Neutrinos in Cosmology & Planck vs. SPT

Lloyd Knox
UC Davis
Planck Collaboration
SPT Collaboration

Outline

- The Standard Cosmological Model pases a precision test
- Why Planck gives low H_0
- Why SPT +WMAP7 gave high H_0
- Neutrino masses, numbers and neutrinos as the (warm) dark matter

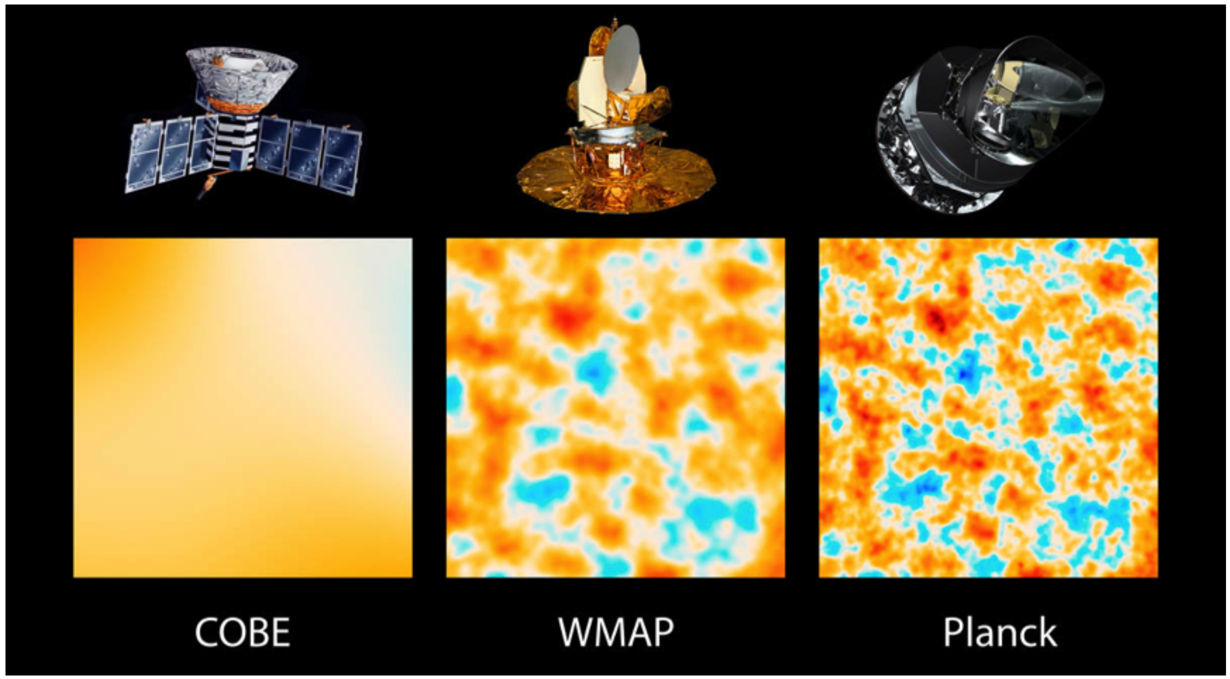
Based a lot on these papers

- Hou, Keisler, LK, Millea & Reichardt (2011 --> 2013)
  - Hou et al. 2013
- Hou + SPT (2012 --> 2013)
  - Hou+SPT 2013
- Story + SPT (2012 --> 2013)
- Planck XVI (2013)

Plus unpublished analyses done since the Planck data release

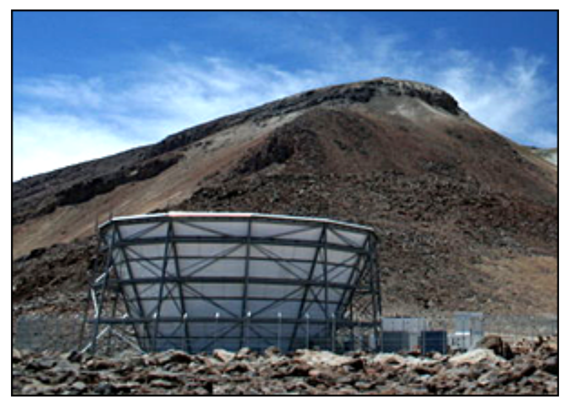
What is Planck?

Full sky:



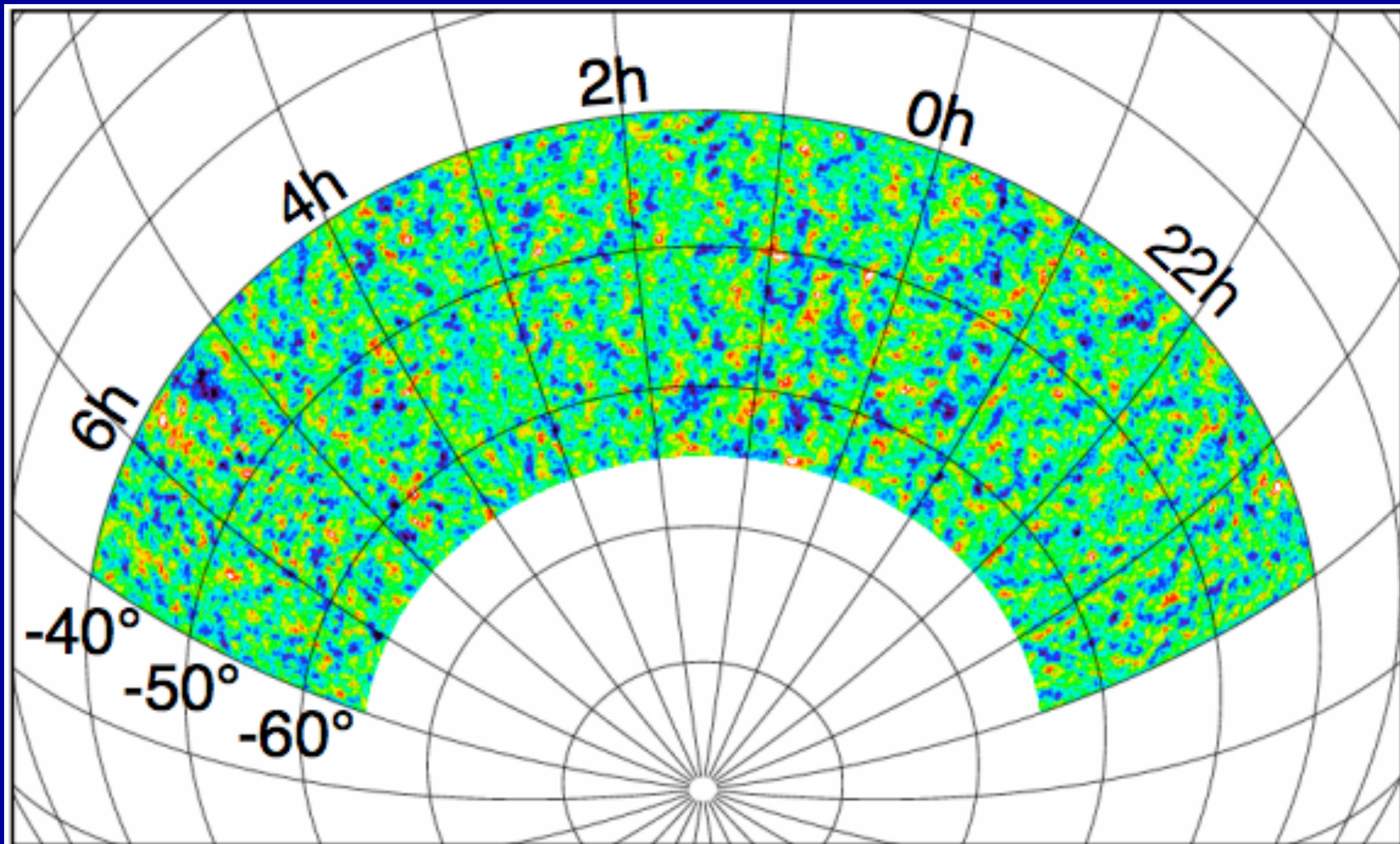
Better resolution:

South Pole Telescope (SPT)



Atacama Cosmology Telescope (ACT)

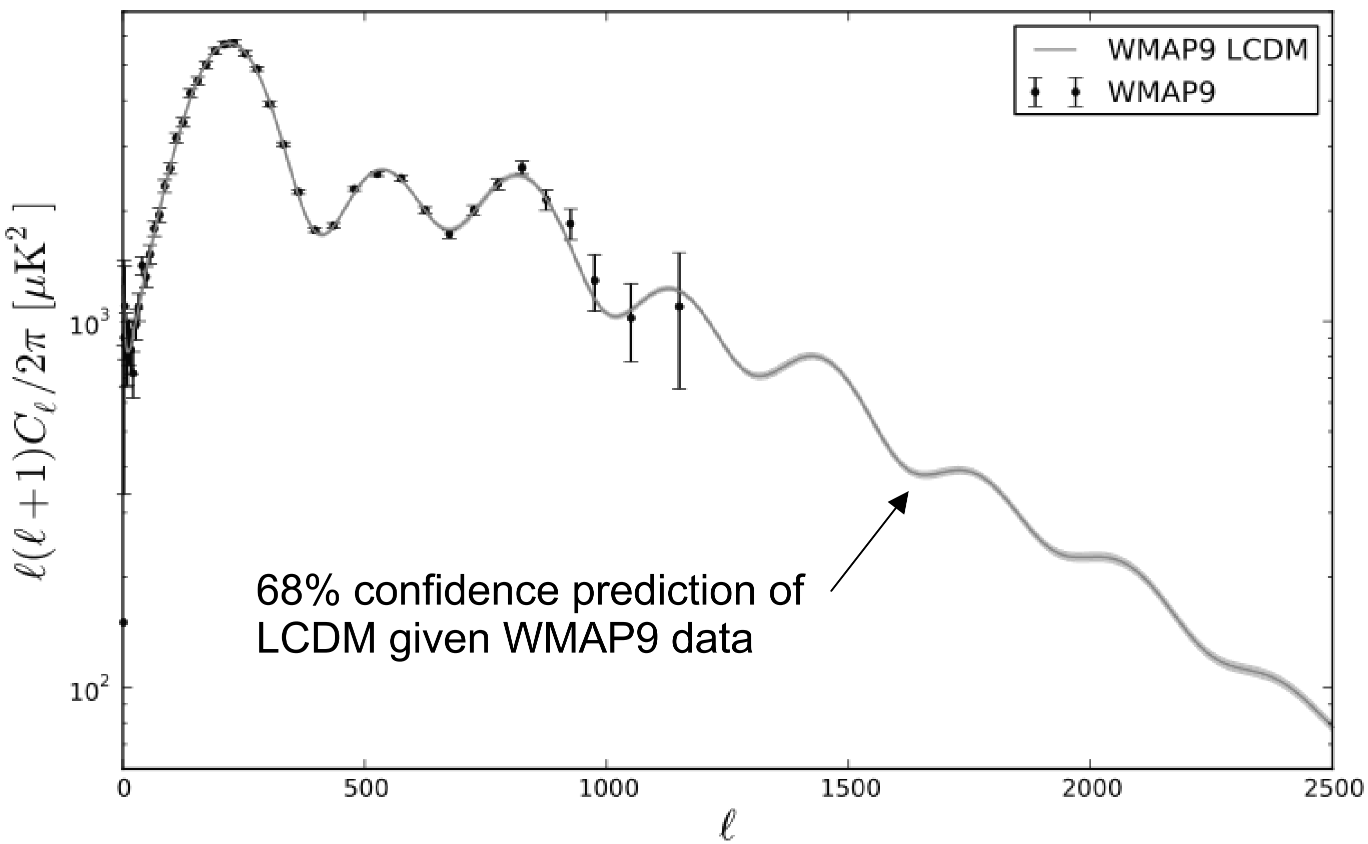
SPT 2500 sq. deg. field



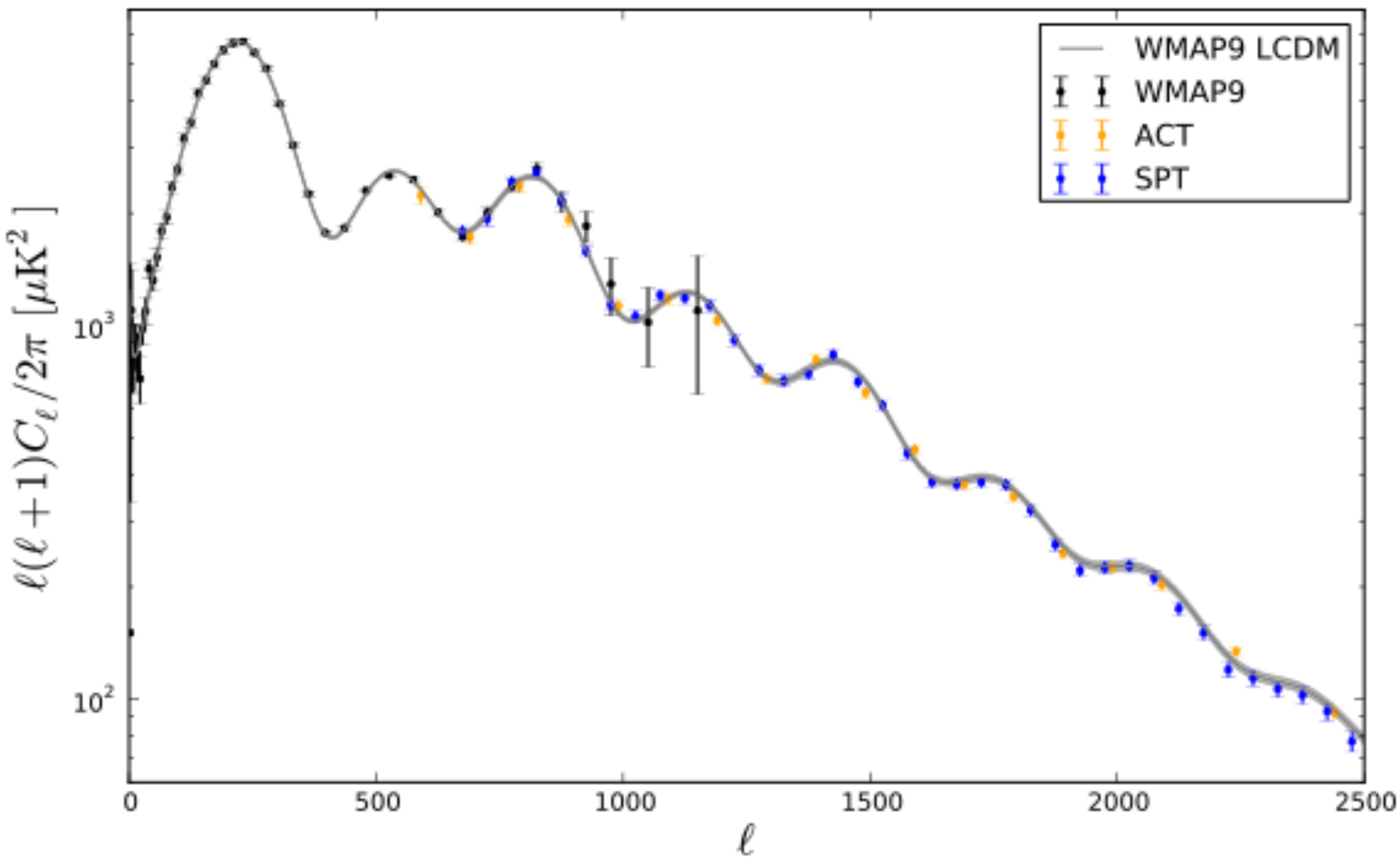
Story+SPT (2013): 150 GHz power spectrum, constraints on LCDM and some extensions by combining with WMAP7

Hou+SPT (2013): Further physical interpretation

LCDM makes a very precise prediction



Slide credit: M. Millea



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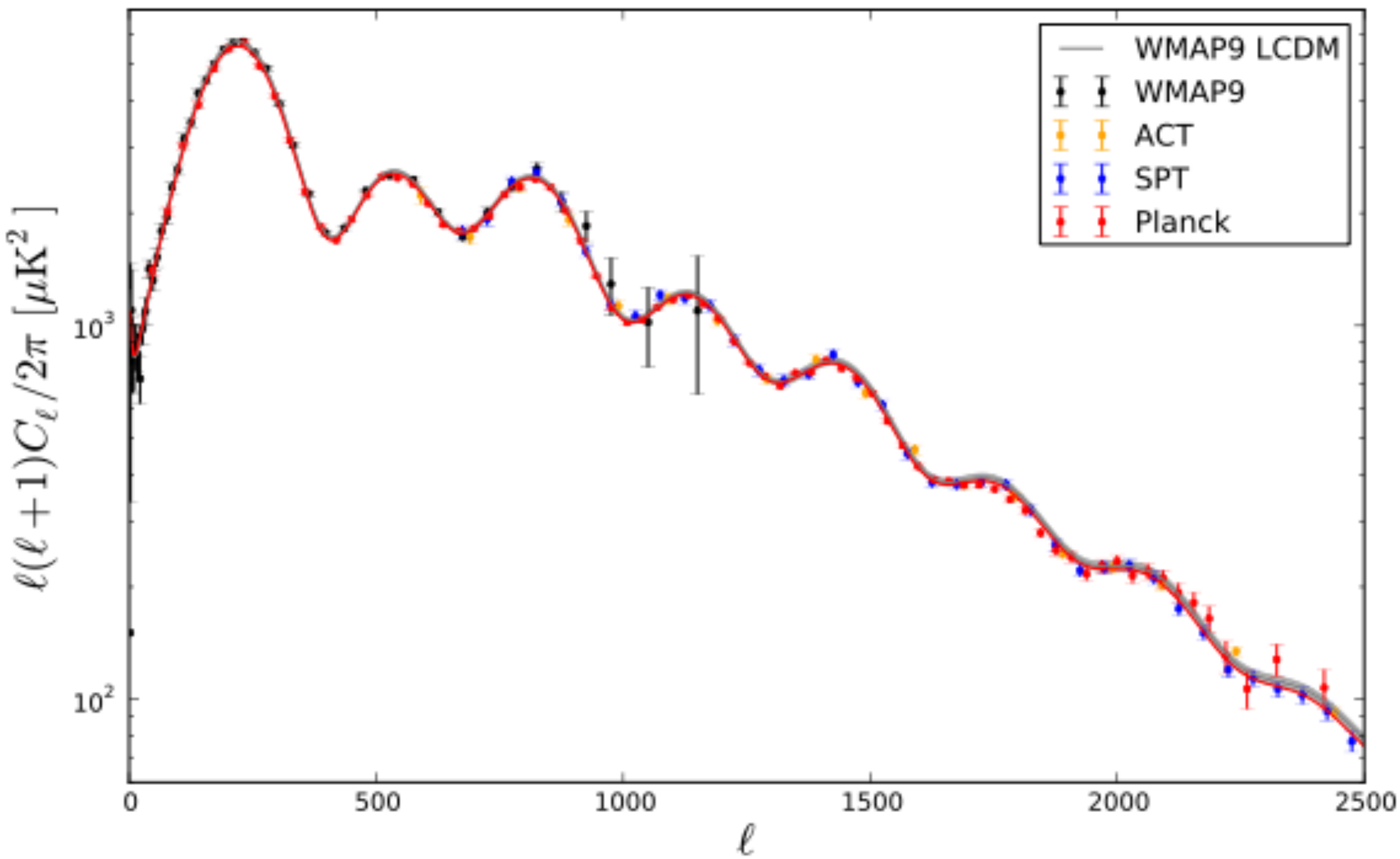
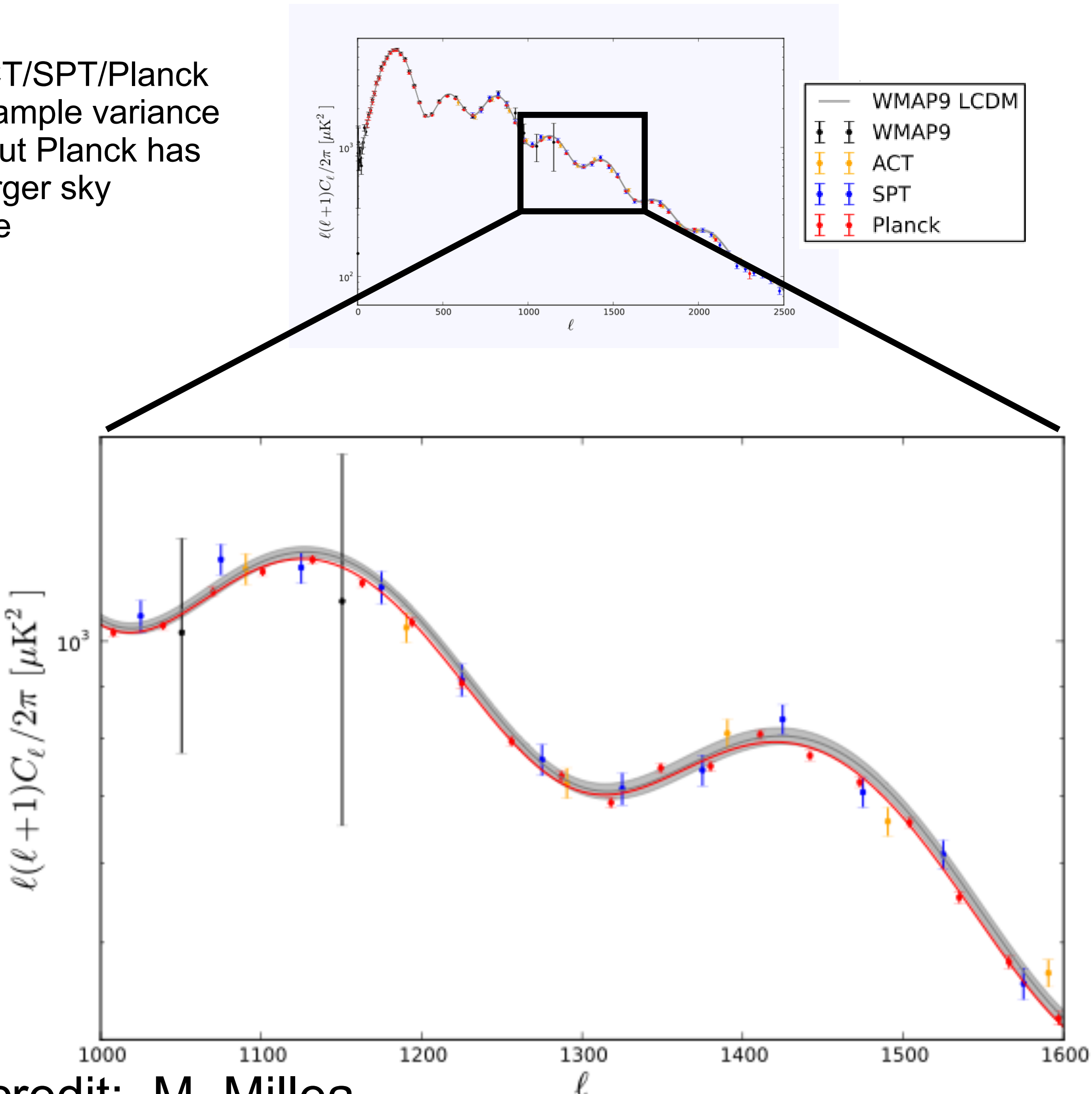


Slide credit: M. Millea

- Here ACT/SPT/Planck are all sample variance limited but Planck has much larger sky coverage



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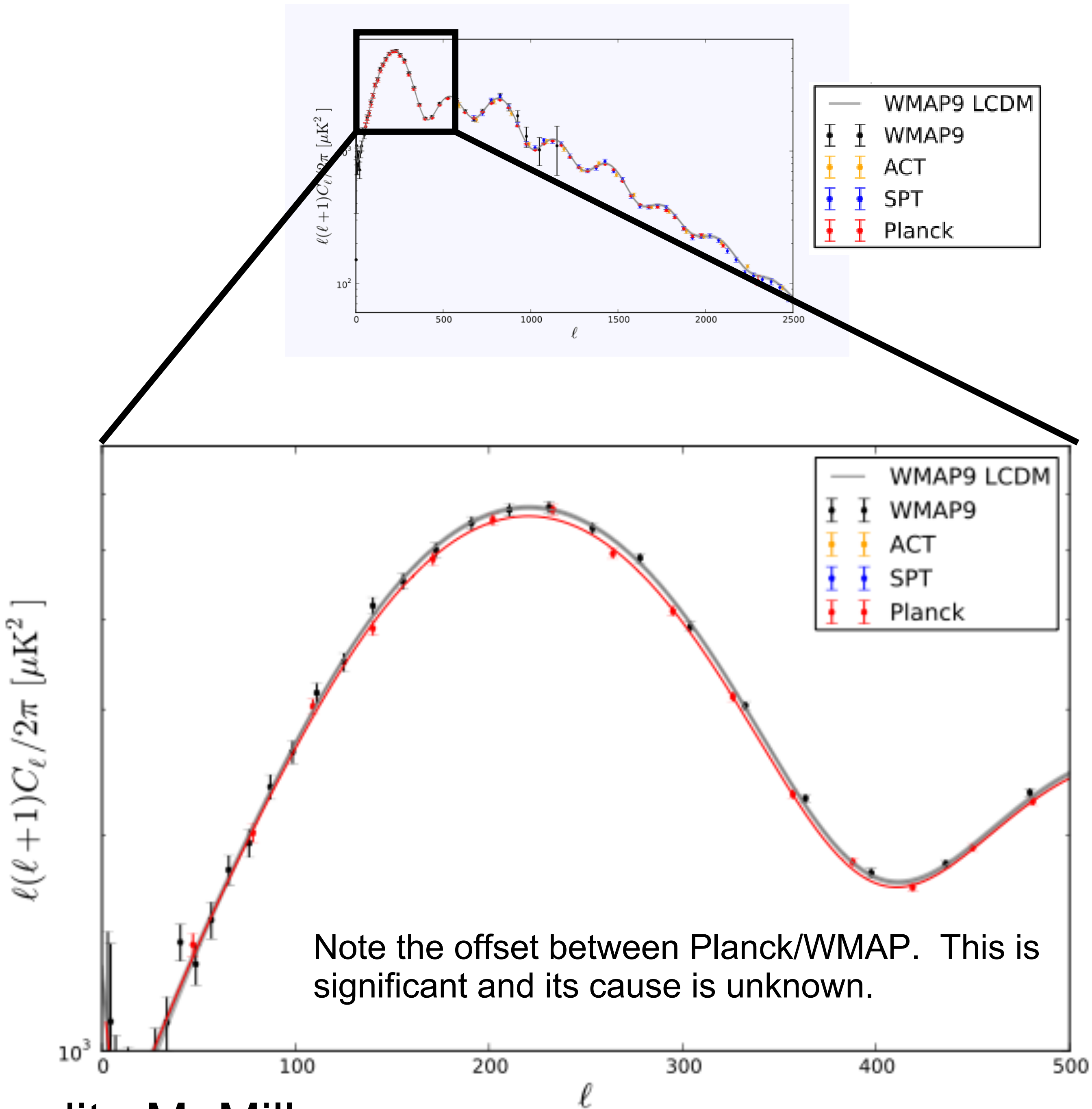

