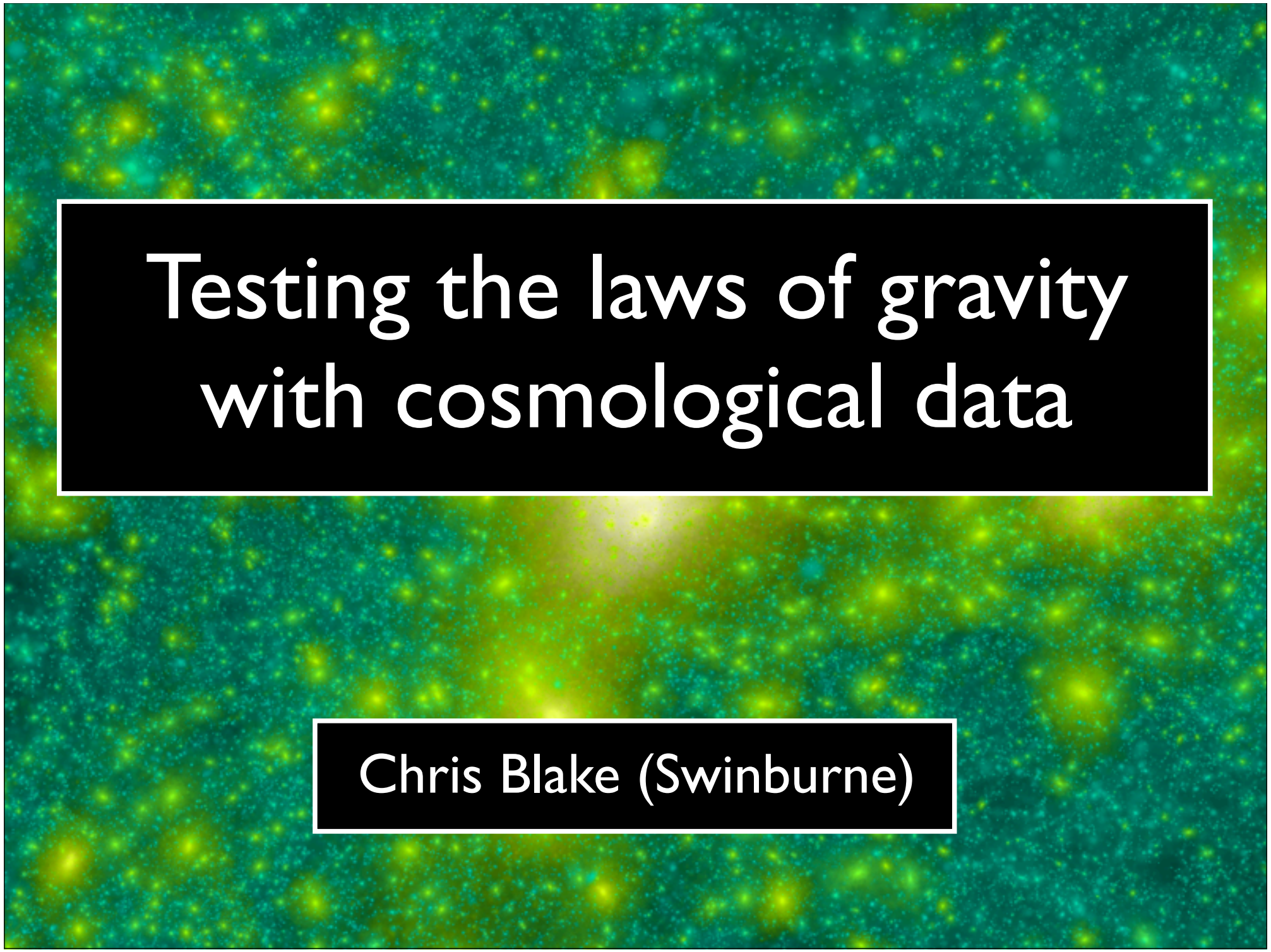
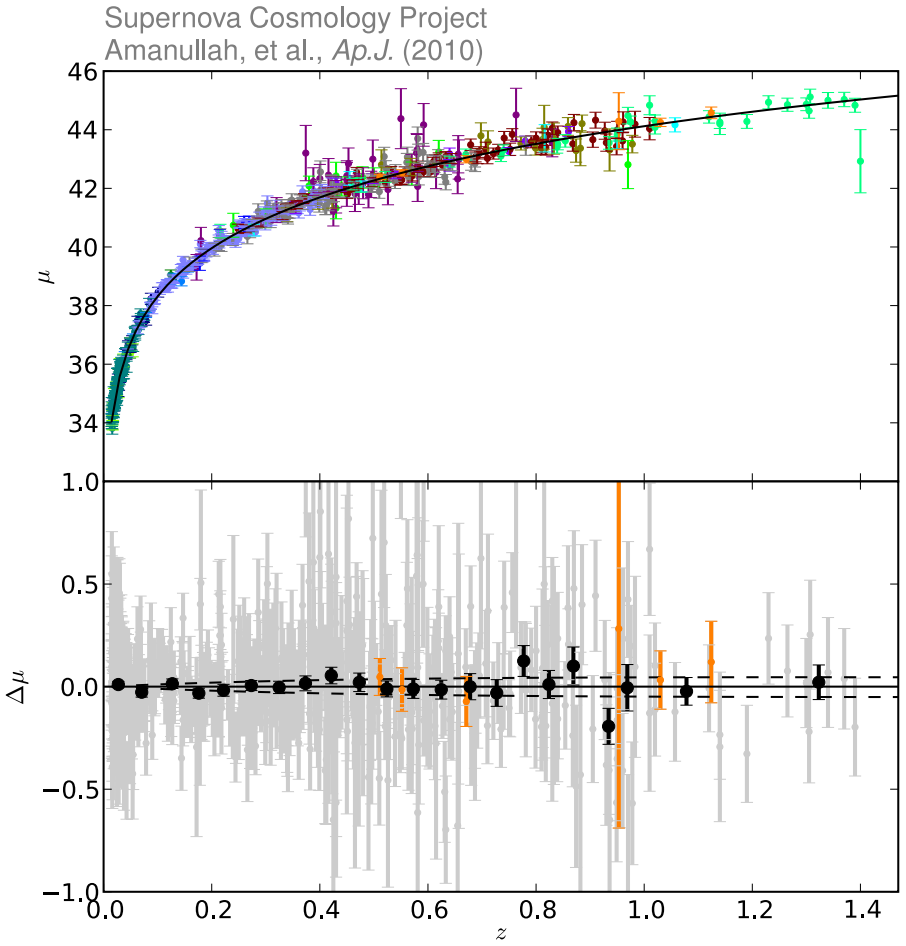
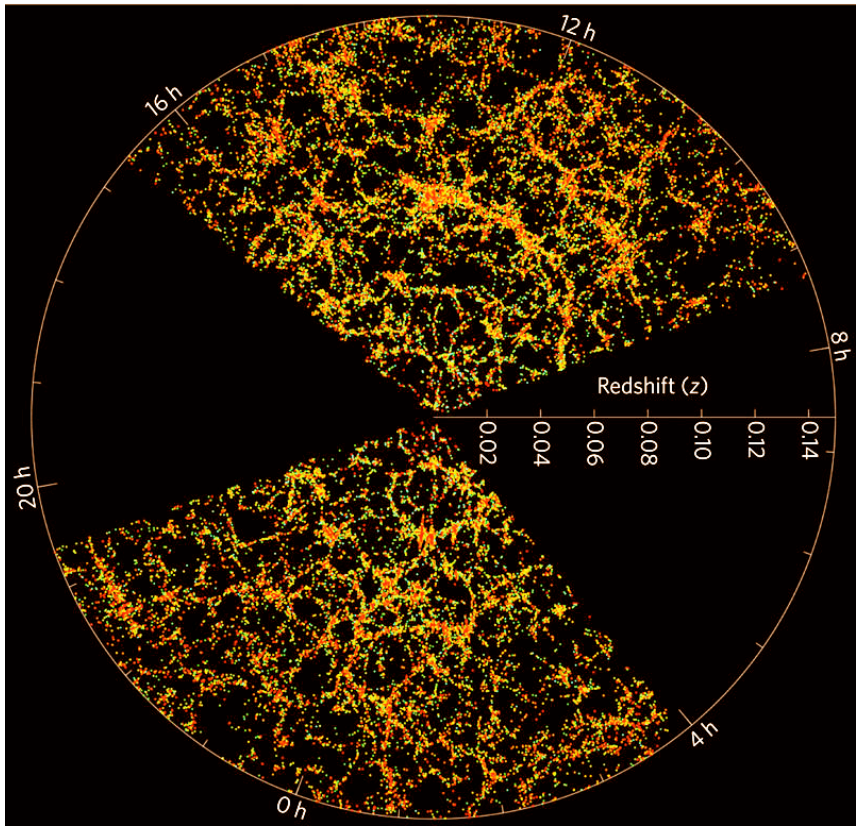

Testing the laws of gravity with cosmological data
Chris Blake (Swinburne)

Probes of the cosmological model

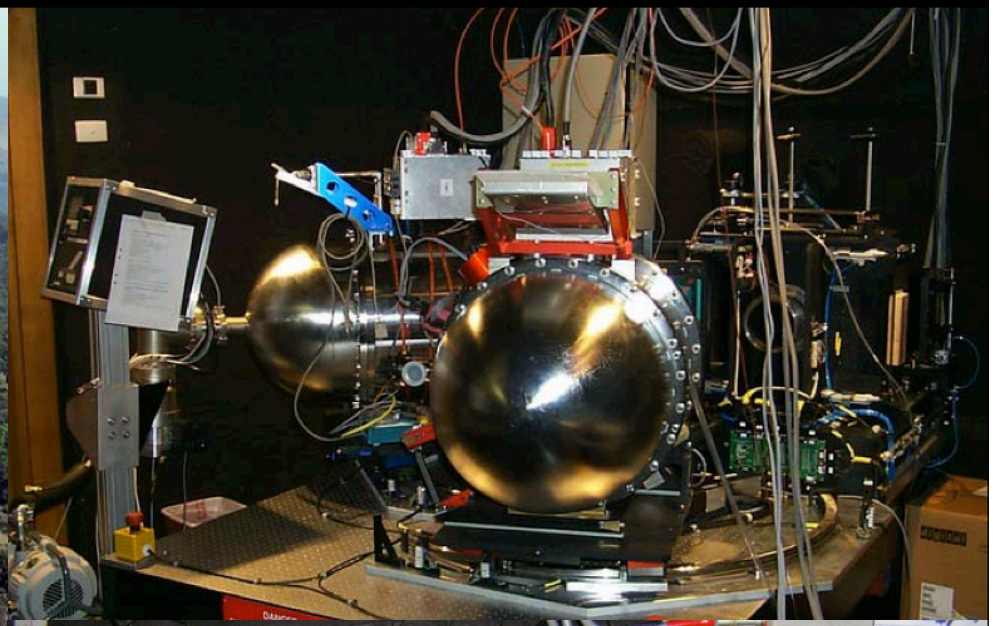
How fast is the Universe expanding with time?

