Understanding Gravity on Cosmic Scales

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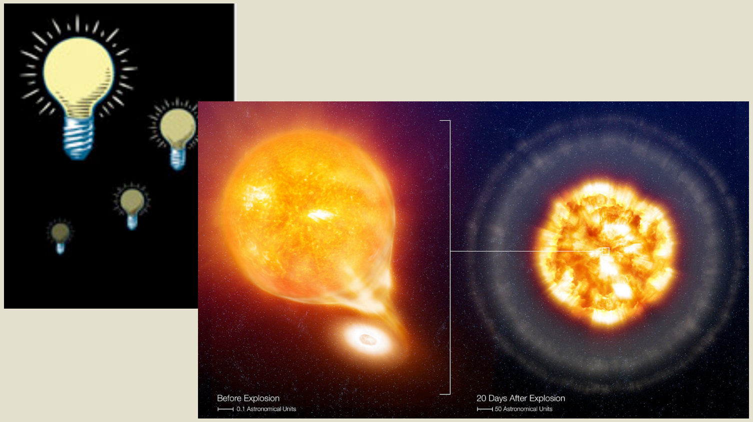
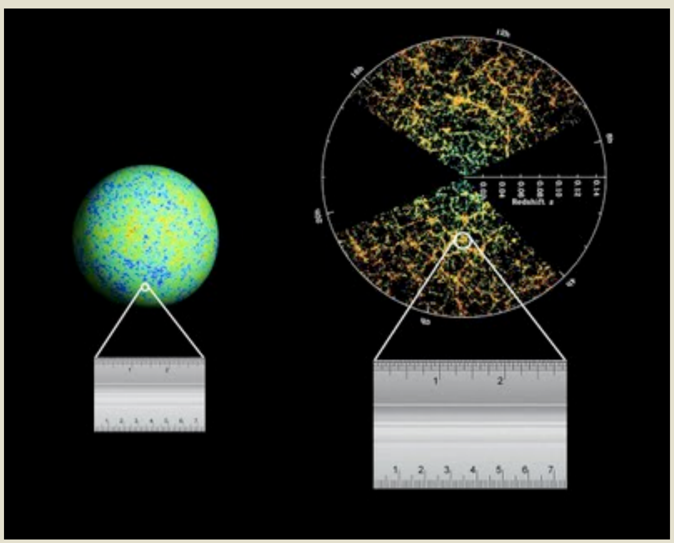
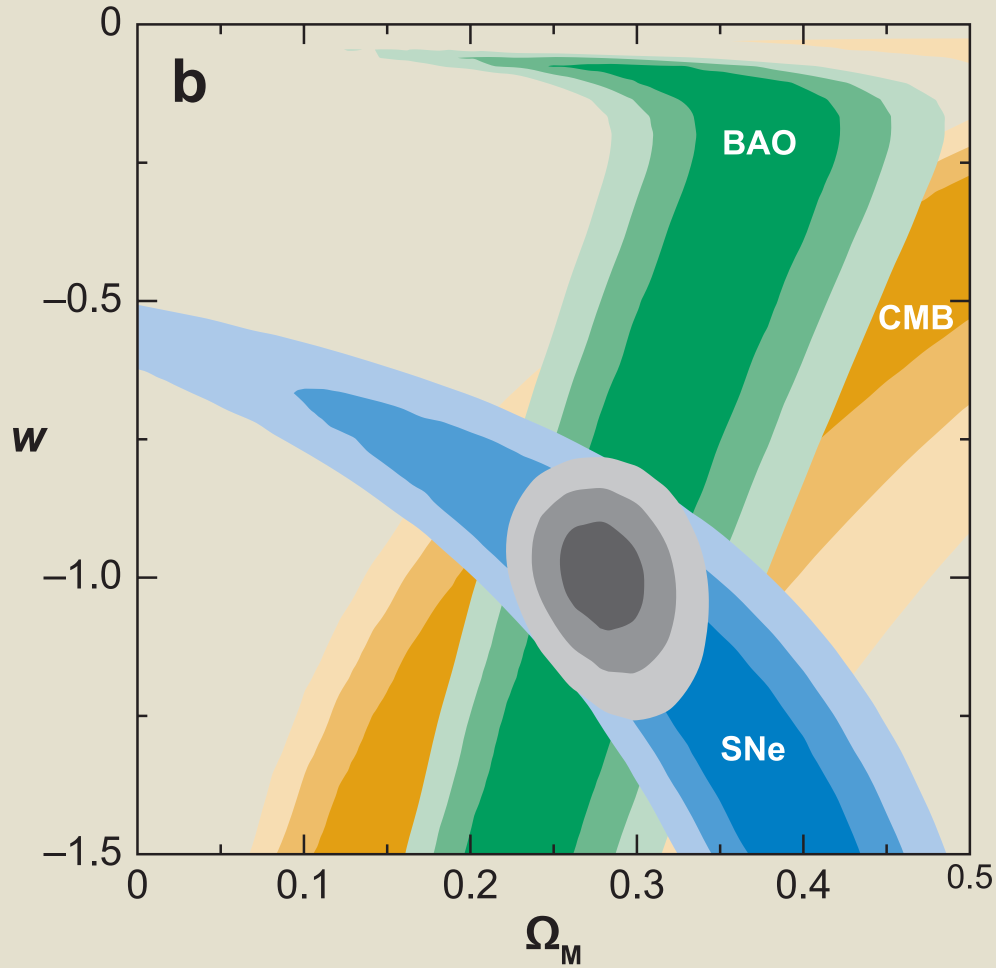
Cosmic geometry: Expansion history constraints

Standard candles



Standard rulers





Kowalski 2008

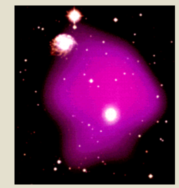
Rachel Bean: Itzykson 2012

Understanding cosmic acceleration

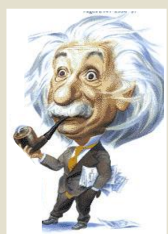
Cosmic acceleration = a modification of Einstein's equations

Deviations from GR?

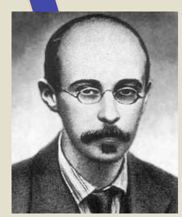
$$G_{\mu\nu} = 8\pi G T_{\mu\nu}$$



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?

Distinguishing with 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

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

e.g. f(R) gravity

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

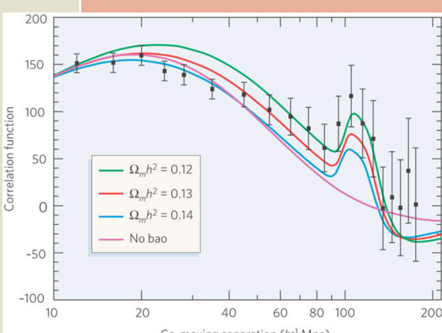
e.g. DGP gravity

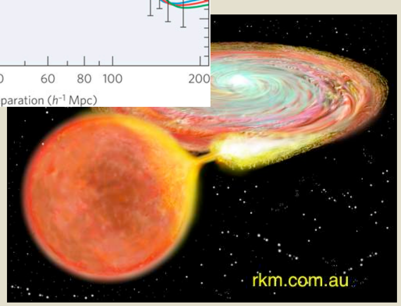
$$-\frac{\dot{H}}{r_c} + \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P)$$

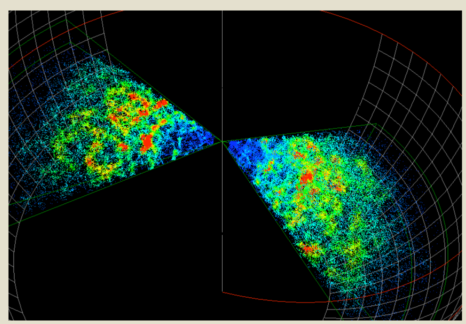
There are benefits to asking more questions…

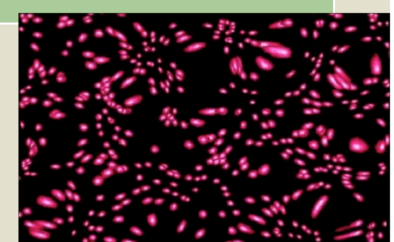
Three groups of extra galactic observations for testing gravity

