Title: Observational Evidence for Massive Gravity

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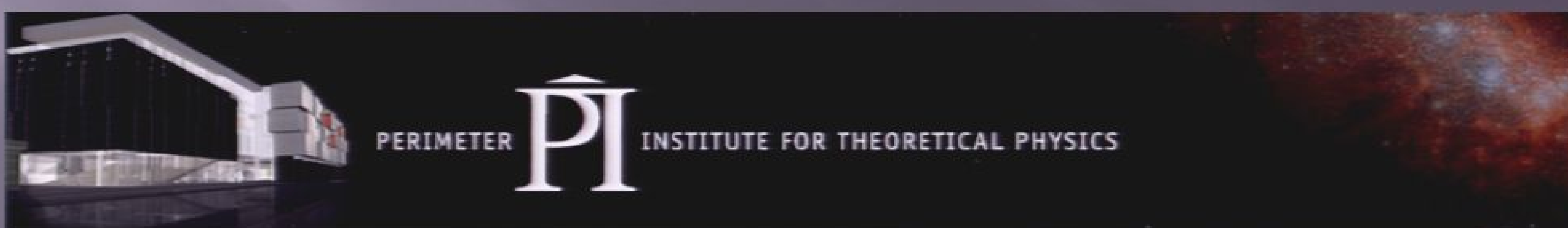
Abstract:

PI/CITA cosmology day
Perimeter Institute
Oct. 23, 2008

OBSERVATIONAL EVIDENCE FOR *MASSIVE GRAVITY*

Niayesh Afshordi



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Niayesh Afshordi

with Ghazal Geshnizjani and Justin Khoury

PERIMETER PI INSTITUTE FOR THEORETICAL PHYSICS

Cosmology: the Golden Era

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- Cosmology is experiencing its renaissance

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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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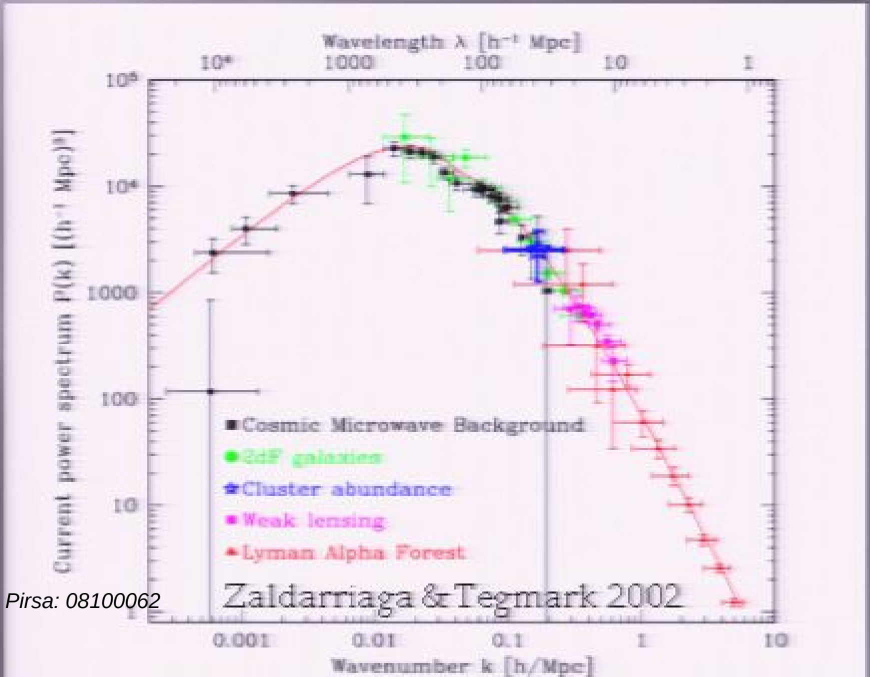
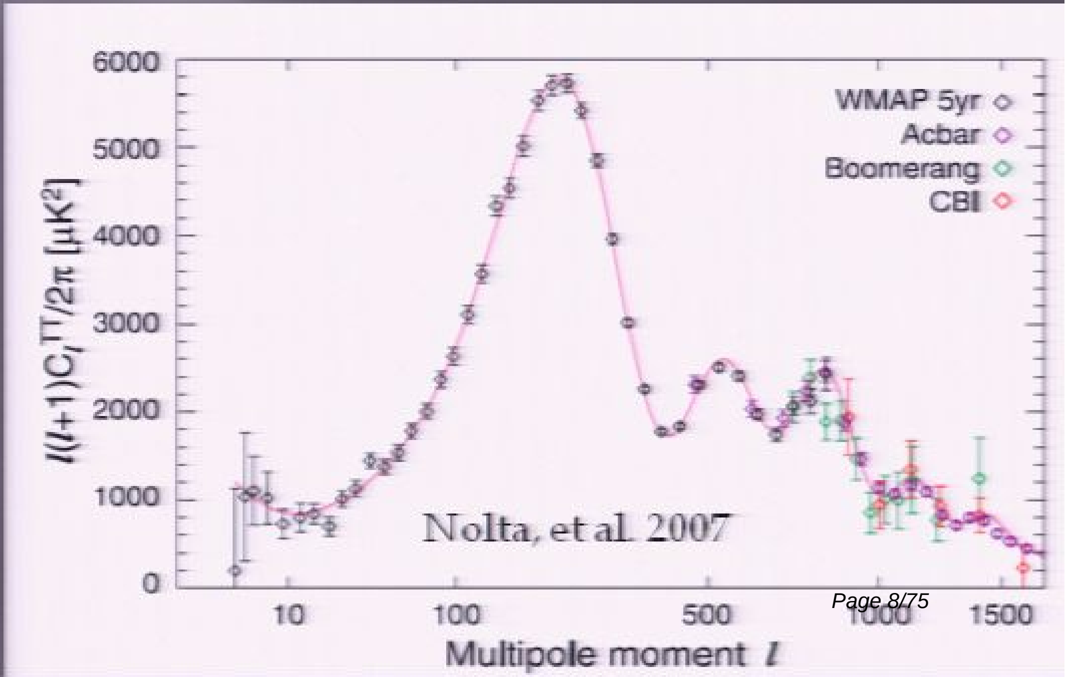
Cosmic density power spectrum



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}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$

- "Cosmologists are often in error but seldom in doubt." Lev Landau (1908-1968)

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30 Oct 1998

IS COSMOLOGY SOLVED?
An Astrophysical Cosmologist's Viewpoint

P. J. E. Peebles
Joseph Henry Laboratories, Princeton University,
and Princeton Institute for Advanced Study

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We have fossil evidence from the thermal background radiation that our universe expanded from a considerably hotter denser state. We have a well defined, testable, and so far quite successful theoretical description of the expansion: the relativistic Friedmann-

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Cosmological Constant Problem

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 $\gg (1\ {\rm meV})^4$

* Relaxation mechanisms not possible with 4d massless graviton

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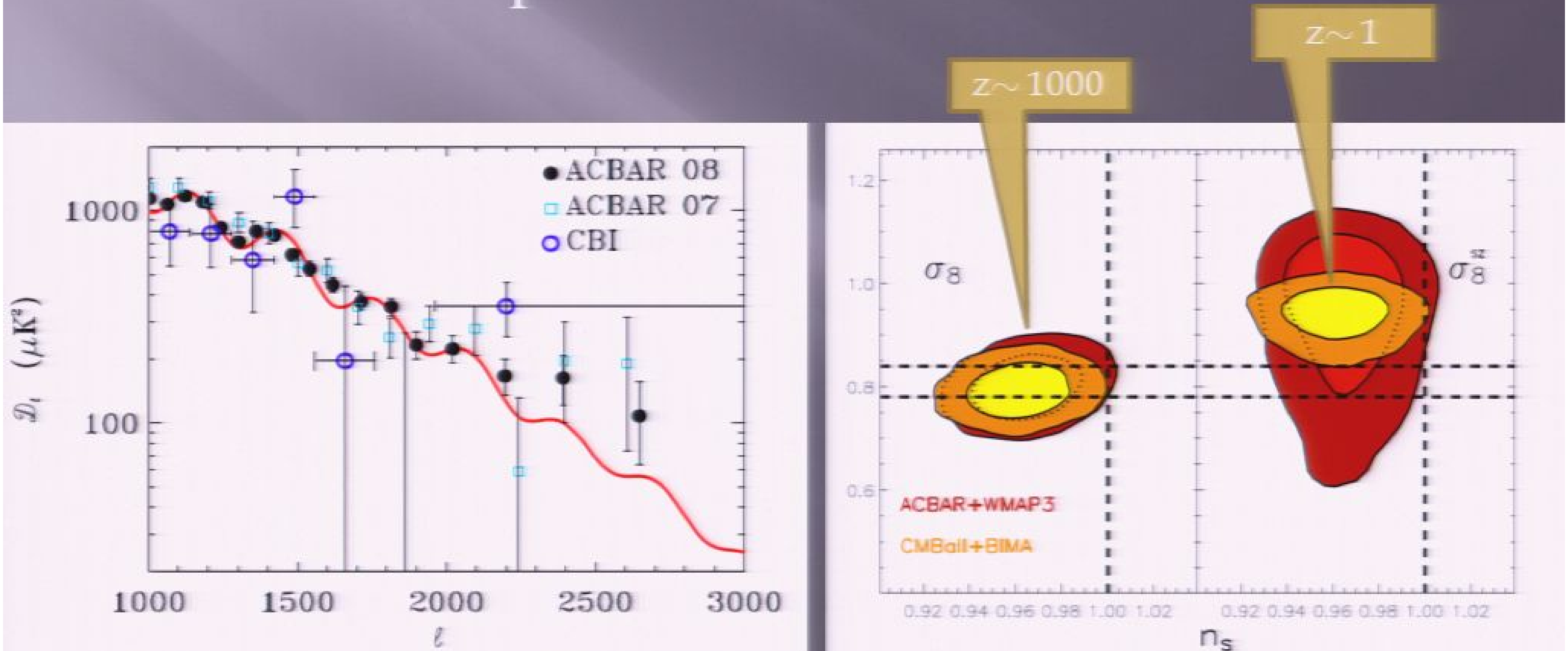
Do we really measure σ_8 at low redshift?

