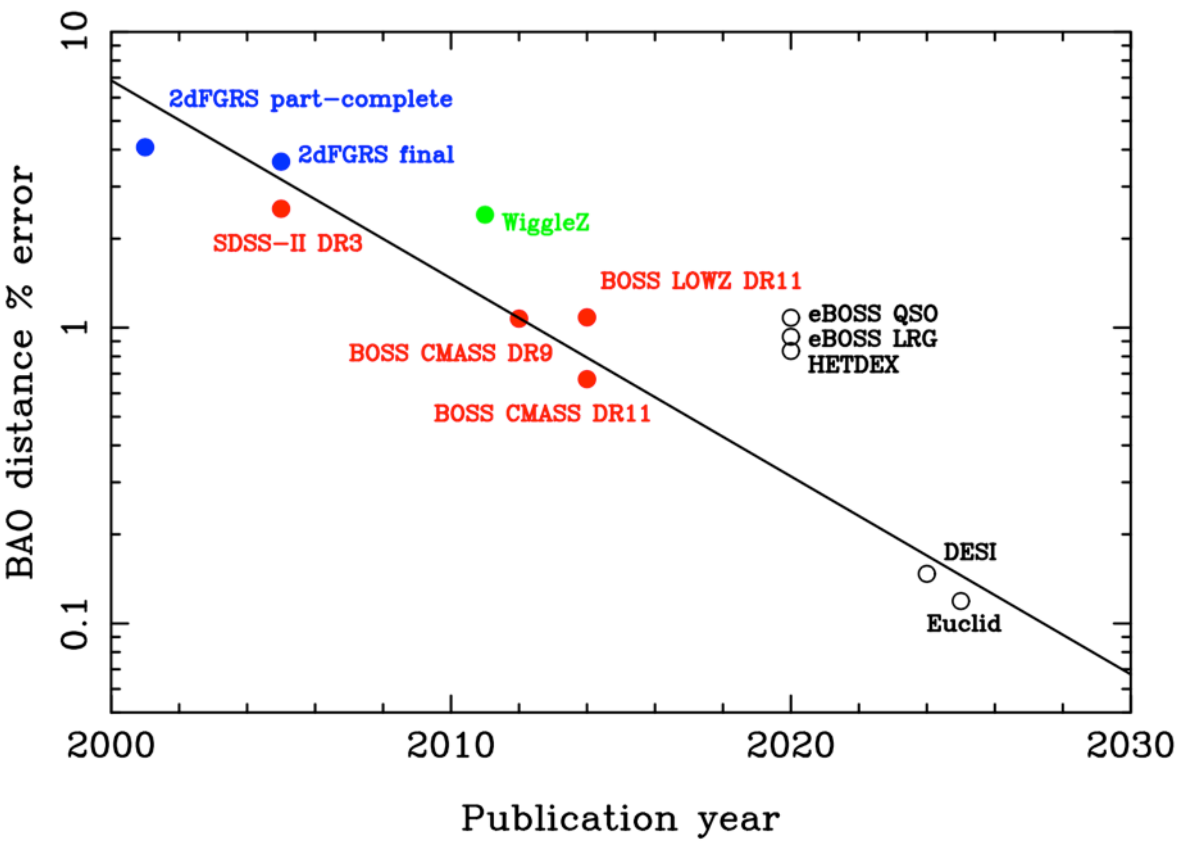
Spectra gives recession velocities and redshifts



Bolton et al. 2012

Galaxy redshift survey "history"

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



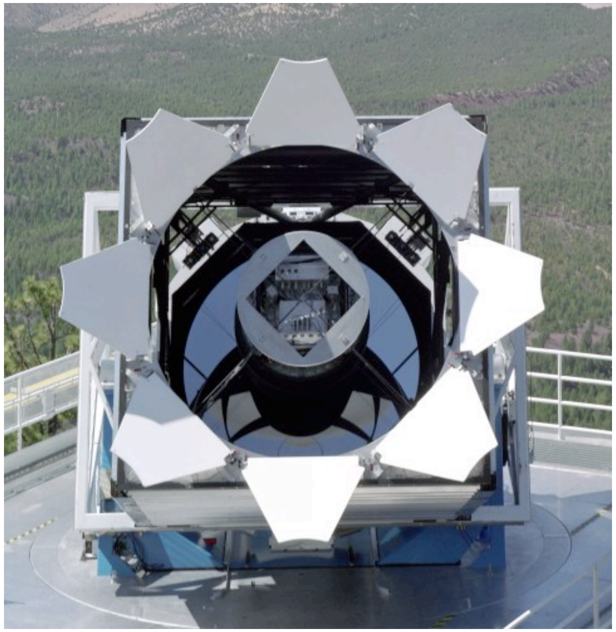
Fractional error in the amplitude of the fluctuation spectrum

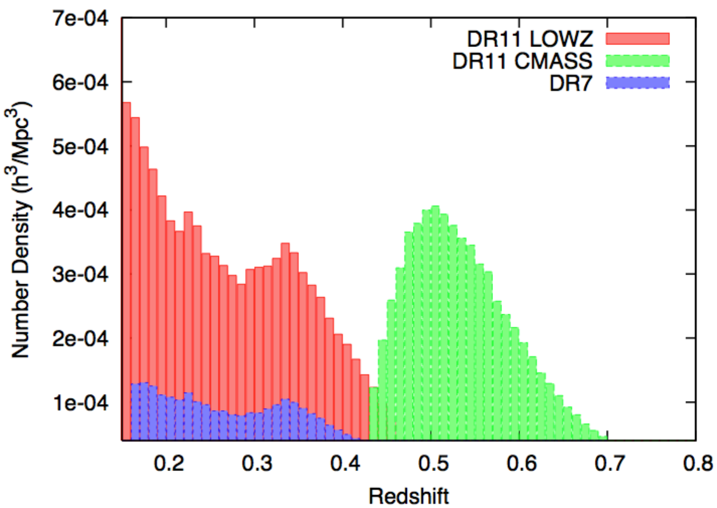
1970	x100
1990	x2
1995	±0.4
1998	±0.2
1999	±0.1
2002	±0.05
2003	±0.03
2009	±0.01
2012	±0.002

Driven by the development of instrumentation

Baryon Oscillation Spectroscopic Survey

- 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





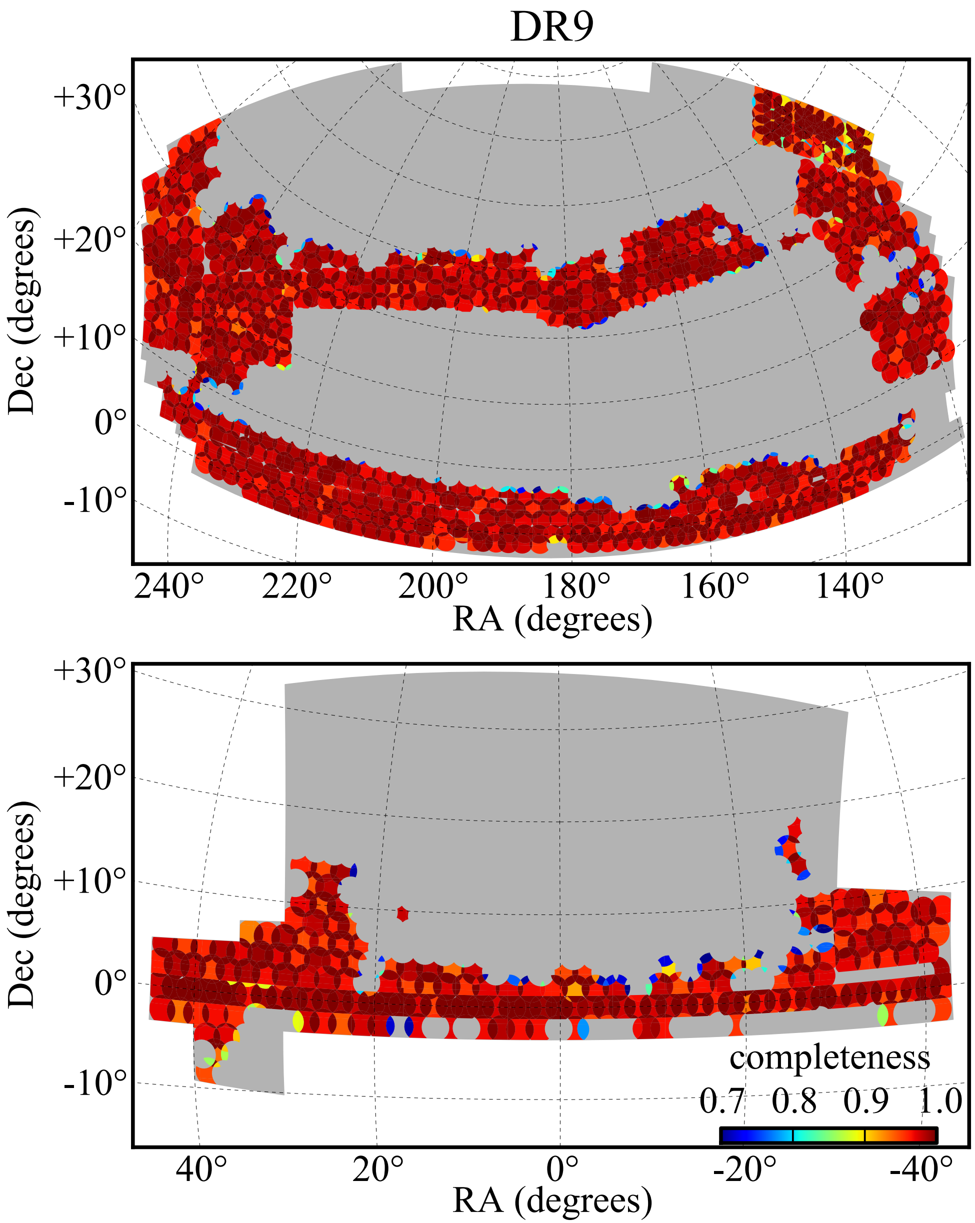
The Sloan Digital Sky Survey telescope

A collaborative effort … BOSS

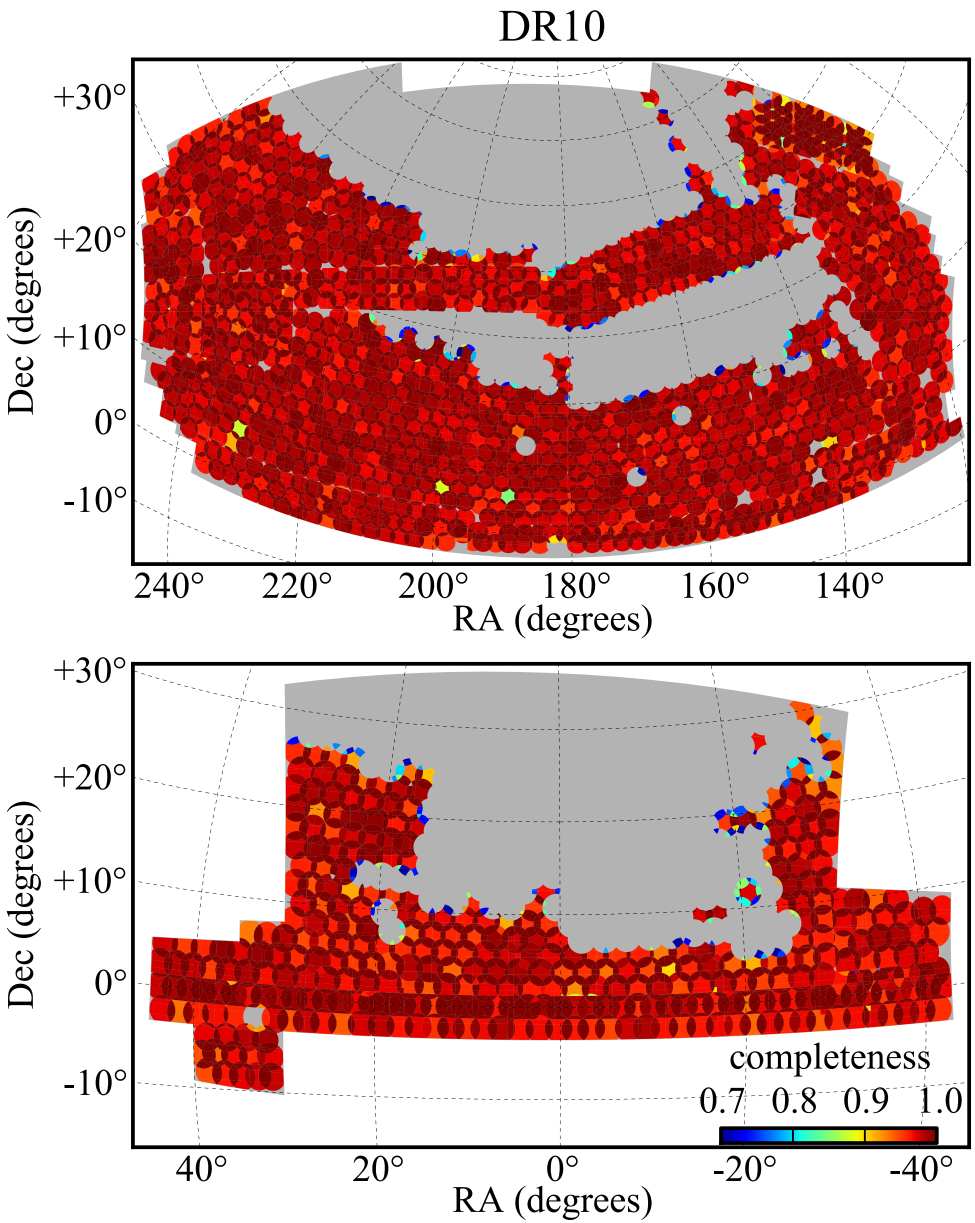
Lauren Anderson[1], Eric Aubourg[2], Stephen Bailey[3], Dmitry Bizyaev[4], Michael Blanton[5], Adam S. Bolton[6], J. Brinkmann[4], Joel R. Brownstein[6], Angela Burden[7], Antonio J. Cuesta[8], Luiz N. A. da Costa[9,10], Kyle S. Dawson[6], Roland de Putter[11,12], Daniel J. Eisenstein[13], James E. Gunn[14], 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

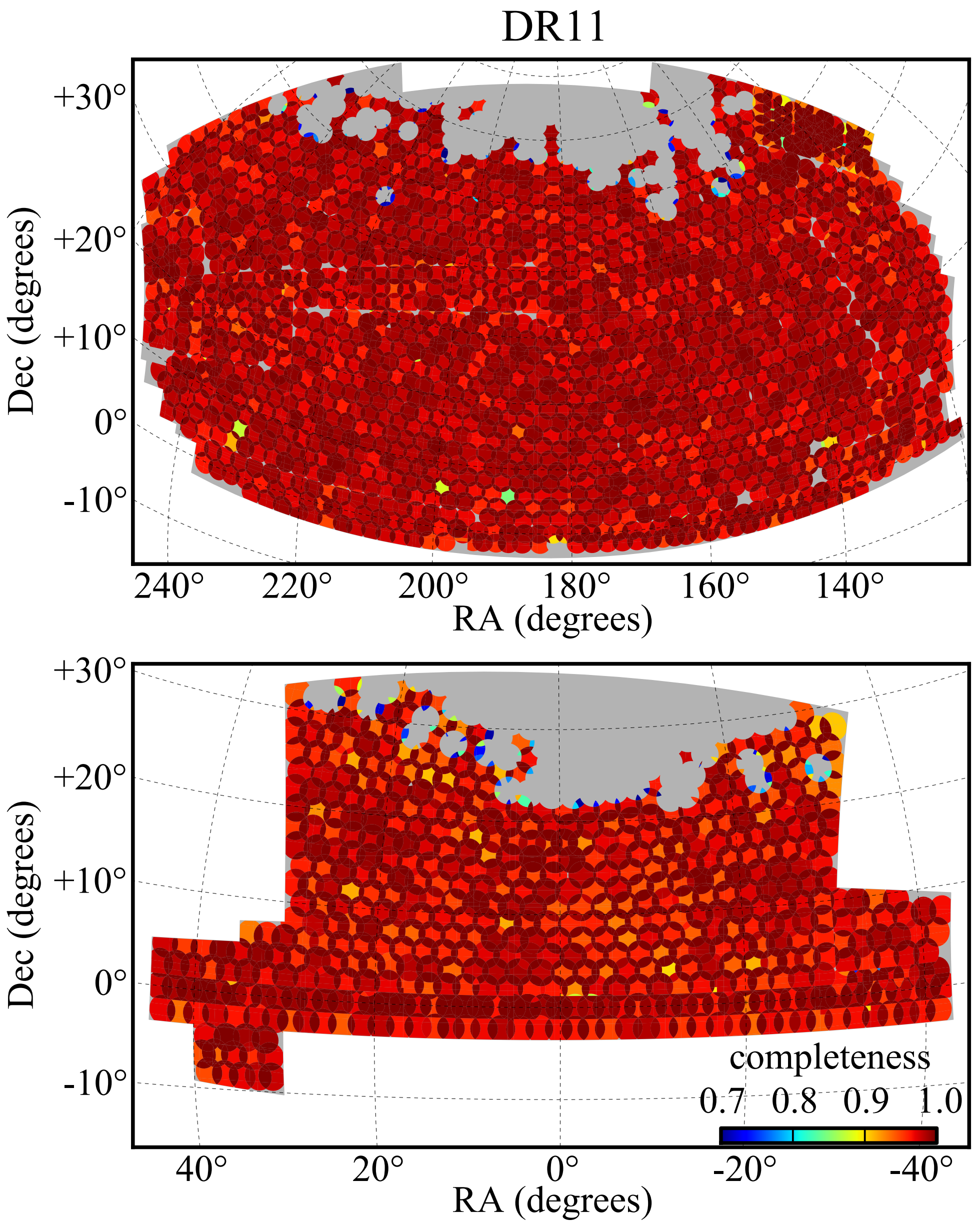
BOSS DR9 galaxies



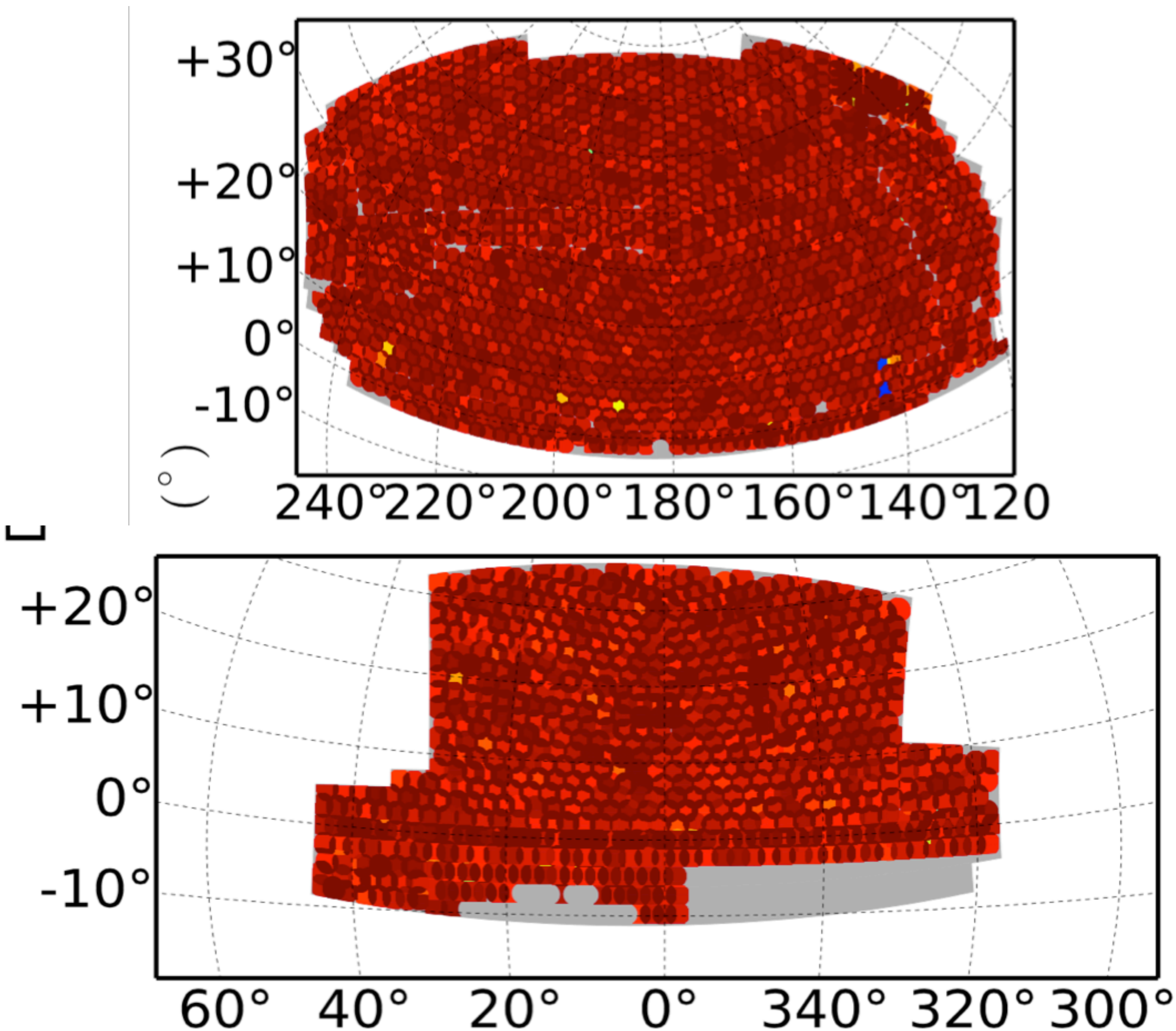
BOSS DR10 galaxies



BOSS DR11 galaxies



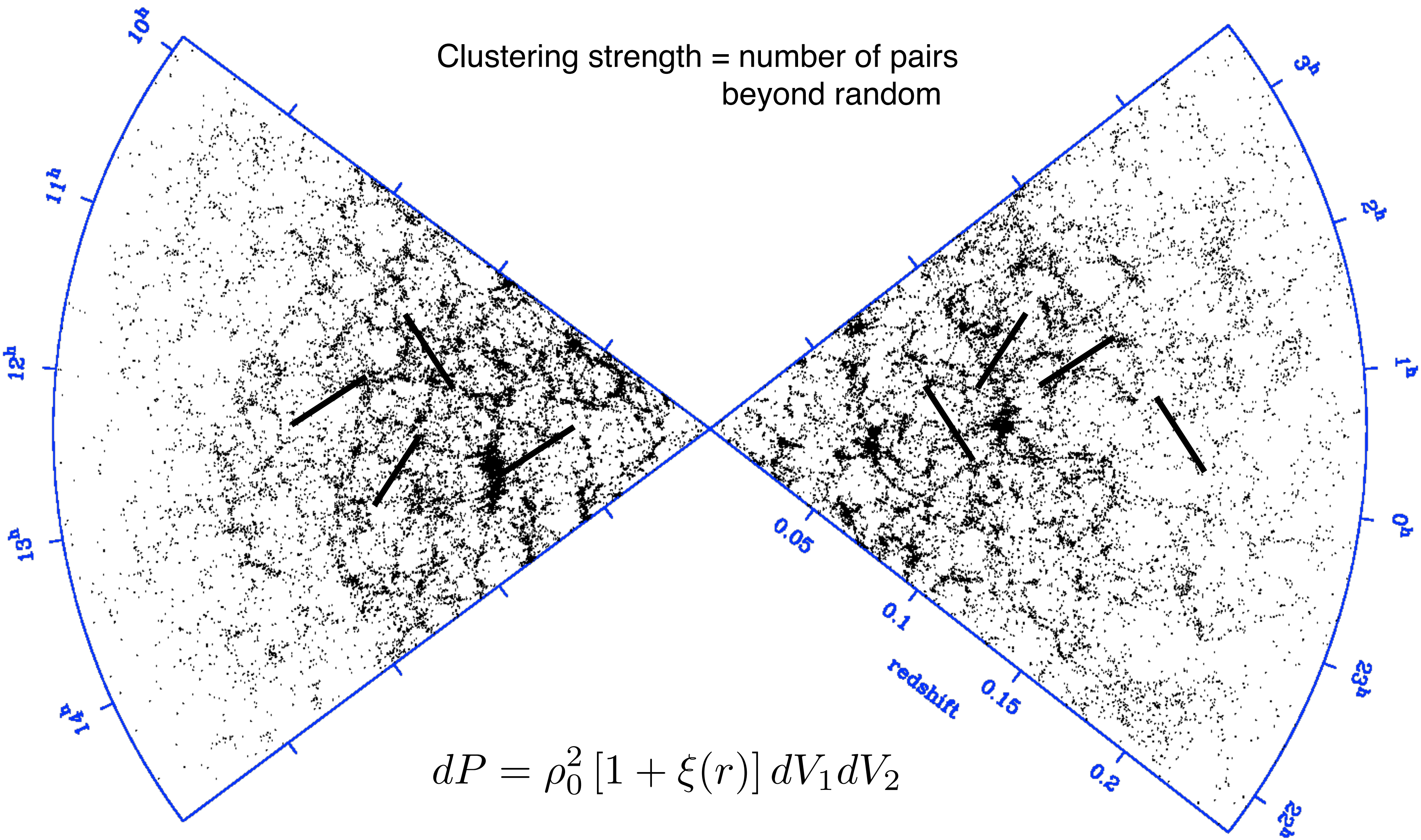
BOSS DR12 galaxies



Clustering

What does “clustering” mean?

