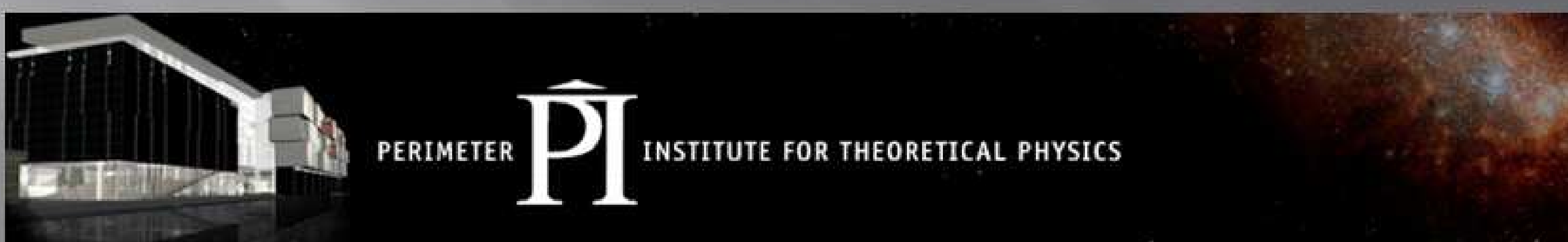
# Observational Evidence For Cosmological-Scale Extra Dimensions

Ghazal Geshnizjani

with Niayesh Afshordi and Justin Khoury

arXiv:0812.2244 [astro-ph]



# Cosmology: the Golden Era

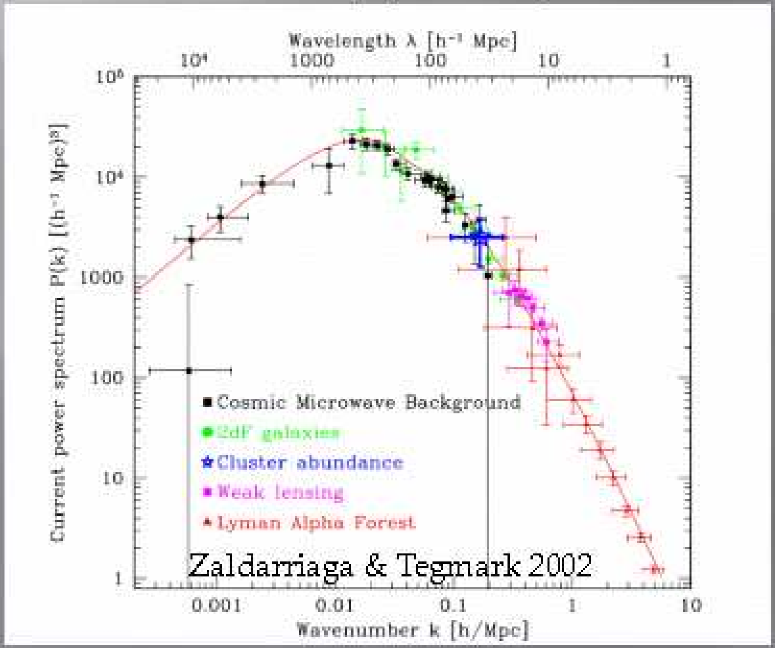
# Cosmology: the Golden Era

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

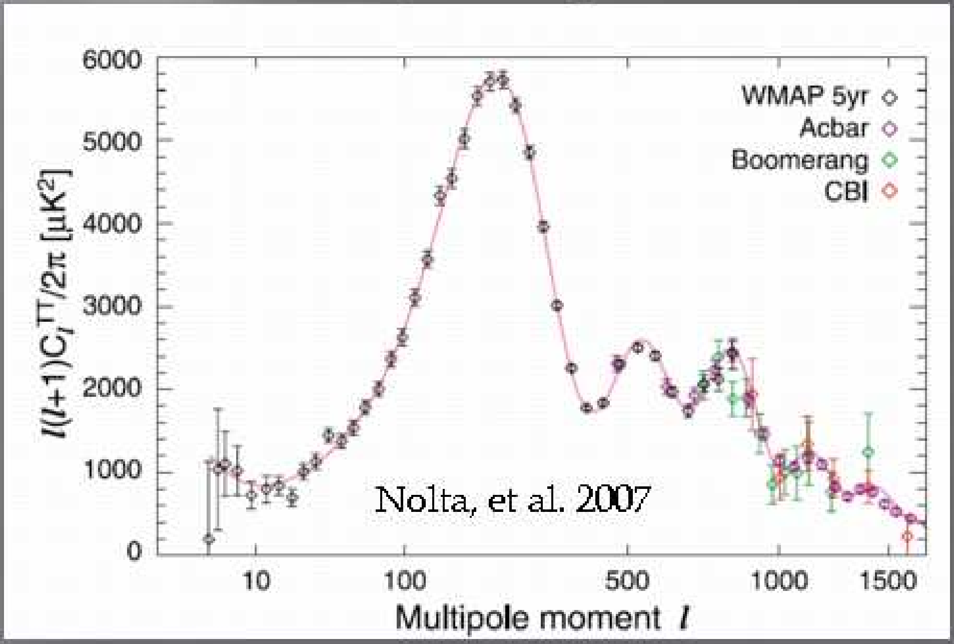
# Cosmology: the Golden Era

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

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 | $2.273 \pm 0.062$ | $2.267^{+0.058}_{-0.059}$ |
| | $\Omega_c h^2$ | 0.1081 | 0.1138 | $0.1099 \pm 0.0062$ | $0.1131 \pm 0.0034$ |
| | $\Omega_\Lambda$ | 0.751 | 0.723 | $0.742 \pm 0.030$ | $0.726 \pm 0.015$ |
| | $n_s$ | 0.961 | 0.962 | $0.963^{+0.014}_{-0.015}$ | $0.960 \pm 0.013$ |
| | $\tau$ | 0.089 | 0.088 | $0.087 \pm 0.017$ | $0.084 \pm 0.016$ |
| | $\Delta^2_{\mathcal{R}}(k_0{}^e)$ | $2.41 \times 10^{-9}$ | $2.46 \times 10^{-9}$ | $(2.41 \pm 0.11) \times 10^{-9}$ | $(2.445 \pm 0.096) \times 10^{-9}$ |

