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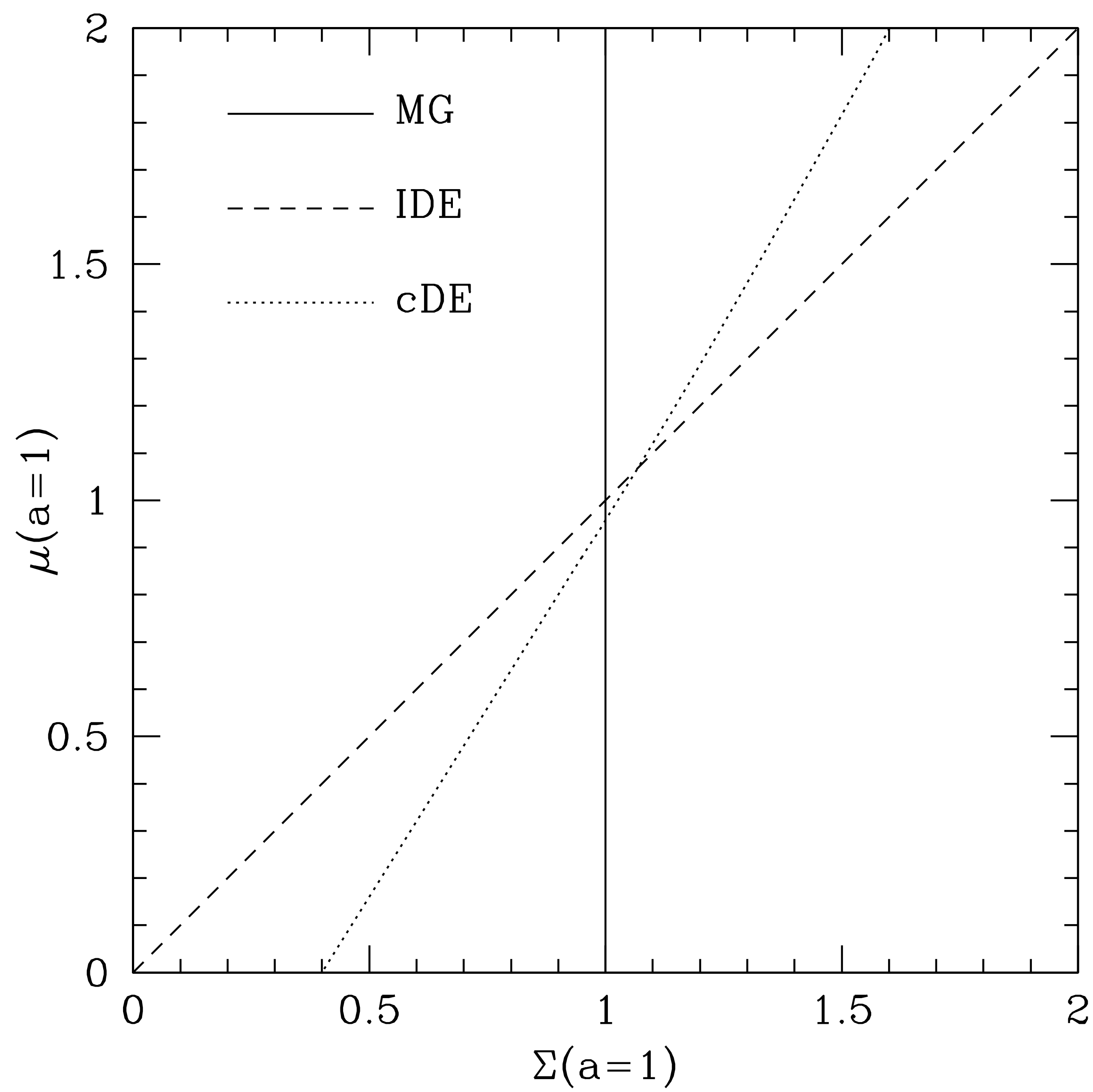
Theoretical priors on modified growth parametrisations

Song, LH, Caldera-Cabral, Koyama (2010)

Predictions in quasistatic-approximation for:
- Brans-Dicke (MG)
- interacting Dark Energy (IDE)
- clustering Dark Energy with anisotropic stress (cDE)



$$\Sigma \sim \Phi - \Psi : \quad \mathrm{WL, ISW}$$

$$\mu \sim \Psi : \quad \text{peculiar velocities, clustering}$$

Theoretical priors on modified growth parametrisations

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Anisotropic stress in dark energy:

$$\ddot{\delta}_{de} + (2-6w_{de})H\dot{\delta}_{de} + 3H\left(\frac{\delta P_{de}}{\rho_{de}}\right)^{\cdot} =$$

$$= 3H\dot{w}_{de}\delta_{de} + 3\left[(2-3w_{de})H^2 + \dot{H}\right]\left[w_{de}\delta_{de} - \frac{\delta P_{de}}{\rho_{de}}\right]$$

$$-(1+w_{de})\frac{k^2}{a^2}\left[\frac{\delta P_{de}}{(1+w_{de})\rho_{de}} - \sigma_{de} + \Psi\right].$$

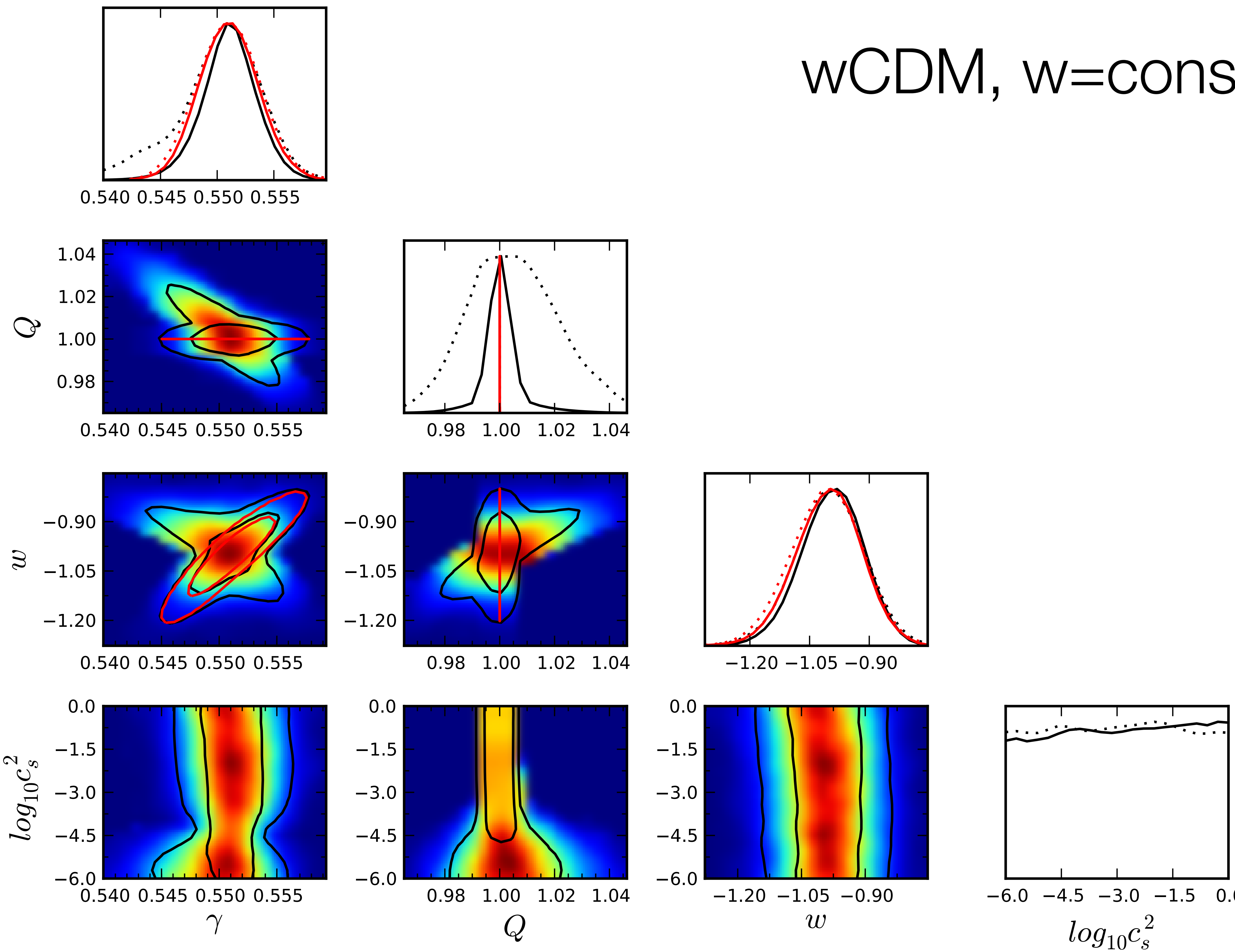
where

$$\sigma_{\rm de} \;=\; f_\sigma \frac{\delta P_{\rm de}}{(1+w)\rho_{\rm de}} \;\simeq\; \frac{f_\sigma\, c_s^2}{1+w}\delta_{\rm de}$$

$f_\sigma = 1 \Rightarrow$ scale invariant growth of DE perts

Growth index vs. effective Newton constant

wCDM, w=const.



Effects of DE anisotropic stress

Another ad-hoc model for anisotropic dark energy:

