Cosmology review

Sylvain de la Torre

Conference « From galaxies to cosmology, tribute to Olivier Le Fèvre»

July 4th 2022, Palais des arts, Marseille

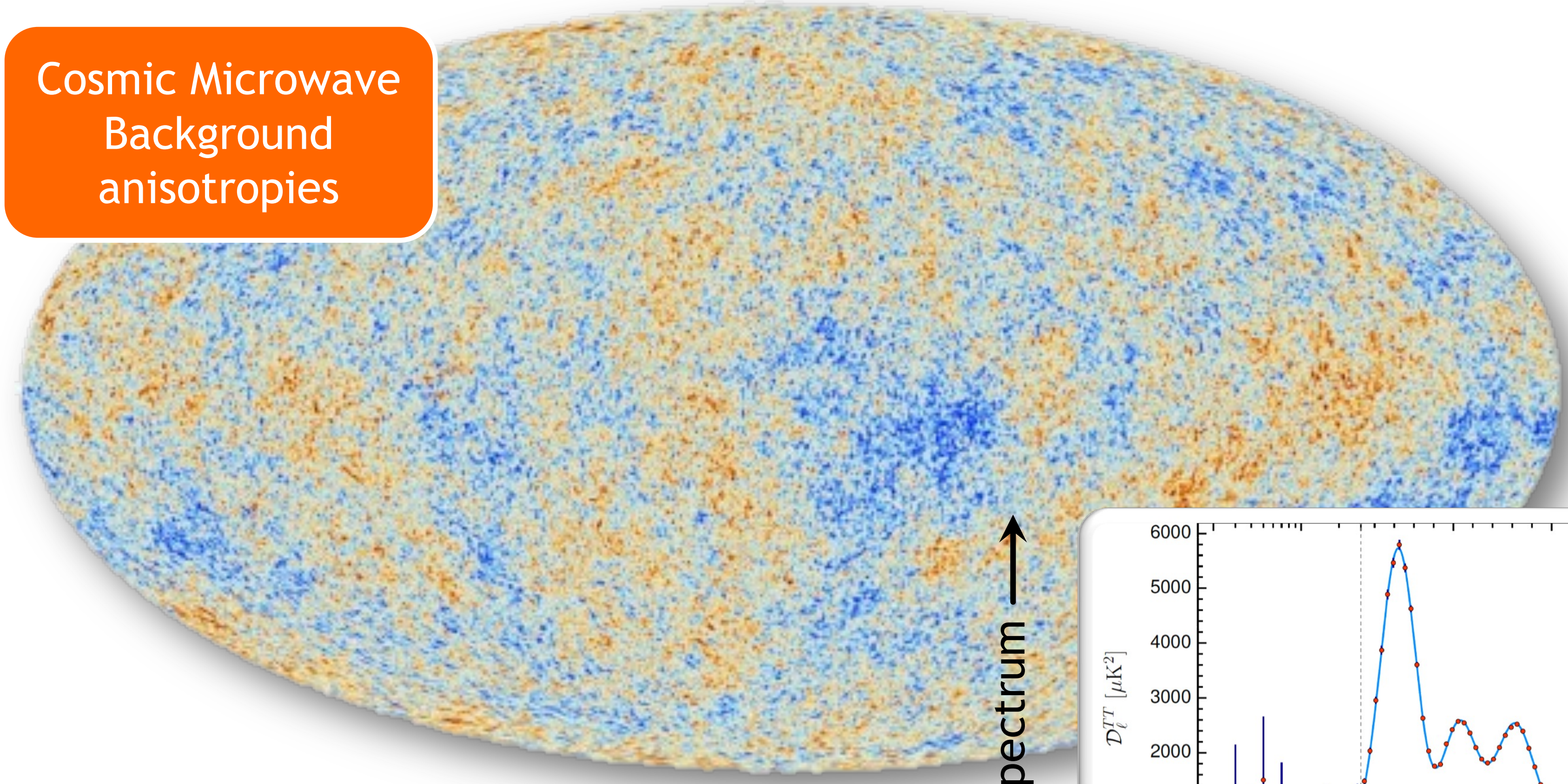
Credits pictures: Marco Scodeggio

Outline

1. Standard cosmological model
2. Cosmic acceleration & dark energy
3. Galaxy redshift survey cosmology
4. Euclid mission
5. Conclusion

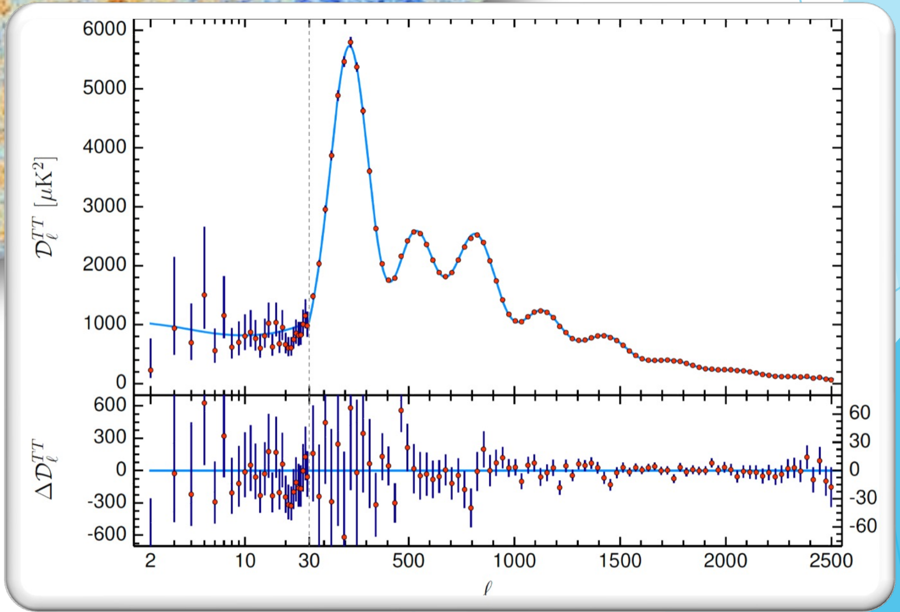
Cosmological probe: CMB

Cosmic Microwave Background anisotropies



- → Probe primordial matter fluctuations
- → Most precise matter power spectrum measurement

Angular power spectrum →

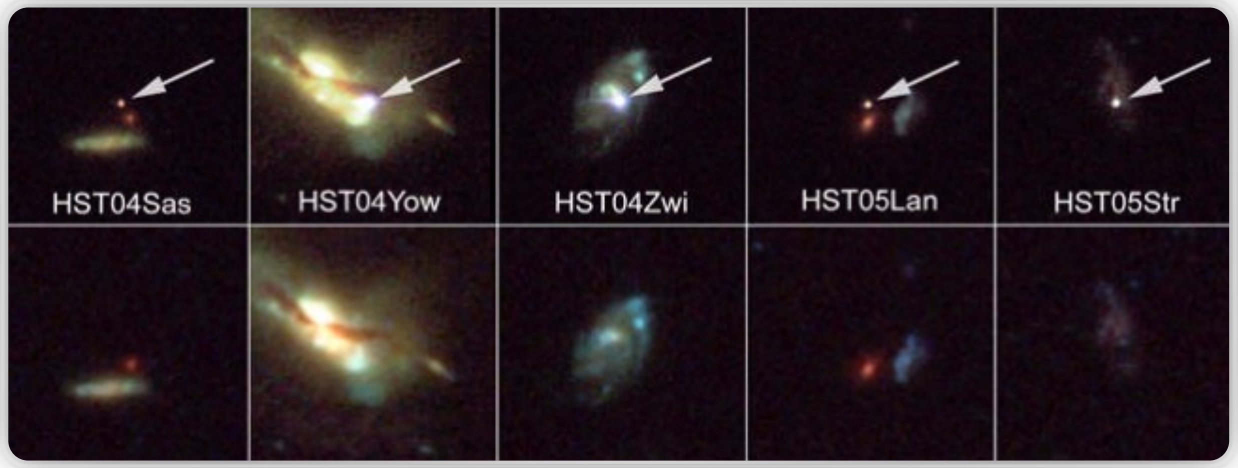


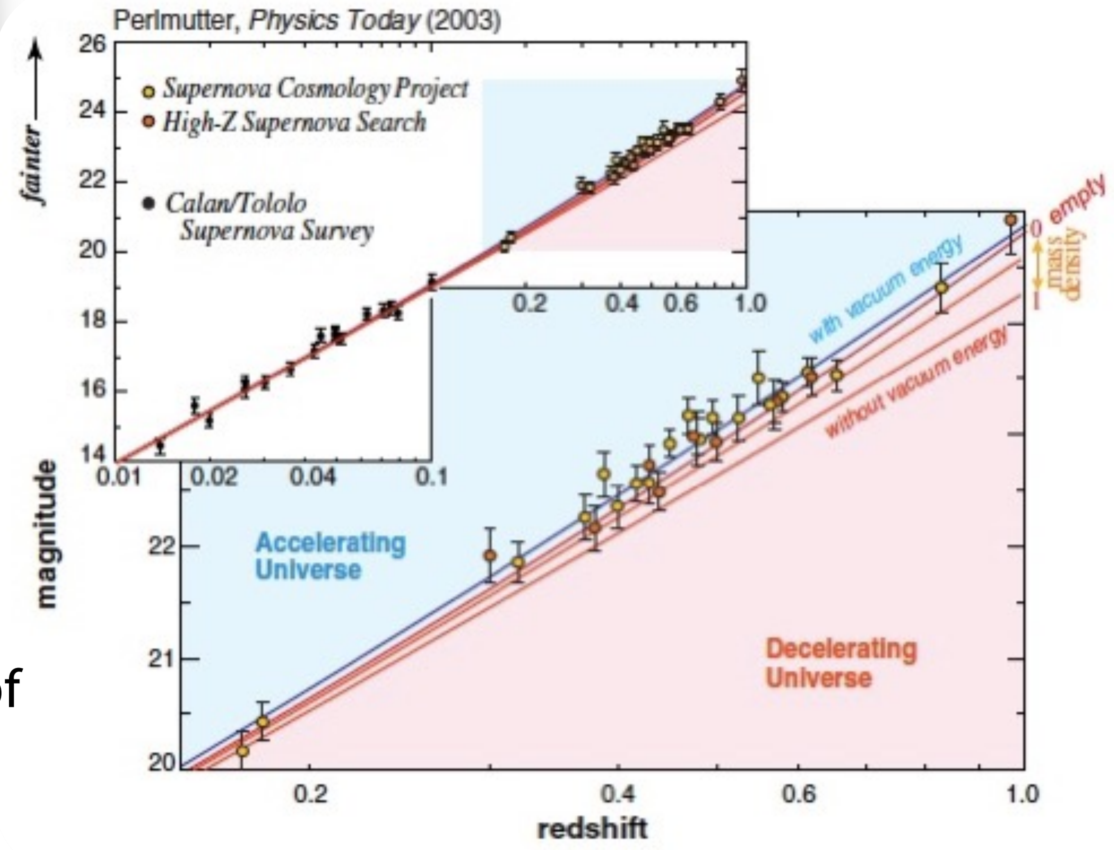
(Planck collaboration 2018)

Cosmological probe: SN1a

SN1a luminosity distance redshift relation

$$d_L(z, H_0, \Theta) = (1+z)c \int_0^z \frac{dz'}{H(z', H_0, \Theta)}$$



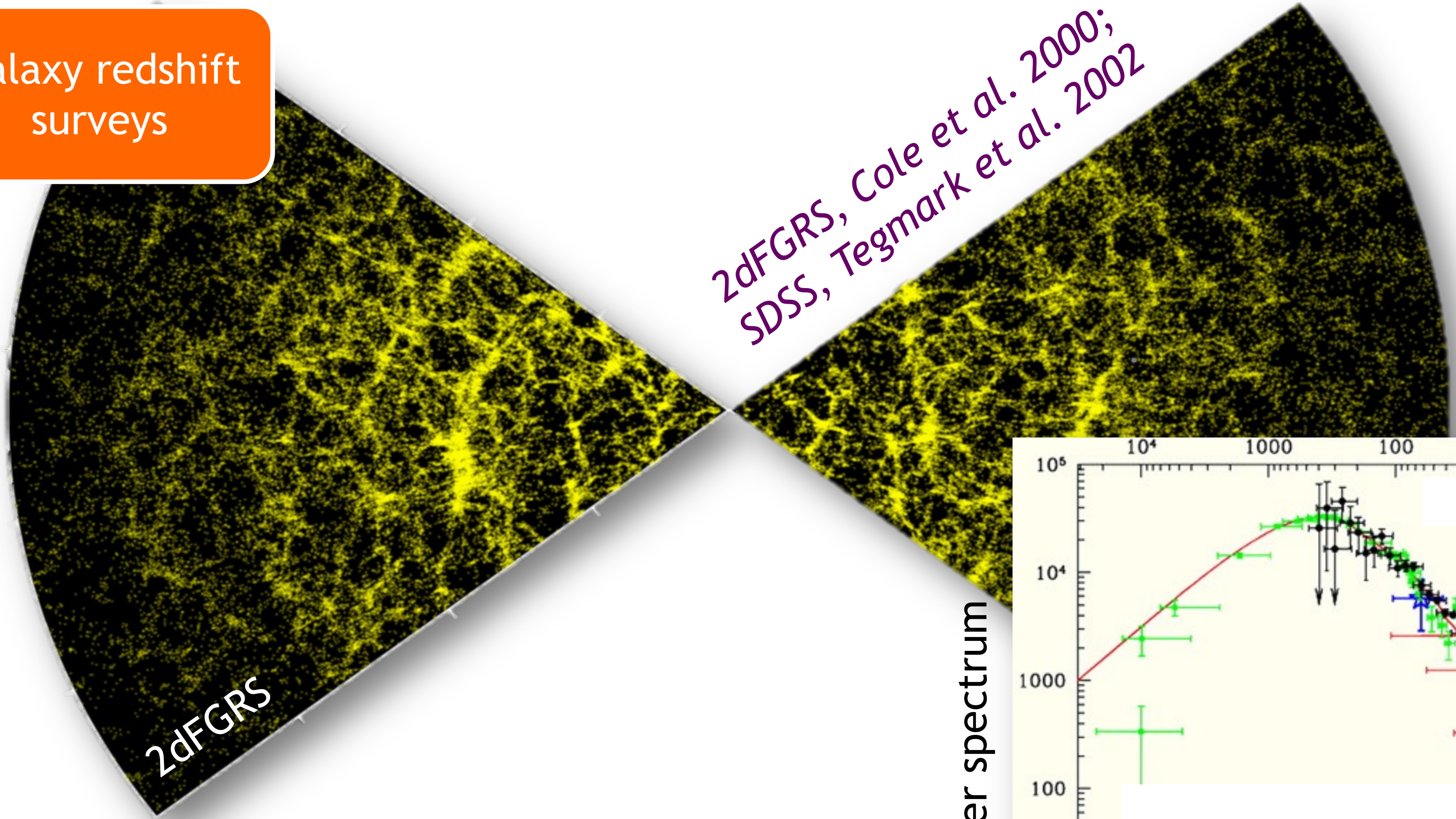


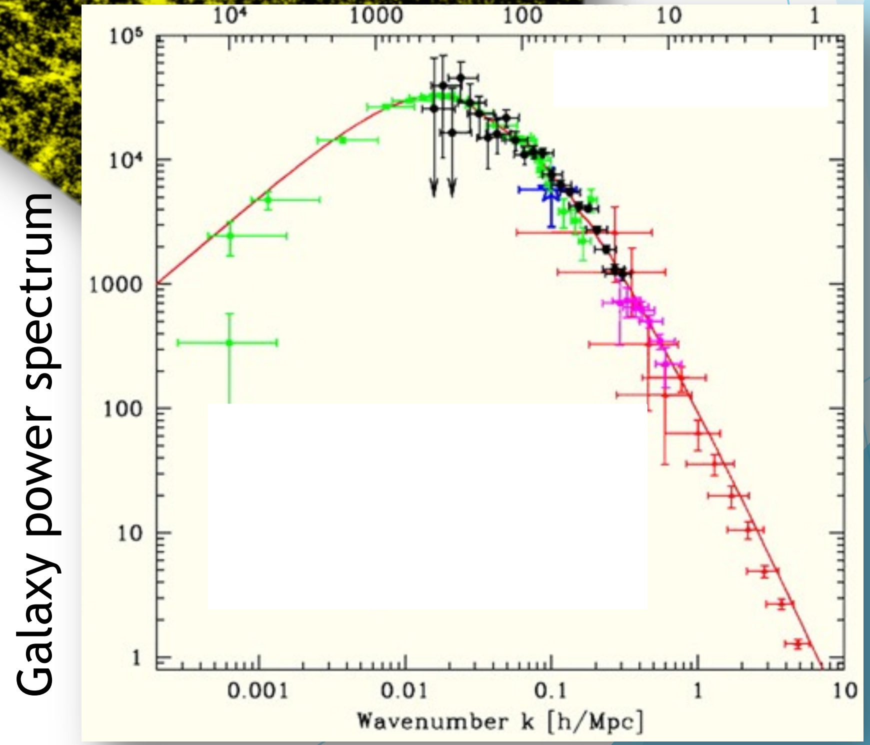
- → Probe distance-redshift relation
- → First evidence of the late-time acceleration of universal expansion and non-vanishing cosmological constant

(Perlmutter et al. 1999, Riess et al. 1998)

Cosmological probe: galaxy 3D clustering

Galaxy redshift surveys

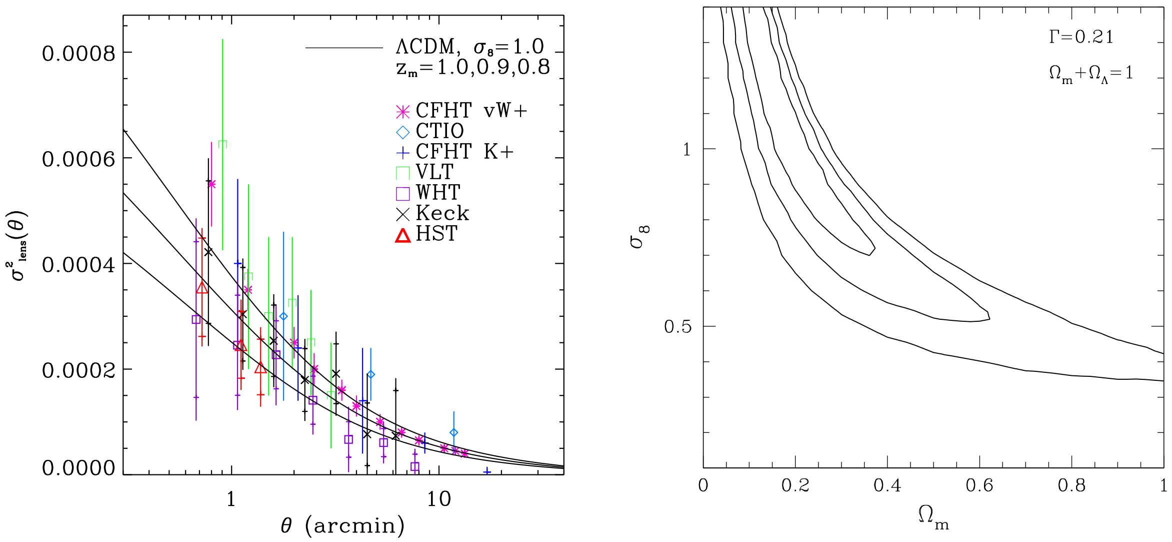




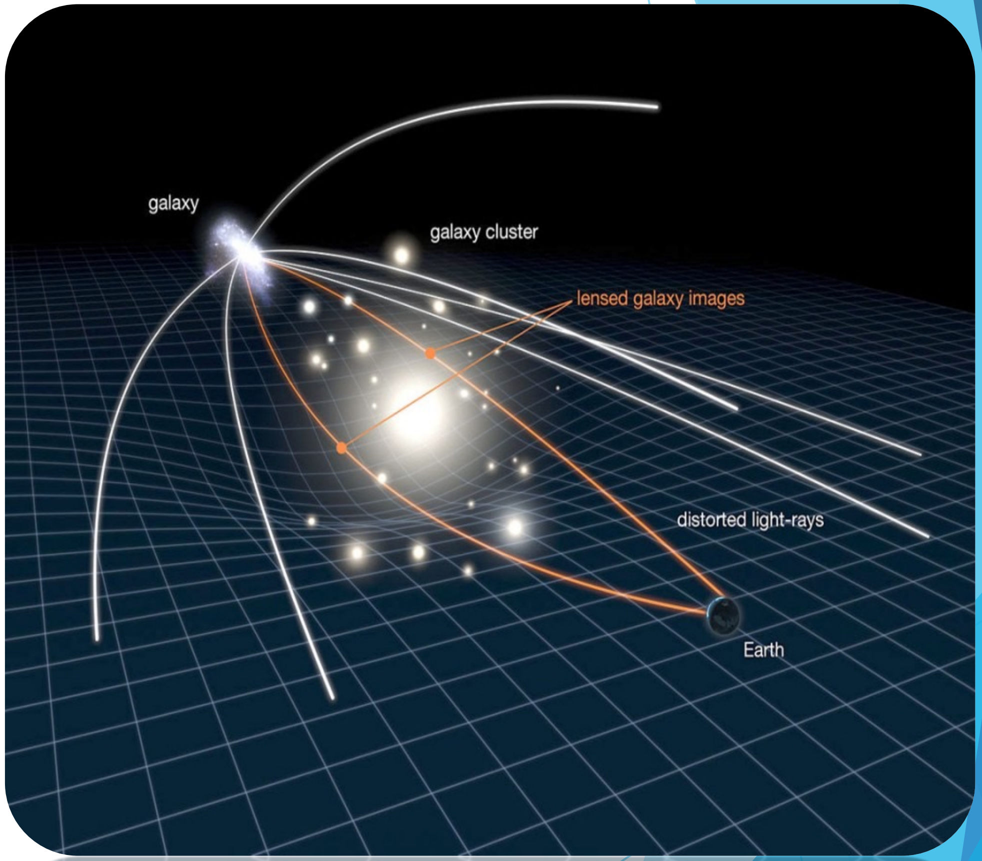
- Probe late-time matter density fluctuations through galaxy distribution
- Sensitive to galaxy bias

