Planck 2014 Constraints on the Cosmic Neutrino(-like) Background

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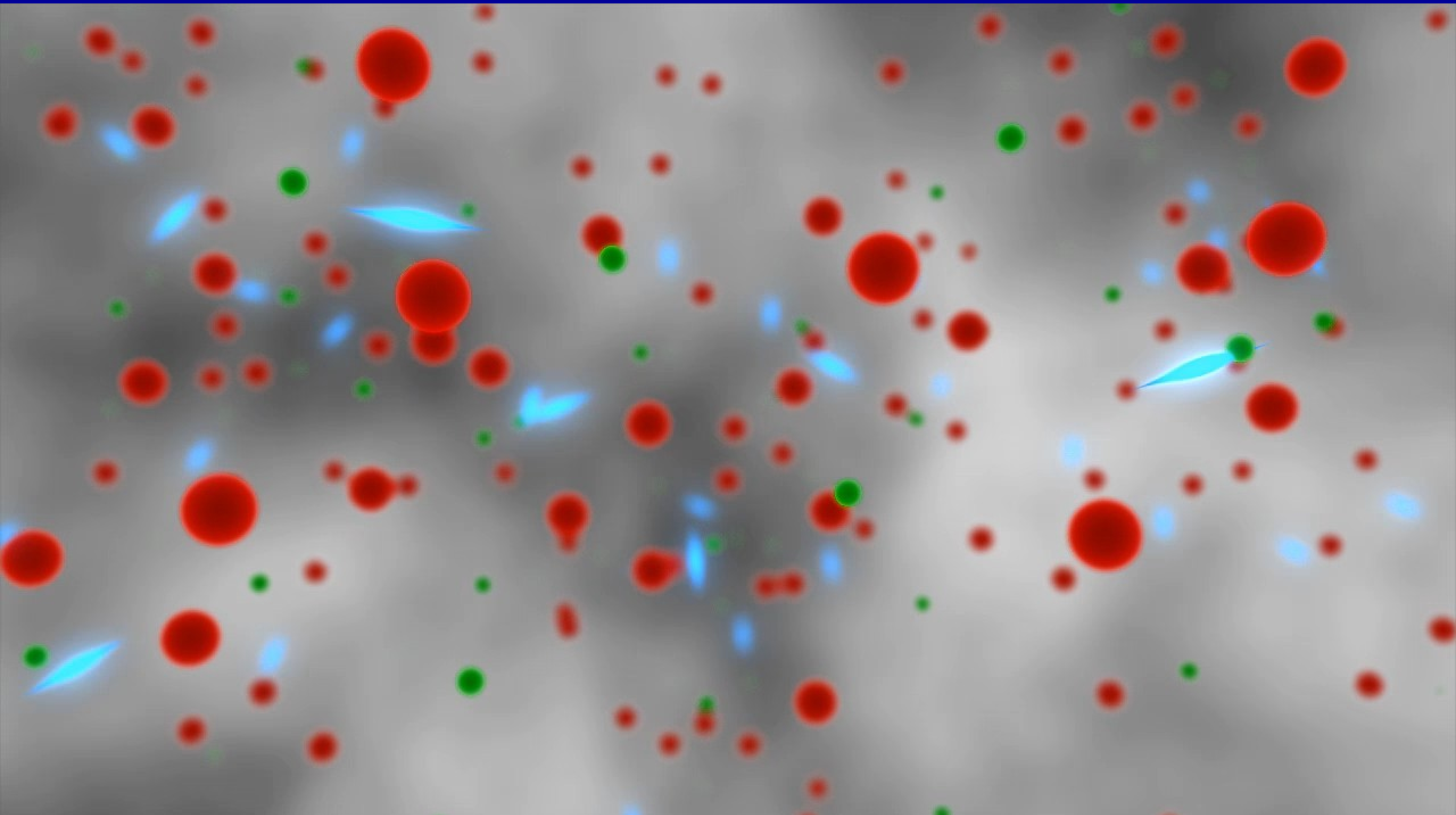
UC Davis

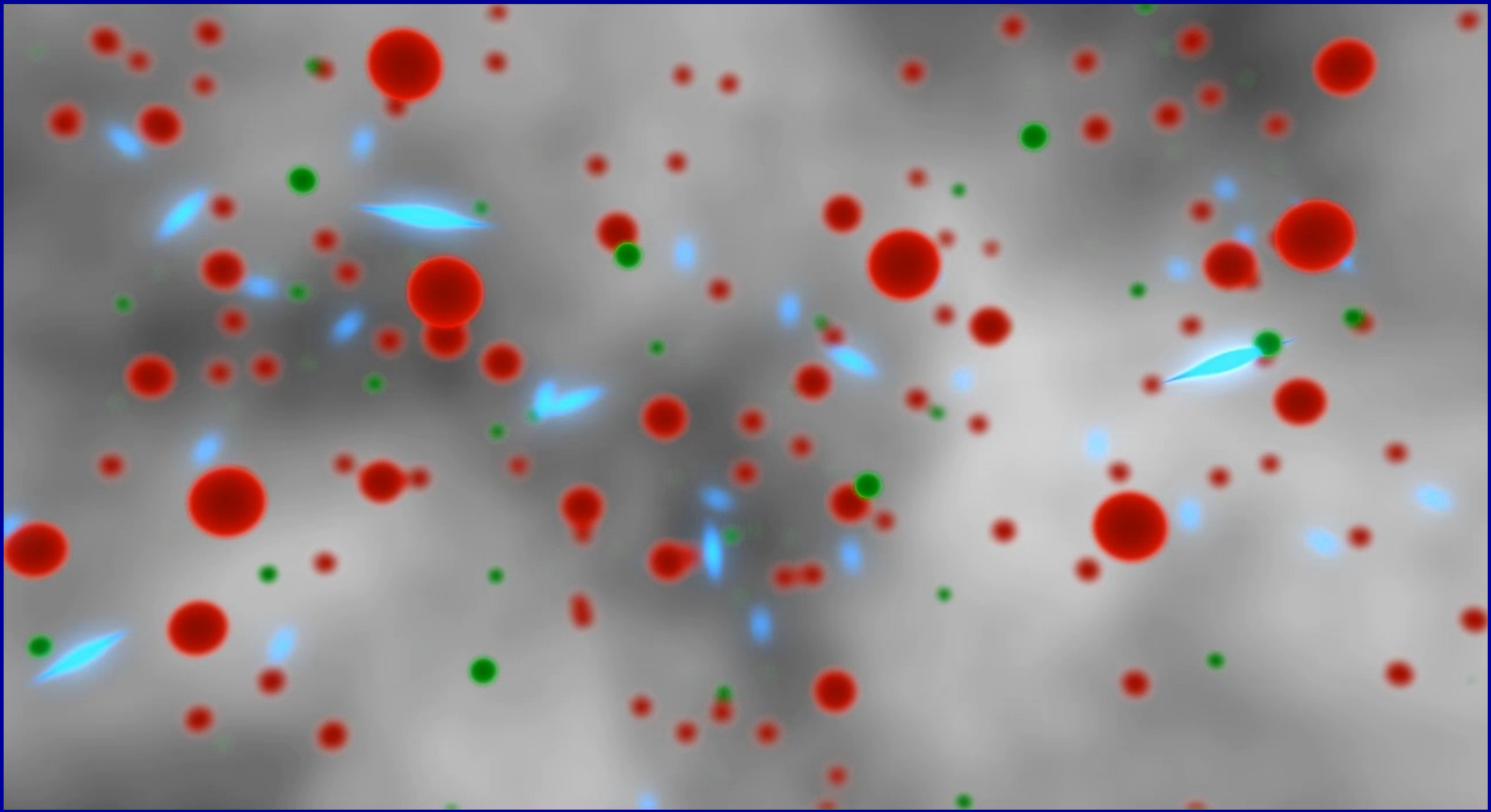
On Behalf of the Planck Collaboration

Special thanks: Lloyd Knox (advisor)

Berkeley RPM

Dec 18, 2014





Caveat: I can show you anything shown at the conferences. For a few plots I will have to use 2013 results, but no major impact to this talk otherwise.

Today

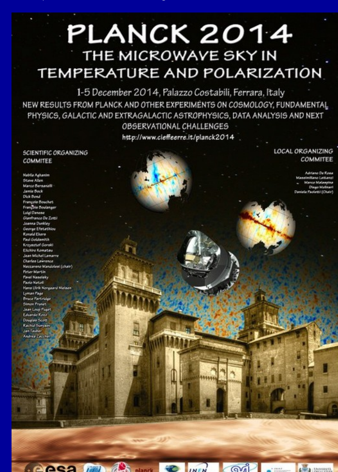
Dec 1

Dec 8

Dec 15

Dec 22

Diligent work



Data comes in

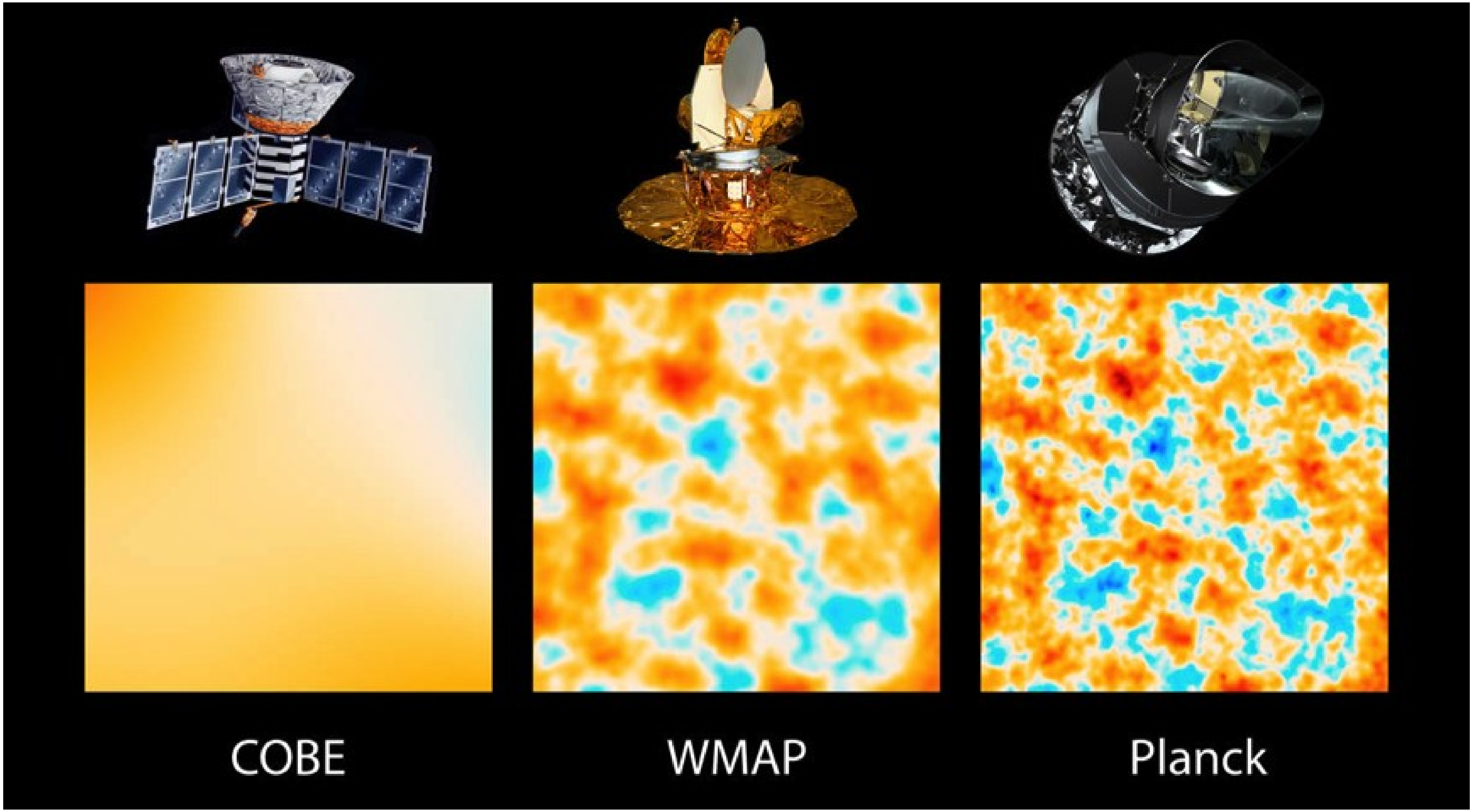
Original planned release date

Planned delayed release date

Outline

- Planck
- Number of neutrino-like species N_{eff}
  - BAO and H_0
  - Damping and acoustic oscillation phase shifts
  - Constraints on axions and axion-like particles (ALPs)
- Sum of neutrino masses Σm_ν
  - Gravitational lensing

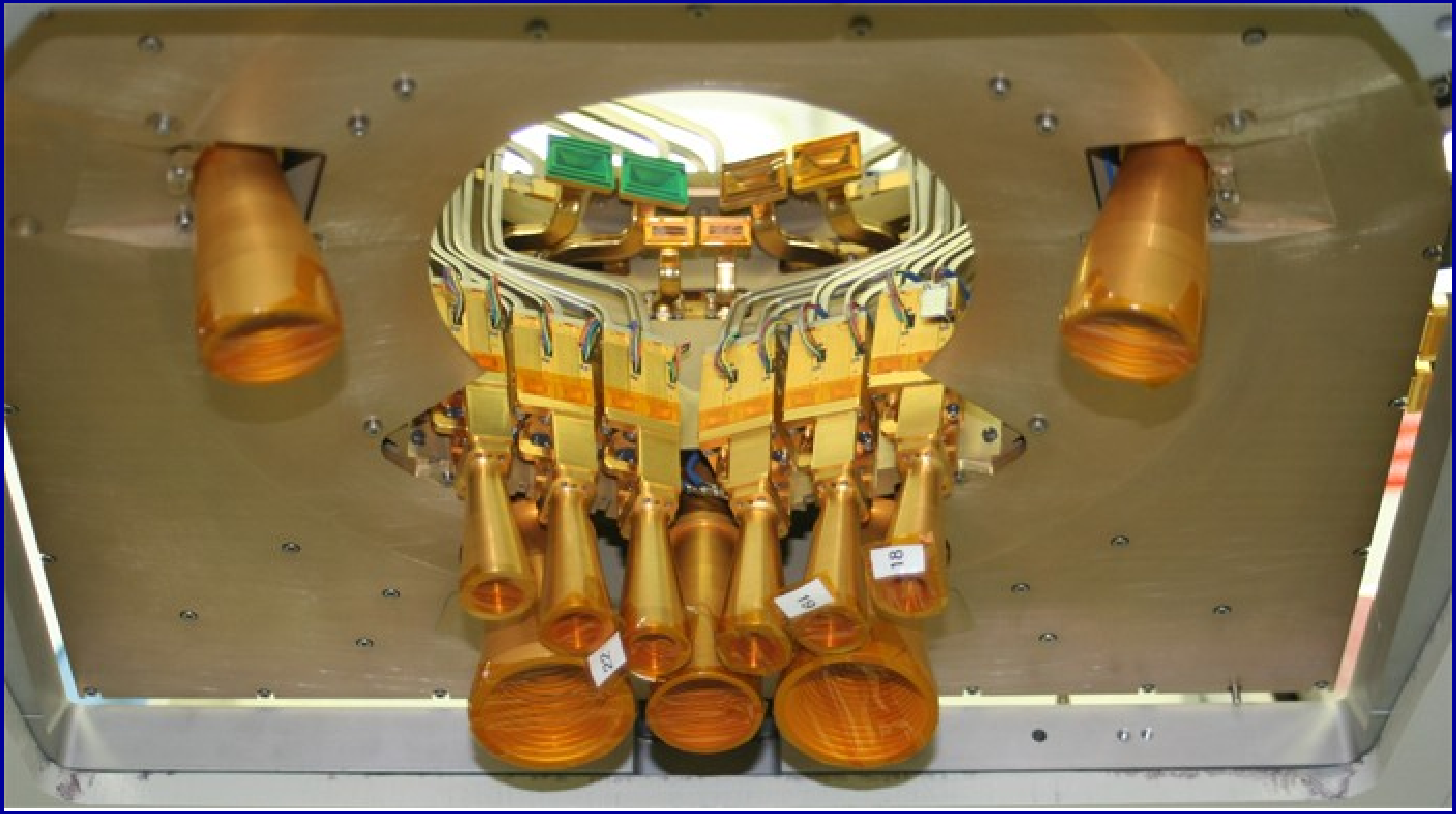
What is Planck?



