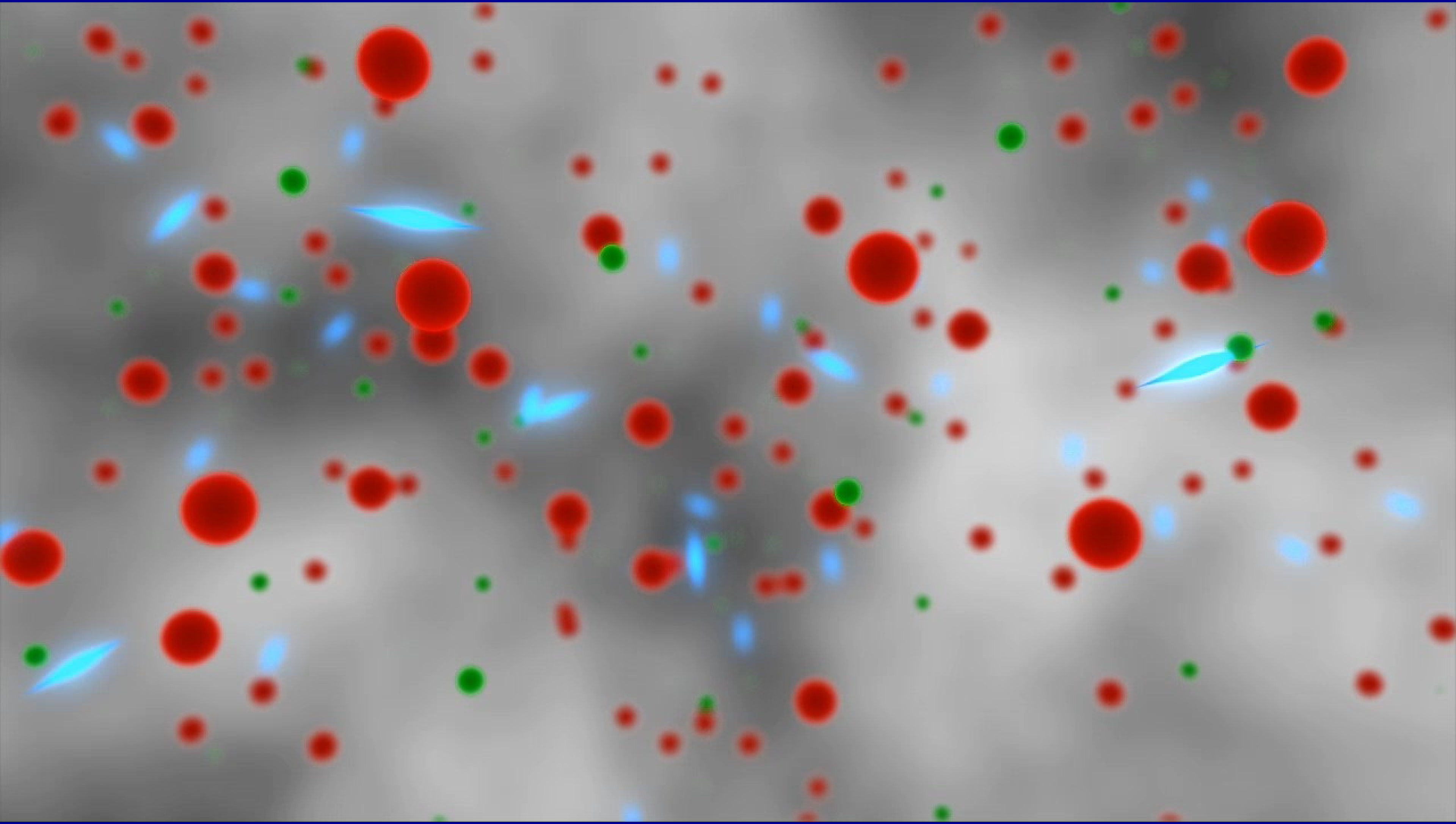
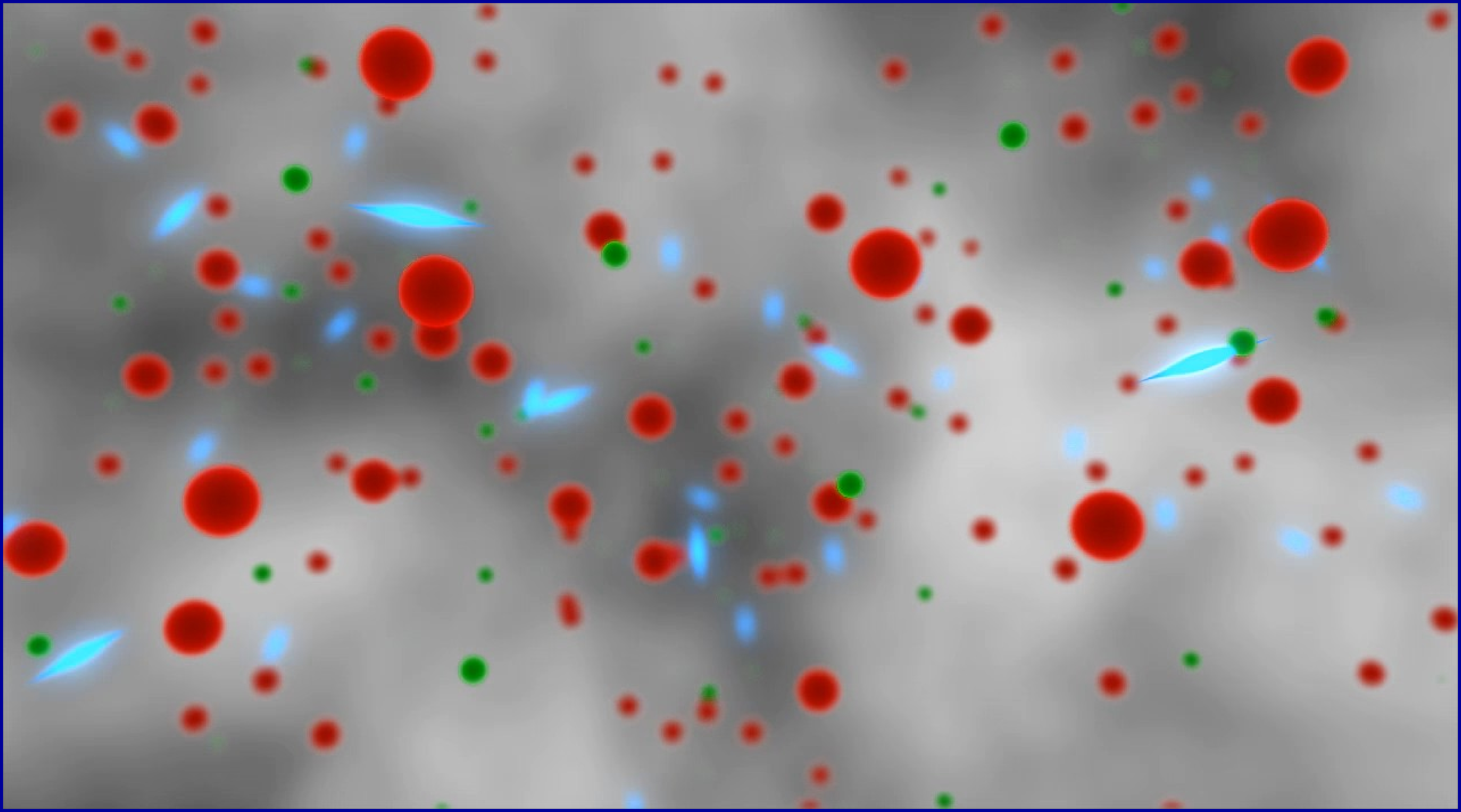
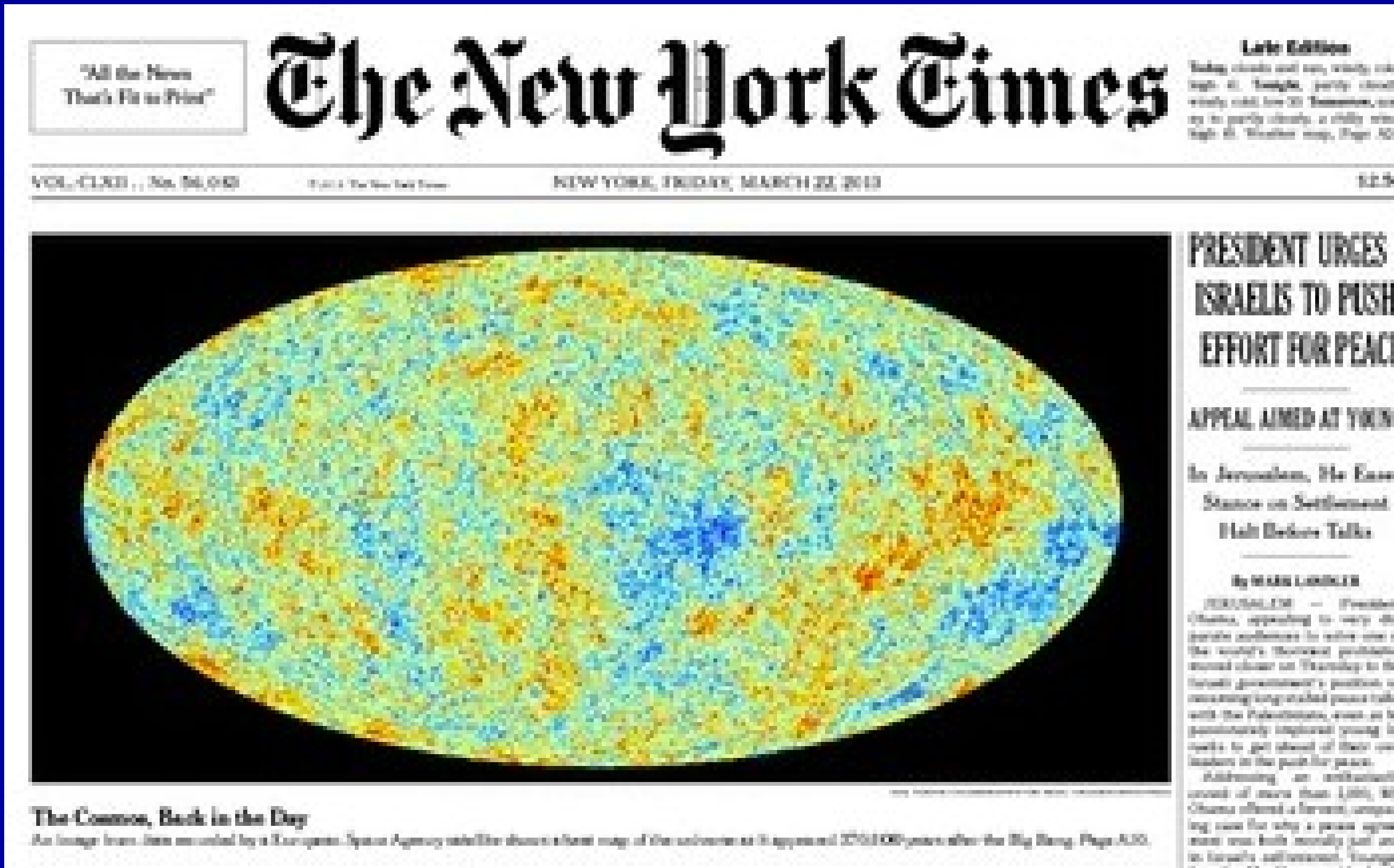
Neutrino physics with the Planck satellite

Marius Millea
UC Davis
On Behalf of the Planck Collaboration







"All the News That's Fit to Print"

The New York Times

Late Edition

NEW YORK, FRIDAY, MARCH 22, 2013

PRESIDENT URGES ISRAELIS TO PUSH EFFORT FOR PEACE

APPEAL AIMED AT YOUNG

In Jerusalem, He Eases Stance on Settlement Halt Before Talks

The Cosmos, Back in the Day

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."

Francois Jenevein –
Hide Trimmer

77° Too hot to wear fat suit

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172 86 4

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Francois Jenevein – Hide Trimmer

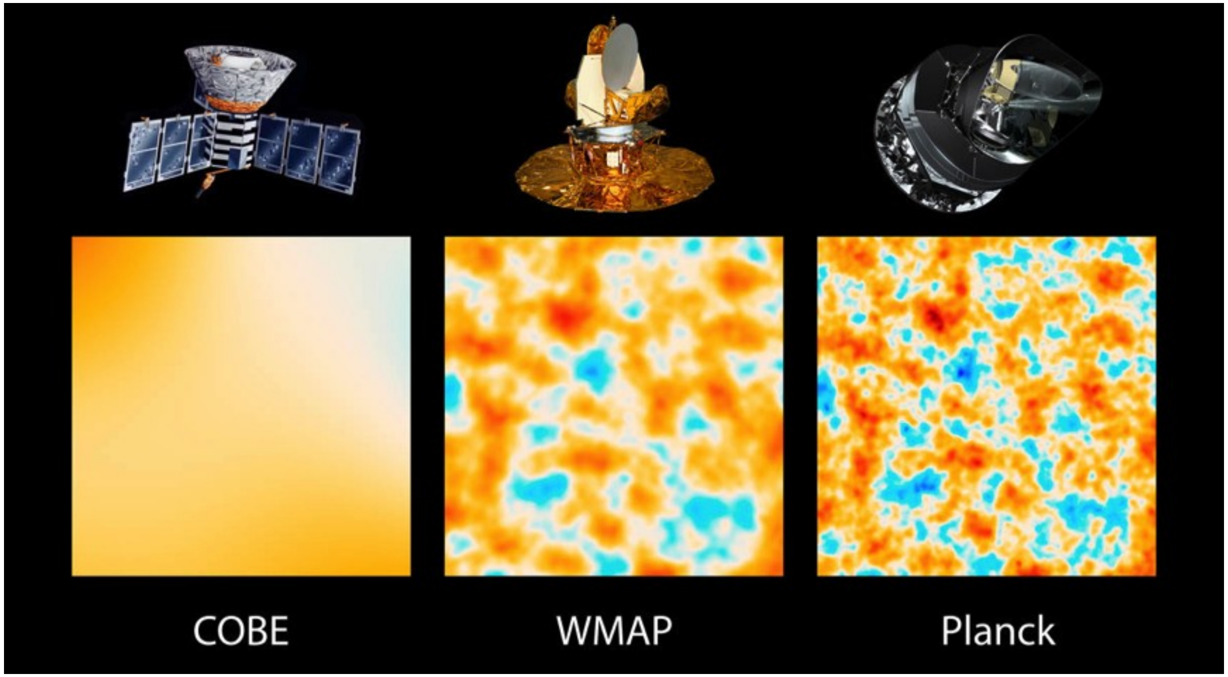
"Probably a non-standard neutrino interaction."
-Alex Friedland

Outline

- Planck
- ΛCDM, the standard model of cosmology, passes a precision test
- Consistency with other cosmological probes
  - BAO and H0
  - WMAP and SPT
- Neutrino physics with Planck
  - Damping and phase shifts $\rightarrow$ Number of relativistic d.o.f
  - Gravitational lensing $\rightarrow$ Sum of neutrino masses

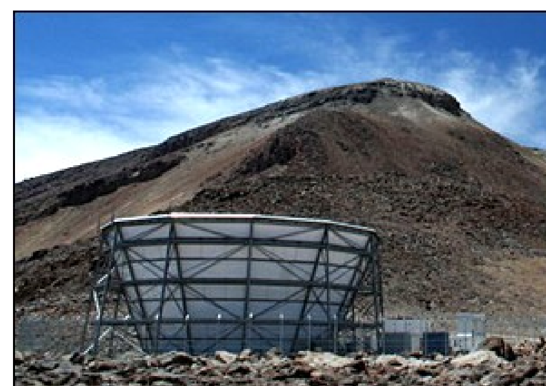
What is Planck?

Full sky:



Better resolution:

South Pole Telescope (SPT)

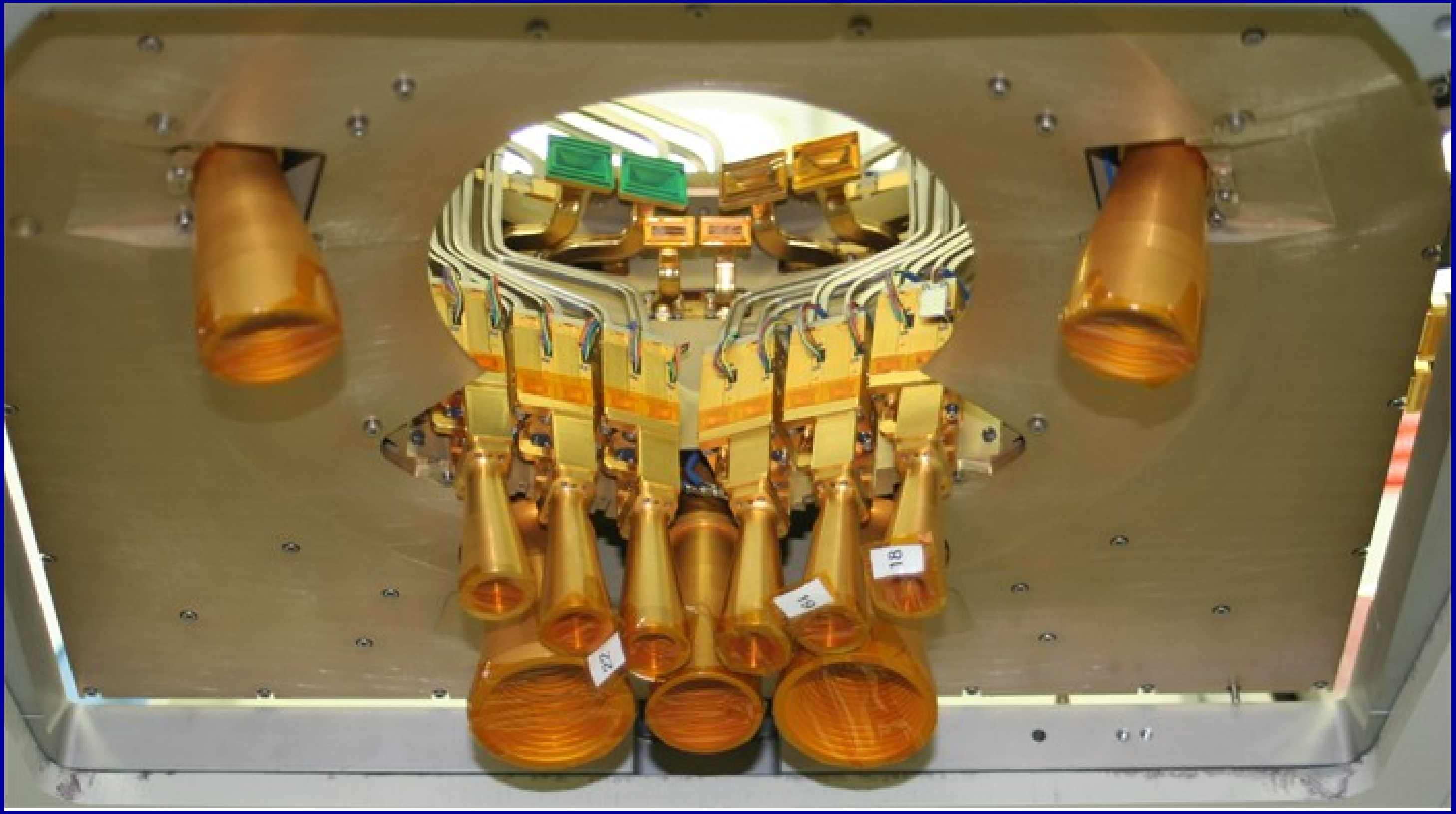


Atacama Cosmology Telescope (ACT)

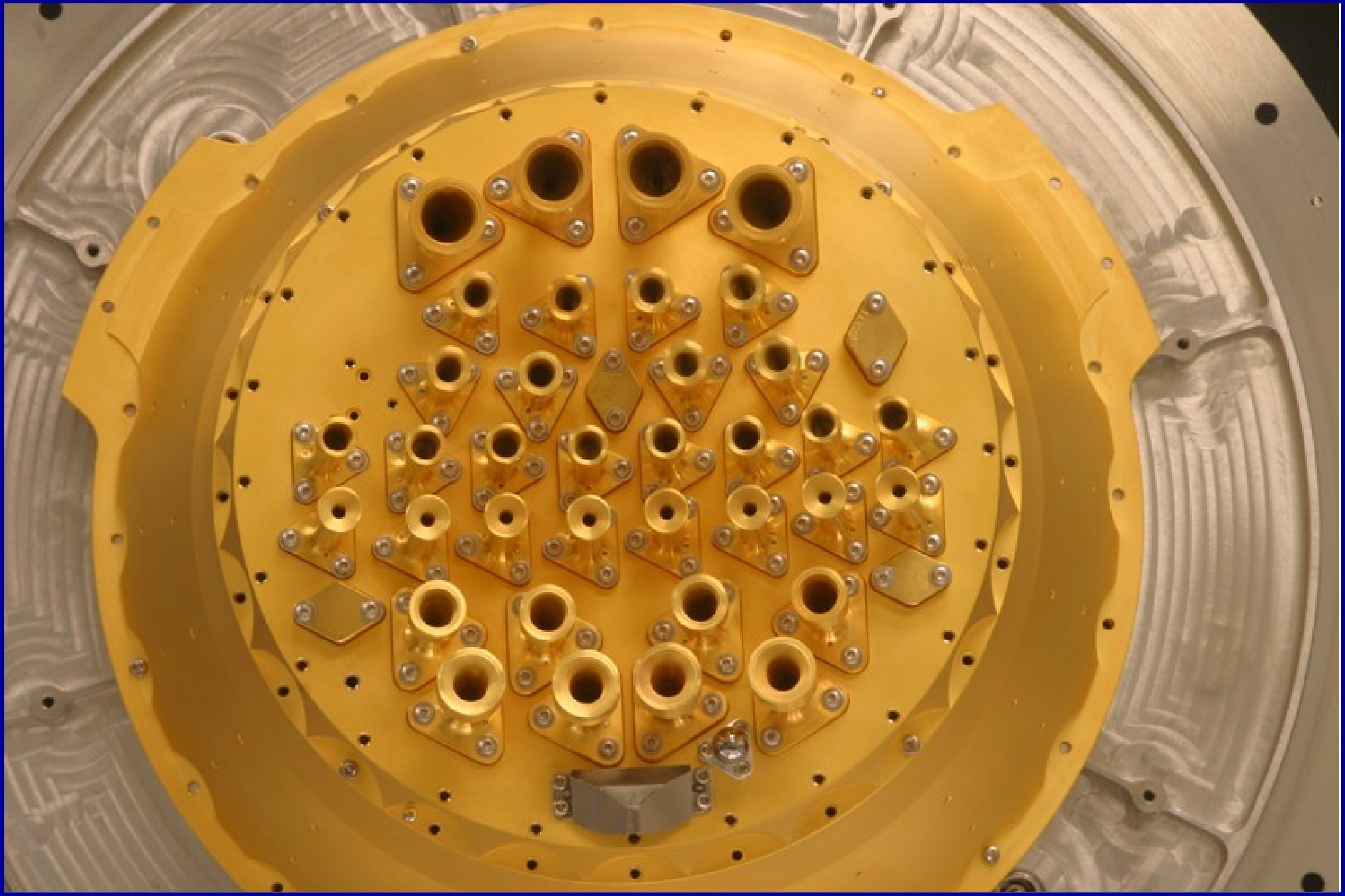
Planck in 2009

Planck in 2009

LFI: 30, 44, 70 GHz

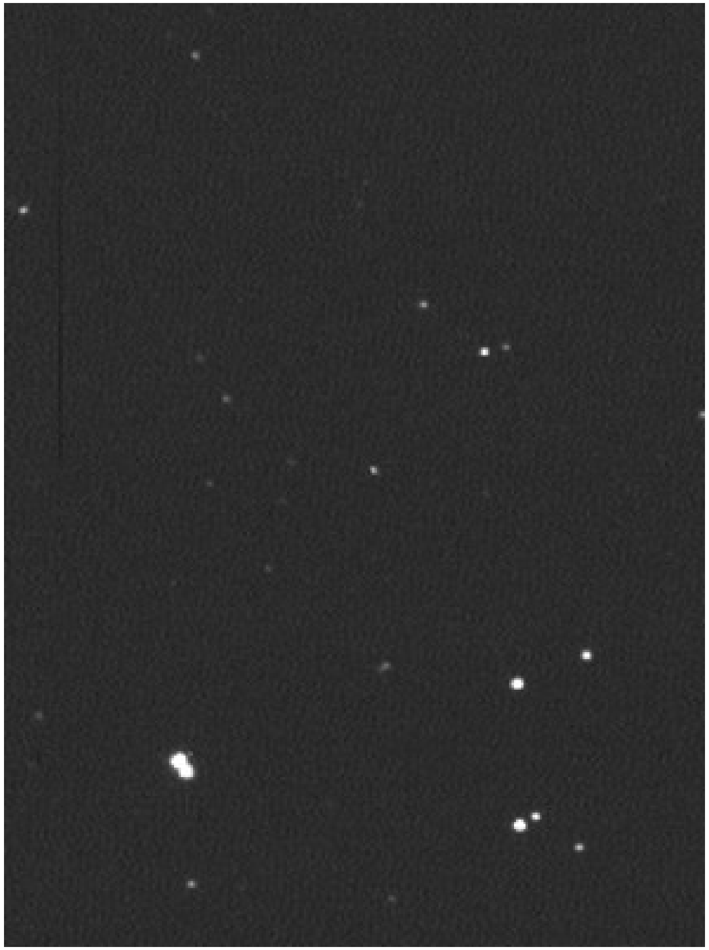


HFI: 100, 143, 217, 353, 545, 853 GHZ



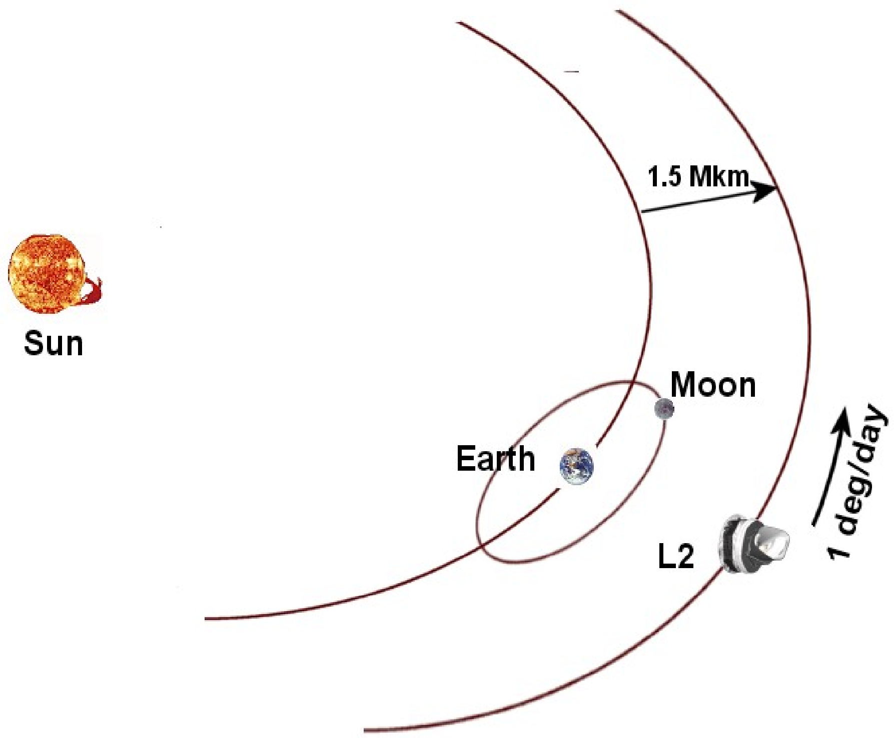
A picture-perfect launch!

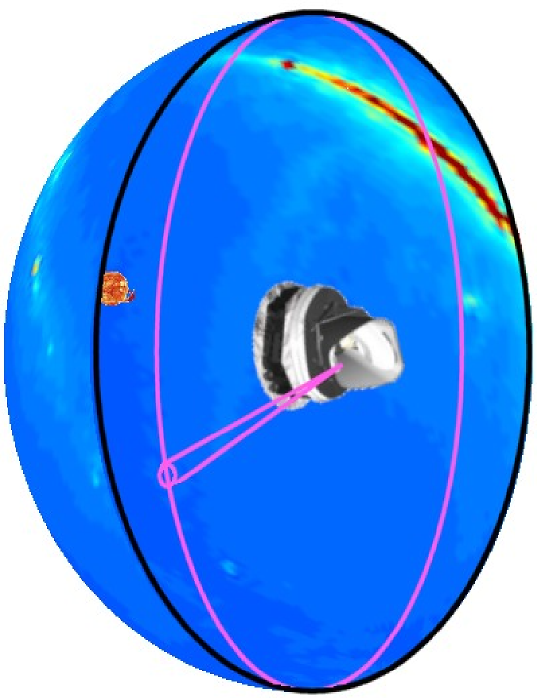
Ariane 5 lifts off with Herschel and Planck on board on

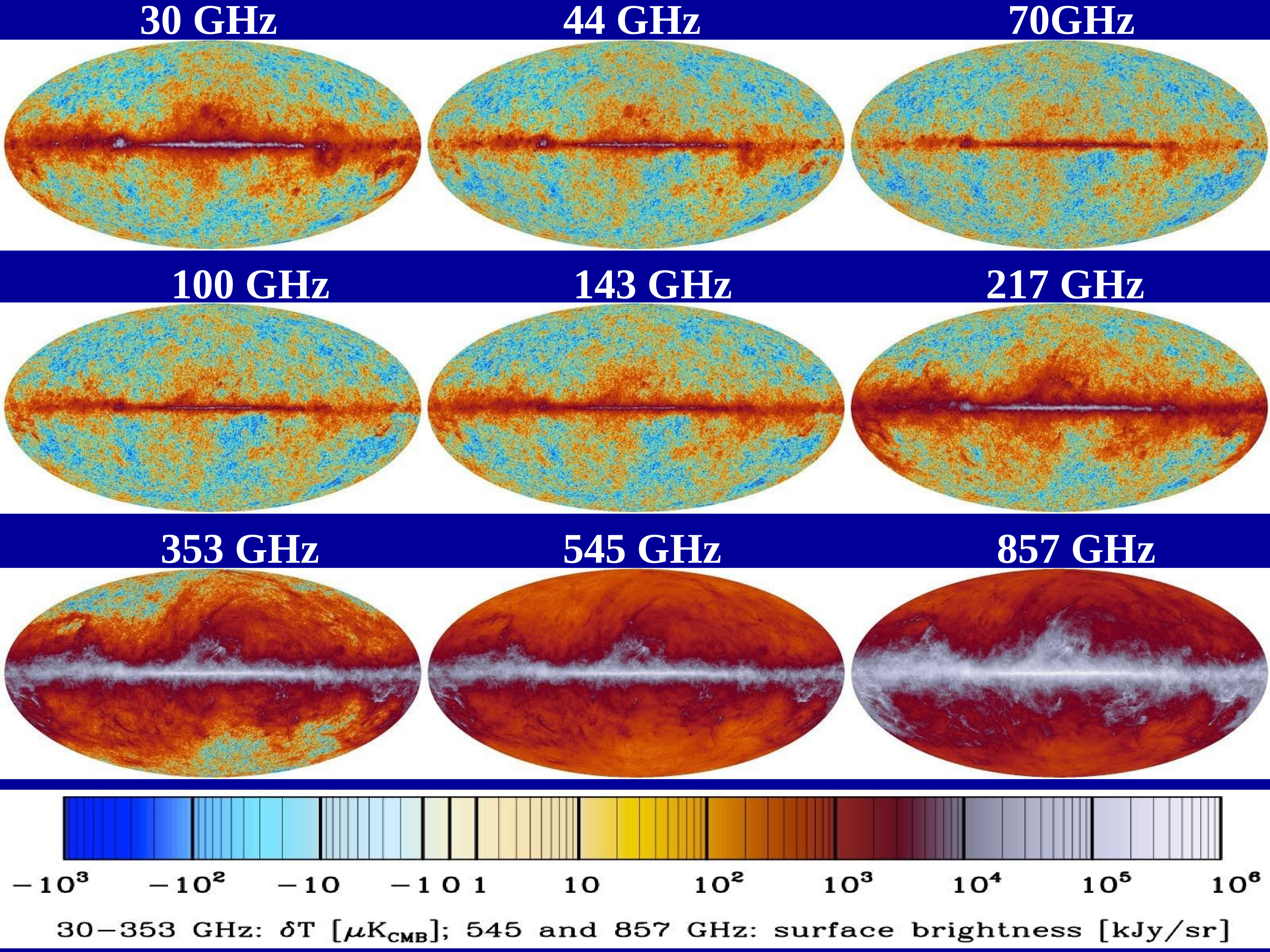


The orbit

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



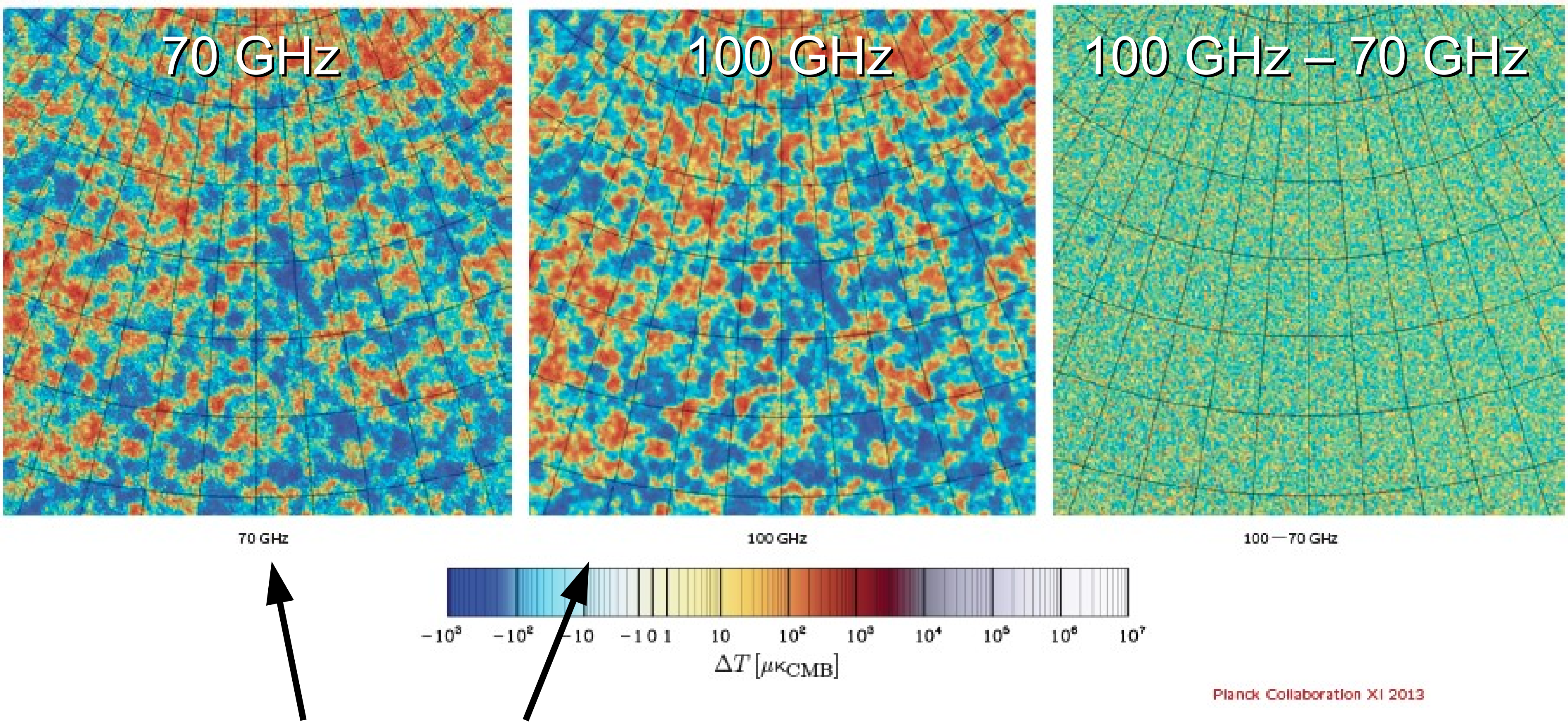




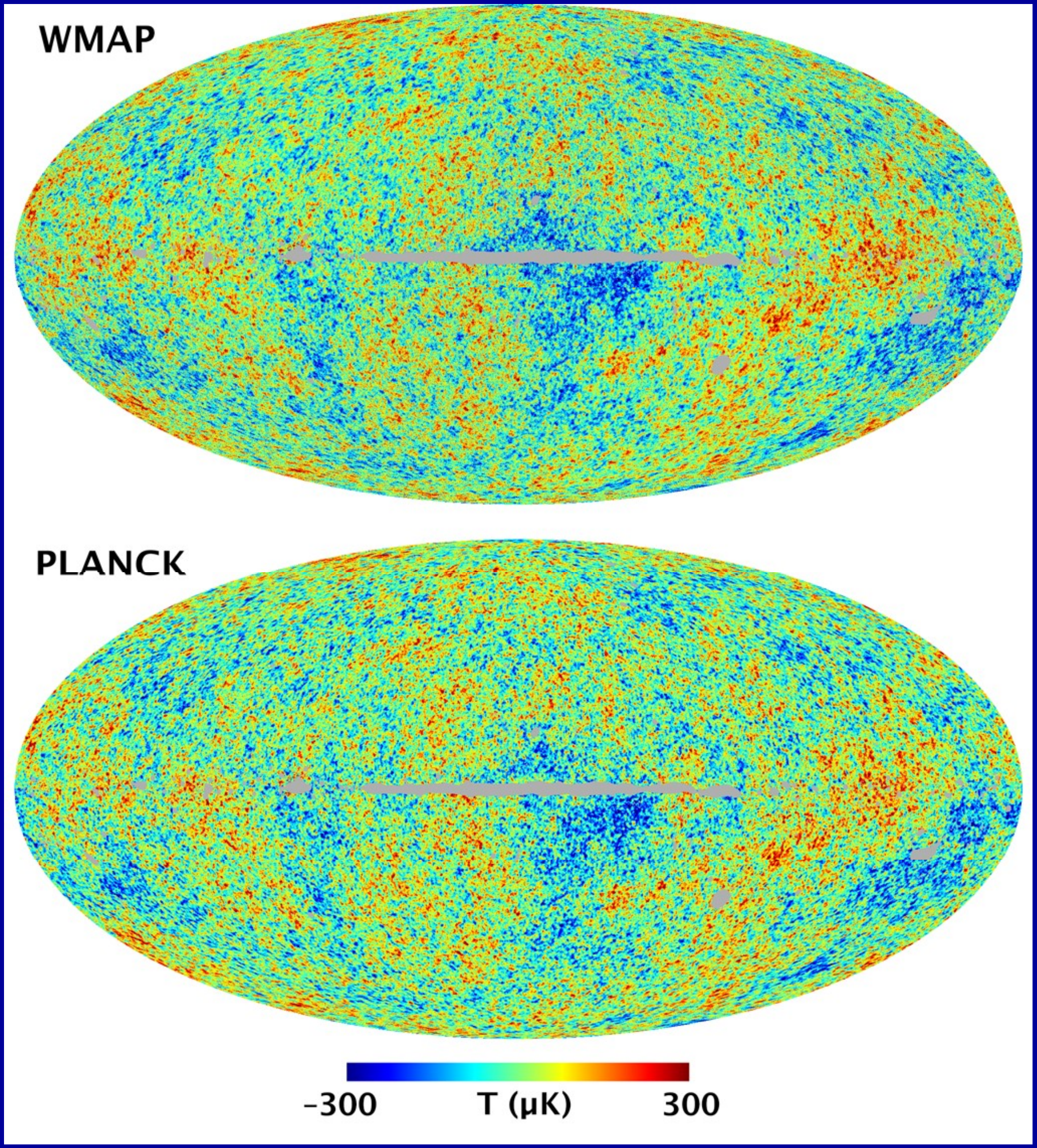
30 GHz
44 GHz
70GHz
100 GHz
143 GHz
217 GHz
353 GHz
545 GHz
857 GHz
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

