Title: Observational Evidence for Massive Gravity

Date: Oct 23, 2008 02:25 PM

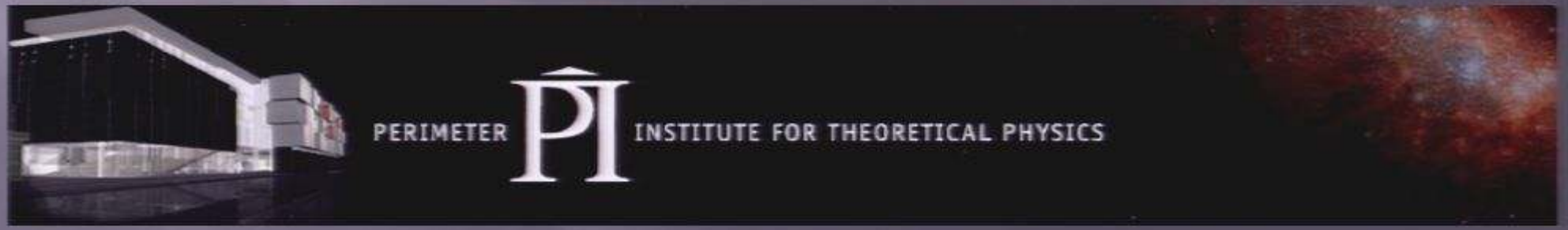
URL: http://pirsa.org/08100062

Abstract:

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

OBSERVATIONAL EVIDENCE FOR *MASSIVE GRAVITY*

Niayesh Afshordi



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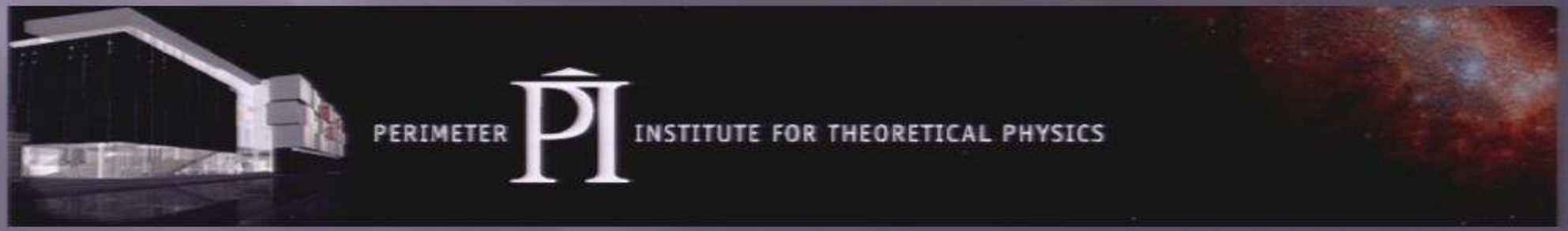

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OBSERVATIONAL EVIDENCE FOR *MASSIVE GRAVITY*

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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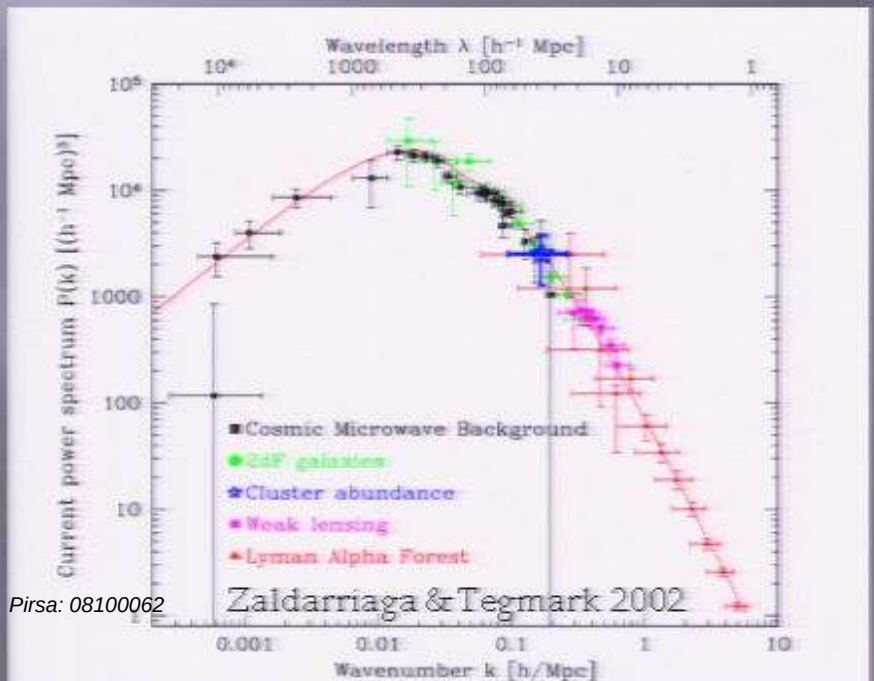
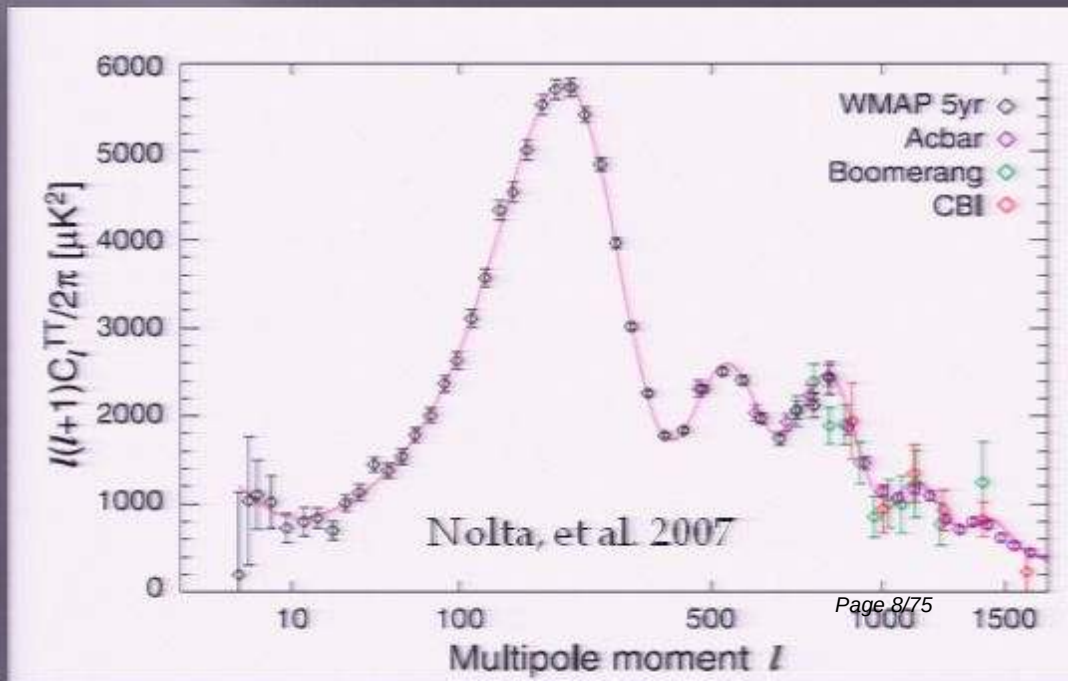
Cosmic density power spectrum



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

- "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

ABSTRACT

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

S. Weinberg, Rev. Mod. Phys. (1989)

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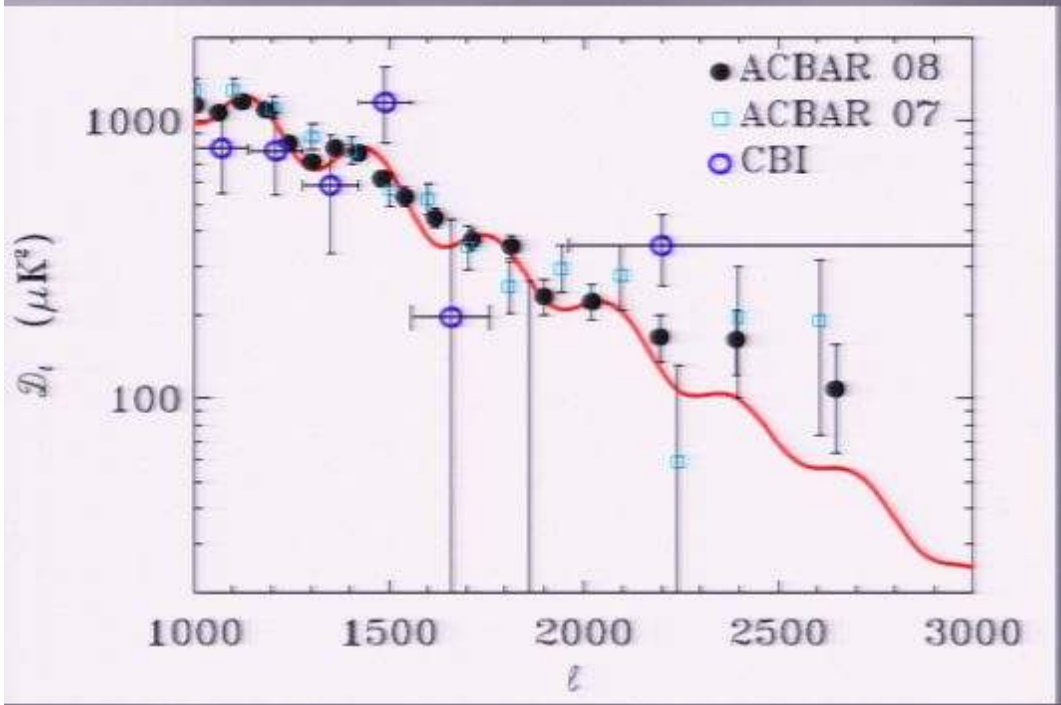
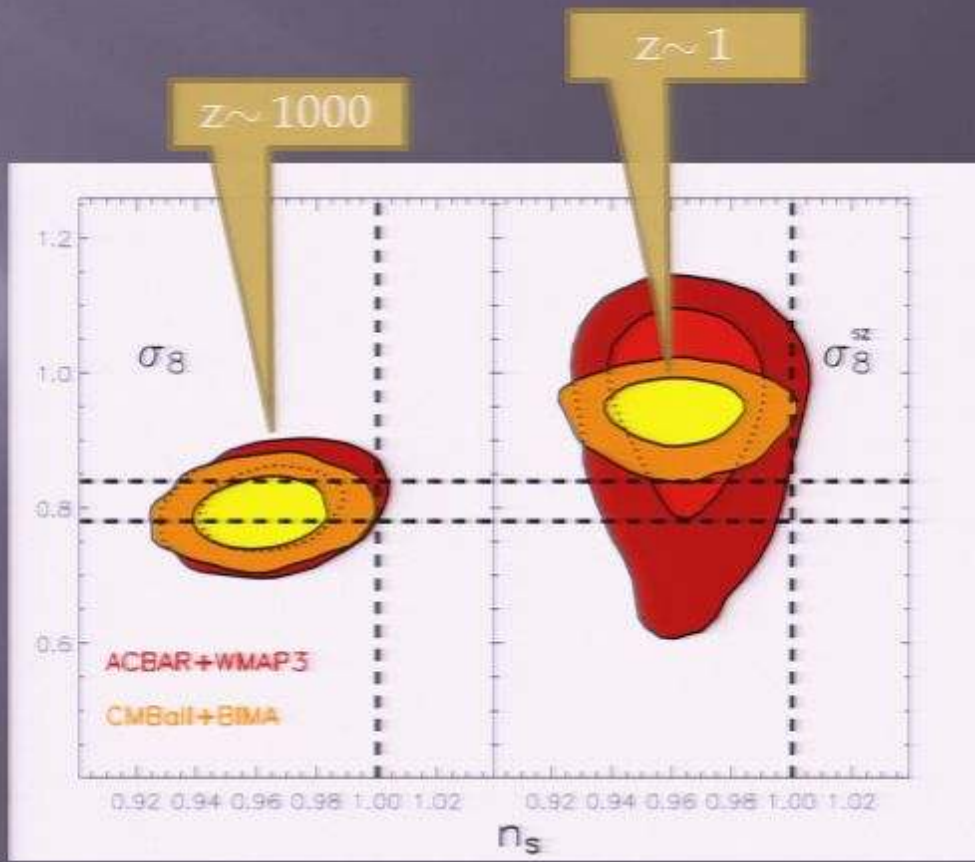
Do we really measure σ_8 at low redshift?