Cosmological probe: weak gravitational lensing

Imaging lensing surveys



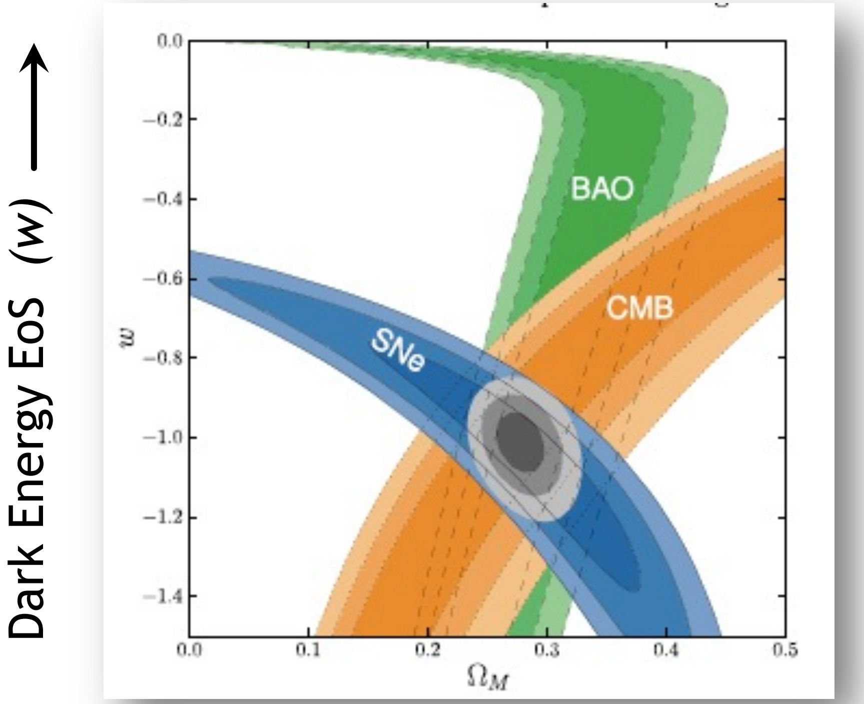
Van Vaerbeke et al. 2002 (compilation)



Gravitational lensing

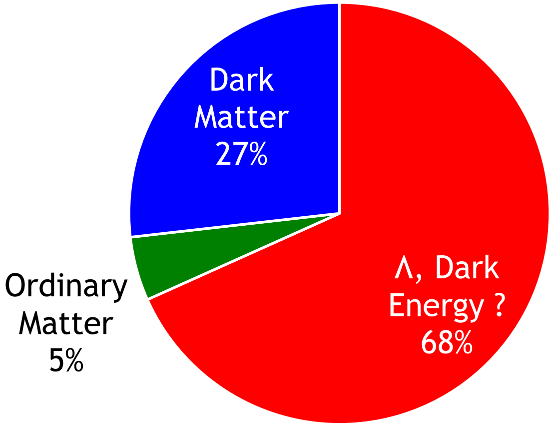
- → Directly probe matter fluctuations
- → Cosmic shear sensitive to mean matter density and growth of structure

Concordance ΛCDM model



Amanullah et al. 2010

Universal content today



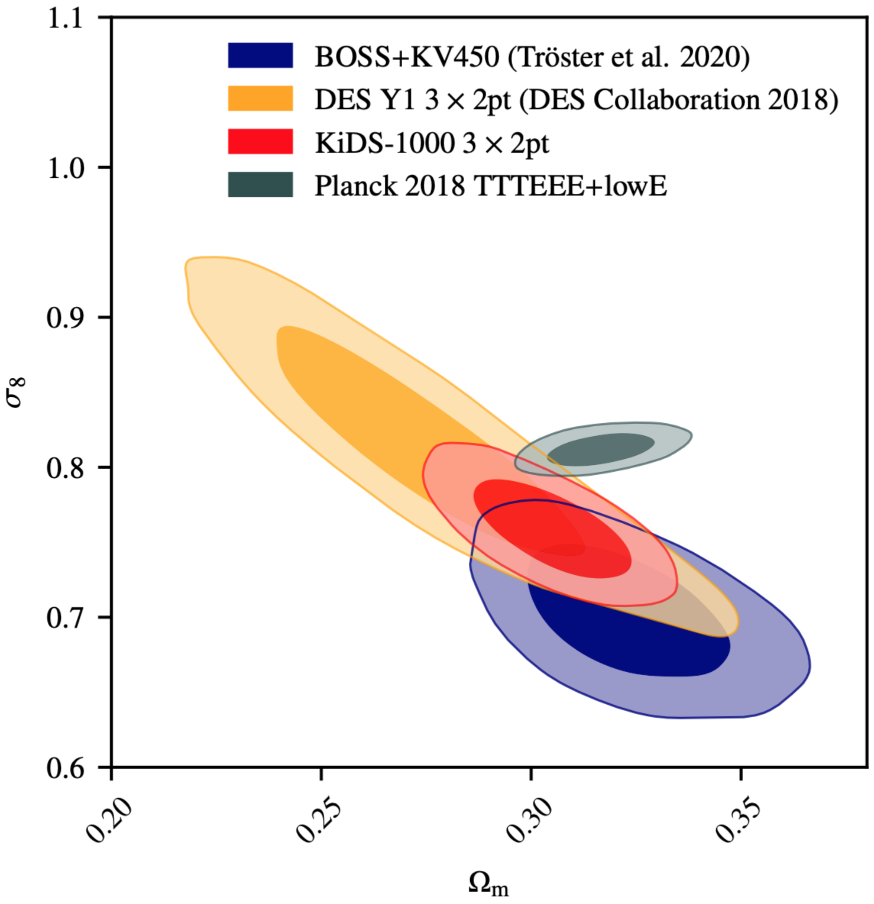
- ΛCDM 6-parameter model well established for few decades now, thanks to SN1a, CMB, galaxy clustering and lensing cosmological probes
- The origin of recent cosmic acceleration is a mystery (physical constant, dark energy, modified gravity …?)
- Improved cosmological constrains led to apparent tensions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

Cosmological tensions: S_8

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

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

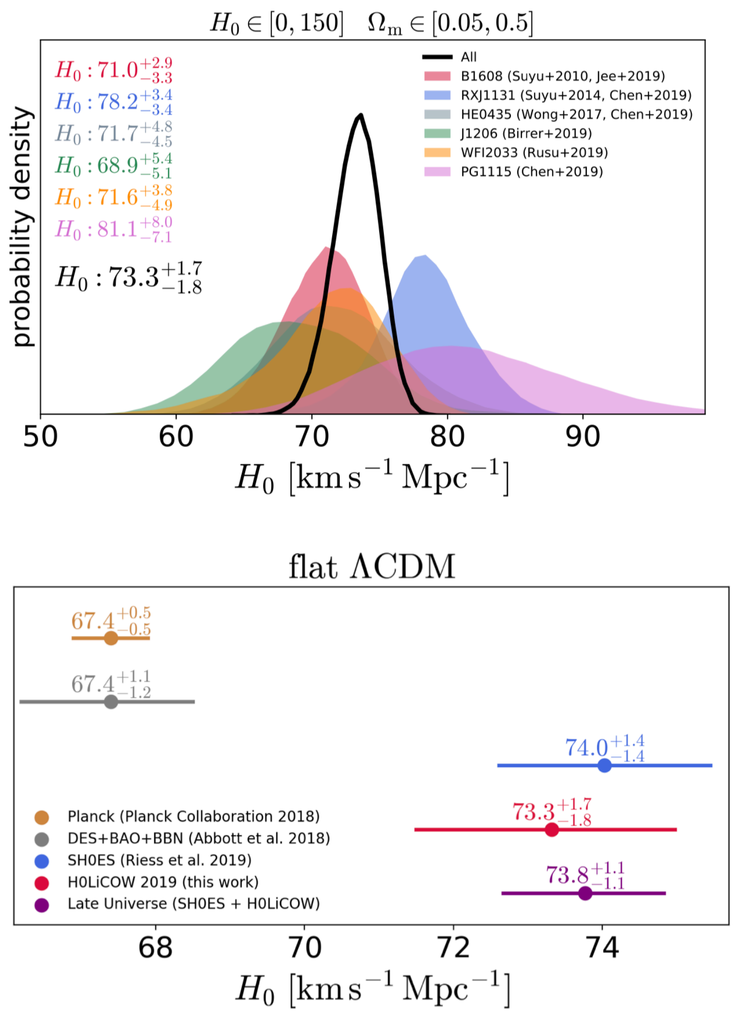
- The S8 tension is at about 2.6σ level between the Planck data in the ΛCDM scenario and KiDS survey
- Mainly driven by σ_8, which is lower in lensing analyses



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



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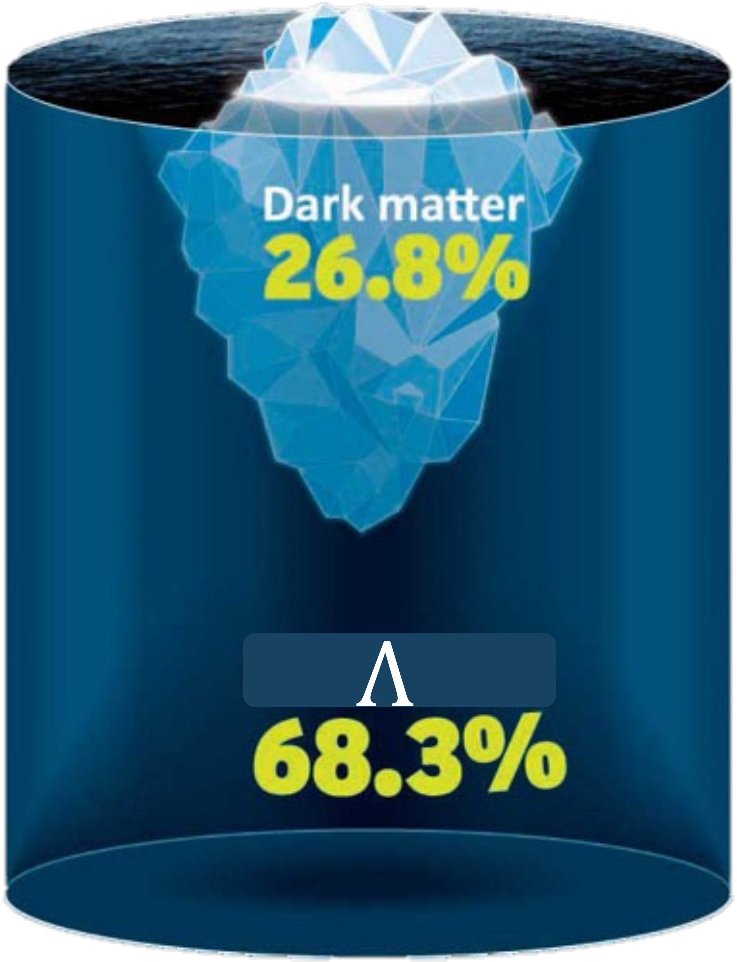
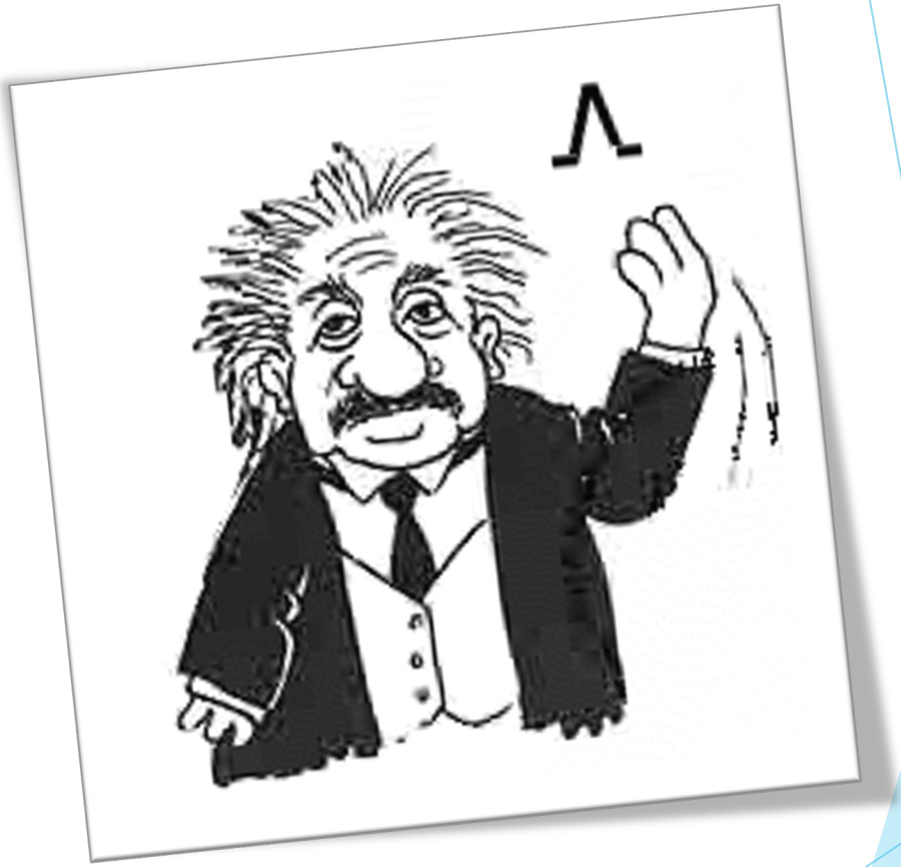
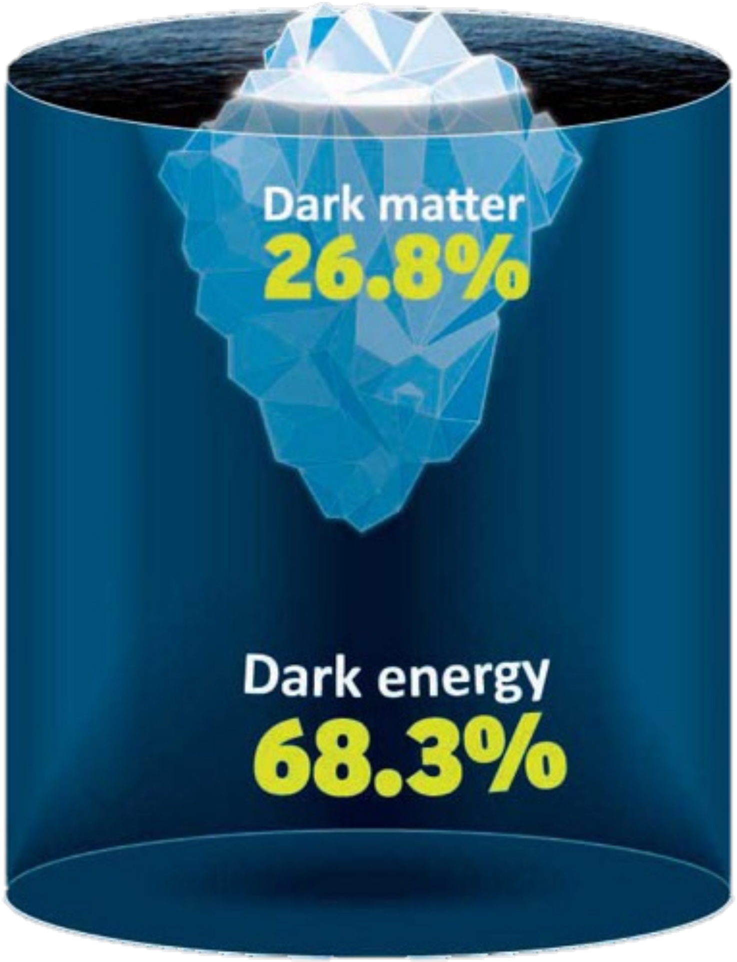
Cosmic acceleration

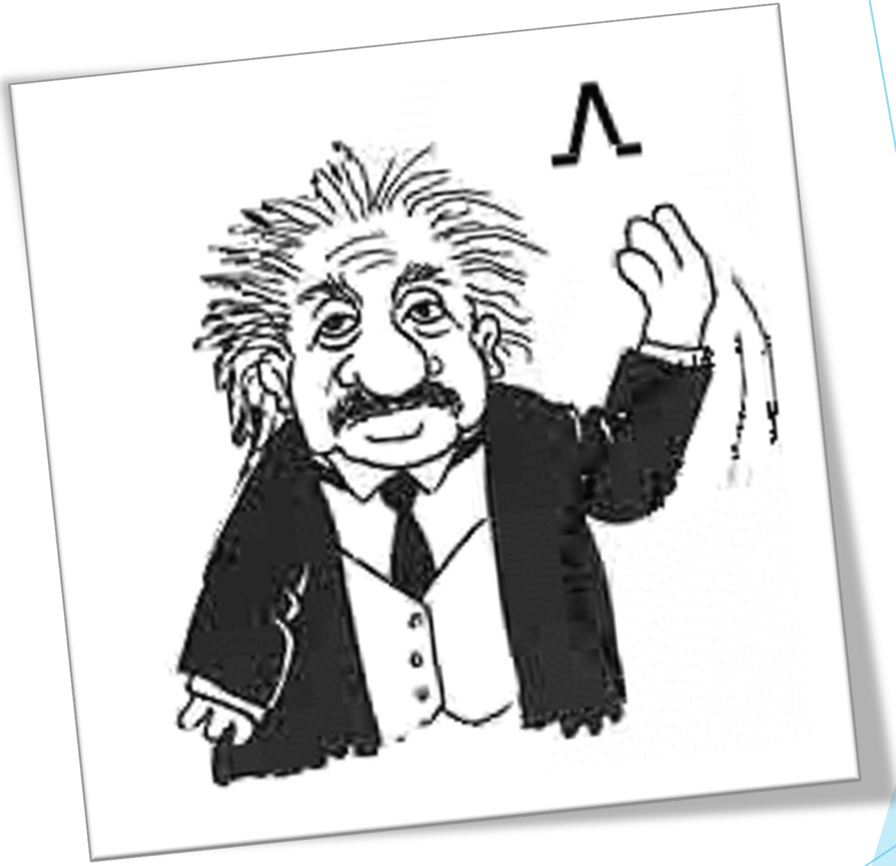




Einstein cosmological constant

Cosmic acceleration





Einstein cosmological constant

Nature of dark energy

- What is the very nature of dark energy? Cosmological constant, vacuum energy, new scalar field?
- Assuming a cosmological fluid with negative pressure, one can introduce its associated equation of state : $\boldsymbol{w = P/\rho}$

$w = -1$	Cosmological constant
$w = -1/3$	Cosmic strings
$w > -1$	Quintessence
$w < -1$	Phantom energy

- Dynamical dark energy models lead to redshift-dependent equation of state, e.g. CPL (Chevallier & Polarsky 2001, Linder 2003) parameterization:

$$w(z) = w_0 + w_a \frac{z}{1+z}$$

Does dark energy really exist?

- What if instead of invoking the existence of dark energy that accelerates the expansion of the Universe, one of the hypotheses of the standard model was wrong?

- Pillars of the standard cosmological model:
  - *Hot big-bang*
  - *Expansion of the Universe*
  - *Laws of gravity described by **General Relativity***
  - *Cosmological principle*

Does dark energy really exist?

