Title: Observational Evidence for Cosmological-Scale Extra Dimensions

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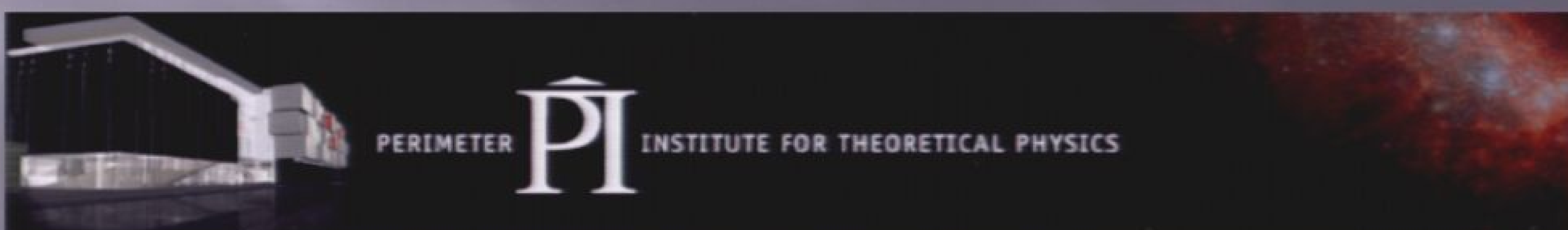
Abstract: TBA

Observational Evidence For Cosmological-Scale Extra Dimensions

Ghazal Geshnizjani

with Niayesh Afshordi and Justin Khoury

arXiv:0812.2244 [astro-ph]



Is there any trouble with ΛCDM?

Given that you are here I assume you are probably not very happy with Anthropic reasoning and looking for a solution with distinctive testable predictions!

A reasonable question is, how well ΛCDM is doing with Data? Are there currently observations that can not be explained by LCDM and whether they have a potential to be explained by programs that aim to solve CC problem.

In the end no matter how unhappy we are with a fined tuned parameter, if it is the only way to explain the data we have to learn to live with it!

So how good is LCDM doing with data?

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

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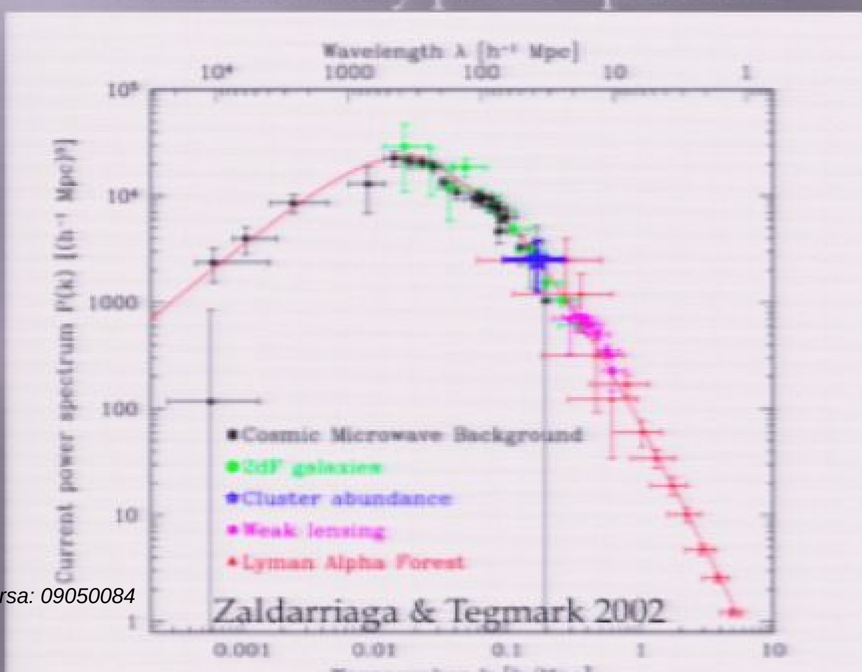
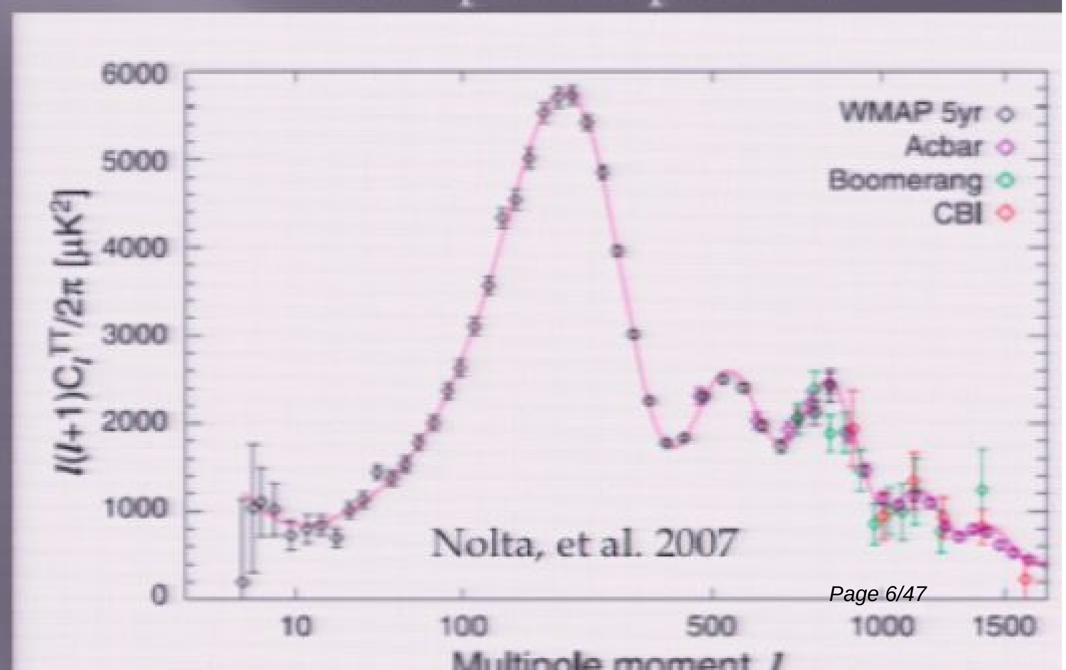
Cosmic density power spectrum



CMB power spectrum



Precision Cosmology

- Cosmological parameters are now **measured** with **exquisite precision**

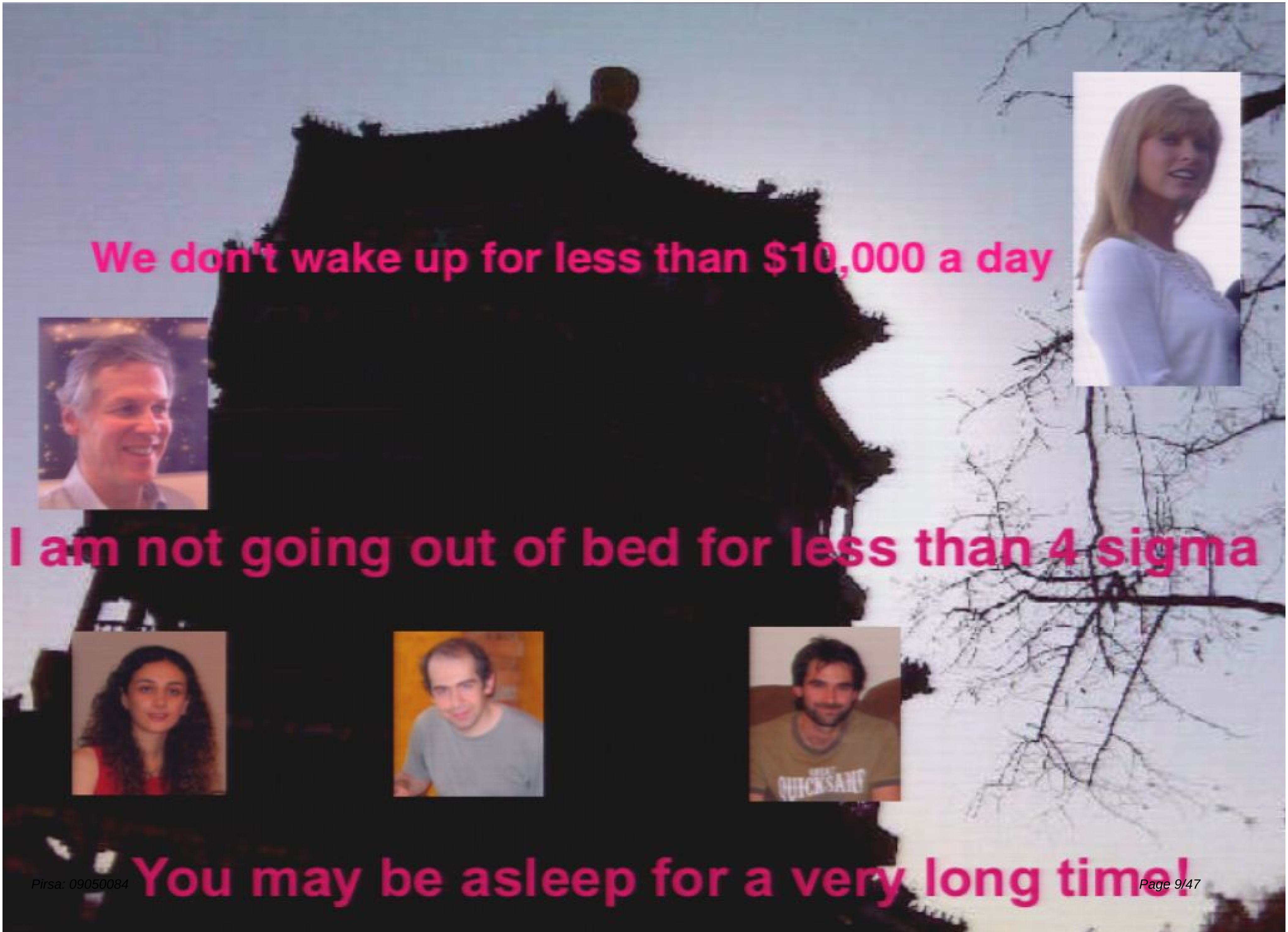
WMAP 5-year Cosmological Interpretation

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
	$\Delta^2_{\mathcal{R}}(k_0{}^c)$	2.41×10^{-9}	2.46×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$

However there are some observational anomalies (to be taken with a grain of salt)


We don't wake up for less than $10,000 a day
I am not going out of bed for less than 4 sigma
QUICKSANT
You may be asleep for a very long time!

