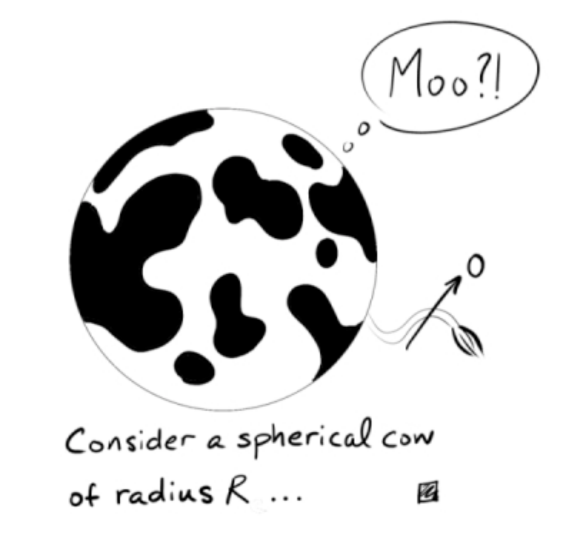
Dark Sector Constraints with Weak Lensing (and other cosmological) Surveys

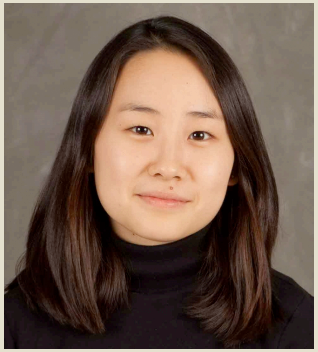
Rachel Bean (Cornell University)

With graduating student Eva-Maria Mueller



Graduating students working on related areas

Joyce Byun

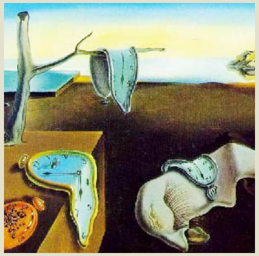


- Efficient generalized descriptions of non-Gaussianity
- Bispectrum extraction from CMB and spectroscopic surveys utilizing information down to quasi-non linear scales

Eva-Maria Mueller

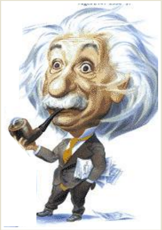
- Testing effective field theories of gravity
- Constraining dark energy and neutrinos with upcoming spectroscopic surveys + CMB, correlations using kinetic SZ.

Missing physics of cosmic acceleration

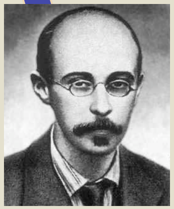


Deviations from GR?

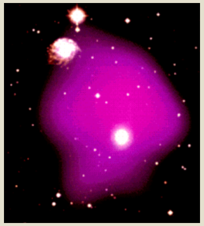
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



Λ?



Inhomogeneous universe?



New matter? interactions?

Ambitious aim = Theory:
Learn something more about the underlying mechanism?

Broad aim = Phenomenology:
Behavior of matter? Gravity?

Frameworks to tie observations to theory

While GR in 4D space-time is a remarkably beautiful, and comparatively minimal metric theory, it is not the only one. We should test it!

- Classification of scalar-tensor theories to connect to phenemonology

$$G_{\mu\nu} = 8\pi G_0 a^2 T_{\mu\nu} + a^2 U_{\mu\nu}$$

$$\delta(\nabla_\mu U^\mu_\nu) = 0.$$

- Simple extension to group changes to to time time and space space terms

$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$$

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

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

Alternative to G_{matter} is growth rate

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

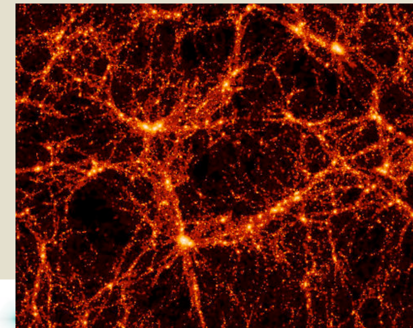
Category	**Theory**
Horndeski Theories	Scalar-Tensor theory (incl. Brans-Dicke)
	$f(R)$ gravity
	$f(\mathcal{G})$ theories
	Covariant Galileons
	The Fab Four
	K-inflation and K-essence
	Generalized G-inflation
	Kinetic Gravity Braiding
	Quintessence (incl. universally coupled models)
	Effective dark 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

Three distinct cosmological tracers

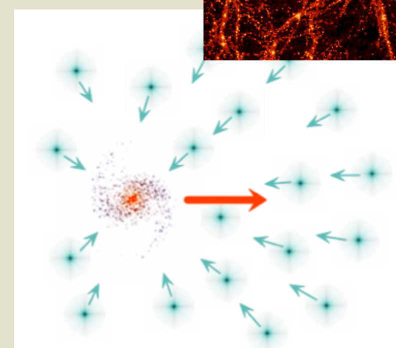
- Clustering of matter

$$\delta(\mathbf{x},t) \equiv \frac{\rho(\mathbf{x},t)}{\bar{\rho}} \qquad \dot{\delta} = -\theta + 3\dot{\phi}$$



