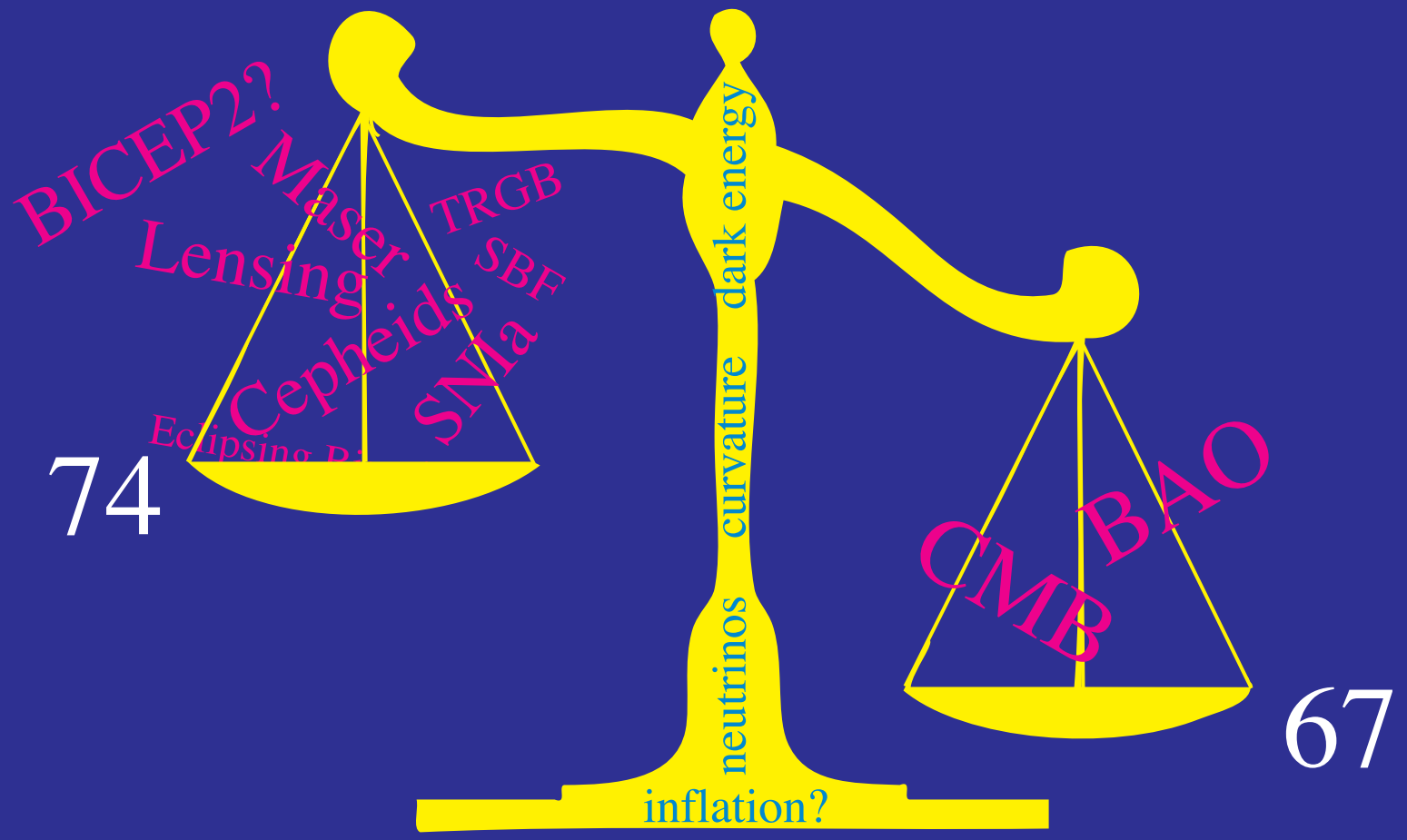
H_0 is Undervalued



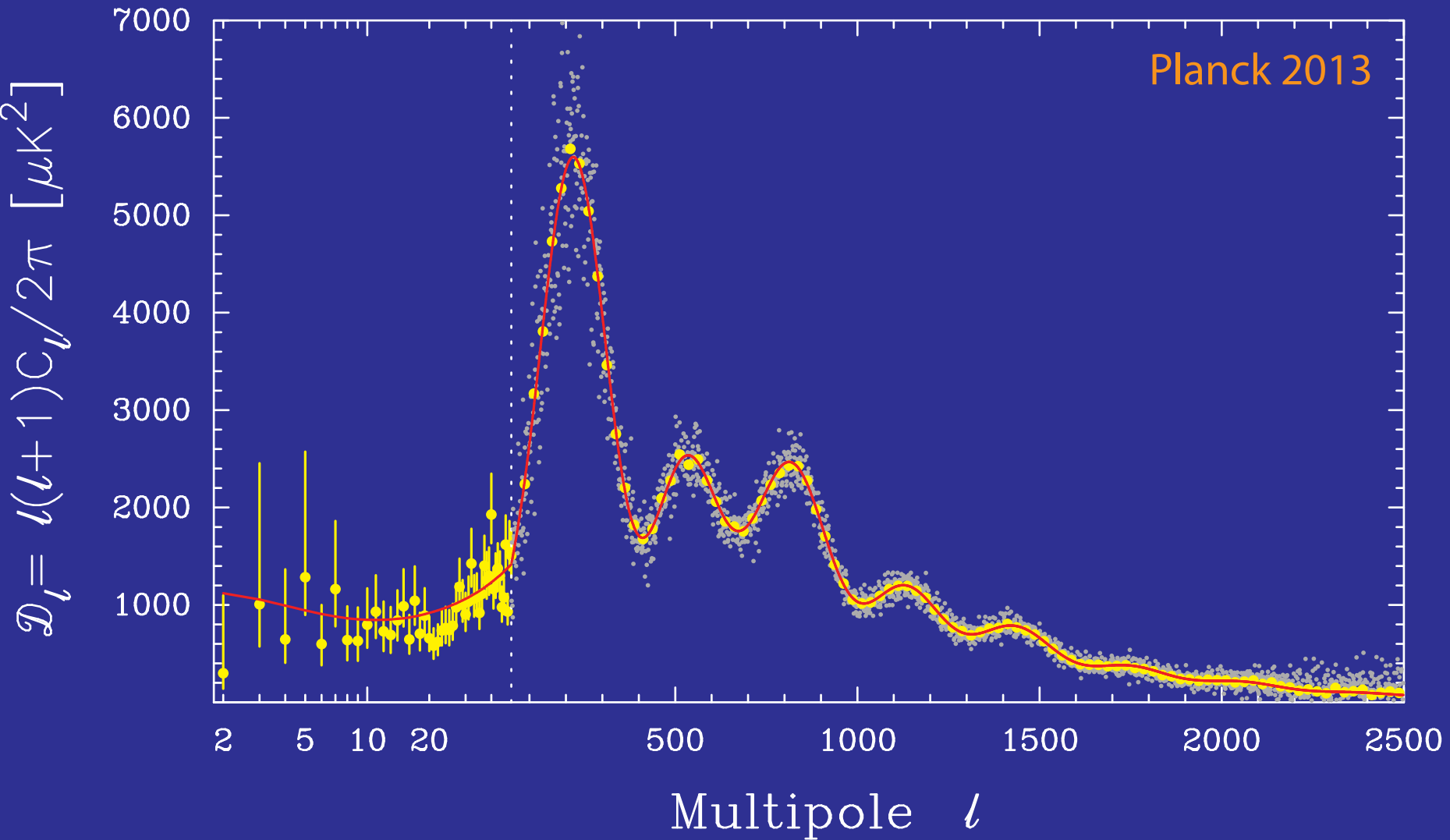
Wayne Hu

STSCI, April 2014

The 1%

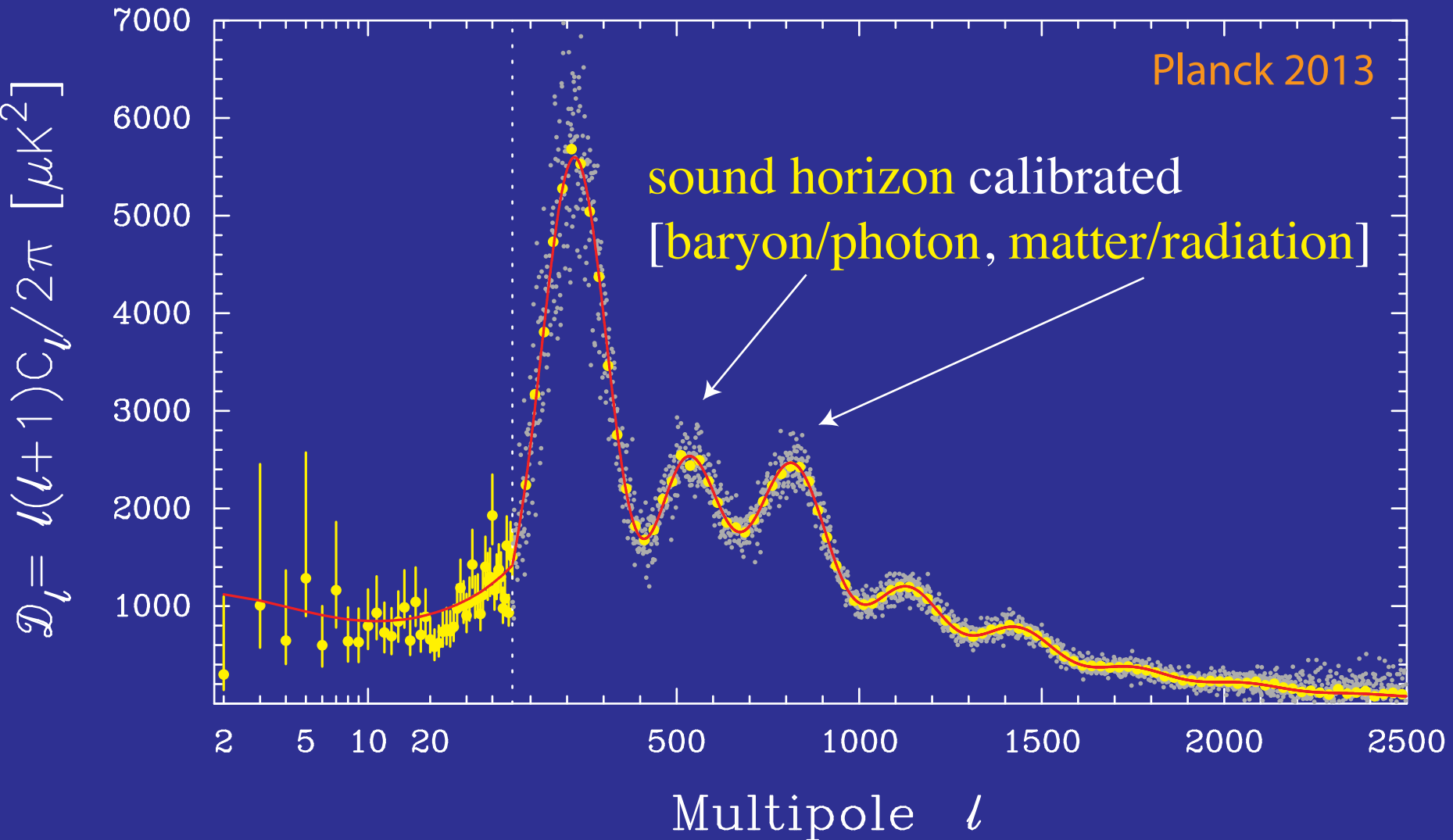
ΔH_0=New Physics

- H_0: an end to end check of the standard cosmology when combined with the CMB



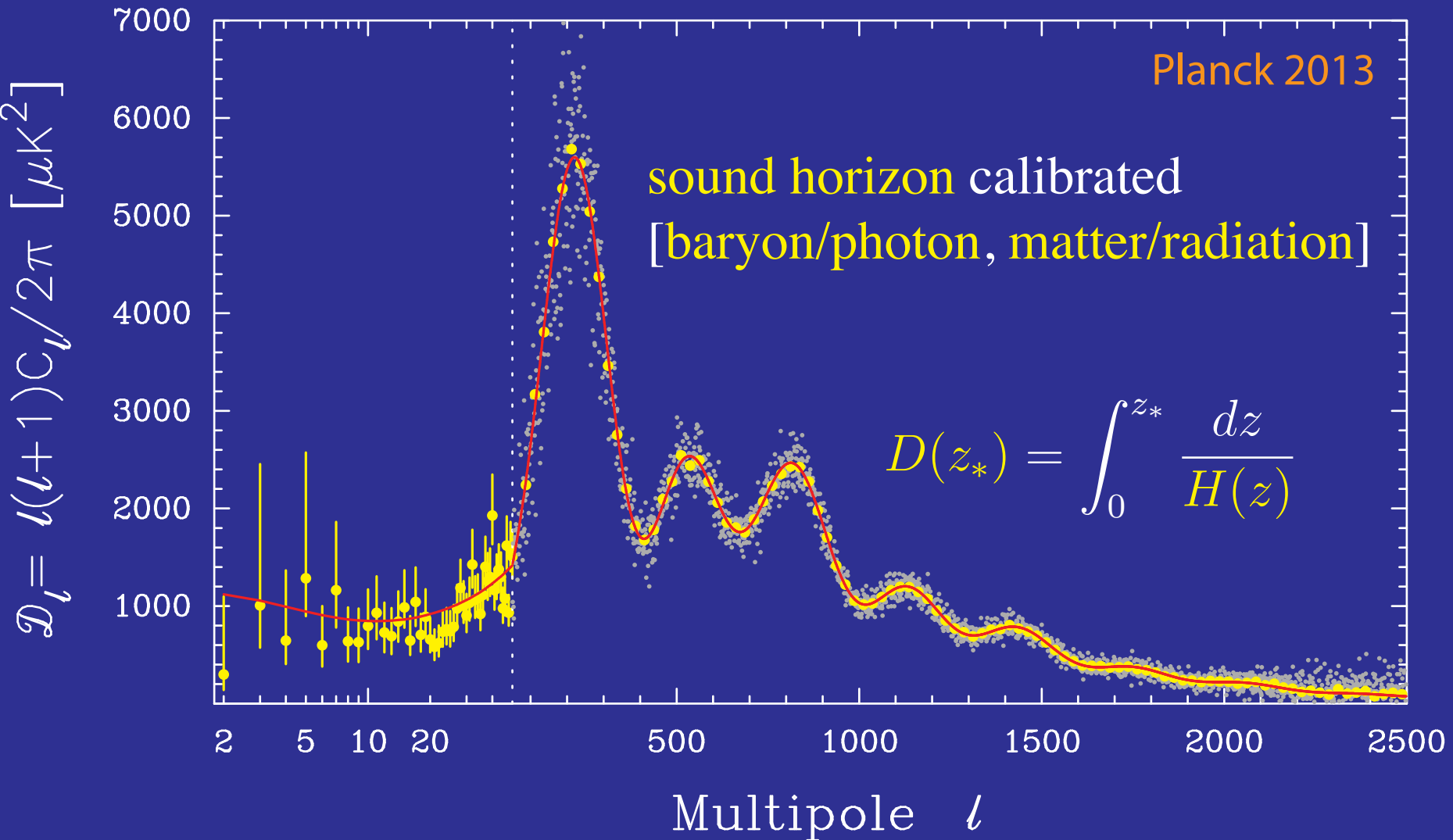
ΔH_0=New Physics

- Standard ruler $D(z_*)$: sound horizon at recombination z_*
- In flat ΛCDM, H_0 only remaining parameter in $D(z_*)$ representing the density contributed by Λ - precisely predicted



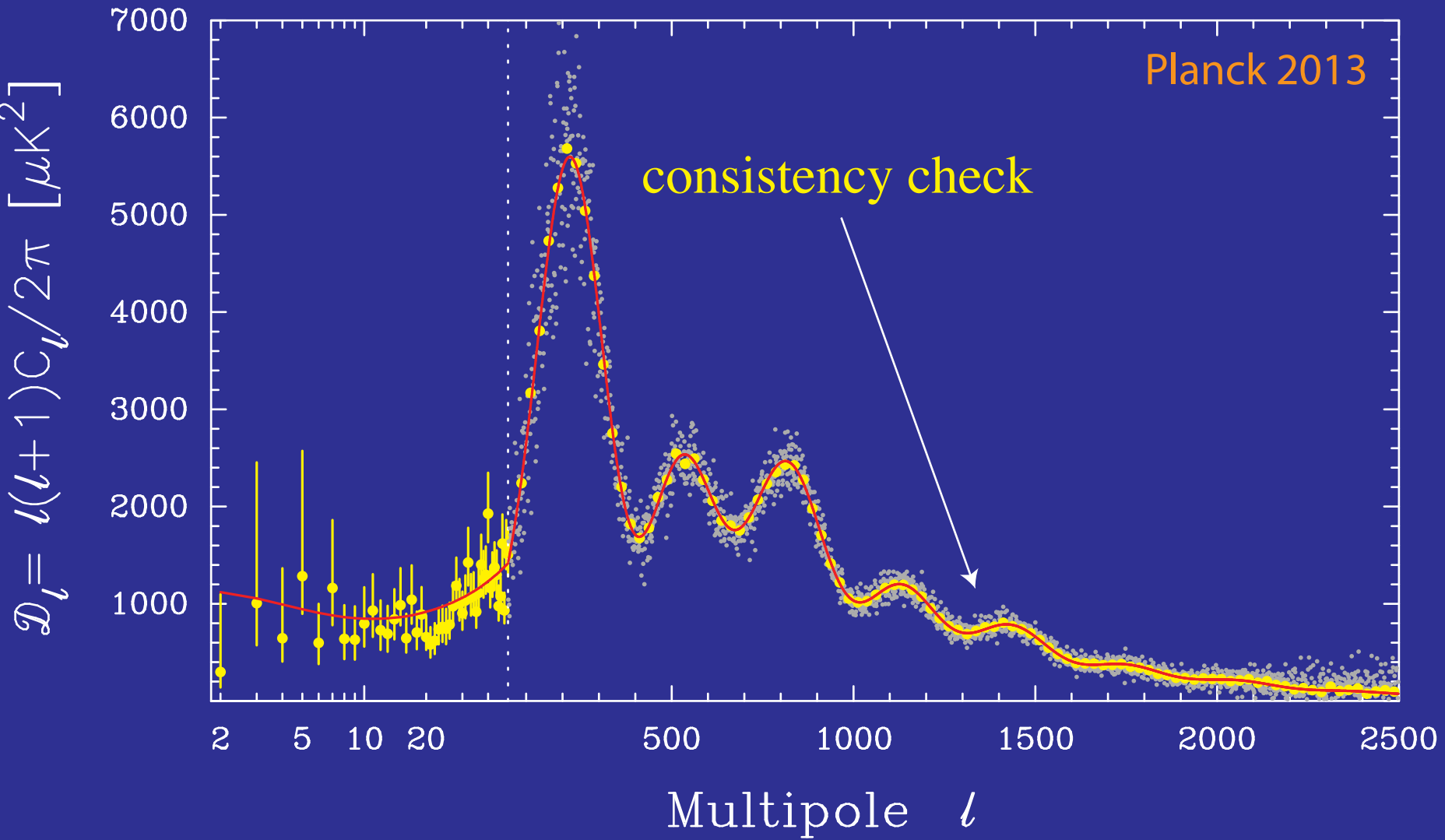
ΔH_0=New Physics

- Compare precise predictions with H_0 measurements
- Any deviations indicate new physics during acceleration epoch or during recombination



ΔH_0=New Physics

- Standard ruler $D(z_*)$: sound horizon at recombination z_*
- Diffusion scale provides consistency check on sound horizon calibration: new physics at recombination, while BAO on acceleration



Falsifying ΛCDM

- CMB determination of matter density controls all determinations in the deceleration (matter dominated) epoch
- Planck: $\Omega_m h^2 = 0.1426 \pm 0.0025 \rightarrow 1.7\%$
- Distance to recombination D_* determined to $\frac{1}{4}1.7\% \approx 0.43\%$ (ΛCDM result 0.46%; $\Delta h/h \approx -\Delta\Omega_m h^2/\Omega_m h^2$)

