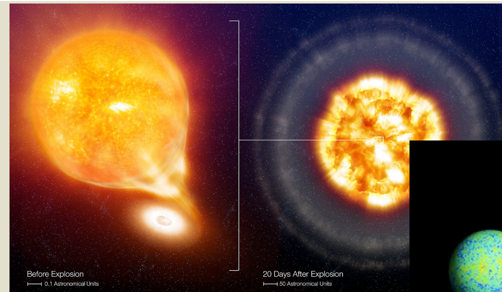
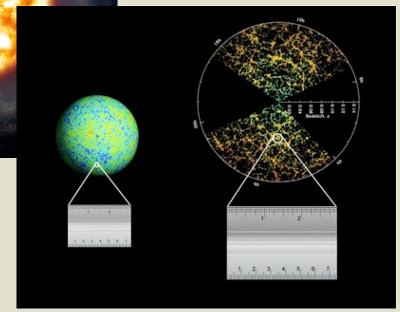
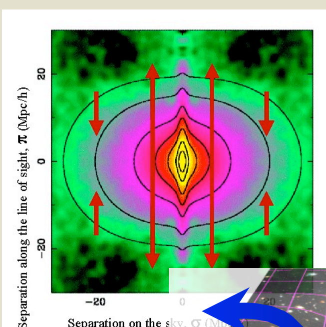
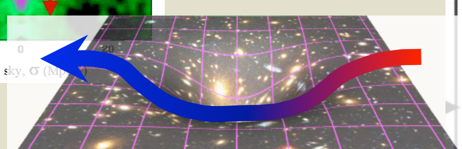


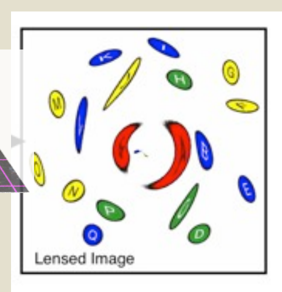


Understanding dark energy

Rachel Bean
Cornell University

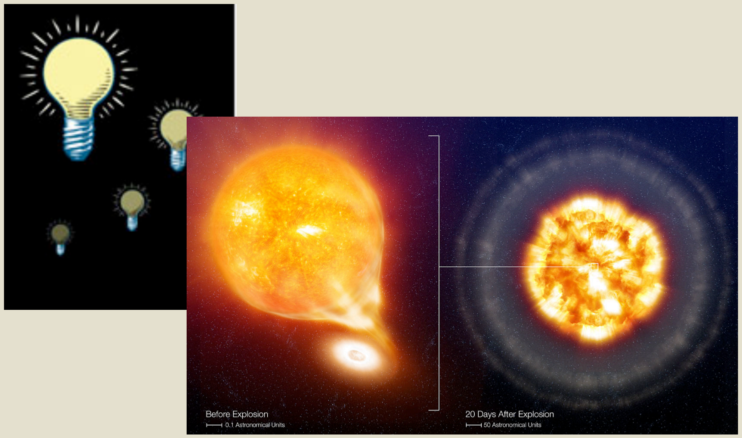




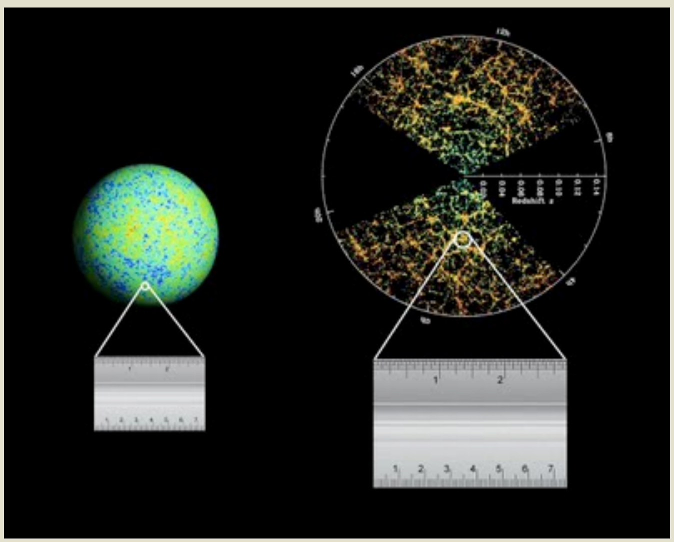


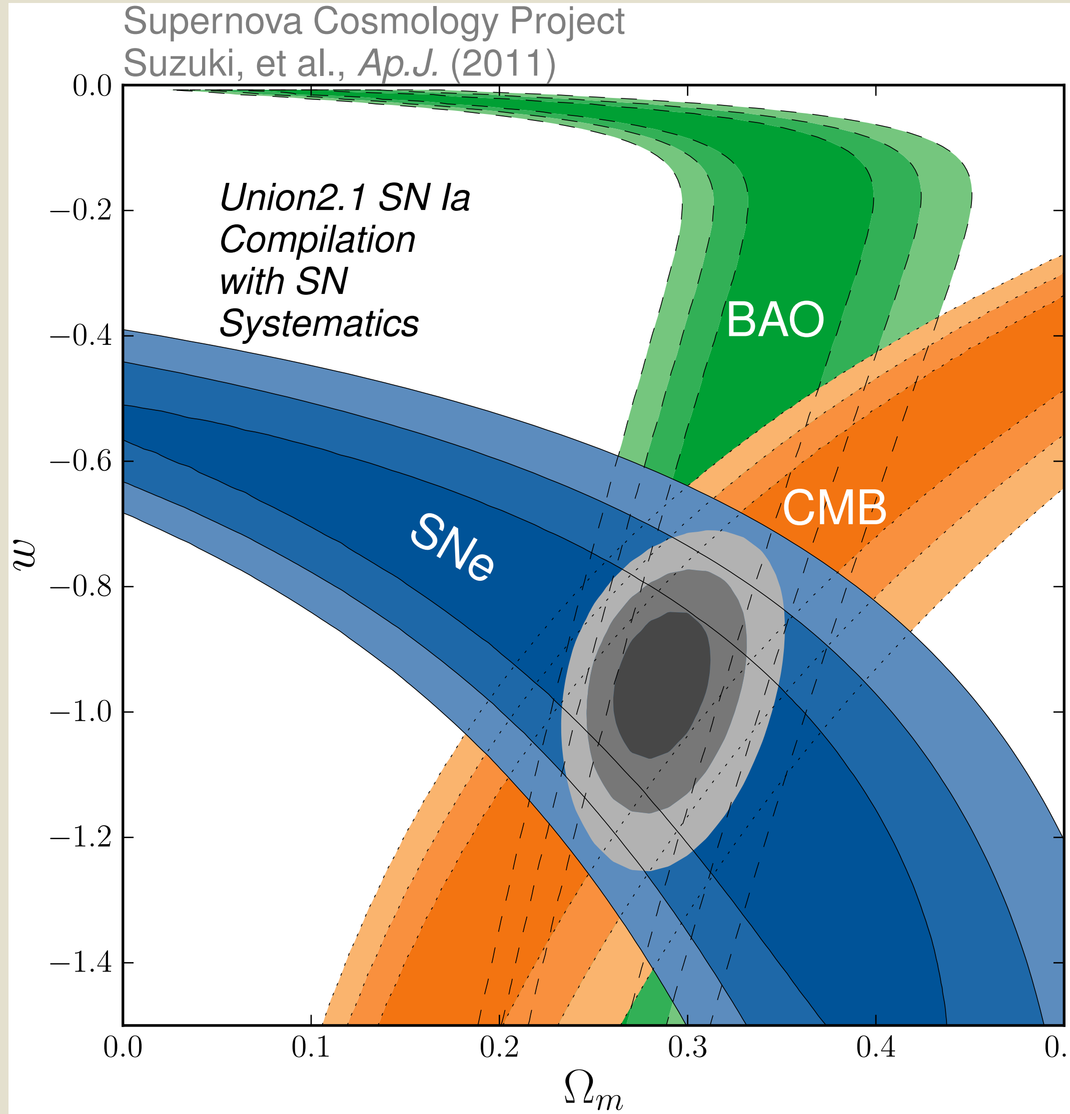
Geometric complementarity gives powerful evidence for dark energy's existence

Standard candles

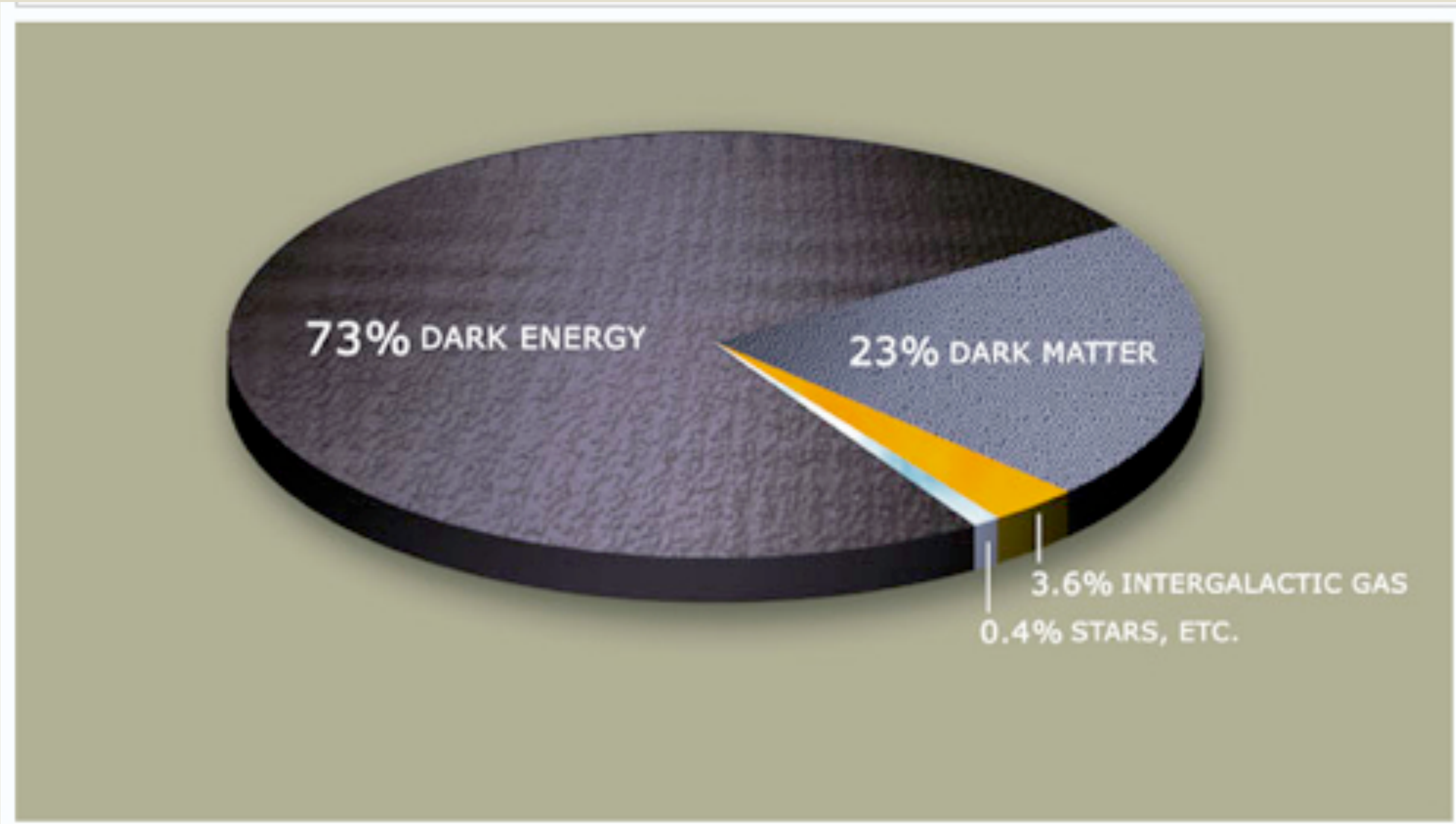


Standard rulers





The concordance camembert

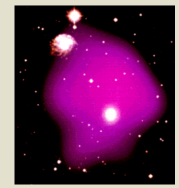


Understanding cosmic acceleration

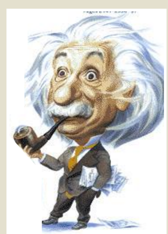
Cosmic acceleration = a modification of Einstein's equations

Deviations from GR?

