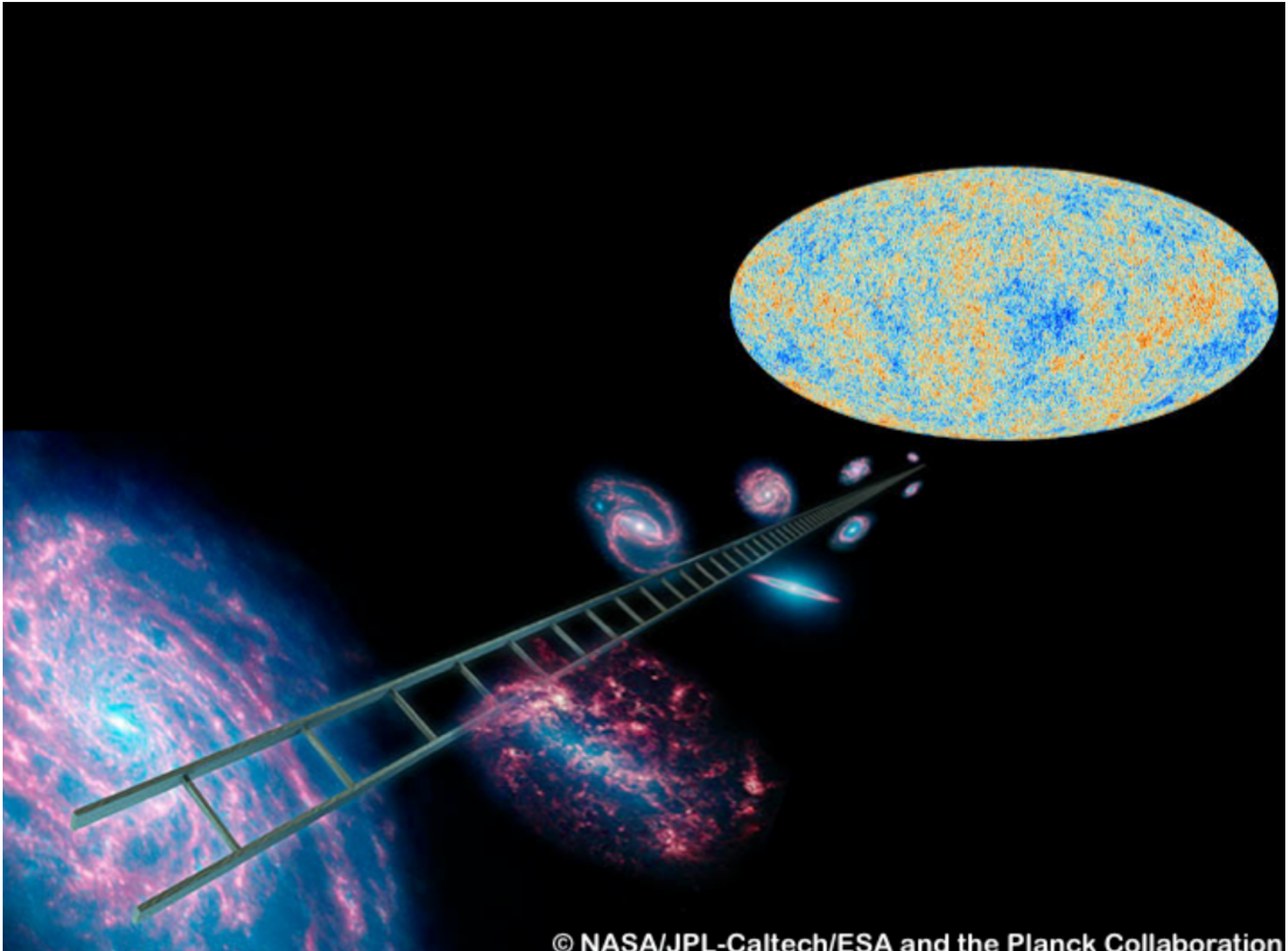
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The Hubble Constant and the Cosmic Microwave Background

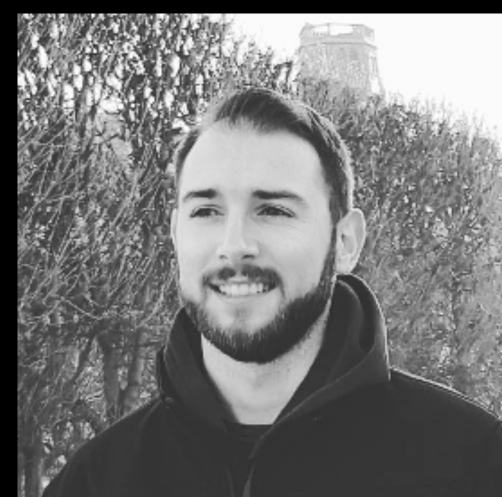
Lloyd Knox
UC Davis

https://arxiv.org/abs/1811.00537 and ApJ

Sounds Discordant: Classical Distance Ladder and ΛCDM-based Determinations of the Cosmological Sound Horizon

Kevin Aylor

Mackenzie Joy



Marius Millea

Srini Raghunathan

Kimmy Wu

^
LK

The Hubble Hunter's Guide
in preparation
LK and Marius Millea

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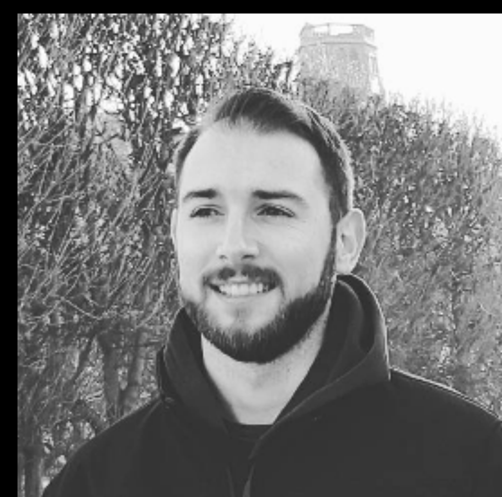
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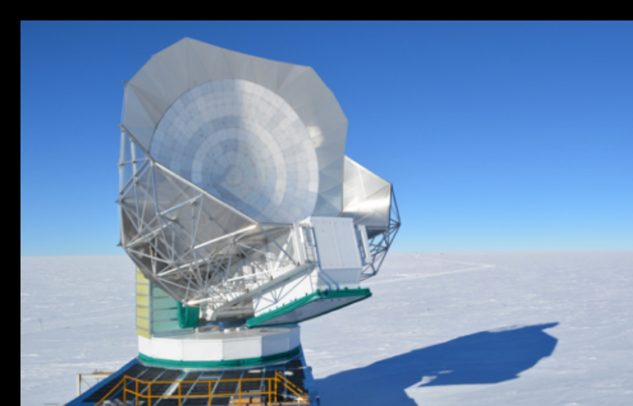

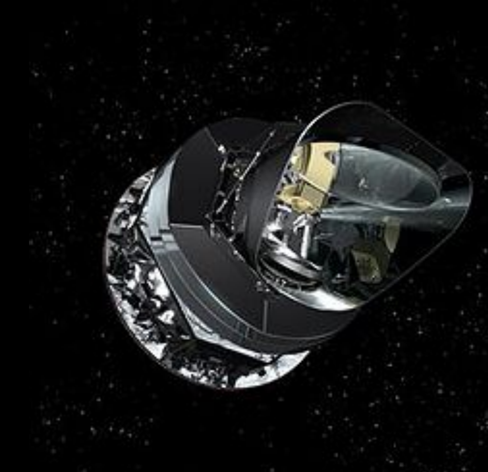

Aylor + SPT, (2017), Hou + SPT (2018)   Planck PIP LI (2018)

Main Messages

1. Systematic errors in CMB data are not a possible route out of our current discord.

2. Model changes away from LCDM are very tightly constrained by CMB measurements.

3. There are some (weak) inconsistencies internal to CMB data, interpreted with LCDM. Speculation: One in particular is due to the presence of additional components that lower the sound horizon.

Outline

- Why have we learned so much from the CMB?
- CMB Measurements are consistent
- LCDM predictions for CMB measurements
- A related tension: the sound horizon
    - Distance Ladder vs. LCDM sound horizon inferences
- How LCDM + CMB ==> H_0
    - Including how LCDM + CMB ==> $\omega_{\rm m} \equiv \Omega_{\rm m} h^2$
- Cosmological Solutions
- The value of CMB observations to come

Why has CMB been so valuable?

- Statistical properties of CMB maps are **calculable** given a model (perturbation theory is highly accurate)
- **Rich** phenomena (TT, TE, EE, BB power spectra with rich features, and non-Gaussianity induced by lensing)
- **Measurable** (demonstrated levels of sensitivity, systematic error control, foreground contamination control)

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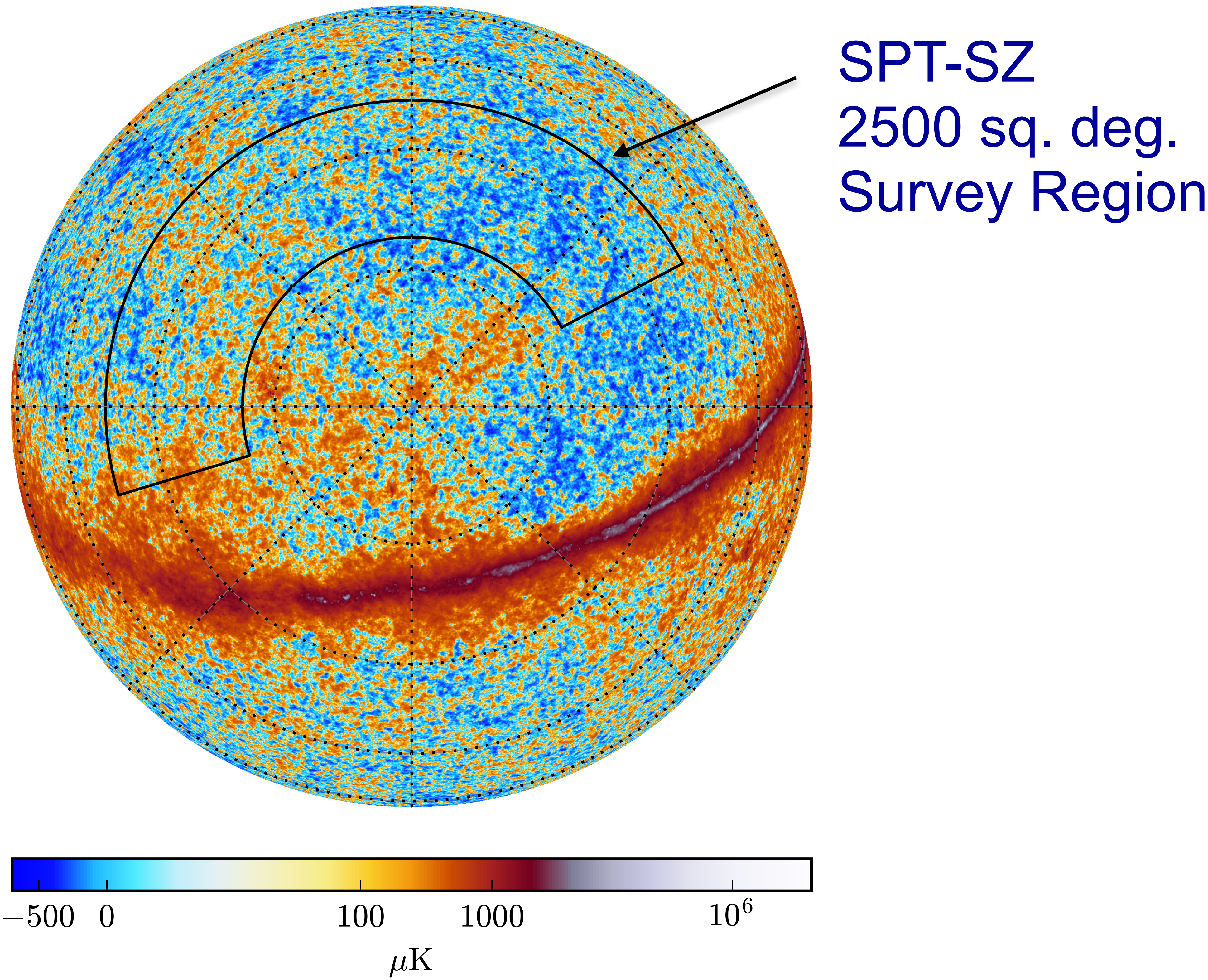
Planck and SPT

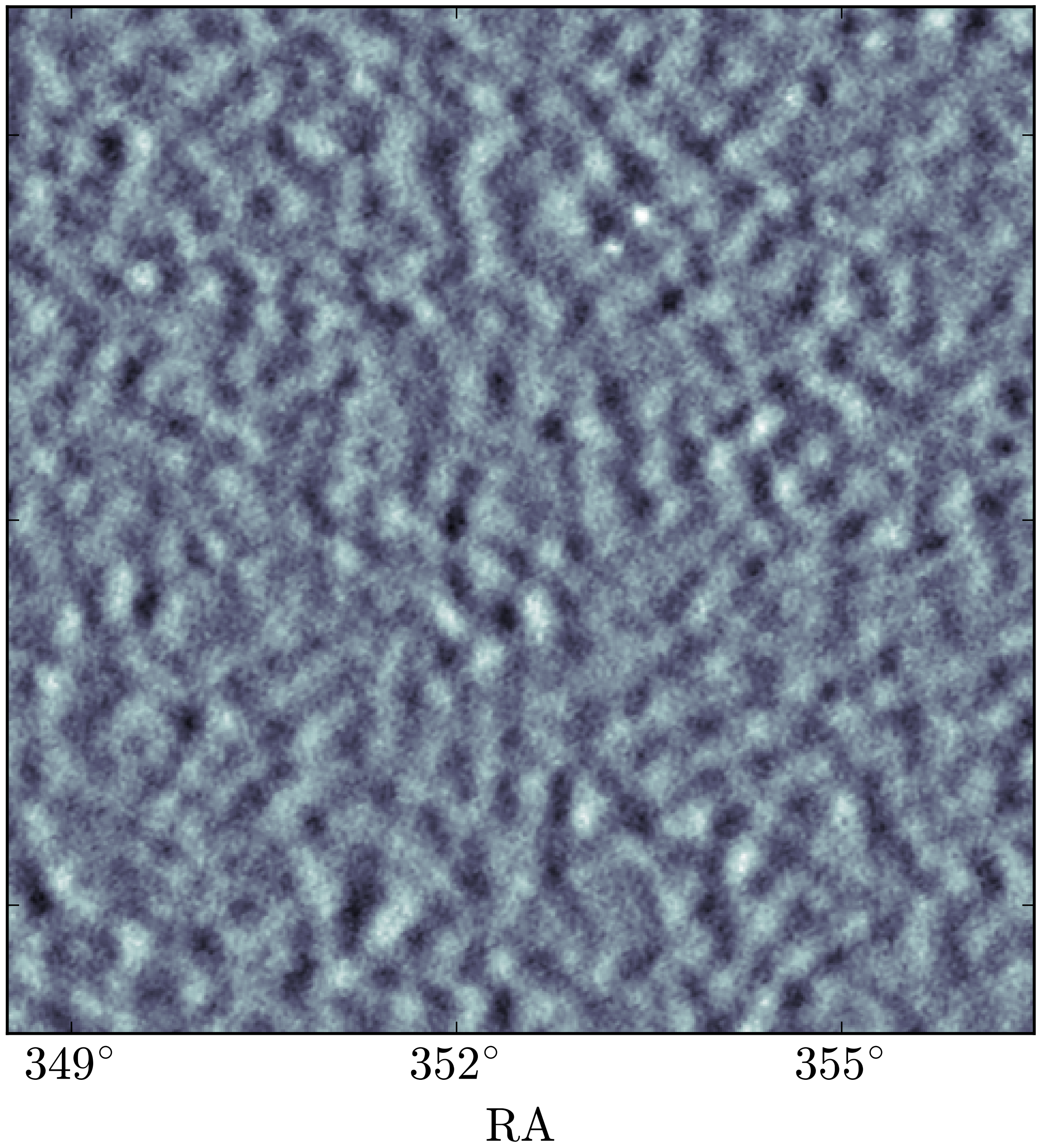
More in Kimmy Wu's talk this p.m.

Hou et al. 2018
Aylor et al. 2017



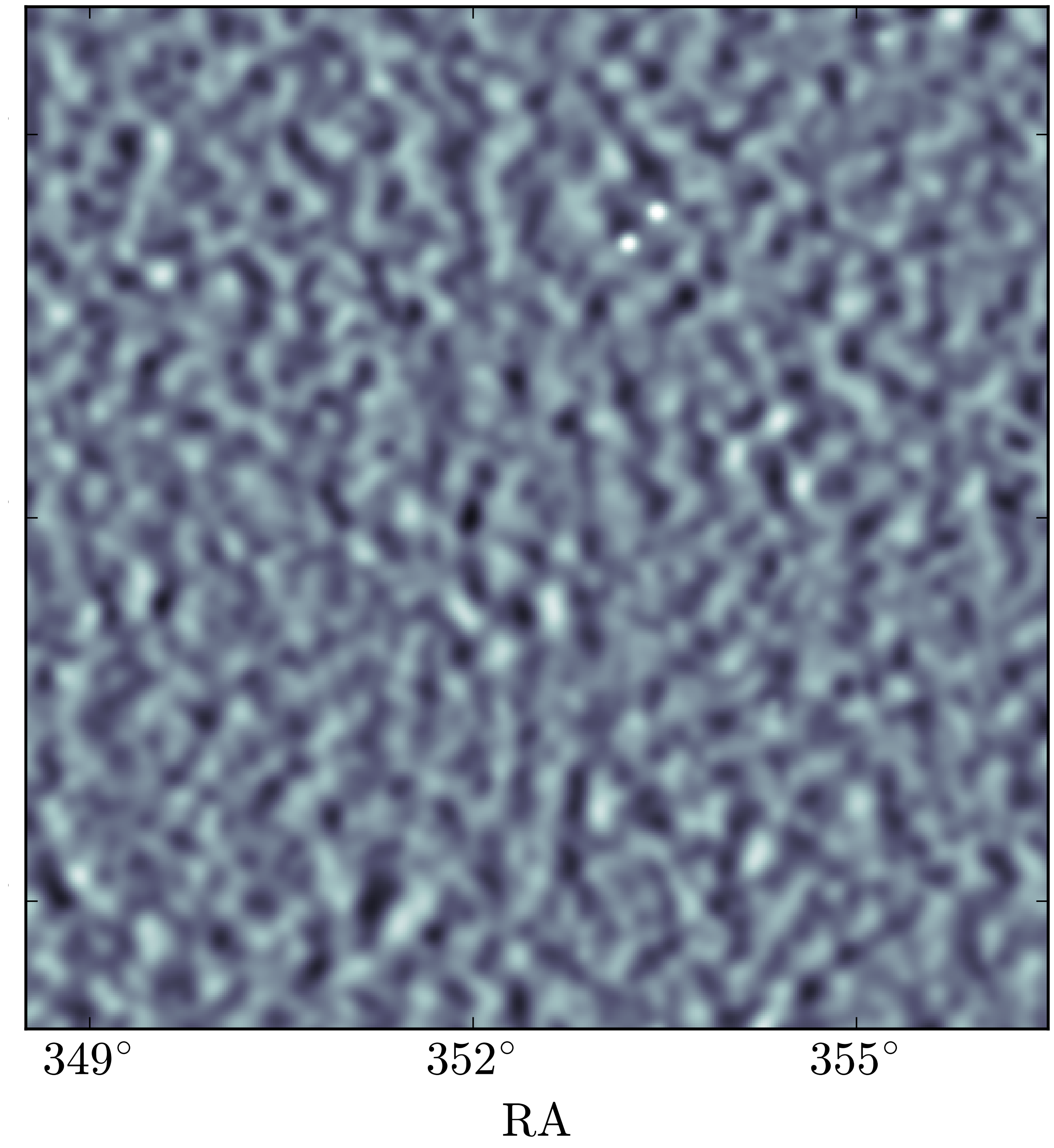
Planck 143 GHz map centered on South Celestial Pole

Planck 143 GHZ Filtered



Hou et al. (2018)

SPT 150 GHZ Smoothed



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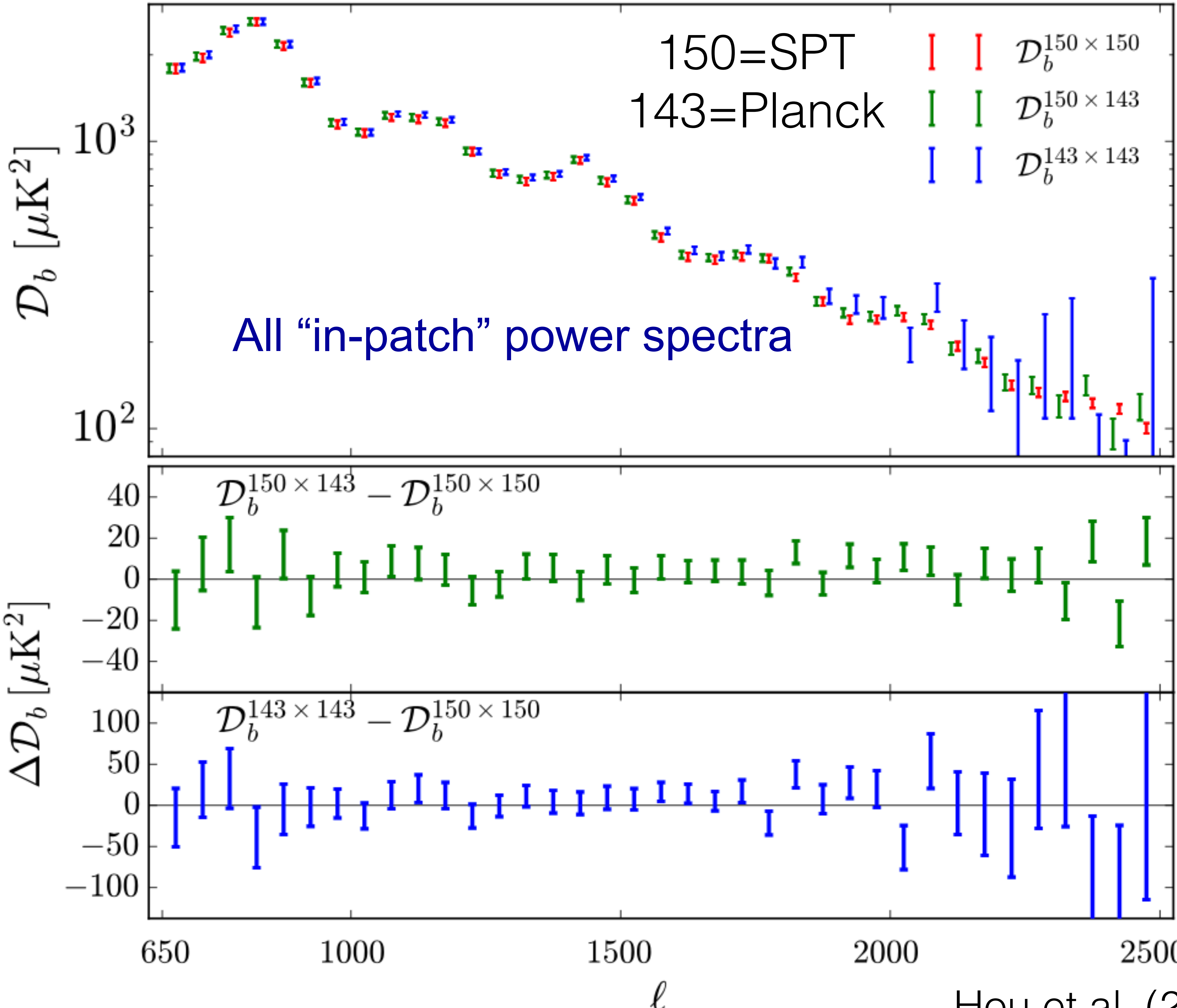