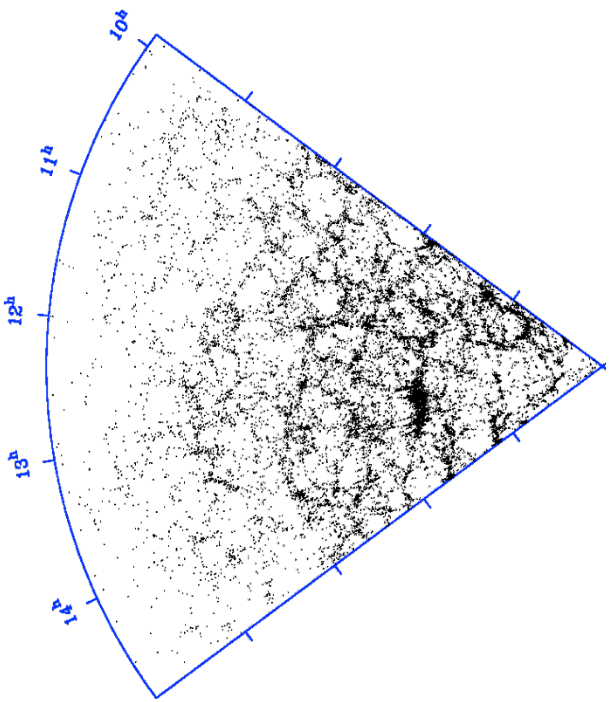
Clustering strength = number of pairs beyond random



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

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

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

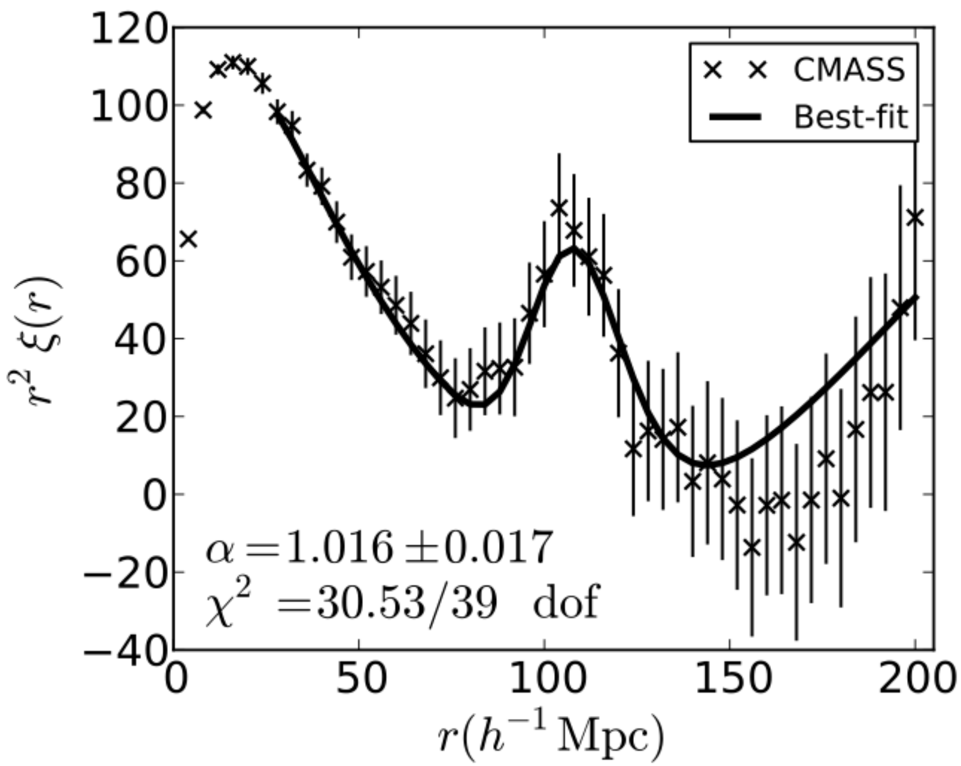
By analogy, one should think of "throwing down" Fourier modes rather than "sticks"

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

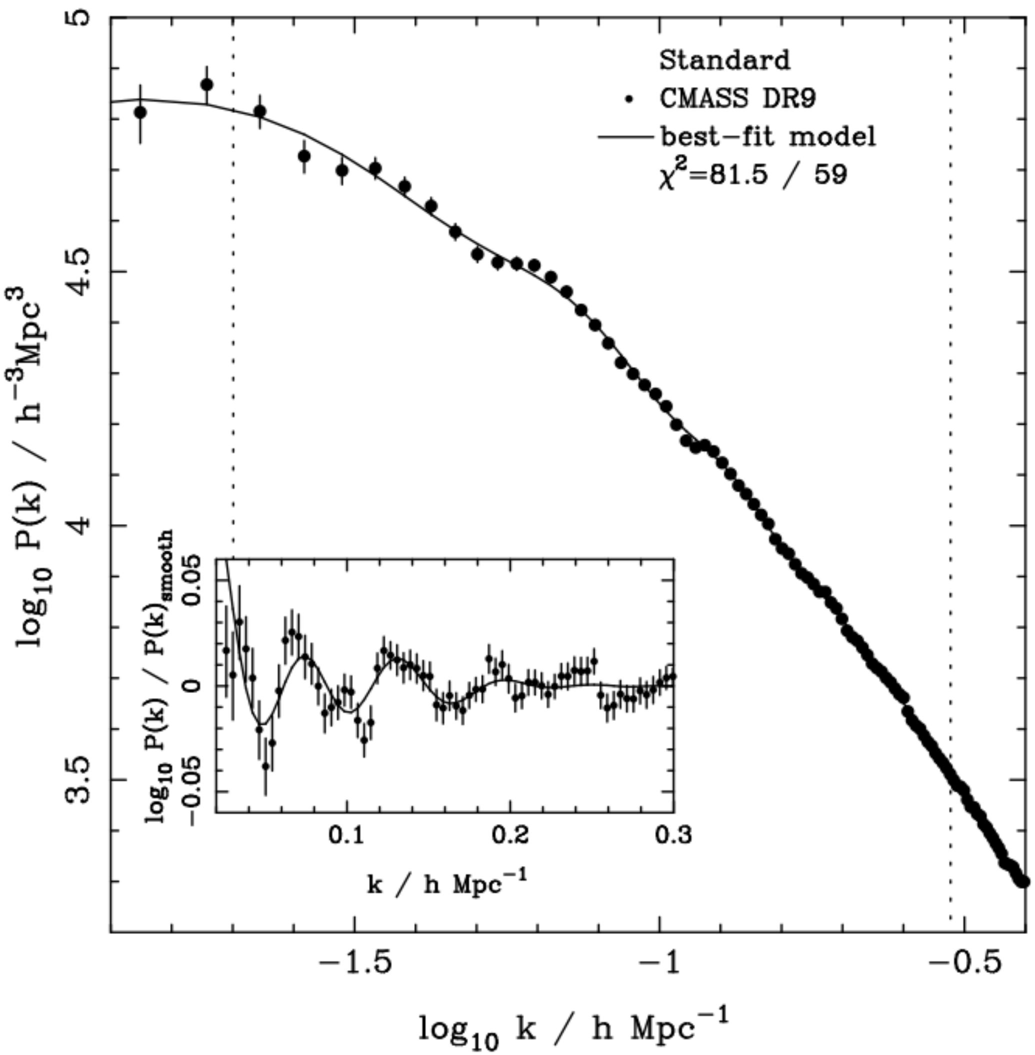


Power spectrum

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

from statistical isotropy

from statistical homogeneity

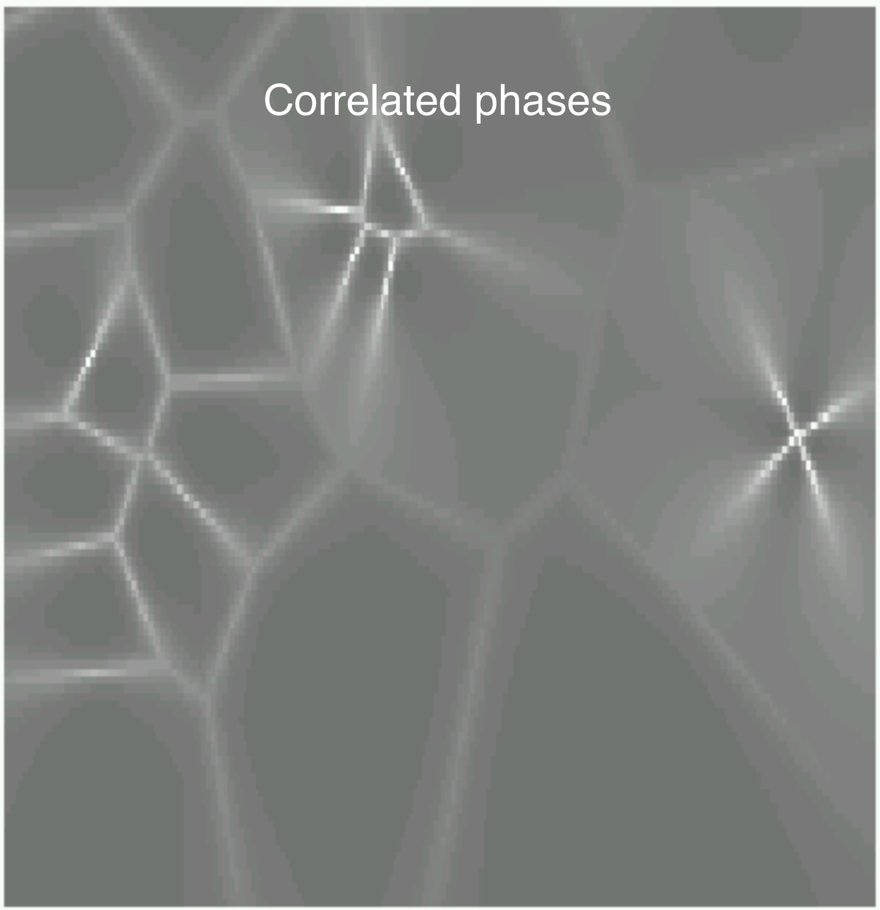


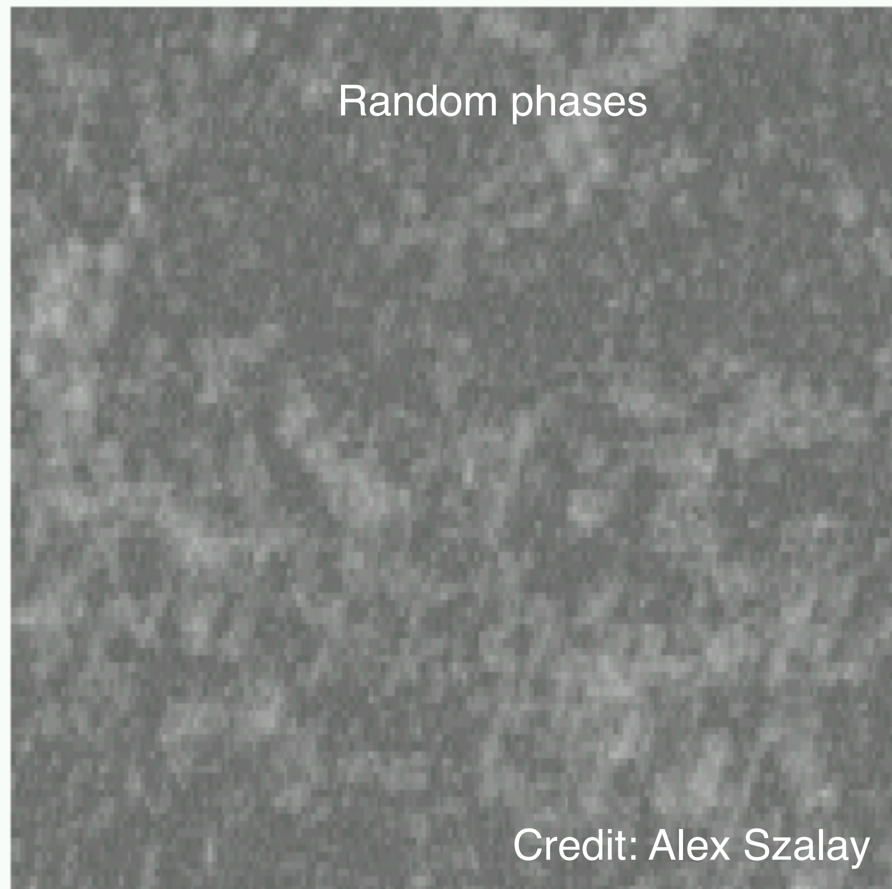
$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

Power spectrum often written in dimensionless form

Statistically complete knowledge?

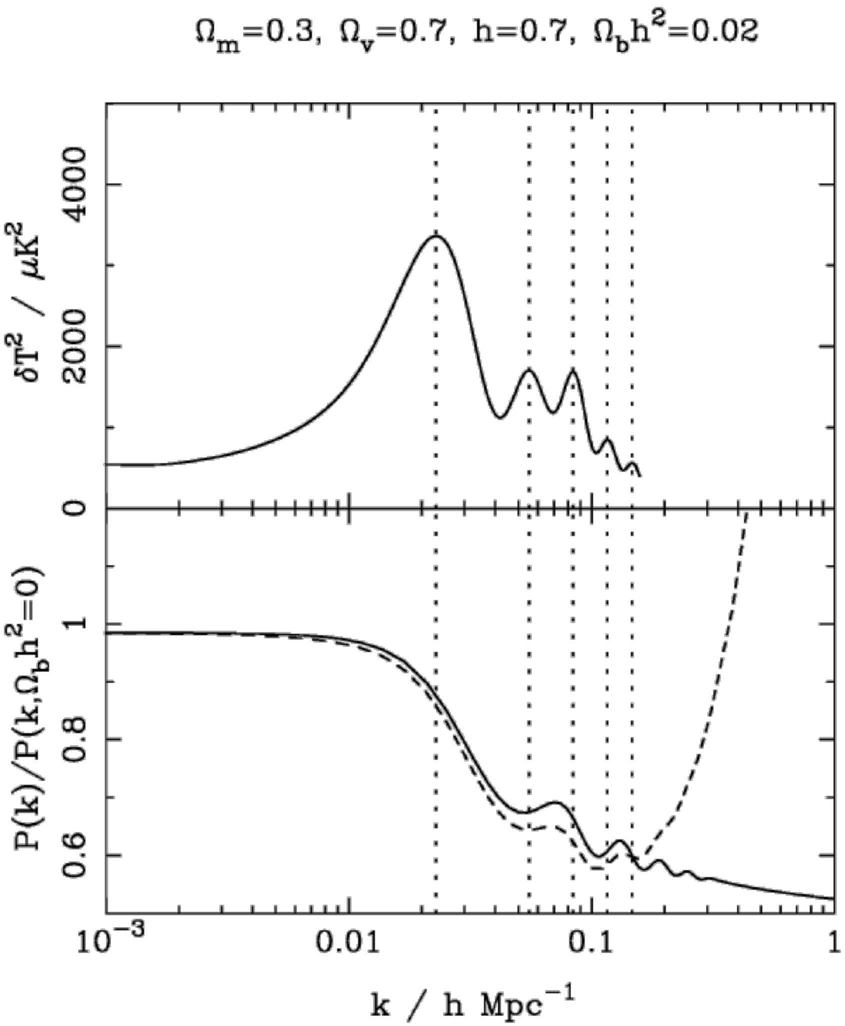
Gaussian random field: knowledge of either the correlation function or power spectrum is sufficient – they are statistically complete … but …

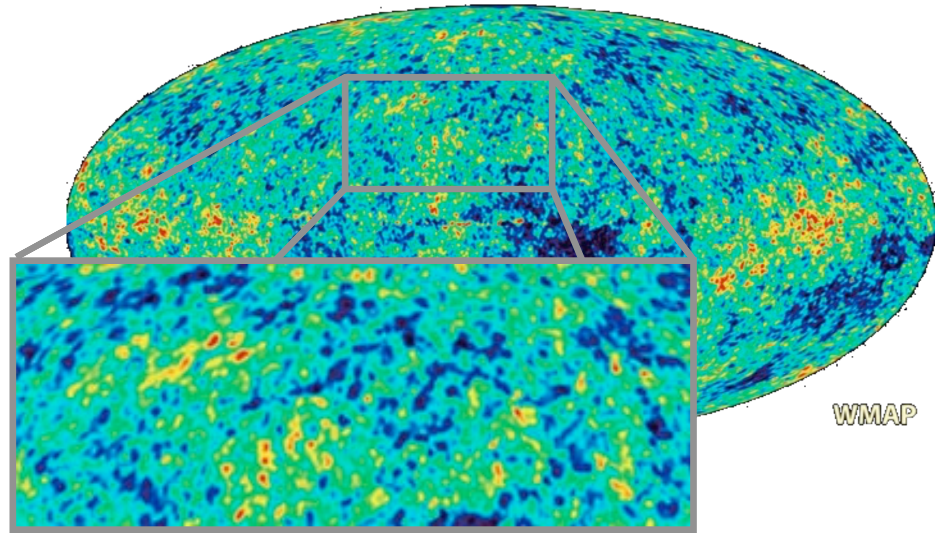


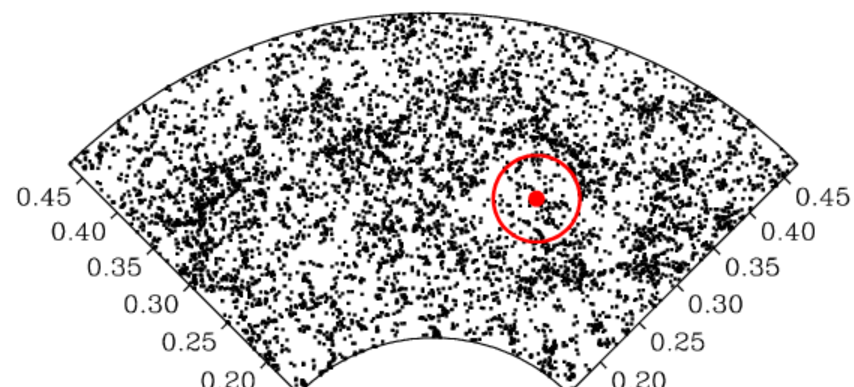


The matter power spectrum

Comparison of CMB and LSS power spectra







SDSS

Physics from the linear galaxy power spectrum

Intrinsic power spectrum shape
- Matter density
- Baryon Acoustic Oscillations
- Neutrino mass
- Inflation fluctuation spectrum
- f_{NL}

Projected clustering
- Galaxy clustering as a standard ruler
- BAO or full power spectrum
- Alcock-Paczynski effect

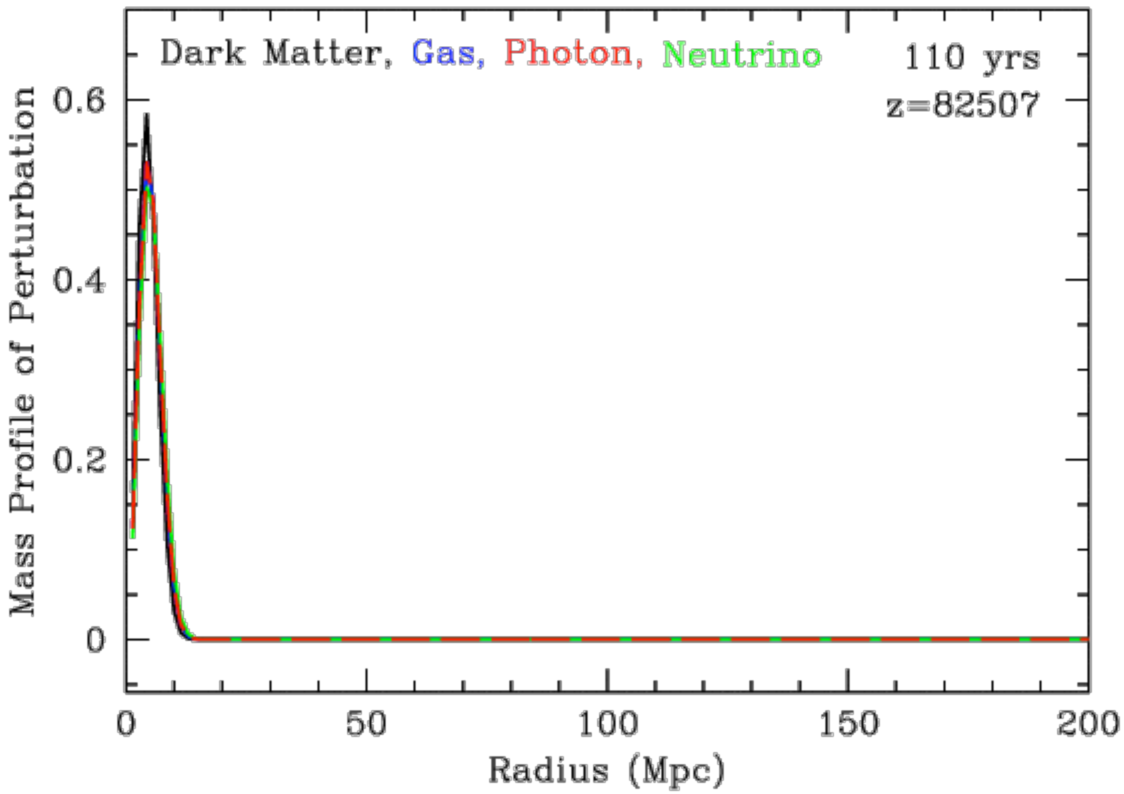
$$P_{\rm gal}(k,\mu,a) = k^n T^2(k) D^2(a) [b(a) + f(a)\mu^2]^2$$

k = comoving wavenumber
μ = cos(angle to line-of-sight)
a = cosmological scale factor
b = galaxy bias factor
D = linear growth rate
f = dlnD/dlna

Structure growth
- amplitude of power spectrum
- redshift-space distortions

Intrinsic clustering - Baryon Acoustic Oscillations

Configuration space description

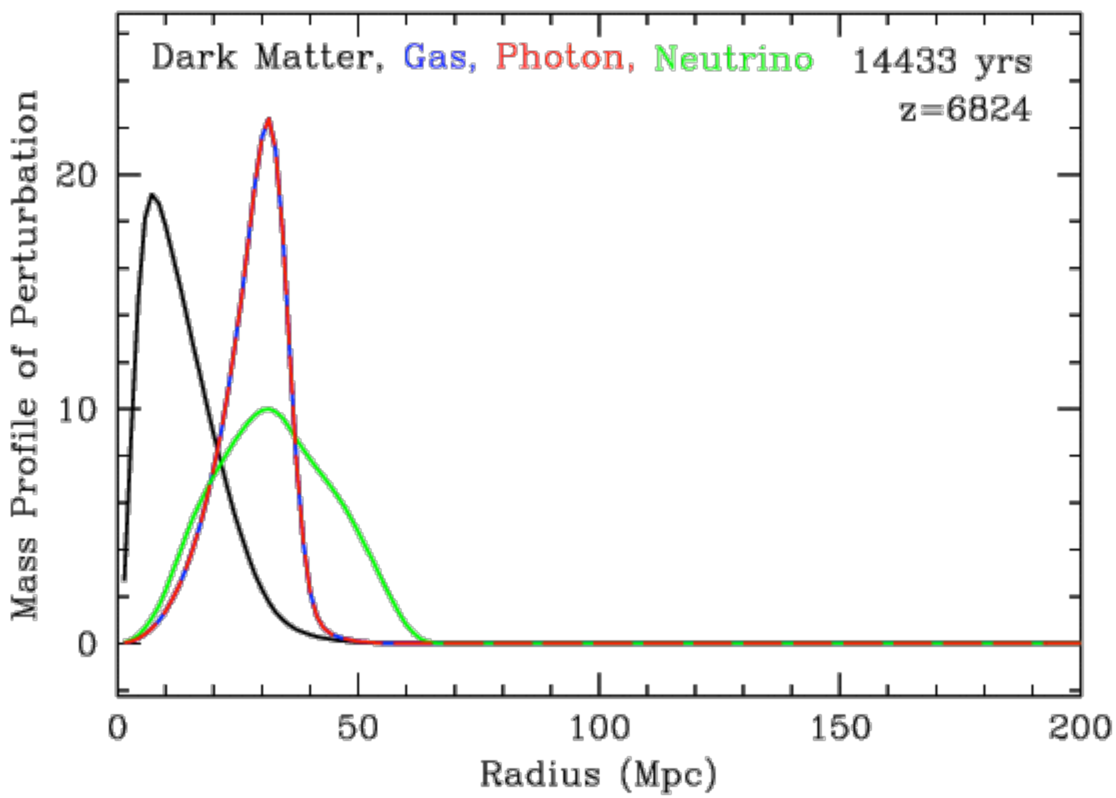


$\Omega_m h^2 = 0.147$, $\Omega_b h^2 = 0.024$

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

plots by Dan Eisenstein

Configuration space description



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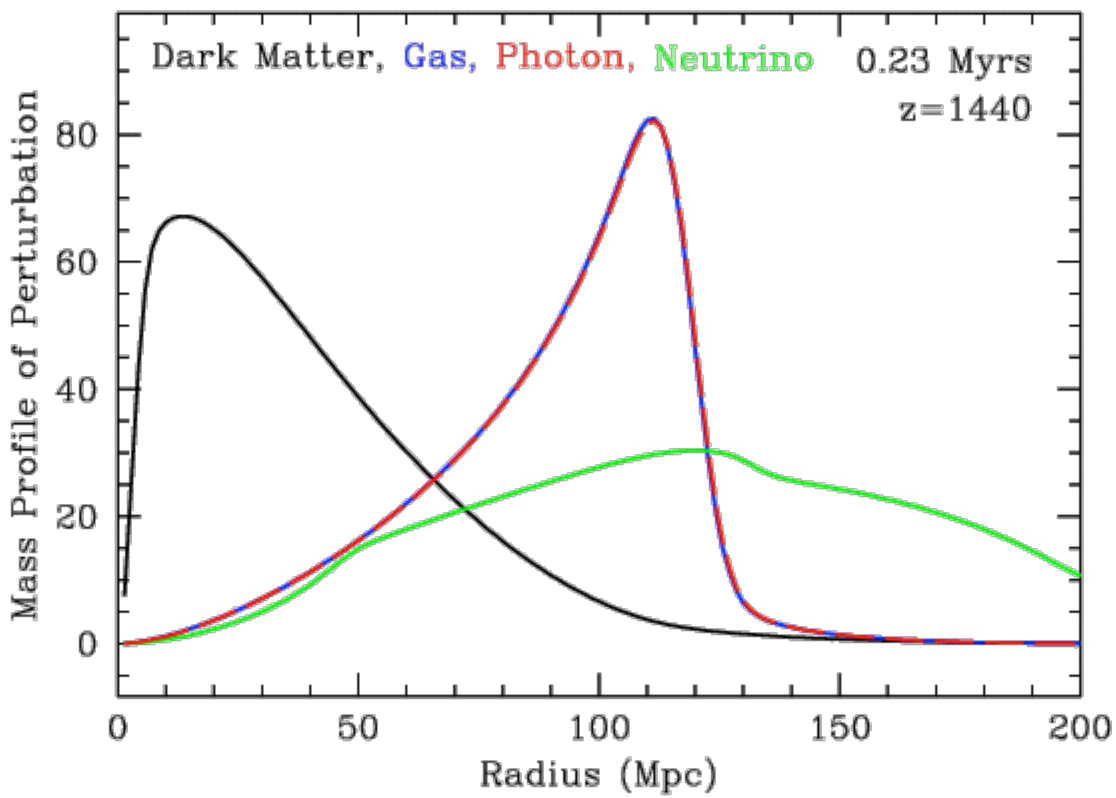