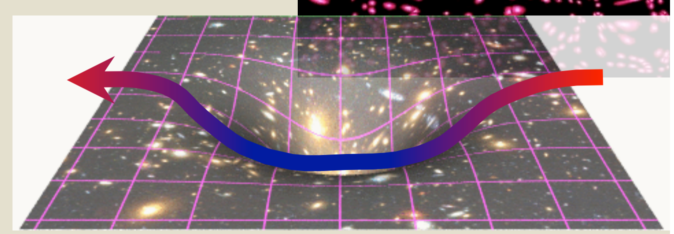
I: Background expansion	II: Growth, up to some normalization	III: Growth directly
CMB angular diameter distance Supernovae luminosity distance BAO angular/radial scale	Galaxy autocorrelations Galaxy – ISW x-corrln Xray and SZ galaxy cluster measurements Ly-alpha measurements	CMB ISW autocorrelation Weak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











Rachel Bean: Itzykson 2012

Phenomenological model of modified 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 energy?) perturbations, or modified dark matter evolution

- An inequality between Newton's potentials, R

$$\psi = R\phi$$

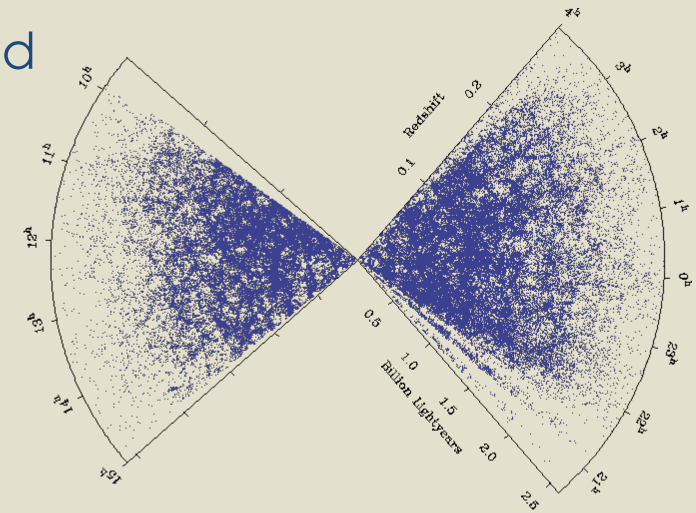
R≠1: not easily mimicked.

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

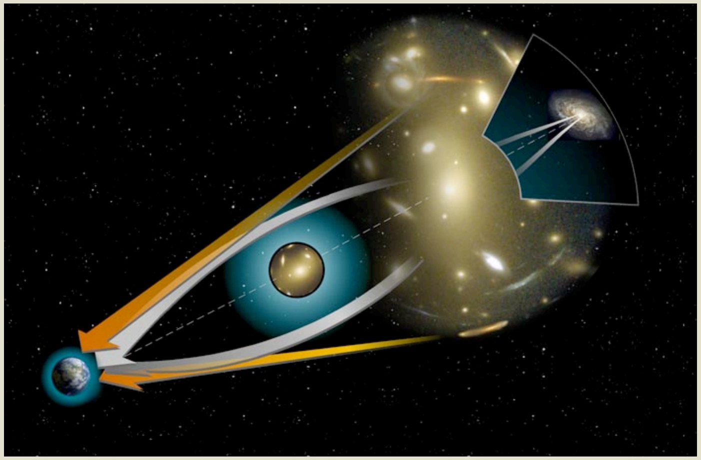
Cosmological tests of gravity

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

$$\delta_g = b\delta_m$$



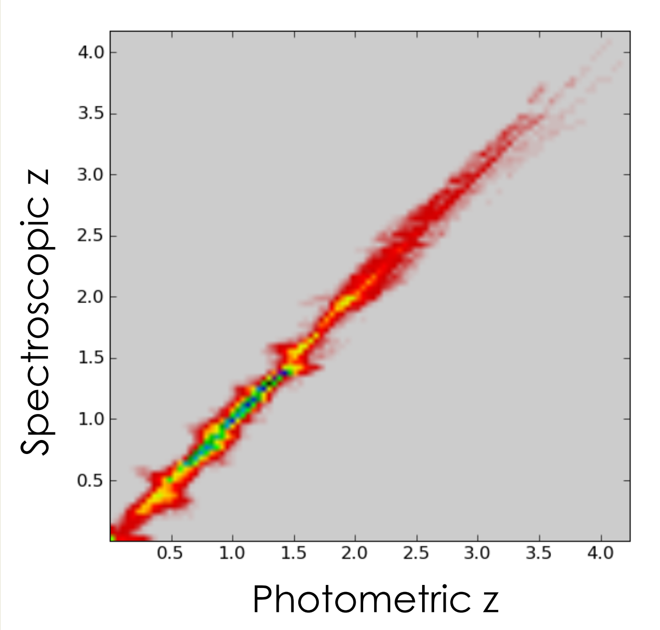
- Relativistic tracers: Weak lensing and CMB
  - Sensitive to $(\phi+\psi) \sim G_{light} = Q(1+R)G_N$ and time derivs
  - In theory direct tracer of potential, but still uncertainties
    - stochasticity relating luminous and all mass r_g Dekel & Lahav '99
    - plenty of systematics (photoz, IAs…)



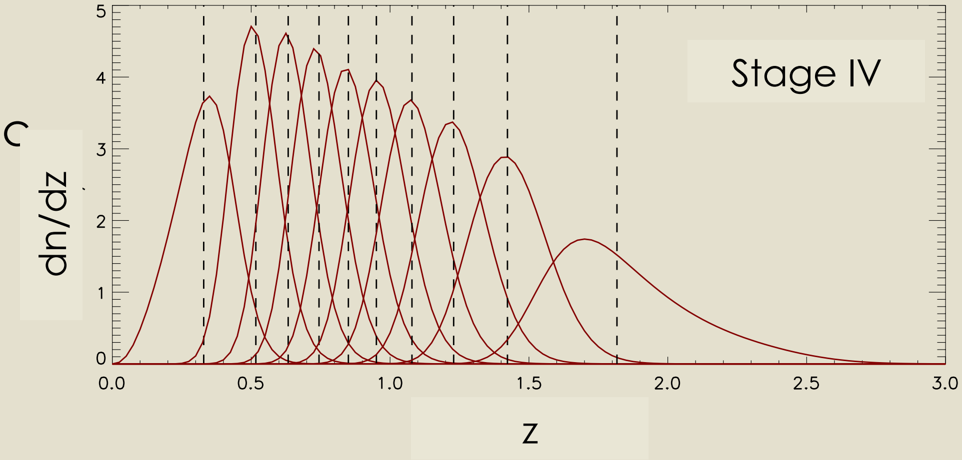
- Complementarity of tracers key to testing gravity

Complications : photometric redshifts

- Faster but less precise alternative to spectroscopic z
- Essential for tomography
  - Measuring evolution on dark energy
  - Cross-correlations between z bins useful for disentangling systematics and cosmology
- Sensitive to modeling
  - galaxy distribution,
  - photo-z statistical accuracy, systematic offsets and catastrophic errors