CBI excess: Census of SZ clusters at z~1

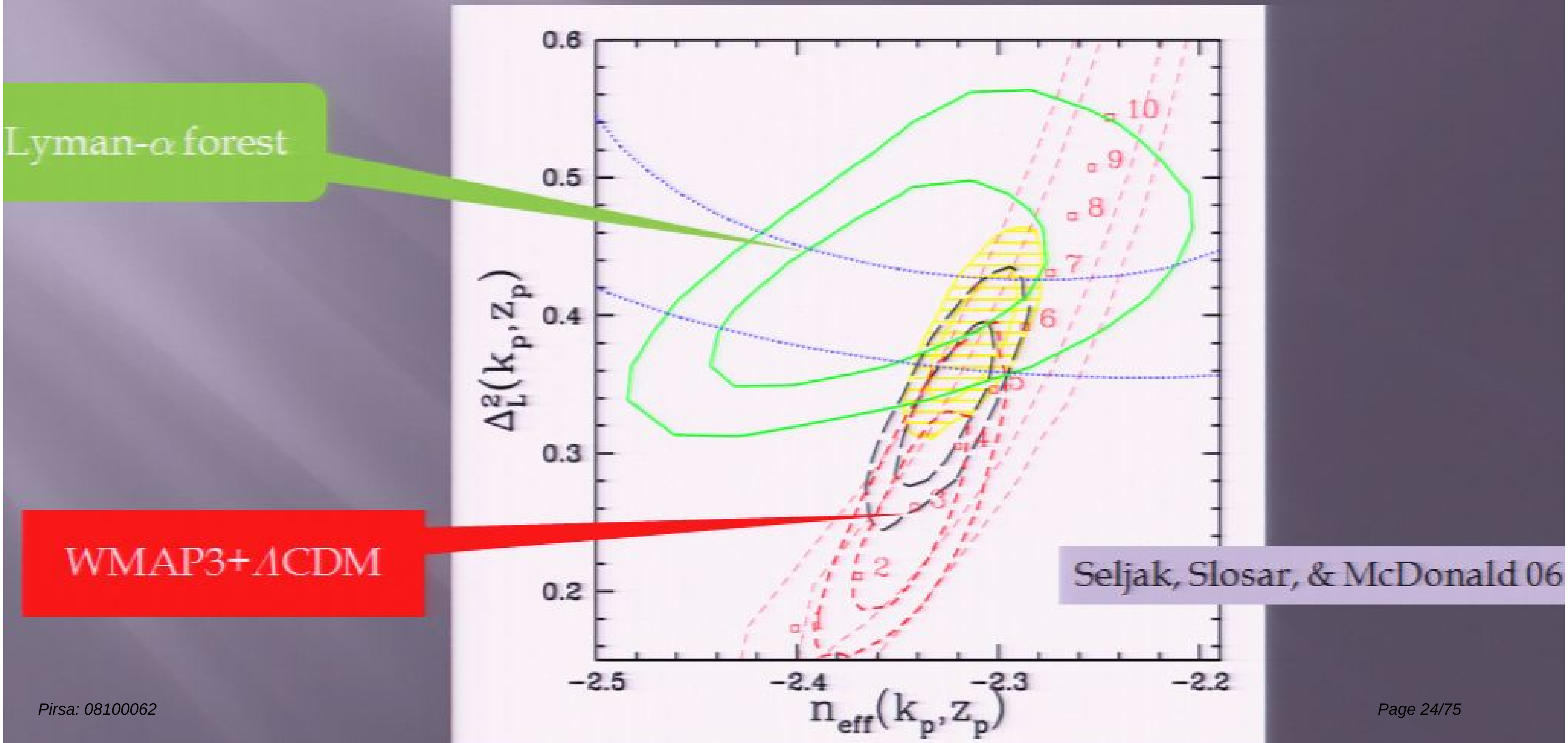
- Do we underpredict the # of clusters?



Reichardt, et al. 2008

Lyman-α excess: structure at z~3

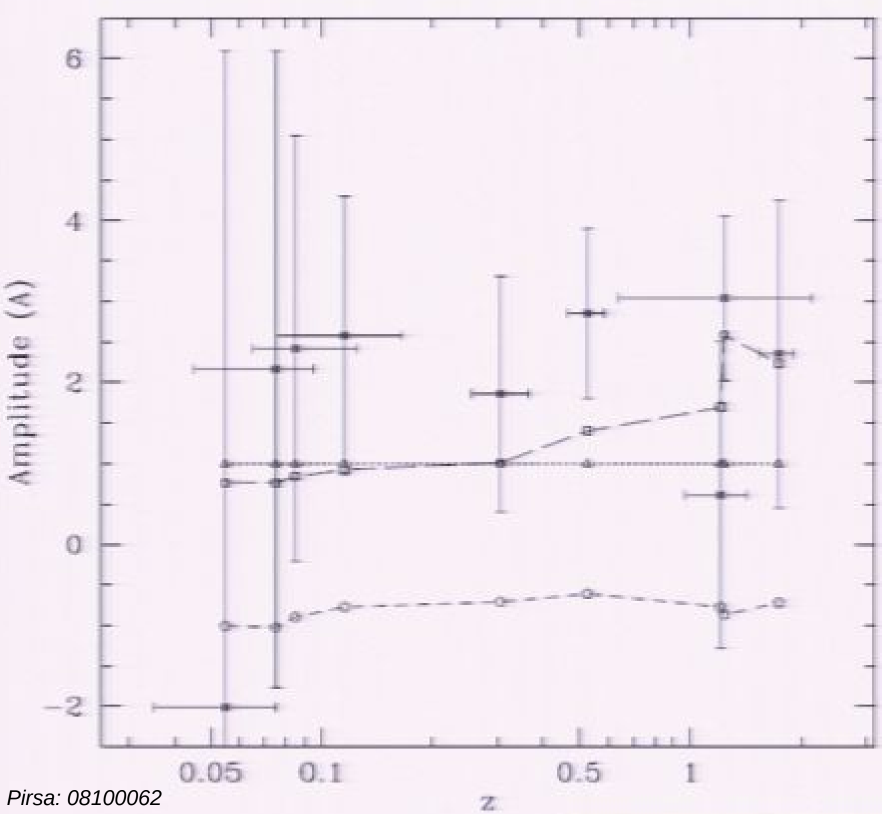
- Ly-α, more clumpy than CMB predicts?



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

- Gravitational Potential: 2.23± 0.60 larger than ΛCDM predicts

$$A \equiv Observed\ ISW / Predicted\ ISW$$



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

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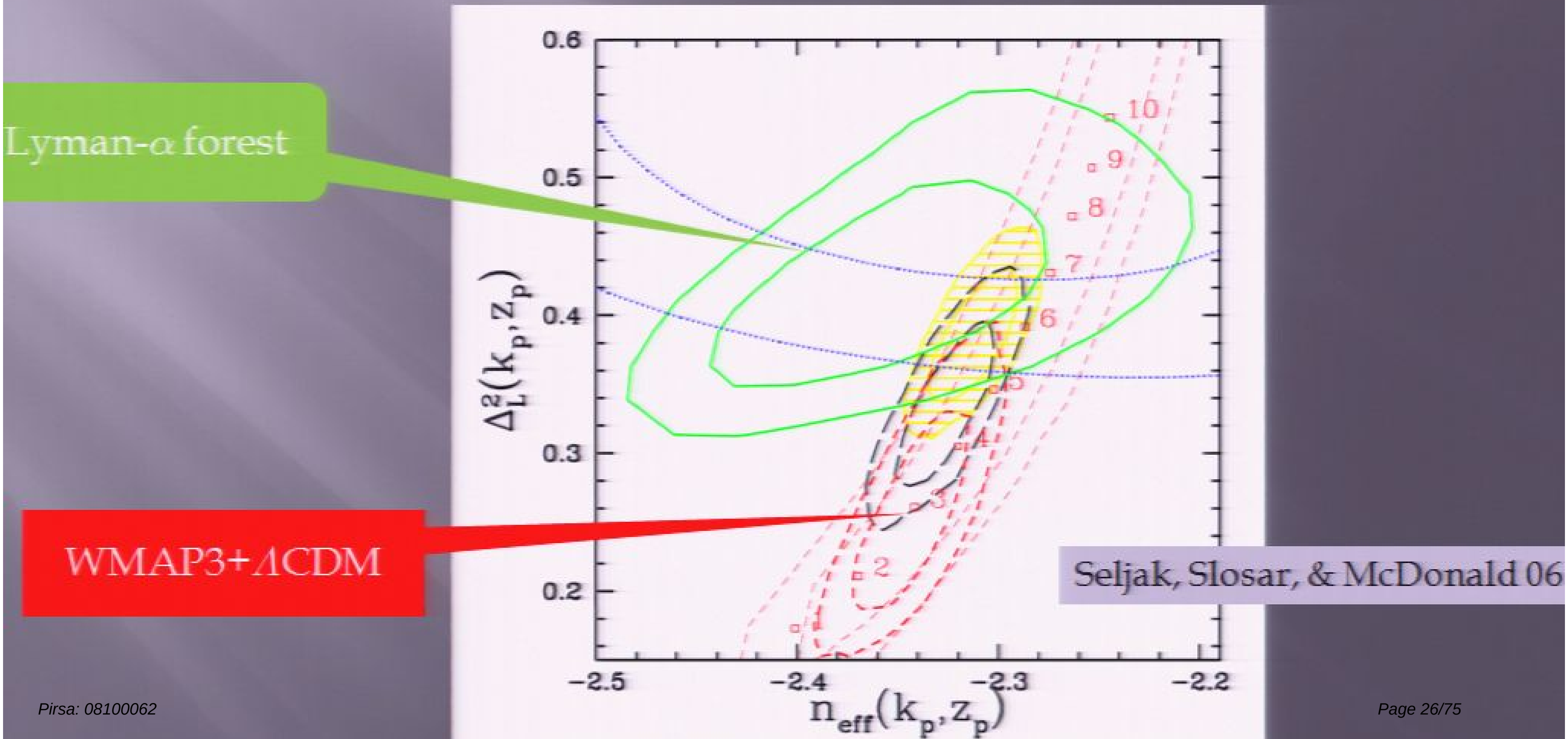

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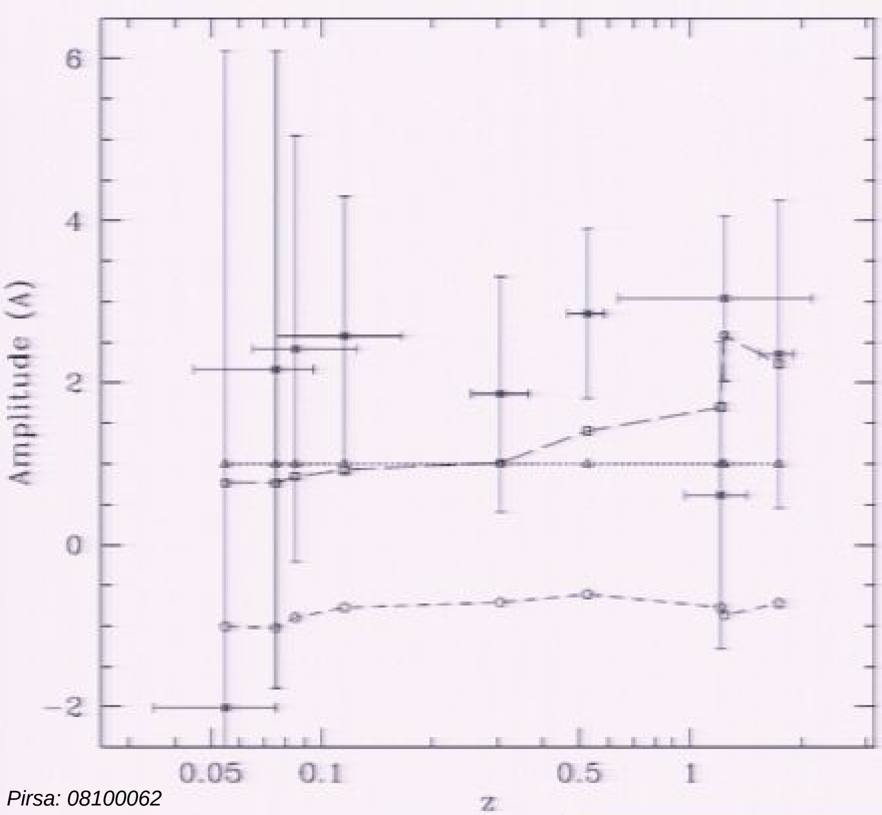

