Galaxy Redshift Surveys

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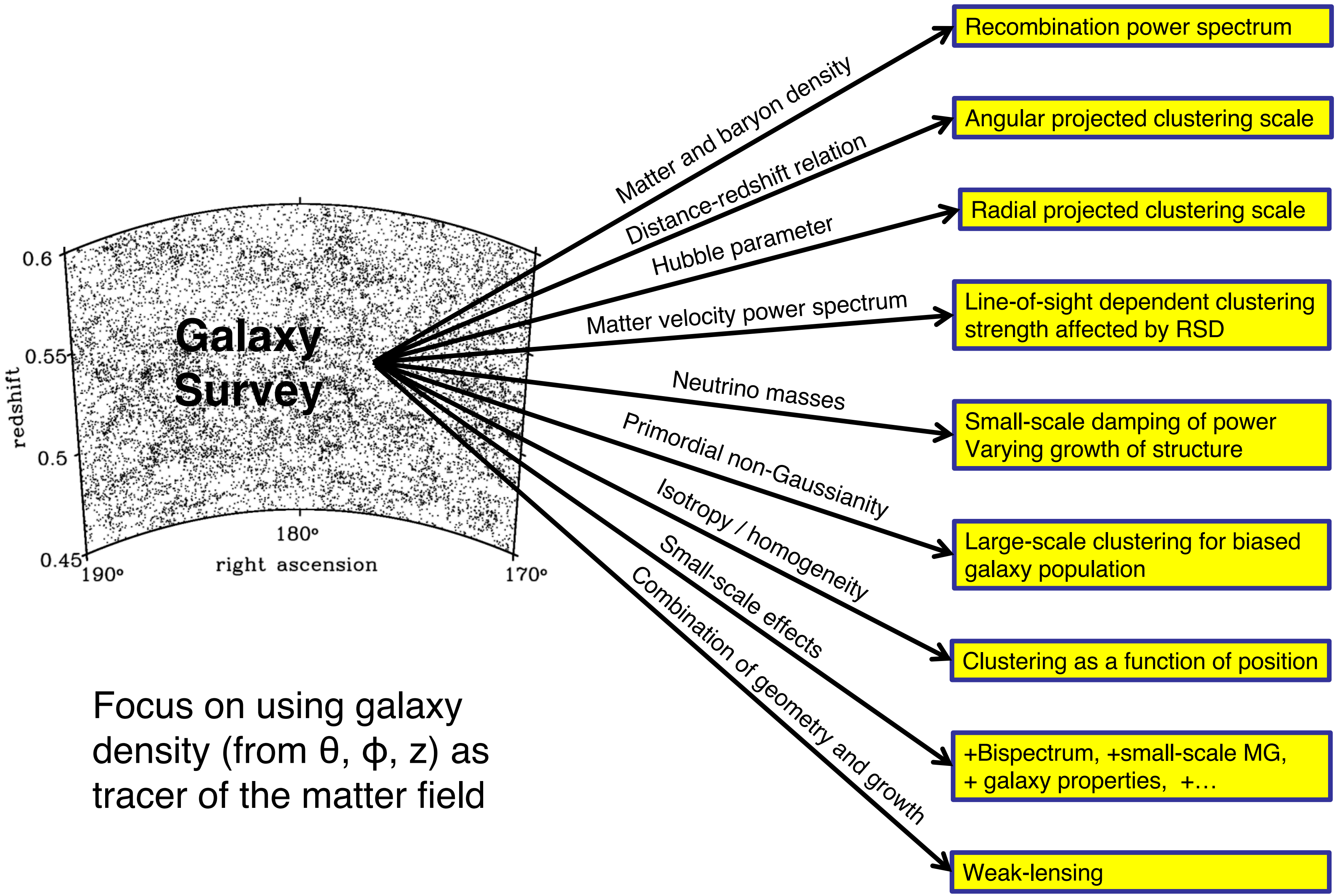
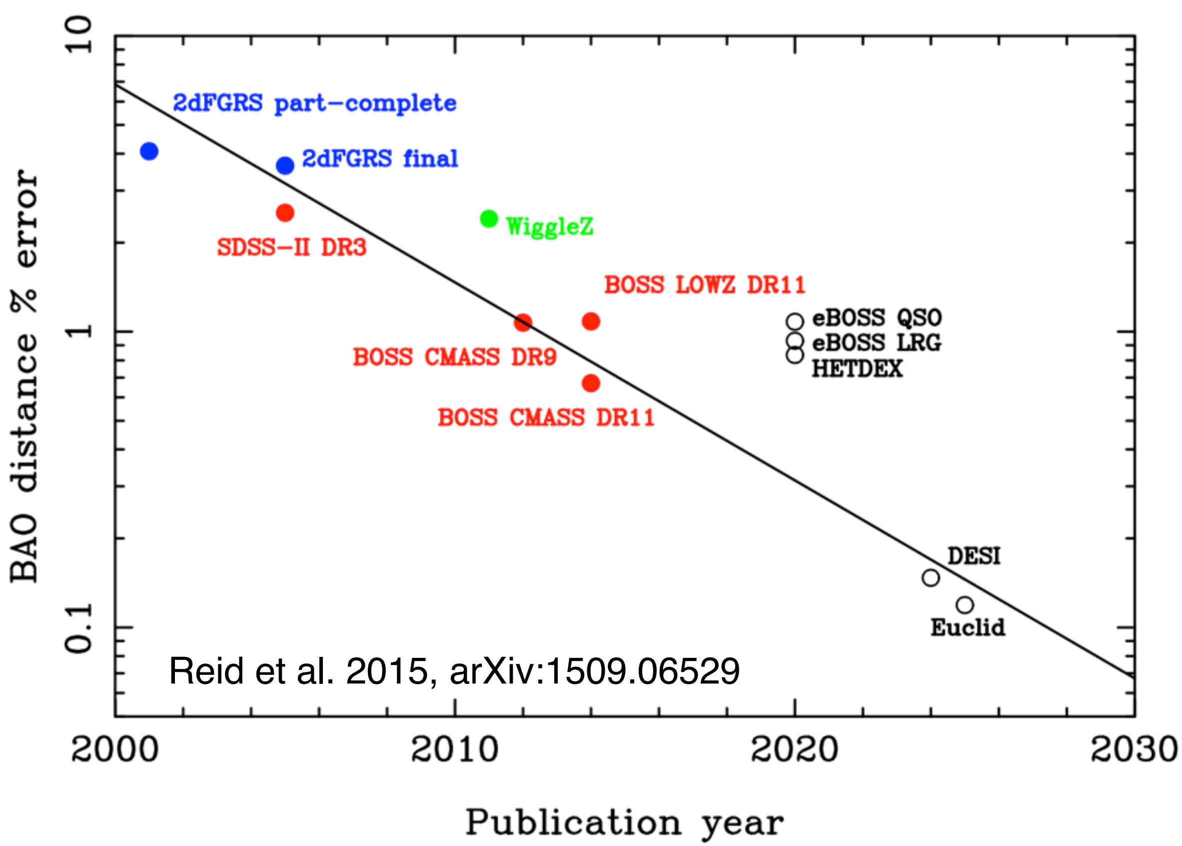
Cosmology from galaxy surveys



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

Galaxy 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

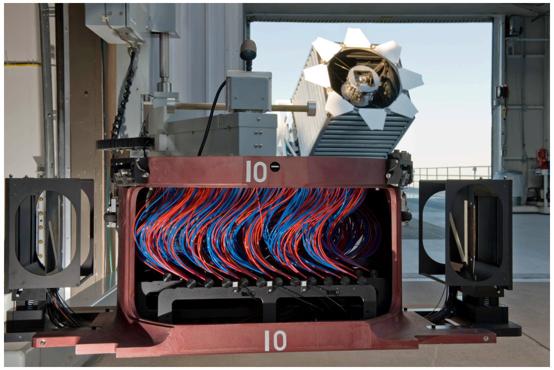
1970	x100
1990	x2
1995	±0.4
1998	±0.2
1999	±0.1
2002	±0.05
2003	±0.03
2009	±0.01
2012	±0.002

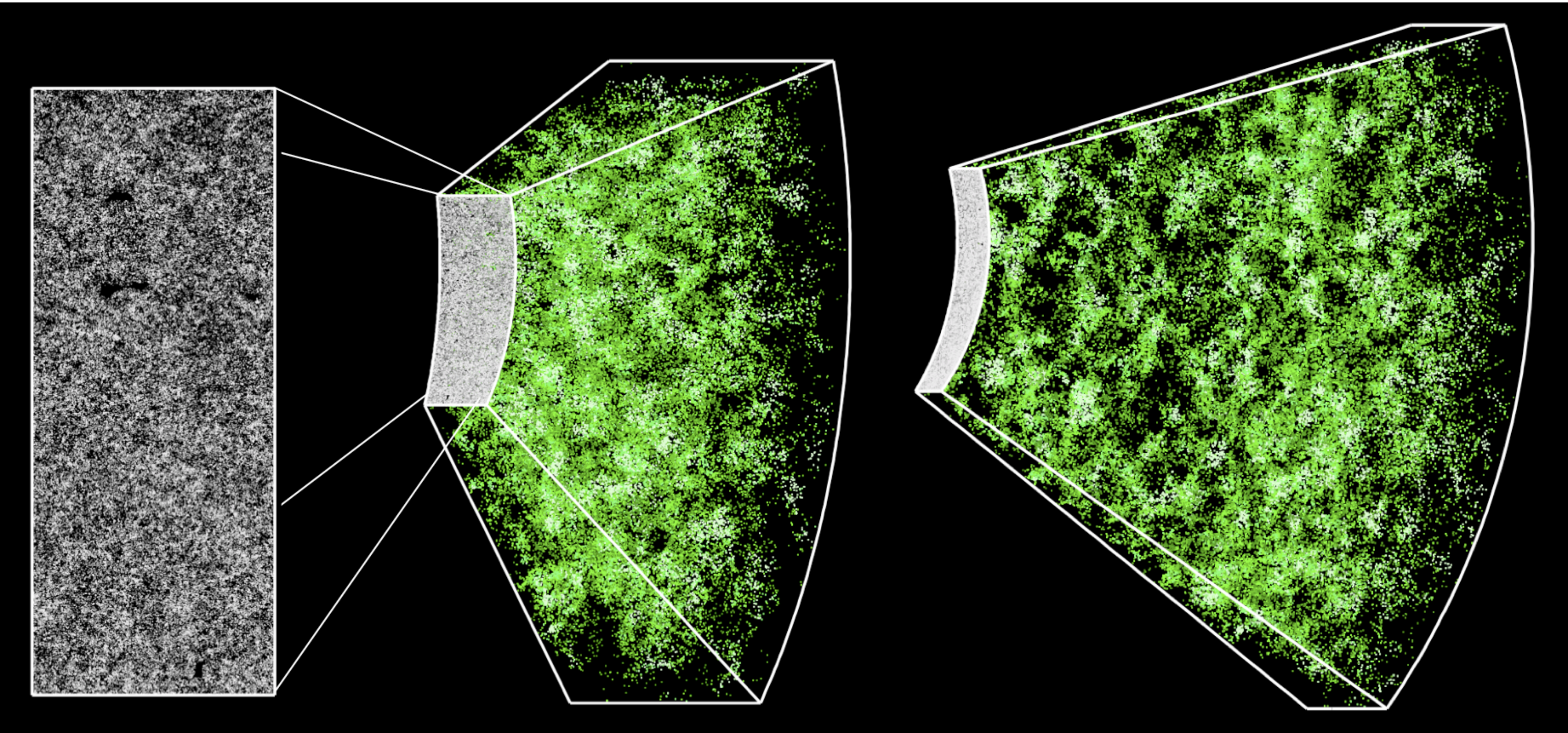
Driven by the development of instrumentation

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:

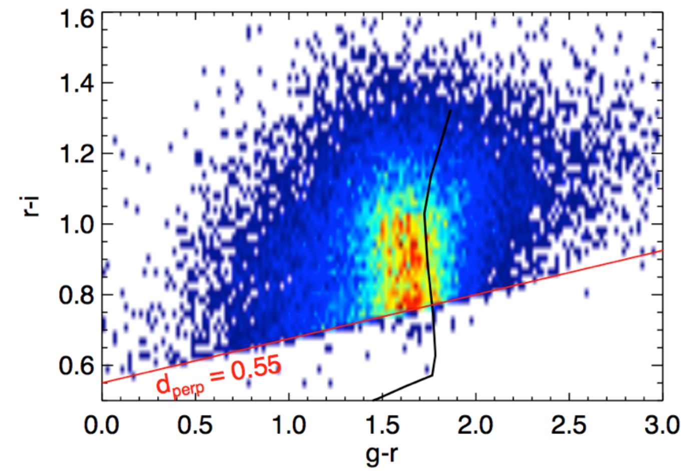
  http://data.sdss3.org/sas/dr12/boss/lss/

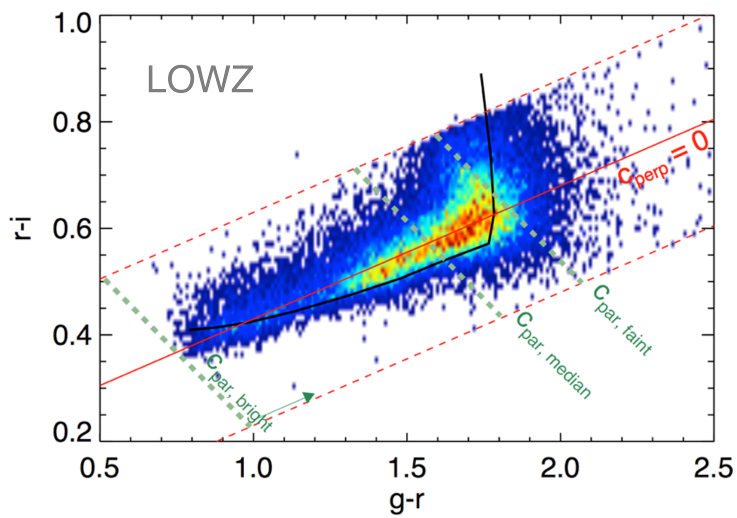


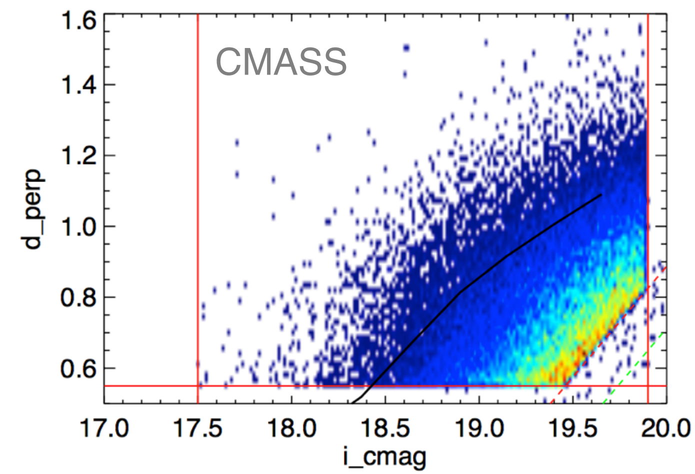


BOSS Data Release 12 galaxies

- 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
  $d_{\perp} = (r_{\mathrm{mod}} - i_{\mathrm{mod}}) - (g_{\mathrm{mod}} - r_{\mathrm{mod}})/8 > 0.55$
  to select to an approximate stellar mass limit



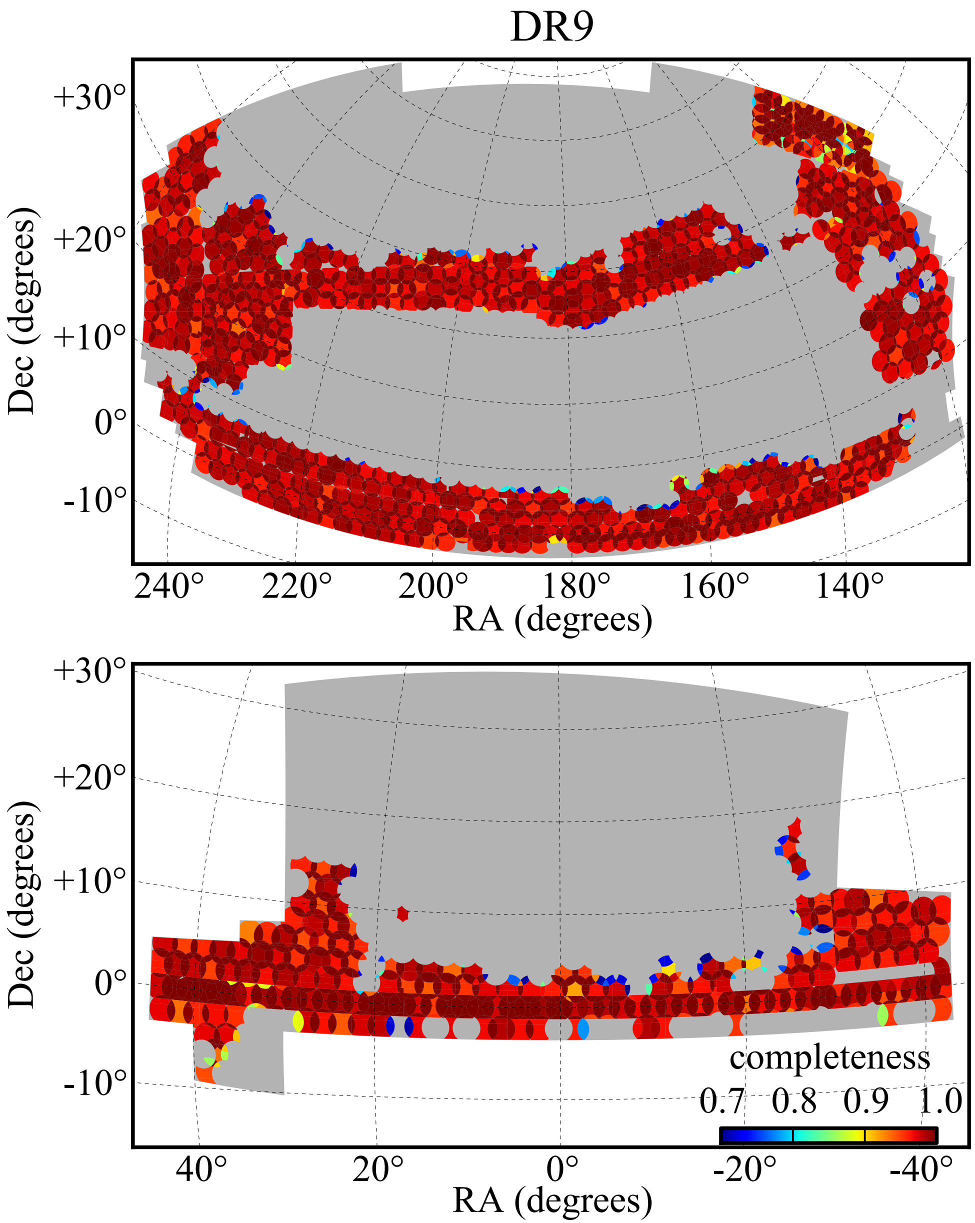




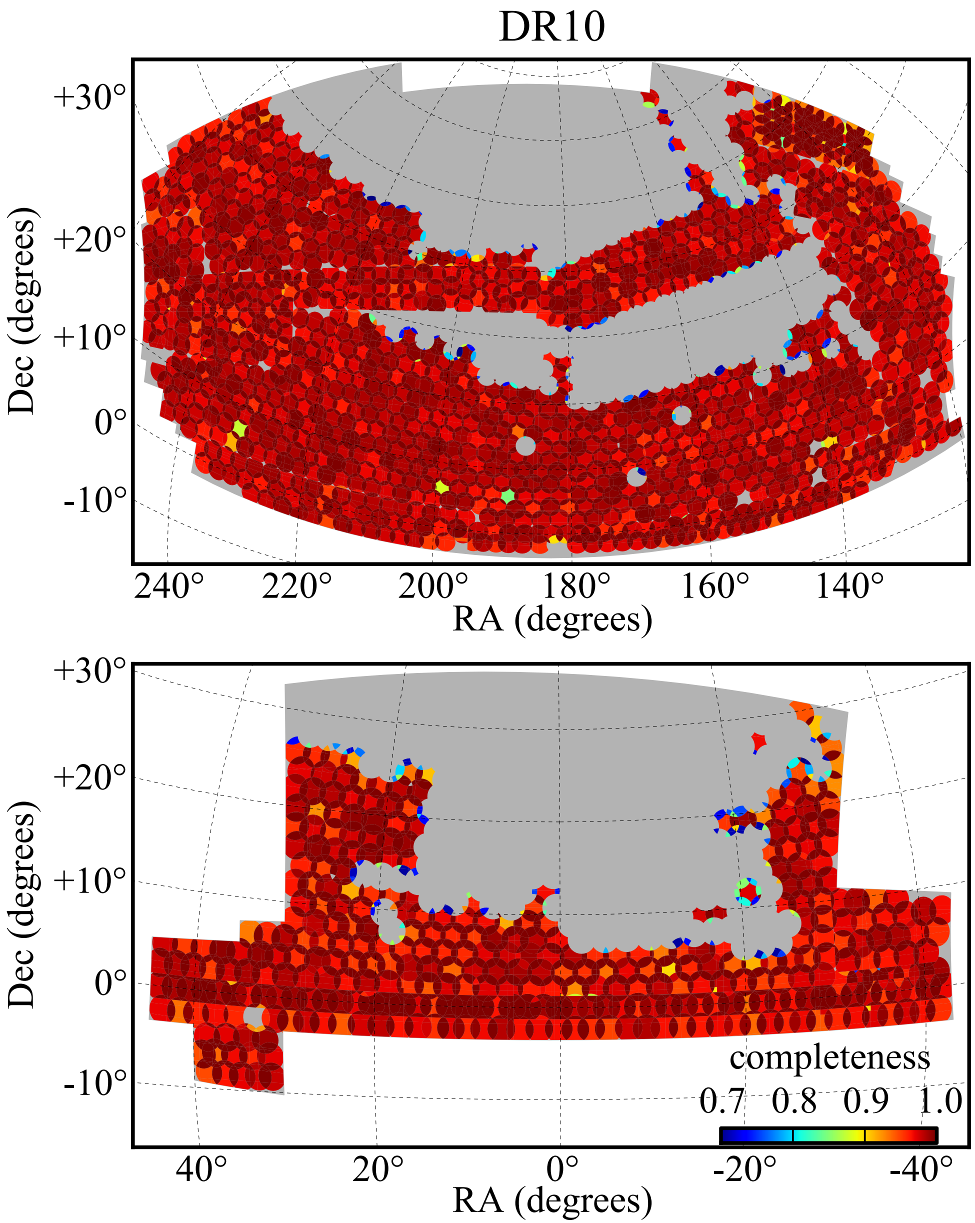
Reid et al. 2015, arXiv:1509.06529

The Sloan Digital Sky Survey telesco

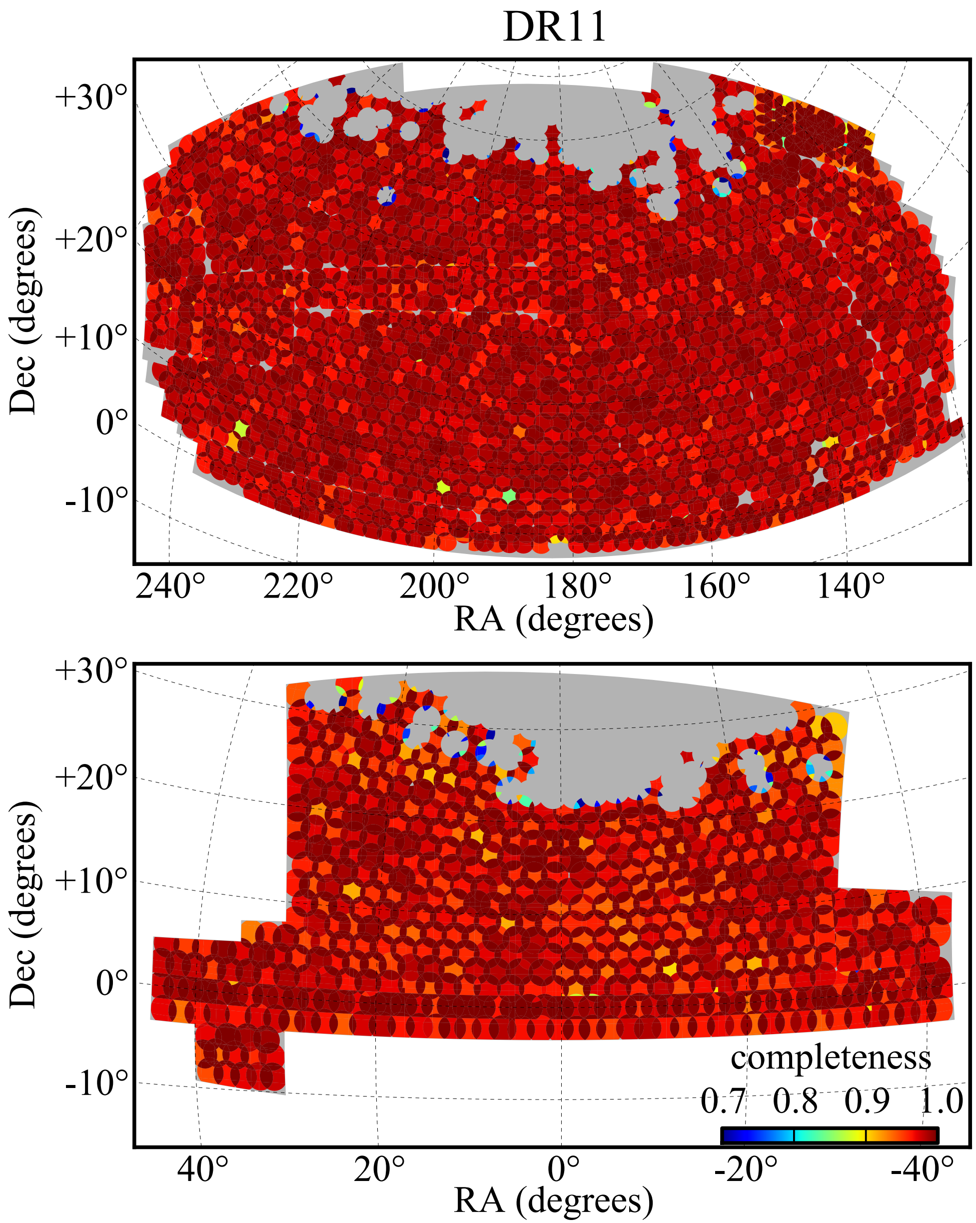
BOSS DR9 galaxies



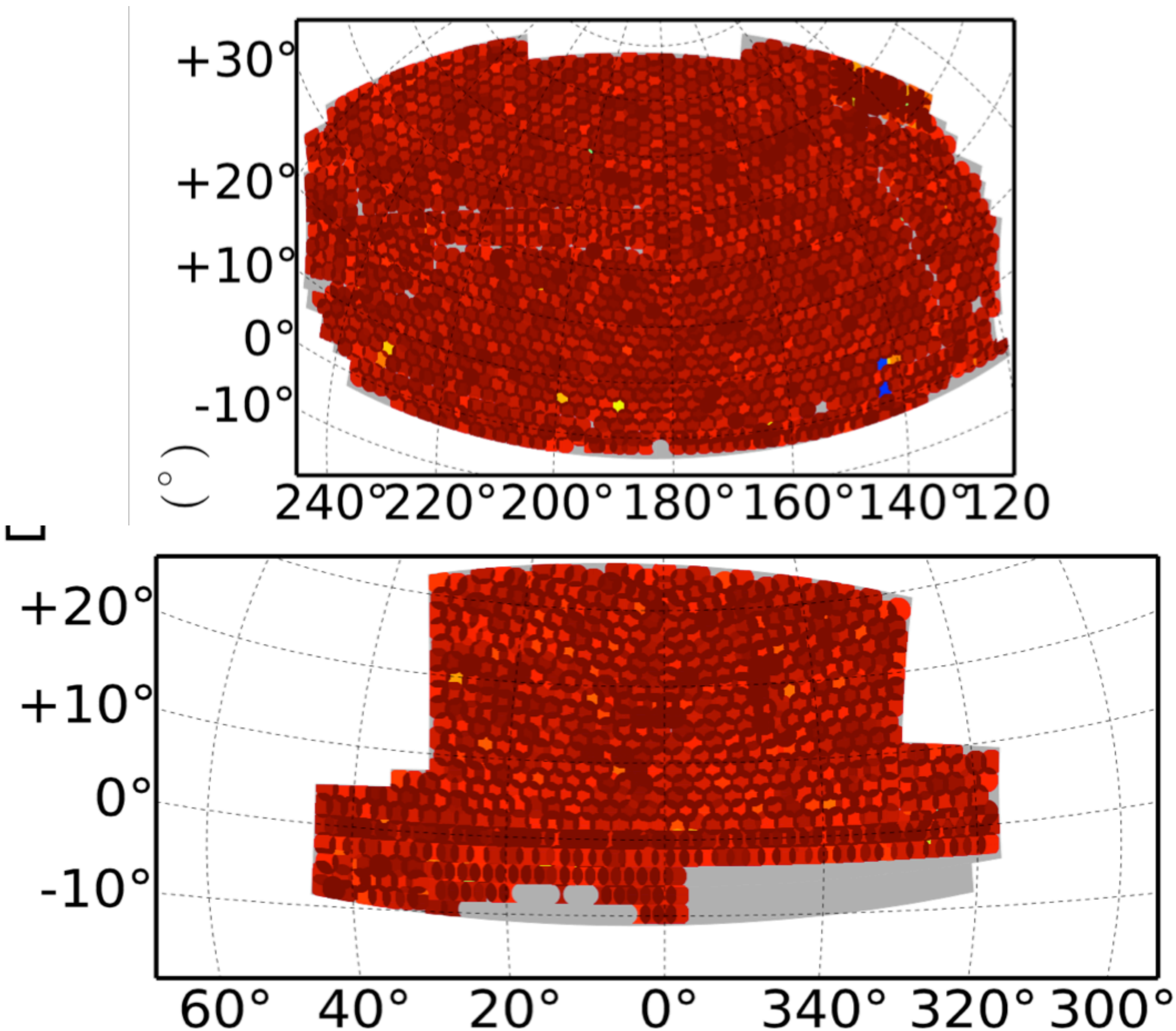
BOSS DR10 galaxies



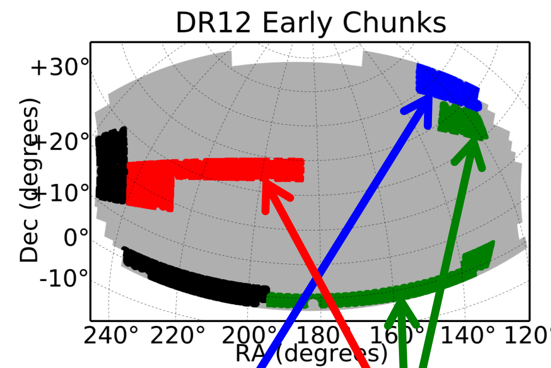
BOSS DR11 galaxies



BOSS DR12 galaxies



The galaxy sample



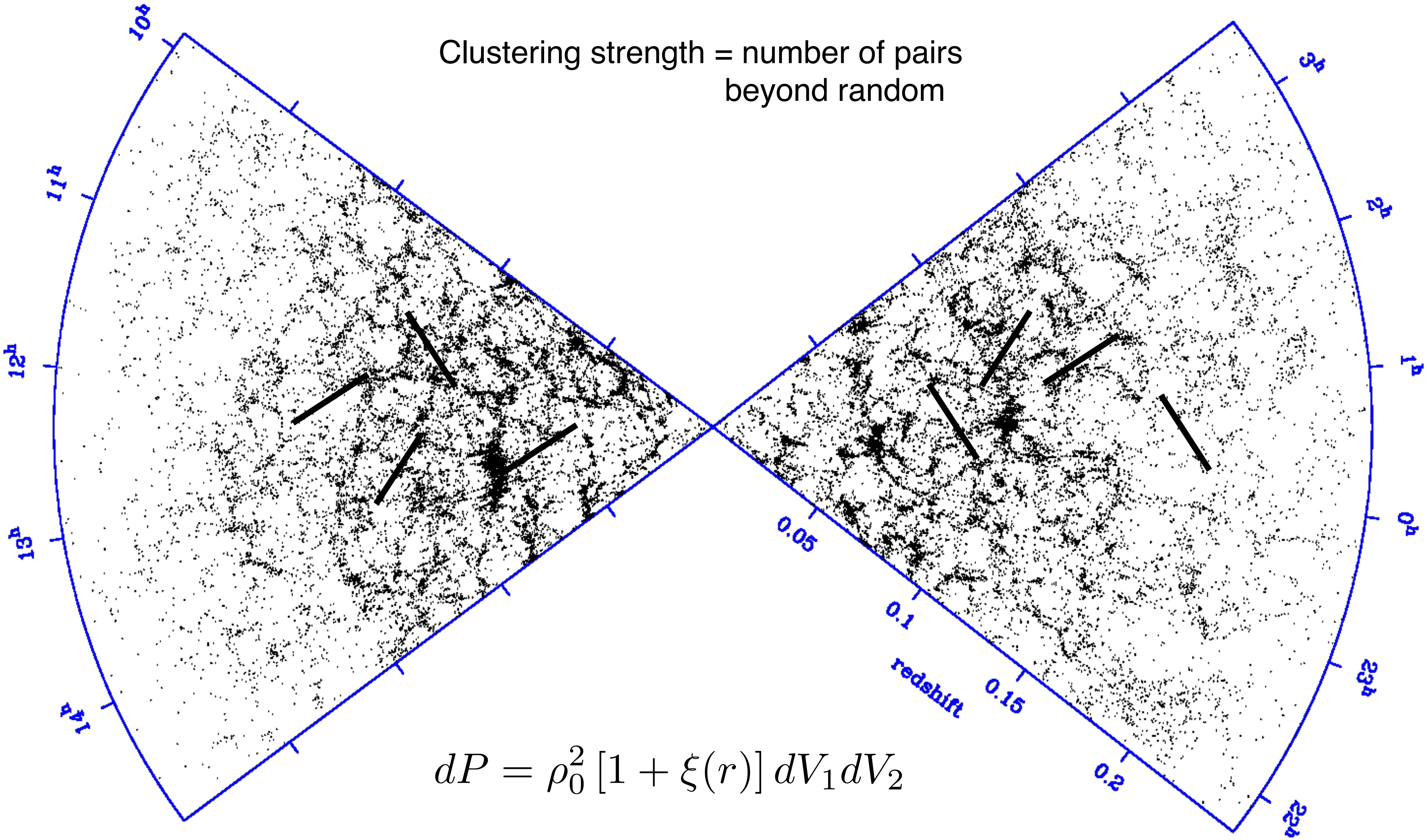
Property	NGC	SGC	total	NGC	SGC	total	NGC	NGC
Sample		CMASS			LOWZ		LOWZE2	LOWZE3
$\bar{N}_{\rm gal}$	607,357	228,990	836,347	177,336	132,191	309,527	2,985	11,195
$\bar{N}_{\rm known}$	11,449	1,841	13,290	140,444	13,073	153,517	2,730	6,371
$\bar{N}_{\rm star}$	14,556	8,262	22,818	1,043	976	2,019	24	61
$\bar{N}_{\rm fail}$	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?

