Cosmological Tests of General Relativity

Rachel Bean (Cornell University)

The challenge: to connect theory to observation

- While GR is a remarkably beautiful, and comparatively minimal metric theory, it is not the only one. We should test it!
- Rich and complex theory space of cosmological relevant modifications to GR
- Motivated by cosmic acceleration, but implications from horizon to solar system scales

Aim: look for and confidently extract out signatures from cosmological observations?

Category	**Theory**
Horndeski Theories	Scalar-Tensor theory (incl. Brans-Dicke)
	$f(R)$ gravity
	$f(\mathcal{G})$ theories
	Covariant Galileons
	The Fab Four
	K-inflation and K-essence
	Generalized G-inflation
	Kinetic Gravity Braiding
	Quintessence (incl. universally coupled models)
	Effective dark fluid
Lorentz-Violating theories	Einstein-Aether theory
	Hořava-Lifschitz theory
>2 new degrees of freedom	DGP (4D effective theory)
	EBI gravity
	TeVeS

Baker et al 2011

Frameworks to tie observations to theory

- Modify homogeneous and perturbed Einstein's equations

Time-time (Newtonian)

$$
\begin{aligned}
& m_0^2\Omega(t)\left[\frac{2k^2-6k_0}{a^2}\phi^N+6H(\dot{\phi}^N+H\psi^N)\right] \\
&= -\,\delta\rho^N-\dot{\rho}_Q\pi^N-2c(t)(\dot{\pi}^N-\psi^N) \\
&\quad +m_0^2\dot{\Omega}\left[3\pi^N\left(H^2-\dot{H}+\frac{k_0}{a^2}\right)+3H\left(\dot{\pi}^N-\psi^N\right)\right. \\
&\quad \left.+3H\left(\dot{\pi}^N-\psi^N\right)+\frac{k^2}{a^2}\pi^N-3\left(\dot{\phi}^N+H\psi^N\right)\right]
\end{aligned}
$$

$$k^2\Psi = -4\pi G_{\rm matter}a^2\rho\Delta$$

Space-space traceless (Newtonian)

$$m_0^2\Omega(t)\frac{k^2}{a^2}\left(\phi^N-\psi^N\right)=\bar{P}_m\Pi+m_0^2\dot{\Omega}\frac{k^2}{a^2}\pi^N$$

$$k^2(\Psi+\Phi) = -8\pi G_{\rm light}a^2\rho\Delta\,,$$

Bloomfield et al 2012

See Alessandra's Talk

Phenomenological modeling of gravity

- Modify perturbed Einstein's equations

$$k^2\Psi = -4\pi \boxed{G_{\rm matter}} a^2\rho\Delta \qquad\qquad k^2(\Psi+\Phi) = -8\pi \boxed{G_{\rm light}} a^2\rho\Delta\,,$$

- A modification to Poisson's equation, G_{matter}
  - Relevant at sub-horizon scales
  - $G_{matter} \neq 1$: can be mimicked by additional, dark sector clustering
- An inequality between Newton's potentials, G_{light}/G_{matter}
  - Remains relevant even at horizon scales
  - $G_{light}/G_{matter} \neq 1$: not easily mimicked.
    - potential smoking gun for modified gravity?
    - Significant stresses exceptionally hard to create in non-relativistic fluids e.g. DM and dark energy.

Alternative descriptor: the growth rate, f_g & γ

- Alternative parameterization: the rate of CDM growth

$$f_g \equiv \frac{d\ln\delta_c^S}{d\ln a} = \Omega_m(a)^\gamma,$$

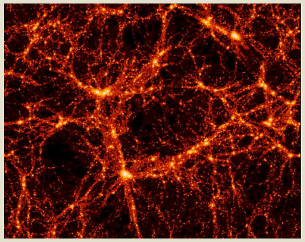
For GR γ~0.55 on subhorizon scales

- f_g related to G_{matter} but does describe G_{light}/G_{matter}

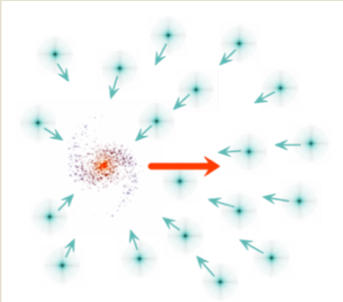
$$G_M \approx \frac{2f_g}{3\Omega_m}\left[1 + f_g + \frac{d\ln f_g}{d\ln a} + \frac{\dot{\mathcal{H}}}{\mathcal{H}^2}\right].$$

Four distinct cosmological tracers

1. Standard candles and rulers

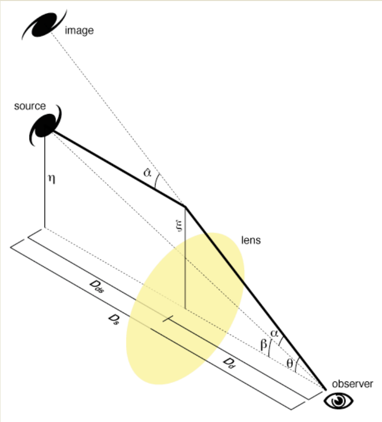


2. Clustering of matter

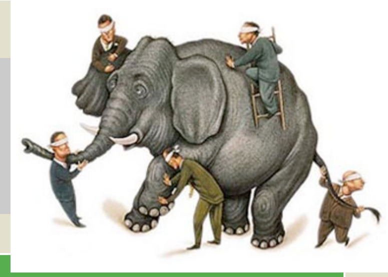


3. Motion of non-relativistic tracers

4. Lensing distortion of light



Different relations to gravitational map



I: Background expansion	II: Growth, up to some normalization	III: Growth directly

I: Background expansion

Probes of homogeneous geometry:

- CMB angular diameter distance
- Supernovae luminosity distance
- BAO angular/radial scale

II: Growth, up to some normalization

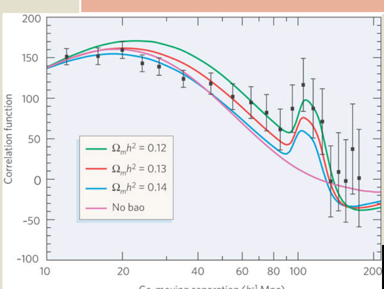
Biased tracers of perturbed gravitational field

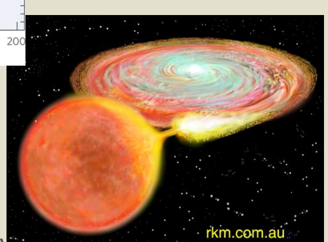
- Galaxy distribution
- Xray and SZ selected galaxy cluster distribution