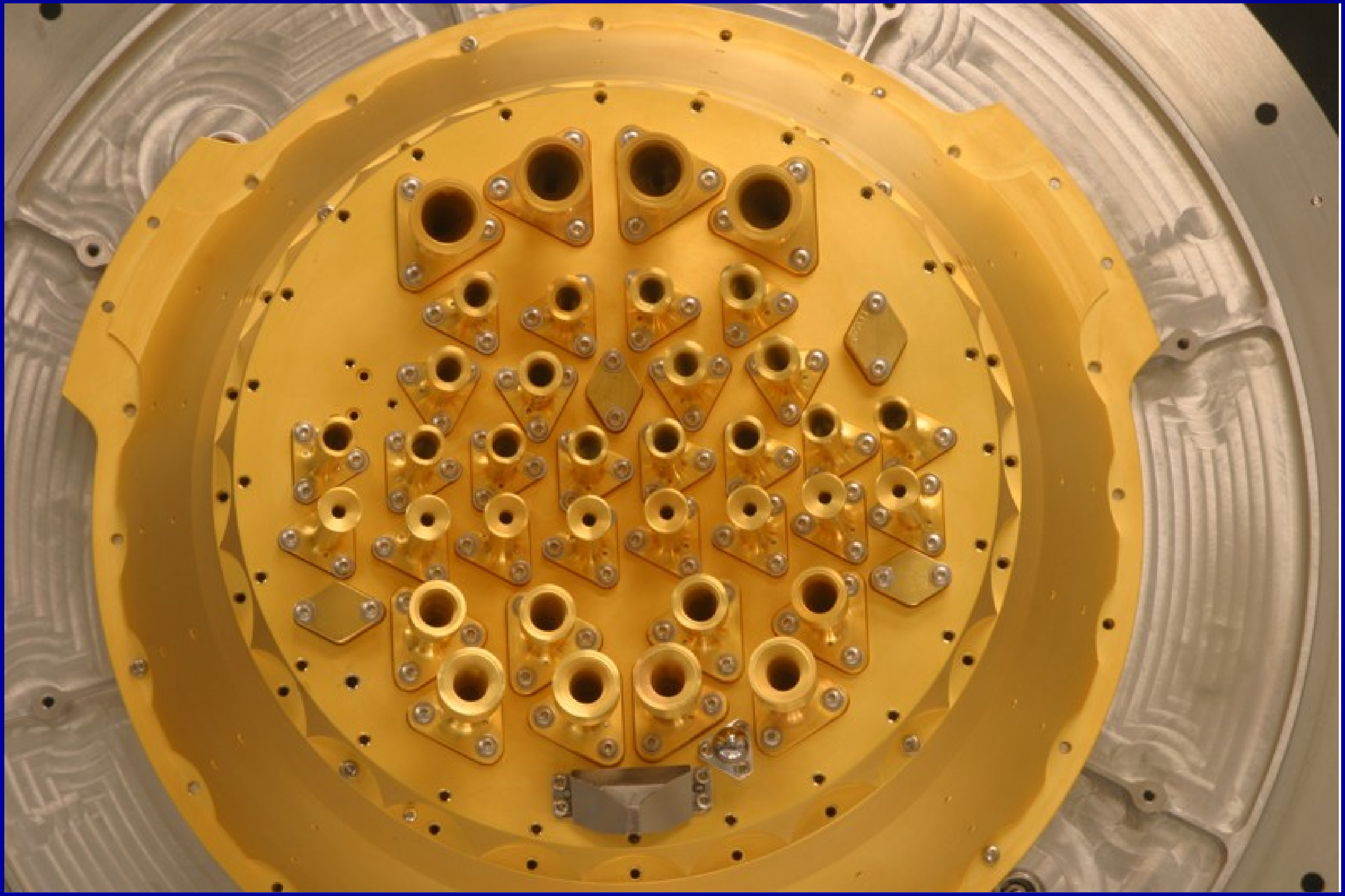
Planck in 2009

Planck in 2009

LFI: 30, 44, 70 GHz

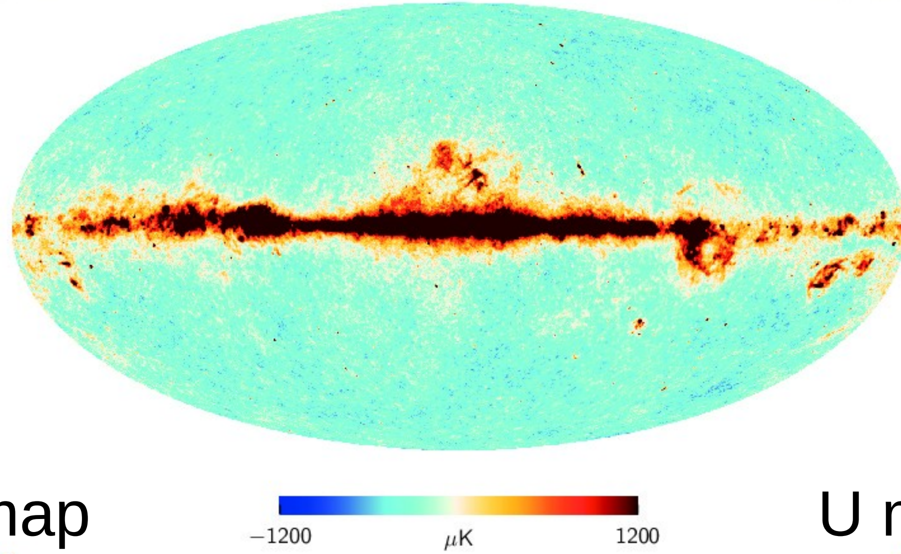


HFI: 100, 143, 217, 353, 545, 853 GHZ



Planck-LFI 30 GHz

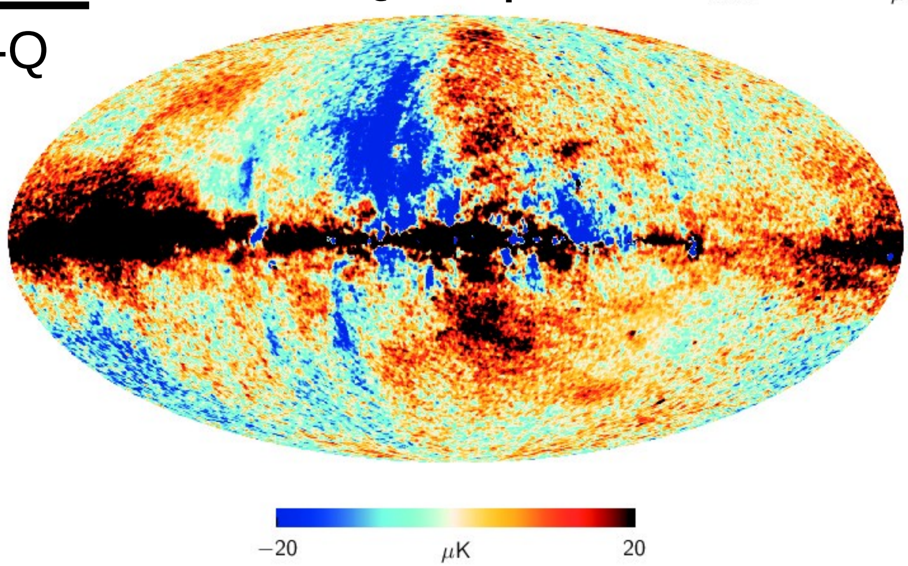
“T” map



+Q

-Q

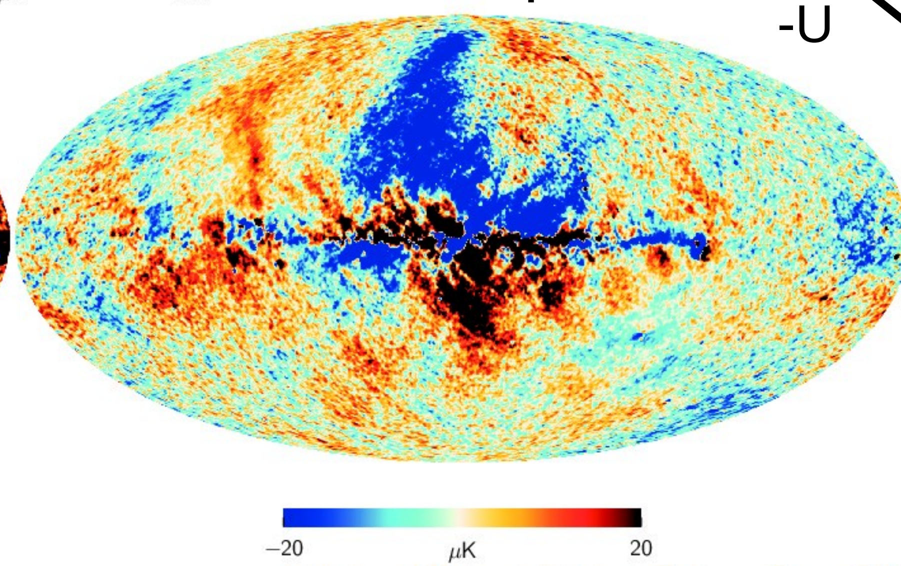
Q map



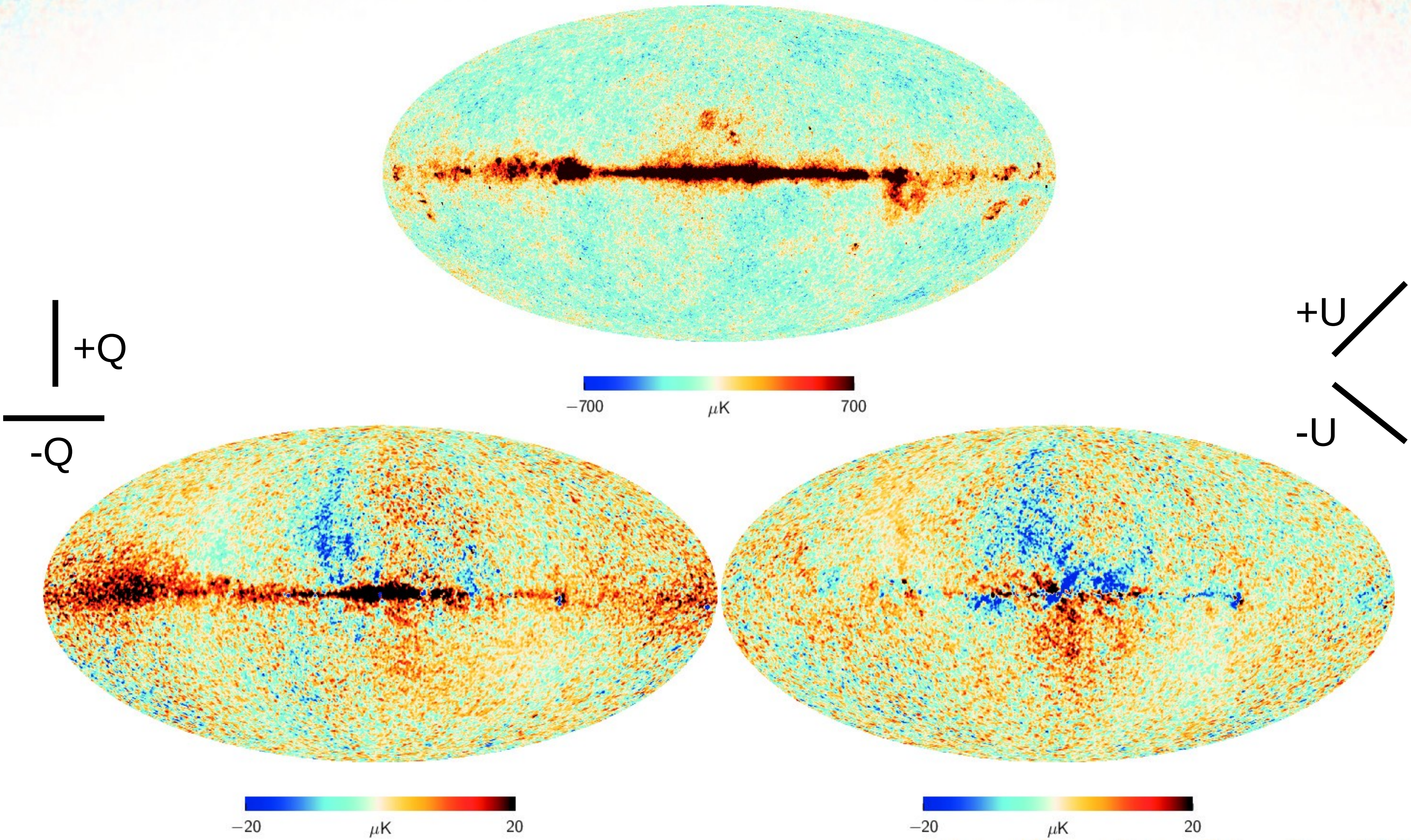
U map

+U

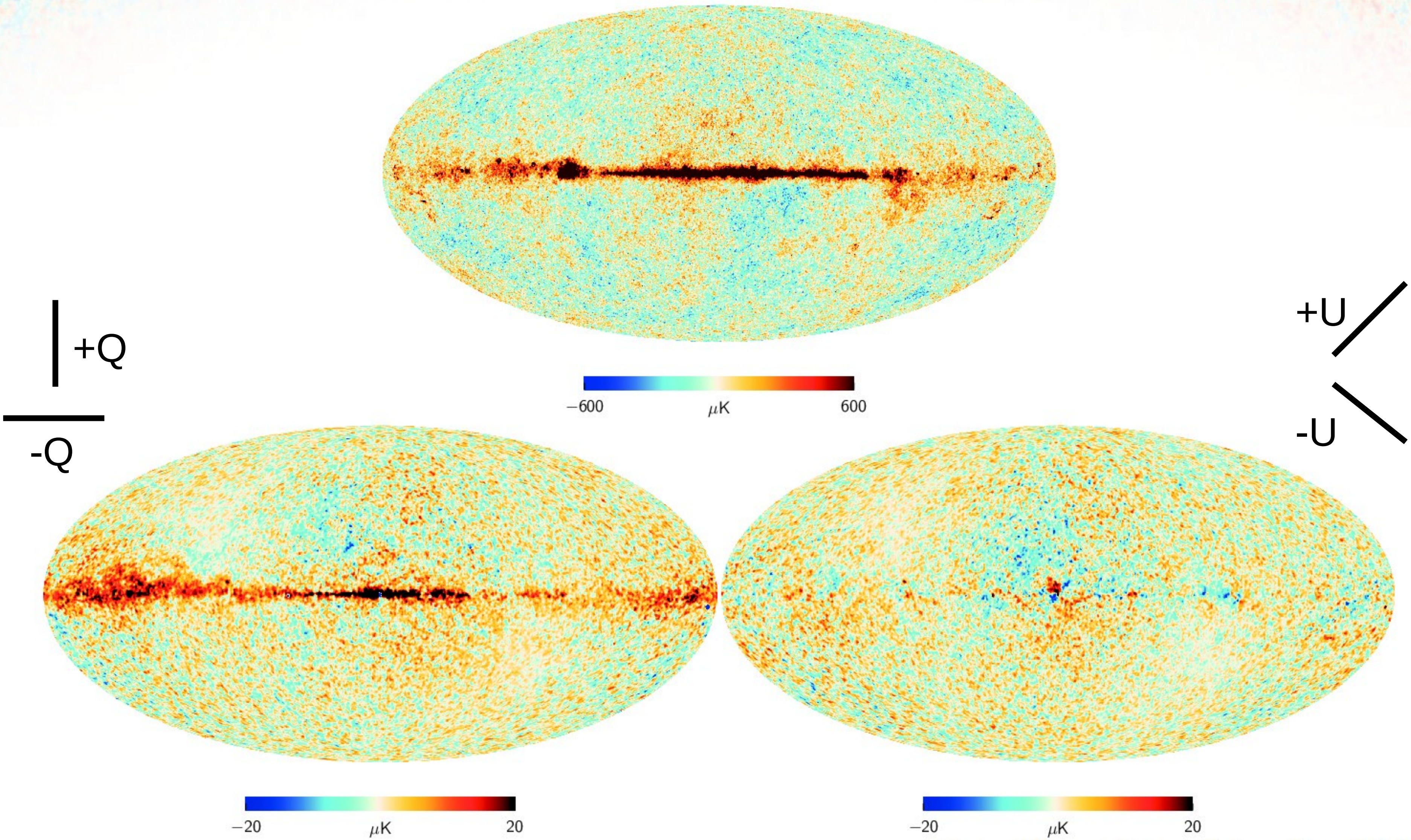
-U



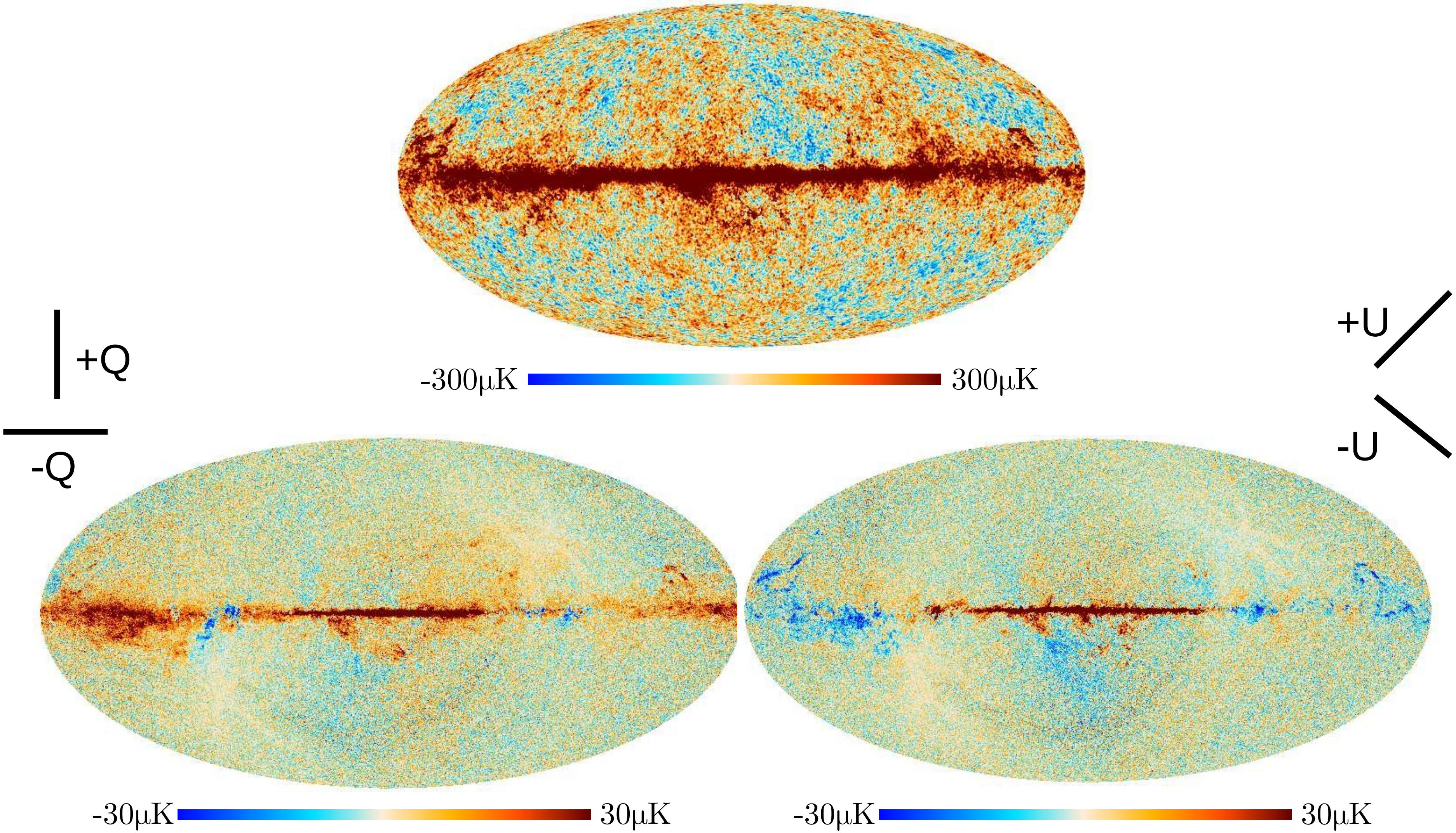
Planck-LFI 44 GHz



Planck-LFI 70 GHz

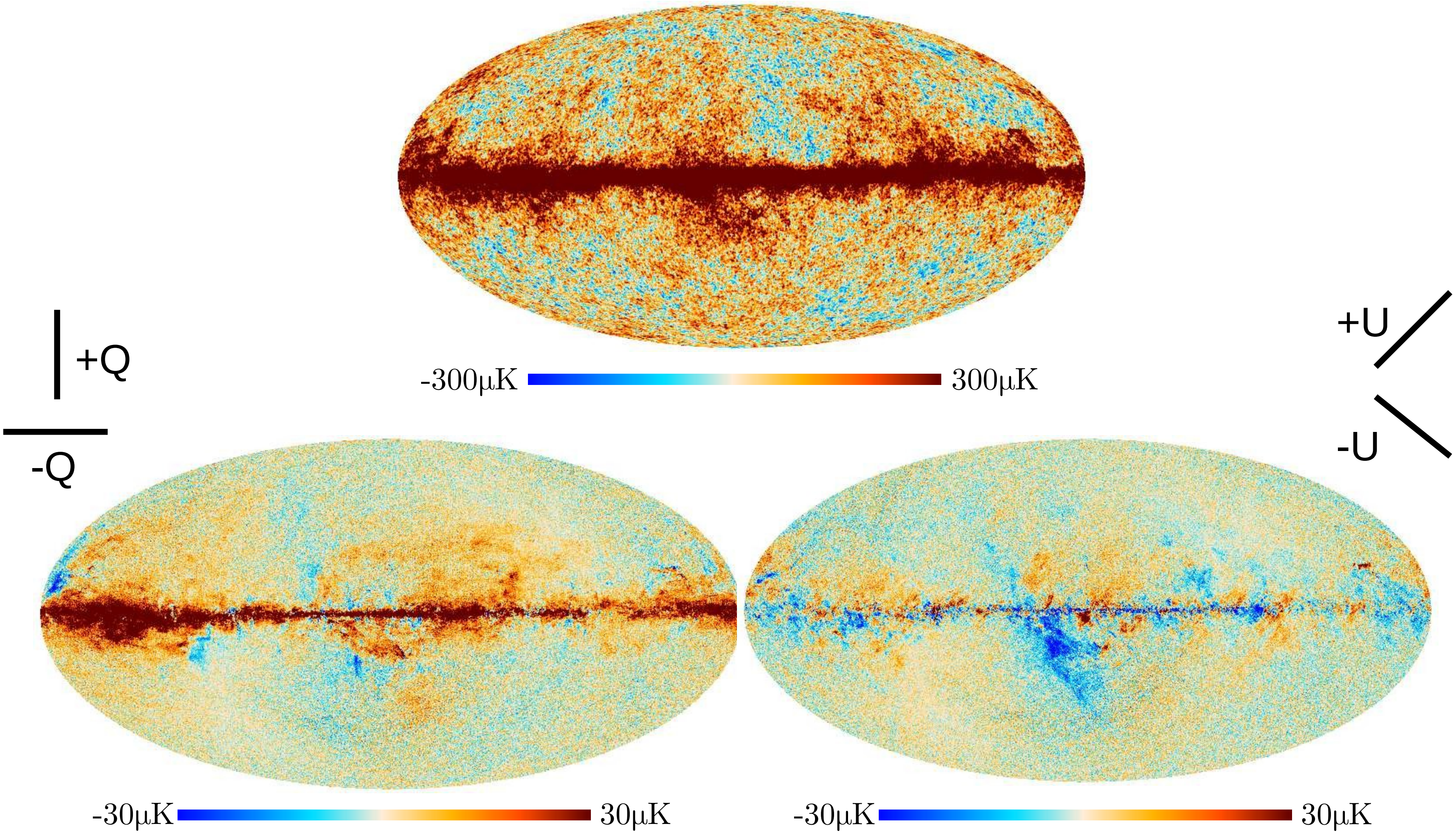


