2dFLenS: Testing Gravity on Cosmic Scales

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Agenda Part 1

- Introduction: Modified Gravity, Weak Lensing, Redshift Space Distortions.
- E_G Test of Gravity: Current Data (RCSLenS+CFHTLenS)/(WiggleZ + BOSS).
- 2dFLenS Galaxy Redshift Survey: Properties and Expected Constraints on Modified Gravity.

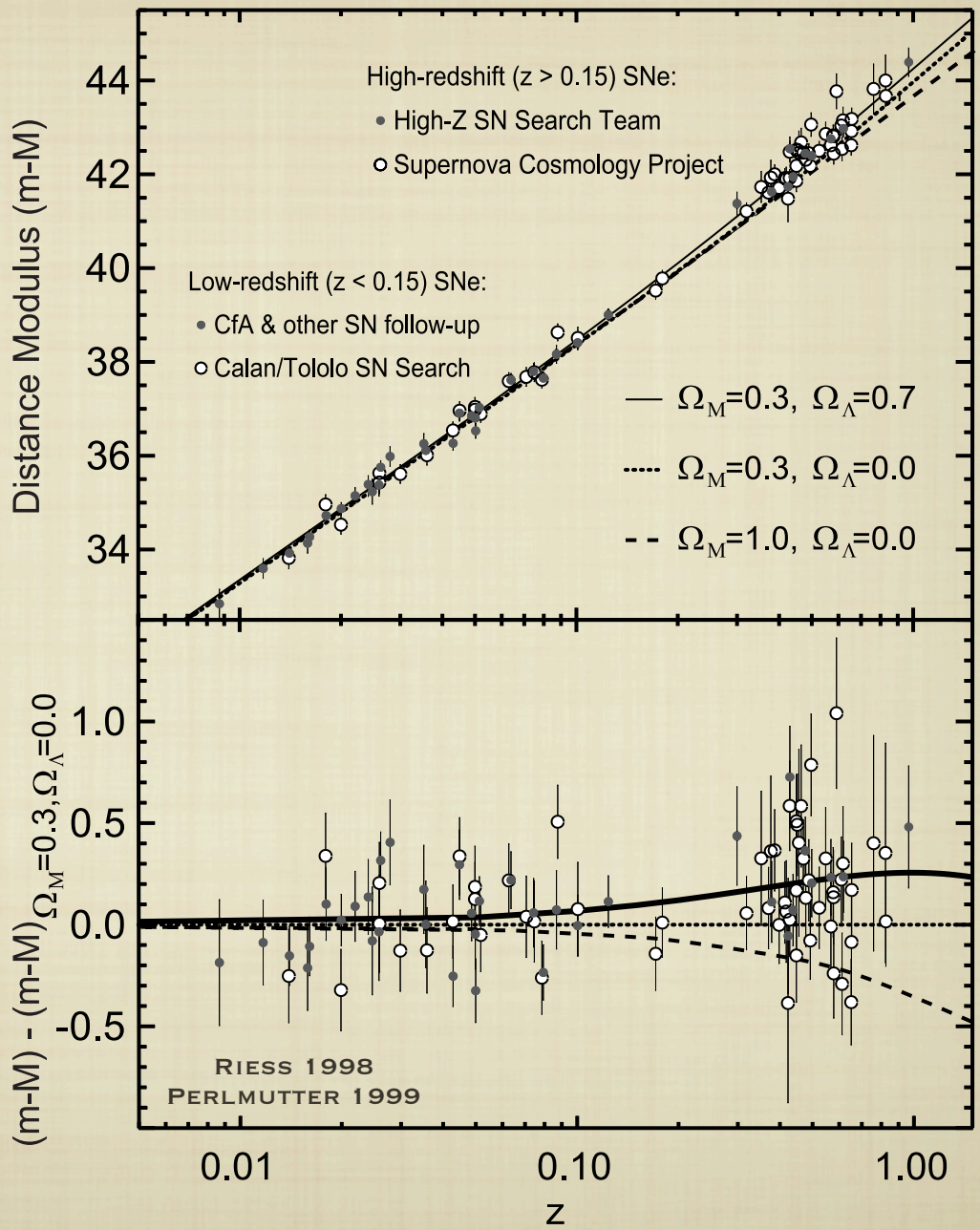
Cosmic acceleration

Universe accelerates

Cosmological constant, DE, or MG?

Expansion: SNe, BAO
Growth: WL, RSD

critical for understanding MG



Perturbed Einstein: Metric Potentials

Newtonian gauge, (small) scalar perturbations:

$$ds^2 = -(1+2\psi)\ dt^2 + (1-2\phi)\ a^2(t)\ d\vec{x}^2$$

Non-relativistic Particles: ψ ← **Newtonian**

Relativistic Particles: $\psi + \phi$

standard GR + no anisotropic stress: $\psi = \phi$

→ **Poisson Equation:**

$$\nabla^2\psi = \nabla^2\phi = 4\pi G a^2 \sum \rho_i \Delta_i$$

Ma & Bertschinger 1995

Perturbed Einstein Equations

General Relativity

$$k^2\phi = -4\pi G a^2 \sum \rho_i \Delta_i$$

$$\psi - \phi = -12\pi G a^2 \sum_i \rho_i (1 + w_i) \frac{\sigma_i}{k^2}$$

Modified Gravity

$$k^2\phi = -4\pi \underbrace{GQ}_{G_{\rm eff}} a^2 \sum_i \rho_i \Delta_i$$

$$\psi = R\phi$$

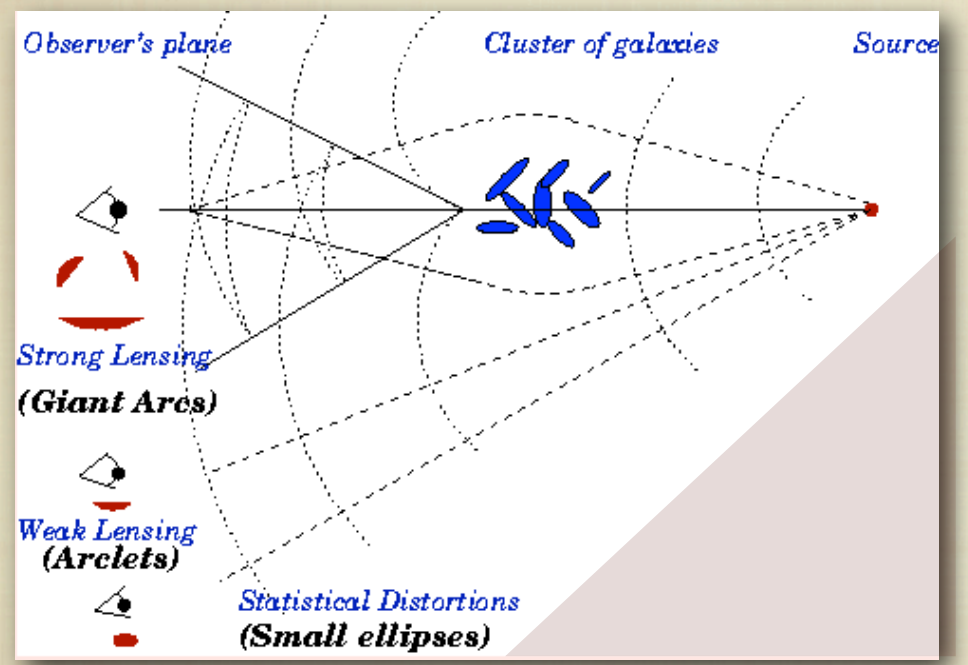
in general: Q(*k*,*a*), R(*k*,*a*)

Jain & Zhang 2007
Bean & Tangmatitham 2010

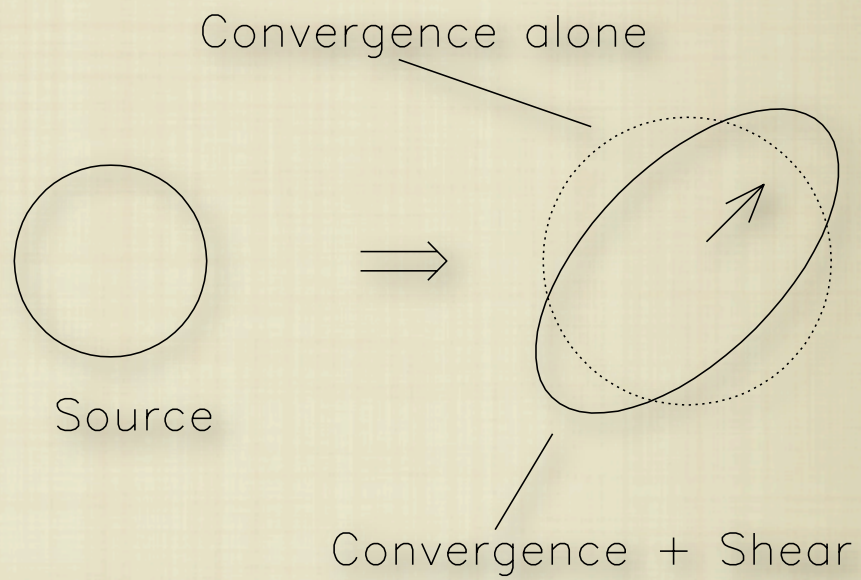
How to probe MG?

1) Weak Gravitational Lensing

Gravitational lensing magnifies (convergence=κ) and distorts shape (shear=γ) of galaxies. In weak lensing limit: $|\gamma|, |\kappa| << 1$.



B. Jain (www.hep.upenn.edu/~bjain/lensing.html)



Bartelmann & Narayan (1996)

$$\kappa = \frac{1}{2}\int_0^{\chi_s} \nabla^2(\psi+\phi)W(\chi,\chi_s)d\chi \longrightarrow C_{\kappa\kappa}(l), C_{\kappa g}(l)$$

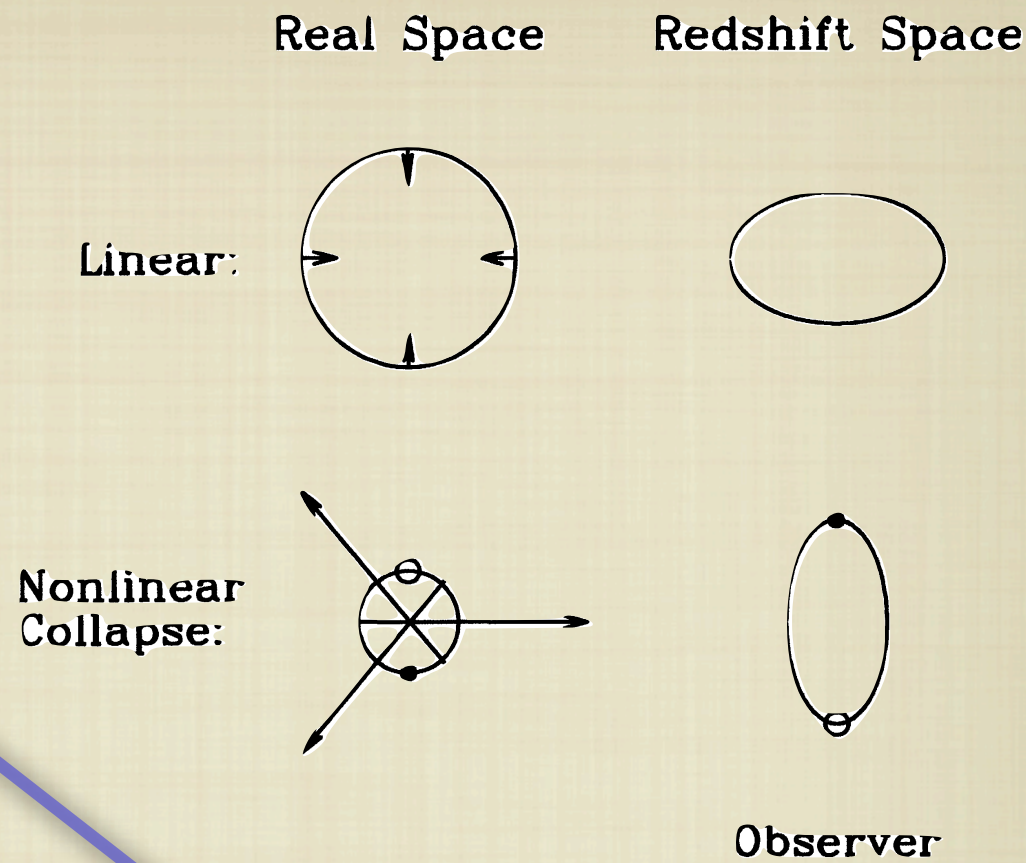
How to probe MG?