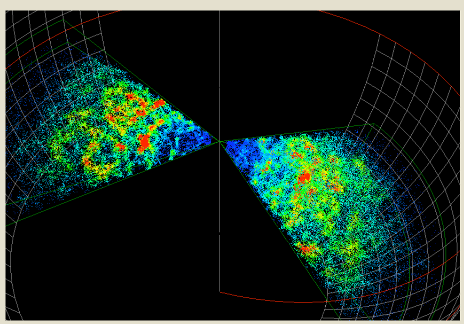
III: Growth directly

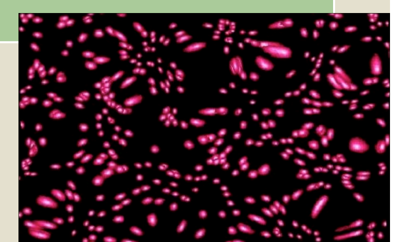
Direct tracers of perturbed gravitational field

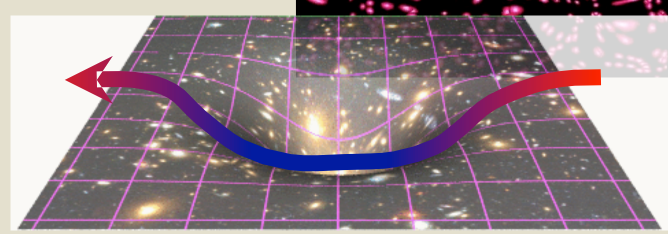
- CMB ISW correlation
- Weak galaxy and cluster lensing correlation
- Peculiar velocities/ bulk flows of galaxies



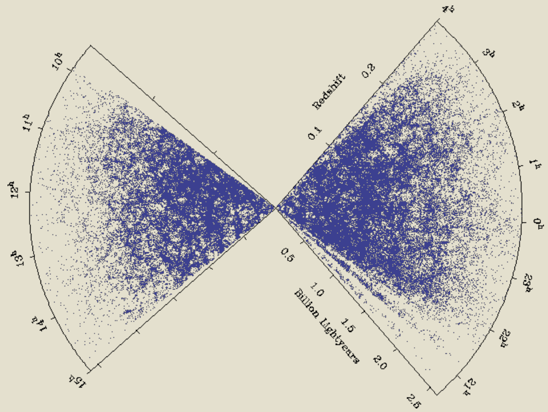


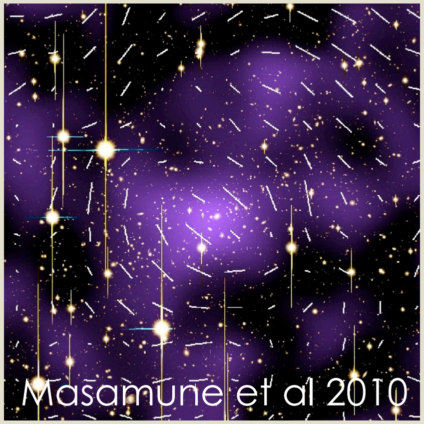






Complementary tracers for testing gravity





- Non-relativistic: Galaxy positions & motions
  - Sensitive to $\psi \sim G_{mat}$
  - Biased tracer
  - Can be measured at specific z

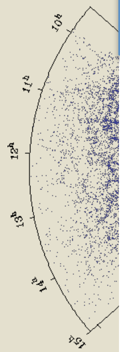
- Relativistic: Weak lensing & CMB lensing & ISW
  - Sensitive to $(\phi+\psi)$: G_{light}
  - Direct tracer of potential,
  - but still plenty of systematics (more on this…)
  - Integrated line of sight info

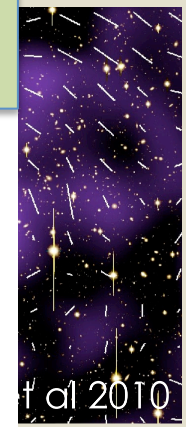
- Contrasting both can get at G_{light}/G_{matter}

Zhang et al 2007

Complementary tracers for testing gravity

Are these the unrealistic dreams of a theorist?





- Non-rel
  position
  - Sensi
  - Biase
  - Can

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ISW

($\phi+\psi$): G_{light}

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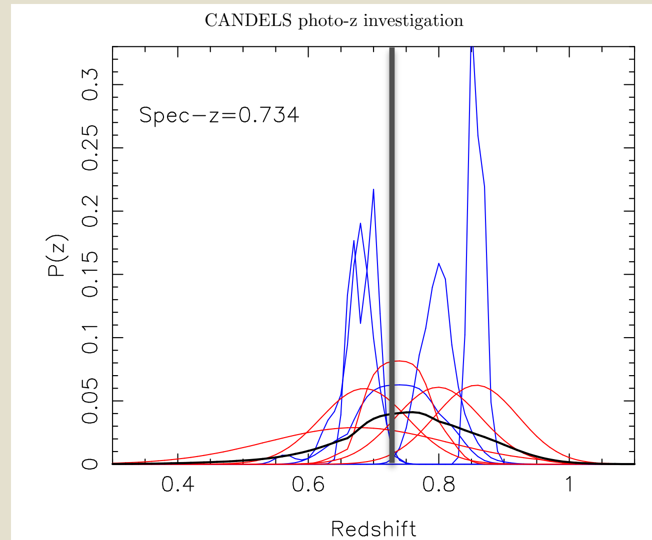
Complications: Photometric redshifts

- Quicker (more galaxies) and concurrent with imaging, but less accurate than spectral z

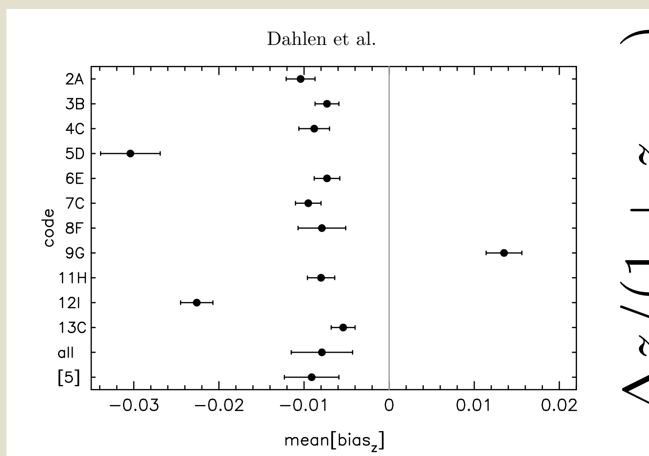
- Challenge to refine photo-z estimates given disparate and incomplete spectroscopic samples