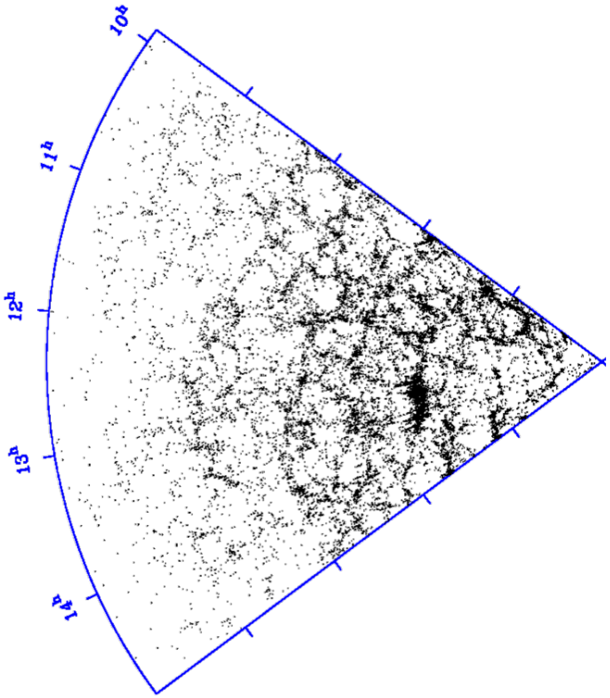
Clustering strength = number of pairs beyond random



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

2dFGRS

Over-density fields



“probability of seeing density excess”, can be recast in terms of the overdensity

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

The correlation function is simply the 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

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

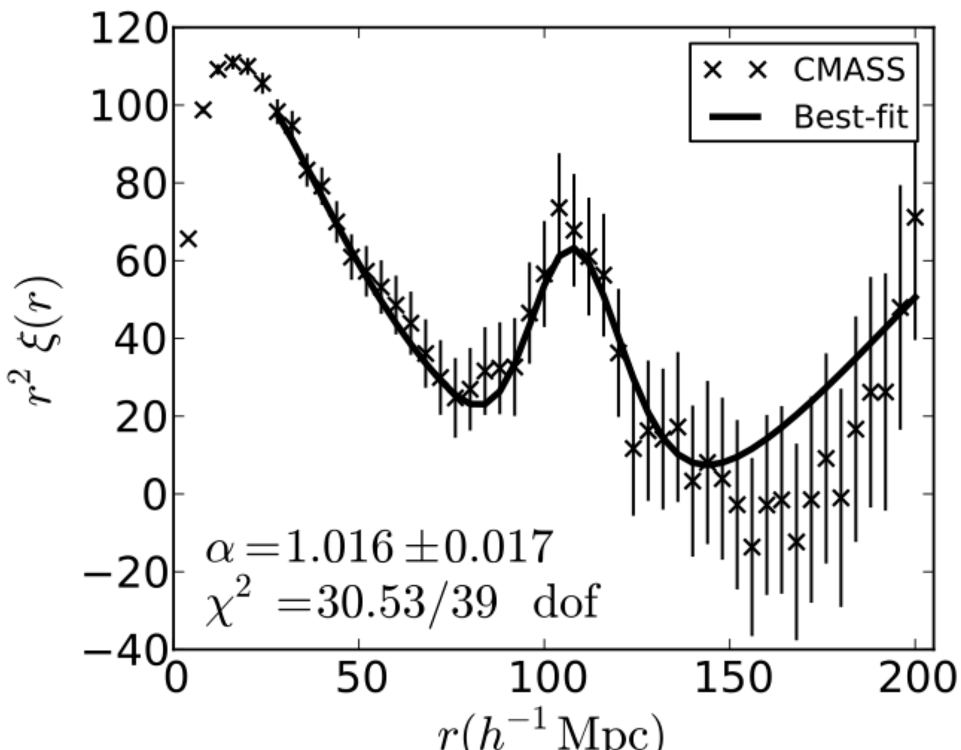
By analogy, one should think of “throwing down” Fourier modes rather than “sticks”

Real-space correlation function

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

from statistical homogeneity

from statistical isotropy

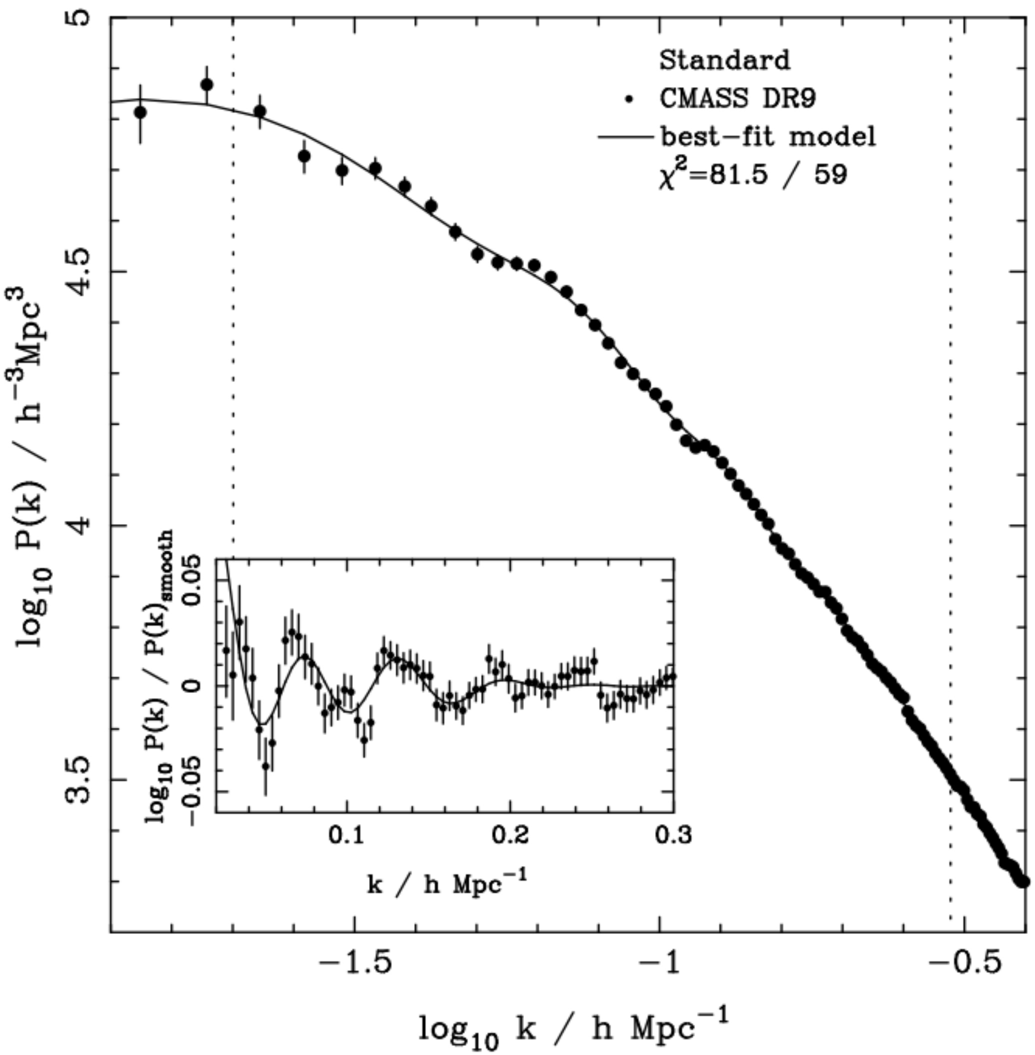


Power spectrum

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

from statistical homogeneity

from statistical isotropy

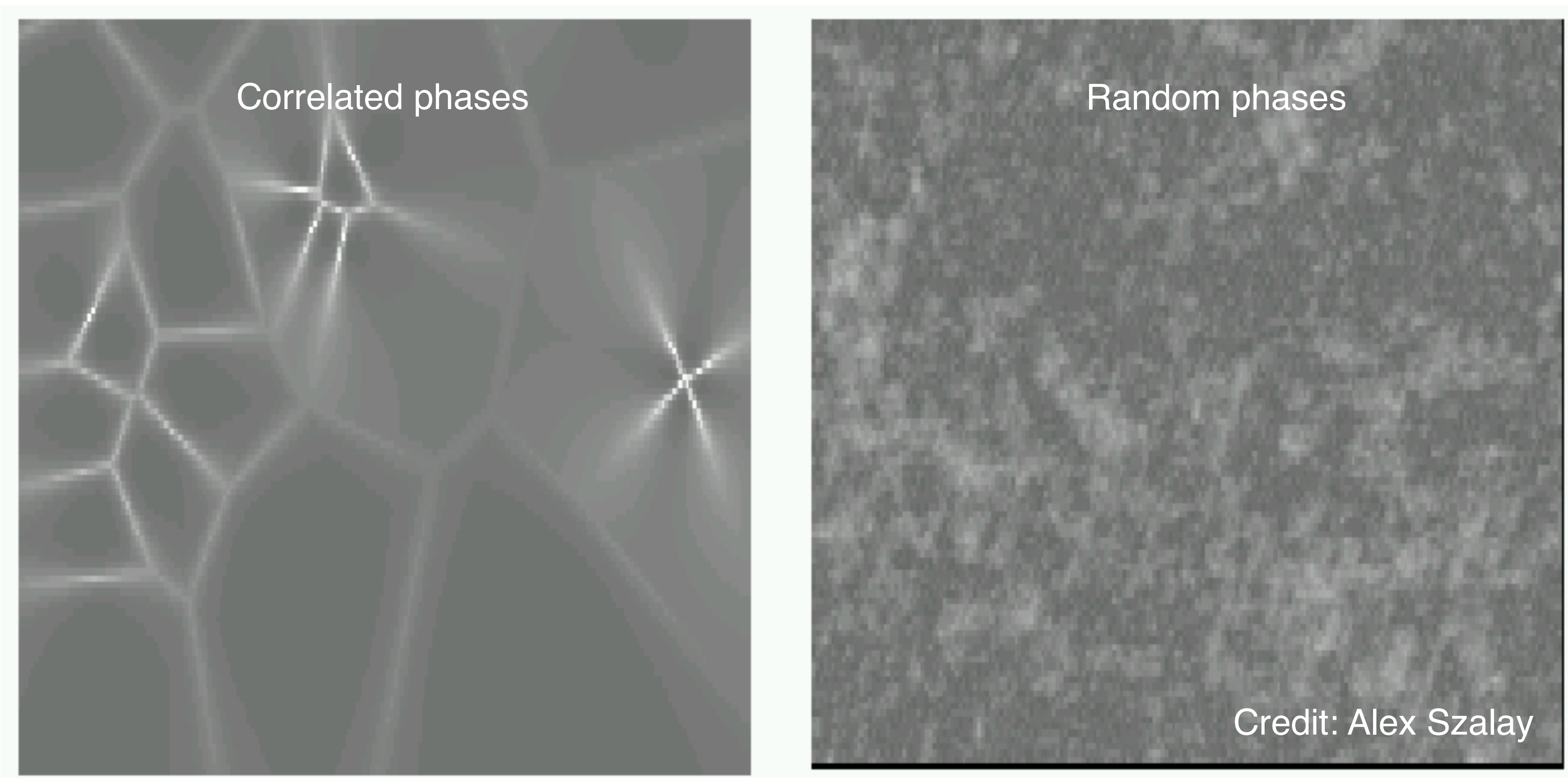


$$\Delta^2(k) = \frac{k^3P(k)}{2\pi^2}$$

Power spectrum often written in dimensionless form

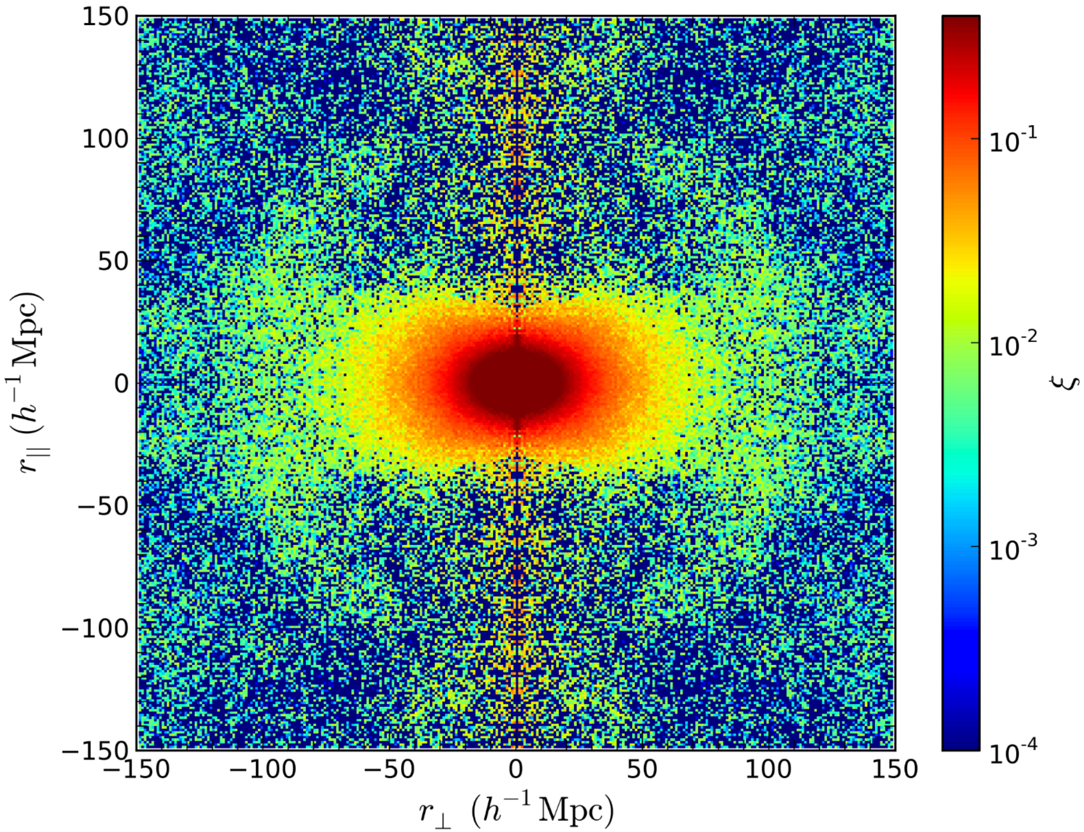
Statistically complete knowledge?

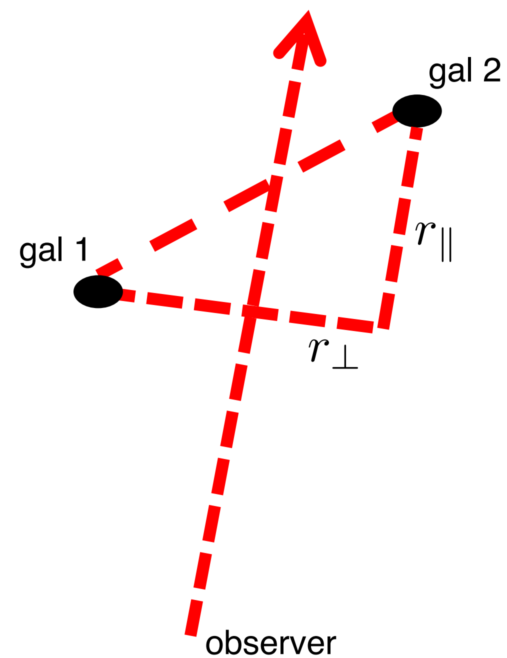
Gaussian random field: knowledge of either the correlation function or power spectrum is sufficient – they are statistically complete … but …



line-of-sight dependent clustering

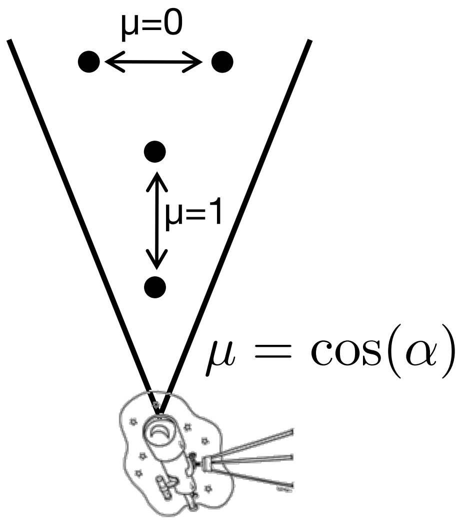
Across the line of sight, positions come from angles
Along the line of sight, positions come from redshifts

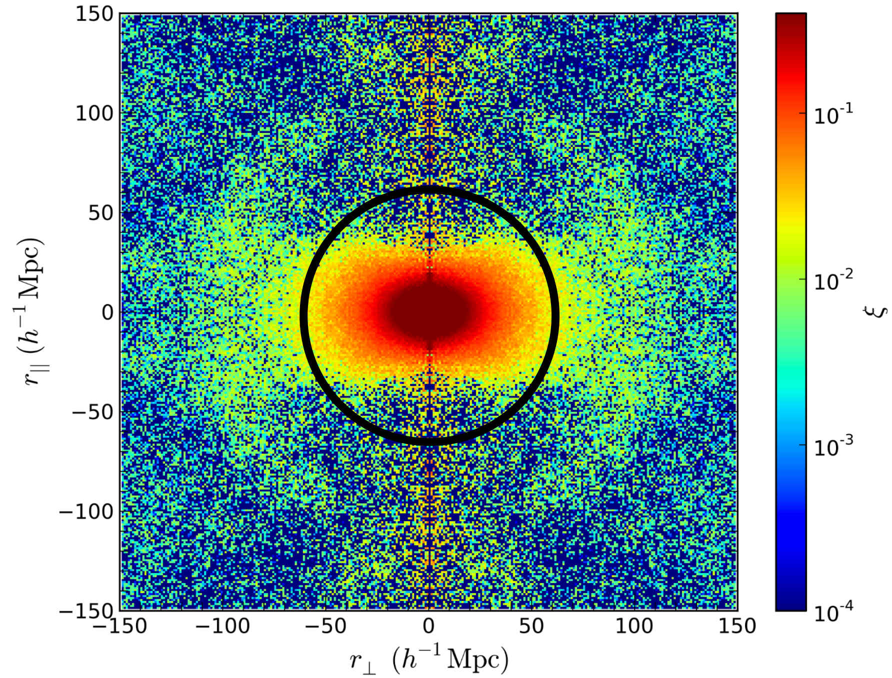




Samushia et al. 2013; MNRAS, 439, 3504

Moments of the clustering signal





Monopole moment:
Integrate ξ over circle

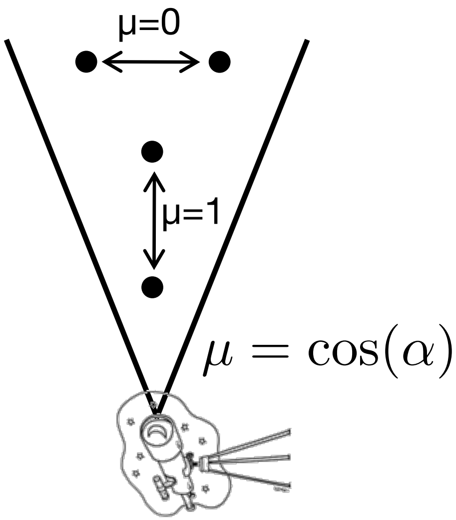
Define moments of the clustering signal

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

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

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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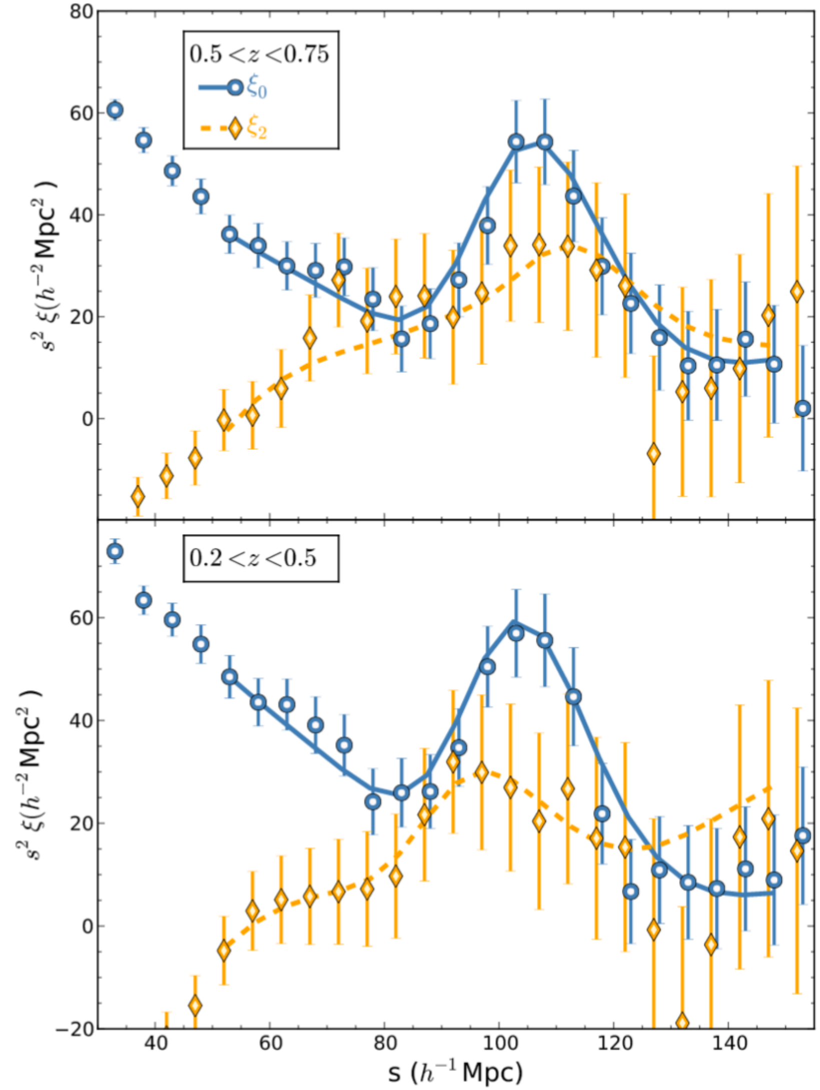
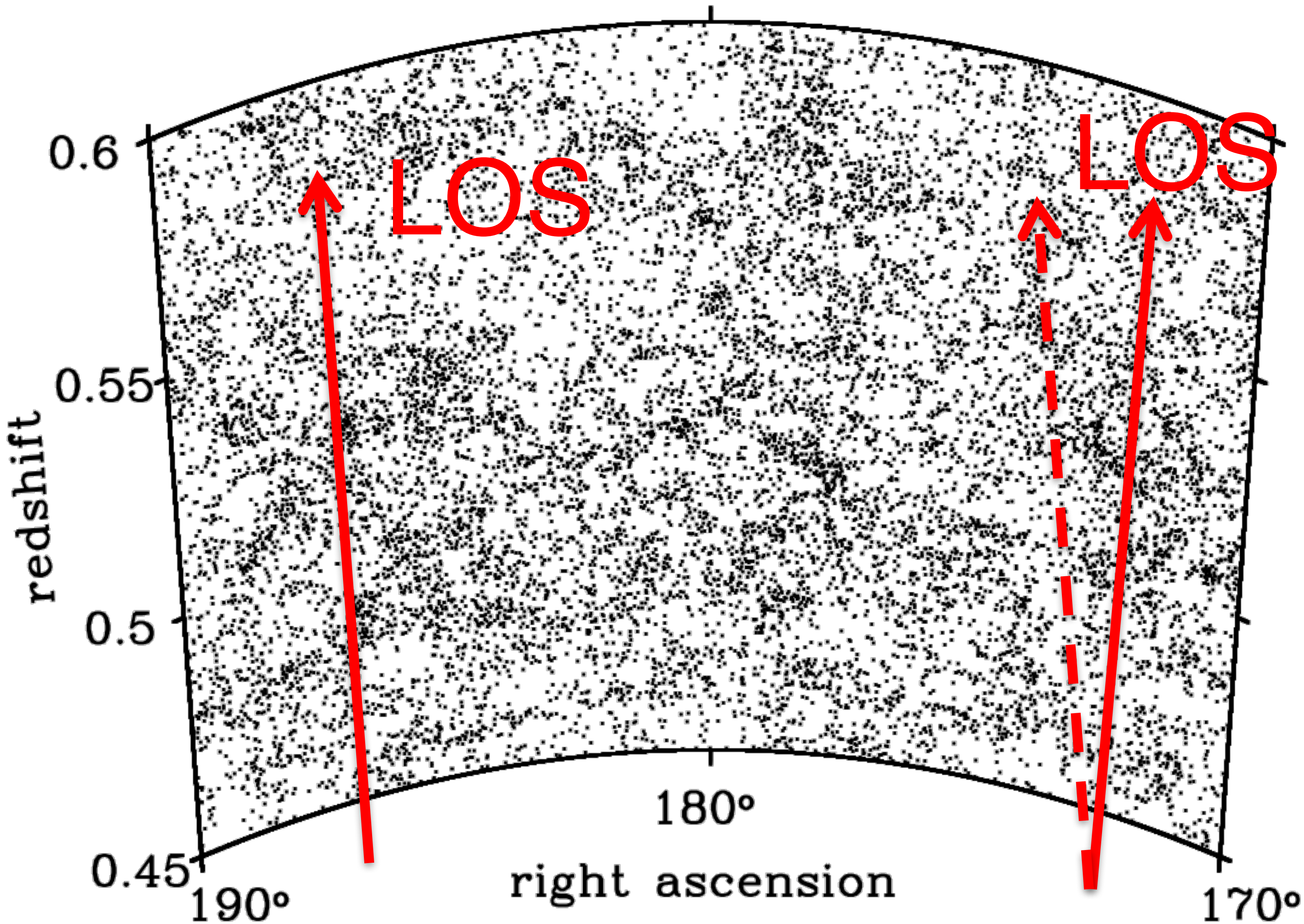


