Cosmological constraints from current and future galaxy (spectroscopic) redshift surveys

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Understanding the Early Universe

CERN TH Institute

13/1/2015

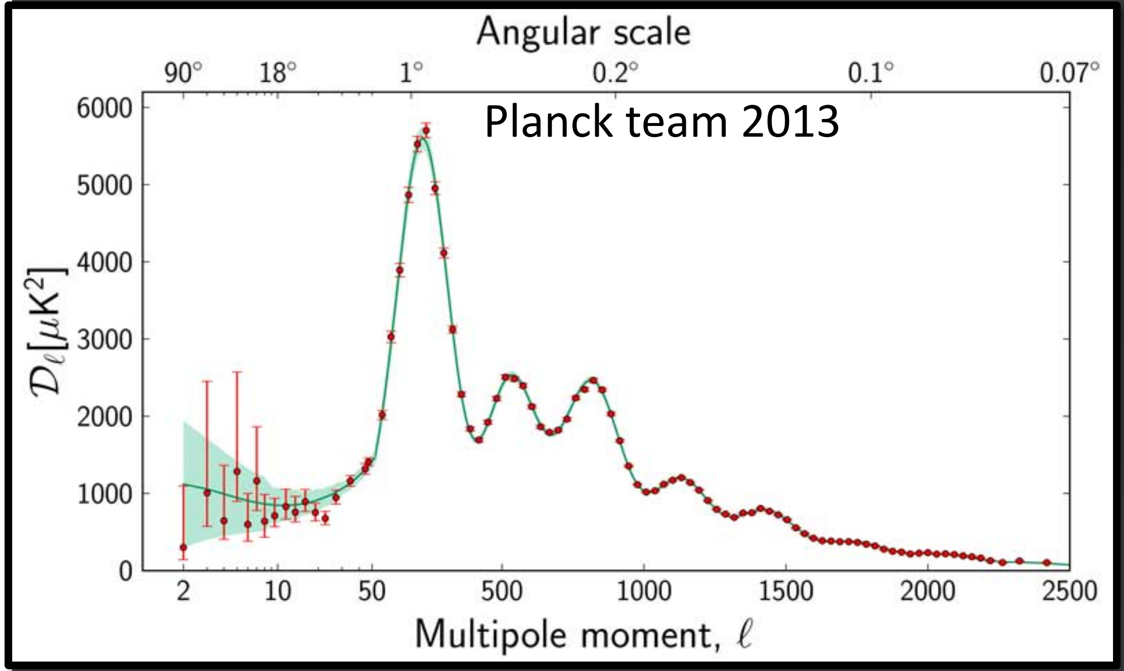
Currently the main science cases for Large Scale Structure analyses are Dark Energy and non-Einstein gravity models. Constraints on initial conditions are complementary to those from the CMB that remains the main window to the Early Universe.

Stating the obvious: CMB provides 2D information at a given epoch. Redshift surveys provide 3D information at different epochs.

Layout of the Talk

- Galaxy Redshift Surveys. Main scientific motivations and probes.
- State of the Art.
- Outlook and forecast: Euclid (and DASI).
- Early Universe constraints.
- Synergy with weak lensing analyses.

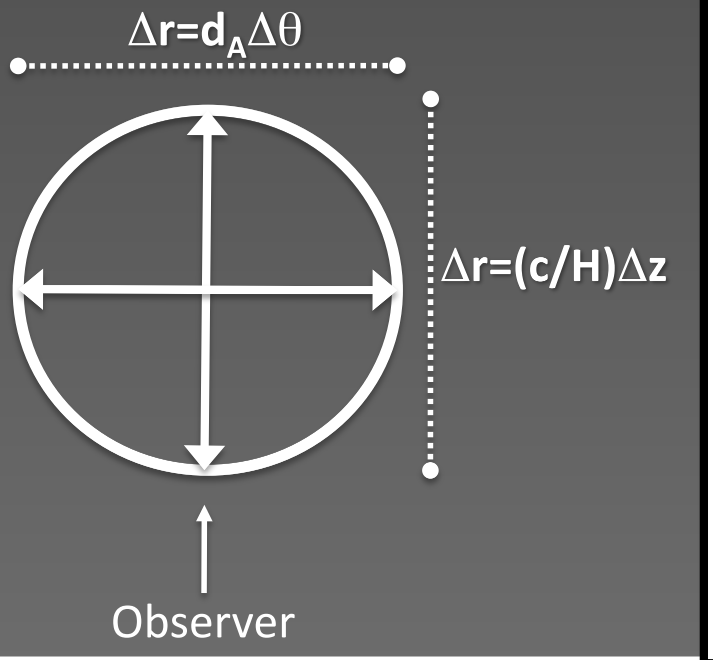
Motivation 1: Geometry of the Universe



Sound waves in the early universe produce a characteristic scale in the CMB anisotropies and a BAO scale in the clustering of matter at later times.

The scale can be calibrated to sub-% accuracy.

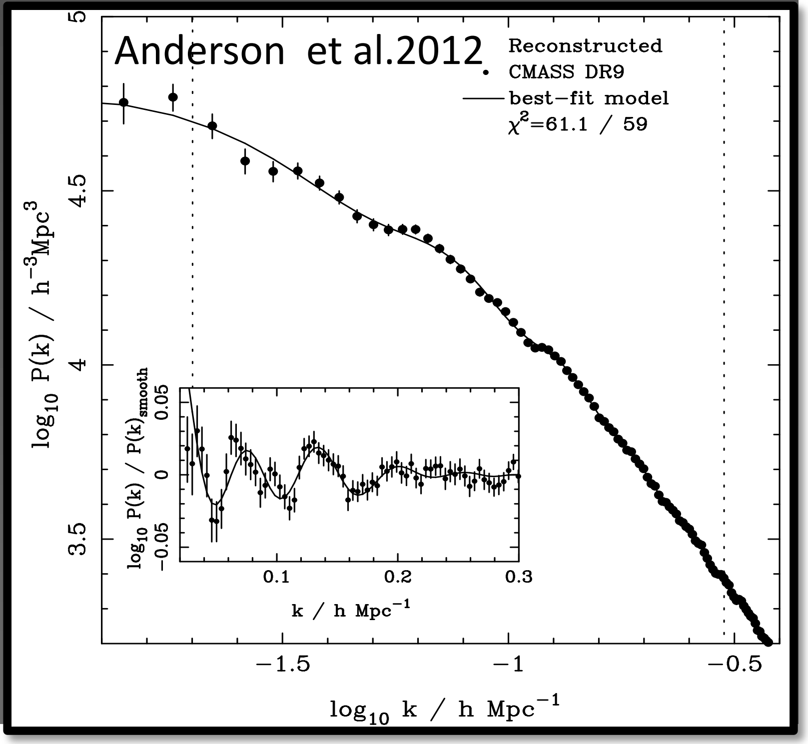
Spectroscopic redshift surveys can measure this scale along and across the line of sight at different epochs.



$\Delta r = d_A \Delta\theta$

$\Delta r = (c/H)\Delta z$

Observer



Classical geometry tests probe the expansion history of the Universe

$$d_L = (1+z)\int_0^z dz'/H(z')$$

$$d_A = (1+z)^{-1}\int_0^z dz'/H(z')$$

From SN1a
at different redshifts

From CMB TT spectrum
and BAO in galaxy clustering

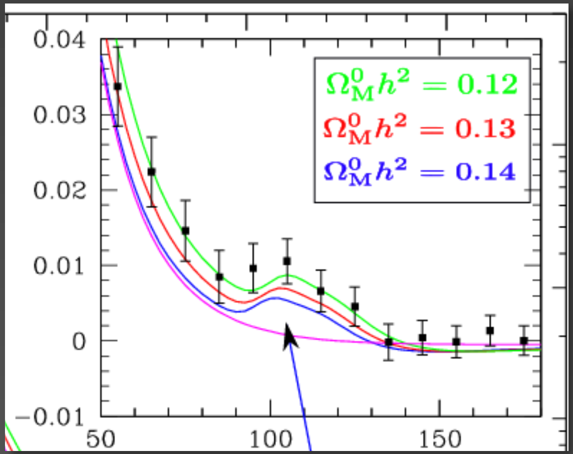
$$H^2(z) = H_0^2\{\Omega_k(1+z)^2 + \Omega_m(1+z)^3 + \Omega_\gamma(1+z)^4 + \Omega_x \exp[W(z)]\}$$

$$W(z) = 3\int_0^z \frac{1+w(z)}{1+z}dz; \quad w(z) \equiv \frac{p_i}{\rho_i c^2}; \quad \Omega_i \equiv \frac{\rho_i}{\rho_c}; \quad \rho_c \equiv \frac{3H_0^2}{8\pi G}; \quad H \equiv \frac{\dot{a}}{a}$$

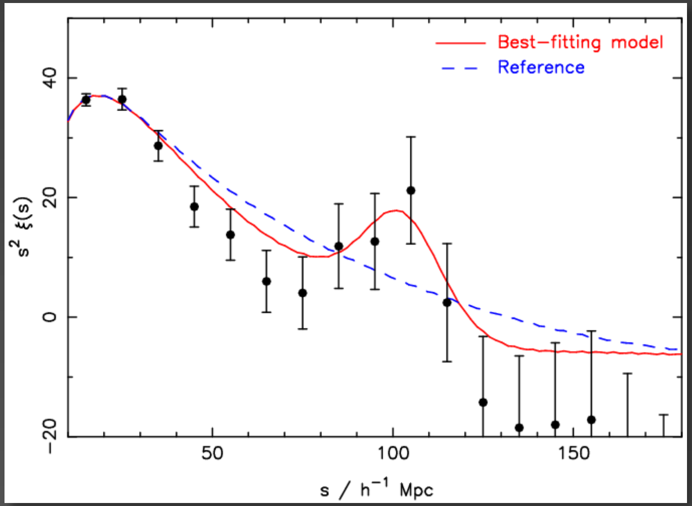
Motivation 1: trace the expansion history of the Universe to constrain Dark Energy (as well as the other parameters)

BAOs State of the Art

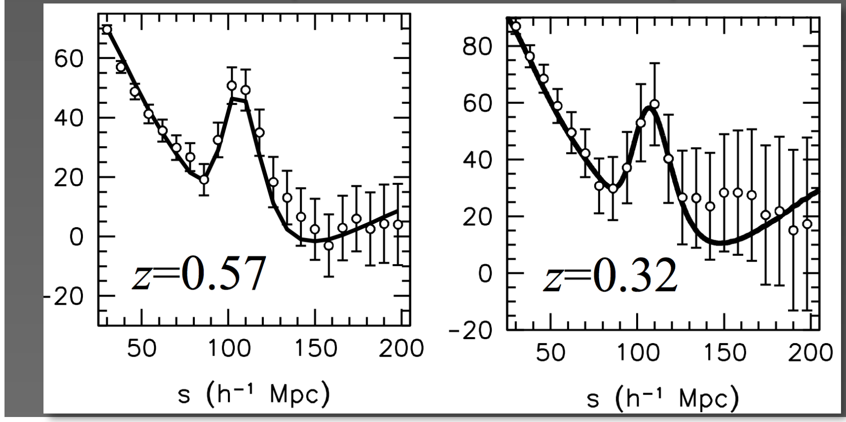
First BAO detection from SDSS-II Galaxies (Eisenstein+ 2005) at z=0.35



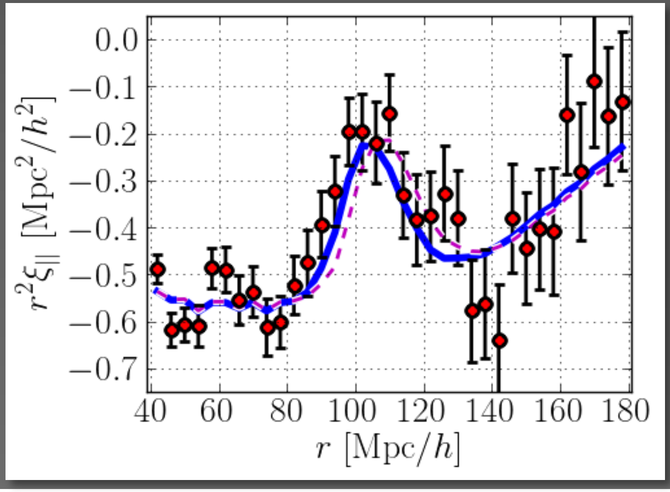
Wigglez galaxies (Blake+ 2011) at z=0.6



SDSS-III BOSS galaxies. BAOs at z=0.32 (Tojeiro+ 2014) and z=0.57 (Anderson+ 2014)



SDSS-III BOSS Ly-a forest at z=2.4 (Delubac+ 2014)



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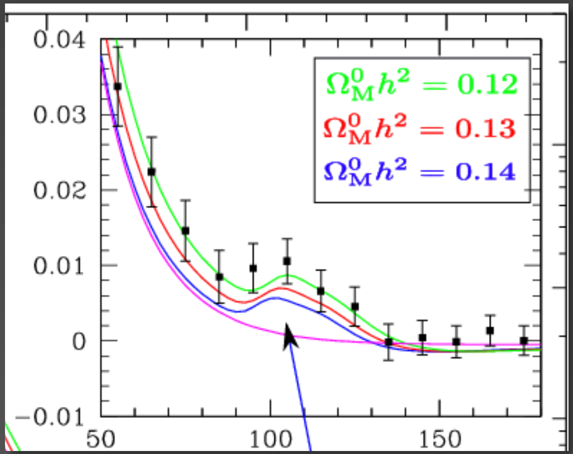

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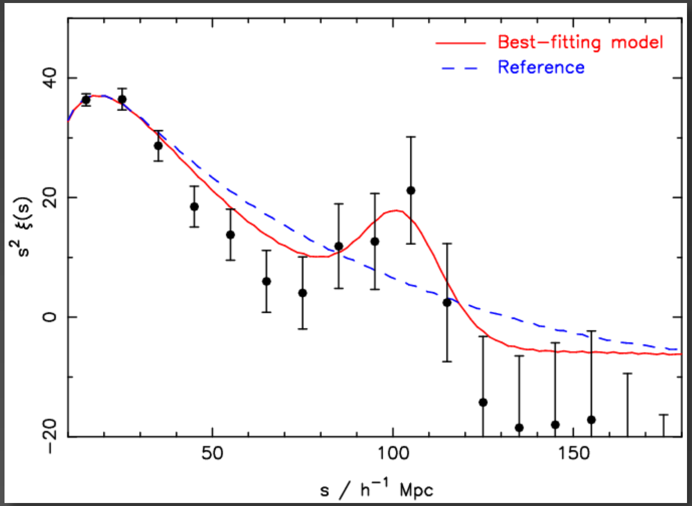