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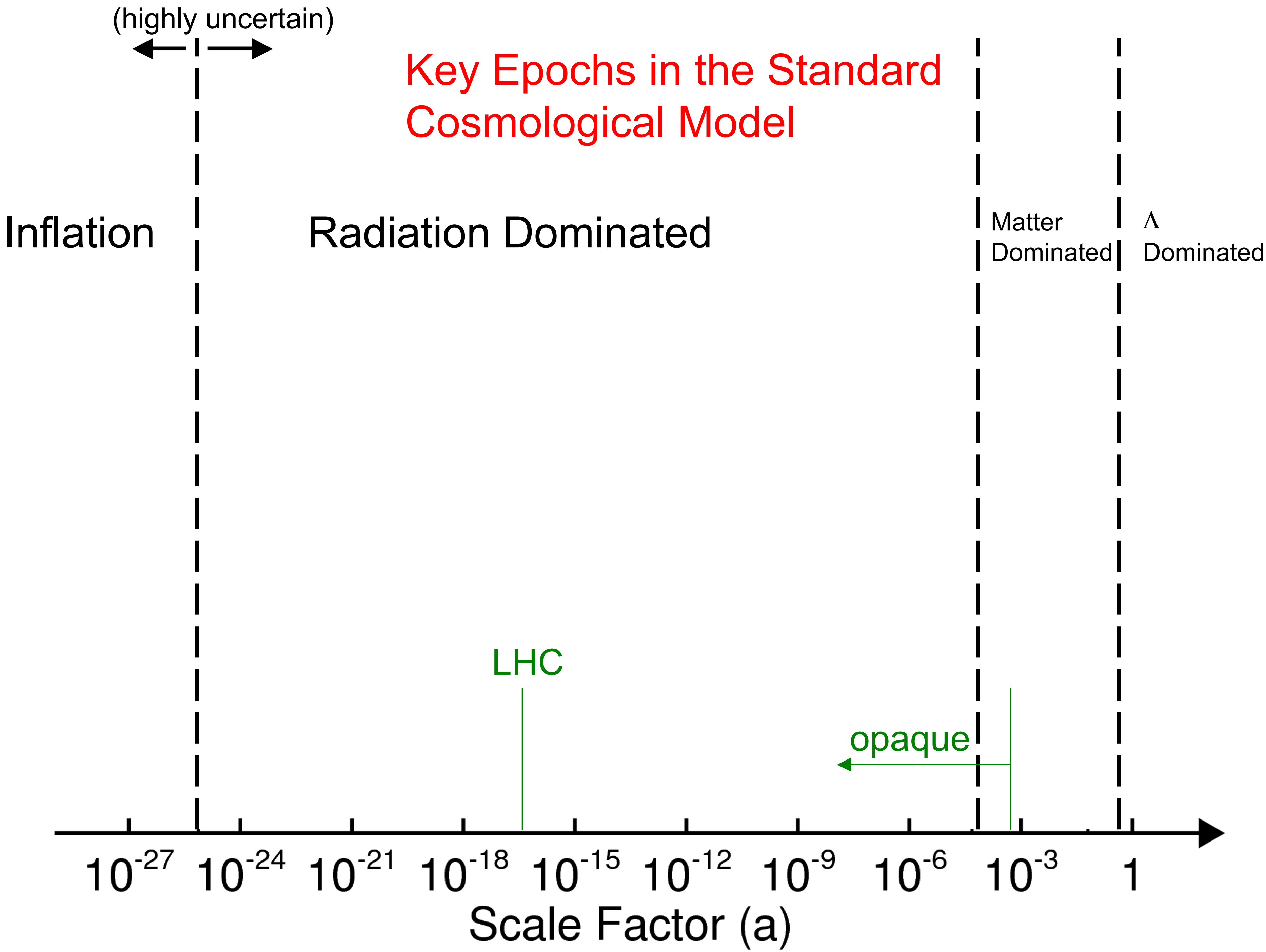
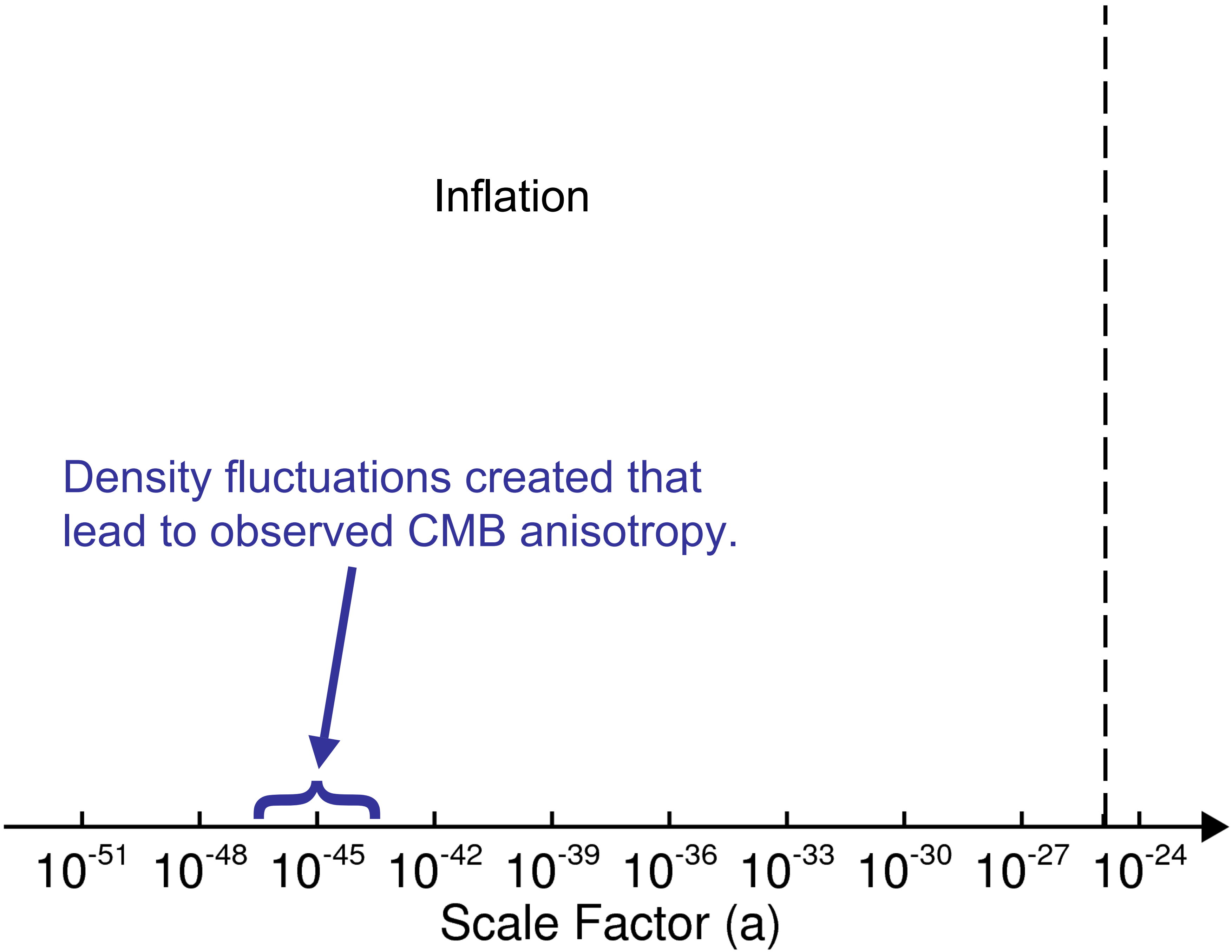
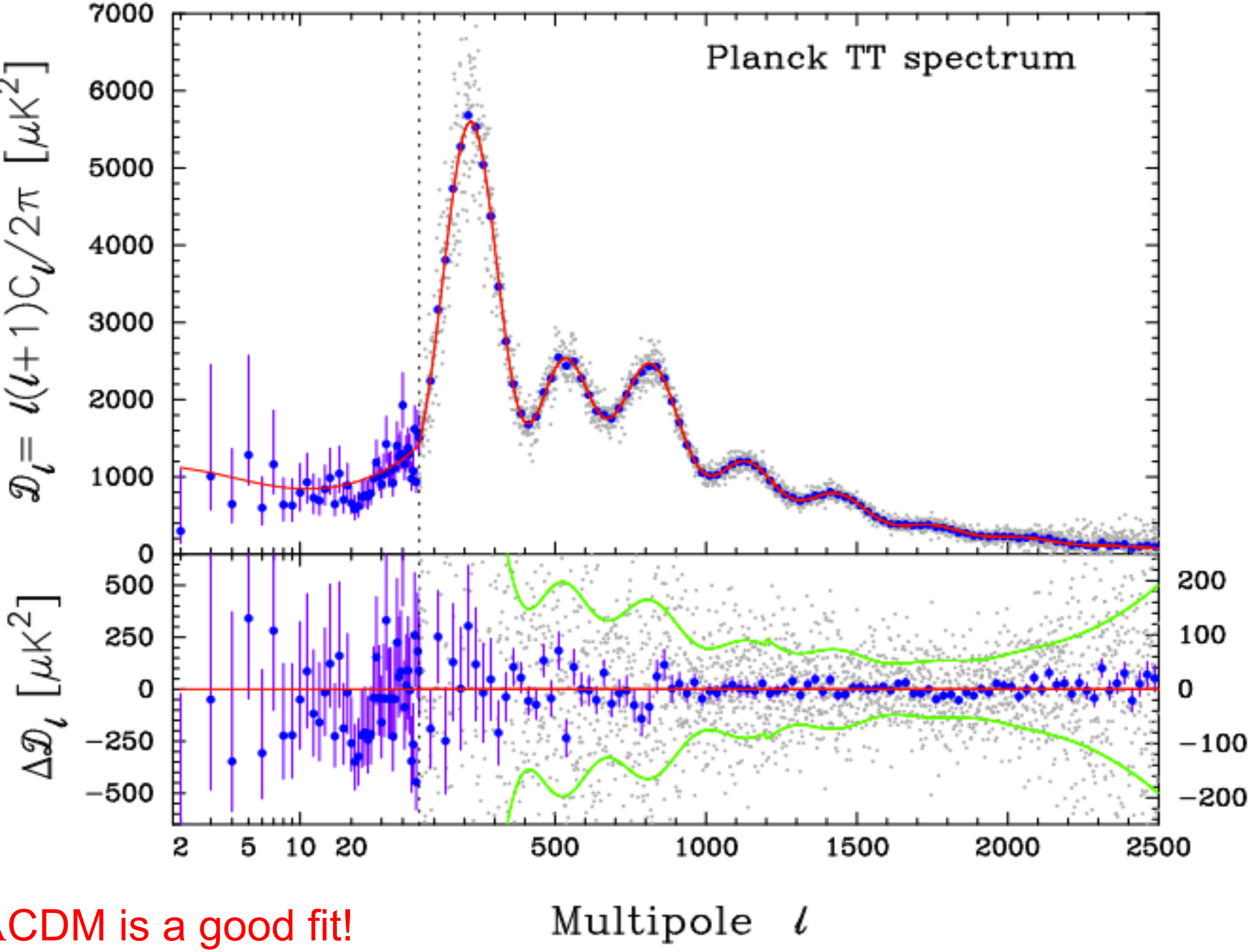
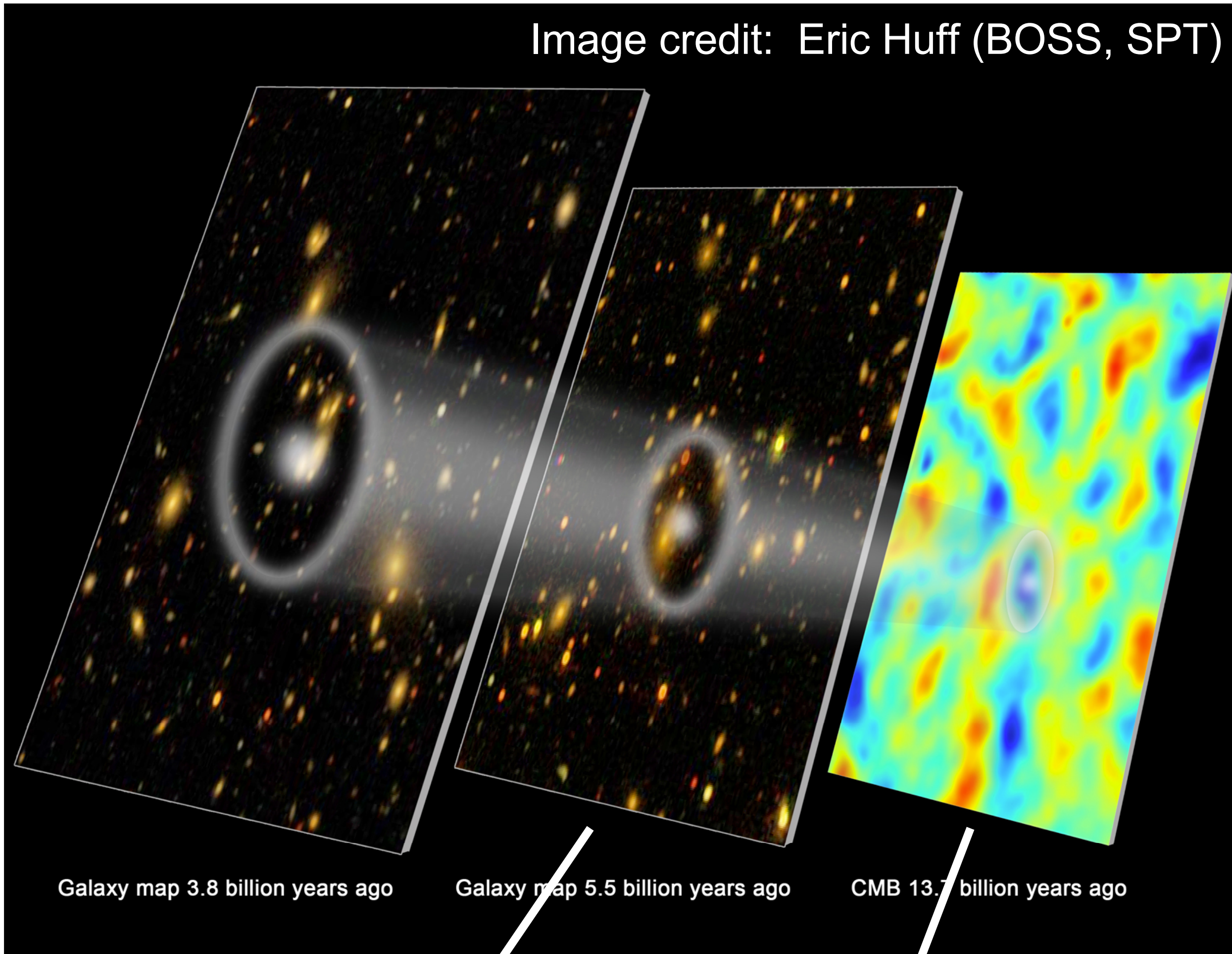

(highly uncertain)
Key Epochs in the Standard Cosmological Model
Inflation
Radiation Dominated
Matter Dominated
Λ Dominated
LHC
opaque
10^-27 10^-24 10^-21 10^-18 10^-15 10^-12 10^-9 10^-6 10^-3 1
Scale Factor (a)



Inflation
Density fluctuations created that
lead to observed CMB anisotropy.
10^-51 10^-48 10^-45 10^-42 10^-39 10^-36 10^-33 10^-30 10^-27 10^-24
Scale Factor (a)



ΛCDM is a good fit!



Planck:

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

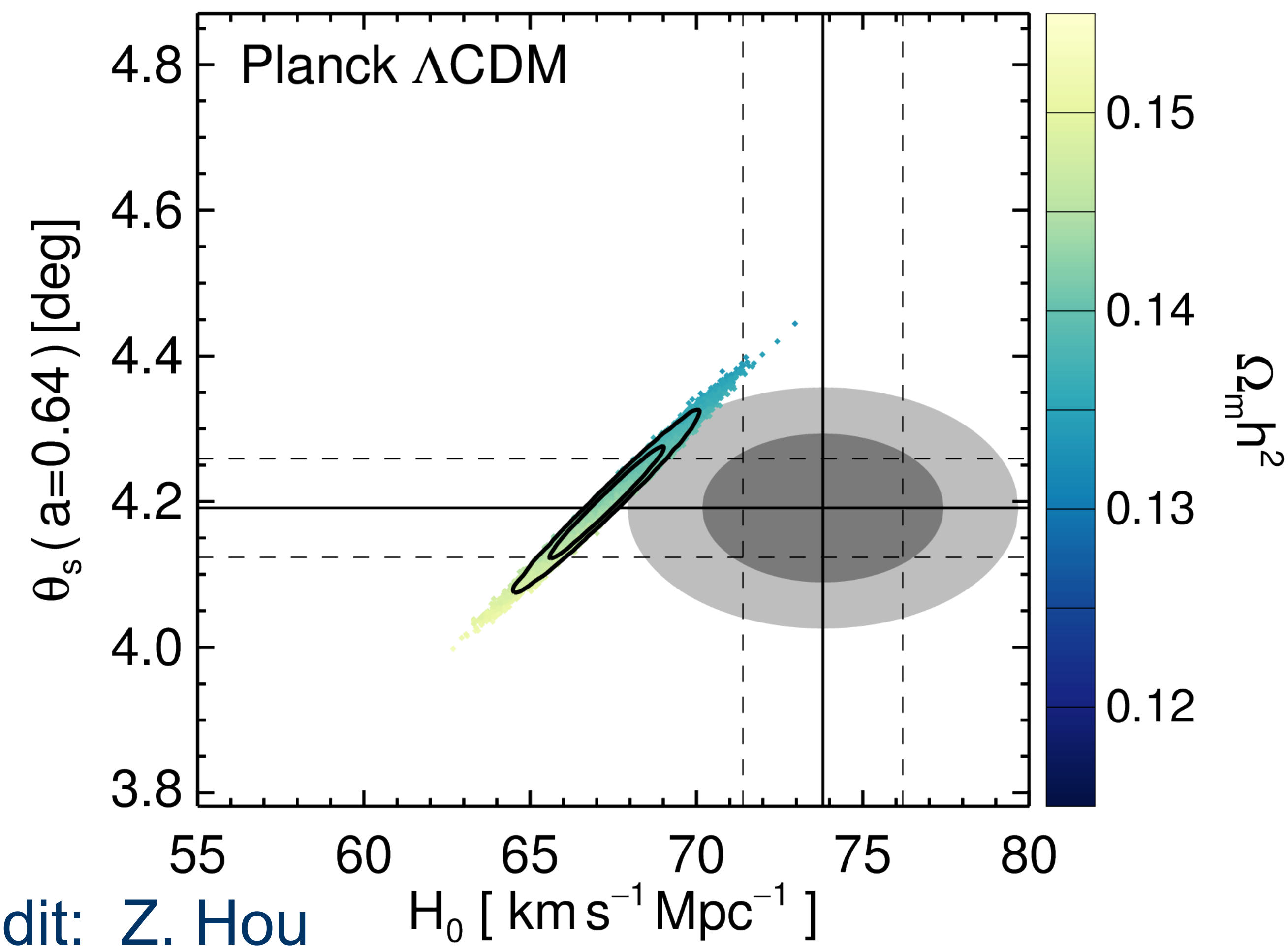
SDSS-BOSS:

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

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

BOSS BAO, Riess et al. (2011) H_0 and Planck LCDM

- Planck is in excellent agreement with BAO measurement, discrepant with Riess et al. H_0



Slide credit: Z. Hou

The Group H_0ug

Details

- To get a good fit we need to include a number of ingredients that have no free parameters:
  - Neutrinos
  - Neutrino “cooling”
  - Helium (BBN consistent)
  - Non-equilibrium recombination
  - Gravitational lensing
- A detail that is not required for a good fit, but make a difference in our parameter estimates:
  - Neutrino masses (Setting Σm_ν = 0.06 eV instead of 0 eV shifts H_0 down by 0.6 km/sec/Mpc = $\sigma/2$)

Story+SPT (2013)+WMAP7 vs. Planck

Slide credit: Z. Hou

BOSS BAO, Riess et al. (2011) H_0 and Planck LCDM

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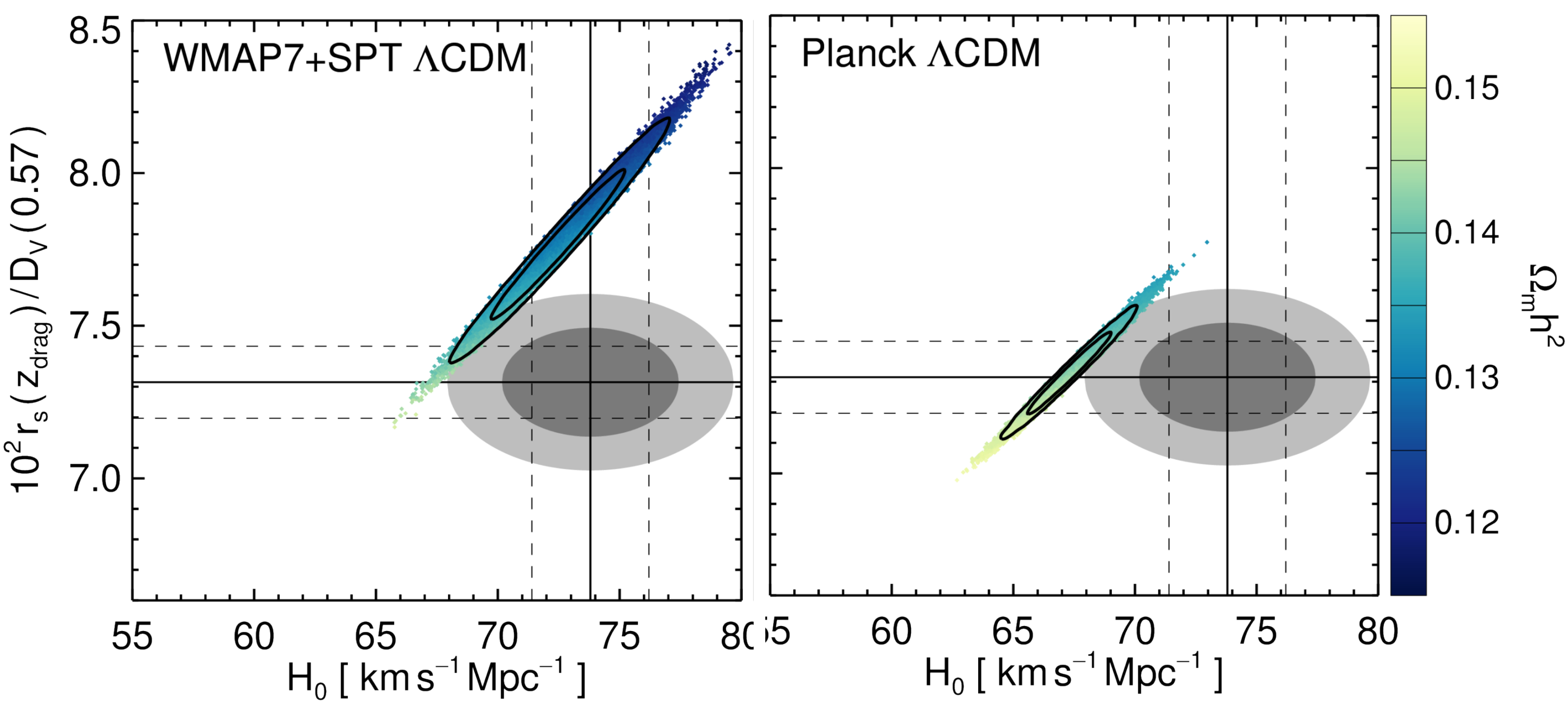

Universe Older, Wider Than Previously Thought

AMERICAN VOICES · Opinion · ISSUE 49·12 · Mar 22, 2013

Astronomers determined that the universe is actually 13.8 billion years old, about 80 to 100 million years older than previously believed, and that it is also a bit wider than once thought. What do *you* think?

"How embarrassing."

Victoria Rosegard – Street Cleaner

"Typical. You give birth to a few trillion galaxies and then people just talk about how old and fat you've gotten."

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149 85 4

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"How embarrassing."