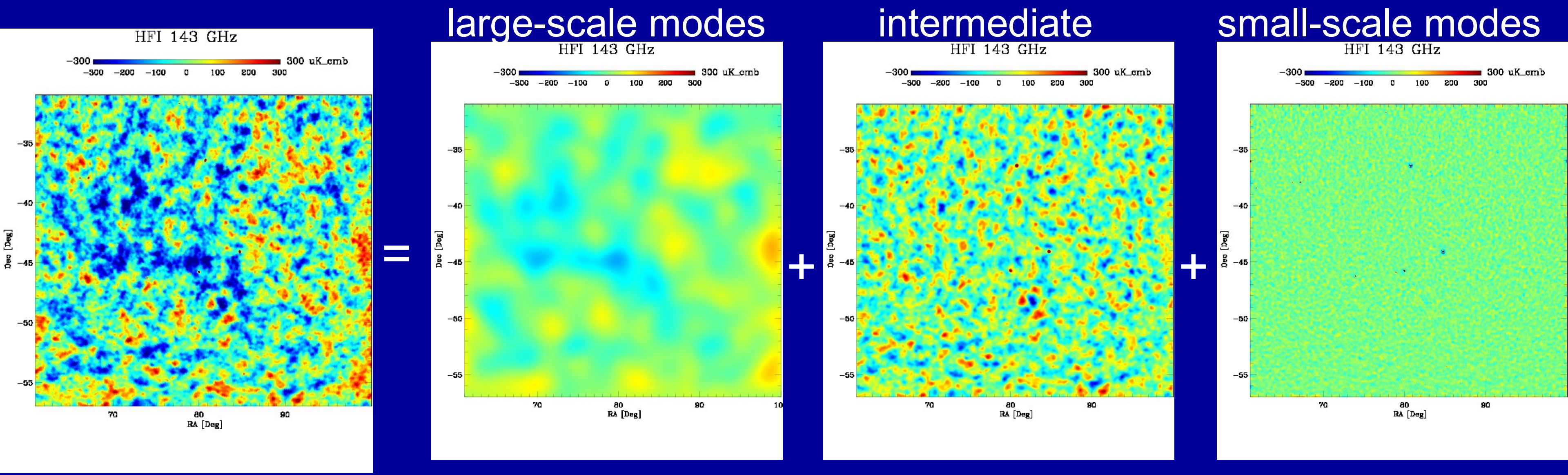
Beautifully Consistent Data

- Low-foreground patch of sky near the NEP



Different detector technologies, different systematics

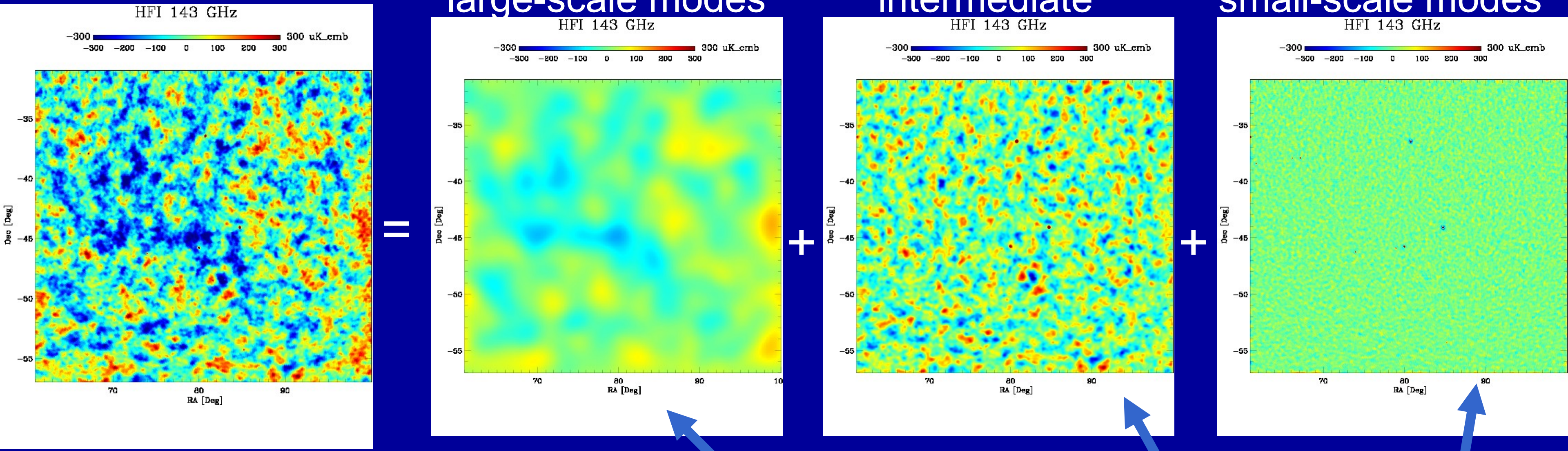

WMAP
PLANCK
-300
T (μK)
300



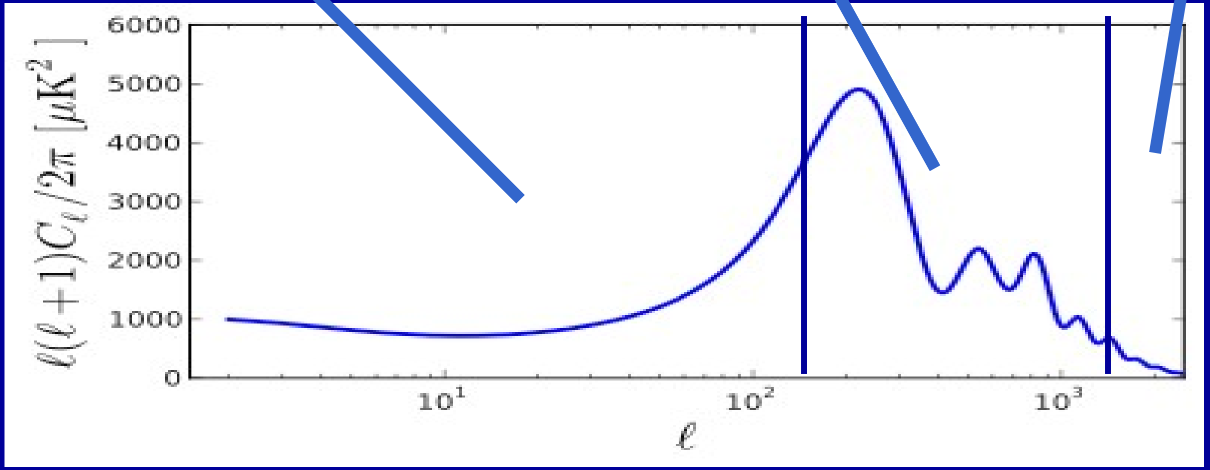
Let's decompose into band-limited maps and compare those

Band-limited Maps

large-scale modes
intermediate
small-scale modes



Fluctuation power



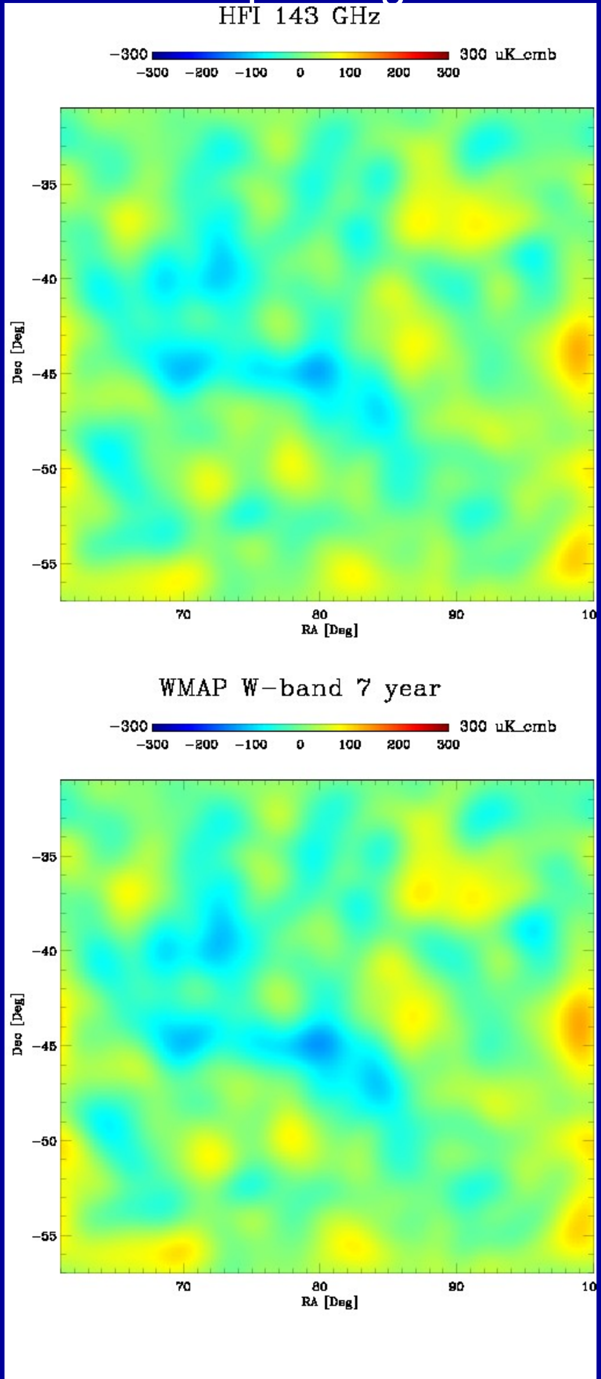
<-- large-scale modes

small-scale modes -->

Filtered to keep: large scales

Planck 143 GHz

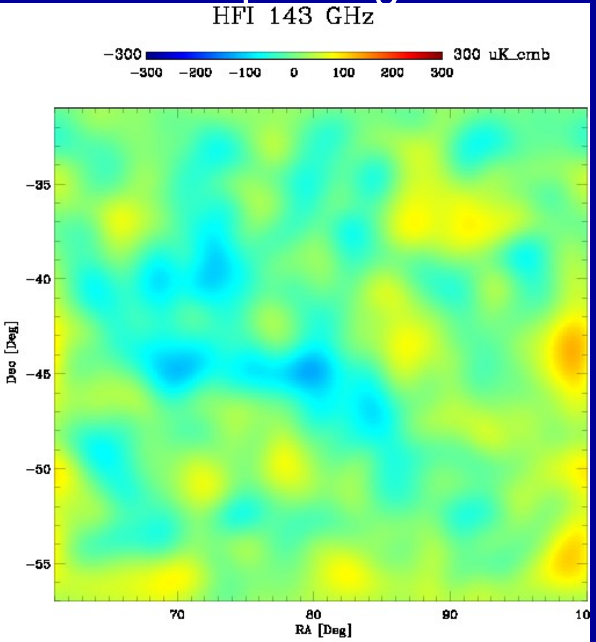
WMAP 94 GHz

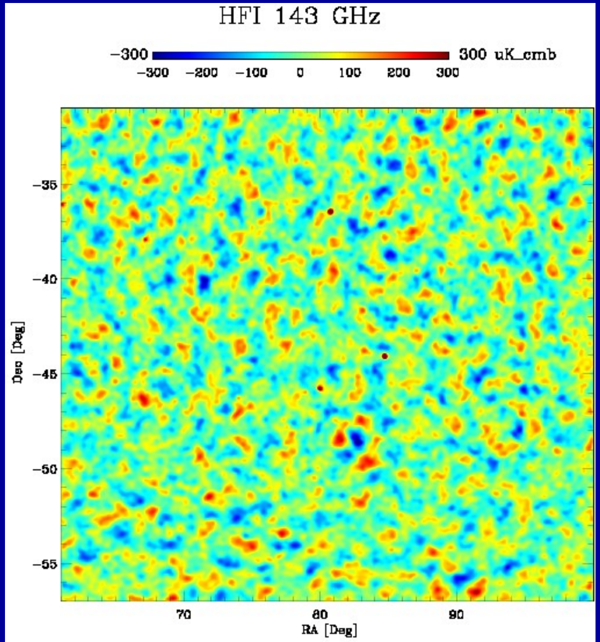


Comparison with WMAP: what’s new?

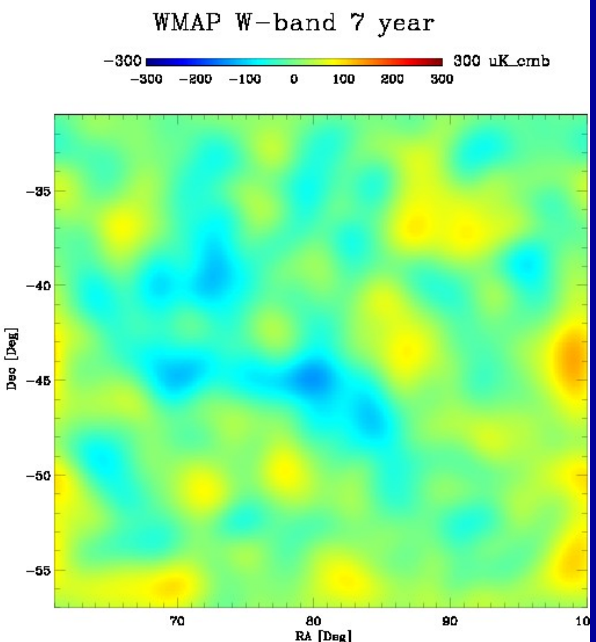
Filtered to keep: large scales intermediate scales

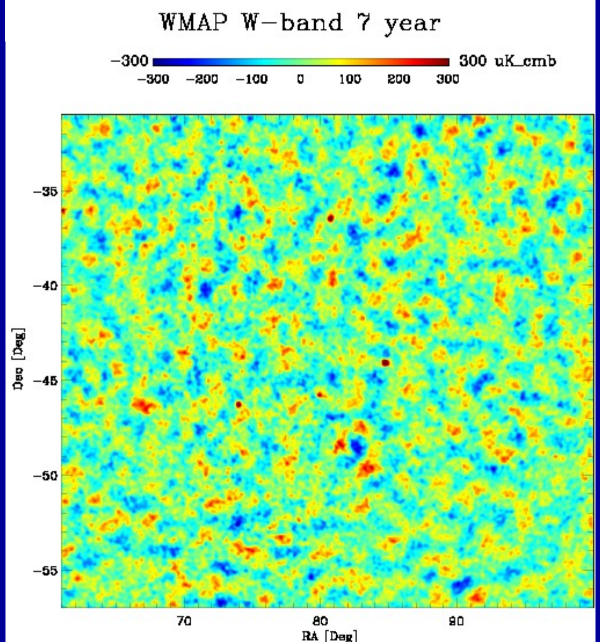
Planck 143 GHz

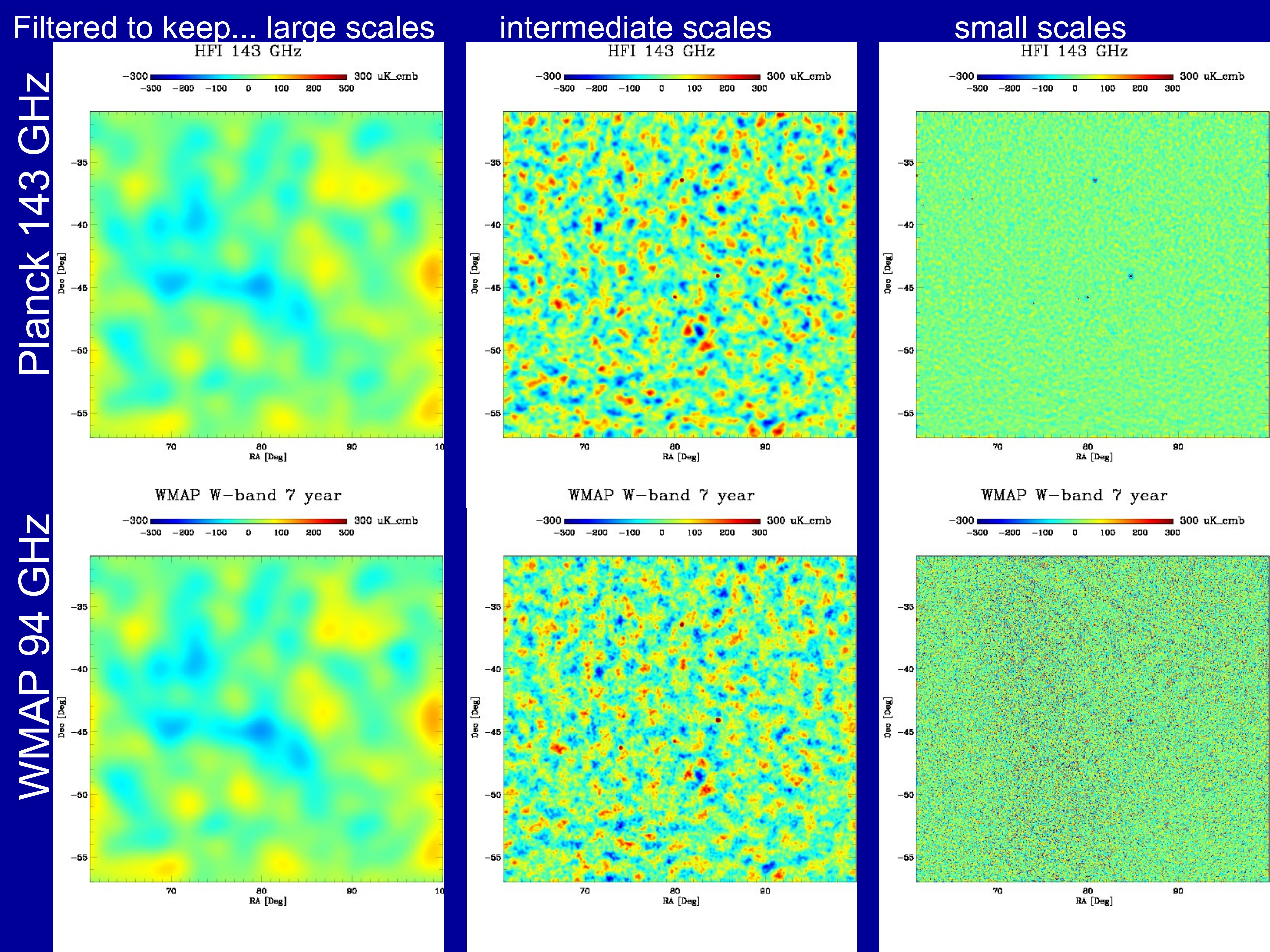




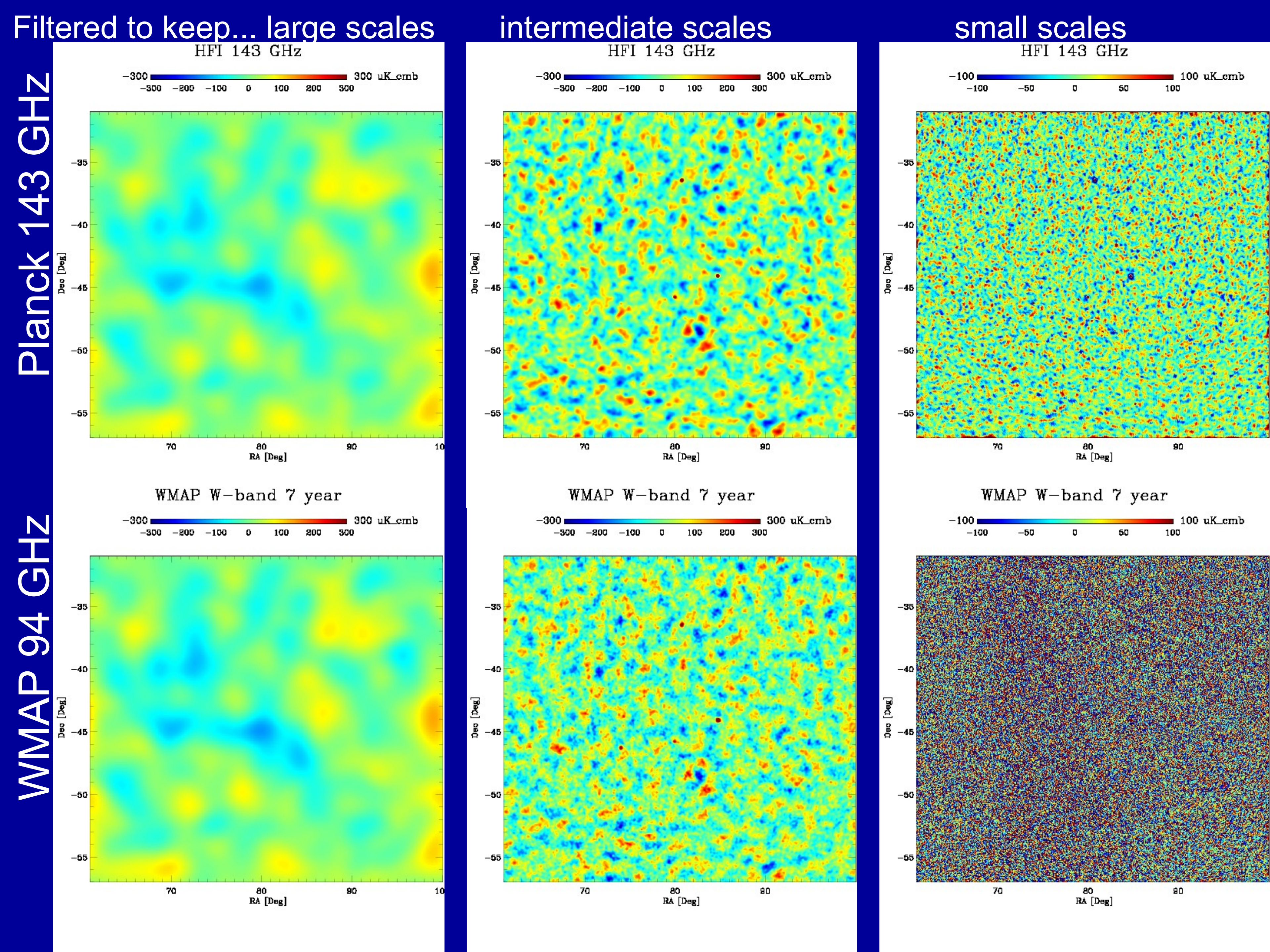
WMAP 94 GHz







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]
−35
−40
−45
−50
−55
70
80
90
RA [Deg]



Filtered to keep... large scales
intermediate scales
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Planck 143 GHz
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WMAP W-band 7 year
−300 300 uK_cmb
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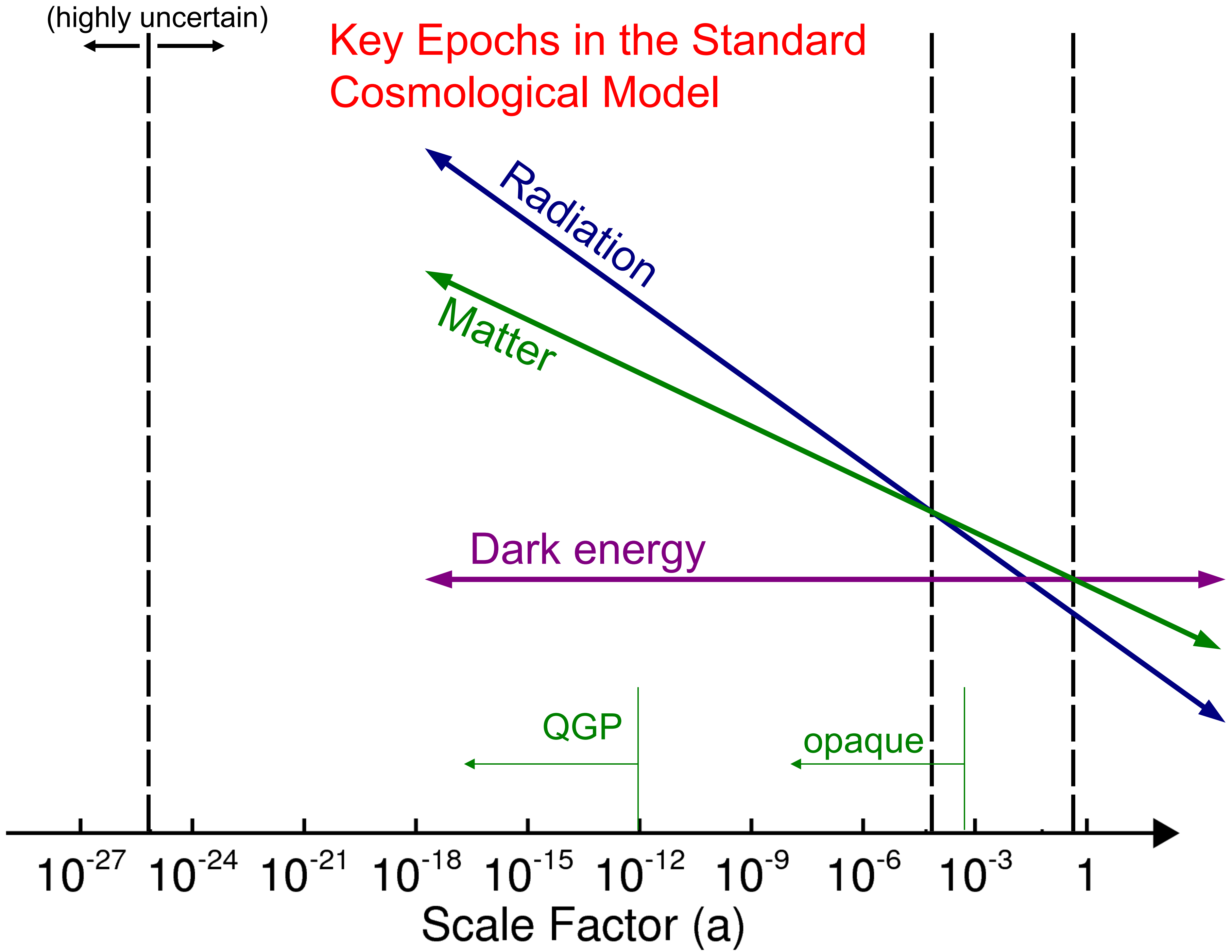
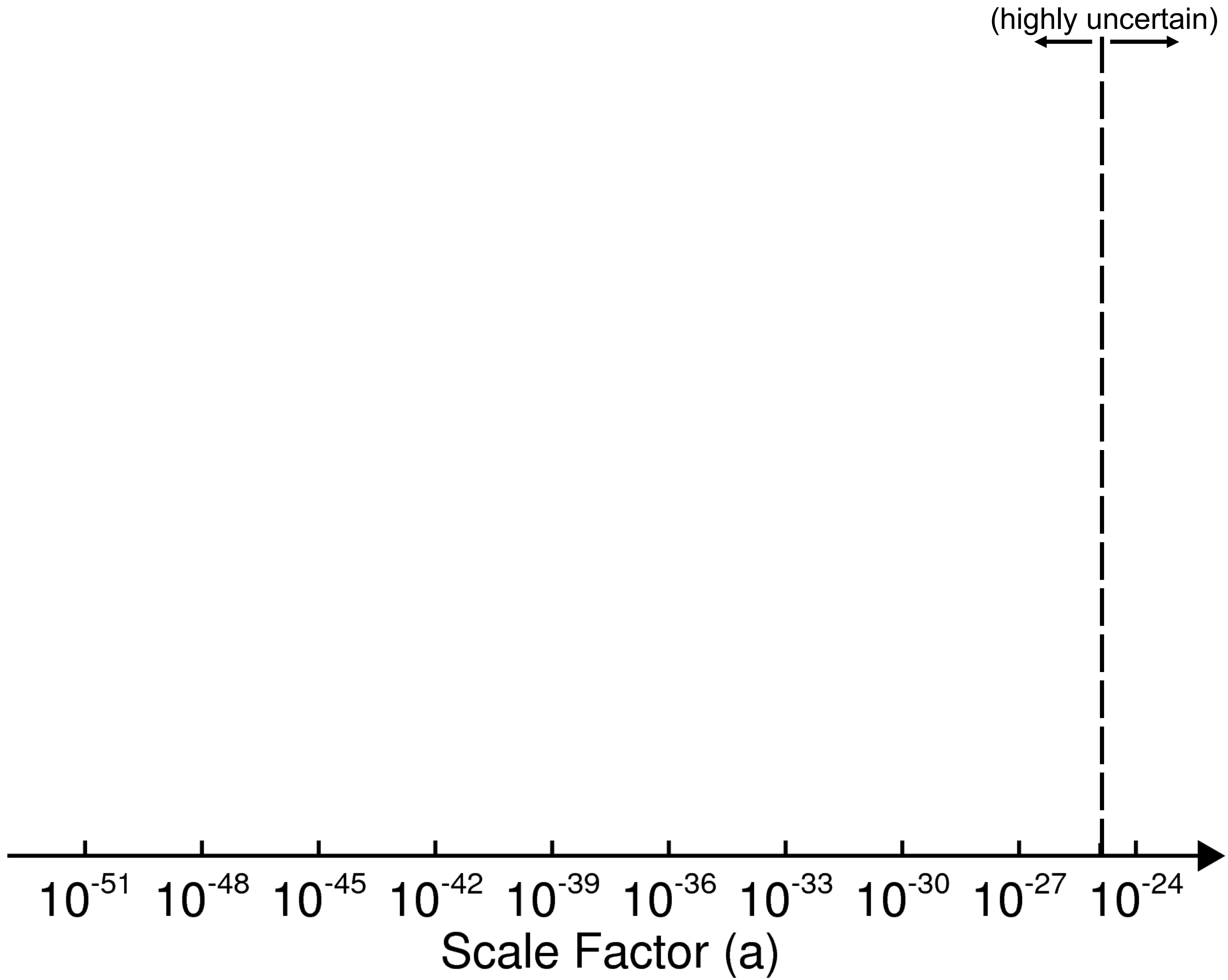
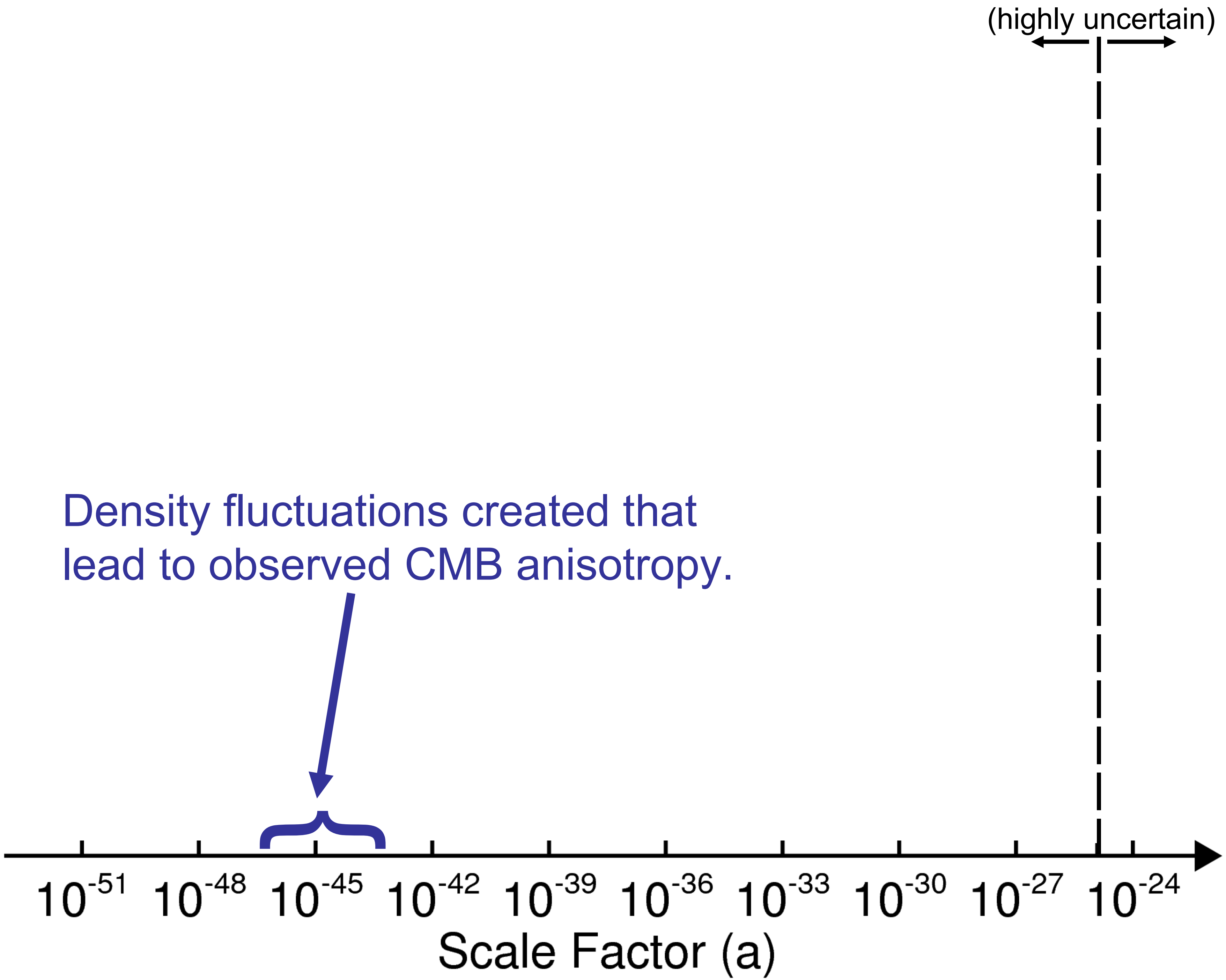
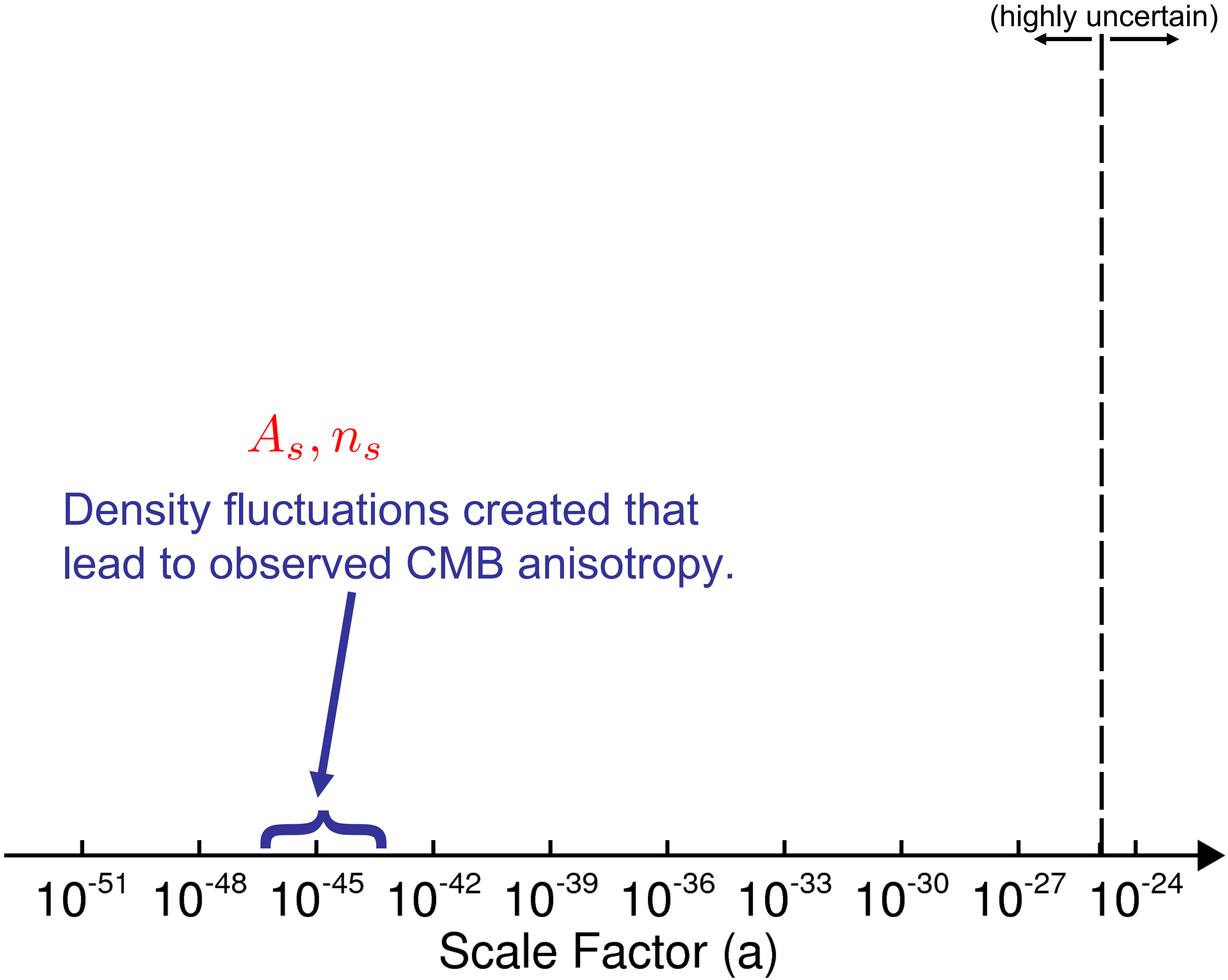
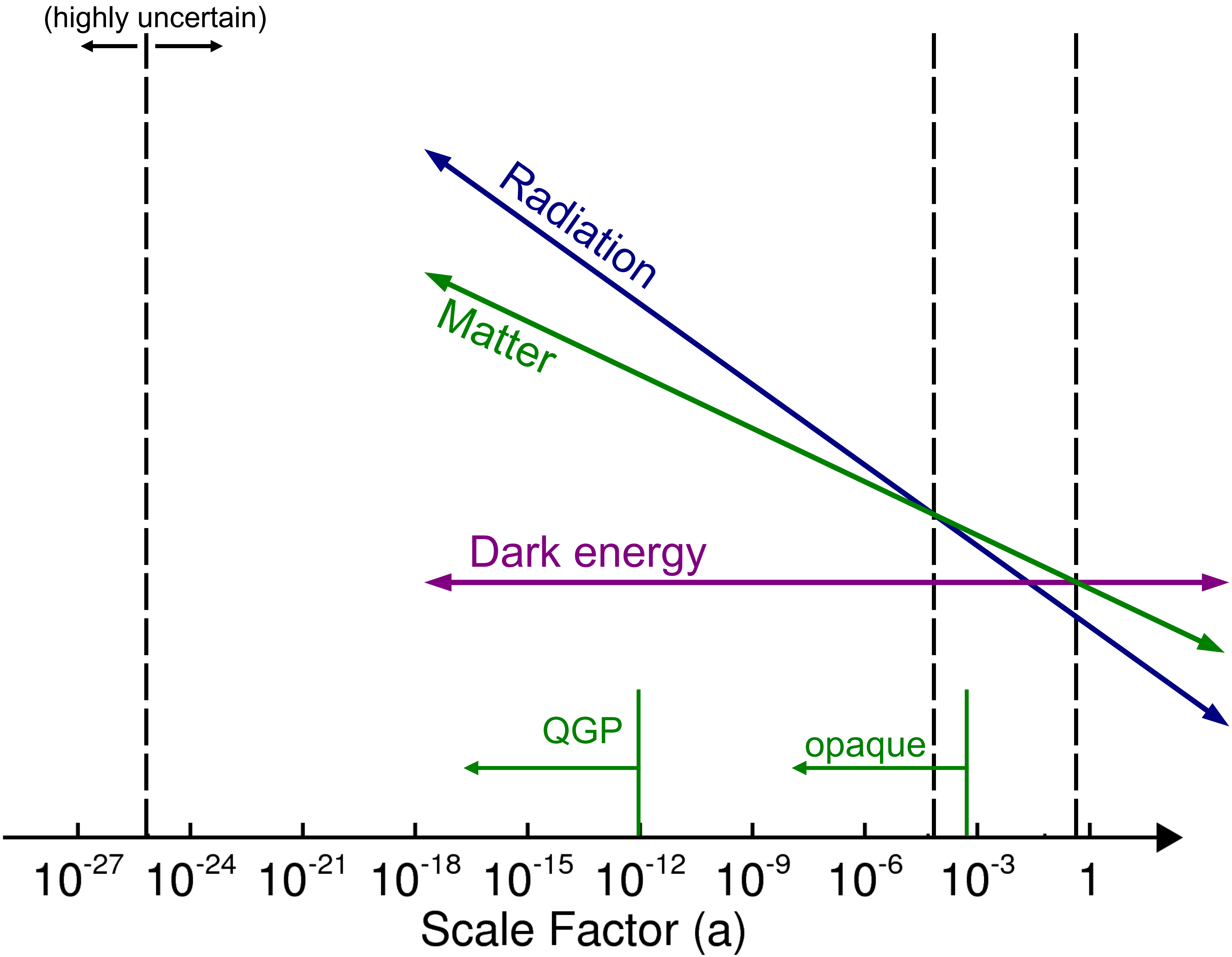

(highly uncertain)
Key Epochs in the Standard Cosmological Model
Radiation
Matter
Dark energy
QGP
opaque
10^-27 10^-24 10^-21 10^-18 10^-15 10^-12 10^-9 10^-6 10^-3 1
Scale Factor (a)


(highly uncertain)
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)
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)
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)
Radiation
Matter
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QGP
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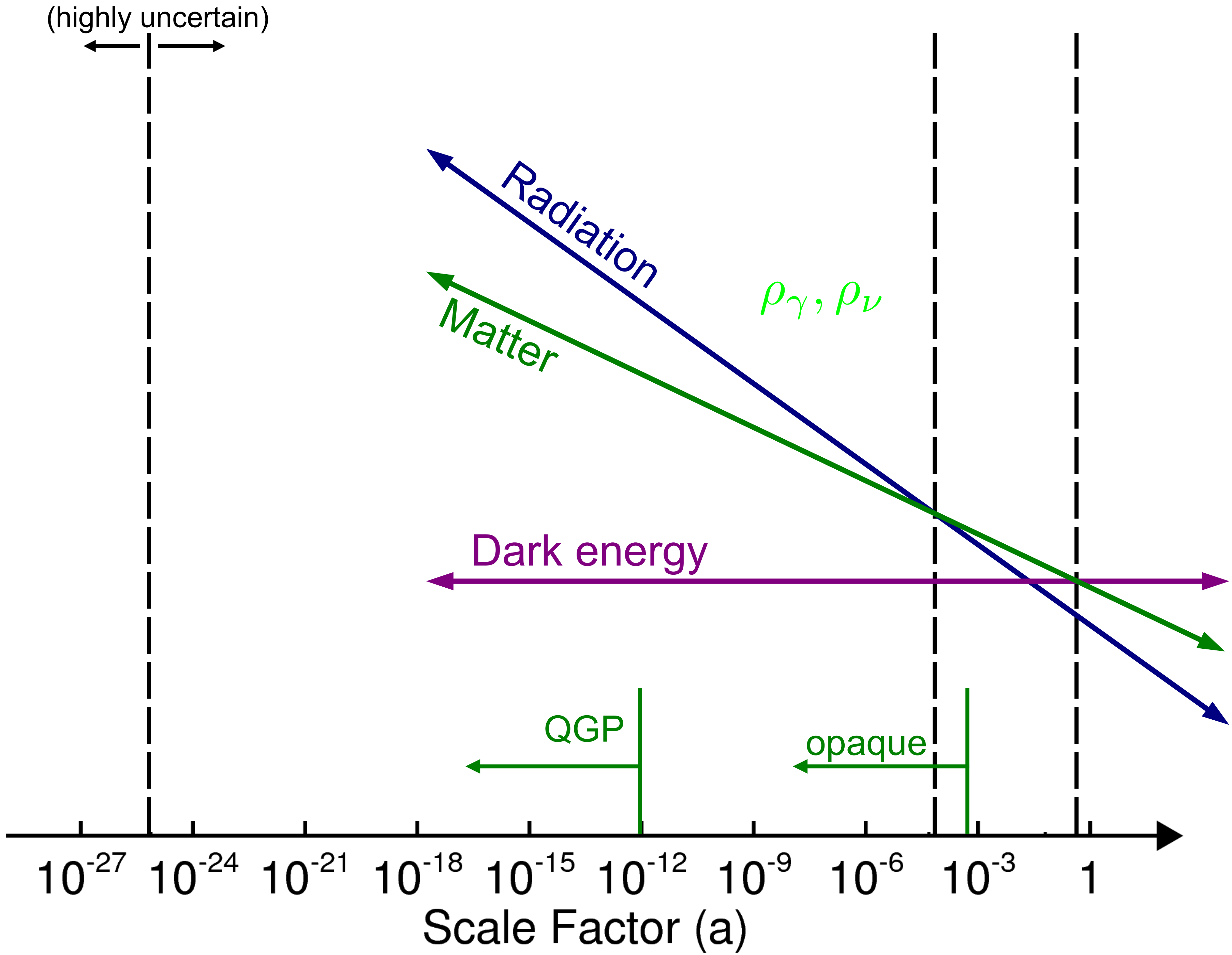
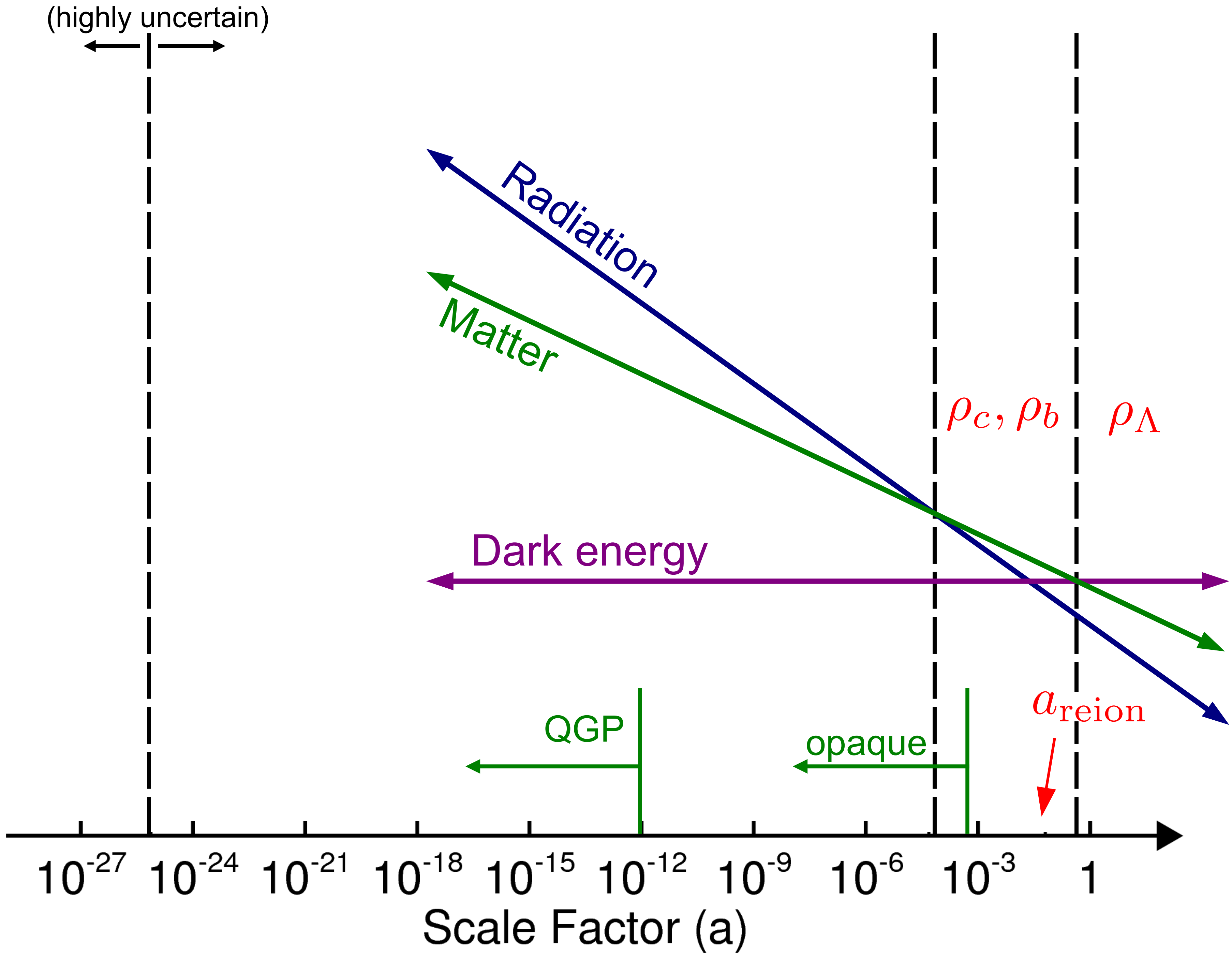
10^-27 10^-24 10^-21 10^-18 10^-15 10^-12 10^-9 10^-6 10^-3 1
Scale Factor (a)