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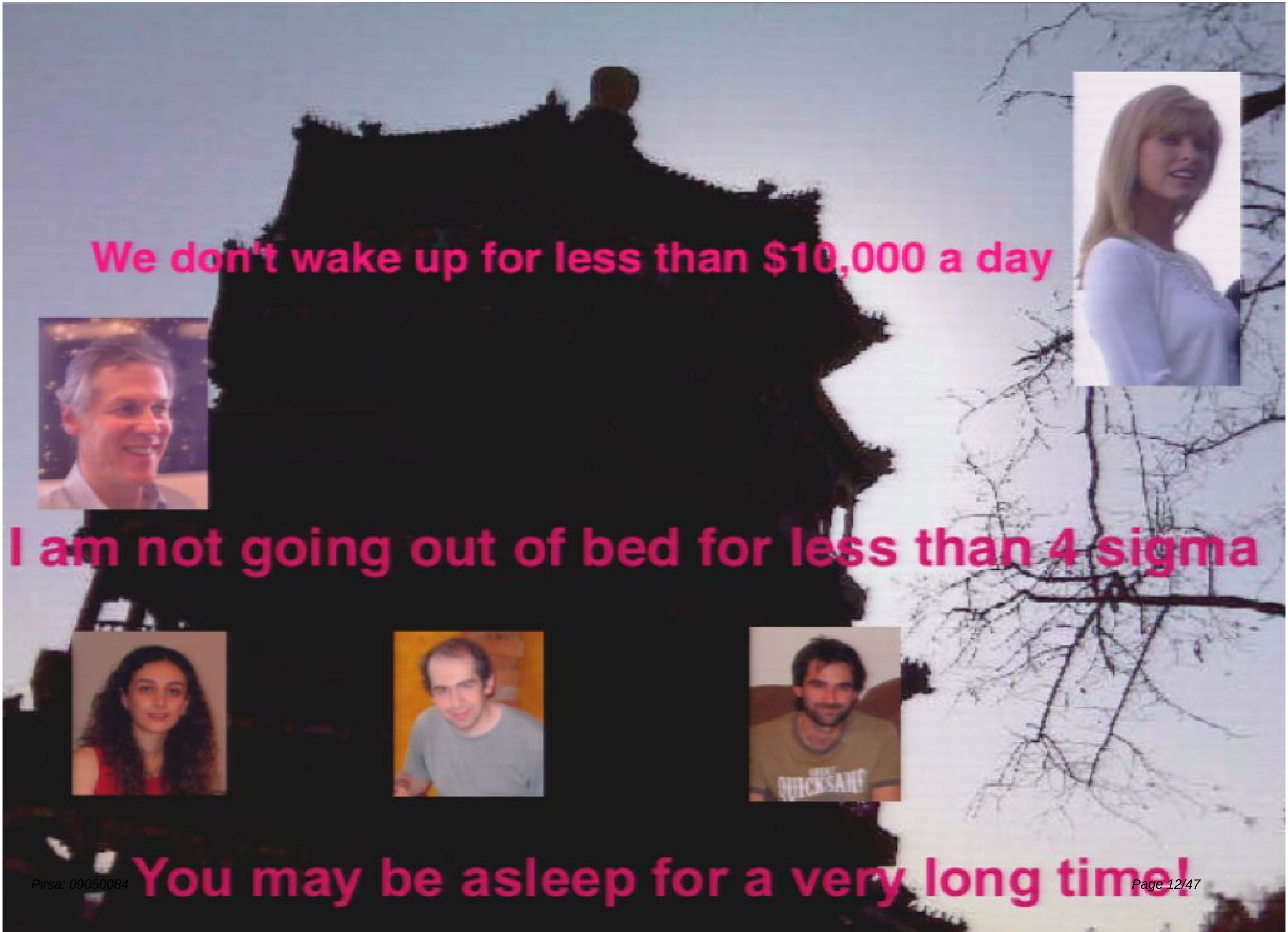
- Structure on small scales
  - CBI excess (X-ray clusters?)
  - Lyman-α forest
- Structure on large scales
  - Integrated Sachs-Wolfe effect
  - Dark flow
- Cosmic Microwave Background
  - CMB auto-correlation vanishes beyond 60 deg's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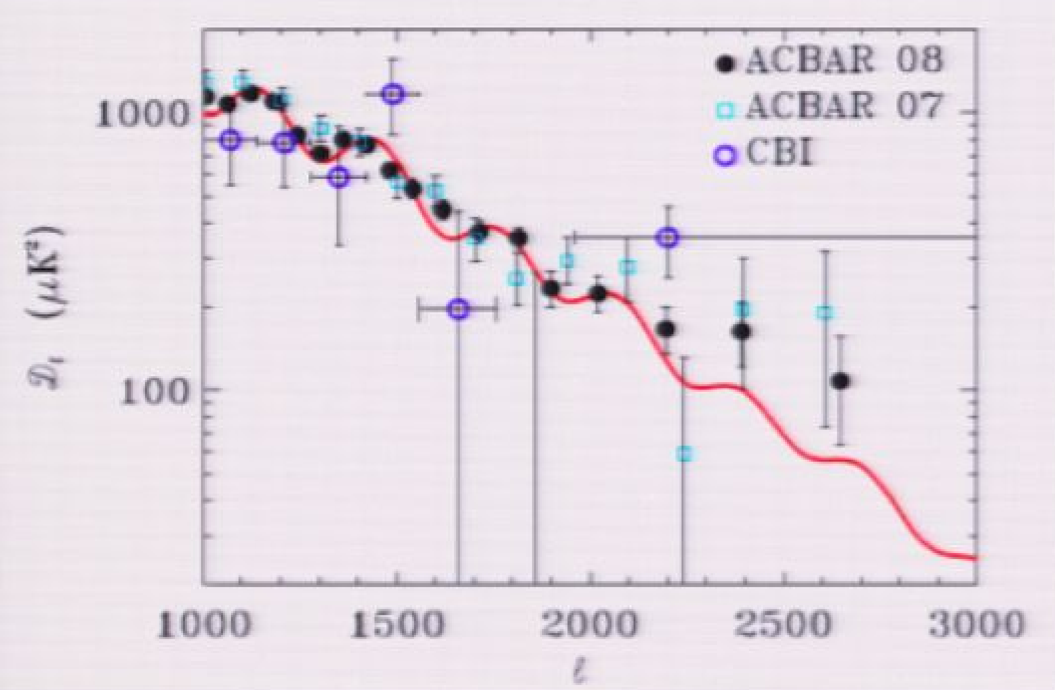
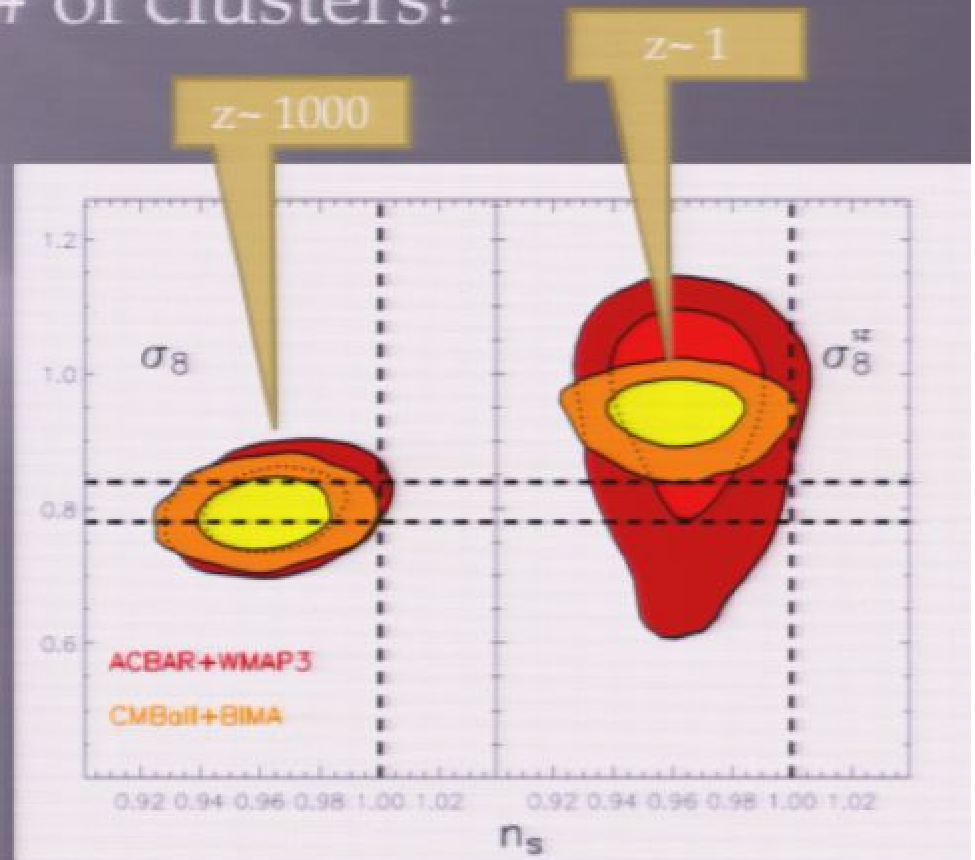
CBI excess:
Census of SZ clusters at z~1

- Do we underpredict the # of clusters?



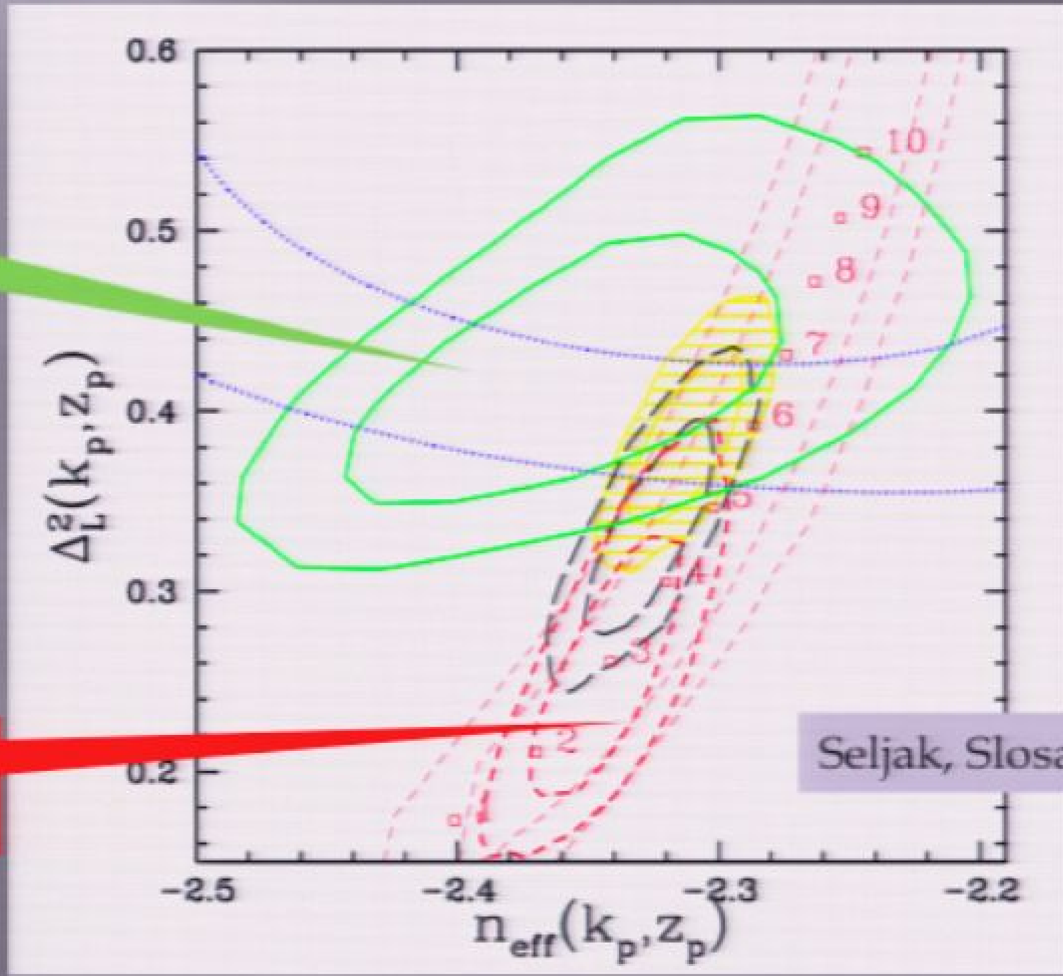


Reichardt, et al. 2008

Lyman-α excess: structure at z~3

- Ly-α, more clumpy than CMB predicts?