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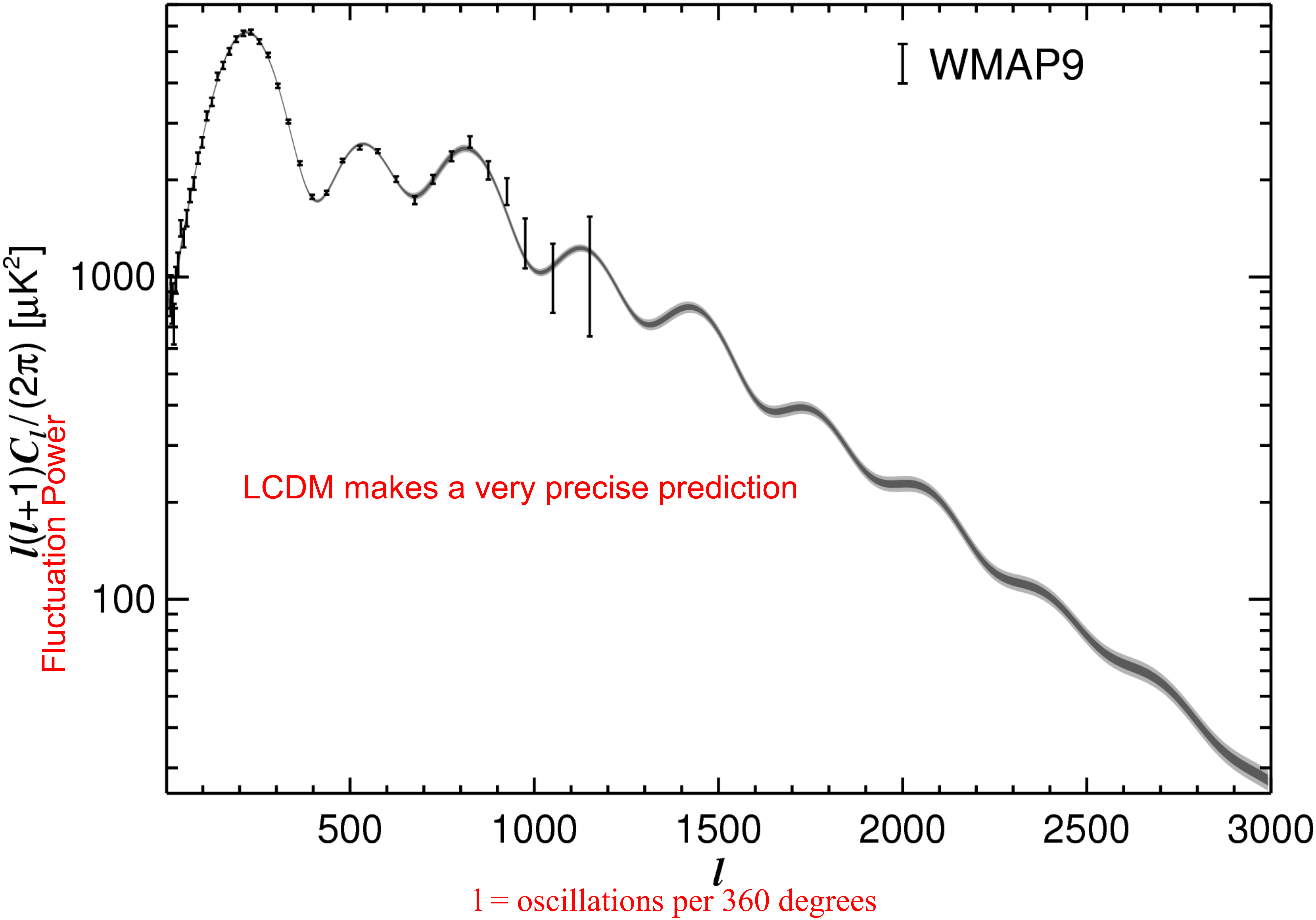
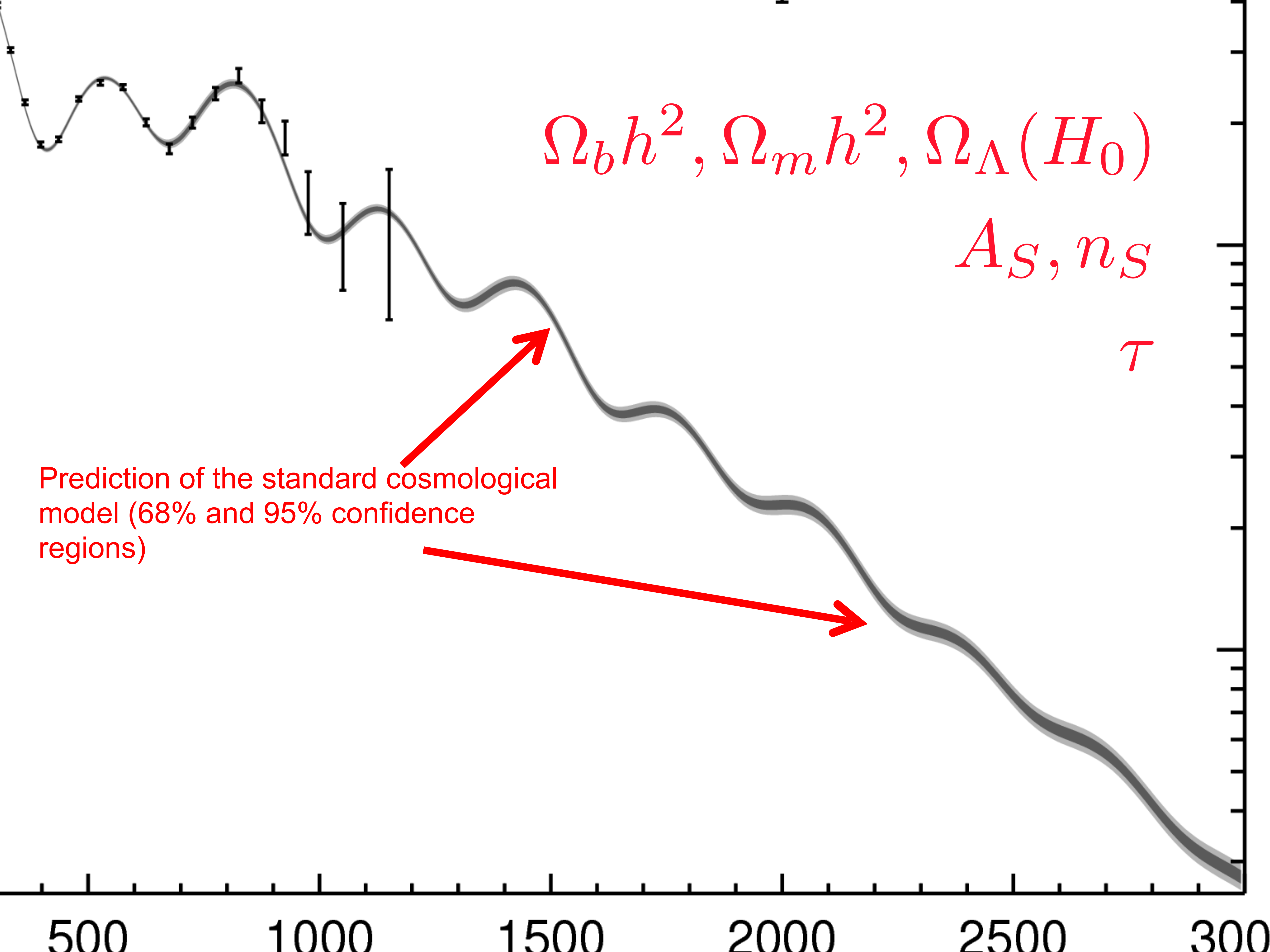
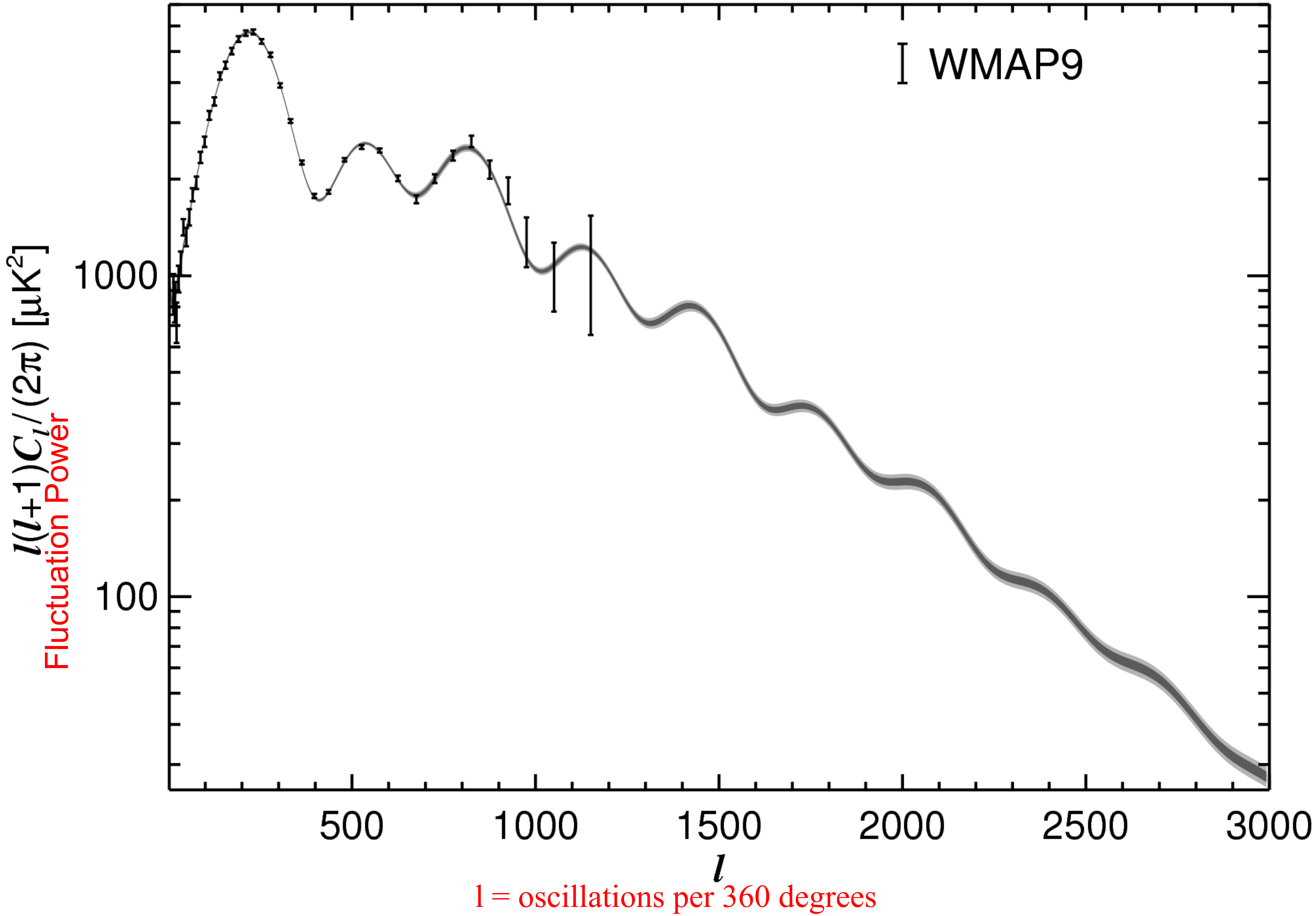
The LCDM Model is a Highly Predictive and Empirically Successful Model

Low ell TT ==predicts==> High ell TT


WMAP9
1000
100
500
1000
1500
2000
2500
3000
$l(l+1)C_l/(2\pi)$ [μK^2]
Fluctuation Power
LCDM makes a very precise prediction
l
l = oscillations per 360 degrees


$\Omega_b h^2, \Omega_m h^2, \Omega_\Lambda (H_0)$
A_S, n_S
τ
Prediction of the standard cosmological model (68% and 95% confidence regions)
500
1000
1500
2000
2500
300


WMAP9
1000
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500
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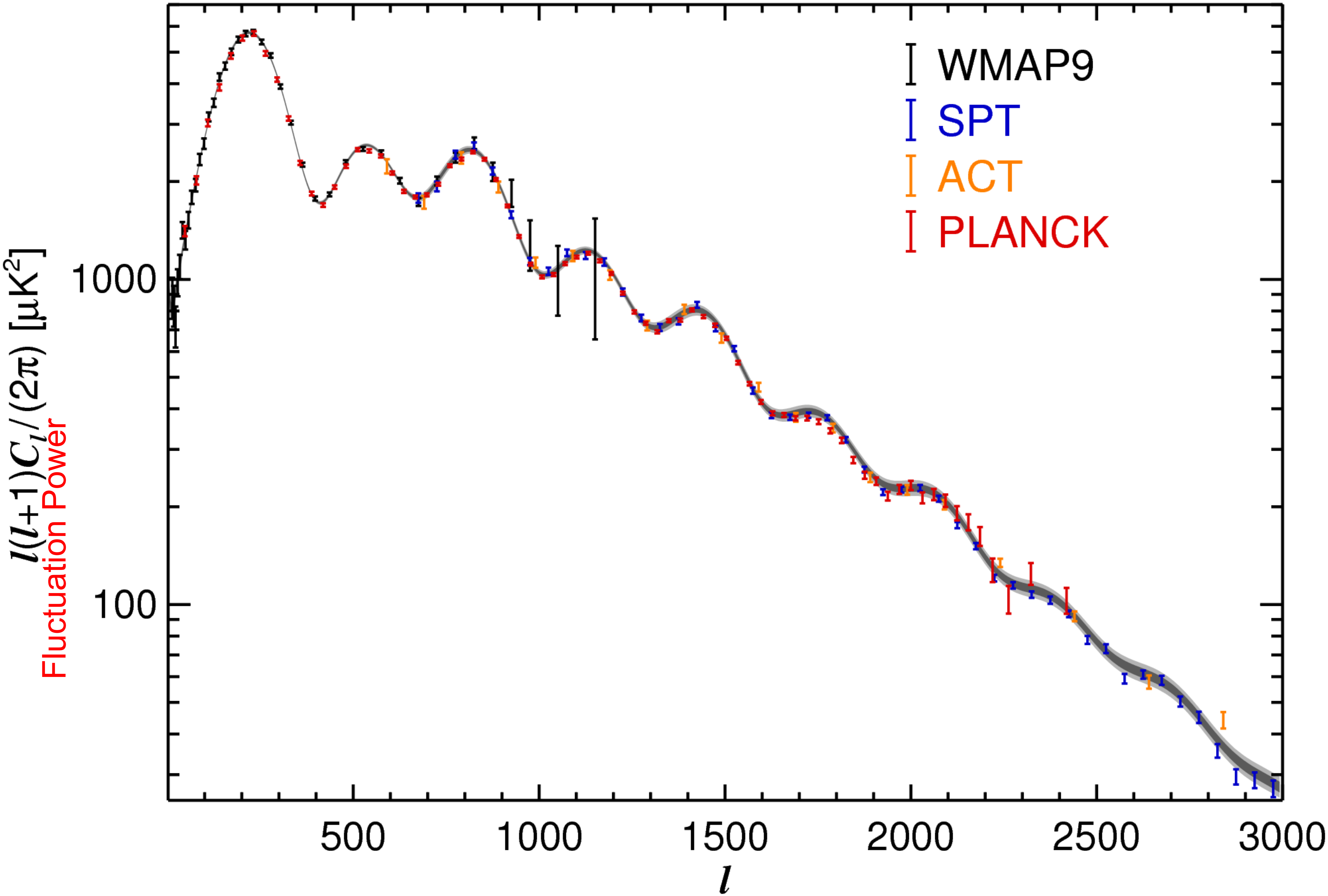
The CMB Power Spectrum

Zhen Hou



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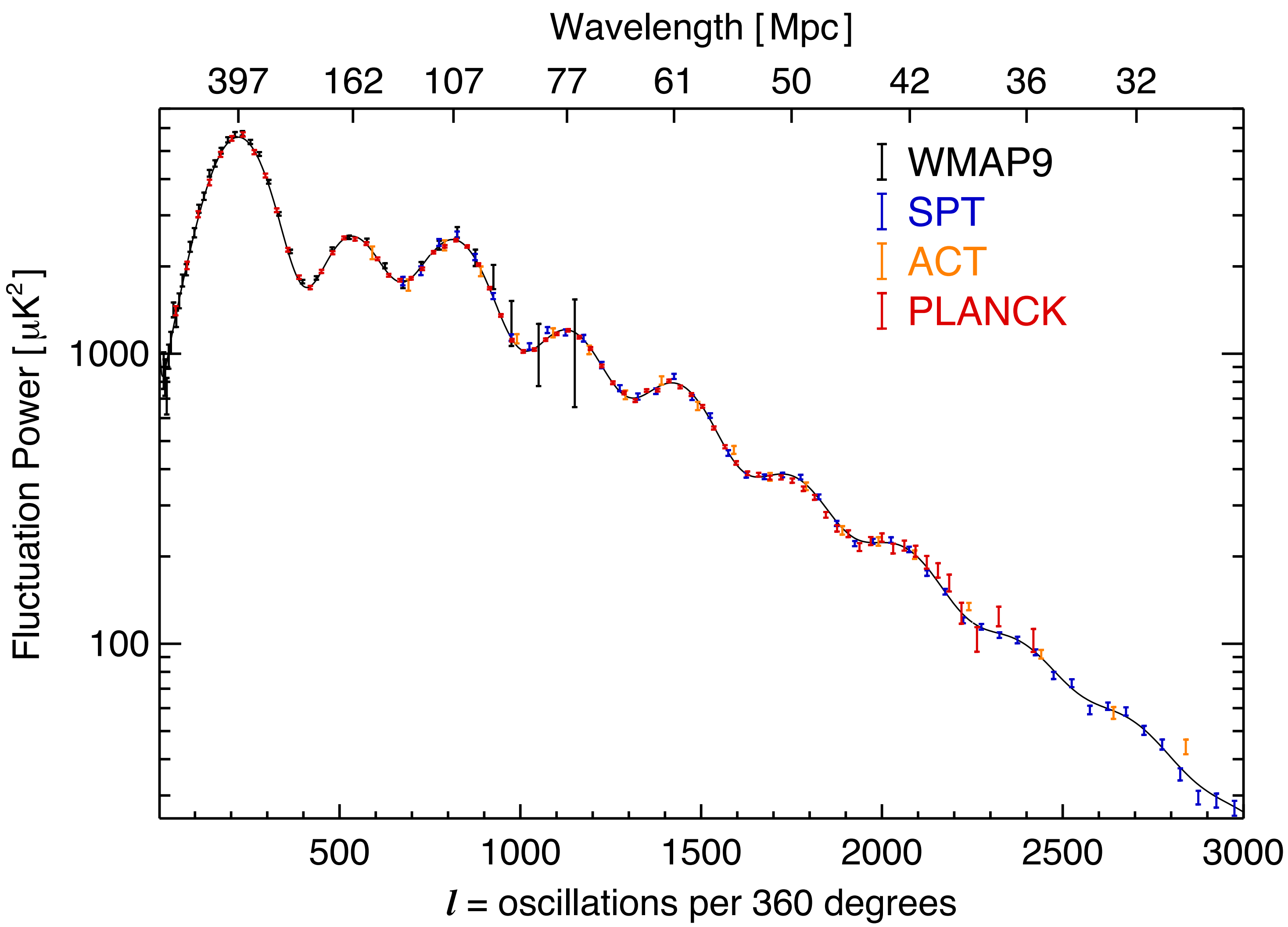
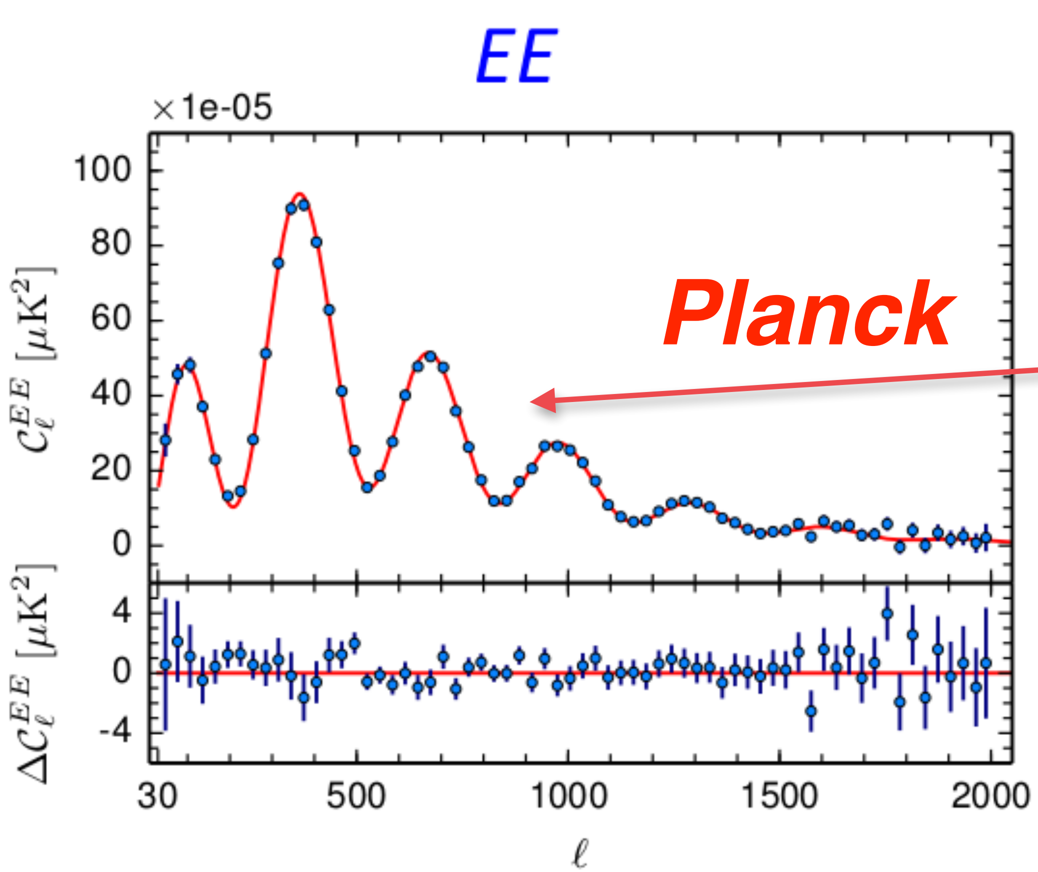
Low ell TT ==predicts==> High ell TT

TT ==predicts==> EE





Theory curve is best-fit LCDM model to Planck TT.

The LCDM Model is a Highly Predictive Model

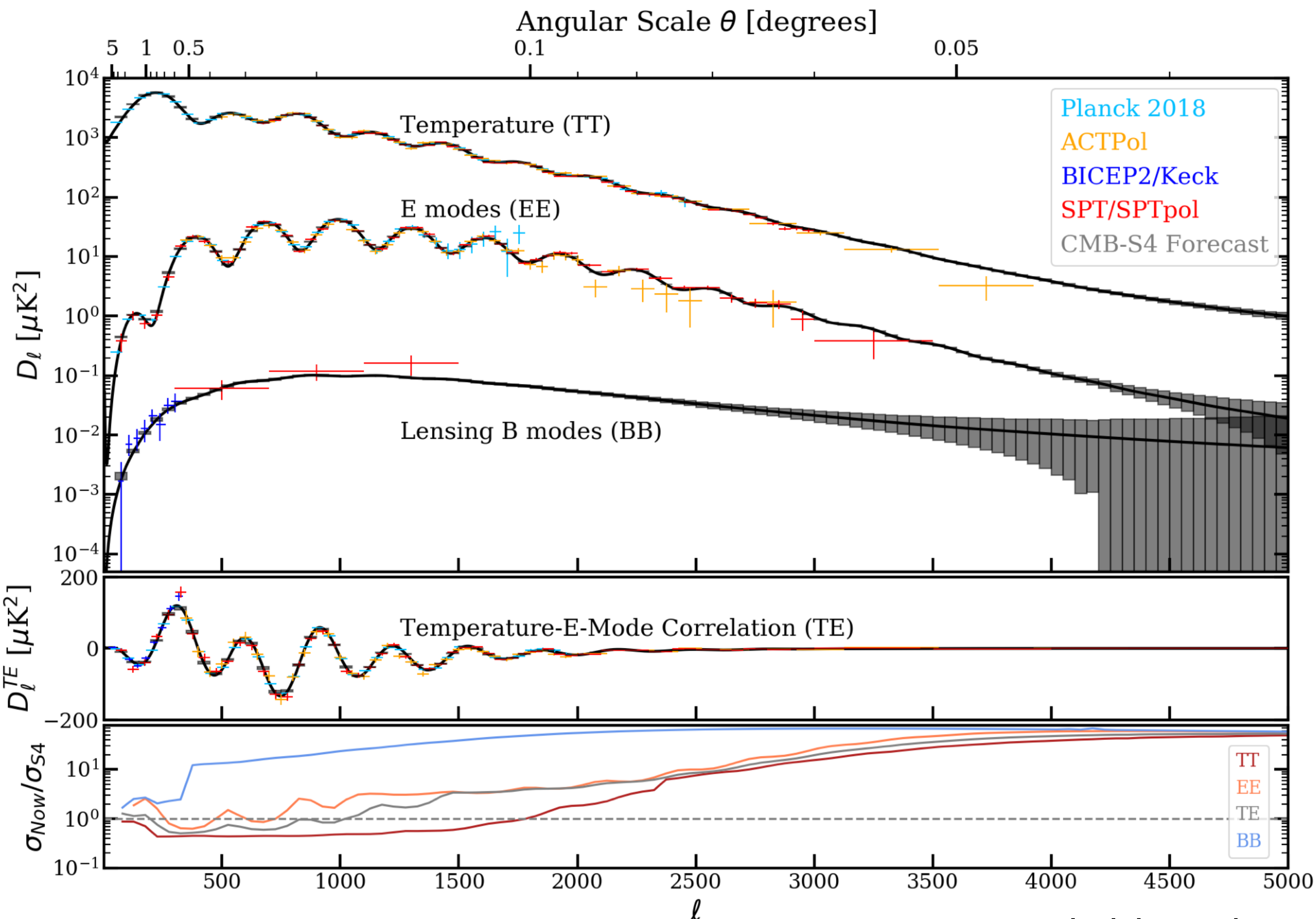
Low ell TT ==predicts==> High ell TT

TT ==predicts==> EE

(and TE, not shown)

TT ==predicts==> BB

Summary of Current Measurements (+CMB-S4 Forecasts)



J. Henning

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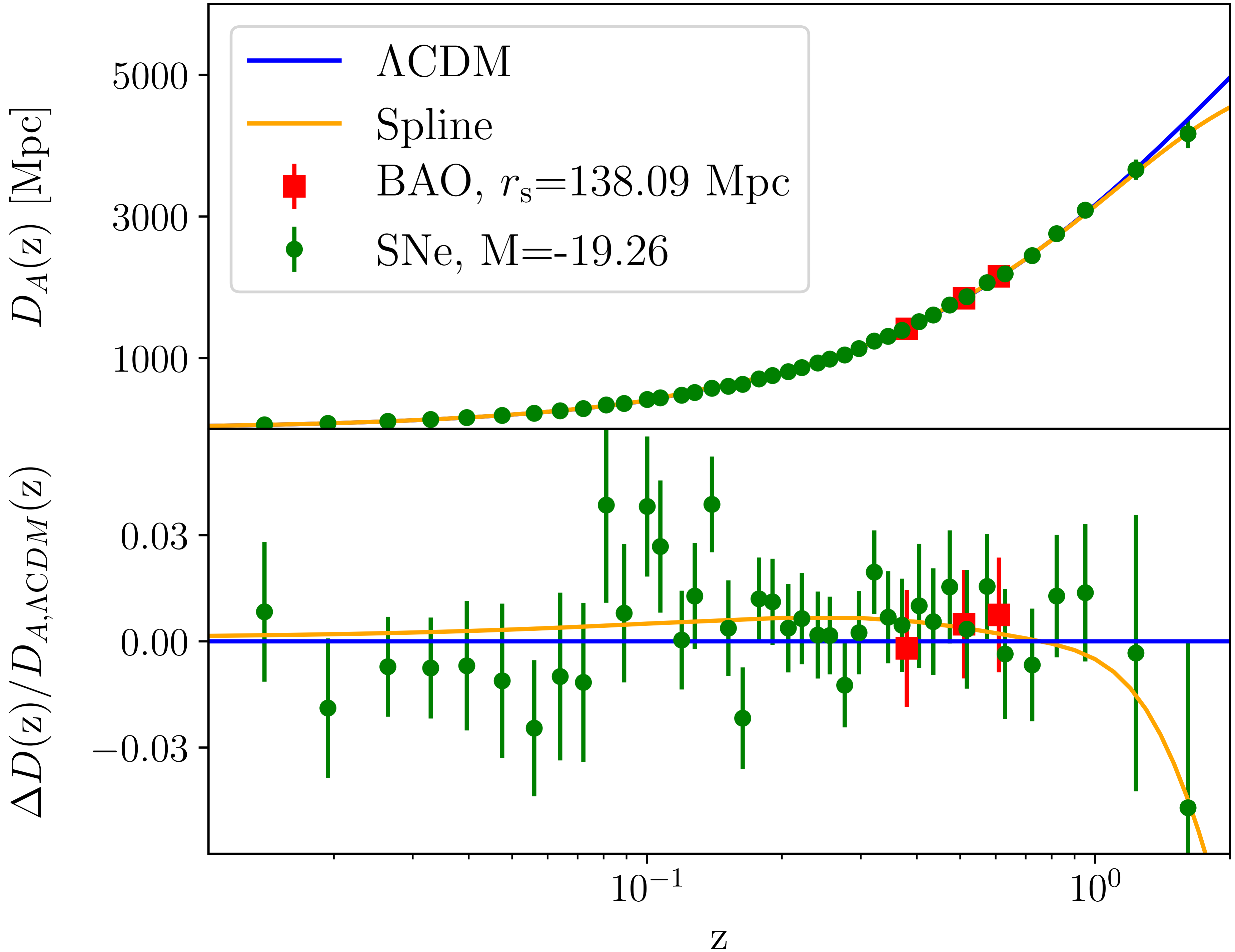
Using Cepheid-calibrated supernovae to determine the sound horizon

SNe=Pantheon (Scolnic et al. 2018), cal. by R18:
BAO = BOSS galaxy BAO (Alam et al. 2017)

$H_0 = 73.52 \pm 1.62$ km/sec/Mpc

Aylor et al. (2019)



See also Bernal, Verde, and Riess 2016, Verde et al. 2017

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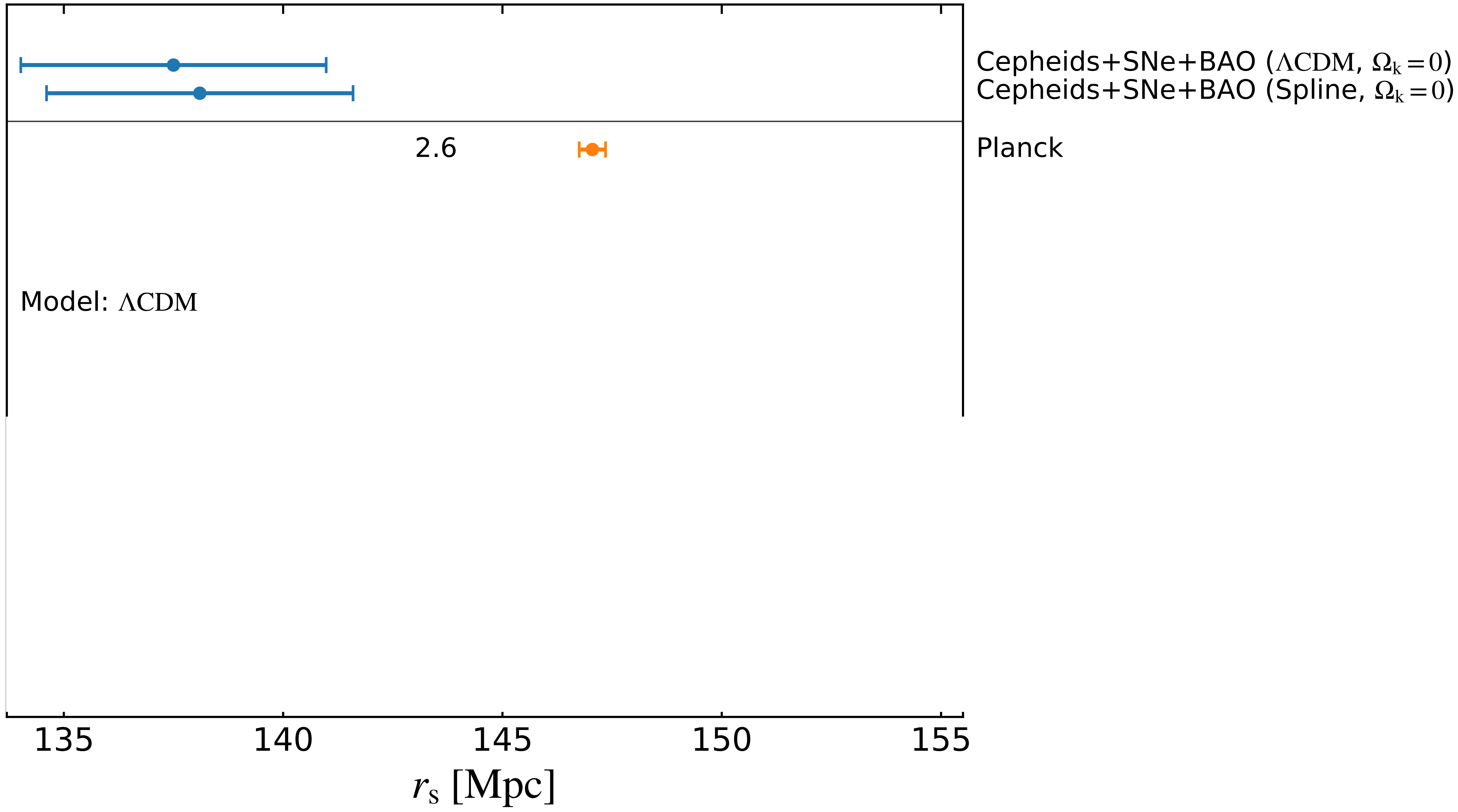

