Constraining Modified Gravity with current cosmological data

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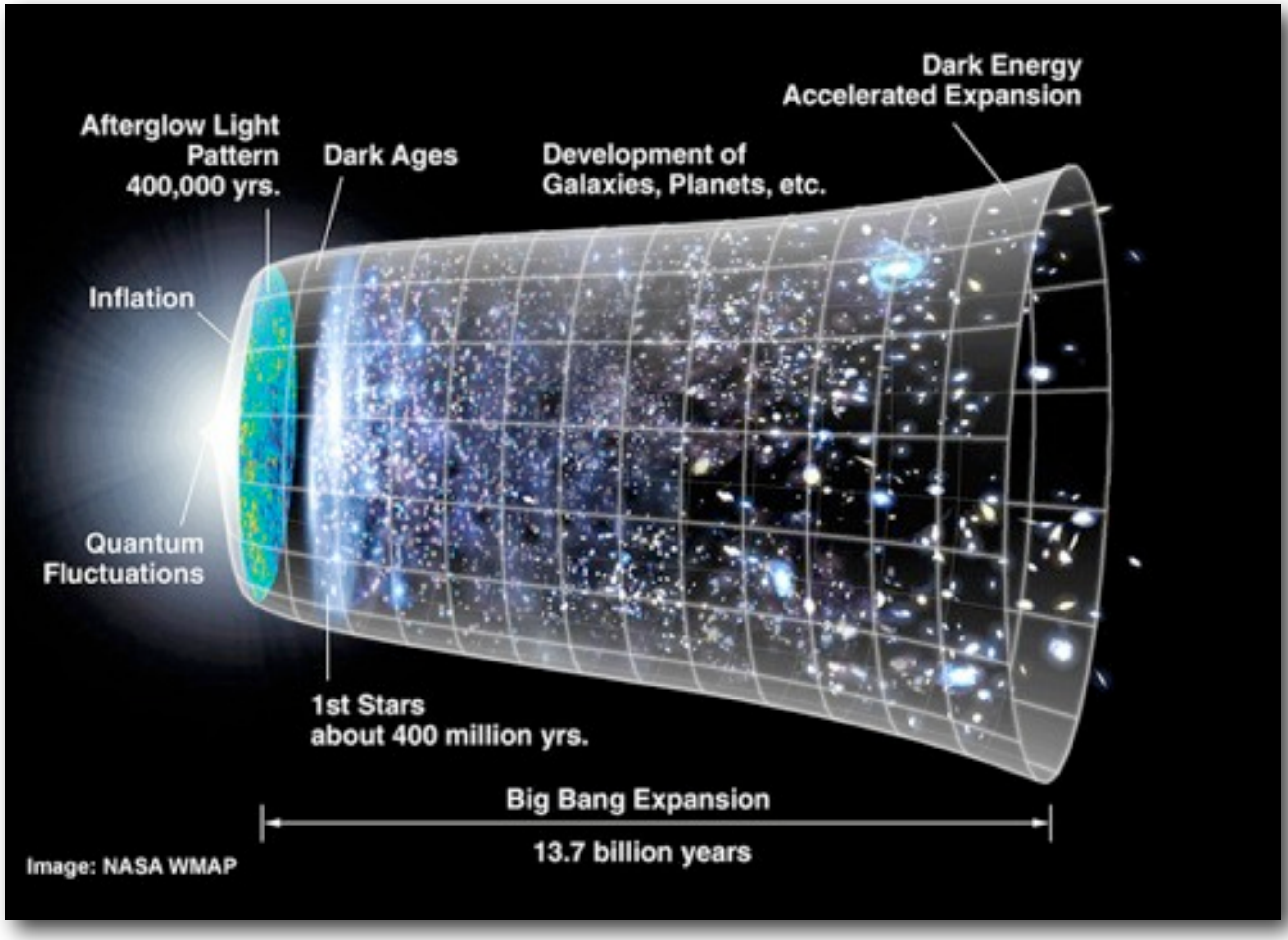
Bonn - Bad Honnef, 5th October 2010

Outline

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

Dark Energy vs Modified Gravity

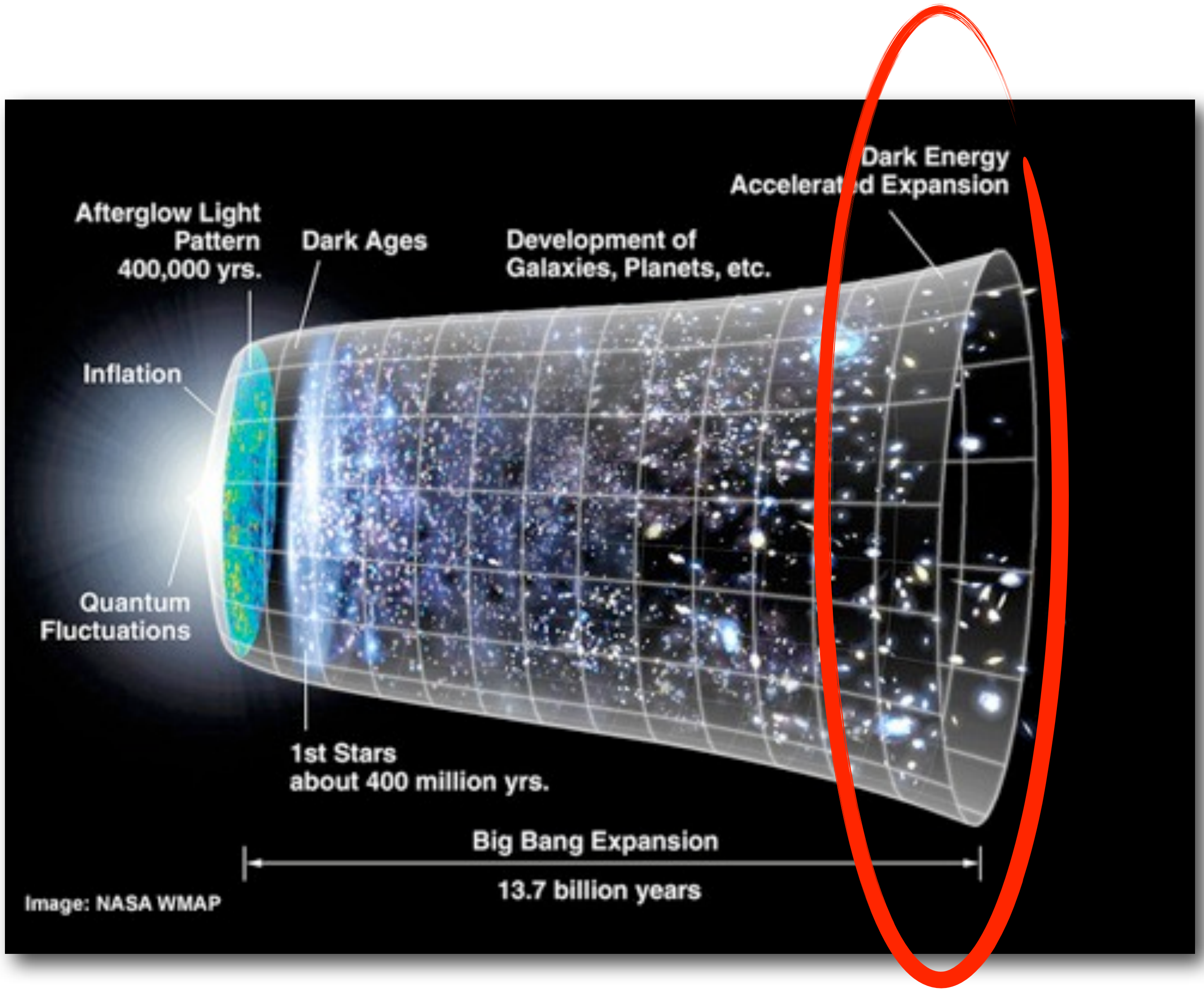


Dark Energy vs Modified Gravity

- Cosmic acceleration: either vacuum, Λ, or ρ_{vac}=0 and new physics
- from either side of Einstein's equation

$$G_{\mu\nu} + G^{darkG}_{\mu\nu} = 8\pi G\,(T_{\mu\nu} + T_{\mu\nu}^{darkE})$$

- Equivalent, MG can be better motivated (Lagrangian)



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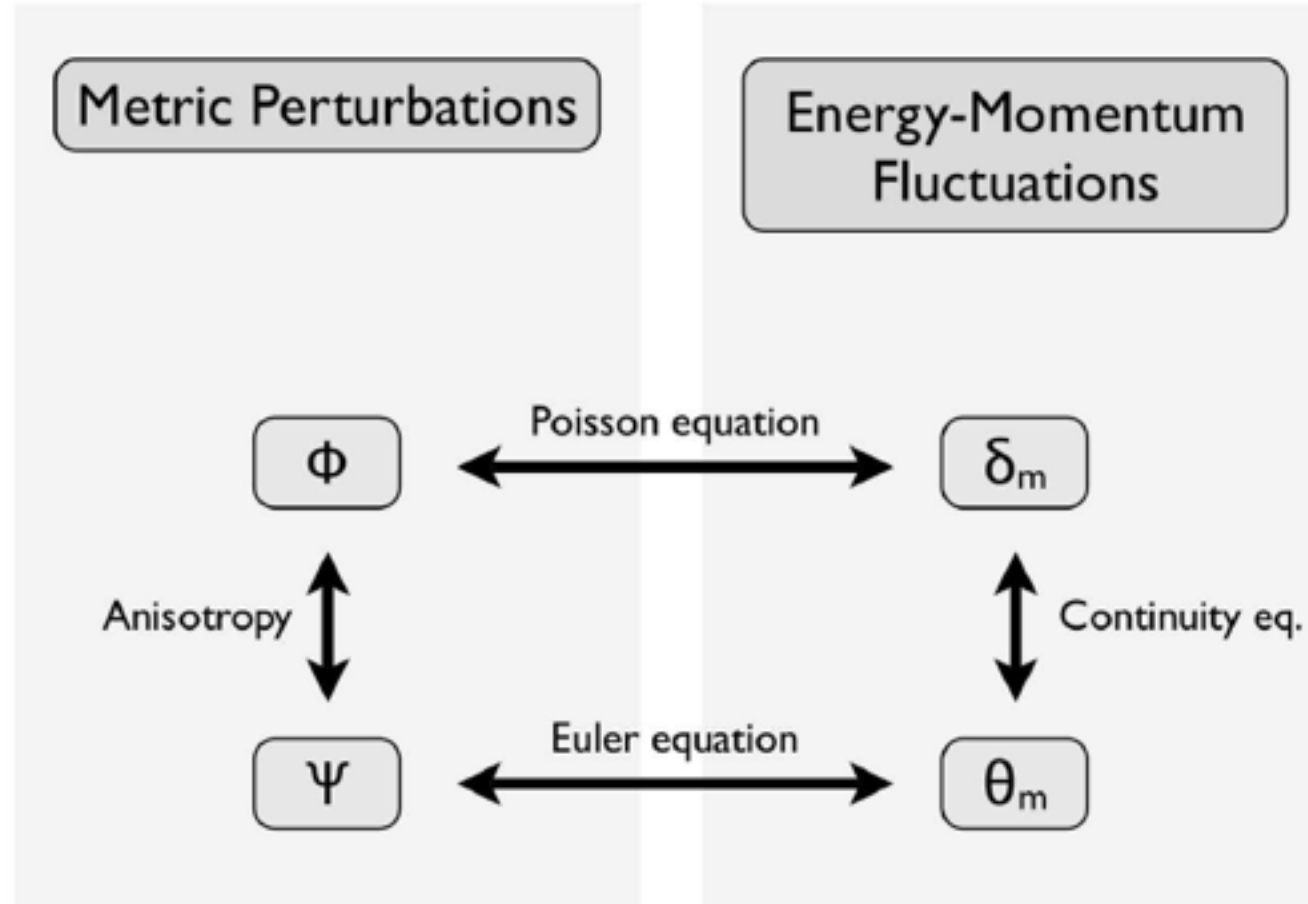
- Equivalent, MG can be better motivated (Lagrangian)
- A gravity theory: must pass all tests GR does!
    - GR limit in Solar System, no ghosts, simple (Occam), Lagrangian
- **Background expansion**
- **Structure formation**



(Song & Dore 08)

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

geometry and energy

Playing with gravity...

