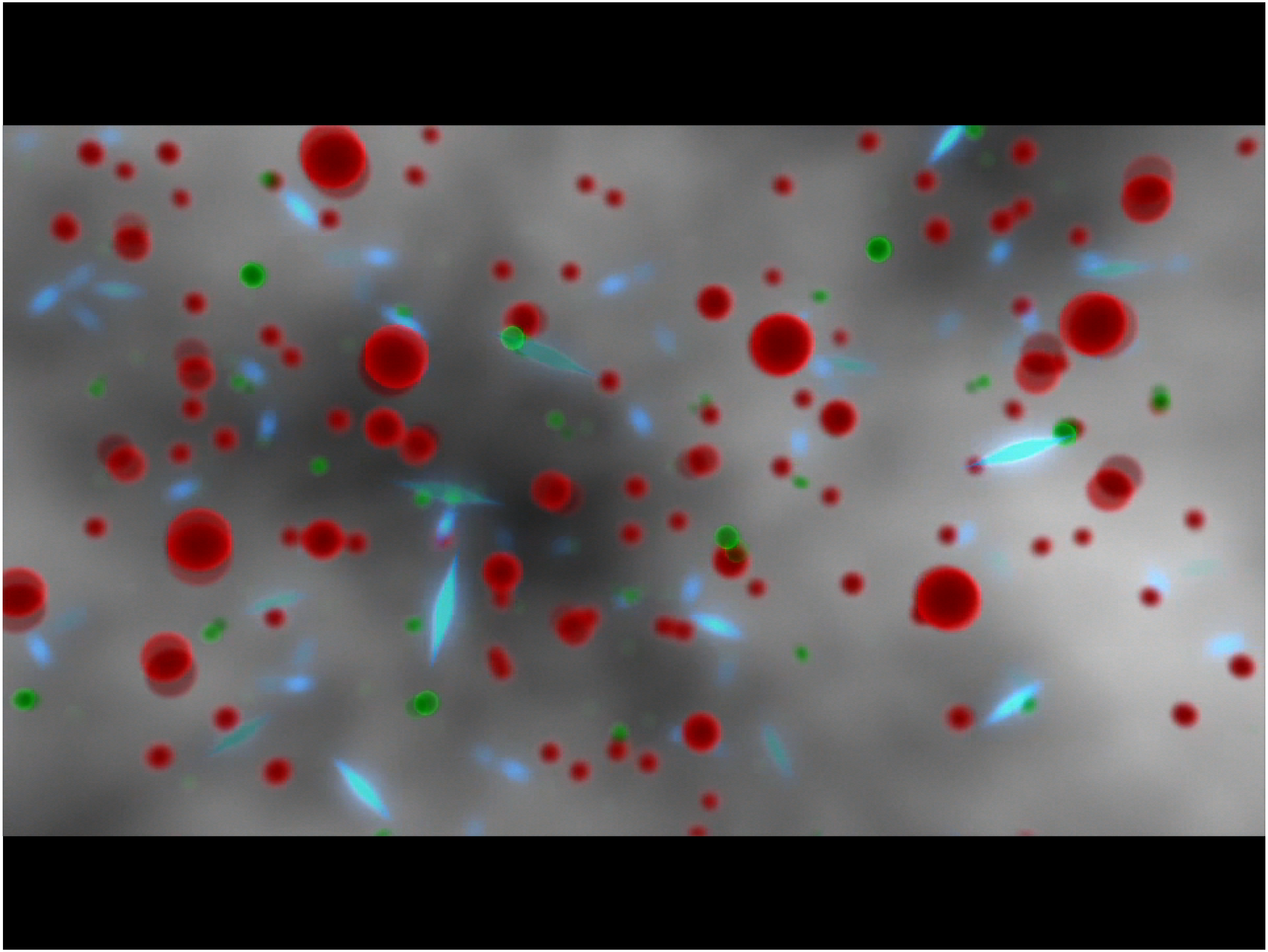
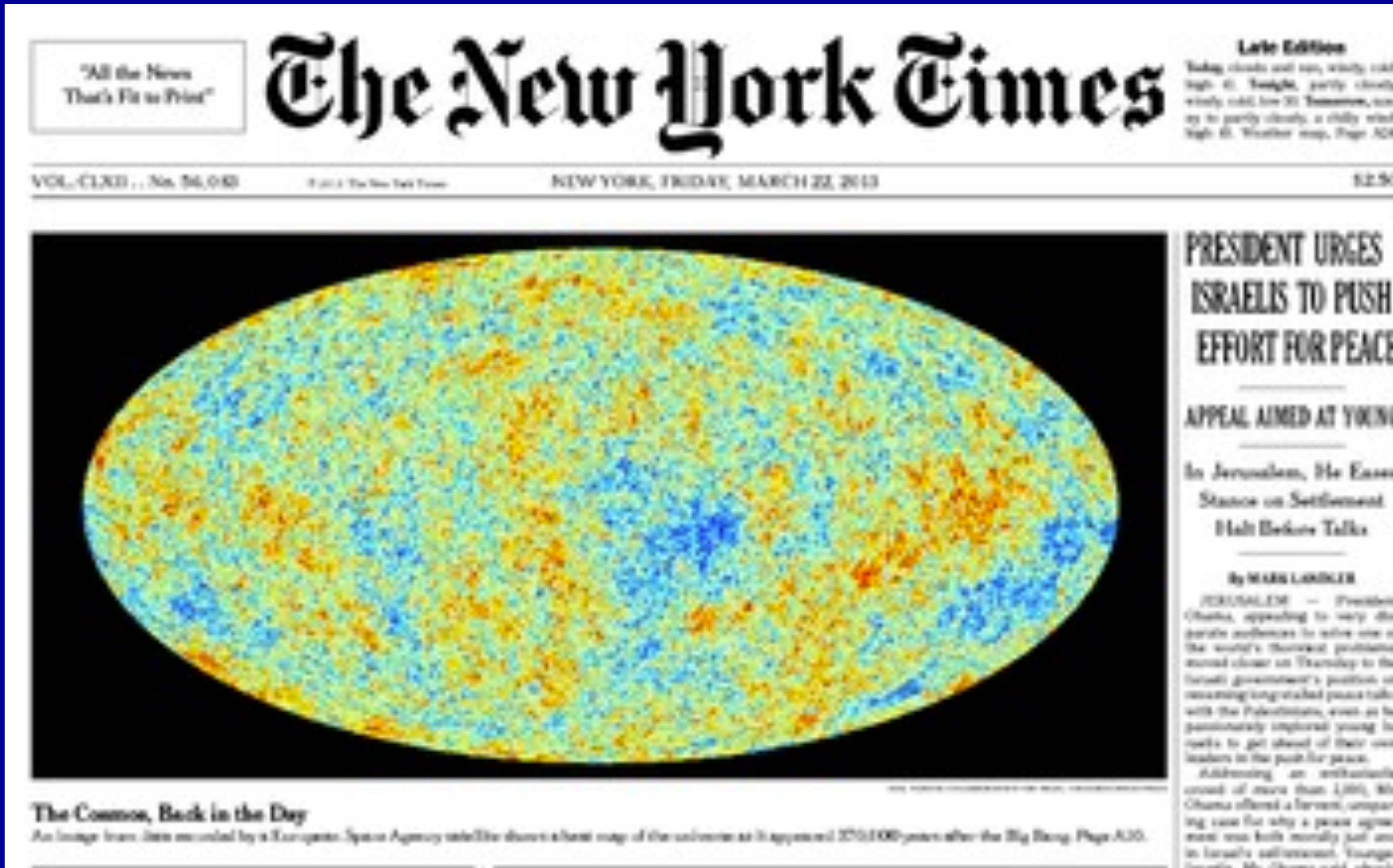
Overview of Planck Results (and some from SPT as well)

Lloyd Knox
UC Davis
Planck Collaboration
SPT Collaboration





"All the News That's Fit to Print"

The New York Times

Late Edition

VOL. CLXII . . No. 56,063 — NEW YORK, FRIDAY, MARCH 22, 2013 — $2.50

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

APPEAL AIMED AT YOUNG

In Jerusalem, He Eases Stance on Settlement Halt Before Talks

By MARK LANDLER

The Cosmos, Back in the Day

Outline

- Planck and the Planck maps
- Comparison with WMAP
- Comparison with SPT
- The power spectrum: ΛCDM, the standard model of cosmology, passes a precision test
- Consistency with Other Cosmological Probes
- Inflation (Gaussianity, scale dependence)
- Lensing (including new SPT result)
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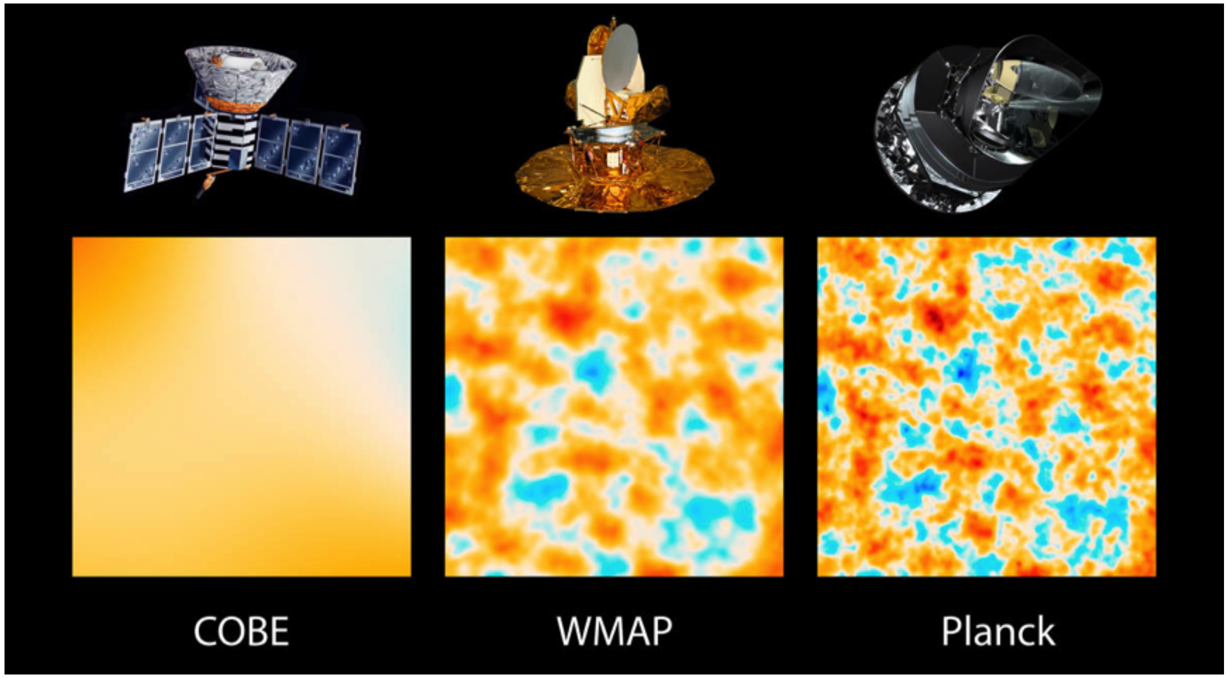
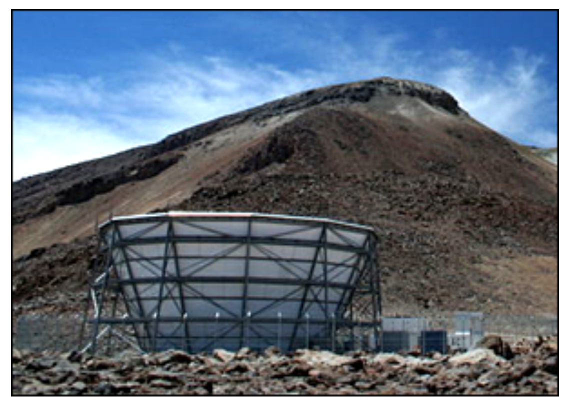
What is Planck?

Full sky:



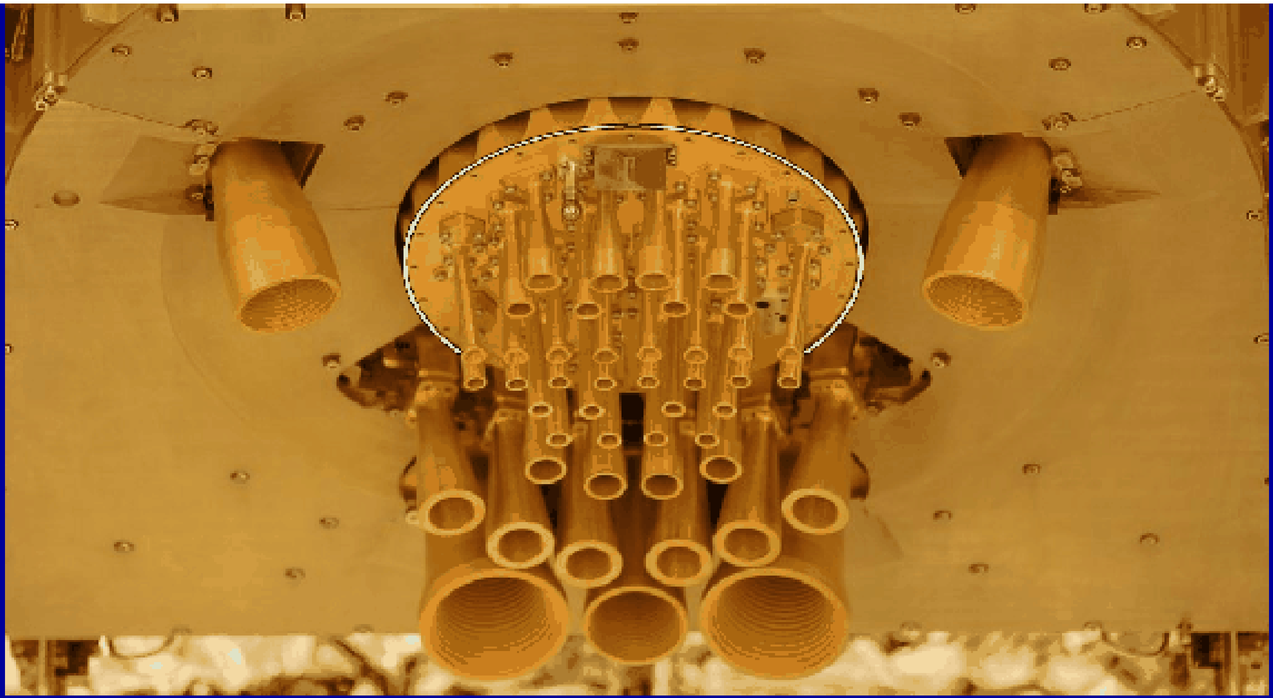
Better resolution:

South Pole Telescope (SPT)

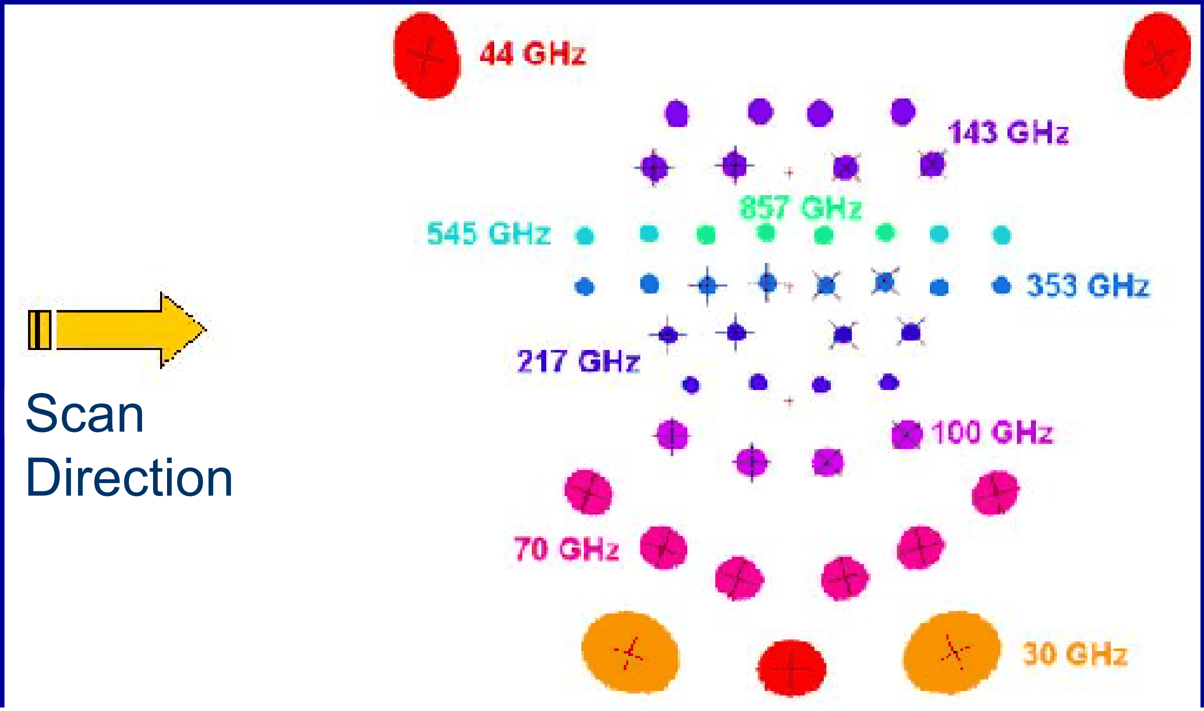


Atacama Cosmology Telescope (ACT)

Planck in February 2009



The Focal Plane

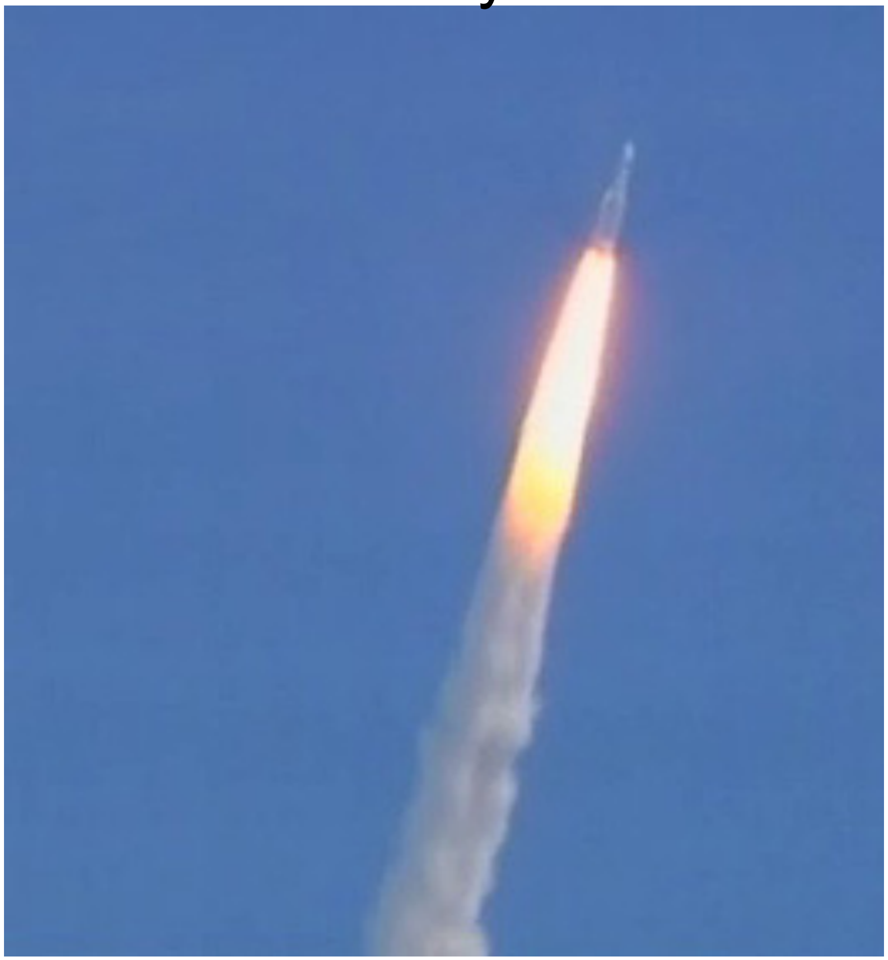


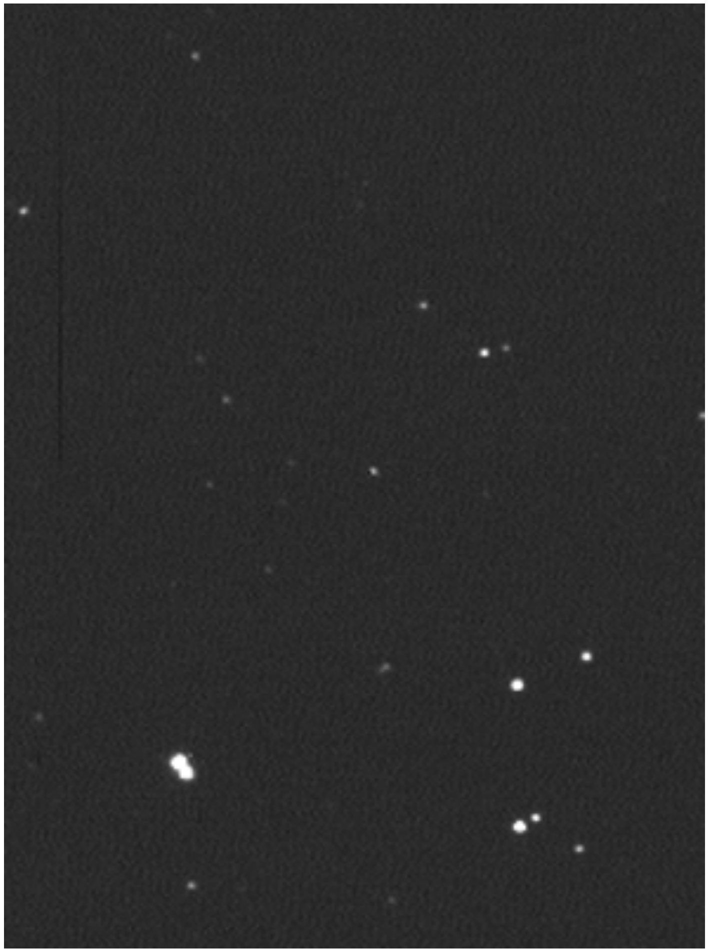
LFI: 30, 44 and 70 GHz, all polarization sensitive

HFI: 100, 143, 217, 353, 545 and 857 GHz, some polarization sensitive

A picture-perfect launch!

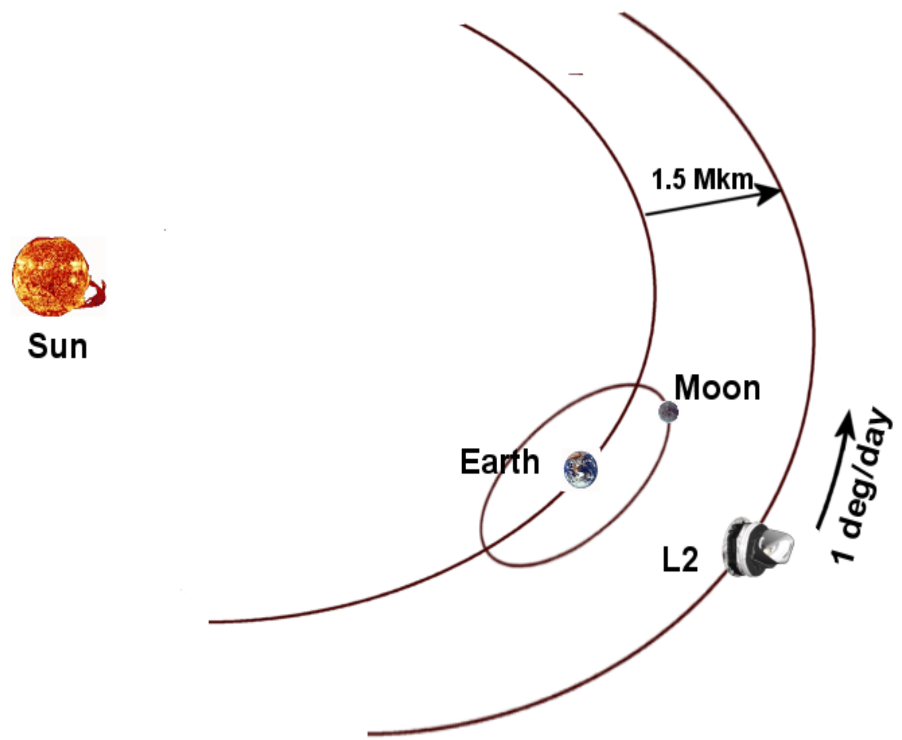
Ariane 5 lifts off with Herschel and Planck on board on 14 May 2009 at 15:12:02 CEST.

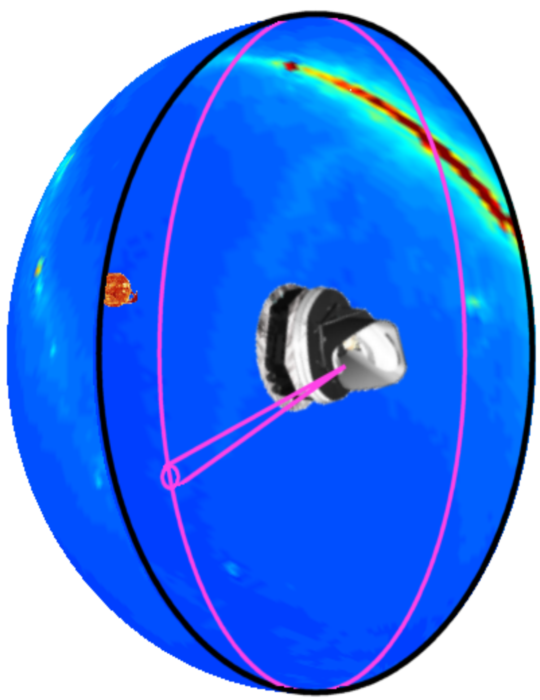


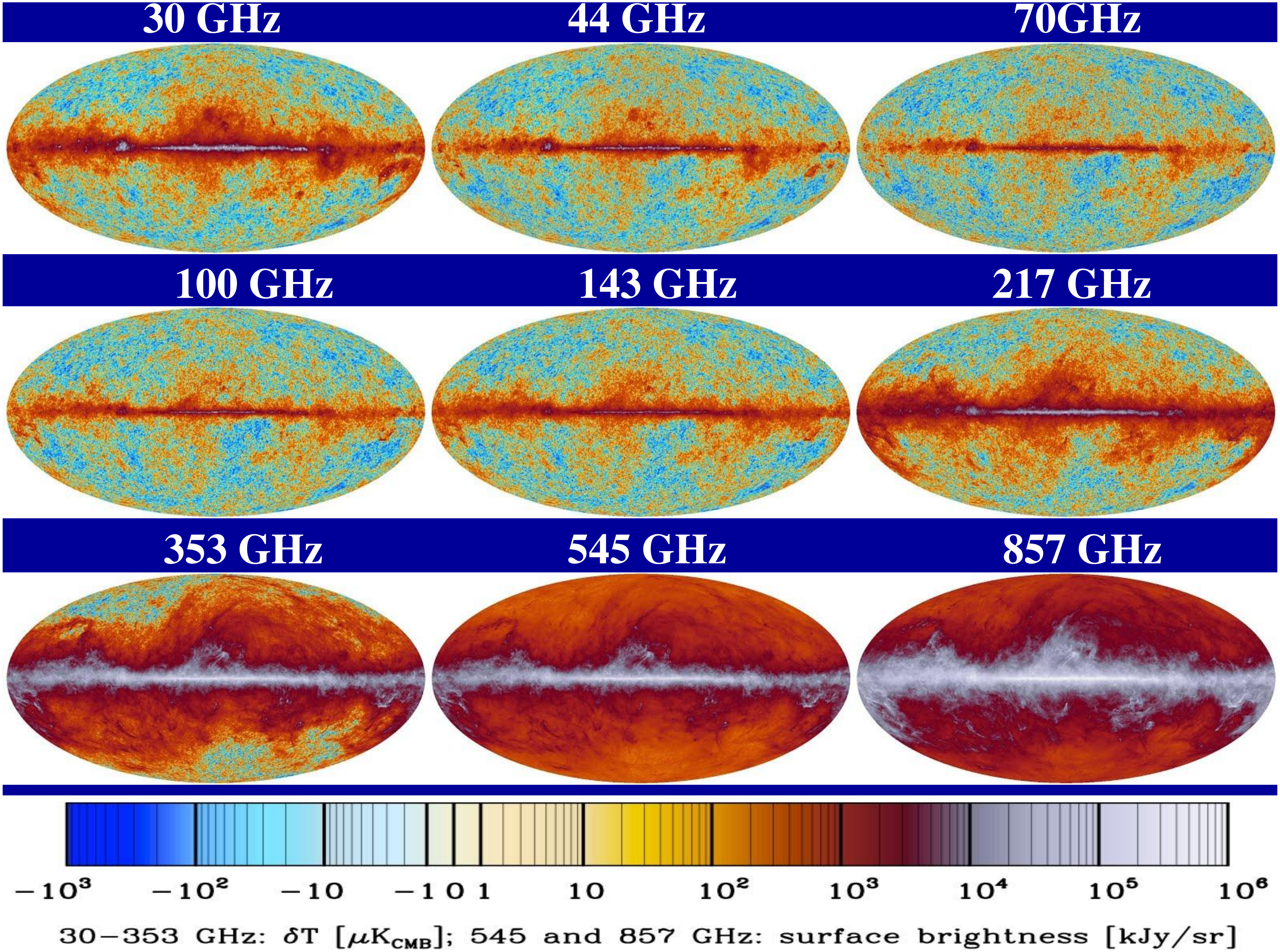


The orbit

Planck makes a map of the full sky every ~6 months.