# 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 $\Lambda$ so unnaturally small?

* In EFT, robust contribution to vacuum energy is

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

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

# Is there any trouble in ΛCDM paradise?

**Live happily: Anthropic reasoning**
**Or …**

* In EFT, robust contribution to vacuum energy is

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

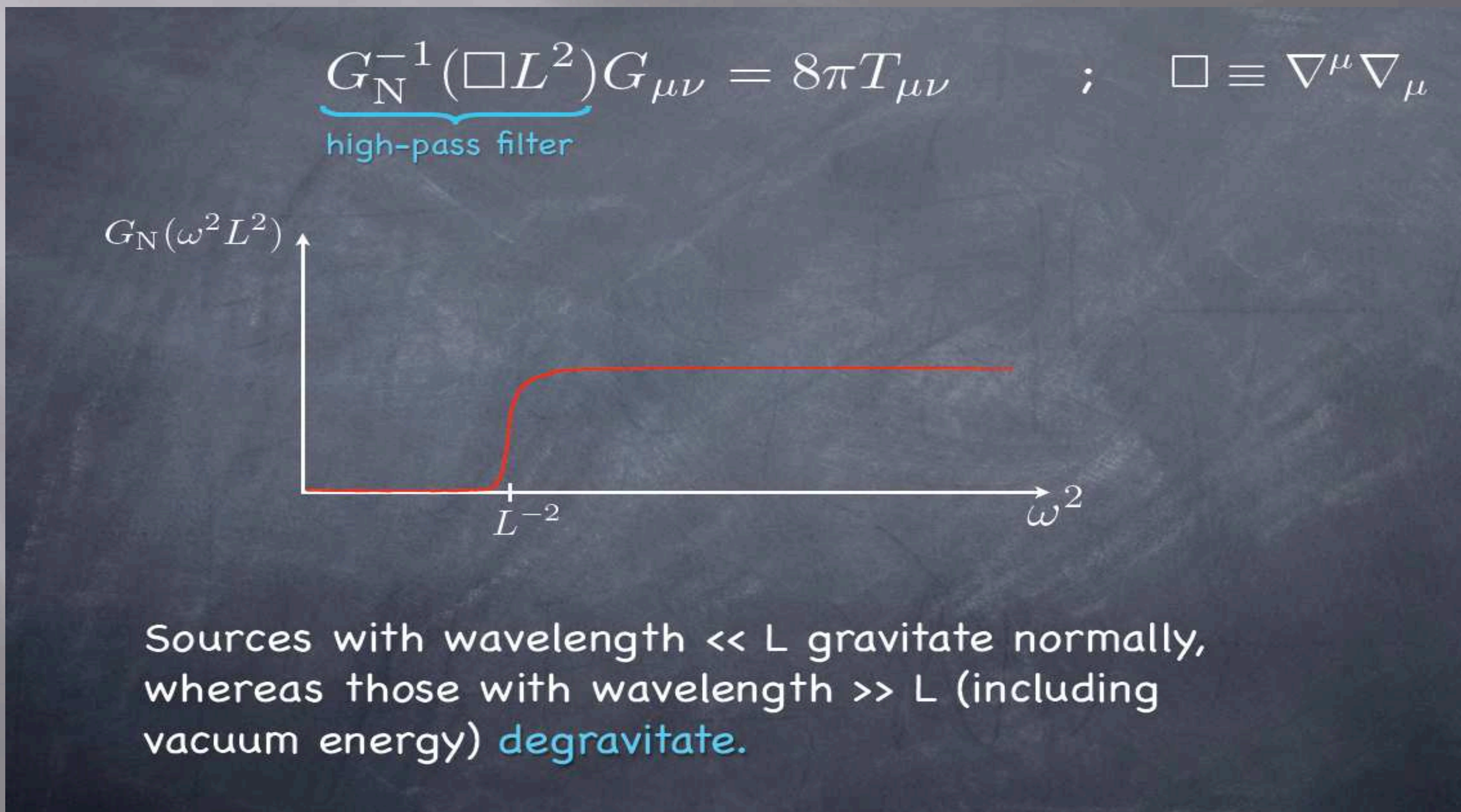
which, already with the electron, is $\gg (1\ {\rm meV})^4$

## looking for a panacea:

# *de-Gravitation*

*Dvali, Hofmann, and Khoury 07*

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



# Cosmological degravitation

- Around Minkowski space:

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

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

- Promising for 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

# Snapshot of the theoretical progress so far

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

- On intermediate (albeit cosmologically relevant) scales, an extra scalar force which enhances gravitational attraction by order unity.

- Non-linear interactions can suppress the 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.

- 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.

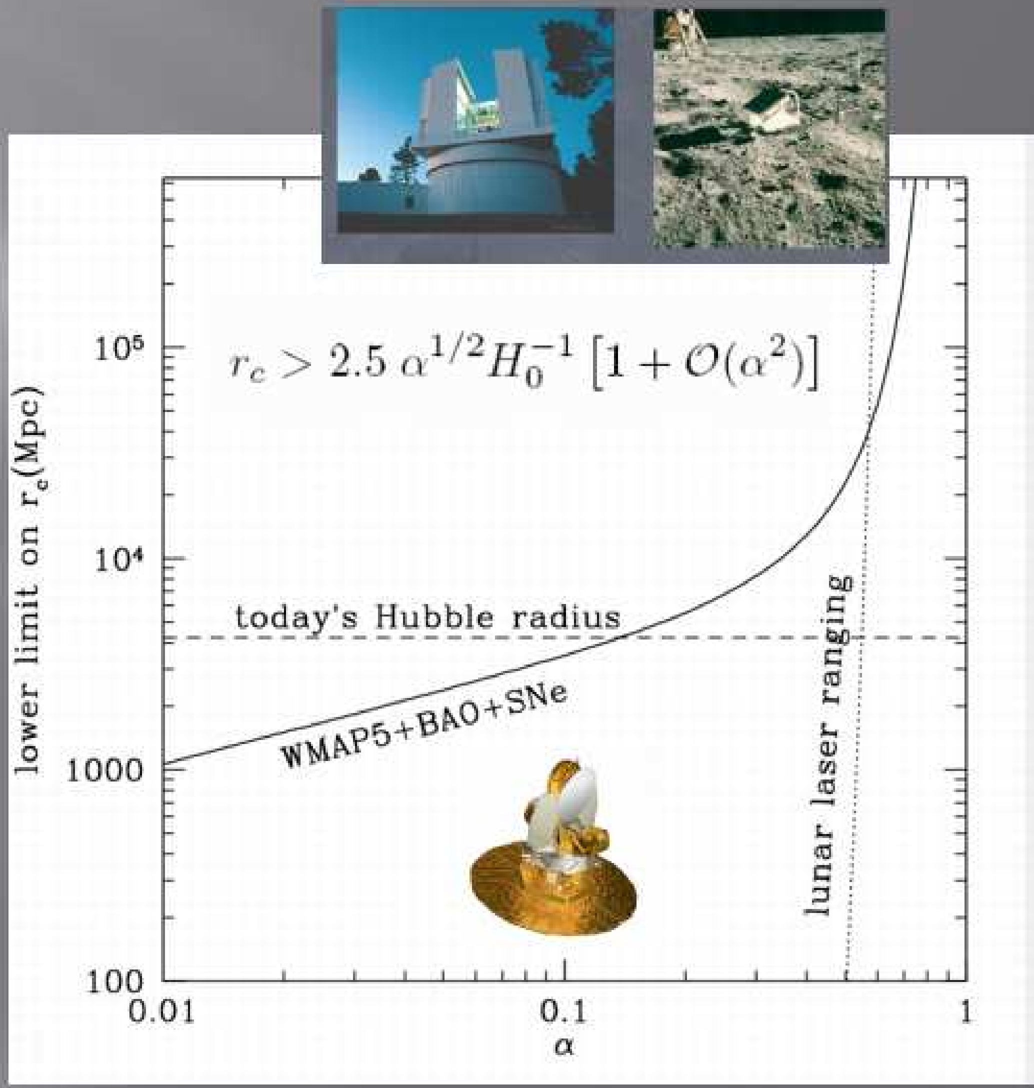
# What are the implications for Cosmological observations?

- General cosmological solution is non-existent ; We pick any hint we can from theory and fill out the holes with observations.