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

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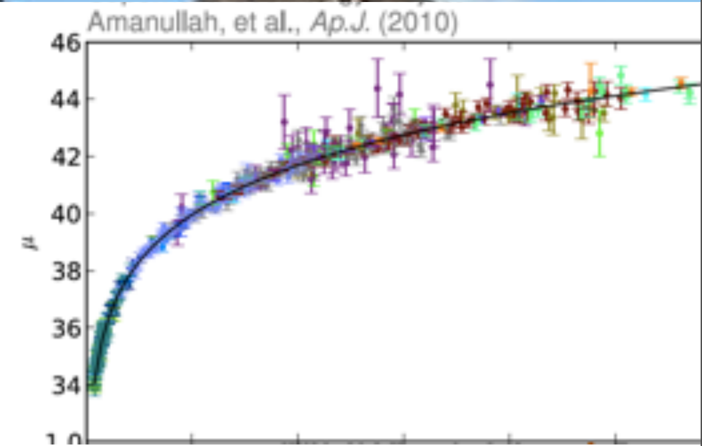
Theory: from degrees of freedom, propagation, interactions

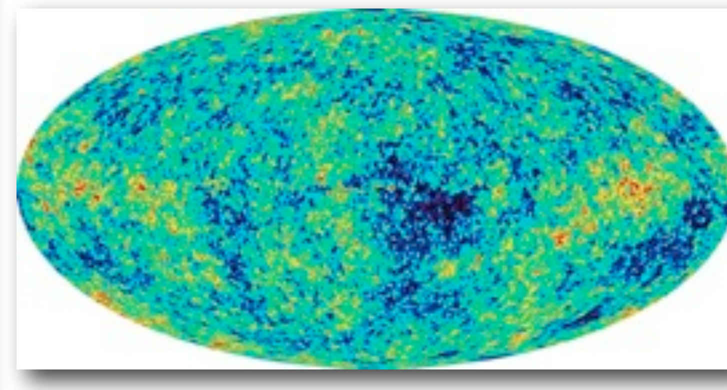
Phenomenology: what can we test? How to distinguish from Λ?

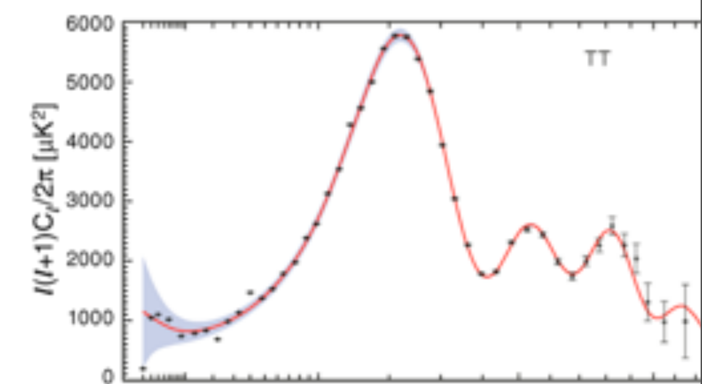
Many cosmological data...

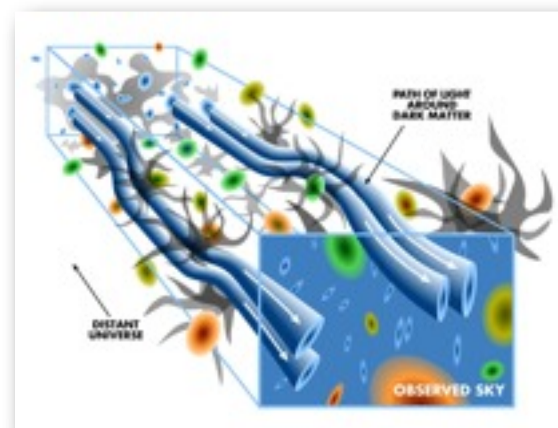
- **Supernovae**: SNLS, SDSS-II, HST, ESSENCE [Kessler et al 09]
- **CMB**: WMAP5
- Hubble constant (HST)

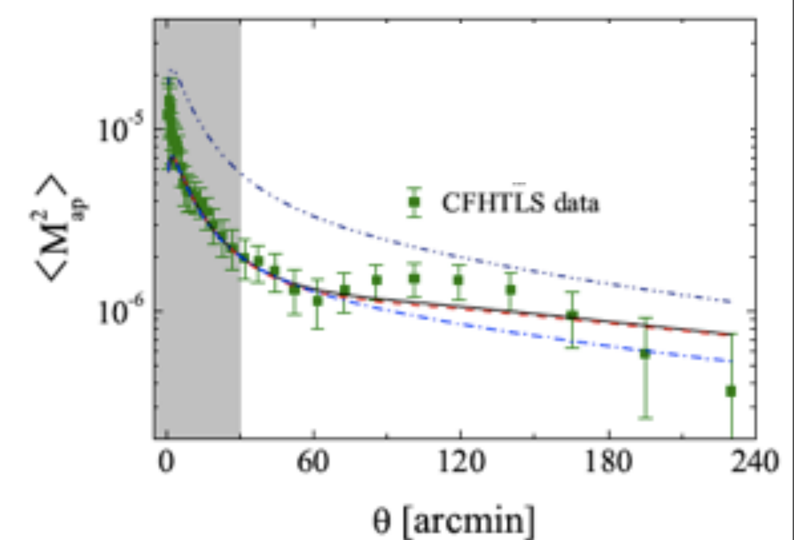
- **Weak lensing**: CFHTLS 3rd year release [Fu et al 08]: **linear range only (>30')**
- **ISW**: our combined analysis [TG et al 08]
- Further probes: **peculiar velocities**, **cluster** counts, ...

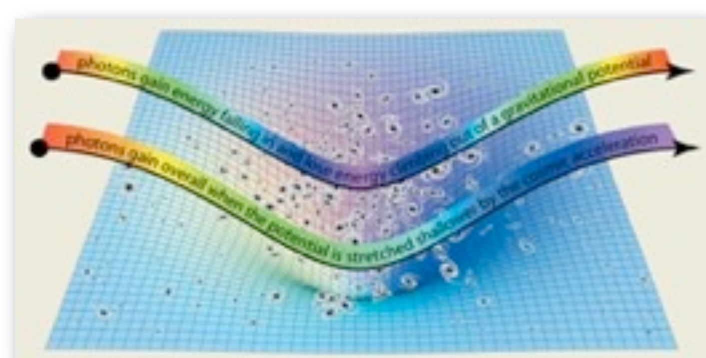


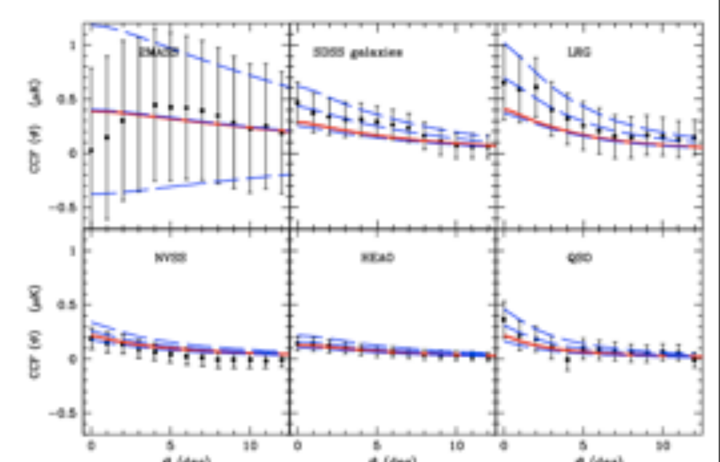












The ISW effect

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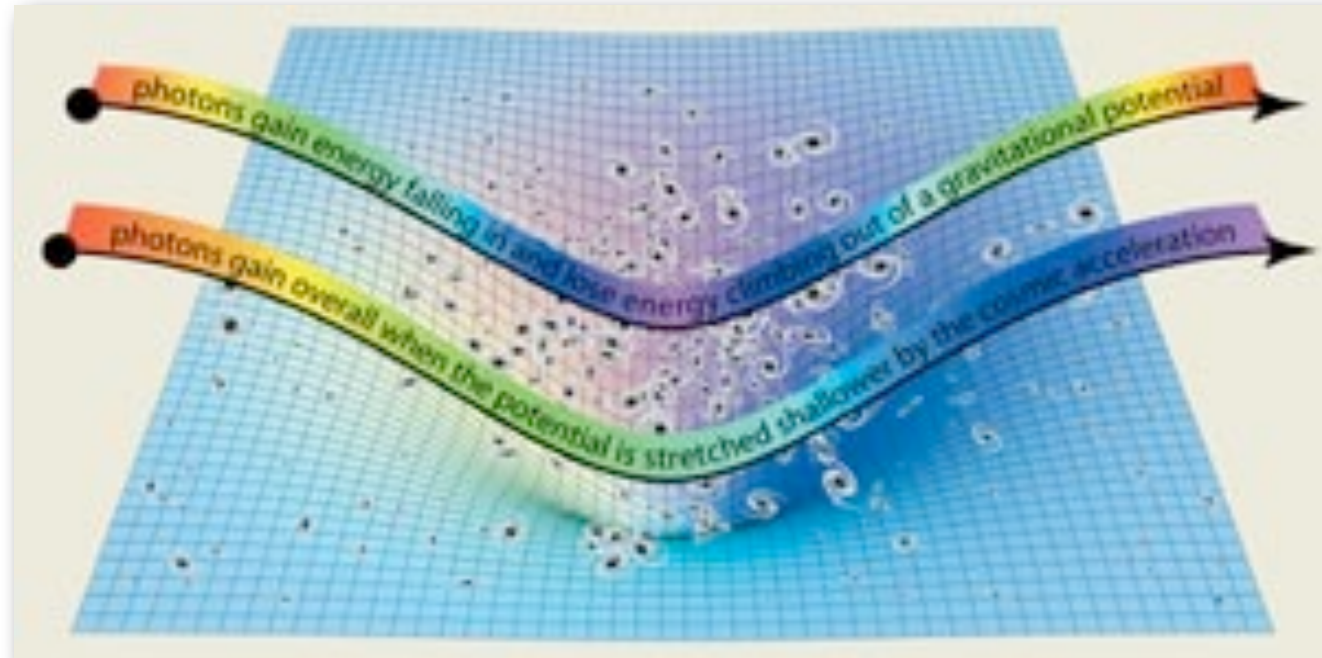

- Secondary CMB anisotropies

$$\frac{\Delta T}{T}(\mathbf{n}) = -\int (\dot{\Phi} + \dot{\Psi})[\tau, \mathbf{n}(\tau_0 - \tau)] d\tau$$

- GR, matter only: $\dot{\Phi} = \dot{\Psi} = 0$
- Nice probe of DE or MG !