2) Peculiar Velocities

$$\theta \equiv \nabla \cdot \mathbf{v}/H$$

$$= -\dot{\delta}/H = -f\delta$$

$$f = d\ln D/d\ln a$$



$$P_g^s(\mathbf{k}) = \left[P_g(k) + 2u^2 P_{g\theta}(k) + u^4 P_\theta(k)\right] F\left(\frac{k^2 u^2 \sigma_v^2}{H^2(z)}\right)$$

Kaiser 1987
Dodelson 2003

Agenda Part 2

- Introduction: Modified Gravity, Weak Lensing, Redshift Space Distortions.
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Probing gravity with E_G: in theory

Fundamental test of whether relation between ψ and $(\psi+\phi)$ follows GR expectation.

$$\hat{E}_G = \frac{C_{\kappa g}(l, \Delta l)}{3H_0^2 a^{-1} \sum_\alpha f_\alpha(l, \Delta l) P_\alpha^{(1)}}$$

Achieved by correlating lens galaxies to both surrounding velocity field using RSD (θg) and shear of background galaxies using galaxy-lensing (κg).

$$\langle \hat{E}_G \rangle = \left[\frac{\nabla^2(\psi + \phi)}{3H_0^2 a^{-1} f \delta} \right]_{k=\frac{l}{\bar{\chi}}, \bar{z}}$$

Does not depend on bias or on initial matter fluctuations. Sensitive to MG via Growth Rate (ψ) and Poisson Eqn (ψ, ϕ).

Zhang et al 2007

Probing gravity with E_G: in practice

Rephrase E_G into more easily observable quantities (3 vs 2), and replace $P_{g\theta}$ with βP_{gg}:

$$E_G(R) = \frac{1}{\beta}\frac{\Upsilon_{gm}(R,R_0)}{\Upsilon_{gg}(R,R_0)}$$

$$\beta \propto 1/b$$
$$\Upsilon_{gm} \propto b\,\sigma_8^2$$
$$\Upsilon_{gg} \propto b^2\,\sigma_8^2$$

Lens-Source correlation:

$$\Upsilon_{gm}(R,R_0) \quad = \quad \Delta\Sigma(R) - \frac{R_0^2}{R^2}\,\Delta\Sigma(R_0)$$

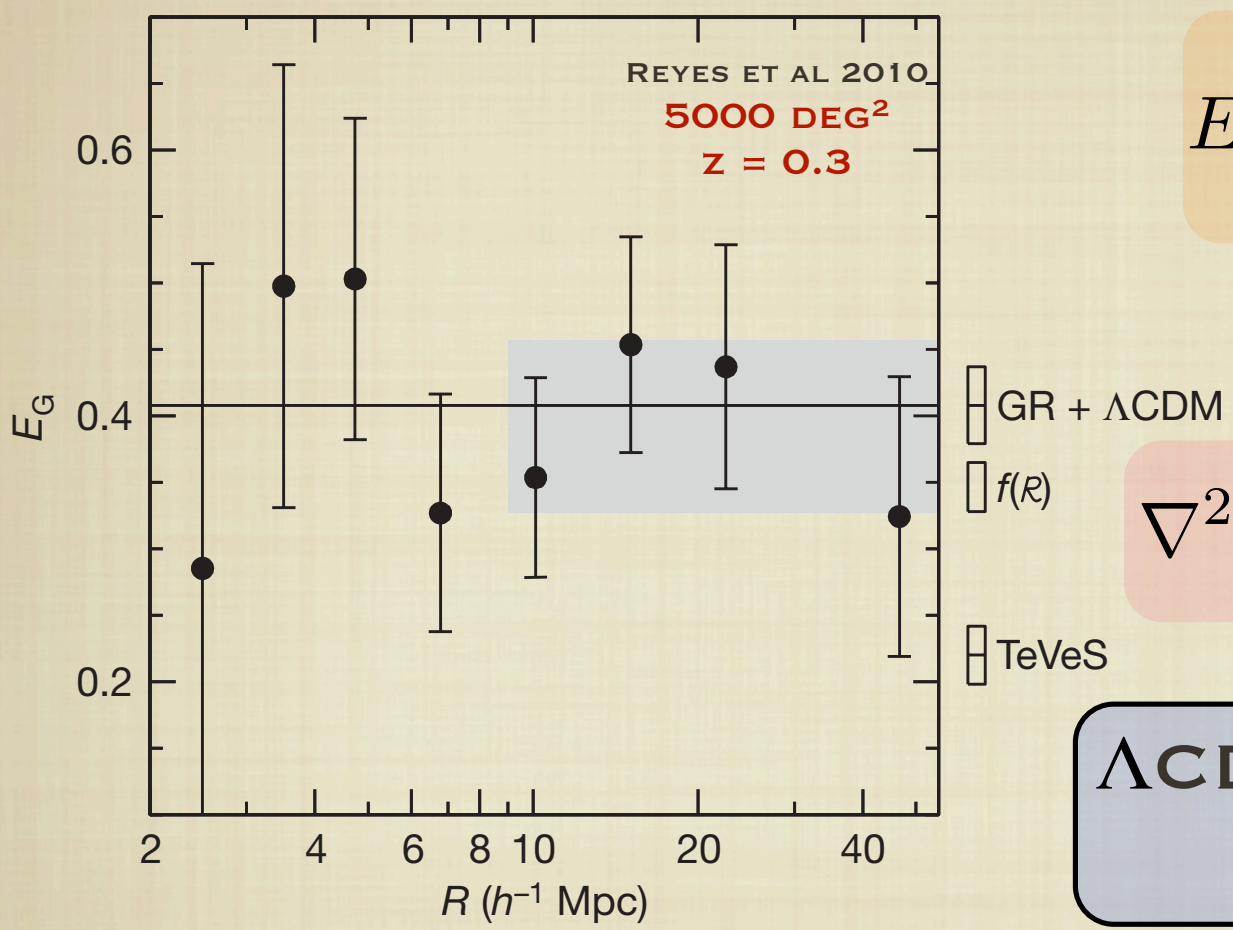
$$\Delta\Sigma(R) = \sum_{\text{lens}-\text{source pairs}} [\text{weights}]\ \gamma_t(\theta)\Sigma_c(z_s,z_l)$$

Lens-Lens correlation:

$$\Upsilon_{gg}(R,R_0) = \rho_c\left[\frac{2}{R^2}\int_{R_0}^{R} R'\,w_p(R')\,dR' - w_p(R) + \frac{R_0^2}{R^2}w_p(R_0)\right]$$