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

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

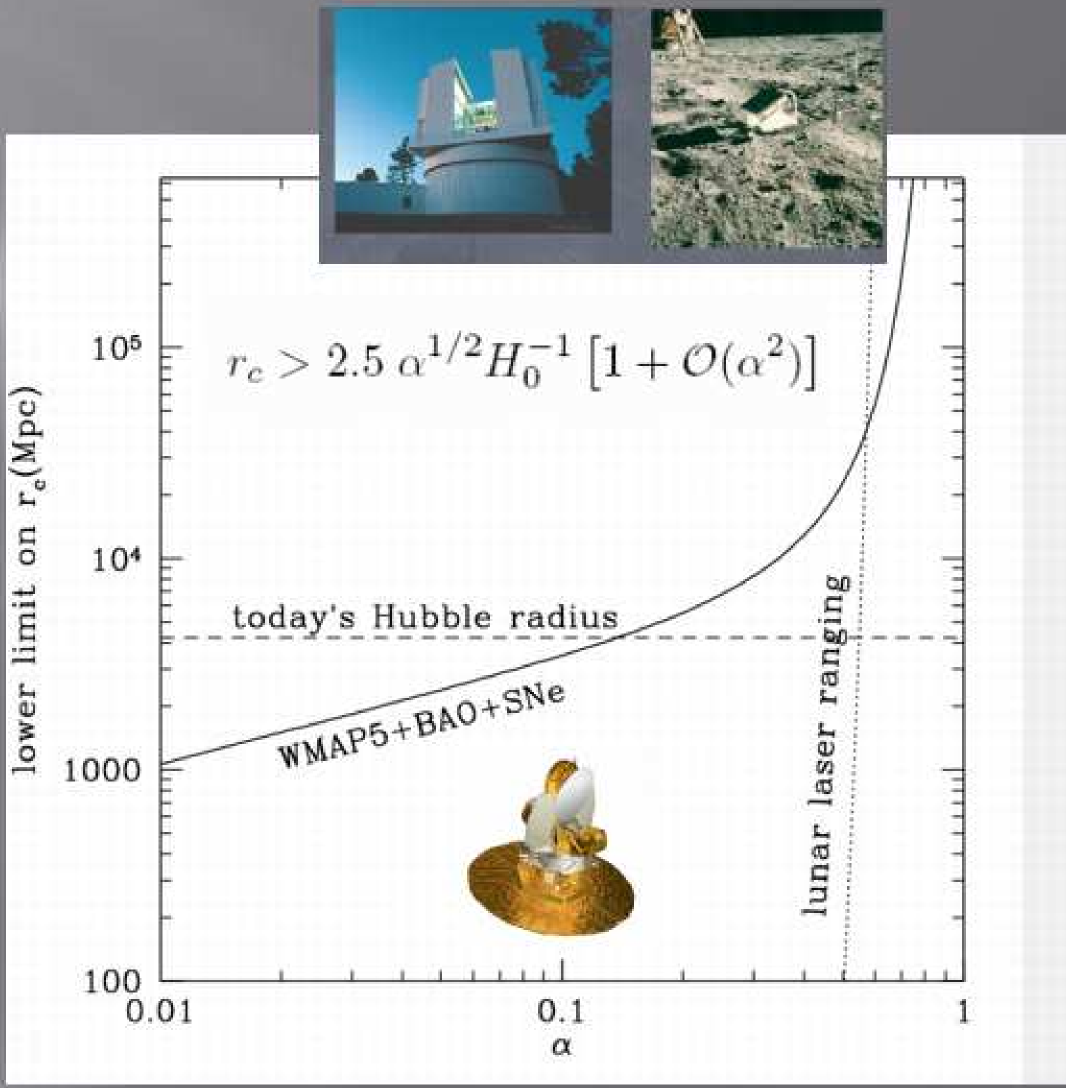
# Degravitating FRW



# Degravitating FRW

- FRW with $\alpha \to 0$

  (massive graviton)
  indistinguishable from $\Lambda$CDM



# *Inhomogeneous Universe could be different*

# *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 $\Phi_- \neq -\Psi$ )
- Possible Large Scale Implications:
  - We will fit our model so that ISW and Sachs-Wolfe effects cancel on super-horizon scales

# *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***

# observational anomalies

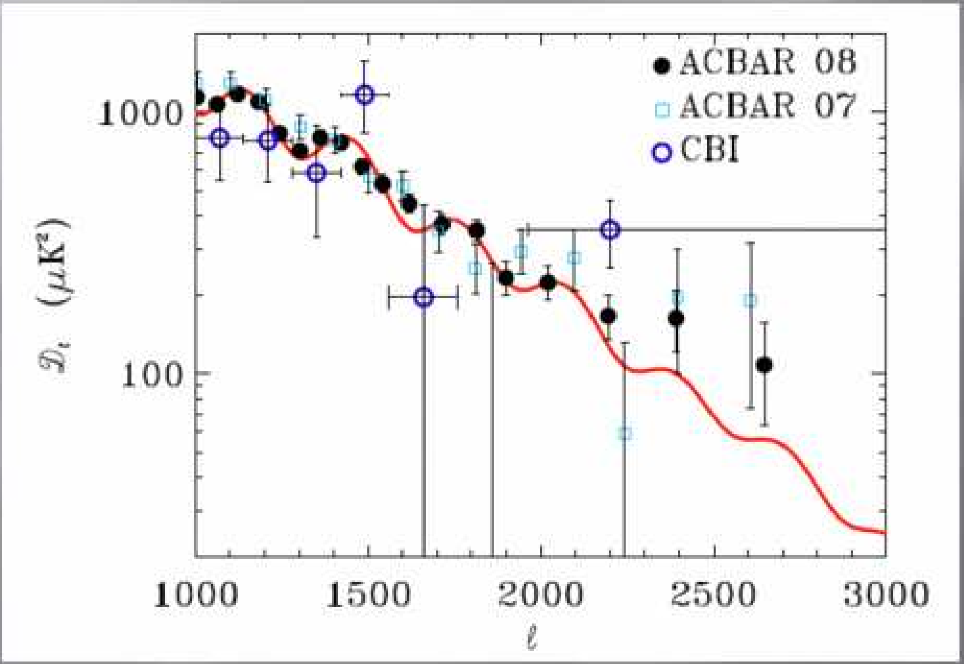
## (to be taken with a grain of salt)

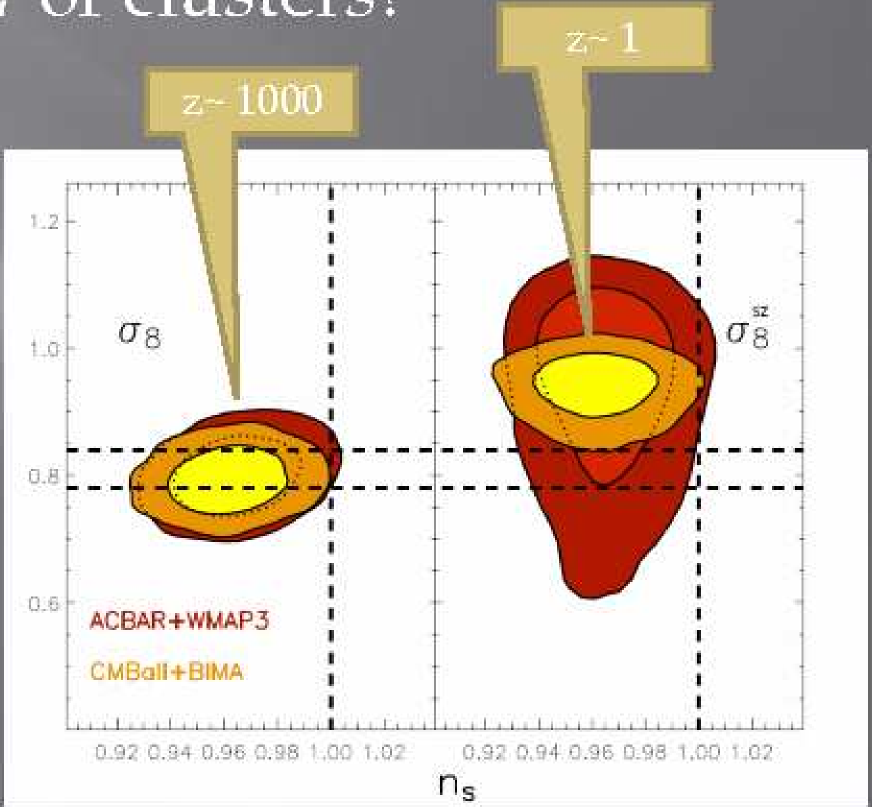
# observational anomalies
## (to be taken with a grain of salt)

- 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

# CBI excess:
# Census of SZ clusters at z~1

- Do we underpredict the # of clusters?