CBI excess: Census of SZ clusters at z~1

- Do we underpredict the # of clusters?





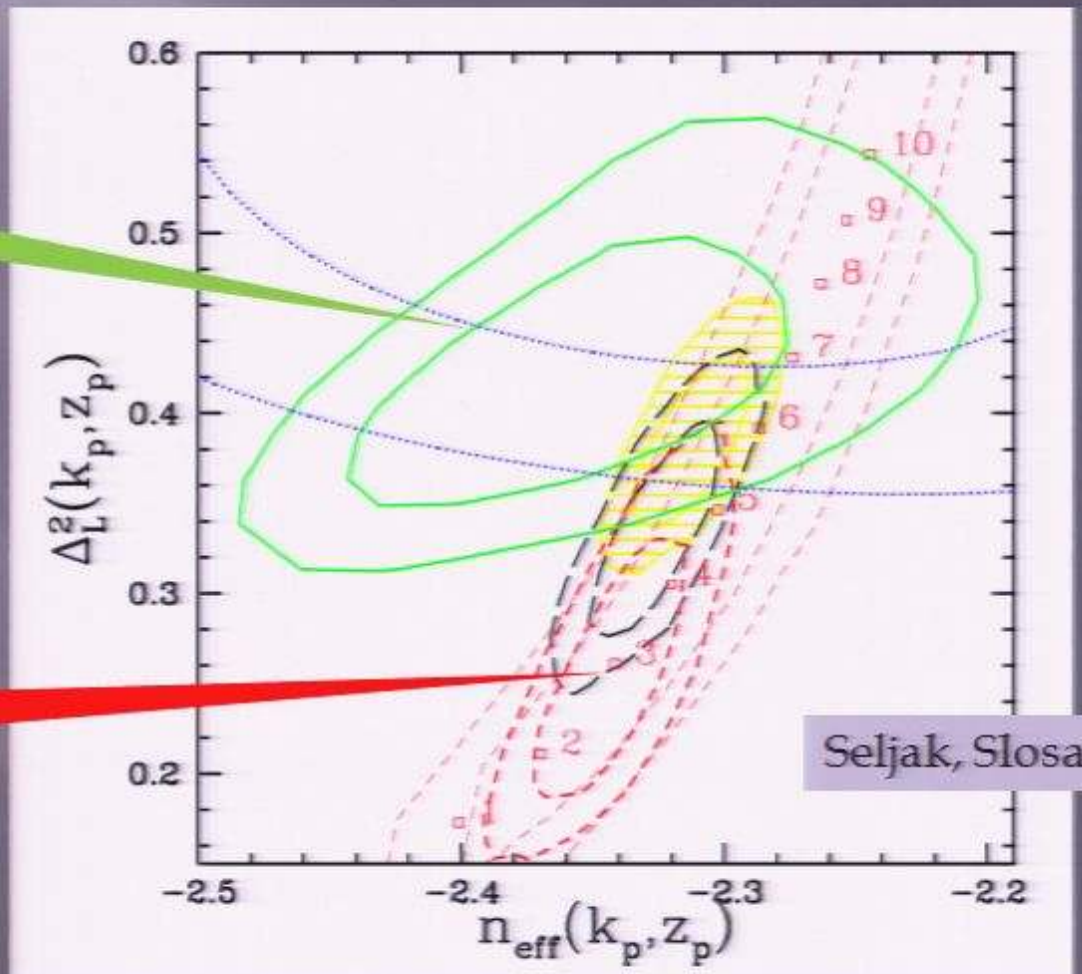
Reichardt, et al. 2008

Lyman-α excess: structure at z$\sim$3

- Ly-α, more clumpy than CMB predicts?

Lyman-α forest

WMAP3+ΛCDM

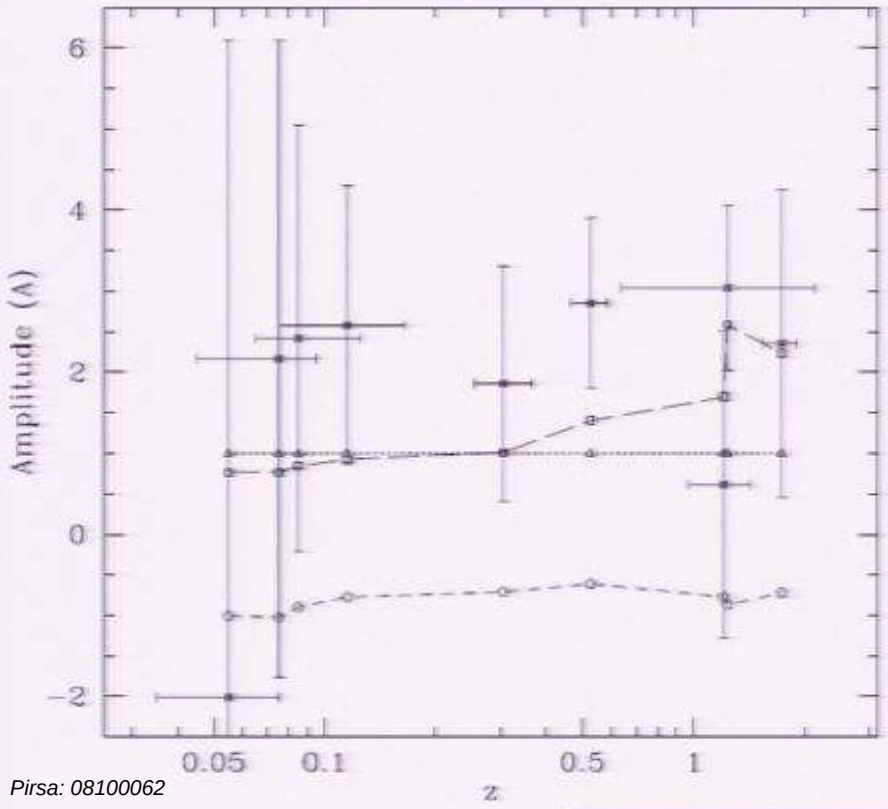


Seljak, Slosar, & McDonald 06

ISW effect X galaxies: metric pert. at z$\sim$ 0.1-1

- Gravitational Potential: 2.23$\pm$ 0.60 larger than ΛCDM predicts

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



Ho, et al. 08

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	$+0.26 \pm 1.69$
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NVSS	$+2.92 \pm 1.02$
All Samples	$+2.23 \pm 0.60$

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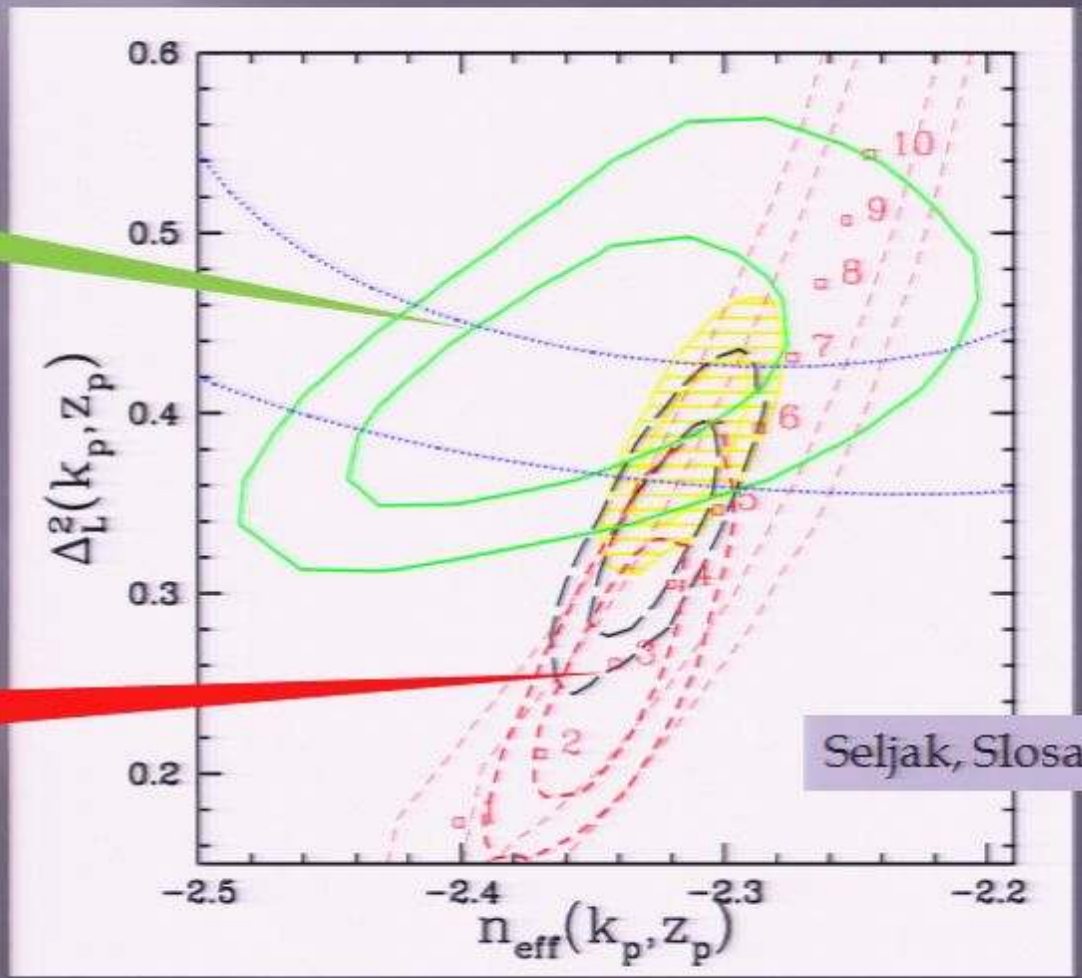

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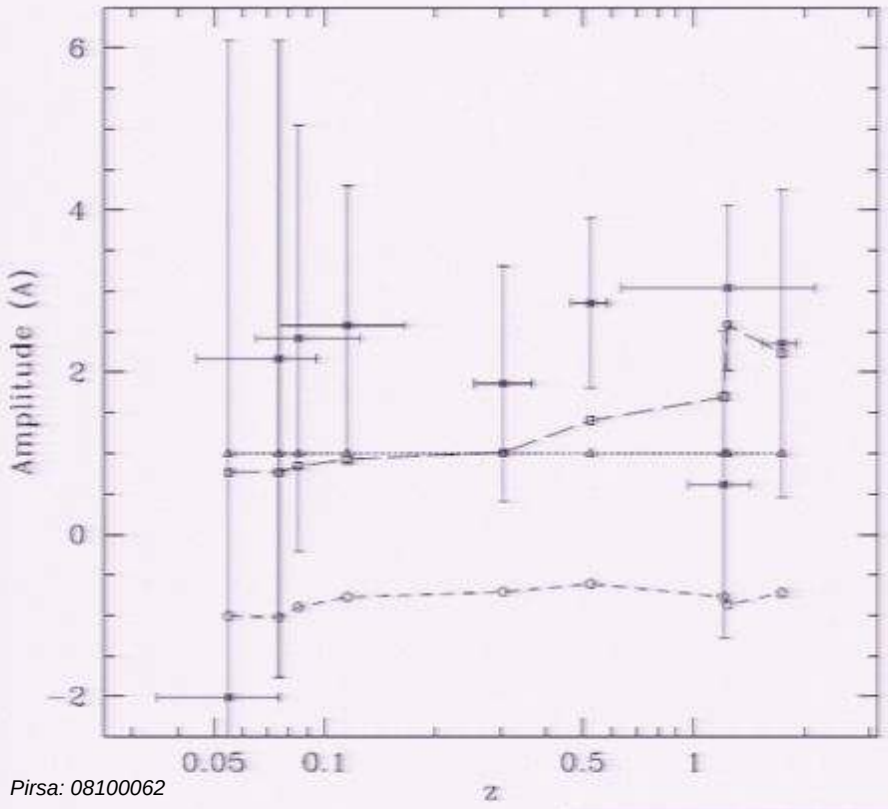