“Sounds Discordant”, Aylor, Joy, LK, Millea, Raghunathan & Wu (2018)

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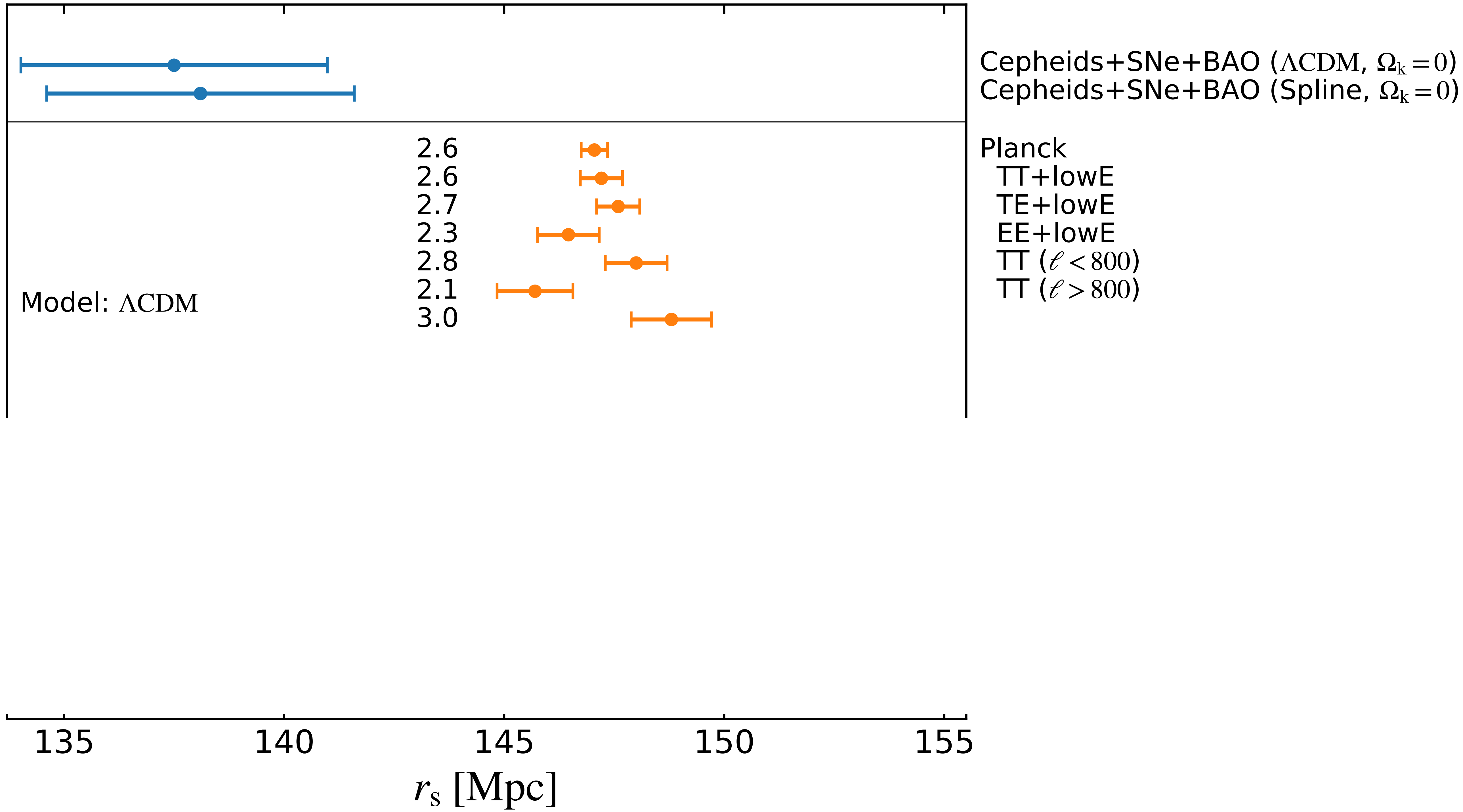

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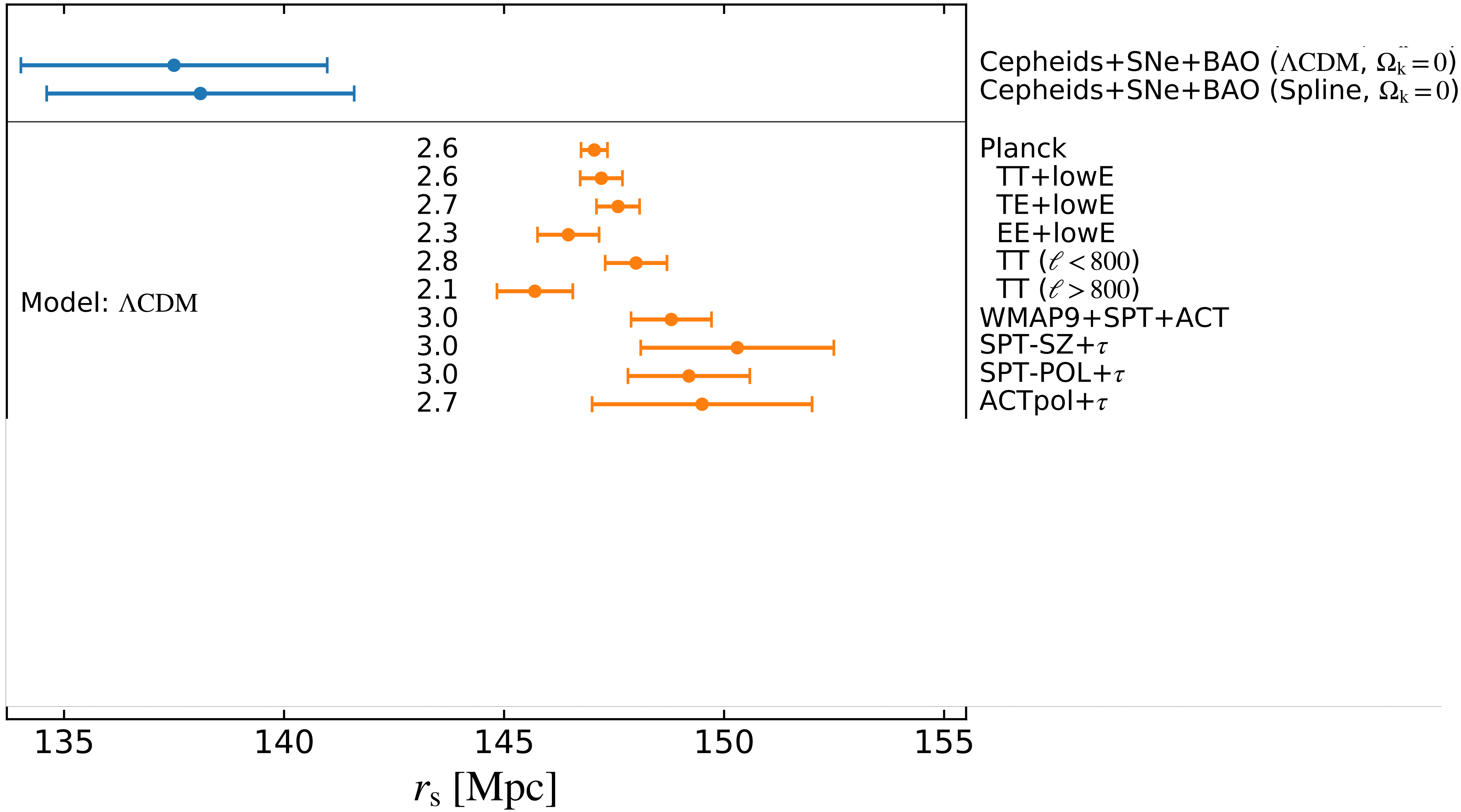

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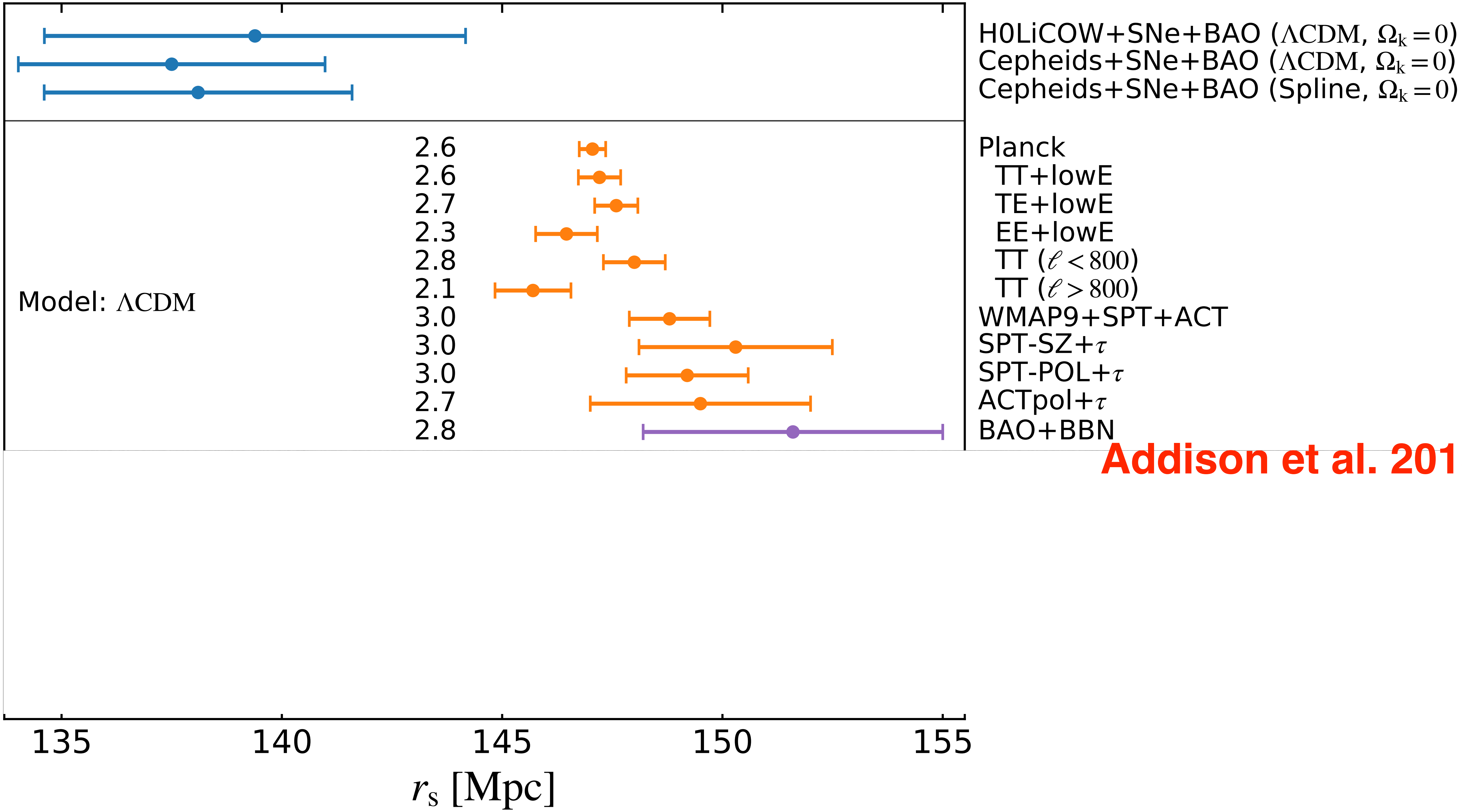
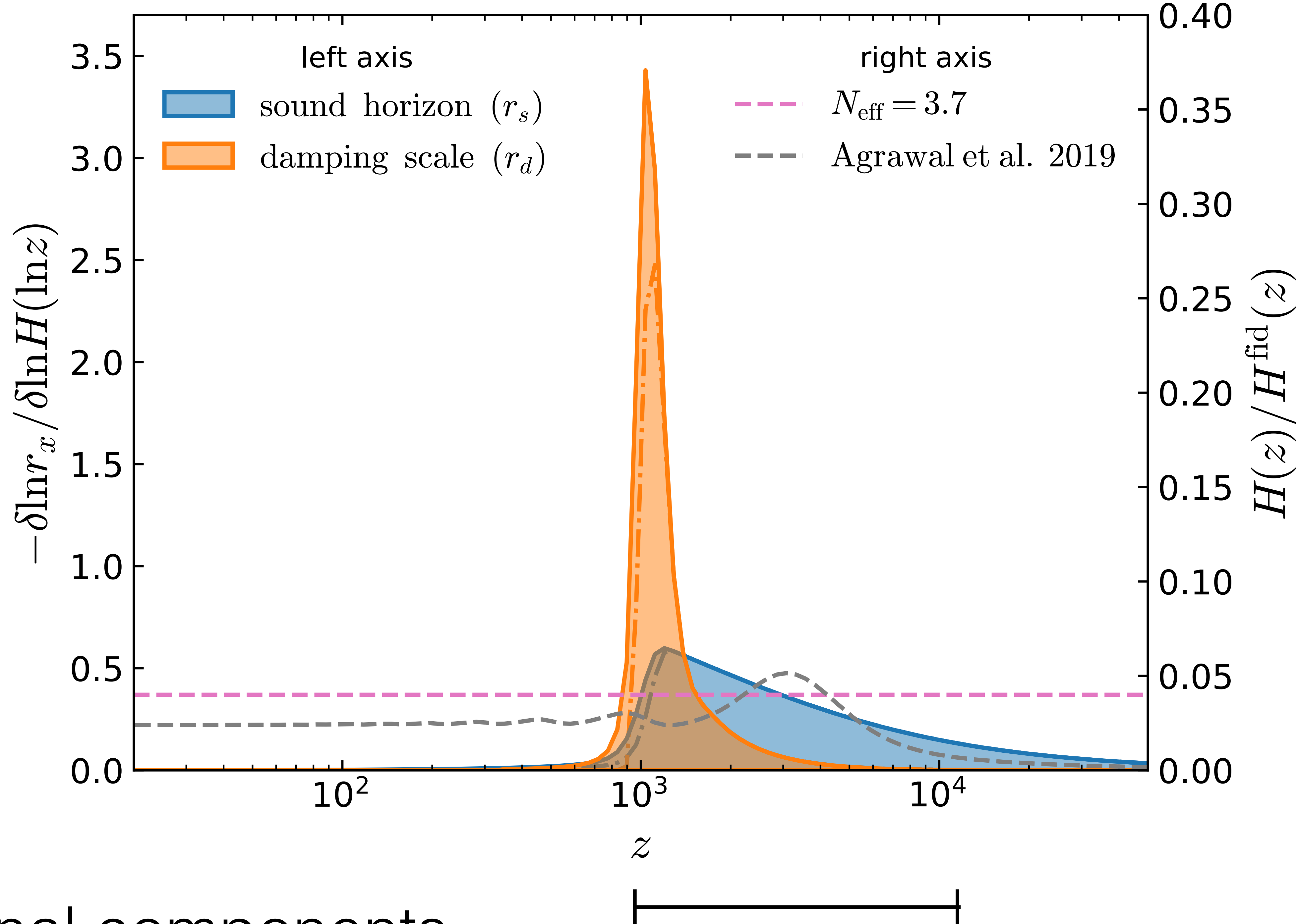


Addison et al. 2018

“Sounds Discordant”, Aylor, Joy, LK, Millea, Raghunathan & Wu (2018)

Hubble Hunter's Guide (M. Millea + LK, in prep)



Additional components must be important in this interval if they are to reduce the sound horizon (Aylor et al. 2019)

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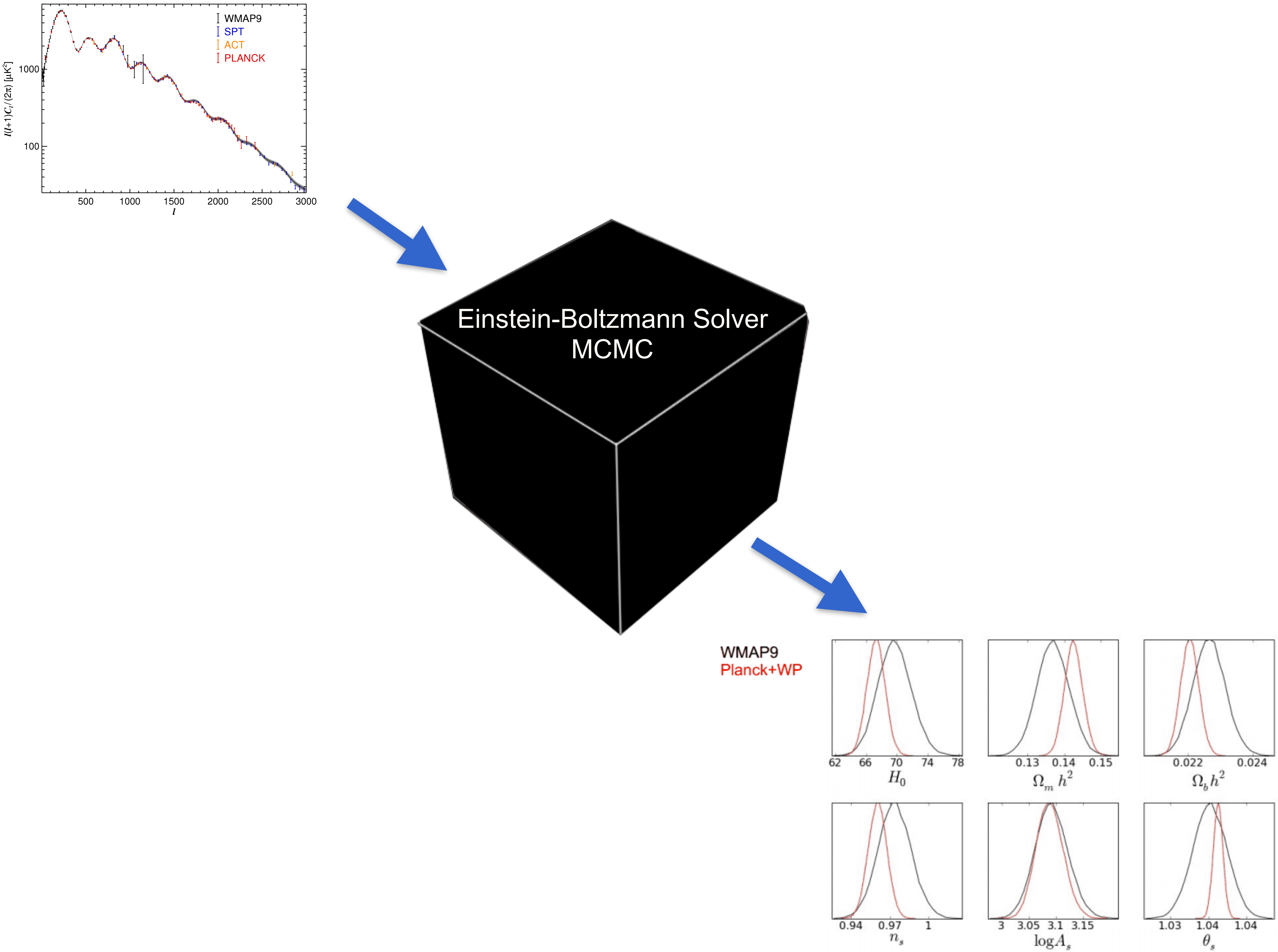

WMAP9
SPT
ACT
PLANCK
1000
100
500 1000 1500 2000 2500 3000
l
l(l+1)C_l/(2π) [μK²]
Einstein-Boltzmann Solver
MCMC
WMAP9
Planck+WP
62 66 70 74 78
H_0
0.13 0.14 0.15
Ω_m h²
0.022 0.024
Ω_b h²
0.94 0.97 1
n_s
3 3.05 3.1 3.15
log A_s
1.03 1.04 1.04
θ_s

Determining H_0 from CMB Data in 3 steps
Step 1: Calibrating a Standard Ruler

$$a\,dr = c_\mathrm{s}\,dt$$

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Decoupling of baryons and photons

$$r_s = \int_0^{t_{\mathrm{d}}} c_{\mathrm{s}}\,dt/a = \int_0^{a_{\mathrm{d}}} c_{\mathrm{s}} \frac{da}{a^2 H(a)}$$

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Need to know $c_s(a)$ and $H(a)$ to calibrate the ruler.

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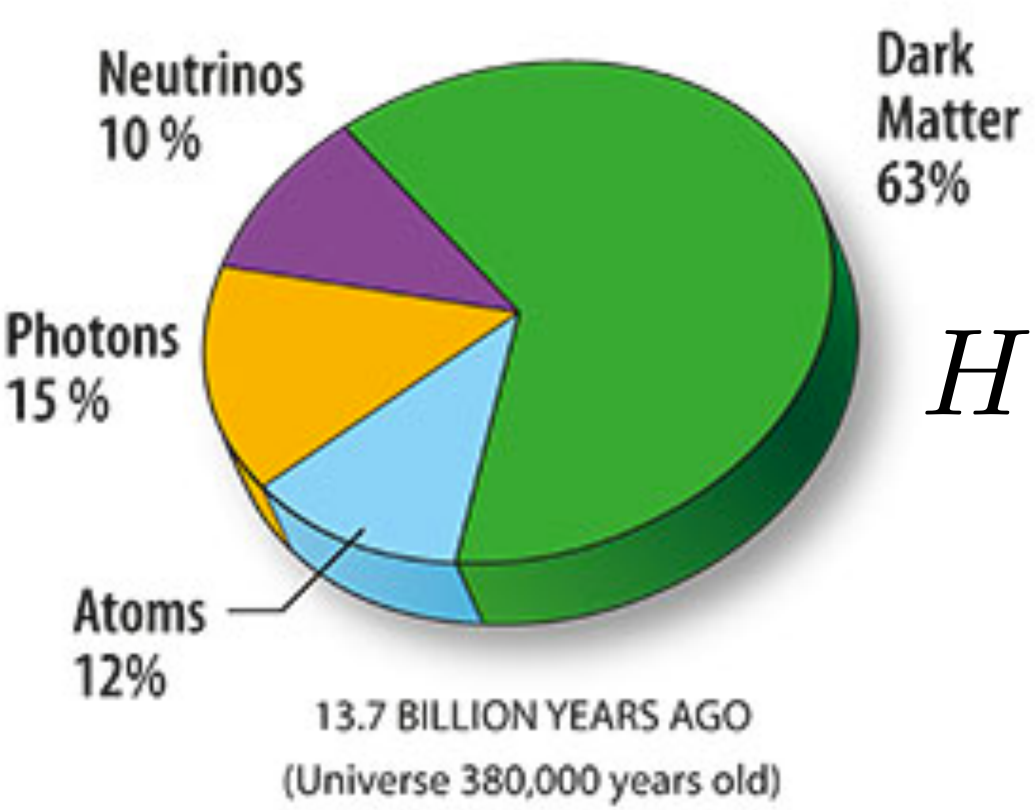
$$c_s^2 = \partial P/\partial \rho \longleftarrow \rho_b/\rho_\gamma$$



$$H^2(a) = 8\pi G/3(\rho_\gamma + \rho_\nu + \rho_m)$$

Determining H_0 from CMB Data
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$$r_s = \int_0^{t_\mathrm{d}} c_\mathrm{s} dt/a = \int_0^{a_\mathrm{d}} c_\mathrm{s} \frac{da}{a^2 H(a)}$$

Need to know c_s(a) and H(a) to calibrate the ruler.

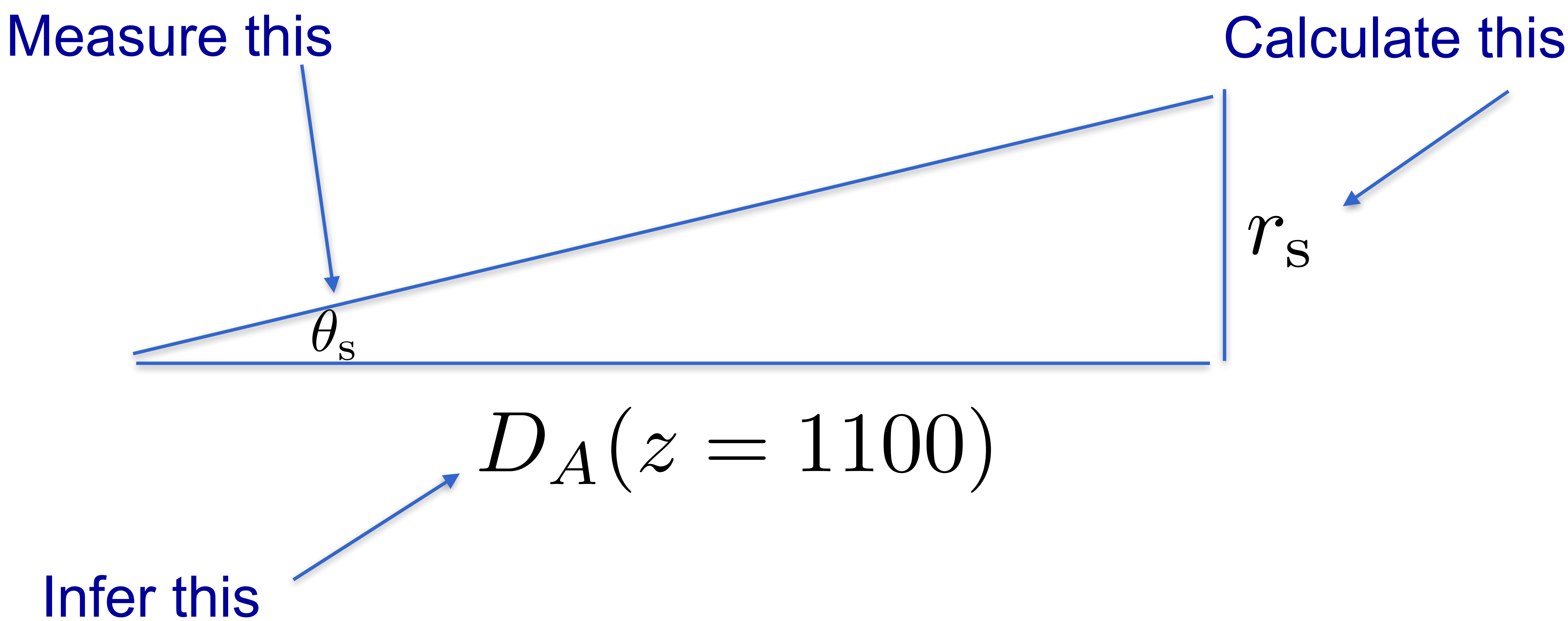
$$c_s^2 = \partial P/\partial\rho$$

Pressure of plasma impacts peak morphology (odd/even height modulation)

$$H^2(a) = 8\pi G/3(\rho_\gamma + \rho_\nu + \rho_\mathrm{m})$$

“Radiation Driving” effect (Hu & White 1997)

Determining H_0 from CMB Data
Step 2: Use the Ruler to Infer Distance



Step 3: $$D_A(z) = \int_0^z dz'/H(z')$$

To get the right D_A, only thing left in the model to adjust is the cosmological constant. With that done, we have H(z).

