# Theoretical ***Challenges*** in the Post-Planck Era

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Bay Area Particle Theory Seminar

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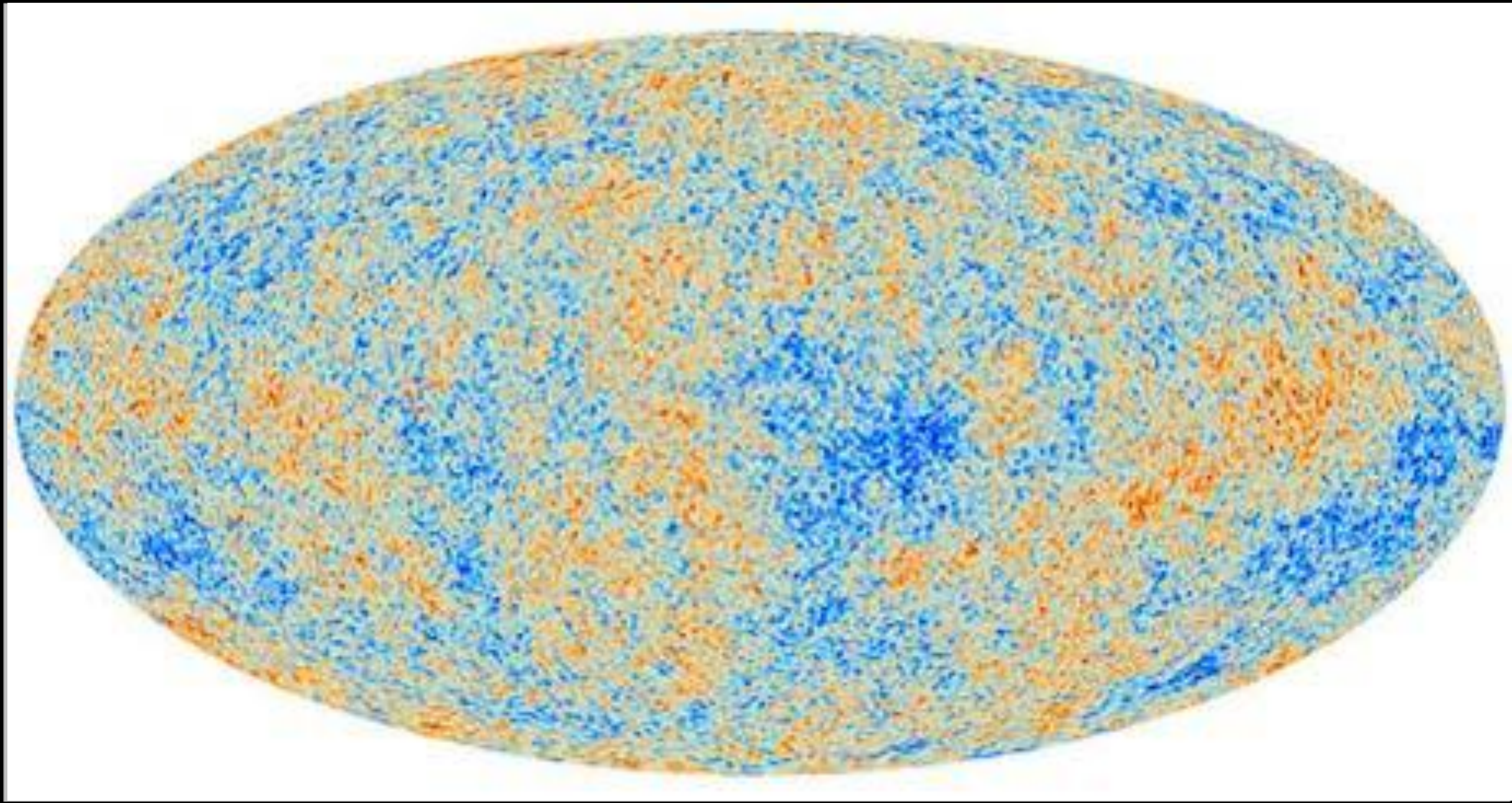
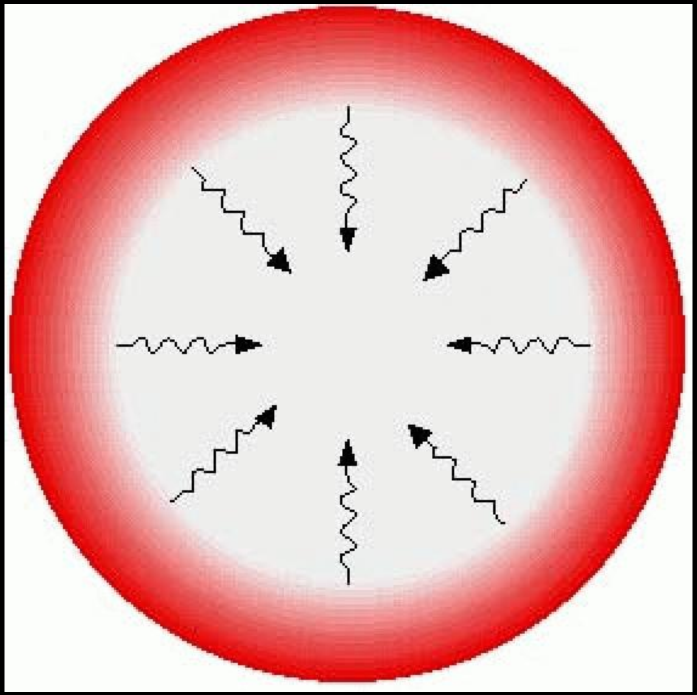
# Theoretical ***Challenges*** in the Post-Planck Era

- What are the pressing open problems in physics in lieu of the Planck results?
- Are we living in a boring Universe?
- I would like to challenge you to consider an unpopular idea designed to address one of these open problems
- Please challenge me if you think this idea is unpopular for a good reason!

# “What are we to make of the Planck results?” (MP)



# We see photons today from last scattering surface at z=1100



# Acoustic Oscillations

Pressure of radiation acts against clumping

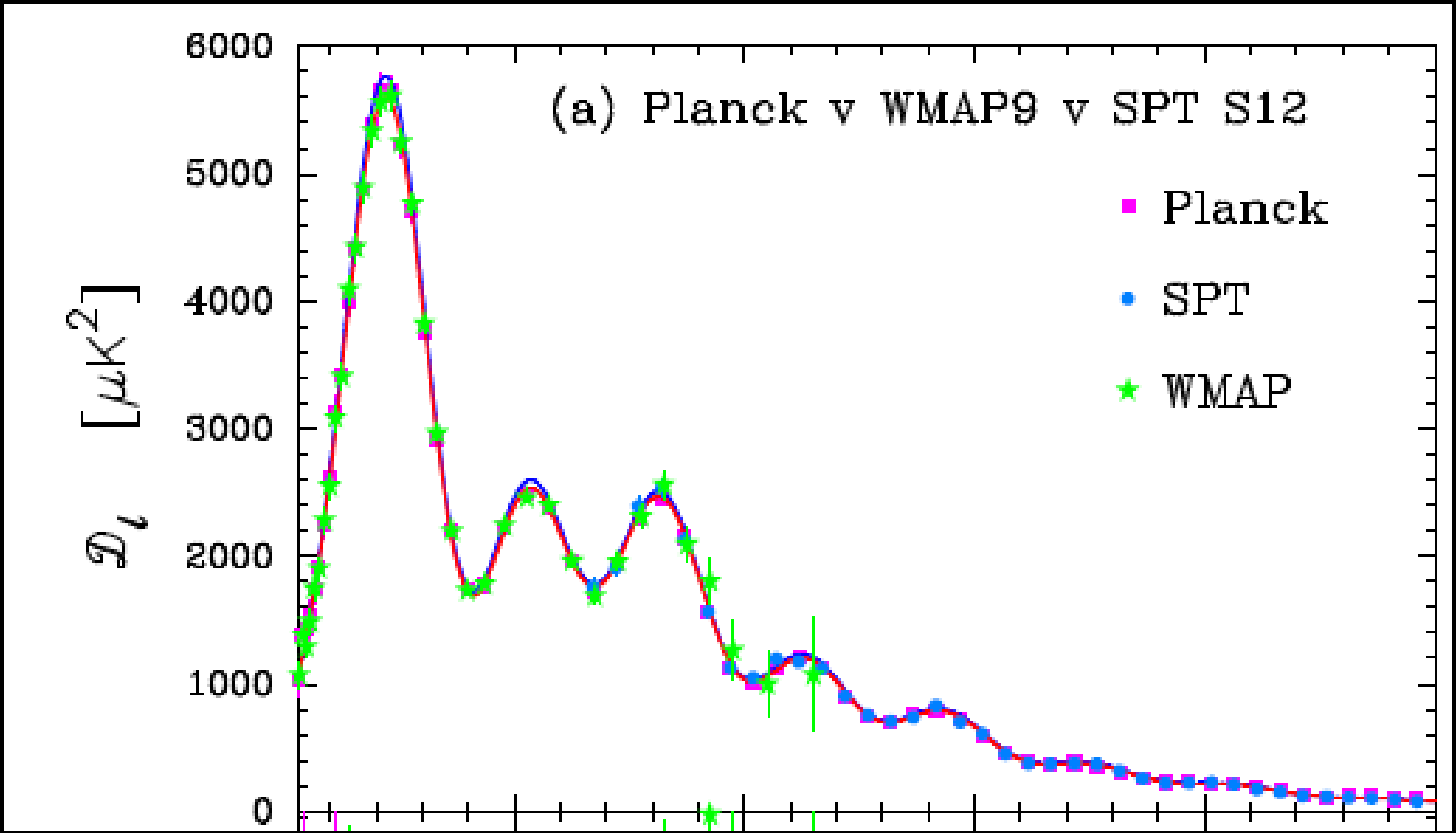
If a region gets overdense, pressure acts to reduce the density: **restoring force**

# A ns

Pressure of radiati g

If a region gets ove o reduce the density: **restoring f**

# Hence peaks and troughs in Spectrum: exactly like harmonics assicated with musical instruments



# CMB is different because …

- Fourier Transform of spatial, not temporal, signal

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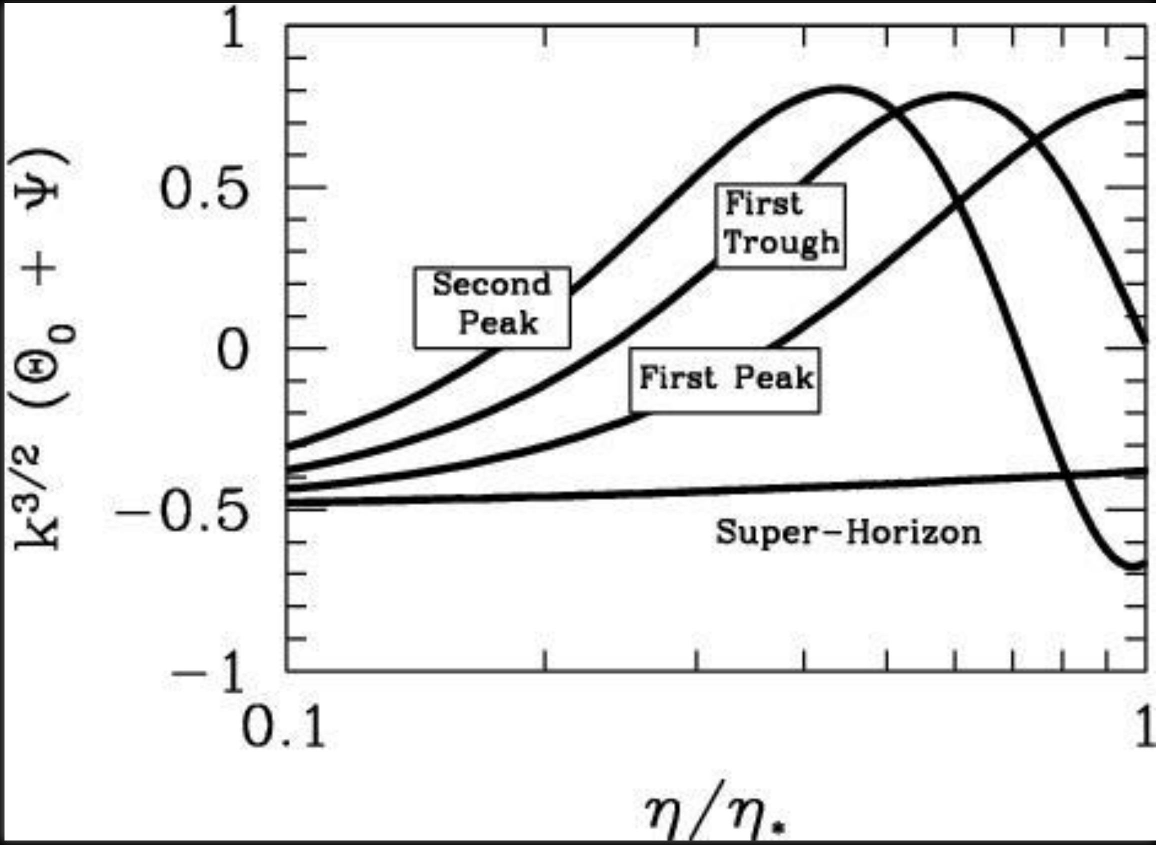
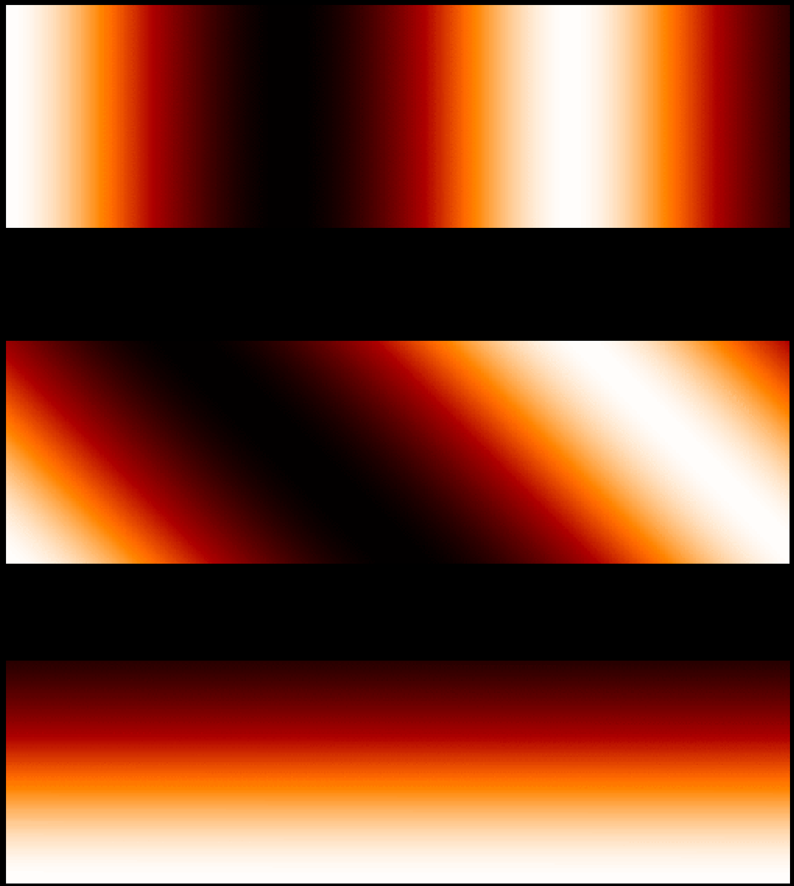
- Fourier Transform of spatial, not temporal, signal
- Time scale much longer (400,000 years vs. 1/1000 seconds)
- No finite length: all frequencies allowed!