(highly uncertain)
Radiation
Matter
ρ_γ, ρ_ν
Dark energy
QGP
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)
Radiation
Matter
ρ_c, ρ_b
ρ_Λ
Dark energy
$a_{\rm reion}$
QGP
opaque
10^{-27} 10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1
Scale Factor (a)

The six-parameter ΛCDM model

A_s, n_s

Governs Spectrum of Primordial fluctuations

$\rho_b = \Omega_b h^2$

$\rho_c = \Omega_c h^2$

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

Matter Content

Scale factor at reionization

$a_{\rm reion}$

The six-parameter ΛCDM model

$$A_s, n_s$$

Governs Spectrum of Primordial fluctuations

$$\rho_b = \Omega_b h^2$$
$$\rho_c = \Omega_c h^2$$
$$\rho_\Lambda = \Omega_\Lambda h^2$$

Matter Content

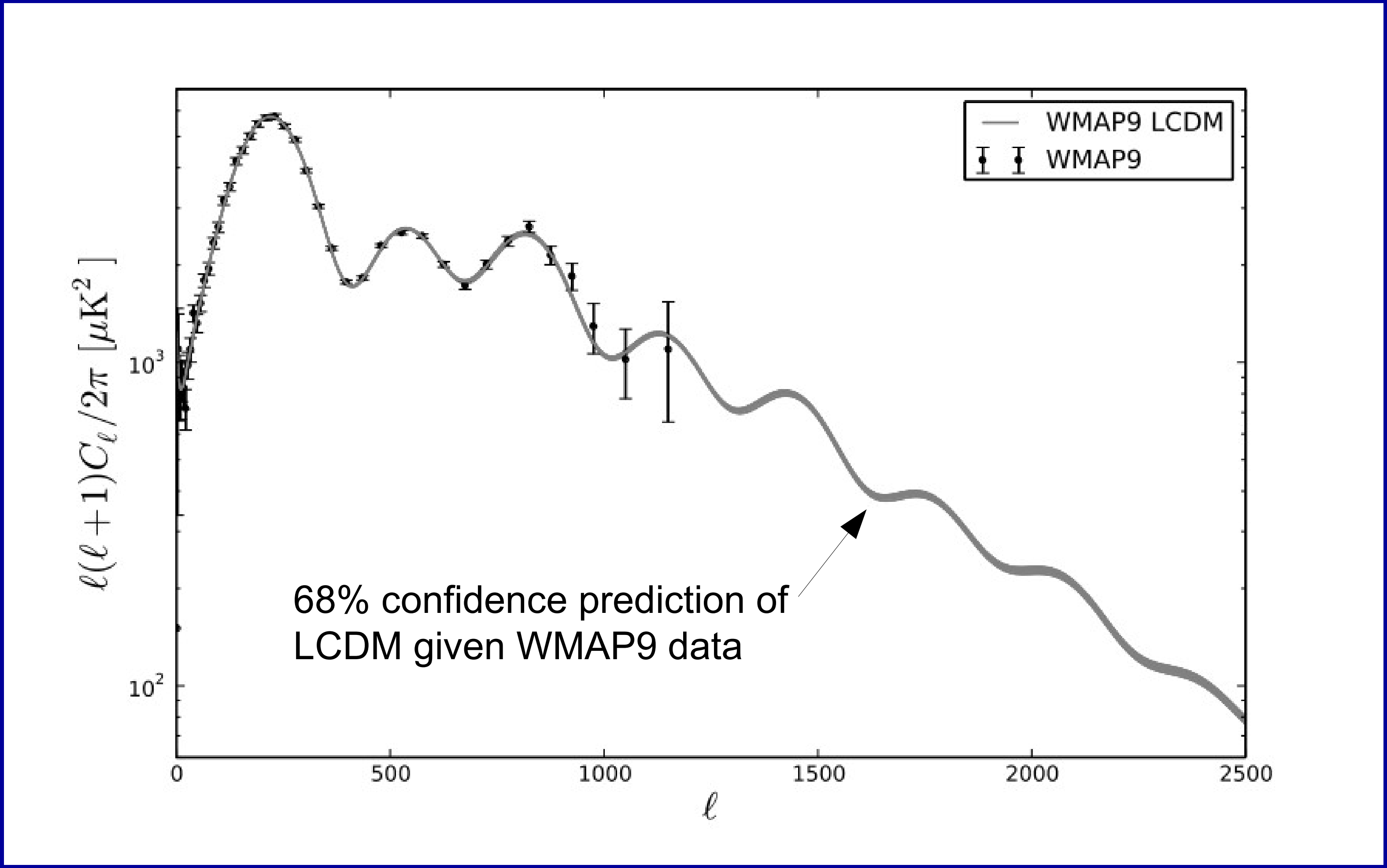
$$N_{\rm eff}, \Sigma m_\nu, w, \Omega_K, \ldots$$

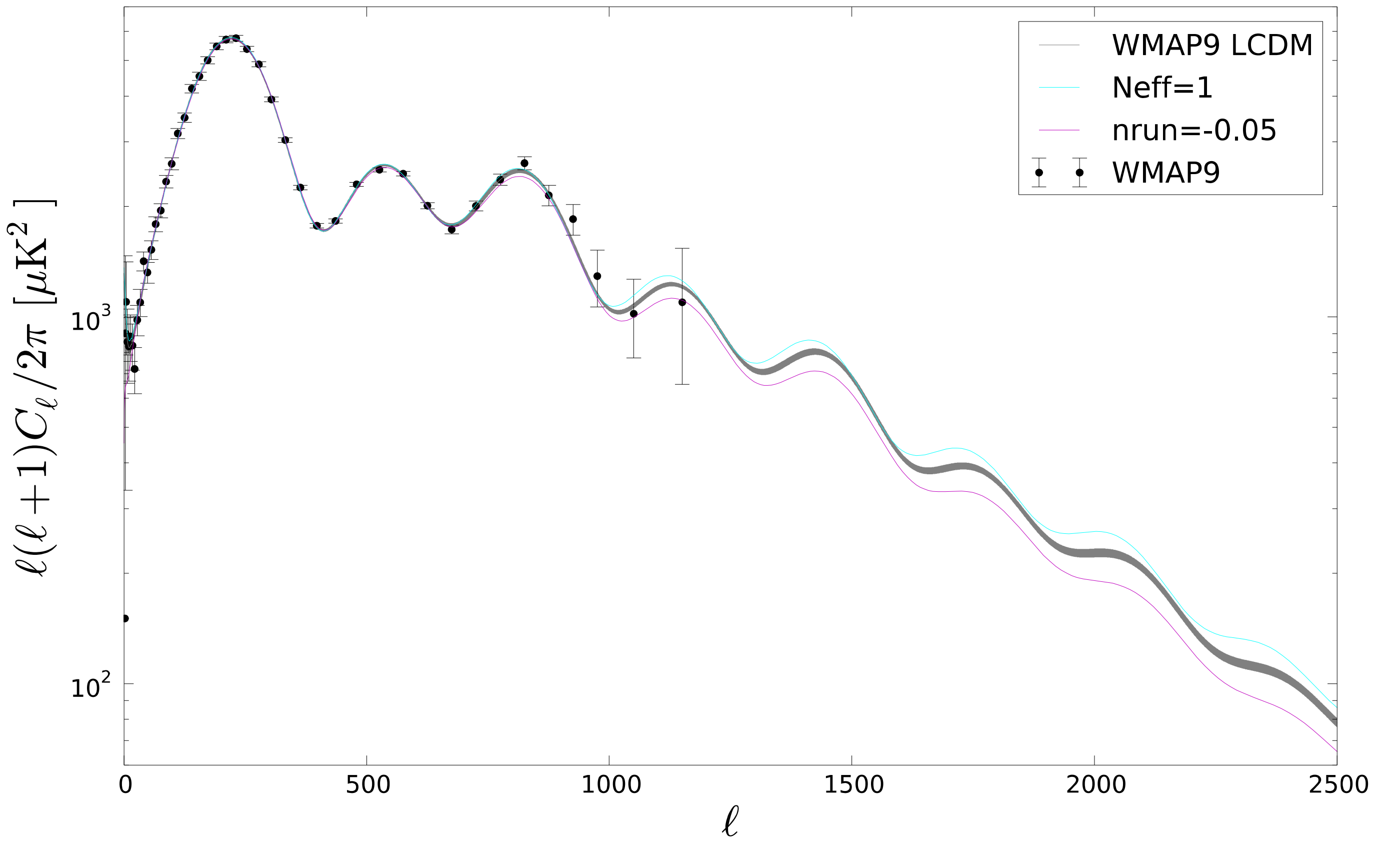
Extensions

Scale factor at reionization

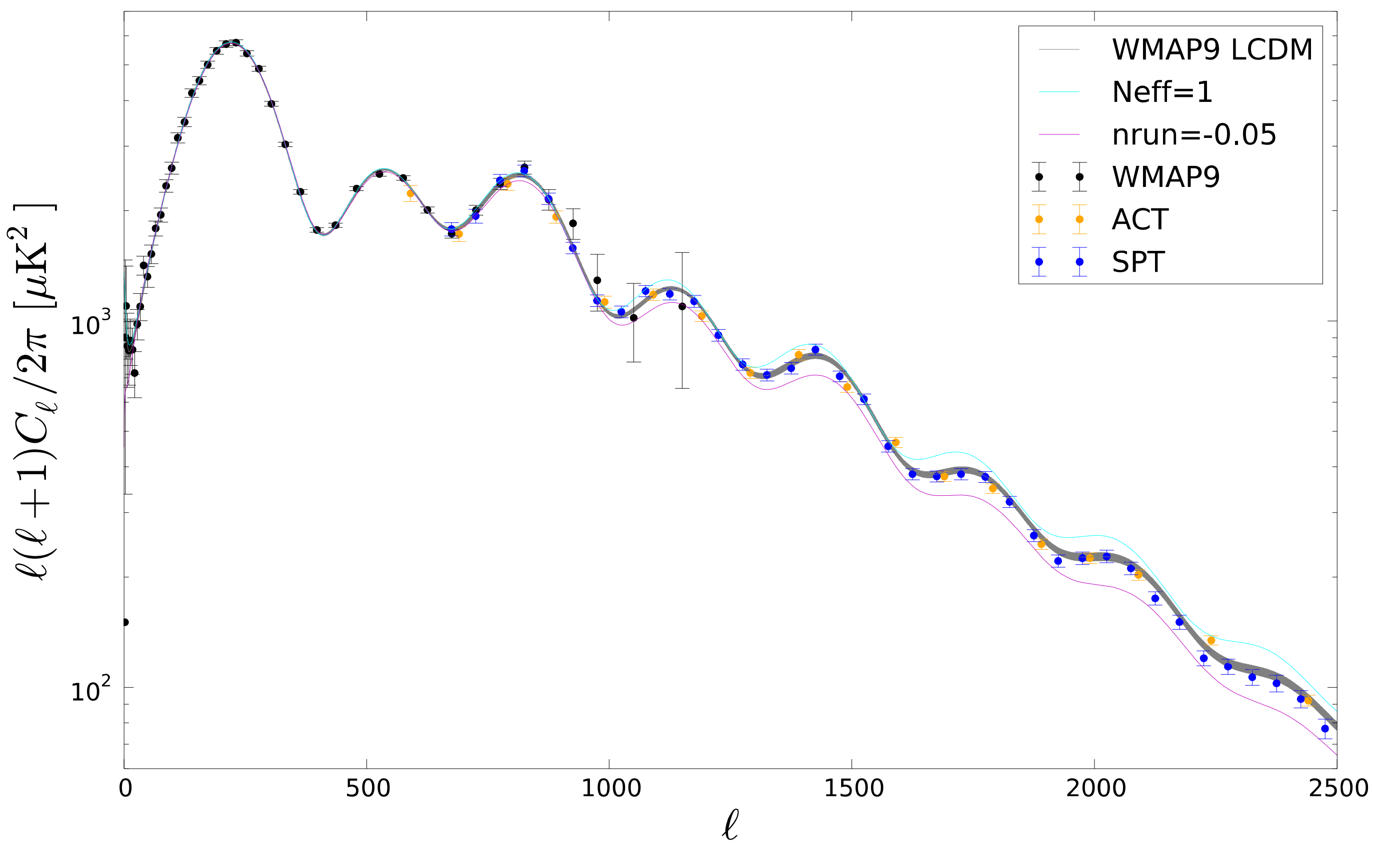
$$a_{\rm reion}$$

LCDM makes a very precise prediction

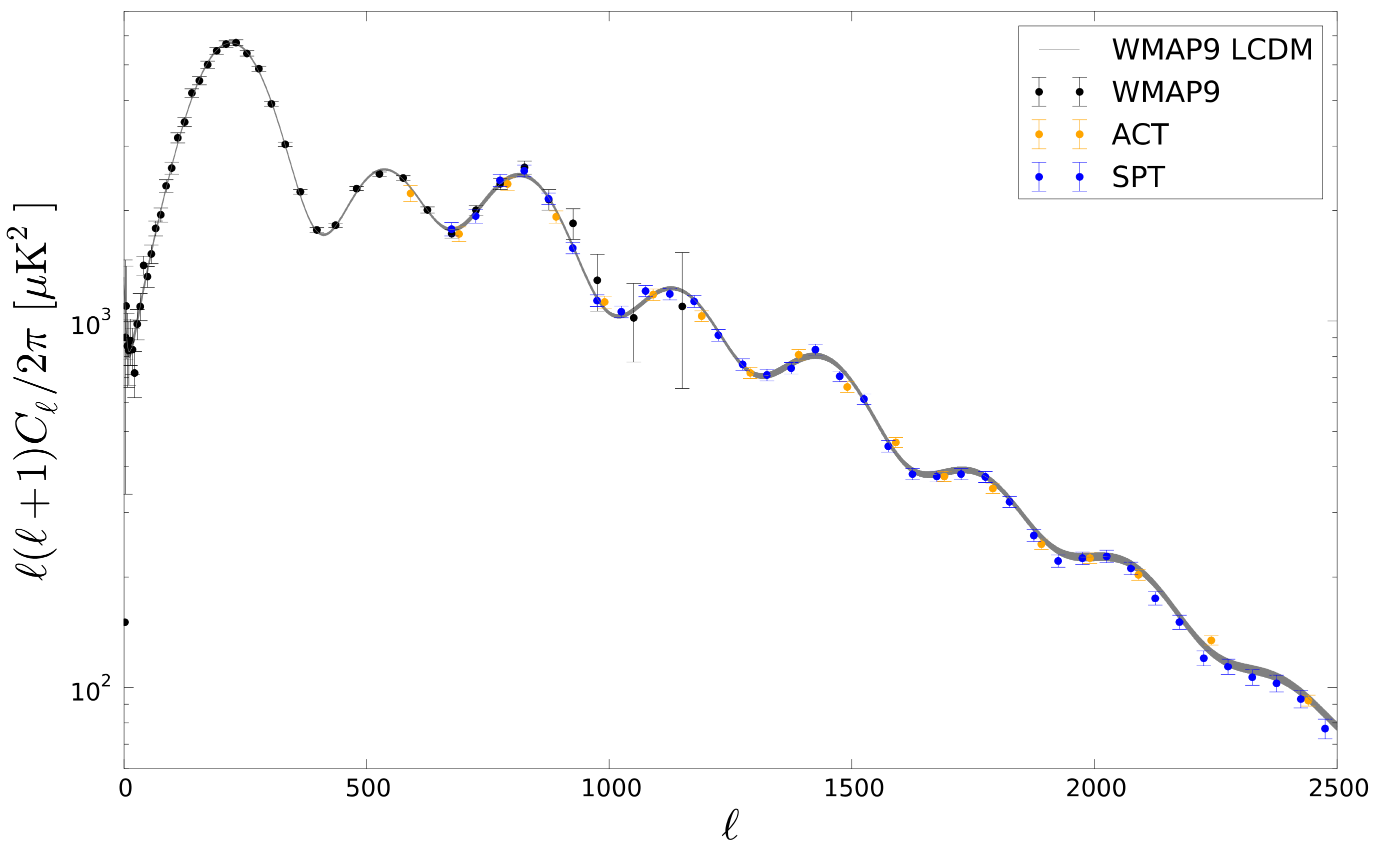




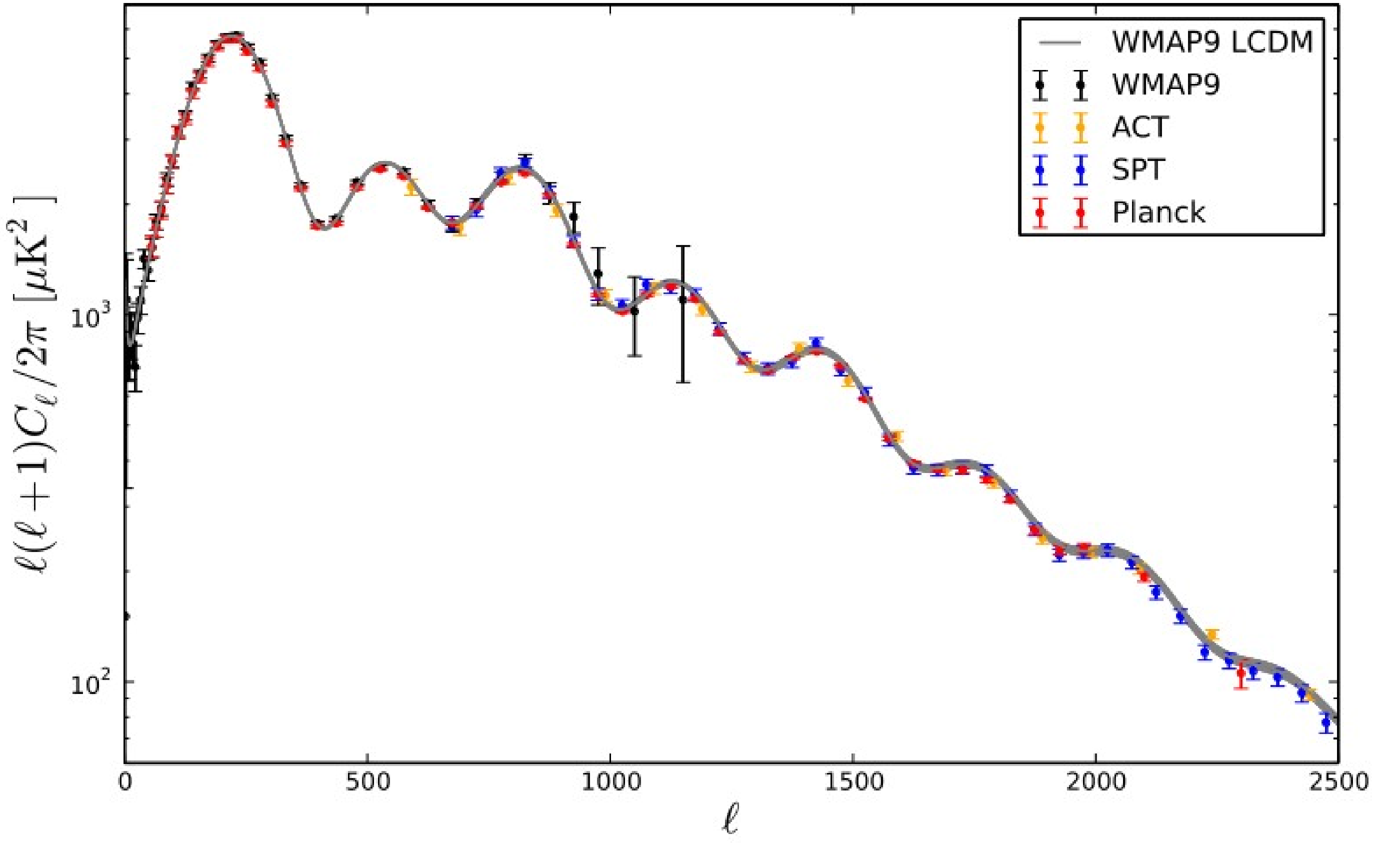
WMAP9 LCDM
Neff=1
nrun=-0.05
WMAP9
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ



WMAP9 LCDM
Neff=1
nrun=-0.05
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
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ



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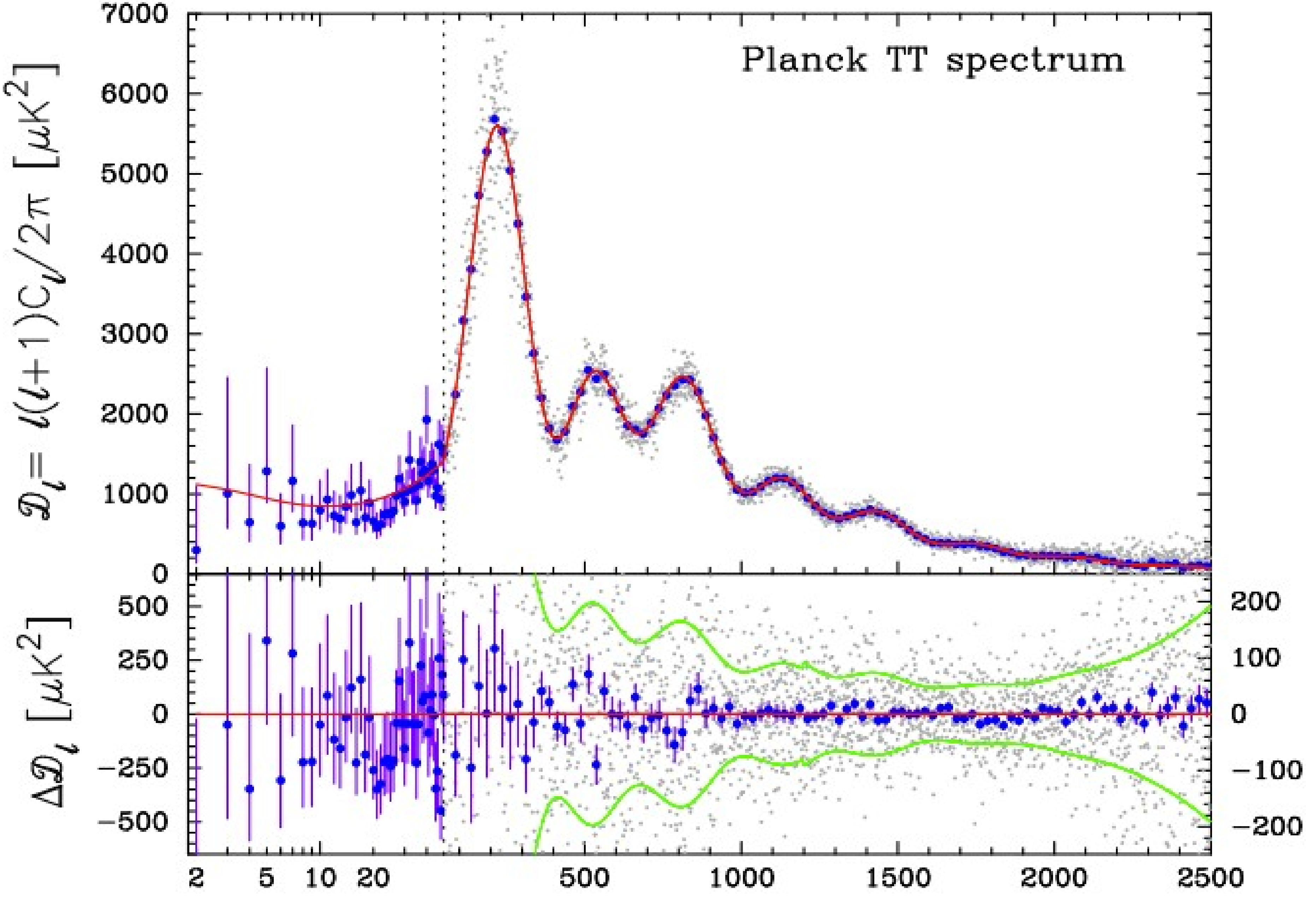
2000
2500
ℓ



ΛCDM is a good fit!

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*

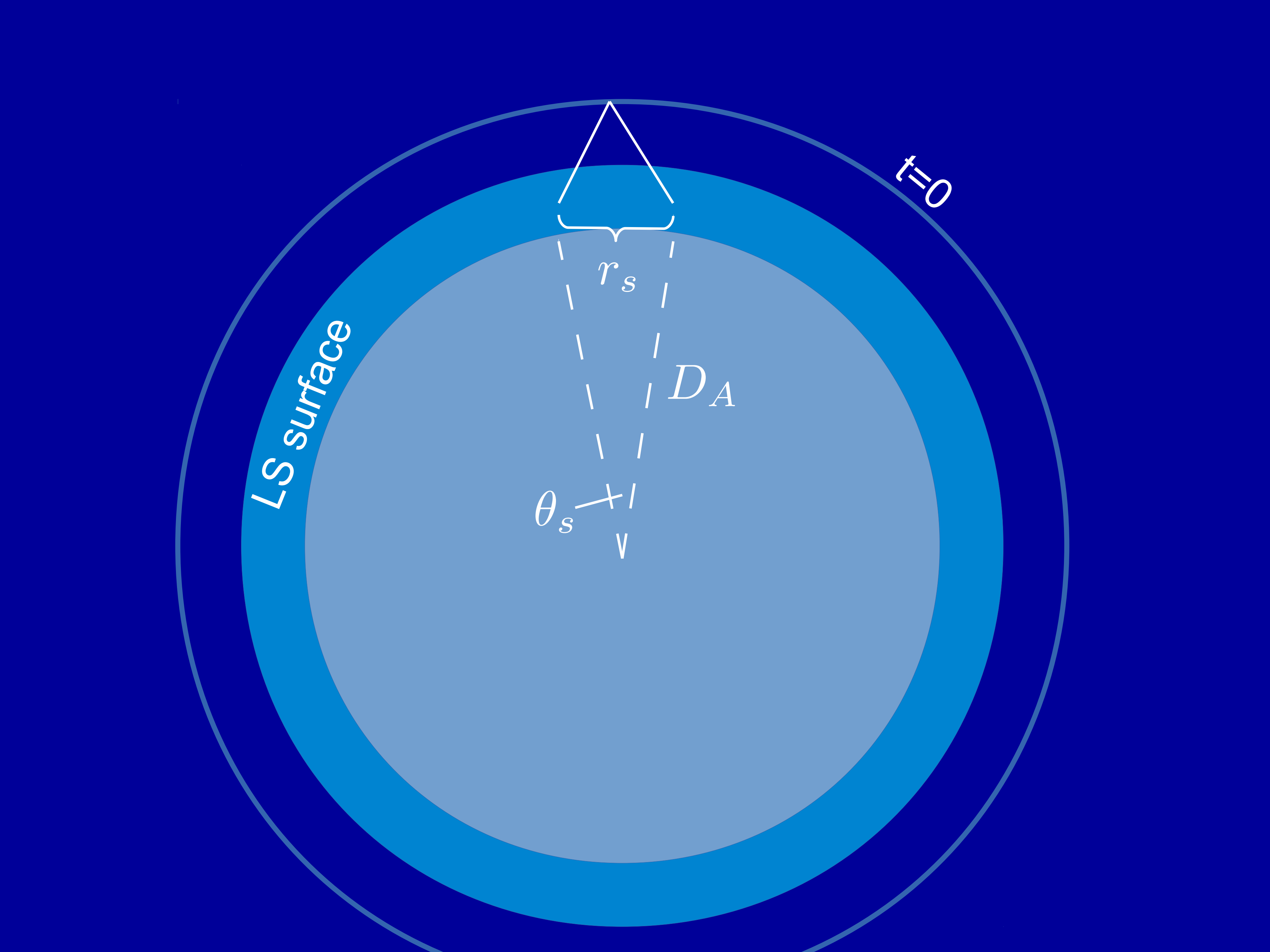
- Other CMB measurements (e.g. WMAP, SPT, and ACT)

Consistent (but not explained well in Planck papers)

- Cepheids + SNe for determining H_0
- CFHTLS cosmic shear power spectrum
- σ_8 inferred from cluster counts

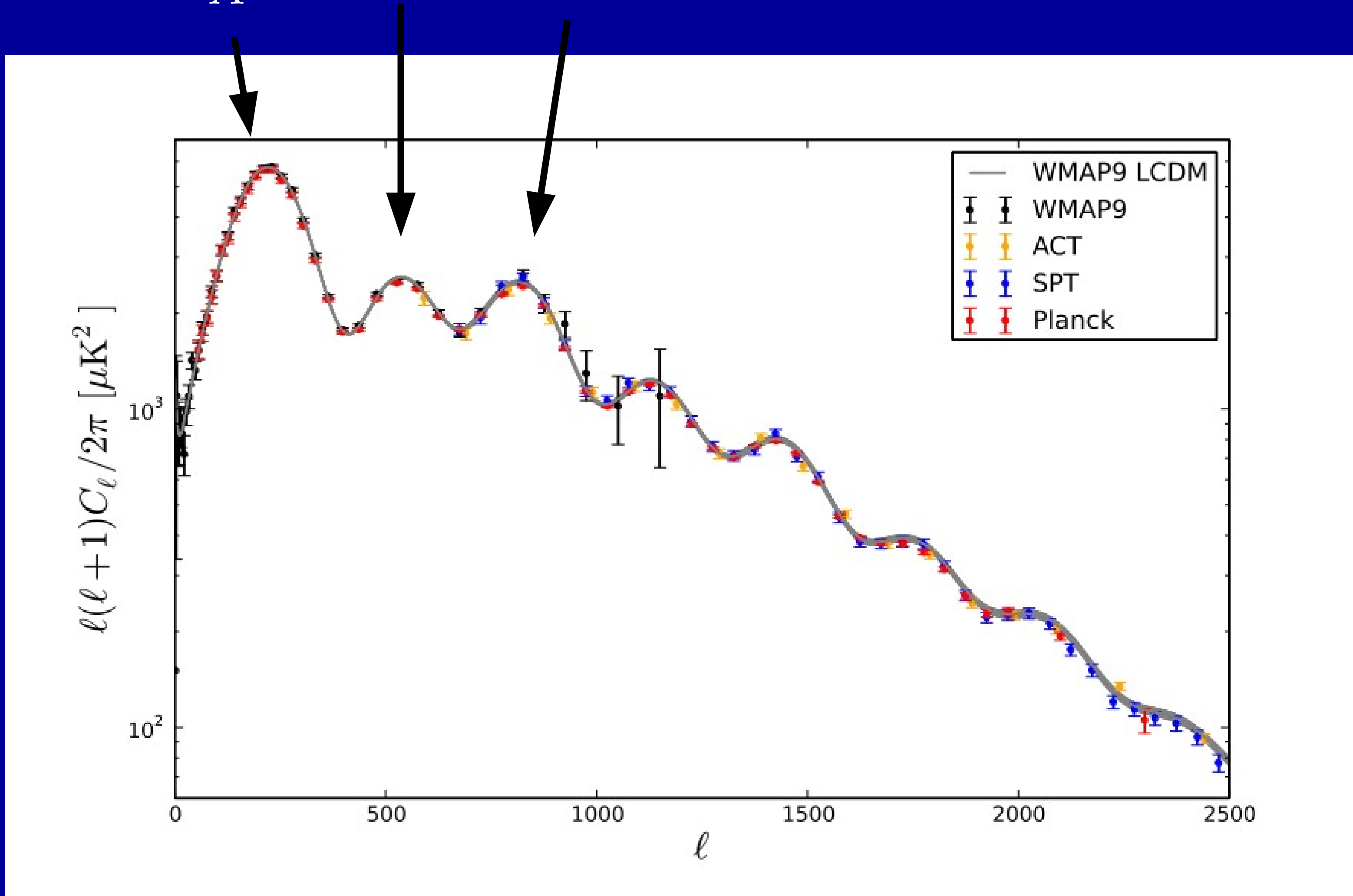
Some tension*

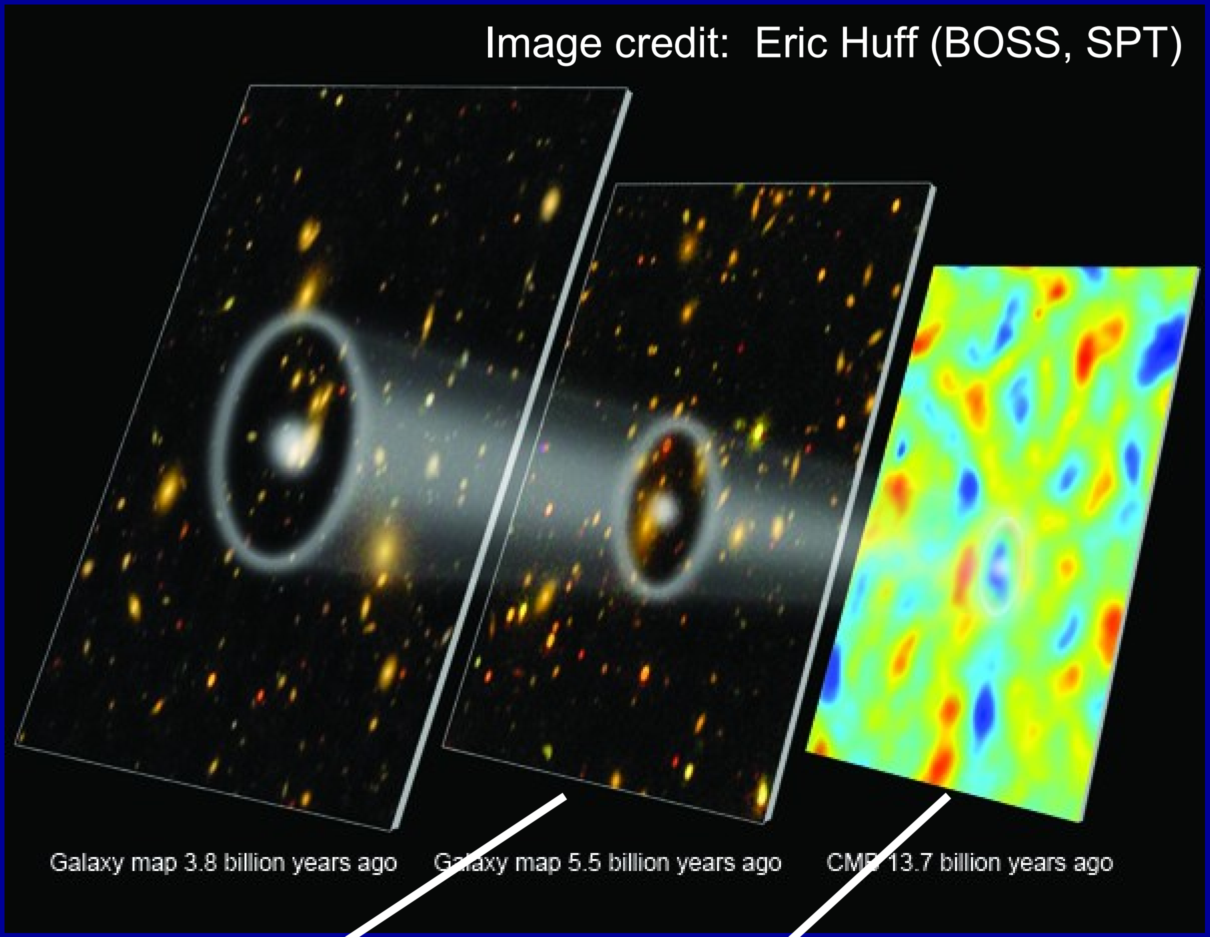
*Assuming the ΛCDM model



t=0
LS surface
r_s
D_A
θ_s

$\theta_s = \frac{r_s}{D_A}$ controls peak locations





Planck:

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

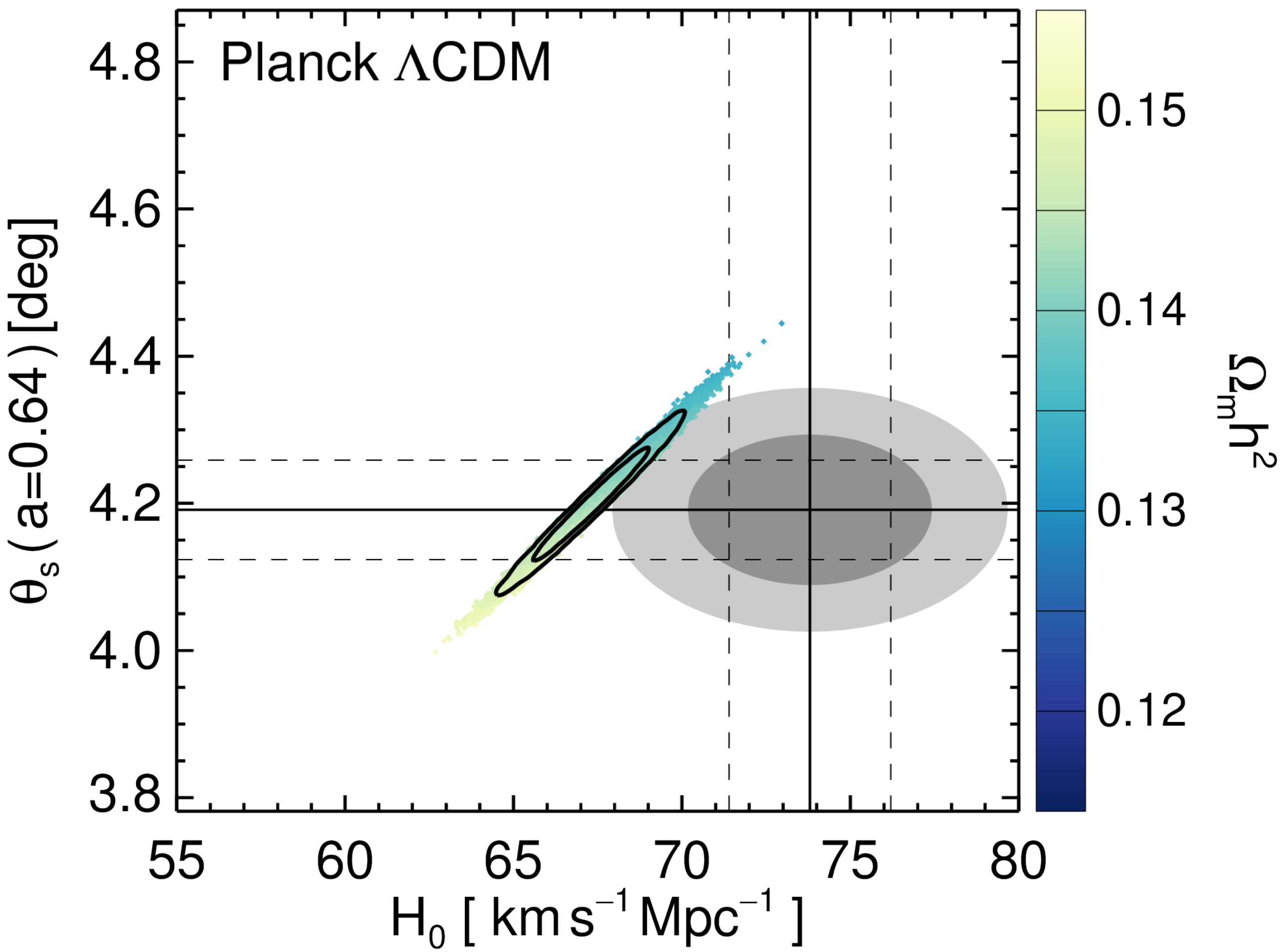
SDSS-BOSS:

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

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

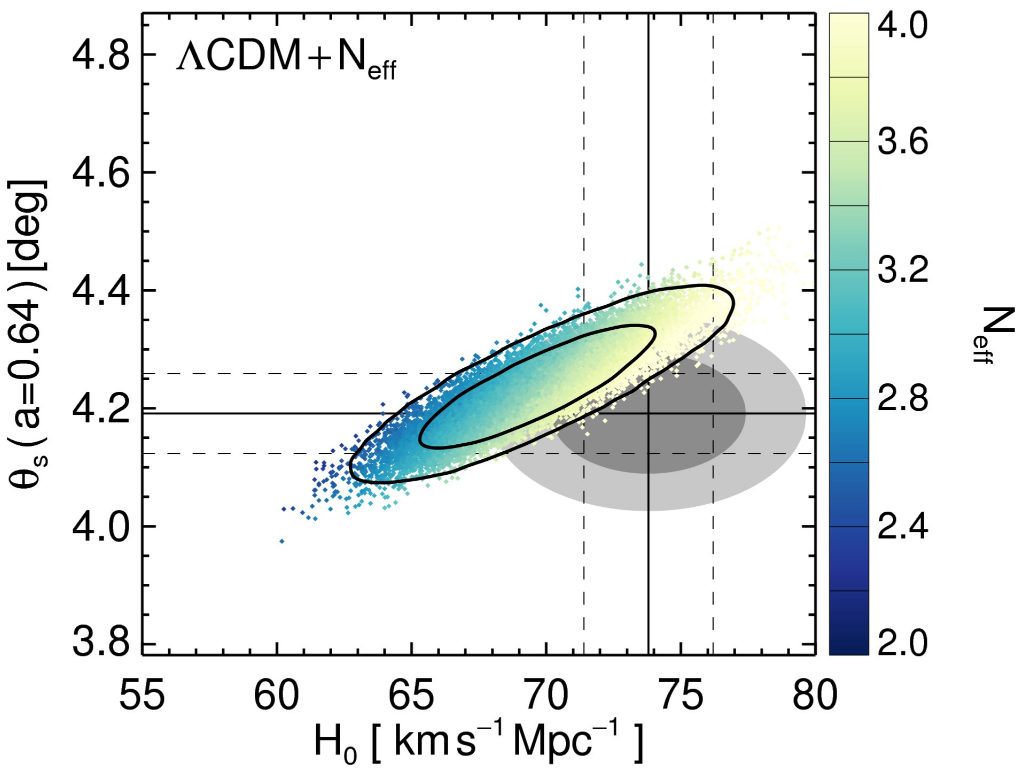
BOSS BAO, Riess et al. (2011) H_0 and Planck LCDM