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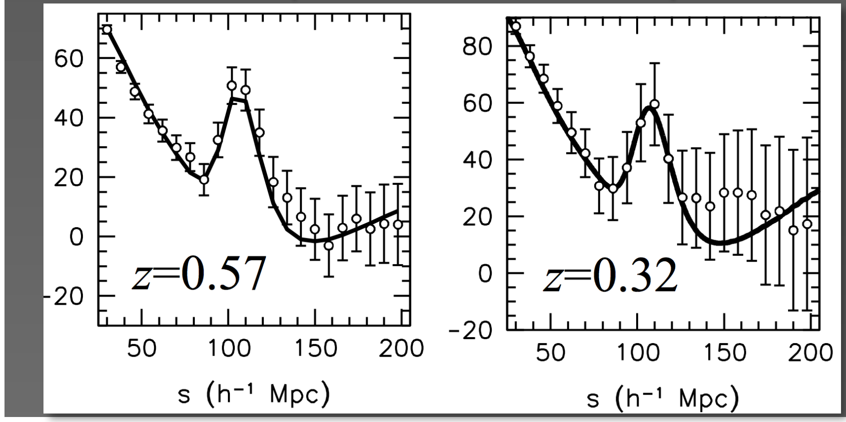

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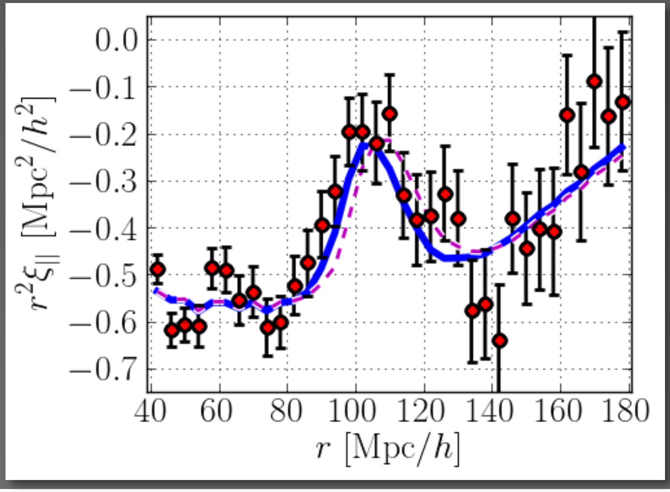

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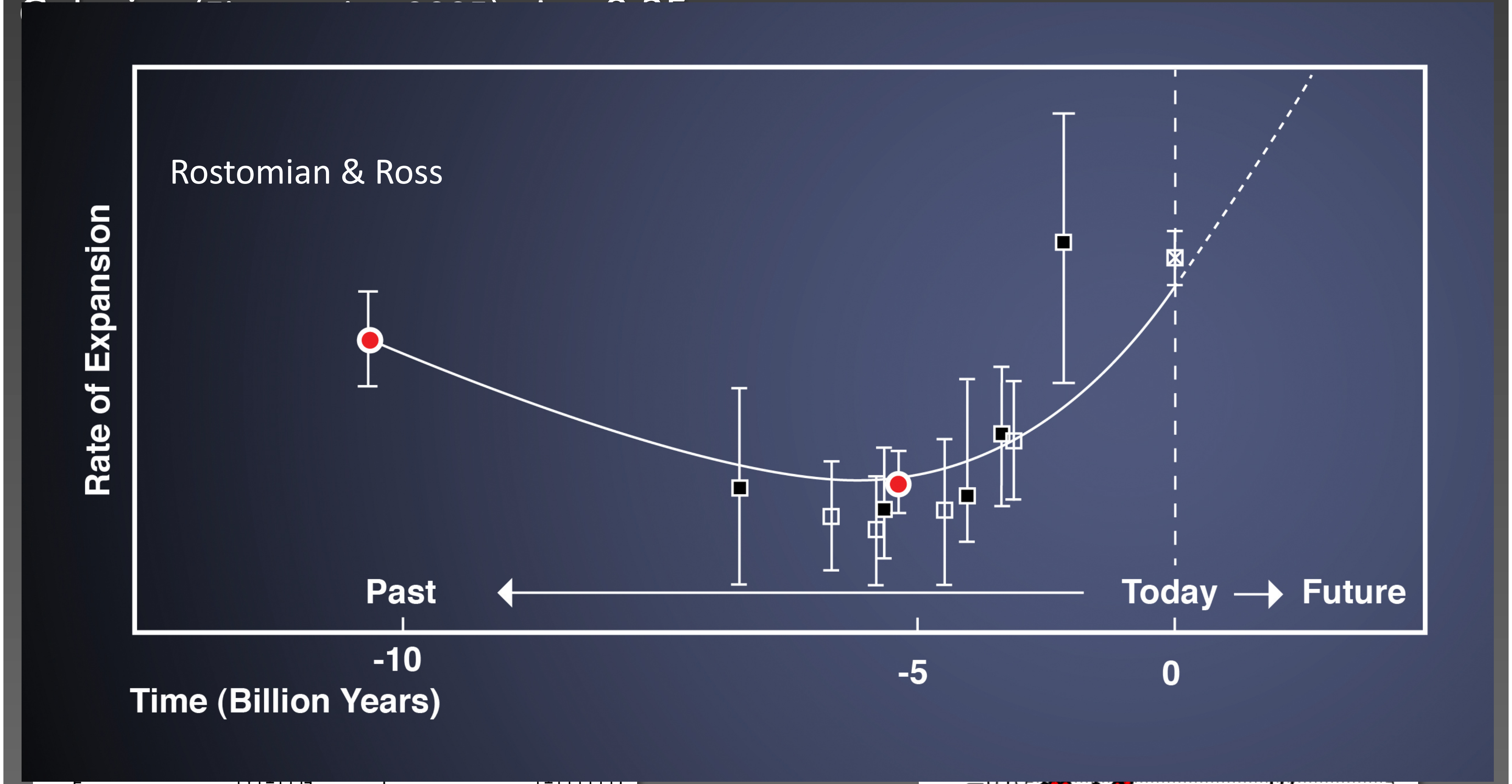
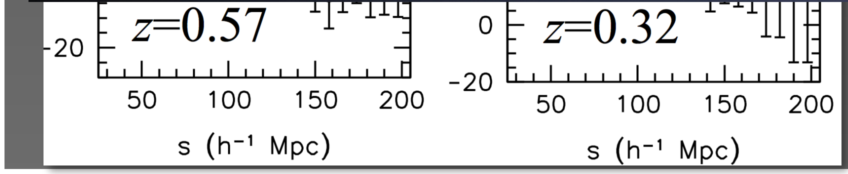
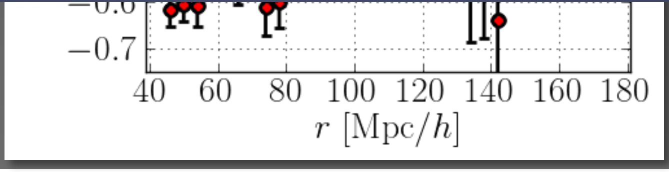
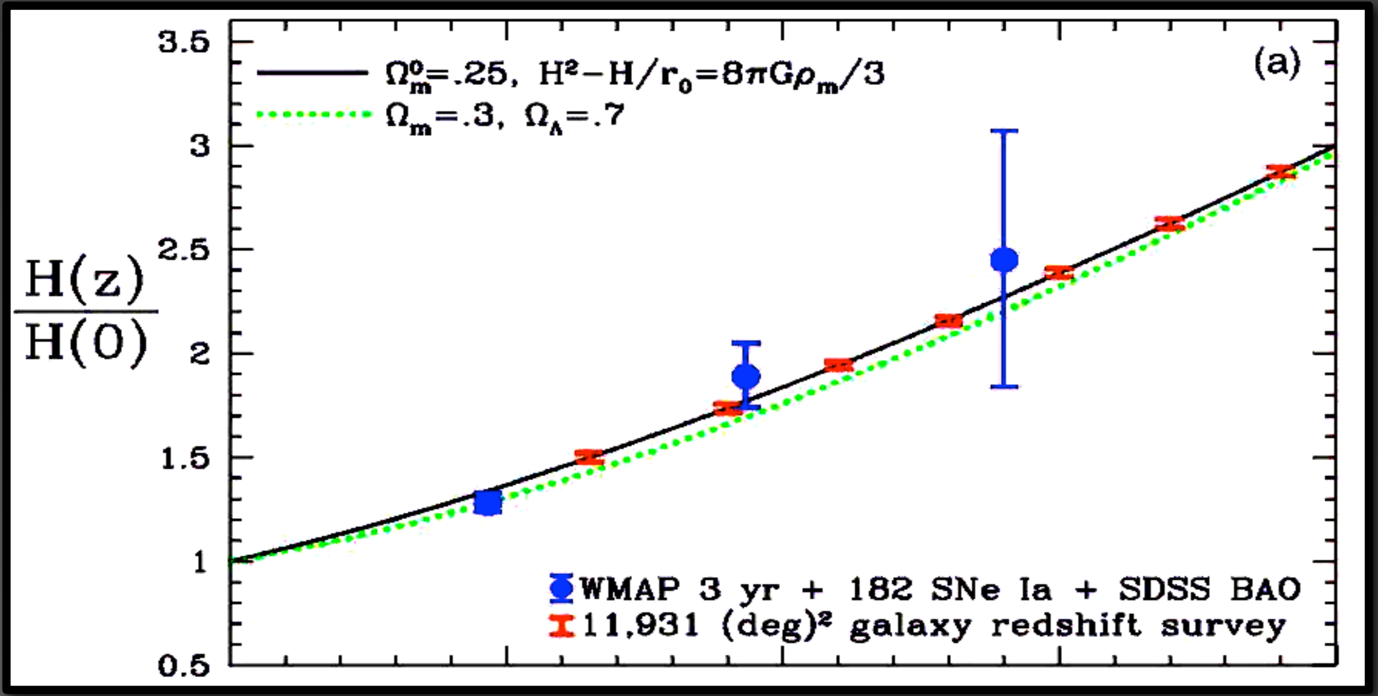






Does the expansion history reveal the nature of the accelerated expansion of the Universe ?

NO



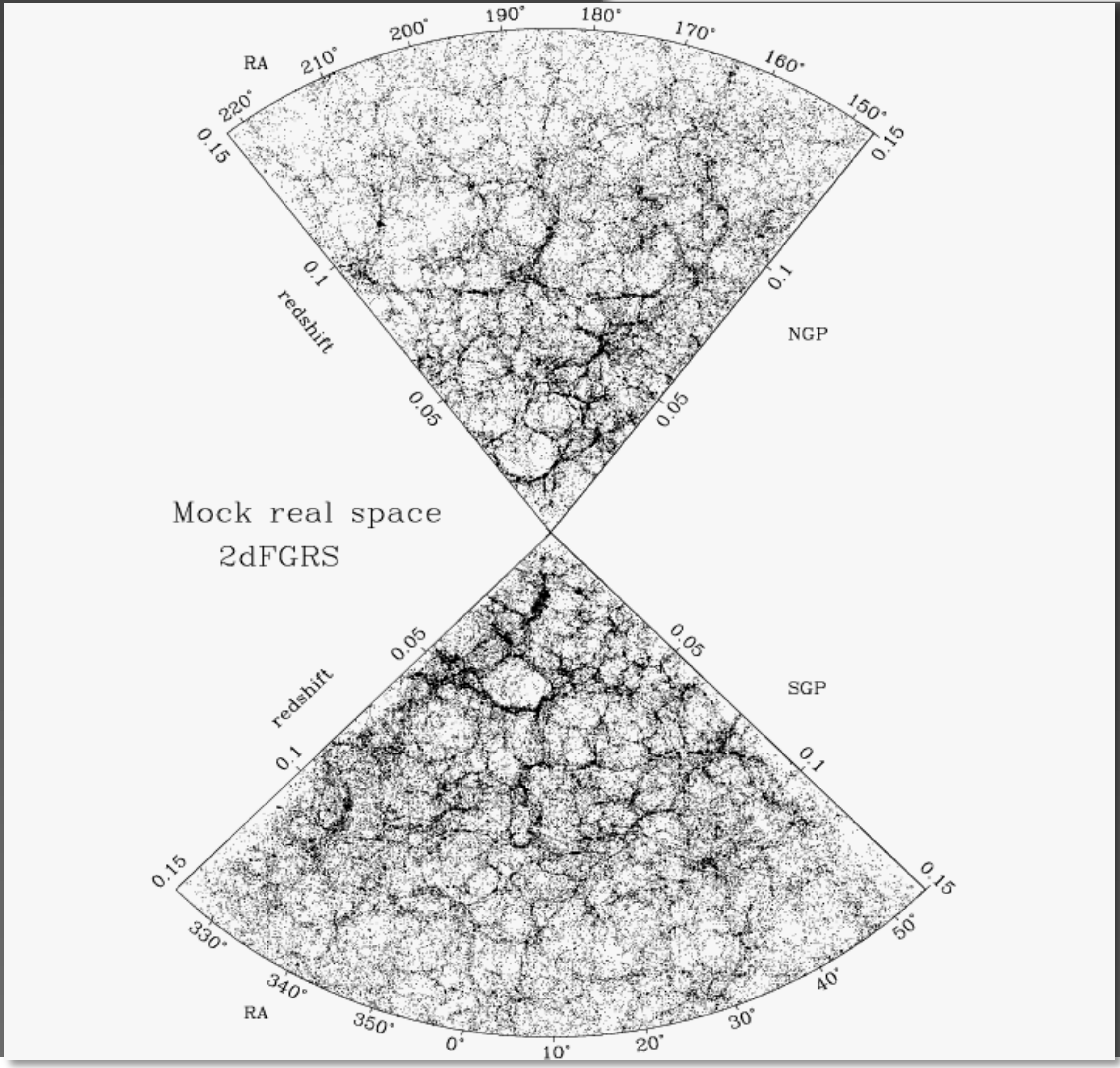
Alternative gravity models can predict the same expansion history as Dark Energy models