# Why peaks and troughs?

- Vibrating String: Characteristic frequencies because ends are tied down
- Temperature in the Universe: Small scale modes enter the horizon earlier than large scale modes

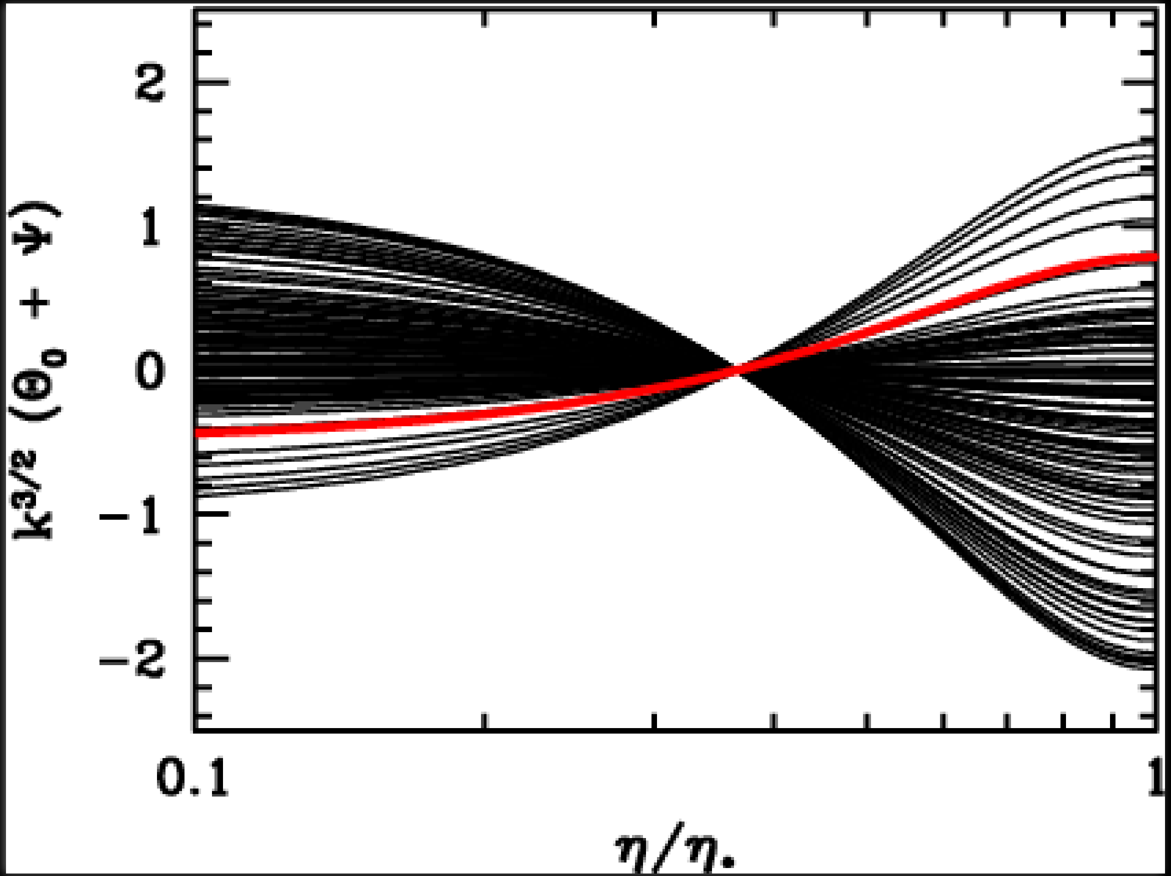


BUT: there are an infinite number of modes associated with a given wavelength. The CMB first peak, first example, comes from a sum over an infinite number of Fourier modes, each with a different orientation.



# Interference should destroy peak structure

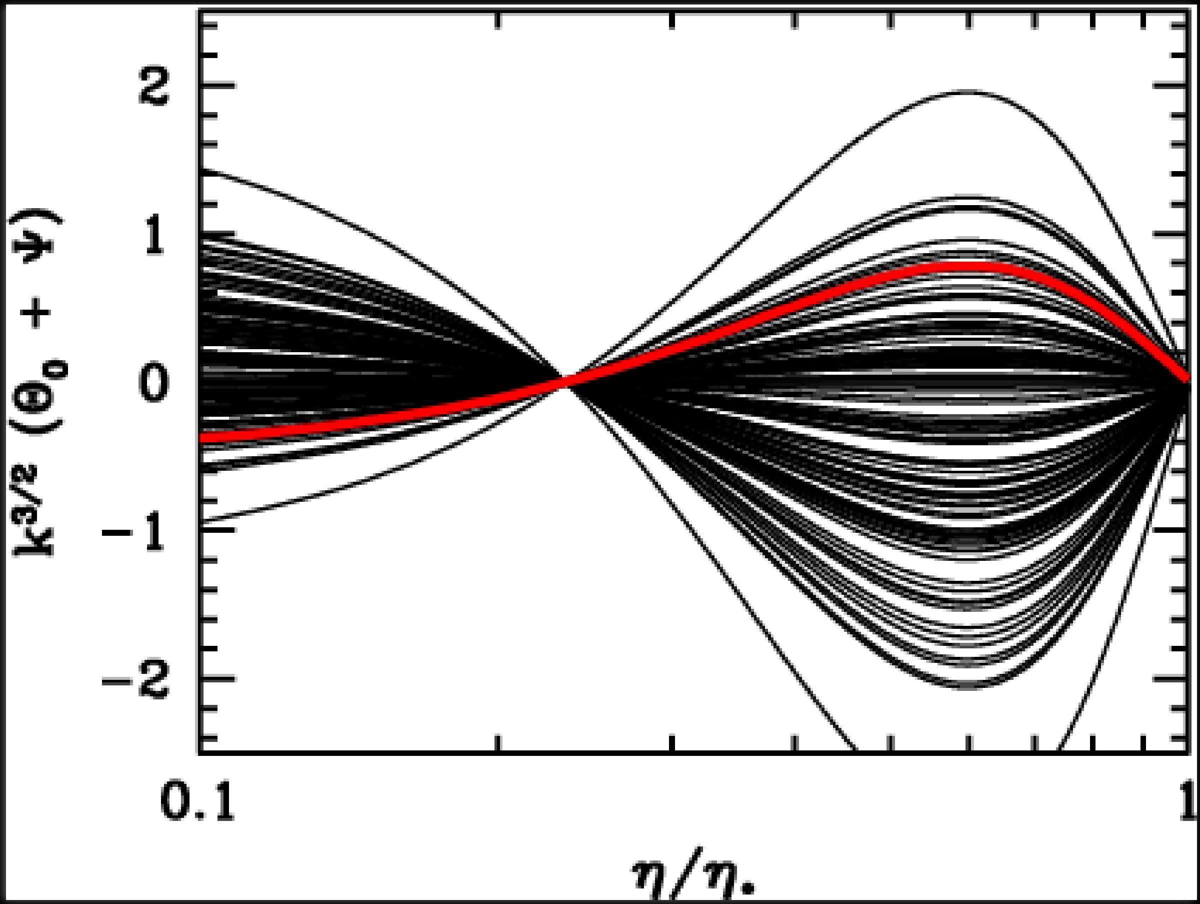
There are many, many modes with similar values of k. All have different initial amplitude. Why are all in phase?




First Peak Modes

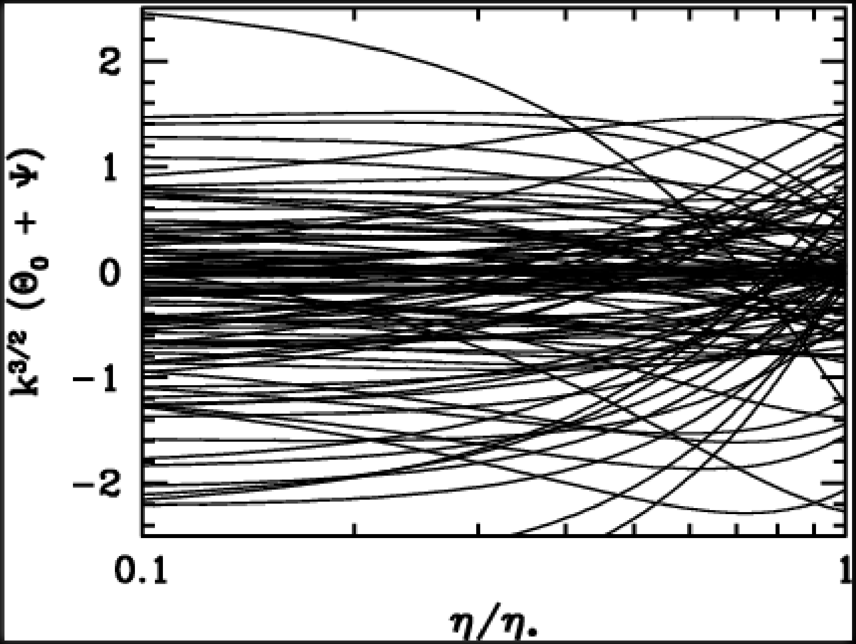
# An infinite number of violins are synchronized

Similarly, all modes corresponding to first trough are in phase: they all have zero amplitude at recombination. Why?

