Cosmology with Galaxy Clustering

Sylvain de la Torre

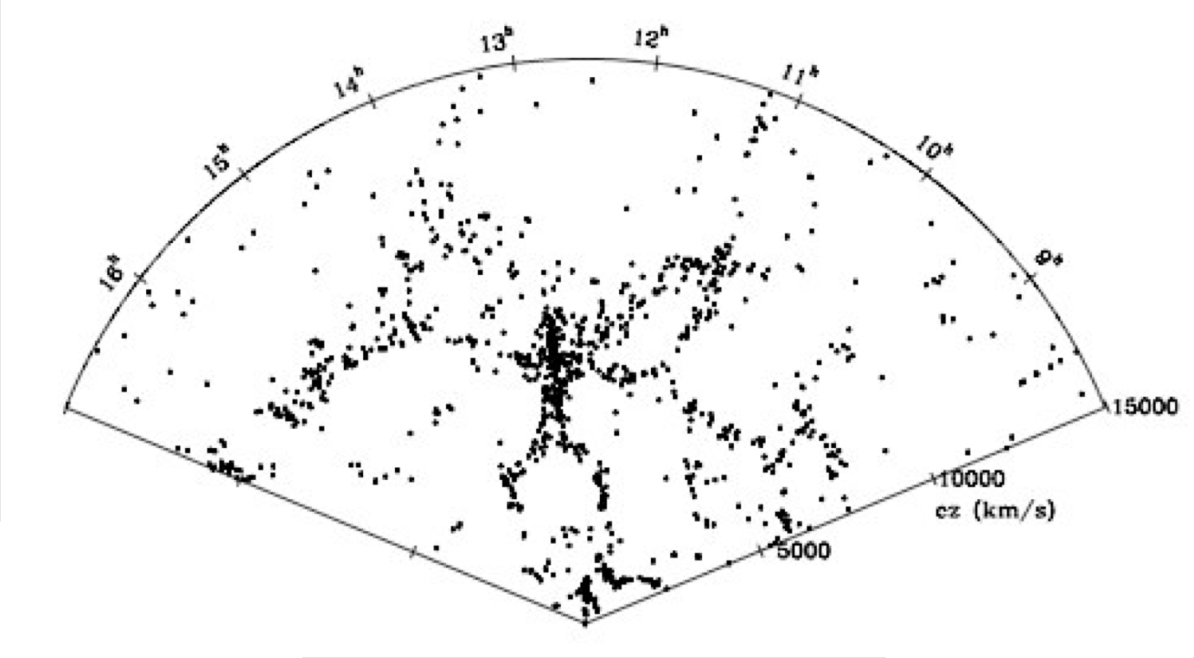
Colloque National Dark Energy

Paris, 24 octobre 2018

LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

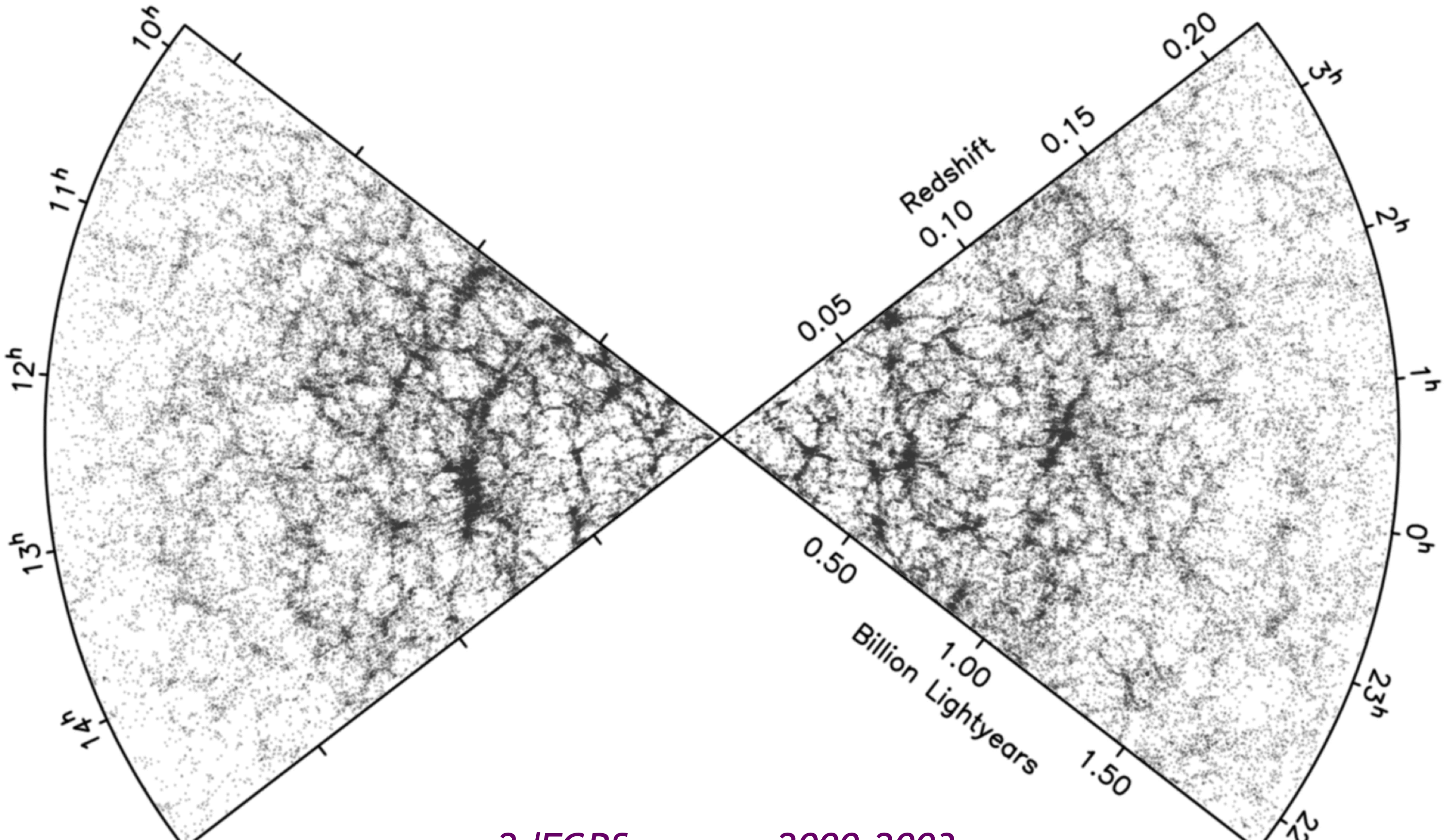
Large-scale structure observations

- In the late universe, LSS is mostly seen through galaxy spatial distribution
- Galaxy spectroscopic surveys map the LSS in detail



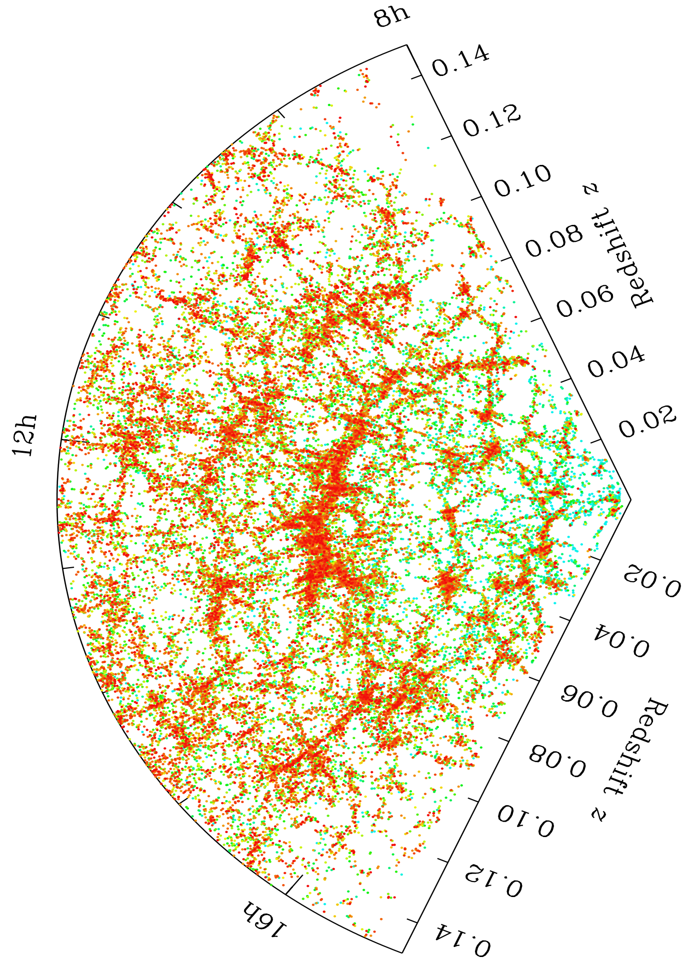
de Lapparent, Geller, Huchra, 1988

Large-scale structure observations



2dFGRS survey, 2000-2003

N-point statistics



Zehavi et al. 2011

- Two-point statistics
  - The "probability of seeing a structure" can be casted in terms of the galaxy overdensity:

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

  - The correlation function is simply the real-space two-point statistic of the galaxy field:

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

  - Its Fourier analogue, the galaxy power spectrum, is defined as:

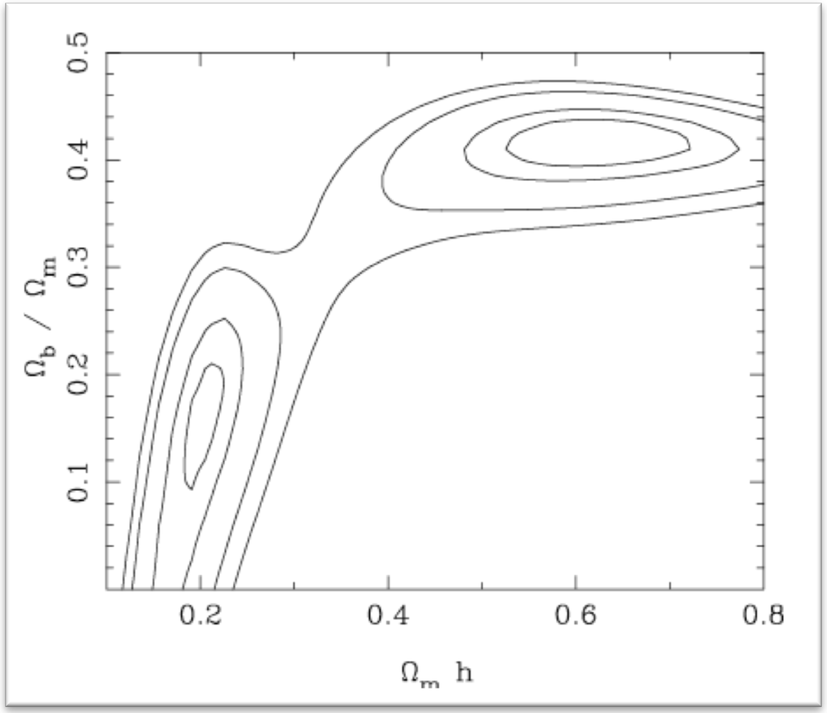
$$P(k) = \langle \delta(\mathbf{k})\delta(\mathbf{k}')\rangle$$

- Higher order statistics

$$\begin{aligned} \xi(r) &= \langle \delta(\mathbf{x_1})\delta(\mathbf{x}+\mathbf{r})\rangle \\ \zeta(r_1, r_2, r_3) &= \langle \delta(\mathbf{x_1})\delta(\mathbf{x_2})\delta(\mathbf{x_3})\rangle \end{aligned}$$