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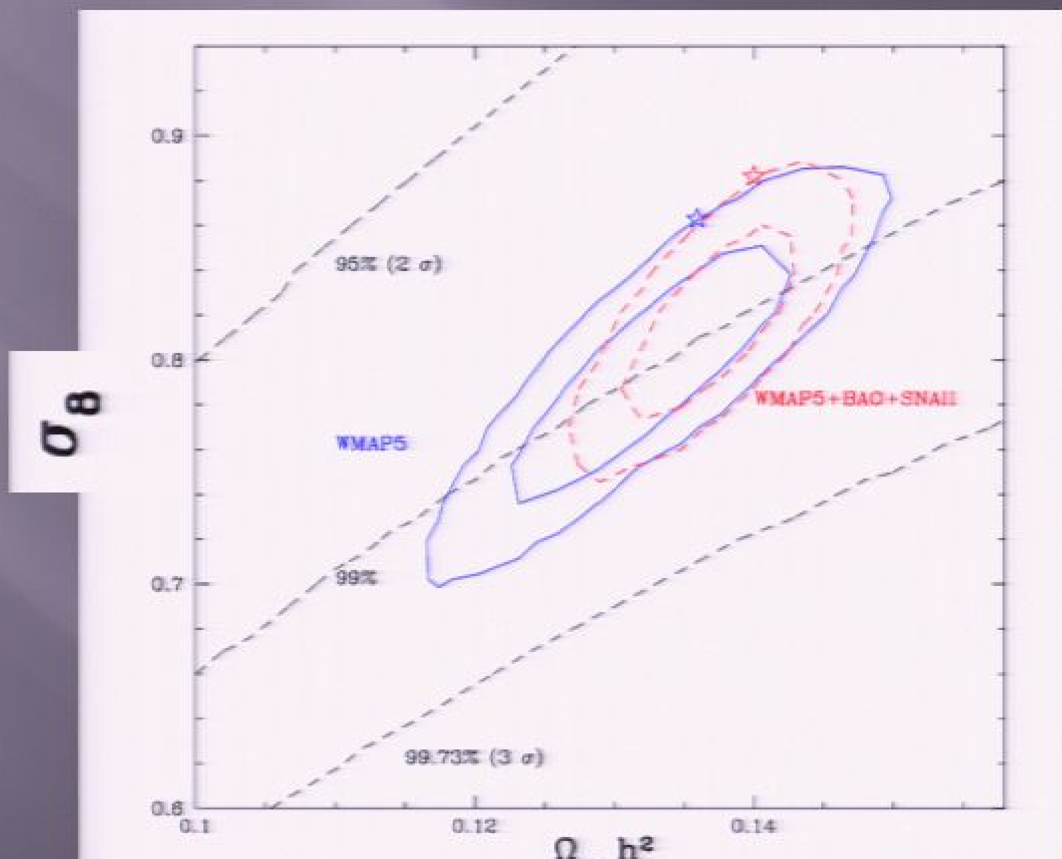
Dark Bulk Flow I: velocities at z=0

- Local bulk flow within 50 Mpc is *407 ± 81 km/s*
  → ΛCDM predicts: v_{rms} = *110 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

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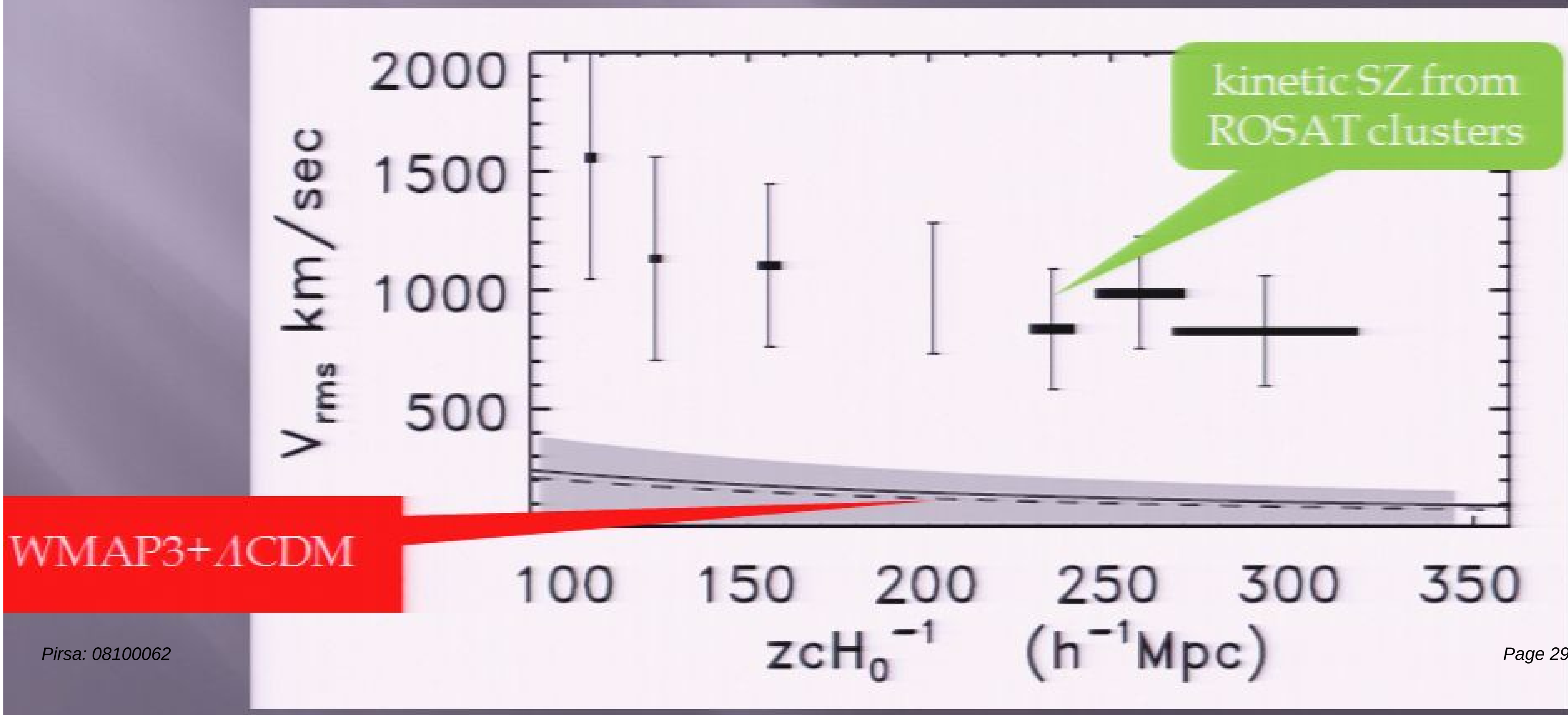

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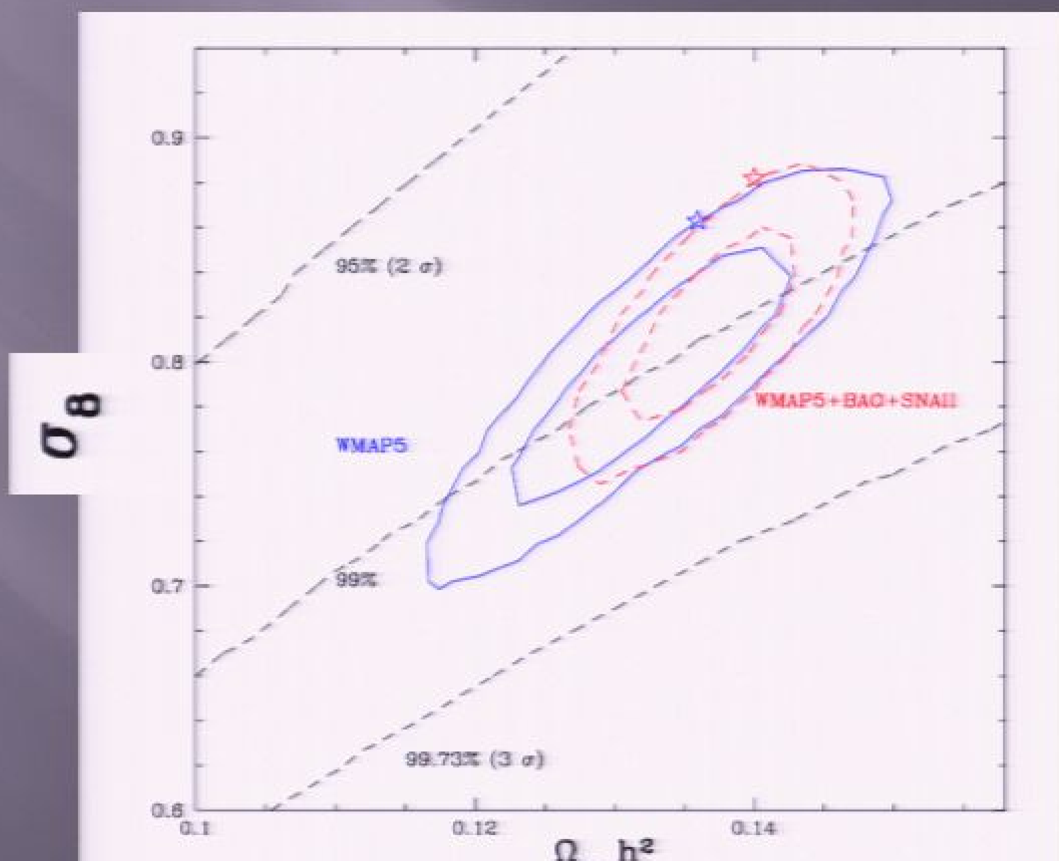

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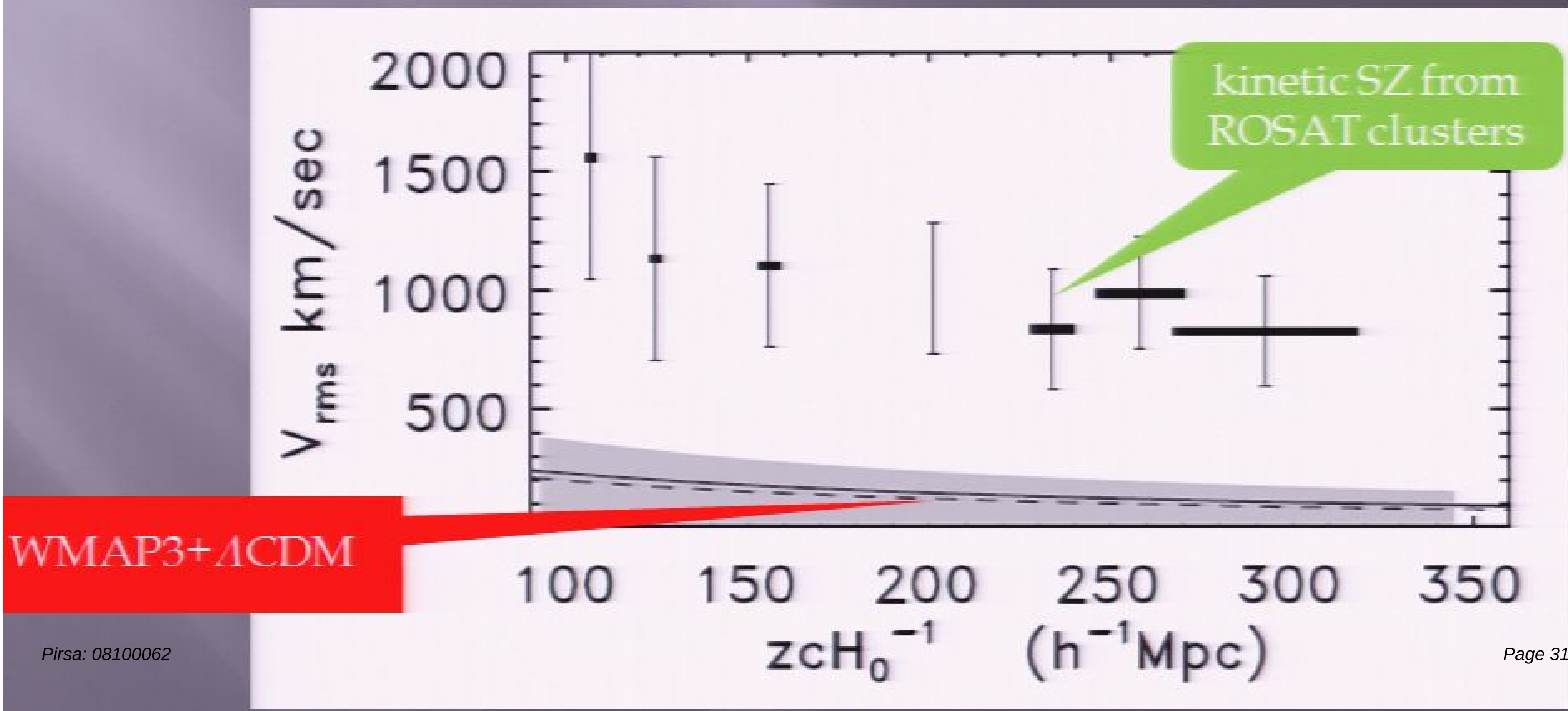