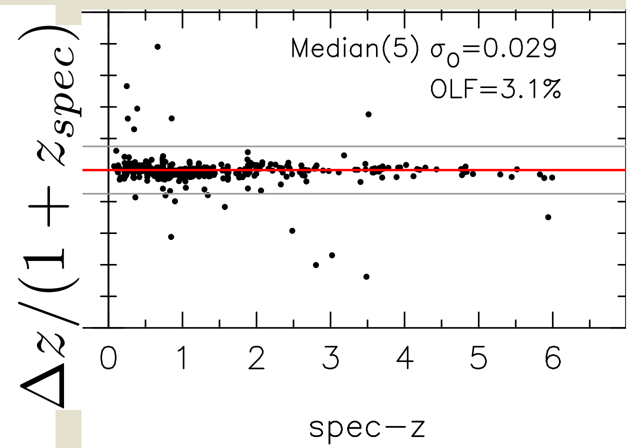
- Redshift probability distribution dispersed and biased relative to the true spectroscopic z.



$$\sigma_z = rms\left[\frac{\Delta z}{1+z_{spec}}\right]$$

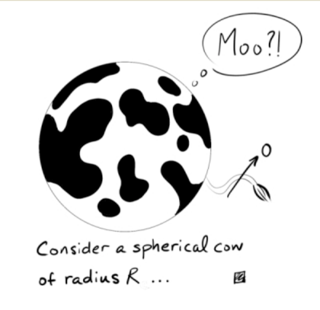
$$bias_z = mean\left[\frac{\Delta z}{1+z_{spec}}\right]$$





Dahlen et al 1308.5353

Complications: Lensed galaxies



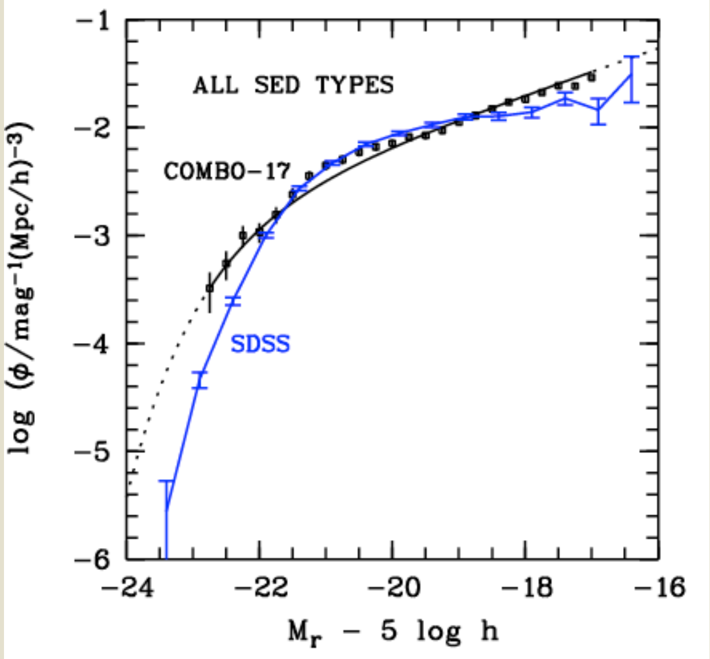
- Lensing distorts observed volume and magnifies faint galaxies (Moessner & Jain 1997)

$$n^{(i)}(\boldsymbol{\theta}) = n_{\rm m}^{(i)}(\boldsymbol{\theta}) + n_{\rm g}^{(i)}(\boldsymbol{\theta}) + n_{\rm rnd}^{(i)}(\boldsymbol{\theta}) \ ,$$

- Number depends on slope of luminosity function

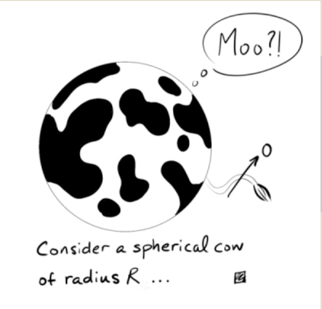
- Galaxy correlations must factor this in

$$C_{n_i n_j} = C_{g_i g_j} + C_{g_i m_j} + C_{m_i g_j} + C_{m_i m_j}$$



Wolf et al 2003

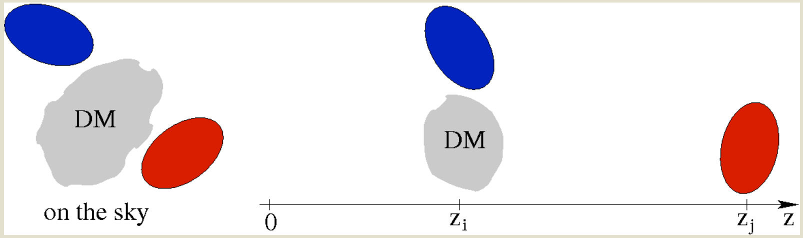
Complications: Intrinsic alignments



- Galaxy Intrinsic shapes are aligned in their host halo

$$\epsilon^{(i)}(\boldsymbol{\theta}) = \gamma_{\rm G}^{(i)}(\boldsymbol{\theta}) + \gamma_{\rm I}^{(i)}(\boldsymbol{\theta}) + \epsilon_{\rm rnd}^{(i)}(\boldsymbol{\theta})$$

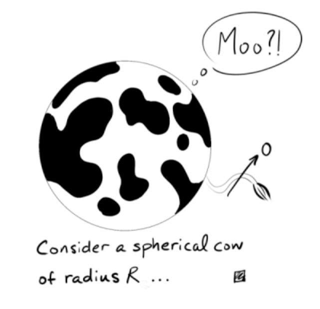
- Observed shape correlations include both lensed and intrinsic terms



$$C_{\epsilon_i\epsilon_j} = C_{G_iG_j} + C_{G_iI_j} + C_{I_iG_j} + C_{I_iI_j}$$
$$C_{n_i\epsilon_j} = C_{g_iG_j} + C_{g_iI_j}$$