  [more general: $-0.11\Delta w - 0.48\Delta \ln h - 0.15\Delta \ln \Omega_m - 1.4\Delta \ln \Omega_{\rm tot} = 0$]
- Expansion rate during any redshift in the deceleration epoch determined to $\frac{1}{2}1.7\%$
- Distance to any redshift in the deceleration epoch determined as

$$D(z) = D_* - \int_z^{z_*} \frac{dz}{H(z)}$$

- Volumes determined by a combination $dV = D_A^2 d\Omega dz/H(z)$
- Structure also determined by growth of fluctuations from z_*

Value of Local Measurements

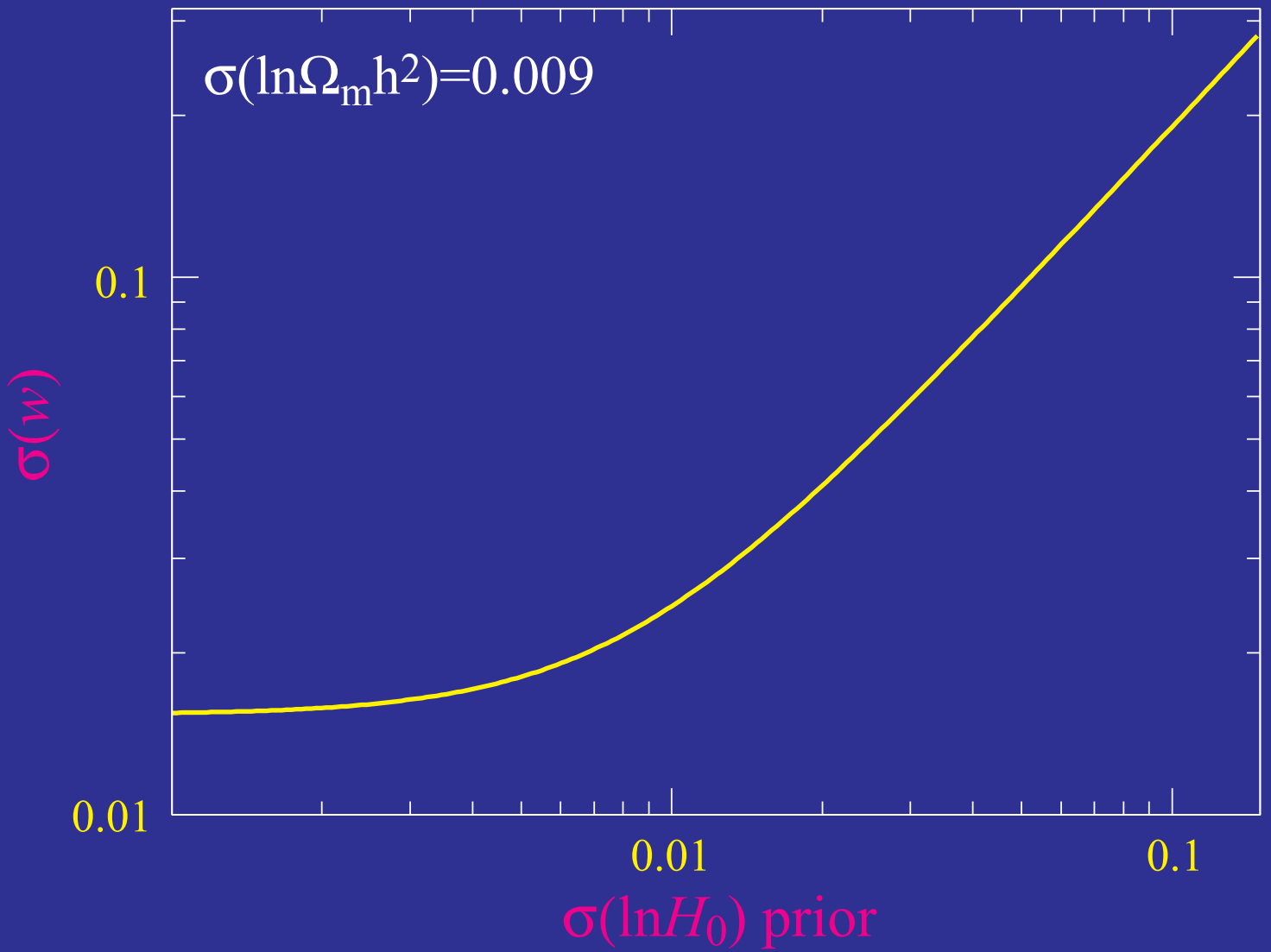
- With high redshifts fixed, the largest deviations from the dark energy appear at low redshift $z \sim 0$
- By the Friedmann equation $H^2 \propto \rho$ and difference between $H(z)$ extrapolated from the CMB $H_0 = 38$ and 67 is entirely due to the dark energy density in a flat universe
- With the dark energy density fixed by H_0, the deviation from the CMB observed D_* from the ΛCDM prediction measures the equation of state (or evolution of the dark energy density)

$$p_{\rm DE} = w\rho_{\rm DE}$$

- Likewise current amplitude of structure, e.g. local cluster abundance, tests the smooth dark energy paradigm