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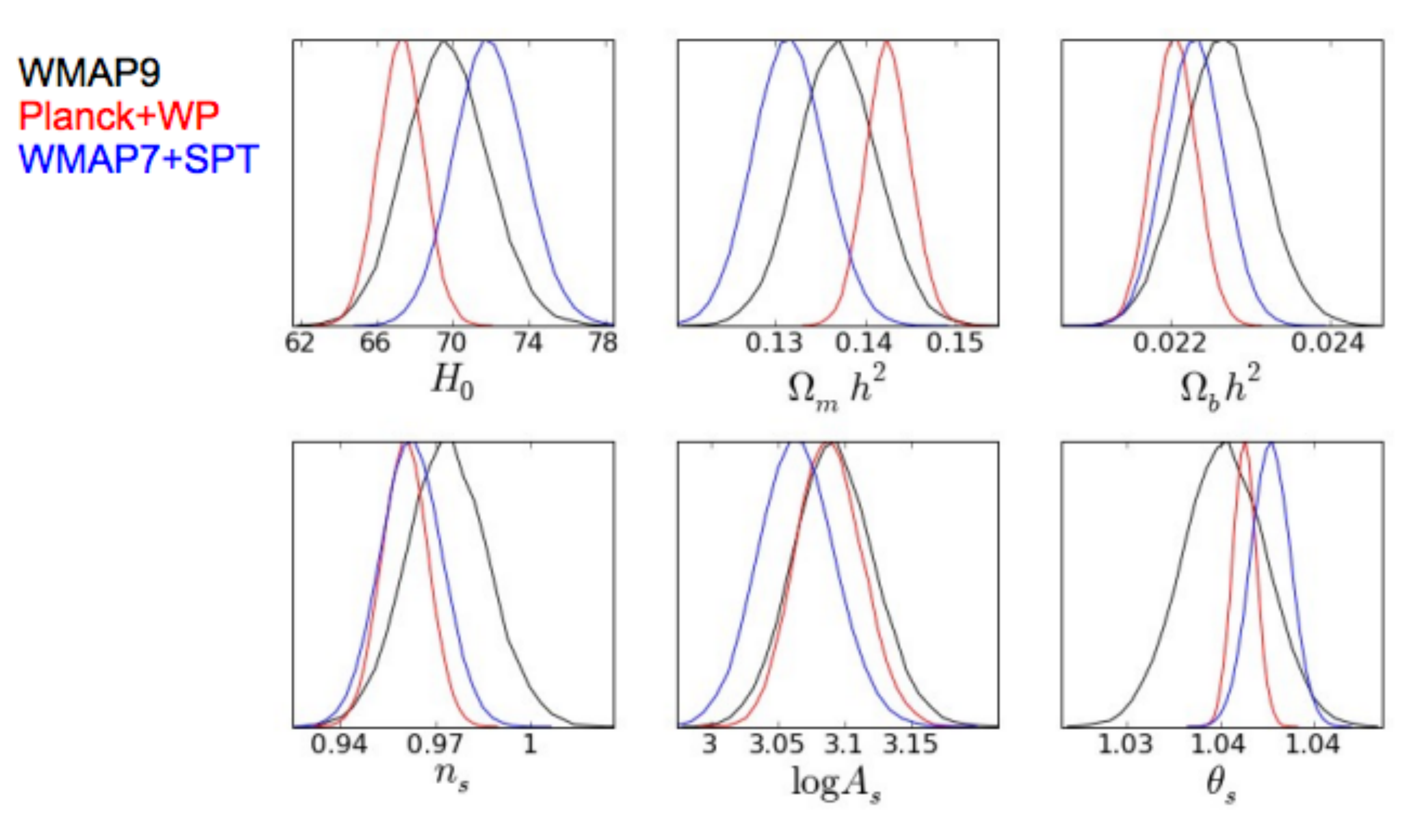
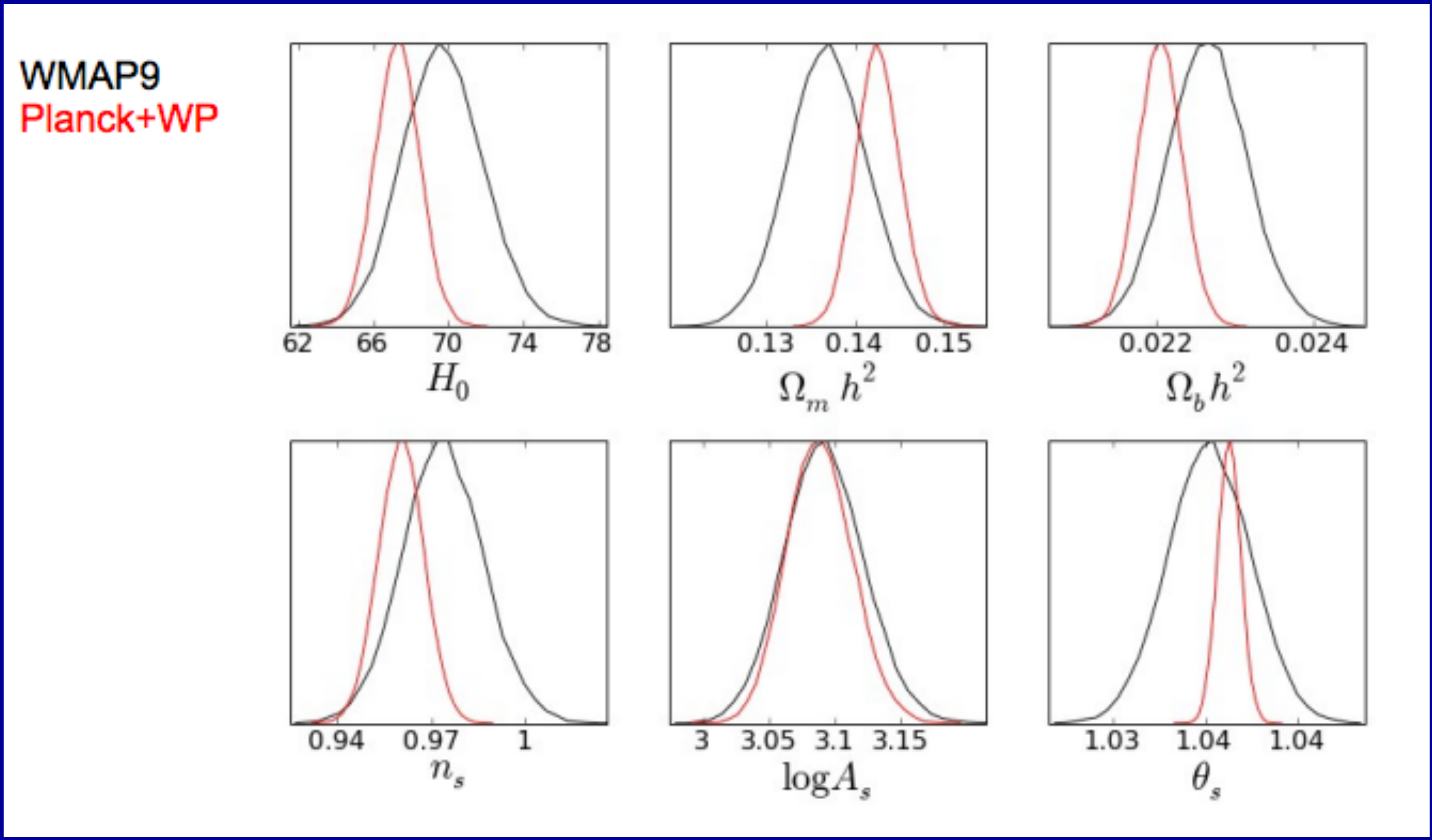
Street Cleaner

"Typical. You give birth to a few trillion galaxies and then people just talk about how old and fat you've gotten."

Who cares? Let me tell you about neutrinos!



Slide credit: M. Millea



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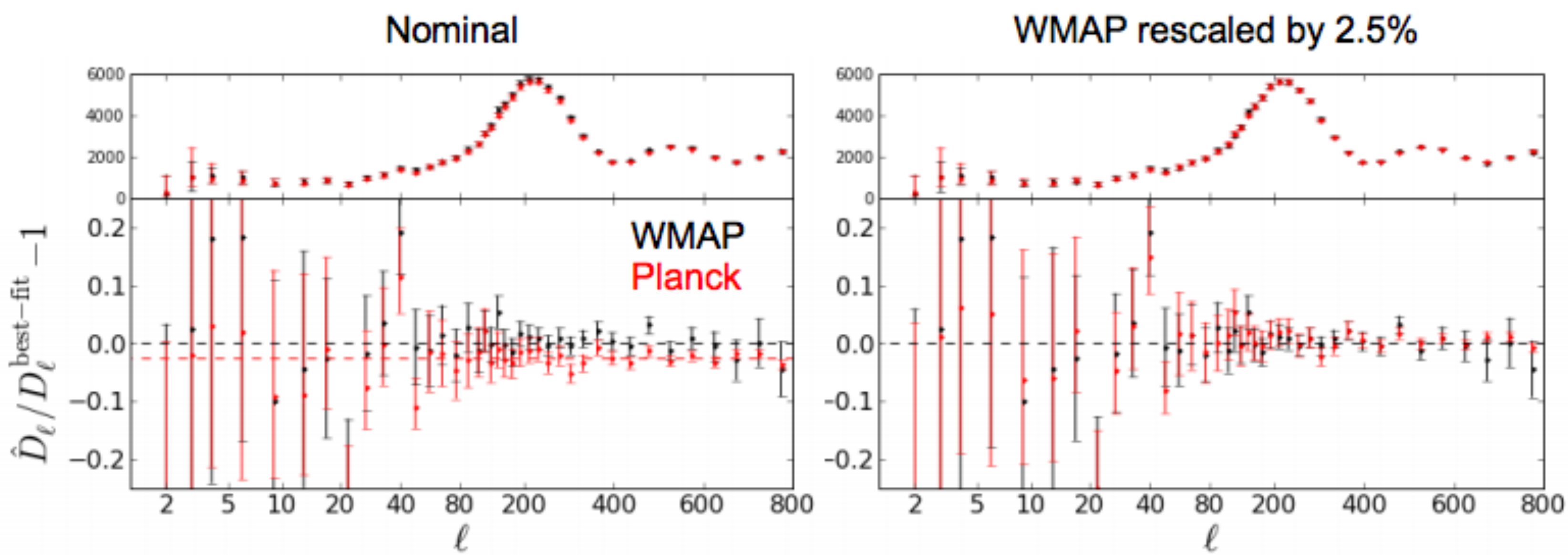
WMAP-Planck Agreement

- A 2.5% rescaling removes most of the differences between WMAP and Planck



Note: different masks, beam uncertainties not included in error bars

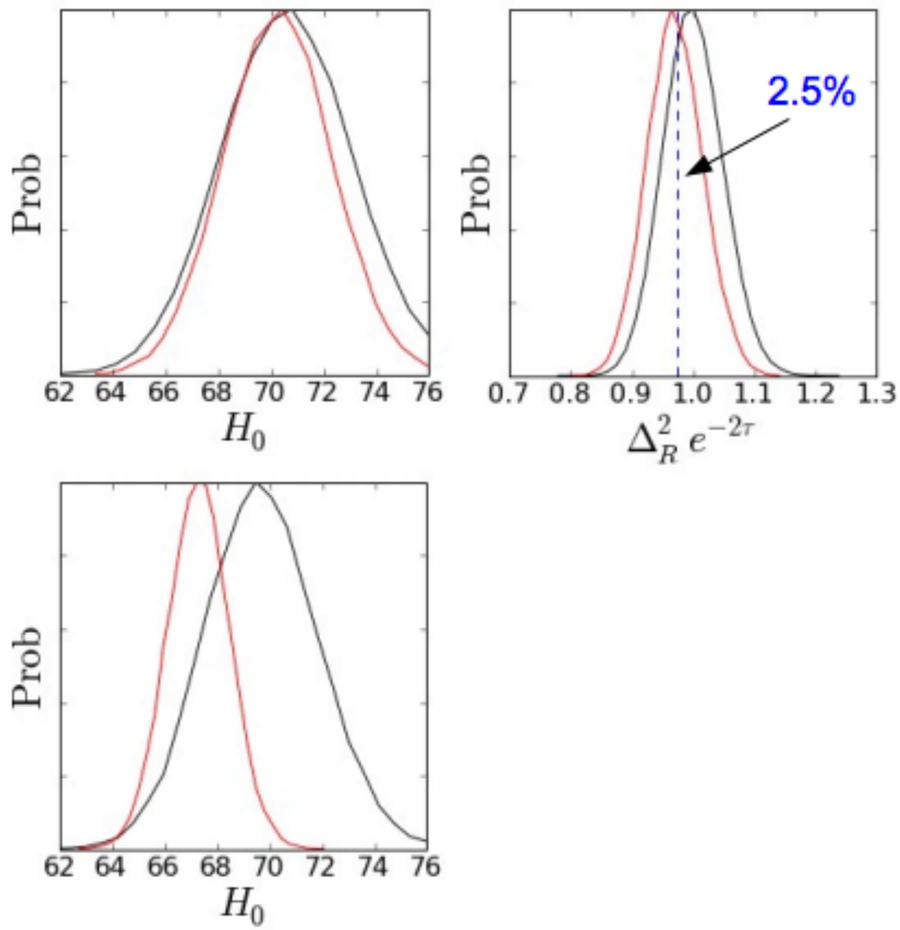
Slide credit: M. Millea

WMAP-Planck

L<800 only

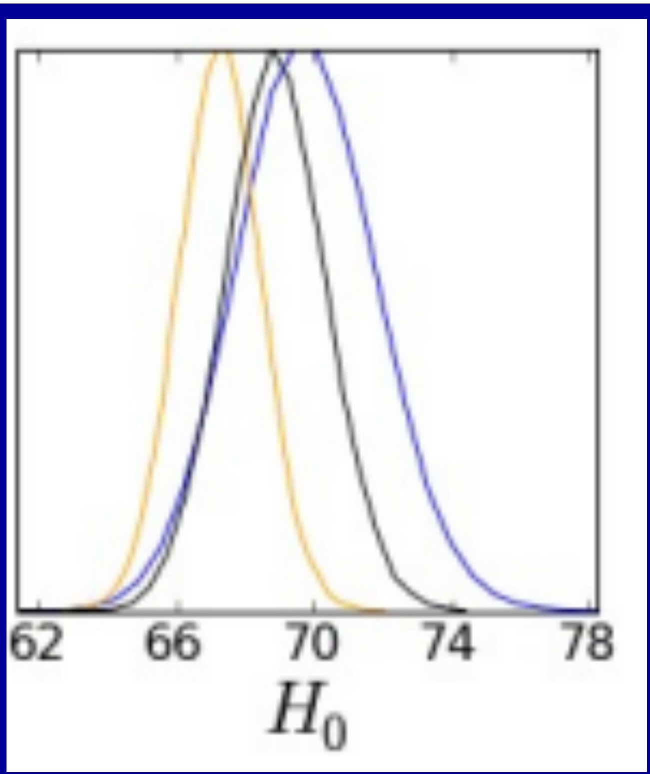
WMAP
Planck

Full L range



To understand WMAP/Planck differences, we need to understand Planck L<800 vs. L>800 differences

Slide credit: M. Millea



Planck (l < 800) LCDM

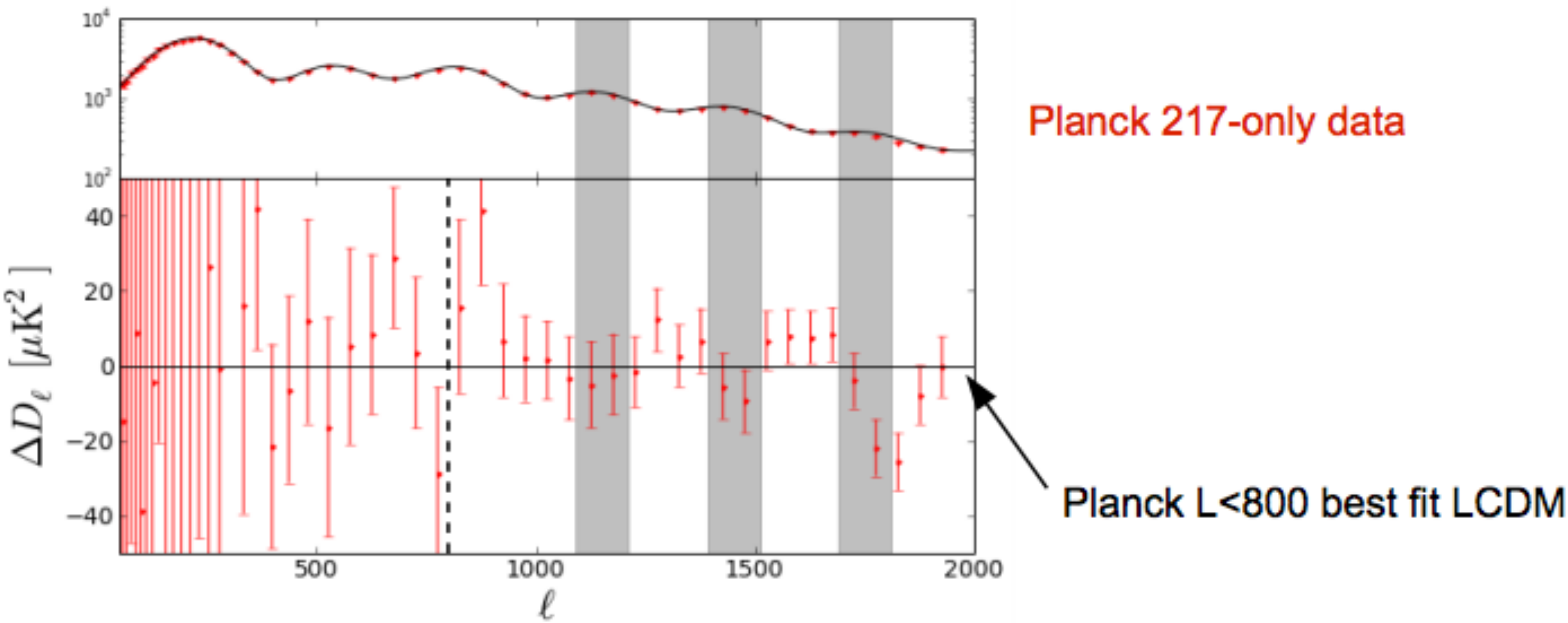
Planck (l < 2500) LCDM

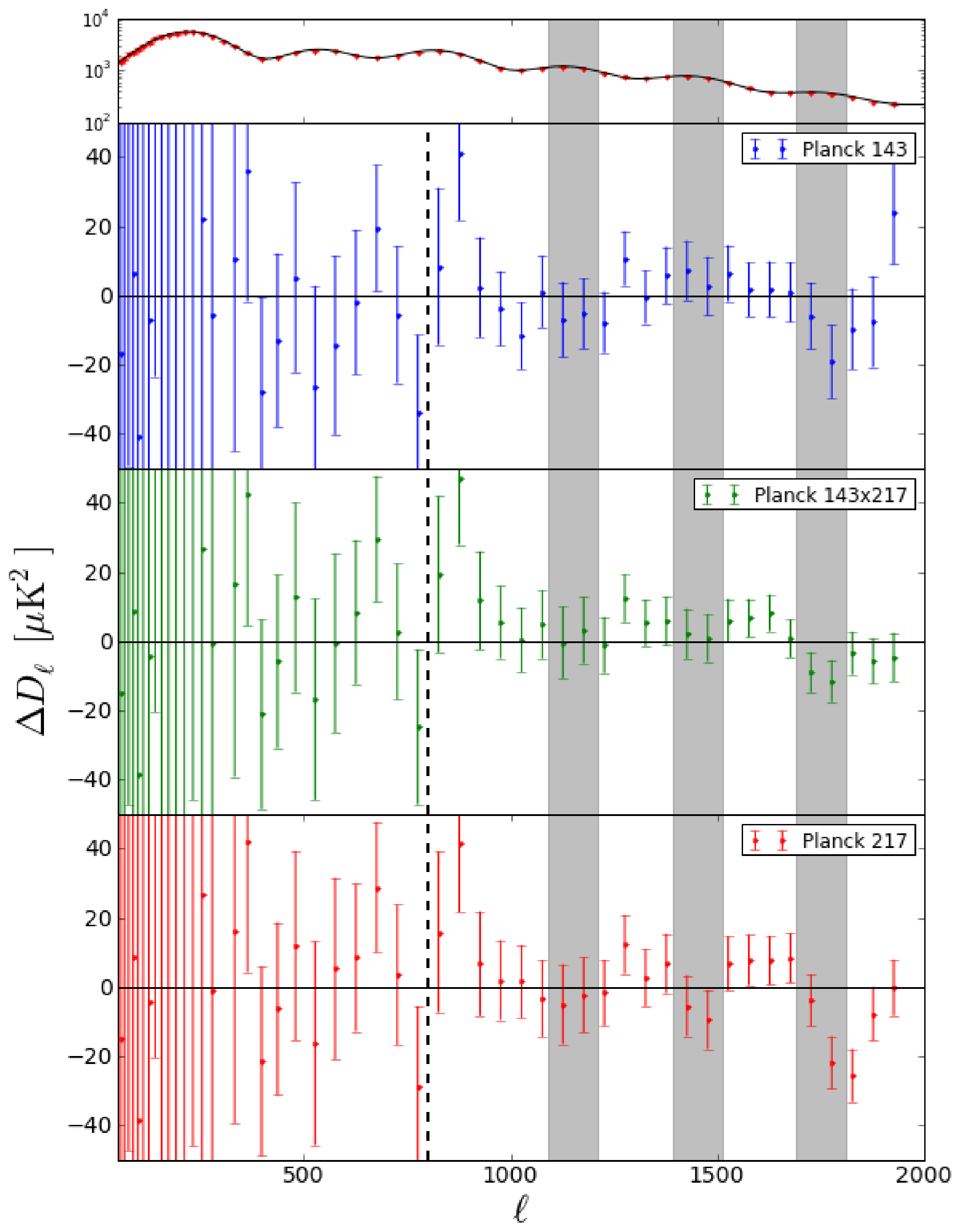
Planck (l < 2500) LCDM+A_L

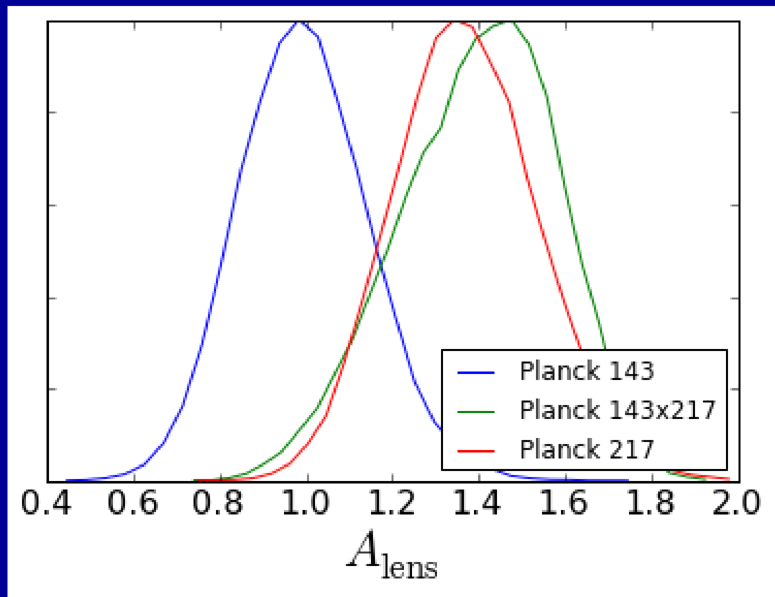
Removing the lensing information in TT increases agreement with the l < 800 value of H_0.

Figure credit: M. Millea

Slide credit: M. Millea







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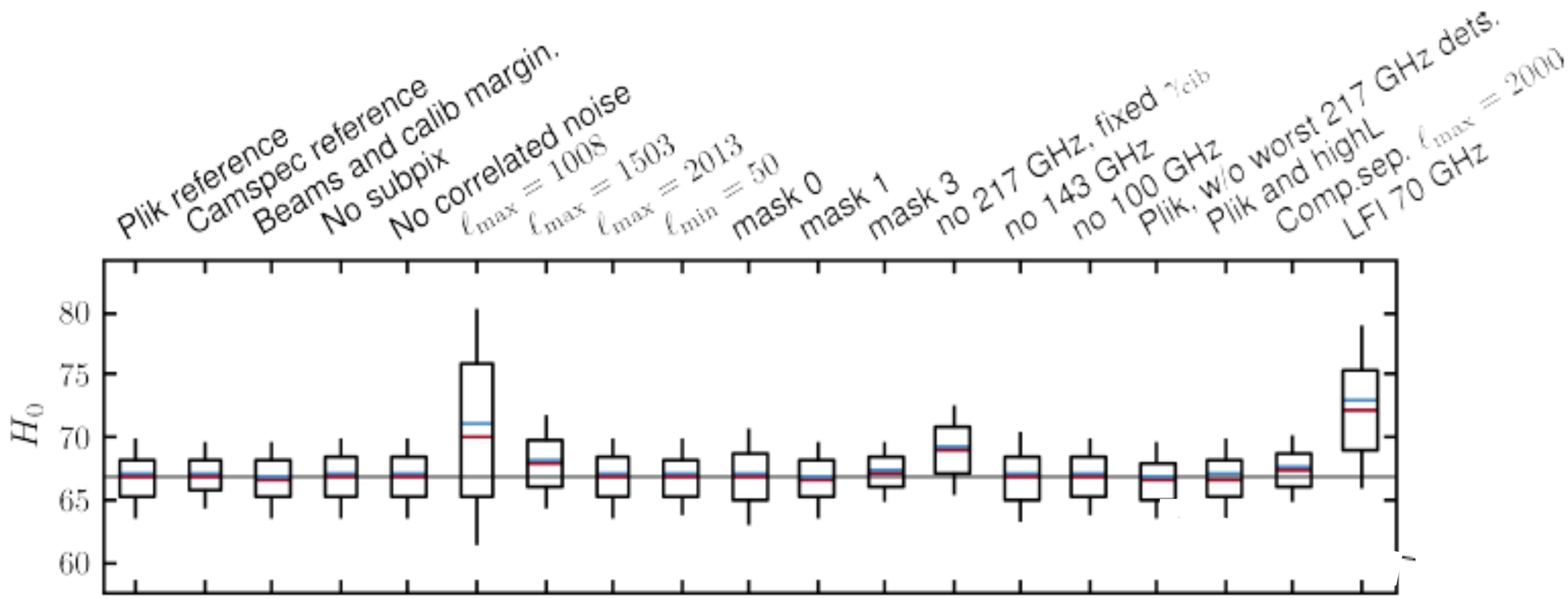
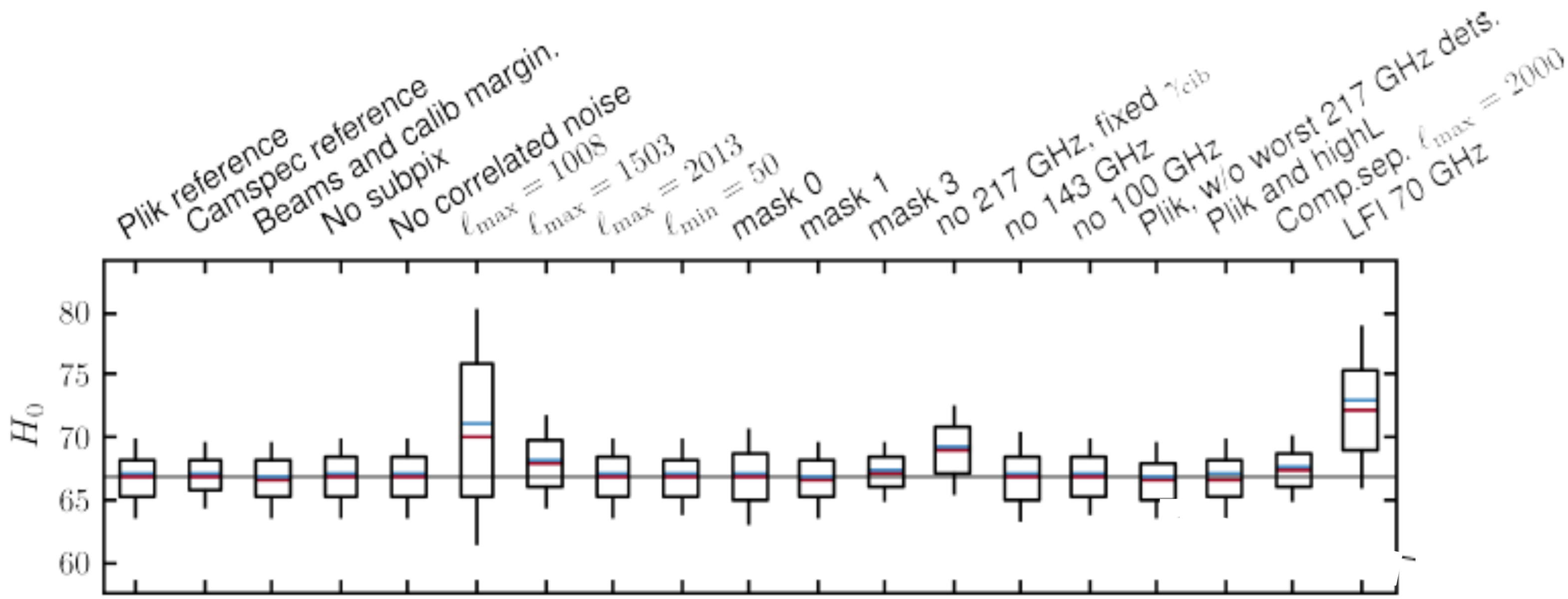
Effect of modeling choices and data selection



Throwing out 217 GHz or high ell data makes H_0 go up.

