Large surveys in cosmology in the Euclid era

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International Conference PUMA 2022

Probing the Universe with Multimessenger Astrophysics

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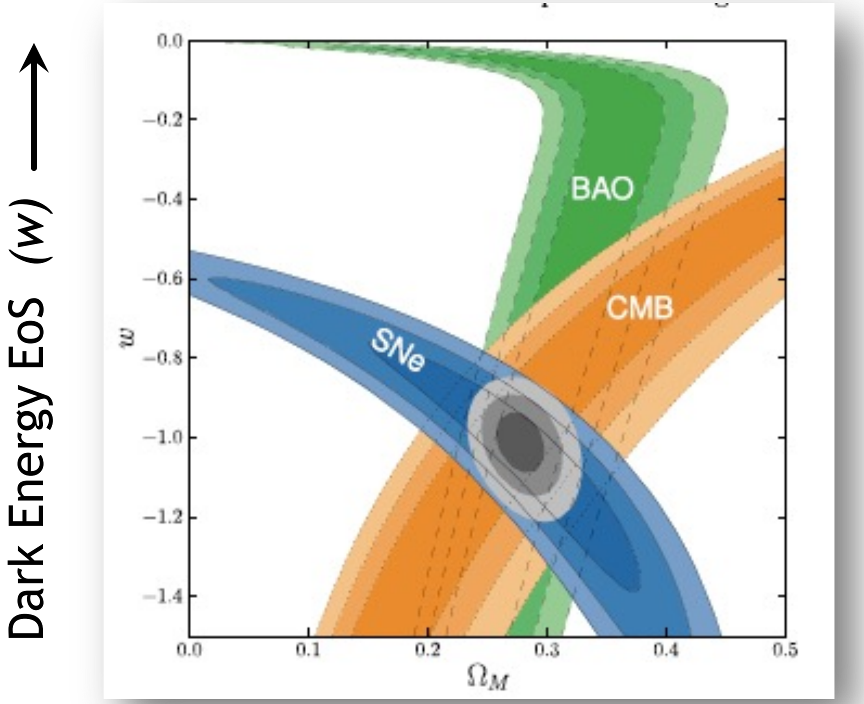
LAM
LABORATOIRE D'ASTROPHYSIQUE DE MARSEILLE

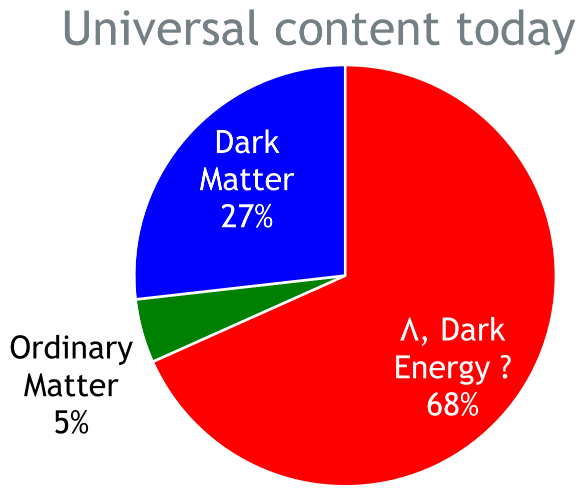
Outline

1. Standard cosmological model
2. Galaxy survey cosmology
3. Euclid mission
4. Conclusion

Concordance ΛCDM model



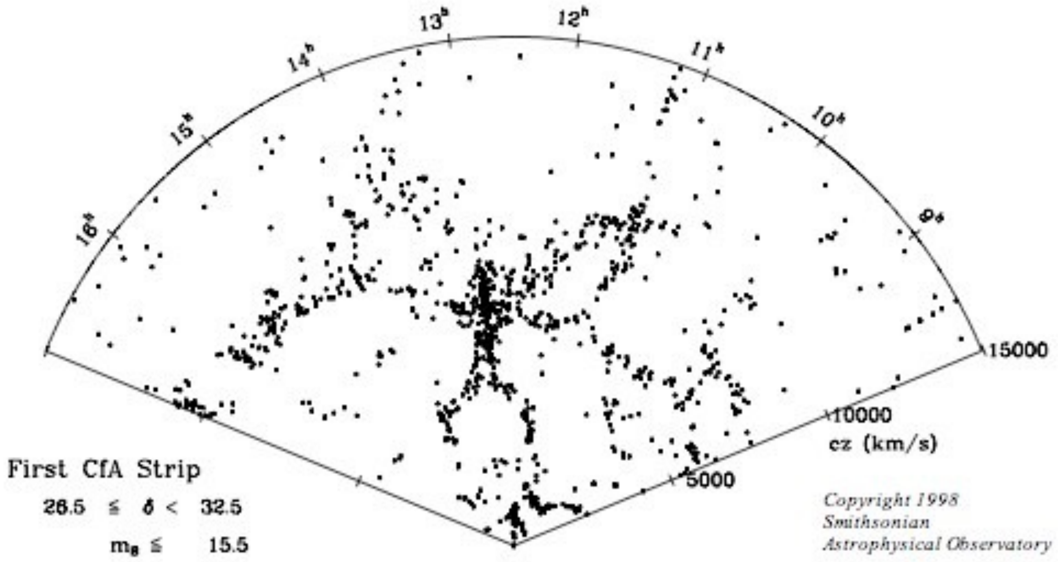
Amanullah et al. 2010



- ΛCDM 6-parameter model well established for few decades now, thanks to SN1a, CMB, galaxy clustering and lensing cosmological probes
- The origin of recent cosmic acceleration is a mystery (physical constant, dark energy, modified gravity ...?)
- Improved cosmological constrains led to apparent tensions between probes

Observed large-scale structure

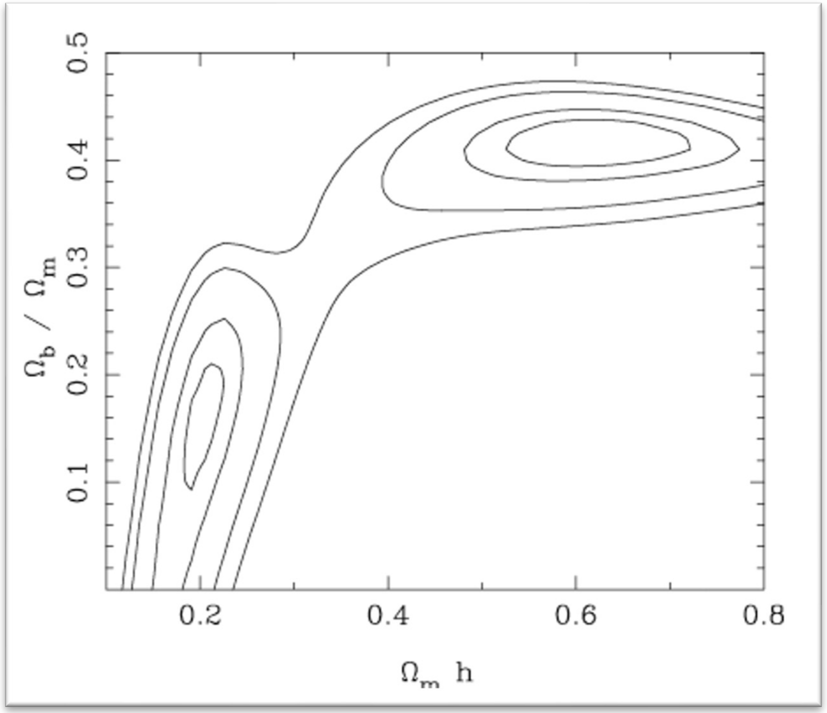
- In the late universe, LSS is mostly seen through galaxy spatial distribution and gravitational lensing
- The large-scale structure of the Universe evolves through the competing effects of universal expansion and structure growth



de Lapparent, Geller, Huchra, 1988

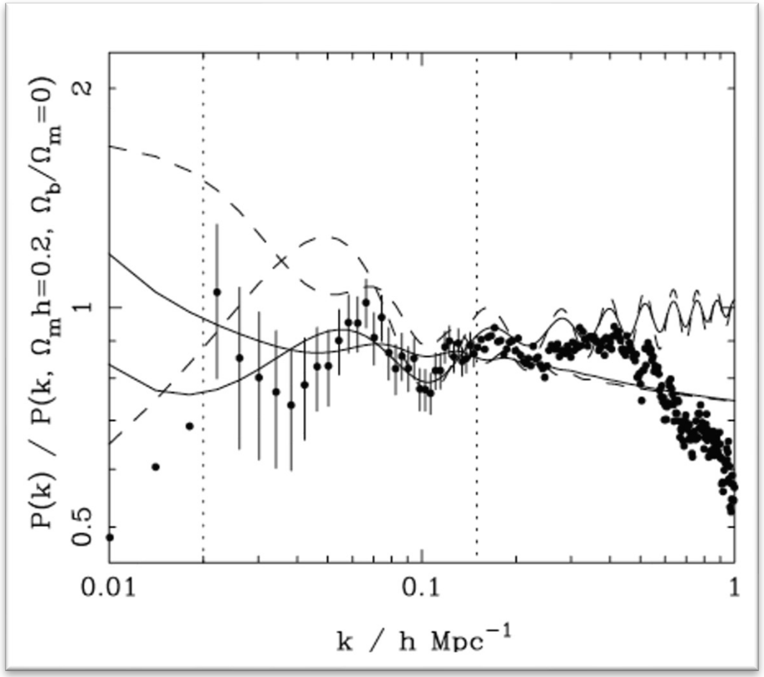
First constraints from galaxy *P(k)*

Constraints on the baryon fraction



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

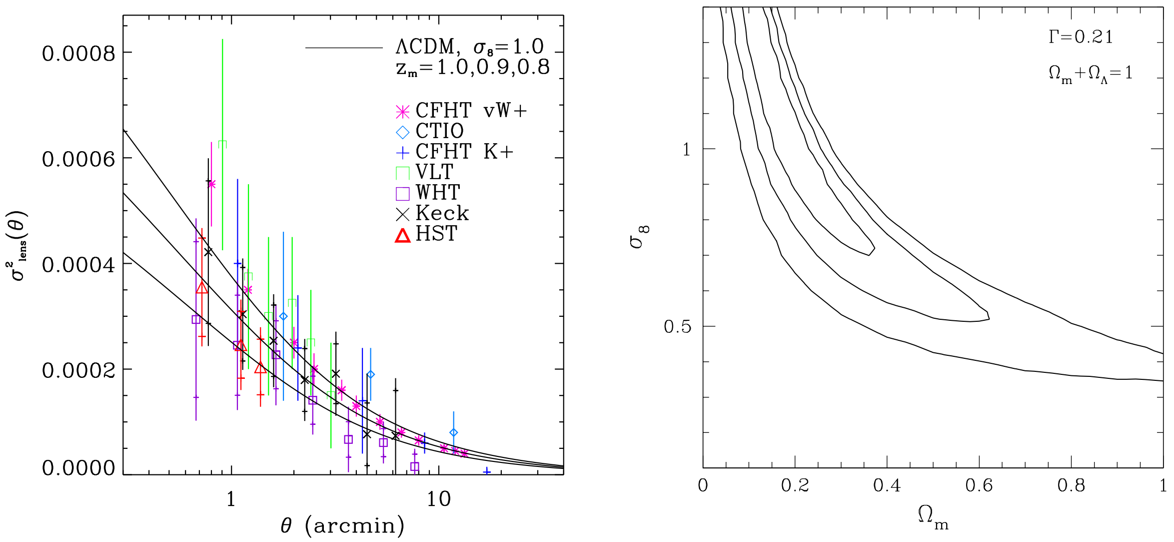
Galaxy power spectrum



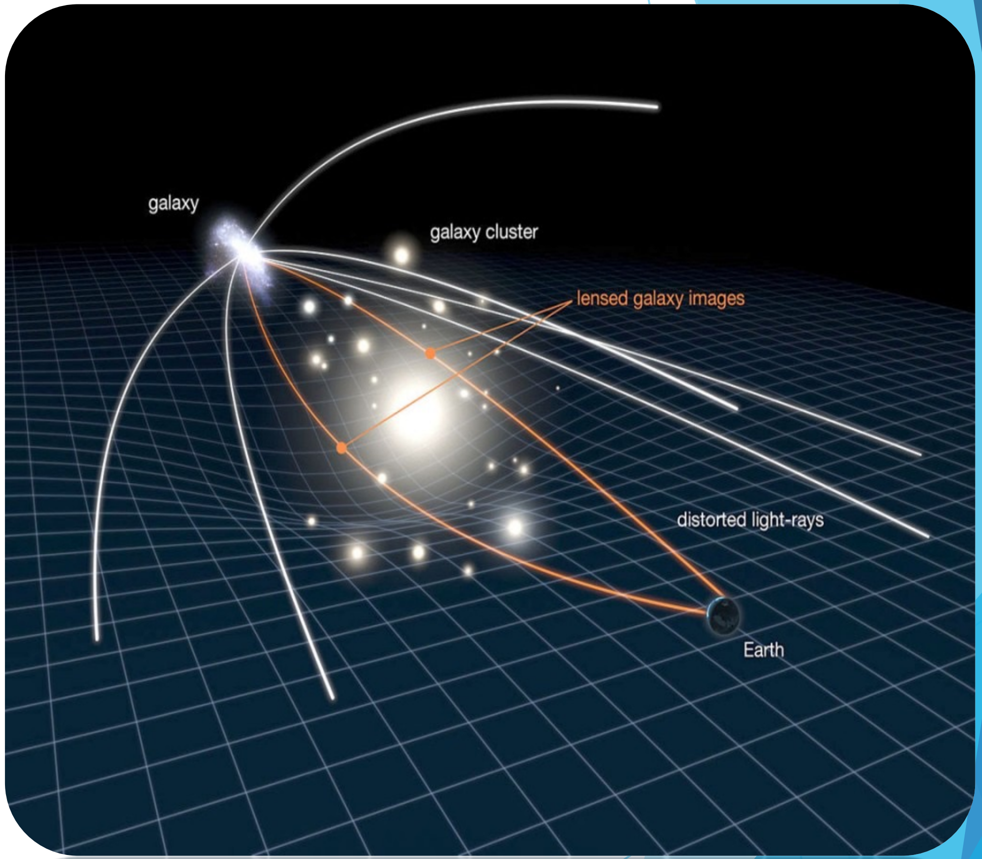
- Galaxy power spectrum full shape (linear scales) sensitive to:

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

Weak gravitational lensing: cosmic shear



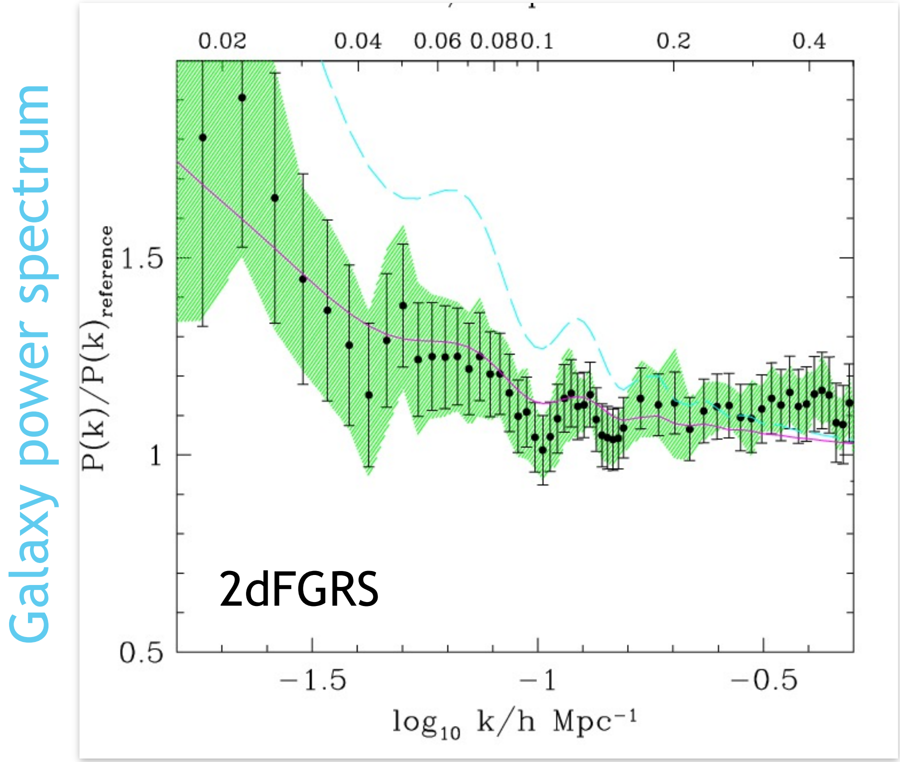
Van Vaerbeke et al. 2002 (compilation)



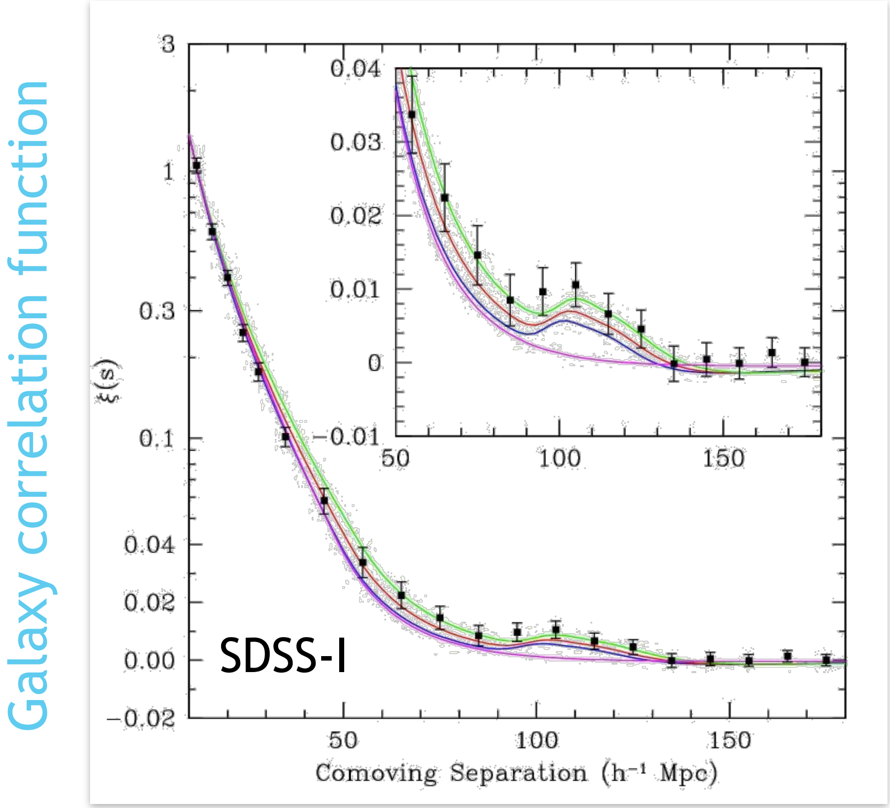
Gravitational lensing

- → Directly probe matter fluctuations
- → Cosmic shear sensitive to mean matter density and growth of structure

