Exploring the Cosmological Observations for Signatures of Extra Dimensions

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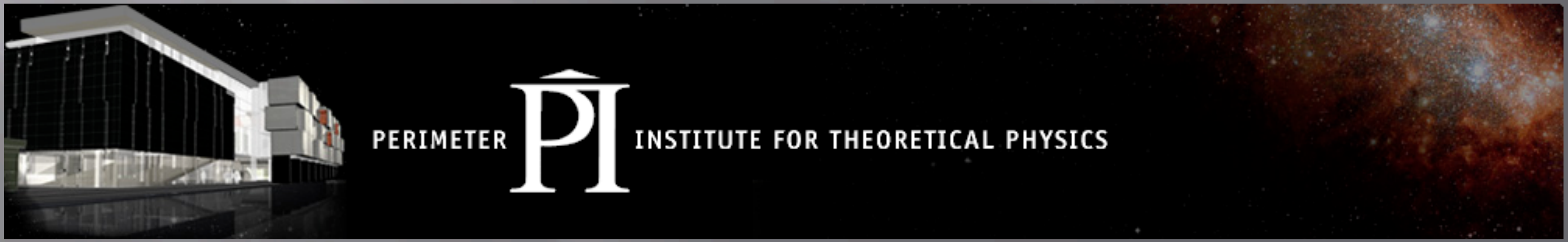
with Niayesh Afshordi and Justin Khoury

JCAP 08:030 (2009)[arXiv:0812.2244]



Cosmology: the Golden Era

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- A six-parameter model can now explain (almost) all observations, ranging from the intergalactic neutral hydrogen to the Cosmic Microwave Background (CMB)

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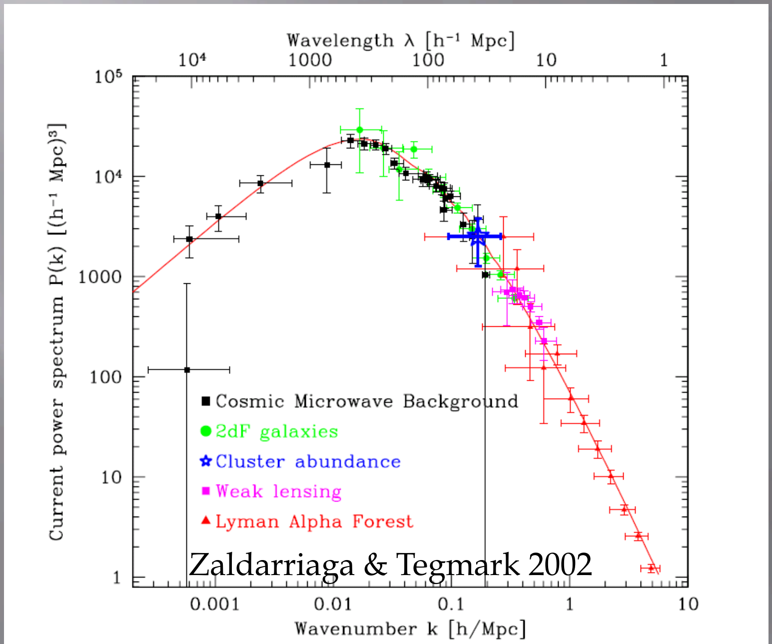
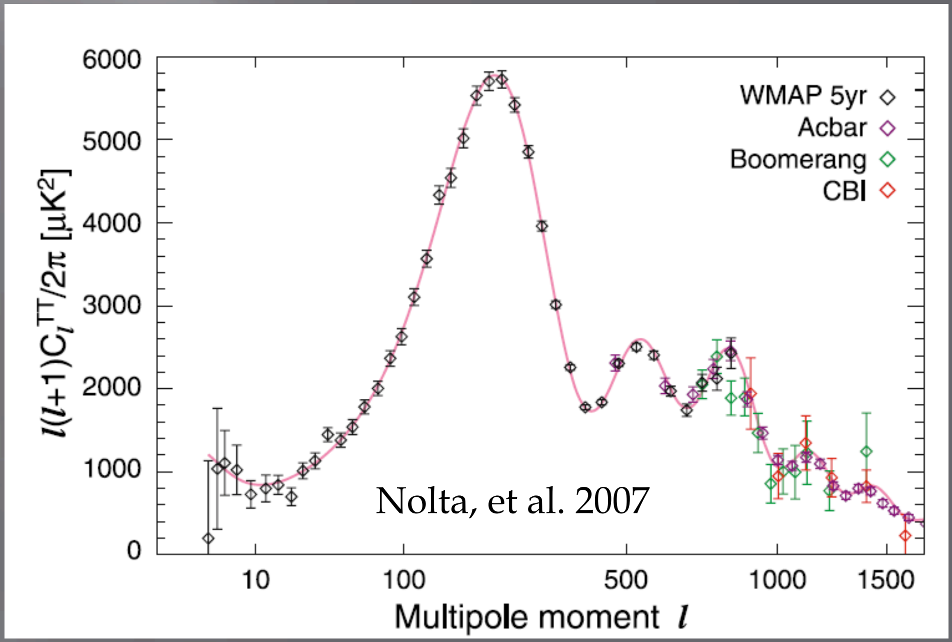
Cosmic density power spectrum



CMB power spectrum



Precision Cosmology

- Cosmological parameters are now measured with exquisite precision

WMAP 5-year Cosmological Interpretation

Komatsu, et al. 2008

TABLE 1
Summary of the cosmological parameters of ΛCDM model and the corresponding 68% intervals

Class	Parameter	*WMAP* 5-year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.262	2.273 ± 0.062	$2.267^{+0.058}_{-0.059}$
	$\Omega_c h^2$	0.1081	0.1138	0.1099 ± 0.0062	0.1131 ± 0.0034
	Ω_Λ	0.751	0.723	0.742 ± 0.030	0.726 ± 0.015
	n_s	0.961	0.962	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
	τ	0.089	0.088	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	2.41×10^{-9}	2.46×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$

Is there any trouble in ΛCDM paradise?

theoretical nightmares

Cosmological Constant Problem:

(what happened to rest of the vacuum energy?)

Standard model presents us with a vexing theoretical problem:

Why is Λ so unnaturally small?

* In EFT, robust contribution to vacuum energy is

$$\delta\rho_{\rm vac} \sim \sum_{\rm SM} m_{\rm SM}^4 \log(\Lambda_{\rm UV}/m_{\rm SM})$$

which, already with the electron, is $\gg (1\ \mathrm{meV})^4$

Is there any trouble in ΛCDM paradise?

Live happily: Anthropic reasoning
or look for a more satisfying solution

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which, already with the electron, is $\gg (1\ {\rm meV})^4$

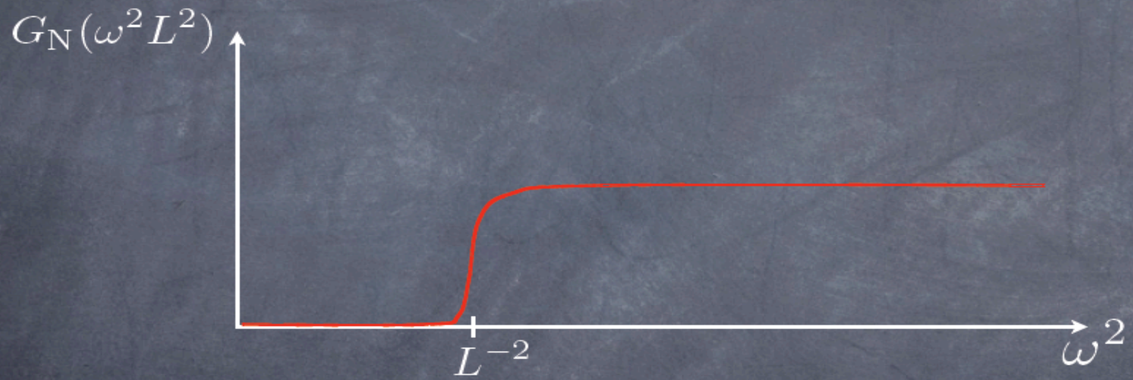
Another approach:

de-Gravitation

Dvali, Hofmann, and Khoury 07

infrared-modified gravity theories, inspired by brane-world constructions with infinite-volume extra dimension

$$\underbrace{G_N^{-1}(\Box L^2)}_{\text{high-pass filter}} G_{\mu\nu} = 8\pi T_{\mu\nu} \qquad ; \qquad \Box \equiv \nabla^\mu \nabla_\mu$$



Sources with wavelength << L gravitate normally, whereas those with wavelength >> L (including vacuum energy) degravitate.