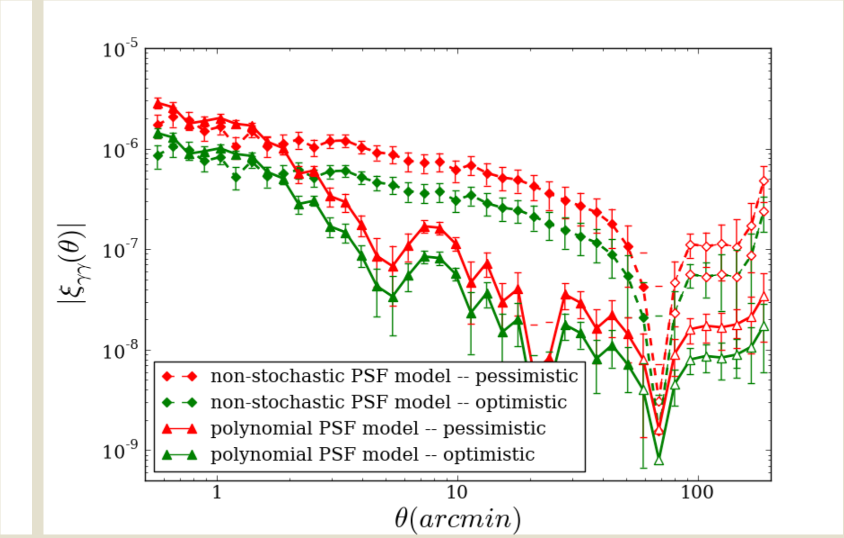
- The amplitude of intrinsic alignments is a function galaxy type, luminosity and redshift

Complications: Shear contamination

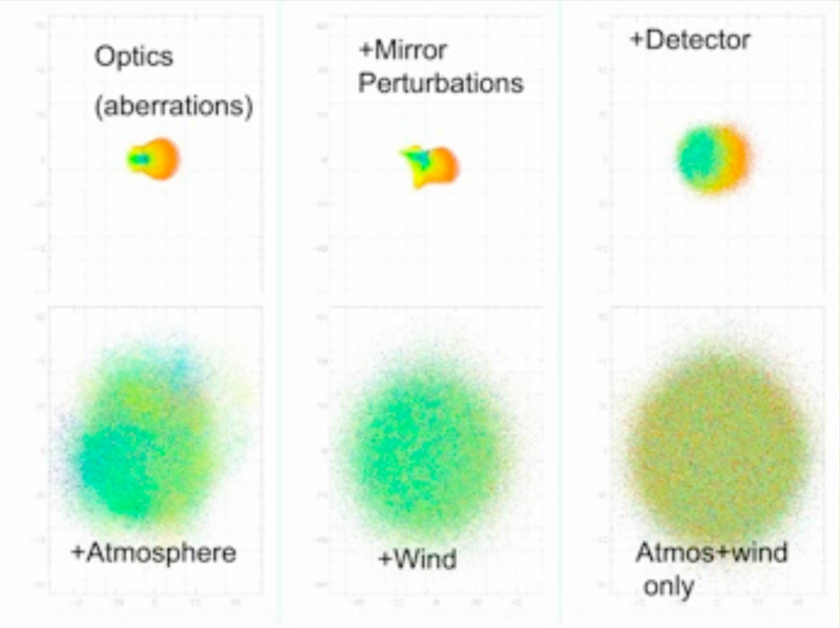


- Incomplete correction of the atmospheric and instrumental PSF can induce additive and multiplicative shear errors

$$\epsilon_i = (1 + m_i)\epsilon_i + a$$

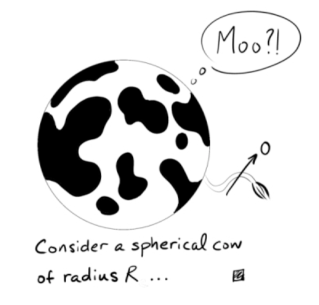


Chang et al 2012



LSST Project

Complications: Non linear scales



- Cosmological extraction in NL scales requires modeling to commensurate accuracy of:
  – the underlying CDM nonlinear power spectrum (for LCDM and other models)
  – Modeling baryonic effects, signal and uncertainties, on halo concentration

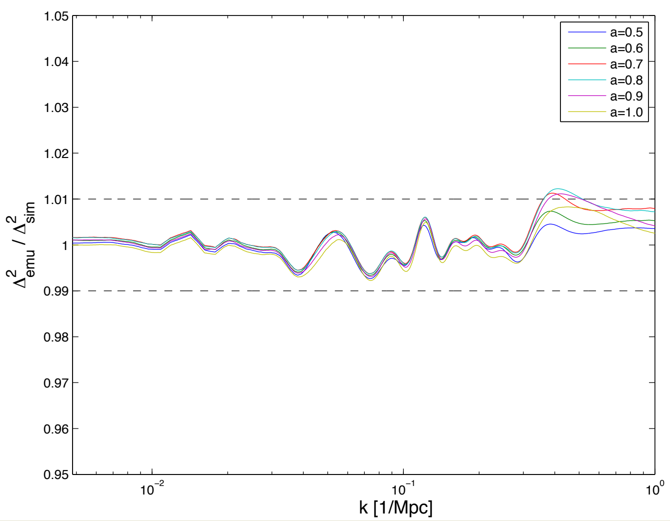
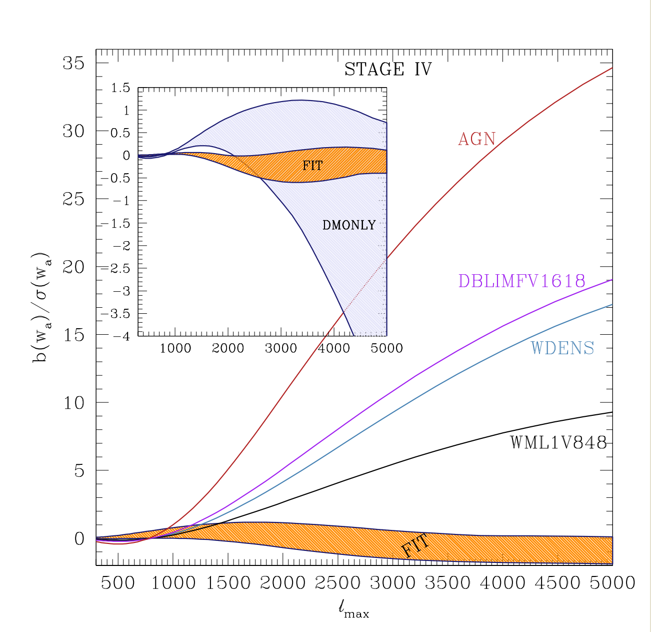


FIG. 9.— Ratio of the emulator prediction to the smooth simulated power spectra for the M000 cosmology at six values of the scale factor a. The error exceeds 1% very slightly in only one part of the domain for the scale factors $a = 0.7, 0.8$, and 0.9.