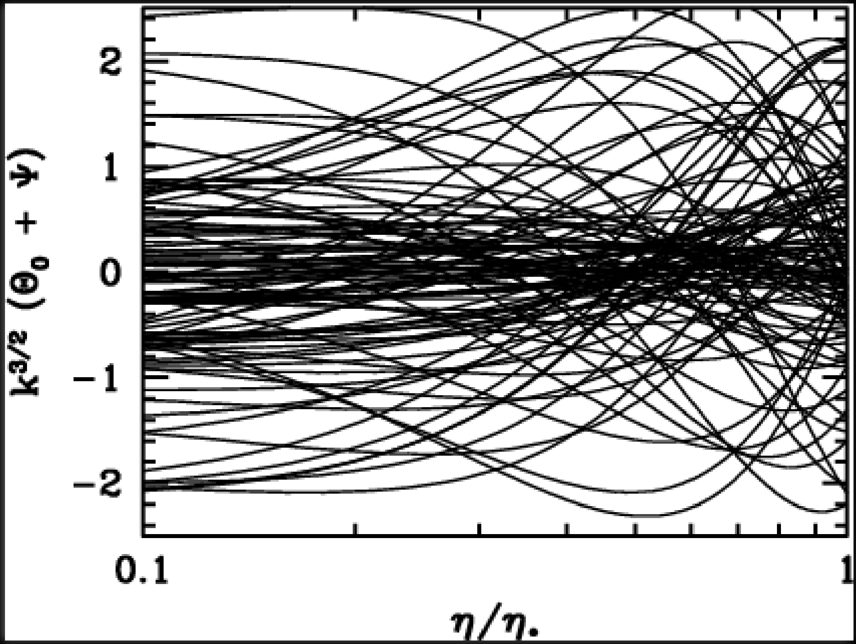


# Without synchronization:

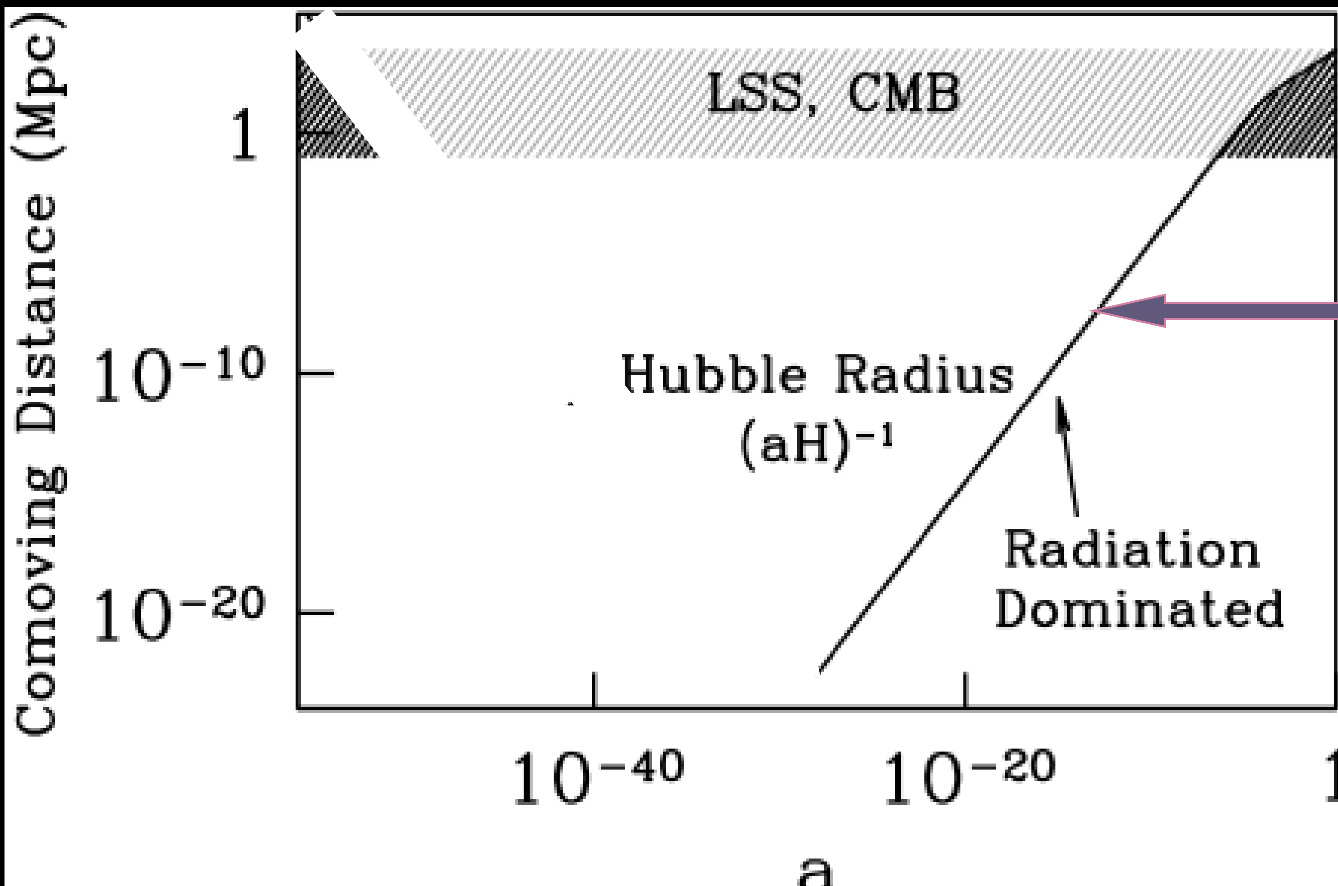
First "Peak"




First "Trough"

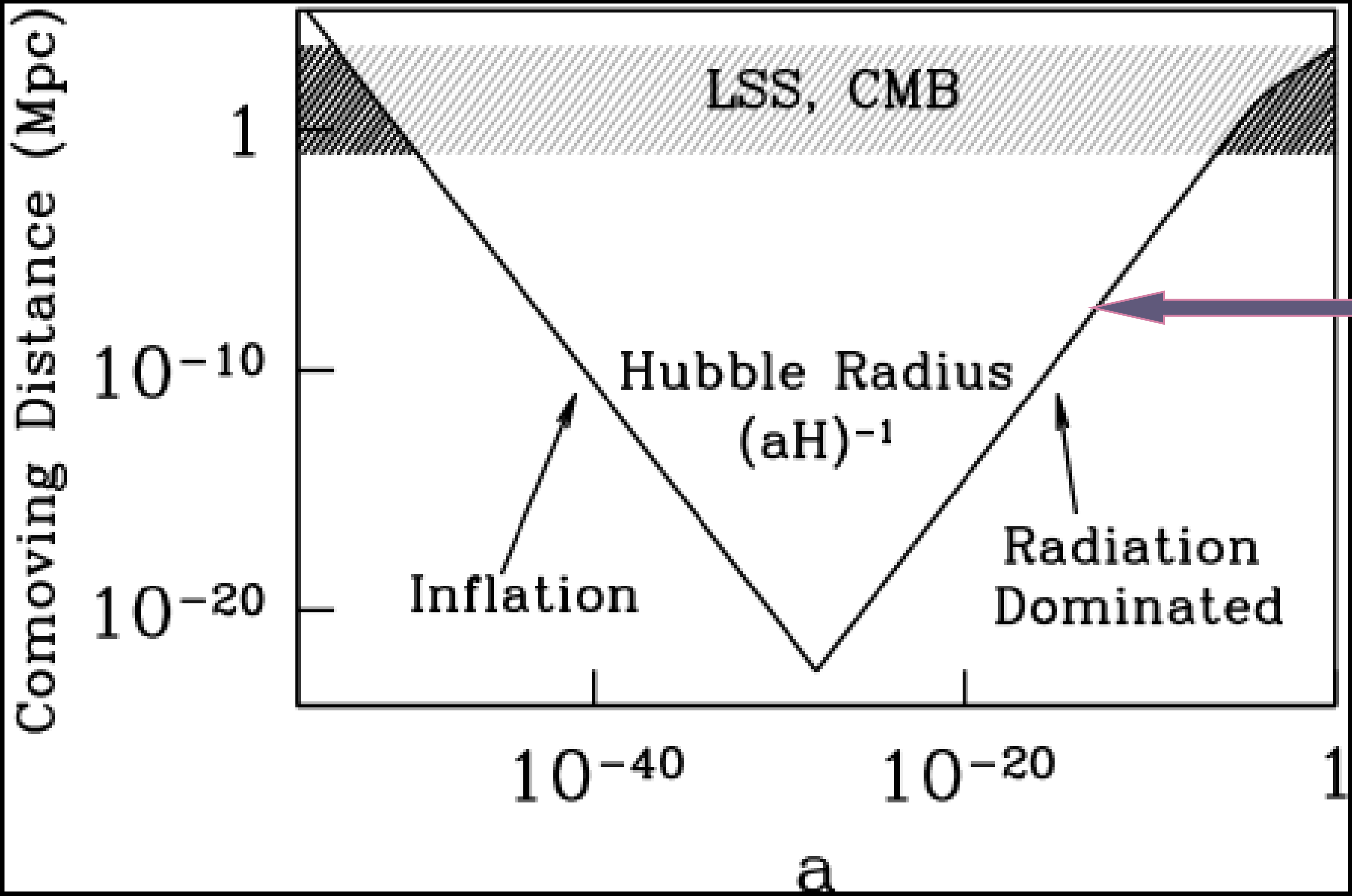


It is worse than this: The Hubble radius is the distance over which information can propagate causally at a given epoch




Perturbations *outside the horizon*

# Inflation is an epoch during which the comoving Hubble radius decreases: perturbations were synchronized before/during inflation

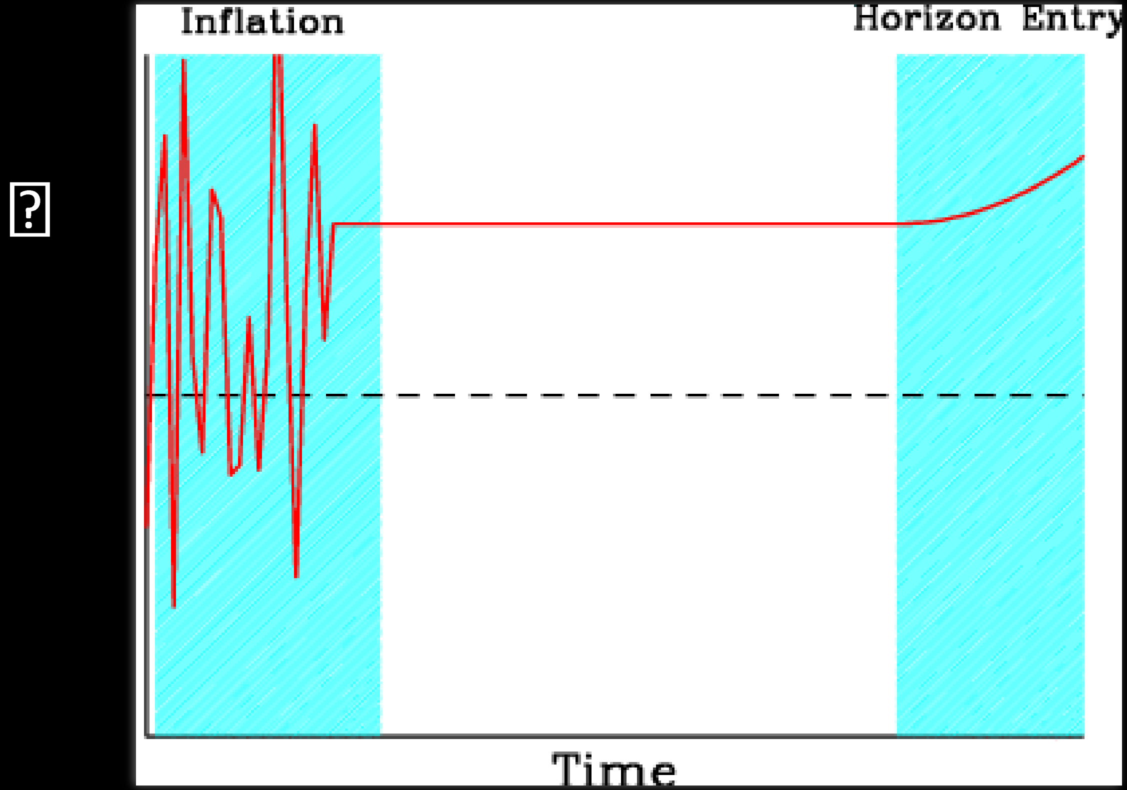



Perturbations *outside the horizon*

# Inflation produces perturbations

- Quantum mechanical fluctuations
  $\langle \Psi(\mathbf{k})\, \Psi(\mathbf{k}') \rangle = (2\pi)^3 \delta^3(\mathbf{k}+\mathbf{k}')\, P_\Psi(\mathbf{k})$
- Inflation stretches wavelength beyond horizon: $\Psi(\mathbf{k},t)$ becomes constant
- Infinite number of independent perturbations w/ independent amplitudes

# Inflation synchronizes all modes




All modes remain constant until they re-enter horizon.

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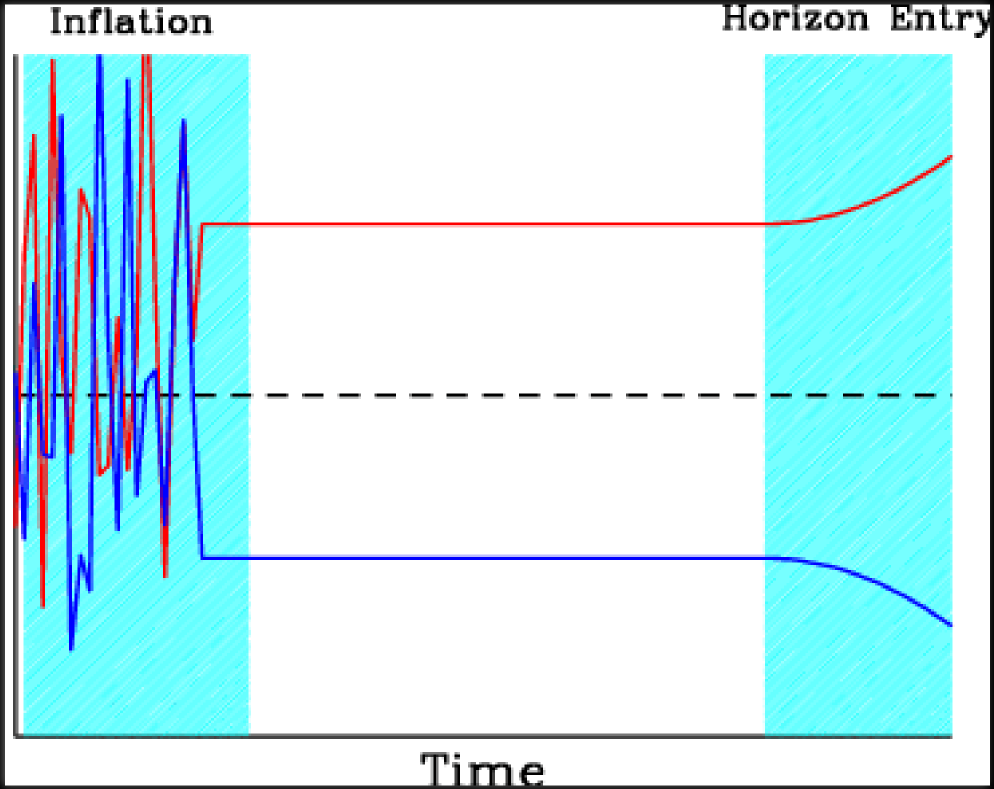
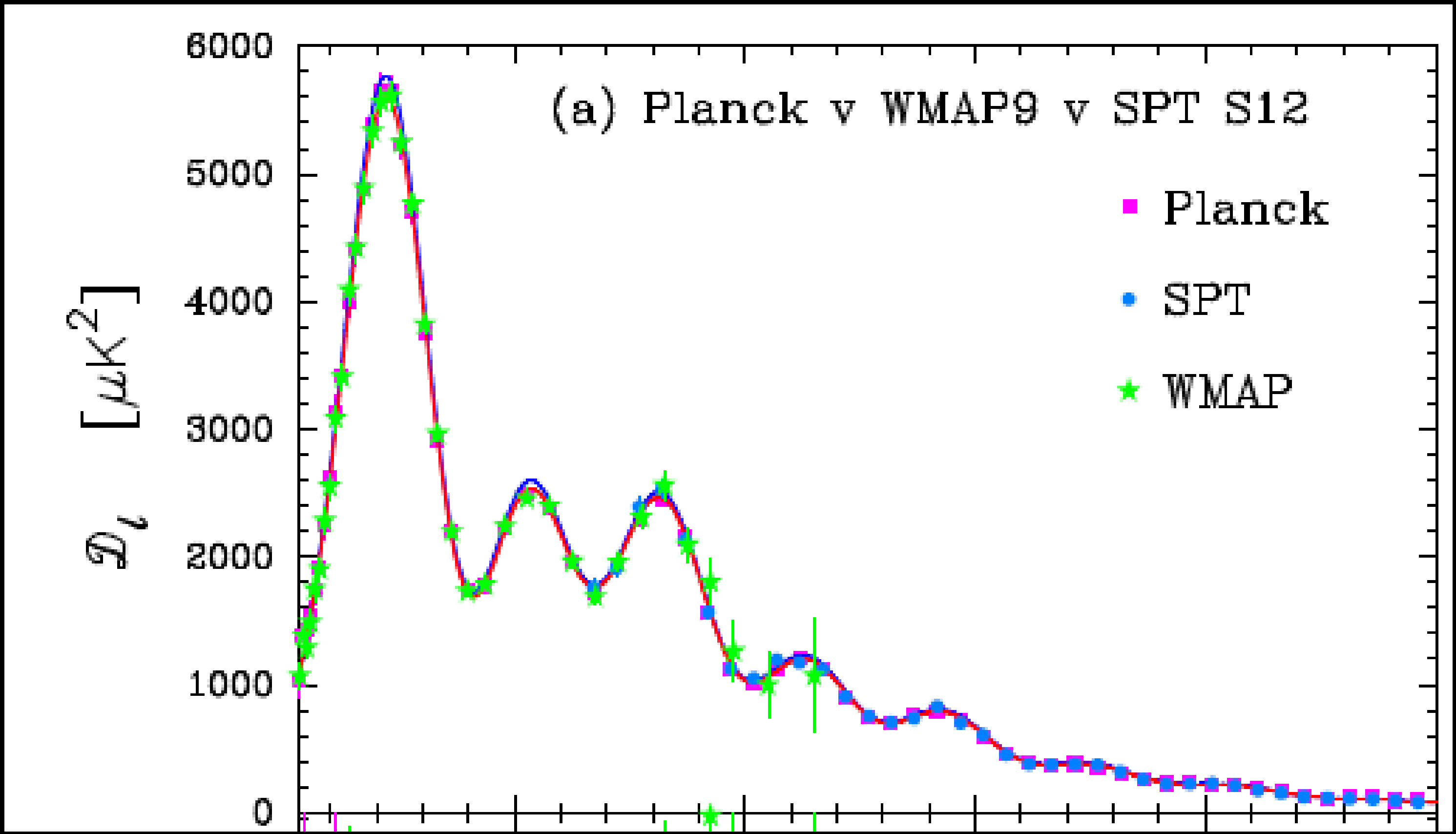