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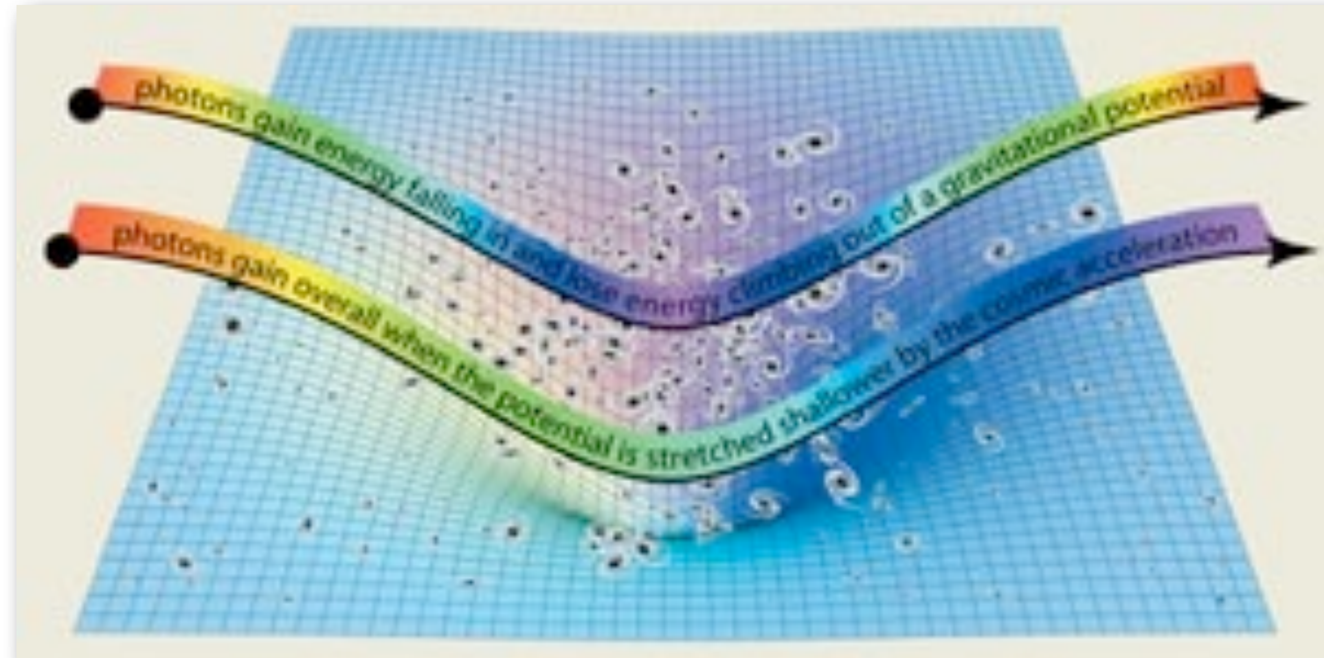
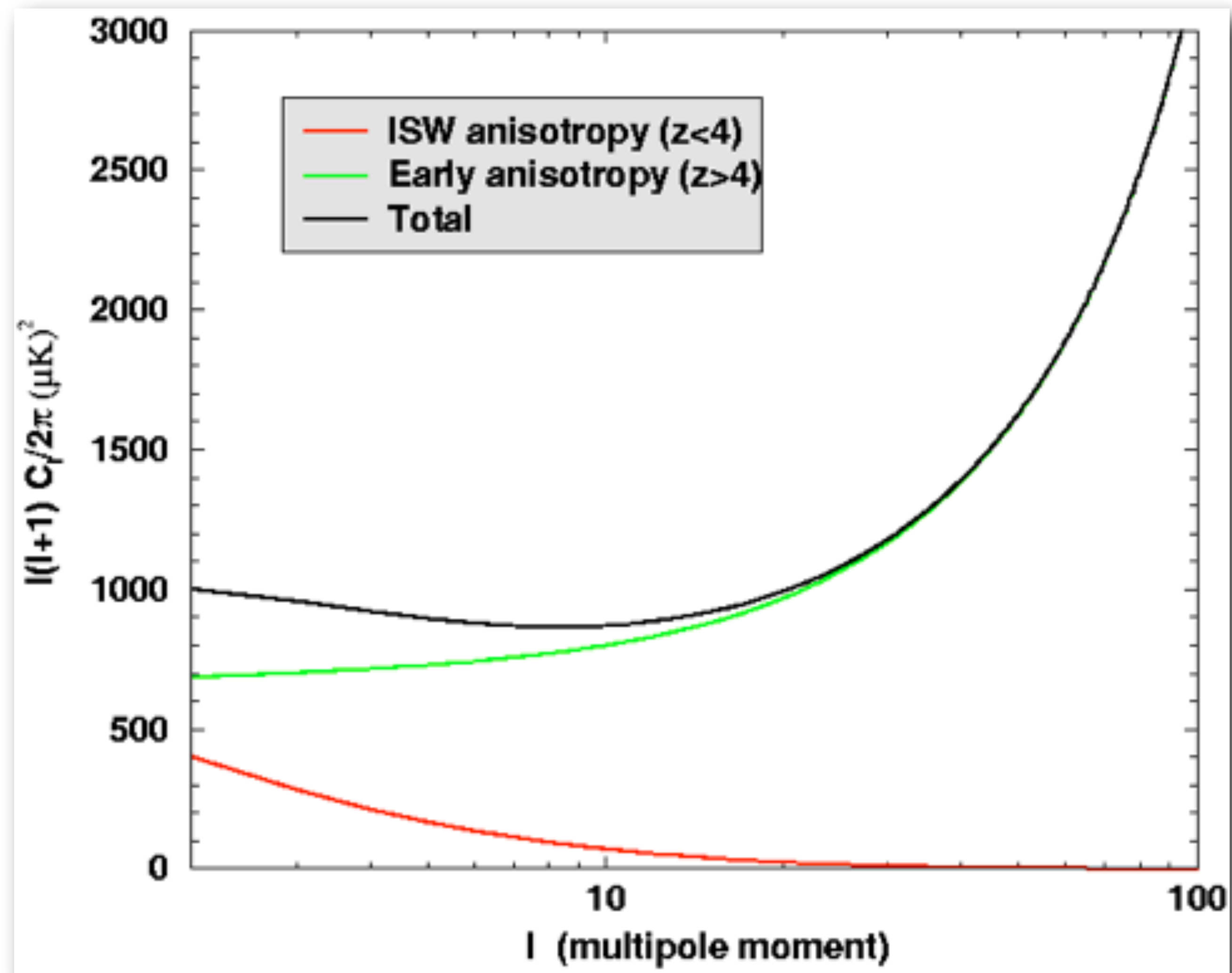
- Nice probe of DE or MG !
- Only 10% contribution to CMB, large scales

Can be measured cross-correlating CMB-galaxies

- Real space 2-point function or power spectra



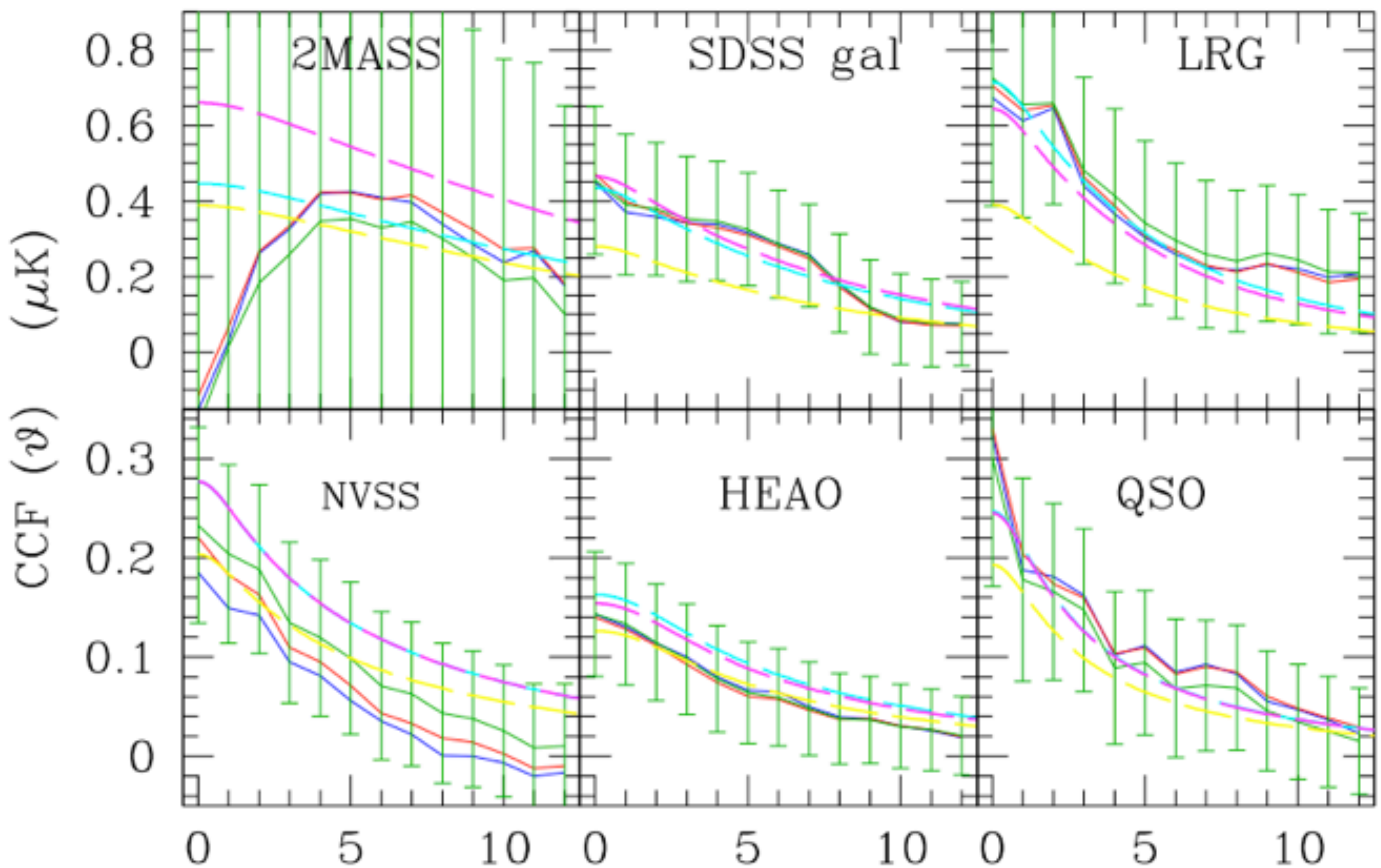


ISW measurements

- WMAP - galaxy correlations: ~2-3σ
- Optical: SDSS (gal, LRG, QSO), APM [Folsalba et al 2003; Scranton et al 2003; Padmanabhan et al 2005; Cabre et al 2006; TG et al 2006; Folsalba Gaztanaga 2004, Xia 09]
- Radio: NVSS, FIRST [Boughn & Crittenden 2004; Nolta et al 2004; Raccanelli et al 2008, wavelet analyses]
- IR: 2MASS [Afshordi et al 2004; Rassat et al 2007; Francis & Peacock 2009]
- X-ray: HEAO [Boughn & Crittenden 2004]
- Localised: [Granett et al. 08a,b]

ISW measurements

- Combined analysis of 6 catalogues: >4σ evidence, *including covariances*! [TG, Crittenden, Nichol et al 08, Ho et al 08]



for WMAP3-5-7

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Future: Pan-STARRS, DES

The ISW rotation test

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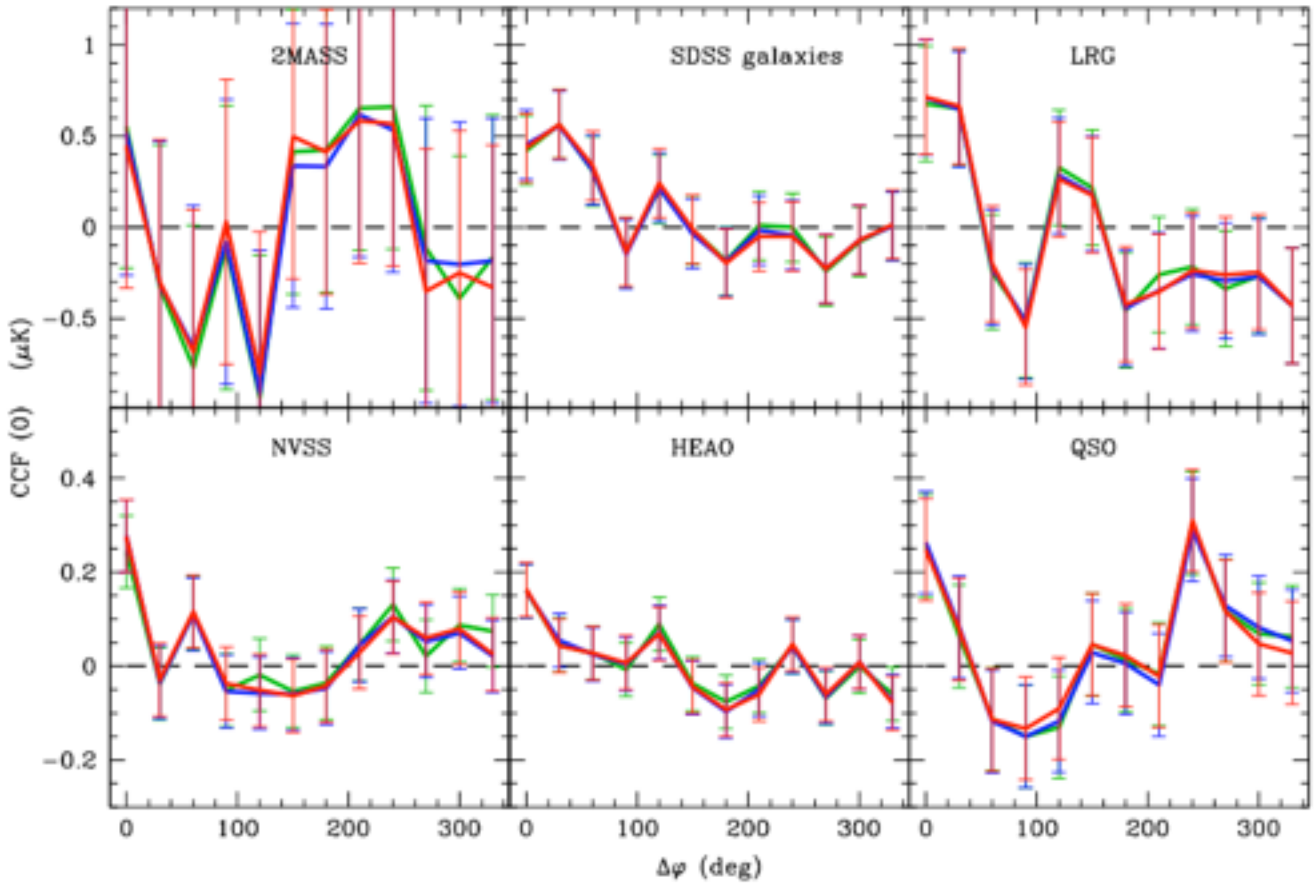
- Criticism by Sawangwit, Shanks, et al. (2009):

  "Rotating the maps, we sometimes see a comparable signals"

- True, but how significant?
- Expected scatter calculated with Monte Carlo simulated maps