- Motion of non-relativistic tracers

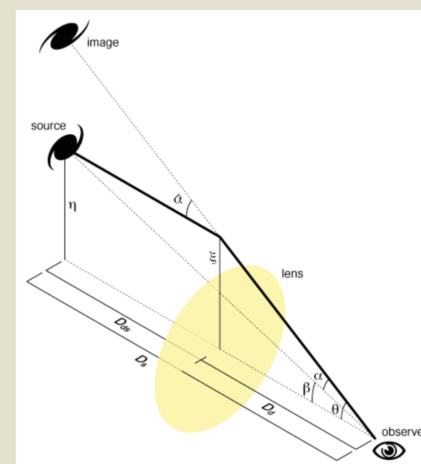
$$\theta \equiv \nabla \cdot \mathbf{v} \qquad \frac{1}{a}\frac{d(a\theta)}{d\tau} = k^2\psi$$



- Distortion of light

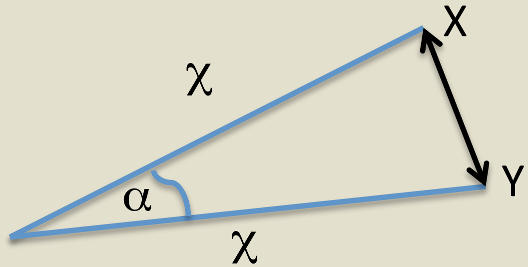
$$\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta}) = \vec{\theta} - \frac{D_{ds}}{D_s}\vec{\hat{\alpha}}(\vec{D_d\theta})$$

$$\frac{\partial \beta_i}{\partial \theta_j} = \int_0^{\chi_{max}} d\chi g(r(\chi)) \frac{\partial^2(\phi+\psi)/2}{\partial x^i \partial x^j}$$



Cross correlation yields growth and geometry info

- Angular correlation between observables X and Y



$$C_\ell^{X_i Y_j} = \int_0^{\chi_{max}} \frac{d\chi}{\chi^2} W_X^i(\chi) W_Y^j(\chi) P_{XY}^{ij}(k = \ell/\chi)$$

Integrated over all sources along the line of sight

Window function
i^{th} photo-z bin

Source density & cosmic geometry

w(z), H(z)…

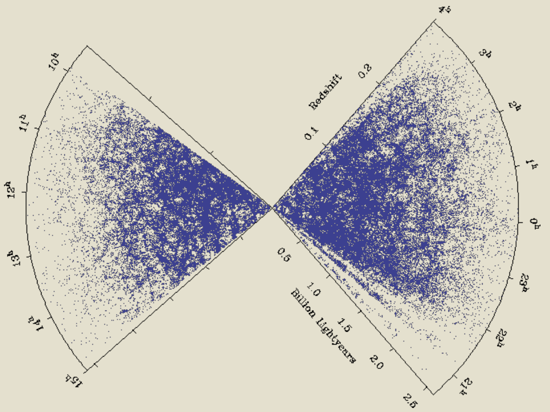
Source function

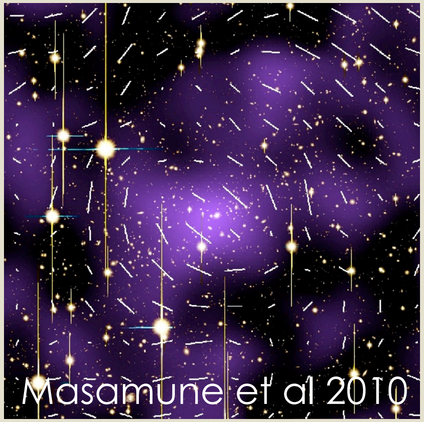
How sources are correlated on scale k=l/χ

Initial conditions and Large scale structure growth history

$G_{matter}(z)$, $G_{light}(z)$…

Complementary tracers for testing gravity





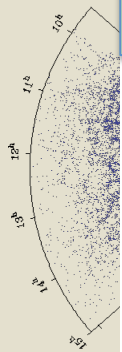
- Non-relativistic: Galaxy positions ‘g’& motions ‘θ’
  - Sensitive to $\psi \sim G_{mat}$
  - Biased tracer
  - Can be measured at specific z

- Relativistic: Weak lensing ‘G’ & 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

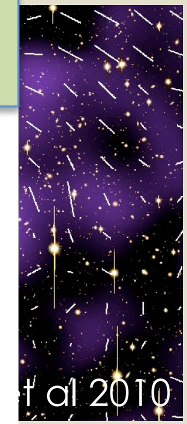
Contrasting both ($E_G \sim C_l^{gG}/C_l^{g\Theta}$) can get at G_{light}/G_{matter}

Zhang et al 2007

Complementary tracers for testing gravity



Are these the unrealistic dreams of a theorist?



- Non-rel ... eak lensing 'G' &
  position ... ISW
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  - Can ... systematics (more

ine of sight info

Co ... $_{ght}/G_{matter}$

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Complications: Photometric redshifts