Reyes et al 2010
Blake et al 2014, in prep

First Measurement of E_G: SDSS



$$E_G = \frac{\nabla^2(\psi + \phi)}{3H_0^2 a^{-1} f \delta}$$

$$\psi = R\phi$$

$$\nabla^2 \phi = \frac{3}{2}\Omega_m H_0^2 Q a^{-1} \delta$$

ΛCDM (Q = 1, R = 1):

$$E_G = \Omega_m / f$$

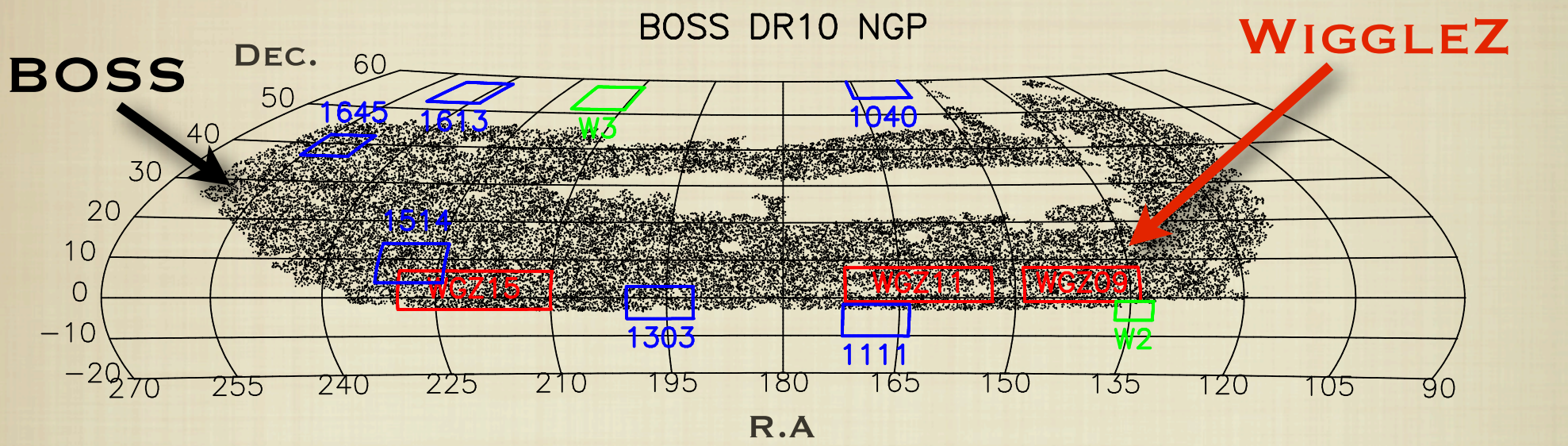
Zhang et al 2007

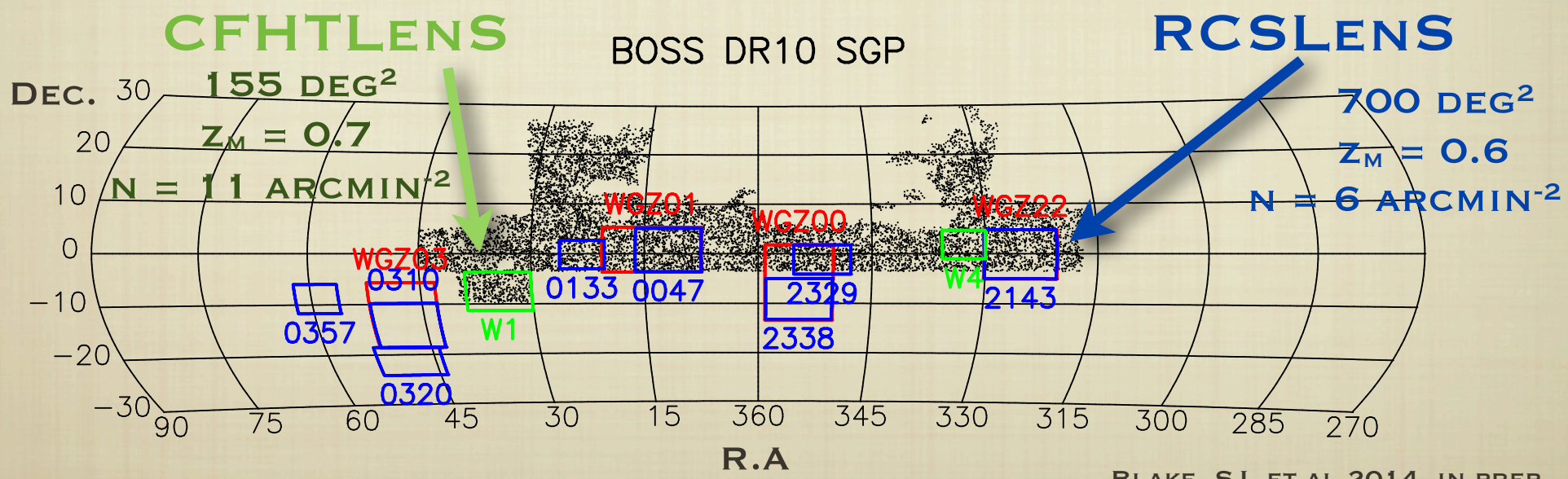
$f(\mathcal{R})$: $Q = (1+f_{\mathcal{R}})^{-1}$, $R = 1$