Planck Paper XV

Effect of modeling choices and data selection



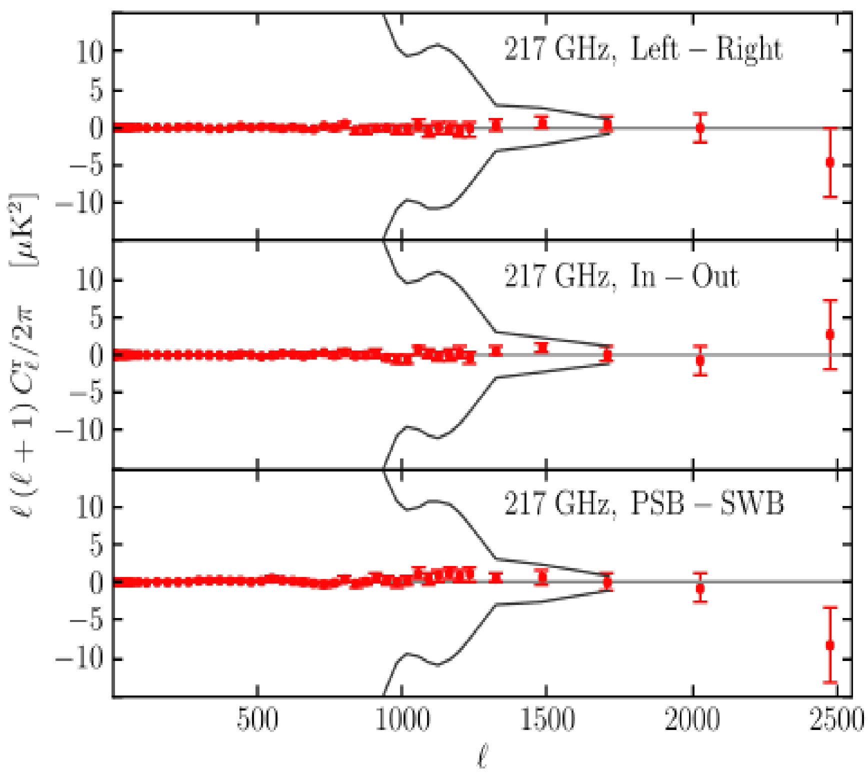
Throwing out 217 GHz or high ell data makes H_0 go up.

Planck Paper XV

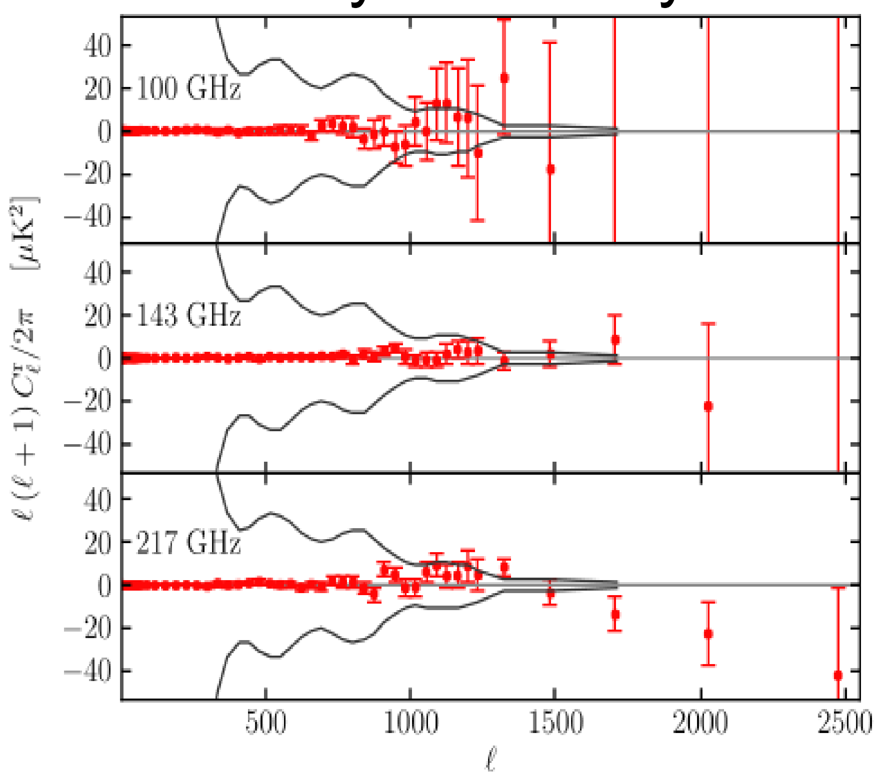
Could it be dust contamination?

But results are stable to increasing sky fraction

Null Tests of 217 GHz maps



Survey 1 - Survey 2



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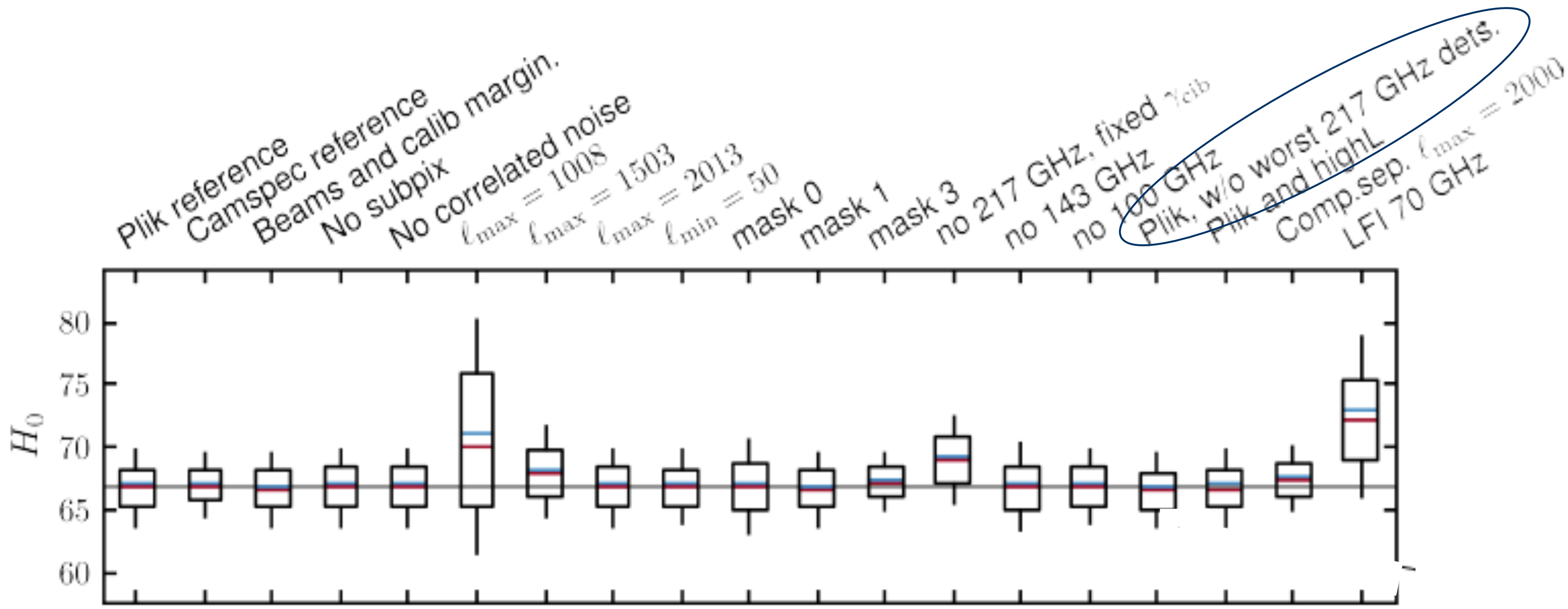


Throwing out 217 GHz or high ell data makes H_0 go up.

Planck Paper XV

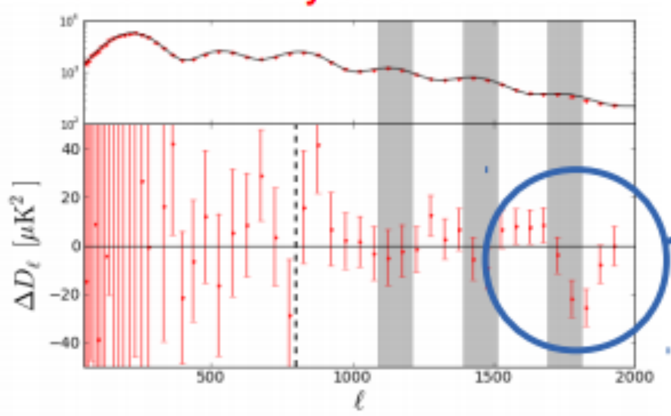
Could it be dust contamination?

But results are stable to increasing sky fraction

And rejection of null-test failing 217 dets

L=1800 feature

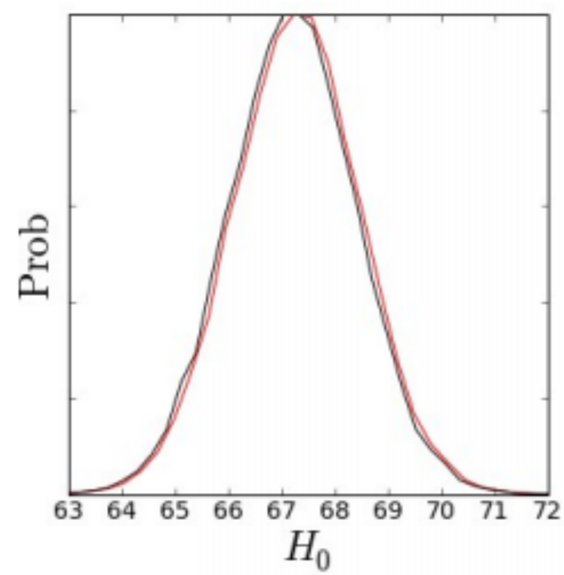
Planck 217-only data



- Pulling towards higher Alens
- Identified in the Inflation paper as the source of a local feature in the primordial power-spectrum reconstruction
- Not present in 143GHz, SPT or ACT

Planck+WP

Planck+WP 1700<L<1900 removed

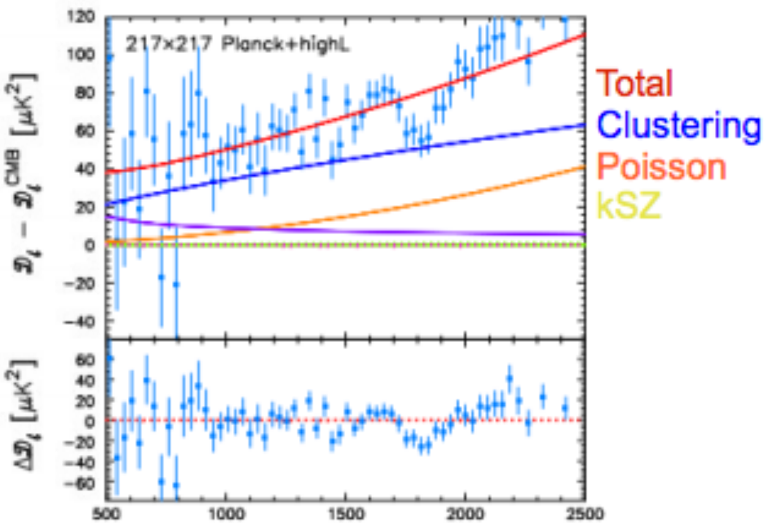


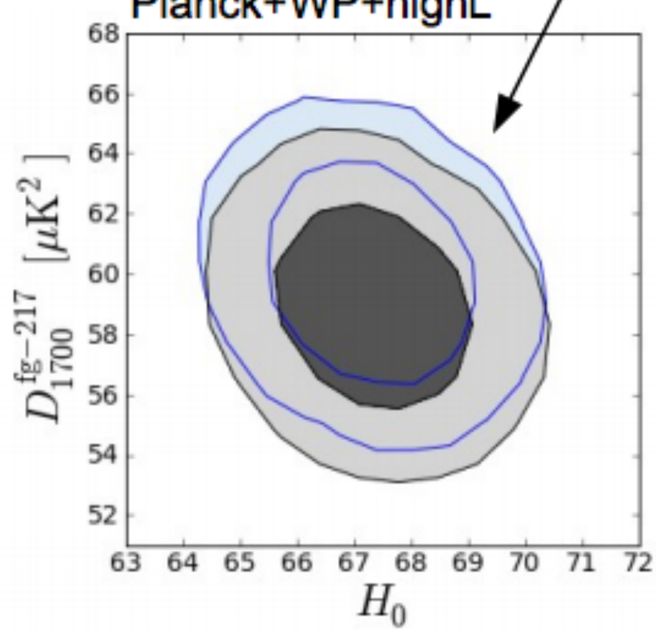
Slide credit: M. Millea

Extra-galactic Foregrounds

Emission from external galaxies and Sunyaev-Zeldovich effects contribute anisotropy power at high L

Planck Collaboration XVI 2013





- Internal tests showed that the choice extra-galactic foreground model at most shifted H_0 by 20% sigma.

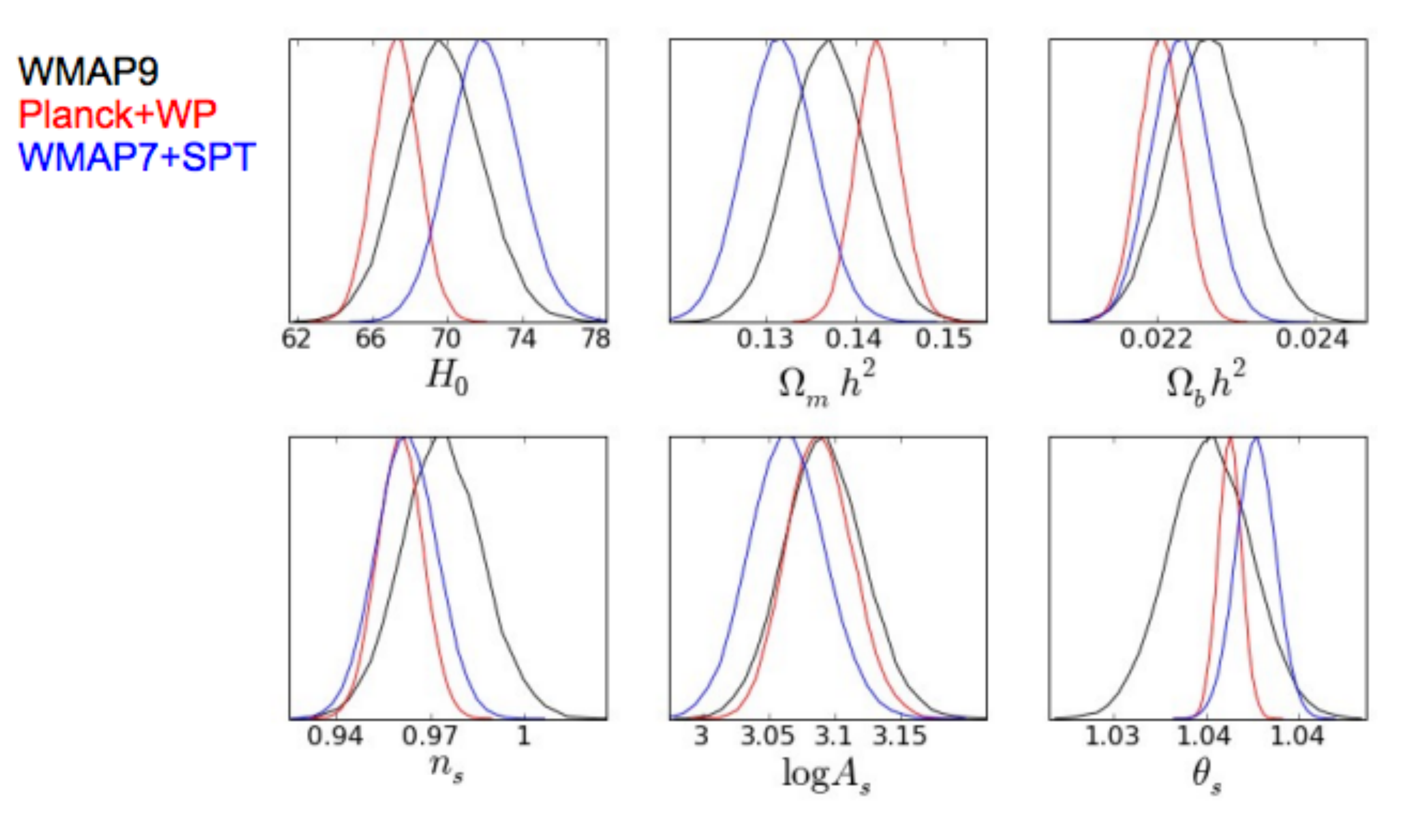
"low" H0 is robust to extra-galactic foreground modeling

Slide credit: M. Millea

God has sent me a sign that 217 GHz is OK

God has sent me a sign that 217 GHz is OK

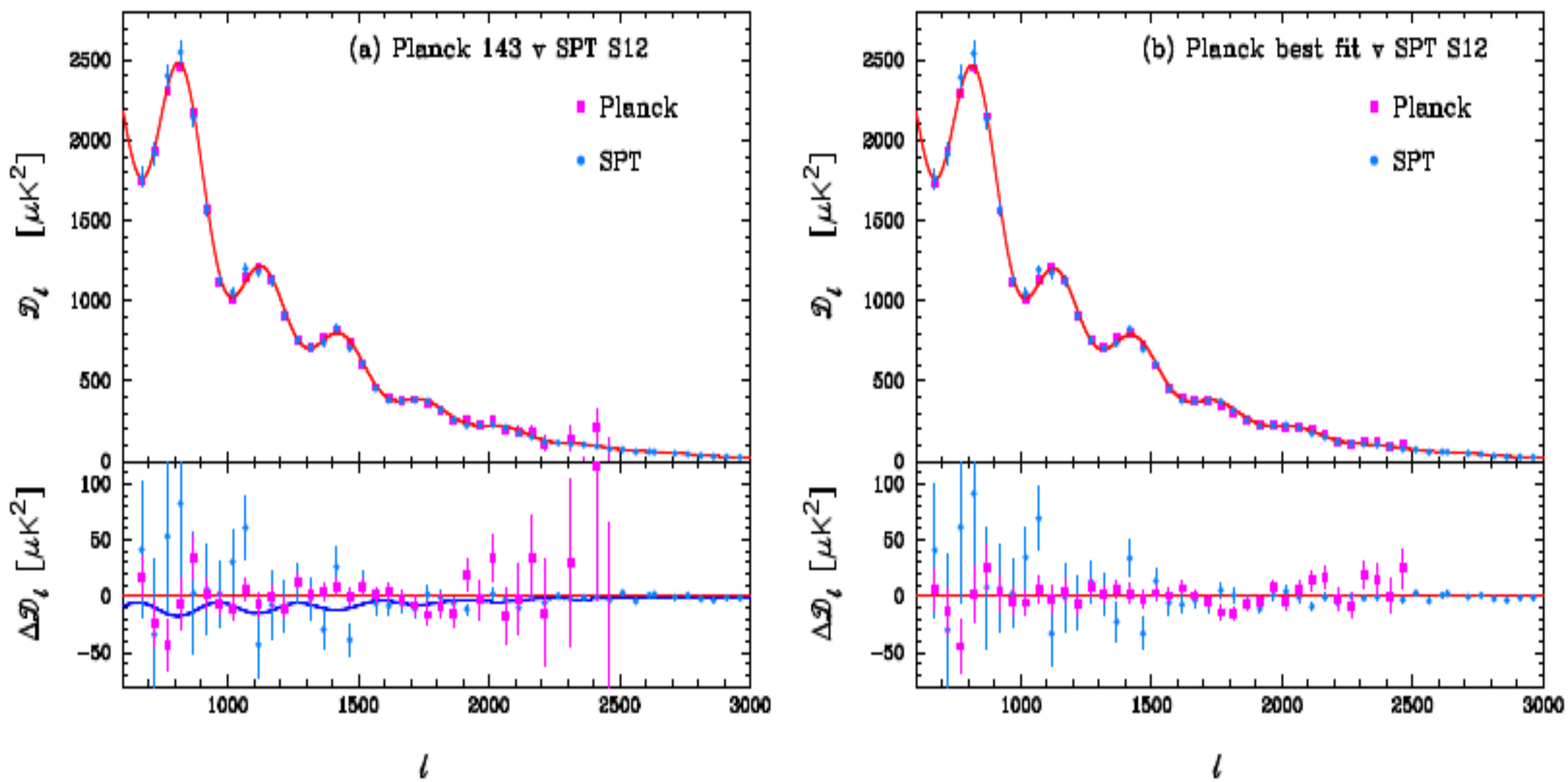
So that's Planck and WMAP. Now what about Planck and WMAP+SPT?



Slide credit: M. Millea

Planck Collaboration: Cosmological parameters

Paper XVI

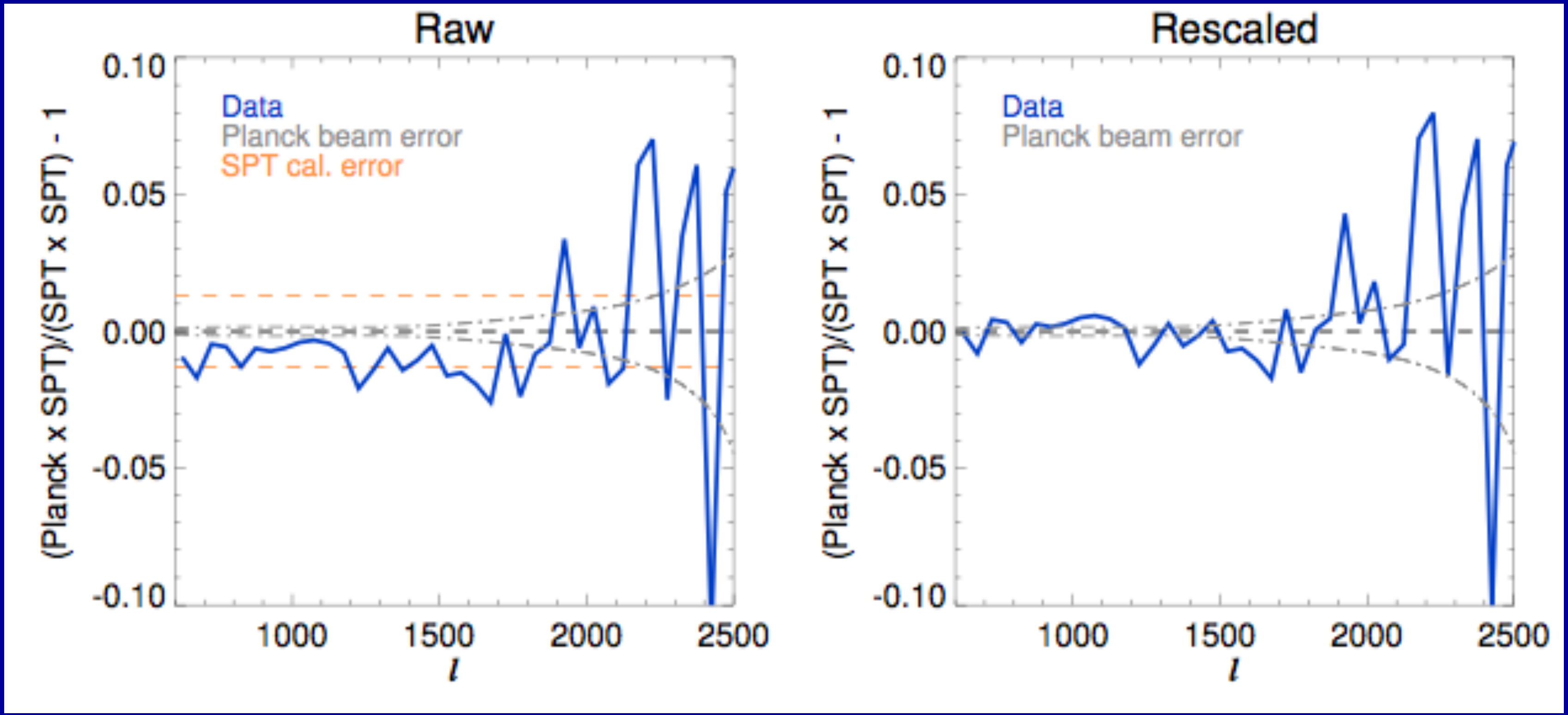


Really good agreement between power spectra!

Planck overwhelms SPT in joint fit.