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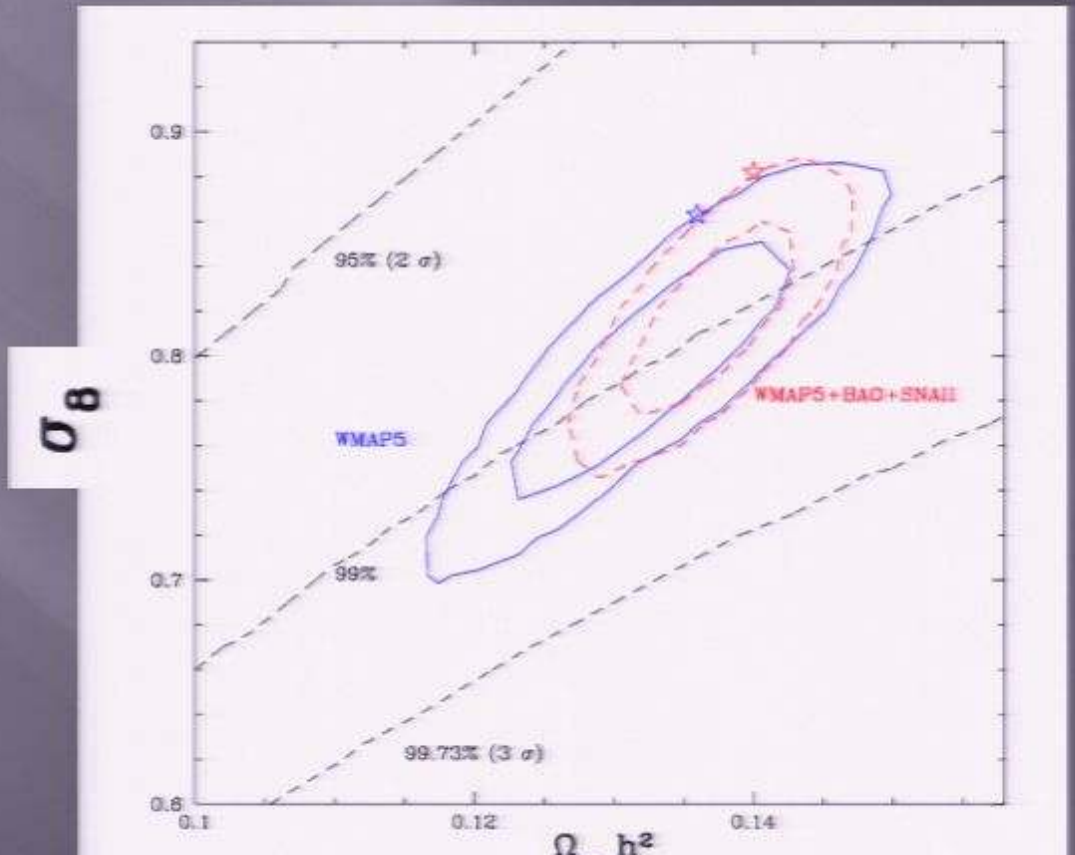
Dark Bulk Flow I: velocities at z=0

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

  Watkins, Feldman, & Hudson 08



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

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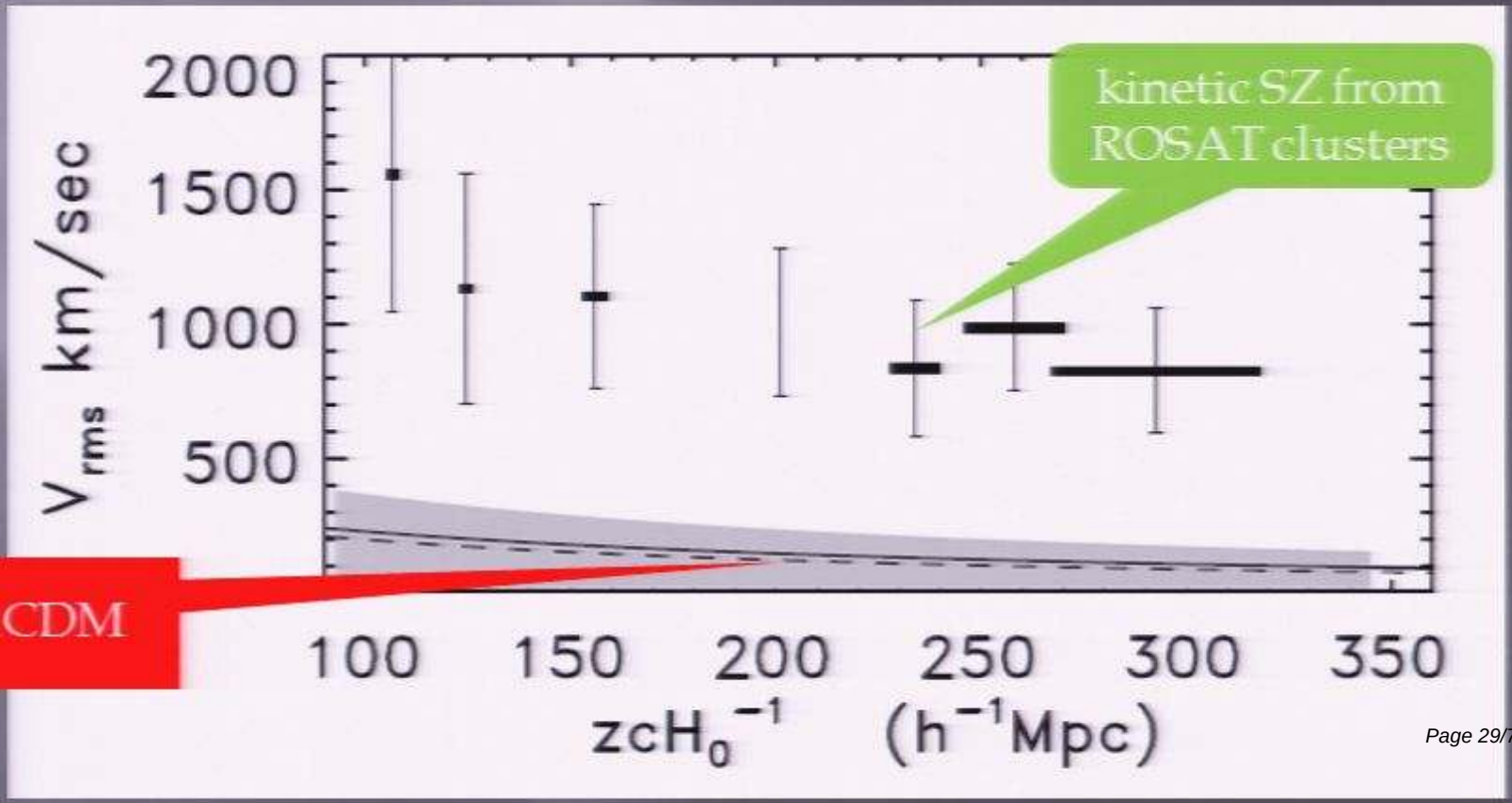

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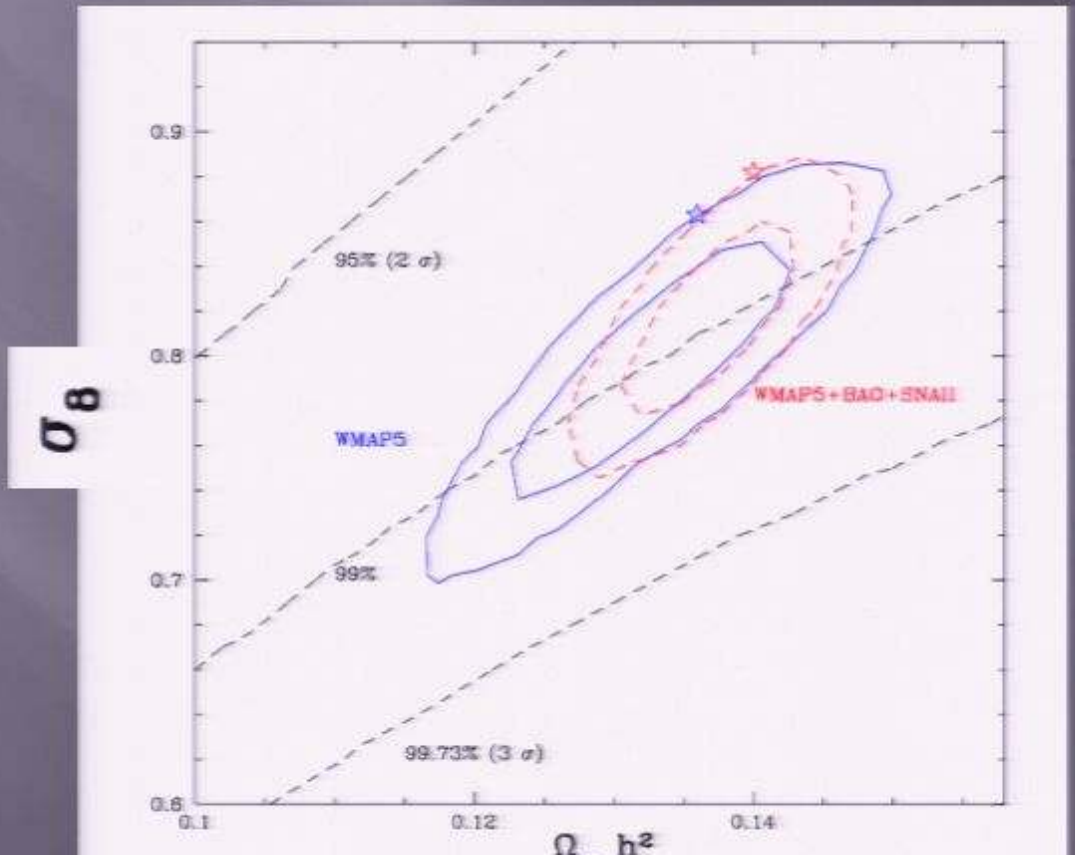

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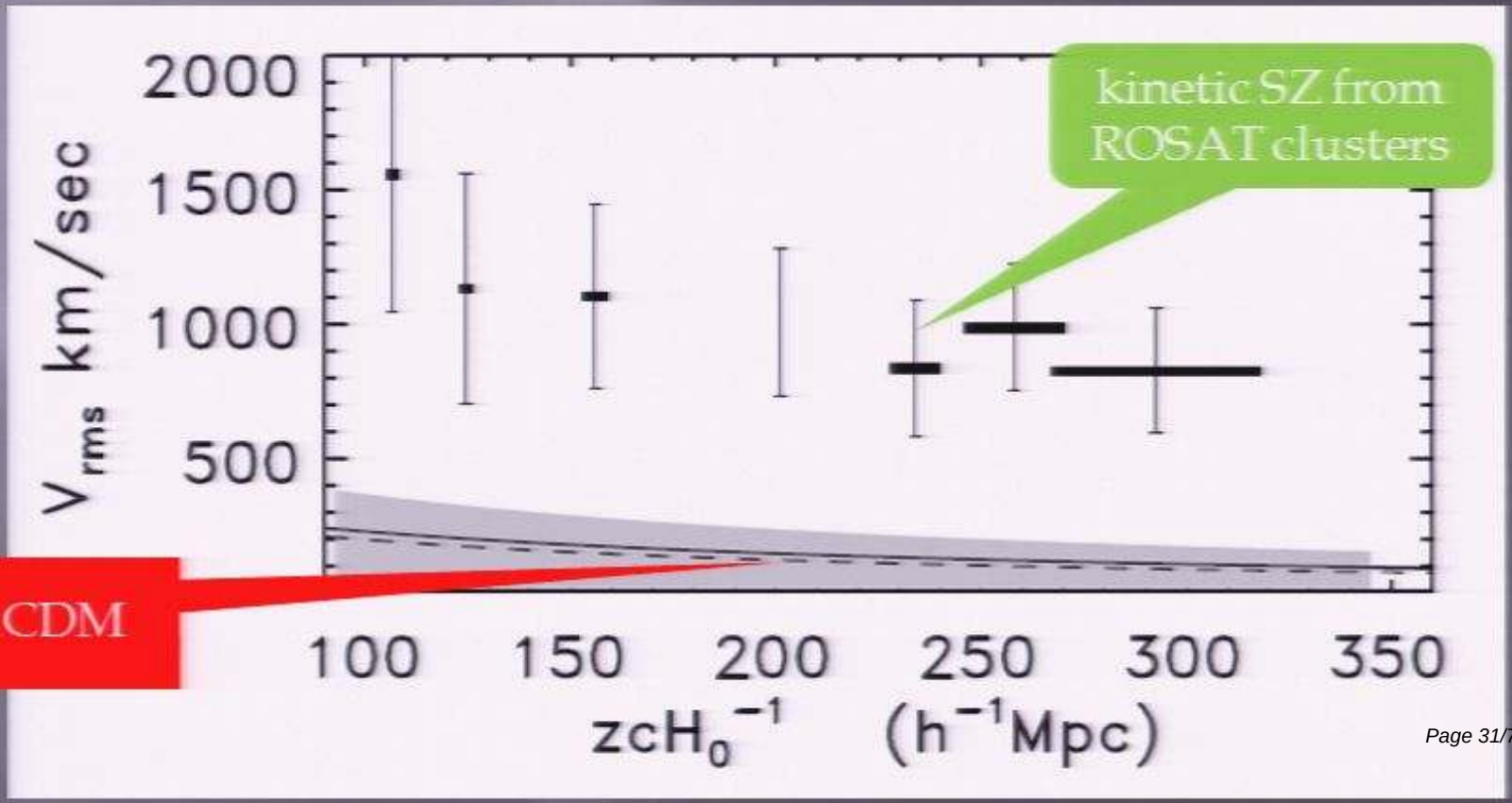