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- Pillars of the standard cosmological model:
  - *Hot big-bang*
  - *Expansion of the Universe*
  - *Laws of gravity described by* ***General Relativity*** *→ modified gravity?*
  - *Cosmological principle → inhomogeneous expansion, backreaction…?*

Outline

1. Standard cosmological model
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3. **Galaxy redshift survey cosmology**
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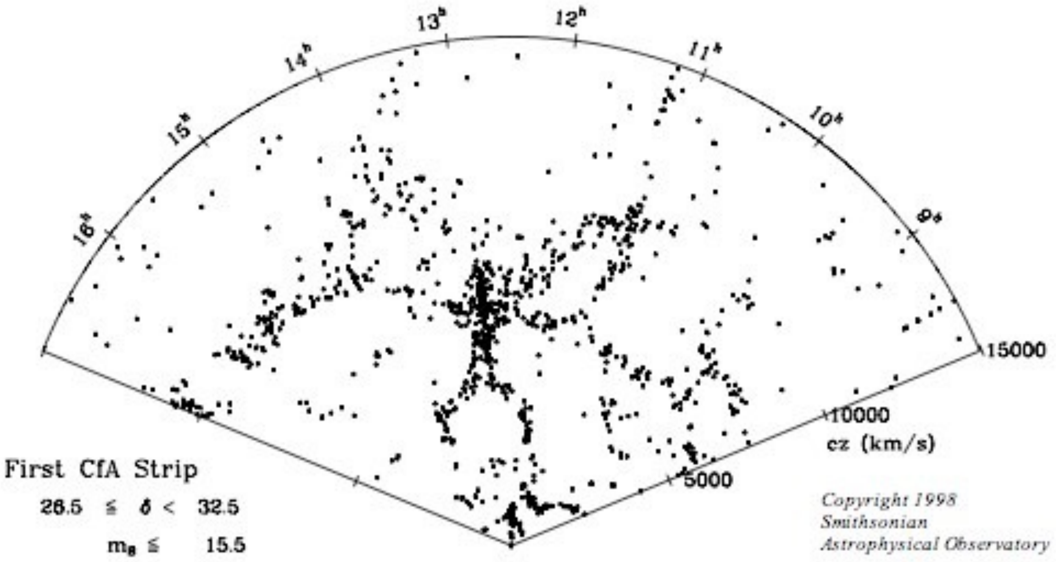
Observed large-scale structure

- 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

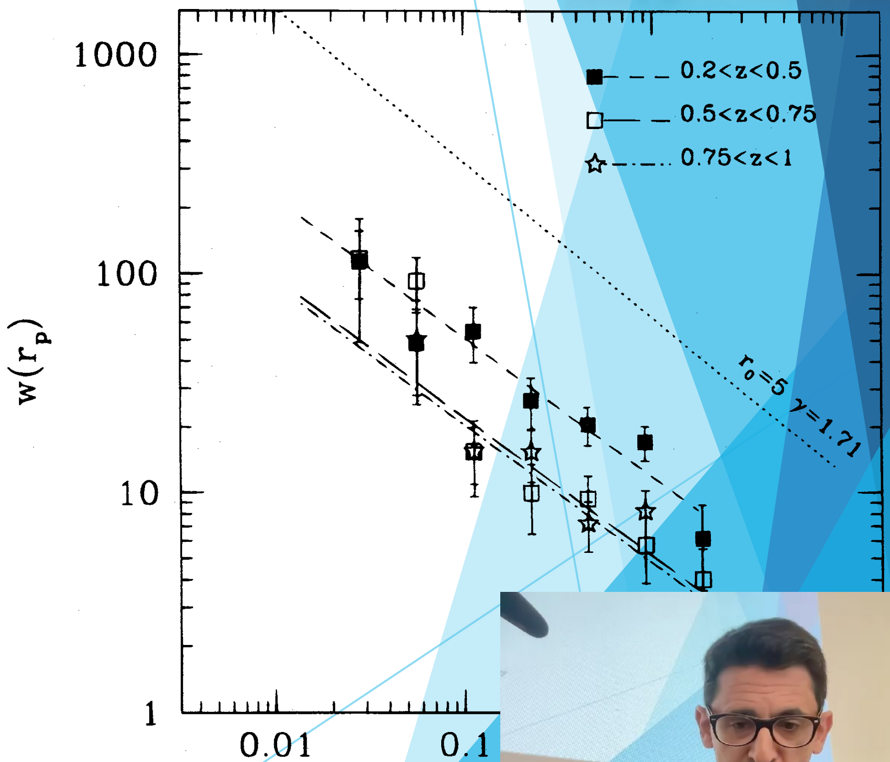


de Lapparent, Geller, Huchra, 1988

Canada France Redshift Survey

THE CANADA-FRANCE REDSHIFT SURVEY. VIII. EVOLUTION OF THE CLUSTERING OF GALAXIES FROM $z \sim 1$

O. Le Fèvre[1]
DAEC, Observatoire de Paris-Meudon, 92195 Meudon, France; lefevre@daec.obspm.fr
D. Hudon and S. J. Lilly[1]
Department of Astronomy, University of Toronto, Toronto, Canada M5S 1A7
David Crampton[1]
Dominion Astrophysical Observatory, National Research Council of Canada, Victoria, Canada
and
F. Hammer[1] and L. Tresse[1]
DAEC, Observatoire de Paris-Meudon, 92195 Meudon, France
Received 1995 August 7; accepted 1995 October 27

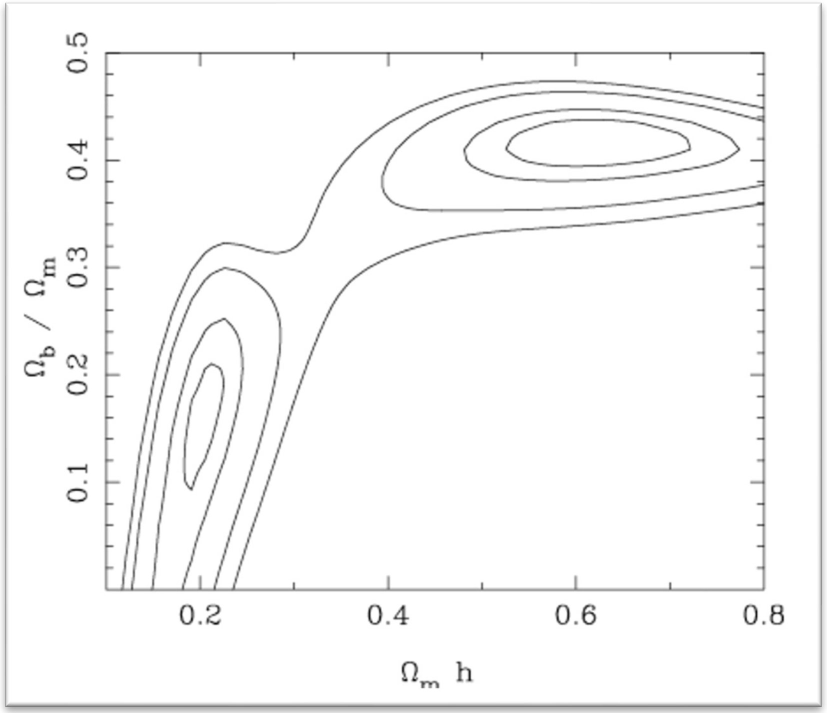


Le Fèvre

- Meanwhile, one of the first attempt to characterize the 3D galaxy clustering at redshift 1 by Olivier

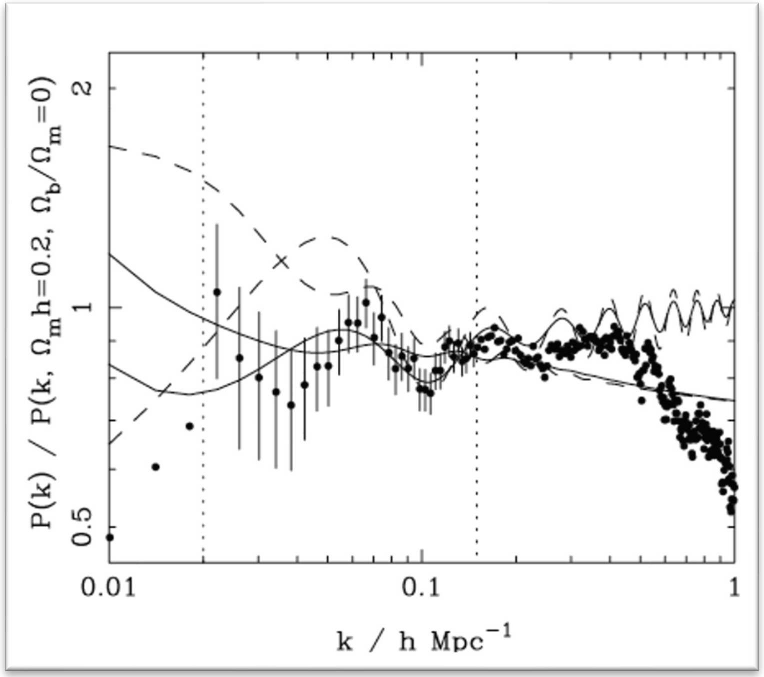
First constraints from galaxy *P(k)*

Constraints on the baryon fraction



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

Galaxy power spectrum

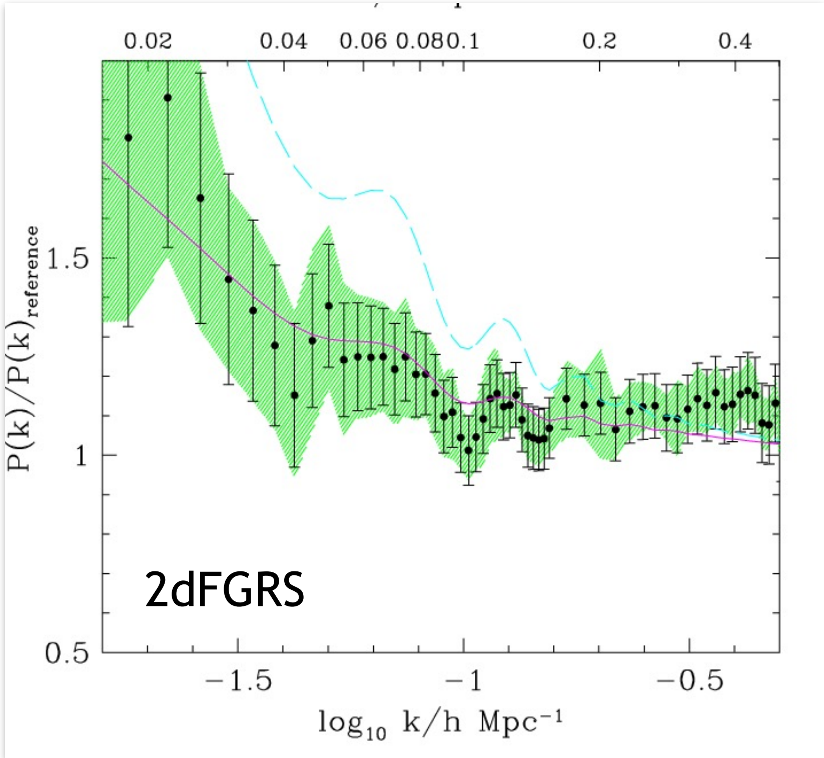


- Galaxy power spectrum full shape (linear scales) sensitive to:

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

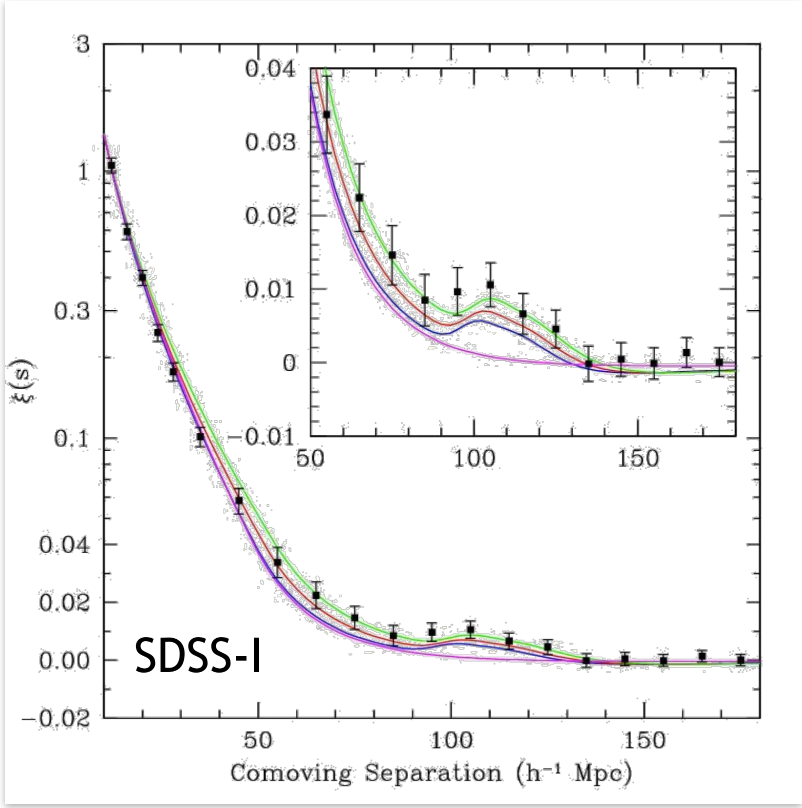
Baryon Acoustic Oscillations

Galaxy power spectrum



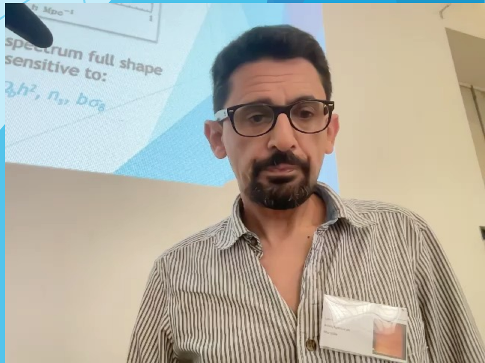
Cole et al. 2005

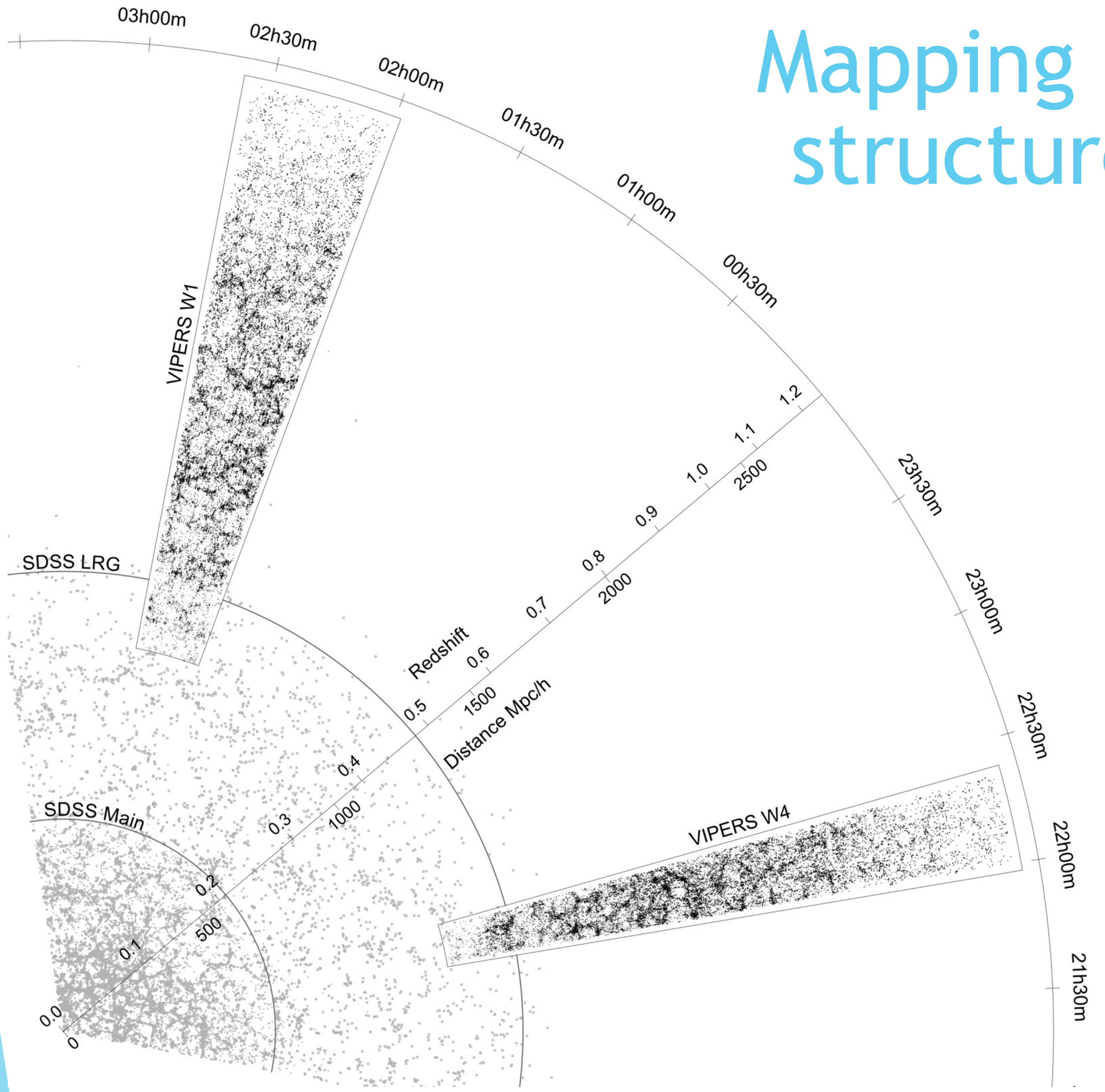
Galaxy correlation function



Eisenstein et al. 2005

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

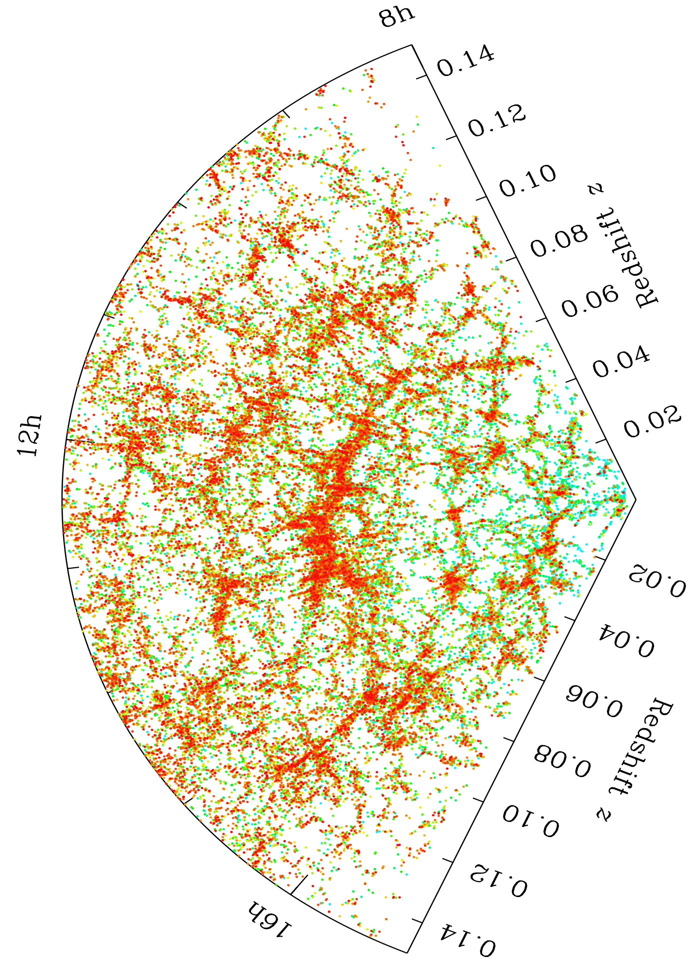




Mapping the large-scale structure with galaxies

- Large redshift surveys for cosmology (non-exhaustive):
  - WiggleZ (*Blake et al., 2011*)
  - SDSS/BOSS (*Dawson et al, 2013*)
  - VIPERS (*Guzzo et al. 2014*)
  - SDSS/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:

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

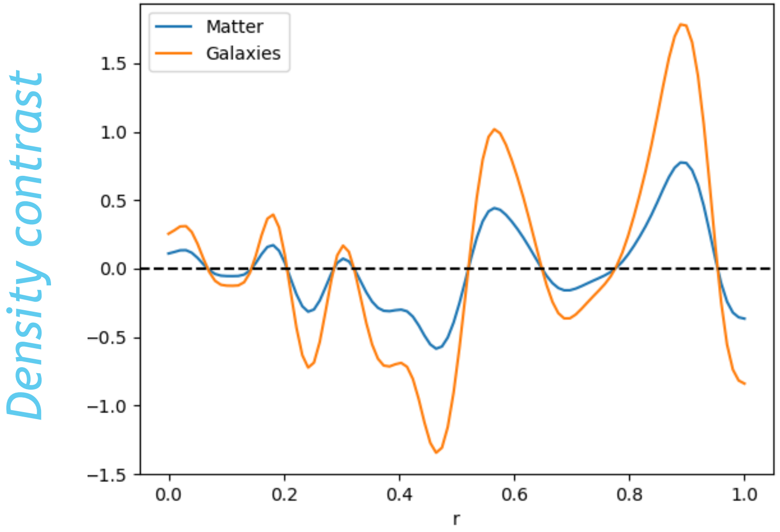
- Higher-order statistics

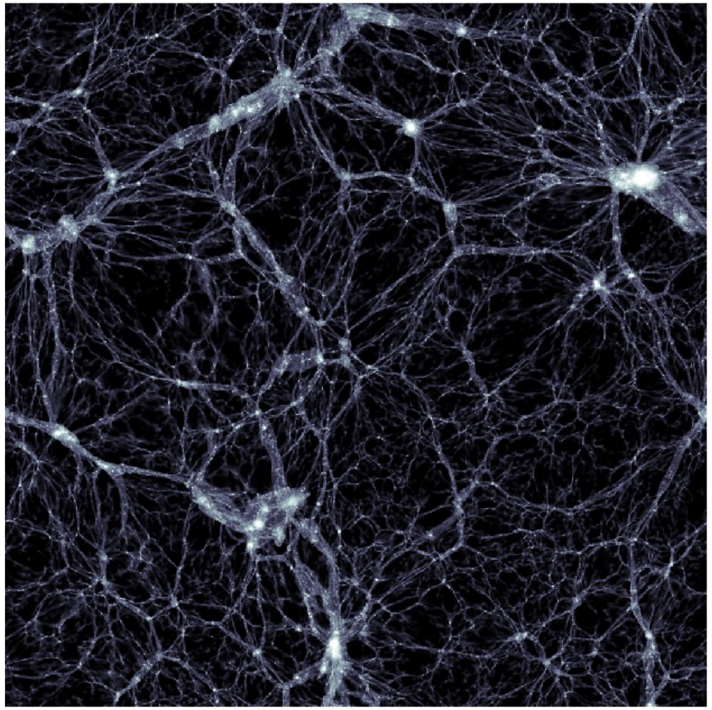
$$\begin{aligned} \xi(r) &= \langle \delta(\mathbf{x_1})\delta(\mathbf{x}+\mathbf{r}) \rangle \\ \zeta(r_1, r_2, r_3) &= \langle \delta(\mathbf{x_1})\delta(\mathbf{x_2})\delta(\mathbf{x_3}) \rangle \end{aligned}$$

...