Flat DGP: $Q = 1$, $R = [1 - 1/3\beta_{DGP}]/[1 + 1/3\beta_{DGP}]$

Current Lensing and RSD Surveys

Need overlapping galaxy redshift and lensing surveys





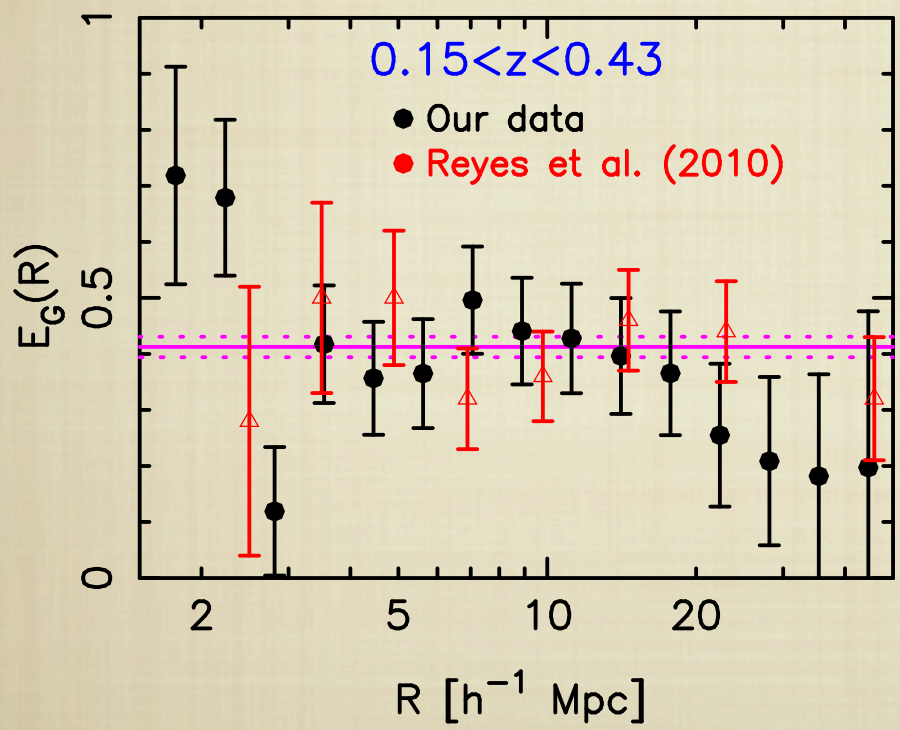
Blake, SJ, et al 2014, in prep

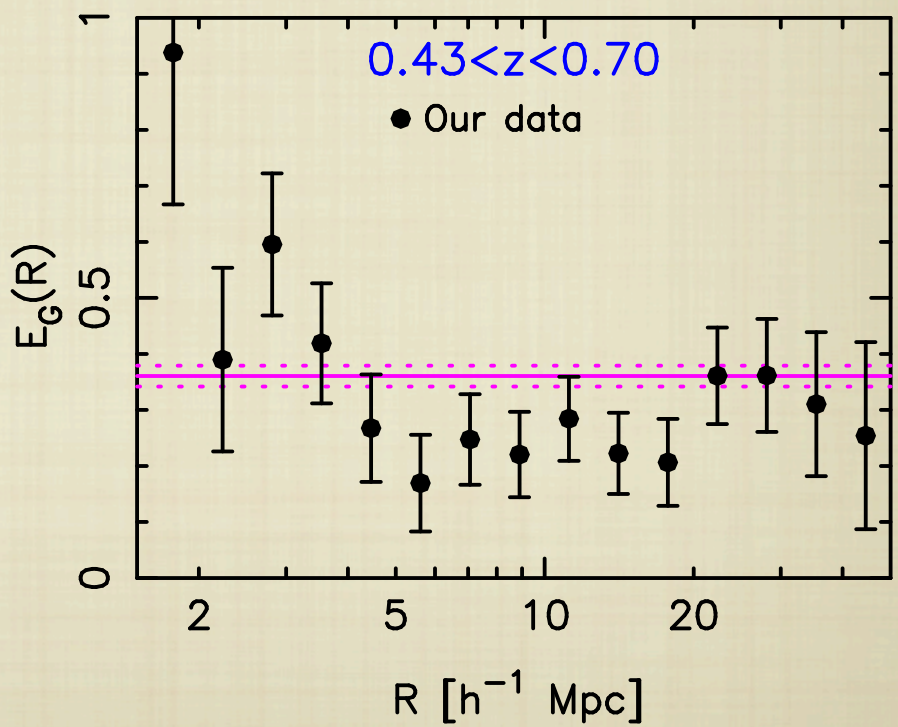
Measuring E_G: scale dependence

For this particular blinding, E_G is found independent of scale with amplitude consistent with standard model

ΛCDM:

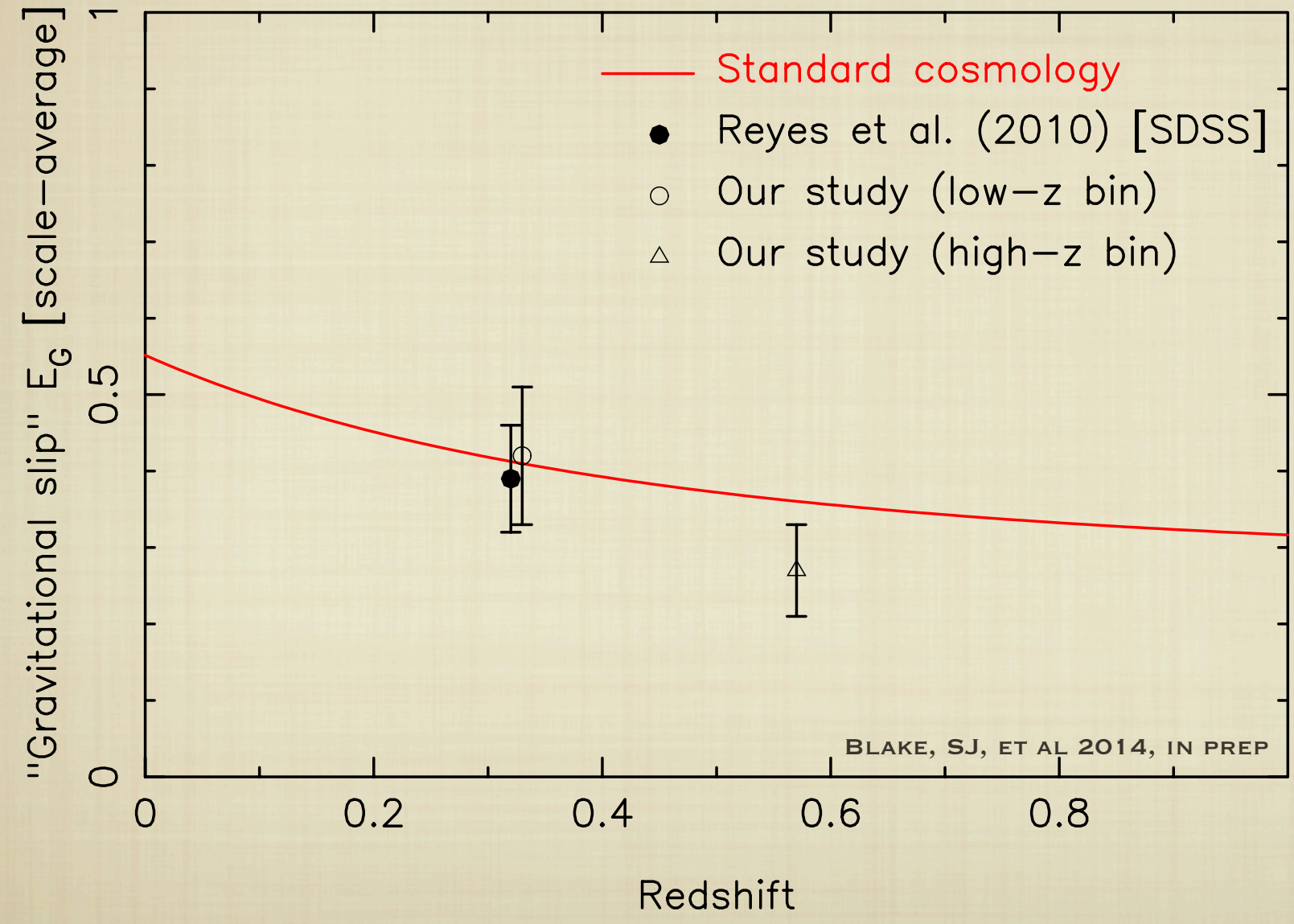
$$E_G = \Omega_m / f$$





Blake, SJ, et al 2014, in prep

Measuring E_G: redshift dependence



Agenda Part 3

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2dFLenS at the AAT in NSW

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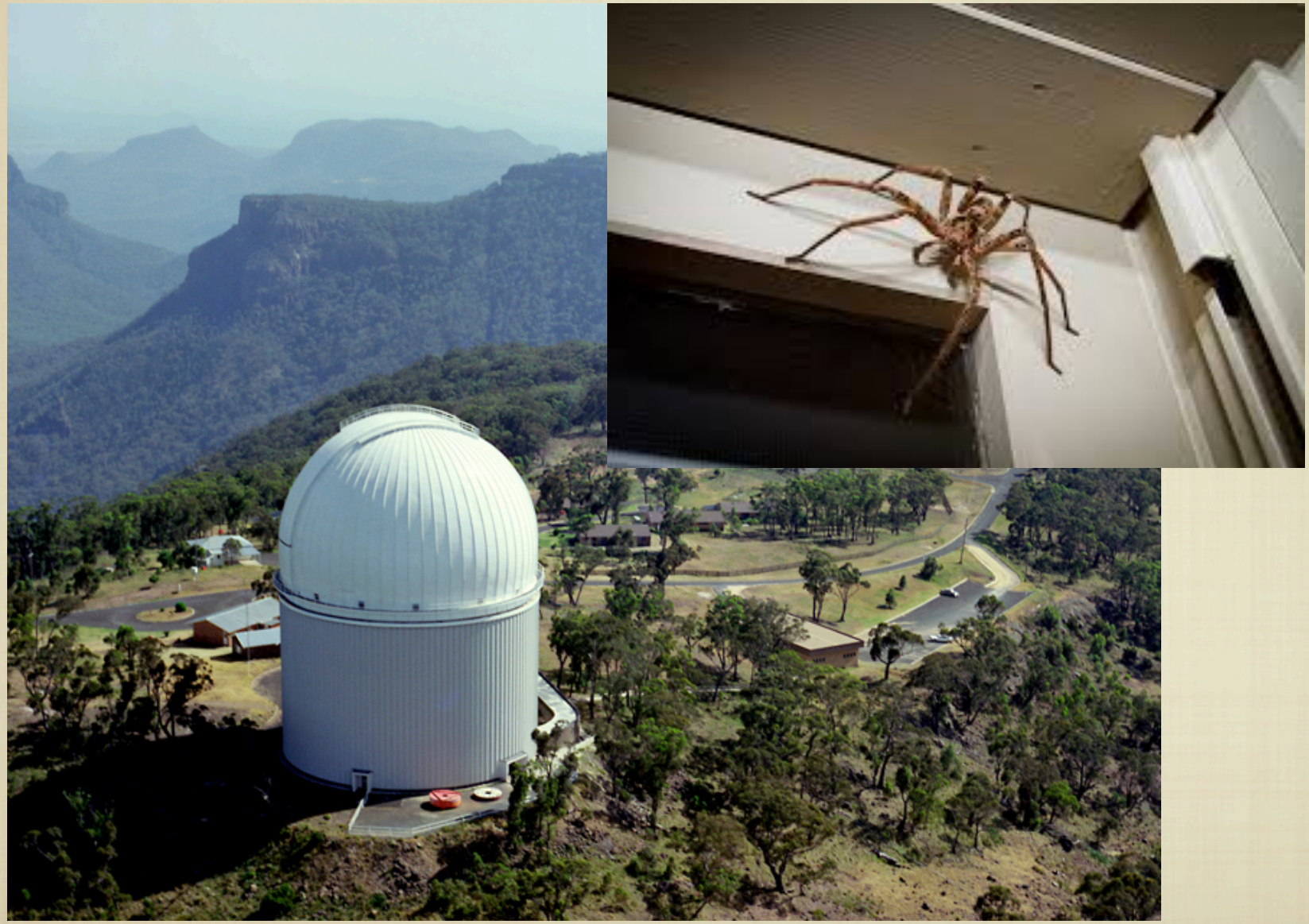
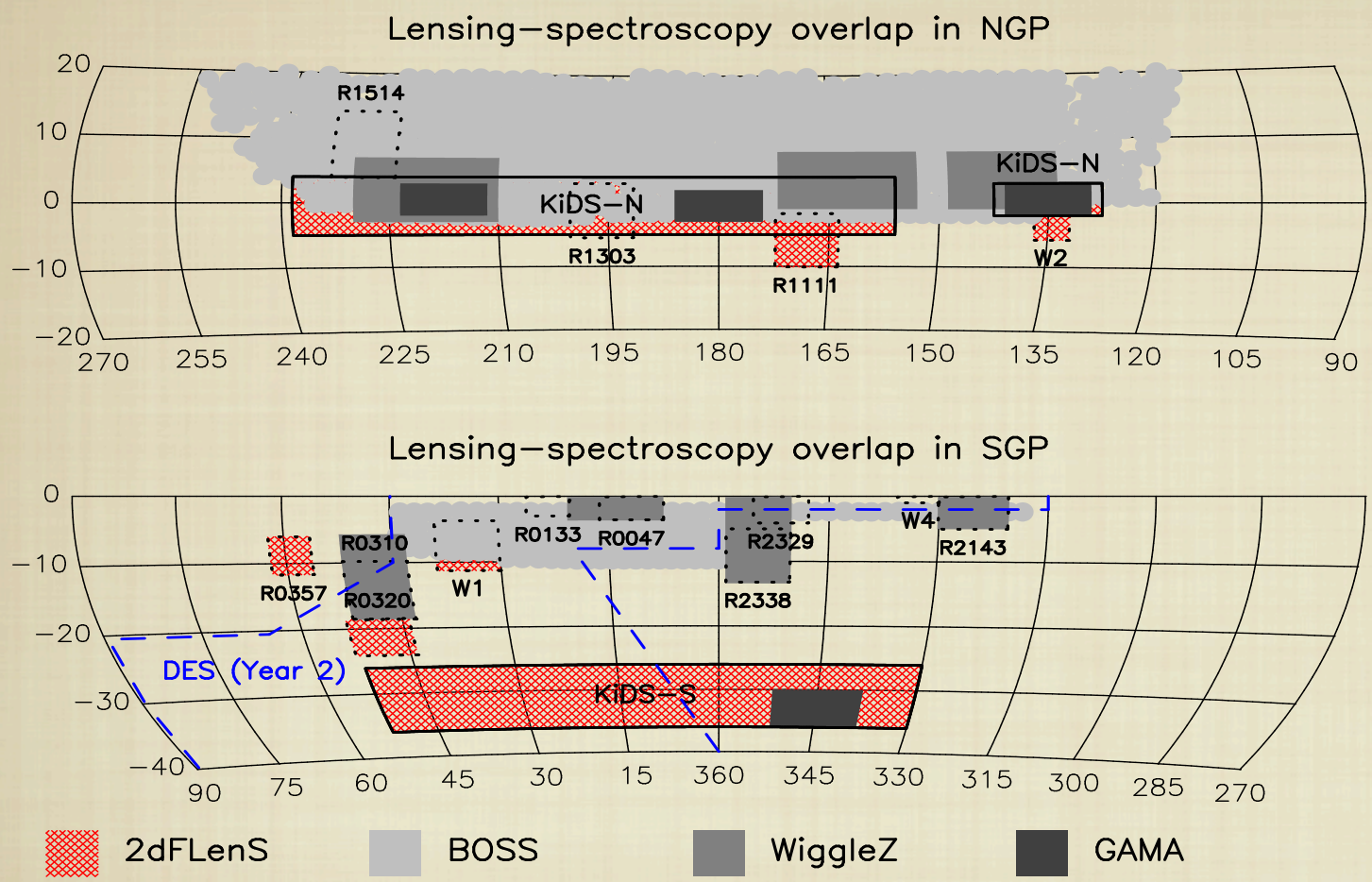