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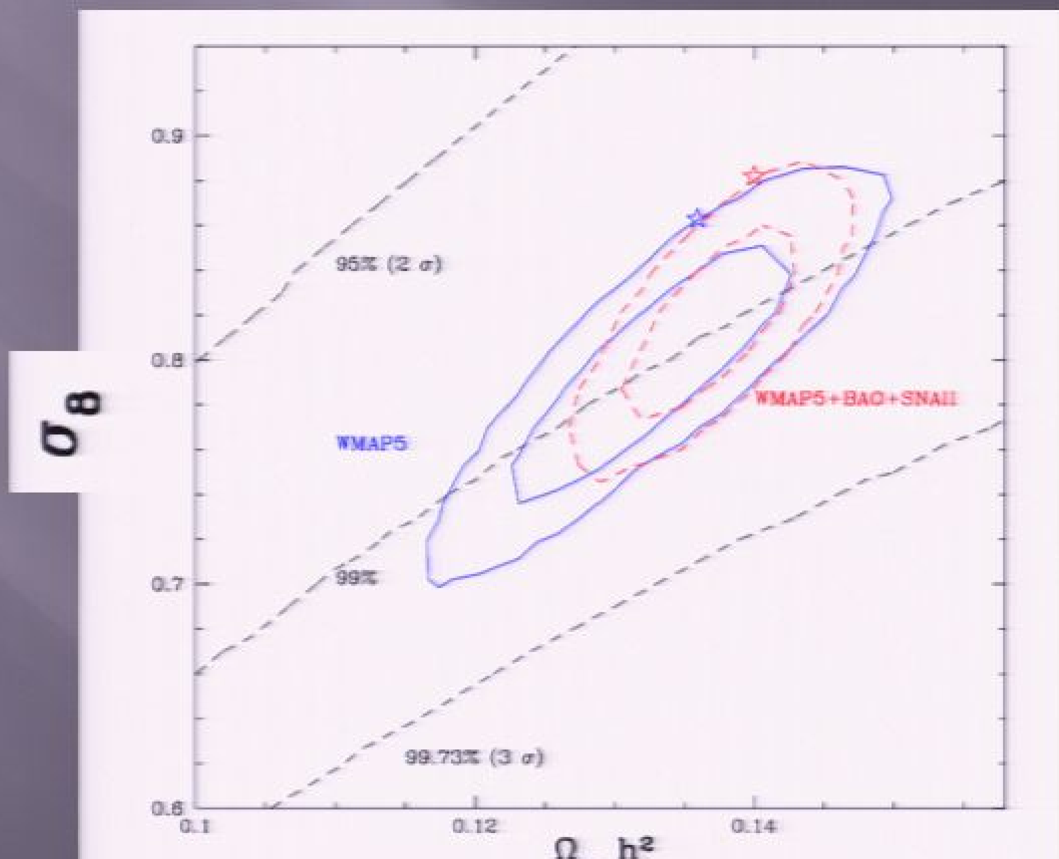

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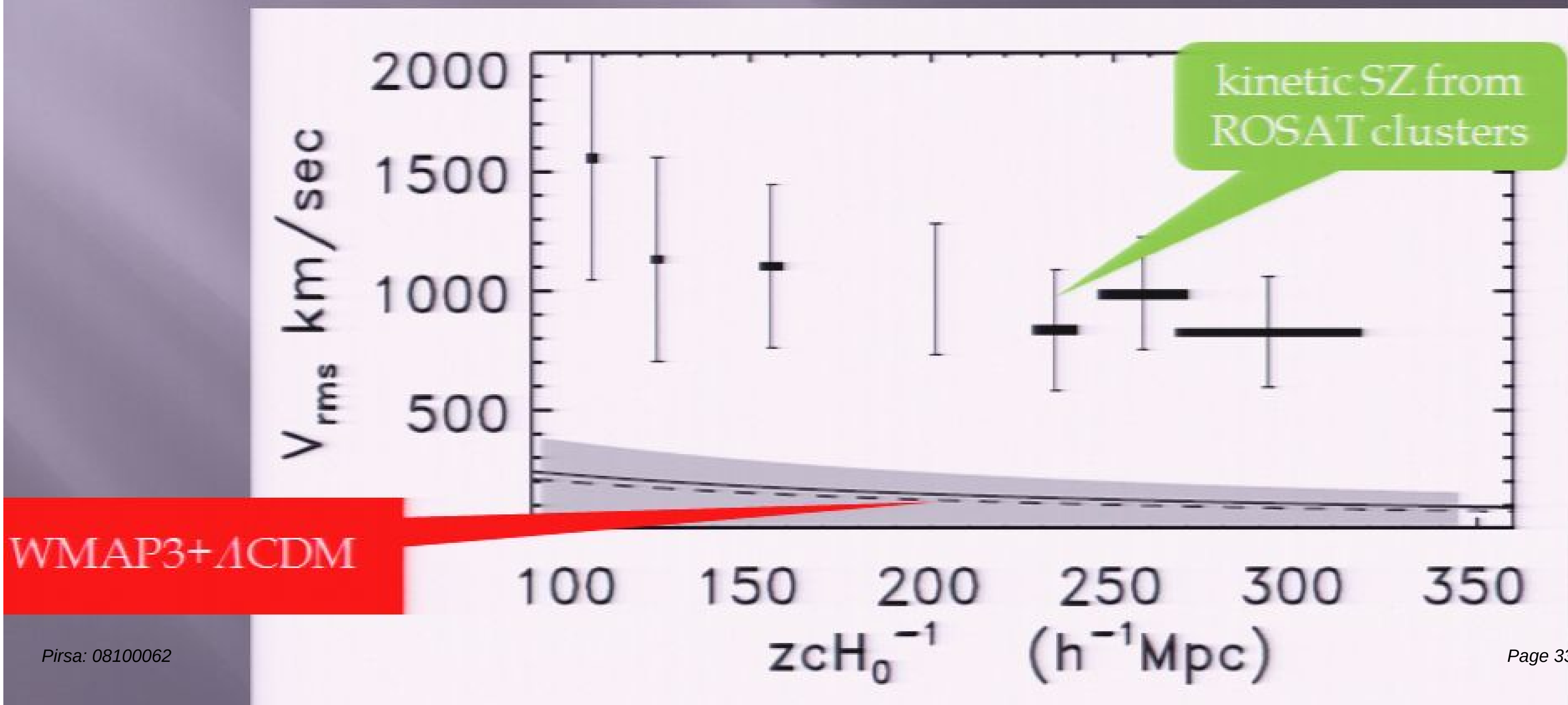
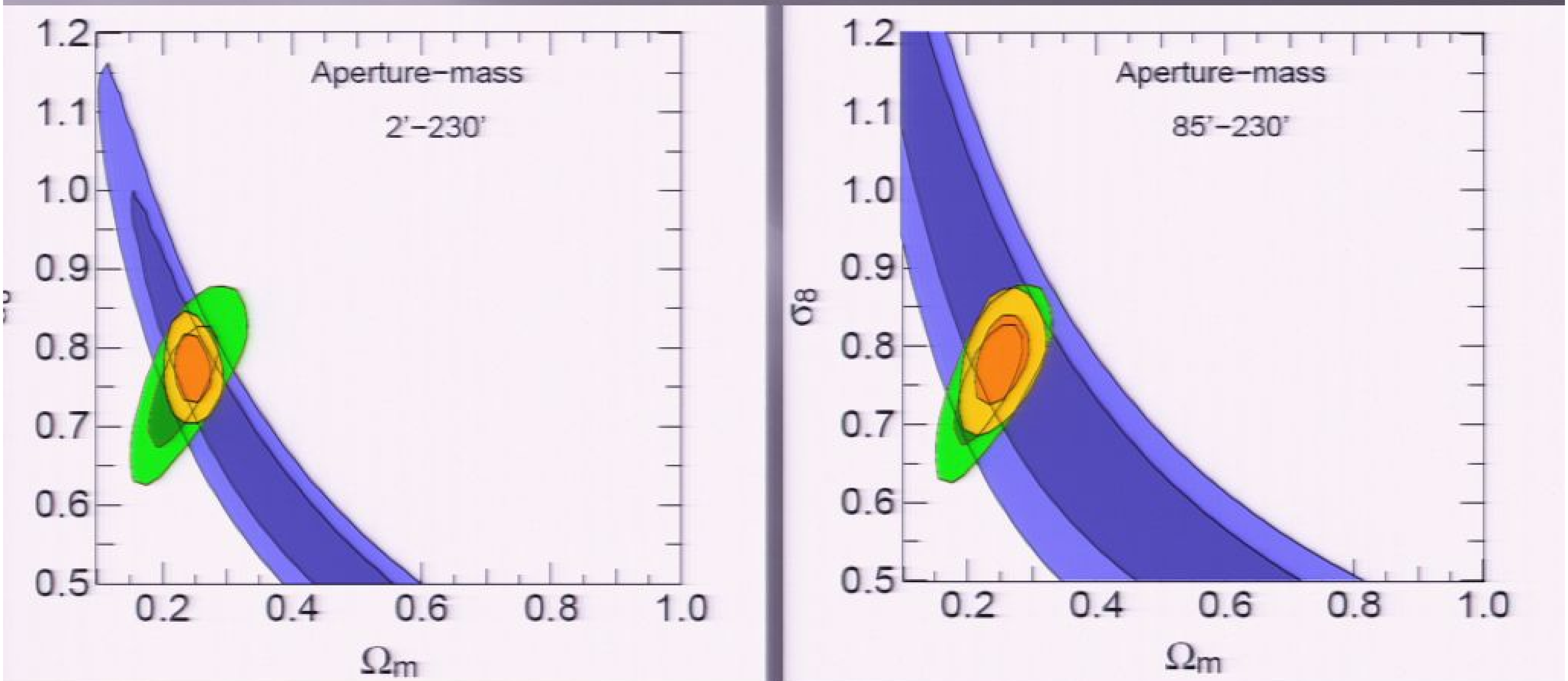


But σ_8 from lensing is consistent with ΛCDM!



