Disentangling cosmological signatures from weak lensing systematics

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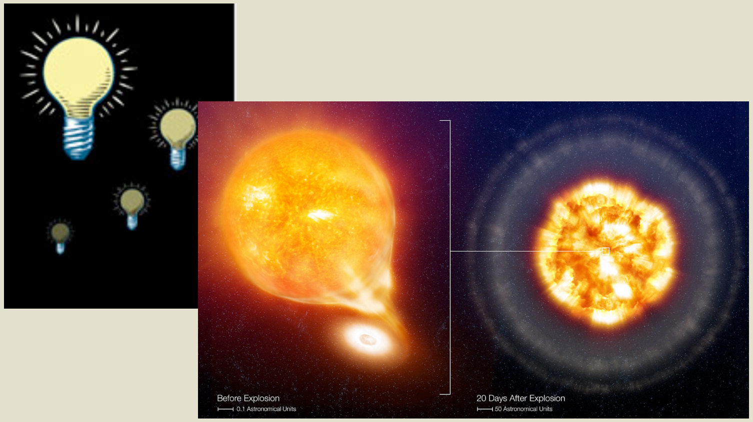
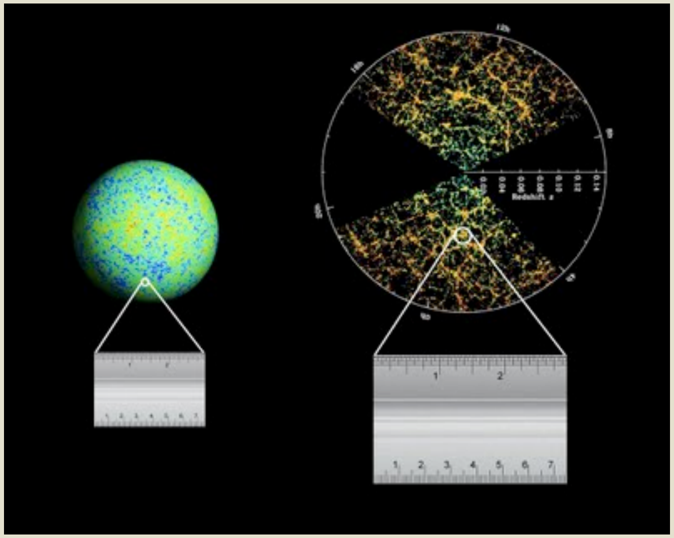
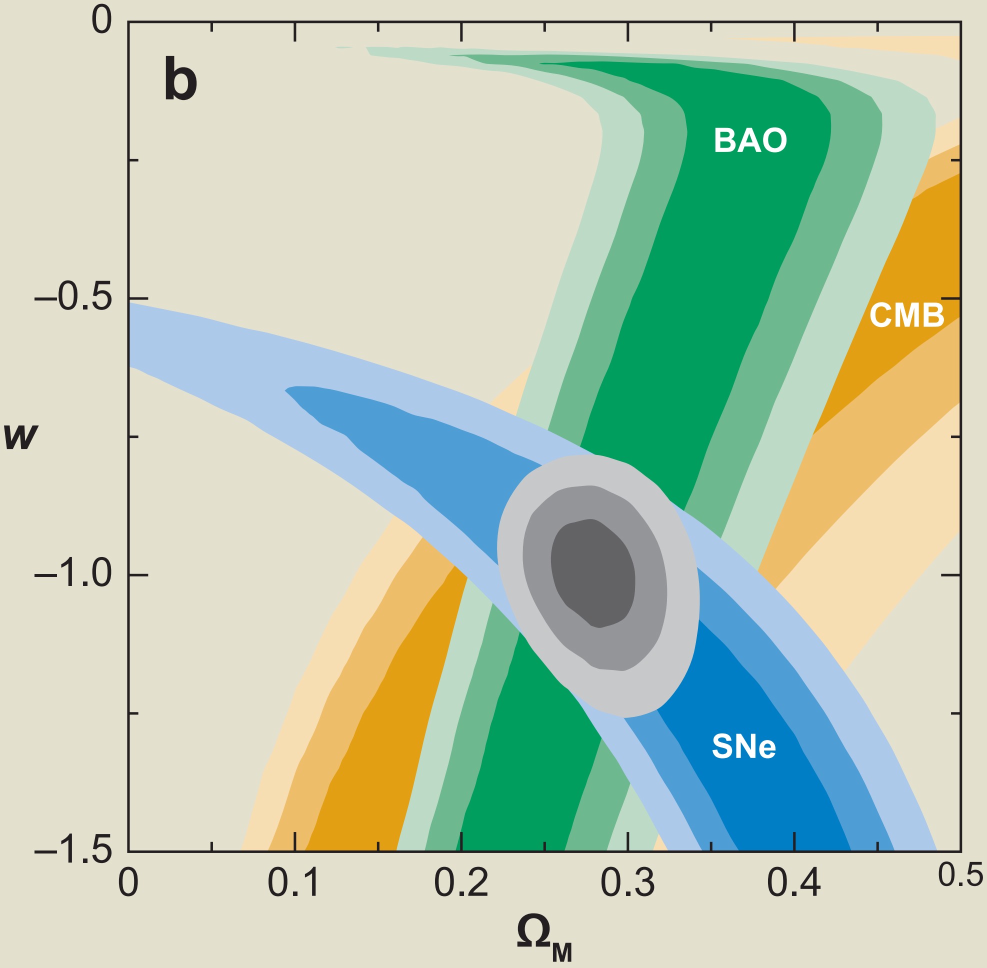
Cosmic geometry: Expansion history constraints