Baryon Acoustic Oscillations



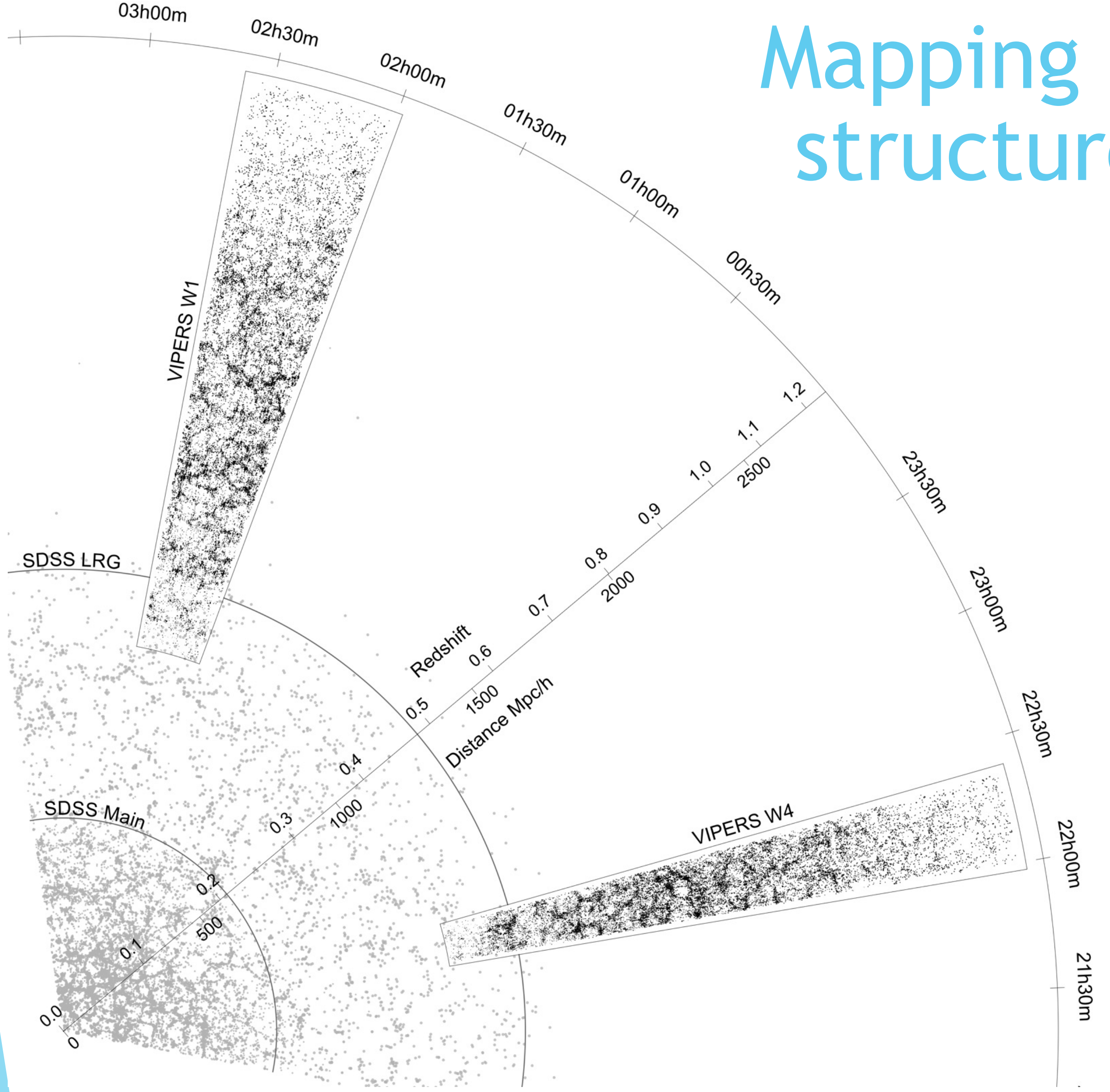
Cole et al. 2005



Eisenstein et al. 2005

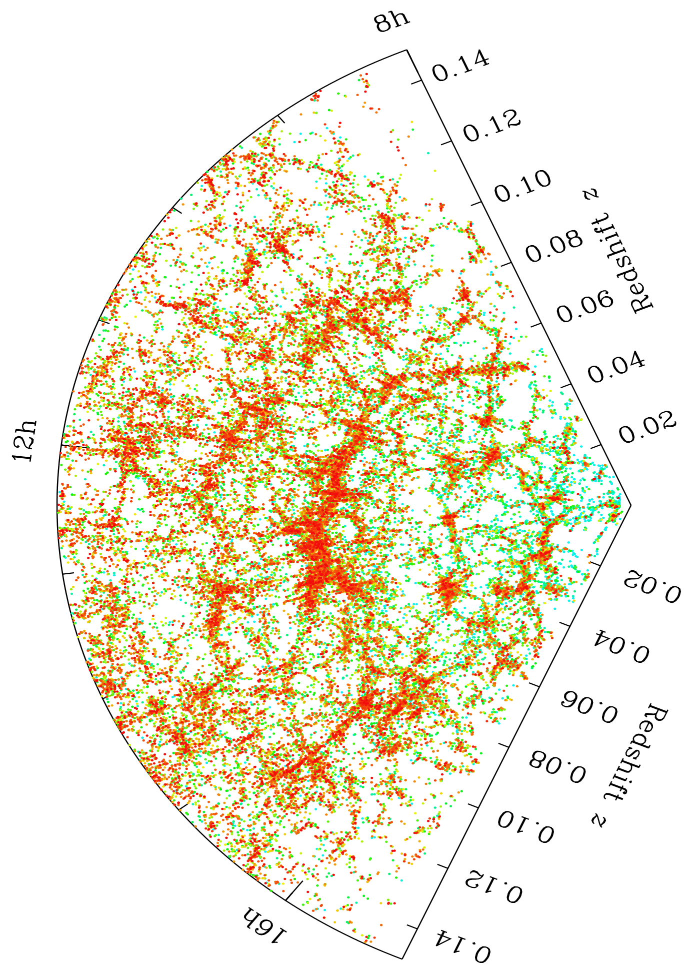
- First detections of BAO in galaxy clustering, sensitive to: *H(z)*, $D_A(z)$

Mapping the large-scale structure with 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/BOSS (*Dawson et al., 2013*)
  - SDSS/eBOSS (*Dawson et al., 2016*)
- More coming in the next years (2021-2027): DESI (on-going), Euclid, PFS, Roman

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:

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

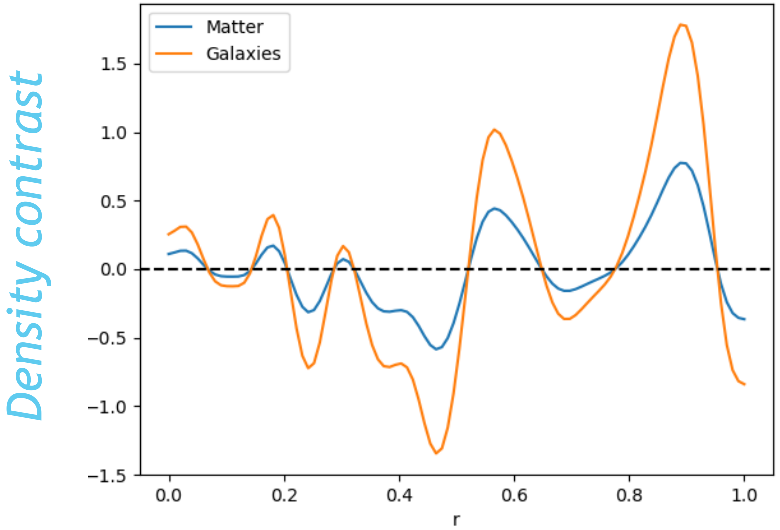
- Higher-order statistics

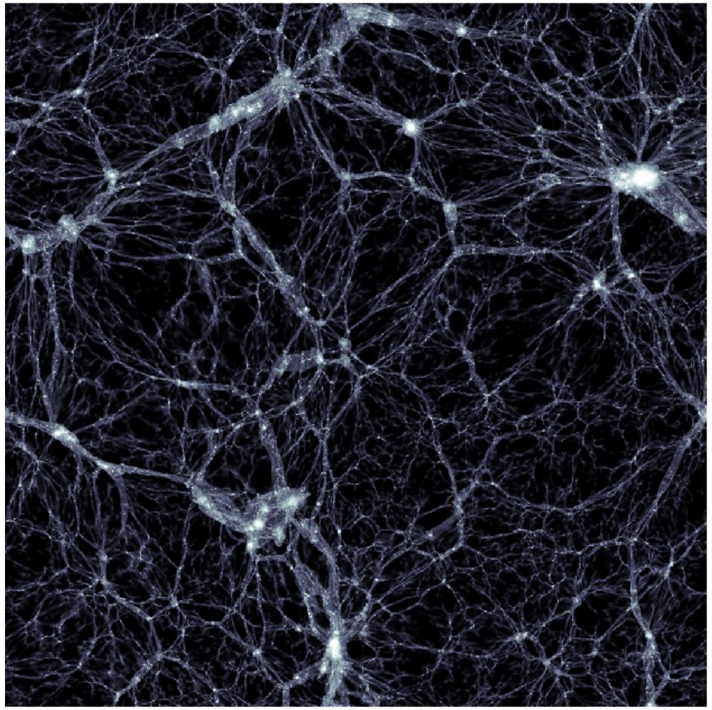
$$\begin{aligned}\xi(r) &= \langle \delta(\mathbf{x_1})\delta(\mathbf{x}+\mathbf{r})\rangle \\ \zeta(r_1, r_2, r_3) &= \langle \delta(\mathbf{x_1})\delta(\mathbf{x_2})\delta(\mathbf{x_3})\rangle\end{aligned}$$

…

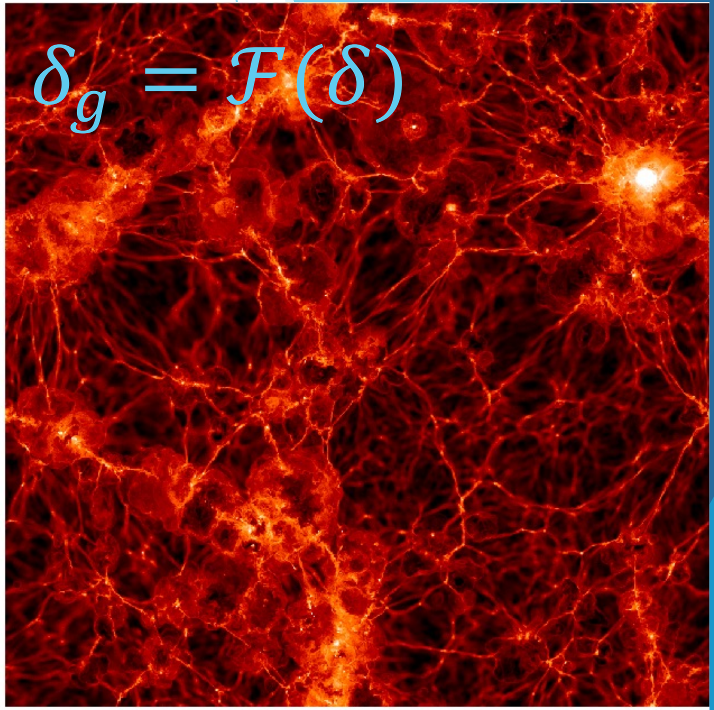
Biased galaxy formation

- Galaxies are biased tracers of the underlying density field





(a) dark matter



(b) baryons

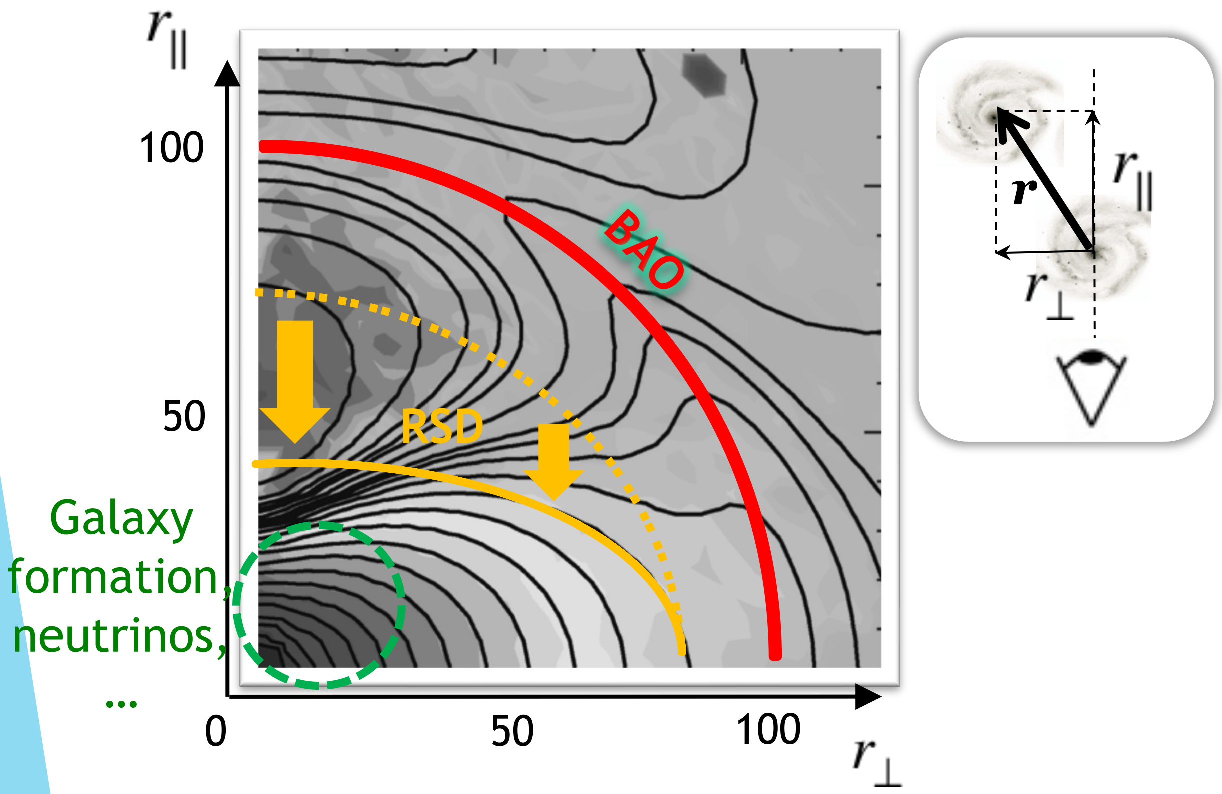
Haider et al., 2016

- Example of perturbative model: *(McDonald & Roy, 2009)*

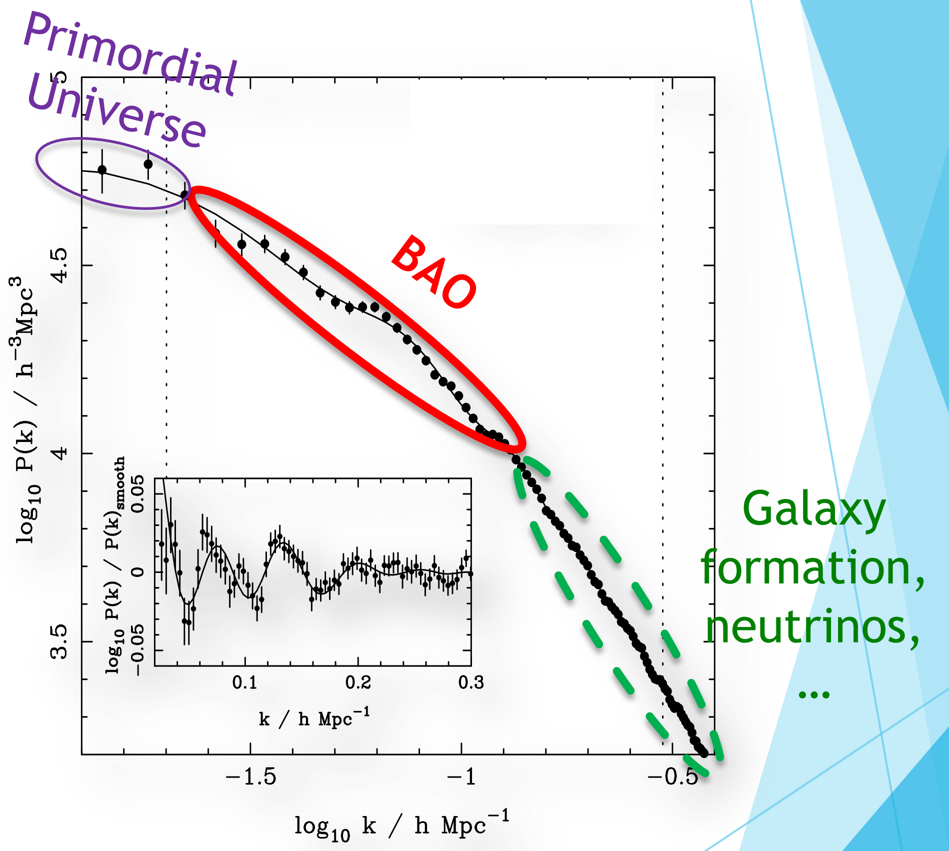
$$\delta_h(\mathbf{x}) = b_1\delta(\mathbf{x}) + \frac{1}{2}b_2[\delta(\mathbf{x})^2 - \sigma_2] + \frac{1}{2}b_{s^2}[s(\mathbf{x})^2 - \langle s^2\rangle]$$

Linear bias *Non-linearities* *Tidal tensor → Non-local*

Cosmology from galaxy clustering



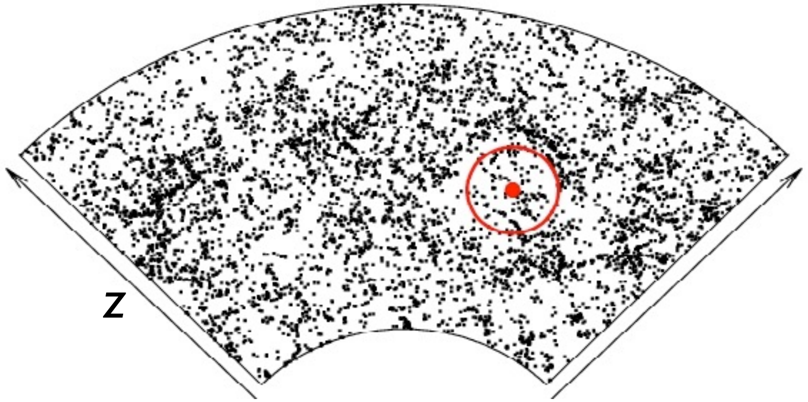
Galaxy anisotropic correlation function



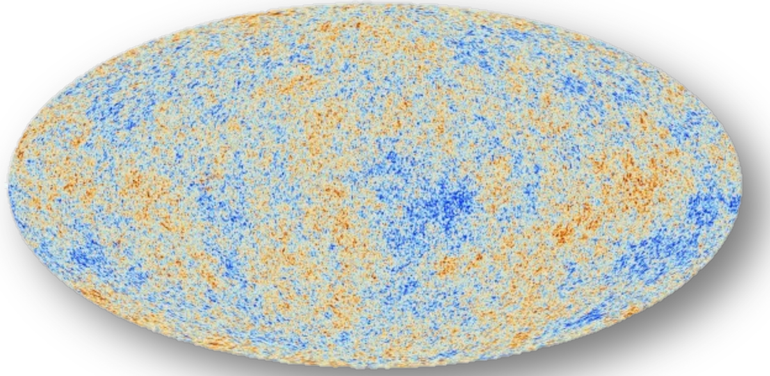
Galaxy power spectrum

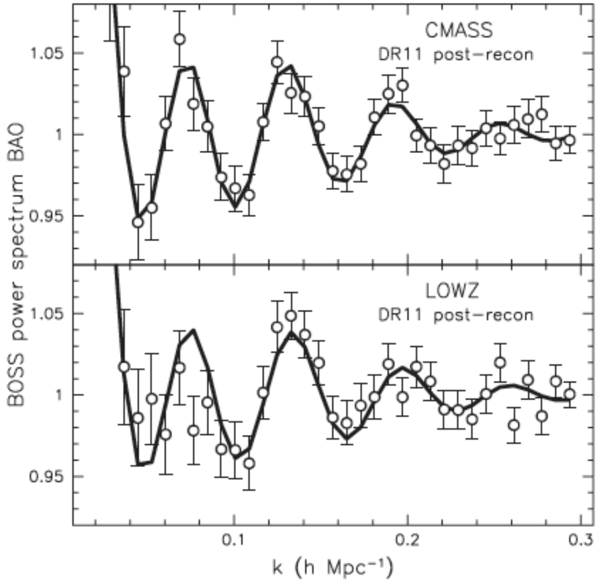
Baryon Acoustic Oscillations

Galaxies

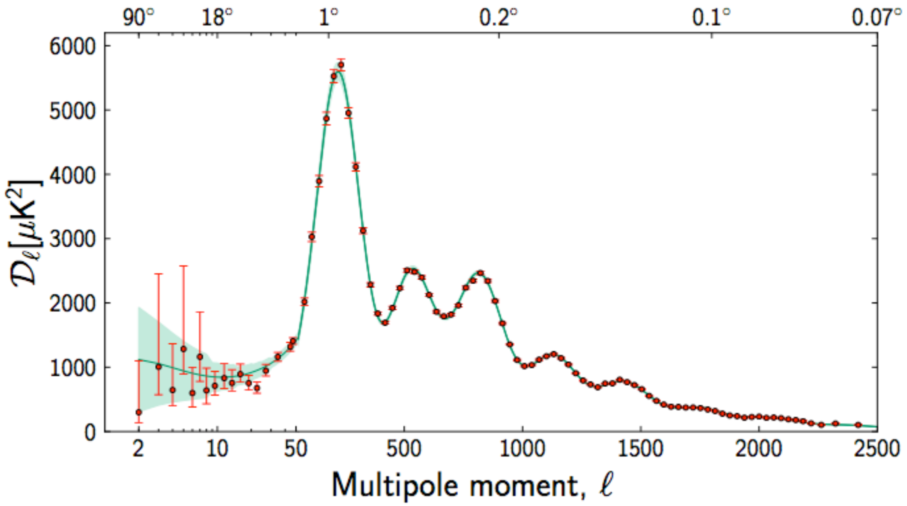


CMB





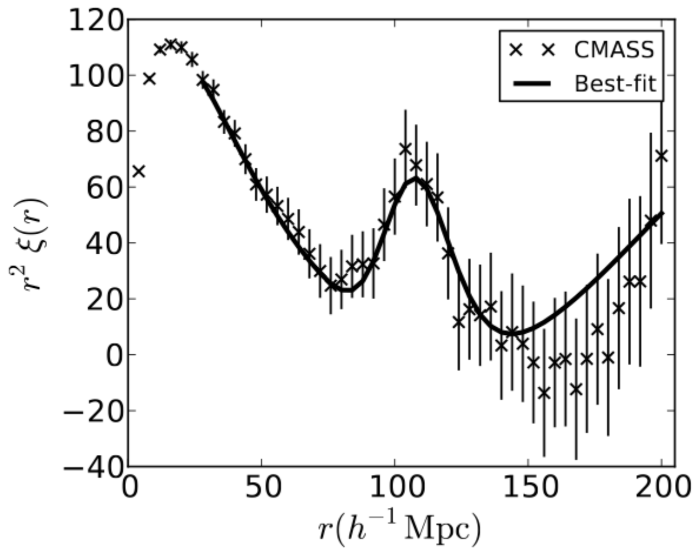
Anderson et al. 2014



Planck Collaboration 2015

Baryon Acoustic Oscillations

Galaxy correlation function



Anderson et al. 2012

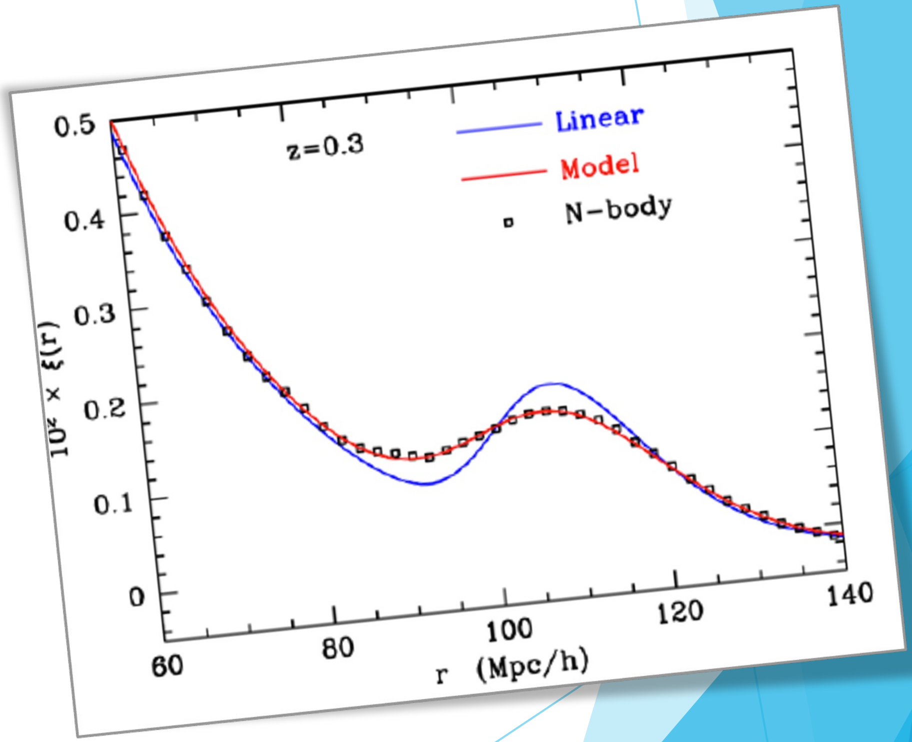
- BAO scale is determined by the sound horizon at drag epoch (z_d):