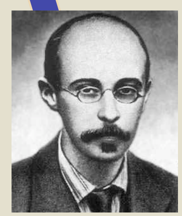
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



New matter? interactions?



Λ?



Inhomogeneous universe?

Broad aim =Phenomenology
Distinguish which sector: new gravity, new matter or Λ?

Ambitious aim = Theoretical model
Learn something more about the underlying theory?

Ways to modify gravity?

- Scalar tensor gravity = simple models we can model effects for

GR $$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}R$$

f(R) gravity $$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}\left(R + f_2(R)\right)$$

Scalar tensor gravity $$S = \int d^4x\sqrt{-g}\frac{1}{16\pi G}f_1(\phi)R$$

Higher dimensional gravity e.g. DGP $$S = \int d^5x\sqrt{-g^{(5)}}\frac{1}{16\pi G^{(5)}}R^{(5)}$$

- Active area of research, many different options, no solutions, yet
- Common theme: A scalar degree of freedom

Alternative explanations to expansion history

- Alter Friedmann and acceleration equations at late times

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 3P_m) + stuff$$

or

$$stuff + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho_m + 3P_m)$$?

e.g. f(R) gravity

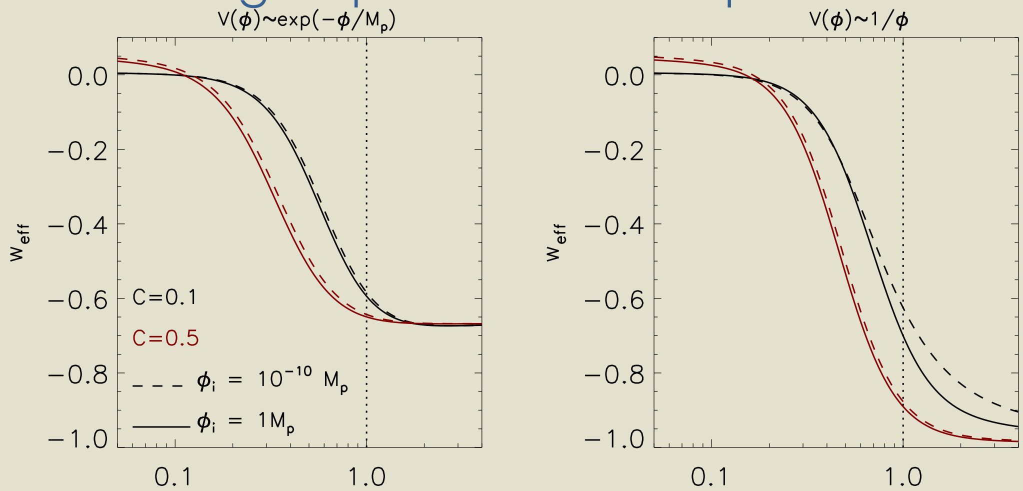
$$-H^2 f_R + \frac{a^2}{6} f + \frac{3}{2} H \dot{f}_R + \frac{1}{2} \ddot{f}_R + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

e.g. DGP gravity

$$-\frac{\dot{H}}{r_c} + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

Palatable and unpalatable attraction…

- Attractor solutions give predictions independent of initial conditions,



RB, Flanagan, Laszlo, Trodden 2008

  - for better or worse e.g. f(R) Amendola et al 2007

- Can evade (unpalatable) attractors, by retrofitting ΛCDM background, but at the high price of more fine-tuning
  - e.g. f(R) Hu and Sawicki 2007

$$f(R) \;=\; -m^2 \frac{c_1 (R/m^2)^n}{c_2 (R/m^2)^n + 1}\,,$$

Can we tie data a step closer to theory?

- What observational properties might the most general action predict?

$$S = \int d^4x\sqrt{-g}\left\{\frac{M_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi)\right.$$

Canonical scalar field

$$+f_{quartic}(\phi)(\nabla\phi)^4$$

Quartic kinetic

$$+f_{curv}(\phi)G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$

Coupling to curvature

$$\left.+f_{GB}(\phi)\left(R^2 - 4R^{\mu\nu}R_{\mu\nu} + R_{\mu\nu\sigma\rho}R^{\mu\nu\sigma\rho}\right)\right\}$$

Gauss-Bonnet (GB) term

$$+S_{\rm m}\left[e^{\alpha(\phi)}g_{\mu\nu}\left(1+f_{kin}(\phi)(\nabla\phi)^2\right),\psi_{\rm m}\right]$$

Non-minimally coupling to matter

Park, Watson, Zurek 2011
Bloomfield & Flanagan 2012
Bean, Mueller, Watson in prep

Attractor behaviors

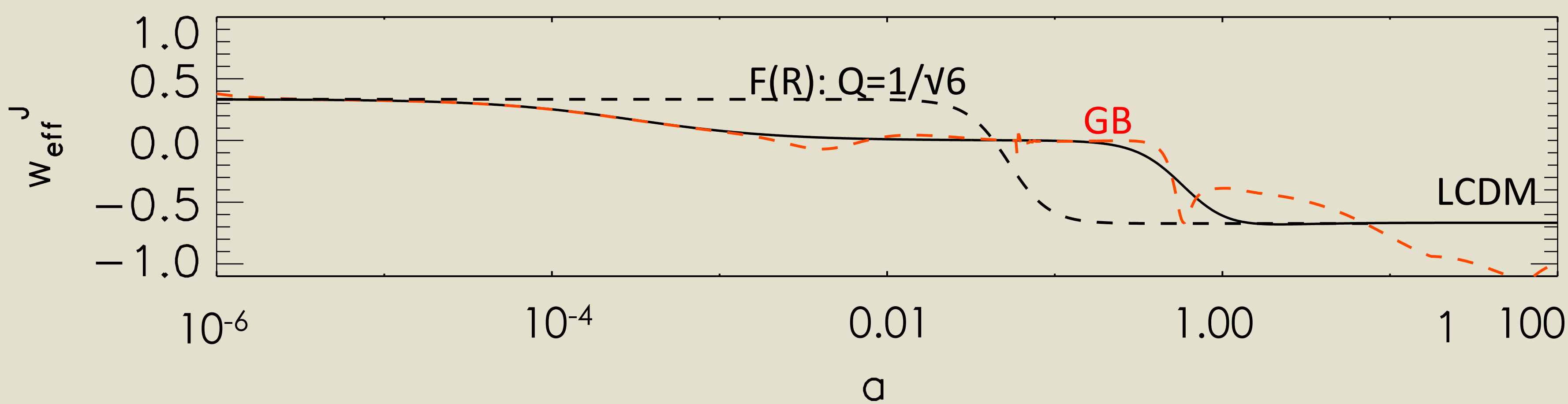
- Simple forms for couplings/interactions yield a small set of predictions

Attractor	Ω_ϕ	w_ϕ	w_E	w_J
MAT$-\lambda$	$\frac{3(1+w_m)}{\lambda^2}$	w_m	w_m	$\frac{w_m+\sqrt{6}Qx/3}{1-\sqrt{6}Qx}$
MAT $-$ Q	$\frac{2Q^2}{3}$	1	$\frac{2Q^2}{3}$	$\frac{4Q^2}{3(1-2Q^2)}$
ACC$-\lambda$	1	$-1+\frac{\lambda^2}{3}$	$-1+\frac{\lambda^2}{3}$	$-1+\frac{\lambda^2-2Q\lambda}{3(1-Q\lambda)}$
ACC $-$ GB	1	-1	-1	-1

$$V = V_0 \exp\left(-\lambda\frac{\phi}{M_p}\right)$$

$$e^\alpha = \exp\left(-2Q\frac{\phi}{M_p}\right)$$

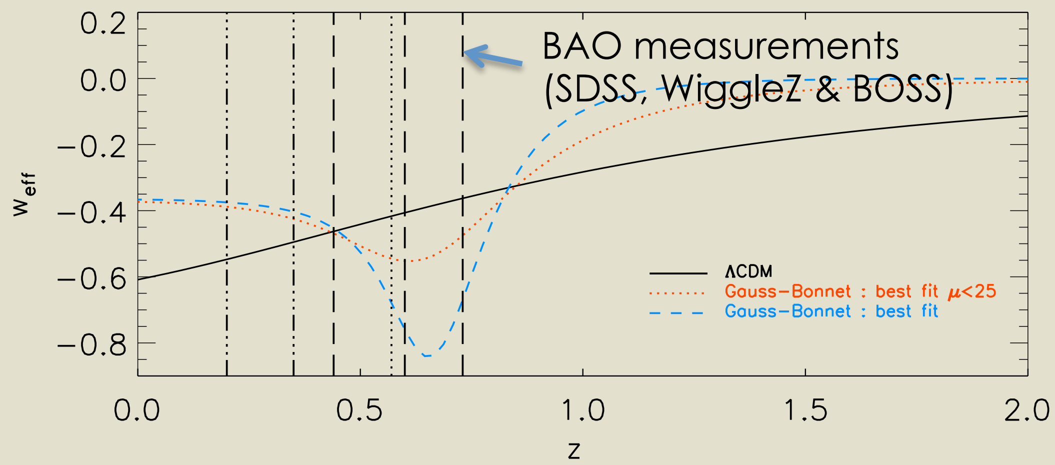
$$f_{GB} = F_0 \exp\left(-\mu\frac{\phi}{M_p}\right)$$