Motivation 2: Tracing the growth of fluctuations

Exploiting Peculiar Velocities

$$\vec{\nabla}\cdot\vec{v}_p = faH\delta_m$$

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



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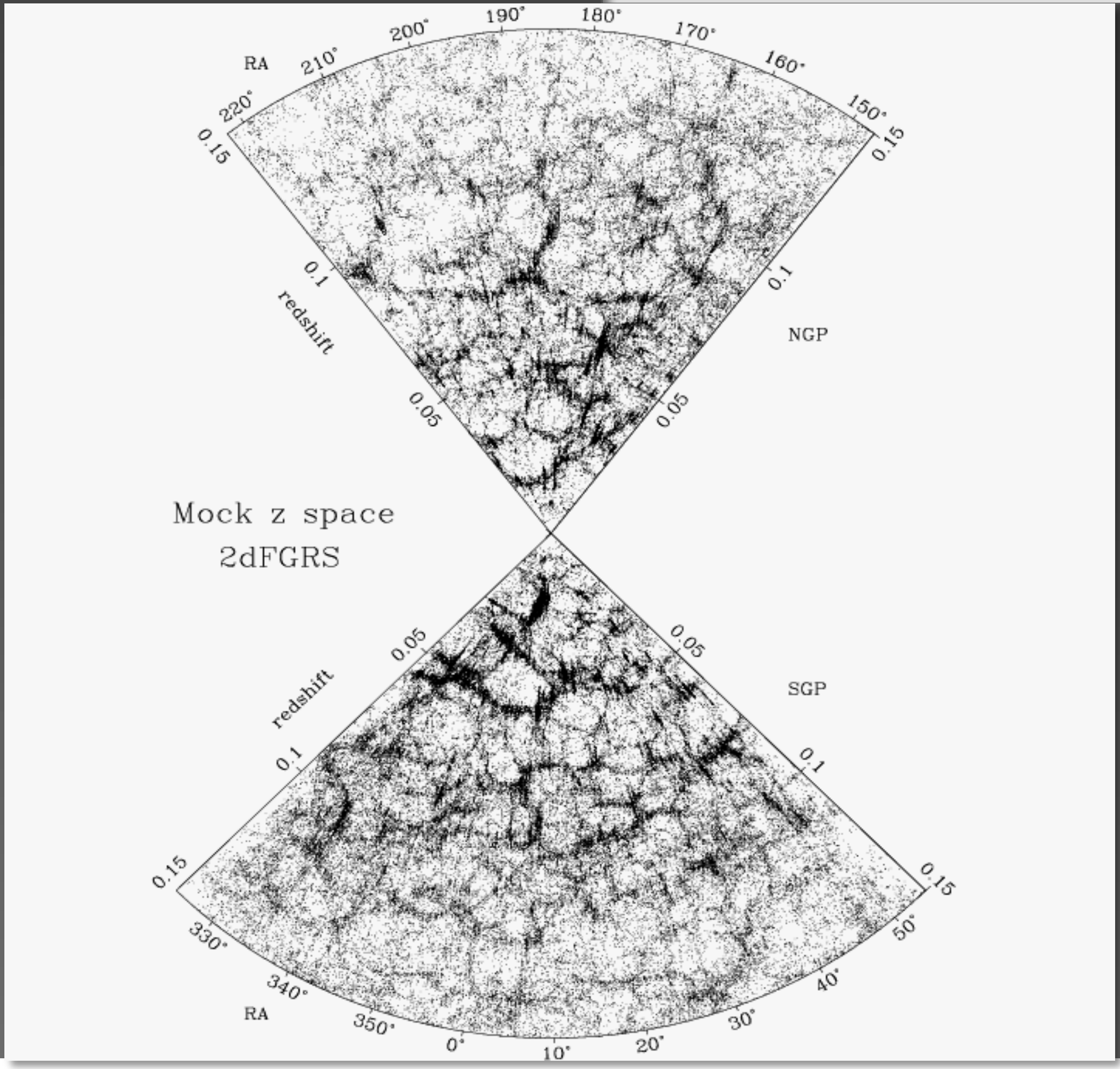
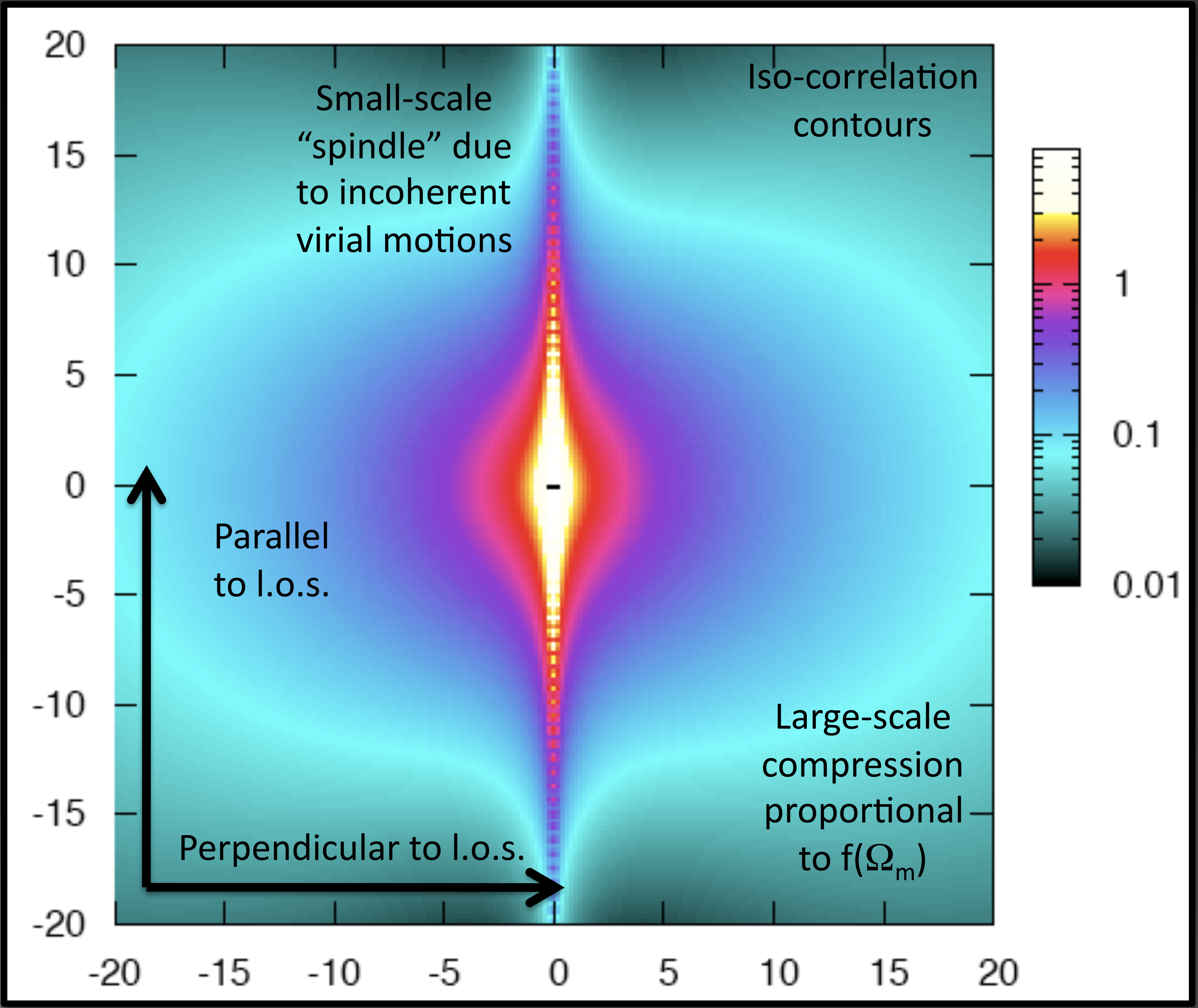


Anisotropic clustering: 2-pt correlation function



Small-scale "spindle" due to incoherent virial motions

Iso-correlation contours

Parallel to l.o.s.

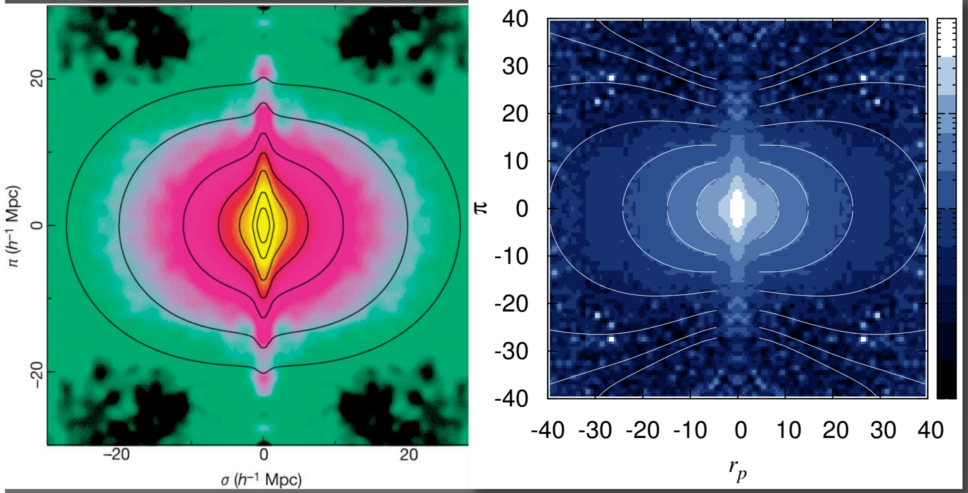
Perpendicular to l.o.s.

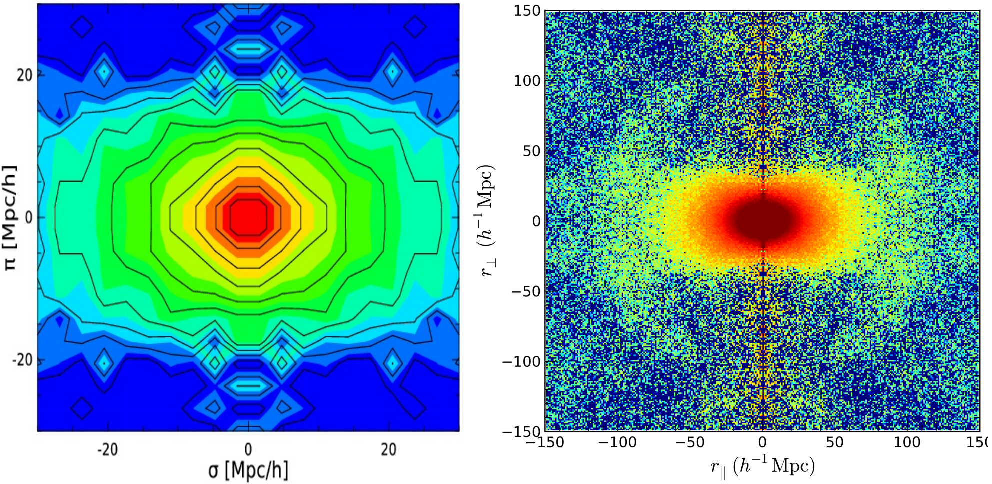
Large-scale compression proportional to $f(\Omega_m)$

Motivation 2: Tracing the growth of fluctuations
Survey Strategy

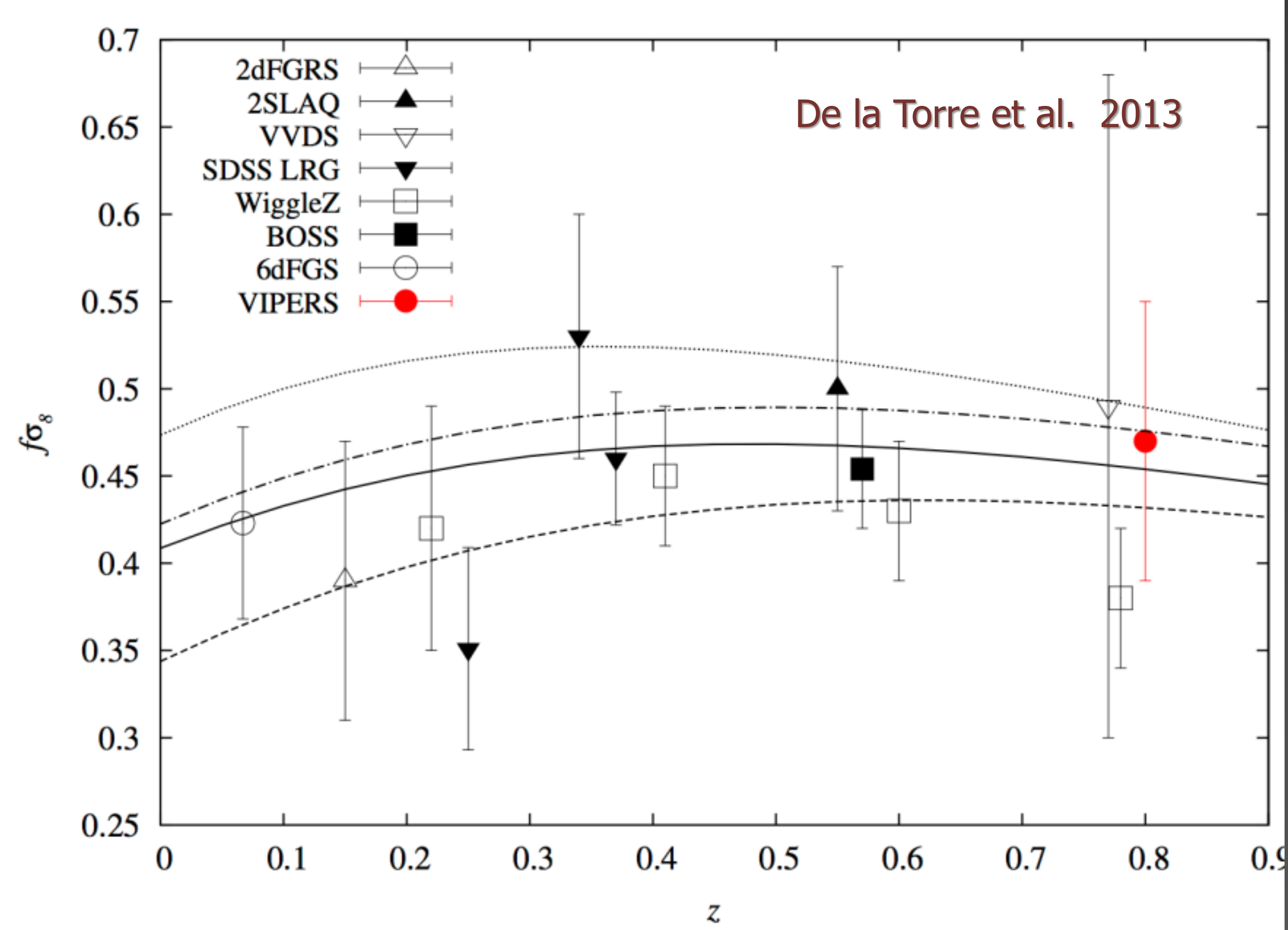
Small and Dense e.g. 2dF, VIPERS
Pros: Multiple Tracers
Low Density Structures