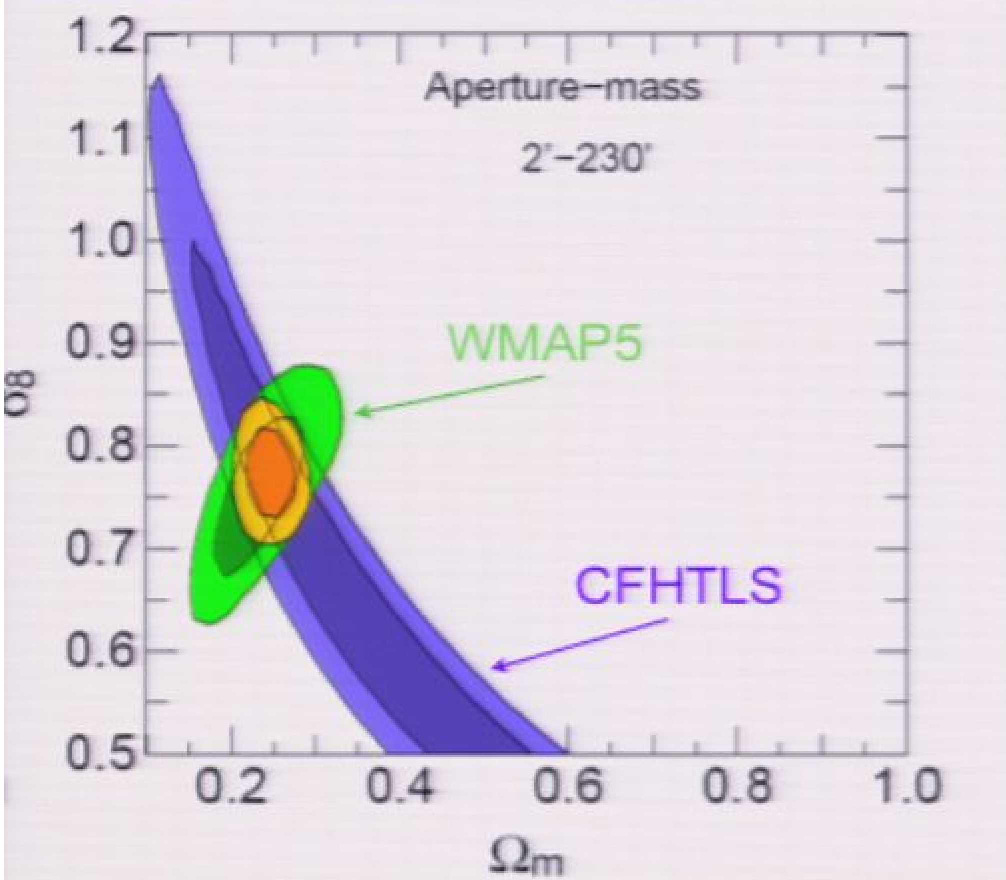
Lyman-α forest
(z=2–4)

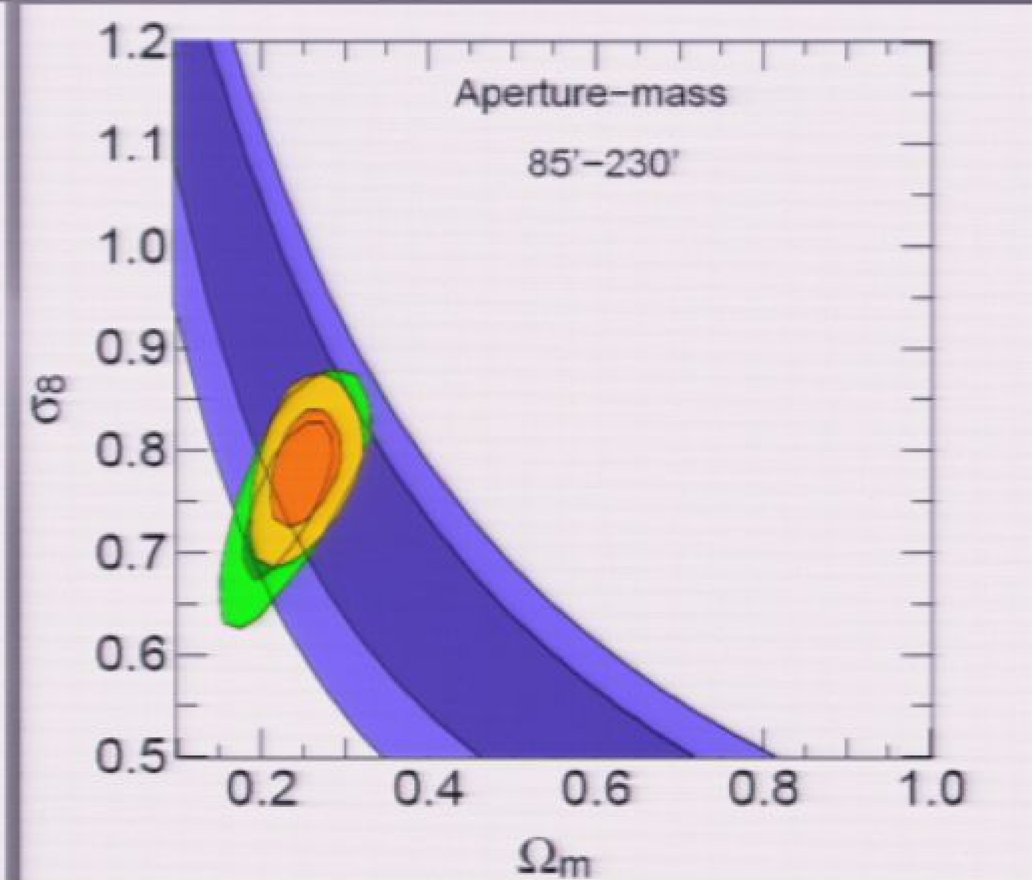


WMAP3+ΛCDM
(z=1000)

Seljak, Slosar, & McDonald 06

But σ_8 from lensing is consistent with ΛCDM



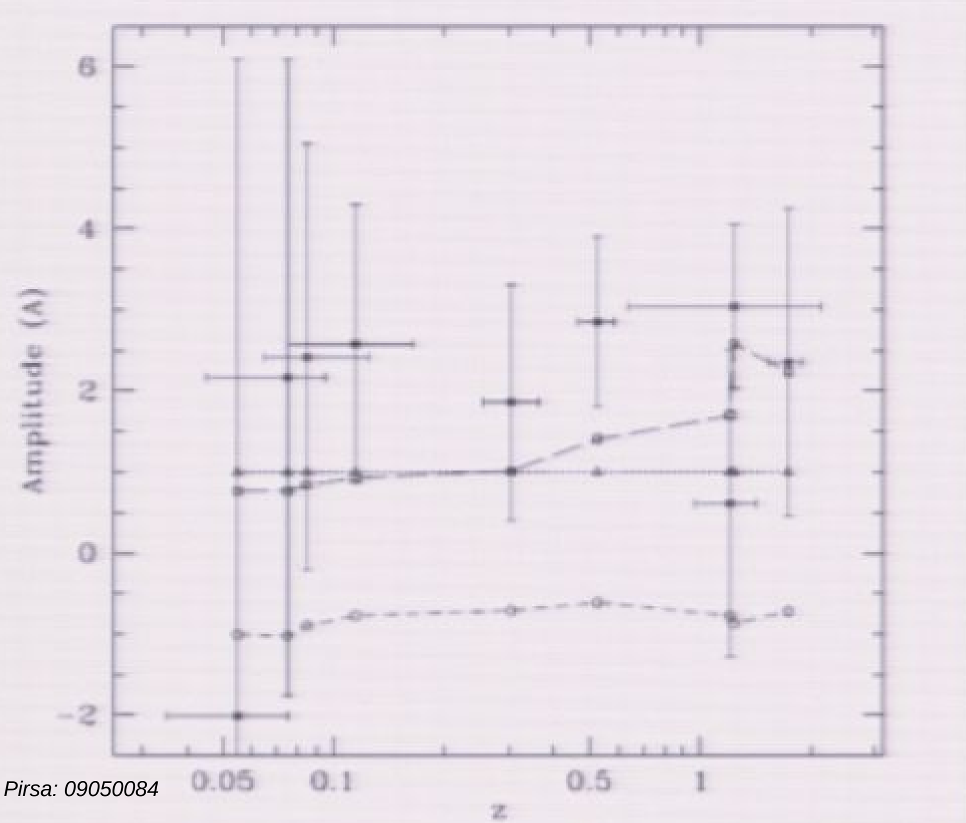


Fu, et al. 2008: Very weak lensing in the CFHTLS

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

- Gravitational Potential: 2.23±0.60 larger than ΛCDM predicts

A = *Observed ISW / Predicted ISW*

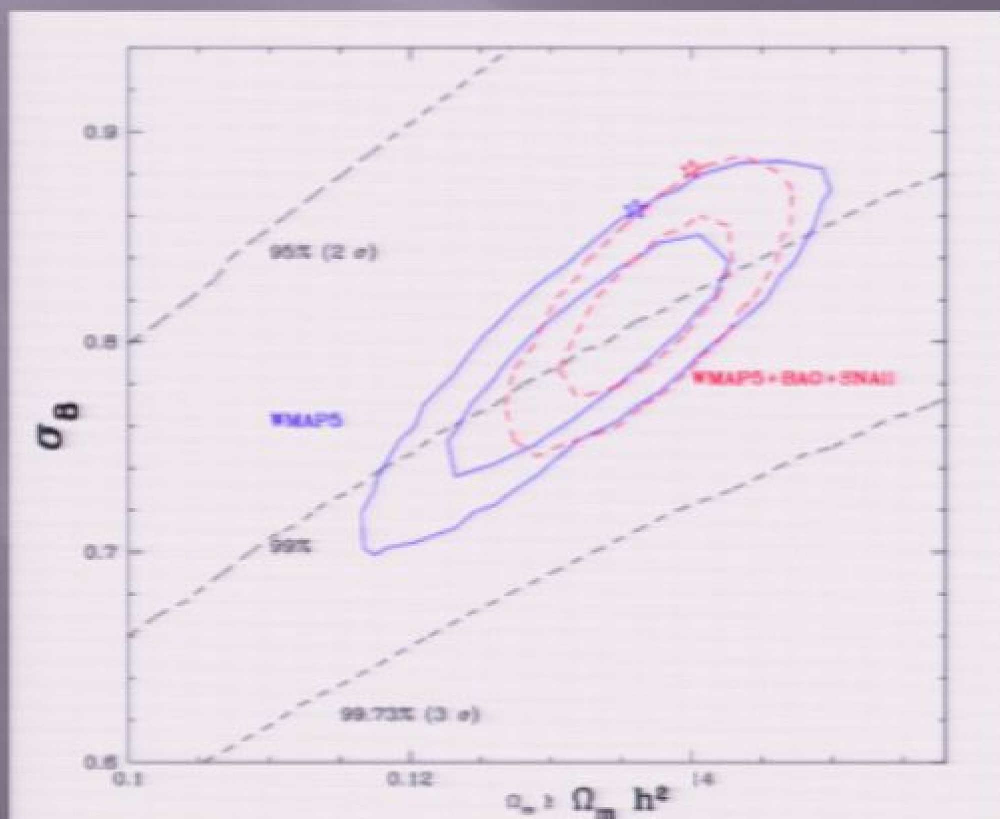


Sample	Amplitude ($A \pm \sigma$)
2MASS0	-2.01 ± 11.41
2MASS1	$+3.44 \pm 4.47$
2MASS2	$+2.86 \pm 2.87$
2MASS3	$+2.44 \pm 1.73$
LRG0	$+1.82 \pm 1.46$
LRG1	$+2.79 \pm 1.14$
QSO0	$+0.26 \pm 1.69$
QSO1	$+2.59 \pm 1.87$
NVSS	$+2.92 \pm 1.02$
All Samples	$+2.23 \pm 0.60$

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



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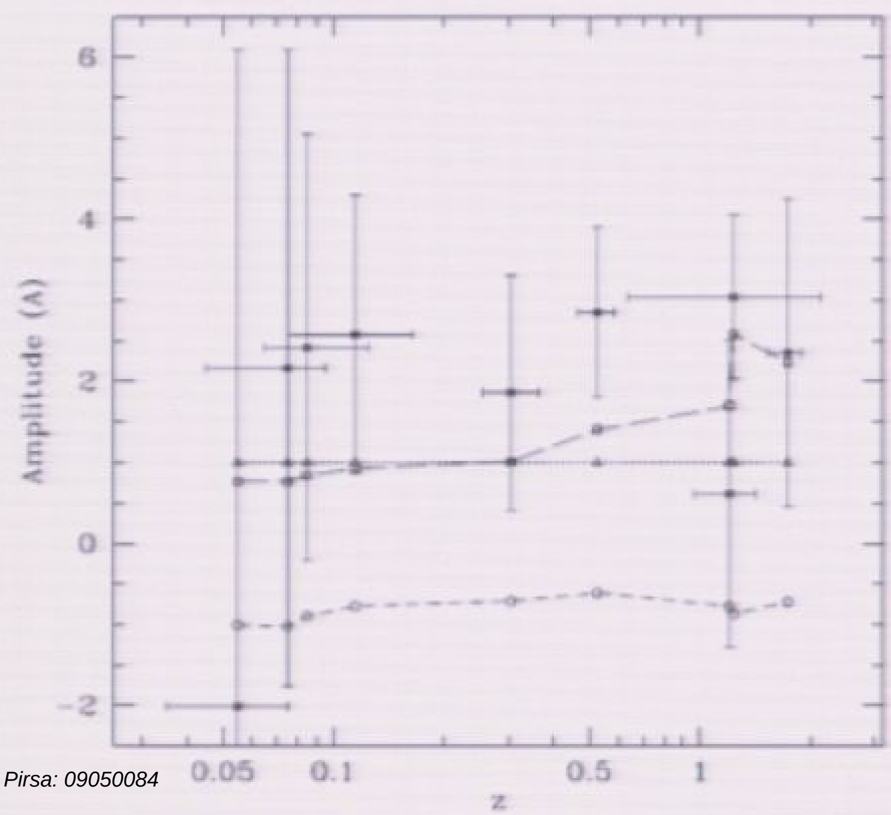