Standard candles



Standard rulers

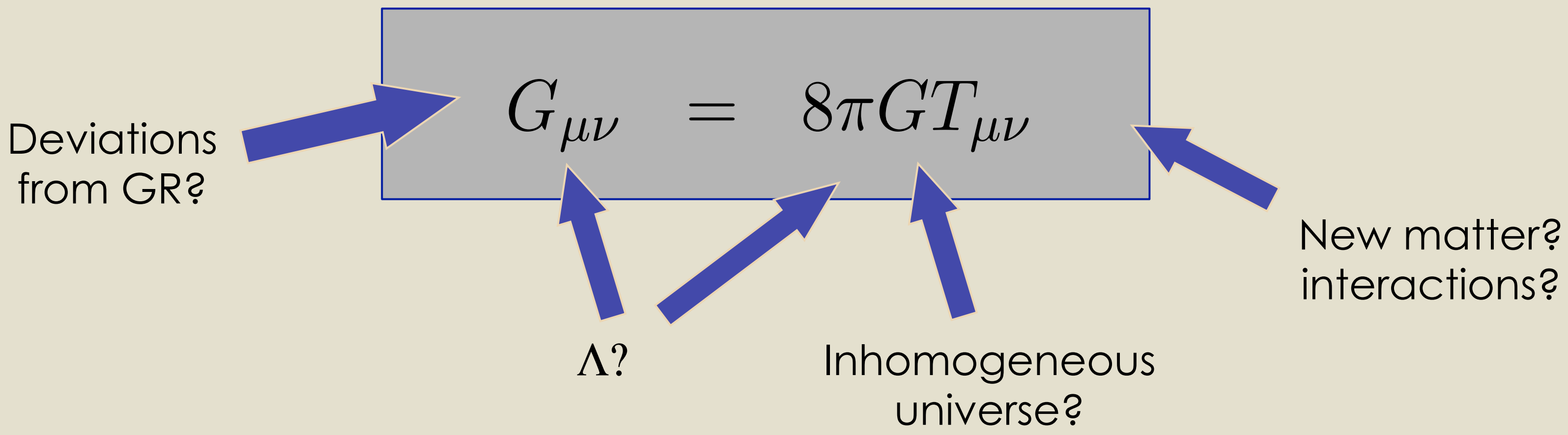




Kowalski 2008

Understanding cosmic acceleration

Cosmic acceleration = a modification of Einstein's equations



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

Deviations from GR?

Λ?

Inhomogeneous universe?

New matter? interactions?

Broad aim = Distinguish which sector:
modified gravity, Λ or a new type of matter?

How might we modify gravity?

- Active area of research, many different options, no solutions (yet)
- 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

$$S = \int d^5x\sqrt{-g^{(5)}}\frac{1}{16\pi G^{(5)}}R^{(5)}$$

Modifications to GR

- Alter Friedmann and acceleration equations at late times

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

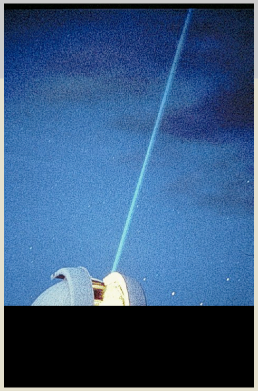
e.g. f(R) gravity

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

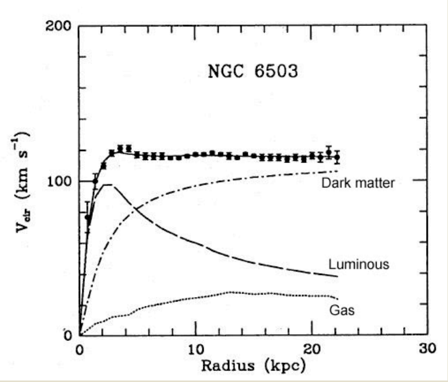
e.g. DGP gravity

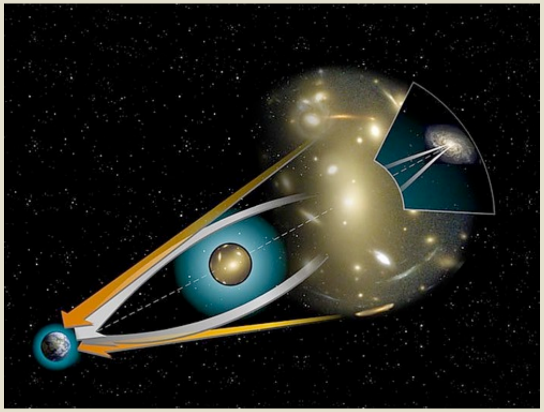
$$-\frac{\dot{H}}{r_c} + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

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
  - Late times: comparing lensing, peculiar velocity, galaxy position, ISW correlations
  - Early times: BBN, CMB peaks





The inhomogeneous universe: Metric and Matter

- Perturbed metric $ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)dx^2$
- Modified Einstein's equations relate matter and metric perturbations
  - Poisson equation: How space responds to to local density

$$k^2\phi \quad = \quad -4\pi G a^2 \sum_j \rho_j \Delta_j$$

  - Relate two potentials

$$k^2\psi = k^2\phi - shear\ stresses$$

Typically shear negligible at late times $\phi \approx \psi$

Changing the relationship between ϕ and ψ

- 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 energy?) perturbations, or modified dark matter evolution

- An inequality between Newton's potentials, R

$$\psi = R\phi$$

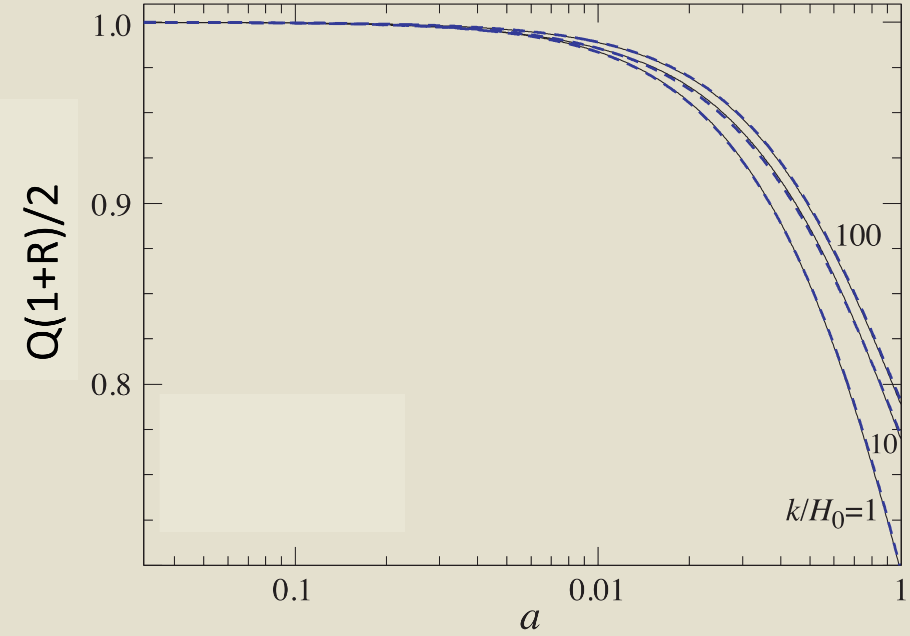
R≠1: not easily mimicked.