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- True, but how significant?
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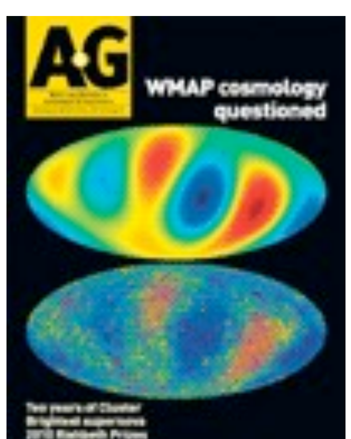
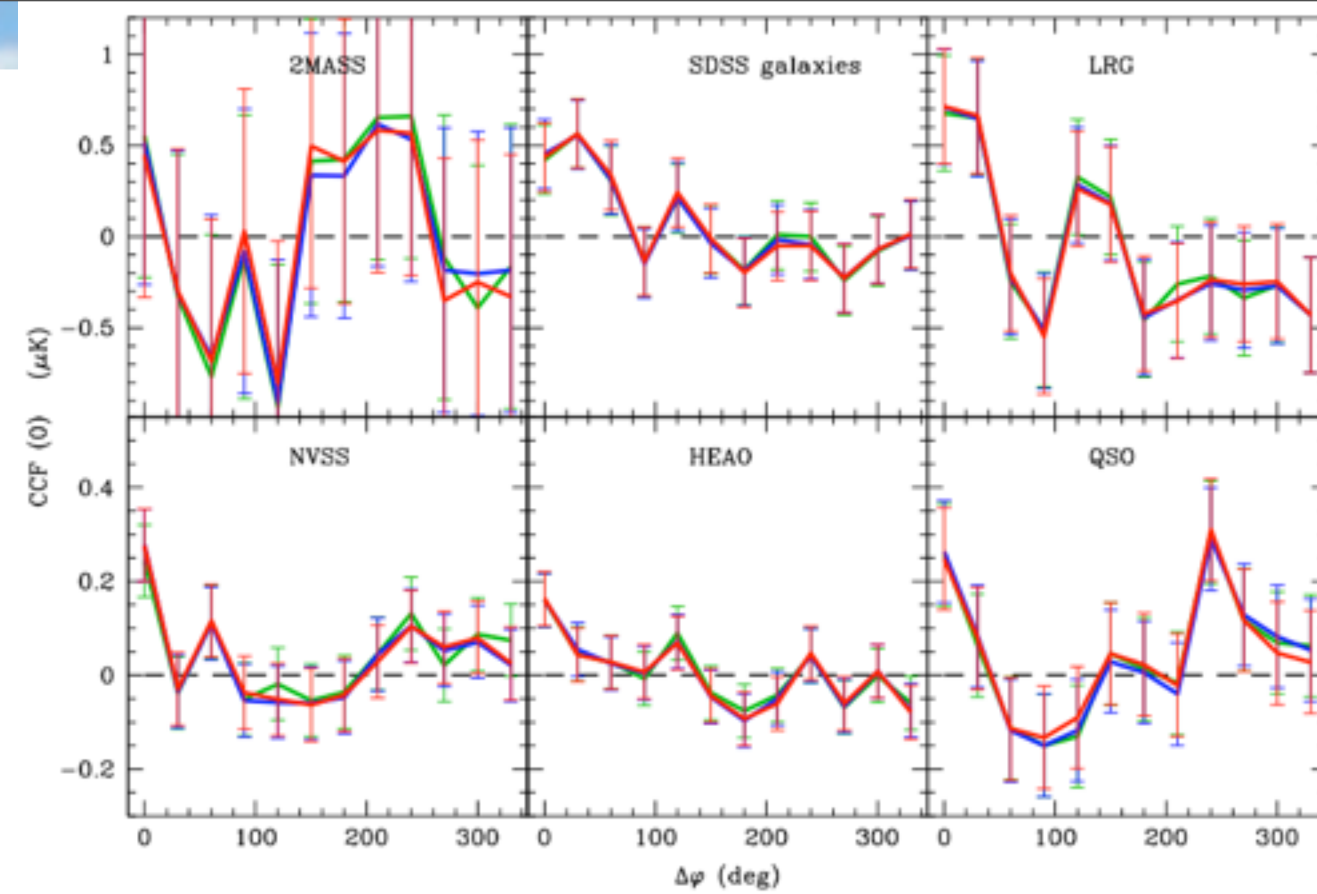
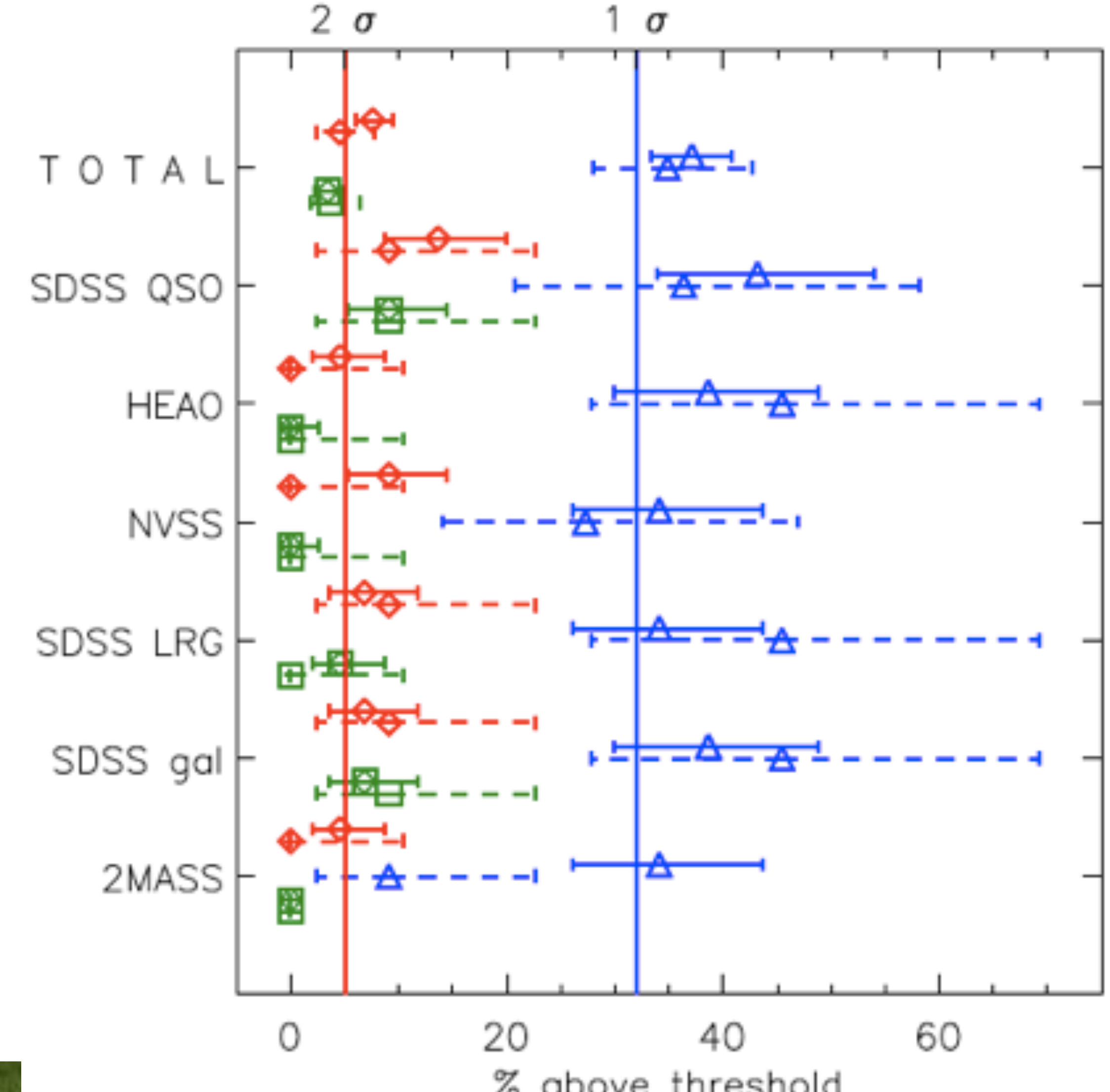
- Number of rotated points above a given threshold:

Is there anything special here?

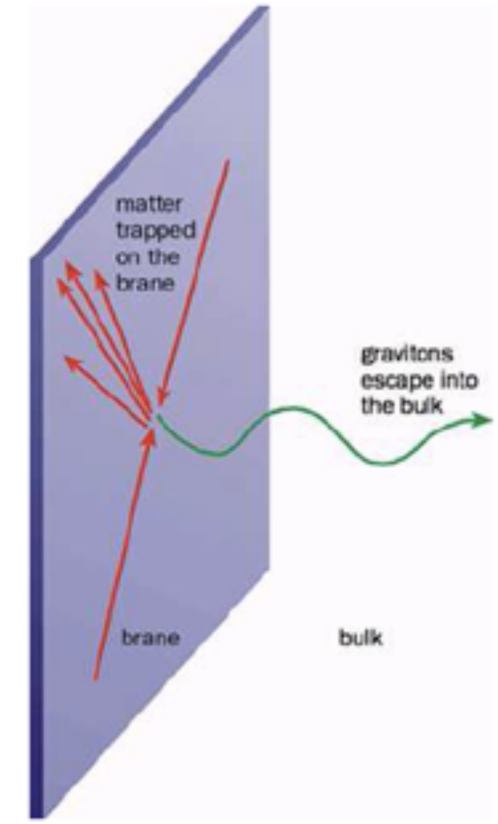






The DGP model

(Dvali, Gabadadze & Porrati 00)



- 4D brane in Minkowski 5D bulk

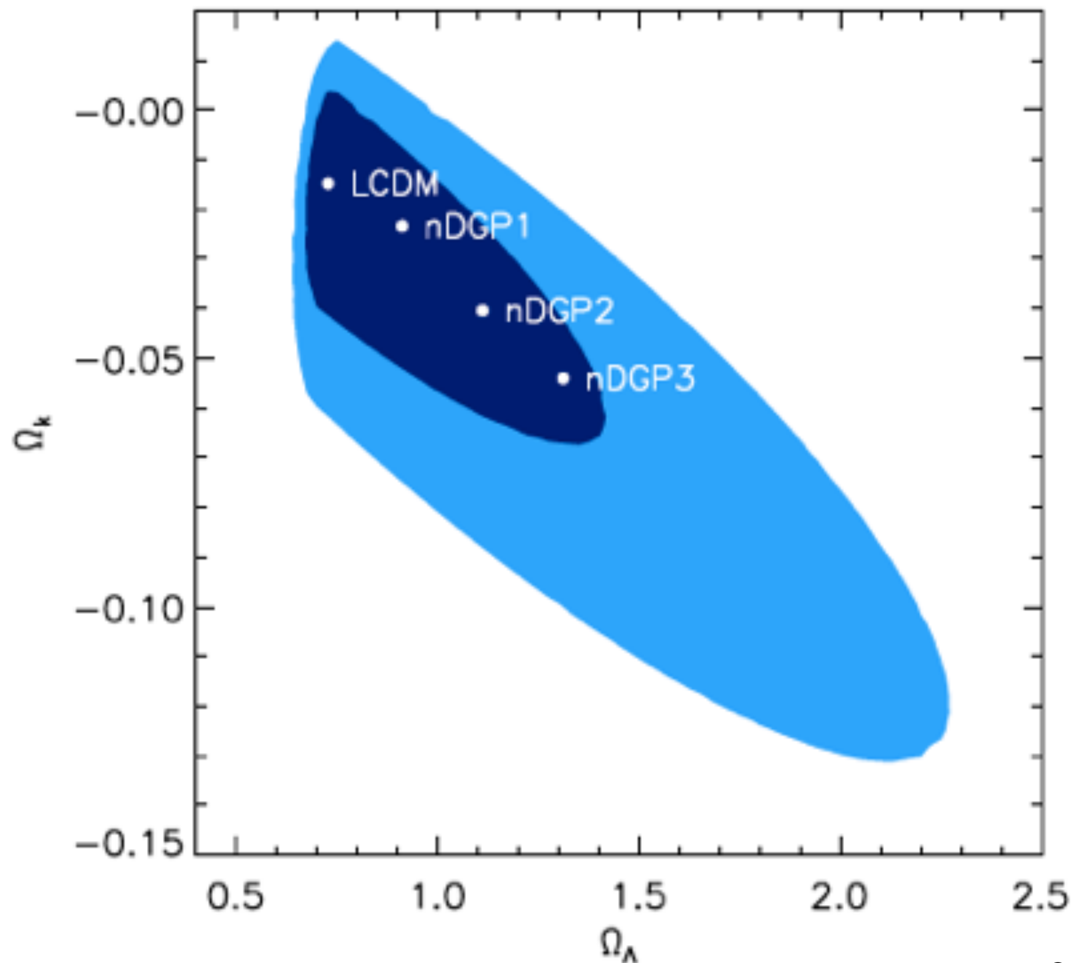
$$S_5 = -\frac{1}{16\pi}M^3 \int d^5x\,\sqrt{-g}\,R - \frac{1}{16\pi}M_P^2 \int d^4x\,\sqrt{-g^{(4)}}\left[R^{(4)} - \frac{16\pi}{M_P^2}\mathcal{L}_{\rm m}\right]$$