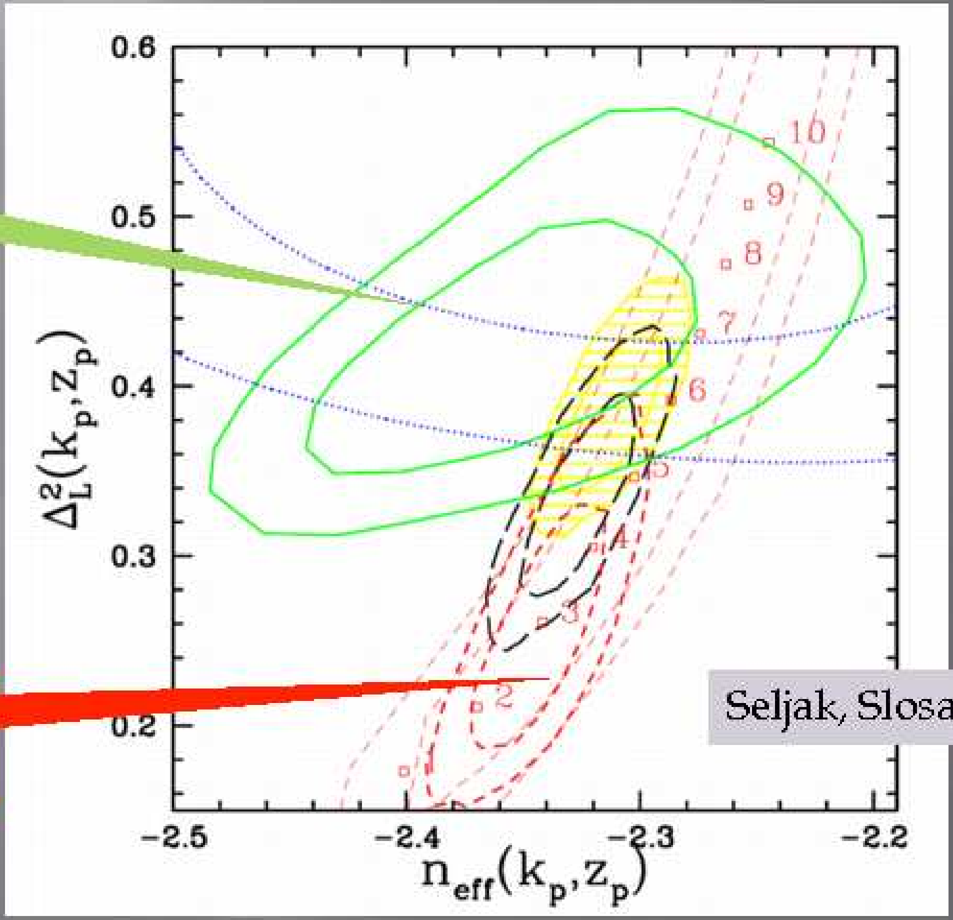


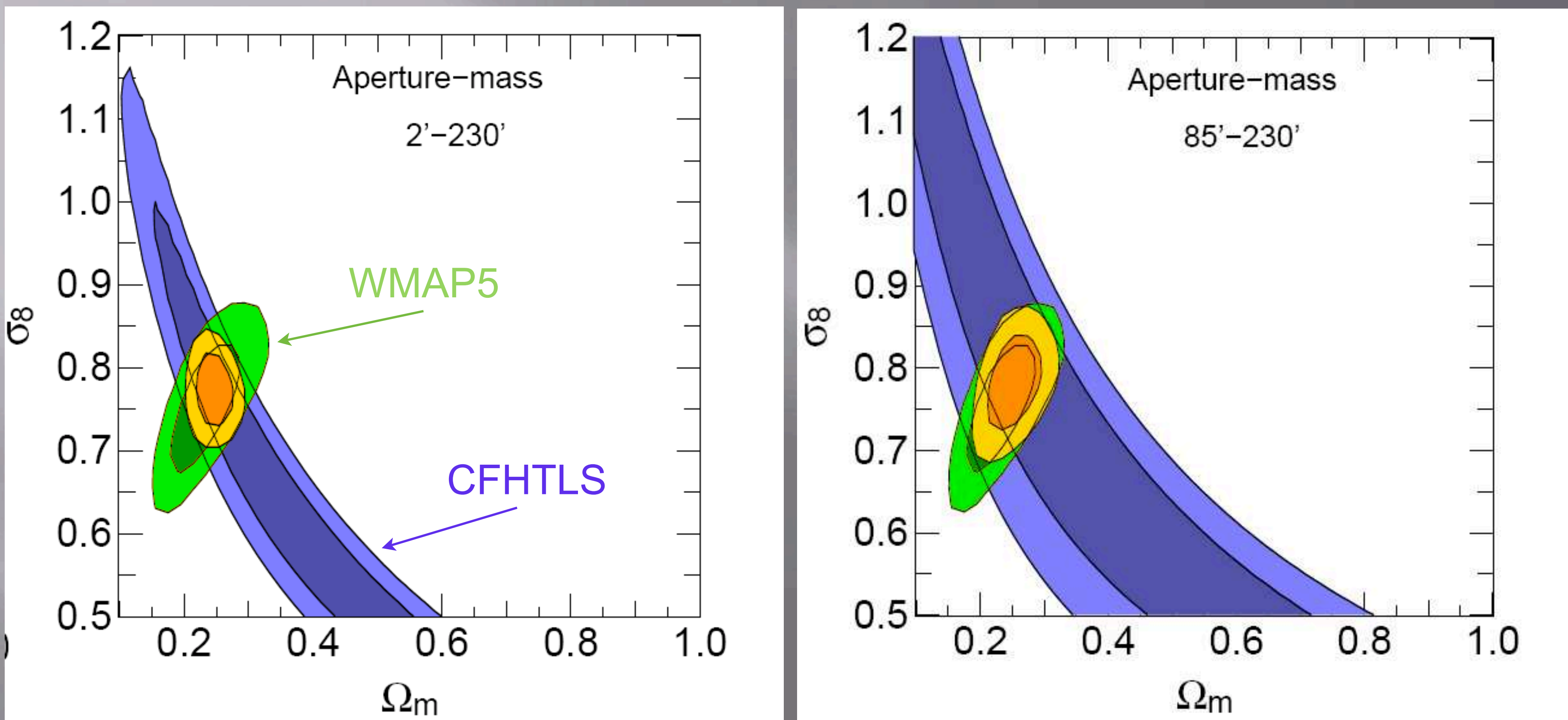

Reichardt, et al. 2008

# Lyman-α excess: structure at z~3

- Ly-α, more clumpy than CMB predicts?