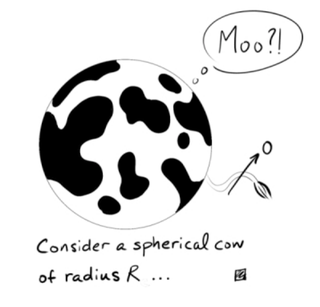
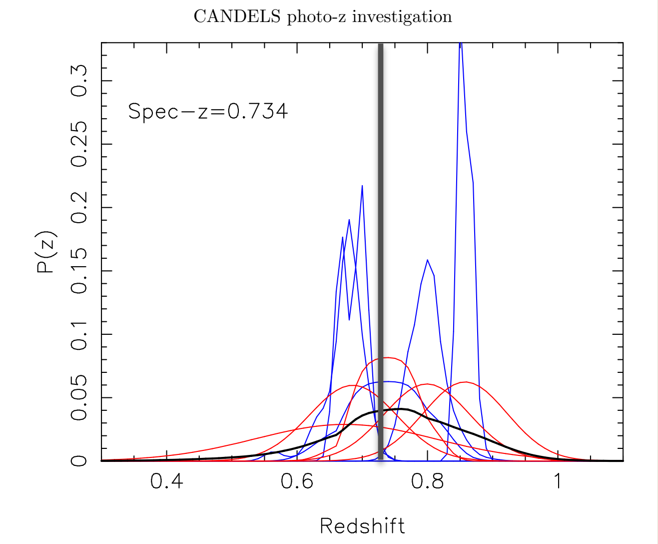


Photo-z codes recover different p(z) for the same spectroscopic training set, both dispersed and biased relative to the true spectroscopic z.

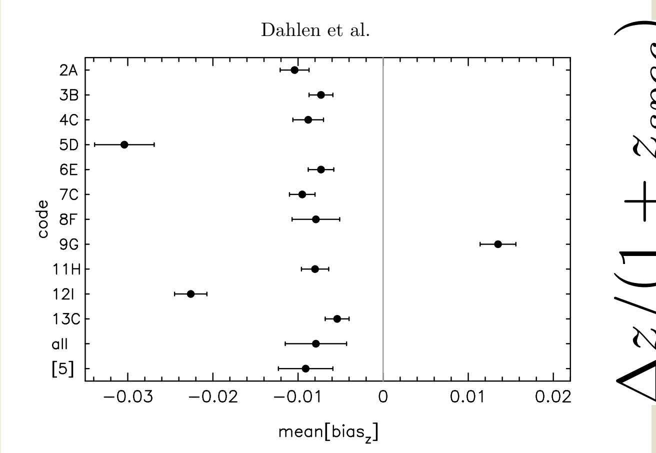


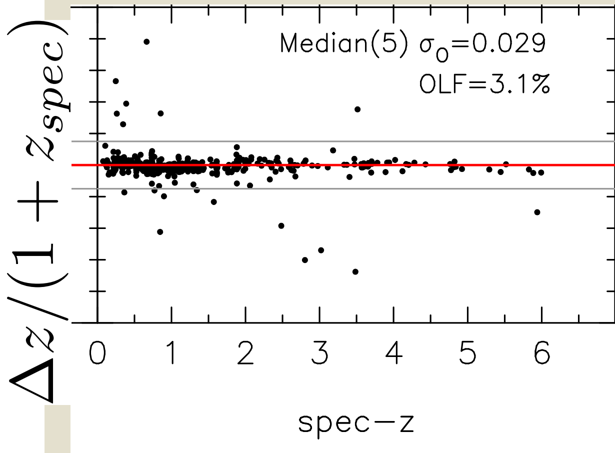
Parameterize with dispersion and bias

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

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

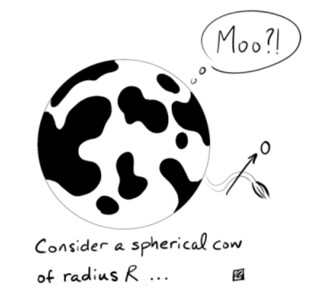
Challenge to fine tune photo-z estimates given disparate and incomplete spectroscopic samples





Dahlen et al 1308.5353

Complications: Additional lensed galaxies



- Faint magnified galaxies also contribute as sources

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

- Number depends on slope of luminosity function

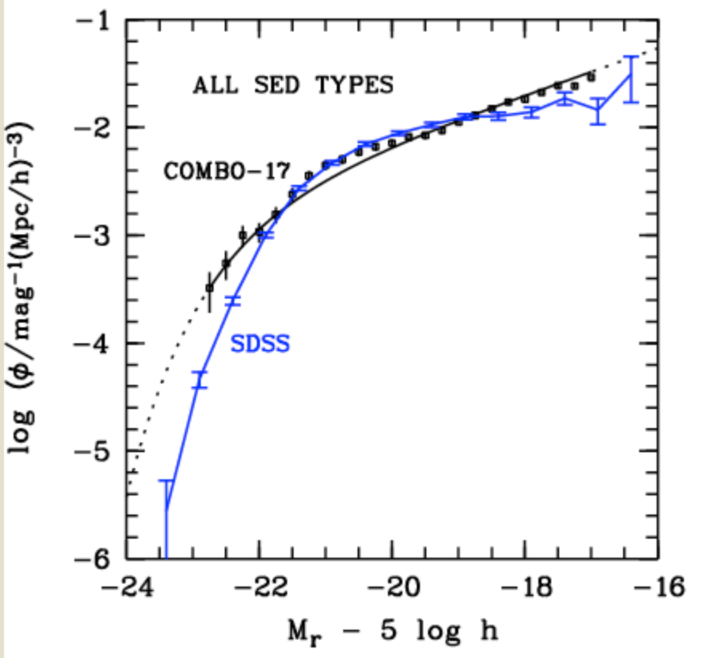
$$n_{\rm m}^{(i)}(\boldsymbol{\theta}) \ = \ 2\,(\alpha^{(i)} - 1)\,\kappa_{\rm G}^{(i)}(\boldsymbol{\theta}) \ .$$

$$\alpha(z, r_{\rm lim}) = a_1(r_{\rm lim}) + a_2(r_{\rm lim})\,z + a_3(r_{\rm lim})\,z^2 \ .$$

$$a_i(r_{\rm lim}) = b_{i\,1} + b_{i\,2}\ (b_{i\,3}\, r_{\rm lim} - b_{i\,4})^{b_{i\,5}} \ \ ,$$