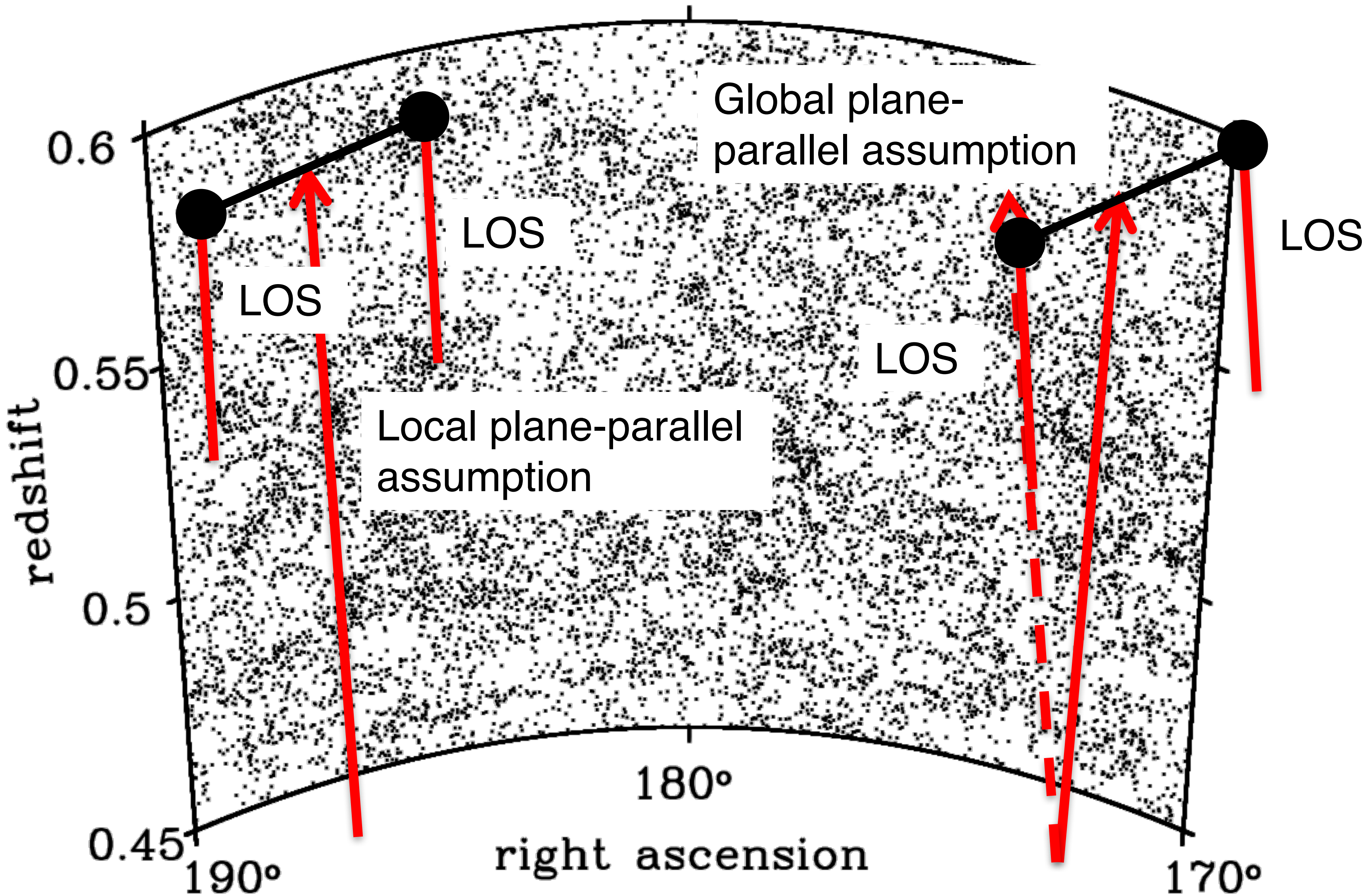
Ross et al. 2016, arXiv:1607.03145

Measuring anisotropic clustering: The correlation function

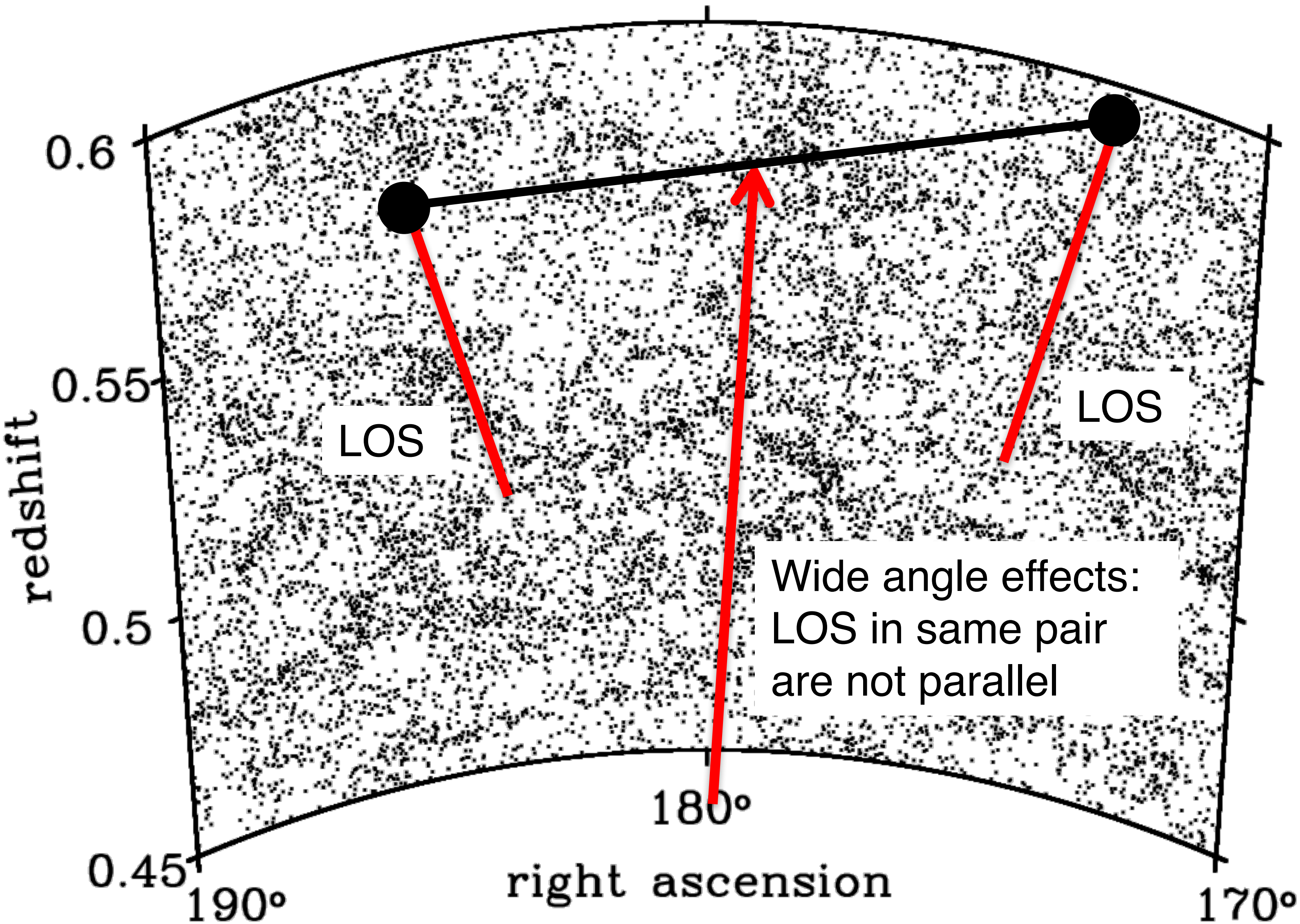
The LOS varies across a survey



Different assumptions made



Different assumptions made

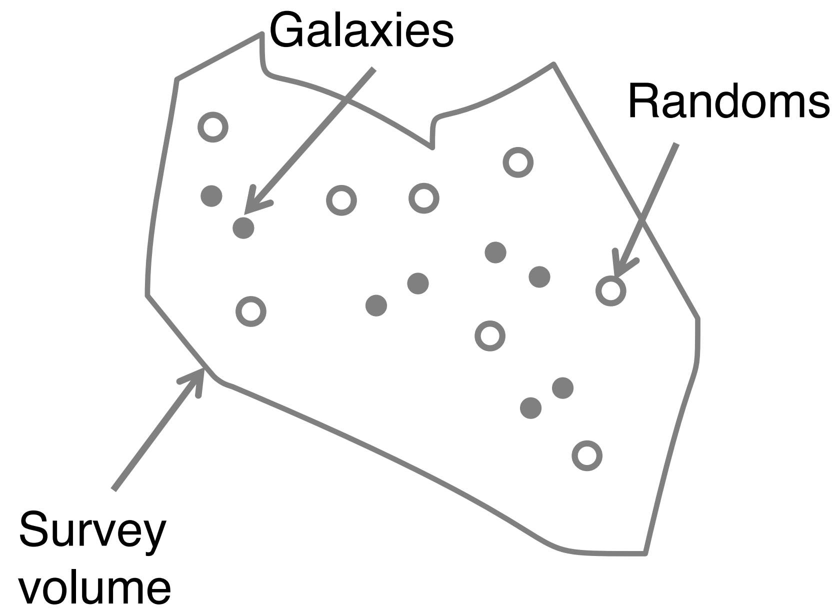


Measuring the correlation function

Define survey mask using Monte-Carlo sampling of volume covered (called random catalogue)

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 of pair to LOS (r,μ)



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

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

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

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

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

Landy & Szalay 1993; ApJ 412, 64

ICG Portsmouth

Angular upweighting for 3D measurements

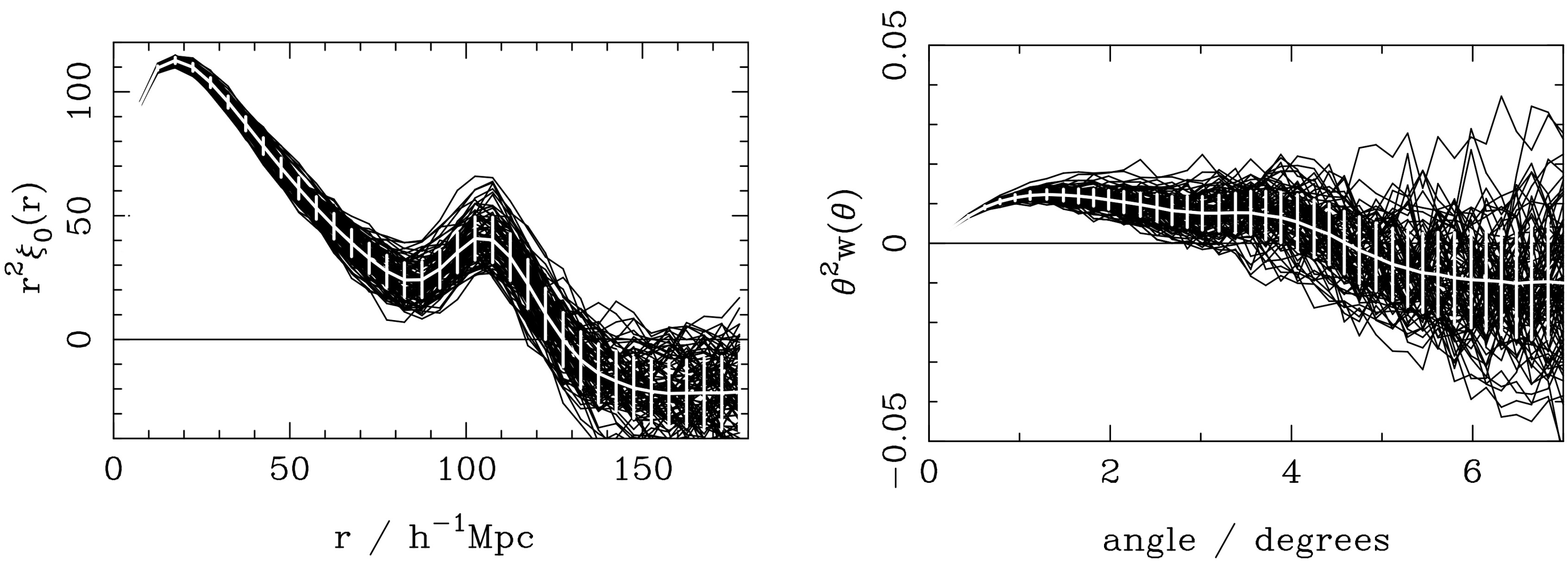
Spectroscopic surveys are never 100% complete

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

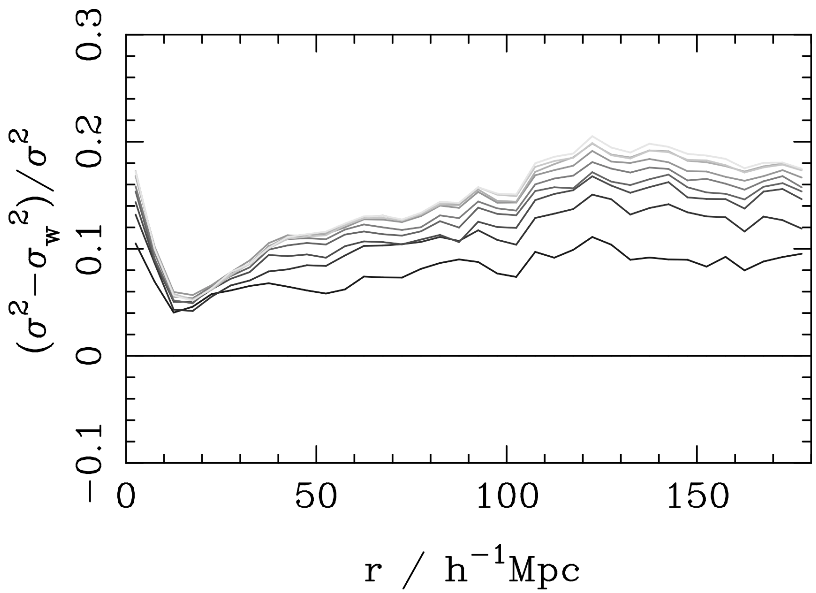
Angular upweighting for 3D measurements

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

Galaxy weighting

Not every galaxy is equal

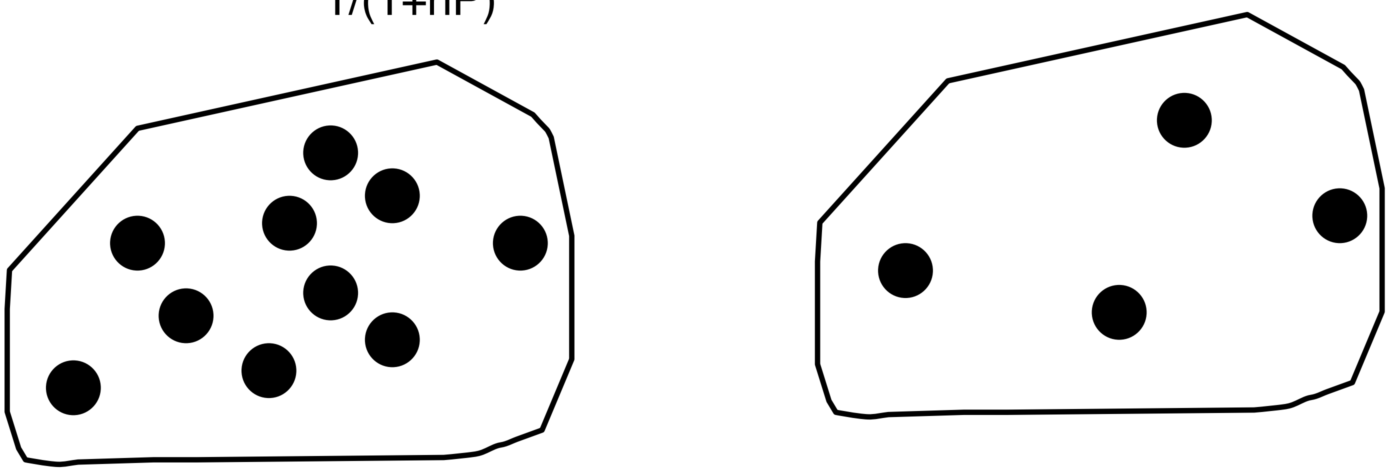
To optimize recovery of power spectrum, need to weight galaxies

- Gaussian statistics ➔ inverse variance (covariance) weights

- Std variance on power, for Poisson sampled density field $\sigma_P^2 = (P+1/n)^2$

  ➔ FKP galaxy weights for density variations

1/(1+nP)



High tracer density

Low tracer density

Feldman, Kaiser & Peacock 1993; astro-ph/9304022

Not every galaxy is equal

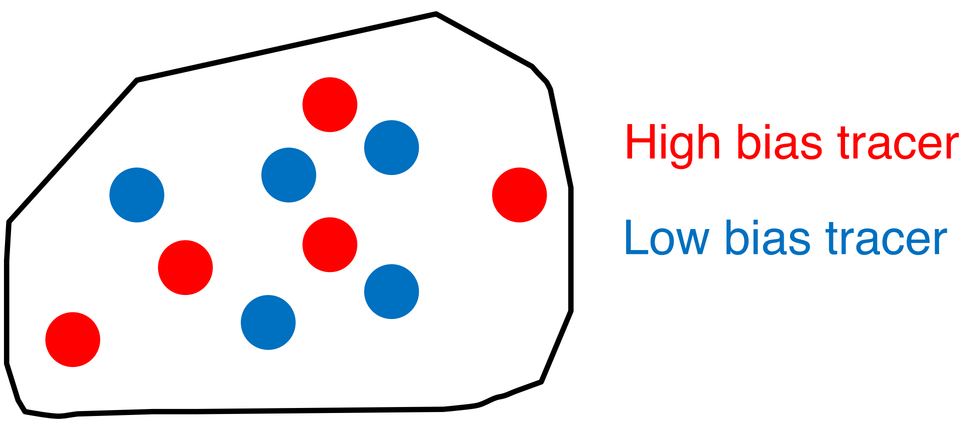
To optimize recovery of cosmological signal, need to weight galaxies

- Gaussian statistics ➔ inverse variance (covariance) weights

- Std variance on power $\sigma_P^2 / P^2 = (P+1/n)^2 / P^2$

  ➔ PVP galaxy weights for power variations

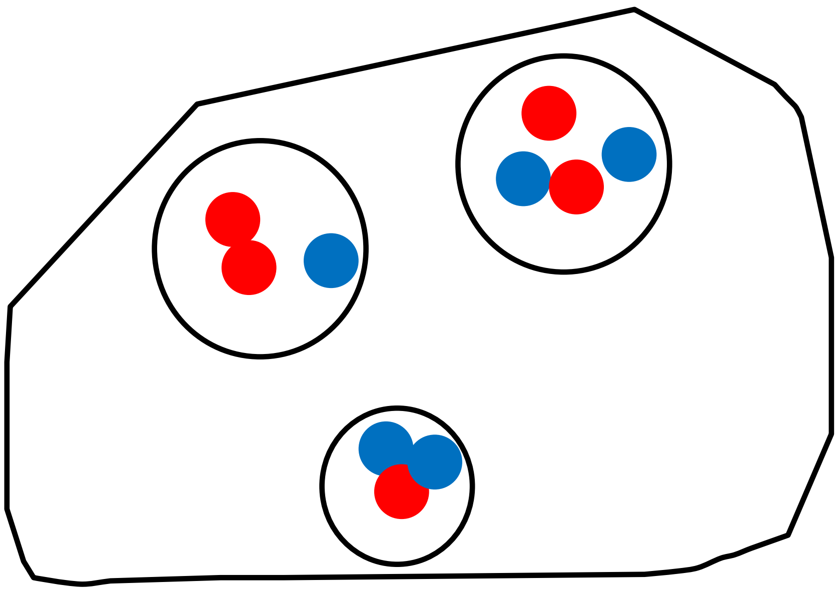
$P^{1/2}/(1+nP)$



Percival, Verde & Peacock 2004; astro-ph/0306511

Not every galaxy is equal

If you drop the Poisson sampling assumption, and follow a more realistic bias model (e.g. the halo model), then the optimal weight changes and depends on halo mass, and concentration.



In general, the weights no longer have a simple form …

Note also that these are not the optimal weights for RSD measurement

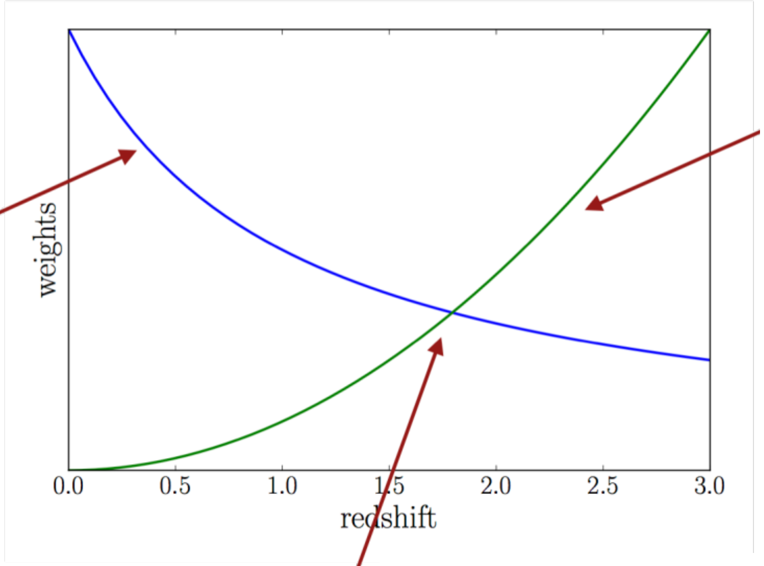
e.g. Smith & Marian 2015; arXiv/1503.06830

Redshift-dependent weights

To optimize recovery of cosmological signal, need to weight galaxies

- Can also optimise for changes in the cosmological signal with redshift:
- Also optimizes for binning: reduces edge effects
- Consistently allows for cosmological evolution

Physical theory



FKP: balance of cosmic variance And shot noise

Survey most sensitive here

Mueller et al. 2017; arXiv:1702.05088

Redshift-dependent weights

To optimize recovery of cosmological signal, need to weight galaxies

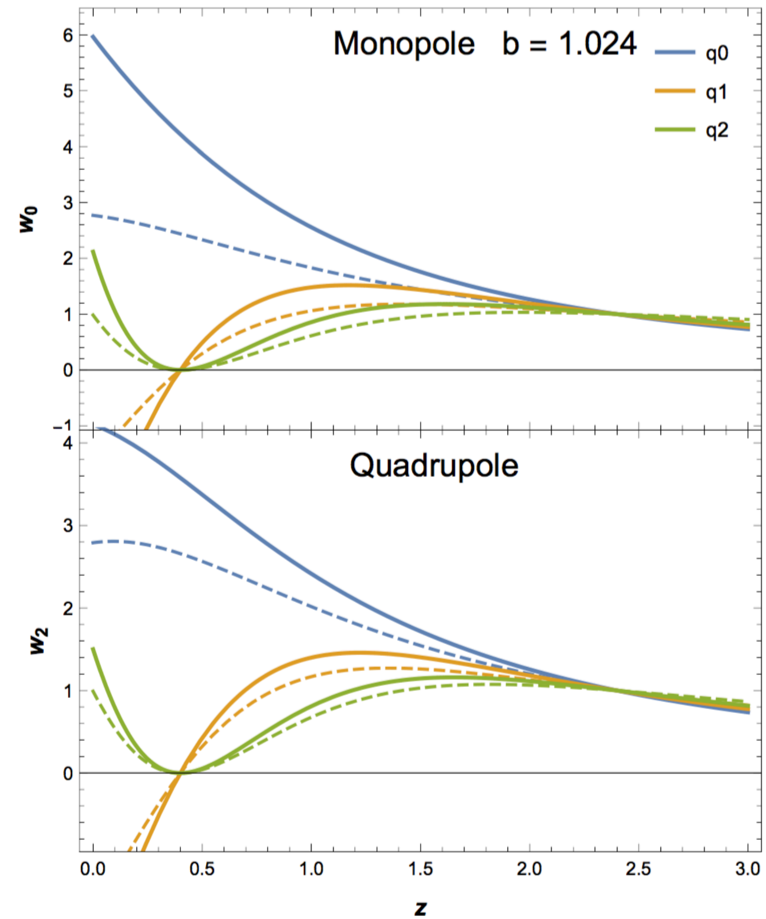
BAO (Zhu et al. 2014; arXiv:1411.1424)

RSD (Ruggeri et al. 2016; arXiv:1602.05195)

f_{NL} (Mueller et al. 2017; arXiv:1702.05088)

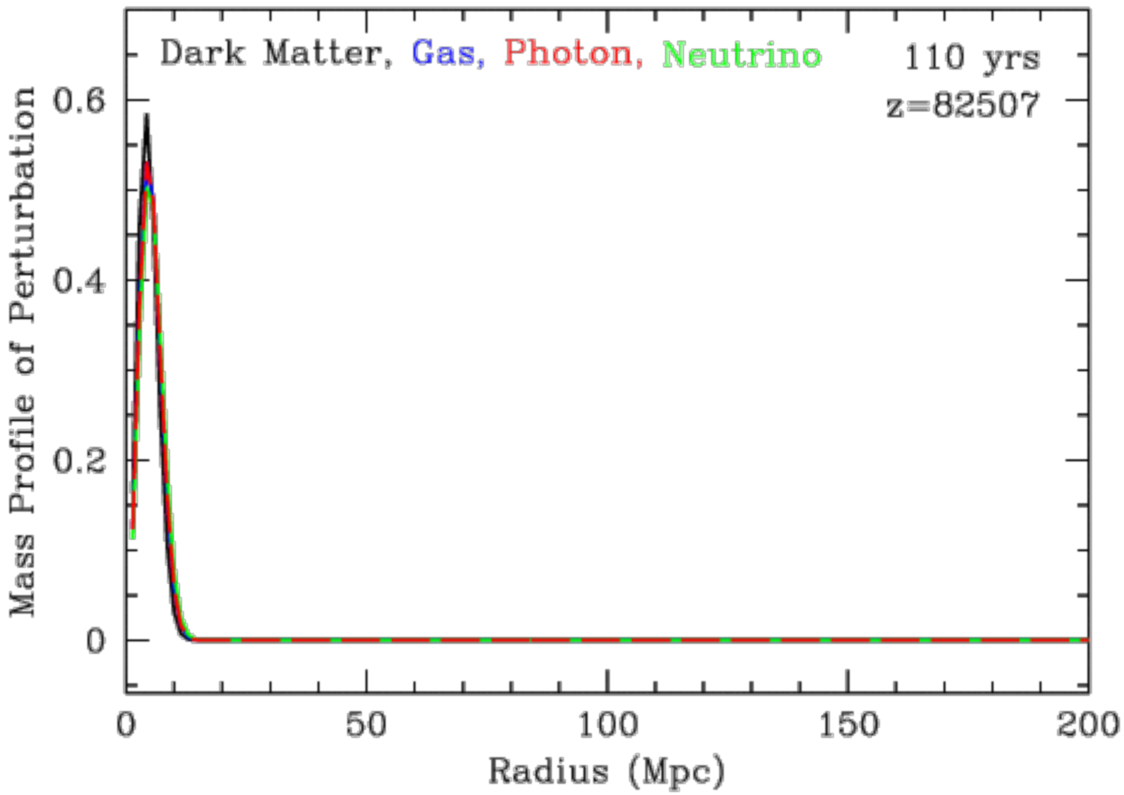
- These weights are optimized for a single model, and in general do not have a simple form
- However no bias, as simply adjusting the weighting

Ruggeri et al. 2016; arXiv:1602.05195



Intrinsic clustering - Baryon Acoustic Oscillations

Configuration space description

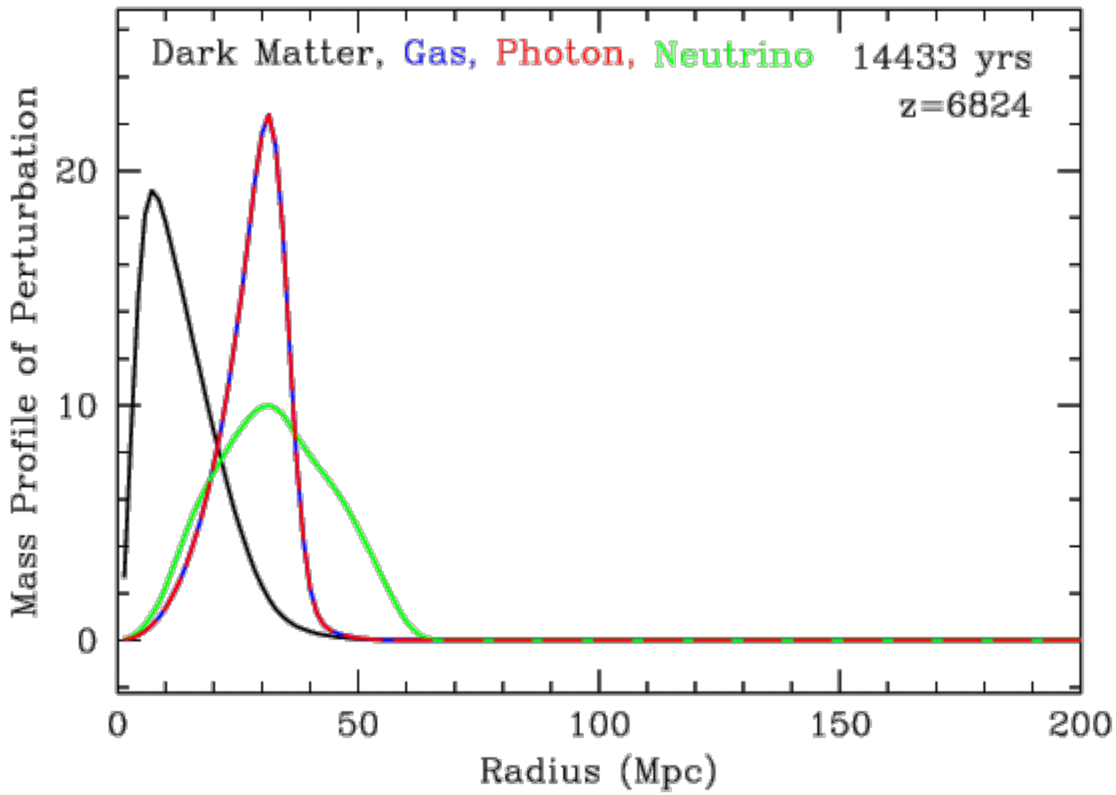


$\Omega_m h^2 = 0.147$, $\Omega_b h^2 = 0.024$

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

plots by Dan Eisenstein

Configuration space description



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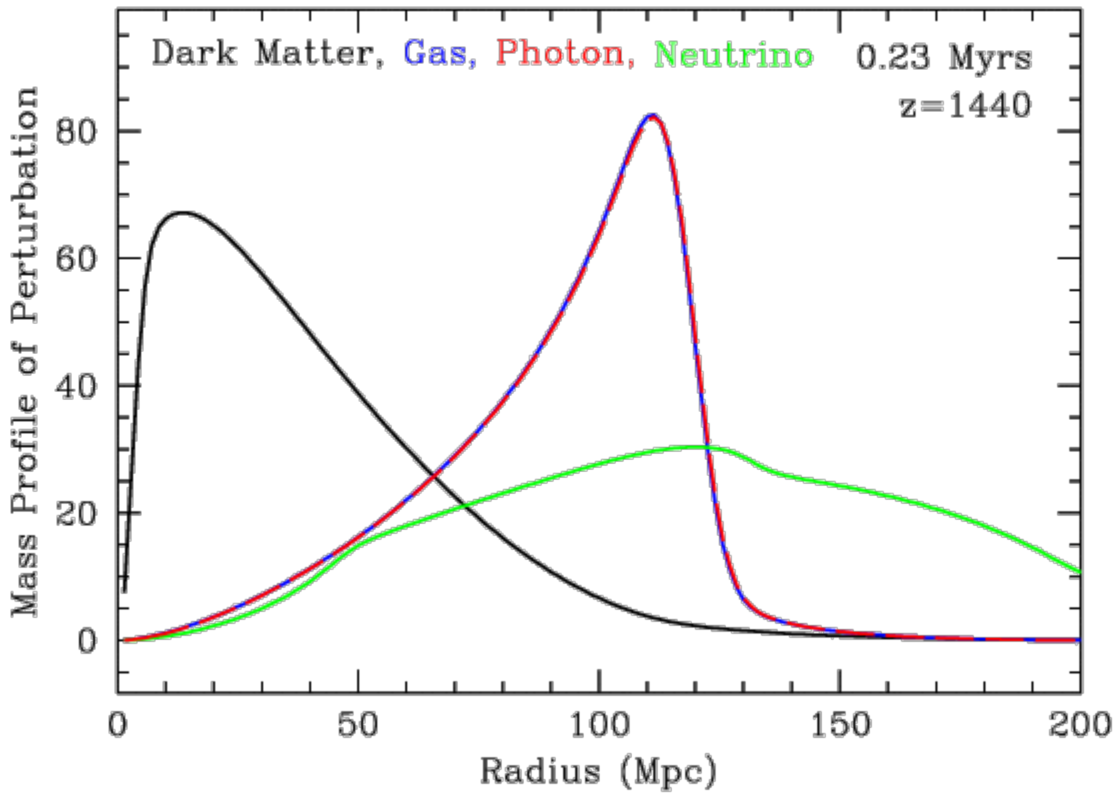

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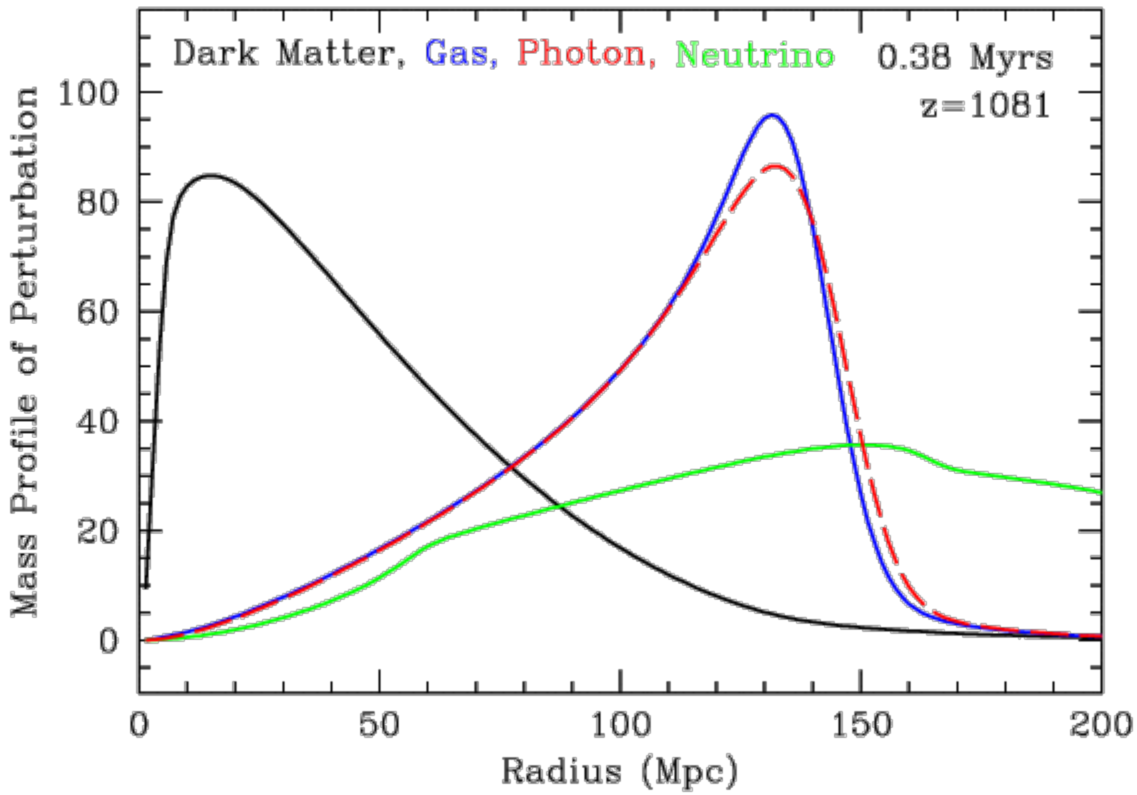