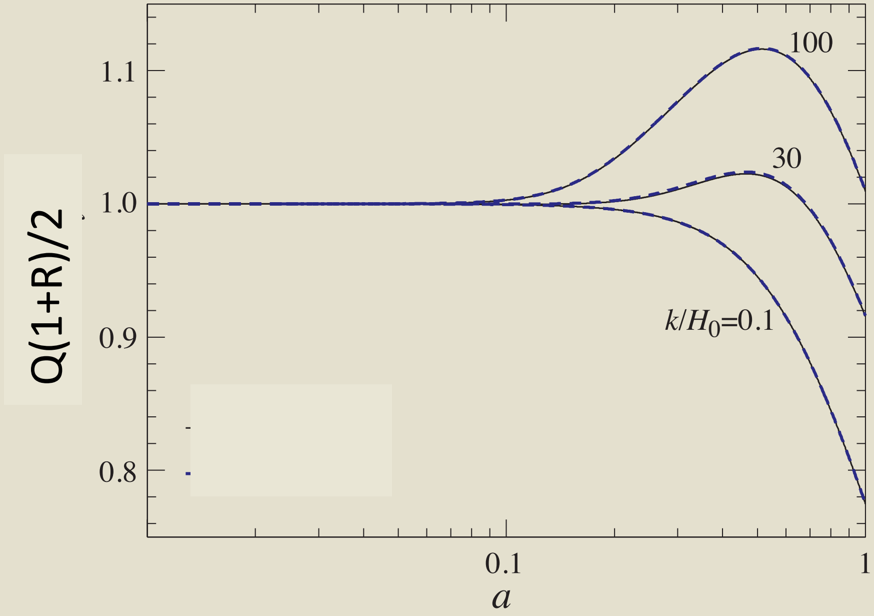
- potential smoking gun for modified gravity?
- Significant stresses exceptionally hard to create in non-relativistic fluids e.g. DM and dark energy.

A modified growth model – Theoretical examples

- DGP: Scale independent modifications

Eric's G_{light}/G





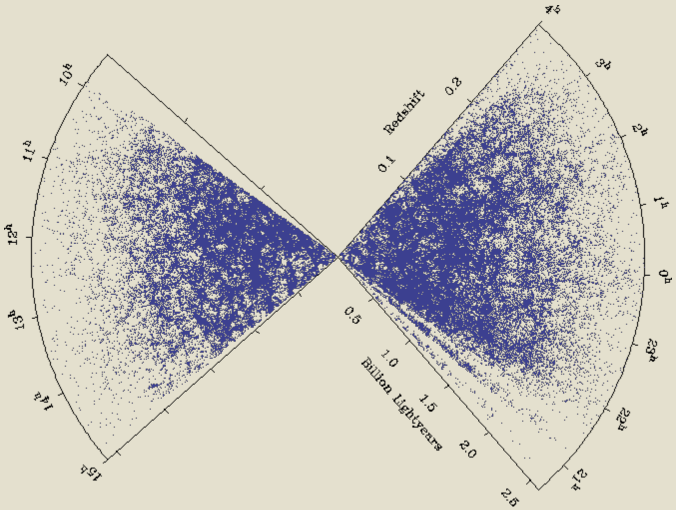
- f(R) gravity : scale dependent modifications

Hu and Sawicki '07

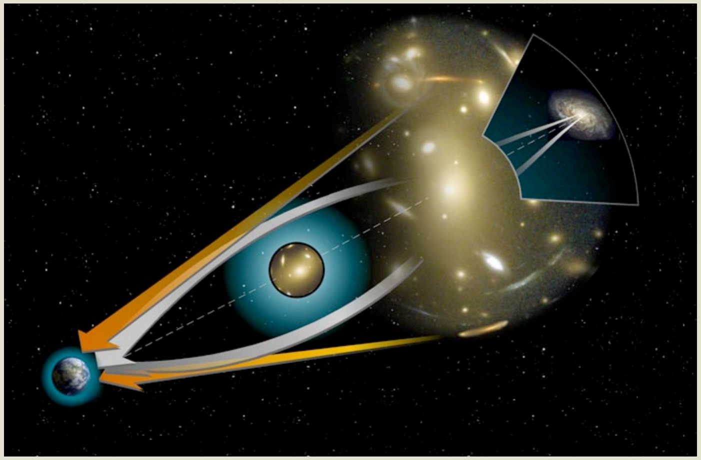
Tying theory to observations

- Galaxy positions and motions
  - trace non-relativistic matter
  - Measure $\psi \sim QR$
  - Biasing of tracer (galaxy) issue

$$\delta_g = b\delta_m$$



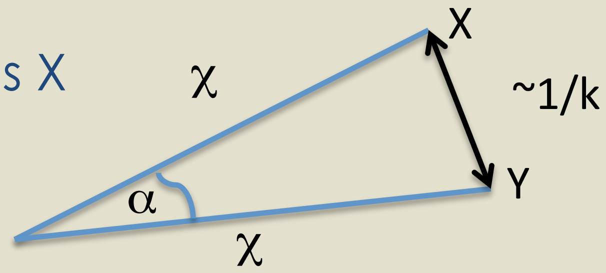
- Weak lensing and CMB
  - trace relavitistic (photon path)
  - Sensitive to $(\phi+\psi) \sim Q(1+R)$ and time derivs
  - No bias (but plenty of systematics…)