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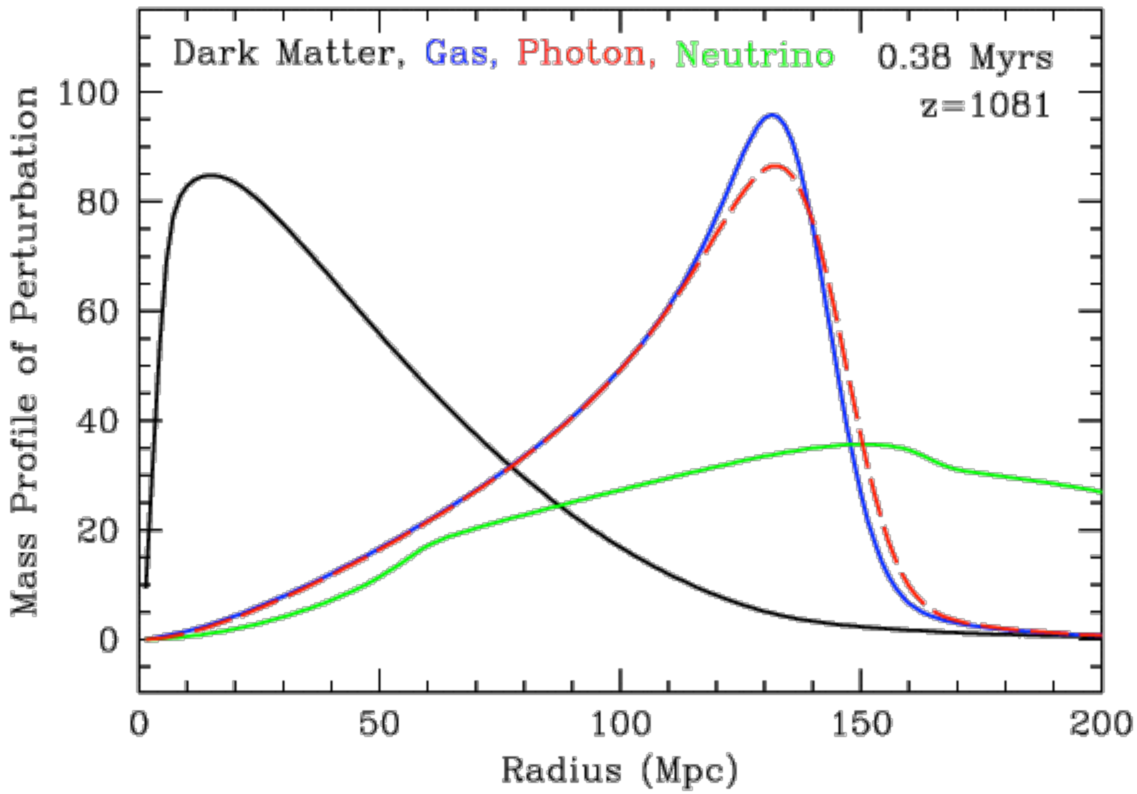

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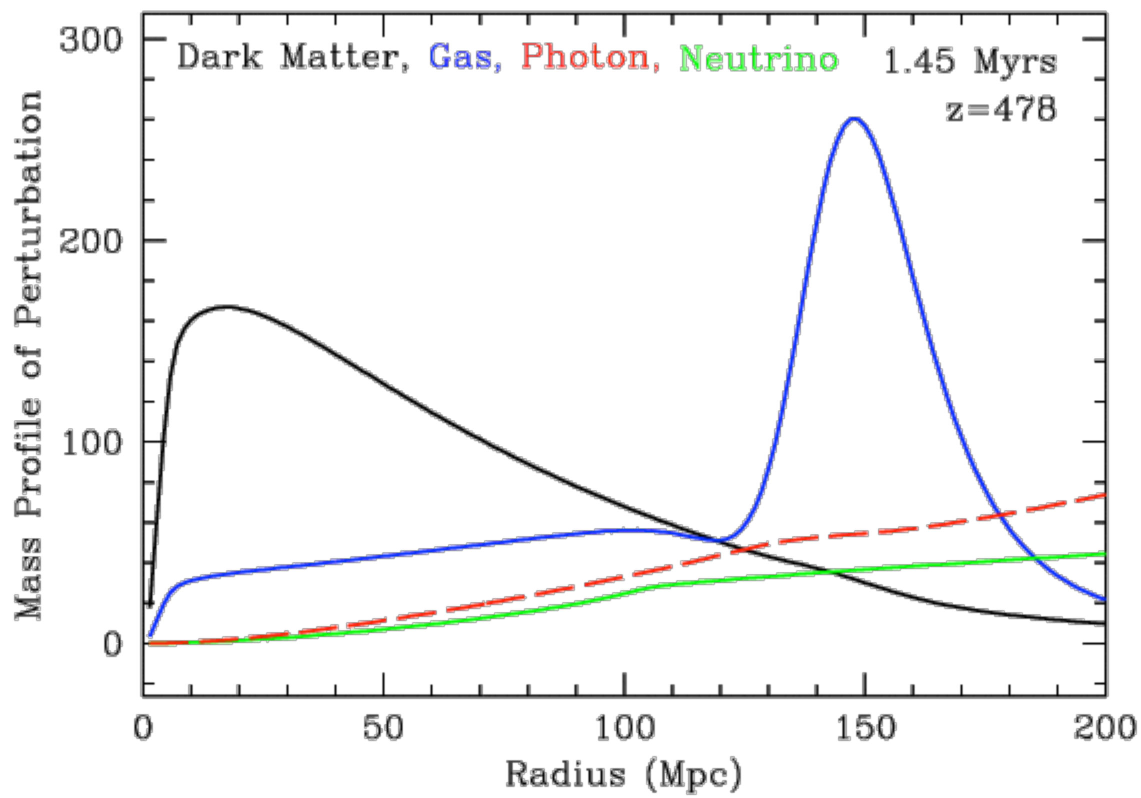

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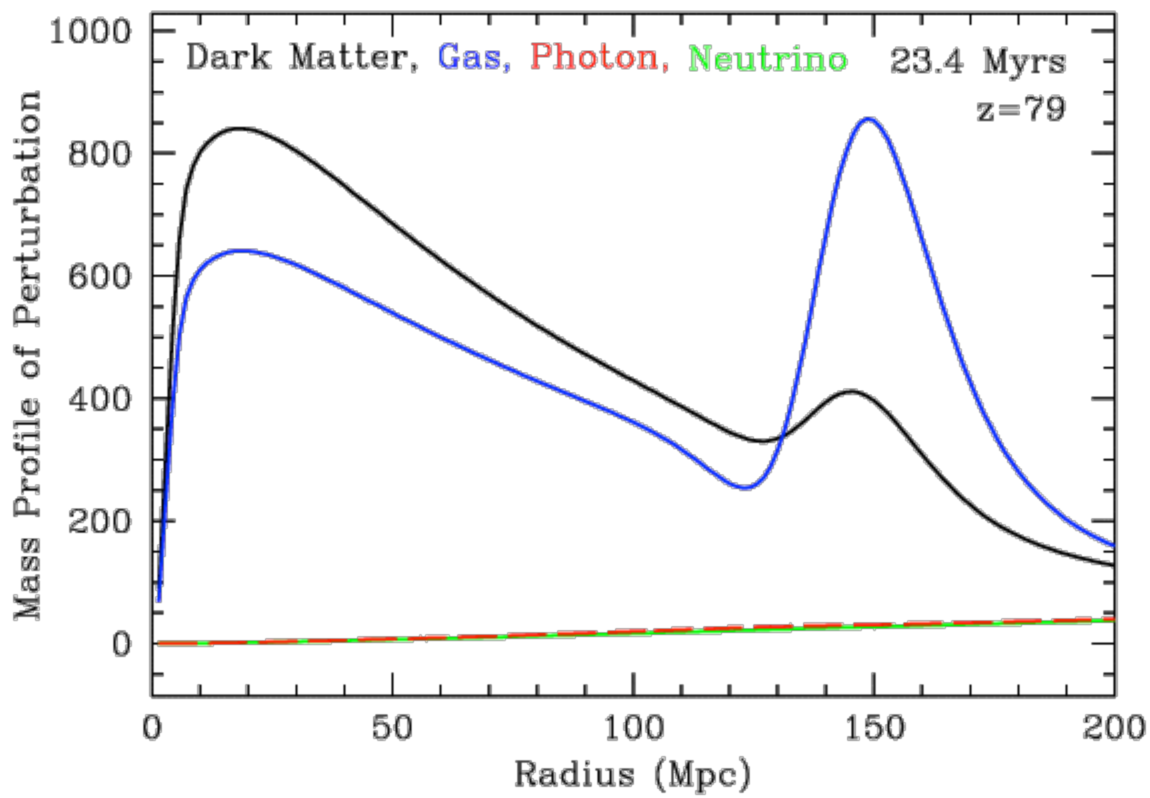

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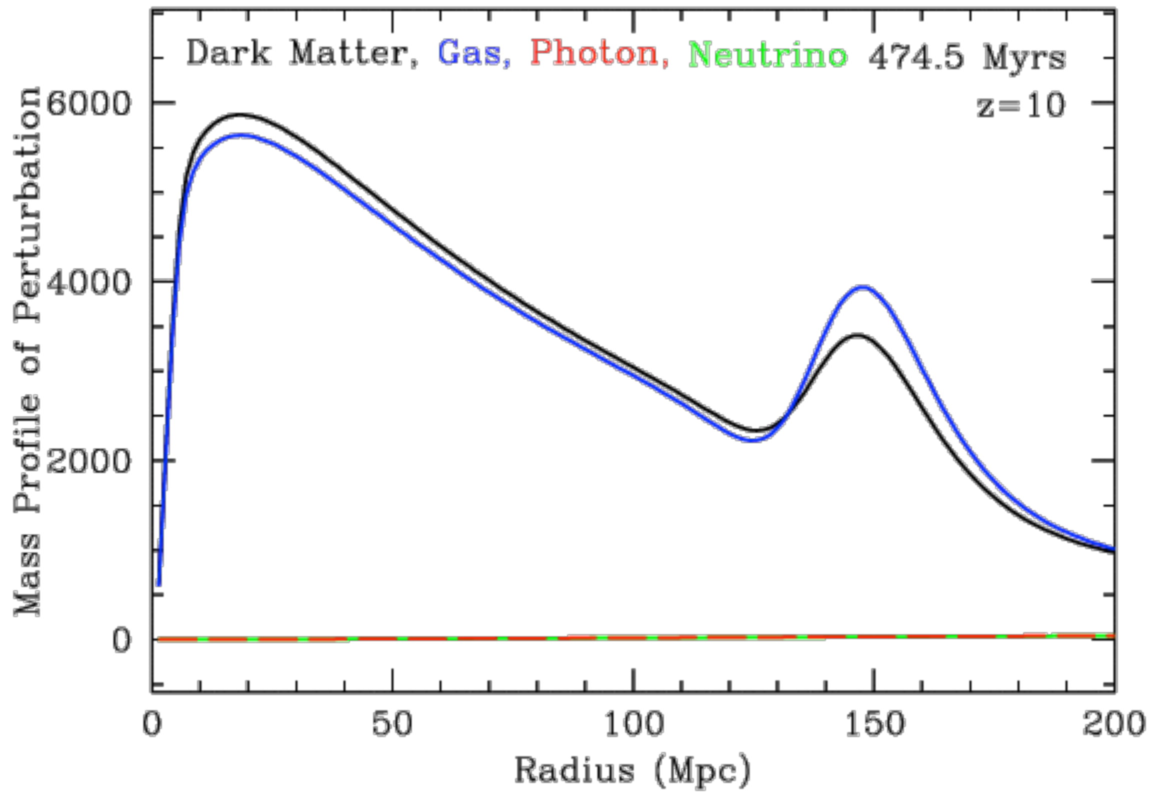

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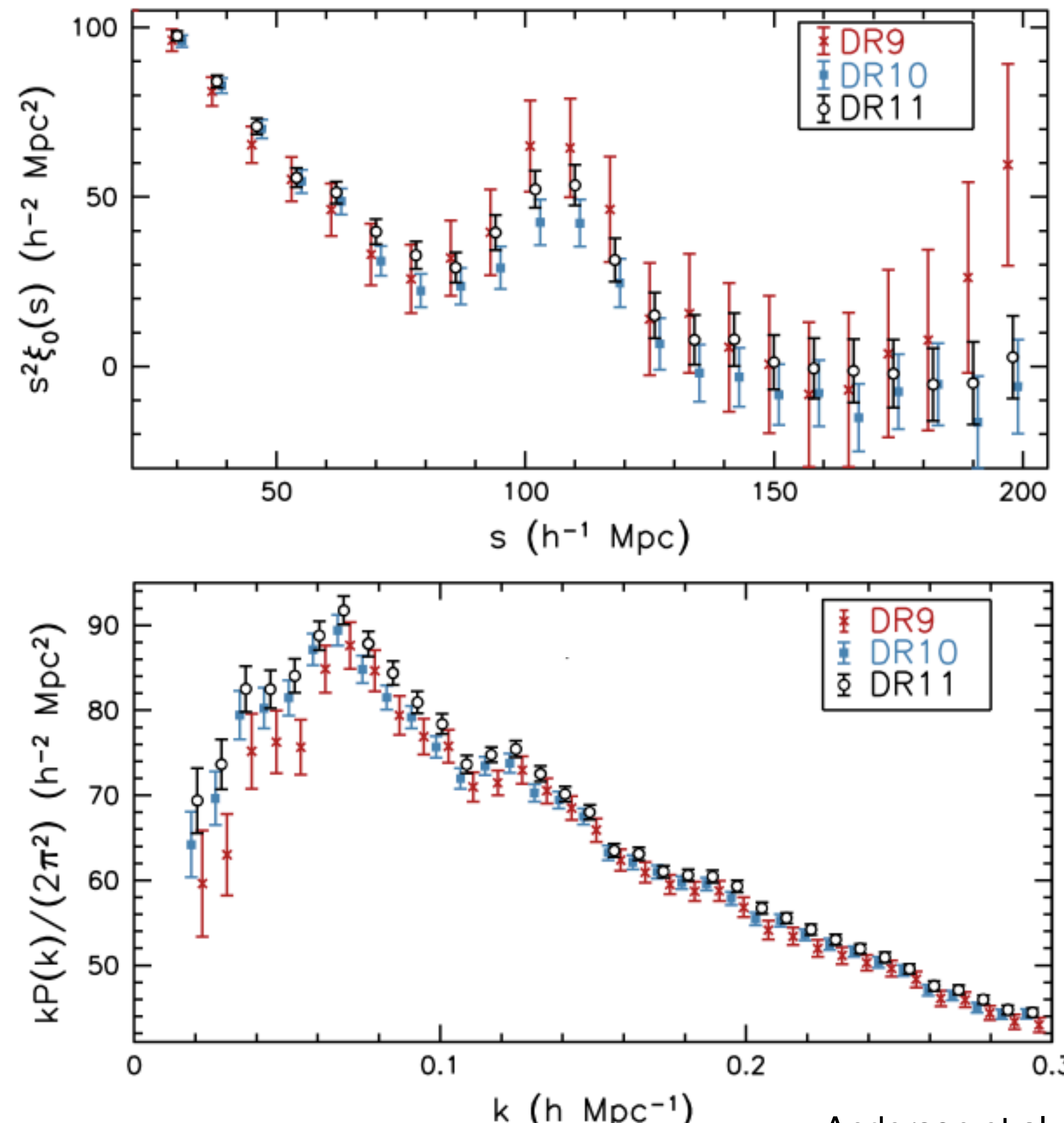
position-space description: Bashinsky & Bertschinger
astro-ph/0012153 & astro-ph/02022153

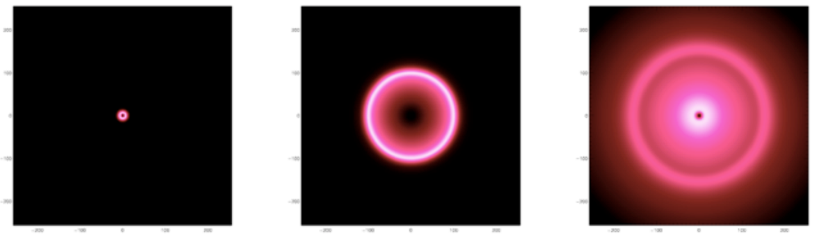
plots by Dan Eisenstein

Measured 2-point functions

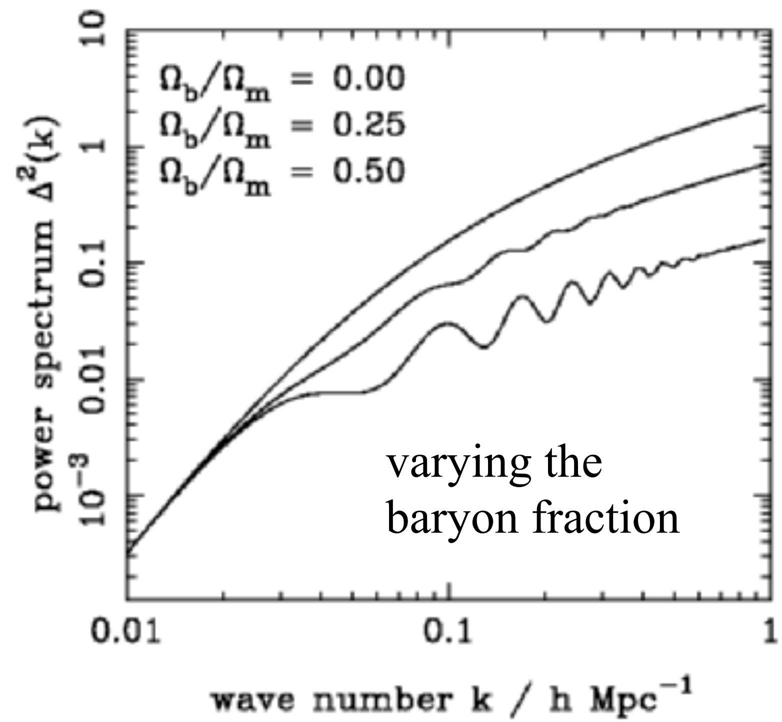


Anderson et al. 2013; arXiv:1312.4877

Baryon Acoustic Oscillations (BAO)



(images from Martin White)



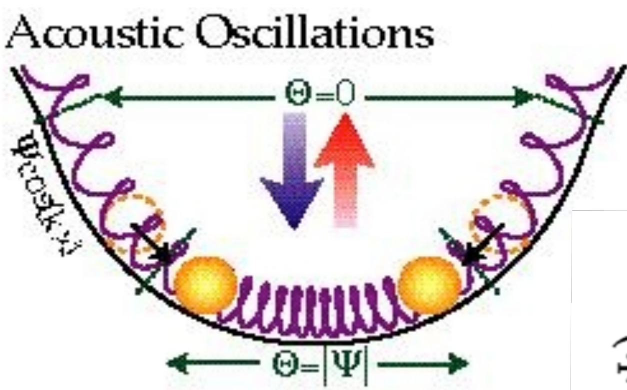
To first approximation, BAO wavelength is determined by the comoving sound horizon at recombination

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

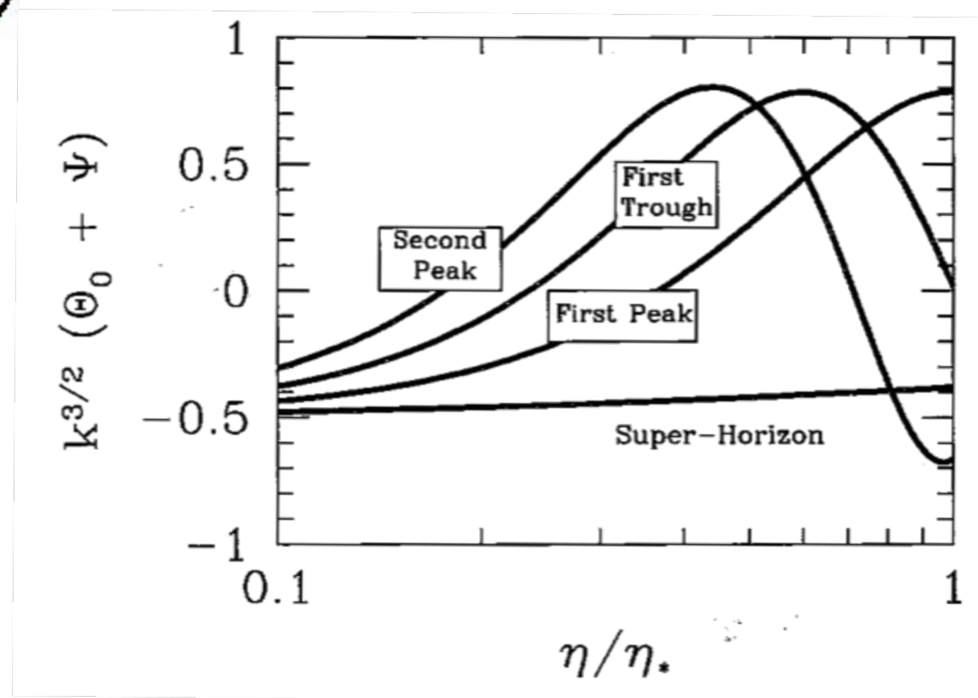
$$s = \frac{1}{H_0\Omega_m^{1/2}}\int_0^{a_*} da \frac{c_s}{(a+a_{\rm eq})^{1/2}}$$

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

Acoustic Oscillations in the matter distribution



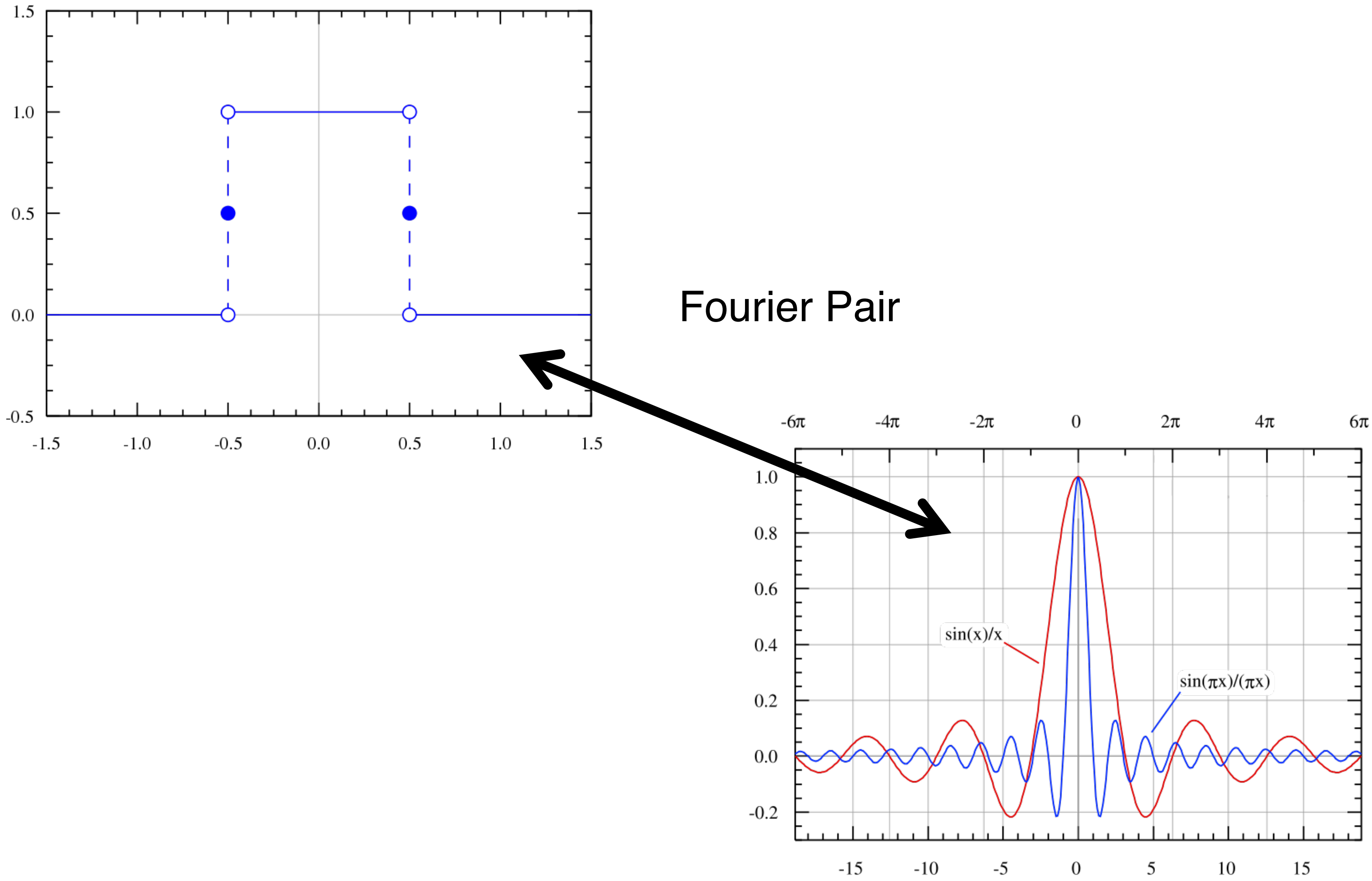
$$\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = F$$



Dodelson "modern cosmology"