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



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



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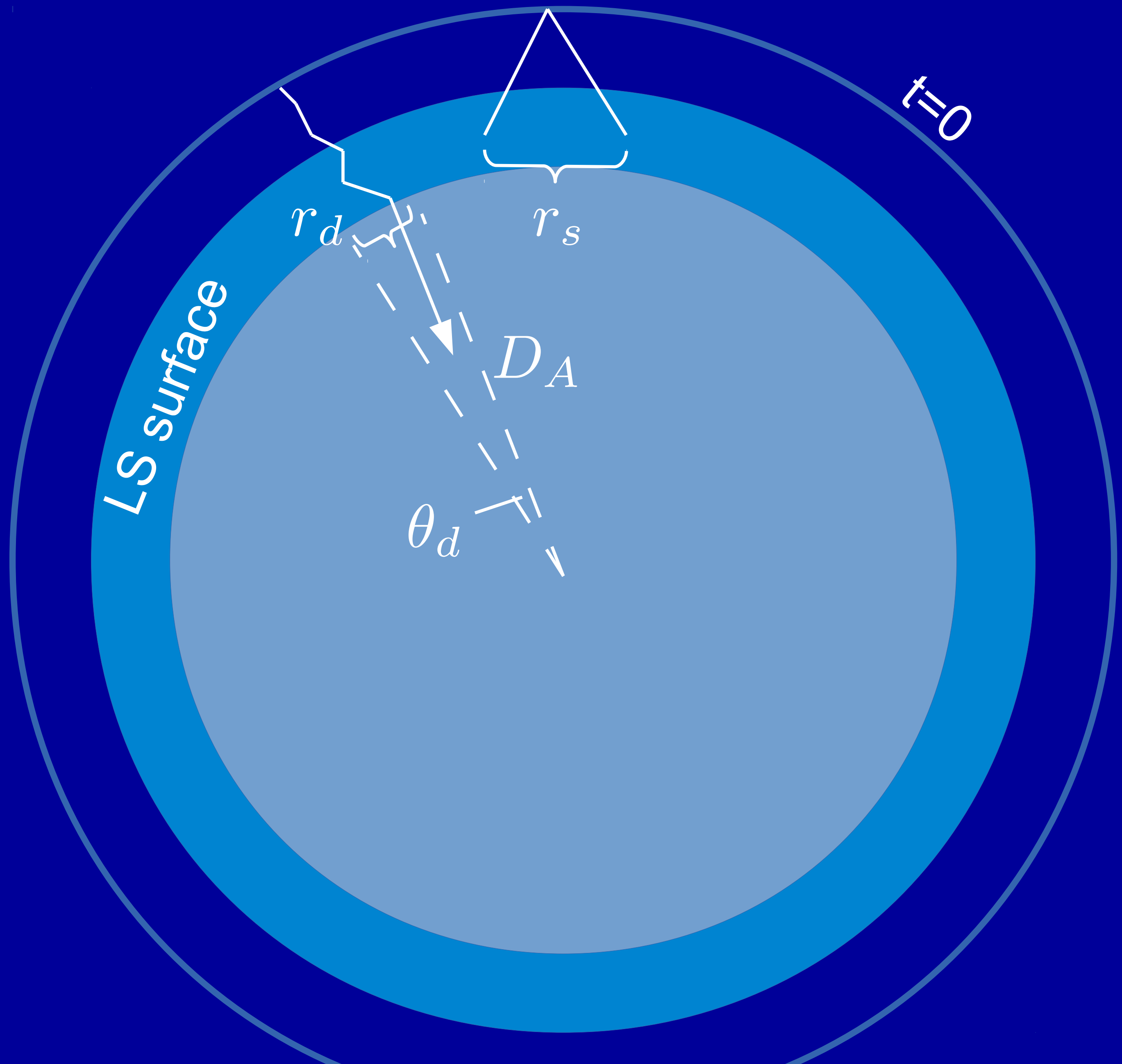
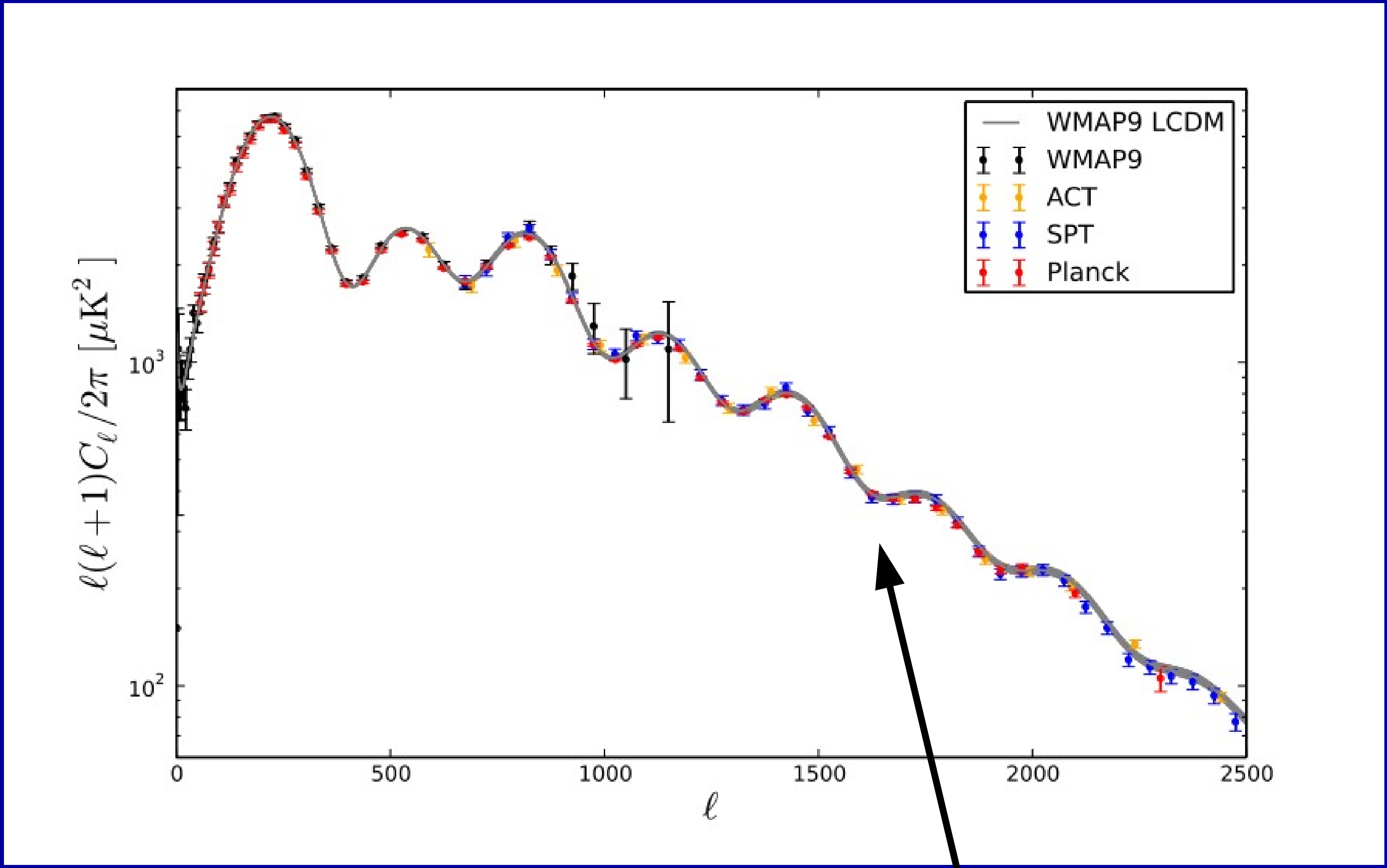

t=0
r_s
r_d
LS surface
D_A
θ_d



$$\theta_d = \frac{r_d}{D_A}$$

tilts the "damping tail"

How does measuring these two scales lead to an N_{eff} constraint?

- Physics is remarkably simple, laid out in Hou et al. (2013), Bashinsky & Seljak (2004), Hu & White (1997)

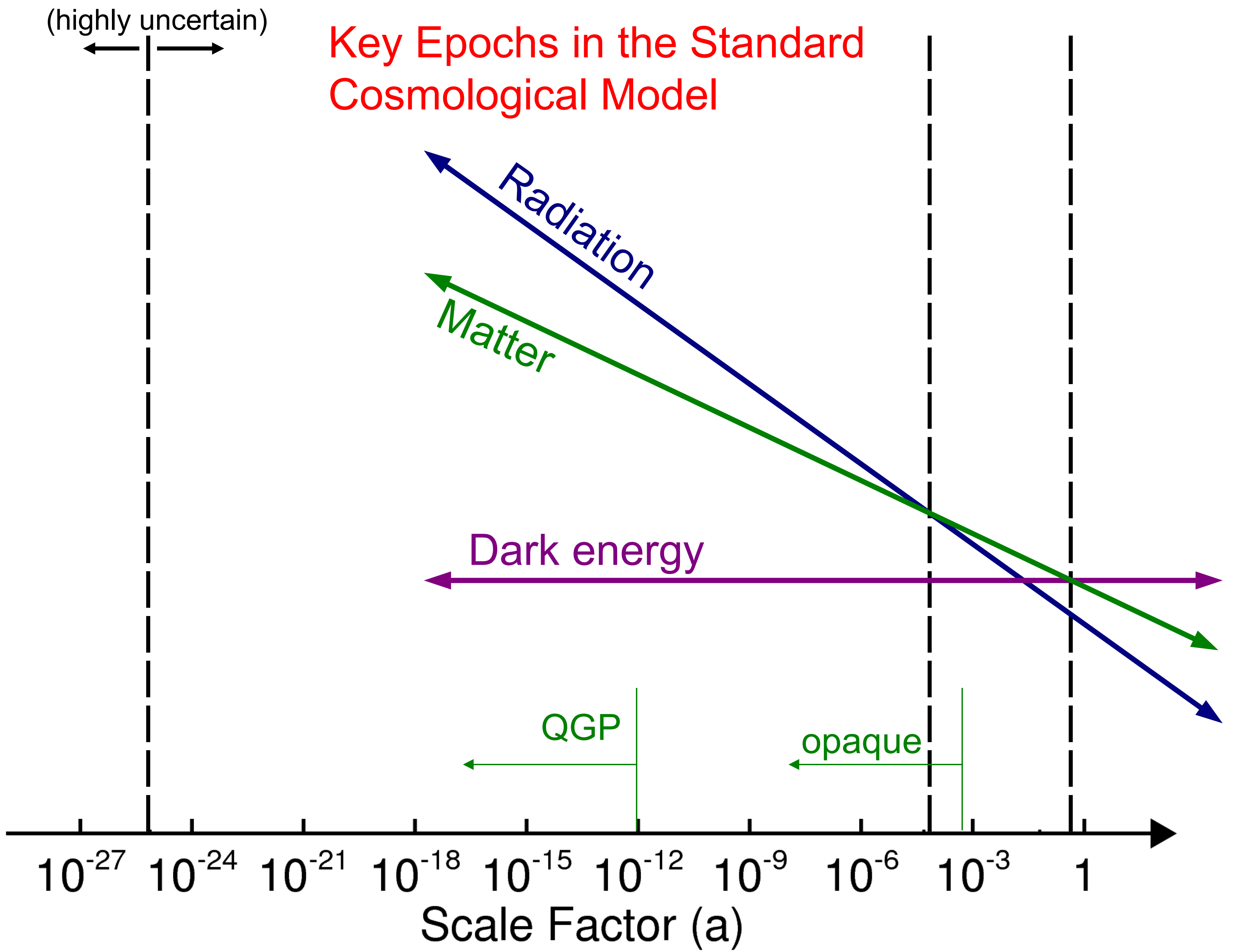
$$r_s = \int_0^{t_*} c_s \frac{dt}{a} = \int_0^{a_*} \frac{c_s da}{a^2 H(a)}$$

$$r_d^2 = \pi^2 \int_0^{a_*} \frac{da}{a^3 \sigma_T n_e H(a)}$$

$$H(a)^2 = \frac{8\pi G}{3} \left[\rho_r(a) + \rho_m(a) + \rho_\Lambda(a)\right]$$

$$\theta_s = \frac{r_s}{D_A} \qquad \theta_d = \frac{r_d}{D_A}$$

$$\frac{\theta_s}{\theta_d} = \frac{r_s}{r_d} \propto \frac{1}{\sqrt{H(a)}}$$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opaque
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Scale Factor (a)

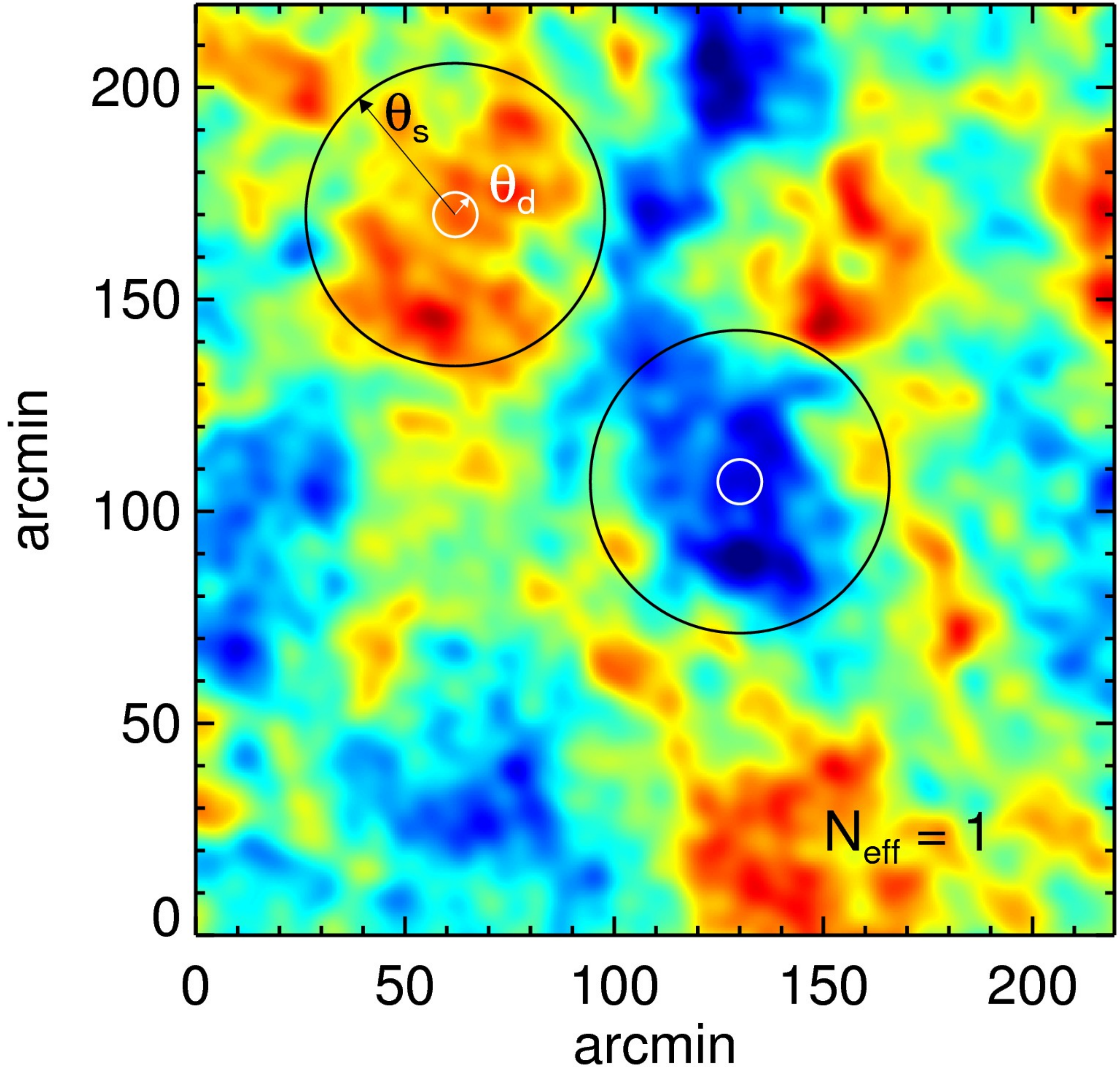
- a_{eq} (scale factor at matter-radiation equality) is very well constrained by the CMB because perturbations whose wavelength enters the horizon before/after this point evolve very differently

$$a_{\text{eq}} = \frac{\rho_m}{\rho_r} = \frac{\rho_m}{\left[1 + \left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\text{eff}}\right] \rho_\gamma}$$

$$H(a)^2 = \frac{8\pi G}{3} \left[\rho_r(a) + \rho_m(a) + \rho_\Lambda(a)\right]$$

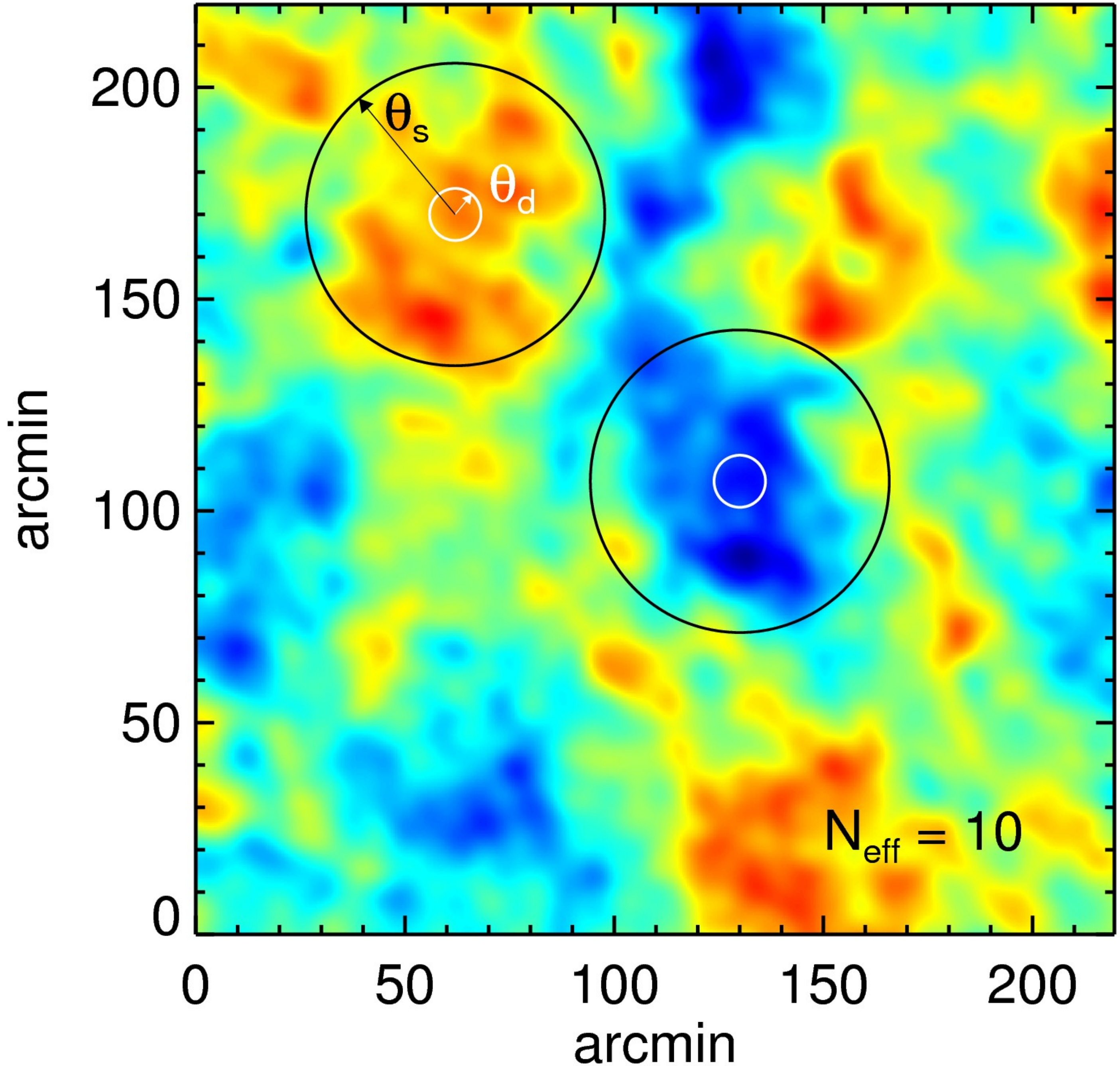
$$\frac{\theta_s}{\theta_d} = \frac{r_s}{r_d} \propto \frac{1}{\sqrt{H(a)}} \propto \frac{1}{N_{\text{eff}}^{1/4}}$$

Neff affects the ratio of sound horizon to diffusion scale



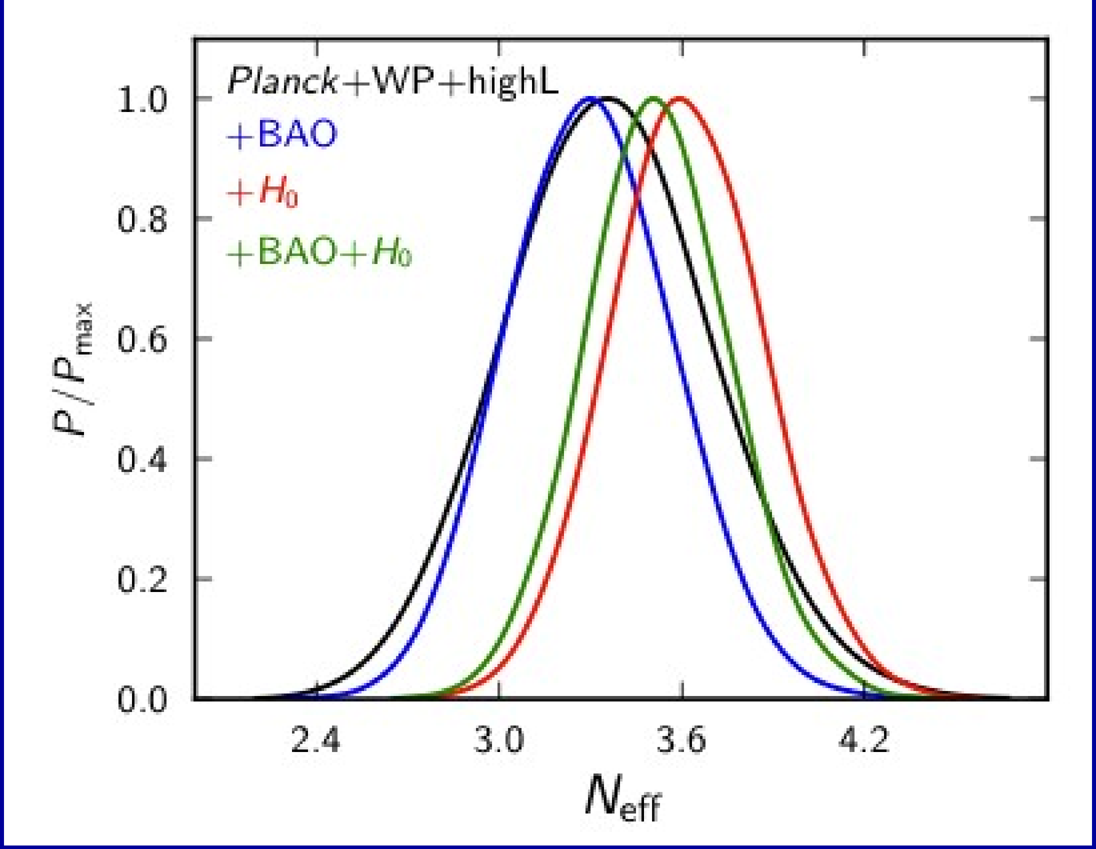
$$\frac{\theta_s}{\theta_d} \propto \frac{1}{N_{\rm eff}^{1/4}}$$

Neff affects the ratio of sound horizon to diffusion scale



$$\frac{\theta_s}{\theta_d} \propto \frac{1}{N_{\rm eff}^{1/4}}$$

Light Degrees of Freedom



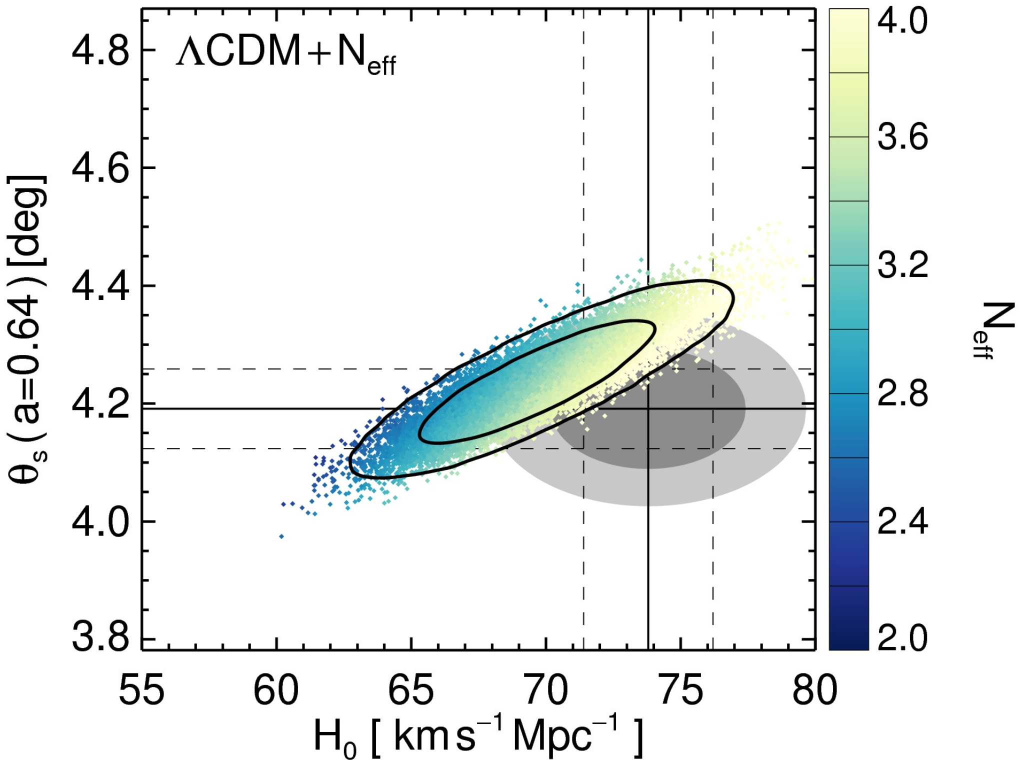
Standard model has Neff = 3.046. No evidence in Planck data, or Planck +BAO for extra species.

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

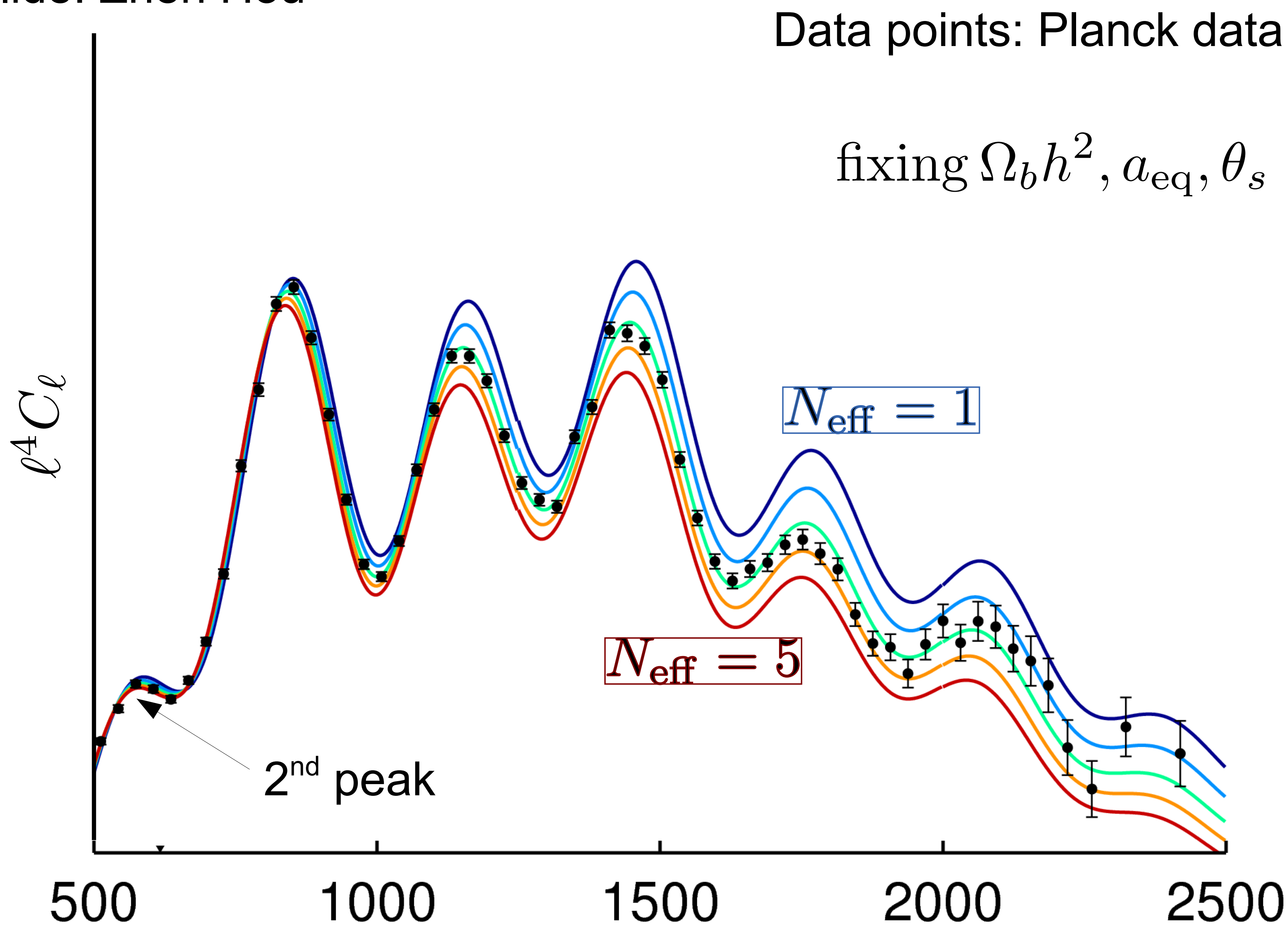
Light Degrees of Freedom - Neff

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

$$H(a)^2 = \frac{8\pi G}{3}\left[\rho_r(a) + \rho_m(a) + \rho_\Lambda(a)\right]$$

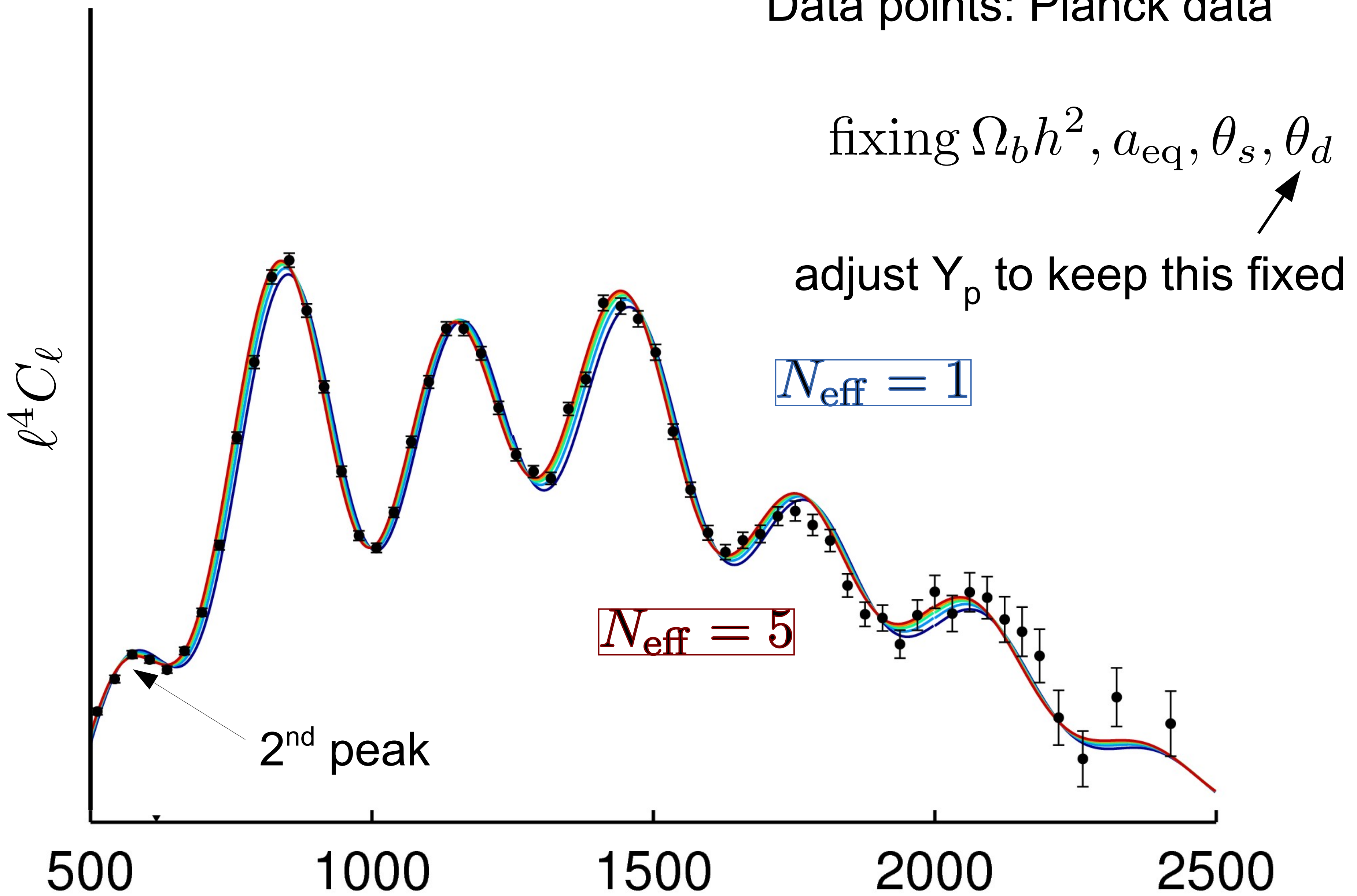


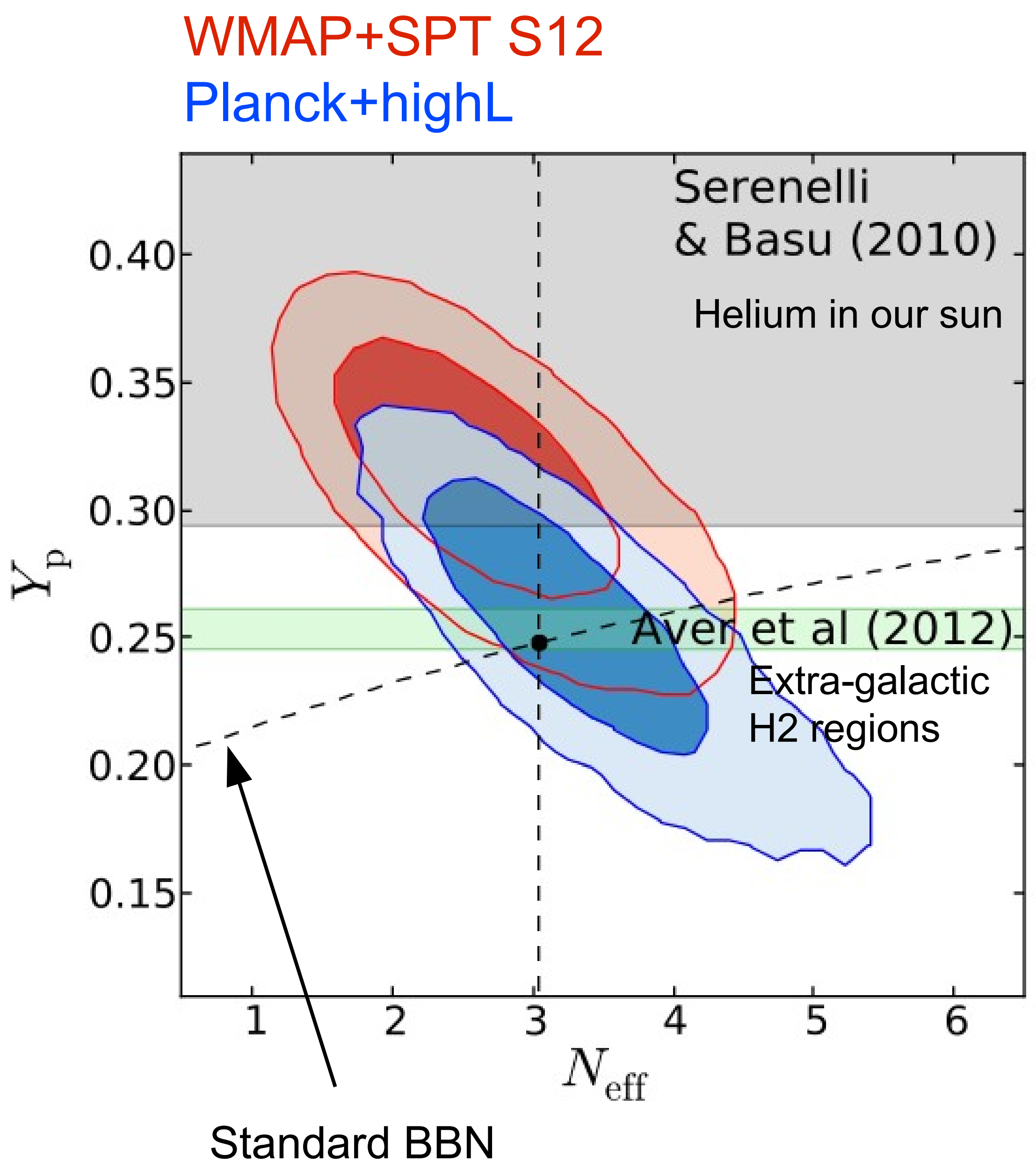
Slide: Zhen Hou



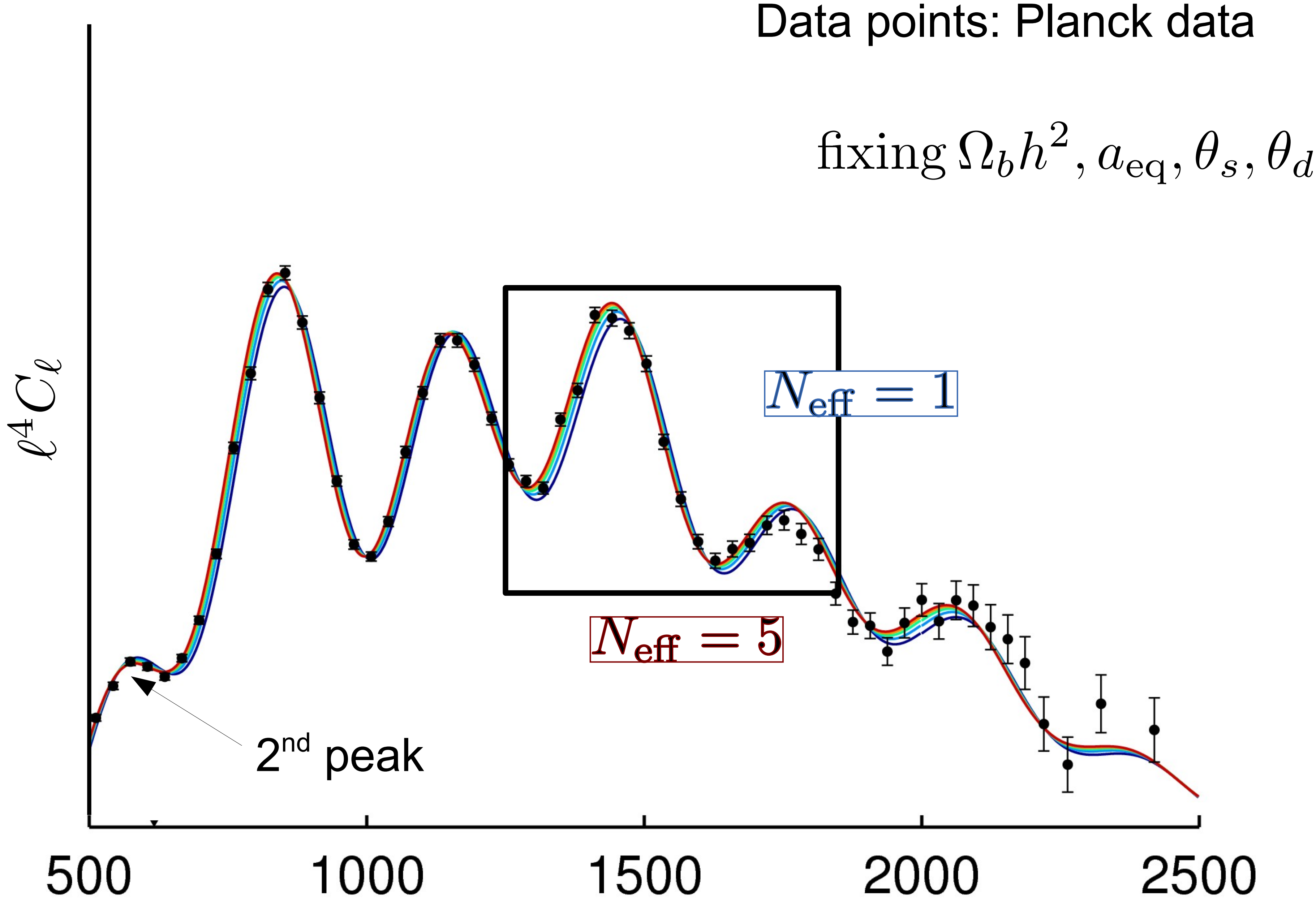
Slide: Zhen Hou

Data points: Planck data




WMAP+SPT S12
Planck+highL
Serenelli
& Basu (2010)
Helium in our sun
Aver et al (2012)
Extra-galactic
H2 regions
0.40
0.35
0.30
0.25
0.20
0.15
Y_p
1
2
3
4
5
6
N_{eff}
Standard BBN