Forecasts for CMB+H_0

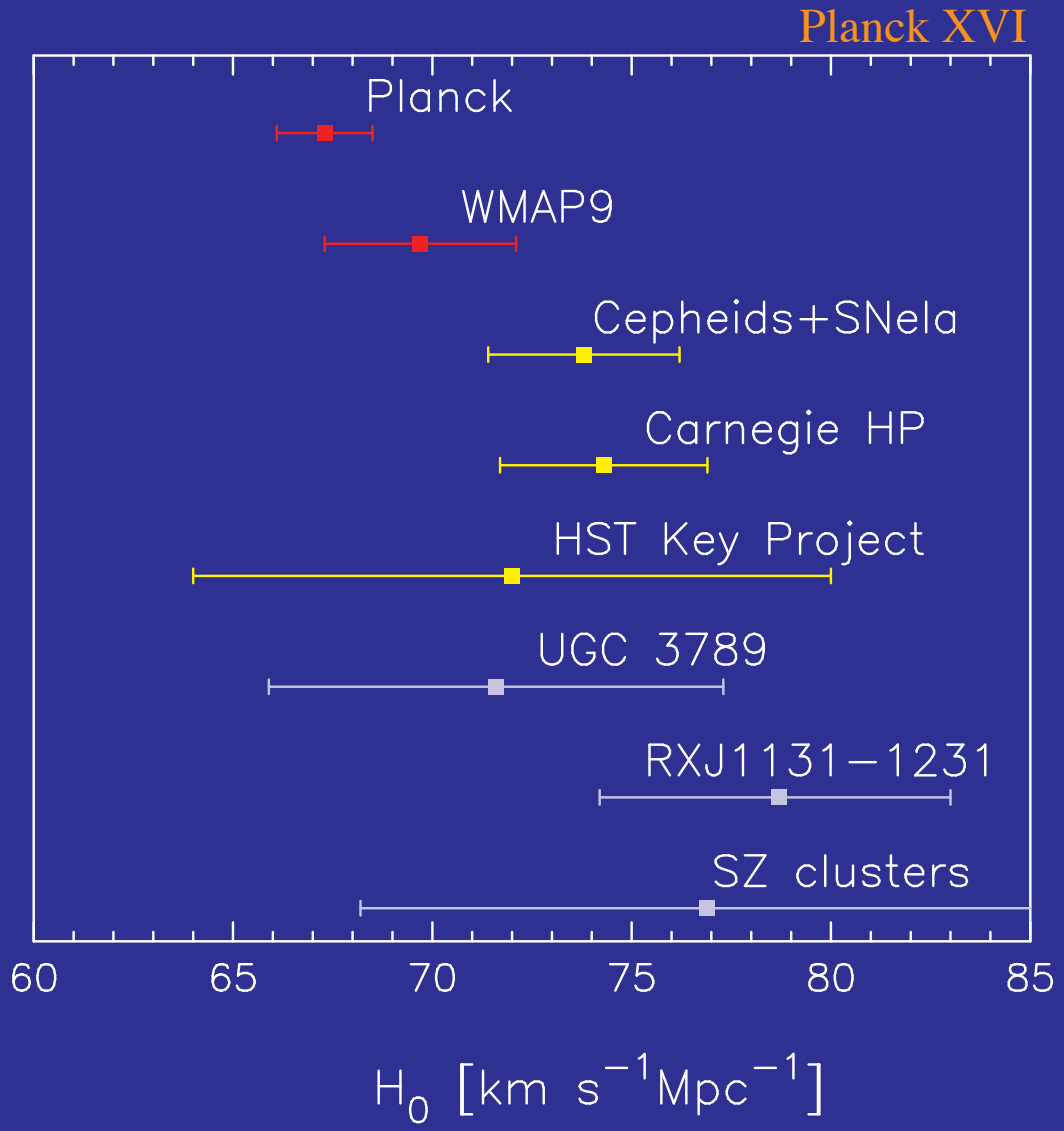
- To complement CMB observations with $\Omega_m h^2$ to 1%, an H_0 of ~1% enables constant w measurement to ~2% in a flat universe



New Physics?

H_0 is for Hints

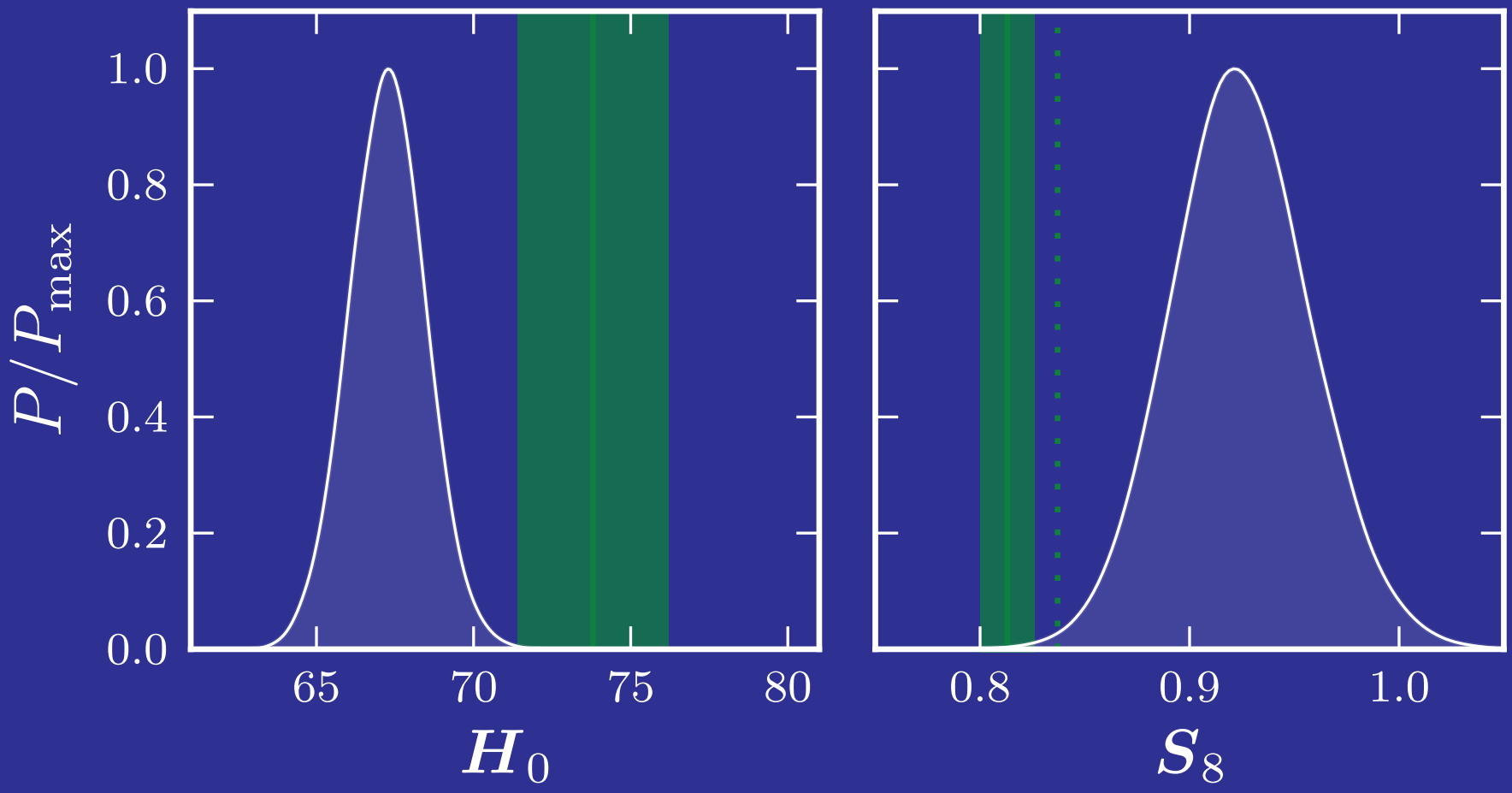
- Actual distance ladder measurements prefer larger value



Quantifying Tension

- Predictions for H_0 and the amplitude of structure from Planck in flat ΛCDM is 2-3+ σ in tension with measurements

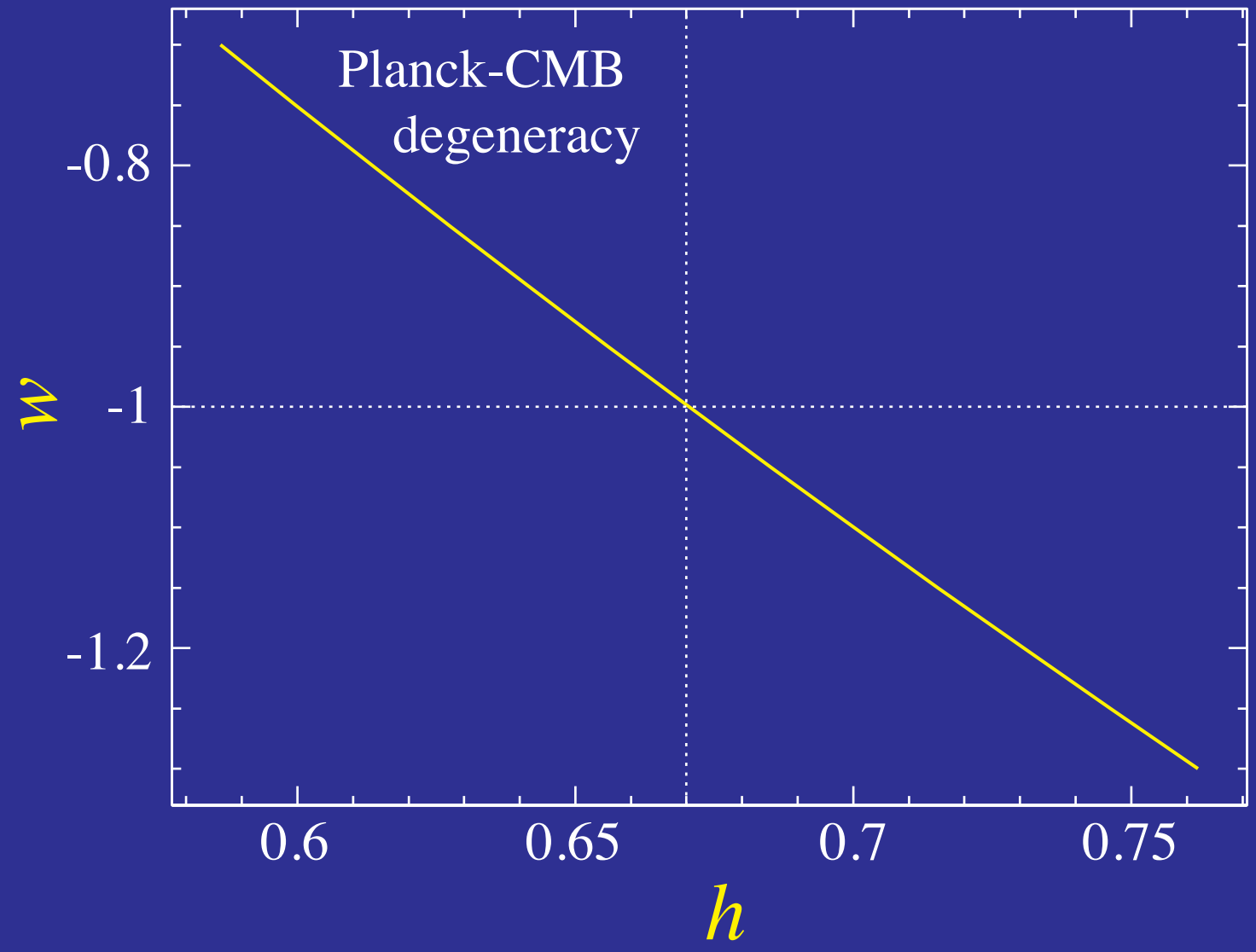
Planck vs Local: ΛCDM



Wyman, Rudd, Vanderveld, Hu (2013)