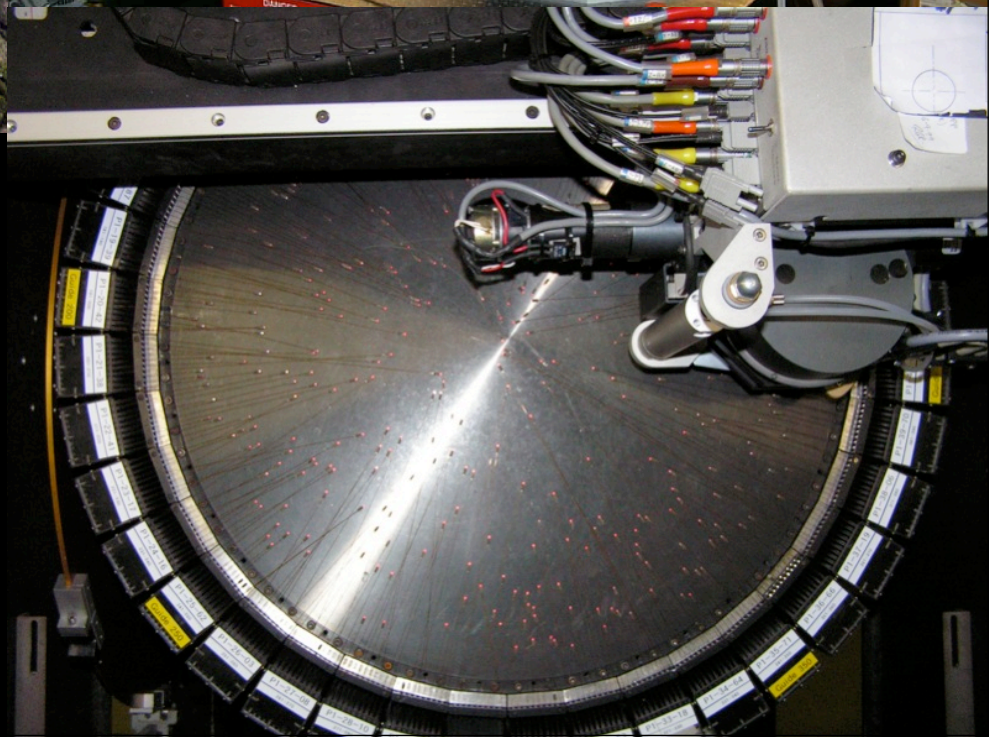
How fast are structures growing within it?





The WiggleZ Dark Energy Survey

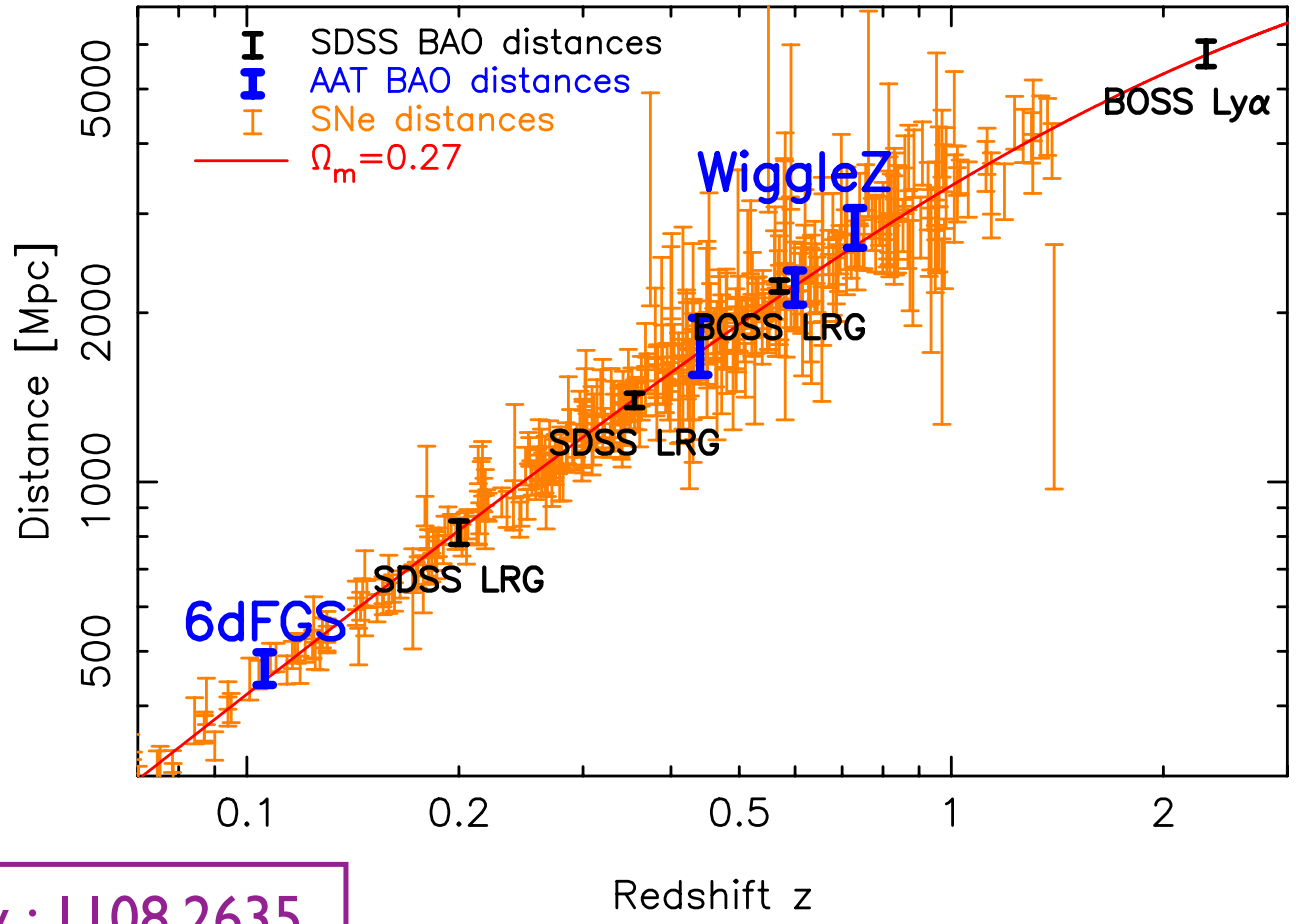




- 1000 sq deg , $0.2 < z < 1.0$
- 200,000 redshifts
- blue star-forming galaxies
- Aug 2006 - Jan 2011

Baryon acoustic peak

- Standard ruler in galaxy clustering pattern which allows the mapping out of cosmic distances



arXiv : 1108.2635

Analysis of BOSS-WiggleZ overlap (1)

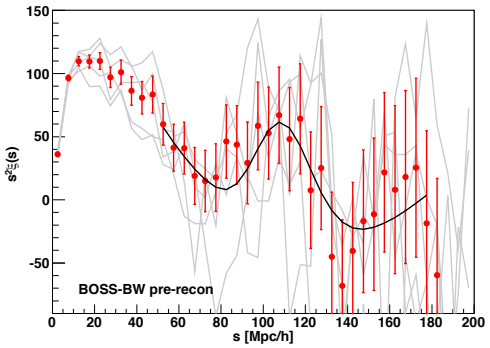
- Baryon acoustic peak in cross-correlation (Beutler et al.)

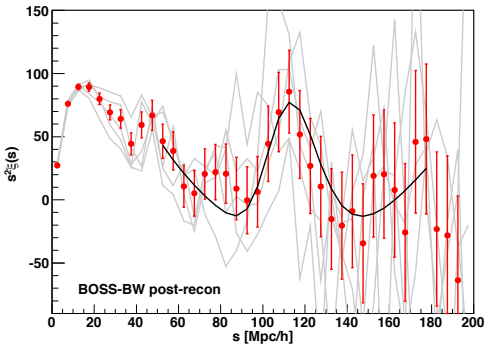
CMASS
[overlap region]

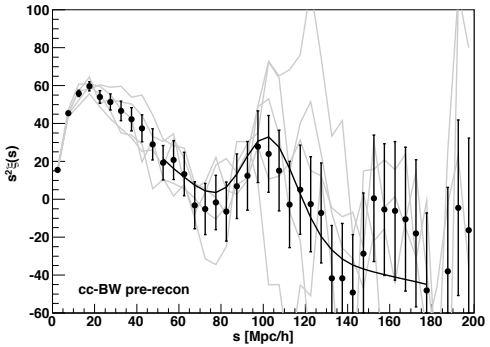
Cross-correlation

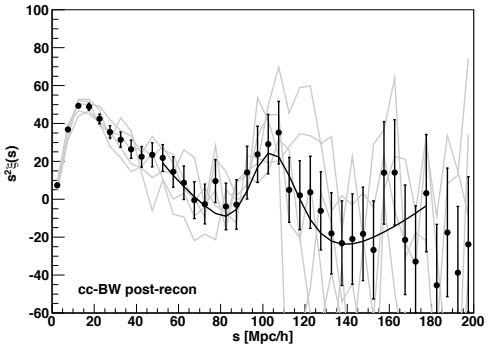
WiggleZ
[overlap region]