- Background: new Friedmann equation

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

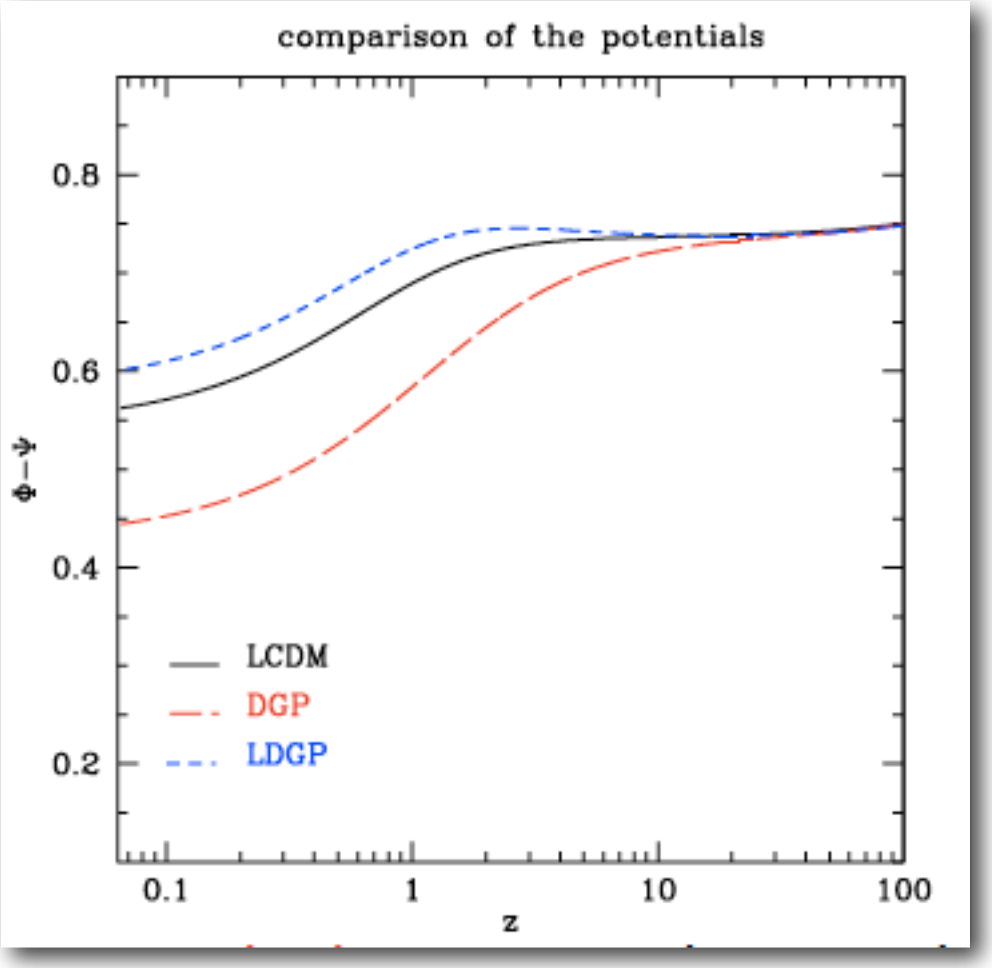
  - minus: self-accelerating branch, acceleration today if $r_c \sim H_0^{-1}$: ruled out already by background (Majerotto & Maartens 06, Fang et al 08)

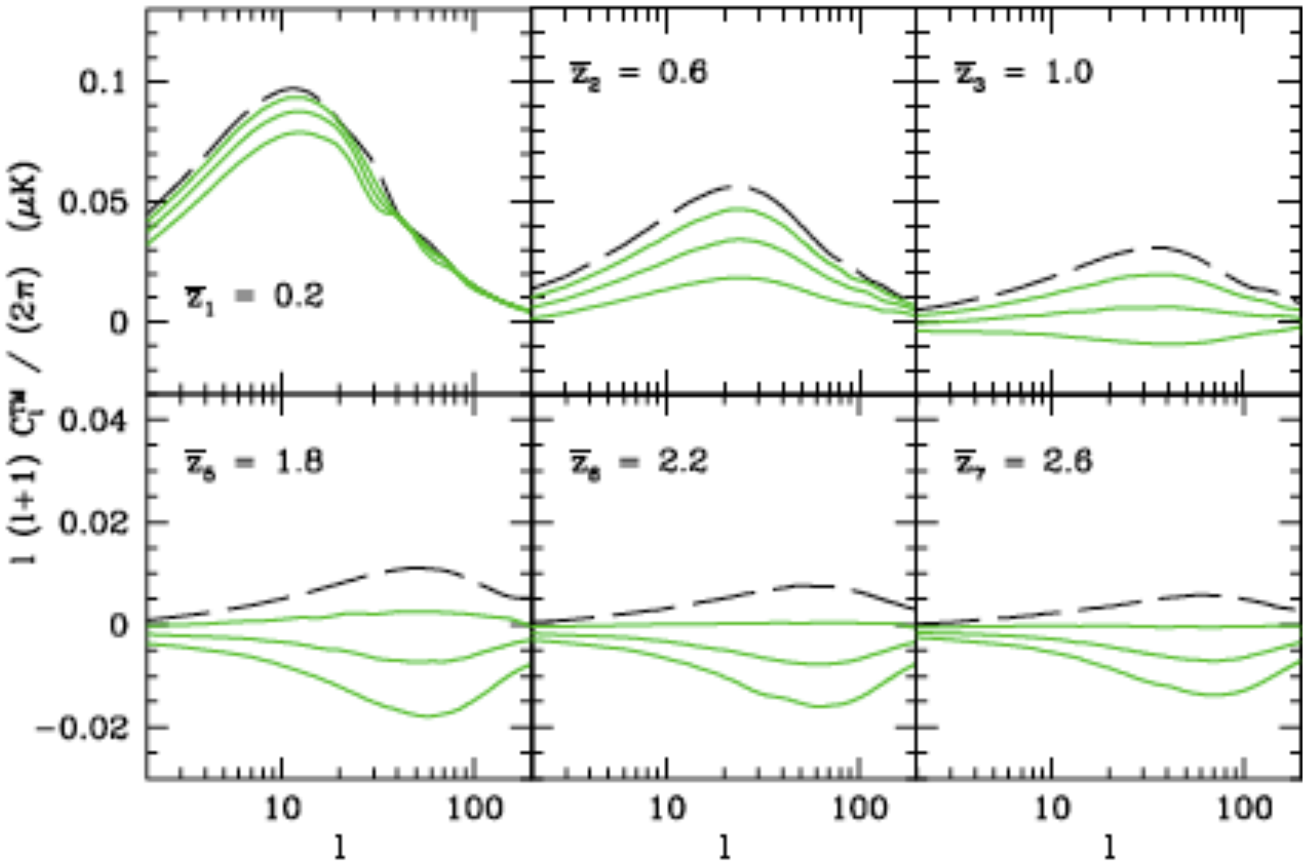
  - plus: normal branch: needs Λ (brane tension) some parameter space unconstrained by background...



Constraints on the DGP model(s)

- Potentials decay different in each model!
- self-accelerating: background (Majerotto & Maartens 06) + CMB + ISW: ruled out at 4σ! (Fang et al. 08)
- normal branch: extra dof, from background 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

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- 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** $f_R \equiv df/dR$
- Effective fluid with eq. of state $w_{\rm eff} = -\frac{1}{3} - \frac{2}{3}\frac{\left[H^2 f_R - \frac{f}{6} - H\dot{f}_R - \frac{1}{2}\ddot{f}_R\right]}{\left[-H^2 f_R - \frac{f}{6} - H\dot{f}_R + \frac{1}{6}f_R R\right]}$
- From expansion history, we solve f_R: **a family of models**!

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- From expansion history, we solve f_R: **a family of models**!
- Associated wawelength, mass $$\lambda_c \equiv \frac{2\pi}{m_{f_R}} \qquad m^2_{f_R} \equiv \frac{\partial^2 V_{\rm eff}}{\partial f_R^2} = \frac{1}{3}\left[\frac{1+f_R}{f_{RR}} - R\right]$$
- 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): $$\frac{\Phi}{\Psi} = \frac{1+\frac{2}{3}\frac{k^2}{a^2}m}{1+\frac{4}{3}\frac{k^2}{a^2}m} \equiv \eta(a,k)$$

Constraints on f(R)

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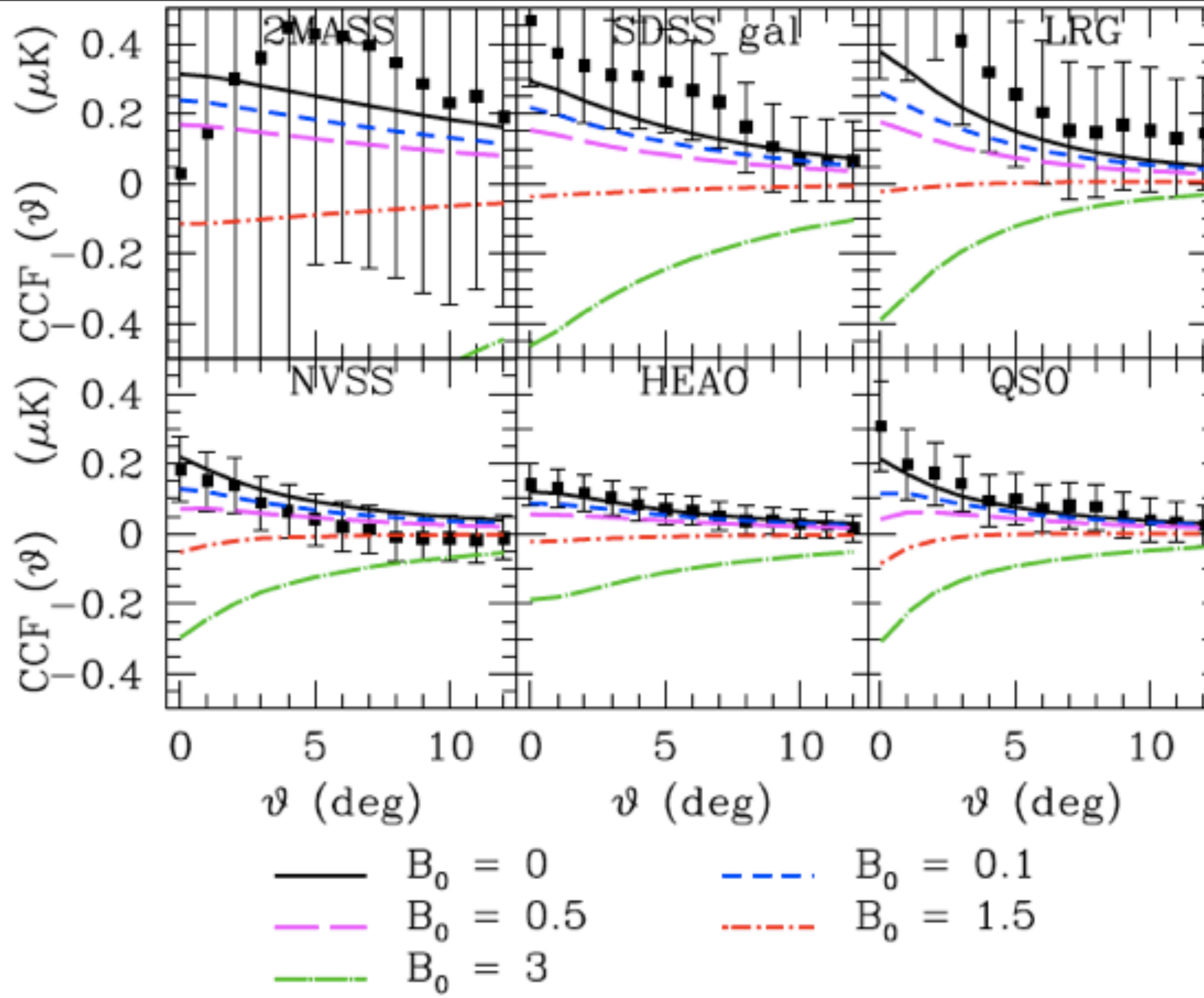
- Background identical to LCDM
- Structure formation different!
- MCMC with CMB + SN + ISW
- One parameter: wavelength today in H units: $B_0 = \frac{2\pi H_0}{mc}$