# But $\sigma_8$ from lensing is consistent with ΛCDM

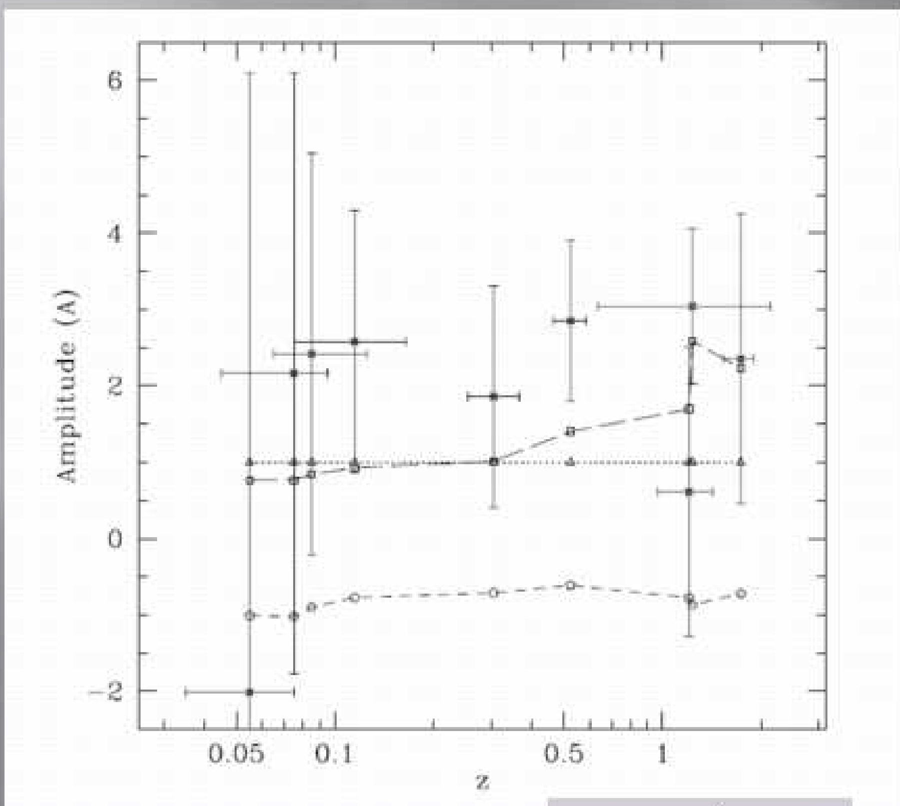



Fu, et al. 2008: Very weak lensing in the CFHTLS

# 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*



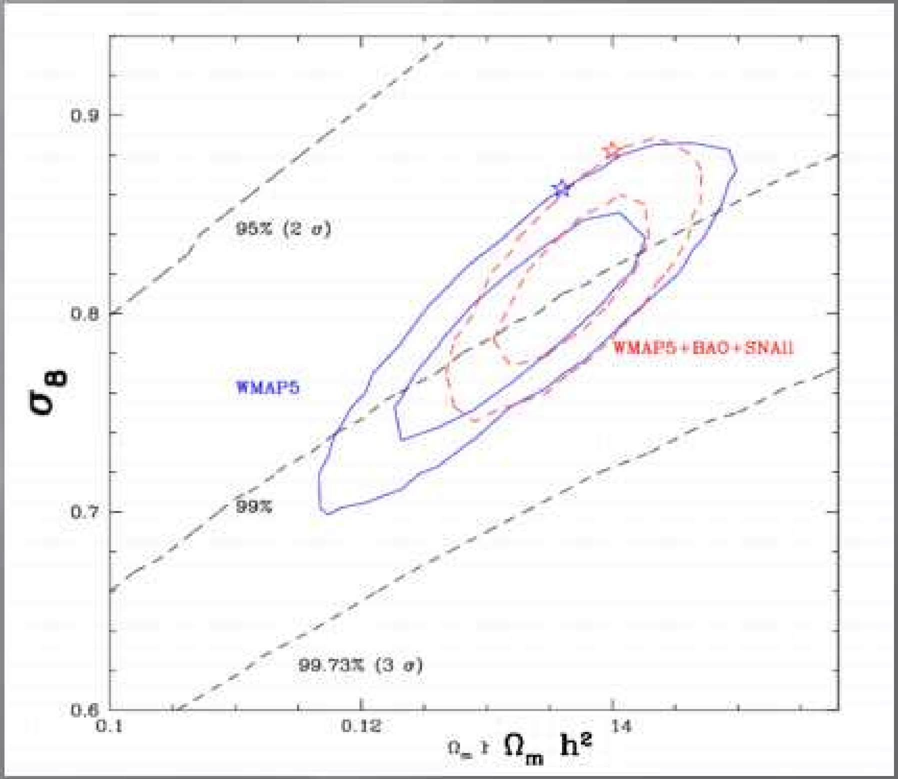

Ho, et al. 08

| Sample | Amplitude ($A \pm \sigma$) |
|---|---|
| 2MASS0 | $-2.01 \pm 11.41$ |
| 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*