All modes remain constant until they re-enter horizon.

# Coherence of Peaks and Troughs Strong Evidence for Inflation (or something even crazier)



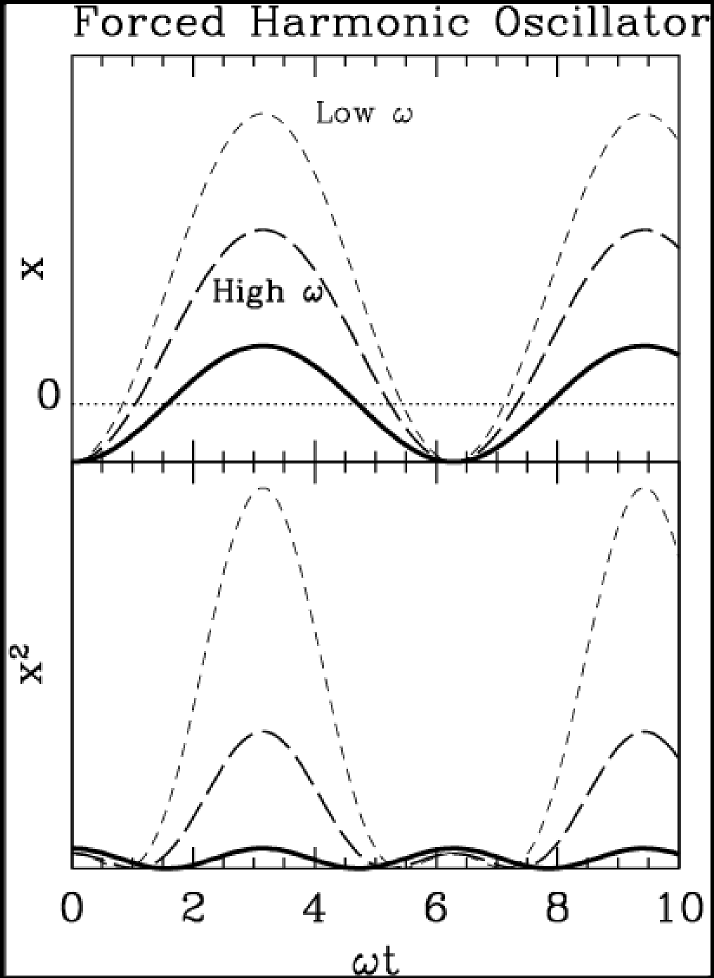
# Harmonics carry information about the "instrument"

$$\ddot{x} + w^2 x = F$$

with frequency inversely proportional to baryon density

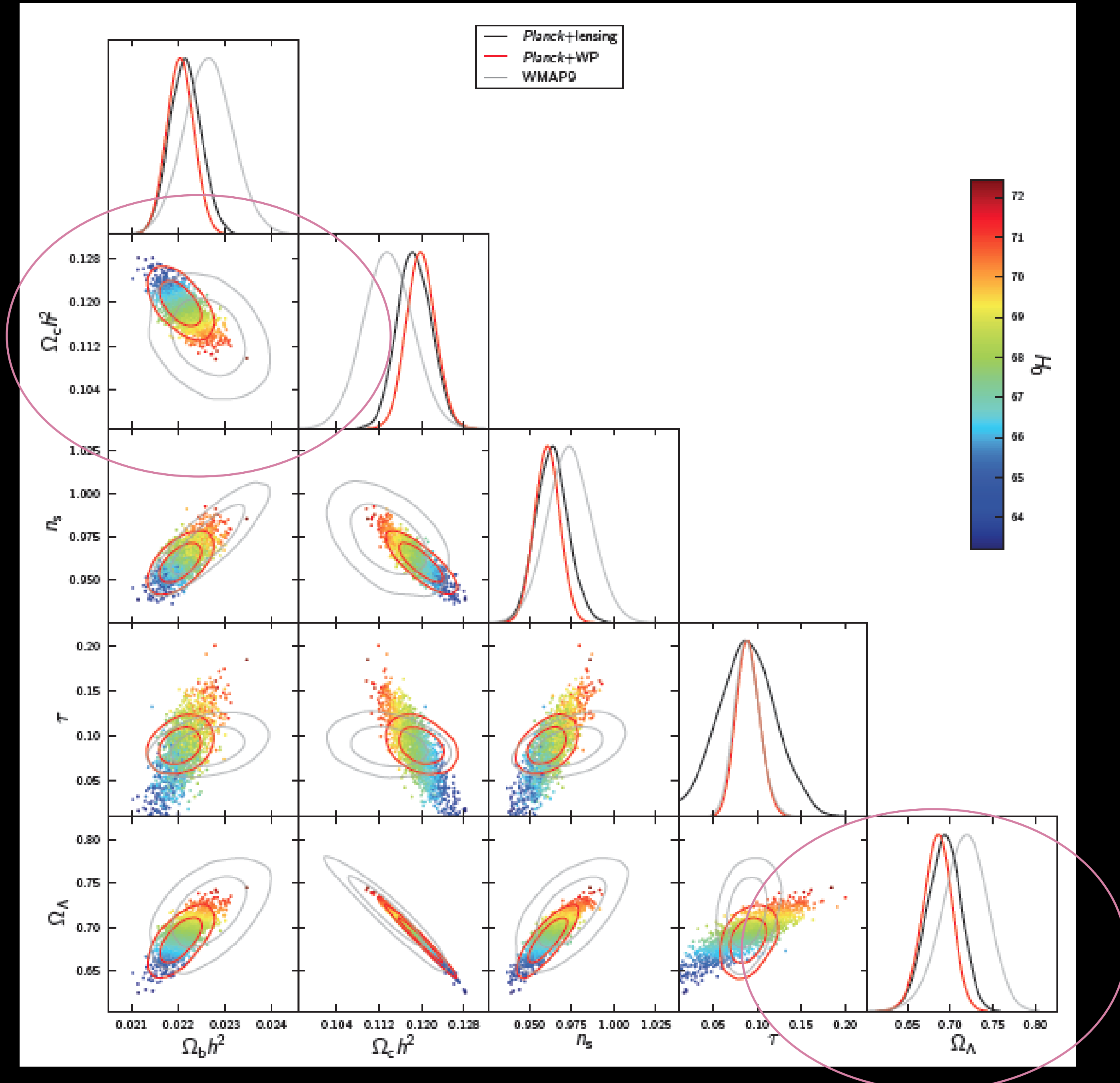
$$\omega = kc_s = \frac{k}{\sqrt{3(1+3\rho_b/4\rho_\gamma)}}$$

Higher ω (e.g. fewer baryons) -> no odd/even peak disparity.



Robust evidence for non-baryonic dark matter

Independent evidence for dark energy



# Challenge: What is this new physics?

- ***Non-Baryonic Dark Matter***: Popular framework with many free parameters. If detected, lots of stuff to do. If not, when do we give up on SUSY and WIMP's? What replaces them?
- ***Inflation:*** Handful of models have risen to prominence. Disappointment that PNG is not large. Wait for B-modes. Then what?
- ***Dark Energy***

# Modified Gravity to explain Accelerating Universe

Can explain acceleration without dark energy (w) by modifying GR:

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\left[R + f(R)\right] + \int d^4x\sqrt{-g}\,L_m$$

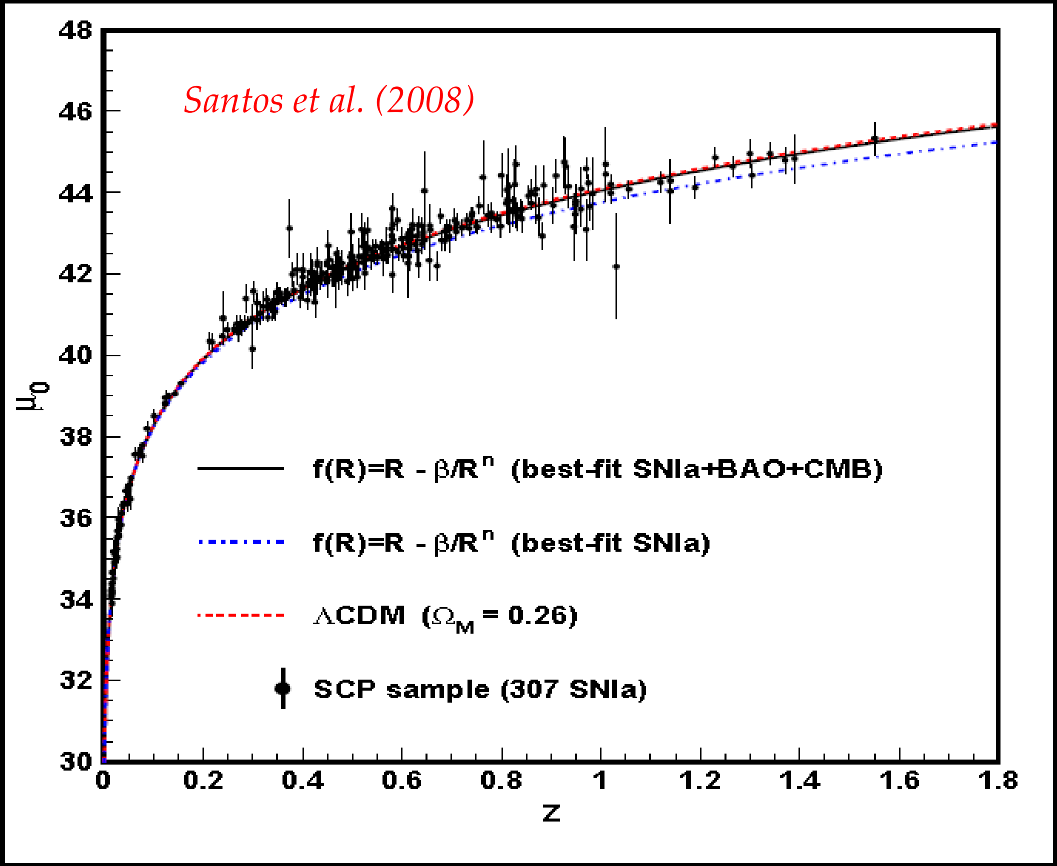
For the cosmological metric, the acceleration equation generalizes to:

Get acceleration if these terms are positive

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + 3P\right) + \left[\frac{\partial f}{\partial R}H^2 - \frac{f}{6} - \frac{\partial \ddot{f}/\partial R}{2}\right]$$

# Easy to fit Supernova Data

More generally, MG models can fit any redshift-distance relation measured by SN and other cosmological probes




f(R) has dimensionful parameter order $10^{-33}$ eV

# Scalar Tensor Models

- *f(R)* models are a subset of *scalar-tensor* models
- Challenge the implicit assumption of General Relativity that the metric in the Einstein-Hilbert action is the same as the metric that couples to matter

$$S_{EH} = \frac{1}{16\pi G}\int d^4x\sqrt{-\tilde{g}}\,R[\tilde{g}] \qquad S_m = \int d^4x\sqrt{-g}\,L_m$$