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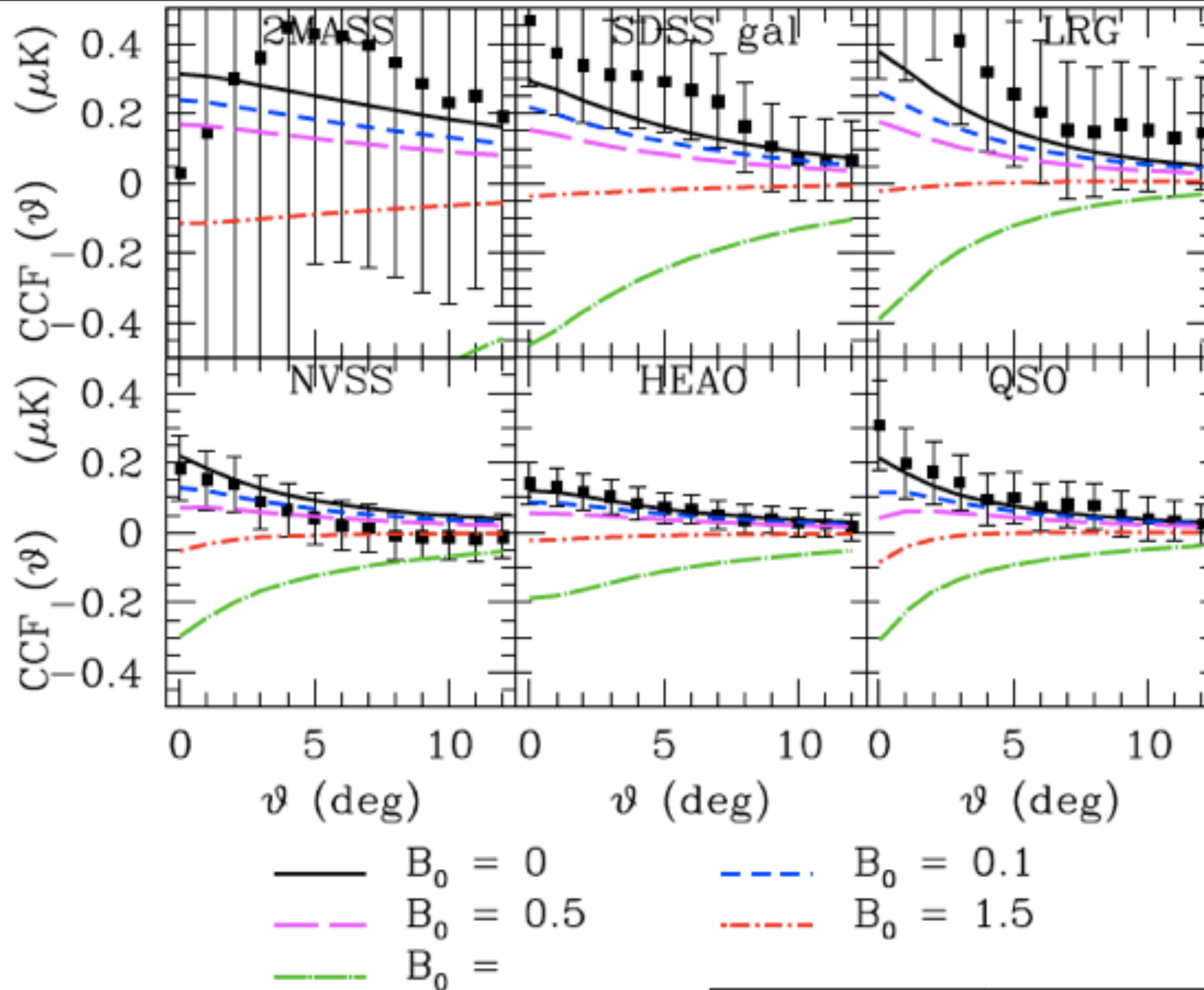
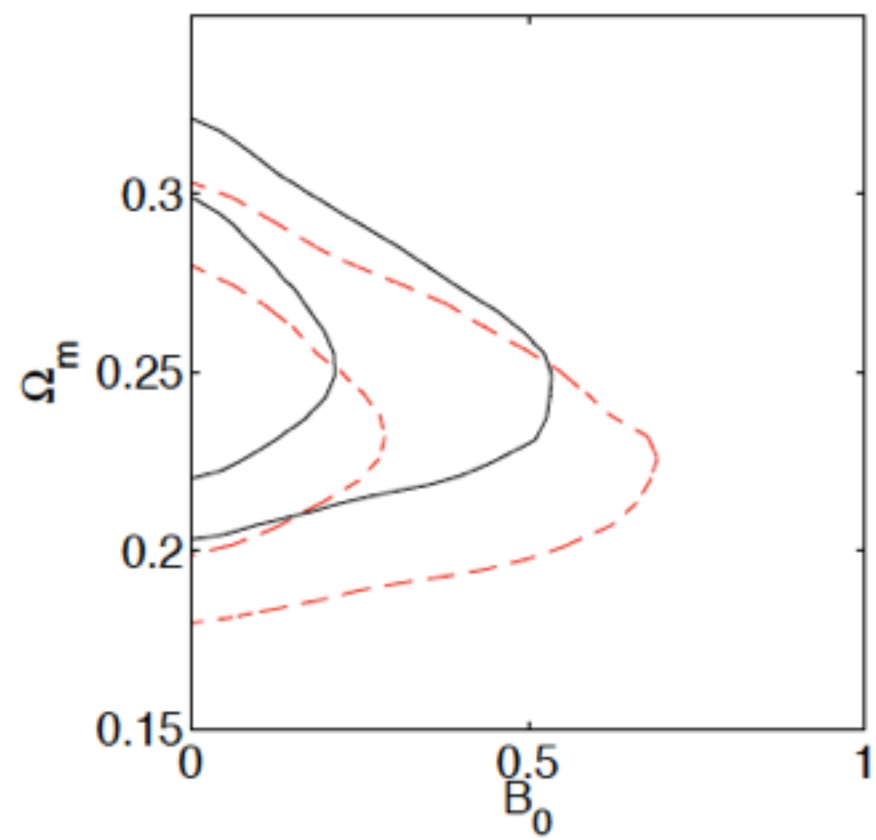
- In GR: $B_0 = 0$
- CMB only: $B_0 < 1$ (Song, Peiris, Hu 07)
- With ISW: $B_0 < 0.4$ @ 95%

Adding non-linear scales (clusters) even tighter (Vihlinkin, Hu et al 09, Lombriser et al 10)





General parametrisation of Modified Gravity [Zhao et al 08, Cooray et al, Daniel et al 10]

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

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- Poisson equation (sub-horizon),
- Anisotropy equation:

$$k^2\Psi = -4\pi G a^2 \mu(a,k)\rho\Delta$$
$$\frac{\Phi}{\Psi} = \eta(a,k)$$

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

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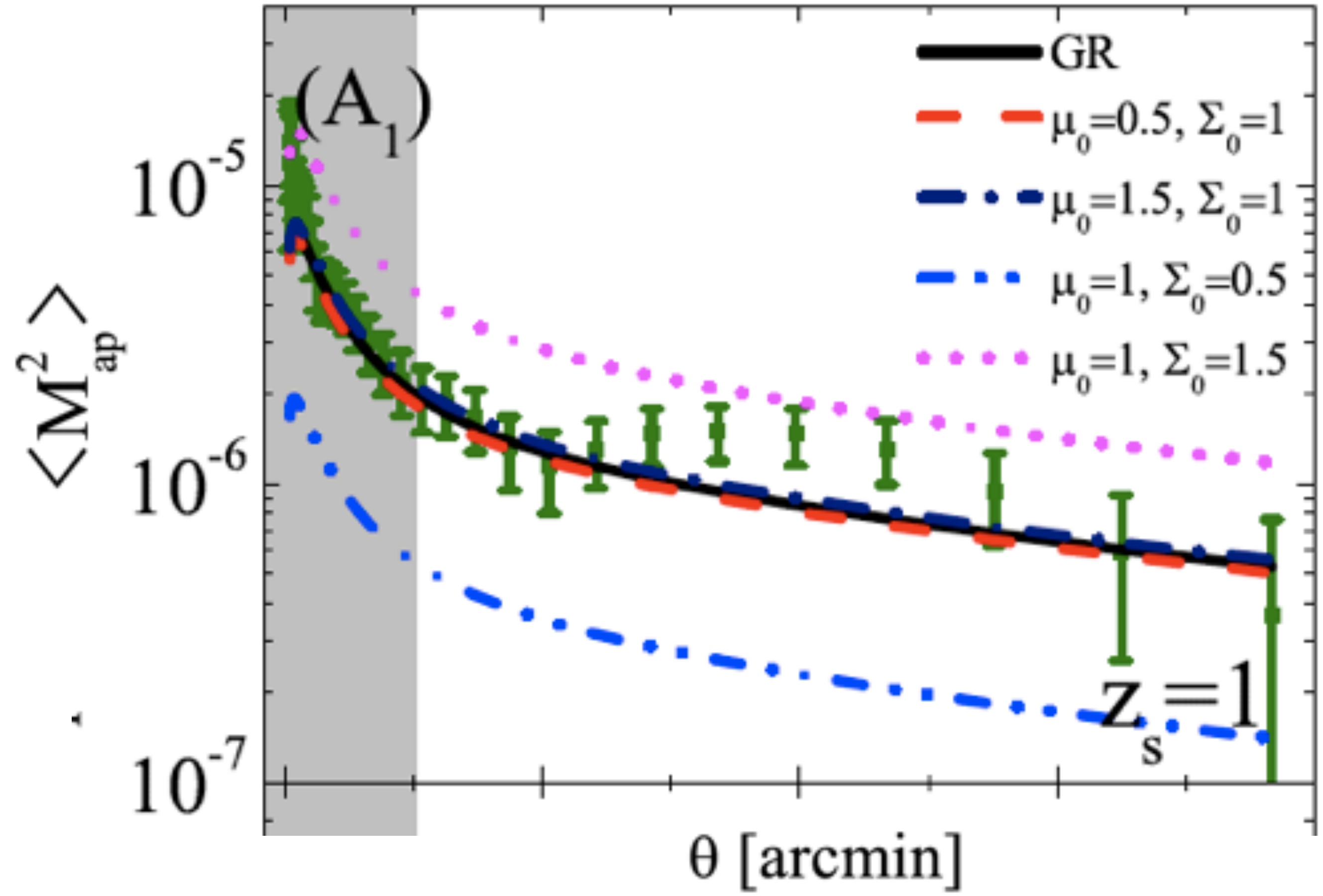
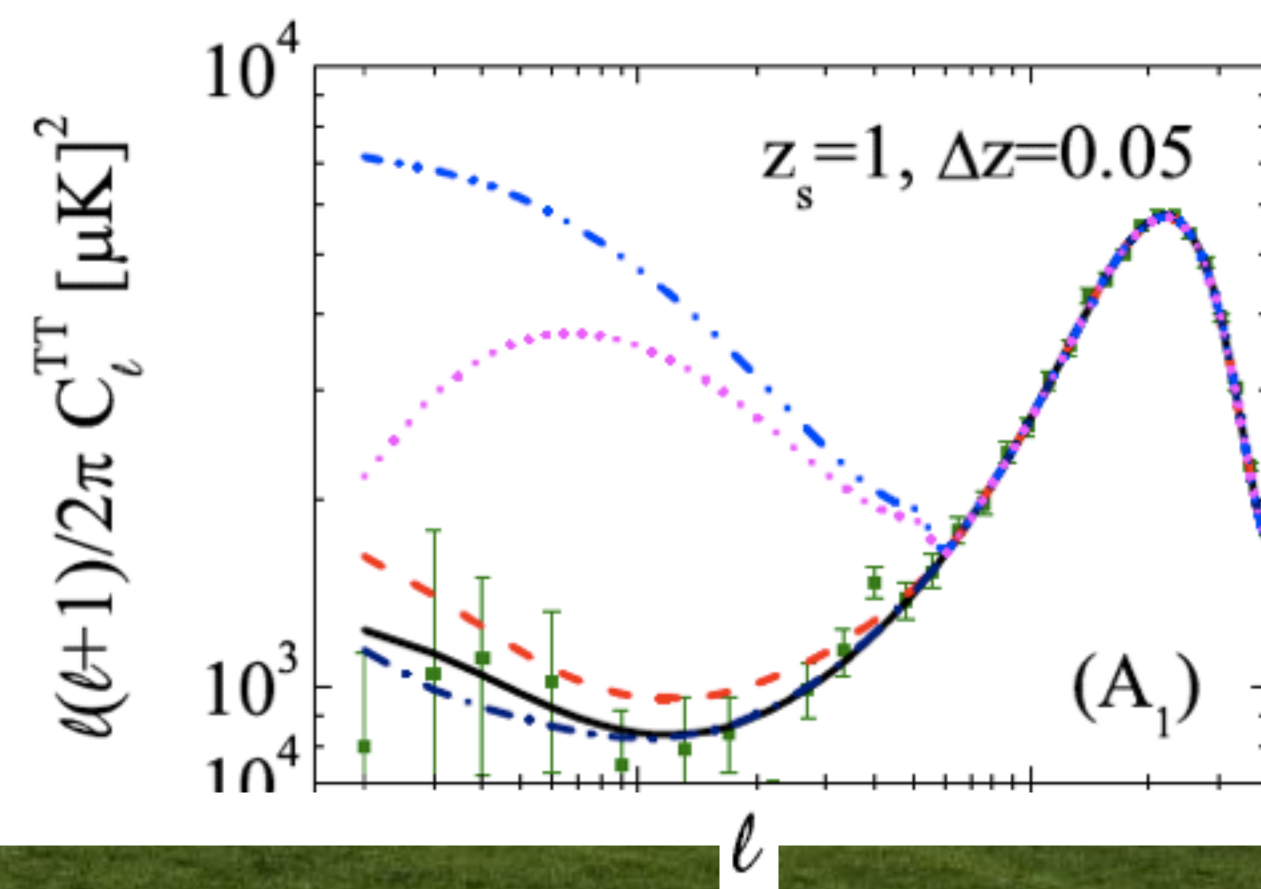
Pixellate μ, η and look for departures from GR!
[Zhao, TG et al. et al 10]