Dark Energy

- Raising H_0 inferred from Planck CMB measurements with dark energy requires phantom equations of state



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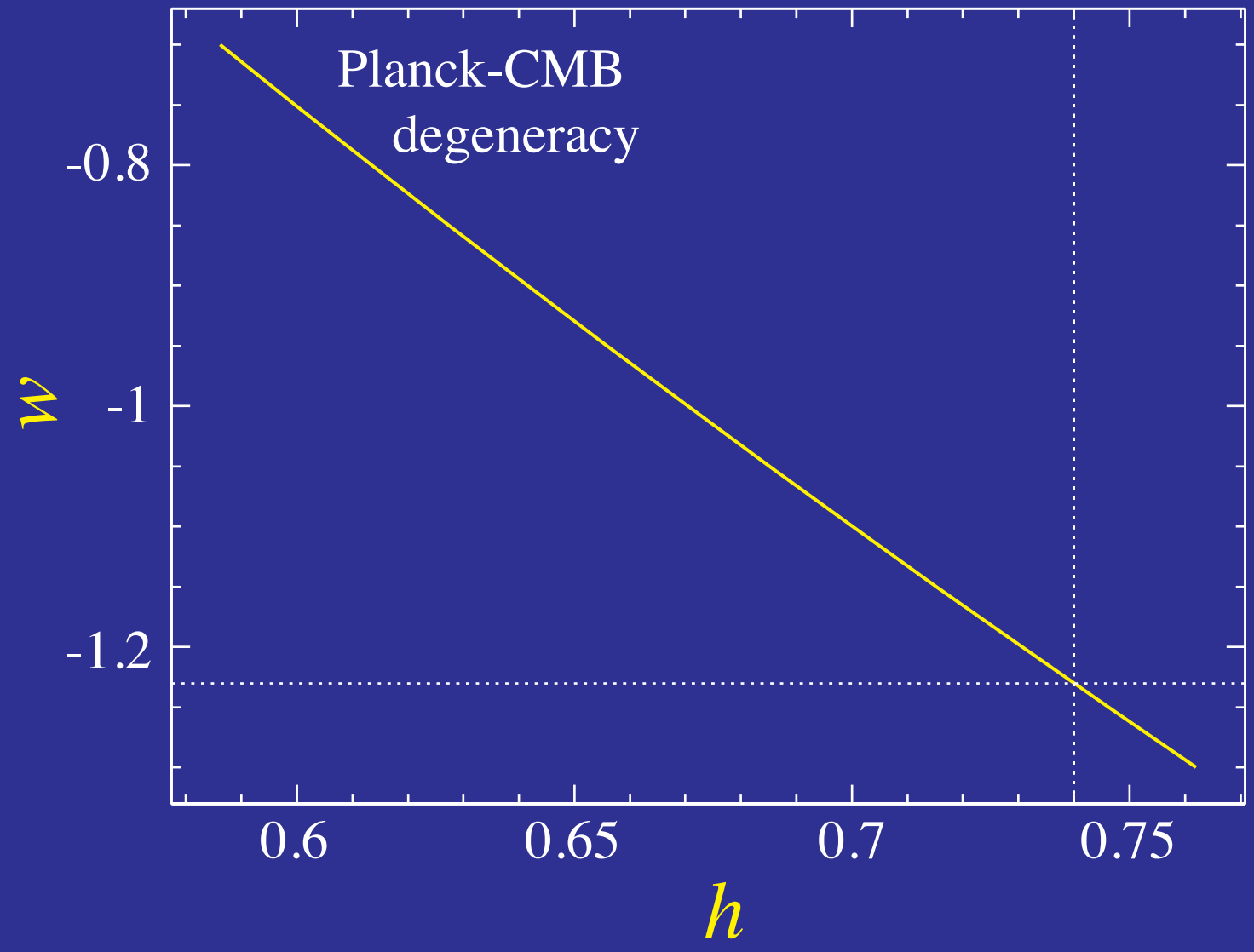
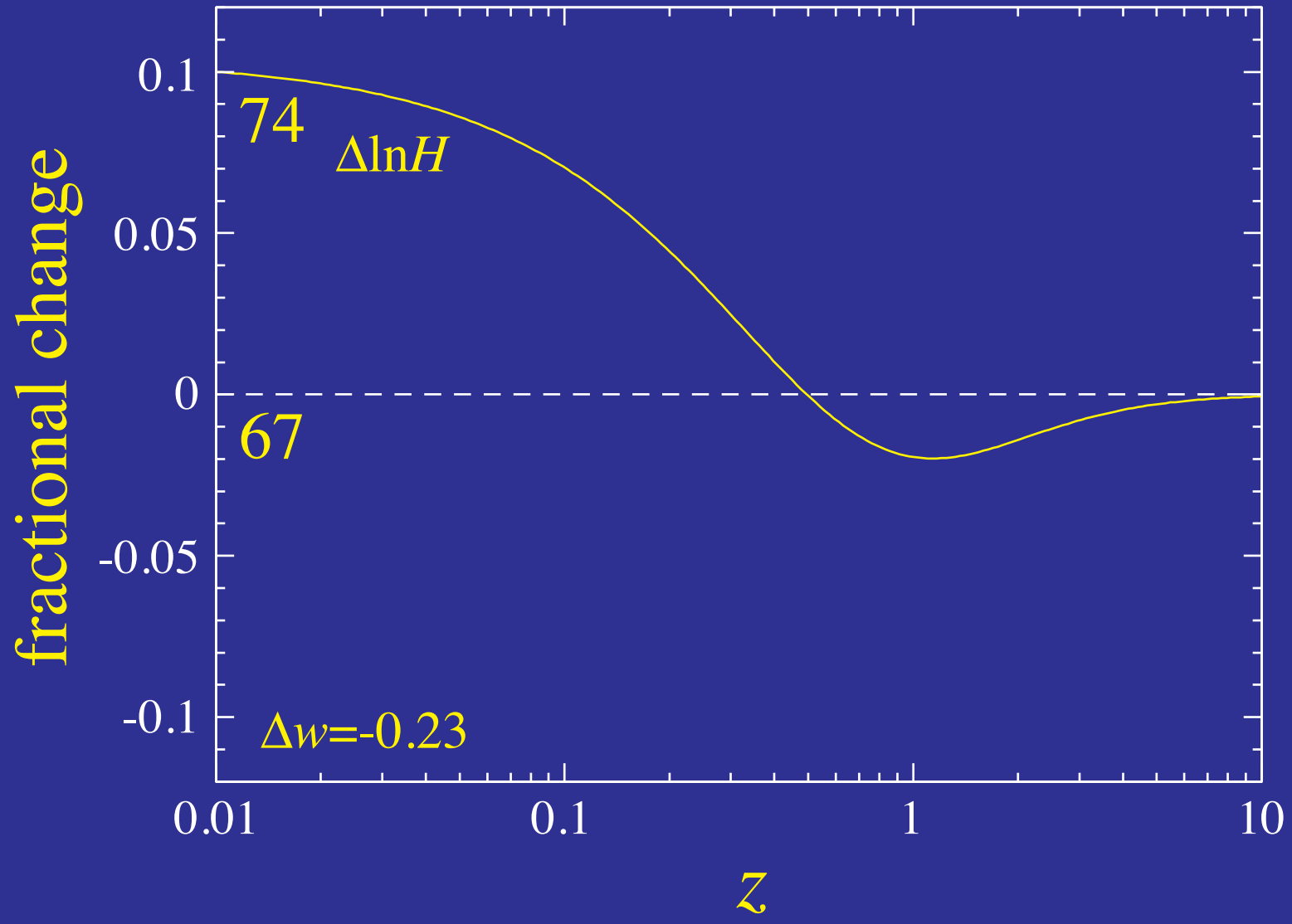


Dark Energy

- Predicts larger BAO (θ) angular and radial (z) scale; larger SN=$H_0 D_A$ relative luminosity distance; larger linear growth



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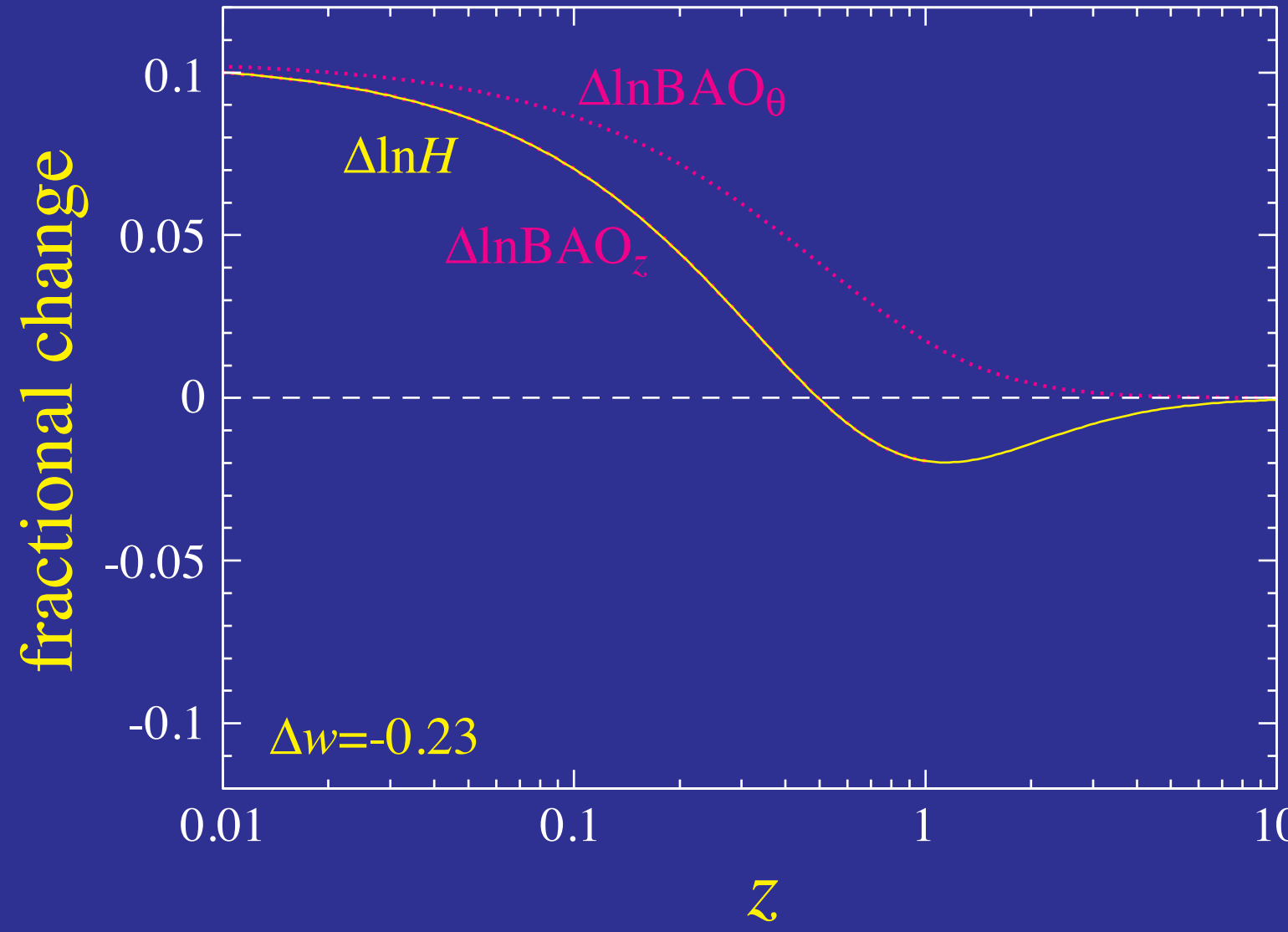

tension with data!