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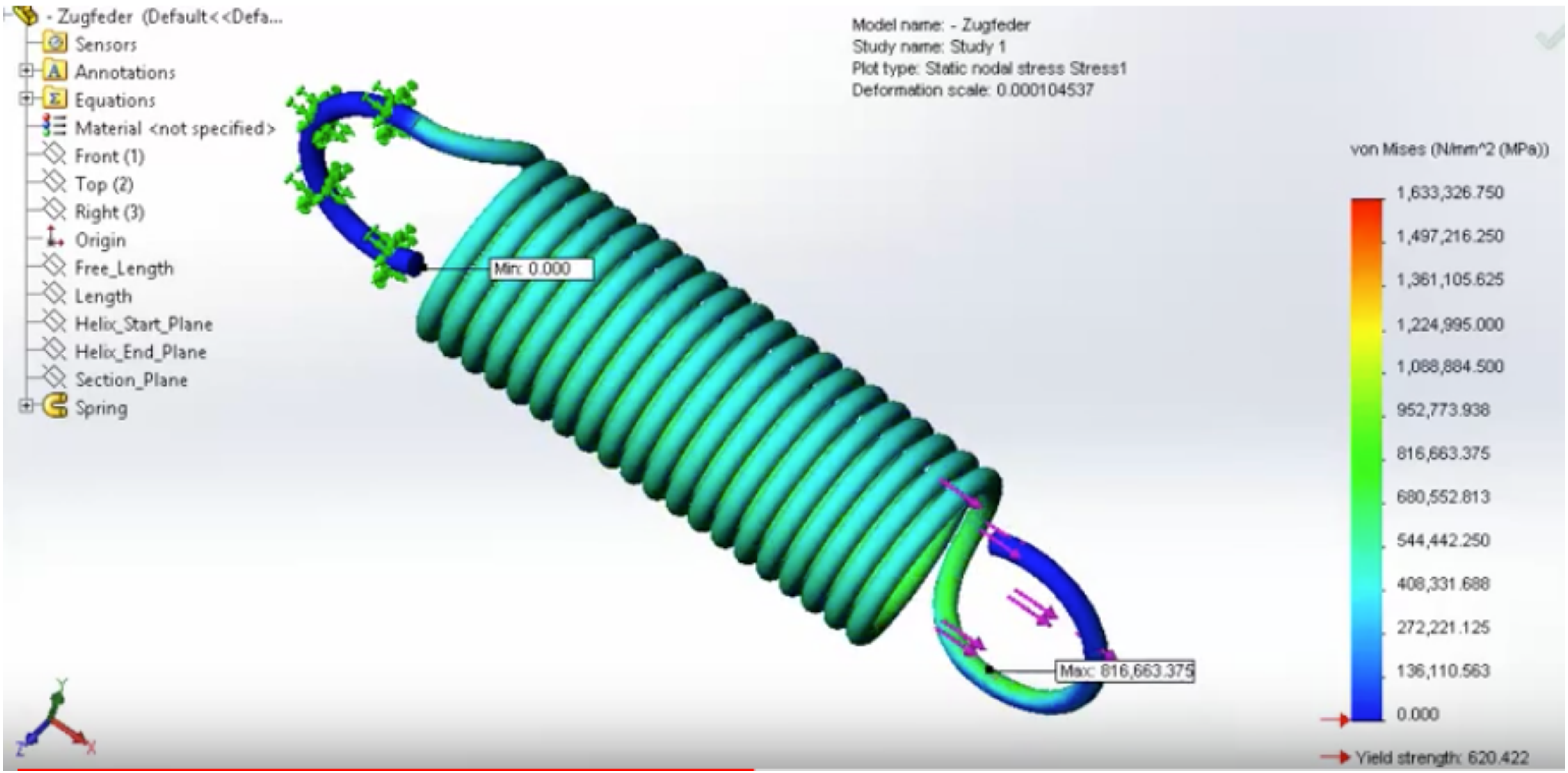
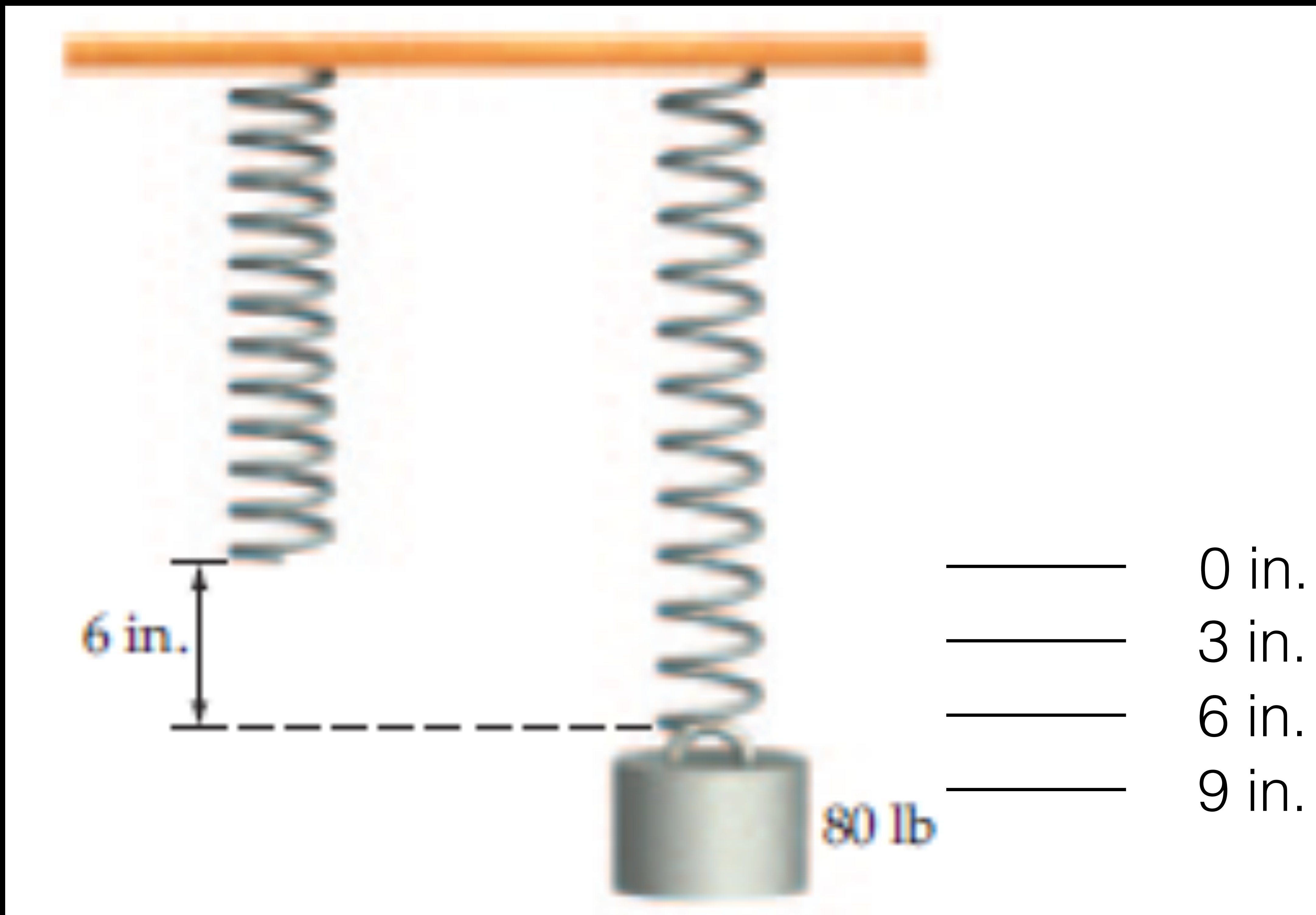
Determining the Matter Density



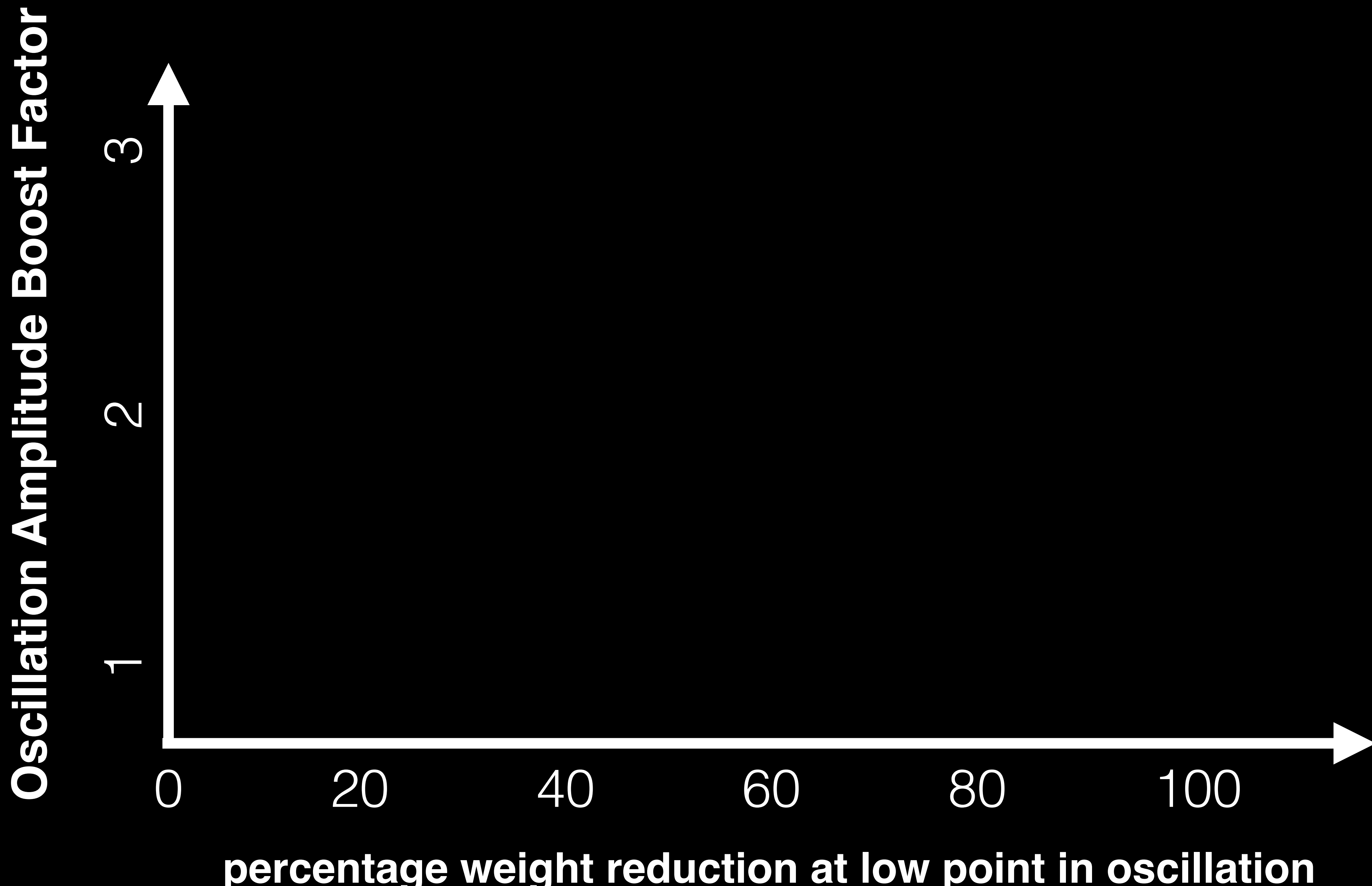
HO Tension

HO

HO under tension



Amplitude Boost vs. Weight Reduction



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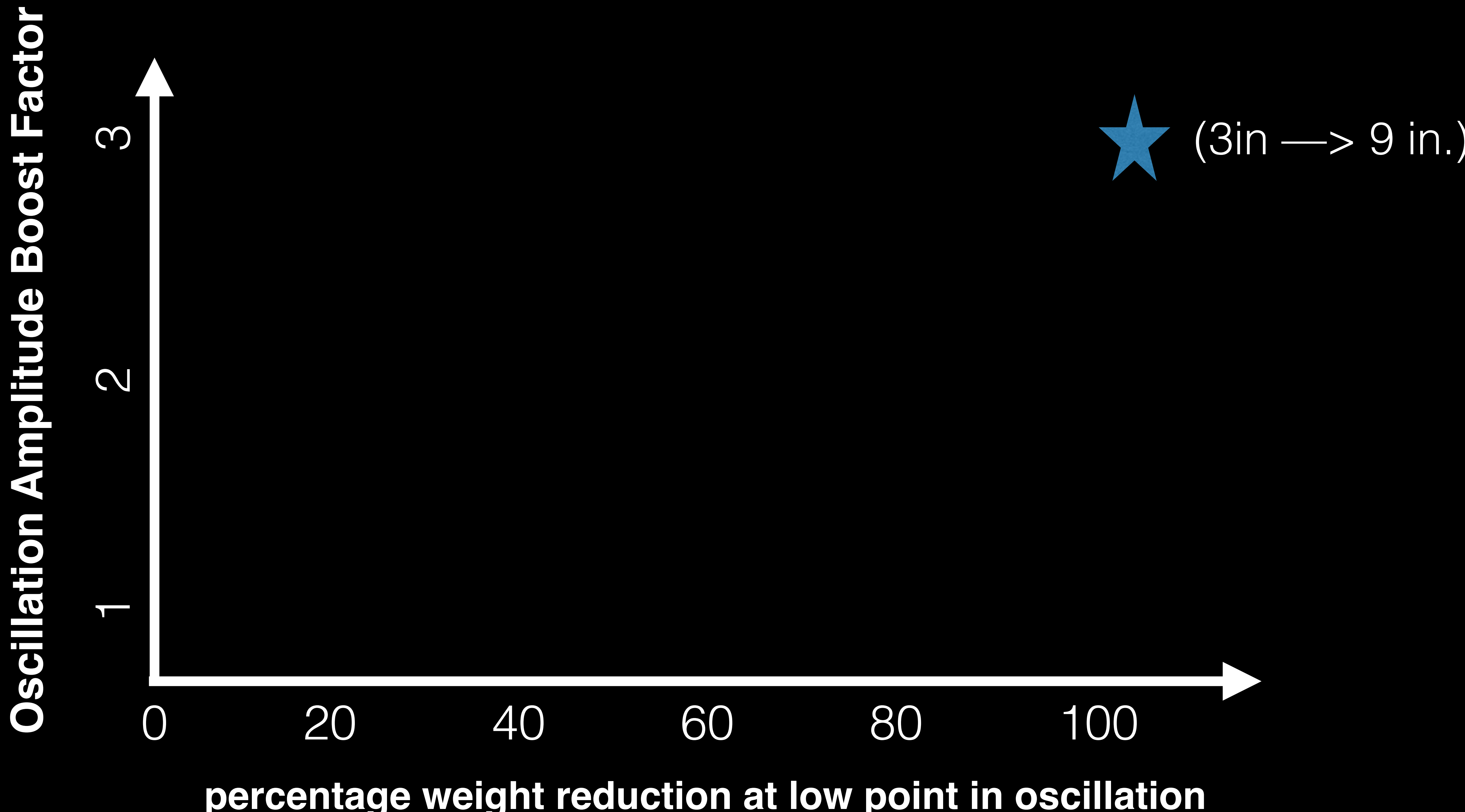

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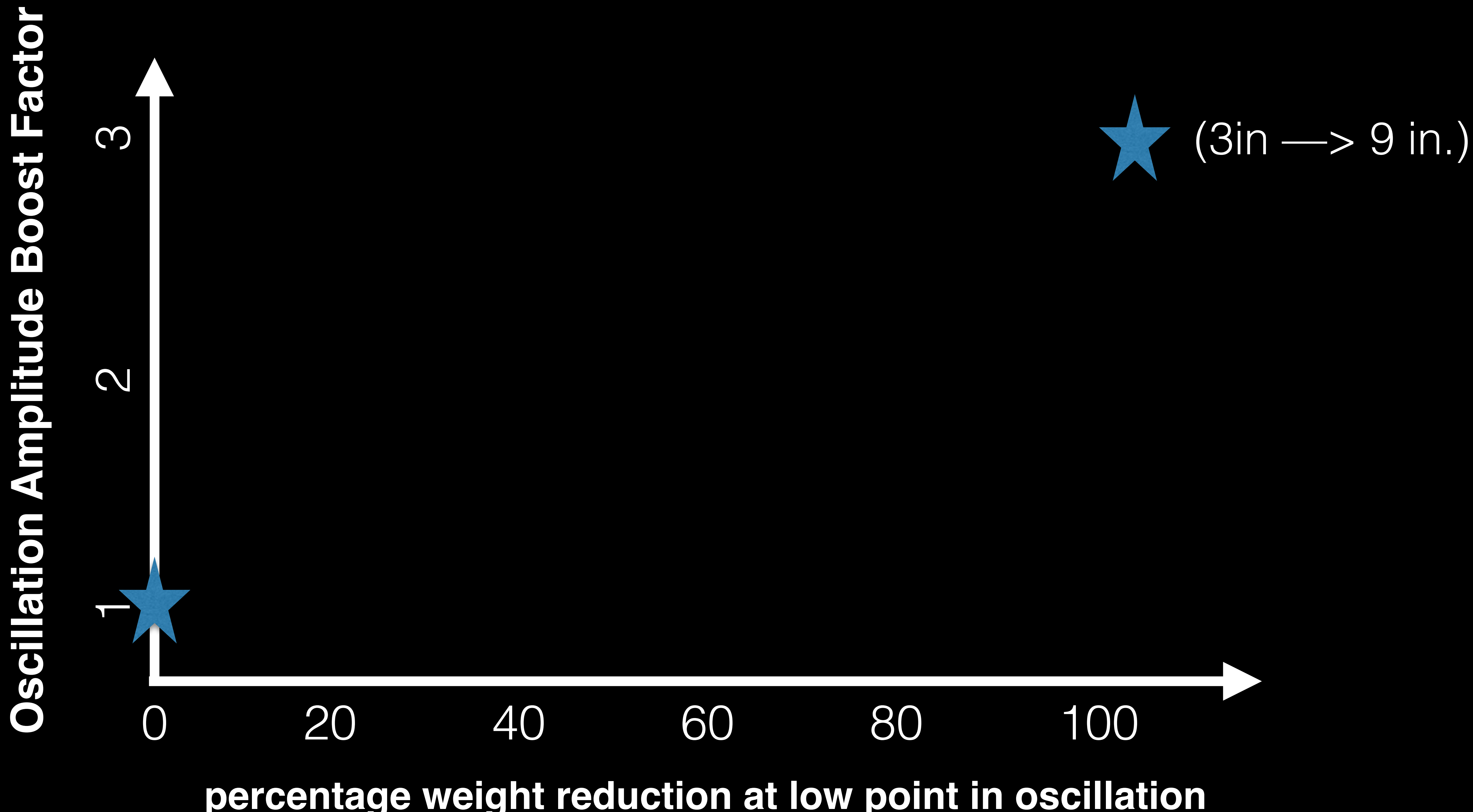

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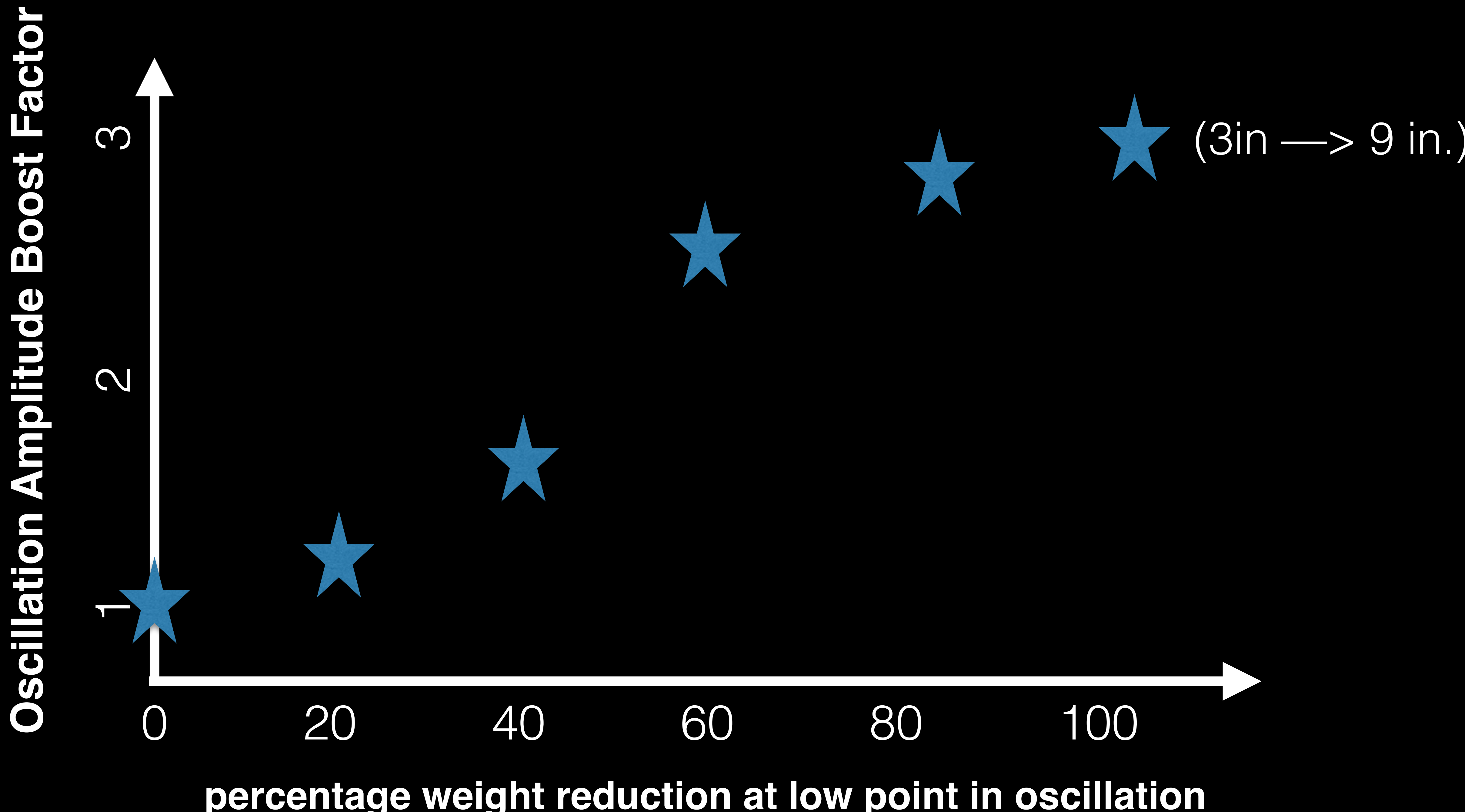
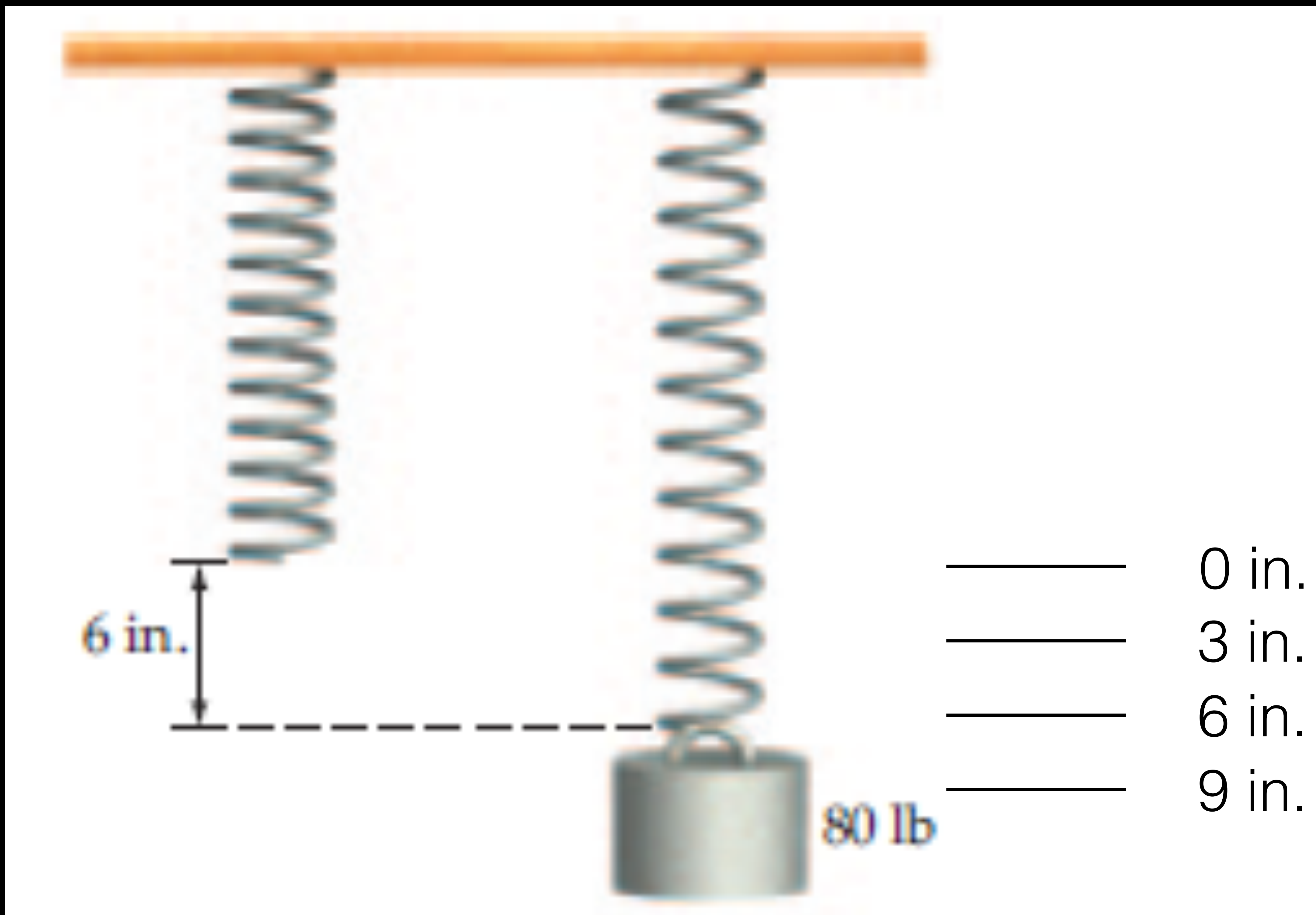
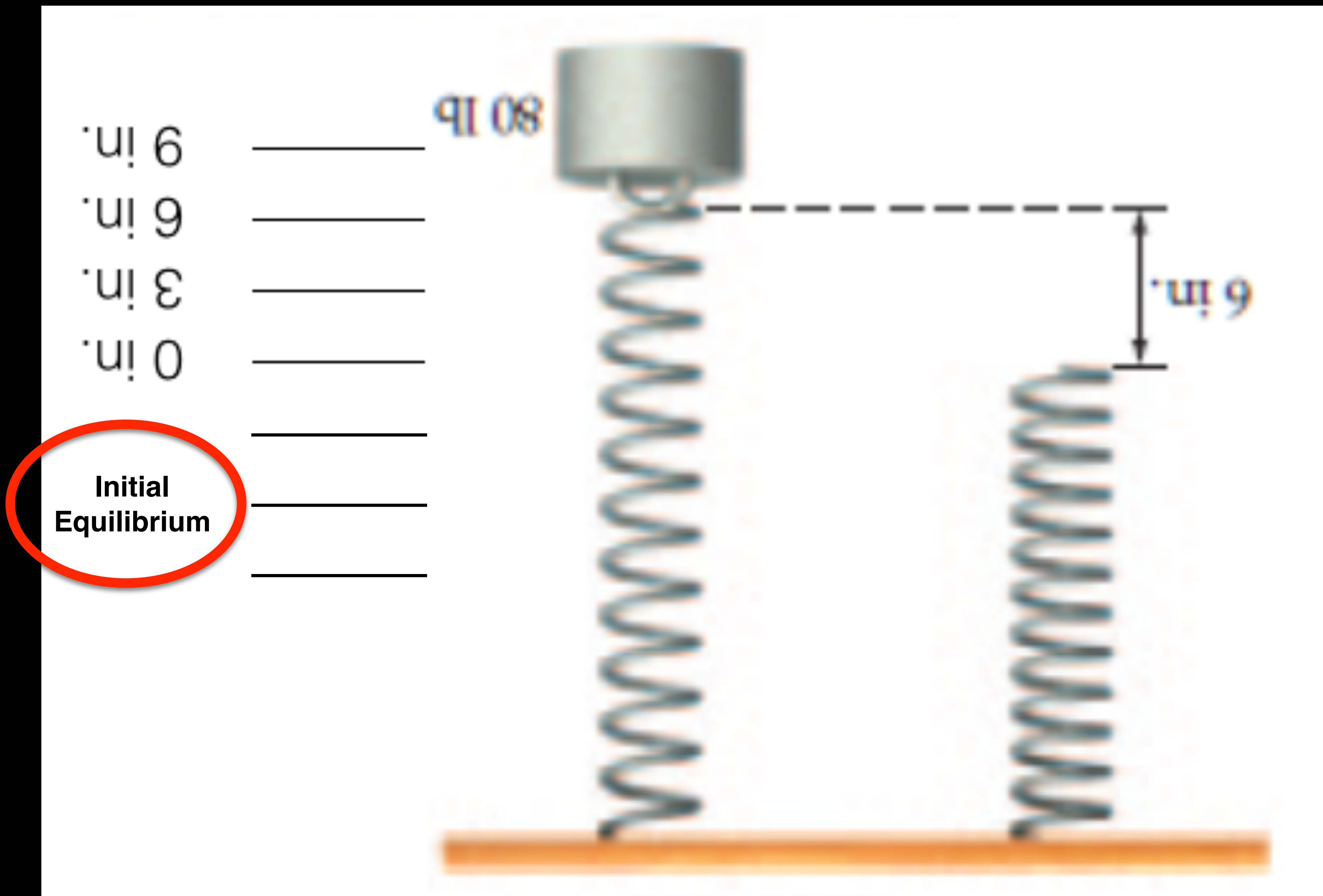