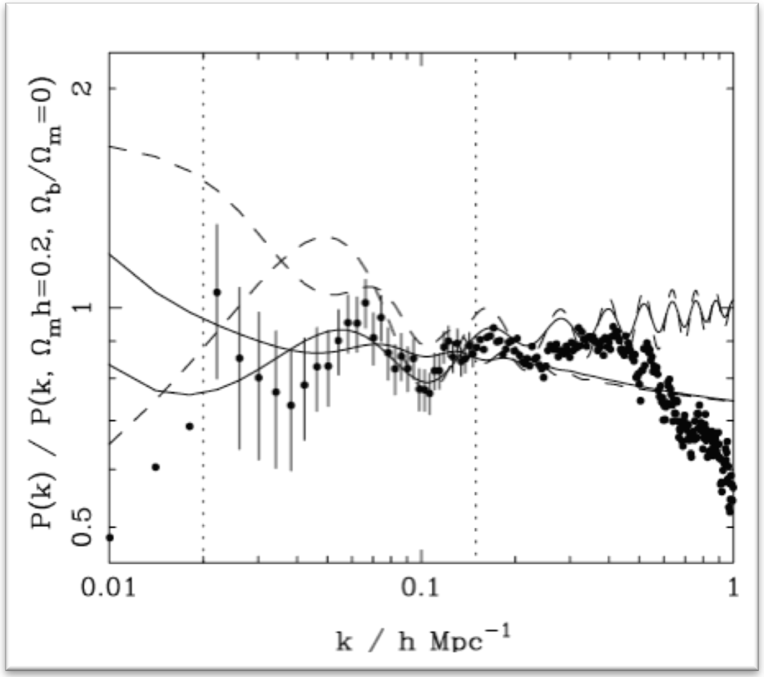
First constraints from galaxy *P(k)*

Constraints on the baryon fraction



2dFGRS, Percival et al. 2001
SDSS, Tegmark et al. 2002

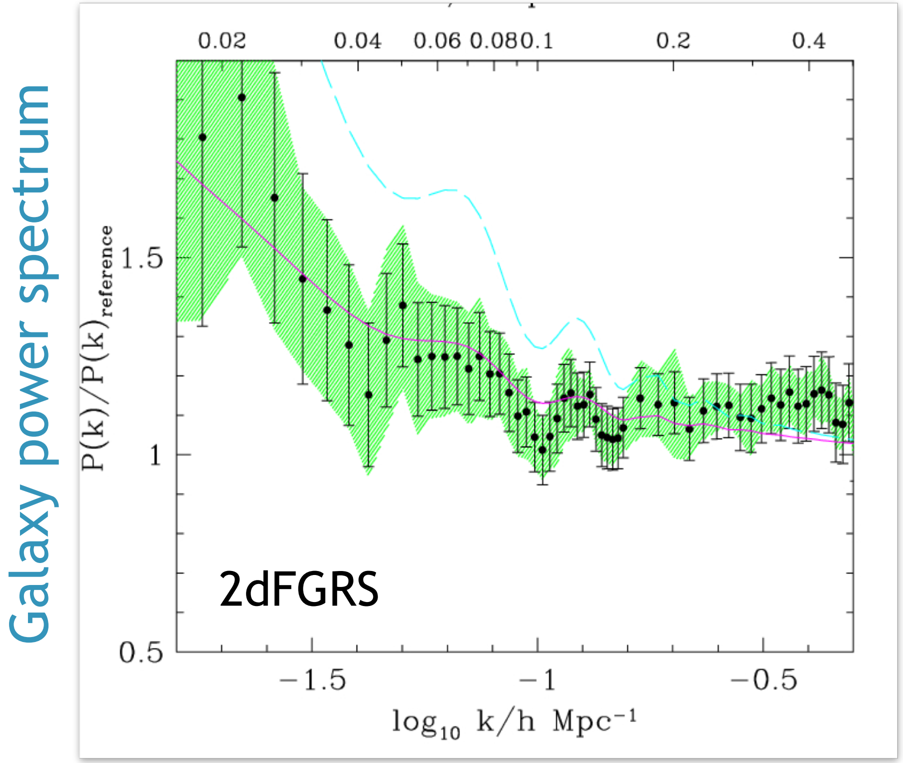
Galaxy power spectrum



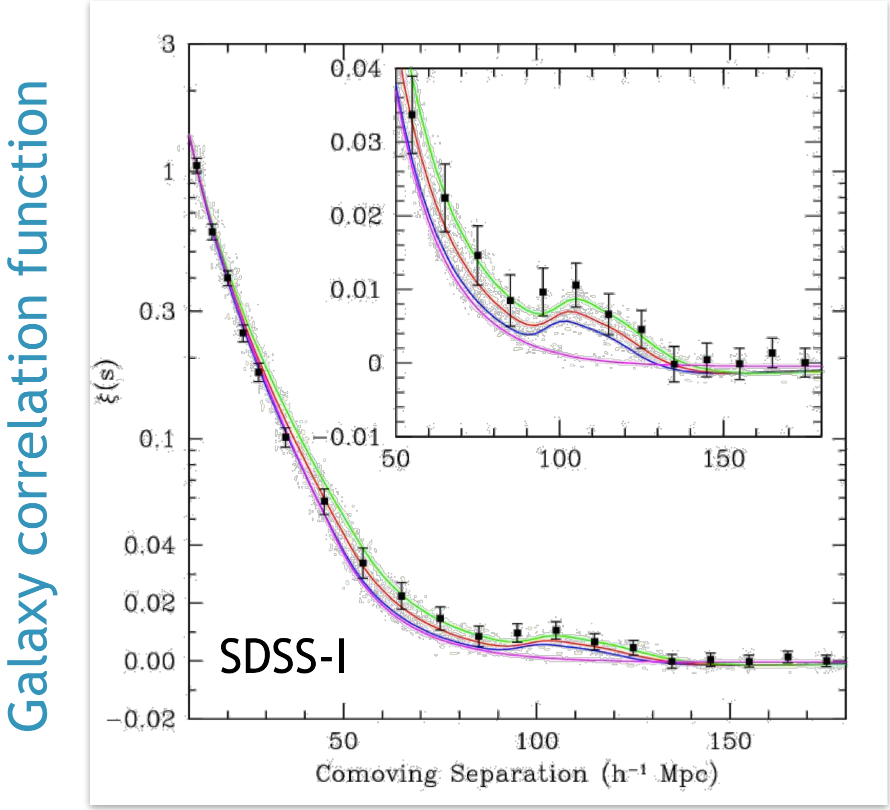
- Galaxy power spectrum full shape (linear scales) sensitive to:

h, $\Omega_m h^2$, $\Omega_b h^2$, n_s, $b\sigma_8$

Baryon Acoustic Oscillations



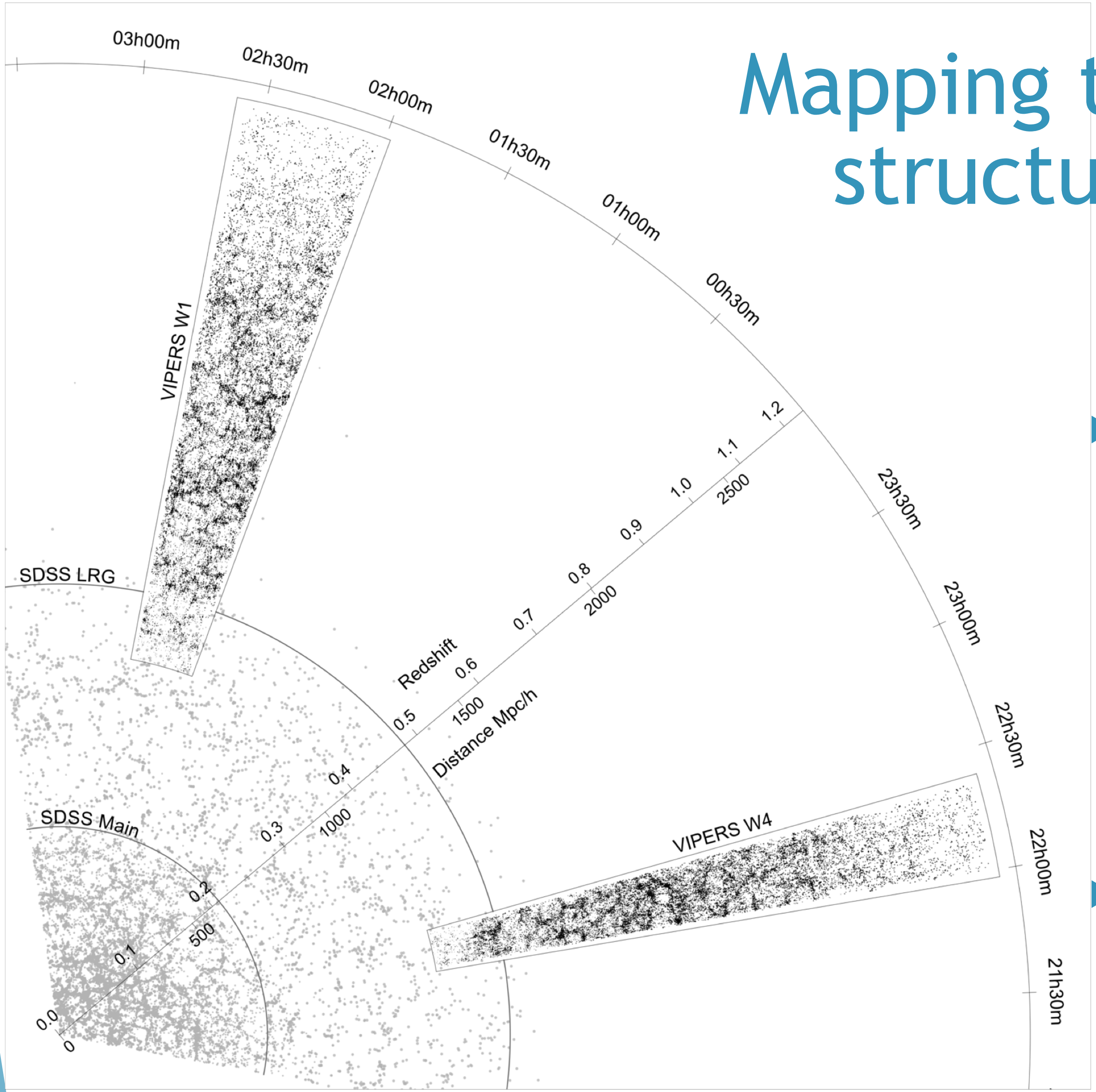
Cole et al. 2005



Eisenstein et al. 2005

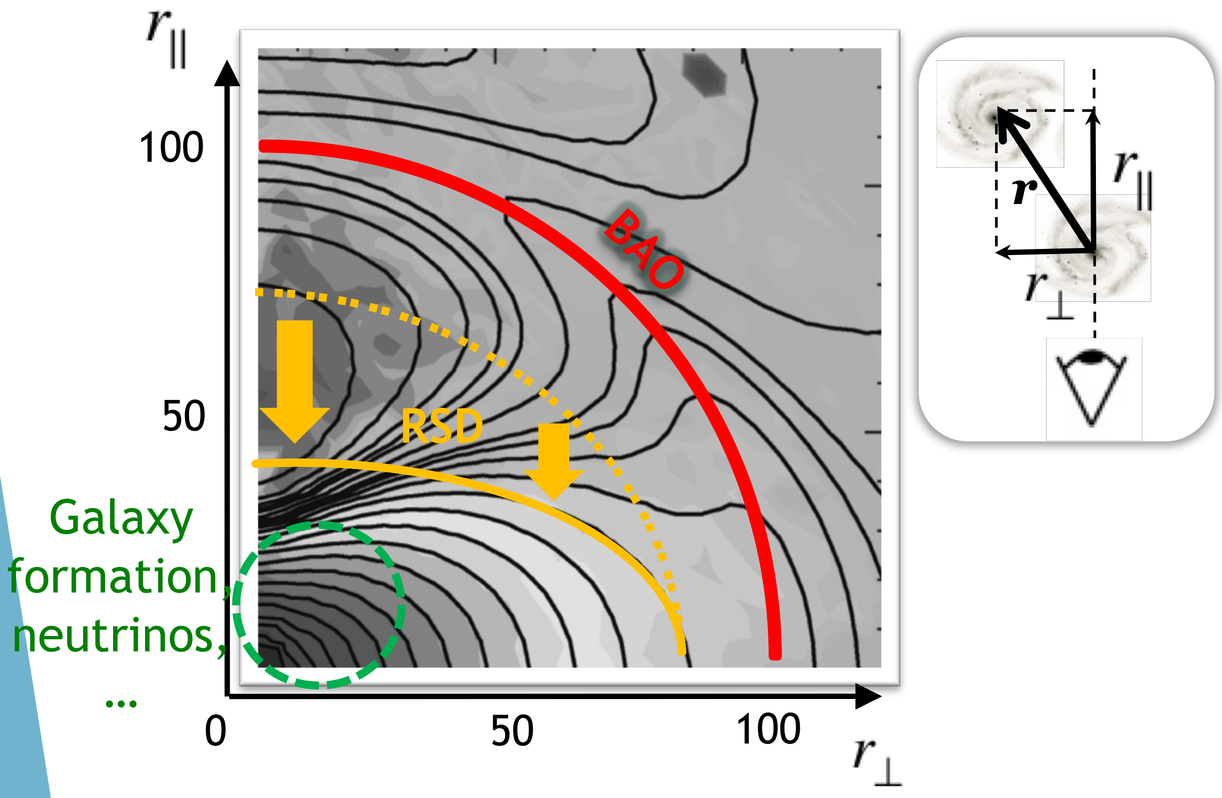
- First detections of BAO in galaxy clustering, sensitive to: *$H(z)$, $D_A(z)$*