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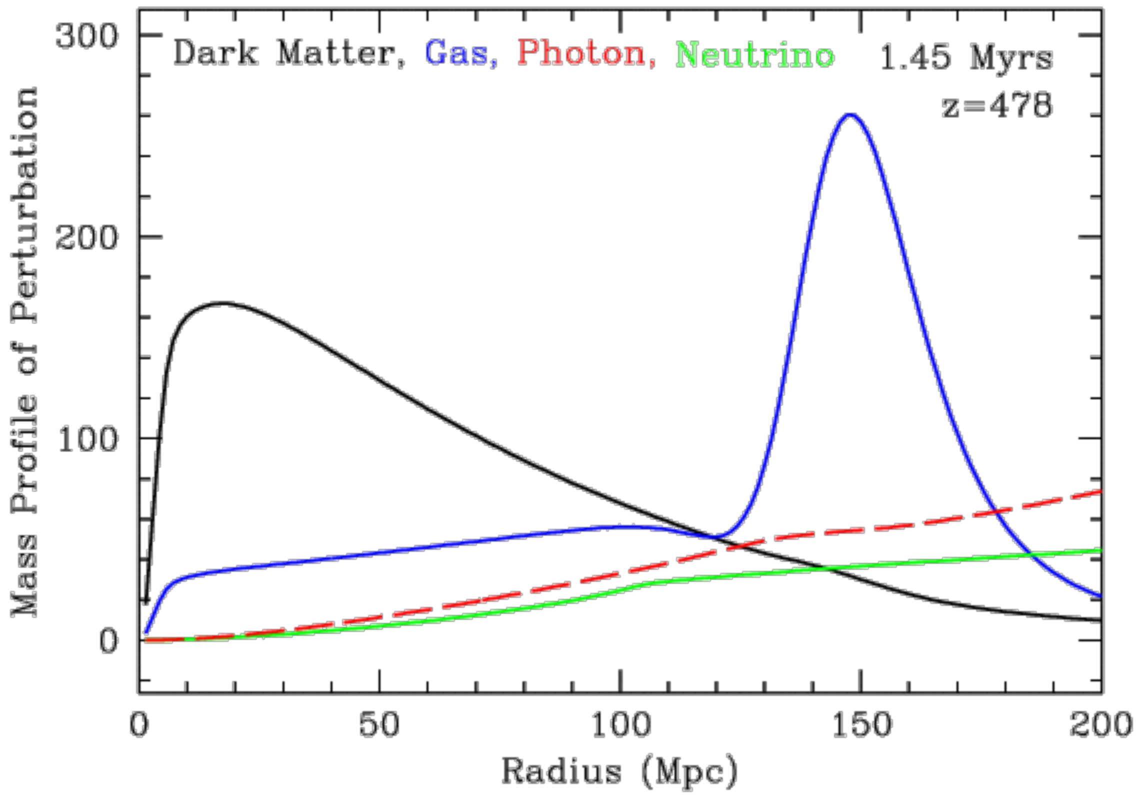

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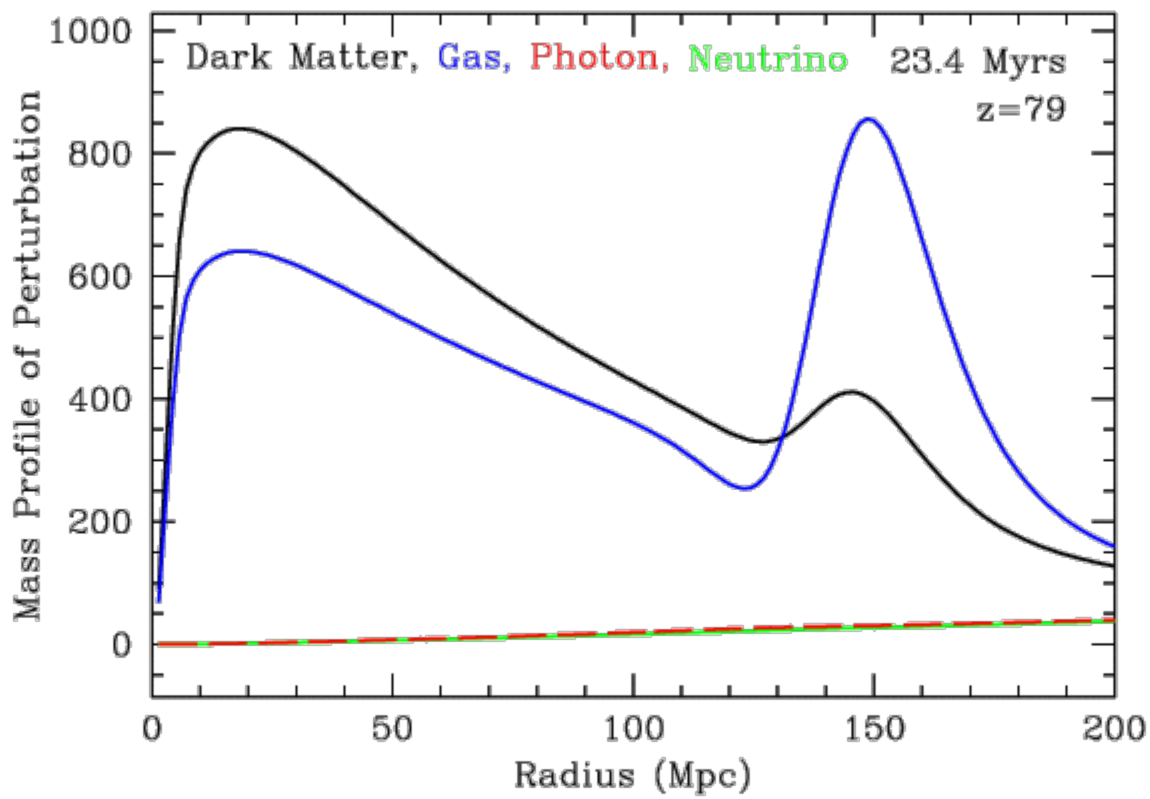

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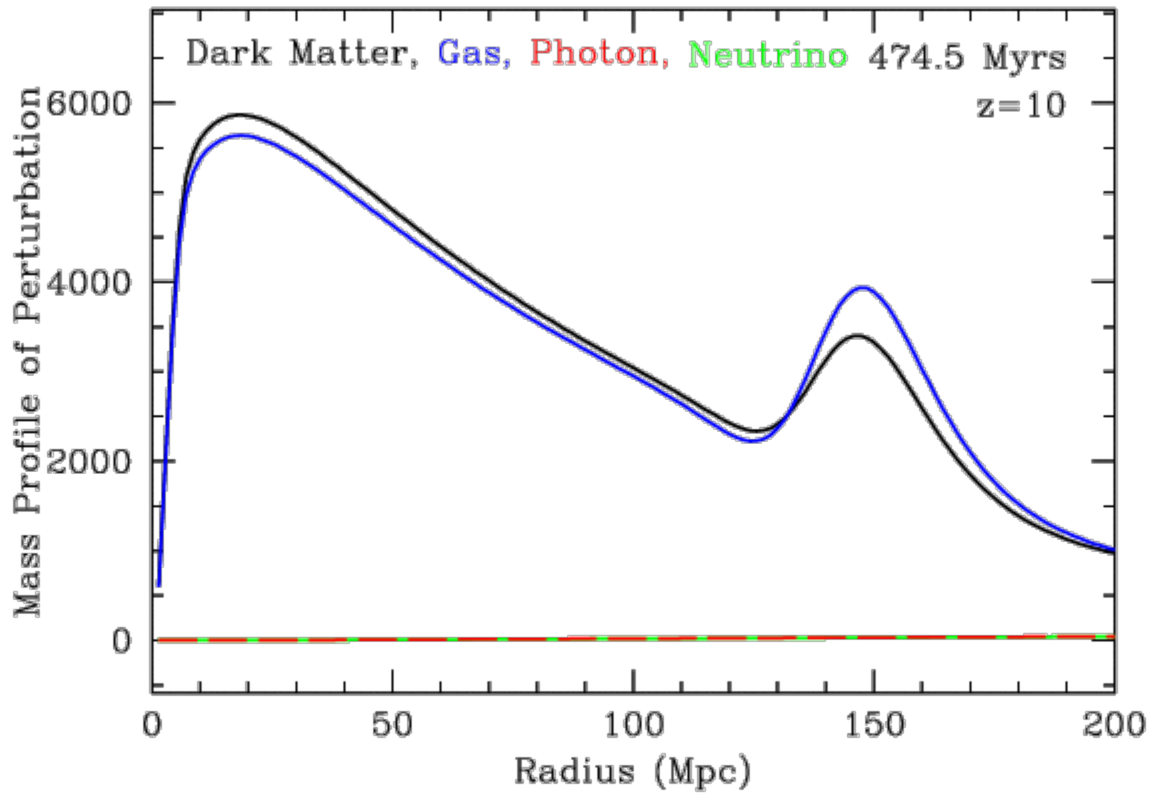

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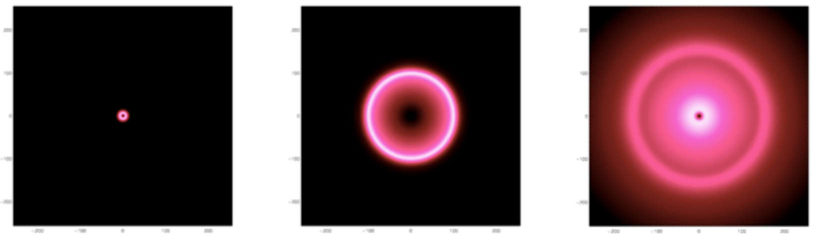
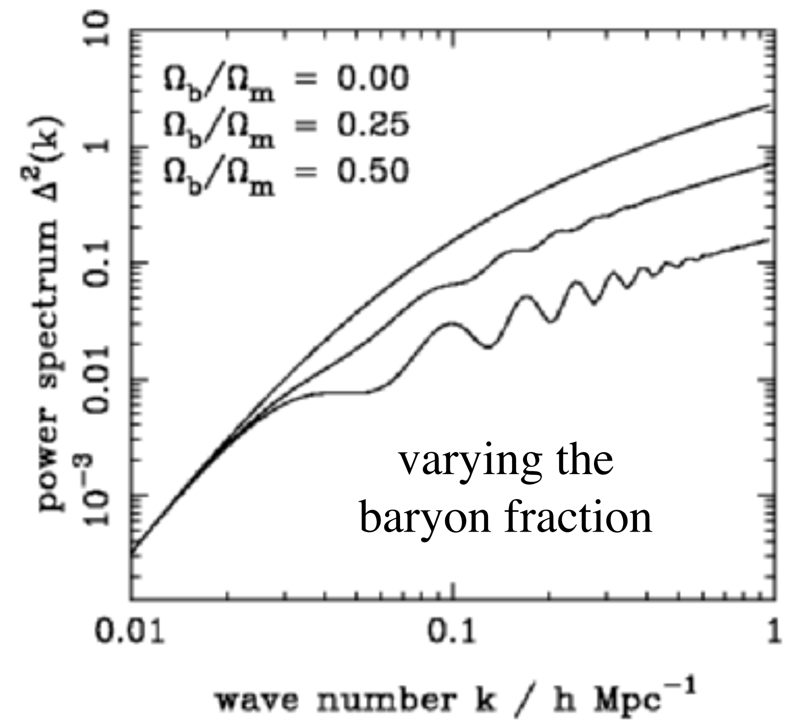
Baryon Acoustic Oscillations (BAO)



(images from Martin White)



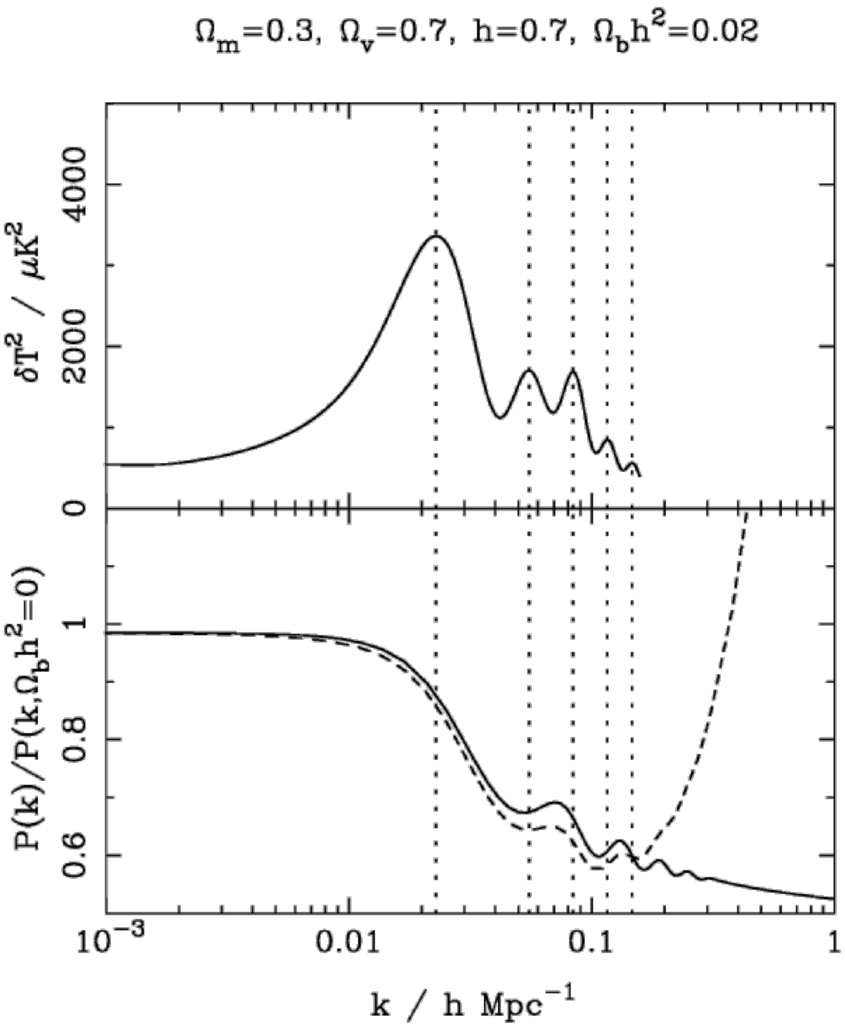
To first approximation, BAO wavelength is determined by the comoving sound horizon at recombination (actually at drag epoch)

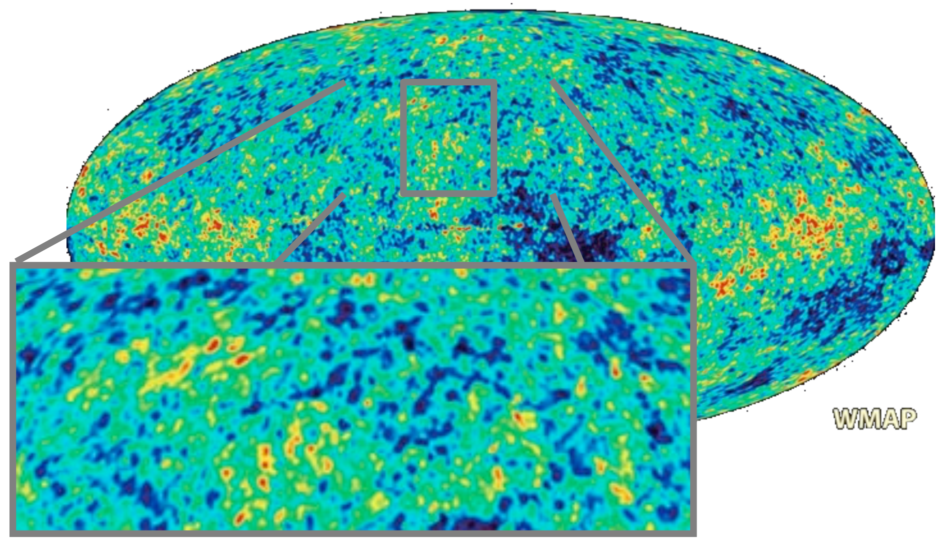
$$k_{\mathrm{bao}} = 2\pi/s$$

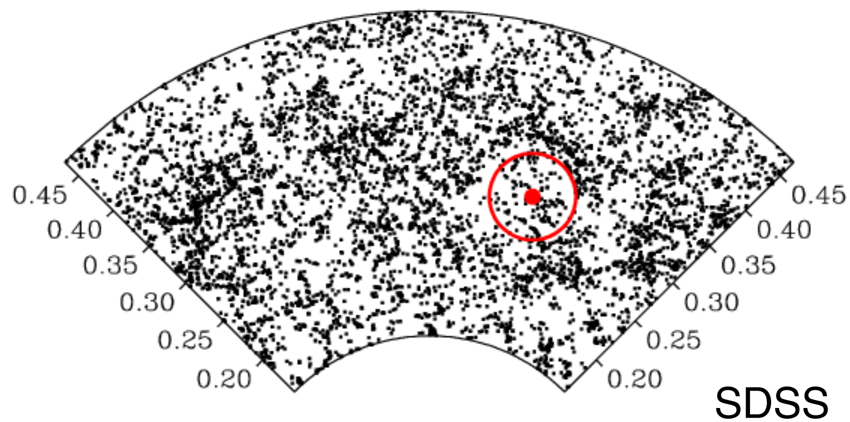
$$s = \frac{1}{H_0\Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{\mathrm{eq}})^{1/2}}$$

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

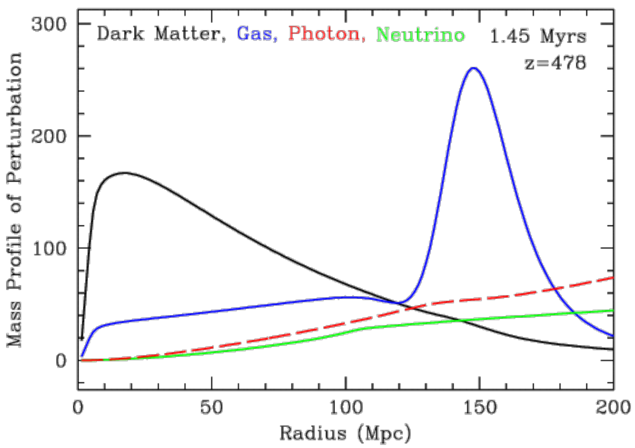
Comparison of CMB and LSS power spectra



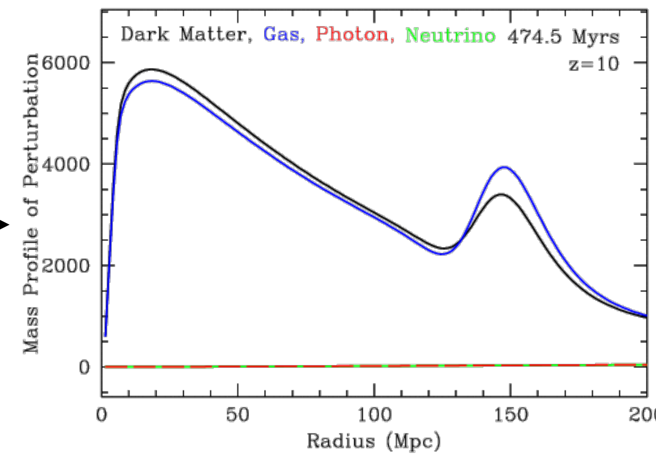




The relative velocity effect



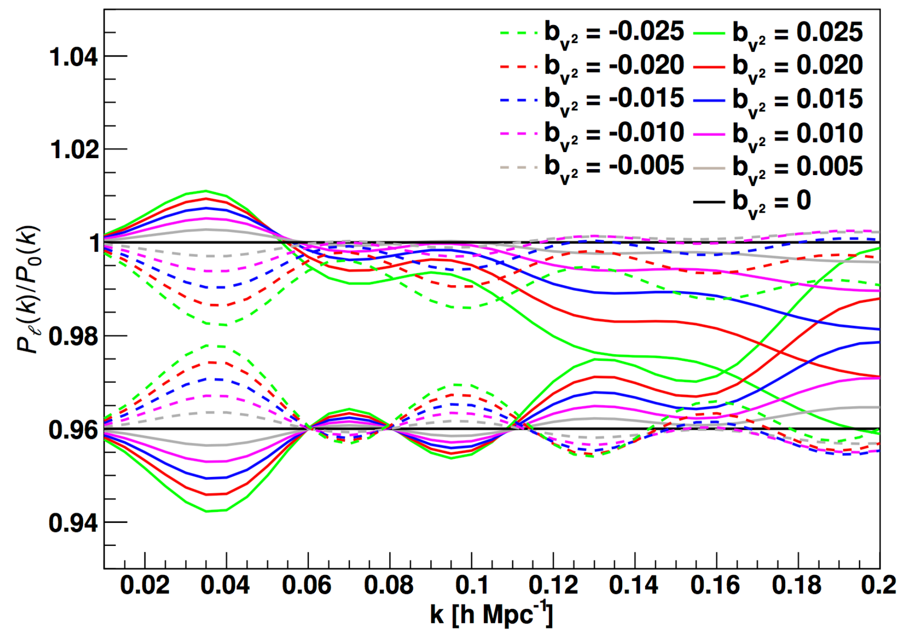
1/a decay due to growth, so will not affect low redshift



But, can affect high-z galaxy formation

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

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



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

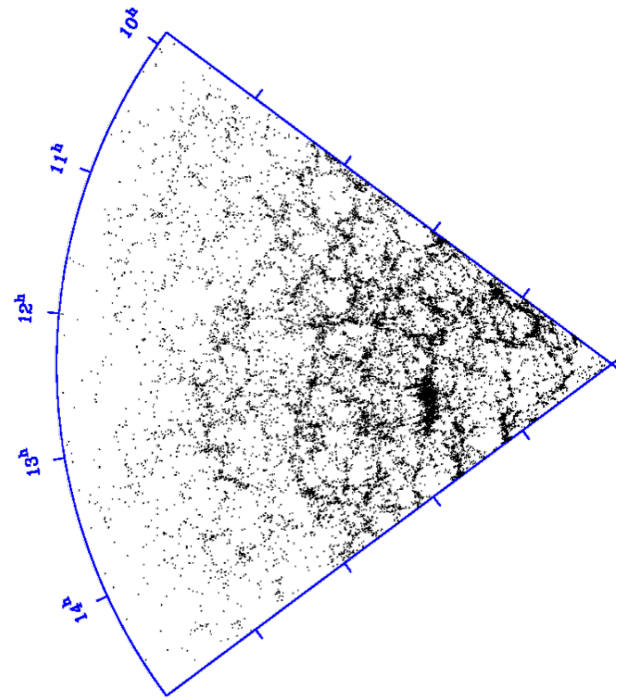
Galaxy clustering as a standard ruler

The evolution of the scale factor

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

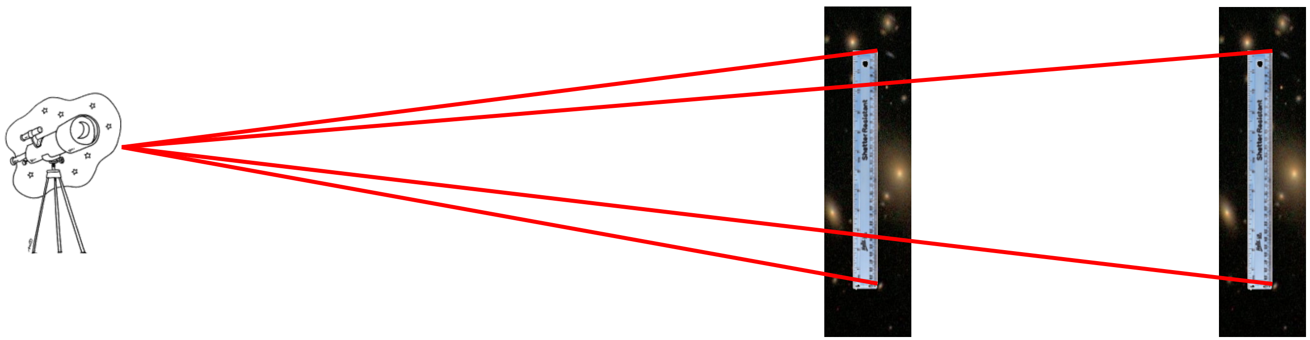
However, we measure galaxy redshifts and angles and infer distances

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



BAO as a standard ruler

Surveys measure angles and redshifts, and we use a fiducial model (denoted “fid”) to translate to comoving coordinates



Changes in apparent BAO position ($\Delta d_{\mathbf{comov}}$) depend on:

Radial direction

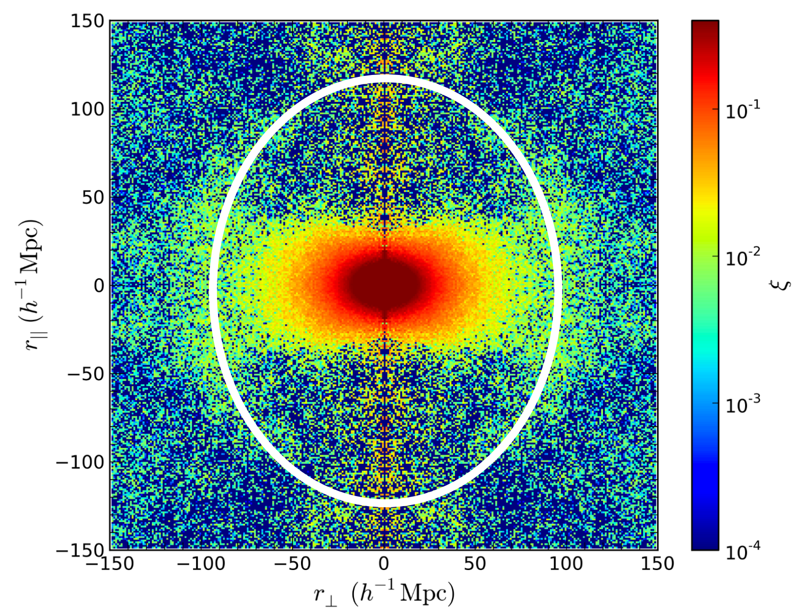
$$\alpha_{\parallel} = \frac{H(z)_{\rm fid}\, r_{d,{\rm fid}}}{H(z)\, r_d}$$

Angular direction

$$\alpha_{\perp} = \frac{D_A(z)\, r_{d,{\rm fid}}}{D_A(z)_{\rm fid}\, r_d}$$

r_d is the sound horizon at recombination

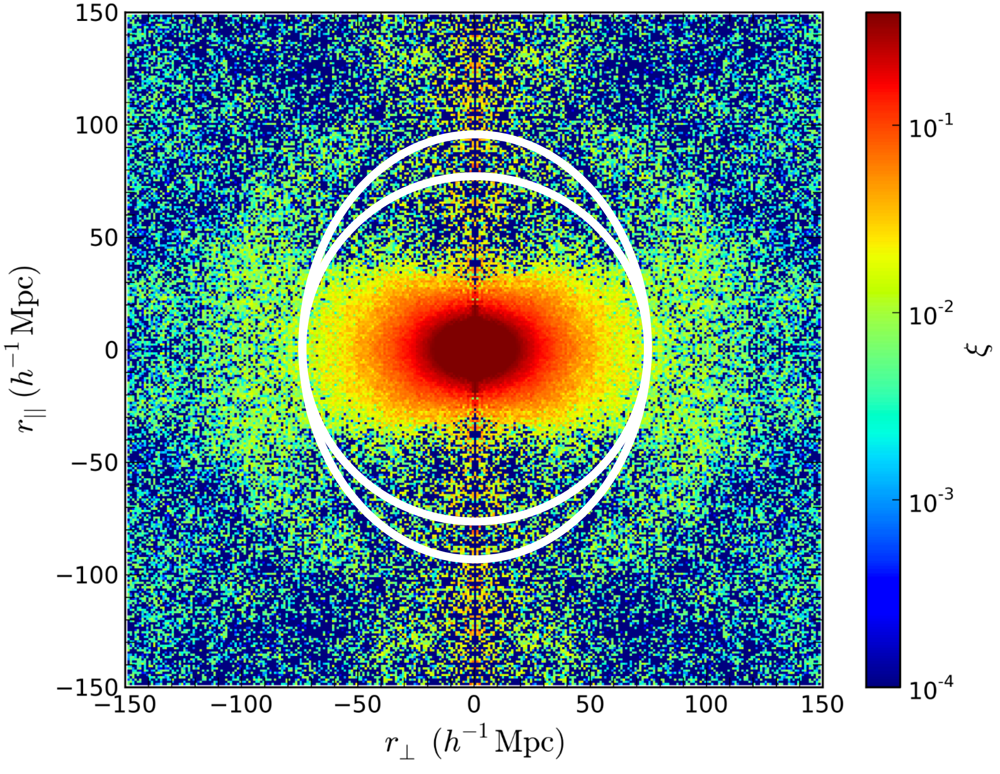
(i.e. these terms anisotropically stretch observed clustering - getting the relative effects to match is known as the **Alcock-Paczynski** test)



The AP effect

If we analyse the Universe using the correct distance-redshift relationship, then (ignoring other effects), we should have a symmetry along and across the LOS.

This requires $H(z)D_A(z)$ to be correct



Can we use the AP effect on small scales?