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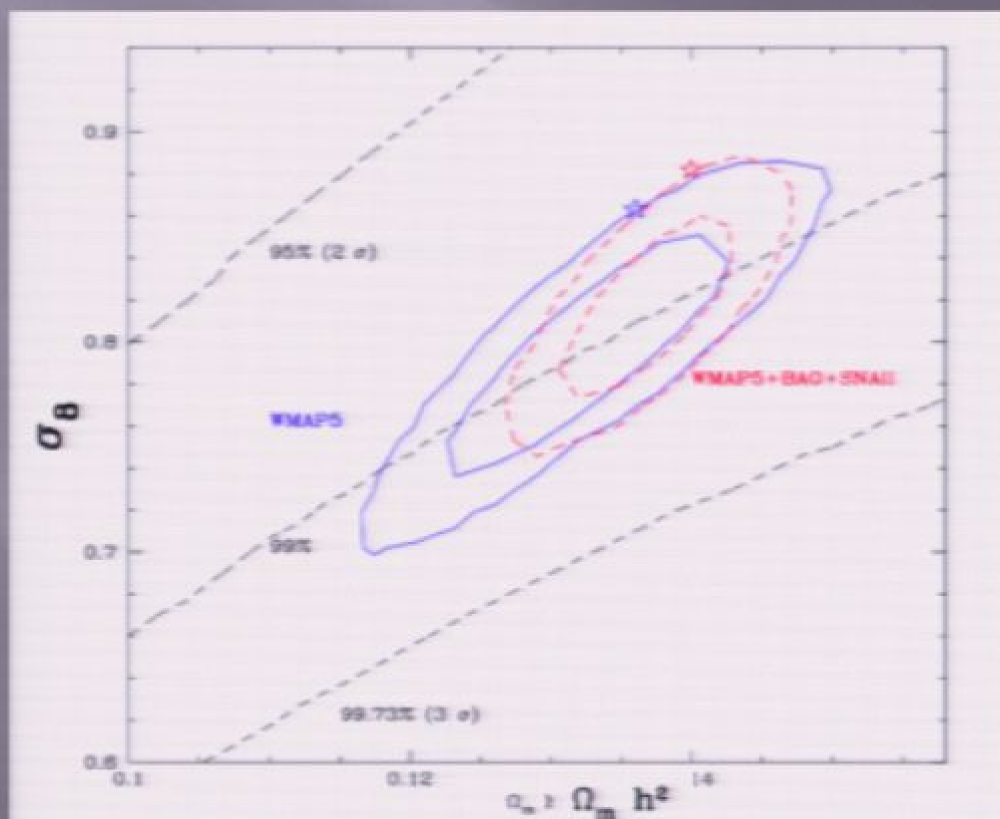
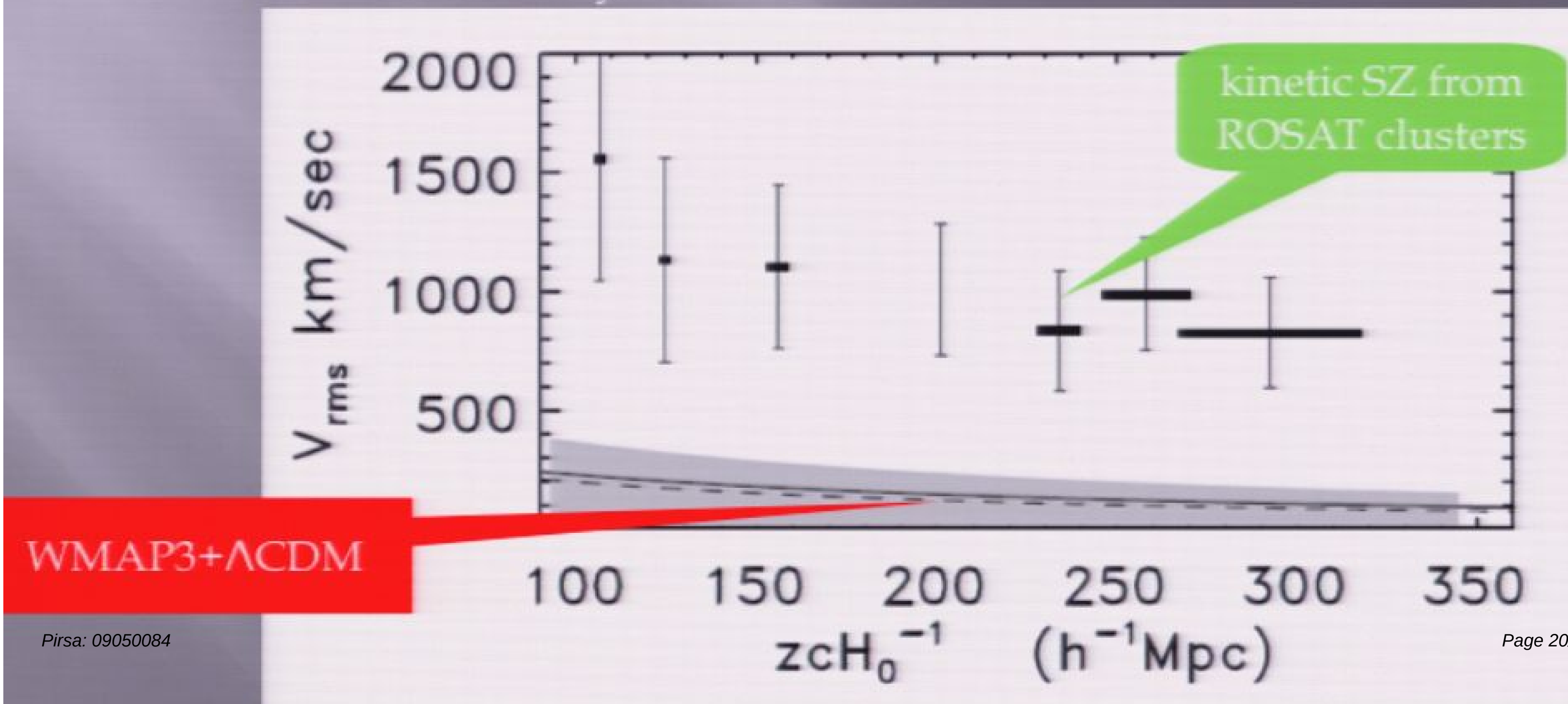


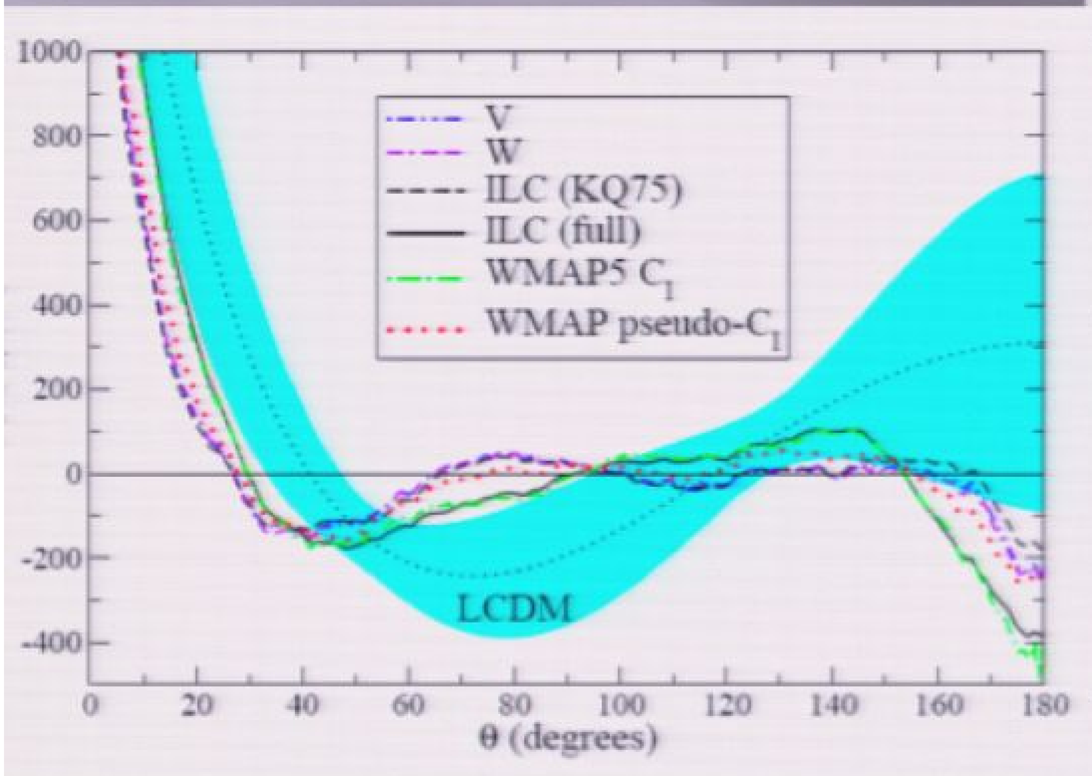
Dark Bulk Flow II: velocities at z=0

- 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



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

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
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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

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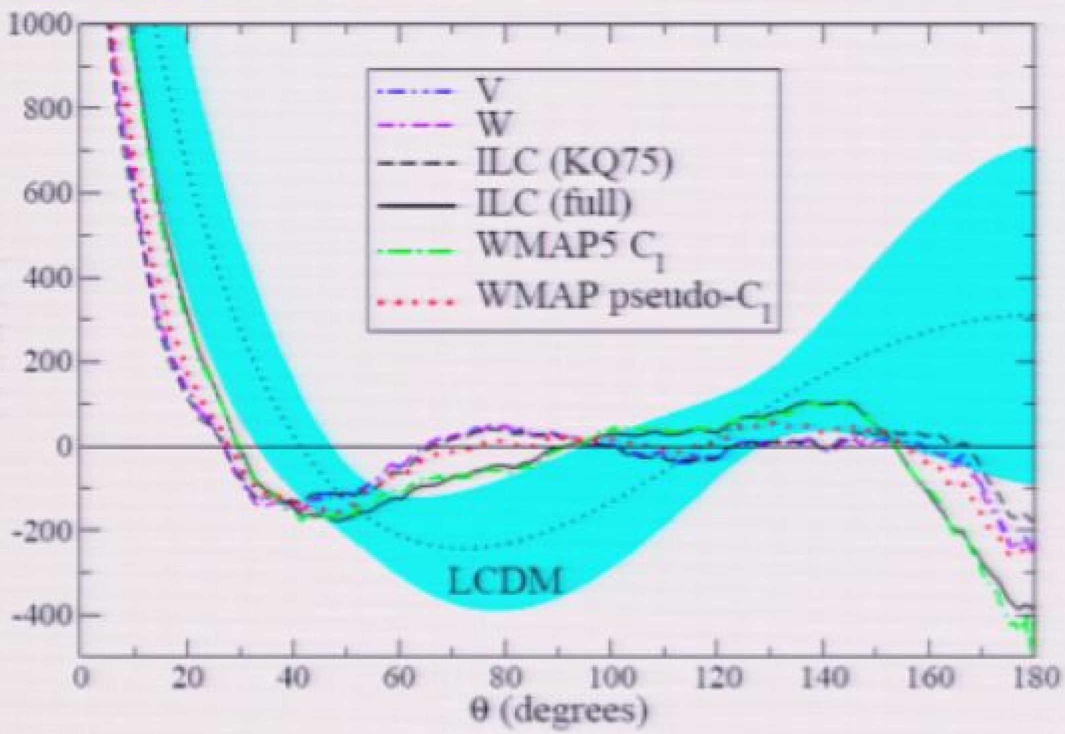

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Copi, Huterer, Schwarz, & Starkman 08

Next:

- These anomalies could be natural consequences of breakdown of GR.
- De-gravitation inspired phenomenological models can do better with these anomalies.