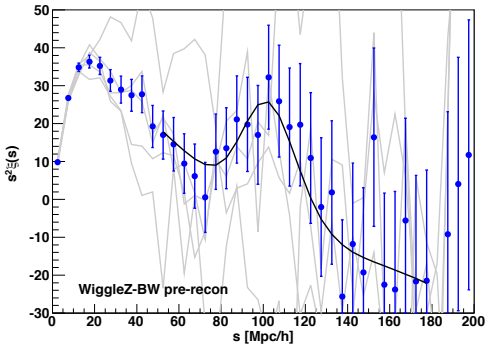
arXiv : 1506.03900

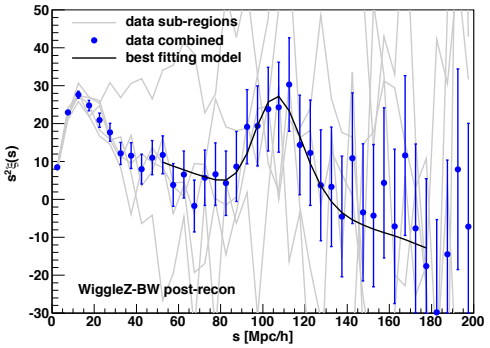






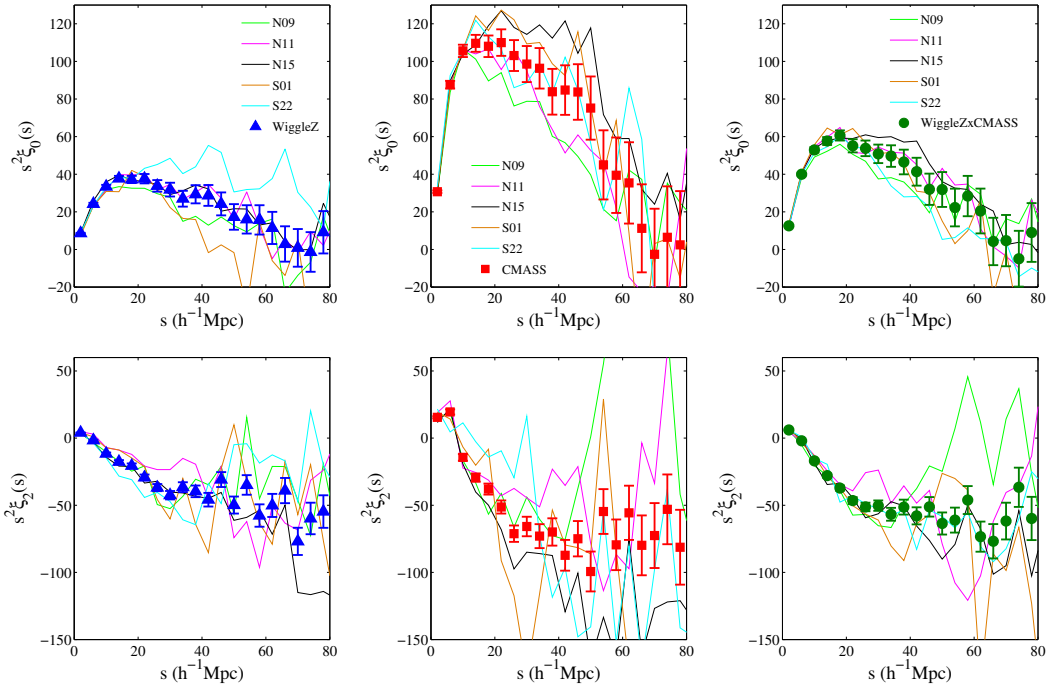


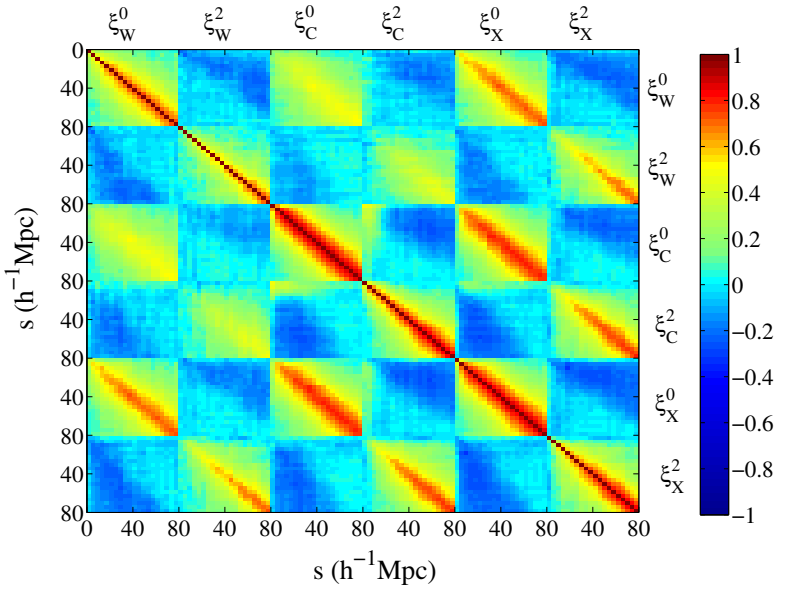


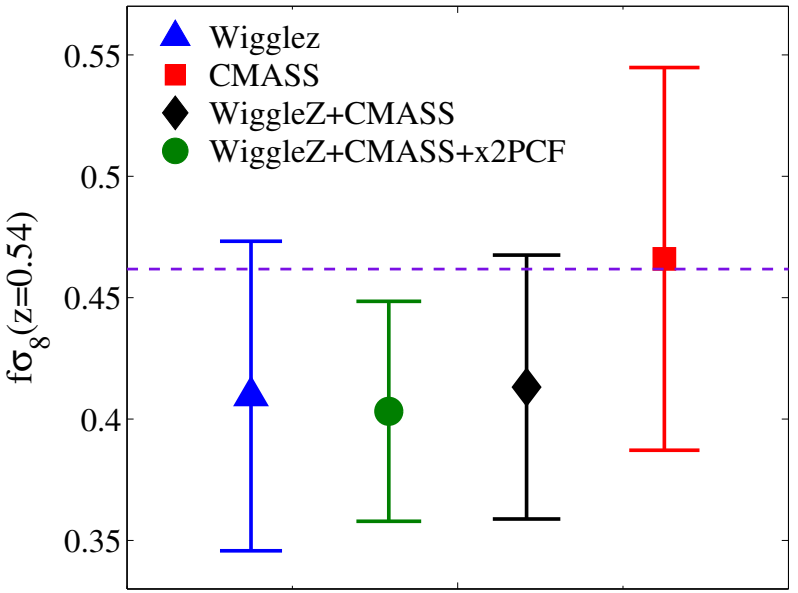


Analysis of BOSS-WiggleZ overlap (2)

- Redshift-space distortions (Marin et al.)



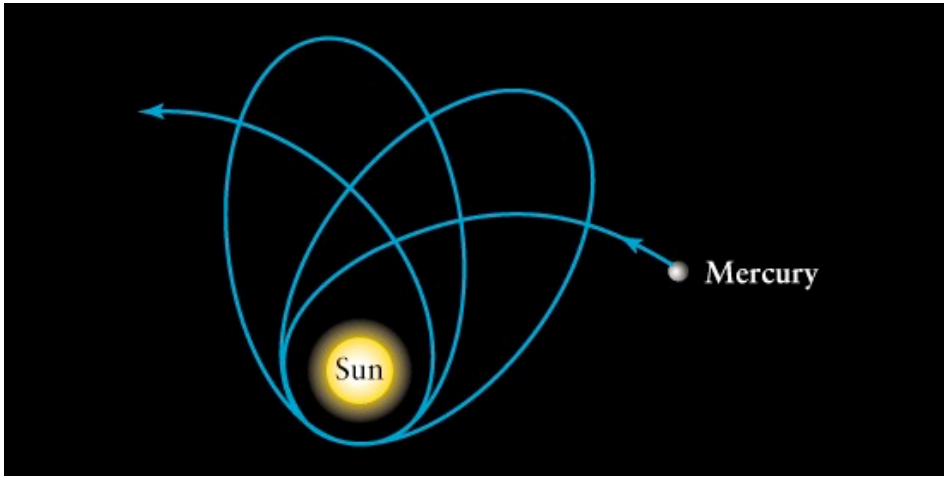


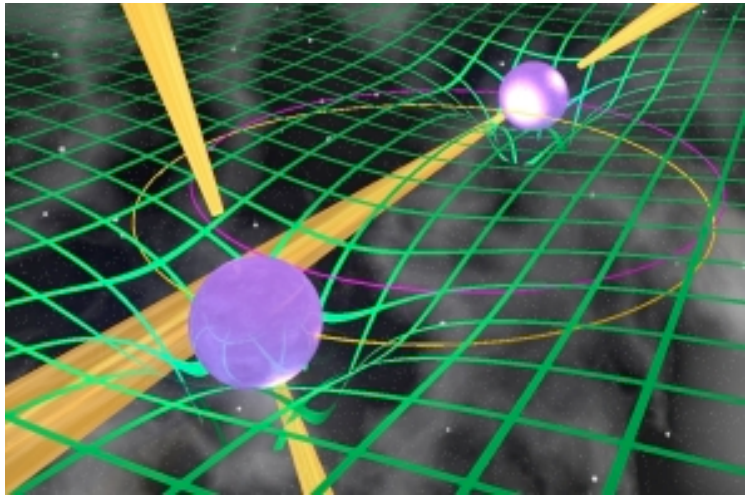


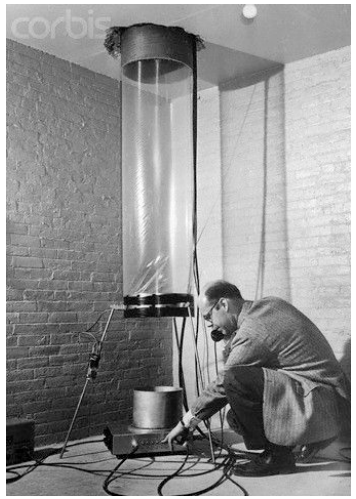
arXiv : 1506.03901

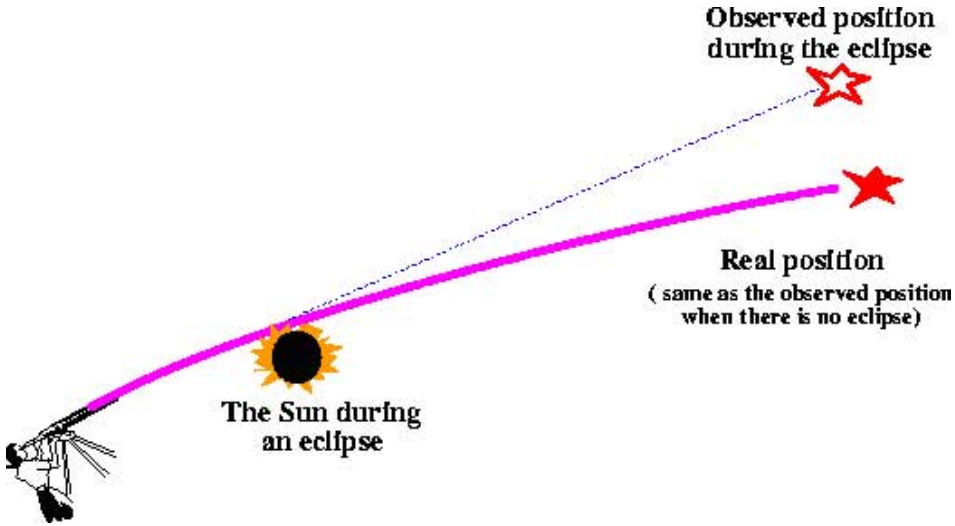
Tests of large-scale gravity

- Can tests of G.R. be extended to cosmic scales?
  And can that yield insight into dark energy?