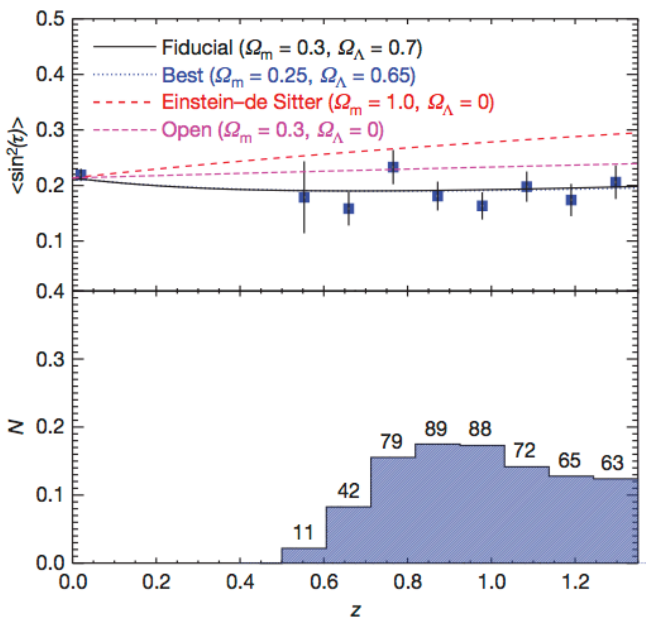
use isolated galaxy pairs

Marinoni & Buzzi 2011

- Nature 468, 539

Jennings et al. 2012

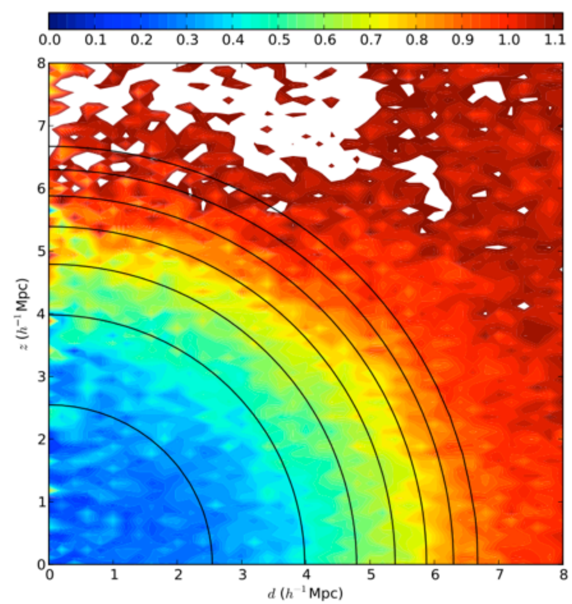
- MNRAS 420, 1079



use voids

Lavaux & Wandelt 2011

- arXiv:1110.0345



Collapsed structures

Live in static region of space-time

Velocity from growth exactly cancels Hubble expansion

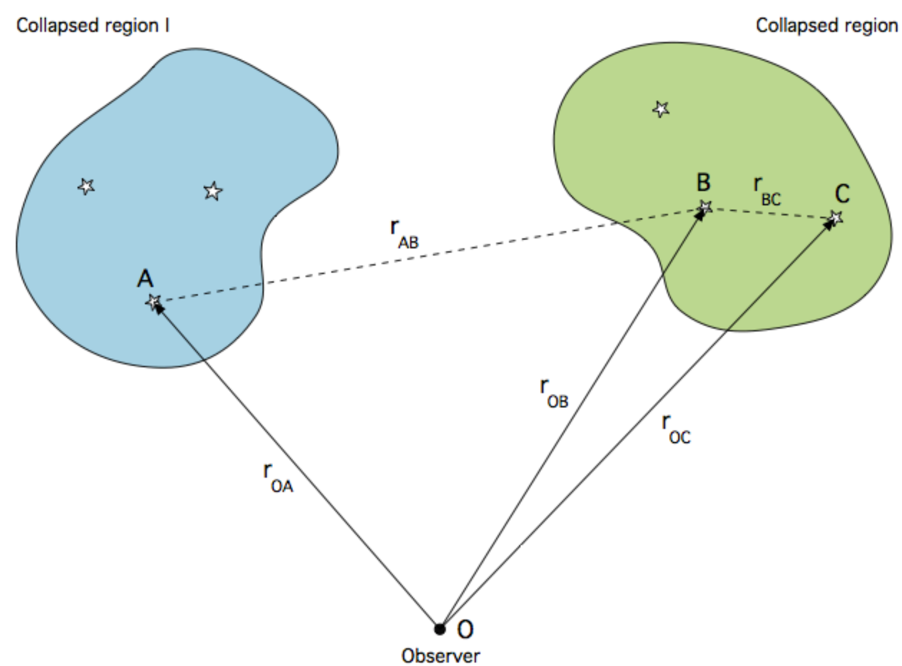
Two static galaxies in same structure have same observed redshift irrespective of distance from us

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

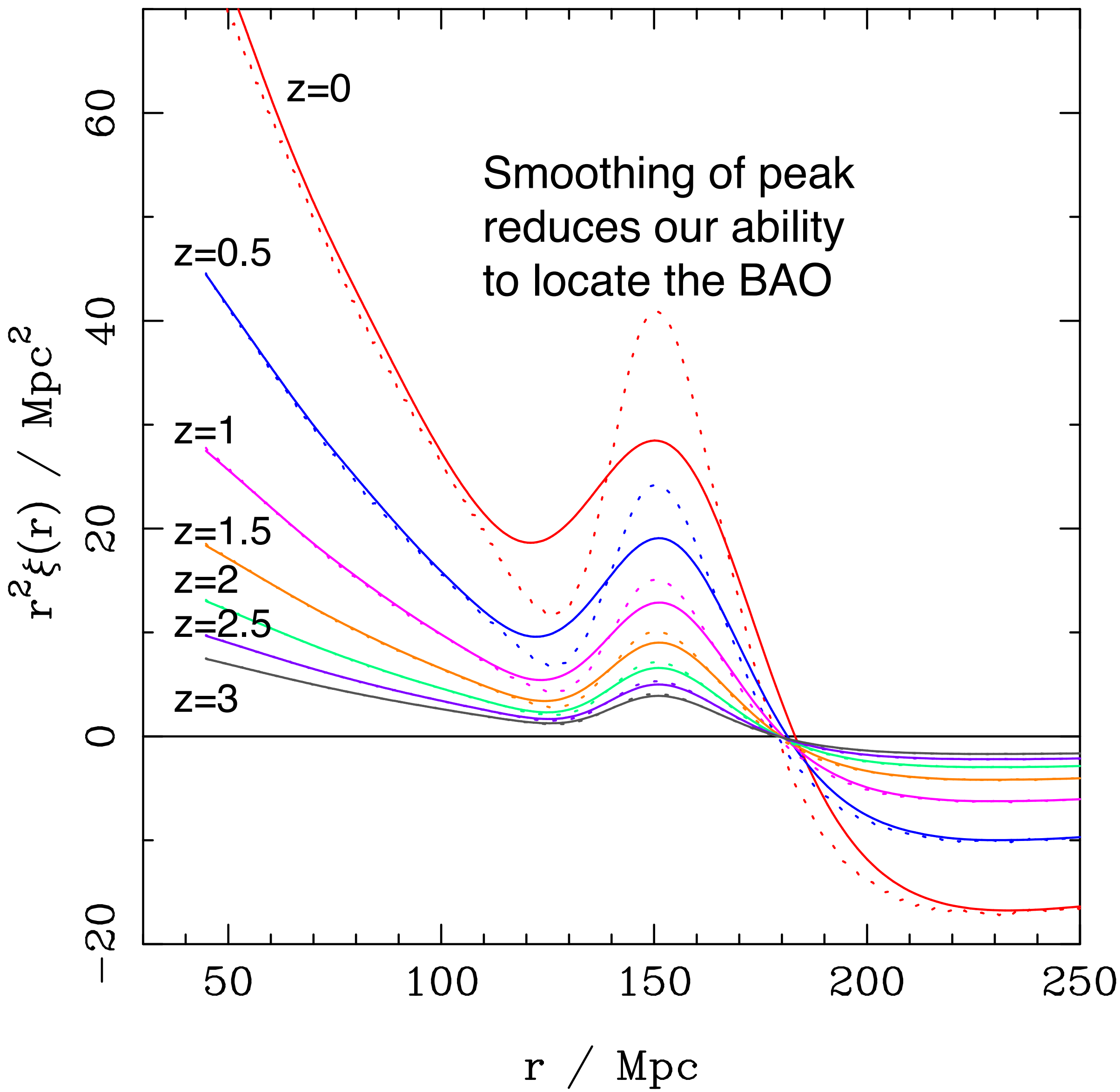


Belloso et al. 2012: arXiv:1204.5761

Moving beyond the linear …

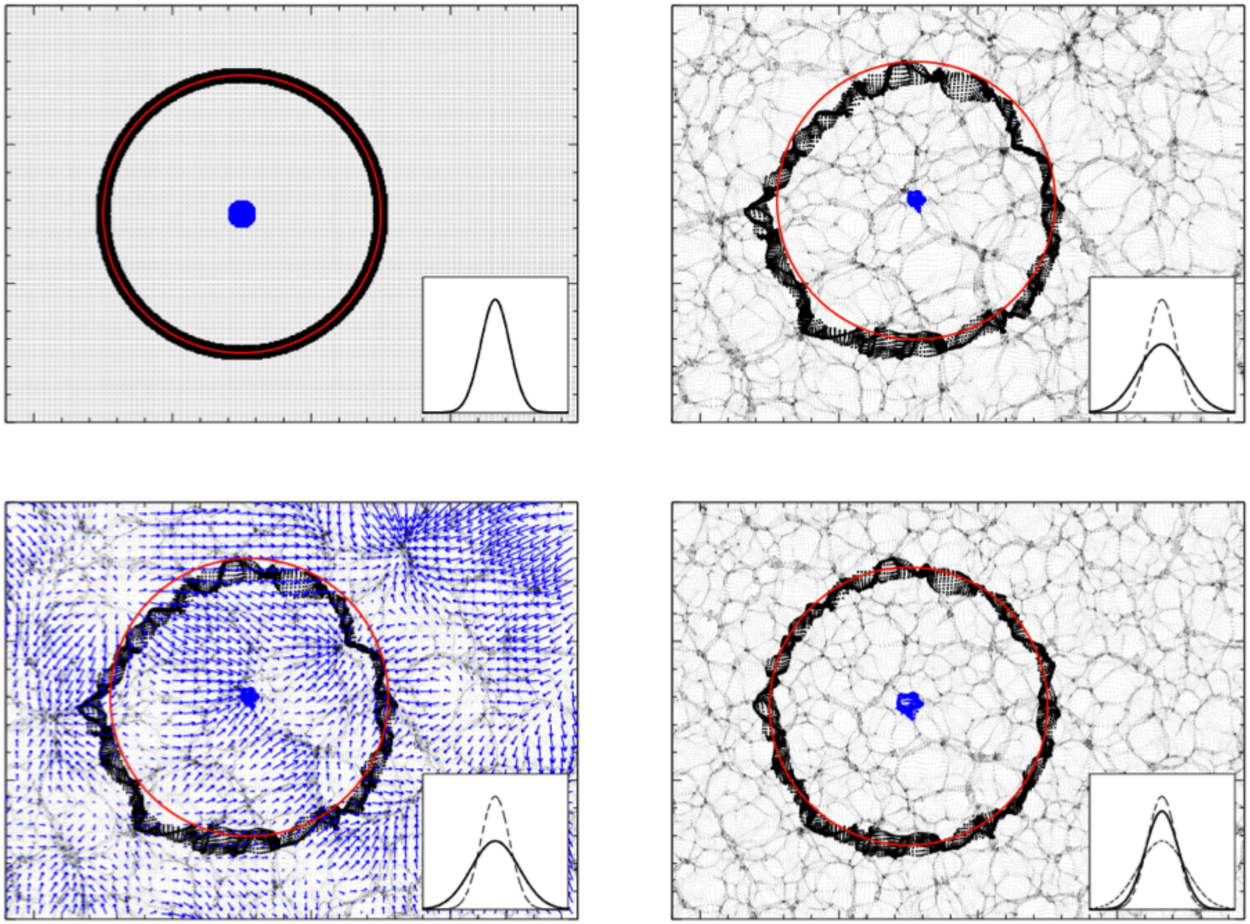
reconstruction of BAO

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

Portsmouth

A simple reconstruction algorithm

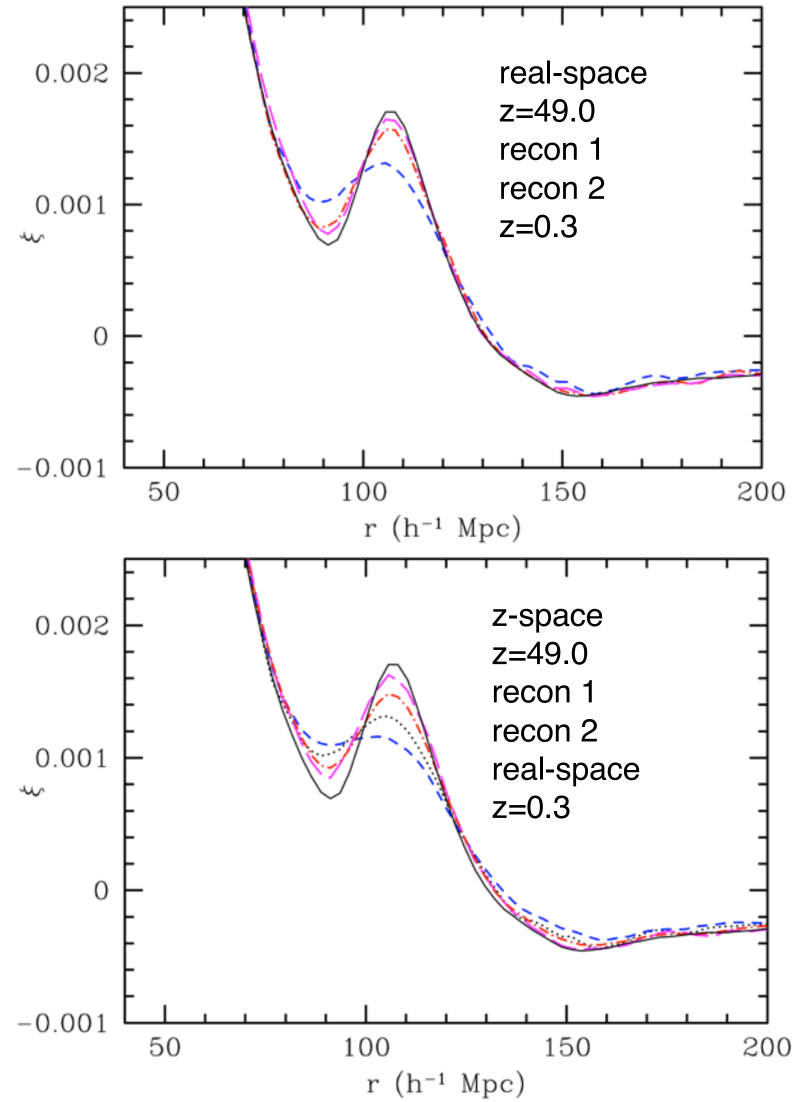
Algorithm: Smooth field and move overdensities by predicted (linear) motion

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

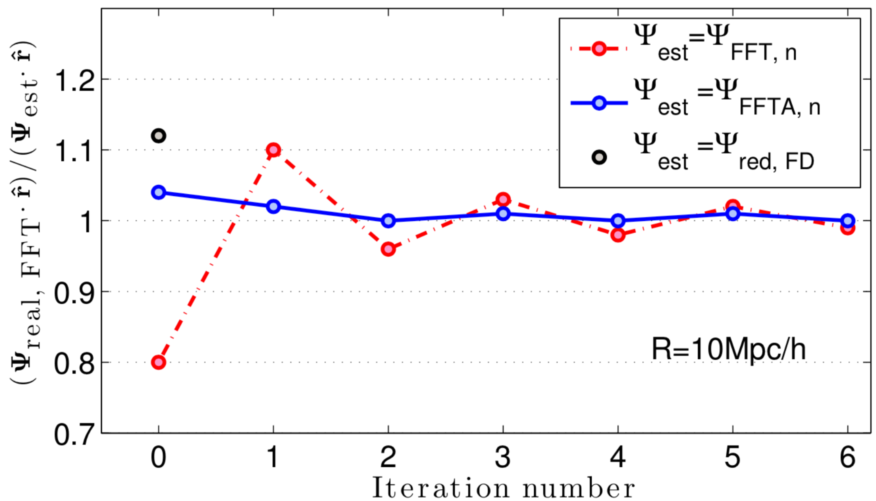
Reconstruction: dealing with RSD

Problem for reconstruction is RSD and dealing with varying line-of-sight across a survey: displacements **Ψ** are (in linear theory) related to overdensities by Poisson Eq + RSD

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

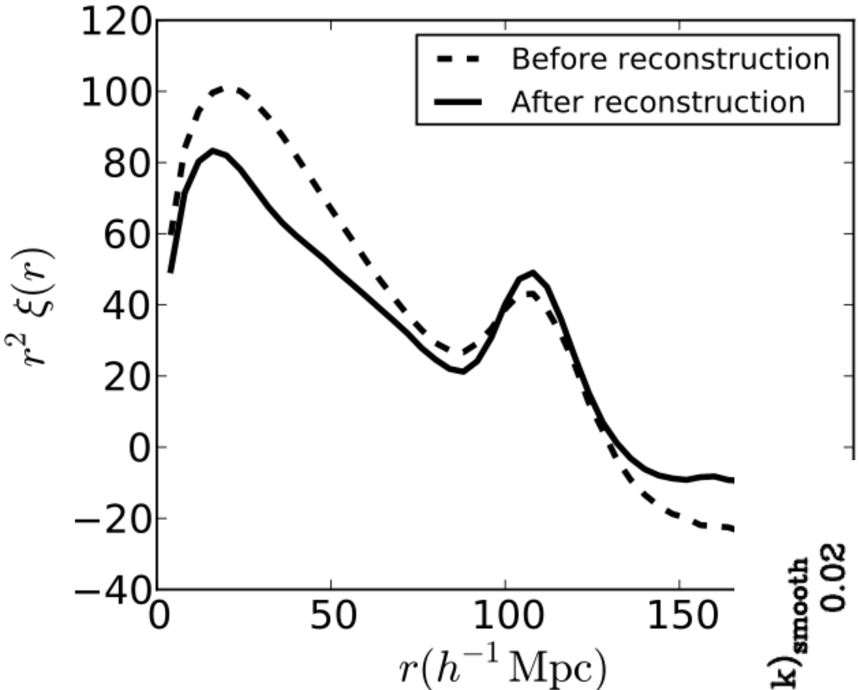
The RSD term limits fast calculation of the expected displacements as it is not irrotational, and depends on a varying line-of-sight

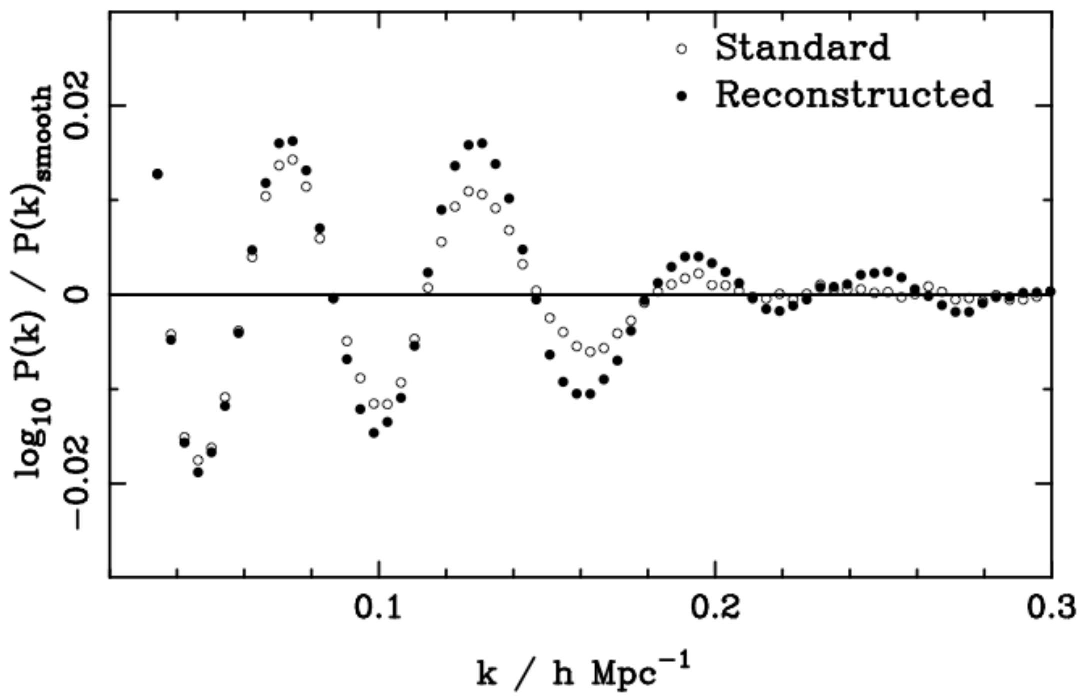
Introduce a new iterative method, allowing use of FFTs, but iterative procedures are a concern for a pipeline …



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

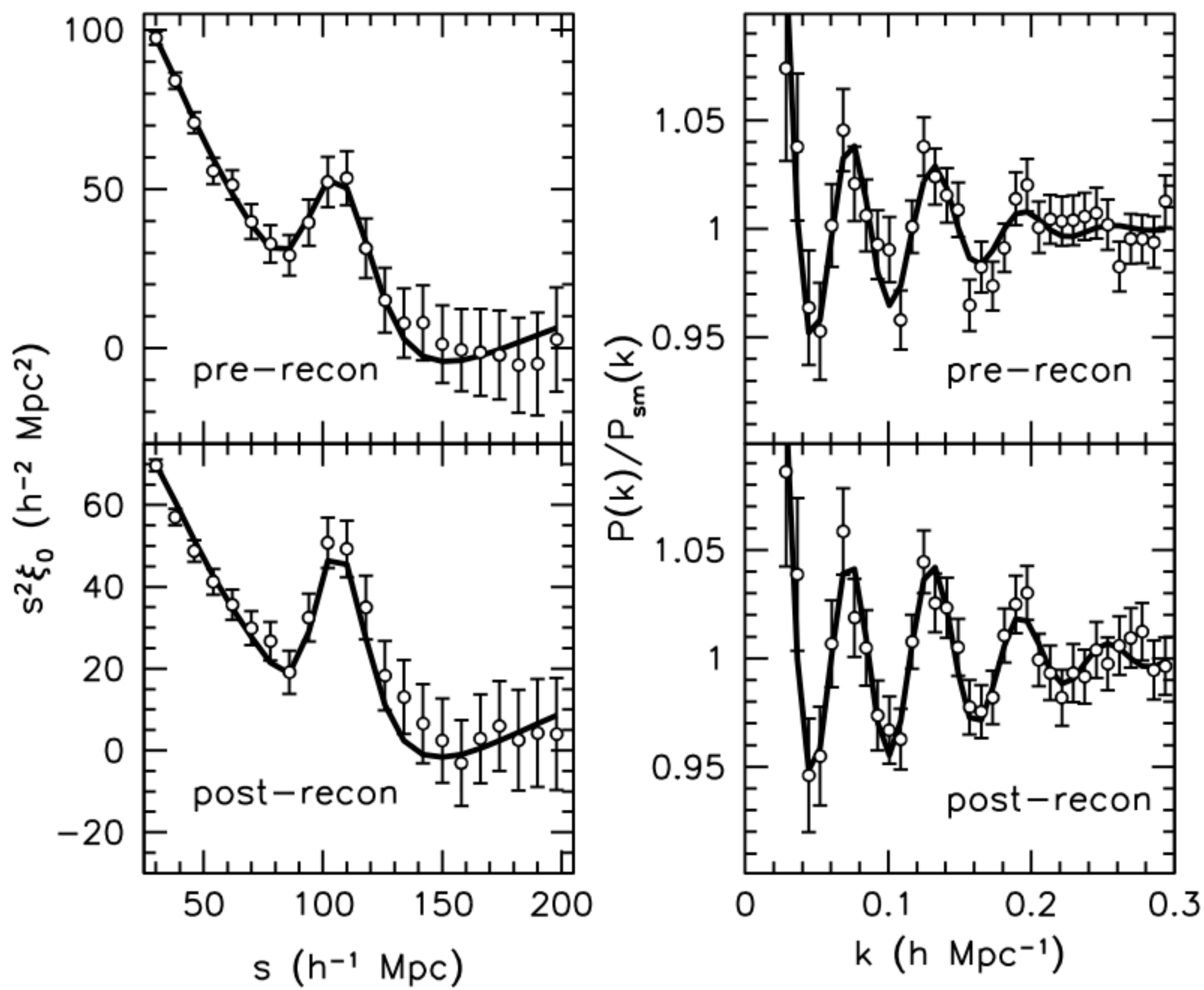
Reconstruction on SDSS-III mocks





Anderson et al. 2012; arXiv:1203.6565

The improvement from reconstruction



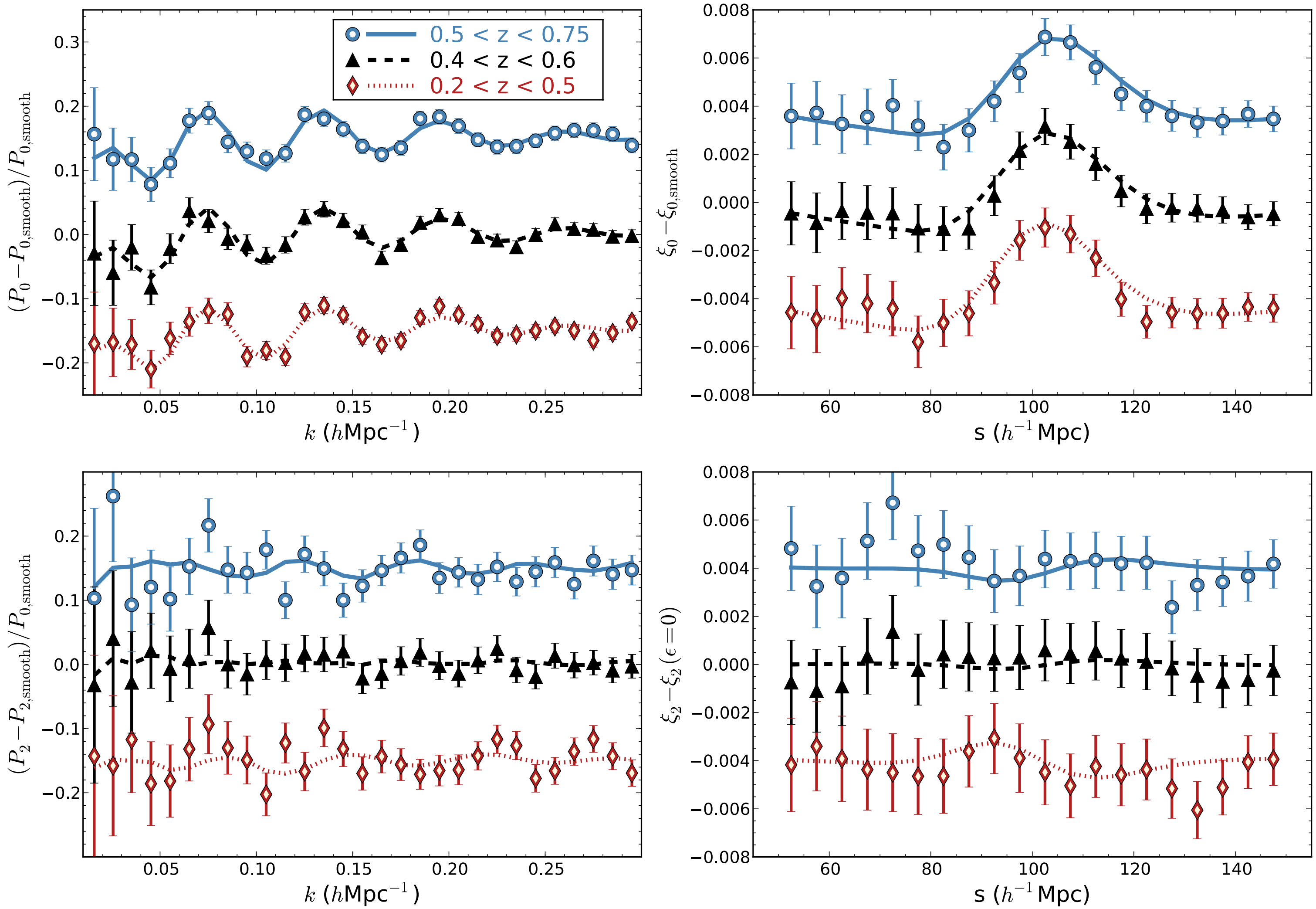
Anderson et al. 2013; arXiv:1312.4877

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

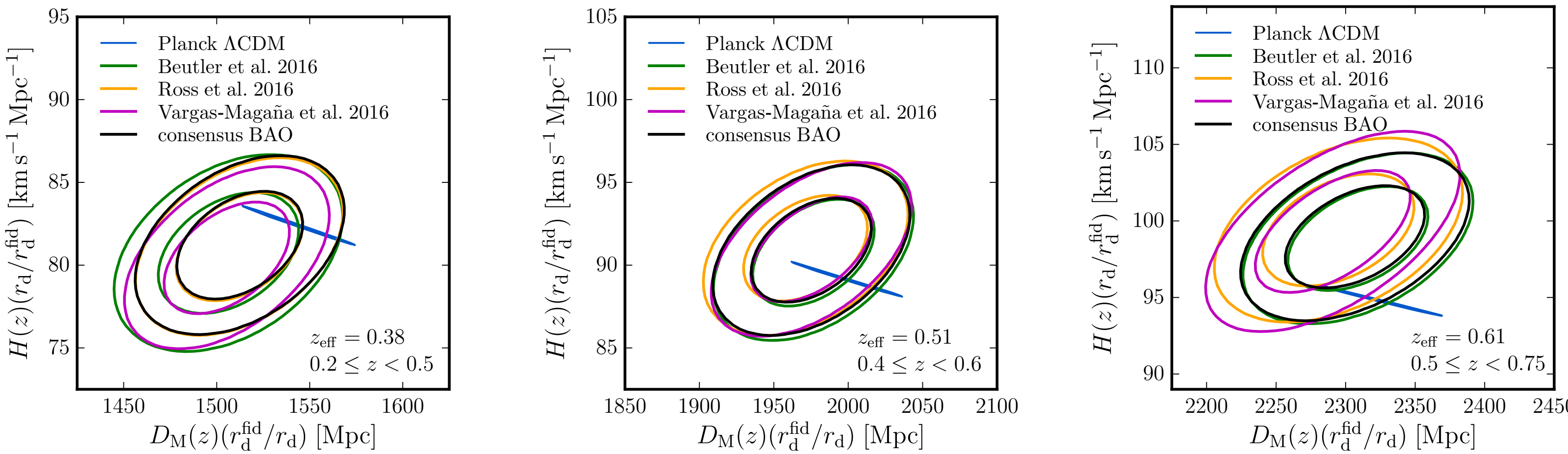
BAO results from BOSS

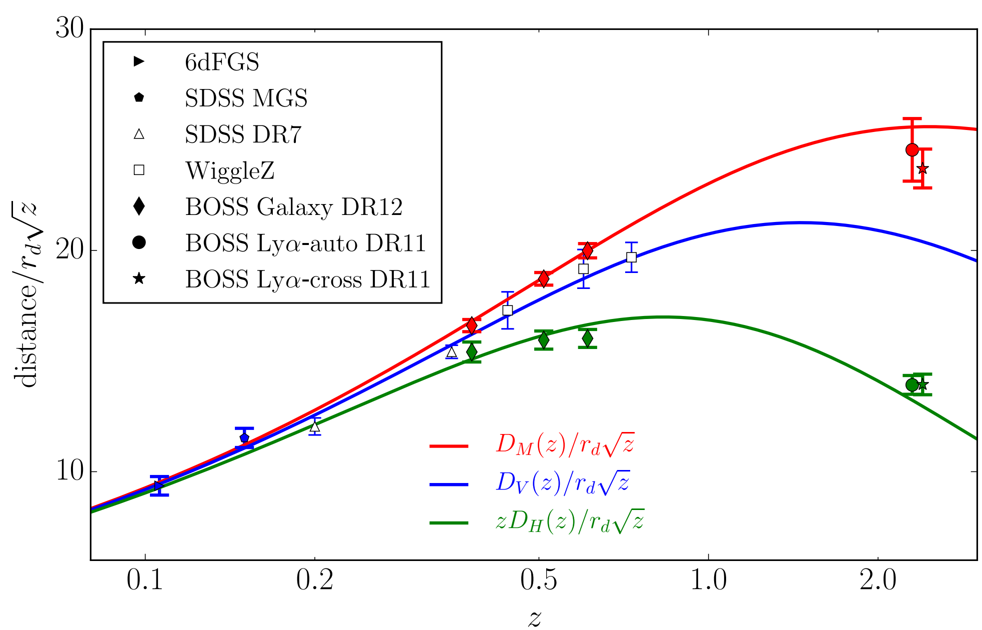
BOSS DR12 clustering measurements



Alam et al. 2016, arXiv:1607.03155

BOSS DR12 BAO measurements



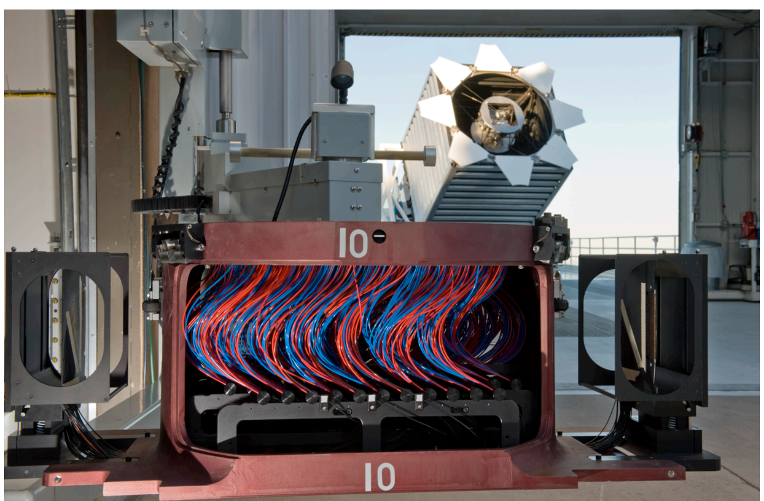


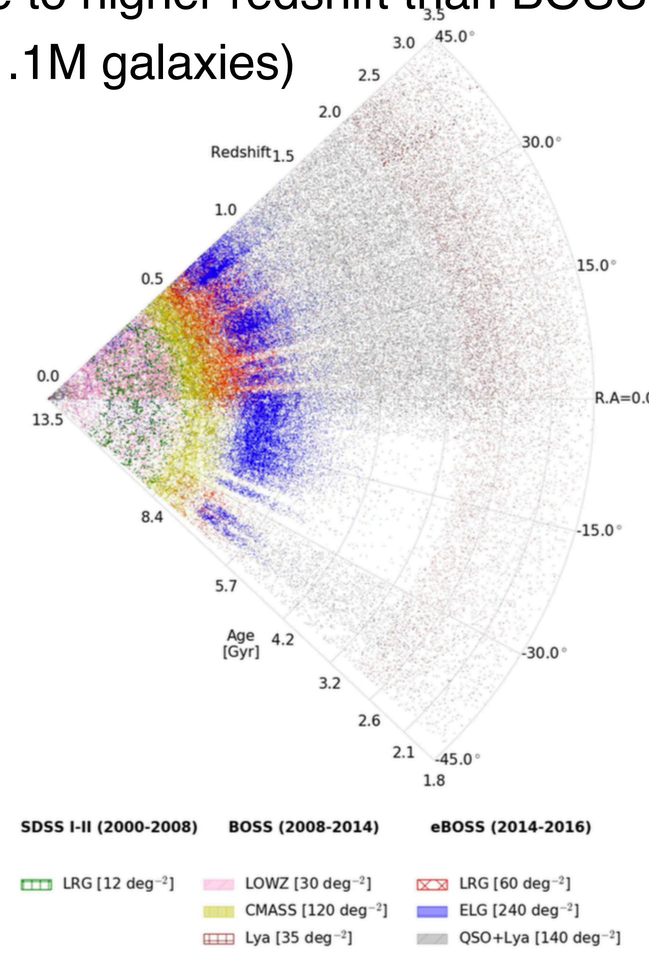
Alam et al. 2016, arXiv:1607.03155

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

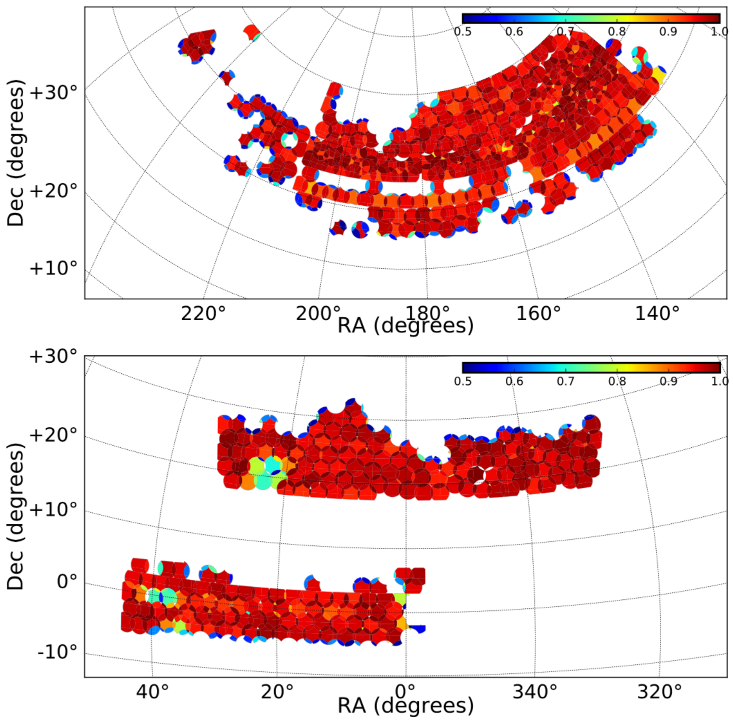




Dawson et al. 2015; arXiv:1508.04473, Zhao et al. 2015; arXiv:1510.08216

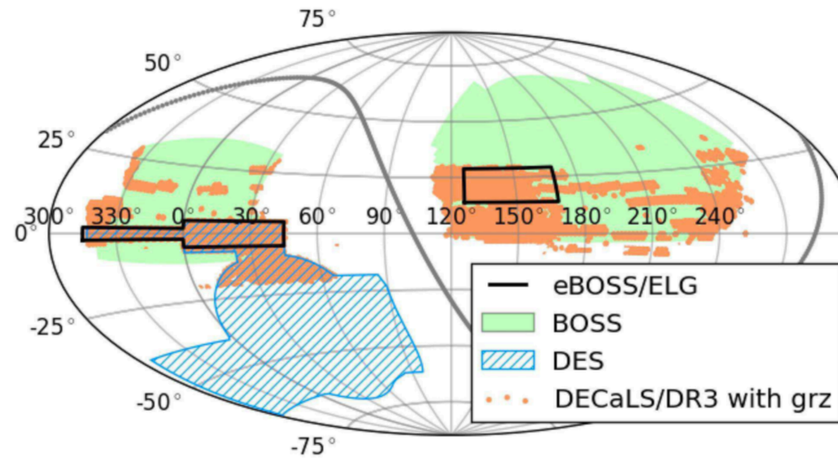
eBOSS footprint

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)