Credit: LSST Consortium



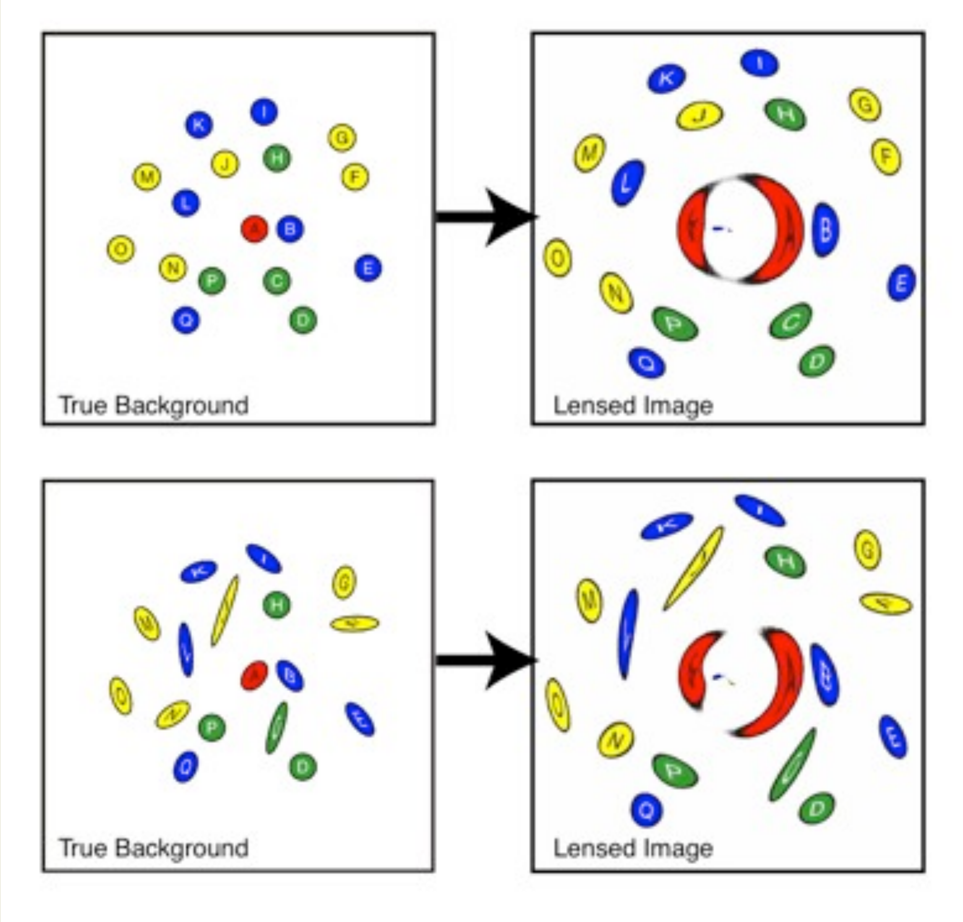
Rachel Bean: Itzykson 2012

Complications : 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 not an issue
  - Instrumental & astrophysical "contaminants" – shear calibration uncertainties
  - Correlated alignments need to be modeled and disentangled from cosmological shear



Credit: Williamson, Oluseyi, Roe 2007

Complications : Intrinsic alignments

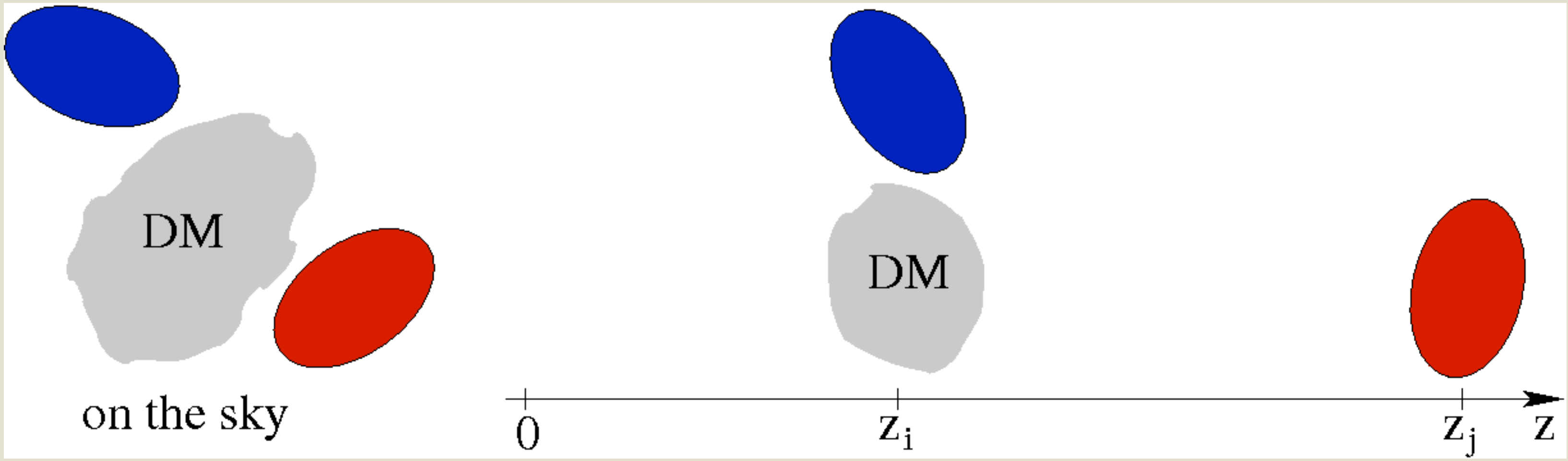
- Significant astrophysical systematic

- 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)

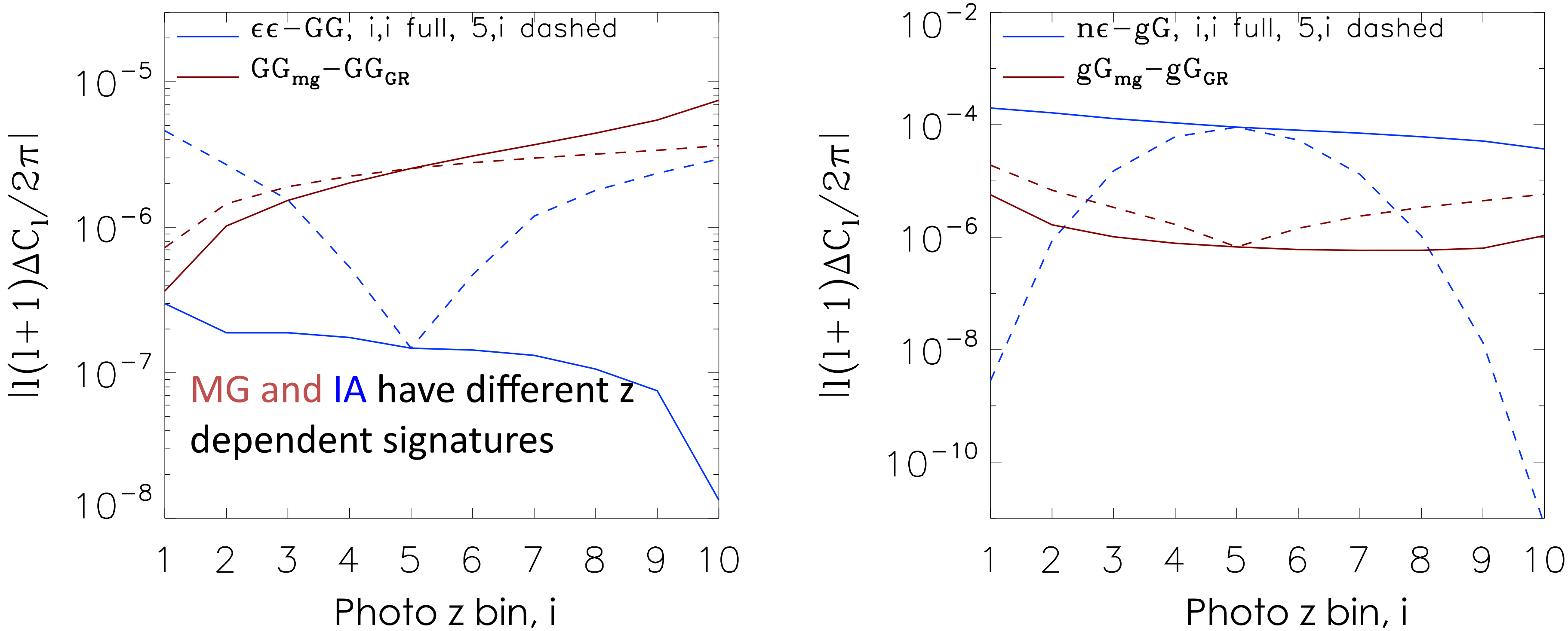
GI shear (anti) correlation



Credit: Benjamin Joachimi, iCosmo

Cross- correlations and tomography: break degeneracy between systematics and theory