- Complementarity of tracers key to testing gravity

Correlating datasets

- 2-point correlation between observables X and Y = δ_g, θ, G,I, T_{CMB}



$$C_l^{X_iY_j} = \int_0^{\chi_{max}} \frac{d\chi}{\chi^2} W_X^i(\chi) W_Y^j(\chi) S_X(k_l,\chi) S_Y(k_\ell,\chi)$$

Window function
i^{th} photo-z bin

Instrument sensitivity &
expansion history

w(z), H(z)…

Source function
$k=l/\chi$

Large scale structure
growth history

Q(z), R(z)…

Putting it all in the mix

- A "smoking gun" for GR on cosmic scales (Zhang et al PRL 2007)

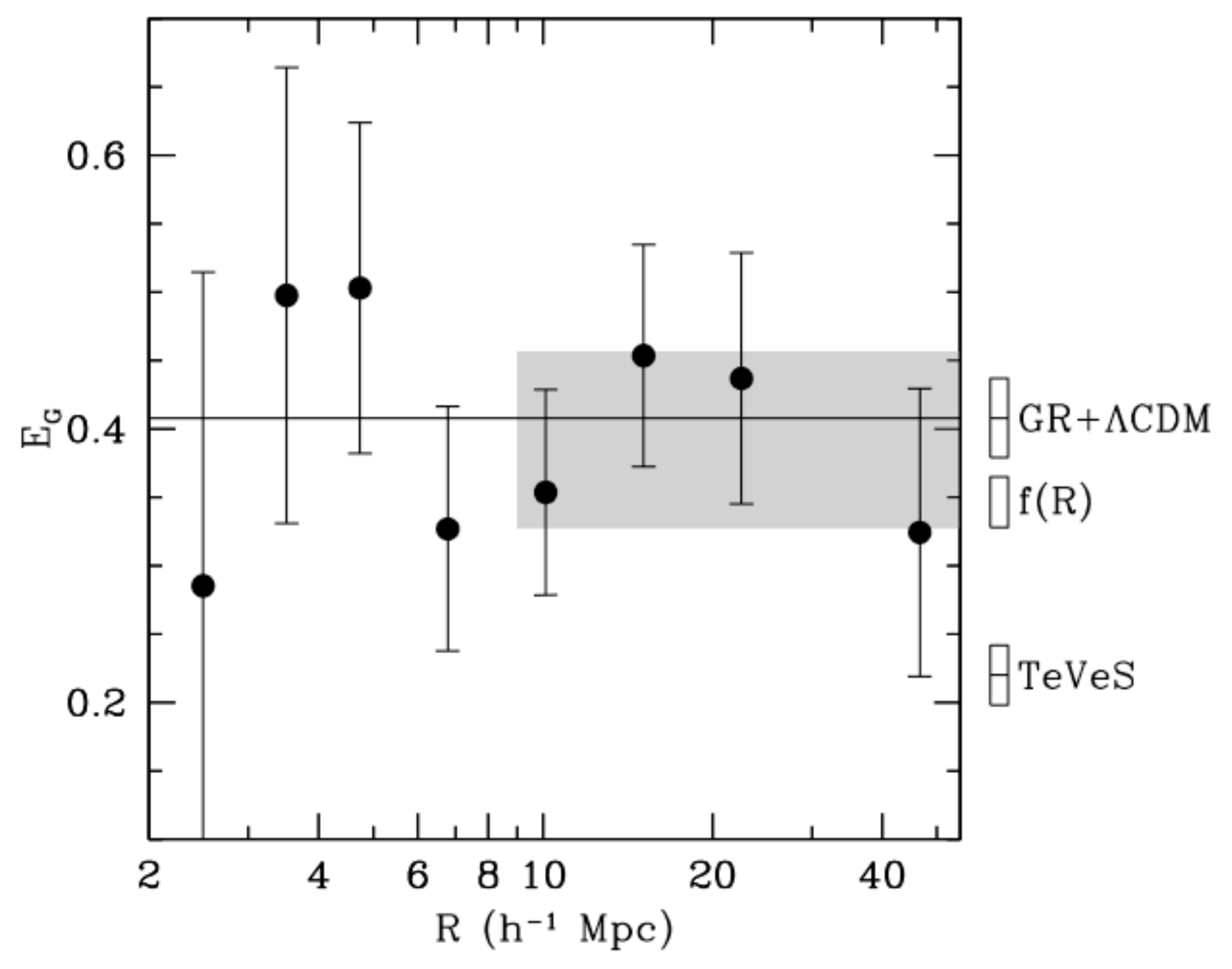
$$E_G \sim \frac{\text{galaxy position-lensing correlation } (C_l^{gG})}{\text{redshift space – galaxy position correlation } (C_l^{g\Theta})}$$

- Contrasts relativistic and non-relativistic tracers => R ≠ 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

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

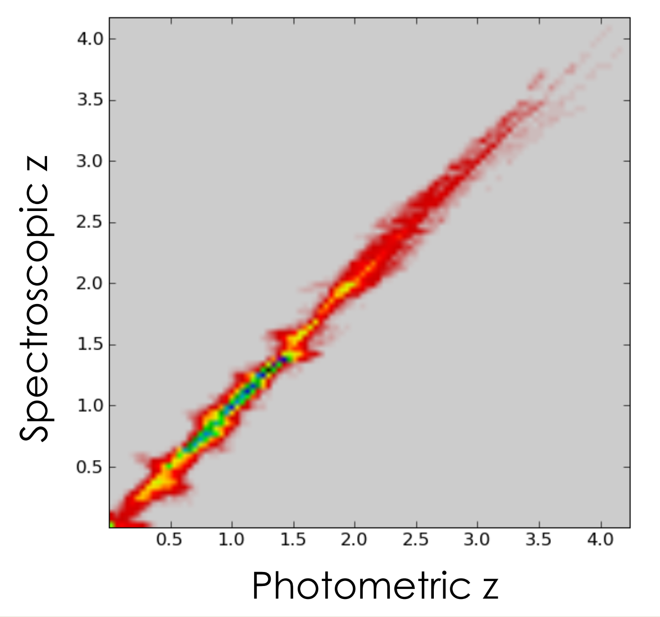
Vital proof of principle with SDSS LRG data