Large and Sparse e.g. Wigglez, LRGs
Pros: Large, linear scales





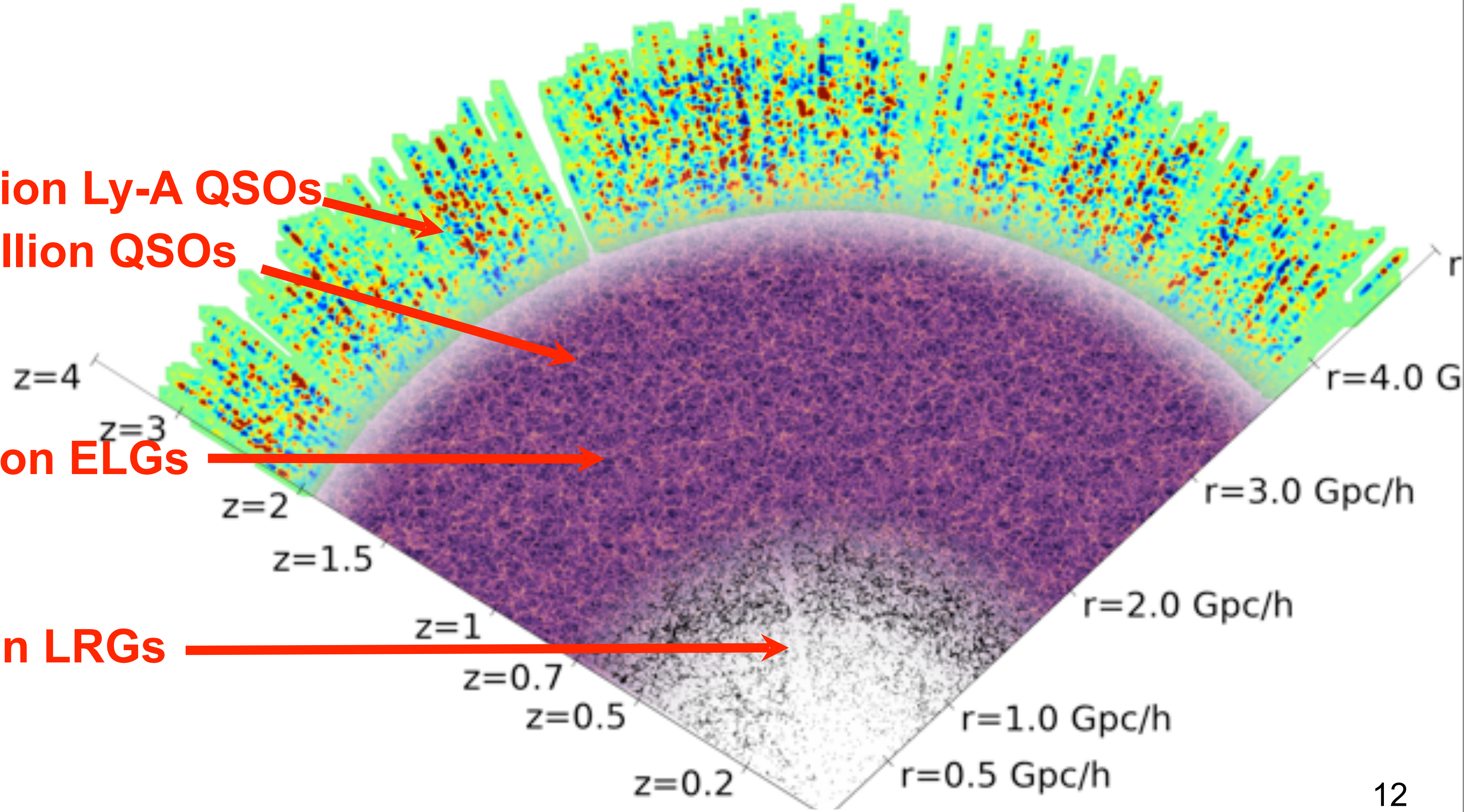
Growth Rate. Current estimates



What is DESI?

Four target classes spanning redshifts z=0 → 3.5

Includes all the massive black holes in the Universe (LRGs + QSOs)