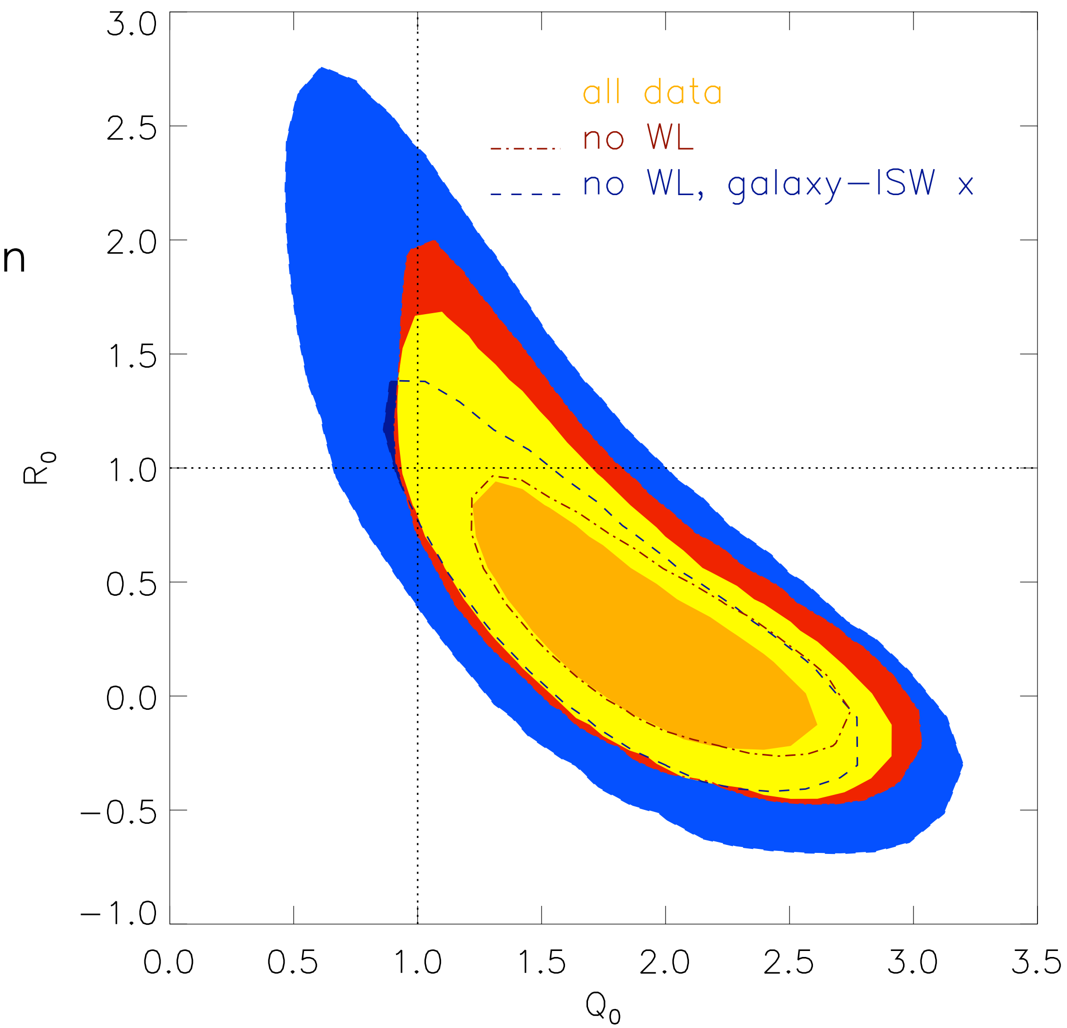
Plots of $C_l^{X_i Y_i}$ and $C_l^{X_5 Y_i}$



Laszlo, Bean, Kirk, Bridle, 2012

Current constraints

- Multiple data
  - WMAP CMB,
  - SDSS LRG auto
  - SDSS-WMAP ISW cross correlation
  - COSMOS weak lensing,
  - Union SN1a
- ISW + ISW-galaxy correlations drive constraints
- Principal degeneracy
  - $(\phi+\psi)$direction ~Q(1+R)/2
- "Figure of Merit"
  - 1/error ellipse area
  - MG FoM ~ 0.03



Bean & Tangmatitham 2010

What about future surveys?

- Fisher matrix analysis = Inverse covariance (error) matrix

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

- 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

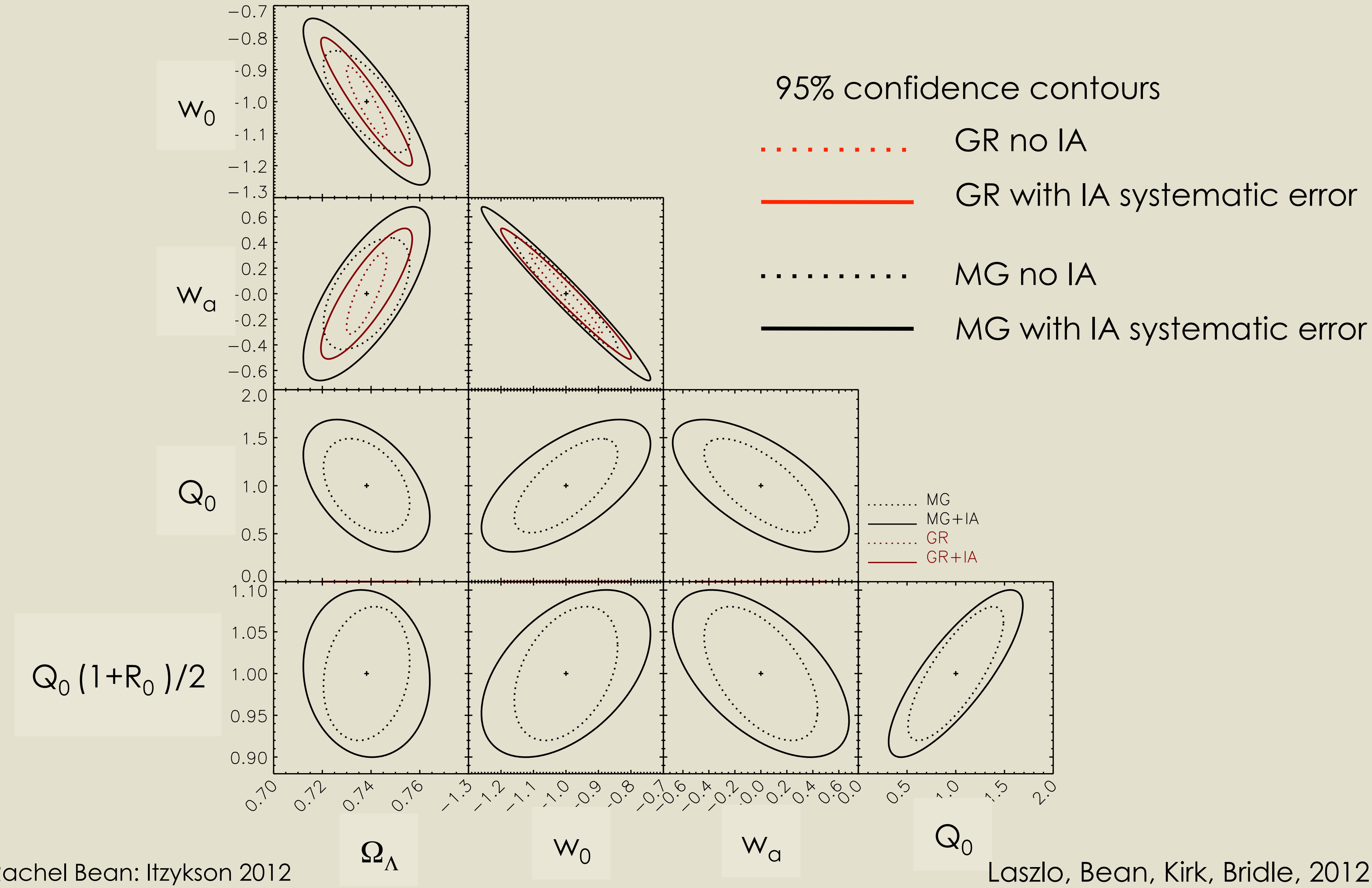
$$\mathbf{t} = \{C_\ell^{TT}, C_\ell^{TE}, C_\ell^{EE}, C_\ell^{Tg_1}, ..., C_\ell^{Eg_1}, ...C_\ell^{g_1 g_1}, C_\ell^{g_1 g_2}, ..., C_\ell^{\kappa_{N_{ph}} \kappa_{N_{ph}}}\}$$

