The large structure of the universe: Galaxy Redshift Surveys

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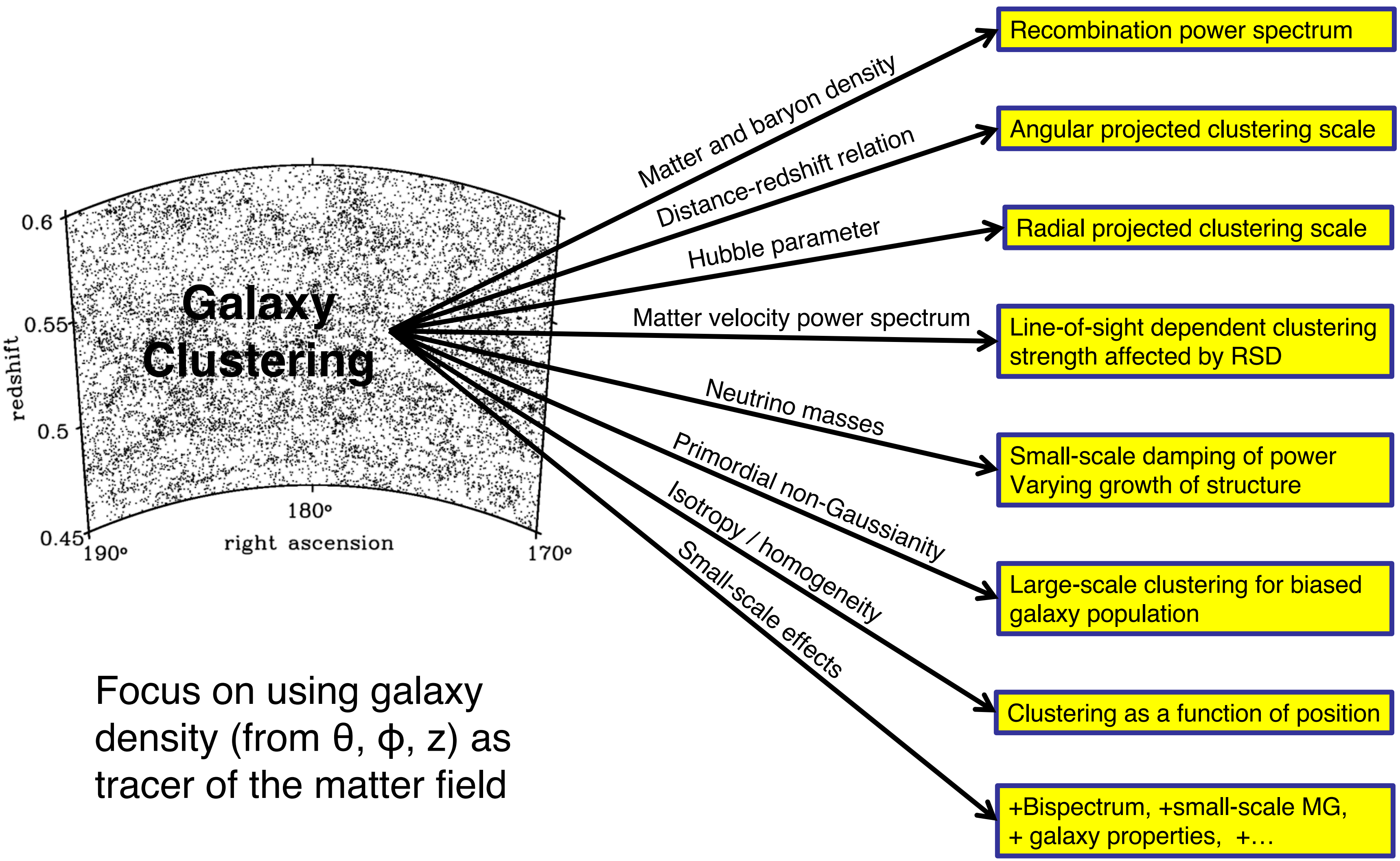
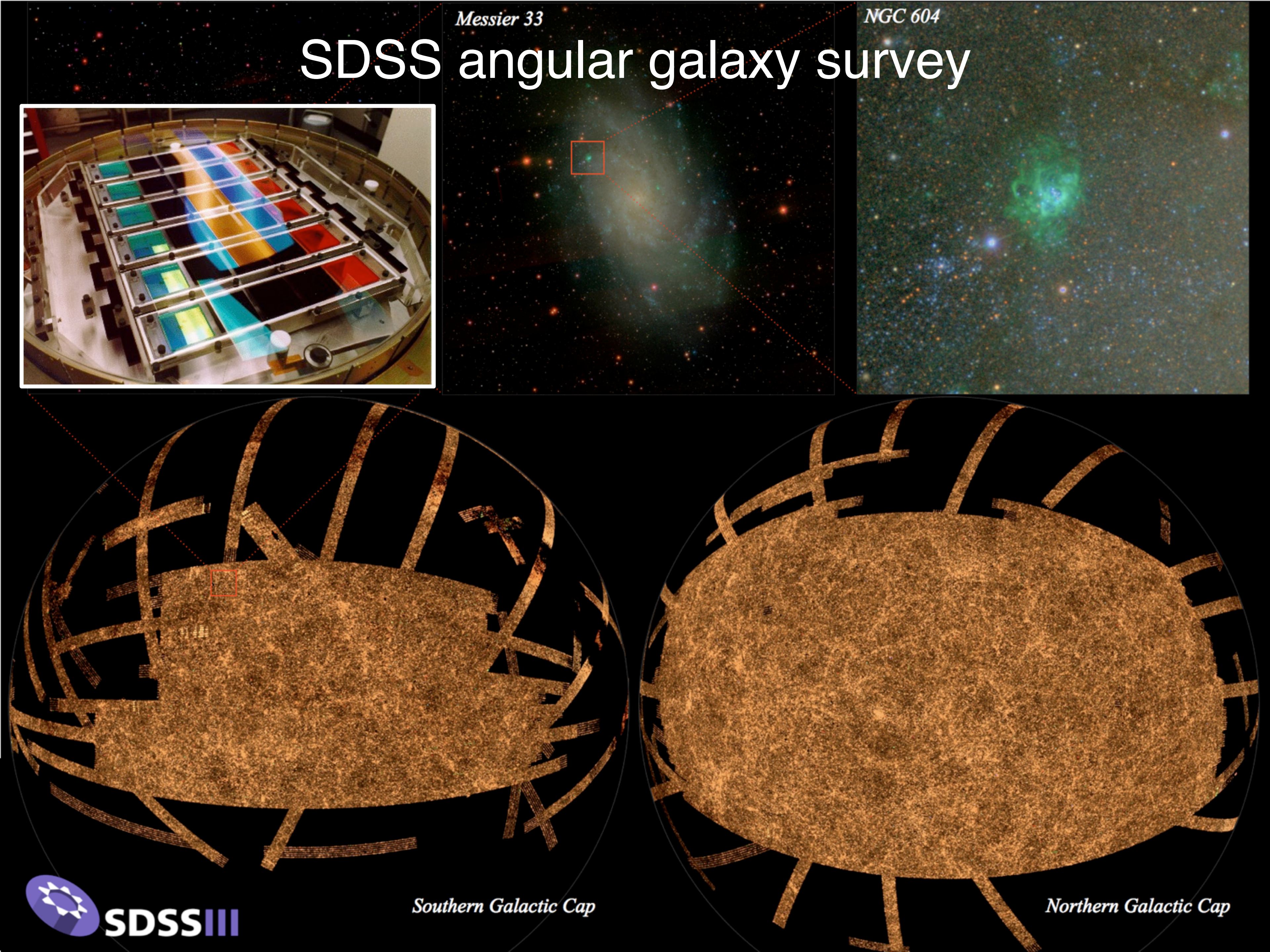
Cosmology from galaxy surveys



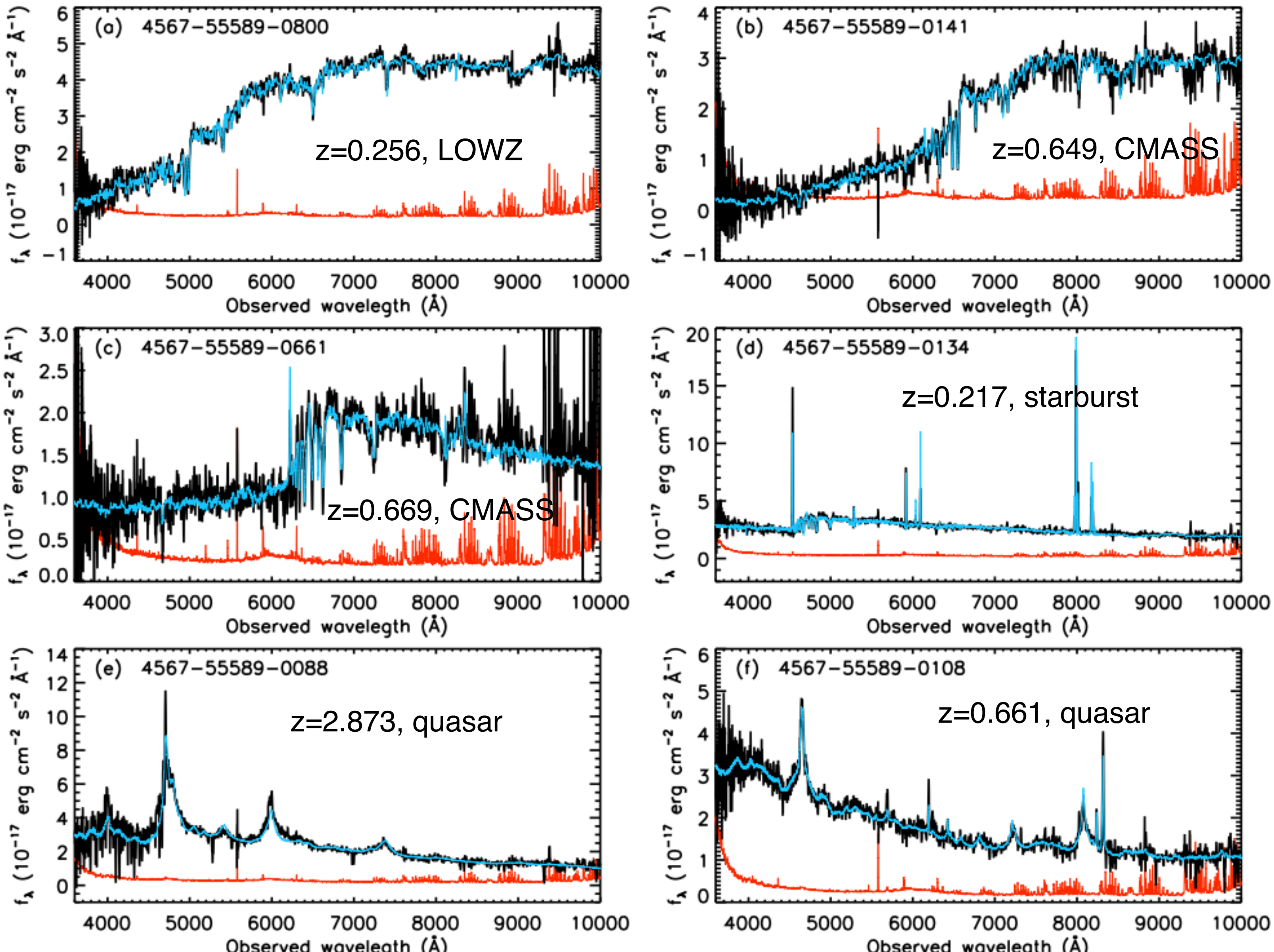
Focus on using galaxy density (from θ, ϕ, z) as tracer of the matter field

Galaxy surveys

SDSS angular galaxy survey



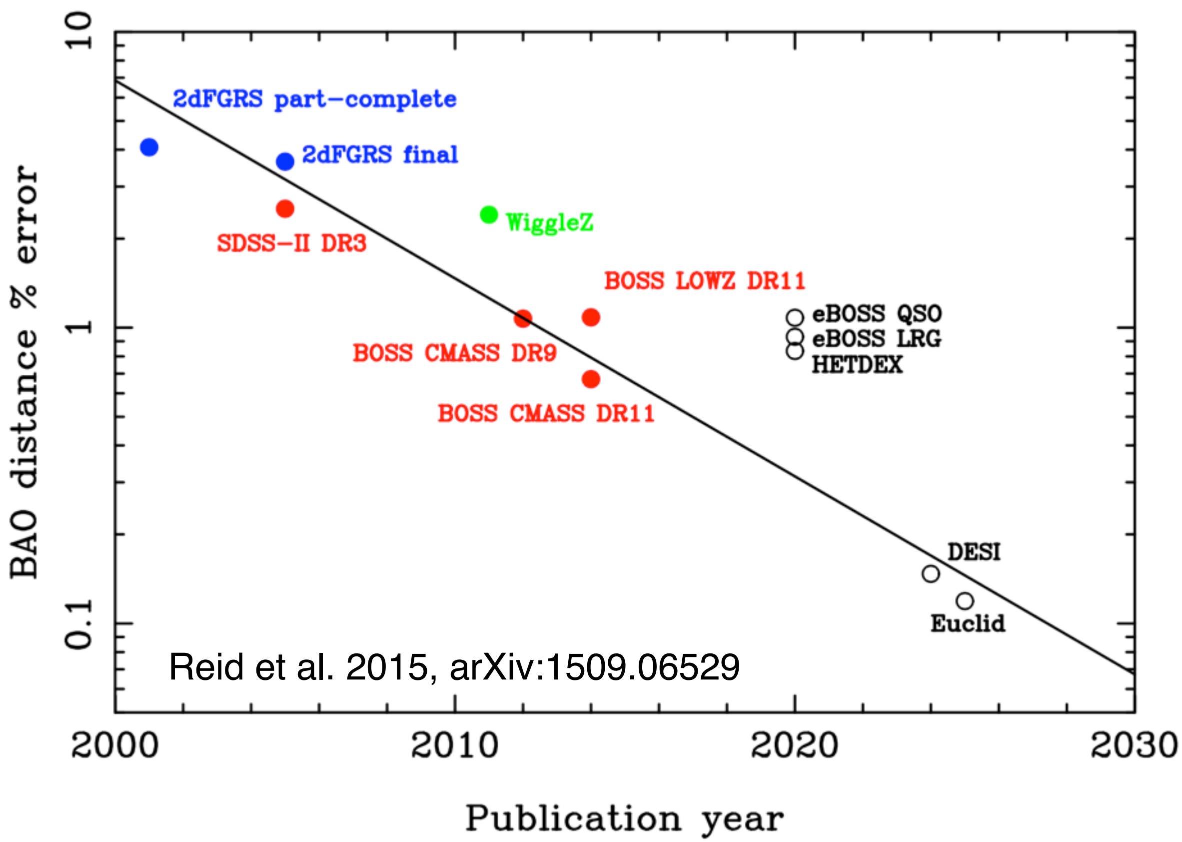
Spectra gives recession velocities



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

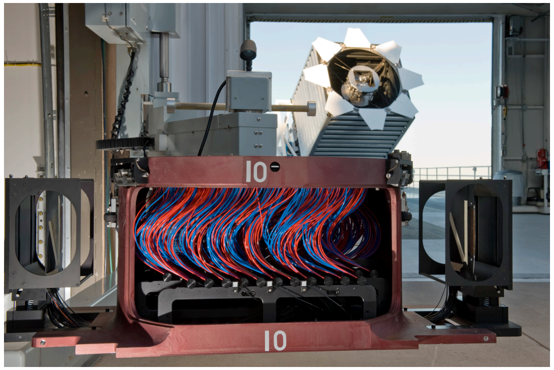
1970	x100
1990	x2
1995	±0.4
1998	±0.2
1999	±0.1
2002	±0.05
2003	±0.03
2009	±0.01
2012	±0.002

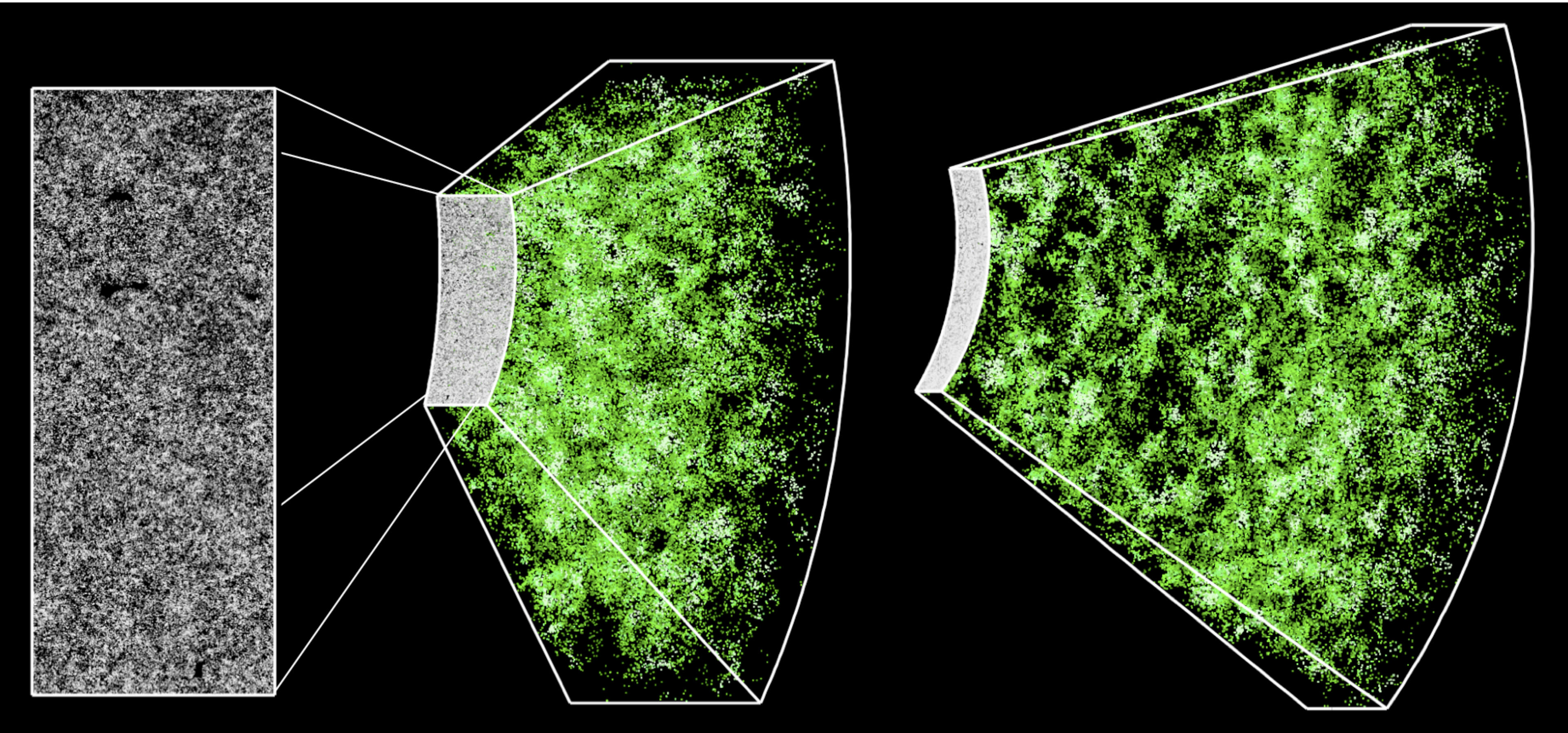
Driven by the development of instrumentation

The BOSS galaxy survey

- Survey now complete, with data taken over 5 years (2009-2014)
- Redshifts for 1,145,874 galaxies
- Data Release 12 galaxy catalogues now available:

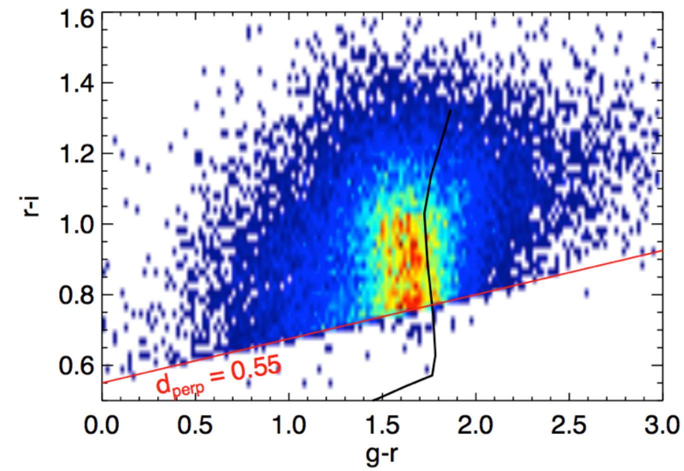
    http://data.sdss3.org/sas/dr12/boss/lss/

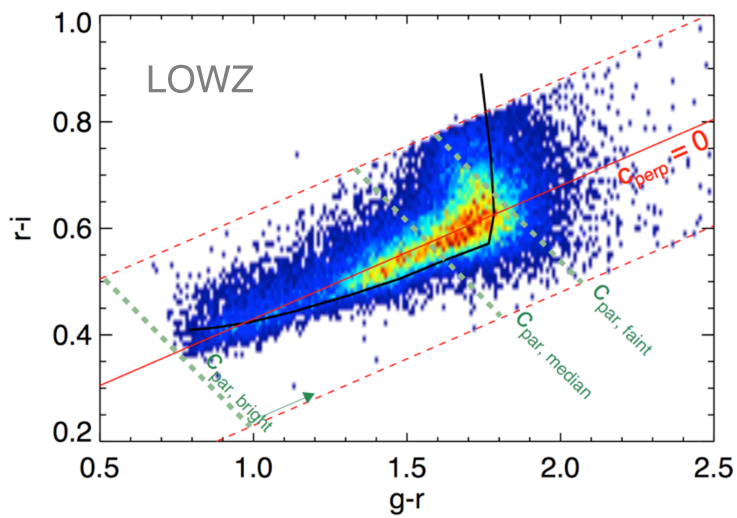


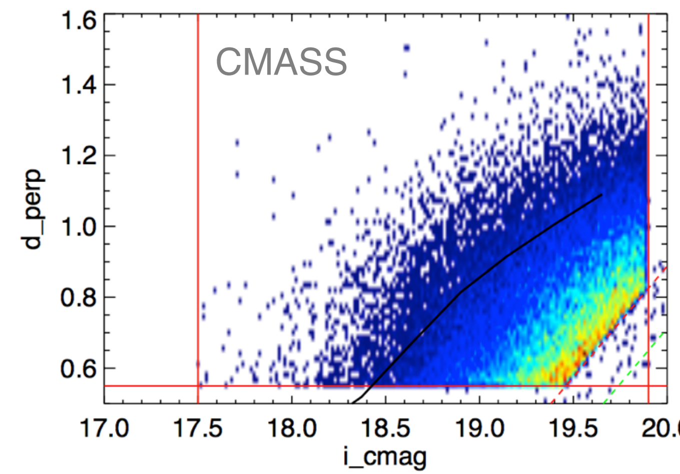


BOSS Data Release 12 galaxies

- Two galaxy samples targeted: LOWZ and CMASS
- Colour cuts to select old, massive galaxies for easy redshift measurement and high bias
- Based on locus of passive galaxies
- CMASS broader (in colour) than LOWZ with a cut
  $d_\perp = (r_{mod} - i_{mod}) - (g_{mod} - r_{mod})/8 > 0.55$
  to select to an approximate stellar mass limit