Mapping the large-scale structure w/ galaxies

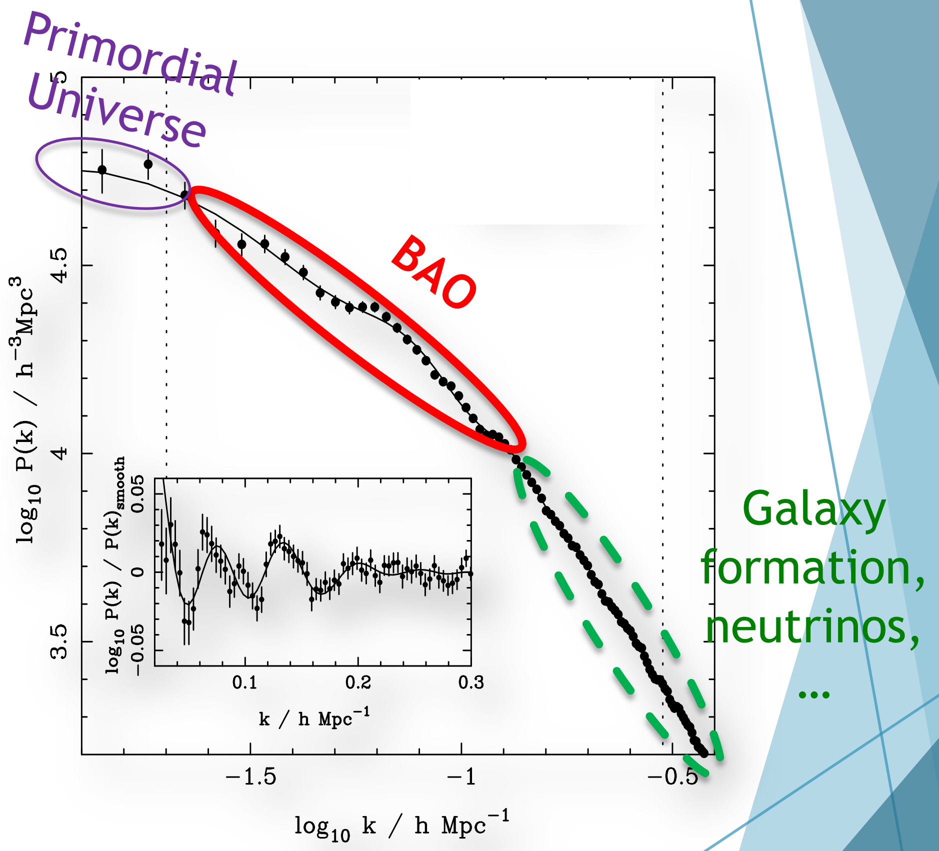


- Large redshift surveys for cosmology (non-exhaustive):
  - WiggleZ (*Blake et al., 2011*)
  - SDSS/BOSS (*Dawson et al, 2013*)
  - VIPERS (*Guzzo et al. 2014*)
  - SDSS/eBOSS (*Dawson et al., 2016)*
- More coming in the next years (2020-2025): PFS, DESI, Euclid, WFIRST

Cosmology from galaxy clustering



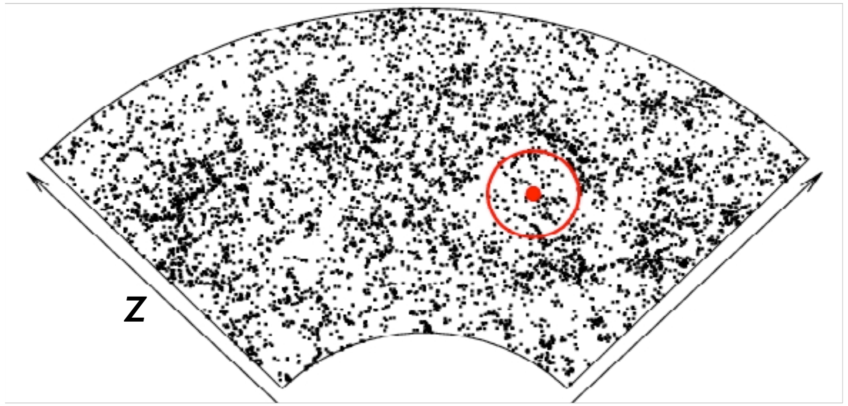
Galaxy anisotropic correlation function



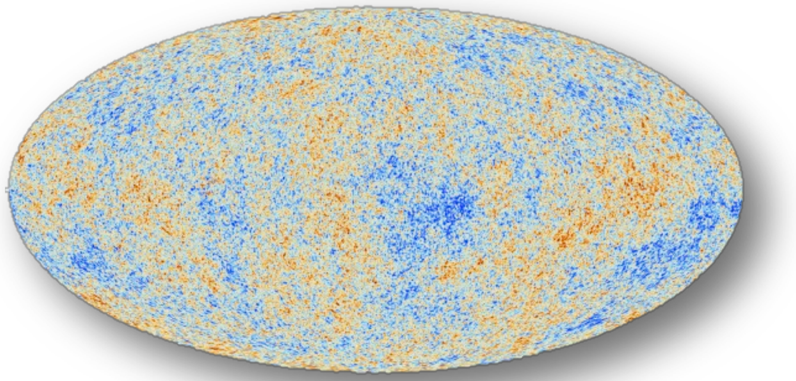
Galaxy power spectrum

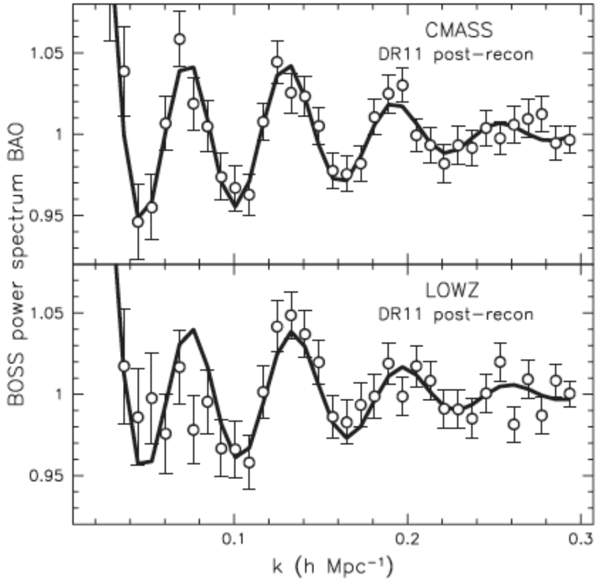
Baryon Acoustic Oscillations

Galaxies

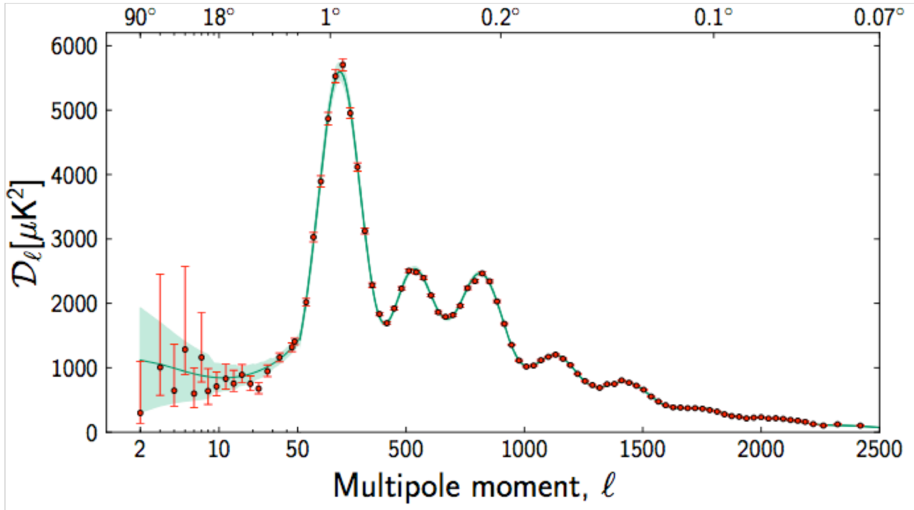


CMB



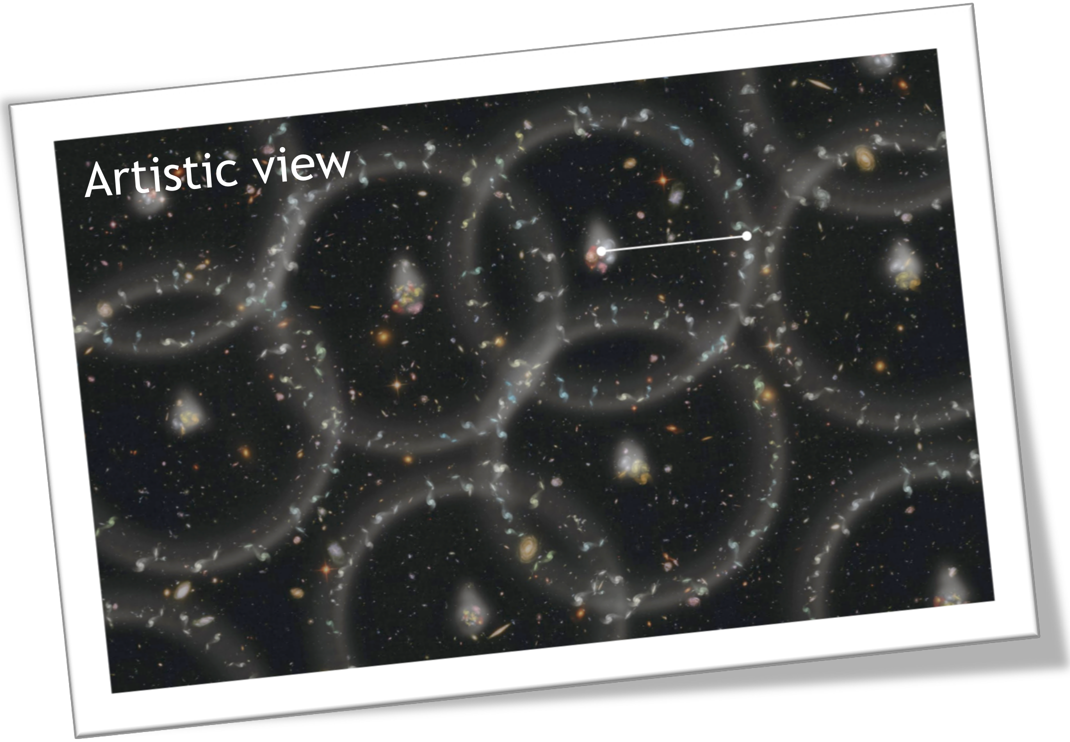


Anderson et al. 2014

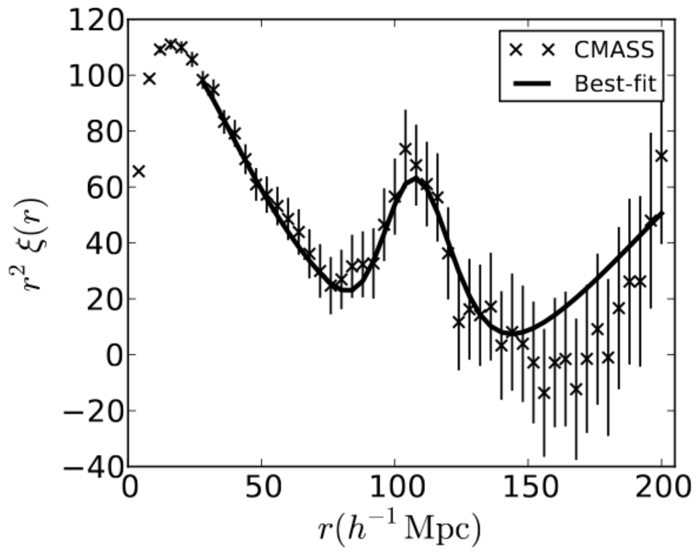


Planck Collaboration 2015

Baryon Acoustic Oscillations



Galaxy correlation function



Anderson et al. 2012

- BAO scale is determined by the sound horizon at drag epoch (z_d):

$$r_d = \int_{z_d}^{\infty} \frac{c_s(z)}{H(z)} dz \quad \approx 150\ \mathrm{Mpc}$$