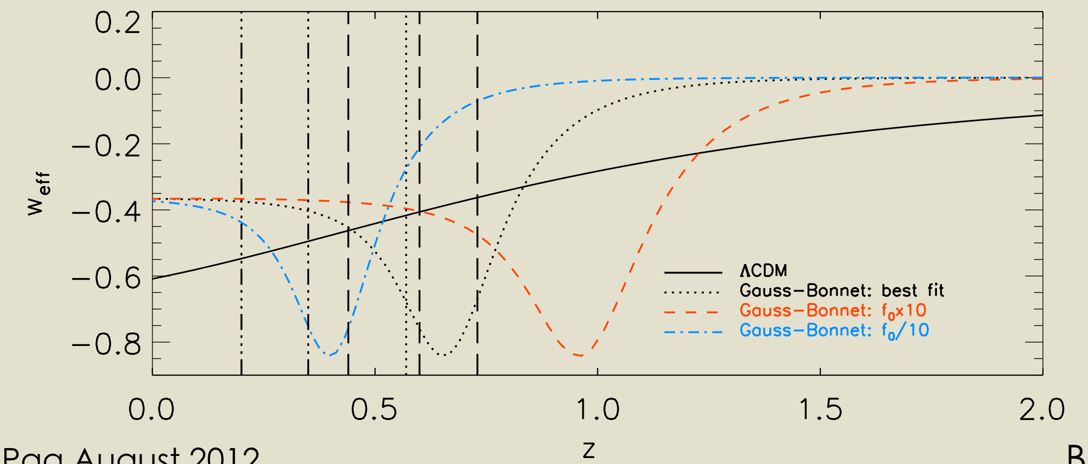


Bean, Mueller, Watson in prep

The power of multi-epoch measurements

- BAO and SN data give multiple tests of cosmic dynamics

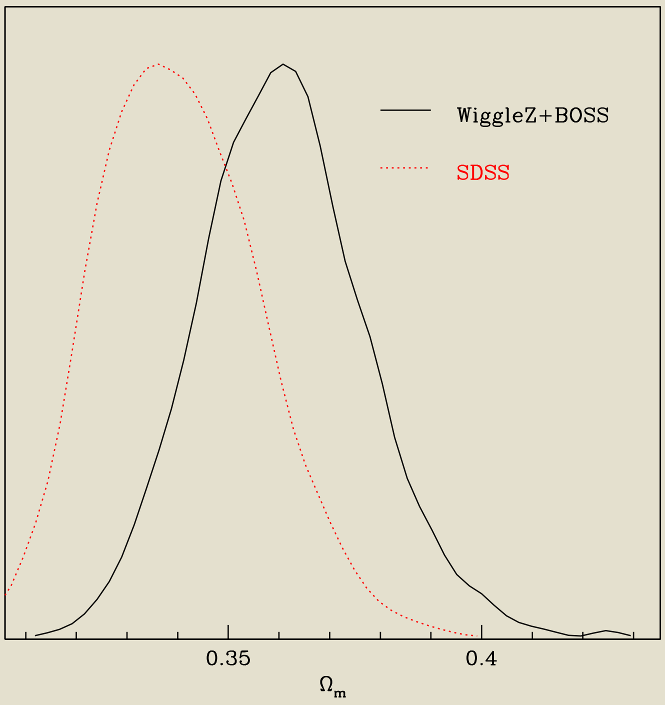


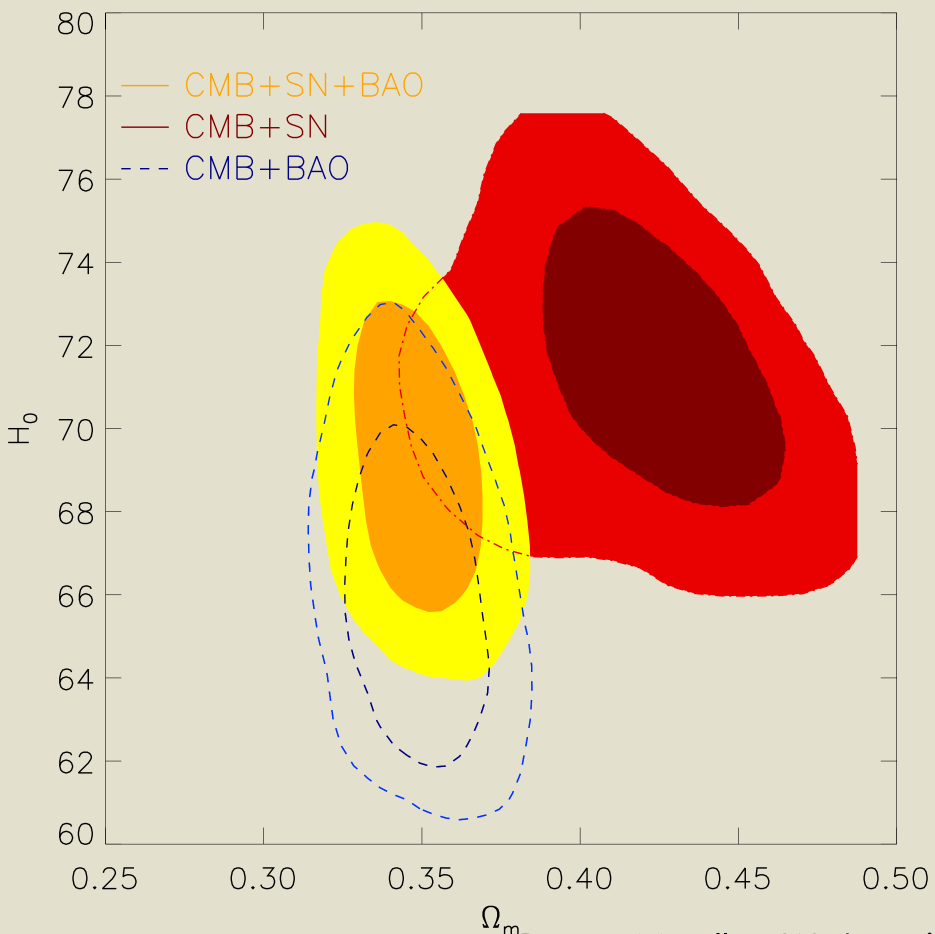


Bean, Mueller, Watson in prep

The power of multi-epoch measurements

- In combination, rule out Gauss-Bonnet term: $\Delta\chi^2$(GB-LCDM)=+17



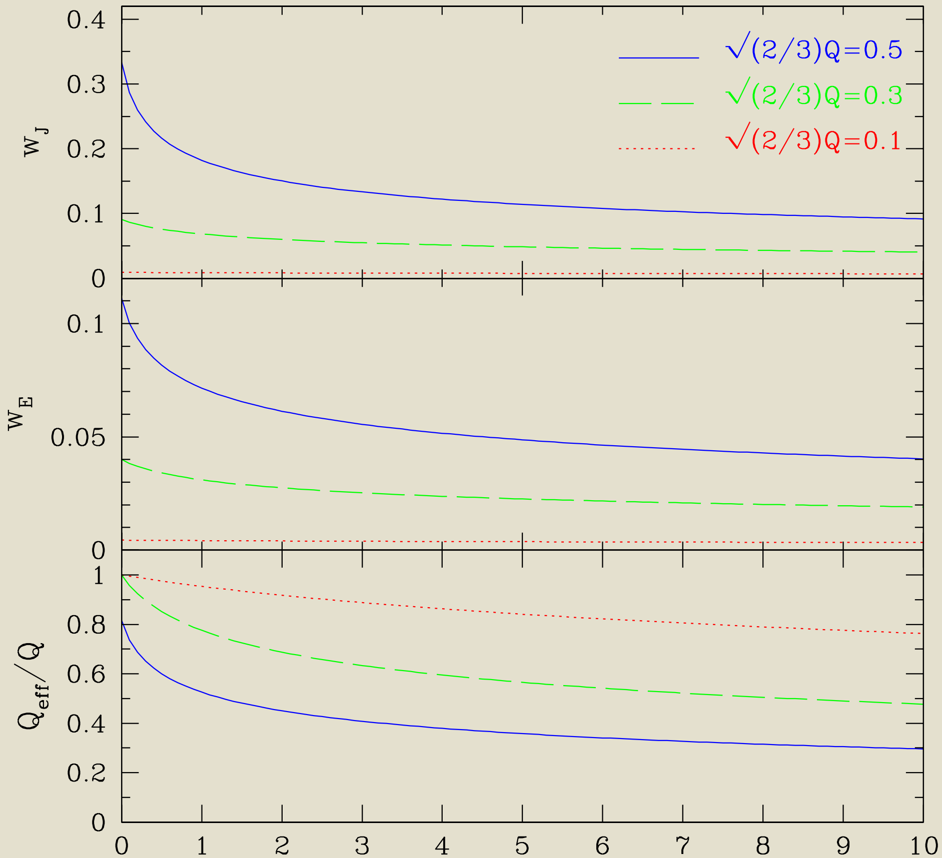


Rachel Bean: PhysPag August 2012

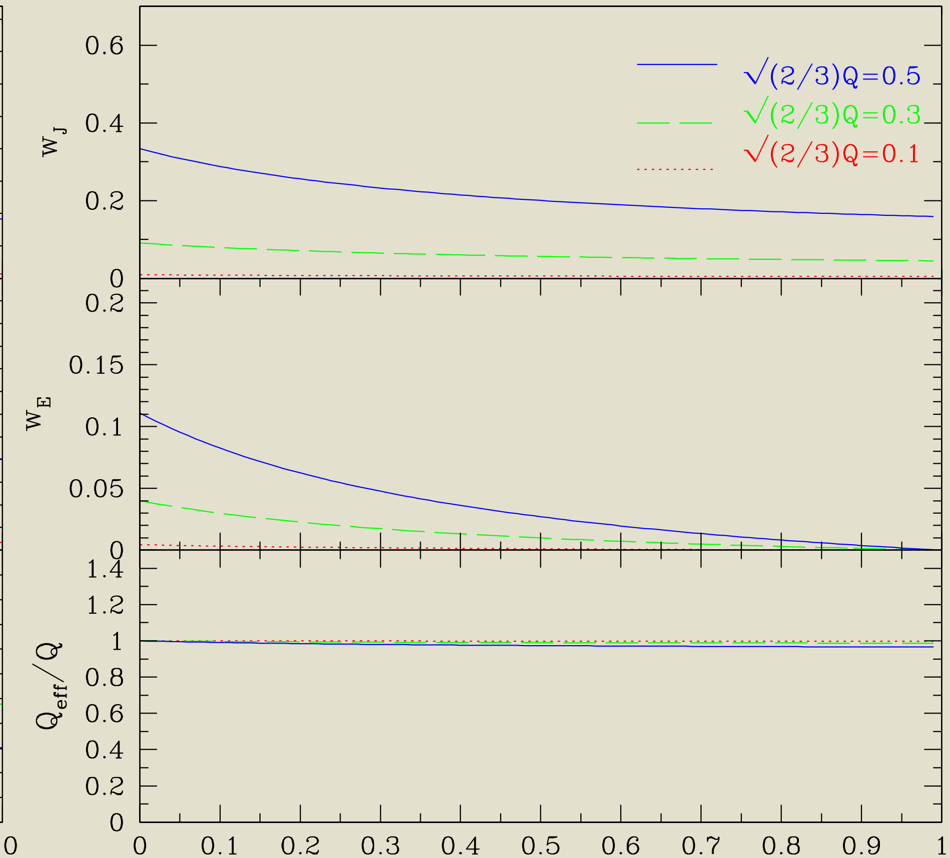
Bean, Mueller, Watson in prep

Quartic and curvature interactions have cosmologically interesting effects

Matter dominated era



Increasing quartic term →

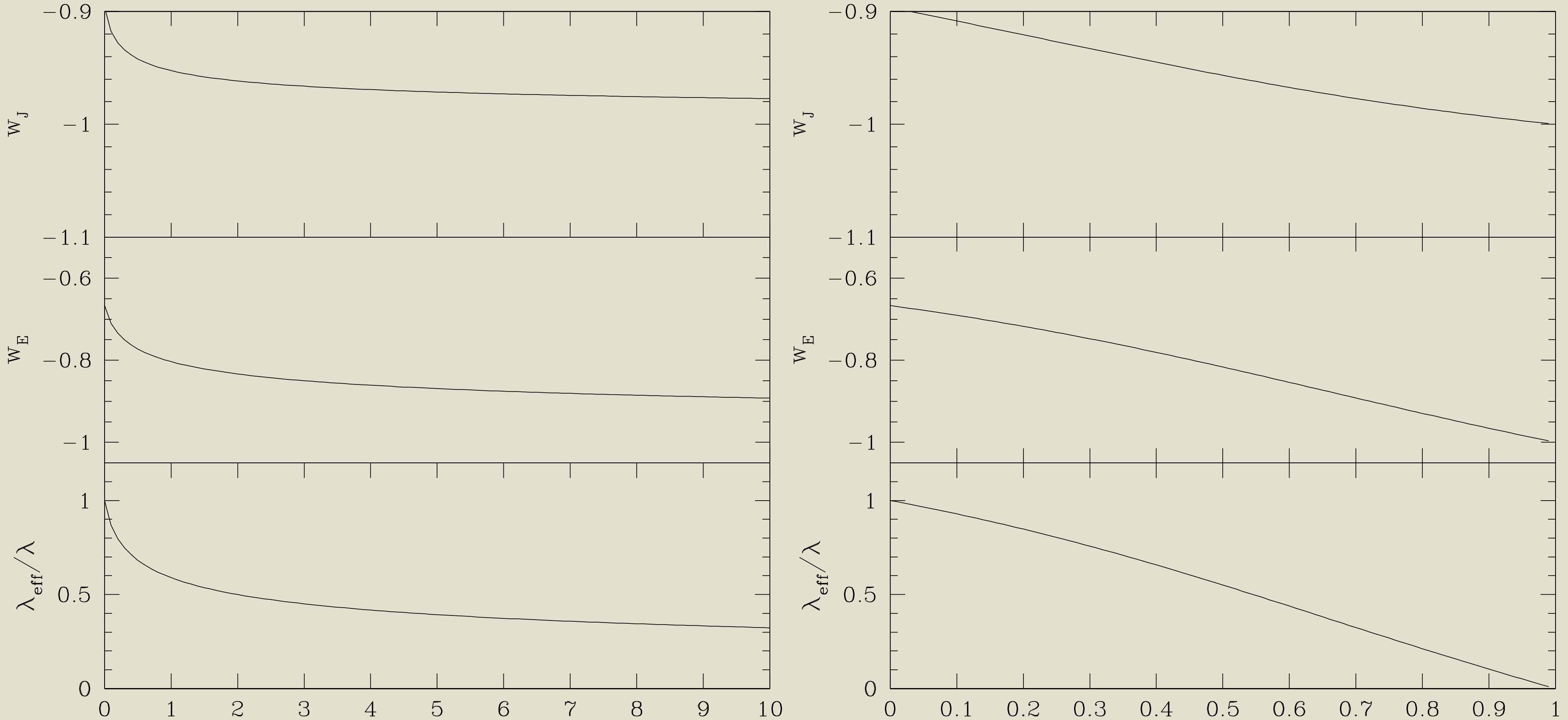


Increasing curvature term →

Bean, Mueller, Watson in prep

Quartic and curvature interactions have cosmologically interesting effects

Late time accelerating era



Increasing quartic term →

Increasing curvature term →

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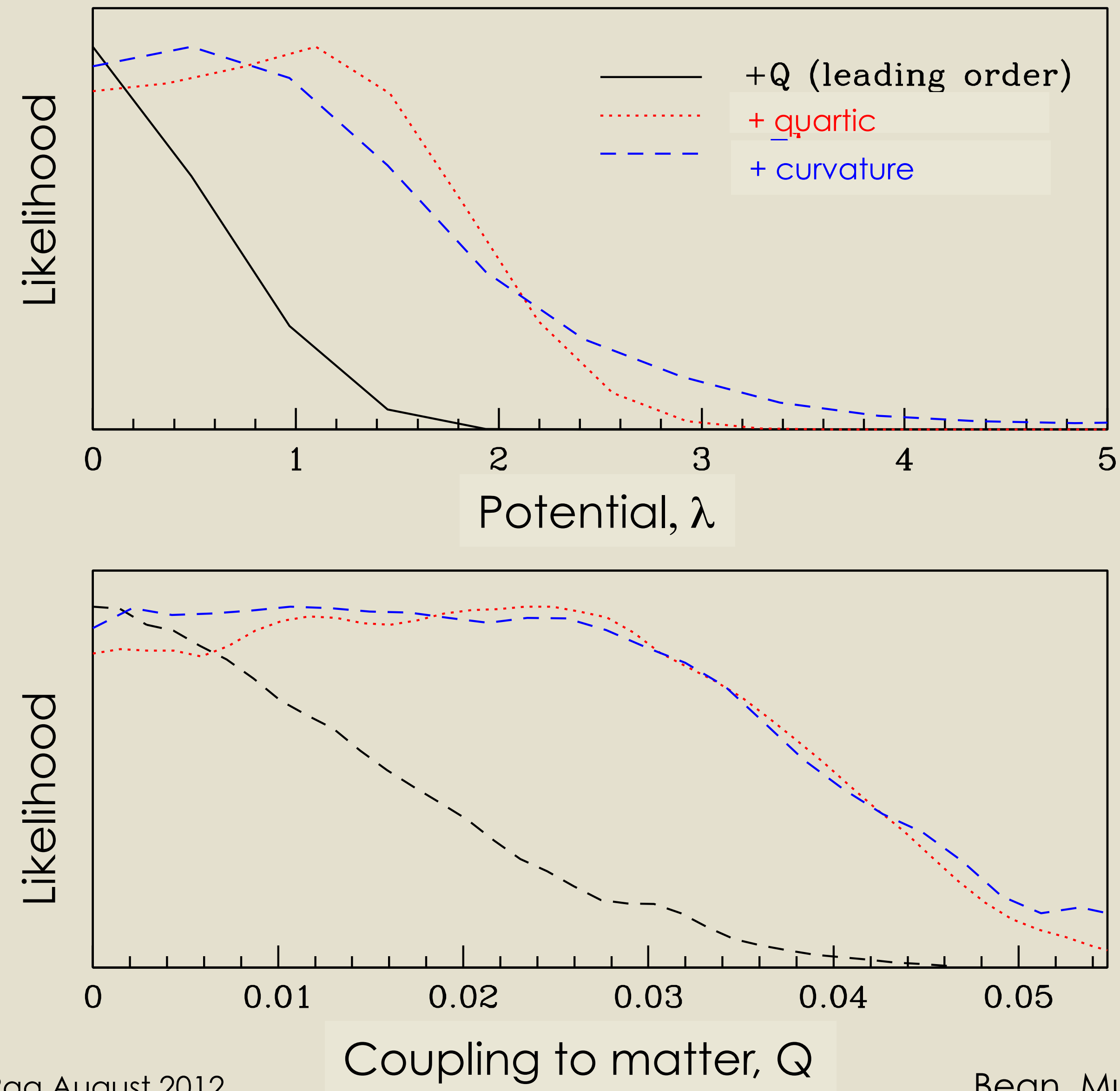
Geometric cosmological constraints

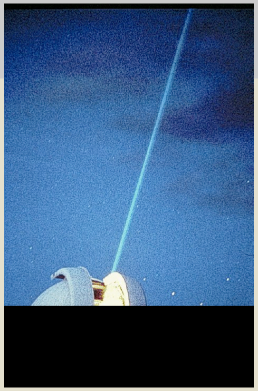


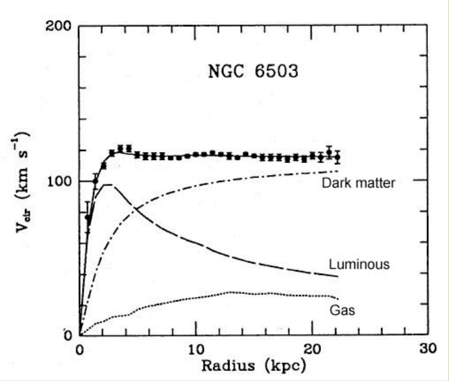
Bean, Mueller, Watson in prep

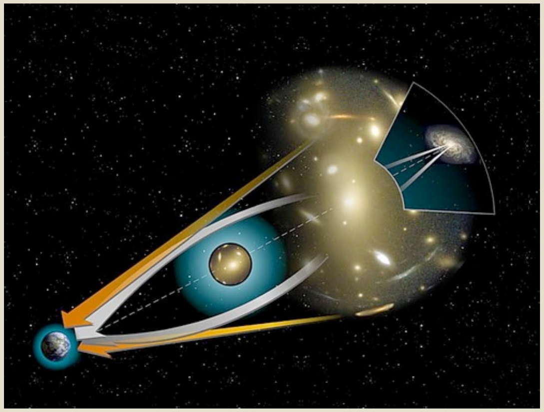
There are always benefits to asking more questions…

Weak field tests of gravity

- Terrestrial and Solar System
  - Lab tests on mm scales
  - Lunar and planetary ranging