- 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

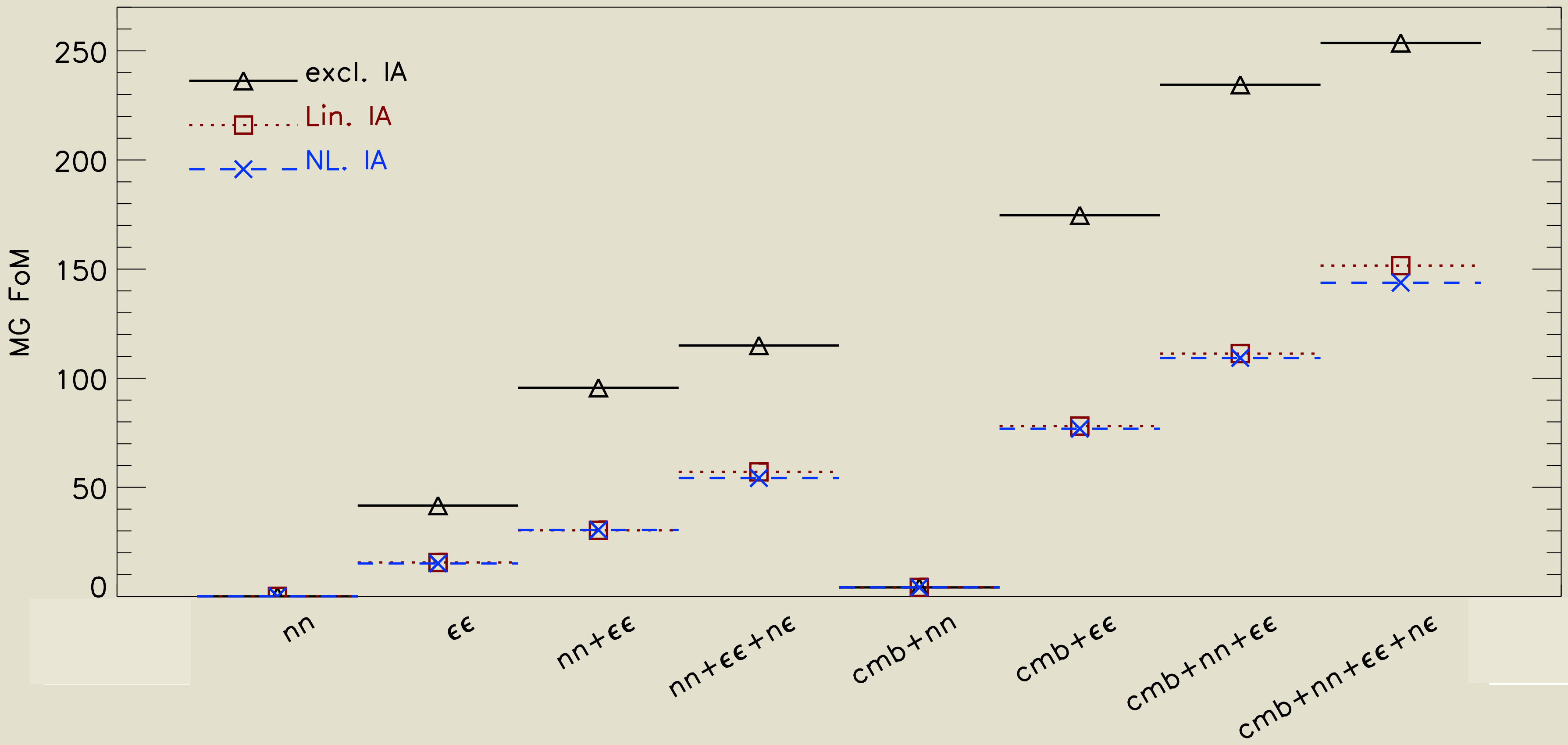
Sensitivity to theory and systematics



Rachel Bean: Itzykson 2012

Laszlo, Bean, Kirk, Bridle, 2012

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



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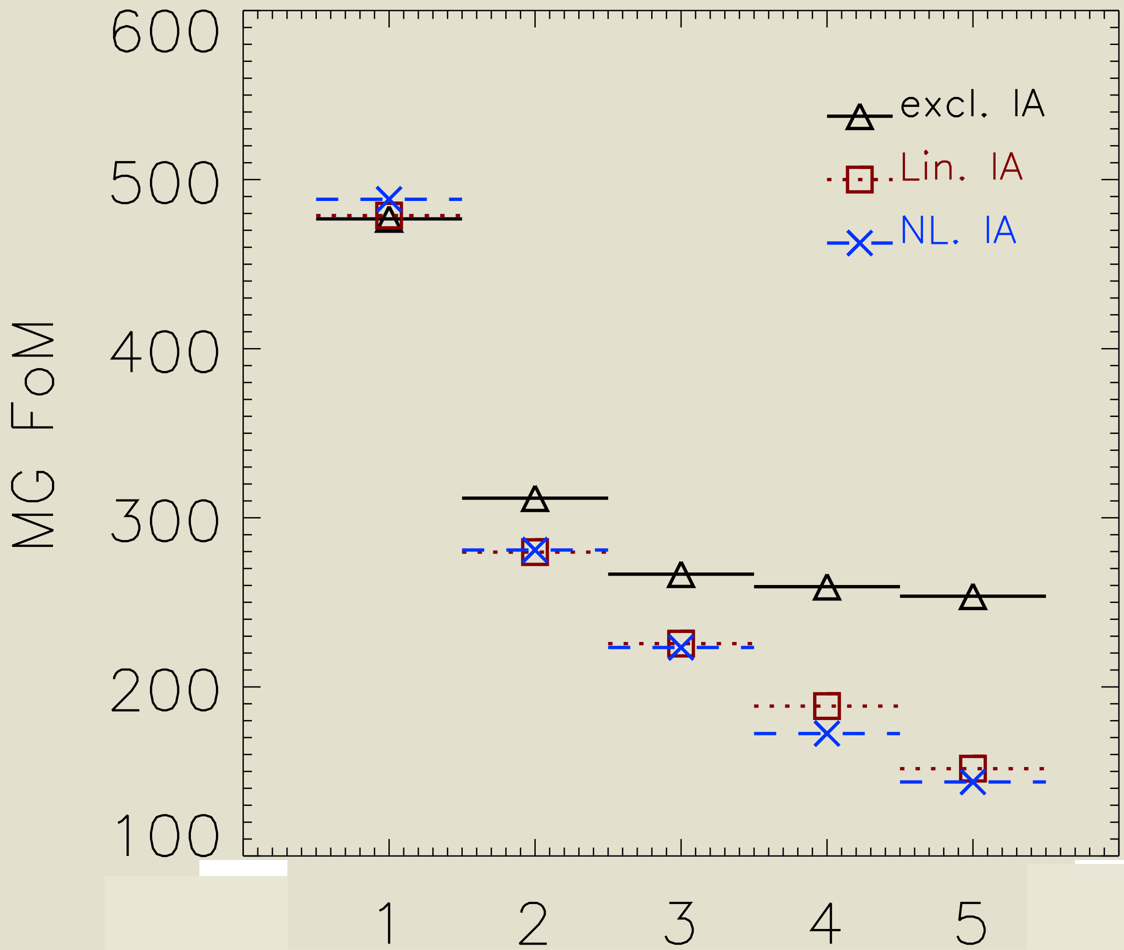
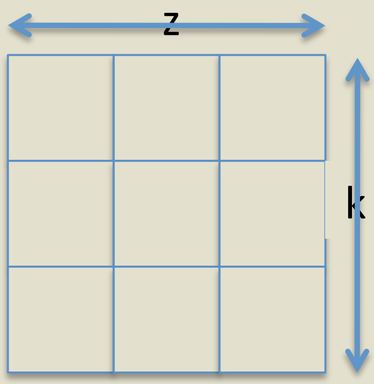
Laszlo, Bean, Kirk, Bridle, MNRAS 2012