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

Could lensing and Newtonian potentials 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-relativsistic matter follows $-\Psi$
- Photons (Lensing and ISW) see $\Phi_- = (\Phi-\Psi)/2$

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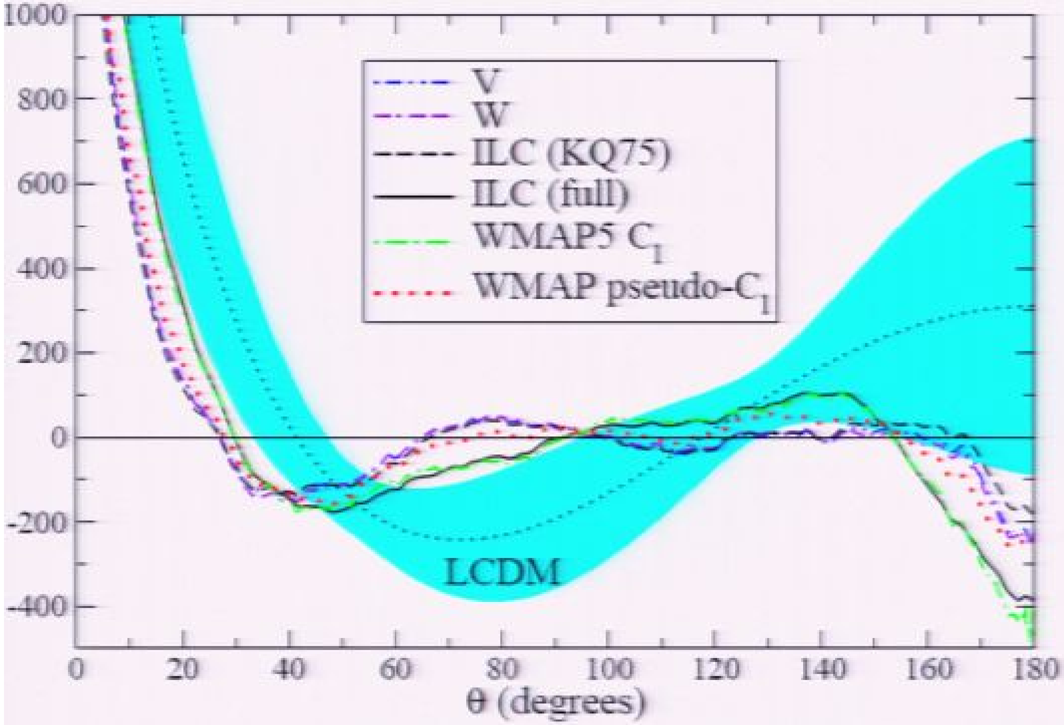
- *$\Phi_- \neq -\Psi$! Could this signal the breakdown of General Relativity ??*

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

Copi, Huterer, Schwarz, & Starkman 08

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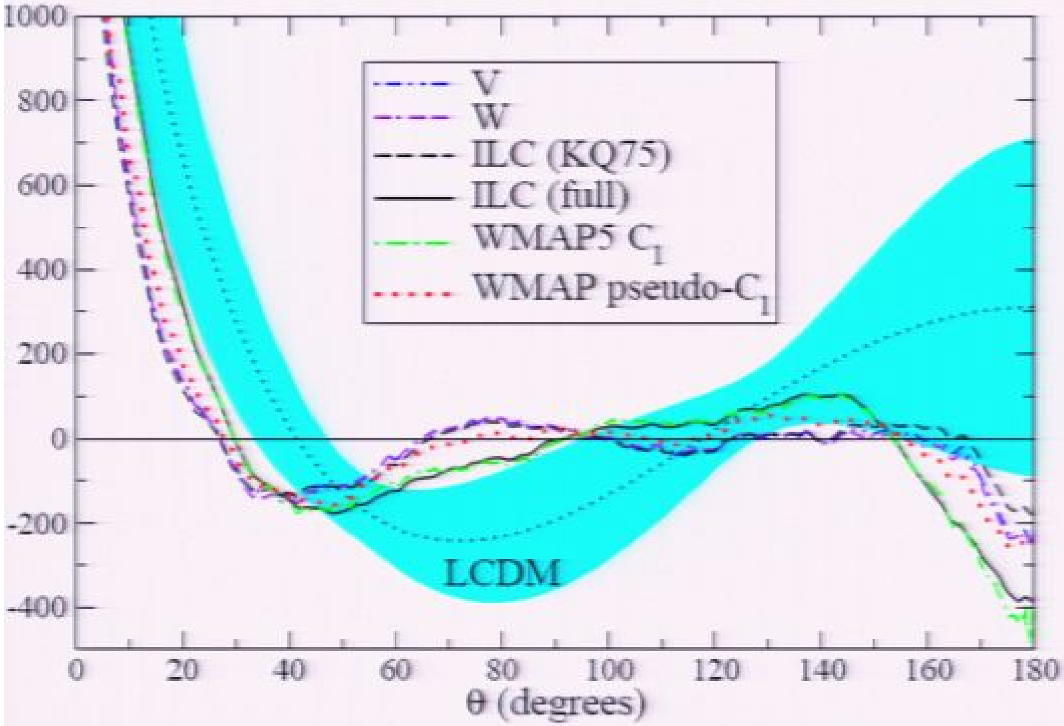

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de-Gravitation: the panacea

Dvali, Hofmann, and Khoury 07

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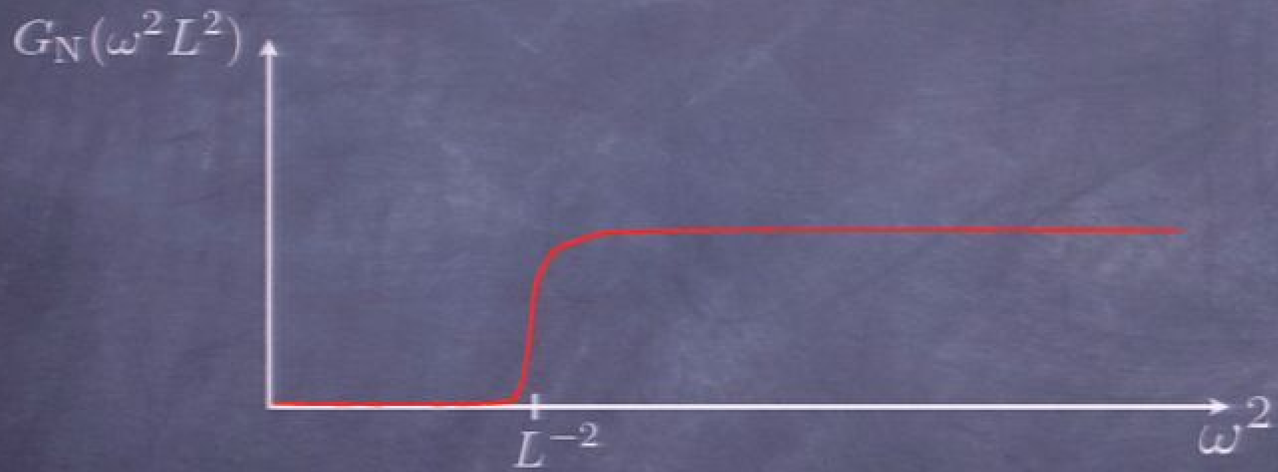

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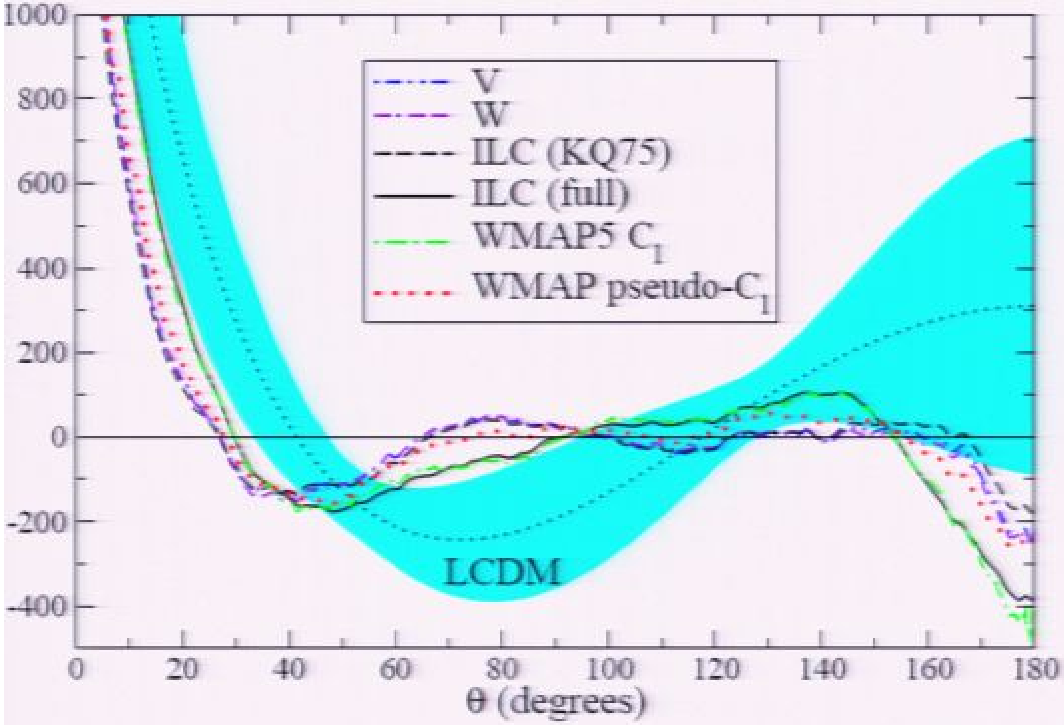

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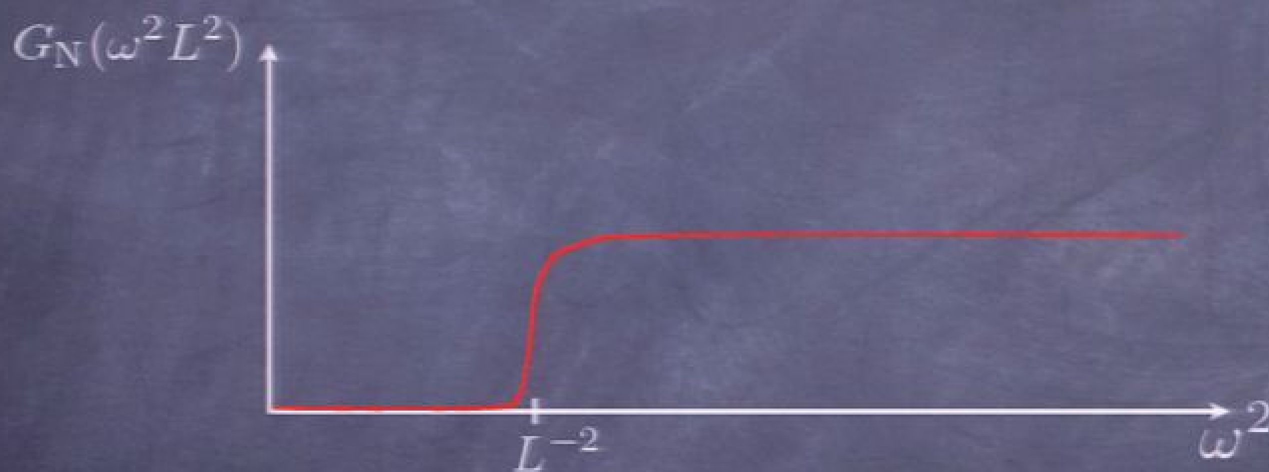