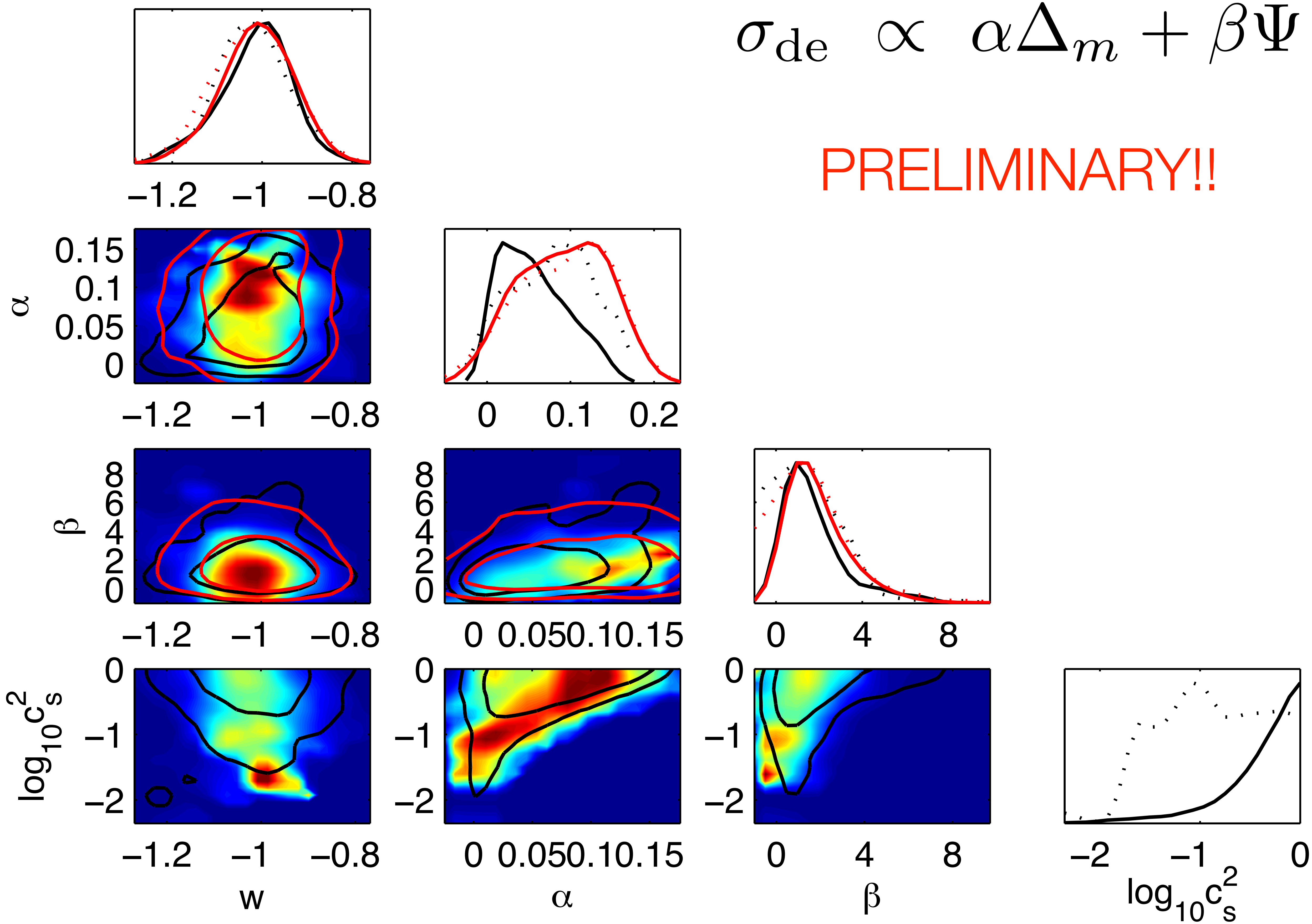
$$\sigma_{\rm de} \;\propto\; \alpha \Delta_m + \beta \Psi$$

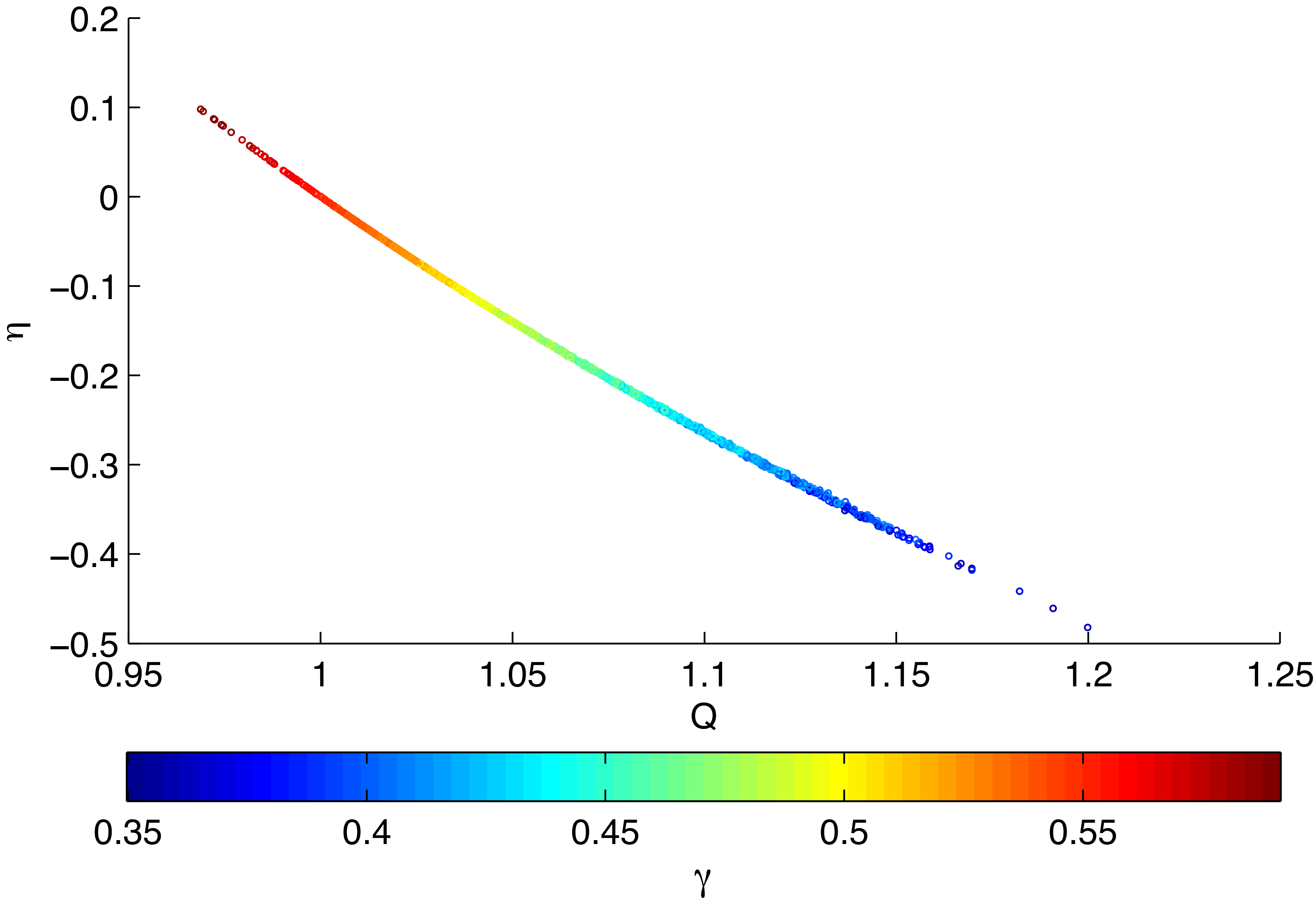
reaction to matter

reaction to metric

$$\sigma_{\rm de} \propto \alpha\Delta_m + \beta\Psi$$

PRELIMINARY!!

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−0.5
η
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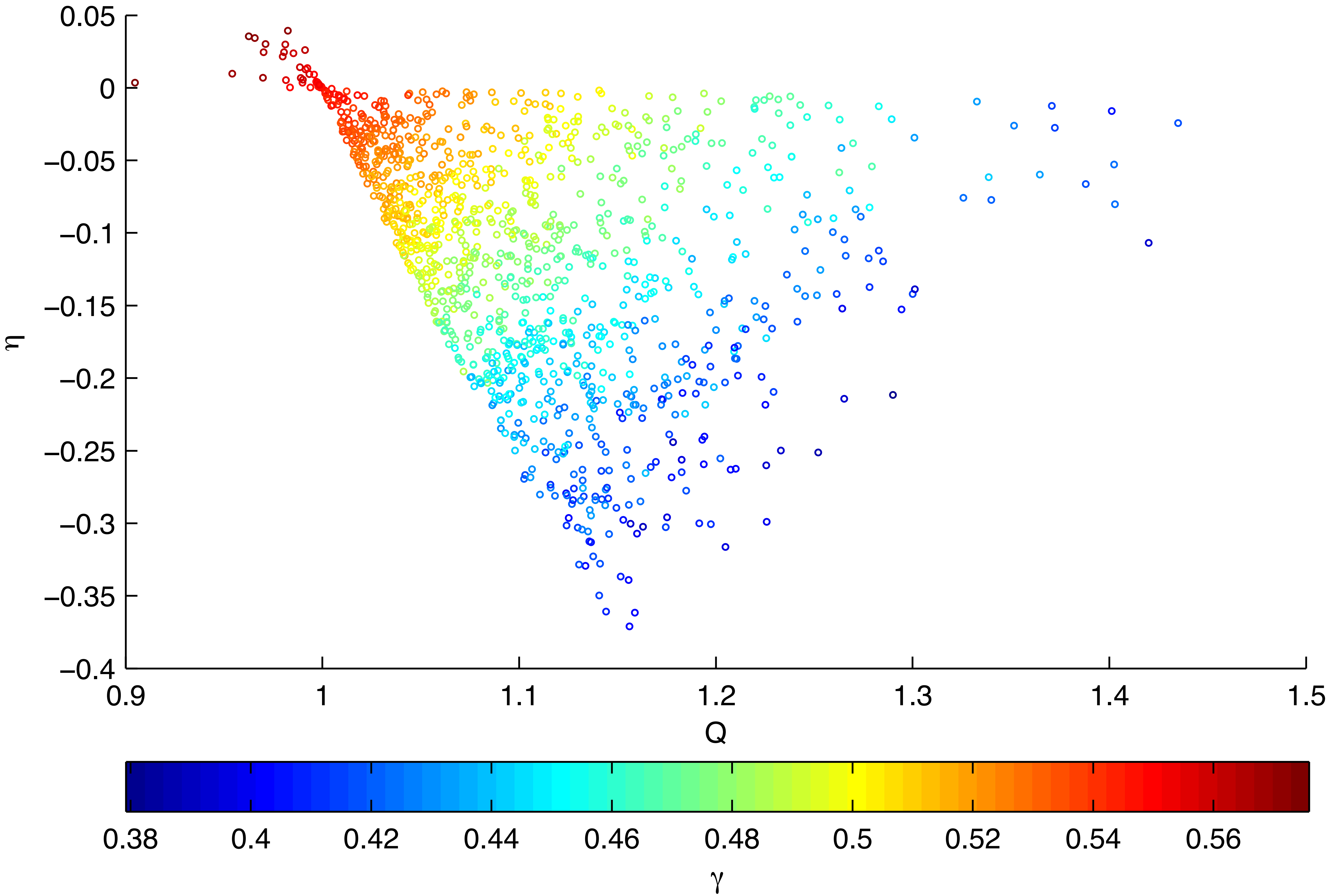
γ