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

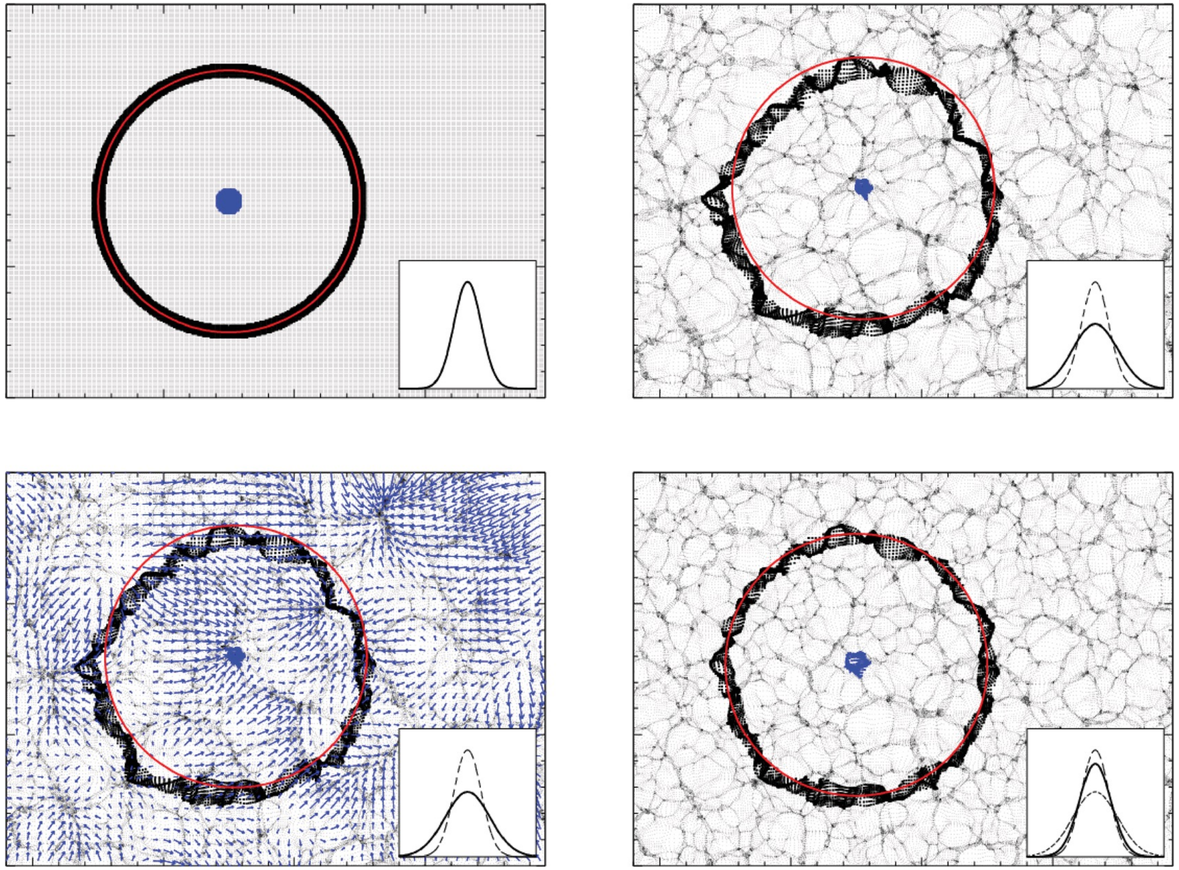
Baryon Acoustic Oscillations

- 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

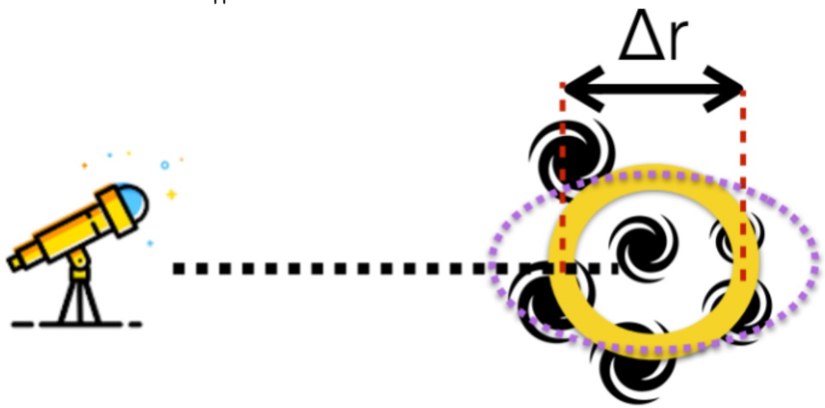
- Reconstruction: mitigate non-linear effects and sharpen the BAO peak (usually based on Zel'dovich approximation)

BAO & Alcock-Pazcynski distortions

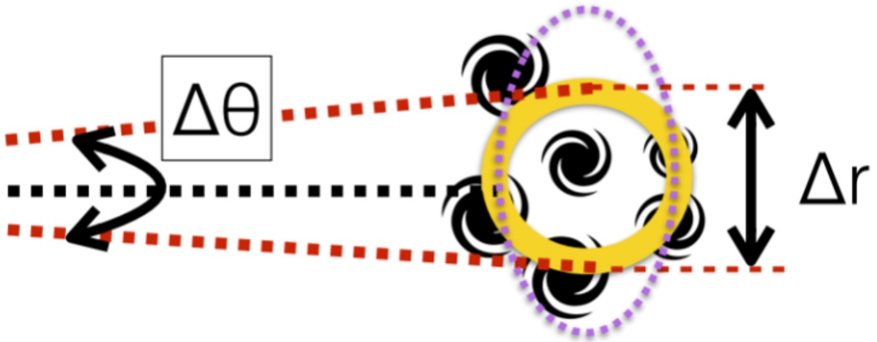
- Anisotropy induced by the assumed (*fiducial)* cosmology which convert redshift into distances.

$$\Delta r_{\parallel} \approx c/H(z) \equiv D_H(z)$$

$$\Delta r_{\perp} \approx D_M(z)$$



Radial distance



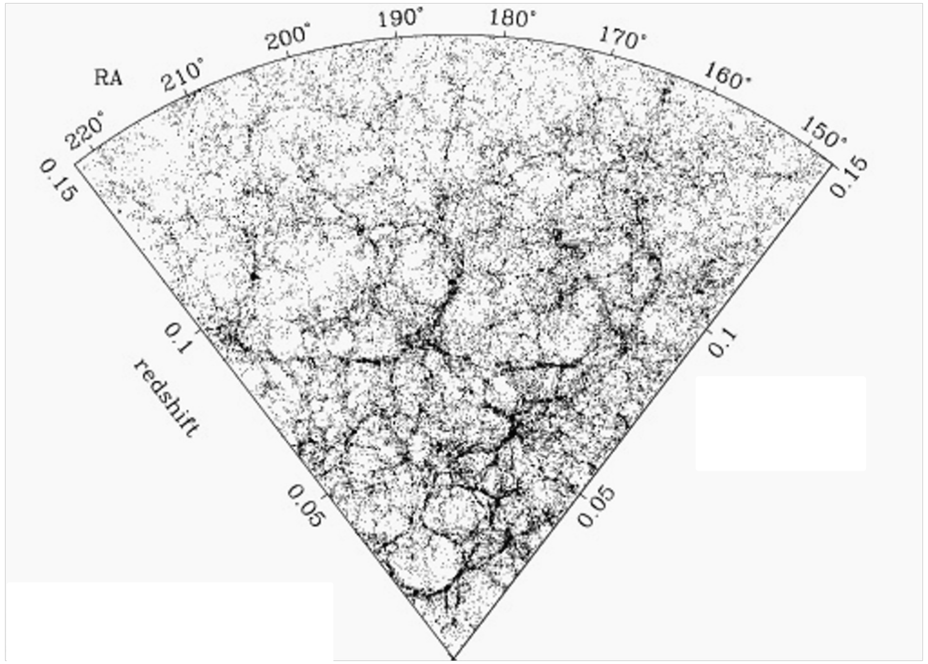
Angular diameter distance

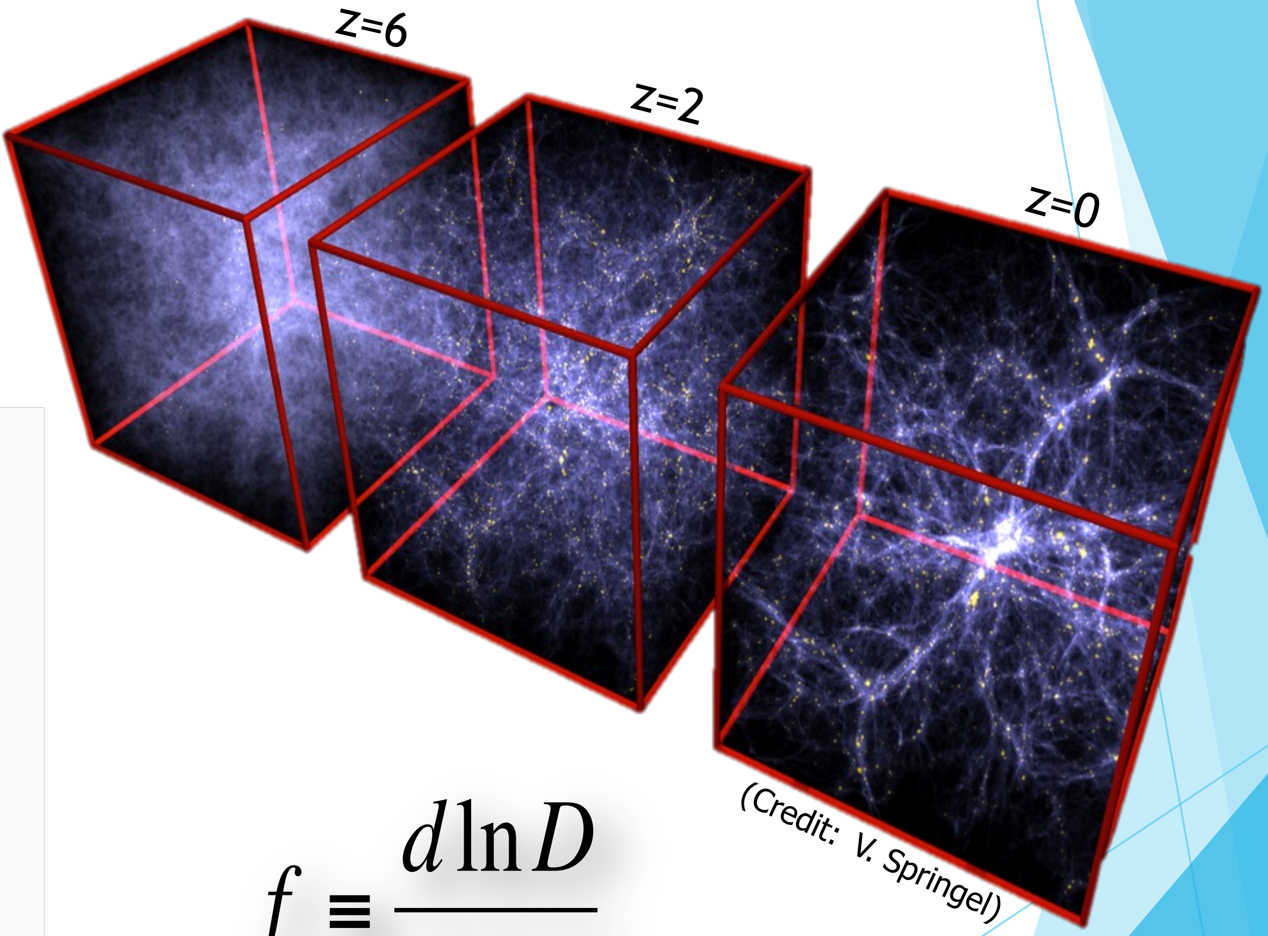
$$\alpha_{\parallel} = \frac{D_H(z_{\text{eff}})/r_d}{D_H^{\text{fid}}(z_{\text{eff}})/r_d^{\text{fid}}}$$

$$\alpha_{\perp} = \frac{D_M(z_{\text{eff}})/r_d}{D_M^{\text{fid}}(z_{\text{eff}})/r_d^{\text{fid}}}$$