Lawrence et al 0912.4490



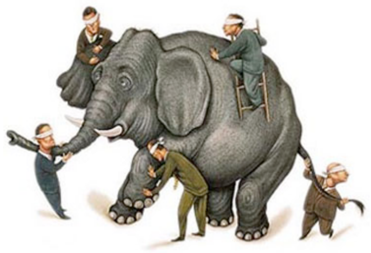
Zentner et al 1212.1177

A single survey can't give the full picture

- Trade offs in
  - Techniques (SN1a, BAO,RSD, WL, Clusters + lensing, motions, positions)
  - Photometric speed vs. spectroscopic precision
  - Angular and spectral resolution
  - Astrophysical tracers used (LRGs, ELGs, Lya/QSOs, clusters)
  - Epochs, scales and environs being studied (cluster vs dwarf galaxies)

- Much more than a DETF FoM:
  - Astrophysical & instrumental systematic mitigation as so easily summarized.
  - Readiness vs technological innovation
  - Survey area vs depth - repeat imaging, dithering, cadence and survey area overlap/config.

- Future surveys distinct and complementary, both with each other and
  - ground based LSS surveys (LSST, DESI and others)
  - Planck and ground-based CMB gravitational lensing measurements

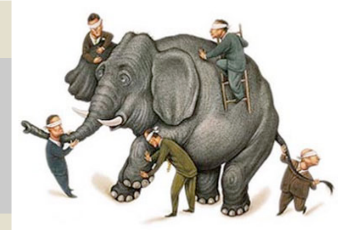


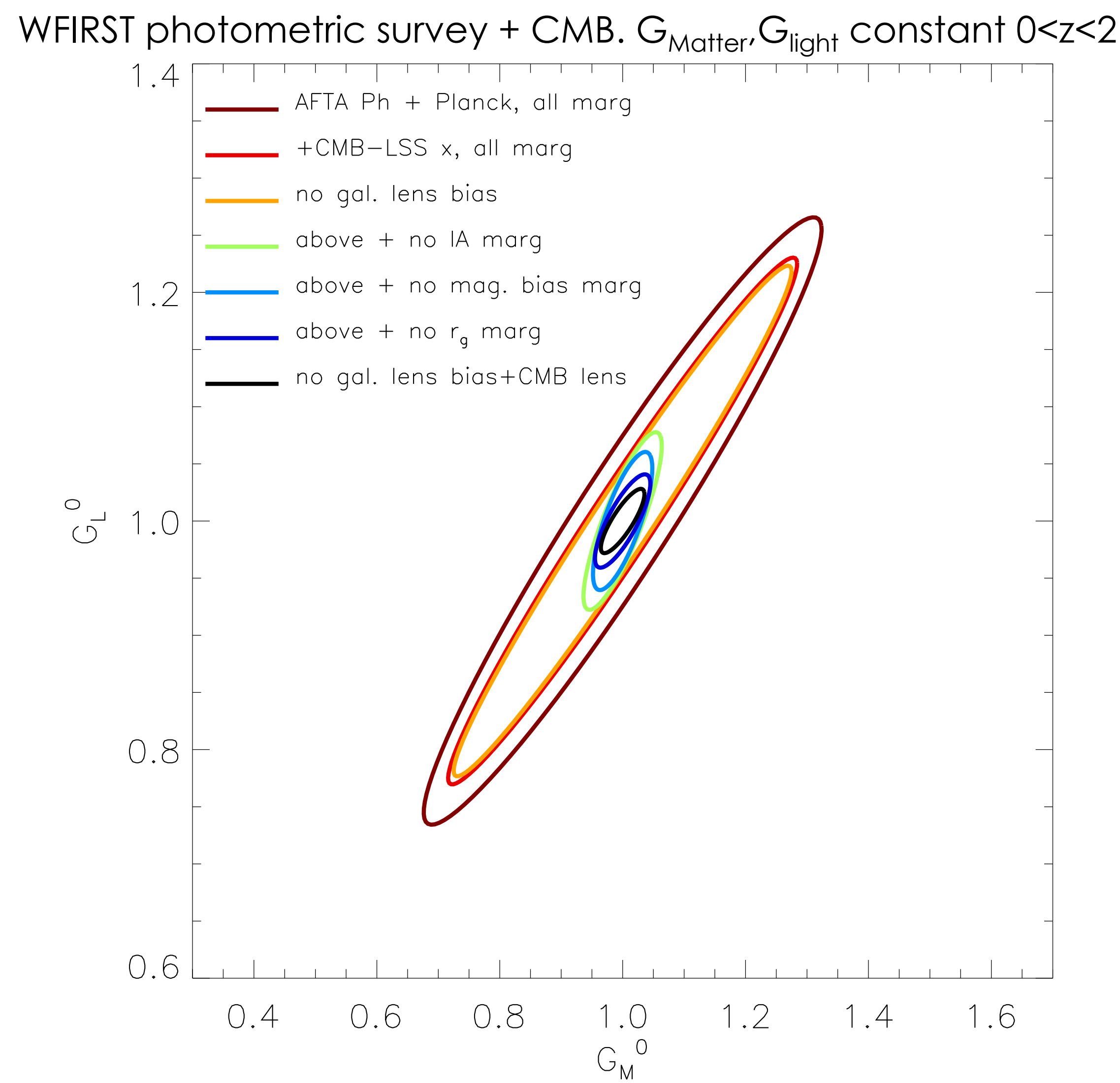
Upcoming Surveys: Different strengths & systematics

(based on publicly available data)