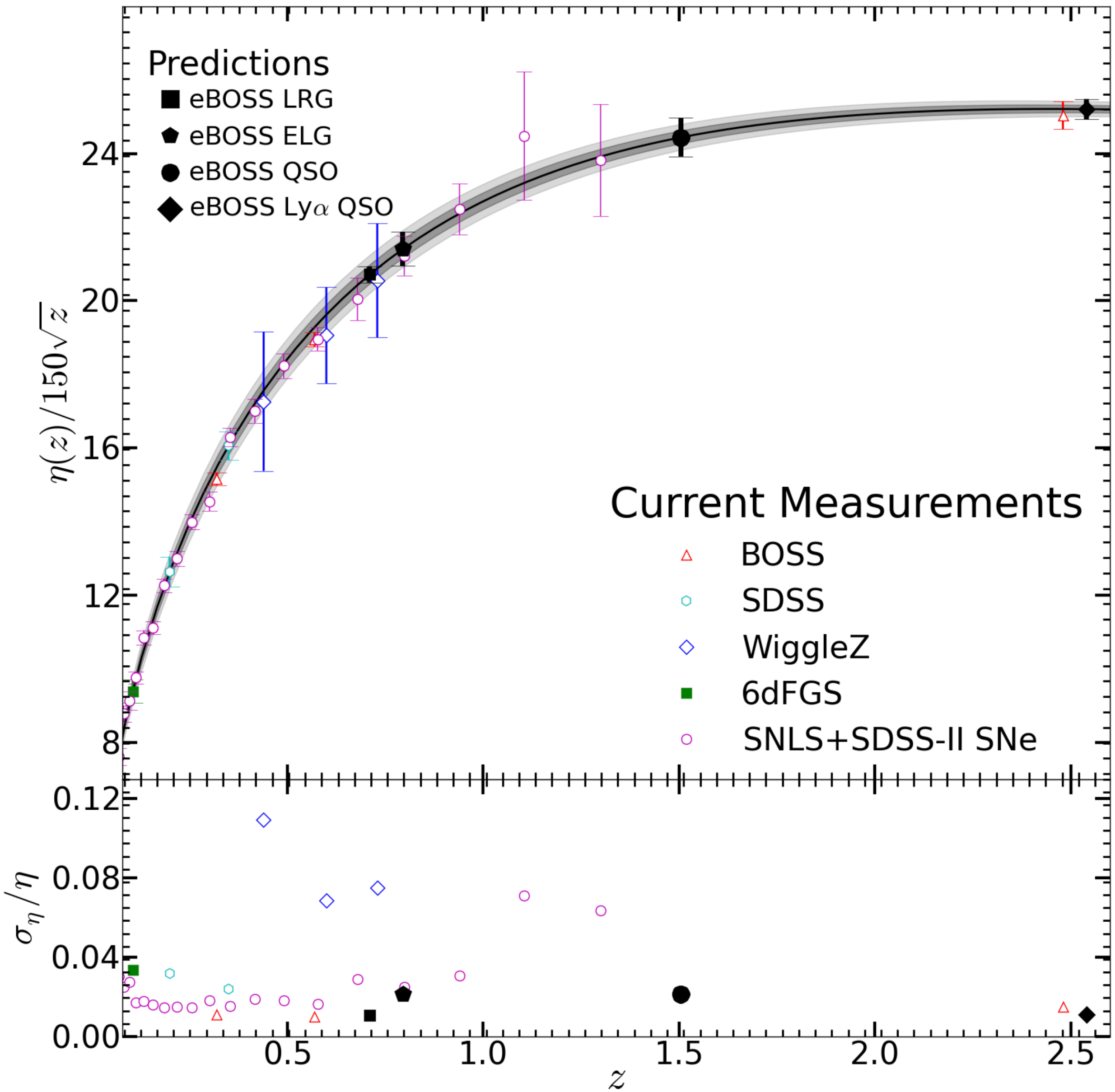


~620 deg^2 over the Fat Stripe 82 in the SGC, covered by DES observations; (317<ra<360 and –2<dec<2) or (0<ra<45 and –5<dec<5);

~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



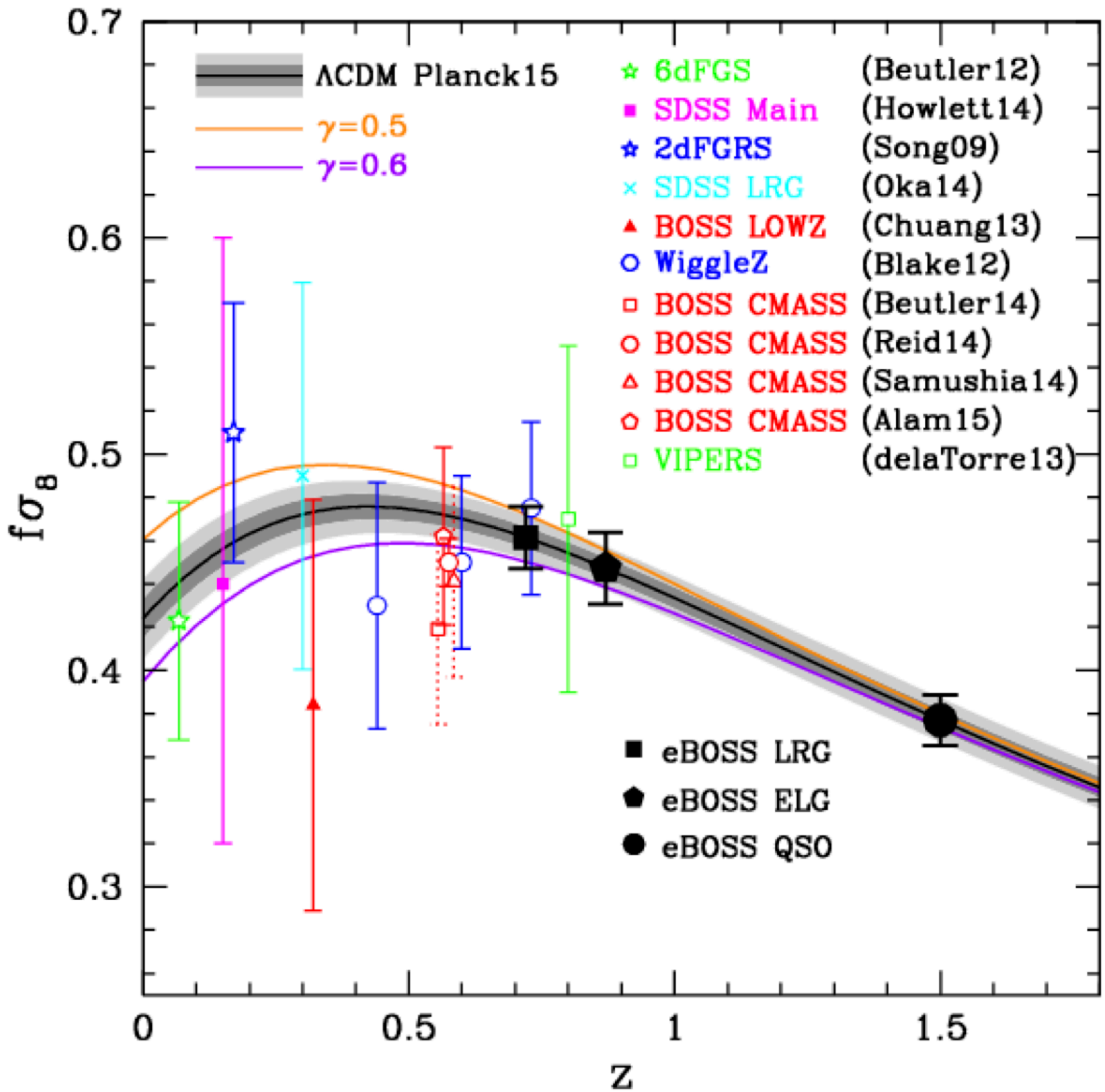
Distance precisions 1-2% on all tracers

- 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



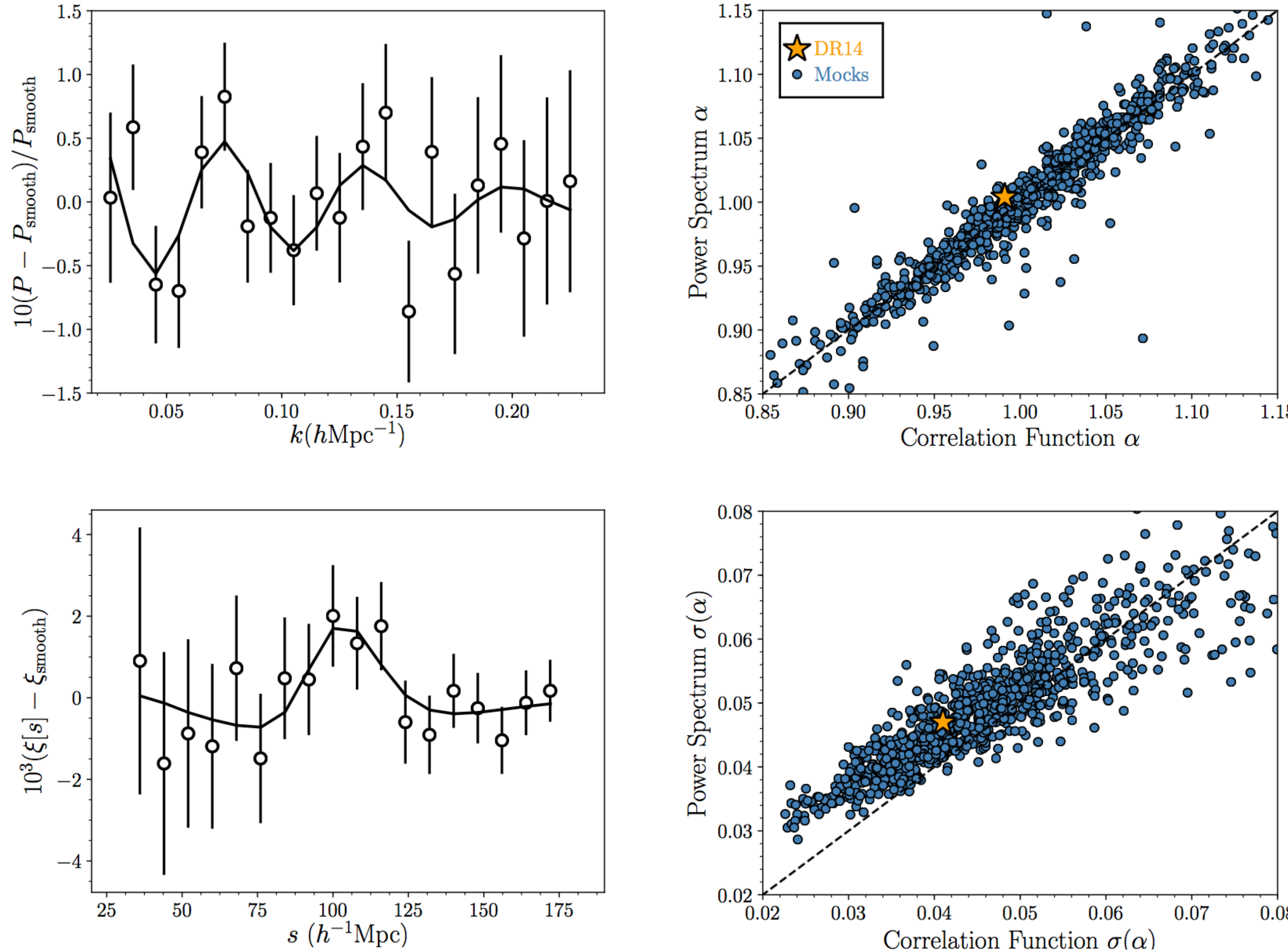
$f\sigma_8$ statistical precisions on galaxy and QSO

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

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

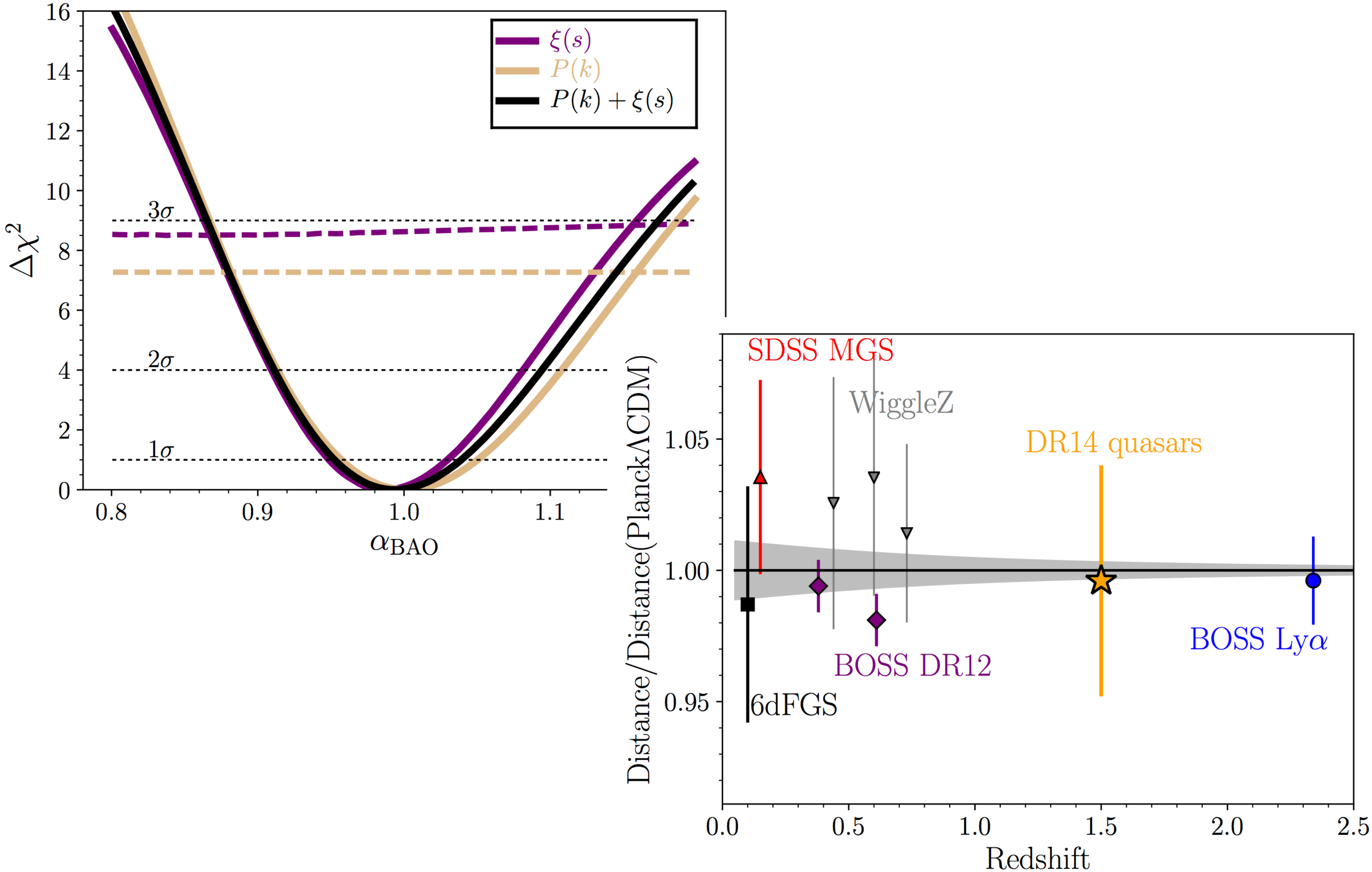
Dawson et al. 2015; arXiv:1508.04473, Zhao et al. 2015; arXiv:1510.08216

eBOSS DR14: 147,000 quasars



Ata et al. 2017; arXiv:1705.06373

eBOSS DR14: 147,000 quasars



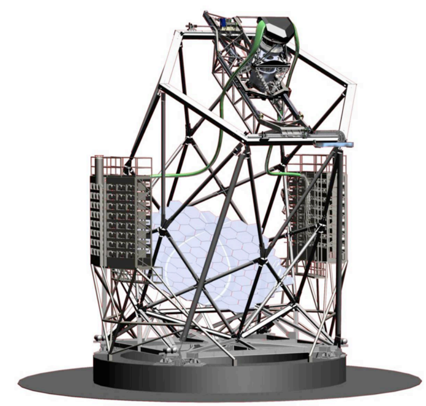
Ata et al. 2017; arXiv:1705.06373

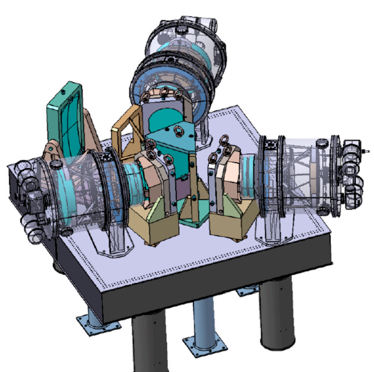
Future surveys

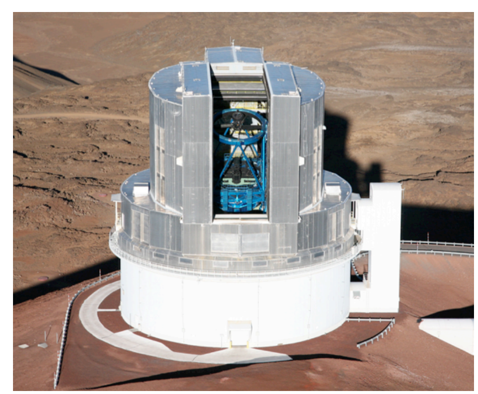
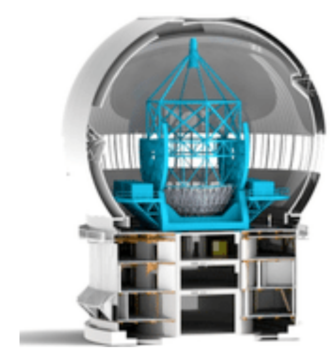
MOS on 10m-telescope

New fibre-fed spectrographs being developed

- HETDEX (on the Hobby-Eberly telecope)
  - 420deg^2 Ly-alpha emitters
  - 800,000 galaxies $1.9<z<3.5$
  - Greig, Komatsu & Wyithe, 2012, arXiv:12120977
- PFS (on the Subaru telescope)
  - 1400deg^2 ELGs
  - 3,000,000 galaxies $0.6<z<2.4$
  - Ellis et al., 2012, arXiv:1206.0737
- MSE (replacement telescope for CFHT)
  - science case not driven by BAO/RSD survey

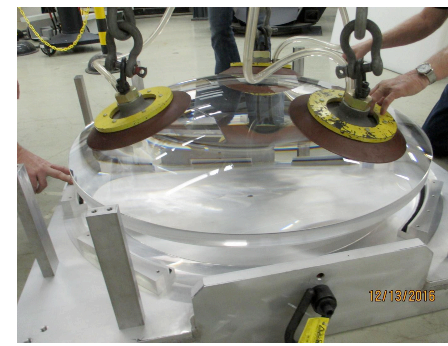



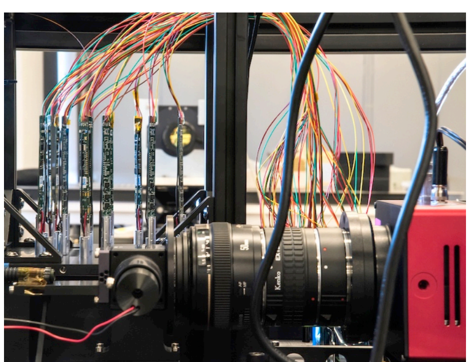


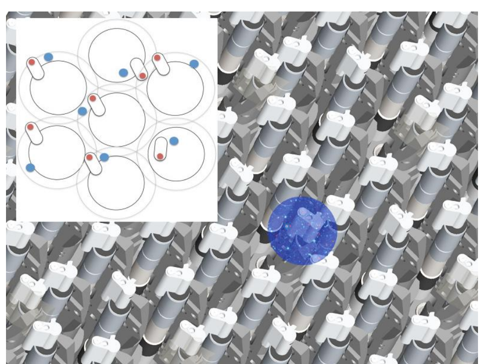



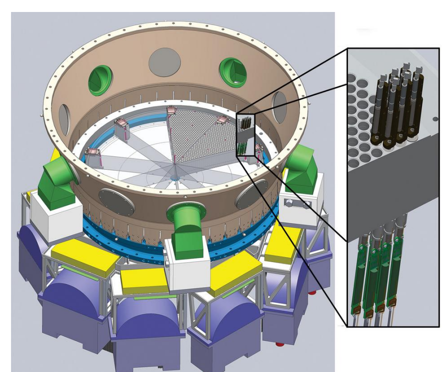
DESI

- 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

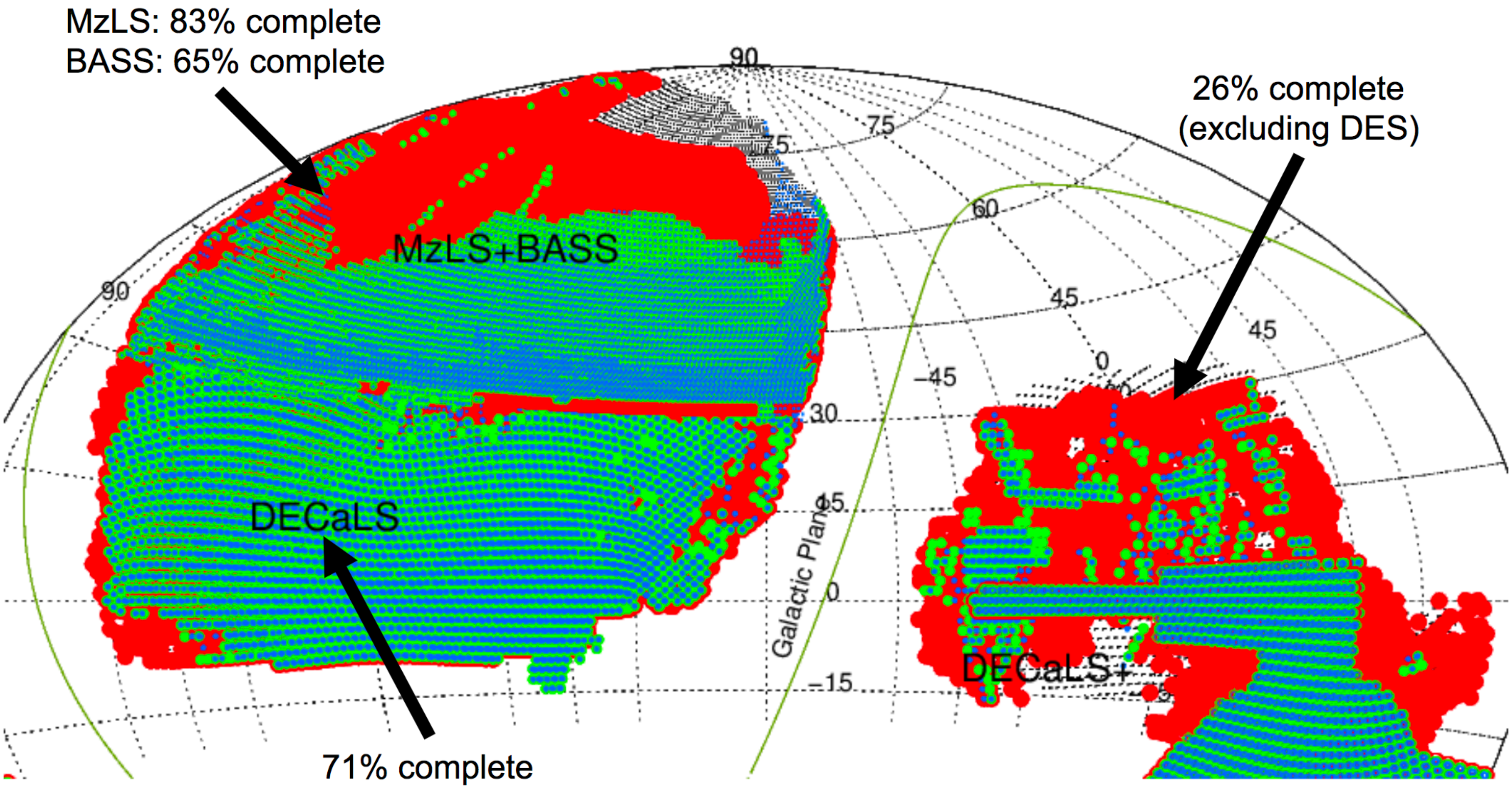






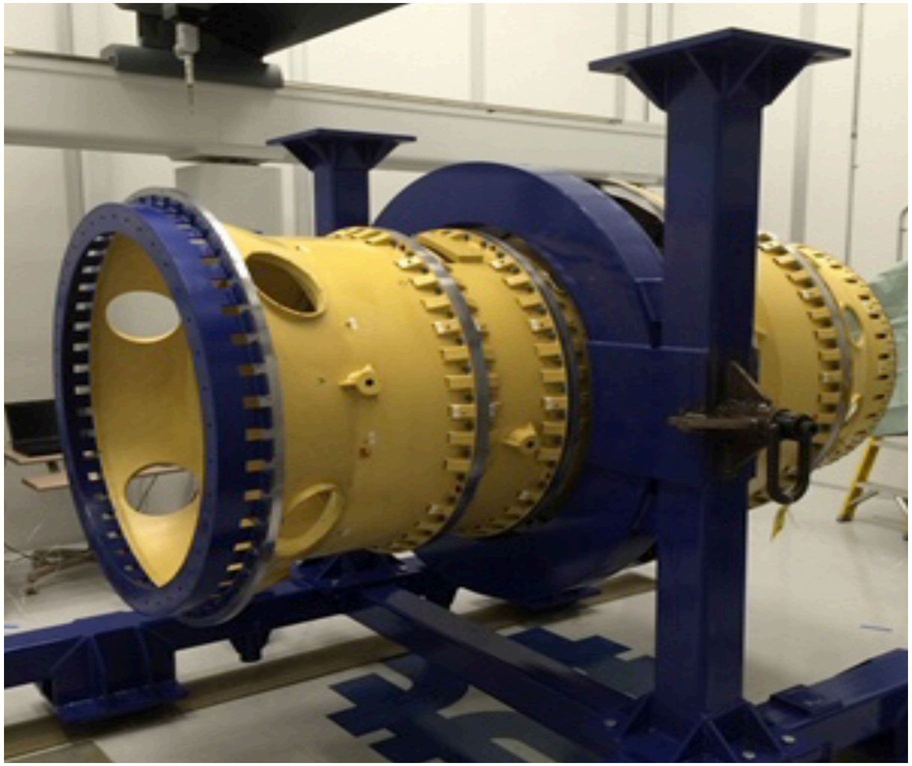


DESI imaging data (from which to target)