Cosmological degravitation

- Around Minkowski space:

$$(\mathcal{E}h)_{\mu\nu} + \frac{m^2(\Box)}{2}(h_{\mu\nu} - \eta_{\mu\nu}h) = T_{\mu\nu}$$

$$m^2(\Box) = r_c^{-2(1-\alpha)}(-\Box)^{\alpha} \qquad 0 < \alpha < 1/2$$

- Aiming at solving the cosmological constant problem *(not the coincidence problem)*
- Due to the higher-dimensional nature of these constructions, extracting cosmological predictions presents a daunting technical challenge.

C. de Rham, S. Hofmann, J. Khoury and A. J. Tolley

Some features can be relevant for our model building scheme

- **The 4d graviton is** no longer massless but a resonance (a continuum of massive states) with a tiny width r_c^{-1} .

- On intermediate scales less than r_c^{-1} existence of an extra scalar force should enhance gravitational attraction by order unity.

- Vainshtein conjecture: Non-linear interactions can decouple the extra scalar and suppress these effects near astrophysical sources.

- **The theories of interest are higher-dimensional gen**eralizations of the Dvali-Gabadadze-Porrati model in which our visible universe is confined to a 3-brane.

- It has been shown instabilities are absent if our 3-brane lies within a succession of higher-dimensional branes, each with their own induced gravity term, and embedded in one another in a flat bulk space-time (Cascading Gravity). In the simplest codimension-2 case, for instance, our 3-brane is embedded in a 4-brane within a 6-dimensional bulk.

How to look for signatures of such theories

What are the implications for Cosmological observations?

General cosmological solution is non-existent,

➡Devise a phenomenological model

➡ Least number of variables

➡ Features known about theory

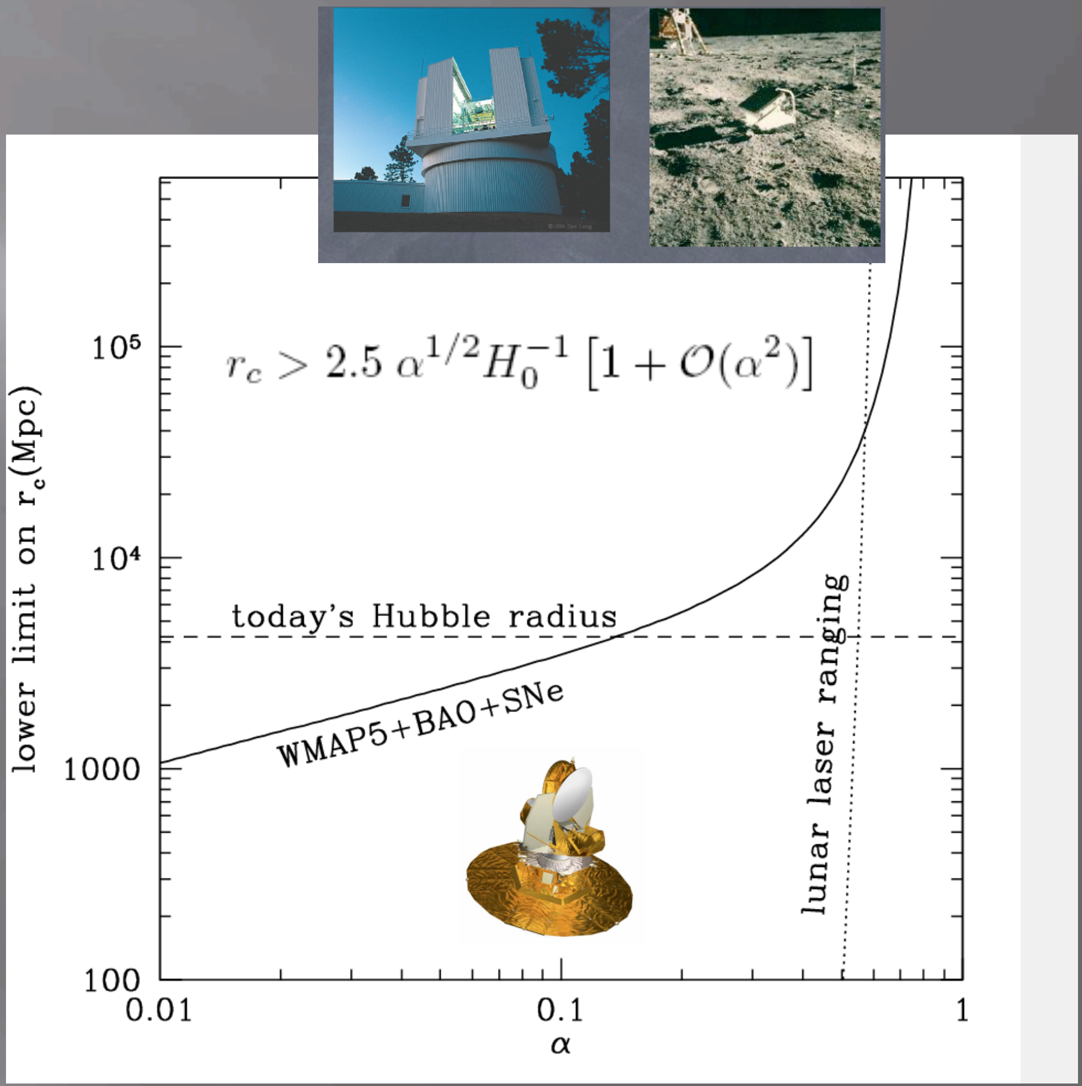
➡ Explore the data

Expansion History Close to ΛCDM

The modifications to Friedmann Equation in cascading gravity suggest slow varying function of Hr_c equation and in analogy with $\alpha=1/2$, Dvali, Gabadadze, Porati model we assume:

$$H^2 = \frac{8\pi G}{3}\rho - \frac{H^{2\alpha}}{r_c^{2(1-\alpha)}}$$

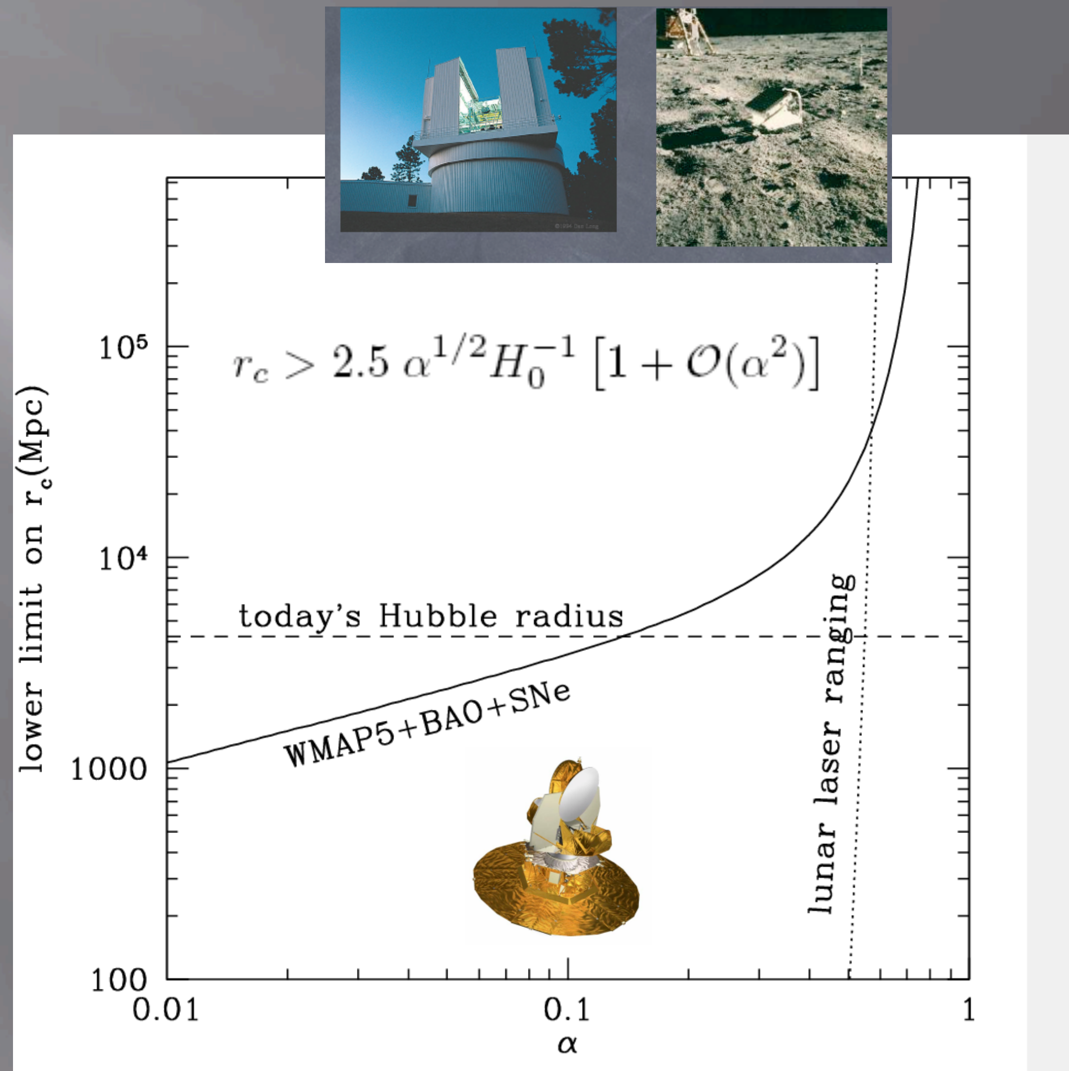
Degravitating FRW



Degravitating FRW

- FRW with α → 0

indistinguishable from ΛCDM



Inhomogeneous Universe could be different

(Lensing and Newtonian potentials can be different)