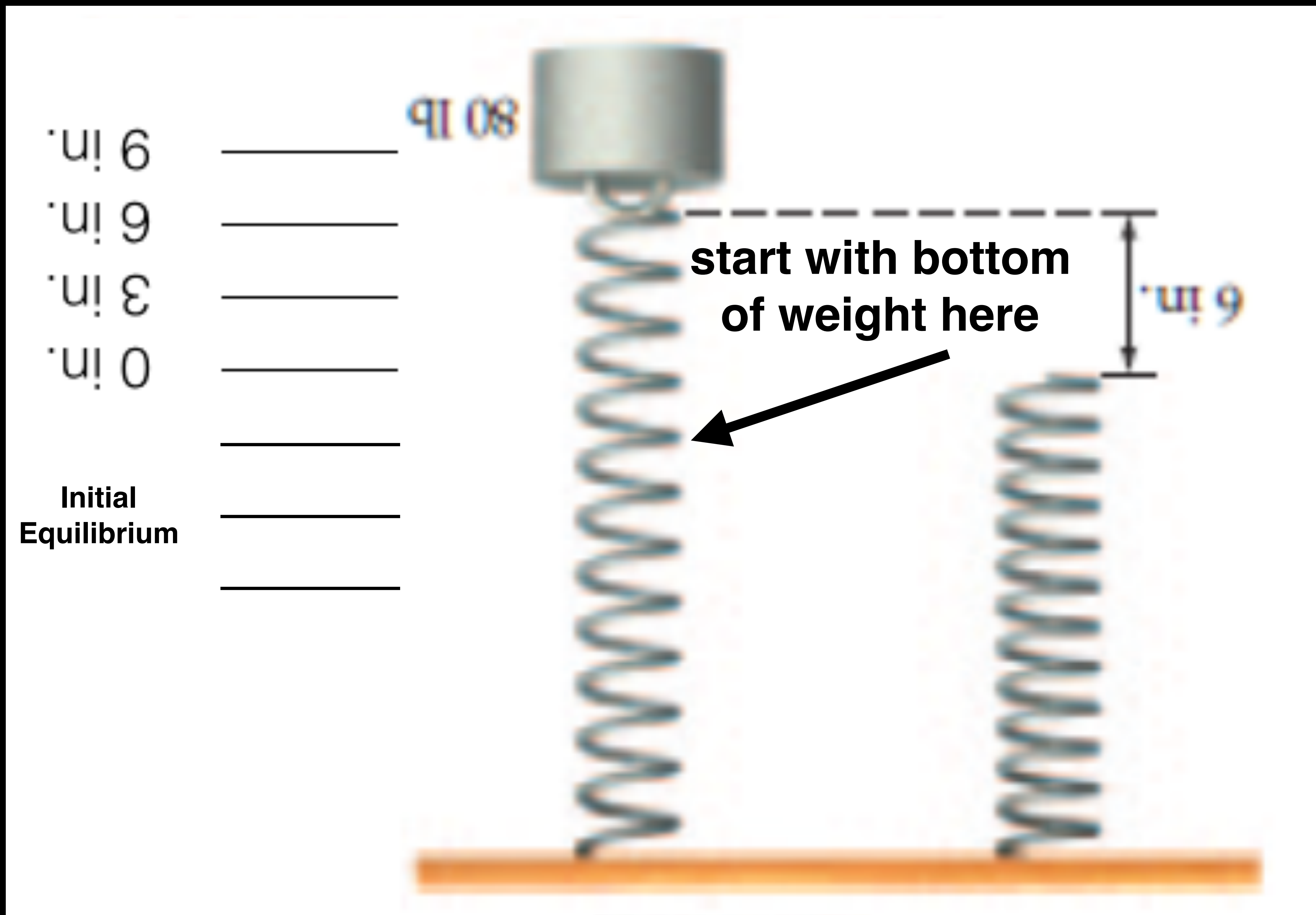
HO under tension



HO under tension

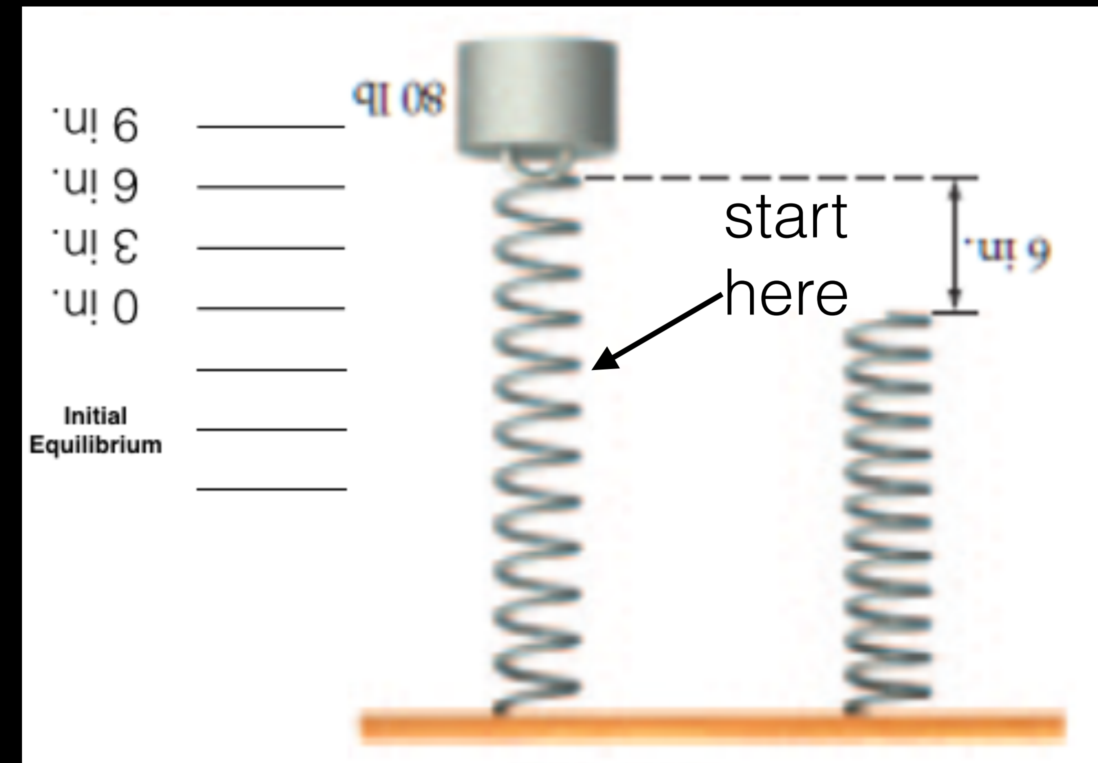


HO under tension



matter domination

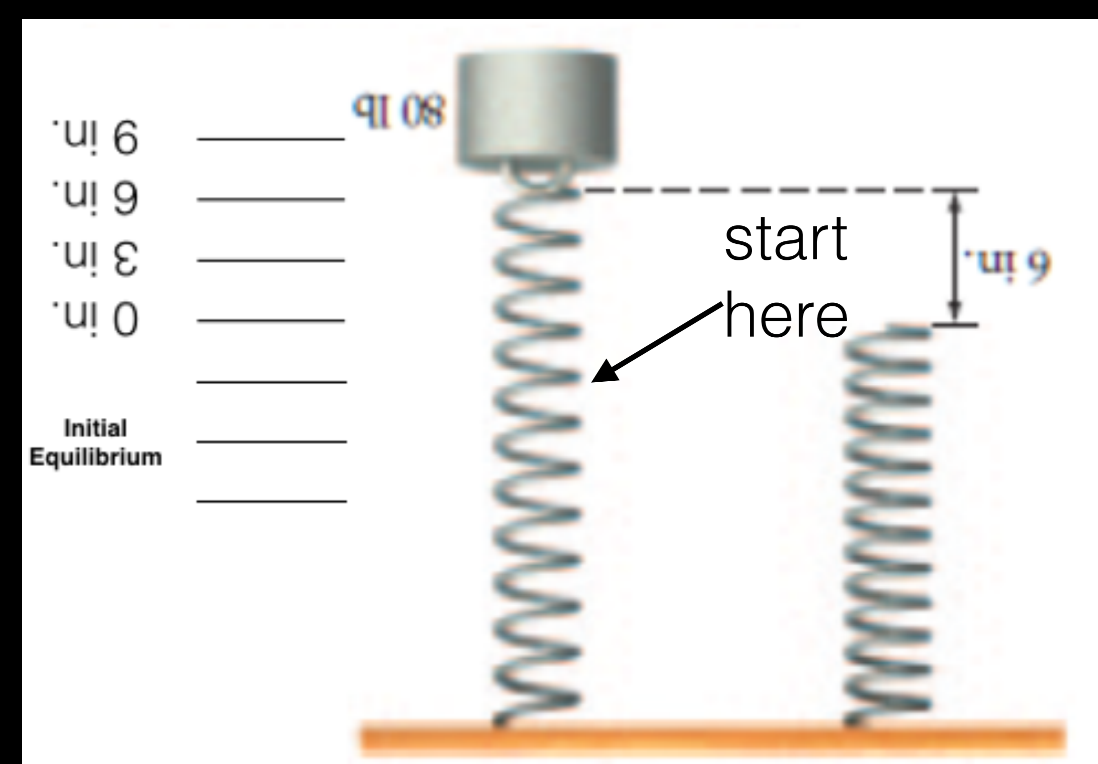
range of oscillation —>



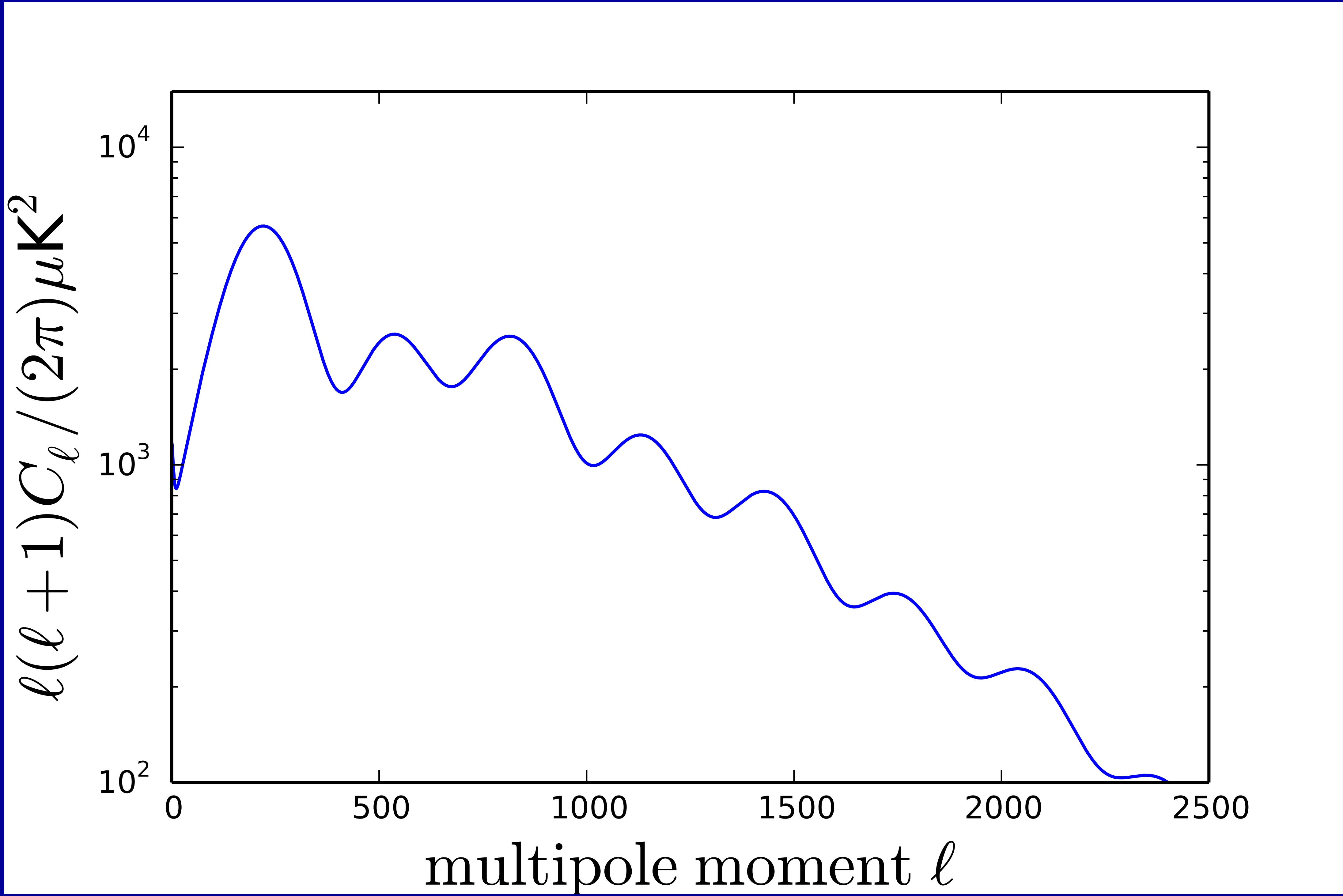
(because grav potential is constant during matter domination)

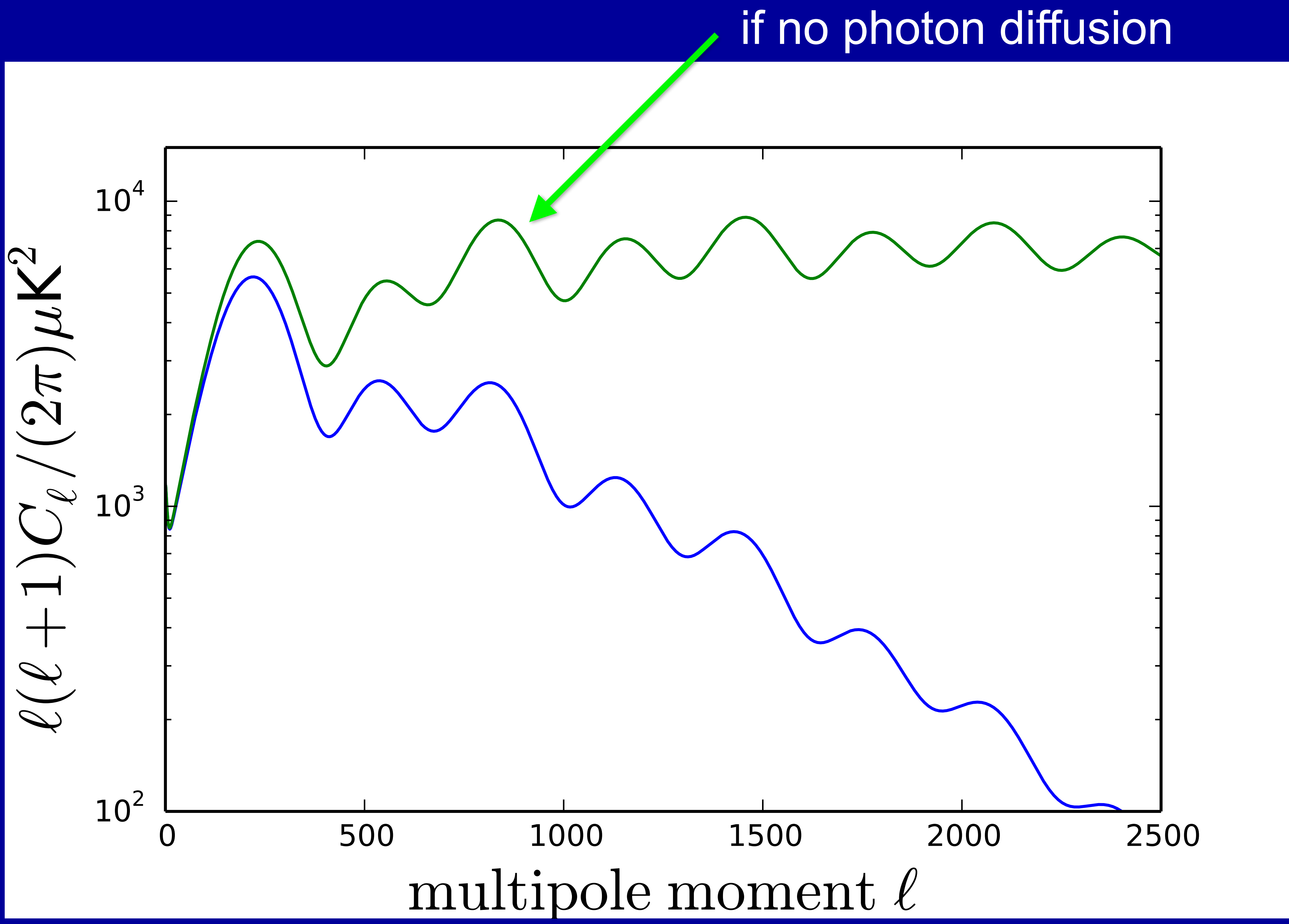
radiation domination

range of oscillation —>

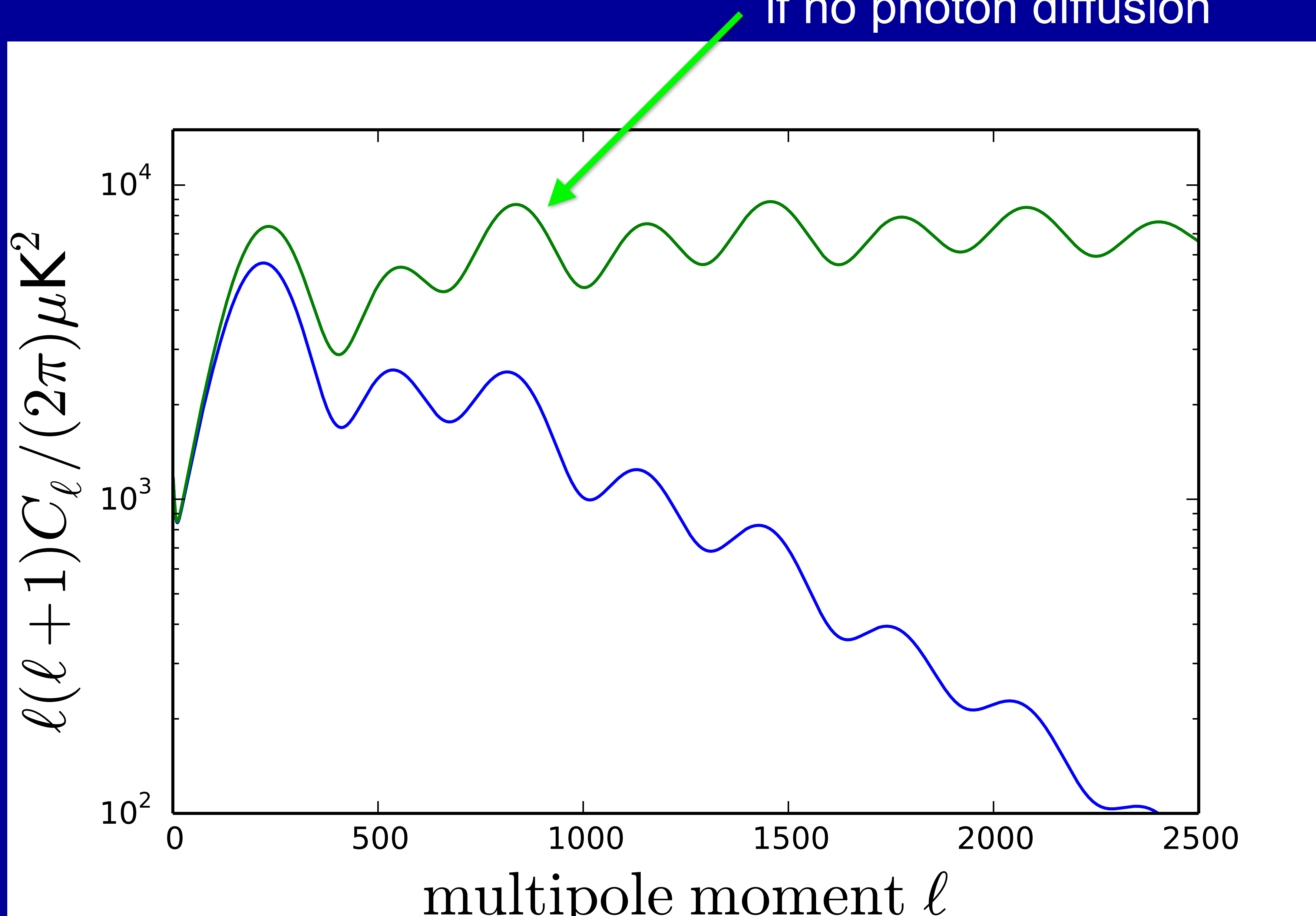


(because grav potential nearly all gone after 1st compression)


10^4
10^3
10^2
0
500
1000
1500
2000
2500
$\ell(\ell+1)C_\ell/(2\pi)\mu\mathrm{K}^2$
multipole moment ℓ



if no photon diffusion
$\ell(\ell+1)C_\ell/(2\pi)\mu\mathrm{K}^2$
10^4
10^3
10^2
0
500
1000
1500
2000
2500
multipole moment ℓ

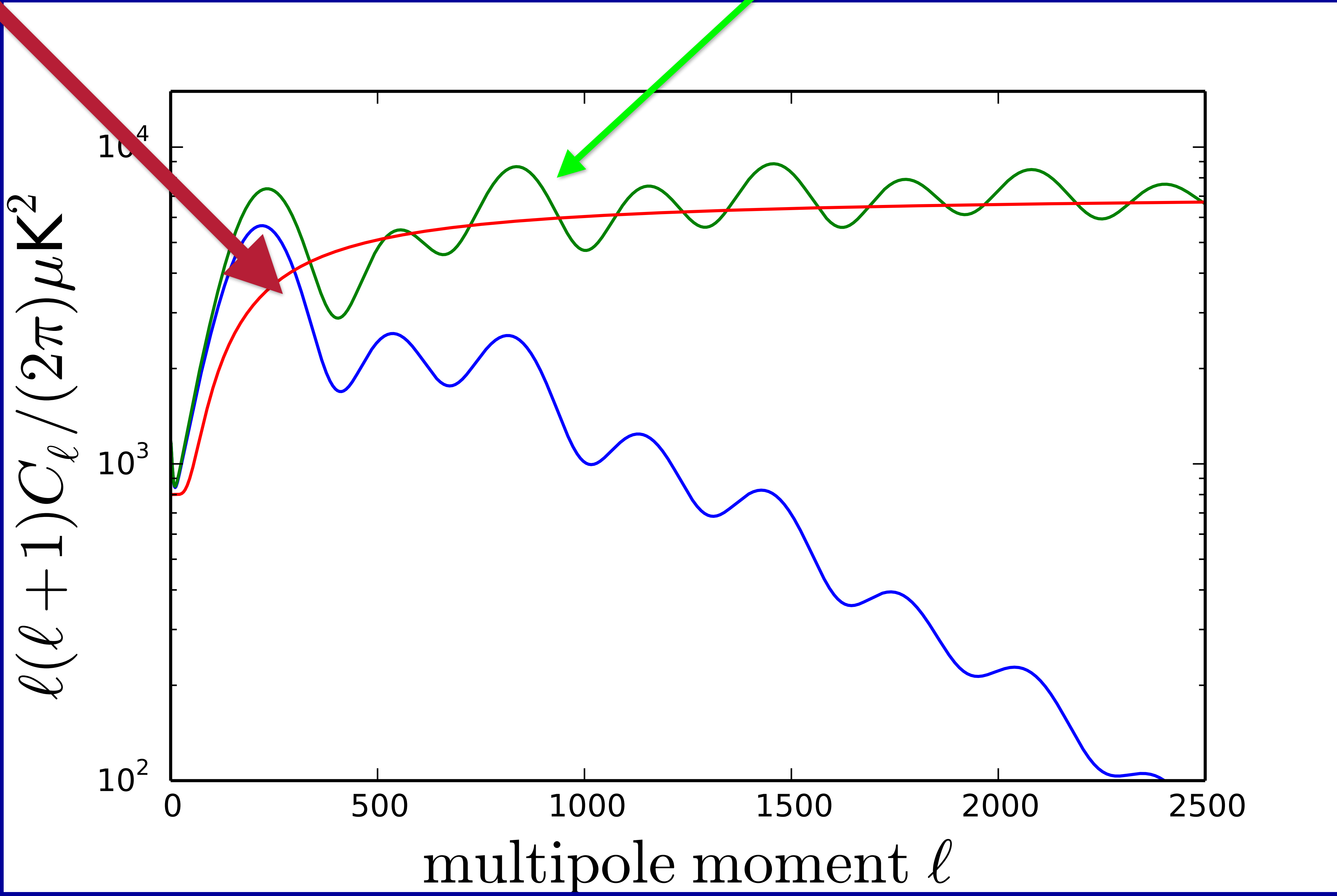


0 78 87 91 93 95

percentage of energy density in relativistic matter when oscillations begin (horizon crossing)

The “potential envelope” of Hu & White (1997)

if no photon diffusion



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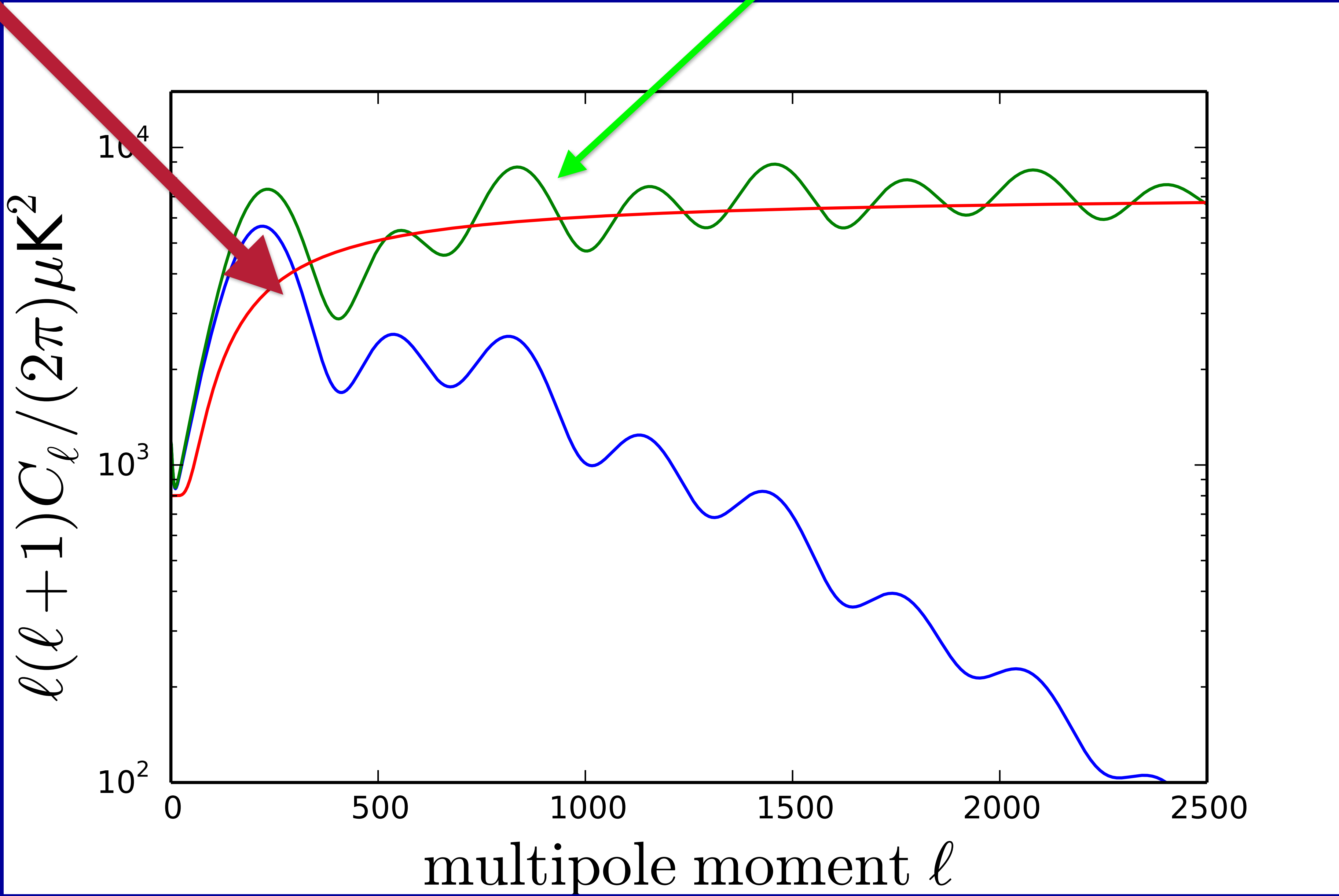