Reyes et al Nature 2010

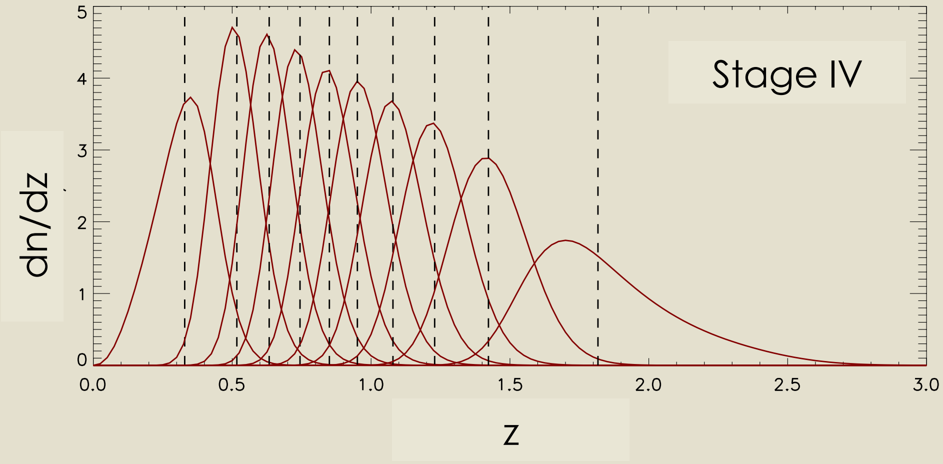
Galaxy positions

- Photometric redshifts locate galaxies in 3D (angular+redshift) space
  - Calibrate galaxy spectral energy densities (SED) – brightness vs frequency --against spectroscopic test set or templates



Credit: LSST Consortium

- Tomography
  - split galaxies into redshift bins
  - X-correlations between z bins useful for disentangling systematics and cosmology

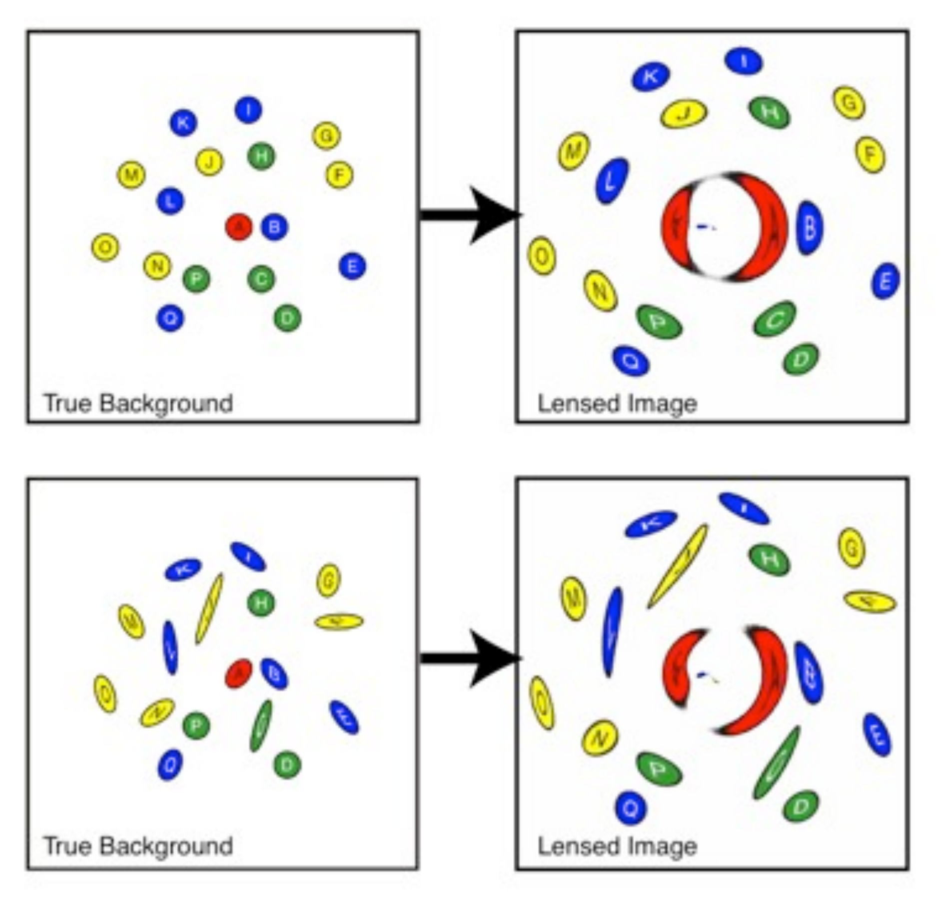


Weak lensing distortions

- 2D map on the sky of galaxy ellipticities

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

- Correlation in ellipticities measured statistically
- Random ellipticities (noise, randomly oriented galaxies) not an issue
- Correlated alignments (instrumental & astrophysical) need to be disentangled from cosmological shear