Planck-HFI 100 GHz

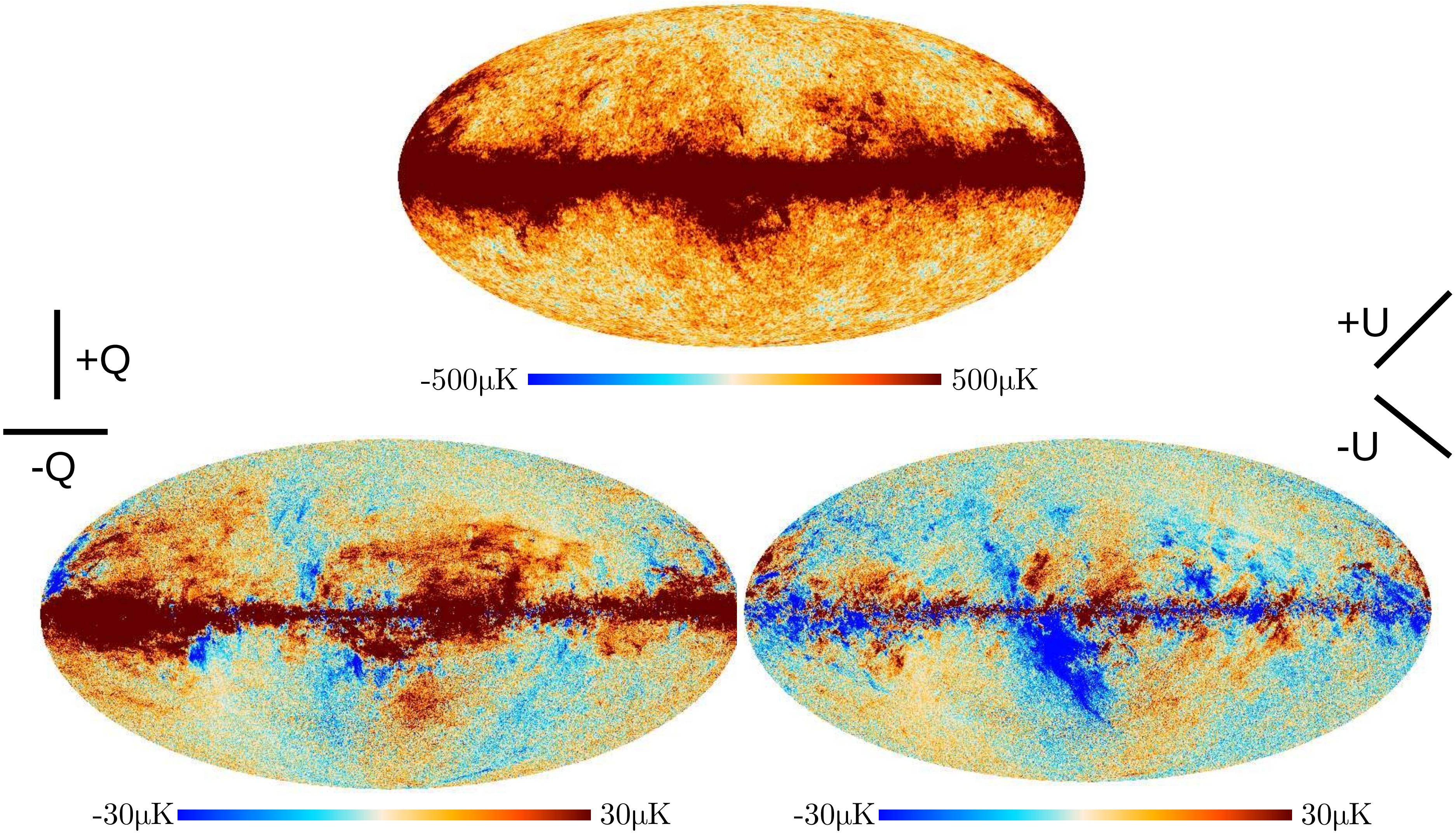


Note: Q/U no longer smoothed, so most of what you see is galaxy + noise

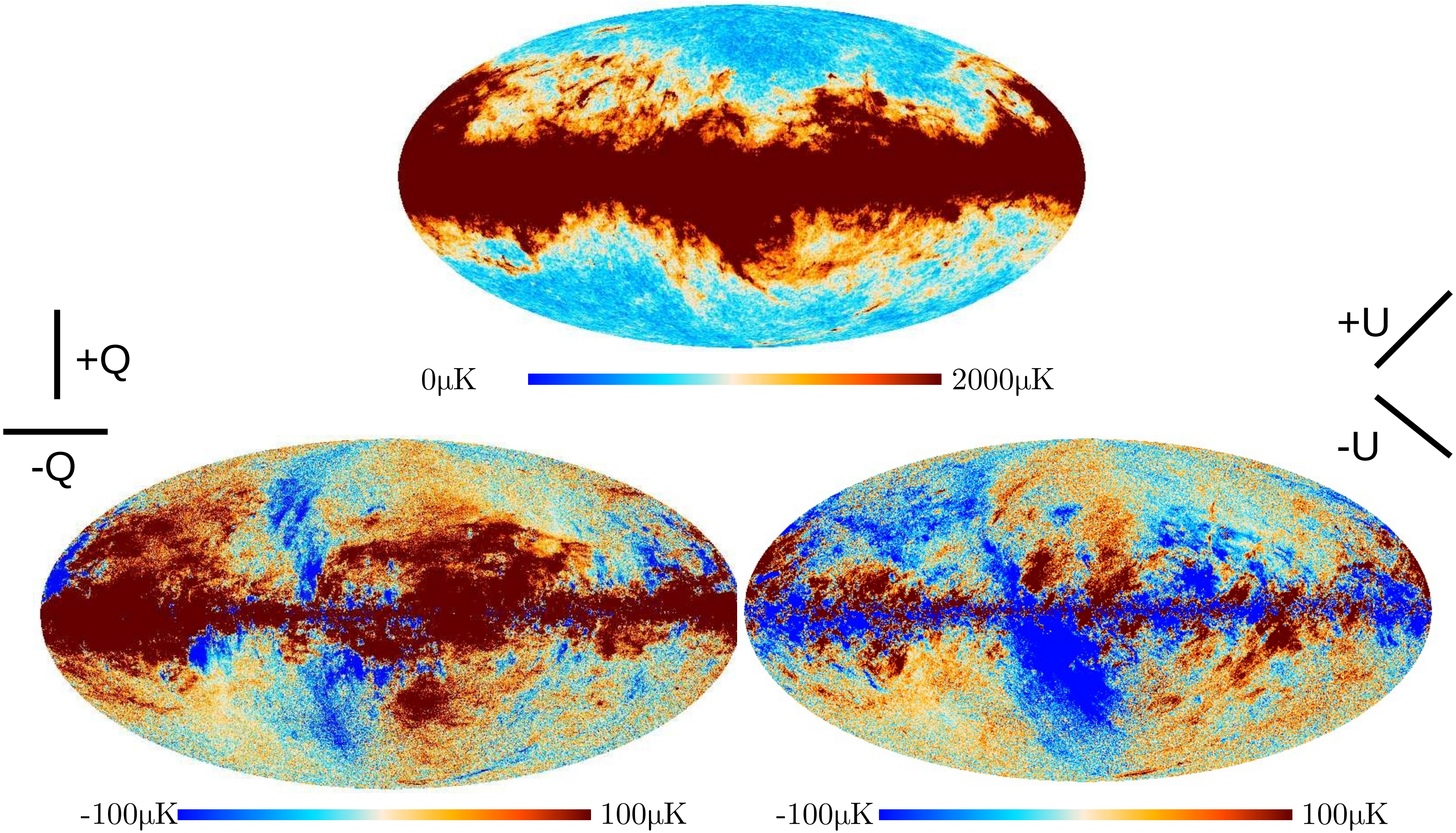
Planck-HFI 143 GHz



Planck-HFI 217 GHz



Planck-HFI 353 GHz

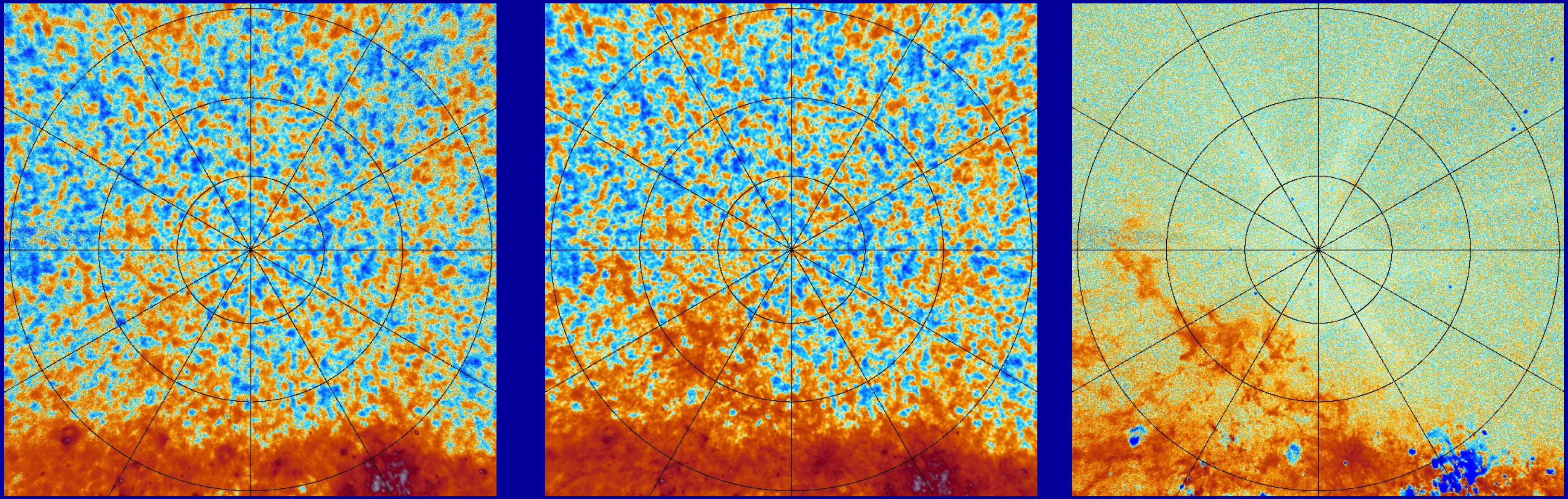


Beautifully Consistent Data

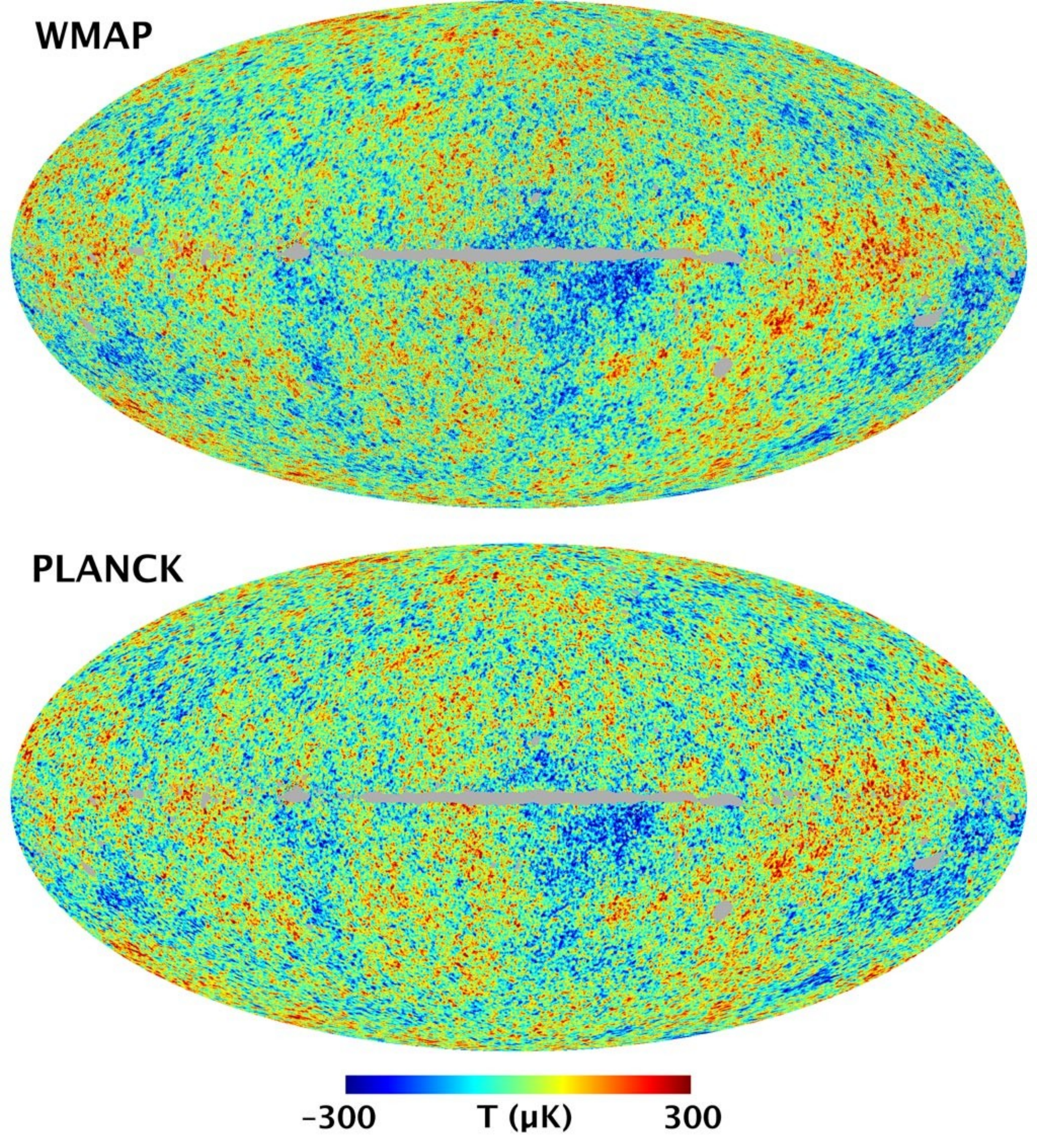
70 GHz

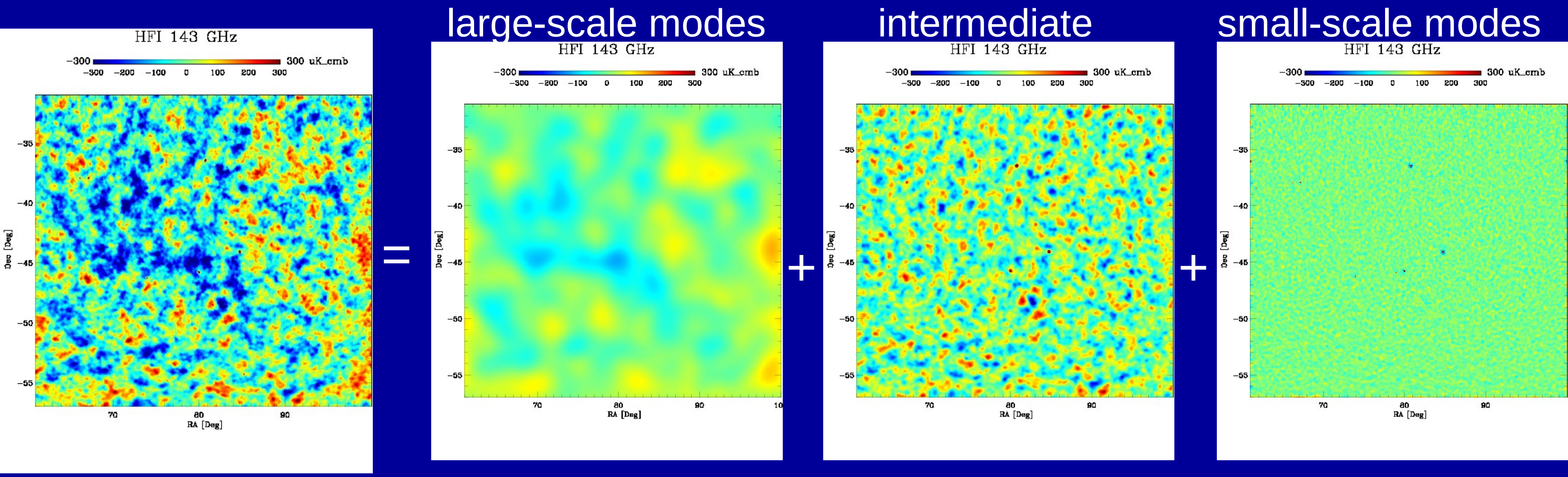
100 GHz

100 GHz – 70 GHz

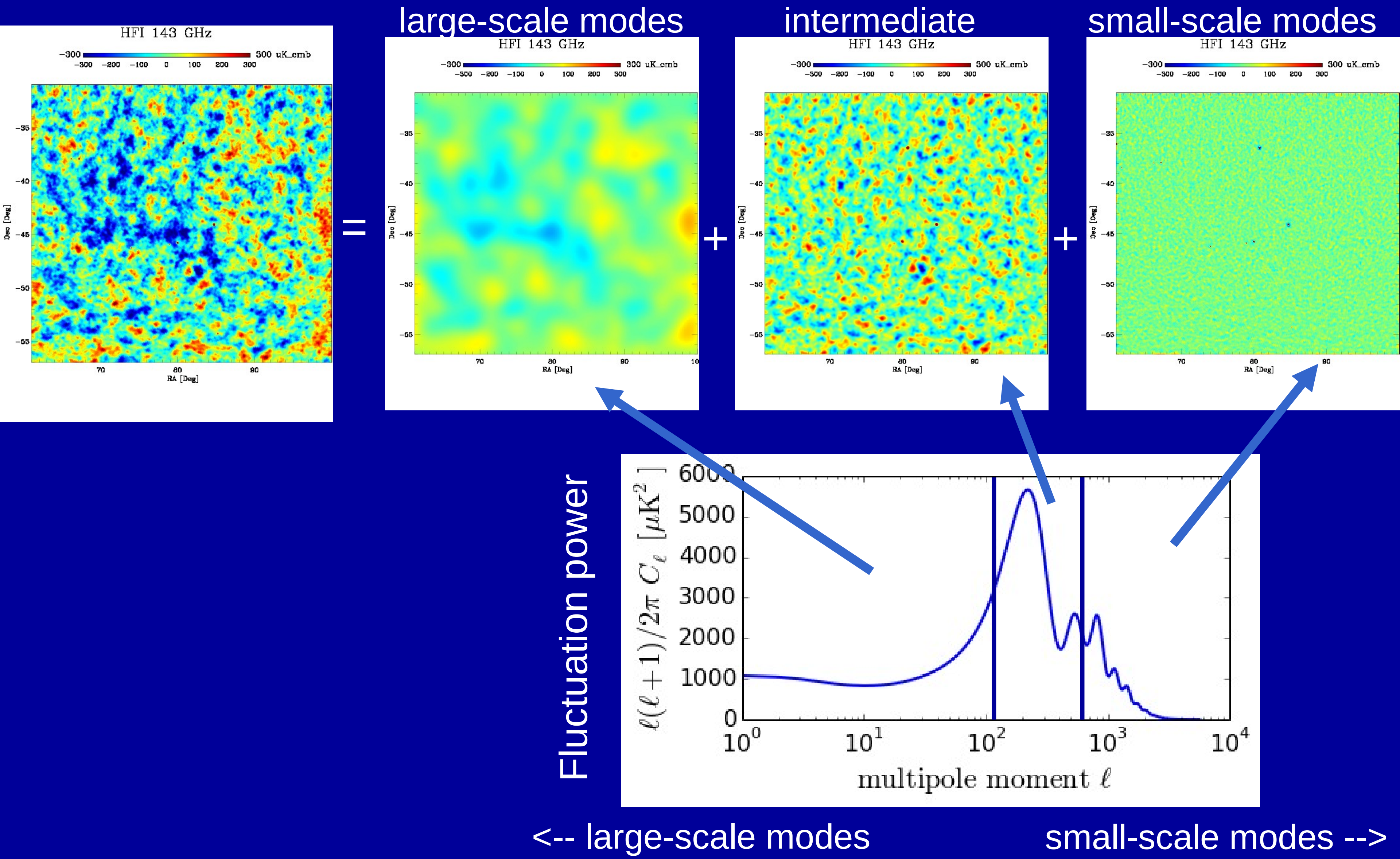