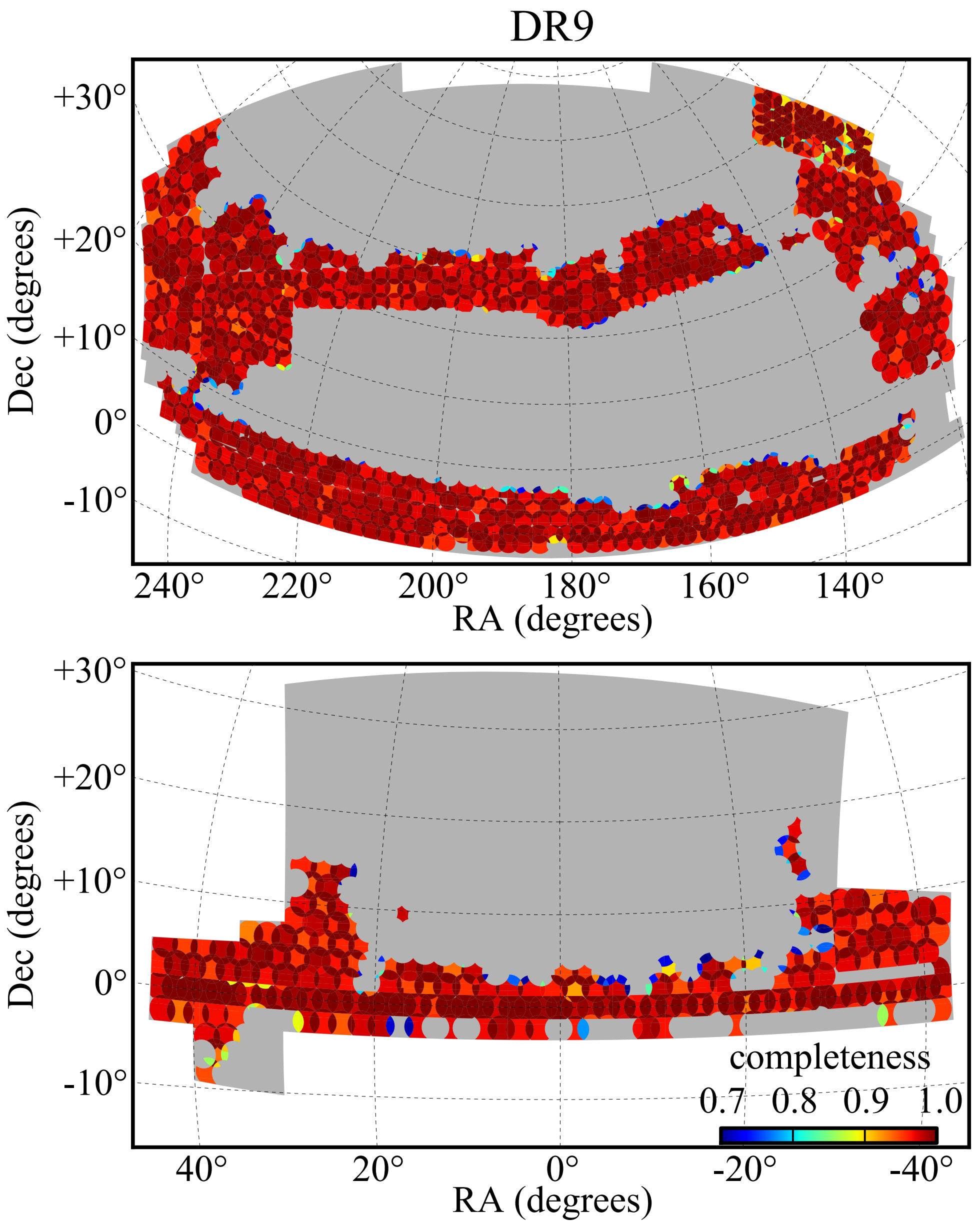




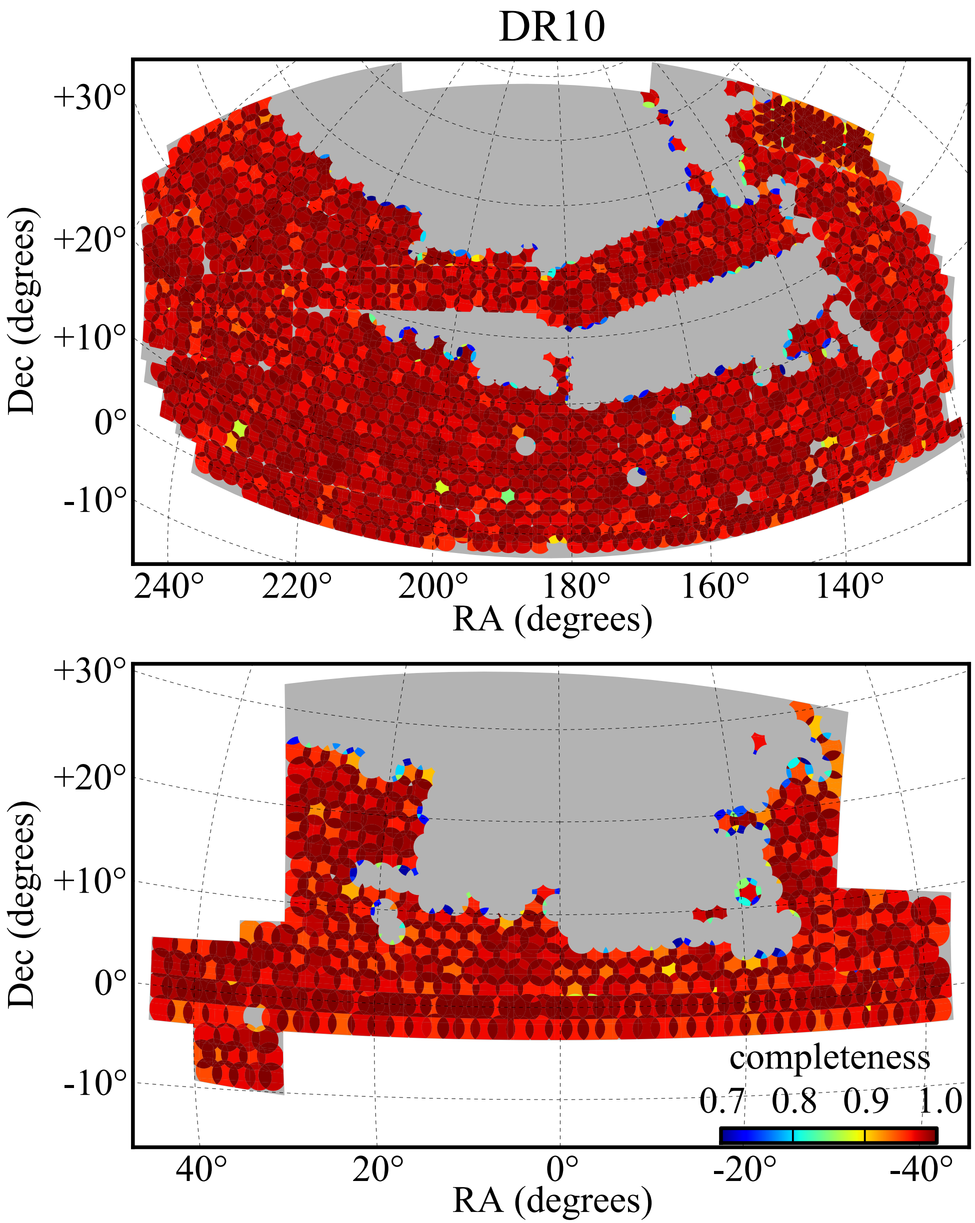
Reid et al. 2015, arXiv:1509.06529

The Sloan Digital Sky Survey telesco

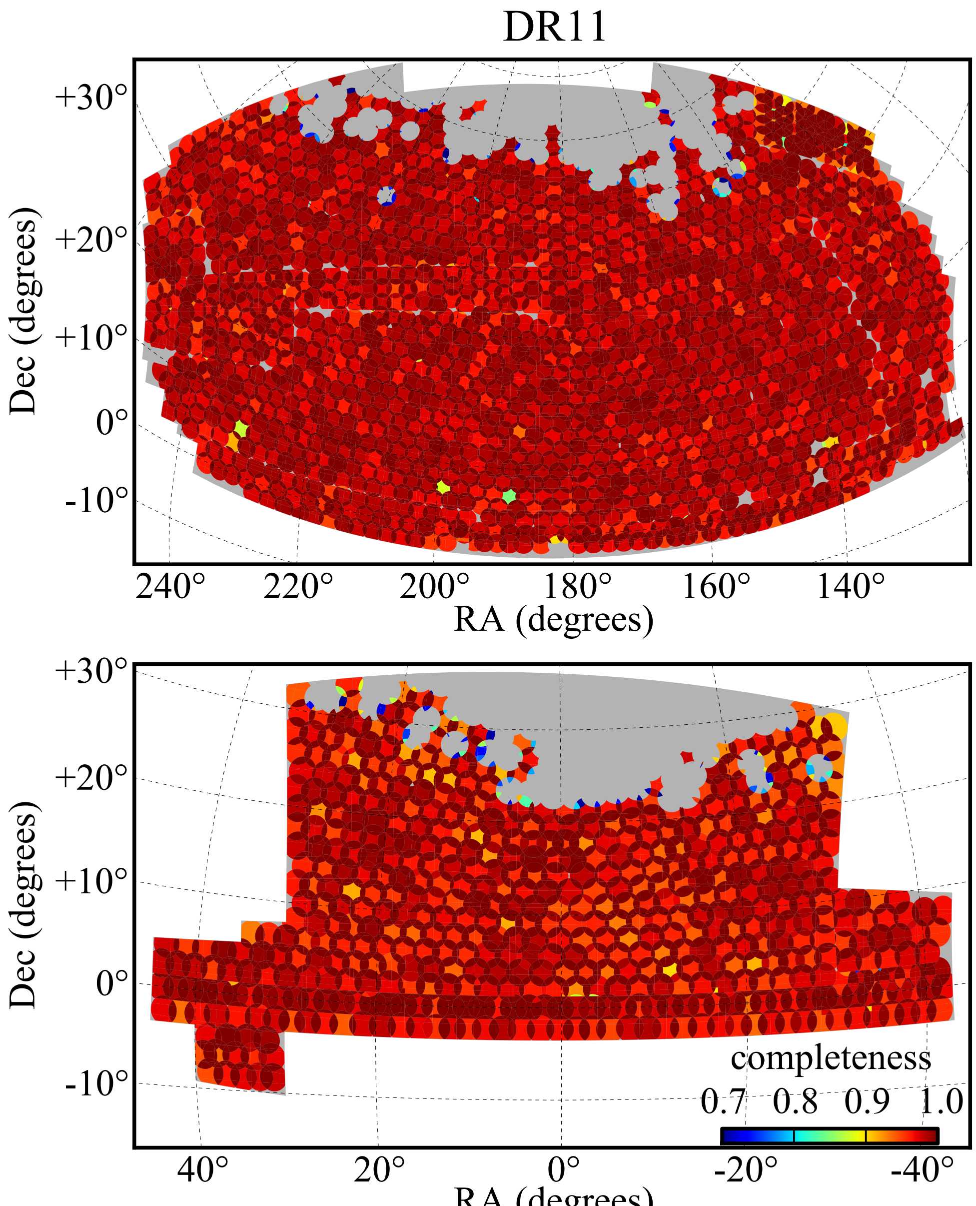
BOSS DR9 galaxies



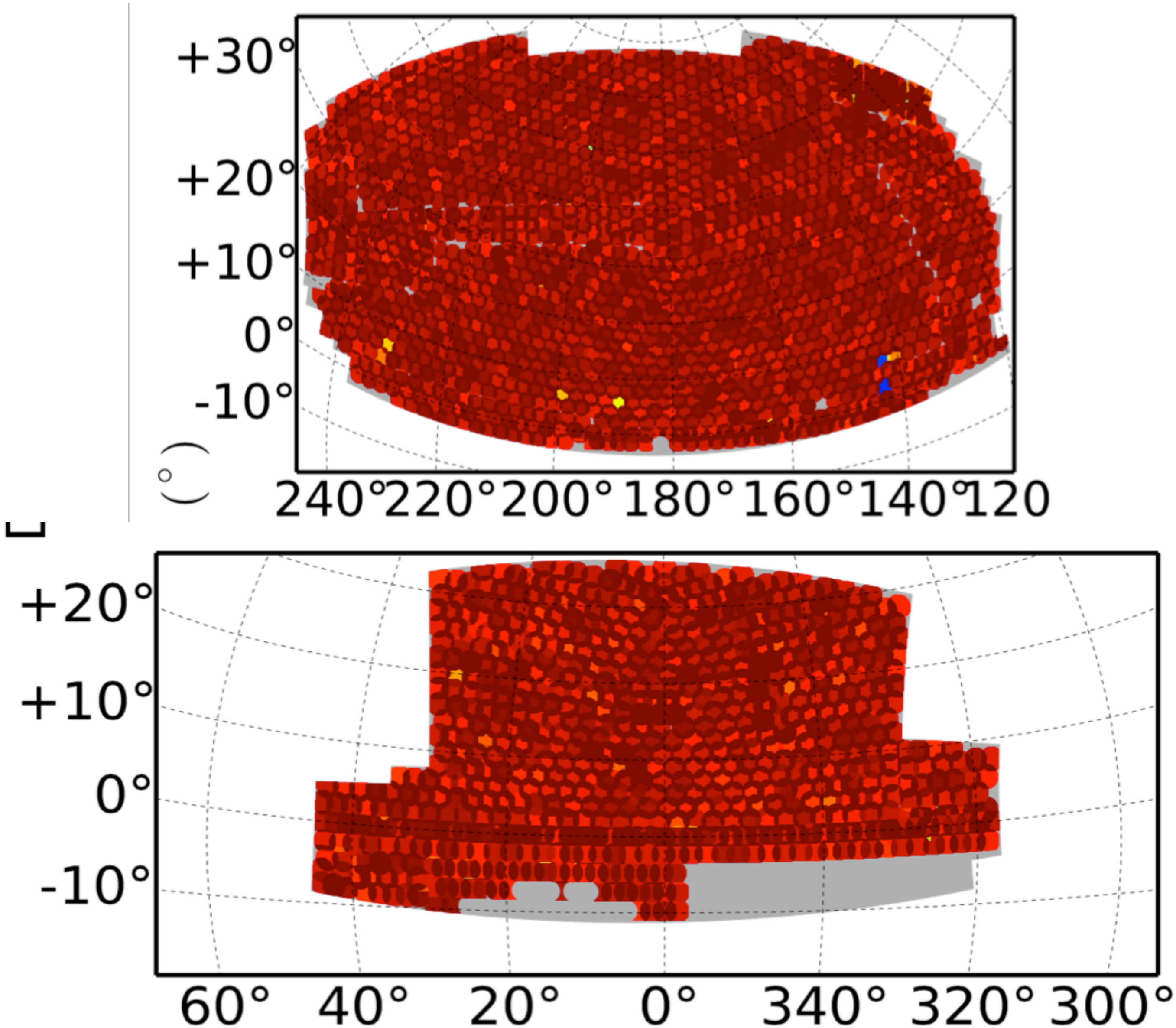
BOSS DR10 galaxies



BOSS DR11 galaxies



BOSS DR12 galaxies



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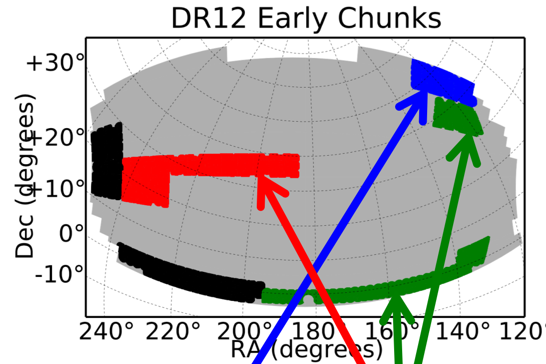
The galaxy sample



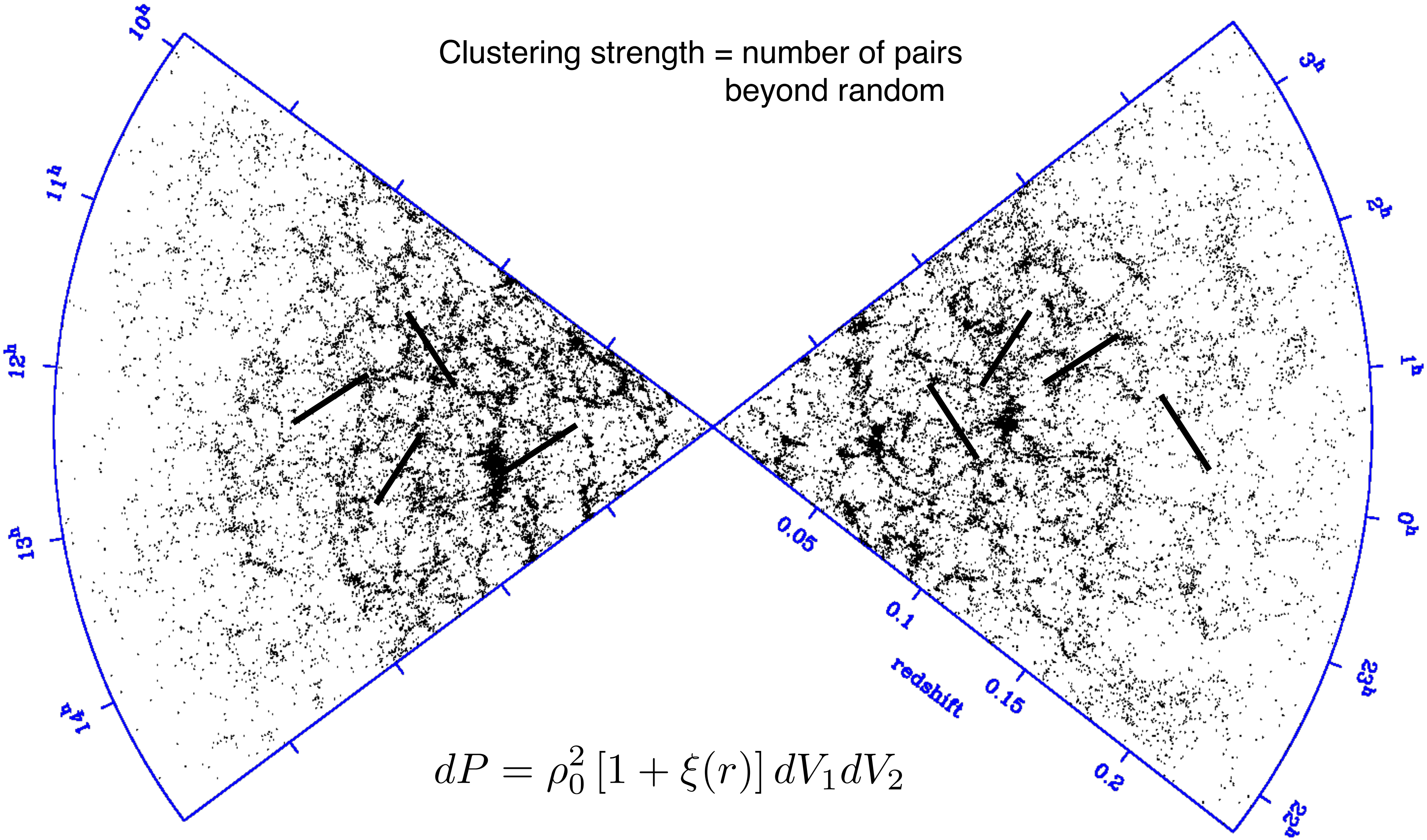
Property	NGC	SGC	total	NGC	SGC	total	NGC	NGC
Sample		CMASS			LOWZ		LOWZE2	LOWZE3
$\bar{N}_{\rm gal}$	607,357	228,990	836,347	177,336	132,191	309,527	2,985	11,195
$\bar{N}_{\rm known}$	11,449	1,841	13,290	140,444	13,073	153,517	2,730	6,371
$\bar{N}_{\rm star}$	14,556	8,262	22,818	1,043	976	2,019	24	61
$\bar{N}_{\rm fail}$	10,188	5,157	15,345	868	602	1,470	21	55
$\bar{N}_{\rm cp}$	34,151	11,163	45,314	4,459	4,422	8,881	16	167
$\bar{N}_{\rm missed}$	7,997	3,488	11,485	10,295	3,499	13,794	114	609
$\bar{N}_{\rm used}$	568,776	208,426	777,202	248,237	113,525	361,762	4,336	15,380
$\bar{N}_{\rm obs}$	632,101	242,409	874,510	179,247	133,769	313,016	3,030	11,311
$\bar{N}_{\rm targ}$	685,698	258,901	944,599	334,445	154,763	489,208	5,890	18,458
Total area (deg^2)	7,429	2,823	10,252	6,451	2,823	9,274	144	834
Veto area (deg^2)	495	263	759	431	264	695	10	55
Used area (deg^2)	6,934	2,560	9,493	6,020	2,559	8,579	134	779
Effective area (deg^2)	6,851	2,525	9,376	5,836	2,501	8,337	131	755
Targets / deg^2	98.9	101.1	99.5	55.6	60.5	57.0	43.4	23.5

Reid et al. 2015, arXiv:1509.06529

Clustering

What does "clustering" mean?

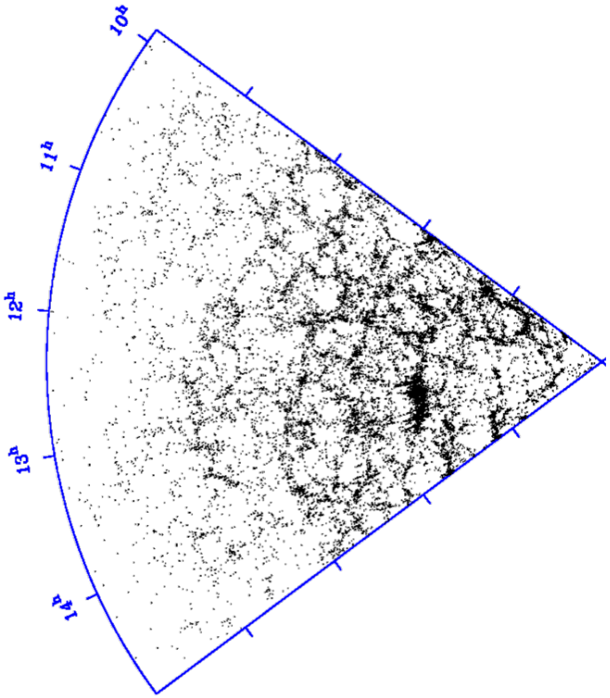
Clustering strength = number of pairs beyond random



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

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

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

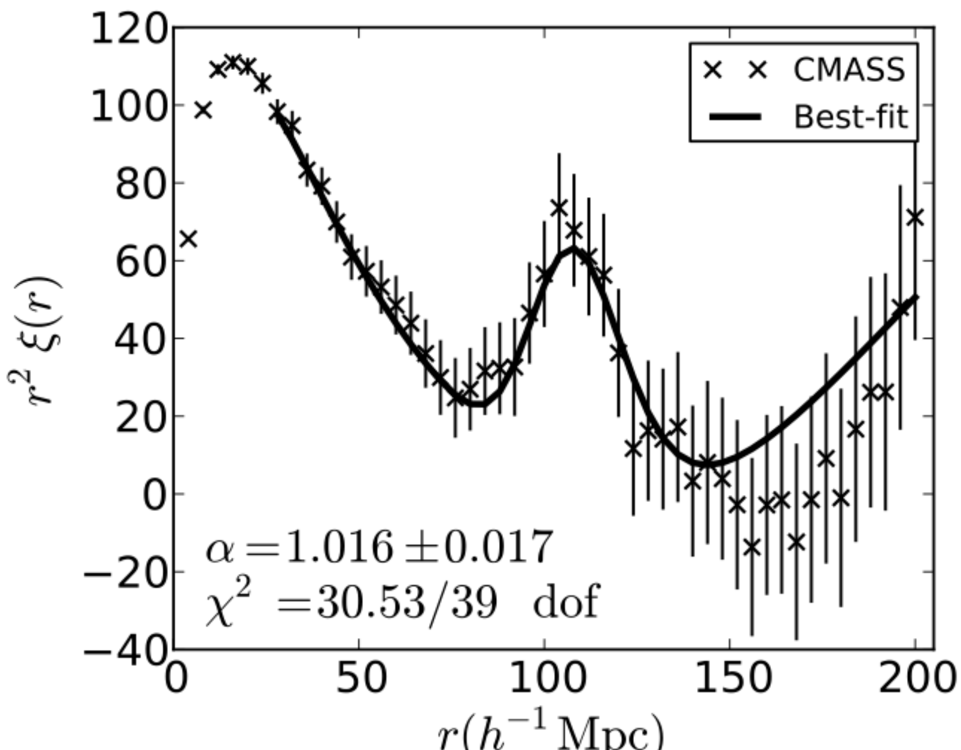
By analogy, one should think of "throwing down" Fourier modes rather than "sticks"

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

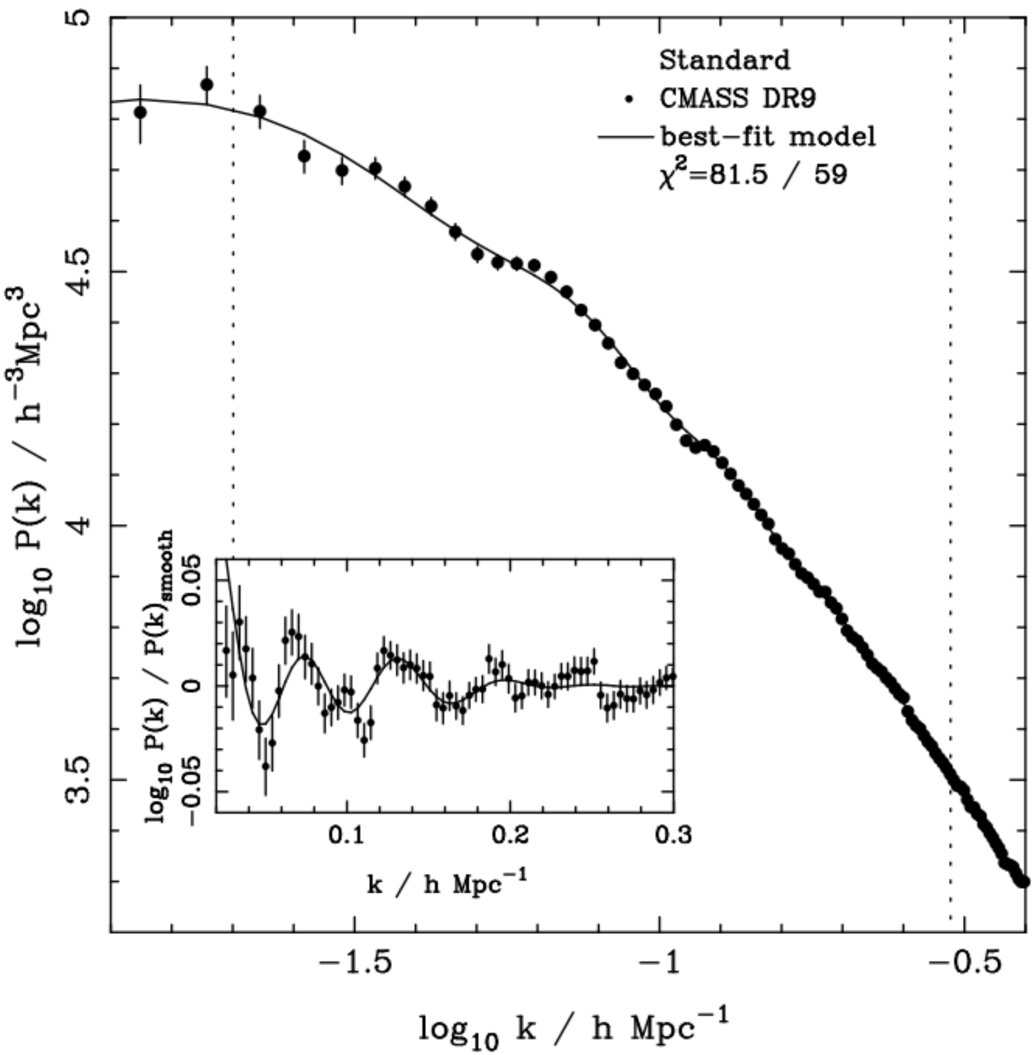


Power spectrum

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

from statistical homogeneity

from statistical isotropy

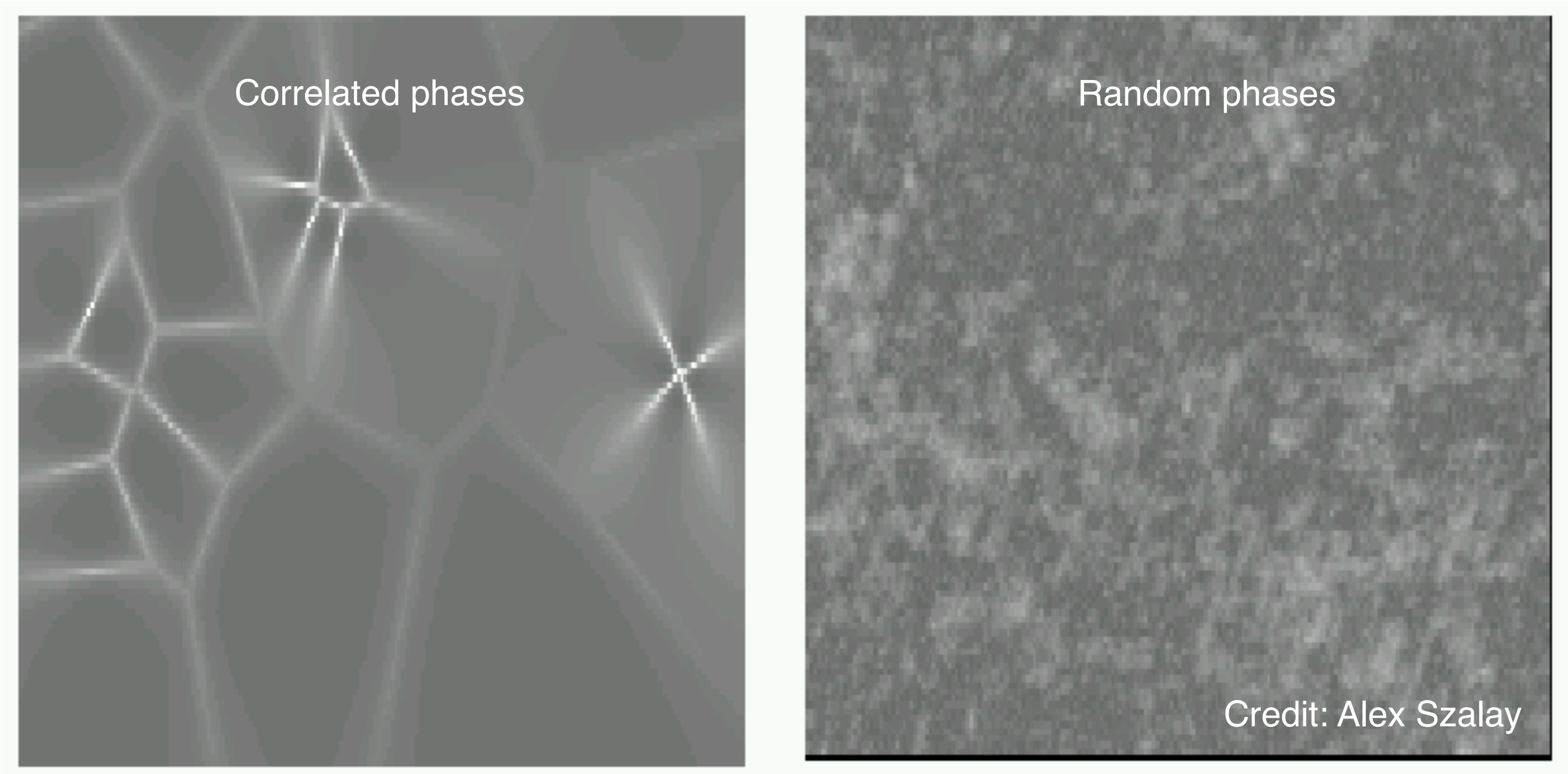


$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

Power spectrum often written in dimensionless form

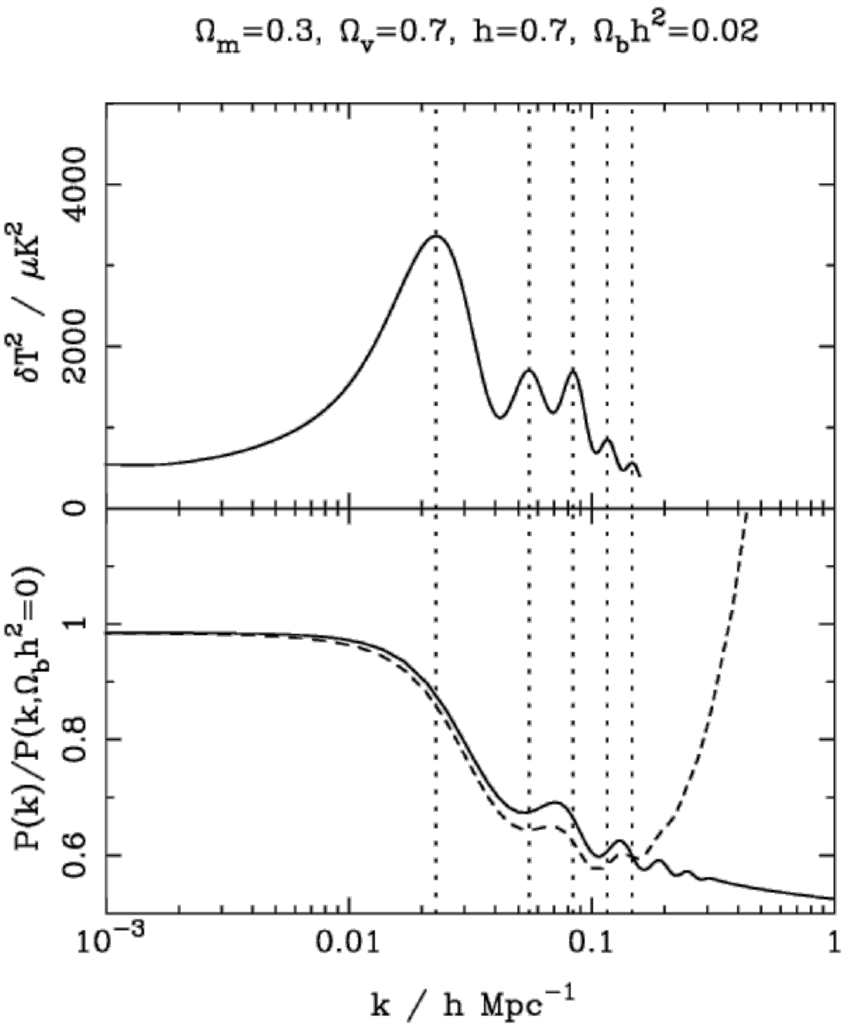
Statistically complete knowledge?

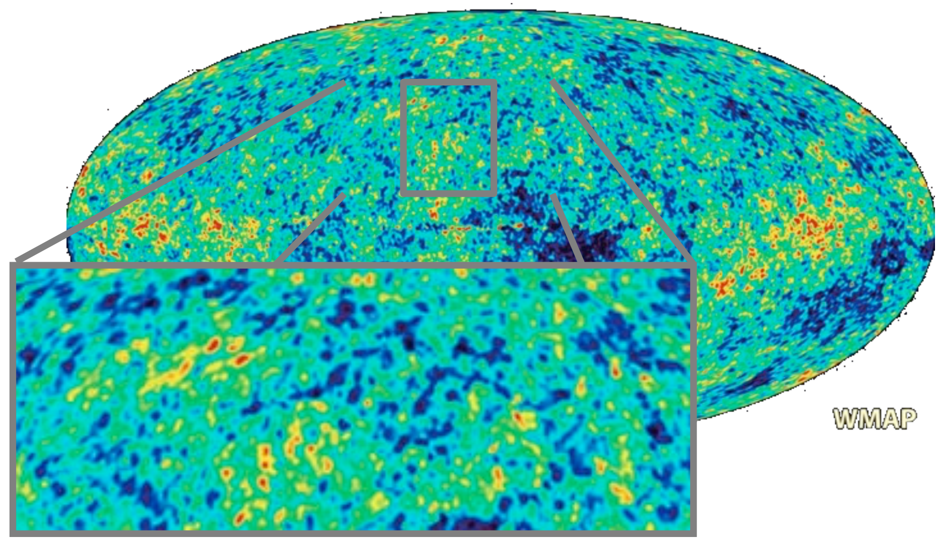
Gaussian random field: knowledge of either the correlation function or power spectrum is sufficient – they are statistically complete … but …

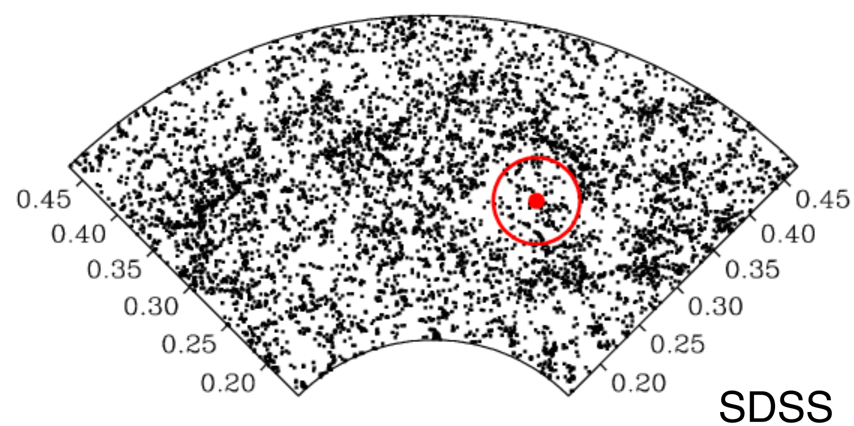


Intrinsic clustering - Baryon Acoustic Oscillations

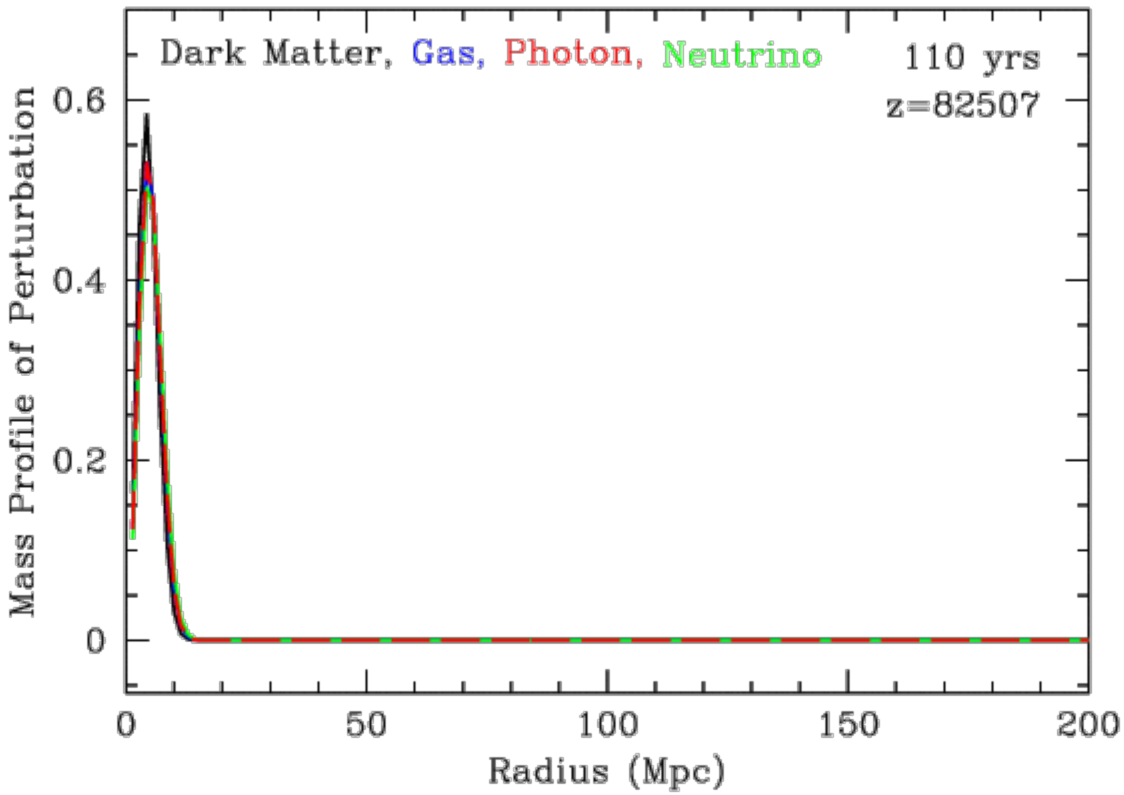
Comparison of CMB and LSS power spectra







Configuration space description

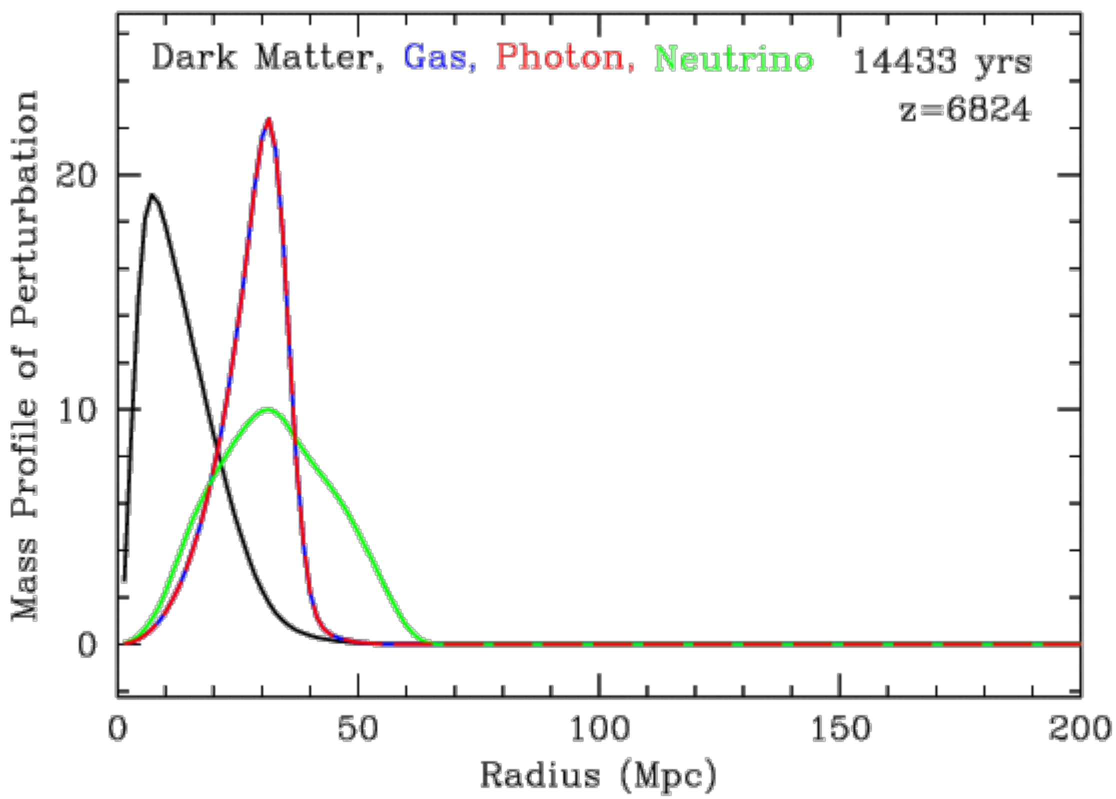


$\Omega_m h^2$=0.147, $\Omega_b h^2$=0.024

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

plots by Dan Eisenstein

Configuration space description



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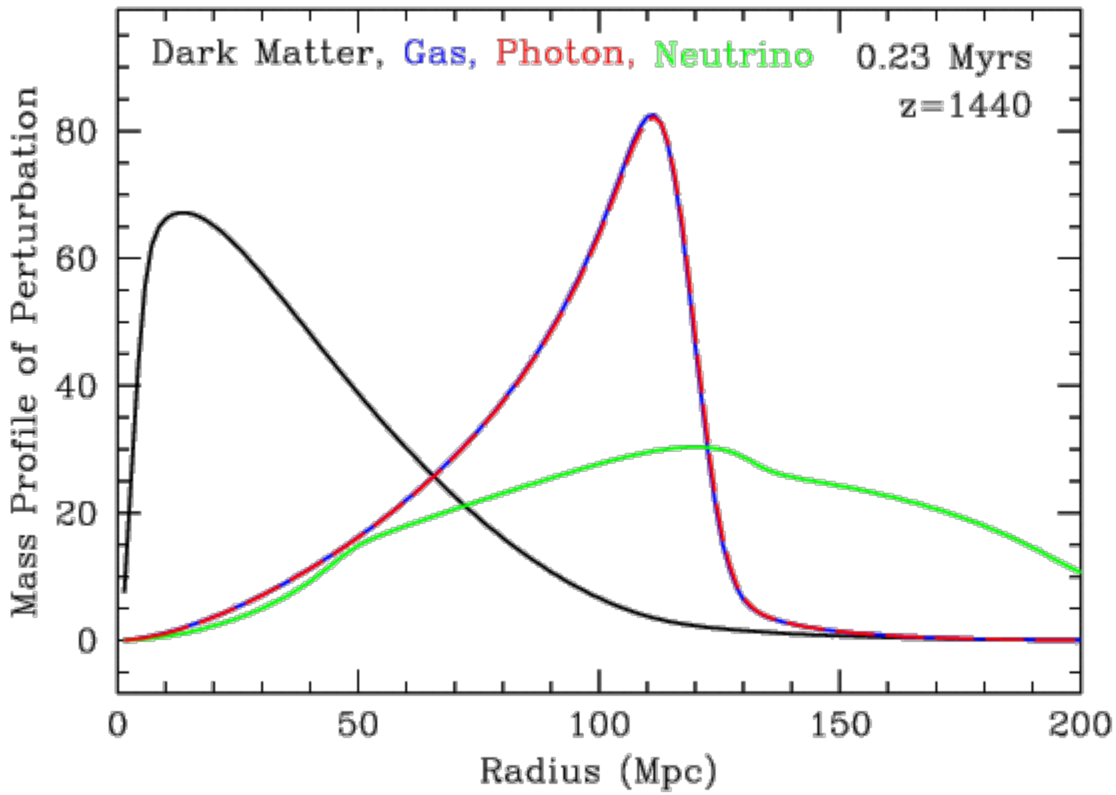