0 10 21 31 42 51

scale factor at recombination divided by scale factor at horizon crossing

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Cosmological Solutions

with no changes at $z > z_*$

- Wiggles in H(z), D(z) (Raveri 2019)
- New photon interactions that make supernovae appear brighter (opposite of axion dimming)
- Post-recombination evolution of the sound horizon
- Something at low-z has confused our inferences of r_s and omega_m from CMB

Hubble Hunter's Guide (in prep)

with changes at $z > z_*$

- Confusion sowing
- Sound speed reduction
- High-temperature recombination (Chiangand & Slosar 2018)
- Photon cooling/conversion
- Increase H(a)
  - Neff
  - Scalar Field (Poulin et al. 2019, Agrawal et al. 2019)
  - Some other additional component

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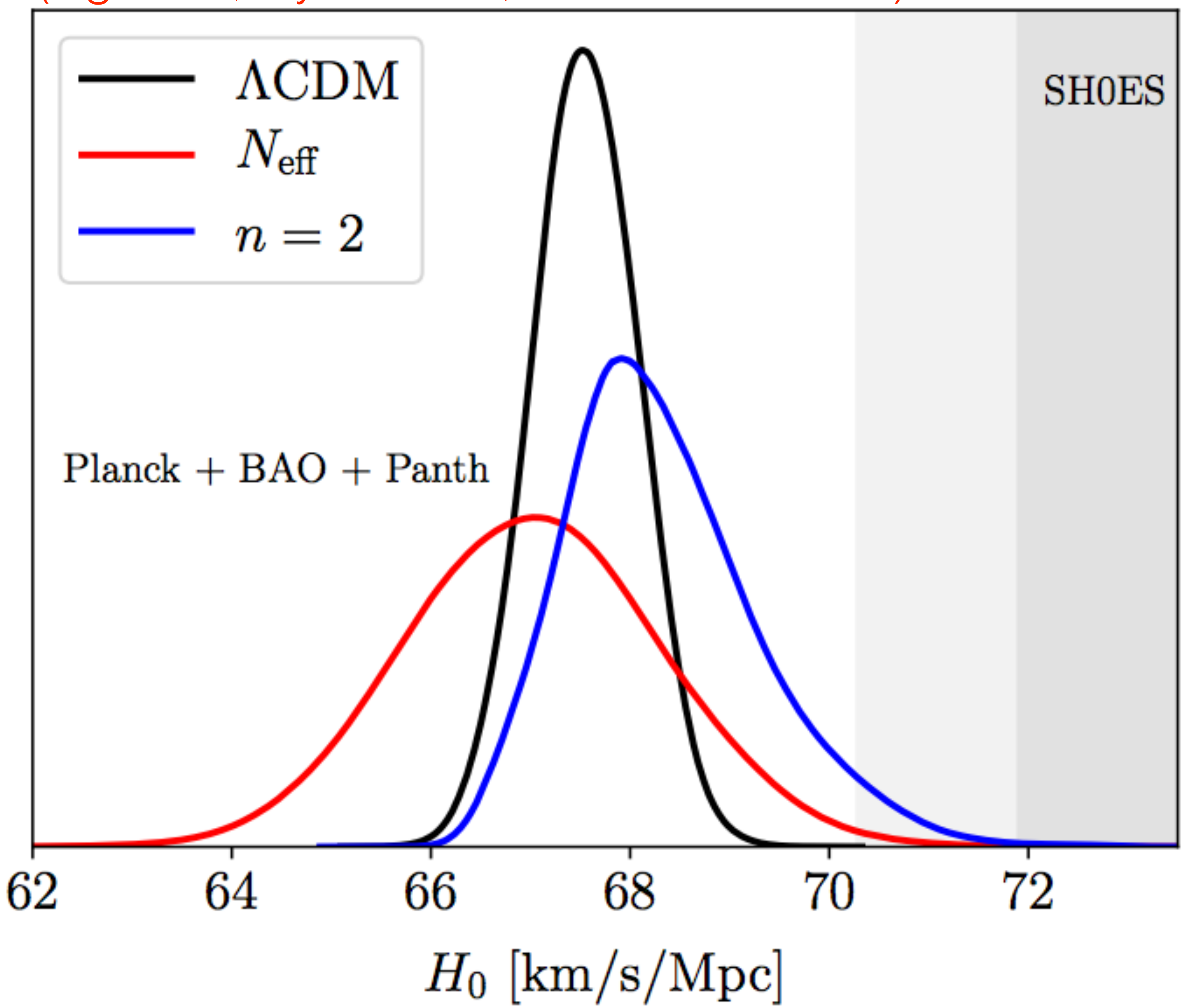
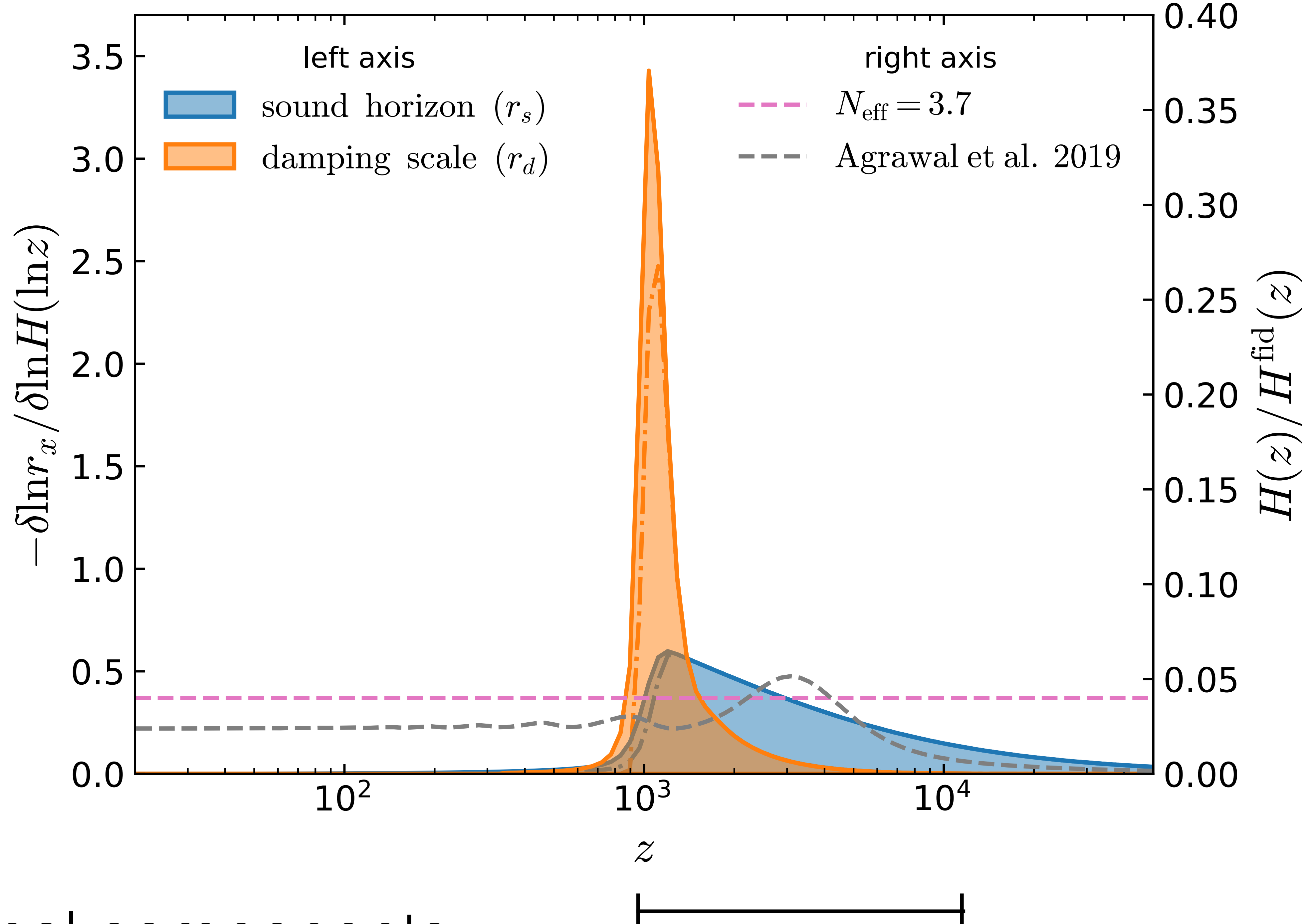
Adding additional components not a panacea: it's hard to make the data consistent with $H_0 > 70$

(Agrawal, Cyr-Racine, Pinner & Randall)



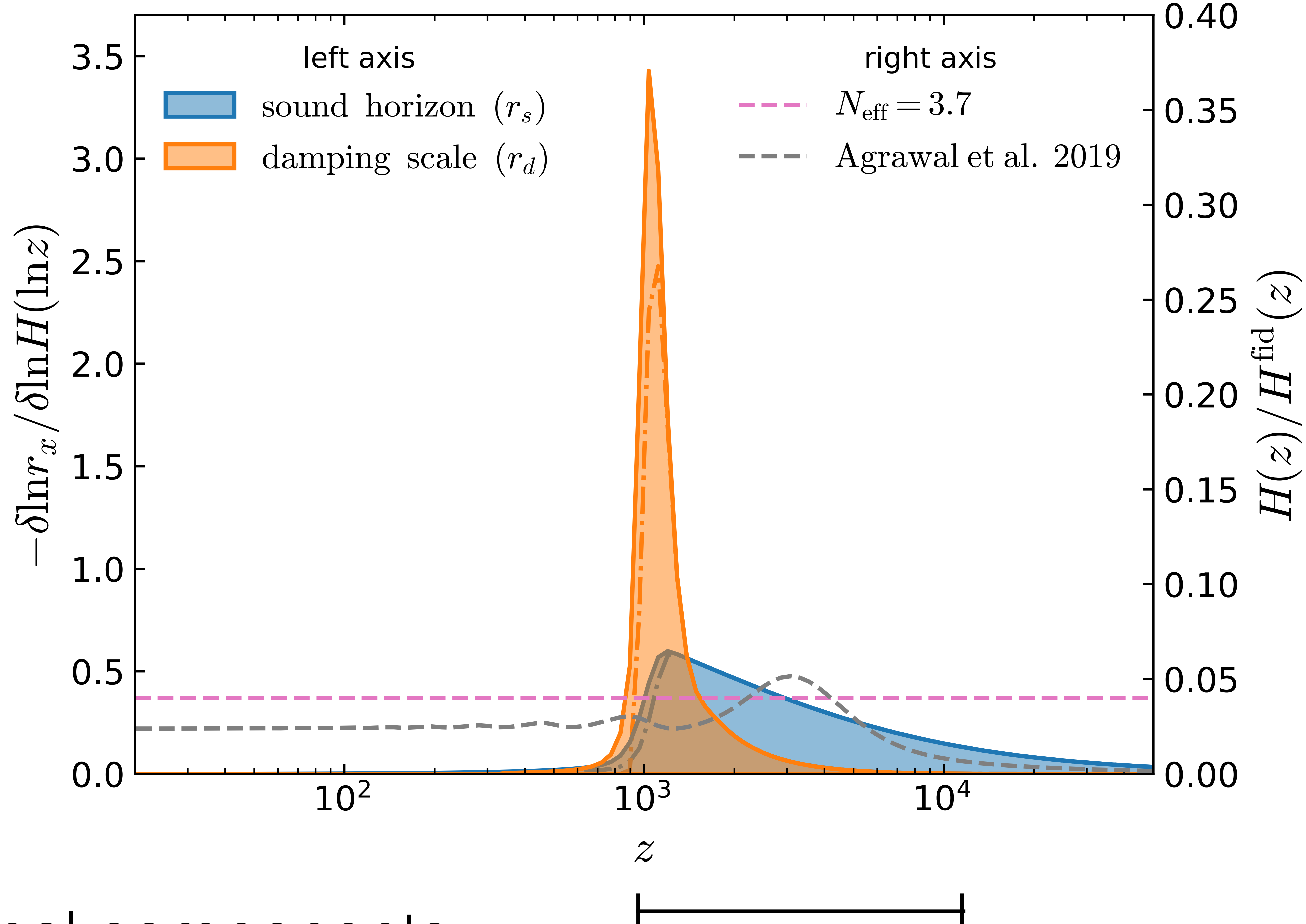
Why?

Hubble Hunter's Guide (M. Millea + LK, in prep)



Additional components must be important in this interval if they are to reduce the sound horizon (Aylor et al. 2019)

Hubble Hunter's Guide (M. Millea + LK, in prep)



Additional components must be important in this interval if they are to reduce the sound horizon (Aylor et al. 2019)

Neff: can keep radiation-driving envelope fixed, but alters r_d/r_s.
Anything else: alters radiation-driving envelope

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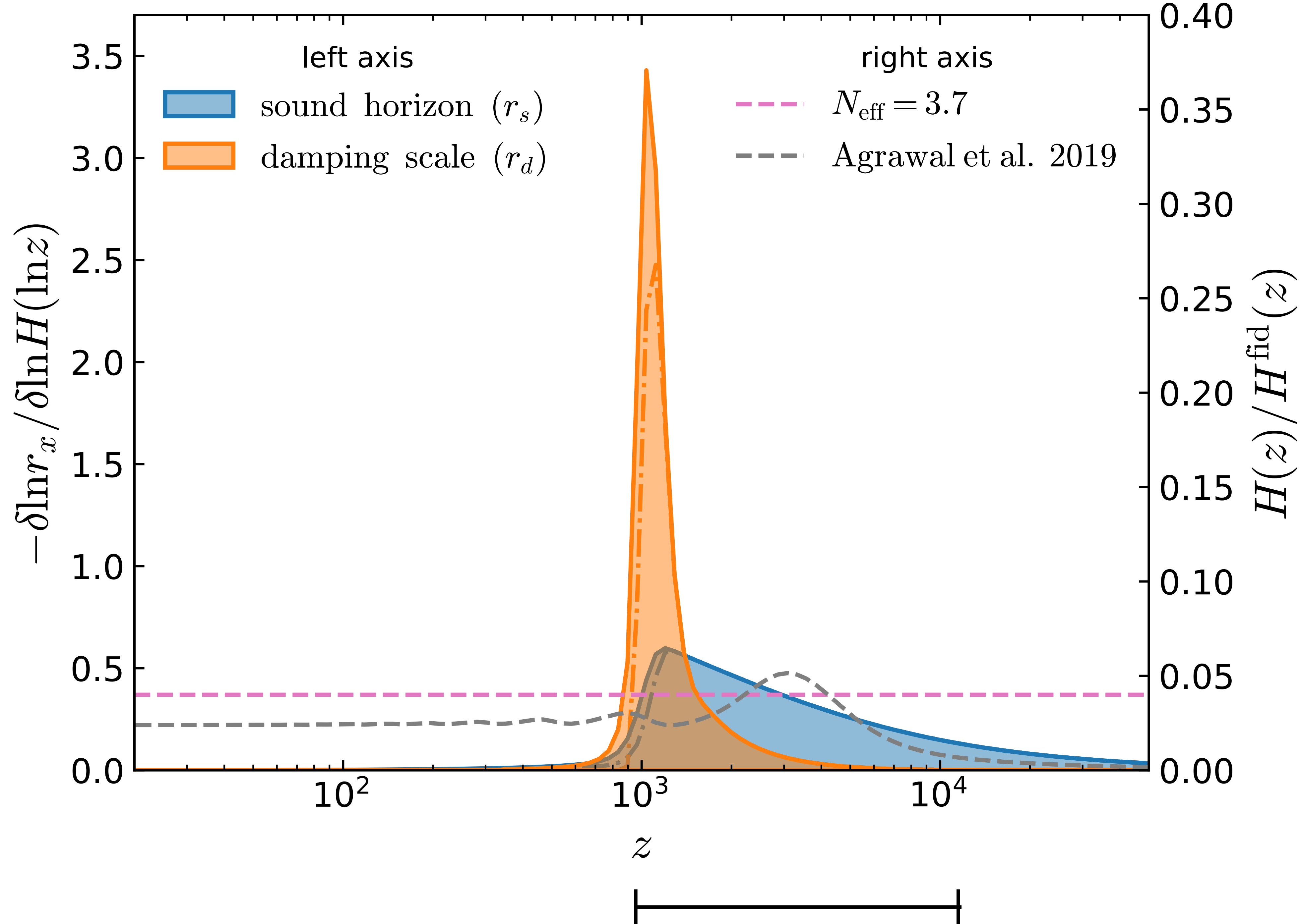
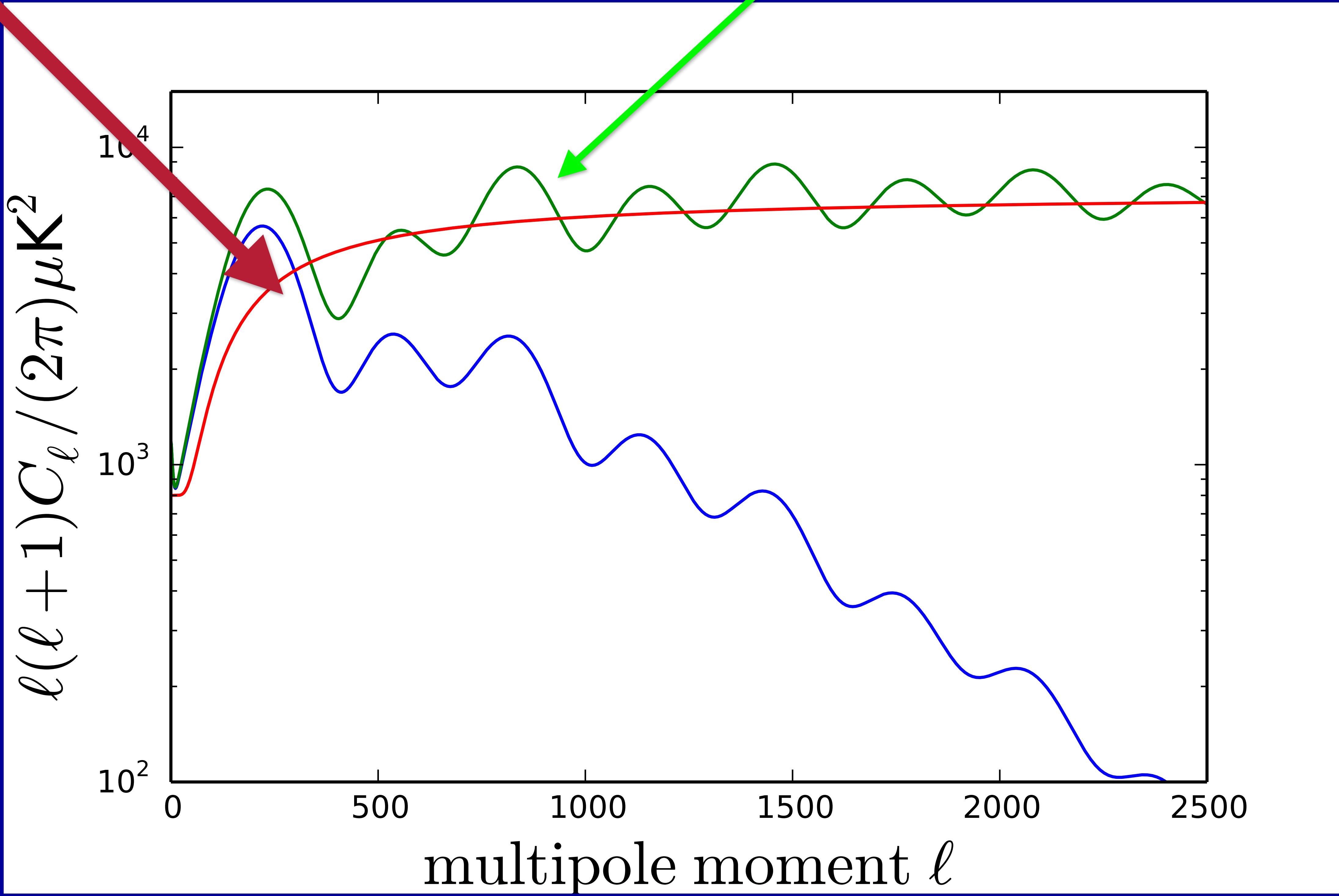


Additional components must be important in this interval if they are to reduce the sound horizon

Radiation-driving envelope altered ==> LCDM-based analyses will find angular-scale dependent inferences of matter density

The “potential envelope” of Hu & White (1997)

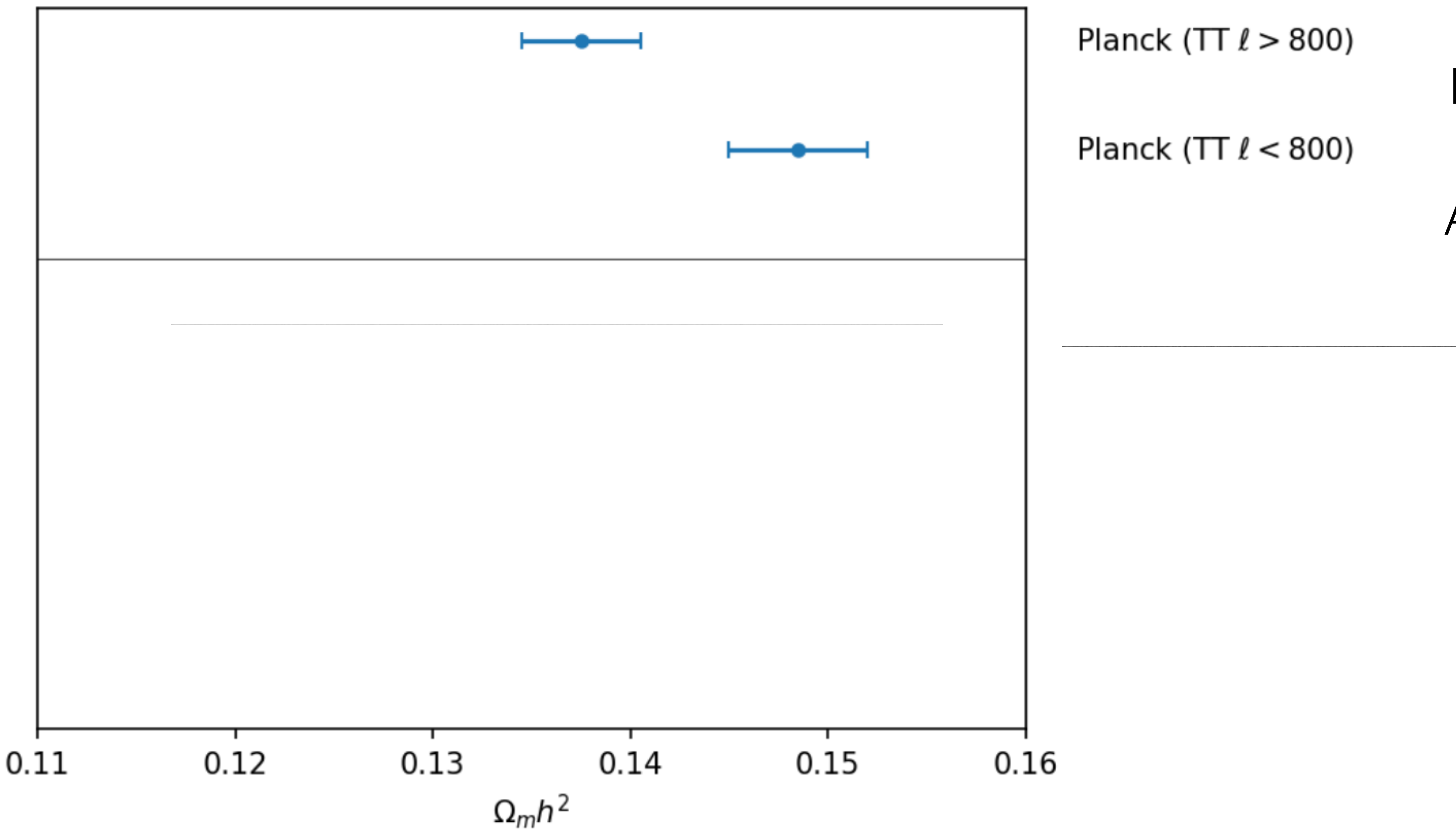
if no photon diffusion



0 10 21 31 42 51

scale factor at recombination divided by scale factor at horizon crossing

Hubble Hunter's Guide (M. Millea + LK, in prep)



Planck PIP LI (2017)

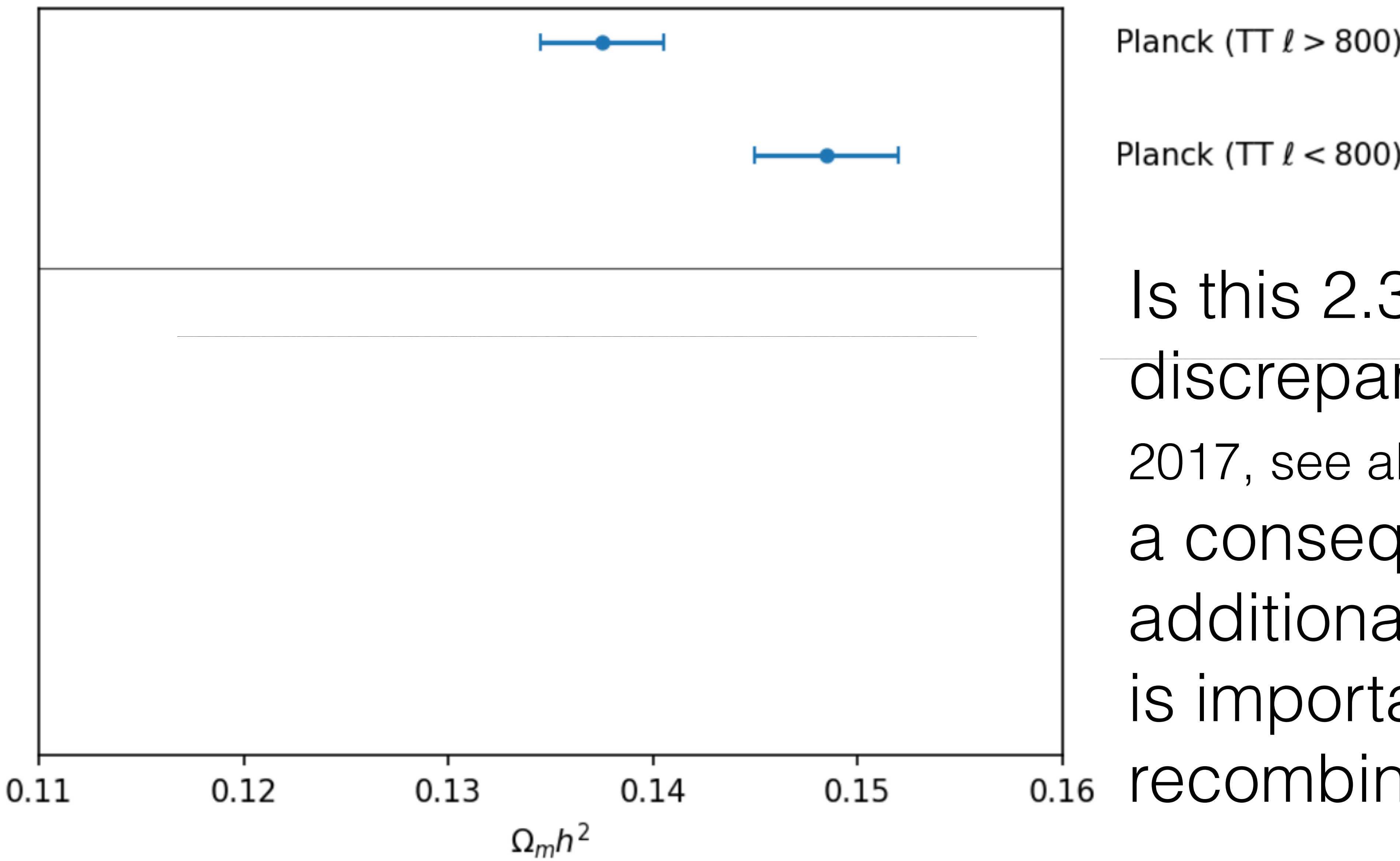
See also

Addison et al. (2016)

Matter Density

Radiation-driving envelope altered ==> LCDM-based analyses will find angular-scale dependent inferences of matter density

Hubble Hunter's Guide (M. Millea + LK, in prep)



Planck PIP LI (2017)
See also
Addison et al. (2016)

Is this 2.3 sigma discrepancy (Planck PIP LI 2017, see also Addison et al. 2016) a consequence of additional component that is important just prior to recombination?