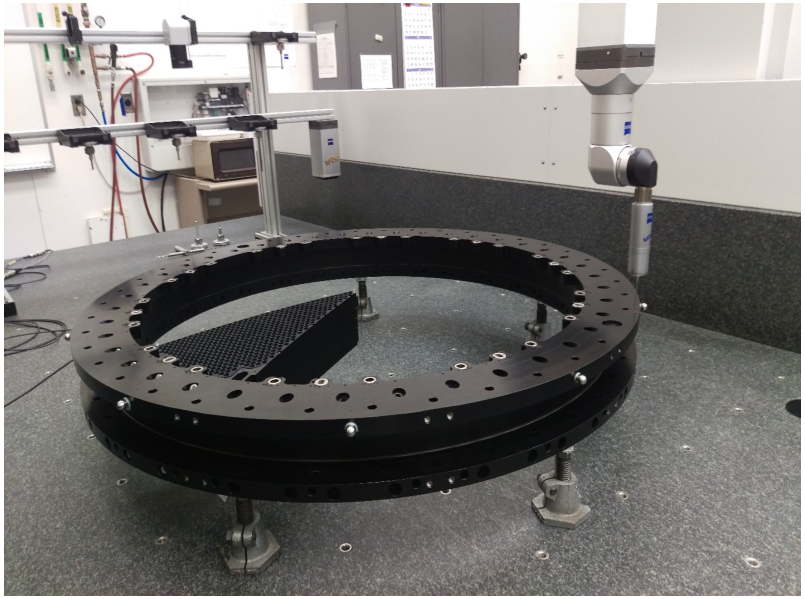
Ata et al. 2017; arXiv:1705.06373

DESI - latest updates

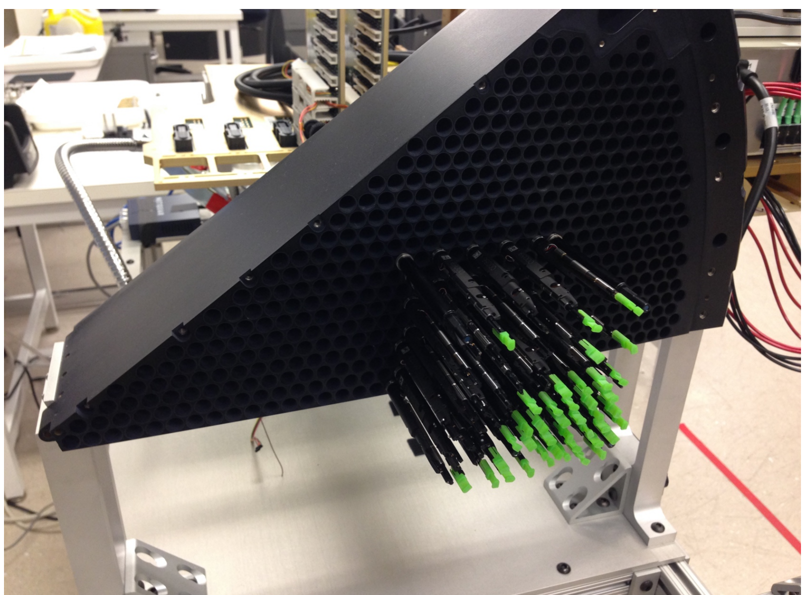


2017 is a critical year for hardware manufacture

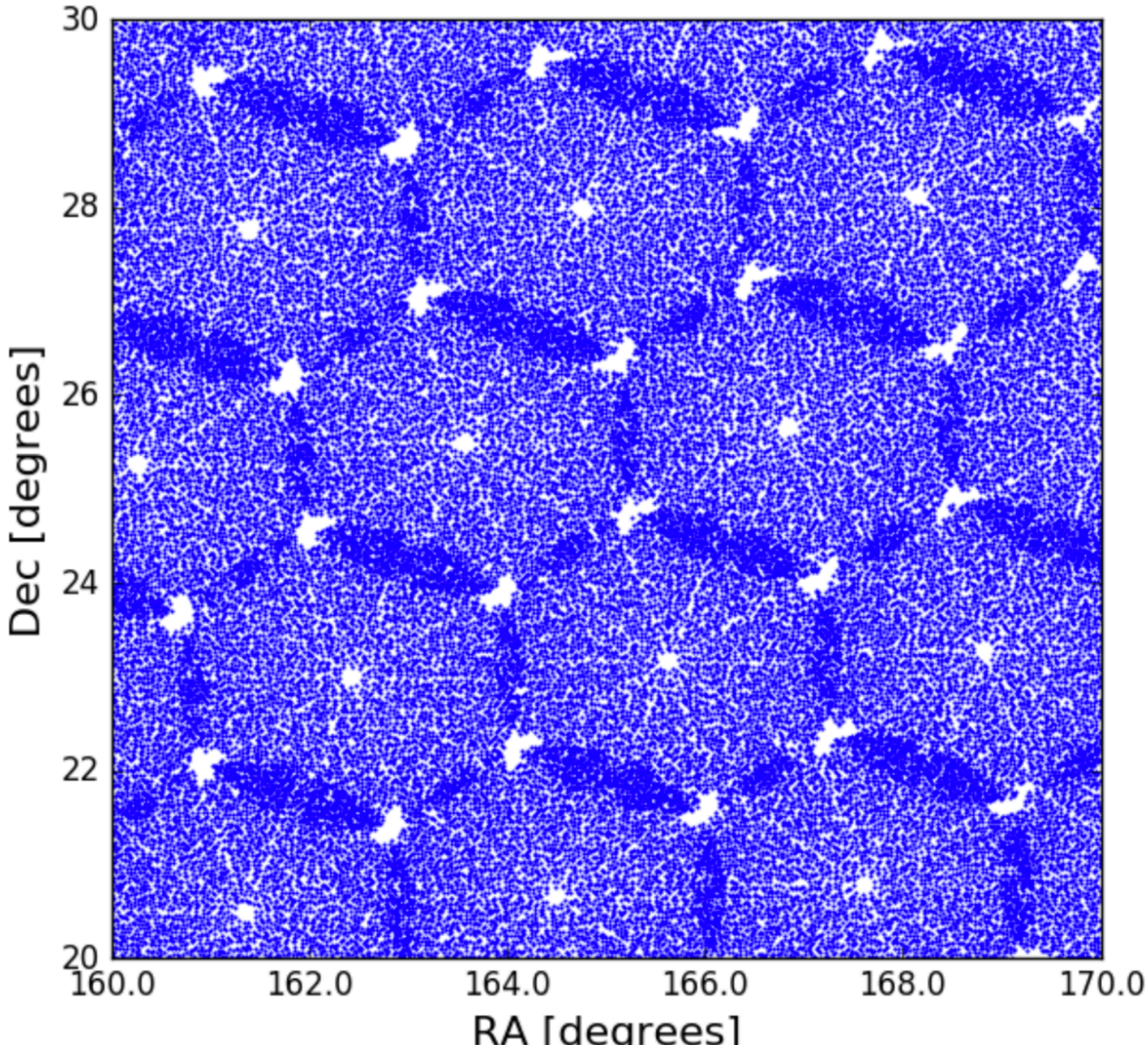
DESI - latest updates



2017 is a critical year for hardware manufacture



DESI observations



Burden et al. 2016; arXiv:1611.04635

Dealing with missing galaxies

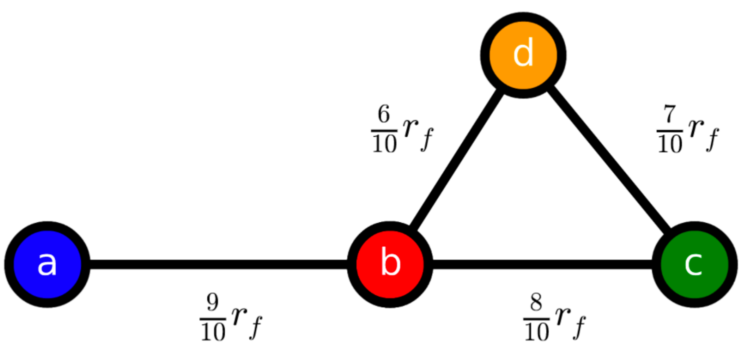
Spectroscopic surveys are always < 100% complete

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!



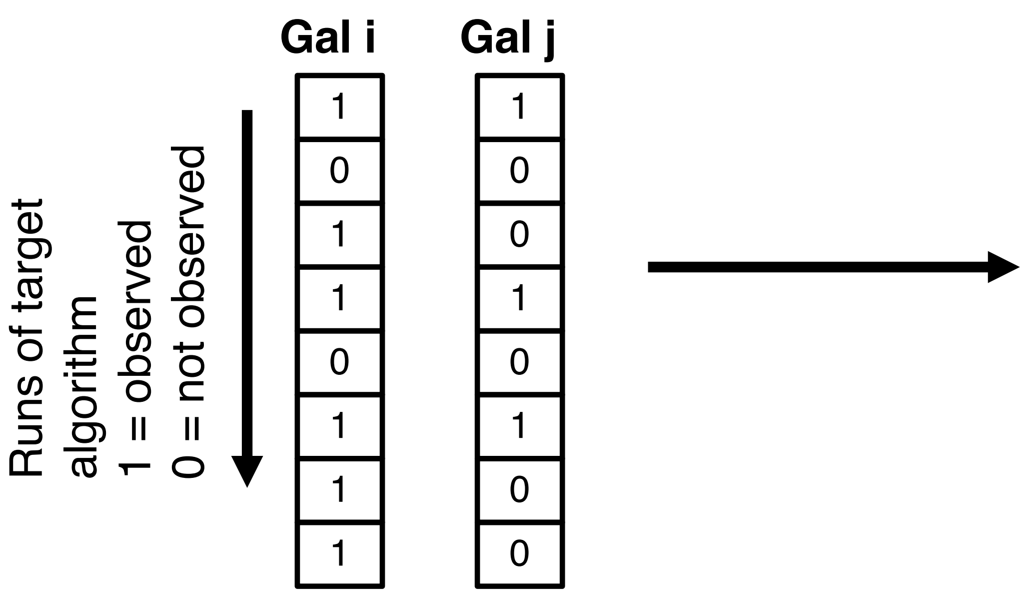
Bianchi & Percival 2017; arXiv:1703.02070

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

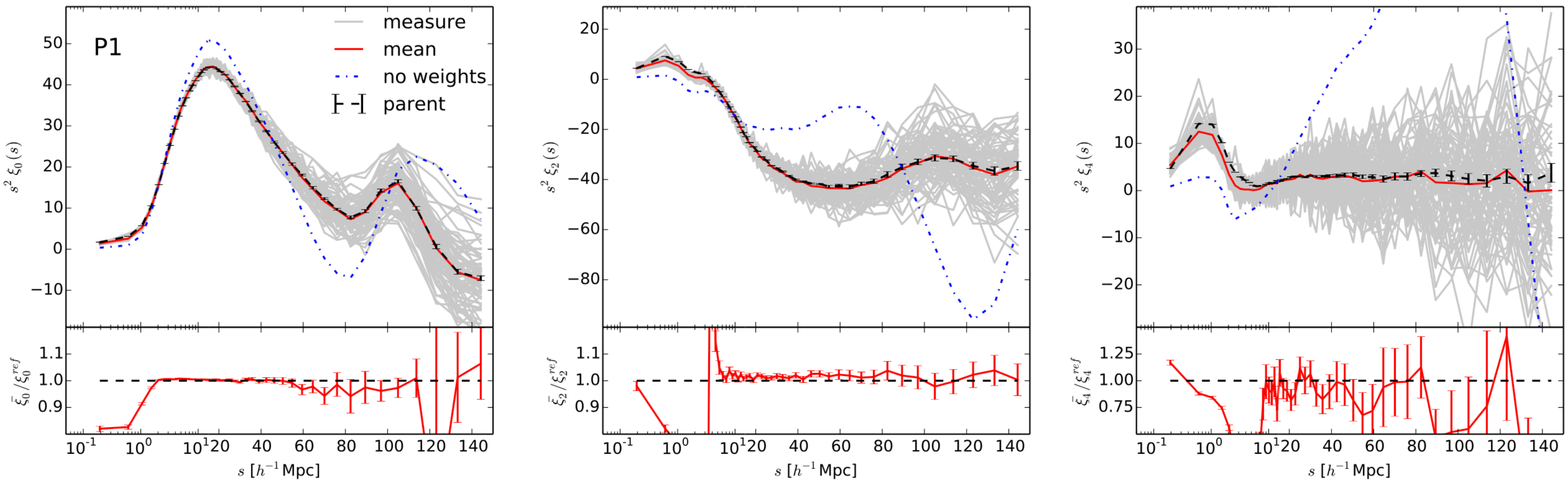
Potentially computationally challenging (storing probabilities), but introduce a new Monte-Carlo scheme based on bitwise weights stored per galaxy, so that pairwise weights can be determined "on the fly"



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

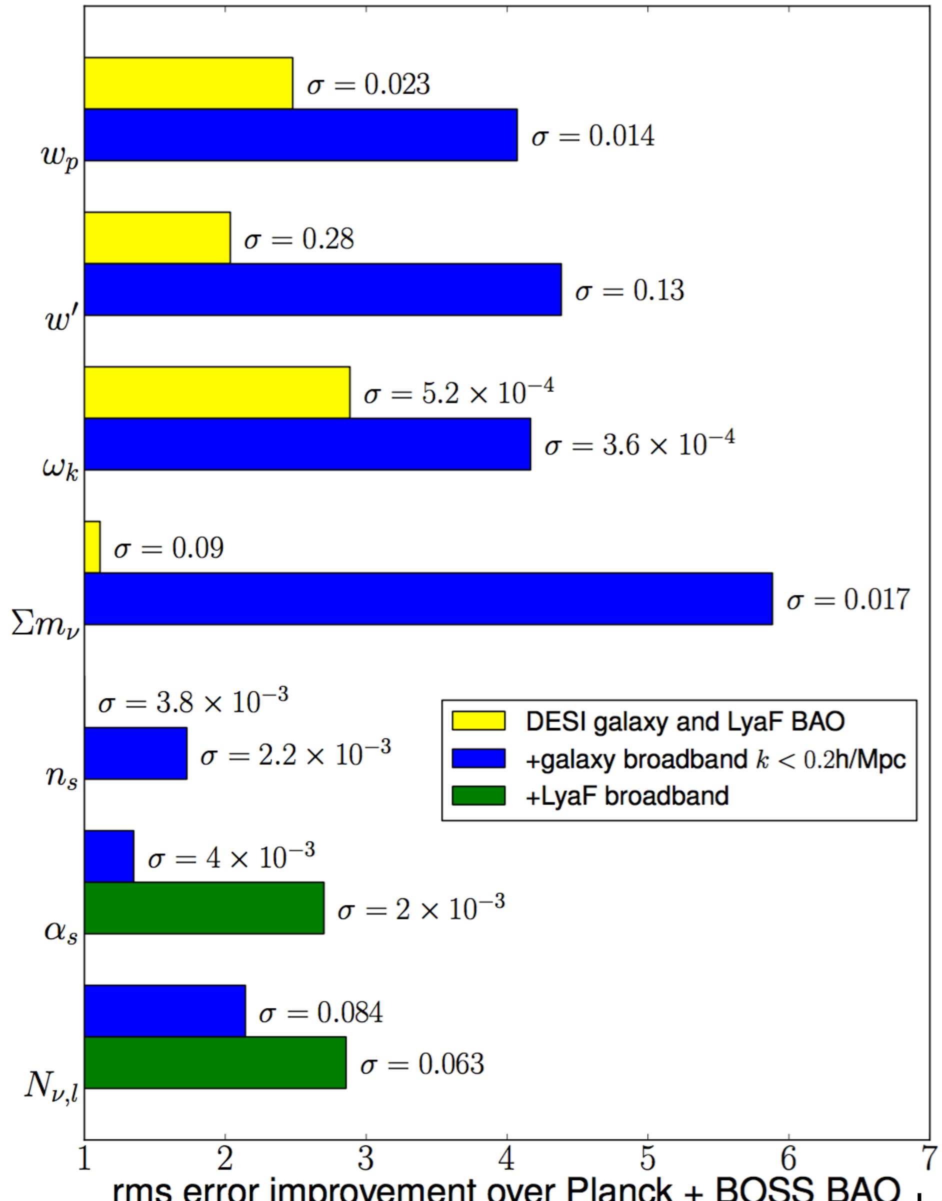
Bianchi & Percival 2017; arXiv:1703.02070

DESI: Fiber assignment



Bianchi & Percival 2017; arXiv:1703.02070

DESI cosmological predictions



Levi et al. 2013; arXiv:1308.0847

Euclid

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

Wide survey:

- 15,000deg^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)
    - 2×10^{-16}ergcm^{-2}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

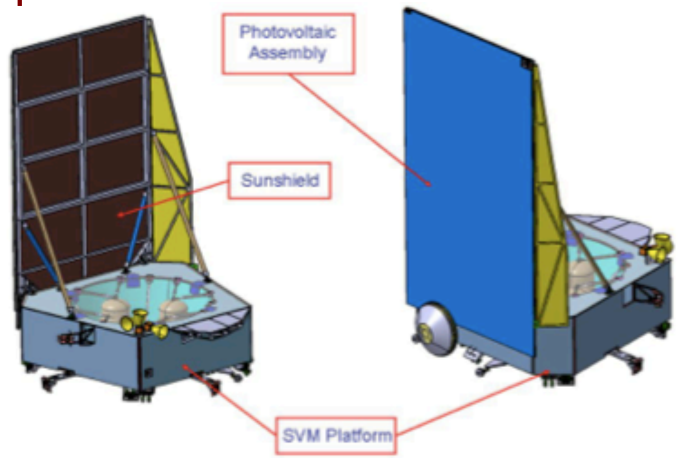
Deep survey:

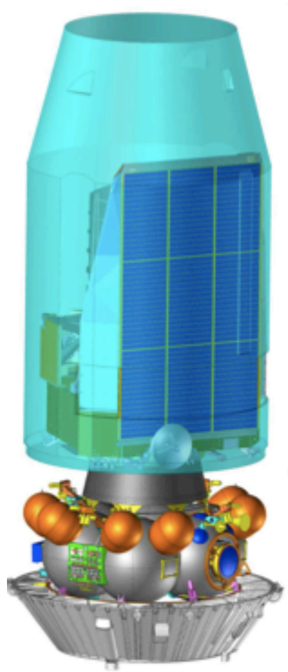
- 40deg^2
- 48 dithers
- 12 passes, as for wide survey
- additional blue spectra: 0.92-1.25μm
- dispersion directions for 12 passes >10deg apart

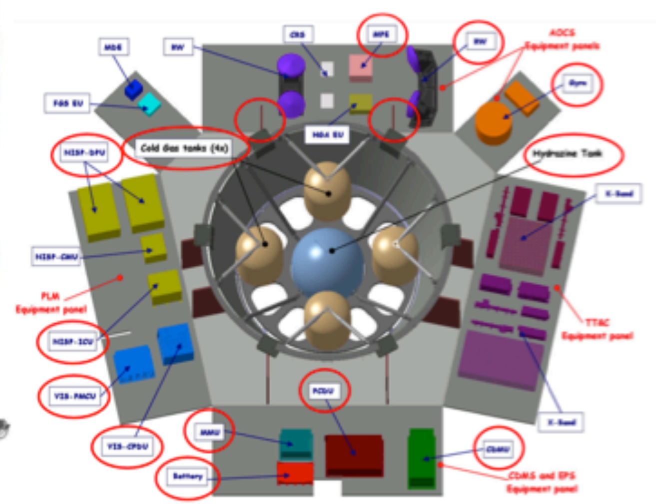
http://www.euclid-ec.org/

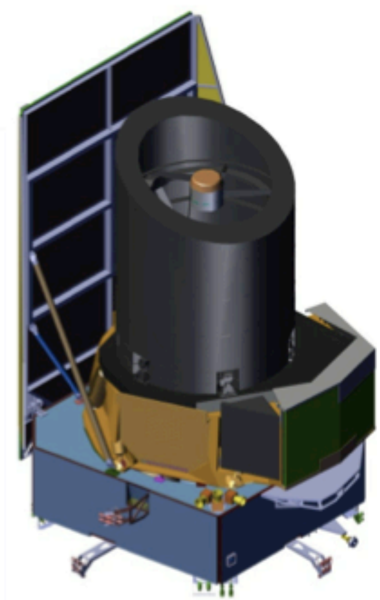
The telescope

Total mass: 2200kg
Dimensions: 4.5m x 3m
Sunshield: Thales Alenia Space
Telescope: Airbus Defence and Space

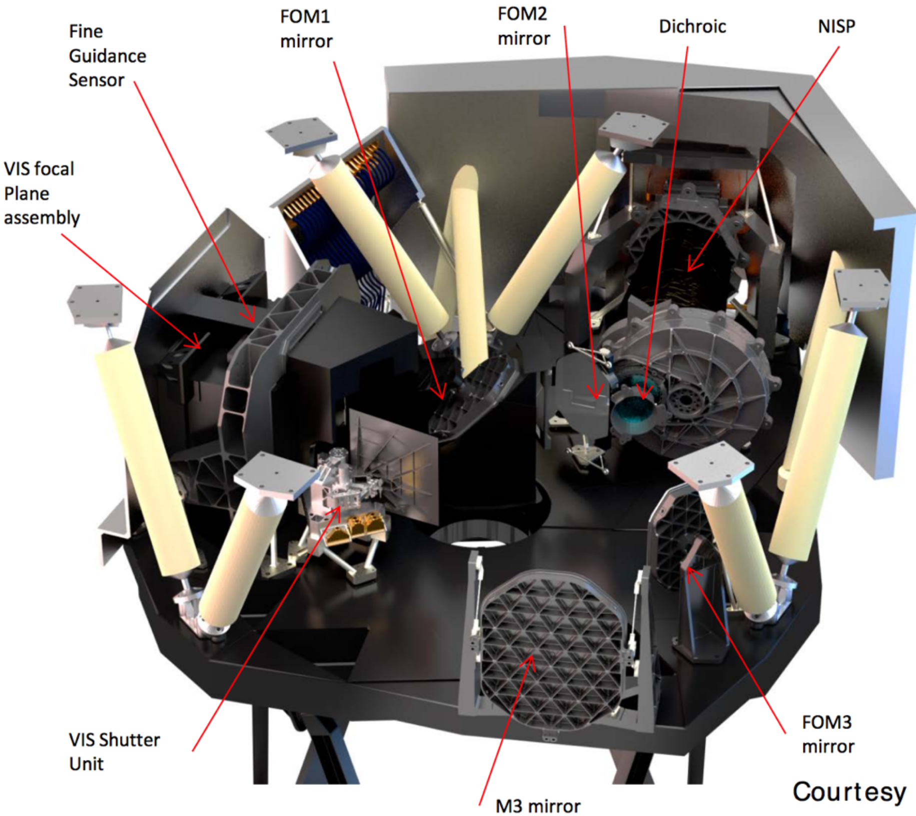




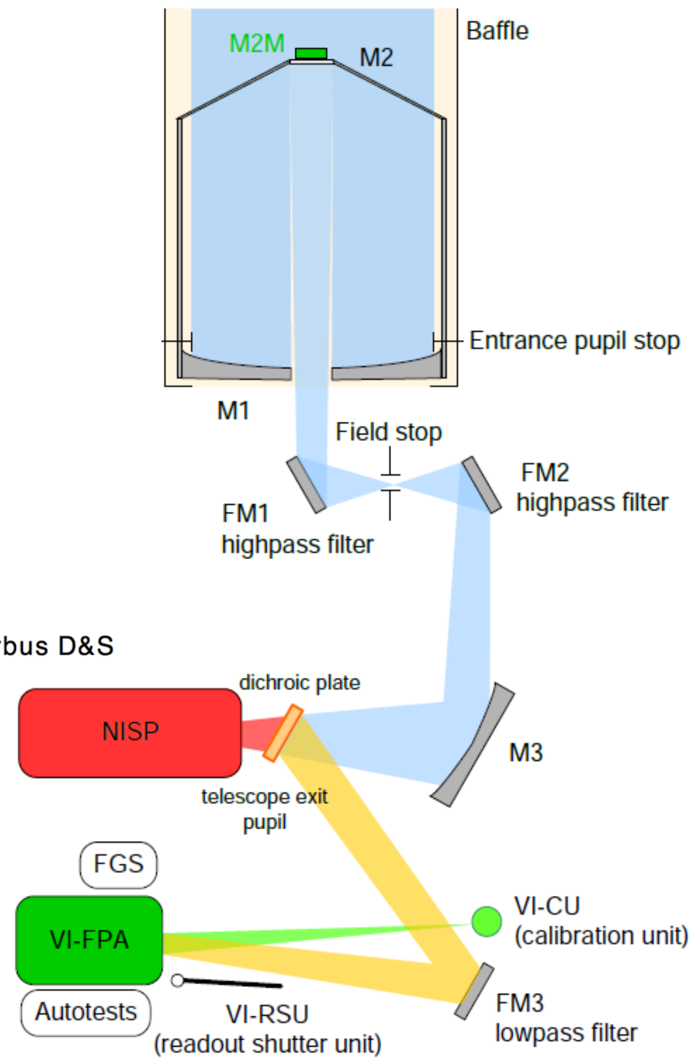




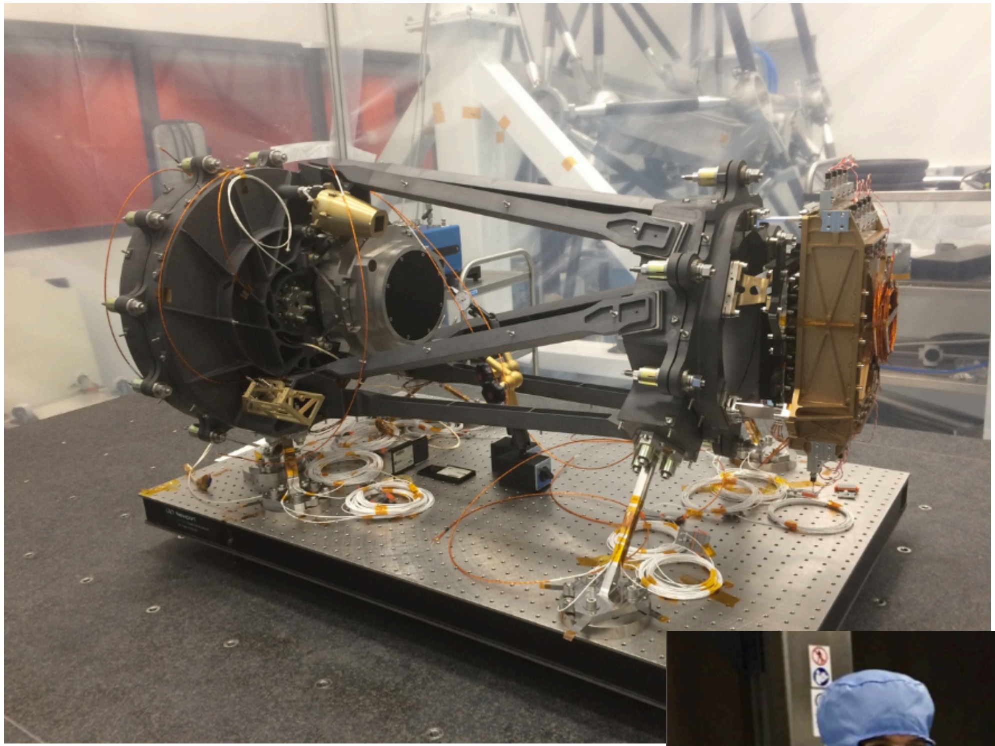
Payload module



Courtesy of Airbus D&S

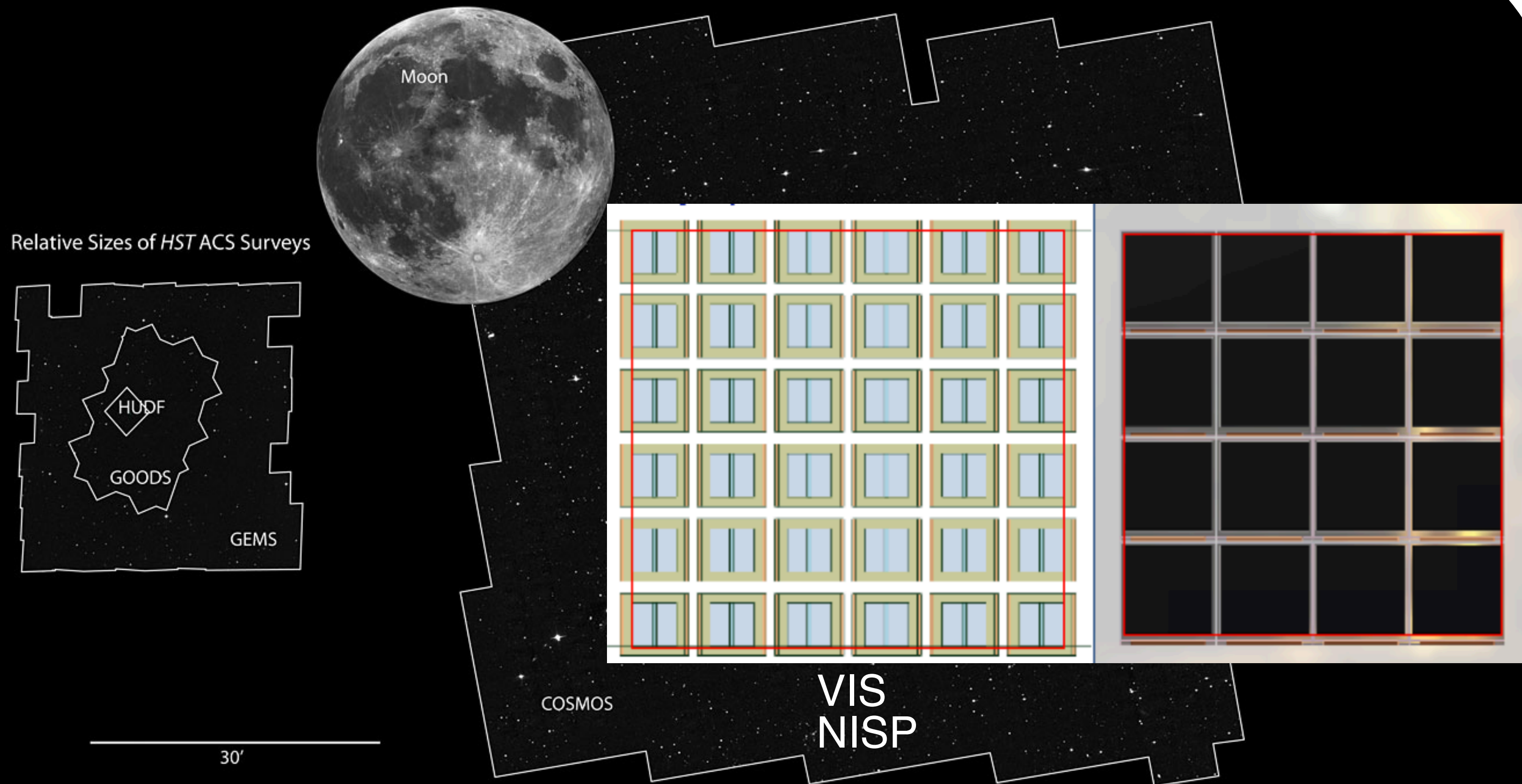


Two channels: Visible and NIR



Structure and Thermal Model (STM) for NISP and VIS delivered and tested

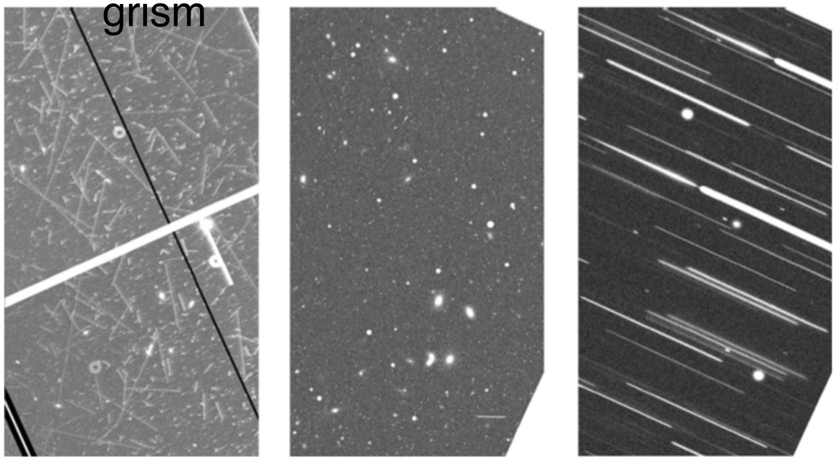
Dual wide-field imagers



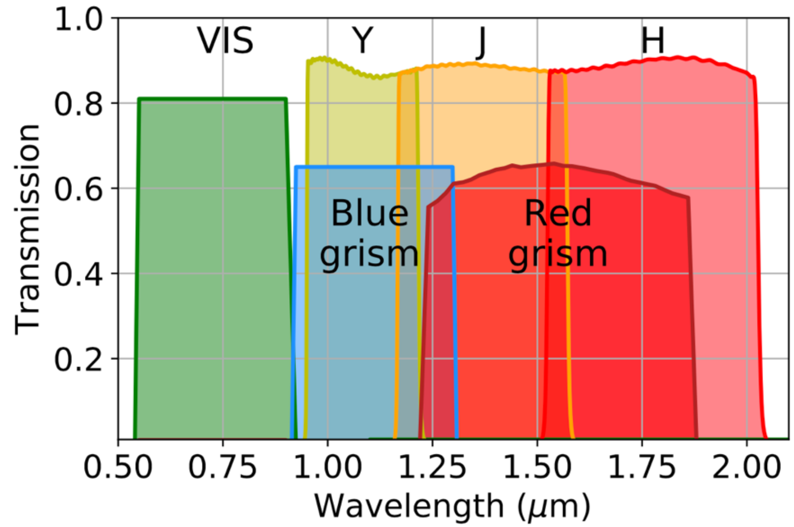
	VIS	NISP
Detectors	36 4096×4132	16 2040x2040
Pixel size	0.1”	0.3”
Dispersion	-	13.4 A/pixel

A panchromatic survey

VIS grism NISP NISP



* NISP simulation does not include cosmic rays



	VIS	Y	J	H	GRISM
Wide	24.5	24	24	24	2×10^{-16} erg/s/cm^2
Deep	26.5	26	26	26	2×10^{-17} erg/s/cm^2