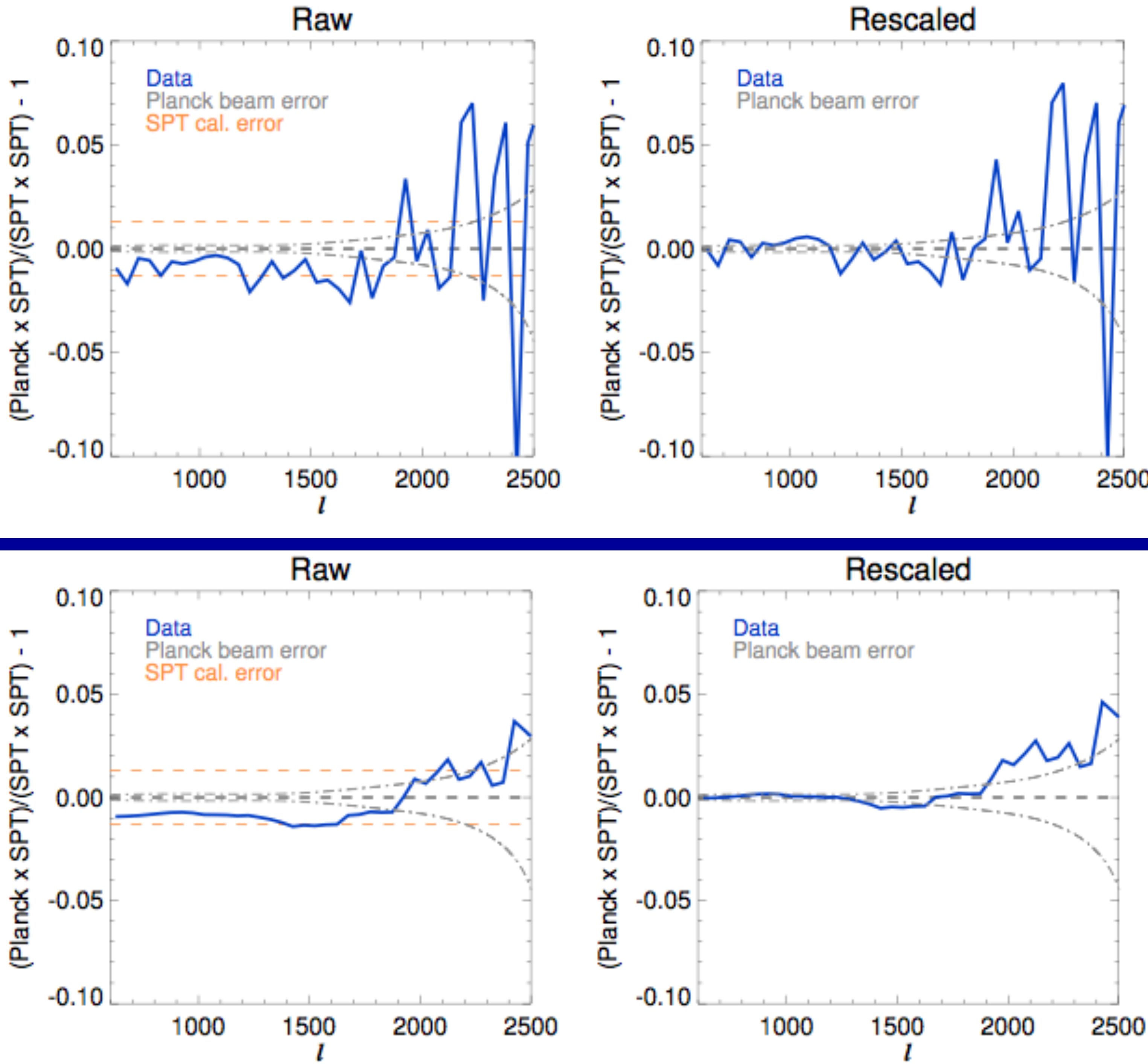
SPT consistent with best fit out to very high ell.

No ell = 1800 feature in SPT data



Agreement is even better when restricted to same part of sky.

Keisler, Crawford and Reichardt took Planck 143 GHz map, "observed" it with SPT, filtered and cross-correlated with SPT 150 GHz map.



With extra smoothing can see consistency with Planck beam uncertainty

So why does WMAP7 +SPT go to *higher* H_0?

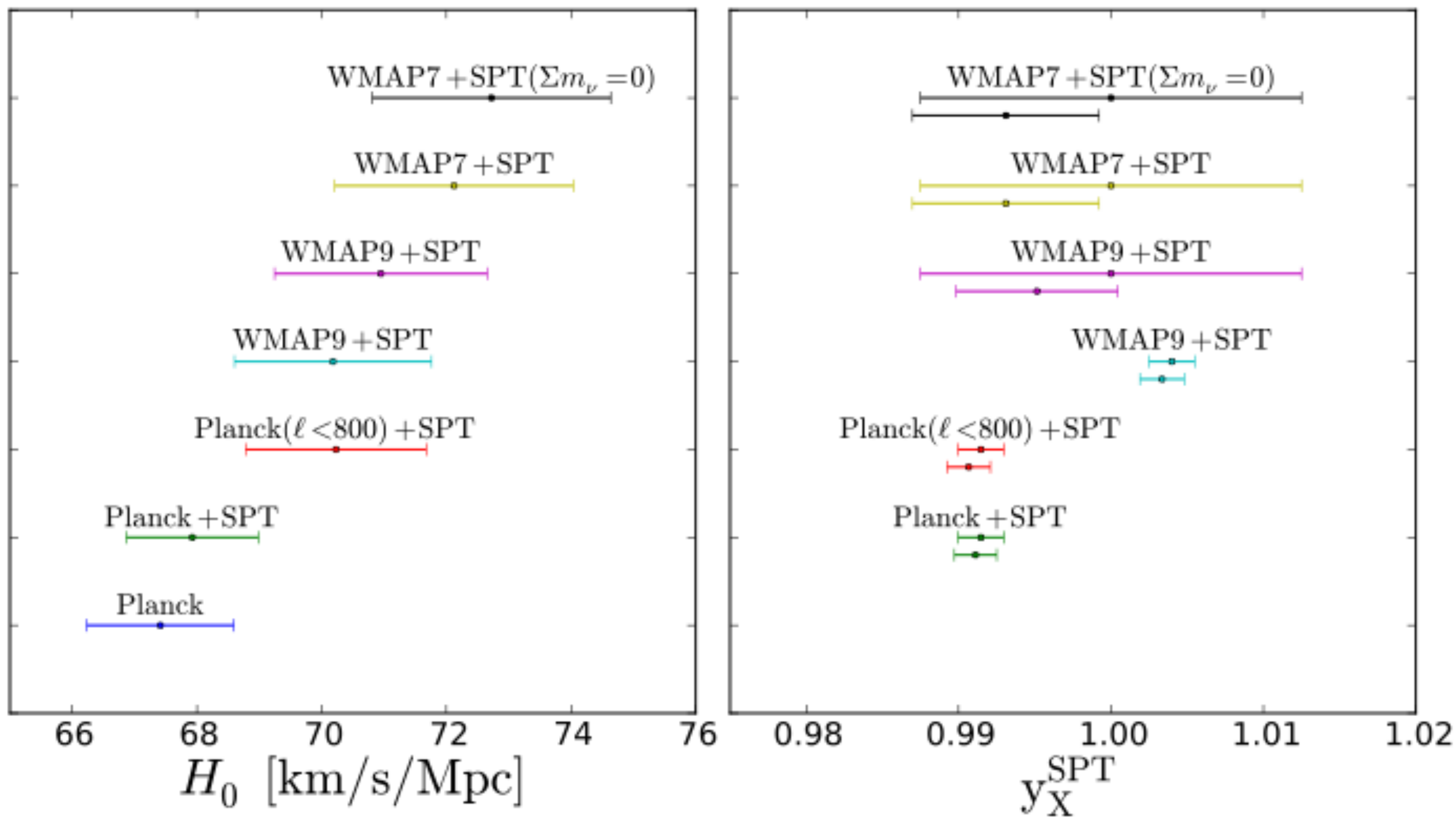
1) Different Σm_ν assumption

2) Preference in SPT region of sky for slightly less lensing power ==> slightly lower matter density (Hou+SPT 2013).

3) Calibration uncertainty could be exploited to make 1st peak (WMAP) relative to 3rd peak (SPT) consistent with (2).

A_L = 0.86 +/- 0.14

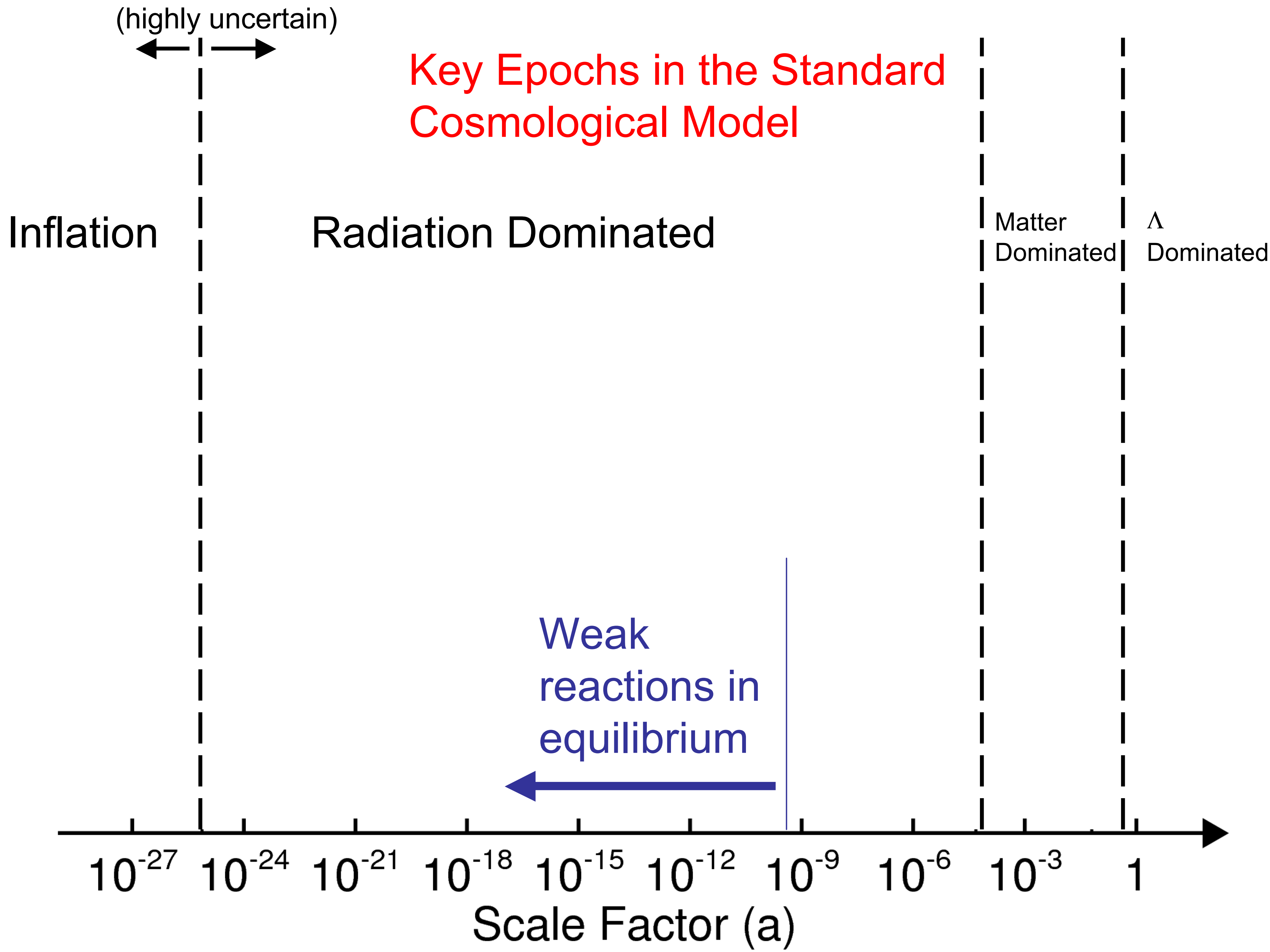
Cosmic Deceleration

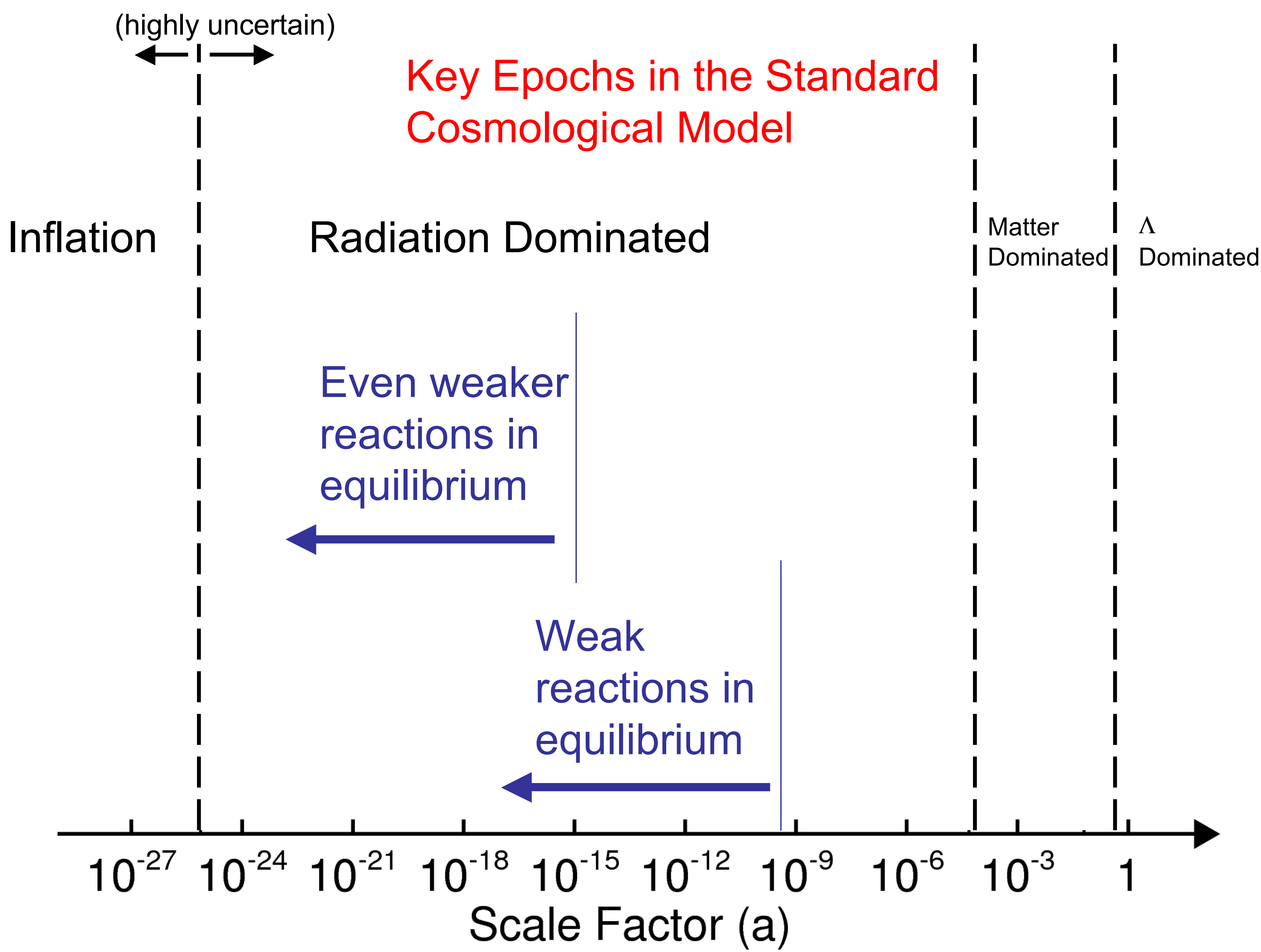


Relative calibration between SPT and x = Planck or WMAP

Extensions in the Neutrino Sector

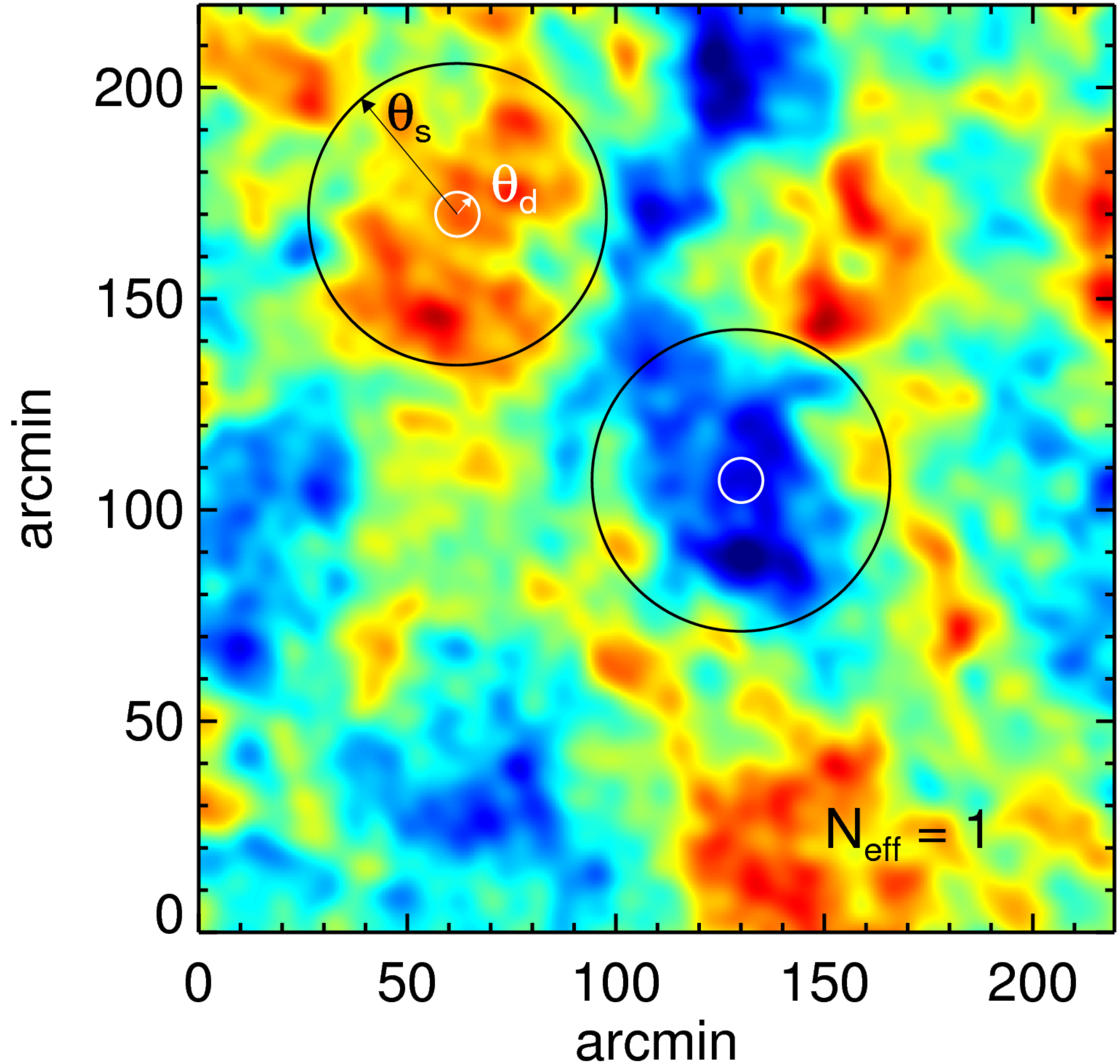
- Σm_ν: We know neutrinos have mass! Our baseline model *artificially* fixes the sum of those masses at 0.06 eV. It could be a little bit lower or a lot higher.
- N_{eff}: This parameter captures a lot more than neutrinos. It's increased by extra dark and light degrees of freedom.
- A sterile neutrino as a dark matter candidate: warm dark matter.


(highly uncertain)
Key Epochs in the Standard Cosmological Model
Inflation
Radiation Dominated
Matter Dominated
Λ Dominated
Weak reactions in equilibrium
10-27
10-24
10-21
10-18
10-15
10-12
10-9
10-6
10-3
1
Scale Factor (a)



(highly uncertain)
Key Epochs in the Standard Cosmological Model
Inflation
Radiation Dominated
Matter Dominated
Λ Dominated
Even weaker reactions in equilibrium
Weak reactions in equilibrium
10^-27 10^-24 10^-21 10^-18 10^-15 10^-12 10^-9 10^-6 10^-3 1
Scale Factor (a)

Neff affects the ratio of sound horizon to diffusion scale



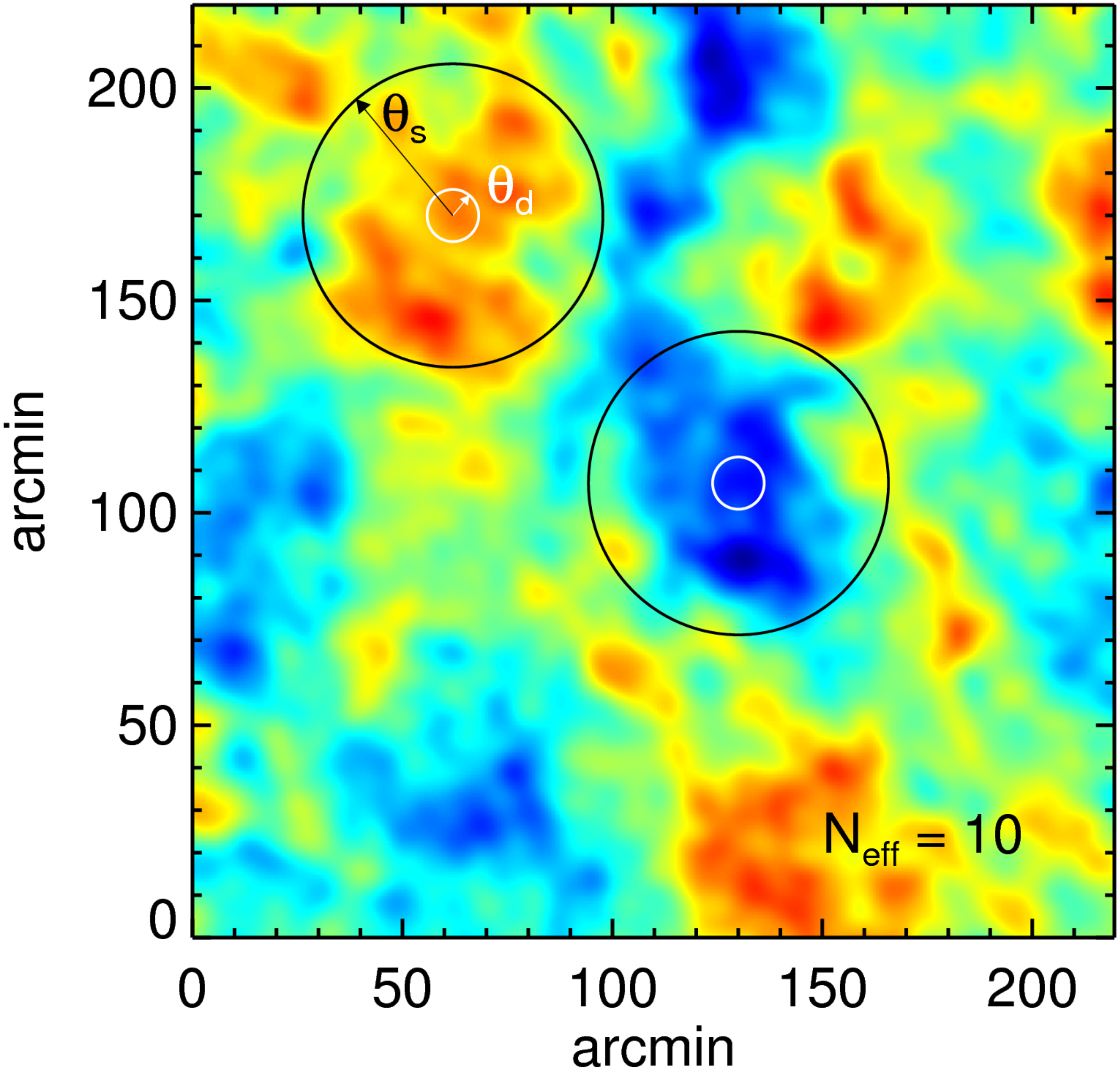
$r_s \sim 1/H$

$r_d \sim 1/H^{1/2}$

==> θ_d/θ_s has dependence on H

Hou et al. (2013), Bashinsky & Seljak (2004), Hu & White (1997)

Neff affects the ratio of sound horizon to diffusion scale



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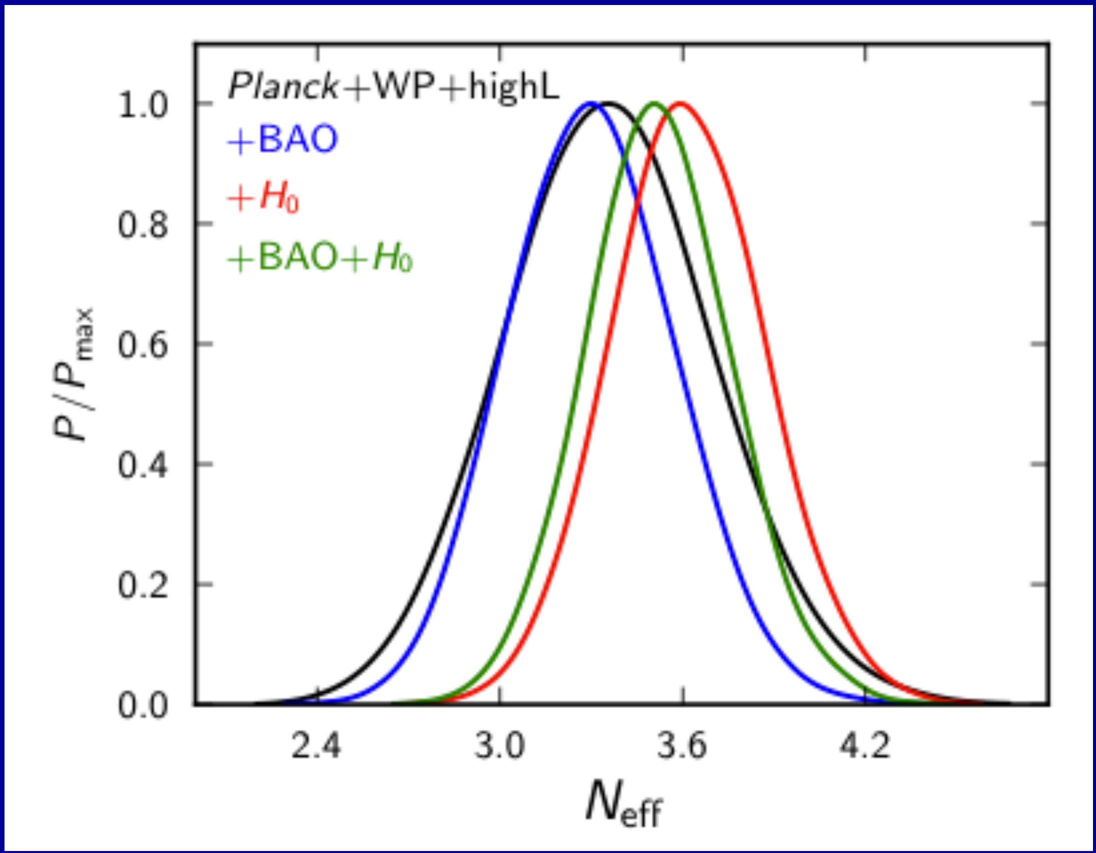
Light Degrees of Freedom



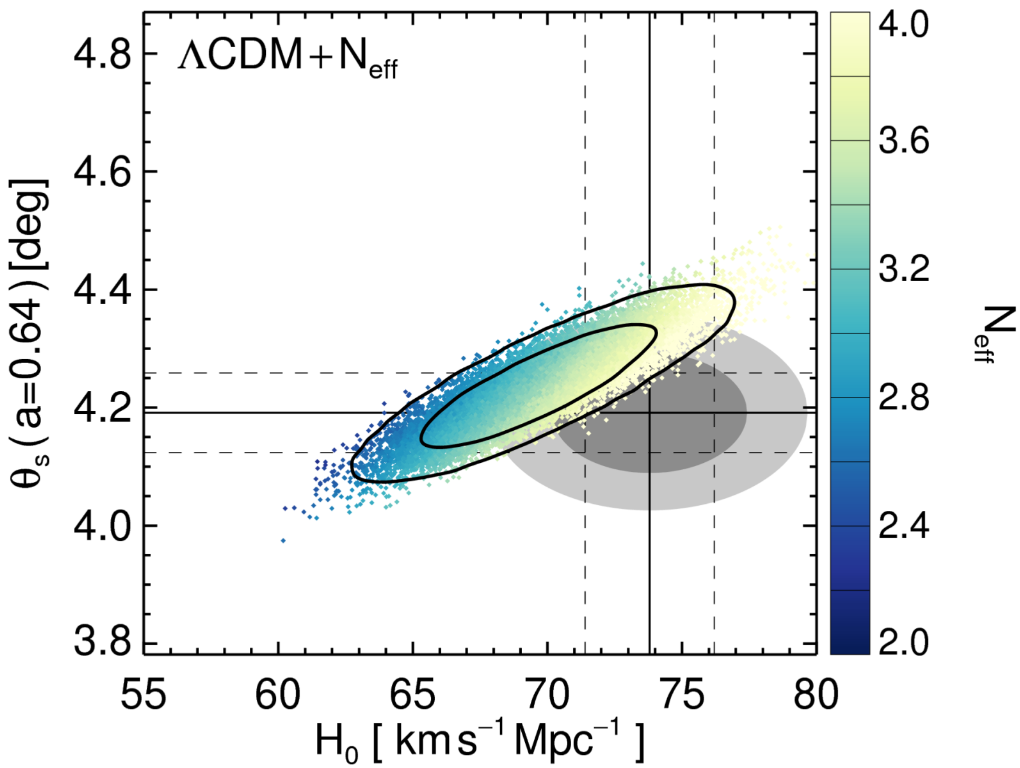
Contribute to the energy density and hence the expansion rate, altering r_s and r_d.