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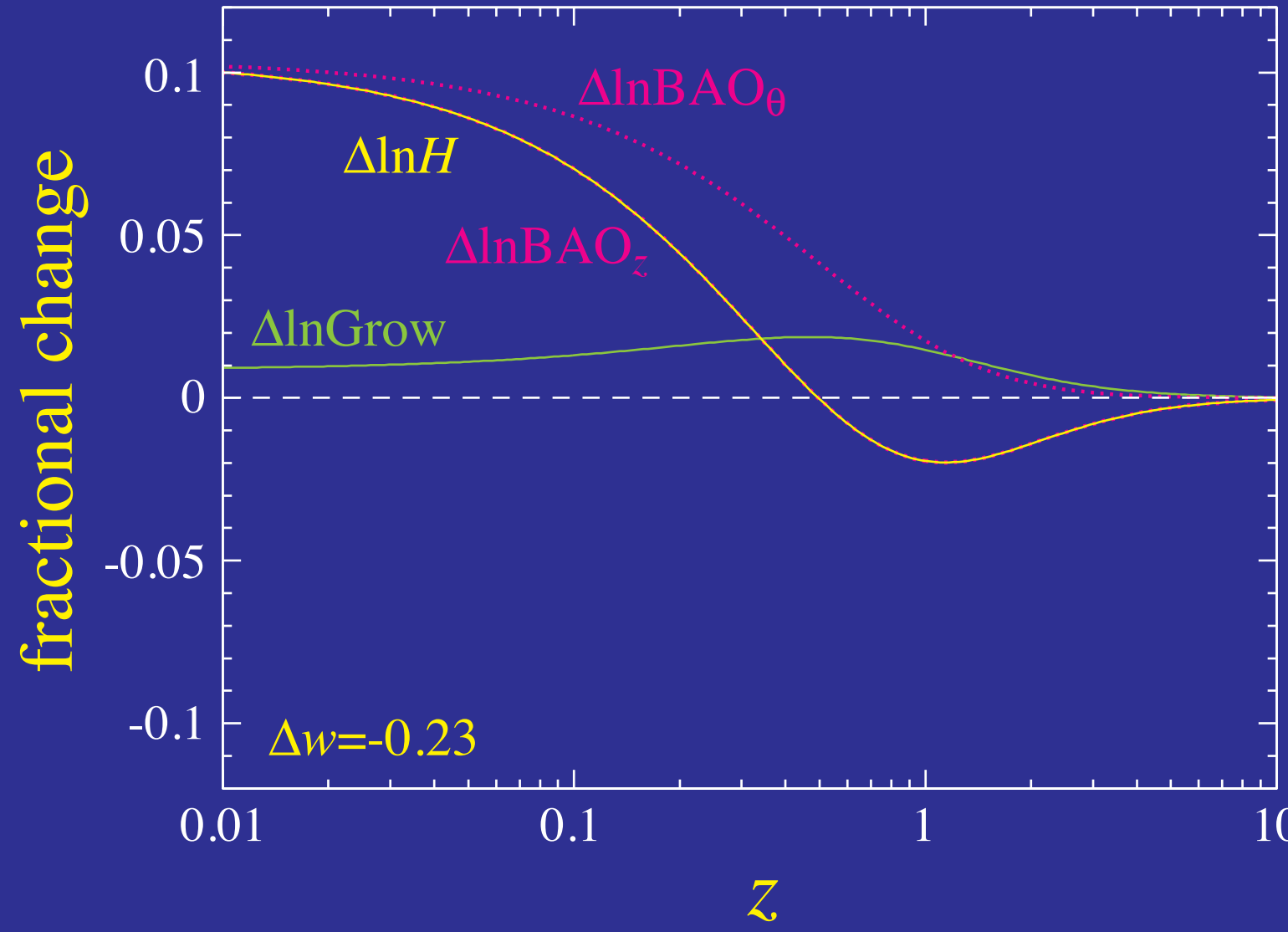

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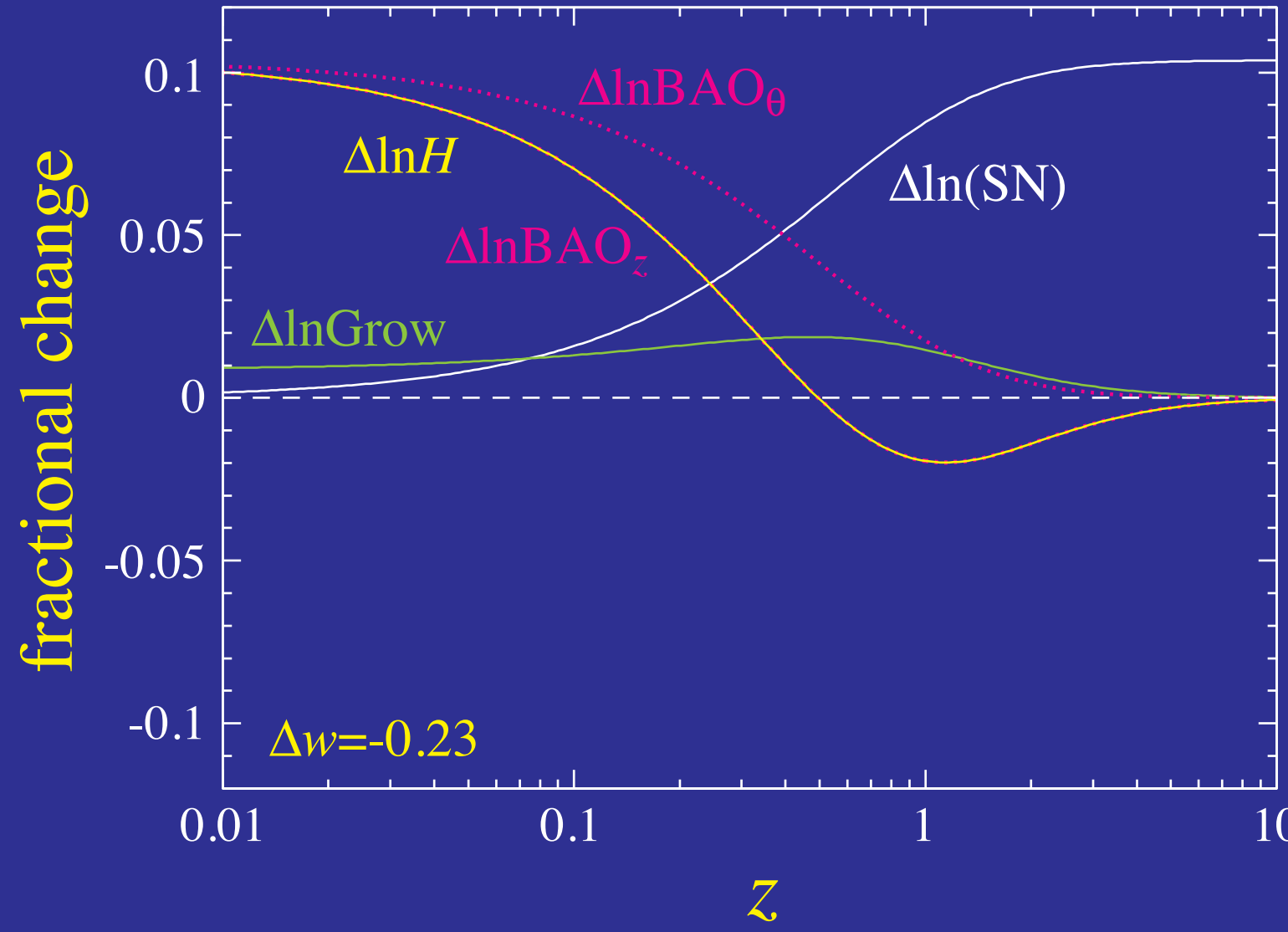
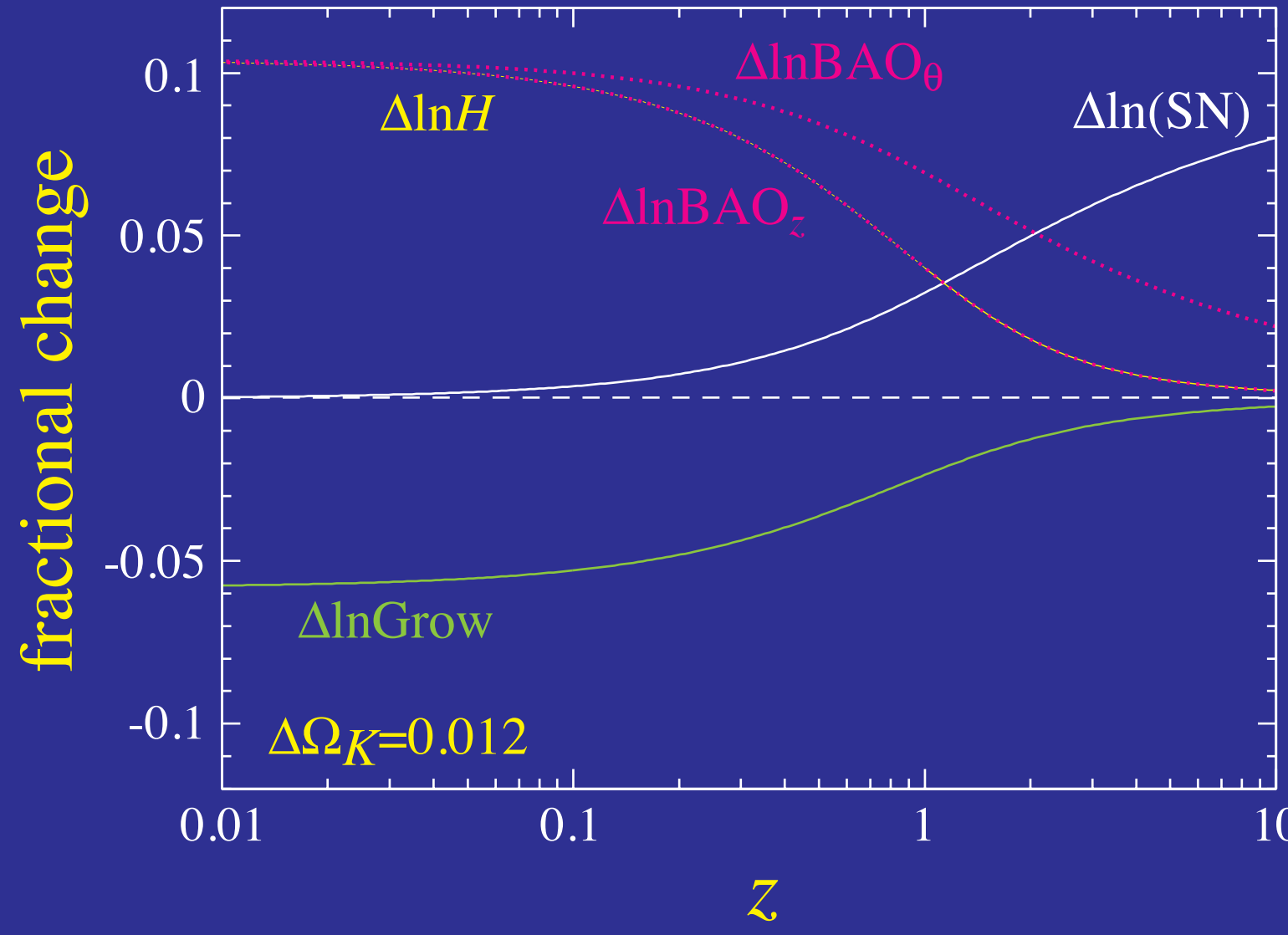


tension with data!