Different detector technologies, different systematics


WMAP
PLANCK
-300
T (μK)
300



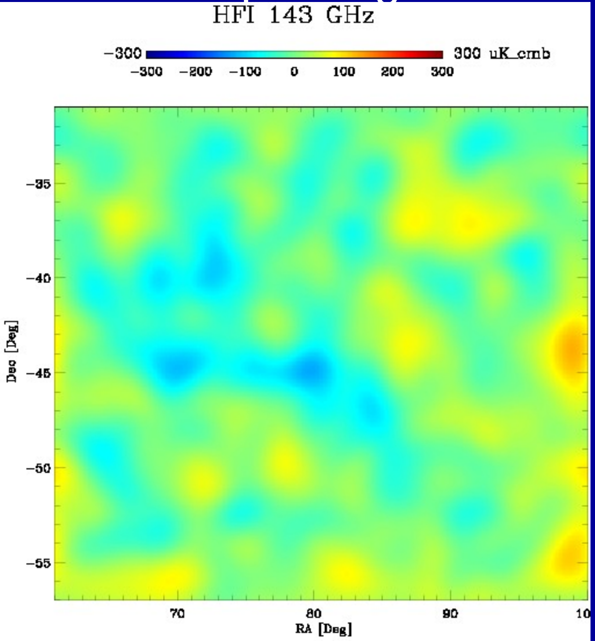
Let’s decompose into band-limited maps and compare those



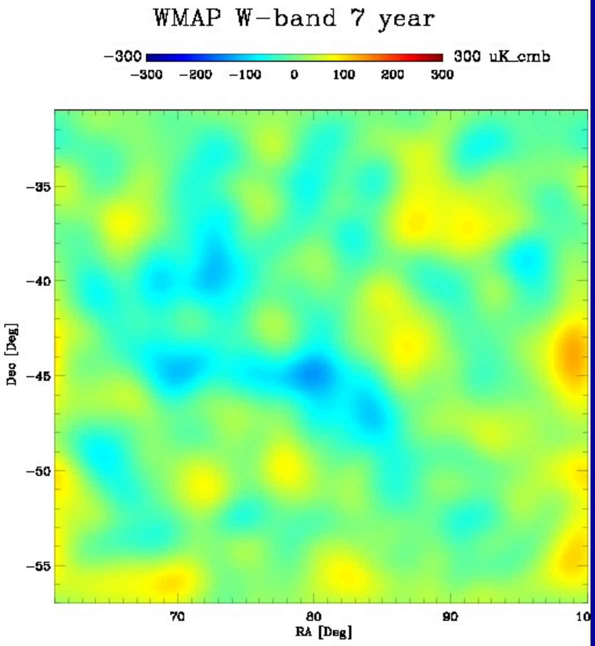
large-scale modes
intermediate
small-scale modes
HFI 143 GHz
−300 300 uK_cmb
−300 −200 −100 0 100 200 300
Dec [Deg]
RA [Deg]
=
+
+
Fluctuation power
$\ell(\ell+1)/2\pi\, C_\ell\ [\mu K^2]$
0
1000
2000
3000
4000
5000
6000
10^0
10^1
10^2
10^3
10^4
multipole moment ℓ
<-- large-scale modes
small-scale modes -->