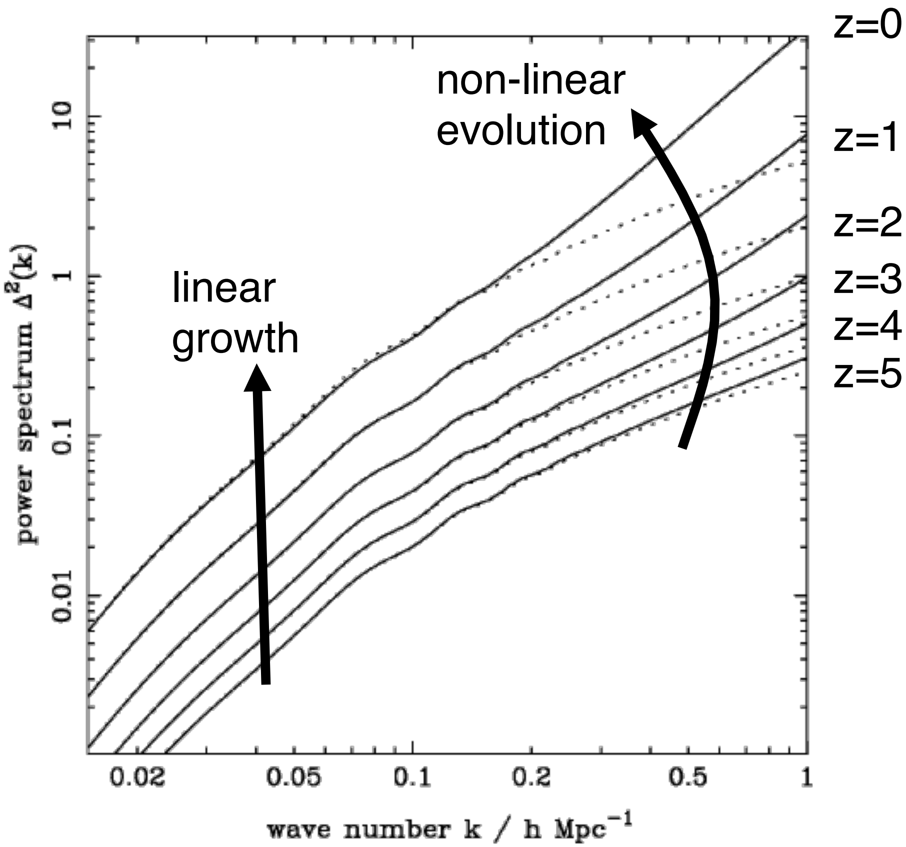
descriptions describe the same physics

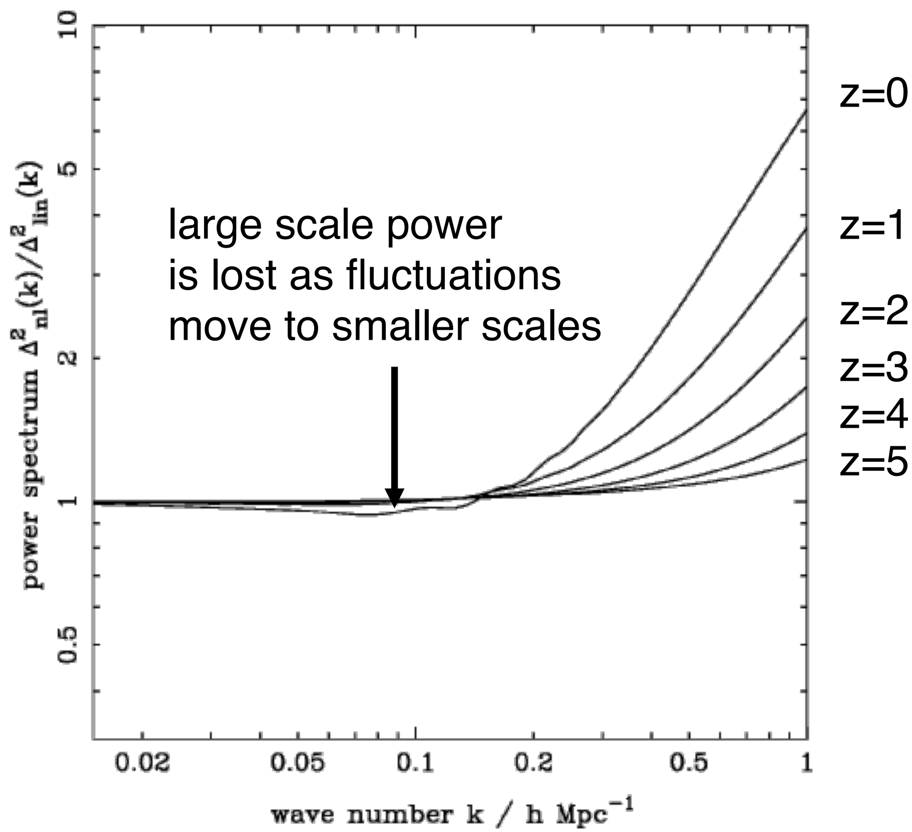
Fourier Pair



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

non-linear BAO damping

- For BAO on non-linear scales, primary effect is damping caused by large-scale bulk motions, well described as being random

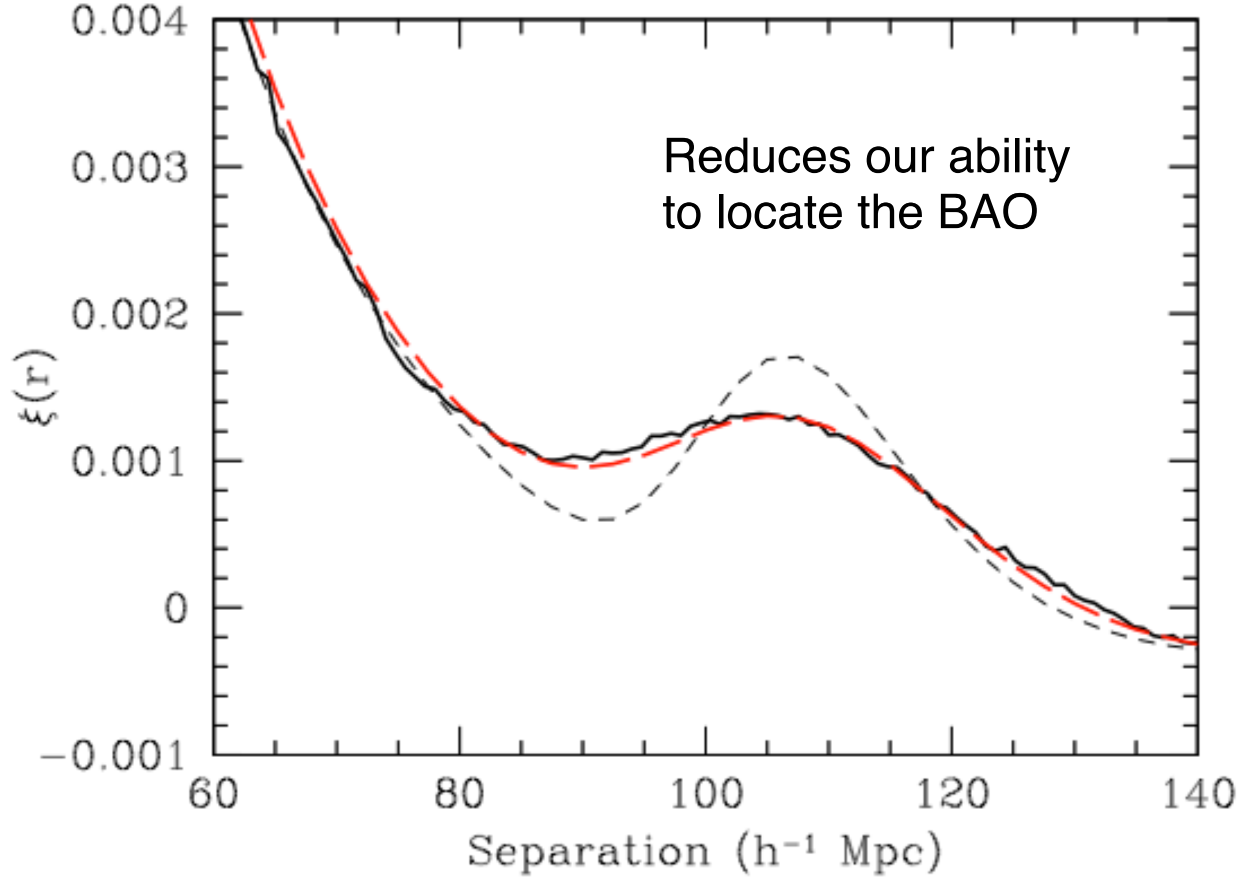
$$P_{\rm damp}(k,\sigma) = P_{\rm lin}(k) e^{\frac{-k^2\sigma^2}{2}} + P_{\rm nw}(k)\left(1 - e^{\frac{-k^2\sigma^2}{2}}\right)$$

- Redshift-Space Distortions in apparent maps cause more damping in radial than angular directions

$$\exp\left(-\frac{k^2\sigma^2}{2}\right) \longrightarrow \exp\left(-\frac{k_\parallel^2\sigma_\parallel^2}{2} - \frac{k_\perp^2\sigma_\perp^2}{2}\right)$$

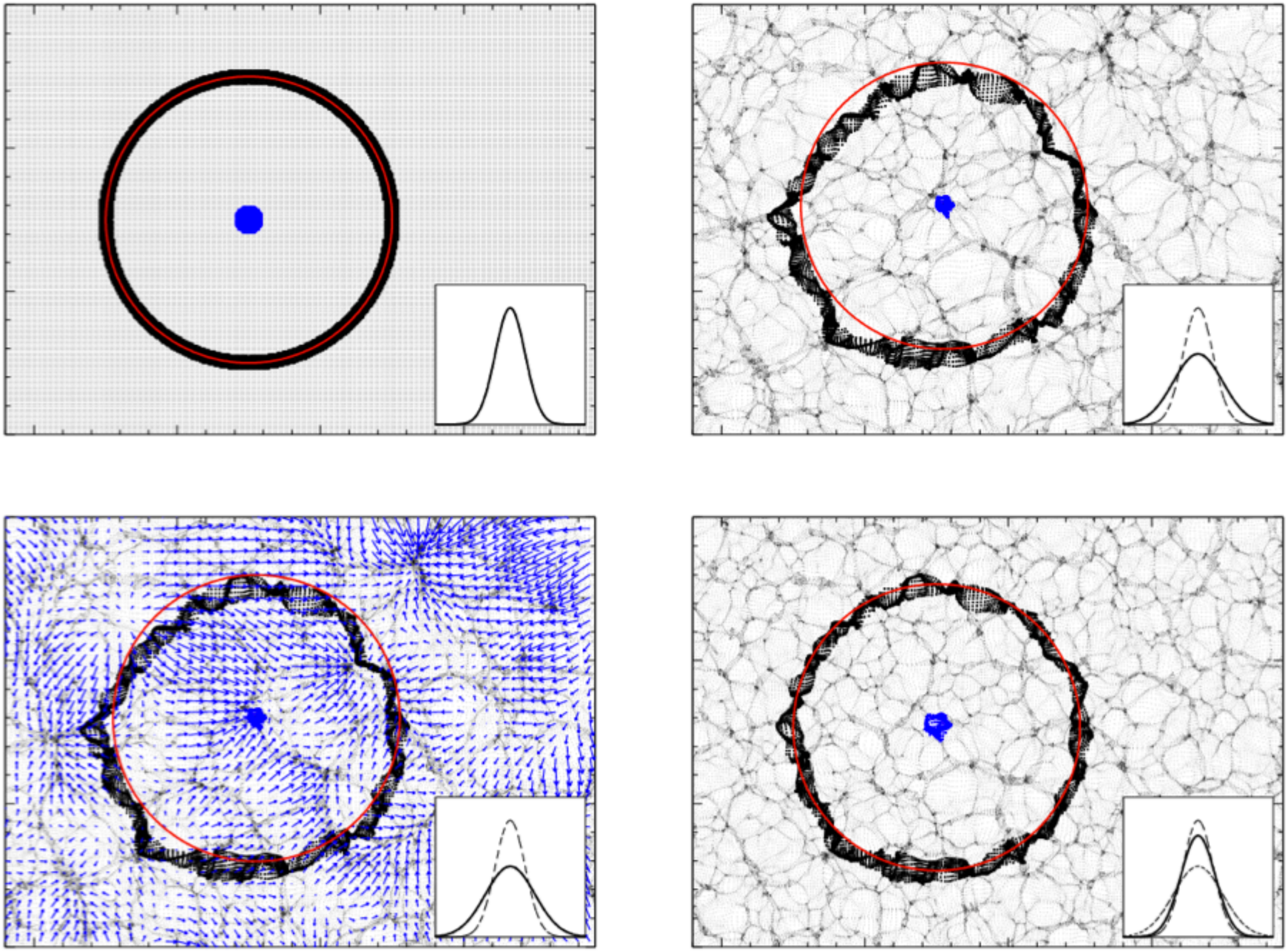
Eisenstein, Seo & White 2007; arXiv:0604361

BAO damping



Eisenstein, Seo & White 2007; arXiv:0604361

Non-linear movement on BAO scales



Padmanabhan et al. 2012; arXiv:1202.0090

A simple reconstruction algorithm

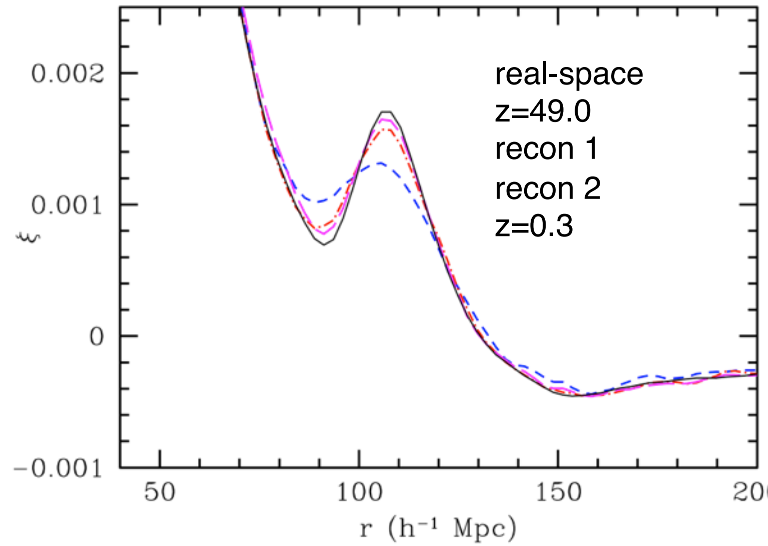
"Smoothing" dominated by large-scale flows

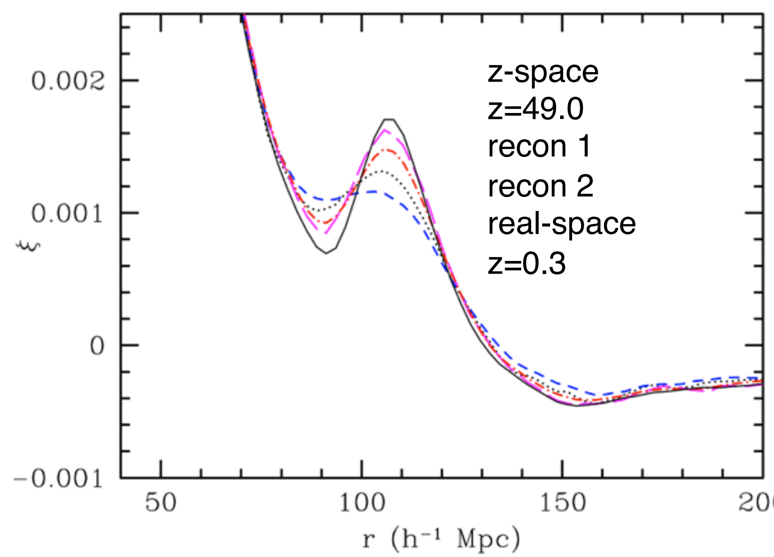
Smooth field and move galaxies by predicted (linear) motion

Breaks coherence between large-scale and small-scale motion

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

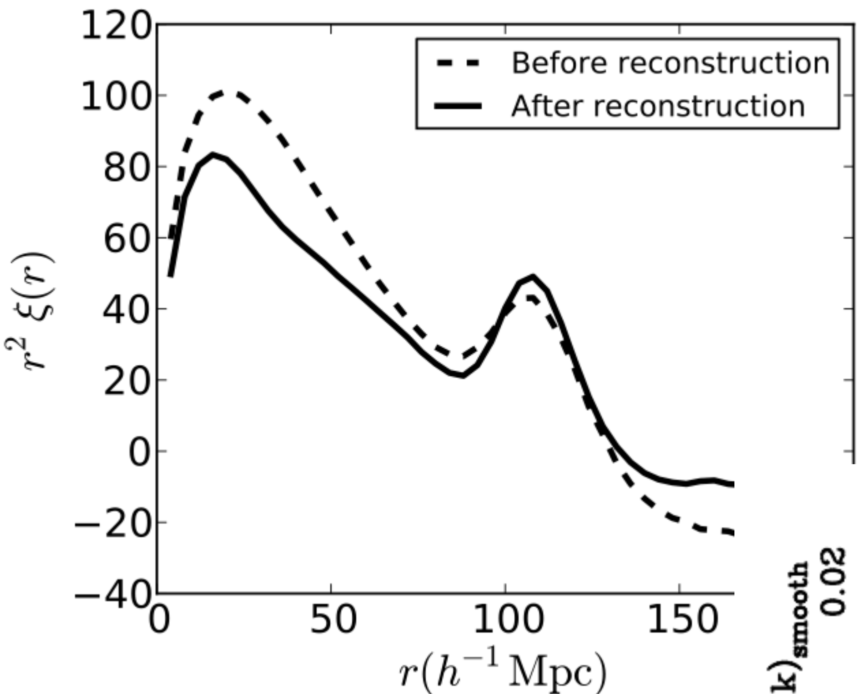
See Padmanabhan et al. (2008; arXiv: 0812.2905) for a perturbation theory derivation of this

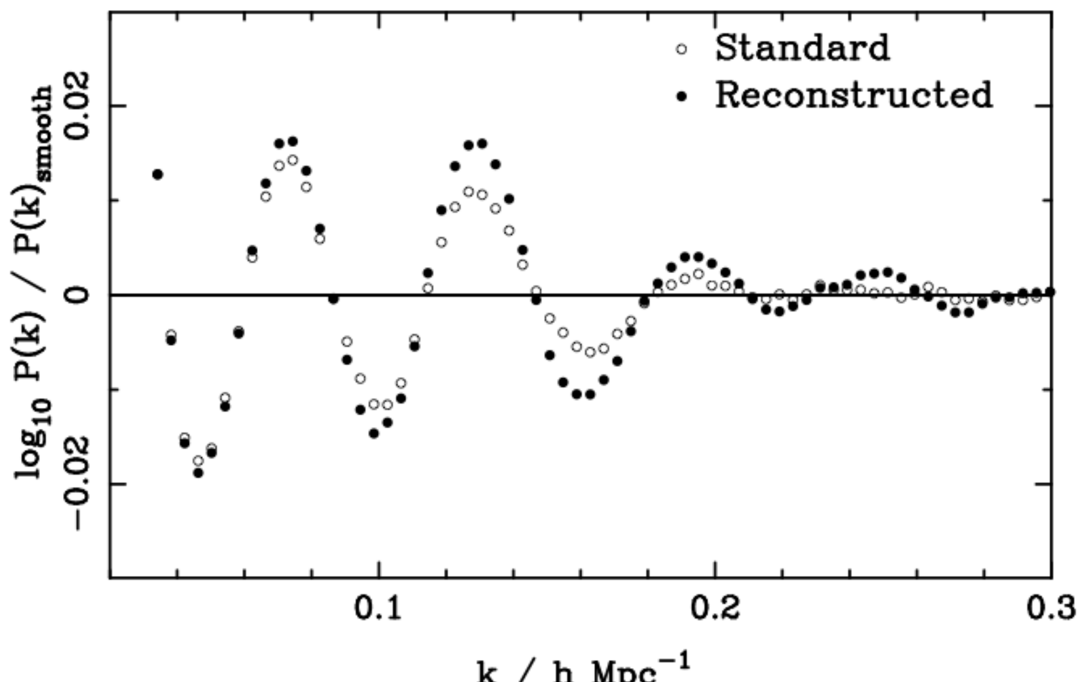




Eisenstein et al. 2006: arXiv:0604362

Reconstruction on SDSS-III mocks



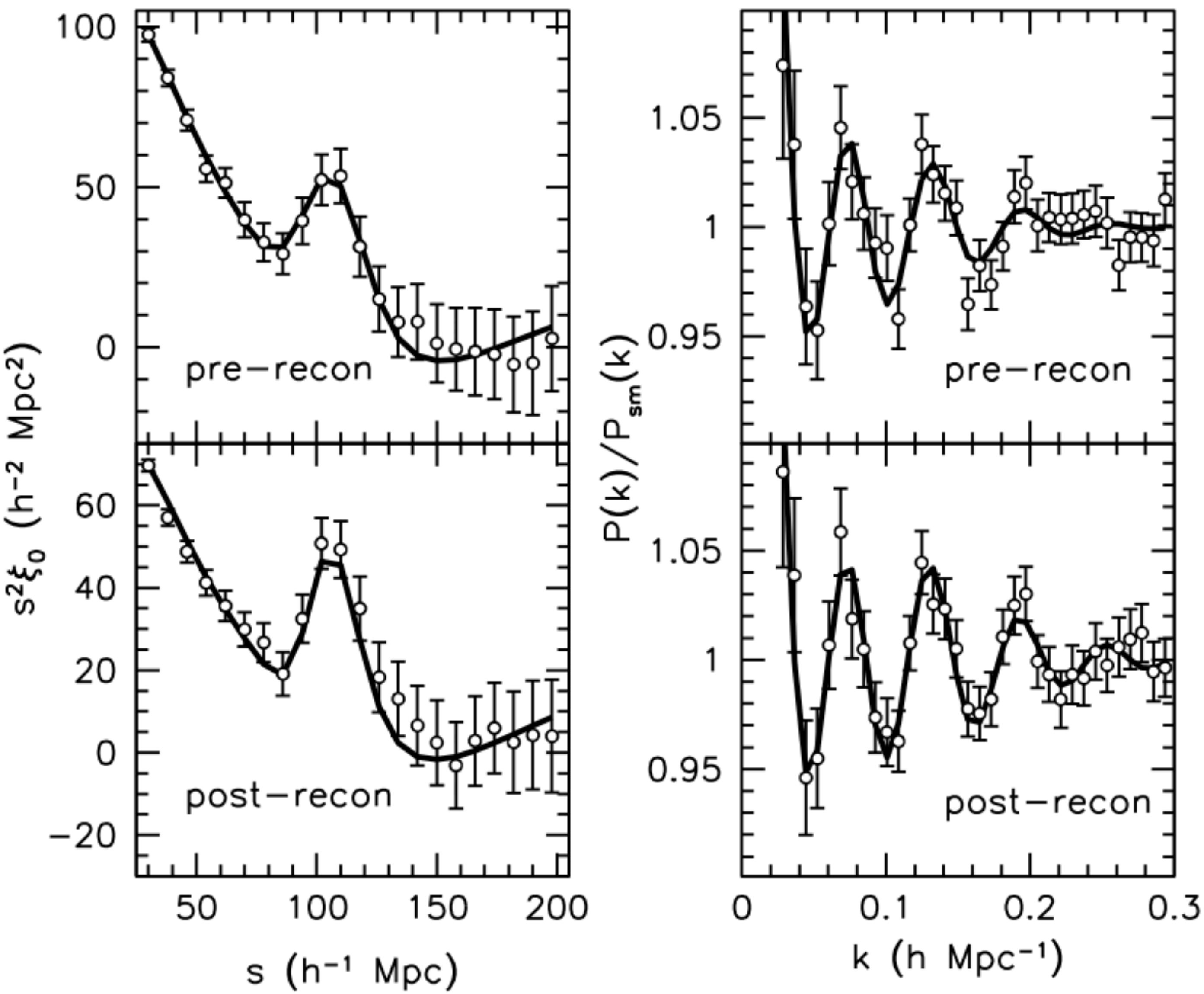


Anderson et al. 2012; arXiv:1203.6565

Other reconstruction methods

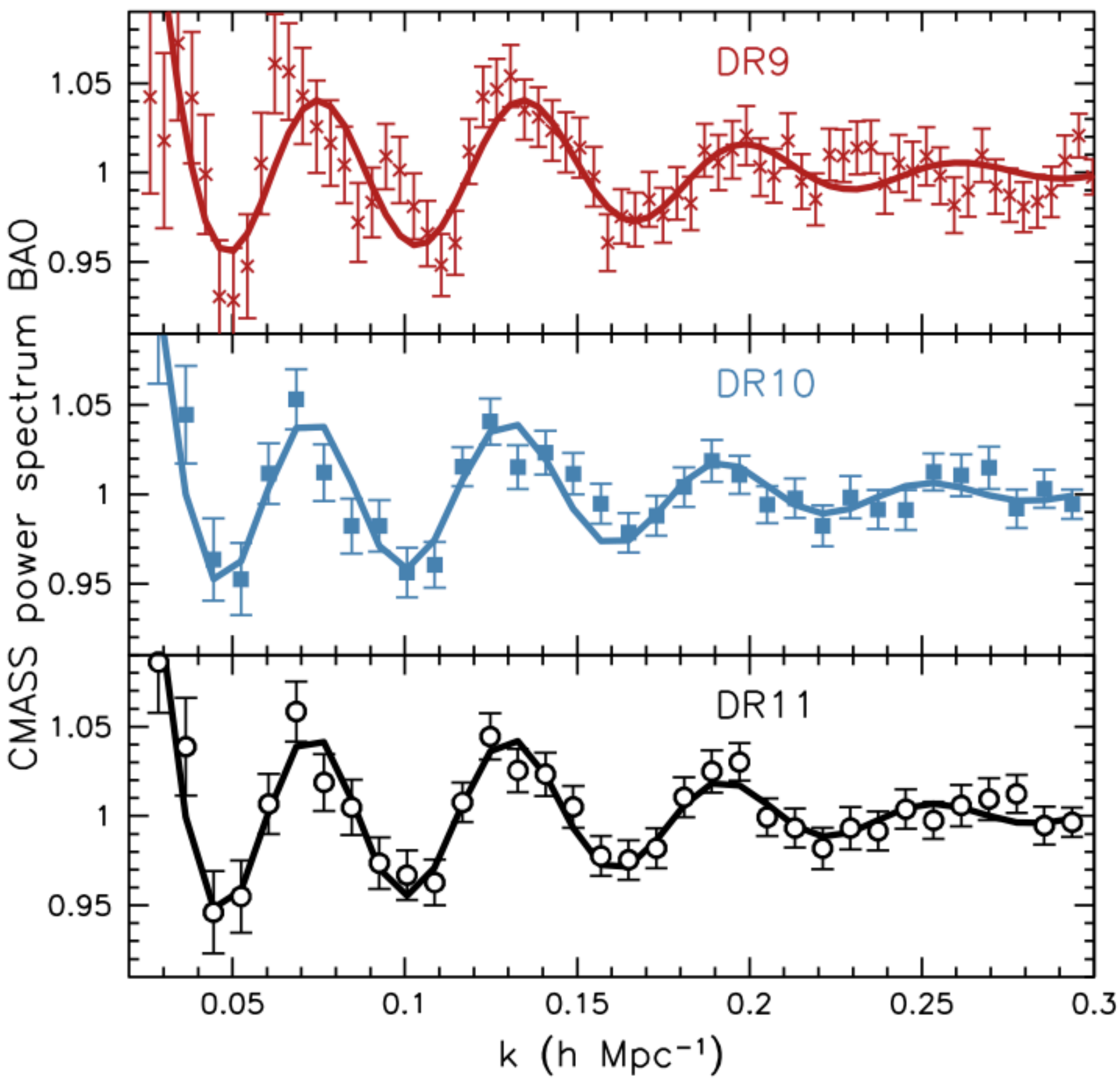
- Gaussianisation
  - Weinberg 1992, MNRAS, 254, 315
- Path interchange Zeldovich approximation (PIZA)
  - Croft & Gaztanaga 1997, MNRAS, 285, 793
- Incompressible fluid assumption
  - Mohayaee & Sobolevskii 2007, arXiv:0712.2561
- Improvement on “simple” scheme using optimized filters
  - Tassev & Zaldarriaga 2012, arXiv:1203.6066
- MCMC fit to observed data
  - Wang et al. 2013, arXiv:1301.1348