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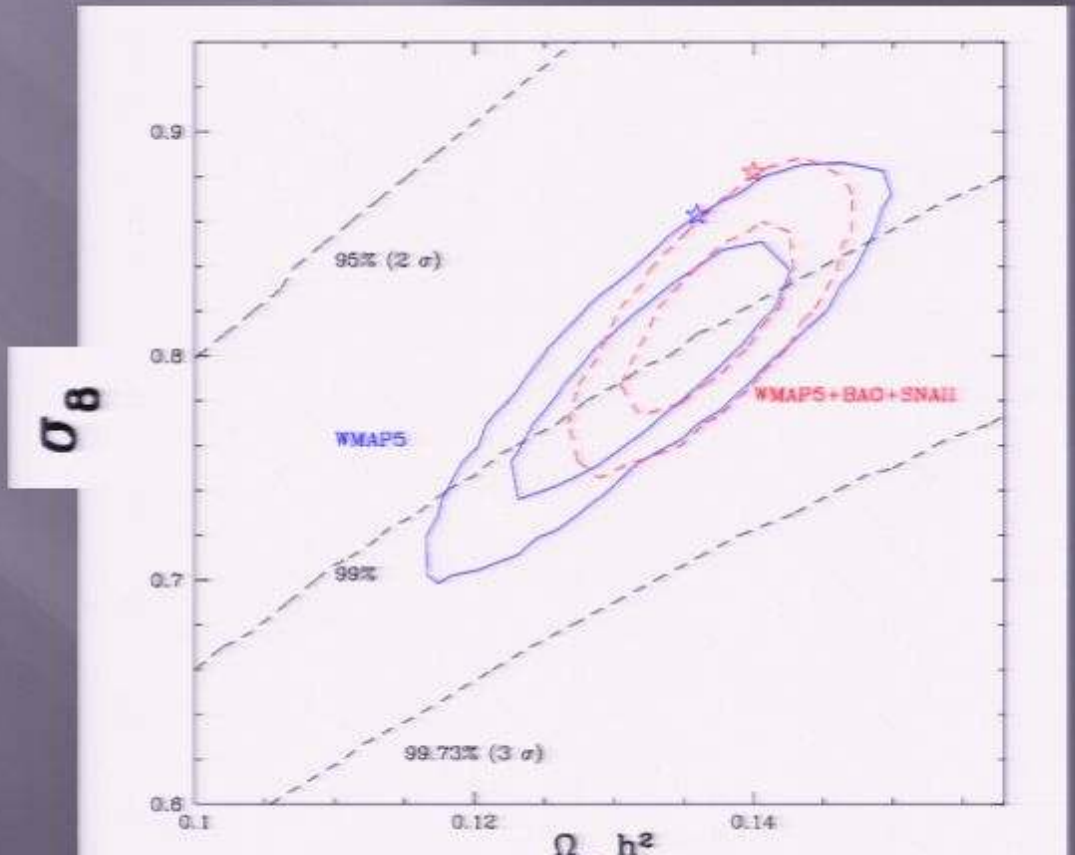

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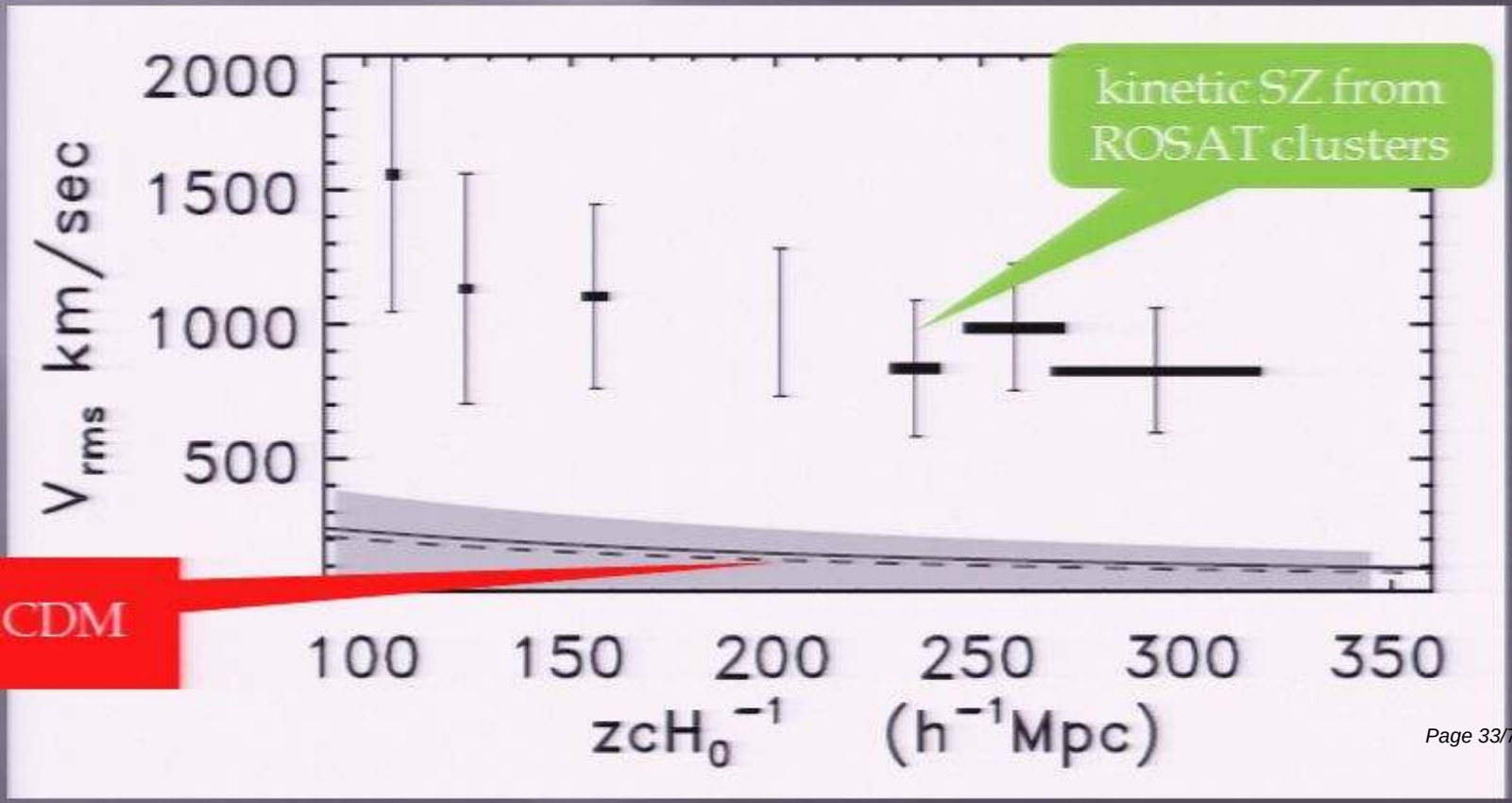
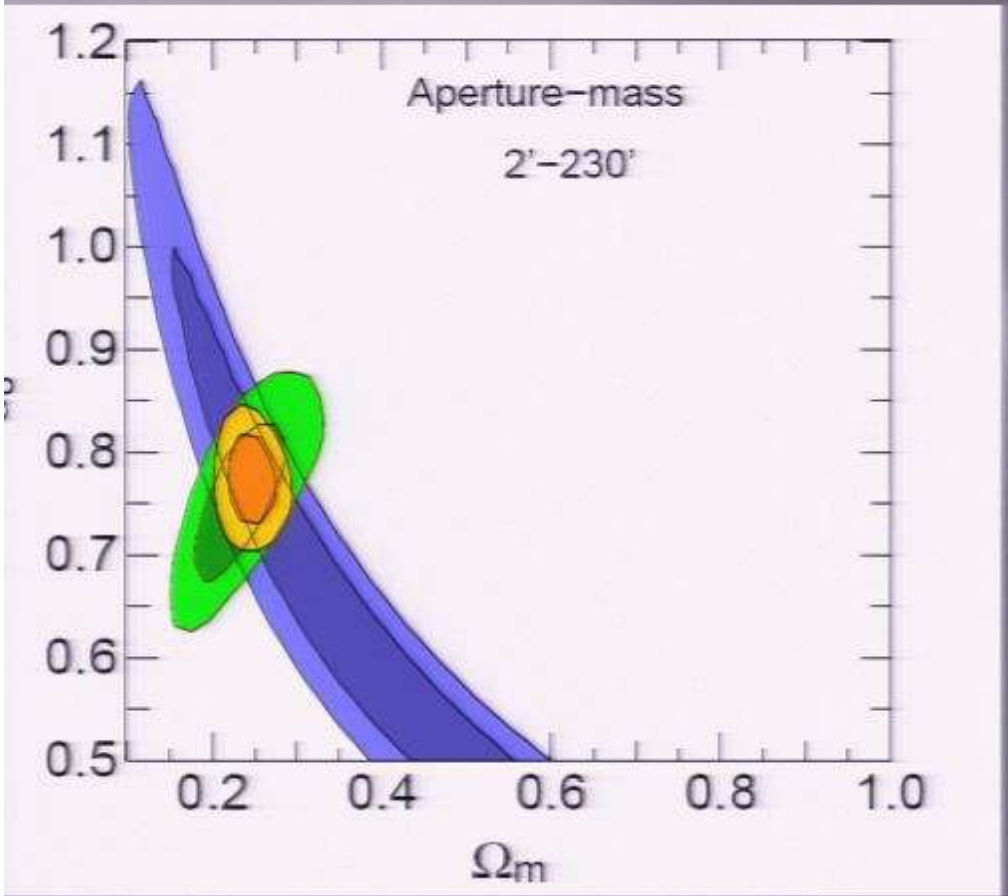
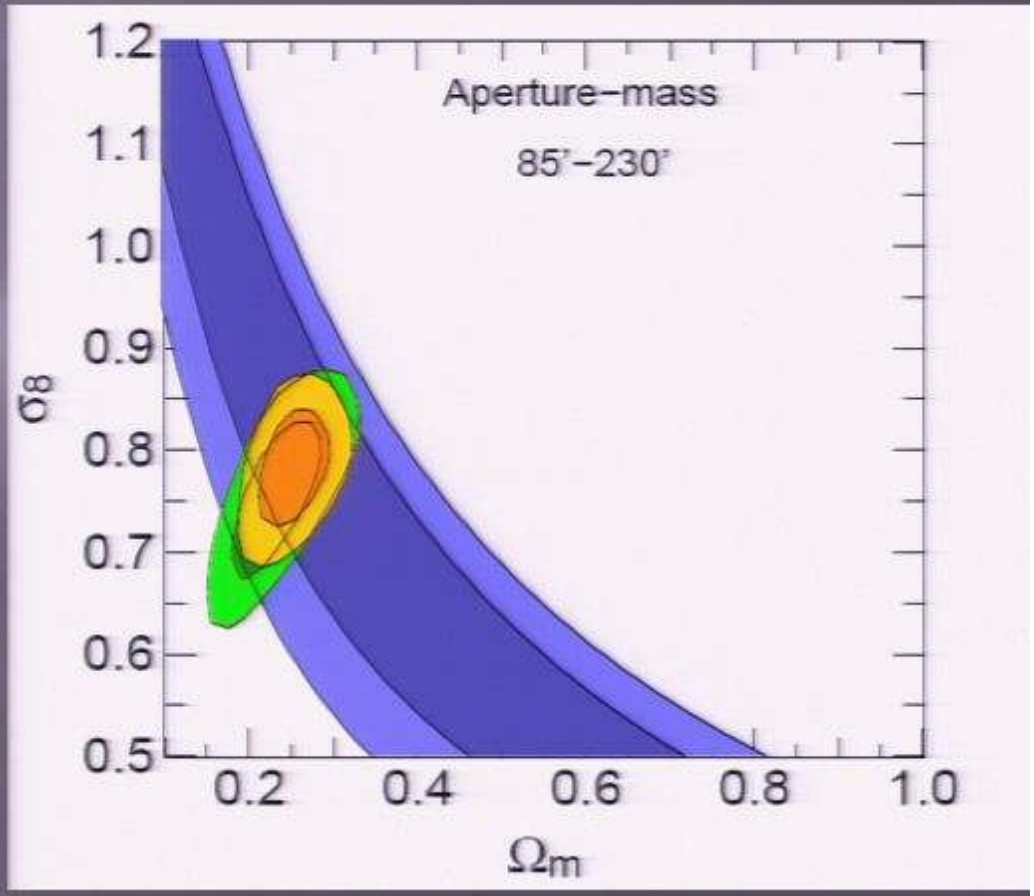