Filtered to keep: large scales

Planck 143 GHz

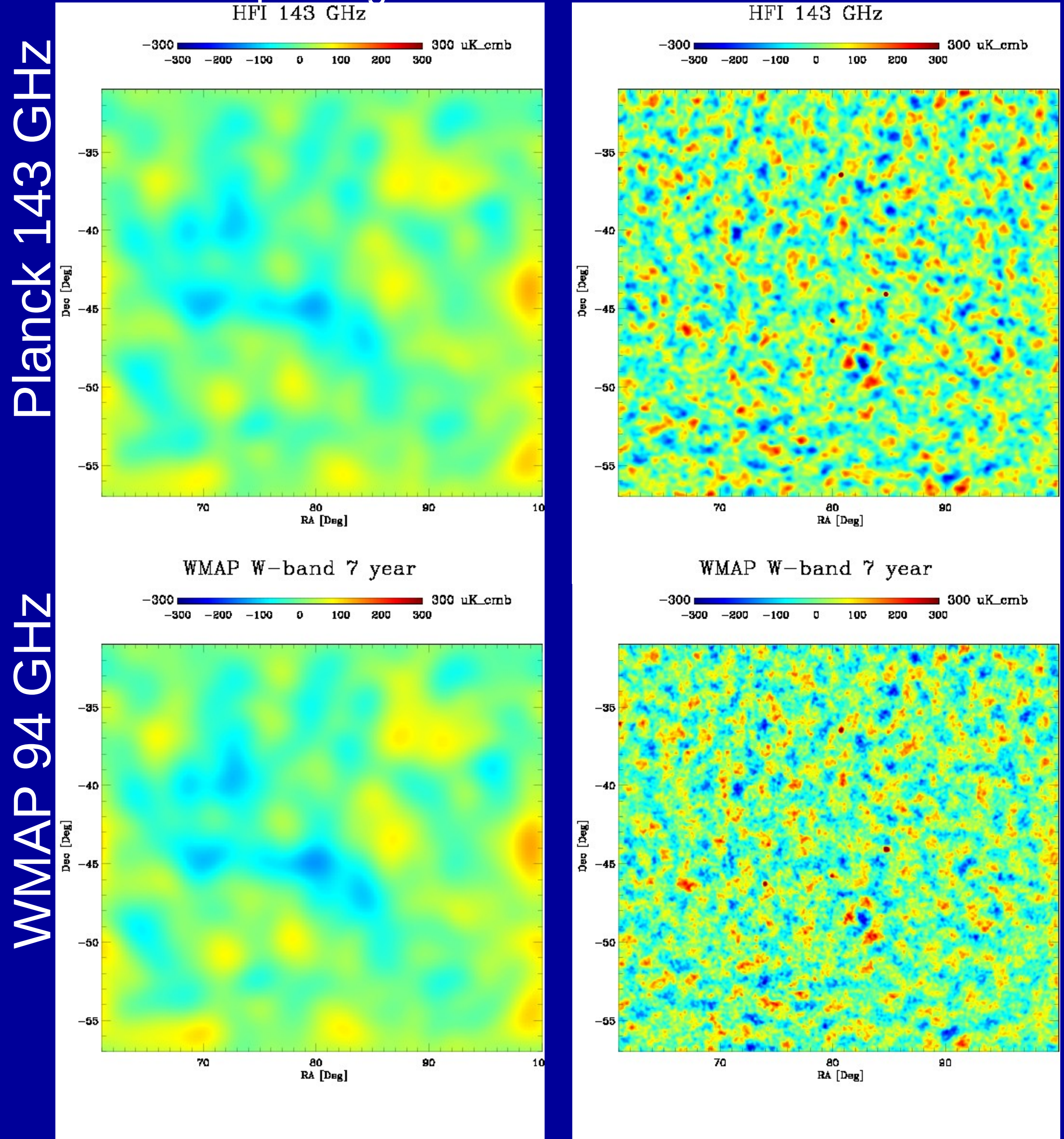


WMAP 94 GHz

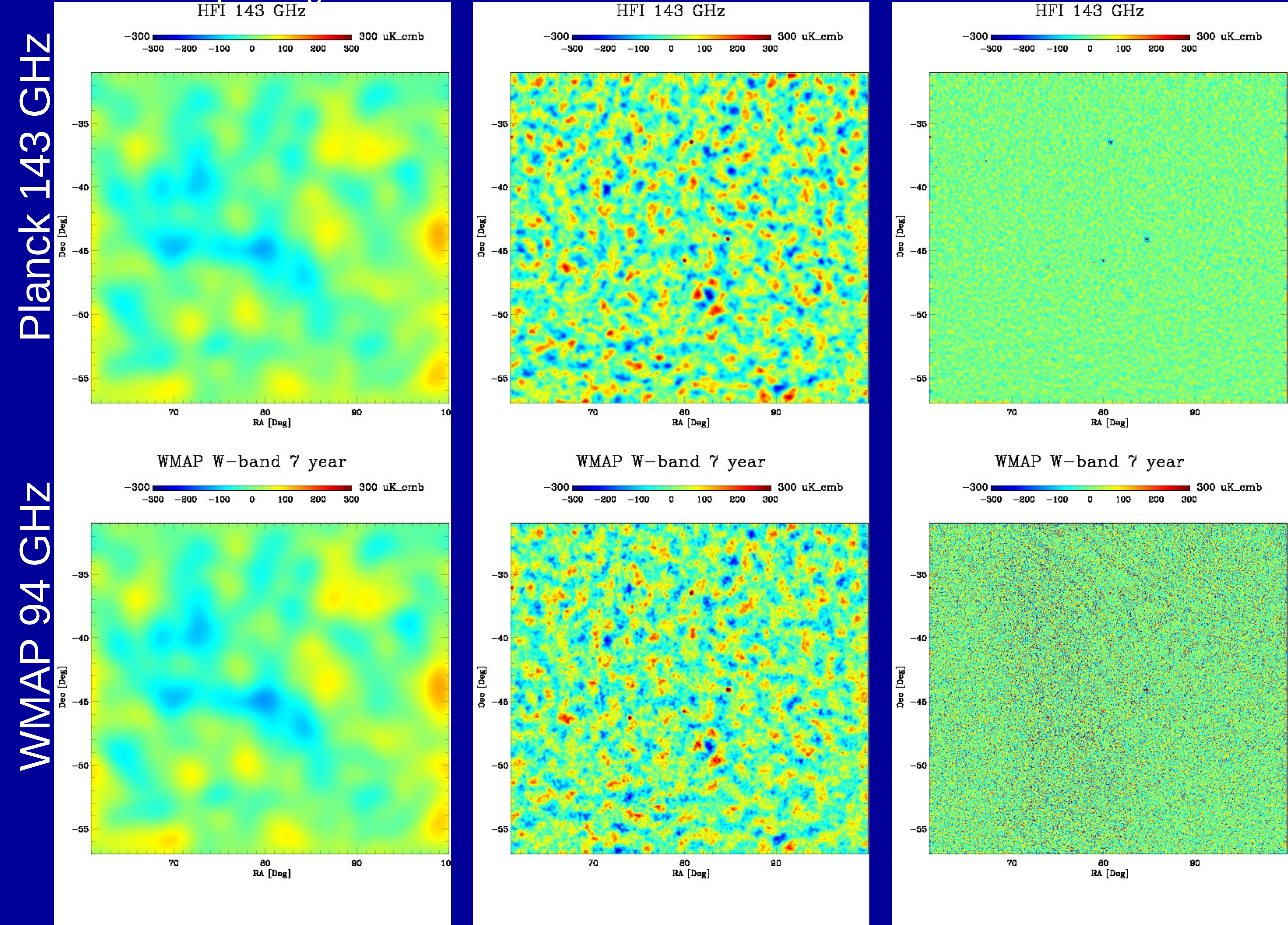


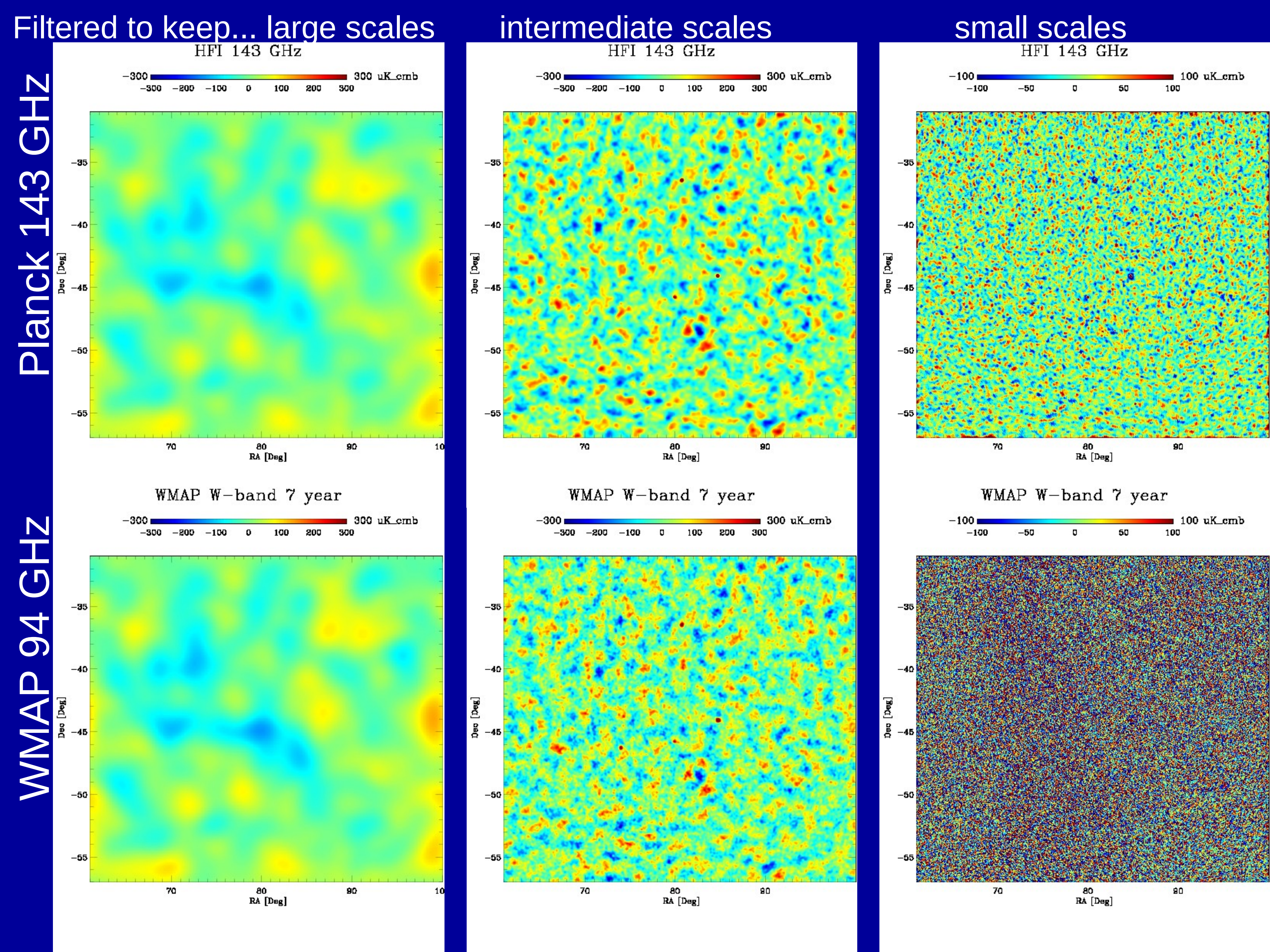
Comparison with WMAP:
what's new?

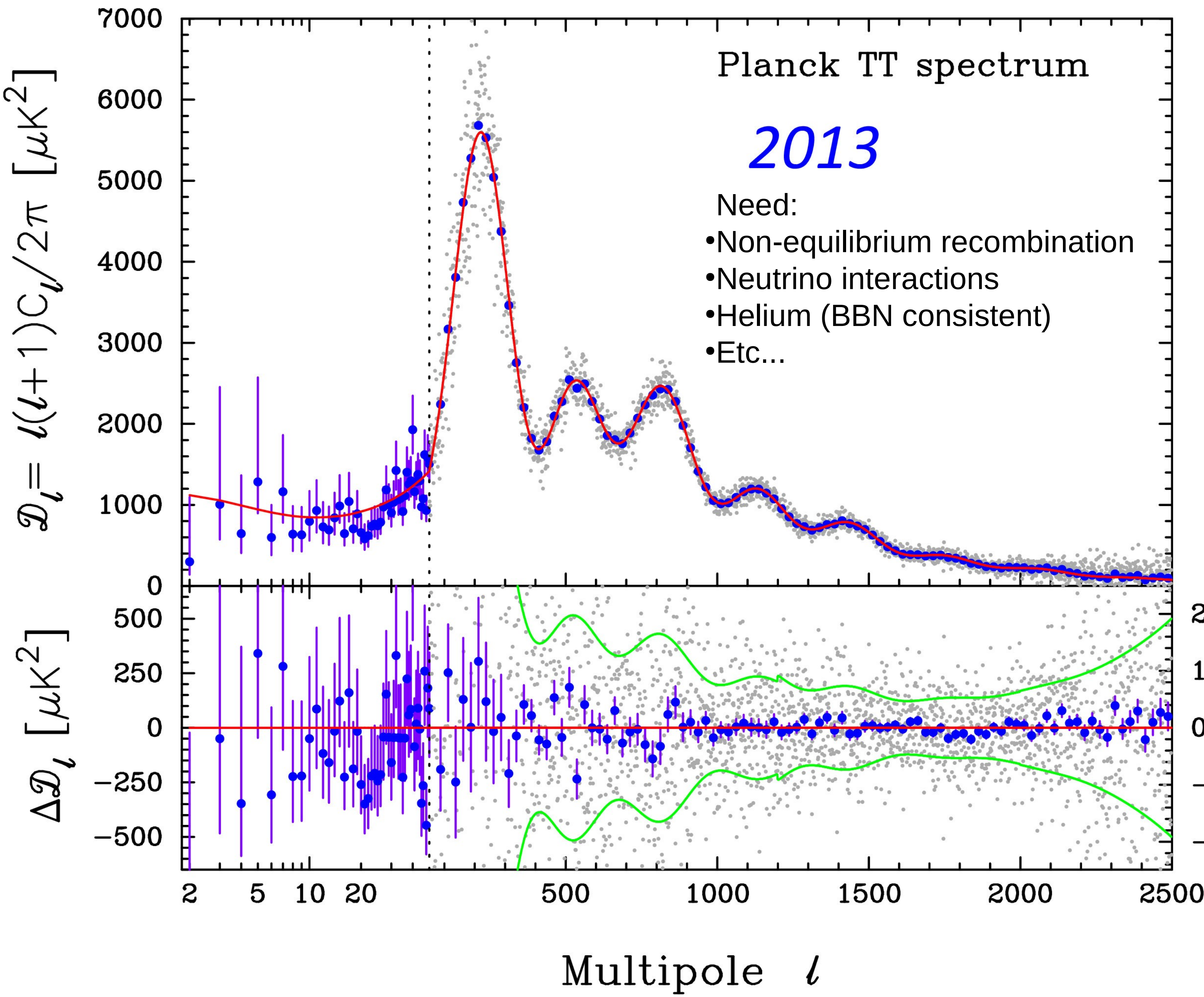
Filtered to keep: large scales intermediate scales



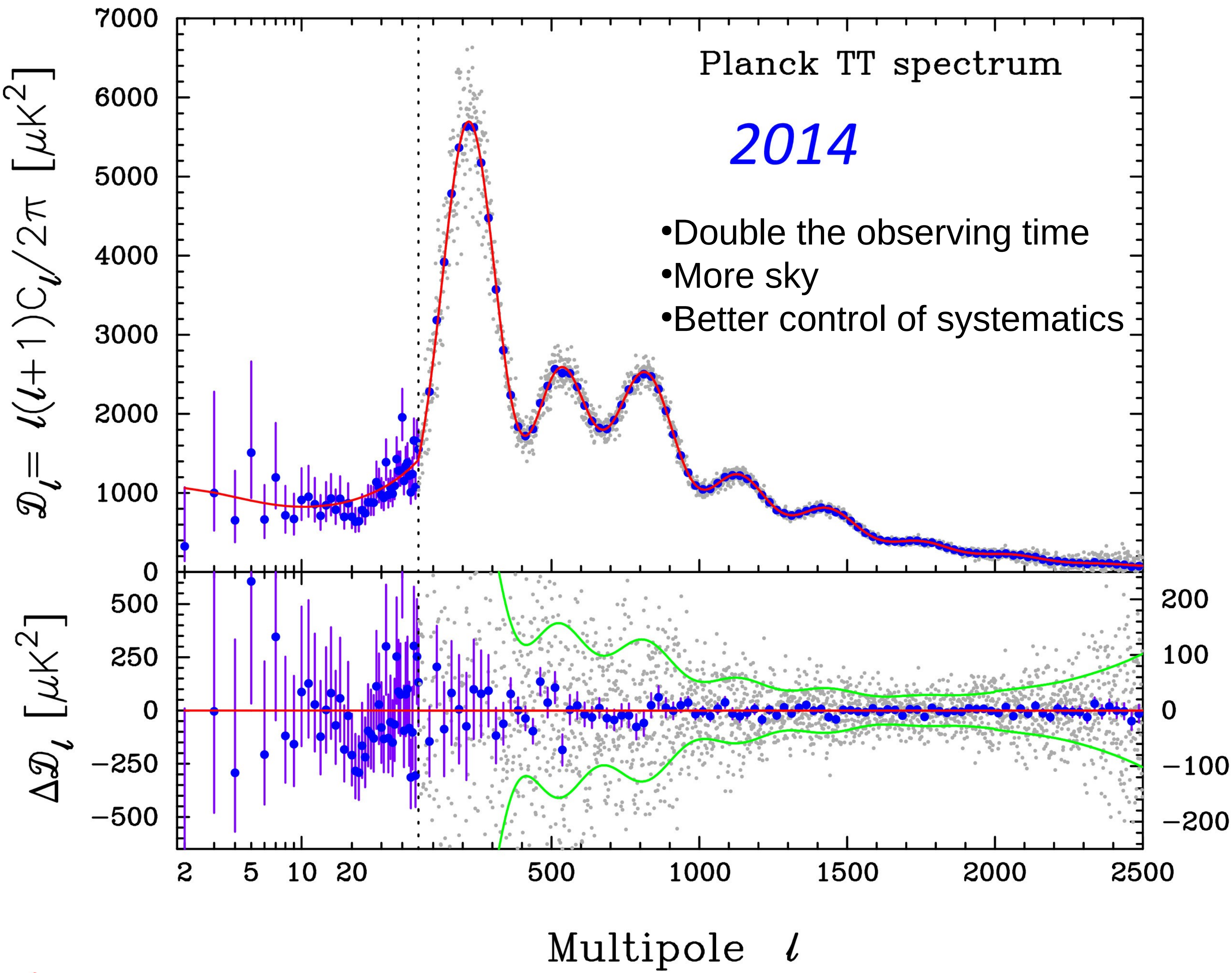
Filtered to keep... large scales intermediate scales small scales




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
Dec [Deg]
RA [Deg]

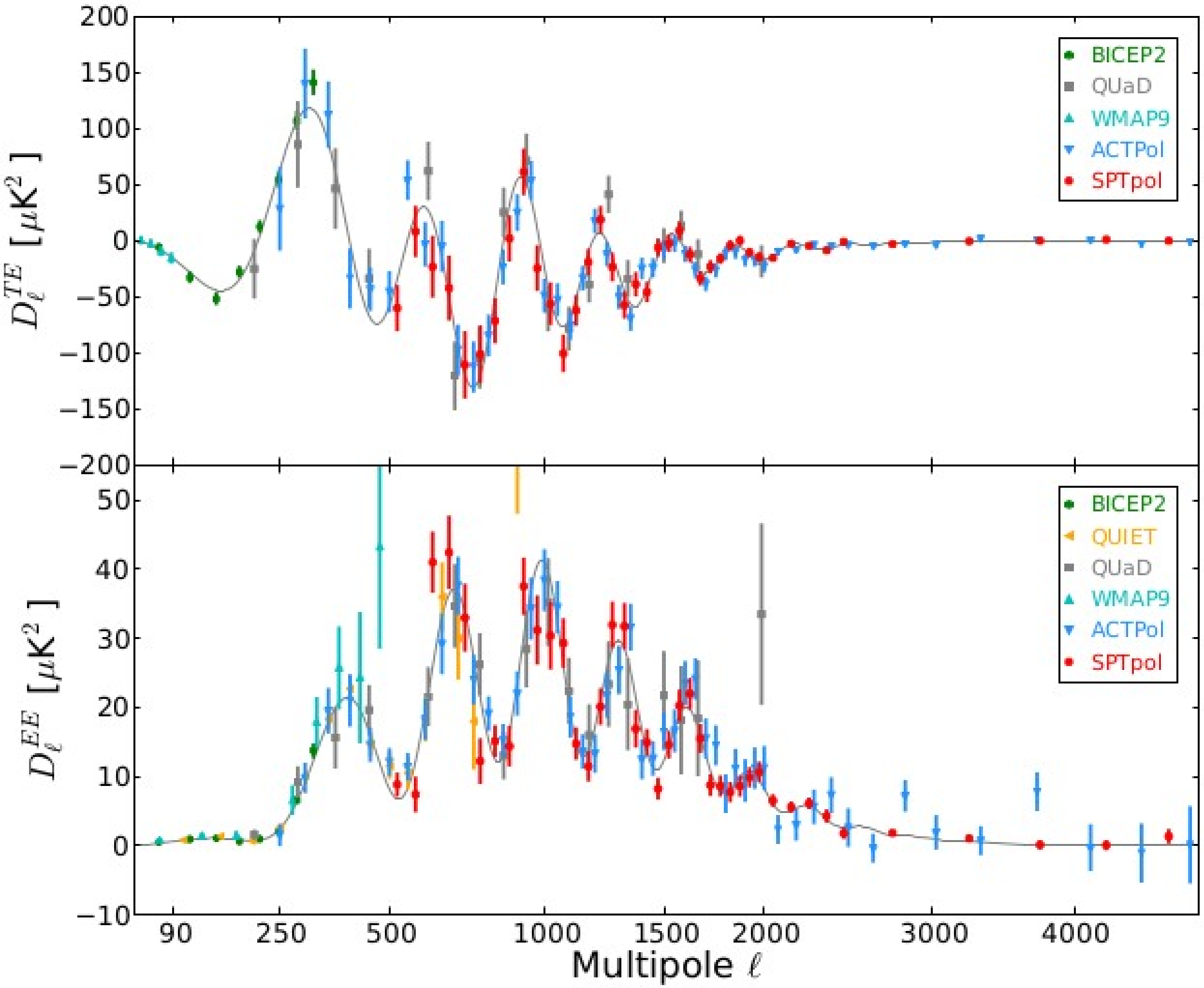


Planck TT spectrum
2013
Need:
•Non-equilibrium recombination
•Neutrino interactions
•Helium (BBN consistent)
•Etc...
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ



preliminary

Previous TE and EE measurements (Crites et al. 2014)



Perturbations in the tightly coupled photon-baryon plasma are just propagating “sound” waves governed by:

$$\delta'' + \frac{1}{c_s^2}\ddot{\delta} = 0$$

$$\ddot{\tilde{\delta}} + k^2 c_s^2 \tilde{\delta} = 0$$

(Caveat: ignores gravitational potentials and electron mass)

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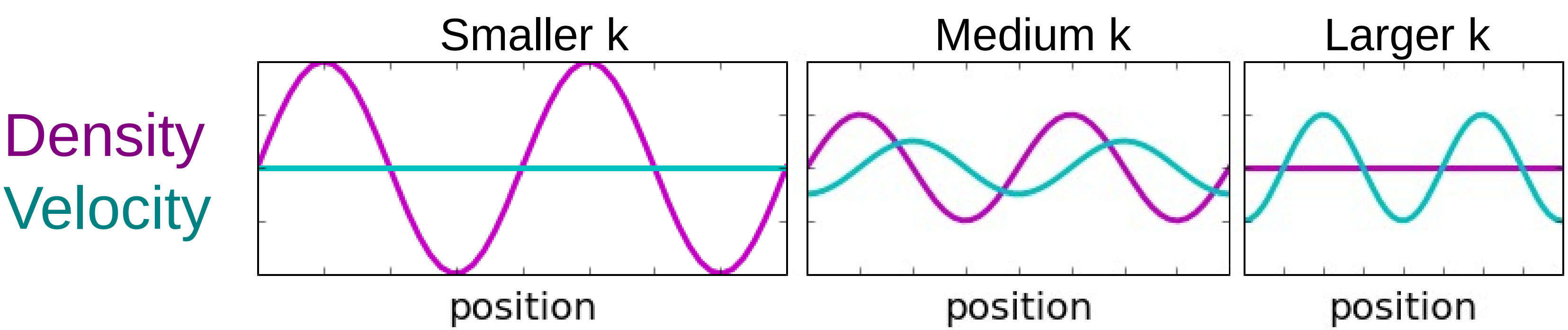
Consider Fourier modes projected onto the last scattering surface:



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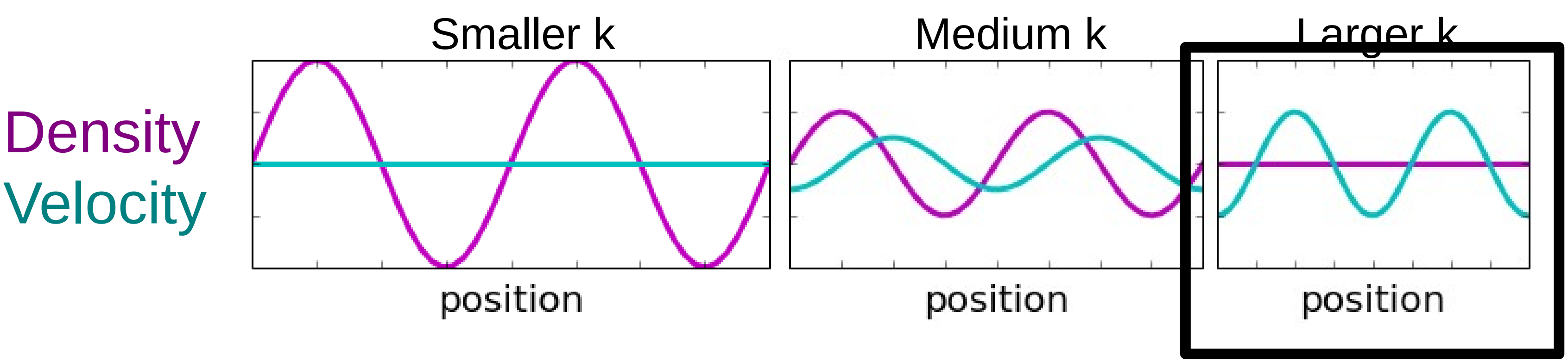
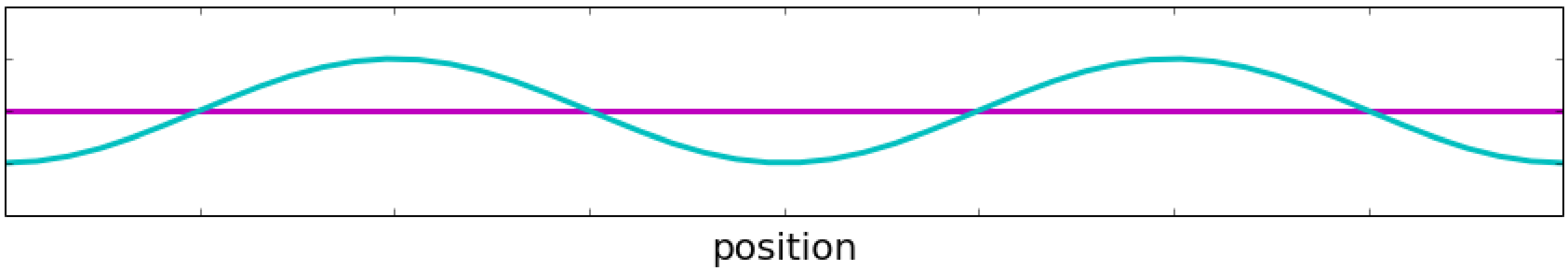
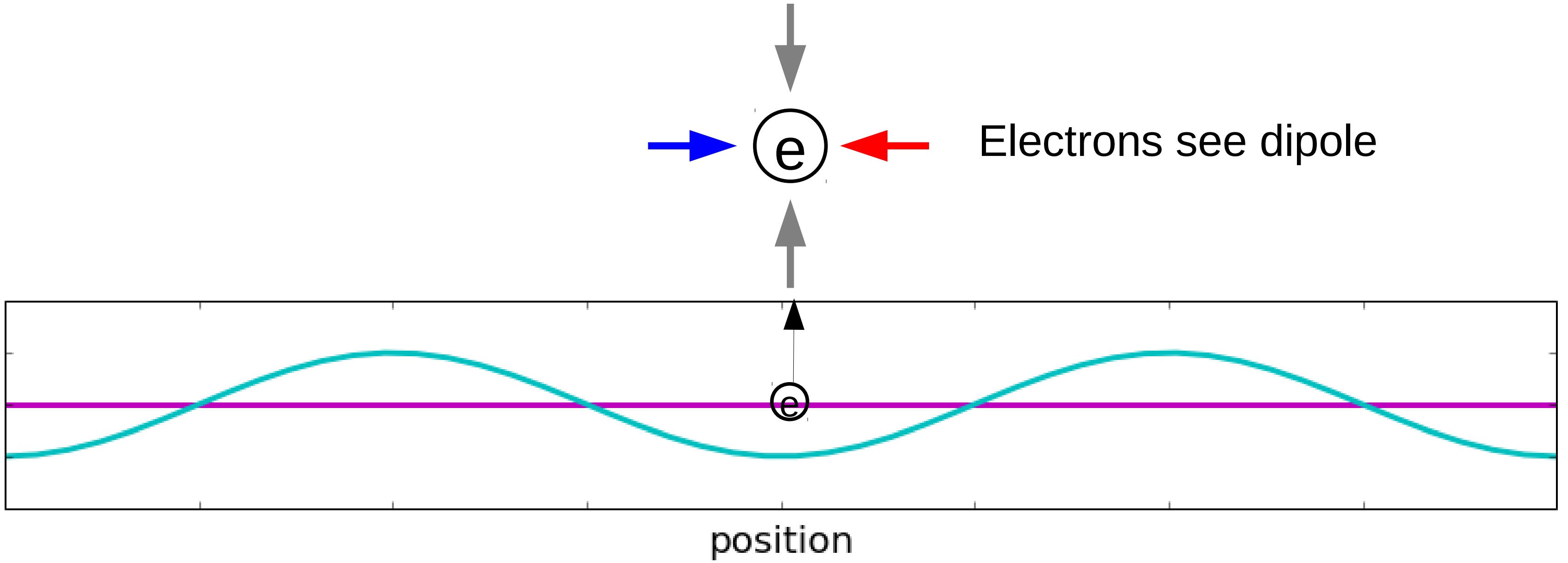
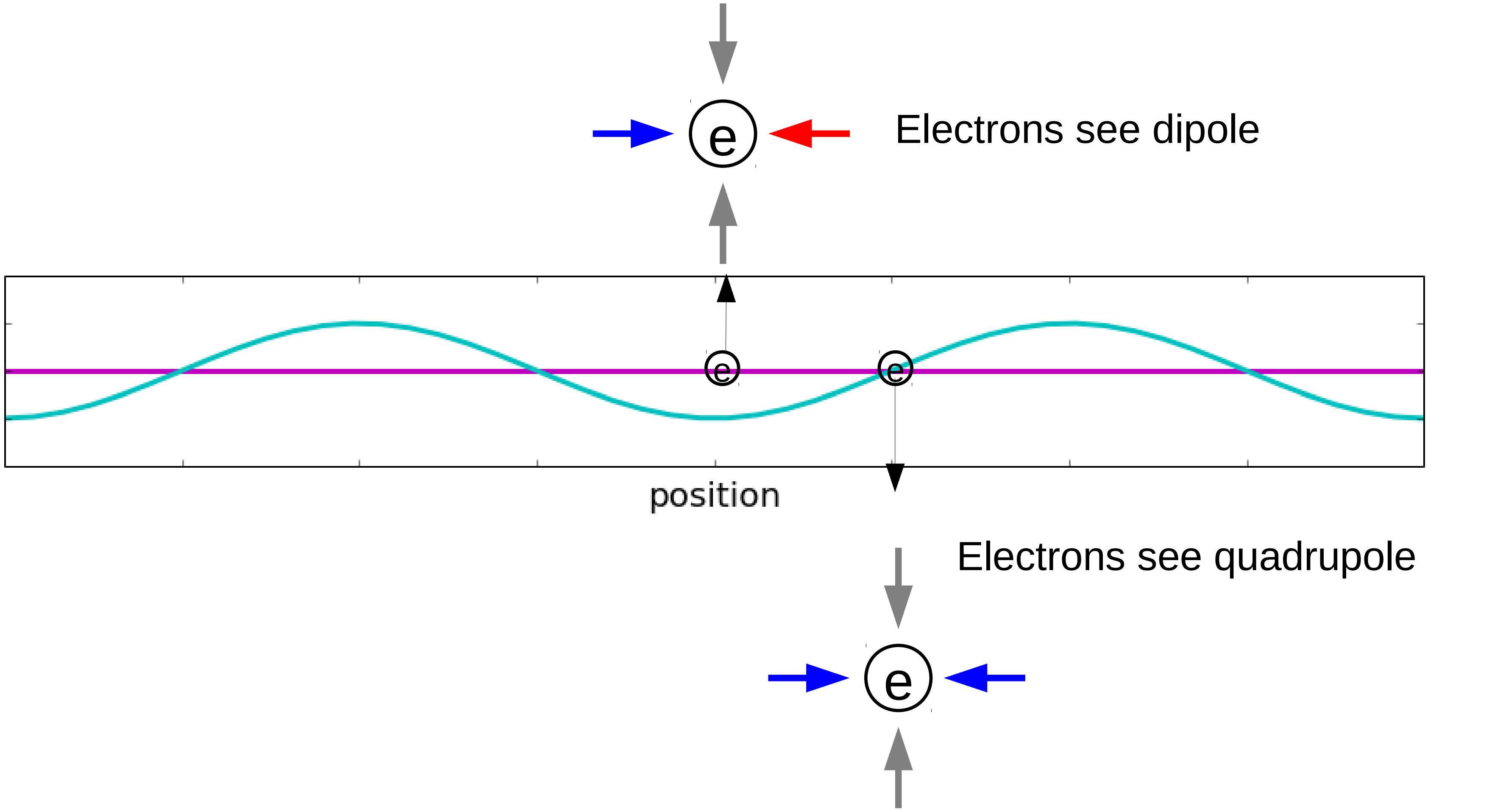
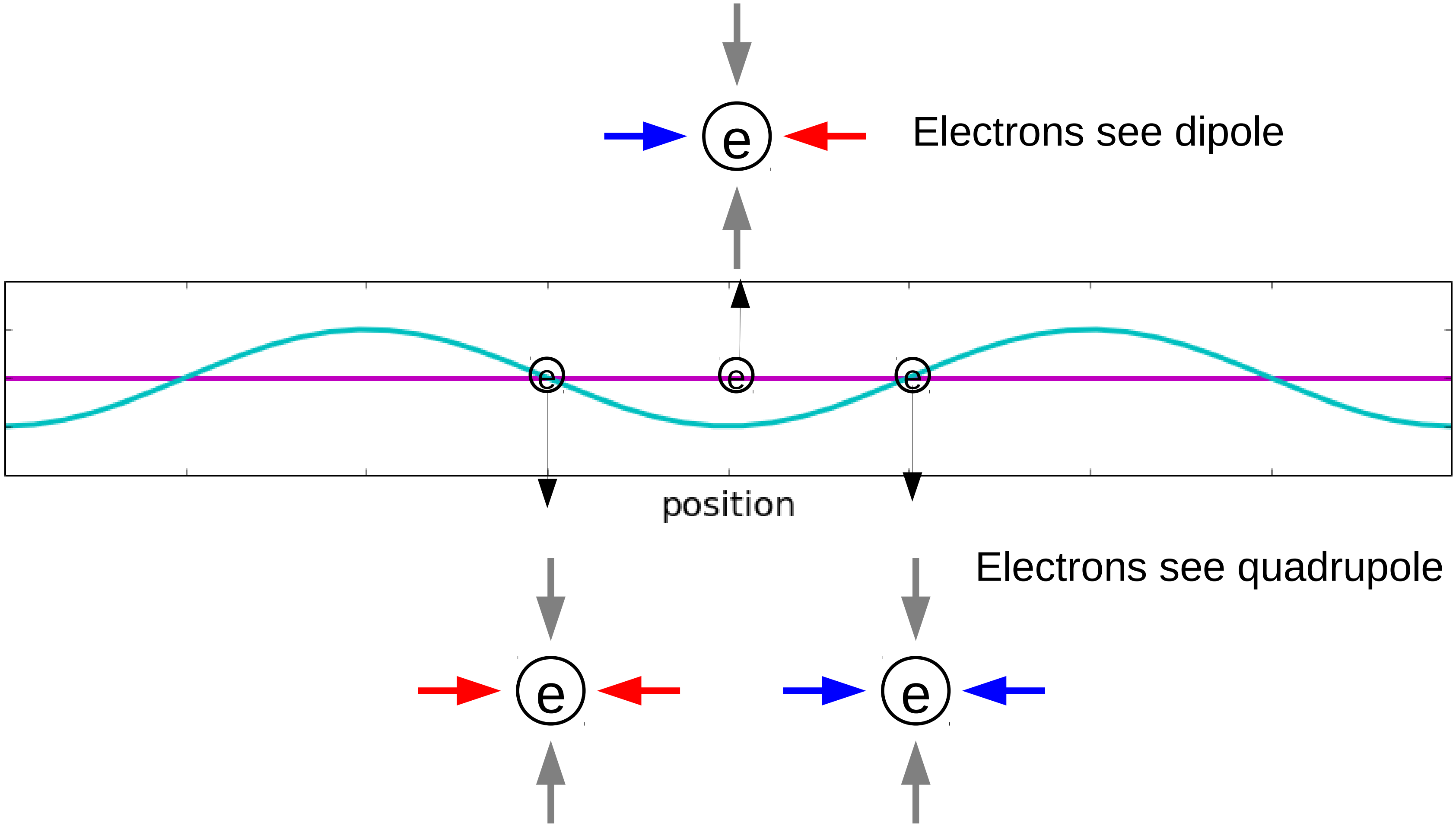



position

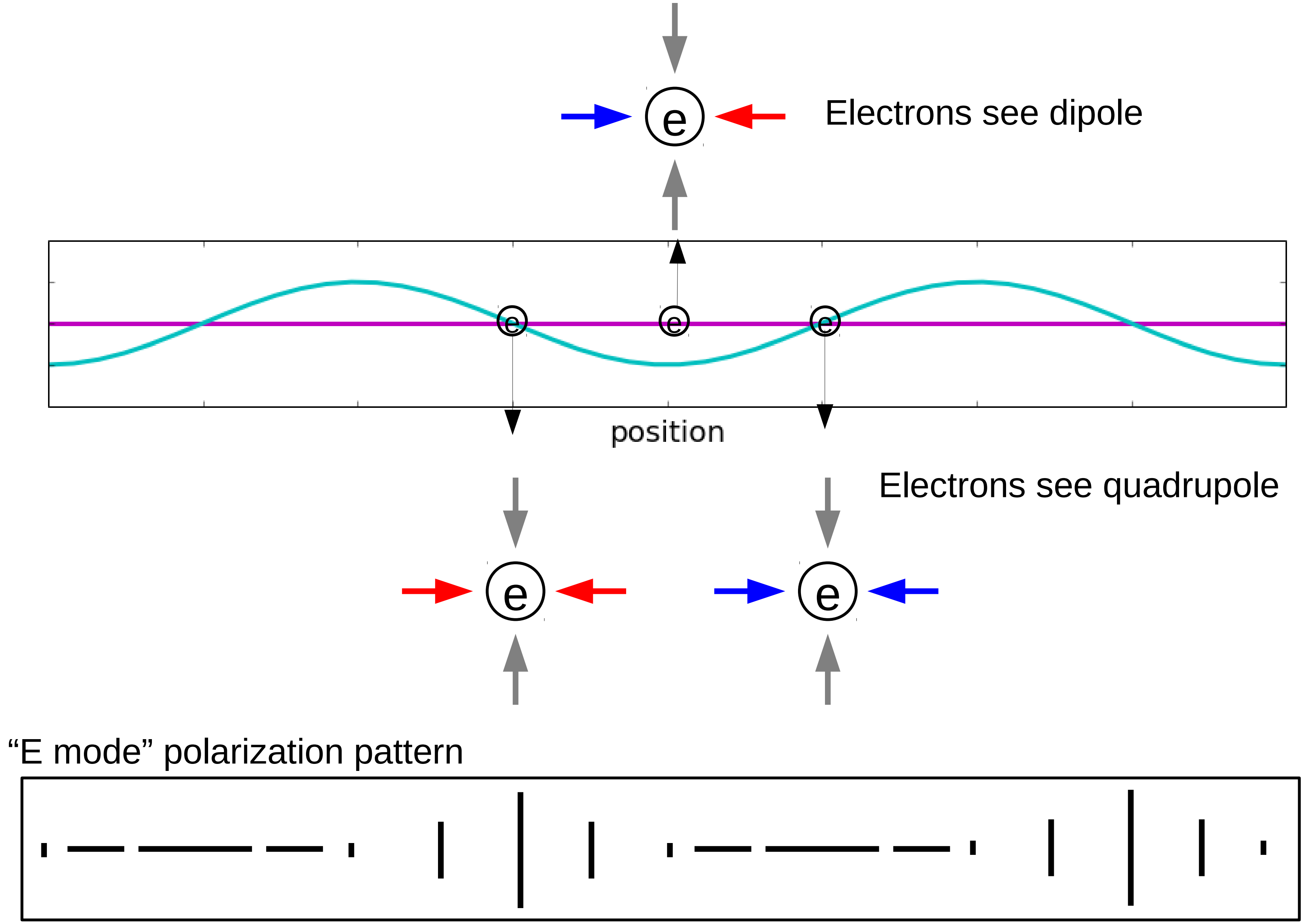

e
Electrons see dipole
e
position



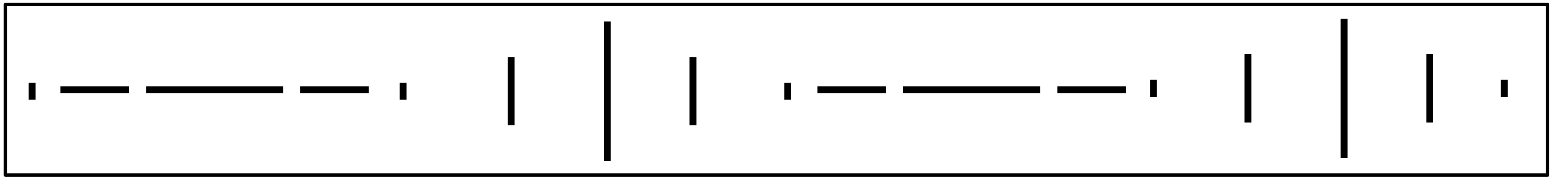
e
Electrons see dipole
e
e
position
Electrons see quadrupole
e