Credit: Williamson, Oluseyi, Roe 2007

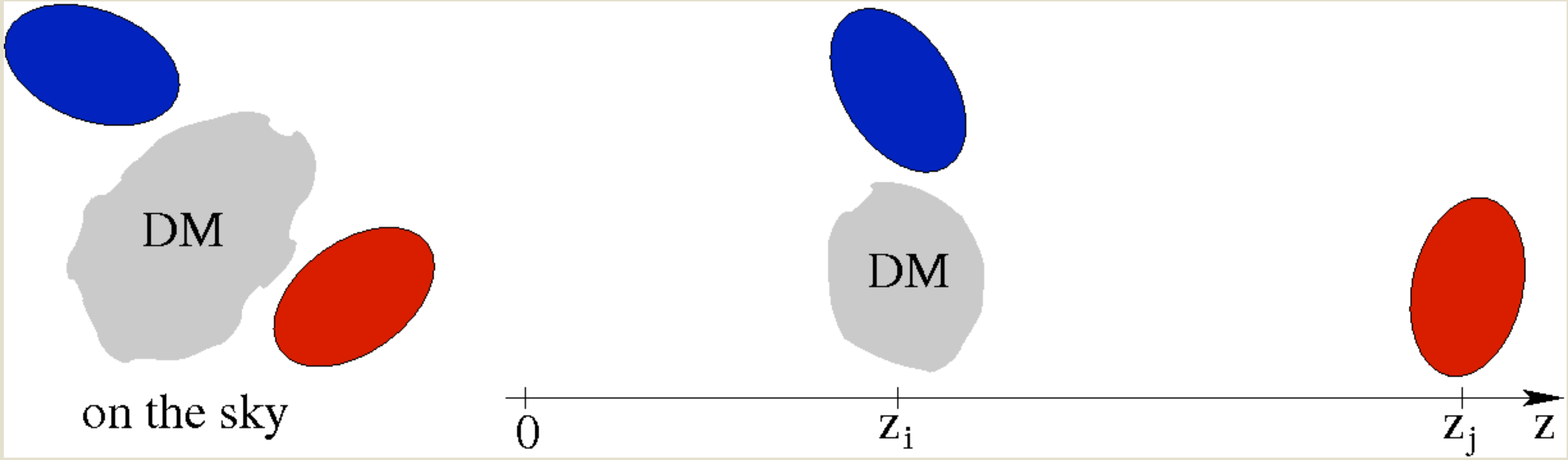
Astrophysical systematic: Intrinsic alignments

- Galaxies align in the potential gradient of their host halo

$$\langle \epsilon^i \epsilon^j \rangle = \langle \gamma_G^i \gamma_G^j \rangle + \langle \gamma_G^i \gamma_I^j \rangle + \langle \gamma_I^i \gamma_G^j \rangle + \langle \gamma_I^i \gamma_I^j \rangle$$

Correlation: Observed Cosmological (GG) Intrinsic (II)