- Galactic
  - Galactic rotation curves and velocity dispersions
  - Satellite galaxy dynamics
- Intergalactic and Cluster
  - Galaxy lensing and peculiar motions
  - Cluster dynamical, X-ray & lensing mass estimates
- Cosmological
  - Early times: BBN, CMB correlations
  - Late times: Large scale structure

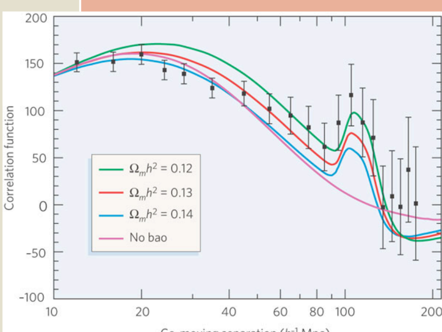


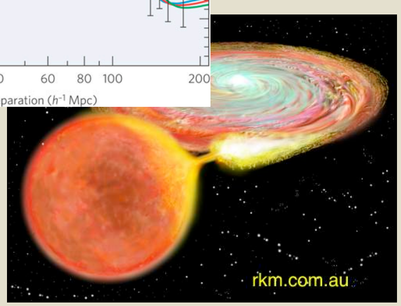


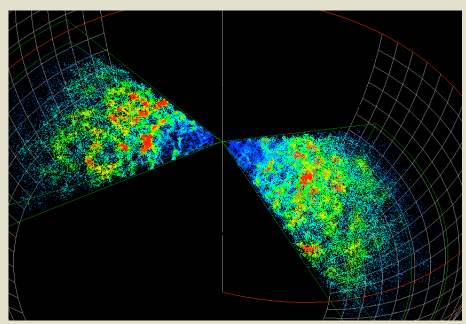


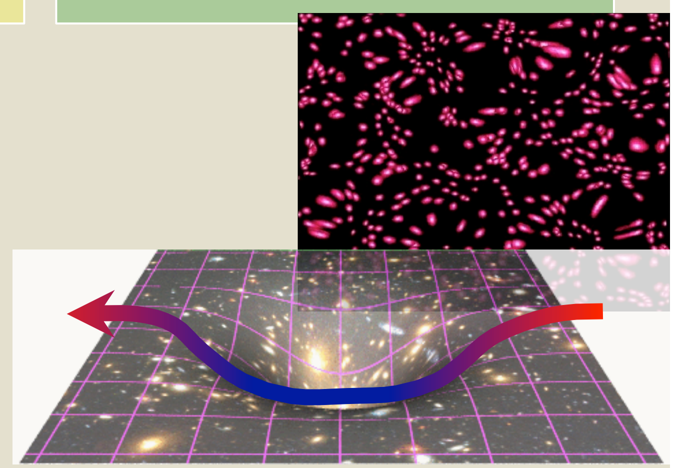
Three groups of extra galactic observations for testing gravity

I: Background expansion	II: Growth, up to some normalization	III: Growth directly
CMB angular diameter distance Supernovae luminosity distance BAO angular/radial scale	Galaxy autocorrelations Galaxy – ISW x-corrln Xray and SZ galaxy cluster measurements Ly-alpha measurements	CMB ISW autocorrelation Weak lensing autocorrelation Peculiar velocity distribution/ bulk flows









Rachel Bean: PhysPag August 2012

Phenomenological model of gravity

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

- Aim to describe phenomenological properties common to theories

  - A modification to Poisson's equation, Q

    $$k^2\phi = -4\pi G Q a^2 \rho\Delta$$

    Q≠1: can be mimicked by additional (dark sector?) clustering/matter

  - An inequality between Newton's potentials, R

    $$\psi = R\phi$$

    R≠1: not easily mimicked.