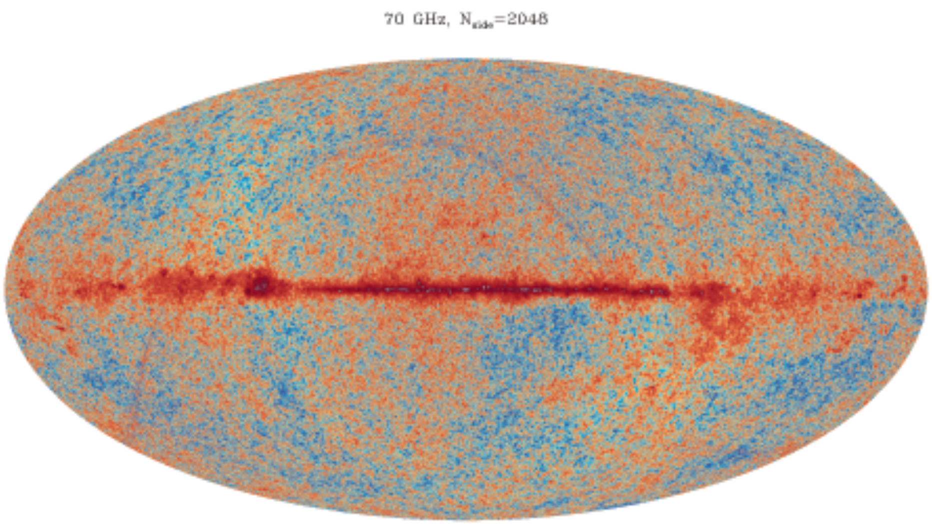




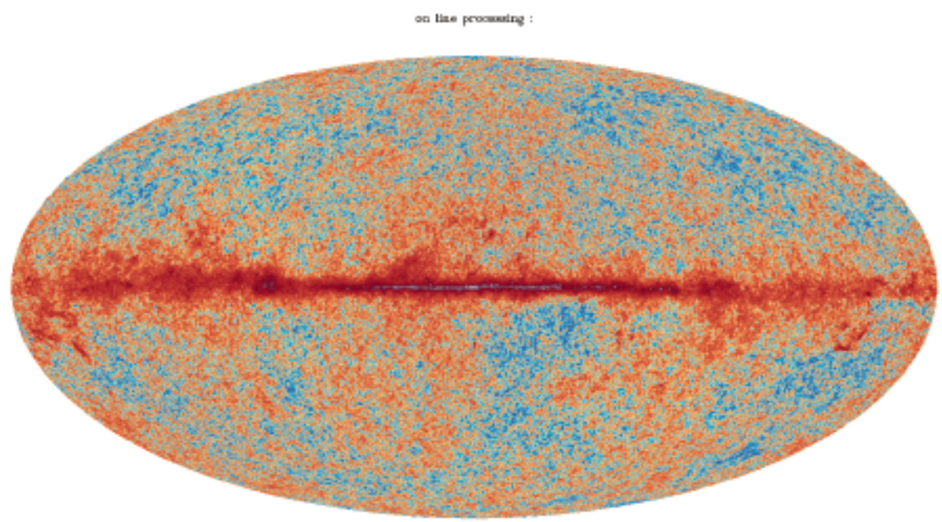

30 GHz
44 GHz
70GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

Beautifully Consistent Data

- Make initial comparison on the observed sky, before foreground separation.
- Foreground minimum at 70 GHz
- Compare LFI 70 GHz with HFI 100 GHz
- Different technologies, different systematics



70 GHz, $N_{\mathrm{side}} = 2048$

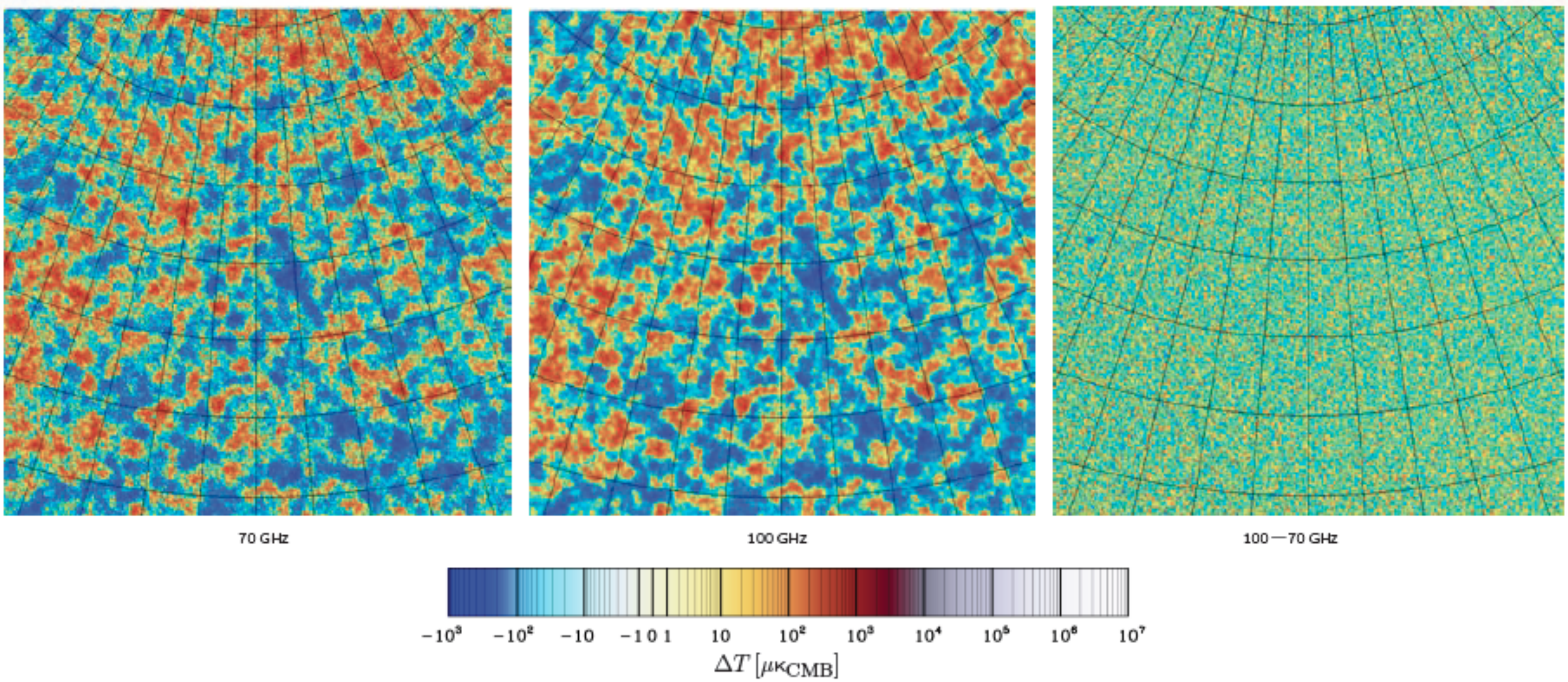


100 GHz, $N_{\mathrm{side}} = 2048$

Planck Collaboration XI 2013

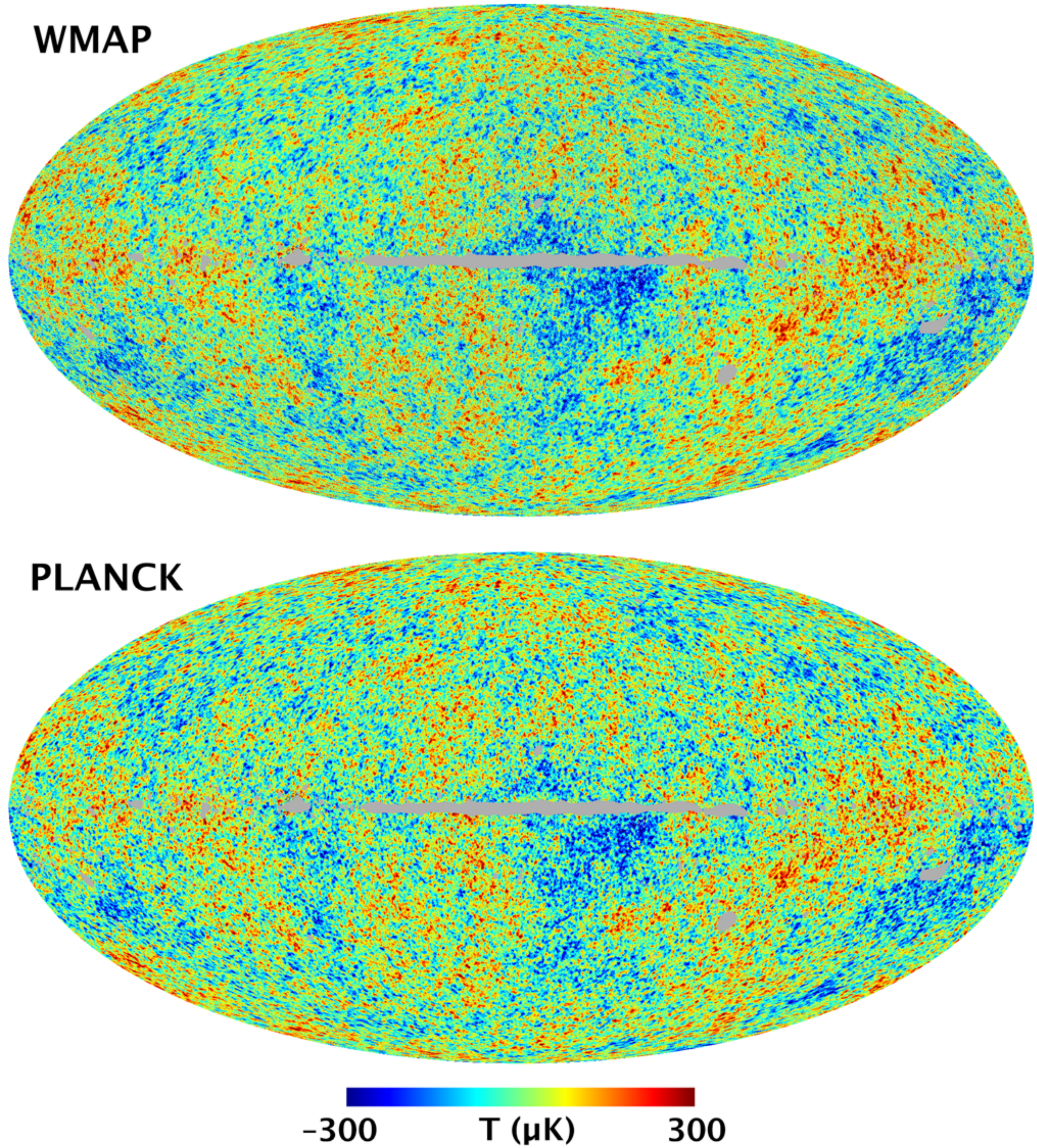
Consistency between LFI 70 GHz and HFI 100 GHz

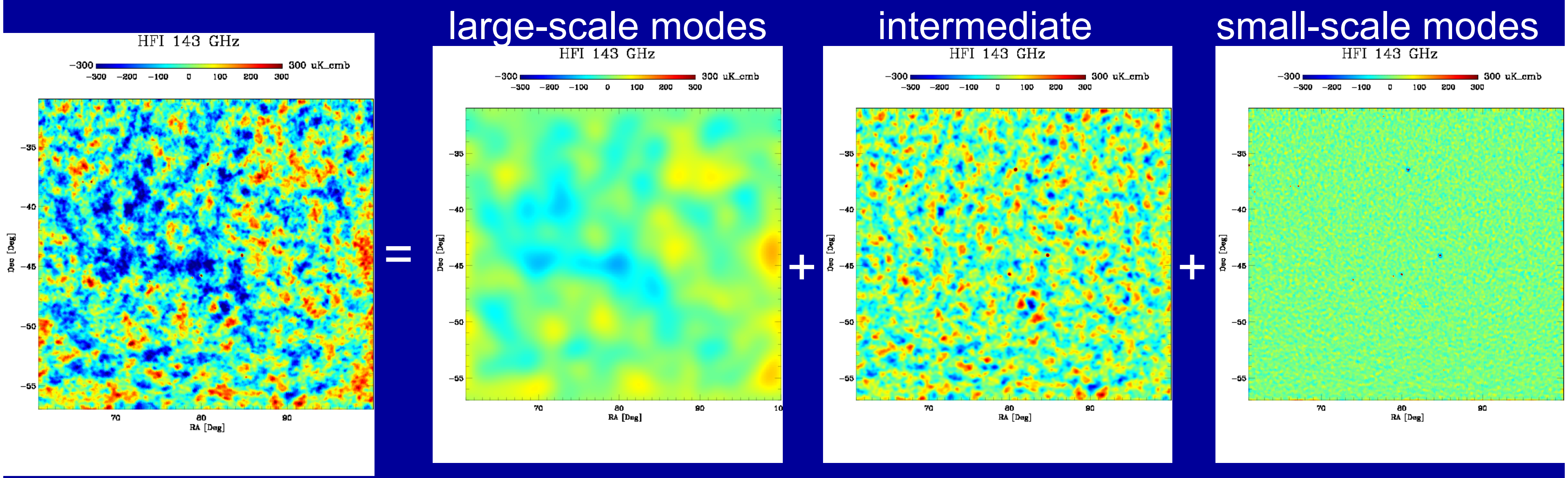
- Low-foreground patch of sky near the NEP



Planck Collaboration XI 2013

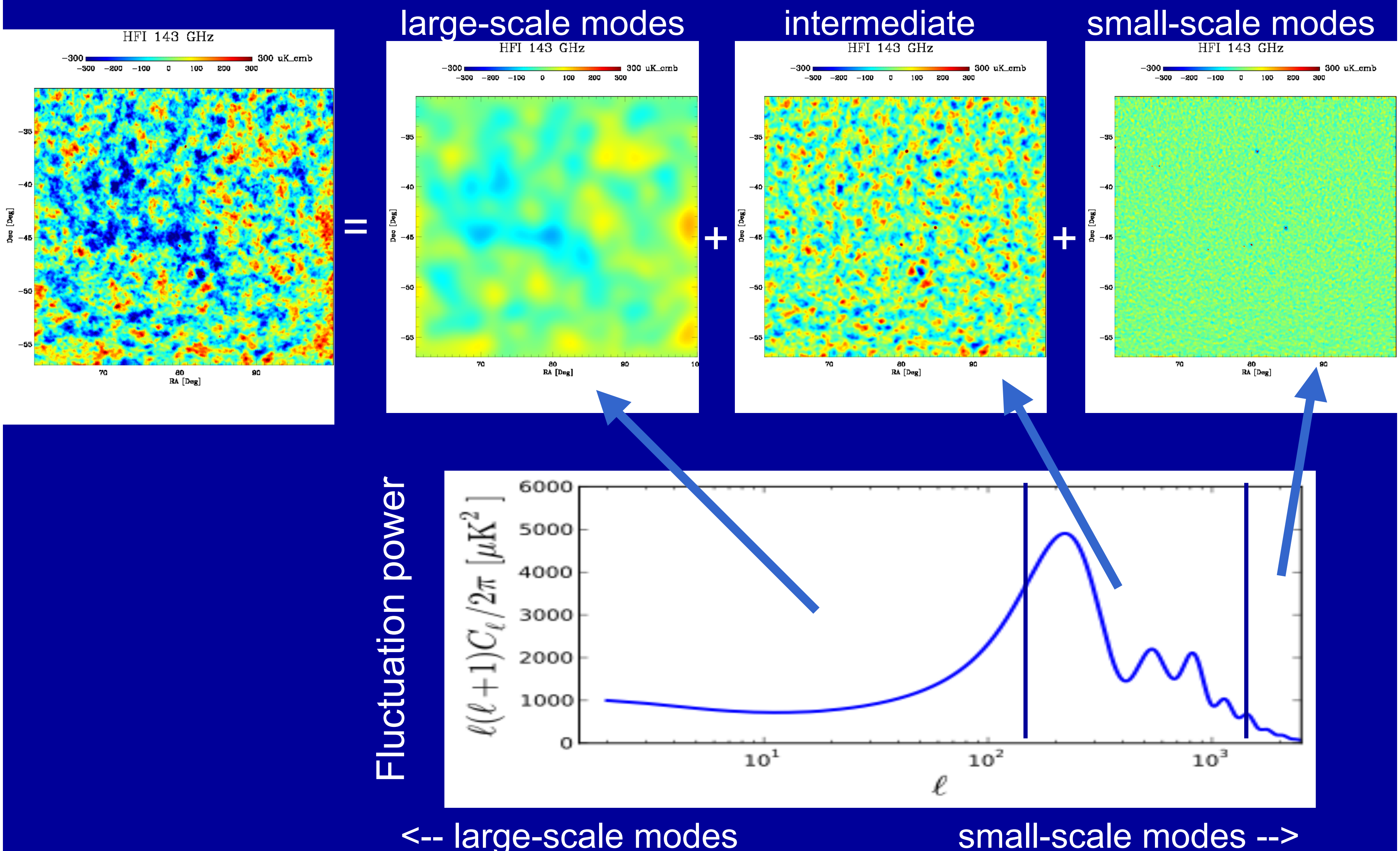
- Difference dominated by 70 GHz noise


WMAP
PLANCK
-300
T (μK)
300



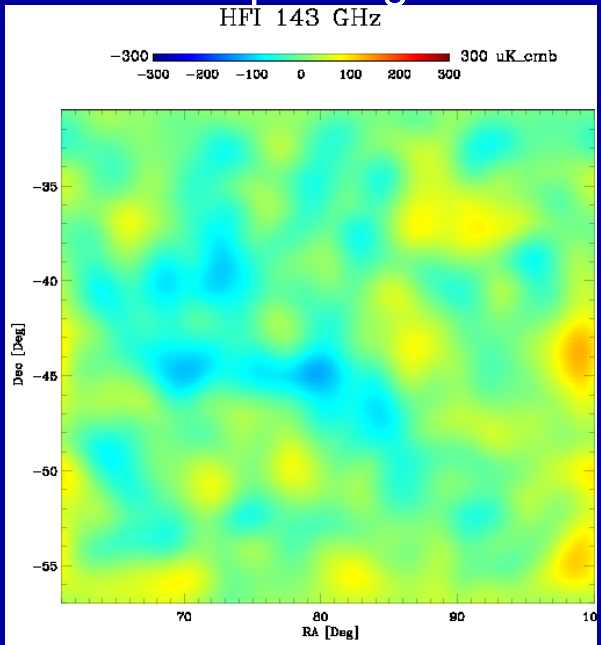
Let’s decompose into band-limited maps and compare those

Band-limited Maps

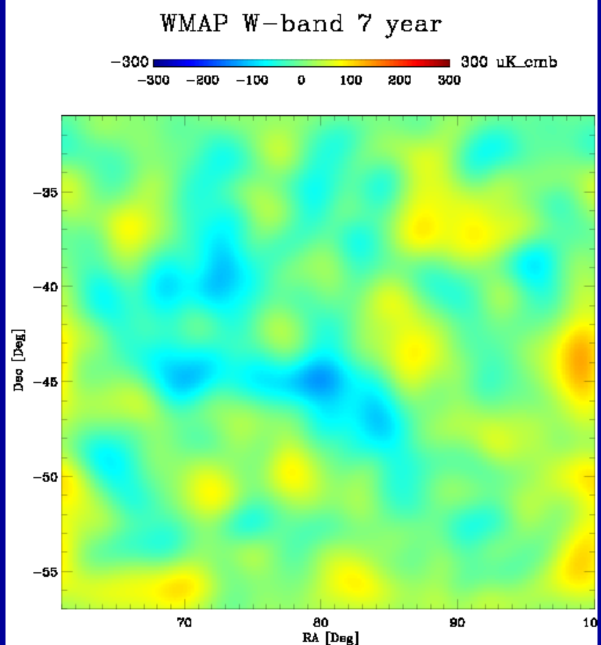


Filtered to keep: large scales

Planck 143 GHz



WMAP 94 GHz

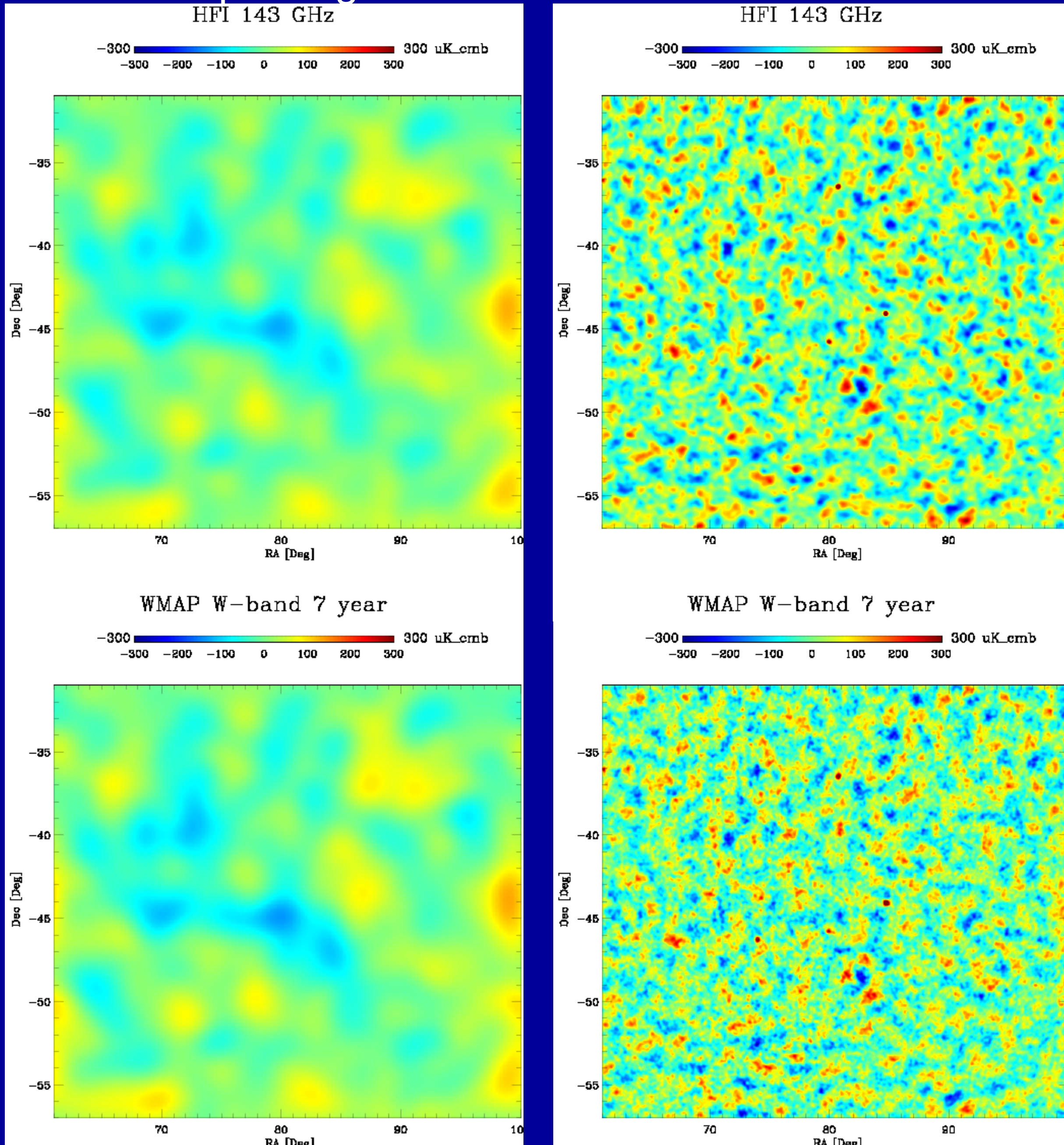


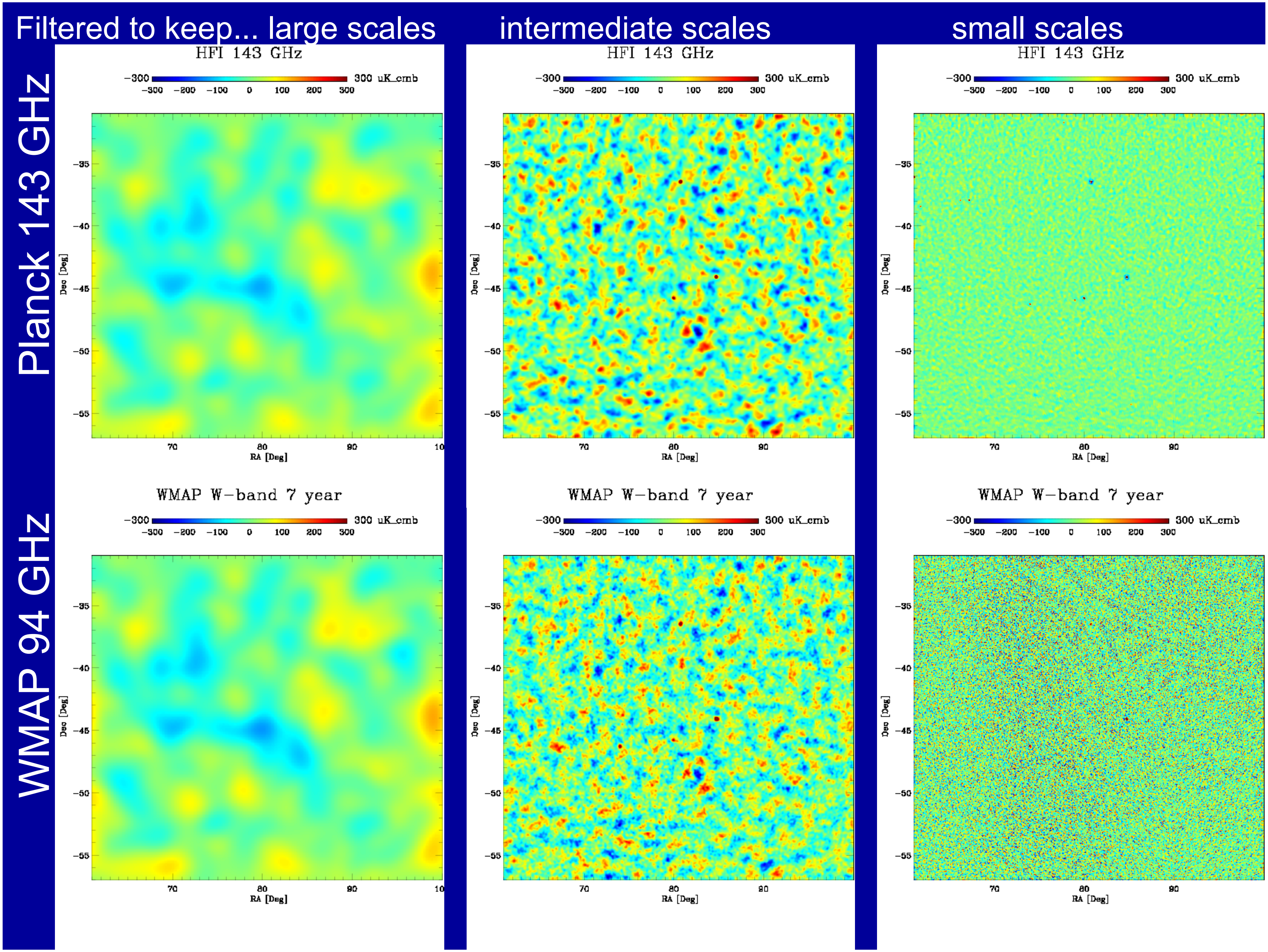
Comparison with WMAP: what’s new?