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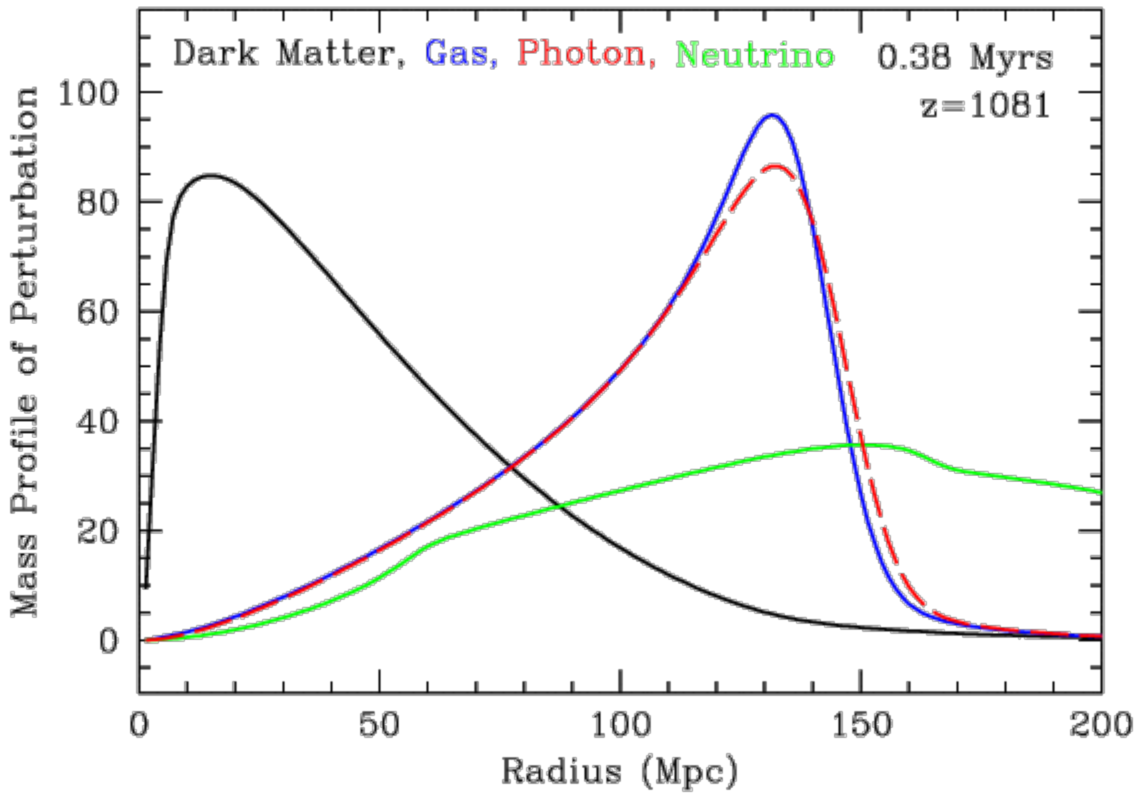

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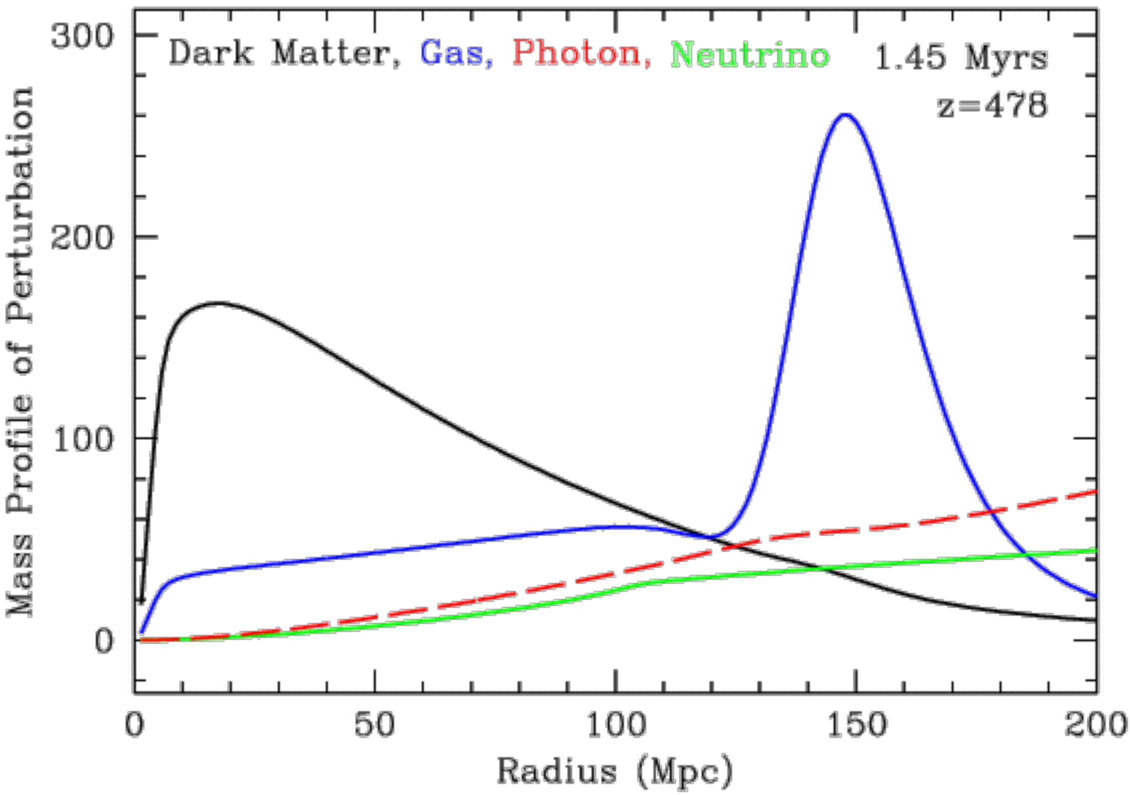

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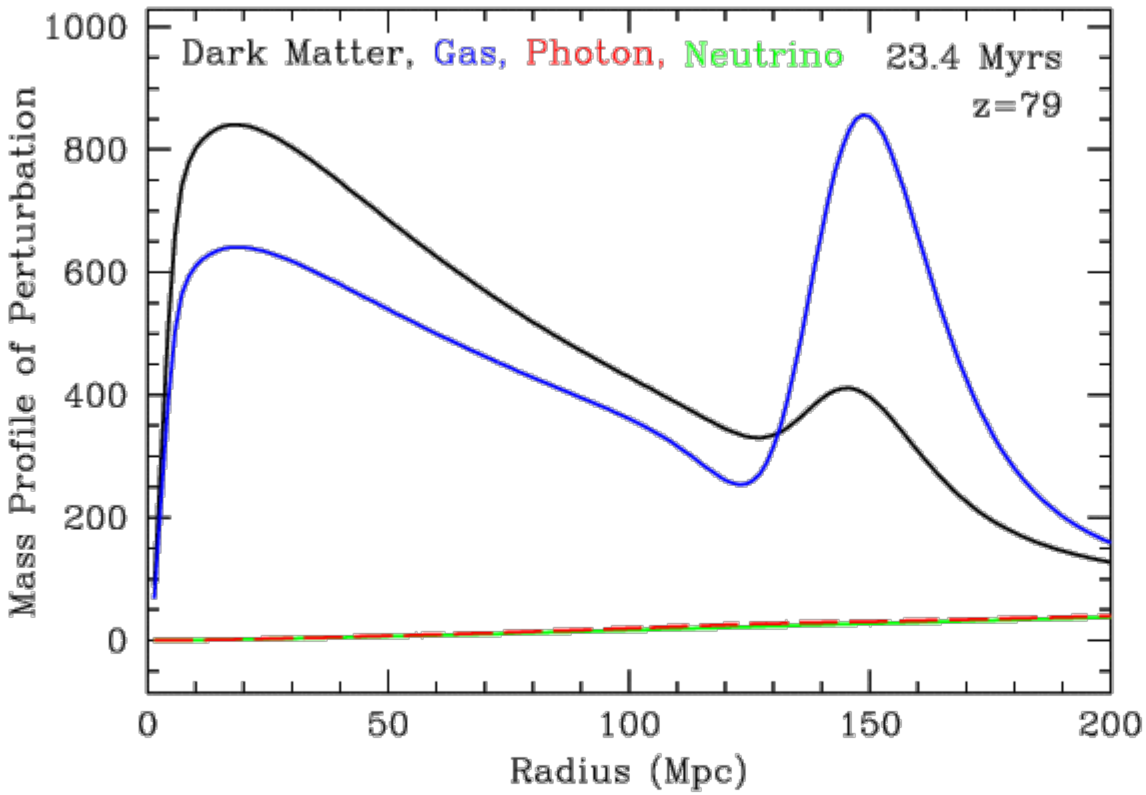

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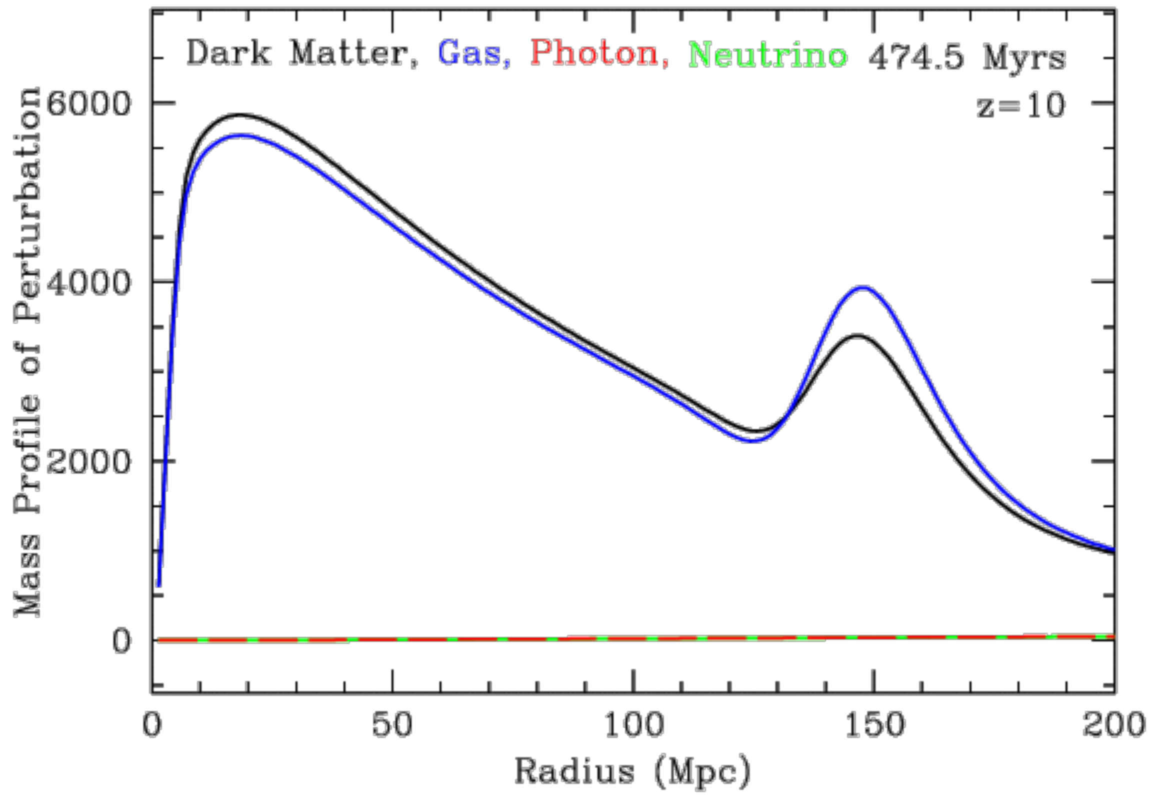

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Real-space correlation function

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from statistical homogeneity

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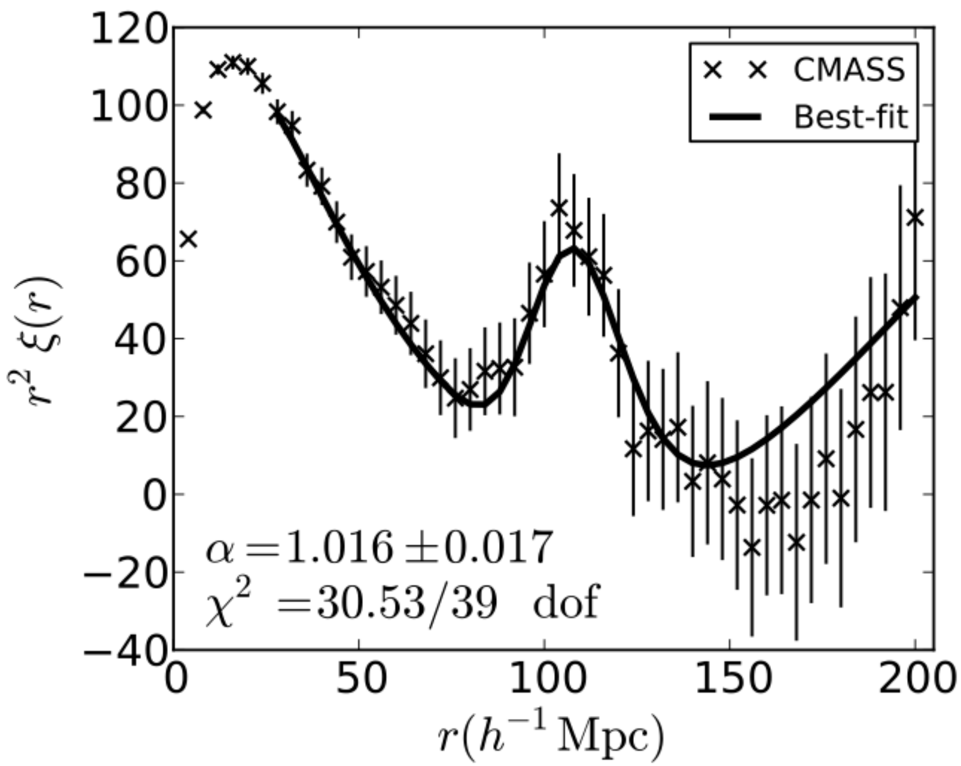
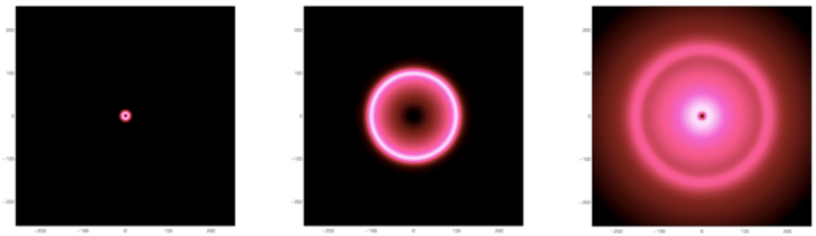
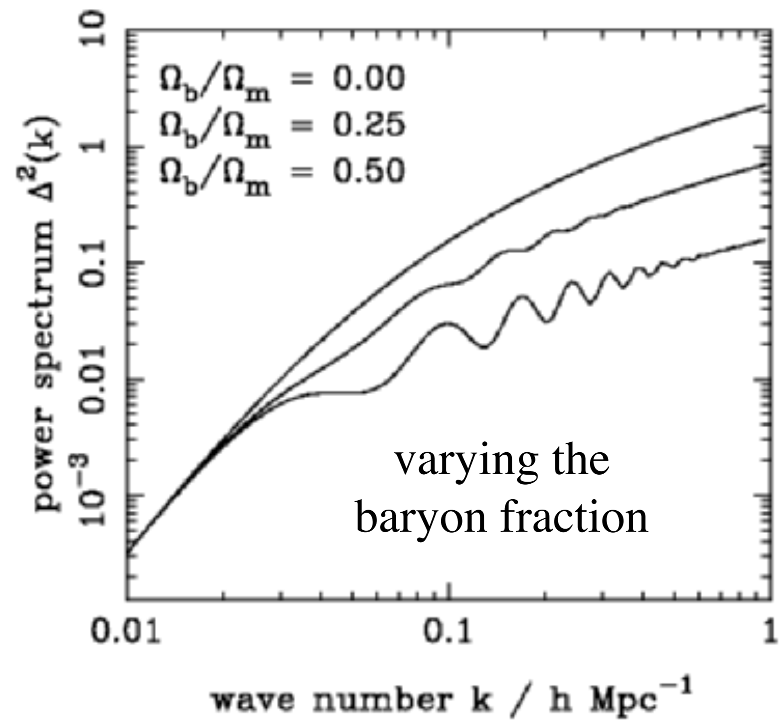


Baryon Acoustic Oscillations (BAO)



(images from Martin White)



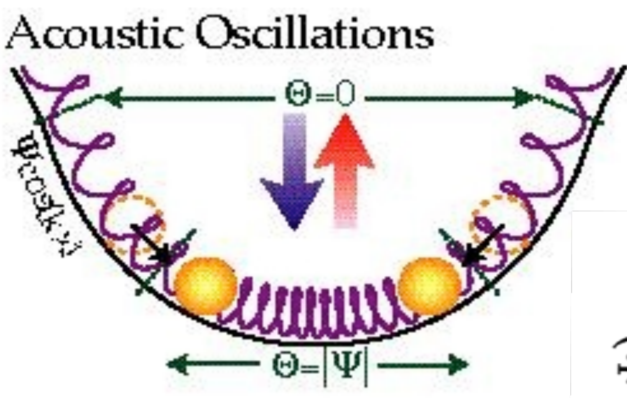
To first approximation, BAO wavelength is determined by the comoving sound horizon at recombination

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

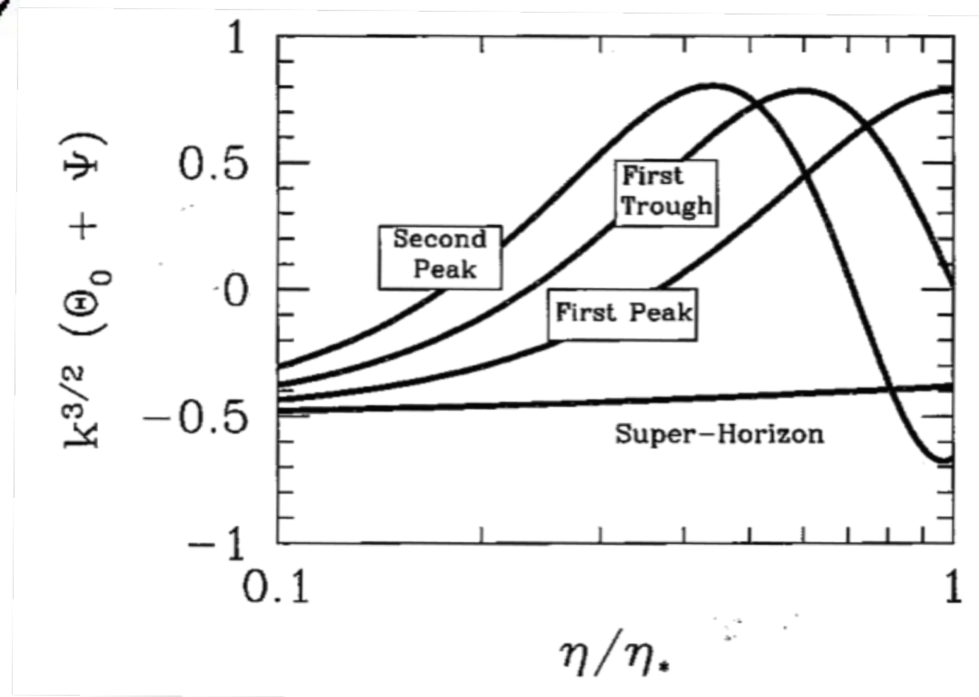
$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{\rm eq})^{1/2}}$$

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

Acoustic Oscillations in the matter distribution

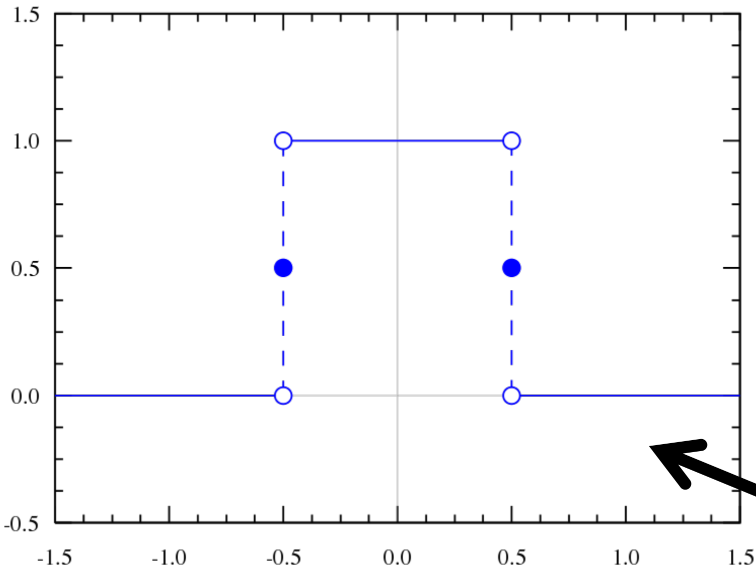


$$\ddot{\Theta}_0 + k^2 c_s^2 \Theta_0 = F$$

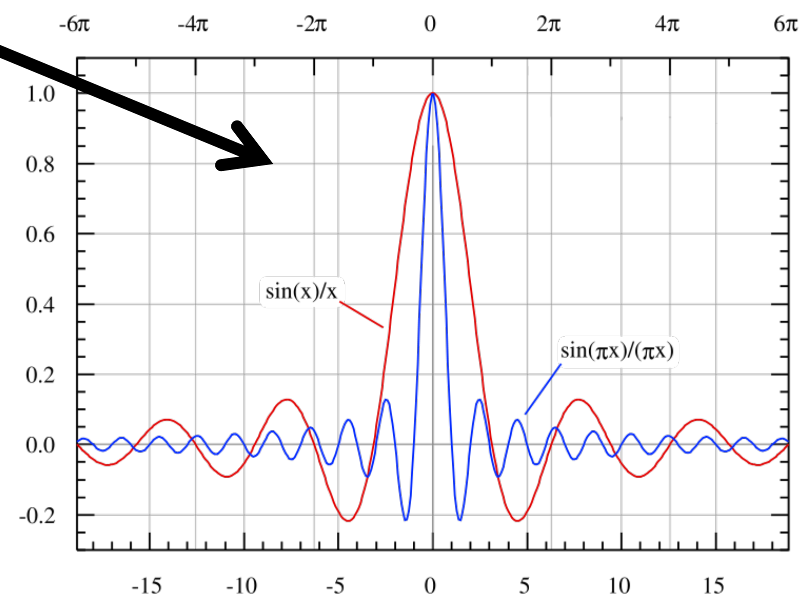


Dodelson "modern cosmology"

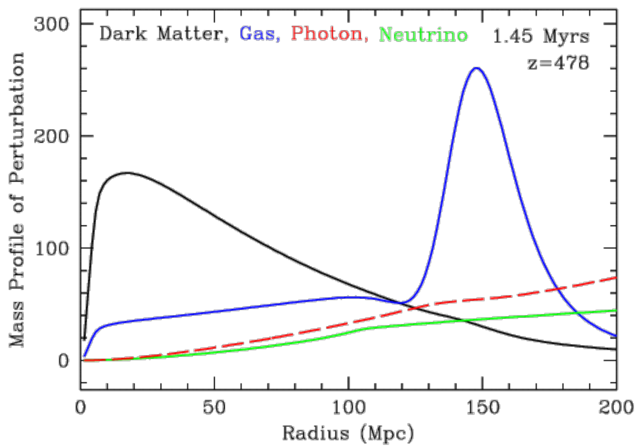
descriptions describe the same physics



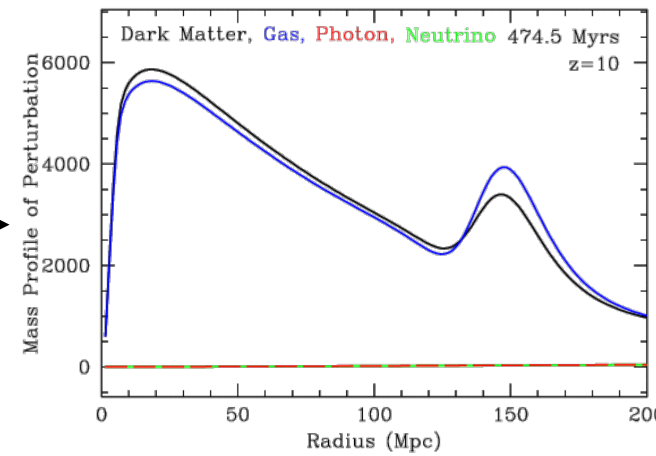
Fourier Pair



The relative velocity effect



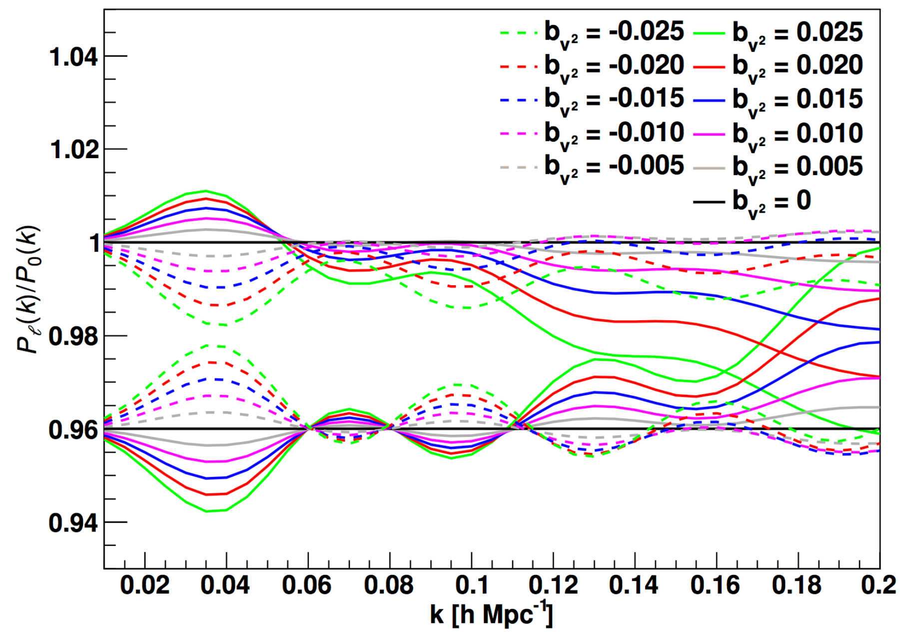
1/a decay due to growth, so will not affect low redshift



But, can affect high-z galaxy formation

Parametrize by b_{v^2}, the bias term related to the relative velocity

$$\delta_g^s(x) = b_1\delta_m(x) + \frac{1}{2}b_2\left[\delta_m^2(x) - \langle\delta_m^2\rangle\right] + \frac{1}{2}b_s\left[s^2(x) - \langle s^2\rangle\right] + \dots$$
$$+ b_{v^2}\left[v_{\rm bc}^2(x) - \langle v_{\rm bc}^2\rangle\right]$$
$$+ b_\delta^{\rm bc}\left[\delta_b(x) - \delta_c(x)\right] + b_\theta^{\rm bc}\left[\theta_b(x) - \theta_c(x)\right]$$
$$+ b_{sv}s_{ij}(x)v_{s,i}(x)v_{s,j}(x) + \dots,$$



Plot from Beutler, Seljak & Vlah 2017; arXiv:1612.04720

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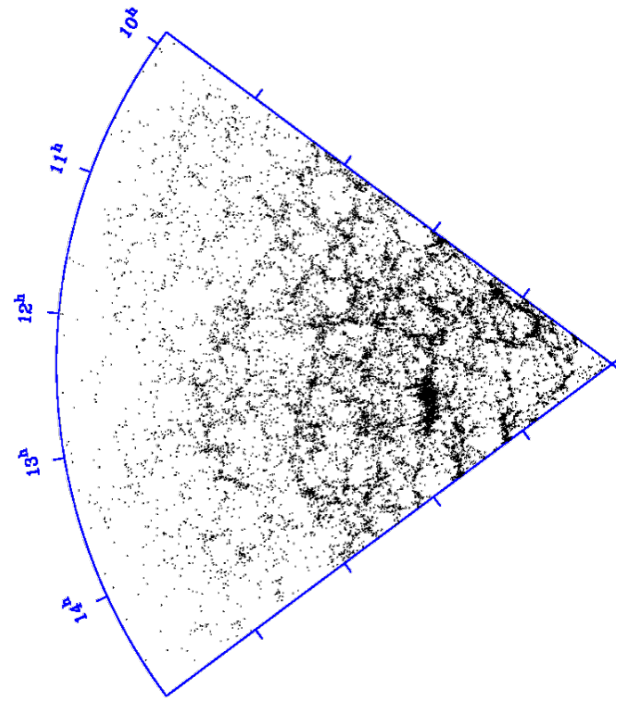
Galaxy clustering as a standard ruler