0.05
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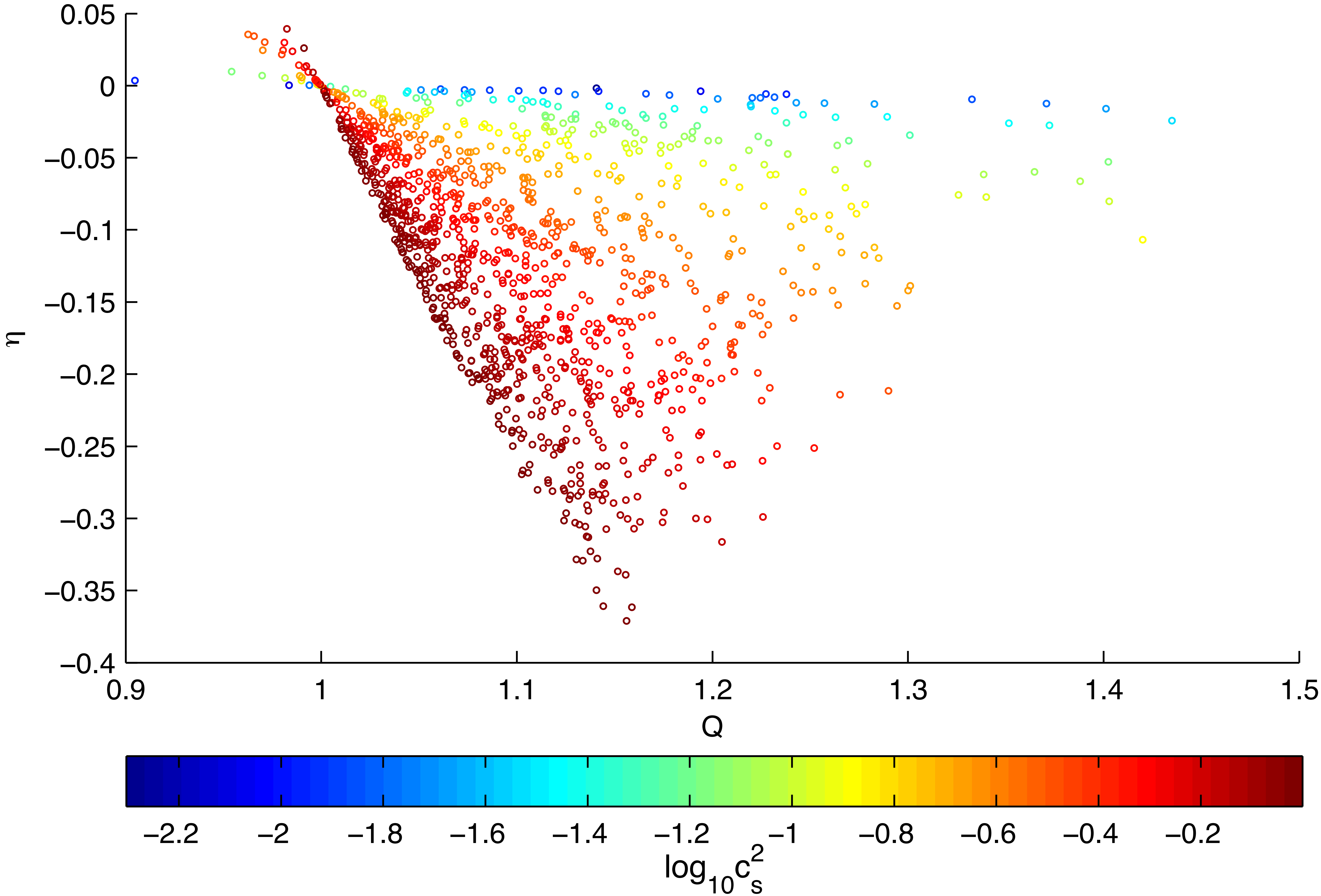
γ



Monday, 9 August 2010

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \approx -8\pi G \, T_{\mu\nu}$$

Constraining Modified Gravity with current cosmological data

Tommaso Giannantonio
Excellence Cluster Universe, Garching by Munich

In collaboration with:
G.B. Zhao, Y.S. Song, L. Pogosian, A.Silvestri, A. Melchiorri, M. Martinelli, K. Koyama, R. Nichol, D. Bacon, A. Cooray

Outline

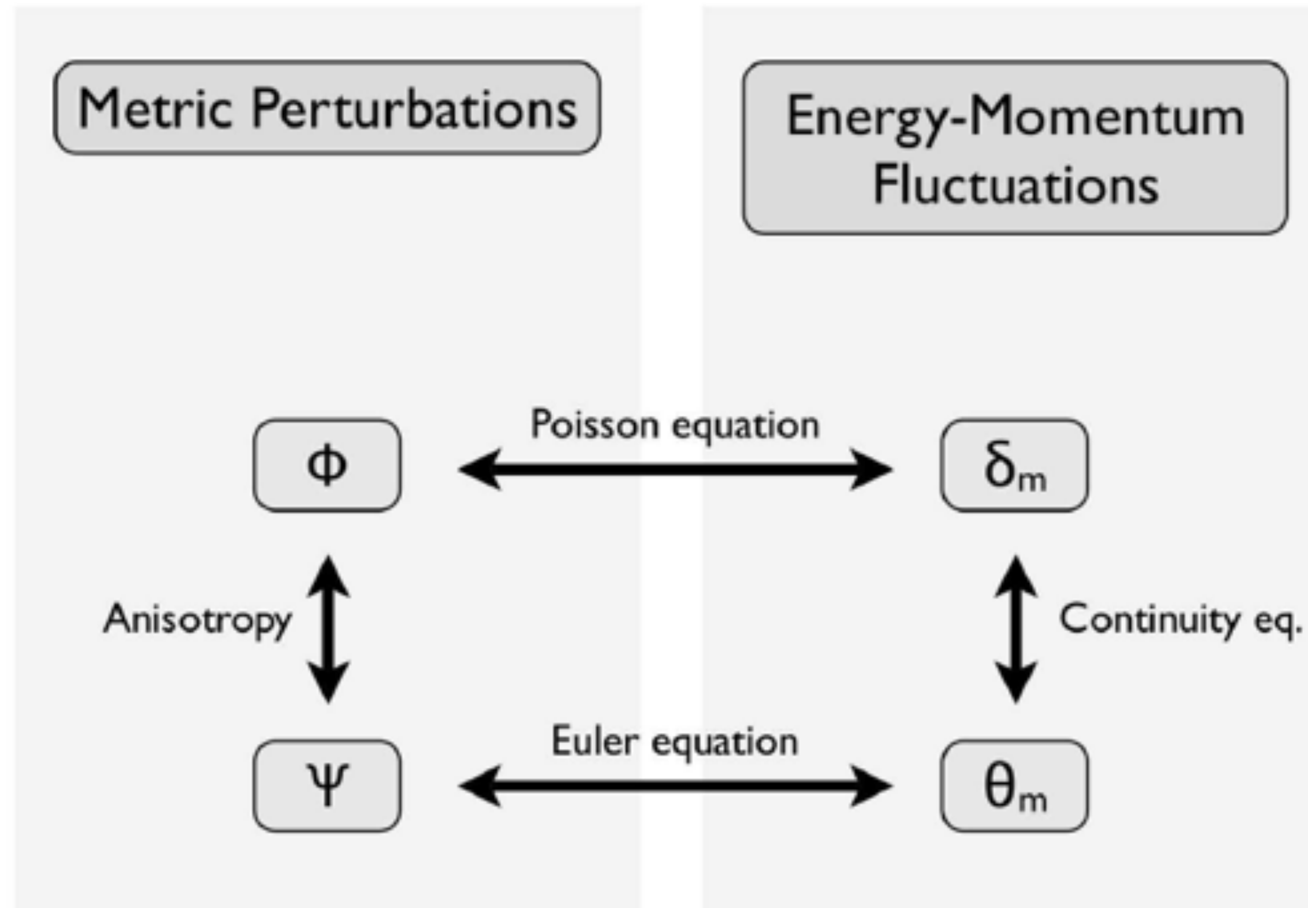
- Why Modified Gravity
- MG theories
  - DGP, f(R), Yukawa, ...
- Constraints
  - CMB, ISW, lensing, ...
- Principal component analysis
- Conclusions

Dark Energy or Modified Gravity?

- Cosmic acceleration: from either side of Einstein's equation

  $$R_{\mu\nu} - ½\, g_{\mu\nu} R = -8\pi G\, T_{\mu\nu}$$

- Equivalent, MG can be better motivated (Lagrangian)
- A gravity theory: must pass all tests GR does!
  - GR limit in Solar System, no ghosts, simple (Occam), Lagrangian
- **Background expansion**
- **Structure formation**



(Song & Dore 08)

Gravity: **testable** relationships between geometry and energy

Which Modified Gravity?

- Phenomenological models for cosmology: Cardassian
- Variations of the 4D GR action: f(R), Gauss-Bonnet, ...
- Extra Dimensions: braneworlds, DGP models, degravitation, cascading gravity, ...

The DGP model

(Dvali, Gabadadze & Porrati 00)

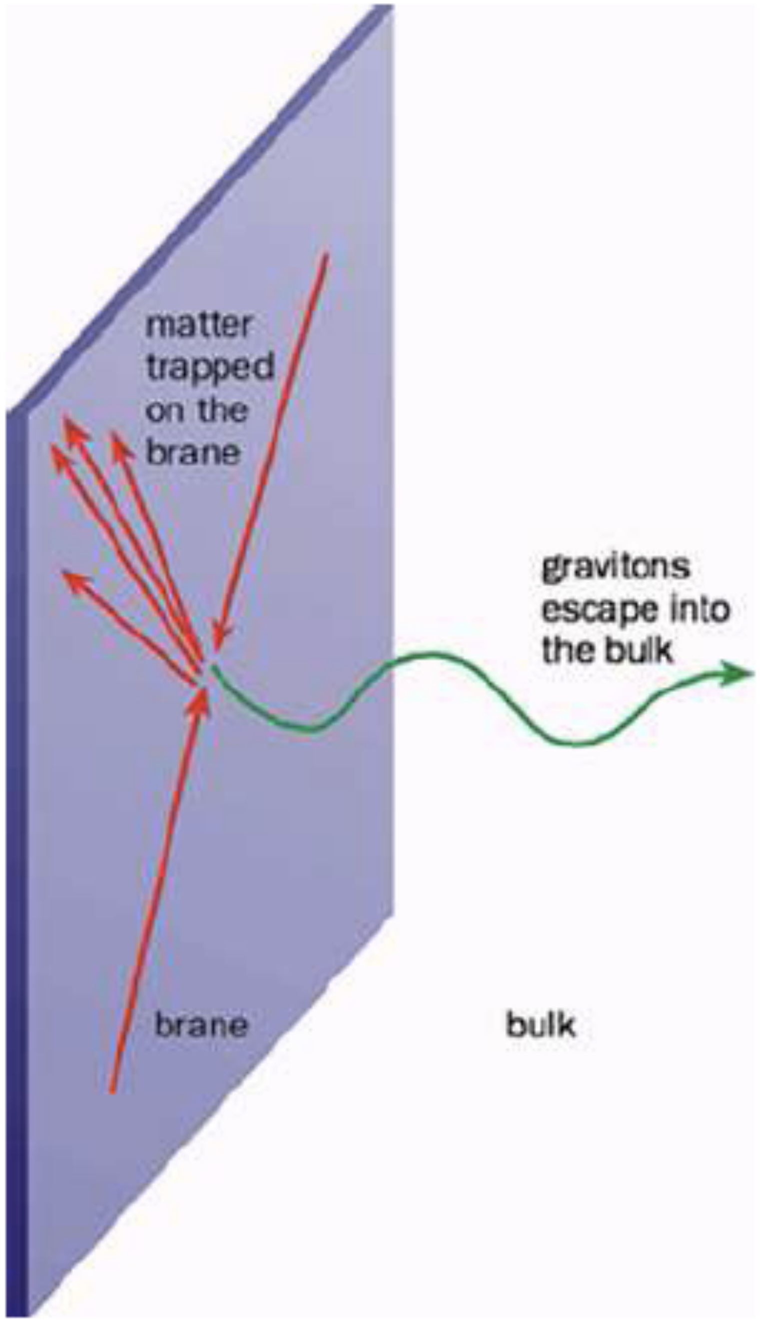
- 4D brane in Minkowski 5D bulk

$$S_5 = -\frac{1}{16\pi} M^3 \int d^5x \sqrt{-g}\, R - \frac{1}{16\pi} M_P^2 \int d^4x \sqrt{-g^{(4)}} \left[R^{(4)} - \frac{16\pi}{M_P^2} \mathcal{L}_{\rm m} \right]$$