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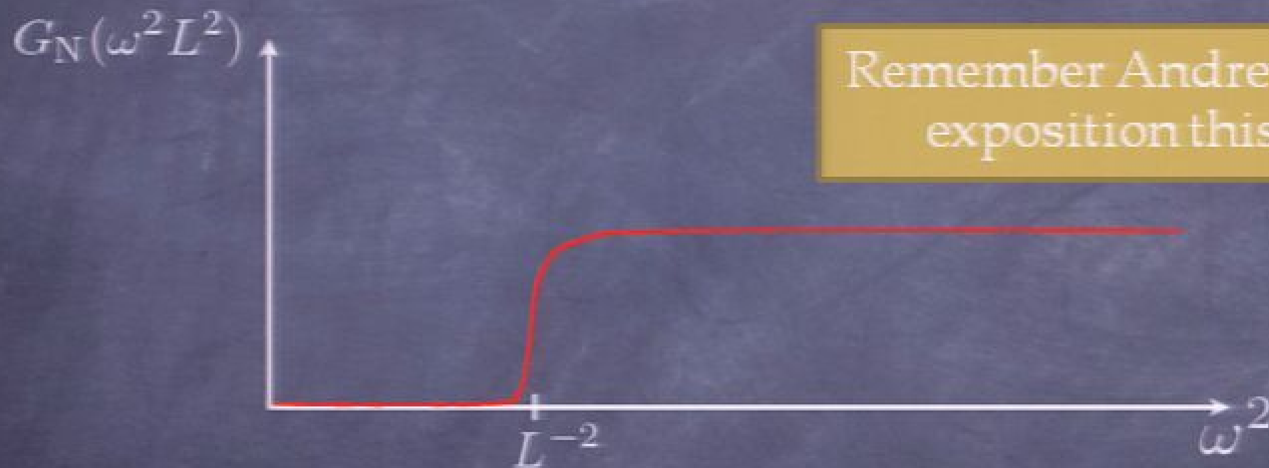

Remember Andrew's excellent exposition this morning

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- Large Scale CMB Cancellation
  - ISW and Sachs-Wolfe effects ***may*** cancel on super-horizon scales

Cosmological degravitation

- Around Minkowski space:

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

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

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- General cosmological solution is non-existant; so let's guess:

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

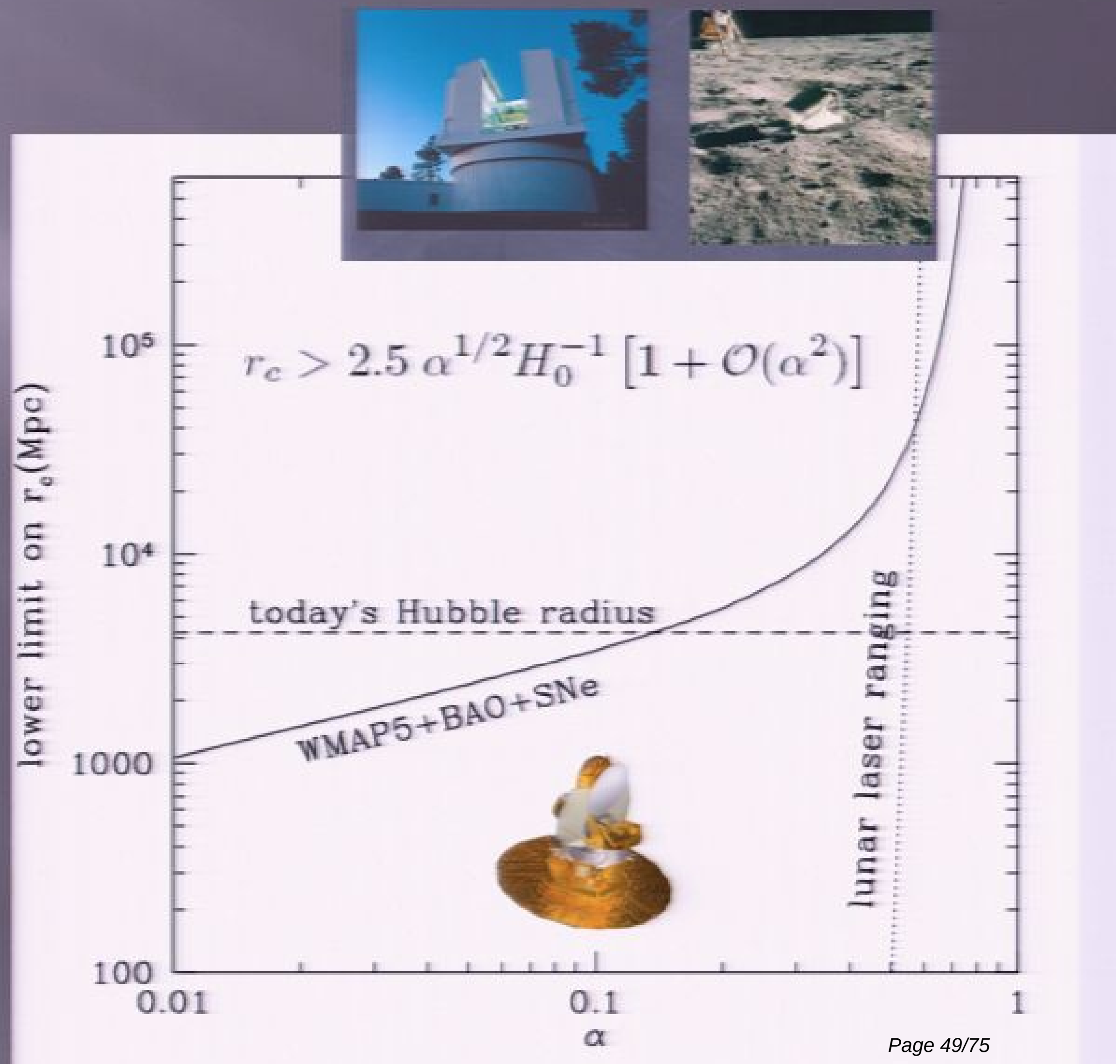
(analogy with α =1/2, Dvali, Gabadadze, Porati model)

Degravitating FRW

- FRW with $\alpha \rightarrow 0$

  (massive graviton)

  indistinguishable from ΛCDM



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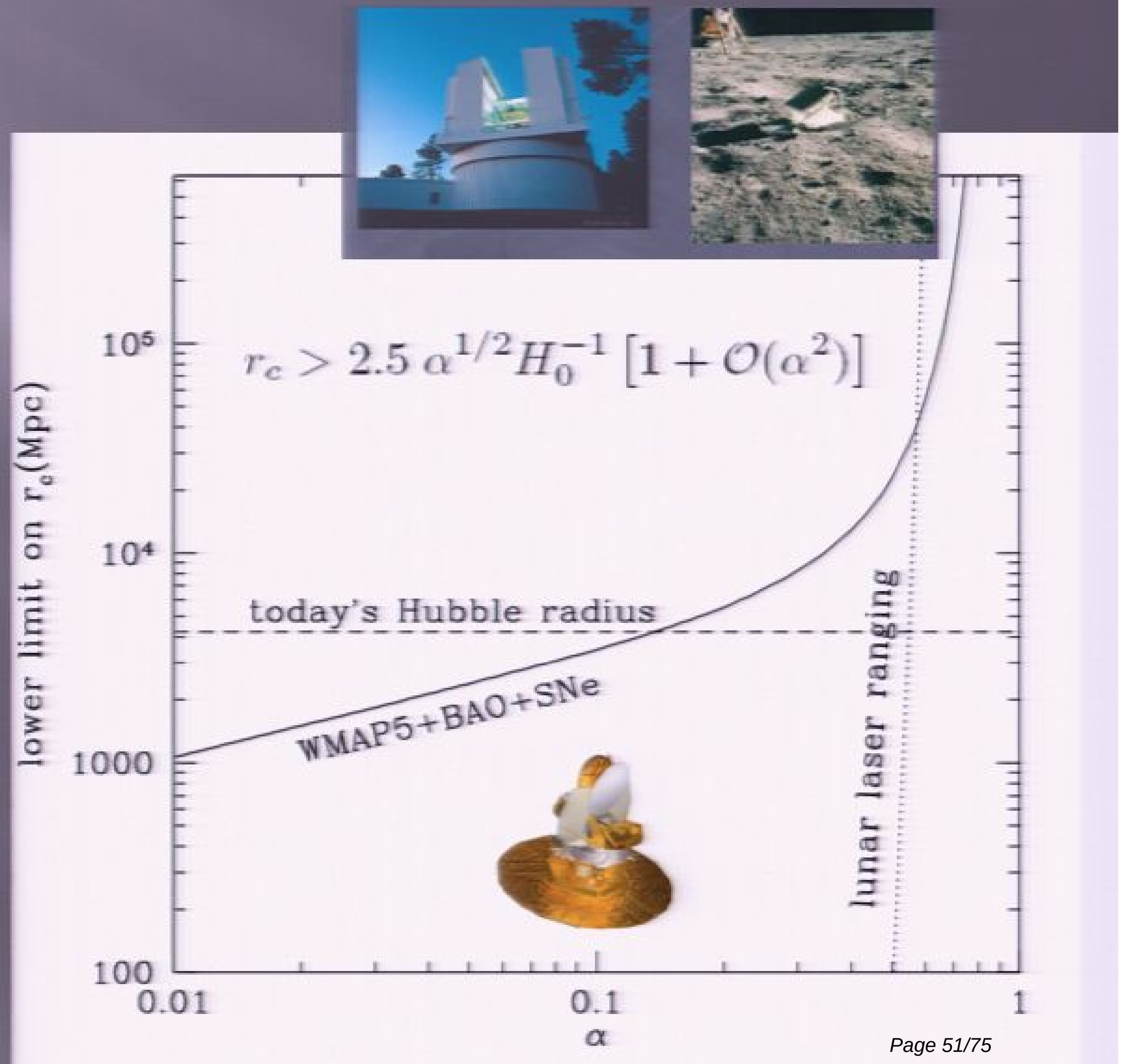