Baryon Acoustic Oscillations

- BAO scale can used as a standard ruler
- For 3D spherically averaged separation, sensitive to:

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

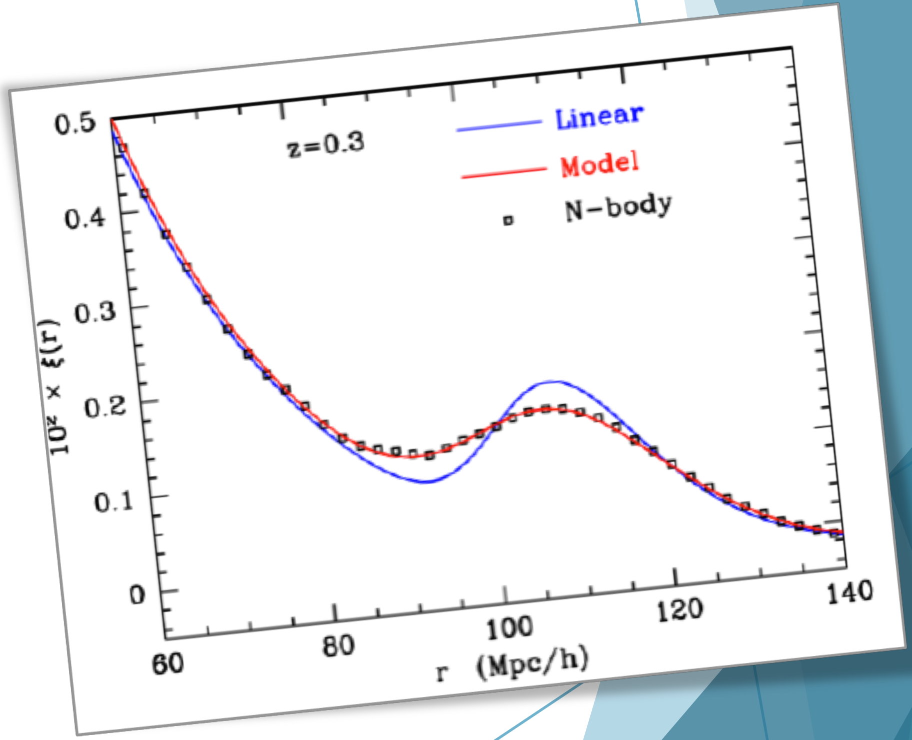
- Fiducial model used for estimating the correlation function, estimates the deviation of BAO peak position with respect to fiducial position (*Alcock-Paczynski effect*):

$$\alpha = \frac{D_V(z) r_d^{\mathrm{fid}}}{D_V^{\mathrm{fid}} r_d}$$

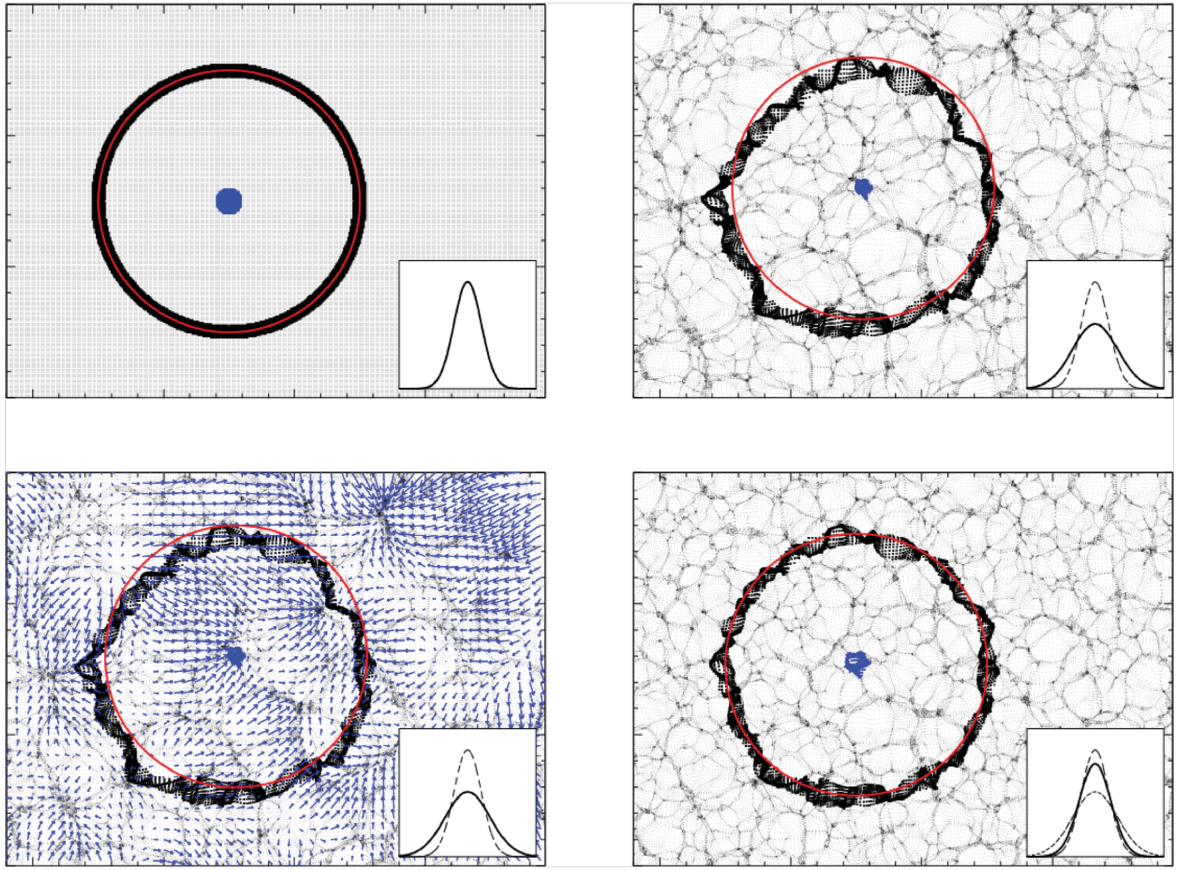
Baryon Acoustic Oscillations

- Non-linear effects on BAO
  - As structure grows, galaxy peculiar velocities smooth out the BAO peak on scales of 15-20 Mpc/h
  - PT or numerical simulations predict a Gaussian damping of the peak

$$\Delta^2(k) = \{\Delta^2_{\rm lin}(k) + \cdots\} \boxed{\exp\left[-k^2\Sigma^2/2\right]} + \Delta^2_{22} + \cdots$$



Baryon Acoustic Oscillations

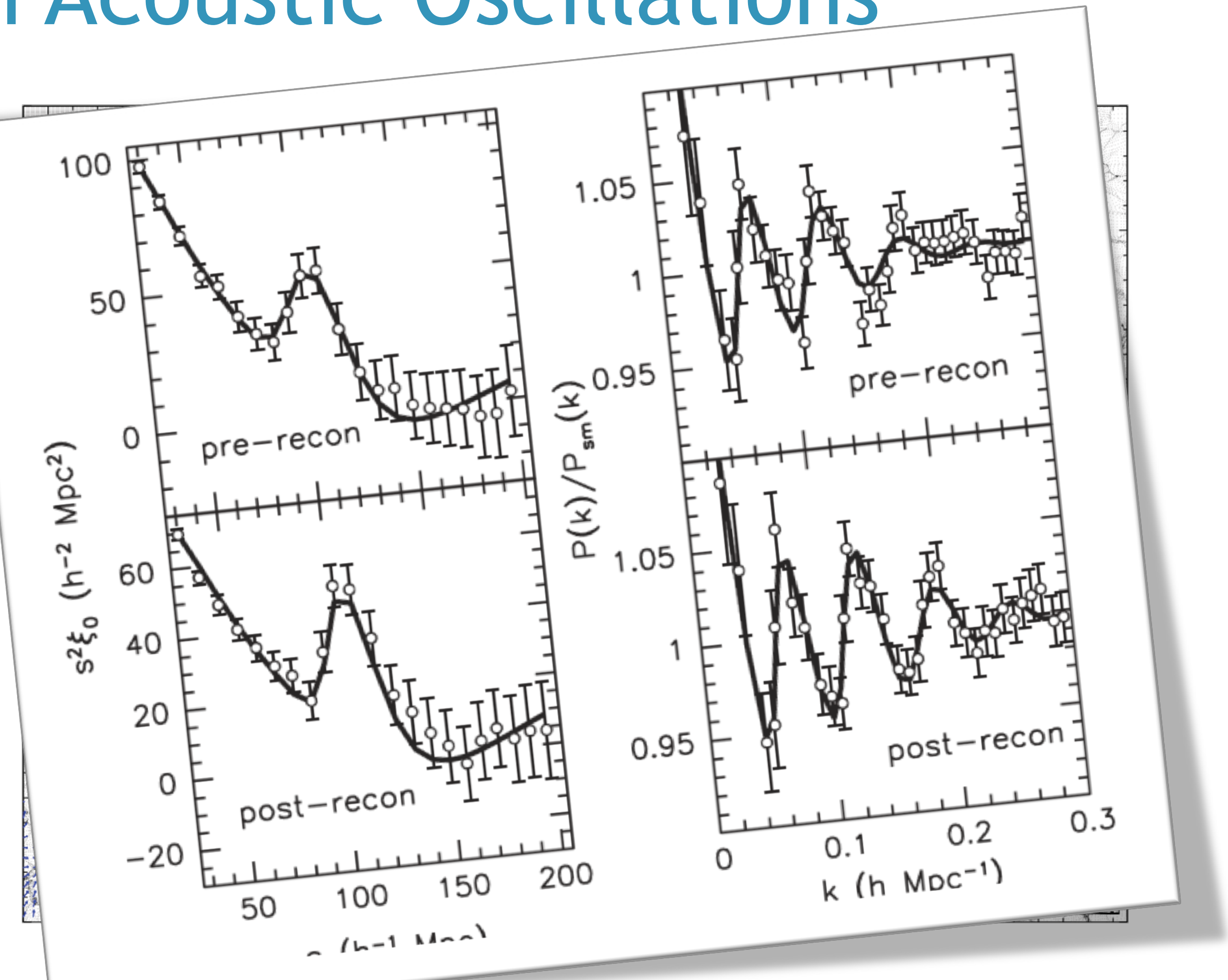


Padmanabhan et al. 2012

- Reconstruction: mitigate non-linear effects and sharpen the BAO peak (usually based on Zel'dovich approximation)