Probing the growth rate of structure

Real space



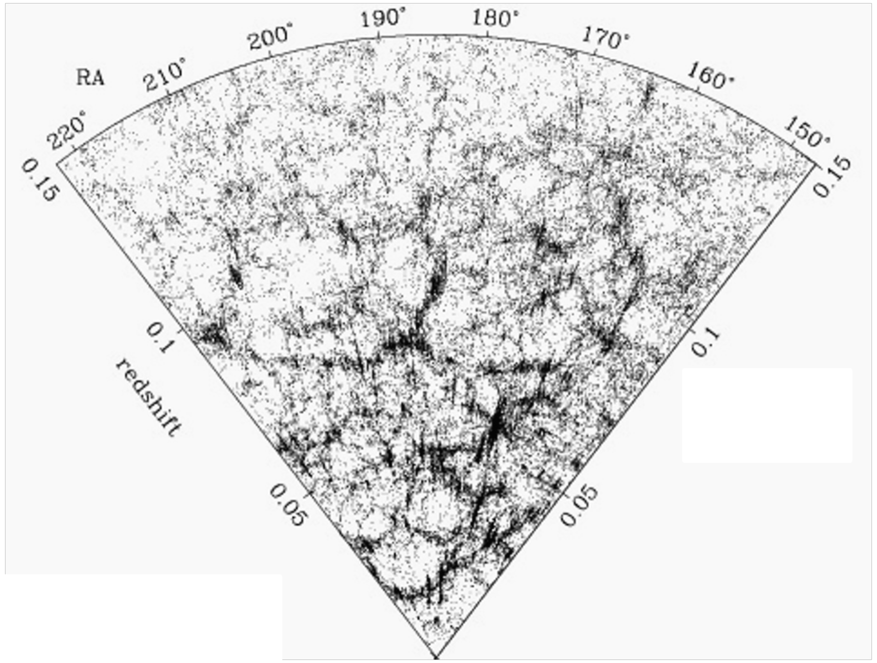


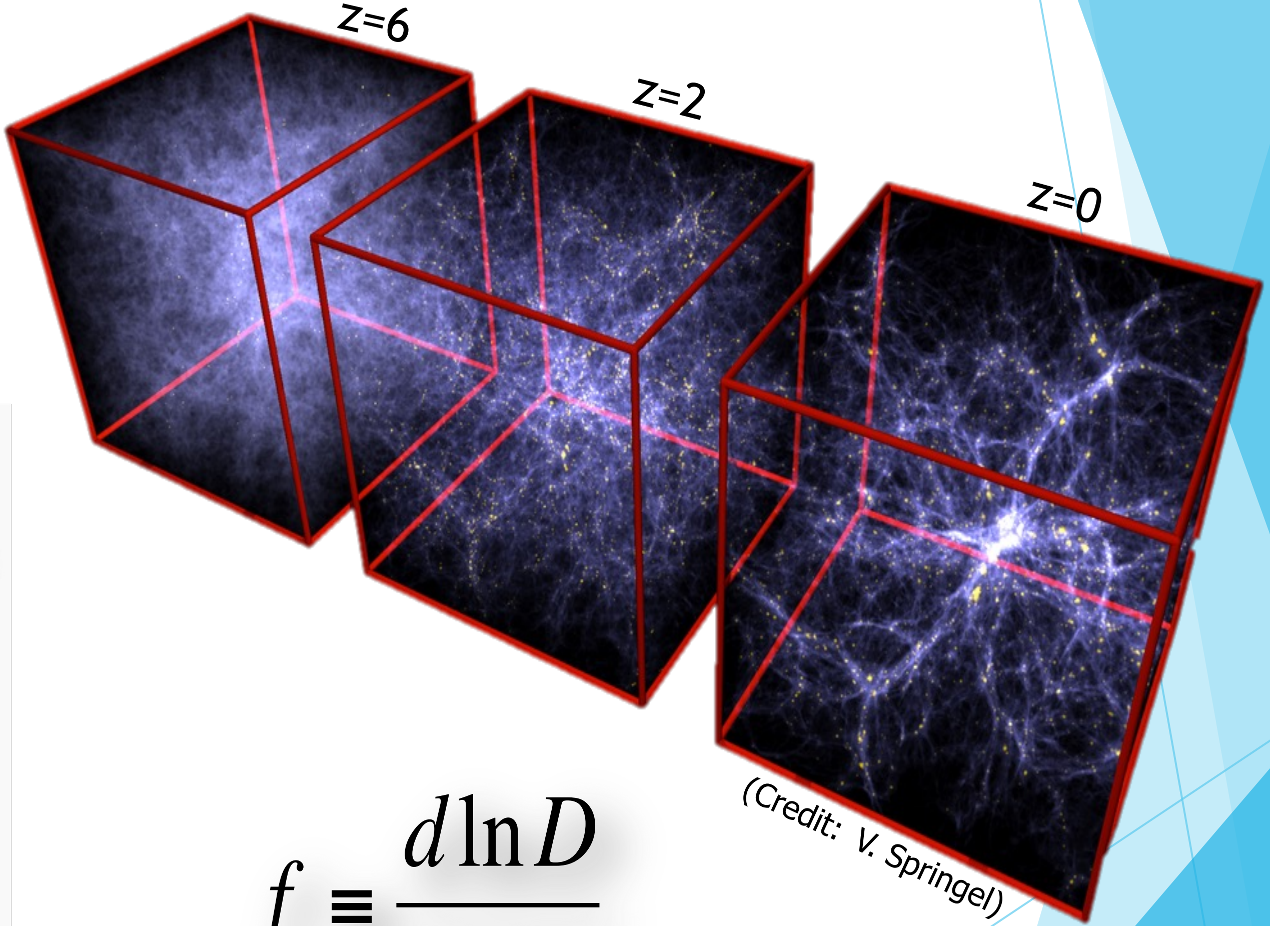
$$f \equiv \frac{d\ln D}{d\ln a}$$

Growth rate of structure

Probing the growth rate of structure

Redshift space

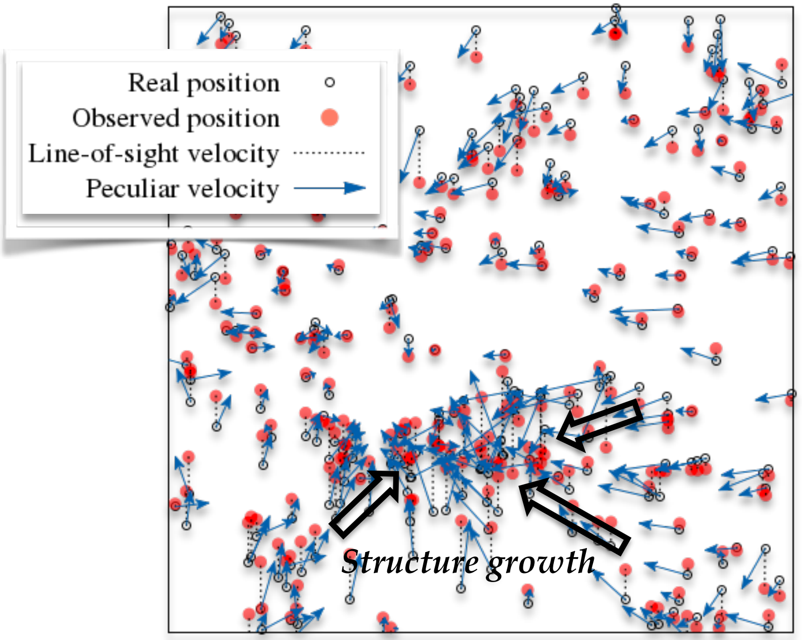


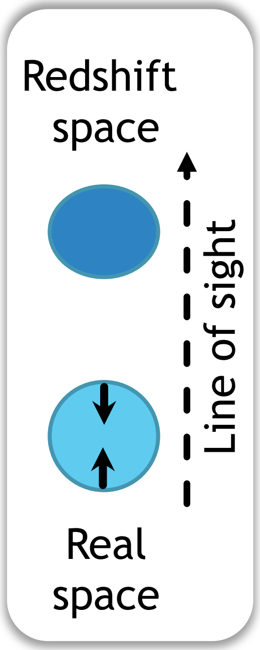


$$f \equiv \frac{d\ln D}{d\ln a}$$

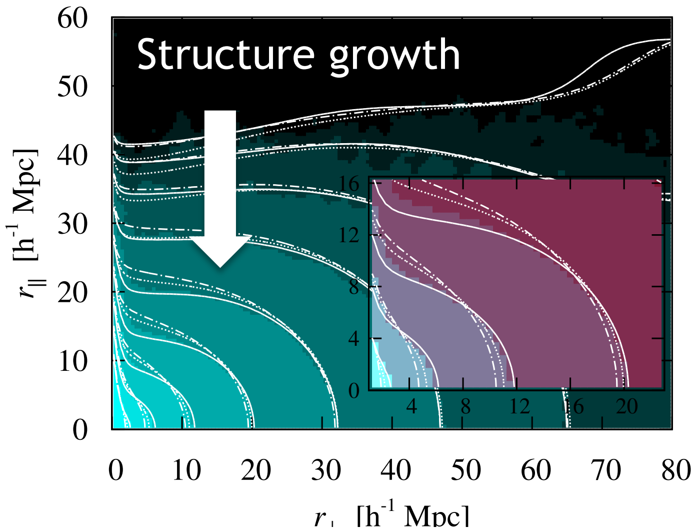
Growth rate of structure

Redshift-space distortions





Galaxy anisotropic correlation function

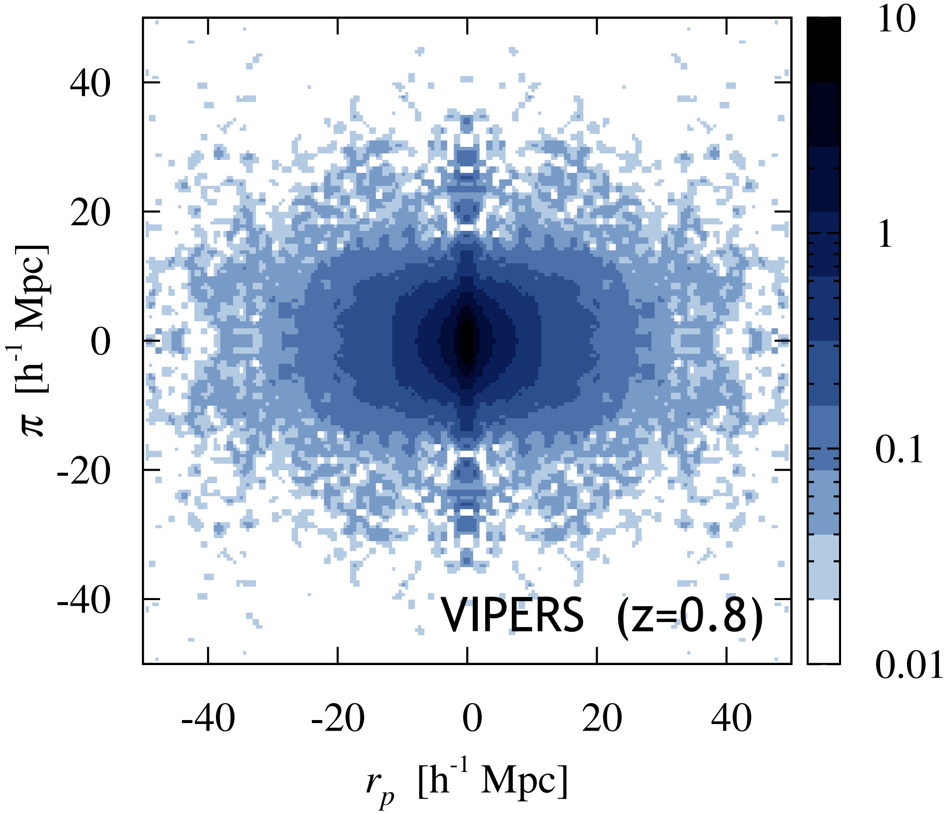


$$f \equiv \frac{d\ln D}{d\ln a} \approx \Omega_m(z)^{\gamma}$$

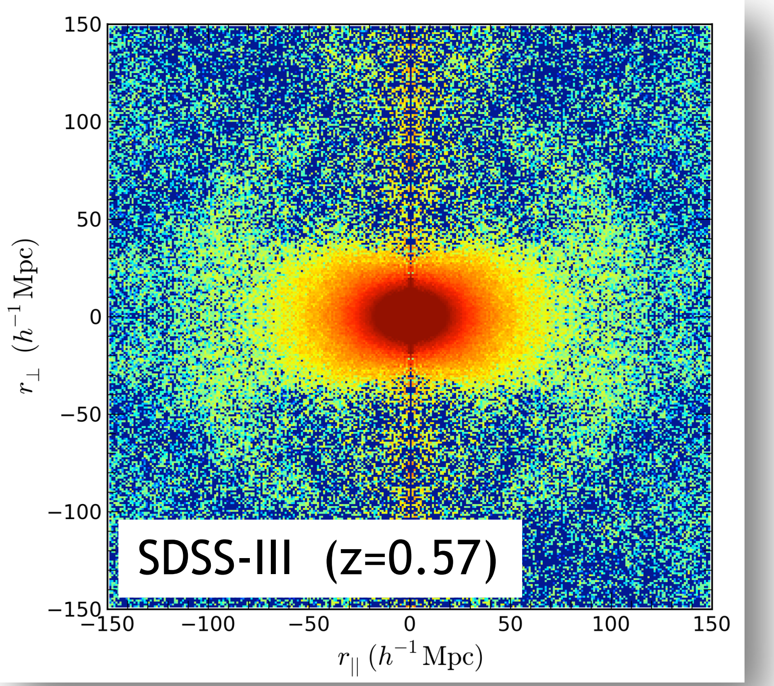
Distance in redshift-space: $s = r + \dfrac{v_{los}}{aH}$

RSD measurements

Anisotropic correlation function : $\xi(r_\perp, r_\parallel) = \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} e^{i\boldsymbol{k}\cdot\boldsymbol{s}} P^s(k,\mu)$



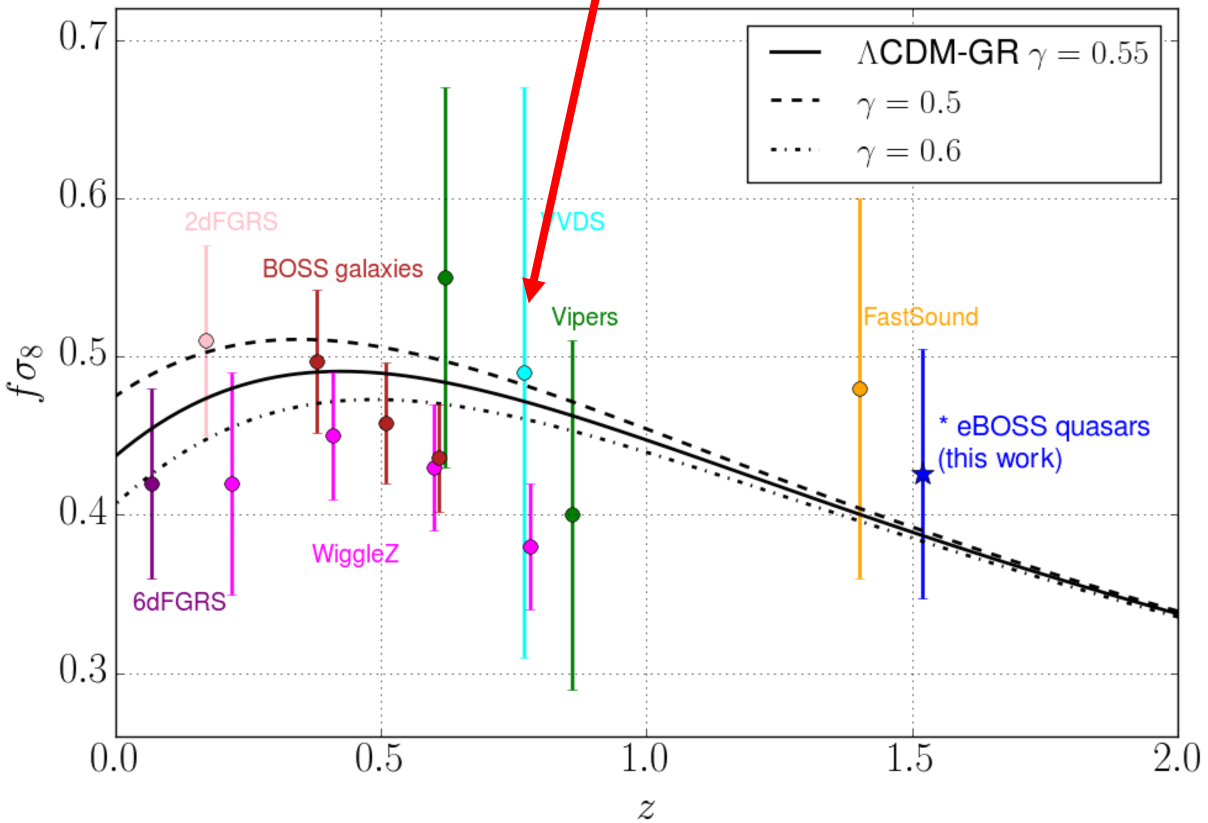
VIPERS, de la Torre et al. 2013)



SDSS/BOSS, Samushia et al. 2014

Redshift-space distortions

Guzzo et al. 2008

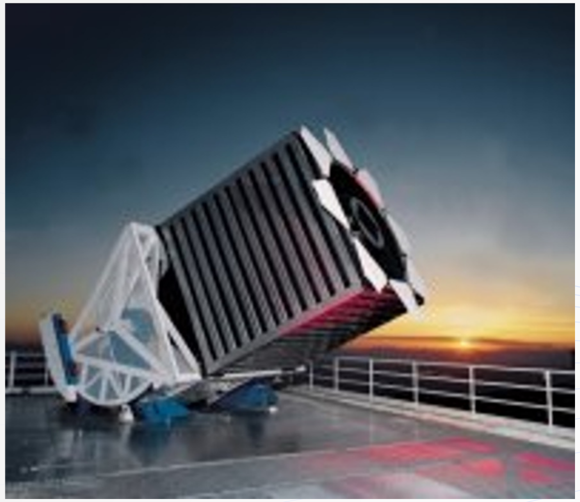


Zarrouk et al. 2018

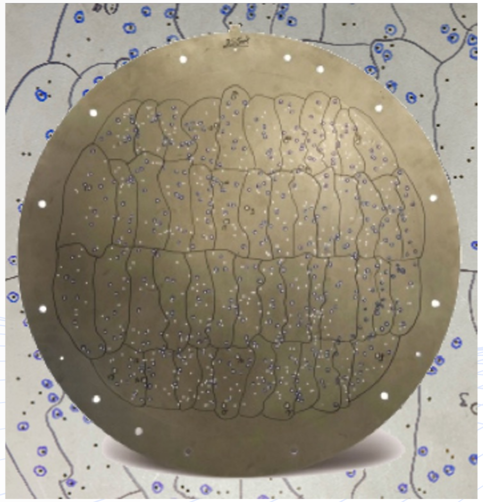
$$f \equiv \frac{d \ln D}{d \ln a} \approx \Omega_m(z)^\gamma$$

State-of-the art: SDSS-IV

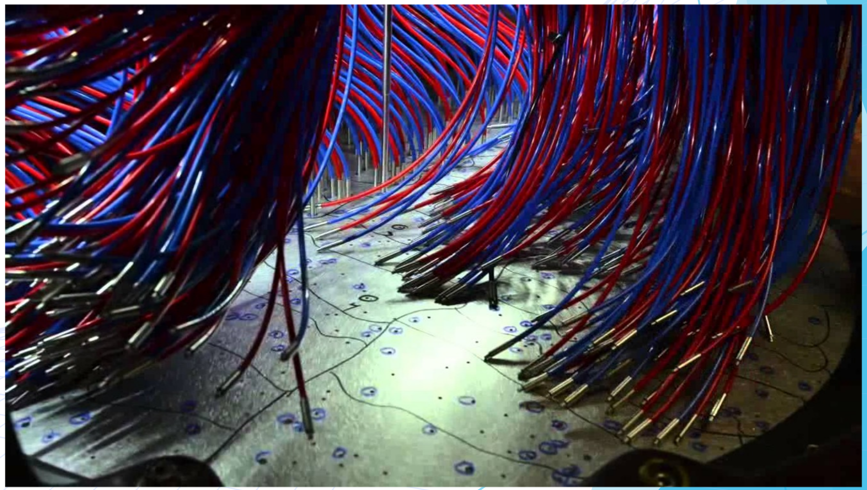
- SDSS: collection of wide-area, multi-band imaging and spectroscopic surveys
- Primary goal to probe the large-scale structure of the universe and cosmology
- SDSS-IV uses 2.5-meters telescope was designed and built at the Apache Point Observatory, at Sunspot, New Mexico, USA
- Observations performed with two multi-objects fiber-fed twin spectrograph



SDSS telescope



SDSS plate

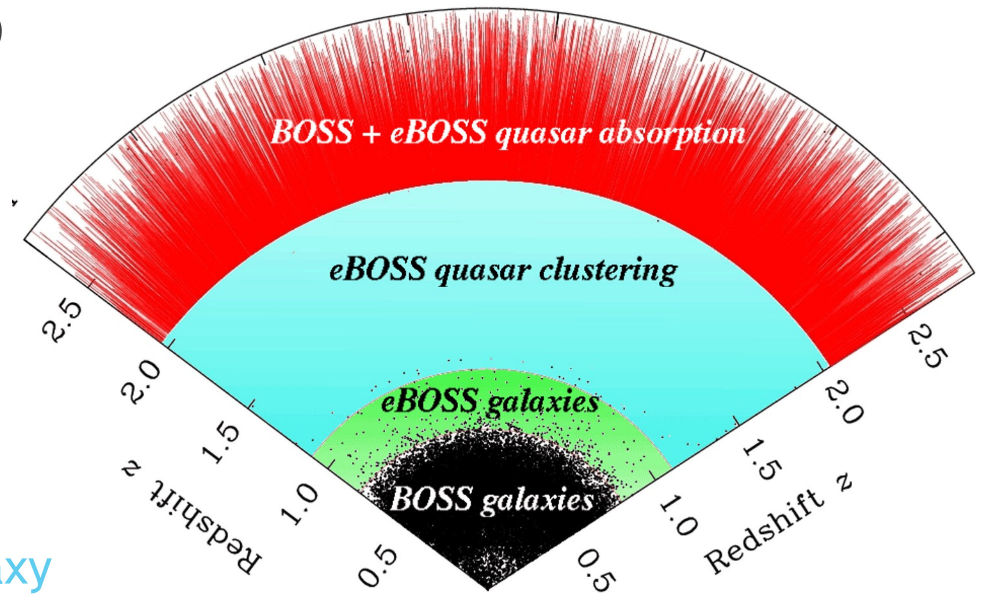


SDSS fibers

SDSS/eBOSS survey

- Galaxies target by eBOSS :
  - Luminous red galaxies (LRGs, mostly elliptical galaxies)
  - Emission lines galaxies (ELGs, spiral/irr. galaxies)
  - Quasars (QSOs)
  - Quasars absorption lines: the Lyman-alpha forest

- Additional data : Constant mass galaxies observed by BOSS (CMASS, 75% red 25 % blue galaxies)