But σ_8 from lensing is consistent with ΛCDM!





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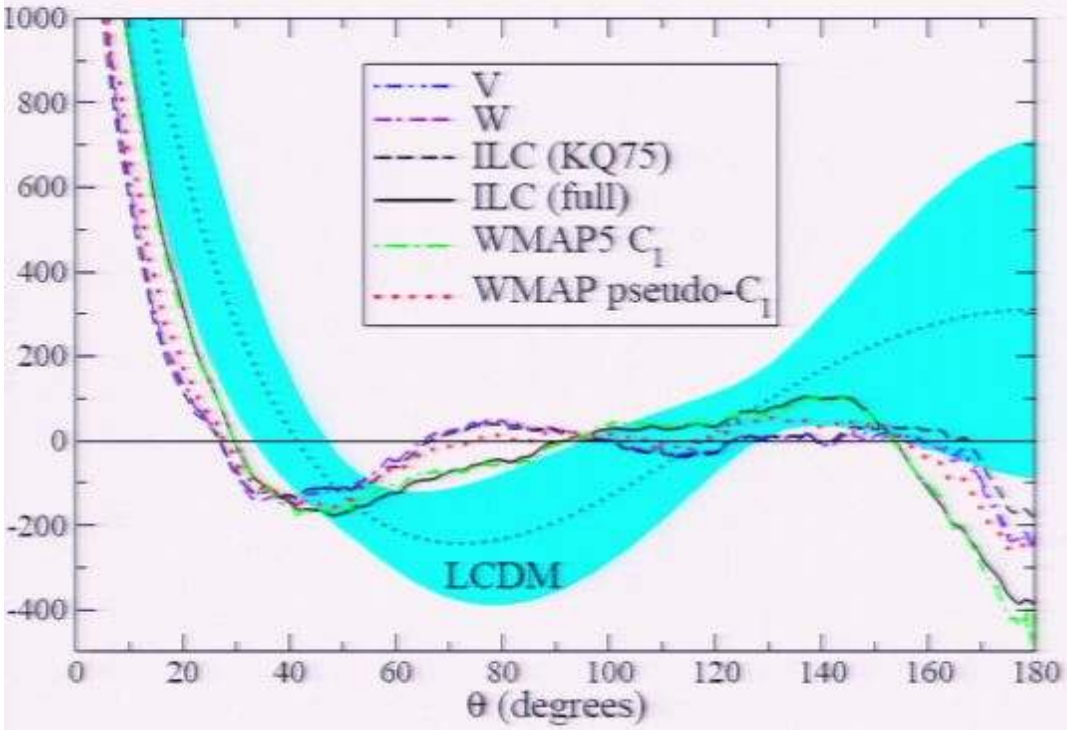
- *$\Phi_- \neq -\Psi$! Could this signal the breakdown of General Relativity ??*

CMB auto-correlation, beyond 60 deg's



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

Data Source	$S_{1/2}$ $(\mu\mathrm{K})^4$	$P(S_{1/2})$ (per cent)
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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
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Copi, Huterer, Schwarz, & Starkman 08

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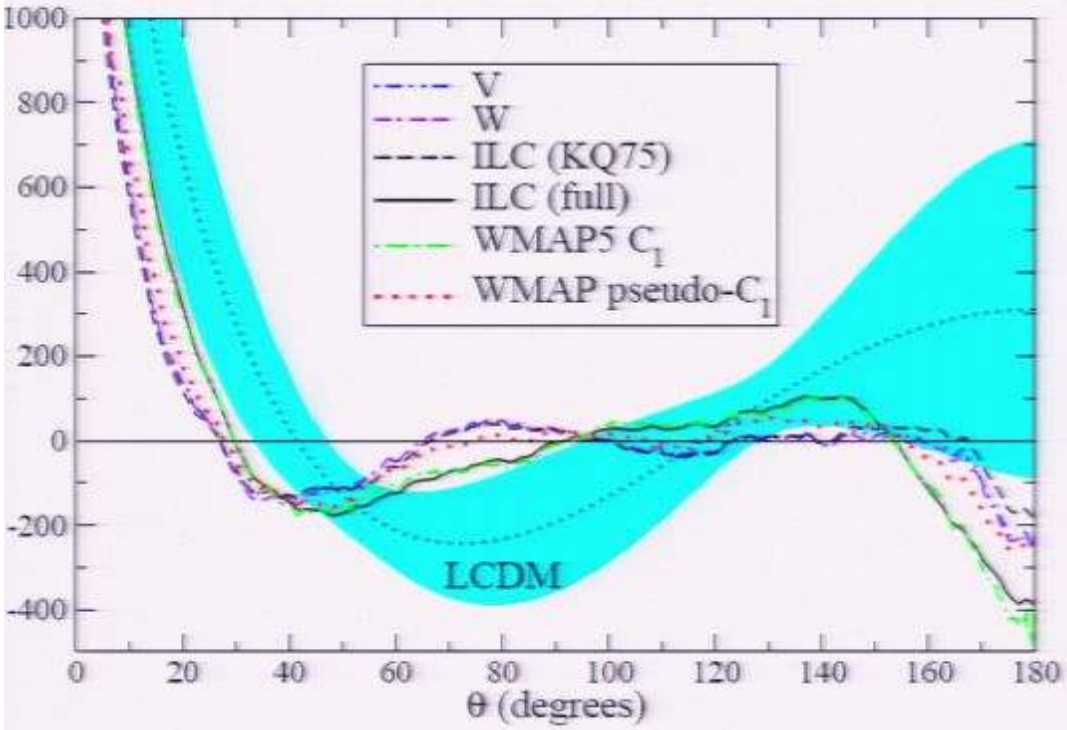

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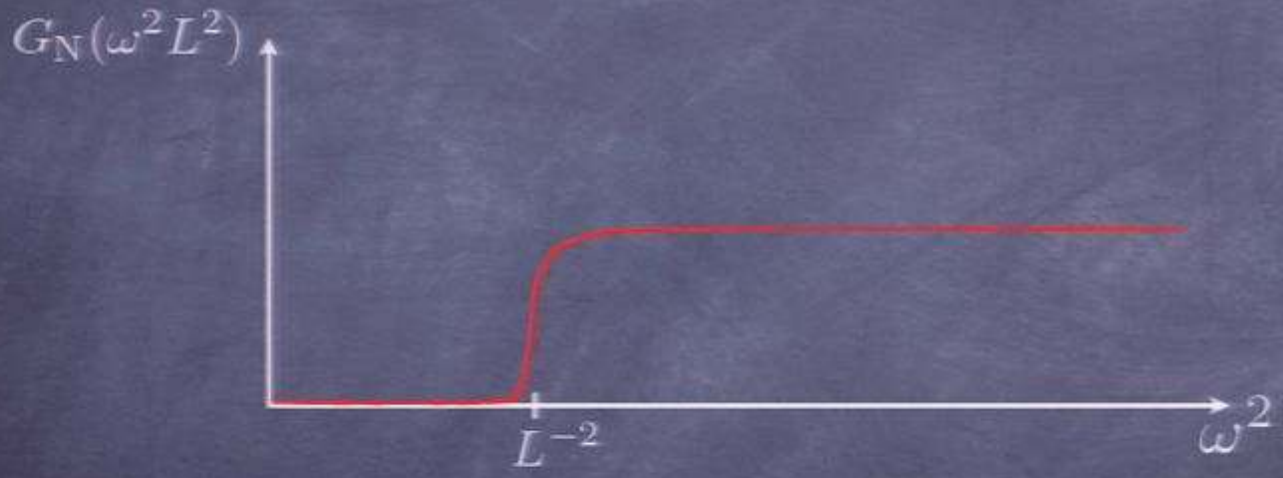
de-Gravitation: the panacea