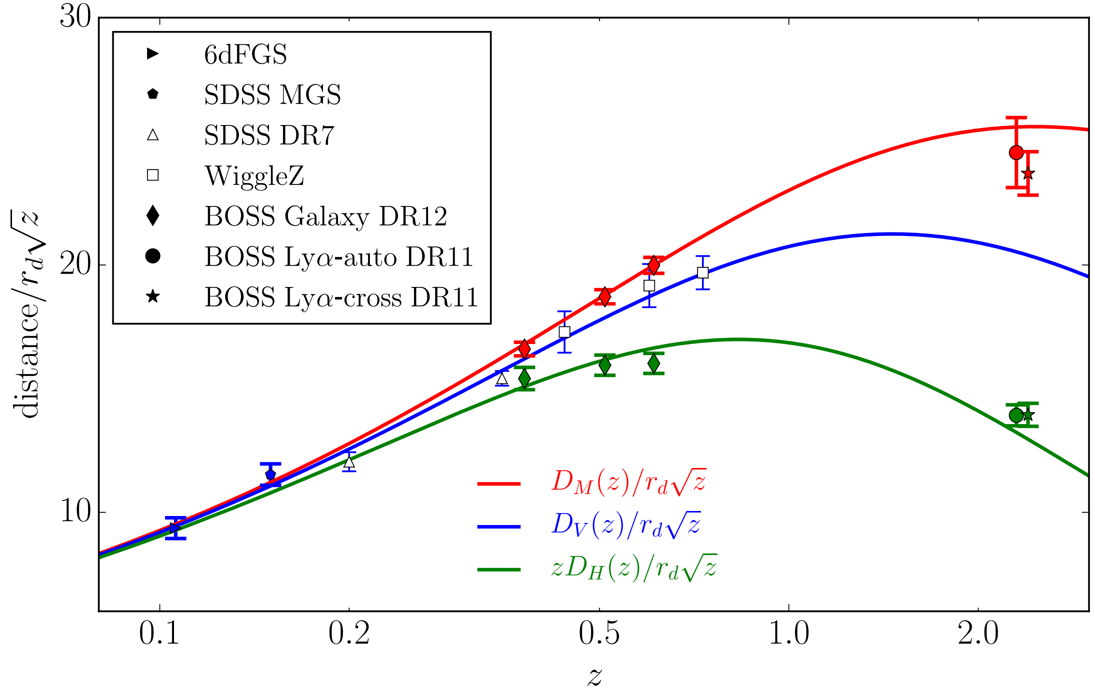
Baryon Acoustic Oscillations

Padmanabhan et al. 2012



- Reconstruction: mitigate non-linear effects and sharpen the BAO peak (usually based on Zel’dovich approximation)

BAO: major cosmological probe



Alam et al. 2017

- BAO provides one of the most accurate geometrical constraints

Understanding Cosmic Acceleration

$$\boxed{R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R} = -\frac{8\pi G}{c^2} T_{\mu\nu} + \Lambda g_{\mu\nu}$$

?

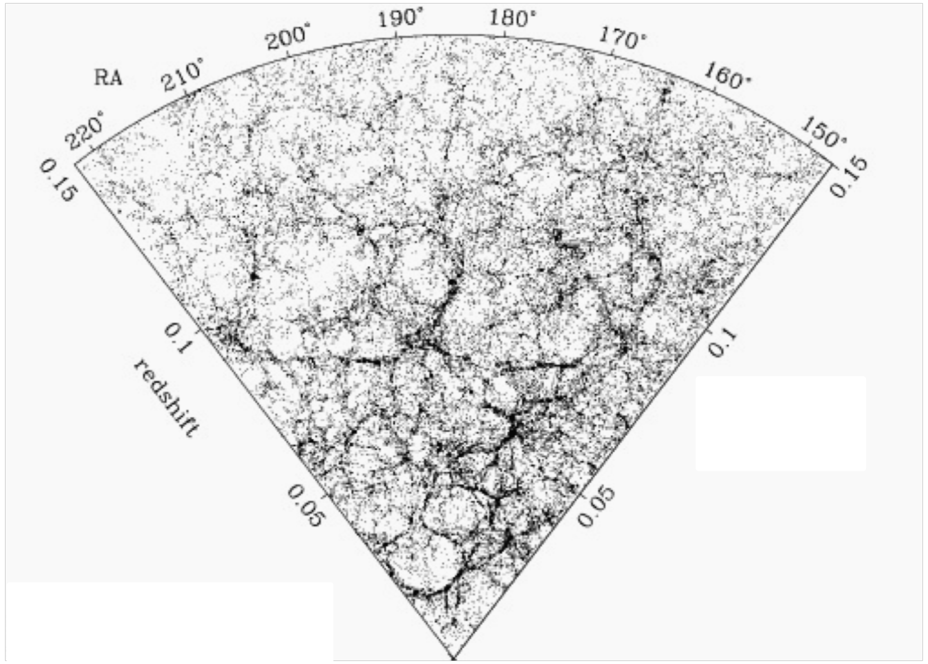
…or modify gravity theory?

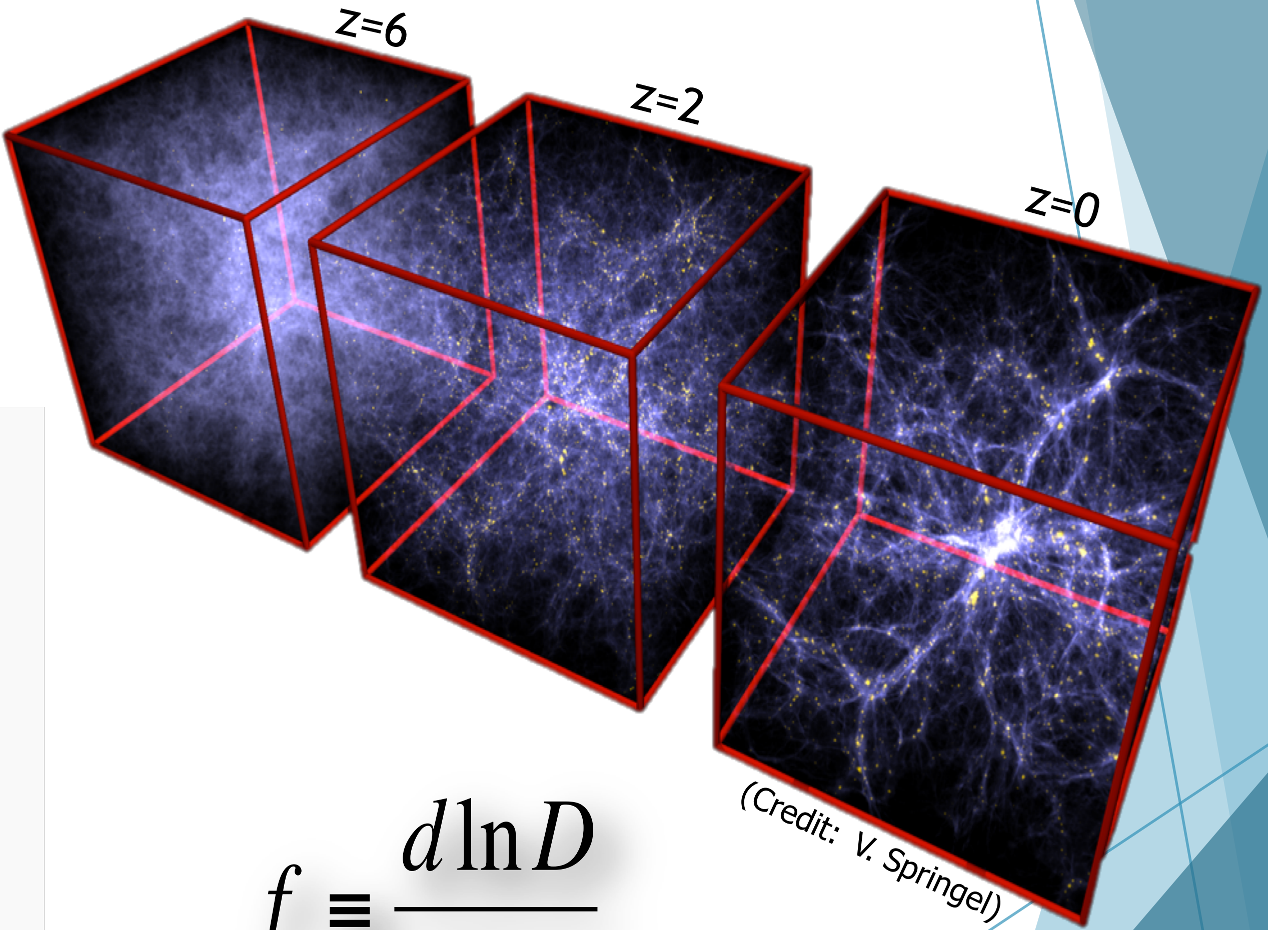
Add Cosmological Constant
or Dark Energy

- To distinguish these two radically different options: **need to probe the dynamics of the Universe**

Probing the growth rate of structure

Real space





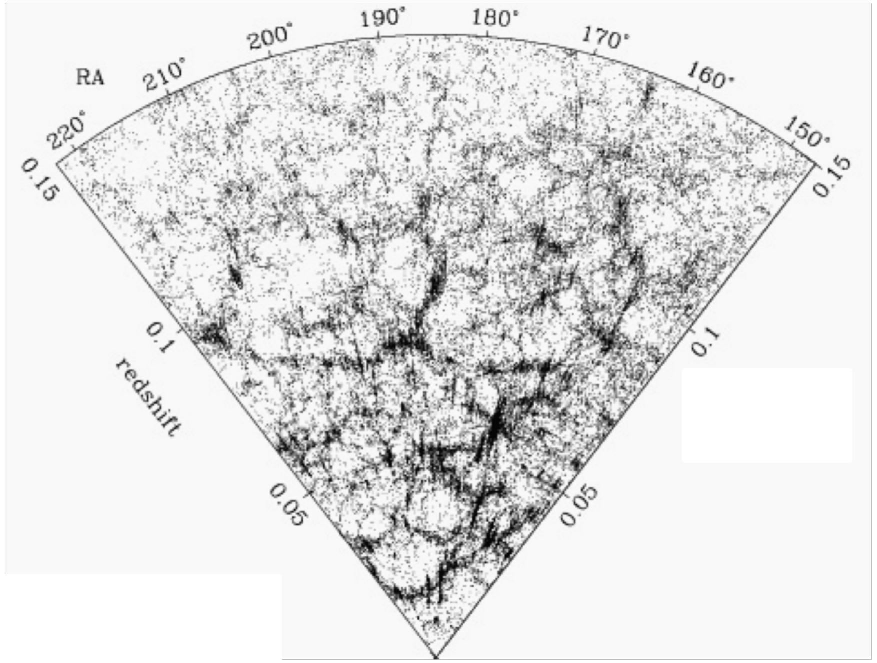
(Credit: V. Springel)