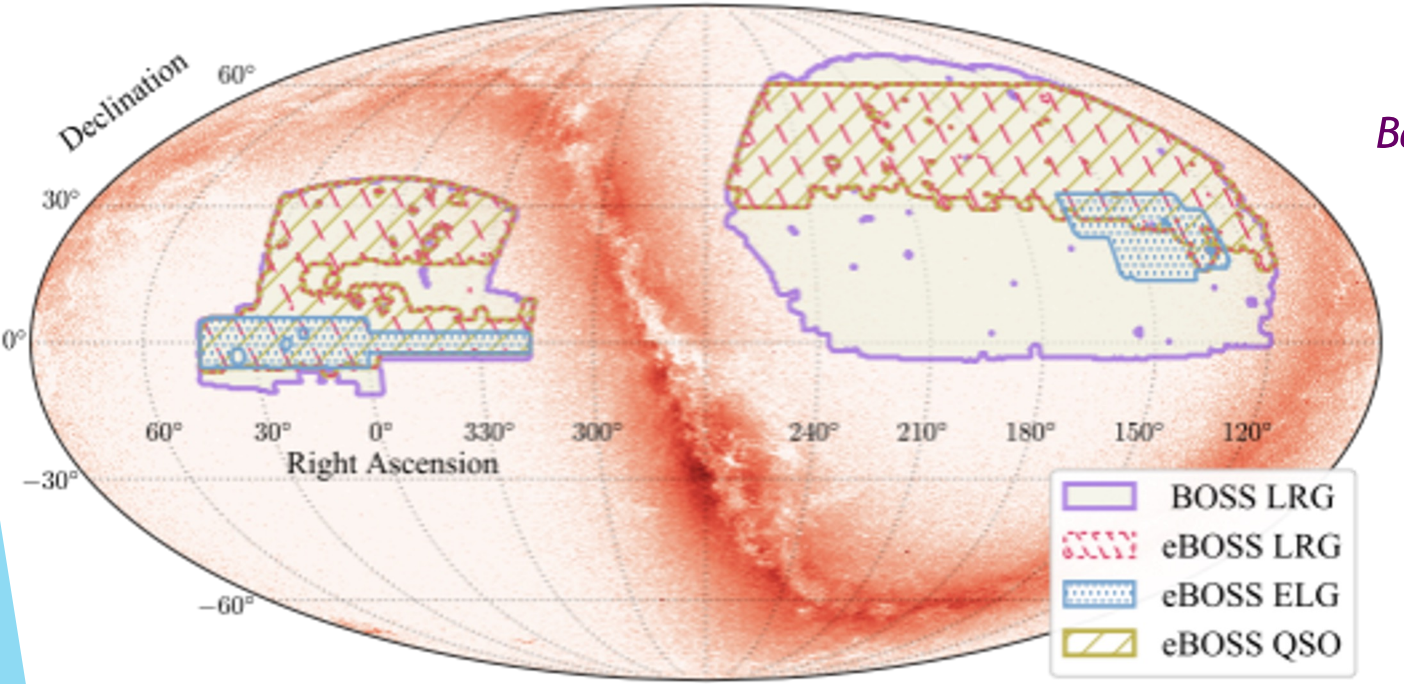


eBOSS galaxies samples

Luminous red galaxy

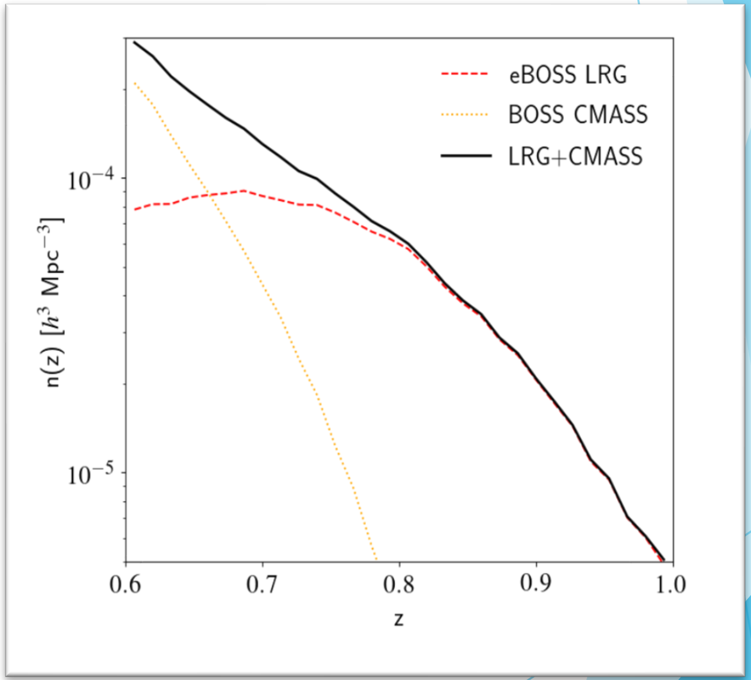
Emission-line galaxy

eBOSS observations



eBOSS angular footprint

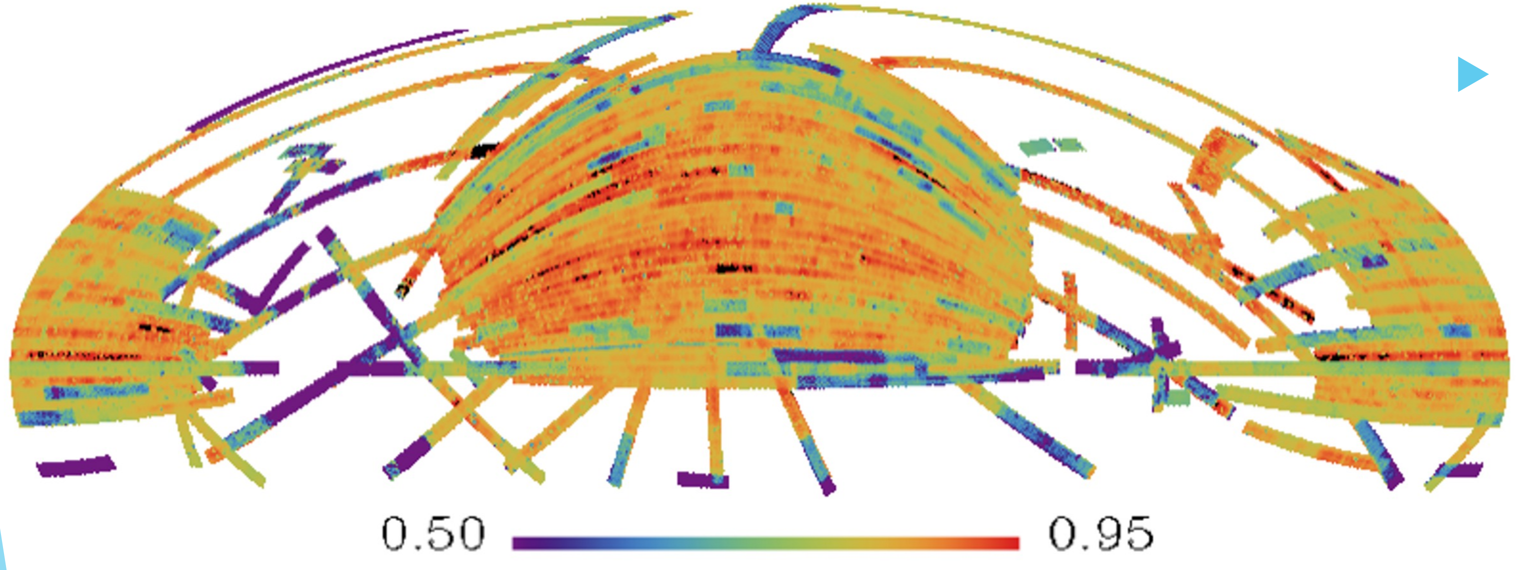
Bautista, Paviot, Vargas, de la Torre 2020



LRG and CMASS radial *selection* function

Control of the observational systematics

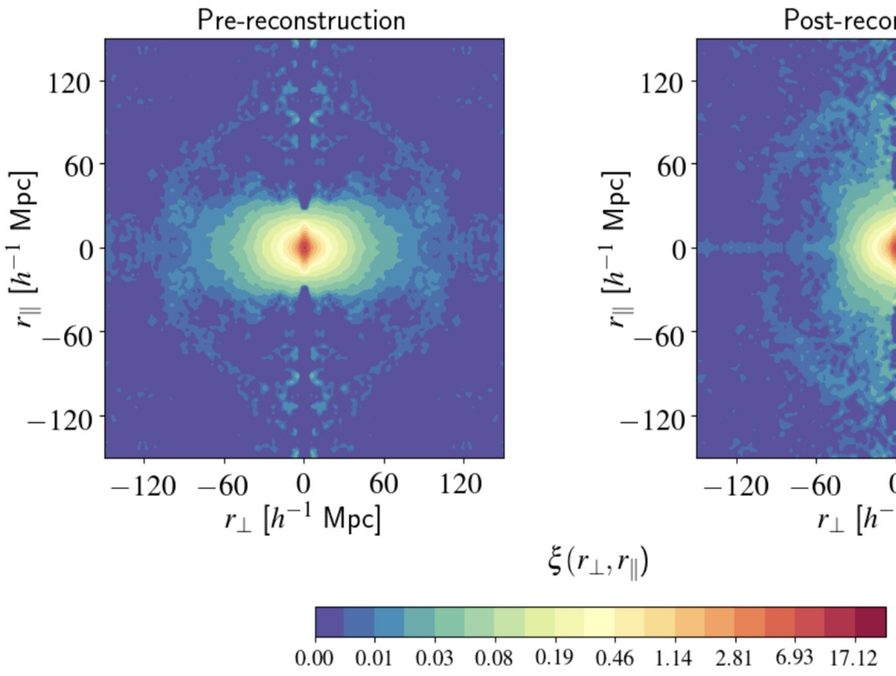
eBOSS spectroscopic sampling



- Three main sources of systematics:
  - Angular fluctuations of the number of targets due to the quality of the imaging
  - Fiber collision (due to the physical size of each fiber)
  - Catastrophic redshift (due to bad redshift determination)

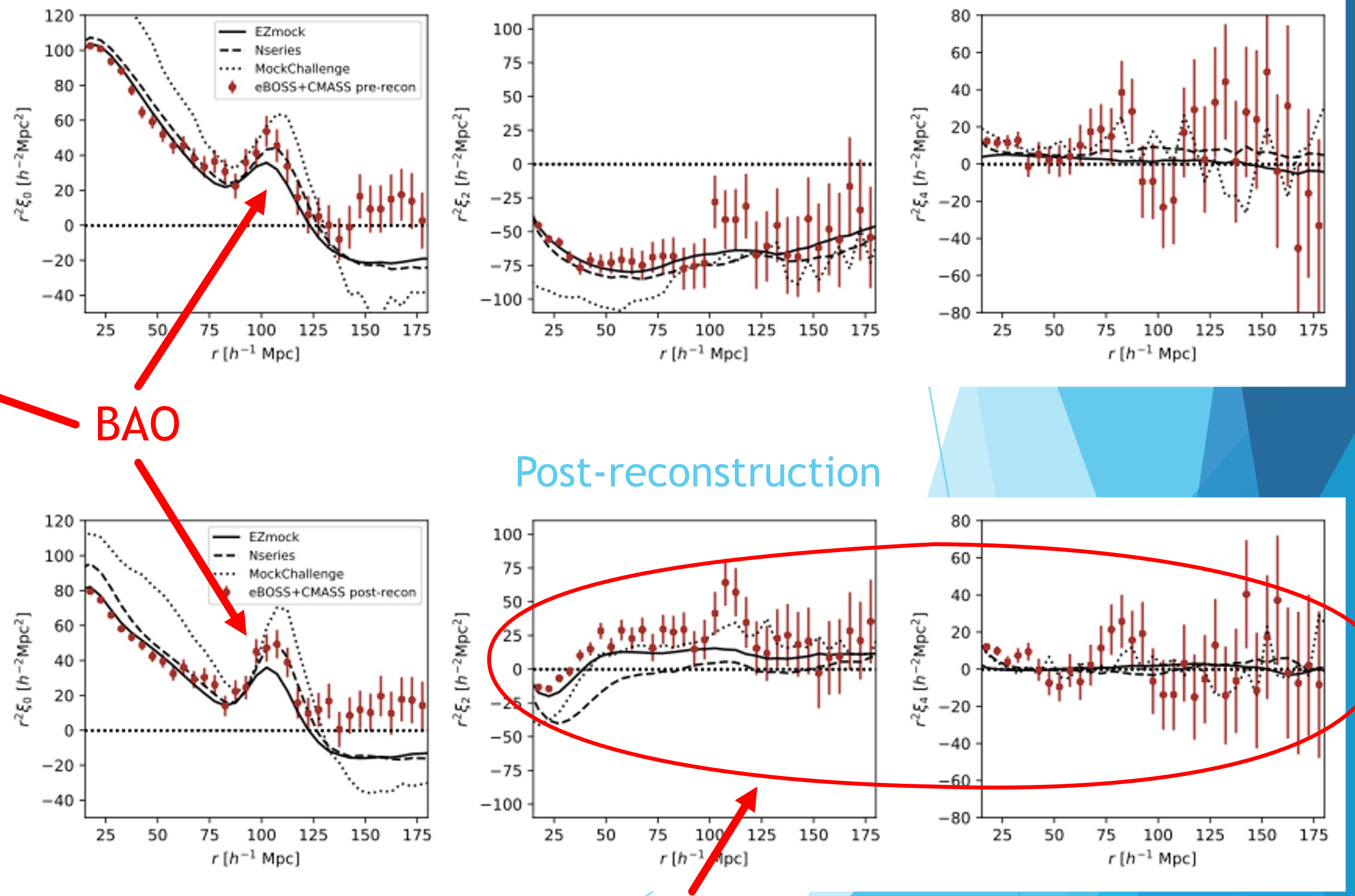
State-of the art: eBOSS survey

- 377 458 LRGs in the range $0.6 < z < 1.0$



Galaxy anisotropic correlation function

Pre-reconstruction



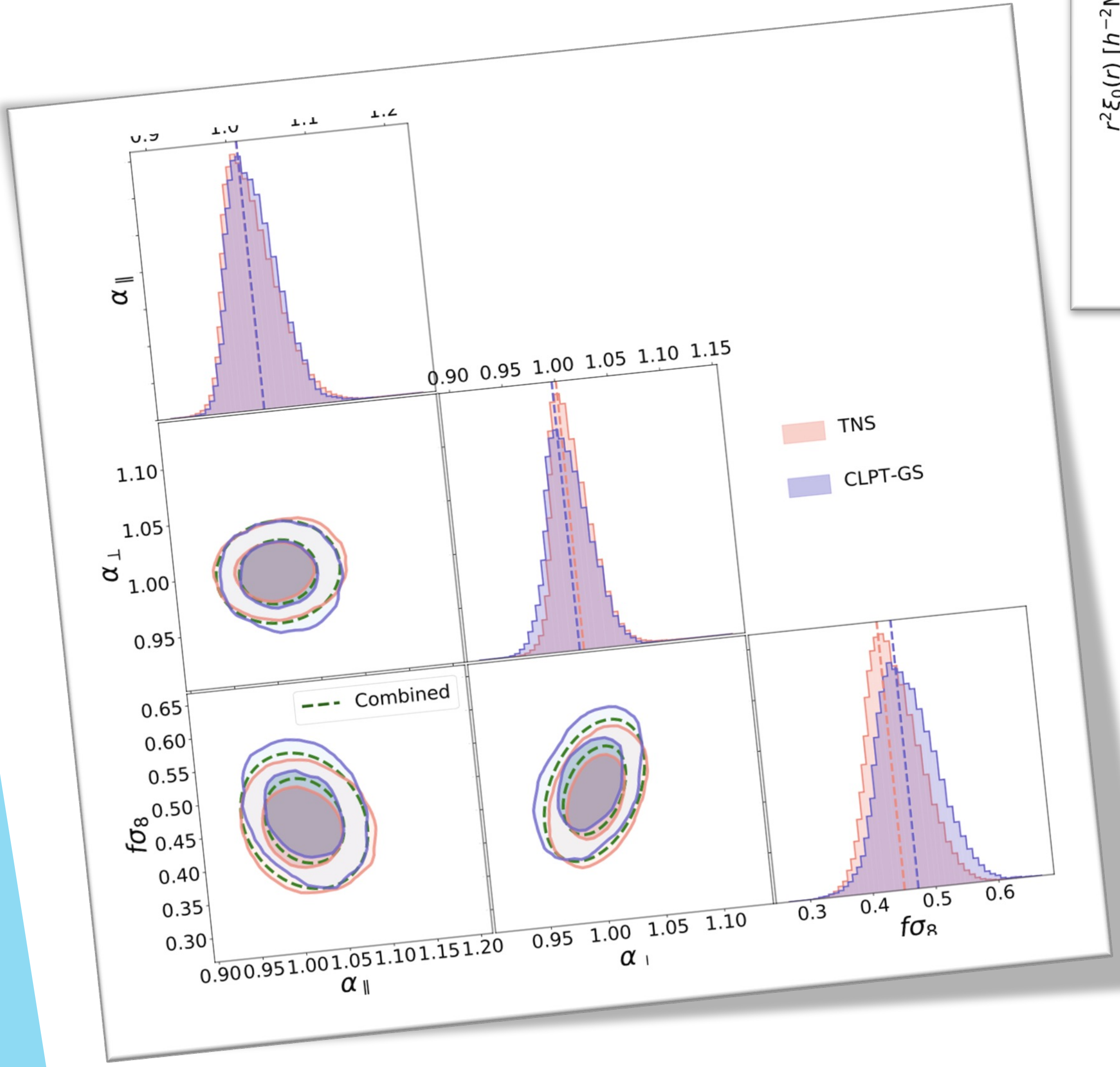
Post-reconstruction

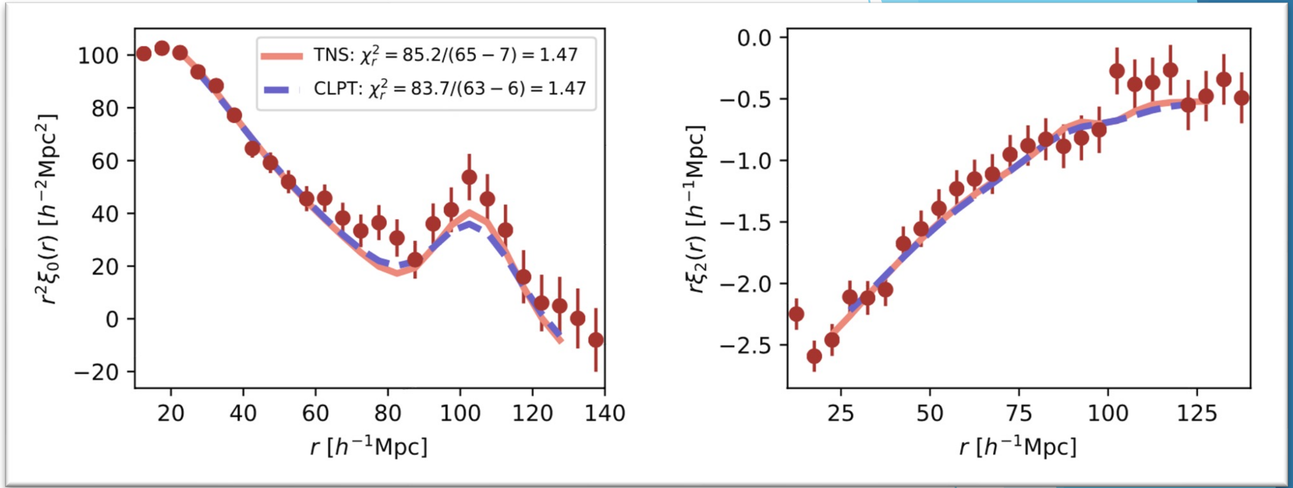
BAO

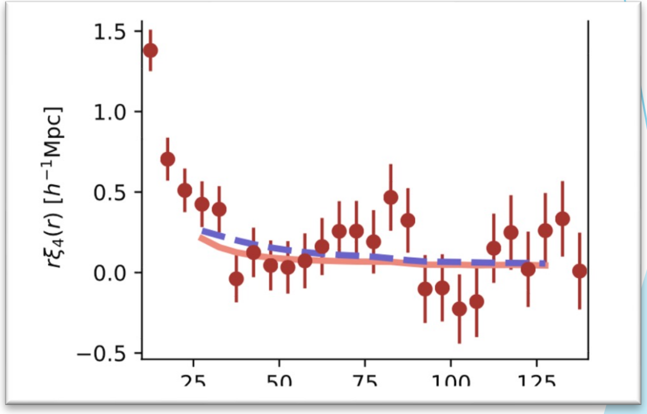
Anisotropy almost removed by reconstructoin

Bautista et al. 2020

RSD measurements







$$\mathbf{D}_{\mathrm{RSD},\xi_\ell} = \begin{pmatrix} D_M/r_d \\ D_H/r_d \\ f\sigma_8 \end{pmatrix} = \begin{pmatrix} 17.42 \pm 0.40 \\ 20.46 \pm 0.70 \\ 0.460 \pm 0.050 \end{pmatrix}$$

Bautista et al. 2020

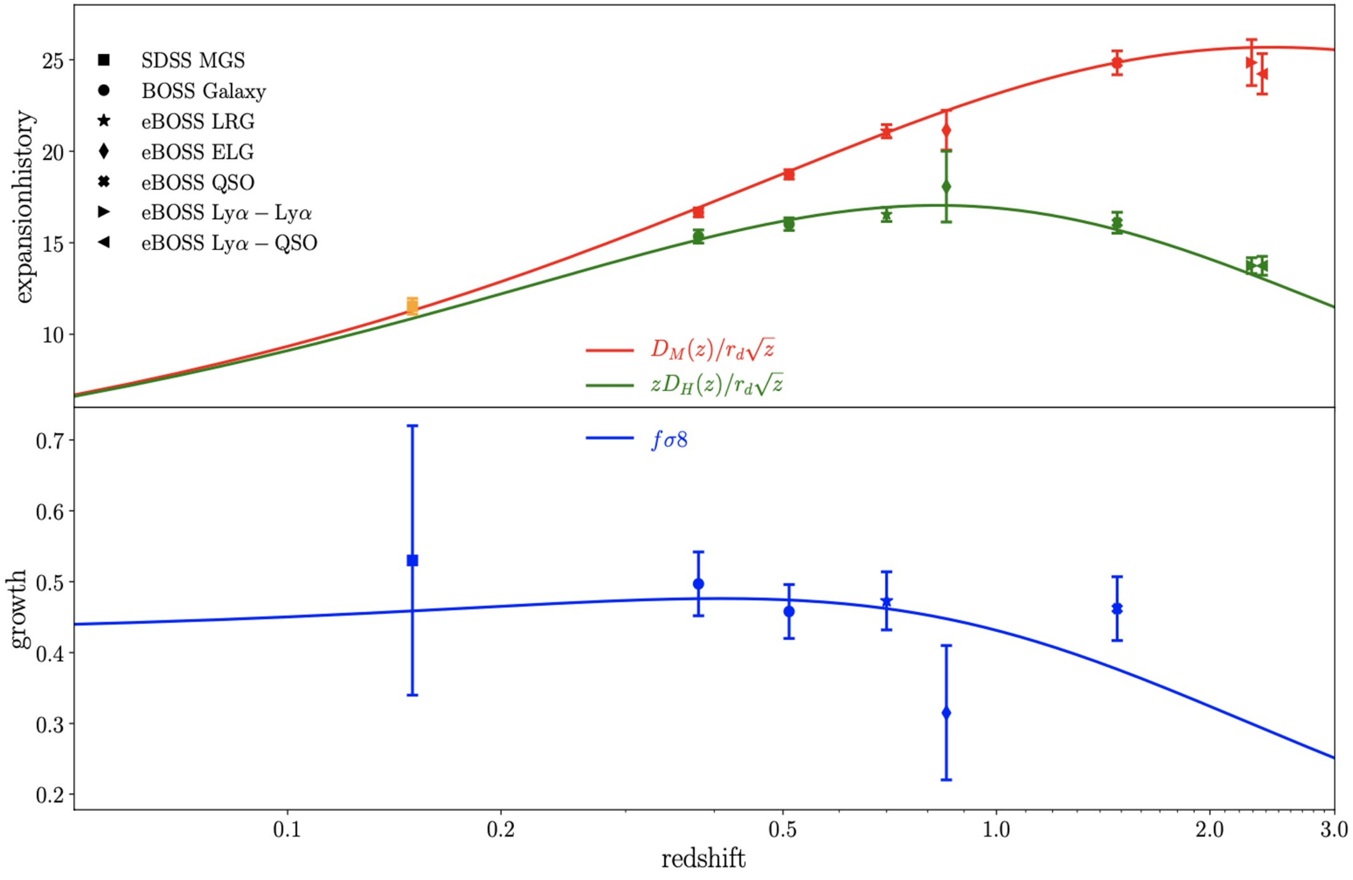
eBOSS Systematic error budget

- For precision cosmology systematic and statistical error need to assessed in great detail
- Total systematic budget :
  - More than 50 % of the statistical error for each parameter
  - Dominated by observational systematics