Slide: Zhen Hou

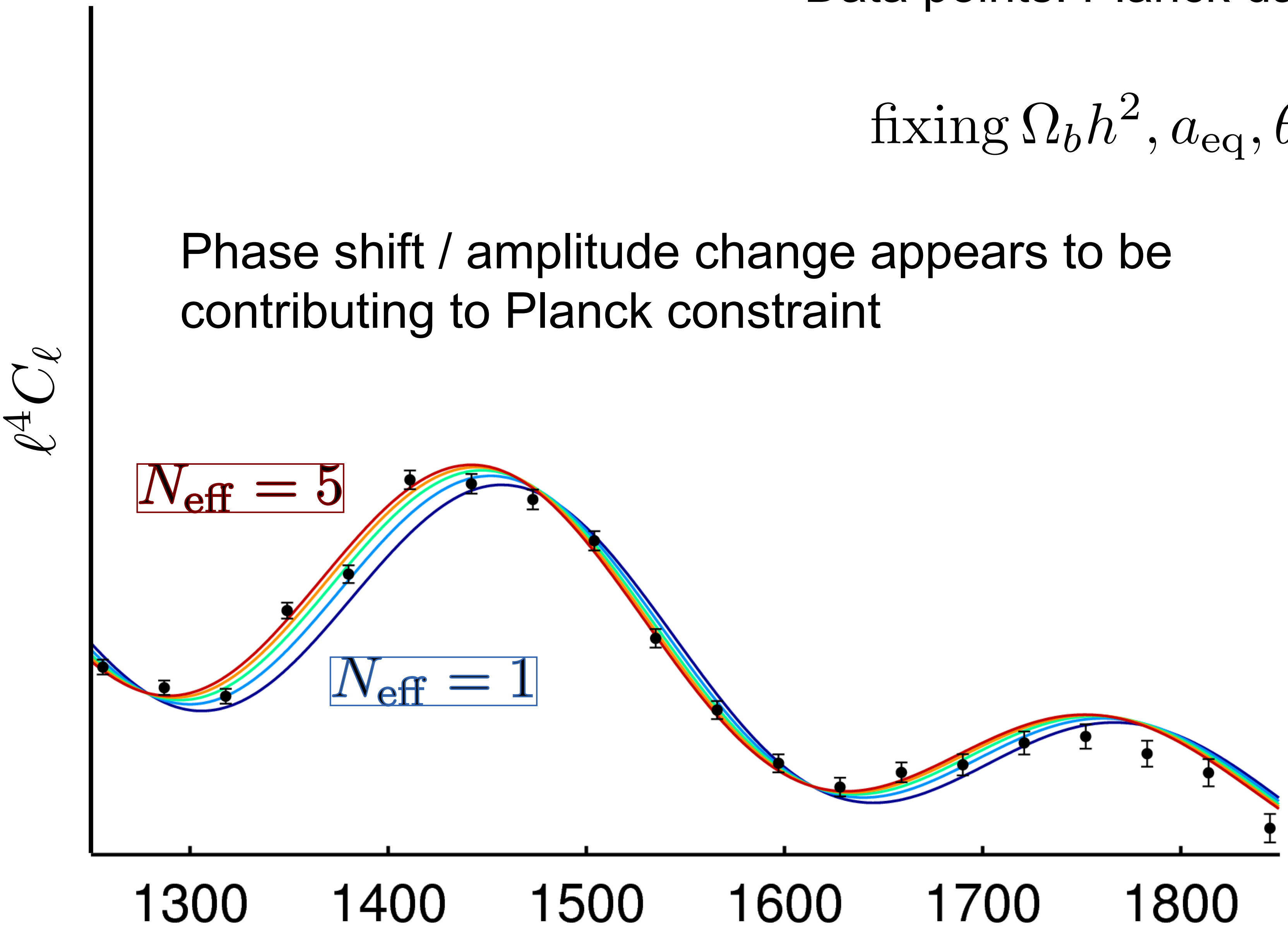


Slide: Zhen Hou

Data points: Planck data

$\text{fixing}\, \Omega_b h^2, a_{\text{eq}}, \theta_s, \theta_d$

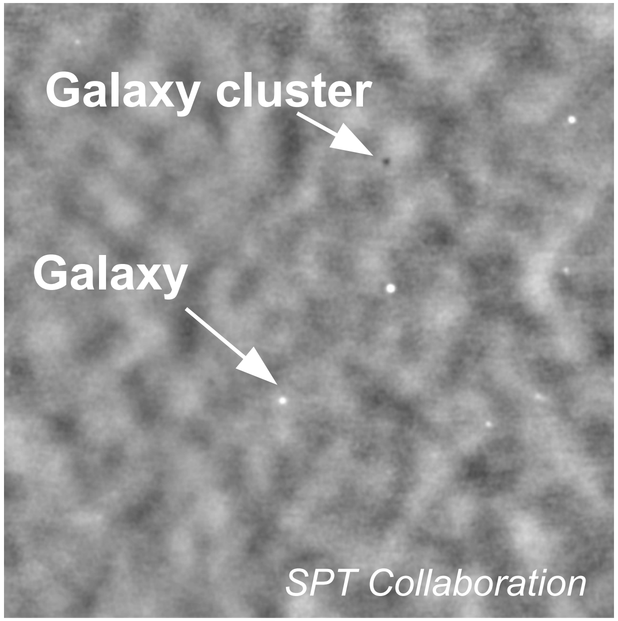
Phase shift / amplitude change appears to be contributing to Planck constraint



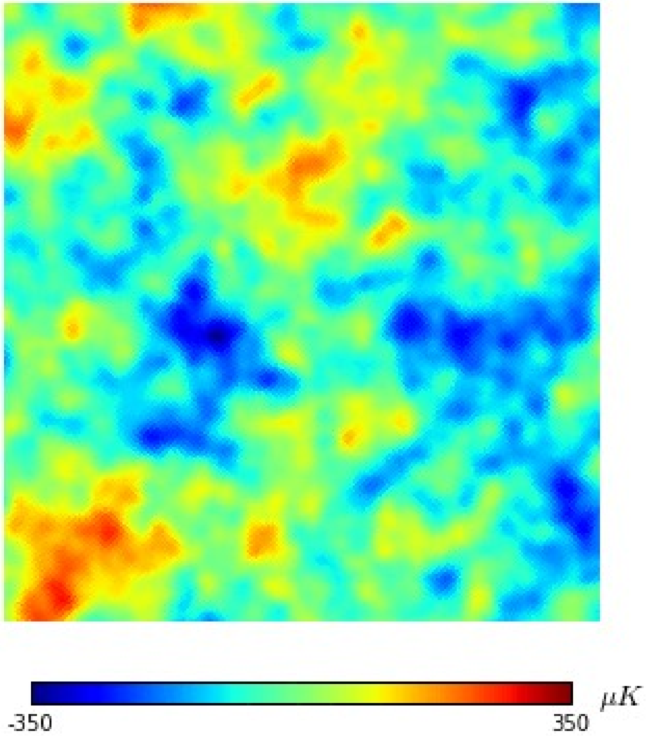
Possible contamination affecting damping: unresolved foregrounds

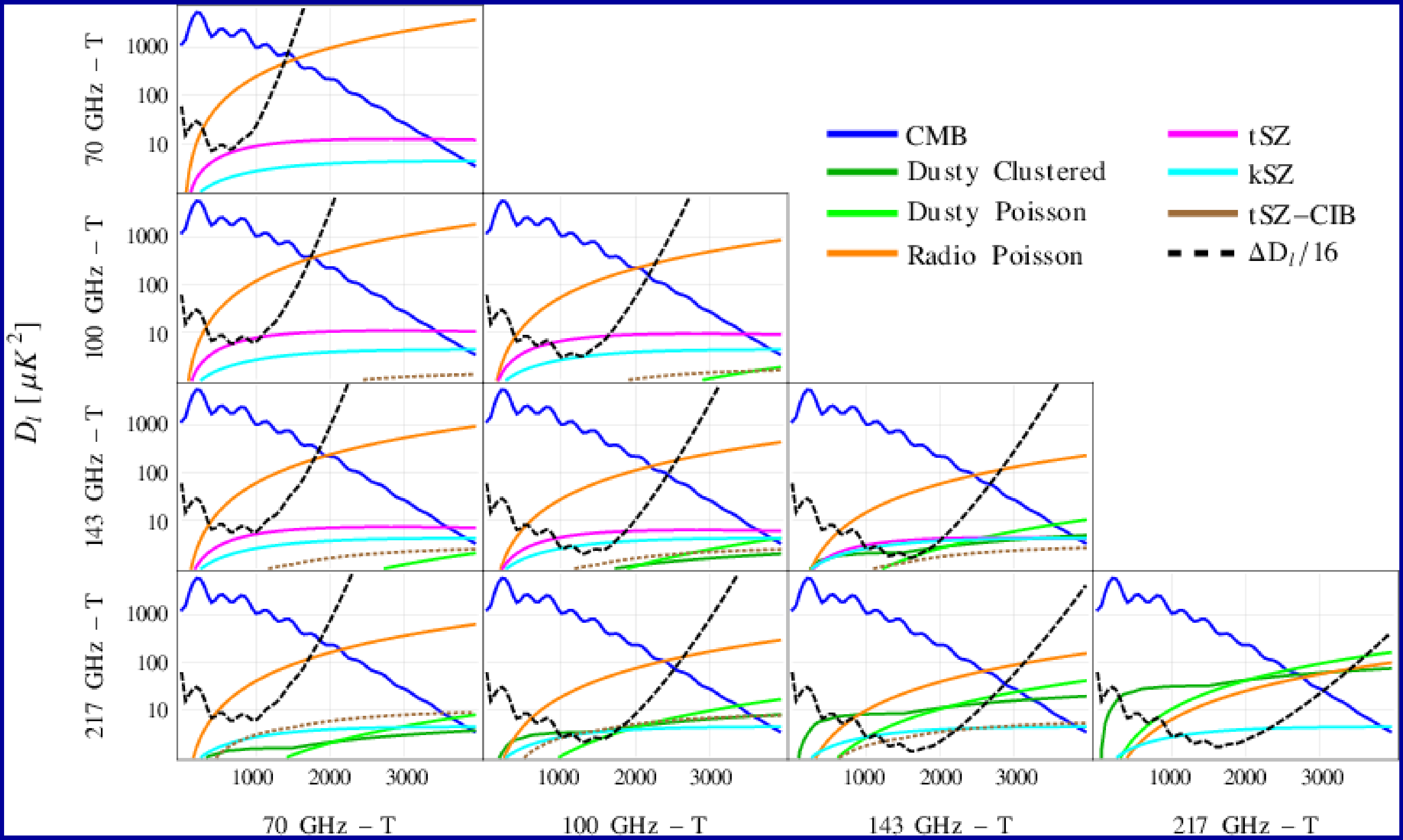
To scale

Resolved foregrounds:



Unresolved foregrounds:
(Noise-free simulation)

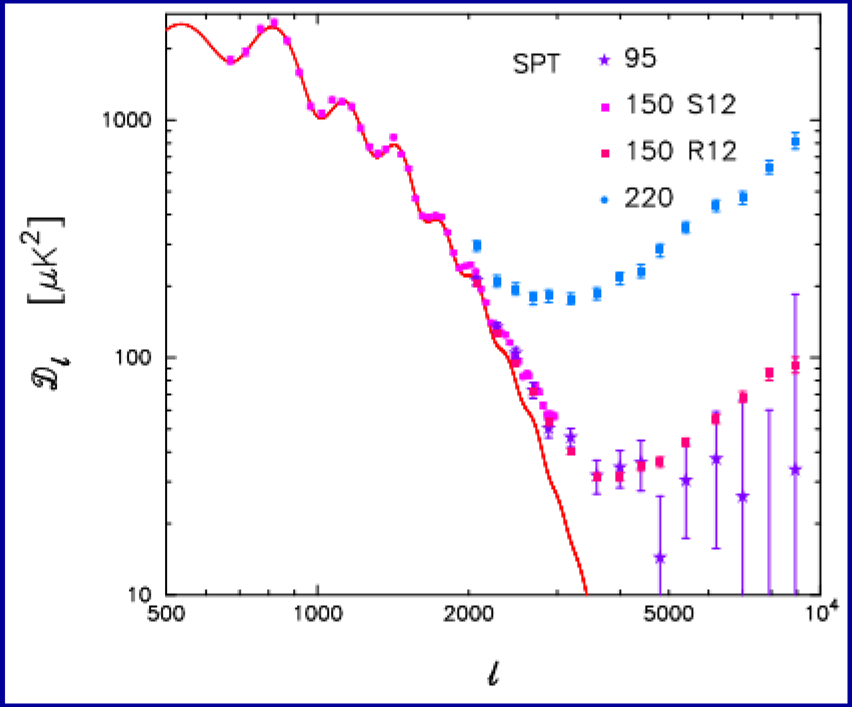


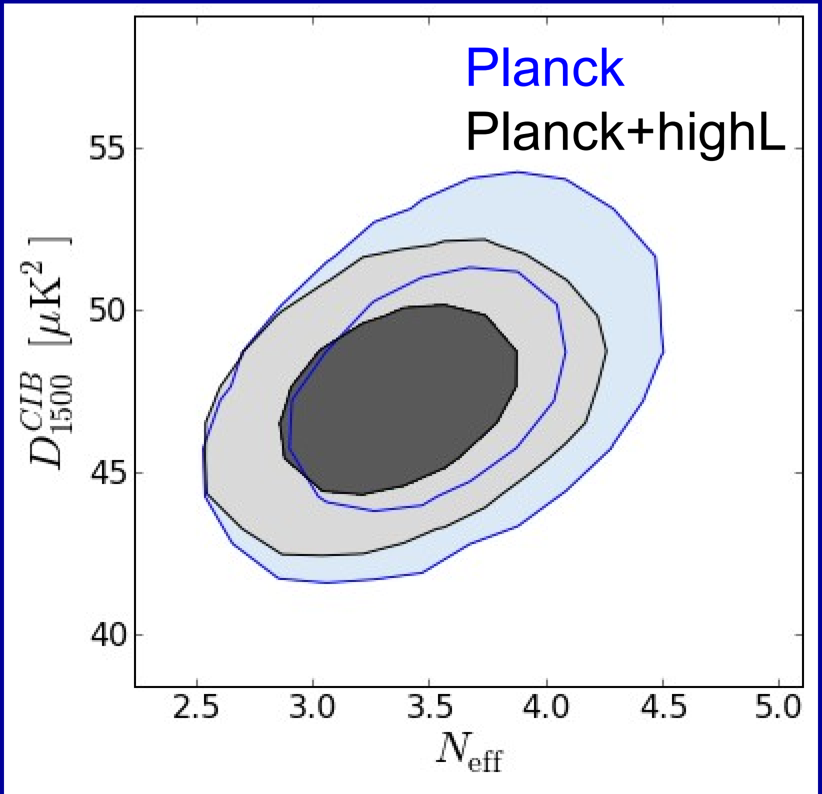


Millea et al 2011

Adding “highL” to help constrain foregrounds

SPT highL





correlation coefficient ~ .5

potential for 20% tighter sigma

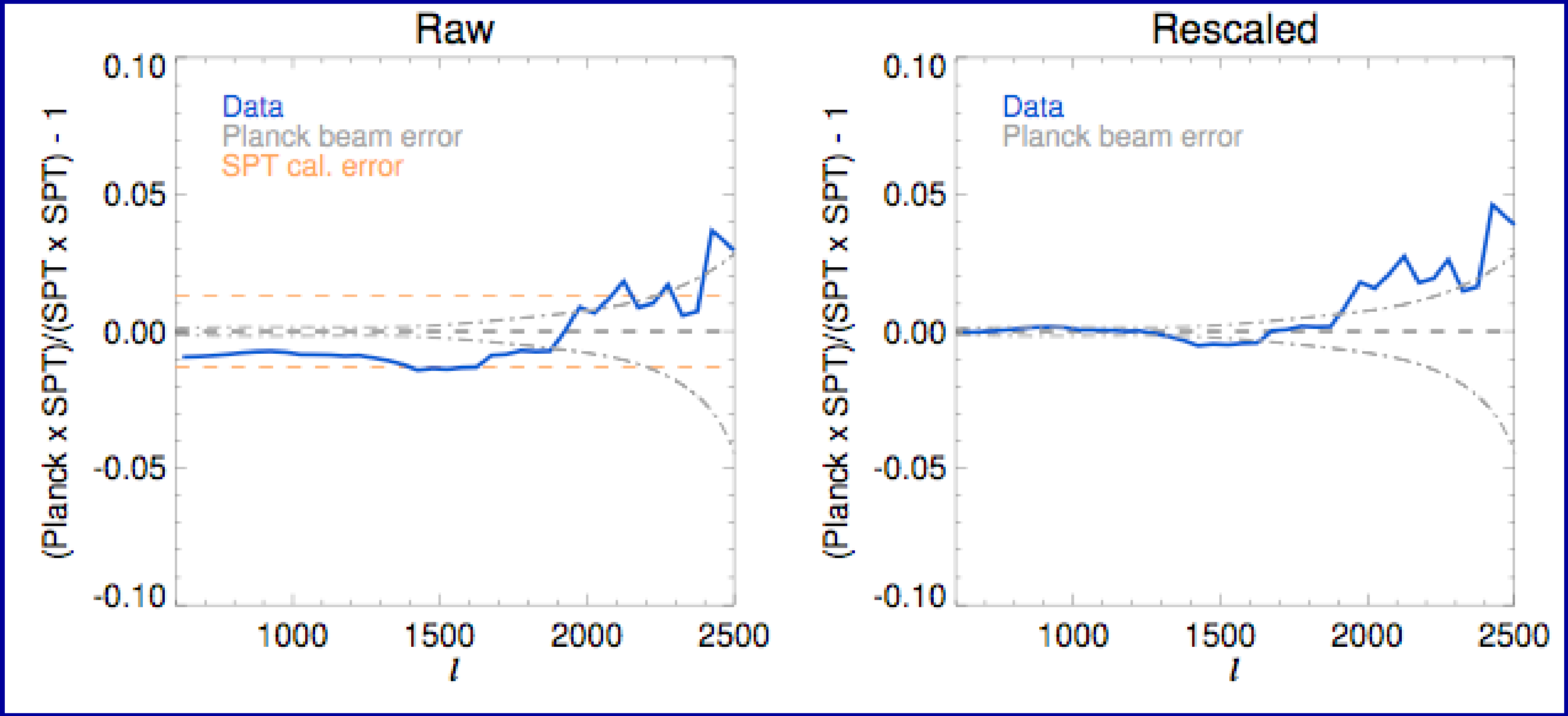
Outline

- Planck
- ΛCDM, the standard model of cosmology, passes a precision test
- Consistency with other cosmological probes
  - BAO and H0
  - WMAP and SPT
- Neutrino physics with Planck
  - Damping and phase shifts → Number of relativistic d.o.f
  - Gravitational lensing → Sum of neutrino masses

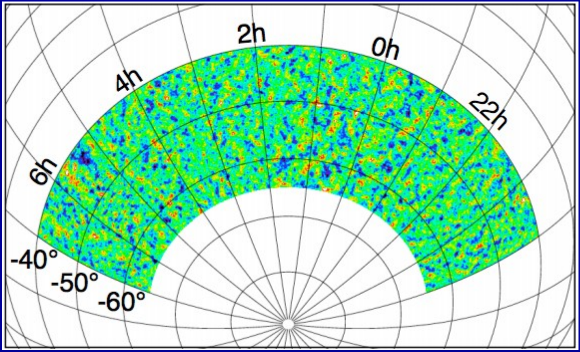
Consistency with other CMB experiments

- Planck and WMAP are consistent (except an overall “calibration”)
- Planck and SPT are consistent
- There *are* seemingly large differences between parameters from the three, but there's no evidence of any systematics.
  - Therefore one should combine them all, in which case Planck tends to dominate the result.

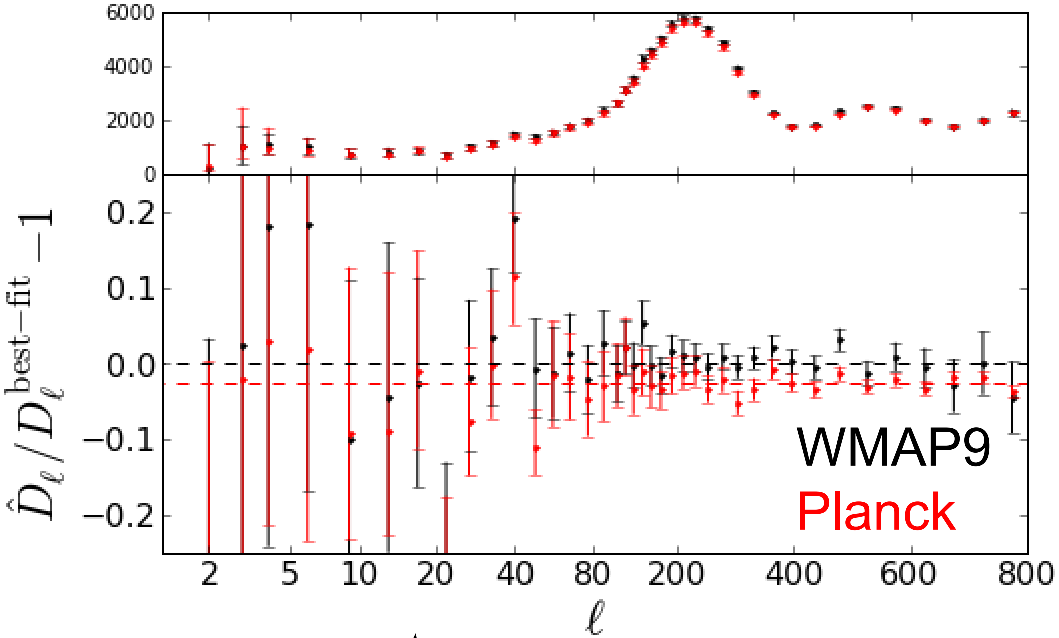
Planck-SPT consistency



SPT team cross-corelated Planck maps with SPT maps on the SPT patch of sky

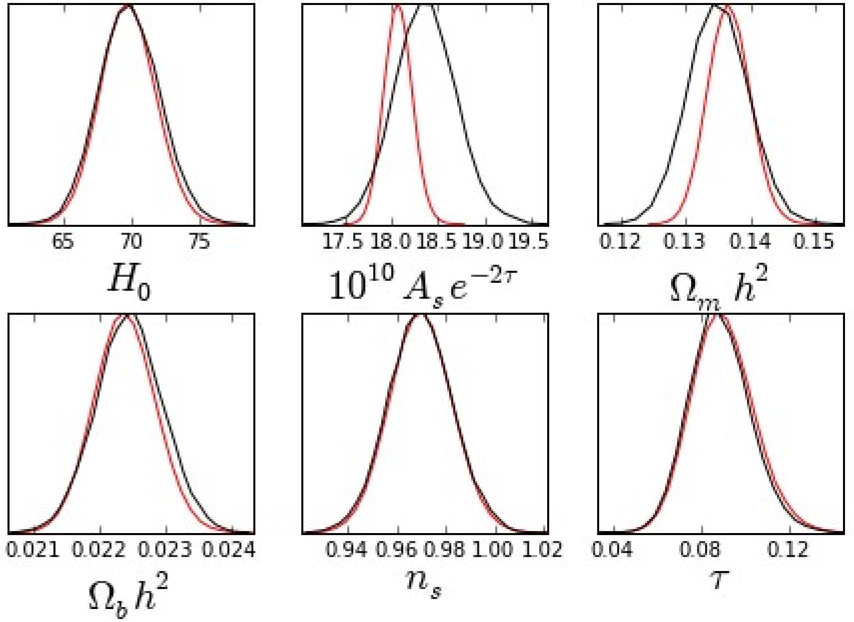


Planck-WMAP consistency



There are differences between Planck and WMAP that look something like a 2.5% rescaling

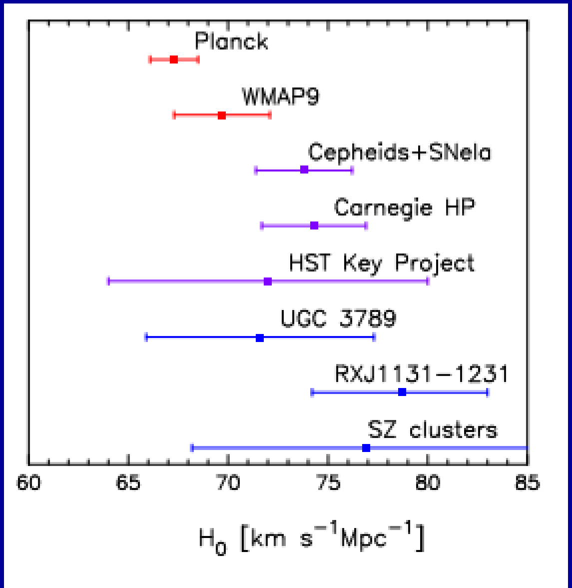
The 2.5% difference is absorbed almost entirely by the amplitude



Parameters from L<800

What at L>800 is causing Planck LCDM parameter shifts?

- Its lensing
- This is going to be very important for the Σm_ν constraint



Outline

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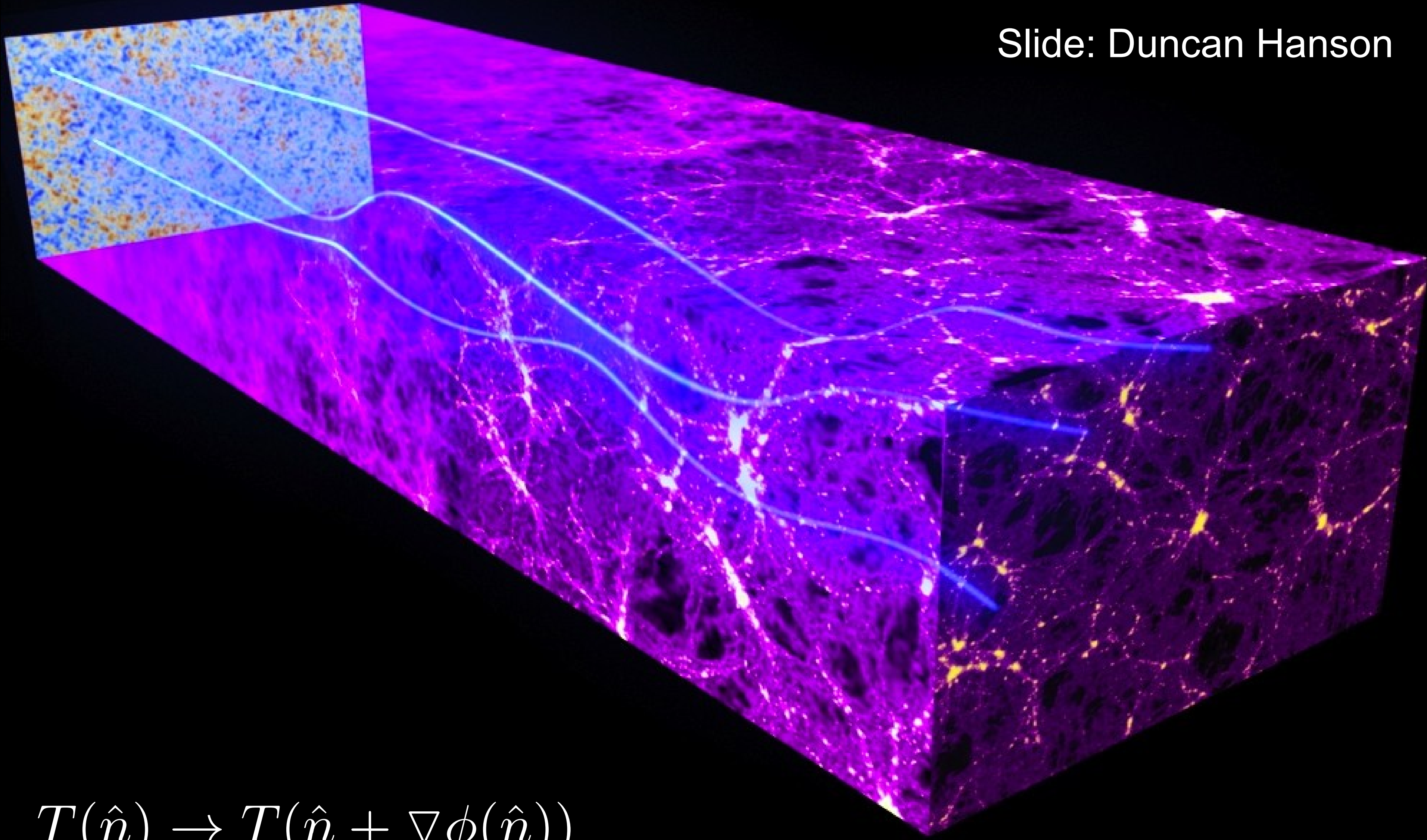
Slide: Duncan Hanson

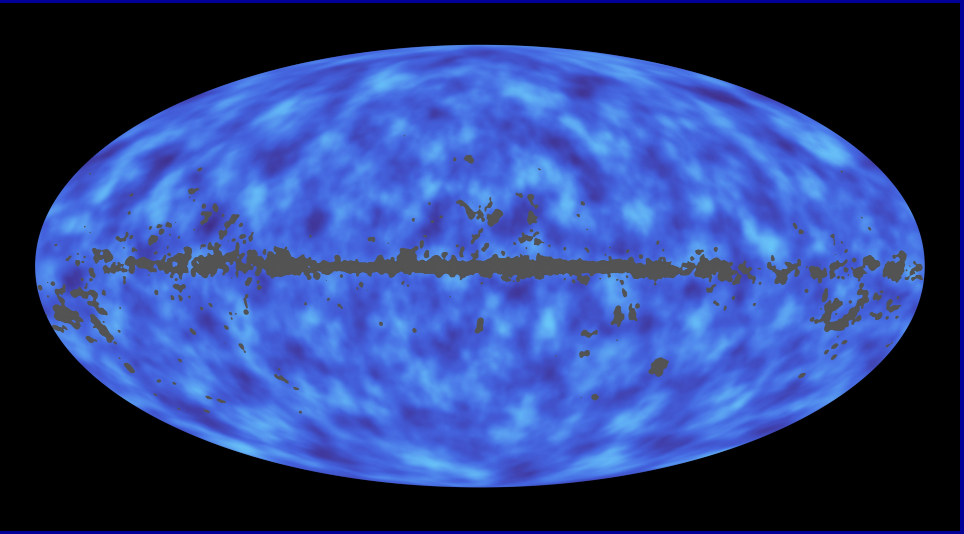


$$T(\hat{n}) \to T(\hat{n} + \nabla\phi(\hat{n}))$$

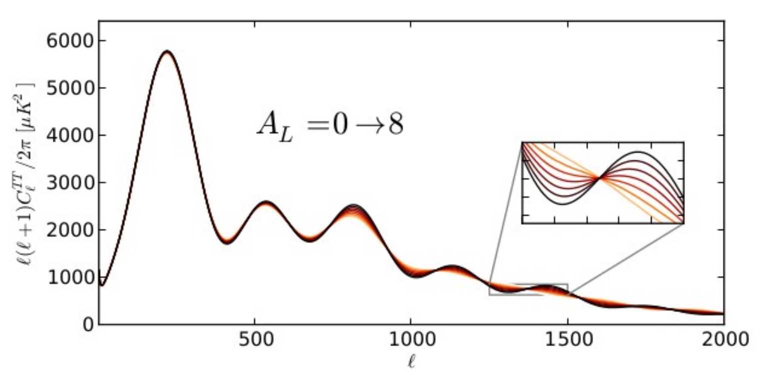
$$\phi(\hat{n}) = -2 \int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$

Two ways to analyze lensing with Planck

- For the first time, lensing contributes the dominant constraining power on neutrino mass



Lensing potential reconstruction



The smoothness of the temperature power spectrum

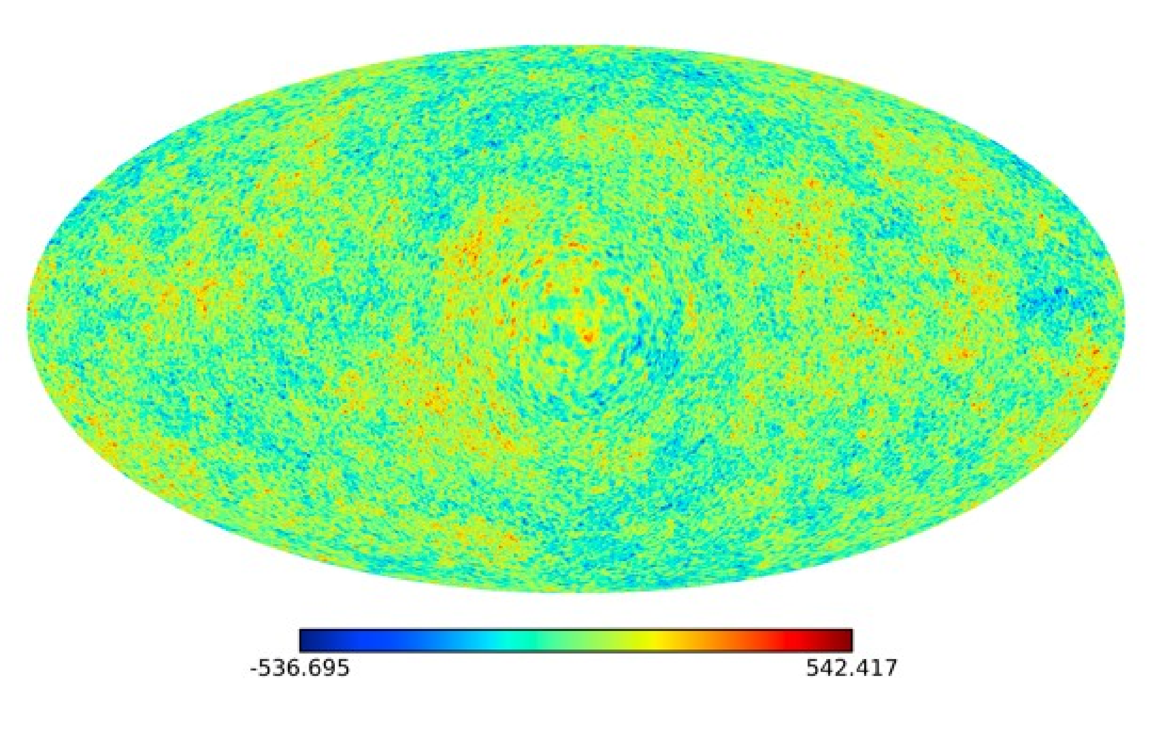
CMB Lensing Measurements

	φ-gal. crosspower	φ autopower	CMB peak-smearing
2007	WMAP3xNVSS 3.4 σ Smith+		ACBAR ~3σ Calabrese+, Reichardt+
2008	WMAP3xNVSS 2.5 σ Hirata+		
2011		ACT 4 σ Das+	ACT ~3 σ Dunkley+ SPT 5 σ Keisler+
2012	SPTx(WISE, *Spitzer*/IRAC, BCS) 4-5 σ Bleem+ ACTxSDSSquasars 3.8 σ Sherwin+ WMAP5xNVSS 4 σ Fang+	SPT 6.3 σ van Engelen+ ACT 4.6 σ Das+	ACT ~3 σ Sievers+ SPT 8 σ Story+
2013	SPTx*Herschel*CIB 7-9 σ Holder+ *Planck*x*Planck*CIB 42 σ Planck Collab. *Planck*x.... 7-20 σ Planck Collab.	*Planck* 25 σ Planck Collab.	*Planck* 10 σ Planck Collab.