2dFLenS - AAT Galaxy redshift survey



Phase 1)
1000 deg^2 (250 NGP, 750 SGP),
130,000 gals

Phase 2)
4100 deg^2,
400,000 gals

KiDS:
1500 deg^2
$z_M = 0.65$
$n = 9$ arcmin^{-2}

2dFLenS proposal document

i) 50 AAT nights over 3 semesters (14B/15A/15B)

ii) 100 AAT nights over 4 yrs (16B/17B/18B/19B)

2dFLenS: Properties

Institutions: Swinburne, AAO, ANU, Bonn, Edinburgh, Leiden, Melbourne, Queensland, UCL

Executive committee: C. Blake (PI, Swinburne), F. Abdalla (UCL/DES), C. Heymans (Edinburgh/KiDS), C. Lidman (AAO/OzDES), D. Parkinson (Queensland)

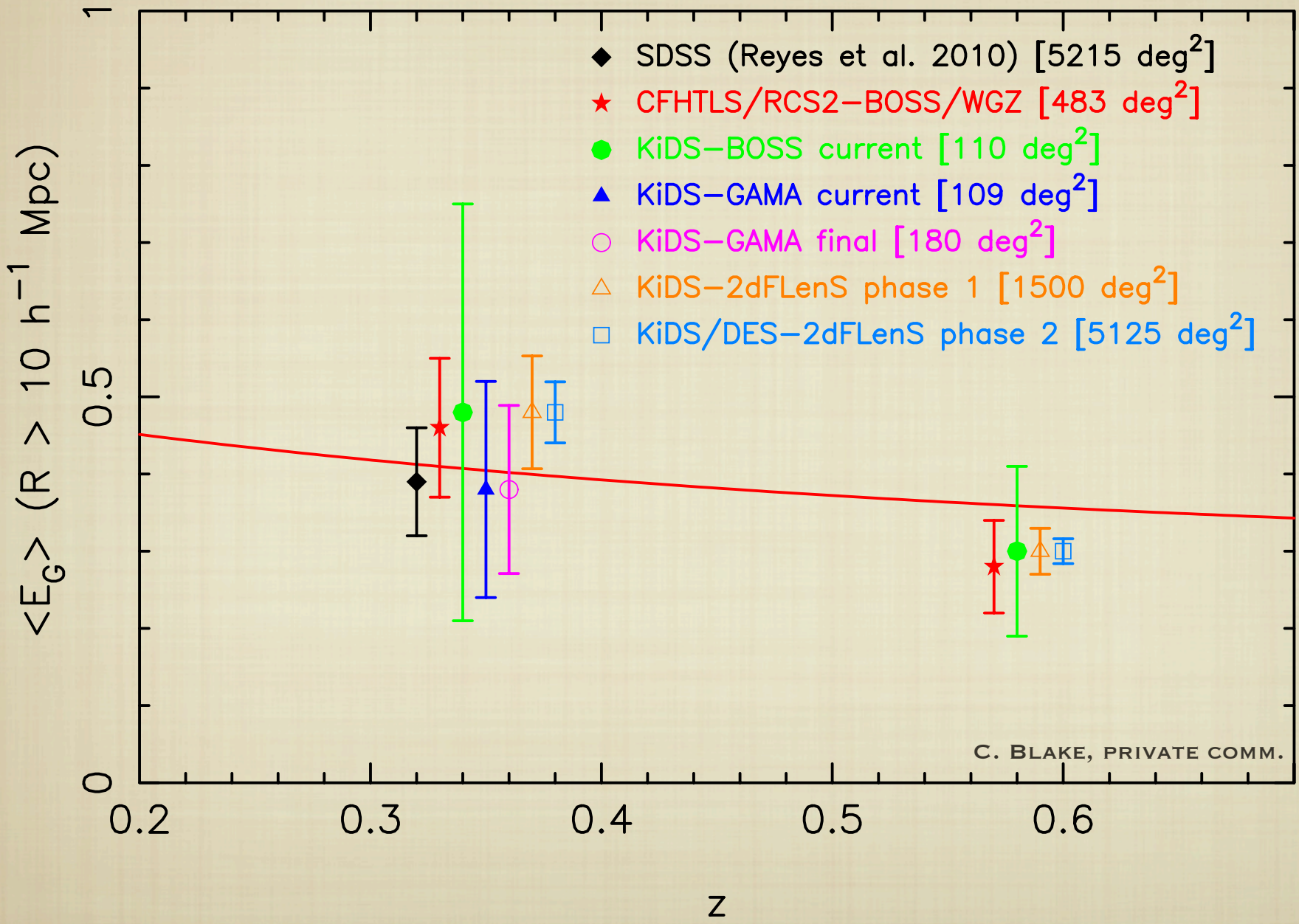
350 spectra per pointing: 280 galaxy lenses (bright LRGs for $0.2 < z < 0.7$), 50 photo-z calibrators ($0.7 < z < 1.0$), 20 other science. On average 10 fields/night. Total 130,000 spectra.

priority of phase 1 is follow-up of KiDS (best existing cosmic shear dataset), covering 1500 deg^2 (1.5 yrs). In phase 2, priority turns to DES (partial overlap with KiDS), covering 5000 deg^2 (4 yrs).