The improvement from reconstruction



Anderson et al. 2013; arXiv:1312.4877

The improvement DR9 - DR11



Anderson et al. 2013; arXiv:1312.4877

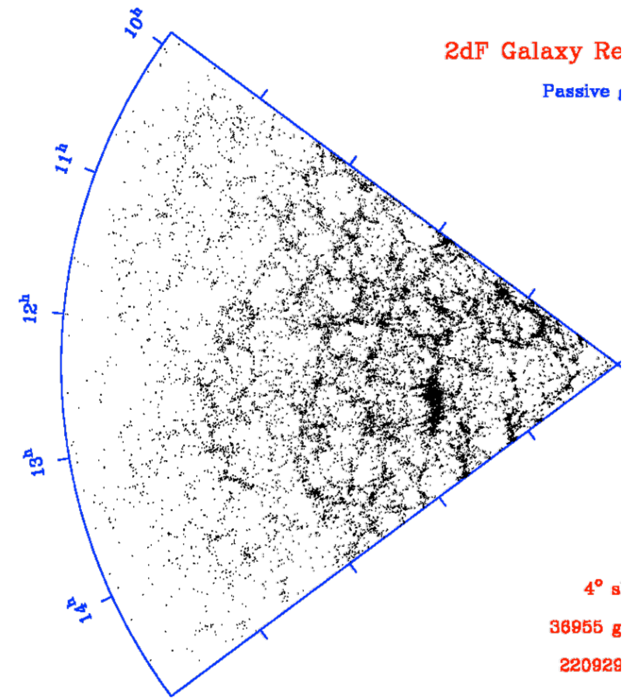
Galaxy clustering as a standard ruler

The evolution of the scale factor

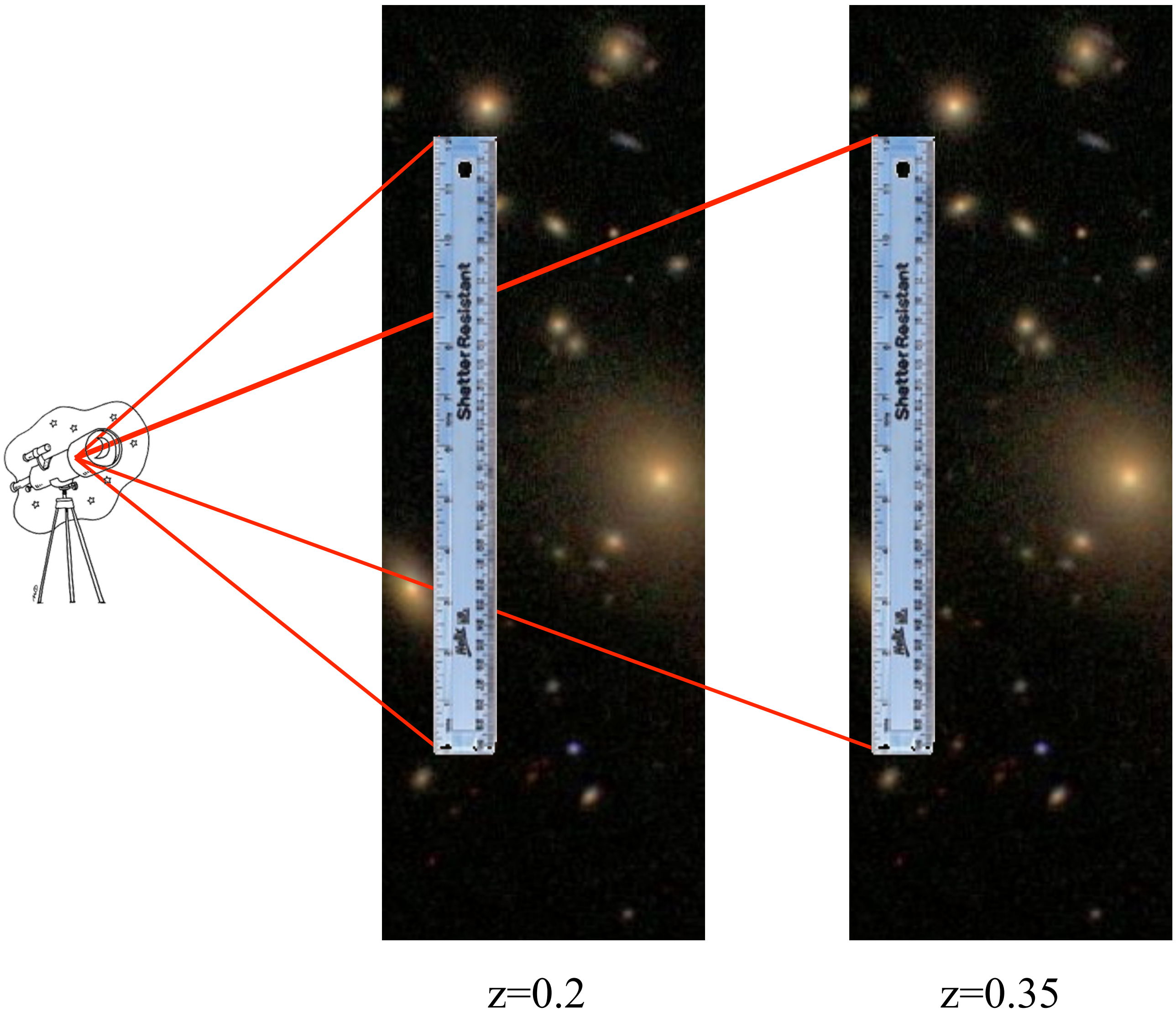
If we observed the comoving power spectrum directly, we would not constrain evolution

However, we measure galaxy redshifts and angles and infer distances

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

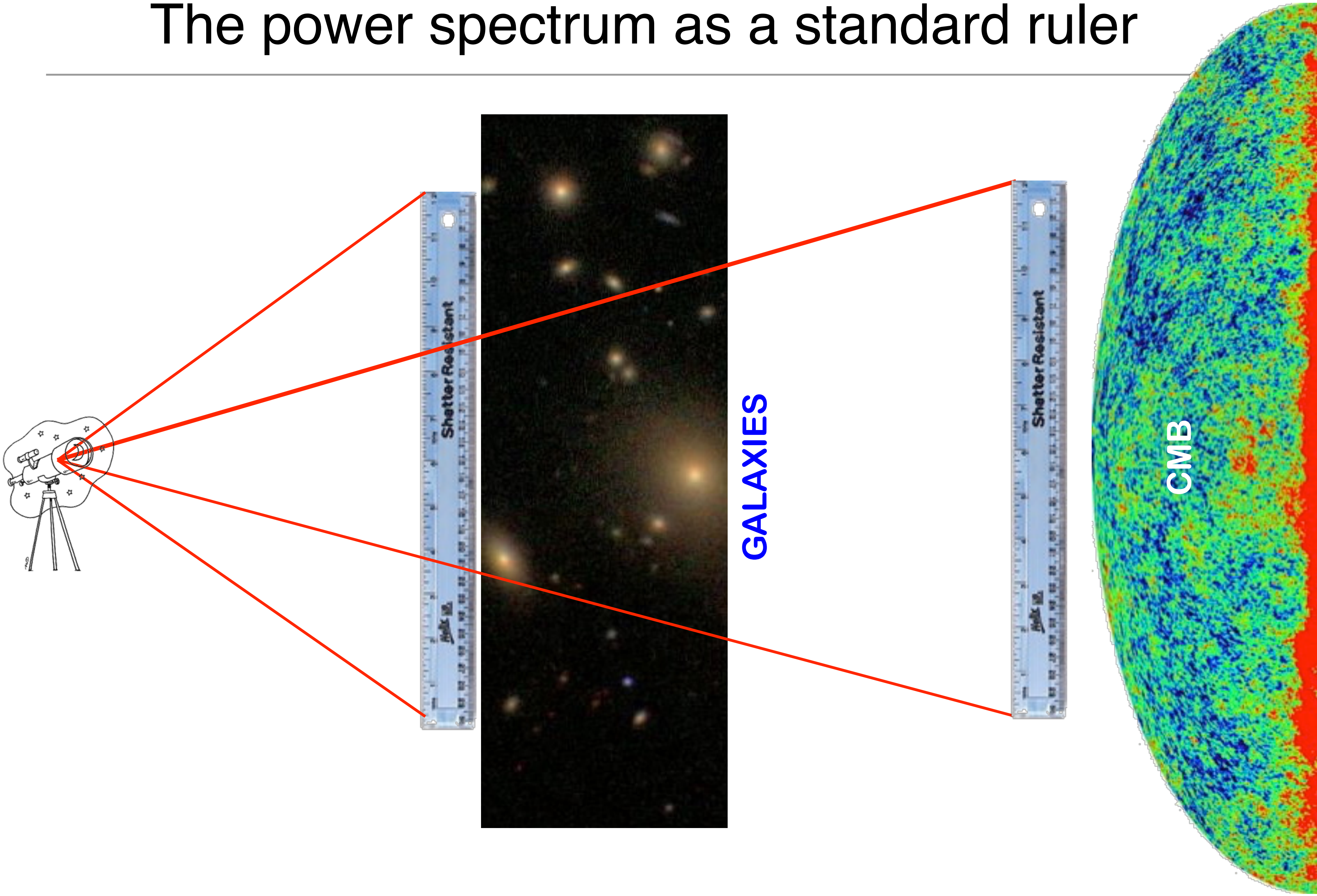


The power spectrum as a standard ruler



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

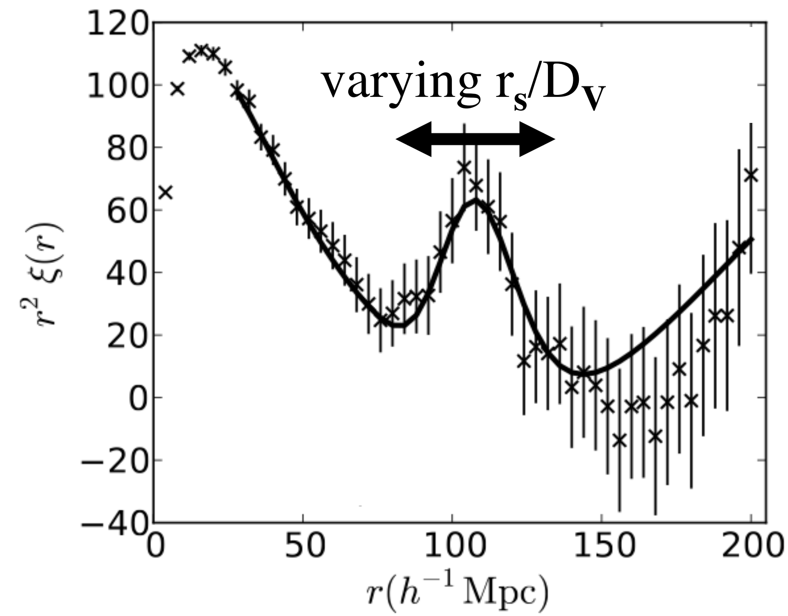
$$(1+z)D_A\Delta\theta$$

(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 $\frac{r_s}{D_V}$



Anisotropic projection

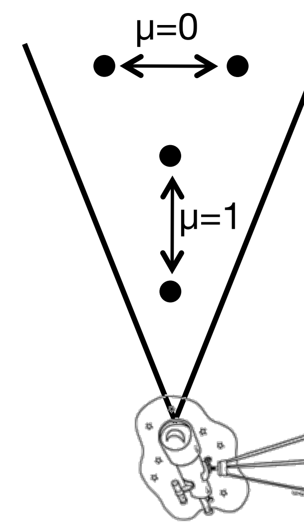
Define:

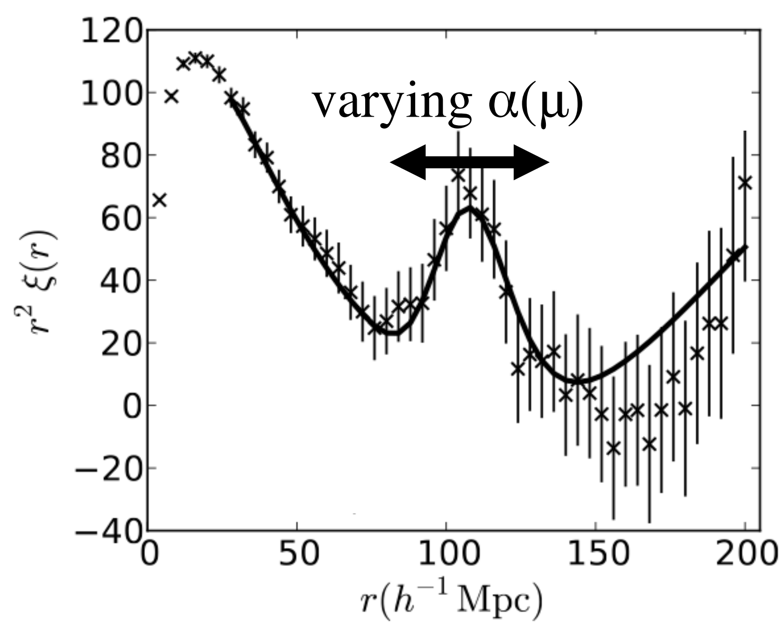
$$\alpha_{||} \equiv H(z)_{\rm fid}/H(z)_{\rm true}; \quad \alpha_\perp \equiv D_{A,\rm true}/D_{A,\rm fid},$$

$$\mu \quad = \quad cos(\alpha)$$

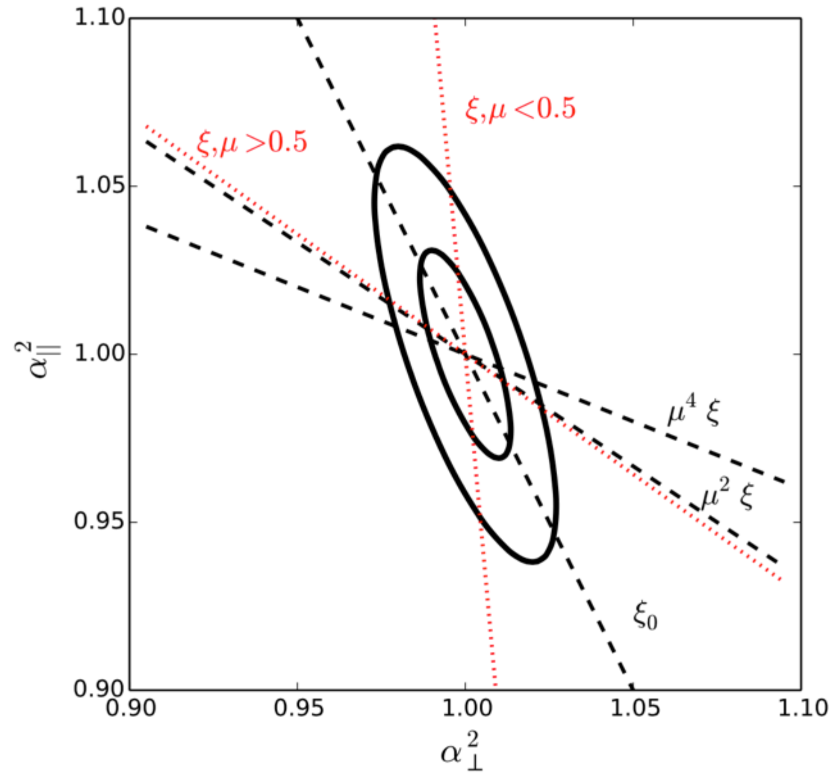
Then the BAO scale measured along a direction given by the angle α with respect to the line-of-sight depends on

$$\alpha(\mu) = \sqrt{\mu^2\alpha_{||}^2 + (1-\mu^2)\alpha_\perp^2}.$$





Anisotropic projection



Define a moment of the correlation function

$$\xi_F(r) = \int_0^1 F(\mu)\xi(r,\mu)d\mu,$$

Then the BAO scale measured in this moment depends on a combination given by

$$\alpha_F = \int_0^1 d\mu F(\mu)\left[\mu^2\alpha_{||}^2 + (1-\mu^2)\alpha_\perp^2\right]^{\frac{1}{2}}$$

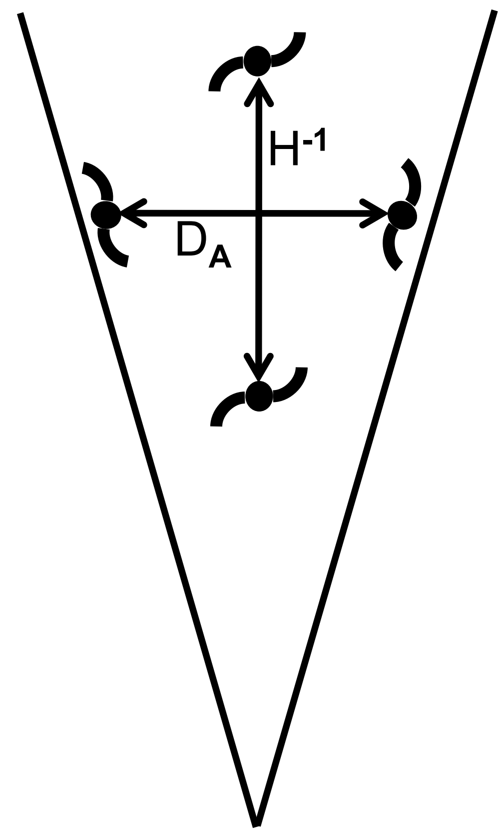
Ross et al. (2015); arXiv:1501.05571

The Alcock-Paczynski Effect

- If the Universe is isotropic, clustering is same radial & tangential
- Stretching at a single redshift slice (for galaxies expanding with Universe) depends on

  $H^{-1}(z)$ (radial)

  $D_A(z)$ (angular)
- Analyze with wrong model -> see anisotropy
- AP effect measures $D_A(z)H(z)$
- RSD limits test to scales where can be modeled - need radial separation to be dependent on H^{-1}



Can we use the AP effect on small scales?

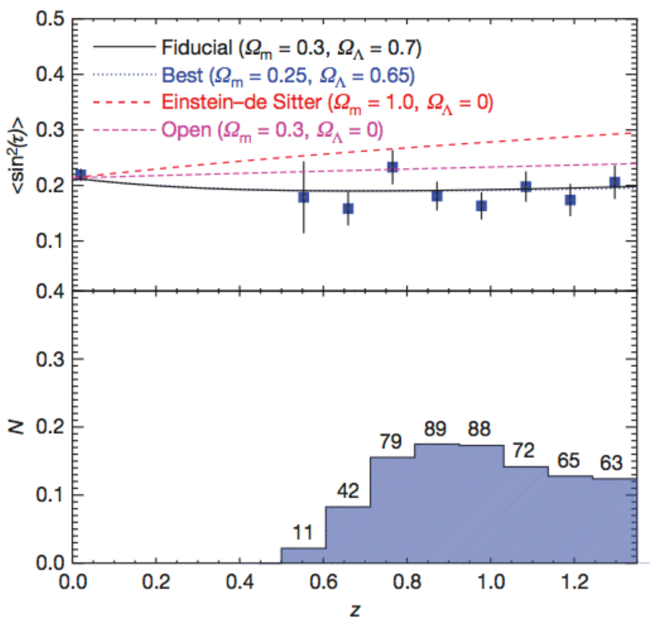
use isolated galaxy pairs

Marinoni & Buzzi 2011

Nature 468, 539

Jennings et al. 2012

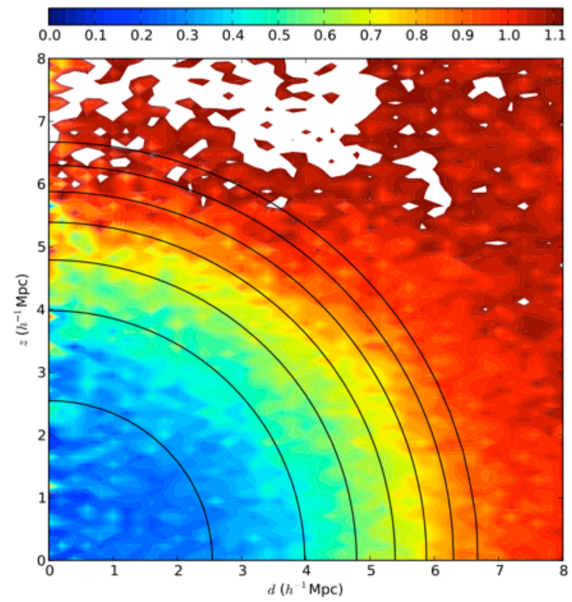
MNRAS 420, 1079



use voids

Lavaux & Wandelt 2011

arXiv:1110.0345



Both try to isolate objects where the RSD signal is known or weak

Collapsed structures

Live in static region of space-time

Velocity from growth exactly cancels Hubble expansion

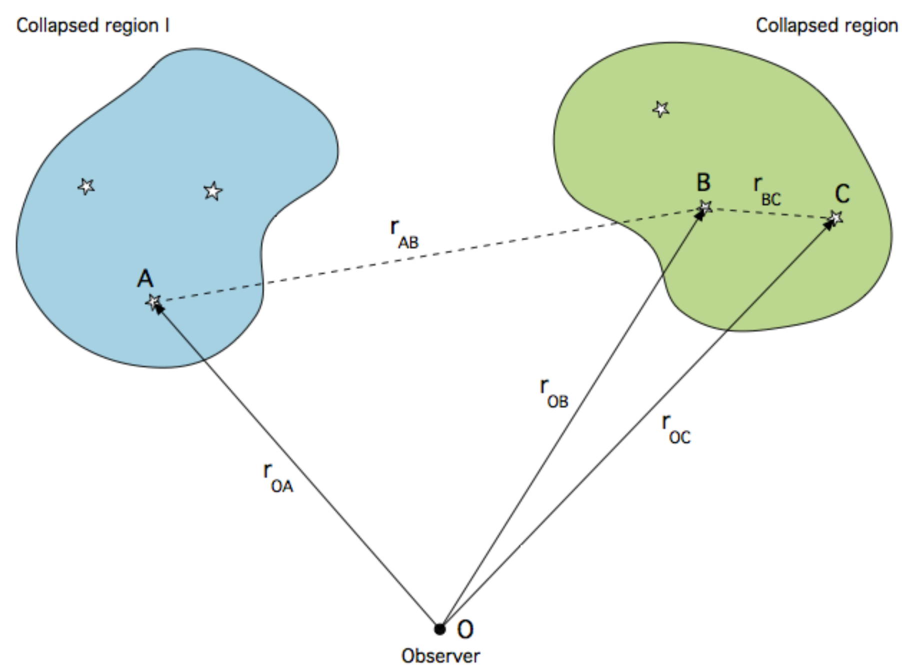
Two static galaxies in same structure have same observed redshift irrespective of distance from us

Redshift difference only tells us properties of system

Two collapsed similar regions observed in different background cosmologies give same Δz