- Allow $\tilde{g} = e^{-2\varphi/m_P}\,g$
- Scalar-Tensor model is defined by dynamics *S[Φ]*, related to *f(R)*
- Extra degree of freedom can cause problems in Solar System: require *screening* mechanism to suppress in high-density/small scale regions

# Massive graviton

- Fierz & Pauli (1939) first inroduced massive graviton; recent interest as cause of acceleration
- Two new degrees of freedom <-> Two problems:
  - Solar System constraints
  - Ghosts (negative kinetic energy term leads to instabilities)
- Nonlinear Fierz-Pauli action produces a screening mechanism
- Subset of nonlinear terms in Fierz-Pauli action ghost-free: *Galileons*

# Distinguishing General Relativity + Dark Energy from Modified Gravity

- Fix expansion history in both models (Zero order cosmology)
- Compare how structure in the universe grows (Perturbations)

# Perturbations in Modified Gravity

*Lue, Scoccimarro, and Starkman (2004); Bertschinger (2006); Hu & Sawicki (2007)*

Start with the perturbed FRW metric

$$ds^2 = -(1+2\Psi)dt^2 + a^2(t)(1-2\Phi)\left(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right)$$

Generally two differences between MG and GR:

| GENERAL RELATIVITY | MODIFIED GRAVITY |
| --- | --- |
| $\Phi - \Psi = 0$ | $\Phi - \Psi \neq 0$ |
| $\nabla^2\Phi = -4\pi G\rho_m a^2\delta$ | $\nabla^2\Phi = -4\pi G_{eff}\rho_m a^2\delta$ |

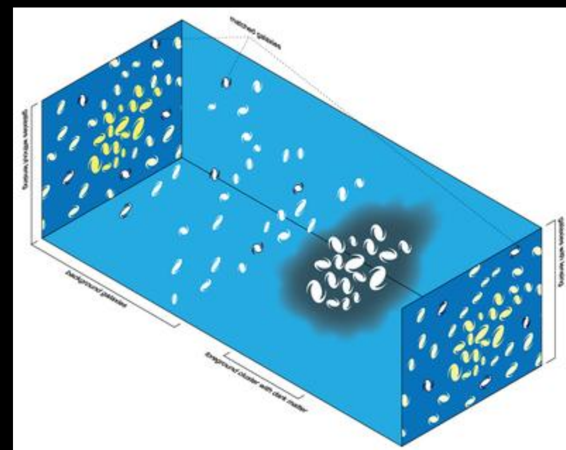
# Deviations from GR

Closer to observations to define:

$$\Psi \equiv [1 + \mu(k,a)]\,\Psi_{GR}$$
$$\Psi - \Phi = [1 + \Sigma(k,a)]\,[\Psi_{GR} - \Phi_{GR}]$$

Massive particles respond to μ, while massless particles (photons) respond to Σ

# Deviations from GR



Lensing can measure Σ

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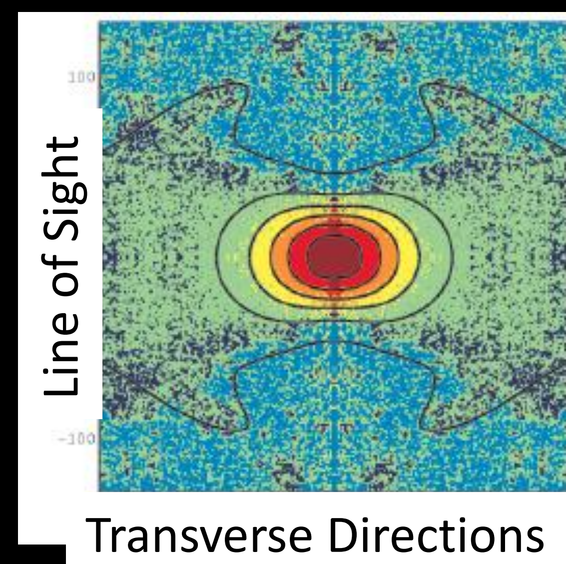
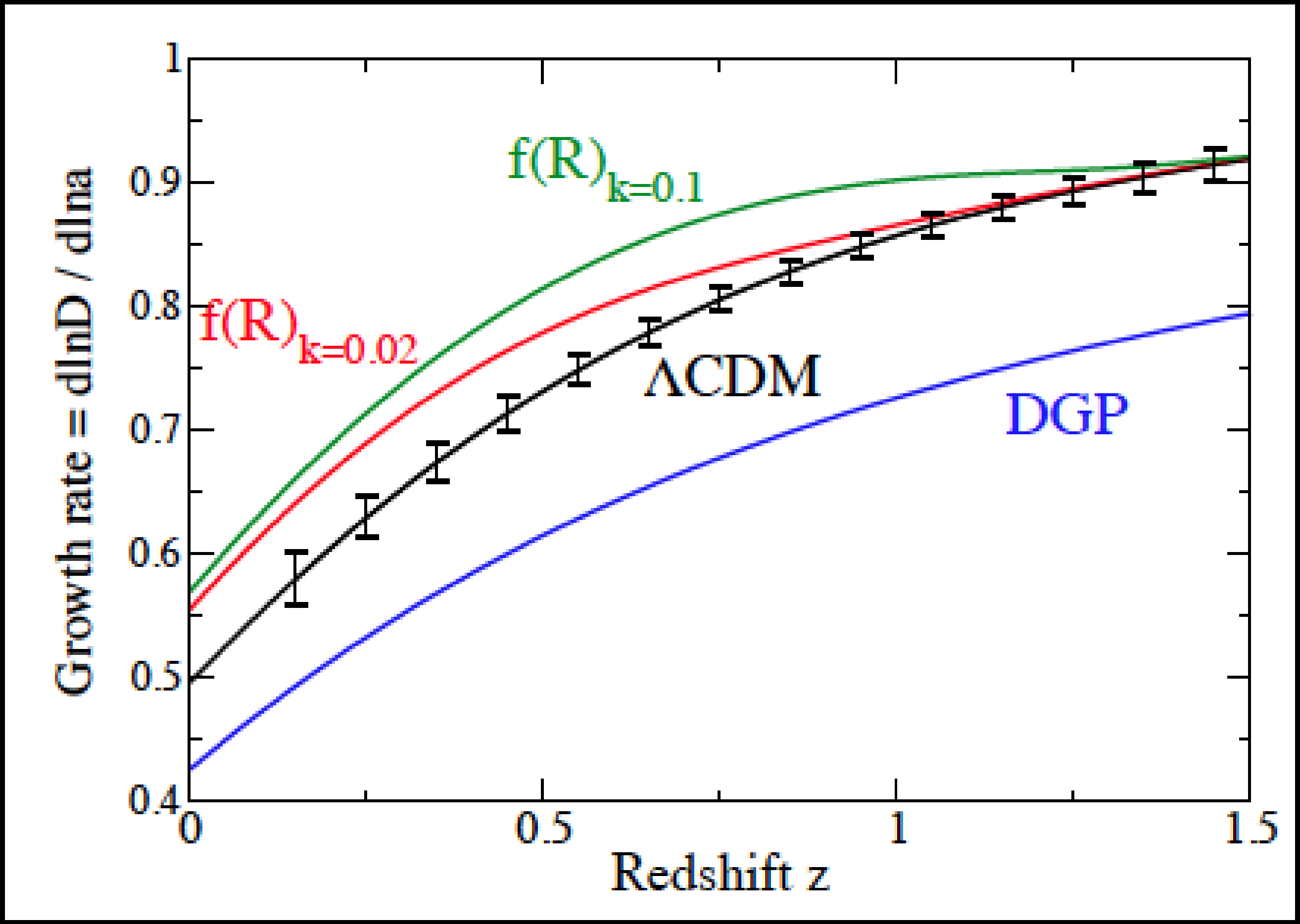
Redshift Space Distortions sensitive to  to μ

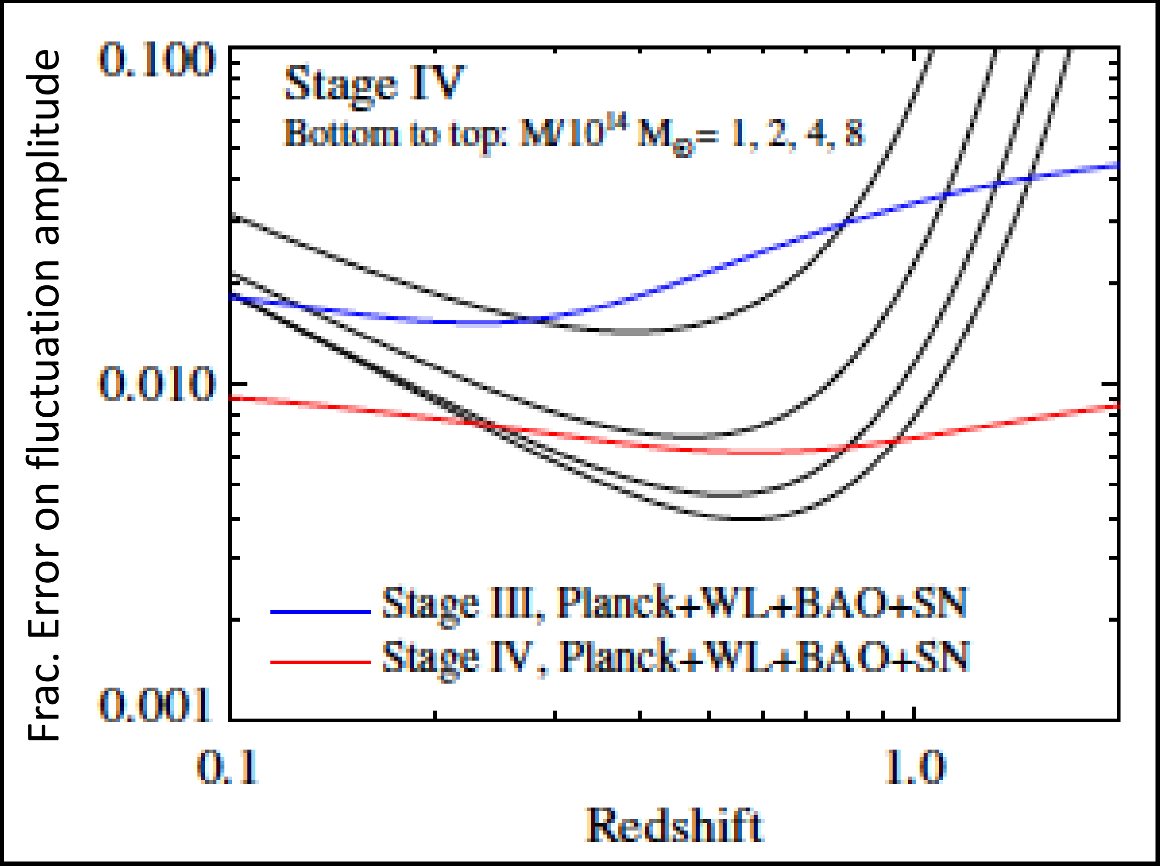


# Projected constraints from RSD




Huterer et al. 2013

# Projected Constraints from Lensing




Huterer et al. 2013

# Example: Nonlocal Gravity

(Deser and Woodard 2007)

$$\mathcal{L}_g = \frac{1}{16\pi G}\sqrt{-g}R\left[1 + f\left(\frac{1}{\Box}R\right)\right]$$

- Argument of *f* is dimensionless: no new parameters (almost all DE/MG models have a mass parameter of order $10^{-33}$ eV)
- Deviations occur only at late times, logarithmically growing from the epoch of equality
- Easy to evade Solar System constraints
- Terms like this generated by quantum corrections in string theory away from critical dimension (Polyakov 1981). Banks (1988) has more general arguments
- Free function *f* can be chosen to fit any expansion history

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- Free function *f*

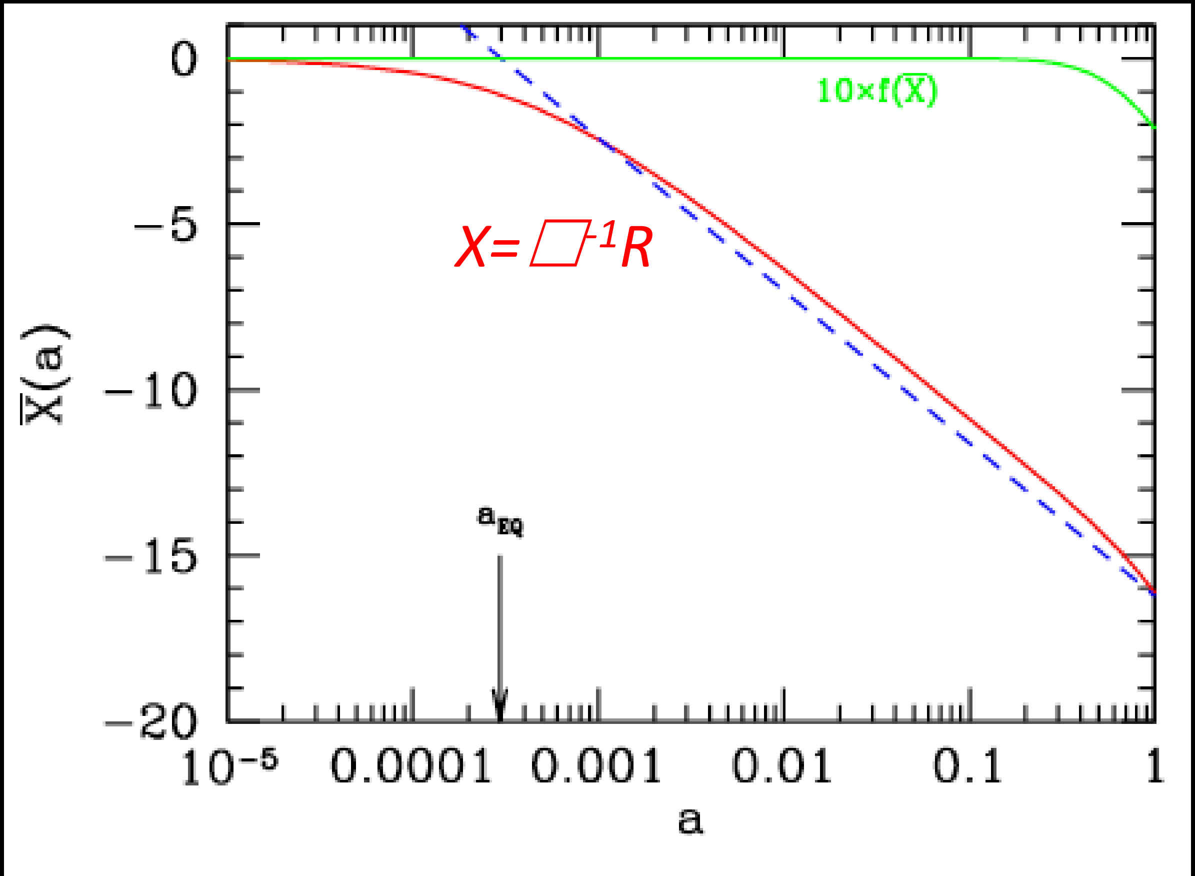
# Nonlocal Gravity

Leads to new terms in Einstein's equation

$$\Delta G_{\mu\nu} = \Big[G_{\mu\nu} + g_{\mu\nu}\Box - D_\mu D_\nu\Big]\left\{f(X) + \frac{1}{\Box}\Big[R f'(X)\Big]\right\}$$
$$+ \Big[\delta_\mu^{(\rho}\delta_\nu^{\sigma)} - \frac{1}{2}g_{\mu\nu}g^{\rho\sigma}\Big]\partial_\rho\Big(X\Big)\partial_\sigma\left(\frac{1}{\Box}\Big[R f'\Big(X\Big)\Big]\right) .$$