1. single high-z transition to MG

- No reason for scale-independency
- Only done for simplicity
- Transition from GR to MG with (η_0, μ_0), or (Σ_0, μ_0)
- WL, ISW very sensitive to Σ_0
- Transition: tanh, of width Δz at z = 1 or 2
- Width Δz: fixed to 0.05, or free and marginalised
- MCMC with CMB, ISW, WL, SN

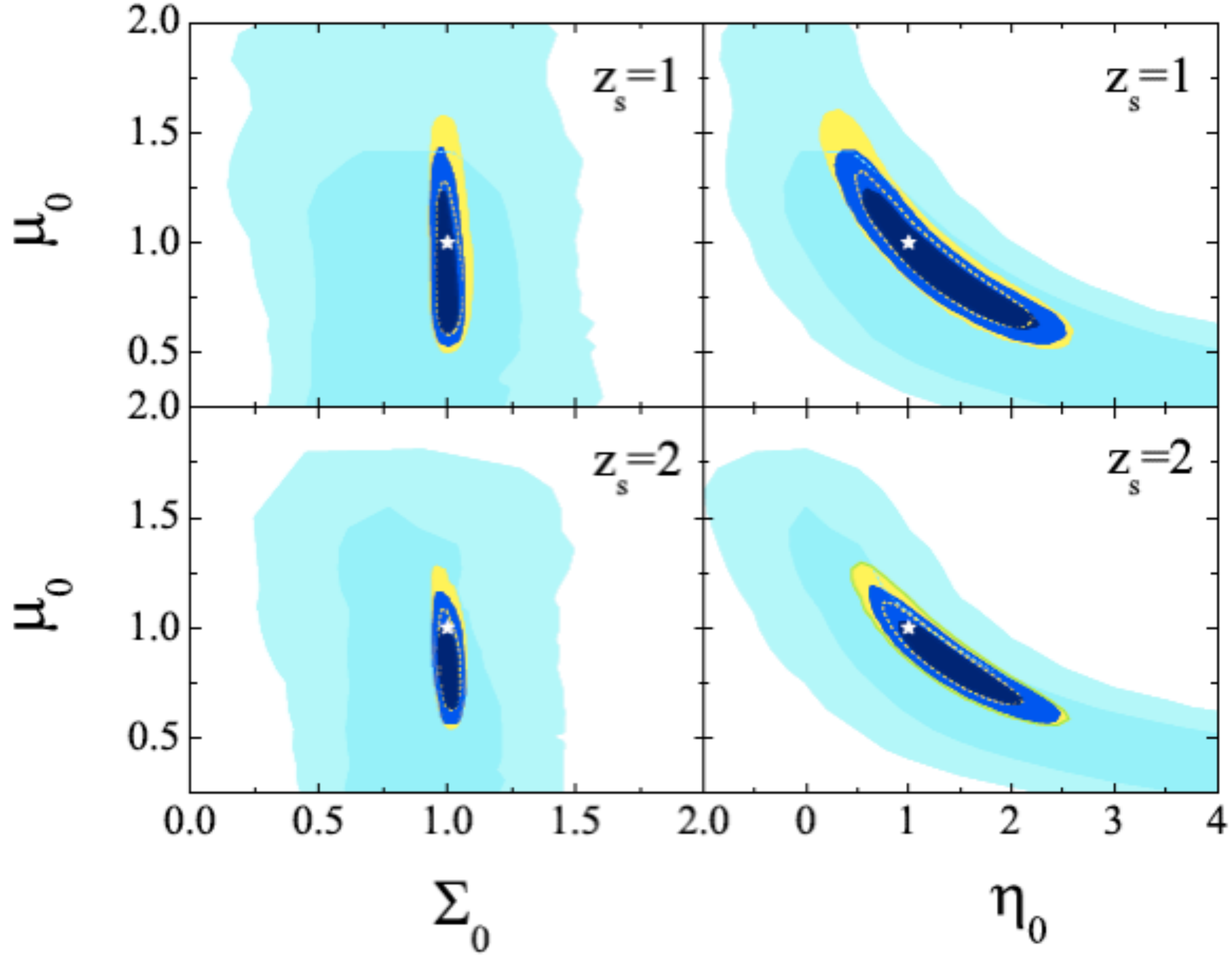




1. Single z transition: results [Zhao, TG et al. et al 10]

- MCMC with CMB, ISW, WL, SN
- With different combinations of data
- Σ_0 parametrisation better (less degenerate)
- MG from high z: more constrained (accumulation effect)
- Marginalisation of Δz or fixed: no big difference at z=2
- ISW alone stronger than WL!

Lensing + CMB shift
+ full WMAP
+ ISW



All consistent with GR

2. 2x2 Pixellation + PCA

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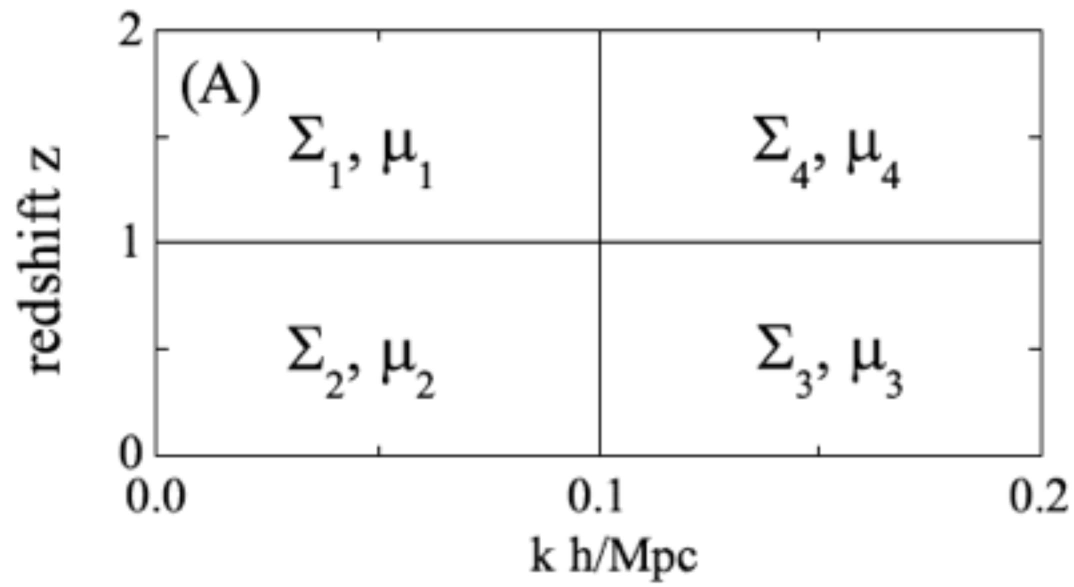
- Scale dependence IS expected in most MG theories
- Parameter pixels in redshift AND scale!
- 2x2 is enough for current data [Zhao et al 09]
- **p**=(Σ_i, μ_i), i = 1, ..., 4 : 8 extra parameters
- MCMC again with all data
- Transitions Δz = 0.05 (converge)



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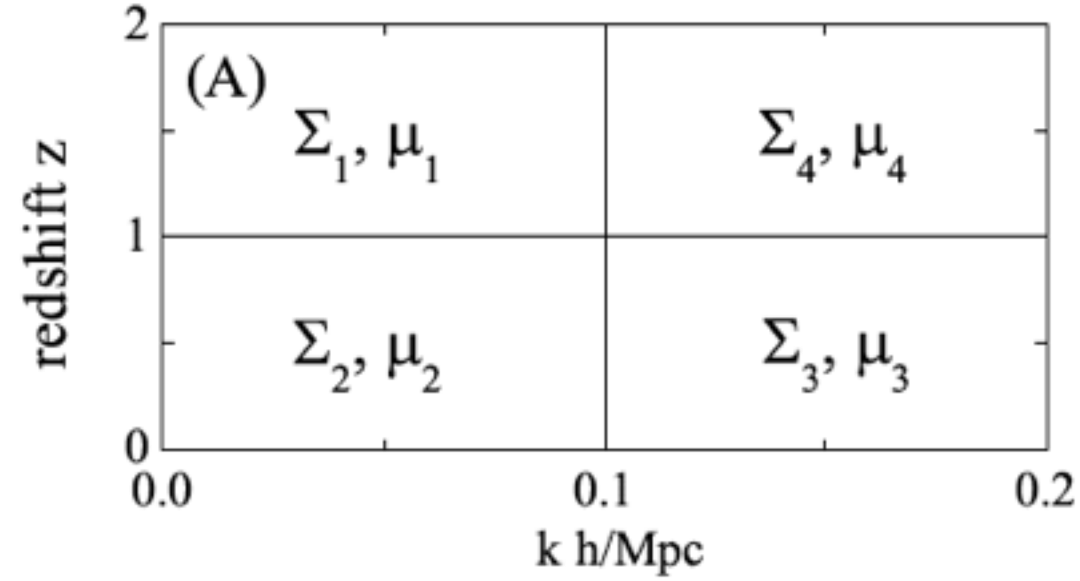
- **p**'s Higly correlated...
- PCA: de-correlating the variables: **q**



Covariance of **p**

Covariance of diagonalised parameters **q**

$$C_{(\mu,\Sigma)} = W \Lambda^{-1} W^T$$

Princ. components

$$q_i = -1 + \sum_j W_{ij} p_j / \sum_j W_{ij}$$

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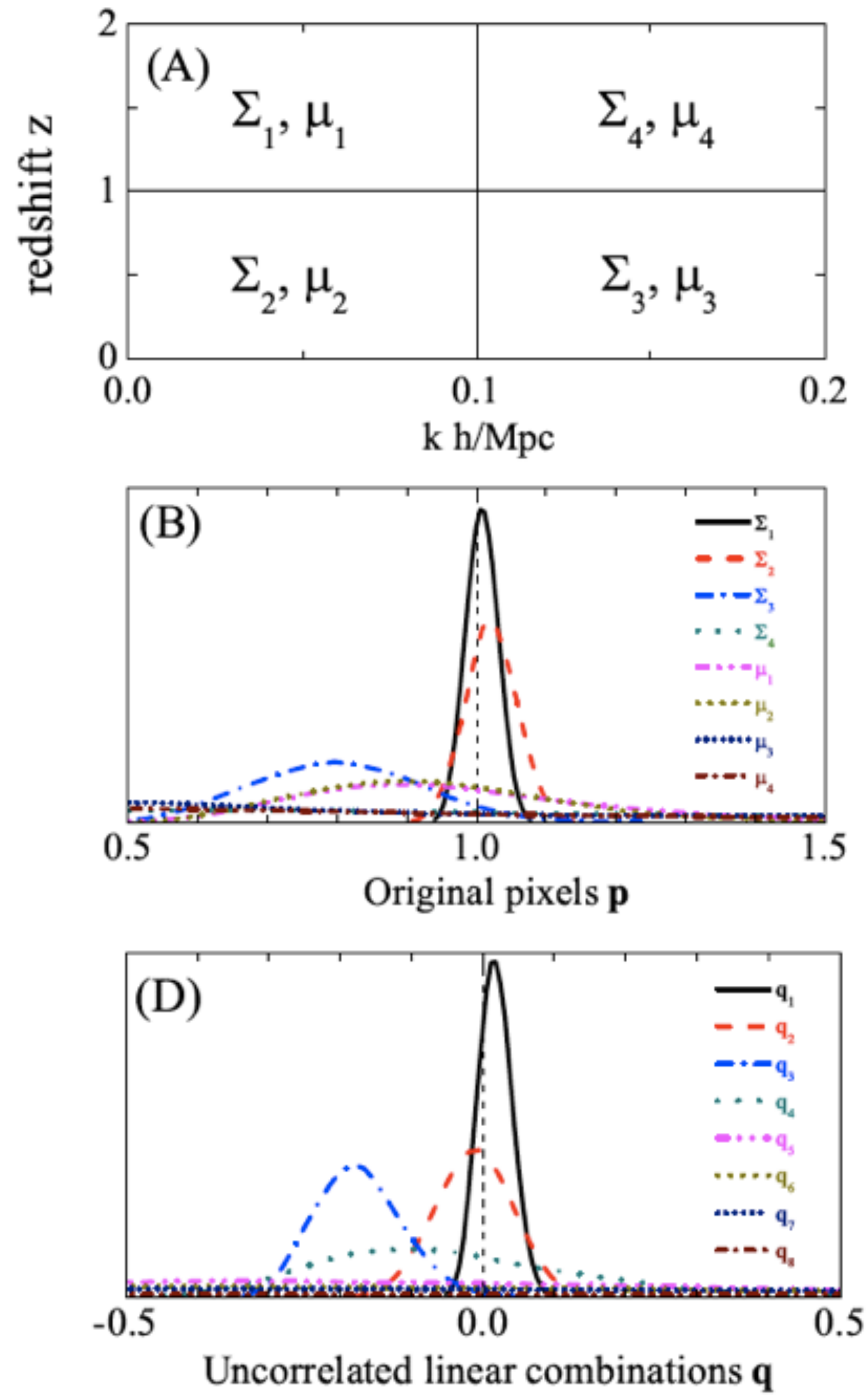