Courtesy of Alex van Engelen

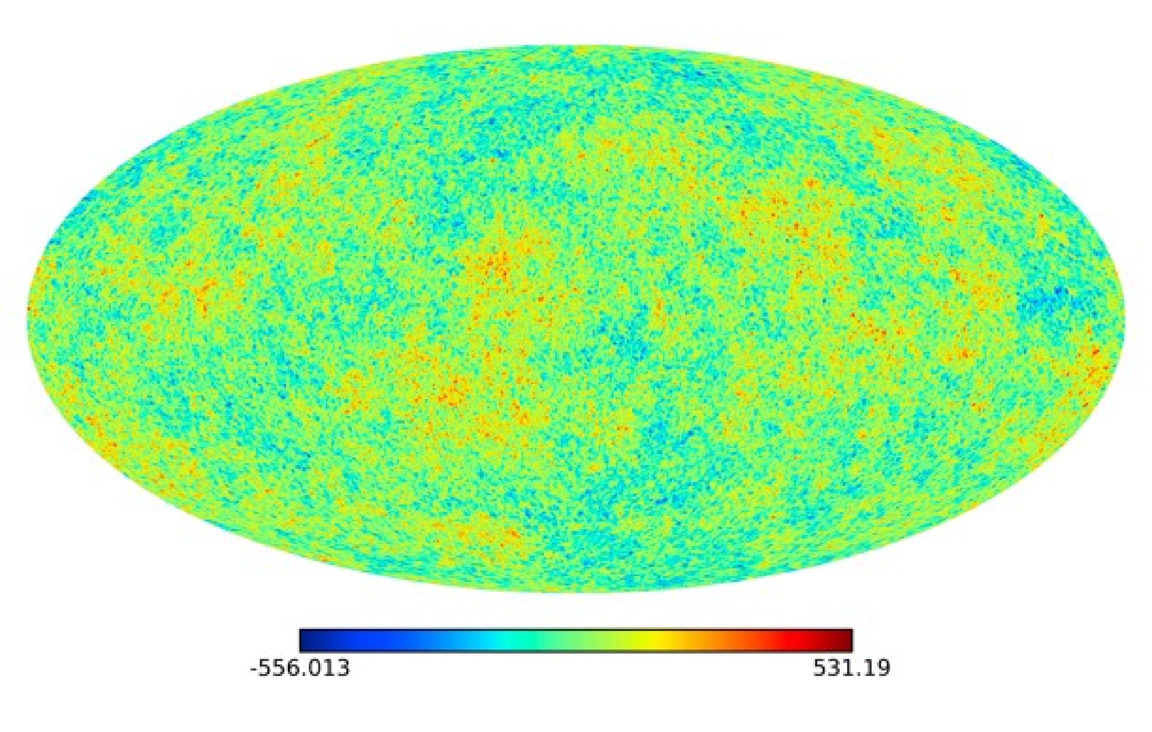
Slide: Duncan Hanson

Gravitational Lensing

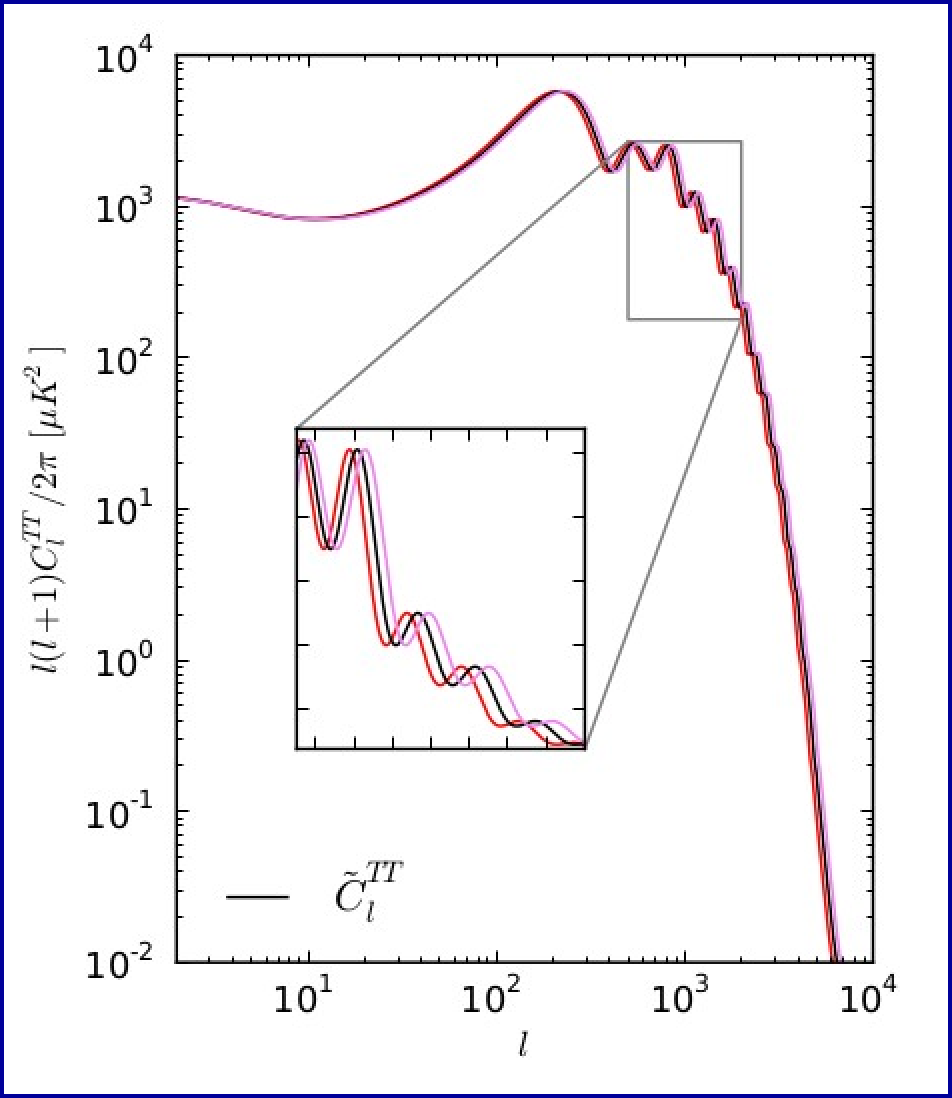


Slide: Duncan Hanson

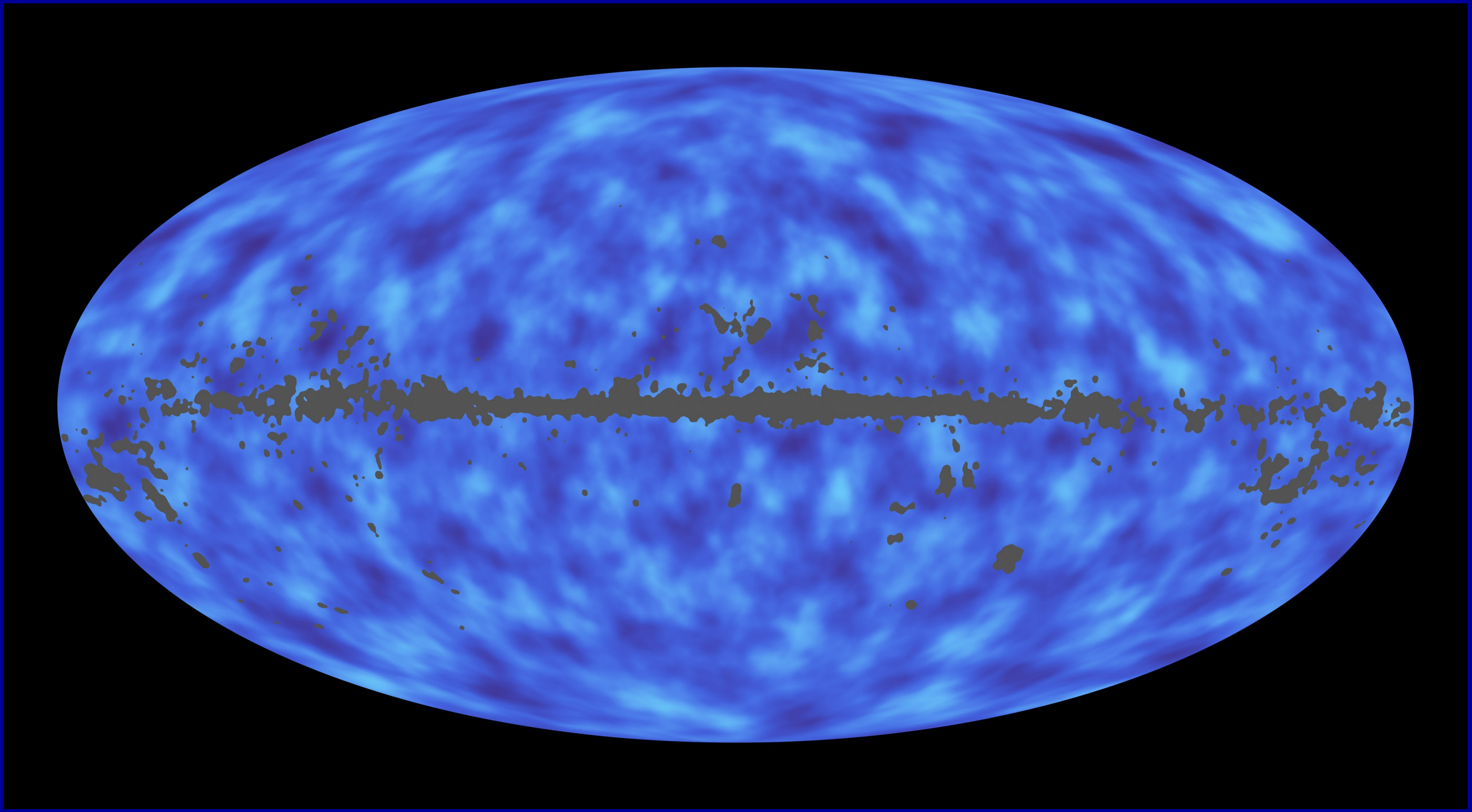
Gravitational Lensing



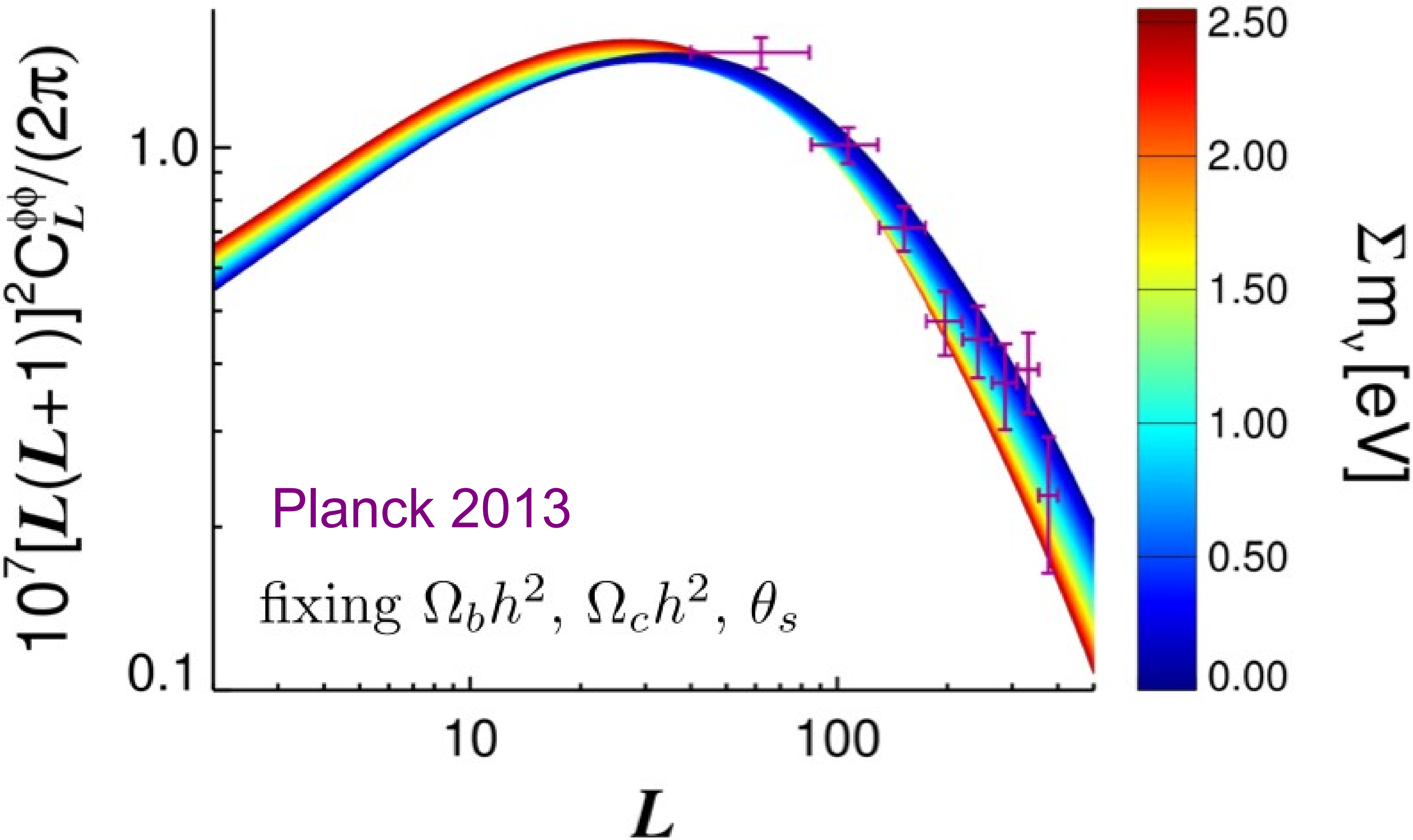
Slide: Duncan Hanson



Map of Lensing Potential



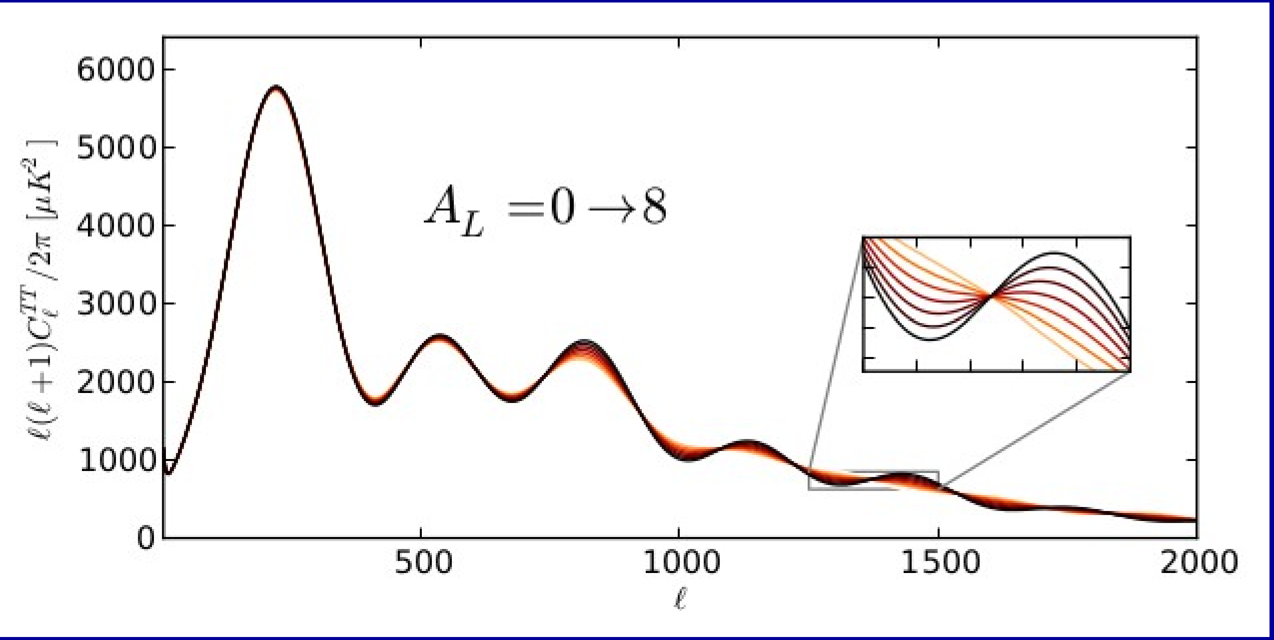
CMB lensing and neutrino mass



Slide: Zhen Hou

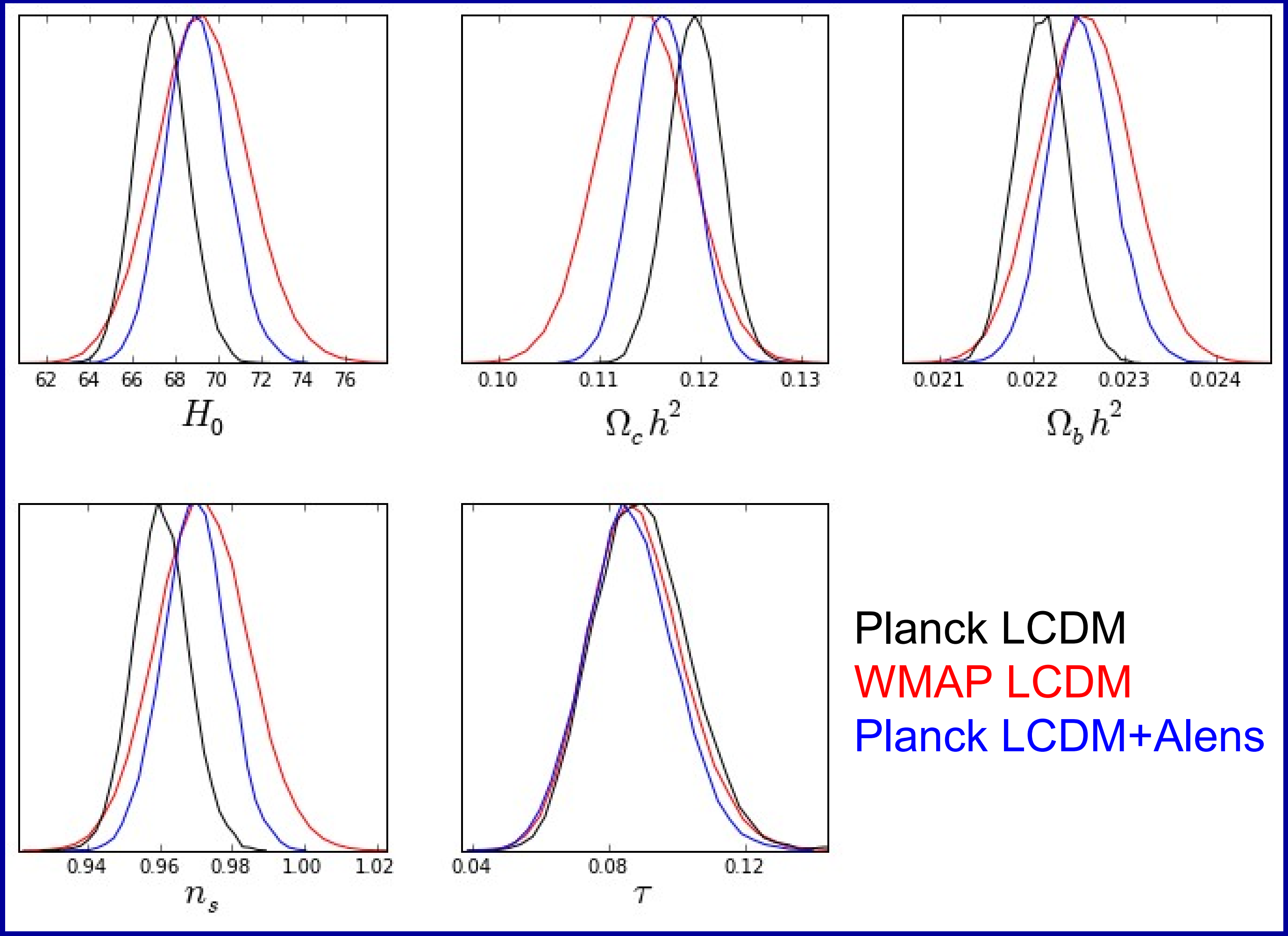
Slide: Duncan Hanson

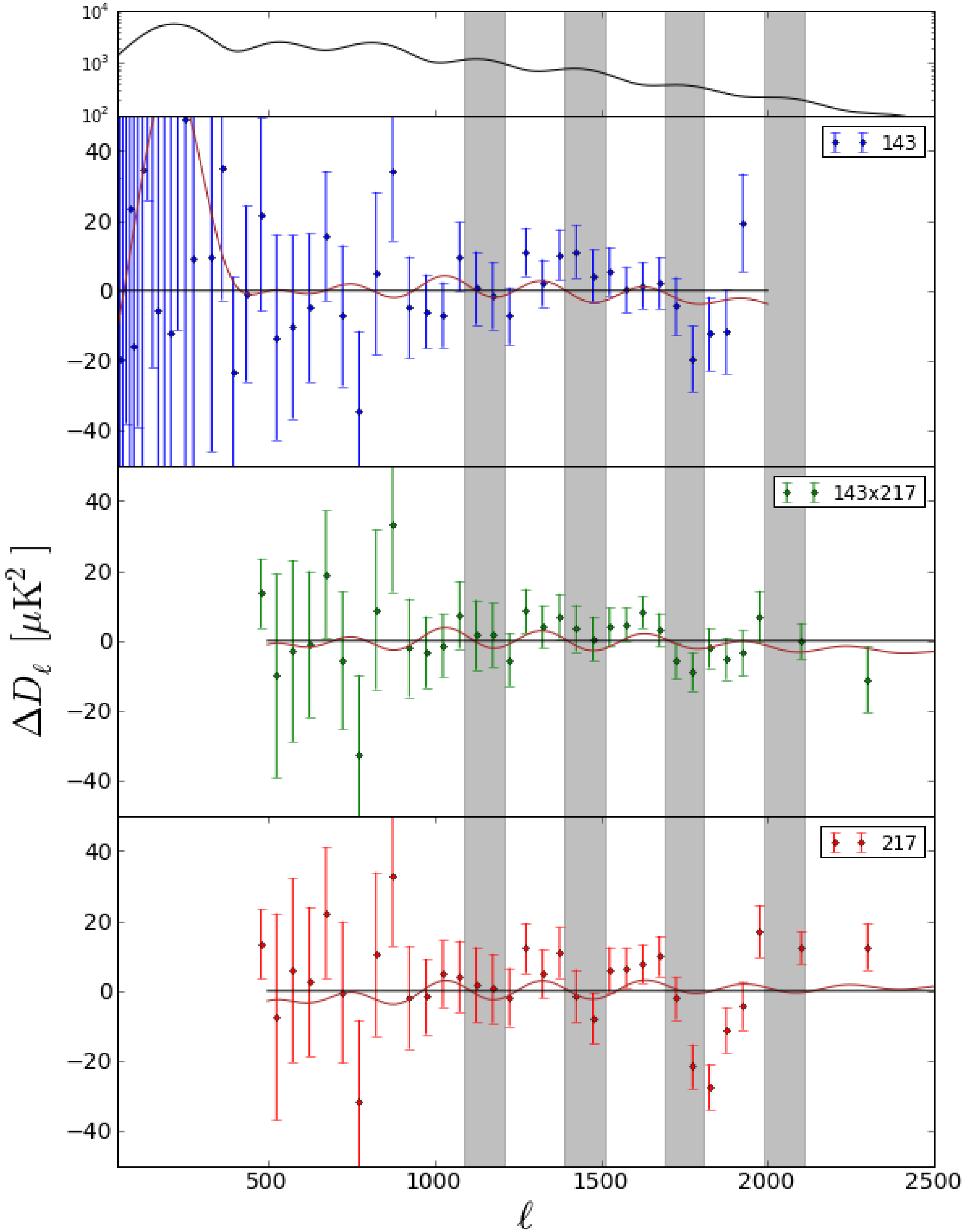
Lensing also smooths out the power spectrum



- Marginalizing over A_L effectively removes lensing information.
- Looking at the preferred value of A_L is a consistency check.

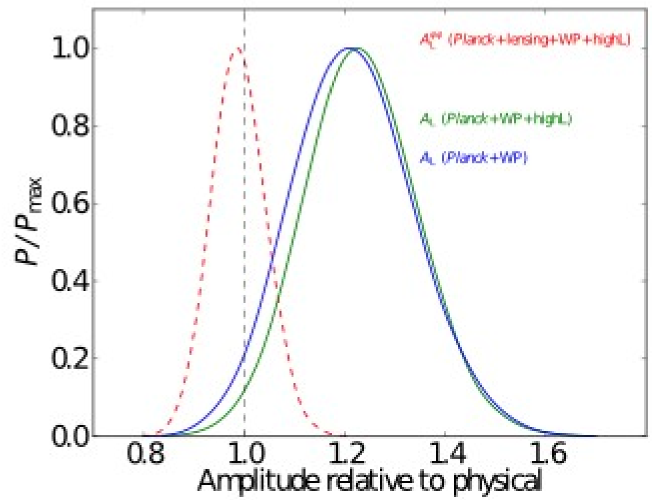
Planck-WMAP LCDM parameter differences are largely tied to the Planck measurement of this peak smoothing effect

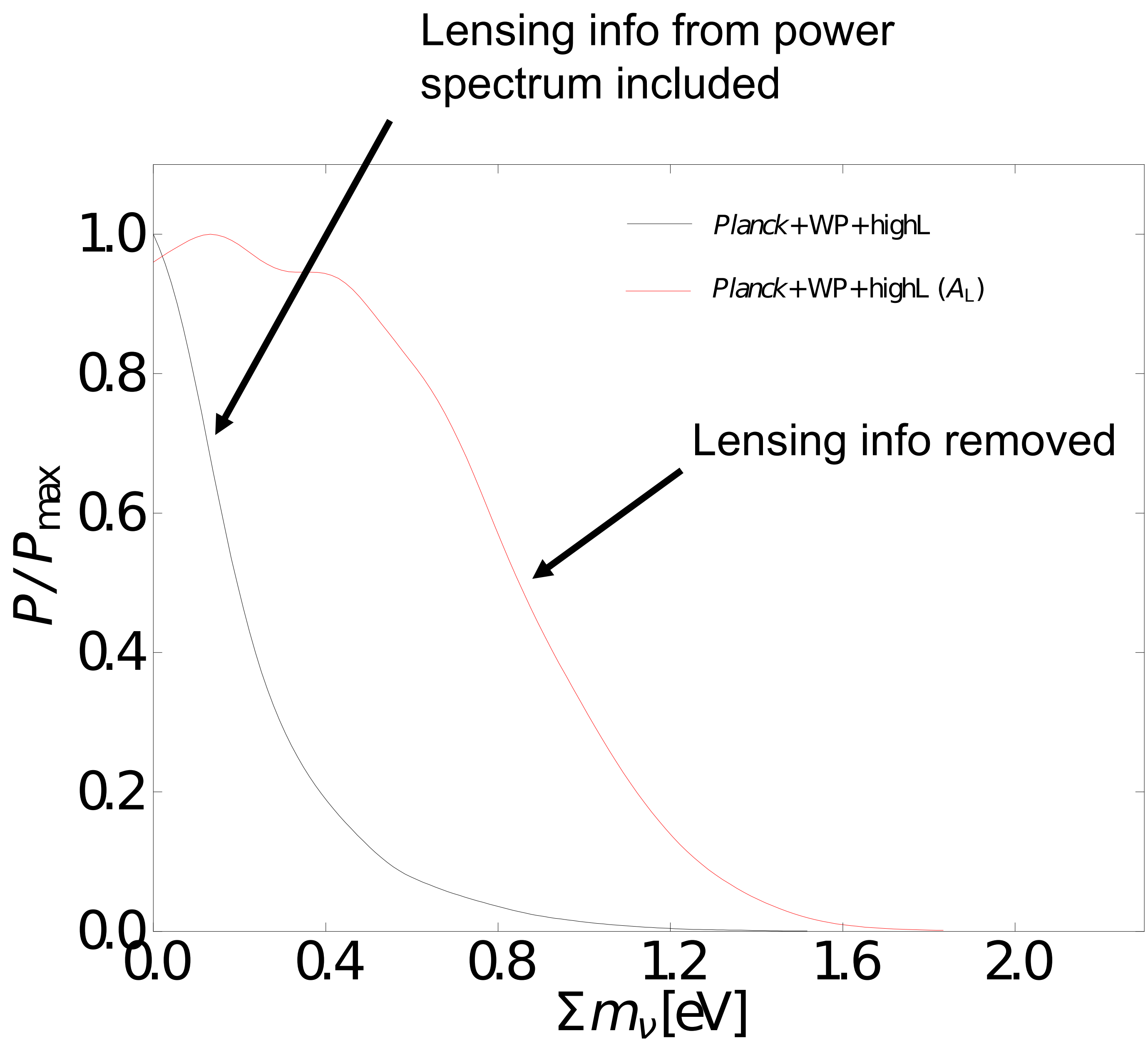




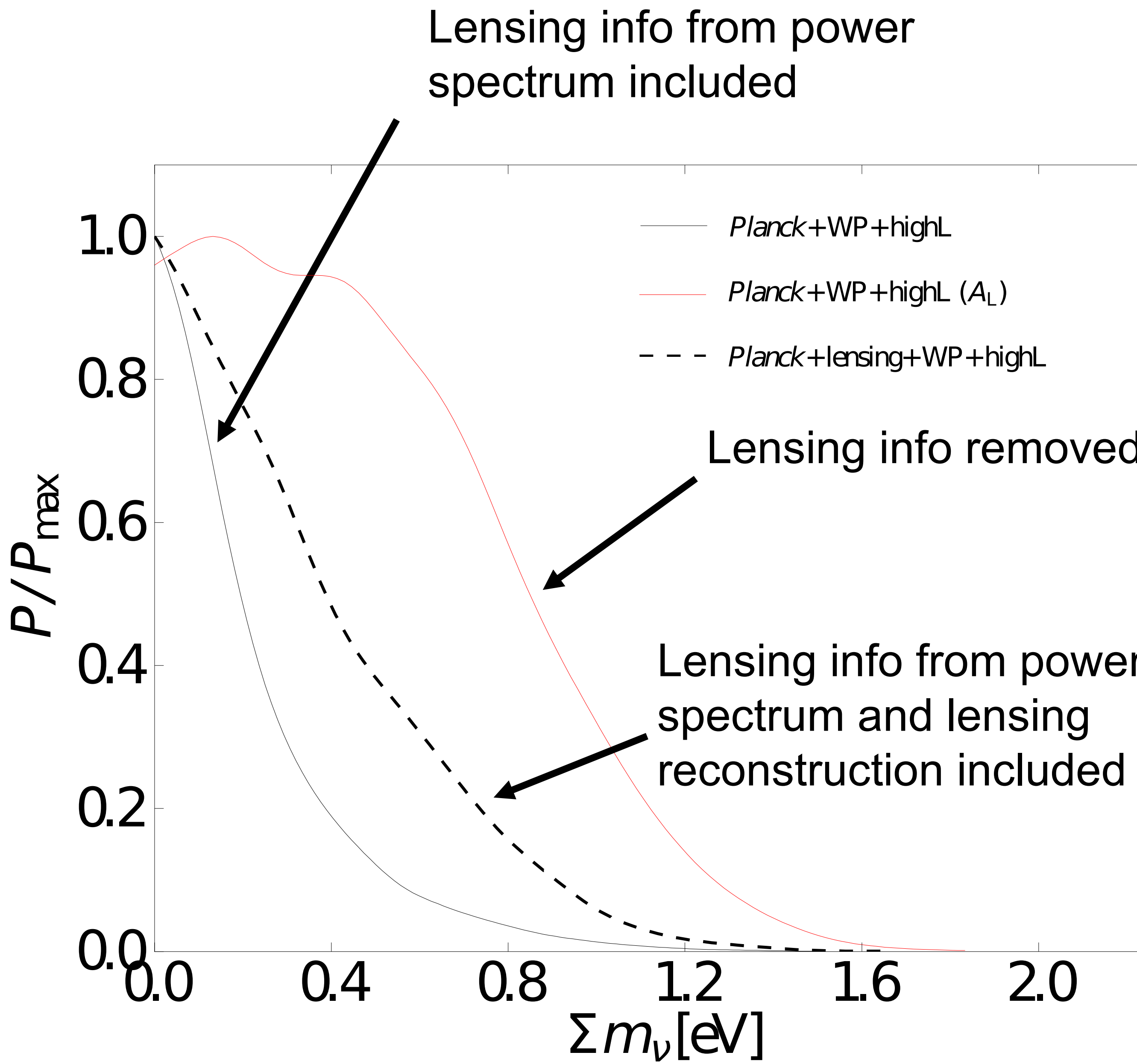
Planck+WP LCDM best-fit

Planck+WP LCDM+Alens best-fit



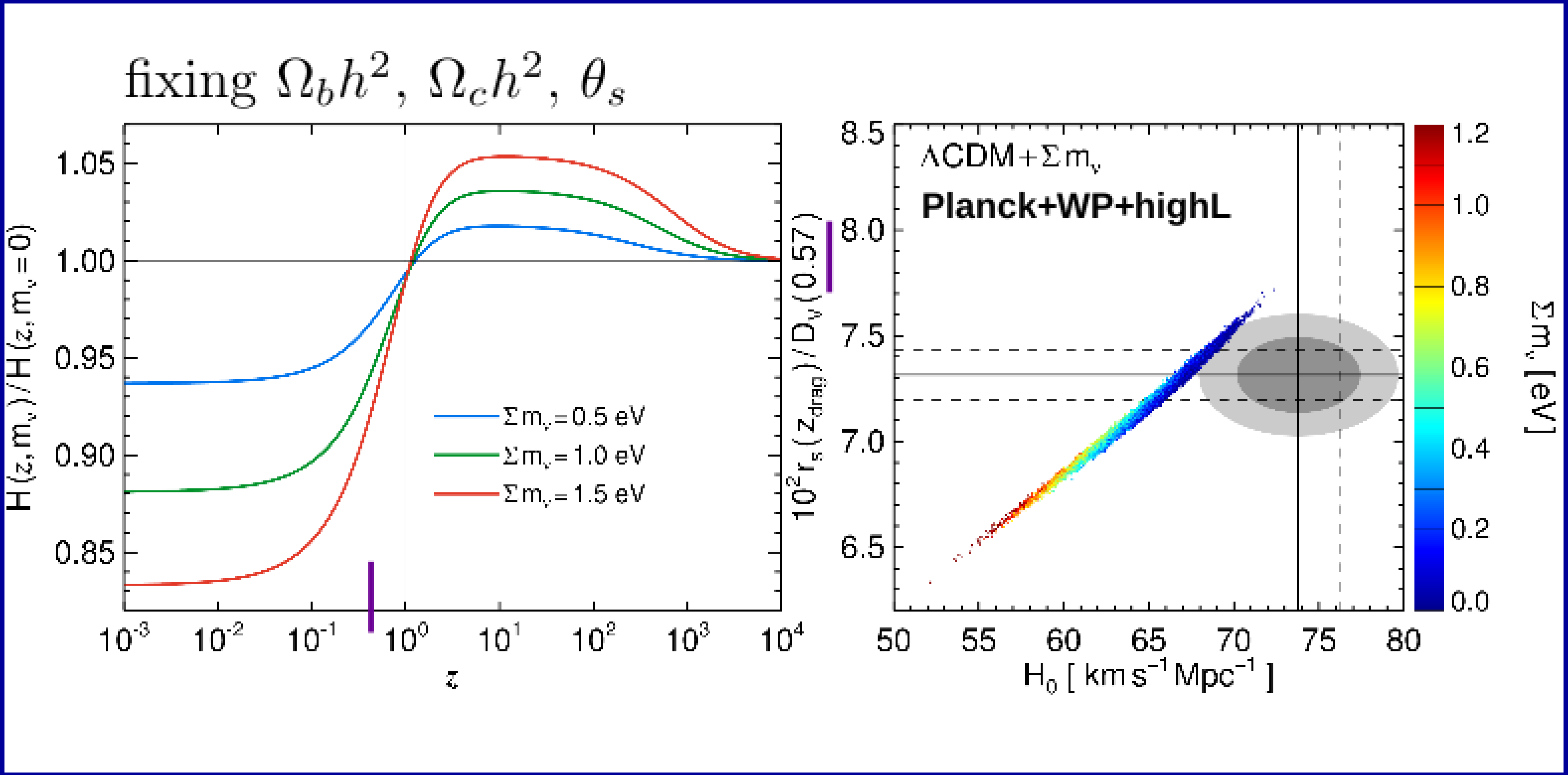


Lensing info from power spectrum included
Lensing info removed
Planck+WP+highL
Planck+WP+highL (A_L)
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.4
0.8
1.2
1.6
2.0
P/P_max
Σm_ν[eV]

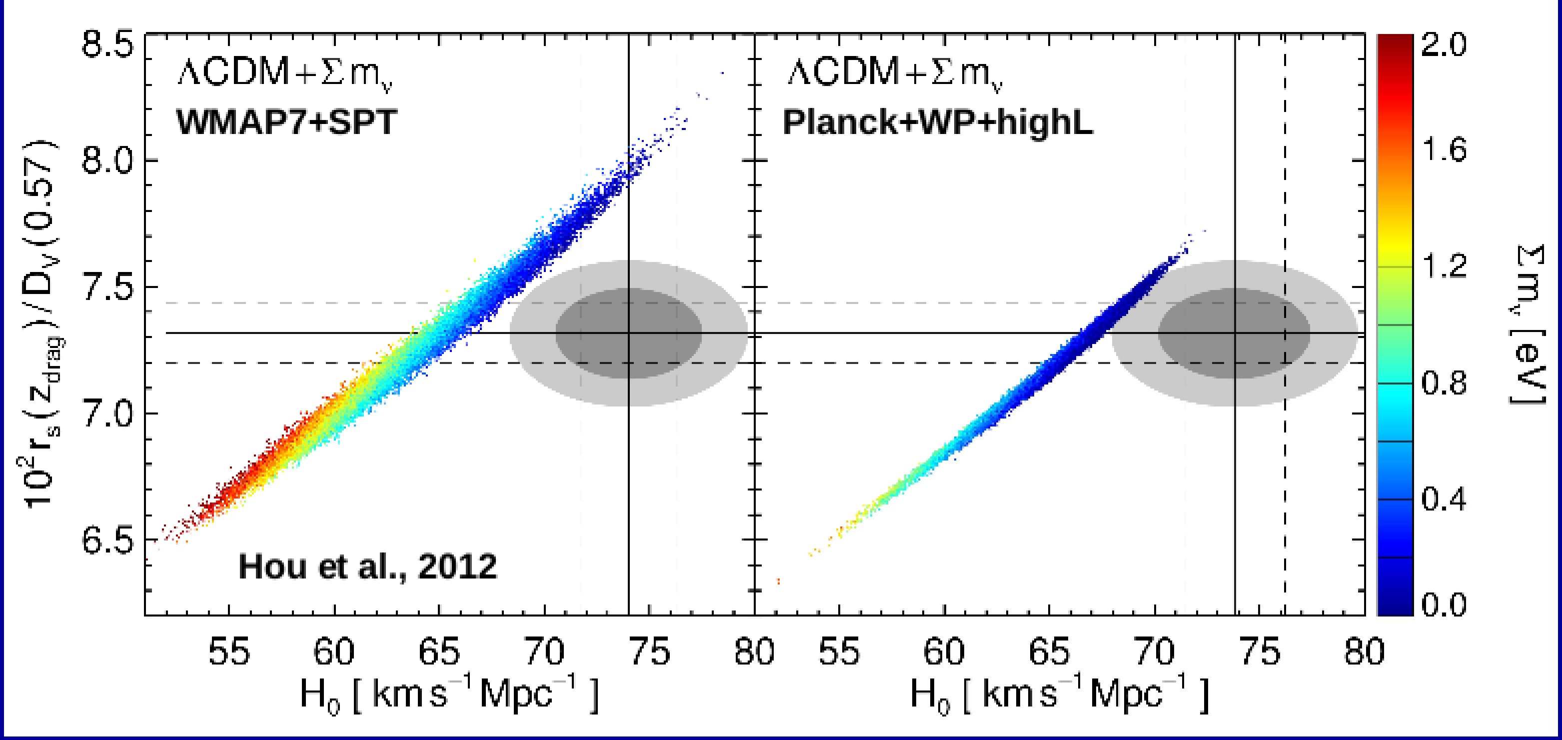


Lensing info from power spectrum included
Lensing info removed
Lensing info from power spectrum and lensing reconstruction included
Planck+WP+highL
Planck+WP+highL (A_L)
Planck+lensing+WP+highL
P/P_{max}
Σm_ν[eV]
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.4
0.8
1.2
1.6
2.0

Massive neutrino impact on BAO-H_0-CMB

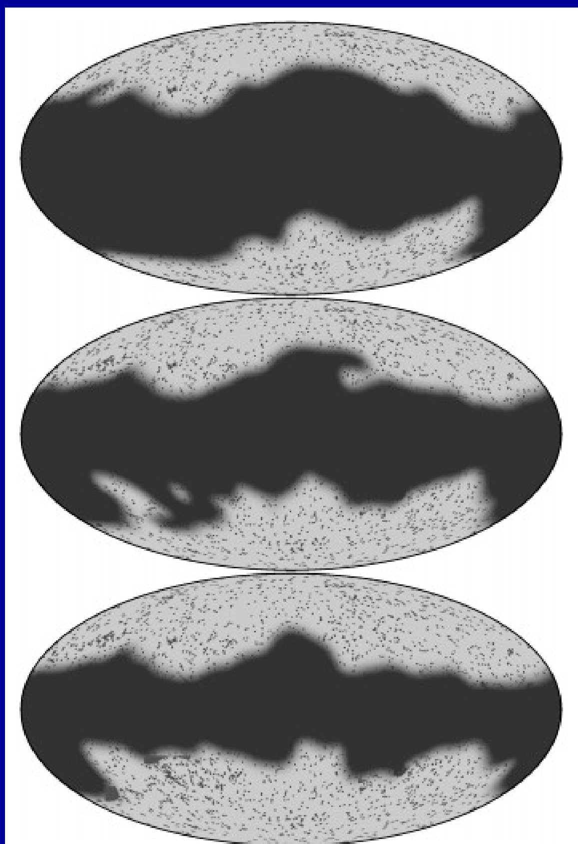


Massive neutrino impact on BAO-H_0-CMB



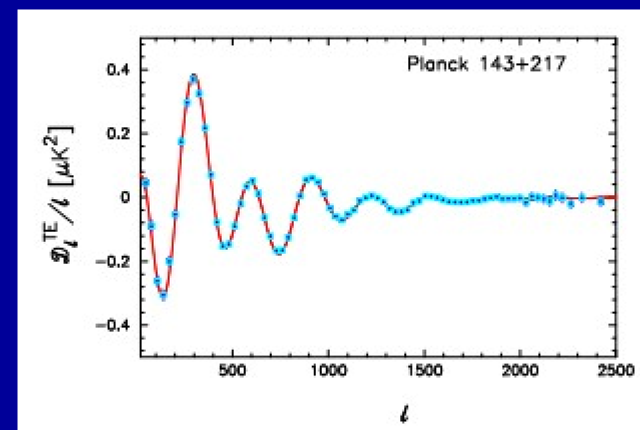
Forecast for Planck data release 2014

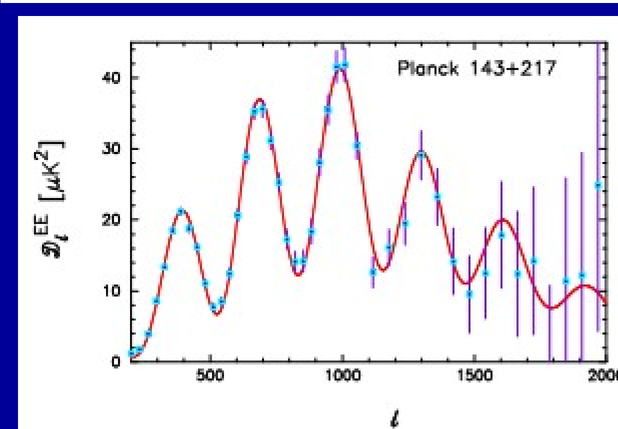
- Twice the integration time



- More sky at 143 & 217 GHz, better handle on small scales

- Polarization



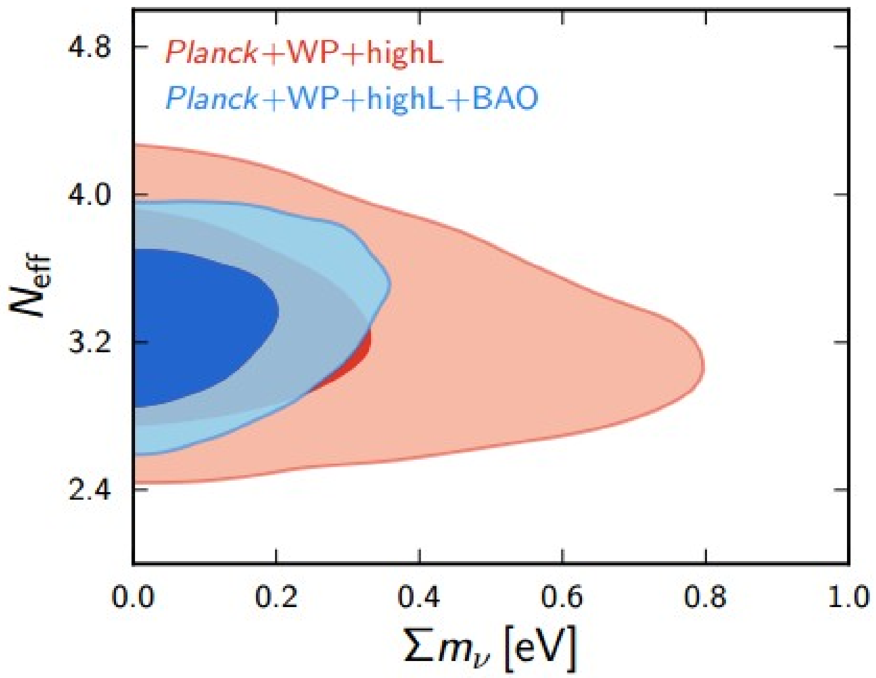


Conclusion

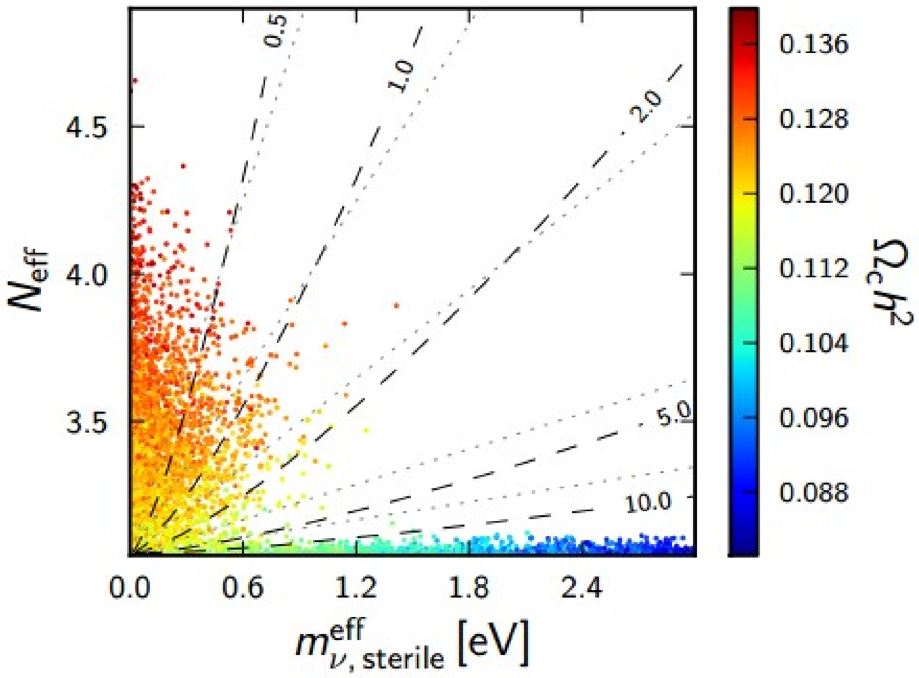
- Planck consistent with LCDM
- Hints of new physics when combining various other probes but nothing definitive
  - Or underestimated systematic errors?
- Probing N_{eff} via damping and newly via phase shift/amplitude due to neutrino anisotropy
- Lensing playing an important role in Planck LCDM parameters compared WMAP, as well as neutrino mass constraints.