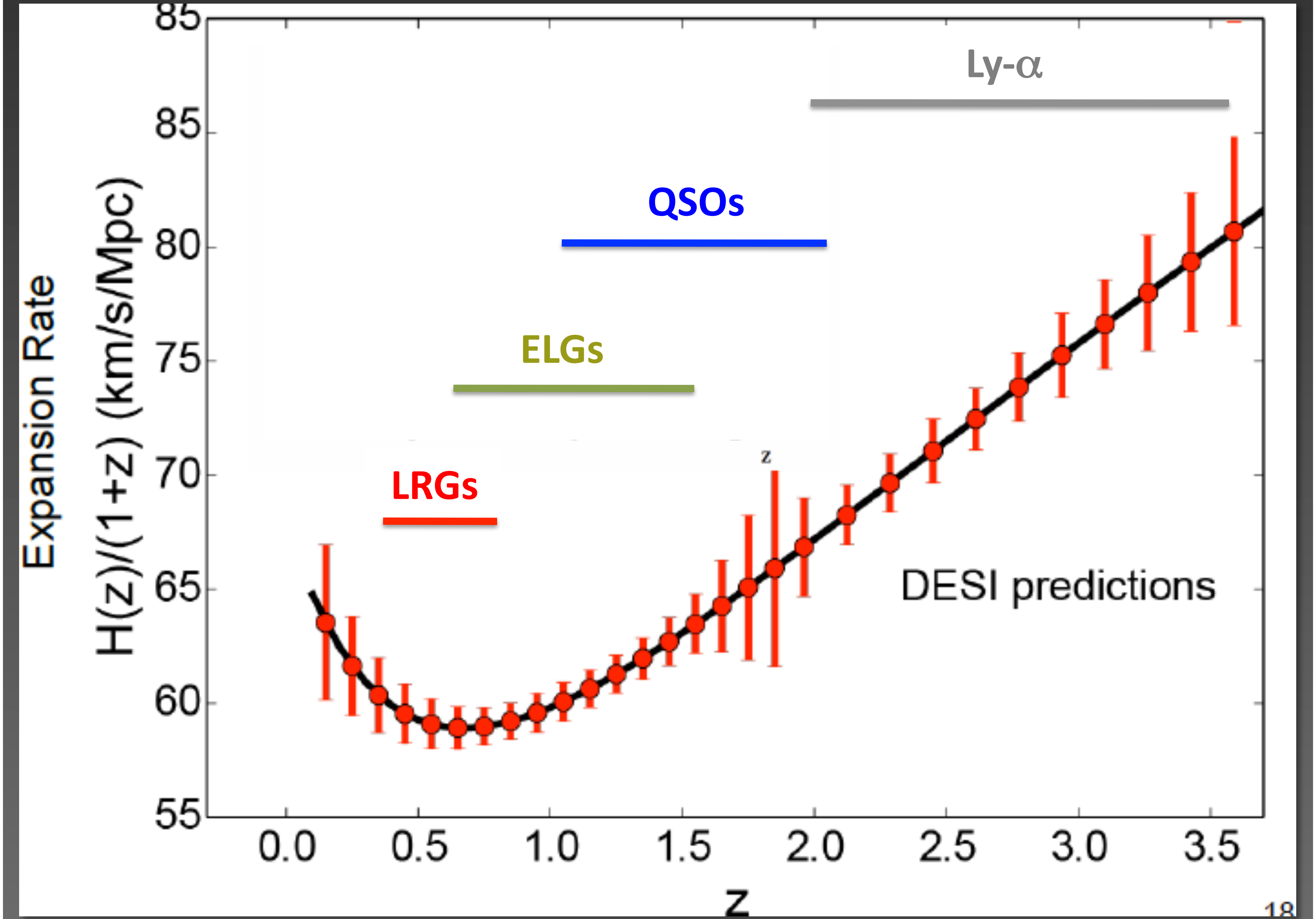


0.6 million Ly-A QSOs

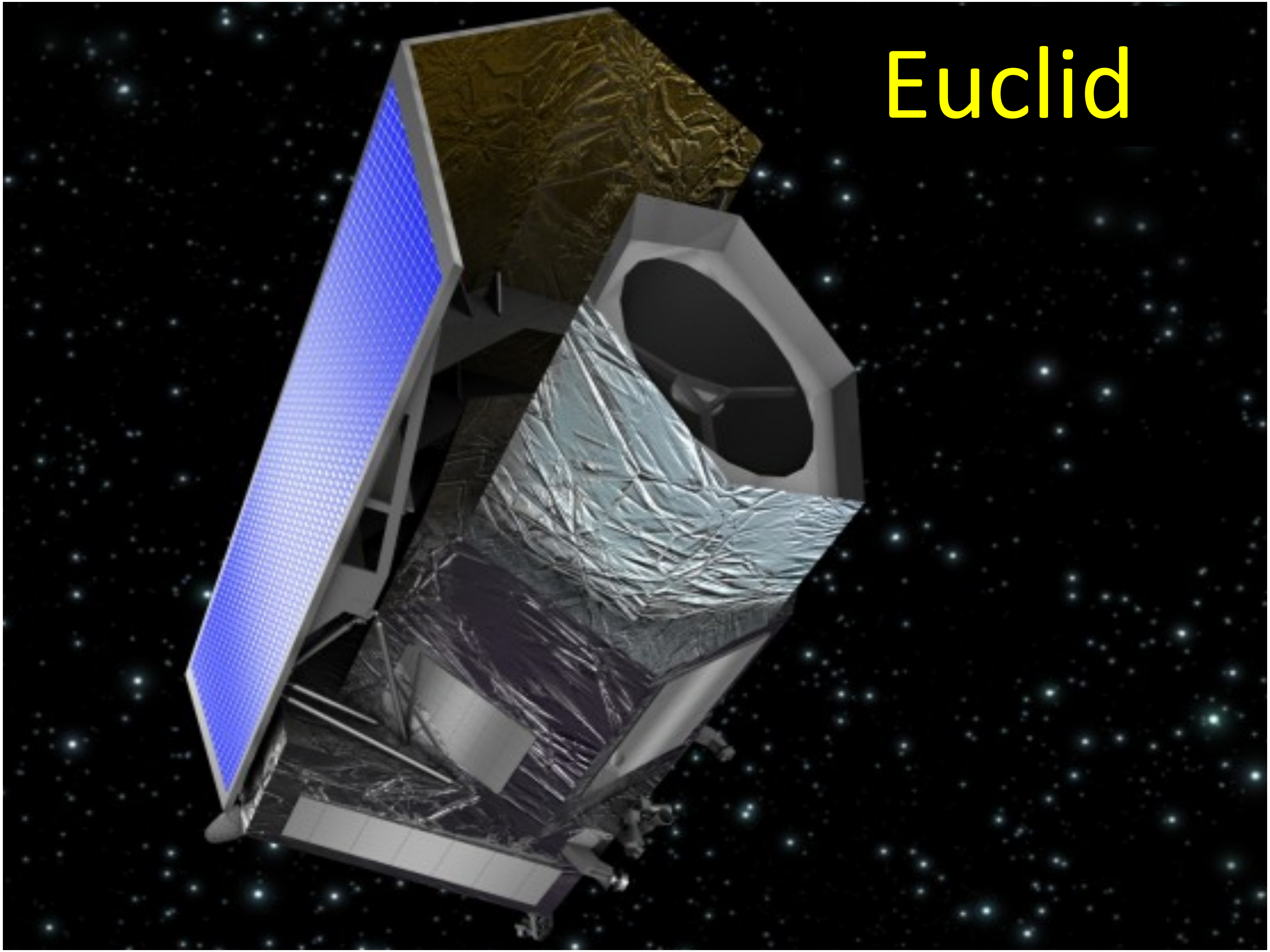
+1.4 million QSOs

23 million ELGs

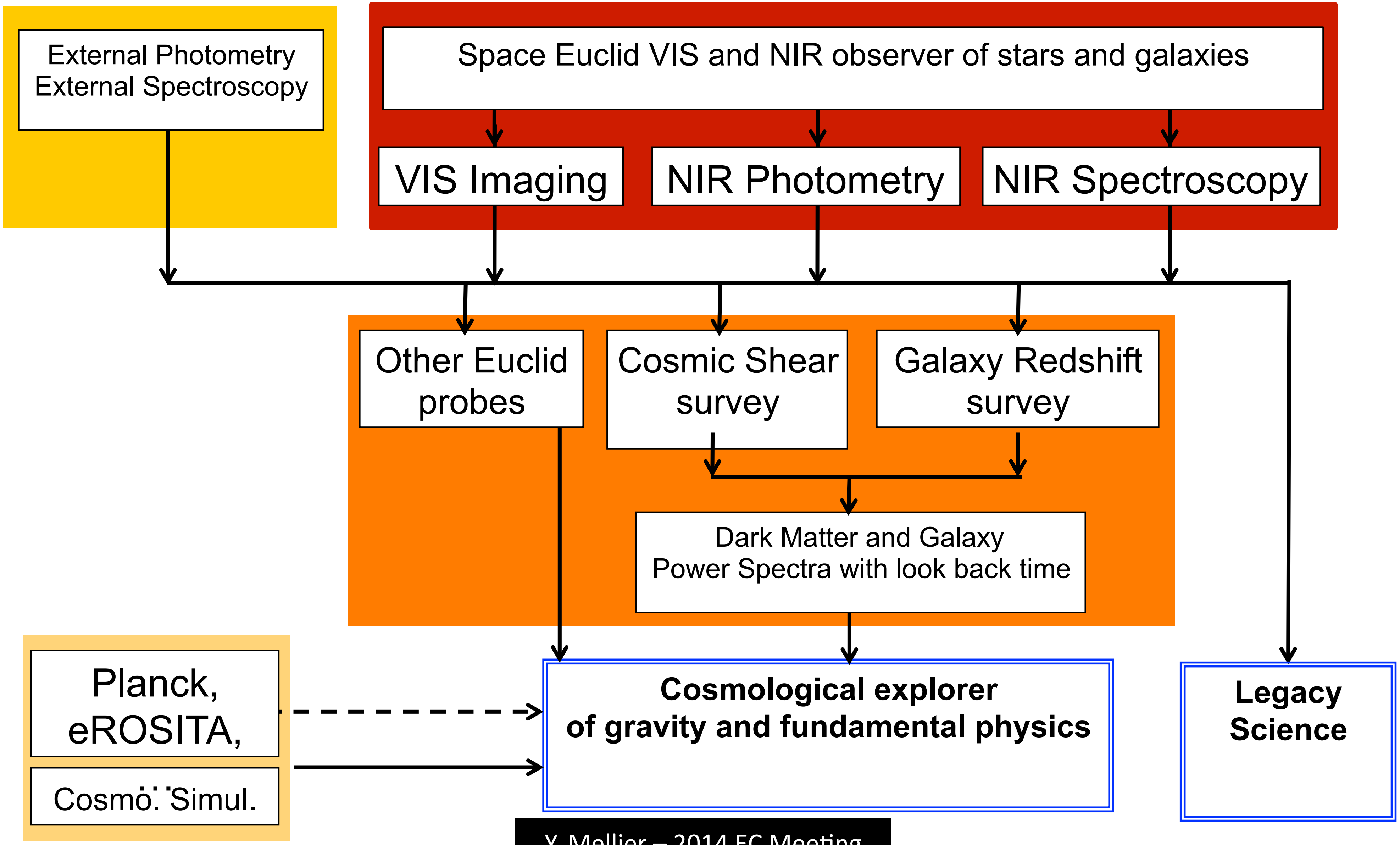
4 million LRGs


Ly-α
QSOs
ELGs
LRGs
z
DESI predictions
Expansion Rate
H(z)/(1+z) (km/s/Mpc)
85
85
80
75
70
65
60
55
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
z

Euclid



The *Euclid Machine*



External Photometry
External Spectroscopy

Space Euclid VIS and NIR observer of stars and galaxies

VIS Imaging

NIR Photometry

NIR Spectroscopy

Other Euclid probes

Cosmic Shear survey

Galaxy Redshift survey

Dark Matter and Galaxy
Power Spectra with look back time

Planck, eROSITA,

Cosmo. Simul.

Cosmological explorer
of gravity and fundamental physics

Legacy Science

Euclid mission baseline: Launch in 2020

Ground based
Photometry and Spectroscopy (photo-z)

SURVEYS **In ~6 years**	Area (deg2)	Description
Wide Survey	**15,000 deg²**	Step and stare with 4 dither pointings per step.
Deep Survey	**40 deg²**	In at least 2 patches of > 10 deg^2 2 magnitudes deeper than wide survey

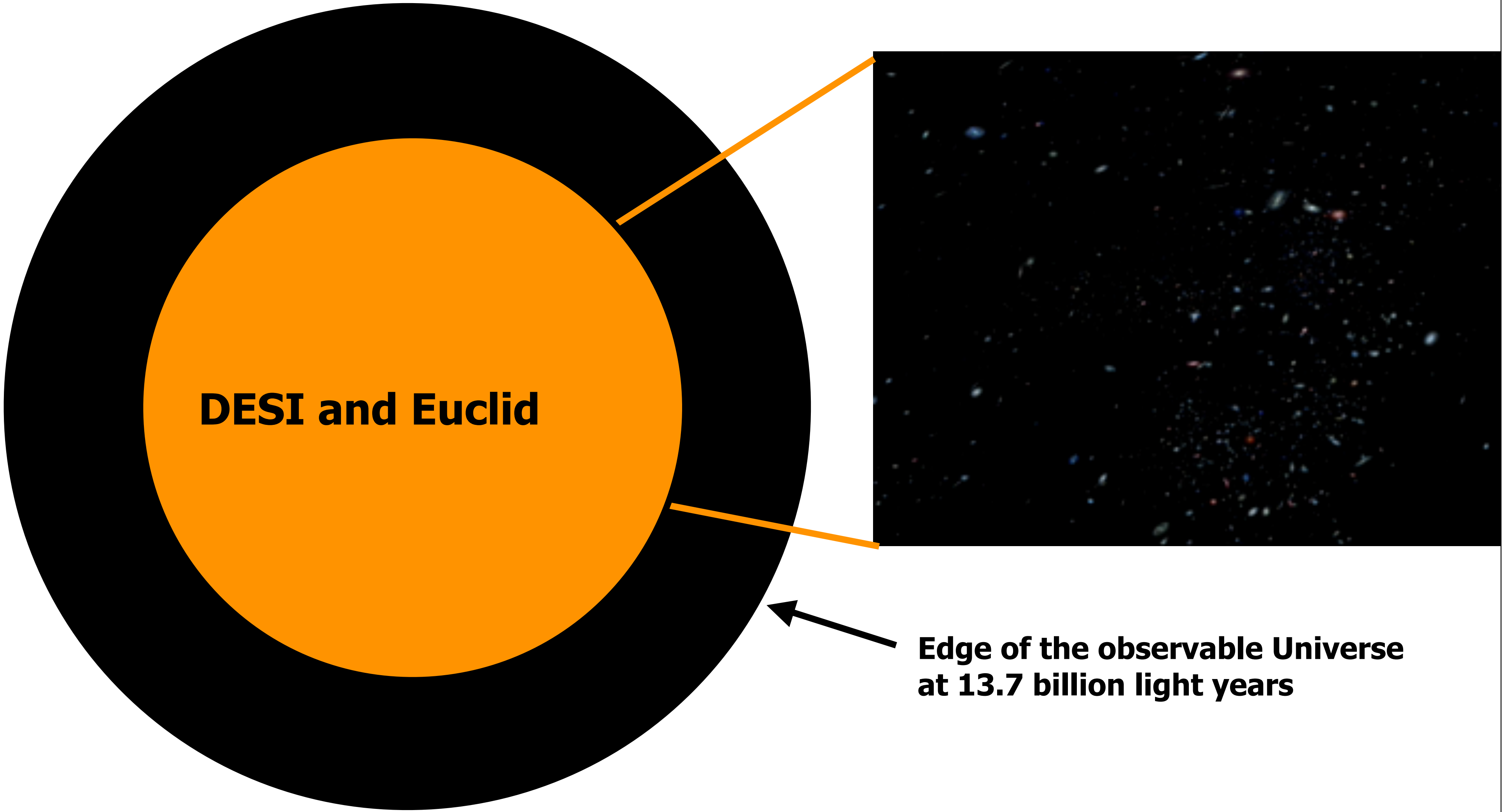
PAYLOAD					
Telescope	1.2 m Korsch, 3 mirror anastigmat, f=24.5 m				
Instrument	VIS	NISP			
Field-of-View	0.787×0.709 deg^2	0.763×0.722 deg^2			
Capability	Visual Imaging	NIR Imaging Photometry			NIR Spectroscopy
Wavelength range	550– 900 nm	Y (920-1146nm),	J (1146-1372 nm)	H (1372-2000nm)	1100-2000 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			***z* of *n*=2.5x10^7 galaxies**	

Possibility other surveys: SN and/or μ-lens surveys, Milky Way (TBC): **after Mission PDR**

Ref: Euclid RB Laureijs et al arXiv:1110.3193

SDSS-III/BOSS has only mapped <1% of the observable Universe

....but only 0.02% of the observable galaxies



DESI and Euclid

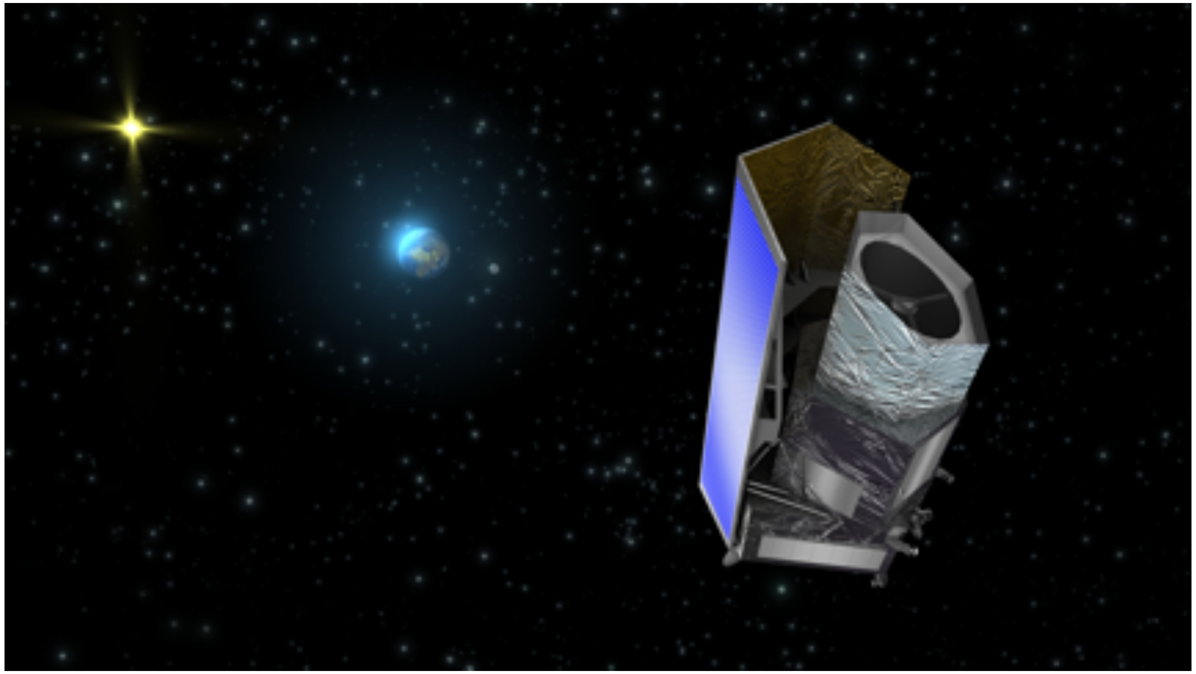
Edge of the observable Universe
at 13.7 billion light years

From D. Schelgel 2014

Focusing on the spectroscopic survey

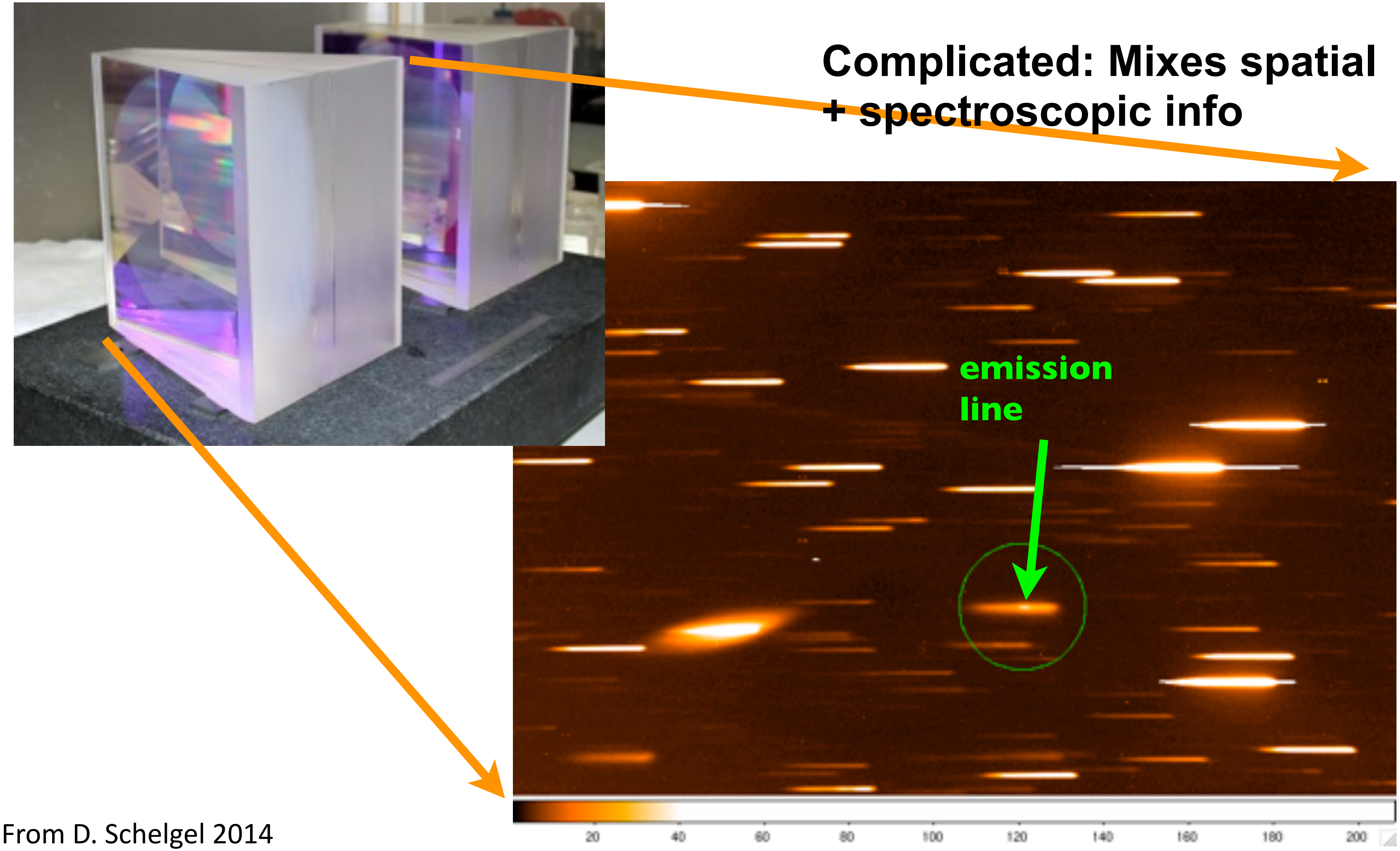
Technique of slit-less spectroscopy ("objective prism") pioneered by Edward Pickering in 1882 to classify stars