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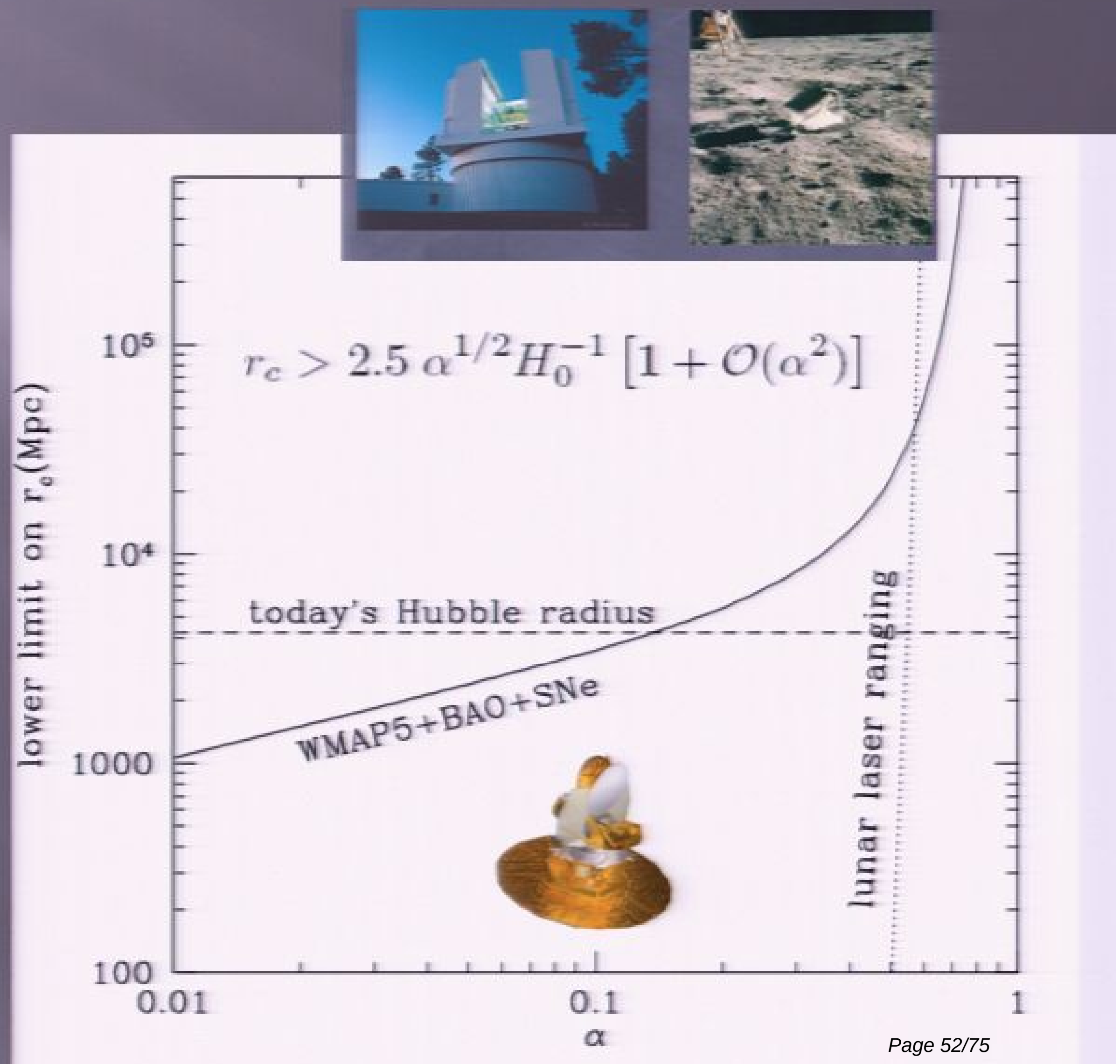
- Inhomogeneous Universe could be different!



How we deal with perturbations

- Use Parametrized Post-Friedmann (PPF) formulation (Hu & Sawicki 2007): $$g = \frac{\Phi + \Psi}{\Phi - \Psi}$$

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- Analogy with DGP model for $\alpha = 1/2$

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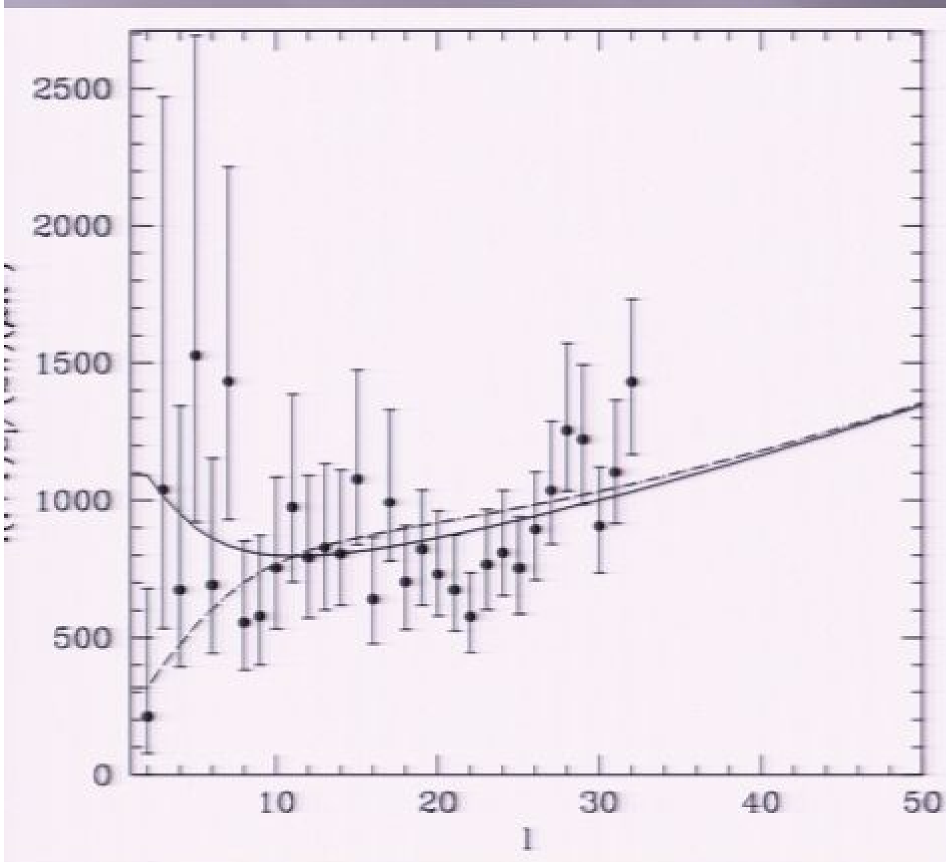
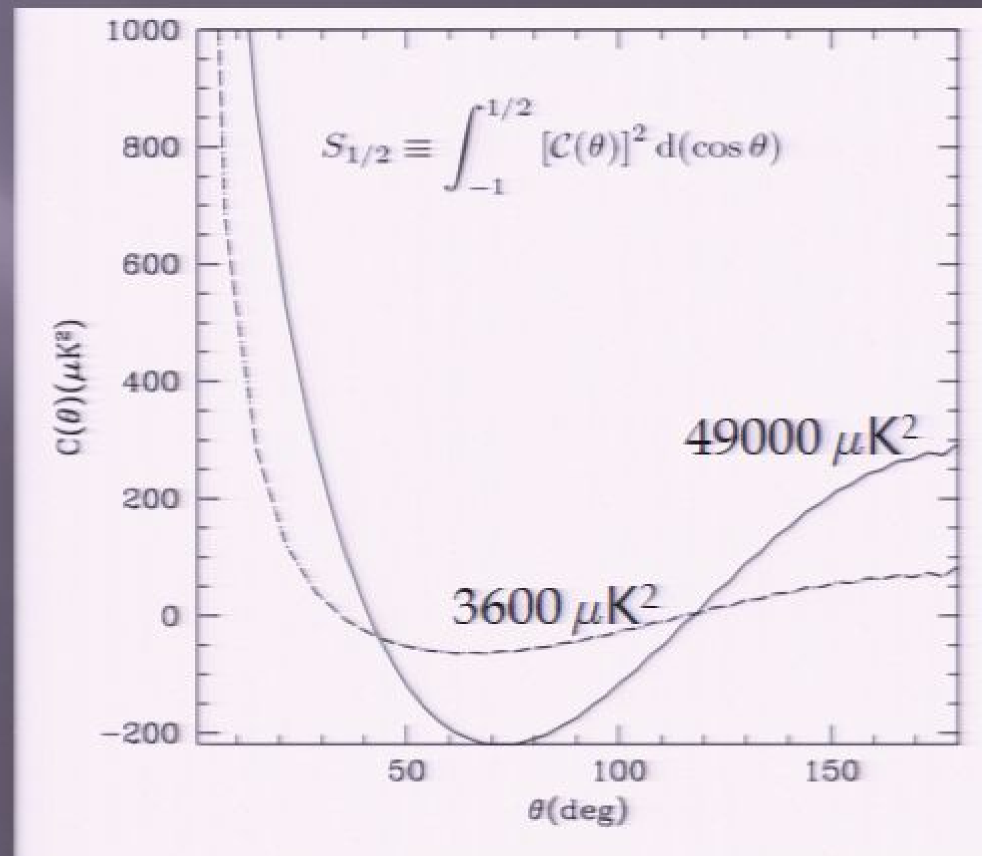
de-Correlating CMB on large angles

$r_c = 100$ Mpc





de-Correlating CMB on large angles

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
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WMAP3 MLE C_ℓ	8334	4.2
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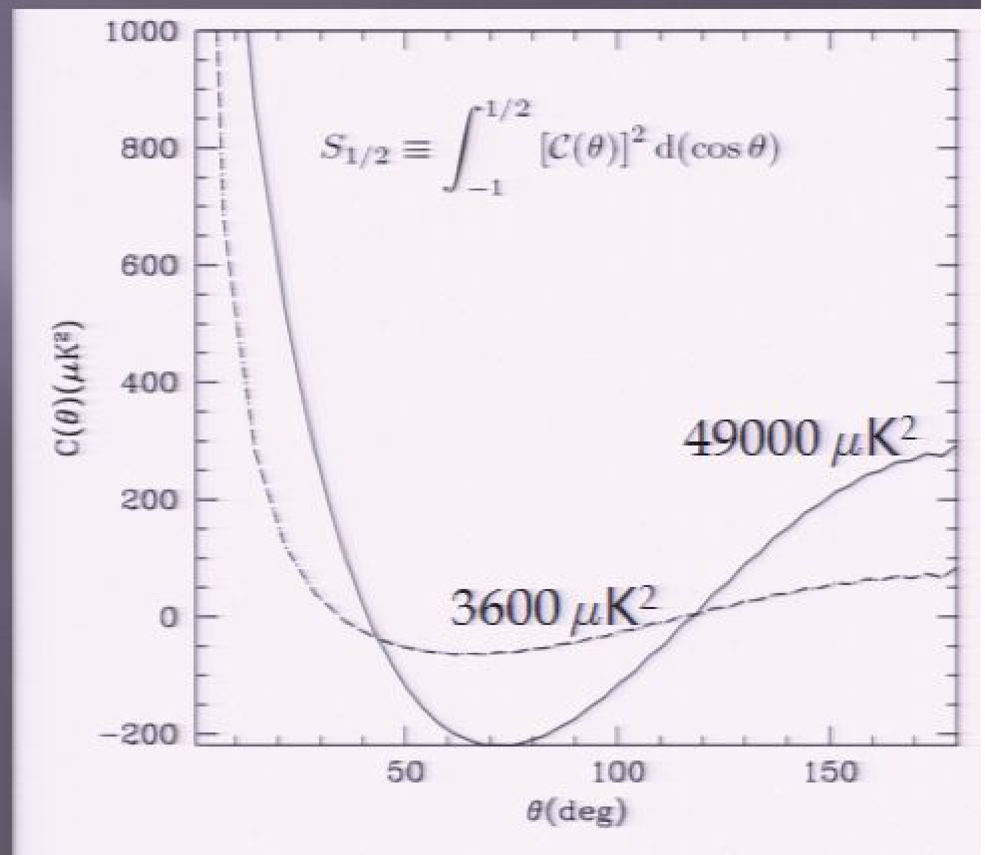