$$ds^2 = -(1+2\Psi)\mathrm{d}t^2 + a^2(1+2\Phi)\mathrm{d}\vec{x}^2$$

- $\Psi = -\Phi$ in ΛCDM+General Relativity
- Non-relativistic matter follows $-\Psi$
- Photons (Lensing and ISW) see $\Phi_- = (\Phi-\Psi)/2$
- ***$\Phi_- \neq -\Psi$ could signal the breakdown of General Relativity***
- Could lead to larger growth on intermediate scales:
  - Gravity becomes massive → fifth force enhances gravitational attraction on non-relativistic matter (not photons)

observational anomalies
(to be taken with a grain of salt)

- Structure on small scales
  - Lyman-α forest
- Structure on large scales
  - Integrated Sachs-Wolfe effect
  - Dark flow

may indicate larger growth

- Cosmic Microwave Background
  - CMB auto-correlation vanishes beyond 60 deg's

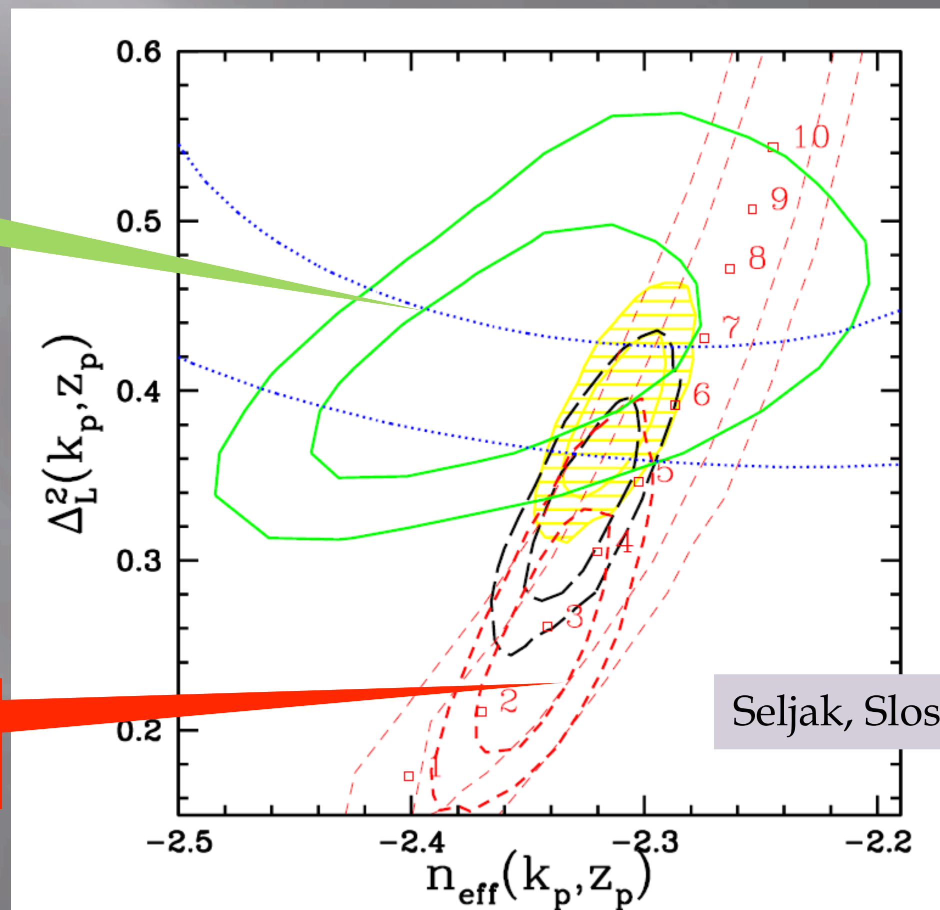
Large Scale modifications provide a new possible way to explain large scale anomaly of CMB:

We will fit our model so that ISW and Sachs-Wolfe effects cancel on super-horizon scales

Lyman-α excess: structure at z~3

- Ly-α, more clumpy than CMB predicts?