Used very little for the past ~70 years
… never used for galaxy redshift surveys



Euclid will use slit-less spectroscopy. A technique very little used for the past 70 years and never for galaxy surveys

Complicated: Mixes spatial + spectroscopic info



From D. Schelgel 2014

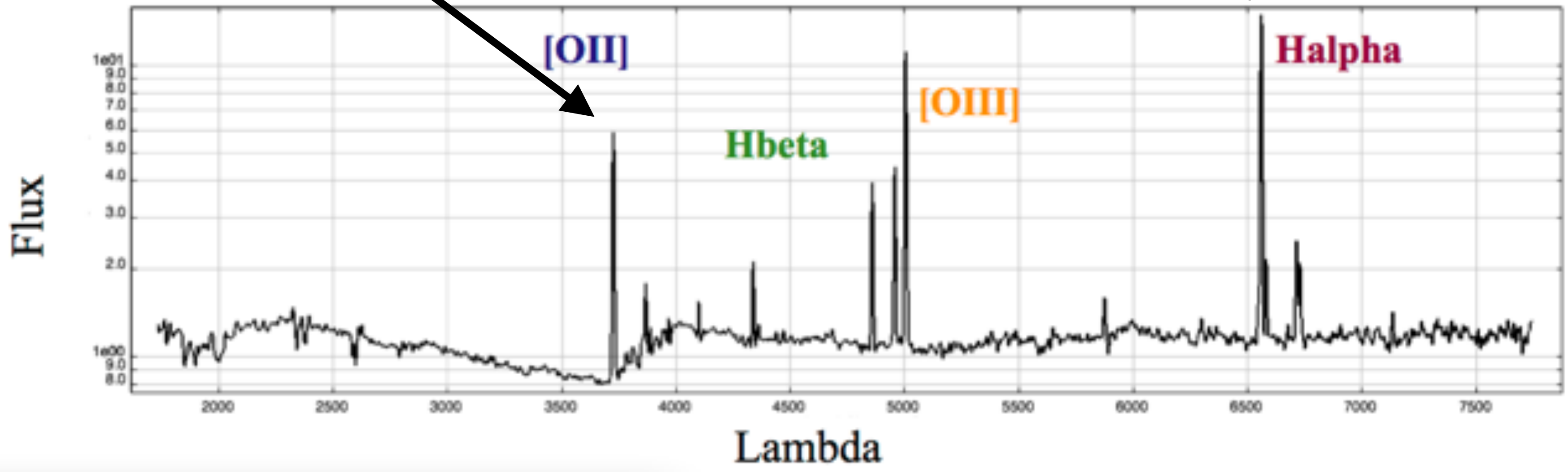
Real grism data from duPont telescope 2.5-m 0.64-0.75 micron (Nick Mostek)

Euclid satellite redshift survey

Why do this crazy prism survey?

1. **Almost no moving parts**
2. **Can observe the brightest H-alpha (H 3-2 transition) from z=1-2**

DESI uses this signature from O^+

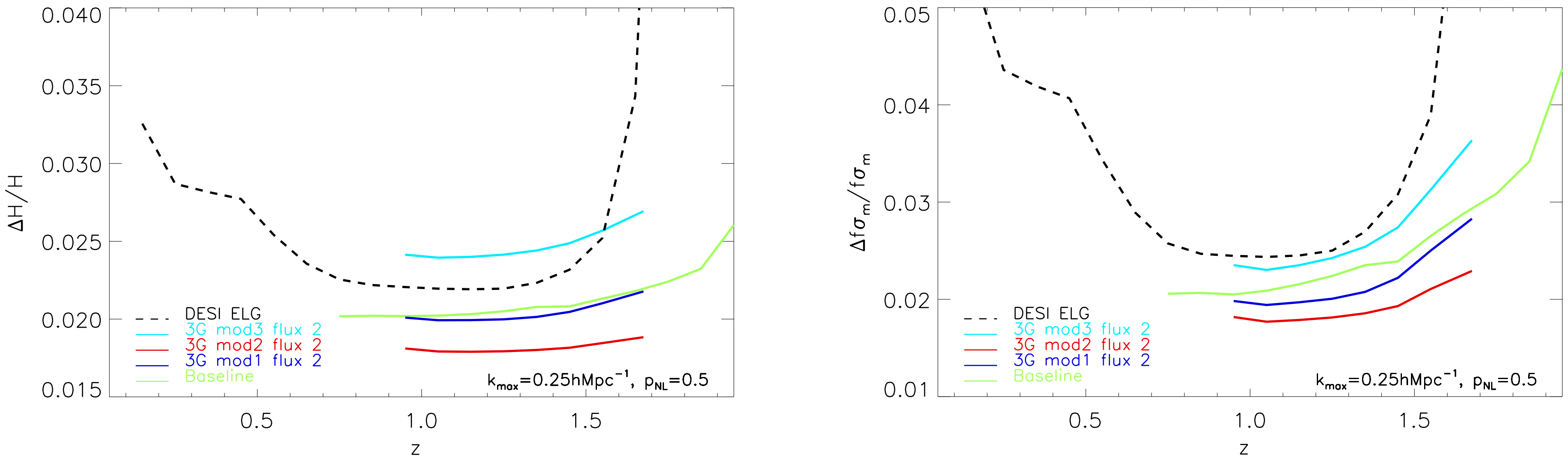


From D. Schelgel 2014

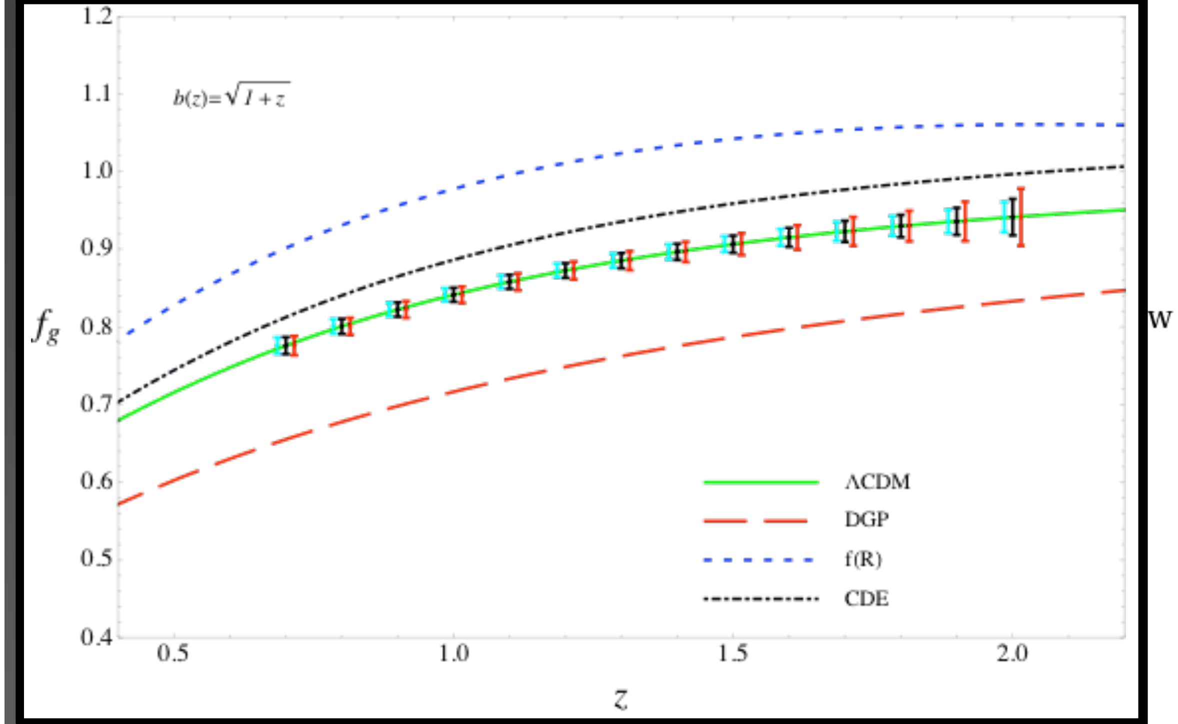
Most updated forecasts on H(z) and growth

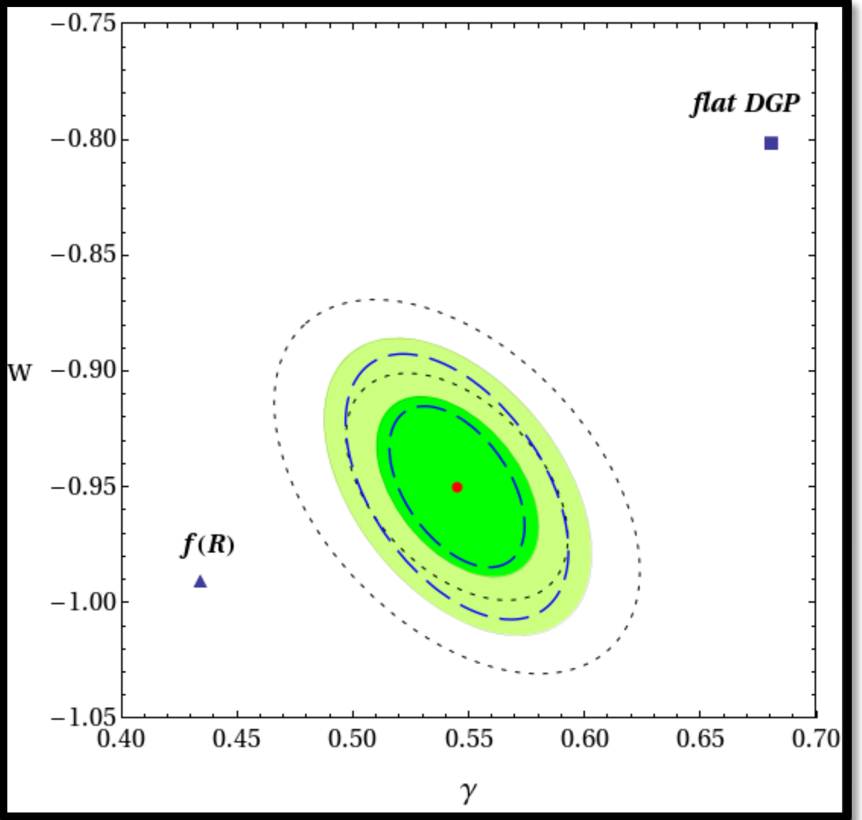
- Deeper flux limit: 2 x 10^{-16} erg cm^{-2} s^{-1}
- Up-to-date instrumental configuration
- 3 up-to-date models for dN/dz by Pozzetti, Geach & Hirata
- Forecast code by R. Bean

Flux>2 x 10^{-16} erg cm^{-2} s^{-1}



Growth from galaxy clustering





Di Porto, Amendola, EB 2011

$$f(\Omega_m) \approx \Omega_m^{\gamma}$$

Forecasts: Euclid primary cosmology programme

	Modified Gravity	Dark Matter	Initial Conditions	Dark Energy		
Parameter	γ	m_ν /eV	f_{NL}	w_p	w_a	***FoM*** $= 1/(\Delta w_0 \times \Delta w_a)$
Euclid primary (WL +GC)	0.010	0.027	5.5	0.015	0.150	430
Euclid All	0.009	0.020	2.0	0.013	0.048	1540
Euclid+Planck	0.007	0.019	2.0	0.007	0.035	4020 → **6000**
Current (2009)	0.200	0.580	100	0.100	1.500	~10
Improvement Factor	**30**	**30**	**50**	**>10**	**>40**	**>400**

Ref: Euclid RB arXiv:1110.3193

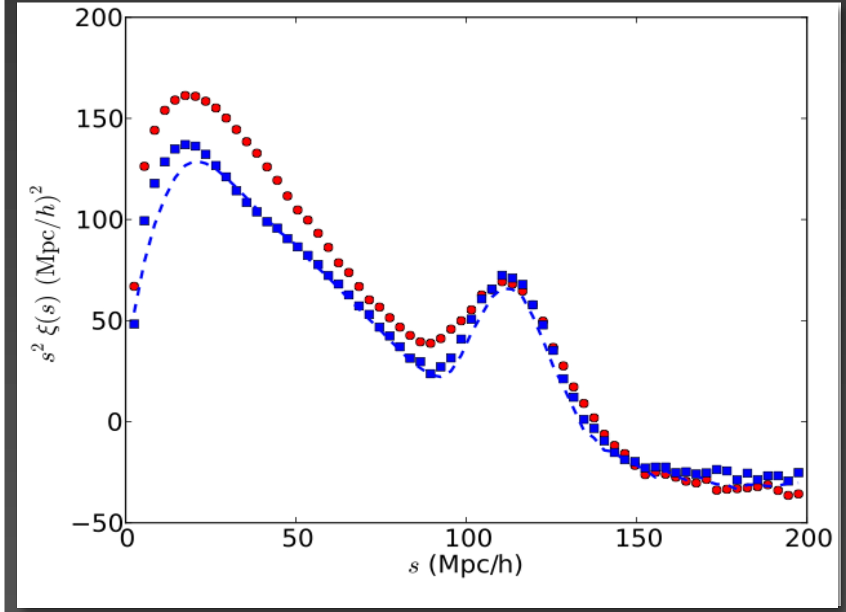
Assume systematic errors are under control