Filtered to keep: large scales intermediate scales

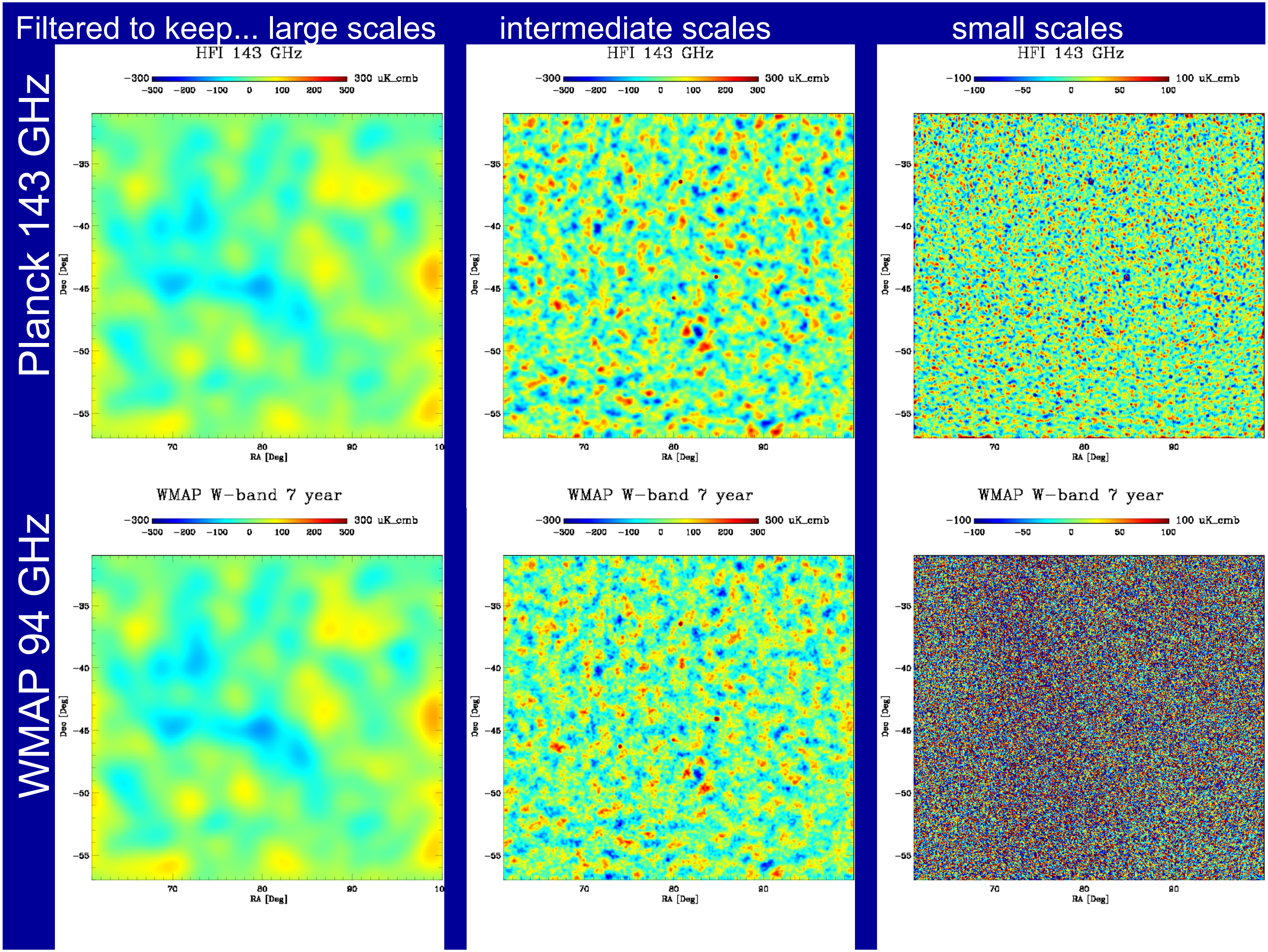
Planck 143 GHz

WMAP 94 GHz



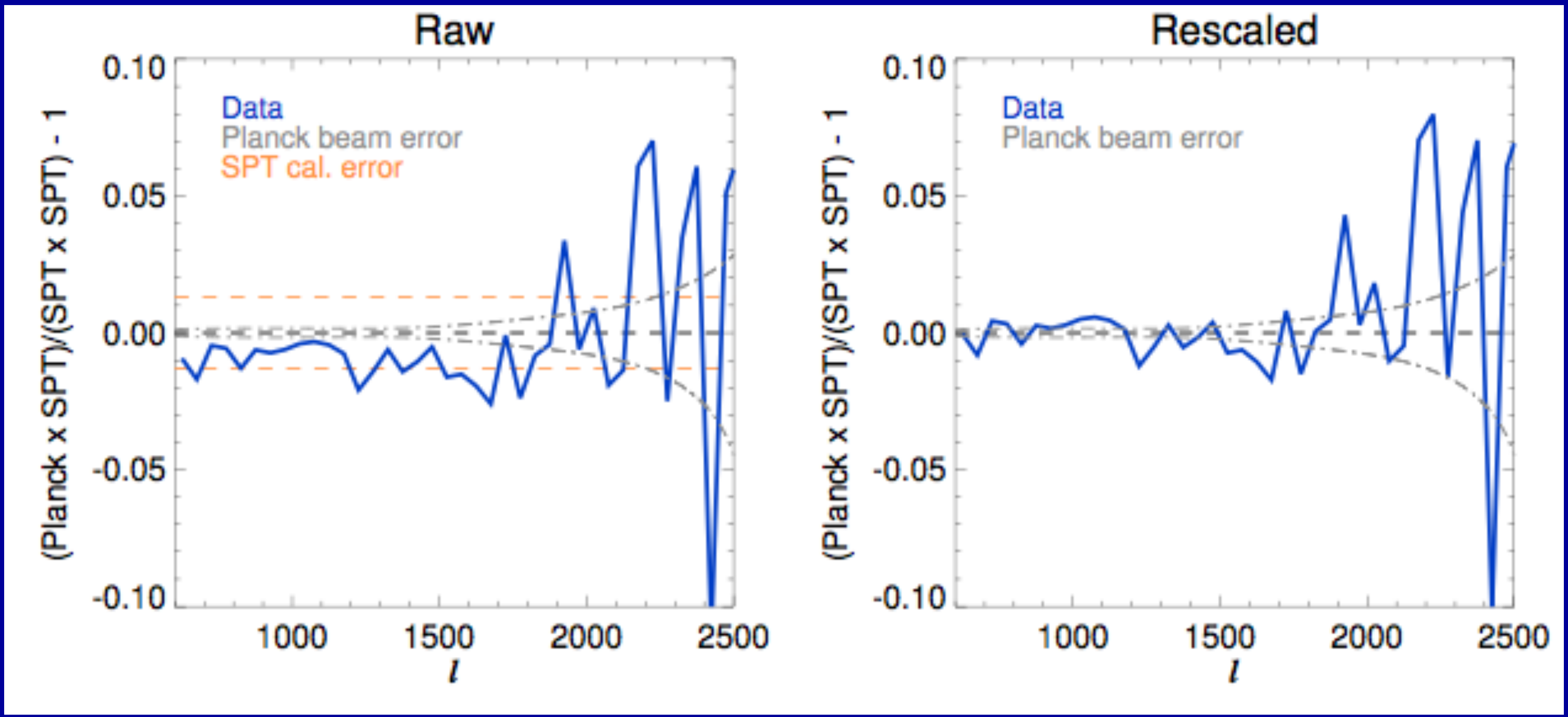


Filtered to keep... large scales
intermediate scales
small scales
Planck 143 GHz
WMAP 94 GHz
HFI 143 GHz
WMAP W−band 7 year
−300
300 uK_cmb
−300 −200 −100 0 100 200 300
Dec [Deg]
RA [Deg]

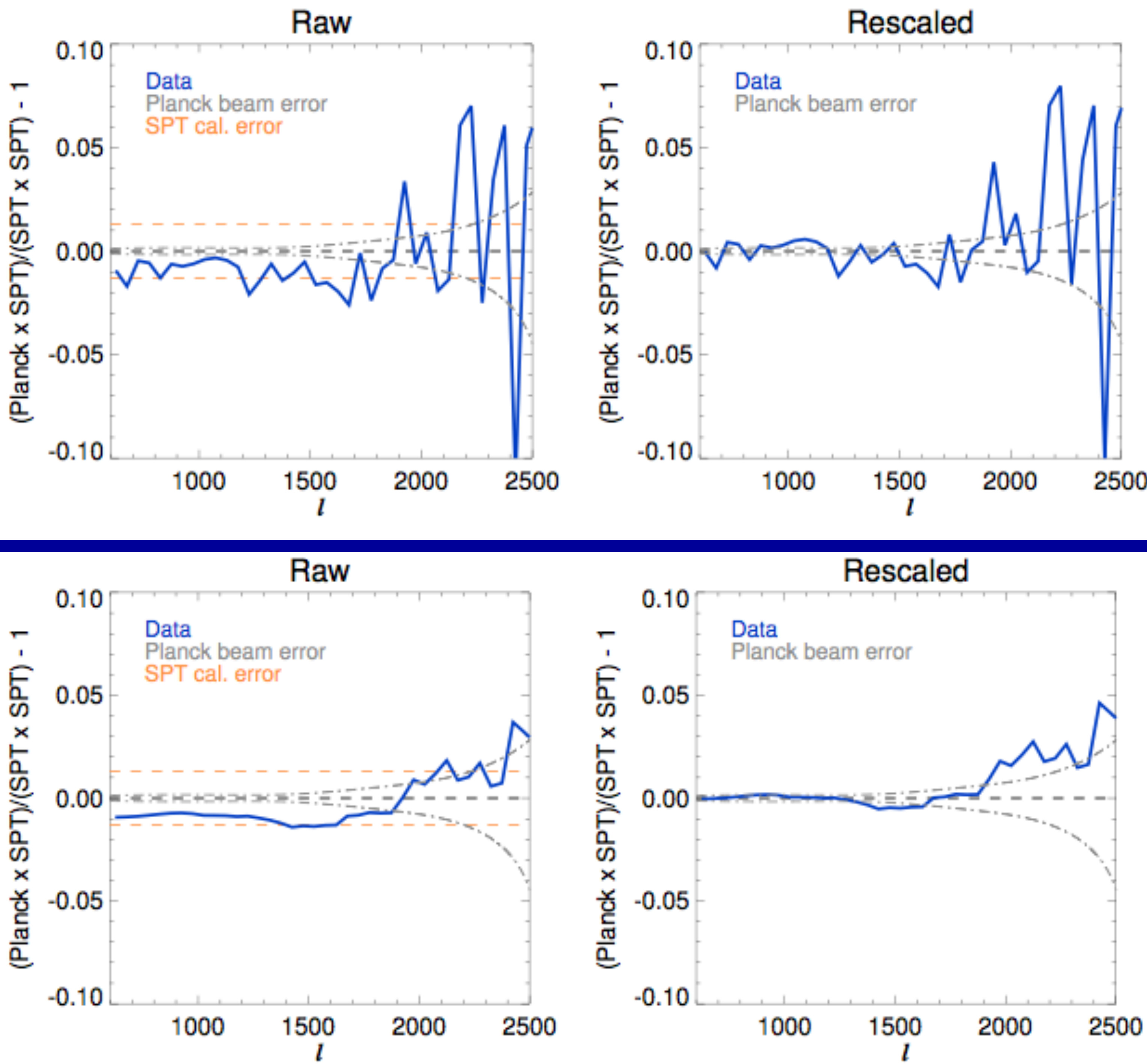


Filtered to keep... large scales
intermediate scales
small scales
Planck 143 GHz
WMAP 94 GHz
HFI 143 GHz
−300 300 uK_cmb
−100 100 uK_cmb
WMAP W−band 7 year
RA [Deg]
Dec [Deg]

Comparison with SPT 2500 sq. deg. Survey



Story, Crawford, Keisler 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

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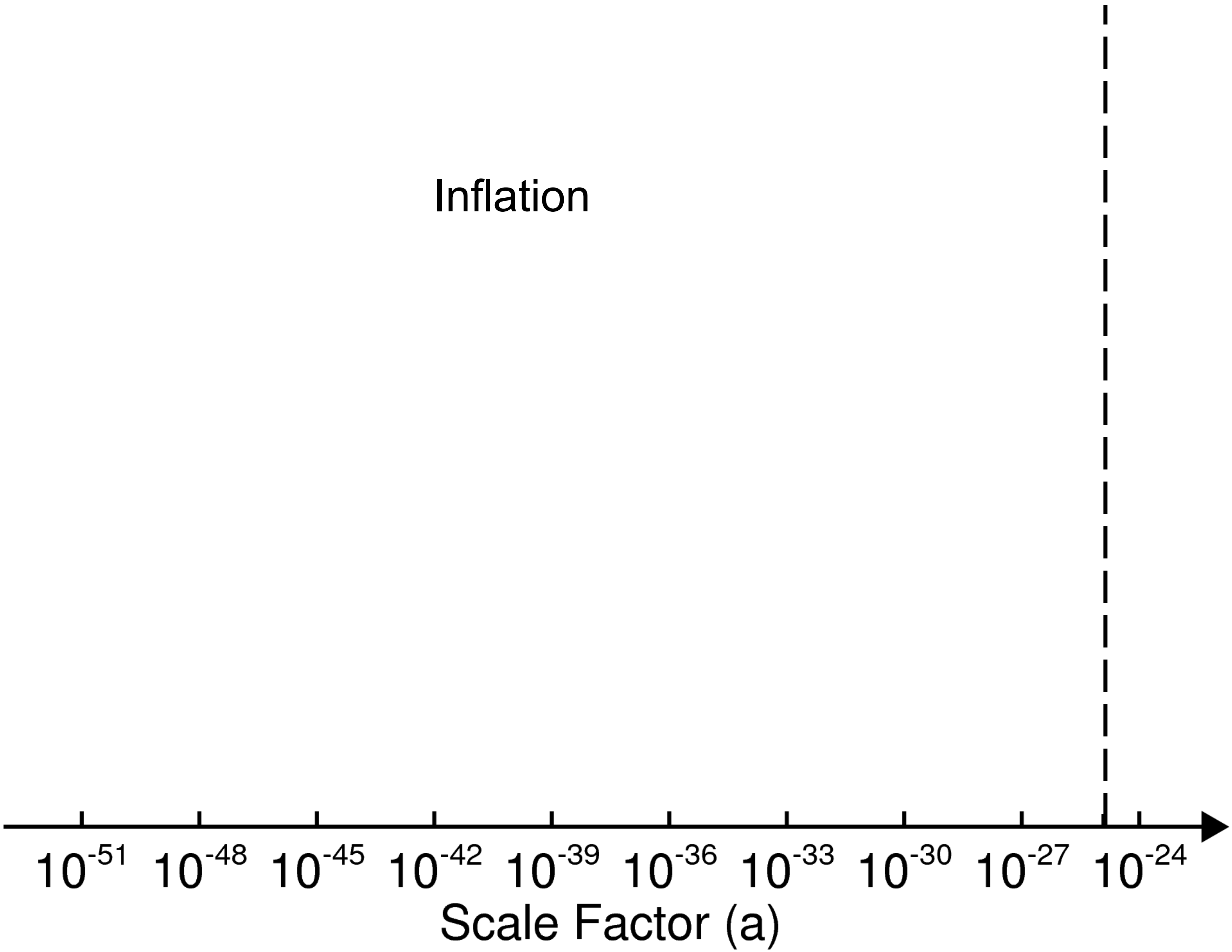
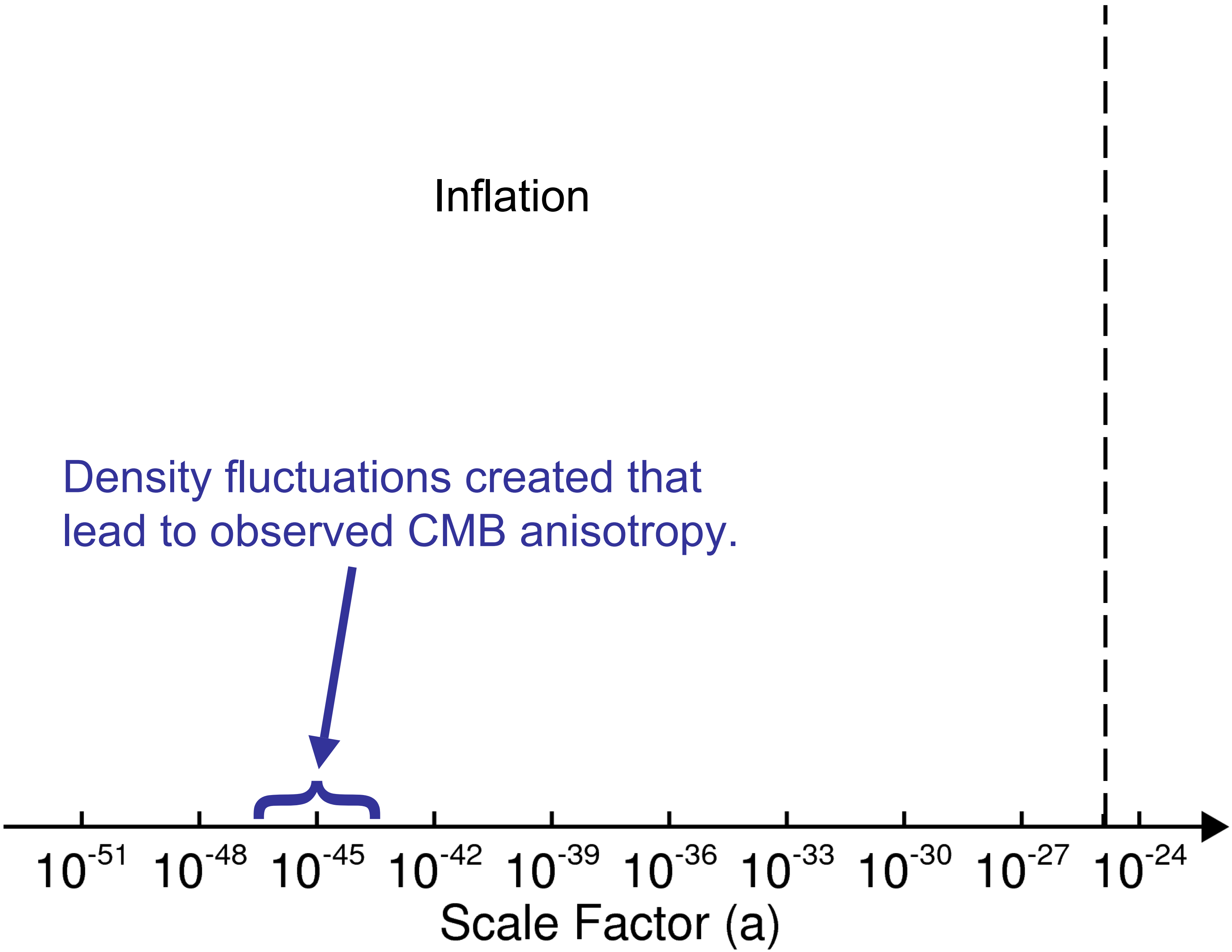
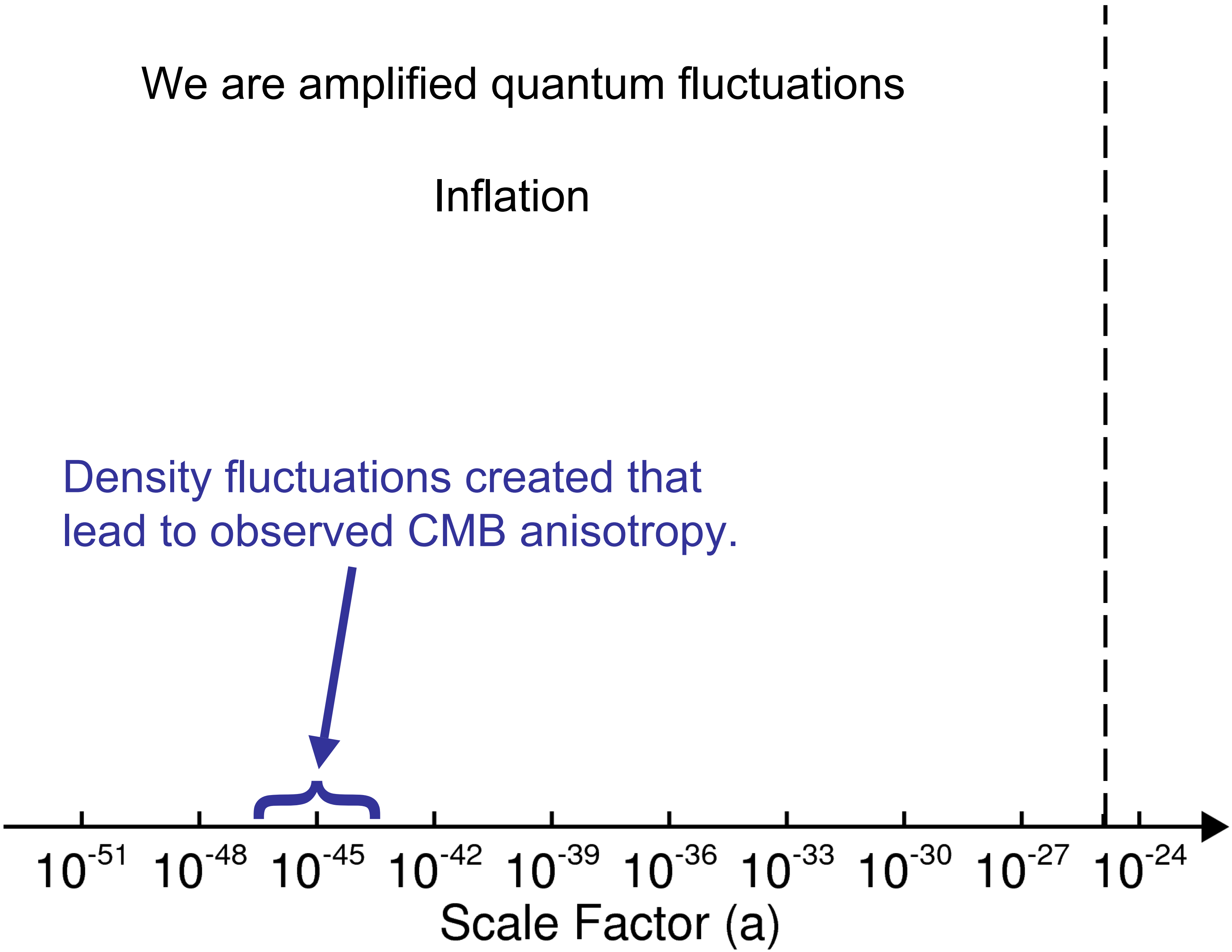
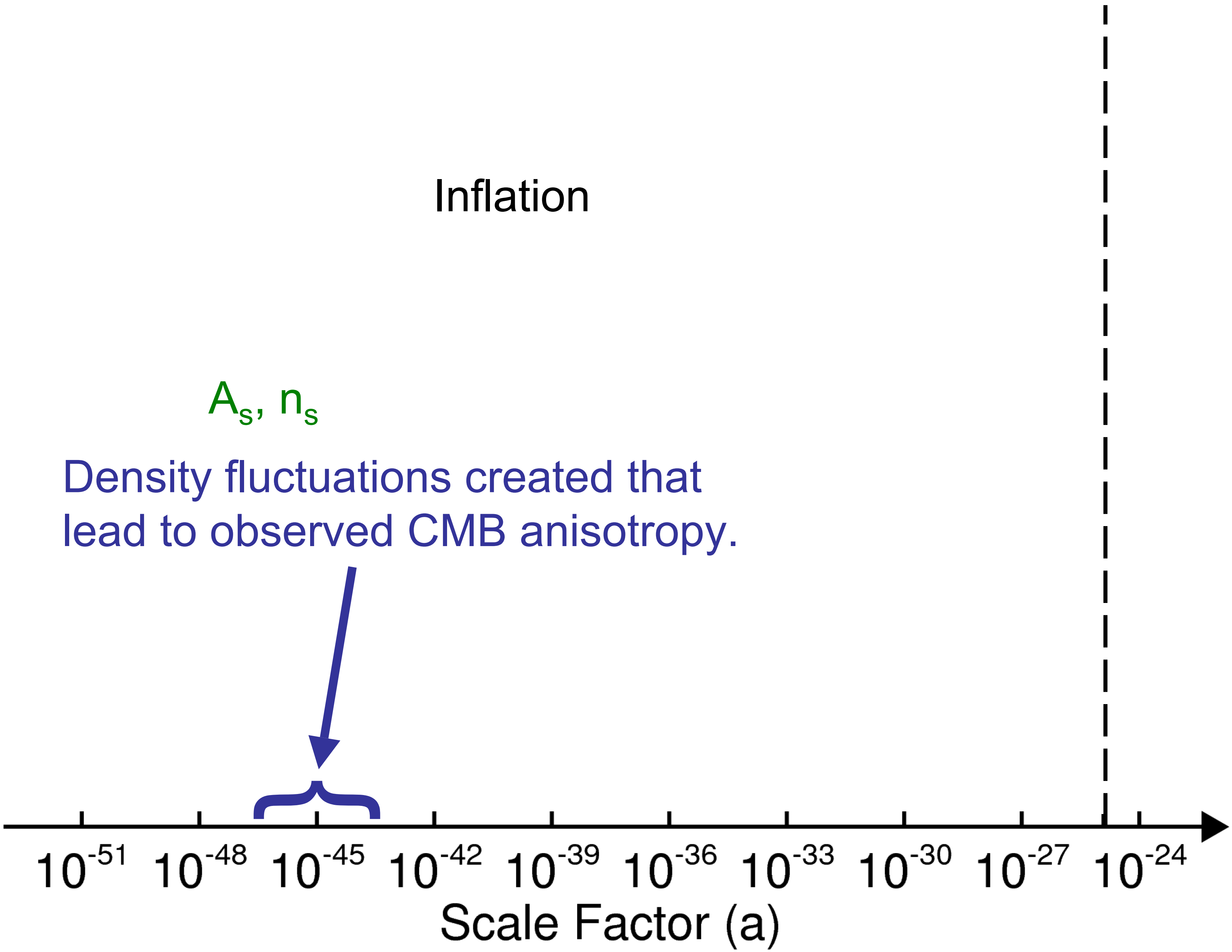
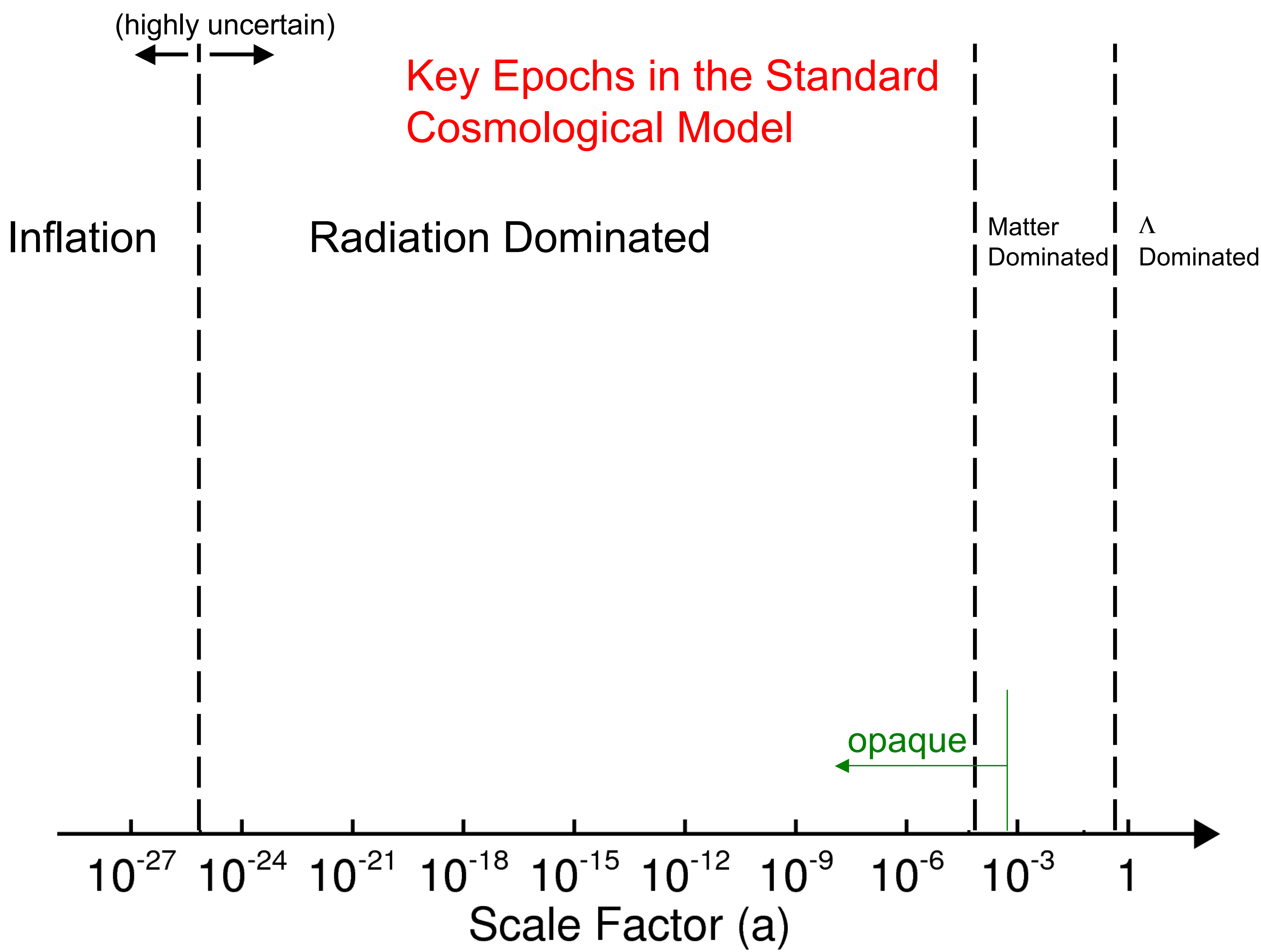