Type	Model	$\sigma_{\alpha_\perp}$	$\sigma_{\alpha_\parallel}$	$\sigma_{f\sigma_8}$
Modelling	CLPT-GS	0.004	0.009	0.010
	TNS	0.004	0.006	0.009
Fid. cosmology	CLPT-GS	0.009	0.010	0.014
	TNS	0.005	0.008	0.012
Obs. effects	CLPT-GS	0.009	0.012	0.017
	TNS	0.010	0.014	0.018
$\sigma_{\rm syst}$	CLPT-GS	0.013	0.018	0.024
	TNS	0.012	0.017	0.023
	P_ℓ	0.012	0.013	0.024
$\sigma_{\rm stat}$	CLPT-GS	0.020	0.028	0.045
	TNS	0.018	0.031	0.040
	P_ℓ	0.027	0.036	0.042
$\sigma_{\rm syst}/\sigma_{\rm stat}$	CLPT-GS	0.66	0.63	0.54
	TNS	0.65	0.55	0.58
	P_ℓ	0.43	0.37	0.58
$\sigma_{\rm tot} = \sqrt{\sigma^2_{\rm syst} + \sigma^2_{\rm stat}}$	CLPT-GS	0.024	0.033	0.051
	TNS	0.021	0.035	0.046
	P_ℓ	0.029	0.038	0.048

Bautista et al. 2020

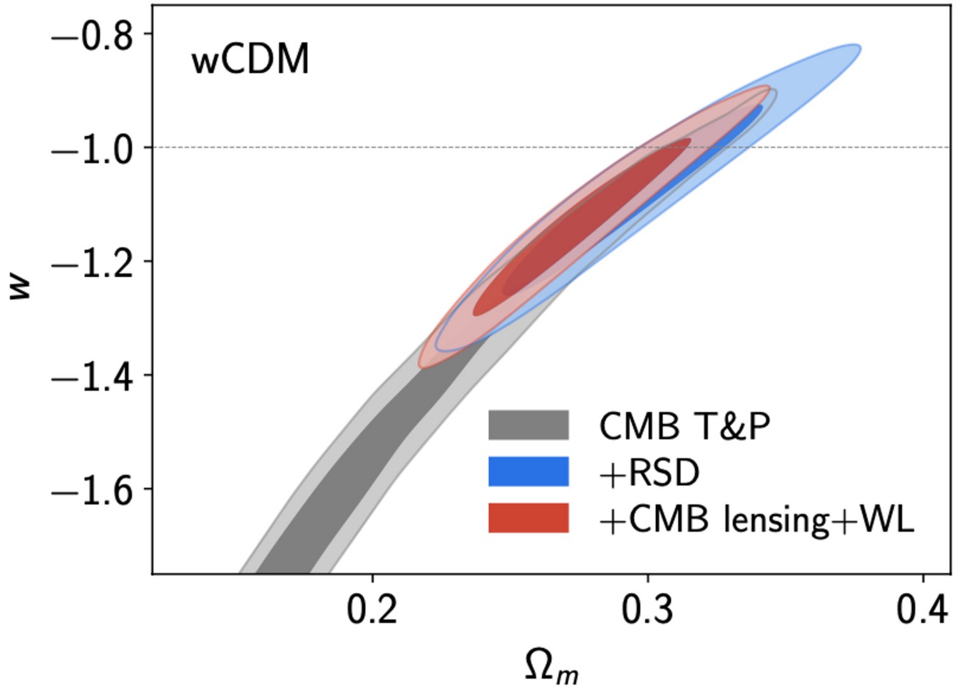
Cosmological implication of 20 years of SDSS

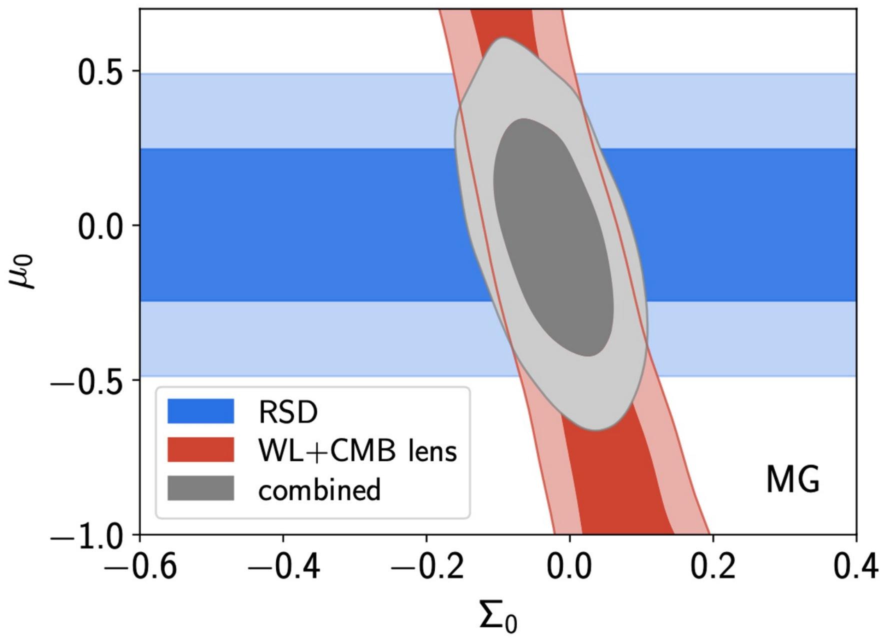


eBOSS collaboration 2021

- 7 independents measurements of expansion rate history
- 6 independents measurements on the growth rate of structure
- By combining geometrical and growth of structure measurements for 20 years of SDSS survey, obtain most precise measurement of expansion and growth history to date

Cosmological implication on gravity/DE





$$k^2\Phi = -4\pi G a^2 (1+\mu)\bar{\rho}\delta$$
$$k^2(\Phi+\Psi) = -8\pi G a^2 (1+\Sigma)\bar{\rho}\delta$$

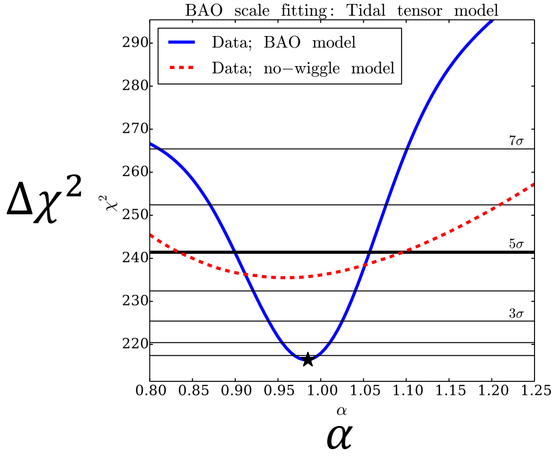
$$w = -1.09 \pm 0.11$$

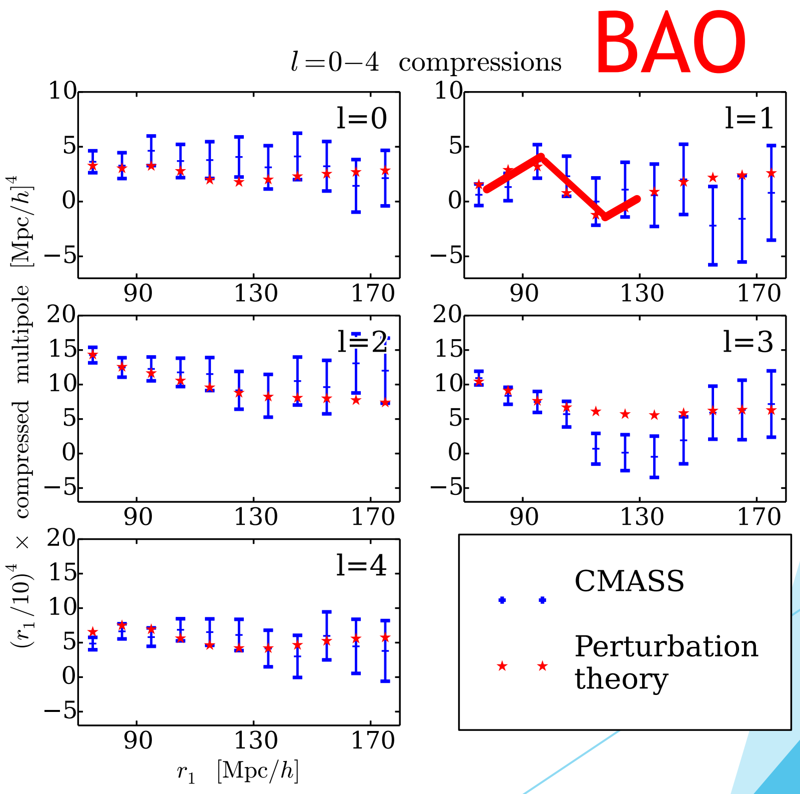
$$\mu_0 = 0.04 \pm 0.25,\ \Sigma_0 = 0.024 \pm 0.054$$

- Observations compatible with the standard model: General Relativity + cosmological constant
- No detection of (parametric) modification to General Relativity prediction

Three-point statistics

- Can we go beyond two-point statistics to probe cosmology?
- BAO feature 4.5σ detection in the 3-point correlation function



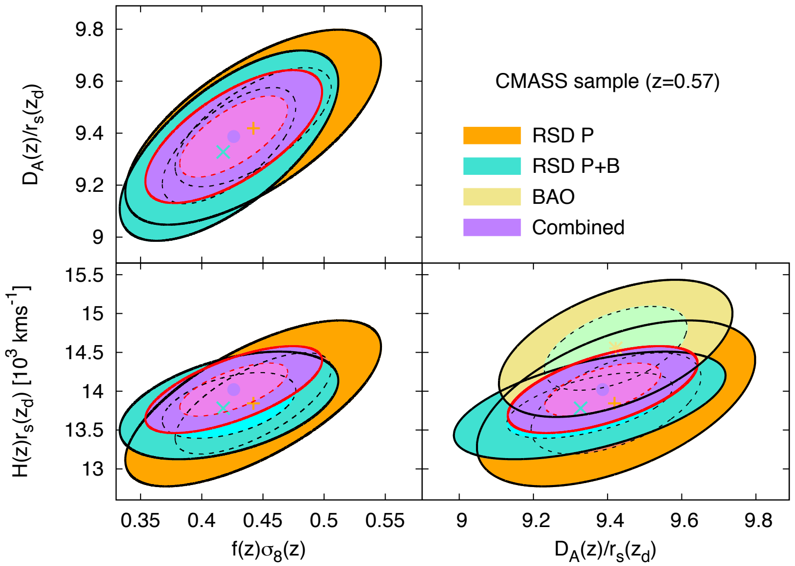


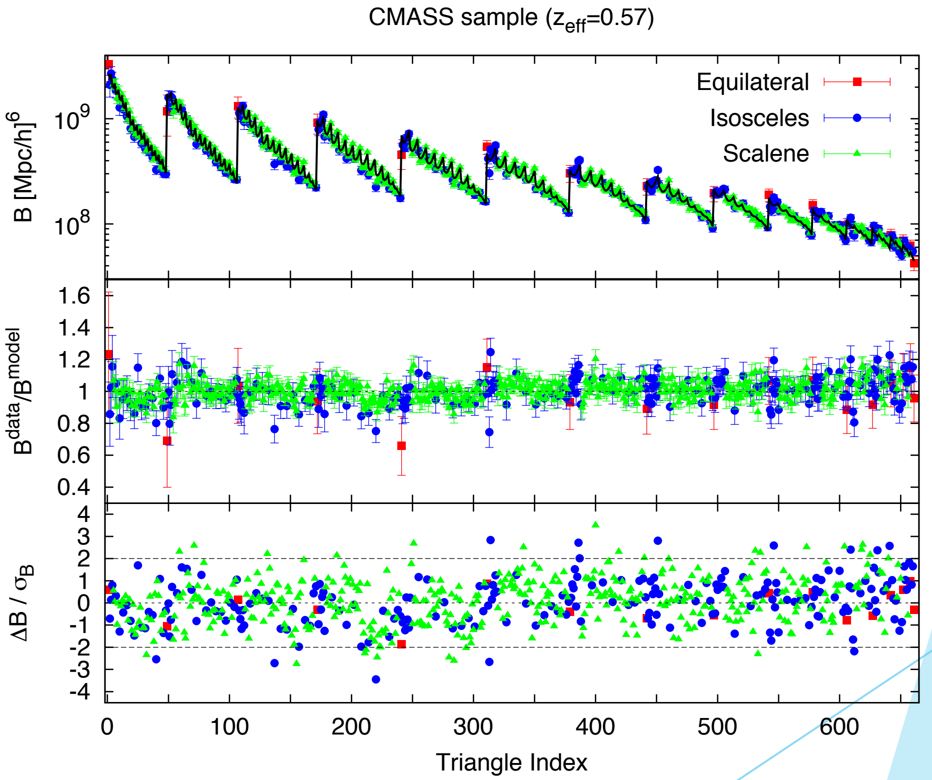
$$B_s(k_1,k_2,x) = b_1^3 P(k_1)P(k_2)\Big[\tilde{F}_2(k_1,k_2;x)\mathcal{D}_{SQ1}(\beta,x) + \tilde{G}_2(k_1,k_2;x)\mathcal{D}_{SQ2}(\beta,k_1,k_2;x) + \mathcal{D}_{NLB}(\beta,\gamma;x) + \mathcal{D}_{FOG}(\beta,k_1,k_2;x)\Big] + \text{cyc.},$$

Slepian et al., 2016, 2017

Combining two- and three-point statistics

- Adding Bispectrum improves cosmological constraints

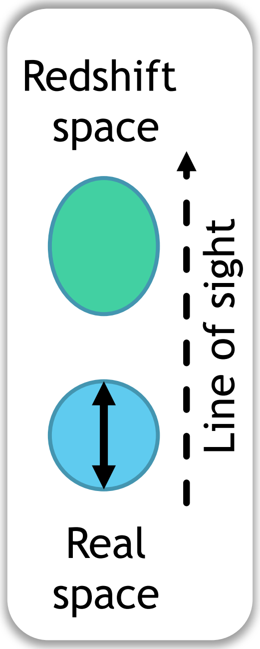


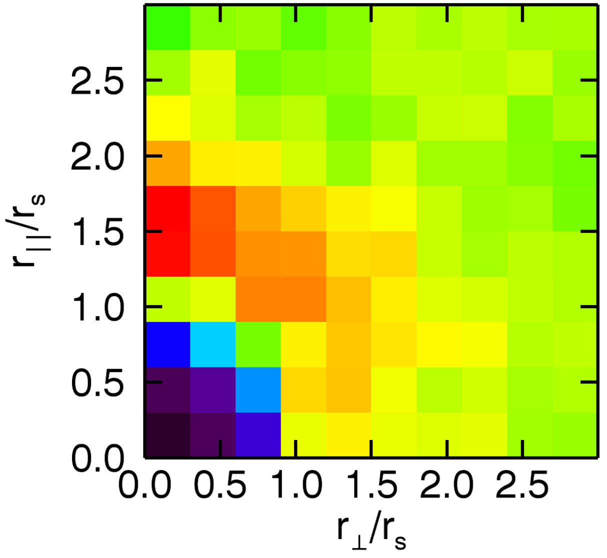


Gil-Marin et al. 2017

Cross-correlation galaxy-void

- Cosmic voids are interesting objects, to some extent simpler to model (linear)
- Used for RSD and Alcock-Pazcynski test