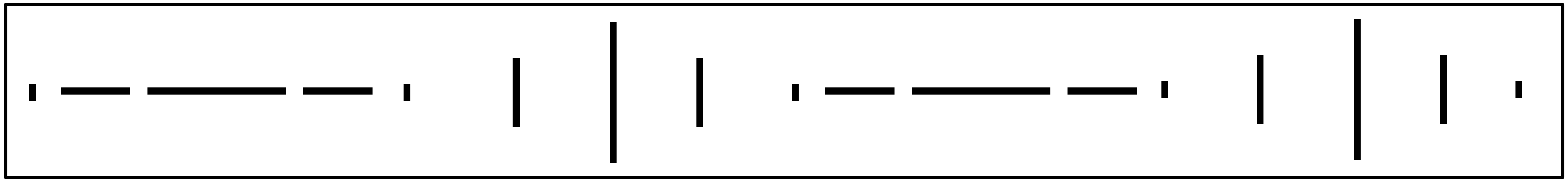
Electrons see dipole
e
e
e
e
position
Electrons see quadrupole
e
e


Electrons see dipole
e
position
Electrons see quadrupole
“E mode” polarization pattern

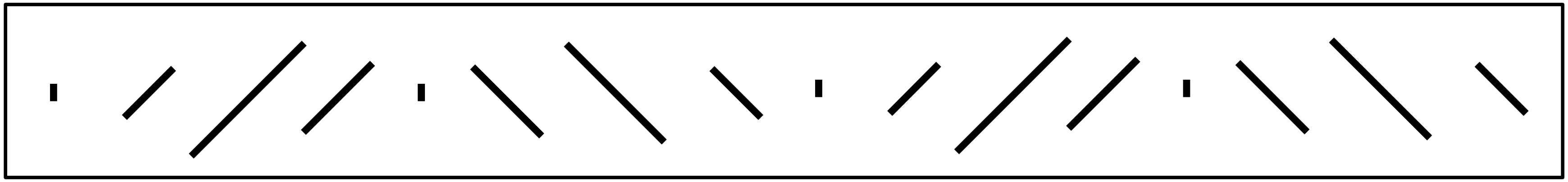
“E mode” polarization pattern



“E mode” polarization pattern



“B mode” polarization pattern (can't be sourced by density/velocity perturbations)



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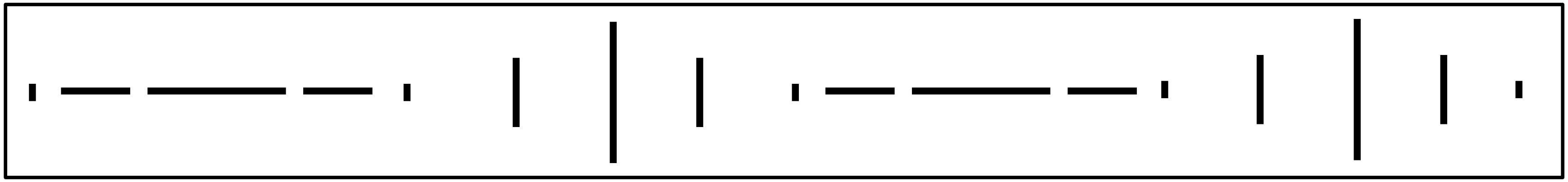

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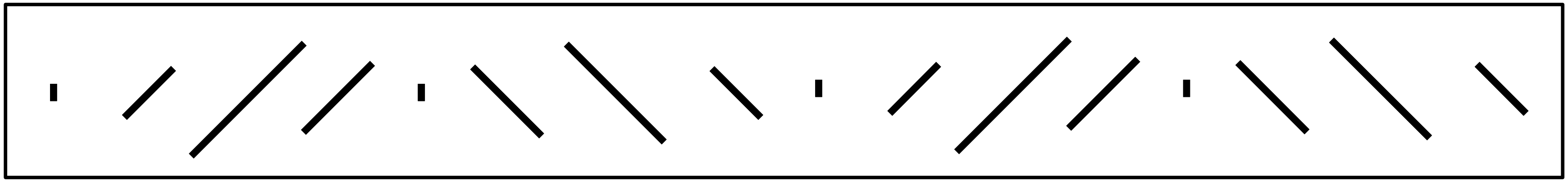
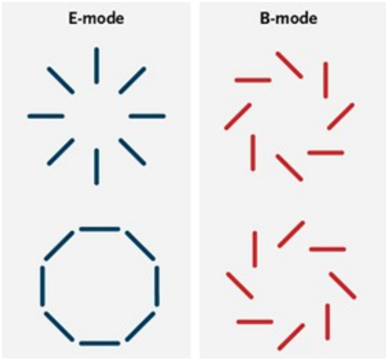
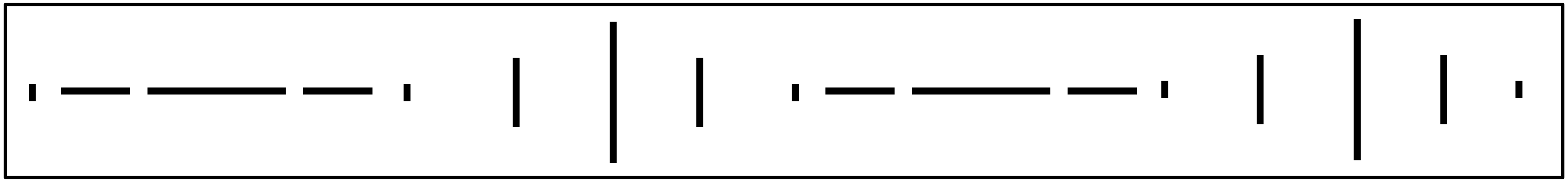


Polarization maps are just linear combinations of the above patterns, e.g.:



"E mode" polarization pattern



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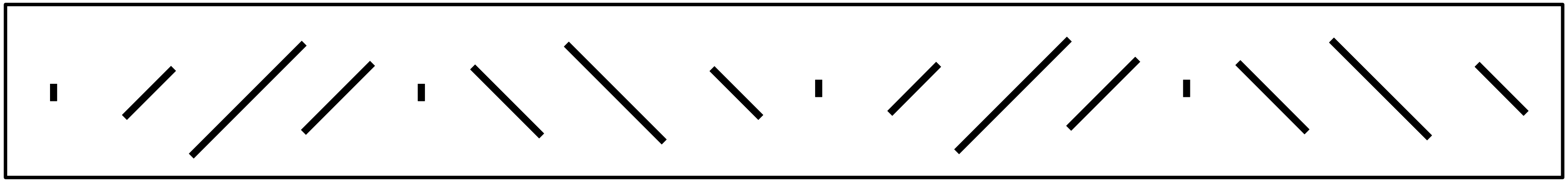

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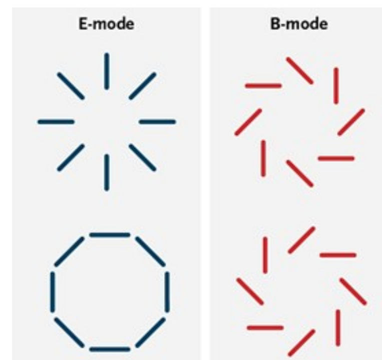
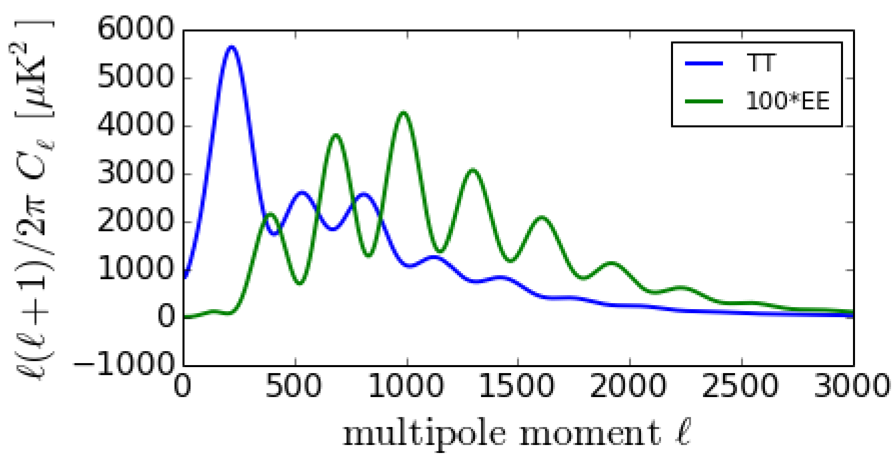


- E modes and T modes out of phase
- With E modes, we are learning about velocities



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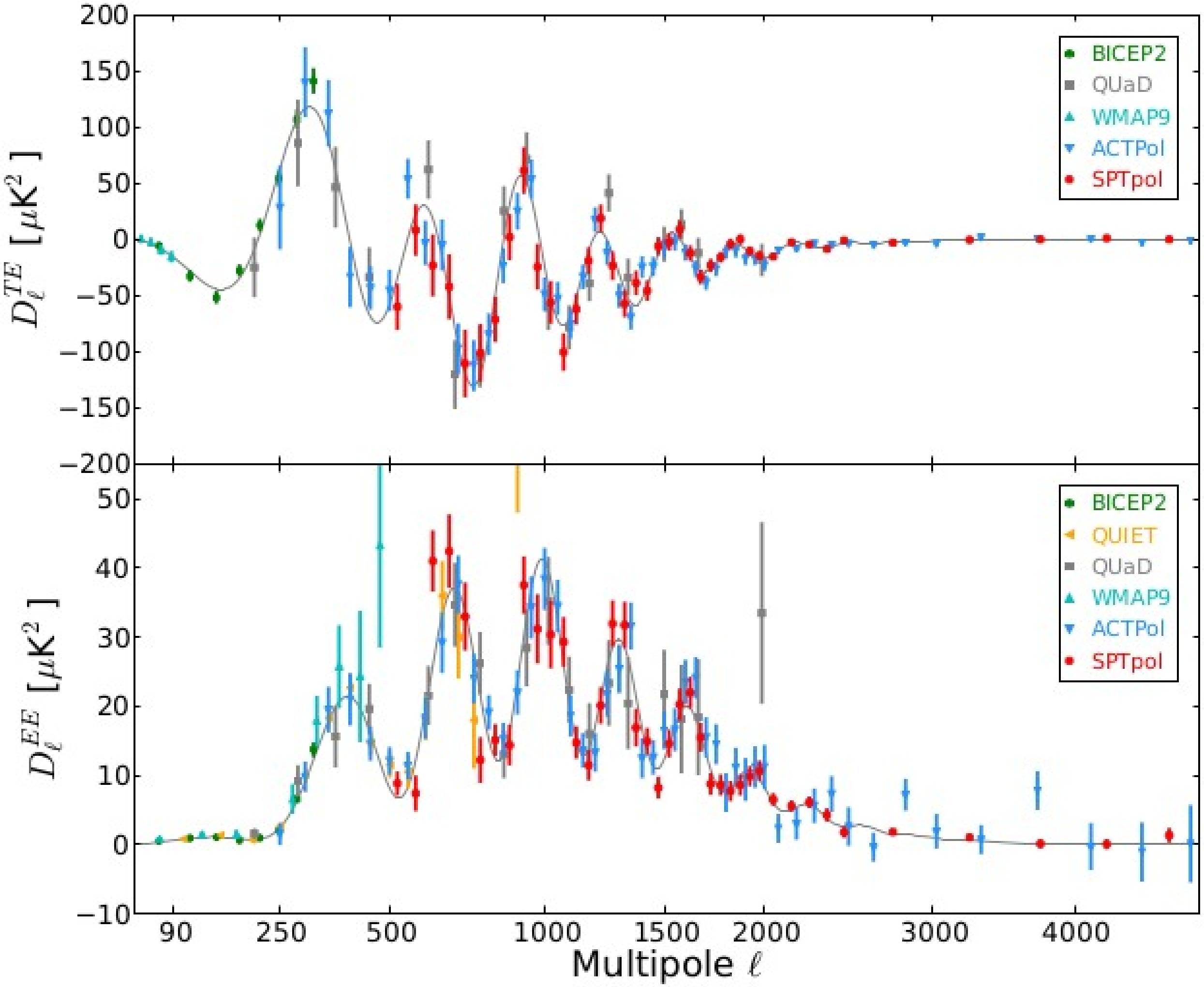
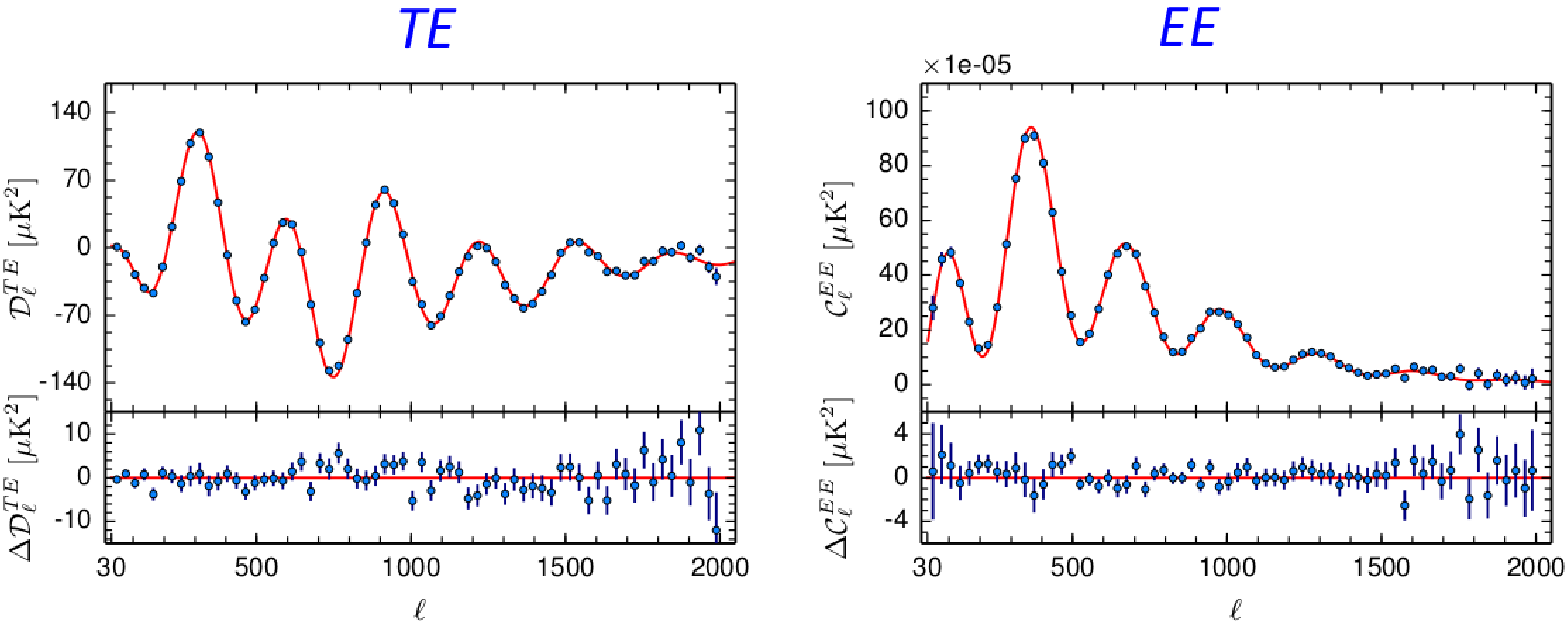
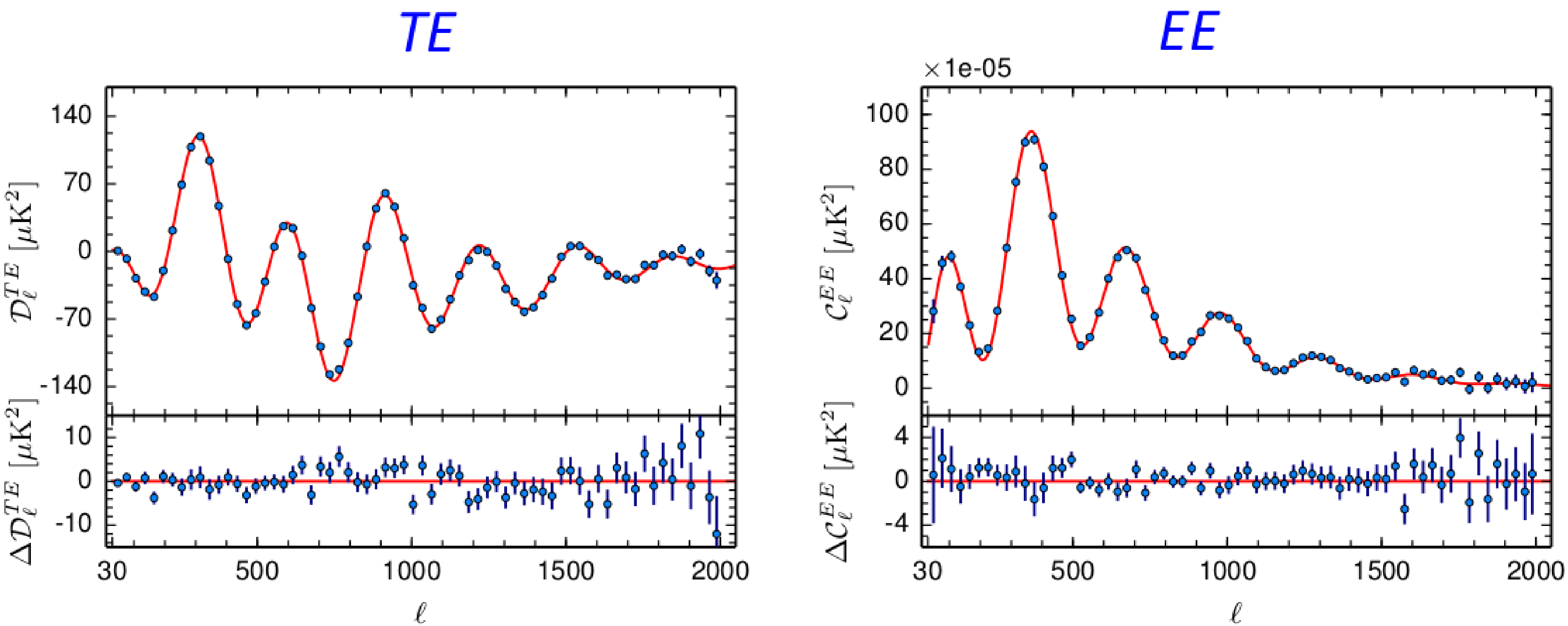



TE
EE
×1e-05
140
70
0
-70
-140
10
0
-10
100
80
60
40
20
0
4
0
-4
30
500
1000
1500
2000
$\mathcal{D}_\ell^{TE}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TE}$ [μK^2]
$\mathcal{C}_\ell^{EE}$ [μK^2]
$\Delta\mathcal{C}_\ell^{EE}$ [μK^2]
ℓ



However, there are low-level systematics (mostly T->P leakage) in the polarization data whose solution was not fully tested in time for 2014.