Extra slides

Neff and mnu

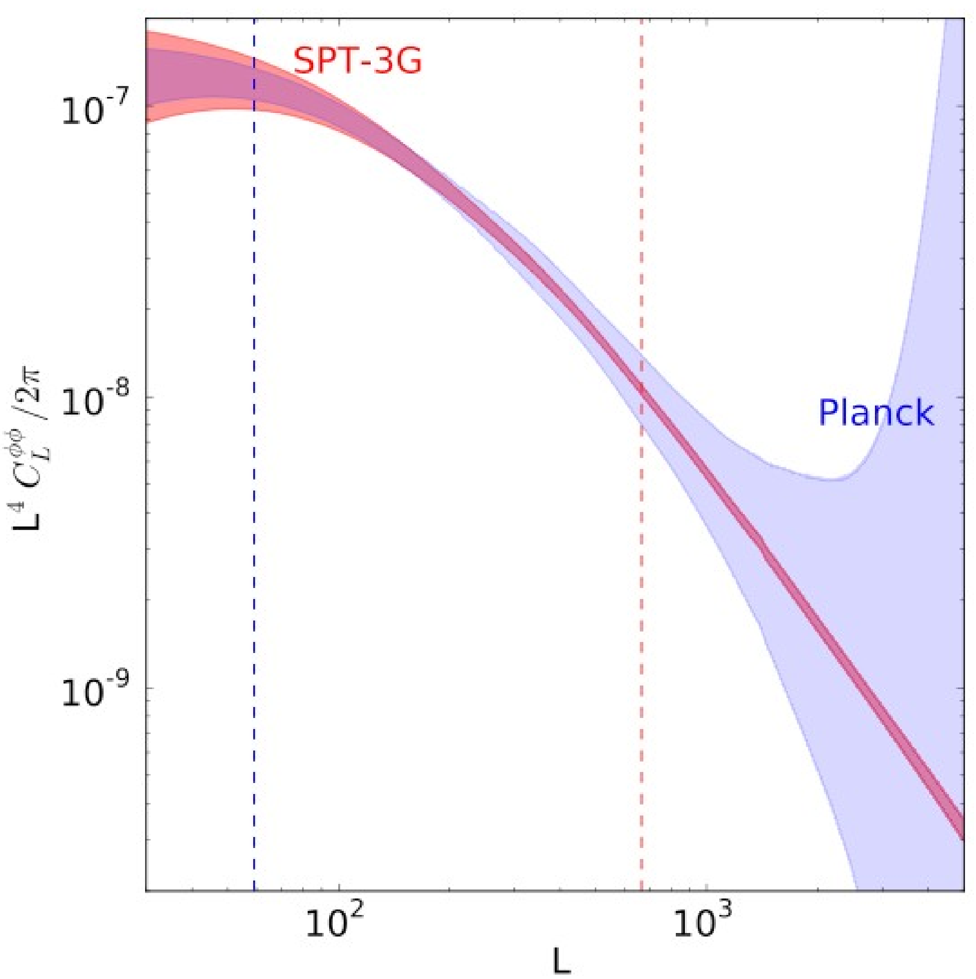


Planck+WP+highL
Planck+WP+highL+BAO
4.8
4.0
3.2
2.4
N_{eff}
0.0
0.2
0.4
0.6
0.8
1.0
Σm_ν [eV]



0.5
1.0
2.0
5.0
10.0
4.5
4.0
3.5
N_{eff}
0.0
0.6
1.2
1.8
2.4
$m^{eff}_{\nu,\,sterile}$ [eV]
0.136
0.128
0.120
0.112
0.104
0.096
0.088
$\Omega_c h^2$

CMB Polarization and Lensing Reconstruction

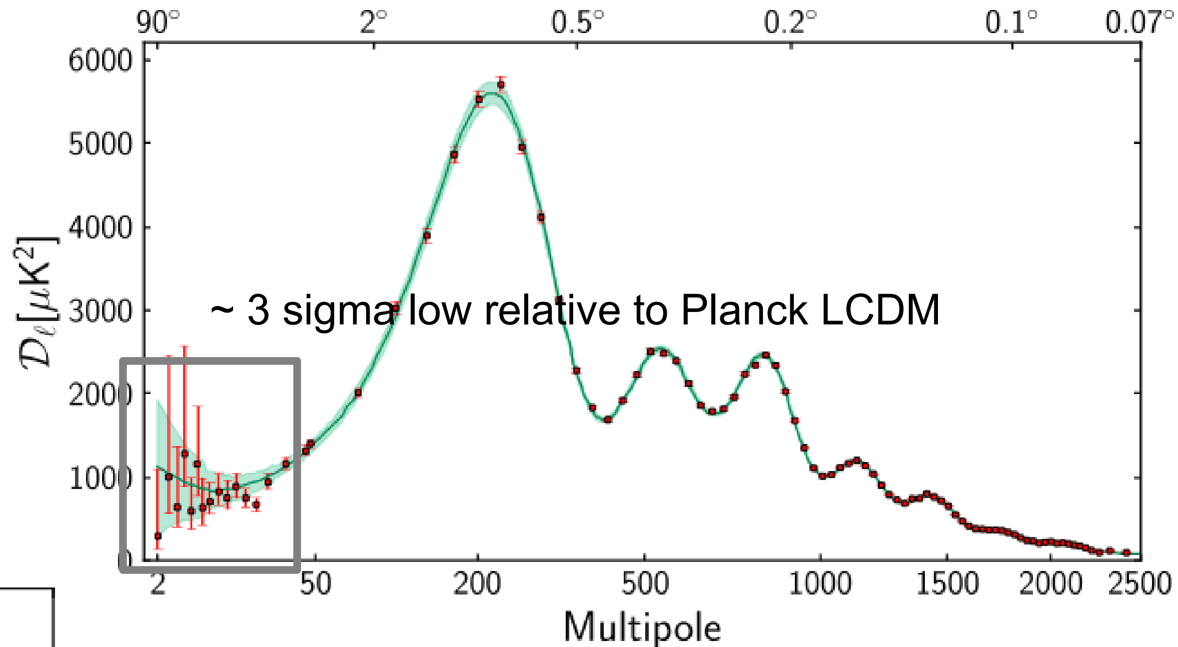


SPT-3G: A proposed 2500 sq. deg. Survey with a 3rd-generation polarization-sensitive focal plane.

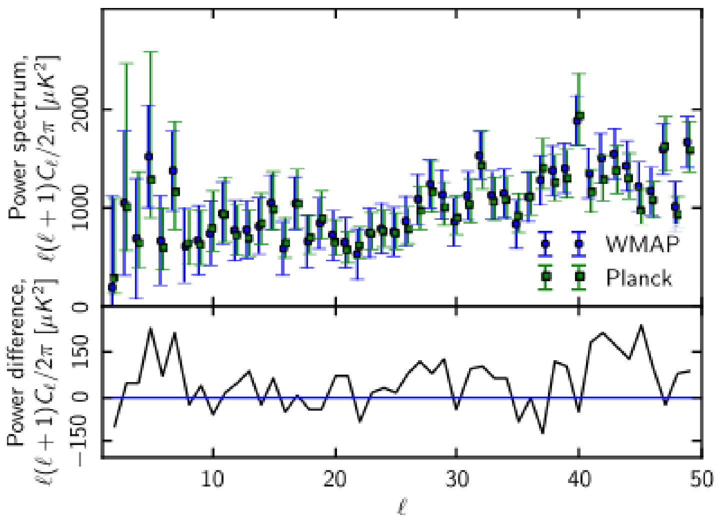
Enabling a deflection angle power spectrum measurement as forecasted here and

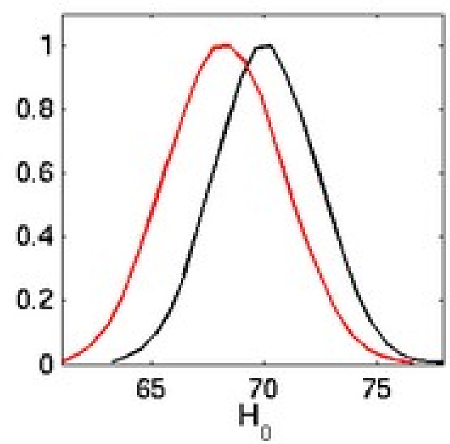
$\sigma(\Sigma m_\nu) = 0.06$ eV

A curiosity: Low-L tension with LCDM



Planck and WMAP in the 2<L<50 region



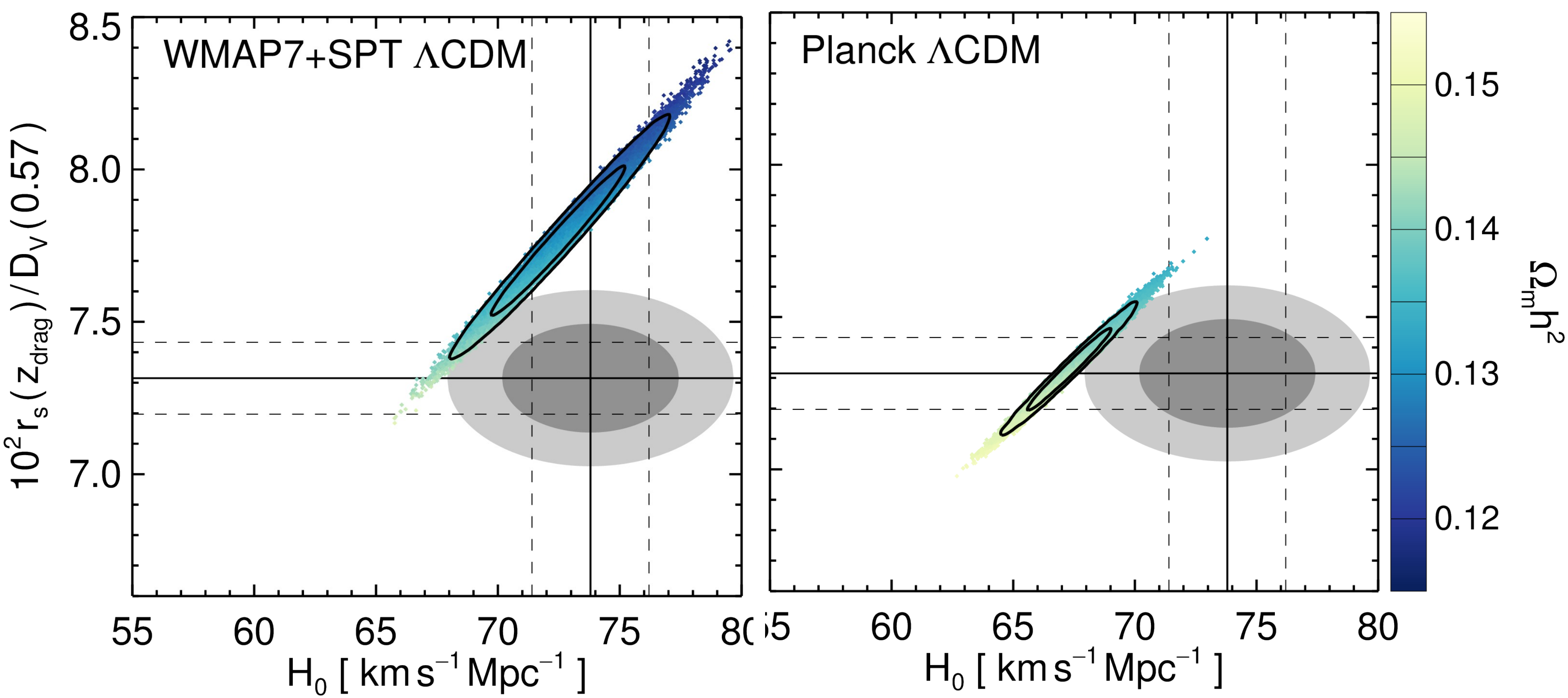


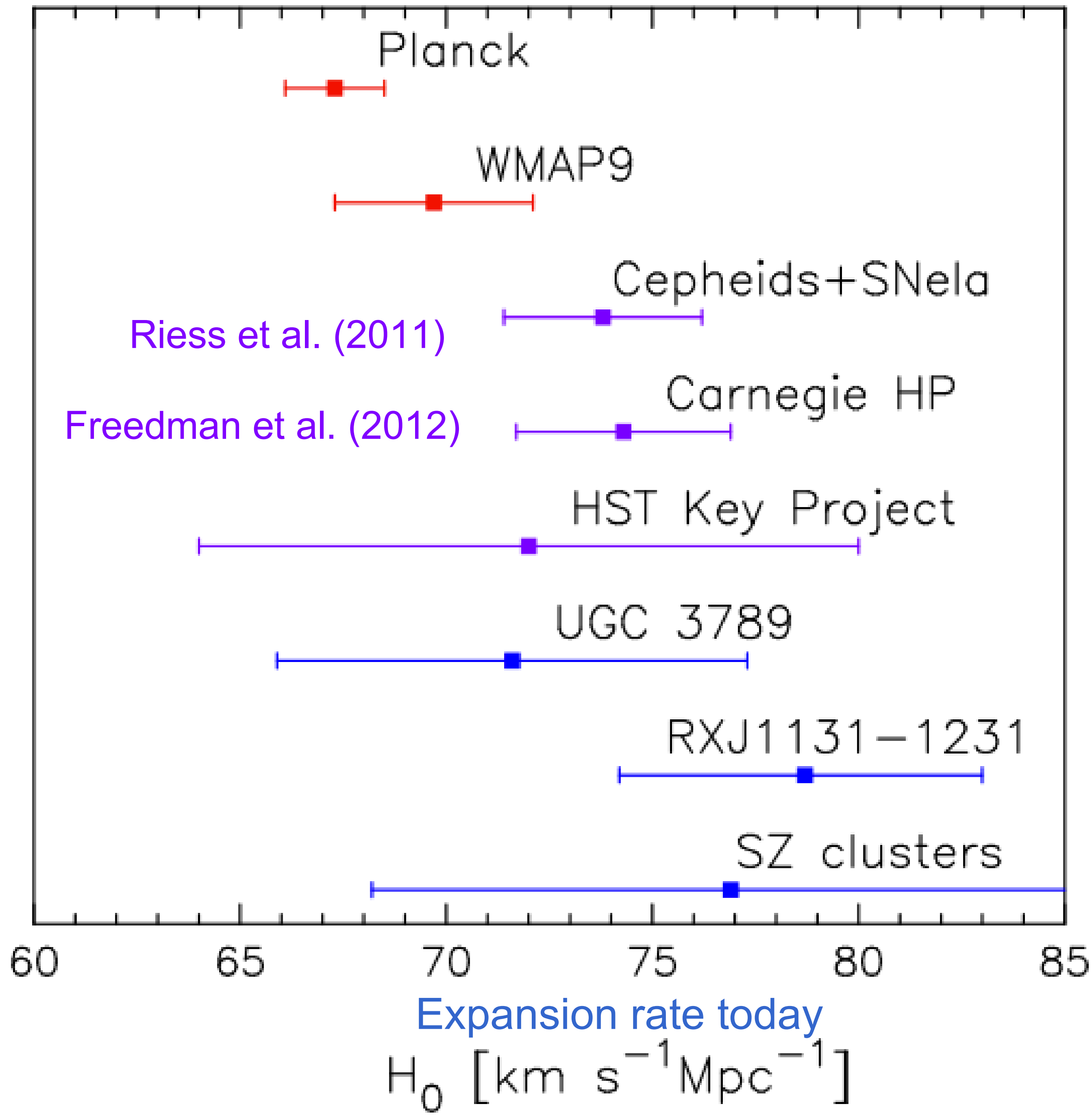
WMAP

WMAP+(no L<30 TT)

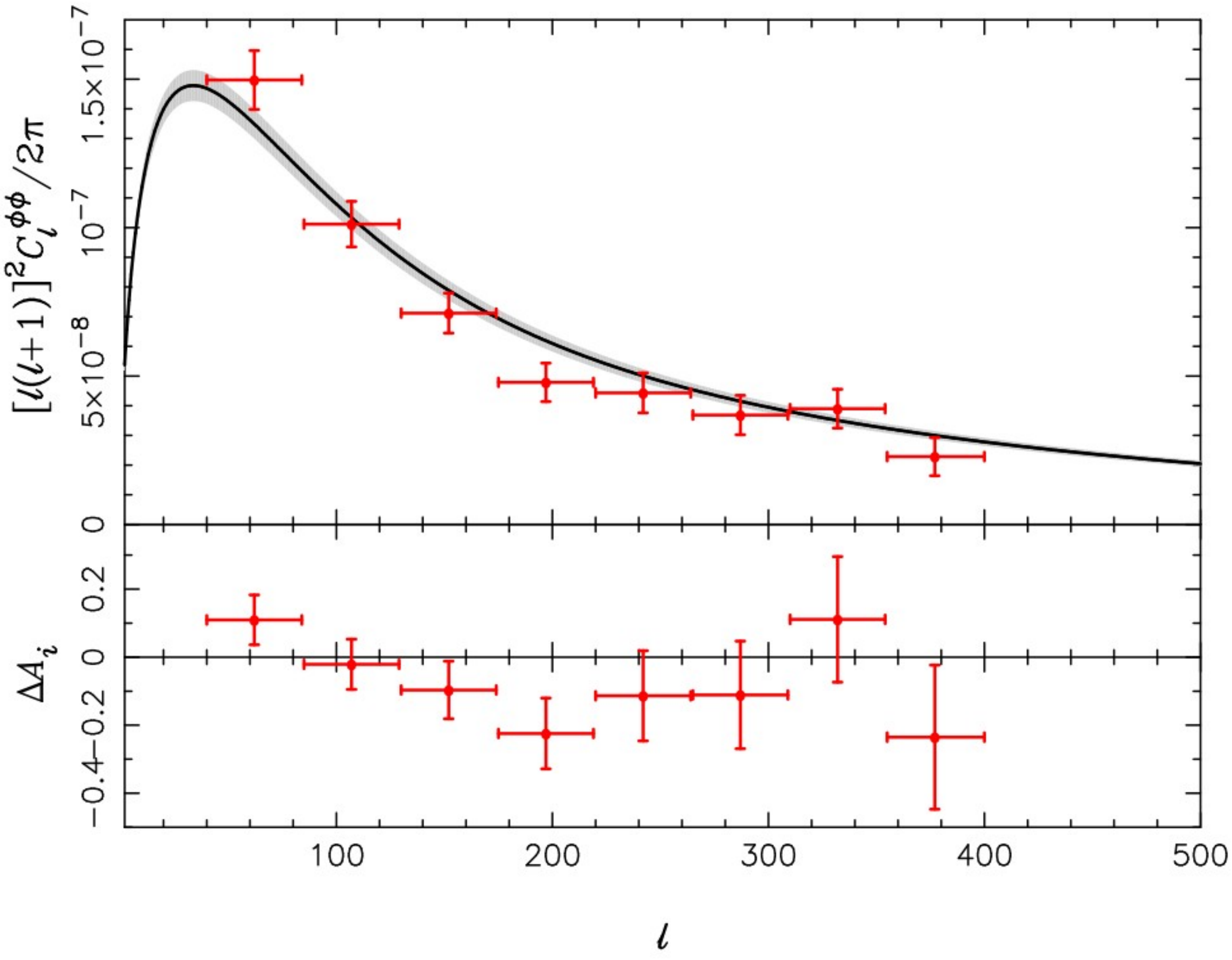
BOSS BAO, Riess et al. (2011) H_0 and Planck LCDM

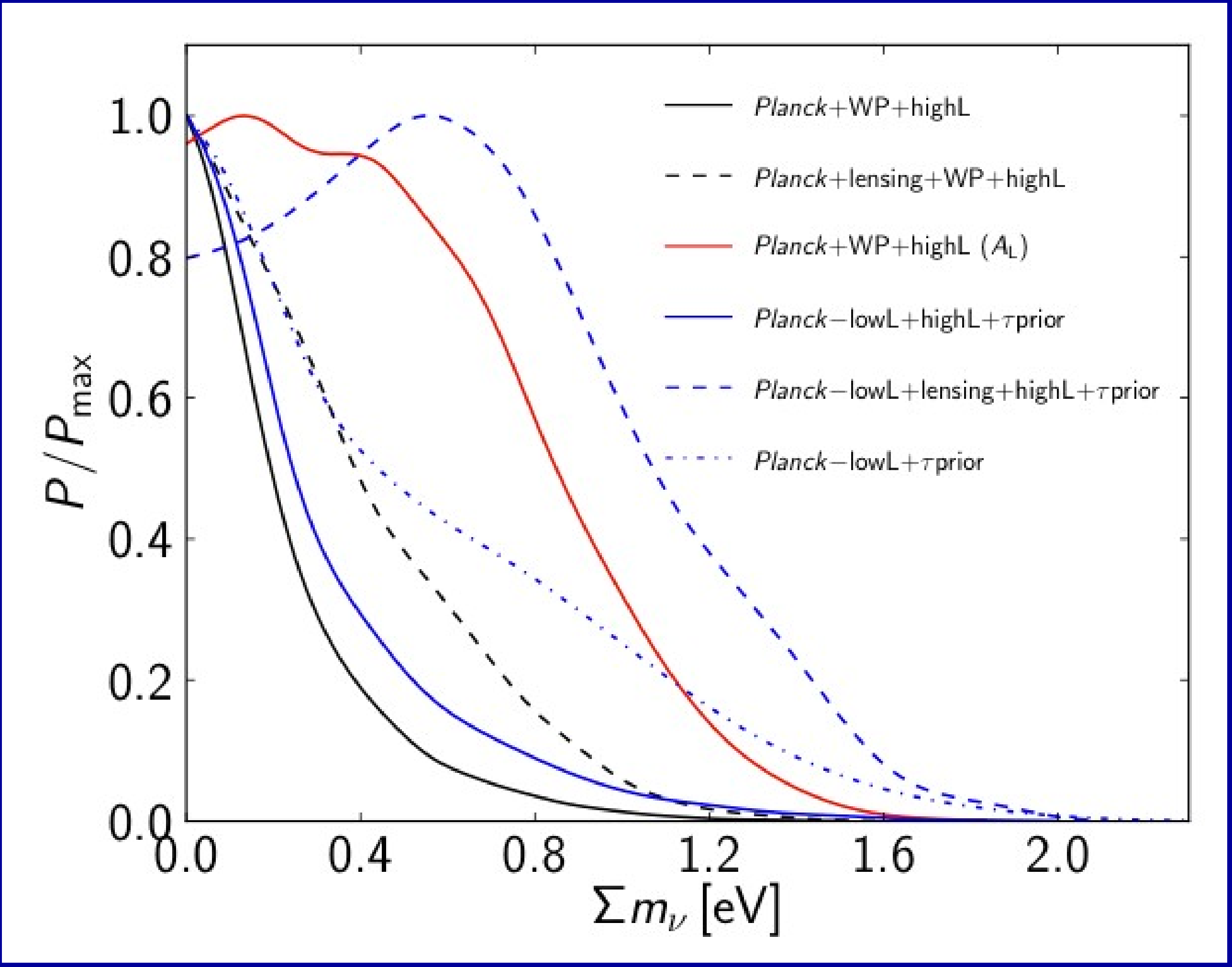
- Planck is in excellent agreement with BAO measurement, discrepant with Riess et al. H_0




Planck
WMAP9
Cepheids+SNeIa
Riess et al. (2011)
Carnegie HP
Freedman et al. (2012)
HST Key Project
UGC 3789
RXJ1131−1231
SZ clusters
60
65
70
75
80
85
Expansion rate today
H_0 [km s^{-1}Mpc^{-1}]

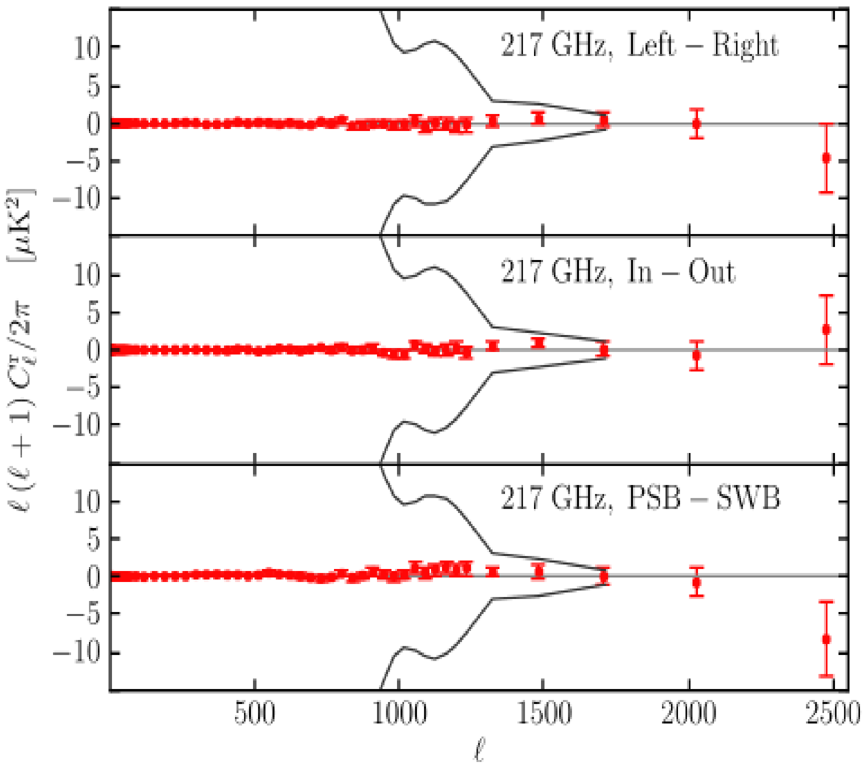
The deflection angle power spectrum

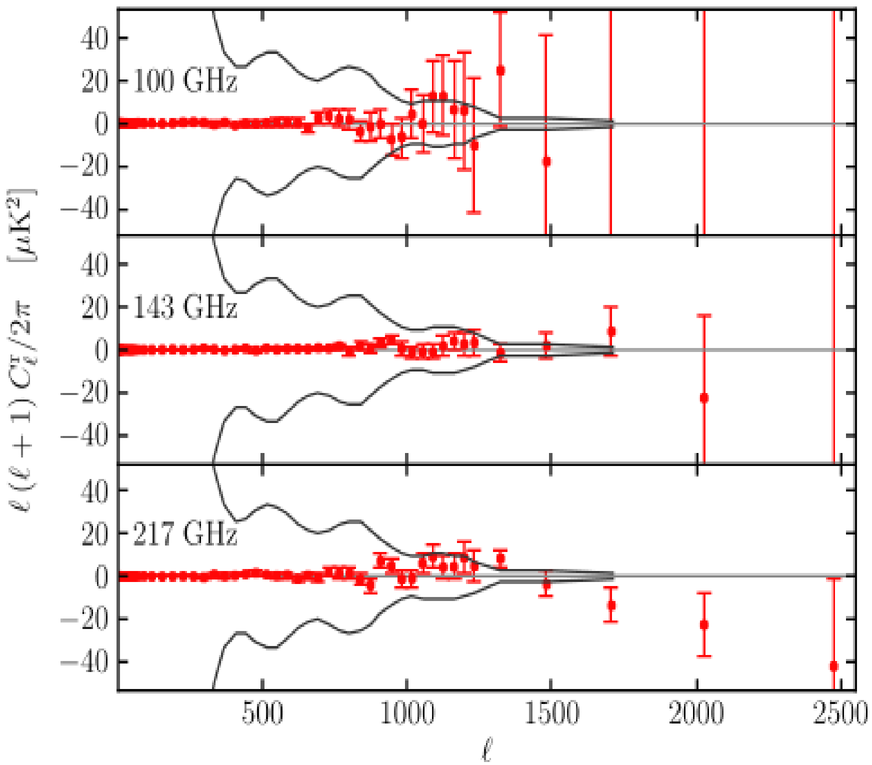




Planck+WP+highL
Planck+lensing+WP+highL
Planck+WP+highL (A_L)
Planck−lowL+highL+τprior
Planck−lowL+lensing+highL+τprior
Planck−lowL+τprior
P/P_{max}
1.0
0.8
0.6
0.4
0.2
0.0
0.0
0.4
0.8
1.2
1.6
2.0
Σm_ν [eV]

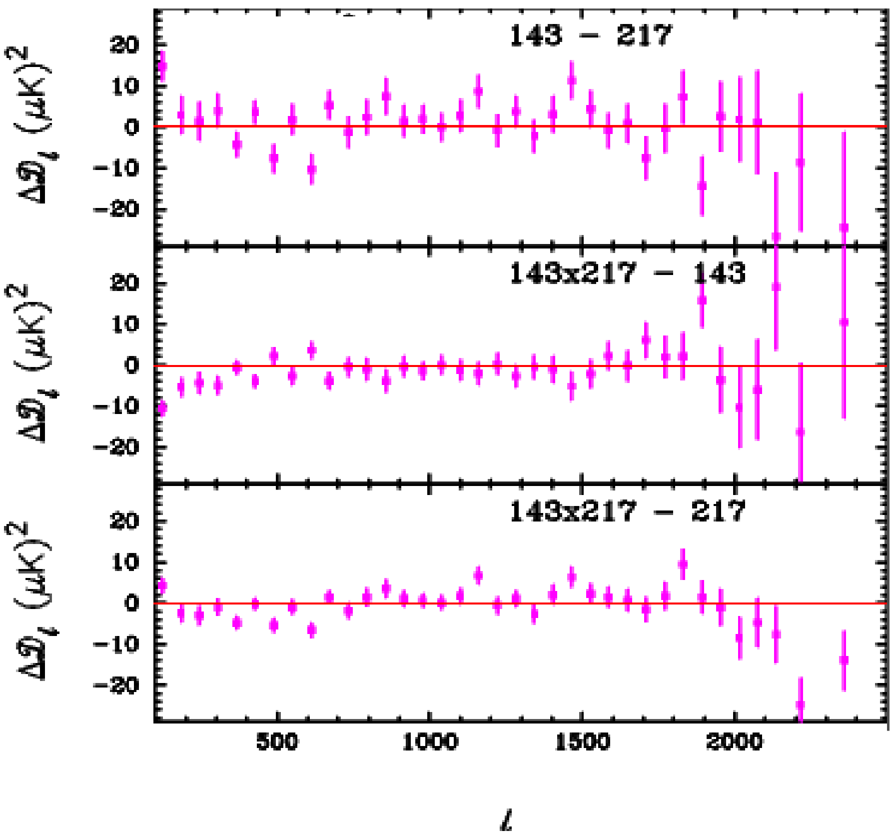
Consistency Tests Within Same Frequency



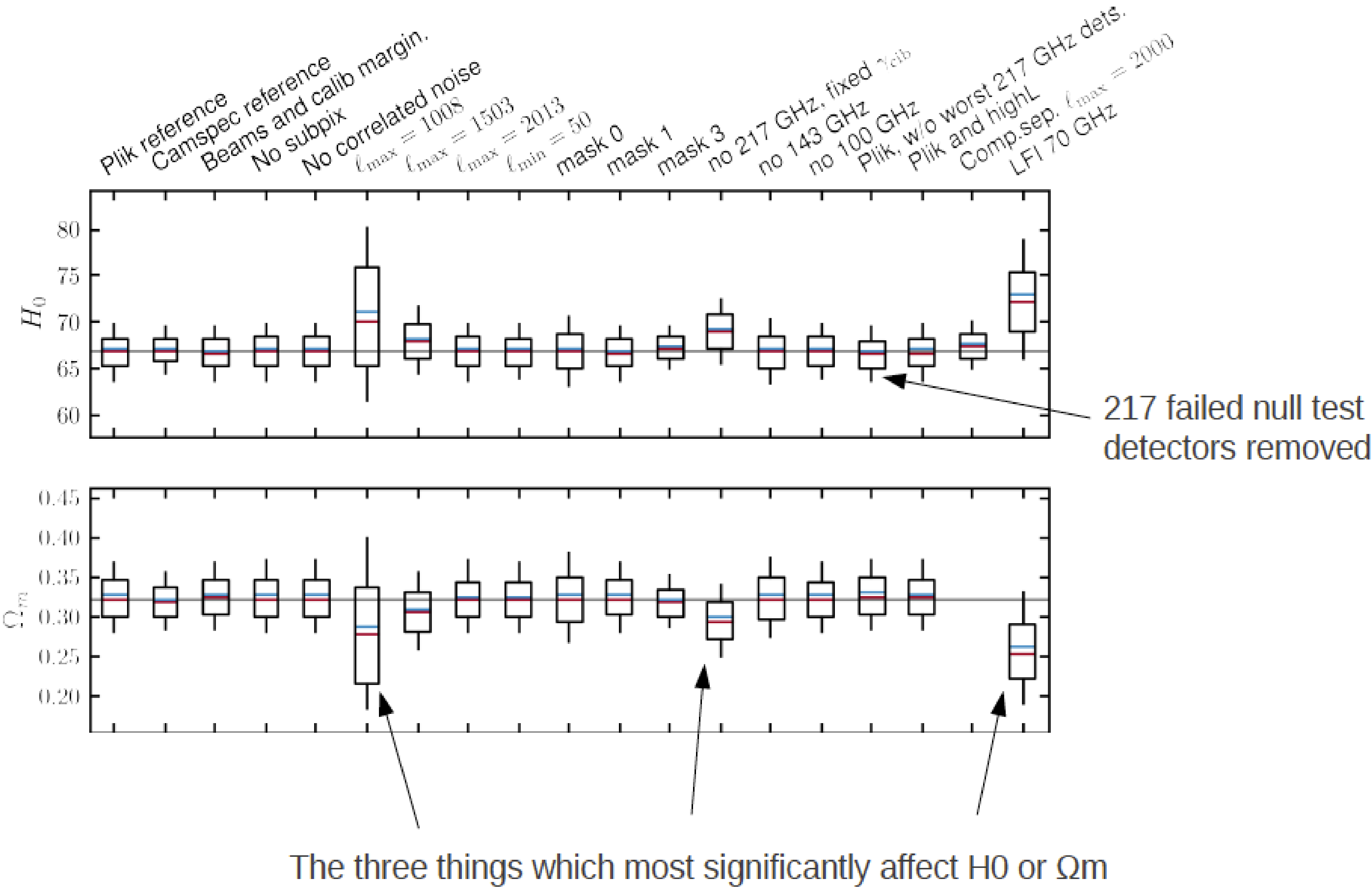


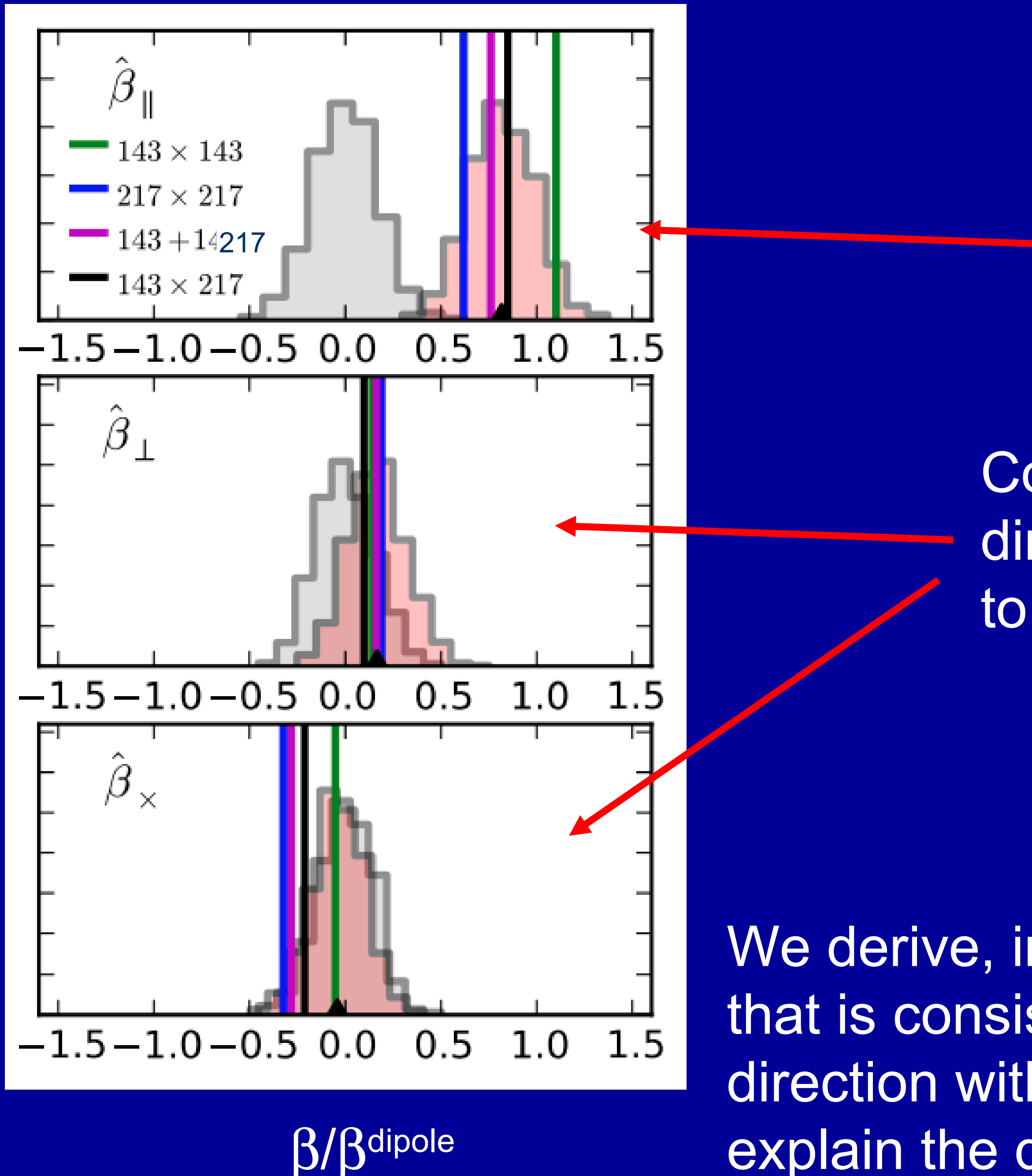
Consistency Tests Between Different Frequencies

- In units of μK, the CMB is the same at all frequencies
- This is a critical tests of galactic foreground cleaning, extra-galactic foreground modeling, and transfer functions



Effect of modeling choices and data selection

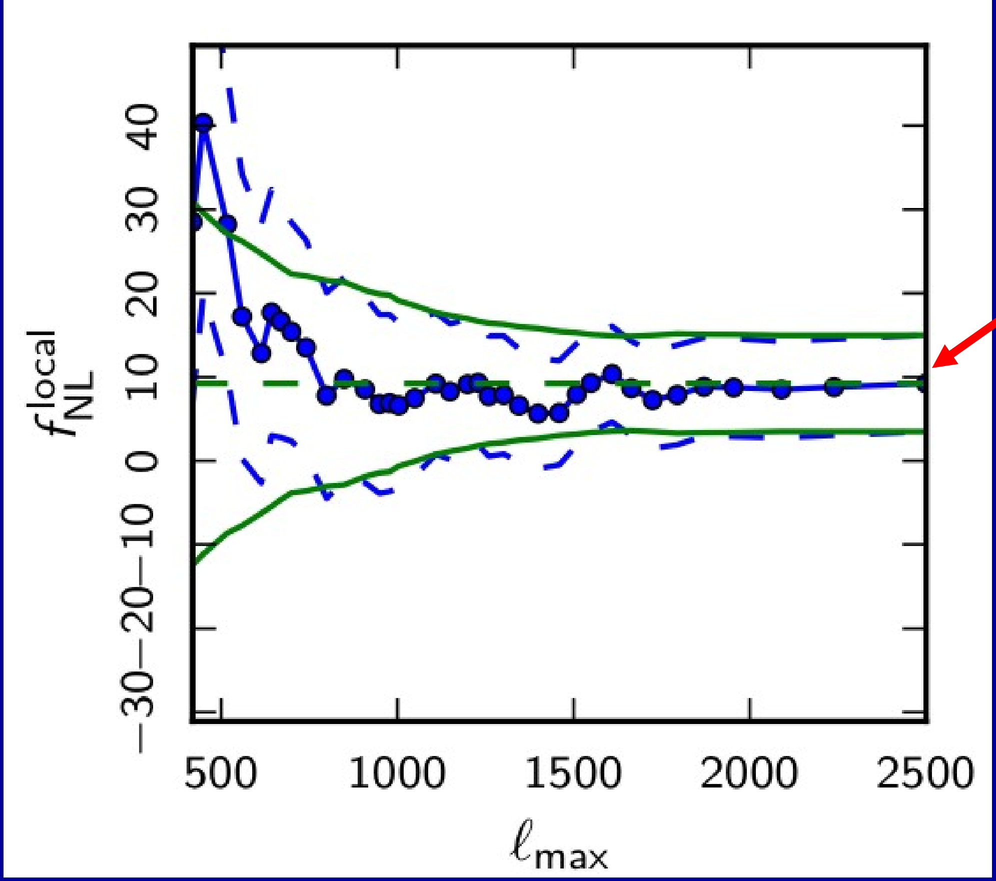




We derive, in multiple ways, a β=v/c that is consistent in magnitude and direction with what's required to explain the dipole.

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

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



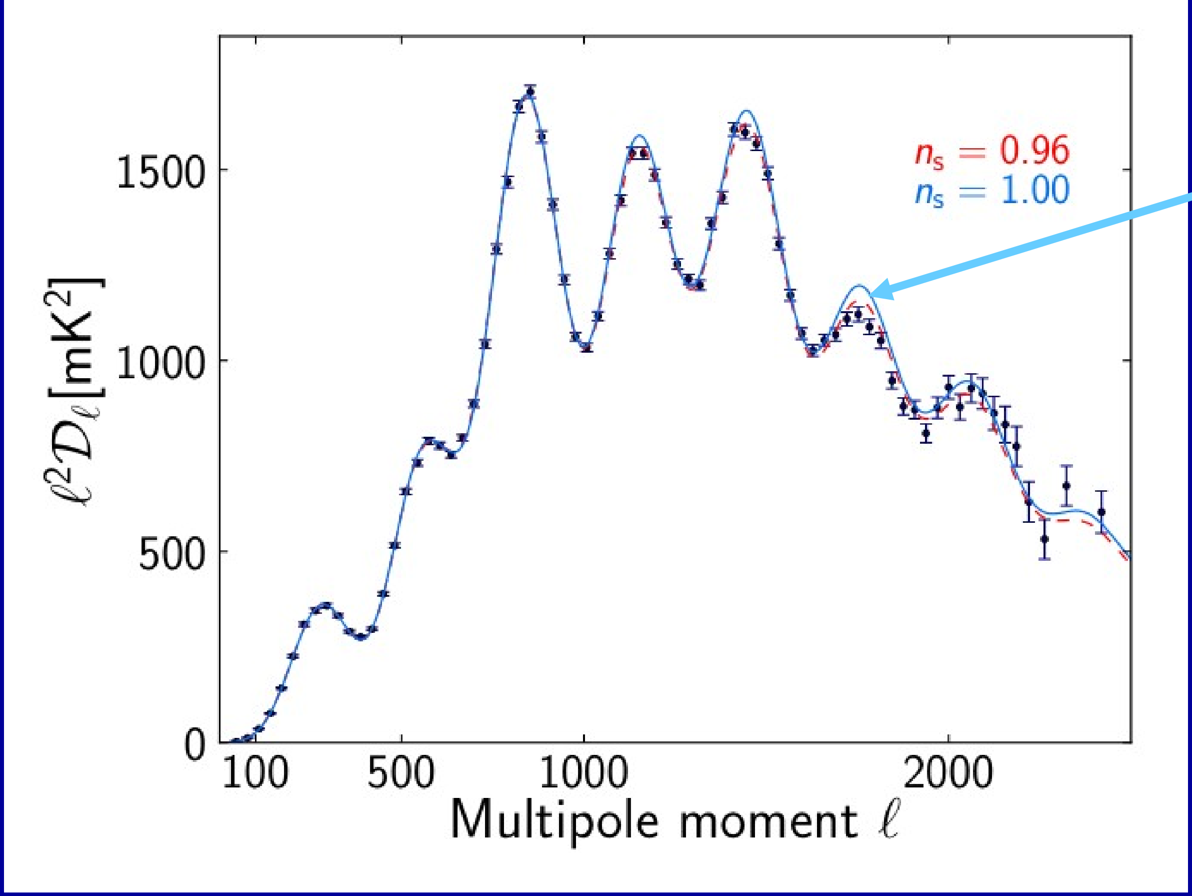
Non-zero!