# Nonlocal Gravity

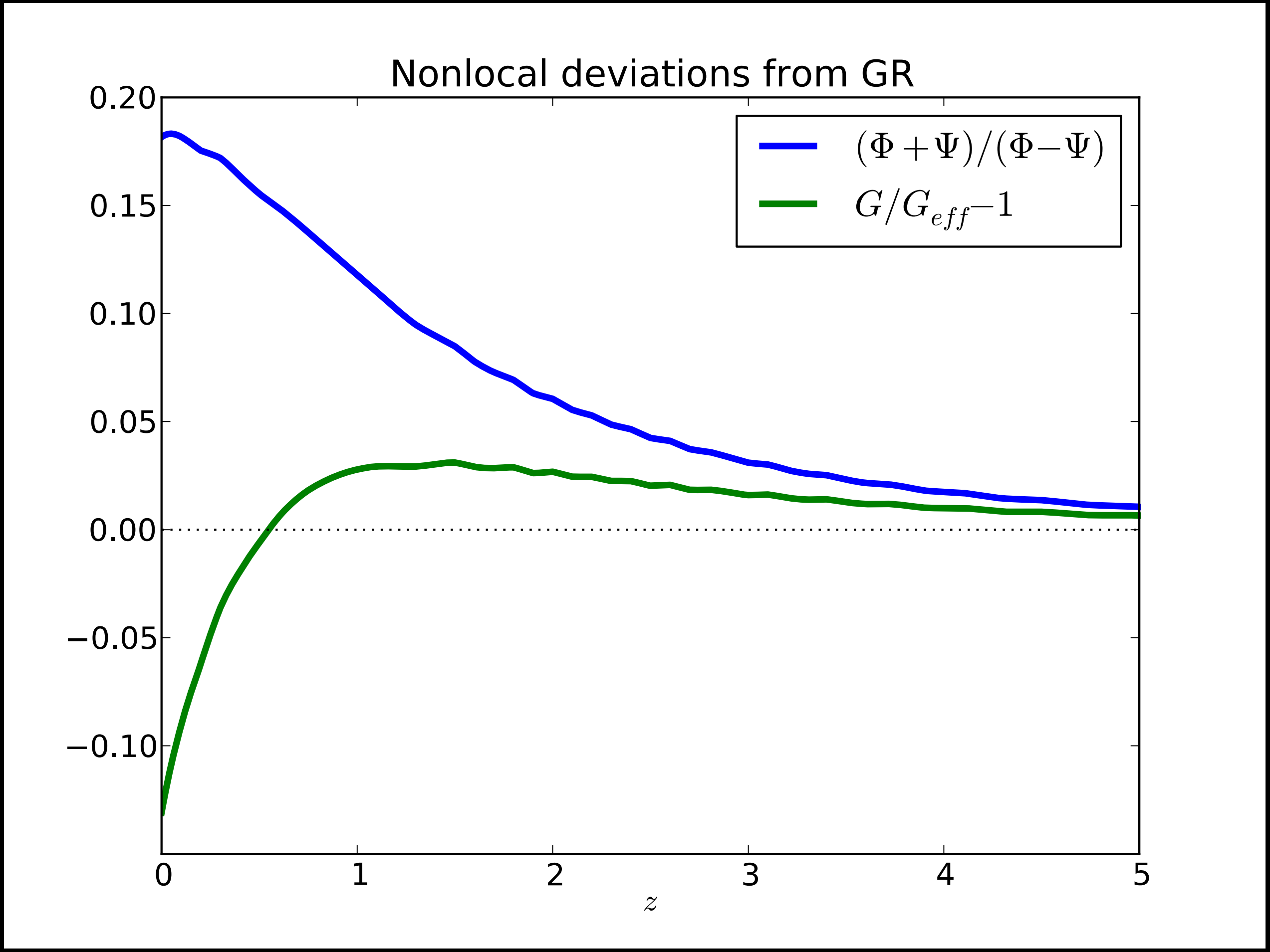
- Solve the new equations in homogeneous cosmology
- Fix free function by matching observed redshift-distance relation (Deffayet & Woodard 2009)



# Nonlocal Gravity: Perturbations

**(Park & Dodelson 2012; Dodelson & Park 2013)**

Gravitational force is weaker at early times but then grows stronger



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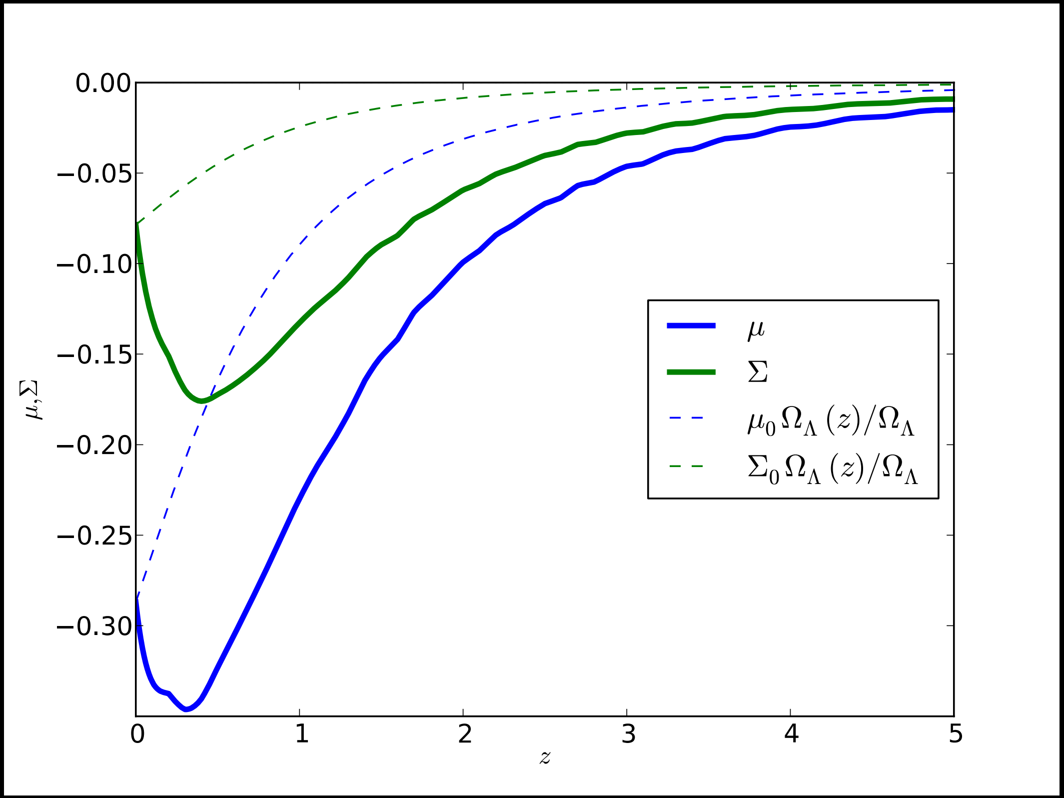
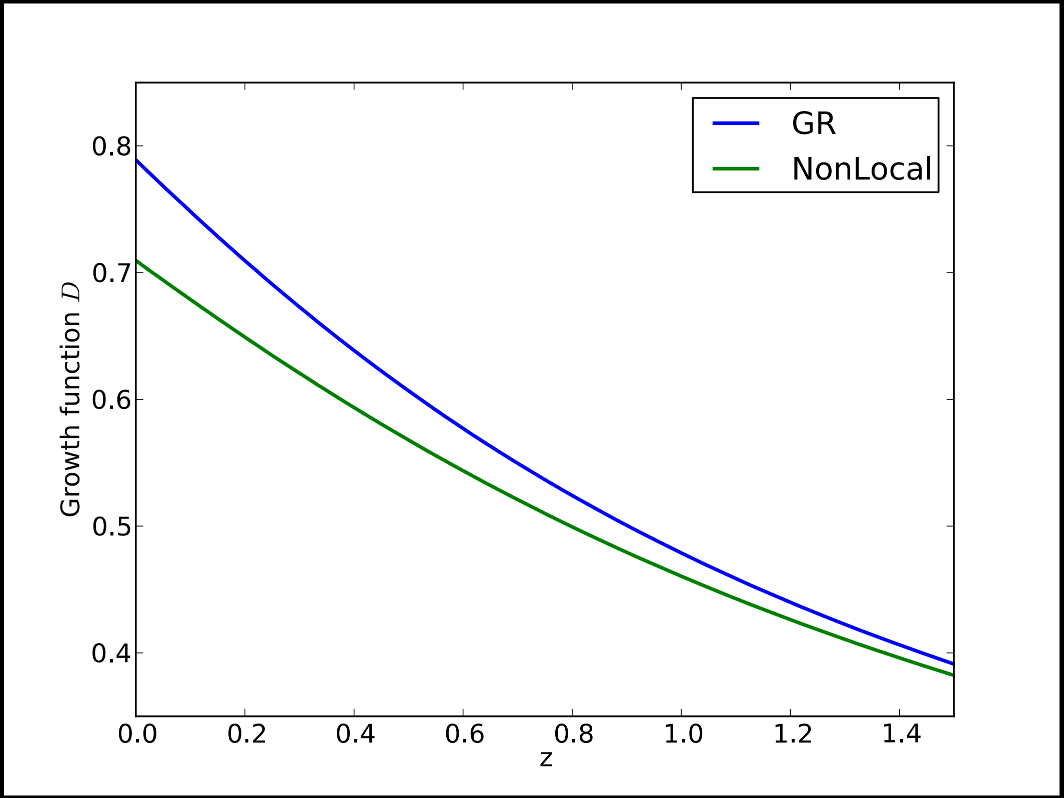


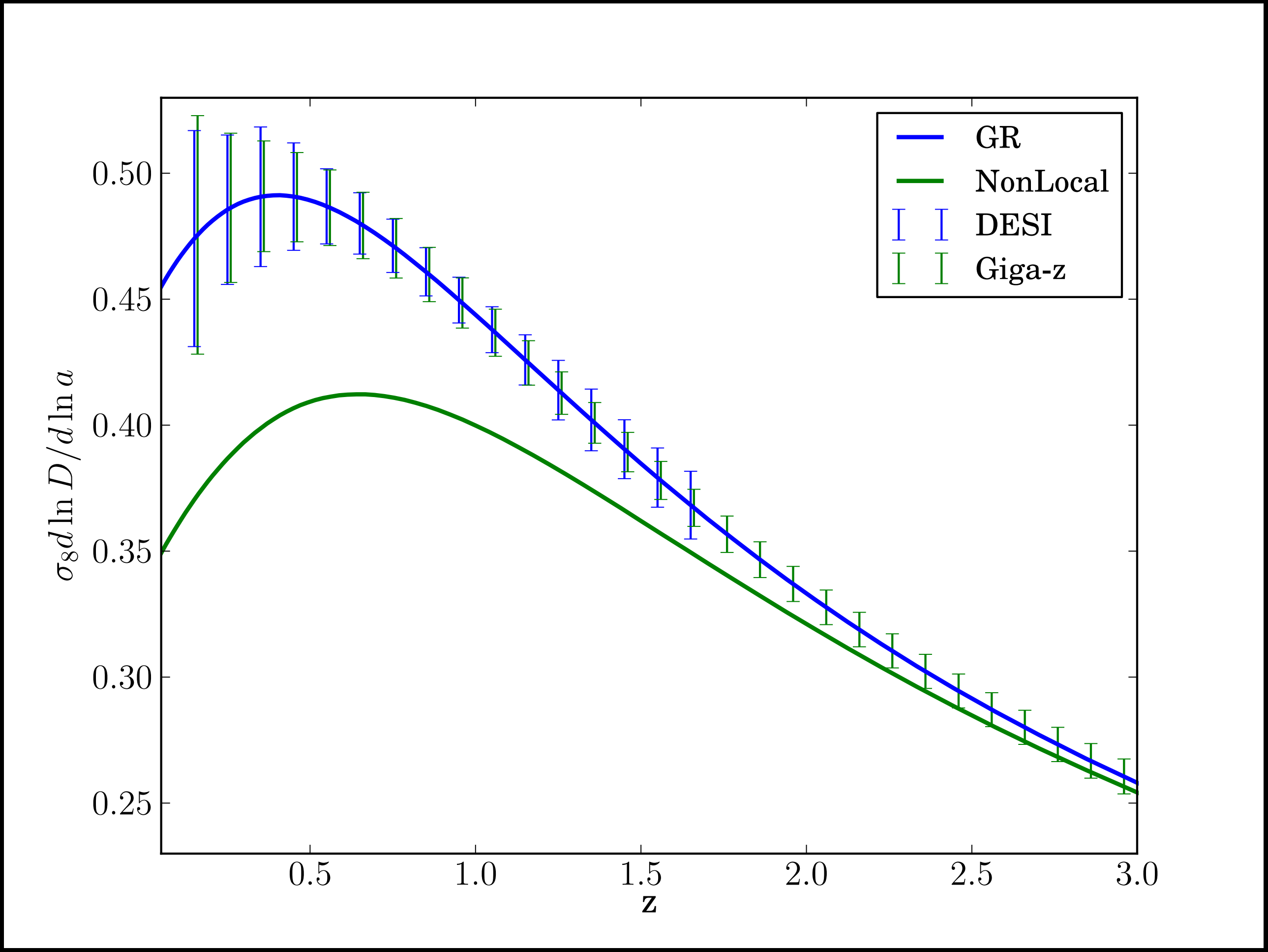
# Nonlocal Gravity: Growth Function

$$\frac{d^2\delta}{da^2} + \left[\frac{d\ln(H)}{da} + \frac{3}{a}\right]\frac{d\delta}{da} - \frac{3}{2}\,[1+\mu]\,\frac{\Omega_m}{E^2(a)a^5}\delta = 0$$