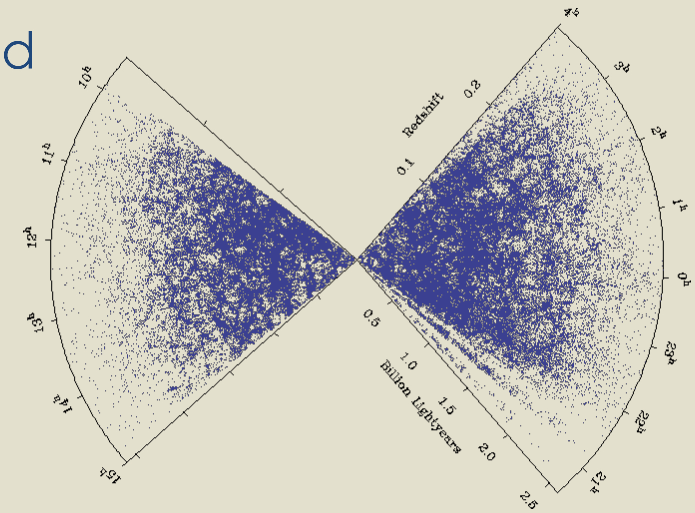
    - potential smoking gun for modified gravity?
    - Significant stresses exceptionally hard to create in non-relativistic fluids e.g. DM and dark energy.

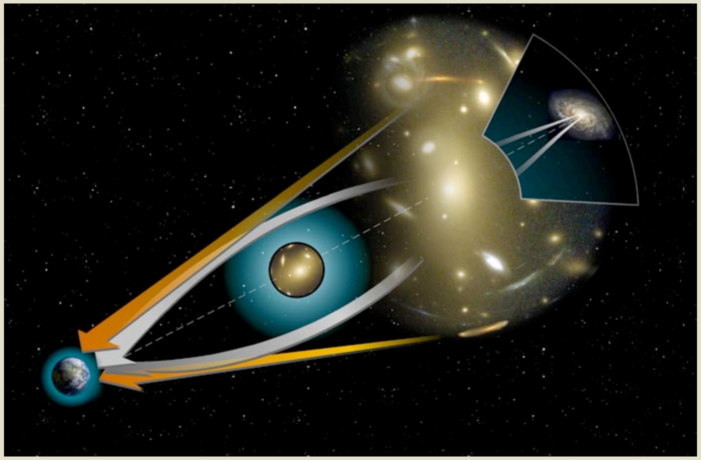
Complementary tests of gravity

- Non-relativistic tracers: Galaxy positions and motions
  - Measure $\psi \sim G_{mat} = QRG_N$
  - Biasing of tracer (galaxy) issue

- Relativistic tracers: Weak lensing and CMB
  - Sensitive to $(\phi+\psi) \sim G_{light} = Q(1+R)G_N$
  - Direct tracer of potential, but still
    - stochasticity relating lensing and surveyed galaxies
    - plenty of systematics (photo-z, IAs…)

- Contrasting tracers are the key to understanding gravity





Putting it all in the mix

- A "smoking gun" for GR on cosmic scales

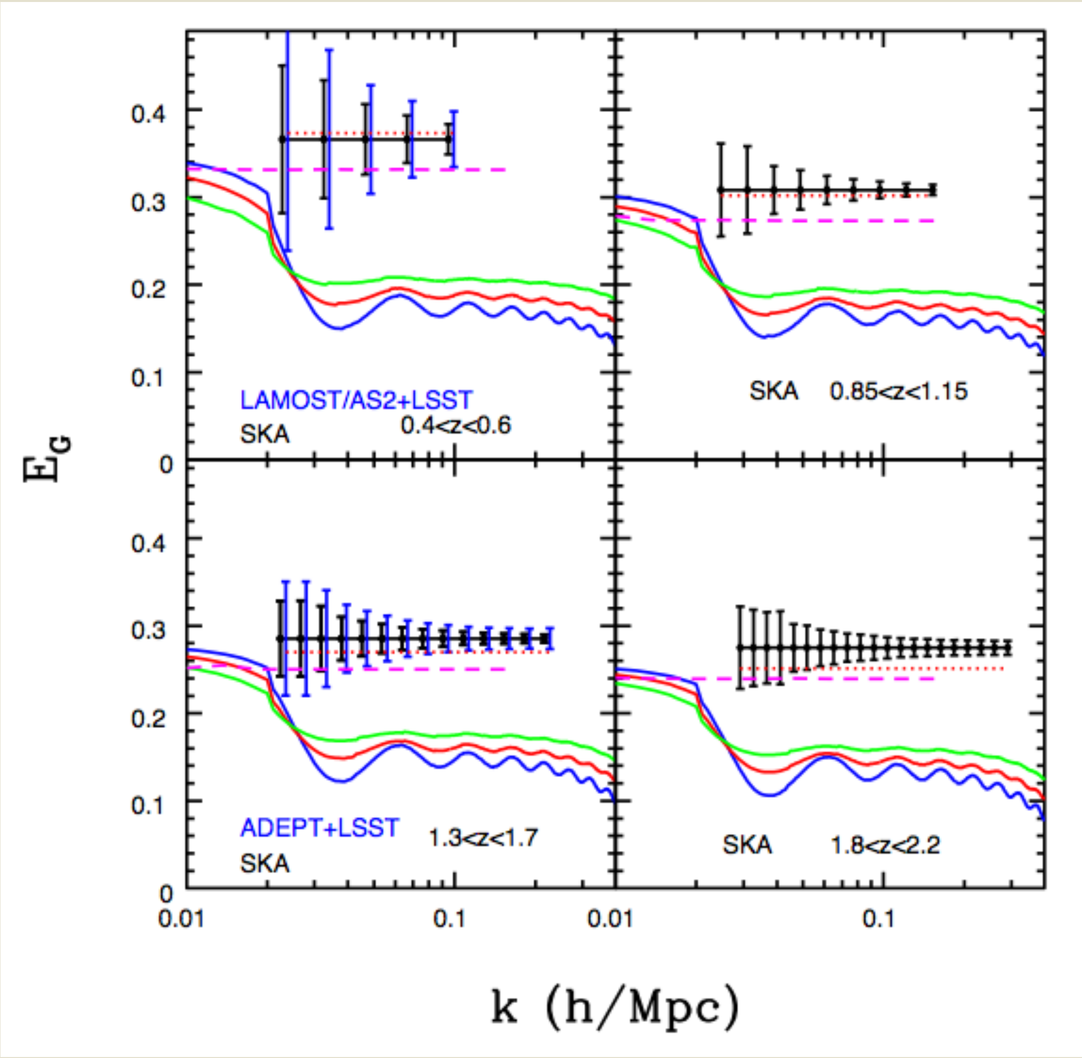
$$E_G \sim \frac{\text{galaxy position-lensing correlation } (C_l^{gG})}{\text{redshift space – galaxy position correlation } (C_l^{g\Theta})}$$

- Contrasts relativistic and non-relativistic tracers => $R \neq 1$?
  - Lensing: $G \sim \phi+\psi \sim Q(1+R)$,
  - Galaxy position and motion: $g,\Theta \sim \psi \sim QR$
- Independent of galaxy bias and initial conditions

$$\frac{C_l^{gG}}{C_l^{g\Theta}} \sim \frac{b\,\sigma_8{}^2}{b\,\sigma_8{}^2}$$

Zhang. Liguori, RB, Dodelson PRL 2007

Distinguishing between modified gravity and Λ



$$E_g \sim \frac{C_l^{g\kappa}}{C_l^{g\Theta}}$$

GR

DGP

f(R)