The evolution of the scale factor

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

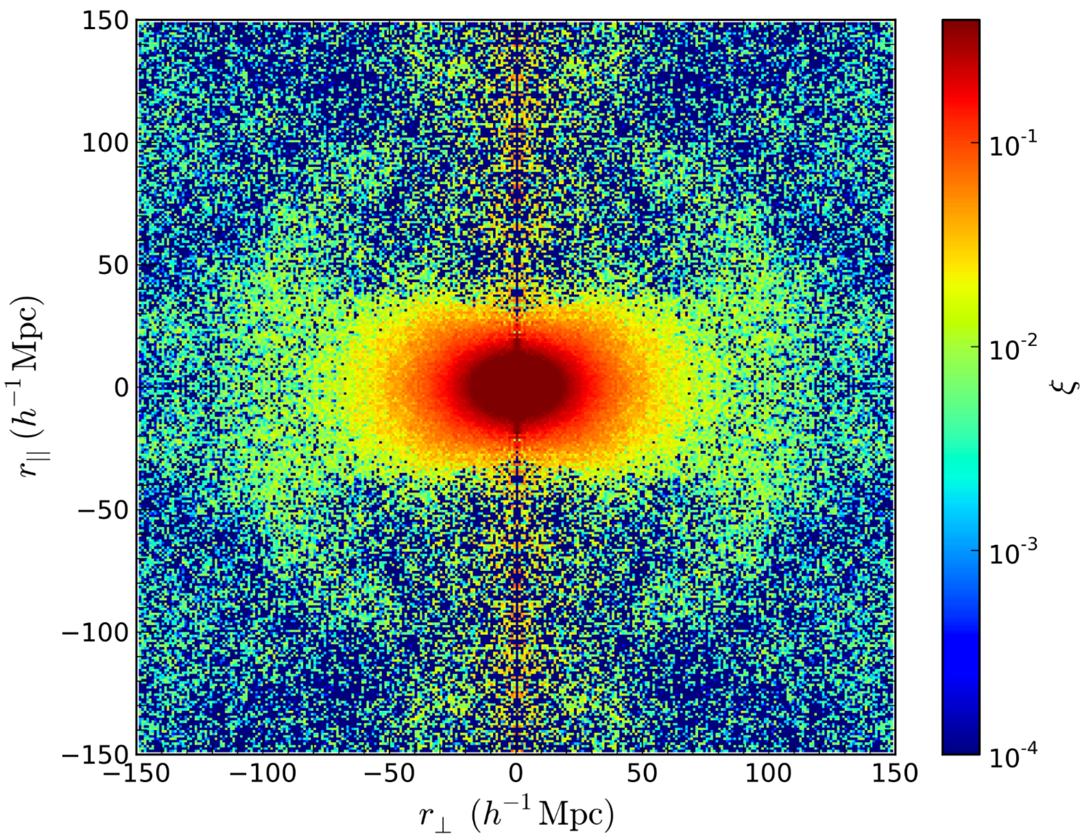
However, we measure galaxy redshifts and angles and infer distances

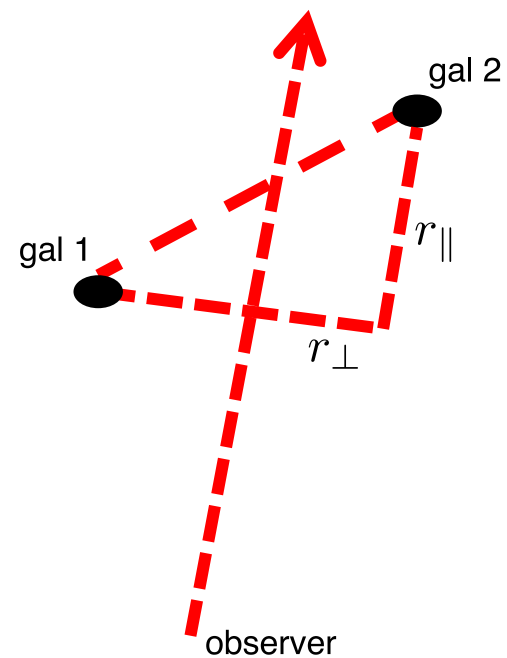
$$d_{\rm comov}(a) = \int_{t(a)}^{t_0} \frac{c\,dt'}{a(t')} = \int_a^1 \frac{c\,da'}{a'^2 H(a')}$$



line-of-sight dependent clustering

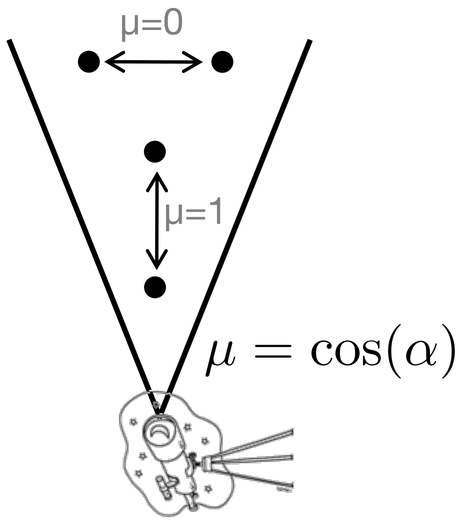
Across the line of sight, positions come from angles
Along the line of sight, positions come from redshifts

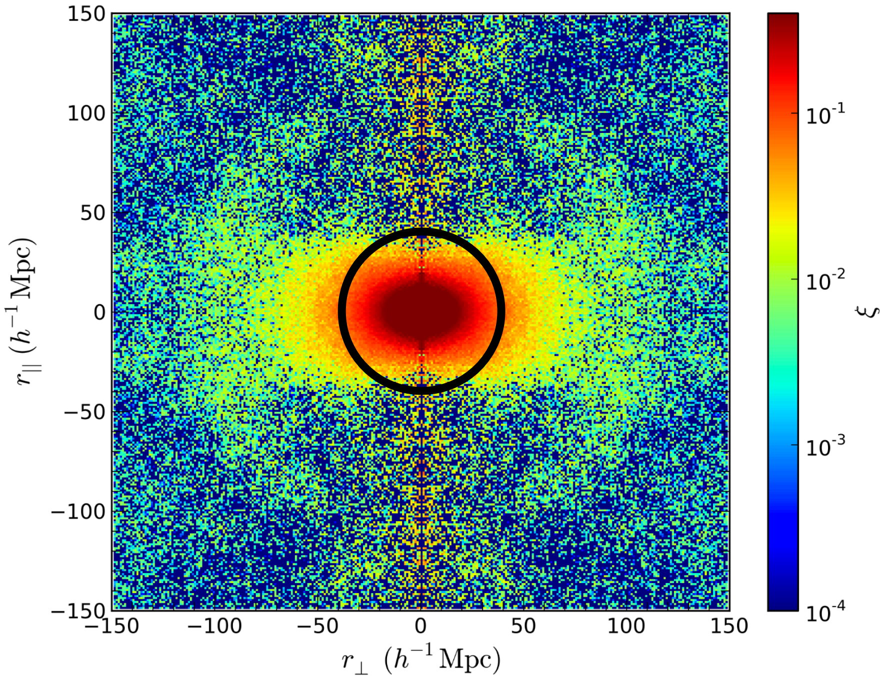




Samushia et al. 2013; MNRAS, 439, 3504

Moments of the clustering signal





Define moments of the clustering signal

$$P_F(k) = \int_0^1 d\mu\, F(\mu) P(k,\mu)$$

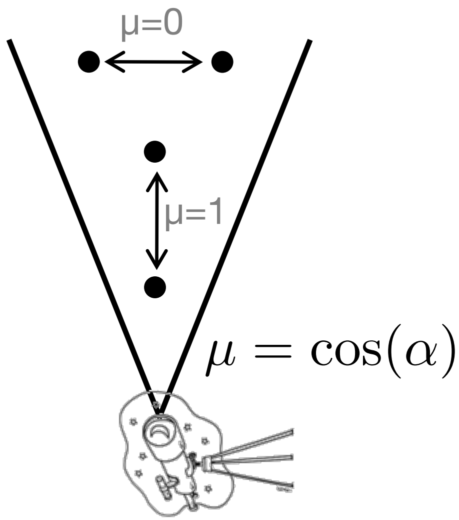
$$\xi_F(r) = \int_0^1 d\mu\, F(\mu) \xi(r,\mu)$$

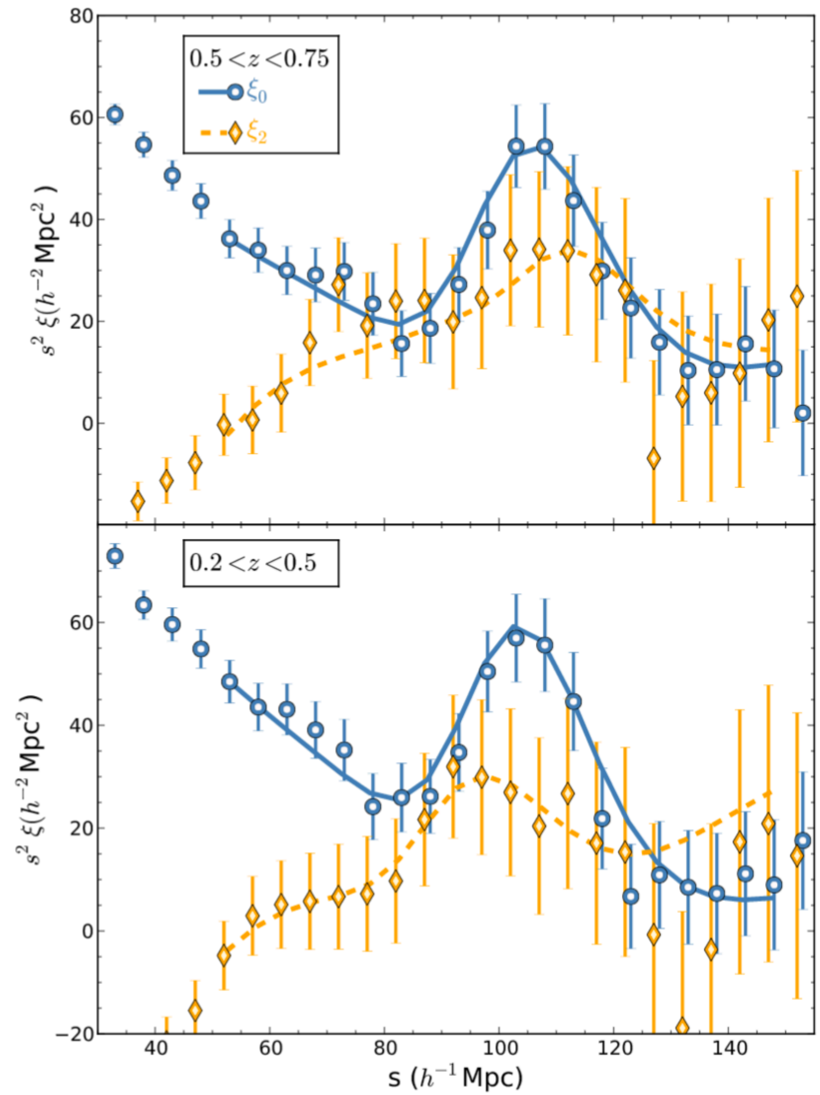
Monopole $F(\mu)=1$,

Quadrupole $F(\mu)=\frac{1}{2}(3\mu^2-1)$,

Hexadecapole $F(\mu)=\frac{1}{8}(35\mu^4-30\mu^2+3)$

Moments of the clustering signal





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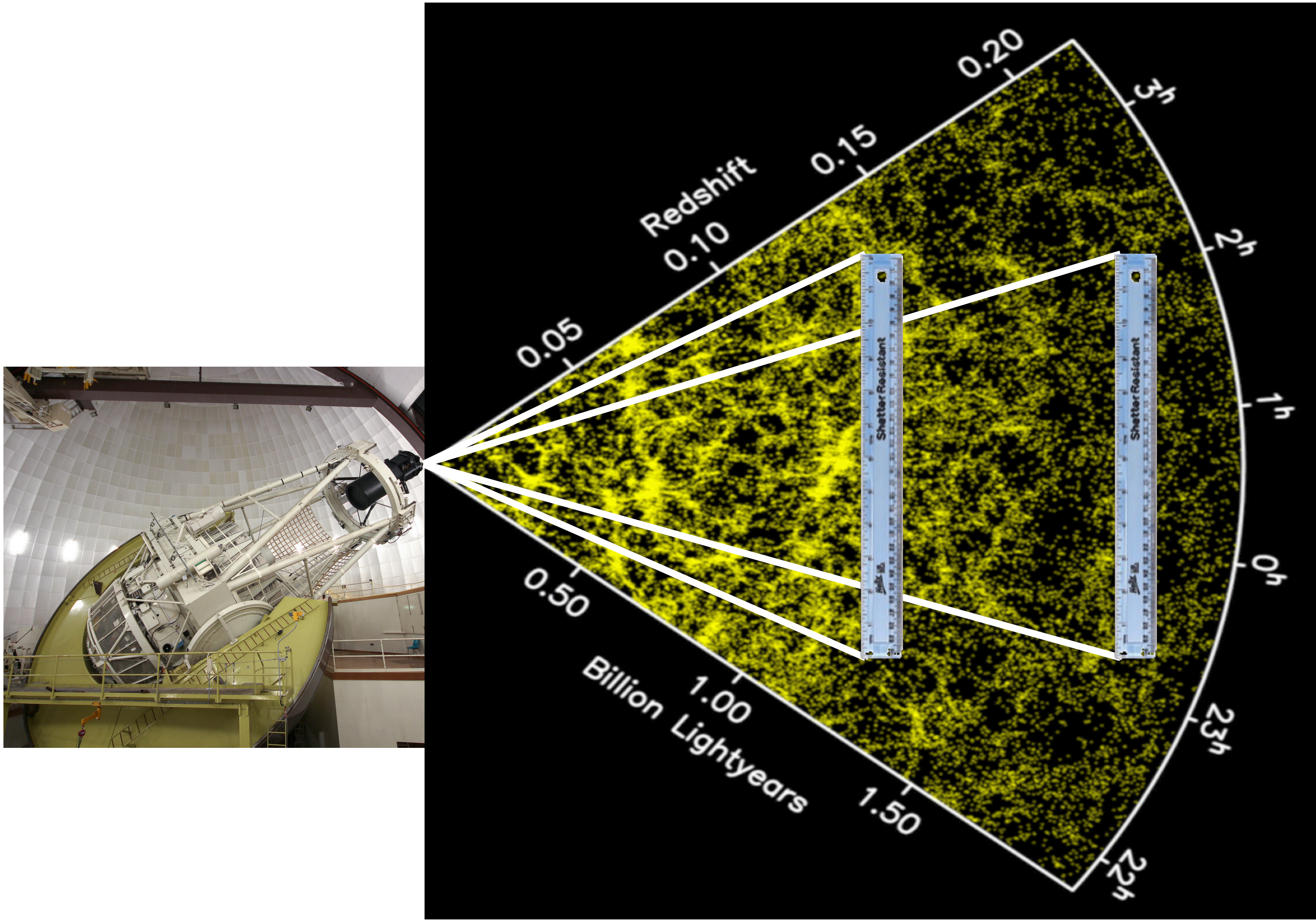
Ross et al. 2016, arXiv:1607.03145

The power spectrum as a standard ruler



BAO as a standard ruler

Surveys measure angles and redshifts, and to estimate comoving clustering, we have to use a fiducial model (denoted "fid") to translate to comoving coordinates (assuming distance-redshift relation only due to Hubble expansion) Changes in apparent BAO position ($\Delta d_{\mathbf{comov}}$) depend on:

Radial direction

$$\alpha_{\|} = \frac{H(z)_{\rm fid}}{H(z)_{\rm true}}$$

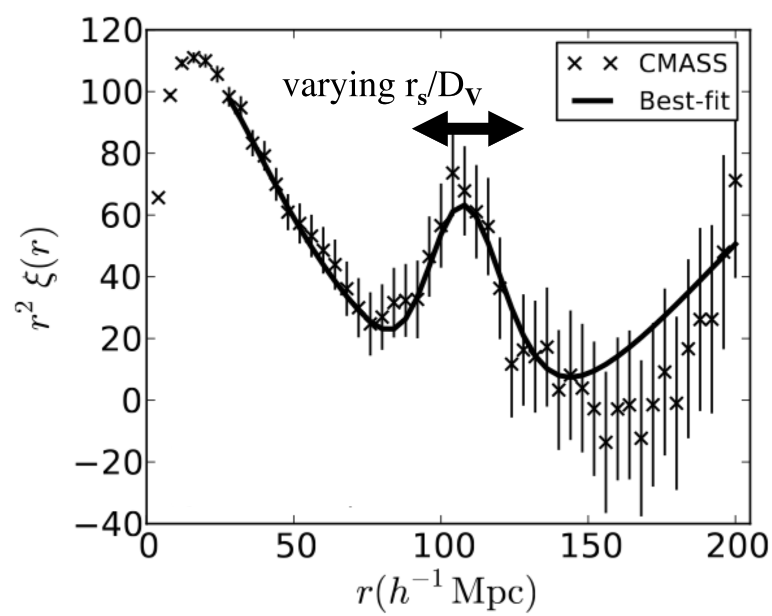
Angular direction

$$\alpha_{\perp} = \frac{D_A(z)_{\rm true}}{D_A(z)_{\rm fid}}$$

(i.e. these terms anisotropically stretch clustering - the relative effect known as **Alcock-Paczynski Effect**)

We see from geometrical arguments that a set of random pairs constrains

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



![ICG Portsmouth logo]

Can we use the AP effect on small scales?

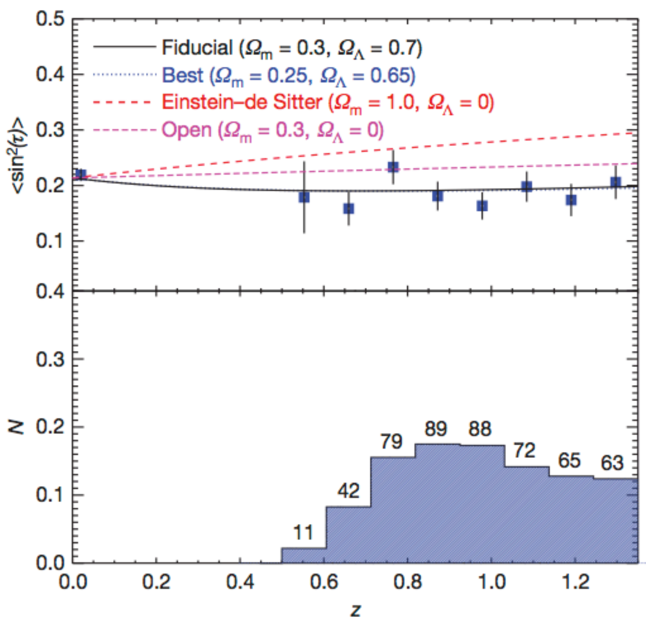
use isolated galaxy pairs

Marinoni & Buzzi 2011

- Nature 468, 539

Jennings et al. 2012

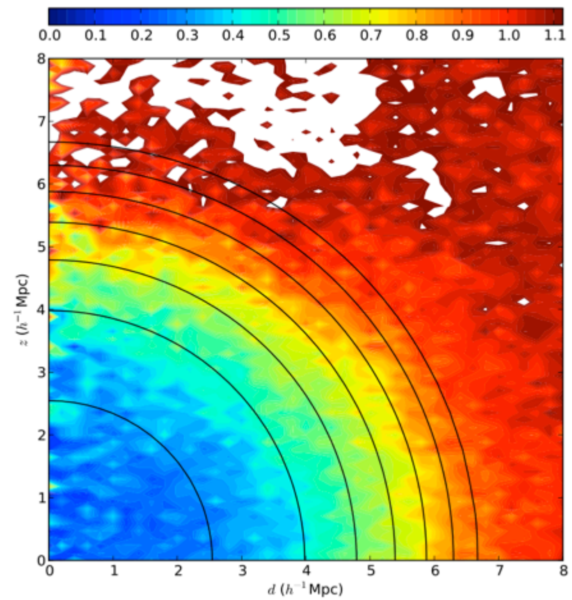
- MNRAS 420, 1079



use voids

Lavaux & Wandelt 2011

- arXiv:1110.0345



Collapsed structures

Live in static region of space-time

Velocity from growth exactly cancels Hubble expansion

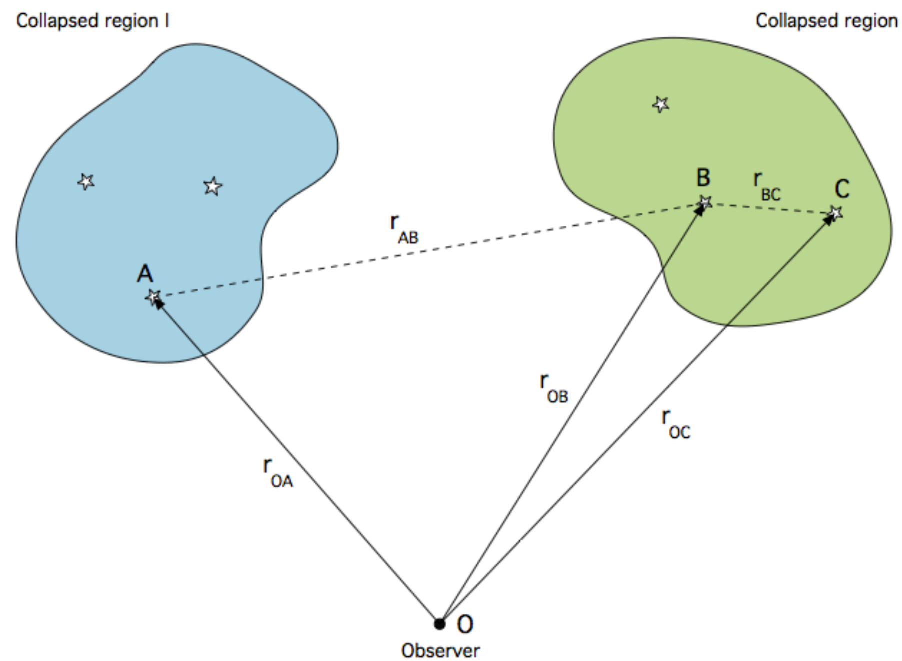
Two static galaxies in same structure have same observed redshift irrespective of distance from us

Redshift difference only tells us properties of system

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

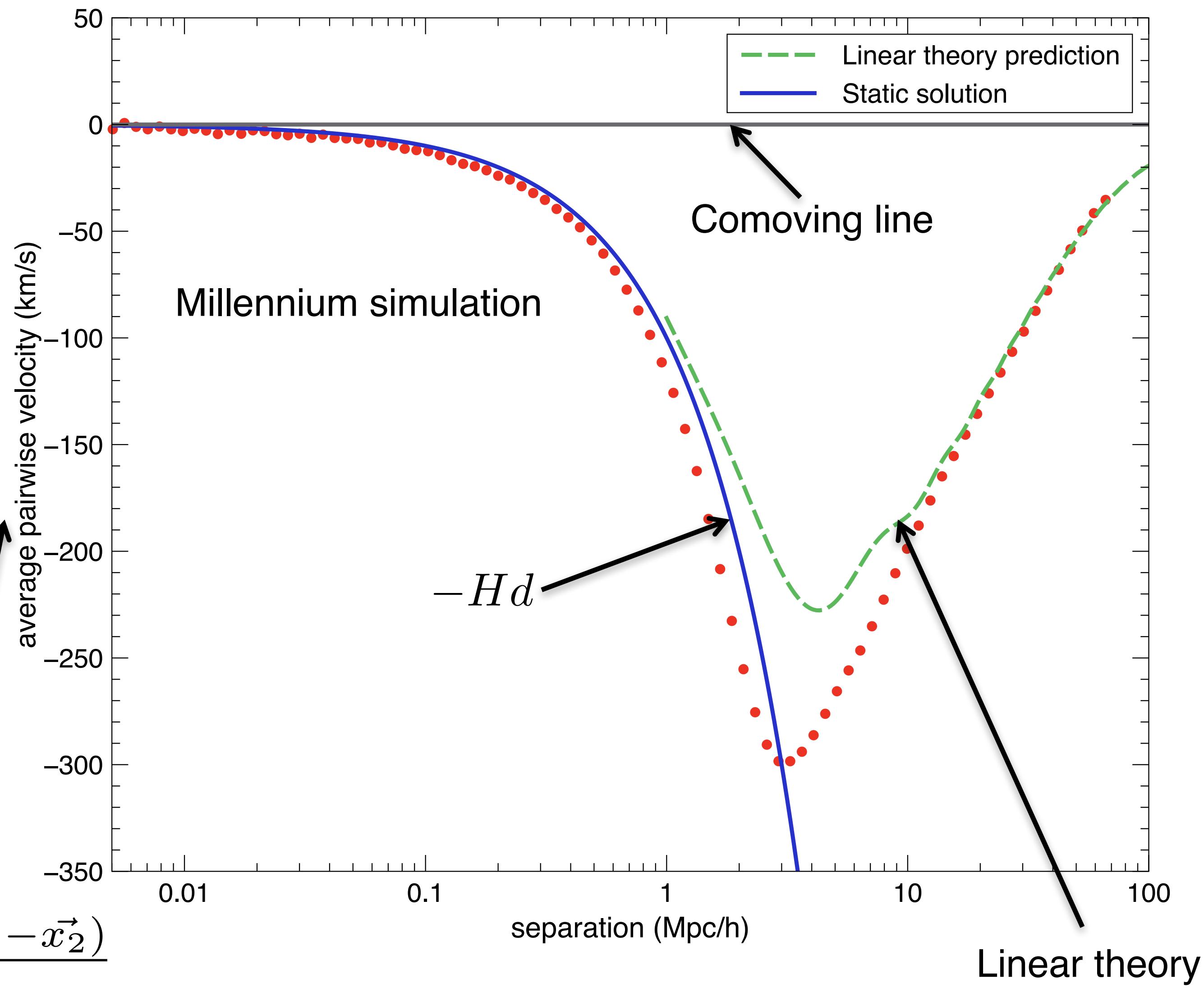
No cosmological information from Δz

Cannot be used for AP tests



Belloso et al. 2012: arXiv:1204.5761

Average galaxy pairwise velocity



$$\frac{(\vec{v_1} - \vec{v_2}) \cdot (\vec{x_1} - \vec{x_2})}{d}$$

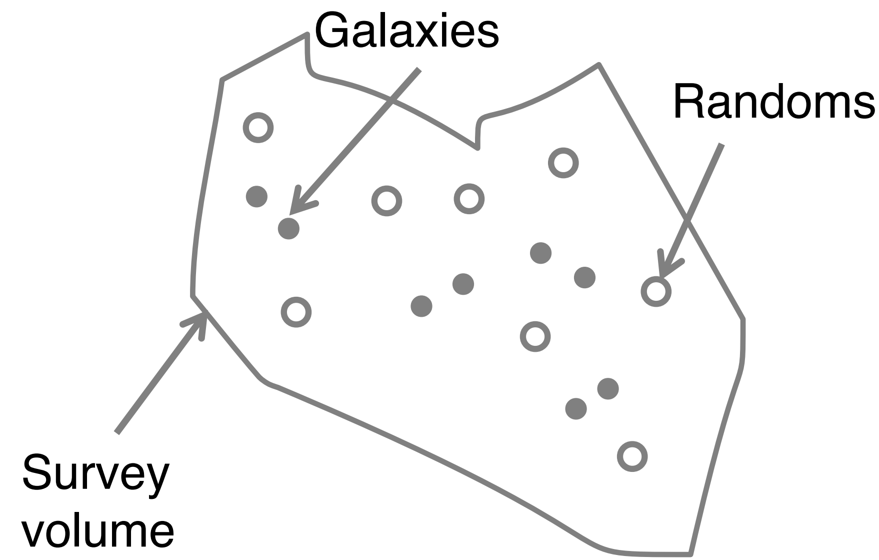
From Belloso et al. 2012: arXiv:1204.5761

Measuring anisotropic clustering: The correlation function

The correlation function wrt LOS

DD = number of galaxy-galaxy pairs
DR = number of galaxy-random pairs
RR = number of random-random pairs

All calculated as a function of separation **and** direction to LOS



$$\xi = \frac{DD}{RR} - 1$$

$$\xi = \frac{DD}{DR} - 1$$

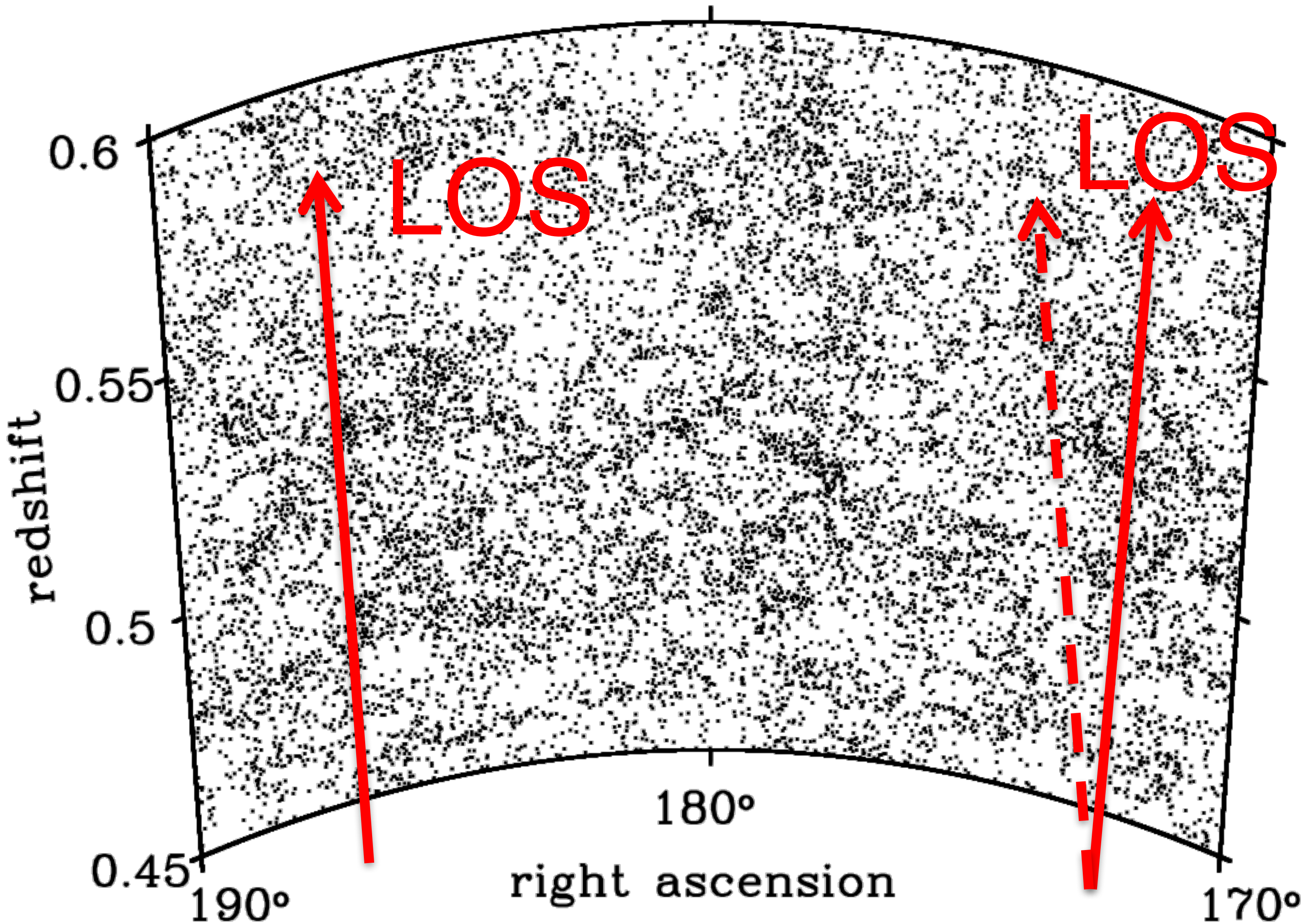
$$\xi = \frac{DD\,RR}{DR^2} - 1$$

$$\xi = \frac{DD - 2DR}{RR} + 1$$

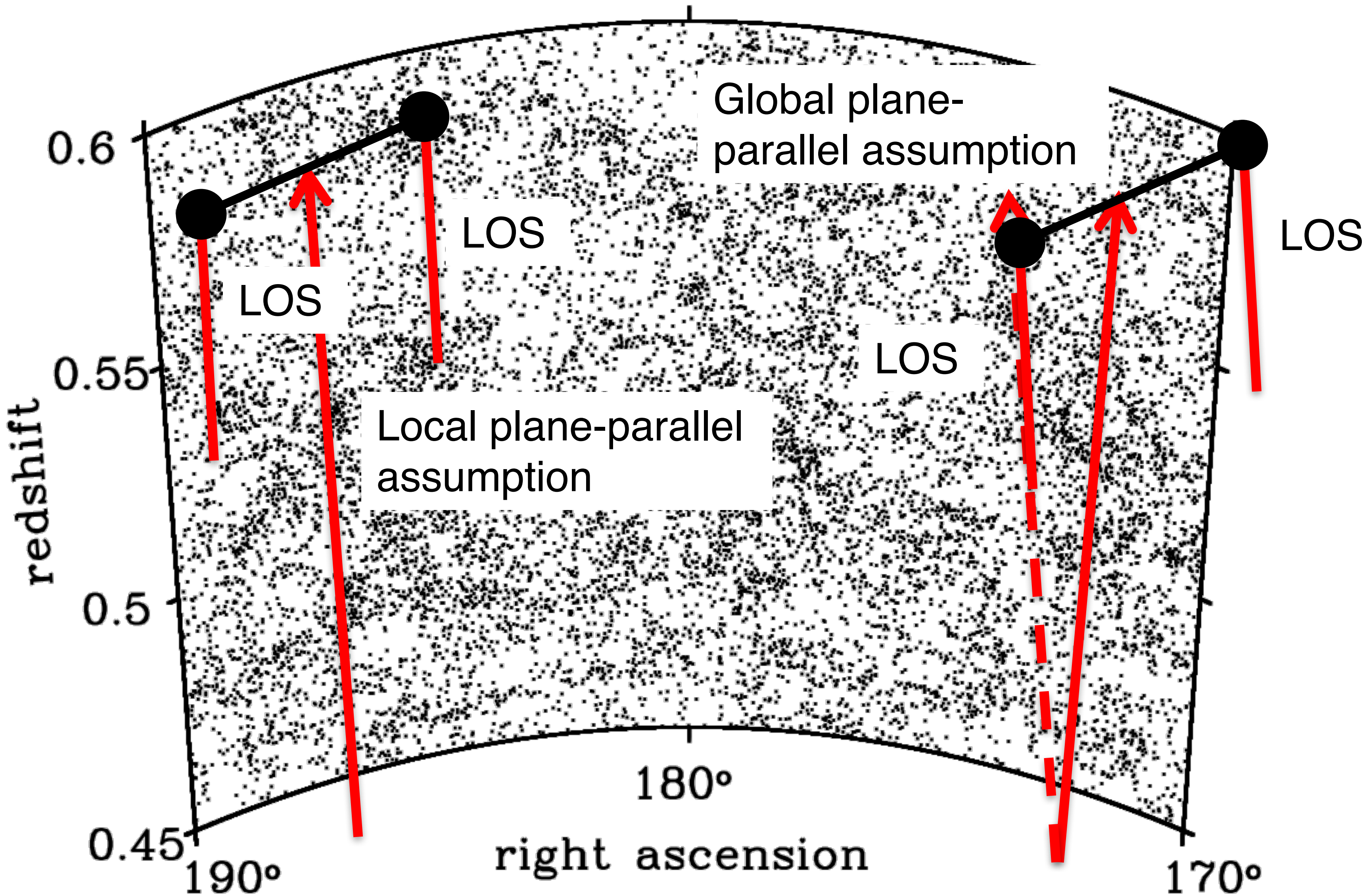
Landy & Szalay (1993) considered noise from these estimators, and showed that this has the best noise properties