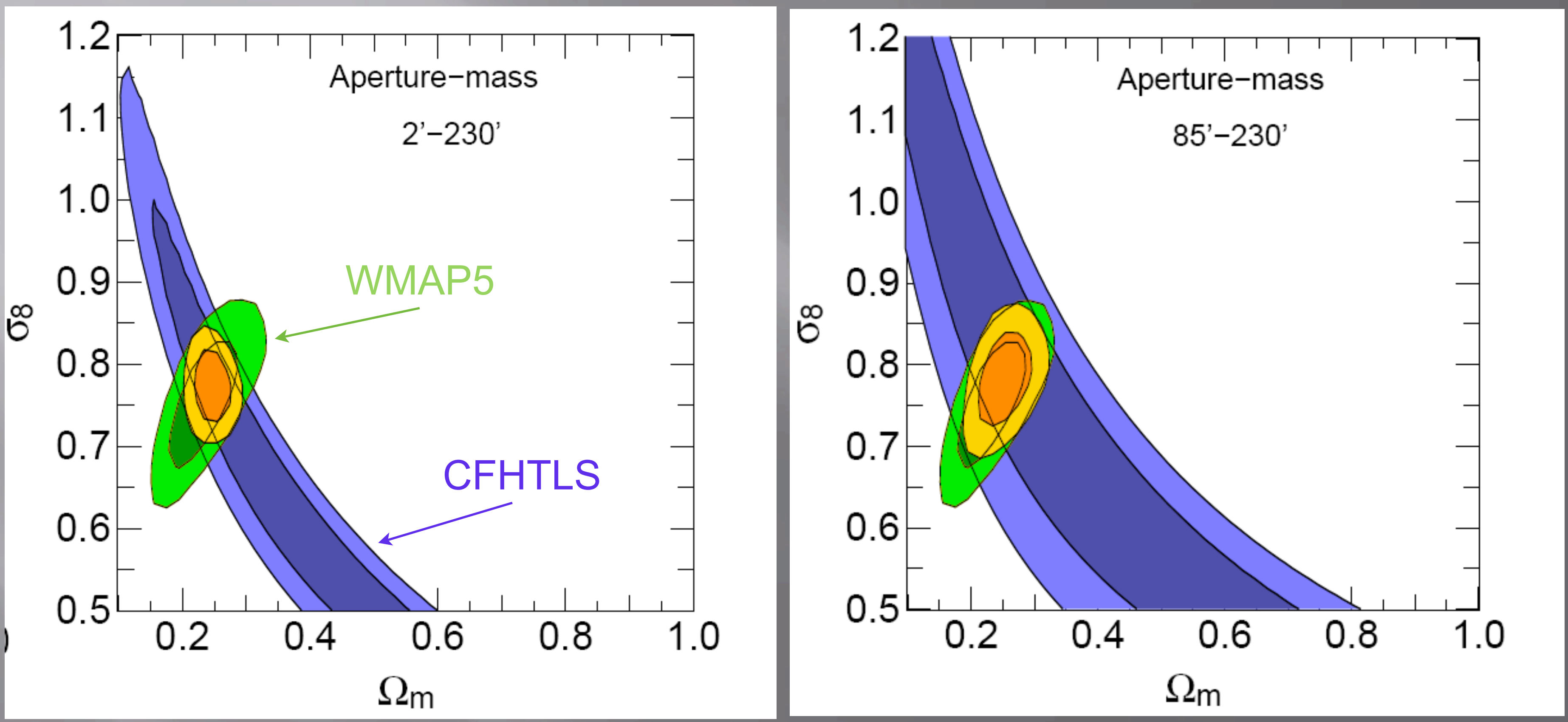
Lyman-α forest



WMAP3+ΛCDM

Seljak, Slosar, & McDonald 06

But σ_8 from lensing is consistent with ΛCDM

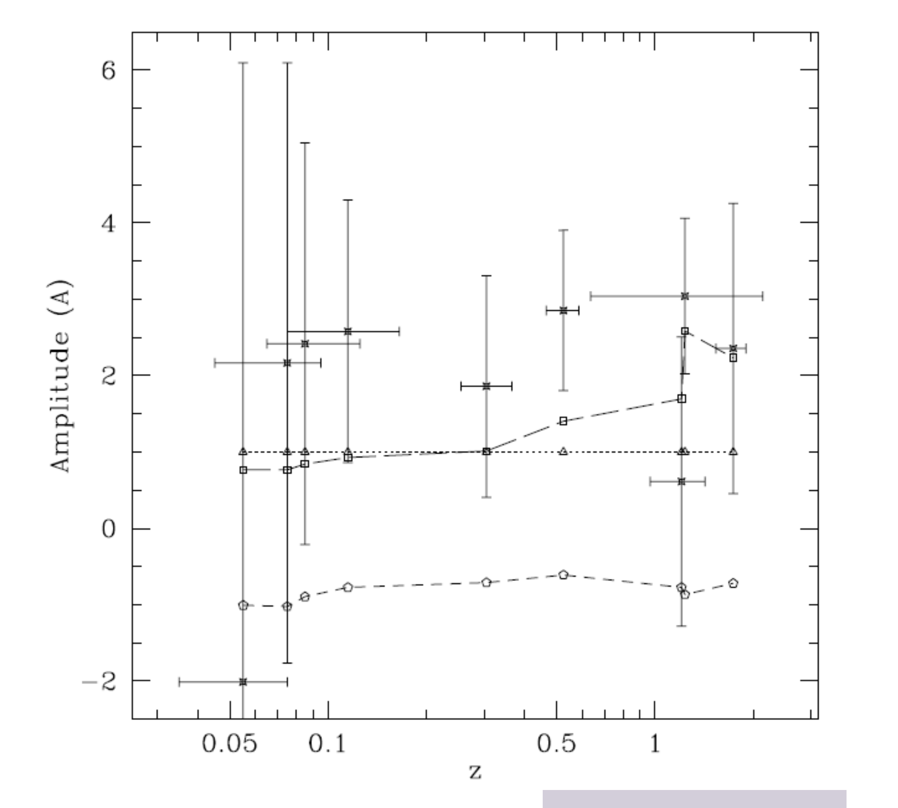


Fu, et al. 2008: Very weak lensing in the CFHTLS

ISW effect X galaxies: metric Pert. at z~0.1-1

- Gravitational Potential: 2.23±0.60 larger than ΛCDM predicts

$$A = \textit{Observed ISW / Predicted ISW}$$



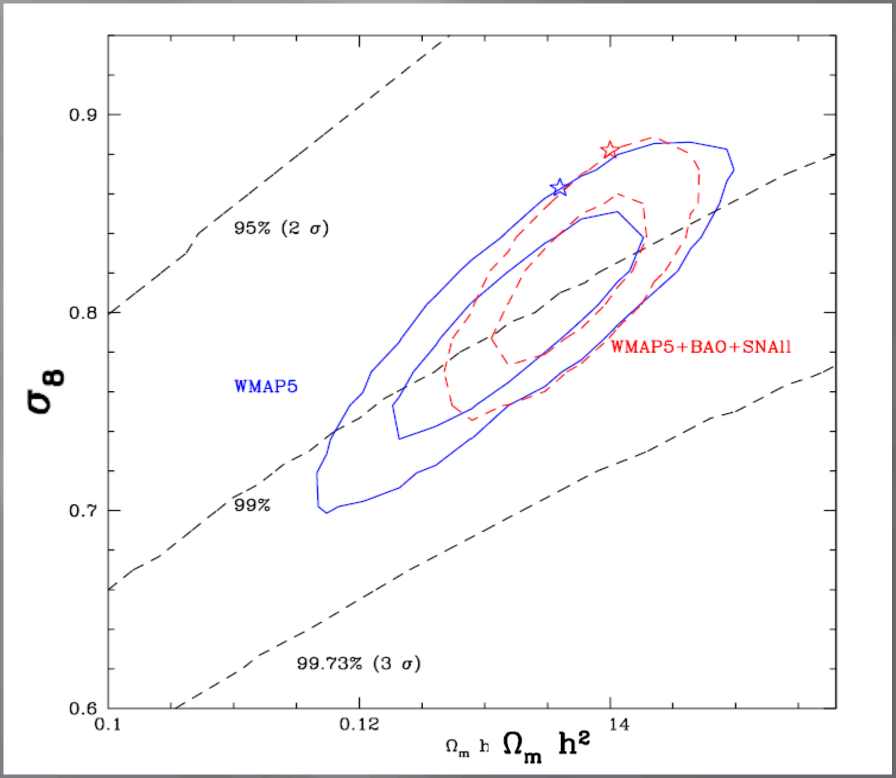
Sample	Amplitude ($A \pm \sigma$)
2MASS0	-2.01 ± 11.41
2MASS1	$+3.44 \pm 4.47$
2MASS2	$+2.86 \pm 2.87$
2MASS3	$+2.44 \pm 1.73$
LRG0	$+1.82 \pm 1.46$
LRG1	$+2.79 \pm 1.14$
QSO0	$+0.26 \pm 1.69$
QSO1	$+2.59 \pm 1.87$
NVSS	$+2.92 \pm 1.02$
All Samples	$+2.23 \pm 0.60$

Ho, et al. 08

Dark Bulk Flow I: velocities at z=0

- Local bulk flow within 50 Mpc is *407 ± 81 km/s*
  → ΛCDM predicts: v_{rms} = *190 km/s*