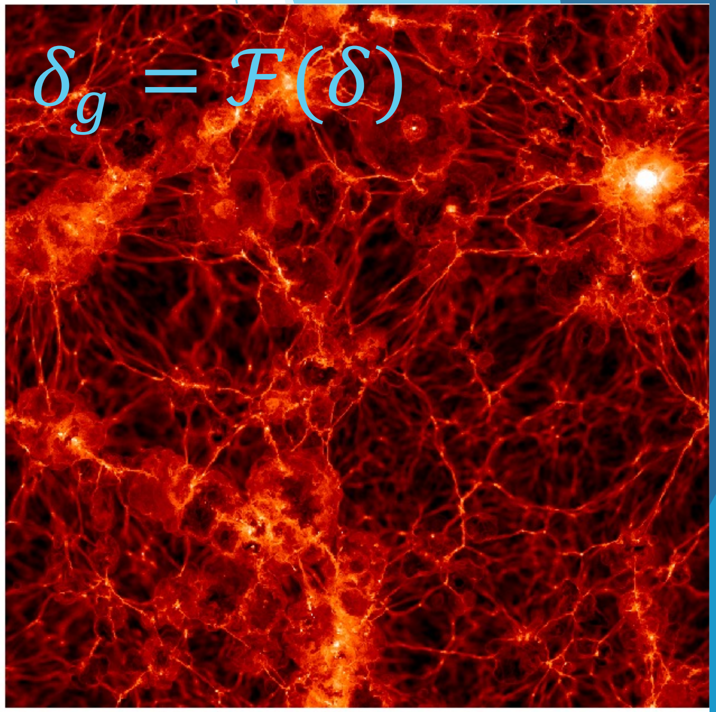
Biased galaxy formation

- Galaxies are biased tracers of the underlying density field





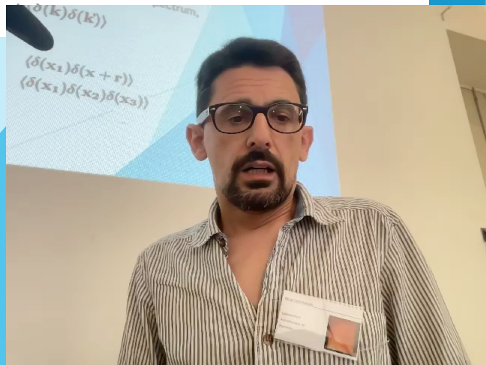
(a) dark matter



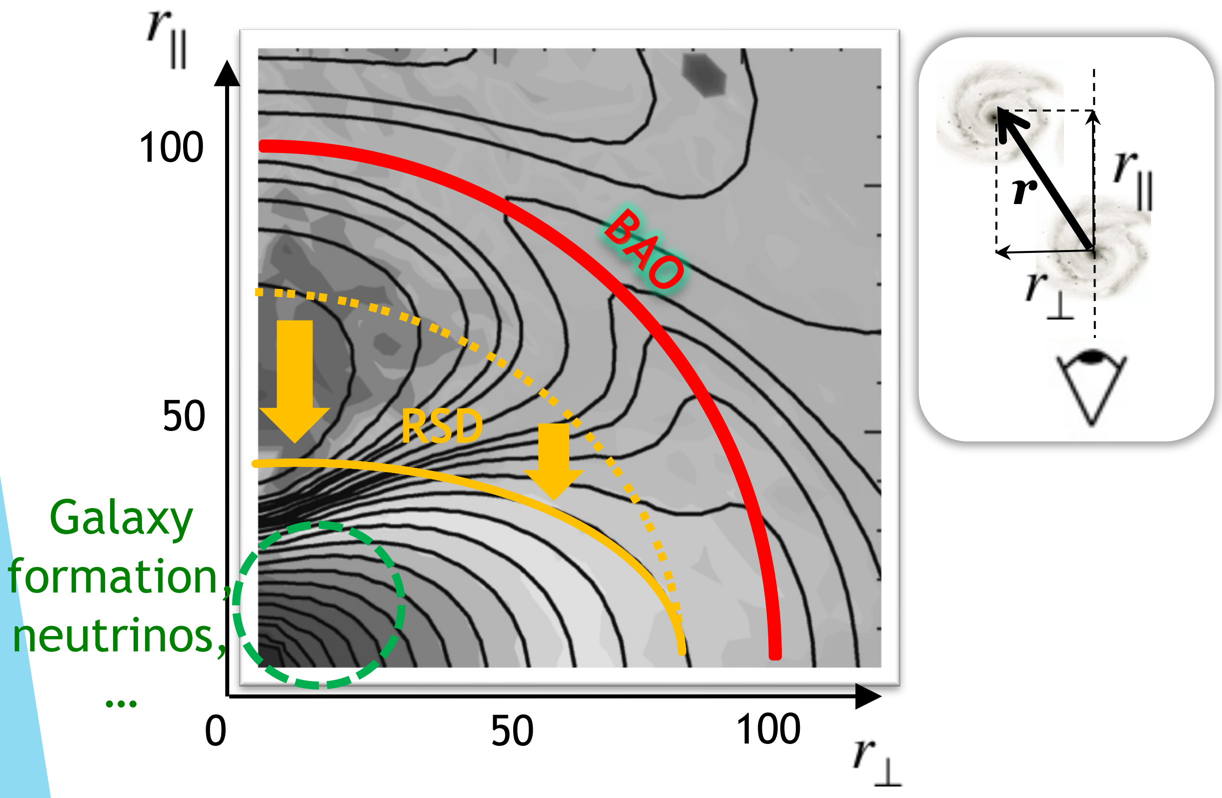
- Example of perturbative model: *(McDonald & Roy, 2009)*

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

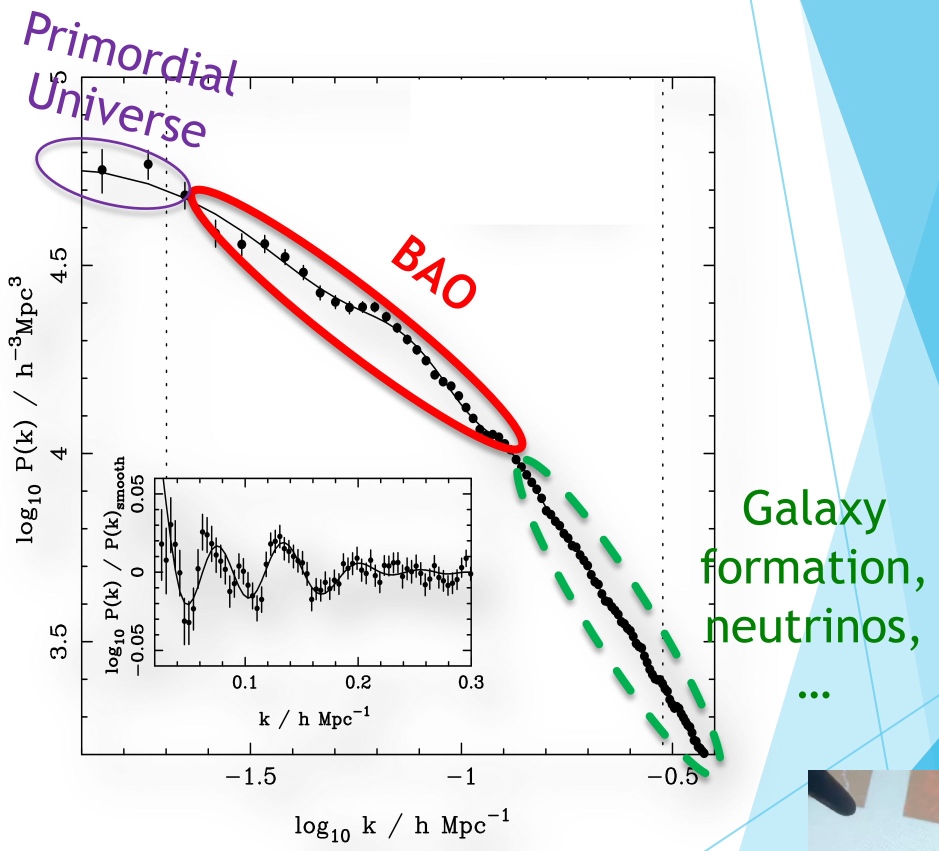
Linear bias — *Non-linearities* — *Tidal tensor → Non-local*



Cosmology from galaxy clustering



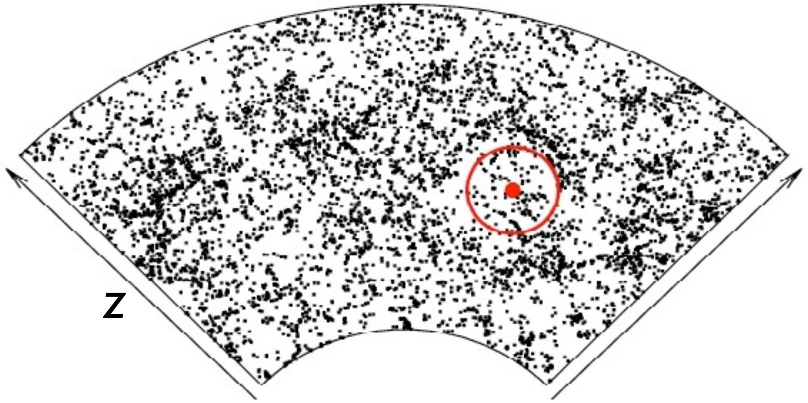
Galaxy anisotropic correlation function



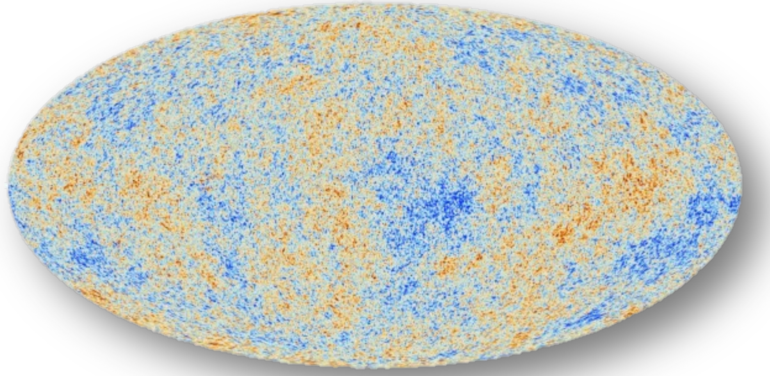
Galaxy power spectrum

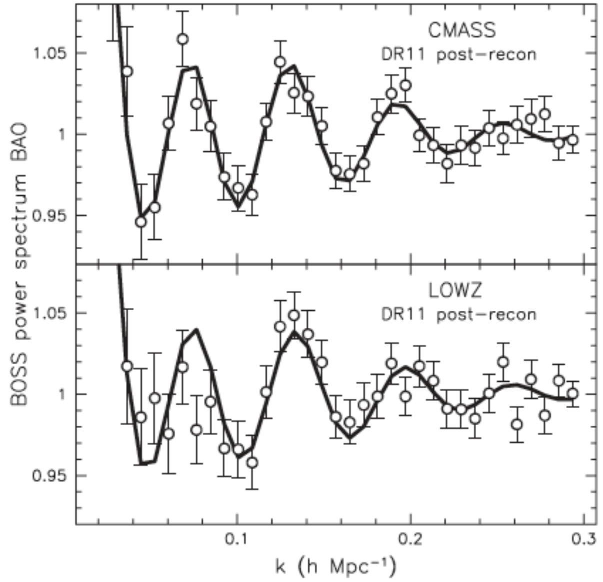
Baryon Acoustic Oscillations

Galaxies

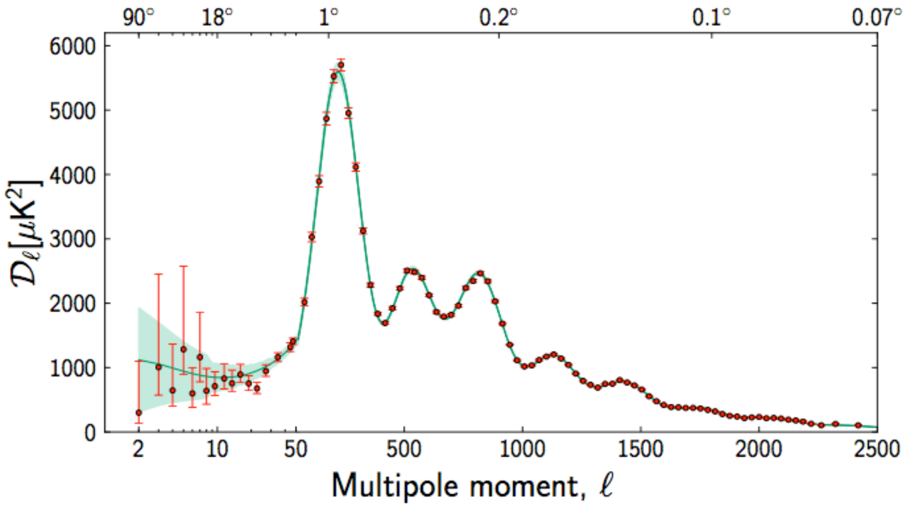


CMB





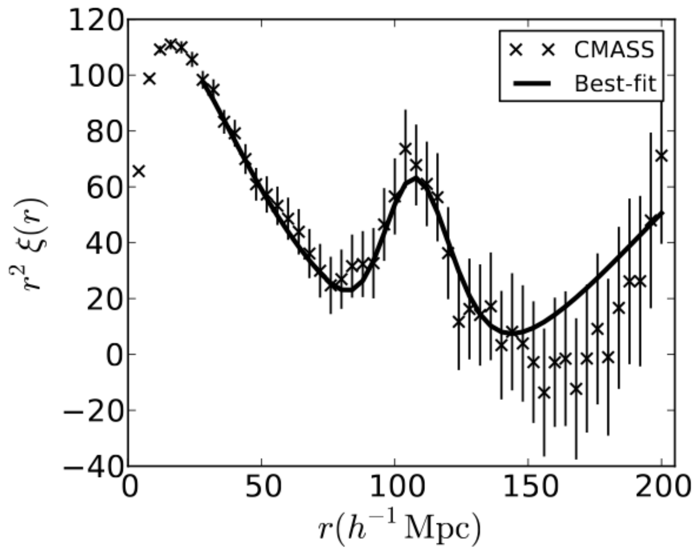
Anderson et al. 2014



Planck Collaboration 2015

Baryon Acoustic Oscillations

Galaxy correlation function



Anderson et al. 2012

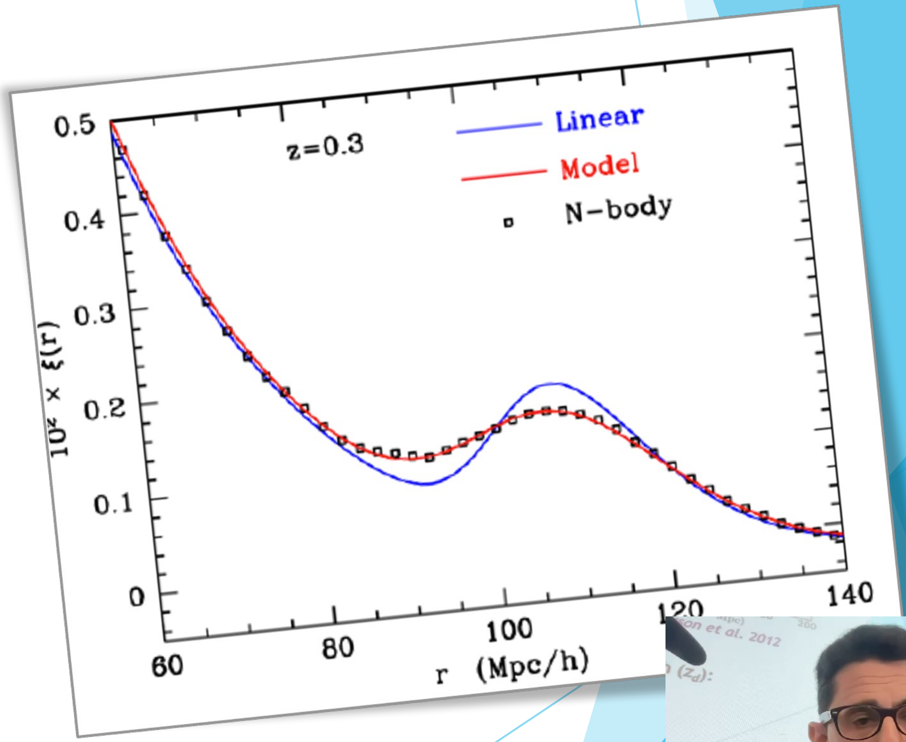
- BAO scale is determined by the sound horizon at drag epoch (z_d):

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

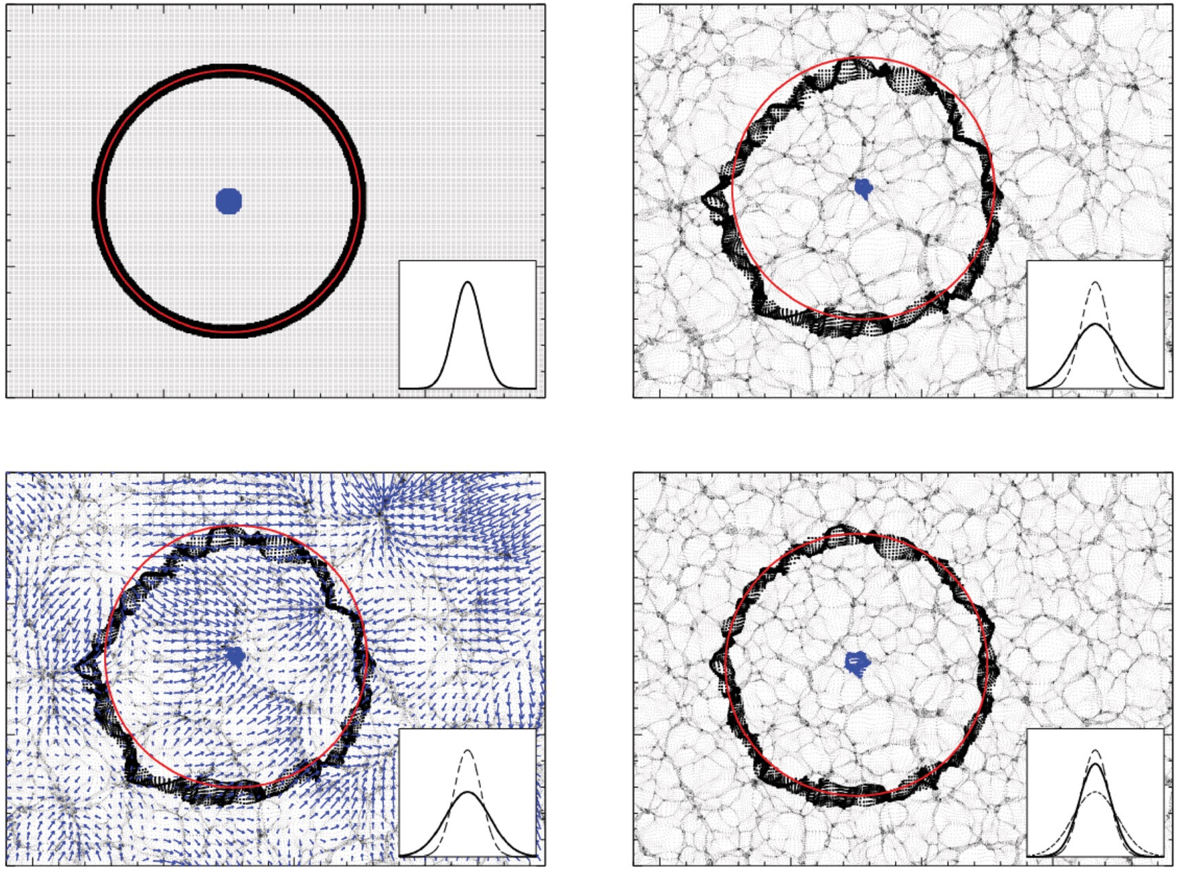
Baryon Acoustic Oscillations

- 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)

Baryon Acoustic Oscillations

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

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

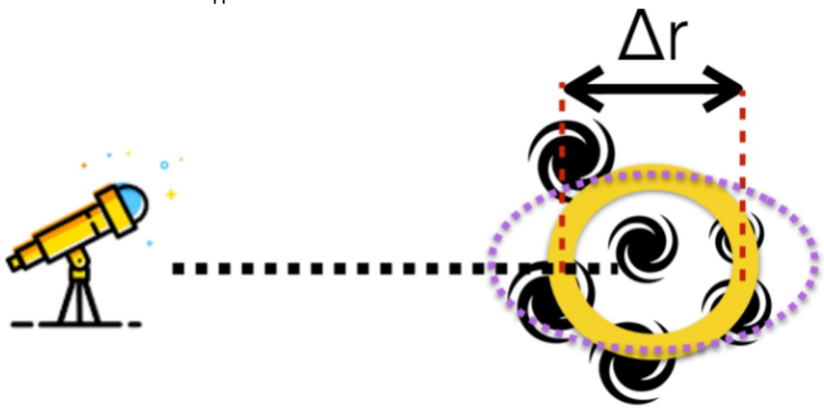
- Fiducial model used for estimating the correlation function, estimates the deviation of BAO peak position with respect to fiducial position (*Alcock-Paczynski effect*):