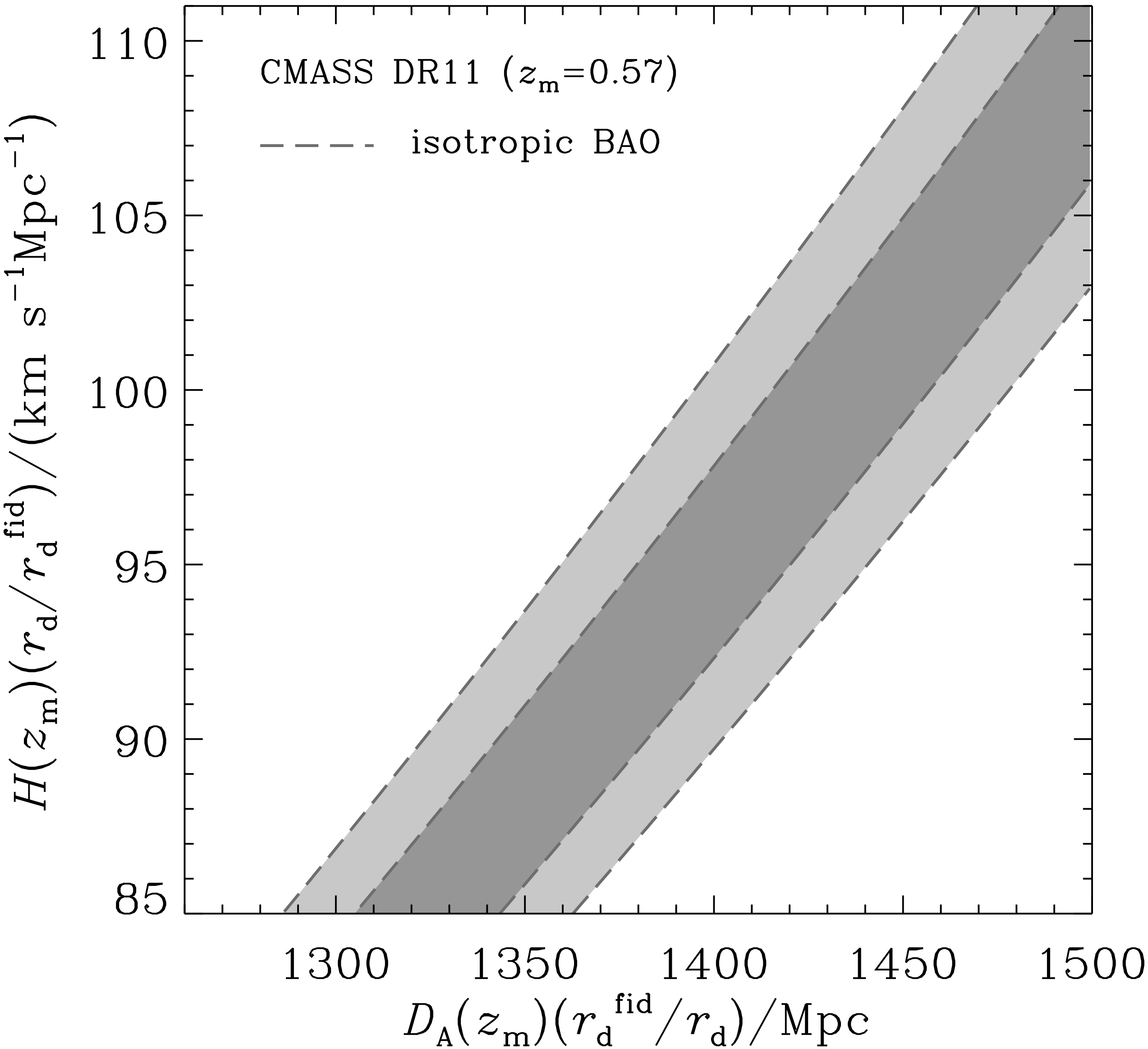
No cosmological information from Δz

Cannot be used for AP tests



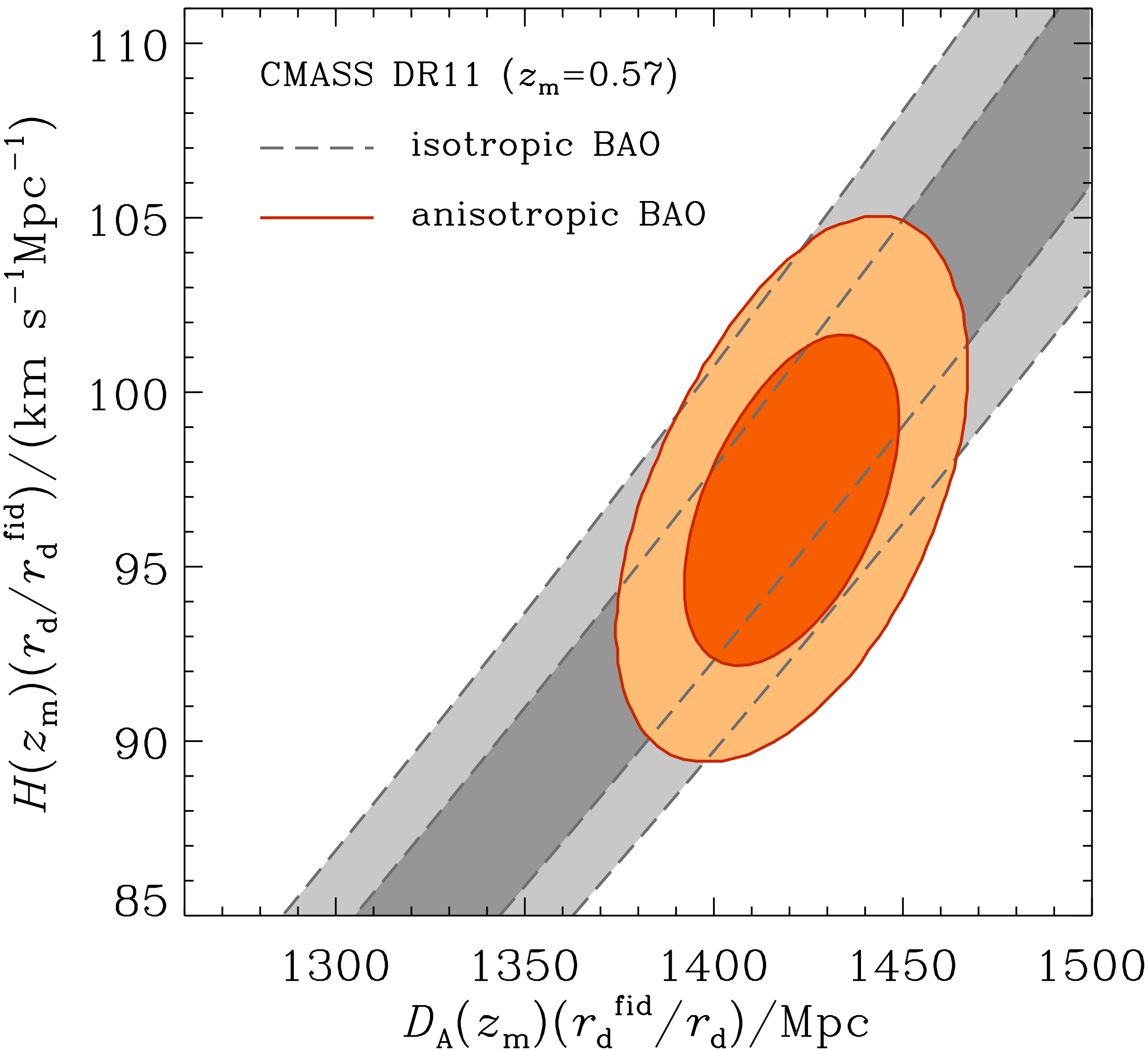
Belloso et al. 2012: arXiv:1204.5761

DR11 BAO Measurements vs CMB



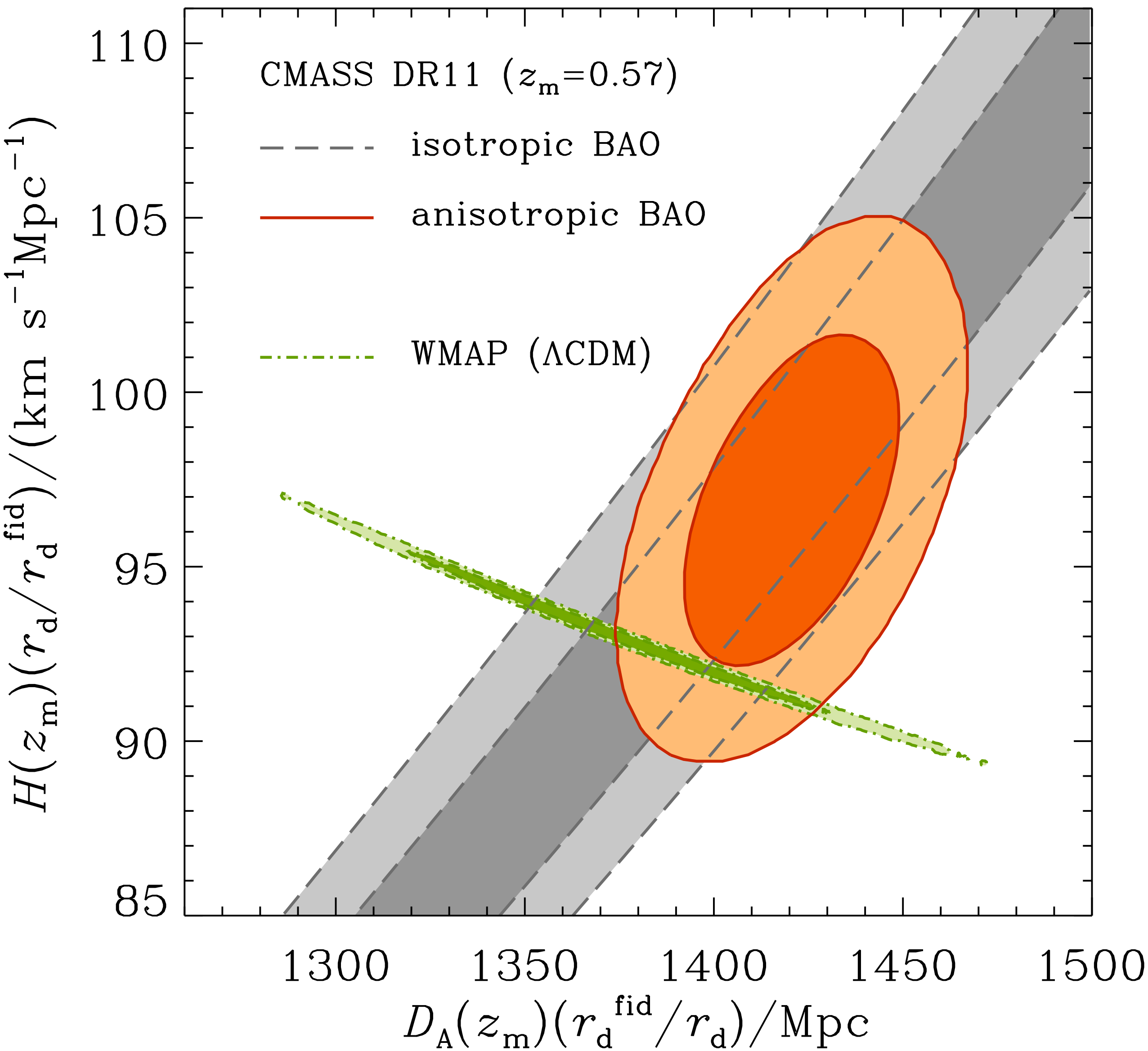
Anderson et al. 2013; arXiv:1312.4877

DR11 BAO Measurements vs CMB



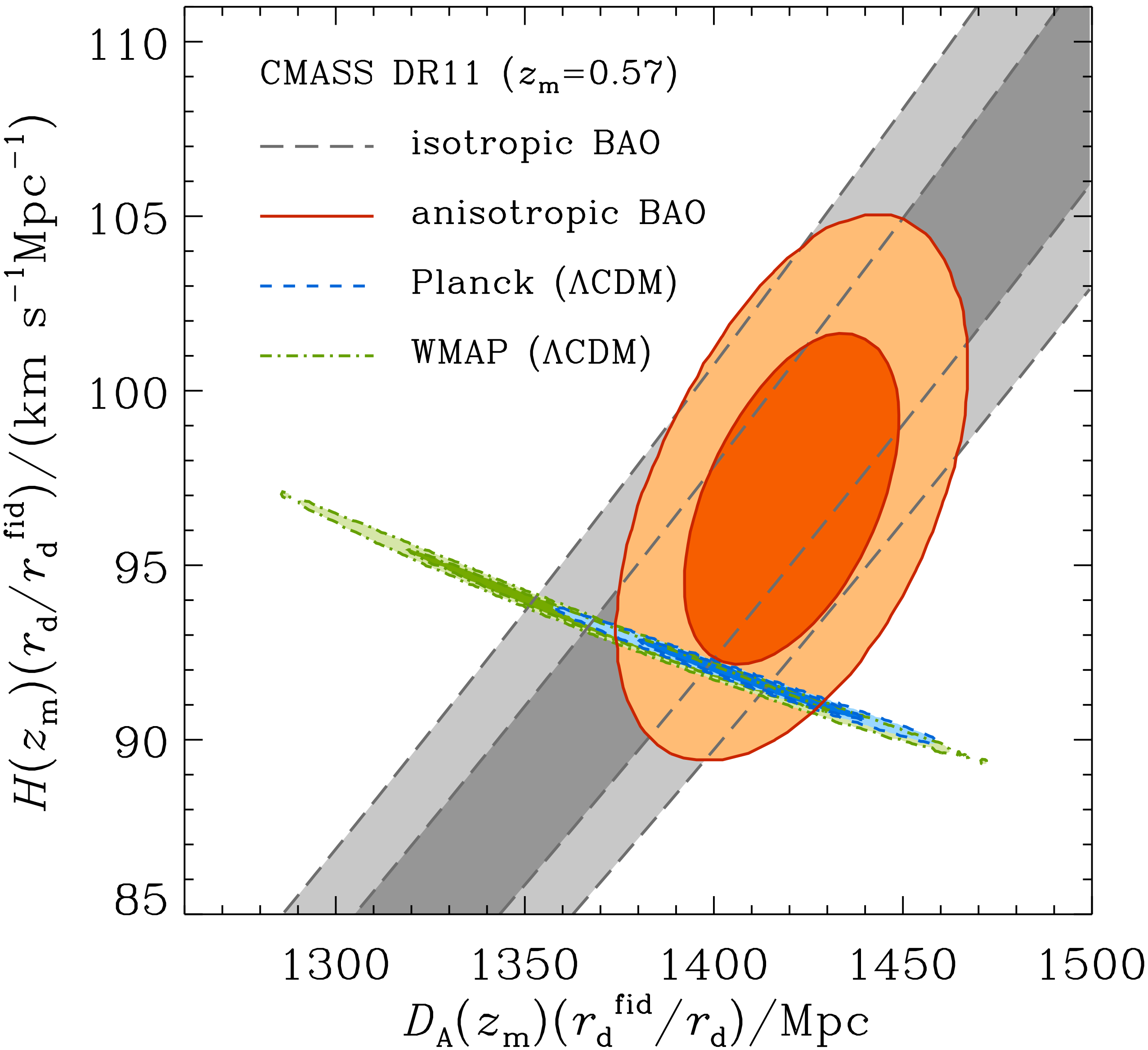
Anderson et al. 2013; arXiv:1312.4877

DR11 BAO Measurements vs CMB



Anderson et al. 2013; arXiv:1312.4877

DR11 BAO Measurements vs CMB



Anderson et al. 2013; arXiv:1312.4877

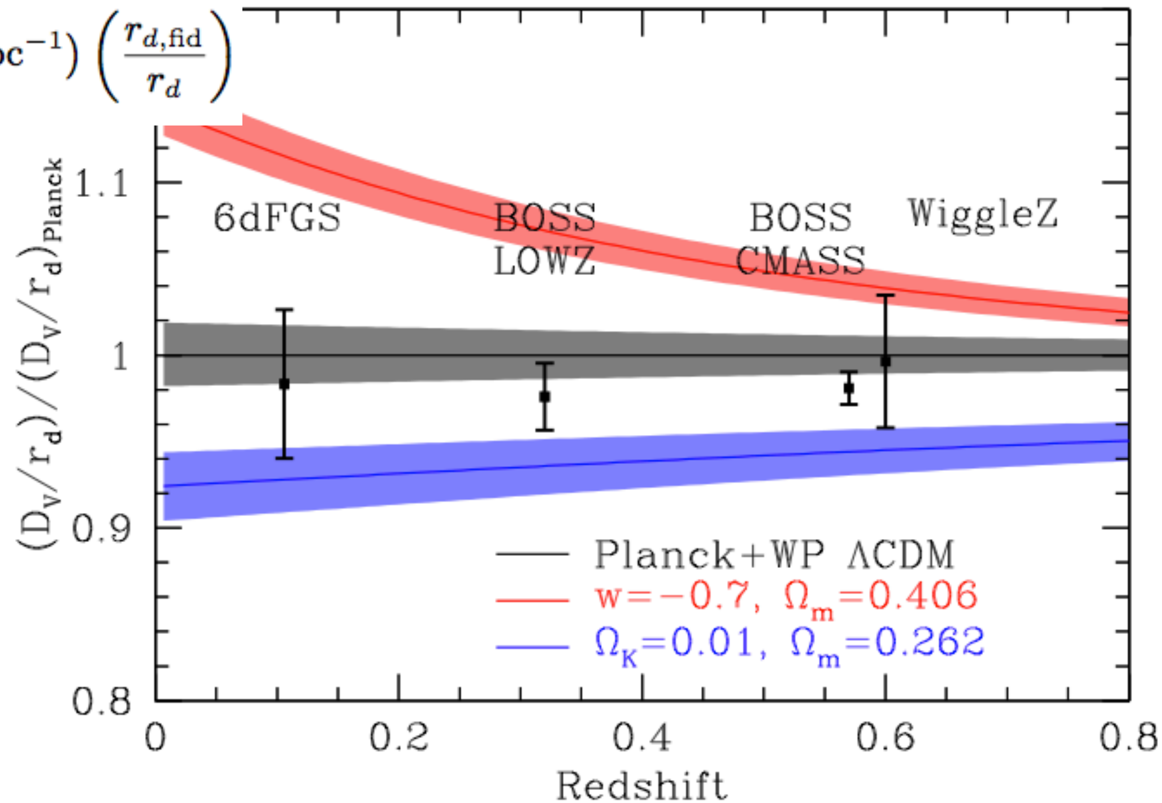
Results

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

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

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

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



Anderson et al. 2013; arXiv:1312.4877

A more direct way of measuring the matter density?

Jeans length

The transfer function depends on the composition of the matter (CDM, baryons, neutrinos, etc.)

An important scale is the Jeans Length which is the scale of fluctuation where pressure support equals gravitational collapse,

$$\lambda_J = \frac{c_s}{\sqrt{G\rho}}$$

where c_s is the sound speed of the material, and ρ is its density.

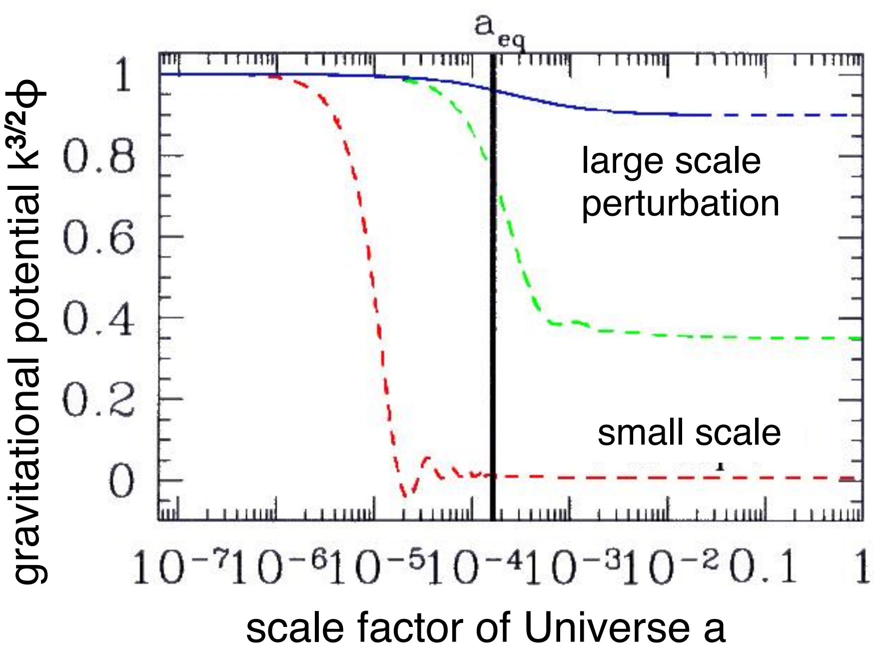
"F=ma" for perturbation growth

$$\ddot{\delta} = (\text{gravity} - \text{pressure})\delta$$

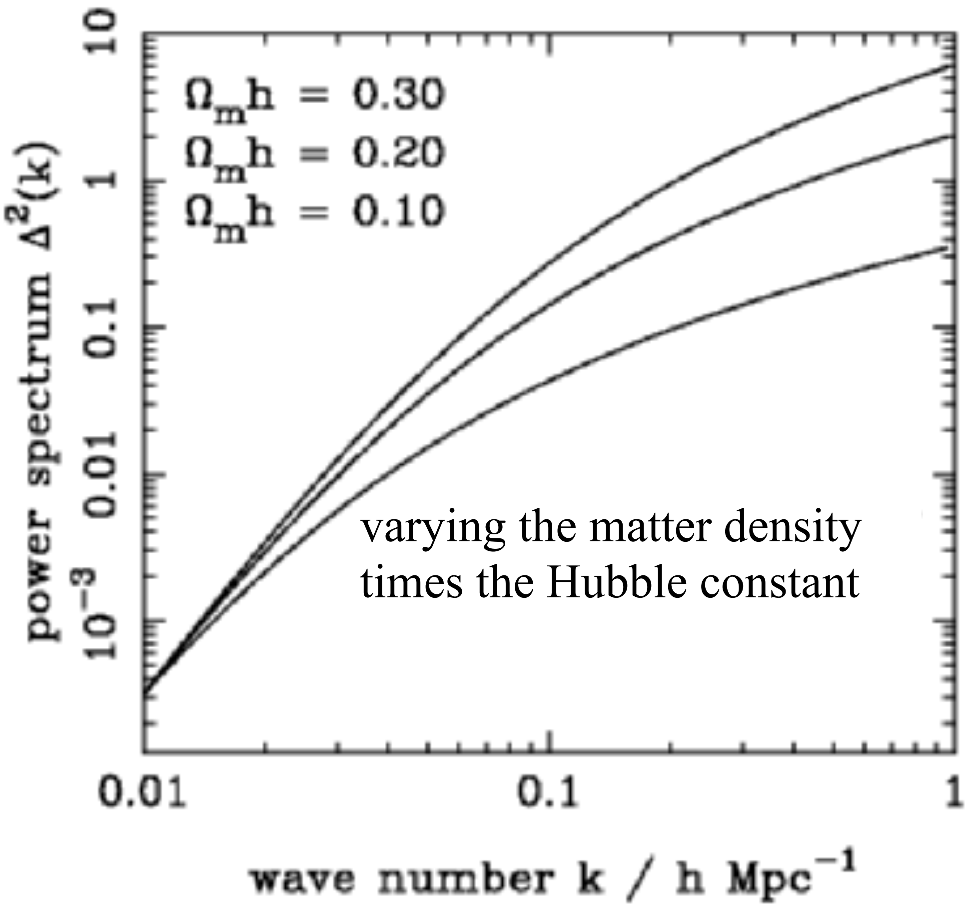
depends on Jeans scale

Transfer function evolution

In radiation dominated Universe, pressure support means that small perturbations cannot collapse. Jeans scale changes with time, leading to smooth turn-over of matter power spectrum. Projected cut-off dependent on matter density times the Hubble parameter $\Omega_m h$.

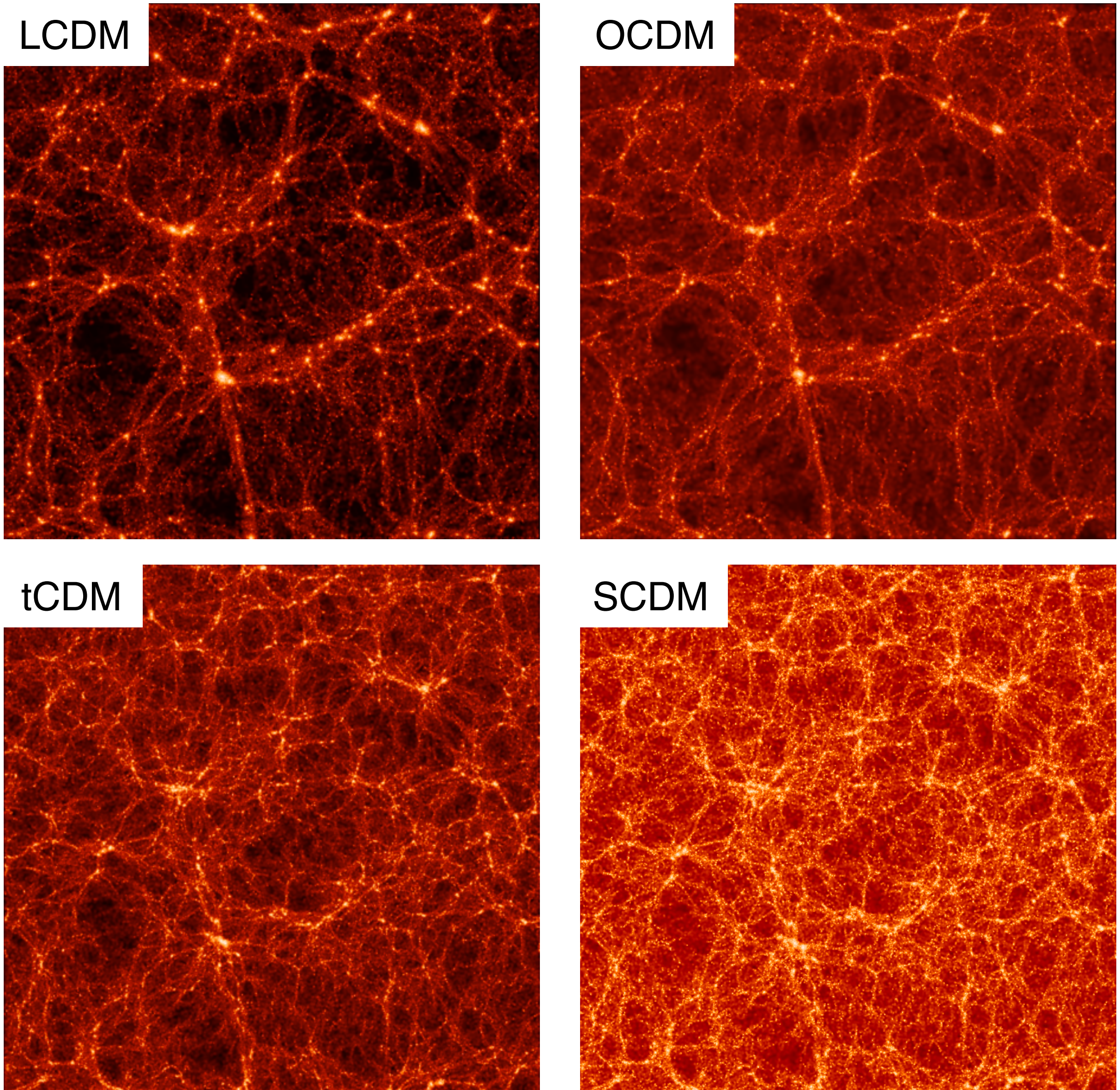


The power spectrum turn-over



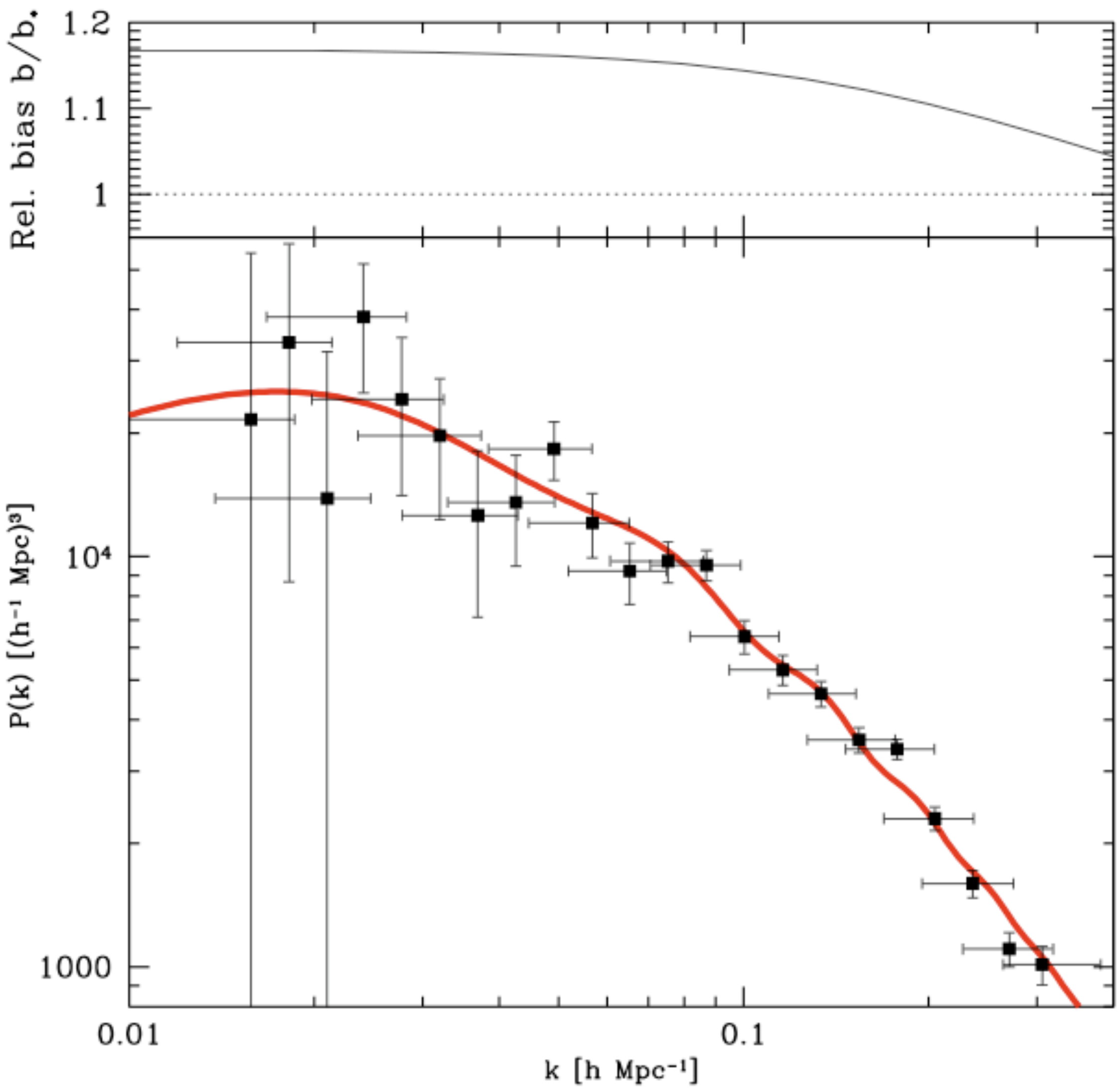
Amplitude of effect depends on matter density – how long before matter-radiation equality