Landy & Szalay 1993; ApJ 412, 64

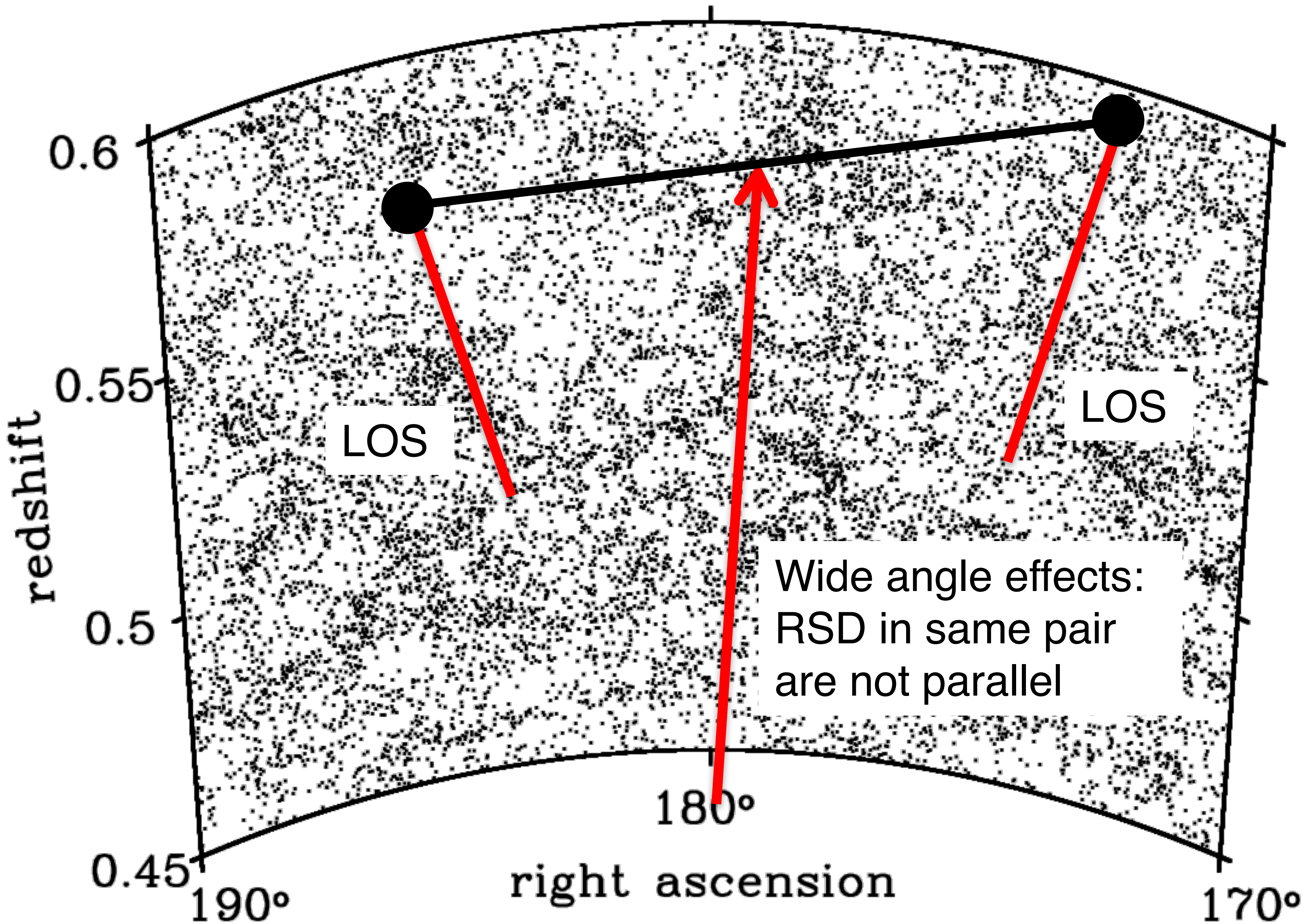
The LOS varies across a survey



Different assumptions made



Different assumptions made



Angular upweighting for 3D measurements

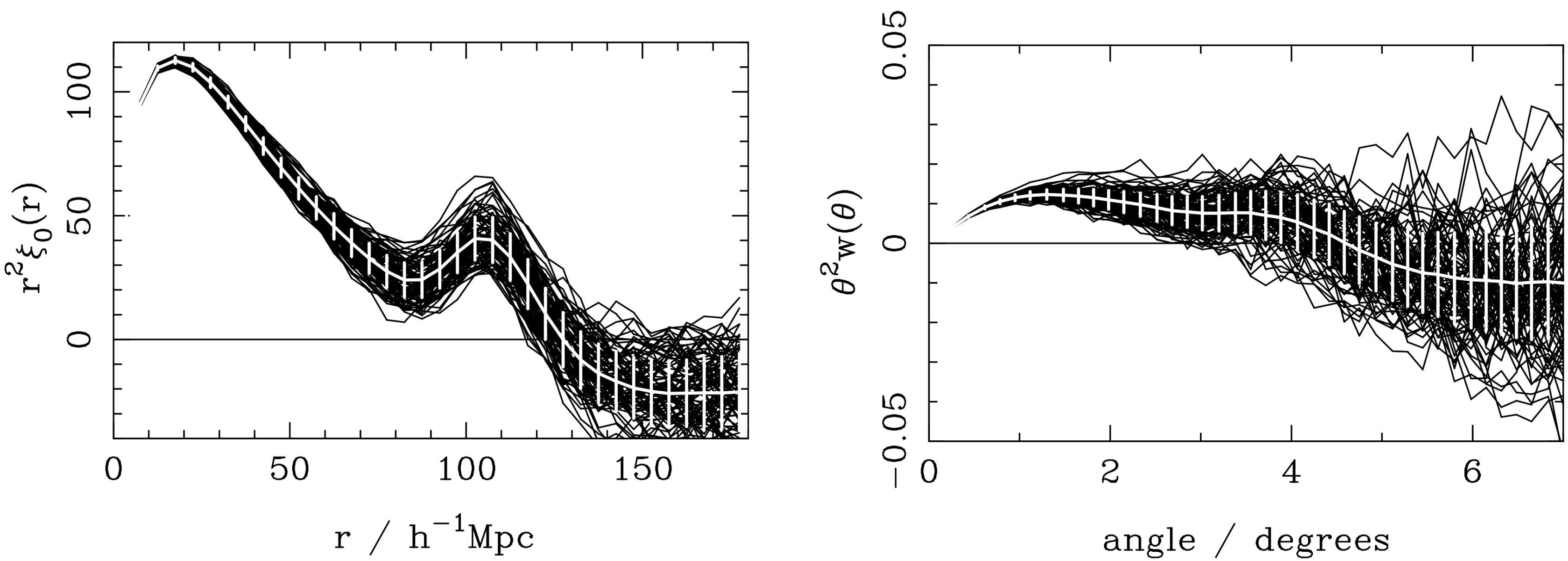
Spectroscopic surveys are never 100% complete

With early data, one often has radial information for only a fraction of galaxies

BUT, you have angular information for the full (target) sample

Why not use it …

$$1 + \xi(r,\theta) = (1 + \xi(r|\theta))(1 + w(\theta))$$



Percival & Bianchi 2017; arXiv:1703.02071

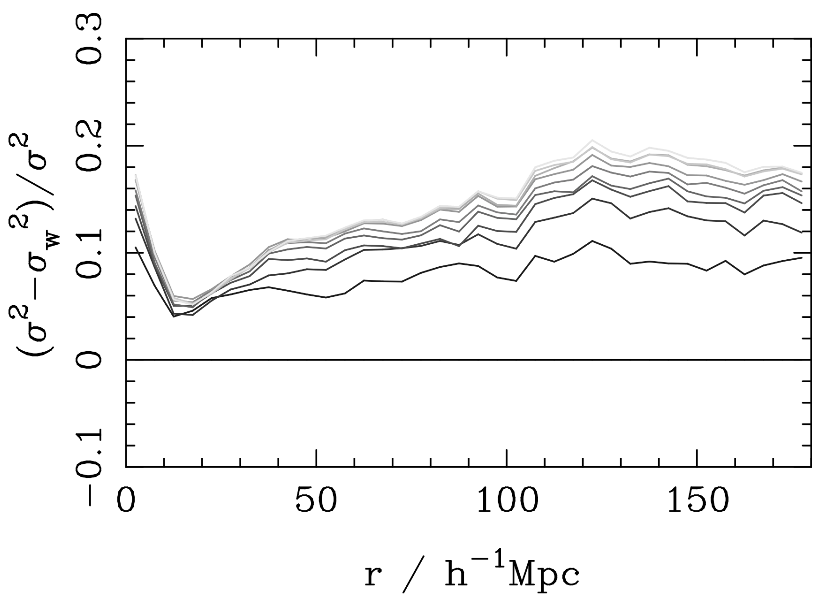
Angular upweighting for 3D measurements

Simple idea:

replace (1+w(θ)) with that calculated from the parent sample

Practically: take 3D clustering and weight by $(1+w(\theta))_{parent} / (1+w(\theta))_{sample}$

Formally unbiased, and gives more accuracy



Fractional improvement for ξ_0 for BOSS CMASS galaxies, if 2x … 10x the Sample is used to determine the angular part of the clustering signal

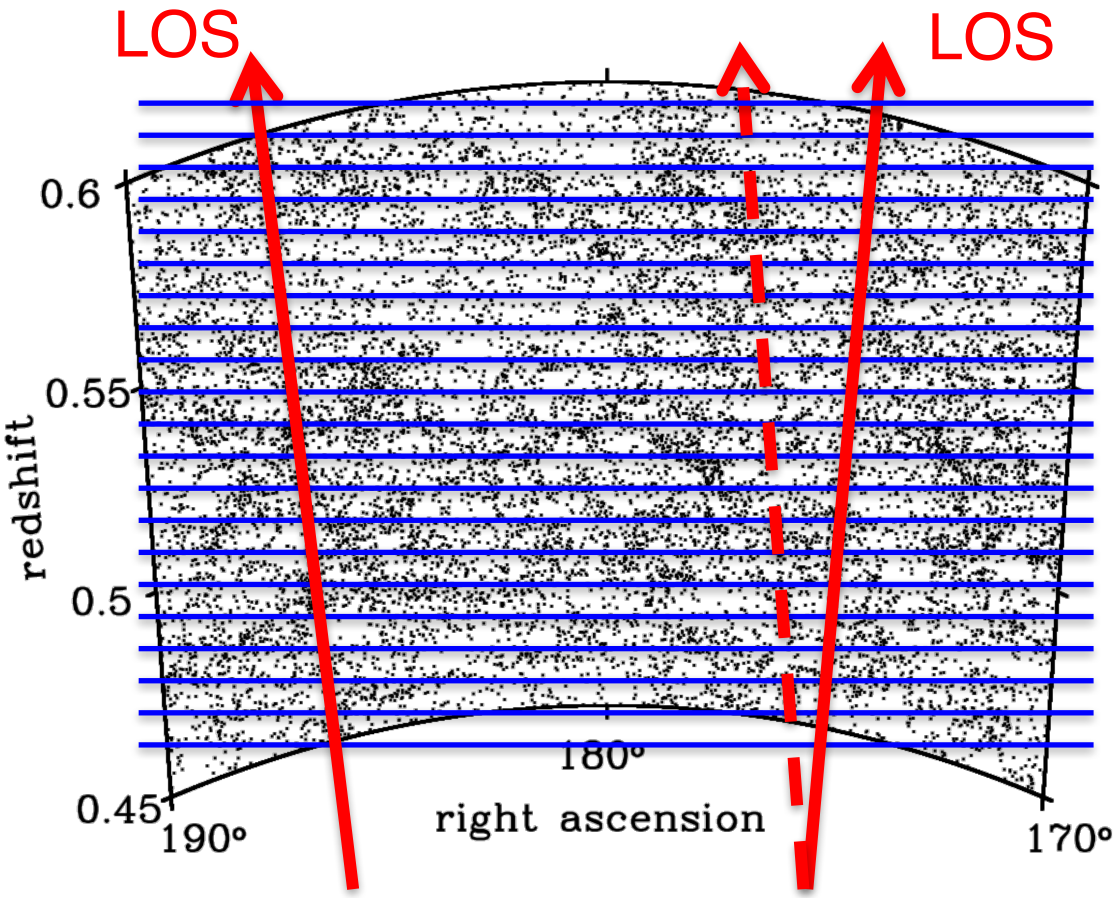
Percival & Bianchi 2017; arXiv:1703.02071

ICG Portsmouth

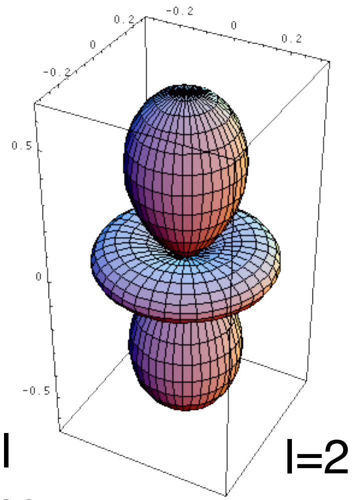
Measuring anisotropic clustering: The power spectrum

The power spectrum wrt LOS

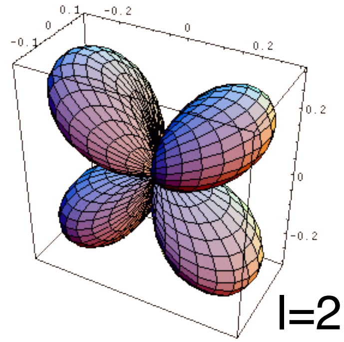
$$P_F(k) = \int_0^1 d\mu\, F(\mu) P(k,\mu)$$



Measuring the anisotropic power spectrum



l=2,m=0

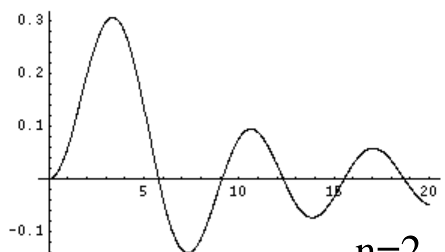


l=2,m=1

Spherical Harmonics (θ,Φ)

+

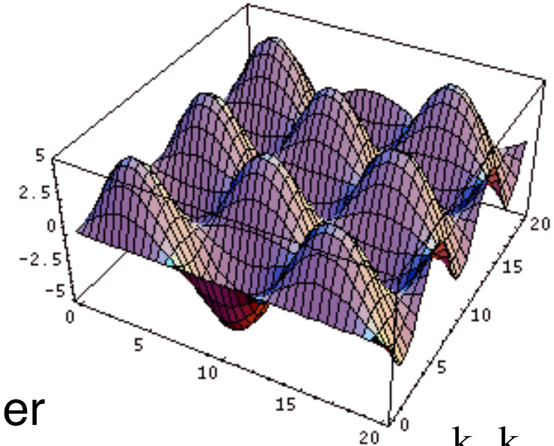
Spherical Bessel function (r)



r

n=2

advantage: radial/angular split – more matched to survey geometry, easily model redshift space distortions

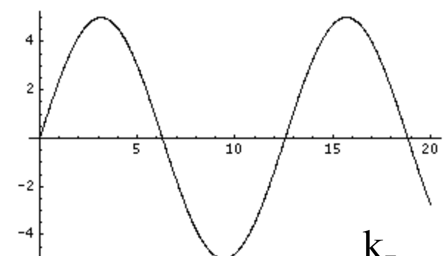


2d Fourier basis (x,y)

k_x,k_y

+

1d Fourier basis (z)



z

k_z

advantage: simplicity, speed

e.g. Heavens & Taylor 1995; MNRAS, 275, 483

Measuring power as a sum over pairs

- Define the overdensity field

$$N(\mathbf{r}) = \frac{n_g(\mathbf{r}) - \bar{n}(\mathbf{r})}{\bar{n}(\mathbf{r})}$$

$$P_F(k) = \int_0^1 d\mu \, F(\mu) P(k,\mu)$$

- Power spectrum moments can be written as a integral over pairs

$$\hat{P}_F(k) \propto \int d\Omega_k \left[\int d\mathbf{r}_1 \int d\mathbf{r}_2 \, N(\mathbf{r}_1) N(\mathbf{r}_2) e^{i\mathbf{k}\cdot(\mathbf{r}_1 - \mathbf{r}_2)} F(\hat{\mathbf{k}} \cdot \hat{\mathbf{r}}_{\rm pair}) \right]$$

- The clever part is defining the LOS to the pair as LOS to one galaxy

$$\hat{P}_F(k) \propto \int d\Omega_k \left[\int d\mathbf{r}_1 \, N(\mathbf{r}_1) e^{i\mathbf{k}\cdot\mathbf{r}_1} \int d\mathbf{r}_2 \, N(\mathbf{r}_2) e^{-i\mathbf{k}\cdot\mathbf{r}_2} F(\hat{\mathbf{k}} \cdot \hat{\mathbf{r}}_2) \right]$$

Yamamoto et al. 2005; astro-ph/0505115

Writing this in terms of FFTs

- For power-law $F(\mu)=\mu^n$, the “unit” to be solved is

$$A_n(\mathbf{k}) = \int d\mathbf{r}\,(\hat{\mathbf{k}}\cdot\hat{\mathbf{r}})^n N(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}} \qquad P_F(k) = \int_0^1 d\mu\, F(\mu) P(k,\mu)$$

- We can expand the dot product on a Cartesian basis

$$\mu \equiv \hat{\mathbf{k}}\cdot\hat{\mathbf{r}} = \frac{k_x r_x + k_y r_y + k_z r_z}{kr}$$

- So that (for example) A_2 is decomposed (similarly for n>2)

$$A_2(\mathbf{k}) = \frac{1}{k^2}\left\{k_x^2 B_{xx}(\mathbf{k}) + k_y^2 B_{yy}(\mathbf{k}) + k_z^2 B_{zz}(\mathbf{k}) + 2\left[k_x k_y B_{xy}(\mathbf{k}) + k_x k_z B_{xz}(\mathbf{k}) + k_y k_z B_{yz}(\mathbf{k})\right]\right\}$$

- Where B_{ij} can be solved with FFTs

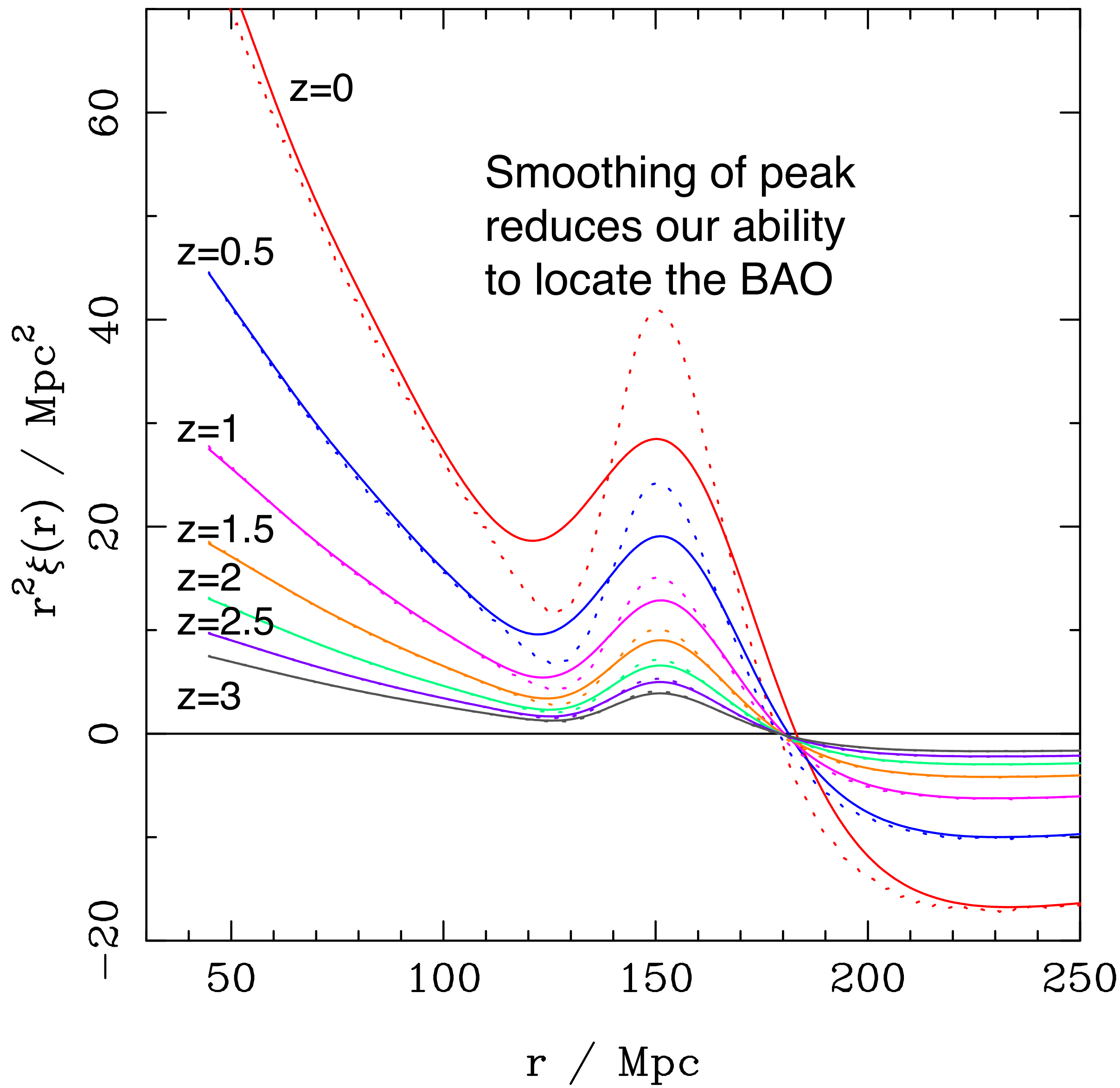
$$B_{ij}(\mathbf{k}) \equiv \int d\mathbf{r}\,\frac{r_i r_j}{r^2} N(\mathbf{r}) e^{i\mathbf{k}\cdot\mathbf{r}}$$

Bianci et al. 2015; arXiv:1505.05341; Scoccimarro; arXiv:1506.02729

Moving beyond the linear …

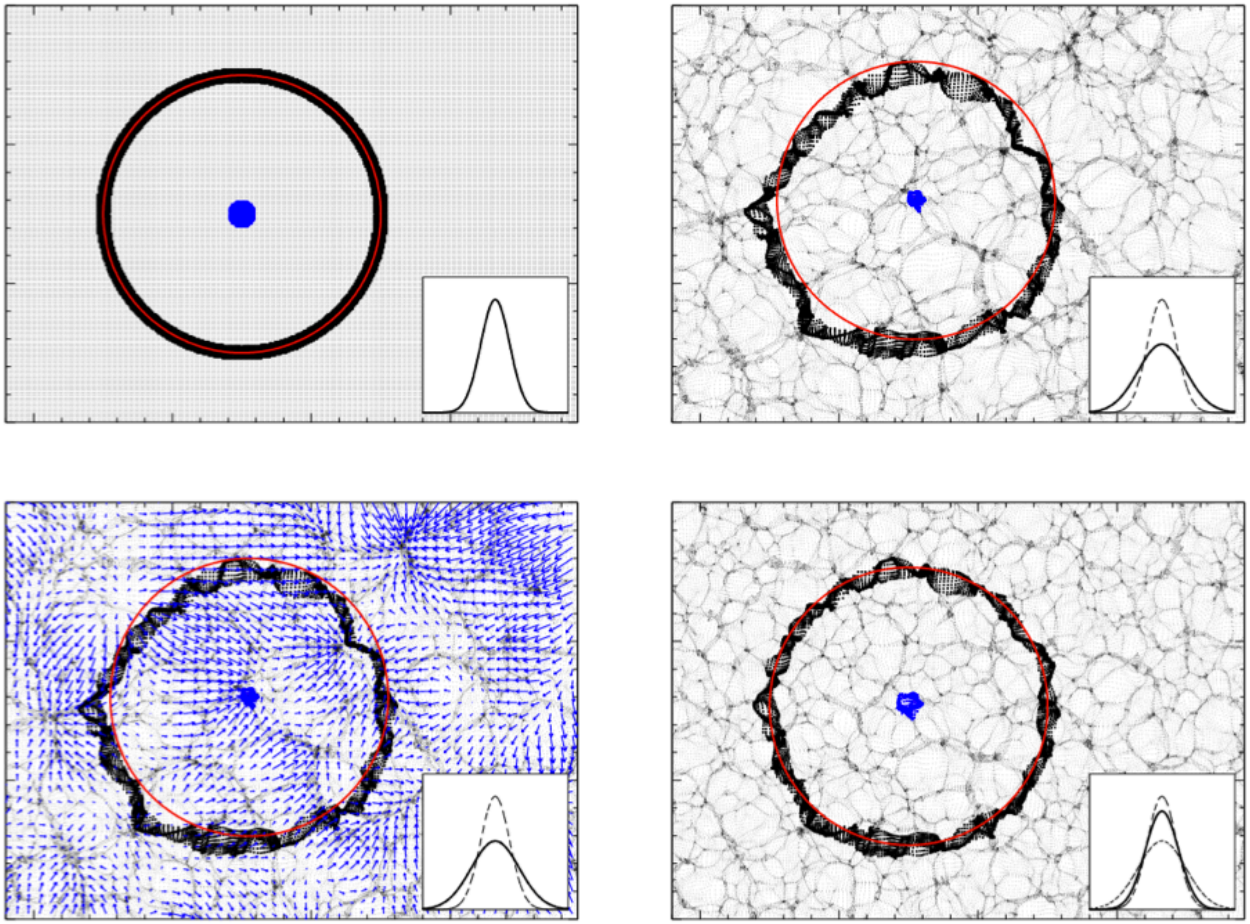
reconstruction of BAO

BAO damping in the correlation function



RegPT; Taruya A., Bernardeau F., Nishimichi T., Codis S., 2012, PRD 86, 10

Non-linear movement on BAO scales



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

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

Padmanabhan et al. 2012; arXiv:1202.0090

A simple reconstruction algorithm

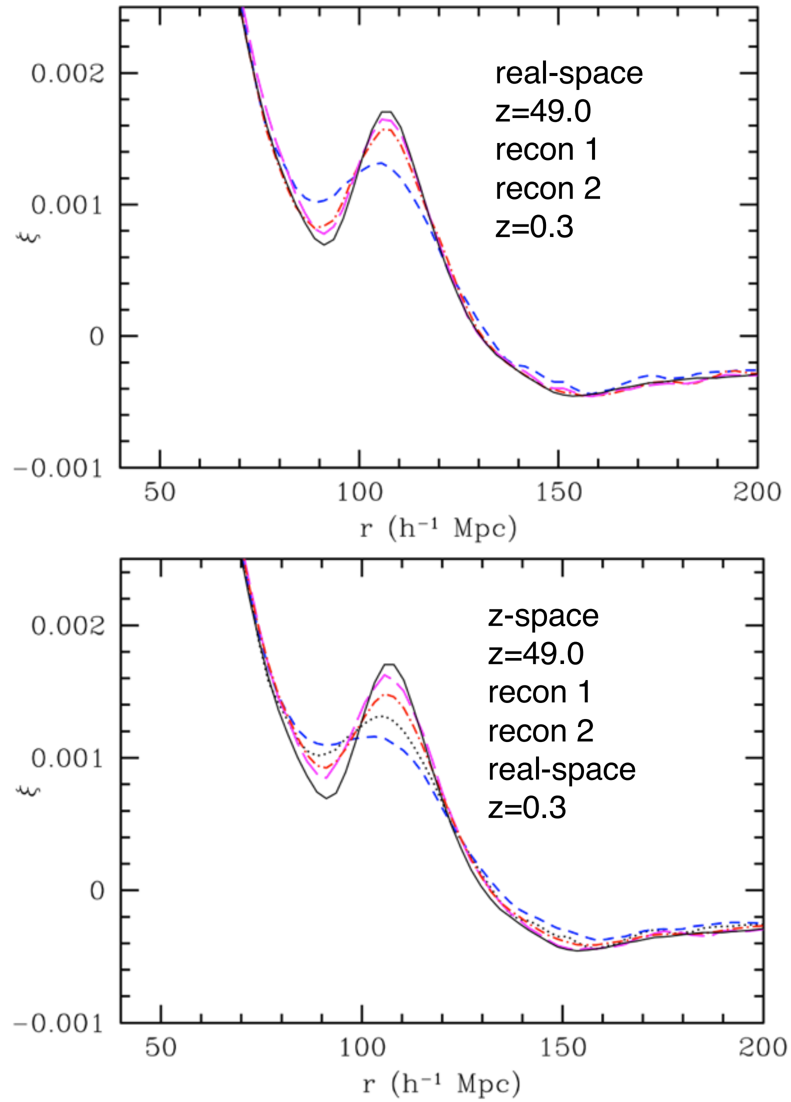
Algorithm: Smooth field and move overdensities by predicted (linear) motion

Smoothed field dominated by large-scale flows - so predicted linear motion is “not too bad”

If you get it wrong, you just affect the efficiency of reconstruction, not the measurement

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

Method now well tested: Burden et al. 2014 *MNRAS*, 445, 3152; 2015 arXiv:1504.2591, Vargas-Magana et al. 2015 arXiv:1509.06384