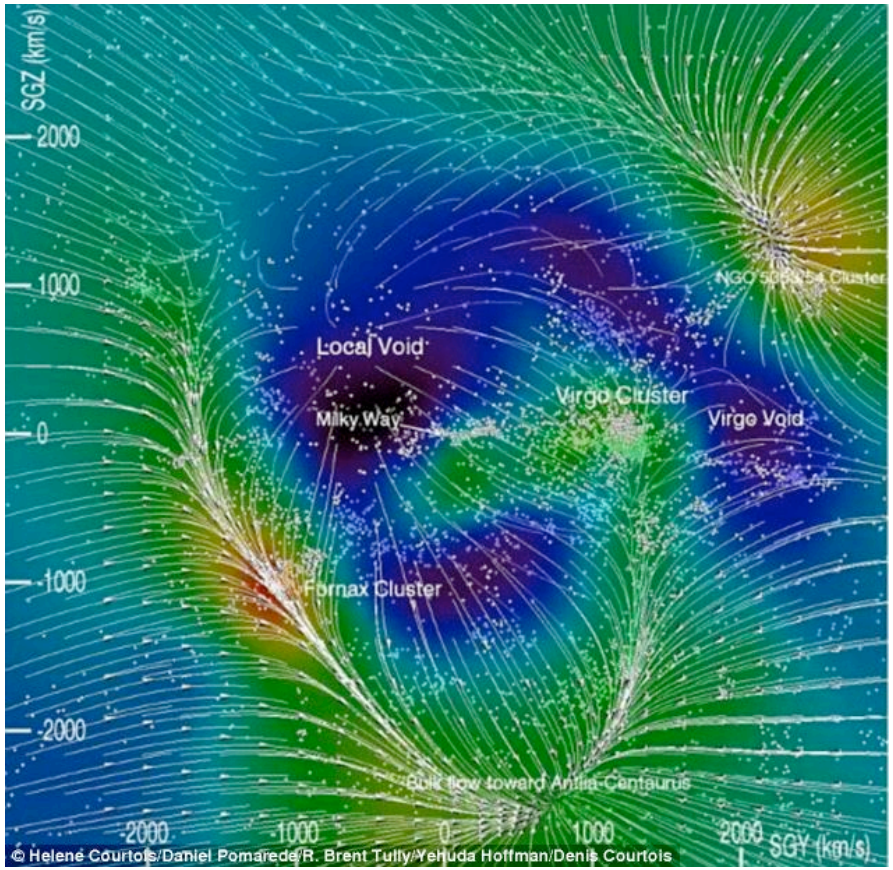




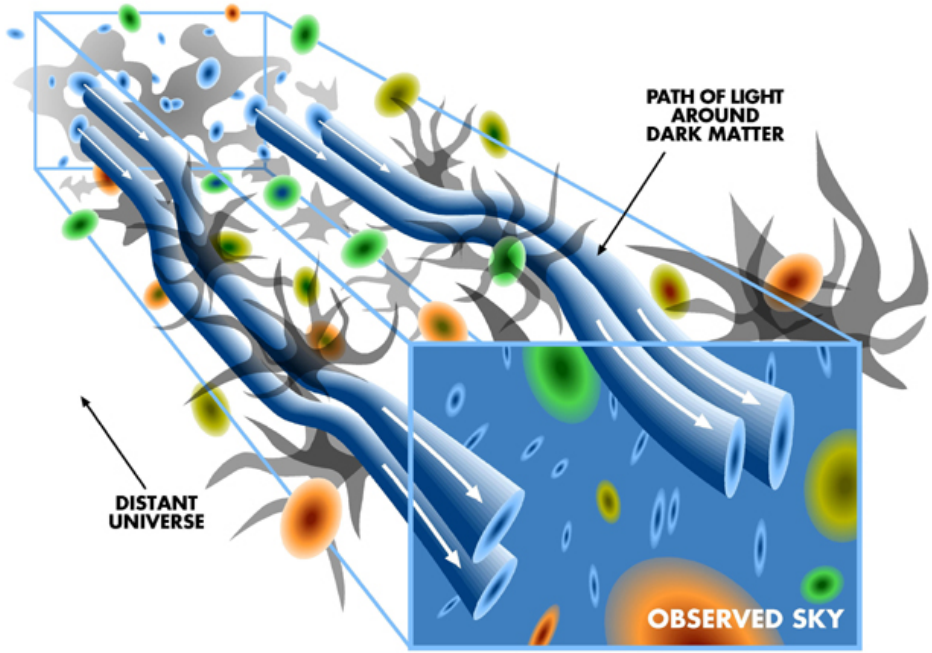
Tests of large-scale gravity

- Two powerful probes of gravitational physics:

Galaxy peculiar velocities

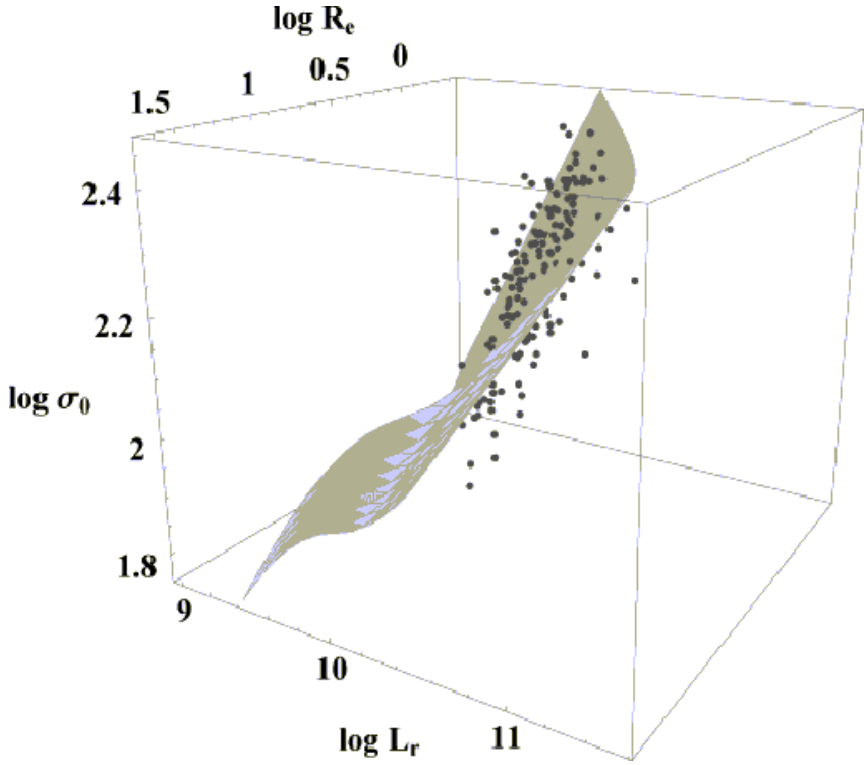


Weak gravitational lensing



Peculiar velocity measurements

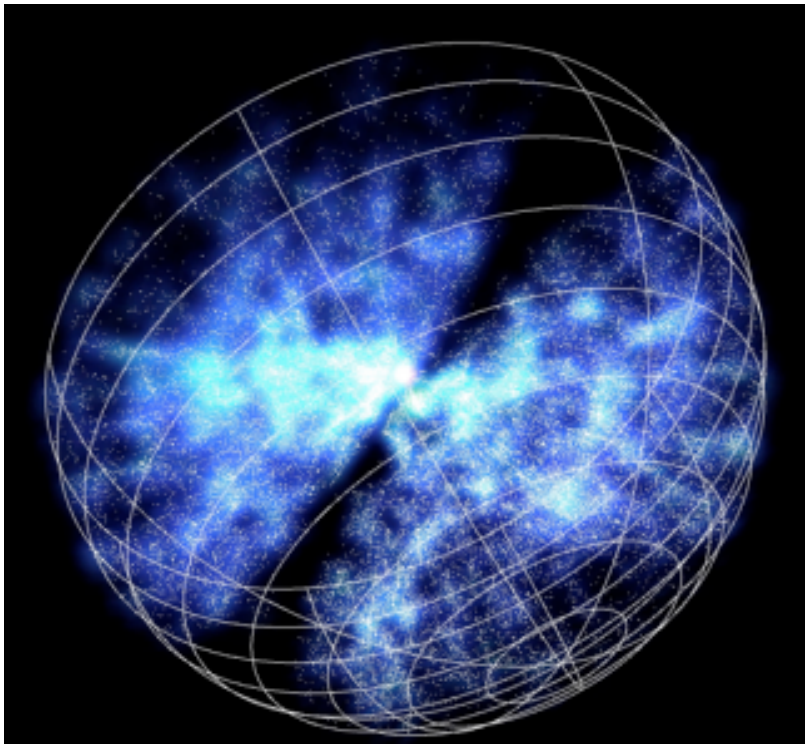
- Simultaneous measurements of distance D and redshift z
- Use standard candle (supernovae, fundamental plane, ...)



$$v_{\text{peculiar}} = c\,z - H_0\,D$$

[Small print :
this equation is not exact!]

Peculiar velocity measurements



- 6dF Galaxy Survey is large southern-sky redshift survey
- 9,000 peculiar velocity measurements using fundamental plane distances [biggest existing sample]
- We measure the velocity power spectrum which is proportional to the growth rate
- Credit to Andrew Johnson!