Assumptions about bias and IA model

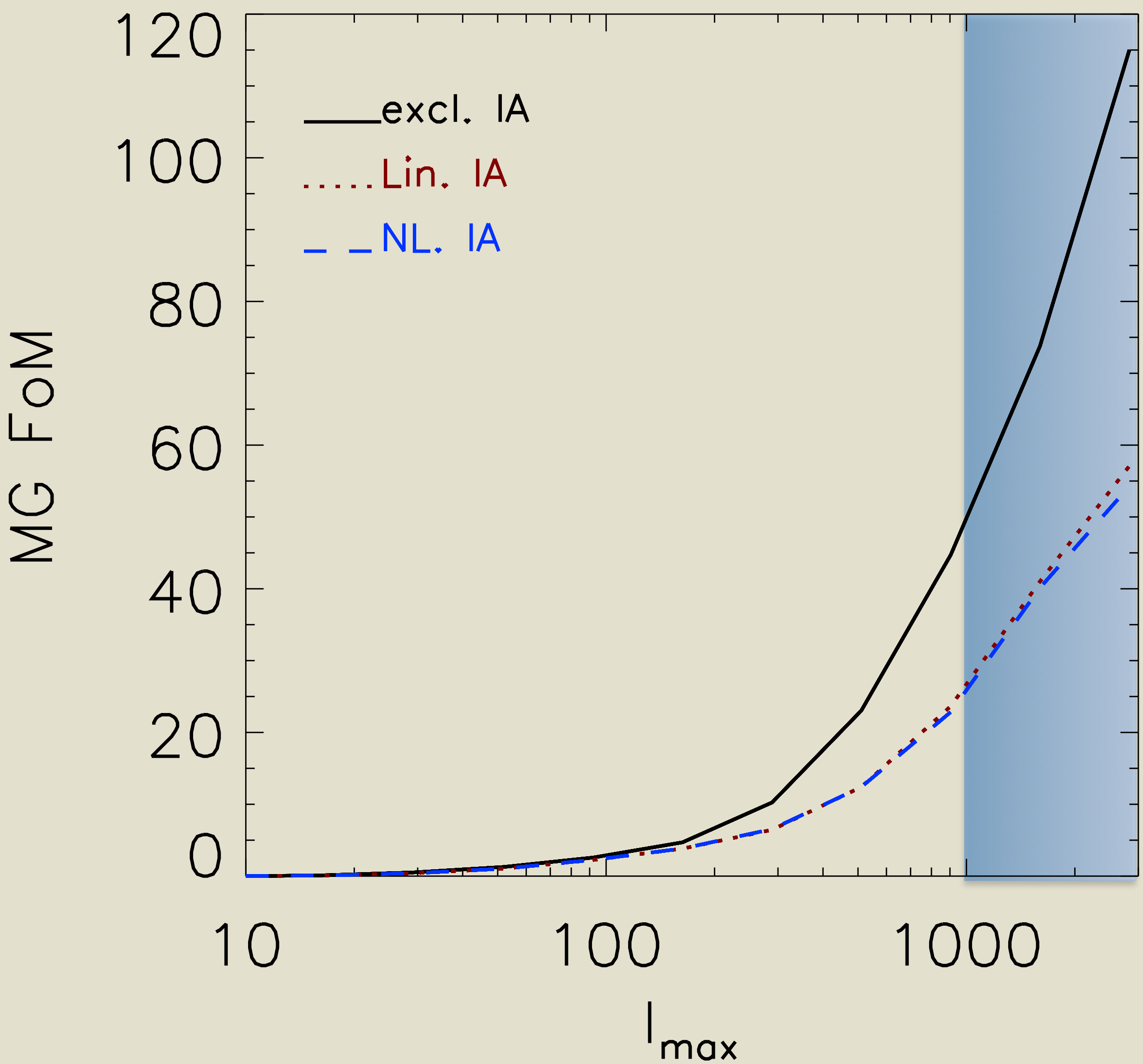




Number of k and z bins for bias & IA nuisance parameters

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

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

Effective field theory of acceleration

- Can we tie phenomenology/data a step closer to theory?
- Write a general action as an expansion in derivative powers

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - U(\phi)\right\} + S_{\rm m}[e^{\alpha(\phi)}g_{\alpha\beta},\psi_{\rm m}]$$
$$+\epsilon\int d^4x\sqrt{-g}\Big\{a_1(\nabla\phi)^4 + b_2T(\nabla\phi)^2 + c_1G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$
$$+ d_3\left(R^2 - 4R^{\mu\nu}R_{\mu\nu} + R_{\mu\nu\sigma\rho}R^{\mu\nu\sigma\rho}\right) + d_4\epsilon^{\mu\nu\lambda\rho}C_{\mu\nu}{}^{\alpha\beta}C_{\lambda\rho\alpha\beta} + e_1T^{\mu\nu}T_{\mu\nu} + e_2T^2\Big\}.$$

  - a_1,a_2 etc are all free functions of ϕ
  - non-minimally coupled to metric in Einstein frame, "modified gravity"

- What observational properties might this type of action have?

Park, Watson, Zurek 2011
Bloomfield & Flanagan 2012

Effective field theory of acceleration

- A subset of terms particularly relevant to late time evolution (Work with Eva-Marie Mueller and Scott Watson)

$$S = \int d^4x\sqrt{-g}\left\{\frac{m_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - U(\phi)\right\} + S_{\rm m}[e^{\alpha(\phi)}g_{\alpha\beta},\psi_{\rm m}]$$
$$+\epsilon\int d^4x\sqrt{-g}\Big\{a_1(\nabla\phi)^4 + b_2T(\nabla\phi)^2 + c_1G^{\mu\nu}\nabla_\mu\phi\nabla_\nu\phi$$
$$+ d_3\left(R^2 - 4R^{\mu\nu}R_{\mu\nu} + R_{\mu\nu\sigma\rho}R^{\mu\nu\sigma\rho}\right) + d_4\epsilon^{\mu\nu\lambda\rho}C_{\mu\nu}{}^{\alpha\beta}C_{\lambda\rho\alpha\beta} + e_1T^{\mu\nu}T_{\mu\nu} + e_2T^2\Big\}.$$

- Canonical scalar field
- Non-minimally coupled matter
- A quartic term
- A Gauss-Bonnet (GB) term
- Other terms here well constrained by early time effects

Effects of extensions to minimally coupled scalar

- Study attractor behavior of this action

$$S_E = \int d^4x\sqrt{-g}\left\{\frac{M_p^2}{2}R - \frac{1}{2}(\nabla\phi)^2 - V(\phi) + X(\dot{\phi}, H) - f(\phi)R_{GB}^2\right\} + S_m[e^{F(\phi)}g_{\mu\nu}]$$

$$F(\phi) \equiv \exp\left(2C\sqrt{\frac{2}{3}}\frac{\phi}{M_p}\right)$$

$$X(\dot{\phi}, H) \equiv \frac{\beta}{M_p^2 H^2}\dot{\phi}^4$$

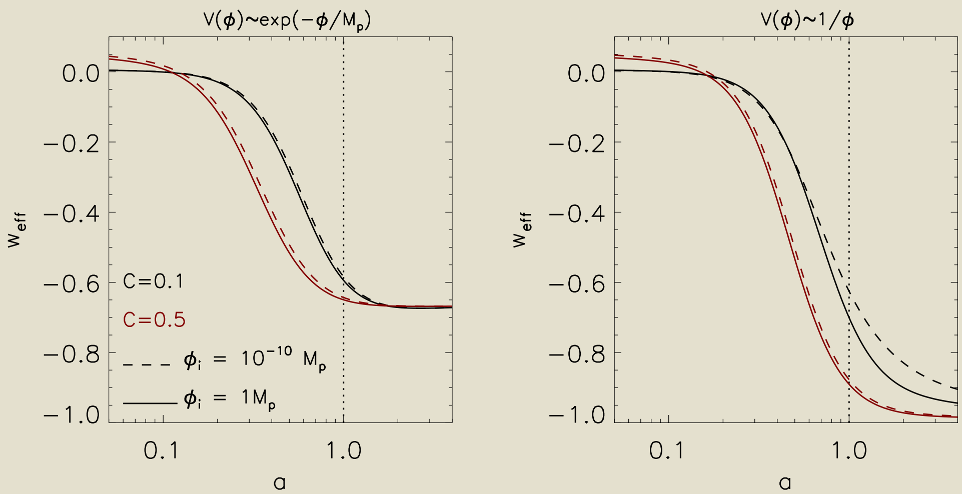
- Effect on Friedmann and equations

$$3M_p^2H^2 = \rho_m(\phi) + \rho_\gamma + \frac{1}{2}\dot{\phi}^2 + V(\phi) + 24\dot{\phi}f'(\phi)H^3 + 3X$$

$$\ddot{\phi} + 3H\dot{\phi} + V' = \sqrt{\frac{2}{3}}\frac{C}{M_p}\rho_m - 24f'H^4\left(\frac{\dot{H}}{H^2} + 1\right) + \frac{X}{H\dot{\phi}}\left[-3\frac{\dot{X}}{XH} - 12\right]$$

To attract or not? A matter of effective potentials

- Potentials with exponential or power law forms allow attractor solutions
  - Independence to initial conditions (for better or worse e.g. f(R) Amendola et al 2007)
  - Transitions from matter to accelerative era



RB, Flanagan, Laszlo, Trodden 2008

- Can postulate potentials that deny attractors, and retrofit to LCDM background.
  - Evades disadvantageous attractor behavior e.g. f(R) Hu and Sawicki 2007