- Background: new Friedmann equation

$$H^2 \mp \frac{1}{r_c} \sqrt{H^2 + \frac{K}{a^2}} = \frac{\kappa^2}{3}\rho + \frac{\Lambda}{3} - \frac{K}{a^2}$$

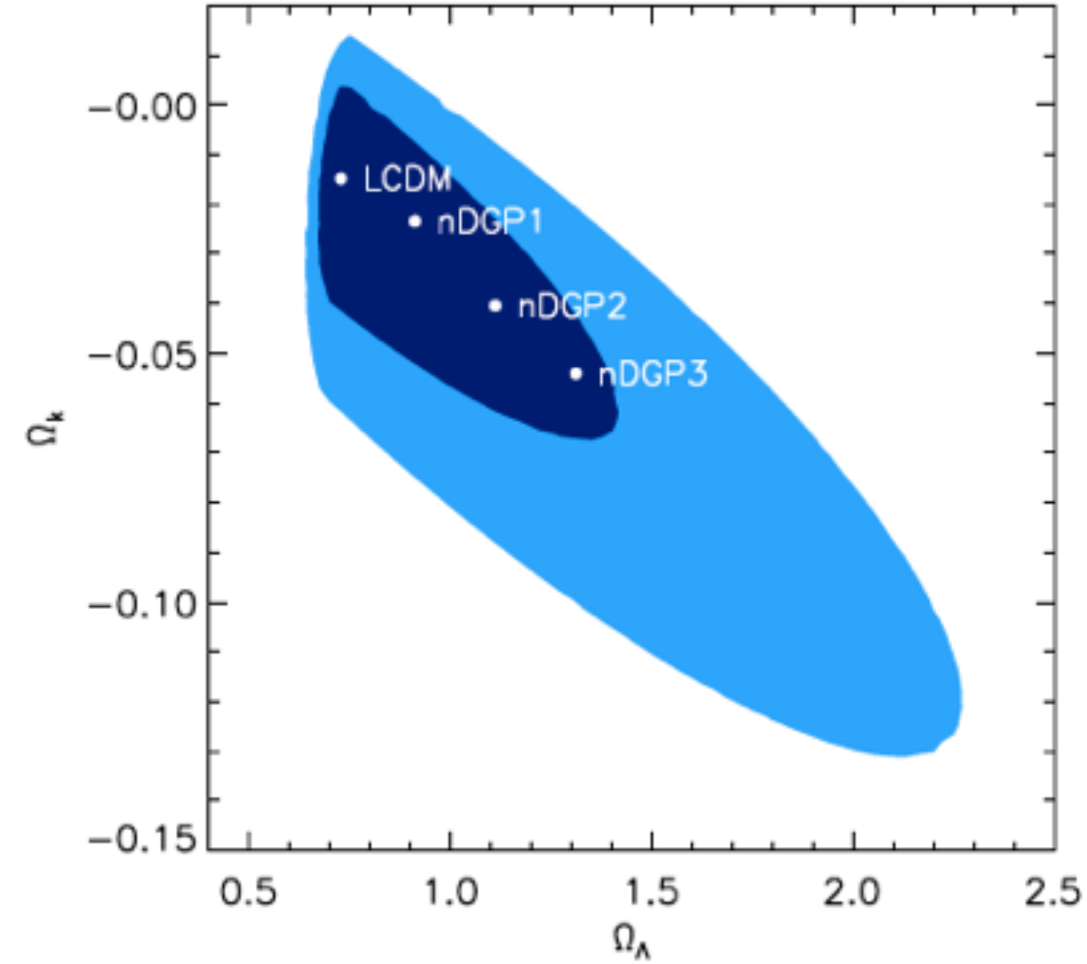
  - minus: self-accelerating branch, acceleration today if $r_c \sim H_0^{-1}$
  - plus: normal branch: still needs Λ (brane tension)

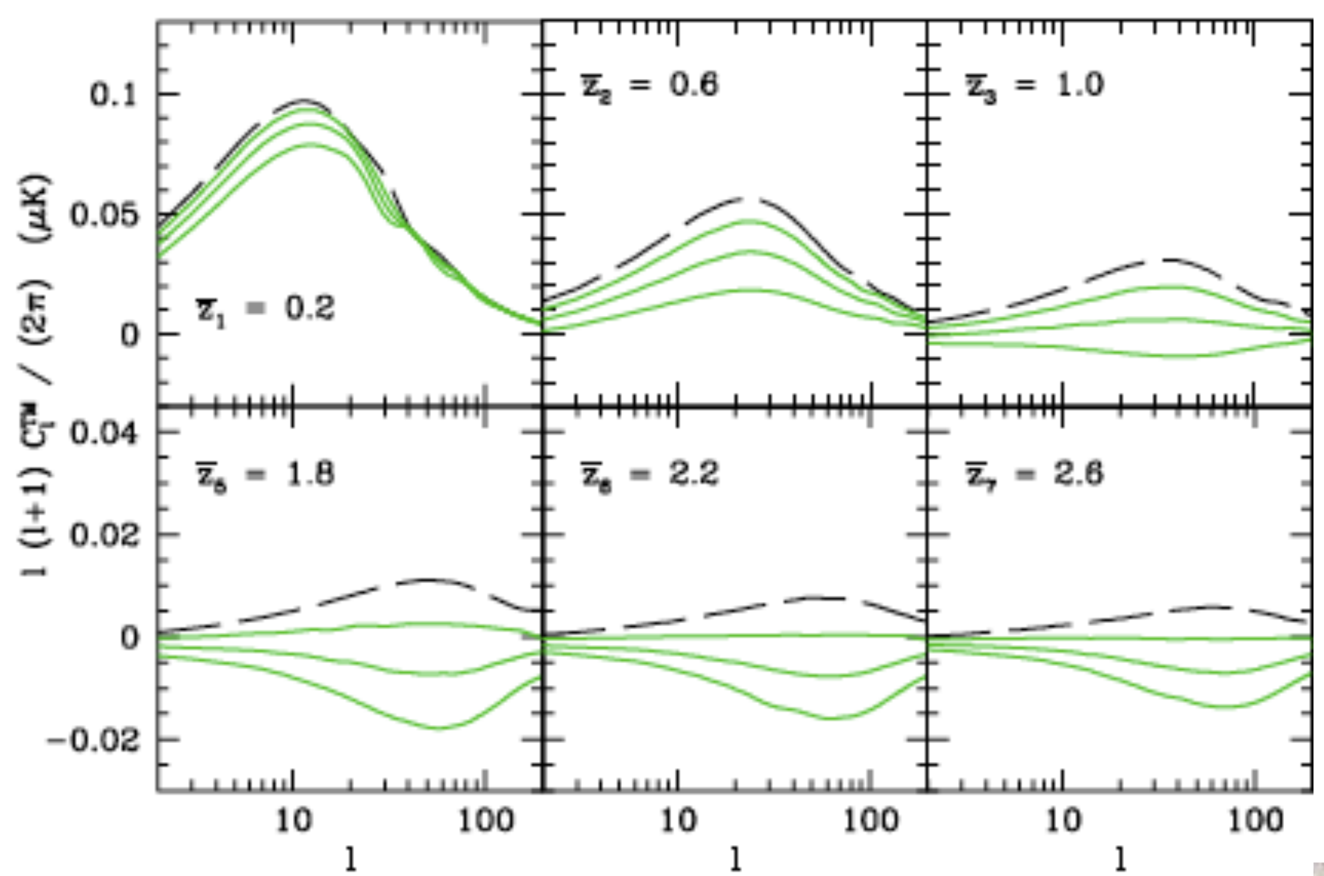


Background already rules out self-acc. (Majerotto & Maartens 06)

Constraints on the DGP model(s)

- From background: sDGP is ruled out (Majerotto & Maartens 06)
- + CMB + ISW: ruled out at 4σ! (Fang et al. 08)
- nDGP: extra dof, from bg still viable (TG, Song, Koyama 08)
- ruled out by full CMB + structure formation tests such as ISW! (TG, Song, Koyama 08, Lombriser et al 09)