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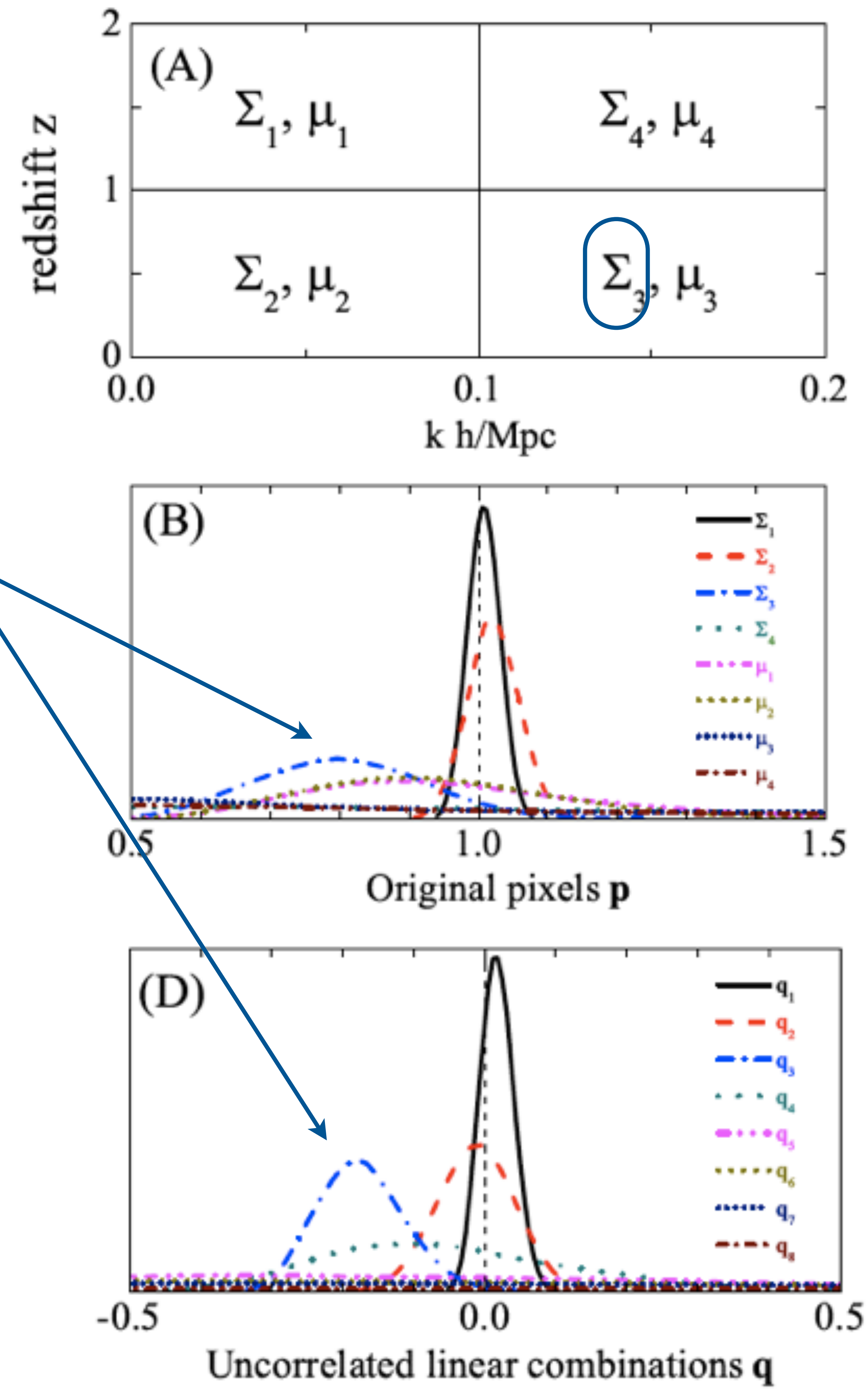
Here a hint of deviation (2σ)!

- A-posteriori model with ONLY Σ_3 would be favoured ($\Delta\chi^2$=2.2)



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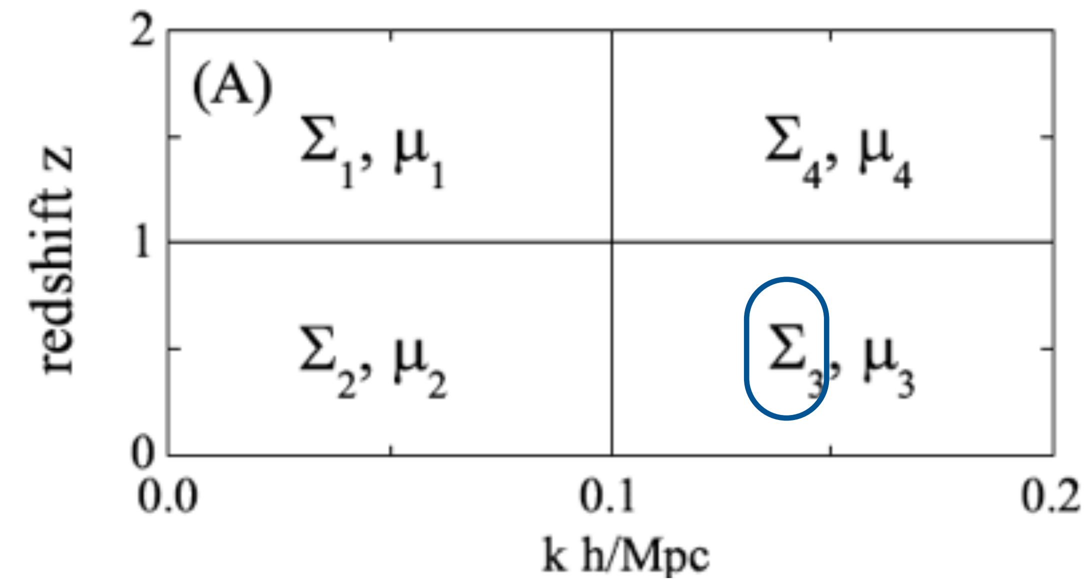

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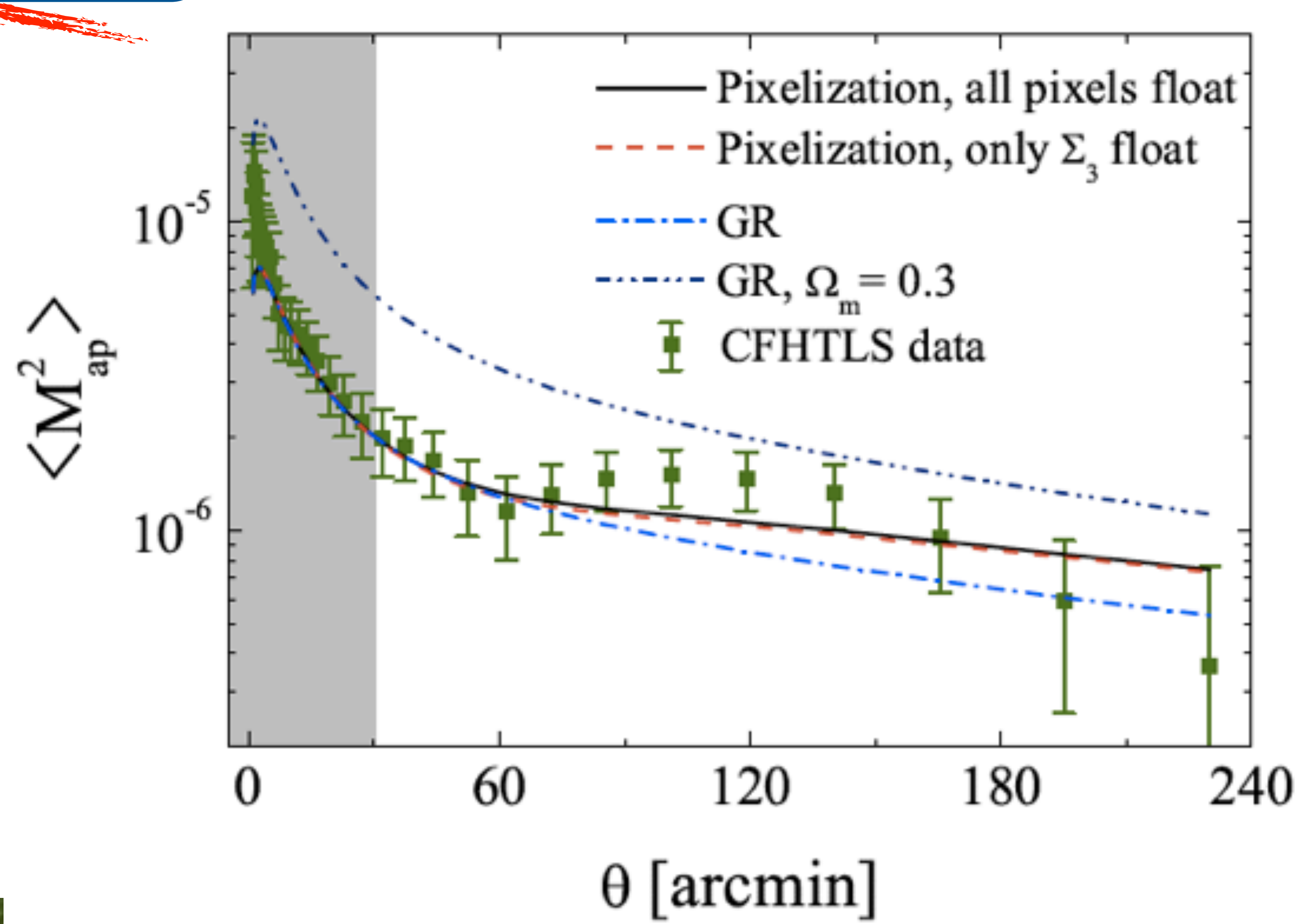
~~Here a hint of deviation (2σ)!~~

- A-posteriori model with ONLY Σ_3 would be favoured ($\Delta\chi^2$=2.2)
- **BUT!**
- Caused by CFHTLS "bump"
- Known systematic (field of view size) [CFHTLS private communication]
- No deviations without WL



Conclusions

- Combined tests of structure formation crucial in distinguishing MG
- In the absence of well-motivated theories, PCA can detect general departures from GR
- **So far NO evidence for MG**
- Future data: MUCH better PCA tests (number of constrained modes)
- For now, ISW is crucial in constraining the potential history
- Future work: including peculiar velocities, clustering, studying degeneracy with other effects (neutrinos?)

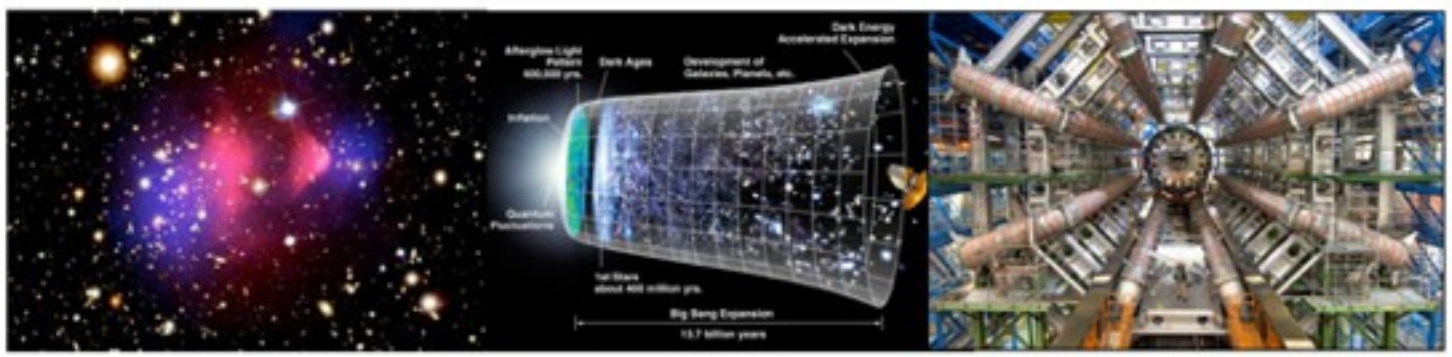
Fourth TRR33 Winter School on Cosmology

Theory for observers
Observations for theorists

5-10 December 2010
Passo del Tonale, Italy

Deadline for registration: November 15th
Deadline for financial support: November 1st

http://darkuniverse.uni-hd.de/winterschool



Overview lecture	Andy Taylor, Royal Observatory, Edinburgh
Inflation and non-Gaussianity	Paul Shellard, DAMTP, Cambridge
LHC physics	Christophe Grojean, CERN, Geneva
Large-scale Structures	Raul Jimenez, University of Barcelona
Weak Lensing	David Bacon, ICG, Portsmouth

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Marco Baldi
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