- Galaxy correlations must factor this in

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

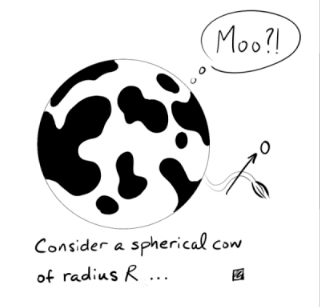


Wolf et al 2003

j	$b_{1\,j}$	$b_{2\,j}$	$b_{3\,j}$
1	0.44827	0	0
2	-1	+1	+1
3	0.05617	0.19658	0.18107
4	0.07704	3.31359	3.05213
5	-11.3768	-2.5028	-2.5027

Joachimi & Bridle 2009

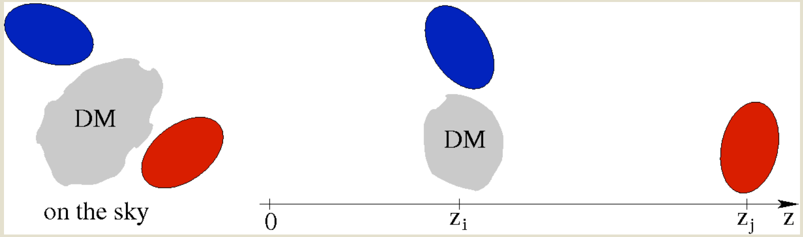
Complications: Intrinsic alignments



- Galaxy Intrinsic shapes are aligned in their host halo

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

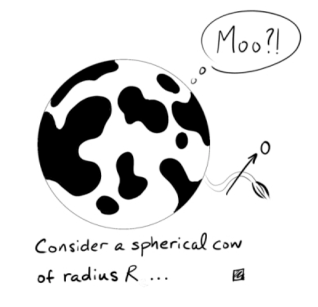
- Observed shape correlations include both lensed and intrinsic distortions



$$C_{\epsilon_i \epsilon_j} = C_{G_i G_j} + C_{G_i I_j} + C_{I_i G_j} + C_{I_i I_j}$$
$$C_{n_i \epsilon_j} = C_{g_i G_j} + C_{g_i I_j}$$

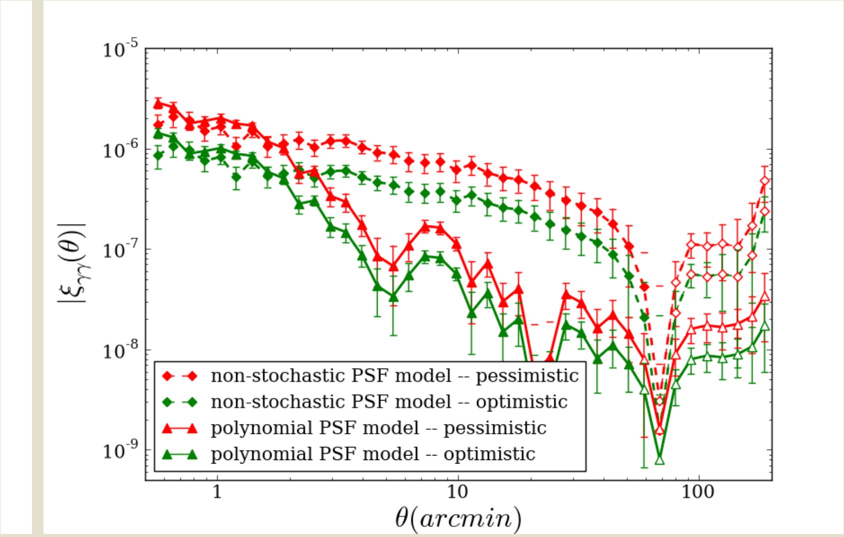
- The amplitude of intrinsic alignments is a function galaxy type, luminosity and redshift

Complications: Shear contamination



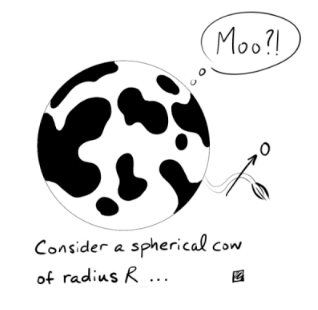
- Incomplete correction of the atmospheric and instrumental PSF can induce additive and multiplicative shear errors