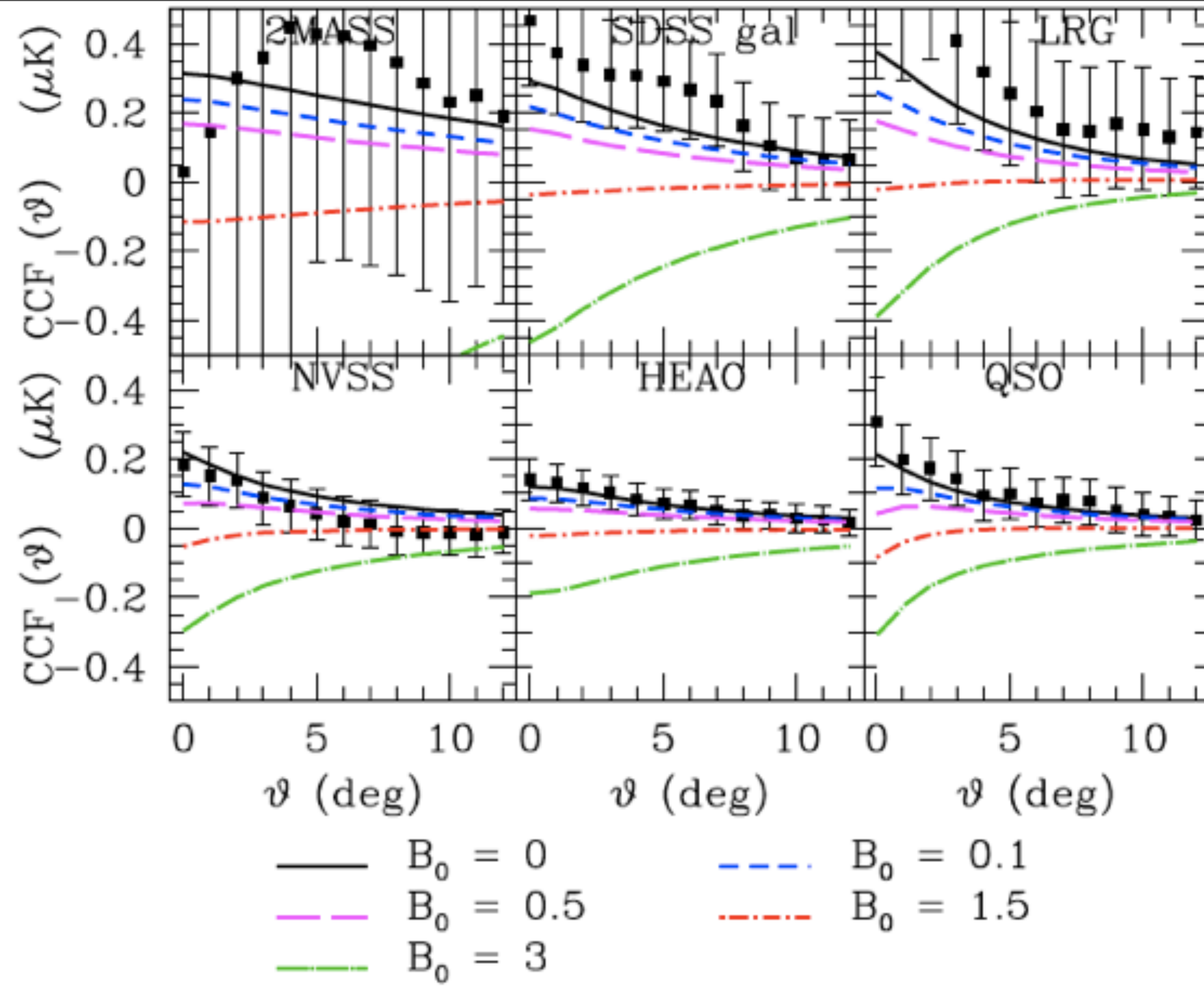


f(R) theories

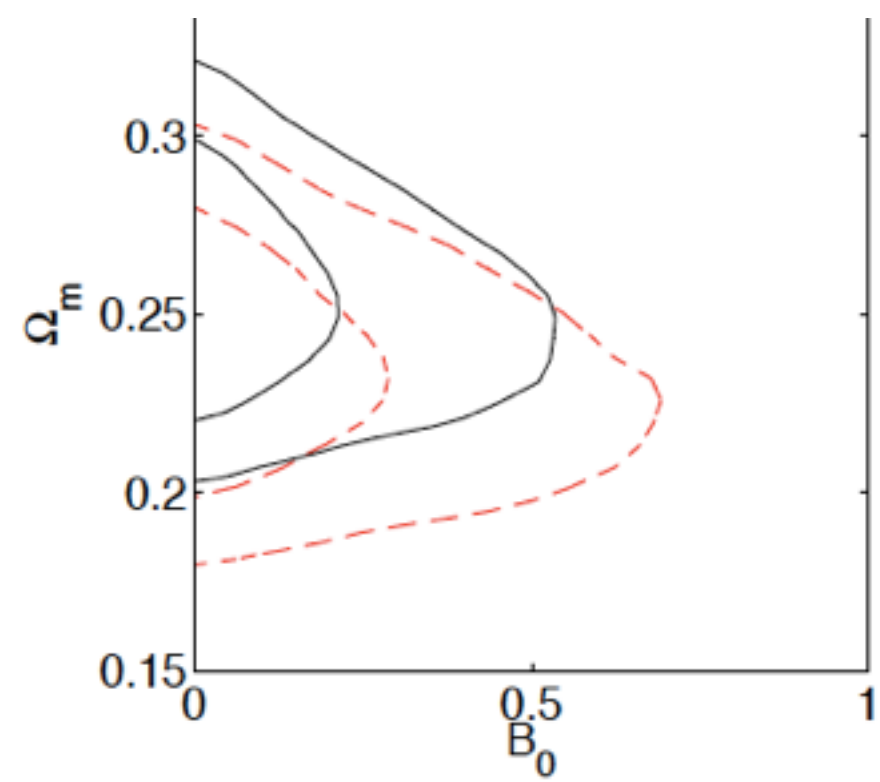
- Extended gravity action: $$S=\frac{1}{2\kappa^2}\int d^4x\sqrt{-g}\,[R+f(R)]+\int d^4x\sqrt{-g}\,\mathcal{L}_{\rm m}[\chi_i,g_{\mu\nu}]$$
- New scalar dof, **scalaron** $\boxed{f_R\equiv df/dR}$
- Effective fluid with eq. of state (family of models) $$w_{\rm eff}=-\frac{1}{3}-\frac{2}{3}\frac{\left[H^2f_R-\frac{f}{6}-H\dot{f}_R-\frac{1}{2}\ddot{f}_R\right]}{\left[-H^2f_R-\frac{f}{6}-H\dot{f}_R+\frac{1}{6}f_RR\right]}$$
- From expansion history, we solve f_R
- **Fifth force**, of wawelength, mass $$\lambda_c\equiv\frac{2\pi}{m_{f_R}}\qquad m_{f_R}^2\equiv\frac{\partial^2V_{\rm eff}}{\partial f_R^2}=\frac{1}{3}\left[\frac{1+f_R}{f_{RR}}-R\right]$$
- Growth of structure can distinguish!
- Poisson: $$\frac{k^2}{a^2}\Psi=-\frac{1}{1+f_R}\,\frac{1+\frac{4}{3}\frac{k^2}{a^2}m}{1+\frac{k^2}{a^2}m}\,\frac{a^2\rho}{2M_P^2}\delta\equiv-\mu(a,k)\frac{a^2\rho\Delta}{2M_P^2}$$
- Anisotropy (Zhao et al 08): $$\frac{\Phi}{\Psi}=\frac{1+\frac{2}{3}\frac{k^2}{a^2}m}{1+\frac{4}{3}\frac{k^2}{a^2}m}\equiv\gamma(a,k)$$

Constraints on f(R)

(TG, Martinelli, Silvestri, Melchiorri 09)



- Background identical to LCDM
- Structure formation different!
- MCMC with CMB + SN + ISW
- One parameter wavelength today in H units: $\boxed{B_0 = \frac{2\pi H_0}{mc}}$
- In GR: $B_0 = 0$
- CMB only: $B_0 < 1$ (Song, Peiris, Hu)
- With ISW: $\boxed{B_0 < 0.4 \text{ @ } 95\%}$
- Adding non-linear scales (clusters) even tighter (Vihlinkin, Hu et al 09, Lombriser et al 10)



Parametrising Modified Gravity

(Zhao et al 08, Cooray et al, Daniel et al 10)

Couplings

Lenghtscales

- Poisson equation (sub-horizon):

$$\frac{k^2}{a^2}\Psi = -\mu(a,k)\frac{a^2\rho\Delta}{2M_P^2} \longrightarrow \mu(a,k) = \frac{1+\beta_1\lambda_1^2 k^2 a^s}{1+\lambda_1^2 k^2 a^s}$$

- Anisotropy equation:

$$\frac{\Phi}{\Psi} = \gamma(a,k) \longrightarrow \gamma(a,k) = \frac{1+\beta_2\lambda_2^2 k^2 a^s}{1+\lambda_2^2 k^2 a^s}$$

- Scalar-tensor theories: $\beta_1 = \frac{\lambda_2^2}{\lambda_1^2} = 2 - \beta_2\frac{\lambda_2^2}{\lambda_1^2}$

- f(R) theories: s=4, $\beta_1 = \frac{4}{3},\ \beta_2 = \frac{1}{2}$

- So many MG theories,

- So few theoretical motivations!

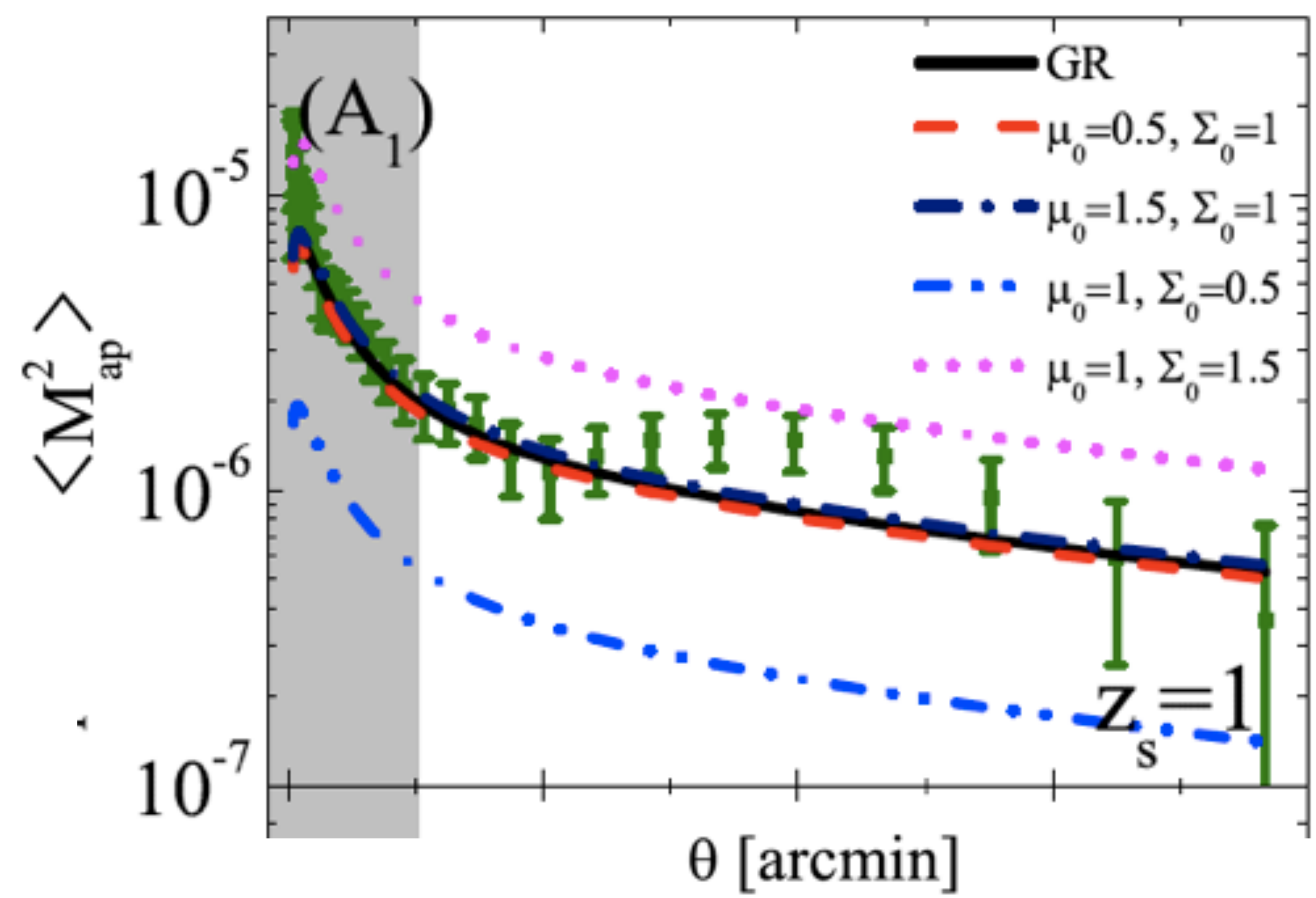
Test of general departures from GR and PCA! (Zhao, TG et al. et al 10)