Inflation
10-51 10-48 10-45 10-42 10-39 10-36 10-33 10-30 10-27 10-24
Scale Factor (a)

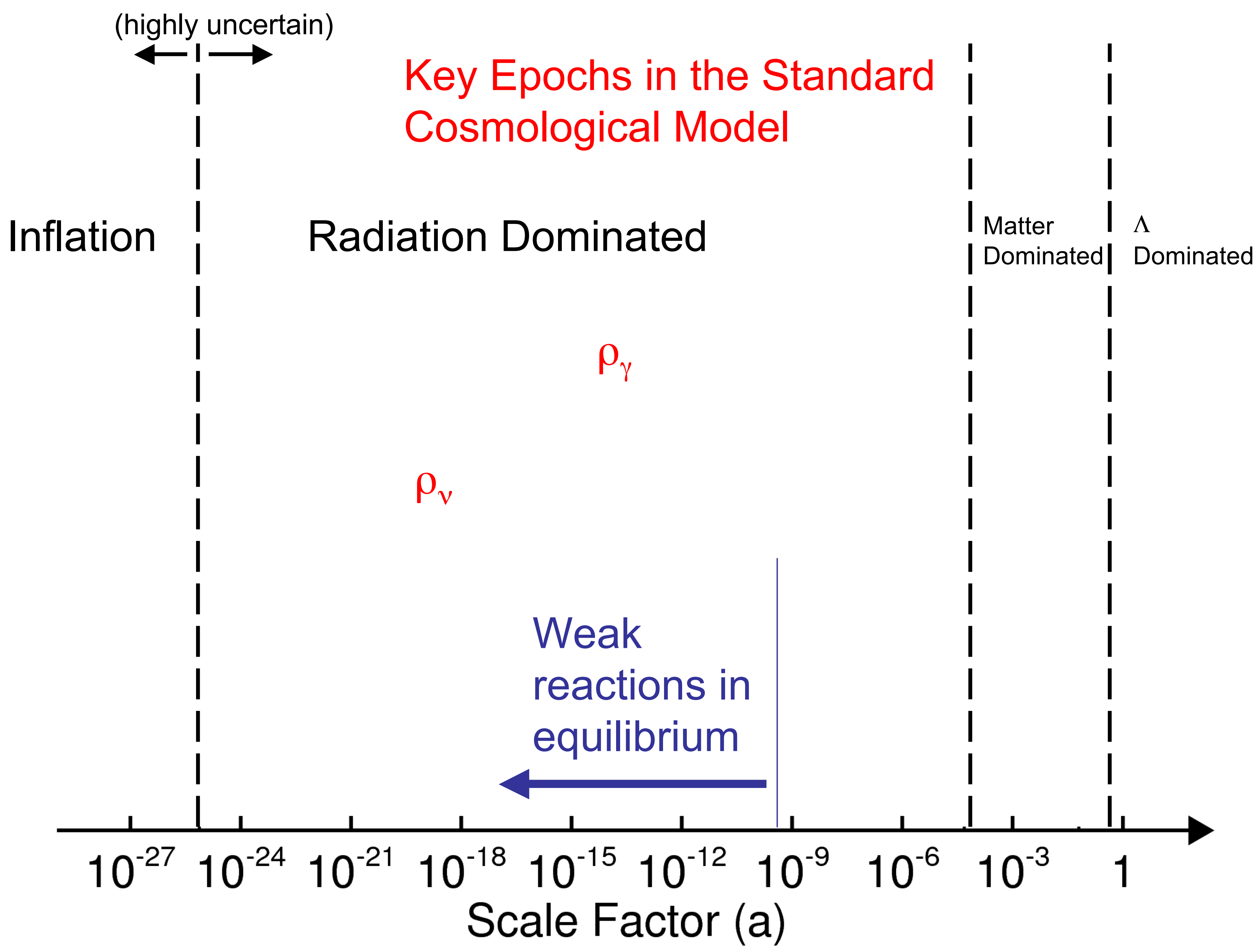

Inflation
Density fluctuations created that lead to observed CMB anisotropy.
10^-51 10^-48 10^-45 10^-42 10^-39 10^-36 10^-33 10^-30 10^-27 10^-24
Scale Factor (a)

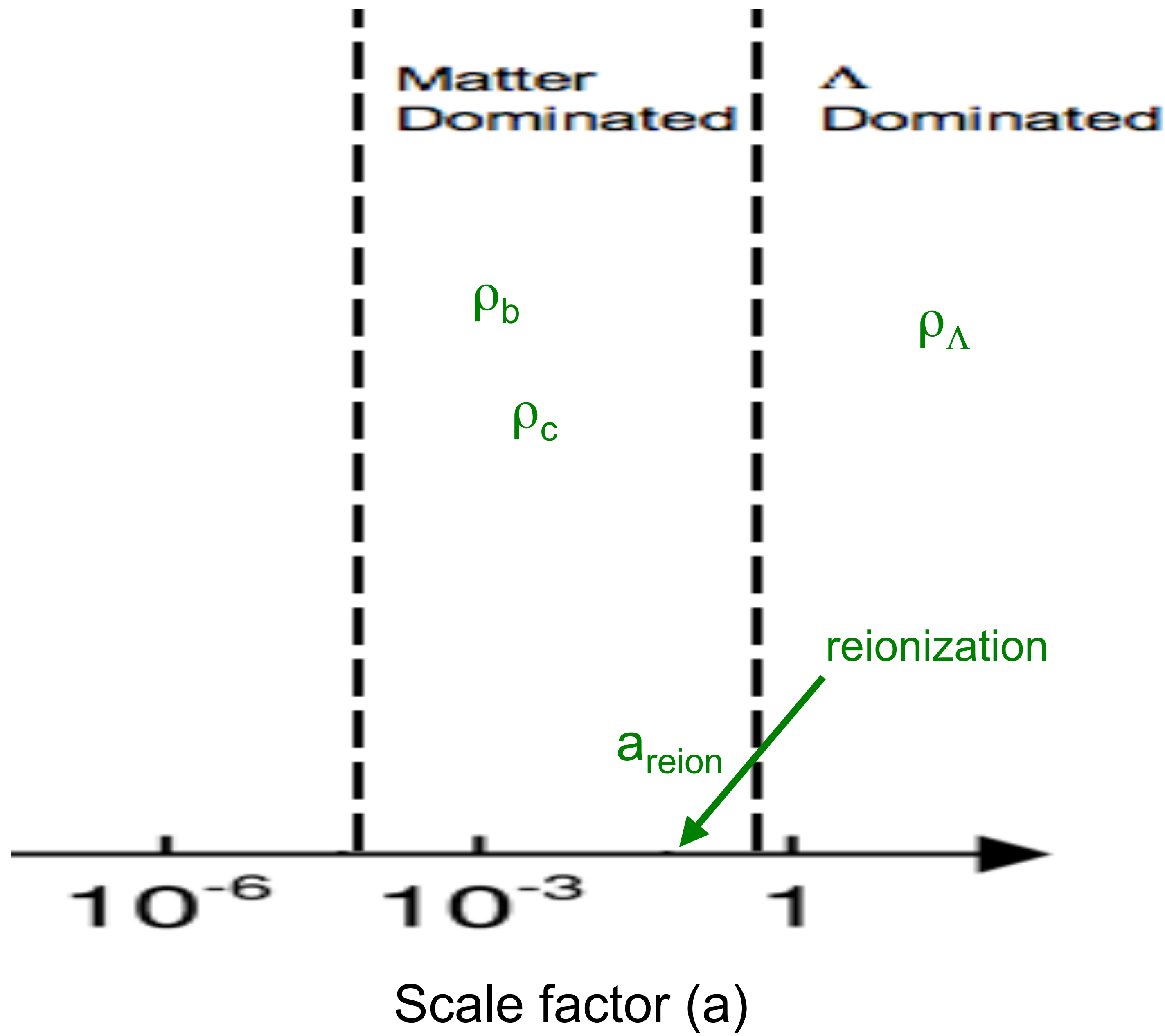

We are amplified quantum fluctuations
Inflation
Density fluctuations created that
lead to observed CMB anisotropy.
10^-51 10^-48 10^-45 10^-42 10^-39 10^-36 10^-33 10^-30 10^-27 10^-24
Scale Factor (a)



Inflation
A_s, n_s
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)


(highly uncertain)
Key Epochs in the Standard Cosmological Model
Inflation
Radiation Dominated
Matter Dominated
Λ Dominated
opaque
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
ρ_γ
ρ_ν
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)


Matter
Dominated
Λ
Dominated
ρ_b
ρ_c
ρ_Λ
reionization
a_{reion}
10^{-6}
10^{-3}
1
Scale factor (a)

The six-parameter ΛCDM model

A_s, n_s

Governs Spectrum of Primordial fluctuations

ρ_b ρ_Λ ρ_c

Matter Content

a_{reion}

Scale factor at reionization

The six-parameter ΛCDM model

A_s, n_s

Governs Spectrum of Primordial fluctuations

$\rho_b = \Omega_b h^2$

$\rho_\Lambda = \Omega_\Lambda h^2$

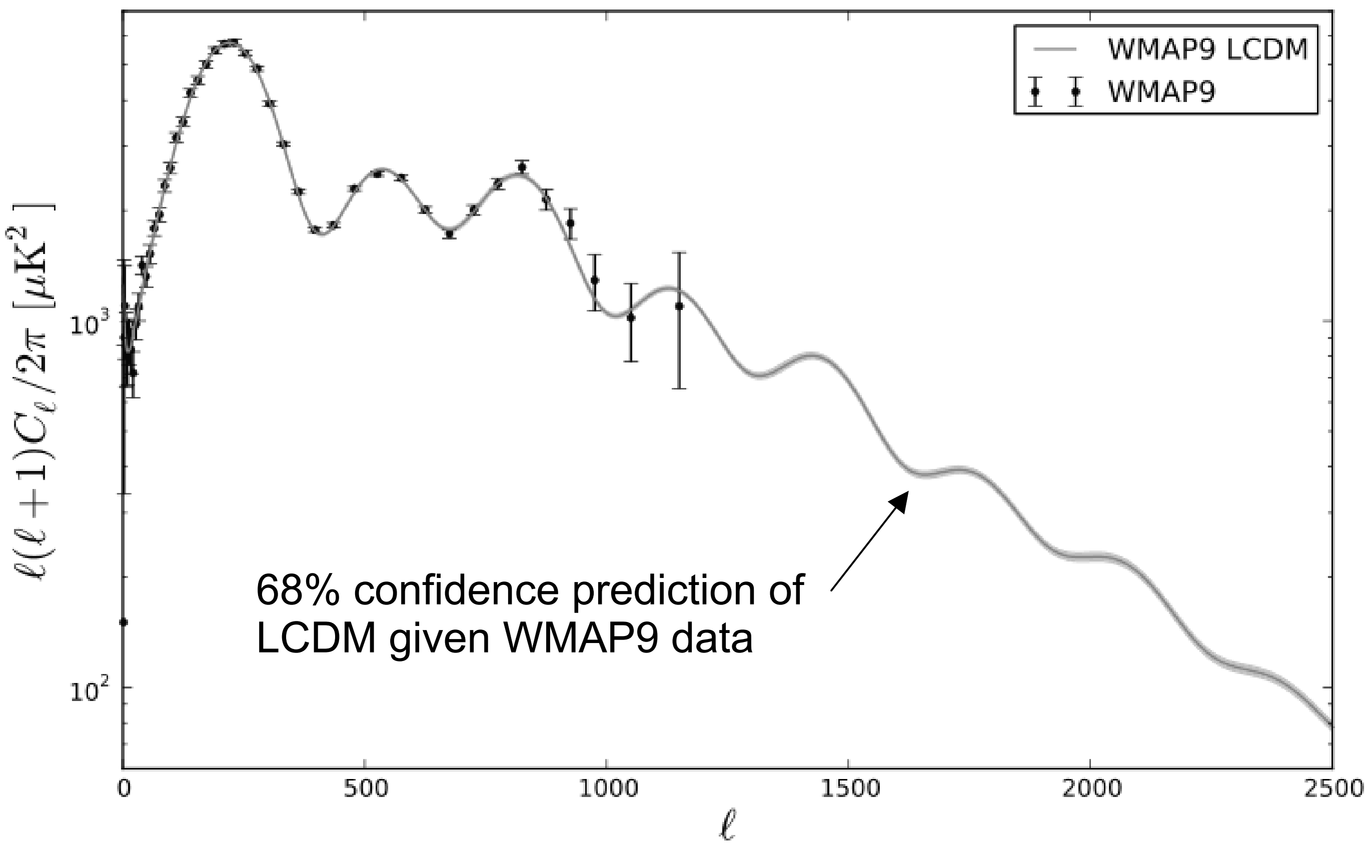
$\rho_c = \Omega_c h^2$

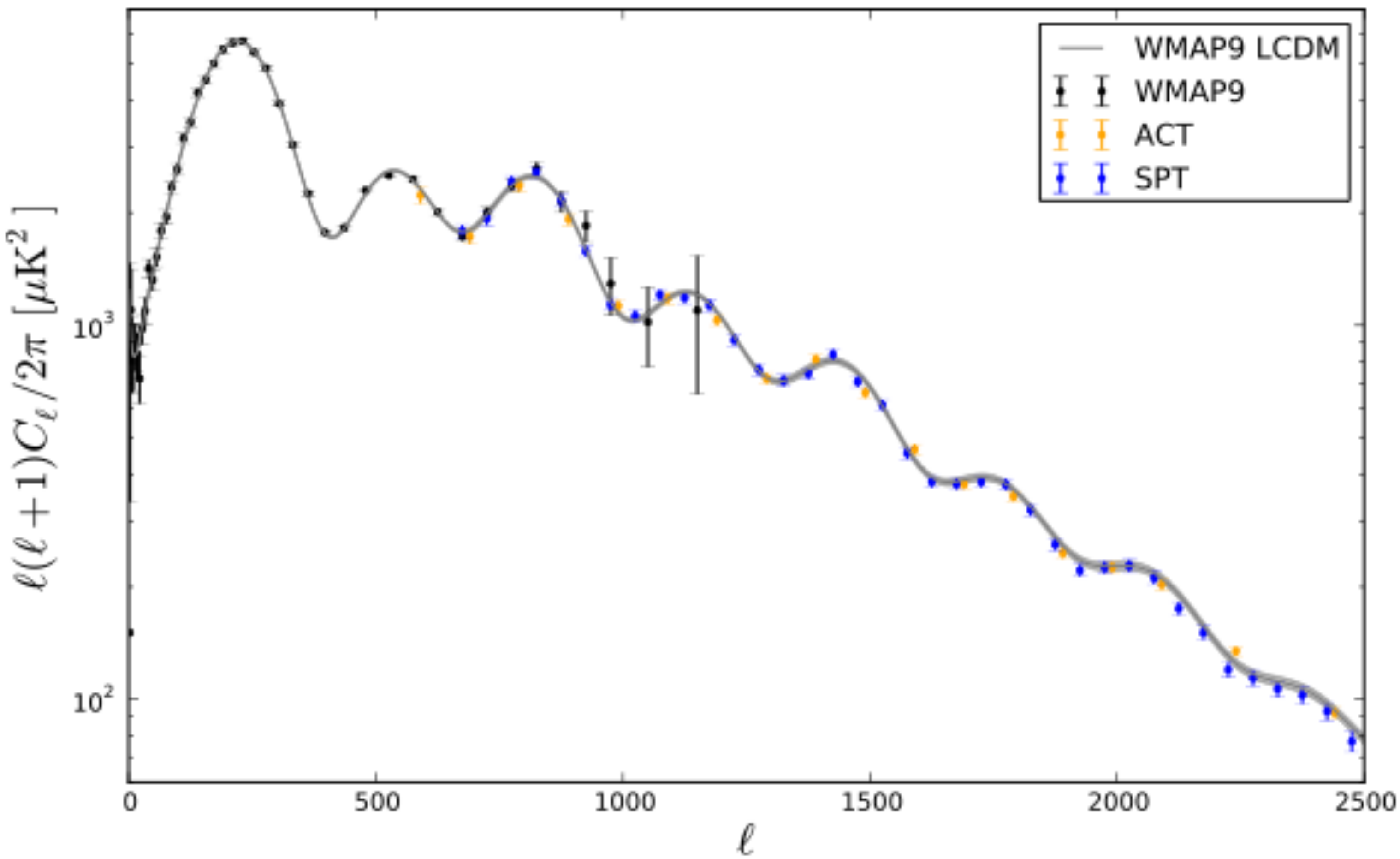
Matter Content

a_{reion}

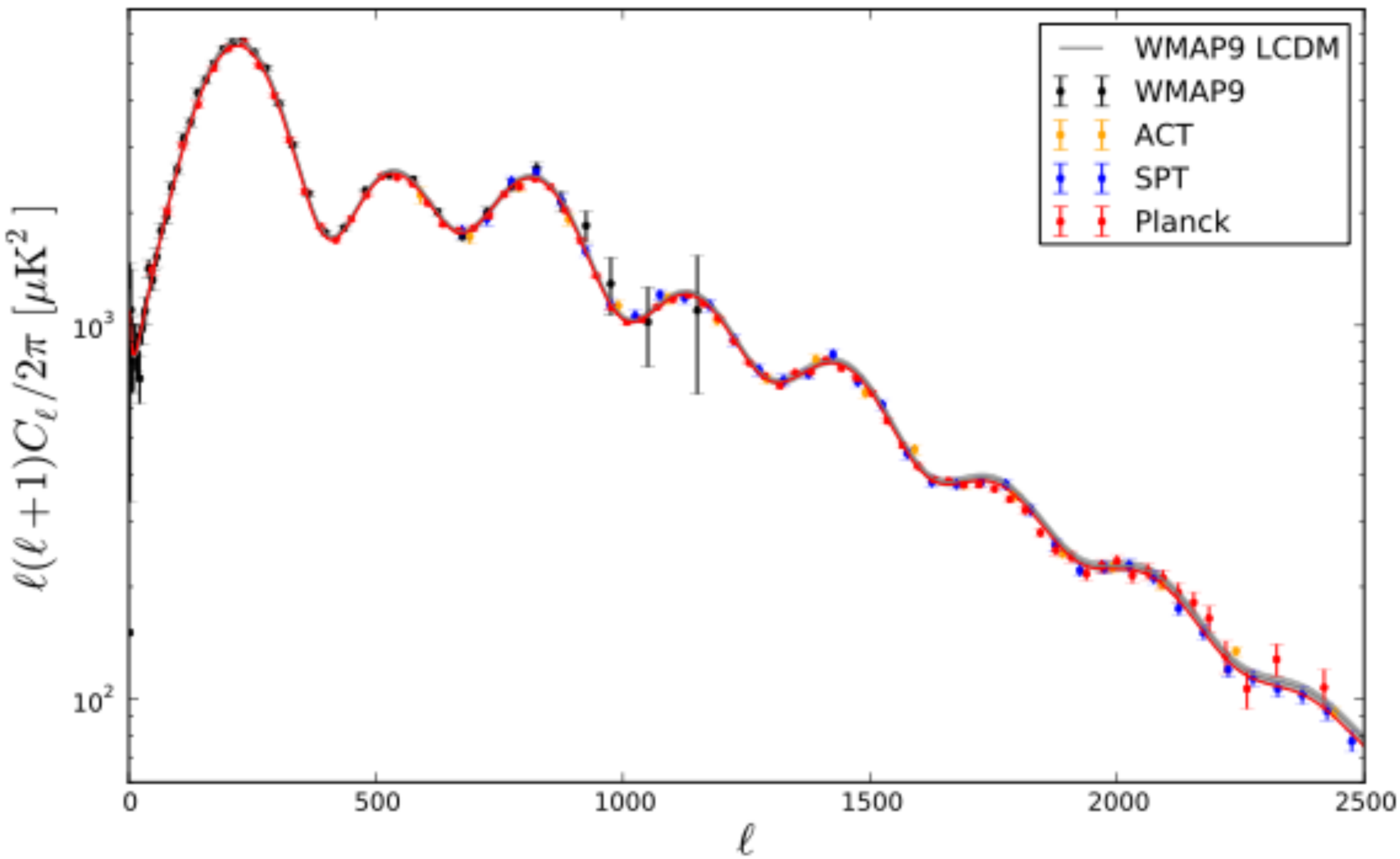
Scale factor at reionization

LCDM makes a very precise prediction



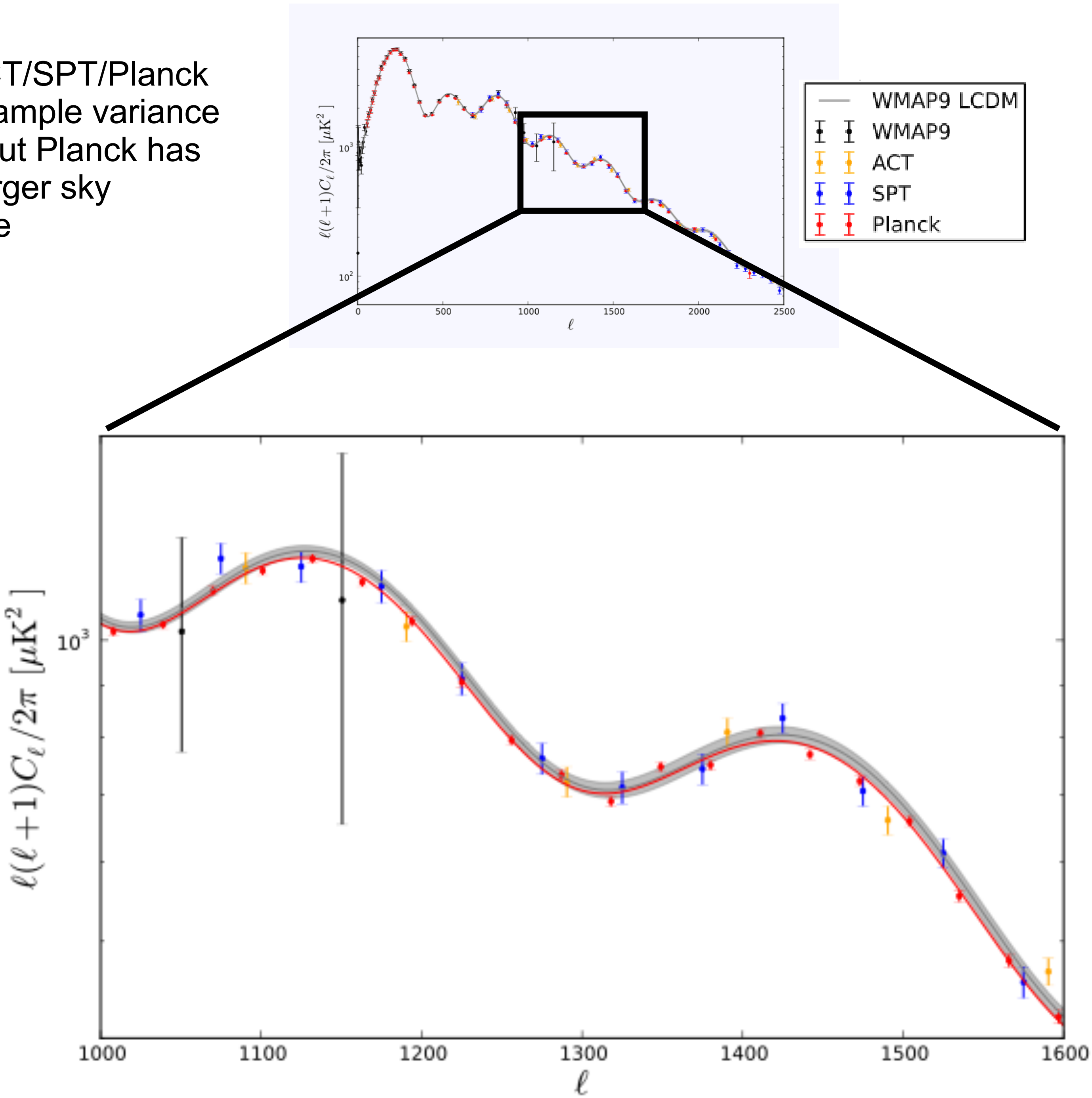


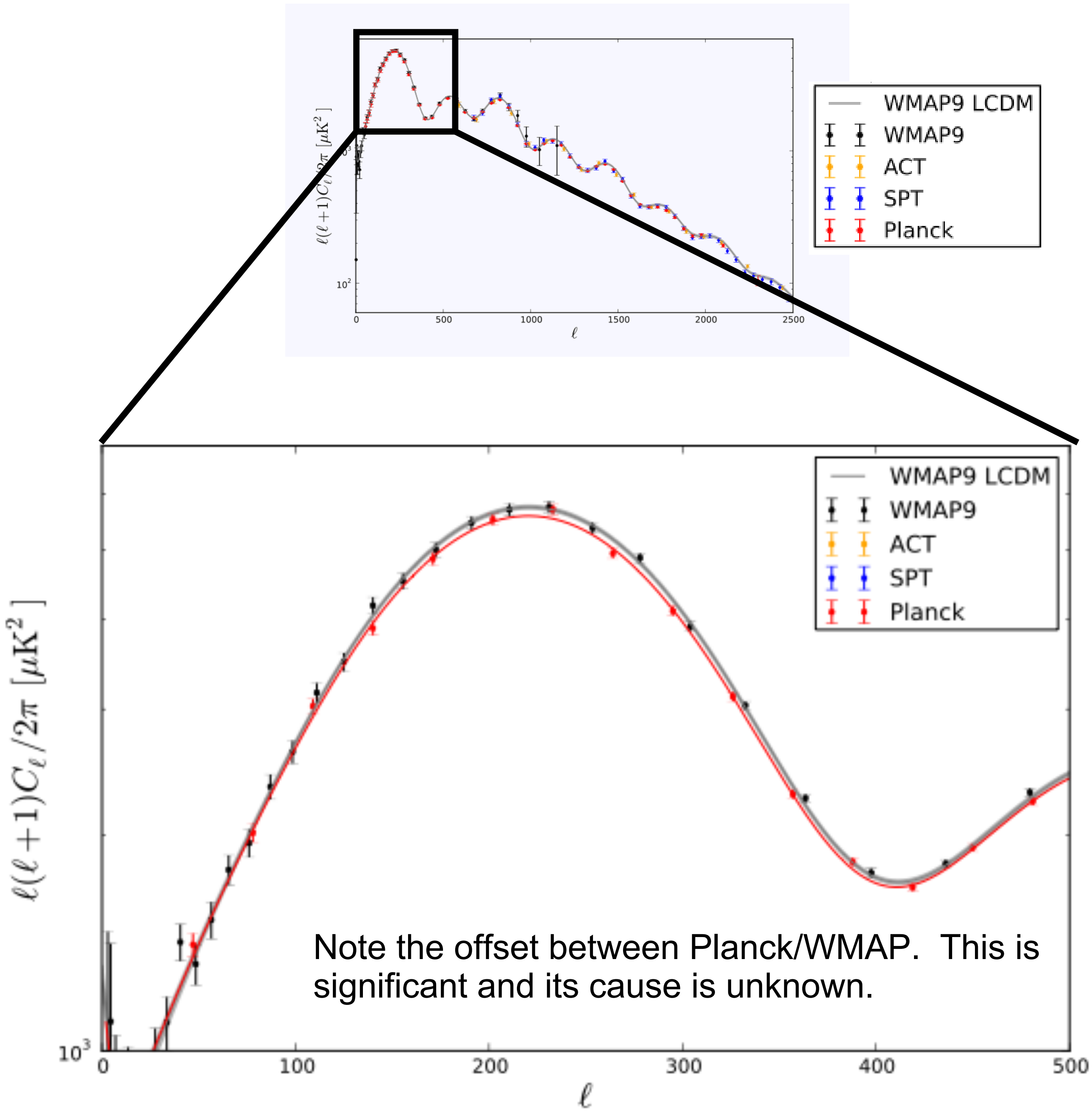
WMAP9 LCDM
WMAP9
ACT
SPT
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ

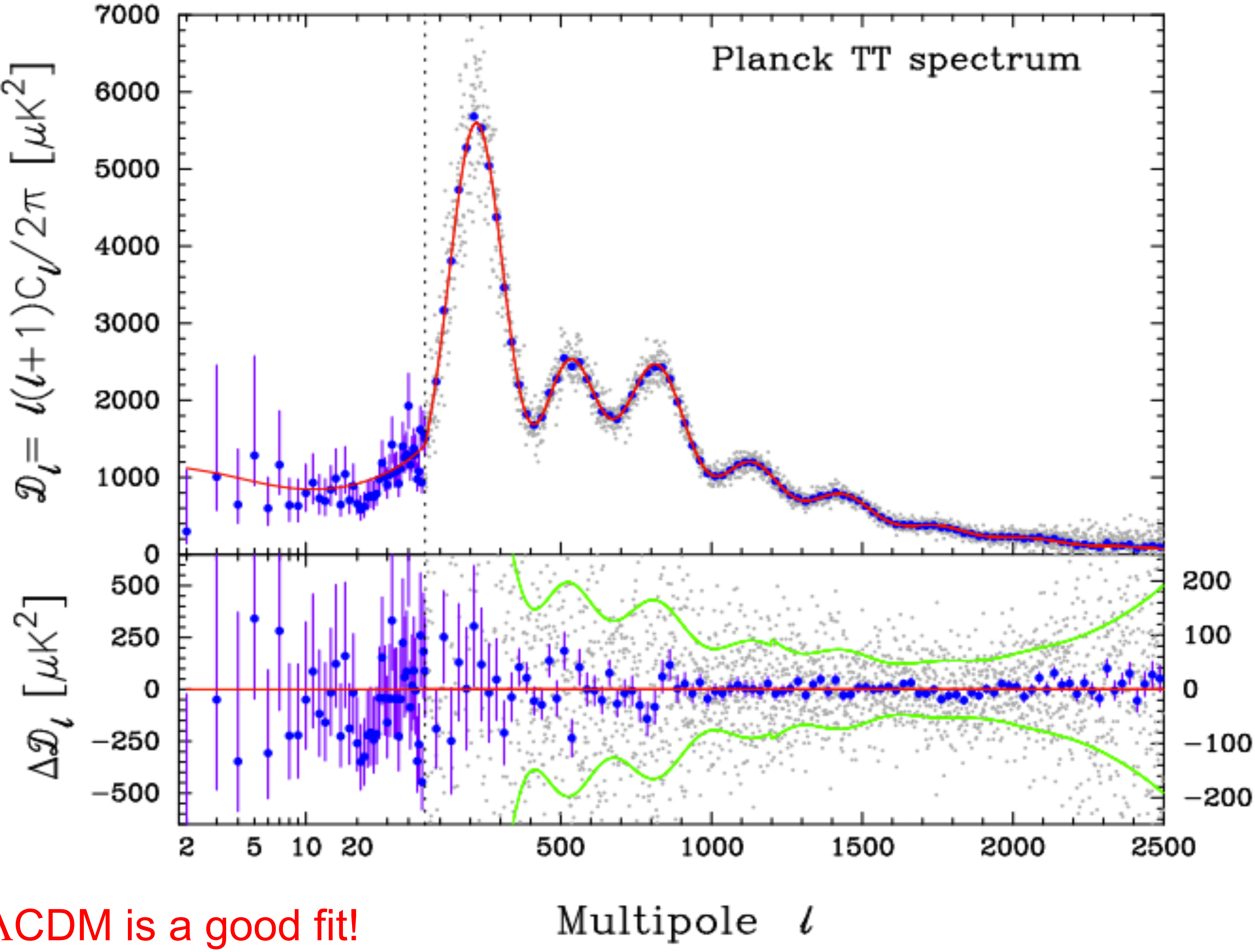


WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ

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



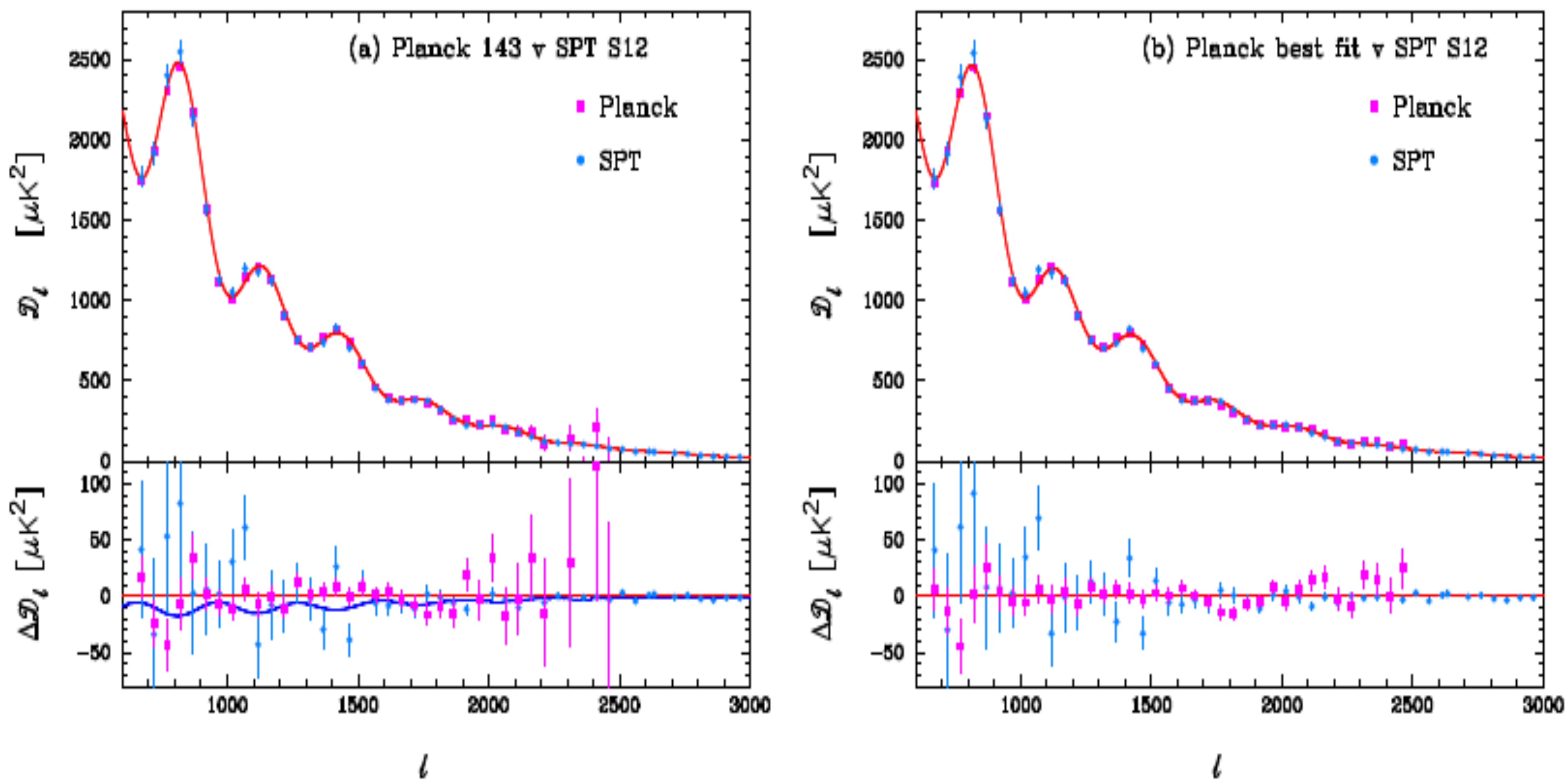

WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
ℓ
Note the offset between Planck/WMAP. This is significant and its cause is unknown.



ΛCDM is a good fit!

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

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
- Some details that are not required for a good fit, but make a difference in our parameter estimates:
  - Non-linear corrections to gravitational lensing influence
  - Neutrino masses (Setting Σm_ν = 0.06 eV instead of 0 eV shifts H_0 down by 0.6 km/sec/Mpc = $\sigma/2$)

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All Aspects of Cosmology are Touched by the Planck Results

Observation-related Examples:

- BAO-determined distance-redshift relation
- SDSS matter power spectrum
- Deep Lens Survey cosmic shear power spectrum

} Consistent*

- Cepheids + SNe for determining H_0
- CFHTLS cosmic shear power spectrum

} Some tension*

*Assuming the ΛCDM model

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Consistent*

Some tension*

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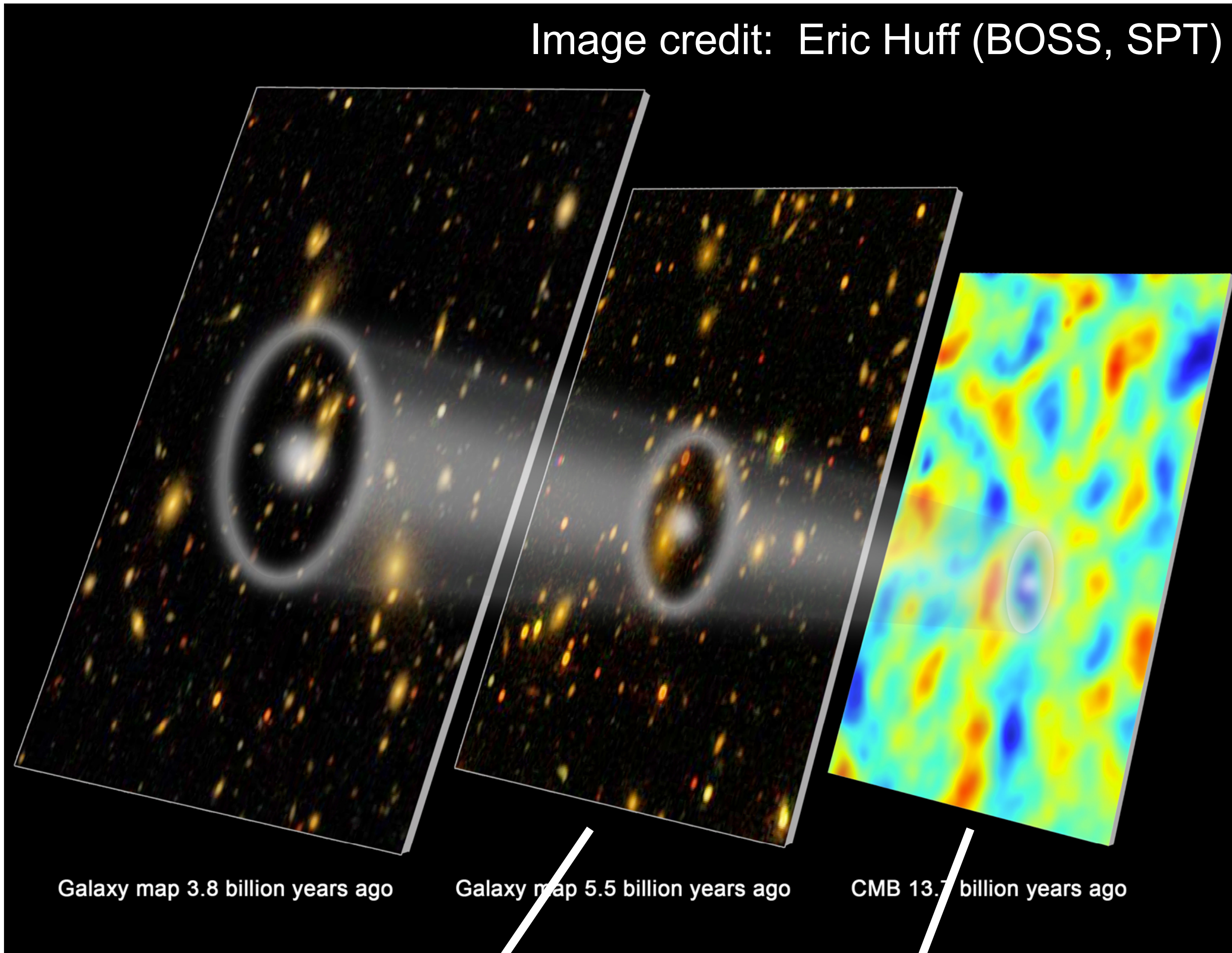


Planck:

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

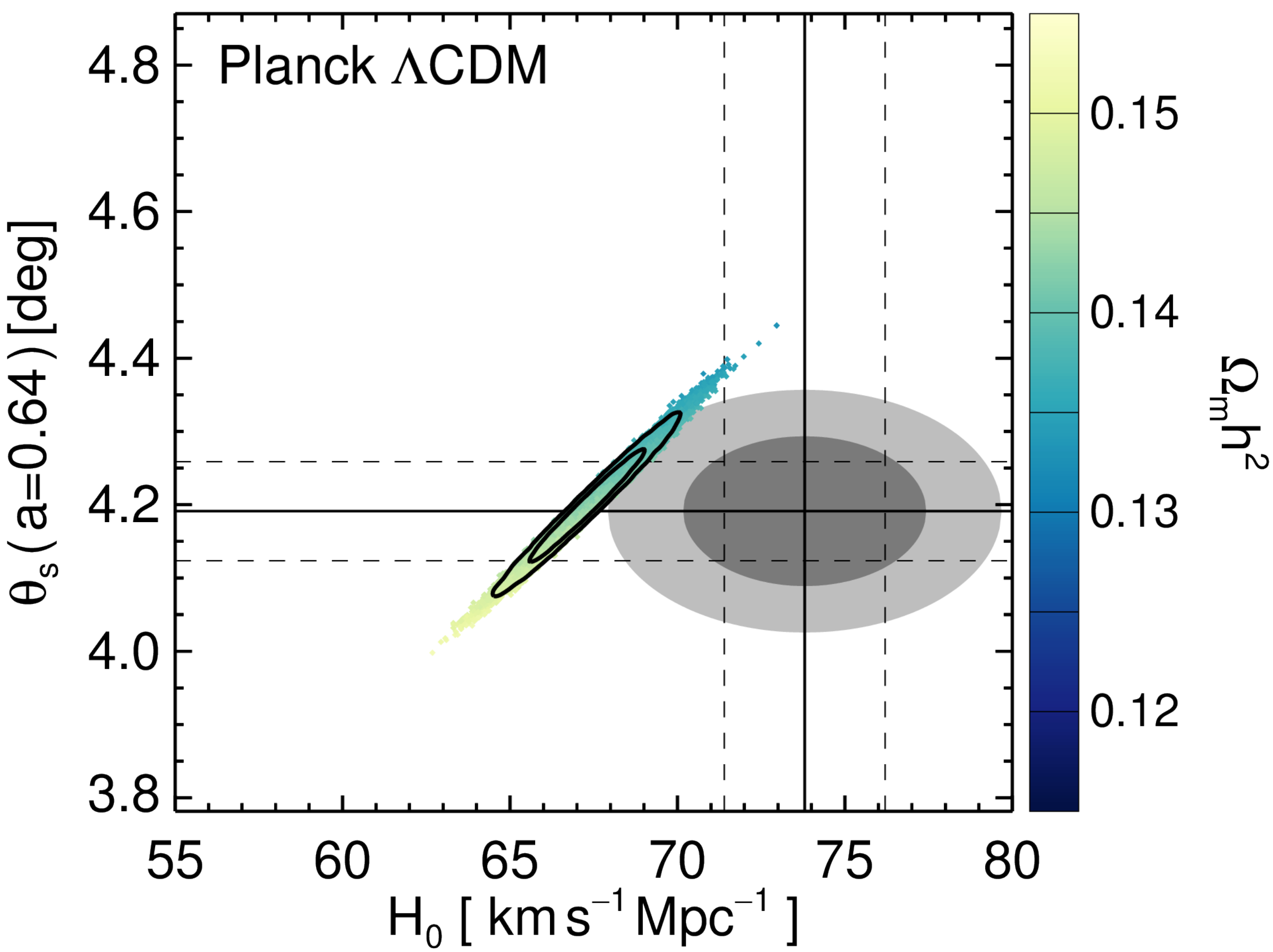
SDSS-BOSS:

$\theta_s(a=0.64) = (4.19 \pm .07)$ 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



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Universe Older, Wider Than Previously Thought

AMERICAN VOICES · Opinion · ISSUE 49·12 · Mar 22, 2013 149 85 4

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."

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

It has to do with gravitational lensing.

The Group H_0ug

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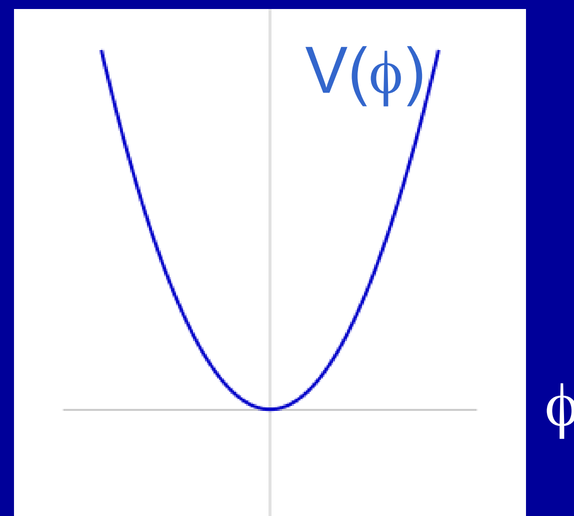
Simplest Models of Inflation Lead to Gaussian Perturbations

$\delta\rho = dV/d\phi \; \delta\phi$

Governed by a harmonic oscillator equation; wave function is a Gaussian.

So $\delta\rho$ is normally distributed.



But what about 2nd order term?

$\delta\rho = dV/d\phi \; \delta\phi + 1/2 \; d^2V/d\phi^2 \; \delta\phi^2$

Leads to non-Gaussian $\delta\rho$

In simplest models, 2nd order term must be negligibly small, or inflation will end prematurely ==> “single-field slow-roll models” produce neglible non-Gaussianity.

Parameterized phenomenological models for primordial non-Gaussianity

Assumed Gaussian gravitational potential perturbation

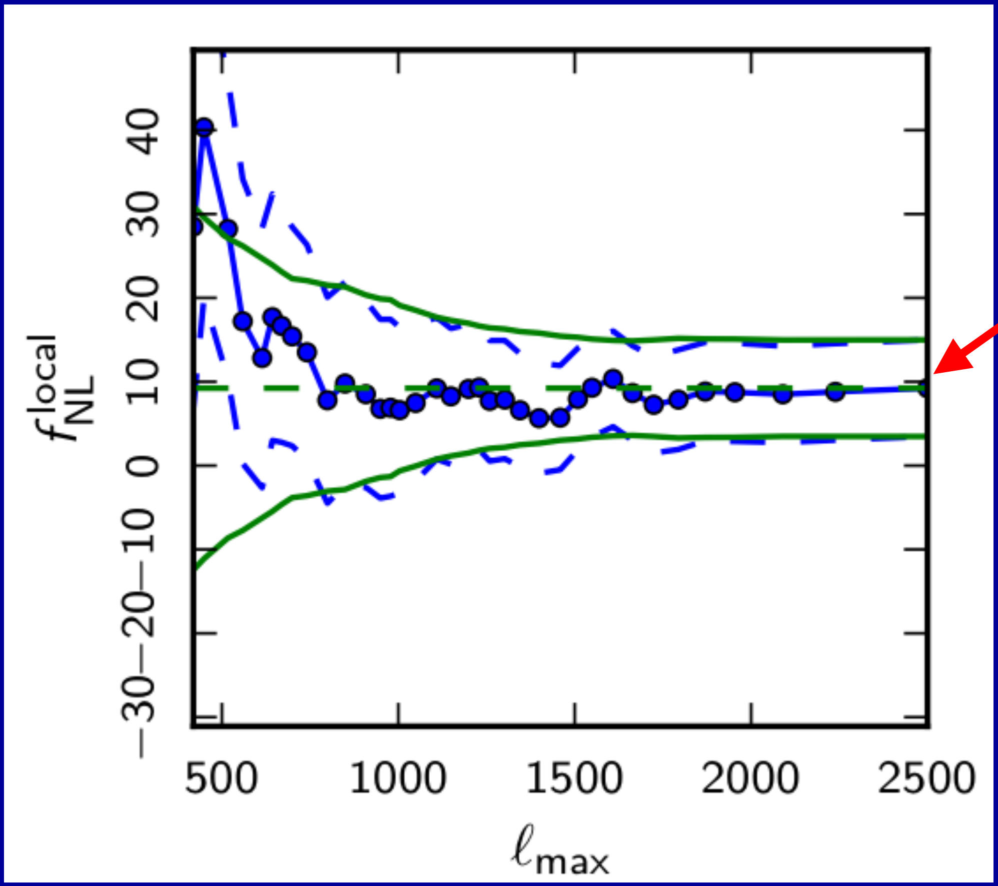
$$\Phi(x) = \Phi_G(x) + f_{NL} \left(\Phi_G^2(x) - \langle\Phi_G^2\rangle\right)$$

Actual gravitational potential perturbation

f_{NL} here is more specifically f_{NL}^{local}

No Primordial Non-Gaussianity, just as expected from "slow-roll" inflation

f_{NL}^{local} is a phenomenological measure of non-Gaussianity

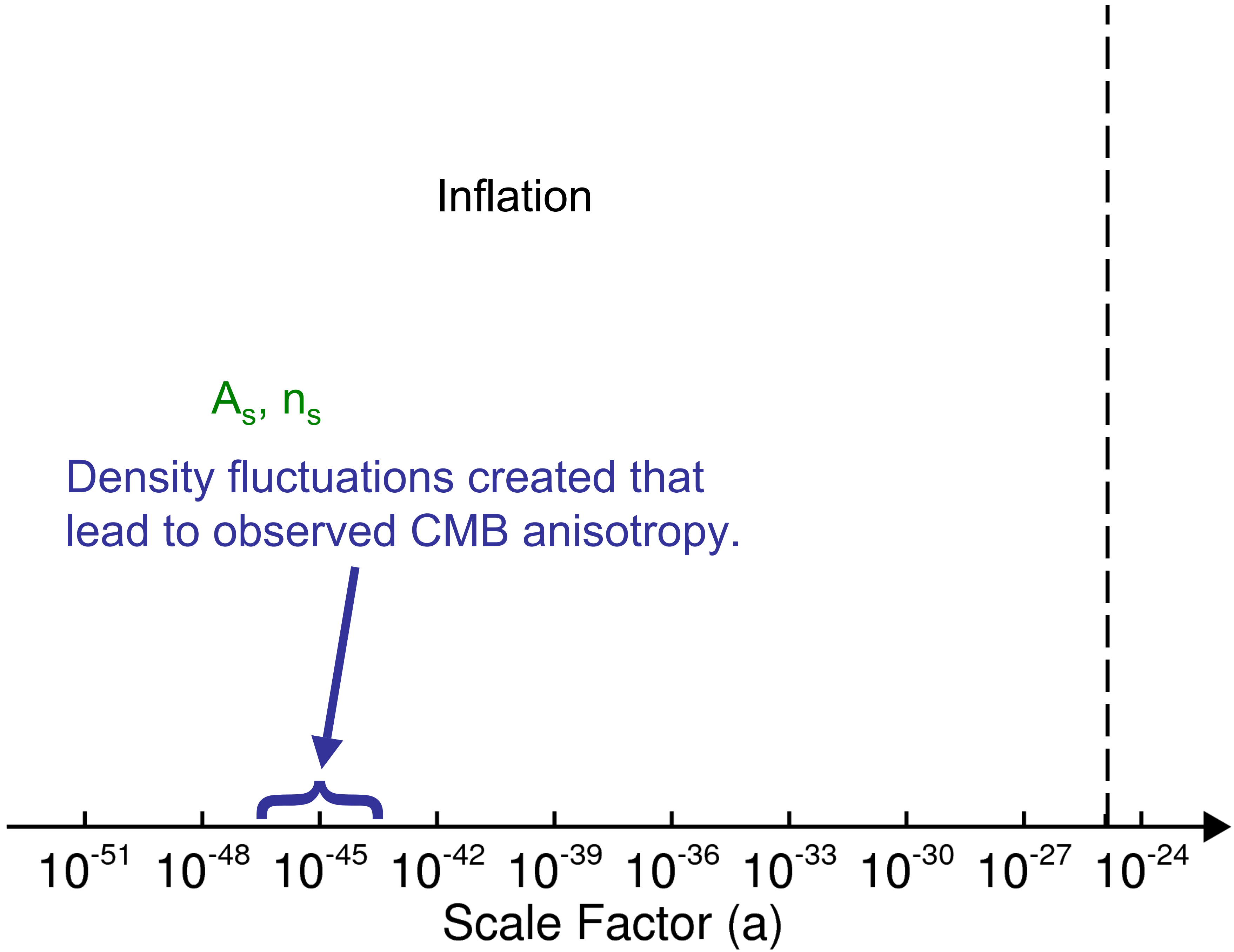


Non-zero!

But some signal expected due to a 2nd-order effect of late-time evolution (not primordial)

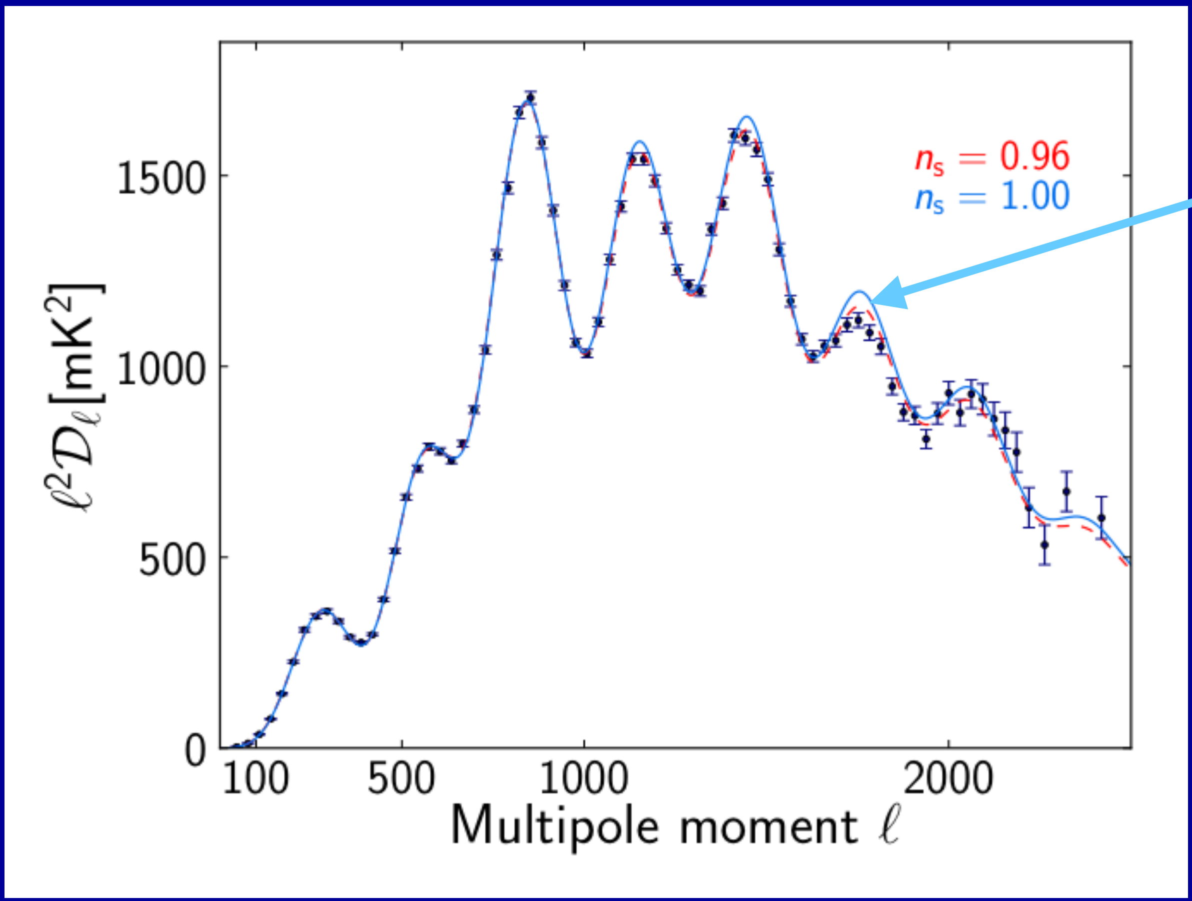
After subtraction of late-time effect:

f_{NL}^{local} = 2.7 +/- 5.8



Inflation
A_s, n_s
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)

> 5σ detection of scale dependence of primordial fluctuations ==> time dependence during inflation