Standard model has Neff = 3.046. No evidence in Planck data, or Planck +BAO for extra species.

Neff > 3 is somewhat preferred by Planck+Riess et al. H_0

Light Degrees of Freedom - Neff

- Increasing Neff, we get better consistency between CMB and Riess et al. H_0 while preserving consistency with BAO.
- Systematic errors or new physics?
- Polarization data will be informative

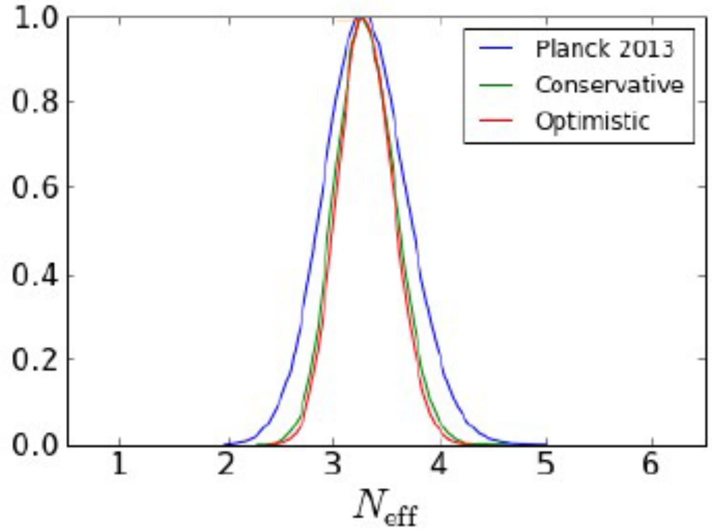


What to expect in 2014 from Planck?

Conservative:
- Double the TT data, no improvement in sky coverage
- TE and EE from 143 GHz on 30% of the sky

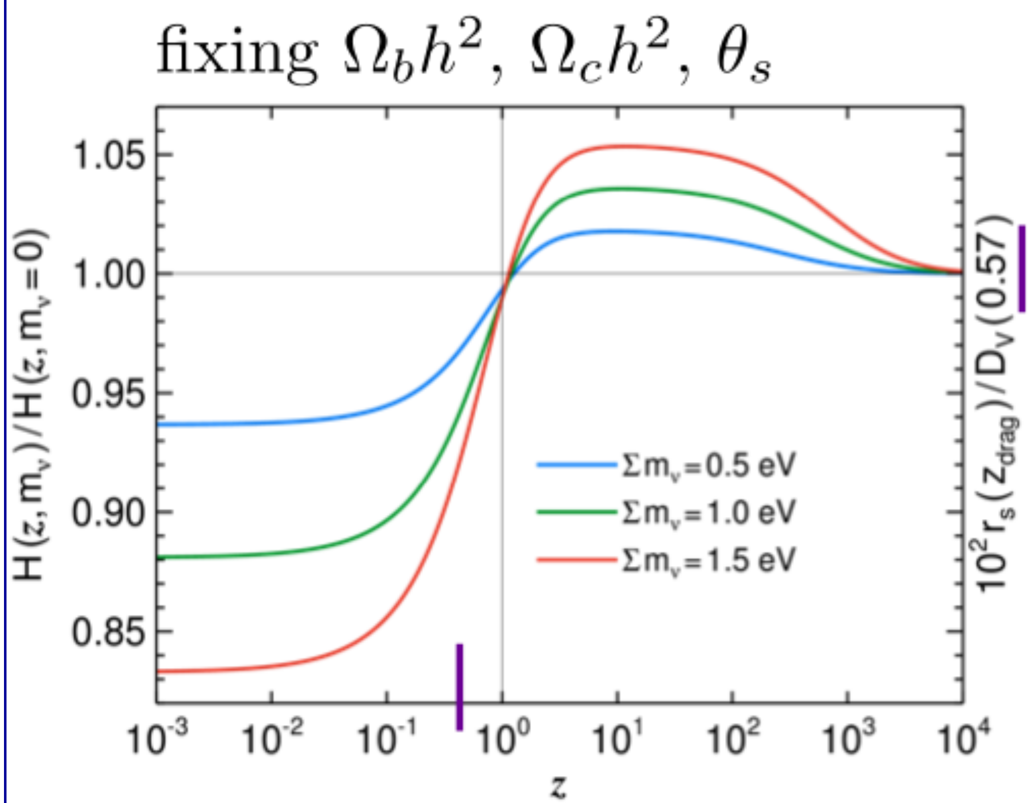
Optimistic:
- Double the TT data, 60% sky at 143/217 (instead of 30%)
- TE and EE from 217 GHz on 60% of the sky

- Blue-book noise/beams for TE, EE
- Actual TT likelihood with covariance adjusted with sqrt(2) or fsky



Slide credit: M. Millea

Expansion rate with neutrino mass



Increasing neutrino mass in the model leads to faster expanion rate, except at low z because -- in order to keep θ_s fixed -- the cosmological constant must be smaller in these models.

Figure credit: Zhen Hou

Expansion rate with neutrino mass

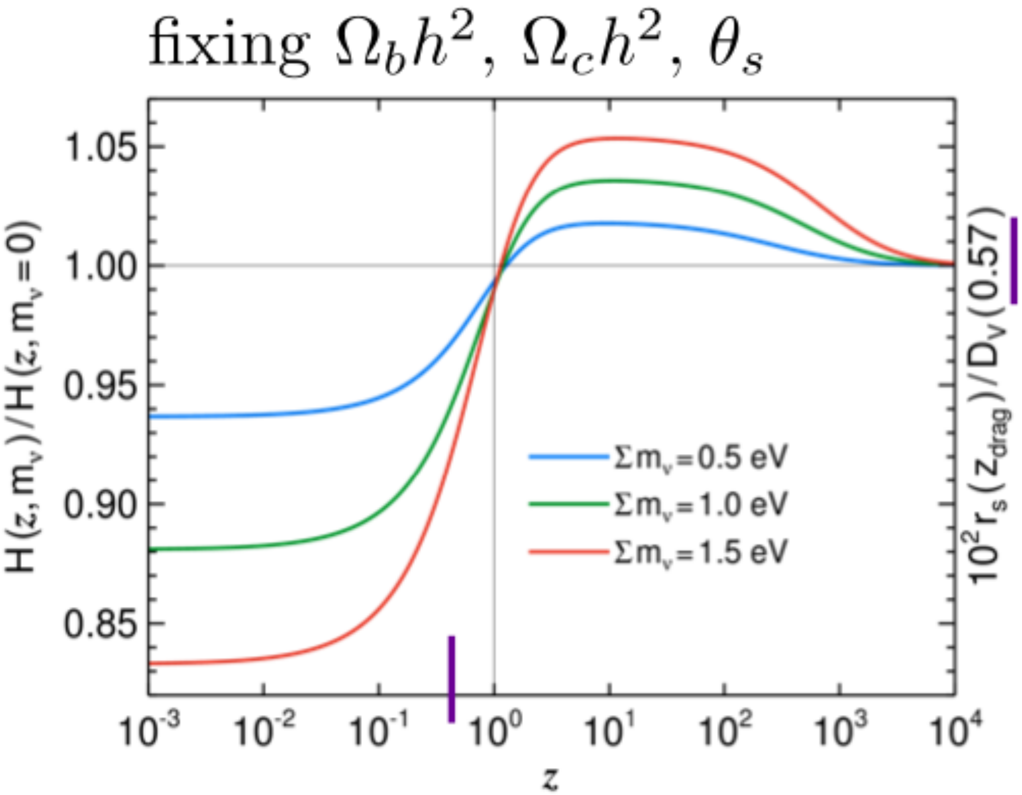


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Figure credit: Zhen Hou

This expansion rate change alters the ISW effect.

ISW is a weak signal!

~ 3σ → "detection"

Patricio Vielva

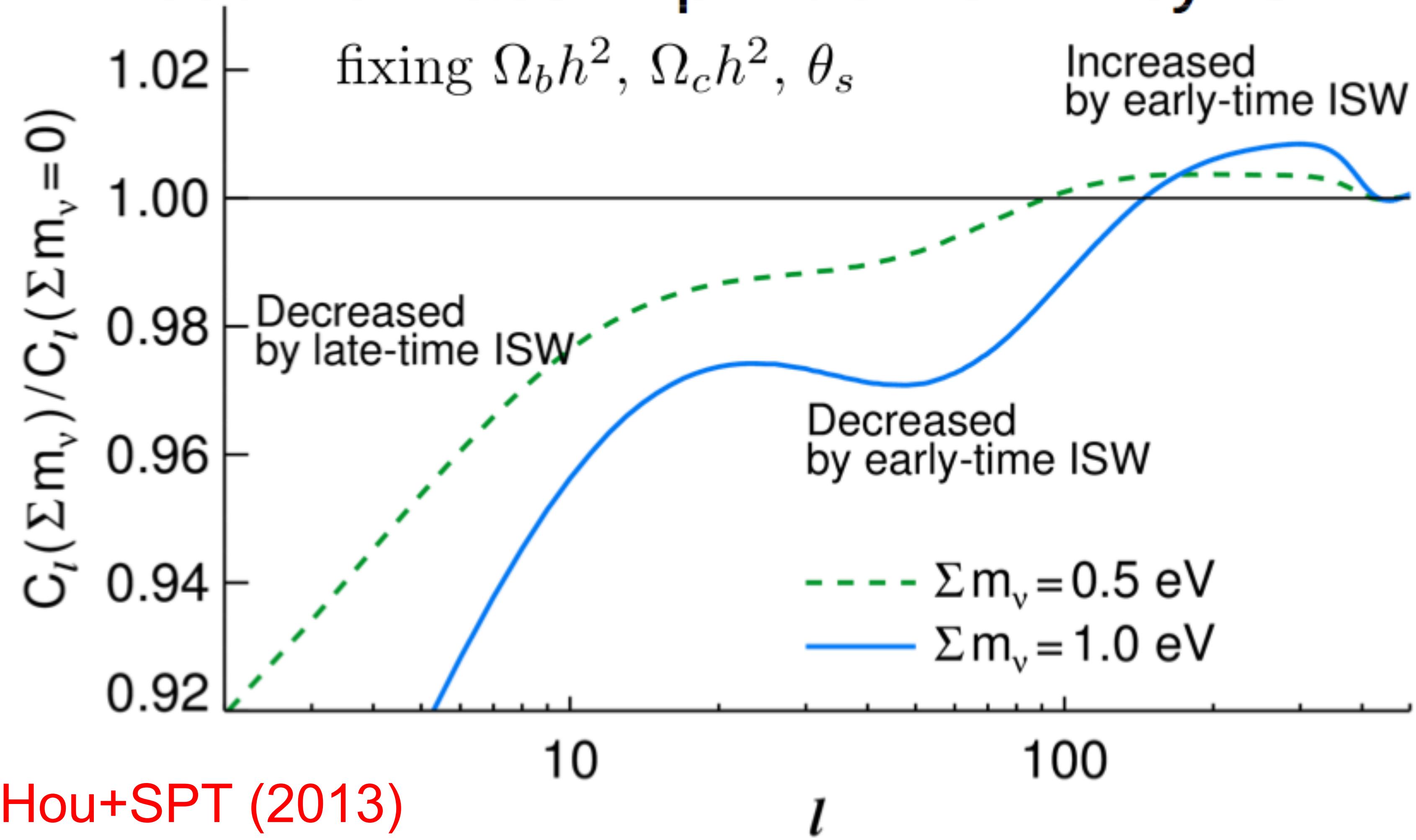
But Patricio Vielva was talking about "late" ISW -- due to potential decay caused by dark energy.

The "early" ISW is a very strong signal.

Early ISW

- Matter-radiation equality is at z = 3400. So there's plenty of radiation around at last scattering (z = 1100).
- Almost 1/3 of the power in the 1st peak is from early ISW.
- Hou et al. (2013) find A_{eISW} = 0.979 +/- 0.055 from WMAP7 + SPT-K11 (800 sq. degrees).

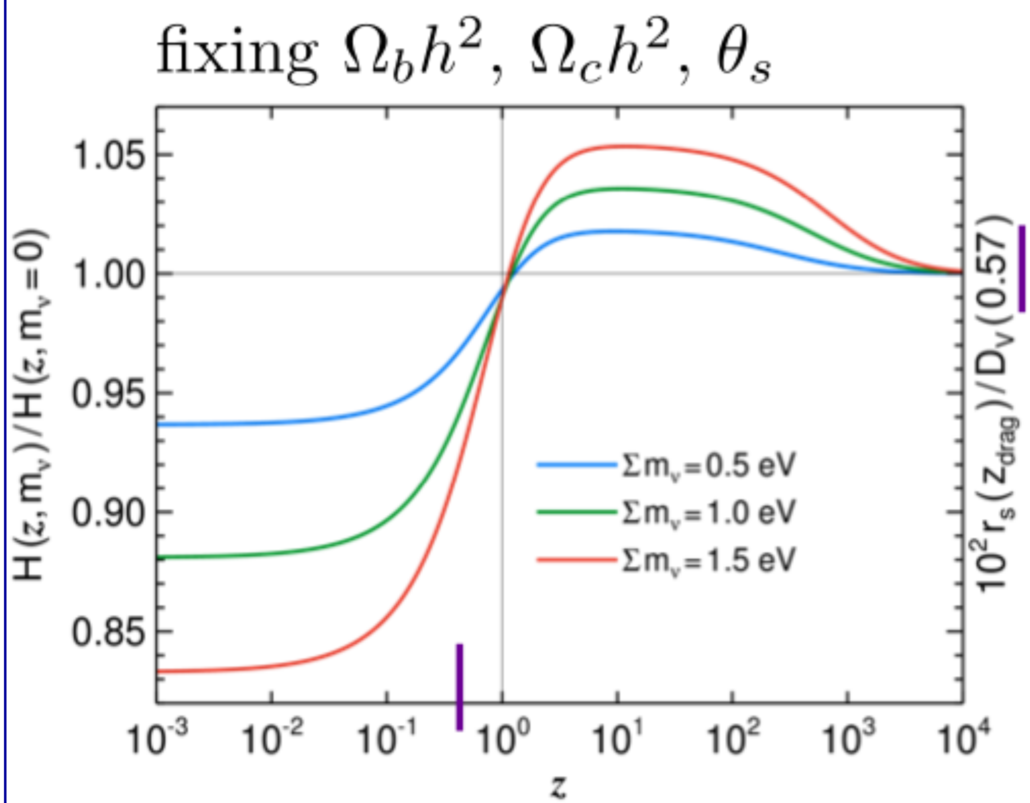
Neutrino mass imprint on CMB by ISW



Hou+SPT (2013)

CMB Σm_ν constraints, prior to Planck, were driven by early ISW

Expansion rate with neutrino mass



Changing H(z), as well as clustering of neutrinos on scales above their free-streaming length, alters the CMB lensing potential.

Figure credit: Zhen Hou

CMB lensing and neutrino mass

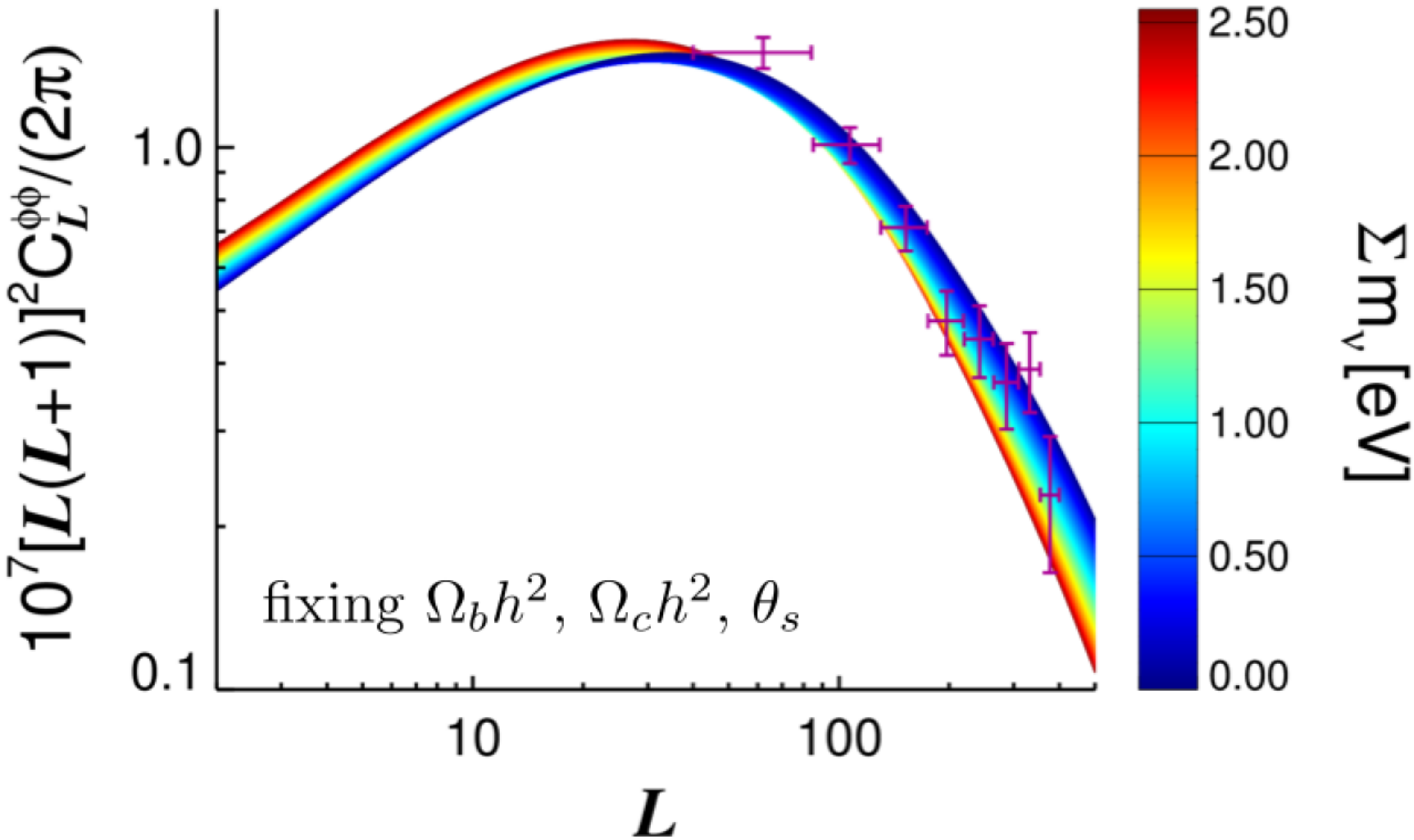
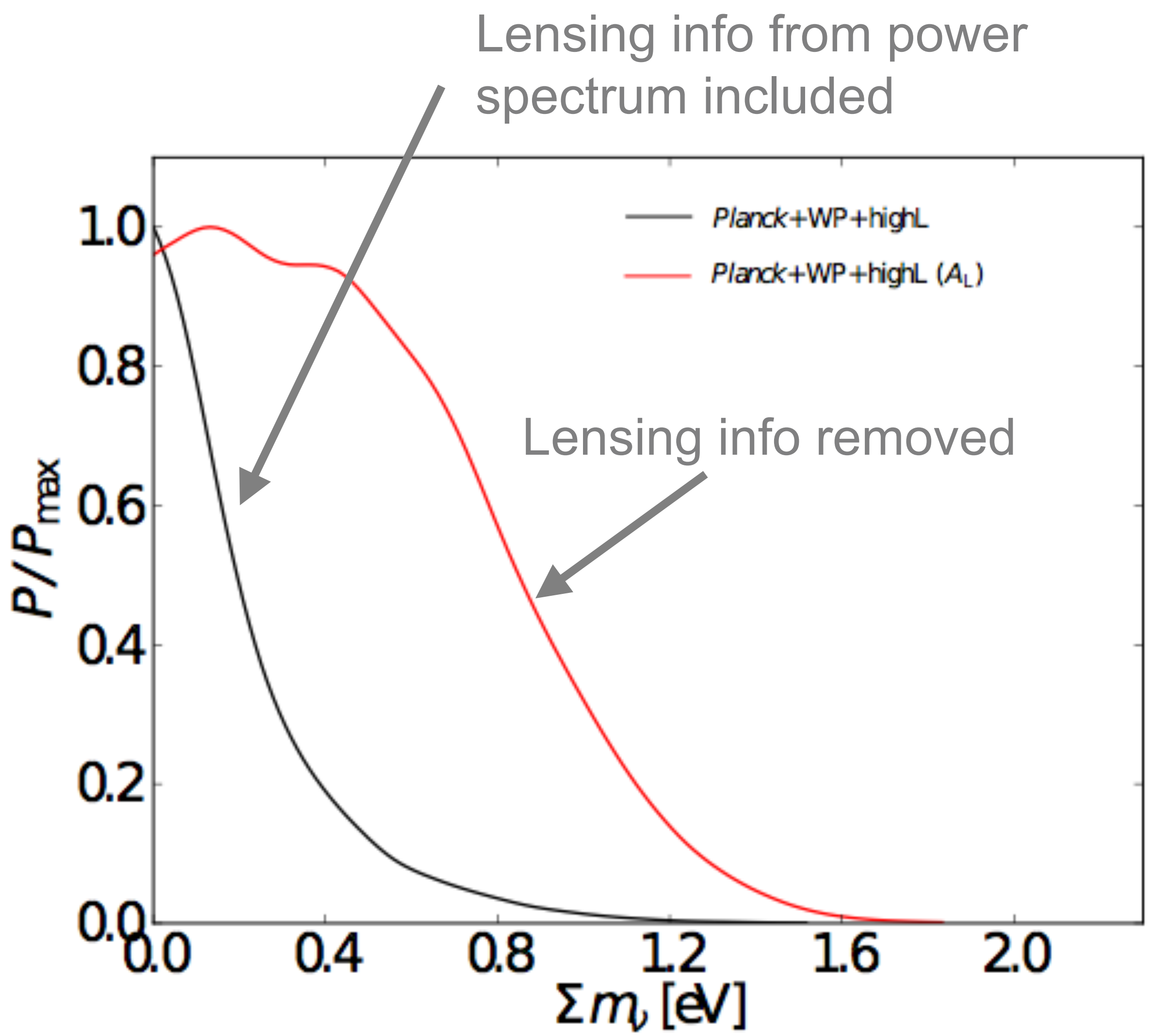


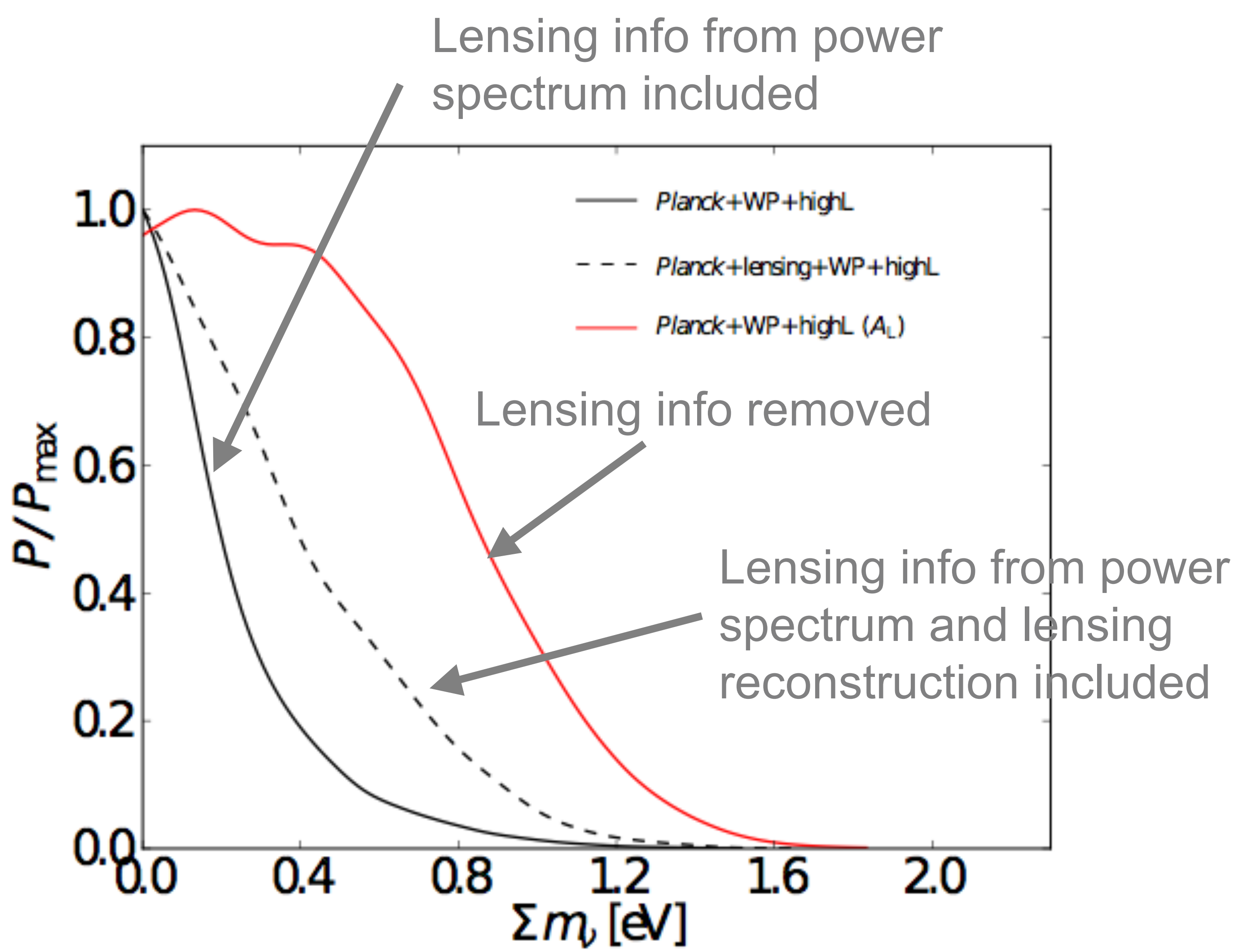
Image credit: Zhen Hou

Data points: Planck XVII

For the first time, lensing information is dominant source of information about m_ν