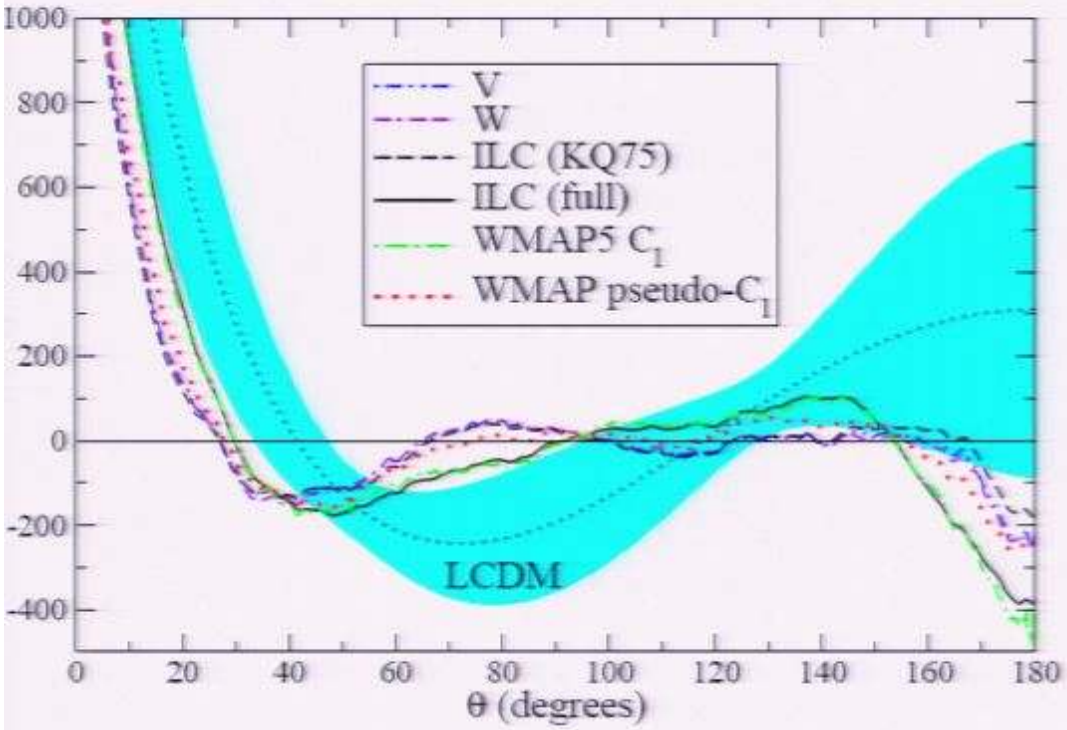
Dvali, Hofmann, and Khoury 07

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



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

CMB auto-correlation, beyond 60 deg's



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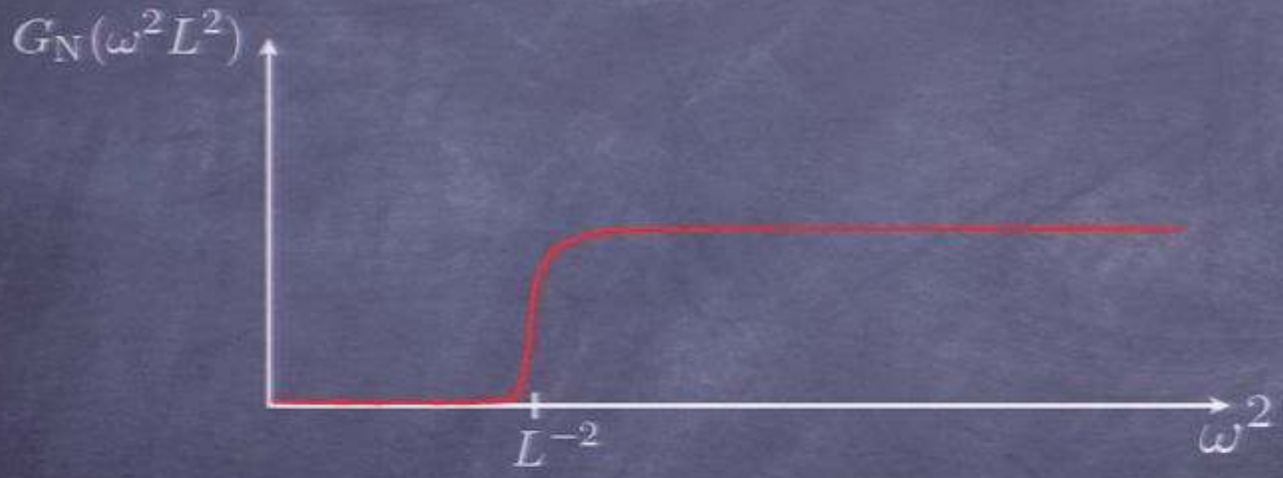

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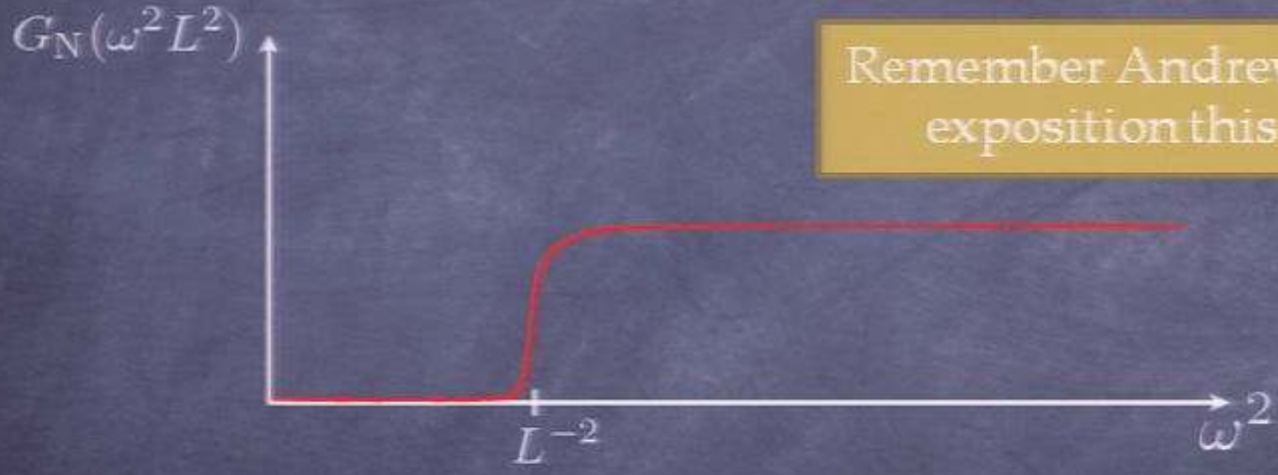

Remember Andrew's excellent exposition this morning

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- Around Minkowski space:

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Degravitating FRW

- FRW with $\alpha \to 0$

  (massive graviton)

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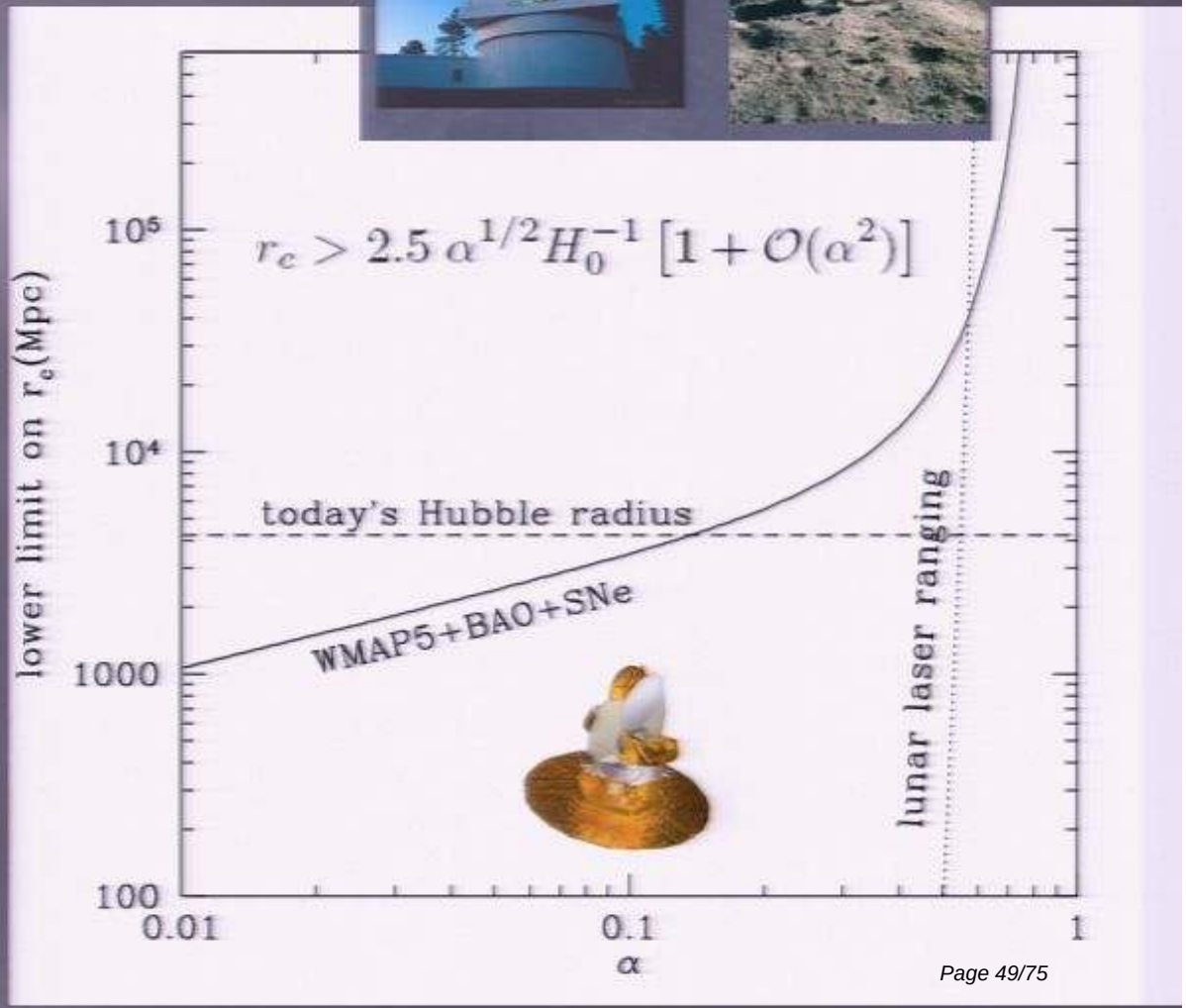

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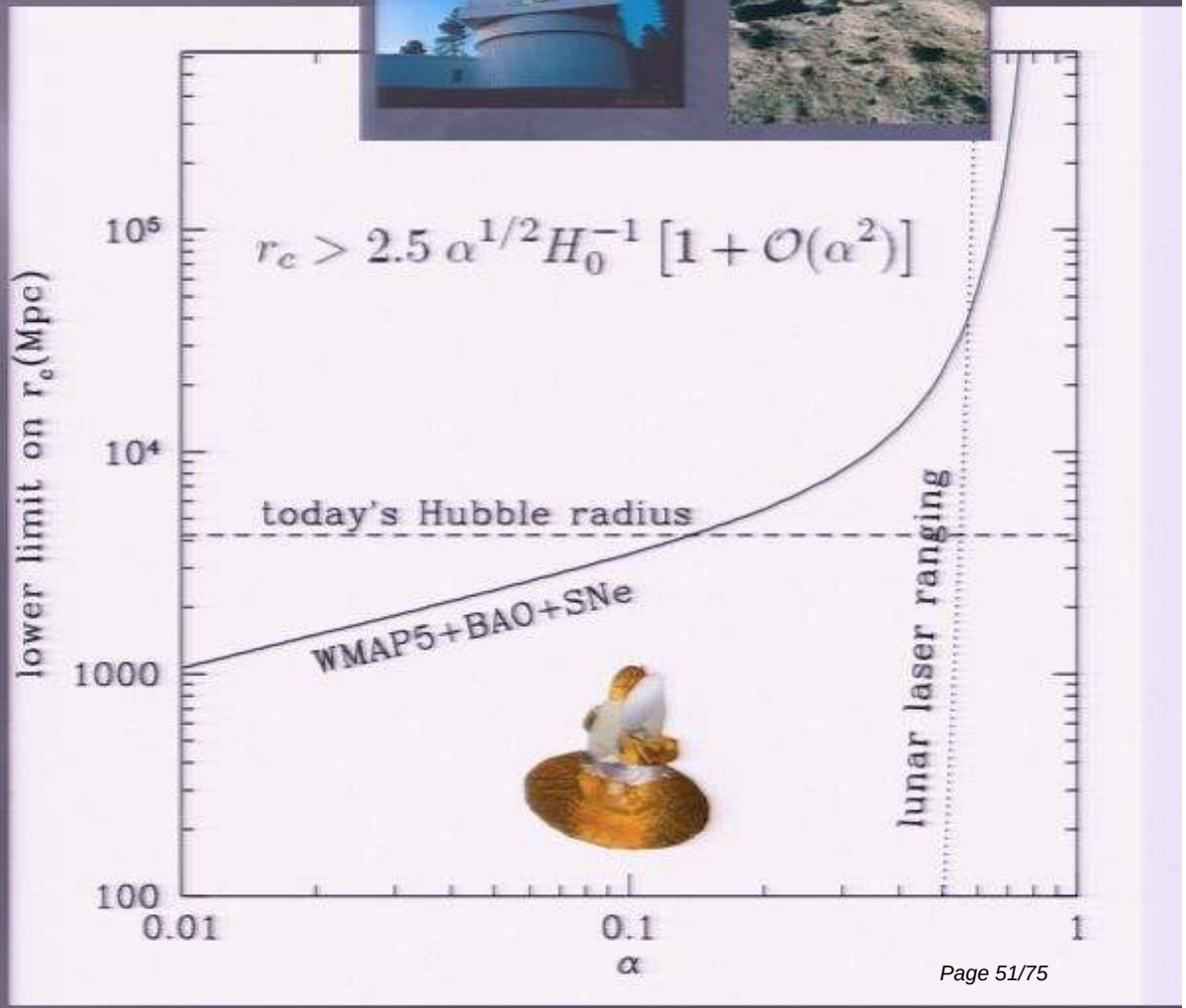