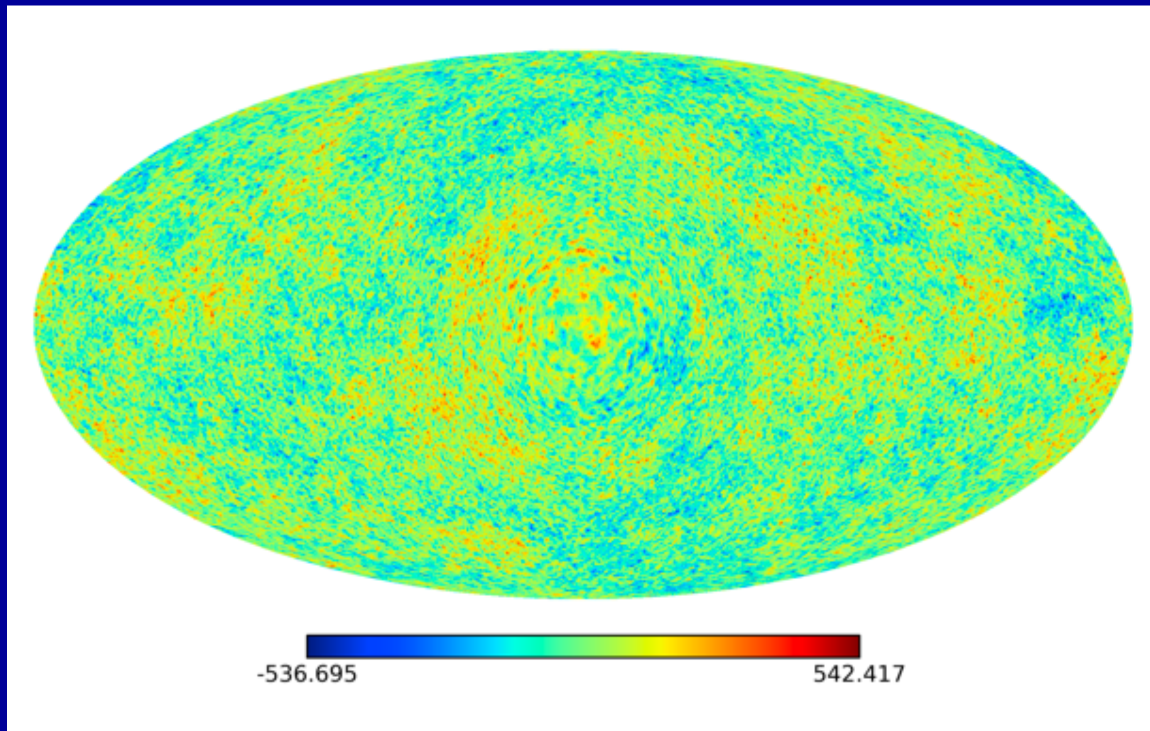


Best-fit scale-invariant (n_s =1) model

Outline

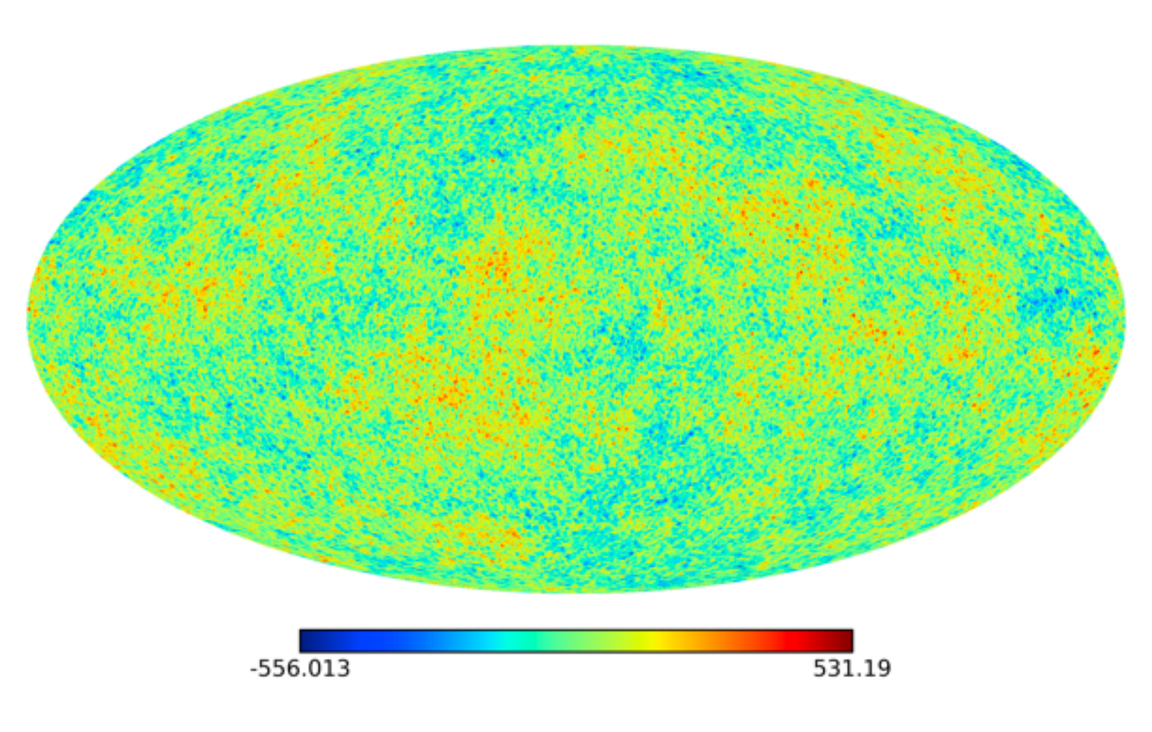
- Planck and the Planck maps
- Comparison with WMAP
- Comparison with SPT
- The power spectrum: ΛCDM, the standard model of cosmology, passes a precision test
- Consistency with Other Cosmological Probes
- Inflation (Gaussianity, scale dependence)
- Lensing (including new SPT result)
- Constraints on neutrinos (and other “dark radiation”)

Gravitational Lensing



- ACT detects lensing at 4σ.
- SPT detects lensing at 6σ.
- Planck detects lensing at 25σ.

Gravitational Lensing



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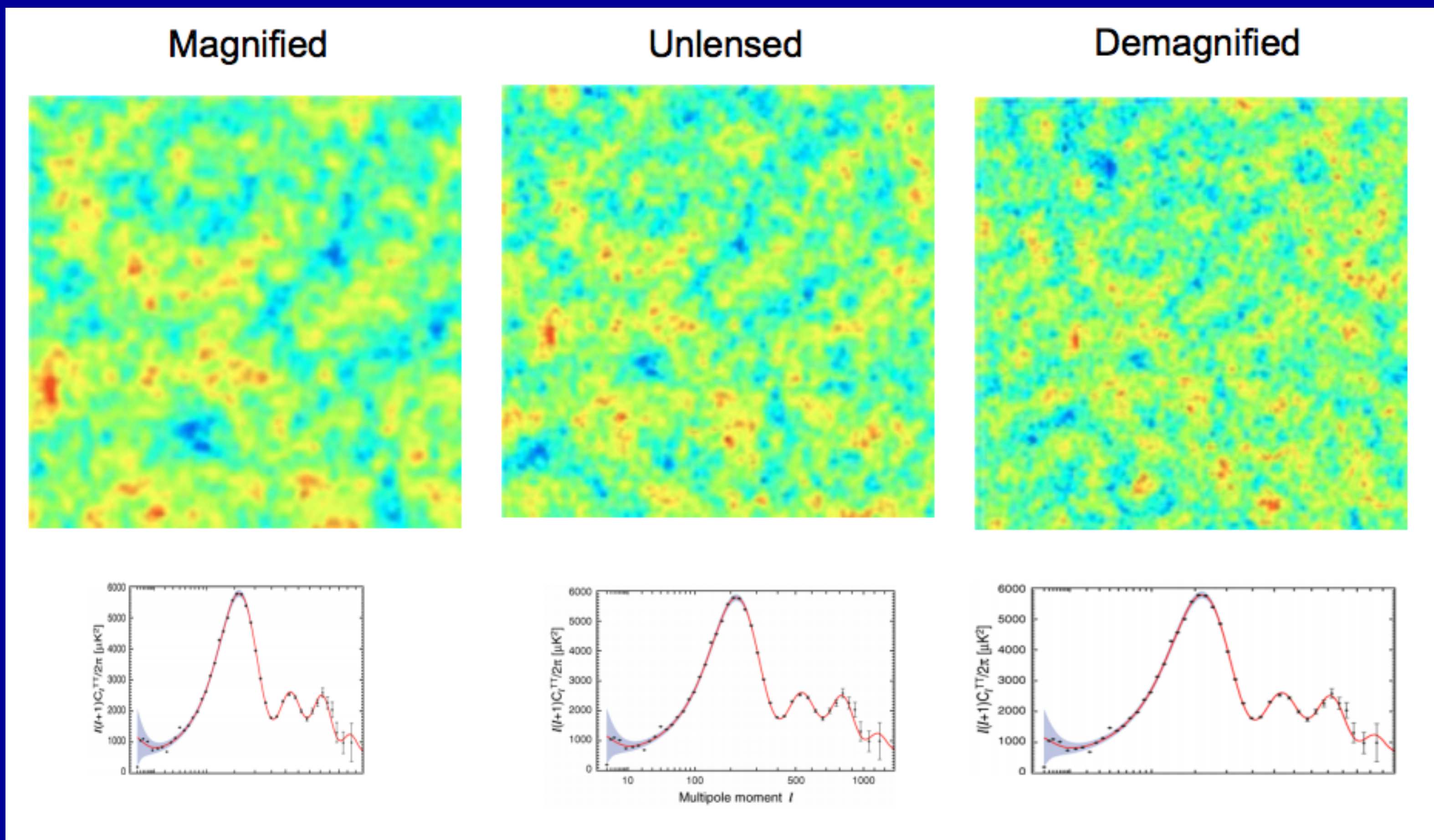
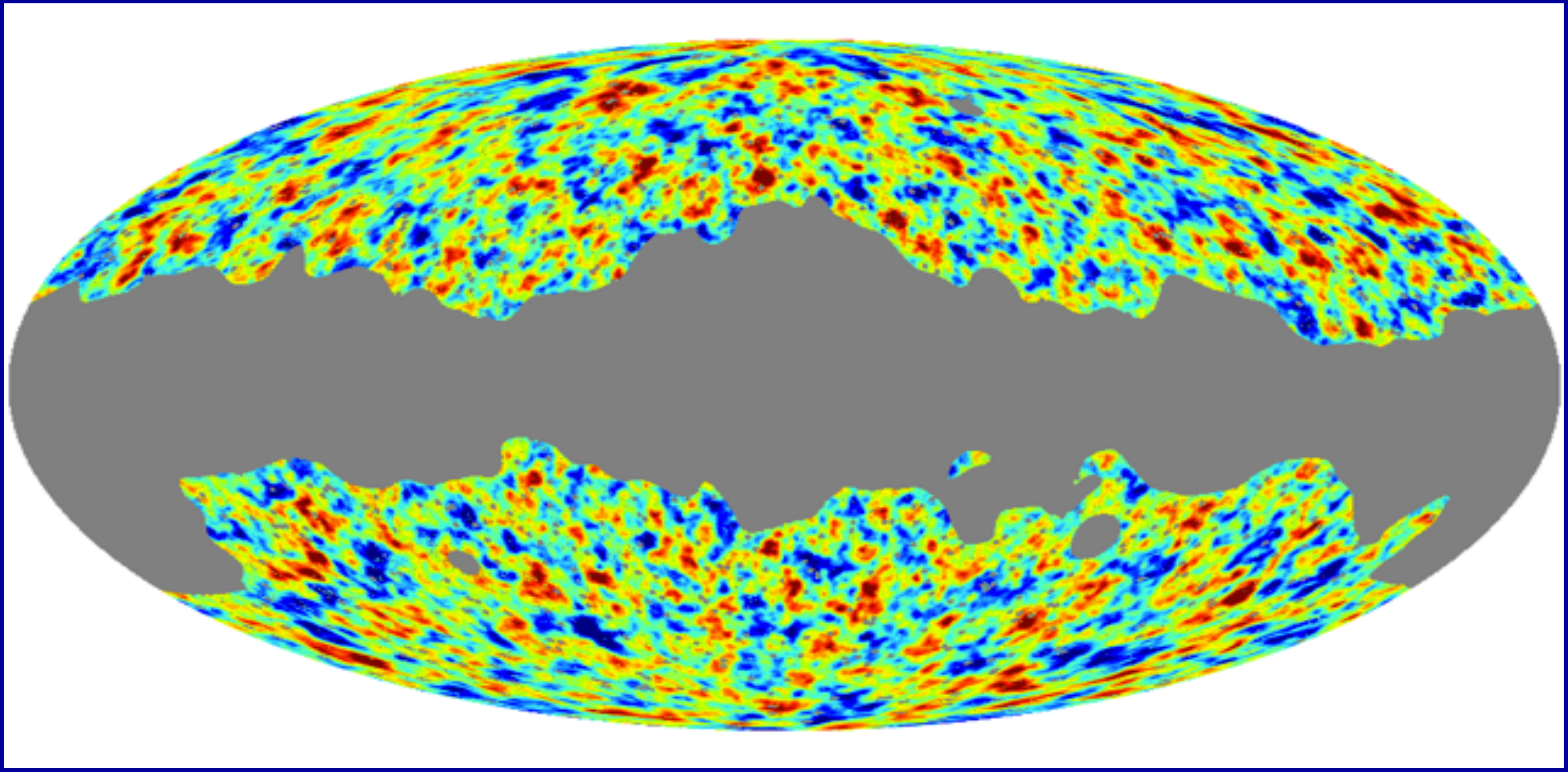
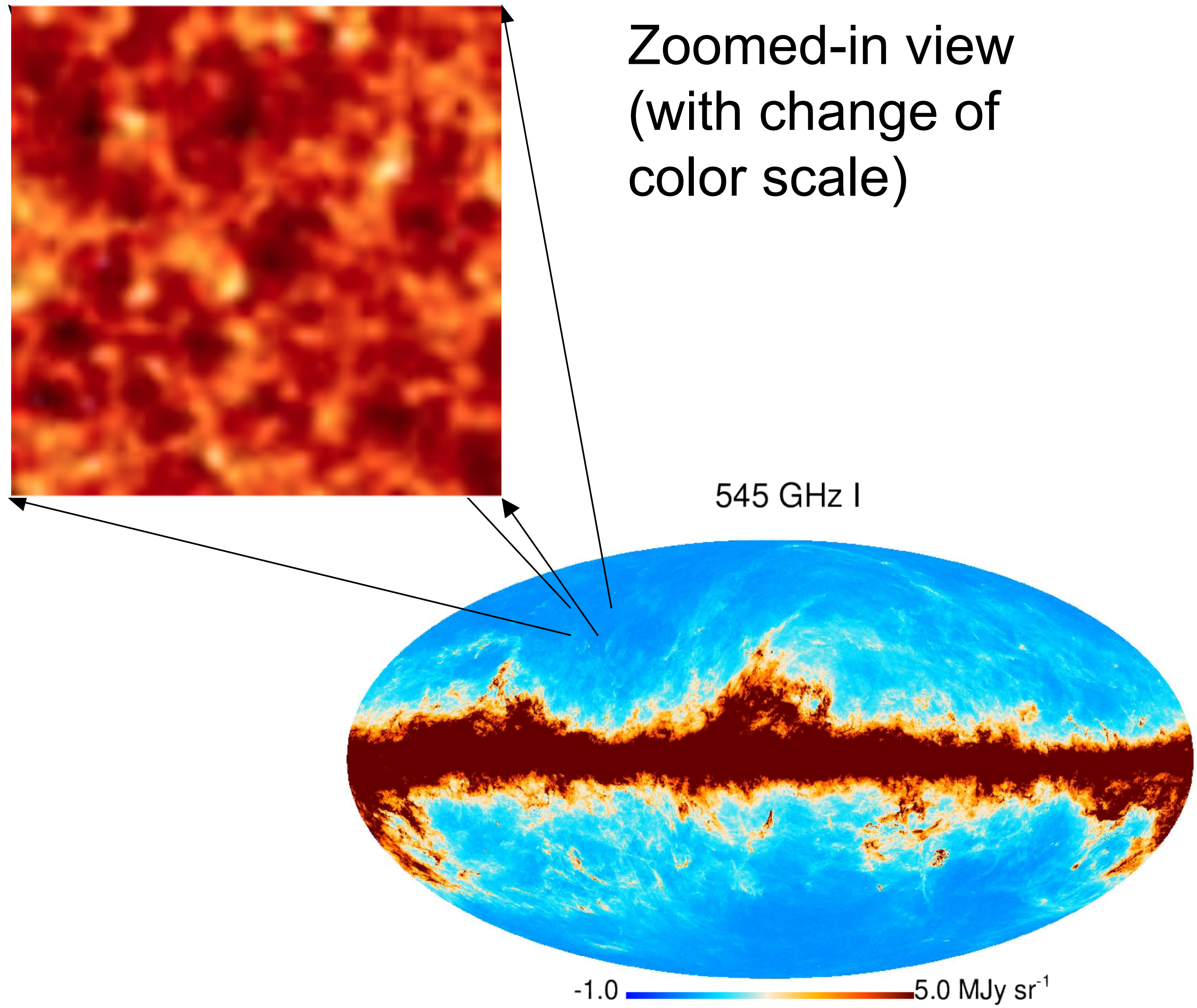

Magnified
Unlensed
Demagnified
Multipole moment l

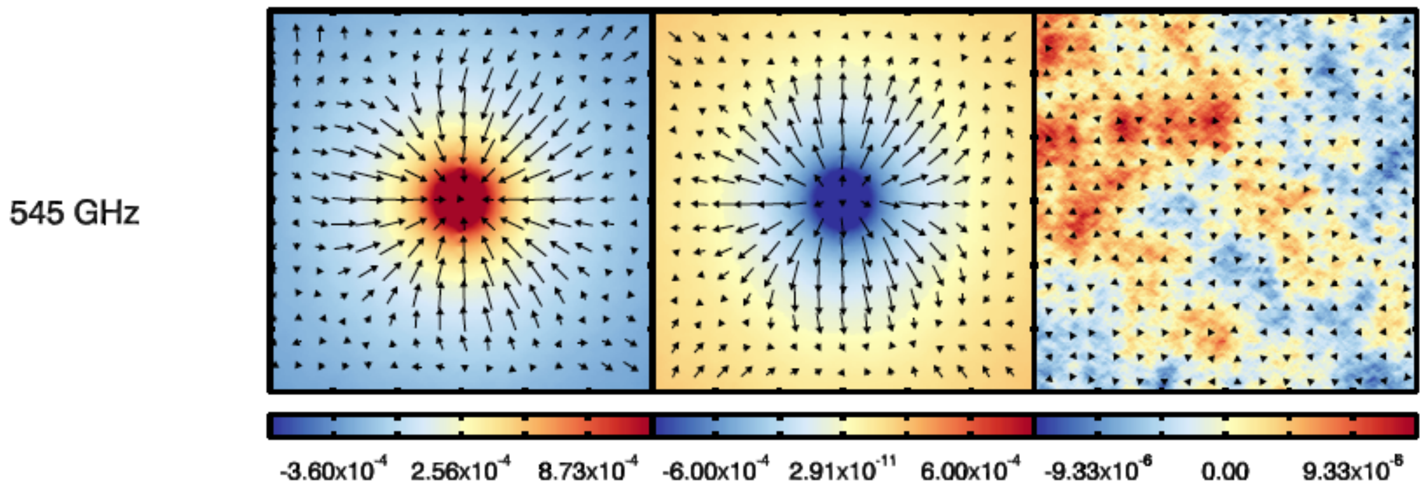
Map of Deflection amplitude





Another deep tracer of mass: the infrared background arising from all other galaxies on our past light cone also being filled with interstellar dust grains heated by starlight

The dusty star-forming galaxies that are the dominant sources of the infrared background trace the mass that lenses the microwave background*



Stacking on hot spots

Stacking on cold spots

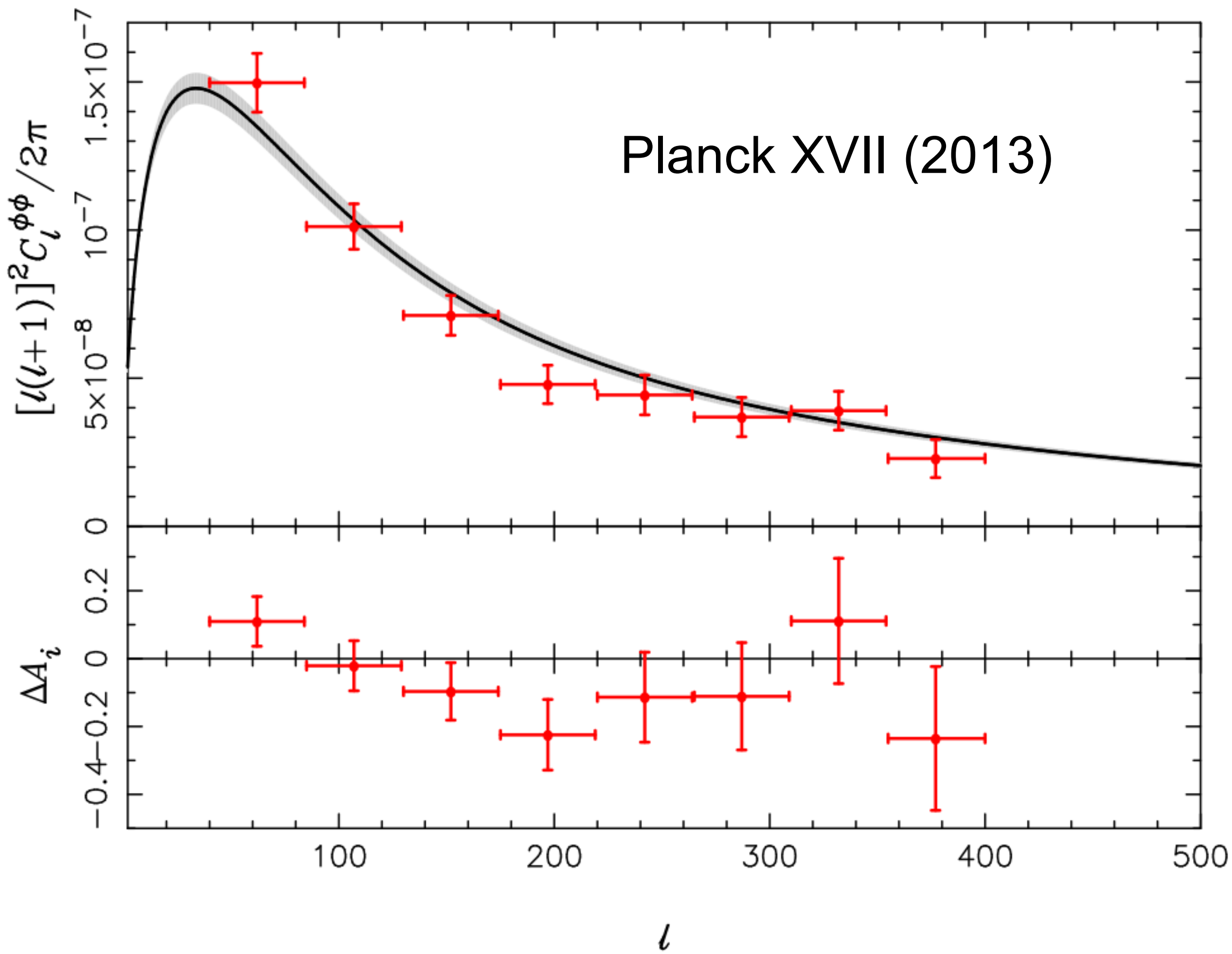
Stacking on random spots

Also seen in SPTxHerschel arXiv:1303.5048

*as predicted by Song et al. (2003)

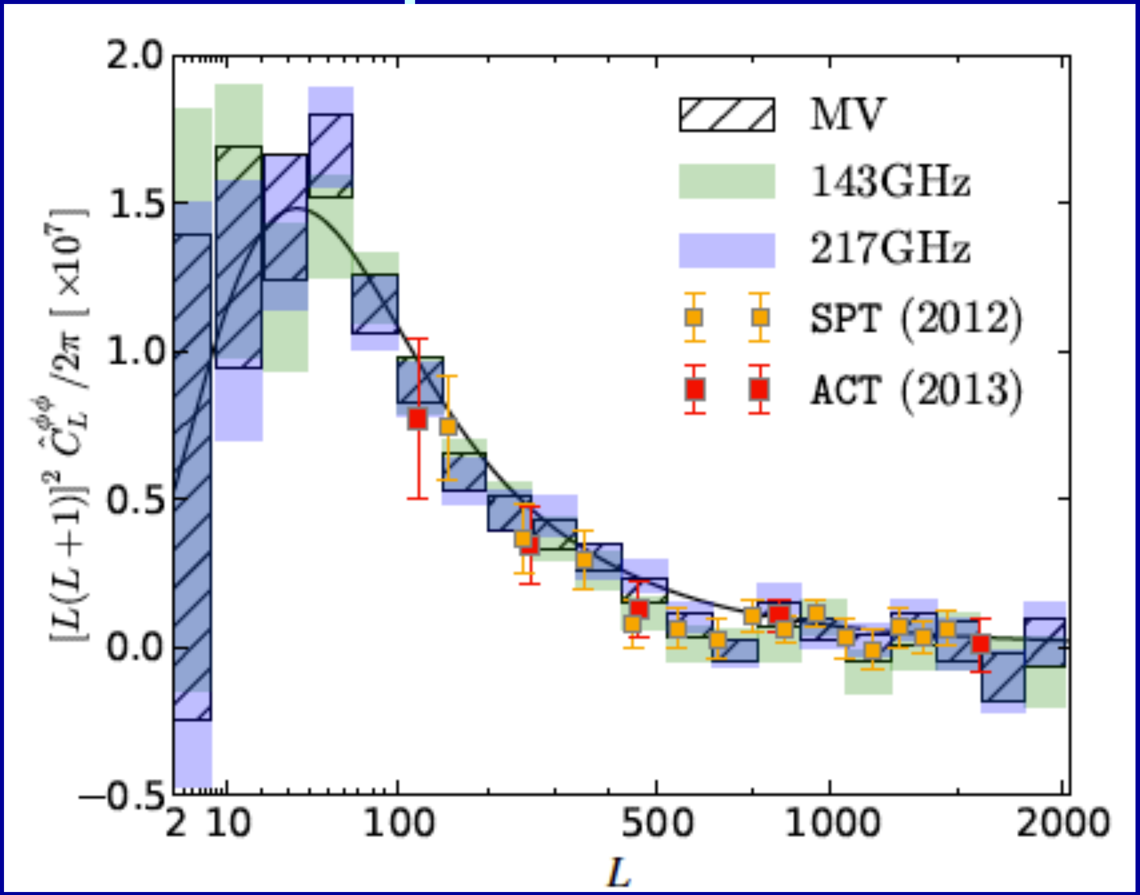
From peak location: Deflections correlated across $\pi/60$ = 3 deg

From peak amplitude: typical angle ~ $(1.5 \times 10^{-7})^{1/2}$ = .0004 = 1.4'



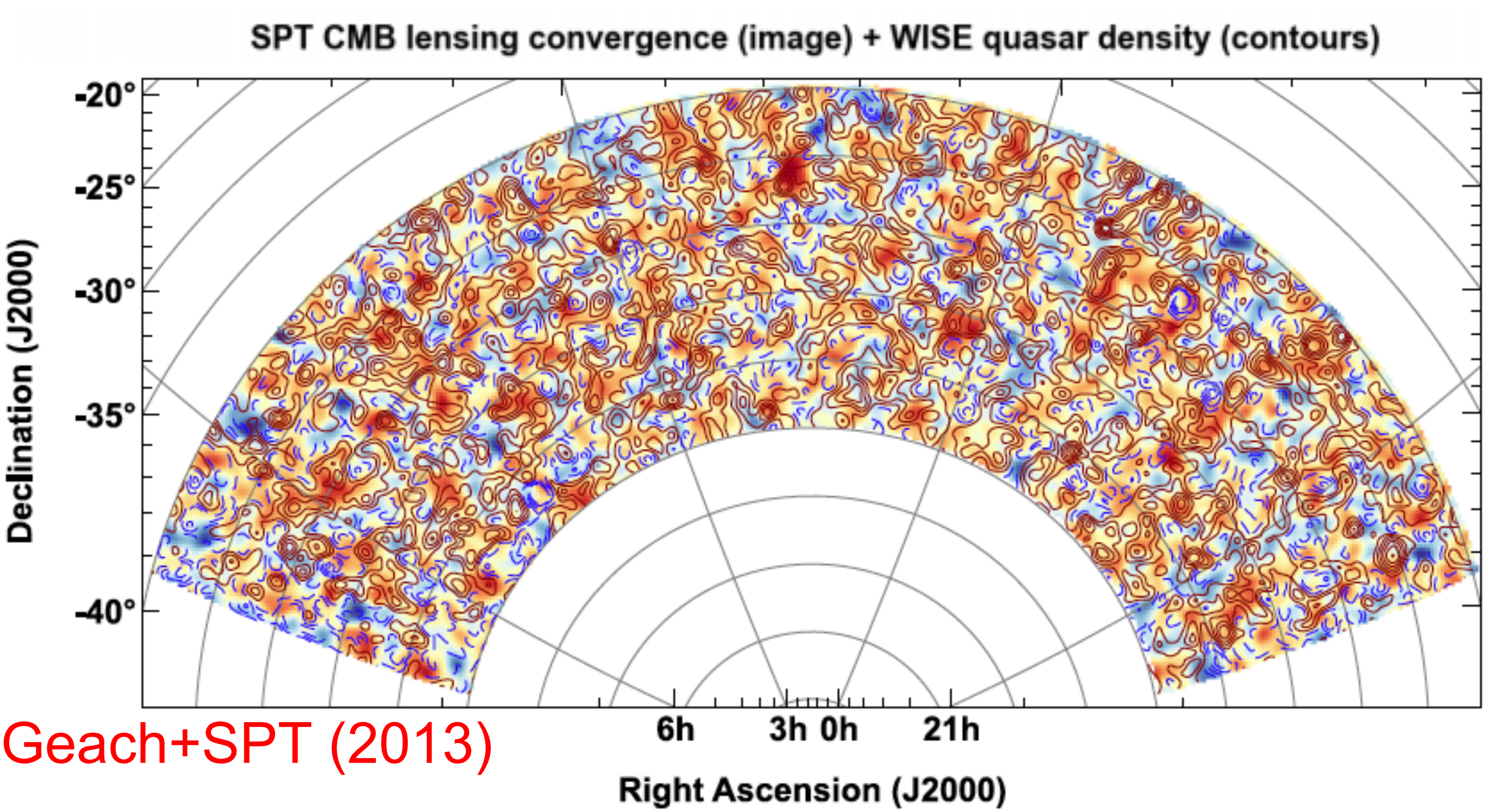
The deflection angle power spectrum

The Deflection Angle Power Spectrum



Planck XVII (2013)