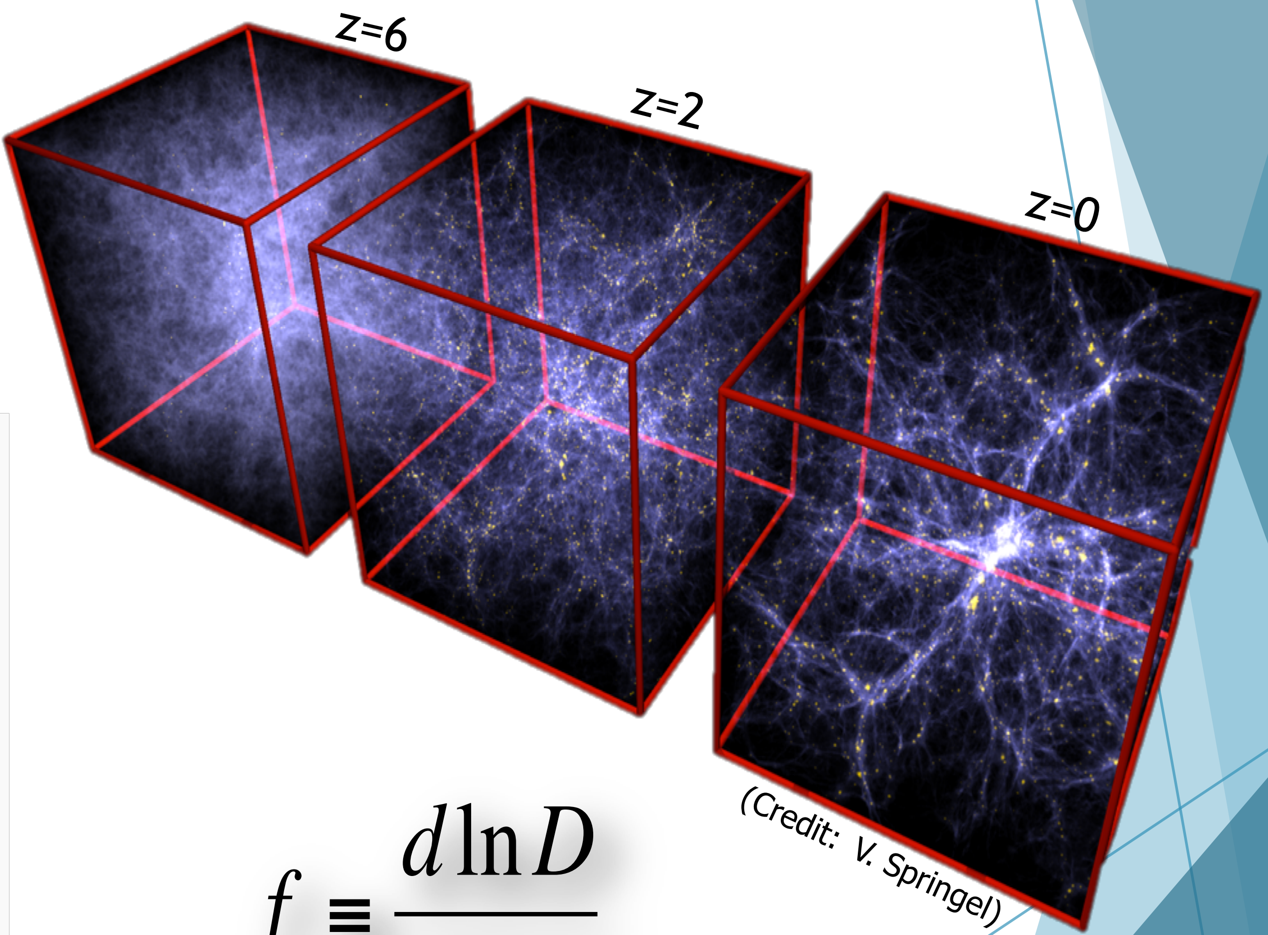
$$f \equiv \frac{d\ln D}{d\ln a}$$

Growth rate of structure

Probing the growth rate of structure

Redshift space



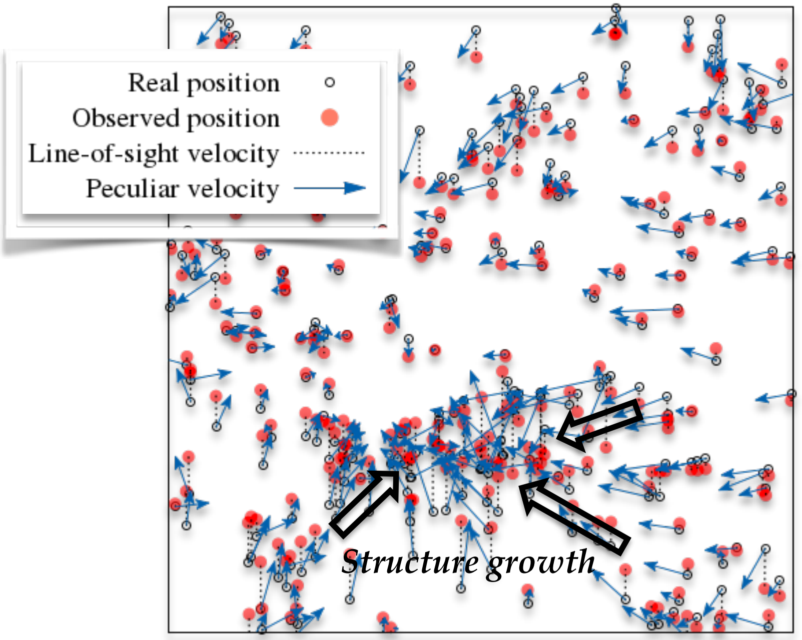


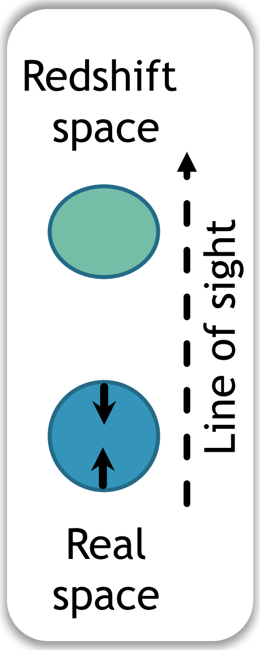
(Credit: V. Springel)

$$f \equiv \frac{d \ln D}{d \ln a}$$

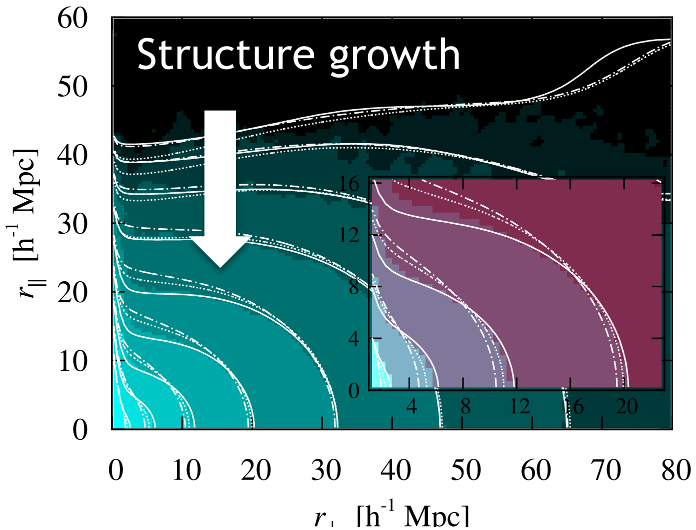
Growth rate of structure

Redshift-space distortions





Galaxy anisotropic correlation function



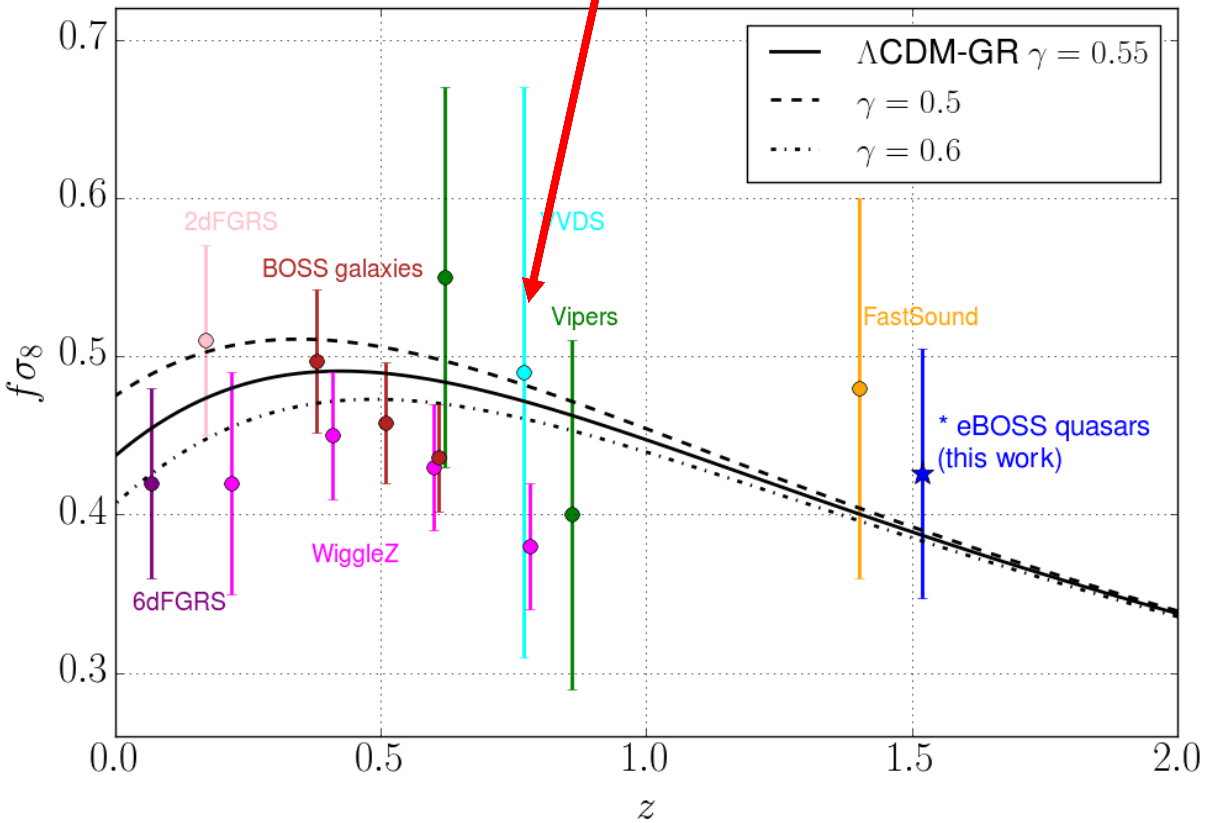
de la Torre et al. 2012

$$f \equiv \frac{d \ln D}{d \ln a} \approx \Omega_m(z)^\gamma$$

Distance in redshift-space: $s = r + \dfrac{v_{los}}{aH}$

Redshift-space distortions

Guzzo et al. 2008



Zarrouk et al. 2018

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu}$$

?

$$f \equiv \frac{d \ln D}{d \ln a} \approx \Omega_m(z)^\gamma$$

Cosmology from galaxy clustering

- Measure expansion history:
  - Baryonic Acoustic Oscillations (BAO), Alcock-Paczynski

Test of the expansion/DE EoS: $H(z)$, $D_A(z)$

- Measure structure growth of structure :
  - Redshift-Space Distortions (RSD)

Test of gravity/acceleration: $f(z)$

- Measure neutrino mass & primordial non-gaussianity
  - P(k) shape on very small or very large scales

Cosmology from galaxy clustering

Methods

- Interpretation of galaxy clustering: model non-linear physics
  - Different approaches: erase NL (e.g. BAO reconstruction) or try model them (e.g. RSD modelling)
  - Currently used theoretical models to predict GC observables break-down in the non-linear regime
  - Improvements are necessary to reduce systematics from modelling (e.g. RSD)
- Optimization can be done on the choice/combination of tracers
  - Use of specific populations or cross-correlations
  - Weak lensing information very complementary (at the level of the observables)

NL modelling with Perturbation Theory

- Eulerian non-local bias *(McDonald & Roy, 2009)*:

$$\delta_{\rm h}(\mathbf{x}) = b_1\delta(\mathbf{x}) + \frac{1}{2}b_2[\delta(\mathbf{x})^2 - \sigma_2] + \frac{1}{2}b_{s^2}[s(\mathbf{x})^2 - \langle s^2\rangle] \cdot$$

Non-linearities *Tidal tensor → Non-local*

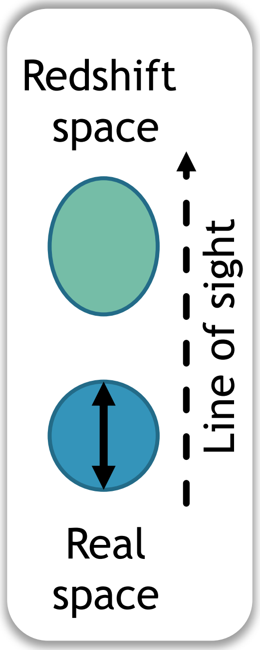
- RSD model *(Taruya et al. 2010)*:

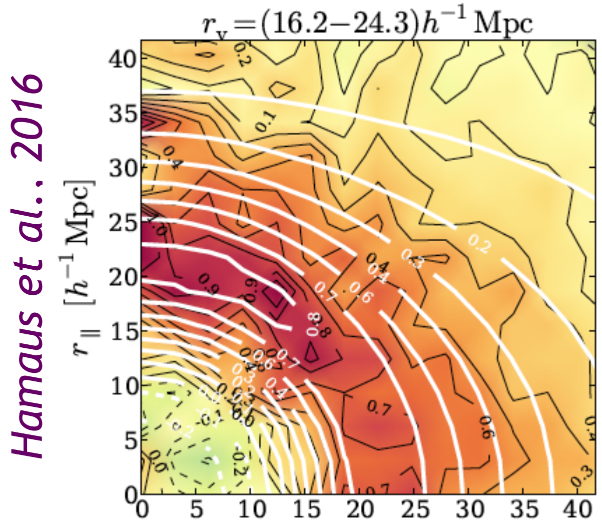
$$P^{(s)}(k,\mu) = D_{\rm FoG}(k,\mu;\sigma_{\rm FoG})\left[P_{g,\delta\delta}(k) + 2f\mu^2 P_{g,\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + \right. \\ \left. + \; b_1^3 A(k,\mu,f/b_1) + b_1^4 B(k,\mu,f/b_1)\right],$$

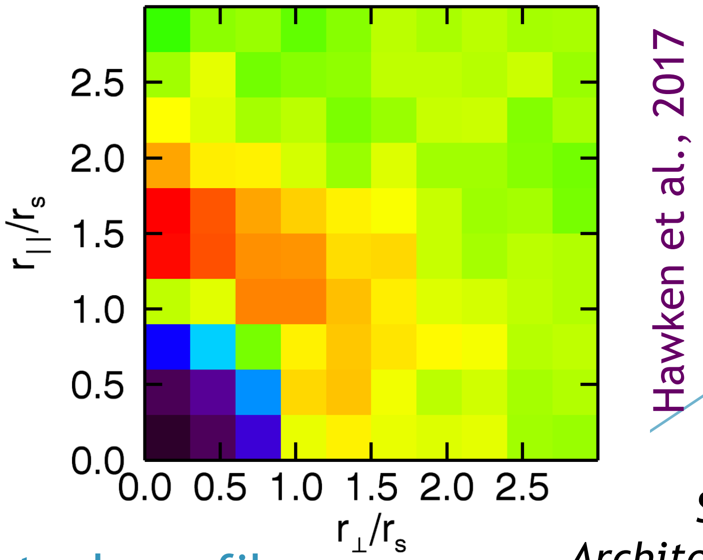
$$\left[\begin{aligned} P_{\rm g,\delta\delta}(k) &= b_1^2 P_{\delta\delta}(k) + 2b_2 b_1 P_{b2,\delta}(k) + 2b_{s2} b_1 P_{bs2,\delta}(k) \\ &+ 2b_{3\rm nl} b_1 \sigma_3^2(k) P_{\rm m}^{\rm L}(k) + b_2^2 P_{b22}(k) \\ &+ 2b_2 b_{s2} P_{b2s2}(k) + b_{s2}^2 P_{bs22}(k) + N, \\ P_{\rm g,\delta\theta}(k) &= b_1 P_{\delta\theta}(k) + b_2 P_{b2,\theta}(k) + b_{s2} P_{bs2,\theta}(k) \\ &+ b_{3\rm nl}\sigma_3^2(k) P_{\rm m}^{\rm lin}(k), \end{aligned}\right.$$

Other LSS tracers

- Cosmic voids
  - Cosmic voids are interesting objects, to some extent simpler to model
  - Can be used for RSD and Alcock-Pazcynski test





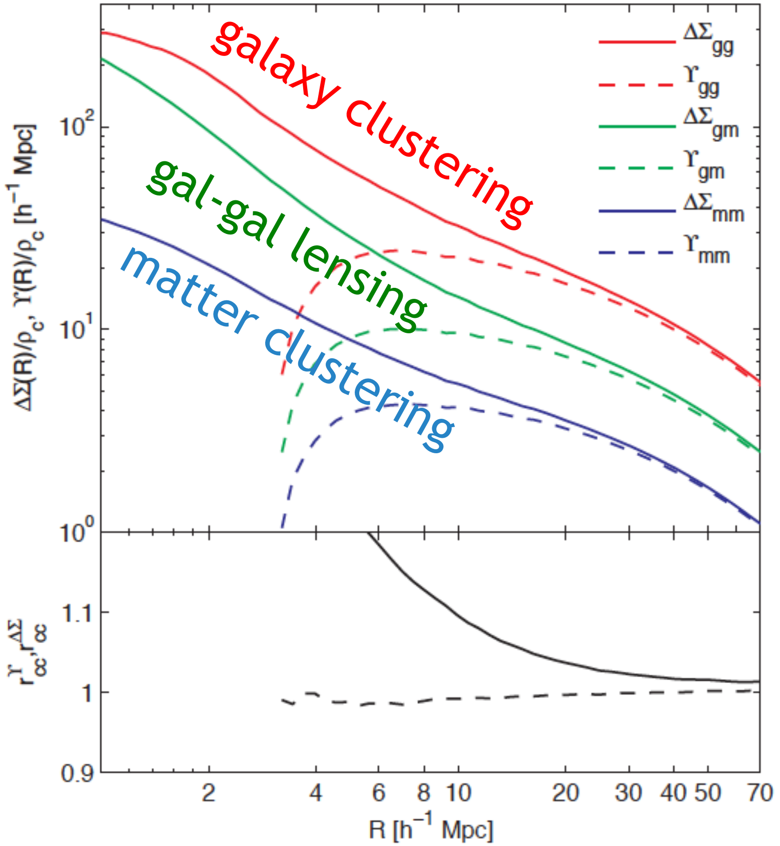


Anisotropic void stack profile

See also Architouv et al., 2017

Complementarity with weak lensing

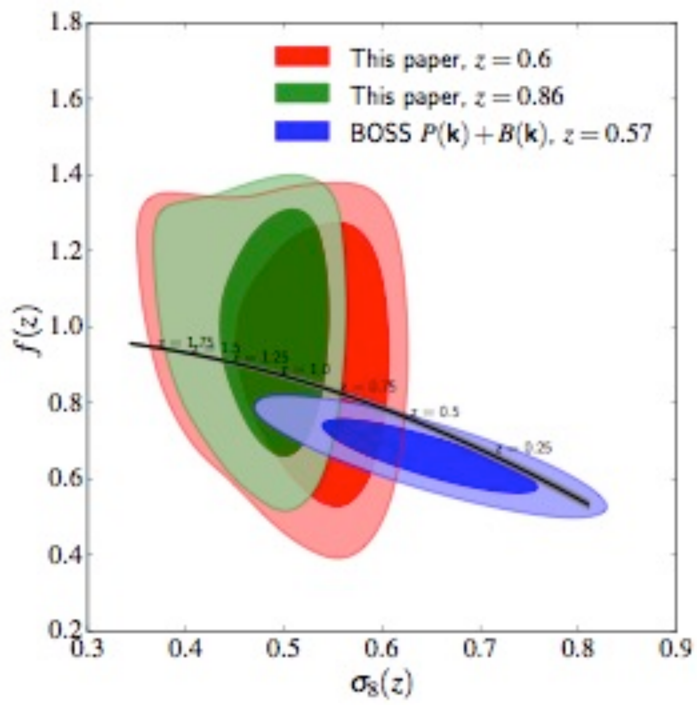
Projected correlation functions



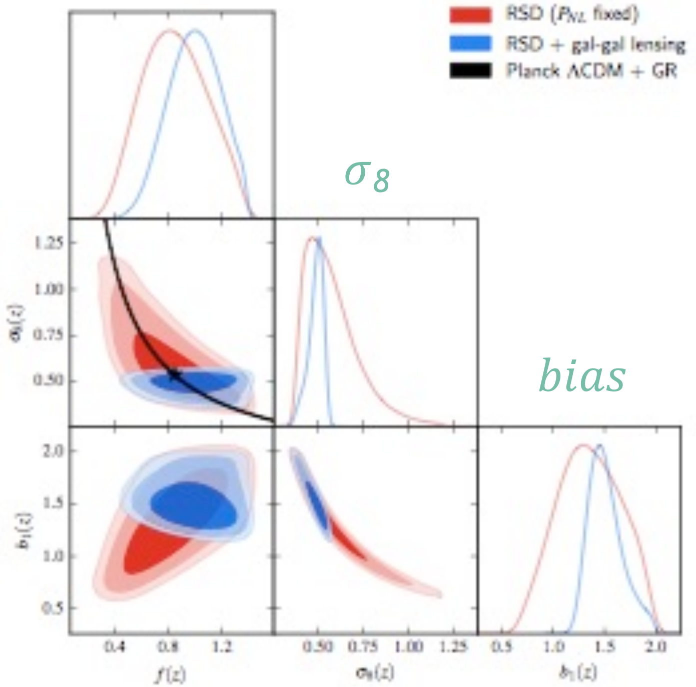
Baldauf et al., 2010

- Weak lensing and galaxy clustering are very complementary
- g-g lensing and galaxy clustering of same foreground galaxies allows breaking degeneracies between cosmological parameters and galaxy bias
- One can also defined combined observables (e.g. E_G)

RSD and galaxy-galaxy lensing



- Weak lensing and galaxy clustering allows breaking the classical f-σ_8-b degeneracy in GC



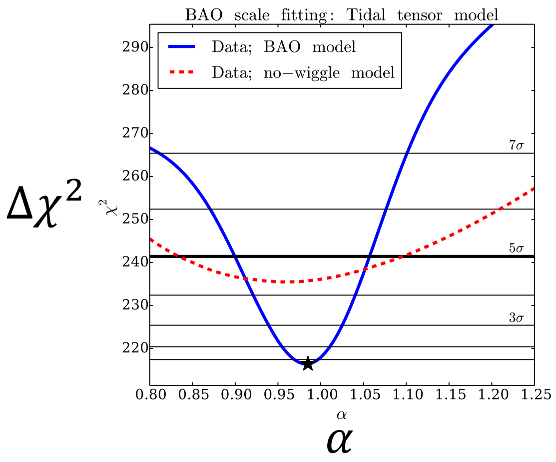
de la Torre et al. 2017

Three-point & higher statistics

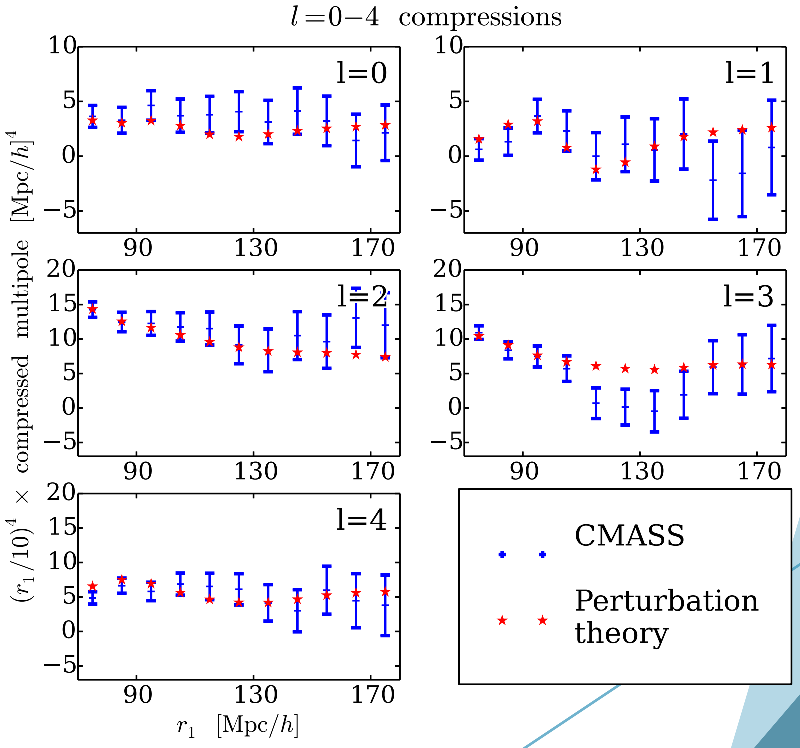
- Galaxy field is non-Gaussian and has non-vanishing higher order statistics
- Three-point statistics is accessible from data (3-point correlation function, bispectrum), higher orders more difficult
- Three-point statistics in combination with two-point statistics allows in principle removing bias degeneracy
- Generally, NL three-point statistics are difficult to model analytically, so hard to include in a likelihood