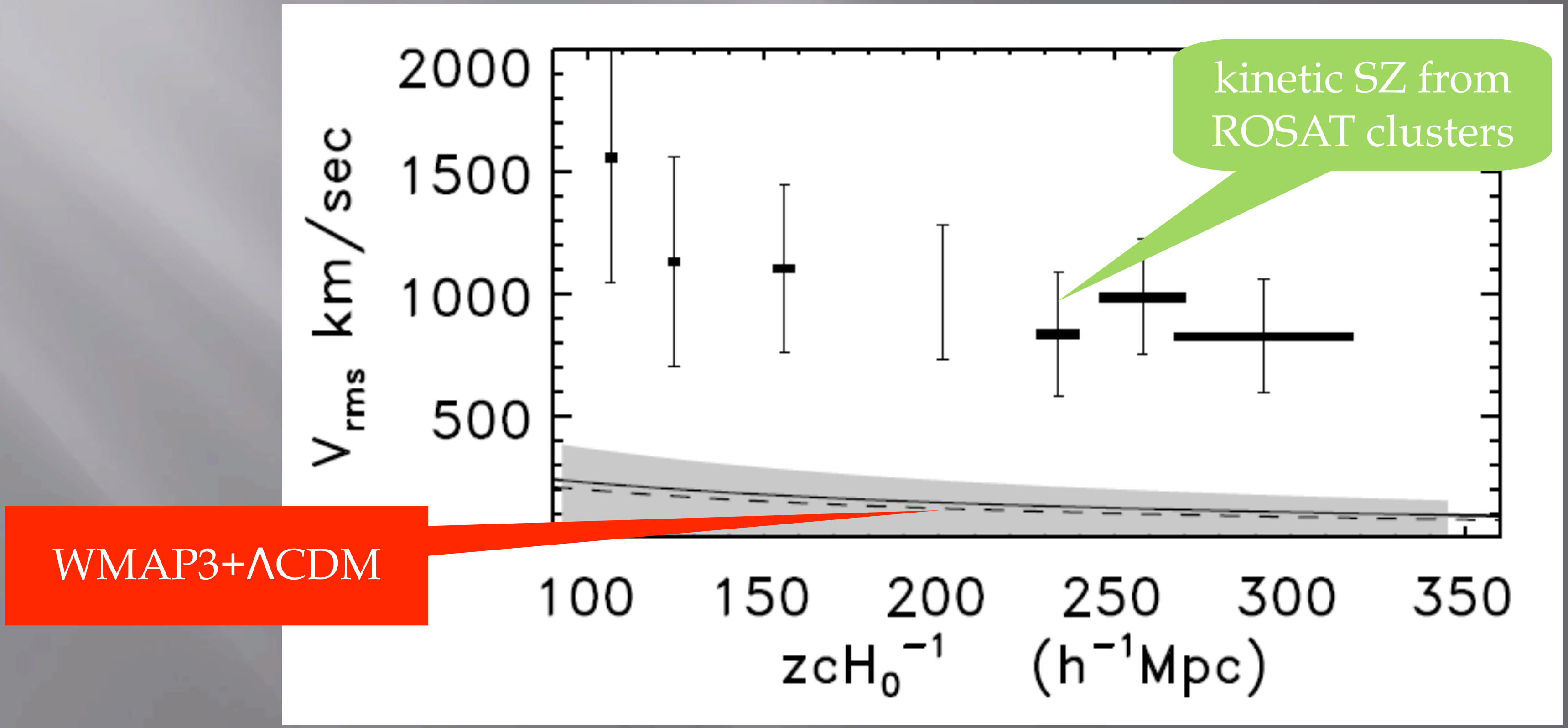
Watkins, Feldman, & Hudson 08



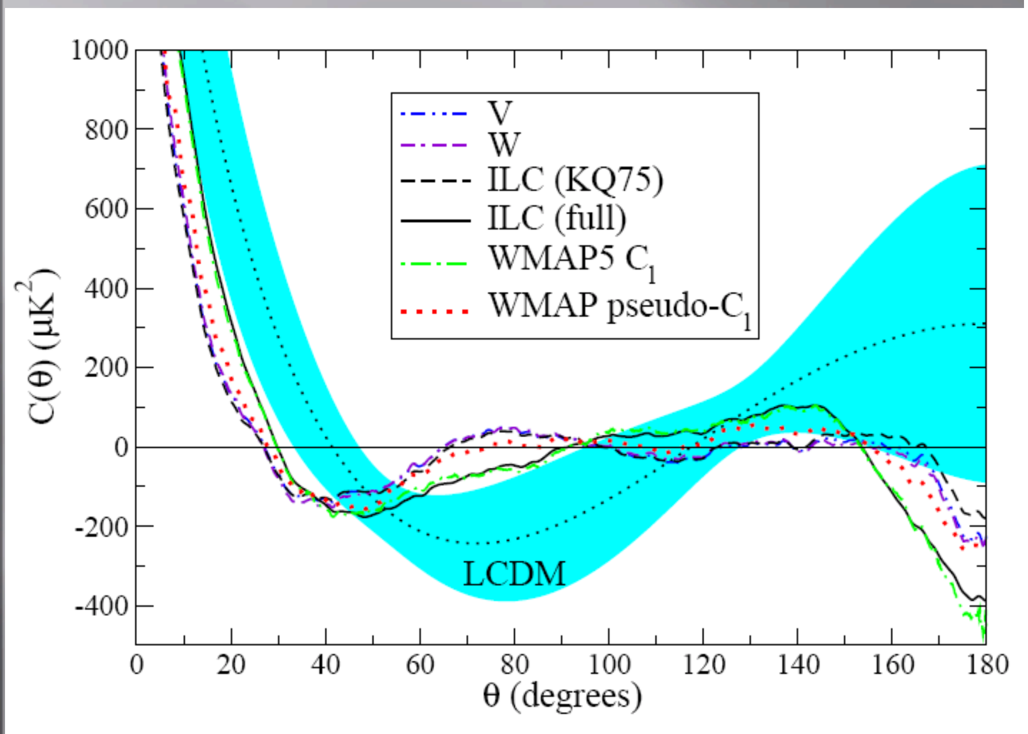
Dark Bulk Flow II: velocities at z=0

- Local bulk flow within 300 Mpc is *~1000 ± 300 km/s:* First statistical detection of kinetic SZ effect

Kashlinsky, et al. 08



CMB auto-correlation, beyond 60 deg's

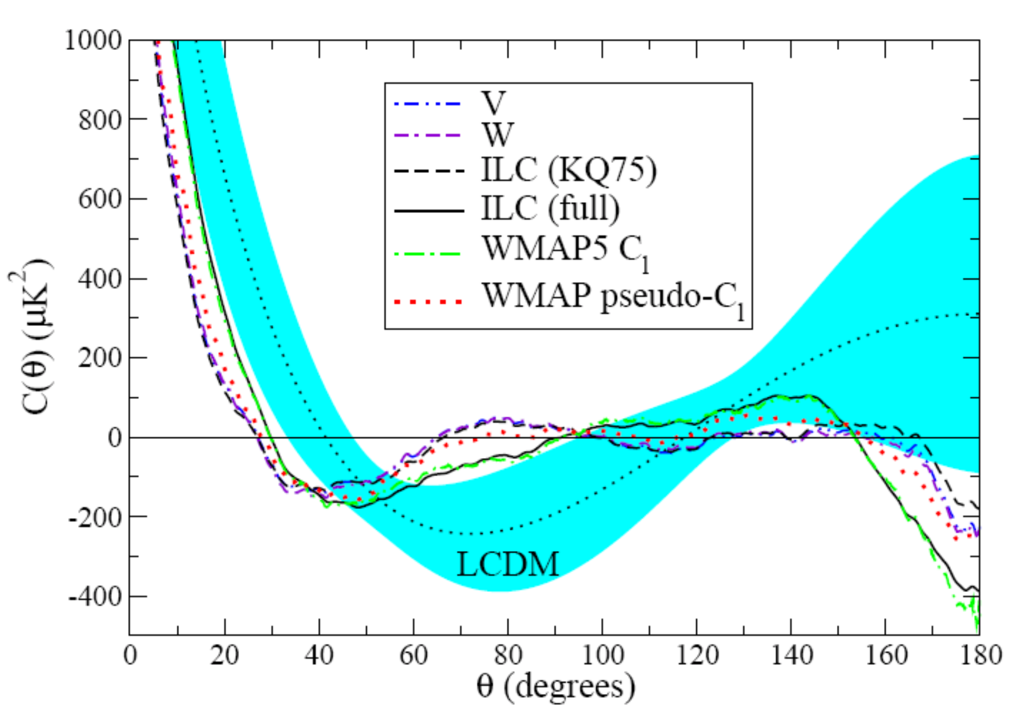


Data Source	$S_{1/2}$ $(\mu K)^4$	$P(S_{1/2})$ (per cent)
V3 (kp0, DQ)	1288	0.04
W3 (kp0, DQ)	1322	0.04
ILC3 (kp0, DQ)	1026	0.017
ILC3 (kp0), $\mathcal{C}(> 60°) = 0$	0	—
ILC3 (full, DQ)	8413	4.9
V5 (KQ75)	1346	0.042
W5 (KQ75)	1330	0.038
V5 (KQ75, DQ)	1304	0.037
W5 (KQ75, DQ)	1284	0.034
ILC5 (KQ75)	1146	0.025
ILC5 (KQ75, DQ)	1152	0.025
ILC5 (full, DQ)	8583	5.1
WMAP3 pseudo-C_ℓ	2093	0.18
WMAP3 MLE C_ℓ	8334	4.2
Theory3 C_ℓ	52857	43
WMAP5 C_ℓ	8833	4.6
Theory5 C_ℓ	49096	41

$$S_{1/2} \equiv \int_{-1}^{1/2} [\mathcal{C}(\theta)]^2 \, \mathrm{d}(\cos\theta)$$

Copi, Huterer, Schwarz, & Starkman 08

CMB auto-correlation, beyond 60 deg's



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Copi, Huterer, Schwarz, & Starkman 08

How we deal with perturbations

- Use Parametrized Post-Friedmann (PPF) formulation (Hu & Sawicki 2007):

$$g = \frac{\Phi + \Psi}{\Phi - \Psi}$$

  (Consistent in analogy with DGP model for $\alpha = 1/2$)
- $g \rightarrow 0$
  - GR: at early times or large densities
- $g \rightarrow -1/2$
  - scalar-tensor theory: on sub-horizon scales at late times
- $g \rightarrow 1$
  - Newtonian potential vanishes on super-horizon scales at late times

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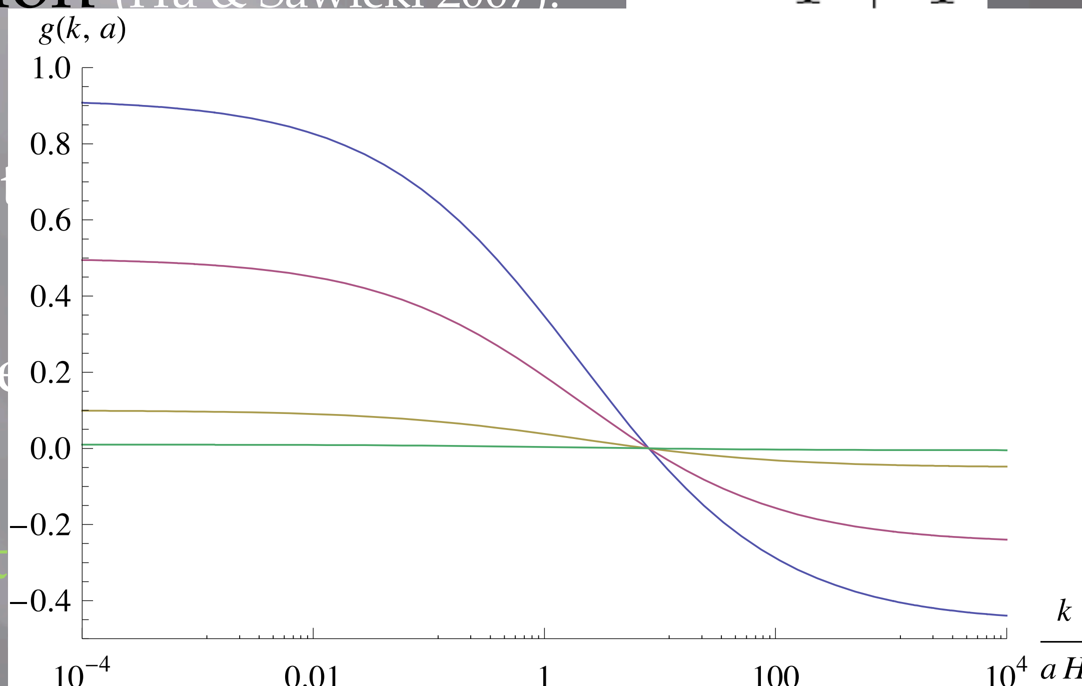