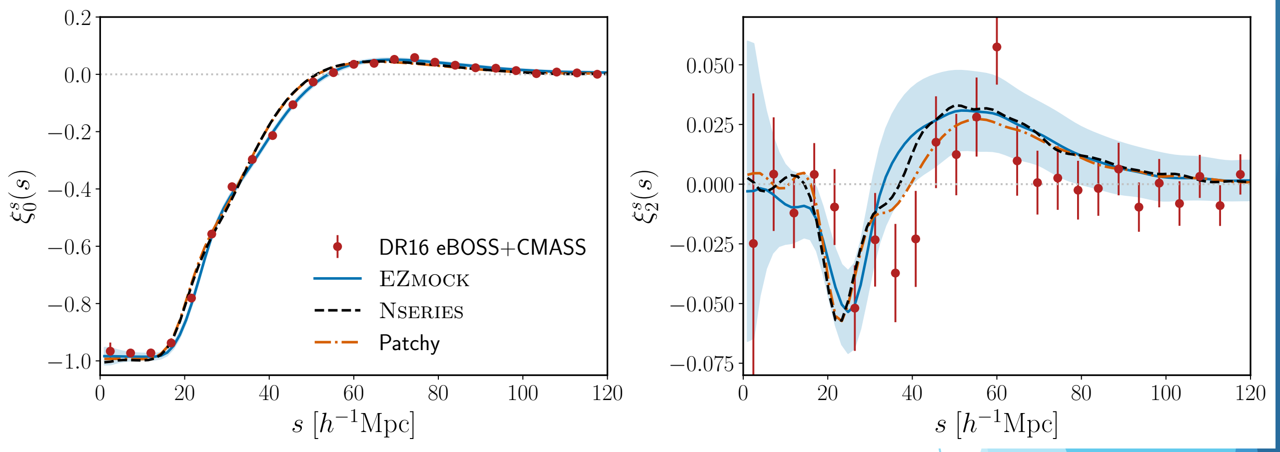


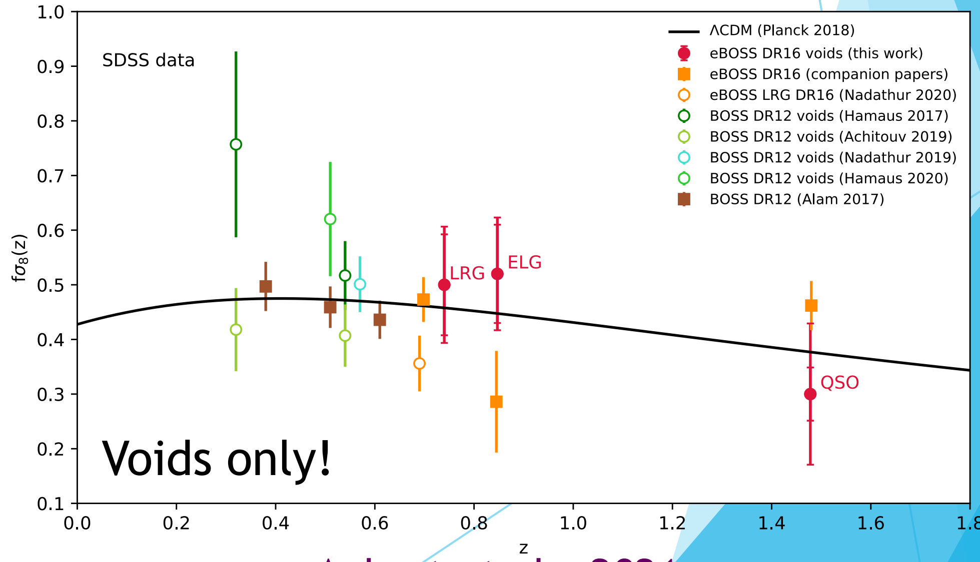


Hawken et al., 2017

Anisotropic galaxy-void CCF

Nadathur et al. 2021

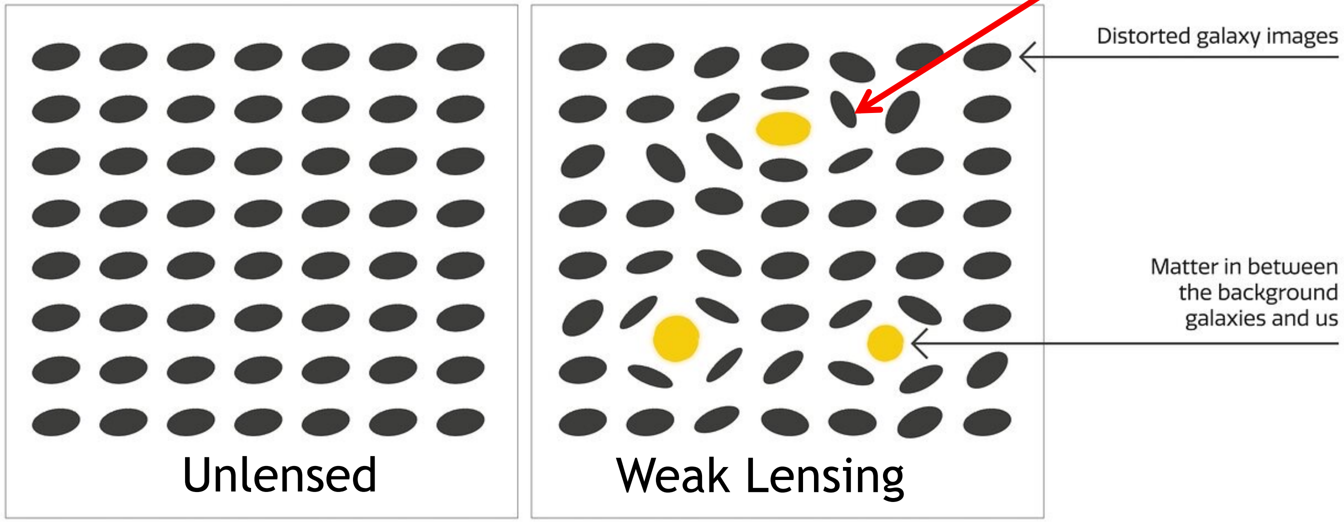


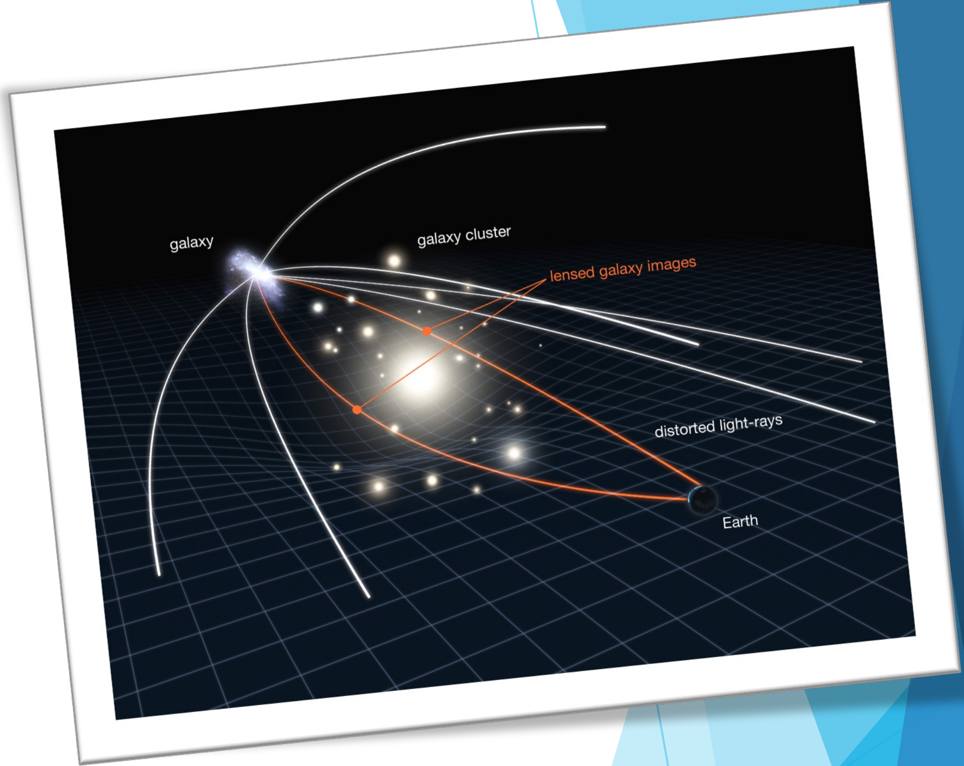


Aubert et al., 2021

Galaxy-galaxy lensing

Tangential shear γ_t



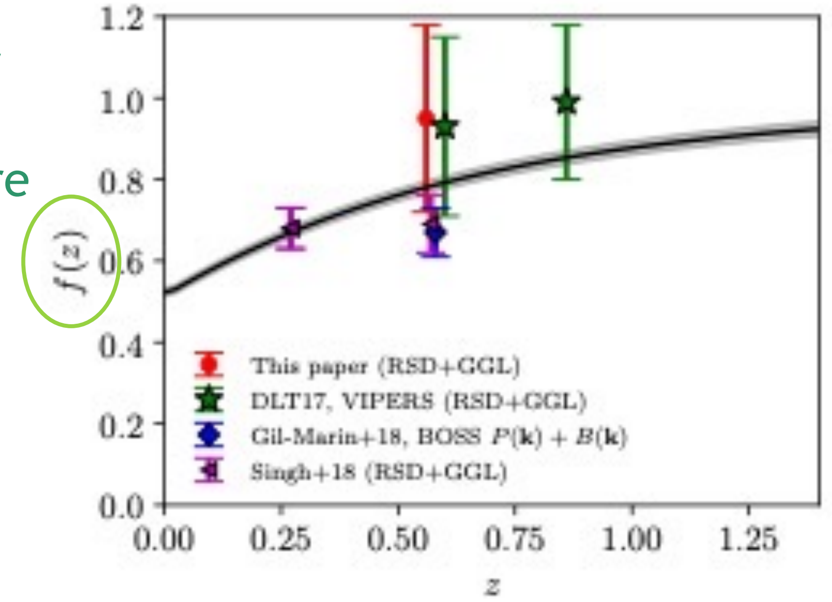


Cross-correlation between background galaxies **shear** and foreground galaxies **position**

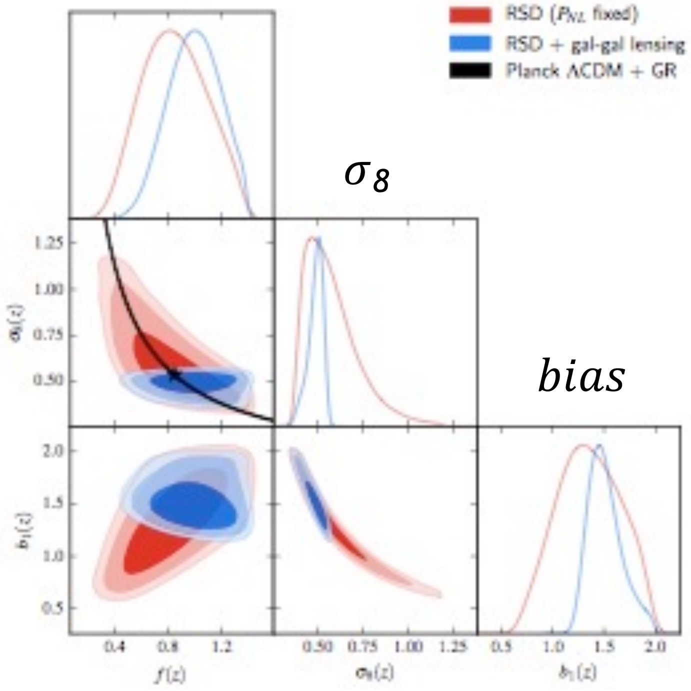
$$\langle \gamma_t(\theta) \rangle = \langle \delta_g(\phi, z_1) \gamma_t(\phi + \theta, z_2) \rangle$$

RSD and galaxy-galaxy lensing

Directly probing structure growth

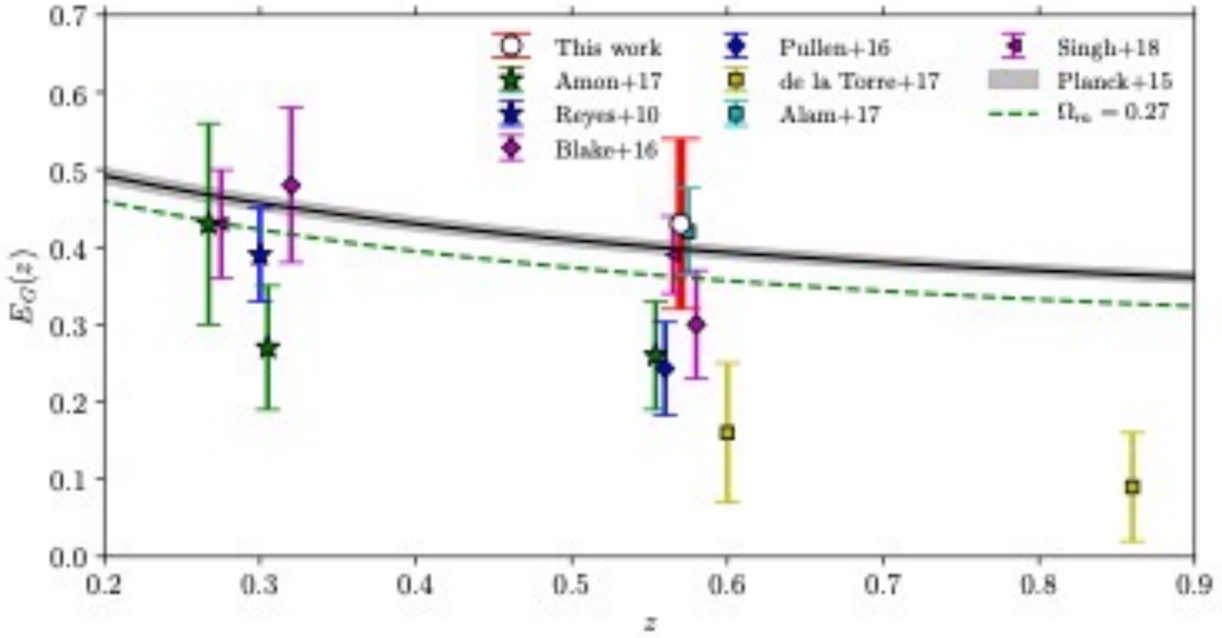


- Weak lensing and galaxy clustering allows breaking the classical f-σ_8-b degeneracy in GC



de la Torre et al. 2017

RSD and galaxy-galaxy lensing



Jullo, de la Torre et al., 2019

$$E_G \equiv \frac{\nabla^2(\psi - \phi)}{3H_0^2 a^{-1} \beta\delta} = \frac{1}{\beta}\frac{\Upsilon_{gm}}{\Upsilon_{gg}} \propto \frac{b}{f}\frac{\Omega_{M0}}{b} \approx \frac{\Omega_{M0}}{f}$$

- An alternative test of gravity related to the **gravitational slip parameter**
- Independent of galaxy bias

Euclid: a space mission to solve dark energy

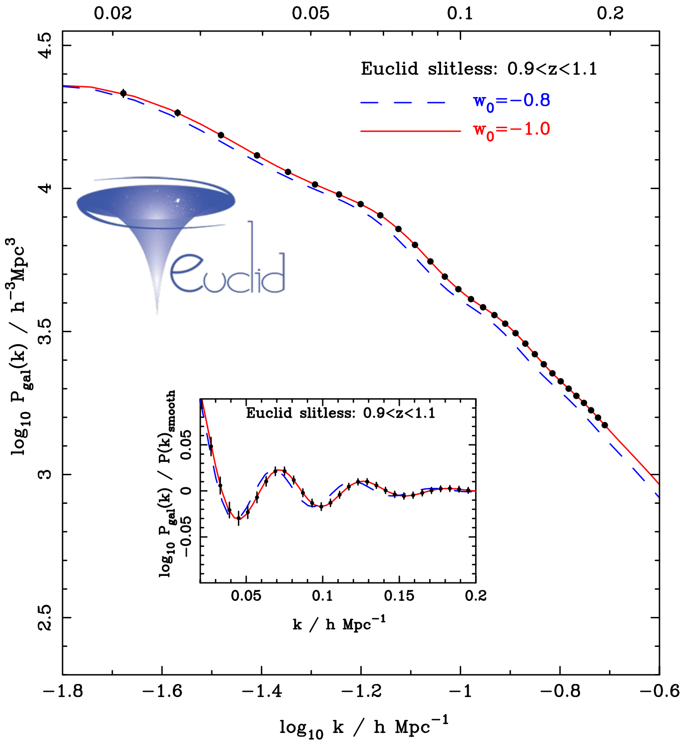
Euclid Satellite: end of assembly in Turin in July 2022

- Euclid is an ESA space mission aiming at:
  - 3D mapping of 50 million galaxies over 15,000 deg2 wih slitless spectroscopy in space
  - A survey of the shapes of over 2 billion galaxies on the same surface
- The aim is to trace the structure of the Universe, both visible (galaxies) and invisible (dark matter), to understand the nature of dark energy

Euclid mission

- Next-generation galaxy surveys designed to extract most of the cosmological information: large probed volumes, sufficiently high galaxy/quasars sampling rate, multitracer, multiprobe…

Galaxy power spectrum



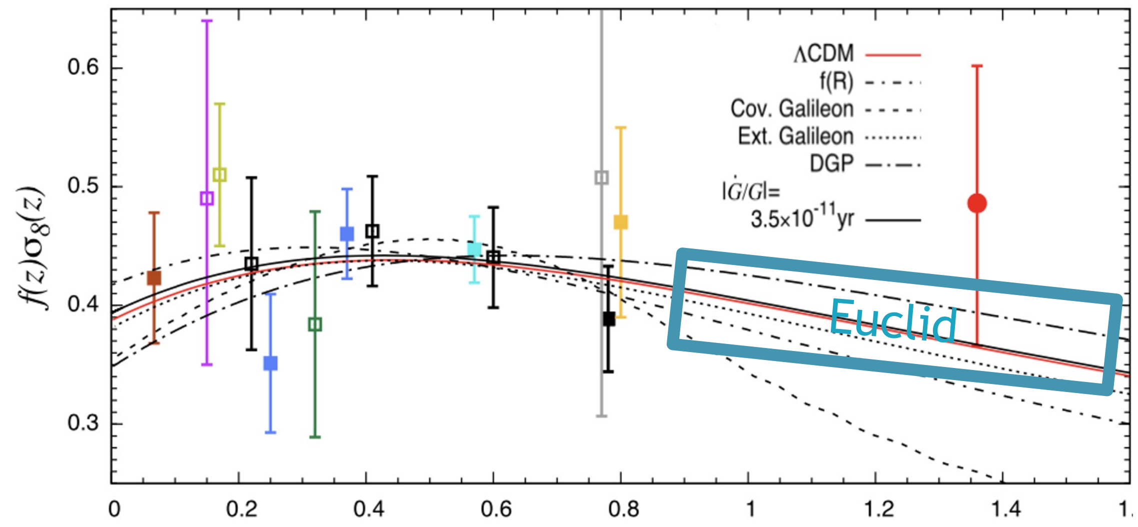
With Euclid (& DESI) we expect:

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

→ Crucial to solve the Dark Energy problem

Euclid will use weak lensing and galaxy clustering to measure the expansion history of the Universe, the dark energy equation of state, and the growth rate of structure to within typically one percent accuracy

Euclid mission

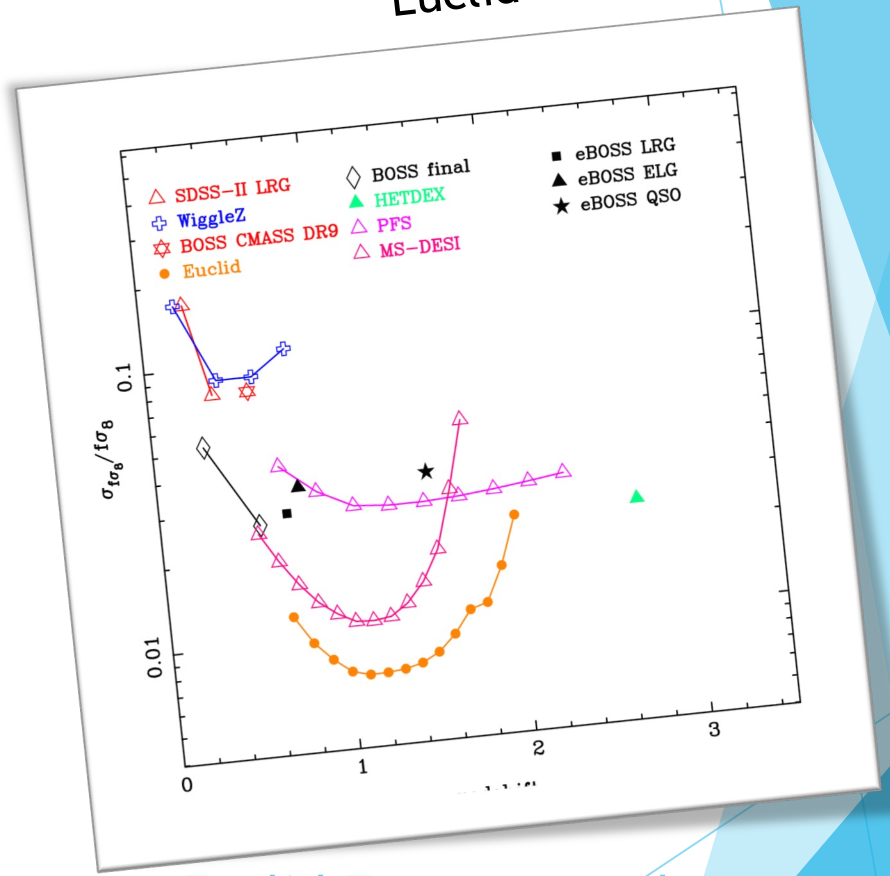


Ishak et al, 2018

Growth of structure / gravity

- **Euclid** will allow testing gravity and cosmology beyond standard model, e.g. be sensitive to modified gravity or DE models

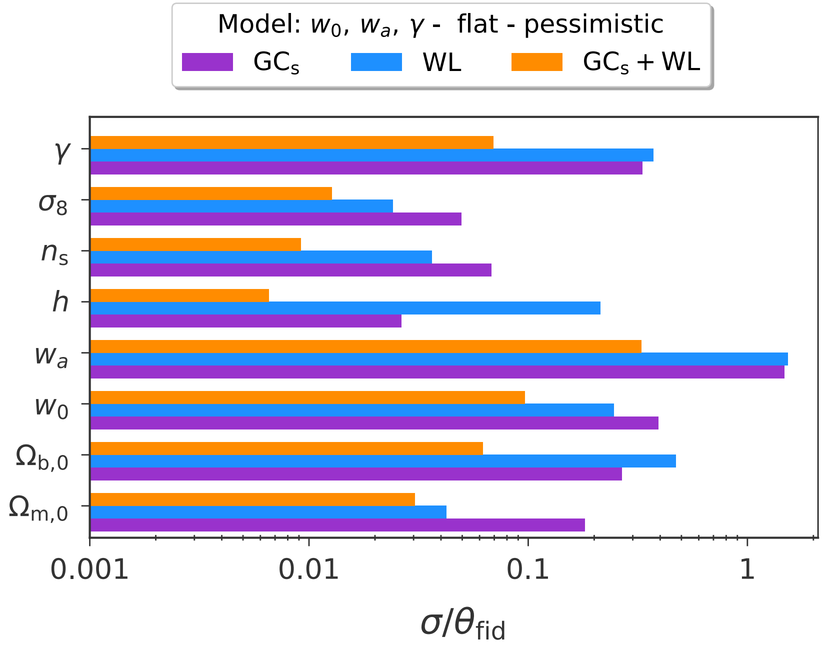
Euclid Consortium

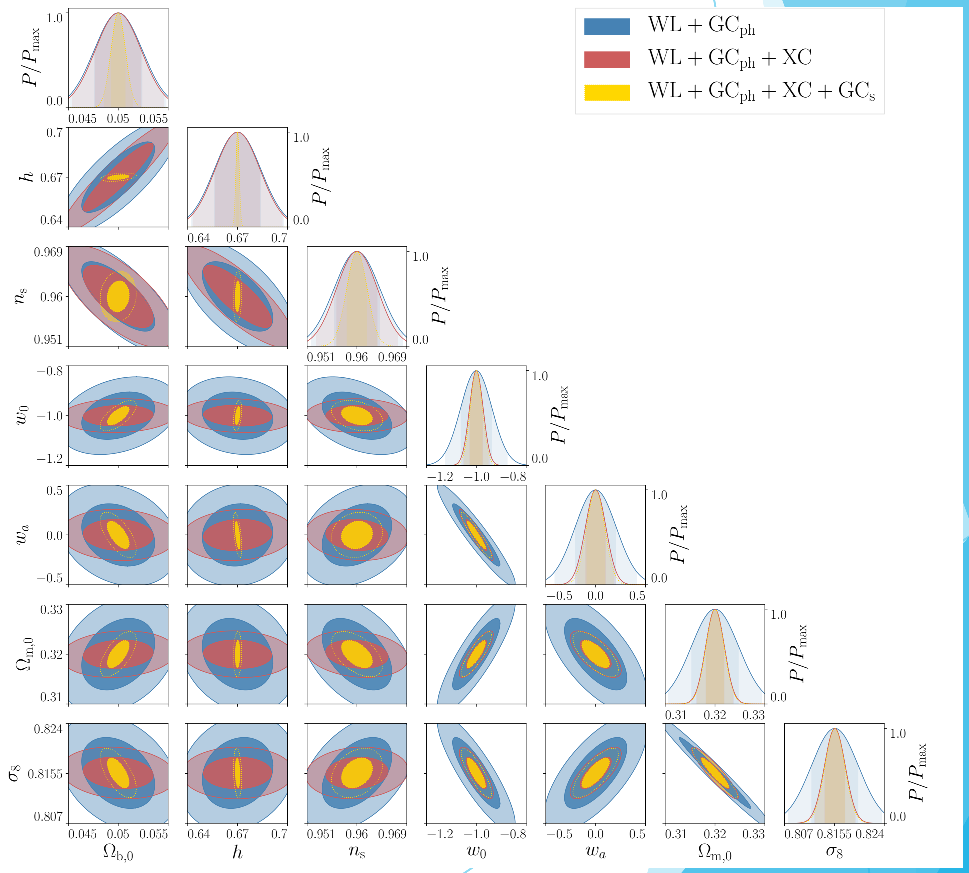


Euclid Forecast on the growth of structure

Euclid era cosmology: combinations & cross-correlations

- Combination of galaxy clustering and weak lensing significantly increases the FoM
- Impact of cross-correlations is particularly relevant for models beyond a cosmological constant

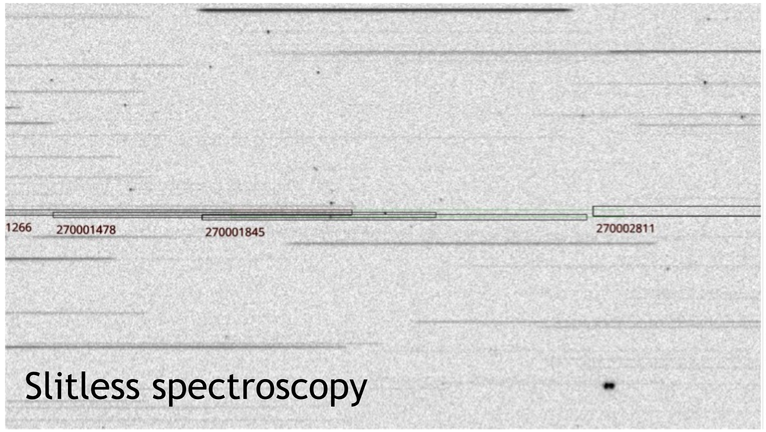


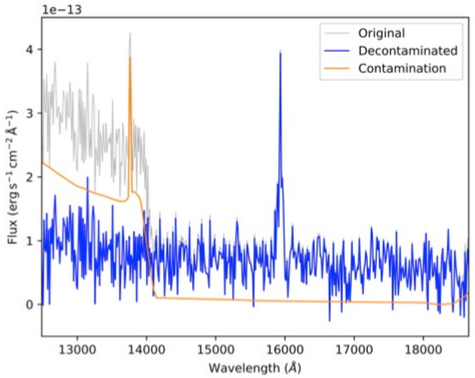


Euclid Collaboration 2021

Challenges

- **Control systematics** to extremely small level: e.g. non-linear modelling, observational effects (slitless spectroscopy), second-order effects usually neglected (magnification, IA, relativistic effects, baryons)





- Combine LSS probe and tracers in a consistent way : covariances, systematic error assessment, etc.