Stage IV	DESI	LSST	Euclid	WFIRST-AFTA
Starts, duration	~2018, 5 yr	2020, 10 yr	2020 Q2, 7 yr	~2023, 5-6 yr
Area (deg^2)	14,000 (N)	20,000 (S)	15,000 (N + S)	2,400 (S)
FoV (deg^2)	7.9	10	0.54	0.281
Diameter (m)	4 (less 1.8+)	6.7	1.3	2.4
Spec. res. $\Delta\lambda/\lambda$	3-4000 (N_{fib}=5000)		250 (slitless)	550-800 (slitless)
Spec. range	360-980 nm		1.1-2 μm	1.35-1.95 μm
BAO/RSD	20-30m LRGs/[OII] ELGs 0.6 < z < 1.7, 1m QSOs/Lya 1.9<z<4		~20-50m Hα ELGs Z~0.7-2.1	20m Hα ELGs z = 1–2, 2m [OIII] ELGS z = 2–3
pixel (arcsec)		0.7	0.13	0.12
Imaging/ weak lensing (0<z<2.)		~30 gal/arcmin^2 5 bands 320-1080 nm	30-35 gal/arcmin^2 1 broad vis. band 550– 900 nm	68 gal/arcmin^2 3 bands 927-2000nm
SN1a		10^4-10^5 SN1a/yr z = 0.–0.7 photometric		2700 SN1a z = 0.1–1.7 IFU spectroscopy

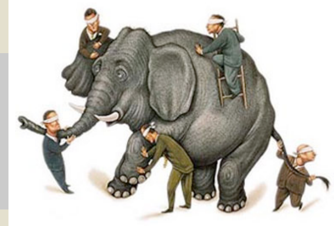
Example constraints on G_{matter}, G_{light}



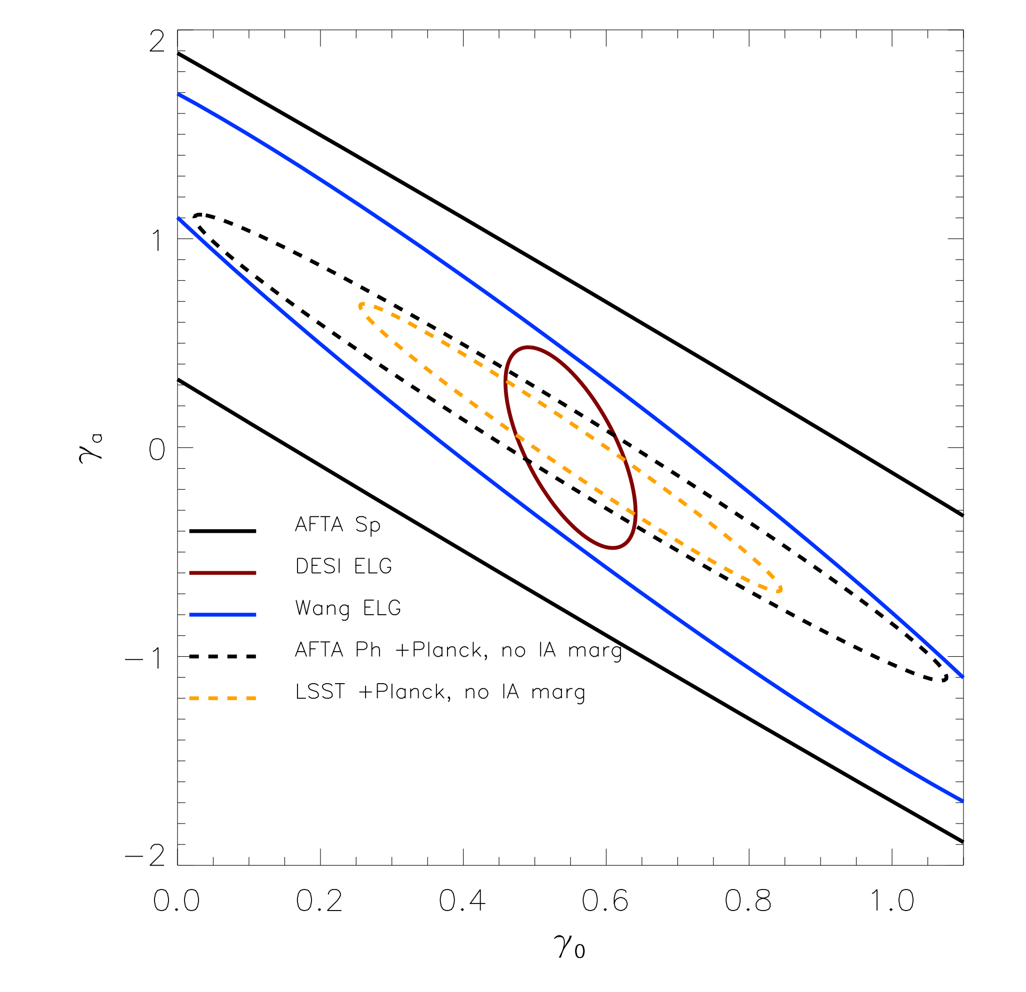


Bean and Mueller, in prep

Spec & Photo survey: constraints on γ_0-γ_a

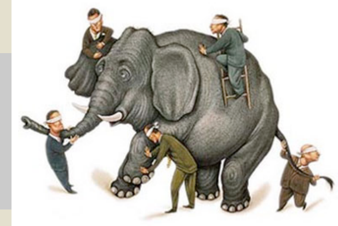


Beware a strong theoretical prior significantly biases redshift range of interest for growth studies (as with equation of state)