Euclid targets

SURVEYS	In ~6 years				
	Area (deg2)	Description			
Wide Survey	15,000 deg^2	Step and stare with 4 dither pointings per step.			
Deep Survey	40 deg^2	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey			
PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 nm
Sensitivity	24.5 mag 10σ extended source	24 mag 5σ point source	24 mag 5σ point source	24 mag 5σ point source	3 10^{-16} erg cm-2 s-1 3.5σ unresolved line flux

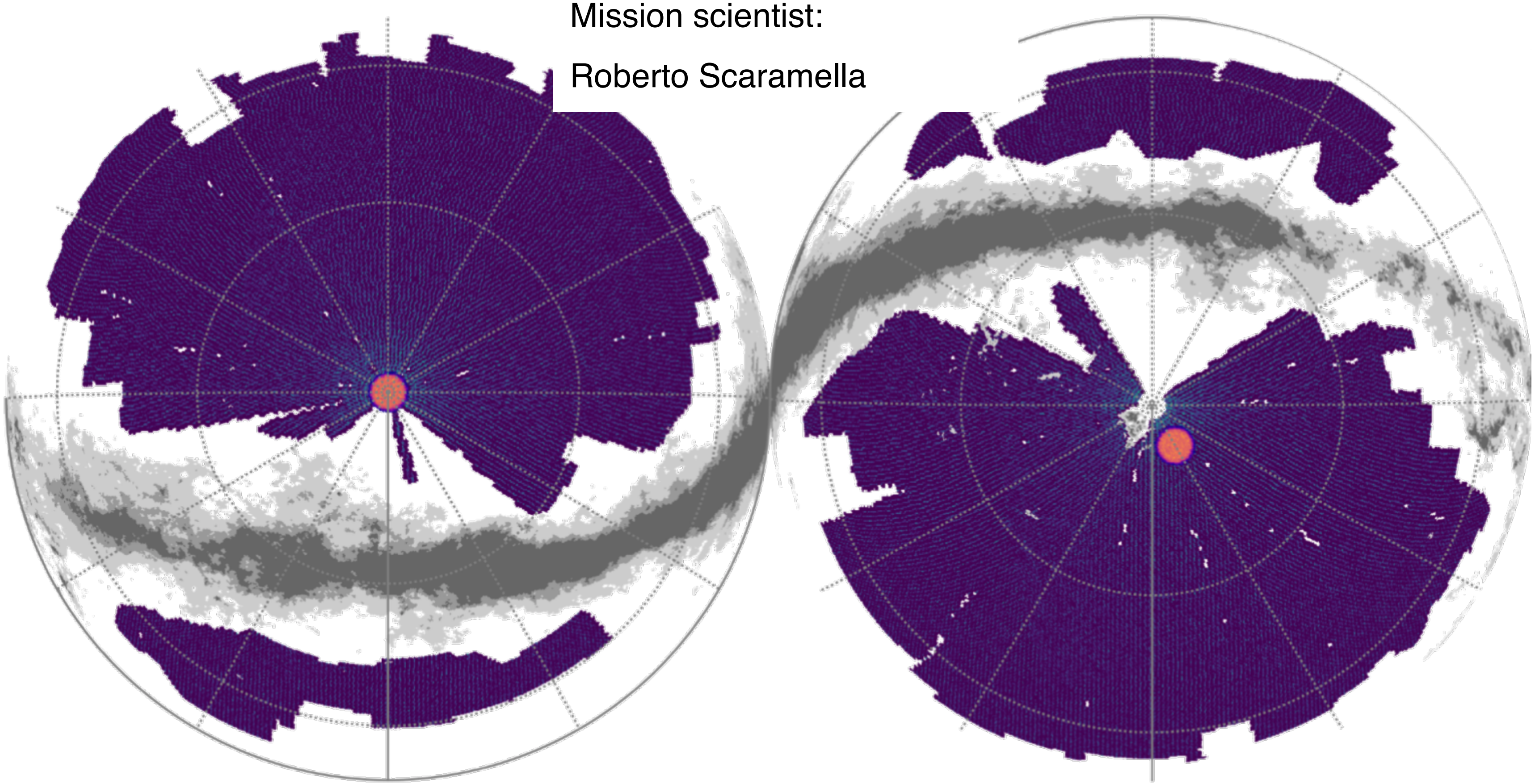
Shapes + Photo-z of n = 1.5 $x10^9$ galaxies,
Spectroscopic redshifts for n = $2.6x10^7$ galaxies

Euclid Definition Study Report: Laureijs et al arXiv:1110.3193

Euclid reference surveys

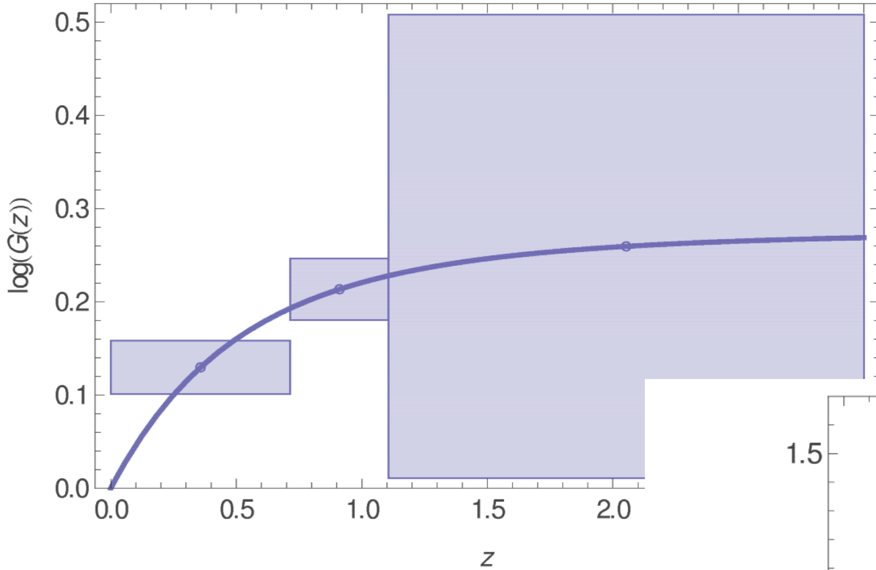
Mission scientist:

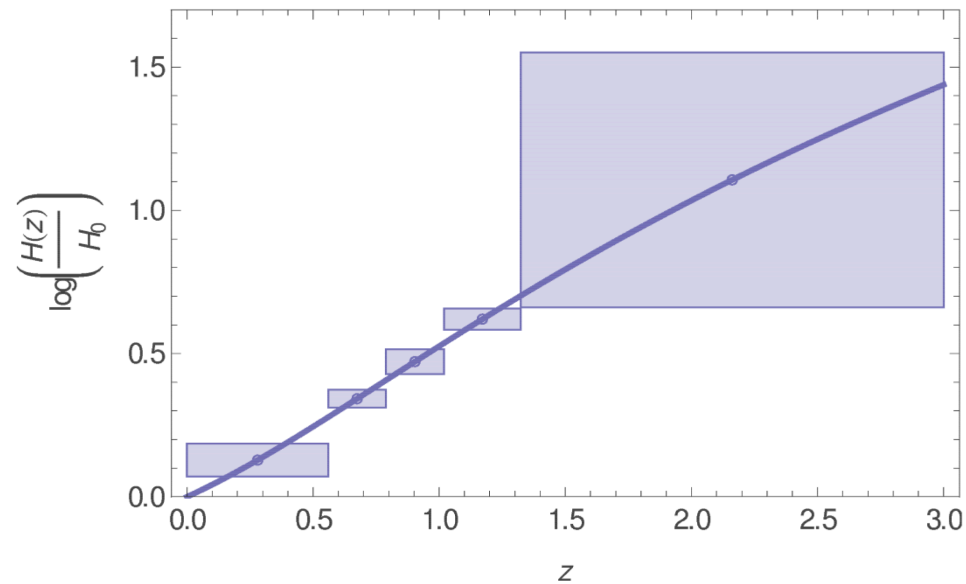
Roberto Scaramella



Wide	15000 deg^2
Deep	40 deg^2 • EDF-N (NEP) • EDF-S (SEP) • EDF-Fornax (CDF-S)

Euclid weak-lensing predictions

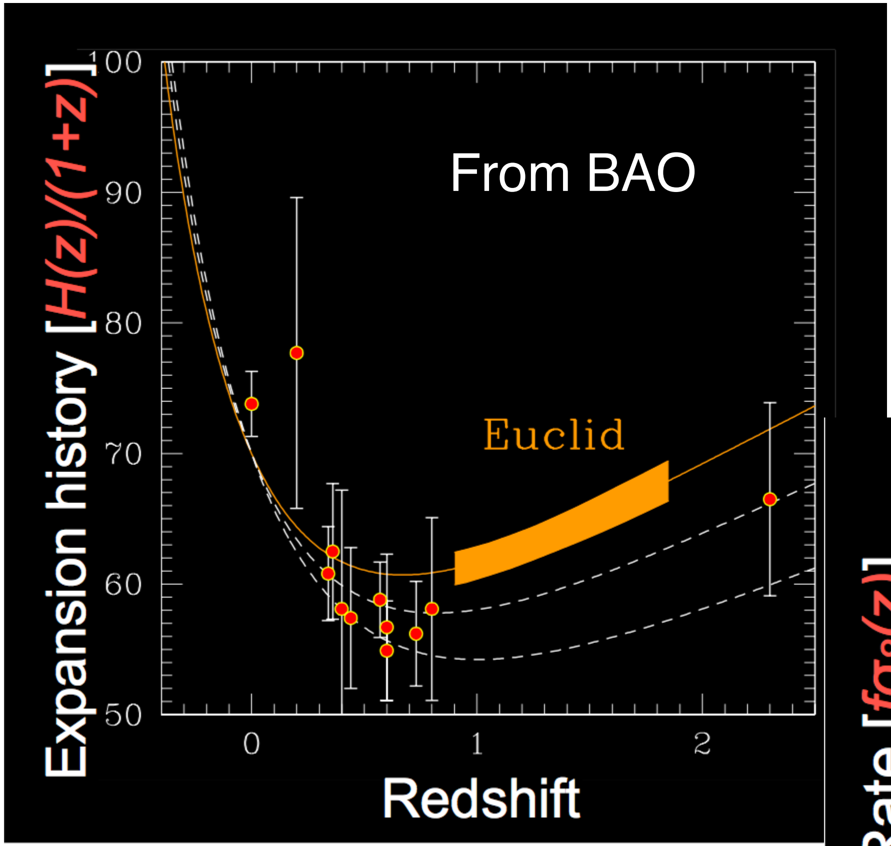


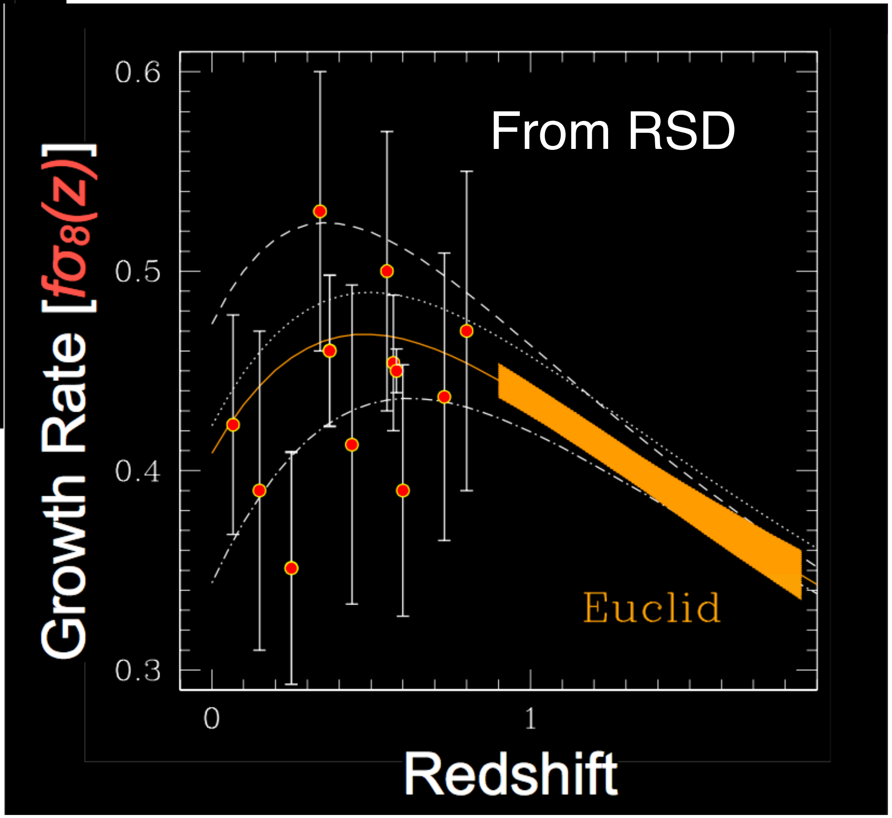


Shown are model-independent constraints on growth and expansion

Amendola et al. 2016; arXiv:1606.00180

Euclid galaxy clustering predictions

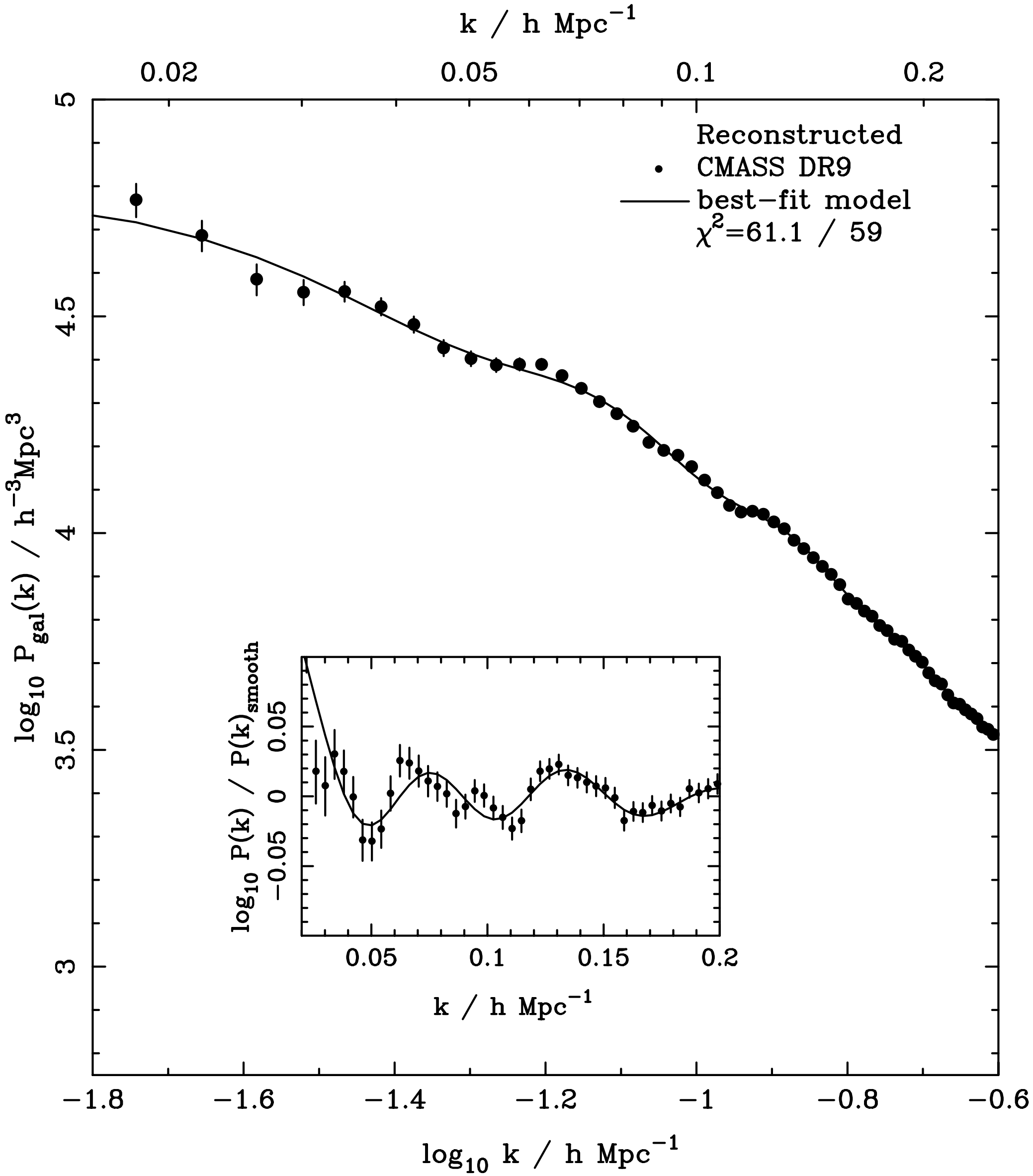




BOSS CMASS DR9 galaxy clustering

BOSS CMASS galaxies at z~0.57

Total effective volume
V_{eff} = 2.2 Gpc^3

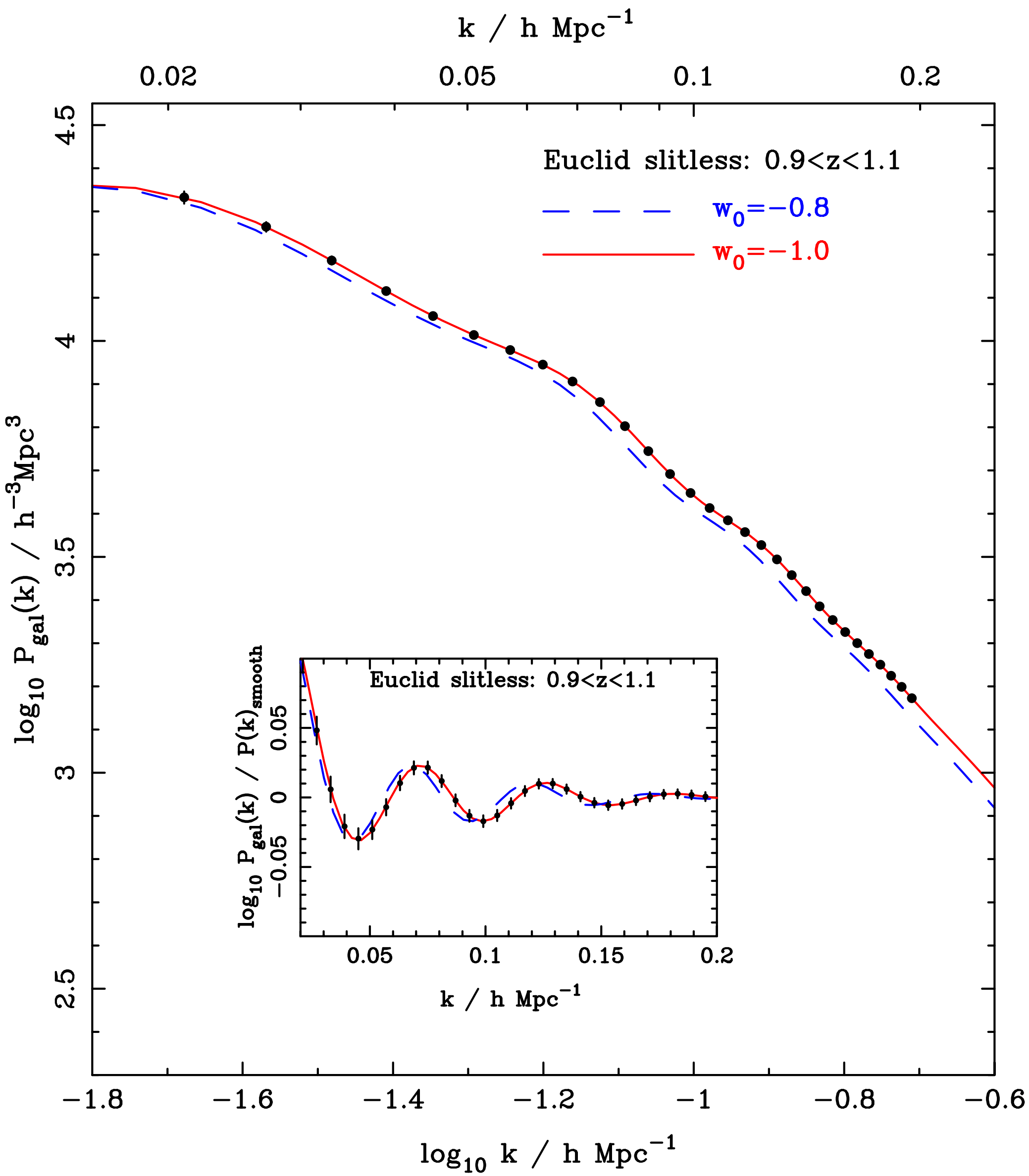


Anderson et al. 2012; arXiv:1203.6565

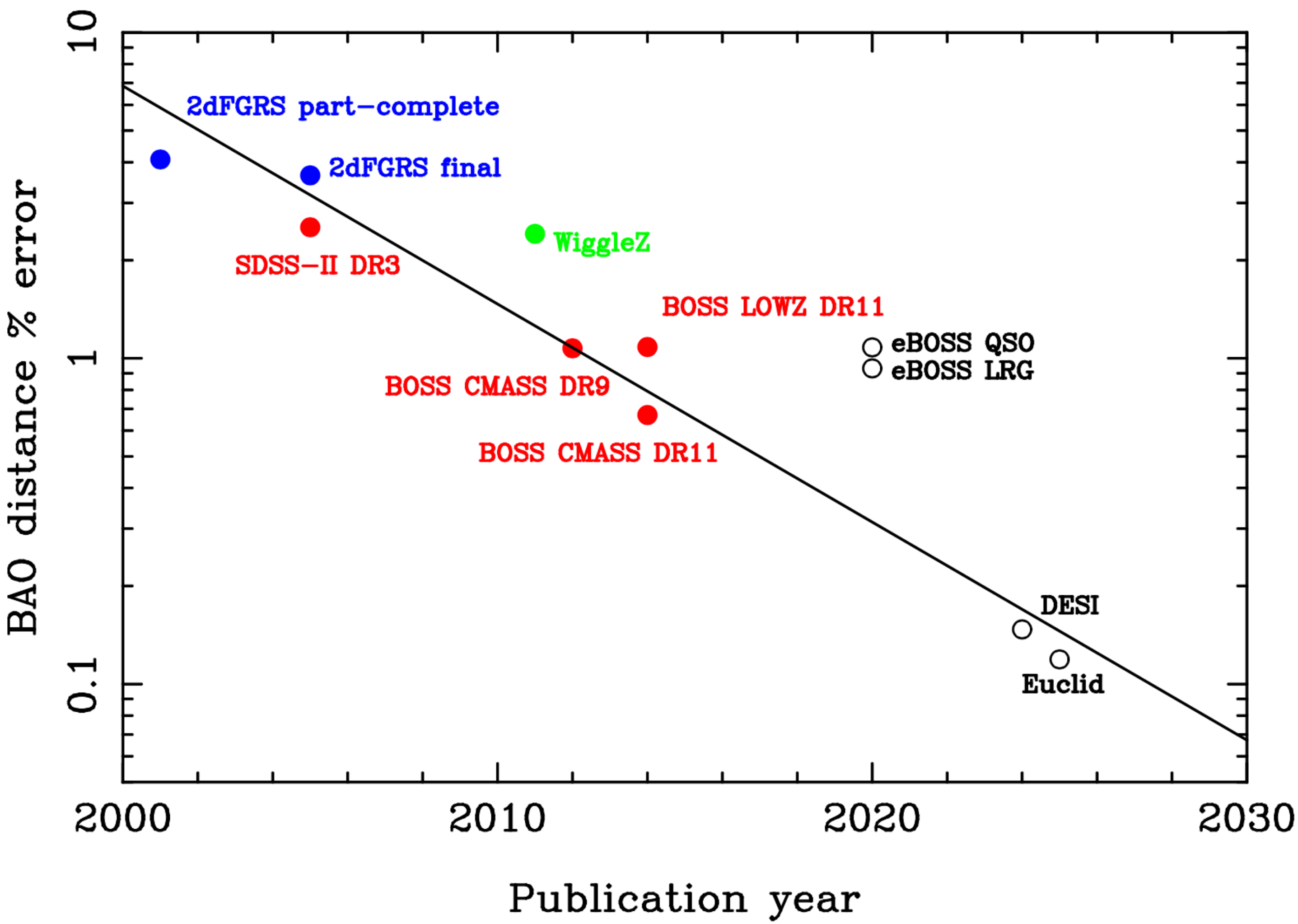
Predicted Euclid galaxy clustering

Redshift slice
$0.9 < z < 1.1$

Total effective volume (of Euclid)
$V_{eff} = 57.4\ Gpc^3$

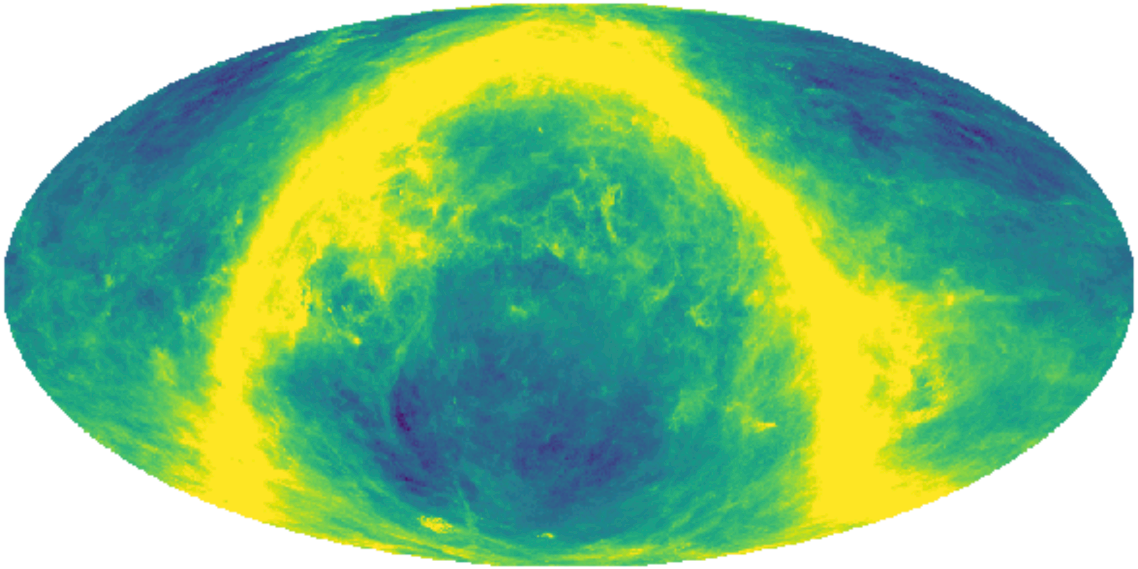


BAO errors from past / future surveys

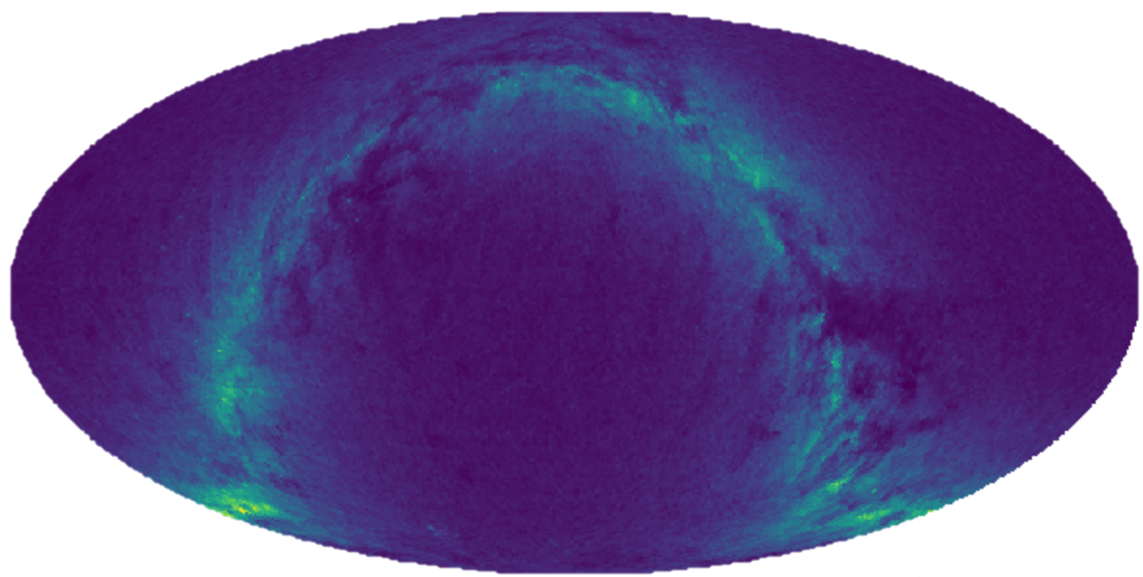


Reid et al. 2015, arXiv:1509.06529

Observational systematics

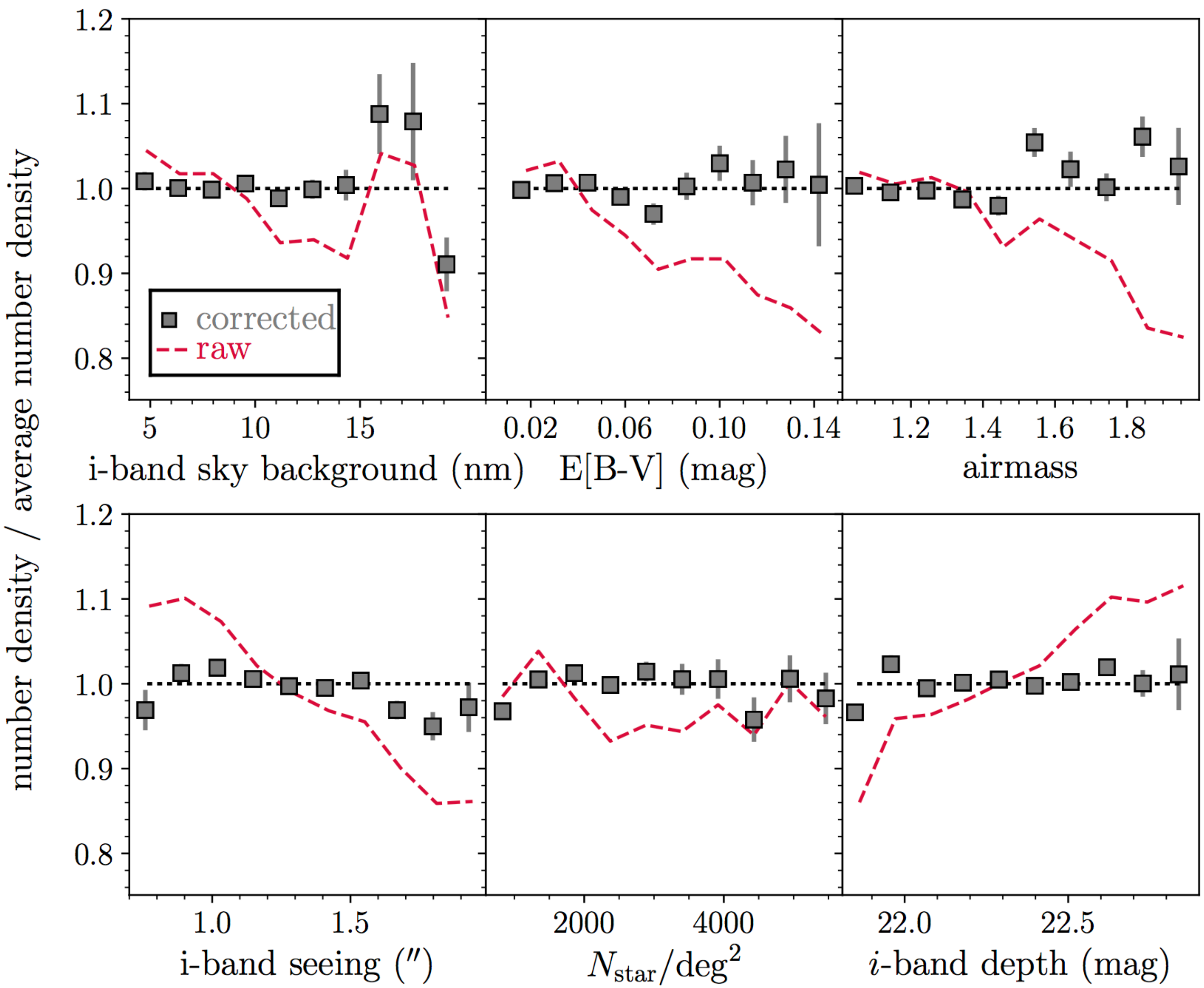


Extinction



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 …)