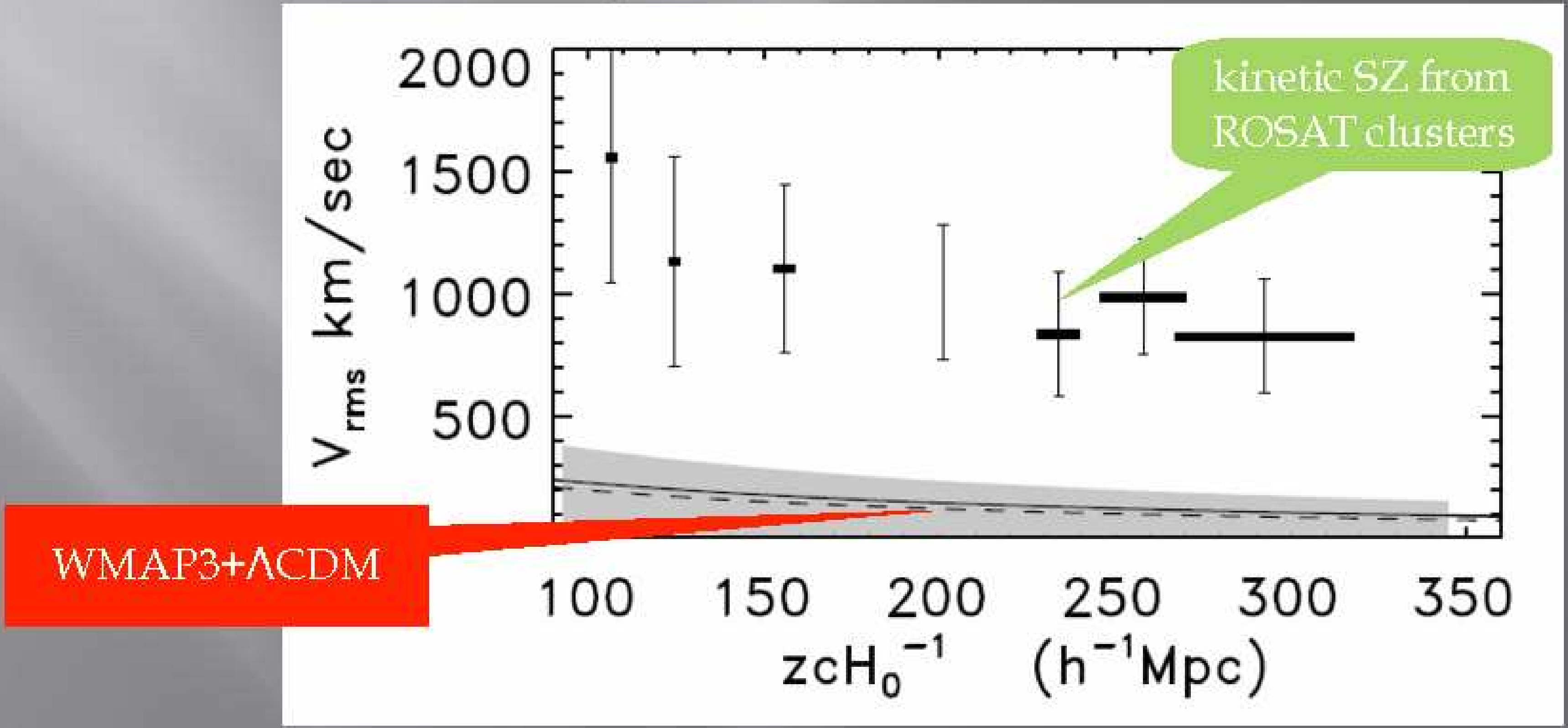
Watkins, Feldman, & Hudson 08



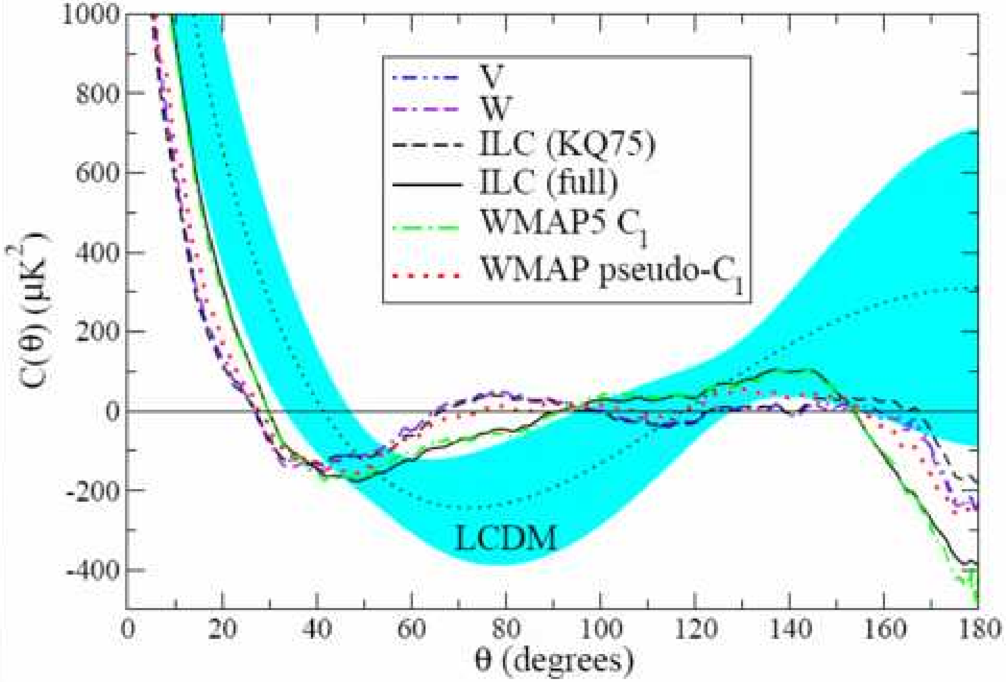
# Dark Bulk Flow II: velocities at z=0

- 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

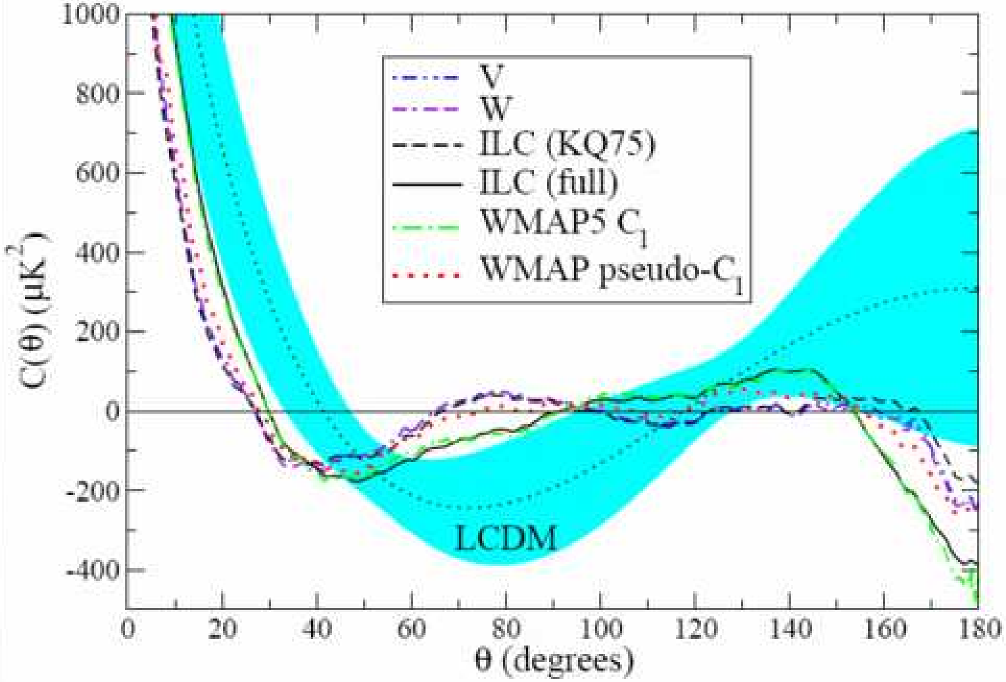



| Data Source | $S_{1/2}$ $(\mu K)^4$ | $P(S_{1/2})$ (per cent) |
|---|---|---|
| V3 (kp0, DQ) | 1288 | 0.04 |
| W3 (kp0, DQ) | 1322 | 0.04 |
| ILC3 (kp0, DQ) | 1026 | 0.017 |
| ILC3 (kp0), $\mathcal{C}(>60°) = 0$ | 0 | — |
| ILC3 (full, DQ) | 8413 | 4.9 |
| V5 (KQ75) | 1346 | 0.042 |
| W5 (KQ75) | 1330 | 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-$C_\ell$ | 2093 | 0.18 |
| WMAP3 MLE $C_\ell$ | 8334 | 4.2 |
| Theory3 $C_\ell$ | 52857 | 43 |
| WMAP5 $C_\ell$ | 8833 | 4.6 |
| Theory5 $C_\ell$ | 49096 | 41 |

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

Copi, Huterer, Schwarz, & Starkman 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), $\mathcal{C}(>60^\circ) = 0$ | 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-$C_\ell$ | 2093 | 0.18 |
| WMAP3 MLE $C_\ell$ | 8334 | 4.2 |
| Theory3 $C_\ell$ | 52857 | 43 |
| WMAP5 $C_\ell$ | 8833 | 4.6 |
| Theory5 $C_\ell$ | 49096 | 41 |