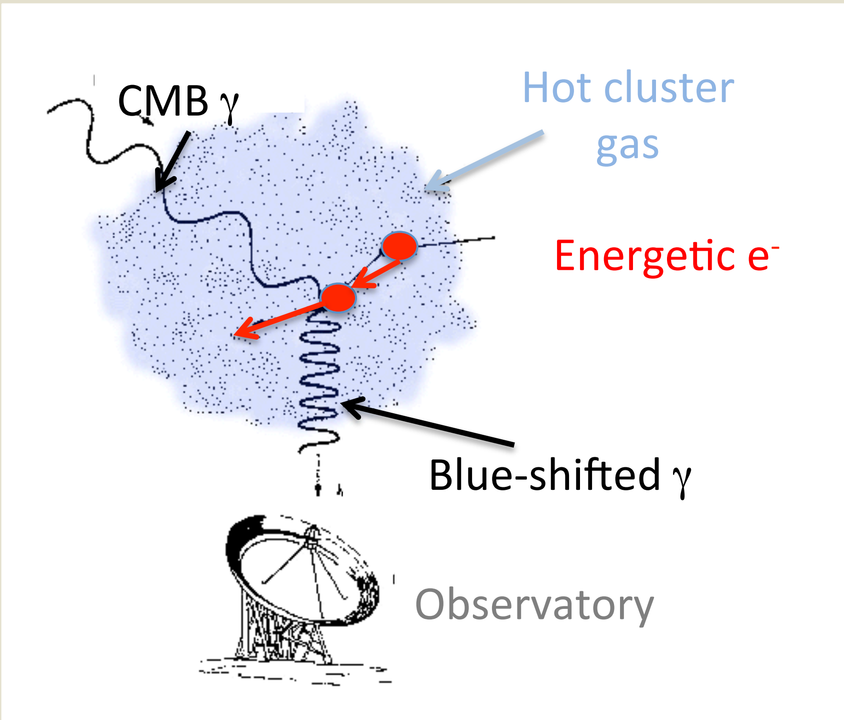
Bean and Mueller, in prep

Clusters as a probe of gravity

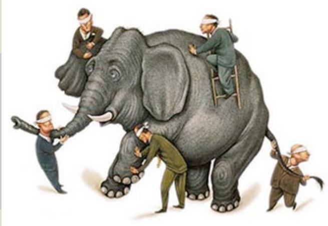


- Cluster dynamics provide an alternative direct probe of the gravitational potential.
- Measurable via the kinetic Sunyaev Zeldovich (kSZ) effect

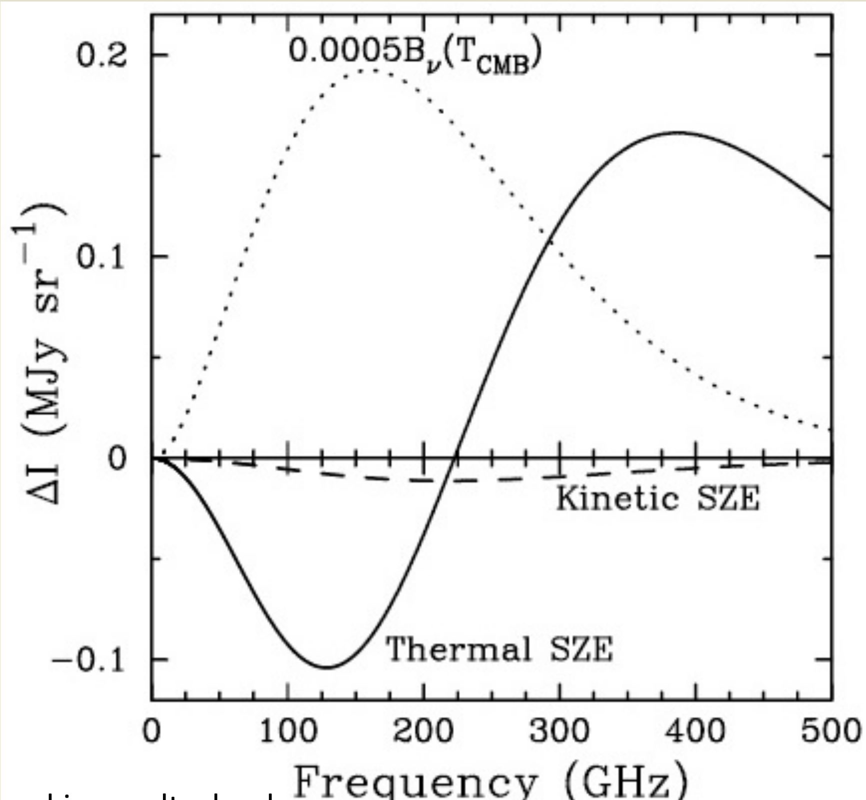
$$\frac{\Delta T_{kSZ}}{T_{CMB}} = -\tau \left(\frac{v_{pec}}{c}\right)$$



Clusters as a probe of gravity

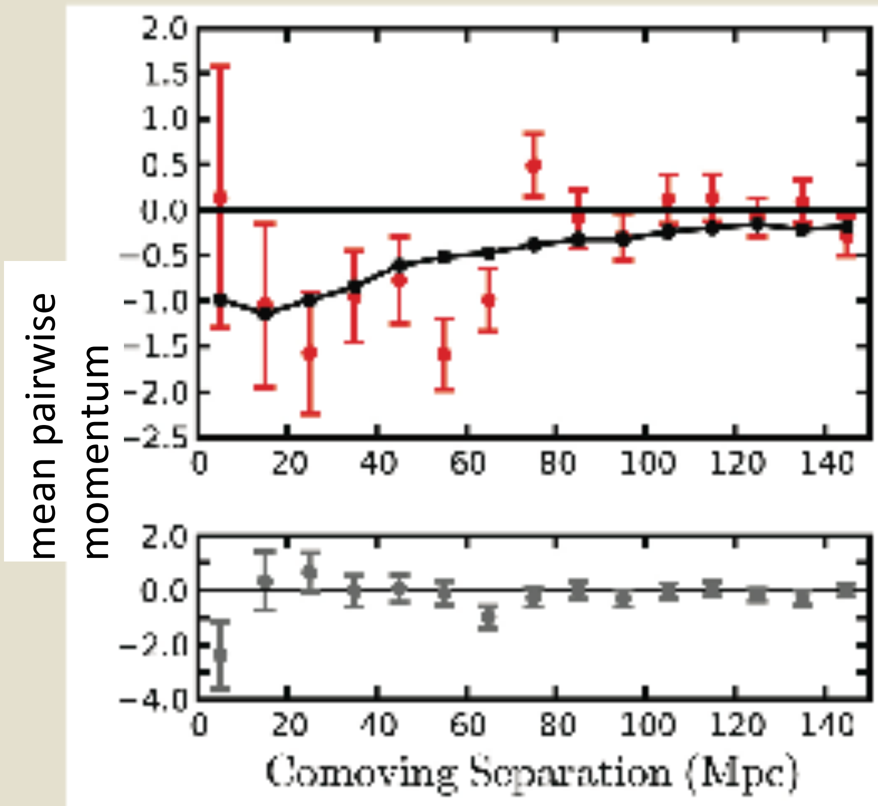


- Problem: kSZ has weak frequency dependence and small amplitude (compared to thermal SZ)