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



Chang et al 2012

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

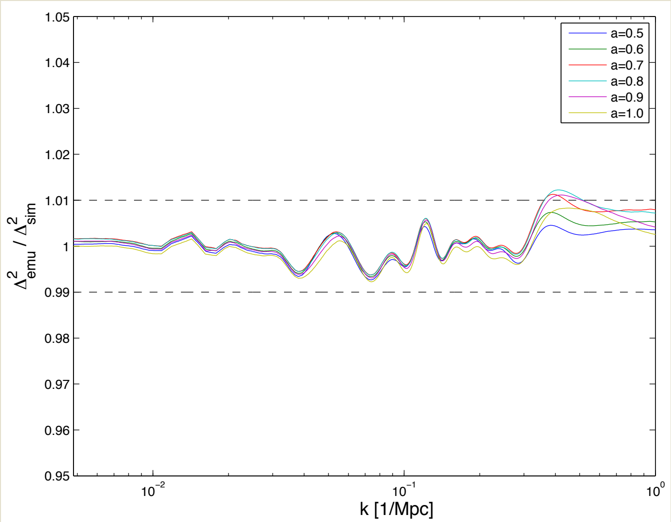
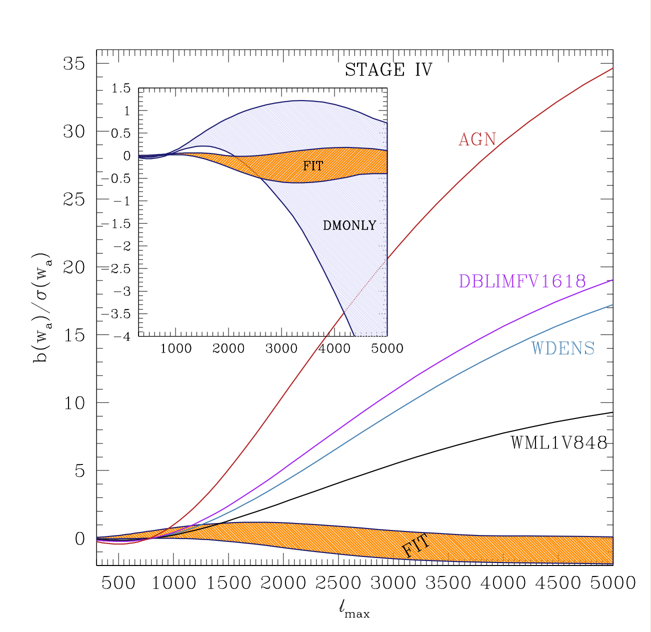


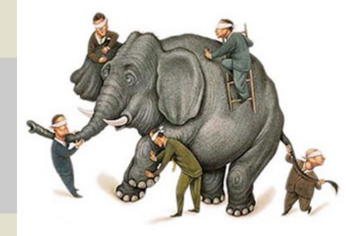
FIG. 9.— Ratio of the emulator prediction to the smooth simulated power spectra for the M000 cosmology at six values of the scale factor a. The error exceeds 1% very slightly in only one part of the domain for the scale factors $a = 0.7, 0.8$, and 0.9.