Order of mag increase in overlap compared to today!

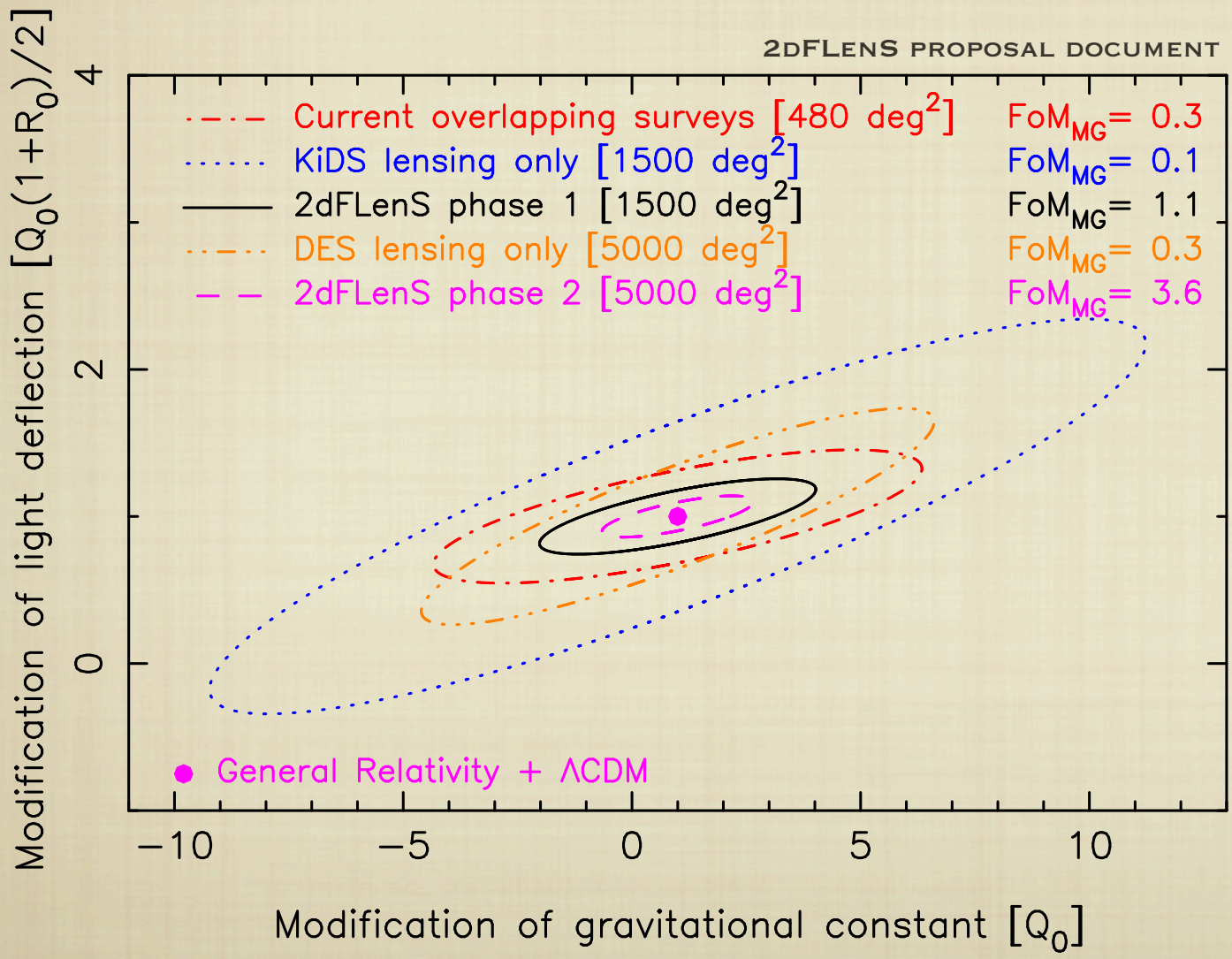
2dFLenS proposal document

Constraints on MG via E_G



2dFLenS forecast

phase 1 of 2dFLenS produces factor 4 improvements w.r.t. either current overlapping surveys or WL alone.



$$Q = Q_0 a^s$$

$$R = R_0 a^s$$

$$s = 3$$

2dFLenS: Additional benefits

WL limited by calibration of photo-z. Require ~0.1% accuracy in mean z of each photo-z bin. Achieved by cross-corr. source sample with overlapping spec. survey containing 5000 gals per $\Delta z = 0.1$ bin (Newman 2008). Lens sample allows calibrating $z < 0.7$. Additionally $0.7 < z < 1.0$.

Overlapping surveys enable range of **other science.**
i) 1000s of clusters with DES. spec-z of central galaxies required for cosmology.
ii) ~1000 strong lenses with KiDS and DES. z-confirmation to understand their geometry and facilitate follow-up by 8m class telescopes.

Aside from MG: Use $\{\xi_+, \xi_-, \gamma_t, \xi_0, \xi_2\}$ for dark energy, curvature, neutrino mass, sterile neutrinos, etc.

2dFLenS proposal document

Conclusions

- Apparent existence of "dark energy" compels us to test laws of gravity across scales of universe in multiple ways. A powerful combination of two observables, gravitational lensing and galaxy velocities, may help pin down physics of gravity.

- The E_G test of gravity, probing relation between metric potentials, is carried out for CFHTLenS +RCSLenS with WiggleZ+BOSS, to higher z than before ($z < 0.7$), at 20% level.

- World's leading imaging surveys, KiDS and DES, are covering the south without wide-area spectroscopic follow-up. Use of 2dFLenS at AAT over 6 years (starting Autumn 2014) will remedy this situation, and allows for significant improvement in our potential to probe gravity via growth of structure.

Thanks for listening.