Matter Density

Radiation-driving envelope altered ==> LCDM-based analyses will find angular-scale dependent inferences of matter density

Outline

- Why have we learned so much from the CMB?
- CMB Measurements are consistent
- LCDM predictions for CMB measurements
- A related tension: the sound horizon
  - Distance Ladder vs. LCDM sound horizon inferences
- Explain how LCDM + CMB ==> H_0
  - Including how LCDM + CMB ==> $\omega_{\rm m} \equiv \Omega_{\rm m} h^2$
- Cosmological Solutions
- The value of CMB observations to come

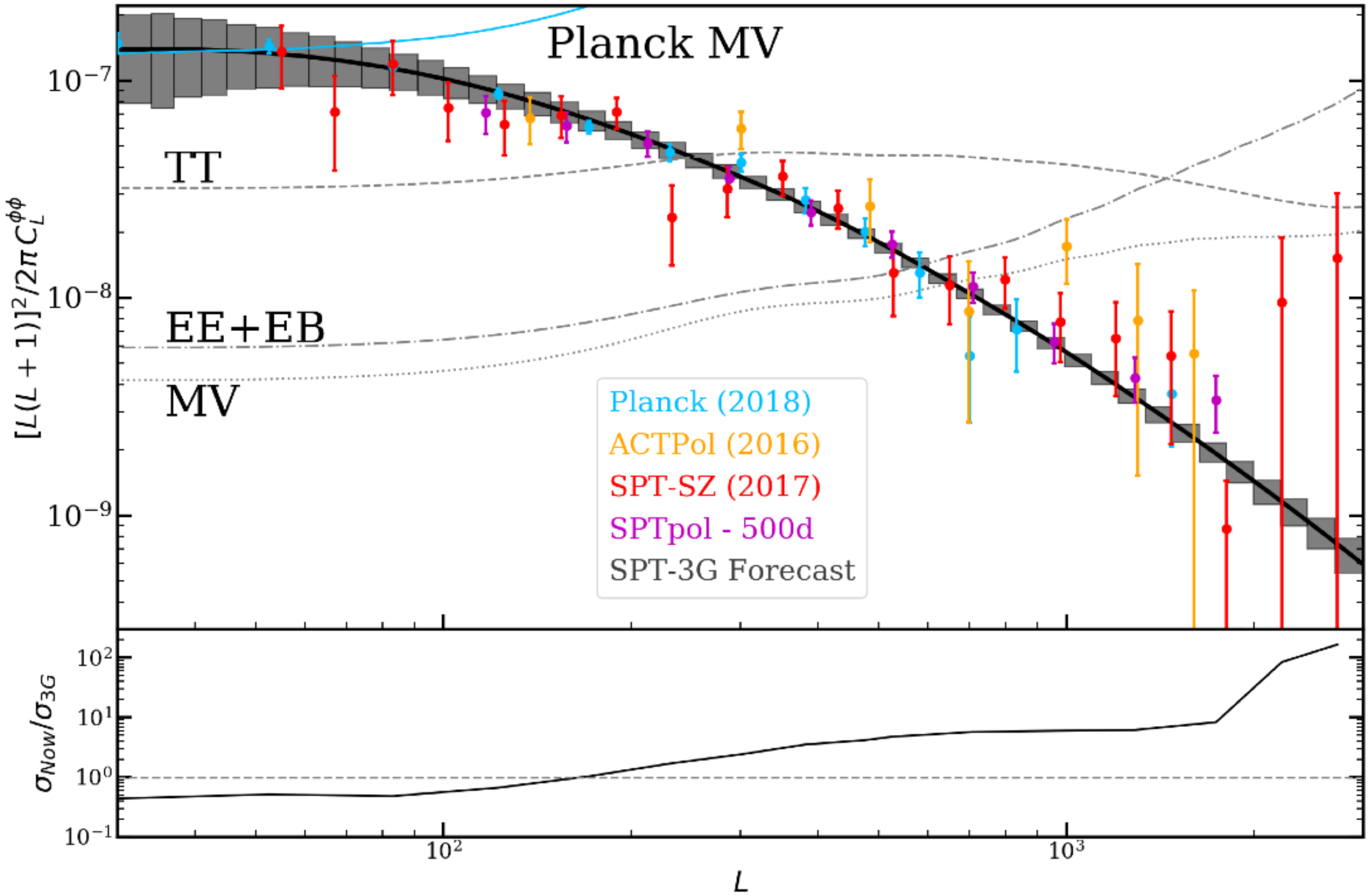
CMB Observations to Come

- **Wide coverage data acquired by ACT collaboration**: coverage of very large amount of sky to provide even more powerful tests of Planck at ell $<$ 1800 (omega_m tension, A_L) and improve over SPT constraints at ell $>$ 1800 that come from just 6% of sky.

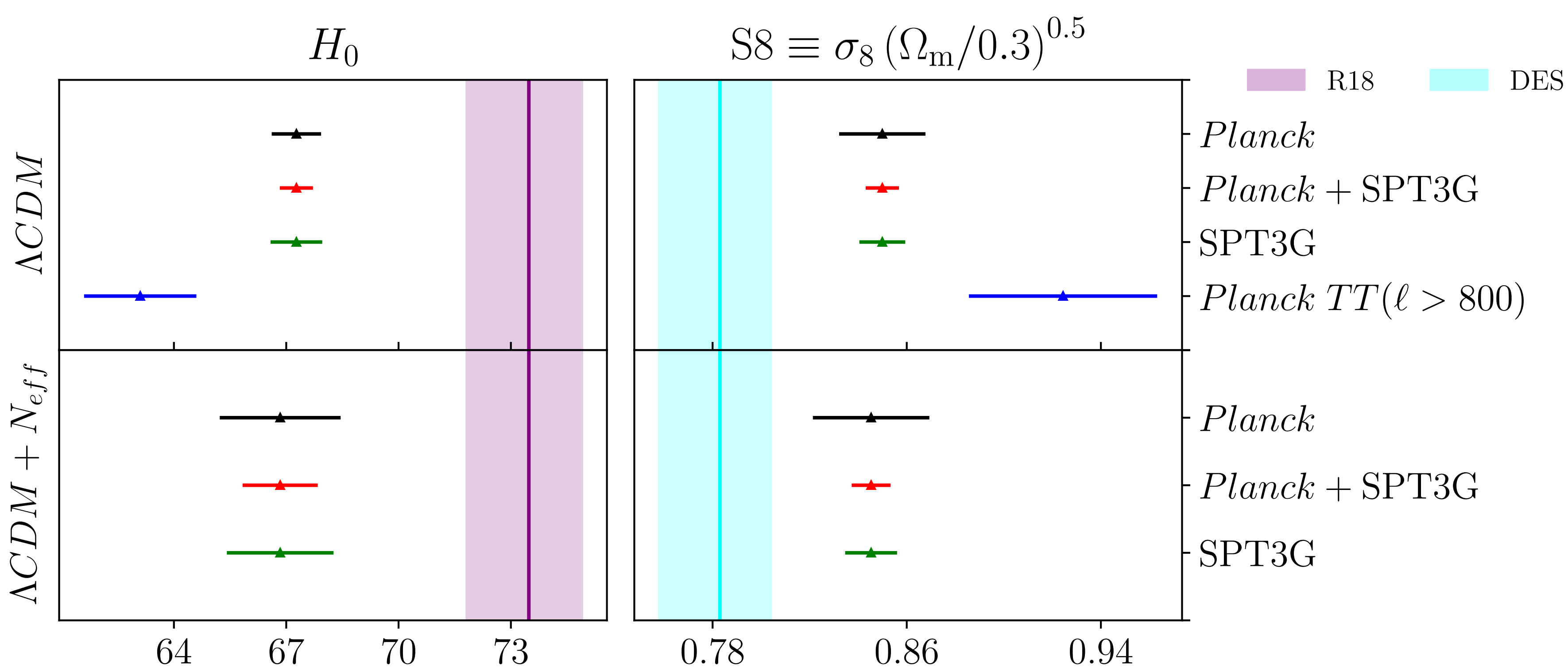
- **Very deep coverage from SPT collaboration**: Instrument noise with 3G survey is consistent with what we assumed for the basis of our forecasts. Perhaps most valuable thing relevant to H_0 will be the lensing reconstruction and its determination of omega_m. Possible clues in shape of lensing power spectrum.

- Beyond this we working toward having CMB-S4 with better than SPT-3G depths over 70% of the sky.

See Kimmy Wu's talk this p.m.



Forested Reconstructed Lensing Potential Power from SPT-3G



Forecasted H_0 and sigma8 Constraints from SPT-3G

Main Messages

1. Systematic errors in CMB data are not a possible route out of our current discord.

    - **Sound horizon tension persists regardless of data set.**

2. Model changes away from LCDM are very tightly constrained by CMB measurements.

    - **To reduce sound horizon with increased H(a) alters horizon crossing dynamics for very well-measured modes.**

    - **Increasing H(a), and other solutions, also change recombination — an out-of-equilibrium process with huge impact on the (well-measured) damping tail.**

3. There are some (weak) inconsistencies internal to CMB data, interpreted with LCDM. Speculation: One in particular is due to the presence of additional components that lower the sound horizon.

    - **We talked about matter density angular scale dependence. Kimmy Wu will talk about A_L.**

STOP

Cosmological Whackamole with Neff

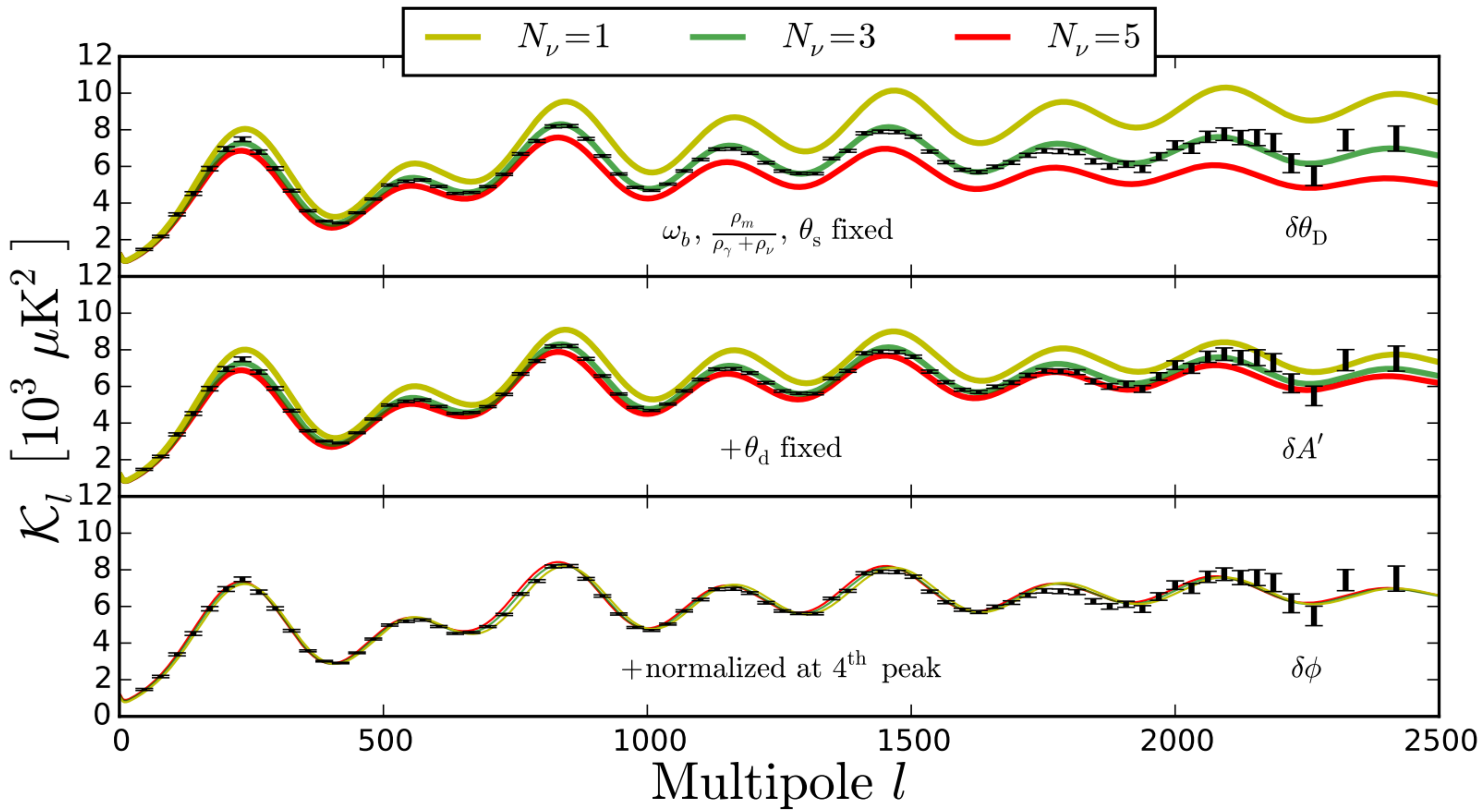
1) To keep rad-driving envelope fixed, change rho matter.

2) To keep theta_s fixed, change cosmological constant.

3) To keep theta_d fixed, change primordial Helium fraction (2nd tooth fairy).

4) To keep delta phi fixed, change… ??

Fiducially Undamped Spectra



Follin, LK, Millea and Pan (2015)

Confusion Sowing

- No new components introduced, but interactions or initial conditions changed somehow to alter inference of matter density and sound horizon.

- Examples:

  - Interacting neutrinos (Cyr-Racine & Sigurdsson 2014, Lancaster et al. 2017)

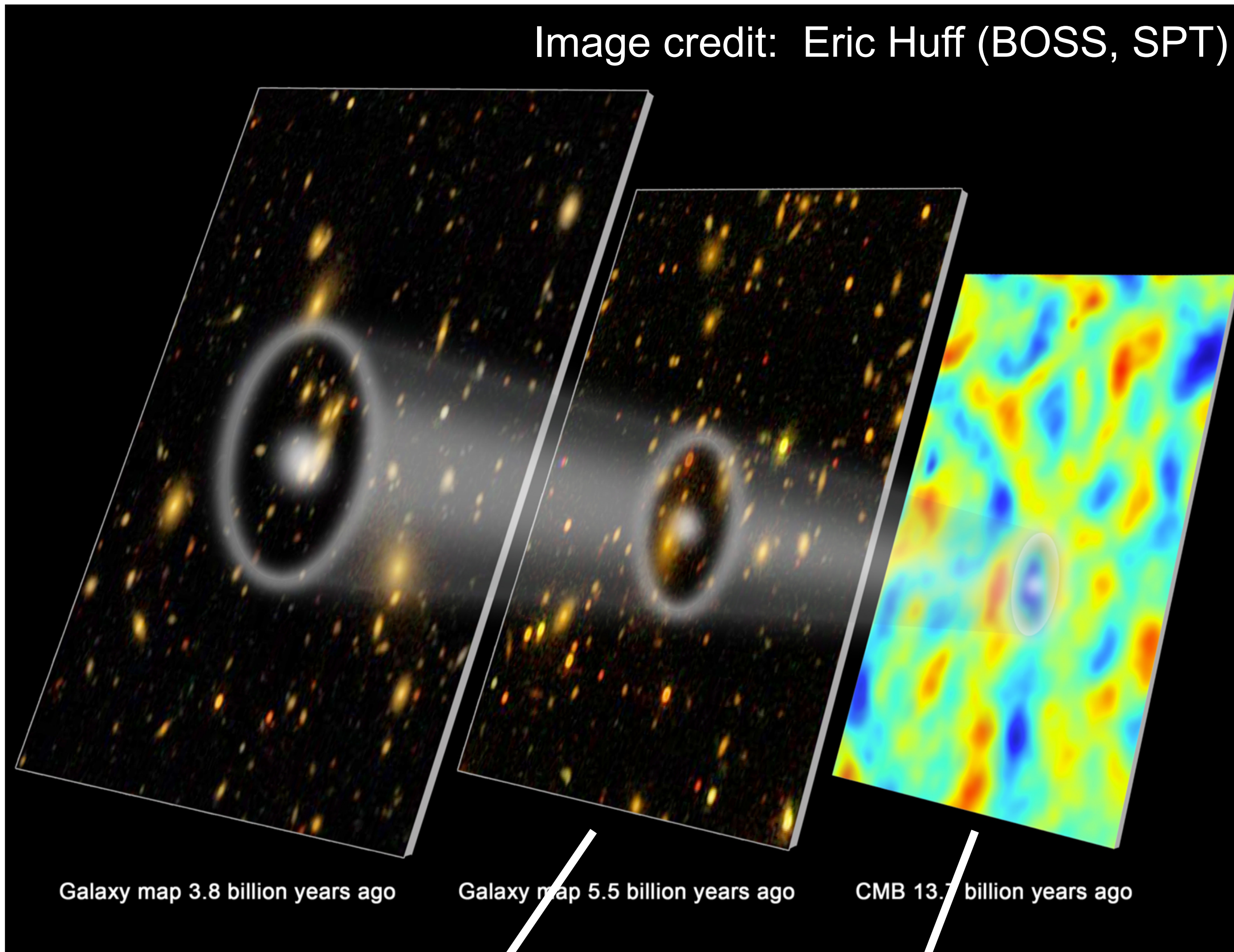
  - Modified gravity (Lin, Raveri & Hu 2019)

  - Extra freedom in primordial power spectrum

  - Super-sample covariance (Adhikariand & Huterer 2019)

- Problem: can’t simultaneously solve sound horizon tension and H_0 tension

The Sound Horizon in Galaxy Surveys Too



(numbers from 2013)

Planck:

$\theta_s(a=9.166 \times 10^{-4}) = (0.59672 +/- 0.00035)$ deg

SDSS-BOSS:

$\theta_s(a=0.64) = (4.19 +/- .07)$ deg

(Scale factor, a, is equal to 1 today)

Strain on LCDM (Tension)

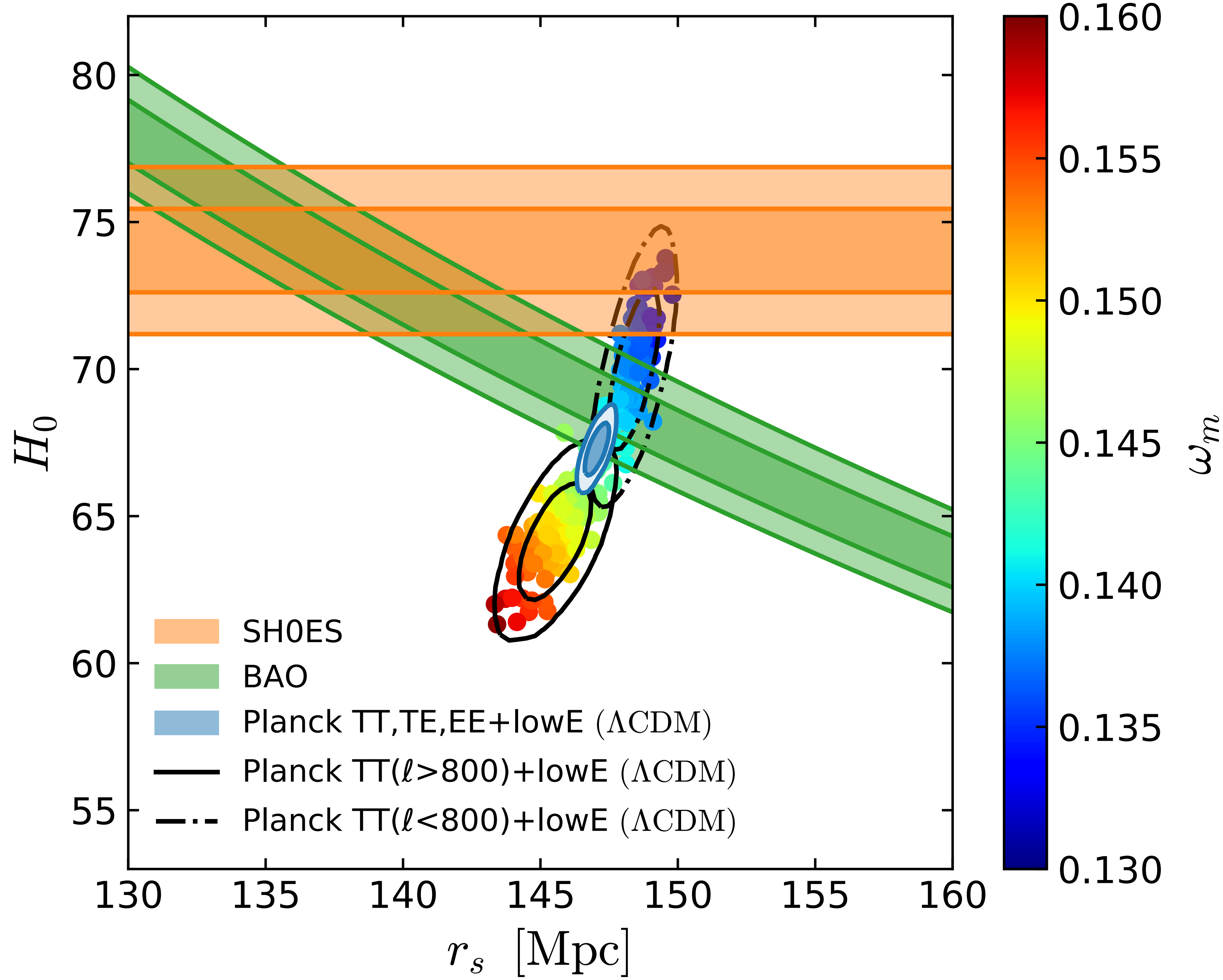
H_0 is statistically most significant tension

BOSS BAO
(no assumption of LCDM*)

SH0ES (2018 Cepheids + Supernovae)
(no assumption of LCDM)

Planck (Assumes LCDM)

For consistency with BAO + Cepheid-calibrated supernovae ==> need alternative model with lower sound horizon (Aylor et al. 2019)



Sound Horizon

*assumes 5-parameter spline model for H(z) and zero mean curvature. Also see Raveri et al. (2019).

The Hubble Hunter's Guide*

L. Knox† and M. Millea‡

Categories of Solution:

- Sound Speed Reduction
- Confusion Sowing
- Post-recombination evolution of r_s
- Reducing Time to Recombination

* with apologies to J. Gunion *et al.*

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  - Additional Components to Increase H(z)

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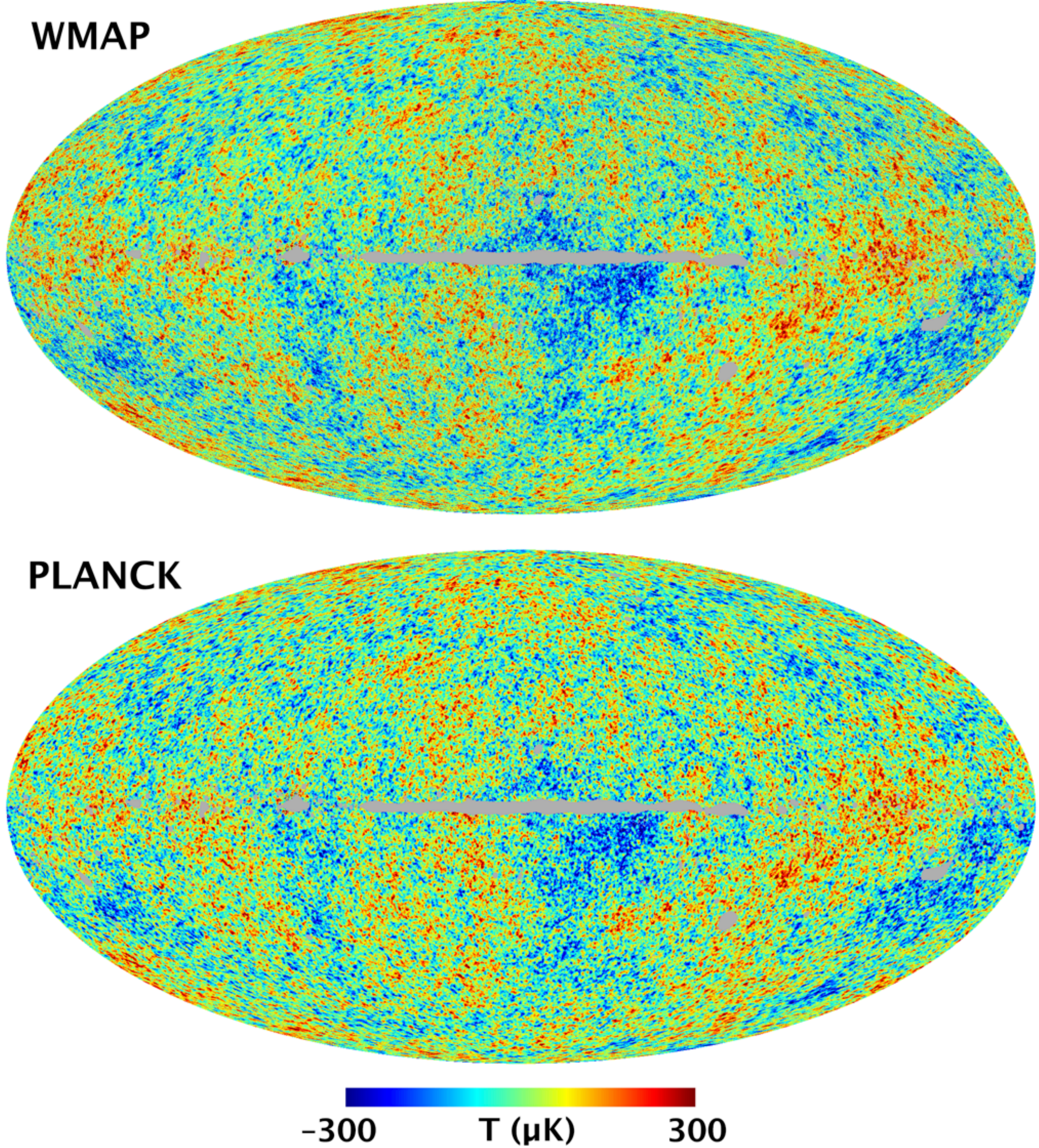
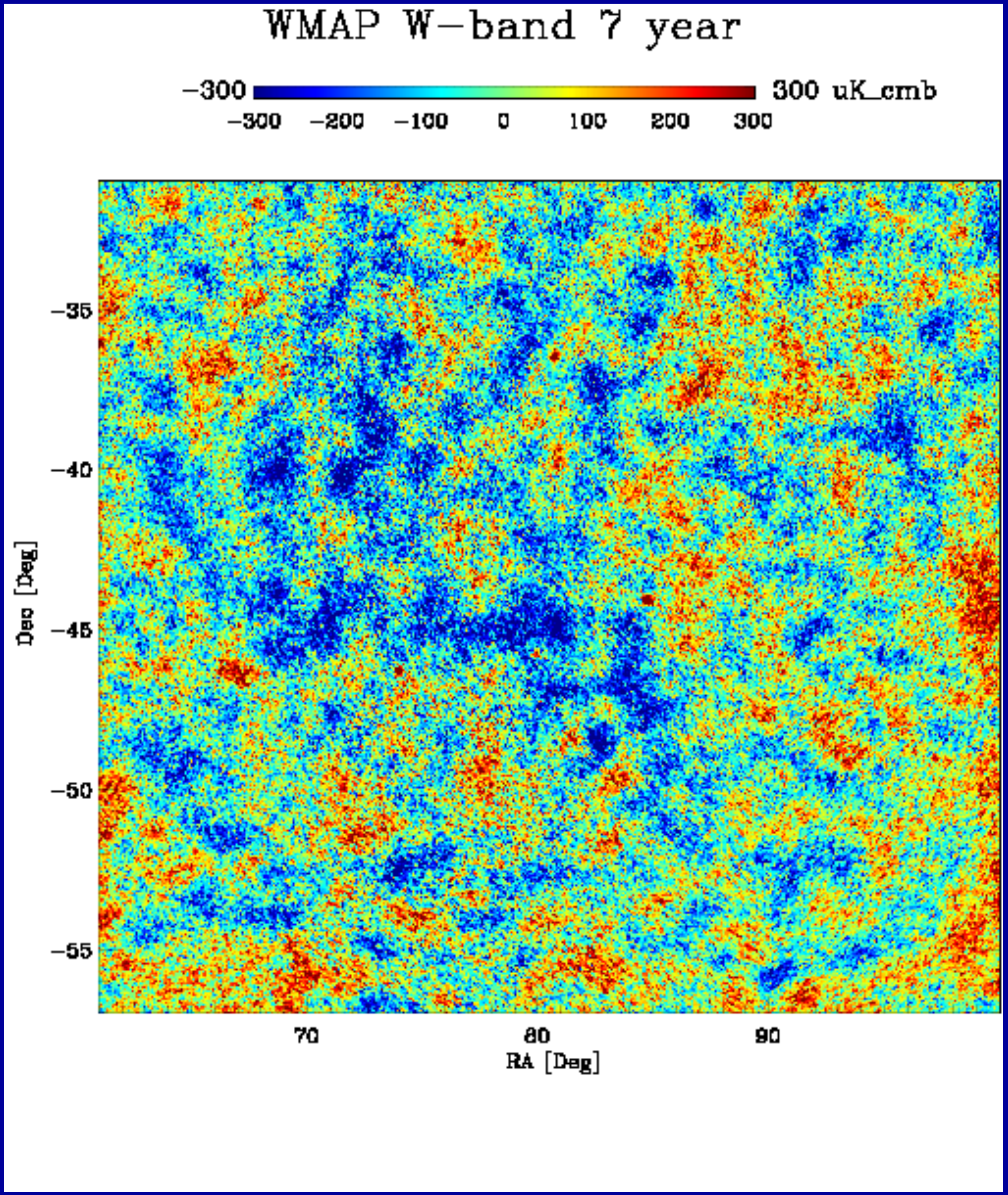
Discussion Questions

Other Questions

- Is tightening up sigma(Neff) of interest? Why?
- Is there interest in the H0 discrepancy? Might it be cosmological?