(Consistent ... /2)

- g → 0
  - GR: at e...
- g → -1/2
  - scalar-t... late times
- g → 1
  - Newtonian potential vanishes on super-horizon scales at late times

Cancelling ISW against Sachs-Wolfe

- On super-horizon scales, in the matter era:

$$\frac{\delta T_{\rm CMB}}{T_{\rm CMB}} = \frac{1}{3}\Phi_- + 2\int dt \frac{\partial \Phi_-}{\partial t} \simeq \frac{1}{3}\Phi_- + 2\Delta\Phi_-$$

- Assuming adiabatic initial condition ς remains constant on large scales (Bertschinger 2006)

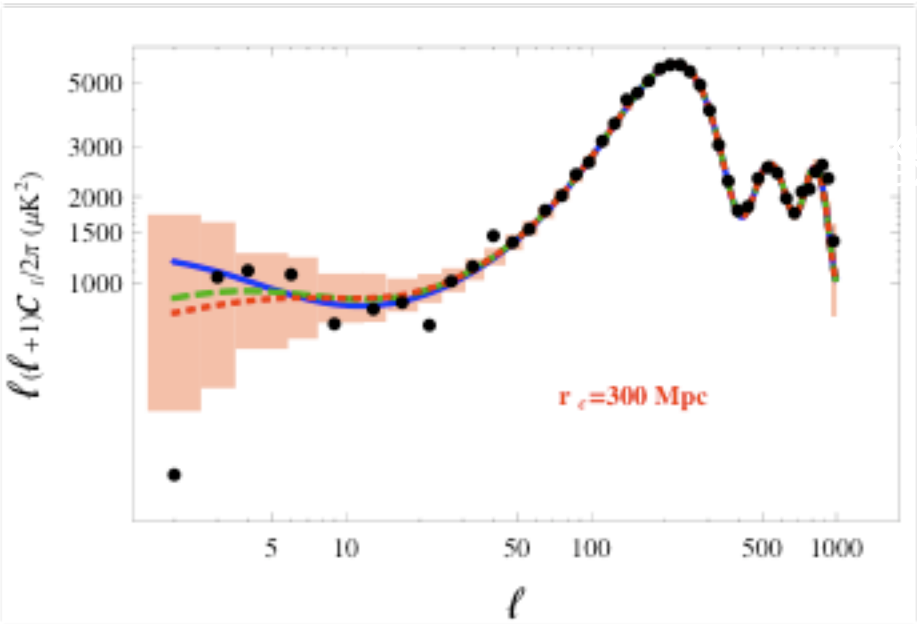
$$\zeta = \text{const.} = \frac{H}{H'}\left[(g-1)\Phi_- - g'\Phi_- - (g+1)\Phi'_-\right] + (g+1)\Phi_- \simeq \frac{(5+g)\Phi_-}{3}$$

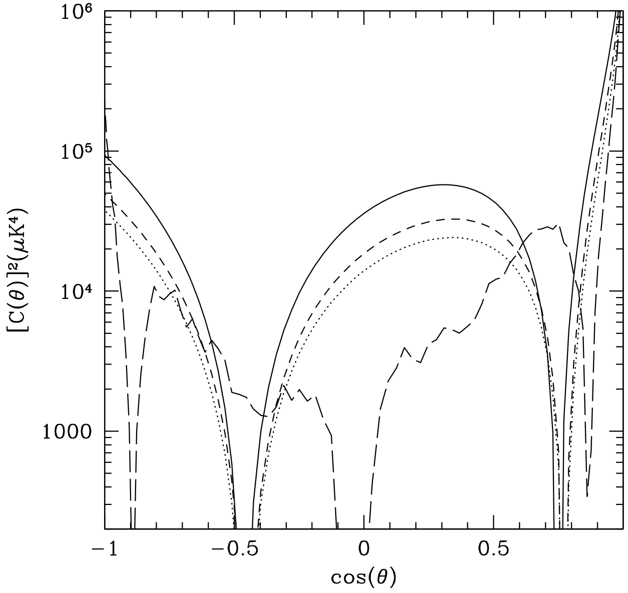
- If g goes from 0 to 1, ISW and Sachs-Wolfe cancel!

de-Correlating CMB on large angles

CMB angular power spectra

best-fit ΛCDM (solid curve), rc = 600 Mpc (dashed curve) and r= 300 Mpc (short-dashed curve)





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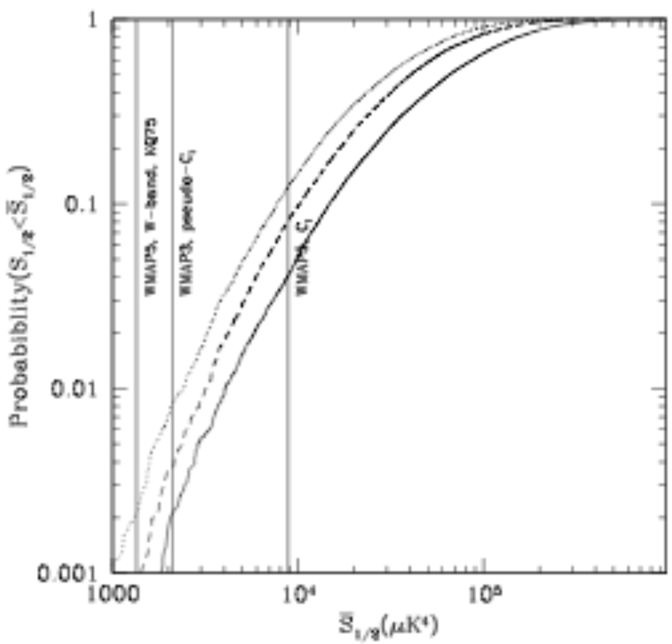
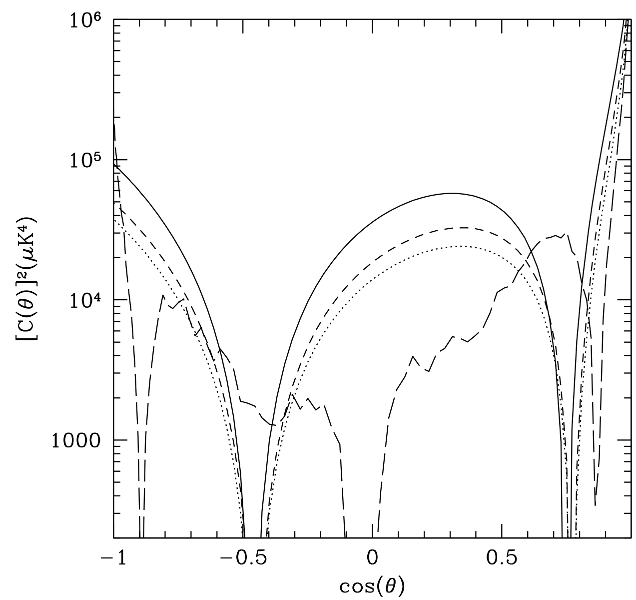
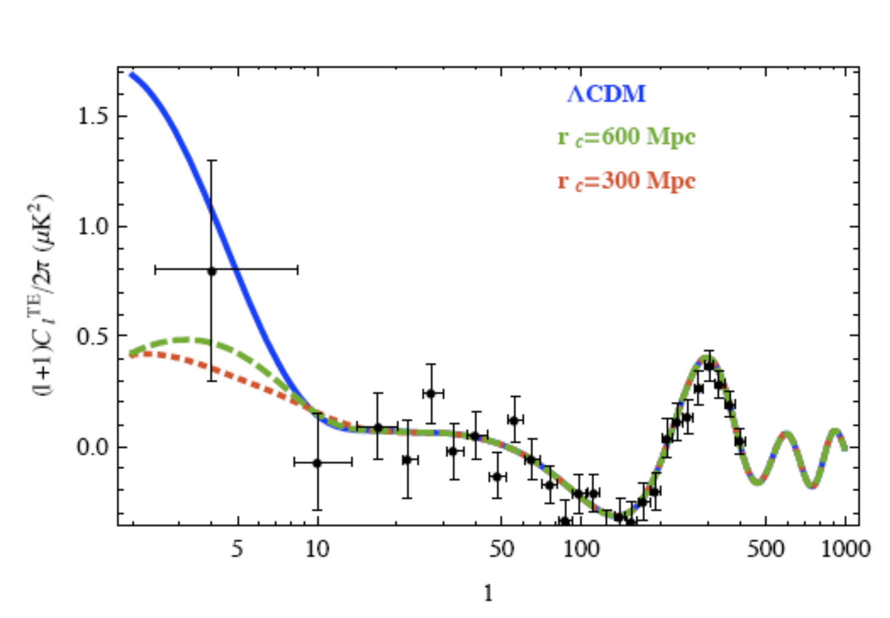
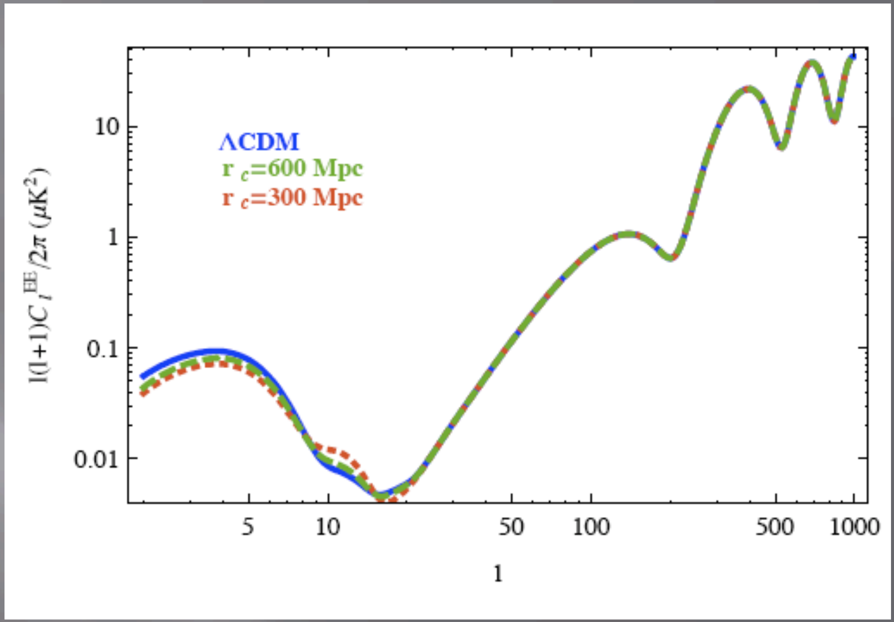