Results from our velocity fits

- We model the likelihood of the observed radial velocities v_i in terms of the covariance C_v

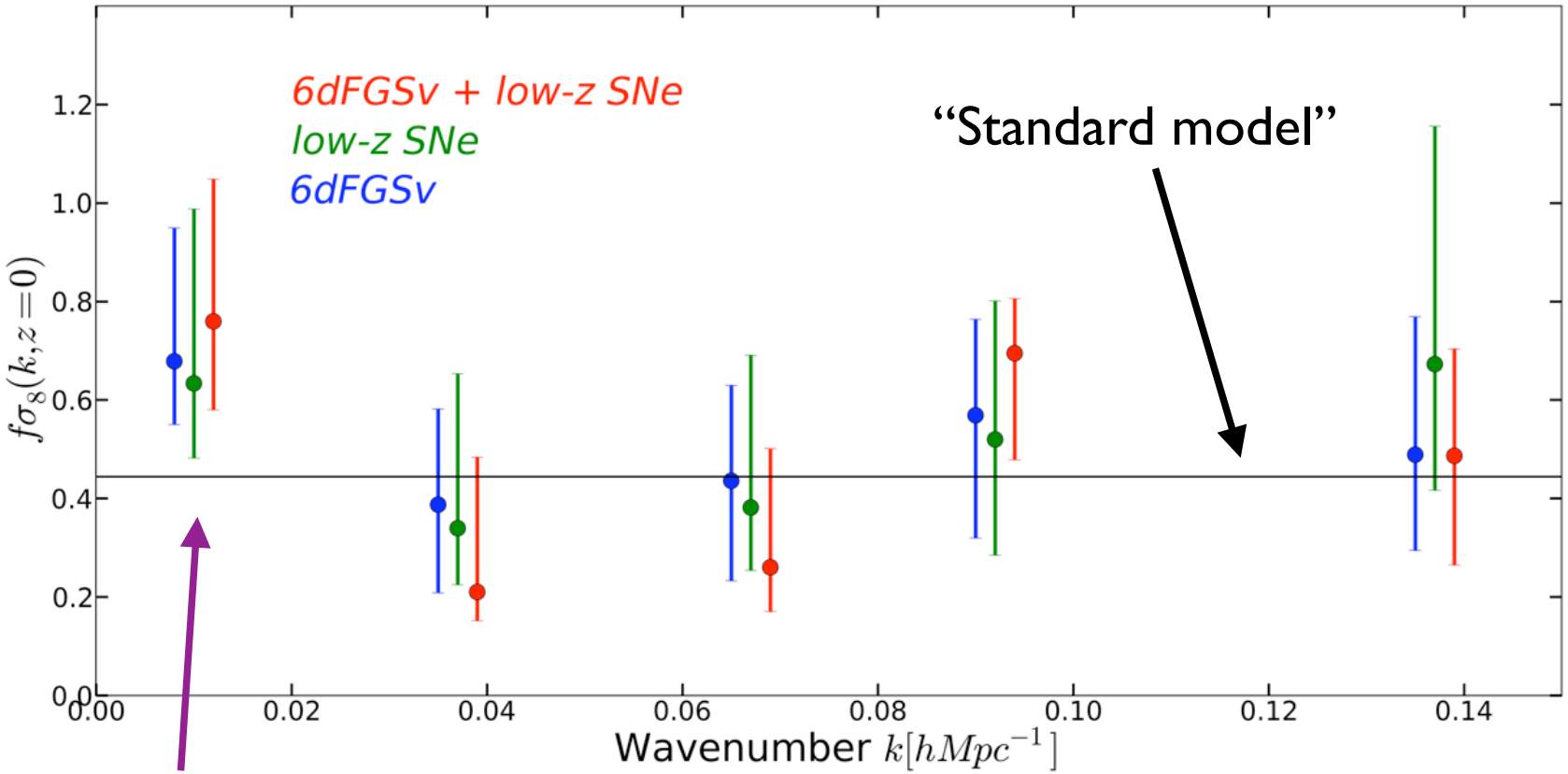
$$L = \frac{1}{\sqrt{2\pi\,|C_v|}} \exp\left(-\frac{1}{2}\sum_{ij} v_i\,(C_v^{-1})_{ij}\,v_j\right)$$

- Covariance matrix depends on the velocity power spectrum $P_v(k)$ and the errors in the data
- We do Monte Carlo Markov Chain fit for amplitude of $P_v(k)$ in k-bins, i.e. growth rate in k-bins

arXiv : 1404.3799

Results from our velocity fits

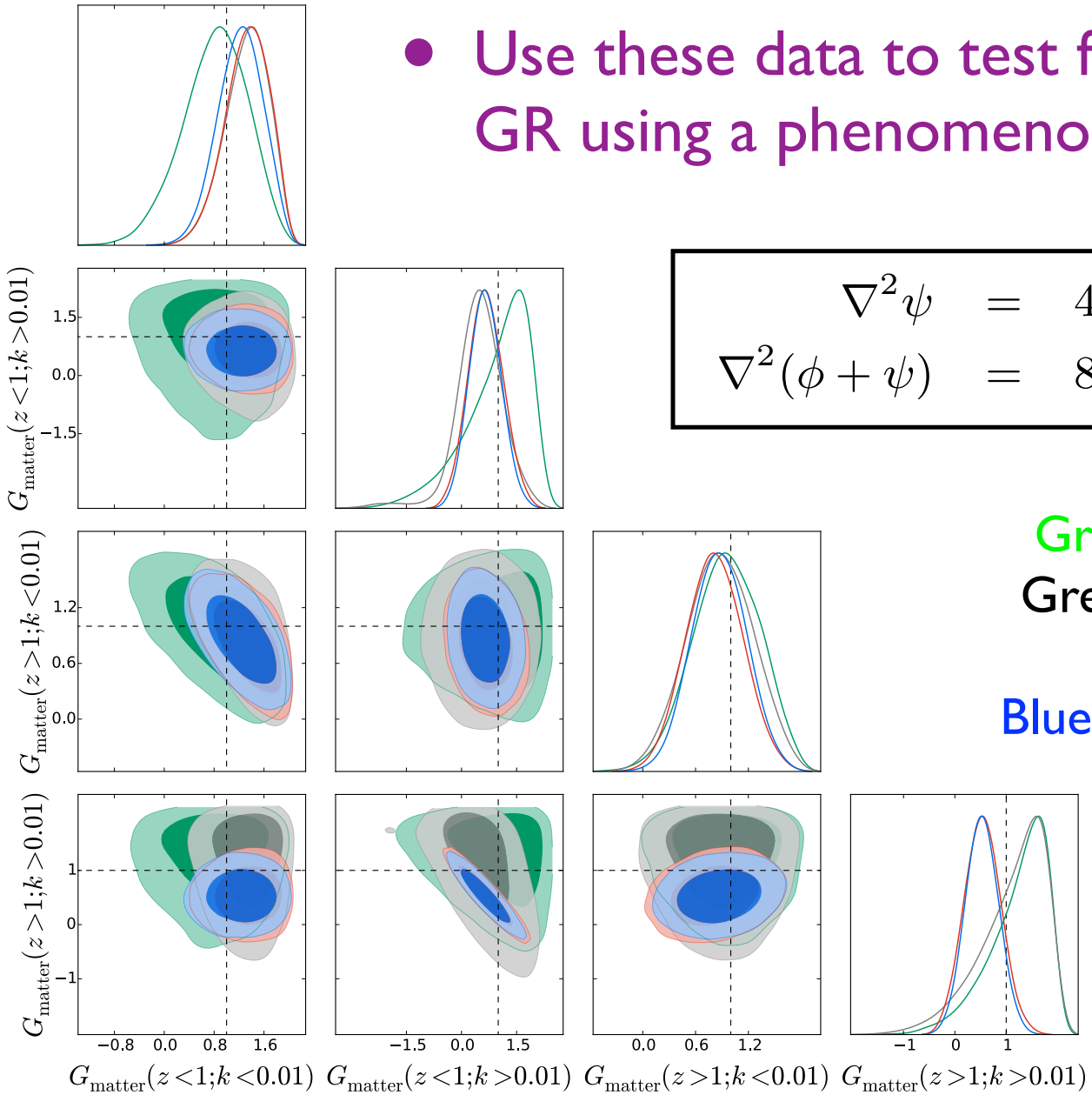
- Here is our result : consistency with the prediction with particular sensitivity to large scales



Gpc scales !

arXiv : 1404.3799

Cosmological consequences



- Use these data to test for deviations from GR using a phenomenological model

$$\nabla^2\psi = 4\pi G_N a^2 \bar{\rho}_m \Delta_m \times G_{\rm matter}$$
$$\nabla^2(\phi+\psi) = 8\pi G_N a^2 \bar{\rho}_m \Delta_m \times G_{\rm light}\ .$$

Green : CMB+BAO+SNe

Grey : + peculiar velocities

Red : + RSD

Blue : + CMB X-correlations

arXiv : 1504.06885

Lensing and clustering : complementarity

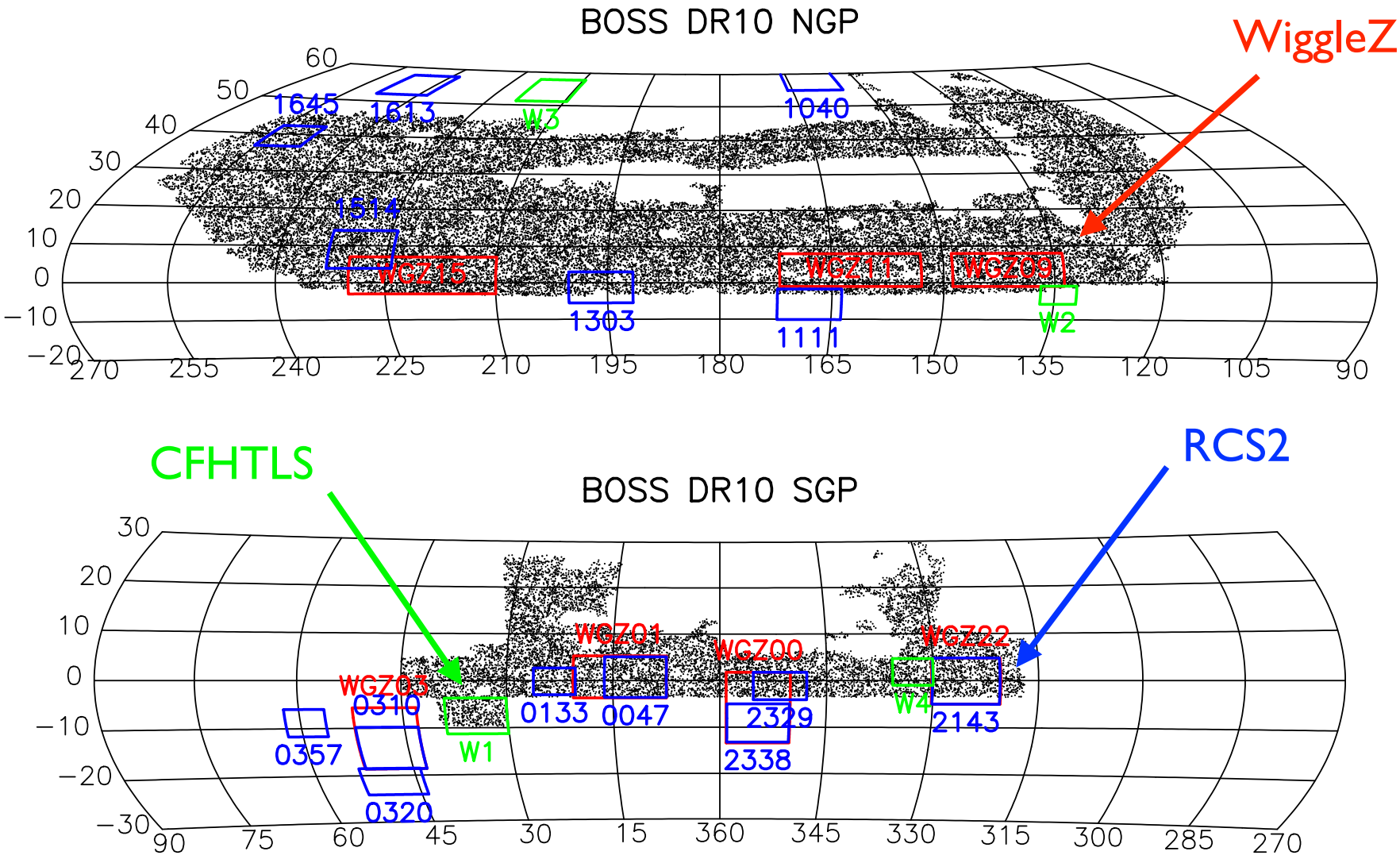
- Sensitive to theories of gravity in complementary ways
- General perturbations to FRW metric:

$$ds^2 = [1+2\psi(x,t)]\,dt^2 - a^2(t)\,[1-2\phi(x,t)]\,dx^2$$

- (ψ, ϕ) are metric gravitational potentials, identical in General Relativity but can differ in general theories
- Relativistic particles (e.g. light rays for lensing) collect equal contributions and are sensitive to $(\psi + \phi)$
- Non-relativistic particles (e.g. galaxies infalling into clusters) experience the Newtonian potential ψ

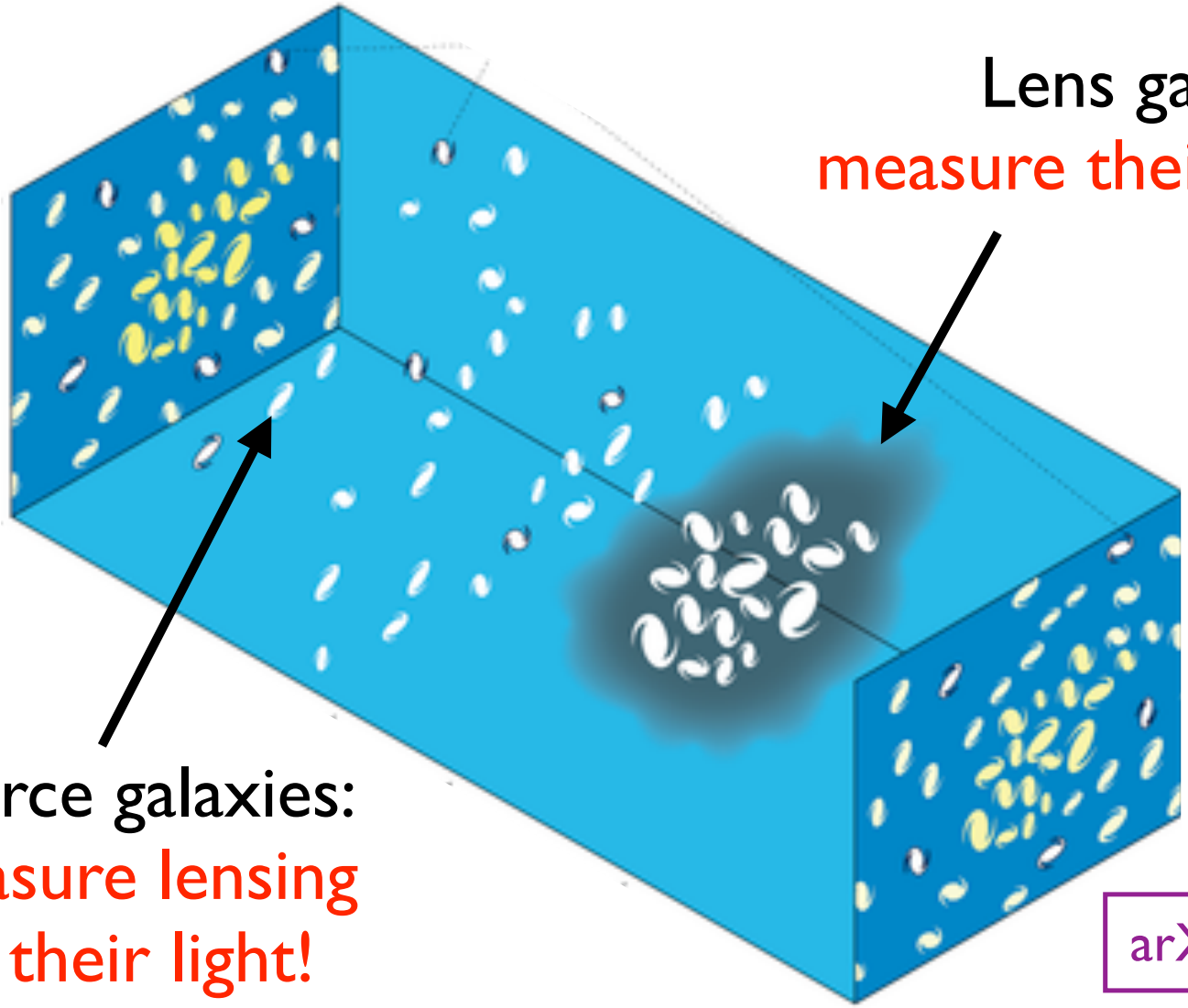
Lensing and clustering : complementarity

- Need overlapping galaxy redshift and lensing surveys!



Testing gravity with galaxy-galaxy lensing

- What is the gravity generated by the density field?



Lens galaxies:
measure their velocities!

Source galaxies:
measure lensing
of their light!

arXiv : 1507.03086

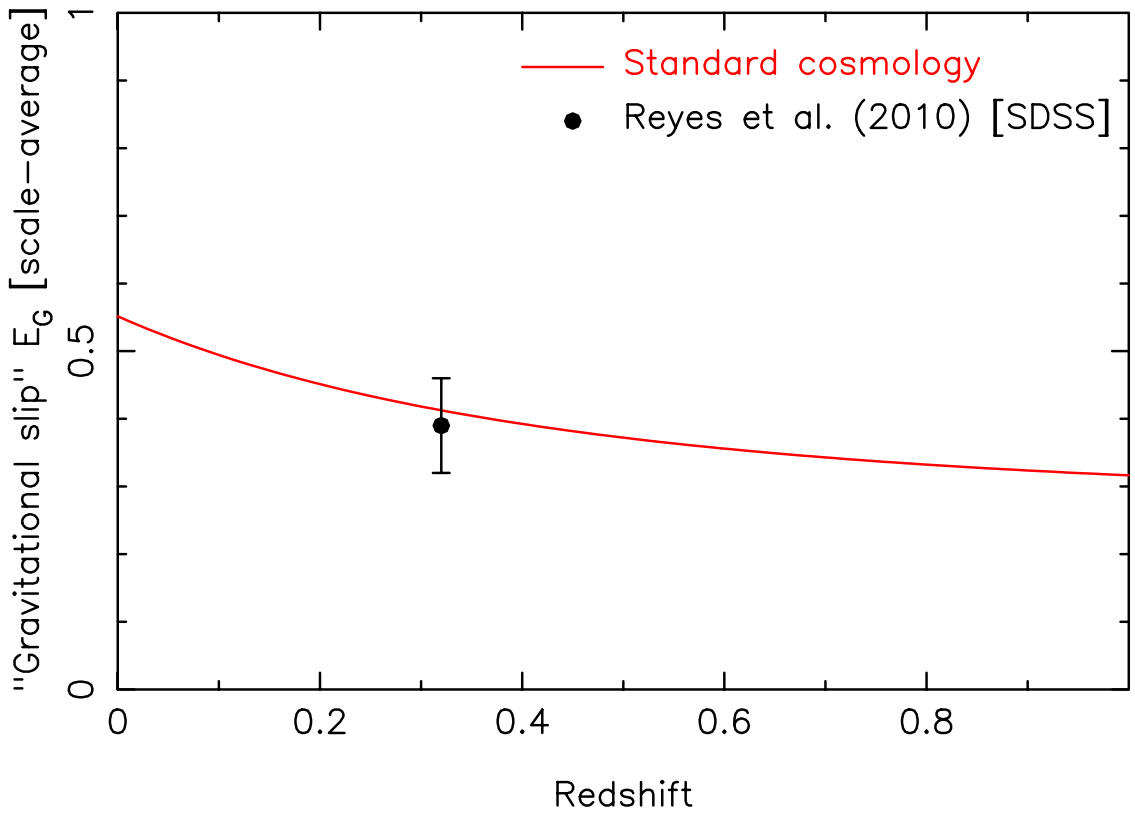
Testing gravity with galaxy-galaxy lensing

- Measure cross-correlations between source shapes from CFHTLenS / RCSLenS (to r ~ 25) and lenses from WiggleZ / BOSS (covering $0.15 < z < 0.7$)
- Total overlap area ~ 500 deg^2
- Shape measurements using "lensfit" give shape density of 14 $arcmin^{-2}$ [CFHTLenS] and 6 $arcmin^{-2}$ [RCSLenS]
- Source photometric redshift catalogue using BPZ
- Battery of systematic tests of shear measurements, results blinded