Update based on WL, GC, TH SWGs

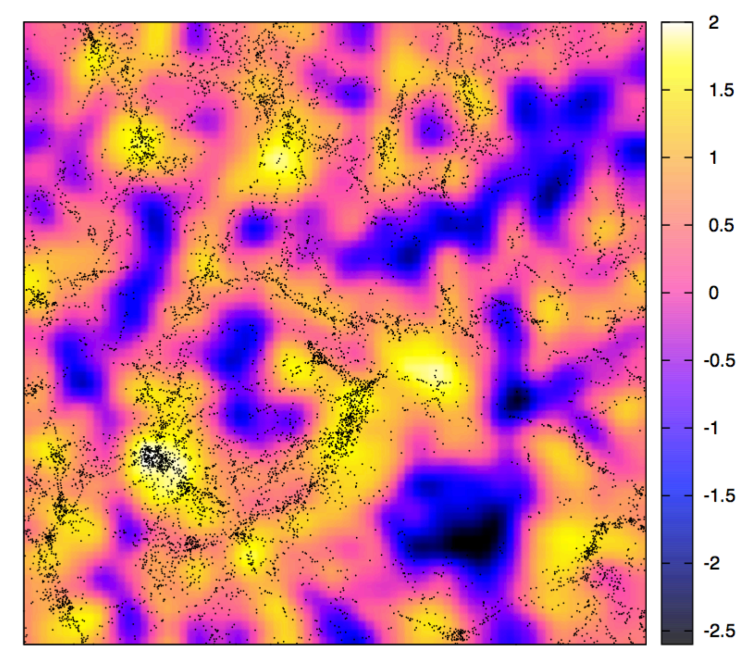
Outstanding Issues

- **Observational**. Completeness, purity and any other observationally-driven issue.
- **Technical.** Statistical estimators for a large number of galaxies (e.g. covariance matrices for 3-pt statistics)
- **Theoretical.** How to interpret results. Non-linearities.
- **Galaxy bias.**

Nonlinear corrections in a reconstruction framework



Use Zel’dovich approximation
sharpen the BAO feature.
BOSS z-survey
Padmanabhan+ 2012



Use Zel’dovich approximation
to identify voids in Lagrangian
coordinates.
Lavaux & Wandelt 2010
Elyiv+ 2014

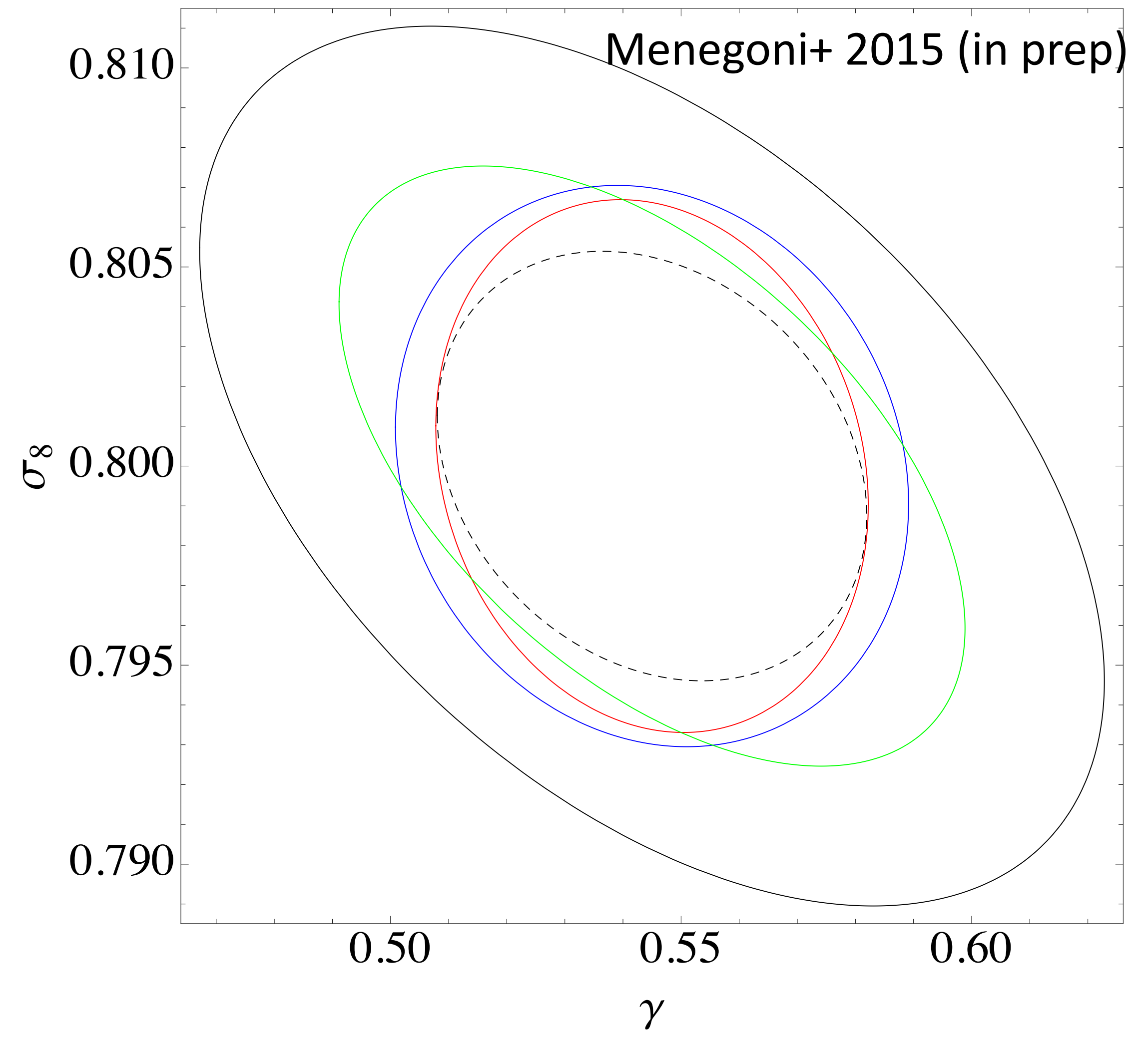
Better methods already available
(e.g. Least Action – based methods)

Handling scale-dependent bias

Fisher Matrix analysis.

$$P(k,z) = D^2(z)b(k,z)^2\left(1+\frac{f(z)}{b(k,z)}\mu^2\right)^2 e^{-\mu^2k^2\sigma_r^2}G(k,\mu,\vec{\Sigma})P_{0L}(k)$$

$H_0,\ \Omega_m,\ \Omega_b,\ n_s,\ \gamma,\ \sigma_8,\ n,\ b_0,\ b_1$



$$b(z,k) = b_0(z) + b_1(z)\left(\frac{k}{k_1}\right)^n$$

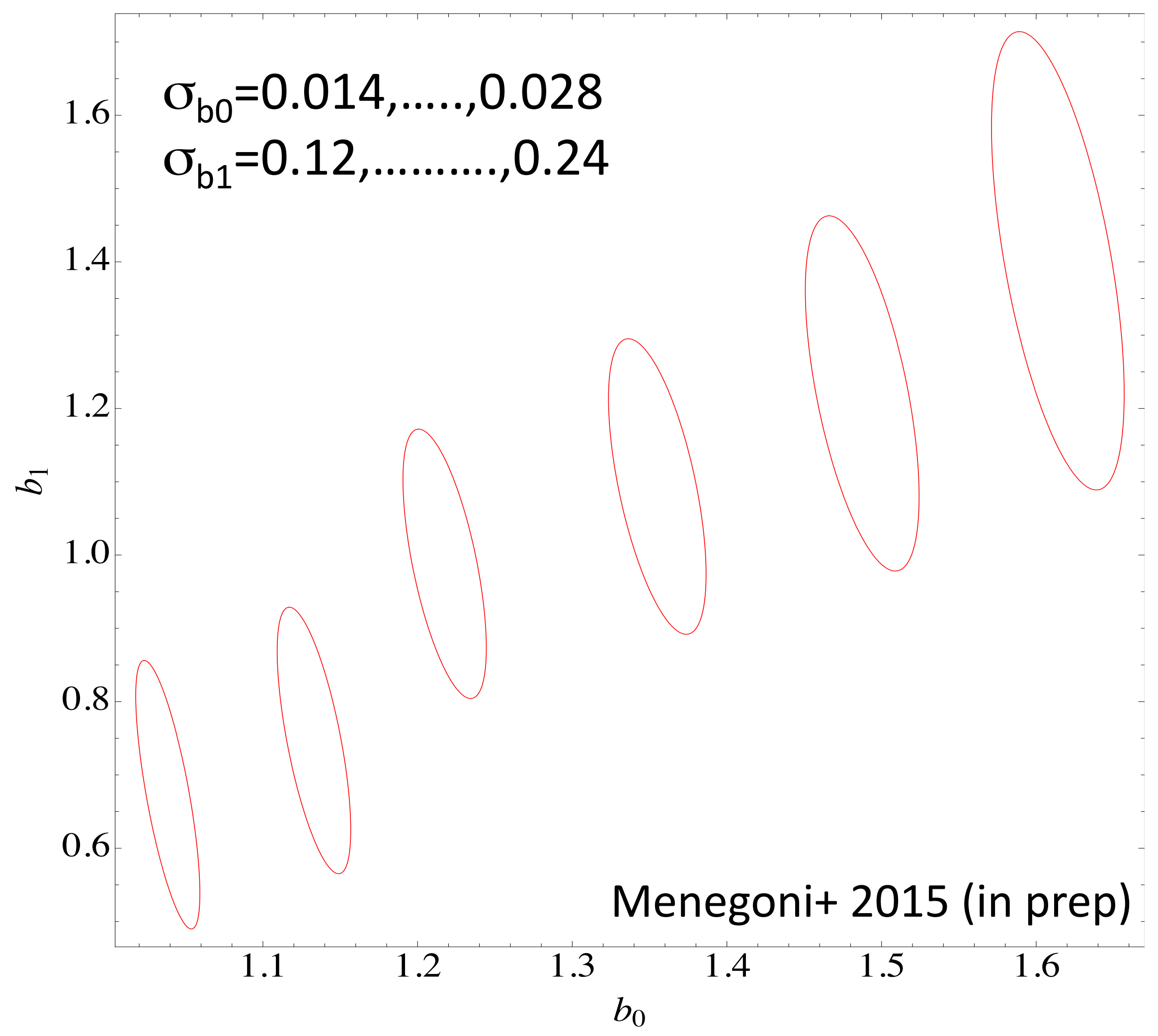
Allowing for scale-dependent Galaxy bias does not have a dramatic impact on γ.

Handling scale-dependent bias

Fisher Matrix analysis.

$$P(k,z) = D^2(z)b(k,z)^2\left(1+\frac{f(z)}{b(k,z)}\mu^2\right)^2 e^{-\mu^2k^2\sigma_r^2}G(k,\mu,\vec{\Sigma})P_{0L}(k)+P_{shot}$$

$H_0,\ \Omega_m,\ \Omega_b,\ n_s,\ \gamma,\ \sigma_8,\ n,\ b_0,\ b_1$



σ_{b0}=0.014,.....,0.028

σ_{b1}=0.12,..........,0.24

Menegoni+ 2015 (in prep)

$$b(z,k) = b_0(z) + b_1(z)\left(\frac{k}{k_1}\right)^n$$

Allowing for scale-dependent Galaxy bias does not have a dramatic impact on γ

Scale dependence can be detected using galaxy clustering only.
How effectively it depends on galaxy bias itself

And now about Early Universe constraints

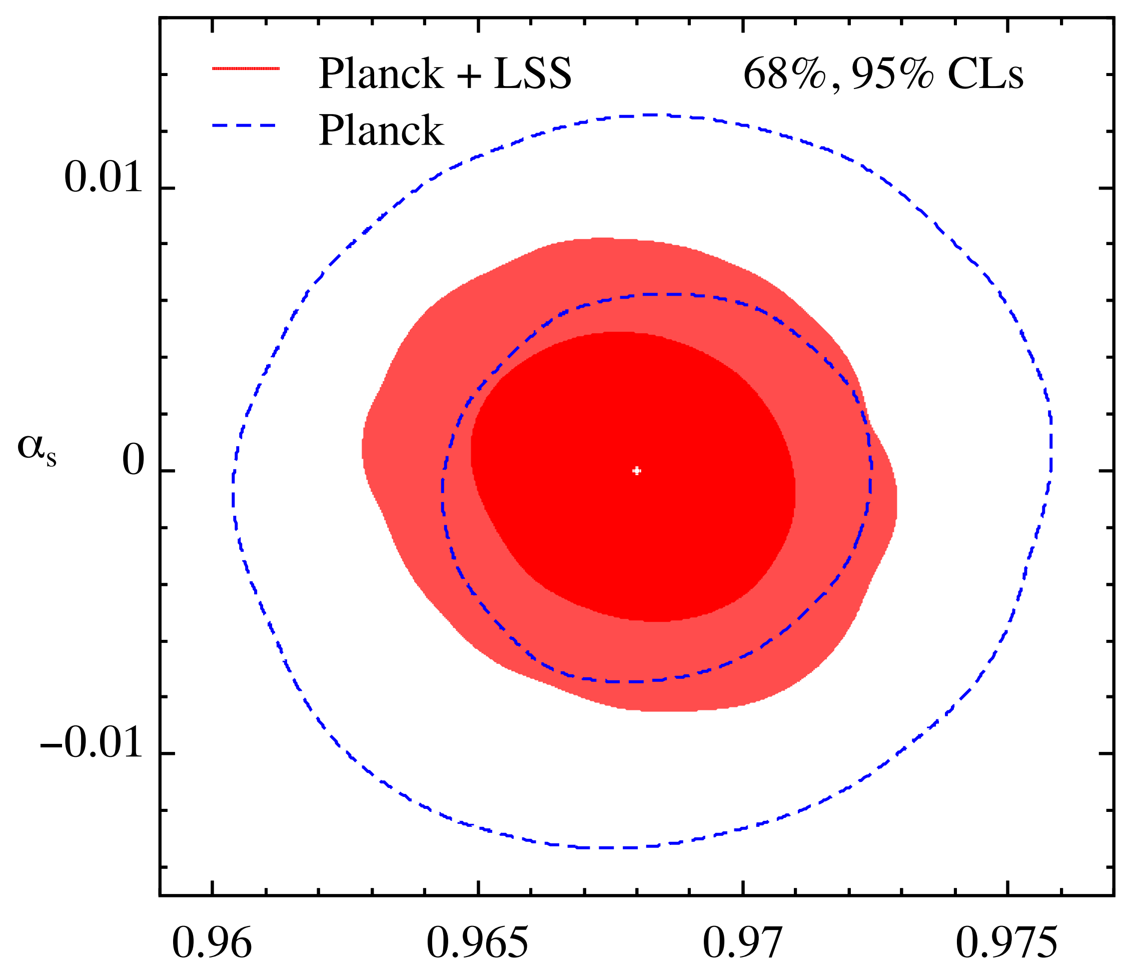
- **2-point clustering statistics. Constraints from primordial and running spectral index)**
- **2-point clustering statistics. Non Gaussianity from halo bias.**
- Primordial non-Gaussianity from 3-point clustering statistics.
- Isocurvature Perturbations.