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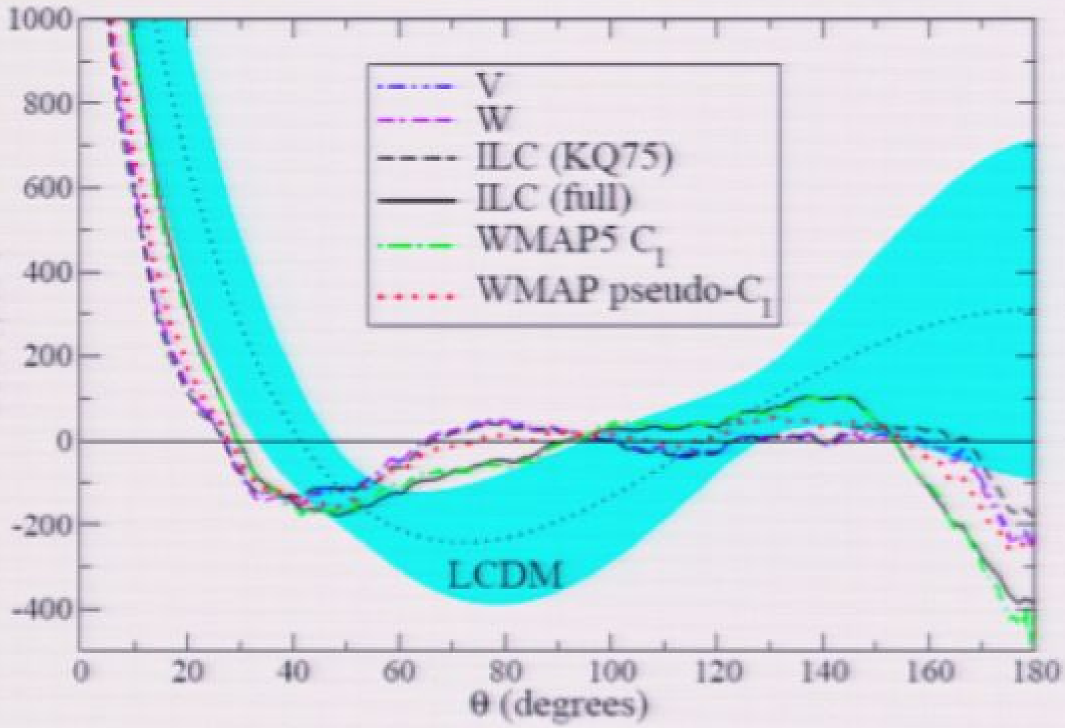

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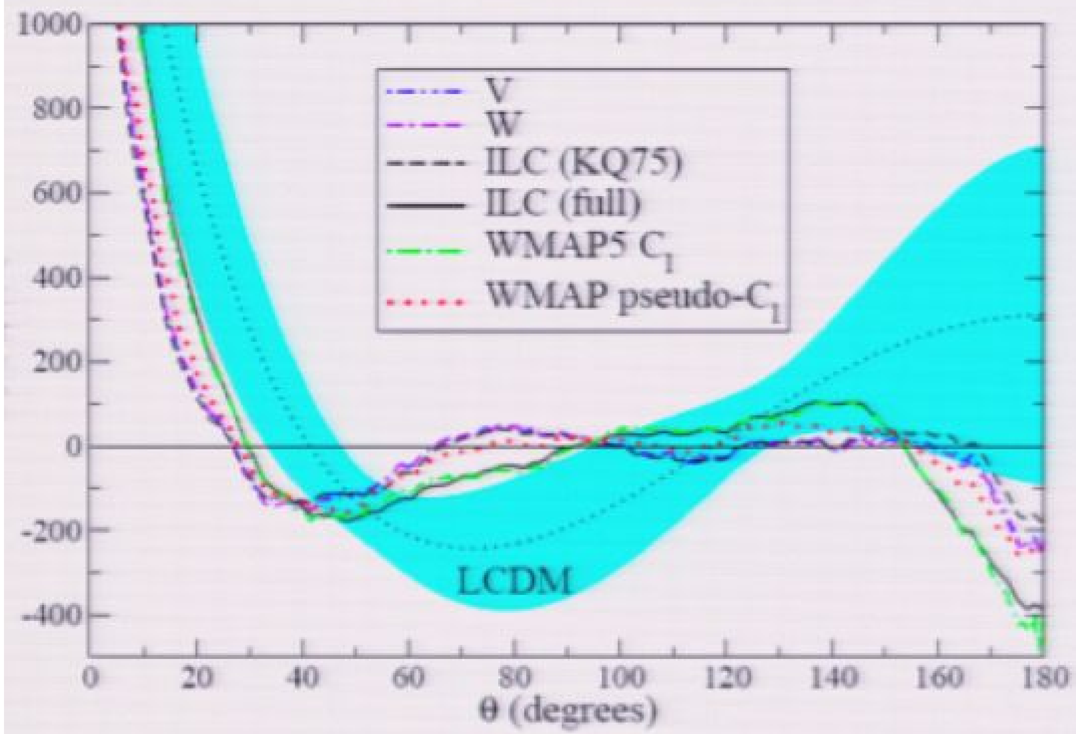

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Copi, Huterer, Schwarz, & Starkman 08

Next:

- These anomalies could be natural consequences of breakdown of GR.

- De-gravitation inspired phenomenological models can do better with these anomalies.

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 effect: Non-linear interactions can decouple the extra scalar and suppress these effects near astrophysical sources.
- The theories of interest are higher-dimensional generalizations of the Dvali-Gabadadze-Porrati model in which our visible universe is confined to a 3-brane (Cascading Gravity). In the simplest codimension-2 case, for instance, our 3-brane is embedded in a 4-brane within a 6-dimensional bulk.

What are the implications for back ground Cosmology?

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

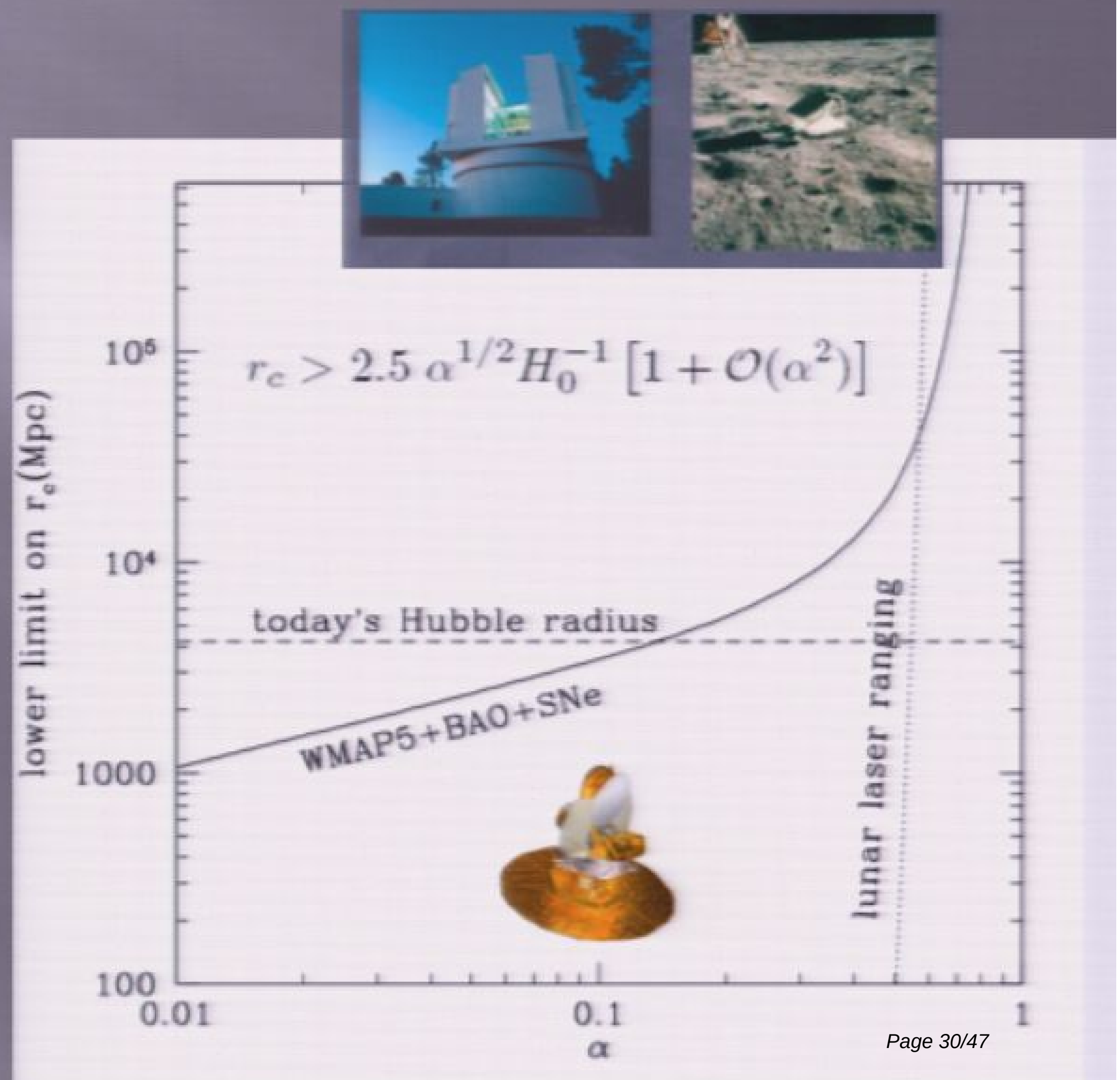
$$H^2 = \frac{8\pi G}{3}\rho_{\rm m} + \frac{\Lambda}{3} - \frac{H}{r_c}$$

- for arbitrary α:

$$H^2 = \frac{8\pi G}{3}\rho_{\rm m} + \frac{\Lambda}{3} - \frac{H^{2\alpha}}{r_c^{2(1-\alpha)}}$$

Note: $\alpha = 0$ has identical expansion history as LCDM!

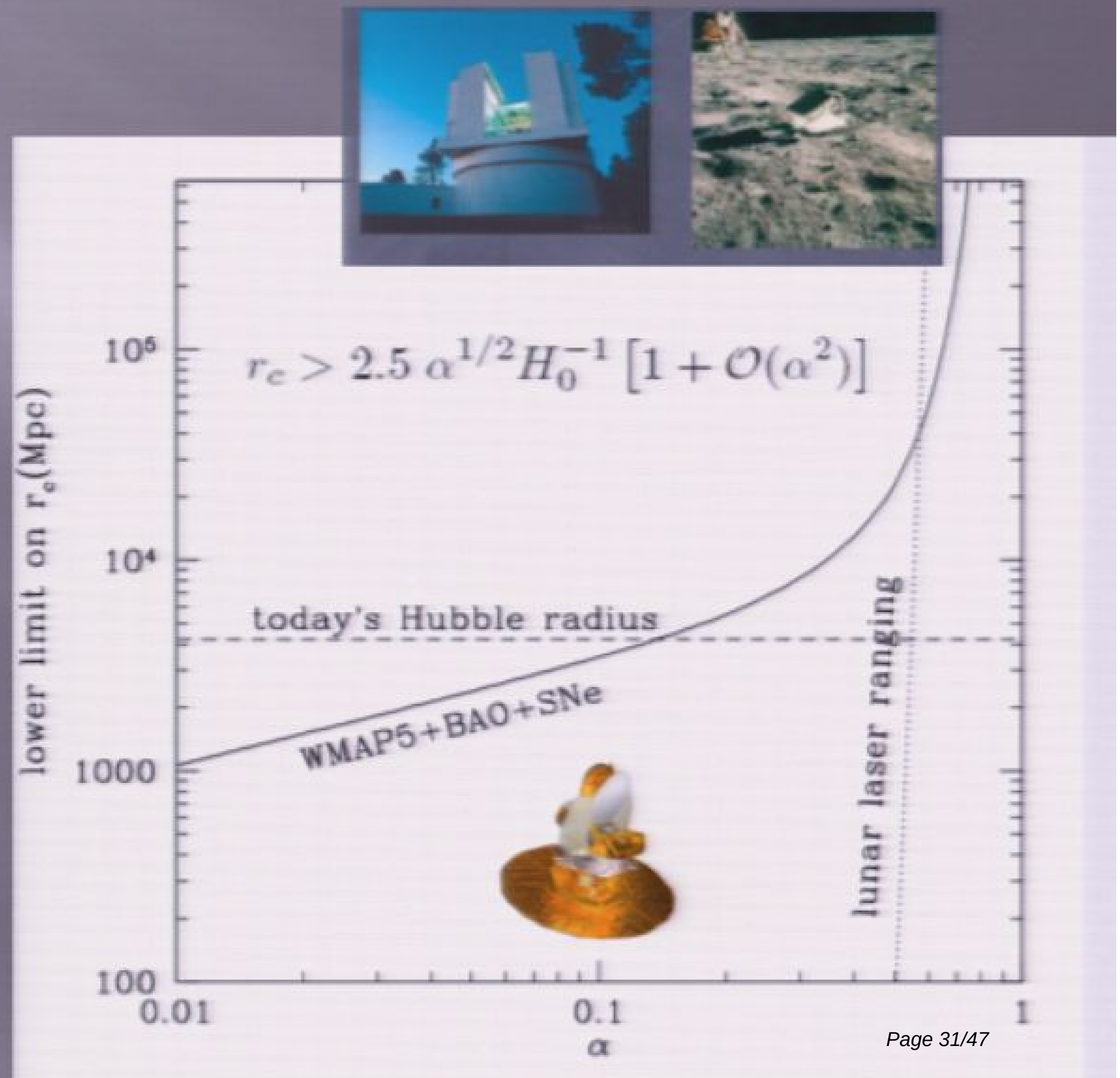
Degravitating FRW



Degravitating FRW

- FRW with α → 0

indistinguishable from ΛCDM



Inhomogeneous Universe could be different

- Could lead to larger growth on intermediate scales:
  - Gravity becomes massive → fifth force enhances gravitational attraction on non-relativistic matter (not photons $\Phi_- \neq -\Psi$)
- 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