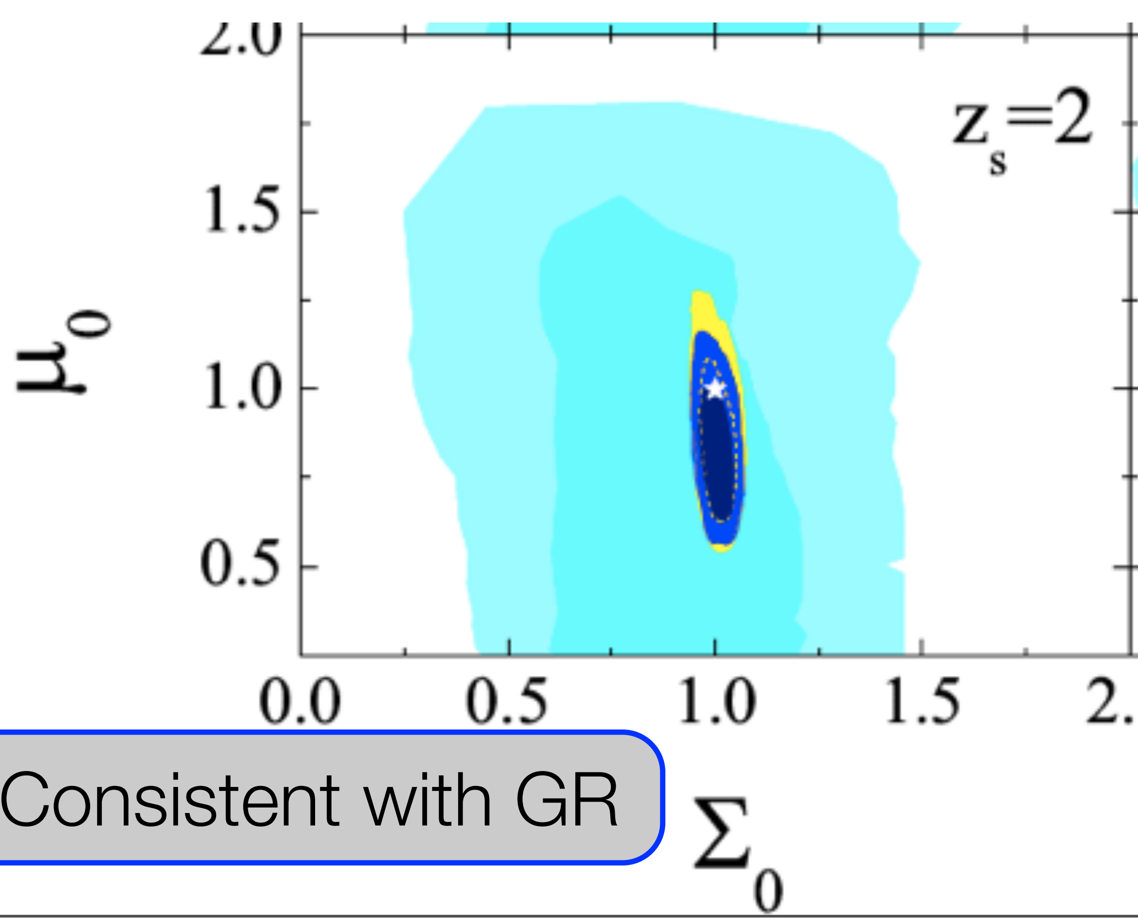
1. single high-z transition to MG

- From GR to MG with (η_0, μ_0), or (Σ_0, μ_0)

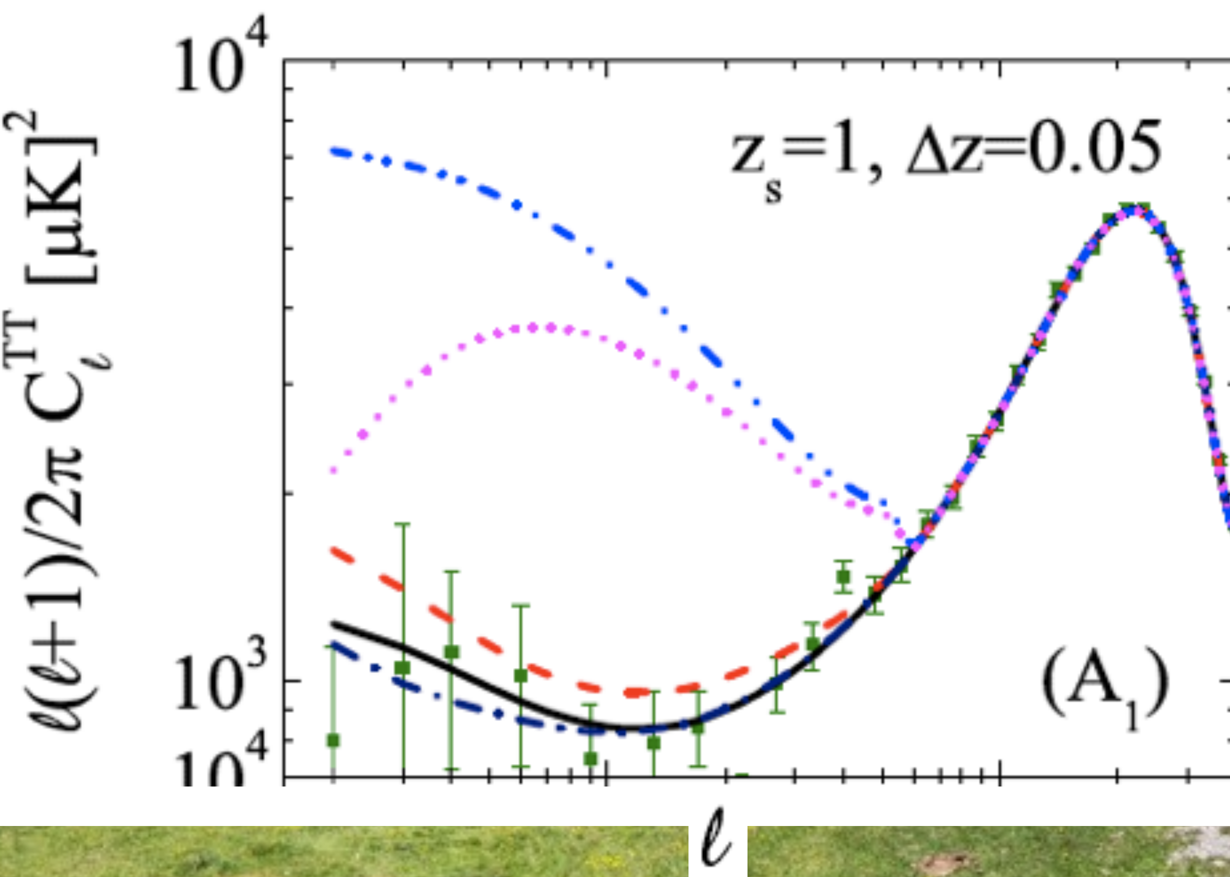
$$\Sigma(a,k) \equiv -\frac{k^2(\Psi+\Phi)}{8\pi G\rho a^2\Delta} = \frac{\mu(1+\eta)}{2}$$

- Σ better for WL, ISW
- transition: tanh, Δz at z=1 or z=2
- MCMC with CMB, ISW, WL, SN





Consistent with GR

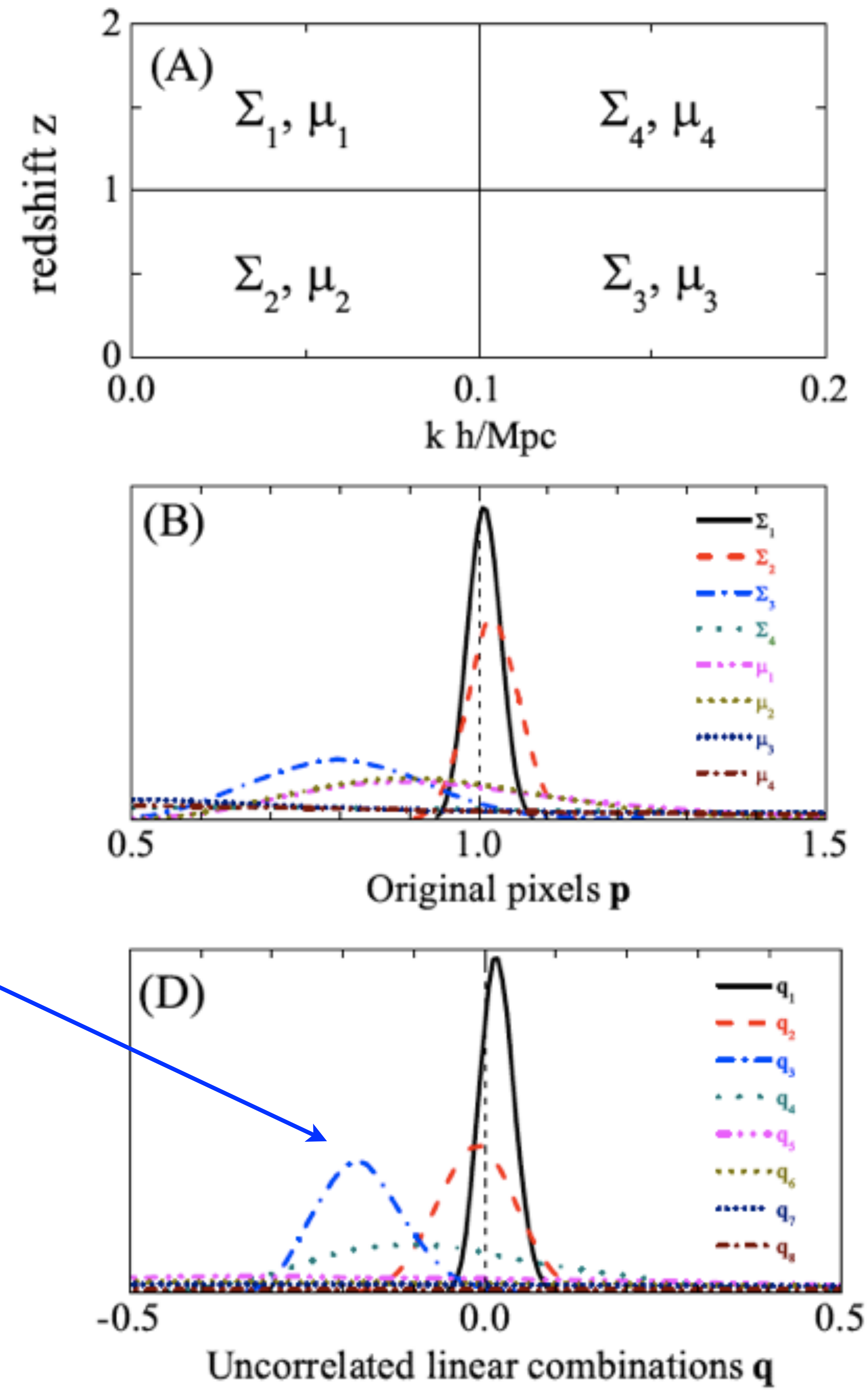


2. 2x2 Pixellation + PCA

- Scale dependence IS expected
- 2 pixels in redshift AND scale!
- (Σ_i, μ_i), i = 1, ..., 4
- MCMC again with all data
- PCA: de-correlating the variables

Here a hint of deviation (2σ)!