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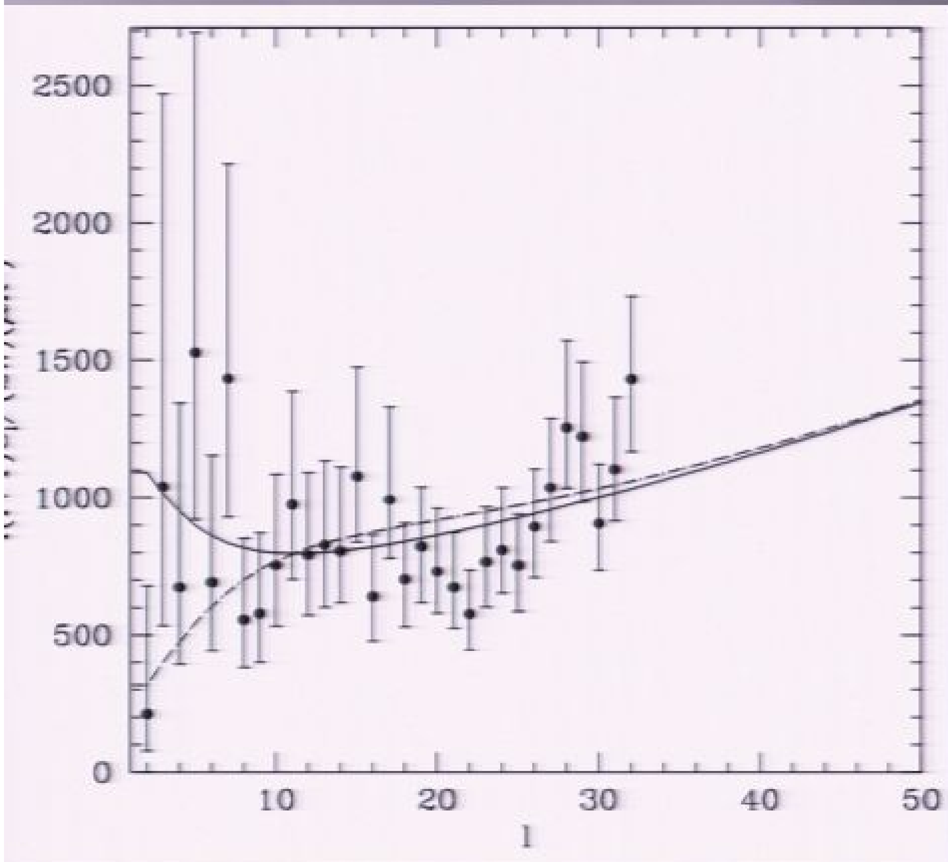

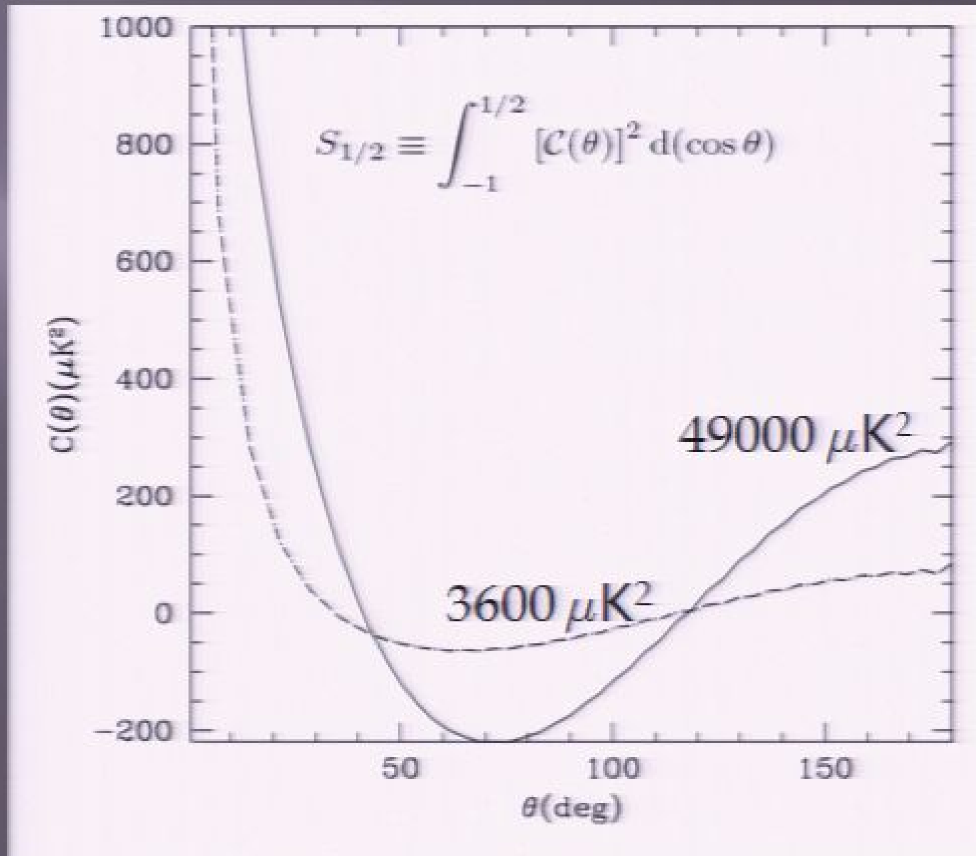

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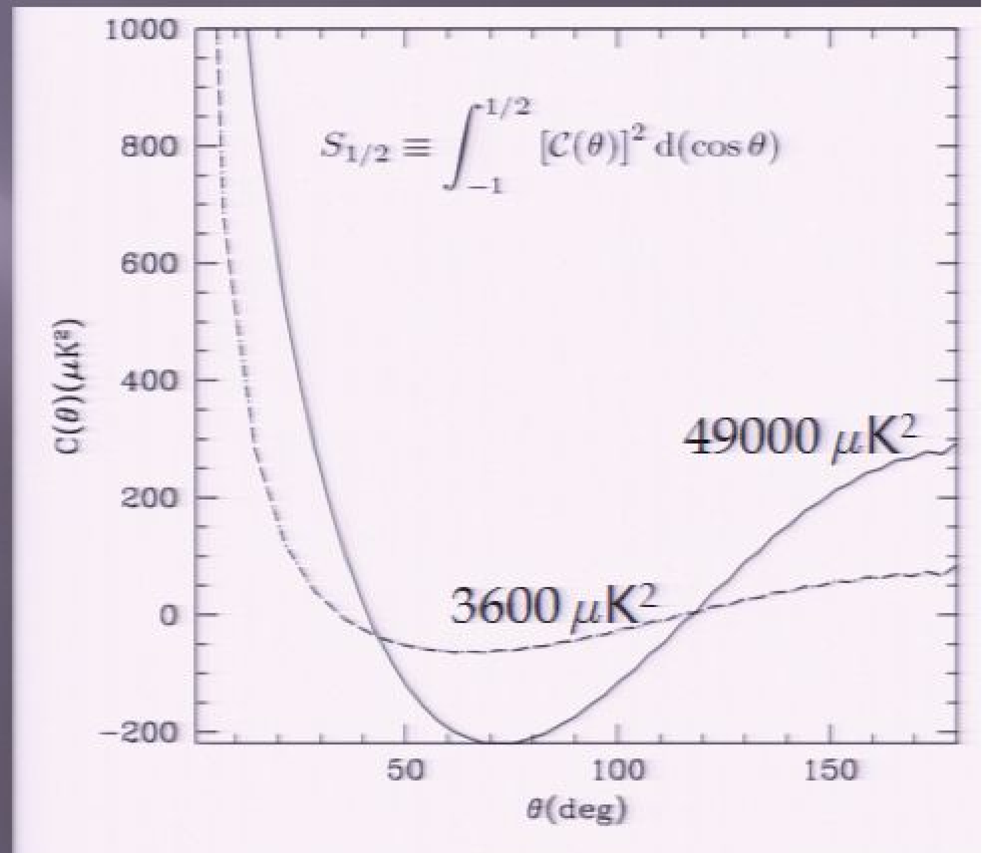

Potential Transfer Function in the matter era

- $z = 0.5;$
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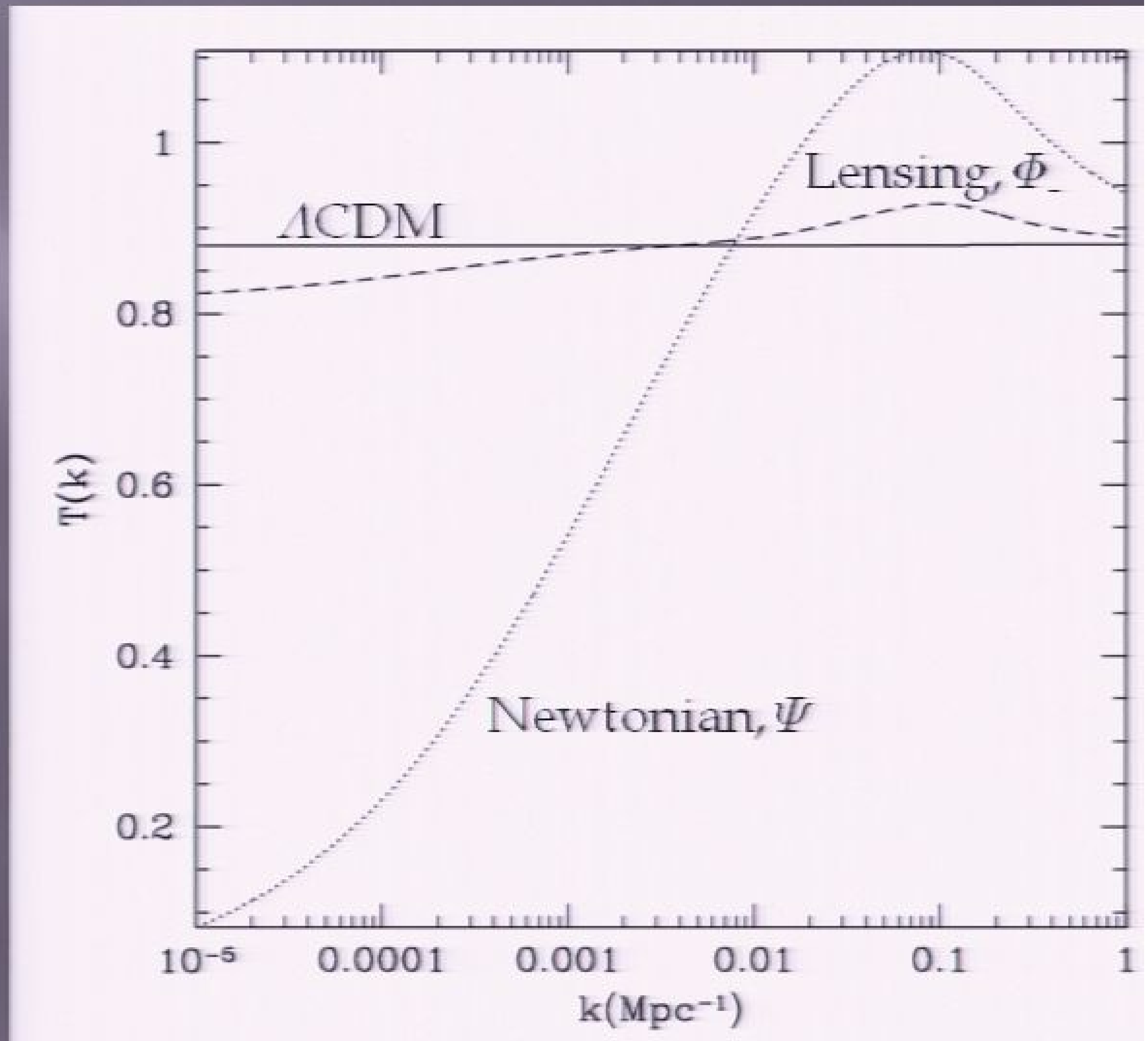

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- The model can roughly explain observations if the graviton Compton wavelength ~ 100 Mpc
- At our present level of understanding, the model is not uniquely fixed by either theory or observations

What should we see?

- Detect many SZ clusters with ACT, SPT, Planck??
  - confirm CBI excess
  - Large kinetic SZ signals from Planck clusters
- Large redshift space distortions, measured by JDEM/Euclid/CHIME
- Scale dependent bias: LSST, Pan-STARRS??
- Subtle distortions in weak lensing map power spectra: LSST, Pan-STARRS??

What should we do?

- Non-linear models of degravitation (e.g. cascading)
- Cosmological solutions+perturbation theory
- If this doesn't work …

→ Alternative models of gravity that have the desired behavior