Also see Khoury & Wyman (2009)

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***

How we deal with perturbations

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

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

- 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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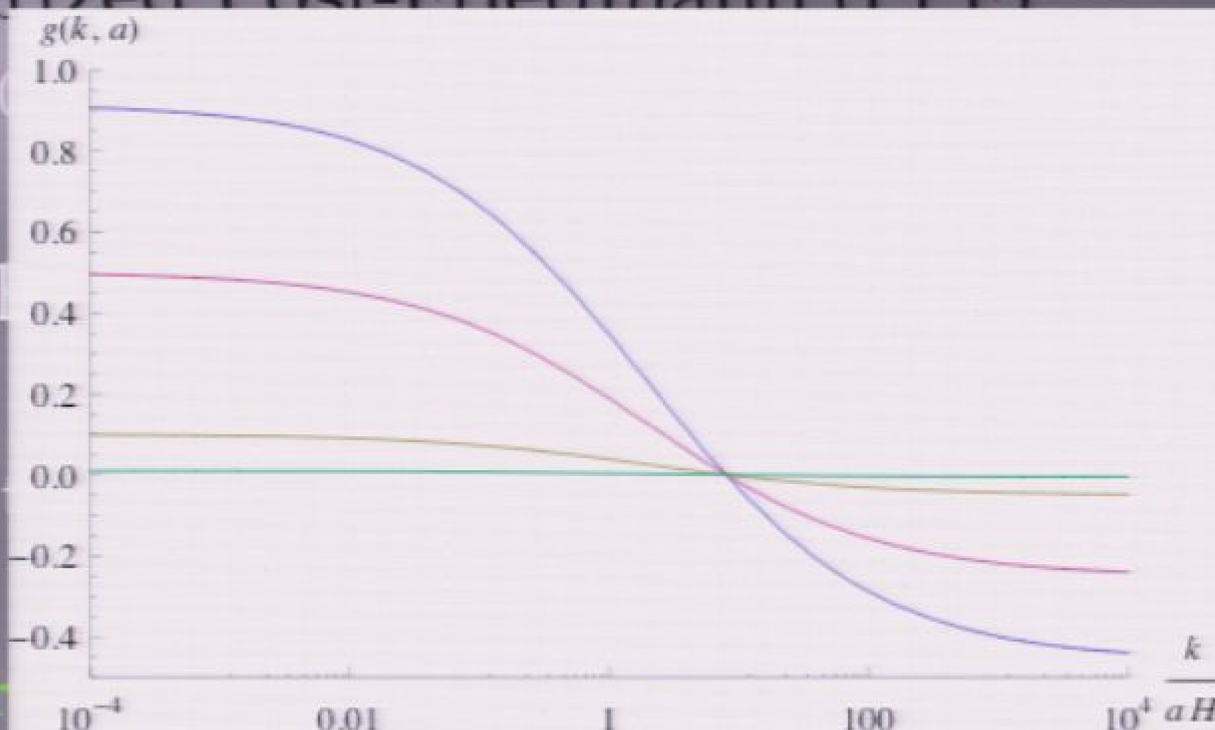
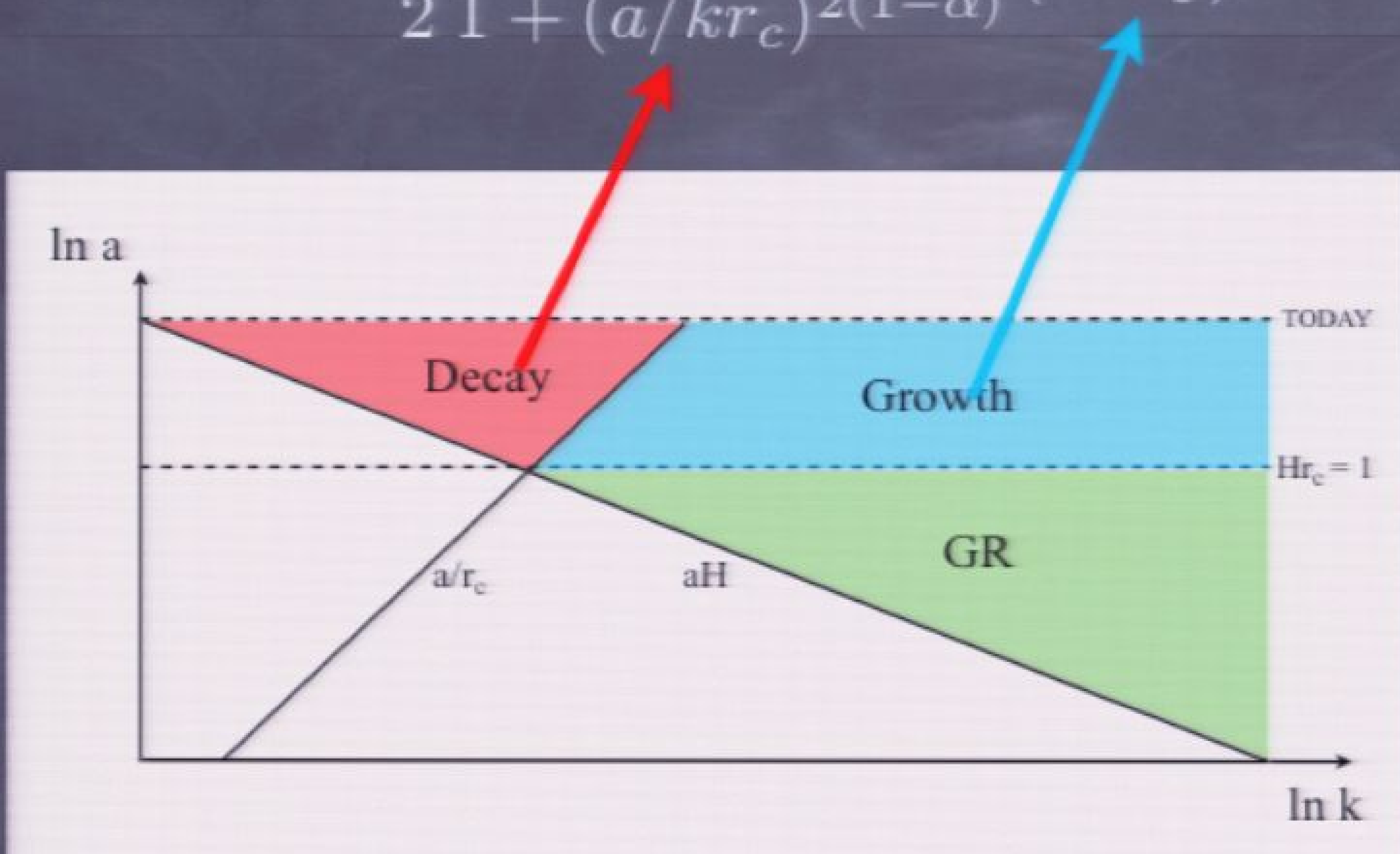
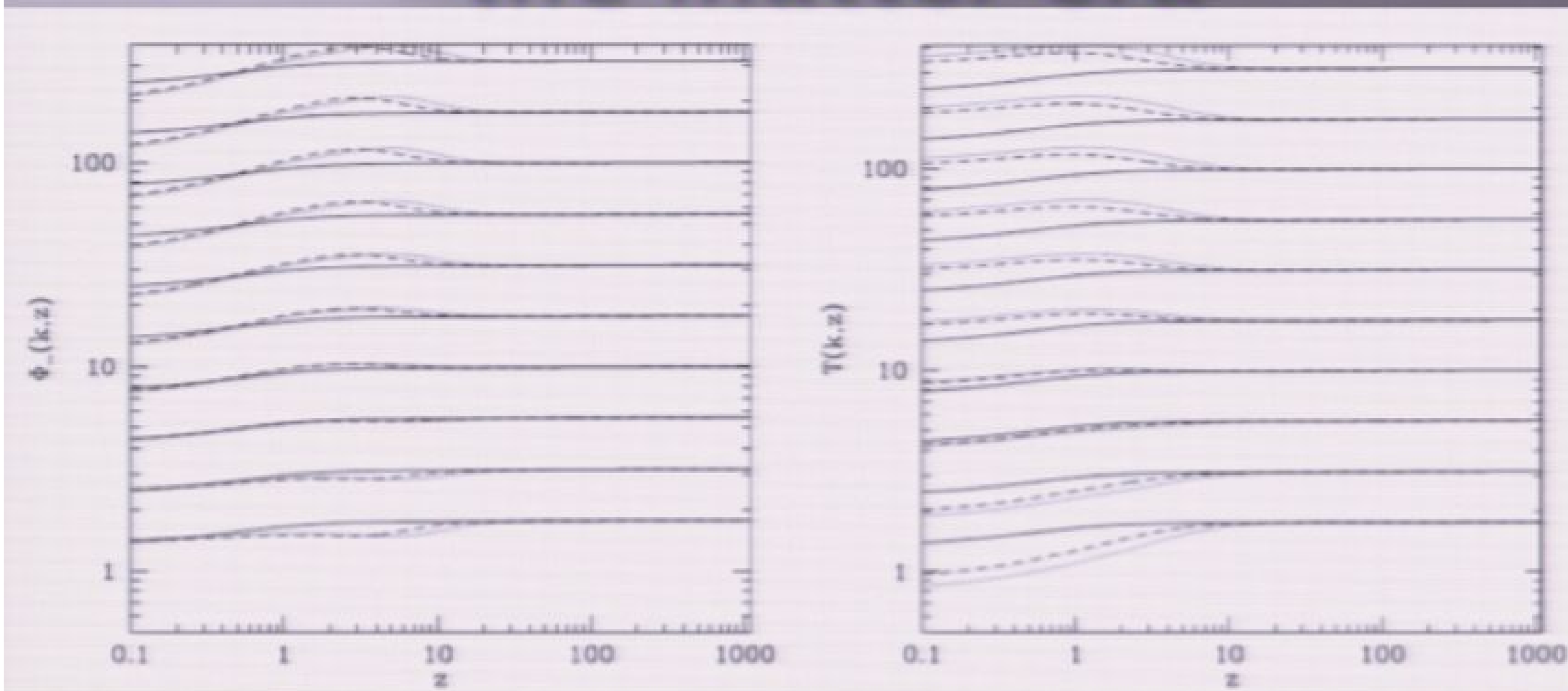


Density Perturbations:

$$\ddot{\delta} + 2H\dot{\delta} = \frac{3}{2}\frac{\Omega_{\rm m} H^2}{1 + (a/kr_c)^{2(1-\alpha)}}(1-g)\delta$$