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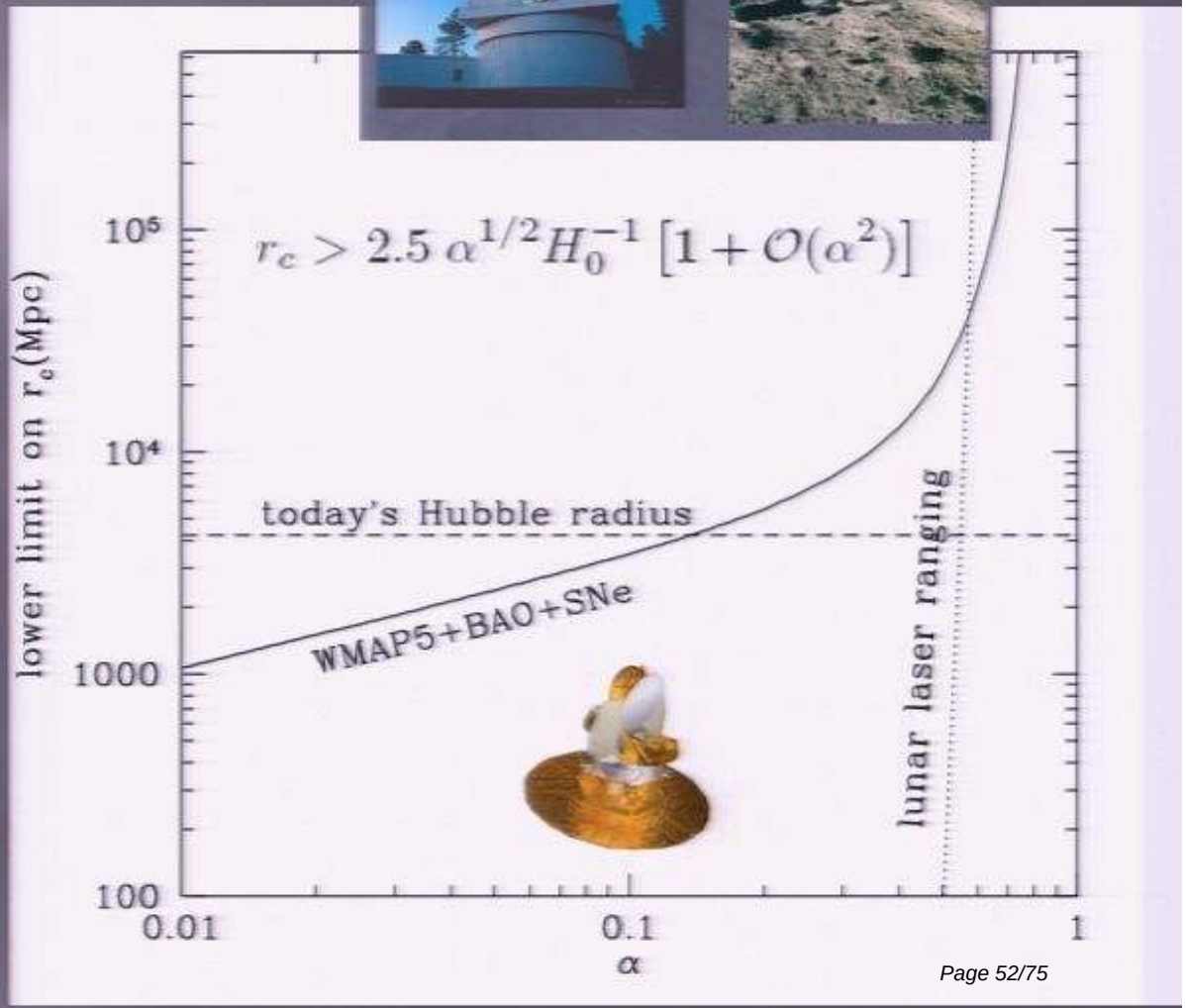

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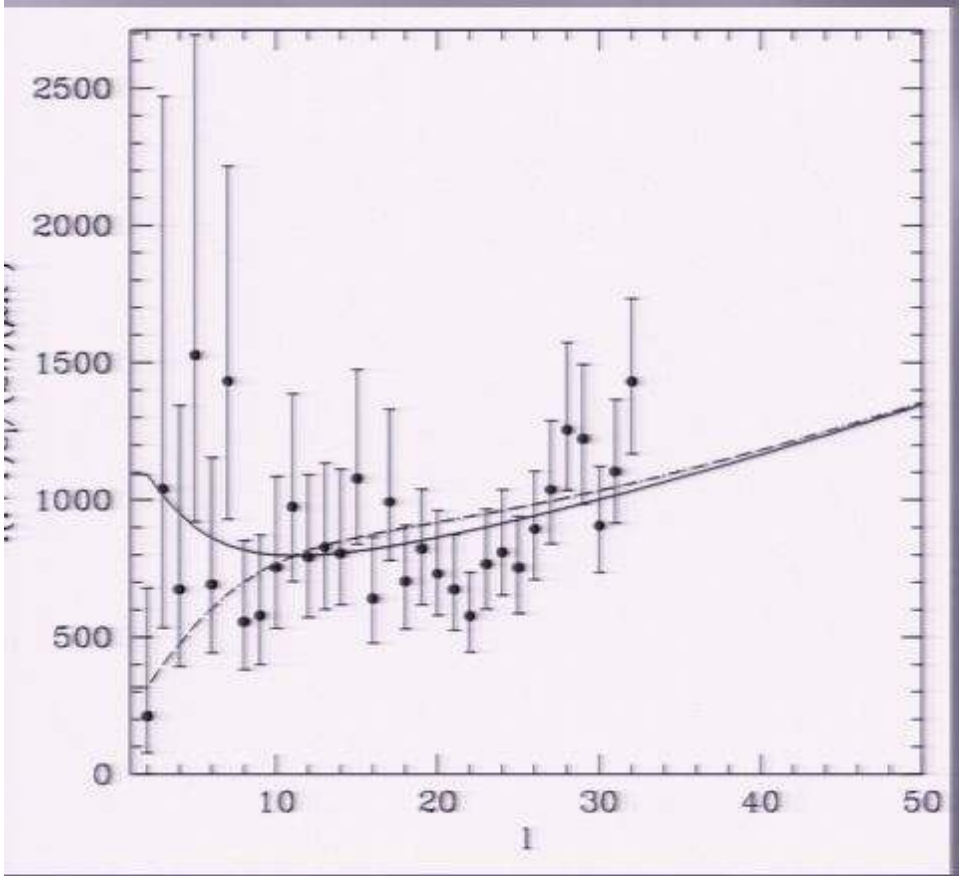

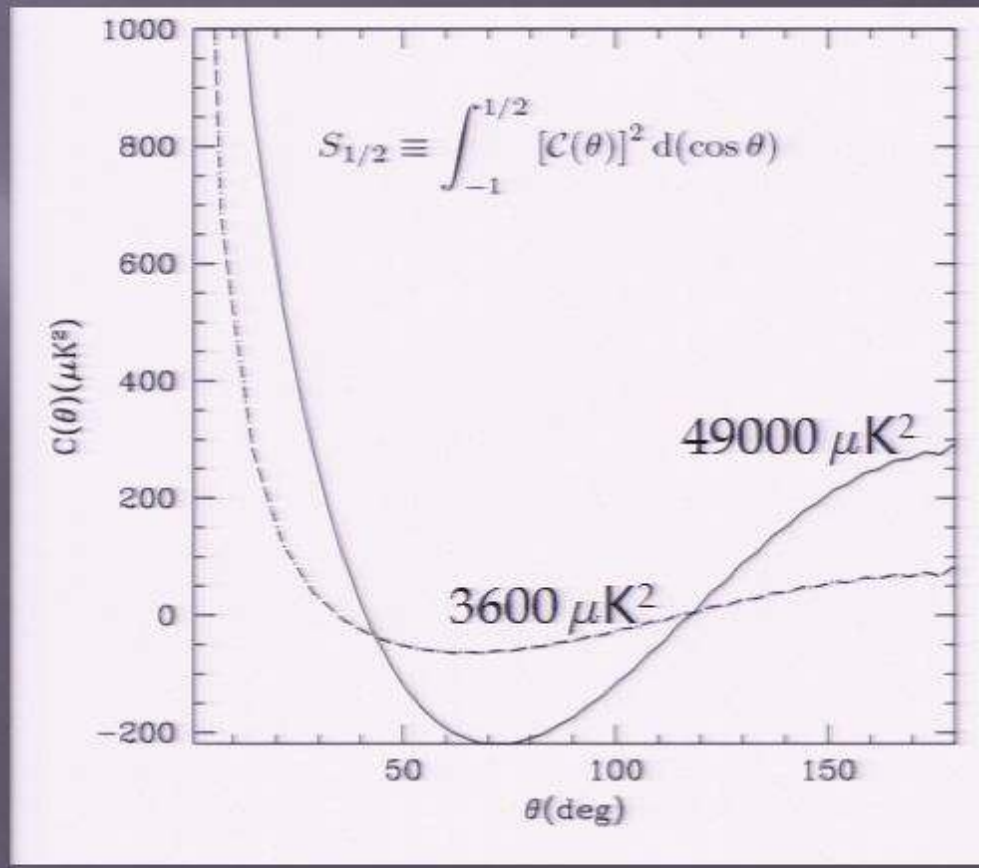

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ILC3 (full, DQ)	8413	4.9
V5 (KQ75)	1346	0.042
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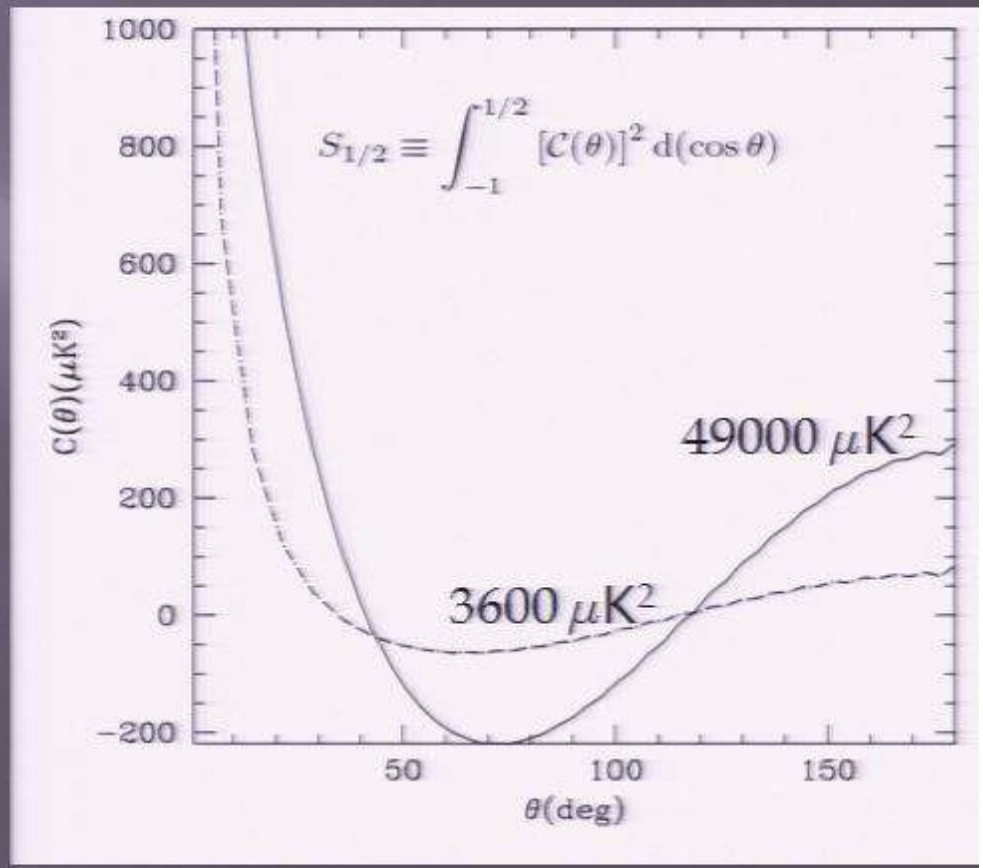