Since μ is non-zero and negative, similar to lower matter density, and perturbations grow slower than in GR

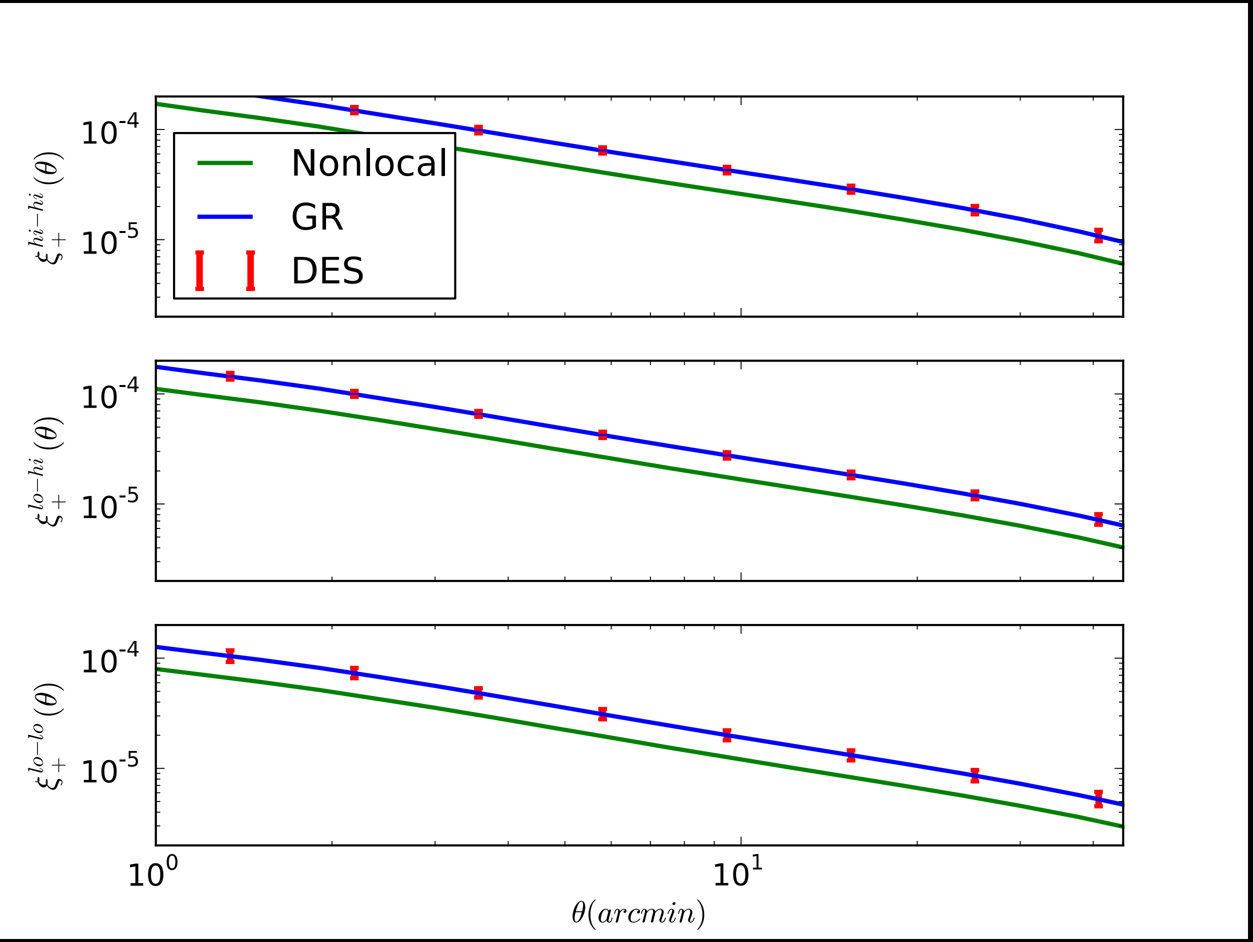


# Nonlocal Gravity: Redshift Space Distortions



# Nonlocal Gravity: Lensing

Correlation function of galaxy ellipticities* in 3 tomographic bins:
Lo-Lo: z<0.8
Hi-Hi: z>0.8
Lo-Hi: Cross

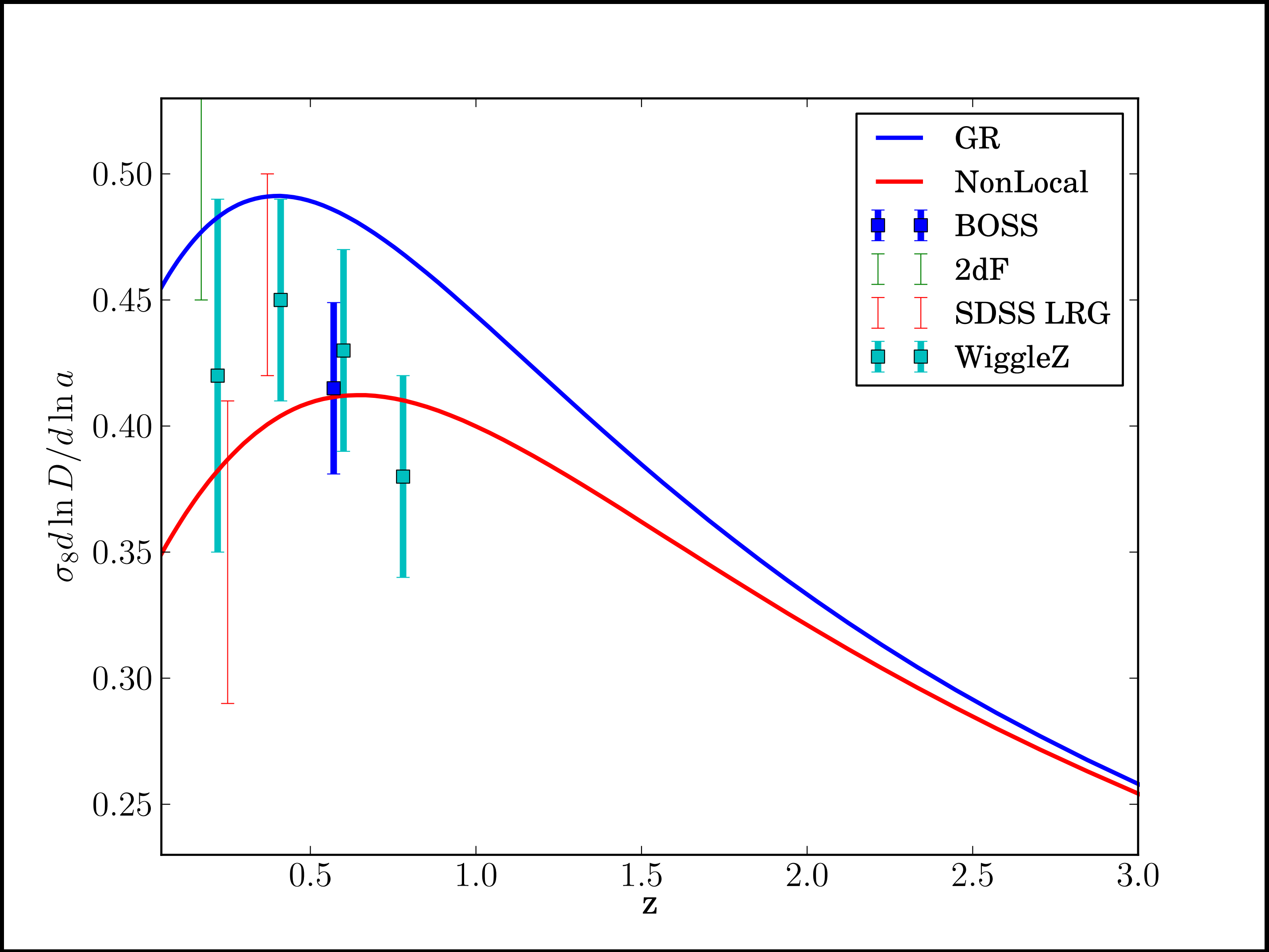



* Distorted by lensing

# Just for fun …

“Stage II” surveys have yielded interesting data already:
-- Redshift space distortions (SDSS LRG’s, 2dF, Wiggle-Z, BOSS)
-- Lensing (SDSS, CFHTLens)