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

Alcock-Pazcynski distortions

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

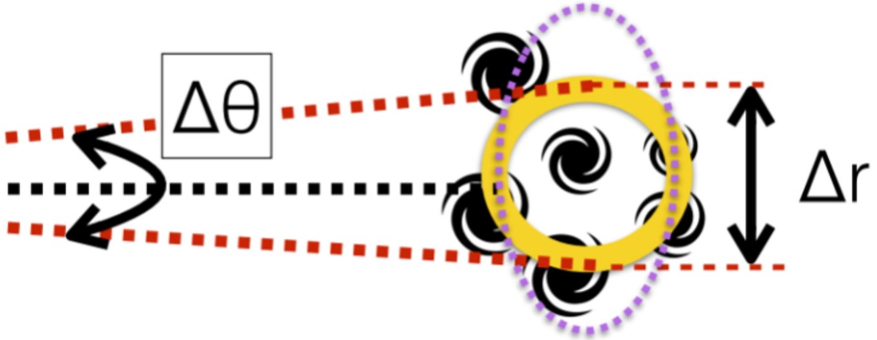
$$\Delta r_{\parallel} \approx c/H(z) \equiv D_H(z)$$



Radial distance

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

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



Angular diameter distance

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

Understanding Cosmic Acceleration

Einstein Field Equation:

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

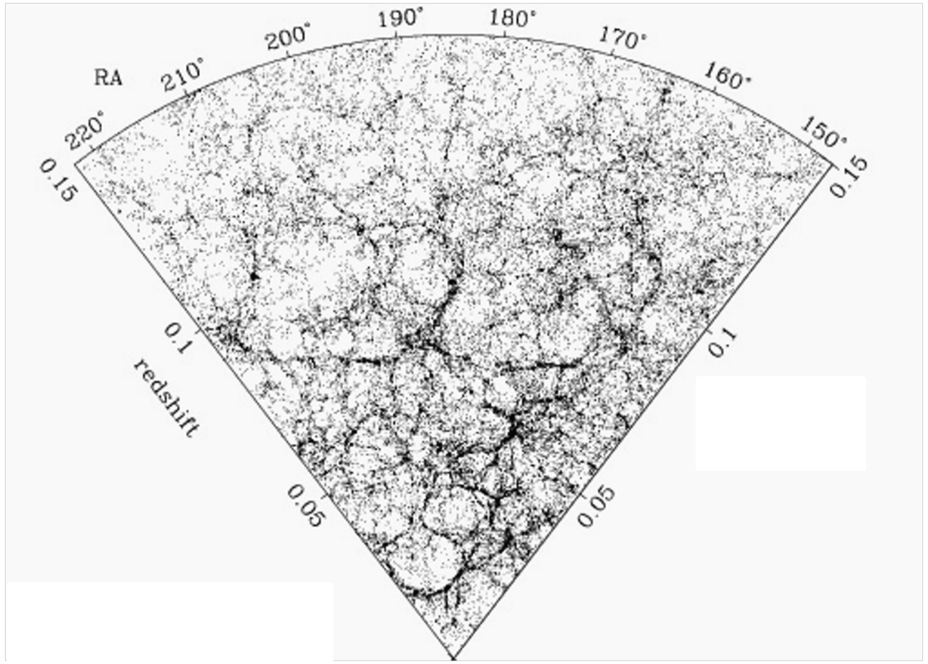
…or modify gravity theory?

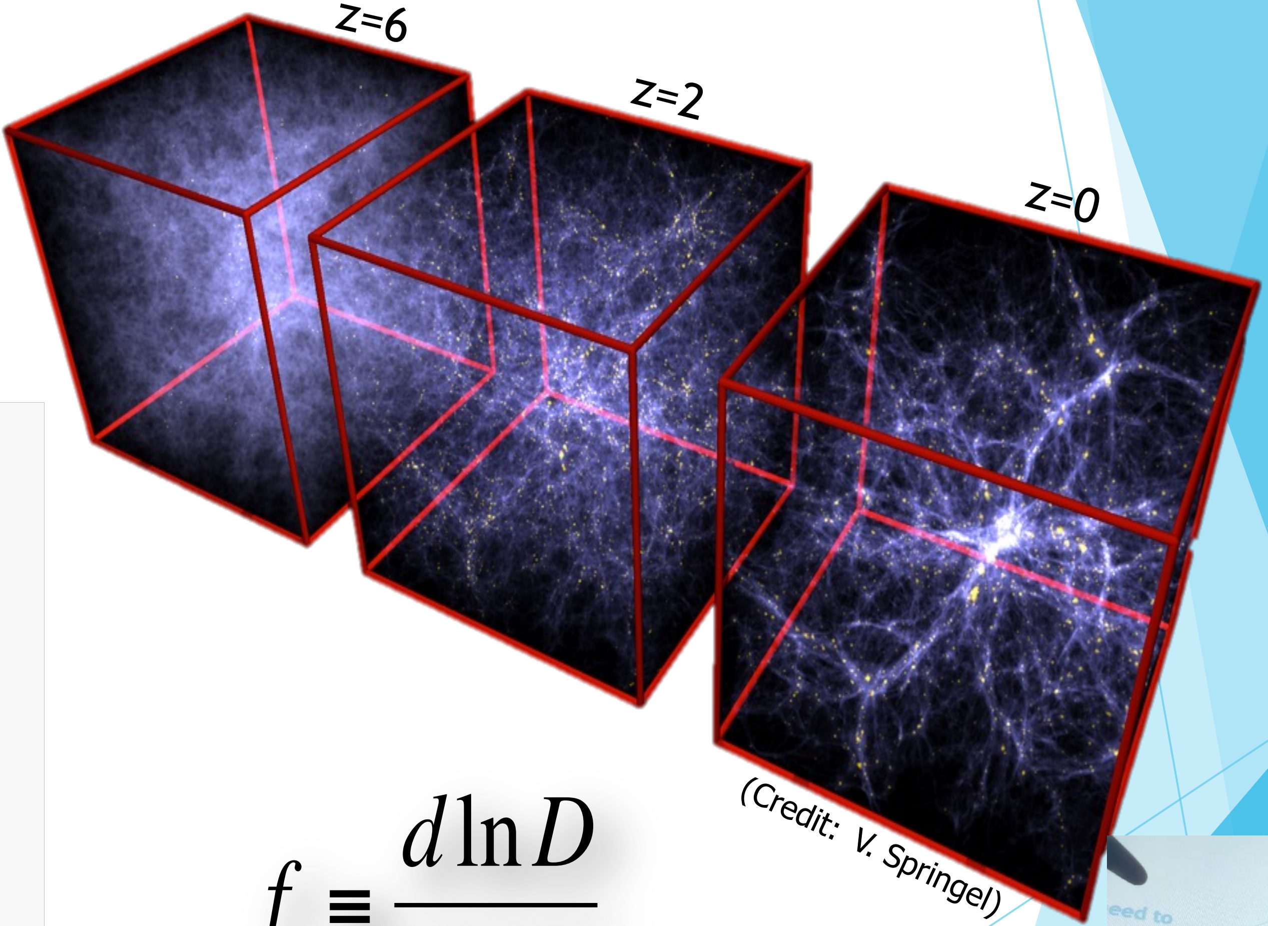
Add Cosmological Constant
or Dark Energy

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

Probing the growth rate of structure

Real space



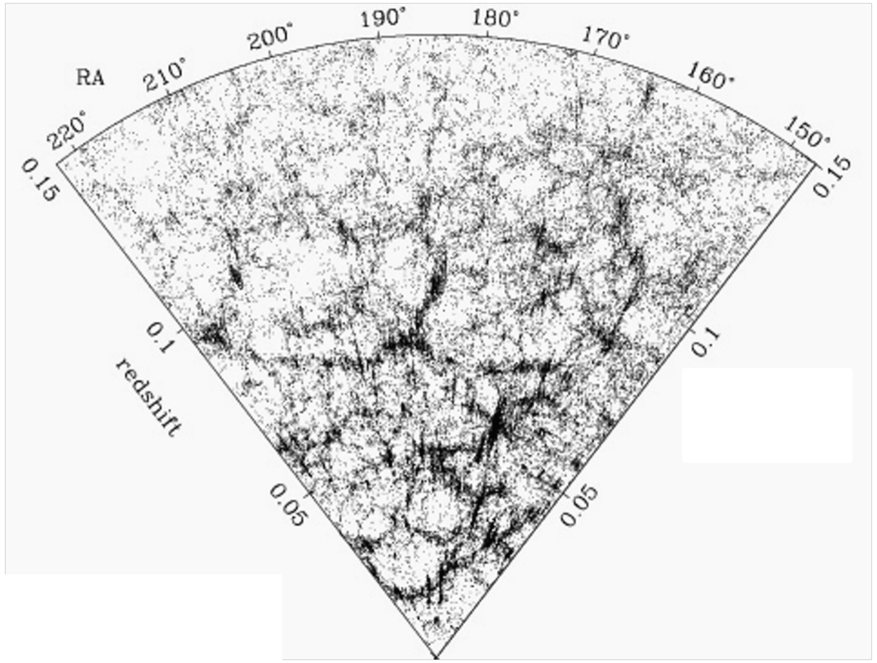


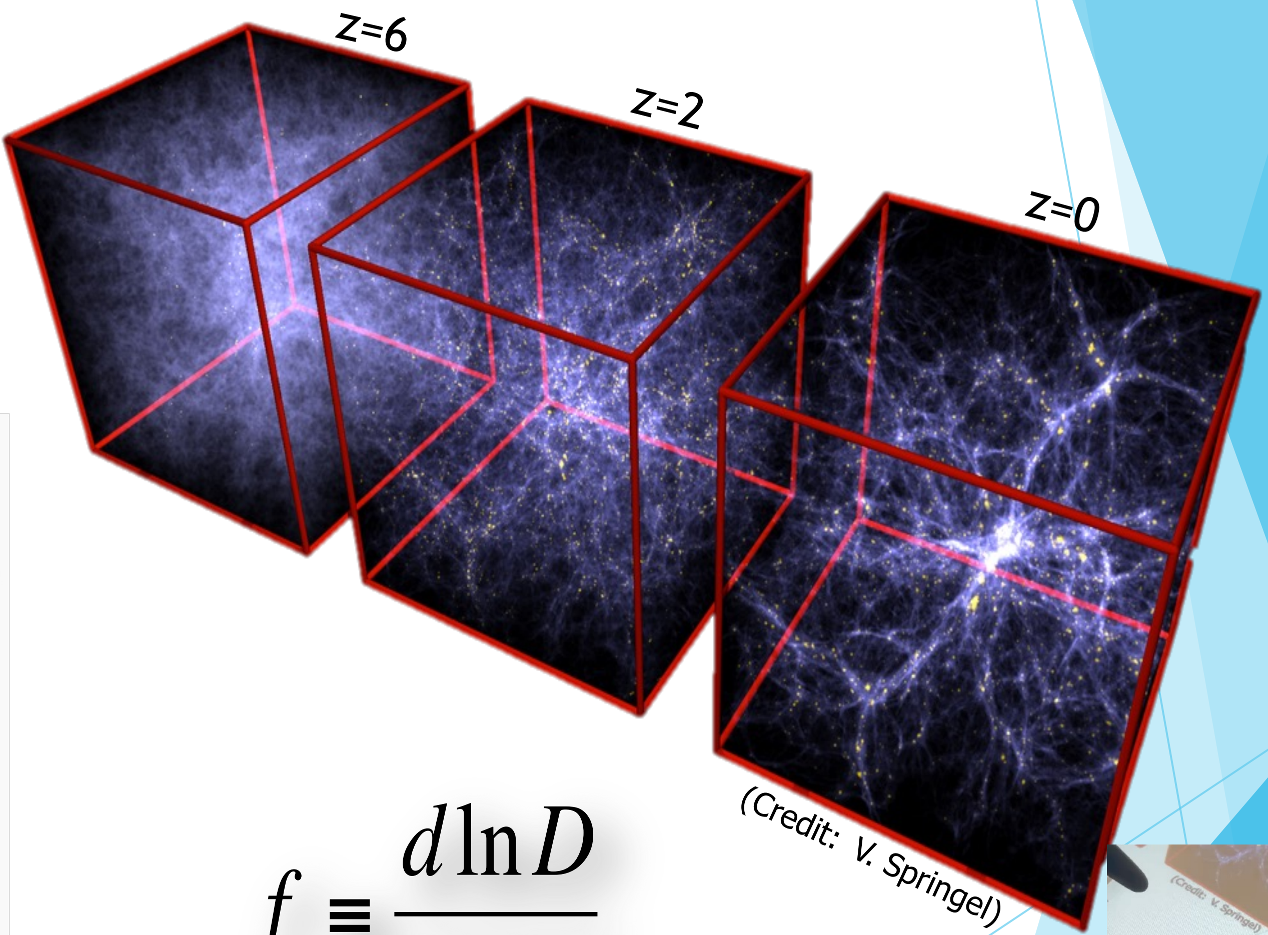
$$f \equiv \frac{d \ln D}{d \ln a}$$

Growth rate of structure

Probing the growth rate of structure

Redshift space

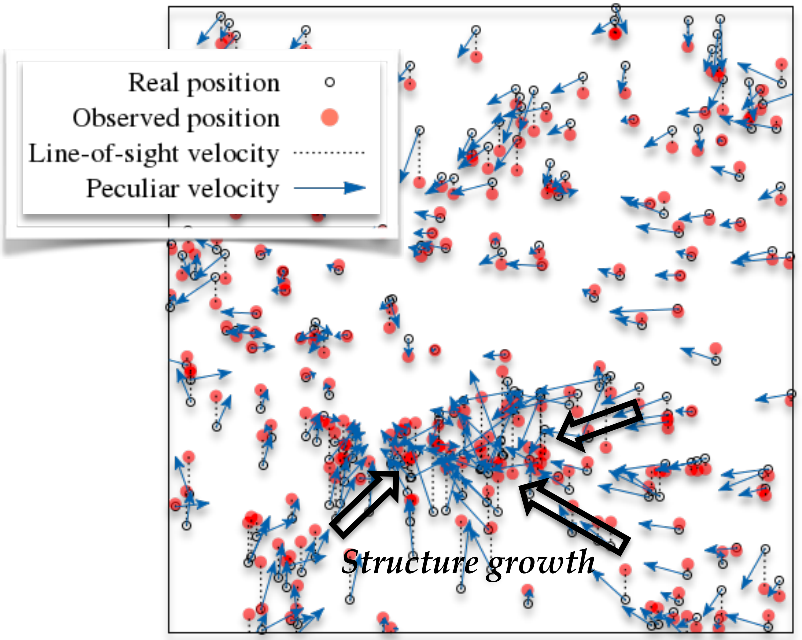


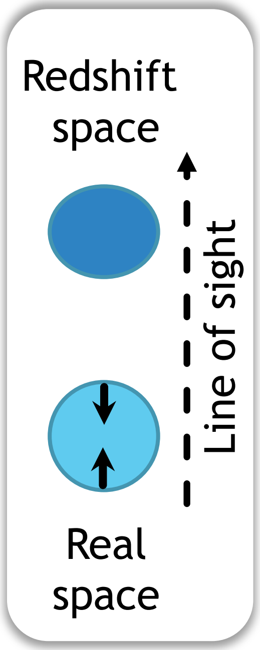


$$f \equiv \frac{d \ln D}{d \ln a}$$

Growth rate of structure

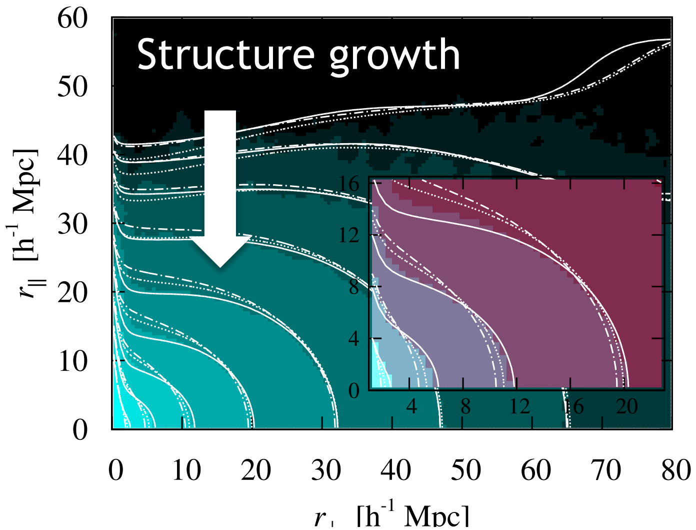
Redshift-space distortions





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

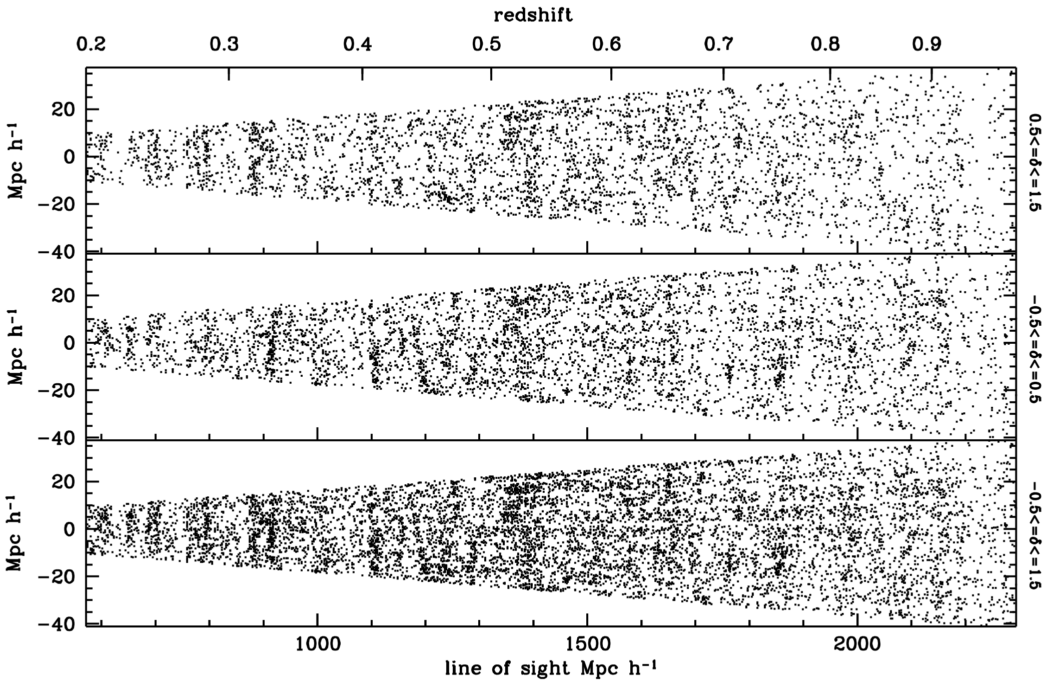
Galaxy anisotropic correlation function

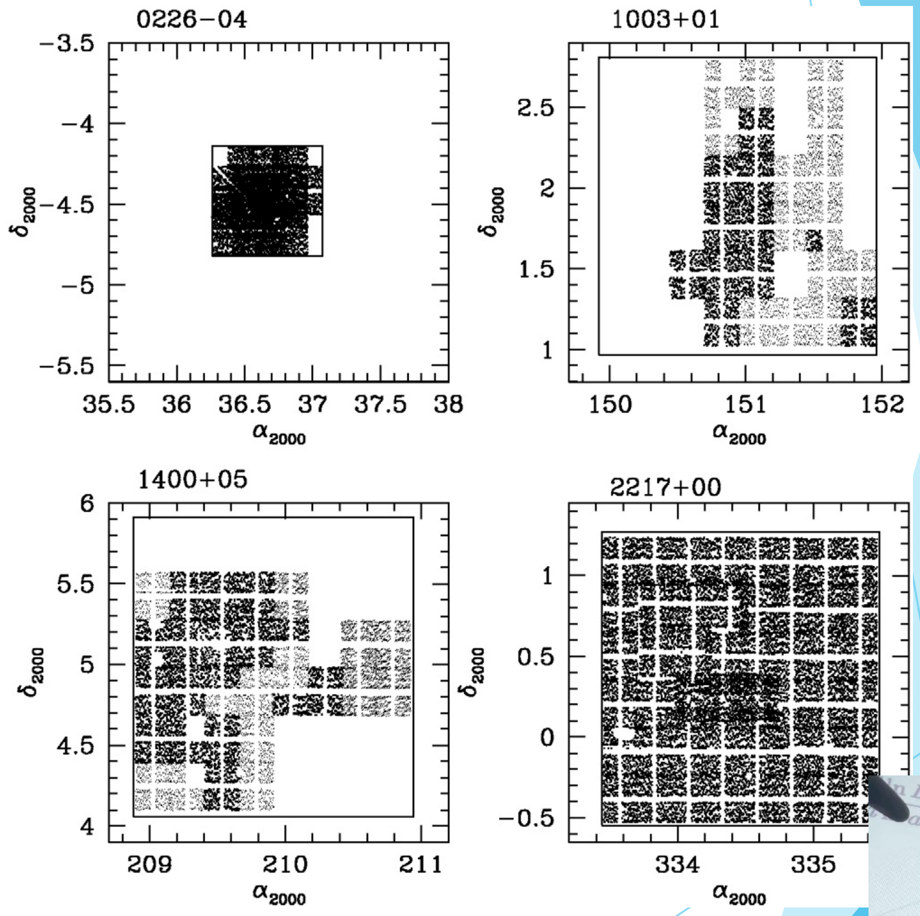


de la Torre et al. 2012

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

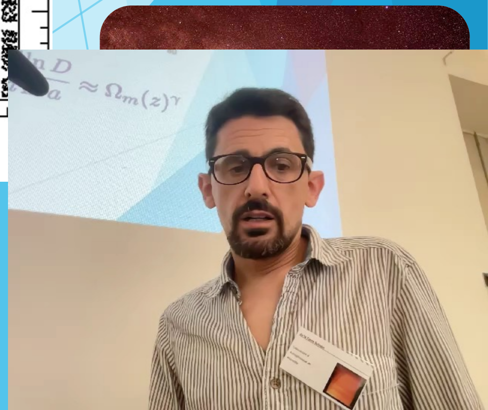
VIMOS VLT Deep Survey Wide





- I<22.5 survey over 8.5 deg^2, part of VVDS
- Less exploited than VVDS-Deep but …