Curvature

- Predicts larger BAO (θ) angular and radial (z) scale; larger SN=$H_0 D_A$ relative luminosity distance; smaller linear growth



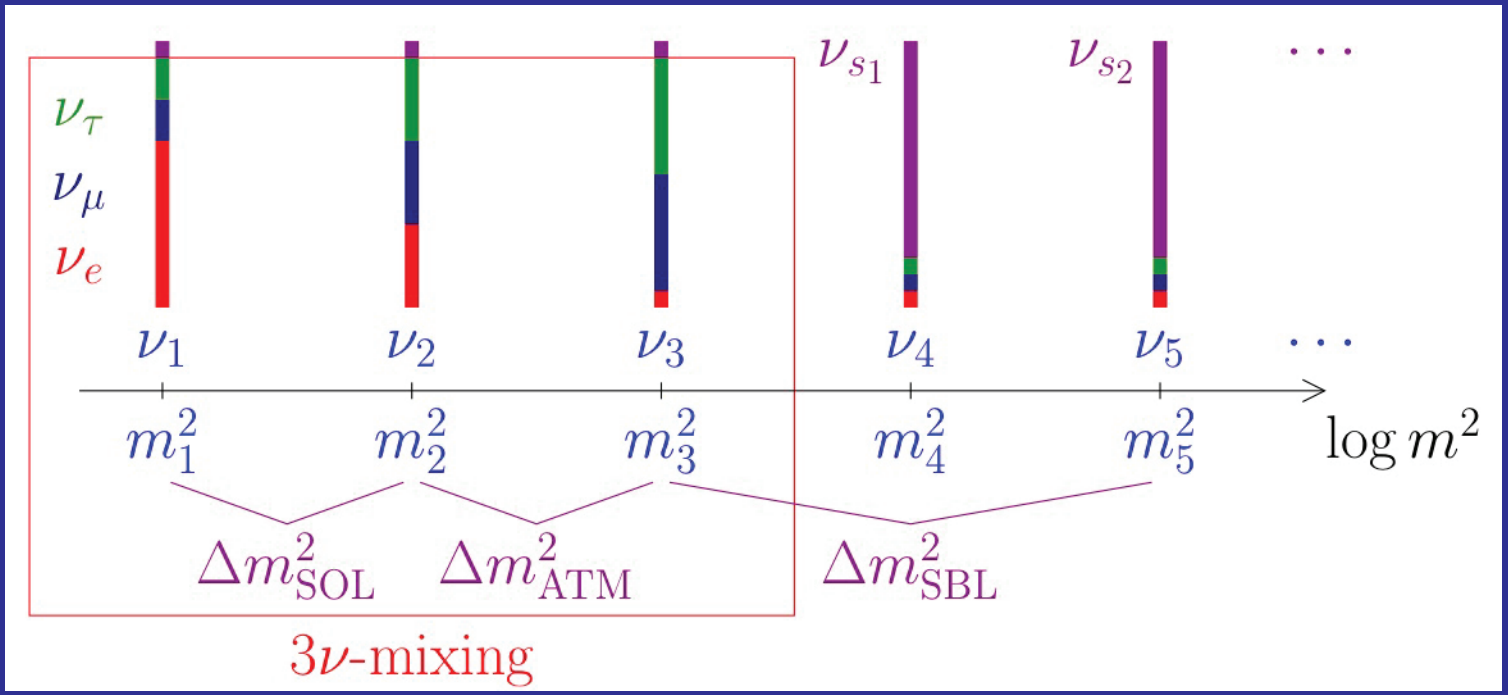
tension with data!

alleviate tension

Neutrinos?

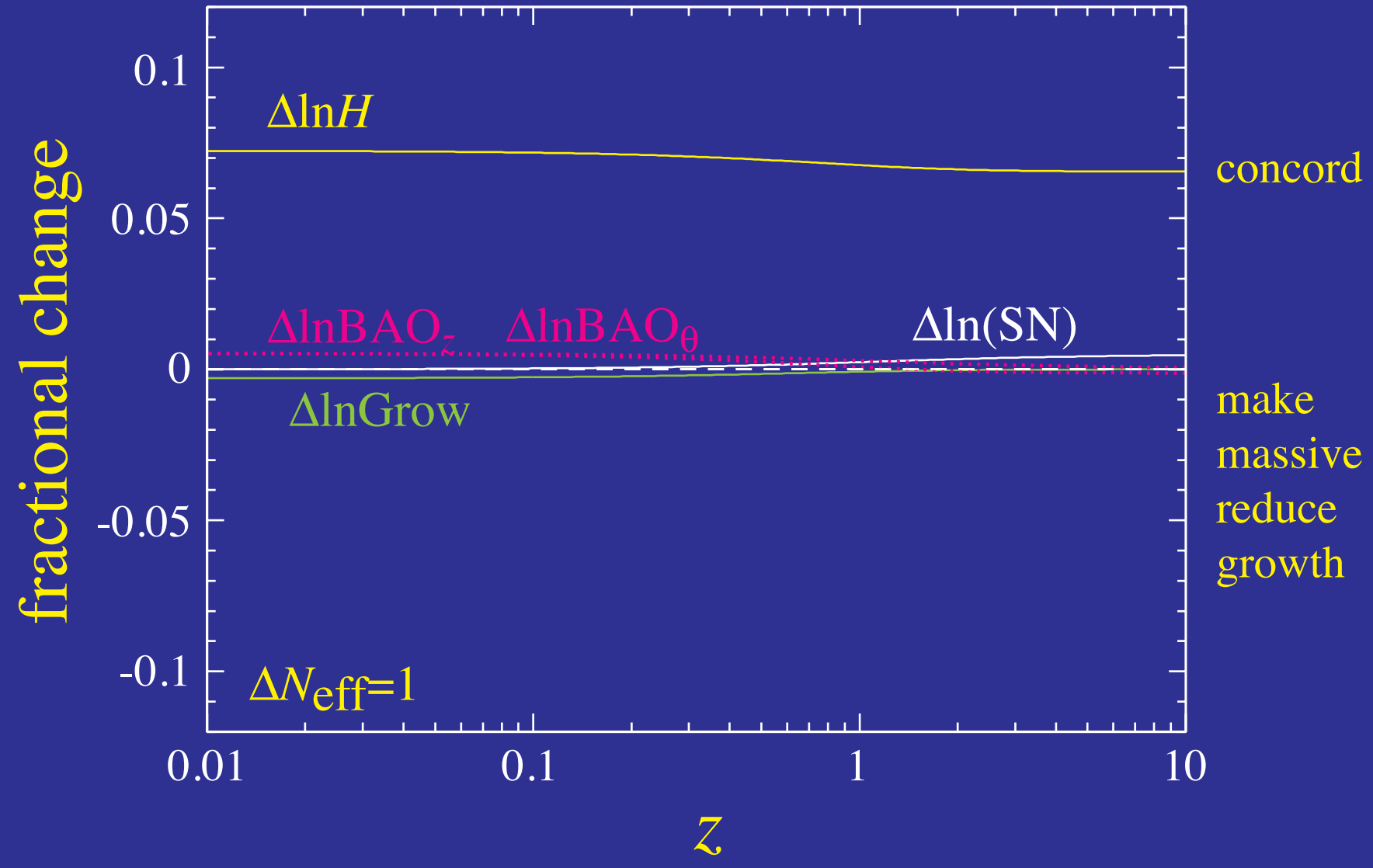
Neutrinos

- Hints of extra sterile neutrino species (~eV) in long-baseline and reactor anomalies
- Potentially populated (partially?) in early universe
- Changes expansion at recombination: age, sound horizon



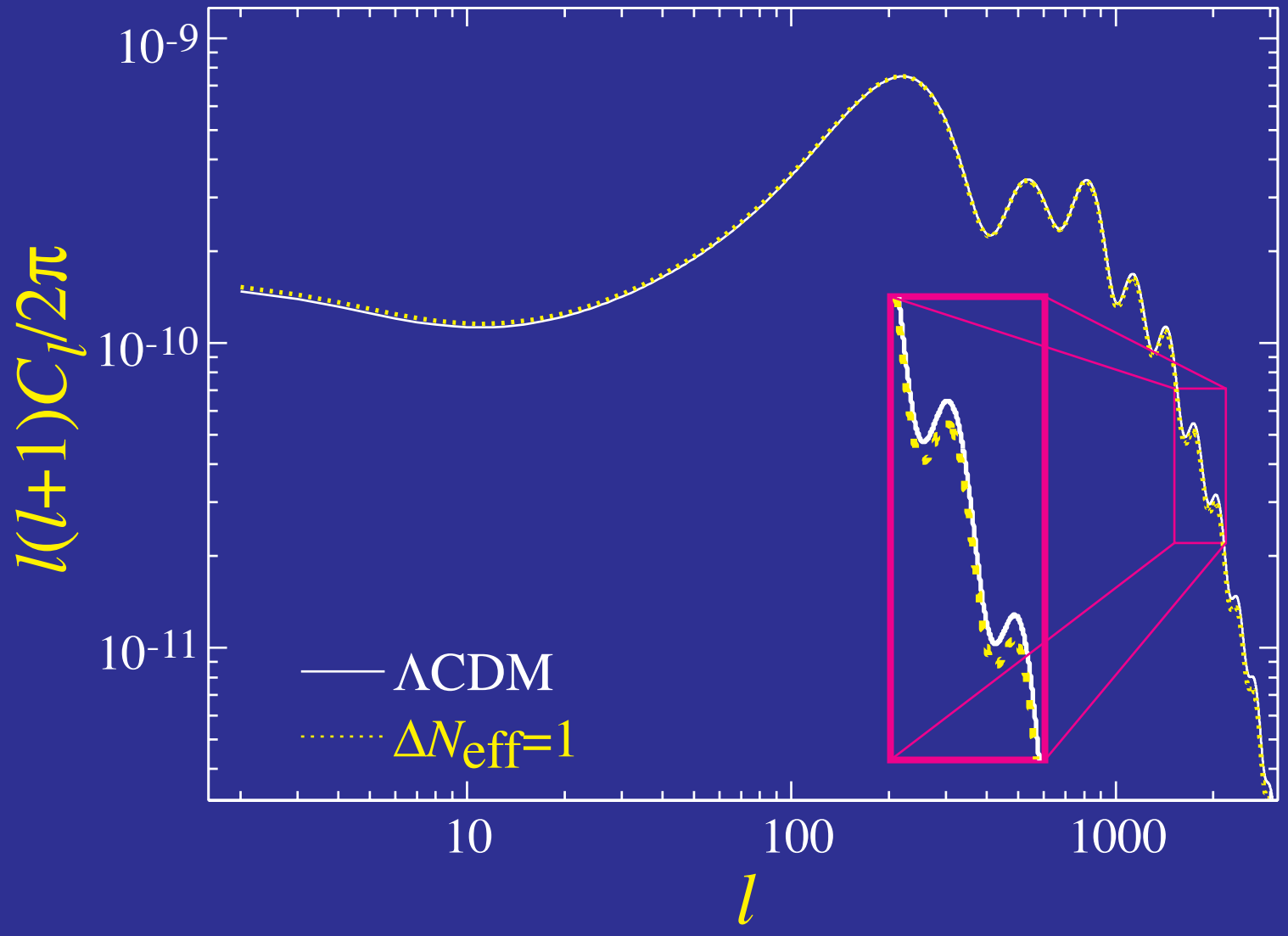
Neutrinos

- Predicts same BAO (θ) angular and radial (z) scale;
  same SN=H_0D_A relative luminosity distance;
  same linear growth - change the ruler not the distance