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

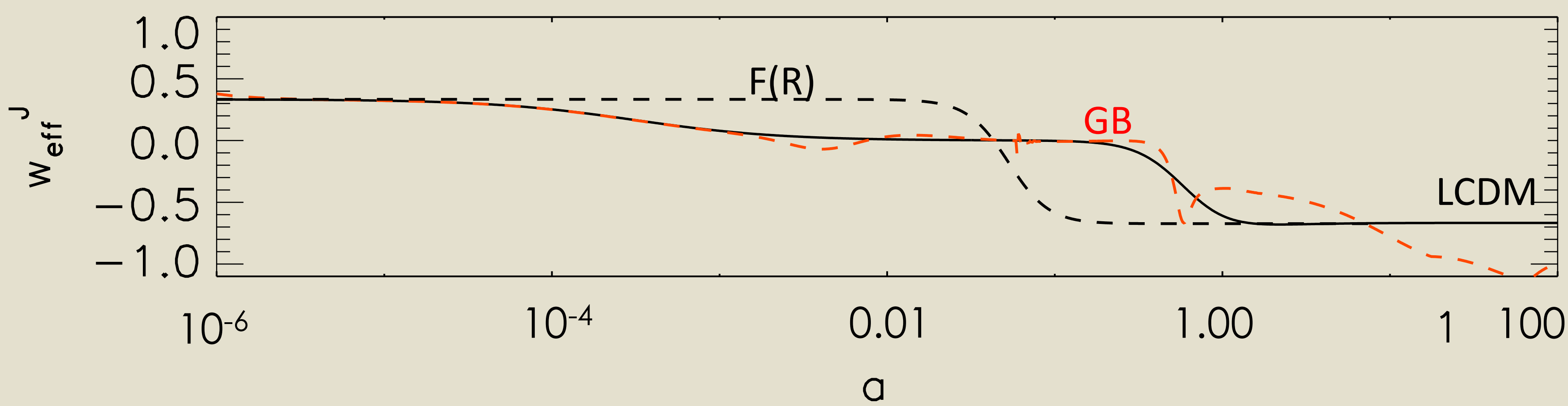
Effect on cosmological attractors

- Express dynamical equations in terms of dimensionless parameters

$$x = \frac{1}{M_p H}\frac{\dot{\phi}}{\sqrt{6}}, \quad y = \frac{1}{M_p H}\frac{\sqrt{V}}{\sqrt{3}}, \quad z = \frac{1}{M_p H}\frac{\sqrt{\rho_\gamma}}{\sqrt{3}},$$

$$\mu_X \equiv \frac{X}{3M_p^2 H^2} = 12\beta x^4 \qquad \mu_{GB} \equiv \frac{f' H^2}{M_p}$$

- Find if stationary solutions exist x'=y'=z'=μ'=0



Rachel Bean: Itzykson 2012

Evolutionary attractor

- Matter dominated era: NMC and kinetic terms important
  - NMC cosmic grease w >0
  - Quartic term adds to Hubble drag, acts to slow expansion

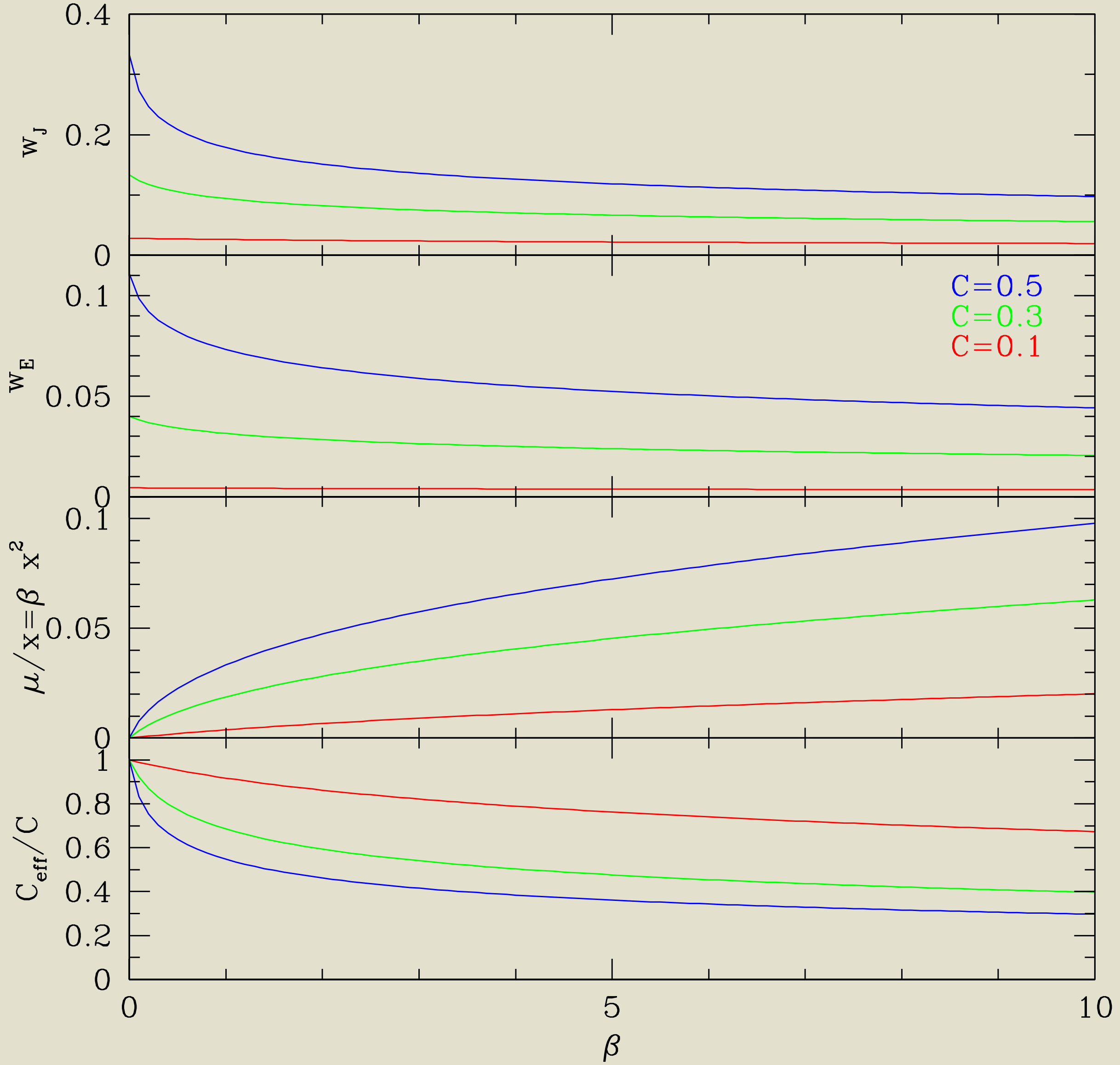
$$x = \frac{2}{3} C_{eff}(C, \beta) \qquad y = 0, z = 0, \mu_{GB} = 0$$

- Accelerative era:
  - GB term gives an accelerative attractor (Koivisto and Mota 2006)

$$x = 0, y = 1, \mu_{GB} = \frac{\lambda}{8}$$

  - In absence of GB term quartic allows acceleration for broader ranges of potentials with $\lambda>2$