Eisenstein et al. 2006: arXiv:0604362

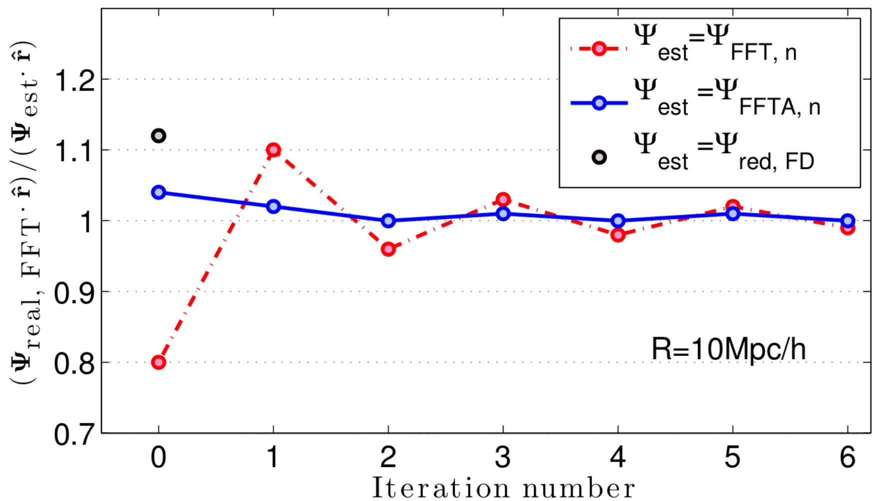
Reconstruction: dealing with RSD

Problem for reconstruction is RSD and dealing with varying line-of-sight across a survey: displacements $\mathbf{\Psi}$ are (in linear theory) related to overdensities by Poisson Eq + RSD

$$\nabla \cdot \mathbf{\Psi} + \frac{f}{b}\nabla \cdot (\mathbf{\Psi} \cdot \hat{\mathbf{r}})\hat{\mathbf{r}} = \frac{-\delta}{b}$$

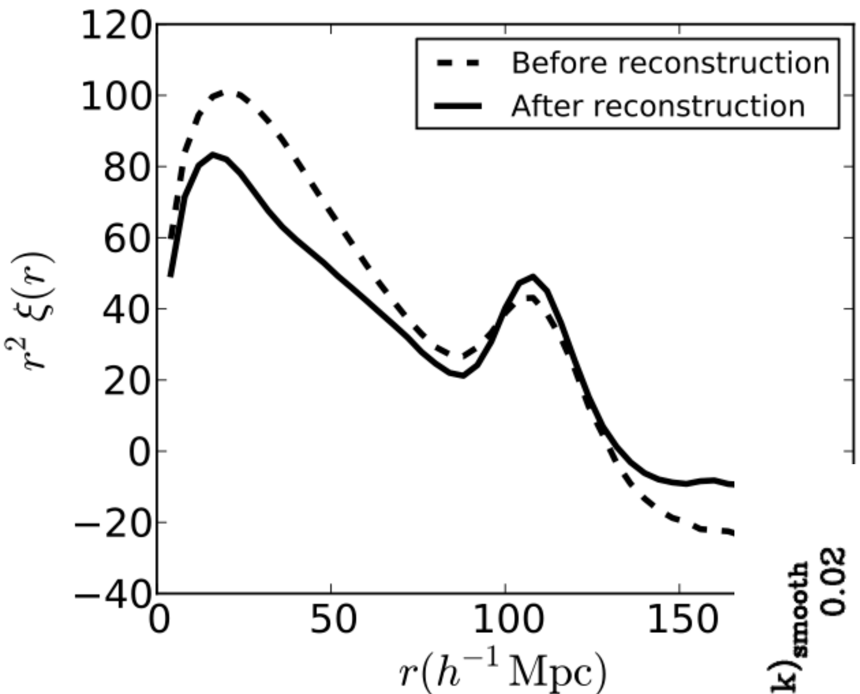
The RSD term limits fast calculation of the expected displacements as it is not irrotational, and depends on a varying line-of-sight

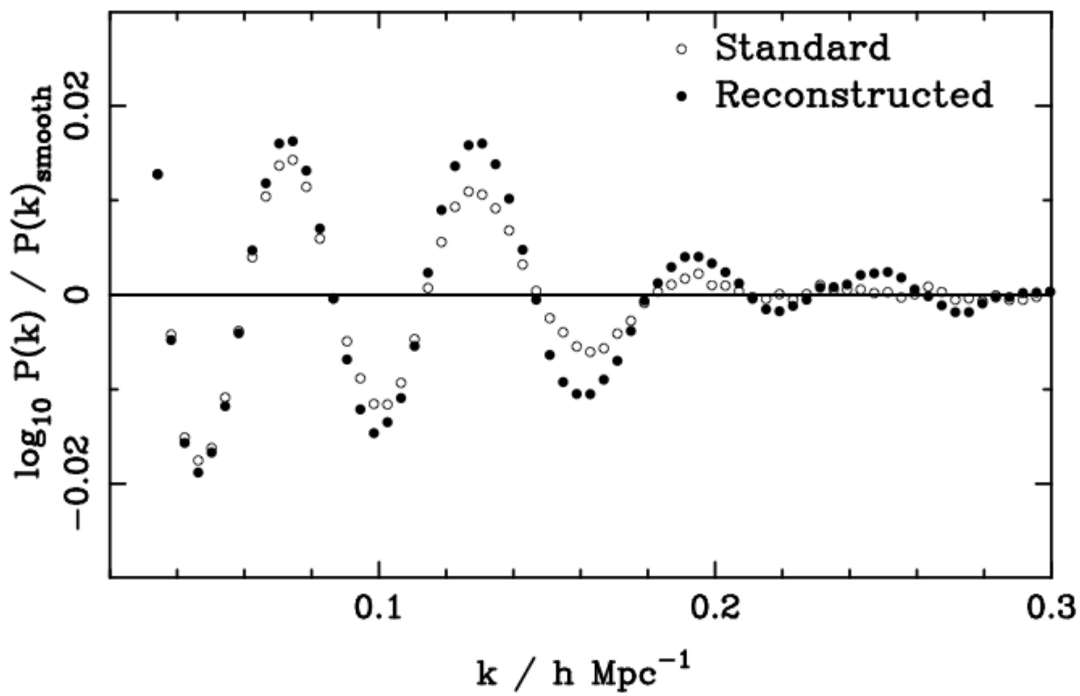
Introduce a new iterative method, allowing use of FFTs, but iterative procedures are a concern for a pipeline …



Burden et al. 2014; arXiv:1408.1348, Burden et al. 2015; arXiv: 1504.02591

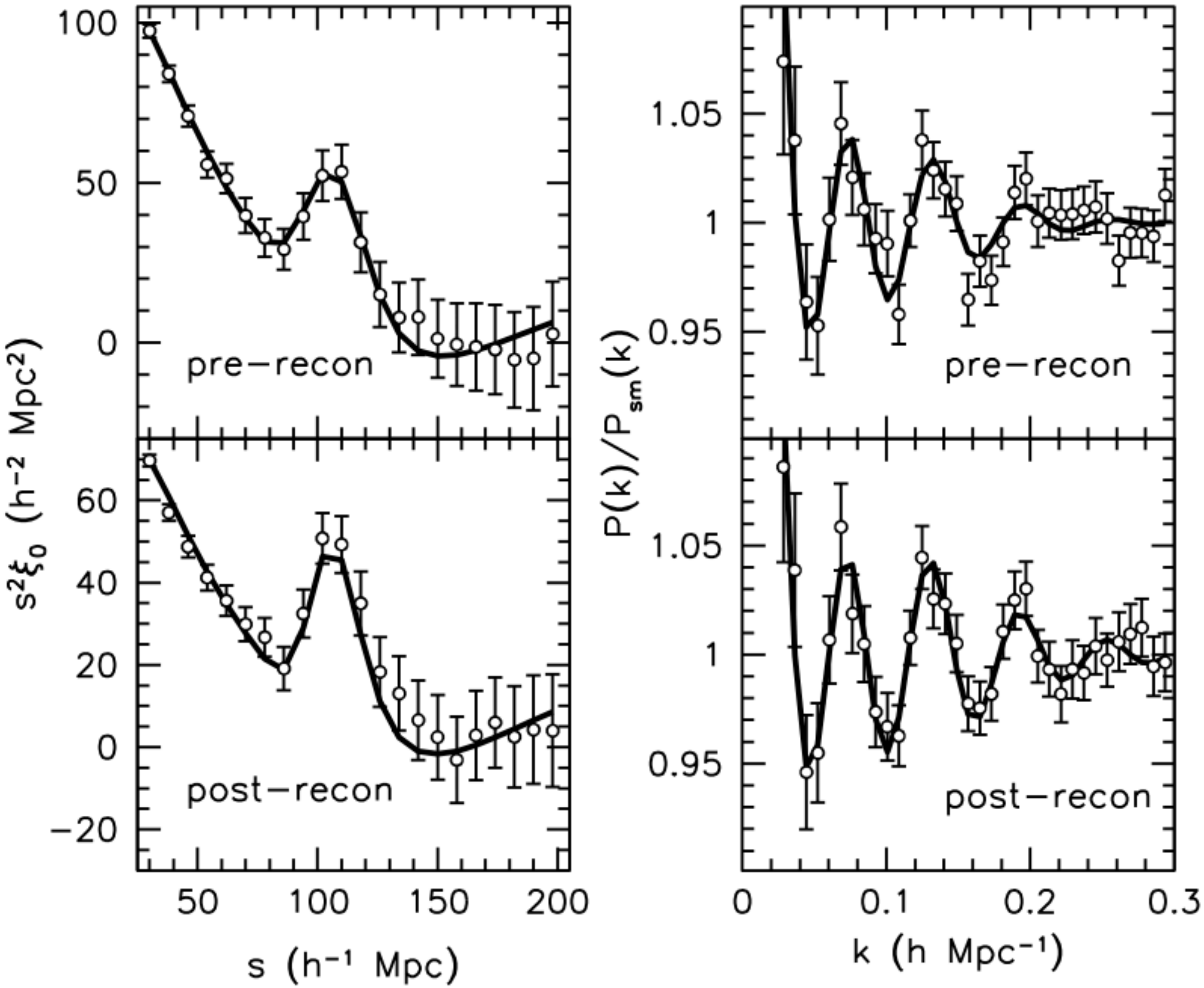
Reconstruction on SDSS-III mocks





Anderson et al. 2012; arXiv:1203.6565

The improvement from reconstruction



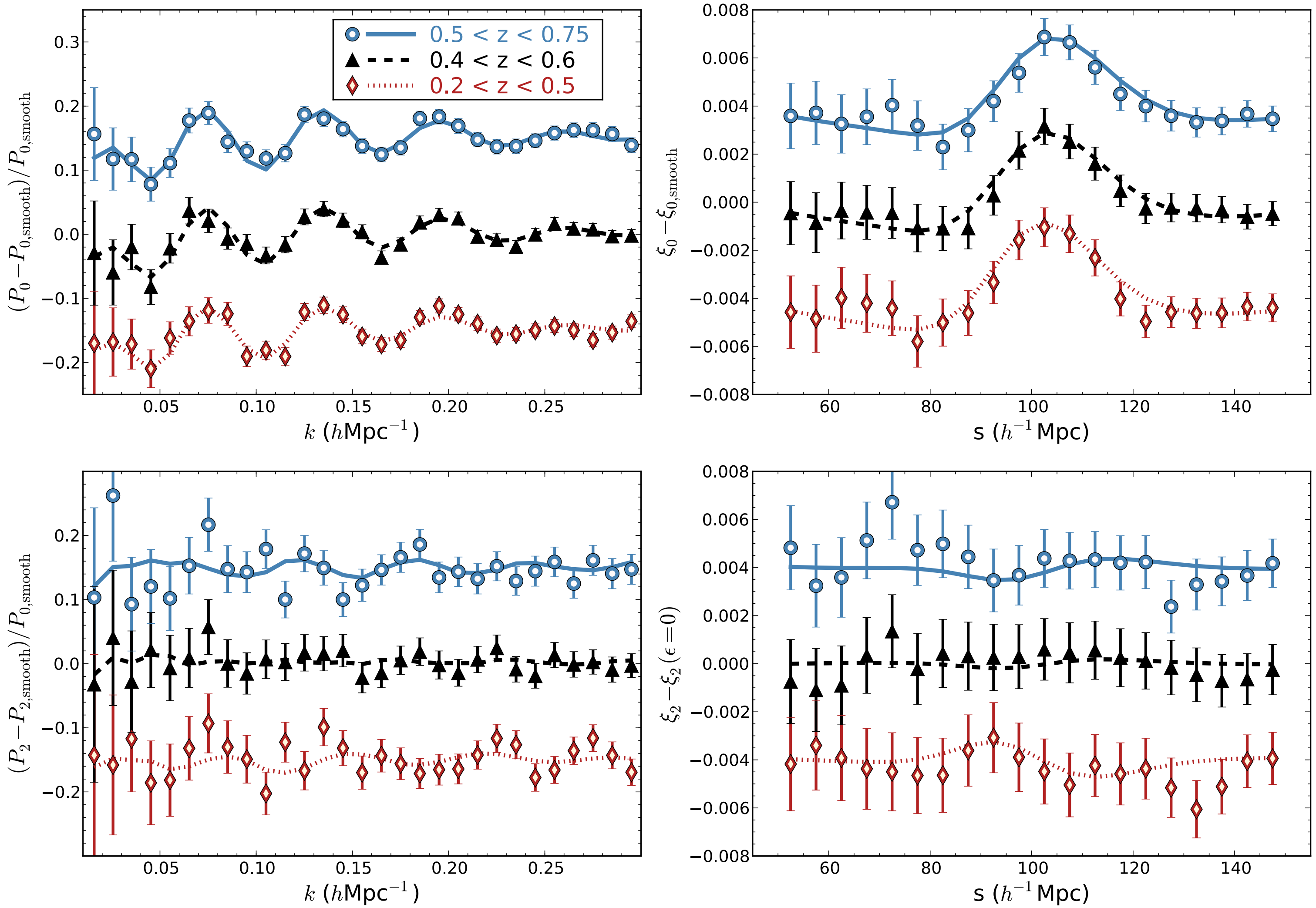
Anderson et al. 2013; arXiv:1312.4877

Other reconstruction methods / devlopments

- Gaussianisation
  - Weinberg 1992, MNRAS, 254, 315
- Path interchange Zeldovich approximation (PIZA)
  - Croft & Gaztanaga 1997, MNRAS, 285, 793
- Incompressible fluid assumption
  - Mohayaee & Sobolevskii 2007, Physica D 237, 2145
- Improvement on “simple” scheme using optimized filters
  - Tassev & Zaldarriaga 2012, JCAP, 10, 6
- MCMC fit to observed data
  - Wang et al. 2013, ApJ, 772, 63
- Full Bayesian reconstruction of initial fluctuations
  - Jasche & Wandelt 2013, MNRAS 432, 894
- Isobaric reconstruction
  - Wang et al. 2017, arXiv:1703.09742
- Iterative reconstruction (repeated standard with different smoothing)
  - Schmittfull, Baldauf & Zaldarriaga, 2017, arXiv:1704.06634

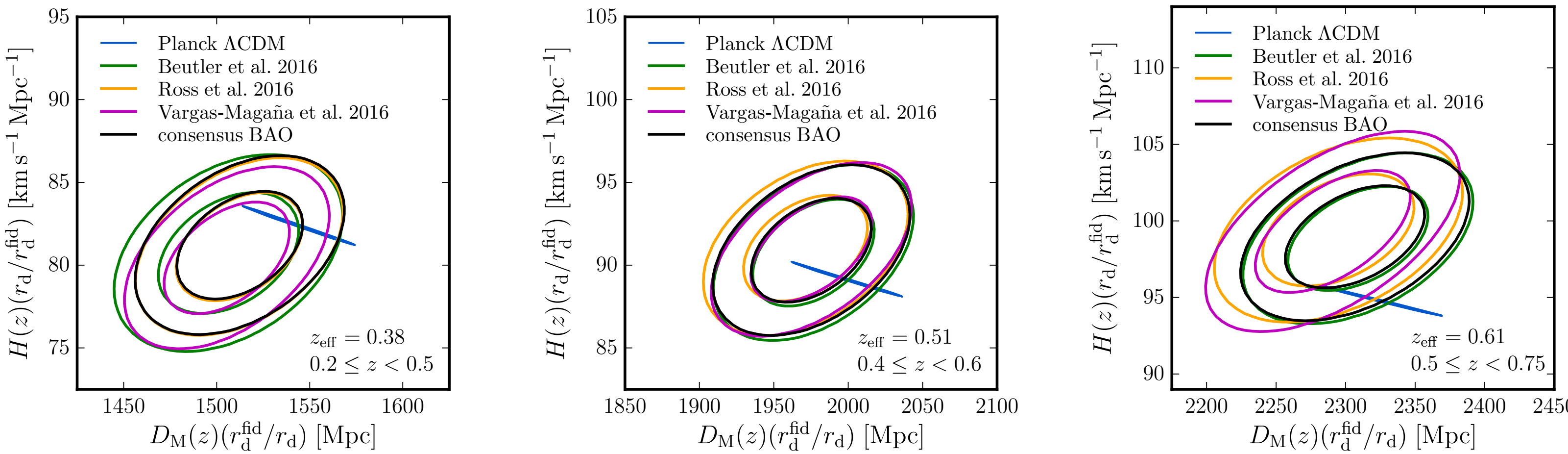
BAO results from BOSS

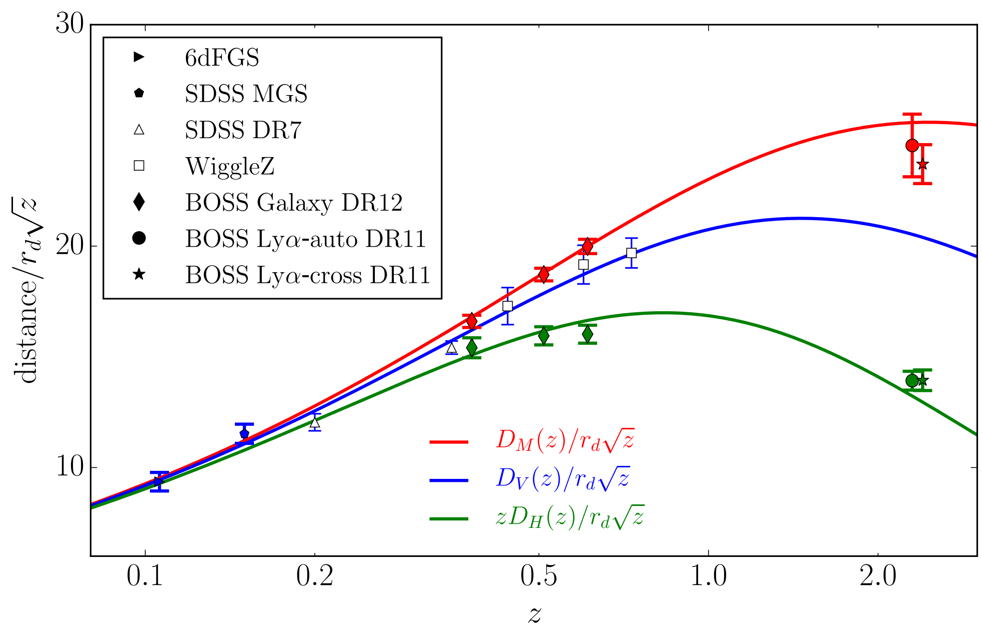
BOSS DR12 clustering measurements



Alam et al. 2016, arXiv:1607.03155

BOSS DR12 BAO measurements





Alam et al. 2016, arXiv:1607.03155

Redshift-space distortions

Comoving velocities

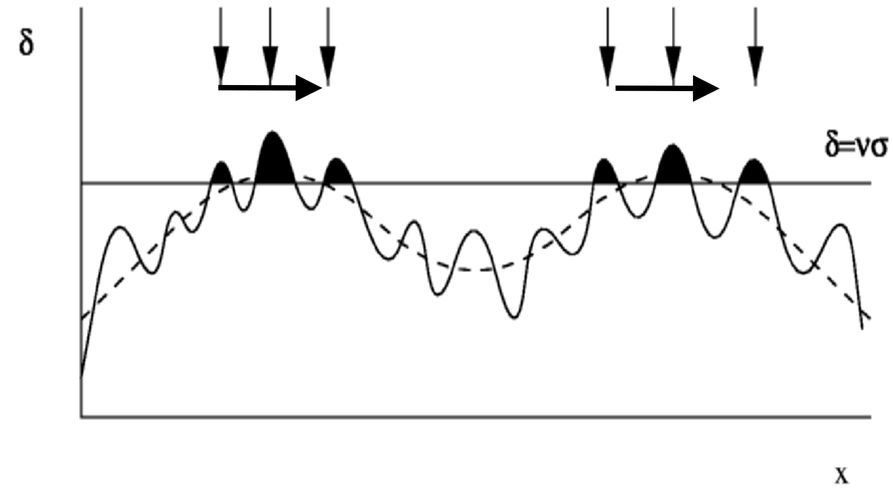
Locally, galaxies act as test particles in the flow of matter

On large-scales, the distribution of galaxy velocities is unbiased if galaxies fully sample the velocity field

expect a small peak velocity-bias due to the statistical distribution of peak motions (in Gaussian random fields) differing from that of the mass

Linear theory:

$$P_u(k) = (aHf)^2 P(k) k^{-2}$$



Redshift-Space Distortions

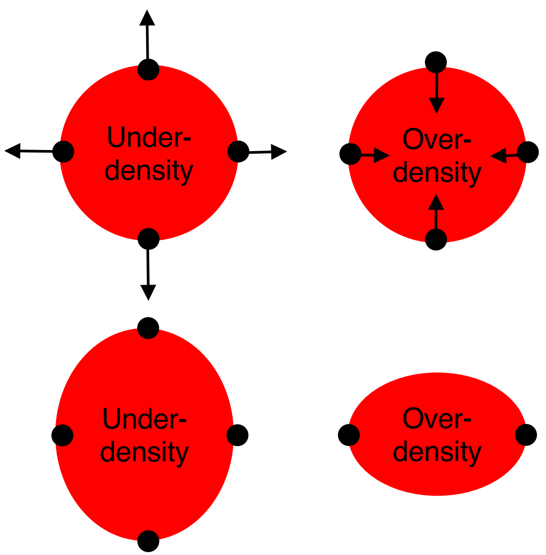
When making a 3D map of the Universe the radial distance is usually obtained from a redshift assuming Hubble's law; this differs from the real-space because of its peculiar velocity:

$$\vec{s}(r) = \vec{r} - v_r(r)\frac{\vec{r}}{r}$$

Where **s** and **r** are positions in redshift- and real-space and v_r is the peculiar velocity in the radial direction

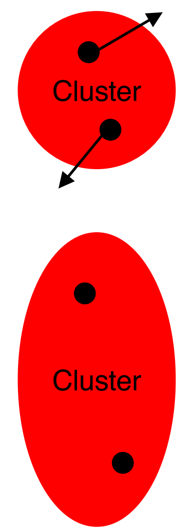
Two key regimes of interest

linear flow



Power is enhanced
on large-scales

non-linear
structure



Actual
shape

Apparent
shape
(viewed from
below)

Power is suppressed
on small-scales

Linear plane-parallel redshift-space

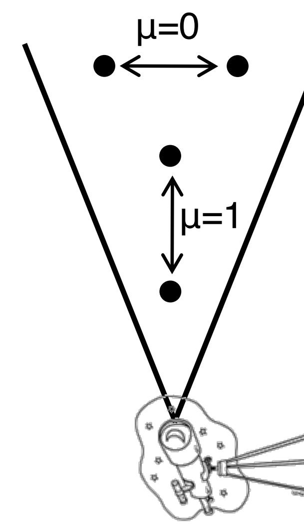
Transition from real to redshift space, with peculiar velocity v **in units of the Hubble flow**

$$\mathbf{s} = \mathbf{r} + v_{\rm los}\hat{\mathbf{r}}_{\rm los}$$

$$\mu = cos(\alpha)$$
$$\theta = \nabla \cdot \mathbf{u}$$

Jacobian for transformation

$$\frac{d^3s}{d^3r} = \left(1 + \frac{v_{\rm los}}{r_{\rm los}}\right)^2 \left(1 + \frac{dv_{\rm los}}{dr_{\rm los}}\right)$$



Conservation of galaxy number

$$n^r(\mathbf{r})d^3r = n^s(\mathbf{s})d^3s \qquad 1 + \delta_g^s = (1 + \delta_g^r)\frac{d^3r}{d^3s}\frac{\bar{n}^r(\mathbf{r})}{\bar{n}^s(\mathbf{s})}$$

Trick to understand velocity field derivative

$$\frac{\partial v_{\rm los}}{\partial r_{\rm los}} = \left(\frac{\partial}{\partial r_{\rm los}}\right)^2 \nabla^{-2}\theta = \left(\frac{k_{\rm los}}{k}\right)^2 \theta = \mu^2\theta, \quad \theta = \nabla \cdot \mathbf{v}$$

Gives to first order

$$\delta_g^s = \delta_g^r - \mu^2\theta$$

Kaiser 1987, MNRAS, 227, 1

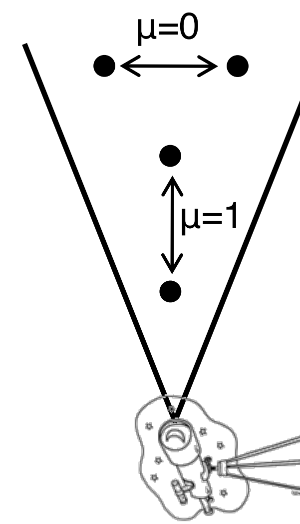
what do linear z-space distortions measure?

Linear scales

Assumed both μ same (local plane-parallel)

$$
\begin{aligned}
\delta_g^s(\mu) &= \delta_g + \mu^2\theta \\
P_g^s(\mu) &= \langle|\delta_g + \mu^2\theta|^2\rangle \\
&= P_{gg} + 2\mu^2 P_{g\theta} + \mu^4 P_{\theta\theta}
\end{aligned}
$$

$$
\begin{aligned}
\mu &= cos(\alpha) \\
\theta &= \nabla\cdot\mathbf{u}
\end{aligned}
$$



Galaxy-galaxy power

Velocity-velocity power

Galaxy-velocity divergence cross power

In linear regime

$$\delta_g = b\delta(\mathrm{mass}),\ \ \theta = -f\delta(\mathrm{mass}),\ \ f \equiv \frac{d\ln G}{d\ln a}$$

Linear growth rate

So, the simplest model for the galaxy power spectrum is

$$P_g^s(k,\mu) = \left[b + \mu^2 f\right]^2 P_{\mathrm{mass}}(k)$$

Kaiser 1987, MNRAS, 227, 1

The break-down of the simple model

- Real-Redshift space mapping
  - Kaiser formula first order in δ and θ
  - on small scales, we need 2nd and 3rd order (δ, θ cross) terms
  - assumes irrotational velocity field
- Non-linear density field evolution
  - P_{gg} breaks from linear behaviour (small scale, late time)
- Non-linear velocity field evolution
  - $P_{\theta\theta}$ breaks from linear behaviour (small scale, late time)
  - Fingers-of-God
- Plane-parallel approximation breaks down for galaxy pairs with wide angular separation
- Assumes local, deterministic density bias

Including small-scale FOG

Include model for linear and FOG damping

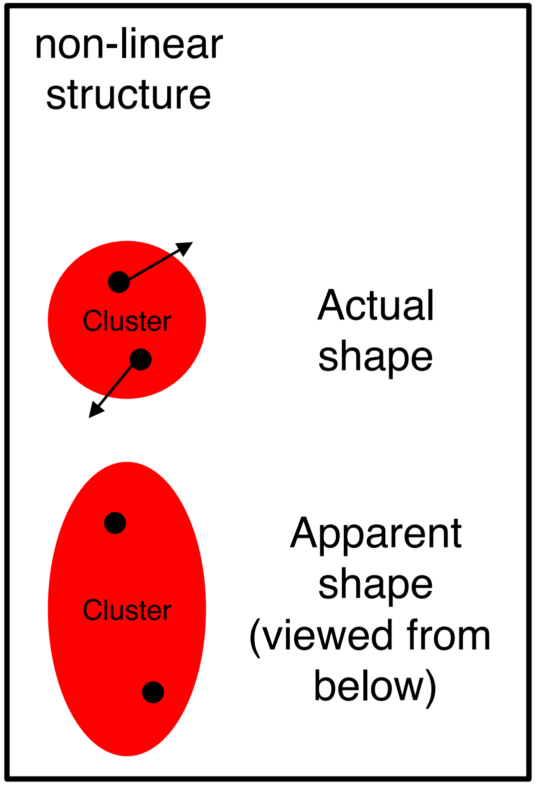
$$P_g^s(k,\mu) = \left[P_{gg}(k) + 2\mu^2 P_{g\theta}(k) + \mu^4 P_{\theta\theta}(k)\right] F(k,\mu^2)$$

If we assume linear bias

$$P_g^s(k,\mu) = P_m^r(k)\left[b^2 + 2\mu^2 fb + \mu^4 f^2\right] F(k,\mu^2)$$

On small scales, galaxies lose all knowledge of initial position. If pairwise velocity dispersion has an exponential distribution (superposition of Gaussians), then we get this damping term for the power spectrum.

$$F(k,\mu^2) = (1 + k^2\mu^2\sigma_p^2/2)^{-1}$$



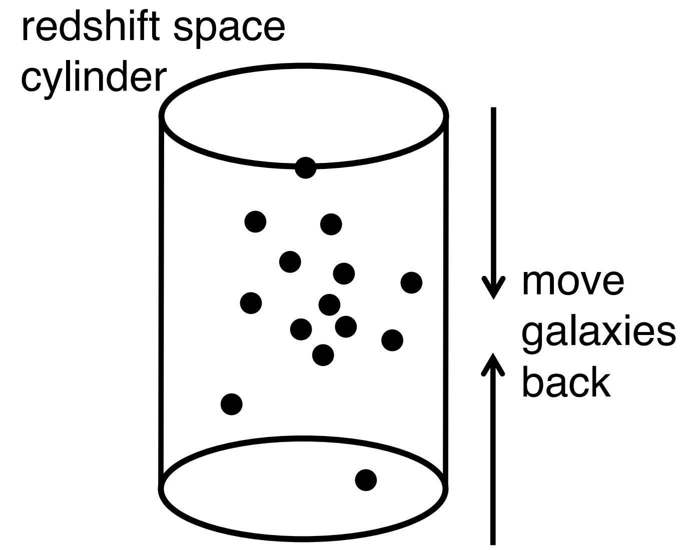
Including small-scale FOG

Alternative for the data is to try to “correct” the data by “collapsing the clusters”

- Velocity dispersion of the Luminous Red Galaxies (LRGs) shifts them along the line of sight by ~ 9 h^{-1}Mpc, and the distribution of intra-halo velocities has long tails.