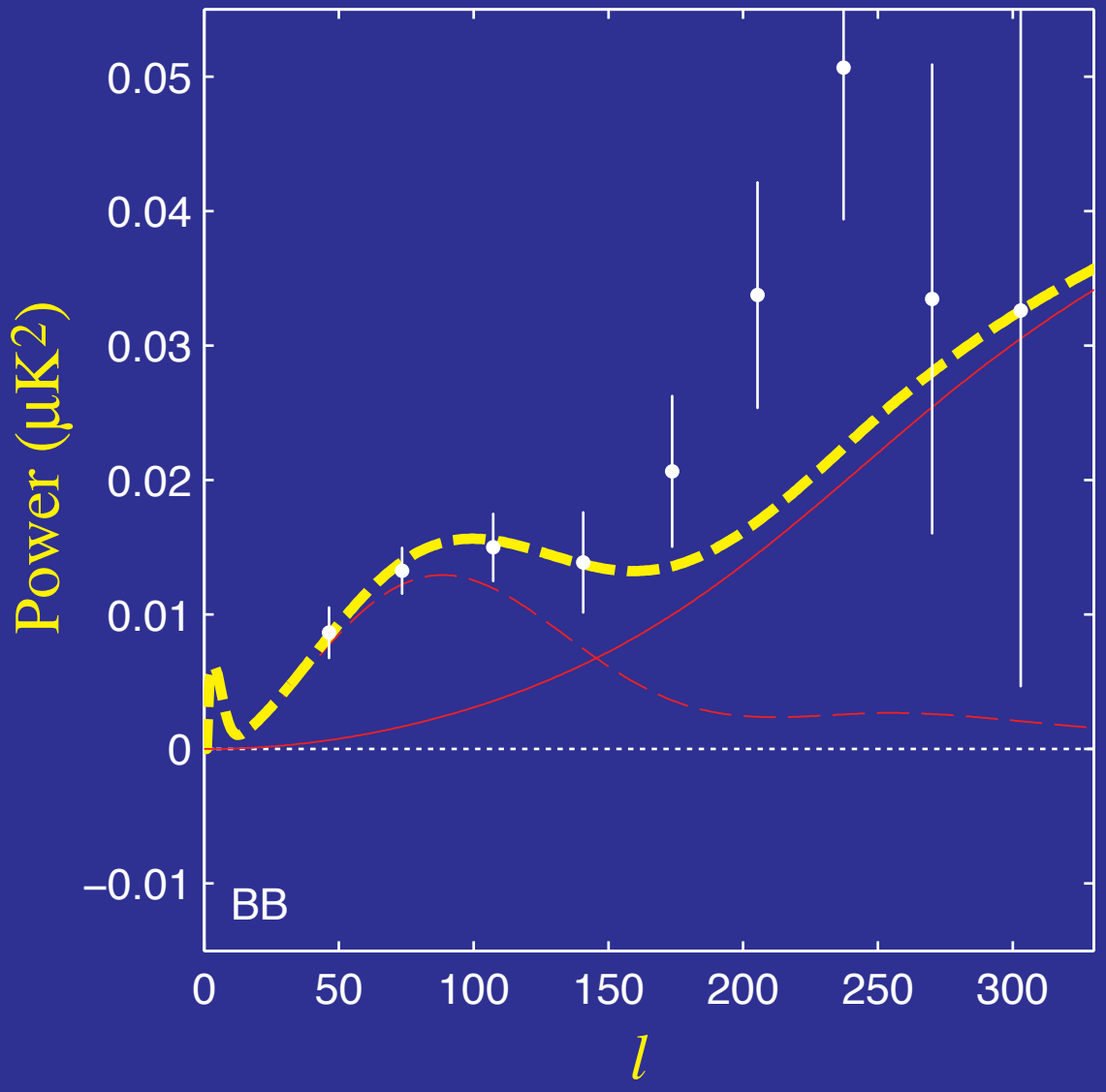
Neutrinos

- Predicts more damping of the CMB: sound horizon scales as conformal time η, random walk diffusion scale $\eta^{1/2}$



Gravitational Wave Excess

- BICEP2 B-polarization inflationary gravitational waves (r=0.2) imply low multipole temperature excess that is not observed (r<0.1)



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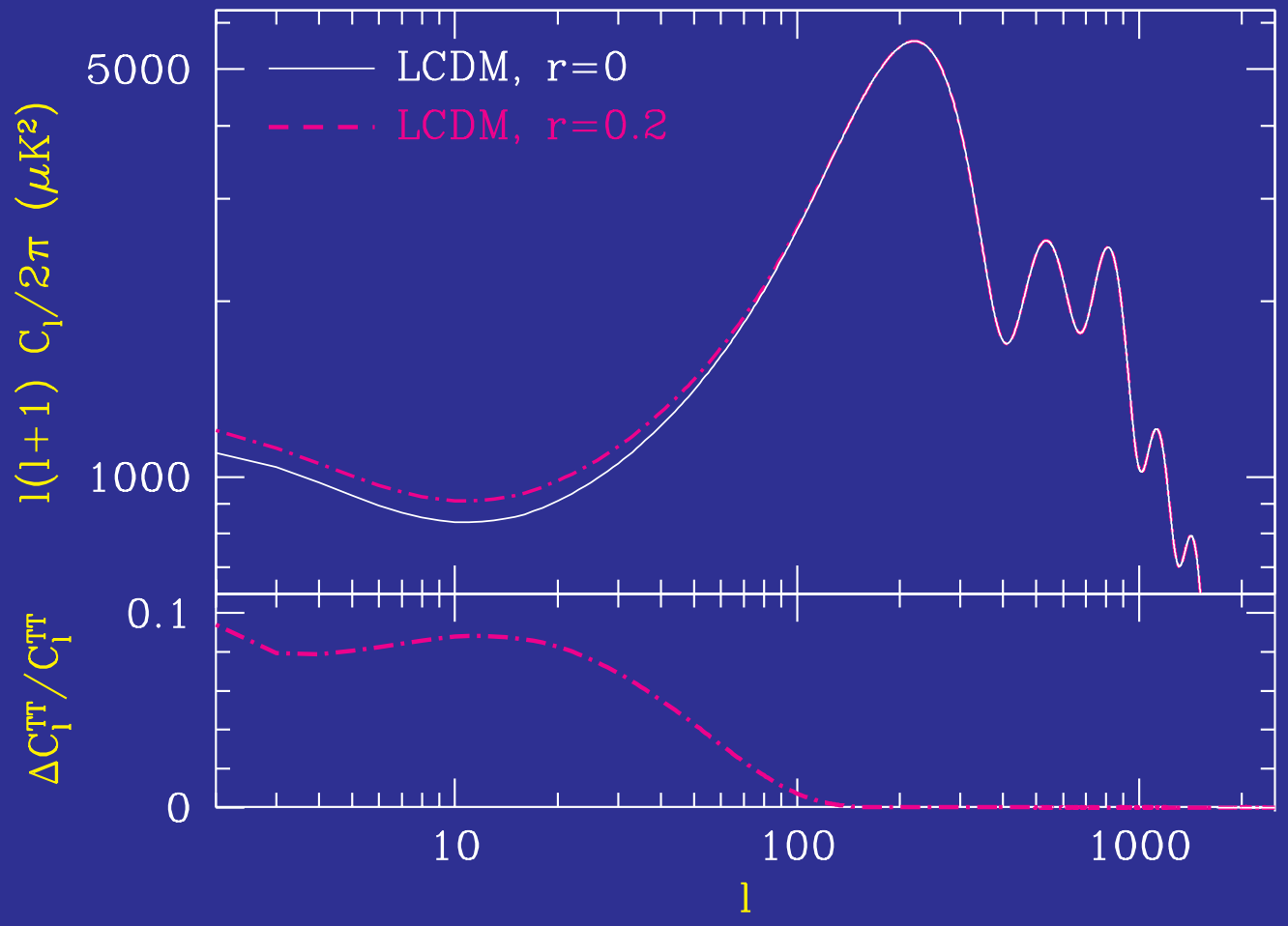
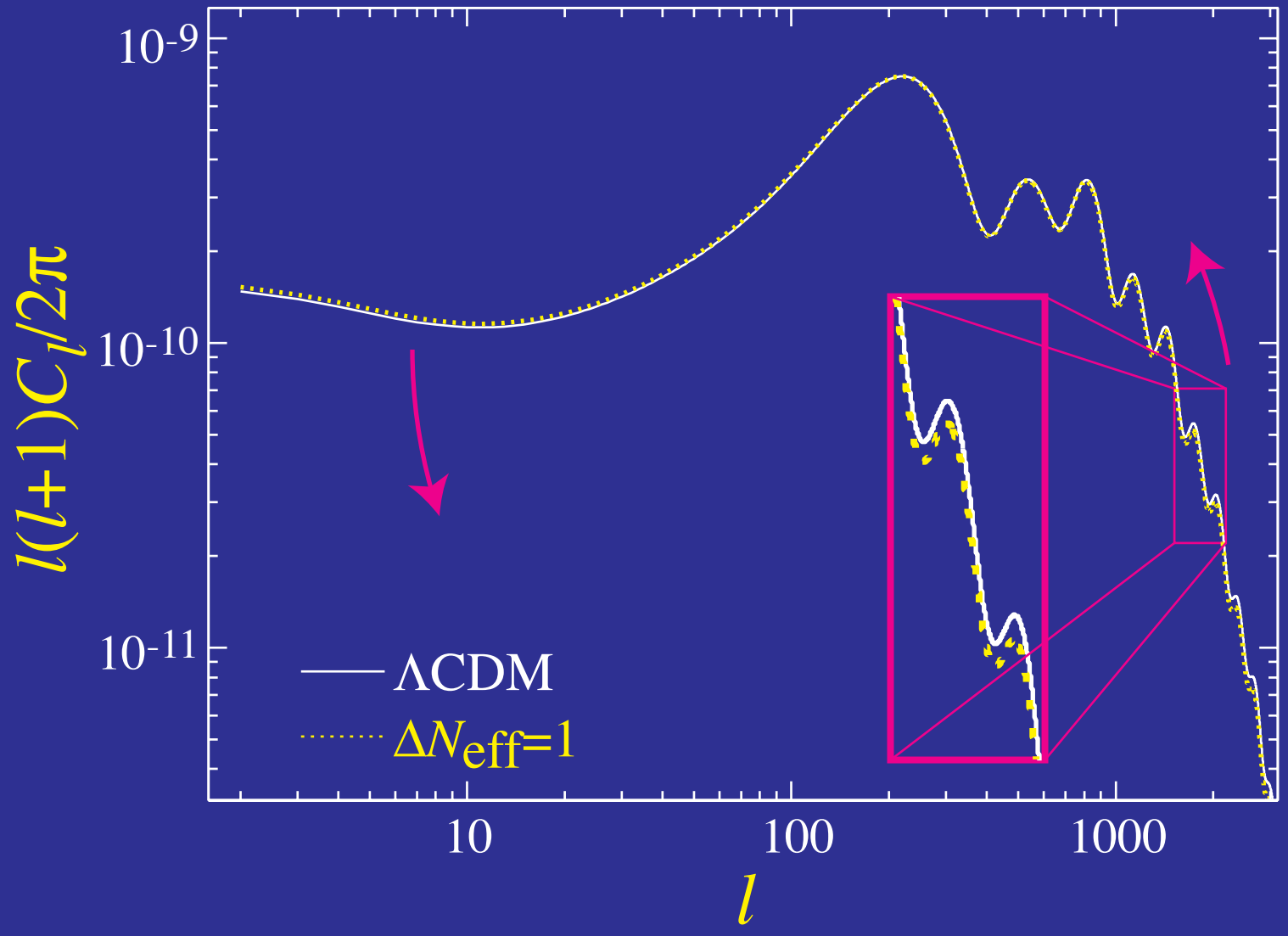


Neutrinos

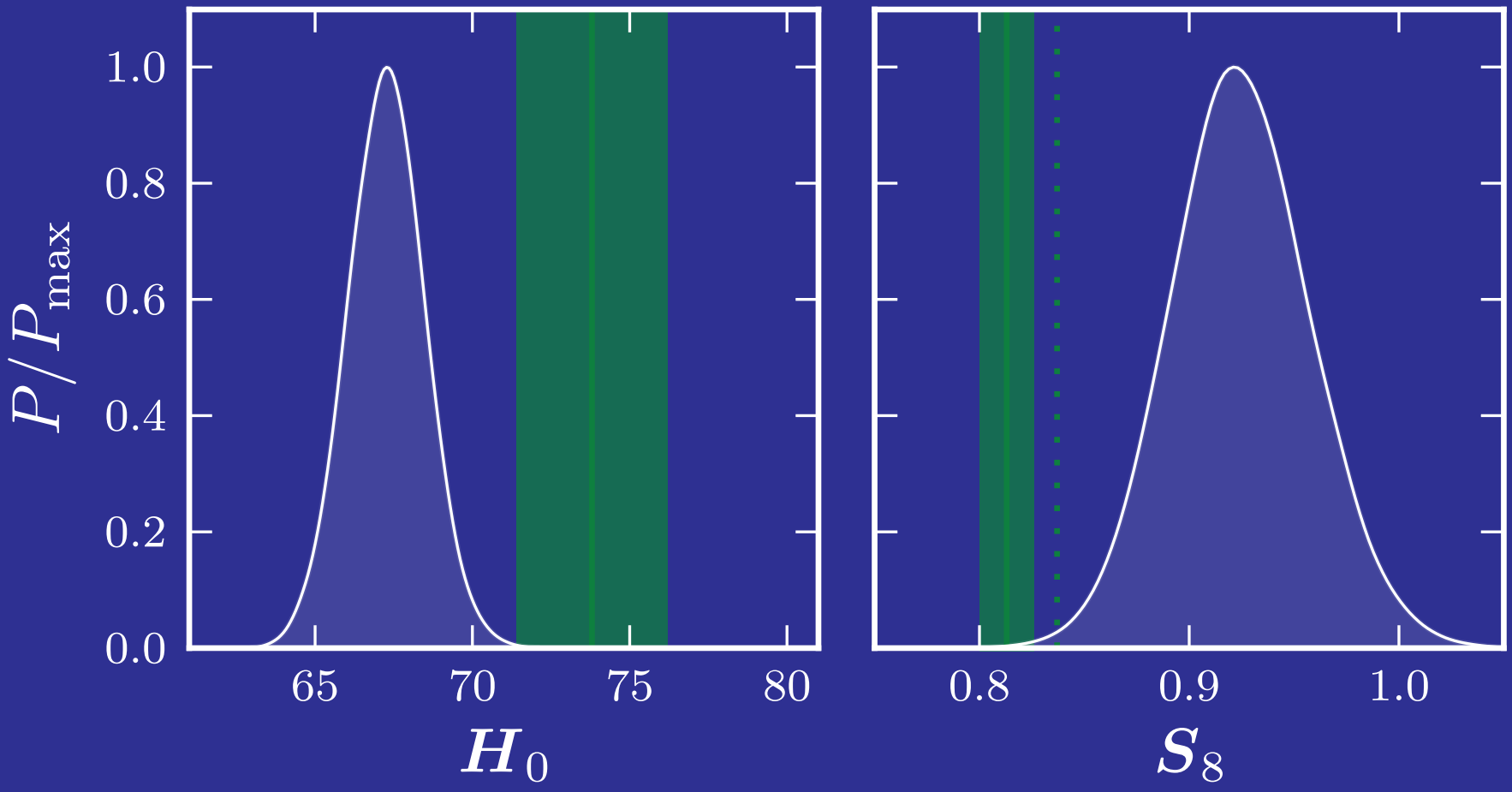
- Extra neutrino requires a blue-ward change in tilt, suppressing excess power at low multipoles