The shape of the power spectrum



credit: VIRGO consortium

Analysis of the SDSS DR2 main galaxies

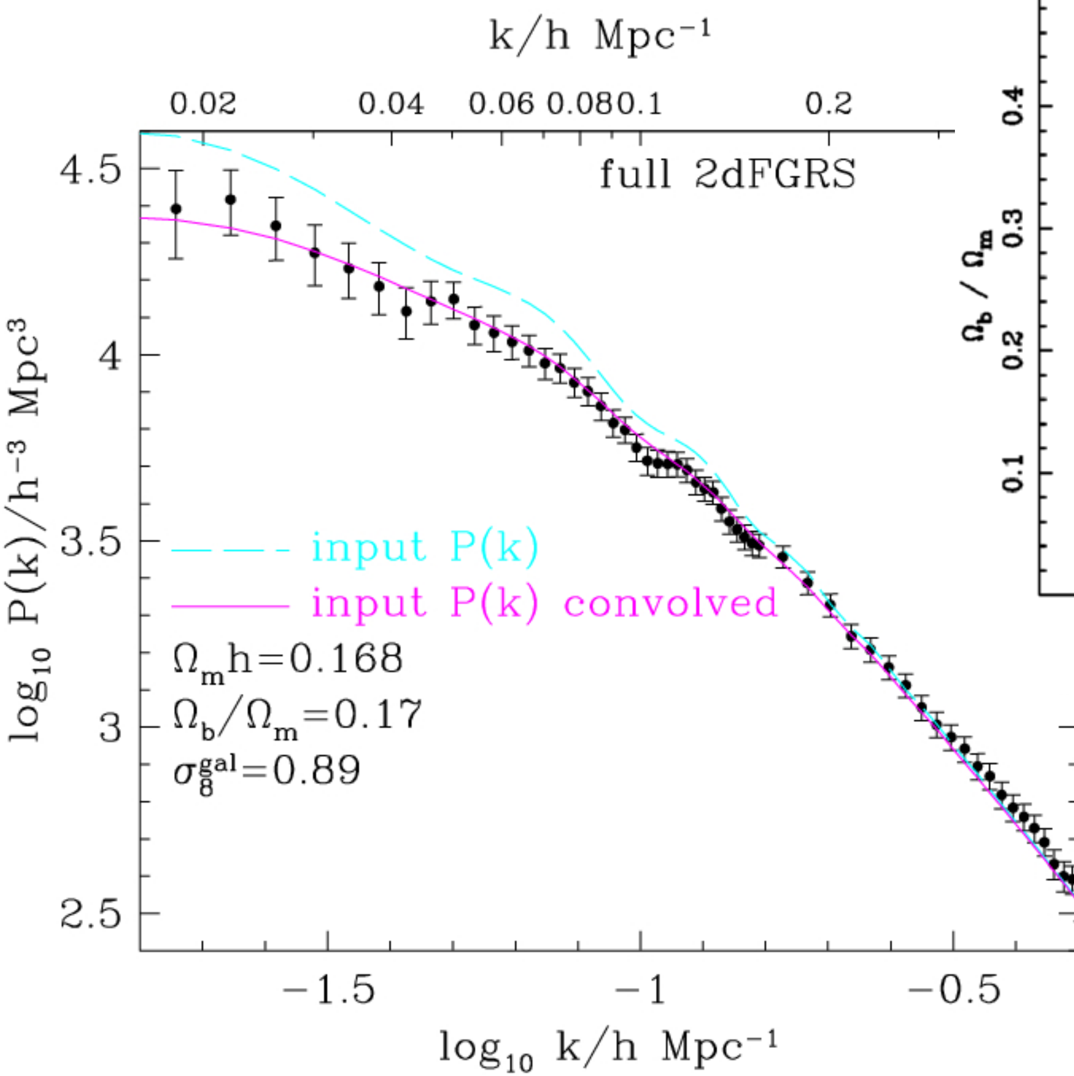


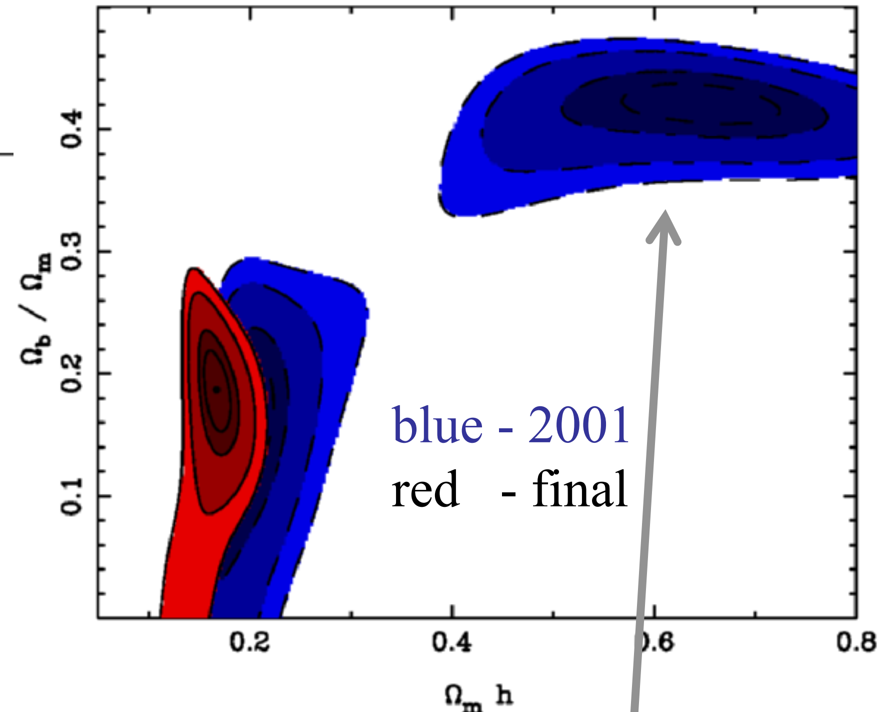
Recovered power spectrum from early sample drawn from the Sloan Digital Sky Survey.

Correction applied for the large-scale bias evolution through the survey

Tegmark et al. 2004, arXiv:0310725

Analysis of the final 2dFGRS sample

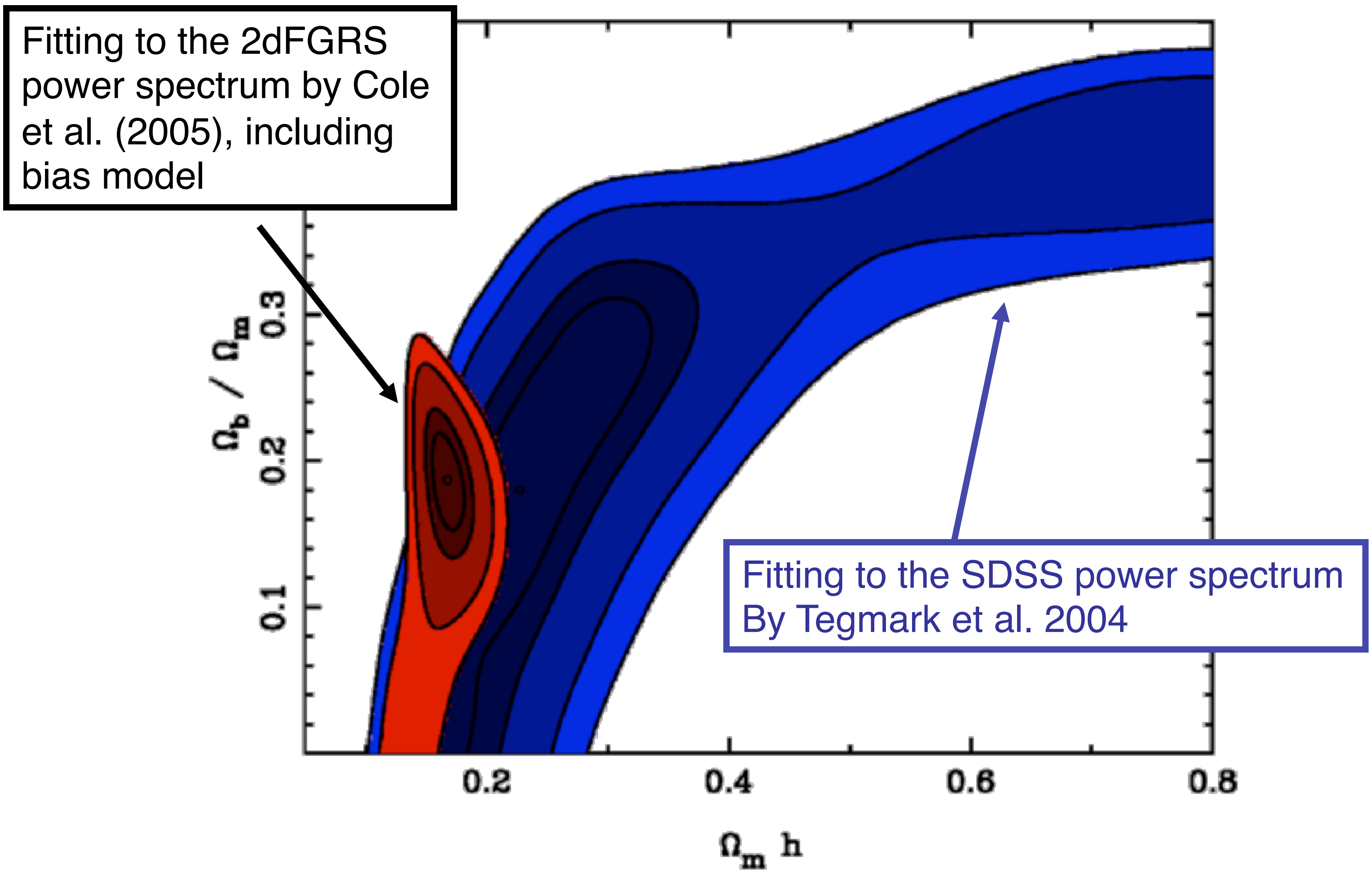




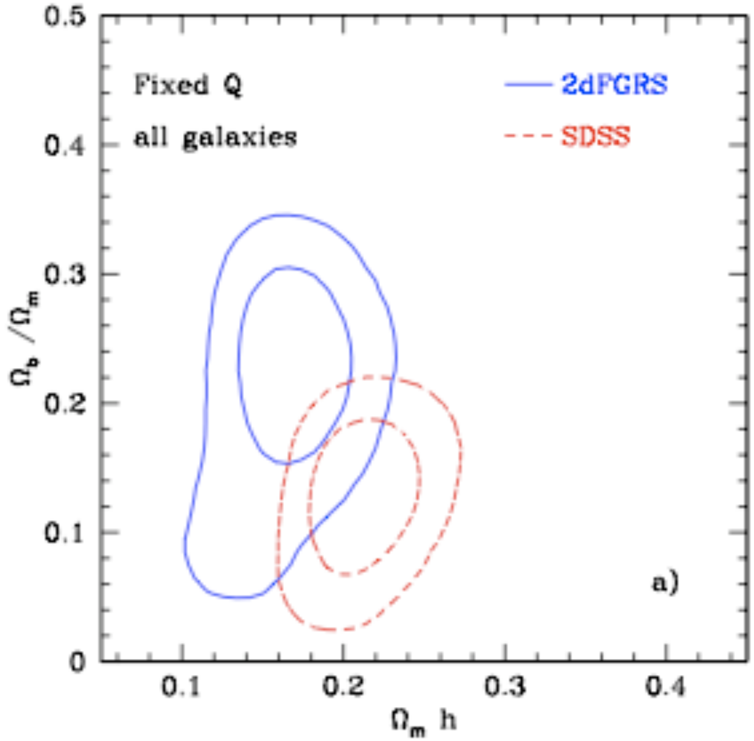
with complete survey,
only one solution
– high baryon solution
has disappeared

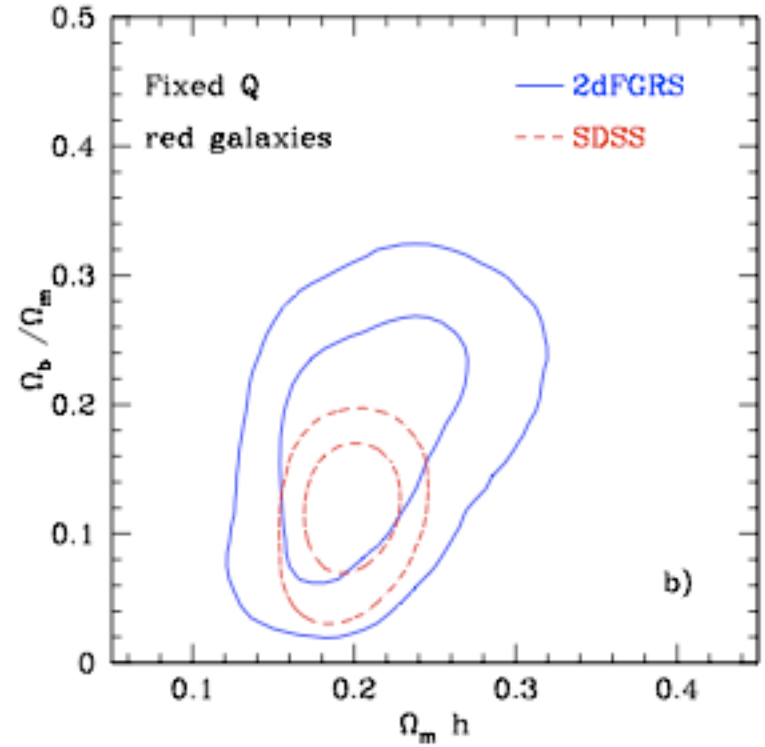
Cole et al. 2005, MNRAS, 362, 505

power spectrum shape constraints



the problem is scale-dependent bias



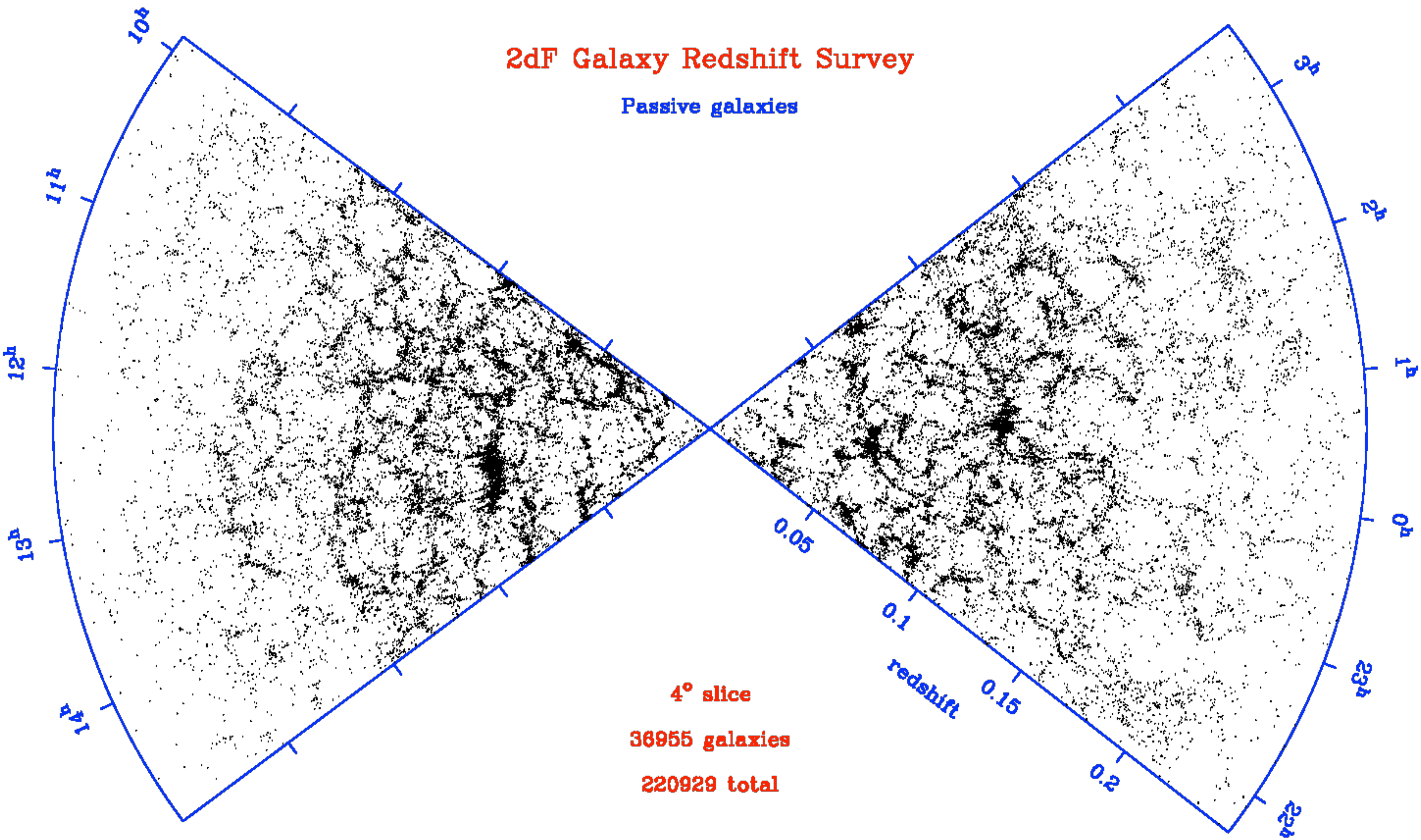


By subdividing 2dFGRS into red and blue galaxies, Sanchez & Cole also concluded that differences with SDSS were caused by scale-dependent galaxy bias

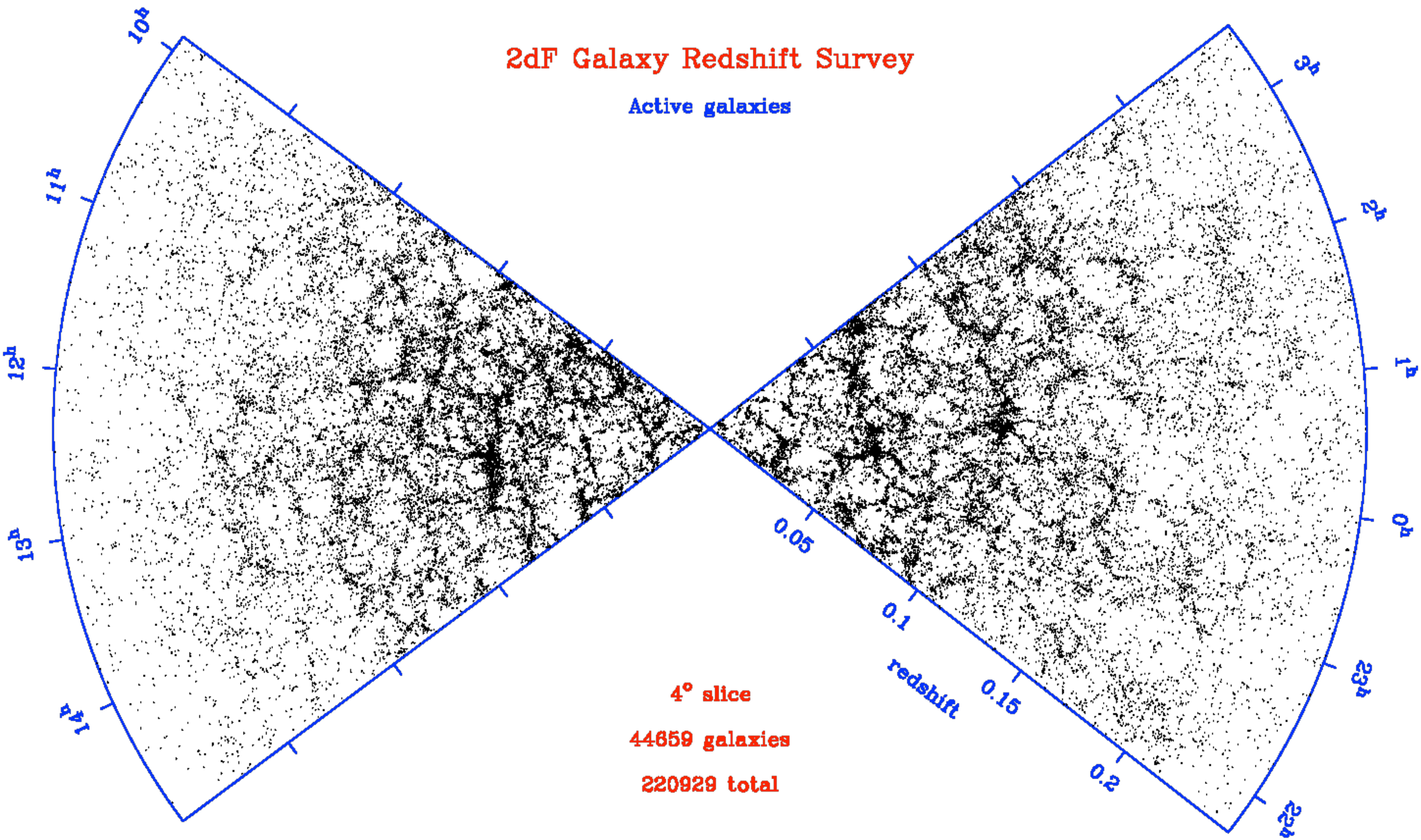
Sanchez & Cole 2007, arXiv:0708.1517

Galaxy bias

Galaxy bias : red galaxies



Galaxy bias: blue galaxies



Galaxy bias

Galaxy bias = relationship between galaxy and matter over-density fields

$$\frac{\Delta\rho_g}{\rho_g} = f\left(\frac{\Delta\rho_m}{\rho_m}\right)$$

“Spherical cow models”

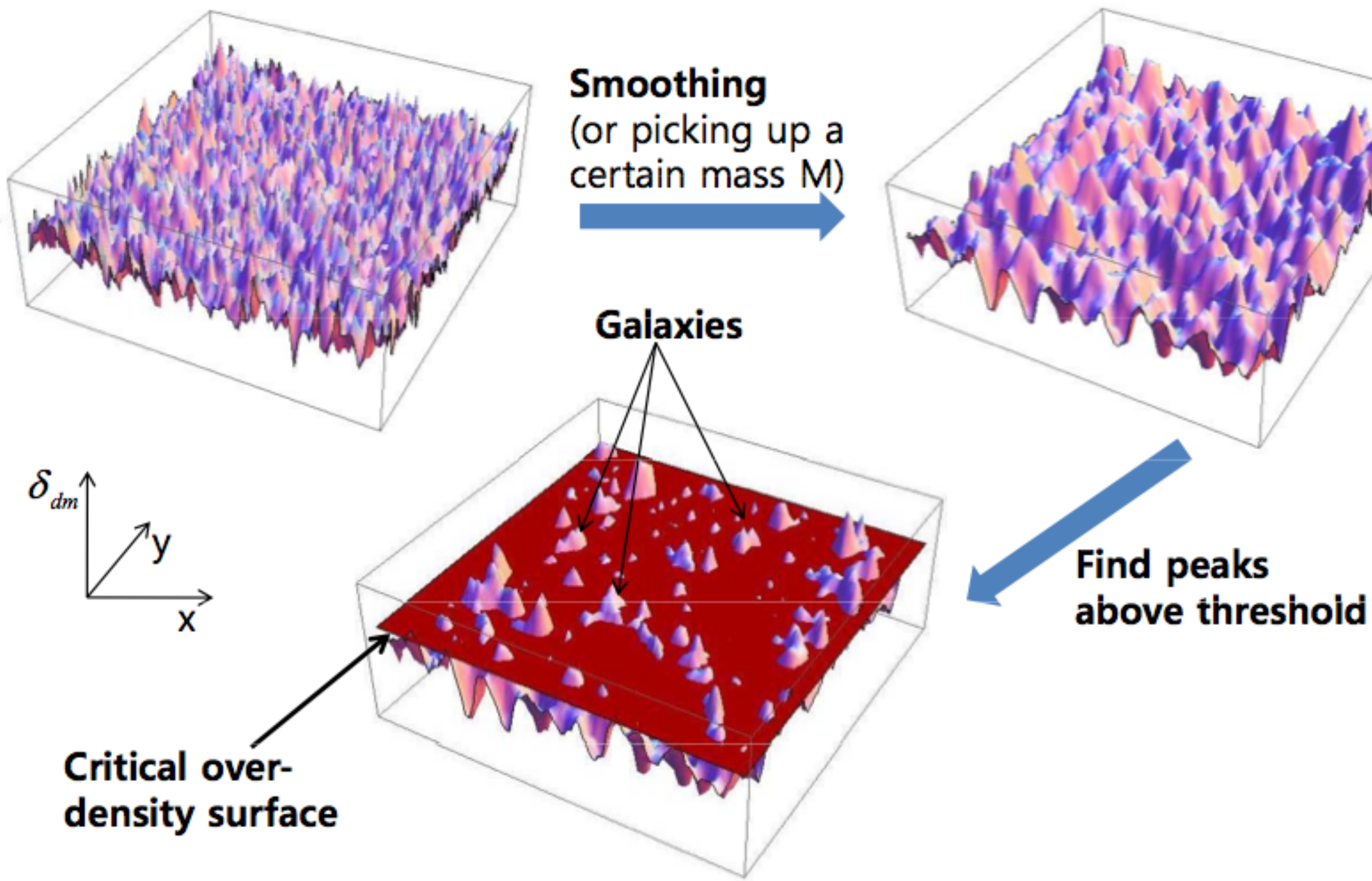
Spherical cow is a metaphor for highly simplified scientific models of complex real life phenomena.