- Use an asymmetric “friends-of-friends” (FOF) finder to match galaxies in the same clusters, and collapse to spherical profile

- Parameters of FOF calculated by matching simulations



Reid et al. 2008, arXiv:0811.1025; Reid et al. 2009, arXiv:0907.1659

The streaming model

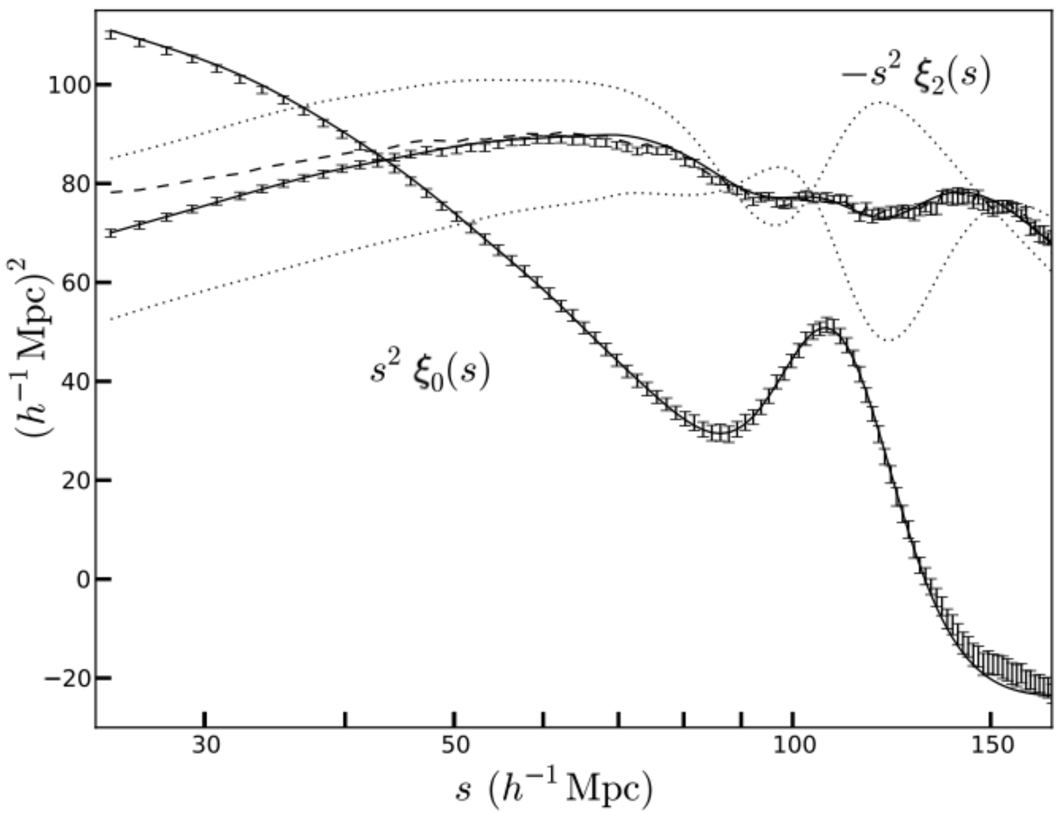
Another way of thinking about RSD is to work with the correlation function using the streaming model

$$1 + \xi_S(s_\perp, s_\parallel) = \int dr_\parallel \; [1 + \xi_R(r)] P(r_\parallel - s_\parallel | \mathbf{r})$$

Modeling RSD is now the same as modeling P, which has previously been modeled with:

- A Gaussian
    - Reid & White 2011, MNRAS 417, 1913
- An Edgeworth streaming model
    - Uhlemann, Kopp & Haugg 2015, PRD 82, 063522)
- A Gaussian distributed set of Gaussians
    - Bianchi, et al. 2015, MNRAS 446, 75
- A skewed distribution of Gaussians
    - Bianchi et al. 2016, MNRAS 463, 3783

RSD versus AP effects



Varying $D_A H$ by 10%, while keeping peak position in monopole fixed

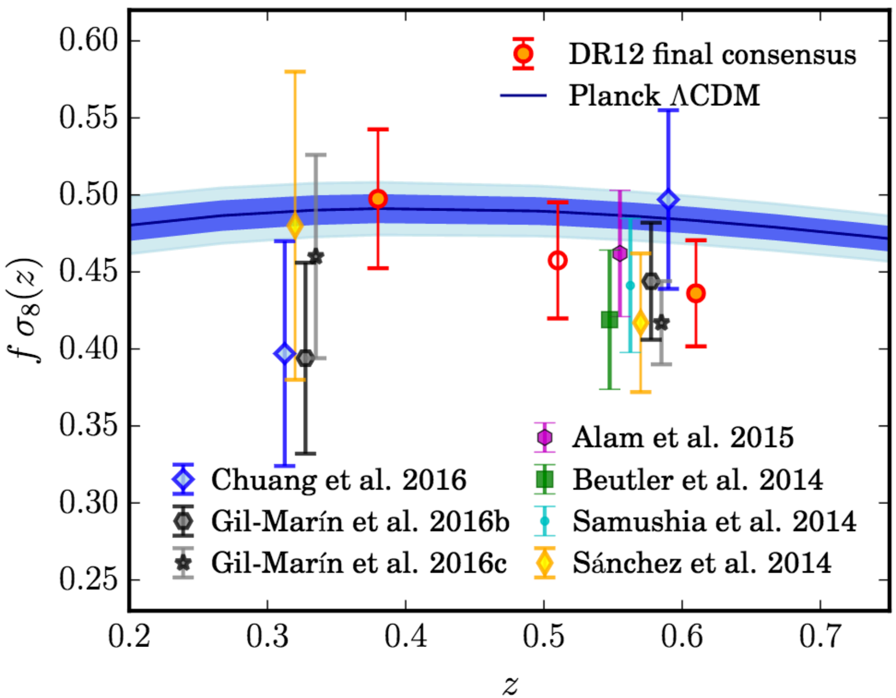
Linear RSD shift is scale-independent for both

- AP moves ξ(r) in scale (left-right).
- Movement of BAO "bump" is clear.
- Shape of ξ(r) close to power law, so AP is very similar to amplitude shift (as RSD).
- Allows measurements of F & $f\sigma_8$ to be separated

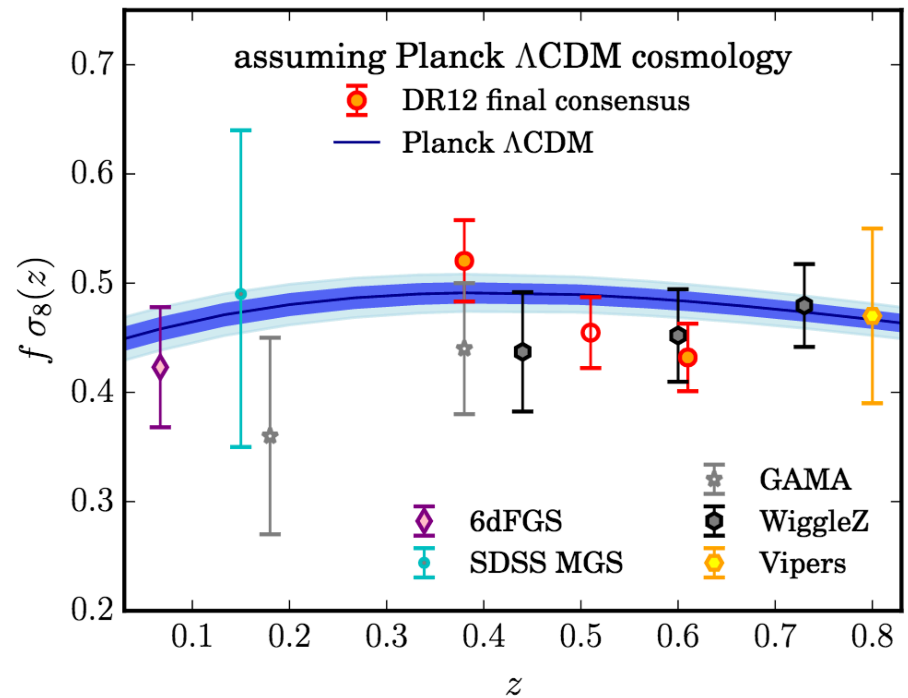
Reid et al. 2012; arXiv:1203.6641

RSD measurements from BOSS

BOSS DR12 RSD measurements



Measurements from BOSS



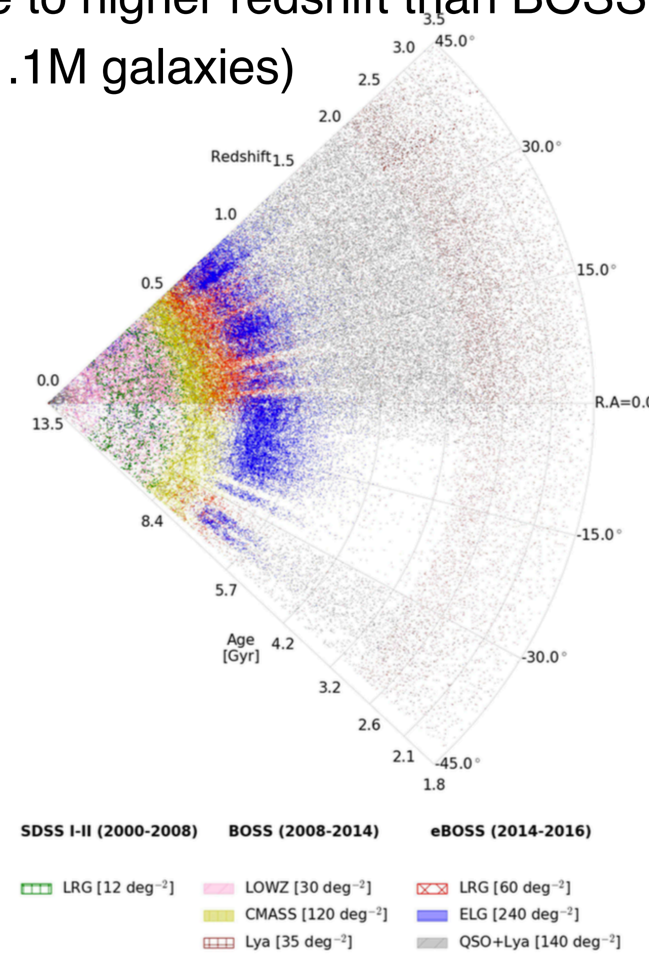
Comparison between BOSS and other surveys

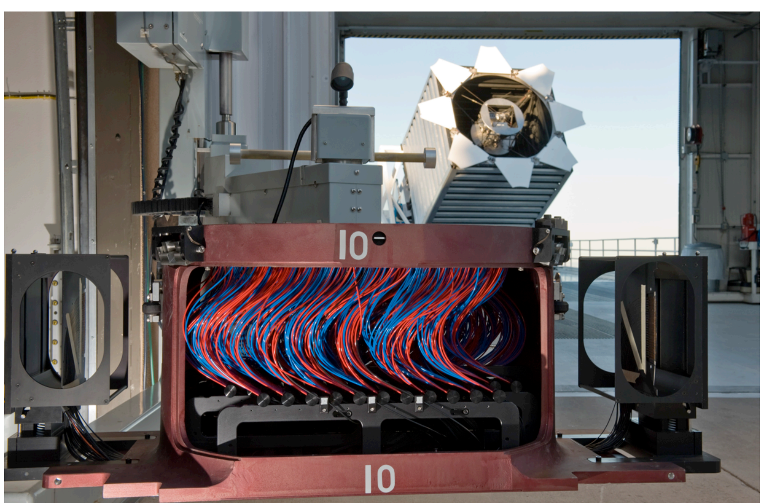
Alam et al. 2016, arXiv:1607.03155

Ongoing survey: eBOSS

eBOSS / SDSS-IV

- extended Baryon Oscillation Spectroscopic Survey (eBOSS)
- Ongoing cosmological galaxy survey within SDSS
- Use the Sloan telescope and MOS to observe to higher redshift than BOSS
- Basic parameters (cmpr BOSS 10,000deg^2, 1.1M galaxies)
  - Ω = 1,500deg^2 – 5,300deg^2
  - 300k 0.6<z<0.9 LRGs (direct BAO, RSD)
  - 200k 0.8<z<1.0 ELGs (direct BAO, RSD)
  - 600k 0.9<z<2.2 QSOs (direct BAO, RSD)
  - 60k QSOs (BAO, RSD from Ly-α forest)
- Survey started 2014, lasting 6 years

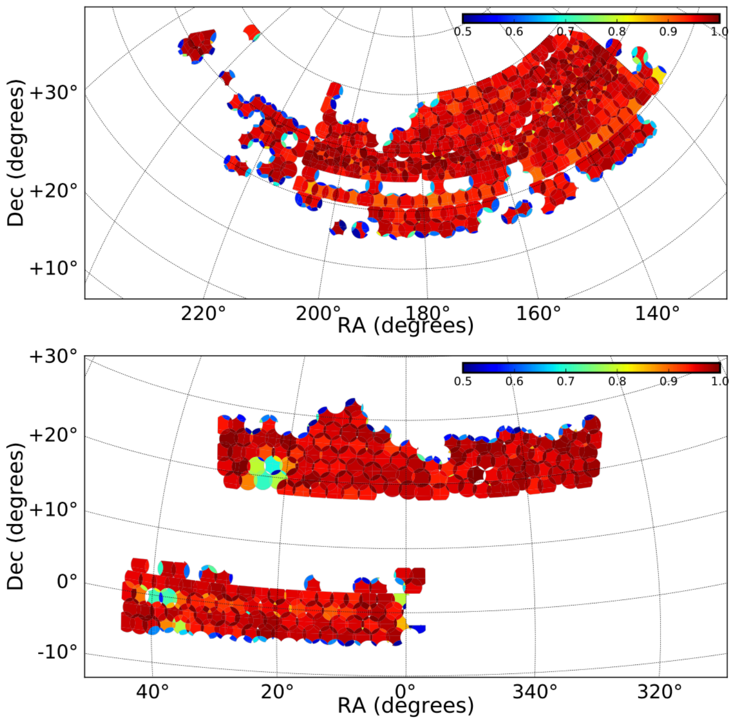




Dawson et al. 2015; arXiv:1508.04473, Zhao et al. 2015; arXiv:1510.08216

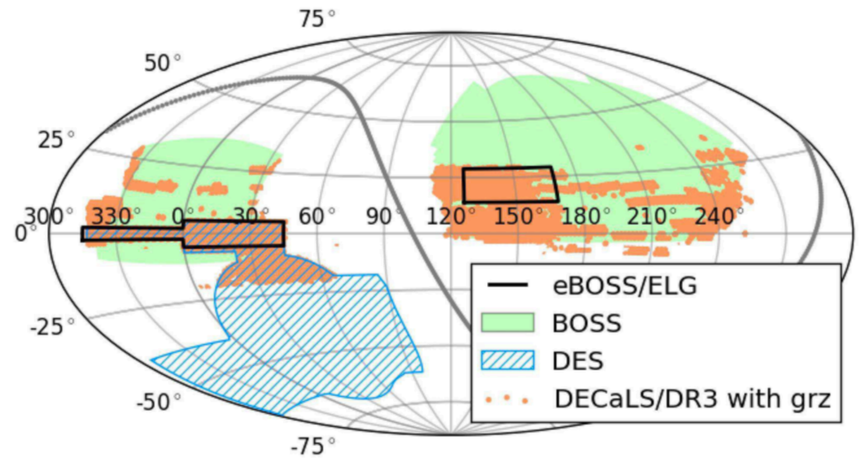
eBOSS footprint

QSO DR14 (data set currently being analysed by the team)



~2,000deg^2 split in the NGC and SGC regions (final area will be ~5,300deg^2)

Projected ELG map (being observed over the next 2 years)

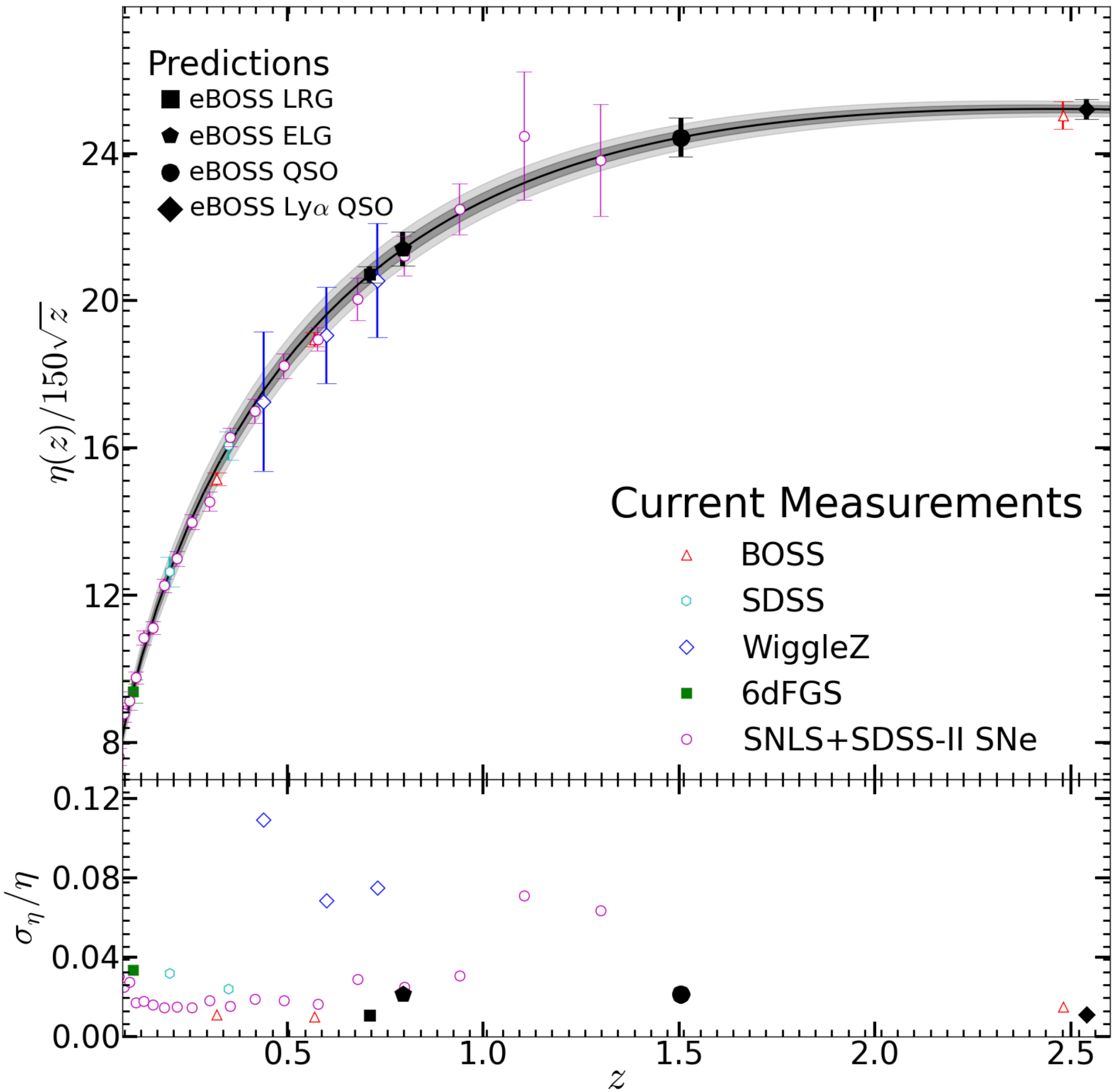


~620 deg^2 over the Fat Stripe 82 in the SGC, covered by DES observations; (317<ra<360 and –2<dec<2) or (0<ra<45 and –5<dec<5);

~600 deg^2 over the NGC, covered by DECaLS observations; (126<ra<169 and 14<dec<29)

Raichoor et al. 2017; arXiv:1704.00338

eBOSS BAO predictions



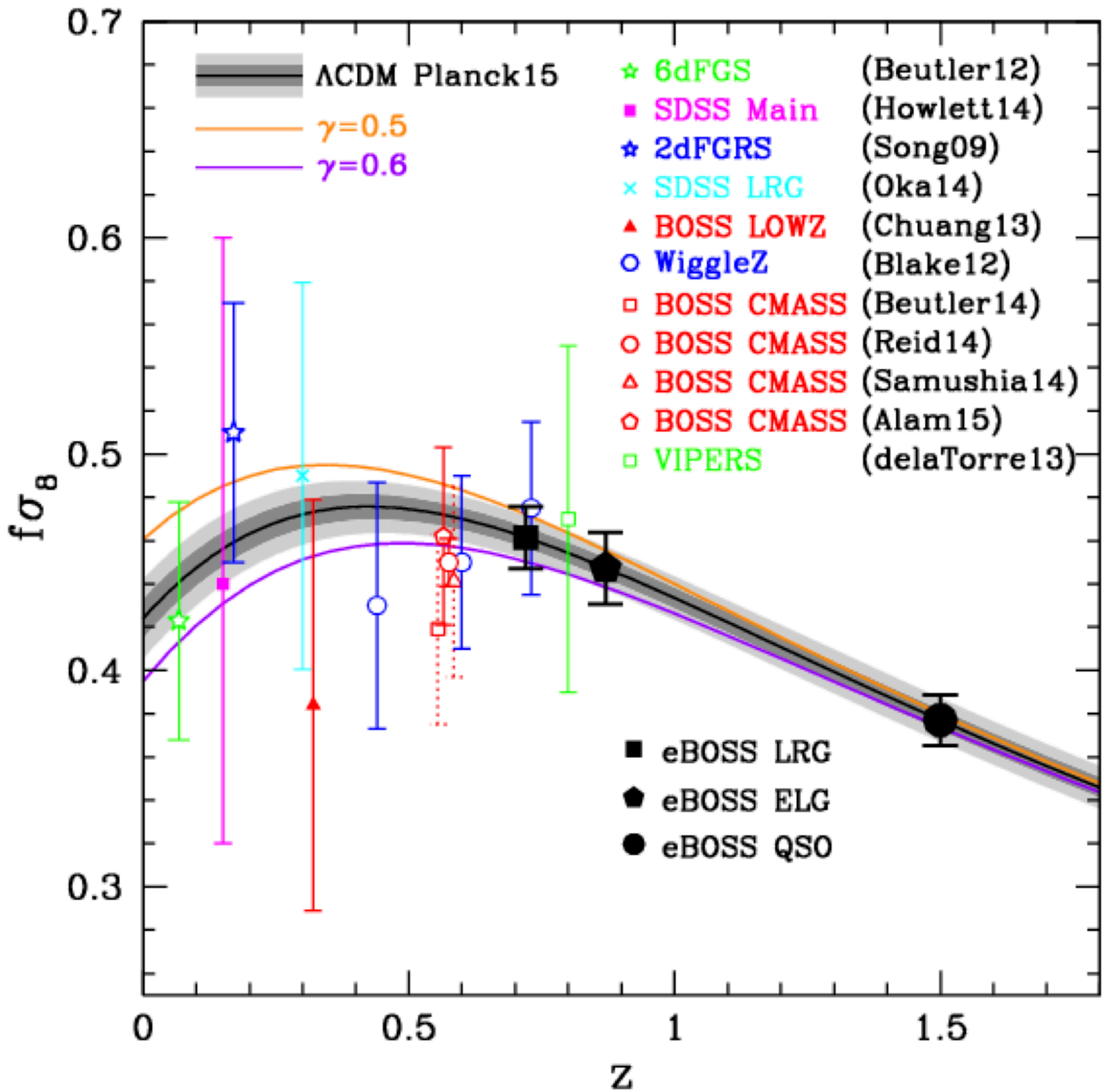
Distance precisions 1-2% on all tracers

- LRG: 0.8%
- ELG: 2%
- QSO: 1.8%

- Lyman-alpha
  - 1.4% on H(z)
  - 1.7% on D_A(z)

Dawson et al. 2015; arXiv:1508.04473, Zhao et al. 2015; arXiv:1510.08216

eBOSS RSD predictions



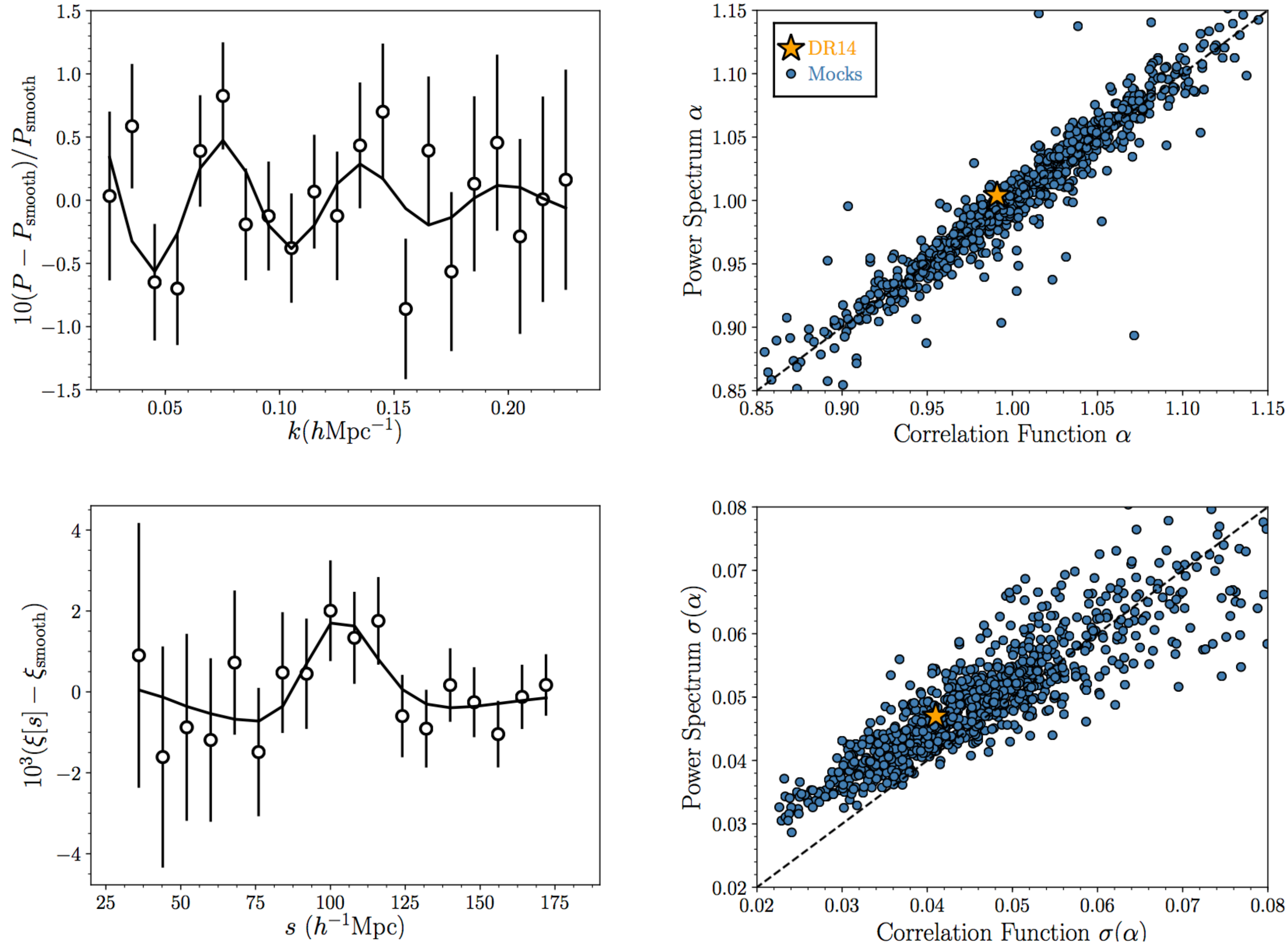
$f\sigma_8$ statistical precisions on galaxy and QSO

- LRG: 2.6%
- ELG: 3.8%
- QSO: 3.2%

Challenge: Theoretical modeling to k_{max}=0.2hMpc^{-1}

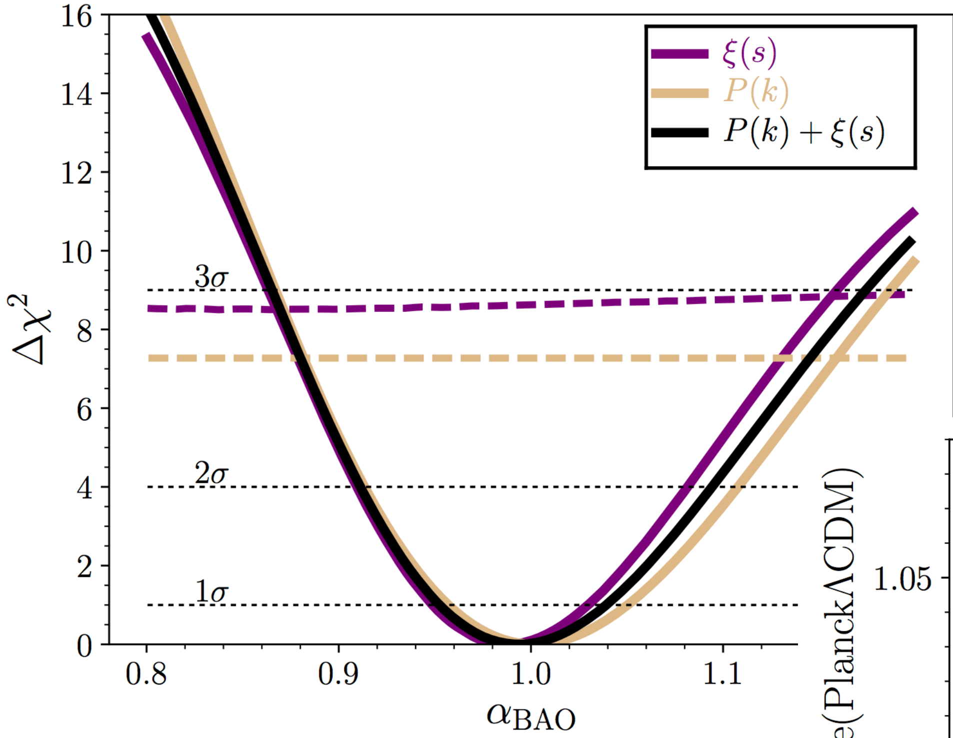
Dawson et al. 2015; arXiv:1508.04473, Zhao et al. 2015; arXiv:1510.08216

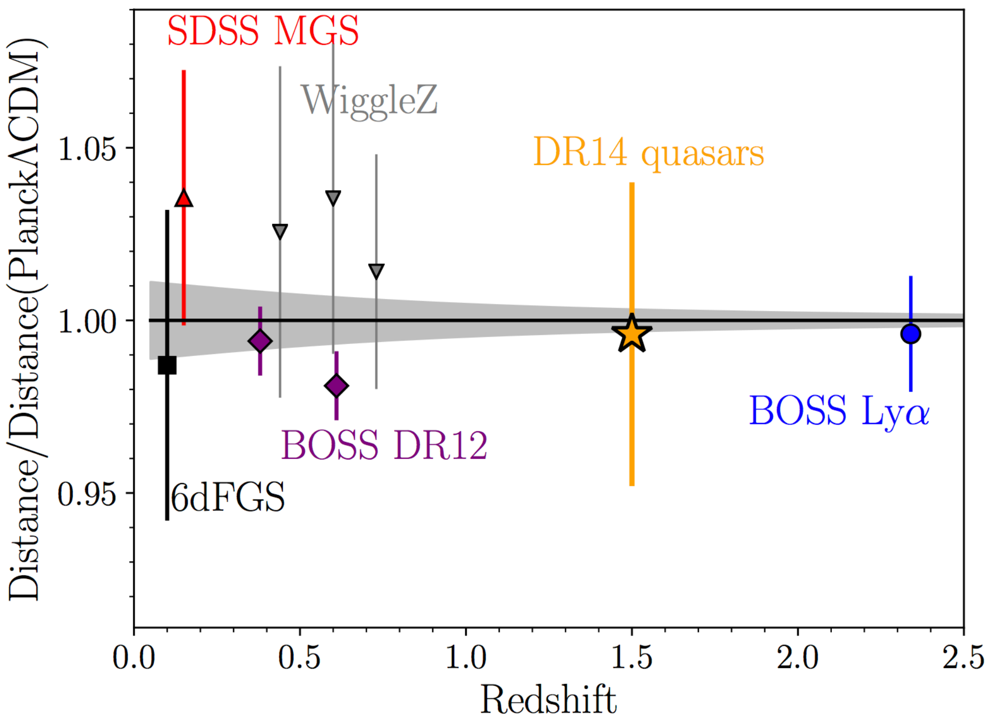
eBOSS DR14: 147,000 quasars



Ata et al. 2017; arXiv:1705.06373

eBOSS DR14: 147,000 quasars



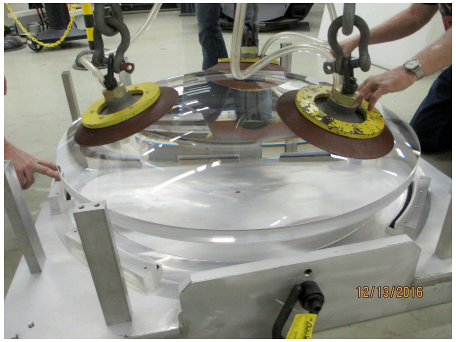


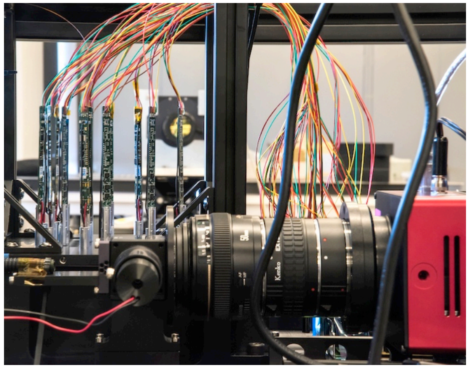
Ata et al. 2017; arXiv:1705.06373

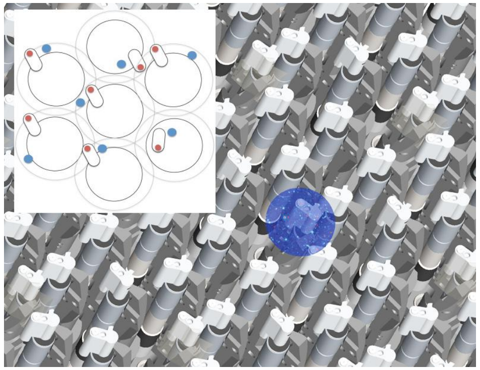
Future surveys: DESI & Euclid

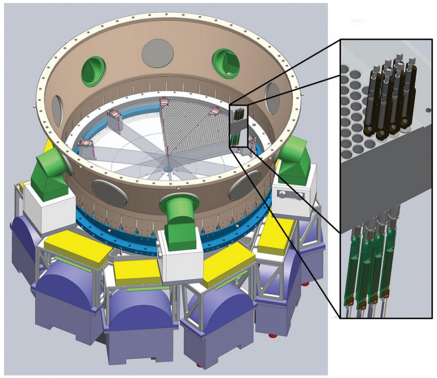
DESI

- Dark Energy Spectroscopic Instrument (DESI)
- New fibre-fed MOS for Mayall
- passed DOE CD-3, on course for 2019 start
- DESI will observe:
  - Ω =14,000deg^2
  - ~20,000,000 high redshift galaxies (direct BAO)
  - ~10,000,000 low redshift (z<0.5) galaxies
  - ~600,000 quasars (BAO from Ly-α forest)
  - Cosmic variance limited to z ~ 1.4
- Also WEAVE (WHT, 2018 start) and 4MOST (VISTA, 2021 start) but fewer fibers, so less optimized for cosmological applications