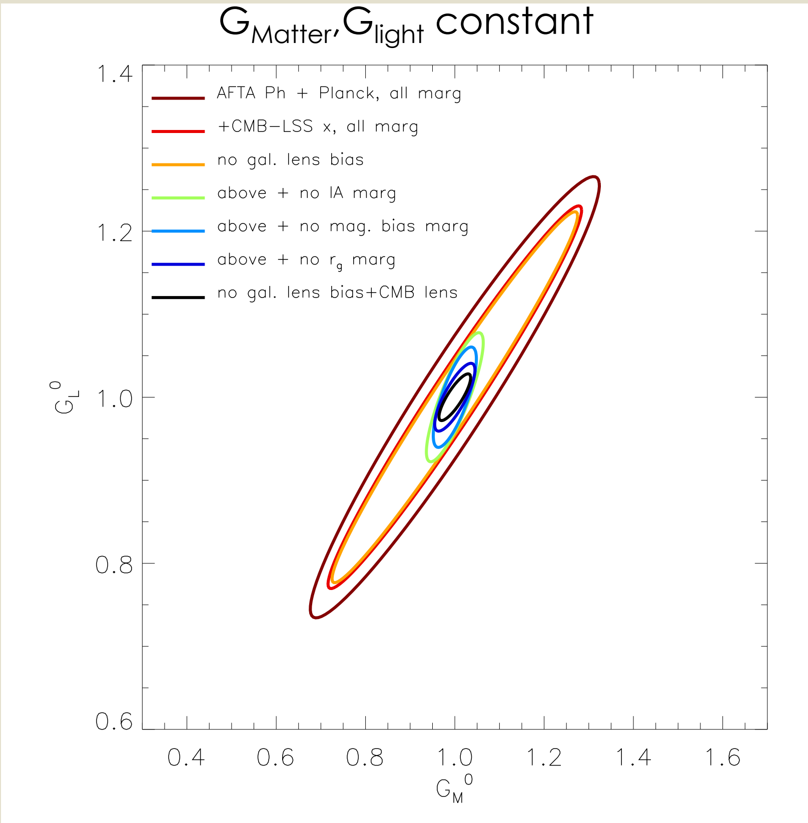
Lawrence et al 0912.4490

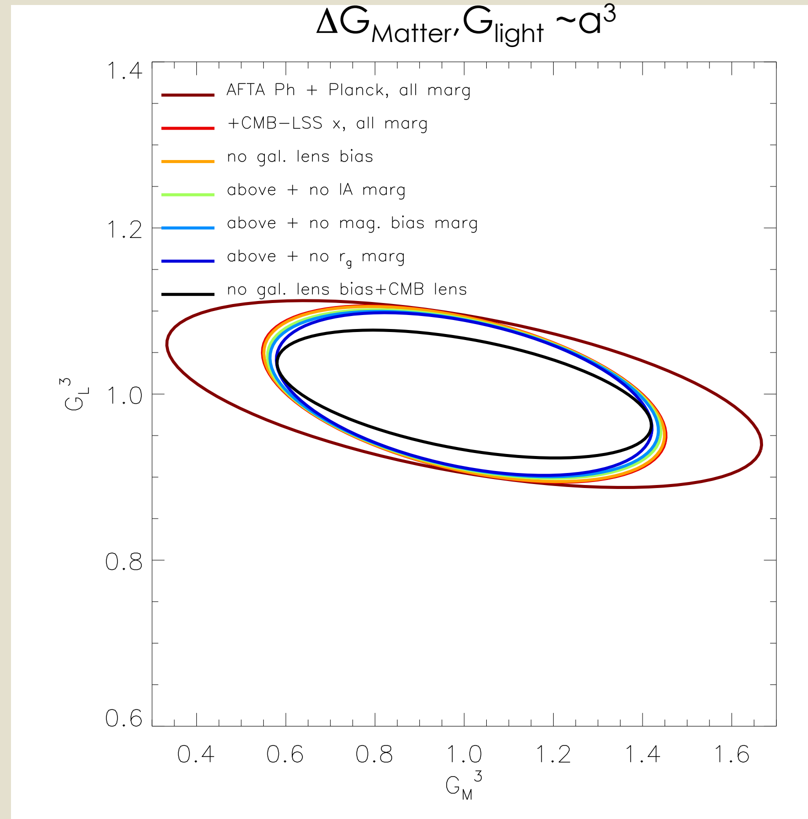


Zentner et al 1212.1177

AFTA Ph: constraints on $G_{matter,}\ G_{light}$



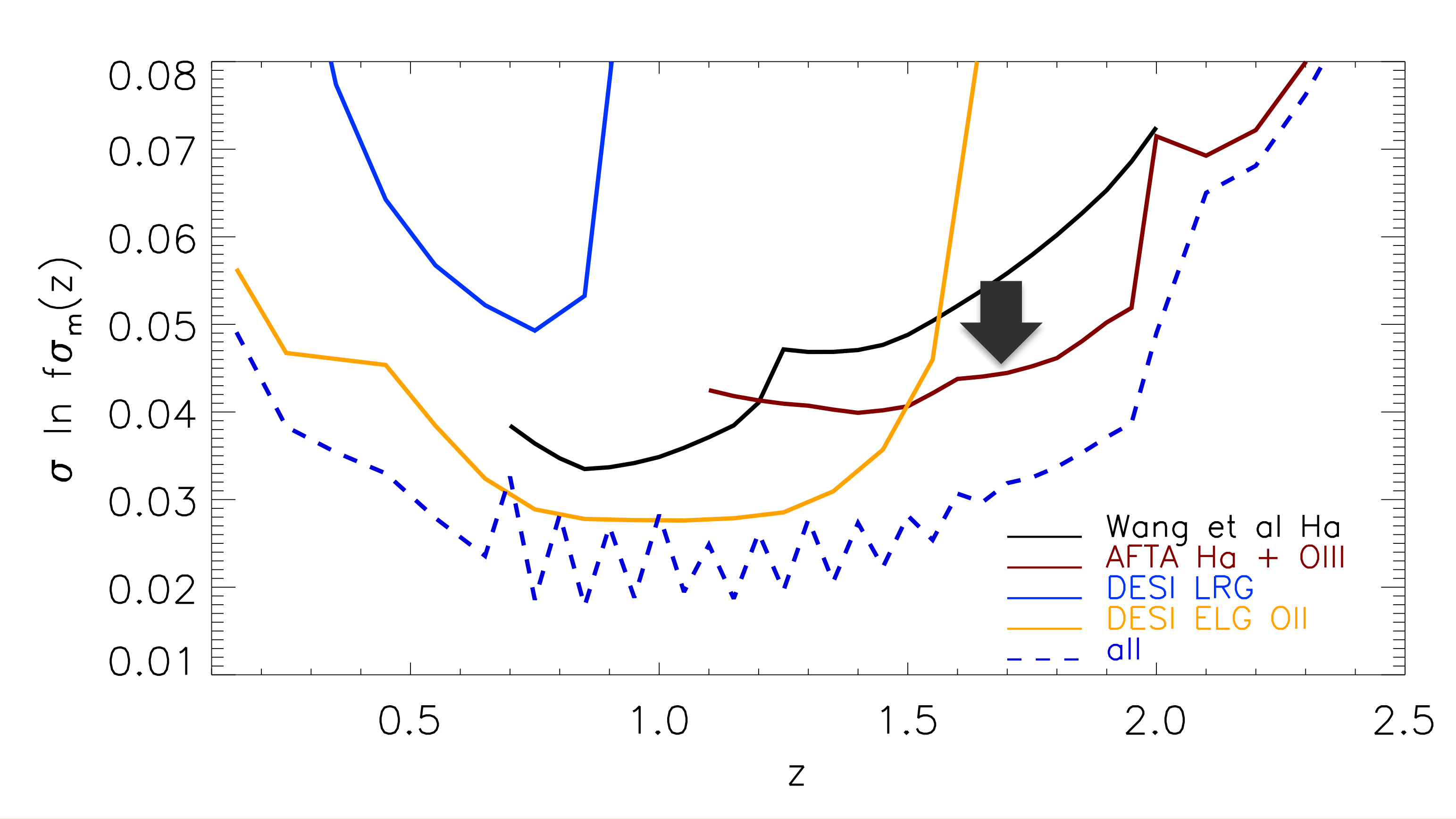




- Priors, as per the SDT report, on: Photo-z bias, Multiplicative shear bias, Additive shear bias
  - Photoz bias prior is limiting impact (need to make sure we can achieve this!)
  - IA marginalization over full galaxy sample – too conservative, this can/will be refined.
- Truncating on linear scales at each redshift (again on the over cautious side, could relax?)
- CMB lensing marginalizing over a lensing reconstruction amplitude A_{lens} without prior (conservative).