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

Copi, Huterer, Schwarz, & Starkman 08

# How we deal with perturbations

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

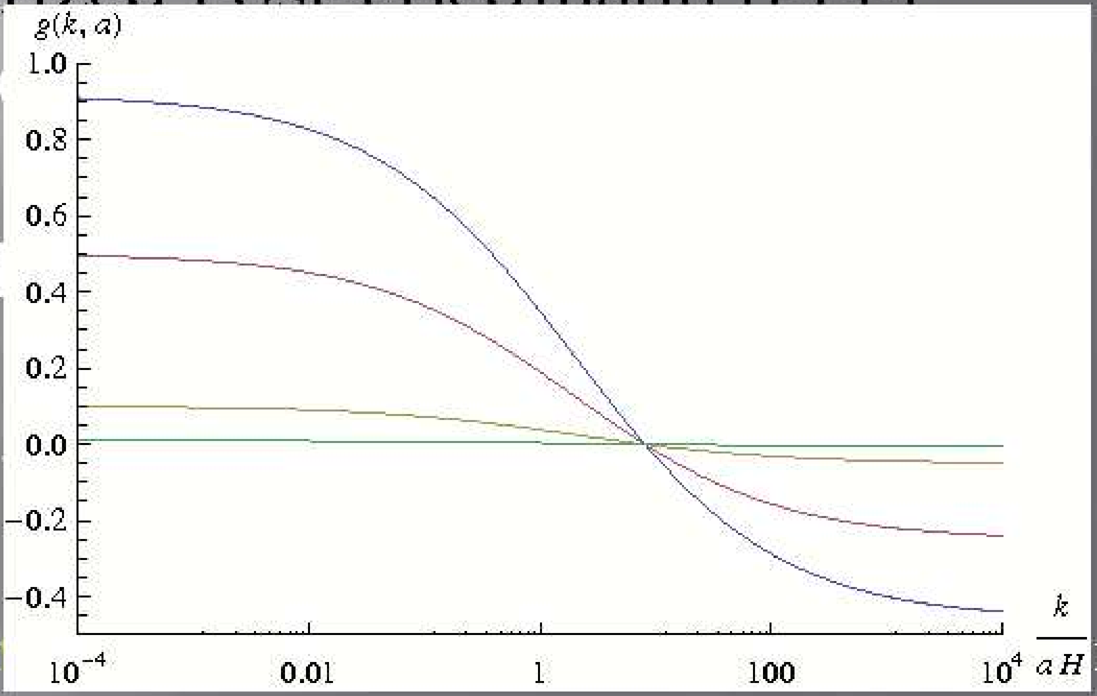
$$g = \frac{\Phi + \Psi}{\Phi - \Psi}$$

- 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

# How we deal with perturbations

- Use Parametrized Post-Friedmann (PPF) formulation

- Analogy wit
- g → 0
  - GR: at early
- g → -1/2
  - scalar-tensor mes




- 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)

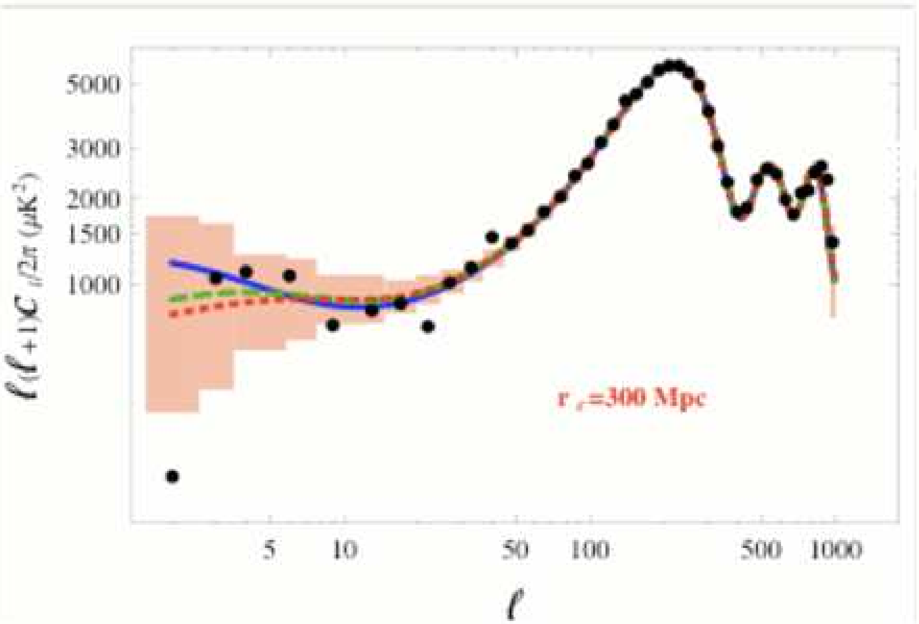
$$\zeta = \text{const.} = \frac{H}{H'}\left[(g-1)\Phi_- - g'\Phi_- - (g+1)\Phi'_-\right] + (g+1)\Phi_- \simeq \frac{(5+g)\Phi_-}{3}$$

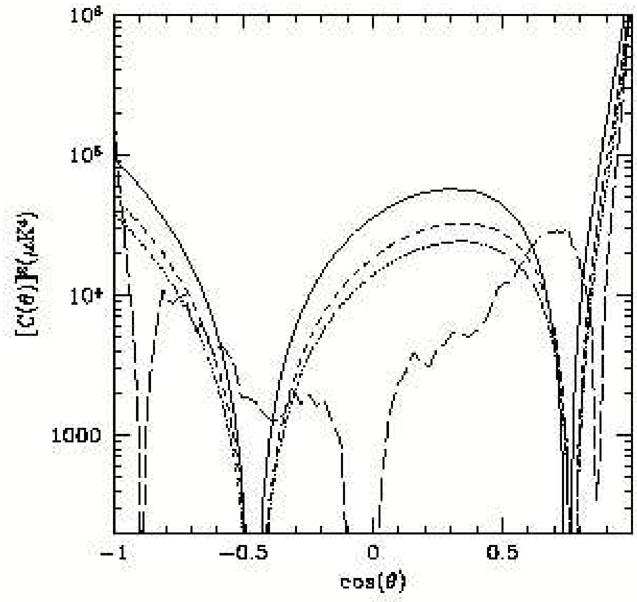
- If g goes from 0 to 1, ISW and Sachs-Wolfe cancel!