Potential Transfer Function in the matter era



smaller scale
(large K=10Mpc

larger scale
(small K=10^{-4}Mpc

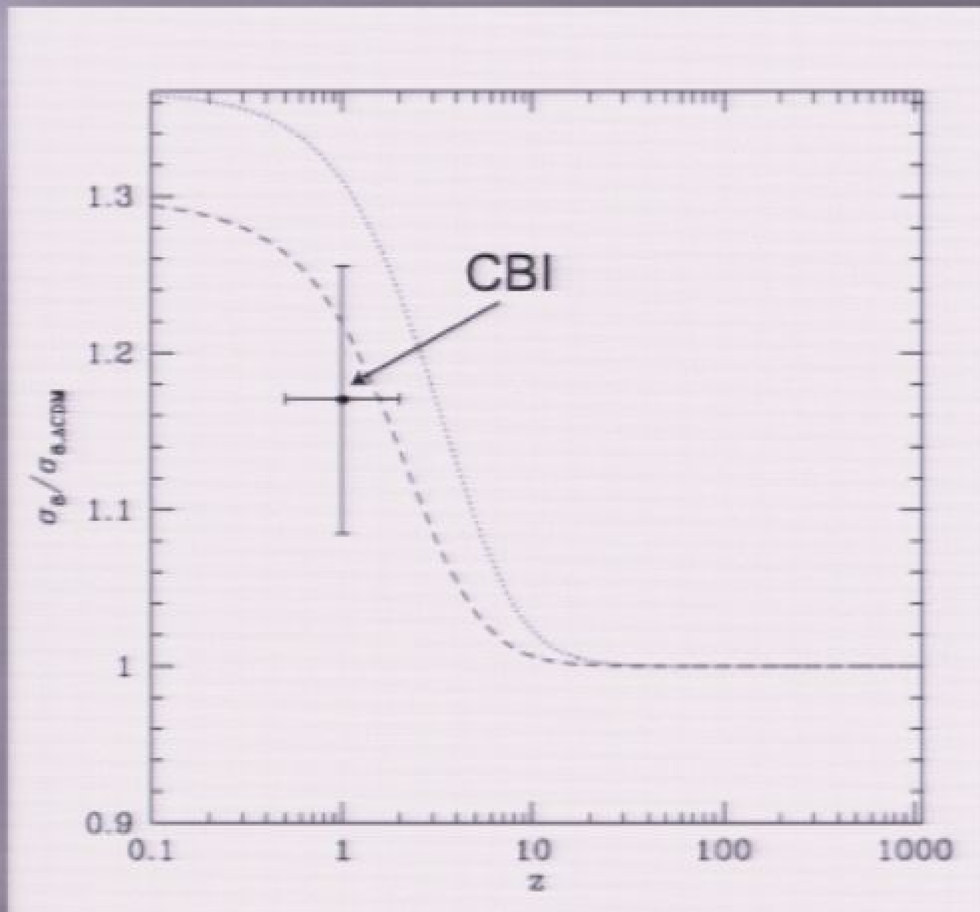
ΛCDM (solid), $r_c = 300$ Mpc (dotted) and $r_c = 600$ Mpc (dashed)

Lensing, Φ_- comoving density perturbations Δ_m/a

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

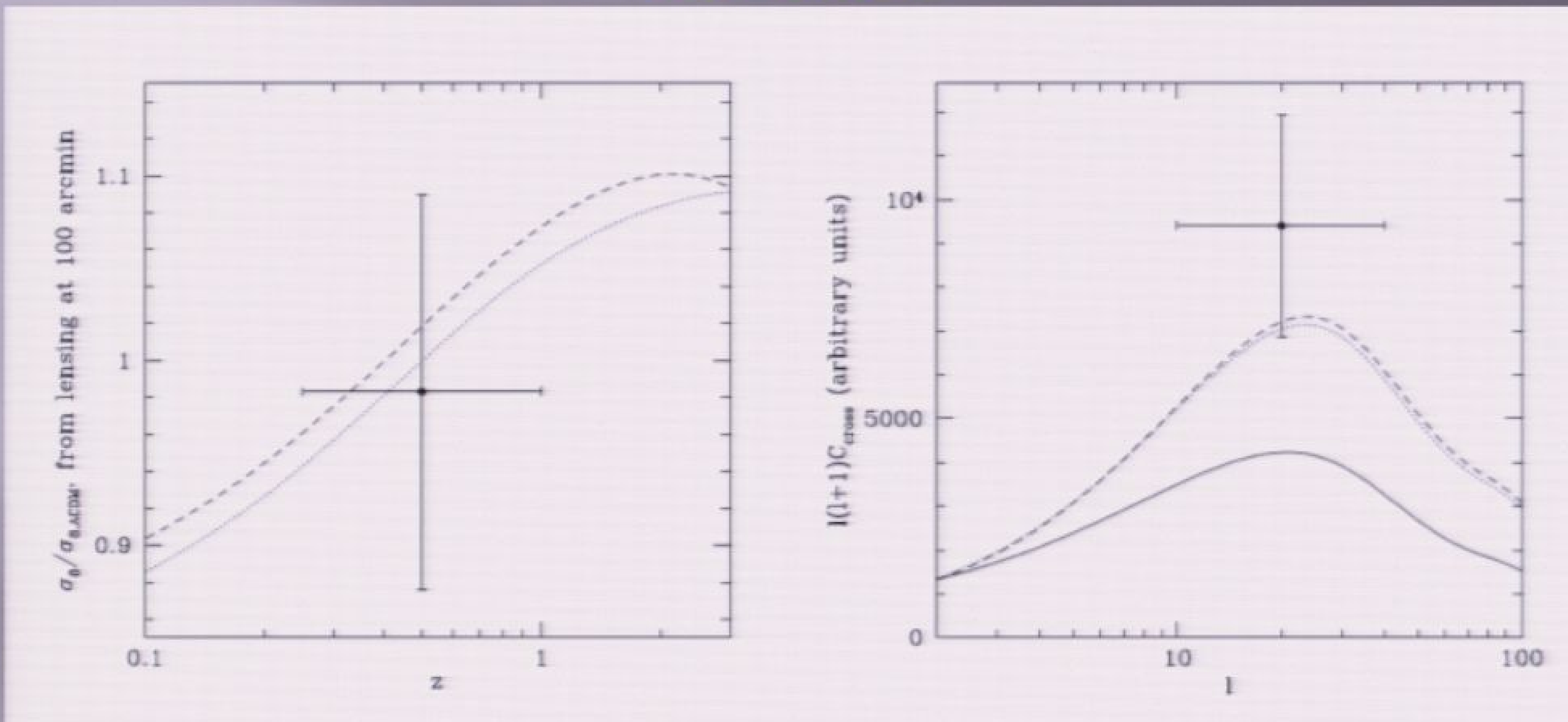
Galaxy clusters and CBI excess

The ratio of σ_8 in our modified gravity models to that of CDM, as a function of redshift.



Higher amplitude of the linear matter density fluctuations close to the scale of cluster formation would result higher cluster abundances

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.

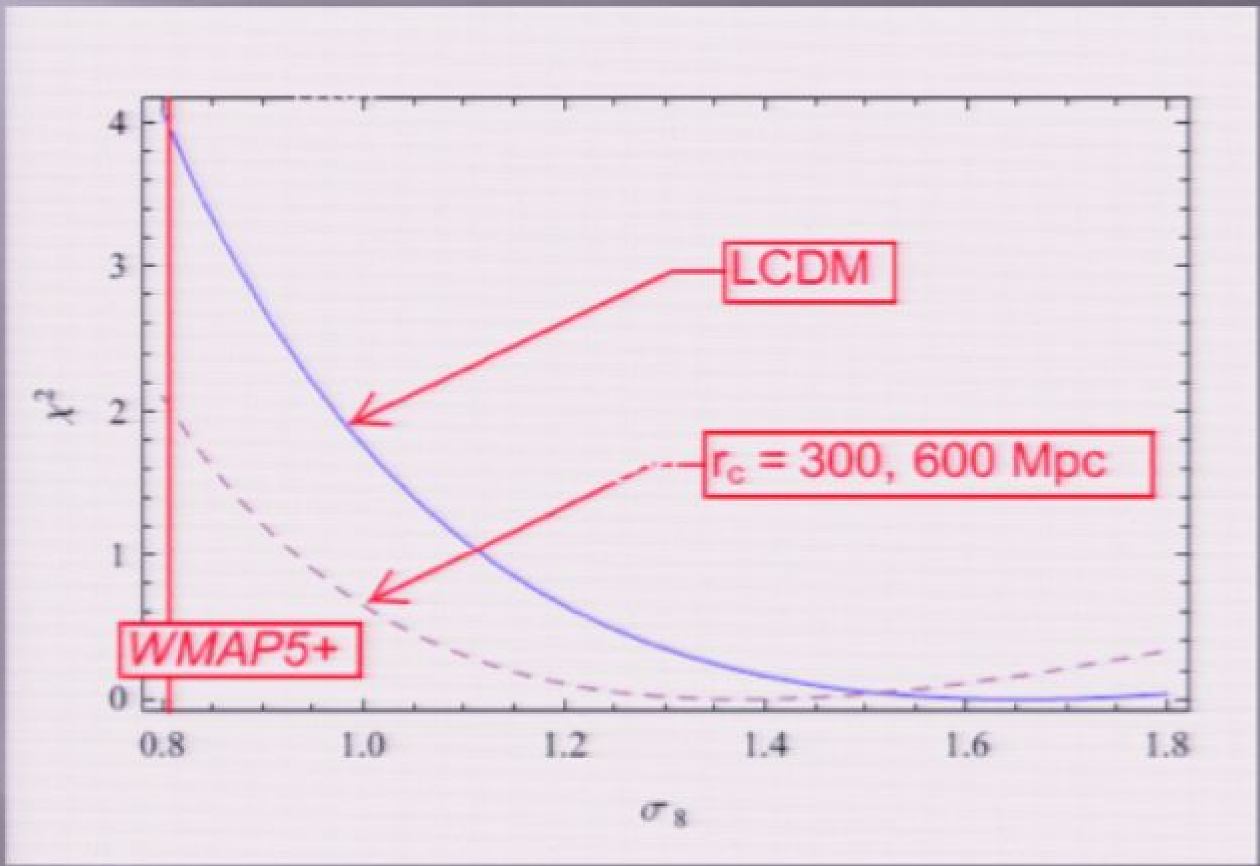
current weak lensing measurements cannot distinguish our predictions from that of the ΛCDM

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

(faster decay of $\Phi\_$)

Bulk Flows

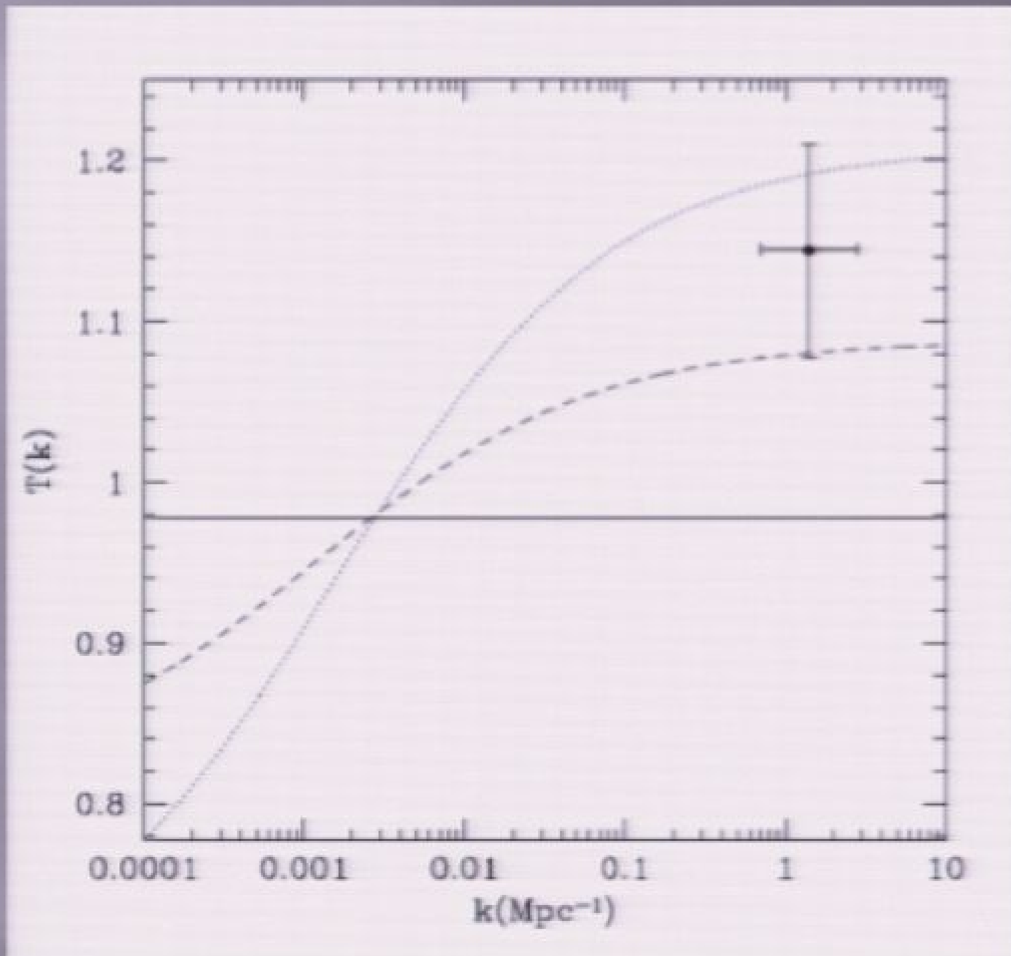
Peculiar velocity measurements through the continuity equation, probe $\dot{\Delta}_m$ in the linear regime



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 through the standard Poisson equation) 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.