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

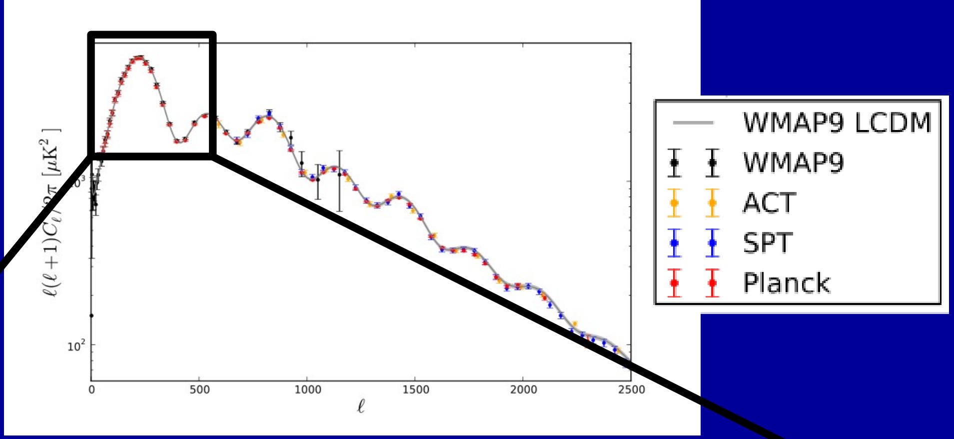
After subtraction of late-time effect:

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

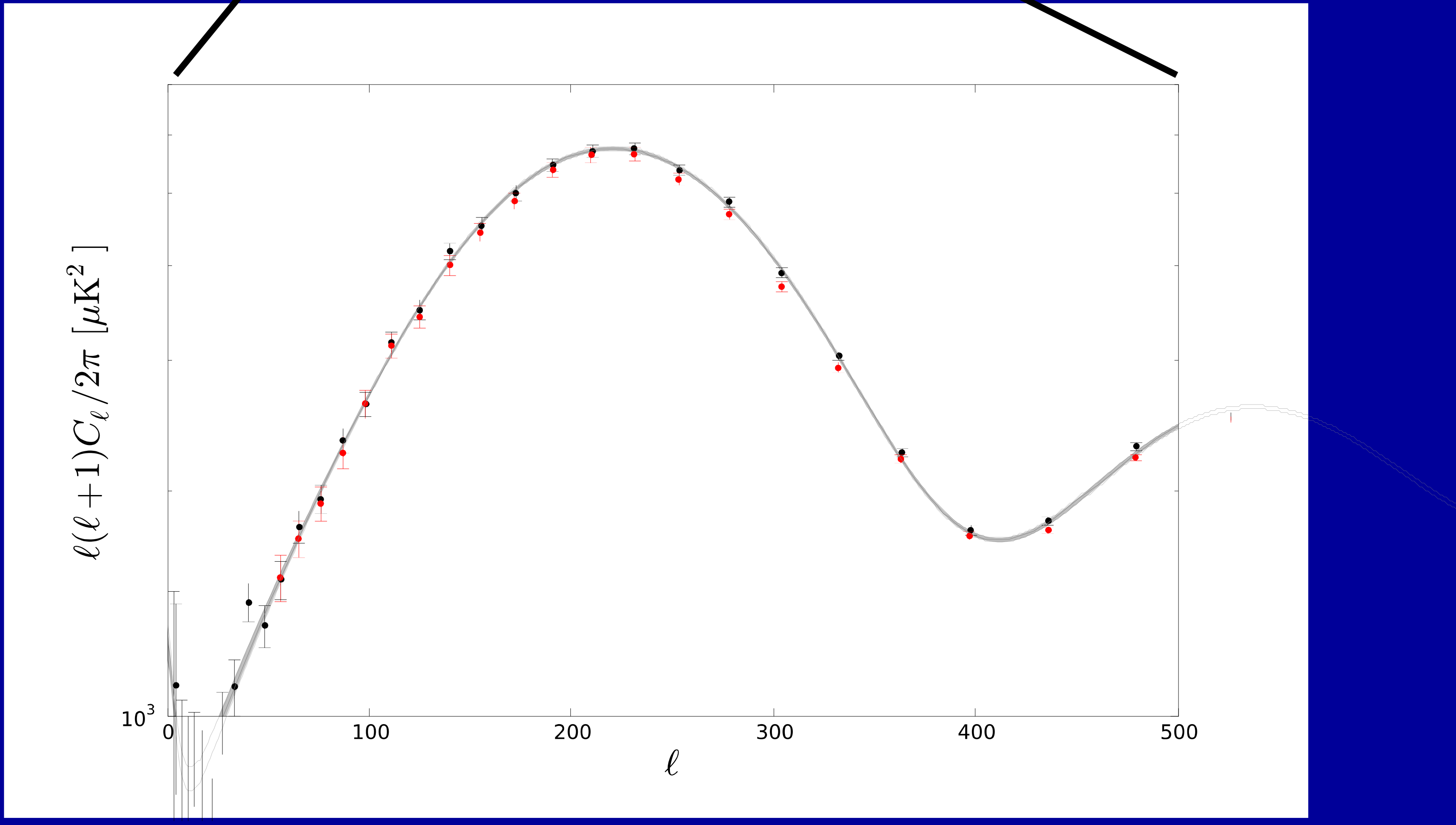
> 5σ detection of scale dependence of primordial fluctuations ==> time dependence during inflation



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

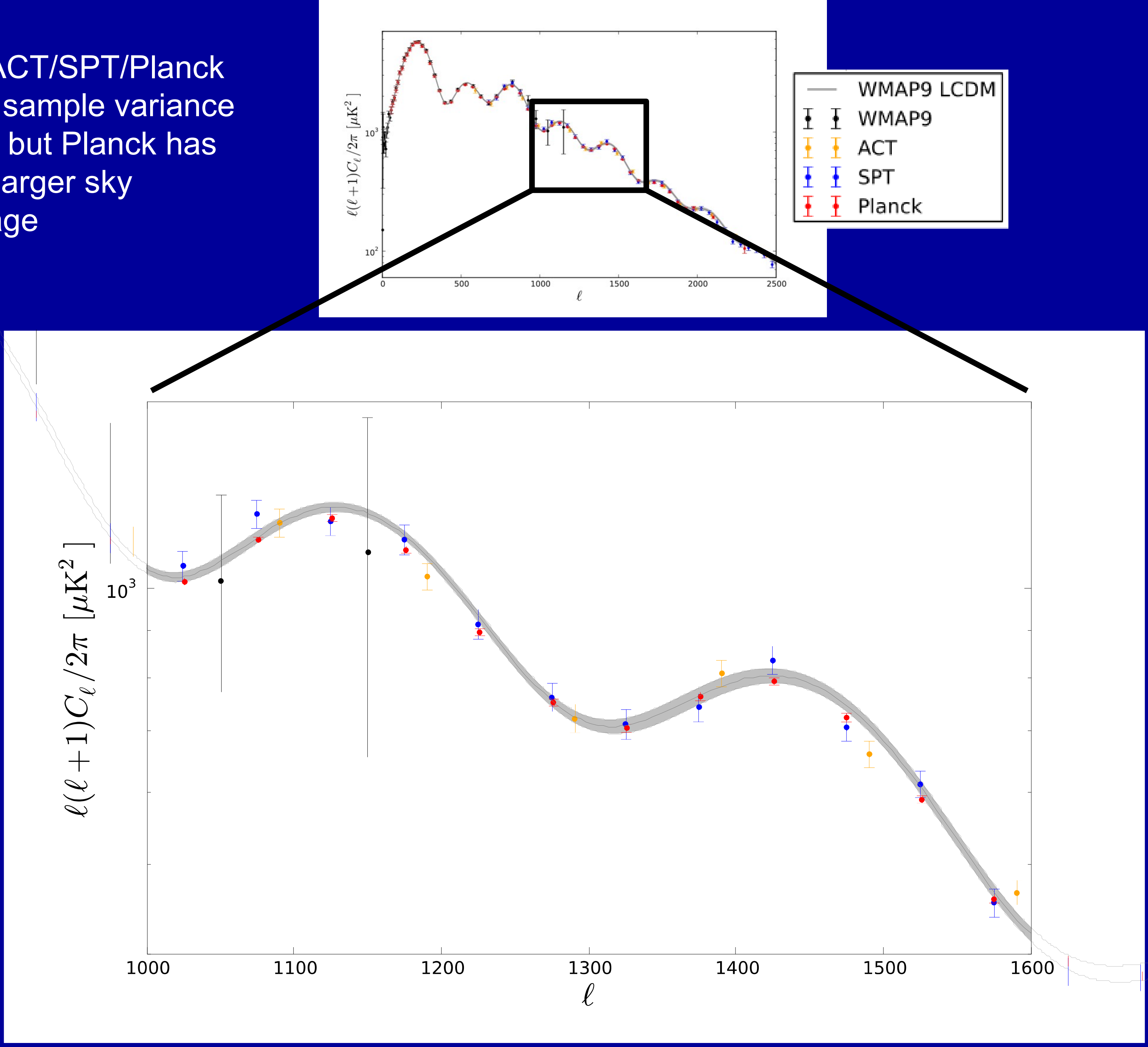


WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
ℓ

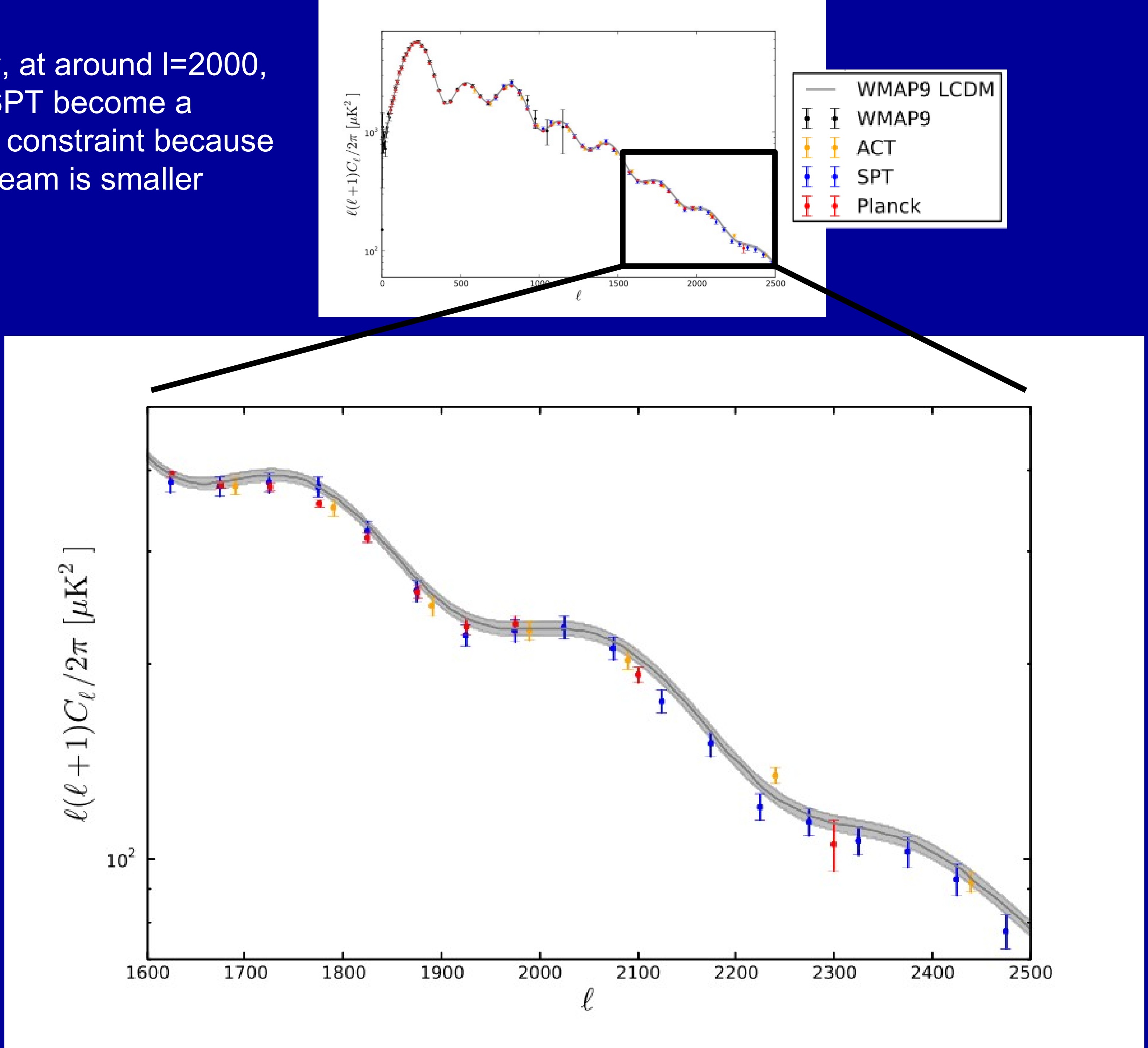


$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^3
0
100
200
300
400
500
ℓ

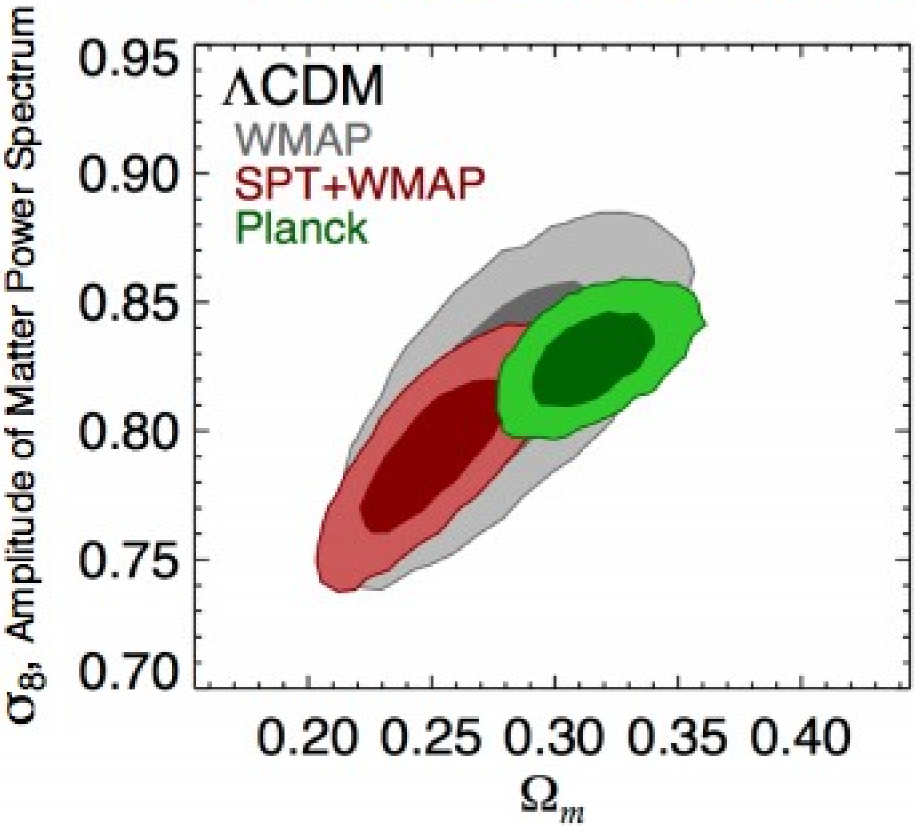
Here ACT/SPT/Planck are all sample variance limited but Planck has much larger sky coverage



Finally, at around l=2000, ACT/SPT become a tighter constraint because their beam is smaller



CMB Constraints on σ_8, Ω_m



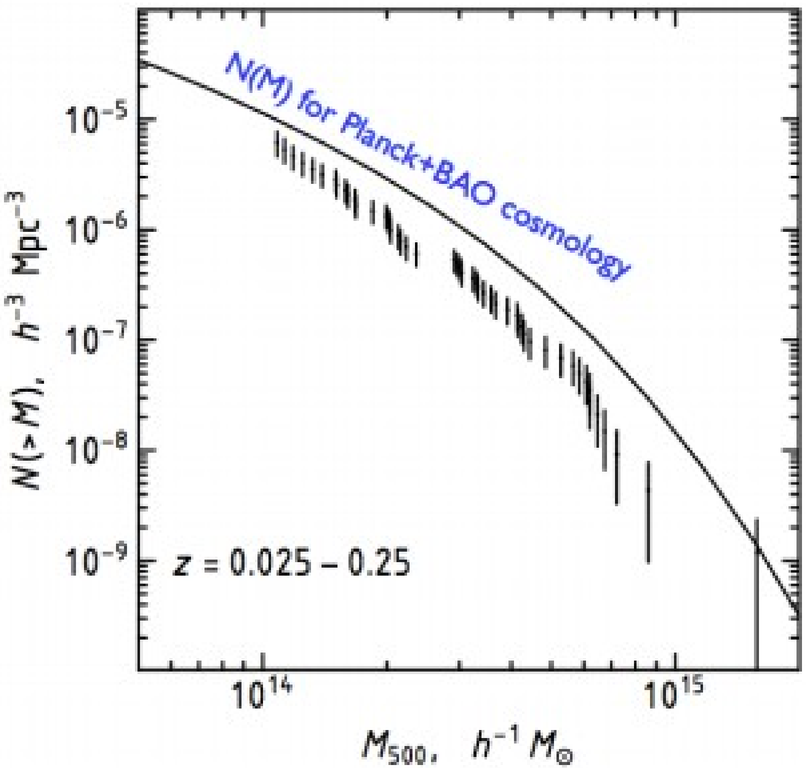
Planck measurements favor a shift in σ_8 and Ω_m Driven by:

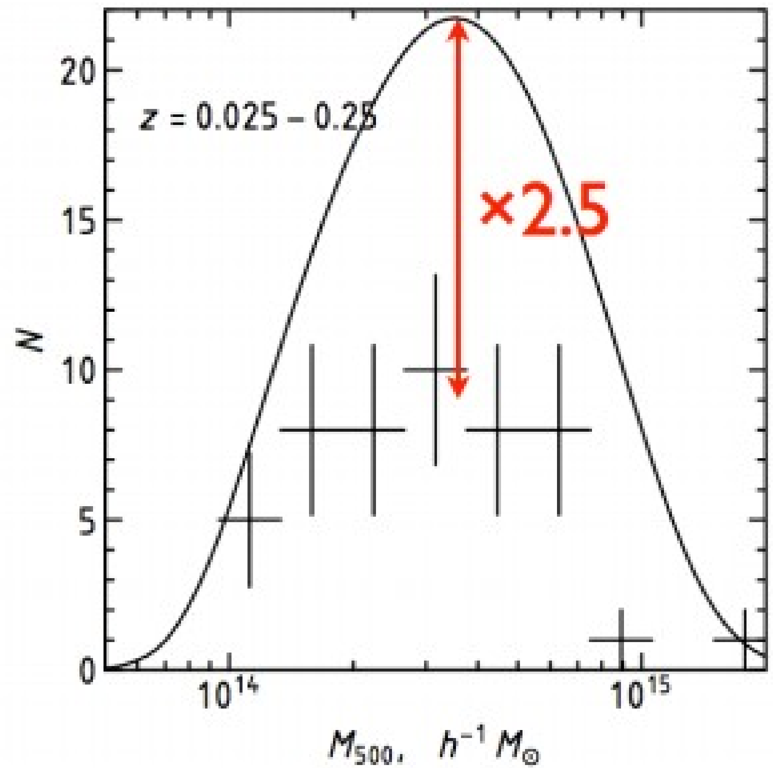
- 1st/3rd acoustic peak power ratio
- Gravitational lensing in the CMB power spectrum (Ω_m goes down by ~1σ when A_{Lens} is free)

	WMAP7	WMAP7+SPT	Planck-CMB
σ_8	0.819 +/- 0.031	0.795 +/- 0.022	0.829 +/- 0.012
Ω_m	0.276 +/- 0.029	0.250 +/- 0.020	0.315 +/- 0.016

(WMAP7) Komatsu +2011
(SPT) Story+2012
Planck XX 2013
Planck XVI 2013

Planck Cosmology has ***profound*** mismatch with Cluster Abundance

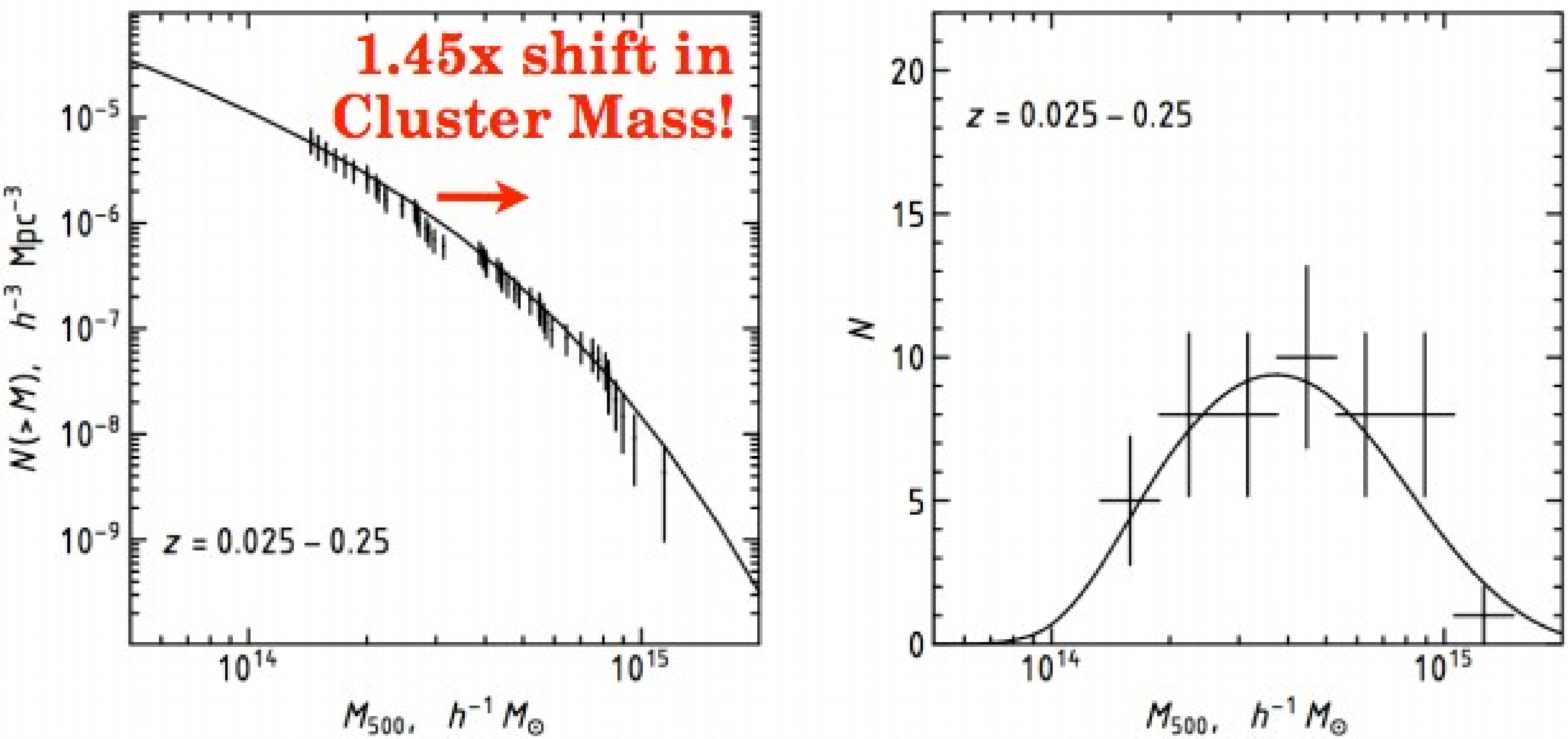




$$\text{Cluster counts} \sim (\sigma_8)^{10}$$

Vikhlinin et al. 2009 (CCCP, X-rays)

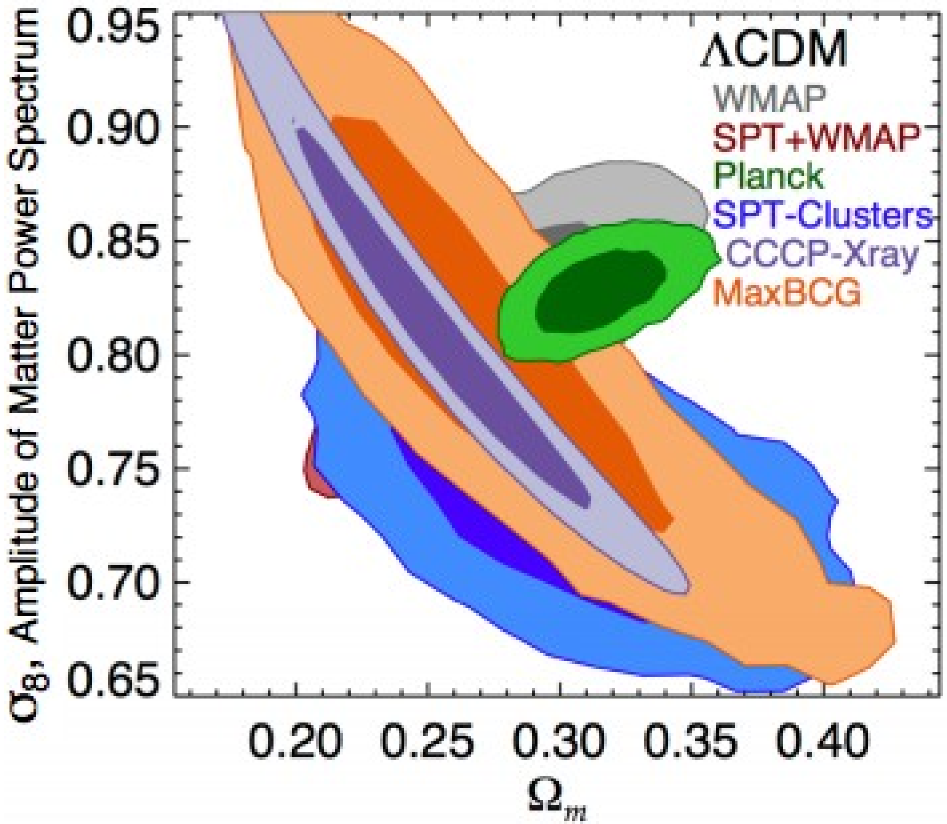
Planck Cosmology has ***profound*** mismatch with Cluster Abundance



$$\text{Cluster counts} \sim (\boldsymbol{\sigma}_8)^{10}$$

Vikhlinin et al. 2009 (CCCP, X-rays)

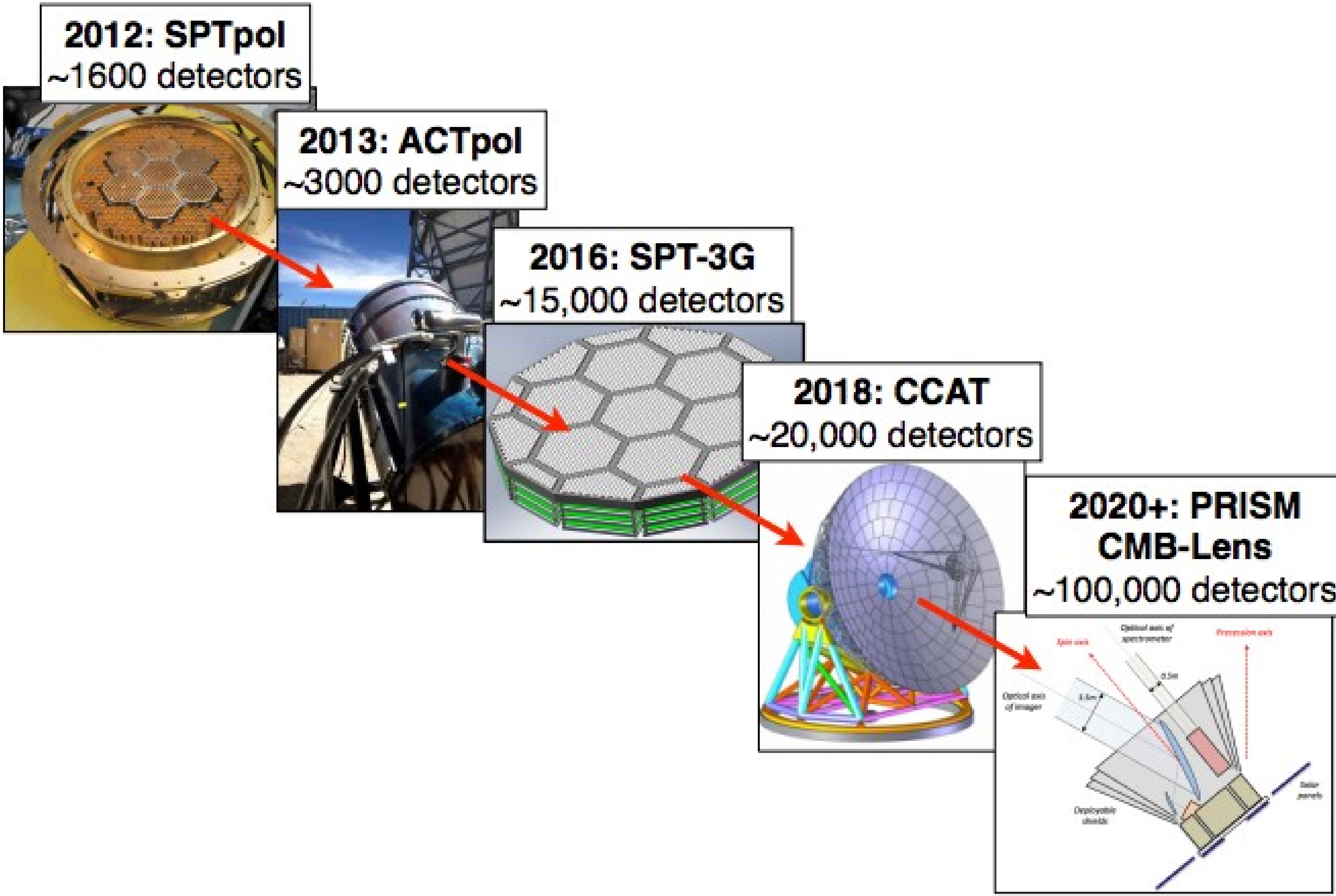
Tension exists for ***SZ, X-ray, Optical*** cluster surveys and other probes of structure



- ***SZ, X-ray, and optical cluster surveys all favor lower σ_8, Ω_m*** (Reichardt+13, Vikhlinin +09, Rozo+10, etc.)
- **Other probes of structure are consistent with clusters**:
  - Weak lensing surveys (e.g. CFHTLS, Kilbinger+13)
  - Redshift space distortions (Macaulay+13)
  - Planck CMB lensing power spectrum (PlanckXVII)
- *A neutrino mass of $\Sigma m_\nu \sim 0.3$ eV would relieve this tension.*

However, I think its still reasonable to question evidence for high σ_8, Ω_m from Planck CMB.

Current and Future SZ Surveys



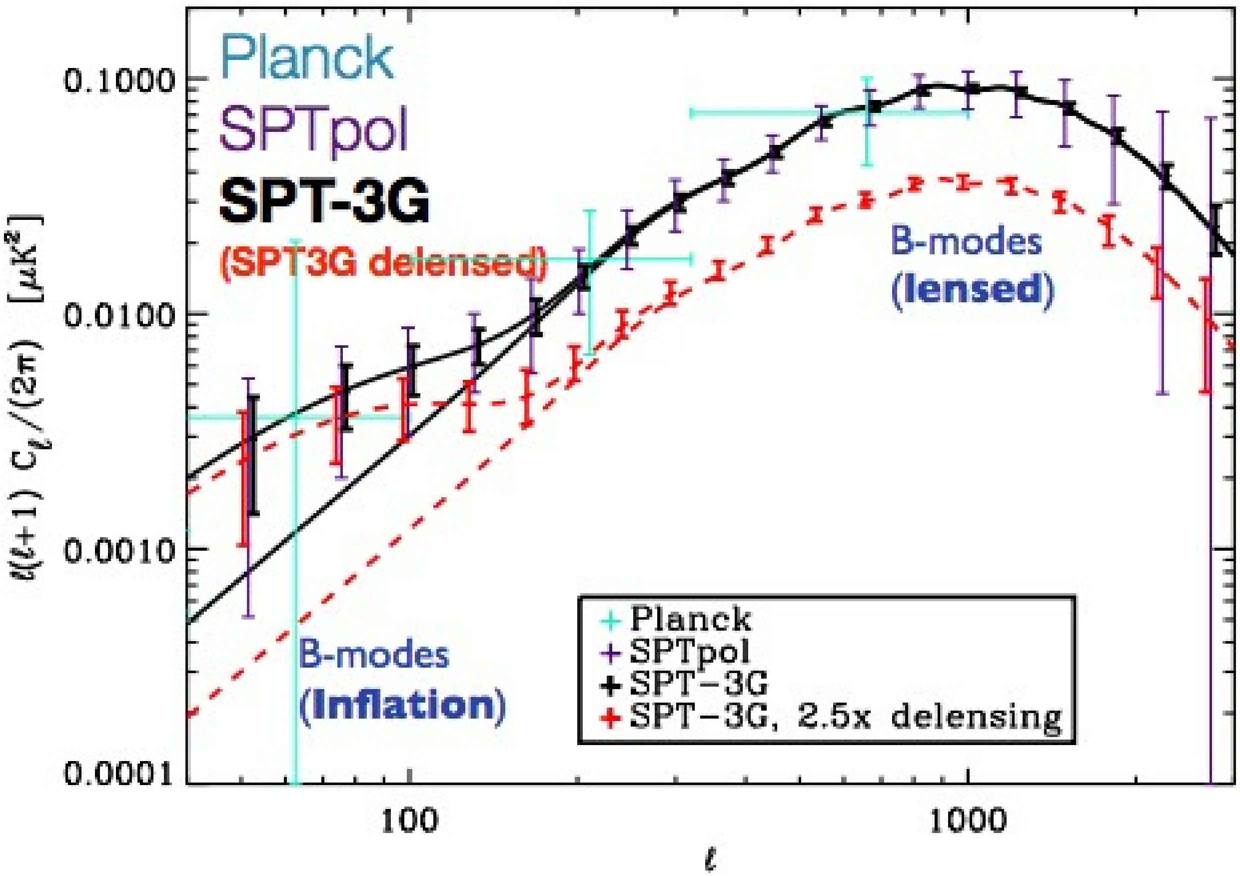
Current and Future SZ Surveys

2012: SPTpol
~1600 detectors

2013: ACTpol

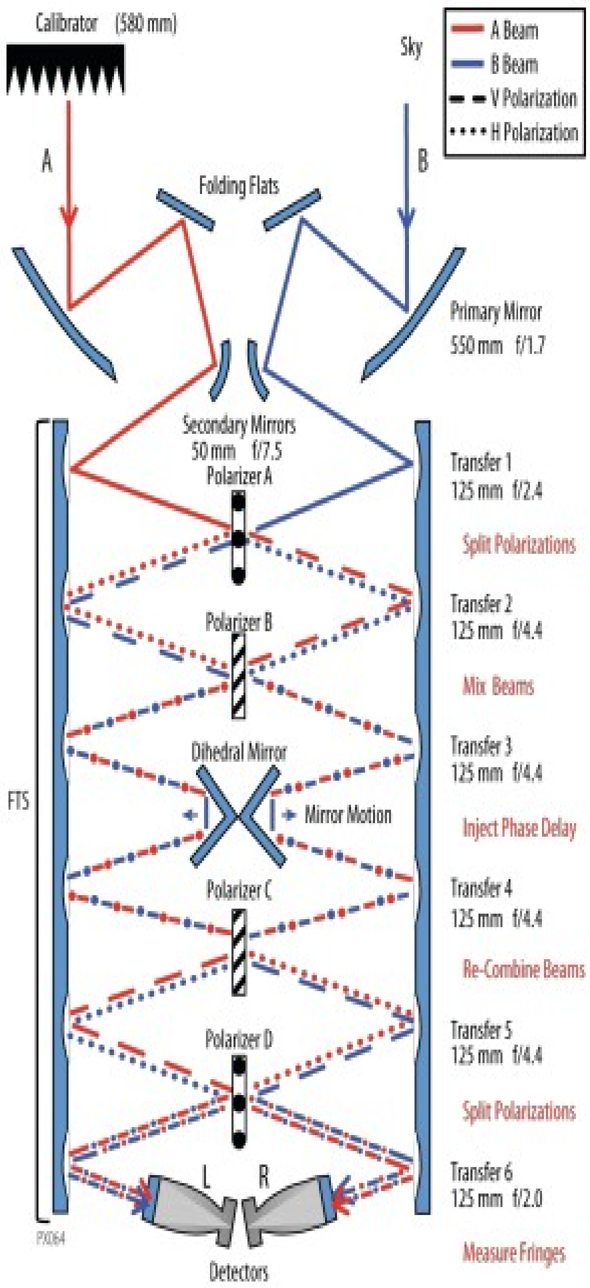
	Start Date	Area (deg^2)	Depth (uK-arcmin)	$N_{clusters}$
SPTpol	2012	500	6	**~1000**
ACTpol	2013	4000/150	20/4	**~1000**
SPT-3G	2016	2500	2	**~10,000**
CCAT	2018	~20,000	15	**~5000**
CMB-Lens	2020+	~20,000	~1	**~150,000**
PRISM	2020+	All-sky	~1	**~1 million**

SPT-3G:
Projected B-mode Power Spectrum



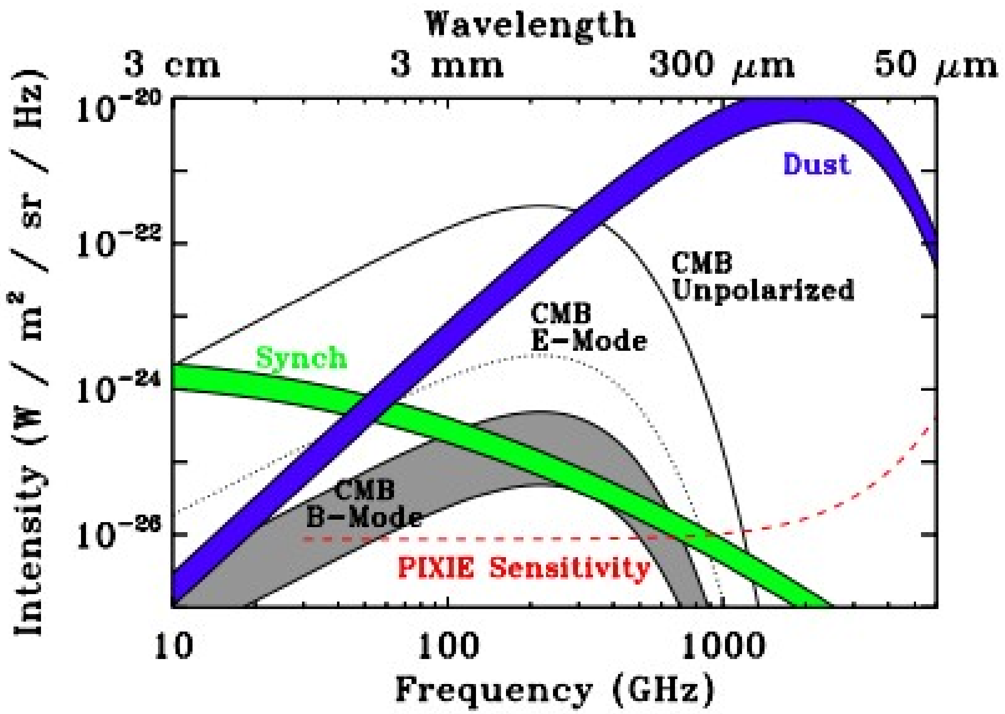
- Neutrino Constraints:
  - ***δ(N_eff) = 0.06***
  - ***δ(Σmν) = 0.06 eV***
- "De-lens" the CMB at large-angular scales and improve "***r***" Inflation constraint
  - ***δ(r) = 0.01***

Credit: T. Crawford

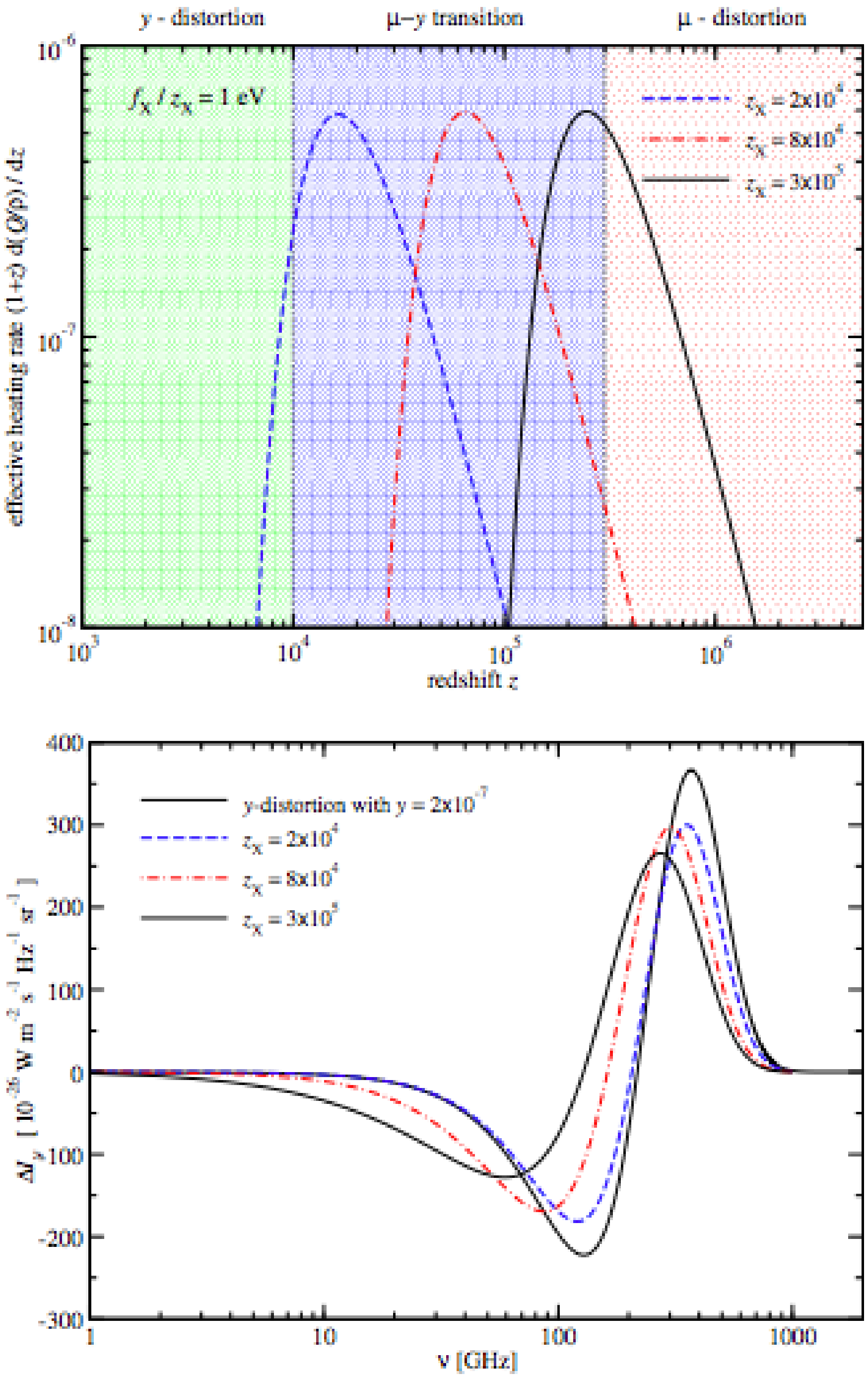


Calibrator (580 mm)
Sky
A Beam
B Beam
V Polarization
H Polarization
A
B
Folding Flats
Primary Mirror
550 mm f/1.7
Secondary Mirrors
50 mm f/7.5
Polarizer A
Transfer 1
125 mm f/2.4
Split Polarizations
Polarizer B
Transfer 2
125 mm f/4.4
Mix Beams
Dihedral Mirror
Transfer 3
125 mm f/4.4
FTS
Mirror Motion
Inject Phase Delay
Polarizer C
Transfer 4
125 mm f/4.4
Re-Combine Beams
Polarizer D
Transfer 5
125 mm f/4.4
Split Polarizations
L
R
Transfer 6
125 mm f/2.0
Measure Fringes
Detectors

PIXIE



Wavelength
3 cm
3 mm
300 μm
50 μm
10^{-20}
10^{-22}
10^{-24}
10^{-26}
Intensity (W / m² / sr / Hz)
Dust
CMB
Unpolarized
CMB
E-Mode
Synch
CMB
B-Mode
PIXIE Sensitivity
10
100
1000
Frequency (GHz)



Spectral Distortions