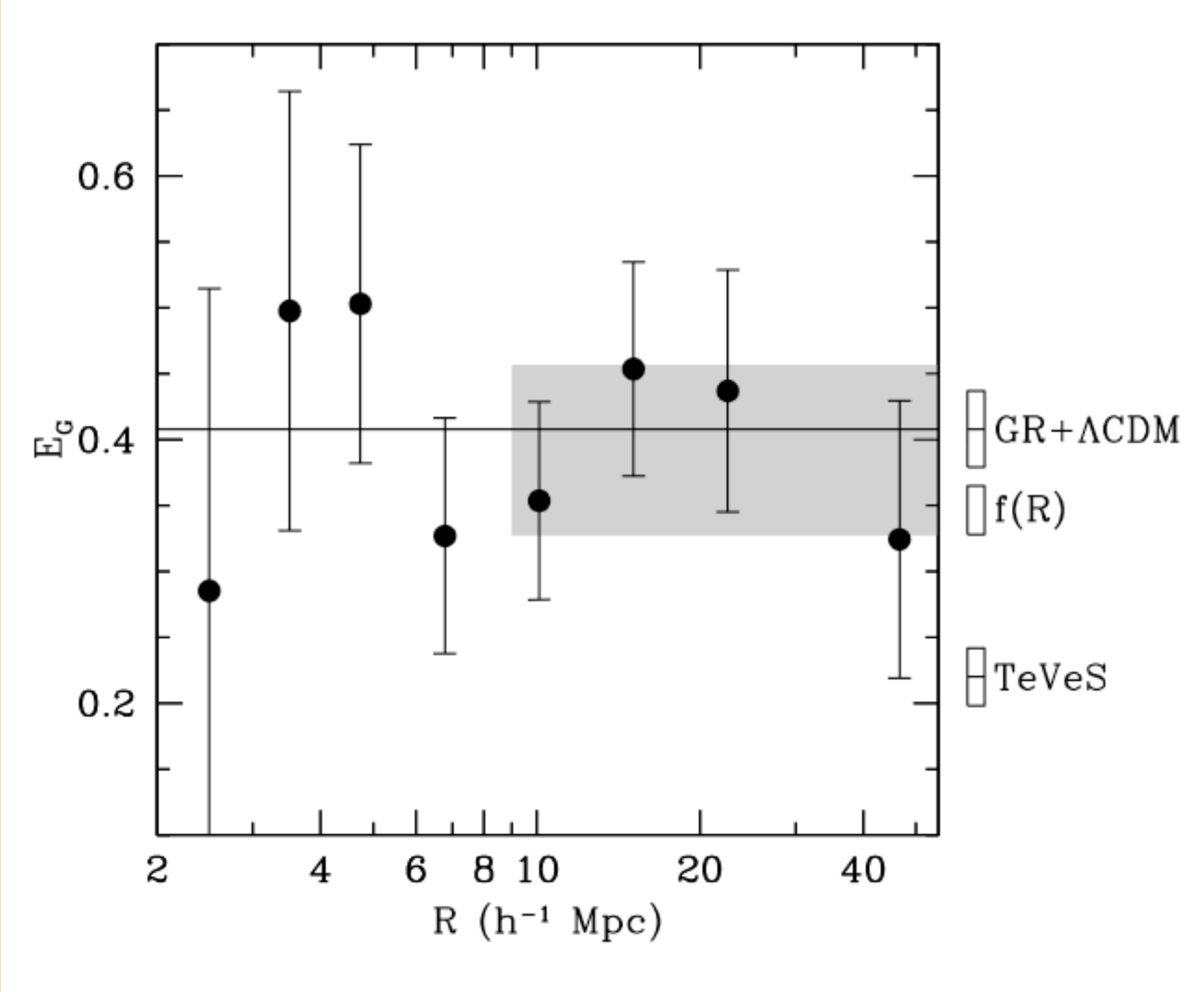
TeVeS K=0.1

TeVeS K=0.09

TeVeS K=0.08

Zhang, Liguori, RB, Dodelson PRL 2007

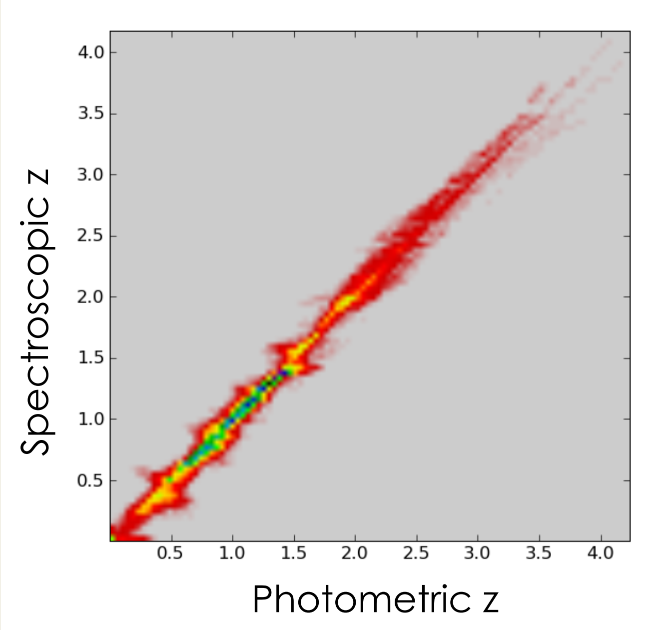
Vital proof of principle with SDSS LRG data



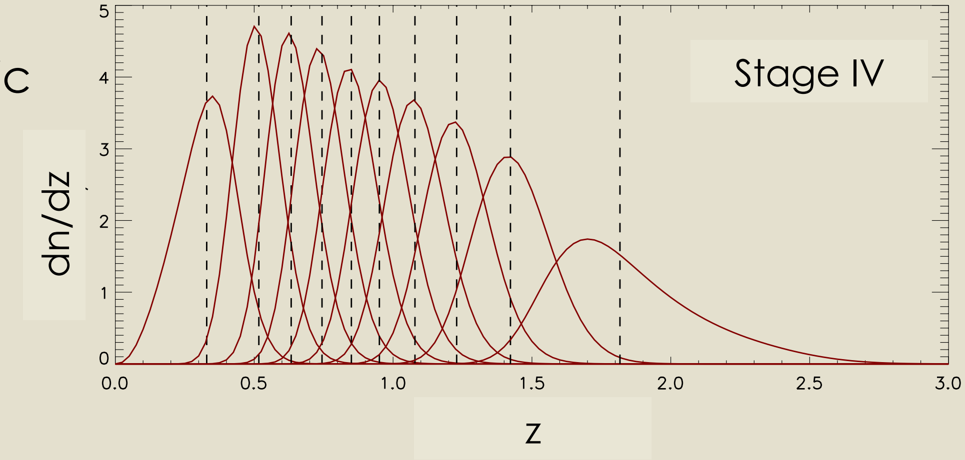
Reyes et al Nature 2010

Complications: photometric redshifts

- Facilitates fast and wide survey
- Enables tomography
  - Measuring evolution on dark energy
  - Cross-correlations between z bins useful for disentangling systematics and cosmology
- But sensitive to modeling
  - galaxy distribution,
  - photo-z statistical accuracy, systematic offsets and catastrophic errors



Credit: LSST Consortium

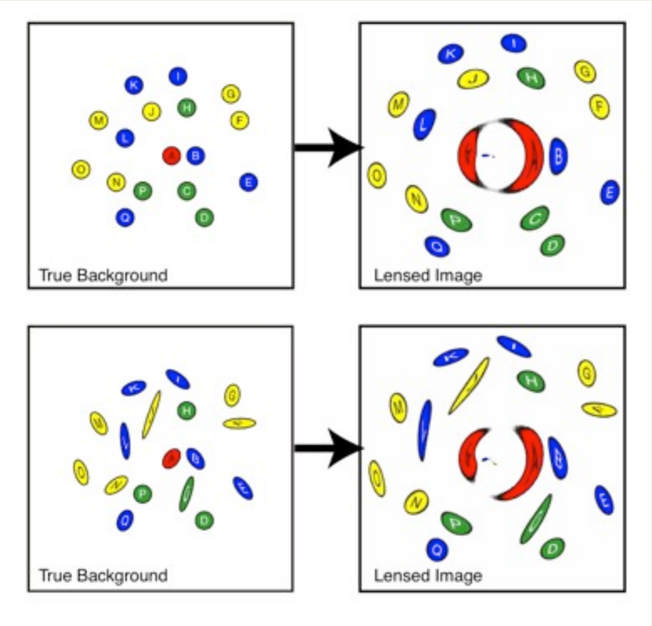


Complications : Intrinsic alignments

- Lensing distortions detected using statistical correlations

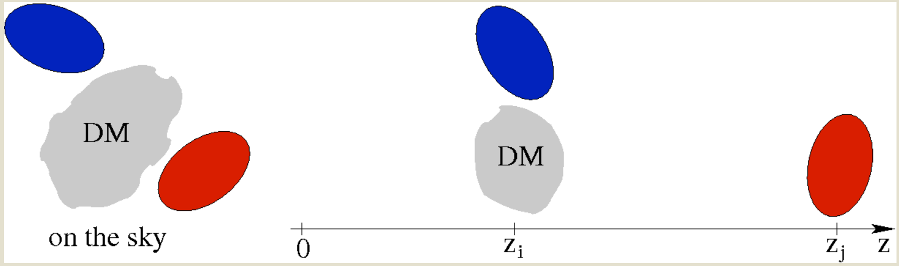
$$\epsilon^i(\theta) \quad = \quad \gamma^i_G(\theta) + \gamma^i_I(\theta) + \epsilon^i_{rnd}(\theta).$$

- Random ellipticity not an issue
- Instrumental & astrophysical “contaminants” introduce systematic shear calibration uncertainties
- Correlated contaminant need to be modeled and disentangled from cosmological shear
  - E.g. Intrinsic galactic alignments



Credit: Williamson, Oluseyi, Roe 2007

Cosmo+Intrinsic shear (anti) correlation

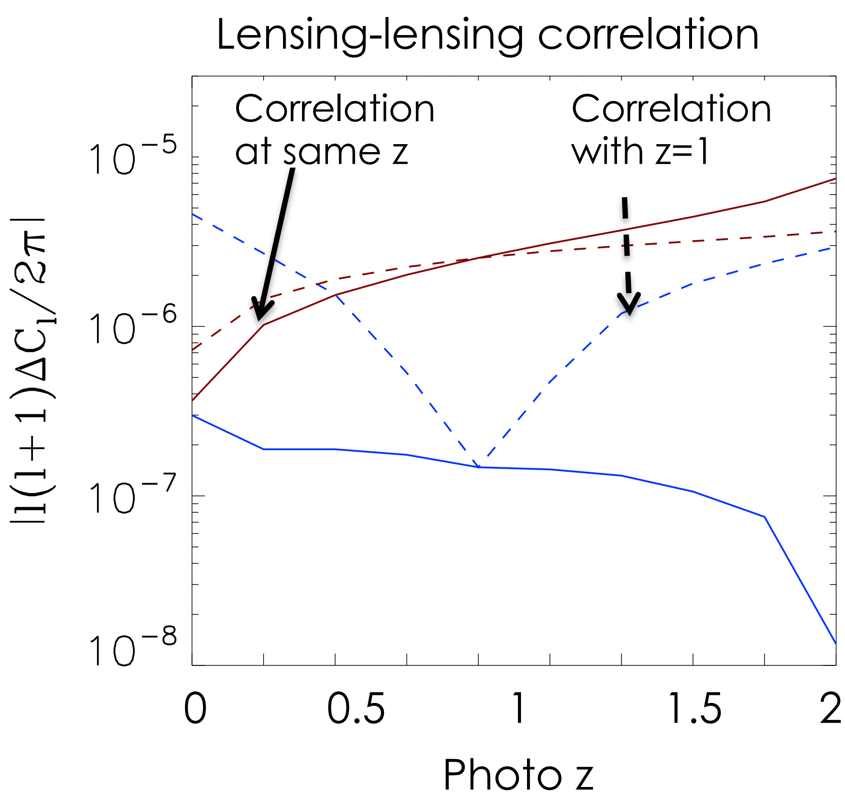


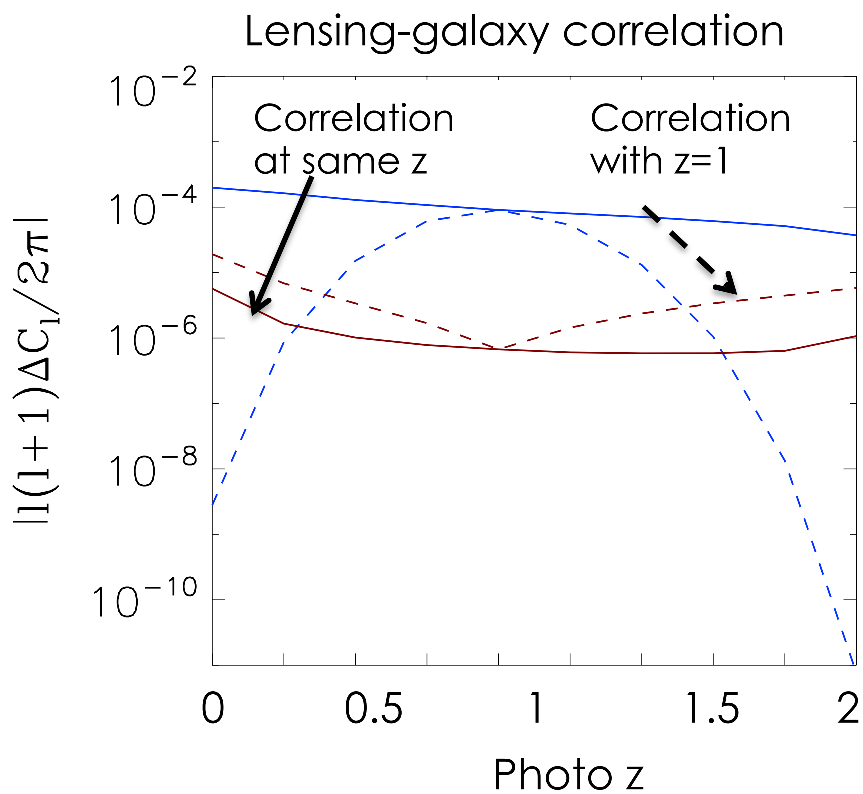
Credit: Benjamin Joachimi, iCosmo

Cross- correlations and tomography

- Use difference in redshift signatures to break degeneracy between systematics and dark energy theory

Differences between LCDM + sys errors vs no sys and MG vs LCDM for lensing and galaxy