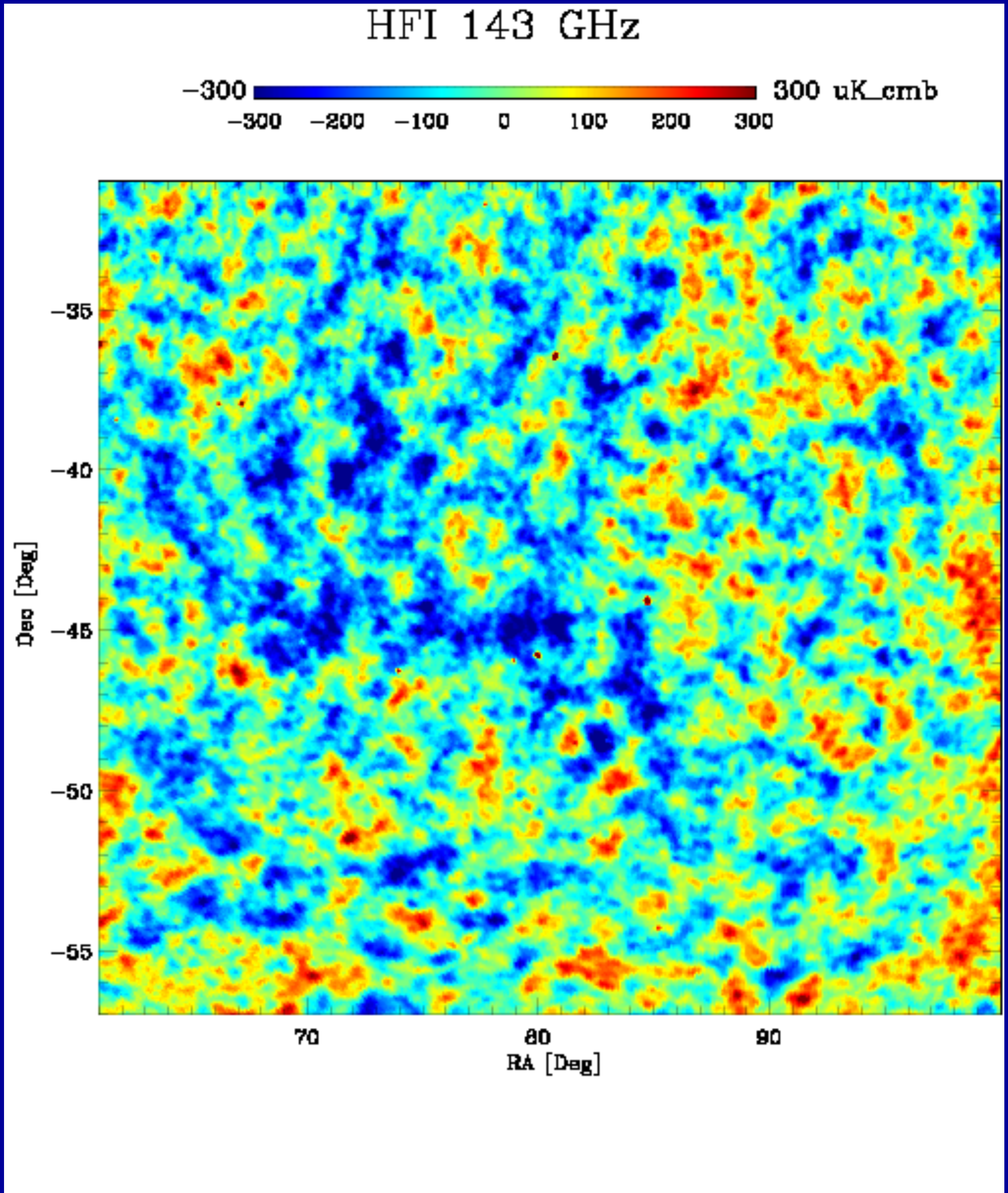

WMAP
PLANCK
-300
T (μK)
300

Zoomed-in view of about 800 square degrees



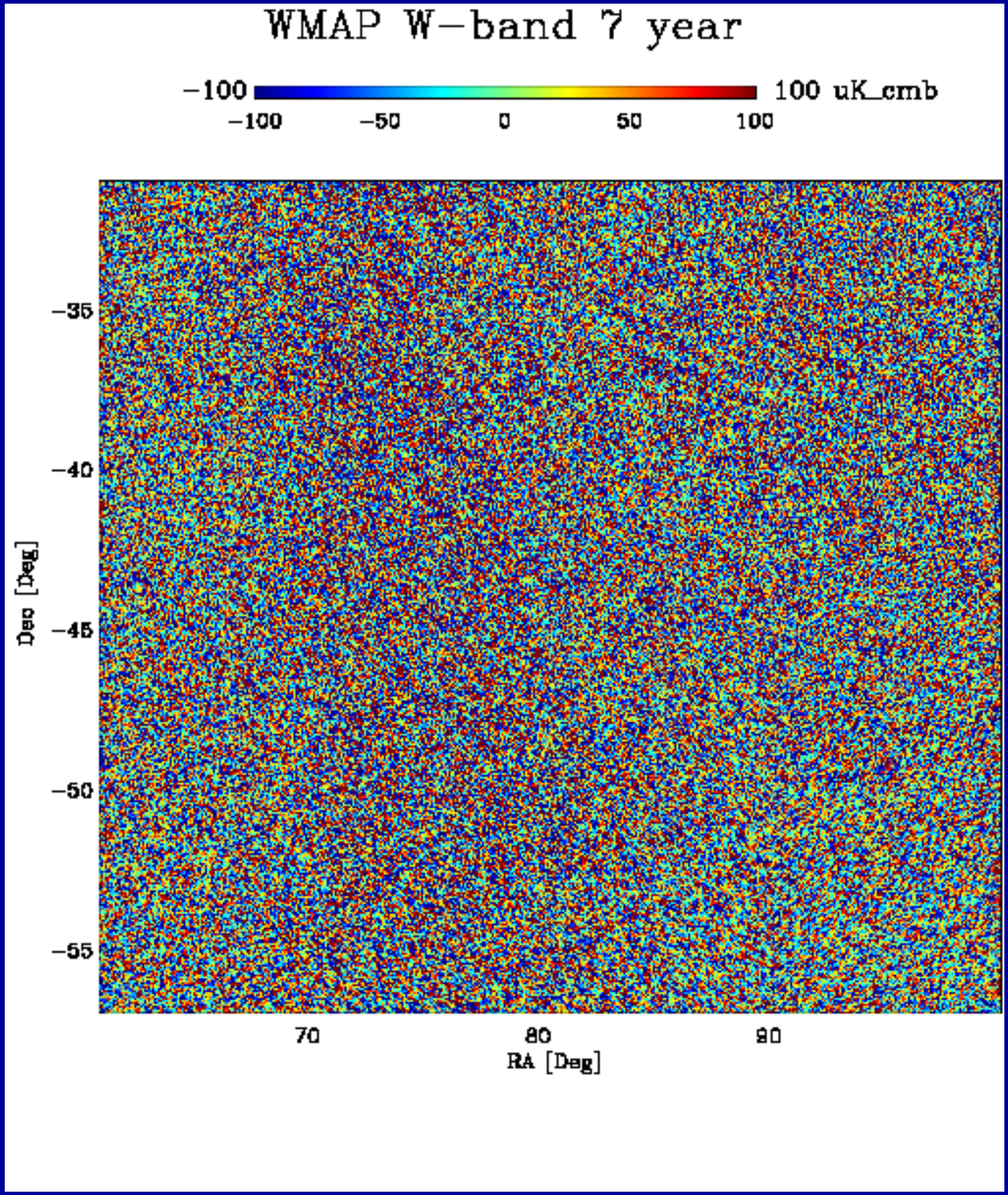
W. Jones

Zoomed-in view of about 800 square degrees



W. Jones

Filtered to remove spatial modes with wavelengths longer than 15’



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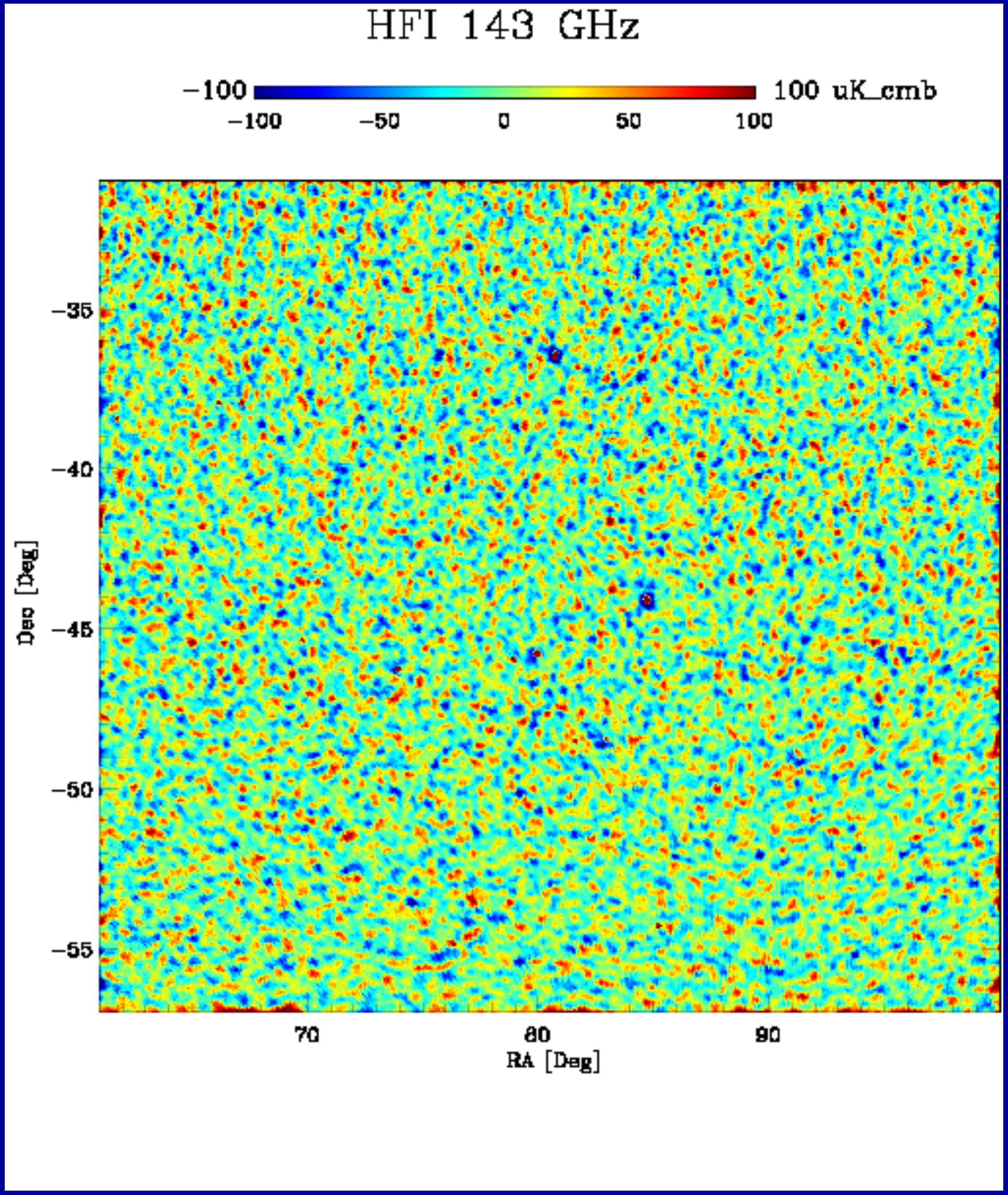
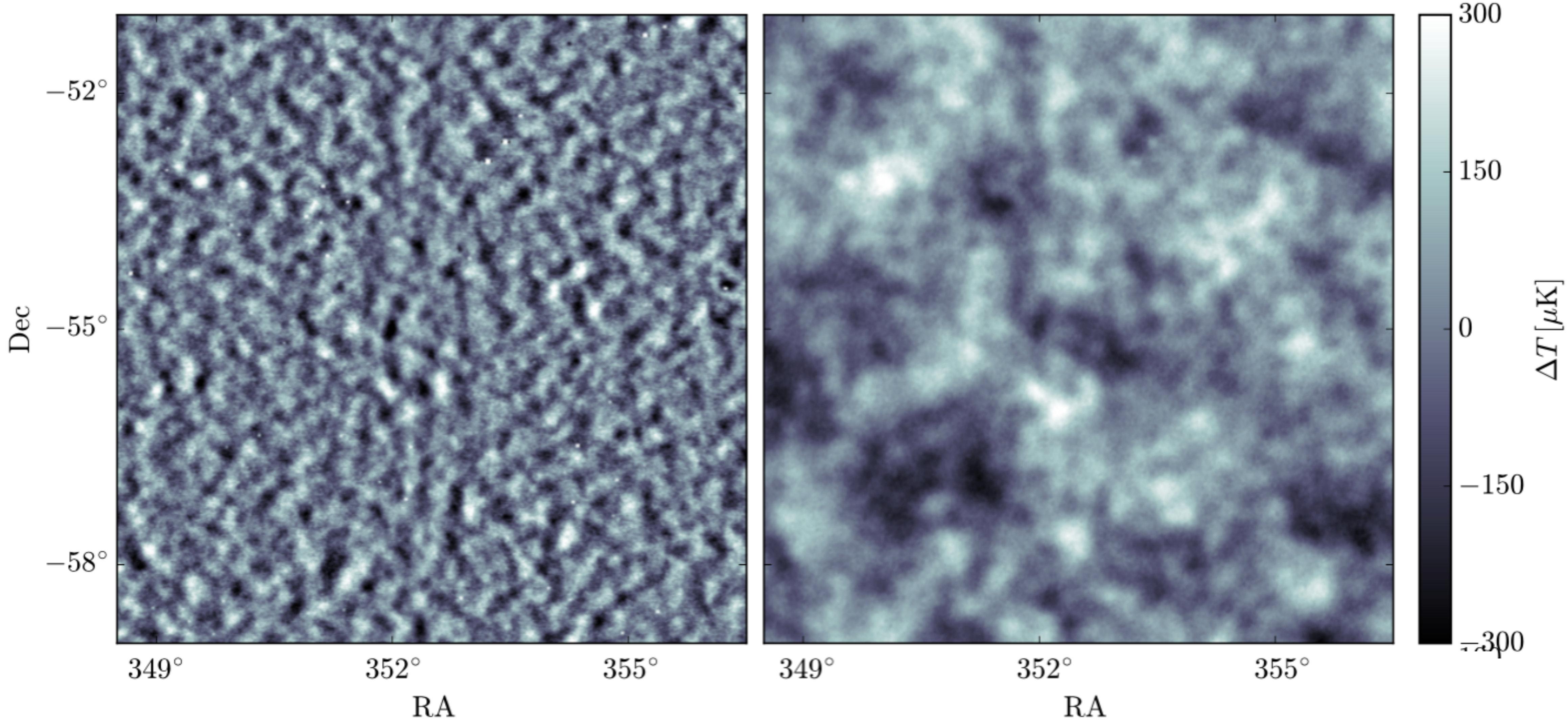


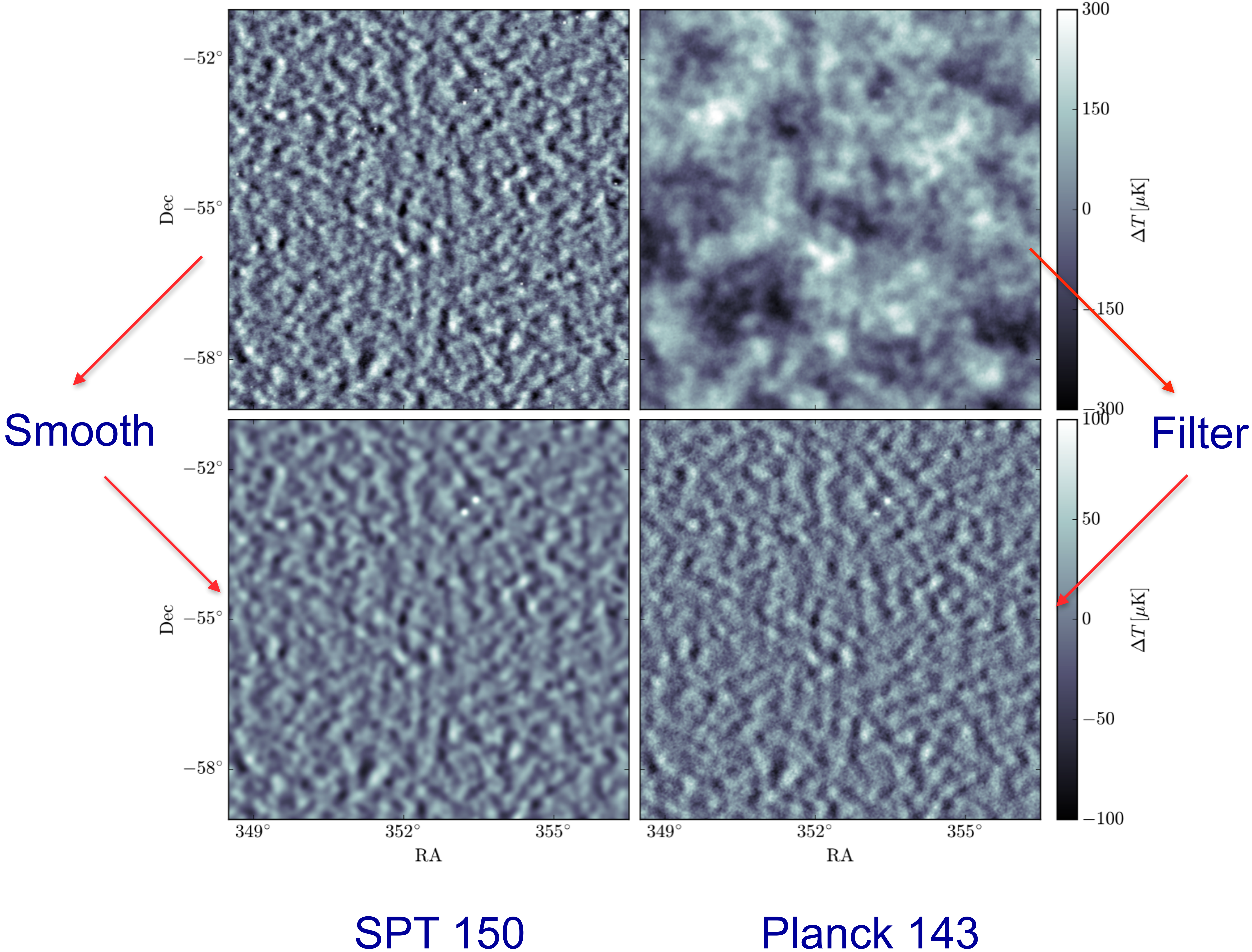
W. Jones



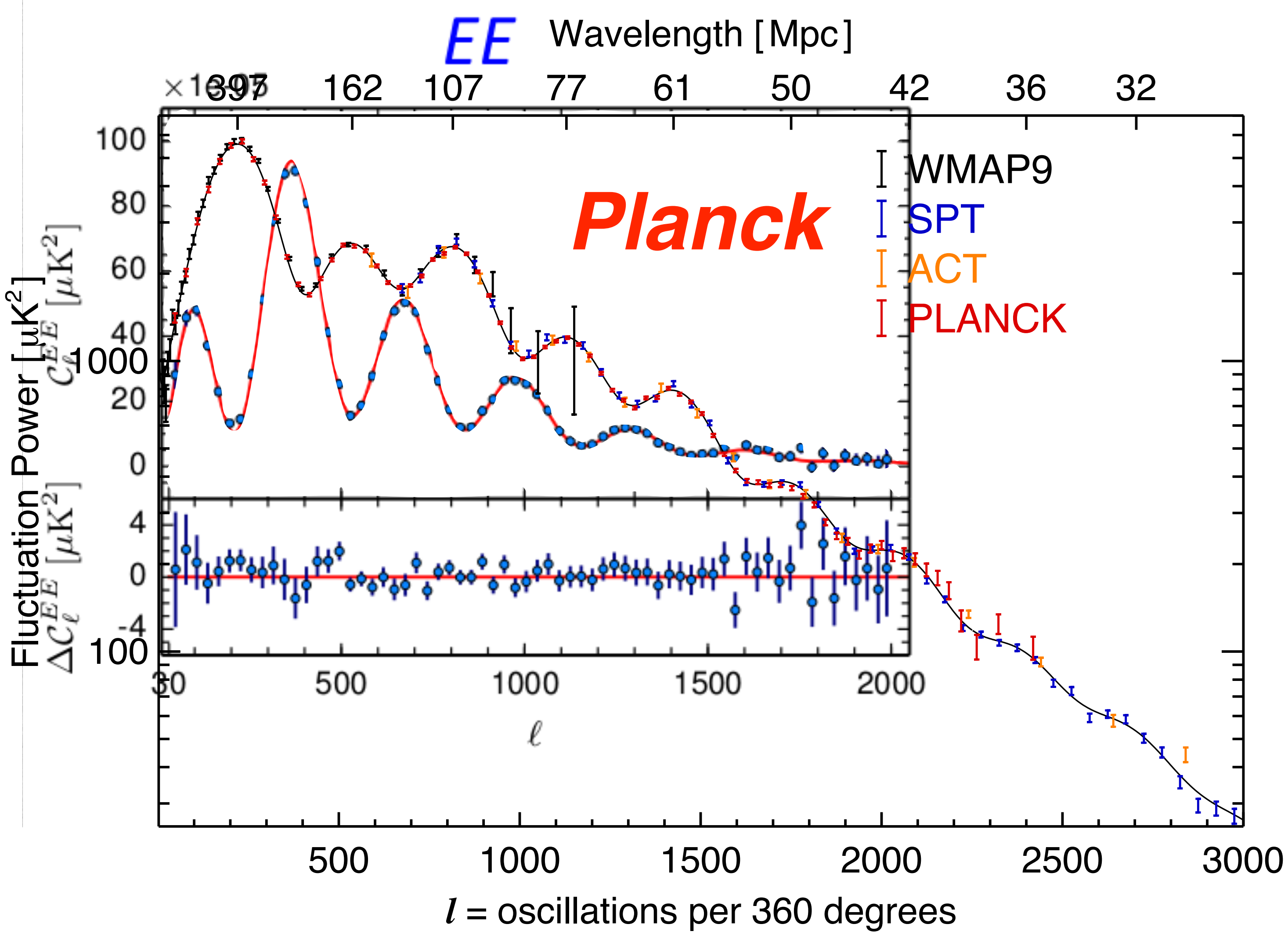
SPT 150 GHz

Planck 143 GHz

Hou et al. (2018)



Hou et al. (2018)



Polarization peaks in temperature troughs as expected!

See Pan et al. (2016) for semi-analytic prediction of locations of all the peaks

Strain on LCDM

BOSS BAO + Pantheon SNe
(no assumption of LCDM*)

SH0ES (2018 Cepheids + Supernovae)
(no assumption of LCDM)

Planck (Assumes LCDM)

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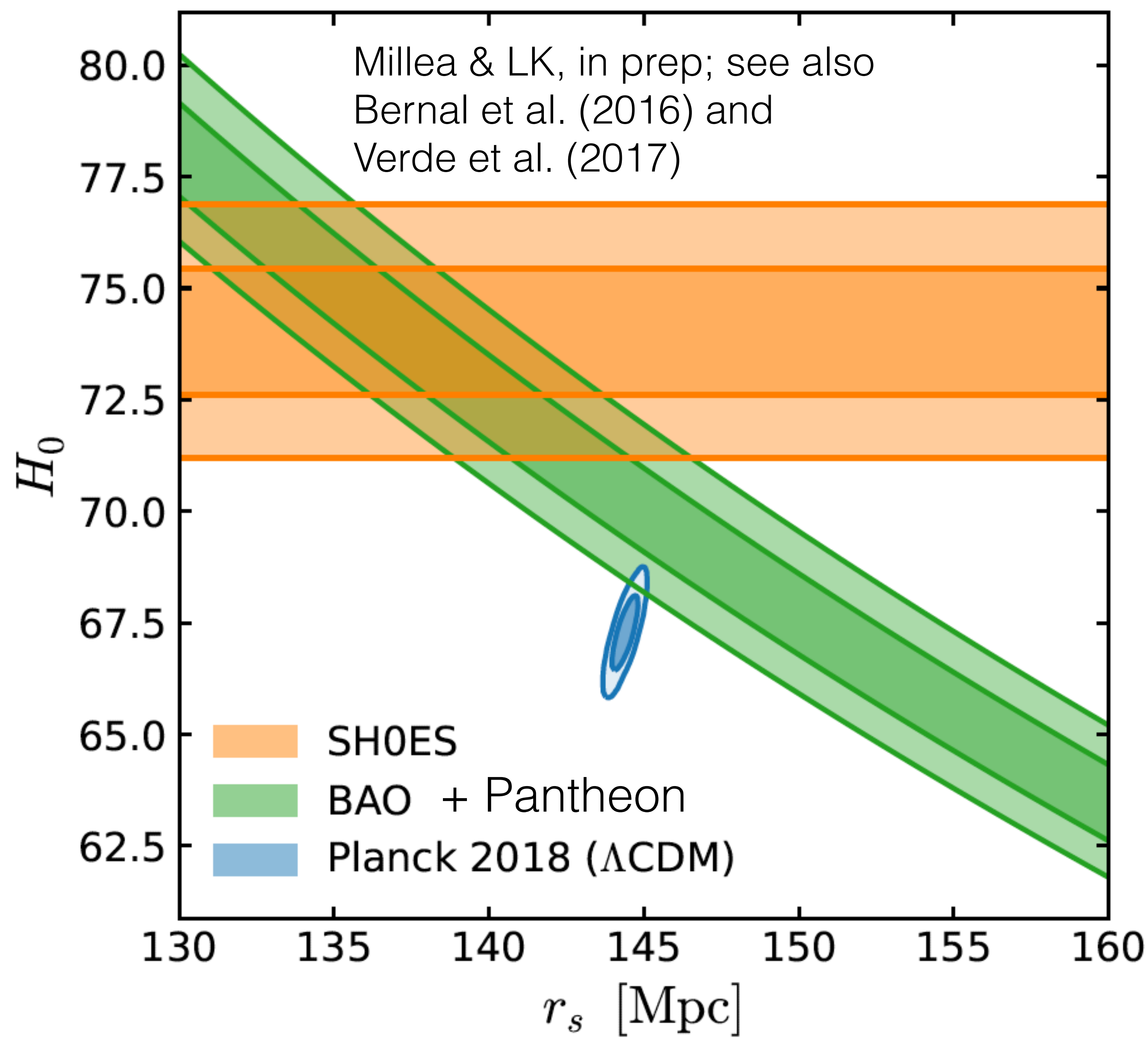

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