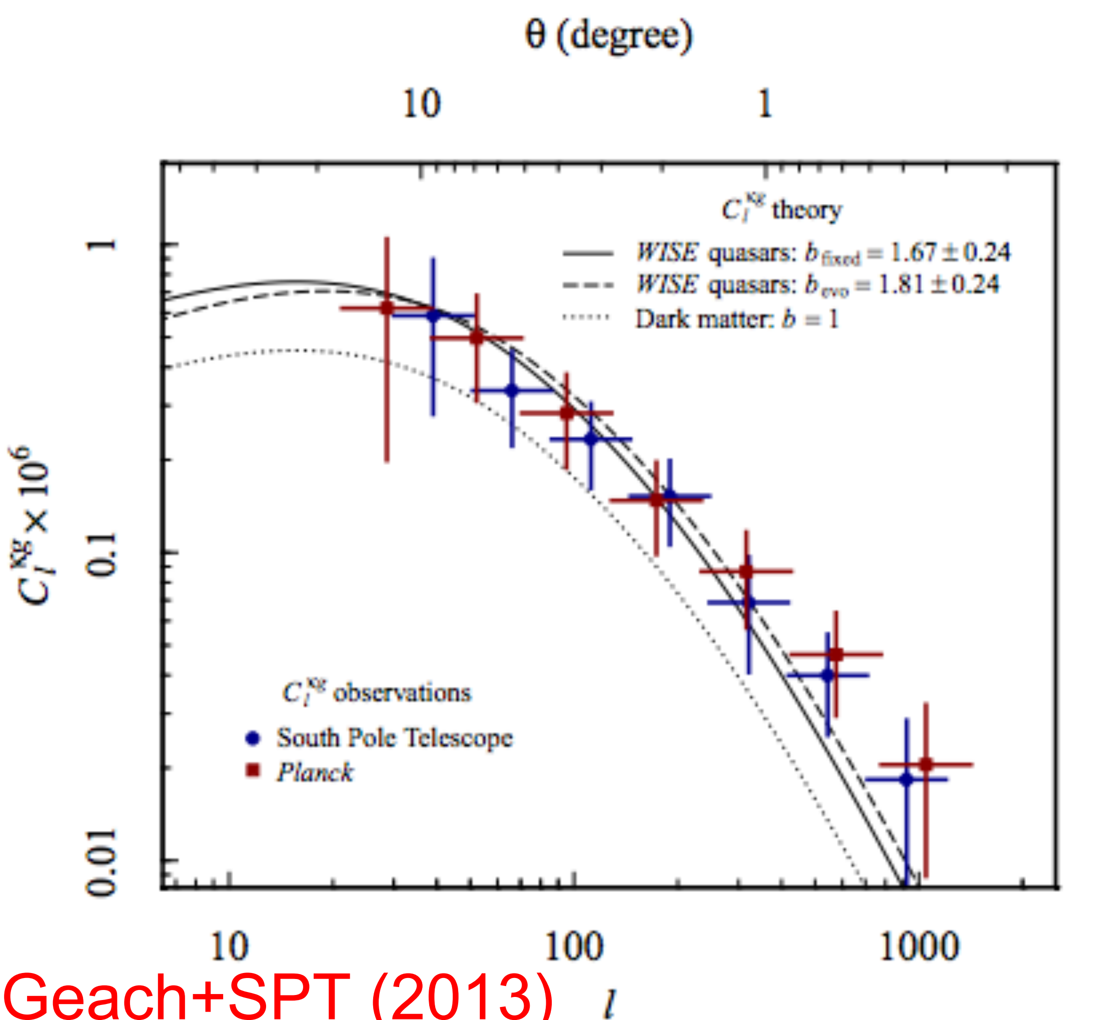
An SPT Lensing Map



Geach+SPT (2013)

This is a higher signal-to-noise lensing map than from Planck, 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.

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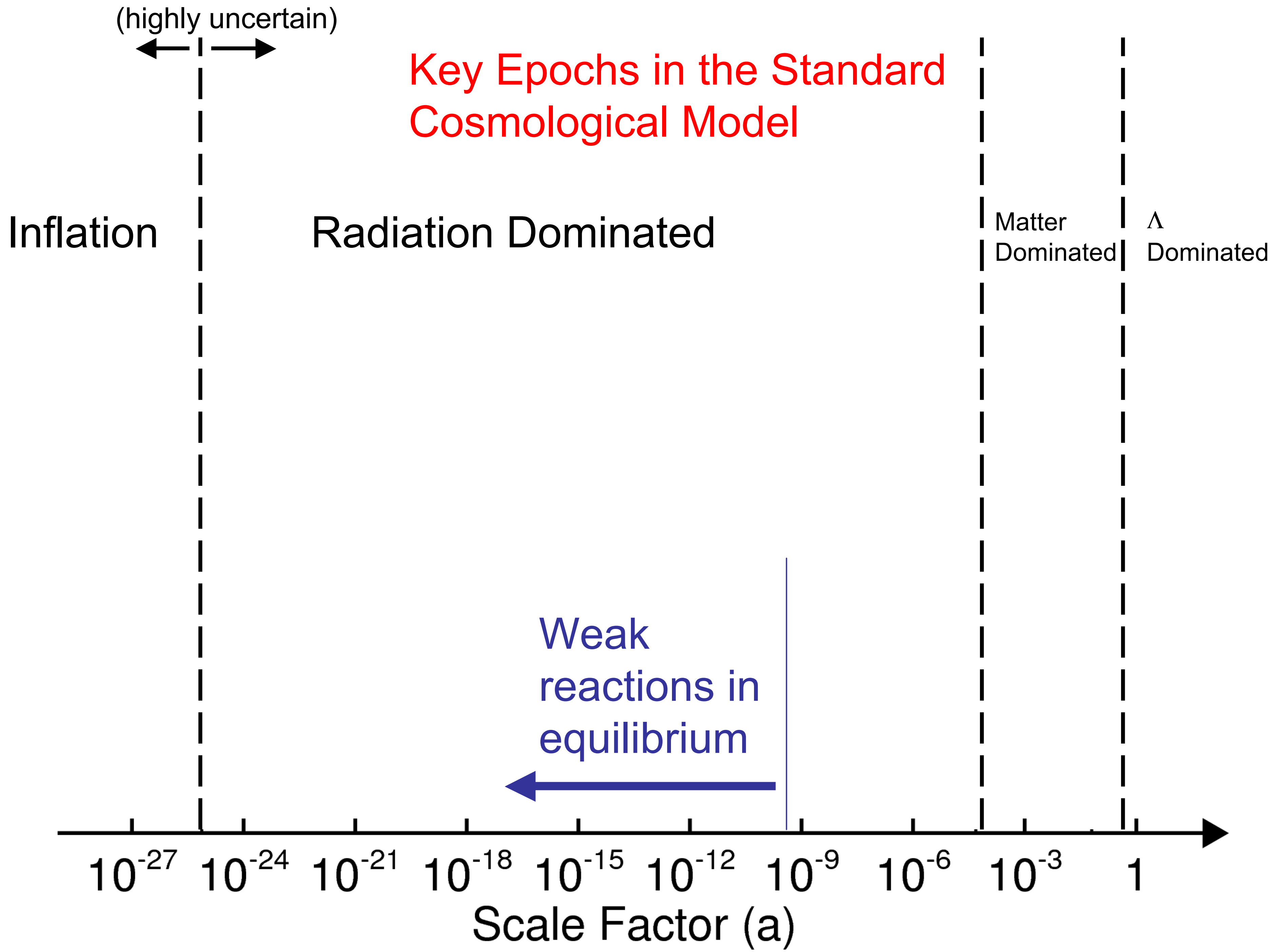
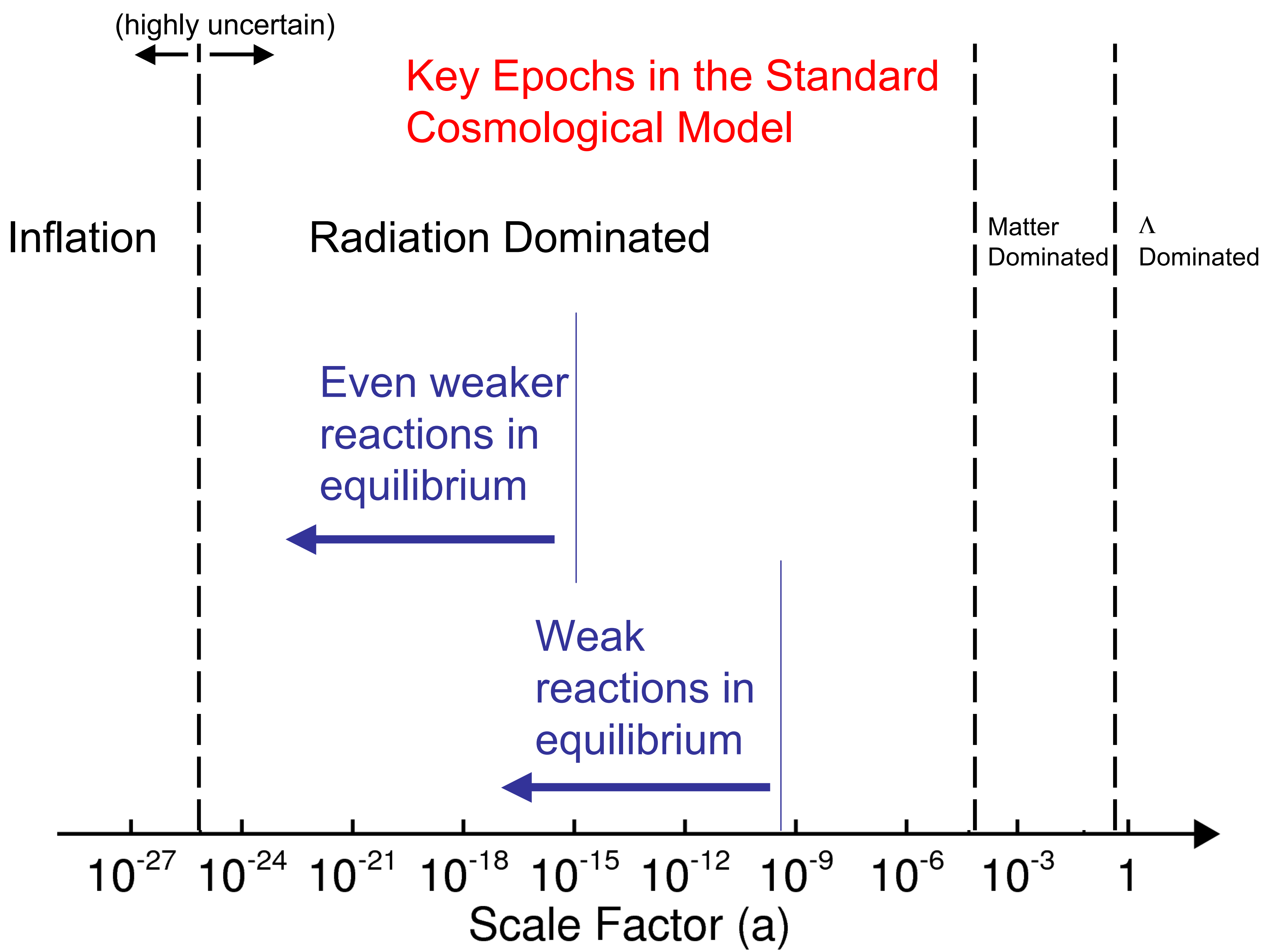
Extensions in the Neutrino Sector

- 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. [I won't get to this, but see Lindsey Bleem's talk from last week about ALMA follow up of SPT-discovered sources and Hezaveh et al., "Dark Matter Substructure Detection Using Spatially Resolved Spectroscopy of Lensed Dusty Galaxies"]


(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
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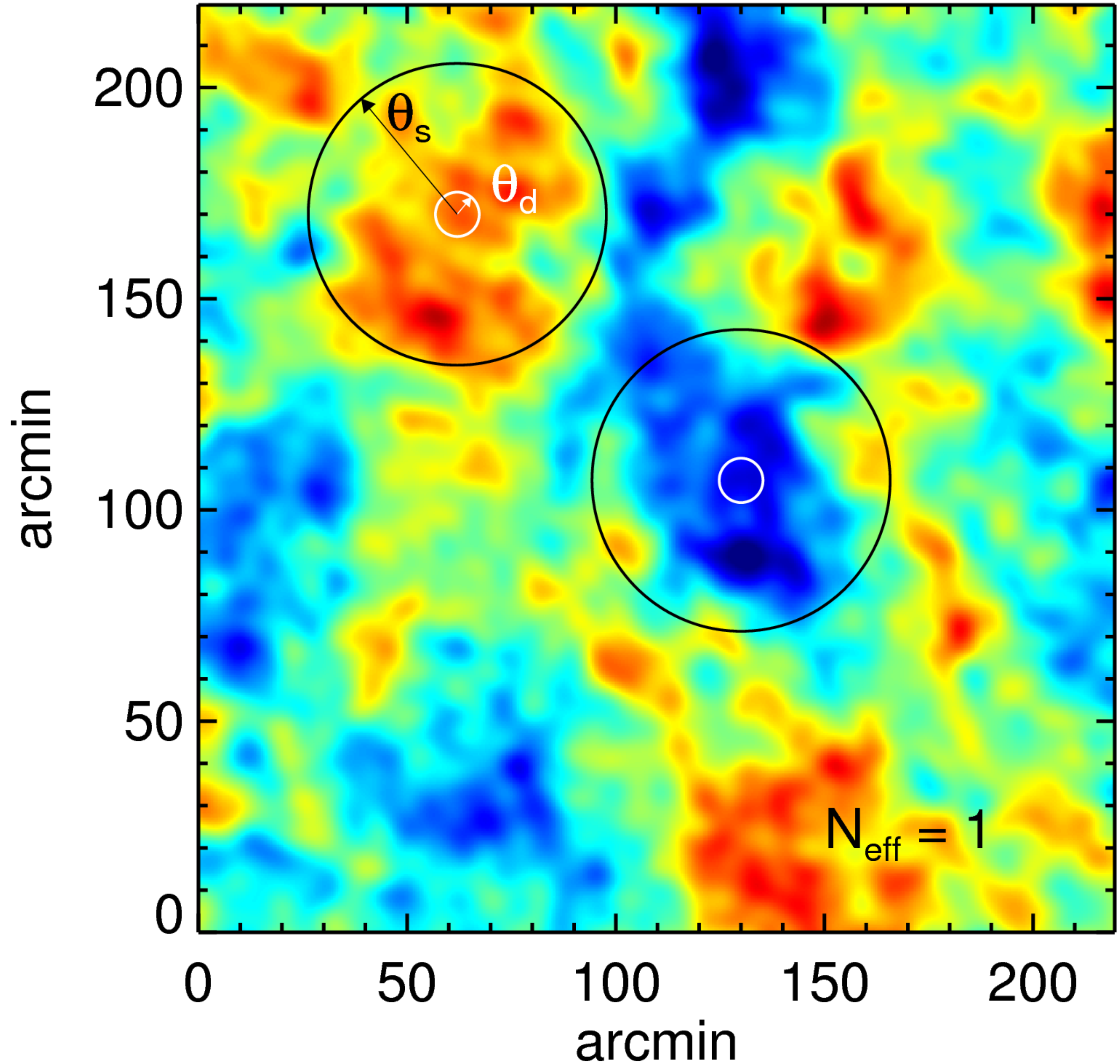
Even weaker reactions in equilibrium
Weak reactions in equilibrium
10-27 10-24 10-21 10-18 10-15 10-12 10-9 10-6 10-3 1
Scale Factor (a)

Neff affects the ratio of sound horizon to diffusion scale



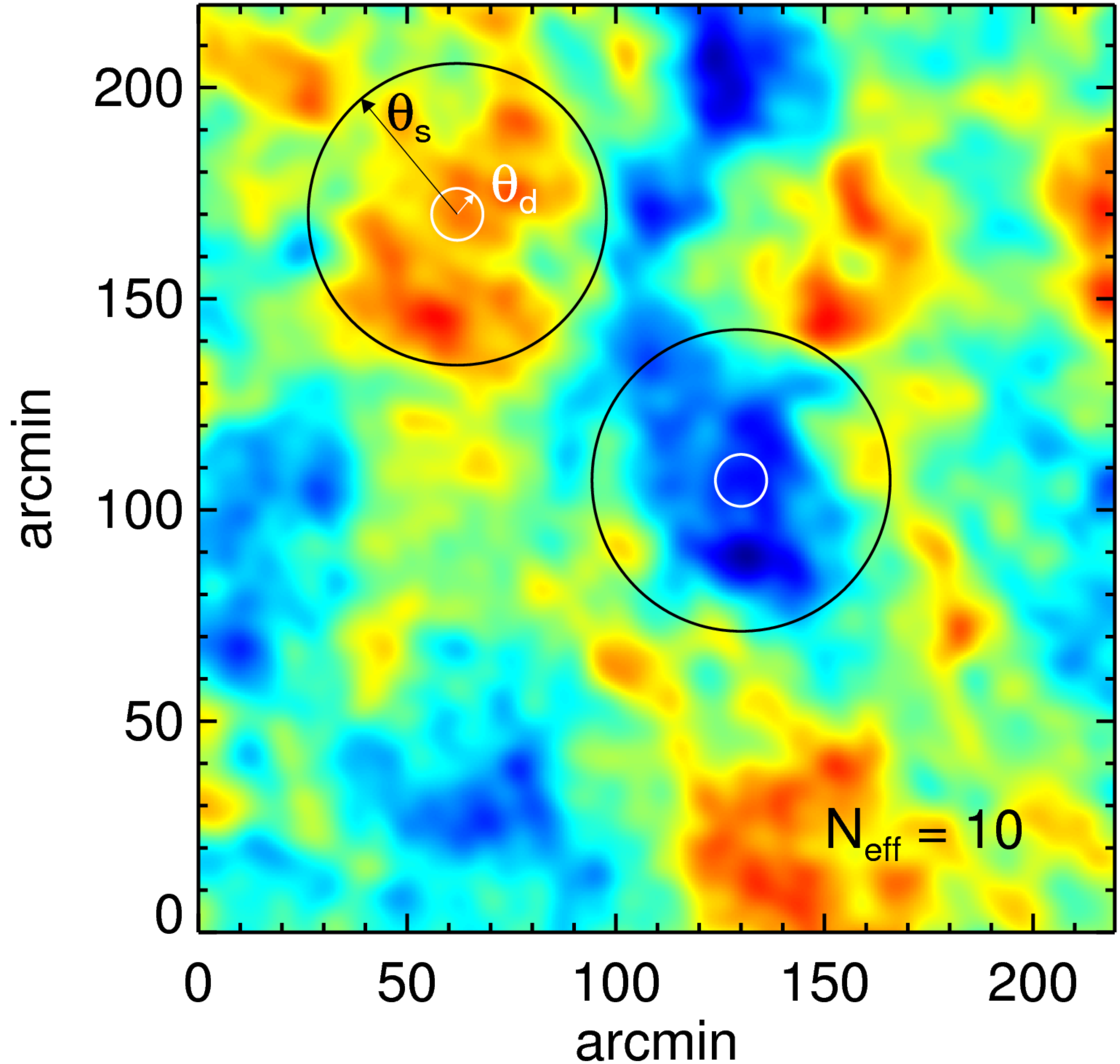
$r_s \sim 1/H$

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

==> 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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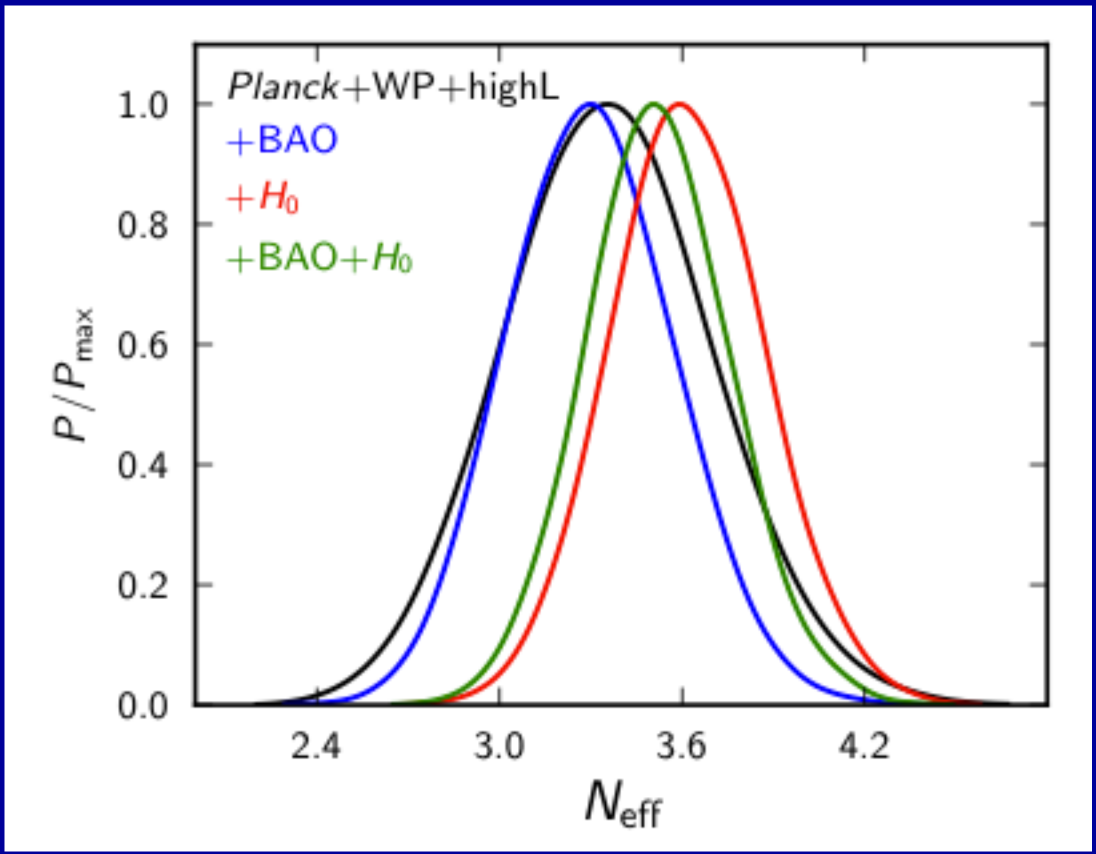
Light Degrees of Freedom



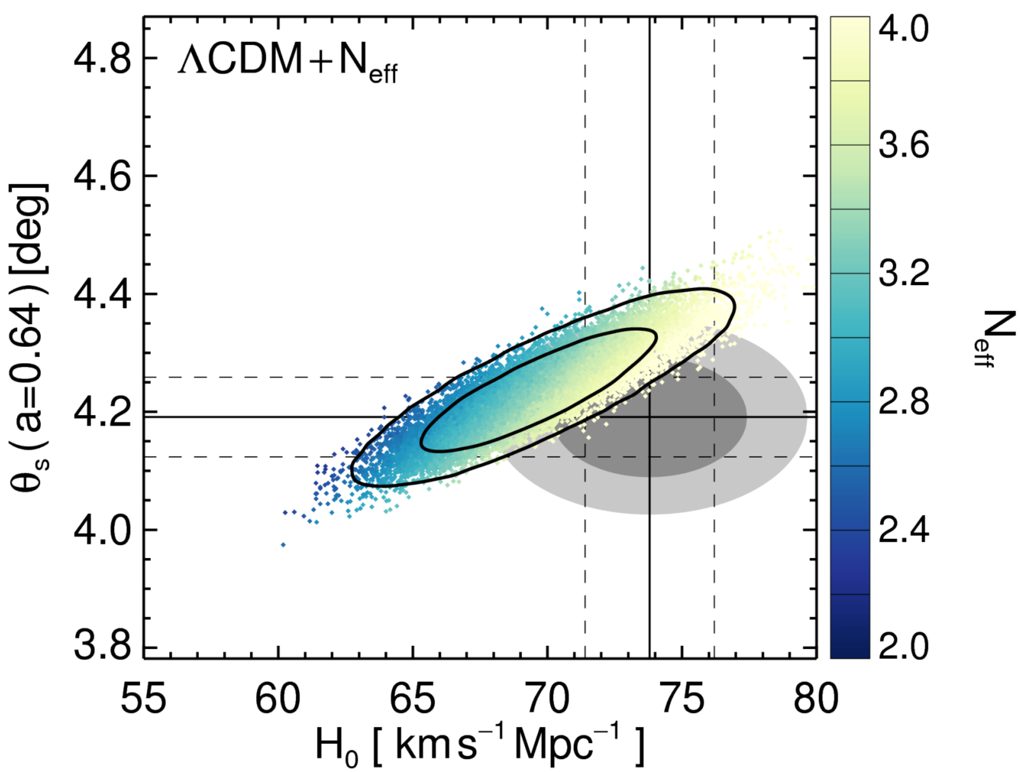
Contribute to the energy density and hence the expansion rate, altering r_s and r_d.

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?