Bean and Mueller, in prep

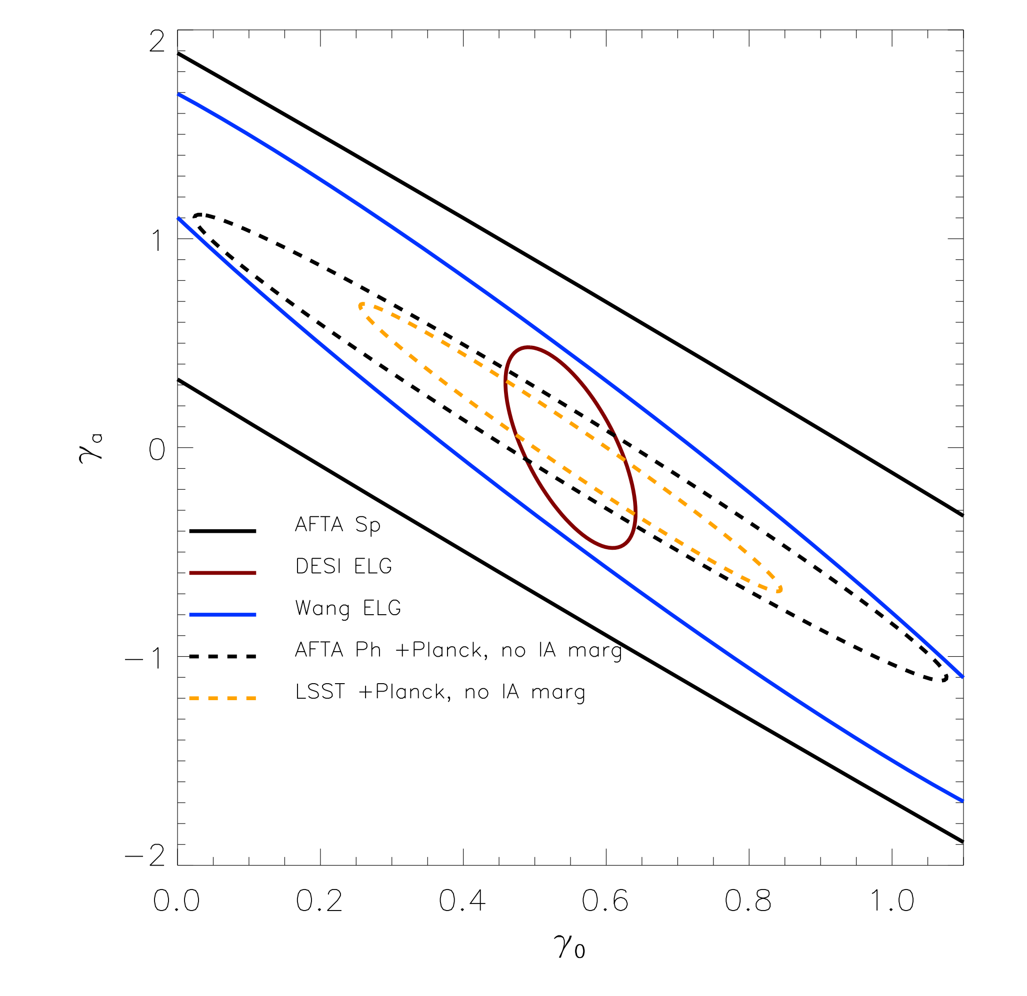
Spec surveys: growth rate constraints



Bean and Mueller, in prep

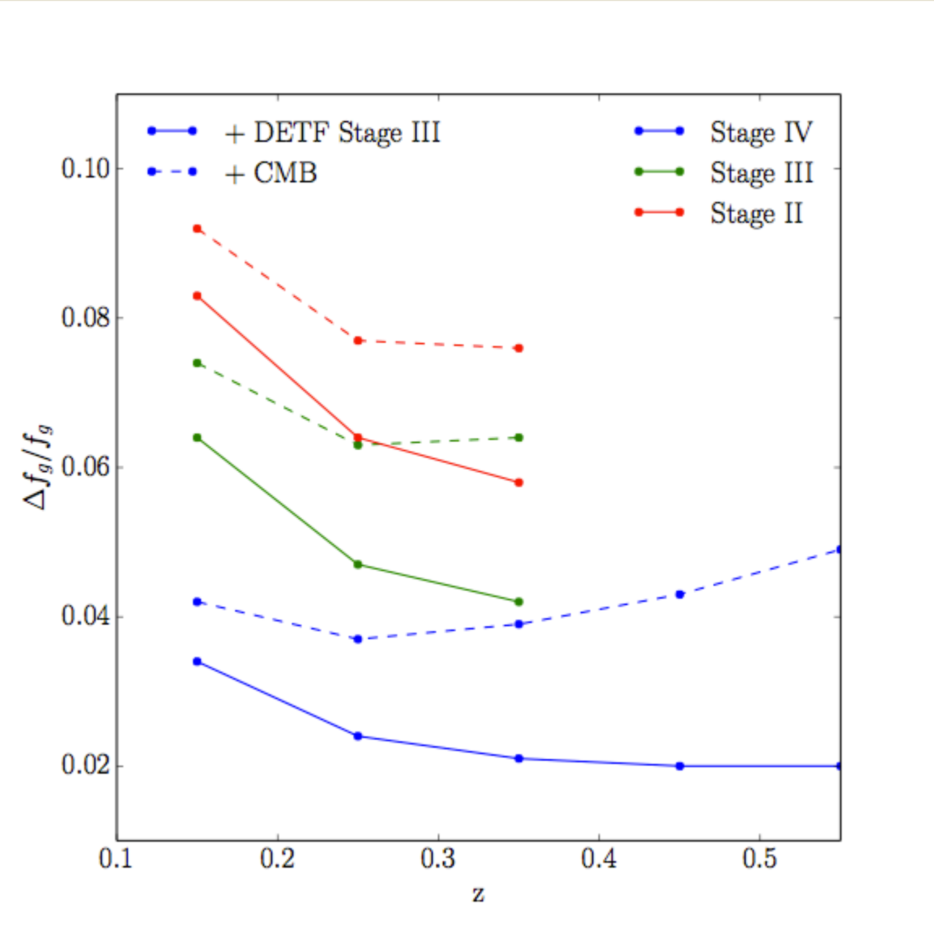
Spec & Photo survey: constraints on γ_0-γ_a

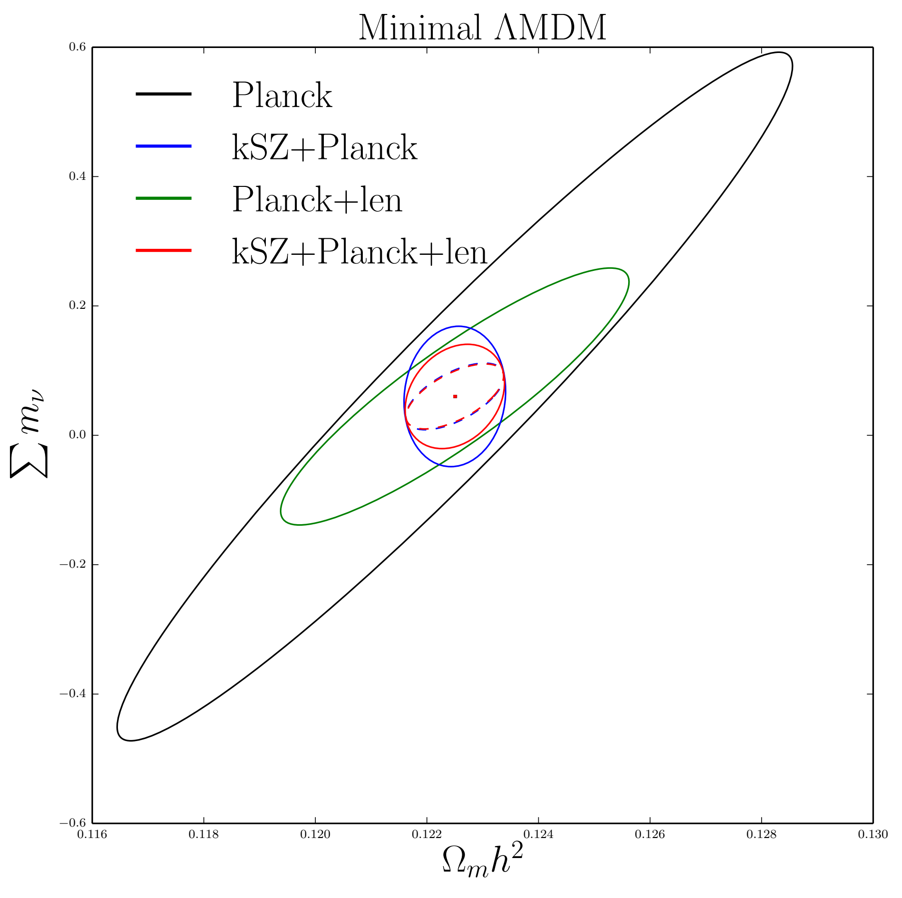
Beware a strong theoretical prior significantly biases redshift range of interest for growth studies (as with equation of state)



Bean and Mueller, in prep

kSZ pairwise dark sector constraints





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

Mueller, De Bernardis, Bean, Niemack 2014
Mueller, De Bernardis, Bean, Niemack in prep

To conclude

- Phenomenology of non-relativistic and relativistic tracers provides powerful tool to connect theory to upcoming observations

- Variety of observations with different systematics and strengths:
  - Different tracers: halo and field galaxies, clusters and CMB;
  - probing geometry and clustering through velocities and lensing;
  - $0<z<3$
  - CMB lensing offers very powerful cross correlation potential

- Understanding and incorporating astrophysical uncertainties key to realizing cosmological aims
  - Galaxy bias, stochasticity, and magnification, shear multiplicative and additive errors and intrinsic alignments
  - IA modeling and restriction to linear regime likely overcautious
  - Need to make sure photo-z dispersion and bias are as we aspire to - central to realize constraints from lensing