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)

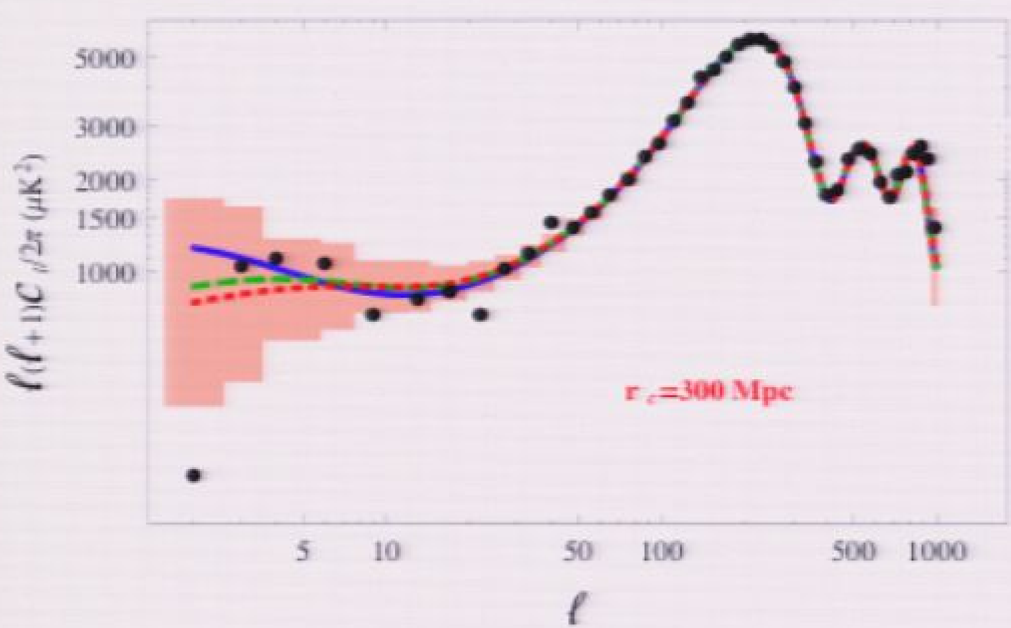
$$\zeta = \text{const.} = \frac{H}{H'}\left[(g-1)\Phi_- - g'\Phi_- - (g+1)\Phi'_-\right] + (g+1)\Phi_- \simeq \frac{(5+g)\Phi_-}{3}$$

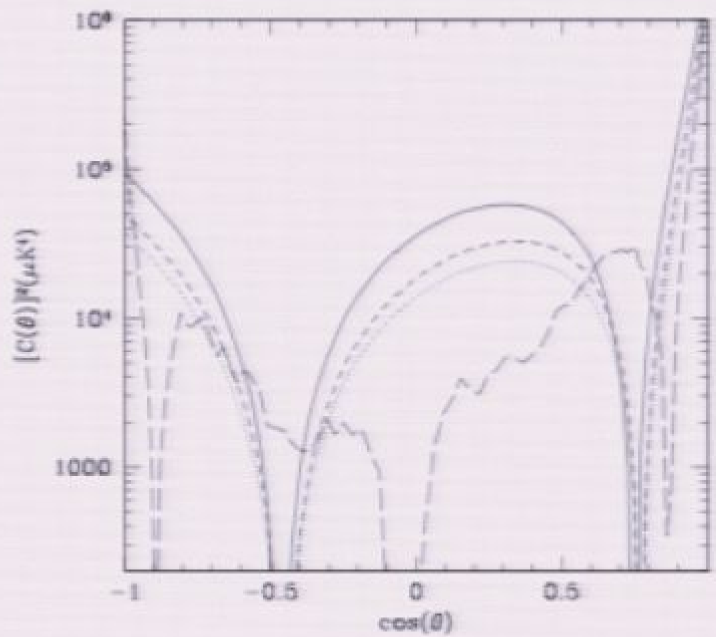
- If g goes from 0 to 1, ISW and Sachs-Wolfe cancel!

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)

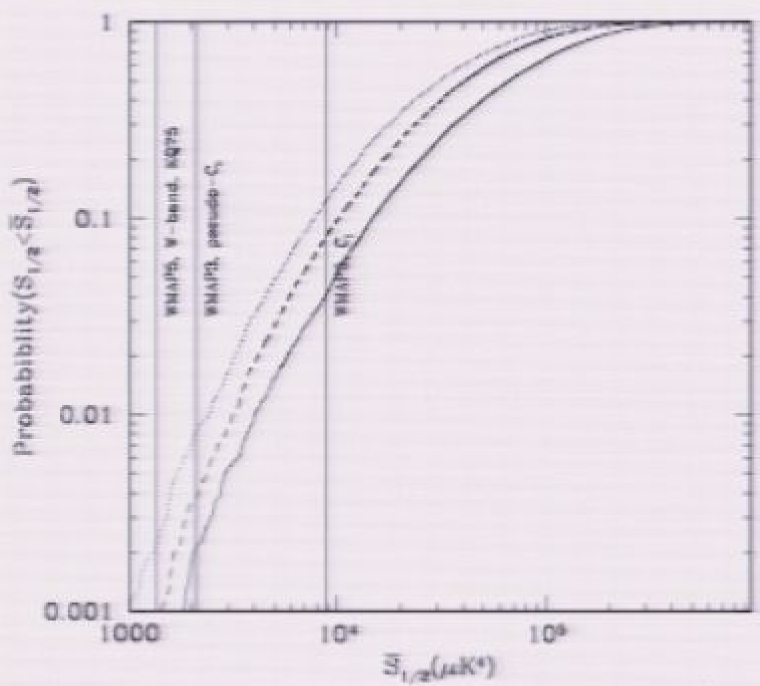


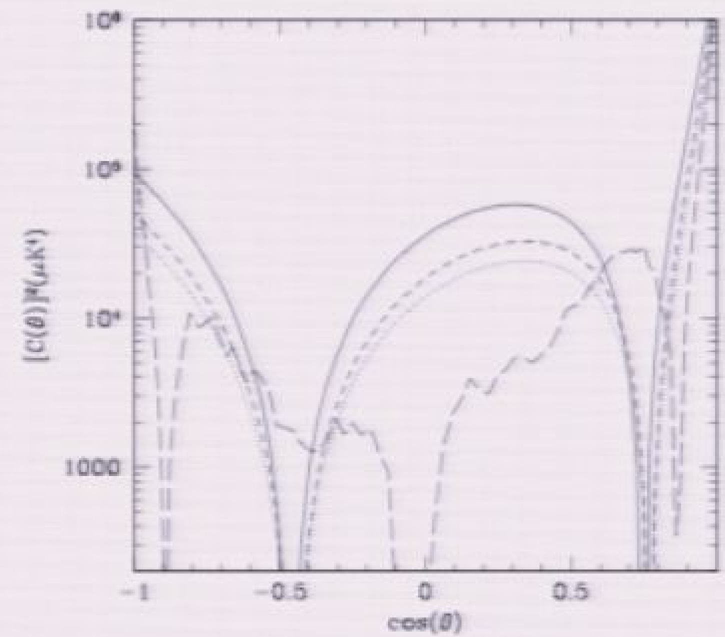


de-Correlating CMB on large angles

CMB angular power spectra

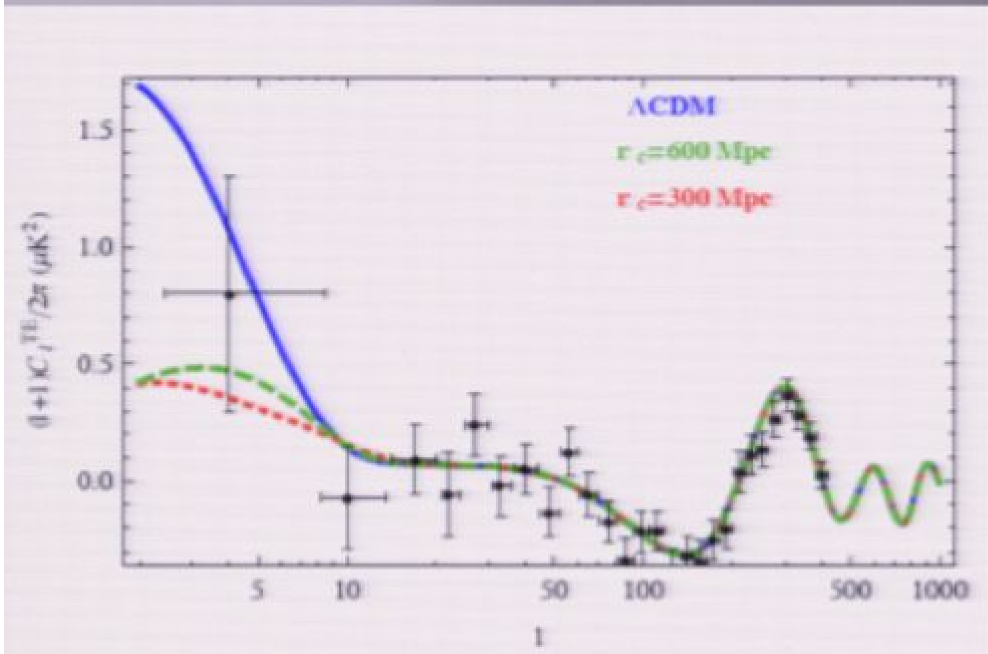
best-fit ΛCDM (solid curve), rc = 600 Mpc (dashed curve) and r= 300 Mpc (short-dashed curve)

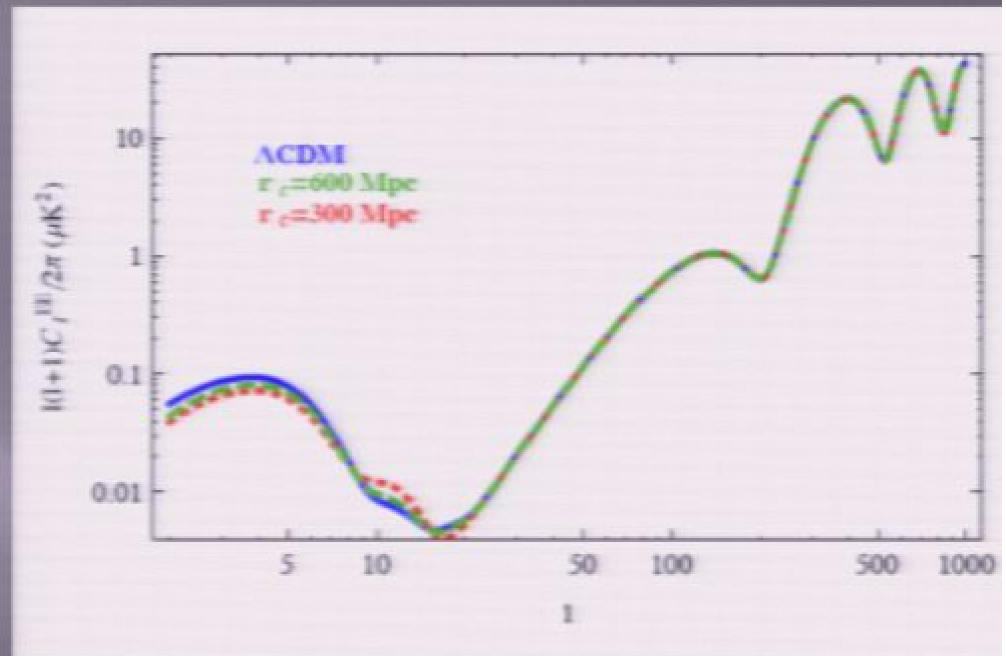




$$S_{1/2} \equiv \int_{-1}^{1/2} [\mathcal{C}(\theta)]^2 \, d(\cos\theta)$$

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

The Moral

The Moral

- Several observations point to excess power (relative to ΛCMB) on small scales at late times
- Massive gravity can (potentially):
  - Explain this excess power
  - Degravitate the vacuum → solve the CC problem
  - Explain lack of power in CMB on large angles
- 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 but probing the Inhomogeneous universe present promising potential to test deviation from LCDM.**