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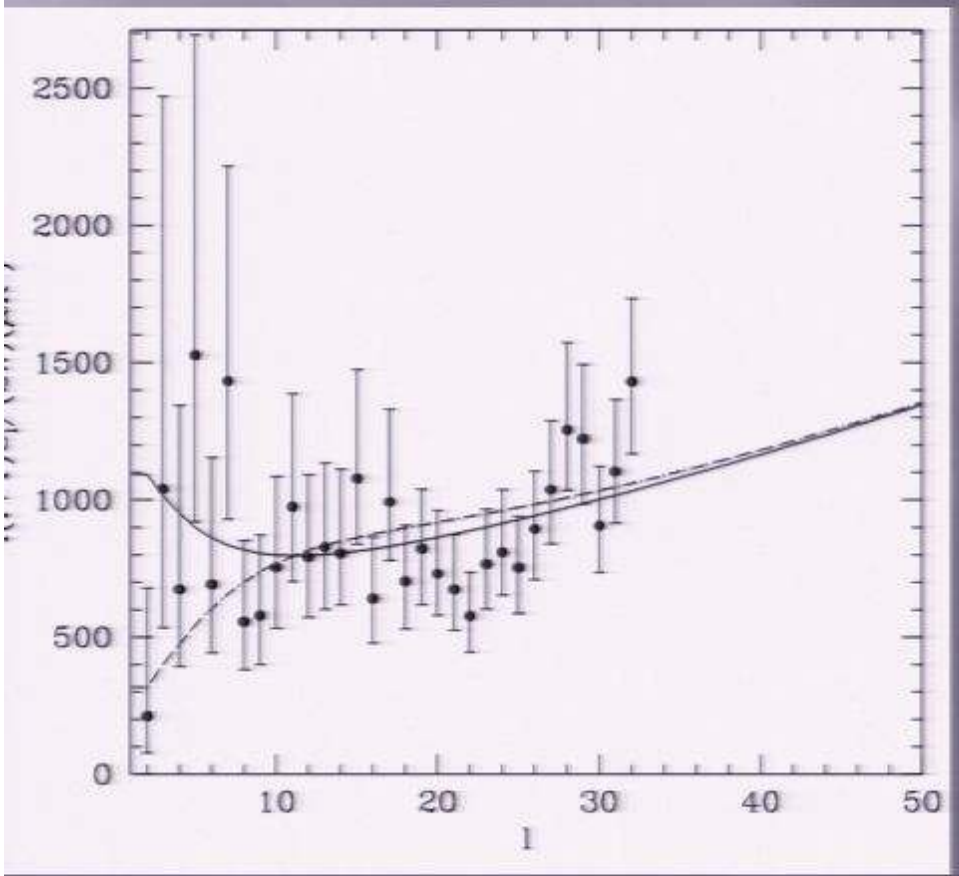

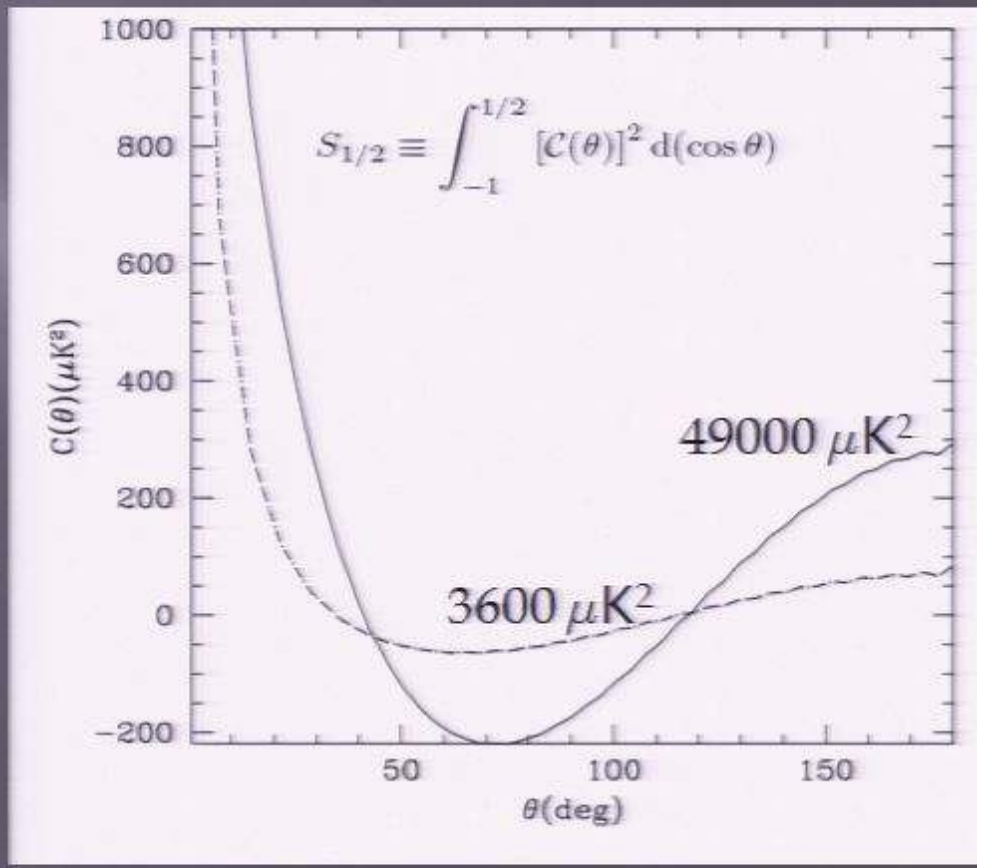

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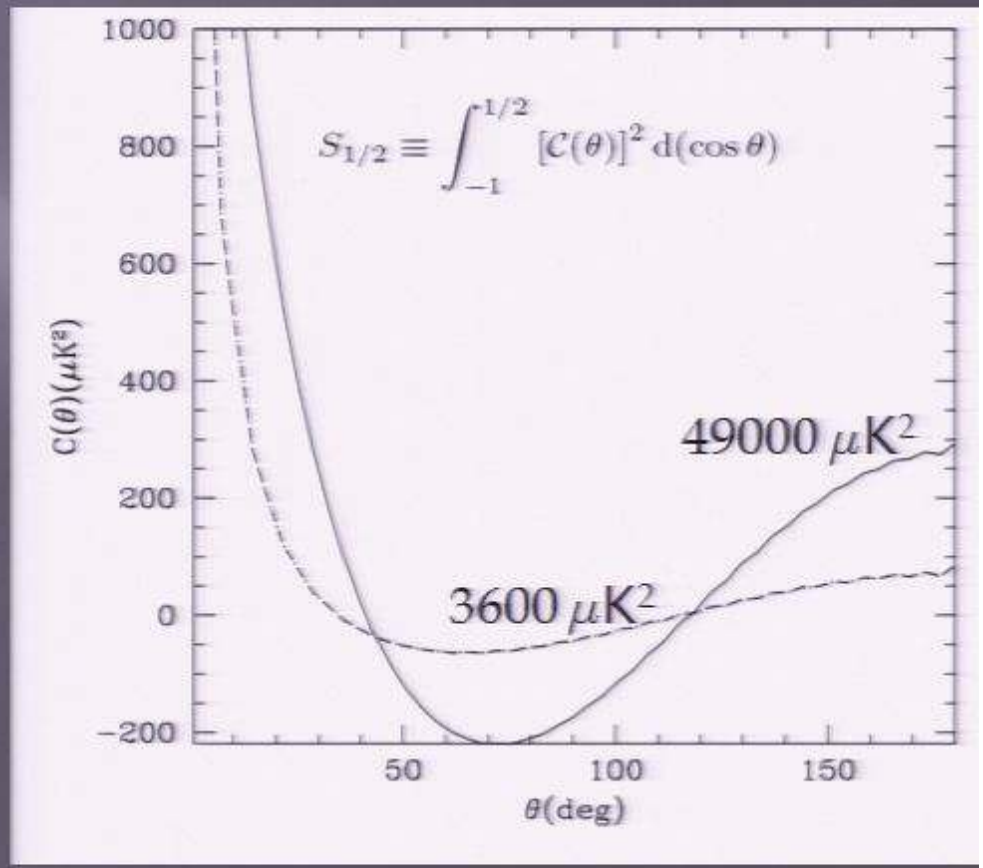

Potential Transfer Function in the matter era

- $z = 0.5$;
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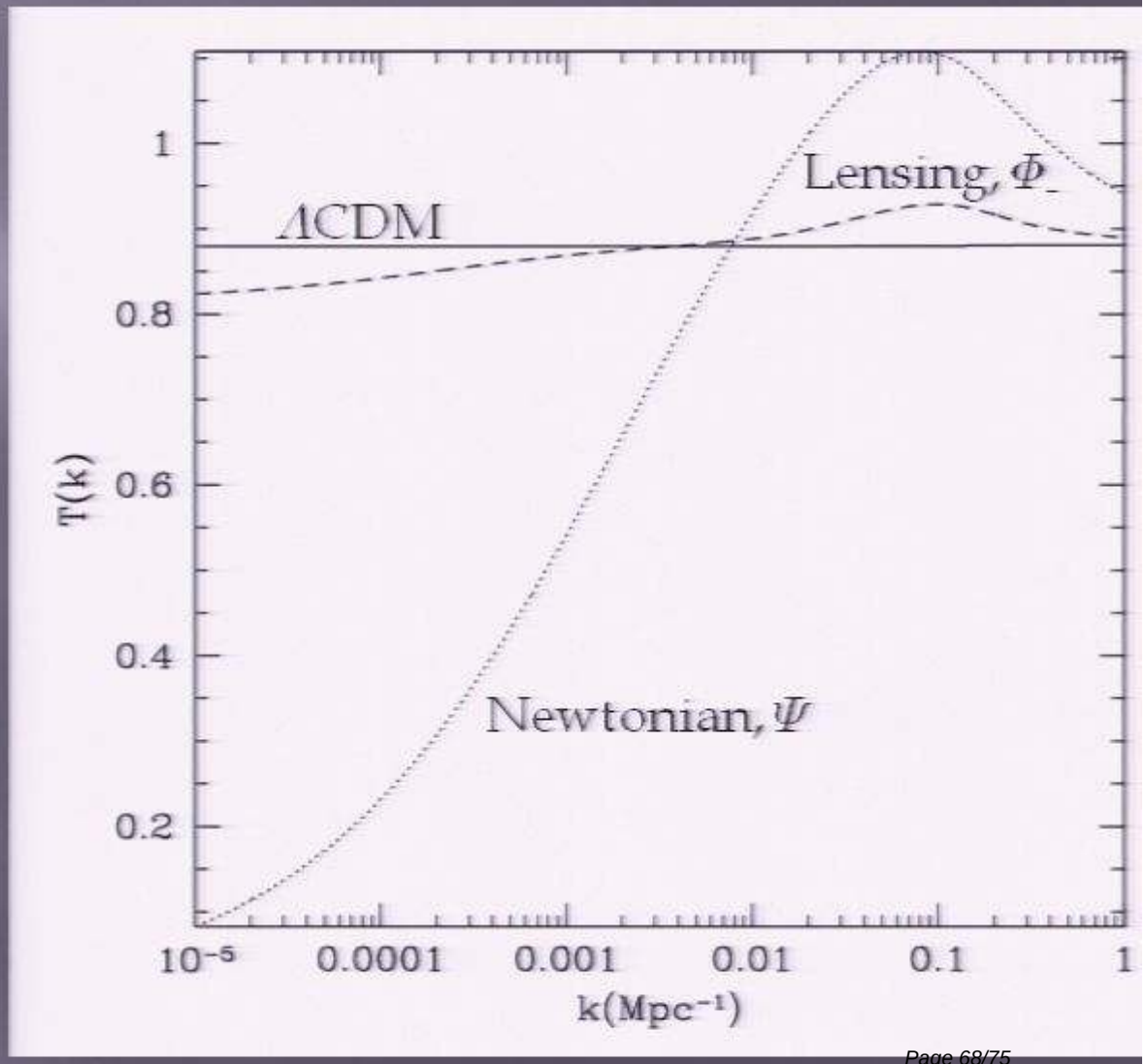

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- The model can roughly explain observations if the graviton Compton wavelength ~ 100 Mpc
- At our present level of understanding, the model is not uniquely fixed by either theory or observations

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