Garilli et al. 2008



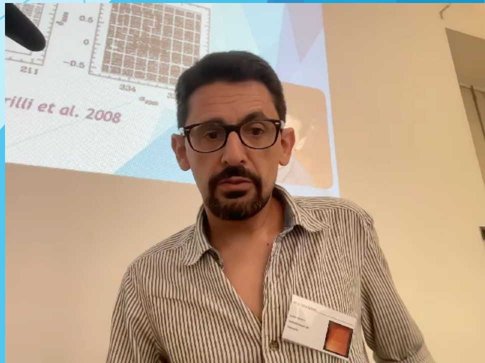
Redshift-space distortions

Nature, 451, 541 (2008)

A test of the nature of cosmic acceleration using galaxy redshift distortions

L. Guzzo[1,2,3,4], M. Pierleoni[3], B. Meneux[5], E. Branchini[6], O. Le Fèvre[7], C. Marinoni[8], B. Garilli[5], J. Blaizot[3], G. De Lucia[3], A. Pollo[7,9], H. J. McCracken[10,11], D. Bottini[5], V. Le Brun[7], D. Maccagni[5], J. P. Picat[12], R. Scaramella[13,14], M. Scodeggio[5], L. Tresse[7], G. Vettolani[13], A. Zanichelli[13], C. Adami[7], S. Arnouts[7], S. Bardelli[15], M. Bolzonella[15], A. Bongiorno[16], A. Cappi[15], S. Charlot[10], P. Ciliegi[15], T. Contini[12], O. Cucciati[1,17], S. de la Torre[7], K. Dolag[3], S. Foucaud[18], P. Franzetti[5], I. Gavignaud[19], O. Ilbert[20], A. Iovino[1], F. Lamareille[15], B. Marano[16], A. Mazure[7], P. Memeo[5], R. Merighi[15], L. Moscardini[16,21], S. Paltani[22,23], R. Pellò[12], E. Perez-Montero[12], L. Pozzetti[15], M. Radovich[24], D. Vergani[5], G. Zamorani[15] & E. Zucca[15]

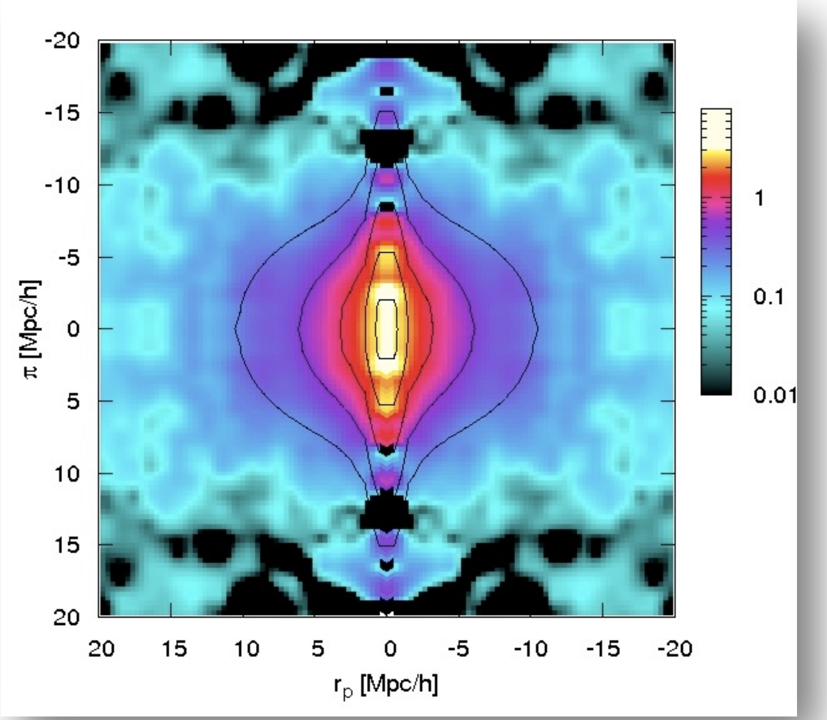
[1]INAF–Osservatorio Astronomico di Brera, Via Bianchi 46, I-23807 Merate (LC), Italy. [2]Max Planck Institut fur extraterrestrische Physik, [3]Max Planck Institut fur Astrophysik, [4]European Southern Observatory, D-85748 Garching, Germany. [5]INAF–IASF, Via Bassini 15, I-20133, Milano, Italy. [6]Dipartimento di Fisica, Universitá Roma III, Via della Vasca Navale 84, I-00146 Roma, Italy. [7]Laboratoire d'Astrophysique de Marseille, UMR6110, CNRS-Université de Provence, BP8, F-13376 Marseille cedex 12, France. [8]Centre de Physique Theorique, UMR 6207 CNRS-Université de Provence, F-13288 Marseille, France. [9]Astronomical Observatory of the Jagiellonian University, ul Orla 171, 30-244 Krakow, Poland. [10]Institut d'Astrophysique de Paris, UMR 7095, 98 bis Bvd Arago, [11]Observatoire de Paris, LERMA, 61 Avenue de l'Observatoire, F-75014 Paris, France. [12]Laboratoire d'Astrophysique de l'Observatoire Midi-Pyrénées (UMR 5572), 14 avenue E. Belin, F-31400 Toulouse, France. [13]INAF–IRA, Via Gobetti 101, I-40129 Bologna, Italy. [14]INAF–Osservatorio Astronomico di Roma, Via di Frascati 33, I-00040 Monte Porzio Catone, Italy. [15]INAF–Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy. [16]Università di Bologna, Dipartimento di Astronomia, Via Ranzani 1, I-40127 Bologna, Italy. [17]Dipartimento di Fisica–Universitá di Milano-Bicocca, Piazza delle Scienze 3, I-20126 Milano, Italy. [18]School of Physics and Astronomy, University of Nottingham, University Park, Nottingham NG72RD, UK. [19]Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany. [20]Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, Hawaii 96822, USA. [21]INFN–Sezione di Bologna, viale Berti-Pichat 6/2, I-40127 Bologna, Italy.[22]Geneva Observatory, ch. des Maillettes 51, CH-1290 Sauverny, Switzerland. [23]Integral Science Data Centre, ch. d'Ecogia 16, CH-1290 Versoix, Switzerland.[24]INAF–Osservatorio Astronomico di Capodimonte, Via Moiariello 16 I-80131, Napoli, Italy.



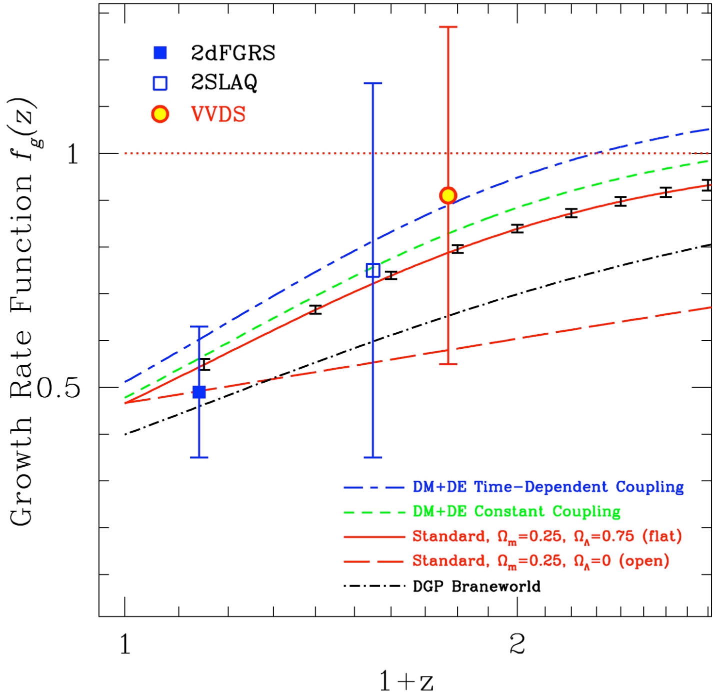
Redshift-space distortions

Redshift-space distortions (RSD) in galaxy redshift surveys are unique to measure the **growth rate of structure *f(z)***

Anisotropic correlation function



Growth rate of structure measurements

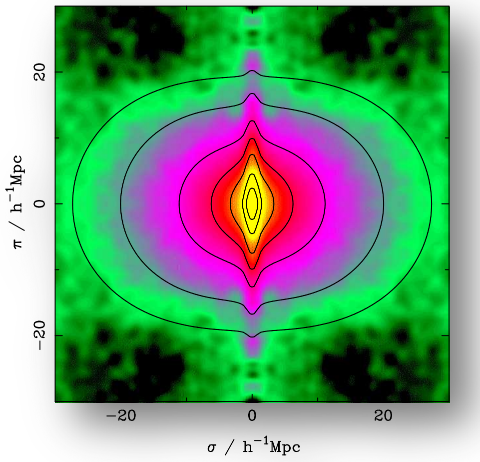


(*Guzzo et al. 2008, Nature*)

→ Proof-of-concept in 2008 with VVDS survey (PI: Le Fèvre)

Redshift-space distortions

- RSD are known for more than 30 years... (Kaiser 1987)



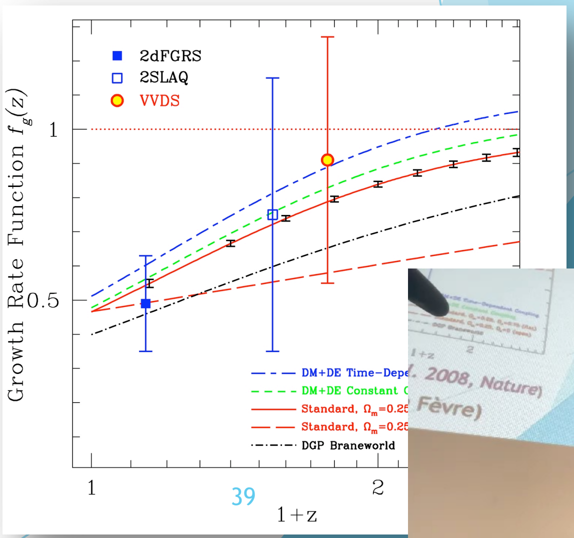
Peacock et al. (2001), Nature

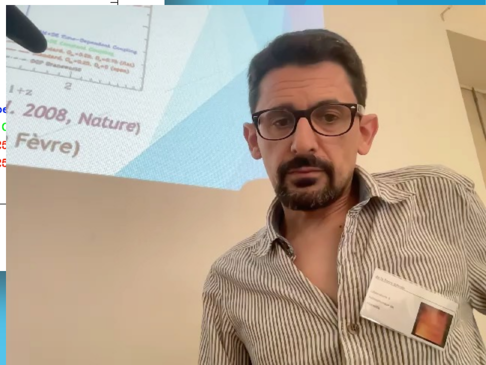
RSD to measure Ω_m : $\beta = f/b = \boldsymbol{\Omega_m}^{\gamma}/b$

- ... but we realised its usefulness for probing gravity lately

Guzzo et al. (2008), Nature

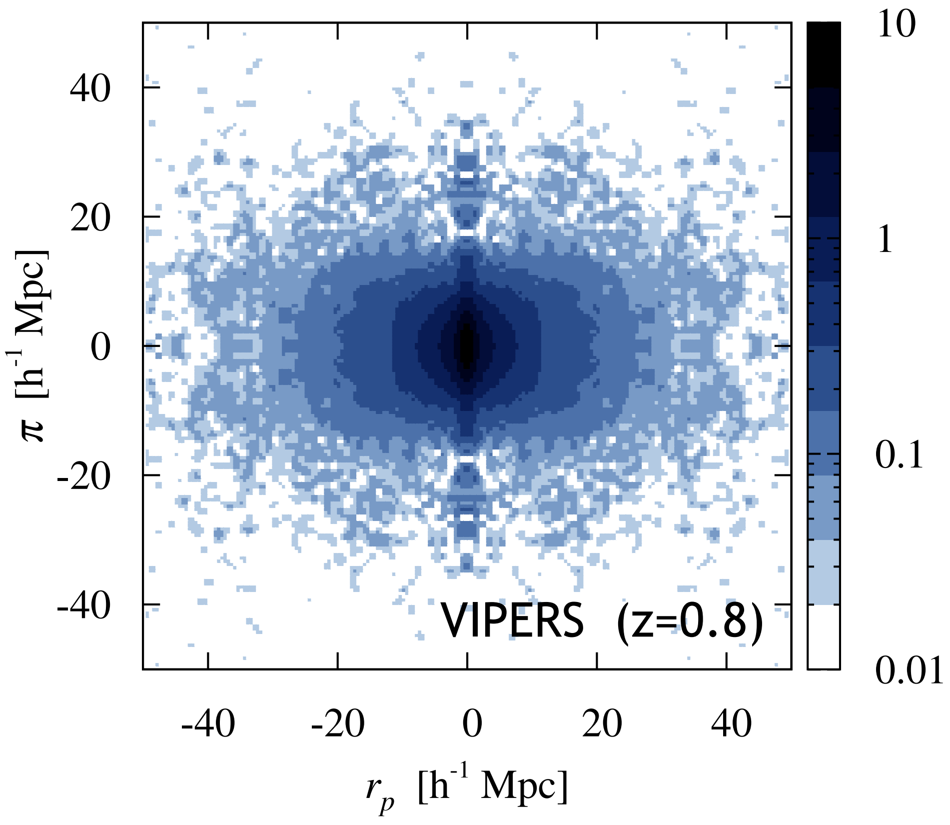
RSD to probe gravity: $\beta = f/b = \Omega_m^{\gamma}/b_L$



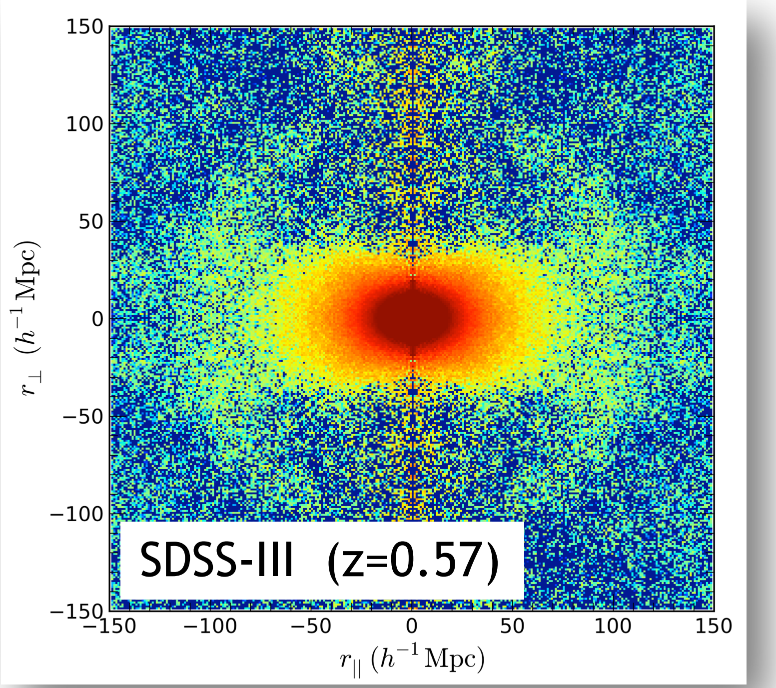


RSD measurements

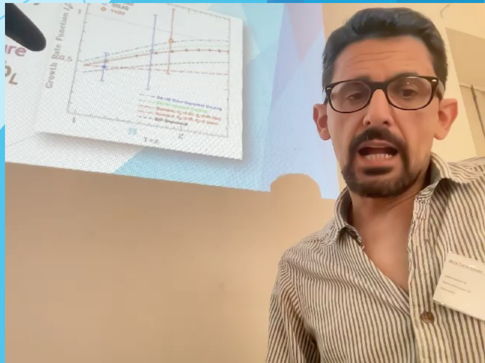
Anisotropic correlation function : $\xi(r_\perp, r_\parallel) = \int \frac{d^3\boldsymbol{k}}{(2\pi)^3} e^{i\boldsymbol{k}\cdot\boldsymbol{s}} P^s(k,\mu)$



VIPERS, de la Torre et al. 2013)

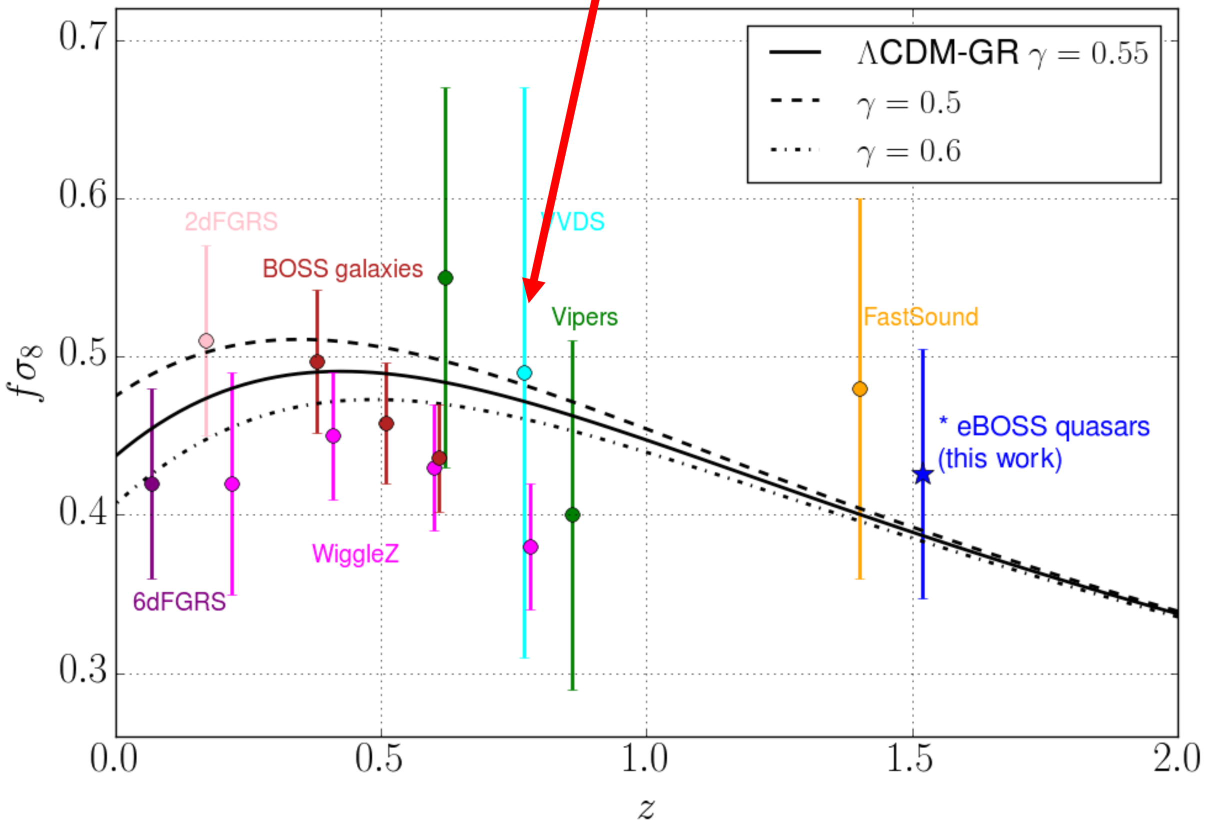


SDSS/BOSS, Samushia et al. 2014



Redshift-space distortions

Guzzo et al. 2008



Zarrouk et al. 2018

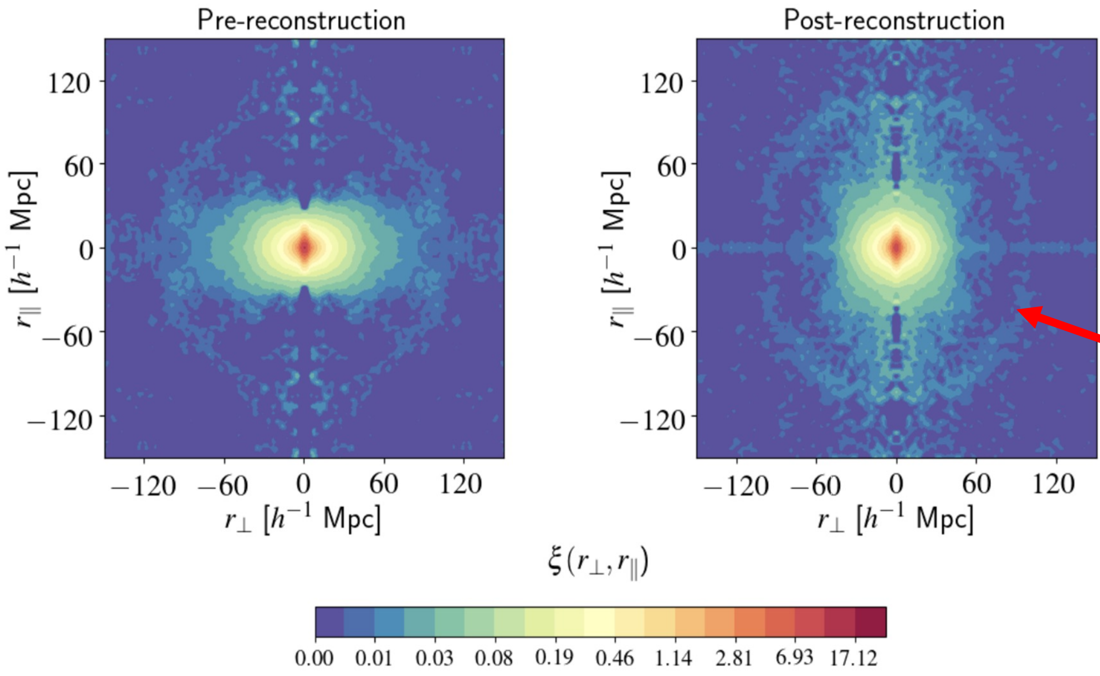
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = -\frac{8\pi G}{c^2} T_{\mu\nu}$$

?