- Caused by CFHTLS “bump”
- Known systematic (field of view size) (CFHTLS private communication)



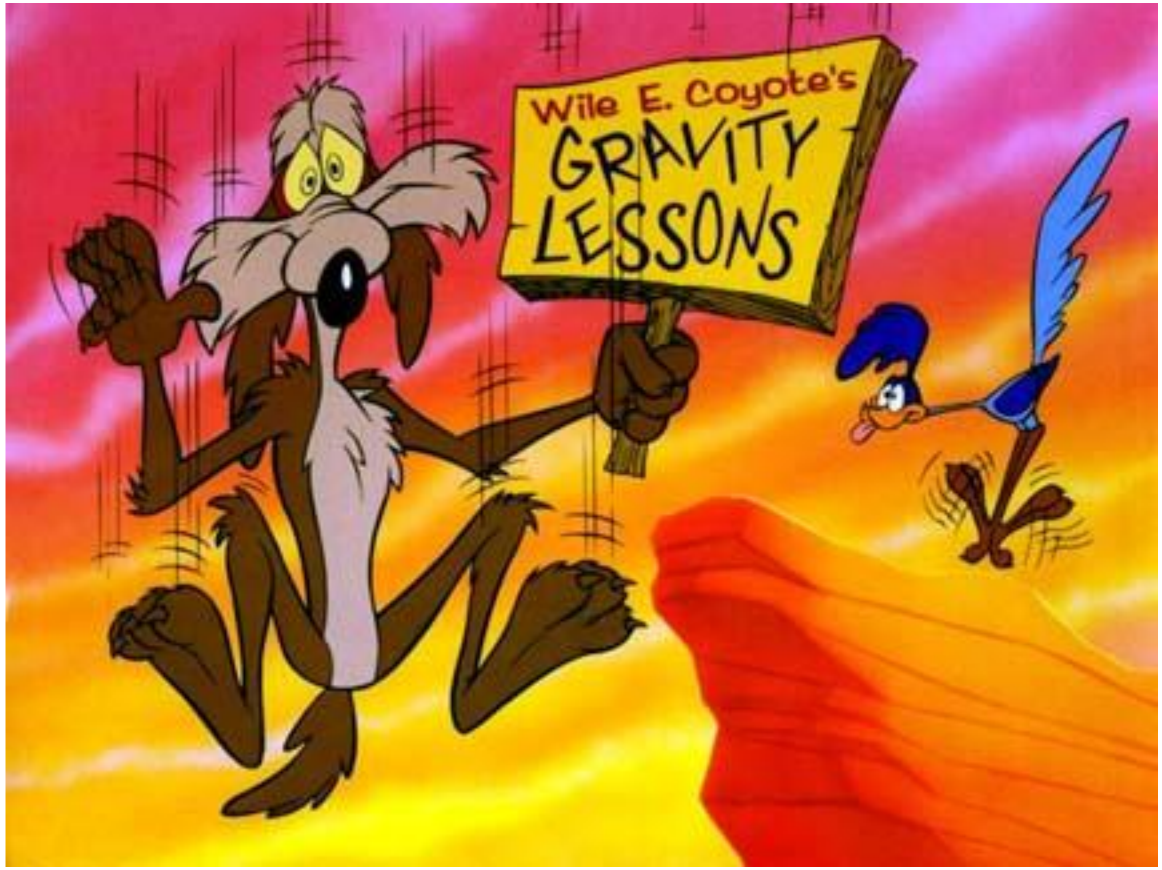
Conclusions

- Combined tests of structure formation crucial in distinguishing MG
- So far NO evidence for MG
- In the absence of well-motivated theories, PCA can detect departures from GR
- Future data will enable MUCH better PCA tests (number of constrained modes)

Pitfalls in Dark Parameterization

Chaz Shapiro (Portsmouth, ICG)

What are the consequences of choosing a wrong model?



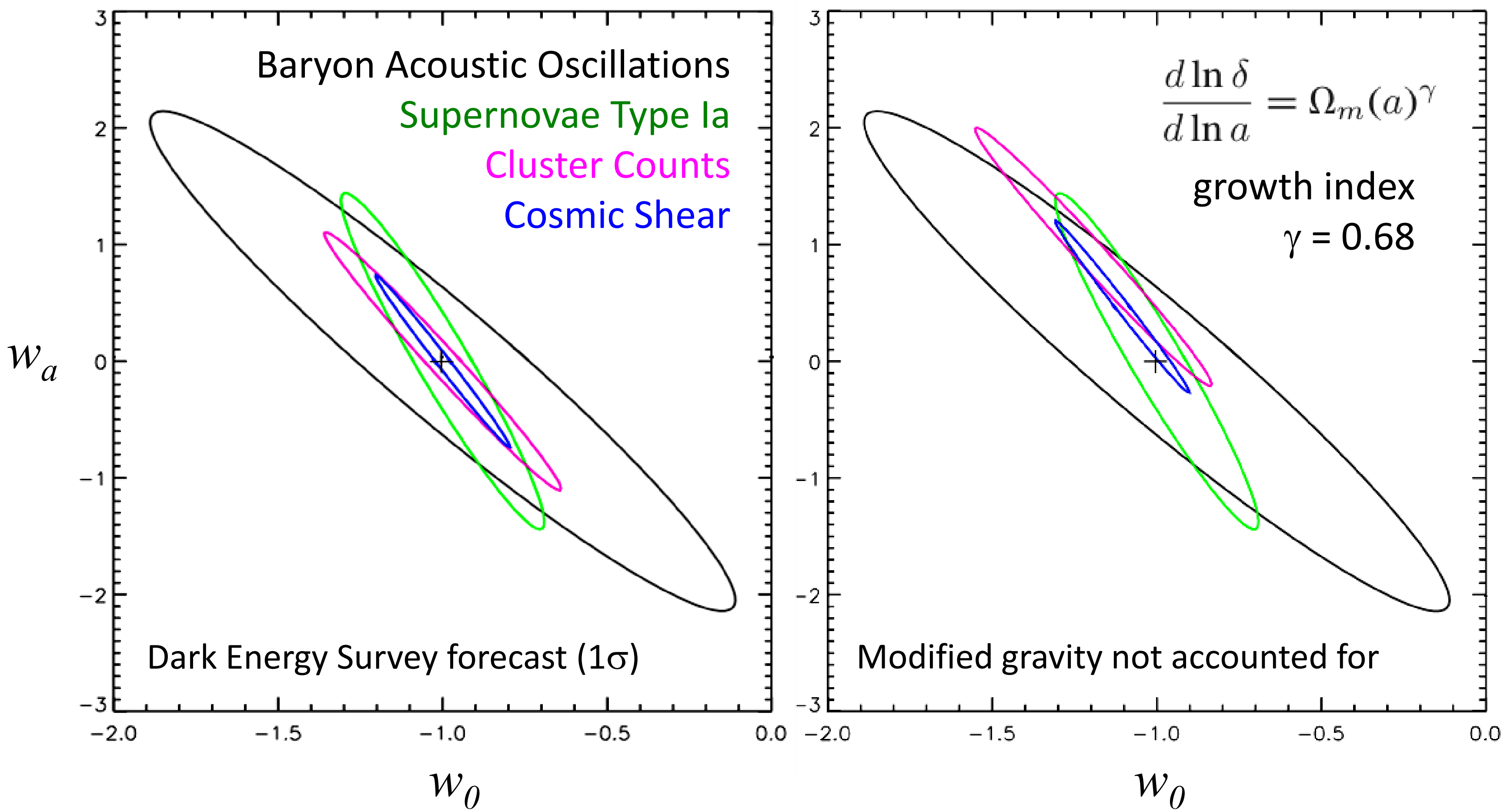
arXiv:1004.4810

With Scott Dodelson, Ben Hoyle, Lado Samushia and Brenna Flaugher

- Claimed detection of GR violation by Bean (false) – at the time, looked large enough to be easily confirmed by Dark Energy Survey.

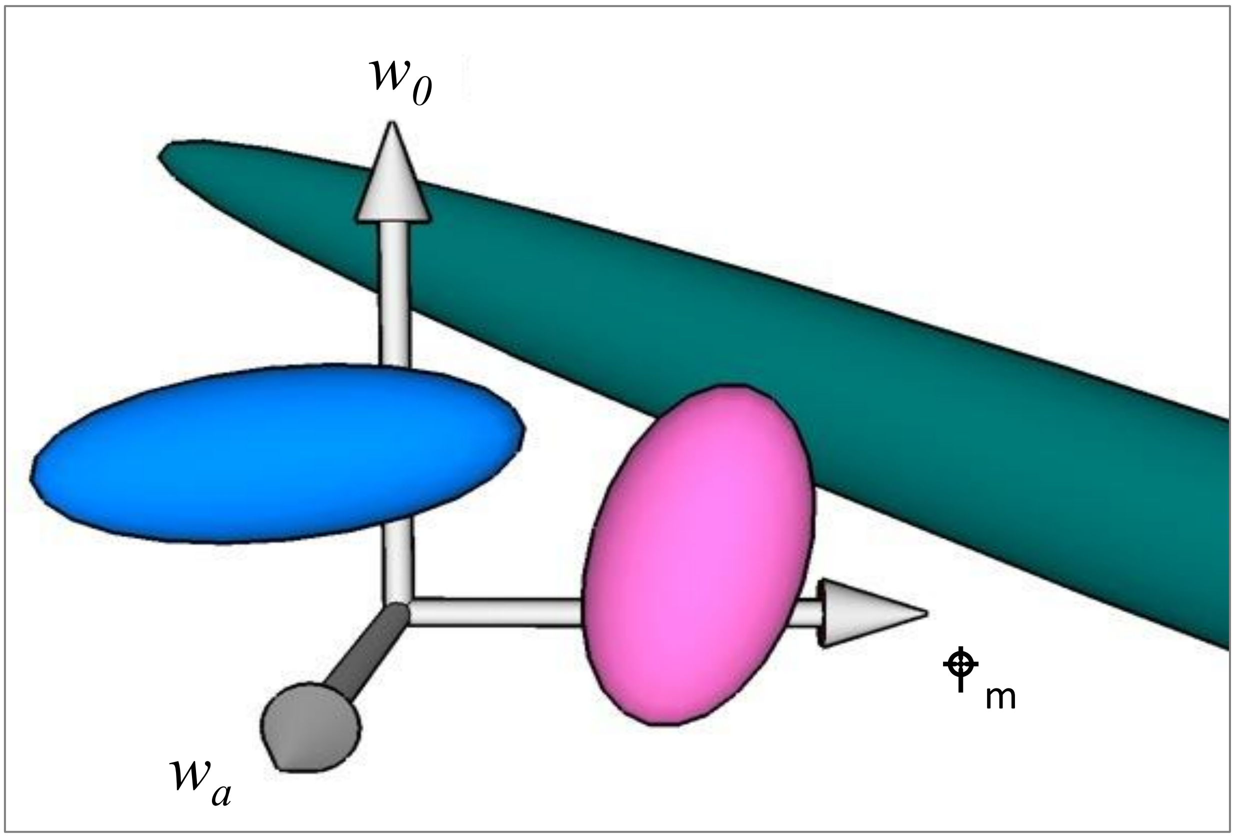
- What is the simplest GR check we can do?