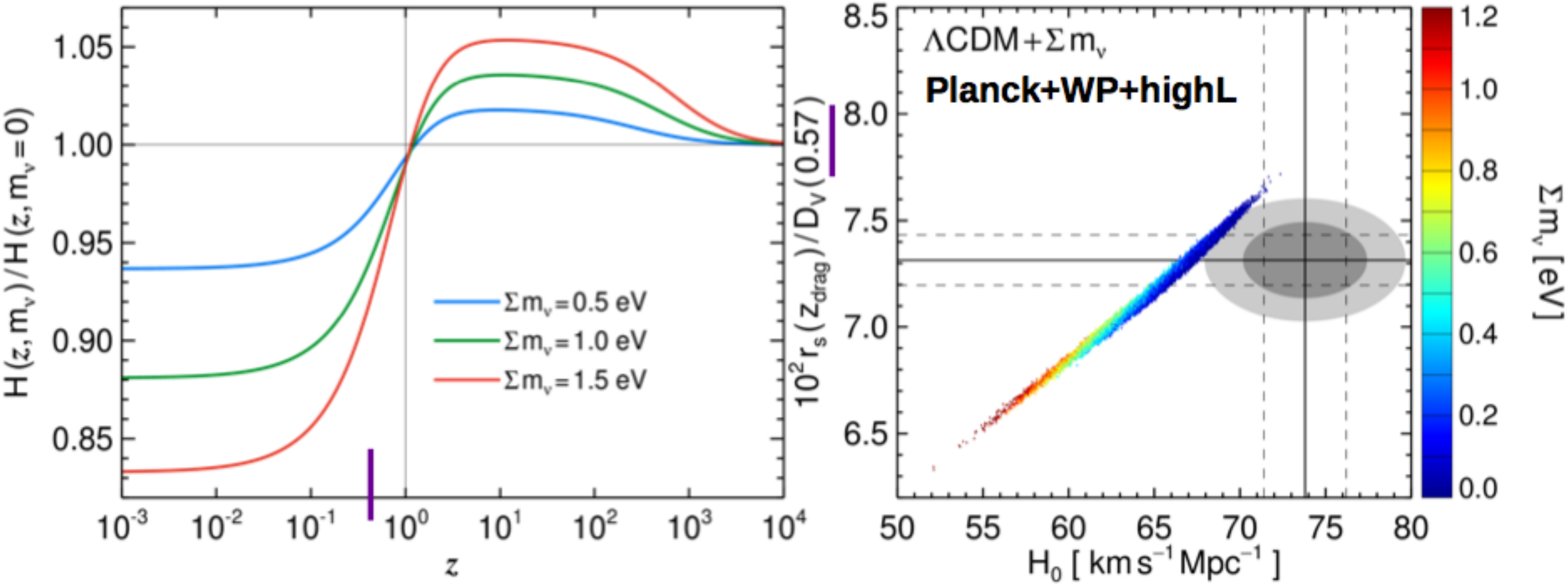


But our two sources of lensing information are pulling in different directions



Expansion rate with neutrino mass

fixing $\Omega_b h^2$, $\Omega_c h^2$, θ_s

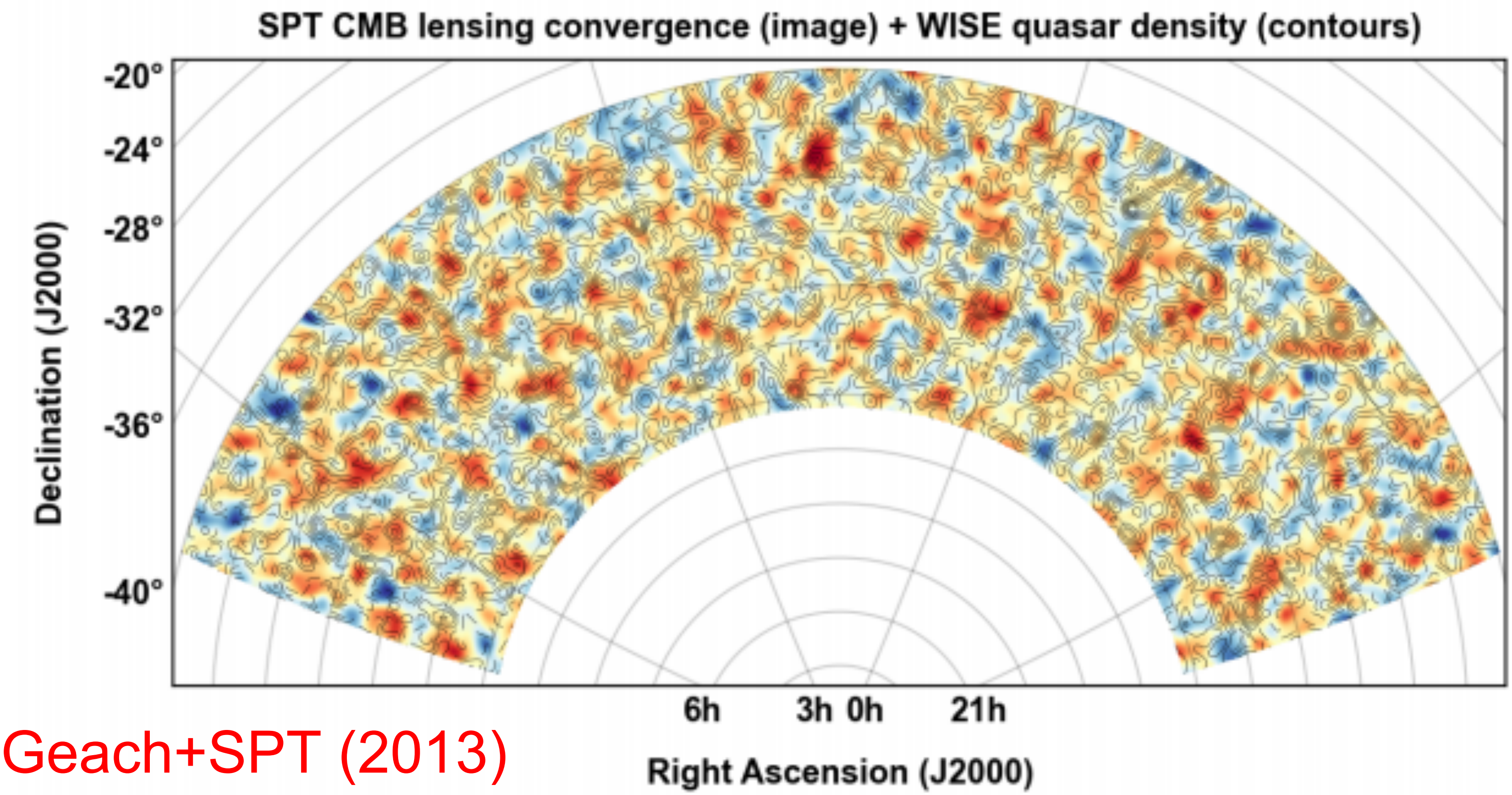


Slide credit: Zhen Hou

Both BAO and H_0 do not want extra Σm_ν

Σm_ν < 0.23 eV (Planck+WP+highL+BAO; 95%)

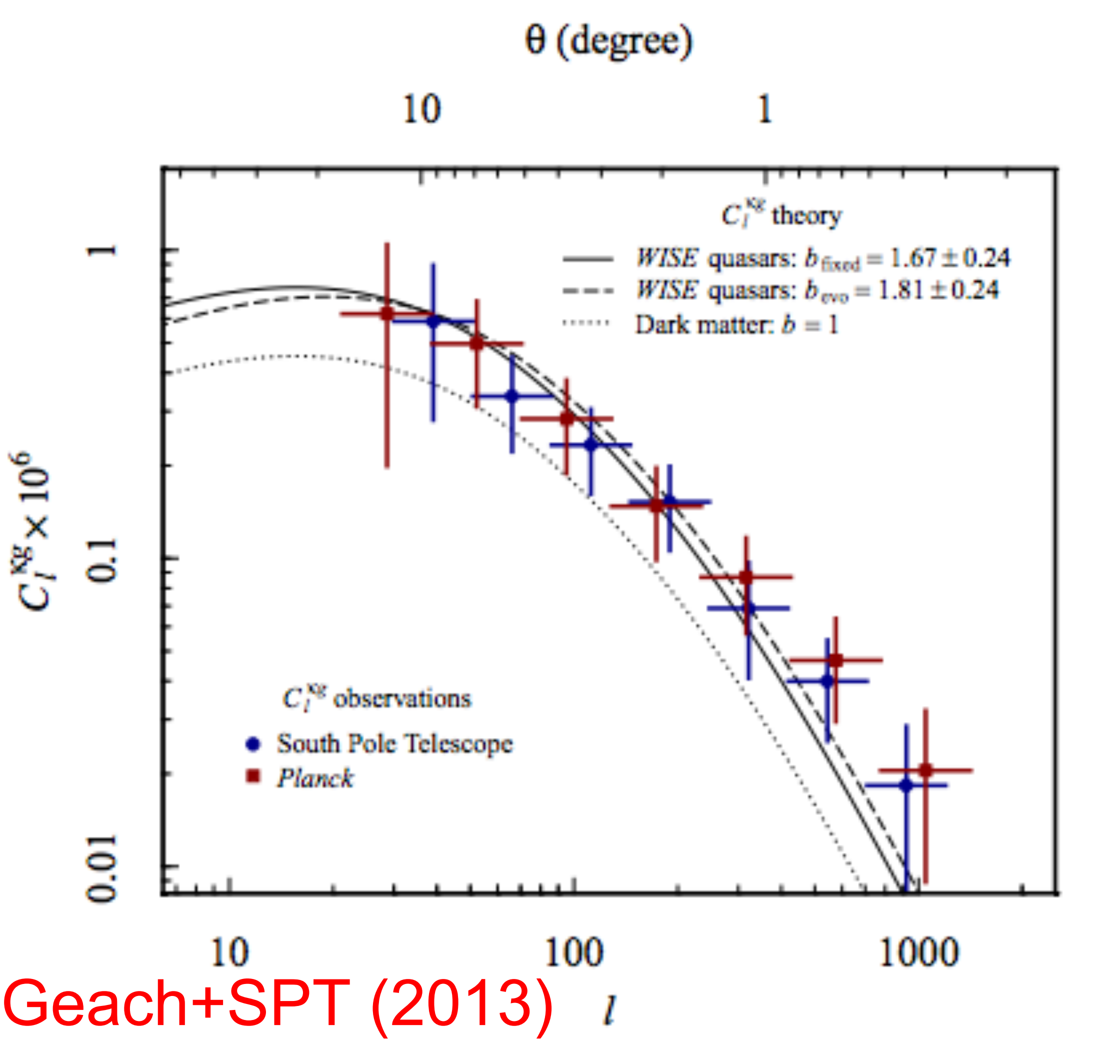
More lensing info coming soon



Geach+SPT (2013)

This is a higher signal-to-noise lensing map than from Planck, but only over 1/16th of the sky. S/N = 20.

WISE quasars cross correlated with SPT lensing, and with Planck lensing over the SPT footprint.



Geach+SPT (2013)

Agreement!

Error bars are dominated by shot noise in the WISE quasar map

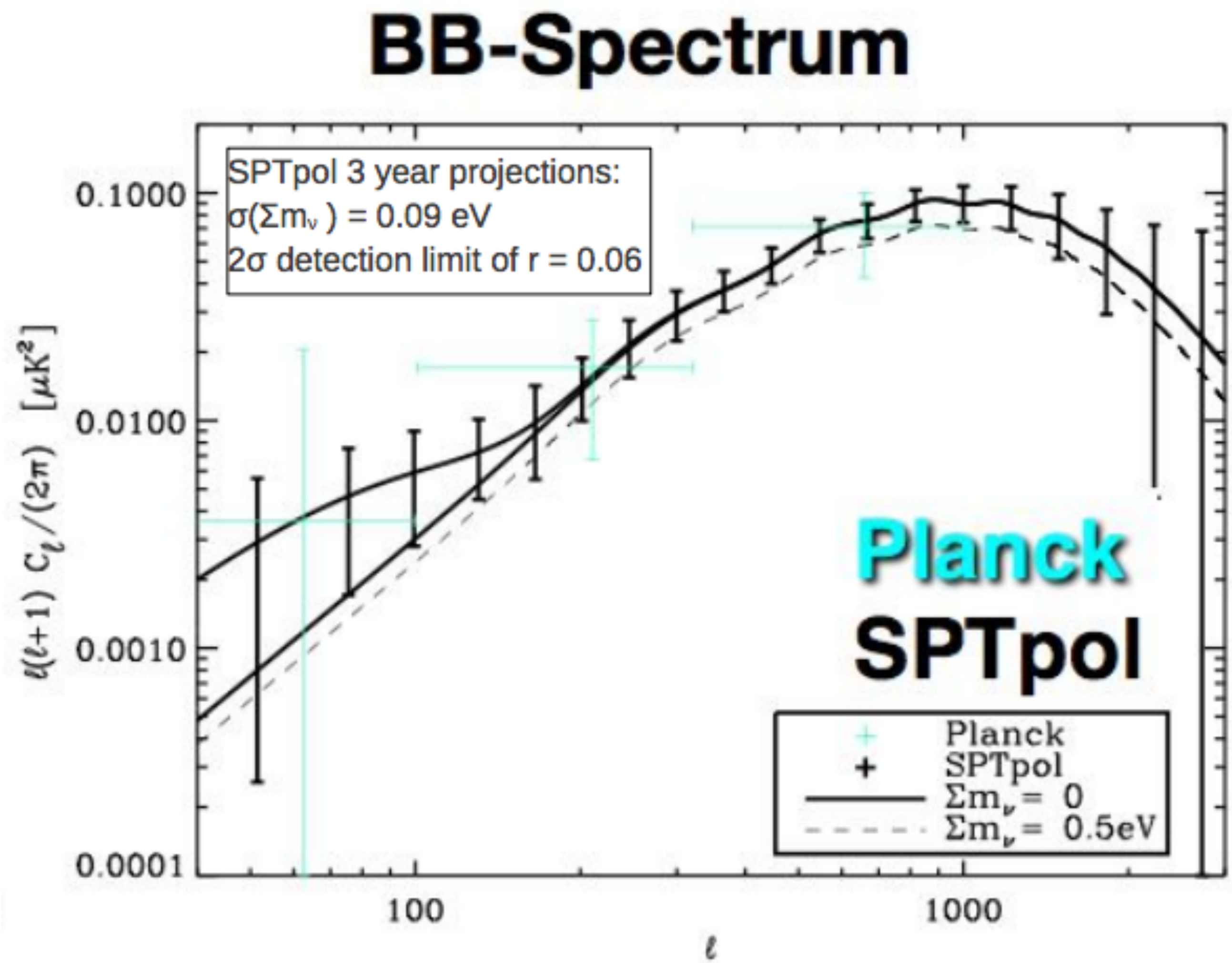
Error bars could be shrunk by doing this with full Planck lensing map.

What's next from SPT?

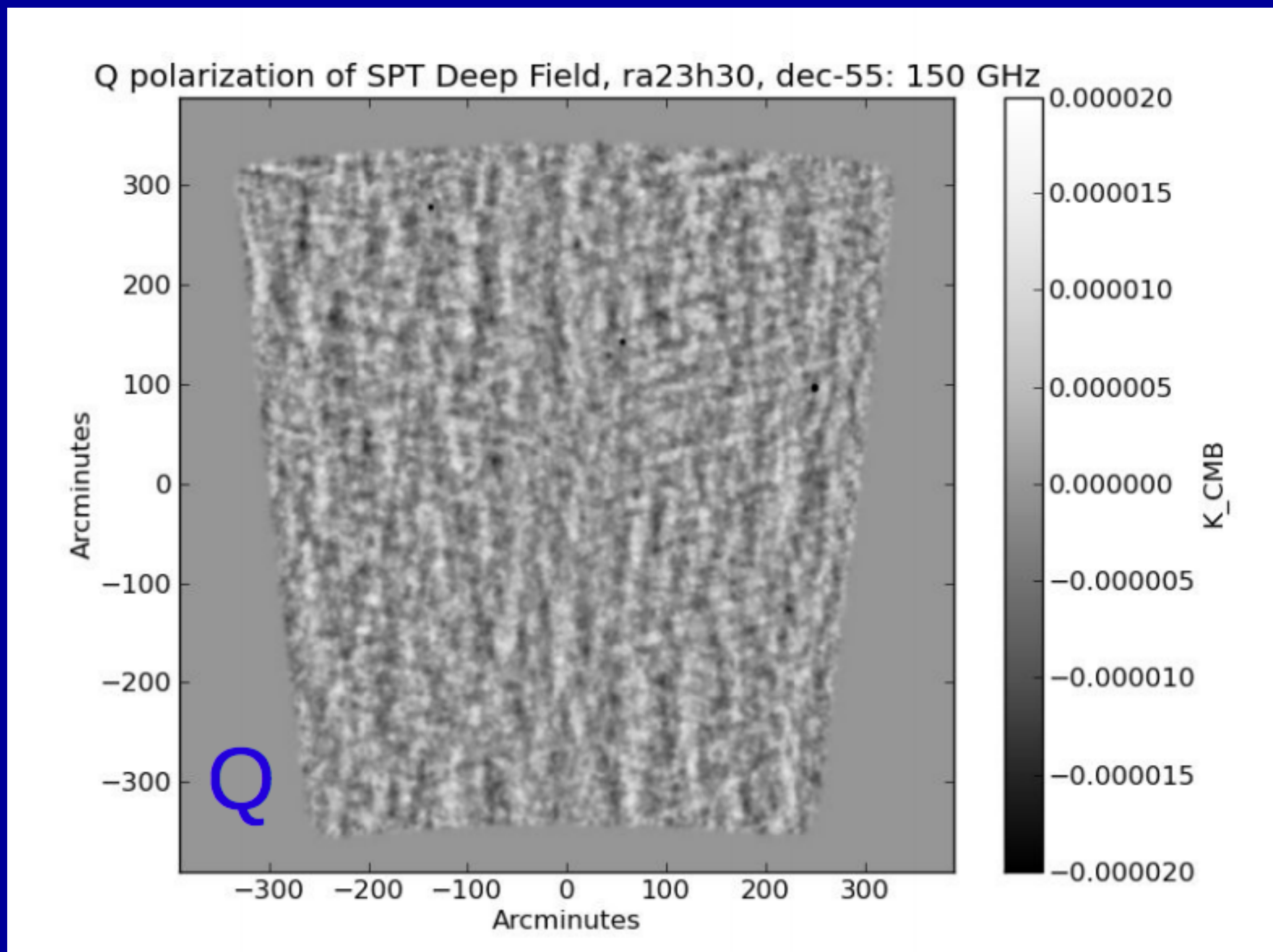
SPTpol, SPT-3G (slides from Stephen Hoover)

ALMA follow-up of SPT-discovered dusty galaxies and constraints on WDM

SPTpol will make a strong detection of B-mode polarization.



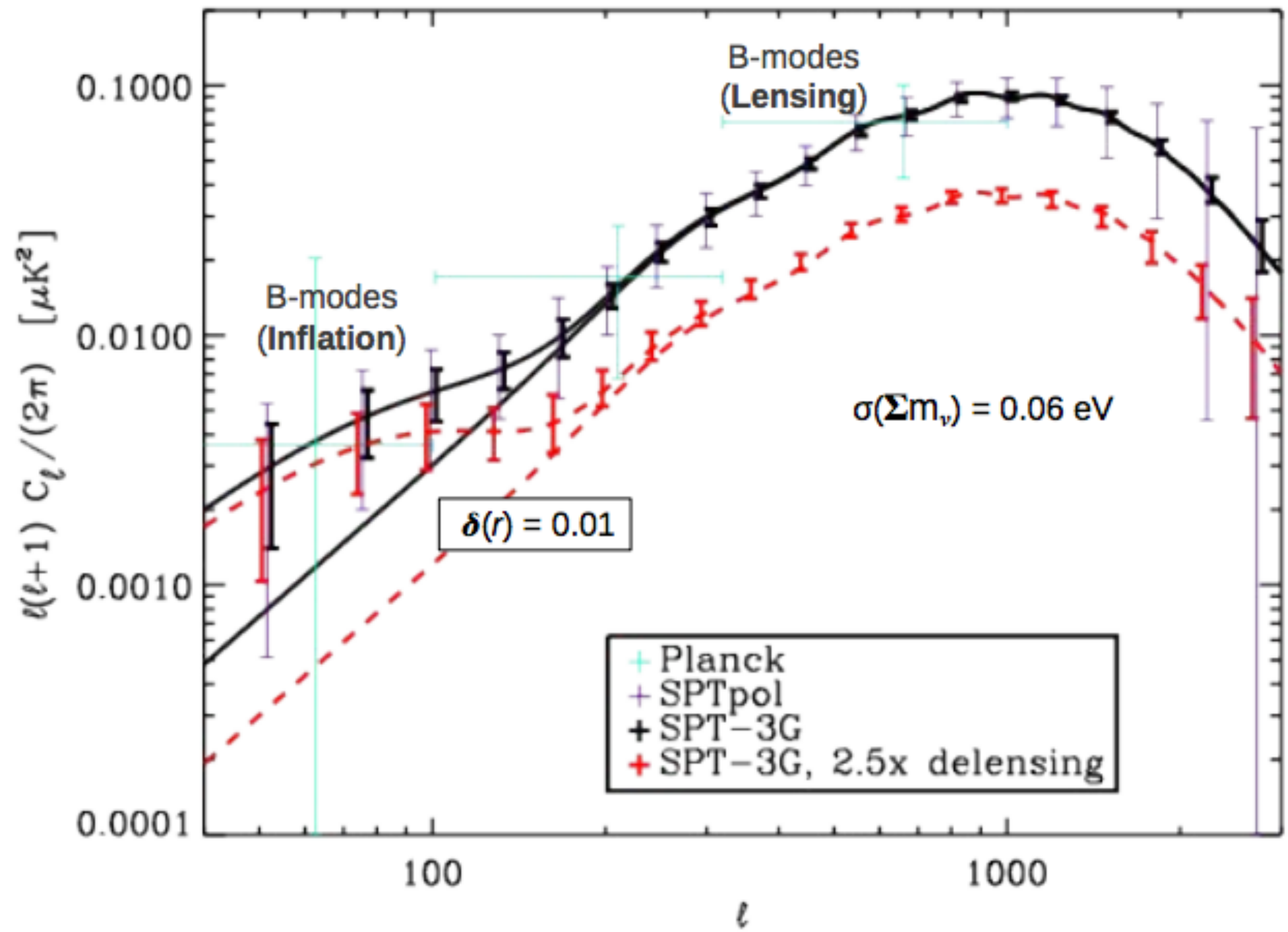
Polarization map from 1st season



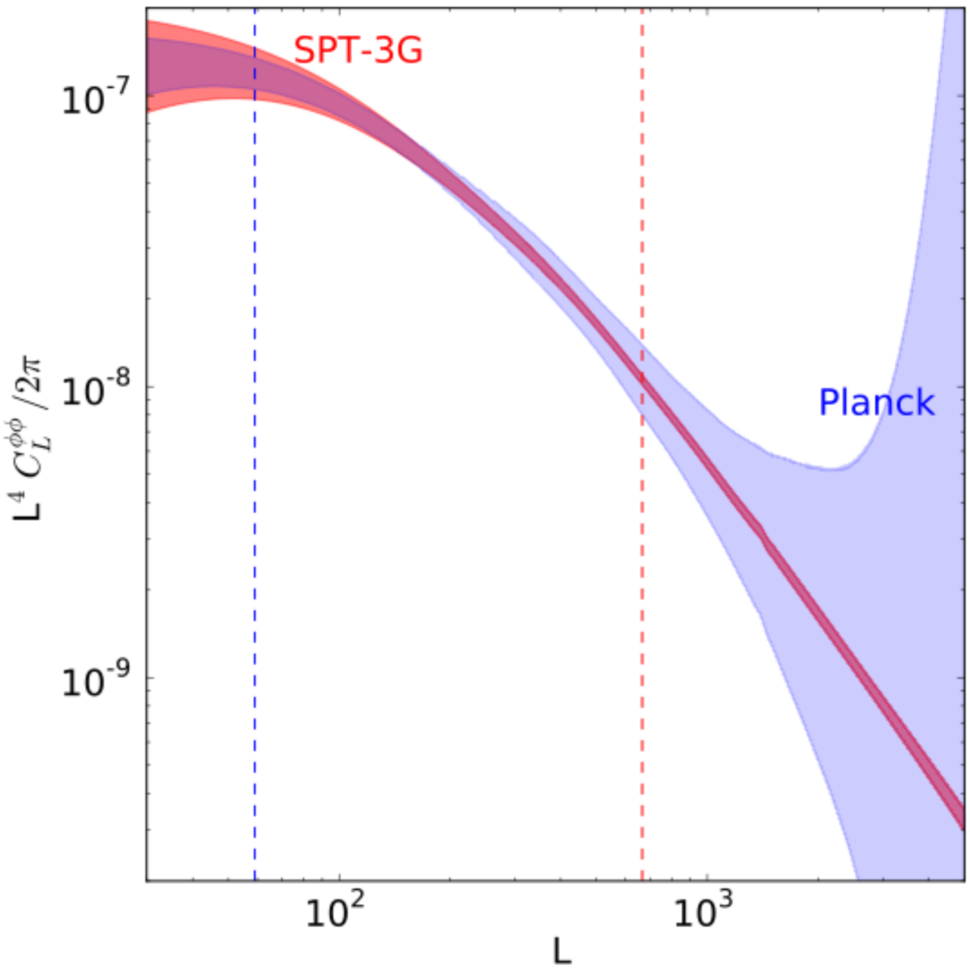
SPTpol has three more years of observing in a larger field.