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

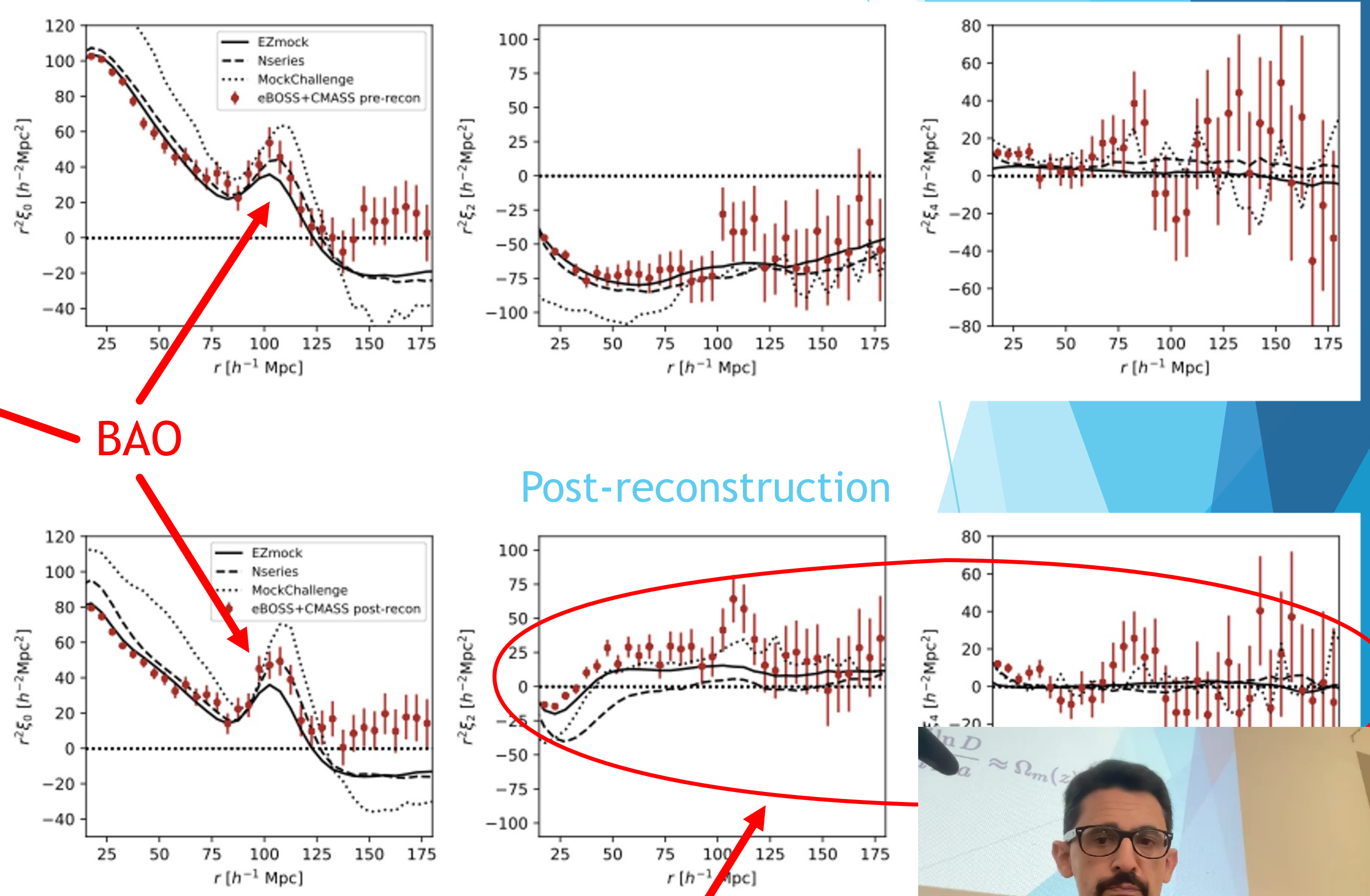
State-of the art: eBOSS survey

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



Galaxy anisotropic correlation function

Pre-reconstruction



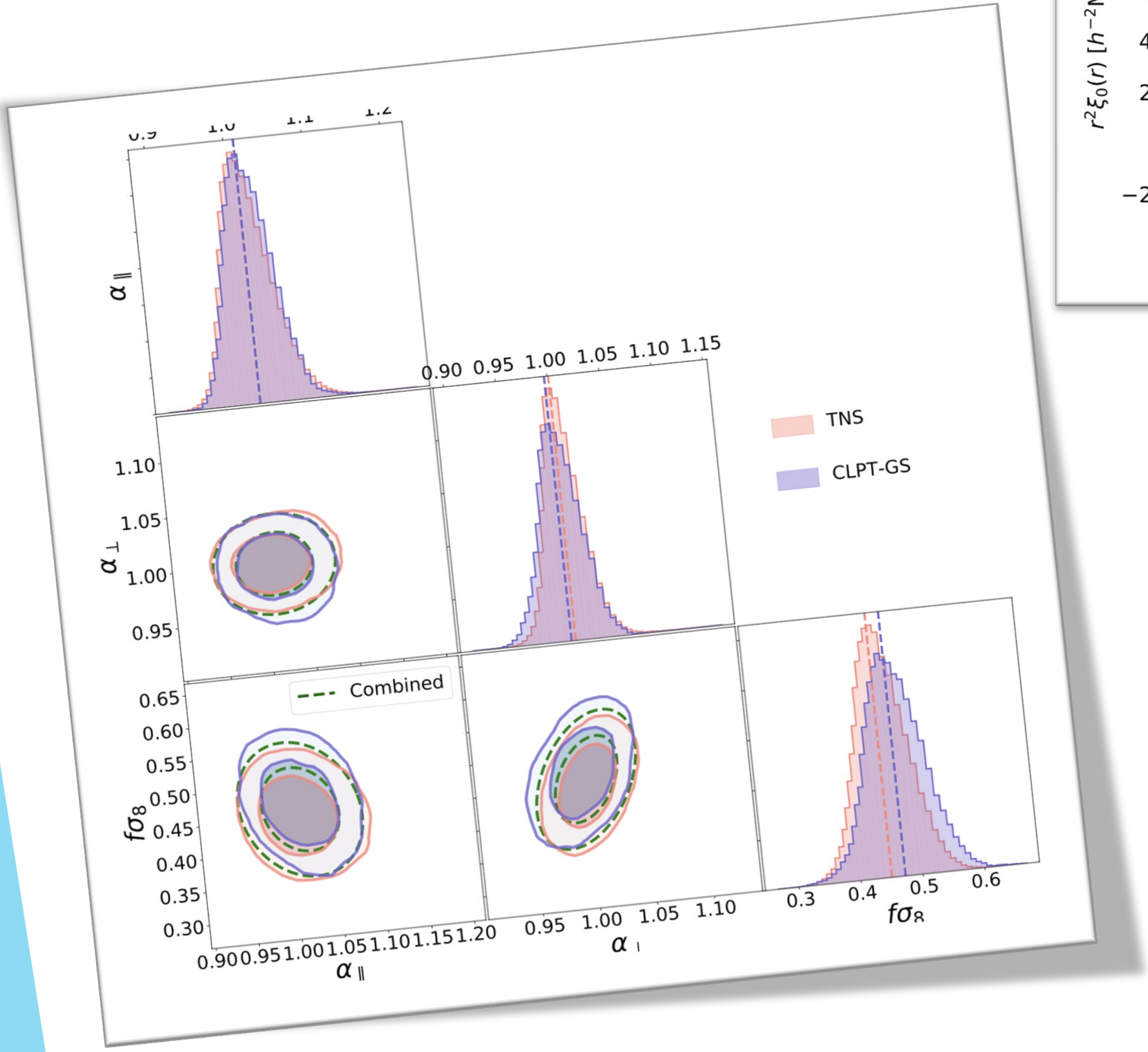
Post-reconstruction

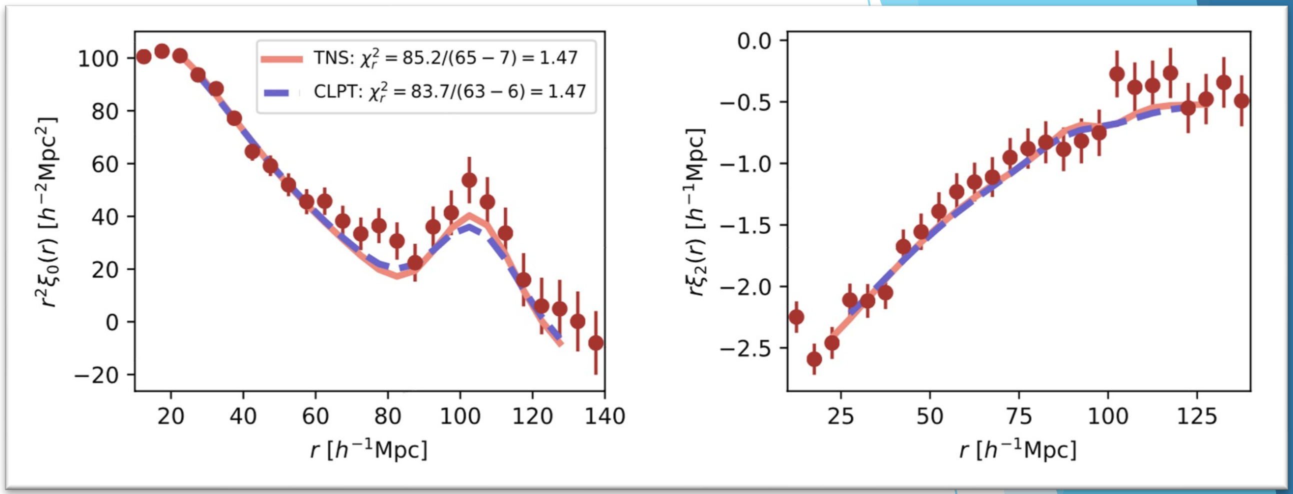
BAO

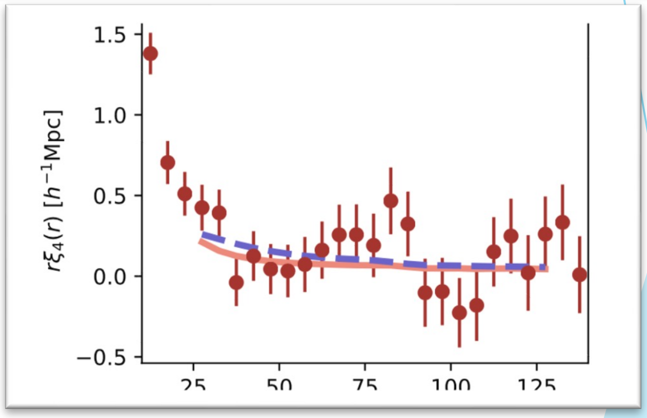
Anisotropy almost remov
reconstructoin

Bautista et al. 2020

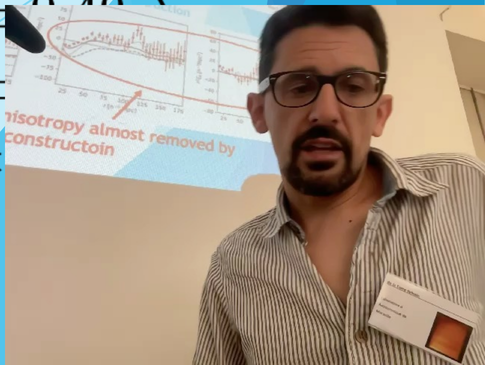
RSD measurements



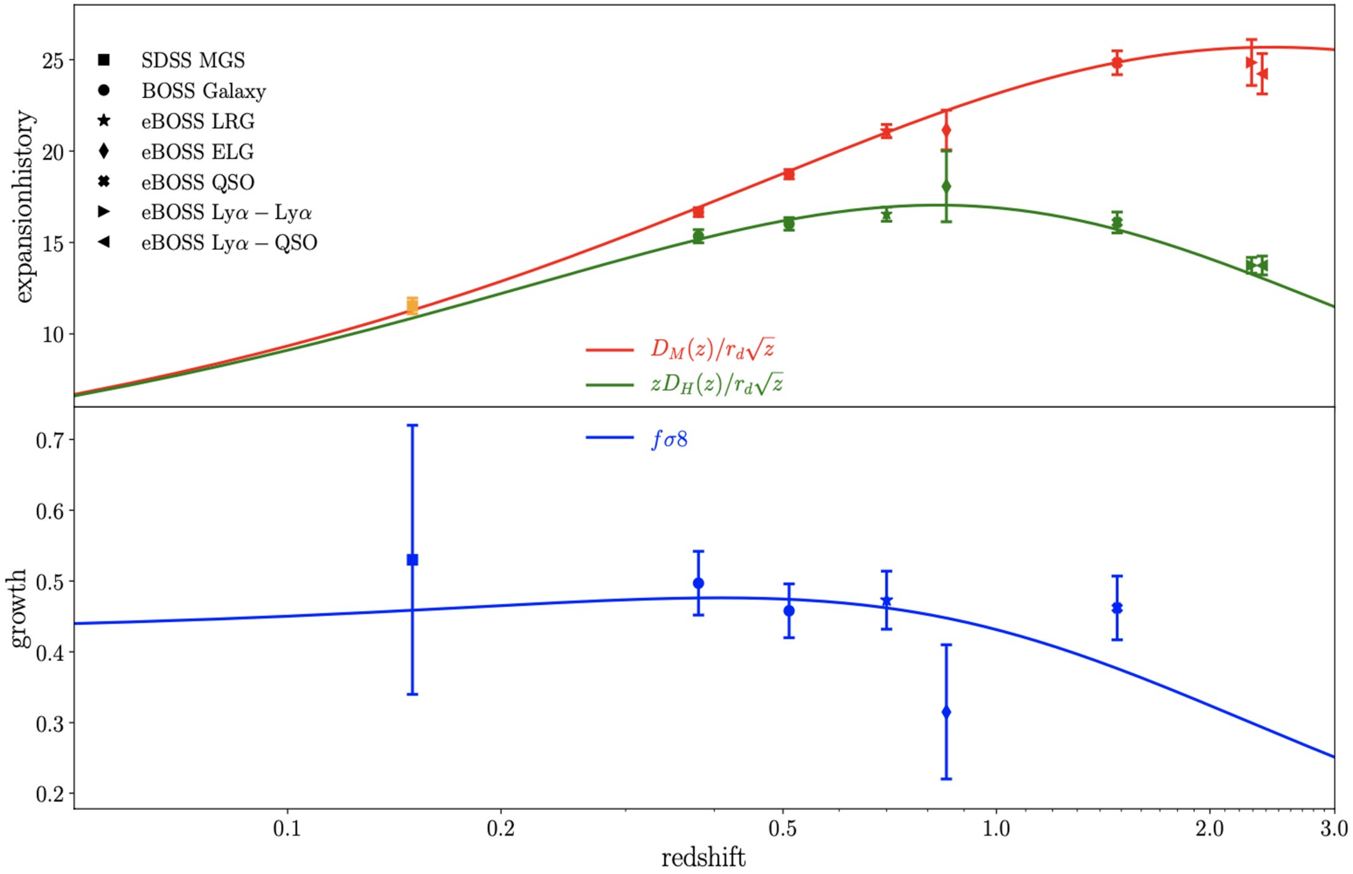




$$\mathbf{D}_{\mathrm{RSD},\xi_\ell} = \begin{pmatrix} D_M/r_d \\ D_H/r_d \\ f\sigma_8 \end{pmatrix} = \begin{pmatrix} 17.42 \pm \\ 20.46 \pm \\ 0.460 \pm \end{pmatrix}$$

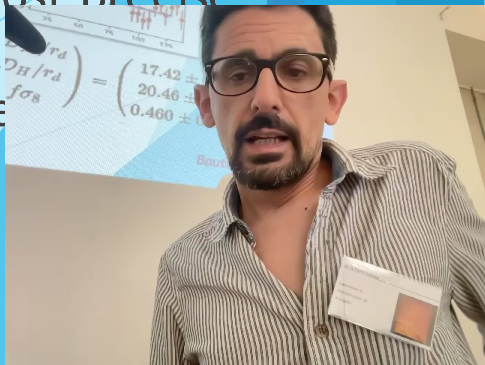


Cosmological implication of SDSS surveys

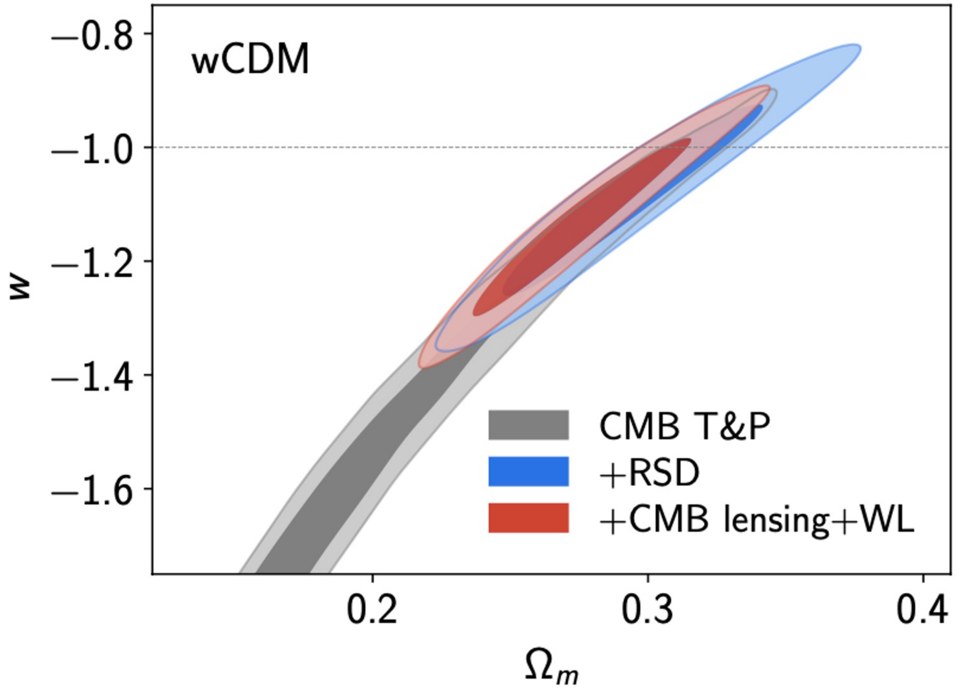


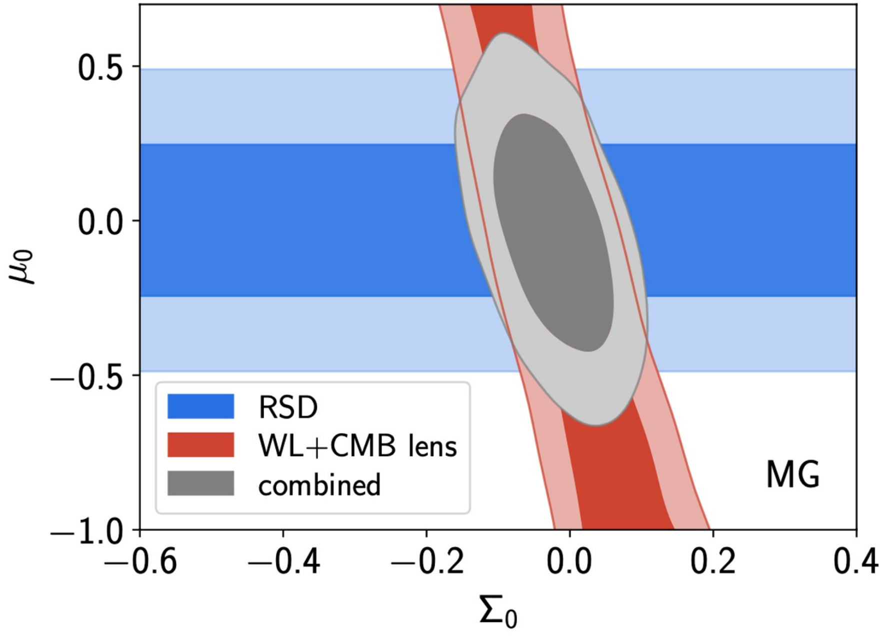
eBOSS collaboration 2021

- 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 expa growth history to date