# 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)

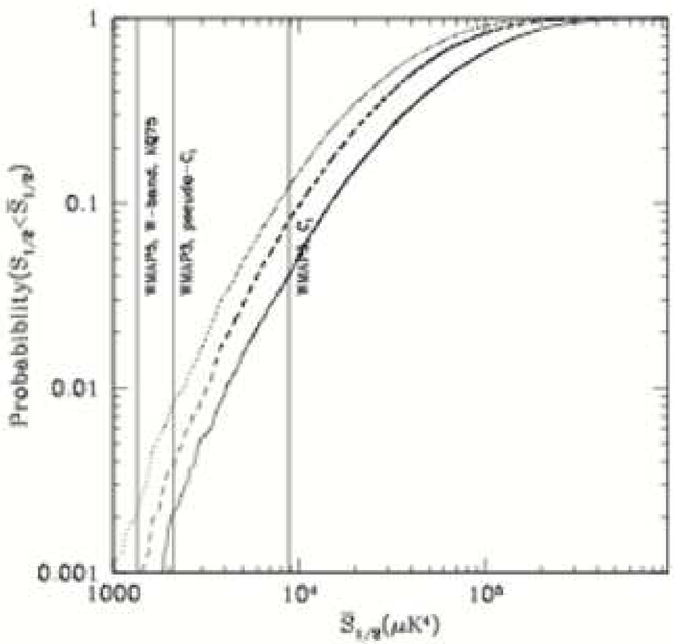


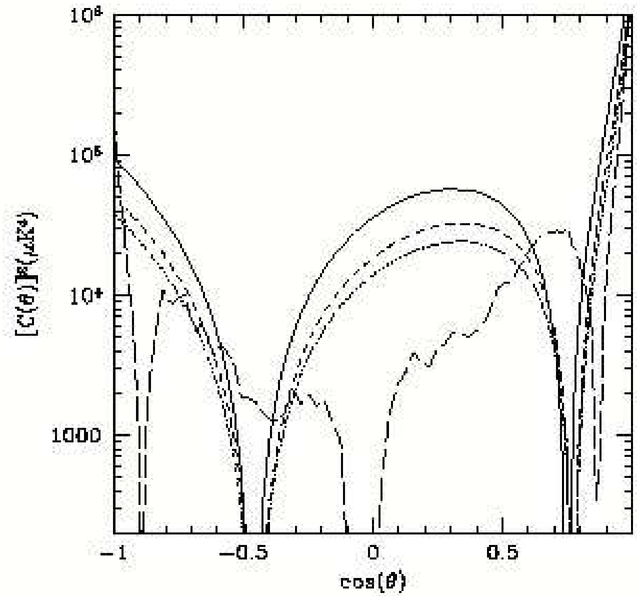



# de-Correlating CMB on large angles

## CMB angular power spectra

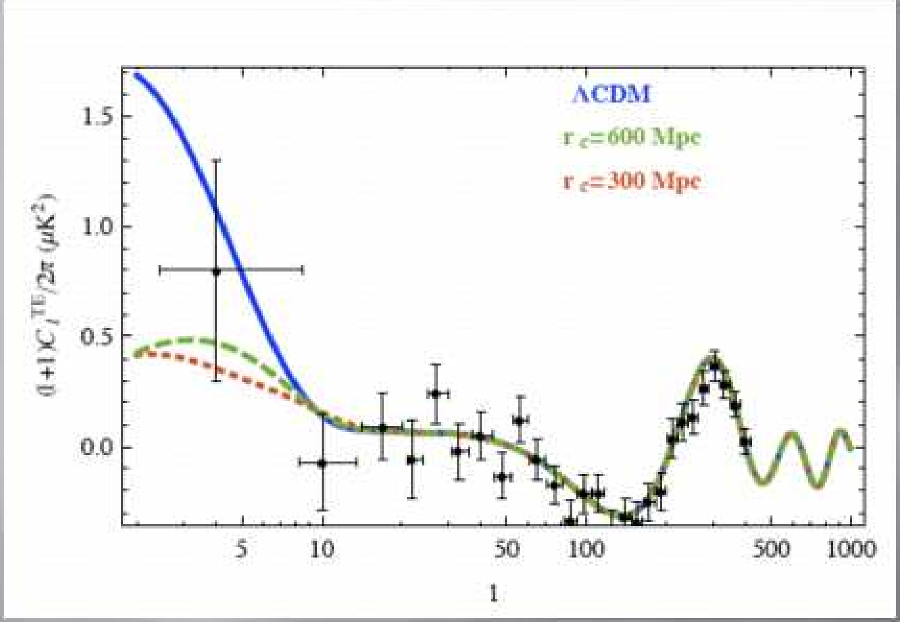
best-fit ΛCDM (solid curve), rc = 600 Mpc (dashed curve) and r= 300 Mpc (short-dashed curve)



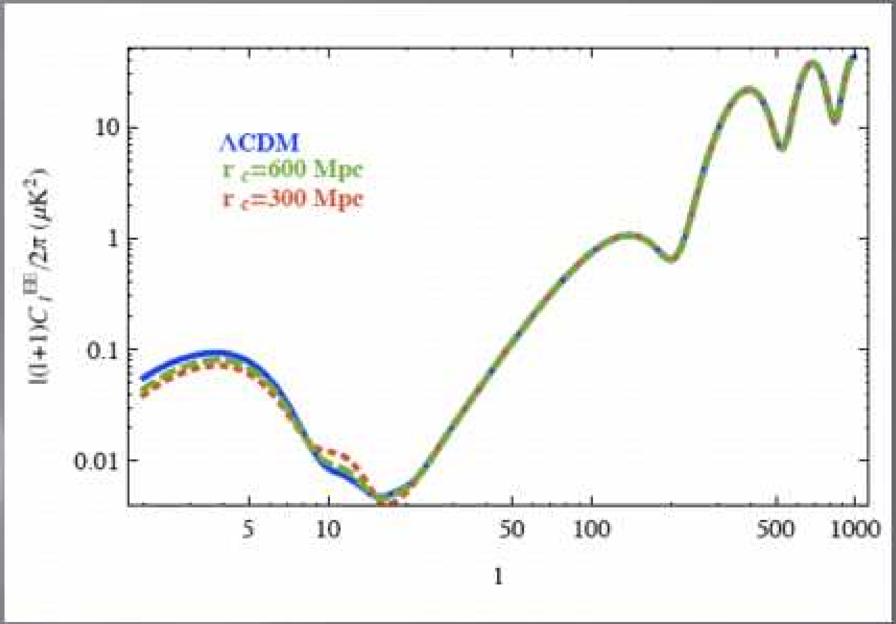




$$S_{1/2} \equiv \int_{-1}^{1/2} [\mathcal{C}(\theta)]^2 \, \mathrm{d}(\cos\theta)$$

# Prediction for CMB Polarization power spectra




Temperature-Polarization (TE) power spectrum

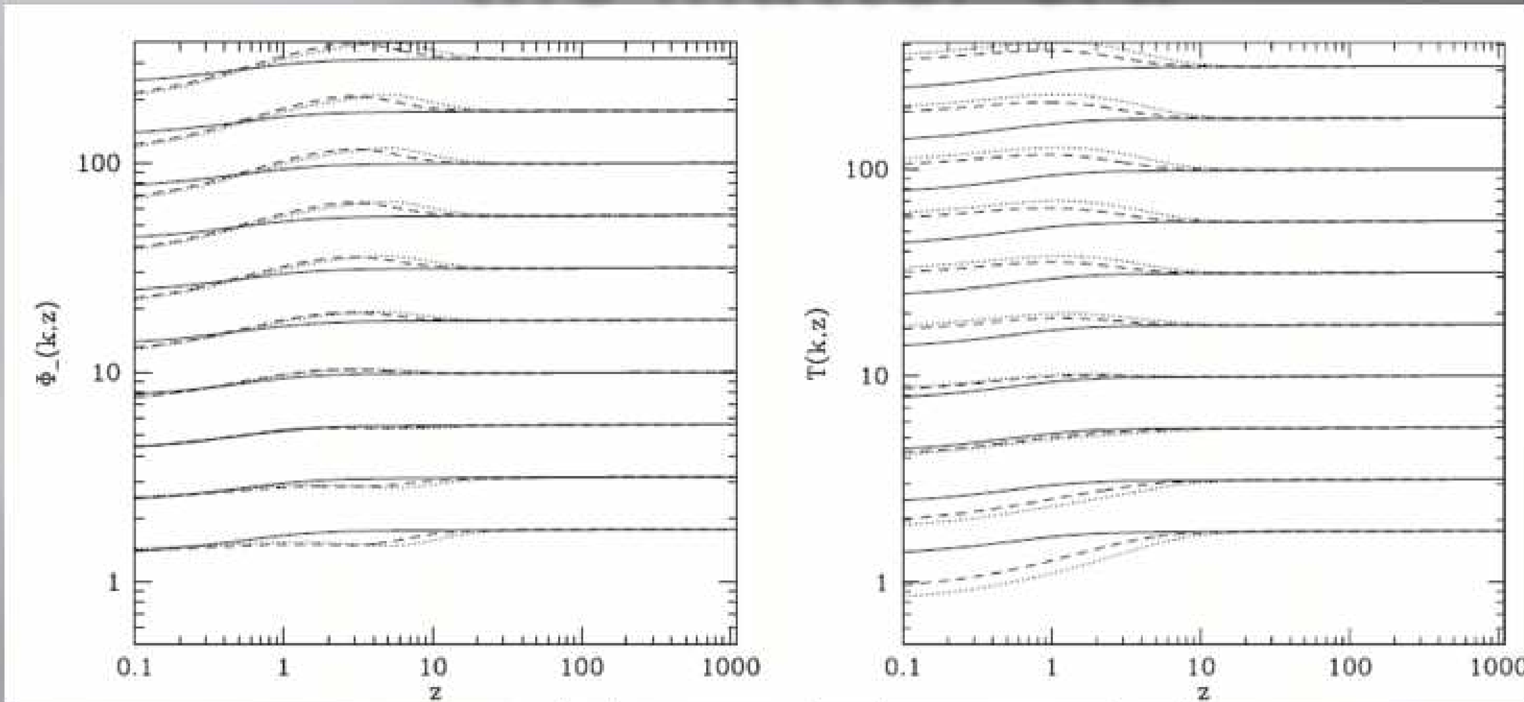



polarization(EE) power spectrum

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 $K = 10 Mpc^{-1}$)




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

$\Lambda$CDM (solid), $r_c = 300$ Mpc (dotted) and $r_c = 600$ Mpc (dashed)

Lensing, $\Phi_-$ comoving density perturbations $\Delta_m/a$

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