$$S_{1/2} \equiv \int_{-1}^{1/2} [\mathcal{C}(\theta)]^2 \, \mathrm{d}(\cos\theta)$$

Prediction for CMB Polarization power spectra



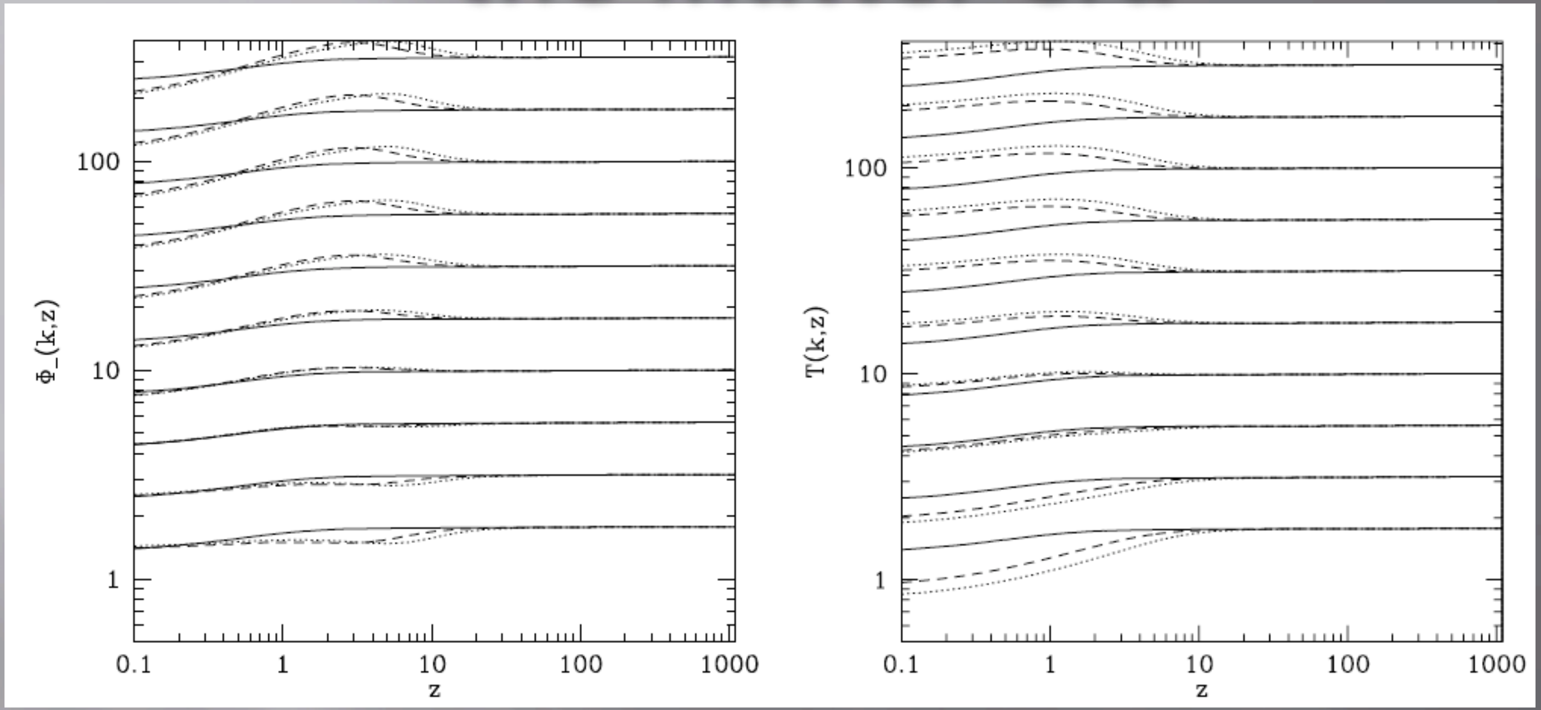


Temperature-Polarization (TE) power spectrum

polarization(EE) power spectrum

predicts a significantly lower TE cross-power spectrum at l < 10, which should be clearly distinguished from ΛCDM by the Planck satellite, due to its better polarization sensitivity and foreground cleaning capabilities

Potential Transfer Function in the matter era



smaller scale (large $K=10\text{Mpc}^{-1}$)

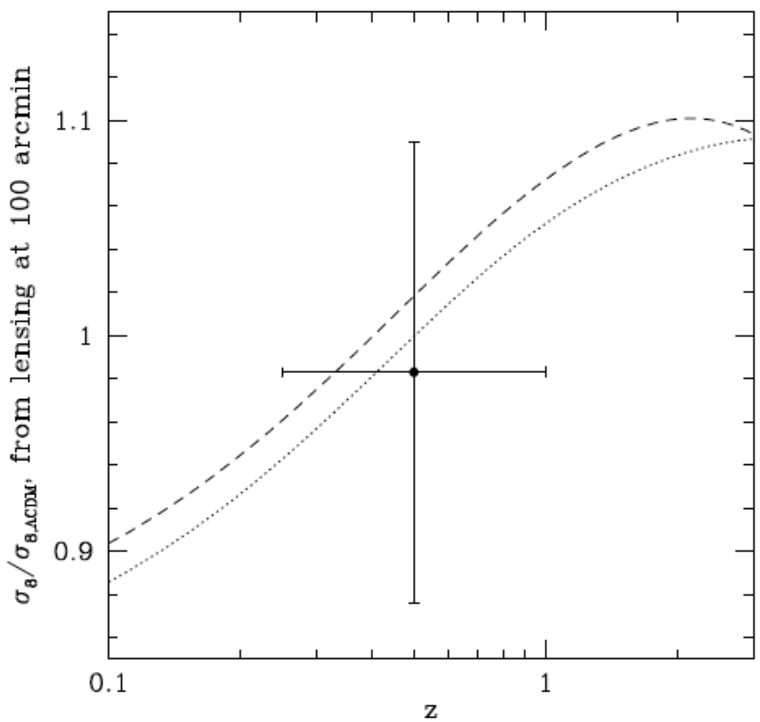
larger scale (small $K=10^{-4}\text{Mpc}^{-1}$)

ΛCDM (solid), $r_c = 300$ Mpc (dotted) and $r_c = 600$ Mpc (dashed)