- **Premise:** Suppose the Universe is described by modified gravity but we mistakenly analyze data assuming General Relativity plus a typical dark energy model, $w = w_0 + (1-a)w_a$



Drawbacks to this simple check:

- "Do the constraints overlap?" is not quantitative
- CMB data used multiple times → vague interpretation
- Parameter space is 8-dimensional – there could be inconsistency in w_0, w_a, Ω_m, Ω_k, Ω_b, H_0, n_s, σ_8



- **Method:** Treat the best-fit parameter set from each experiment as a "data point" with an "error bar" (confidence region). Find the parameter set λ_α most consistent with all data by minimizing

$$\chi^2(\lambda_\alpha) = \sum_i \sum_{\alpha\beta} (\lambda_\alpha - {\lambda_\alpha}^{(i)}) \left[C^{(i)}\right]^{-1}_{\alpha\beta} (\lambda_\beta - {\lambda_\beta}^{(i)})$$

$\lambda_\alpha^{(i)}$ = αth parameter obtained from *i*th probe

$C^{(i)}$ = covariance matrix for parameters from *i*th probe

- We find that $\langle \chi^2_{\mathrm{min}} \rangle = (N-1)M - \sum_i S^{(i)} + B$
  - M = #parameters , N = #probes , S = #degeneracies , B = "tension"
  - B is a function of Fisher matrices and **prediction errors** for all probes (see Fig 1). B=0 when we expect the same parameter set from all probes.
- **Large *B* indicates non-overlapping parameter constraints.** We'd interpret this as inconsistency with a goodness-of-fit given by the χ^2 probability distribution for ν degrees of freedom:

$$P(\chi^2_{\mathrm{min}} > \nu + B; \nu) \qquad \nu = (N-1)M - \sum_i S^{(i)}$$

Results: In our scenario, using a GR+dark energy model instead of the (true) modified gravity model yields **non-overlapping 8D parameter constraints** from the 4 DES probes + Planck.

WL	CL	SN	BAO	CMB	ν	B	$P(\chi^2_{\min} > \nu + B; \nu)$
	√		√	√	5	2.06	0.2164
	√	√		√	5	1.67	0.2466
	√	√	√		4	0.02	0.4030
	√	√	√	√	9	3.02	0.2121
√			√	√	6	2.08	0.2326
√		√		√	6	1.96	0.2414
√		√	√		5	0.75	0.3313
√		√	√	√	10	2.21	0.2715
√	√			√	6	6.71	0.0478
√	√		√		5	0.61	0.3462
√	√		√	√	10	8.23	0.0512
√	√	√			5	2.29	0.2003
√	√	√		√	10	9.22	0.0376
√	√	√	√		9	2.76	0.2271
√	√	√	√	√	14	15.58	0.0087

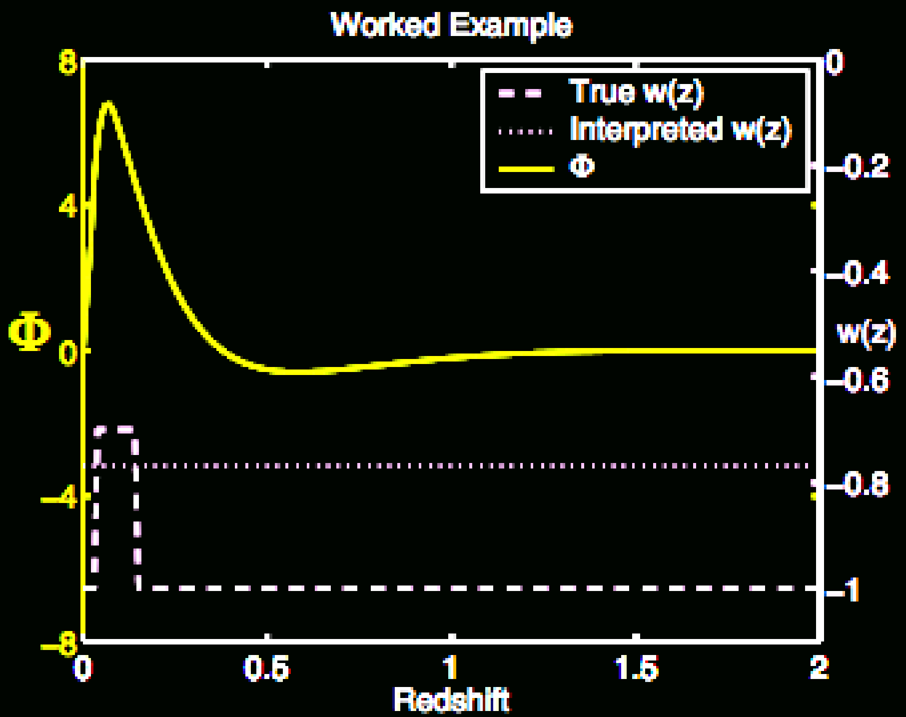
CMB and WL Fisher matrices have 3 degeneracies. SN, BAO, CL have 4.

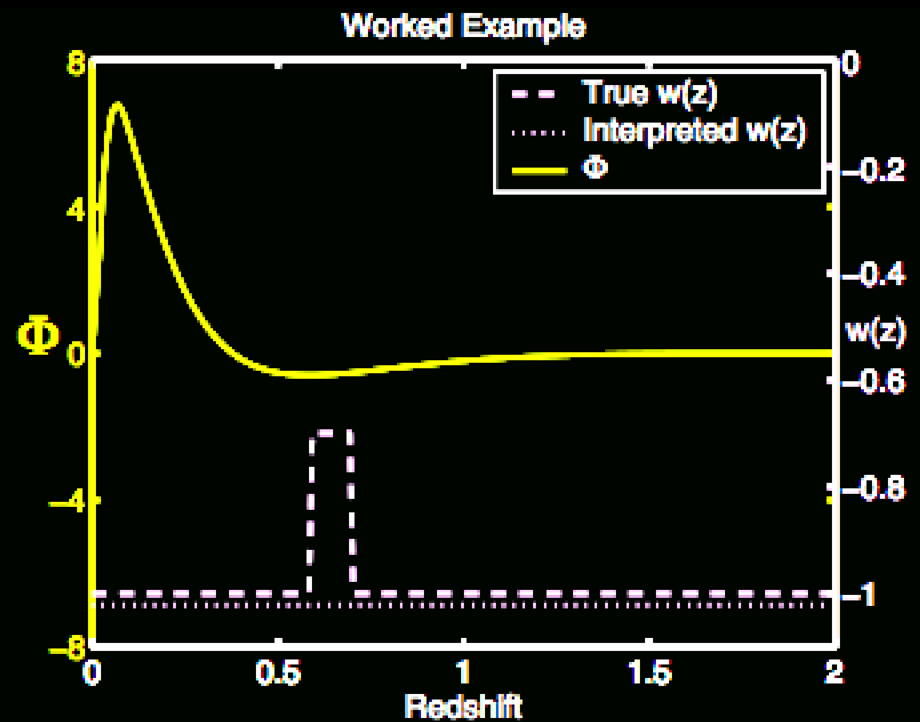
- Combining all probes gives 99% inconsistency. For 2♦ inconsistency, we need at least CMB, clusters and lensing.
- CMB is crucial, indicating that tension occurs in parameters that are well-measured by Planck.
- Tension exists despite degeneracies (infinite error bars) in each probe.
- If we generally expect tension from MG but do not see it, we can cite this as evidence for GR.

What if we just guess the wrong function? Simpson & Bridle (2006)

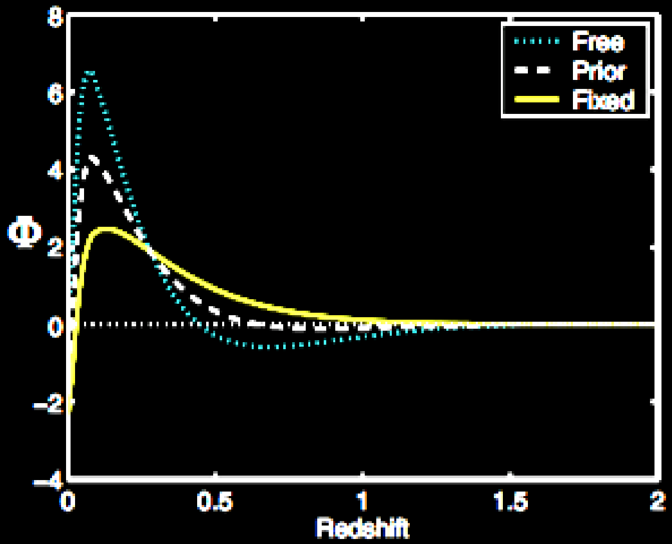
$$w^{\text{fit}} = \int \Phi(z) w(z) \mathrm{d}z.$$

Worst case scenario

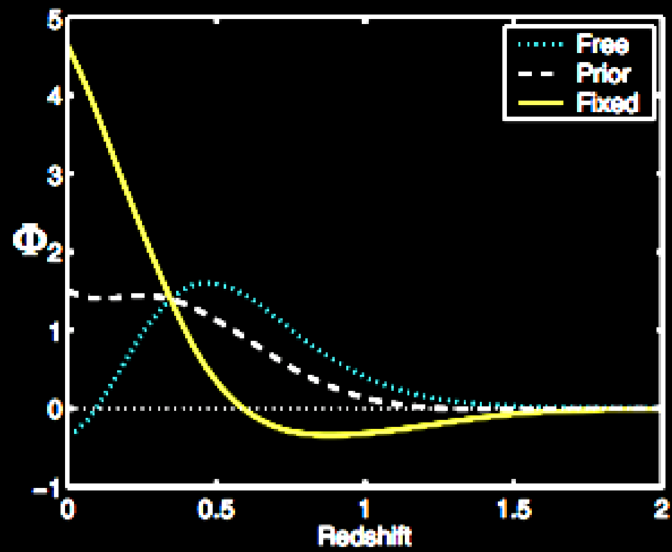




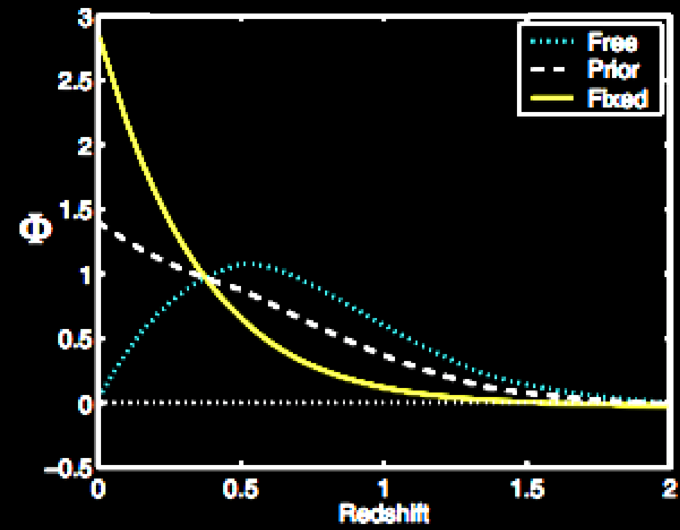
SNAP-like SNe



SNAP-like Cosmic Shear



WFMOS-like BAO



If we guess the wrong function, different weighting functions among several probes could lead to non-overlapping constraints on various parameters