Laszlo, Bean, Kirk, Bridle, MNRAS 2012

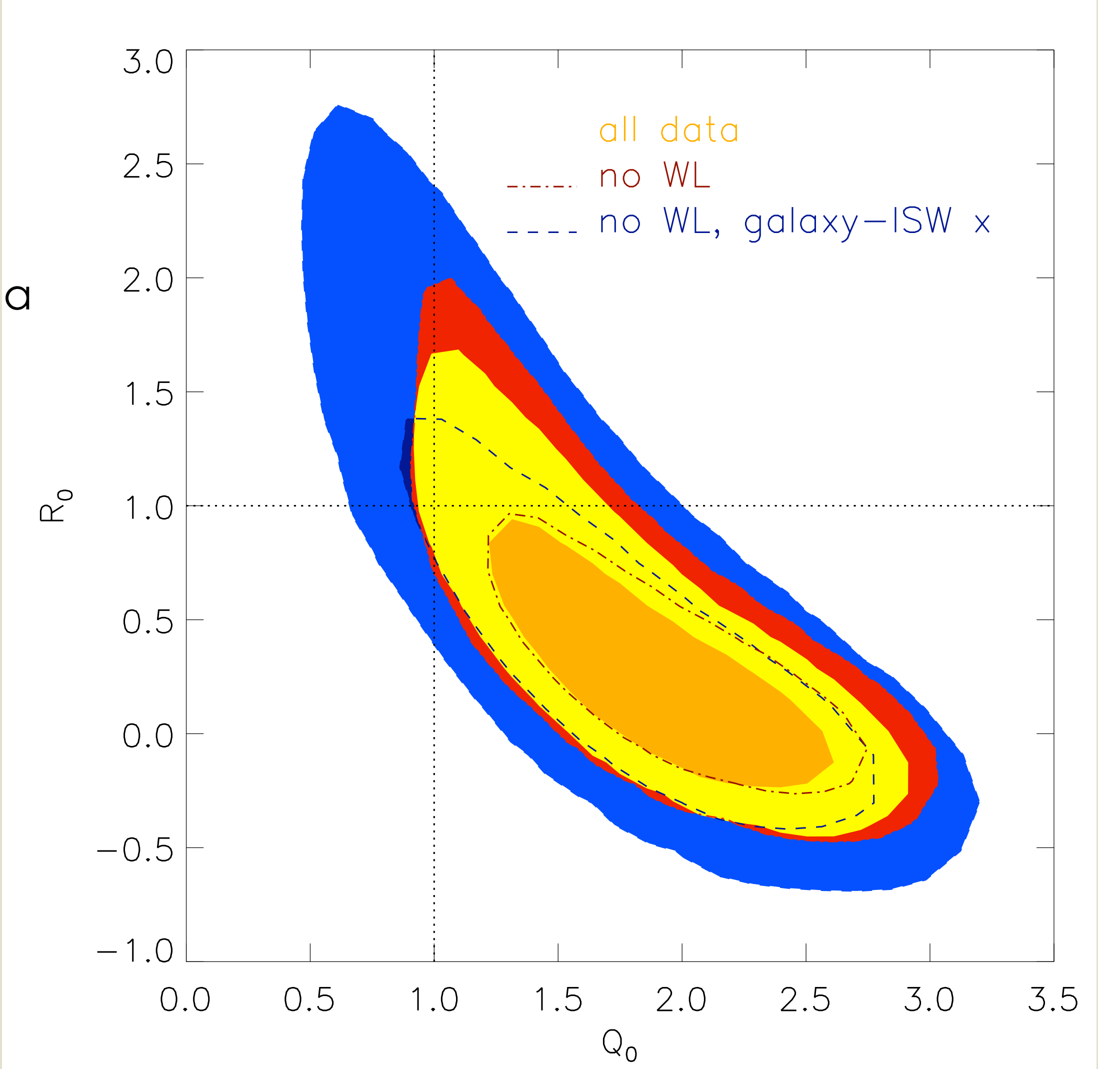
Current constraints

- Multiple data
  WMAP CMB, SDSS LRG auto ,
  SDSS-WMAP cross correlation,
  COSMOS weak lensing, Union SN1a

- CMB-galaxy correlations
  give best constraints

- Worst constraint from lensing +CMB
  - $(\phi+\psi)$direction ~Q(1+R)/2

- "Figure of Merit"
  - 1/error ellipse area
  - MG FoM ~ 0.03



Bean & Tangmatitham PRD 2010

What about future surveys?

- Fisher matrix analysis = Inverse covariance (error) matrix

$$Cov_{ij}^{-1} = F_{ij} = \frac{\partial t_a}{\partial p_i} Cov_{ab}^{-1} \frac{\partial t_b}{\partial p_j}$$

- Assumed cosmology and parameterization

$$\mathbf{p} = \{\Omega_b h^2, \Omega_m h^2, \Omega_k, \tau, w_0, w_a, Q_0, Q_0(1+R_0)/2, n_s, \Delta^2_{\mathcal{R}}(k_0), \\ +\text{systematic nuisance parameters}\}$$

- Datasets

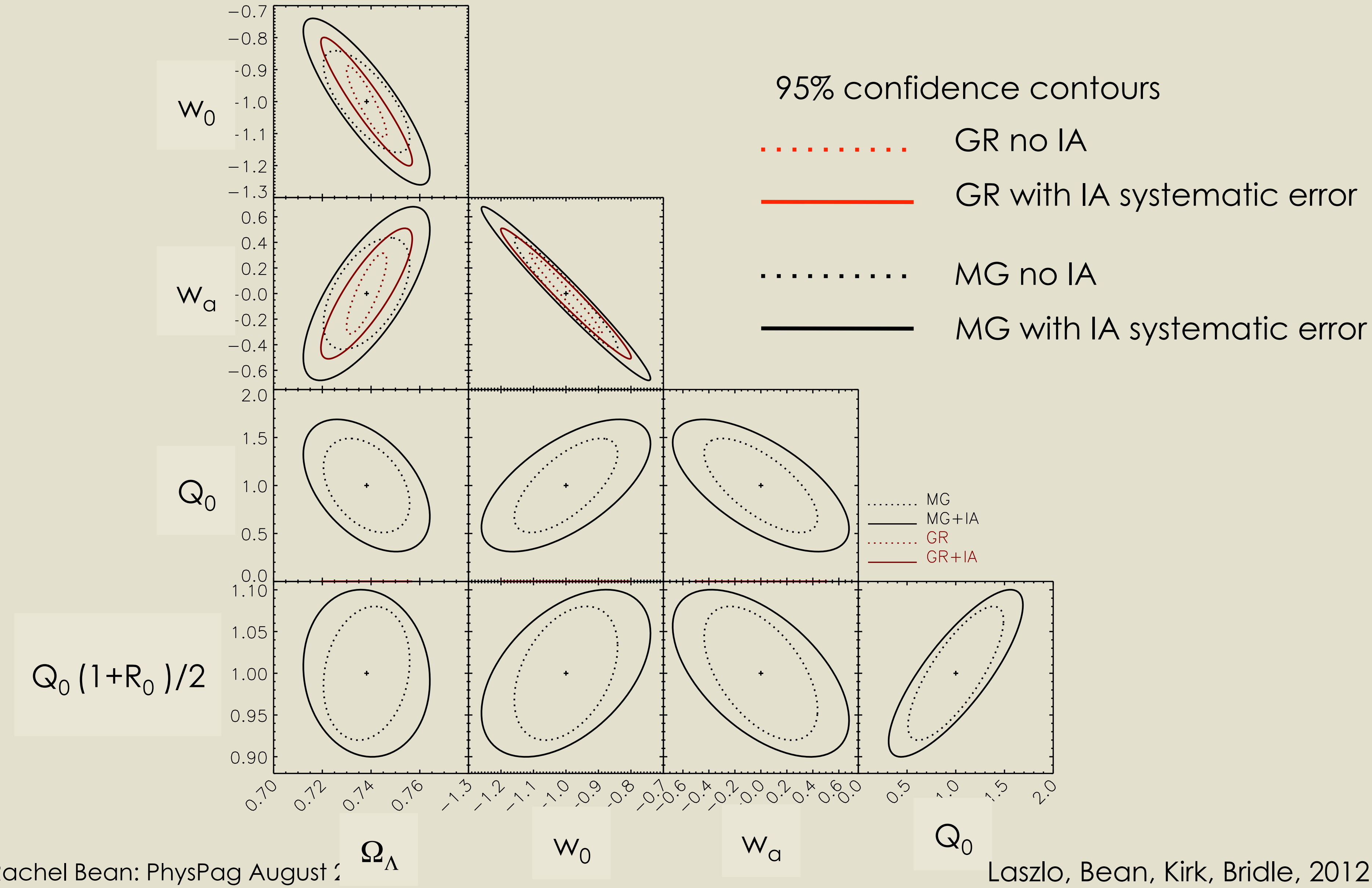
$$\mathbf{t} = \{C_\ell^{TT}, C_\ell^{TE}, C_\ell^{EE}, C_\ell^{Tg_1}, ..., C_\ell^{Eg_1}, ...C_\ell^{g_1 g_1}, C_\ell^{g_1 g_2}, ..., C_\ell^{\kappa_{N_{ph}} \kappa_{N_{ph}}}\}$$

- Survey specifications
  - near future (stage III) and end of decade (stage IV) surveys
  - Stage III = Planck CMB + DES-like imaging + BOSS spectroscopic surveys
  - Stage IV = Planck CMB + EUCLID-like imaging and spectroscopy

Forecasting: what you put in=what you get out

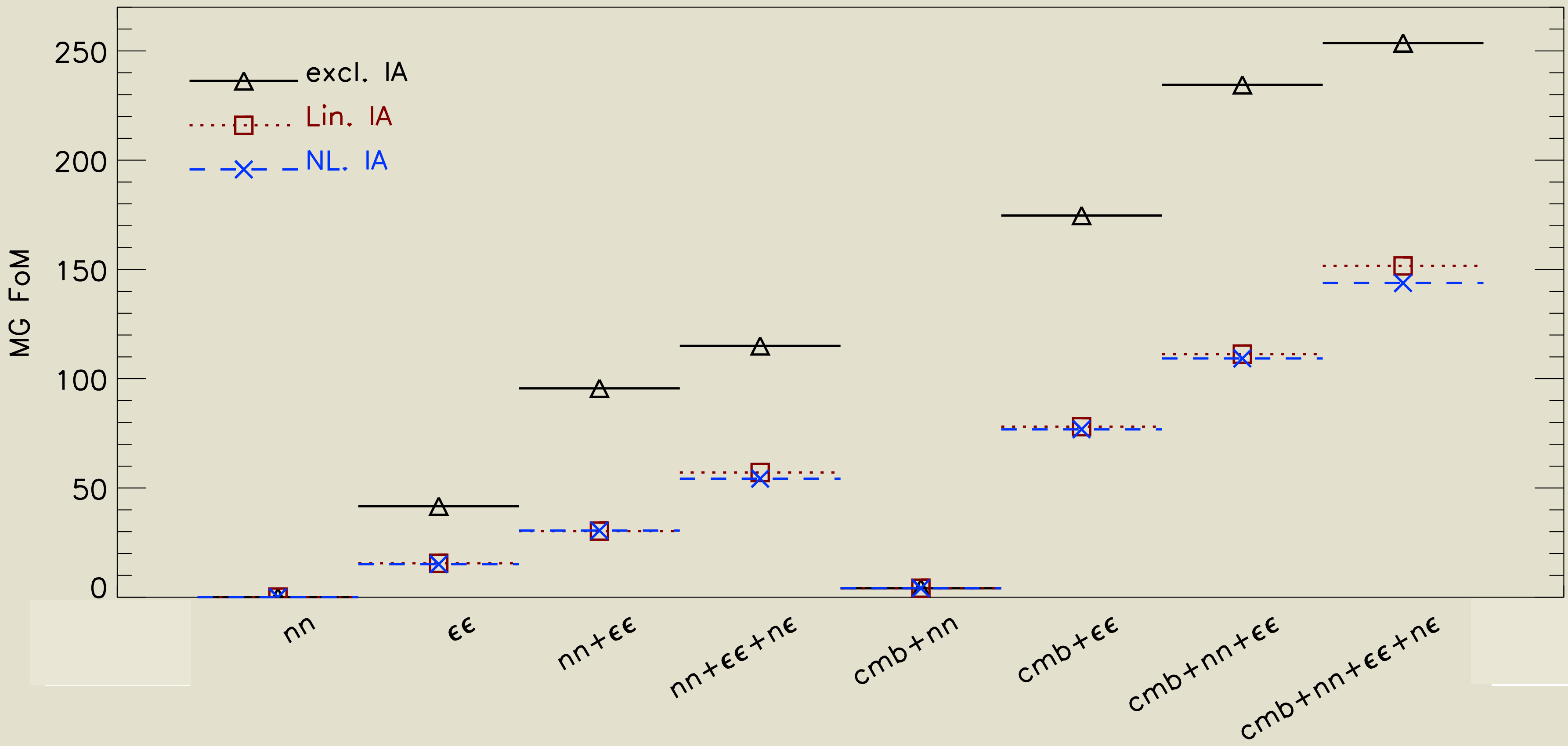
- Figures of merit /Fisher insightful but
- Model dependent – e.g. w0/wa or functions of z?
- Systematic errors difficult but important!
  - Instrumental e.g. calibration uncertainties
    - Internal cross-checks: inter-filter, concurrent & repetition ≠ redundancy
  - Modeling: e.g. Photo z modeling errors, nonlinearity
    - Access to ground based facilities,
    - Training sets, simulation suites
  - Astrophysical: e.g. IAs , Hα z distribution, galaxy bias, baryonic effects
    - At what scale should one truncate the analysis?
    - Analytical modeling, gridded k& z bins, simulations?
- Buyer beware!
  - risky to compare FoM unless apples-for-apples treatment