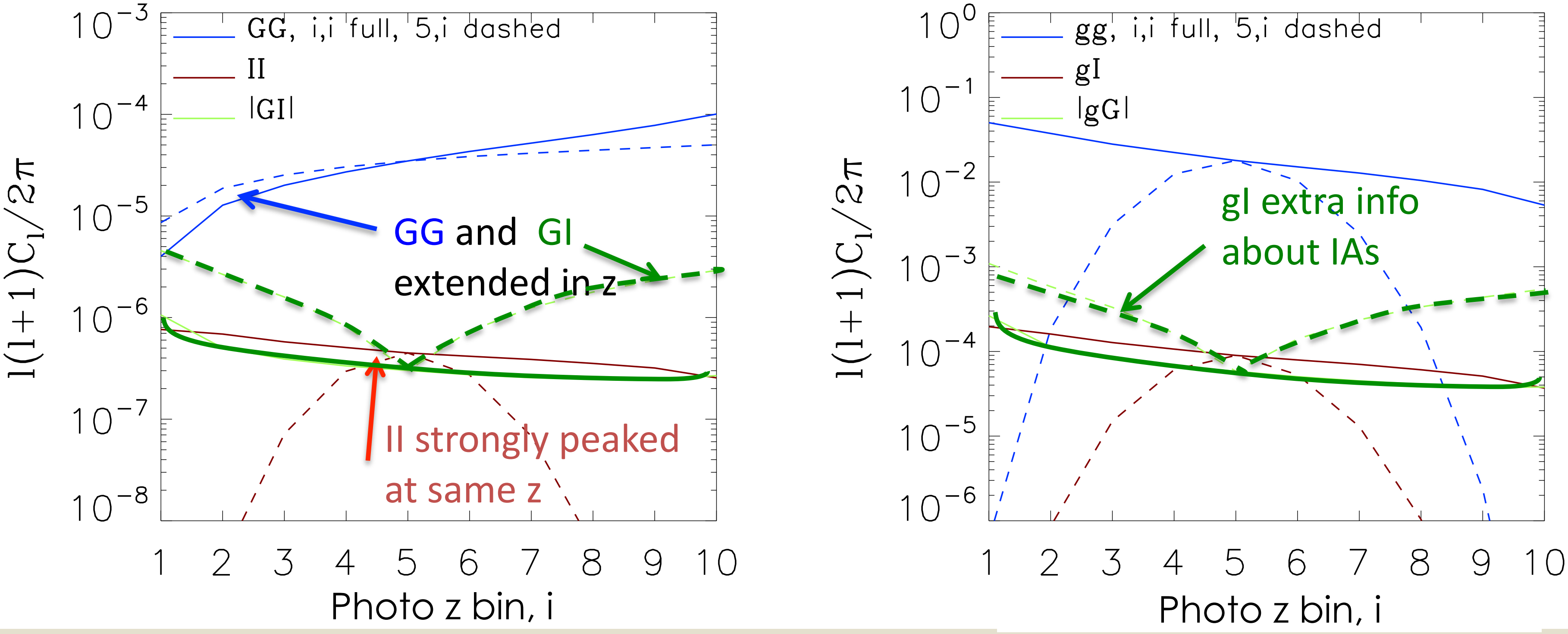
GI shear (anti) correlation



Credit: Benjamin Joachimi, iCosmo

Cross correlations and tomography help mitigate astrophysical systematics

Plots of $C_l^{X_i Y_i}$ and $C_l^{X_5 Y_i}$



GG and GI extended in z

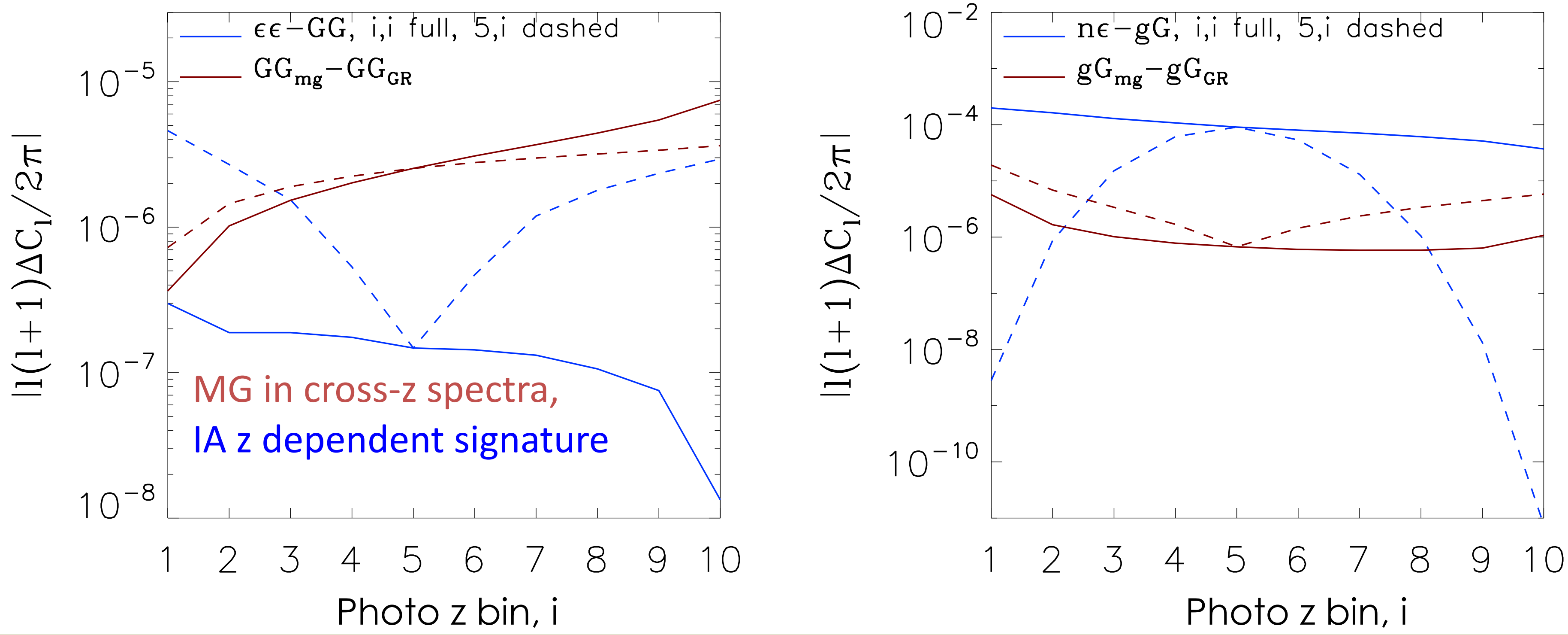
II strongly peaked at same z

gI extra info about IAs

Laszlo, RB, Kirk, Bridle, 2011

Cross- correlations can break theory degeneracies

Plots of $C_l^{X_iY_i}$ and $C_l^{X_5Y_i}$



MG in cross-z spectra,

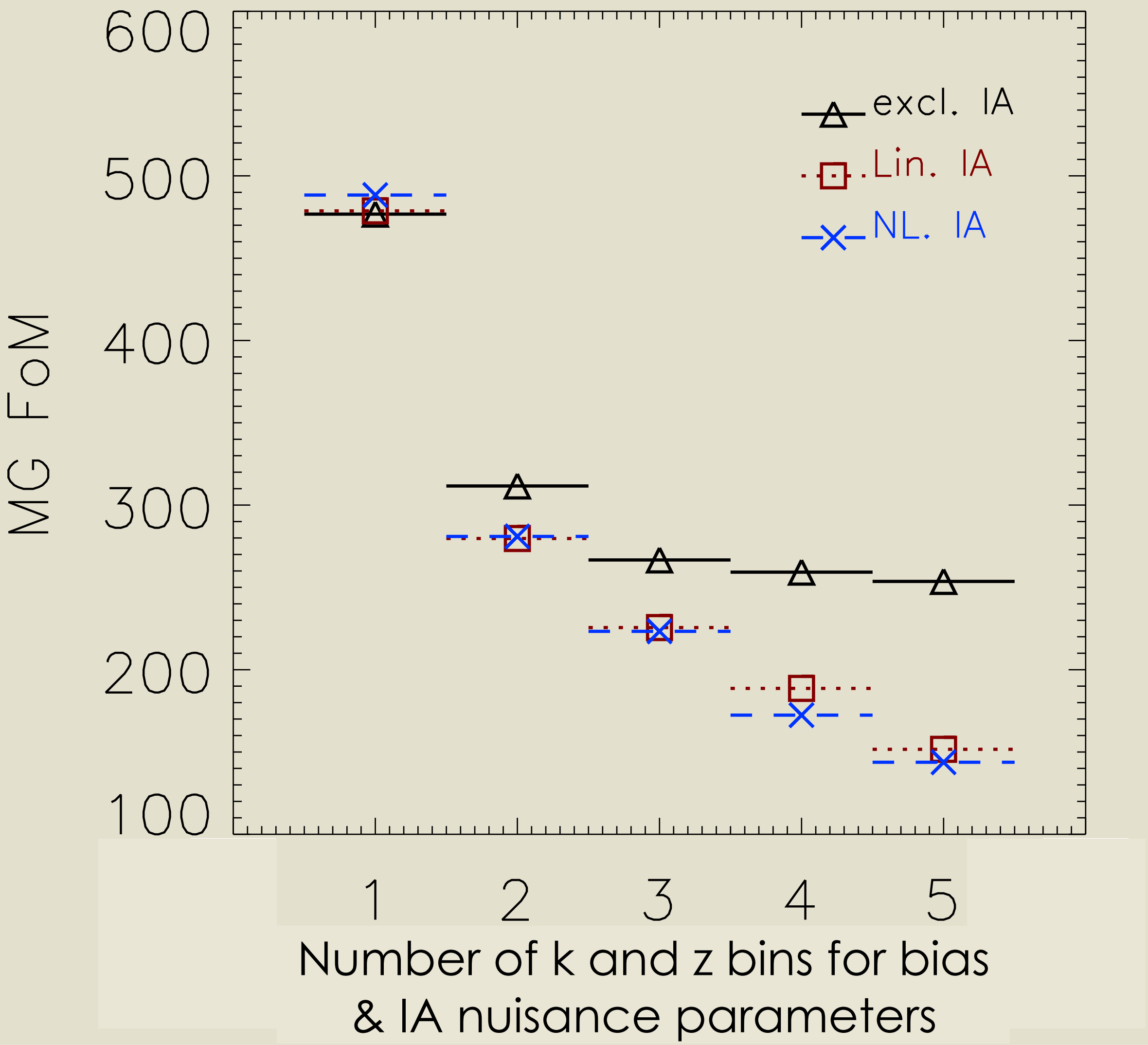
IA z dependent signature

Laszlo, RB, Kirk, Bridle, 2011

Forecasting: what you put in= what you get out

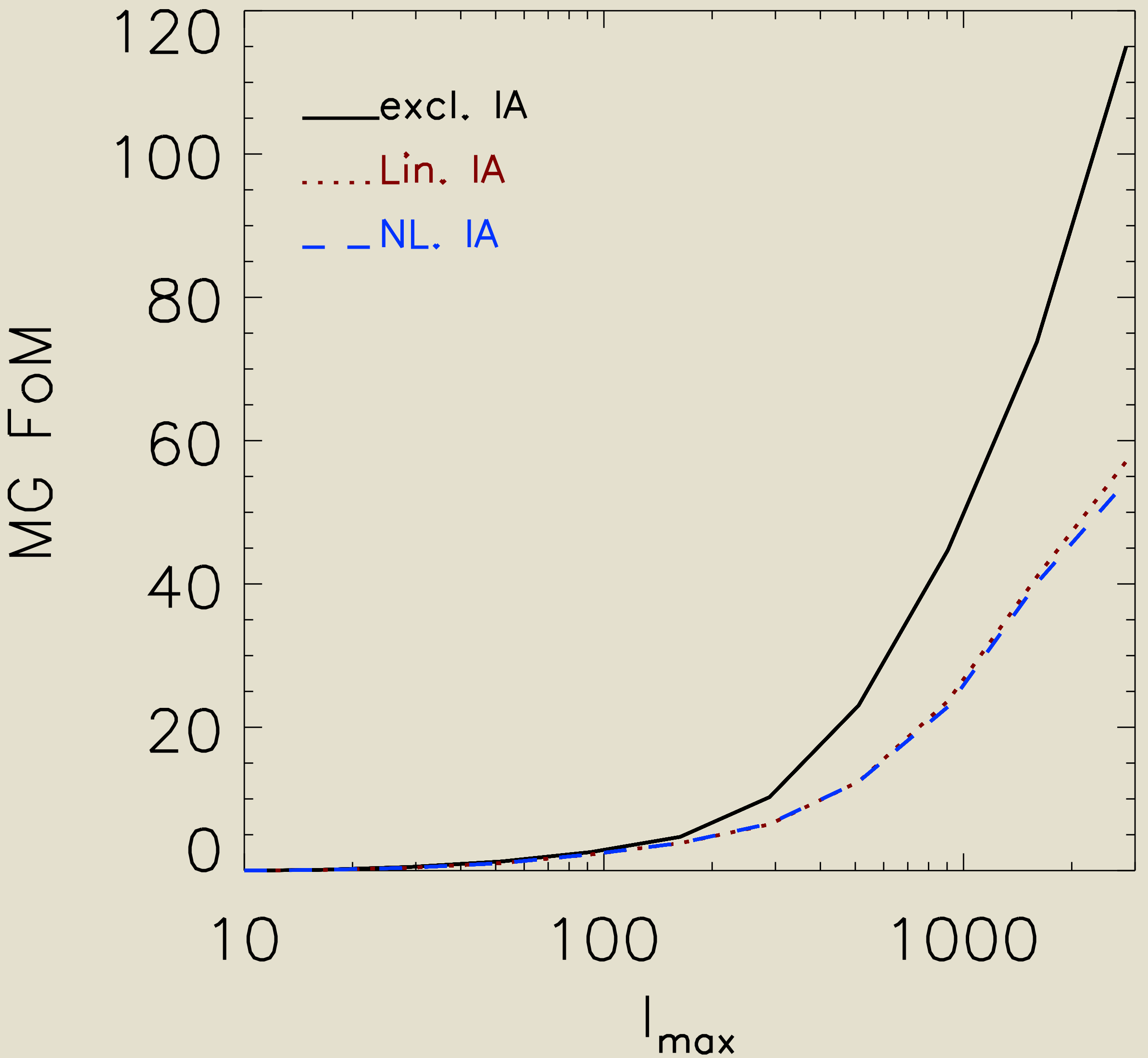
- FoM/Fisher insightful but
- Model dependent – e.g. w0/wa or functions of z?
- Systematic errors difficult but important!
  - Instrumental e.g. calibration uncertainties
    - Internal cross-checks: inter-filter, concurrent & repetition ≠ redundancy
  - Modeling: e.g. Photo z modeling errors, nonlinearity
    - 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

Assumptions about bias and IA model



Laszlo, RB, Kirk, Bridle, 2011

Assumptions about non-linear scales



Laszlo, RB, Kirk, Bridle, 2011

Cross-checks (and theory/simulations) are key to realizing tantalizing weak lensing science!

- “The WFIRST multiband approach to weak gravitational lensing is more robust than Euclid’s single very broad band, which is potentially vulnerable to galaxy color gradients. Because WFIRST measures lensing in three passbands, its data can be internally cross-correlated to help mitigate systematic measurement error. Since the WFIRST approach to weak gravitational lensing measurement appears to be more robust, it may produce better constraints on dark energy properties.”

- “Euclid’s and WFIRST’s measurements are not duplicative and the combinations will be more powerful than any single measurement. Combining WFIRST with Euclid and with ground-based data sets, such as that expected from LSST, should further enable astronomers to address the systematic challenges that previous ground-based weak gravitational lensing measurements have experienced. These combined data sets will likely overcome systematic limitations and realize the full potential of this powerful technique.”

NRC report Feb 2012