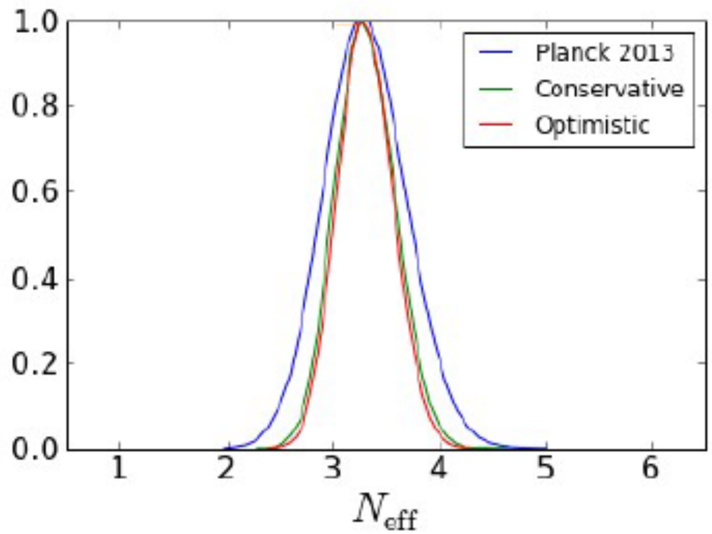
Conservative:

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

Optimistic:

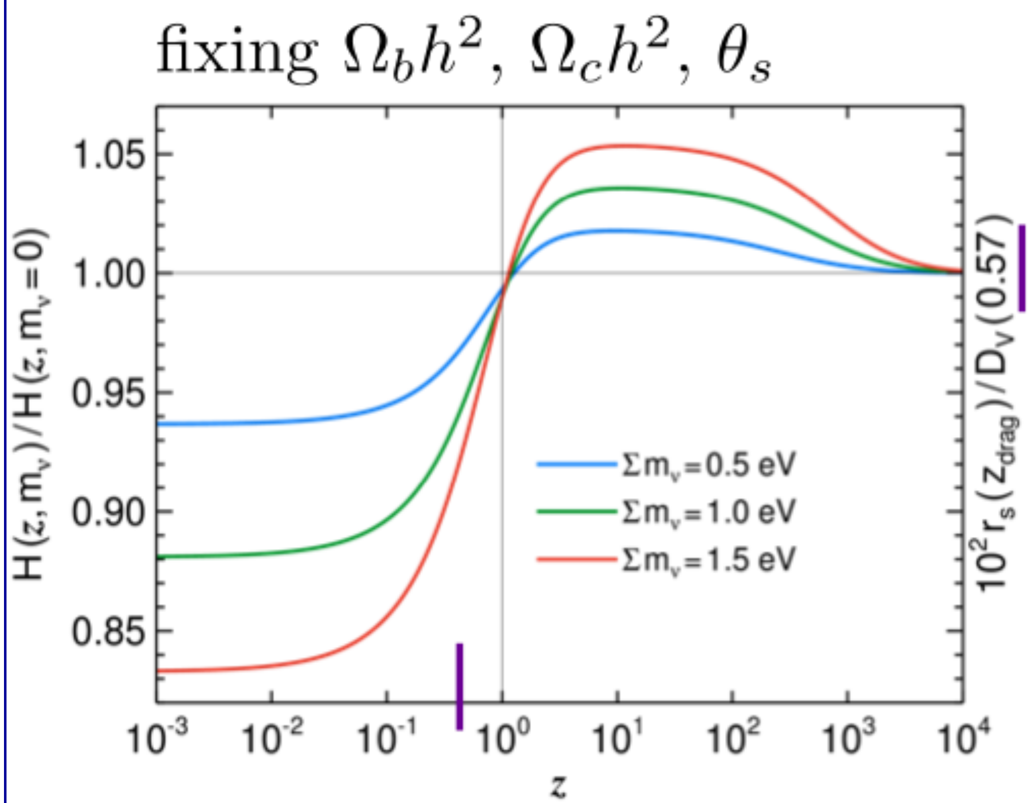
- Double the TT data, 60% sky at 143/217 (instead of 30%)
- TE and EE from 217 GHz on 60% of the sky

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



Slide credit: M. Millea

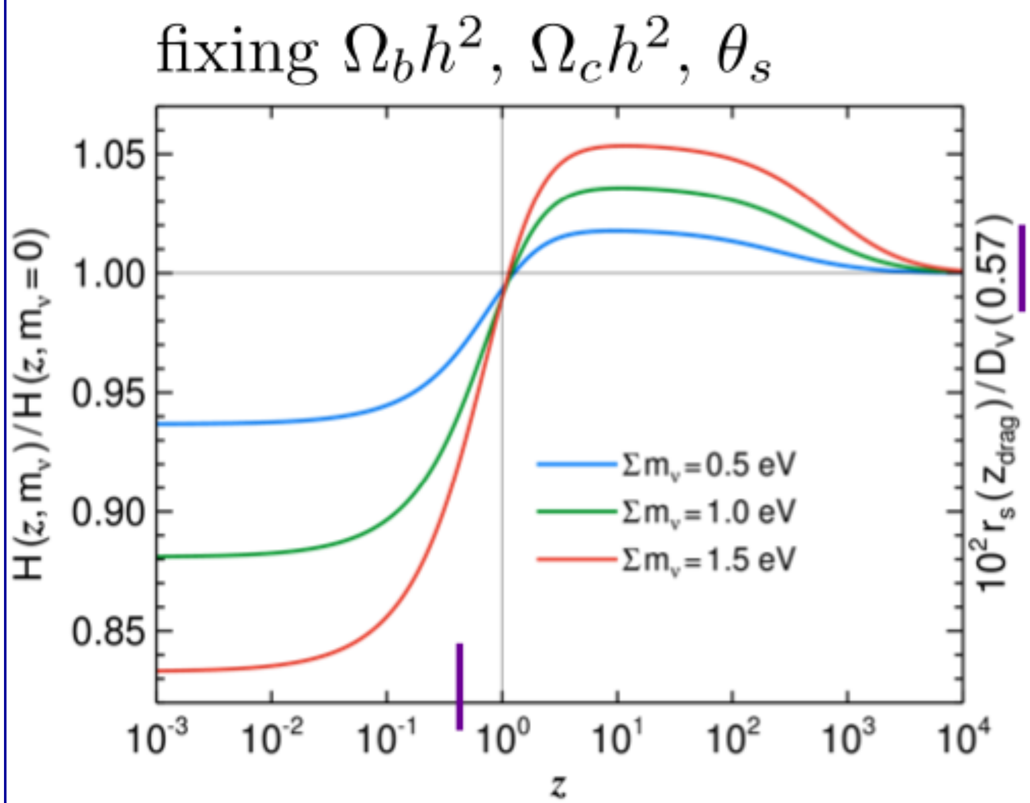
Expansion rate with neutrino mass



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



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.

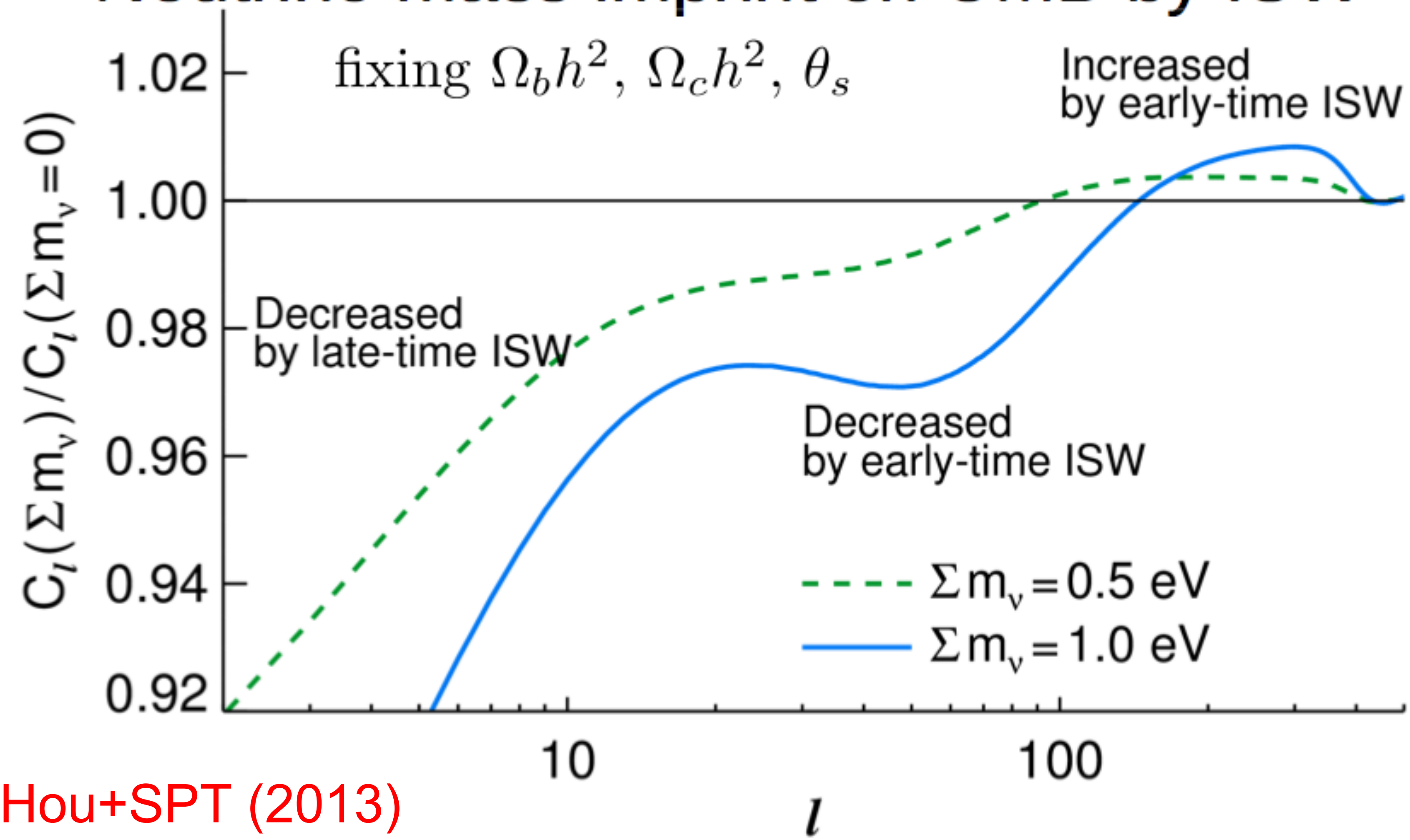
Figure credit: Zhen Hou

This expansion rate change alters the ISW effect.

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).

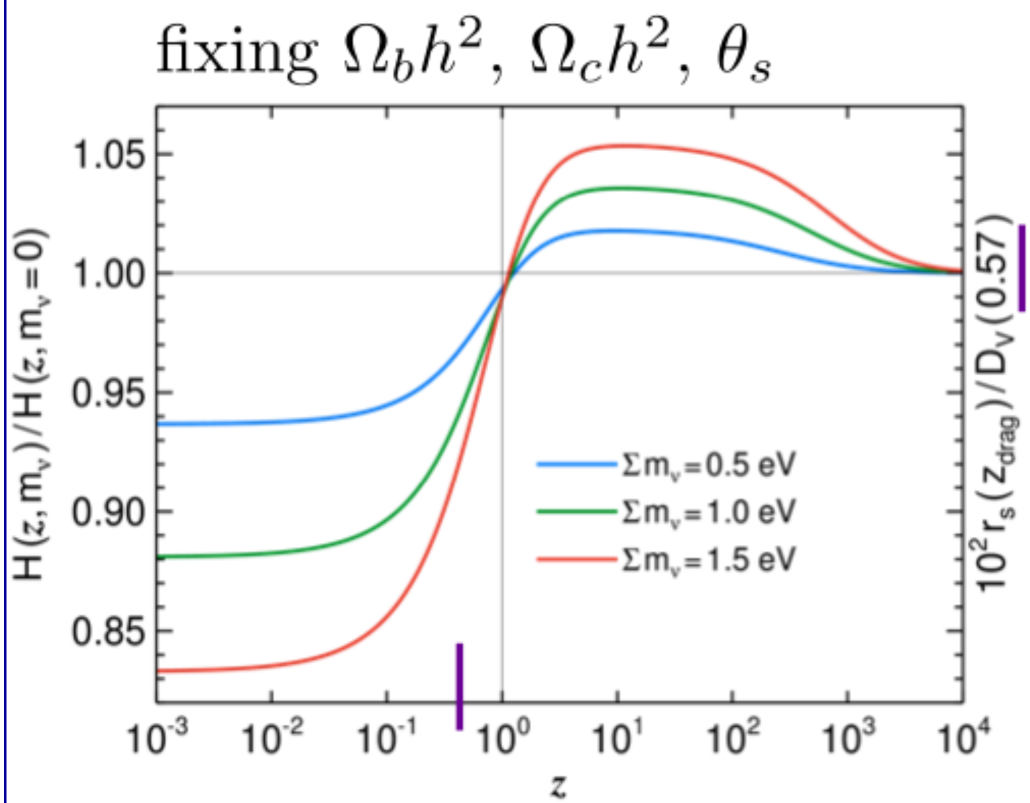
Neutrino mass imprint on CMB by ISW



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

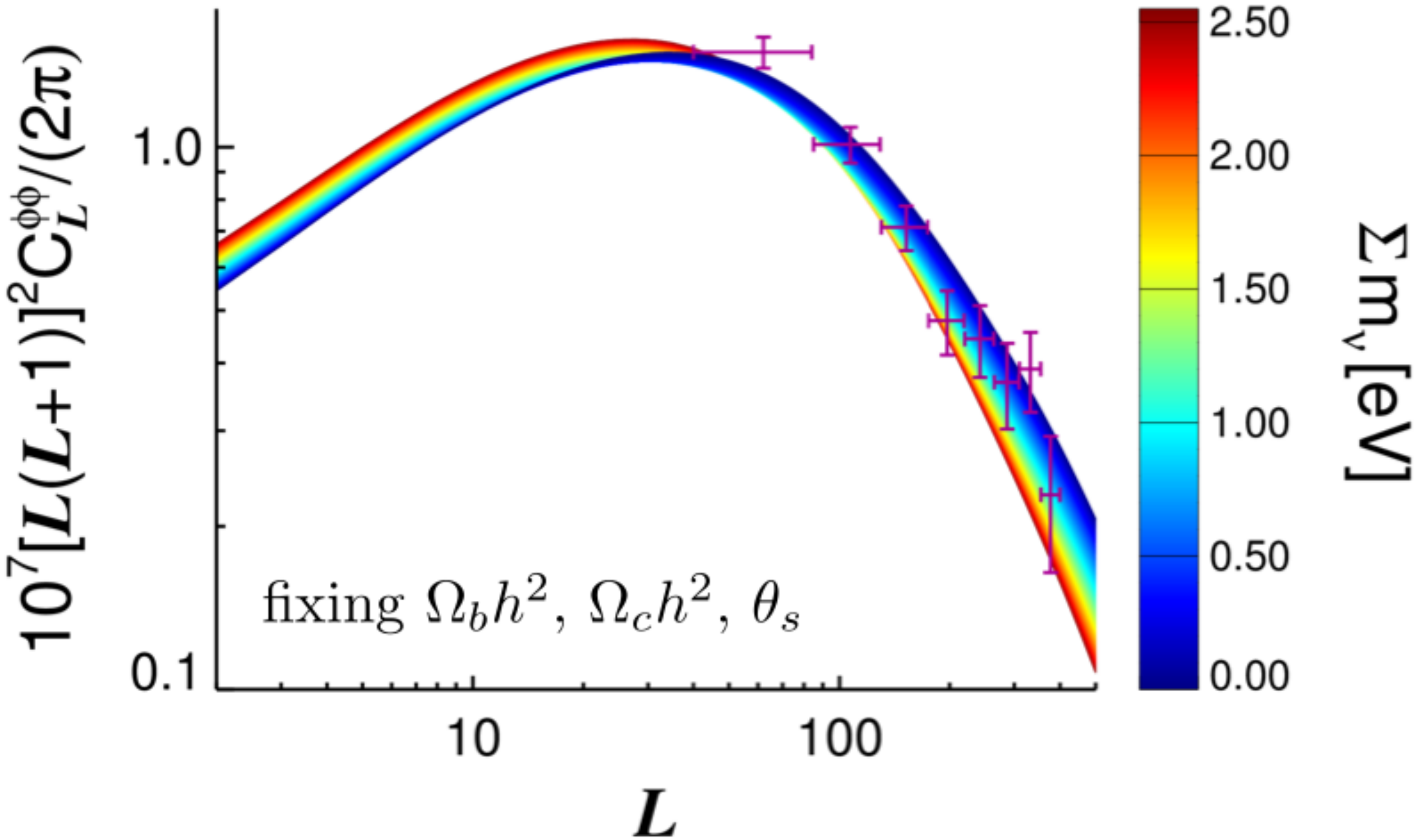
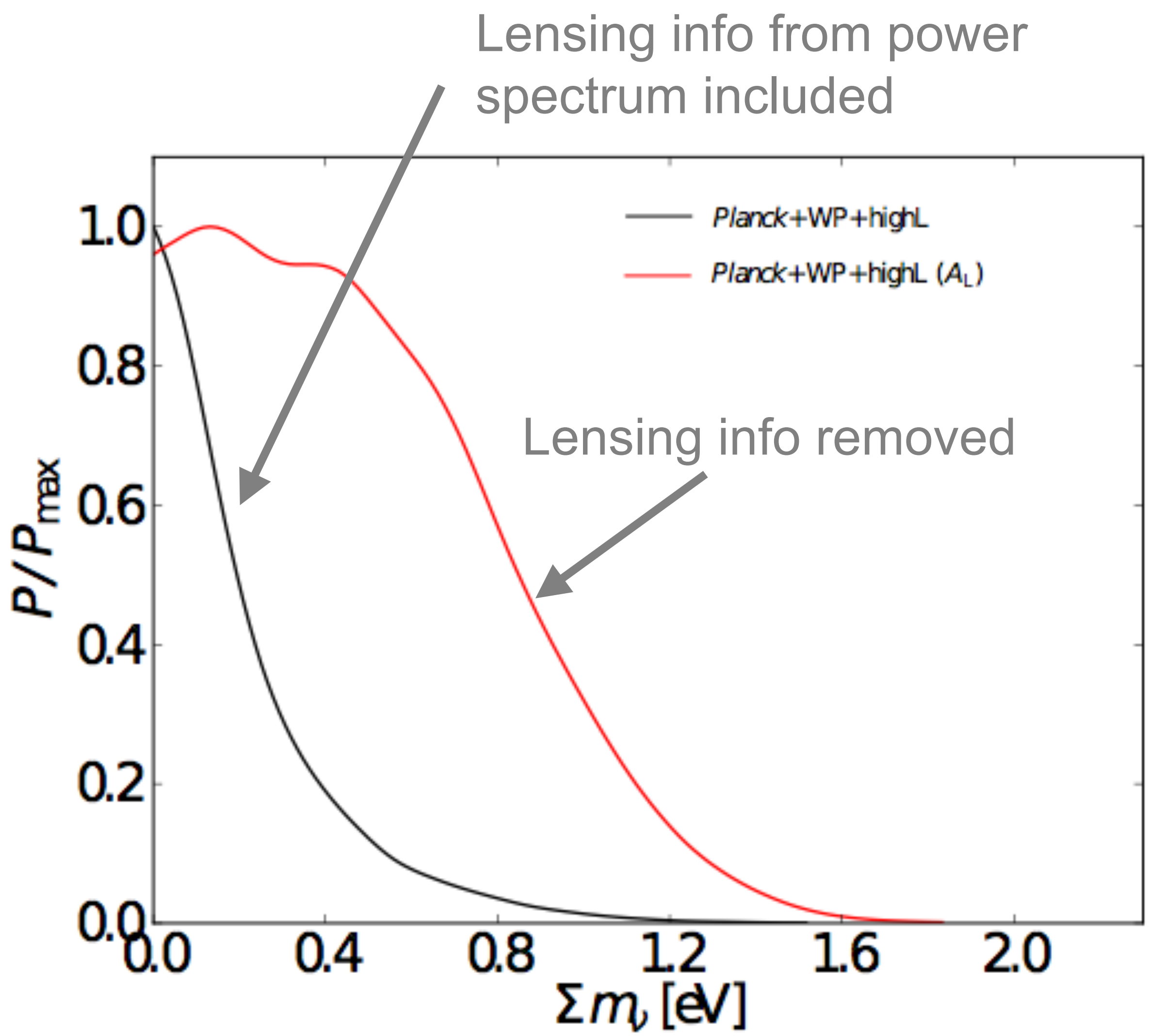


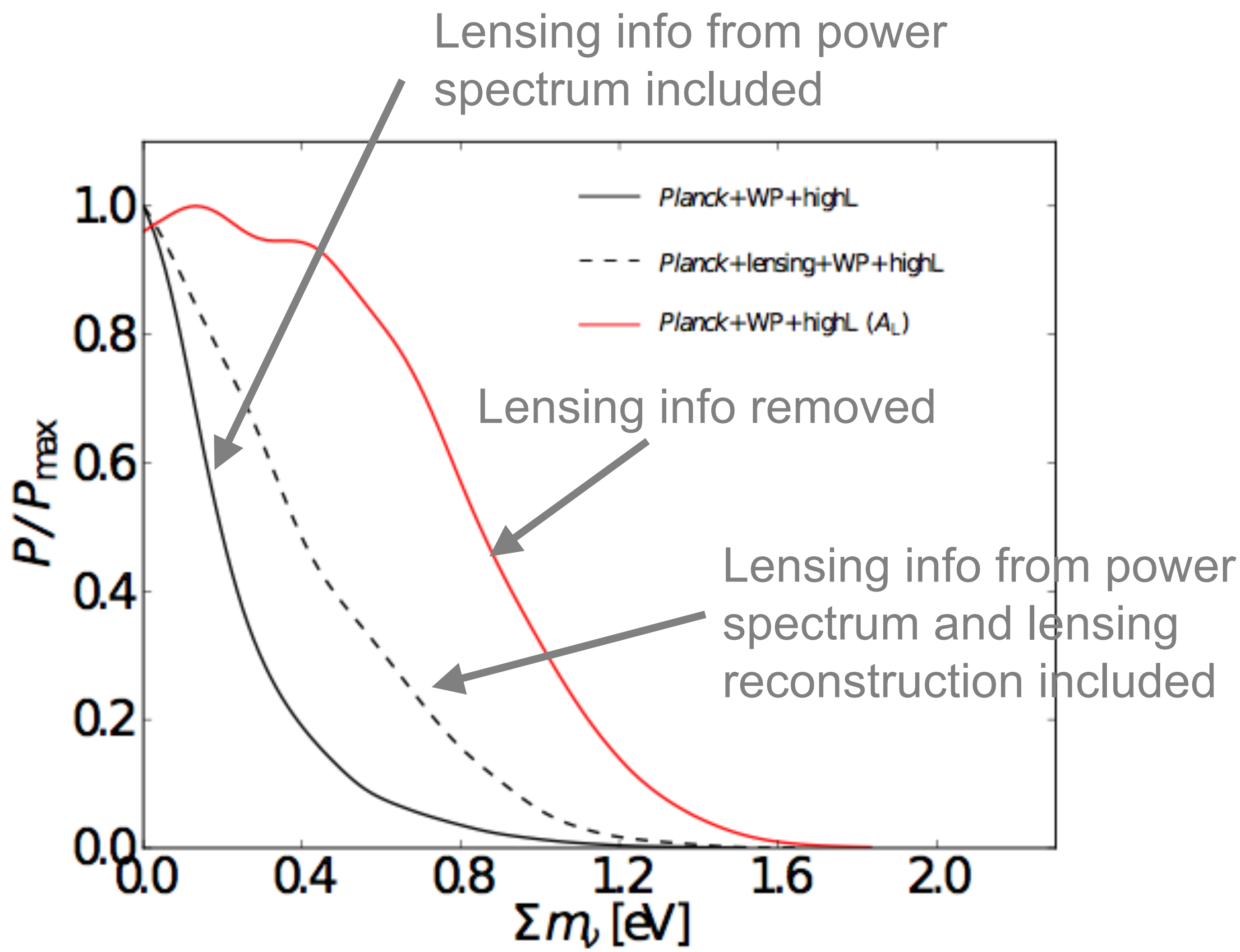
Image credit: Zhen Hou

Data points: Planck XVII

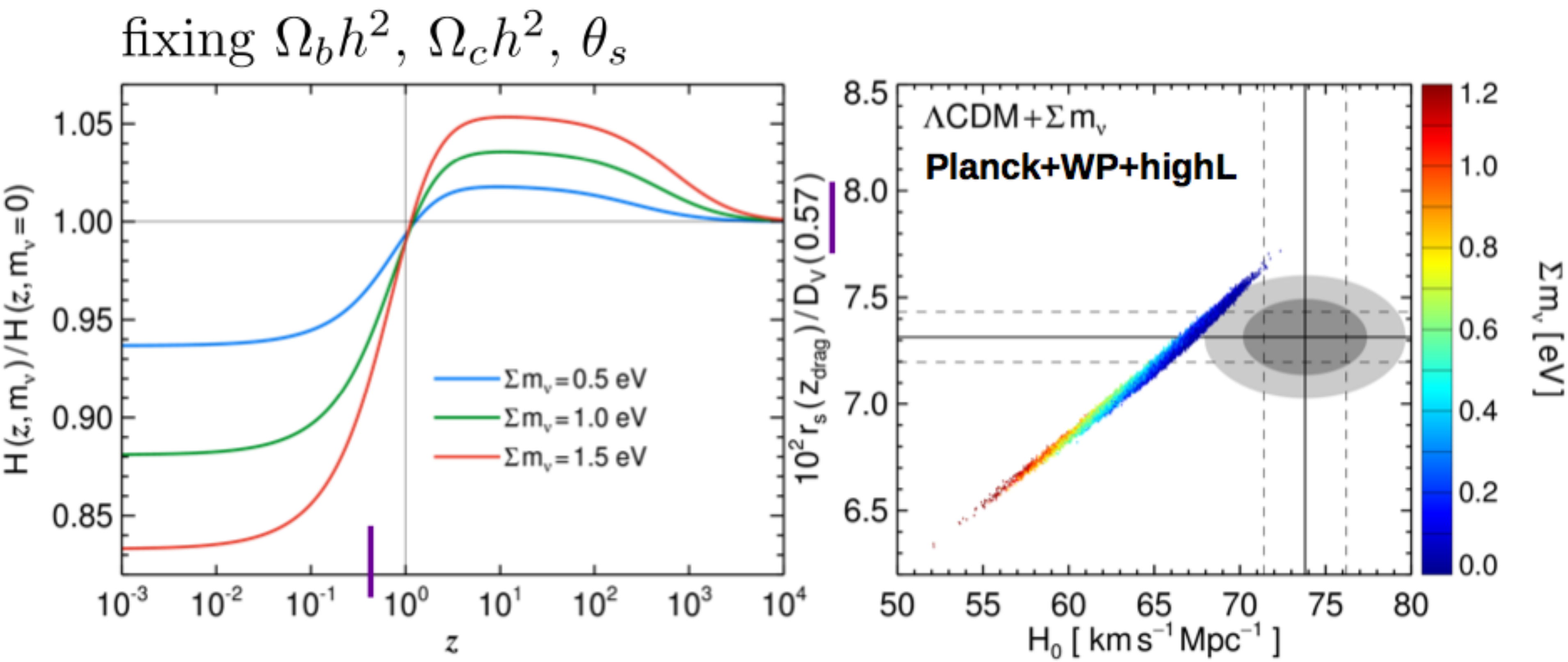
For the first time, lensing information is dominant source of information about m_ν



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



Expansion rate with neutrino mass

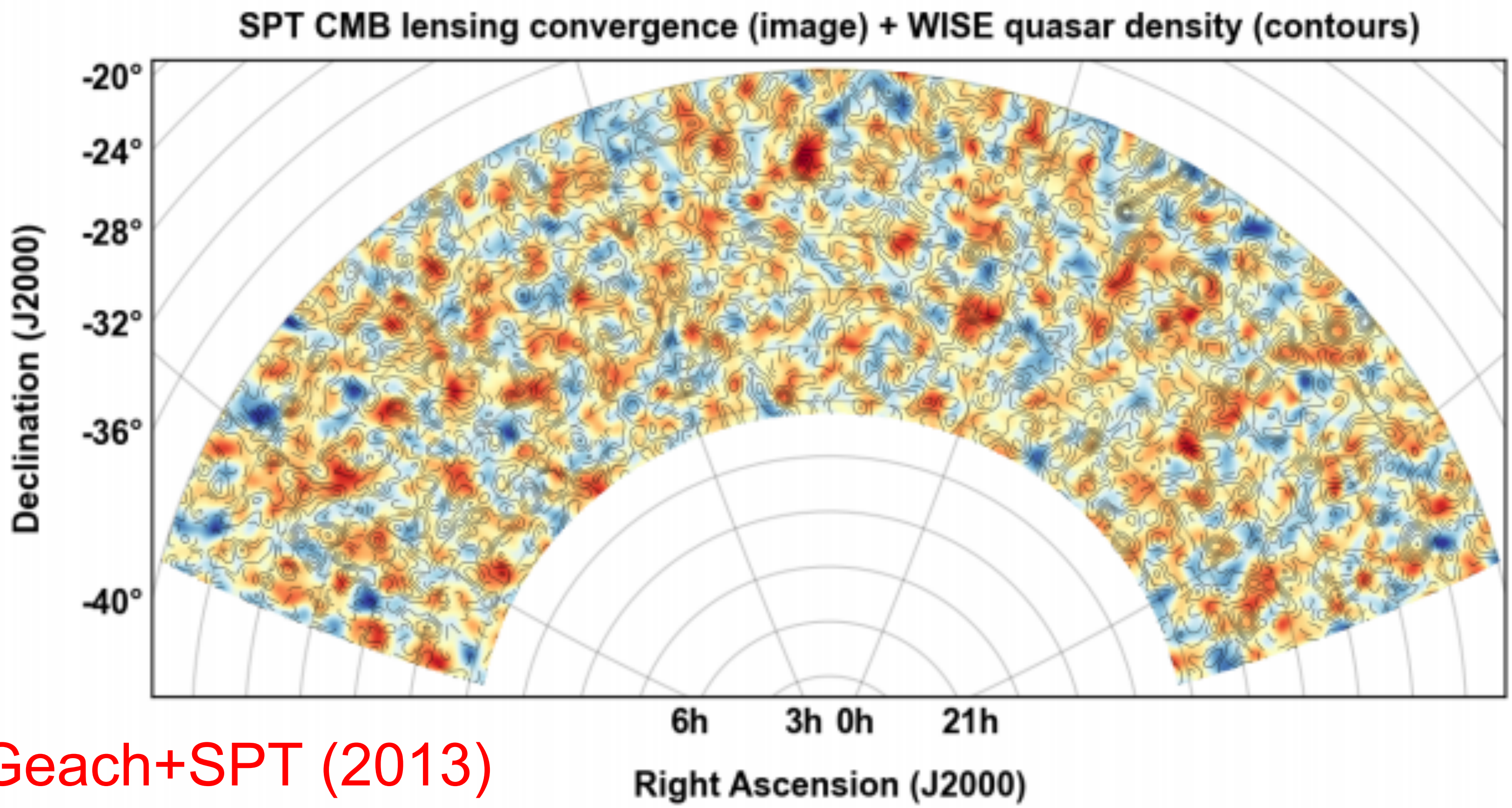


Slide credit: Zhen Hou

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.

Summary

- Planck has performed beautifully
- The ΛCDM model provides a very good fit to the Planck data.
- The Planck-calibrated LCDM predictions for BAO observables agree perfectly with the BAO data, while the predictions for H_0 disagree with the most precise, more direct methods.
- Neutrino background detected, with expected impact on the damping tail.
- Data are consistent with simplest inflation models.
- CMB lensing is playing an important role in cosmological constraints, particularly on the sum of neutrino masses.