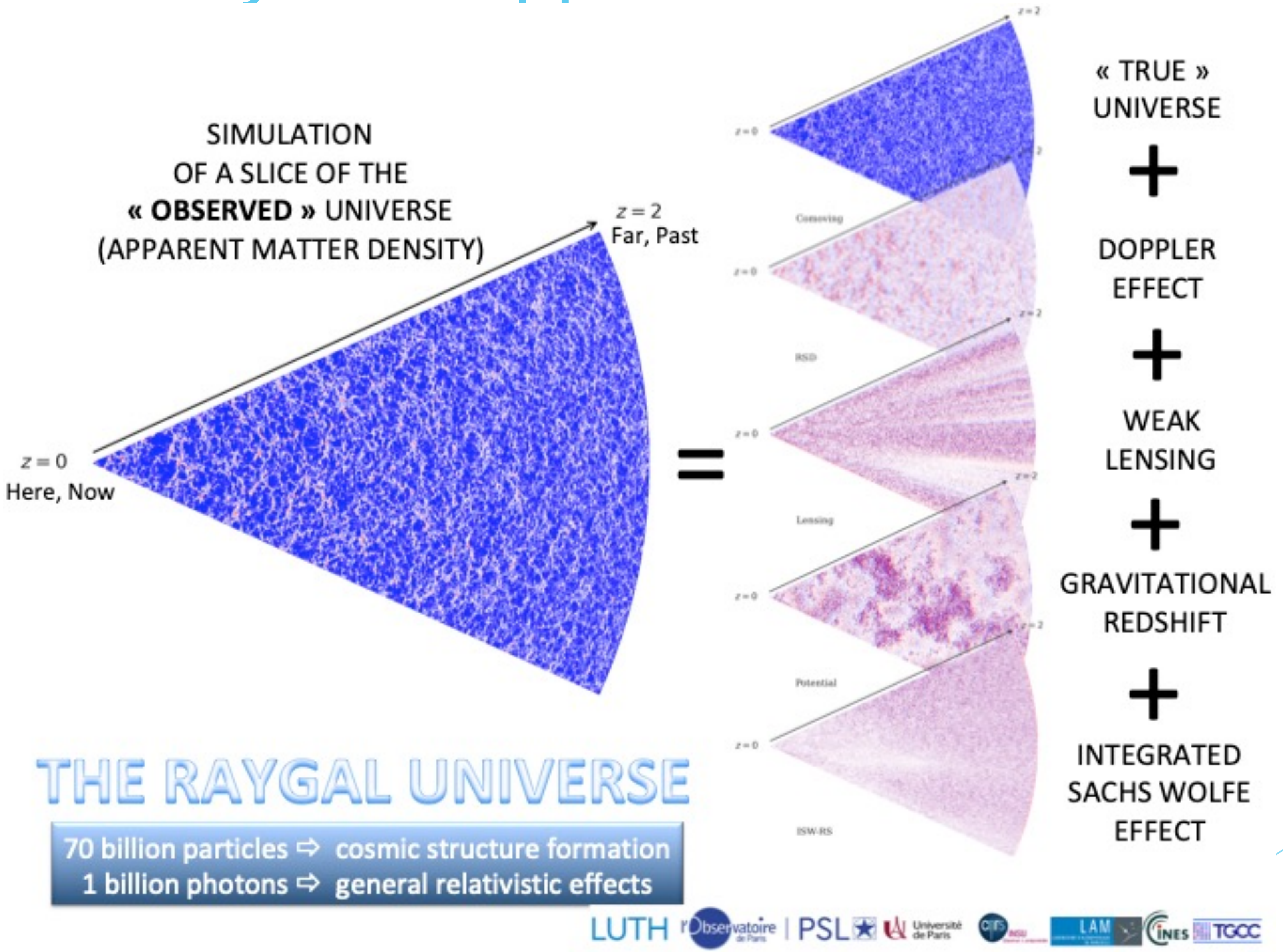
Precision cosmology with galaxy clustering

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?

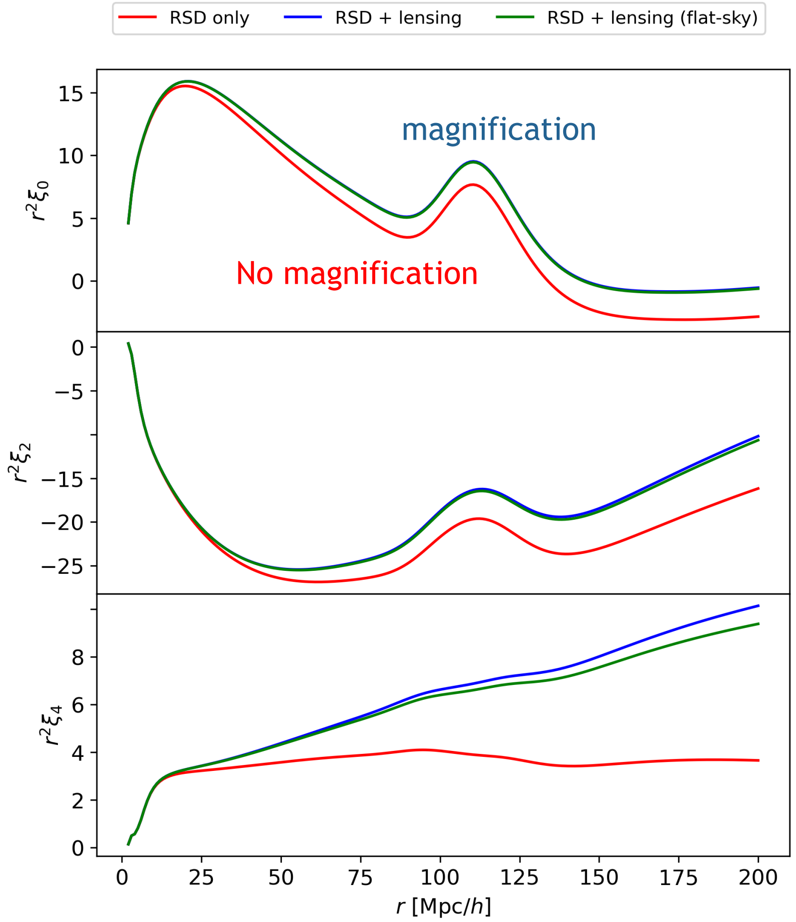
- Galaxy clustering cosmology is mature but still, methods need further refinement to reach the exquisite statistical accuracy provided by next-generation cosmological surveys

RSD beyond Doppler



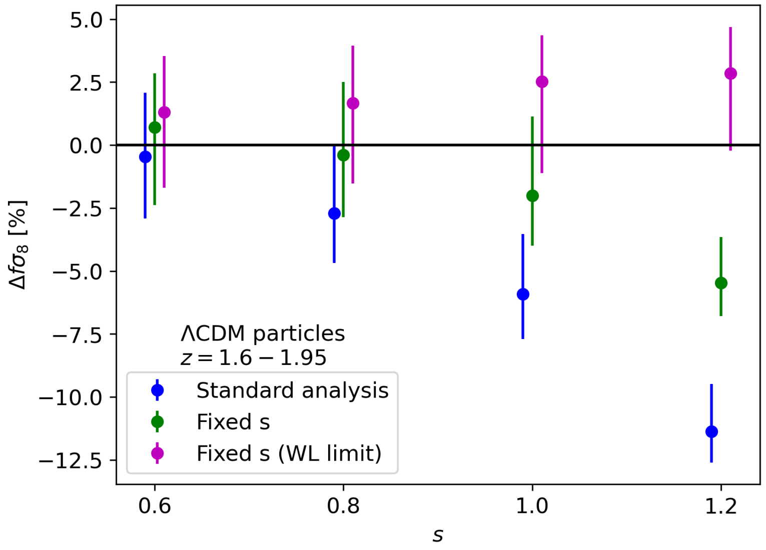
Impact of magnification on RSD

Correlation function multipoles



Breton, de la Torre 2022

- Impact in the worst case mostly on large scales, but anisotropic
- Generally, linear correction is good enough for galaxy clustering



- Weak lensing limit may break down for some cases (high redshift and s)

Conclusion

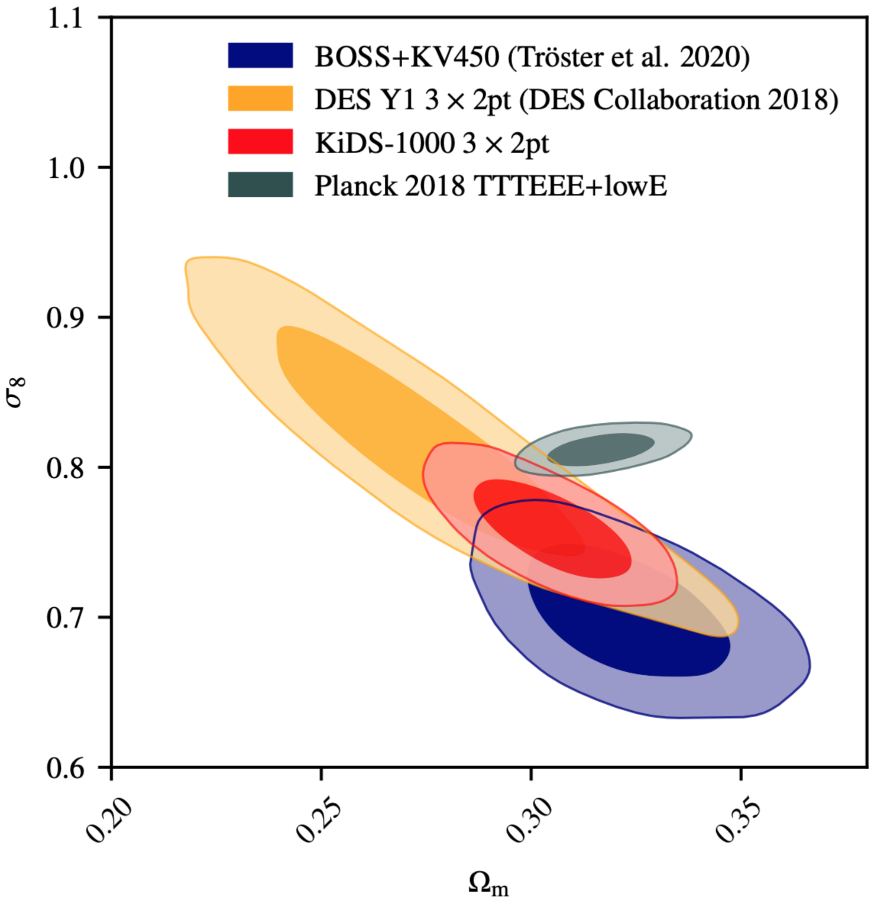
- Understanding gravity on cosmological scales is key to understand Dark Energy and cosmic acceleration
- LSS observations from galaxy and lensing survey are crucial to get insights on the strength of gravity through the characterization of the growth of structure
- Future large spectroscopic+lensing surveys such as DESI and Euclid will allow to make a big step towads understaning gravity on cosmological scales and cosmology
- Galaxy clustering and lensing observables are interconnected, and be efficiently combined to improved constraints constraints
- Importance of controling systematic errors in surveys at exquisite level to achieve this goal

Cosmological tensions: S_8

- Discrepancies between CMB and weak-lensing constraints on S_8:

$$S_8 \equiv \sigma_8 \sqrt{\Omega_m / 0.3}$$

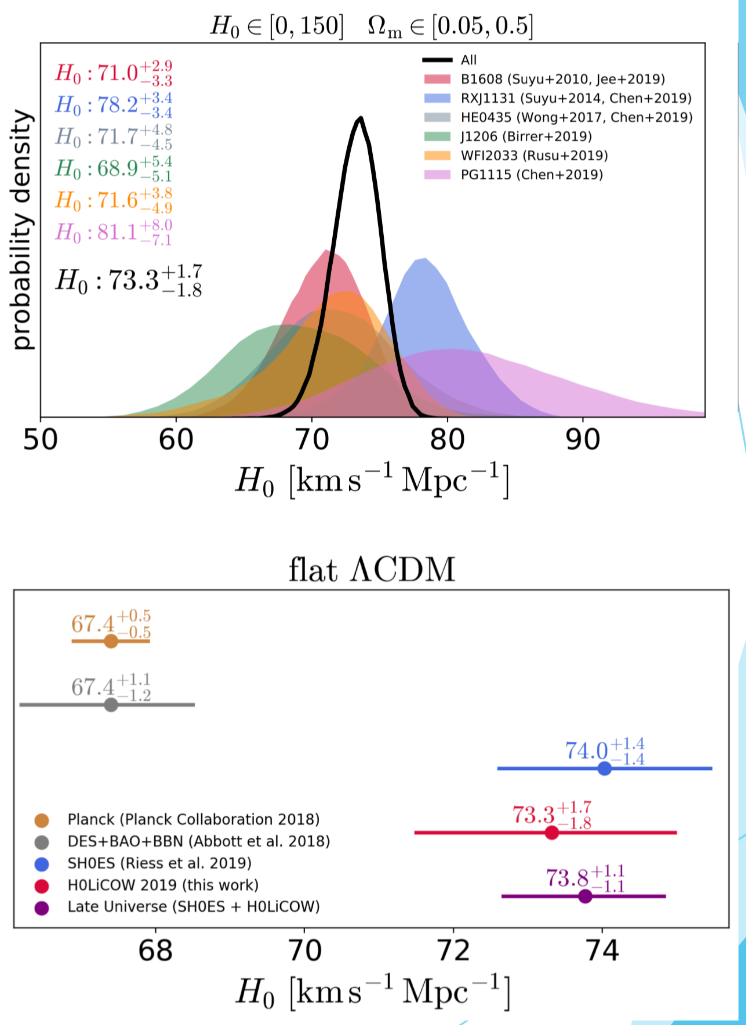
- The S8 tension is at about 2.6σ level between the Planck data in the ΛCDM scenario and KiDS survey
- Mainly driven by σ_8, which is lower in lensing analyses



Heymans et al. 2020

Cosmological tensions: H_0

- 3-4σ discrepancy beteween Planck/LSS contraints and local direct measurements from SN1a/cepheids
- In the CMB, constraints are obtained by assuming a cosmological model and are therefore model dependent
- Planck constraints change when modifying the assumptions of the underlying cosmological model
- Local distance ladder measurements based on the combination of different geometric distance calibrations of cepheids



Relativistic effects

- Apparent comoving position of a source:

$$\boldsymbol{s} = \chi \boldsymbol{n} + \frac{c}{H}\delta z \boldsymbol{n} - \boldsymbol{n}\int_0^{\chi} (\phi + \psi)/c^2 \mathrm{d}\chi' - \int_0^{\chi} (\chi - \chi')\nabla_{\perp}(\phi + \psi)/c^2 \mathrm{d}\chi'$$

Redshift perturbations   Shapiro effect   Transverse lensing

- Redshift perturbations:

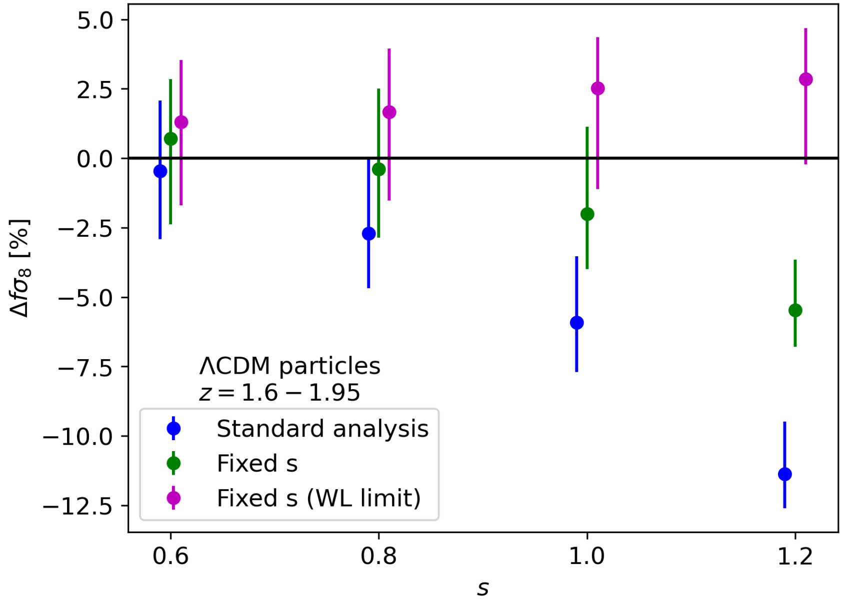
$$\delta z = \frac{a_0}{a}\left\{\frac{\boldsymbol{v}\cdot\boldsymbol{n}}{c} - \frac{(\psi - \psi_0)}{c^2} + \frac{1}{2}\left(\frac{v}{c}\right)^2 - \frac{1}{c^2}\int_{\eta}^{\eta_0} \frac{\partial(\phi + \psi)}{\partial \eta}\mathrm{d}\eta'\right\}$$

Doppler   Gravitational redshift (transverse Doppler…)   …

- Effects usually neglegted, but detectable with next-generation surveys such as Euclid or DESI

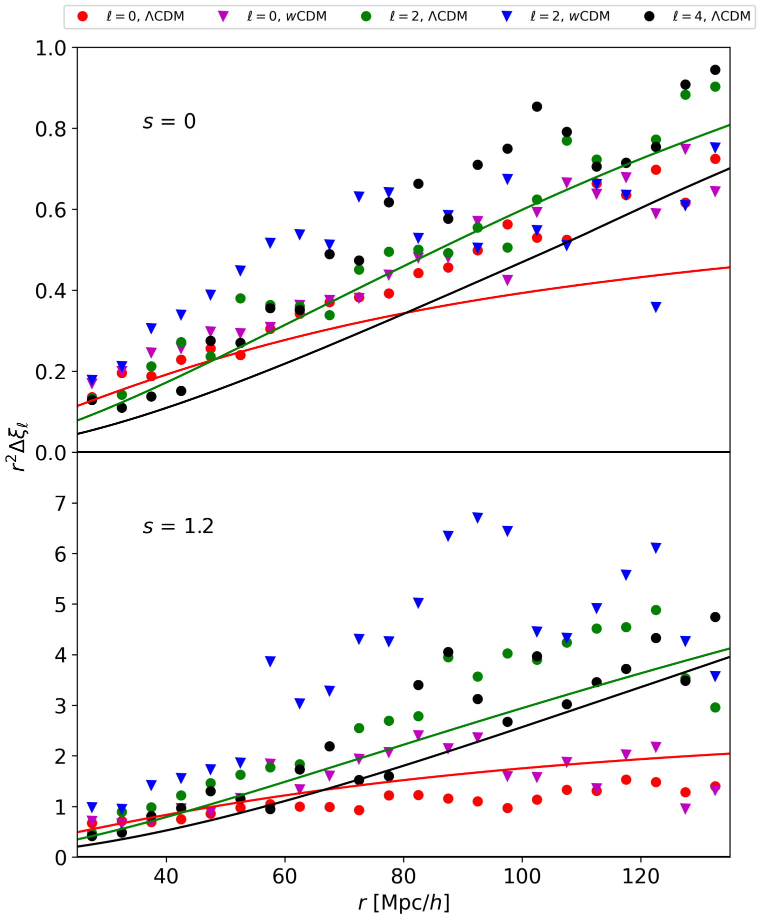
Magnification correction

- Generally, linear correction is good enough for galaxy clustering



- Weak lensing limit may break down for some cases (high redshift and s)

Linear predictions vs simulation



Breton, de la Torre 2022