Three-point statistics

- BAO feature 4.5σ detection in the 3-point correlation function



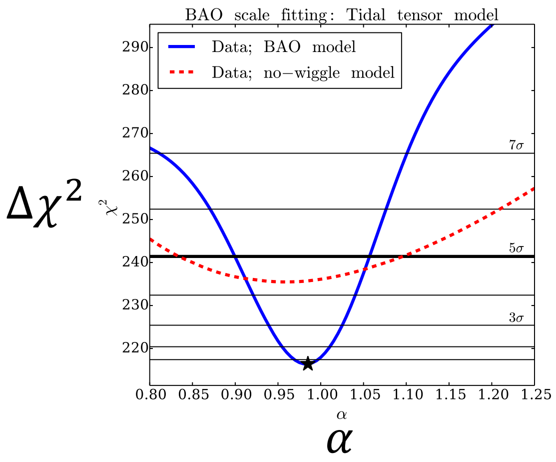
$$
\begin{aligned}
B_s(k_1,k_2,x) = & b_1^3 P(k_1)P(k_2)\Big[\tilde{F}_2(k_1,k_2;x)\mathcal{D}_{\mathrm{SQ1}}(\beta,x) + \\
& \tilde{G}_2(k_1,k_2;x)\mathcal{D}_{\mathrm{SQ2}}(\beta,k_1,k_2;x) + \\
& \mathcal{D}_{\mathrm{NLB}}(\beta,\gamma;x) + \mathcal{D}_{\mathrm{FOG}}(\beta,k_1,k_2;x)\Big] + \mathrm{cyc.},
\end{aligned}
$$

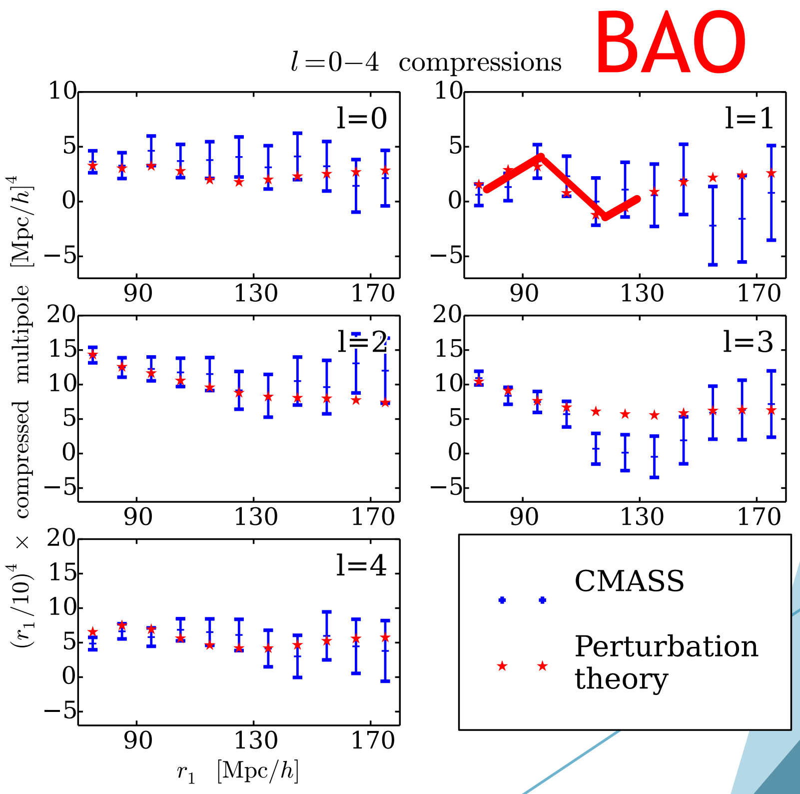


Slepian et al., 2016, 2017

Three-point statistics

- BAO feature 4.5σ detection in the 3-point correlation function



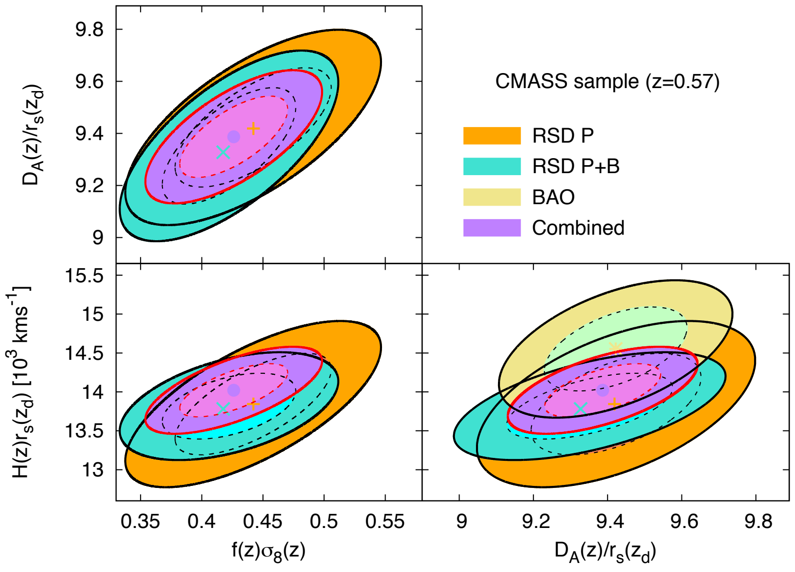


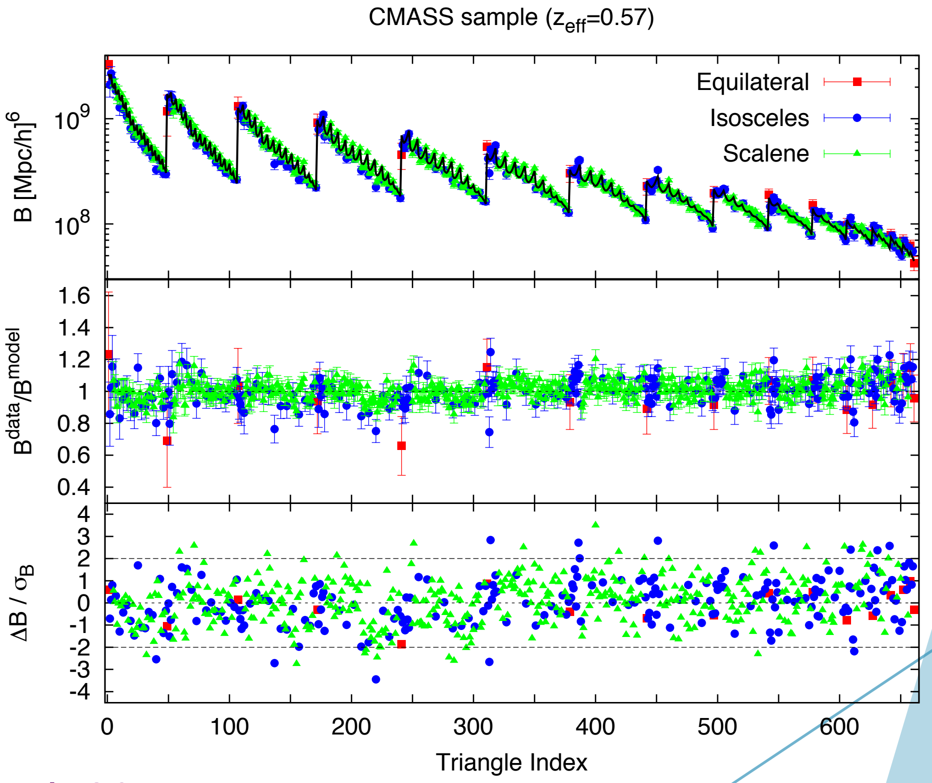
$$B_{\mathrm{s}}(k_1,k_2,x) = b_1^3 P(k_1)P(k_2)\Big[\tilde{F}_2(k_1,k_2;x)\mathcal{D}_{\mathrm{SQ1}}(\beta,x) + \tilde{G}_2(k_1,k_2;x)\mathcal{D}_{\mathrm{SQ2}}(\beta,k_1,k_2;x) + \mathcal{D}_{\mathrm{NLB}}(\beta,\gamma;x) + \mathcal{D}_{\mathrm{FOG}}(\beta,k_1,k_2;x)\Big] + \mathrm{cyc.},$$

Slepian et al., 2016, 2017

Combining two- and three-point statistics

- Adding Bispectrum improves constraints



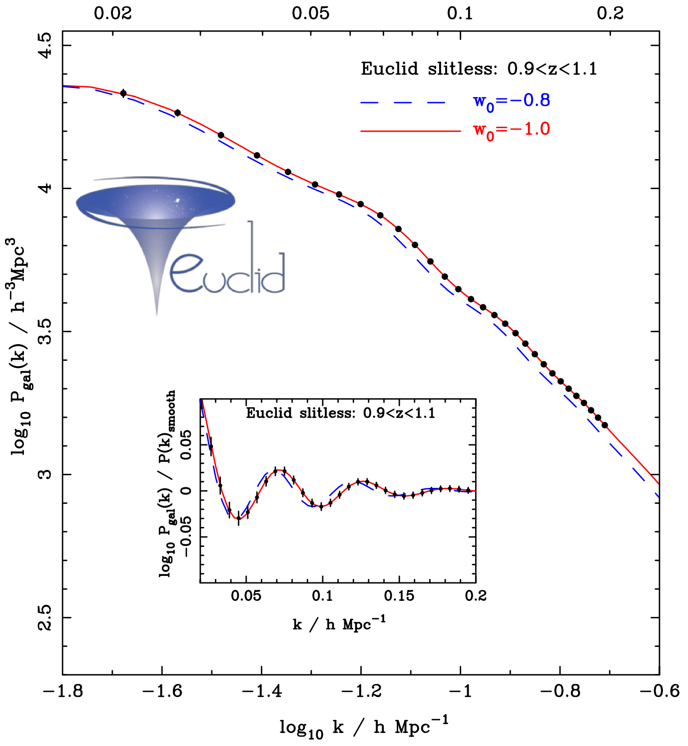


Gil-Marin et al. 2017

Future

- Future is bright! Next-generation galaxy surveys designed to extract most of the cosmological information from galaxy clustering: large probed volumes, sufficiently high galaxy/quasars sampling rate

Galaxy power spectrum



With Euclid & DESI we expect:

- Subpercent accuracy on the BAO scale
- Percent accuracy on the growth rate of structure and γ

→ Crucial to solve the Dark Energy problem

Precision cosmology with galaxy clustering

Report of the Euclid galaxy clustering systematic error budget tiger team

Systematic effect		impact on BAO	impact on RSD	Maturity of mitigation
Reconstruction		large	none	medium
Nonlinear evolution of dark-matter		medium	large	medium
Redshift-space distortions		low	large	low
Galaxy density bias		low	large	low
Massive neutrinos		low	large	medium
Galaxy velocity bias		low	large	low
Variations of model template with cosmology		low	unknown	low
Lightcone & projection effects		low?	low?	low
Relative velocity and density perturbations between baryons and dark matter		small?	small?	small?

- Galaxy clustering cosmology is mature but still, methods need further refinement to reach the exquisite statistical accuracy provided by next-generation cosmological surveys (e.g. DESI, Euclid)