Testing gravity with galaxy-galaxy lensing

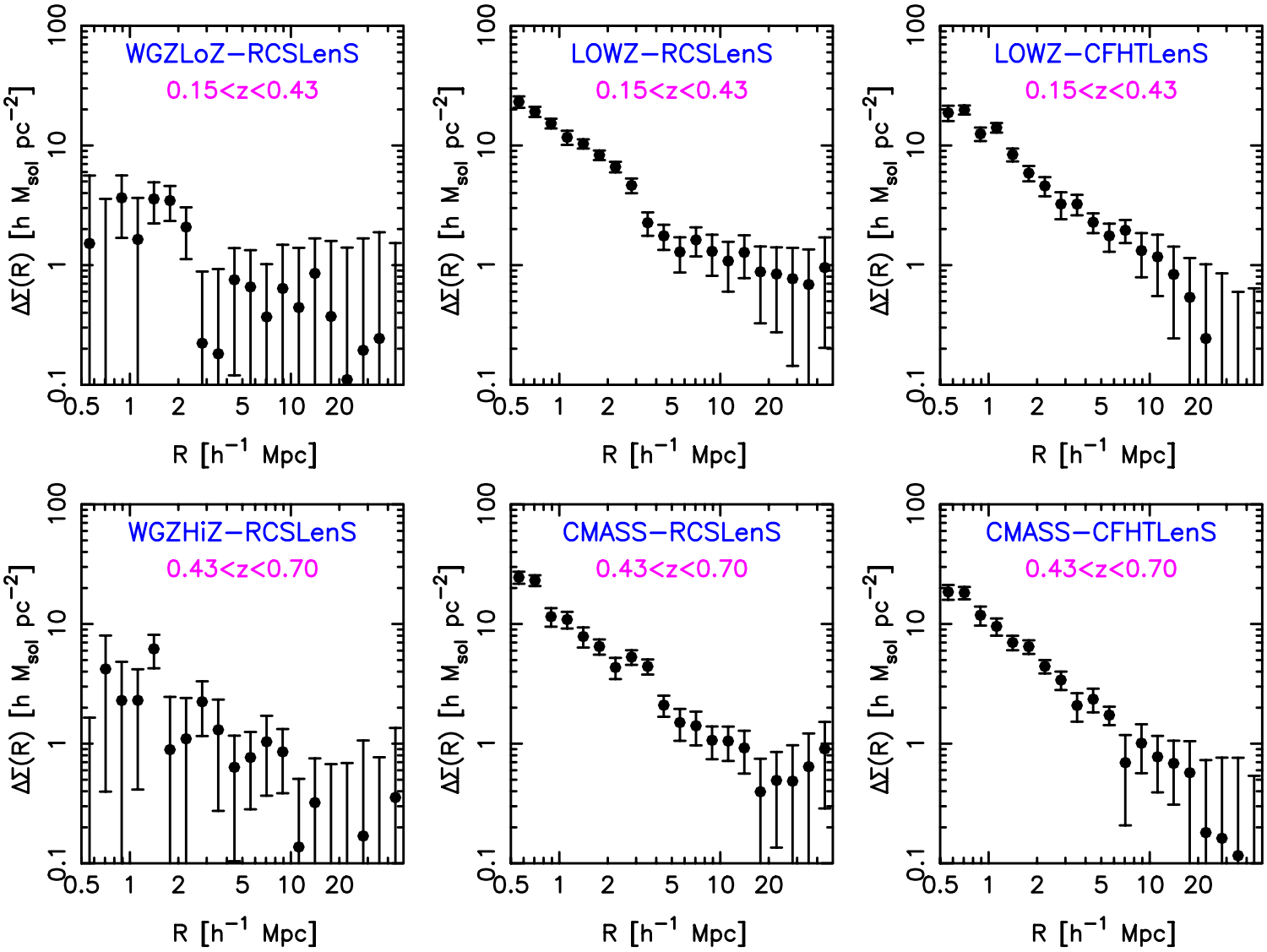
$$\text{Measurement [scale]} = \frac{\text{Amplitude of lensing [scale]}}{\text{Amplitude of velocities [scale]}} \qquad E_G(R) = \frac{1}{\beta}\frac{\Upsilon_{gm}(R, R_0)}{\Upsilon_{gg}(R, R_0)}$$

$$\text{Prediction} = \frac{\text{Matter density}}{\text{Cosmic growth rate}} \qquad E_G = \Omega_m / f$$



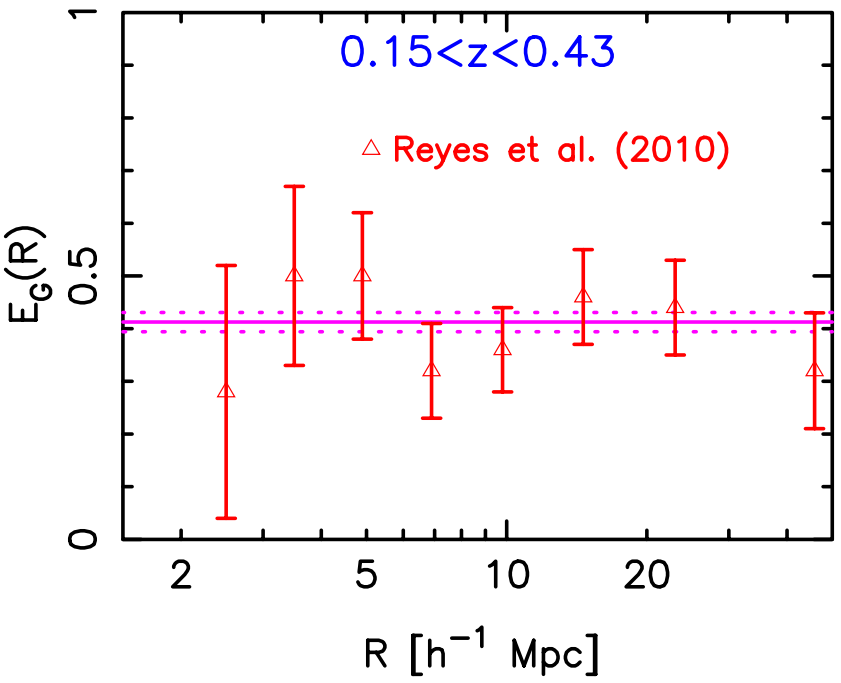
Testing gravity with galaxy-galaxy lensing

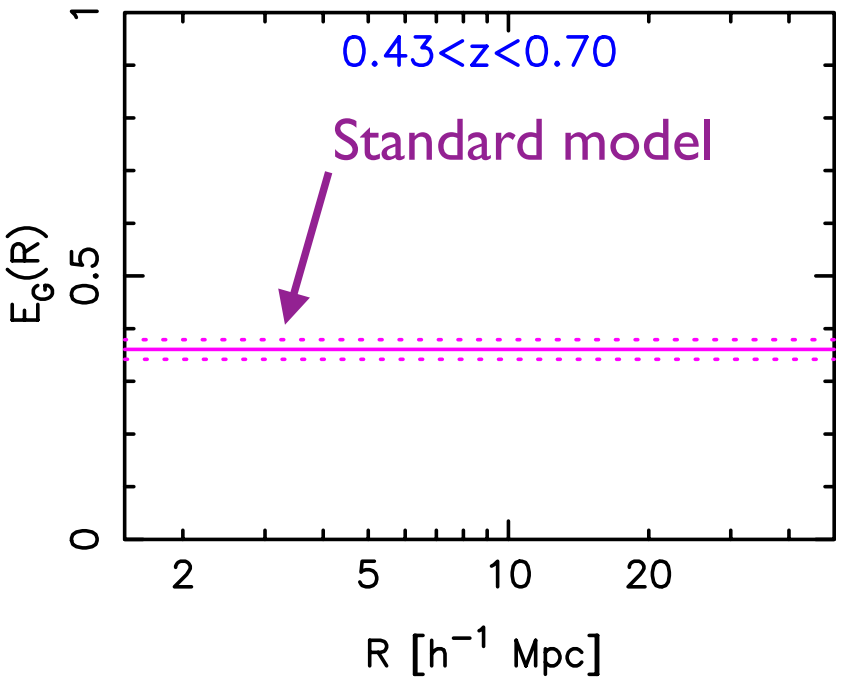
- Galaxy-galaxy lensing measurements



Testing gravity with galaxy-galaxy lensing

- Is E_G scale-independent, and what is its value?

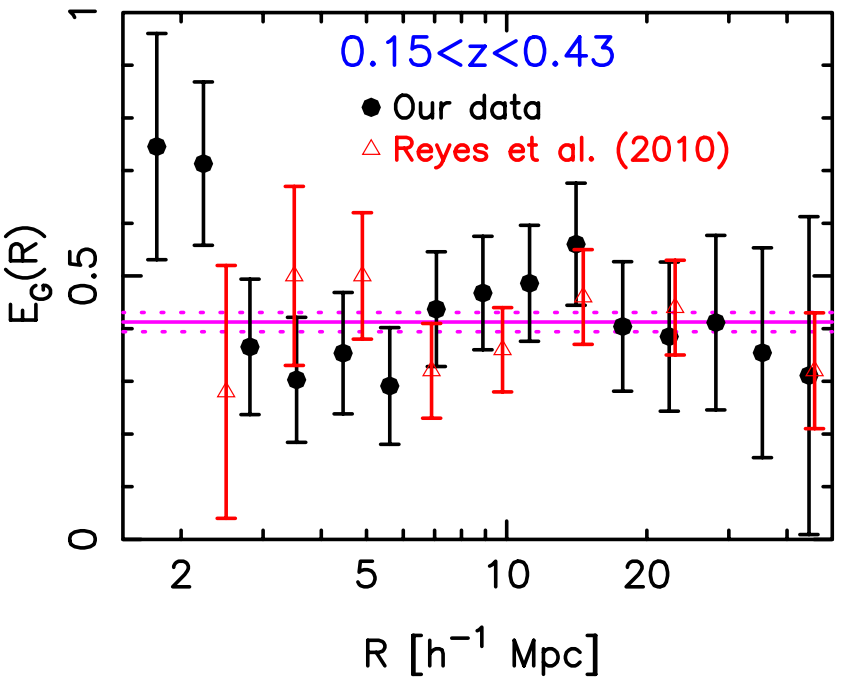


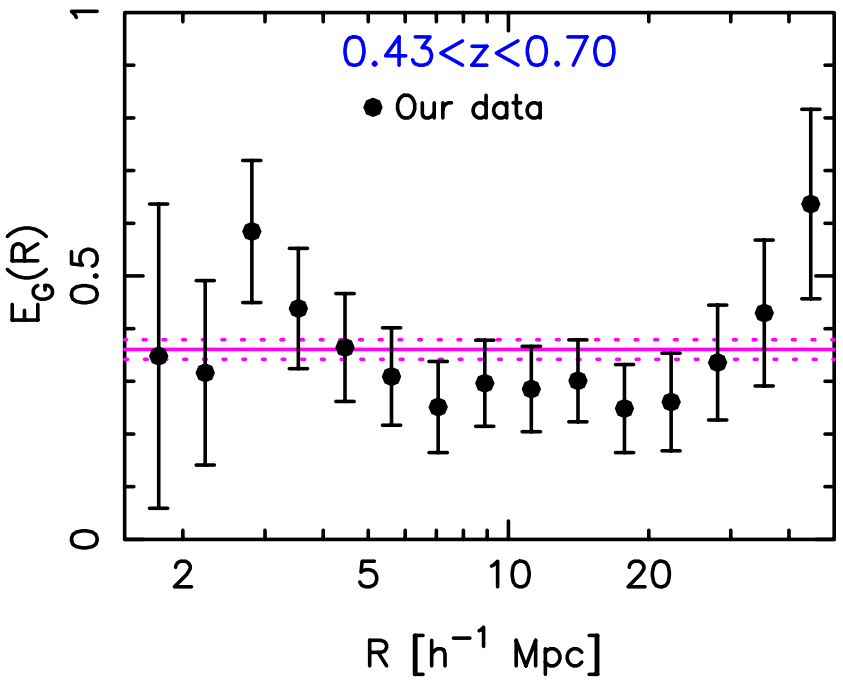


arXiv : 1507.03086

Testing gravity with galaxy-galaxy lensing

- We find the "gravitational slip" E_G is independent of scale with amplitude consistent with the standard model