The phrase comes from a joke about theoretical physicists:

Milk production at a dairy farm was low, so the farmer wrote to the local university, asking for help. A multidisciplinary team of professors was assembled, headed by a theoretical physicist, and two weeks of intensive on-site investigation took place. The scholars then returned to the university, where the task of writing the report was left to the team leader. Shortly thereafter the physicist returned to the farm, saying to the farmer "I have the solution, but it only works in the case of spherical cows in a vacuum." … at which point the farmer went back to his work.

wikipedia

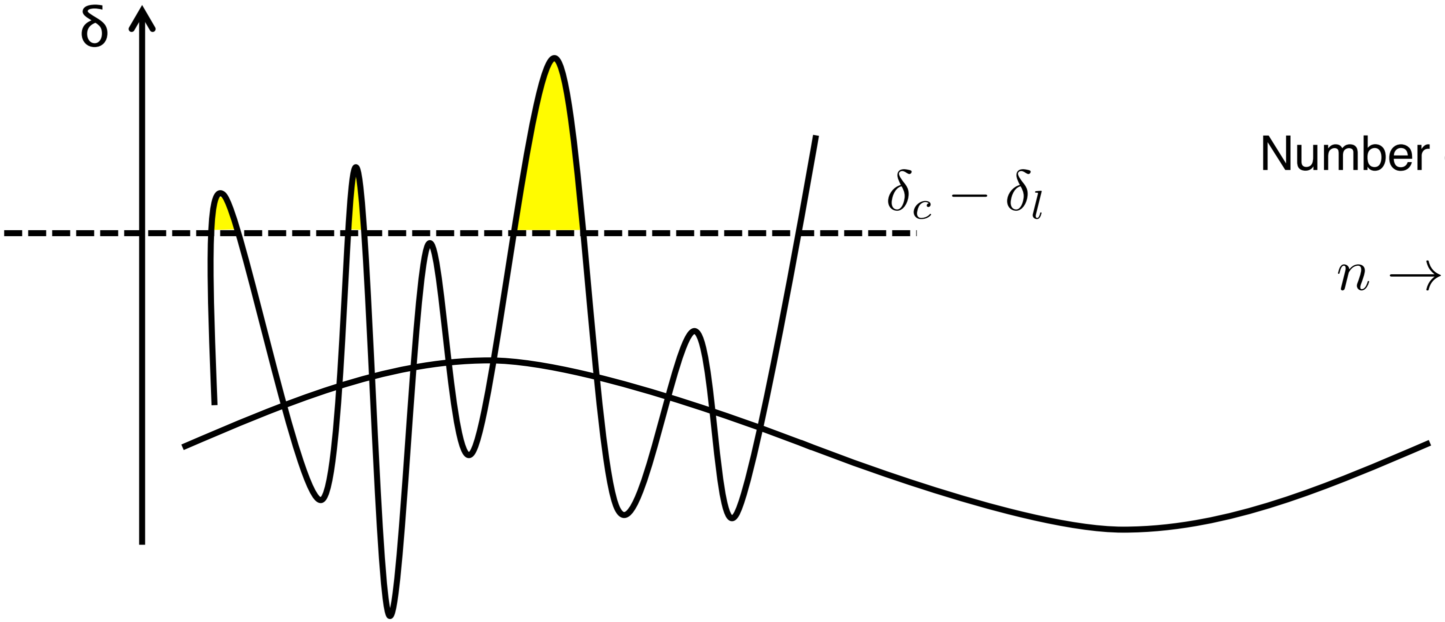
Finding galaxies (2D example: peaks)



Plot stolen from: Donghui Jeong

Peak-background split bias model

Halo formation much easier with additional long-wavelength fluctuation



Number density of halos

$$n \rightarrow n - \frac{dn}{d\delta_c}\delta_l$$

Directly from the
large-scale mode

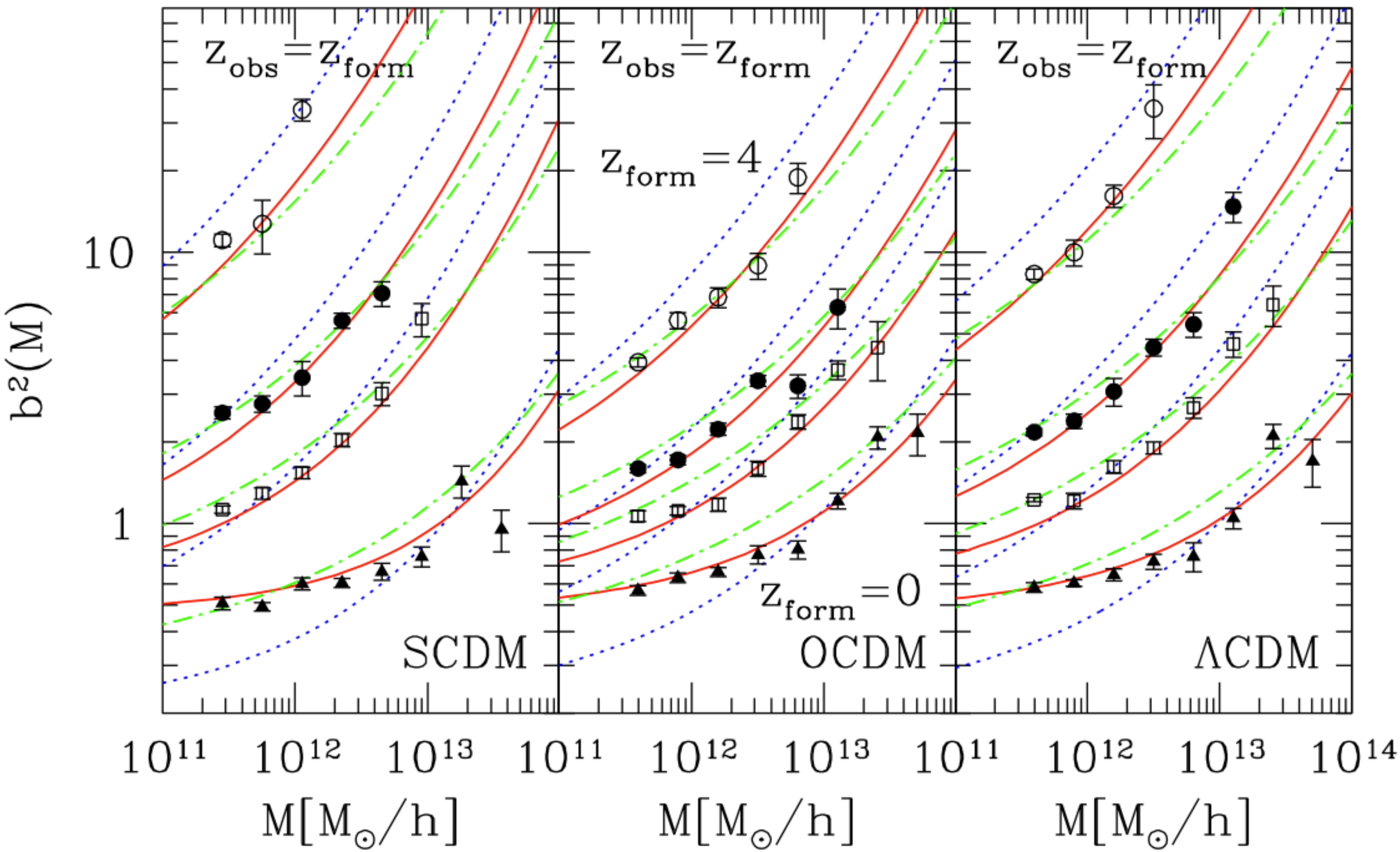
Leads to a revised density $(1+\delta_{\rm new}) = \left(1 + \frac{\Delta n}{n}\right)(1+\delta_l)$

From the change in
Number of haloes

To first order, this leads to a bias

$$\delta_{\rm new} = \left(\delta_l + \frac{\Delta n}{n}\right) \qquad b = \frac{\delta_{\rm new}}{\delta_l} = 1 + \frac{\Delta n}{n\delta_l} = 1 - \frac{d\ln n}{d\delta_c}$$

Peak-background split galaxy bias model



Sheth & Tormen 1999, arXiv:9901122

Mass function gives bias

The mass function contains information about bias!

$$\frac{\delta\rho_g}{\rho_g} = \frac{n(m,\delta_c - \delta_{dm}) - n(m,\delta_c)}{n(m,\delta_c)} = -\frac{\partial \ln n(m,\delta_c)}{\partial \delta_c}\delta_m$$

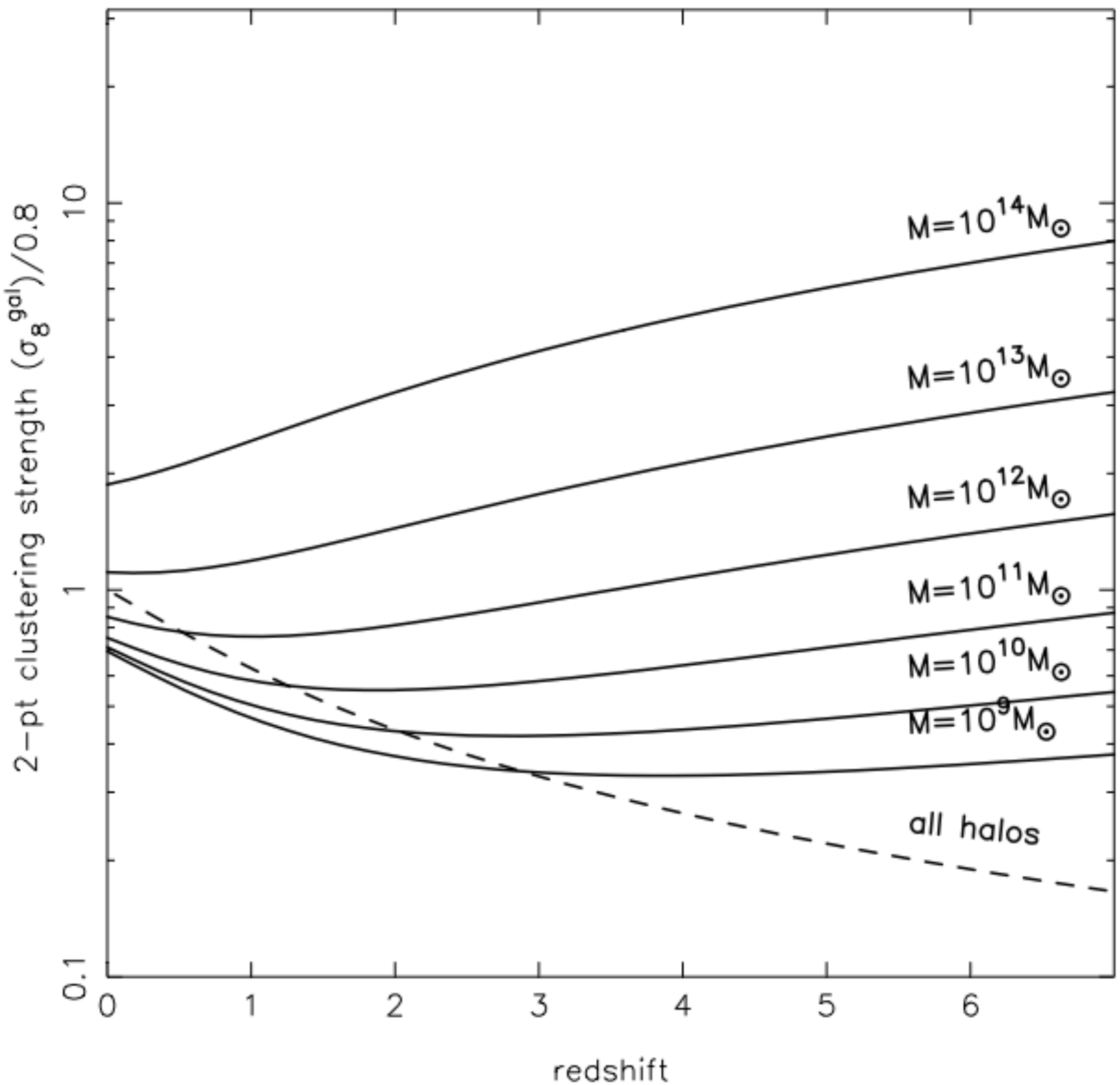
For example, the Press-Schechter mass function gives a bias

$$n(m,\delta_c) = -\frac{2\hat{\rho}}{\sqrt{2\pi}m^2}\frac{d\ln\sigma_m^2}{d\ln m}\frac{\delta_c}{\sigma_m}\exp\left[-\frac{\delta_c^2}{2\sigma_m^2}\right]$$

$$\frac{\delta\rho_g}{\rho_g} = \left(\frac{\delta_c}{\sigma_m^2} - \frac{1}{\delta_c}\right)\frac{\delta\rho_m}{\rho_m}$$

Thus bias tells you halo mass!

large-scale bias <=> halo mass



Peak-background split galaxy bias

Local bias

$$\delta_g(z,k) = b(z,k)\delta_m(z,k)$$

Scale-independent bias

$$\delta_g(z,k) = b(z)\delta_m(z,k)$$

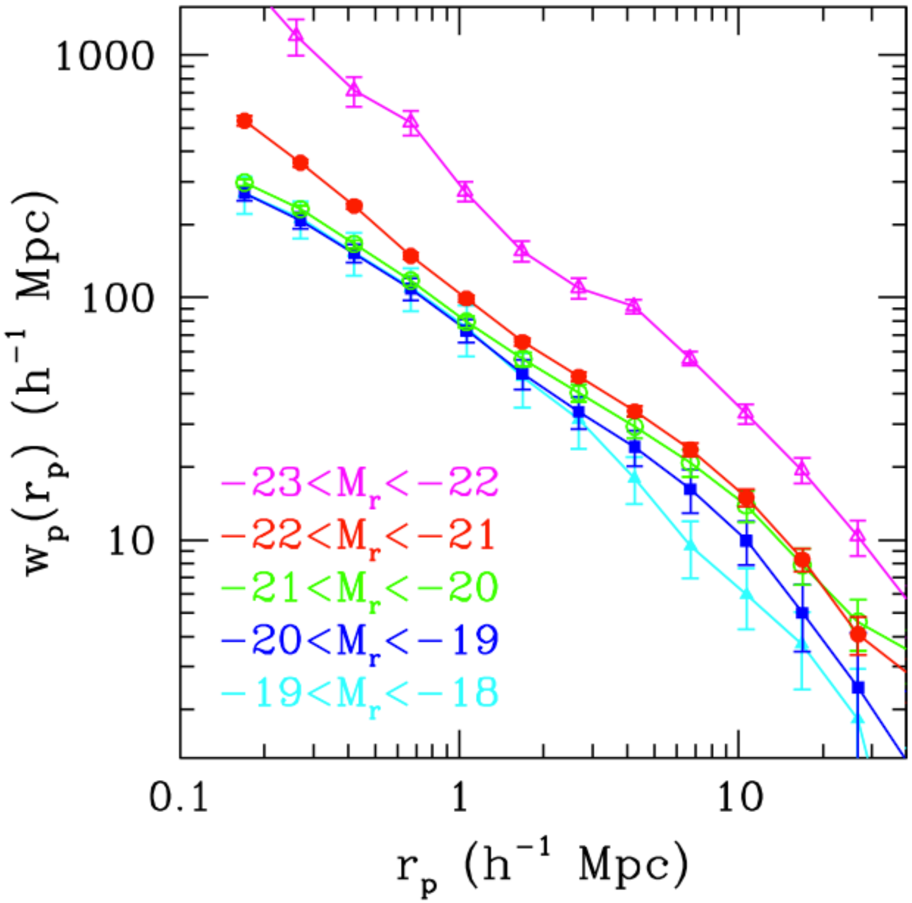
Translates to a perfect degeneracy in the amplitude of the power spectrum or correlation function

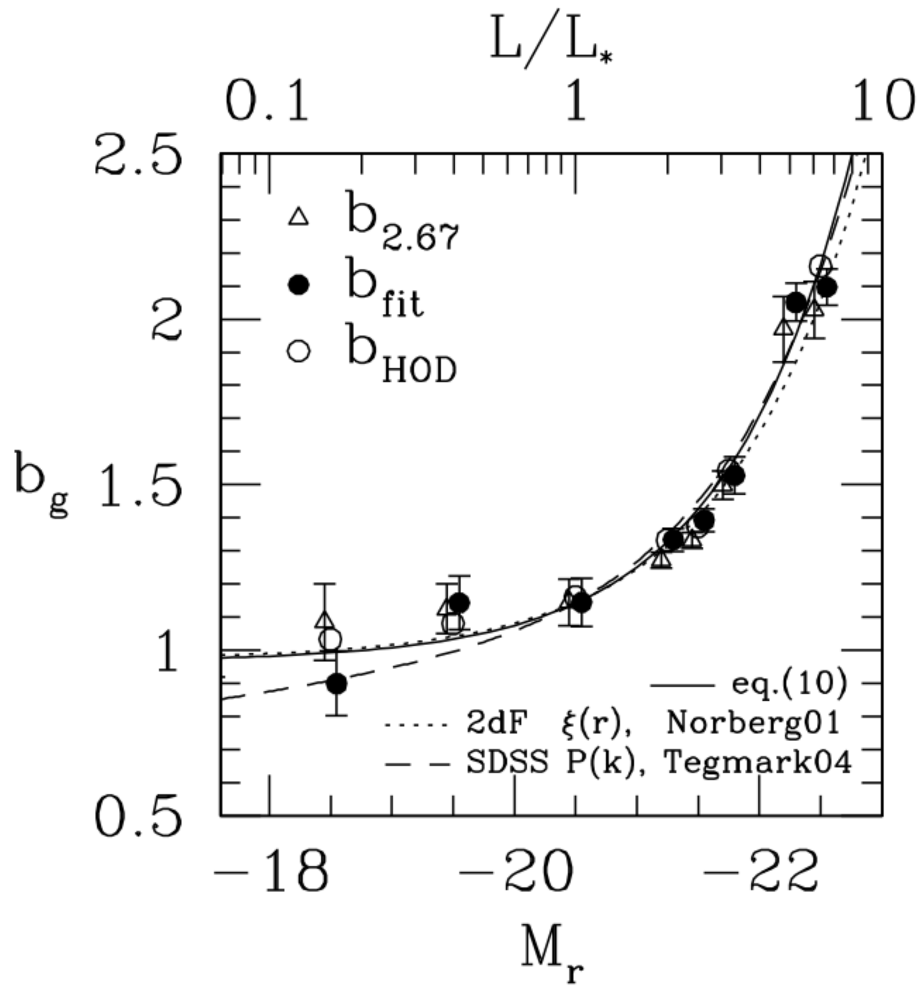
$$P_g(z,k) = b^2(z)P_m(z,k)$$

Theoretical evidence for this model comes from the peak-background split model

More powerful ways of quantifying “galaxy bias” exist, such as the “halo model”, which links a large-scale local bias model, with a small-scale “inside halo” form

Galaxy bias observations

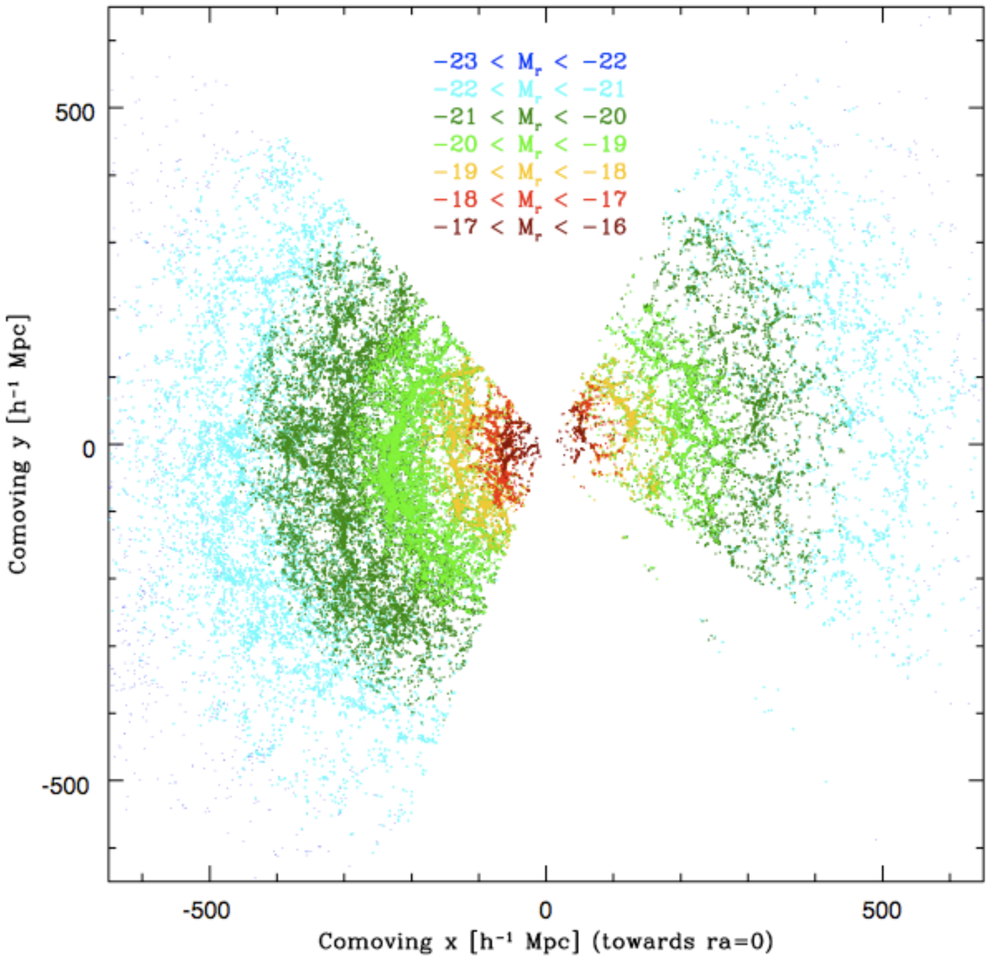




Zehavi et al. 2010, arXiv:1005.2413

Galaxy bias in surveys

In general, galaxy surveys do not produce homogeneous samples of galaxies

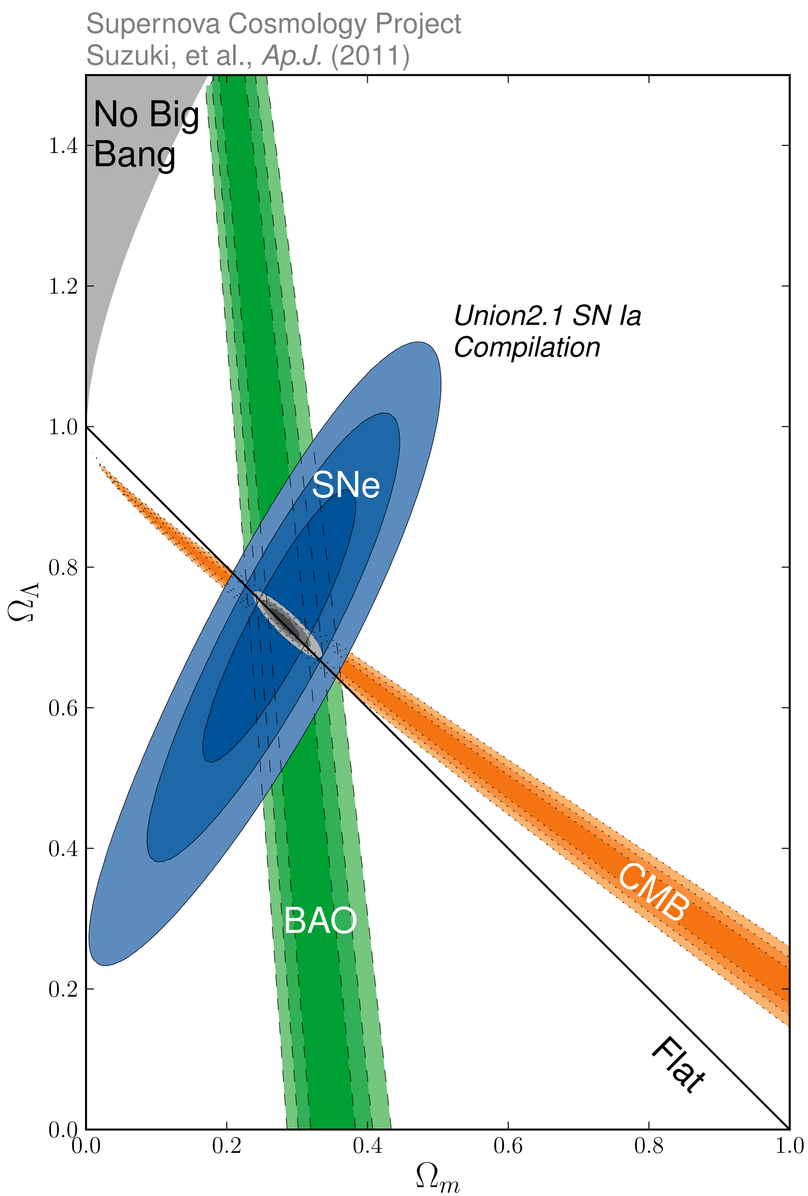


Galaxy luminosity varies systematically

Galaxy density varies systematically

To test differences caused only by galaxy properties, need to define "volume limited sub-catalogs"

Goal of this lecture



How did we get here?

Supernovae tell us we live in a lambda dominated Universe

BAO tell us we live in a low matter density Universe