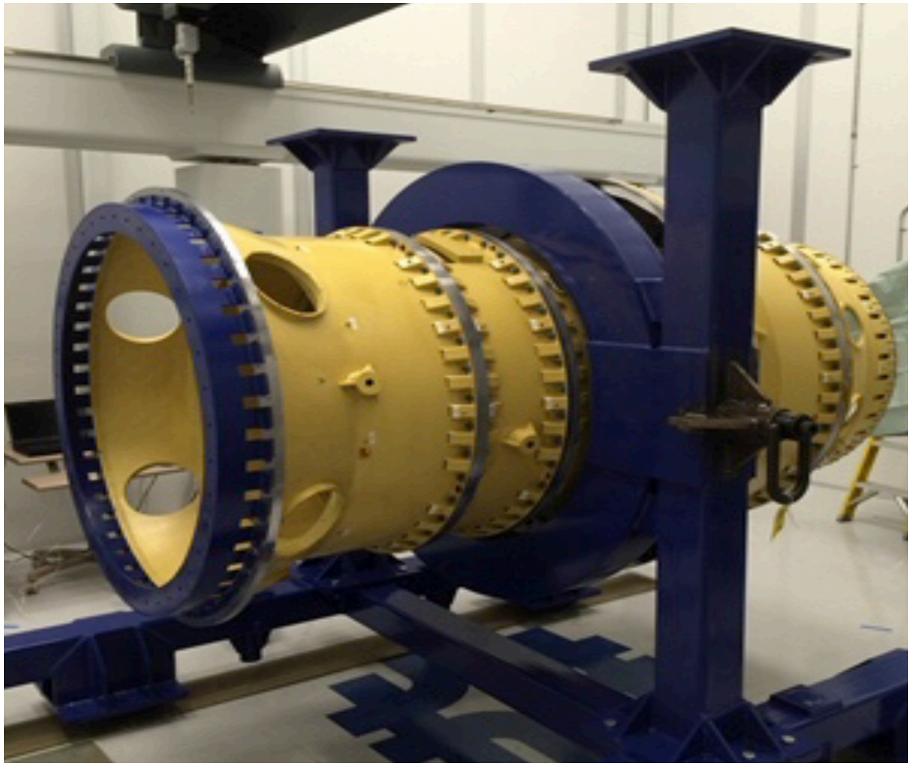






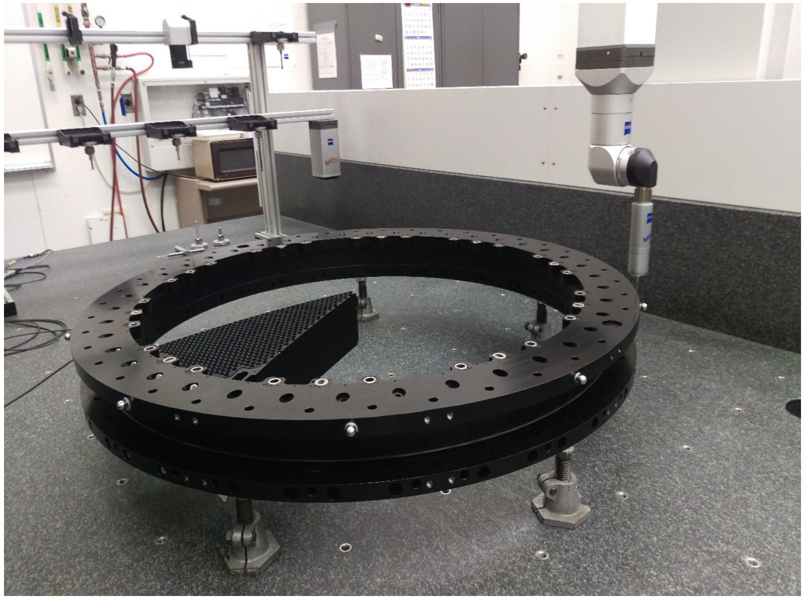


DESI - latest updates

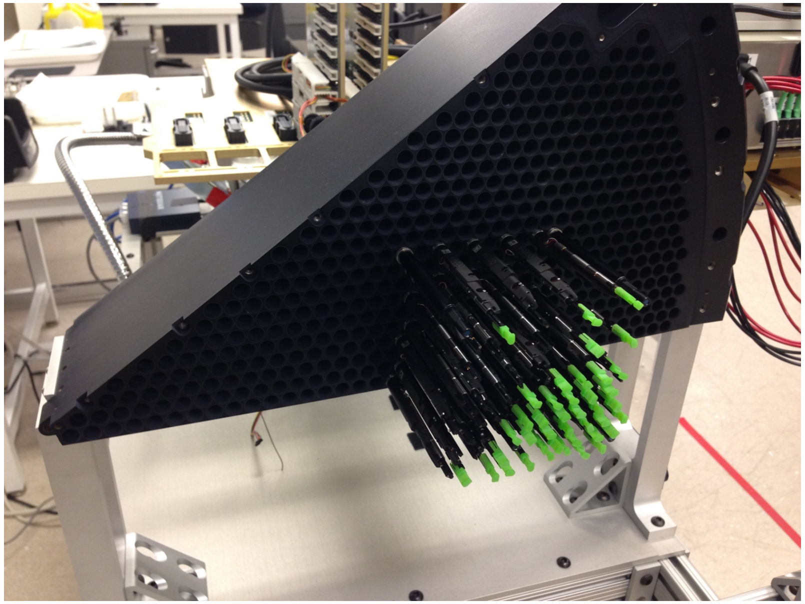


2017 is a critical year for hardware manufacture

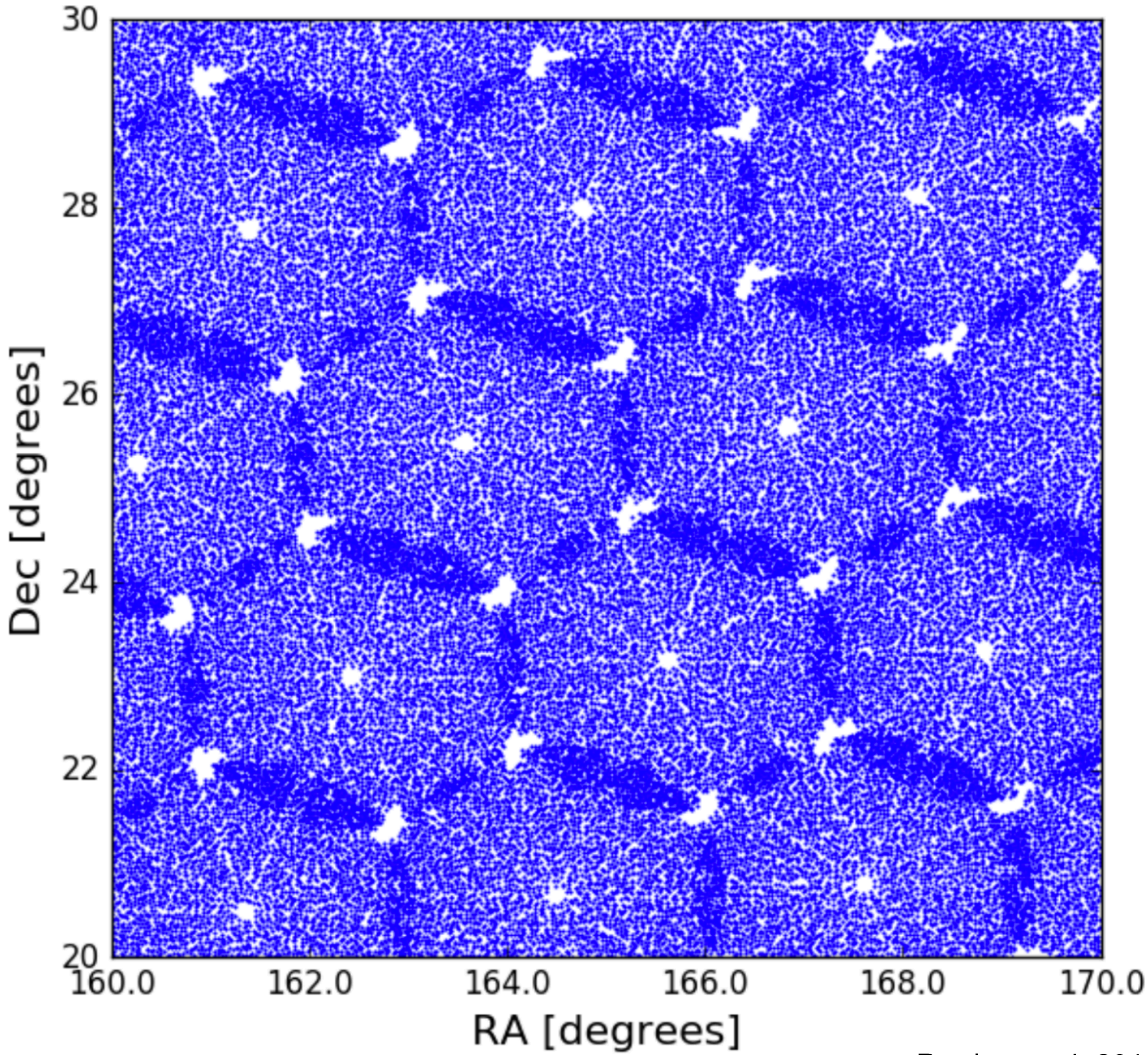
DESI - latest updates



2017 is a critical year for hardware manufacture



DESI observations



Burden et al. 2016; arXiv:1611.04635

Dealing with missing galaxies

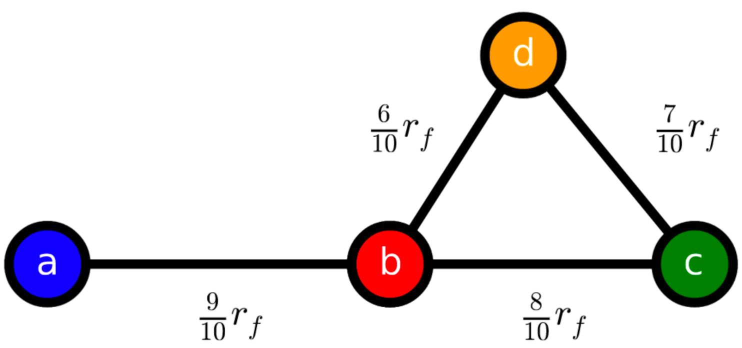
Spectroscopic surveys are always < 100% complete

Missed galaxies are often correlated – either intrinsically (e.g. regions of low S/N), or with the density field (e.g. cannot observe all galaxies in a dense region)

This affects the measured clustering

Bianchi & Percival (2017) Proposed a new correction statistically matching missed pairs (whose radial separation is unknown) with those observed

This has to be done for every pair: 10^6 galaxies -> 10^{12} pairs!



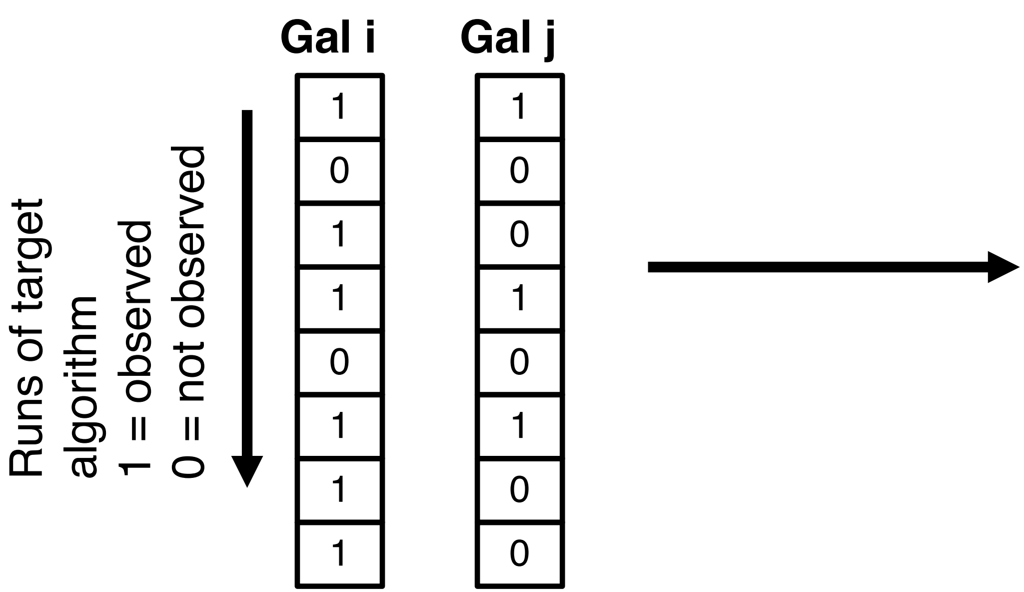
Bianchi & Percival 2017; arXiv:1703.02070

A practical implementation

Link between observed and non-observed pairs based on selection probability:
- different random choices for observations
- different spatial positions of observations

To find the selection probabilities, need to rerun simulation of observing strategy ~1000 times

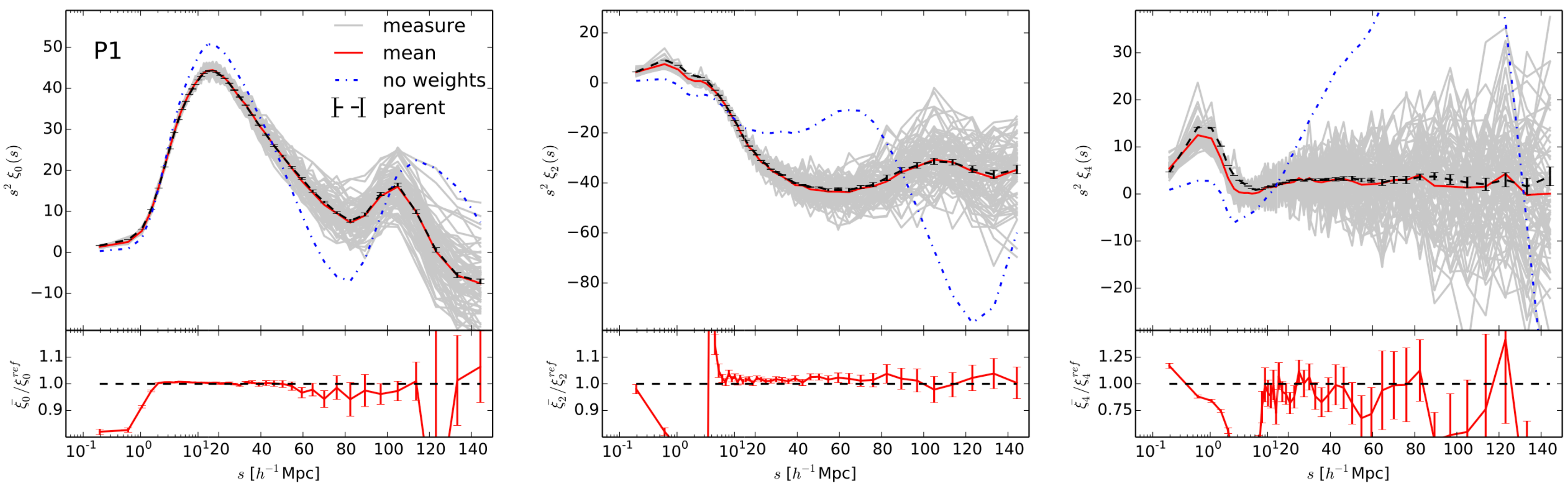
Potentially computationally challenging (storing probabilities), but introduce a new Monte-Carlo scheme based on bitwise weights stored per galaxy, so that pairwise weights can be determined "on the fly"



Probability of observing pair *ij* is 3/8, so weight is 8/3

Bianchi & Percival 2017; arXiv:1703.02070

DESI: Fiber assignment



Bianchi & Percival, in prep

Euclid

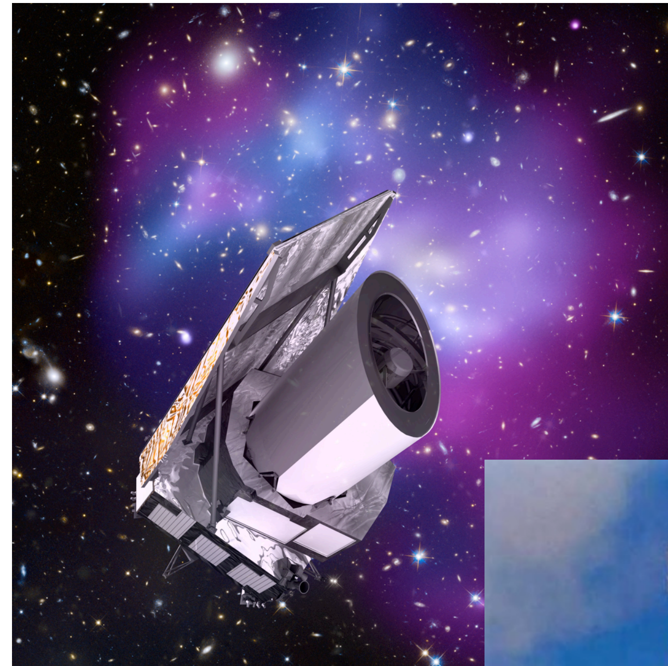
M2 mission in ESA cosmic visions program due to launch late 2020

Wide survey:

- $15{,}000\text{deg}^2$
- 4 passes over sky
- NIR Photometry
  - Y, J, H
  - 24mag, 5σ point source
- NIR slitless spectroscopy
  - red: 1.25-1.85μm (0.9<z<1.8 Hα)
  - $2 \times 10^{-16}\text{ergcm}^{-2}\text{s}^{-1}$ 3.5σ line flux
  - 3 dispersion directions
  - 1 broad waveband 0.9<z<1.8
  - ~25M galaxies
- wide-band visible image for WL

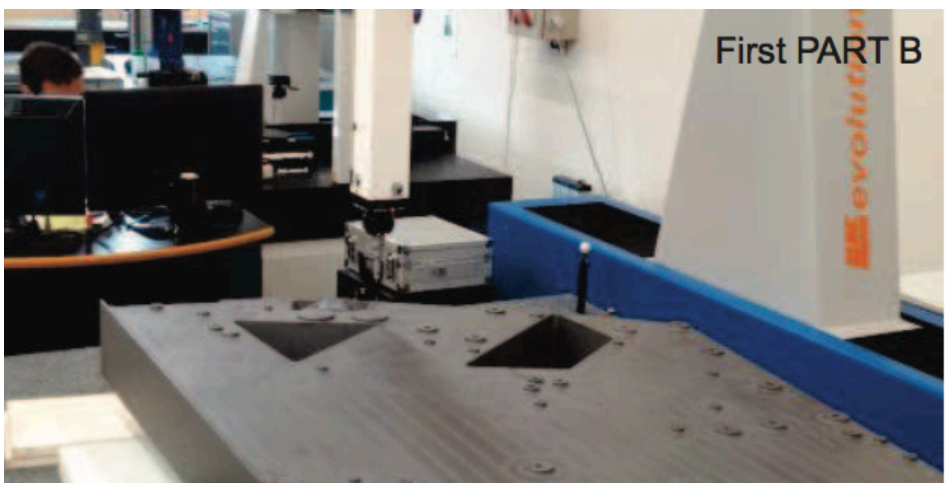
Deep survey:

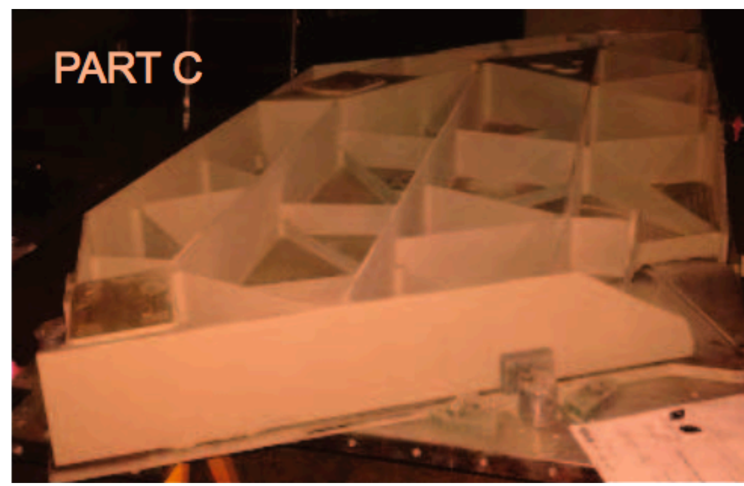
- 40deg^2
- 48 dithers
- 12 passes, as for wide survey
- additional blue spectra: 0.92-1.25μm
- dispersion directions for 12 passes >10deg apart



http://www.euclid-ec.org/

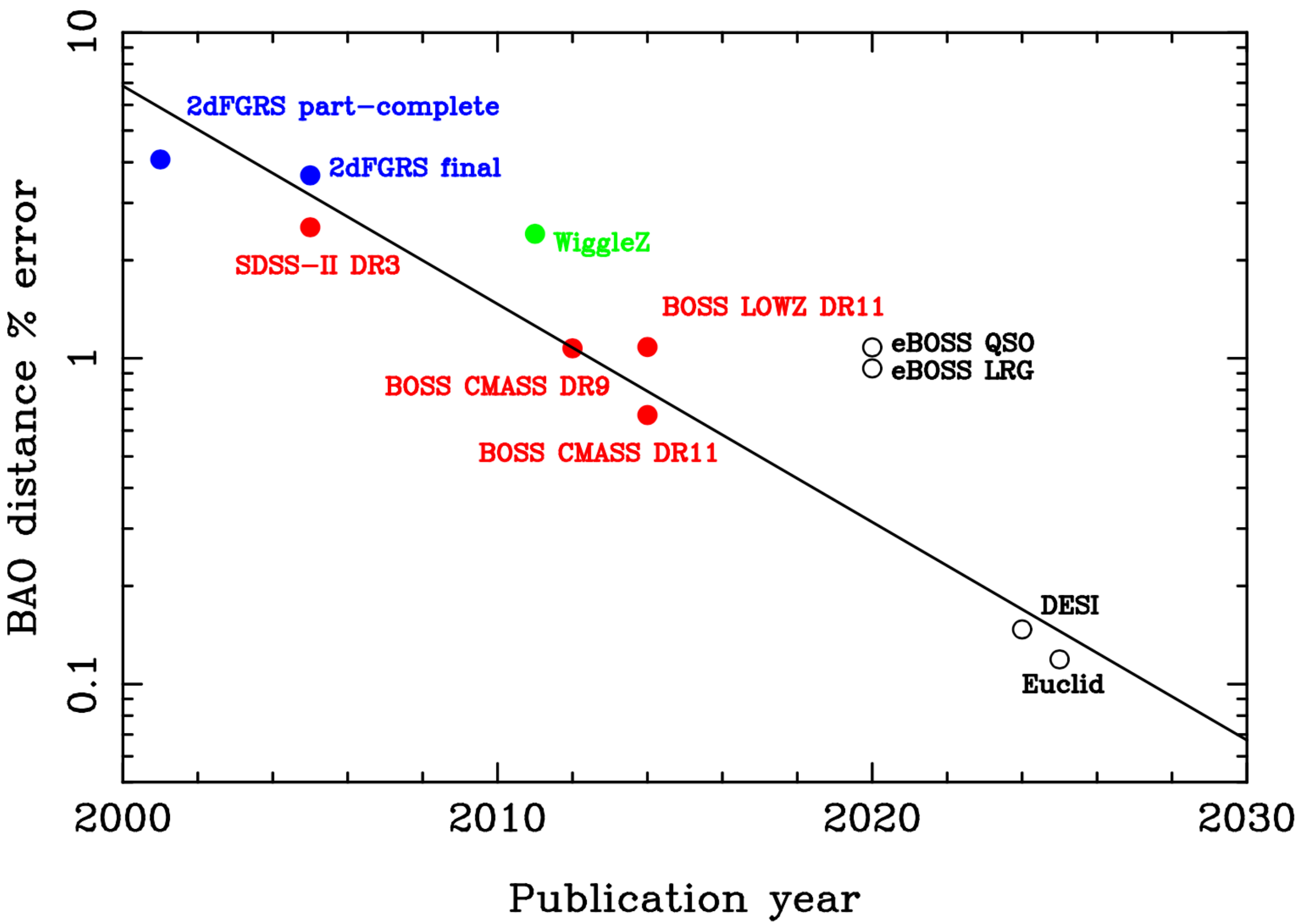
Euclid





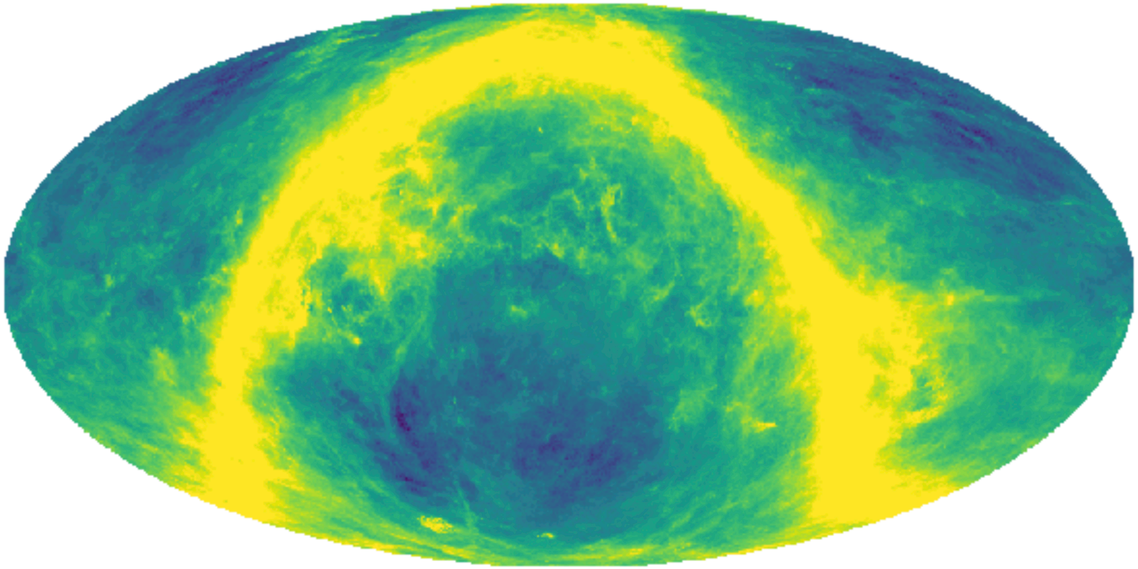
http://www.euclid-ec.org/

BAO errors from past / future surveys

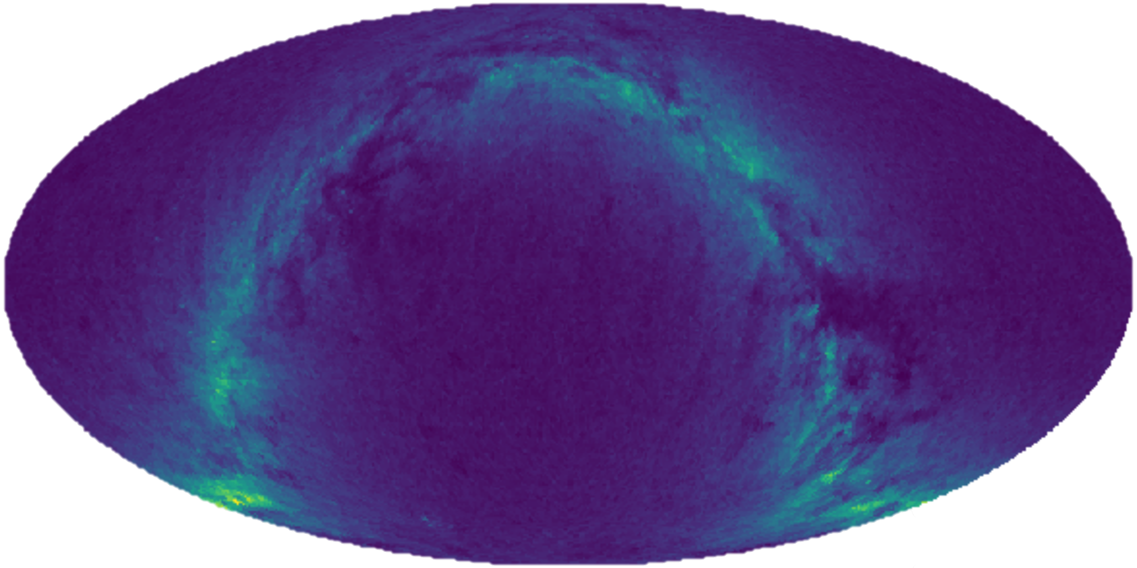


Reid et al. 2015, arXiv:1509.06529

Observational systematics

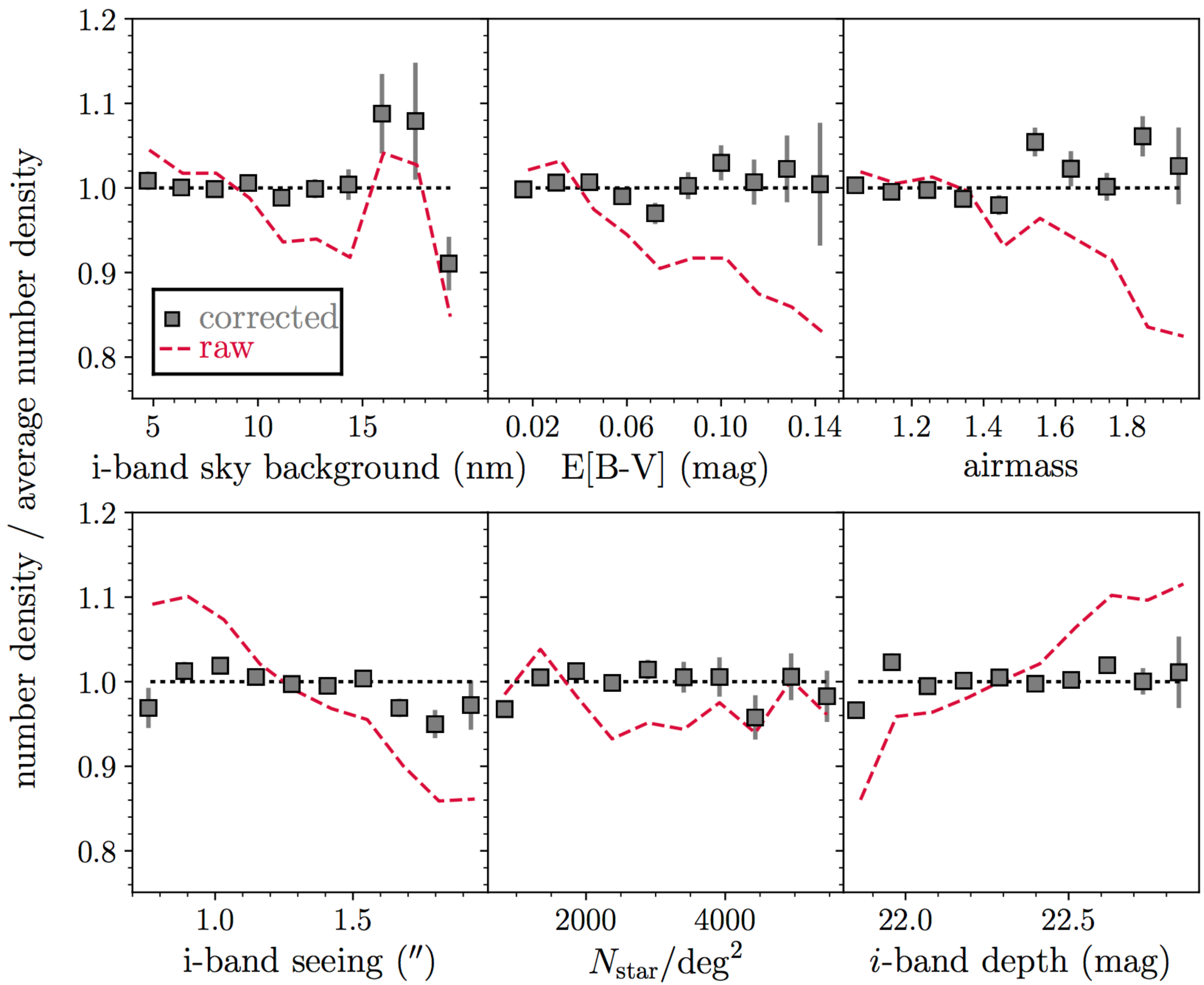


Extinction



Stellar density

Observational systematics



Ata et al. 2017; arXiv:1705.06373

Conclusions - looking to the future

- BOSS DR12 data & measurements publicly now released
  - ξ, P - BAO - agree with Planck LCDM
  - ξ, P - RSD - agree with Planck LCDM

- Future projects will push further out in redshift, number of galaxies and volume covered
  - eBOSS already driving developments in techniques
  - Next generation of surveys (DESI, Euclid) will get an order more galaxies
  - DESI+Euclid complimentary redshift ranges

- Although BAO / RSD now a mature field, still lots of development required
  - better calibration, removal of contaminants
  - Faster, better calculations (computational data challenge)
  - including more information: weights, including Bispectrum
  - Better models (perturbation theory, EFT, baryons …)