# Nonlocal Gravity: Redshift Space Distortions



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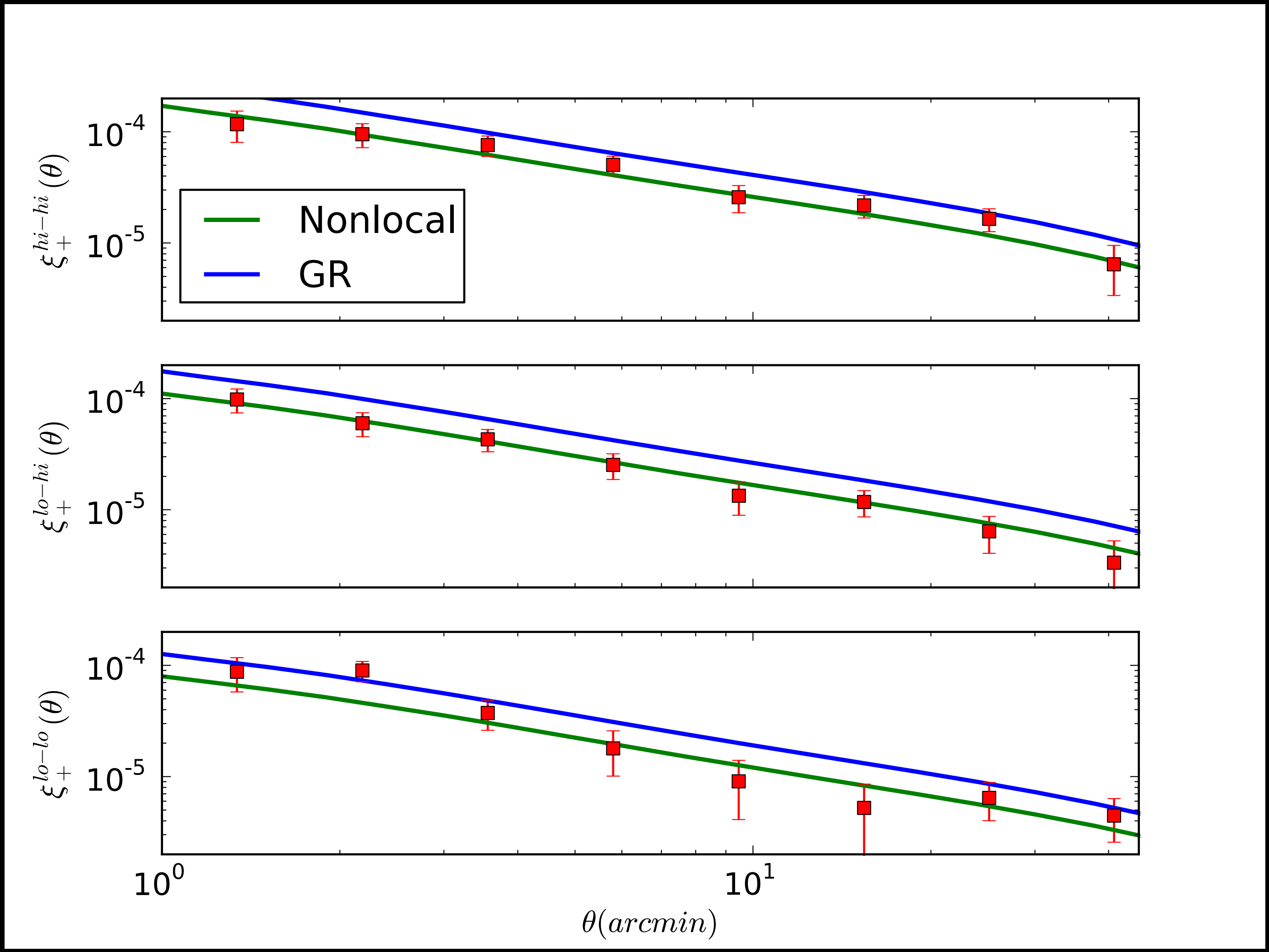
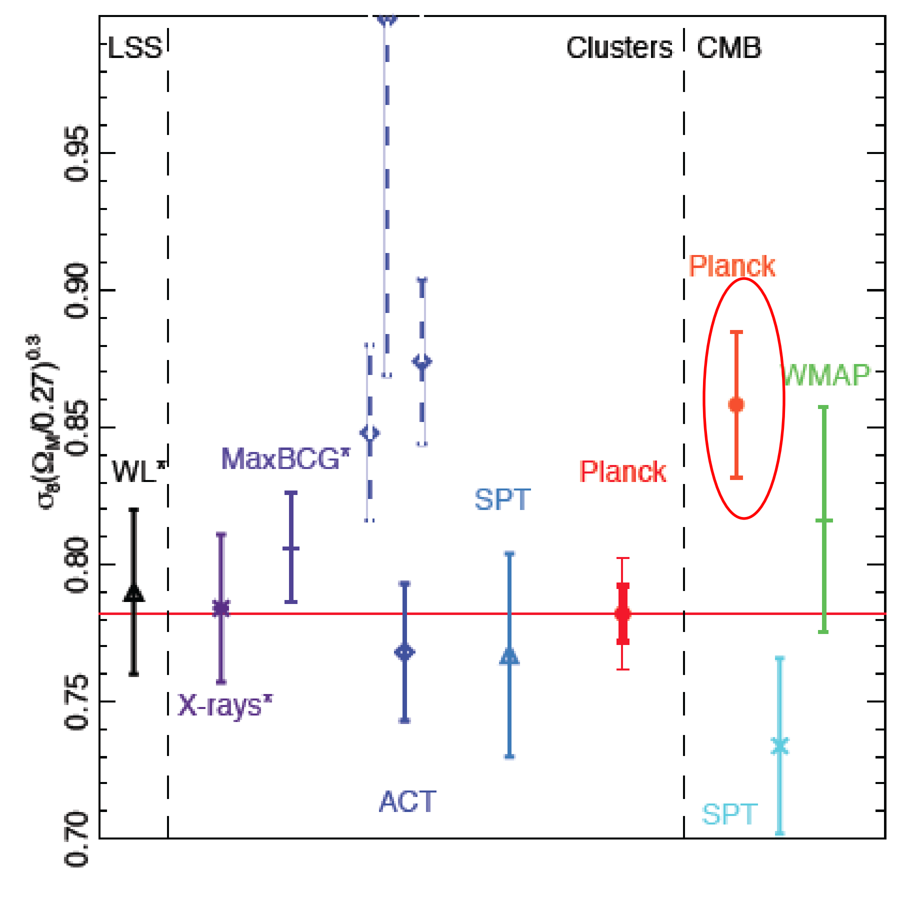
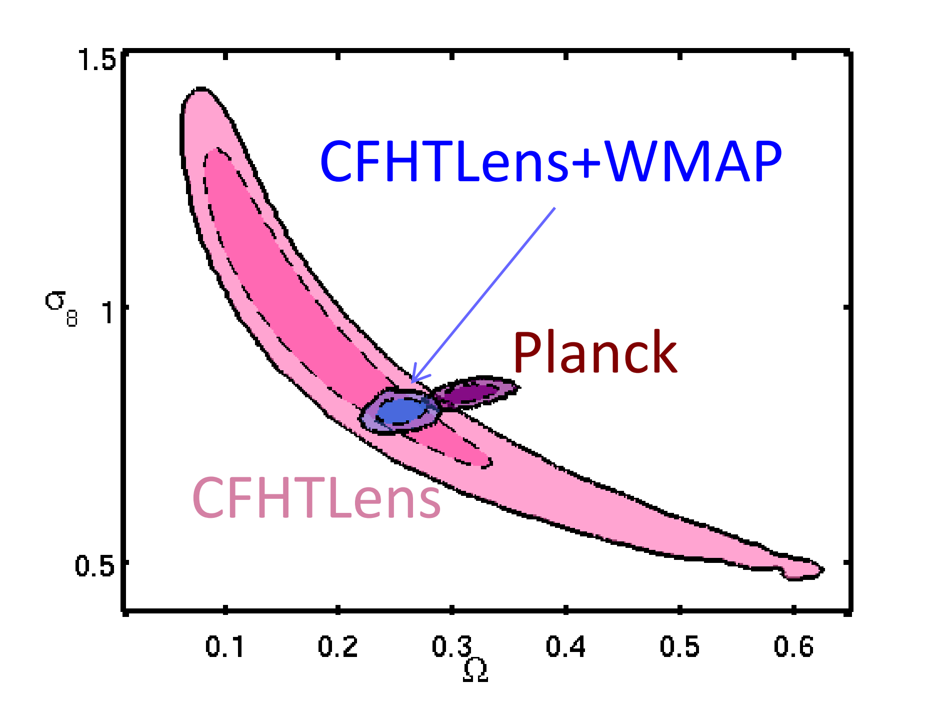


# Some of this tension has been noted




Planck 2013




Courtesy: Catherine Heymans, CFHTLens

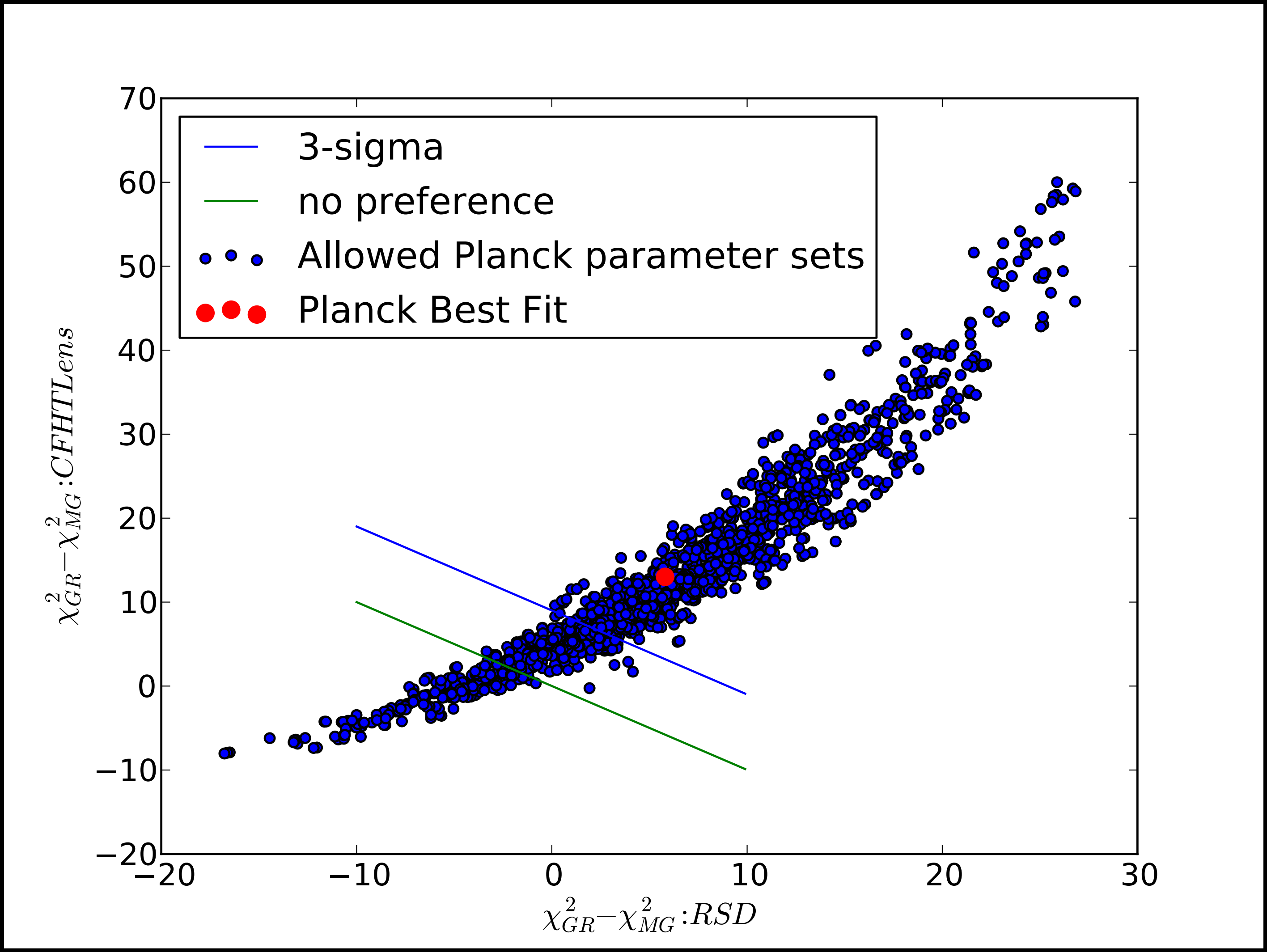
# Statistical Significance

With parameters fixed from Planck, no free parameters for either GR or nonlocal gravity. Can compare $\chi^2$ straight up:

RSD points are essentially uncorrelated: $\Delta\chi^2$=8.8 → 3-sigma preference for nonlocal model

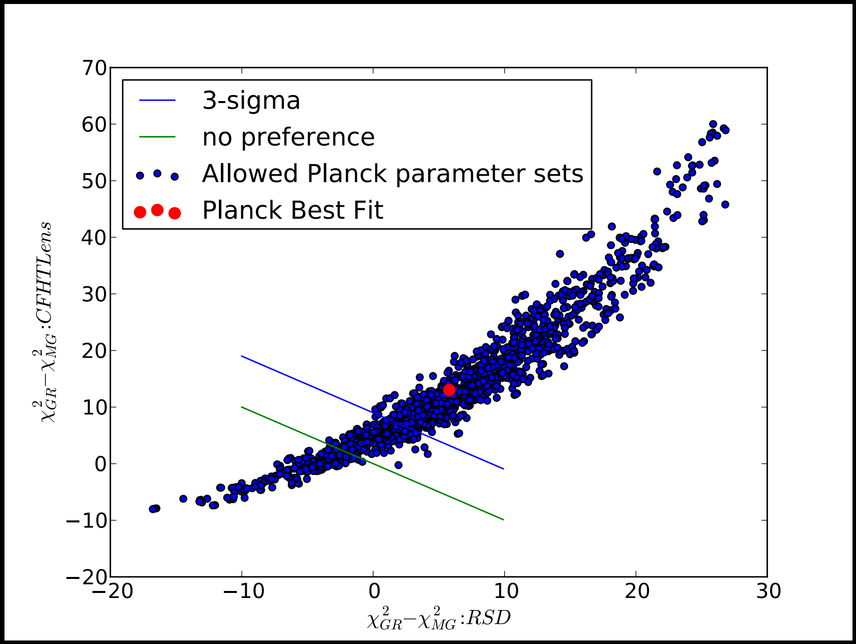
Lensing points are highly correlated, so chi-by-eye fails. Including the proper covariance matrix leads to $\Delta\chi^2$=13 → 3.6-sigma preference for nonlocal model

# Allow parameters to vary over Planck range



# Allow parameters to vary over Planck range

Naïve interpretation: 68% of allowed region still yield 3-sigma preference; 49% yields 4-sigma, so still very strong preference for nonlocal model

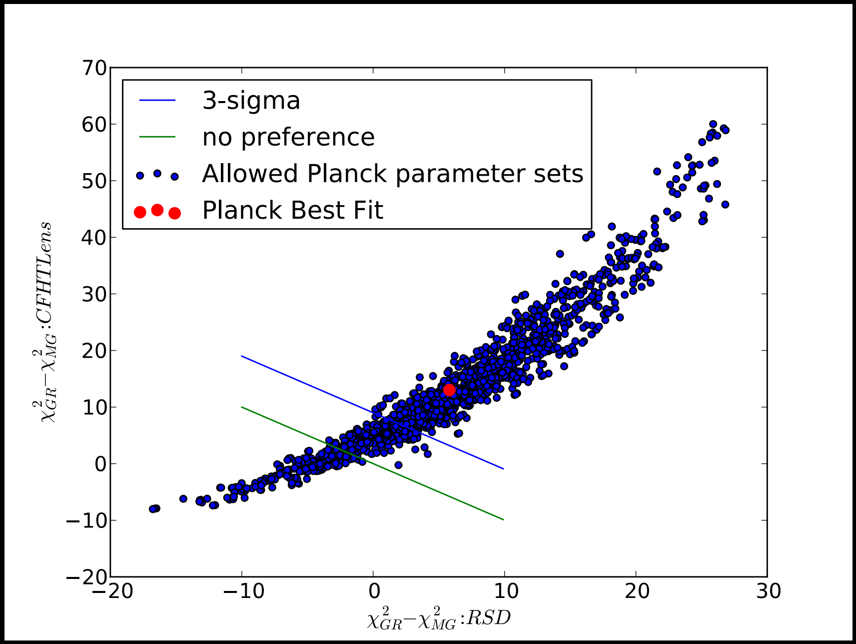


# Allow parameters to vary over Planck range

More carefully:

$$\frac{P_{mg} = \int dp P_{mg}(D\,|\,p)}{P_{gr} = \int dp P_{gr}(D\,|\,p)} = 20 \equiv \exp\left[ - \frac{\mathrm{D}c^{2}}{2} \right]$$

2.4-sigma preference for nonlocal model



# Theoretical Challenges in post-Planck era

- Evidence for BSM physics (dark matter, inflation, neutrino masses, dark energy) stronger than ever: ***What is this new physics?***
- Is Modified Gravity a viable alternative to dark energy?
- Tension between Planck and galaxy surveys: ***Hint that we are not living in a boring universe?***