Matter era



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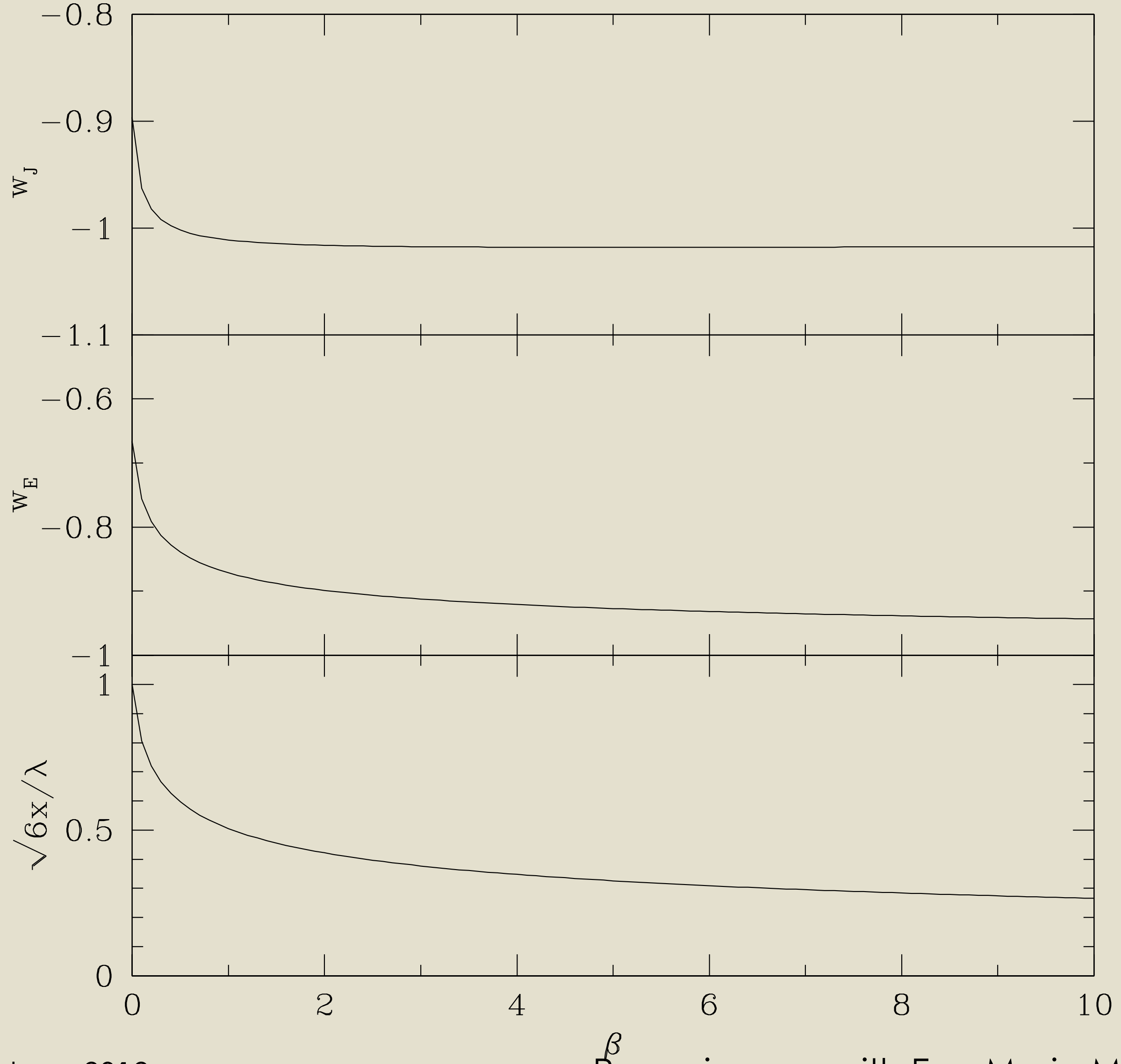
Paper in prep with Eva-Marie Mueller and Scott Watson

Accelerative era



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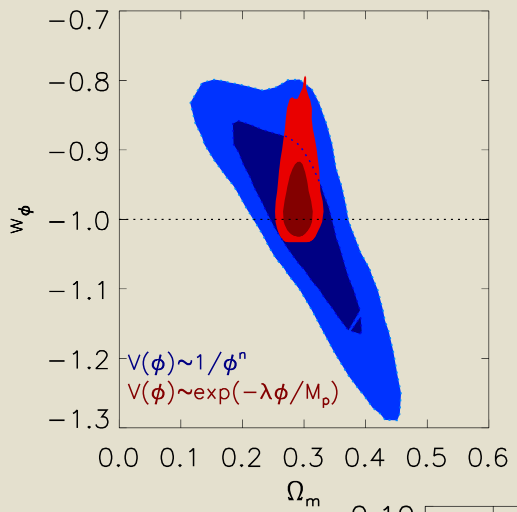
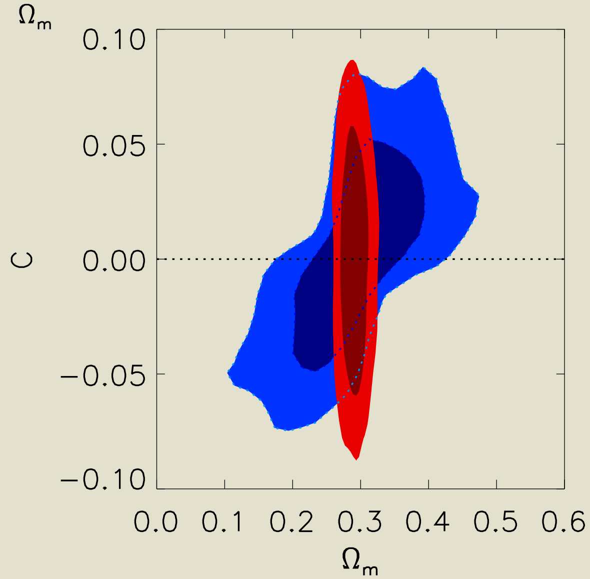
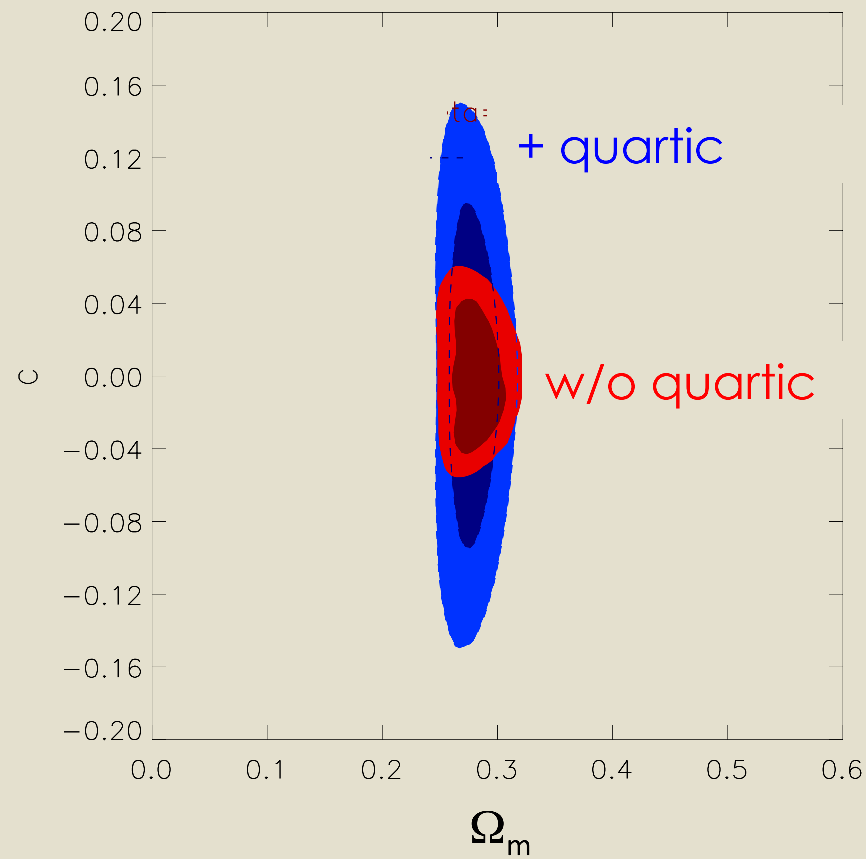
Impacts on geometric cosmological constraints





Einstein frame (just coupling to CDM)

Geometric constraints CMB + BAO + SN



Jordan frame (coupling to all matter)

Bean, Flanagan, Laszlo,Trodden 2008
Paper in prep with Eva-Marie Mueller and Scott Watson

Concluding thoughts

- Upcoming datasets provide invaluable opportunity to test the origins of cosmic acceleration and weak field gravity on cosmic scales
  - Complementary techniques important to break cosmological and systematic degeneracies
  - Relativistic and non-relativistic LSS tracers of gravity equivalent to complementary geometric techniques to measure expansion history/ curvature

- Inclusion of systematics modeling essential to forecasting
  - Can significantly impact predictions (beware apples vs oranges)
  - Theory and systematics can be tightly coupled.
  - How important are specific systematics/ algorithms to model them to a technique's ability to constrain DE?

- Phenomenological modeling/ FoMs useful but a high pass filter on full info. Mapping to theory is the ultimate goal.
  - Surveys will give us information about z and k dependence
  - General effective field theory for DE is a first step, with interesting implications for both expansion history and growth history