Neu(trino) Concordance

- Partially populated sterile, massive neutrinos change both the acoustic standard ruler and suppress structure and fixes both H_0 and clusters

Planck vs Local: ΛCDM



Wyman, Rudd, Vanderveld, Hu (2013)

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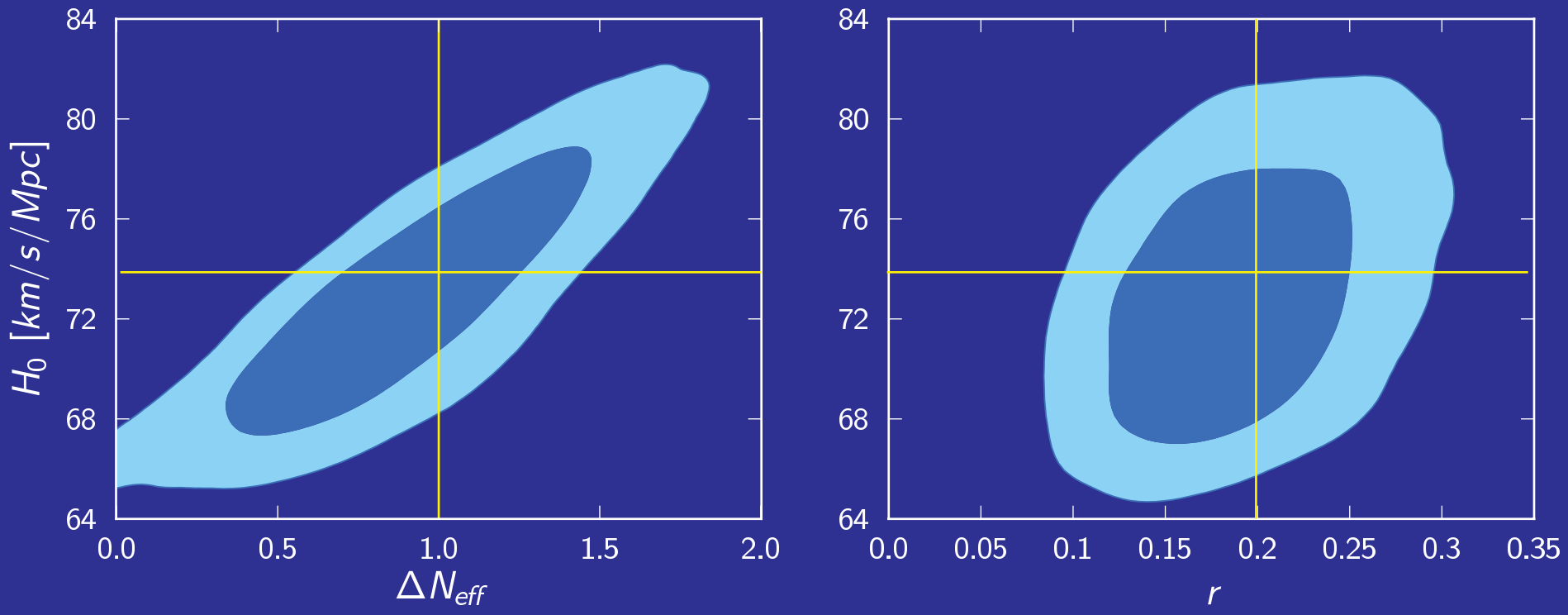
$\nu r\Lambda$CDM: CMB predictions



Dvorkin, Wyman, Rudd, Hu (2014) [Zhang, Li, Zhang 2014]

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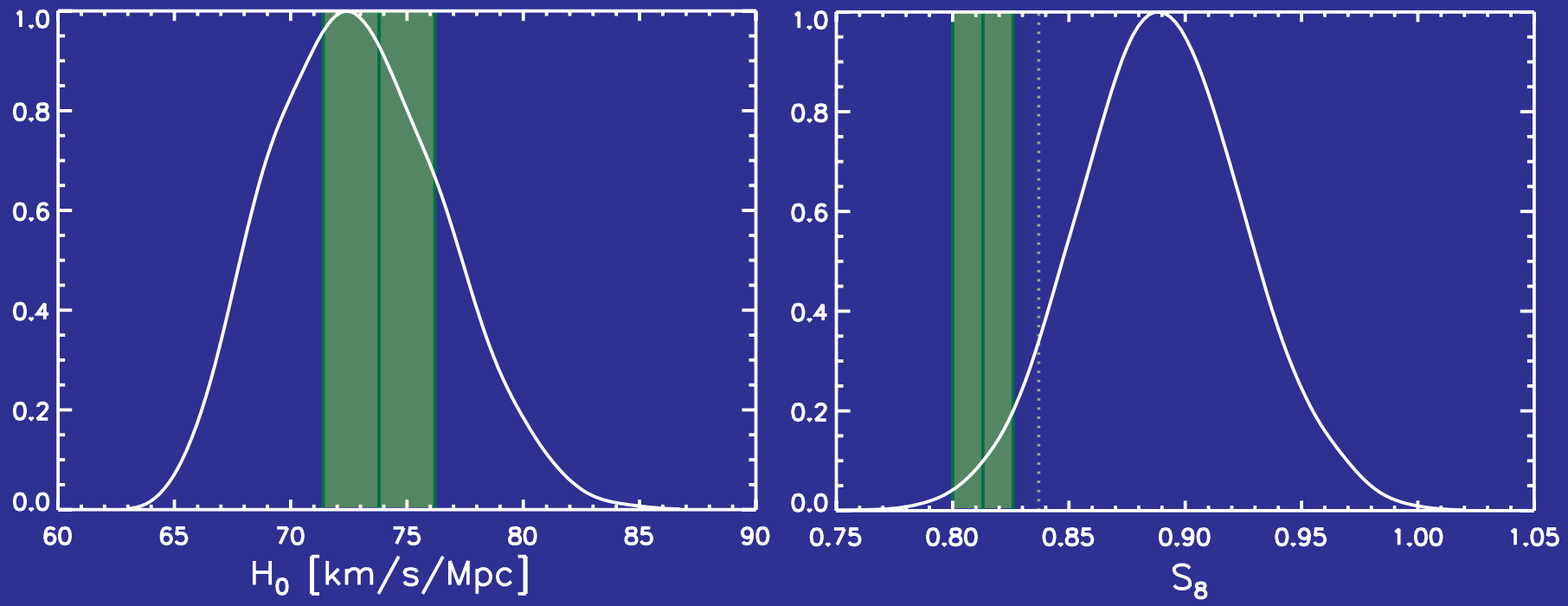
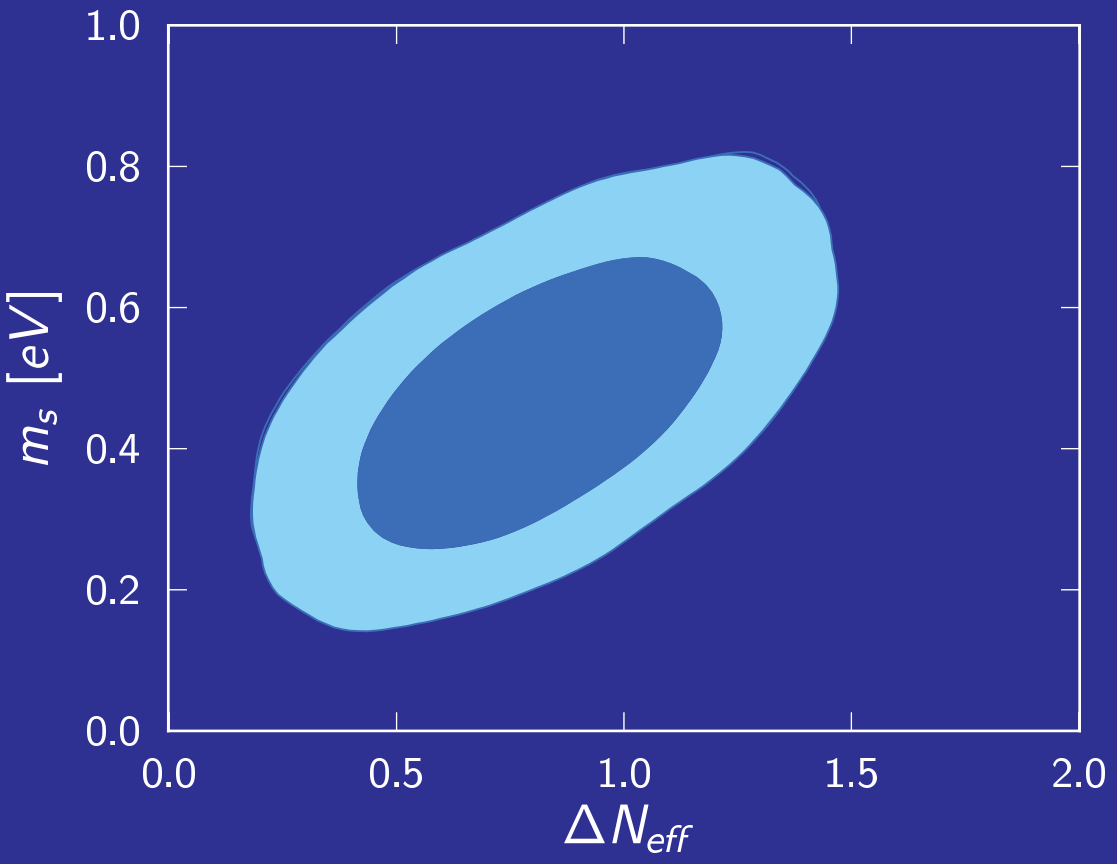


Dvorkin, Wyman, Rudd, Hu (2014) [Zhang, Li, Zhang 2014]

Neu(trino) Concordance

- Allows a fully populated extra sterile neutrino of 0.5eV

Sterile Neutrinos: >3σ stat



oscillation populated
mass=$m_s/\Delta N_{eff}$ (eV)

ΔN_{eff}=1, 1 fully populated species

Dvorkin, Wyman, Rudd, Hu (2014) [Zhang, Li, Zhang 2014]

Summary

- ΔH_0 from flat ΛCDM prediction indicates new physics
- Predictions from CMB are as precise as standard ruler calibration $|\Delta h/h| \approx |\Delta\Omega_m h^2/\Omega_m h^2| \approx 1.7\%$ currently
- To test predictions require direct measurements at this precision
- New physics either additions to ΛCDM at recombination (standard ruler) or during acceleration (distance-redshift)
- Consistency with damping tail, BAO distinguishes cases

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- New physics either additions to ΛCDM at recombination (standard ruler) or during acceleration (distance-redshift)
- Consistency with damping tail, BAO distinguishes cases
- Current mismatch between $H_0 \approx 67$ prediction and $H_0 \approx 74$ measurements may indicate extra relativistic species at recombination
- Simultaneously alleviates tension with BICEP2 inflationary tensor detection
- If massive neutrino, also alleviates tension with cluster abundance