Cosmological implication of RSD





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

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

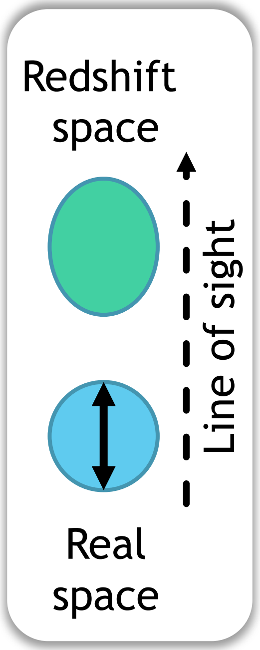
$$w = -1.09 \pm 0.11$$

$$\mu_0 = 0.04 \pm 0.25,\ \Sigma_0 = 0.0$$

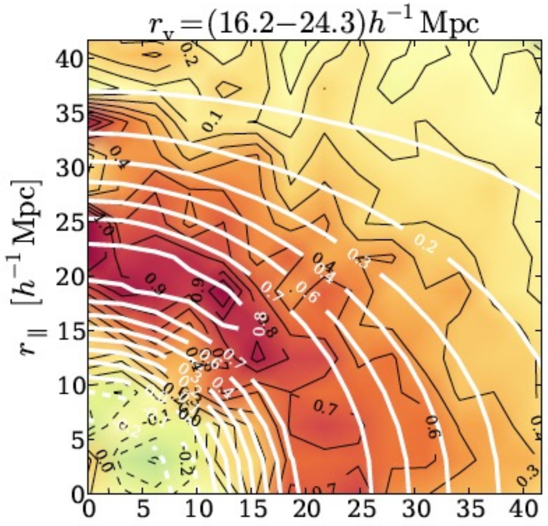
- Observations compatible with the standard model: General Relativity + cosmological constant
- No detection of (parametric) modification to General Relativity prediction

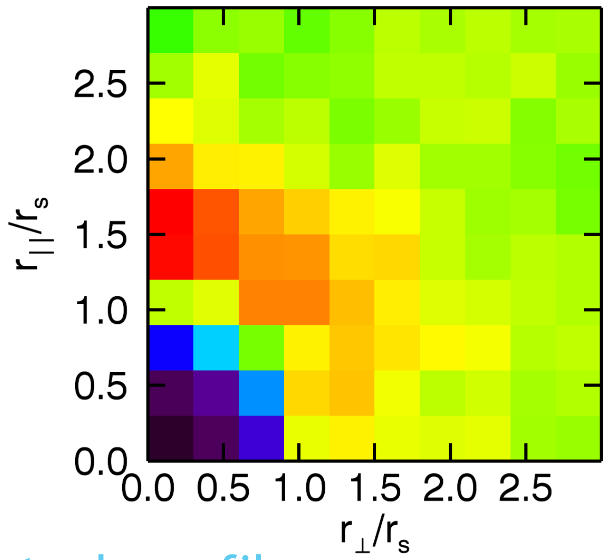
Other LSS tracers

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



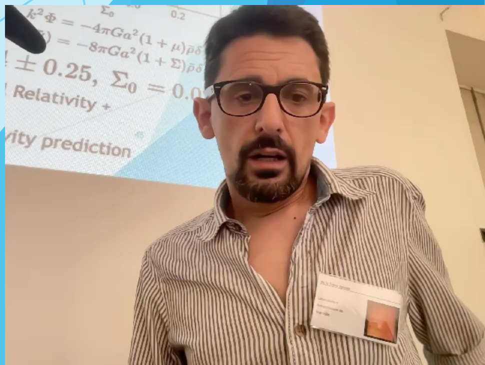
Hamaus et al., 2016





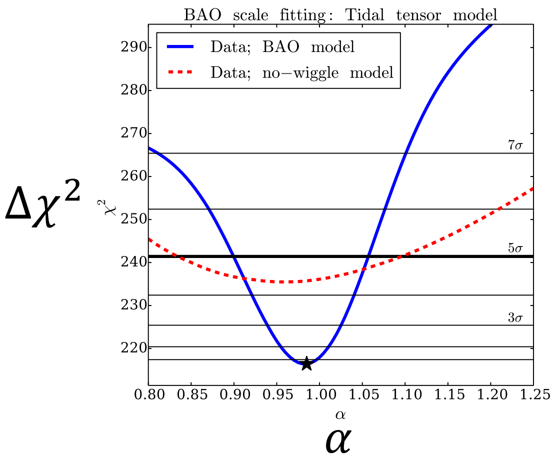
Hawken et al., 2017

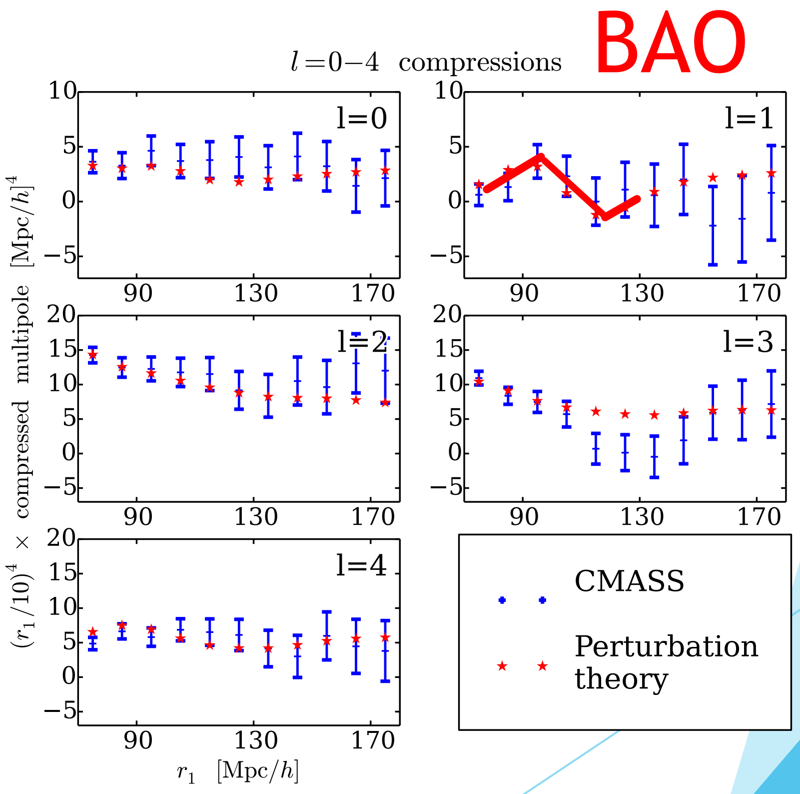
Anisotropic void stack profile



Three-point statistics

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



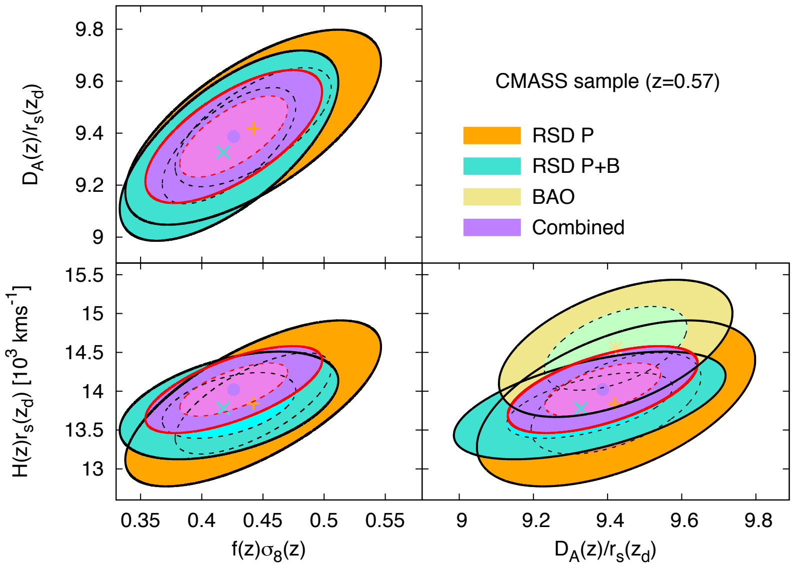


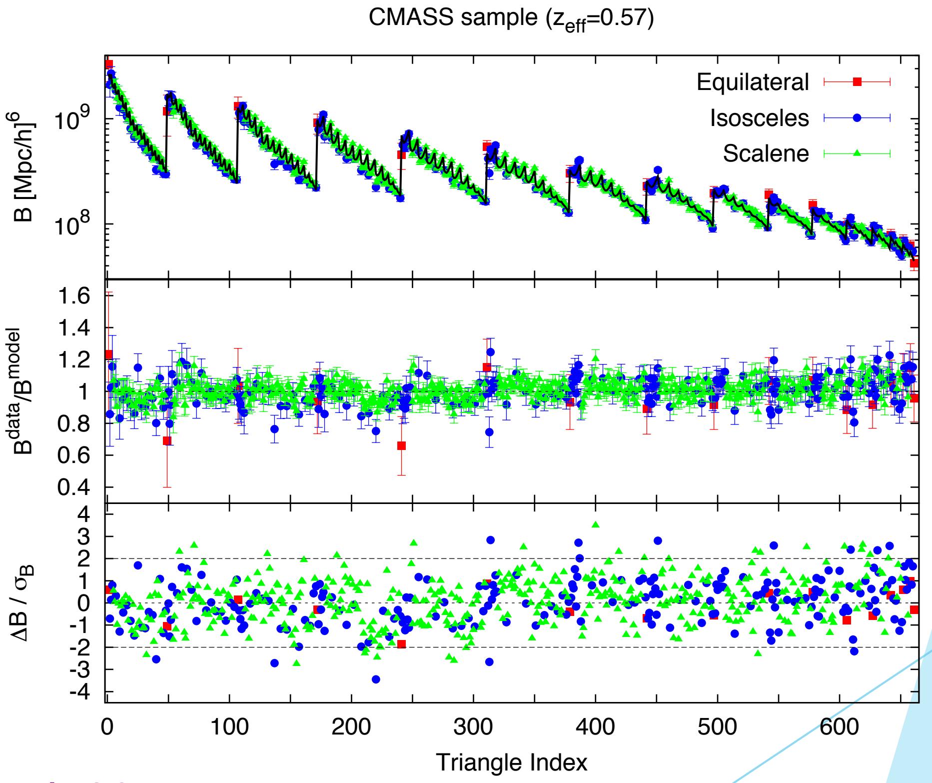
$$B_s(k_1,k_2,x) = b_1^3 P(k_1)P(k_2)\Big[\tilde{F}_2(k_1,k_2;x)\mathcal{D}_{\mathrm{SQ1}}(\beta,x) + \tilde{G}_2(k_1,k_2;x)\mathcal{D}_{\mathrm{SQ2}}(\beta,k_1,k_2;x) + \mathcal{D}_{\mathrm{NLB}}(\beta,\gamma;x) + \mathcal{D}_{\mathrm{FOG}}(\beta,k_1,k_2;x)\Big] + \text{cyc.},$$

Slepian et al., 2016, 2017

Combining two- and three-point statistics

- Adding Bispectrum improves cosmological constraints





Gil-Marin et al. 2017

Outline

1. Standard cosmological model
2. Cosmic acceleration & dark energy
3. Galaxy redshift survey cosmology
4. **Euclid mission**
5. Conclusion

Euclid Satellite: end of assembly in Turin last week

Euclid: a space mission to solve dark energy

- 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

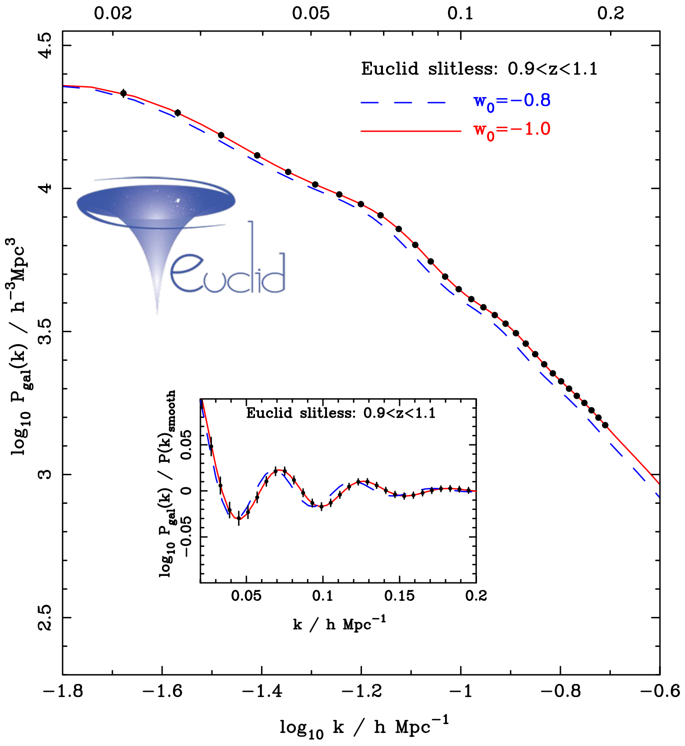
NISP at LAM

Over 200
and e
Europe
strong
also tha

Euclid mission

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

Galaxy power spectrum

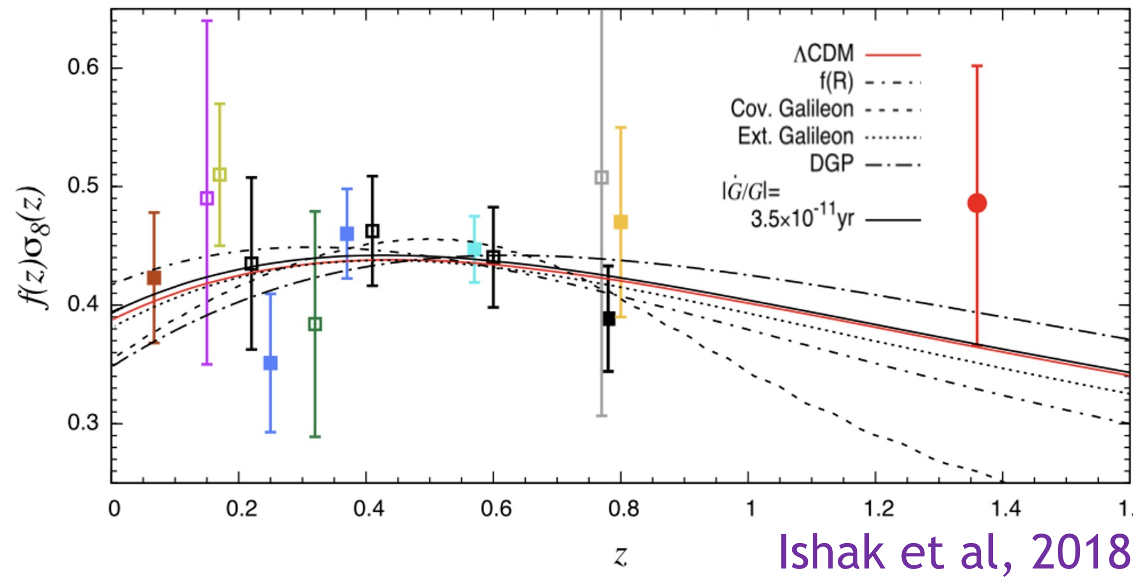


With Euclid & DESI we expect:

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

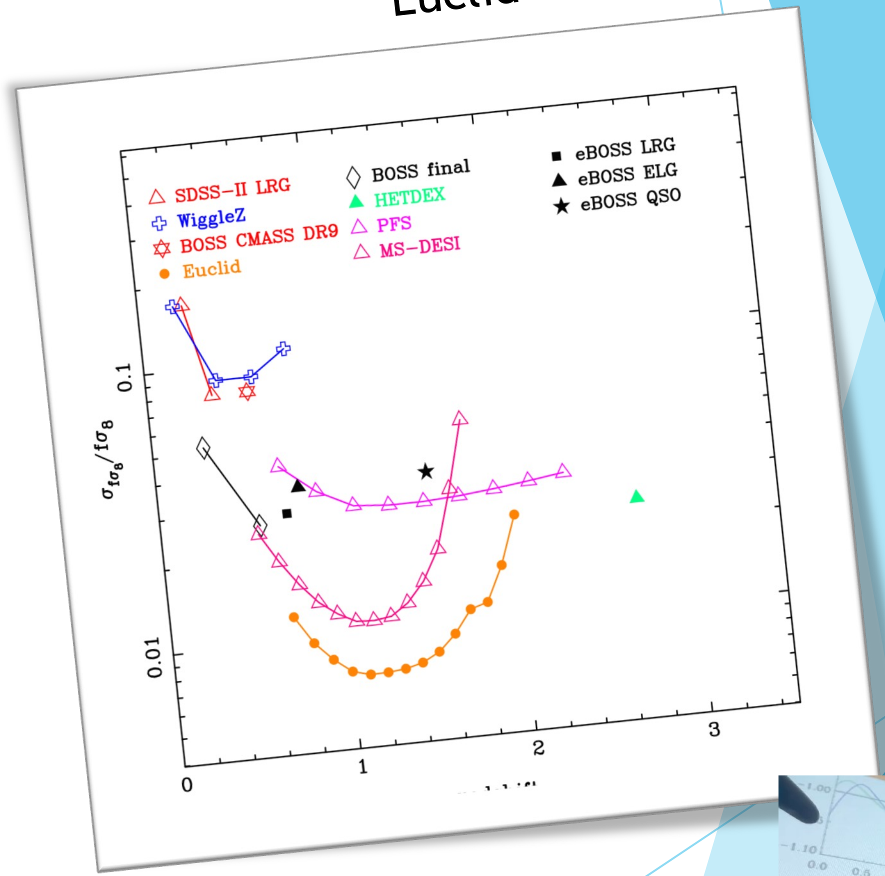
→ Crucial to solve the Dark Energy problem

Euclid mission



Ishak et al, 2018

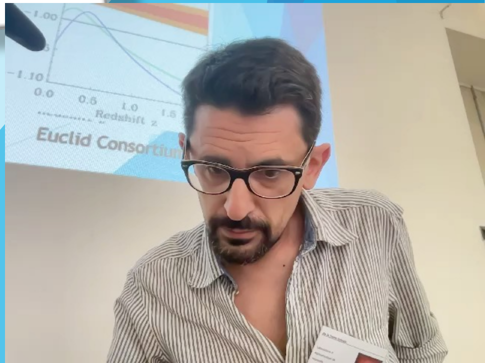
Euclid Consortium



Growth of structure / gravity

- Next-generation show allow testing gravity and cosmology beyond standard model, e.g. be sensitive to modified gravity or DE models

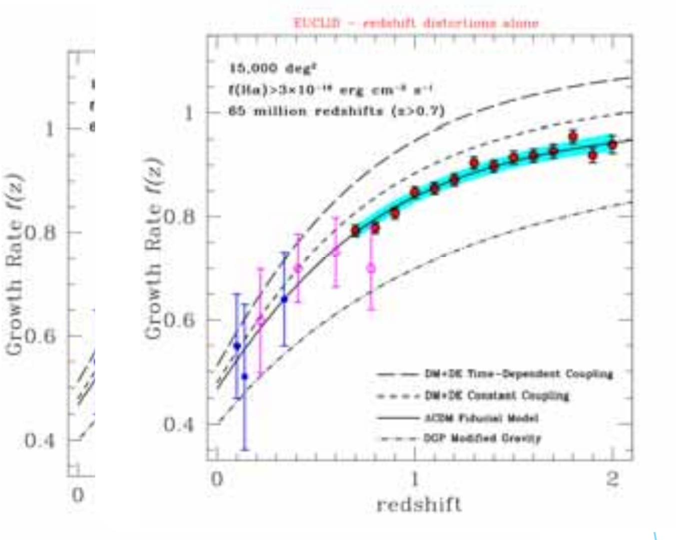
Euclid Forecast on the growth of structure

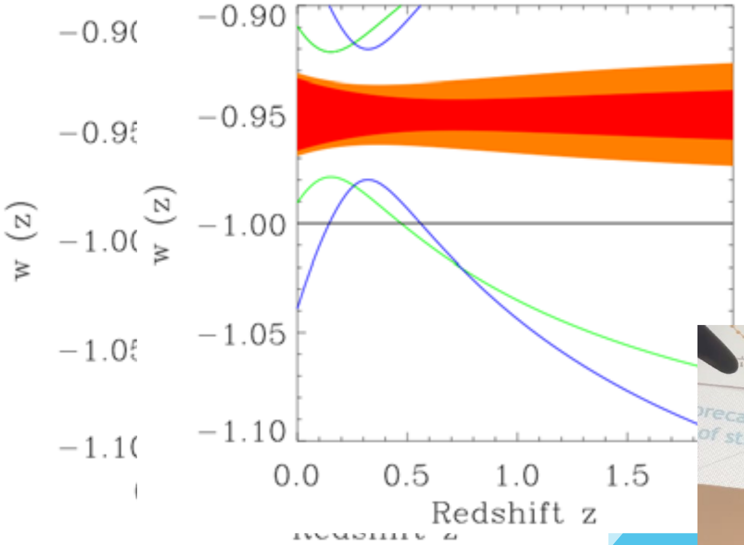


Euclid mission

- Euclid will use gravitational lensing and galaxy aggregation to measure the expansion history of the Universe, the dark energy equation of state, and the growth rate of structures to within one percent accuracy

- 1% precision needed to break the degeneracies between dark energy and modified gravitation models





Euclid Consortium

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
- Importance of controling systematic errors in surveys at exquisite level to achieve this goal