Sensitivity to theory and systematics



Laszlo, Bean, Kirk, Bridle, 2012

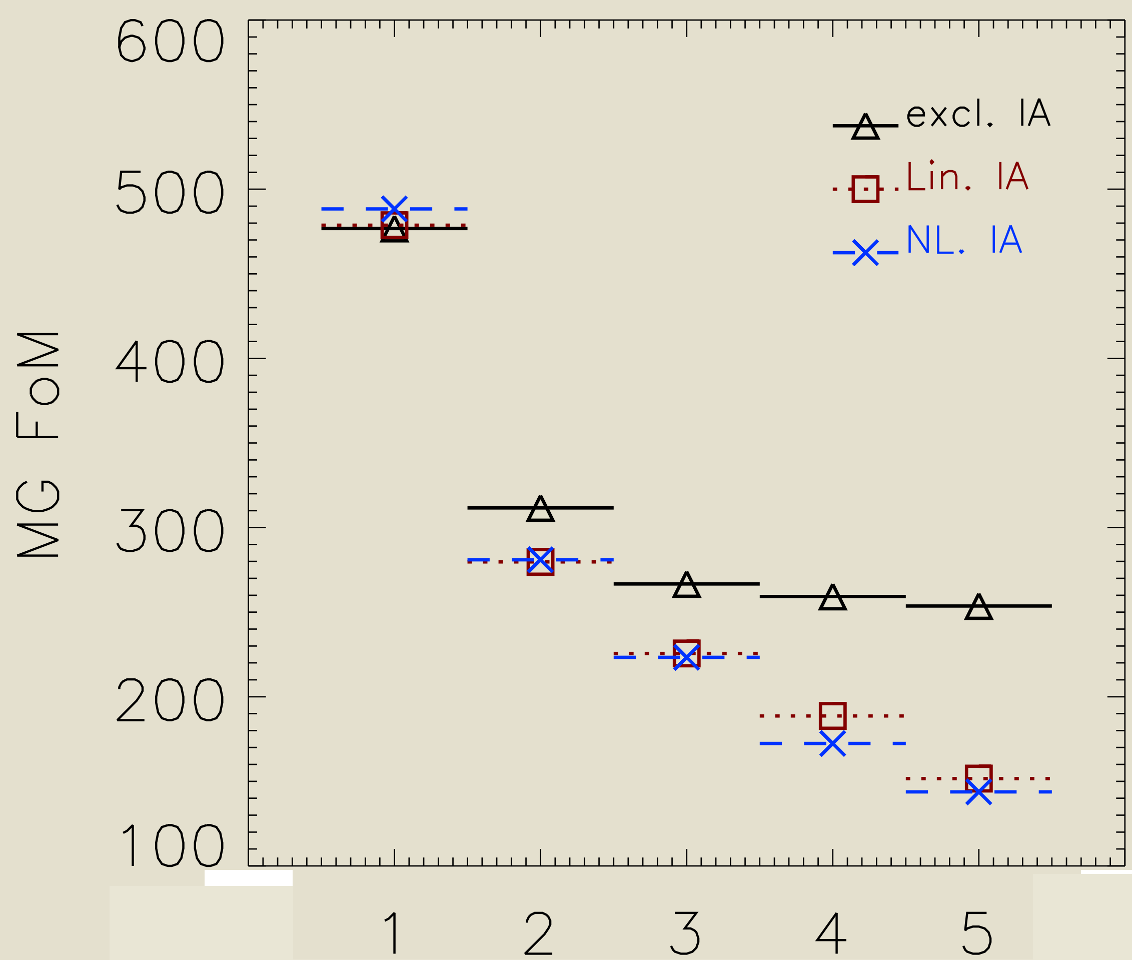
Impact of cross-correlations: reducing systematics, breaking theory degeneracies



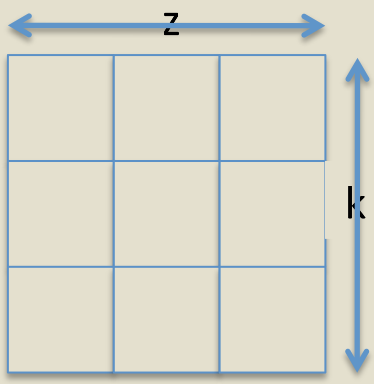
Rachel Bean: PhysPag August 2012

Laszlo, Bean, Kirk, Bridle, MNRAS 2012

Our level of understanding about bias and IA is important

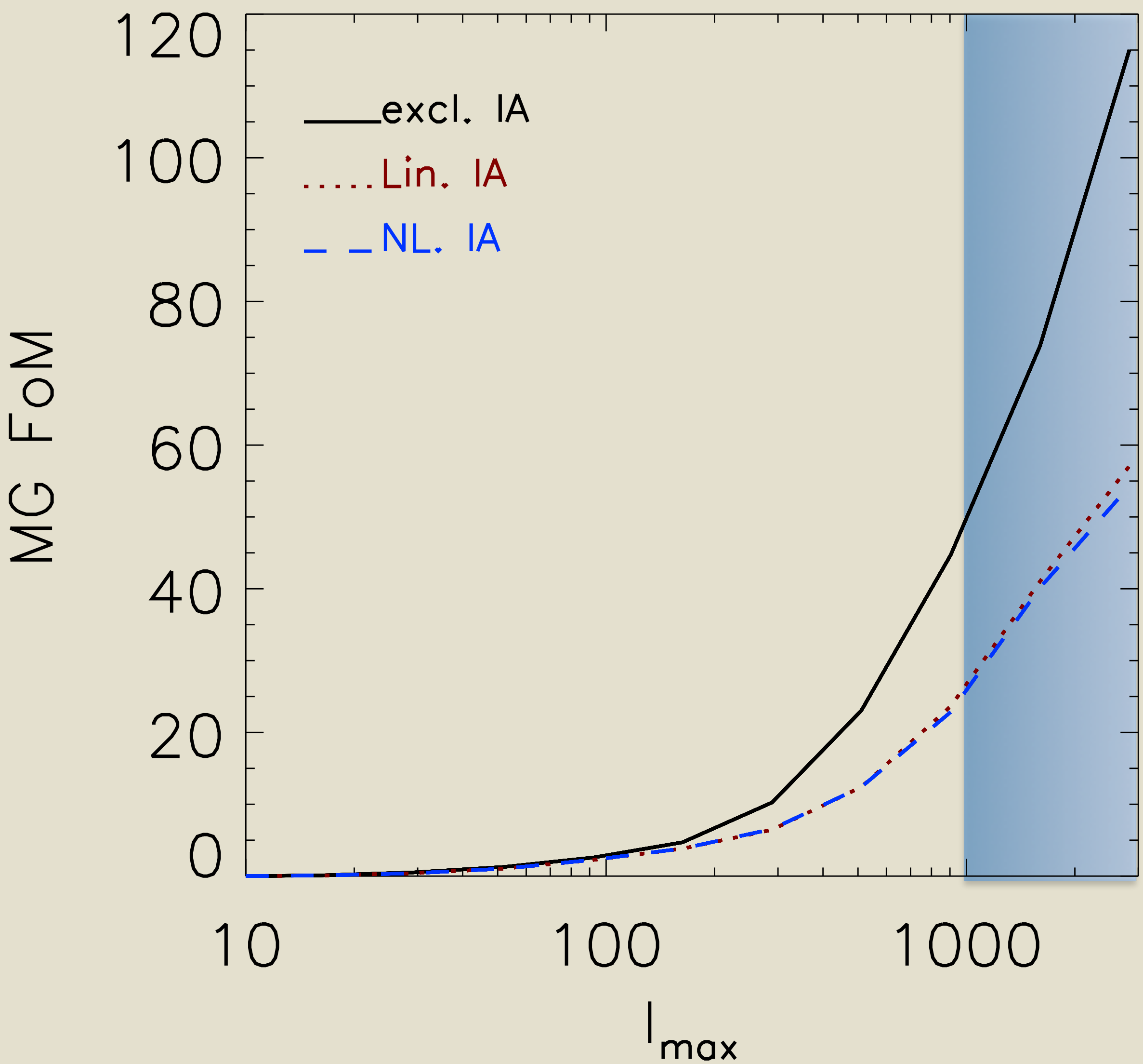


Number of k and z bins for bias
& IA nuisance parameters



Laszlo, Bean, Kirk, Bridle, MNRAS 2012

If you understand non-linear scales they could make a big difference



On scales <~ a few Mpc

- Baryonic effects?
- Non-linear modeling?
- Screening effects?

Include small scale modeling uncertainties in forecasts.

Laszlo, Bean, Kirk, Bridle, MNRAS 2012

Concluding thoughts

- Invaluable opportunity to test the origins of cosmic acceleration and weak field gravity on cosmic scales
  - Theoretical developments, fast evolving.
  - General effective field theory for DE a useful phenomenological approach, with interesting implications for both expansion history and growth history

- Multiple, complementary astrophysical tracers key to finding DE origin
  - geometric techniques important record of expansion history
  - relativistic & non-relativistic LSS tracers distinguish gravity's properties
  - Surveys will give us information across z and from horizon to sub-halo scales

- Honest assessment of systematics essential
  - Theory and systematics can be tightly coupled.
  - Can significantly impact predictions (beware apples vs oranges)
  - Survey and algorithm development + x-corr key to mitigate these.

- FoMs useful but a high pass filter on data. Mapping to the underlying theory is the ultimate goal.