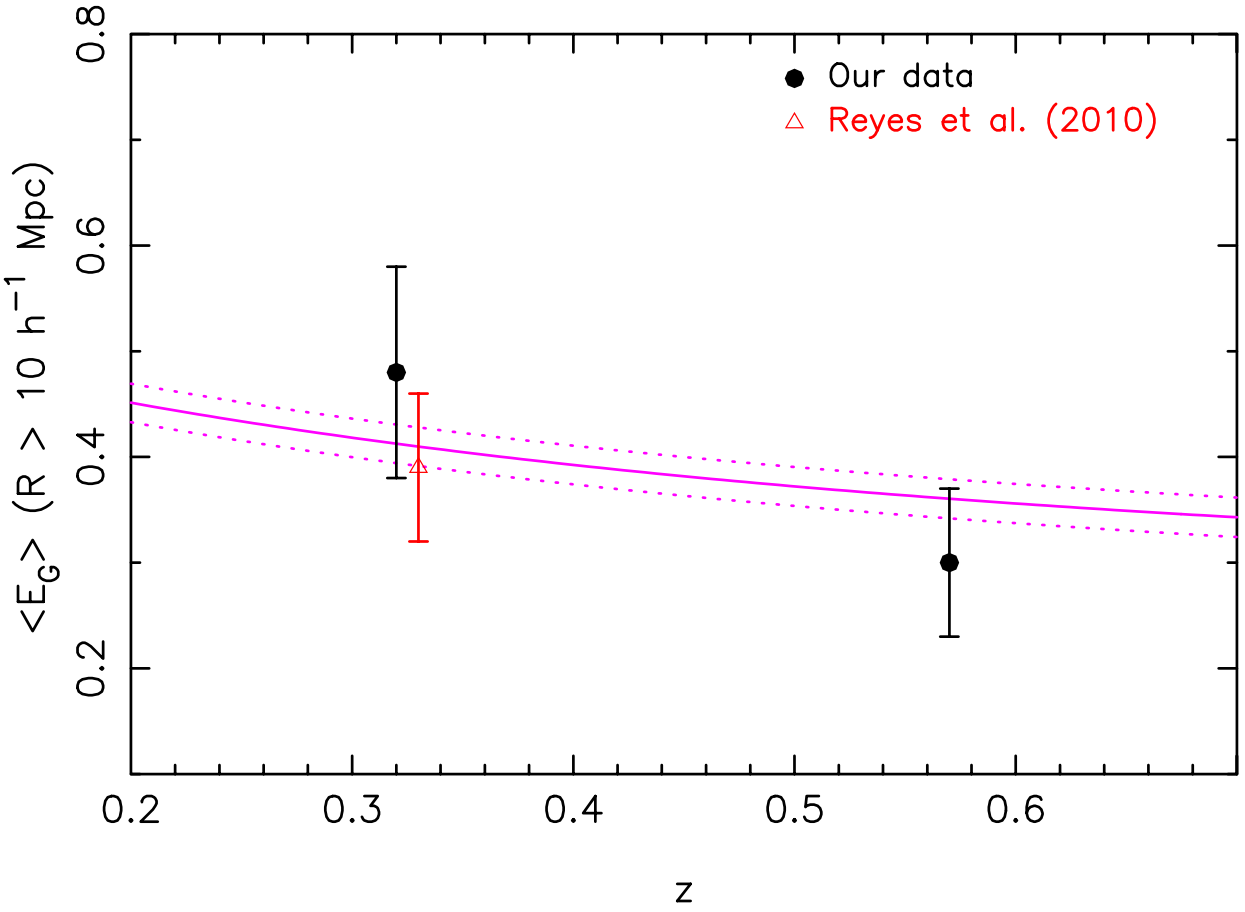




arXiv : 1507.03086

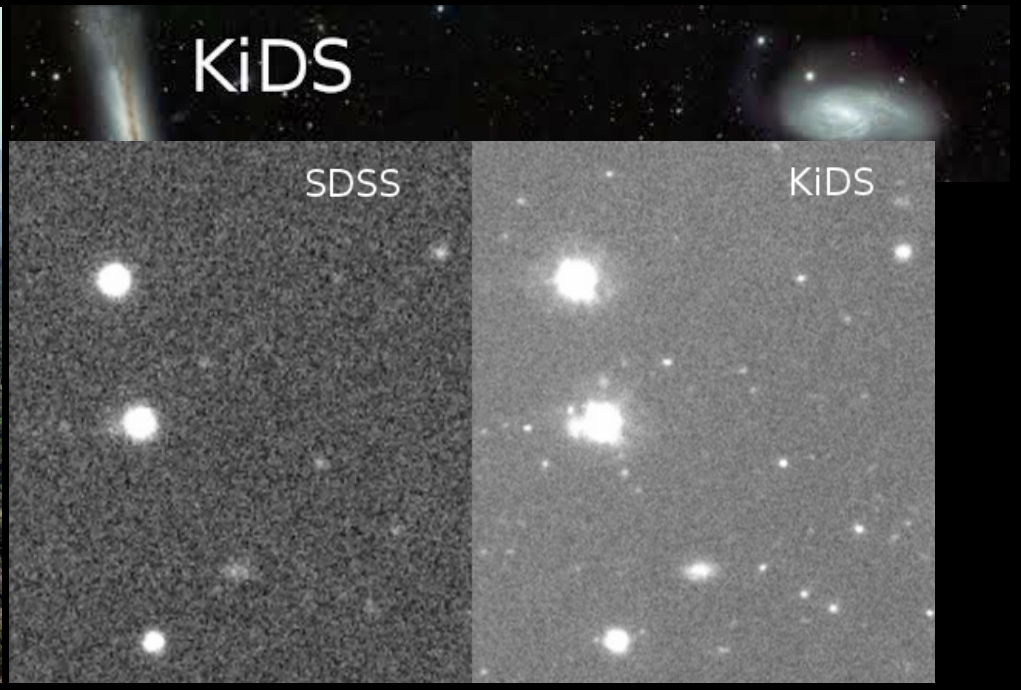
Testing gravity with galaxy-galaxy lensing

- Extension of these tests to higher redshift



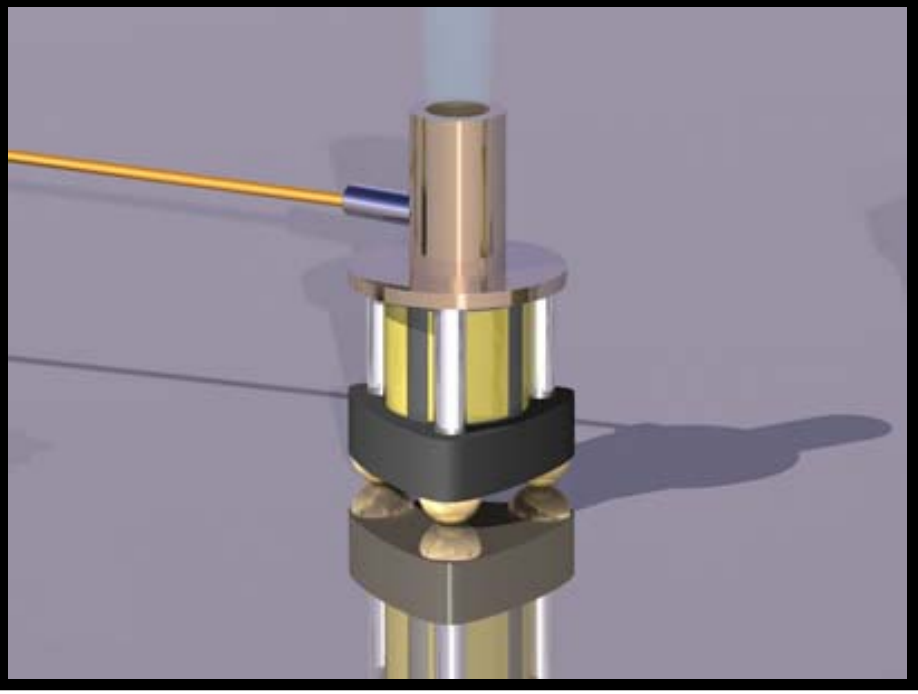
How can we take this further?

2dF Lensing Survey (2dFLenS)



- 50 AAT nights granted for spectroscopic follow-up of southern lensing surveys such as KiDS and DES
- Galaxy lens sample to test gravity by cross-correlating weak lensing distortions and galaxy velocities
- Photo-z calibration samples (direct / cross-correlation)

Taipan Galaxy Survey



- Local Universe survey of ~1M galaxy redshifts ($z < 0.3$) and ~100,000 velocities ($z < 0.1$) starting next year
- 1% measurement of H_0 through baryon acoustic peak
- Perform new tests of General Relativity using combined analyses of the density and velocity fields

Summary

- Apparent existence of dark energy motivates new tests of large-scale gravitational physics
- Two observable signatures are non-relativistic galaxy velocities and relativistic lensing of light
- We have performed new measurements using the latest galaxy redshift, velocity and lensing surveys
- General Relativity + cosmological constant + perturbed FRW metric models remain a good fit
- The quest to understand dark energy continues!