Constraining n_s and α_s using galaxy power spectrum

MCMC +
Fisher Matrix analysis.

$$P(k,\mu,z) = D^2(z)\left(b + f(z)\mu^2\right)^2 e^{-\mu^2 k^2 \sigma_r^2} P_0(k) + P_{shot}$$

$$\Omega_m,\ \Omega_b h^2, \Omega_c h^2,\ n_s,\ \alpha_s,\ \gamma,\ \sigma_8,\ n,\ \tau_{RE}$$



Huang, Verde, Vernizzi 2012

8 z-bins z=[0.6,2.0] Δz=0.2
K_{max}=0.15 – 0.23 h/Mpc

LSS allows to access a larger number of k-modes on smaller scales than CMB

Accuracy on n_s and α_s=dn_s/dlnk improves by a factor 2.2

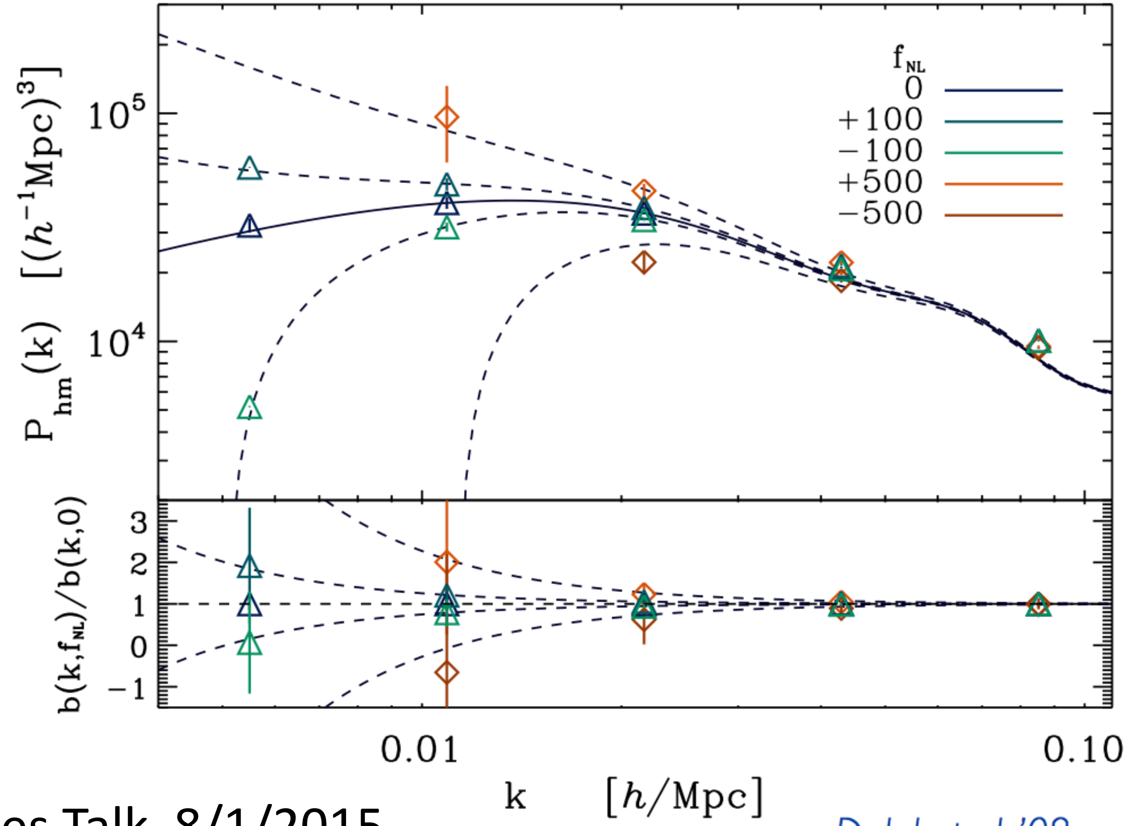
WORK IN PROGRESS

Constraining non-Gaussianity using halo power spectrum

The non-Gaussian bias for local quadratic NG:

$$P_{\rm gg}(k) = \left(b_1 + \Delta b_1^{\rm NG}(k)\right)^2 P_{\rm mm}(k)$$

$$\Delta b_1^{\rm NG}(k) = \frac{2 f_{\rm NL} b_{\rm NG}}{\mathcal{M}(k)} \sim \frac{2 f_{\rm NL} b_{\rm NG}}{k^2}$$



V. Desjacques Talk 8/1/2015

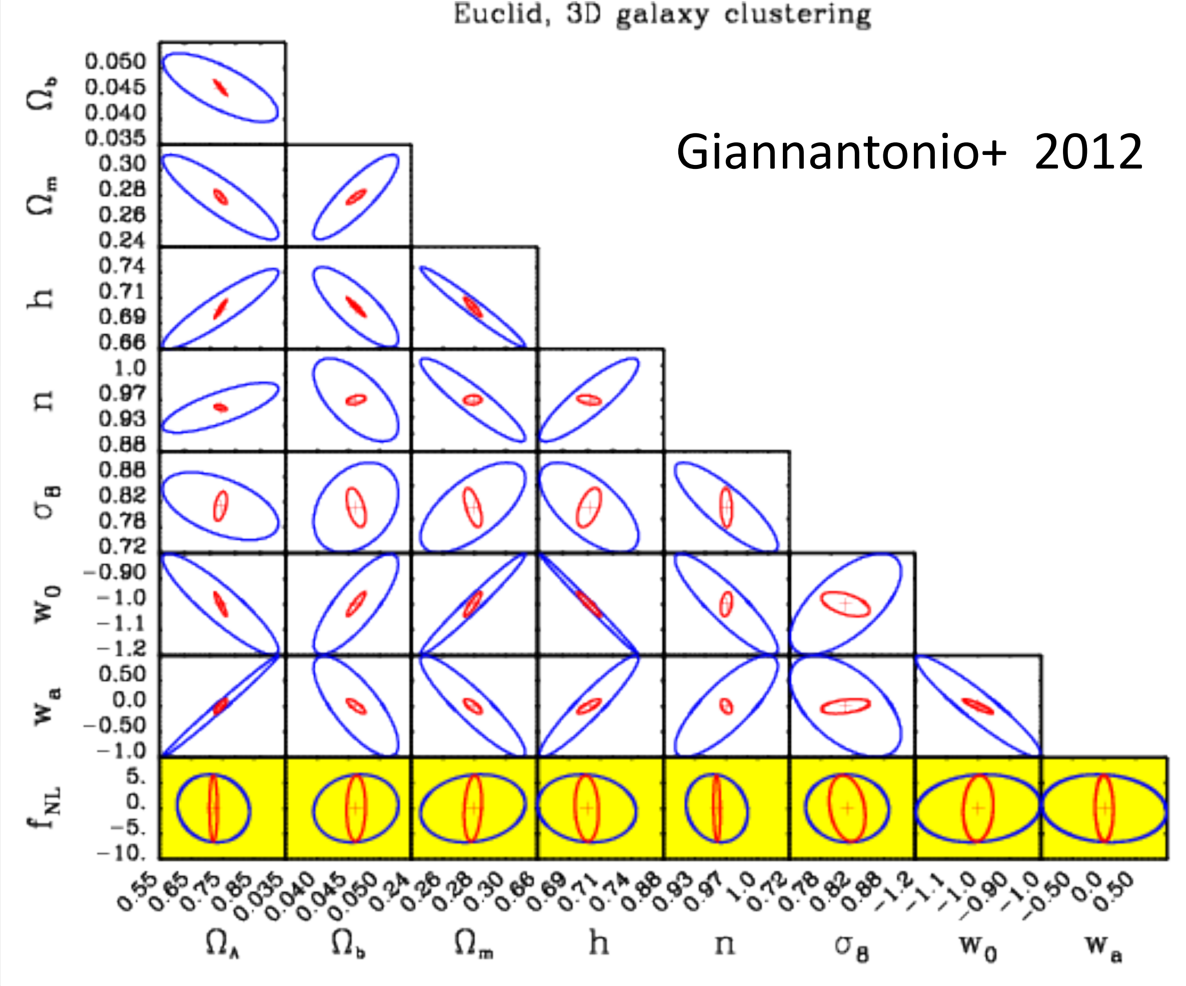
Dalal et al. '08

Constraining non-Gaussianity using halo power spectrum

Fisher Matrix analysis.

$$P(k,z) = D^2(z)b(k,z)^2\left(1+\frac{f(z)}{b(k,z)}\mu^2\right)^2 e^{-\mu^2k^2\sigma_r^2}P_m(k,z)$$

$h,\ \Omega_m,\ \Omega_b,\ n_s,\ w_0,\ w_a,\ \sigma_8, f_{NL}$



Euclid, 3D galaxy clustering

Giannantonio+ 2012

12 z-bins z=[0.5,2.0] Δz=var.

K_{max}=0.15 h/Mpc

Constraints from 2D clustering, 3D clustering, lensing.

From 3D only σf_{NL}=4.4(4.2)

From 2D+lens σf_{NL}=2.8(2.6)

WORK IN PROGRESS

Combining weak lensing and 3D clustering

(linear, scalar) perturbed FRW metric

$$ds^2 = (1+2\Psi)dt^2 - a^2(t)(1-2\Phi)(dx^2+dy^2+dz^2)$$

Metric reconstruction requires three scalar functions

$$H(z) \qquad \Psi(k,z) \qquad \Phi(k,z)$$

Massive particles respond to Ψ

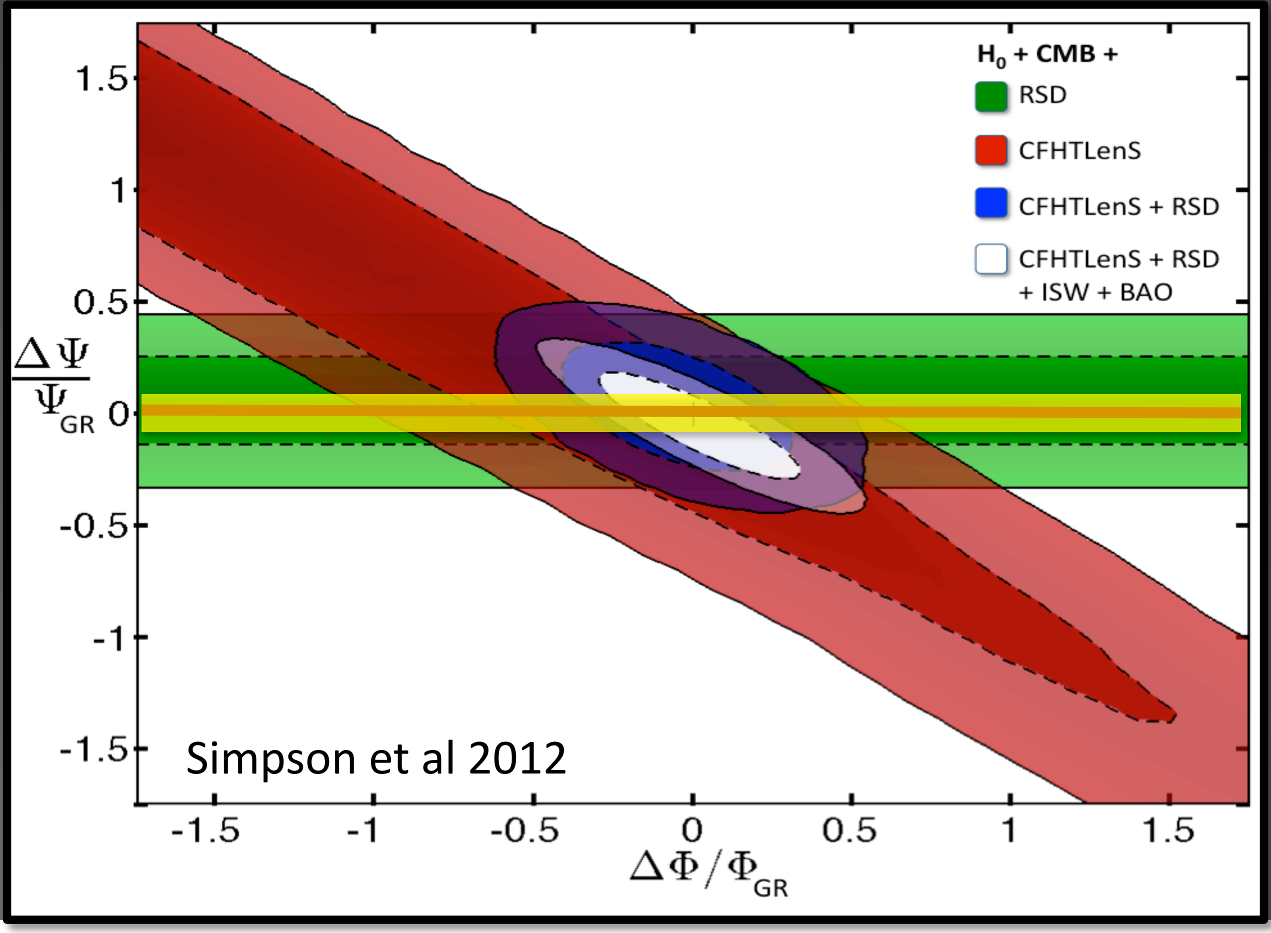
$$\delta''(a) + \left(1+\frac{H'}{H}\right)\delta' = \frac{k^2}{a}\Psi \; ; \qquad ' = d/d\ln(a)$$

Relativistic particles respond to $\Psi+\Phi$

$$\alpha \propto \int \nabla_\perp(\Psi+\Phi)dz$$

A worked out example

- CHFTLenS: Cosmic Shear
- WiggleZ and 6dFGS: z-distortions and galaxy clustering.
- SN1a+Cepheids+megamaser: H_0
- LRGs + CMASS BAO: geometry
- WMAP 7-year small scales: cosmological parameters
- WMAP 7-year large scales: ISW



Simpson et al 2012

Conclusions

- LSS from galaxy redshift surveys will be a major (main ?) probe to Dark Energy and alternative gravity theories in the next few years.
- It will have a significant impact on Dark Matter and Early Universe studies.
- Devil is in details. An exquisite control of systematic errors is needed to reach the required accuracy.