- March 2012 – May 2013
  - 100 square degree deep field
- May 2013 – end of 2015
  - -50 < dec < -65
  - 22h < RA < 2h
  - ~500 square degrees
  - Overlap with BICEP and Keck array / SPICE
- 2016 -
  - SPT-3G

SPT-3G will go beyond the pioneering B-mode measurements of SPTpol.



CMB Polarization and Lensing Reconstruction

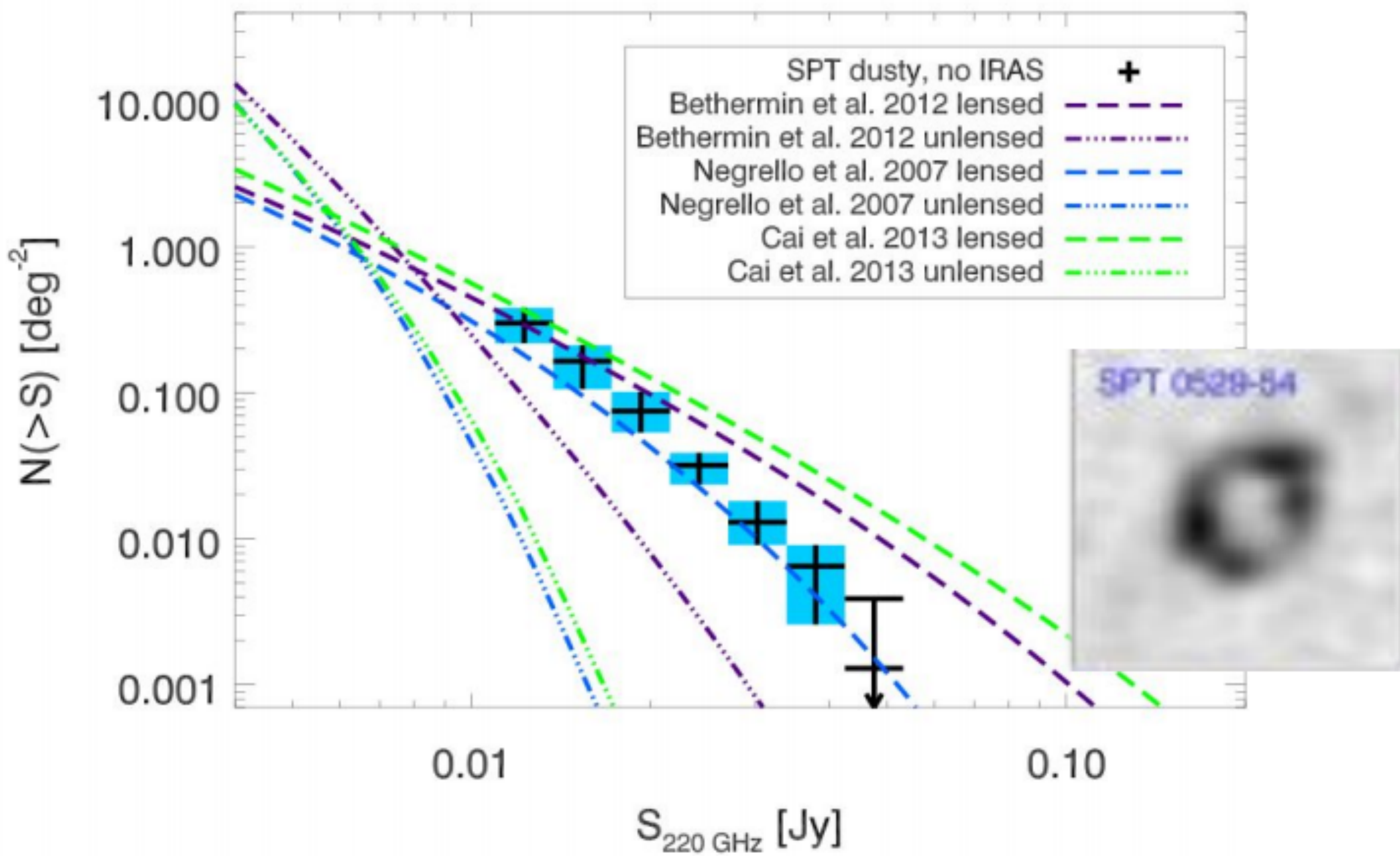


SPT-3G: A proposed 2500 sq. deg. survey with a 3rd-generation polarization-sensitive focal plane.

Enabling a deflection angle power spectrum measurement as forecasted here and

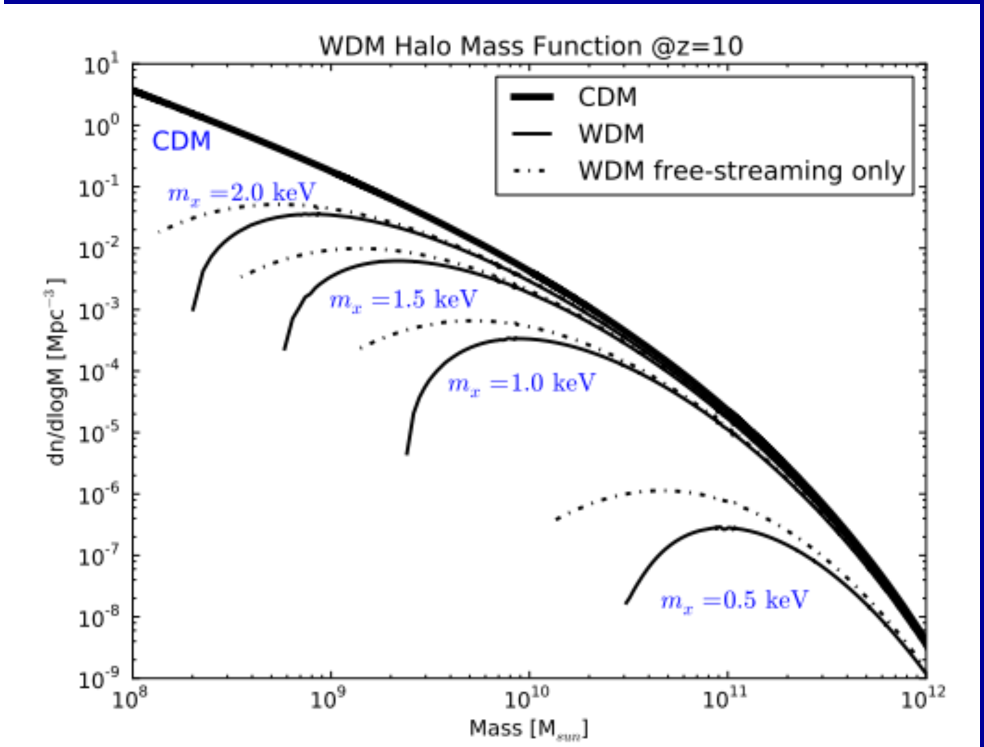
$\sigma(\Sigma m_\nu) = 0.06$ eV

We catalog extragalactic foregrounds.



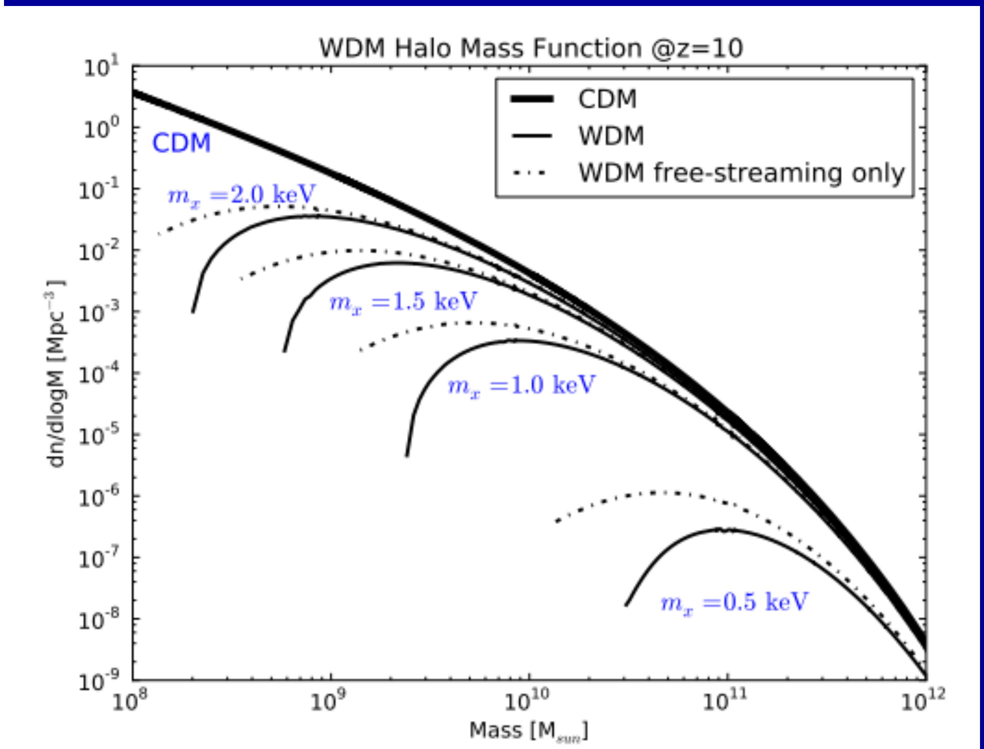
Mocanu et al., arXiv:1306.3470

Warm Dark Matter (e.g., sterile neutrino)



Pacucci, Mesinger & Haiman (2013)

Warm Dark Matter (e.g., sterile neutrino)



Subhalos in a halo must be similarly affected by WDM

Pacucci, Mesinger & Haiman (2013)

Slide credit: N. Dalal

subhalo lensing

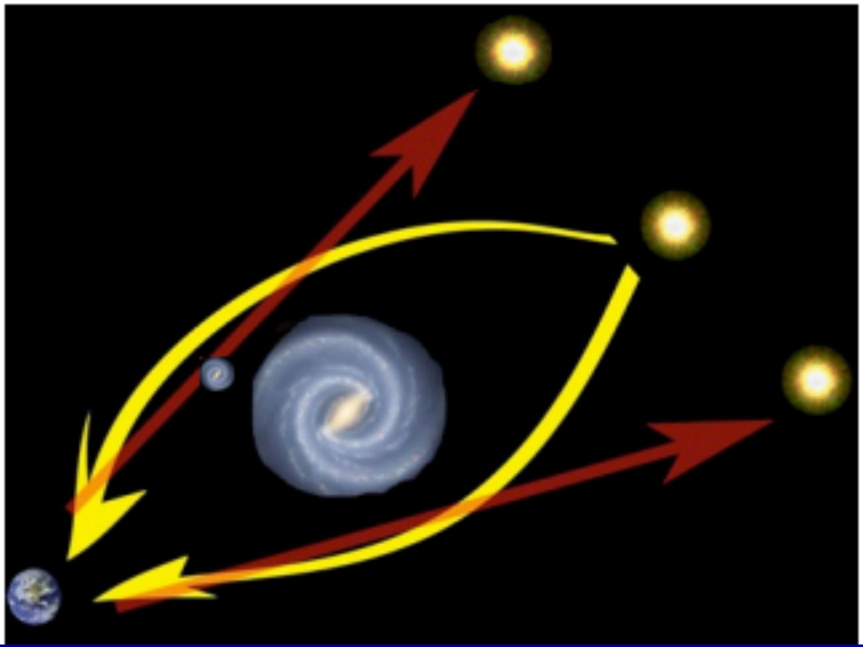
small ($M<10^8\ M_\odot$) halos and subhalos are wimpy lenses!

- small size ($\lesssim$ kpc), so each one affects a small fraction of the sky
- lensing amplitude is weak (central $\kappa,\gamma \lesssim 0.1$)
- need a way to boost their effect to detect them...

Slide credit: N. Dalal

strong lensing

- if a small halo/subhalo projects near a **strong lens**, then the big lens can magnify the lensing effect of the small halo

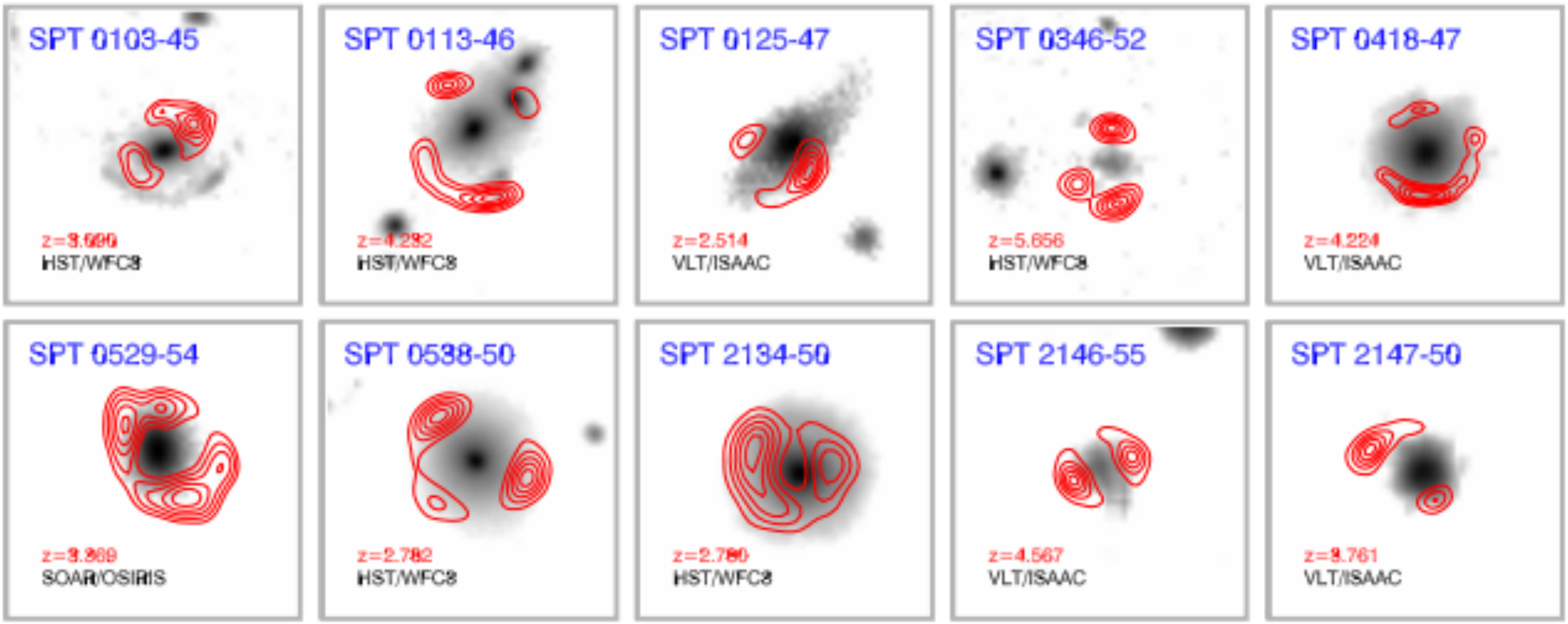


$$\Delta\theta \approx \mathbf{M} \cdot \Delta\alpha$$

if high magnification, then perturbation can have big effect!
(Mao & Schneider 1998)

ALMA Cycle 0 Band 7 350 GHz
2 minute snapshots

Slide credit: N. Dalal

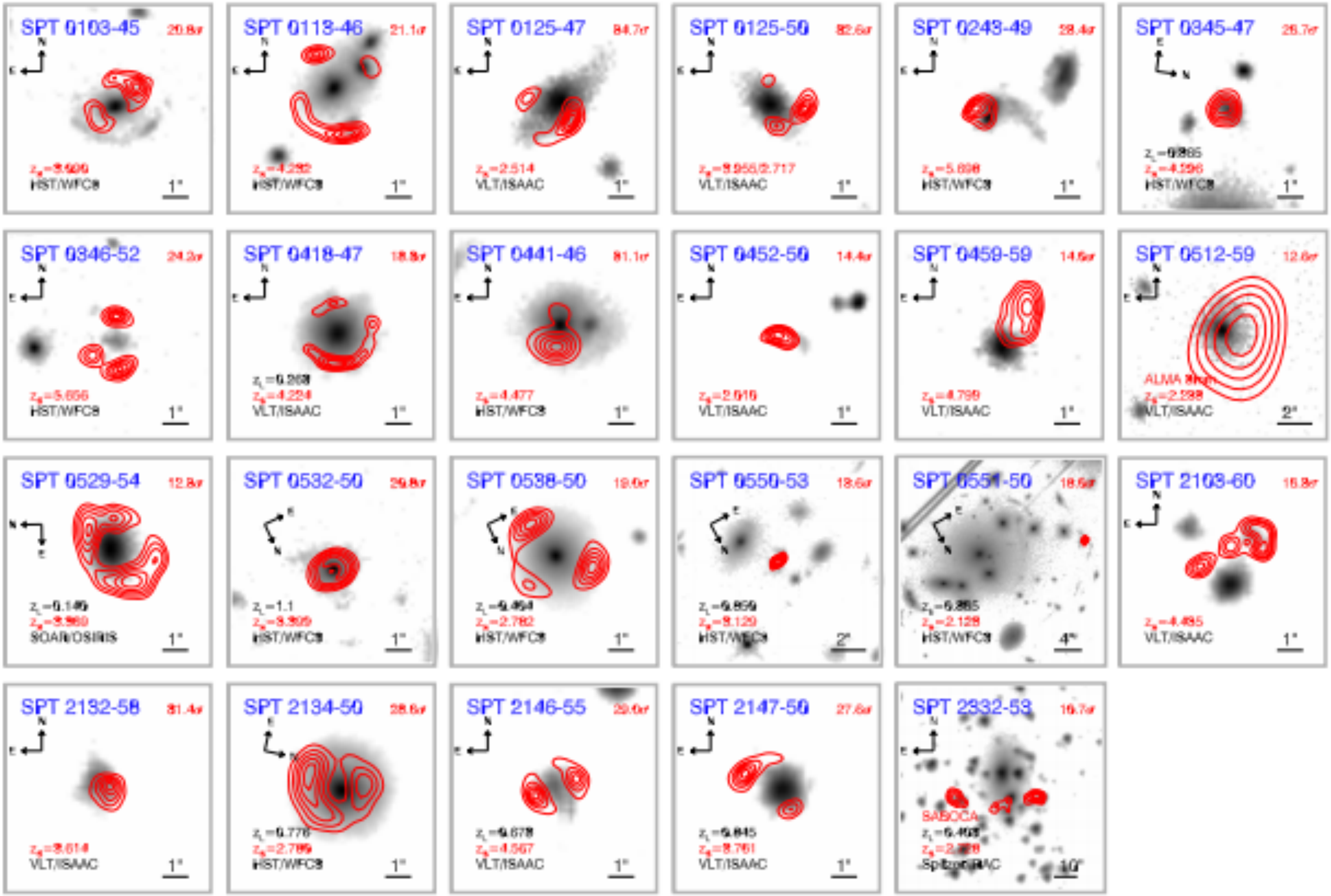


8" x 8" boxes

= deep NIR imaging

= 2 minute ALMA 350 GHz snapshot

Only through the combination of strong gravitational lensing, the SPT selection, and ALMA followup is this result possible



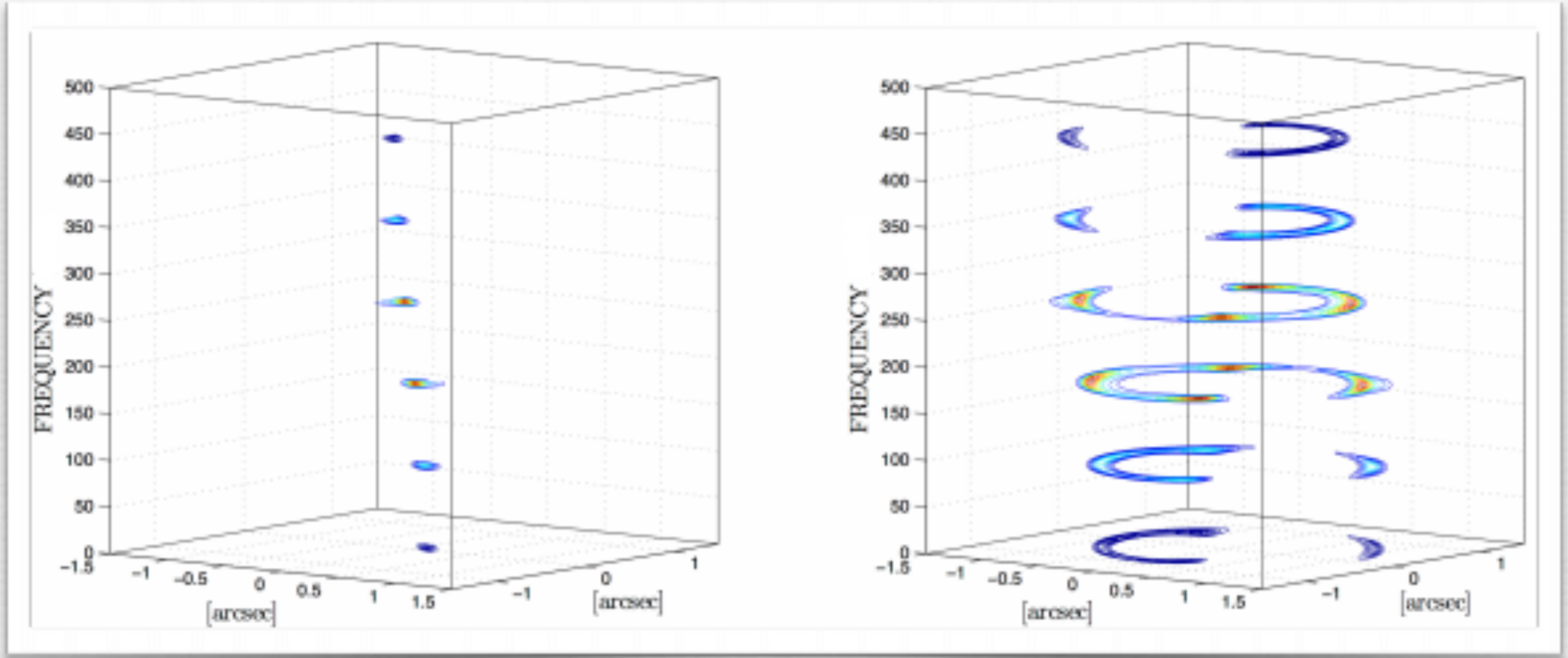
= NIR imaging

= submm imaging

Slide credit: N. Dalal

Slide credit: N. Dalal

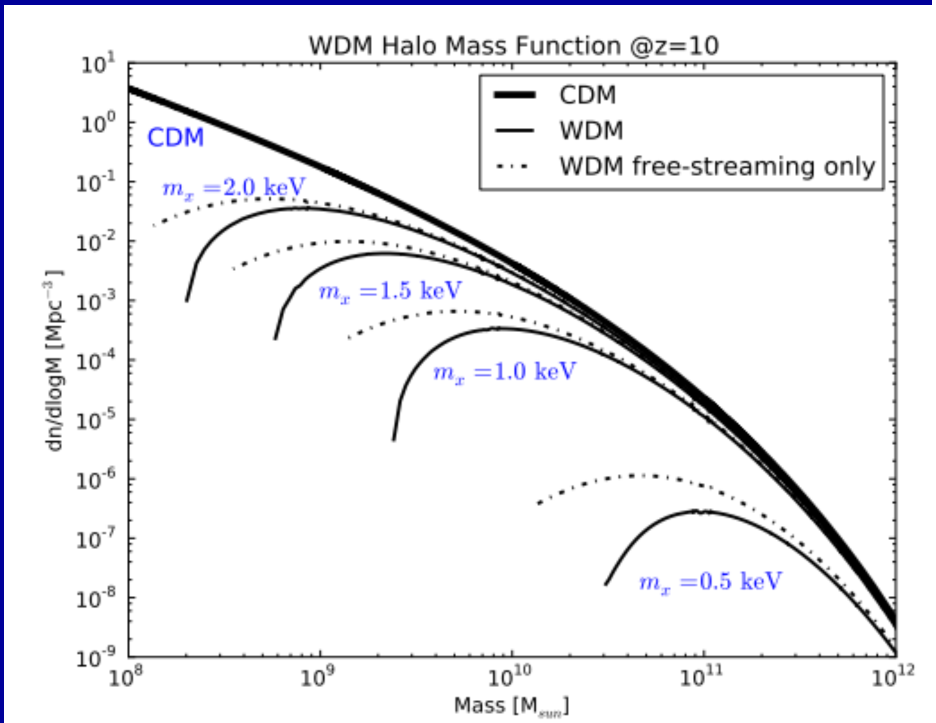
Velocity decomposition can separate small features of the source



so each SMG is equivalent to having **many** sources behind each lens!

From Abstract of Hezaveh, Dalal, Holder, Kuhlen, Marrone, Murray & Vieira (2013)

Specifically, we find that in typical DSFG lenses, there is a ~55% probability of detecting a substructure with M > 10^8 M$\odot$ with more than 5σ detection significance in each lens, if the abundance of substructure is consistent with previous lensing results. The full ALMA array, with its significantly enhanced sensitivity and resolution, should improve these estimates considerably. Given the sample of ~100 lenses provided by surveys such as the South Pole Telescope, our understanding of dark matter substructure in typical galaxy halos is poised to improve dramatically over the next few years.



Slide credit: N. Dalal

cosmology constraints

- existing sample (DK02) is **7** quasar lenses
- from SPT we expect ~100 SMG lenses, and each SMG lens is **much** more constraining than a quasar
- How do these measurements translate into bounds on cosmology?
- We don't know – currently limited by theory! we don't know how to calculate substructure as a function of WDM, etc.
  - we're working on it (Arka Banerjee)
  - other statistics besides mass function might be more useful, e.g. substructure power spectrum

Summary

- ΛCDM has passed a precision test
- Lensing plays an important role in (small) parameter shifts
- SPT and Planck agree really well
  - SPT provides independent check on Planck beams at 143
  - SPT lensing map appears consistent with Planck lensing map
- Progress coming on lensing, Σm_ν and WDM