Lensing, Φ_- comoving density perturbations Δ_m/a

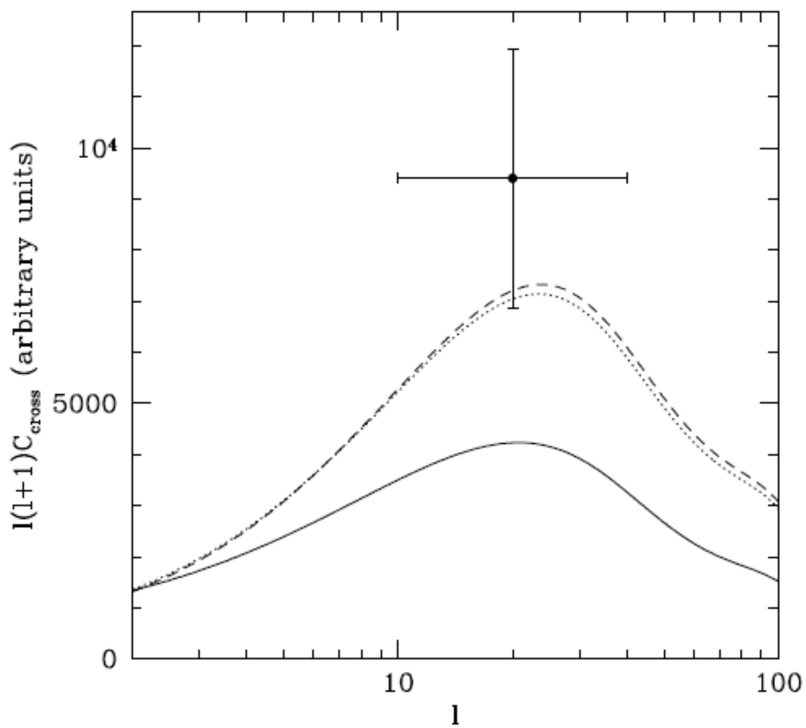
- Plenty of excess power on small scales
- Lensing potential is much less affected

Weak lensing power spectrum and Integrated Sachs-Wolfe Cross Correlation



The ratio of lensing correlation measured within 100′ radius for rc = 300 Mpc (dotted) and rc = 600 Mpc (dashed) to the ΛCDM prediction. The data point from CFHTLS Wide weak lensing measurements, the vertical error bar: 1σ range.

current weak lensing measurements cannot distinguish our predictions from that of the ΛCDM (small change in value of Φ_-)

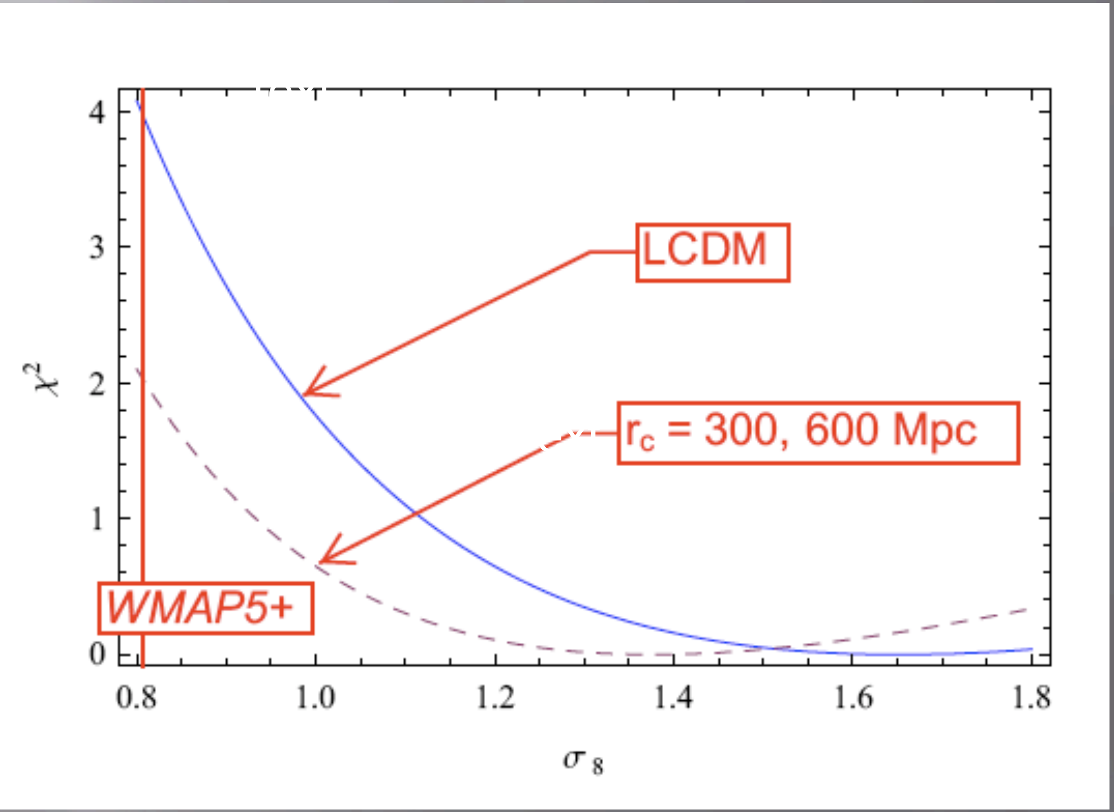


Cross-power spectrum of a galaxy survey at z≅0.5 with the CMB, for ΛCDM (solid), rc = 300 Mpc (dotted) and rc = 600 Mpc (dashed)

(faster decay of Φ_-)

Bulk Flows

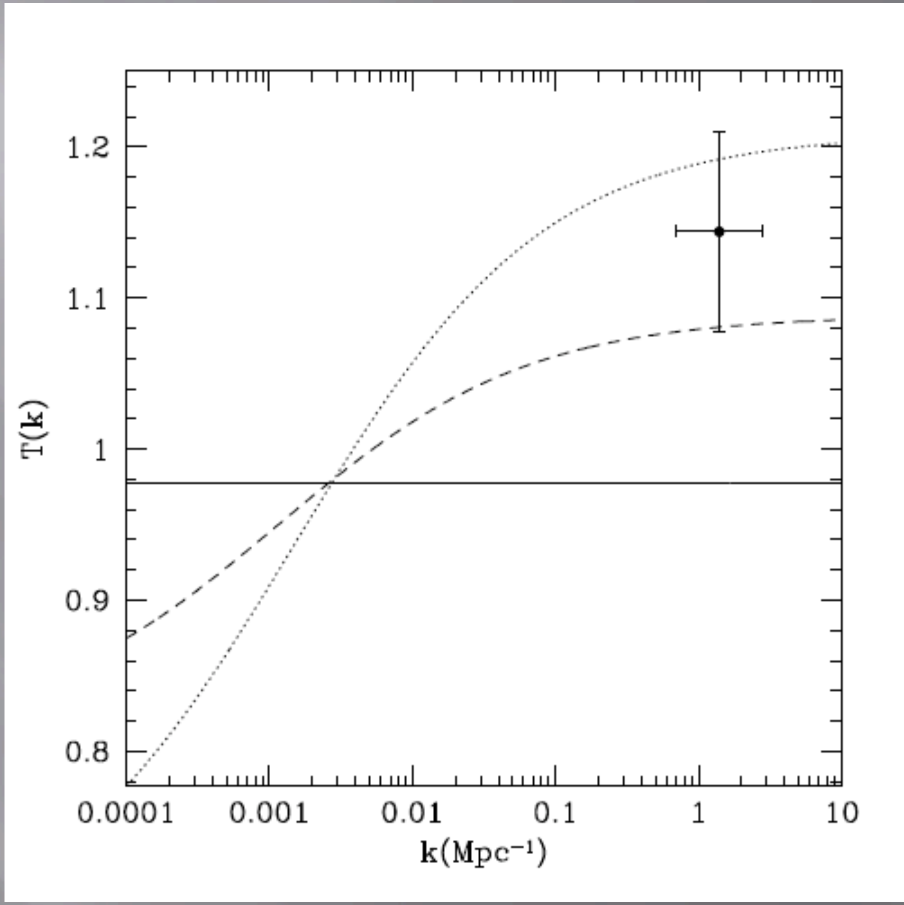
Peculiar velocity measurements through the continuity equation, probe $\dot{\Delta}_m$ in the linear regime



producing the observed bulk flows on 100 Mpc scales. The vertical line shows the WMAP5+BAO+SN best fit value

Lyman-α forest

1



The transfer function of the density potential related to Δ_m , at z = 3 and k = 1.4 Mpc^{-1} for CDM (solid), rc = 300 Mpc (dotted)and rc = 600 Mpc (dashed).

The data point (with 1σ errorbar) characterizes the excess power observed in Lyman-forest observations.

The Moral

The Moral

- Massive gravity potentially:
  - Degravitate the vacuum → solve the CC problem
  - Cause excess power on small scales at late times
  - Explain lack of power in CMB on large angles
- Several observations point to excess power (relative to ΛCMB) on small scales at late times
- Our phenomenological model can roughly explain observations if the $r_c \sim 600$ Mpc
- At our present level of understanding, the model is not uniquely fixed by either theory or observations