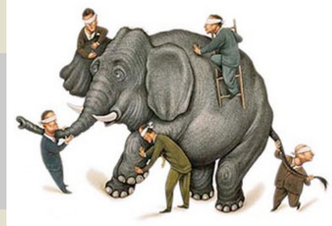
ned.ipac.caltech.edu

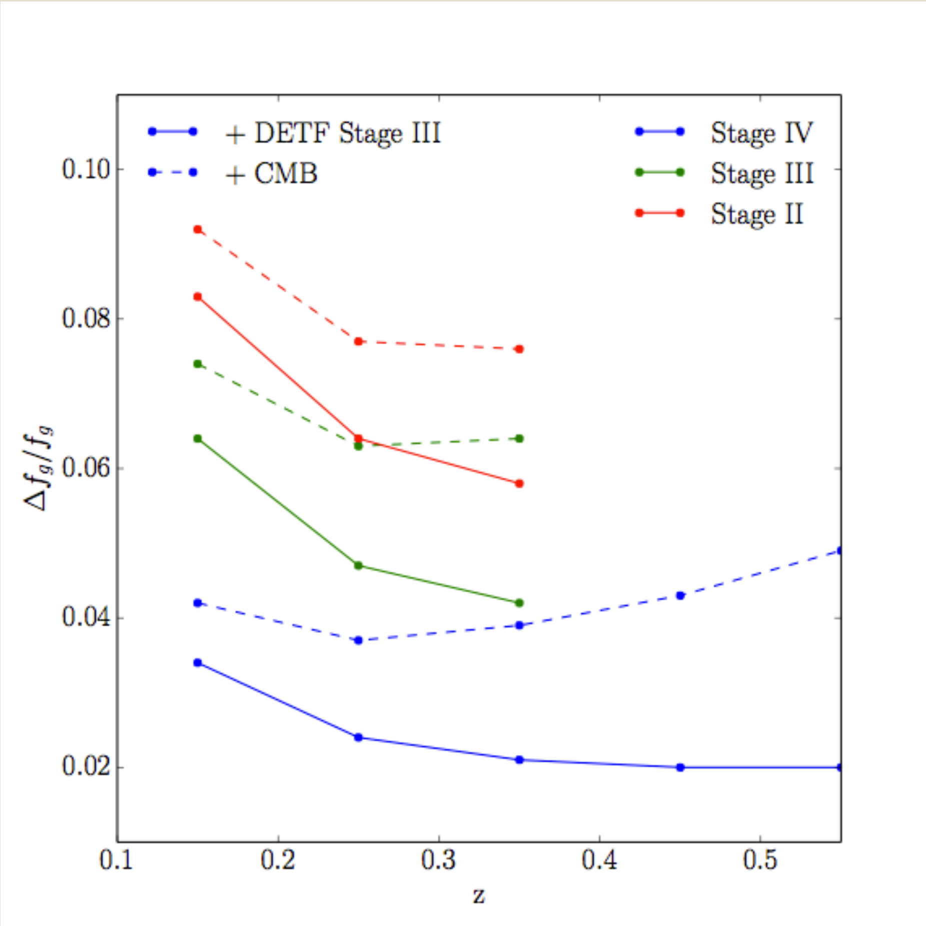
- Solution: isolate kSZ through cross-correlation

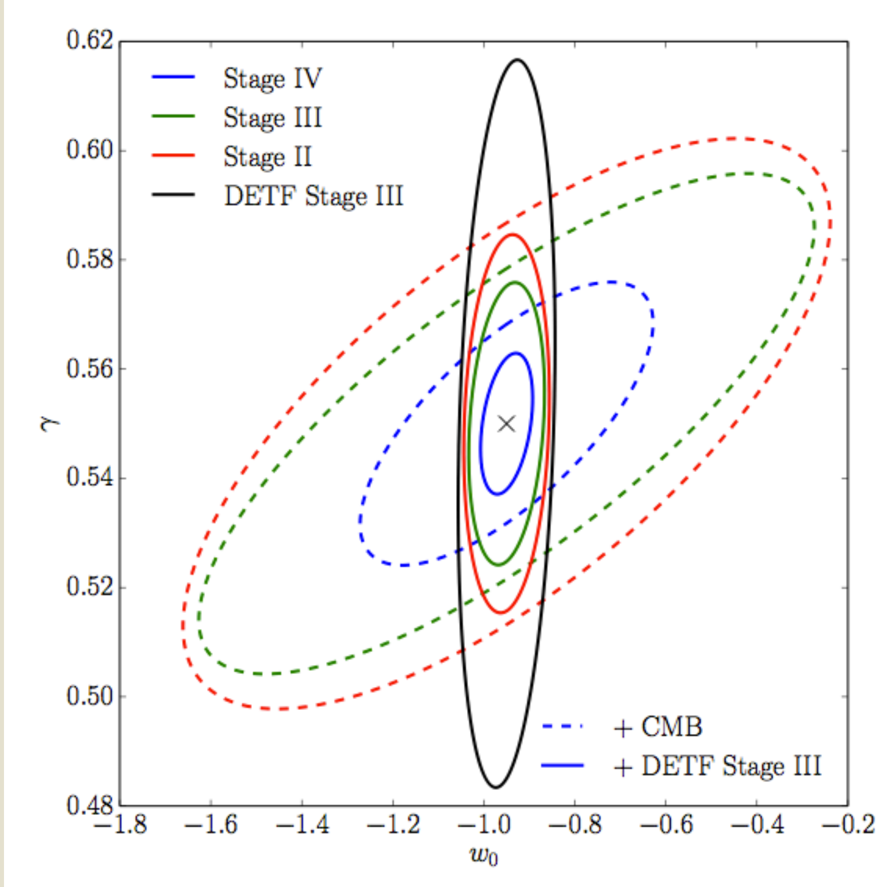


Hand et. al 2012

kSZ pairwise dark energy constraints





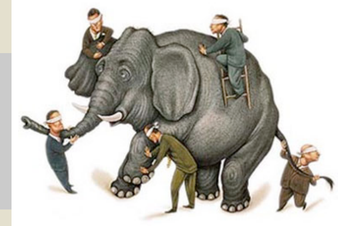


Current constraints:

BOSS: $\gamma = 0.71^{+0.12}_{-0.11}$

Mueller, De Bernardis, Bean, Niemack 2014

To conclude



- Phenomenology, a powerful tool to connect theoretical modeling of gravity to observations on cosmological scales

- Variety is critical to achieve required sensitivities over range of redshifts and environments:
  - Non-relativistic (peculiar velocities) and relativistic (lensing)
  - Different systematics (e.g. CMB and galaxy lensing)
  - Different epochs and scales
  - Different tracers: halo and field galaxies, clusters and CMB

- Understanding and incorporating instrumental and astrophysical uncertainties key to realizing cosmological aims
  - Photometric redshift uncertainties
  - Effect of baryons processes on dark matter clustering
  - Disentangling instrumental (e.g. PSF) and astrophysical (e.g IAs) signals from cosmological