The TT results are robust. The TE,EE results are more tentative and we don't quote them in our “baseline” results.

Summary of 2014 Results

- ΛCDM still consistent with the data, no clear preference for extensions
- Mean value for τ (optical depth to reionization) shifts lower by 1σ compared to WMAP
- Power spectrum preference for low H_0 & high σ_8 persists
- Some dark matter interpretations of the AMS/Fermi/Pamela excess are tentatively ruled out
- 40σ detection of CMB lensing, 715 new SZ clusters, etc...
- Cosmic Neutrino-(like) Background

This talk

Outline

- Planck
- Number of neutrino-like species N_{eff}
  - BAO and H_0
  - Damping and acoustic oscillation phase shifts
  - Constraints on axions and axion-like particles (ALPs)
- Sum of neutrino masses Σm_ν
  - Gravitational lensing

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

Consistent*

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

Some tension*

*Assuming the ΛCDM model

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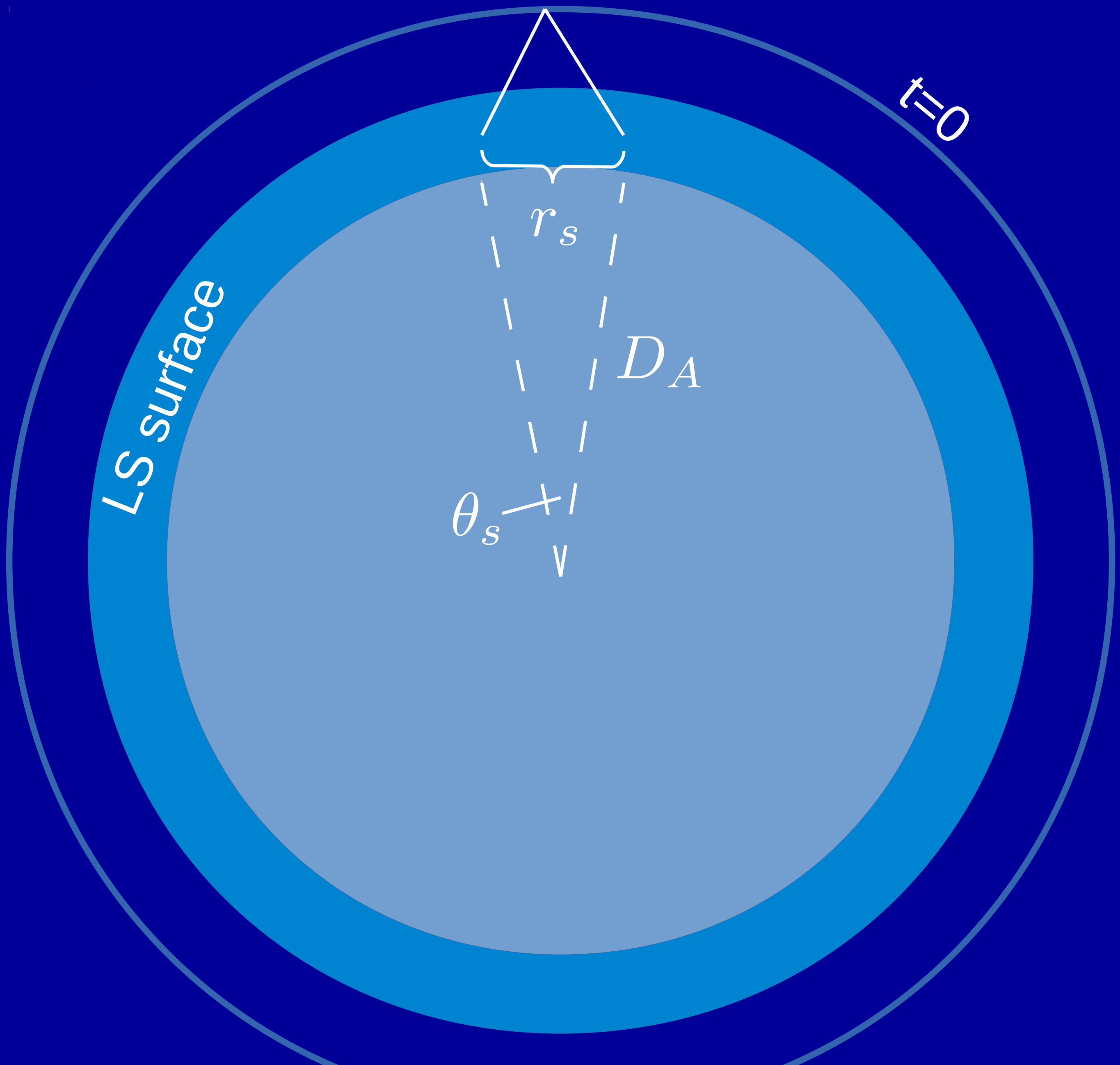
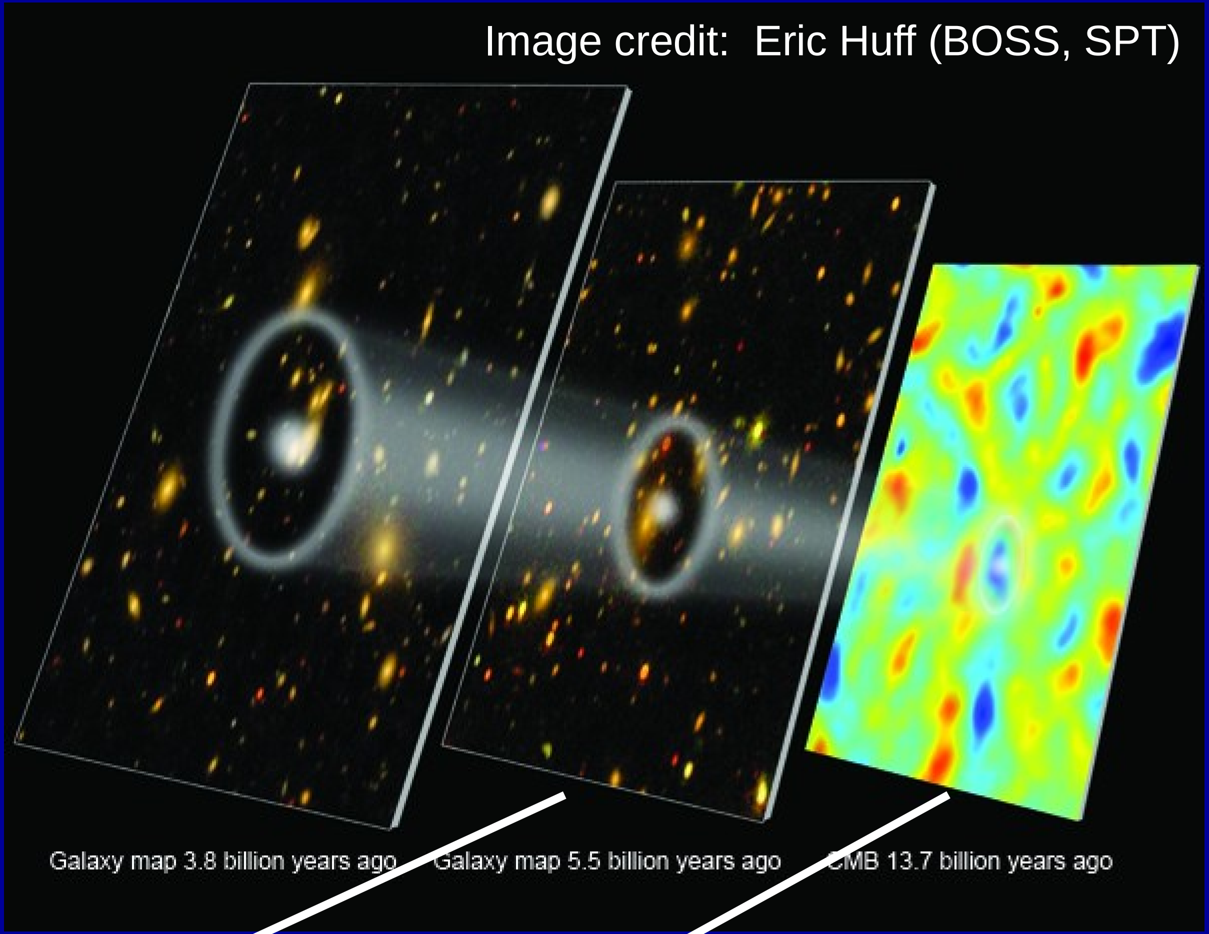


t=0
LS surface
r_s
D_A
θ_s



Planck:

$$\theta_s(z = 1090) = (0.59672 \pm 0.00035)\mathrm{deg}$$

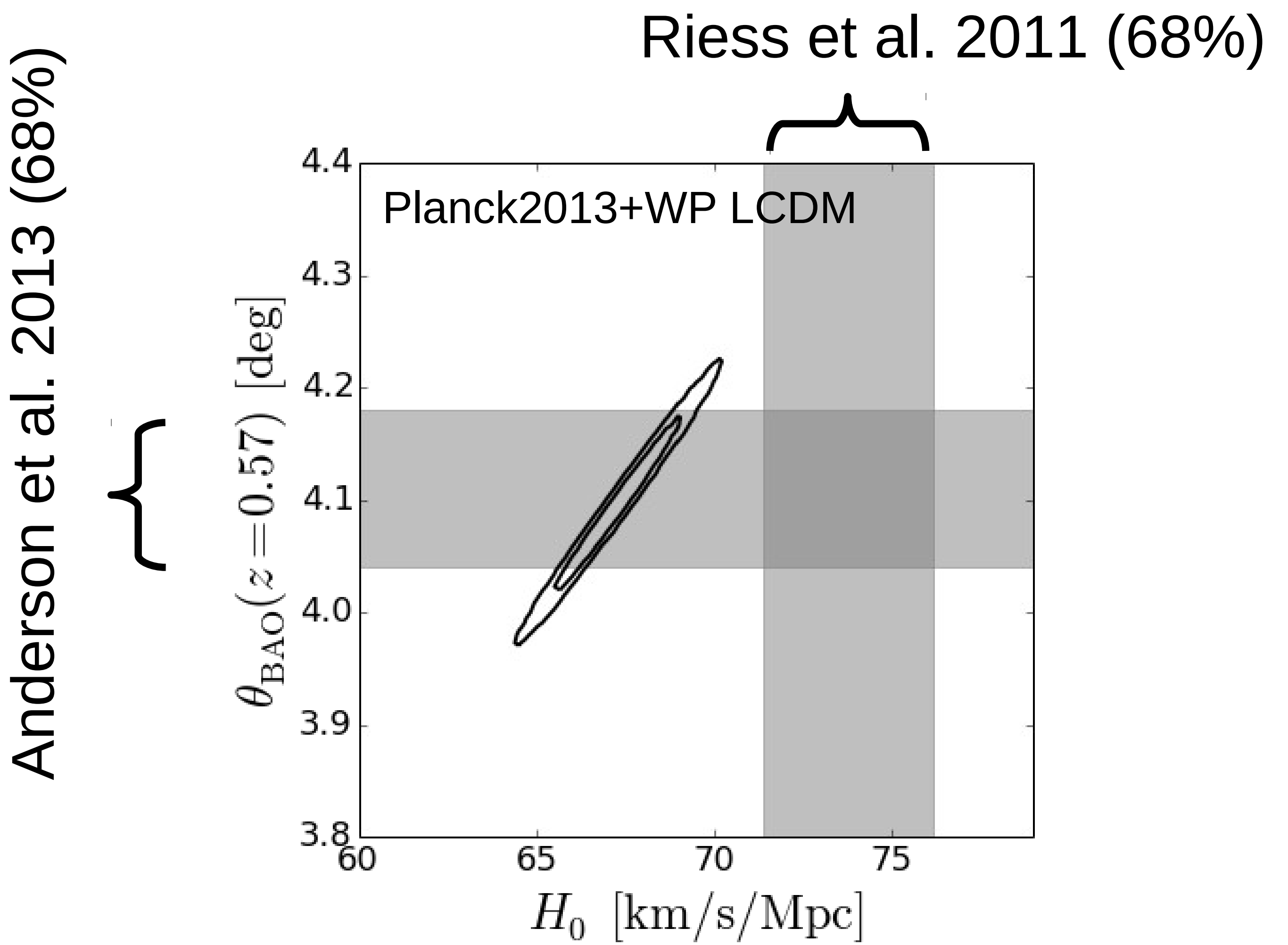
SDSS-BOSS:

$$\theta_{\mathrm{BAO}}(z = 0.57) = (4.1 \pm 0.07)\mathrm{deg}$$

$$\theta_{\mathrm{BAO}} \equiv r_s(z_{\mathrm{drag}})/(D_A^2/H)^{1/3}$$

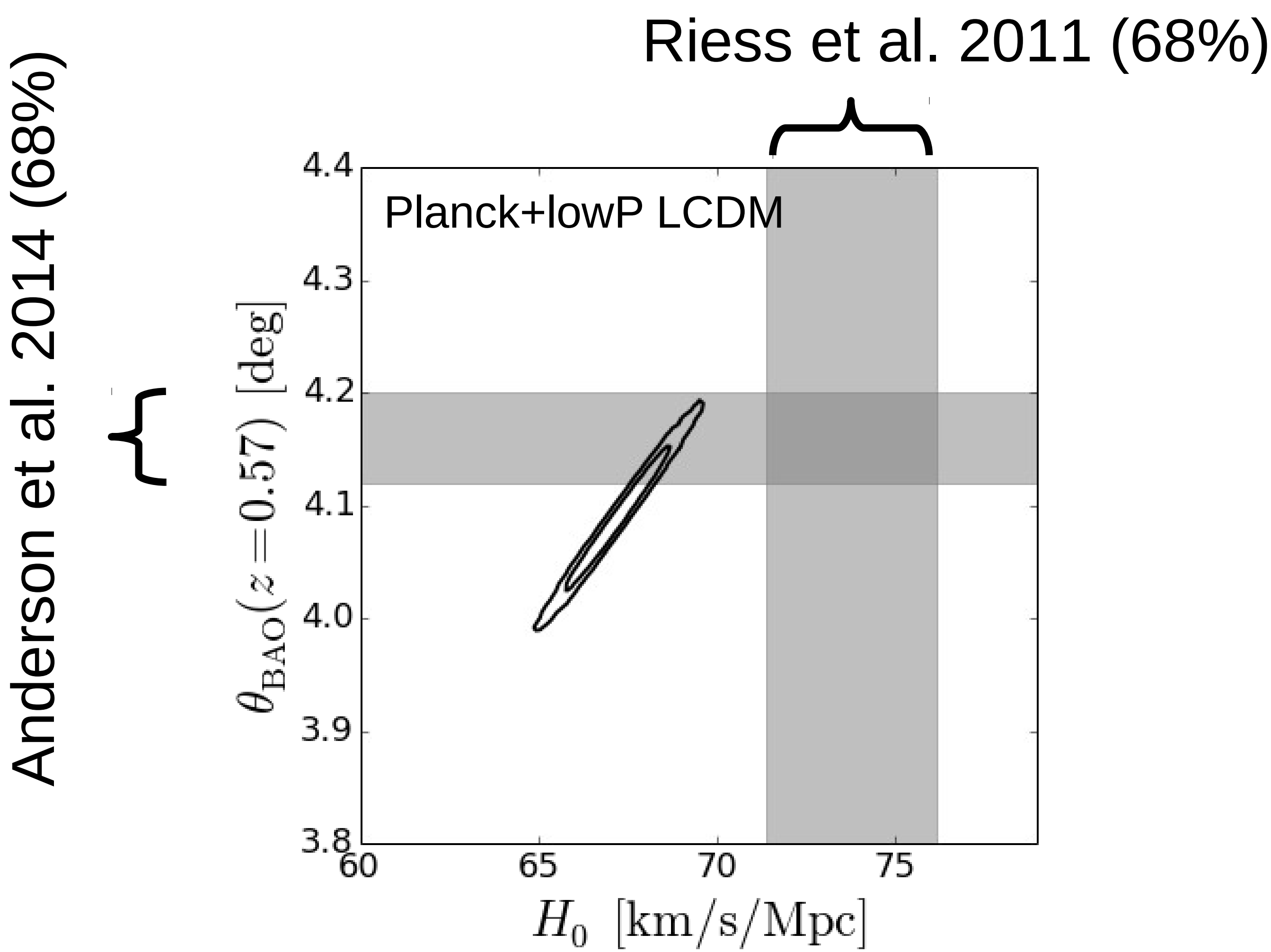
BOSS BAO, Riess et al. (2011) H_0 and Planck

- Good agreement with BOSS BAO
- 2.4σ tension with Riess et al. H_0



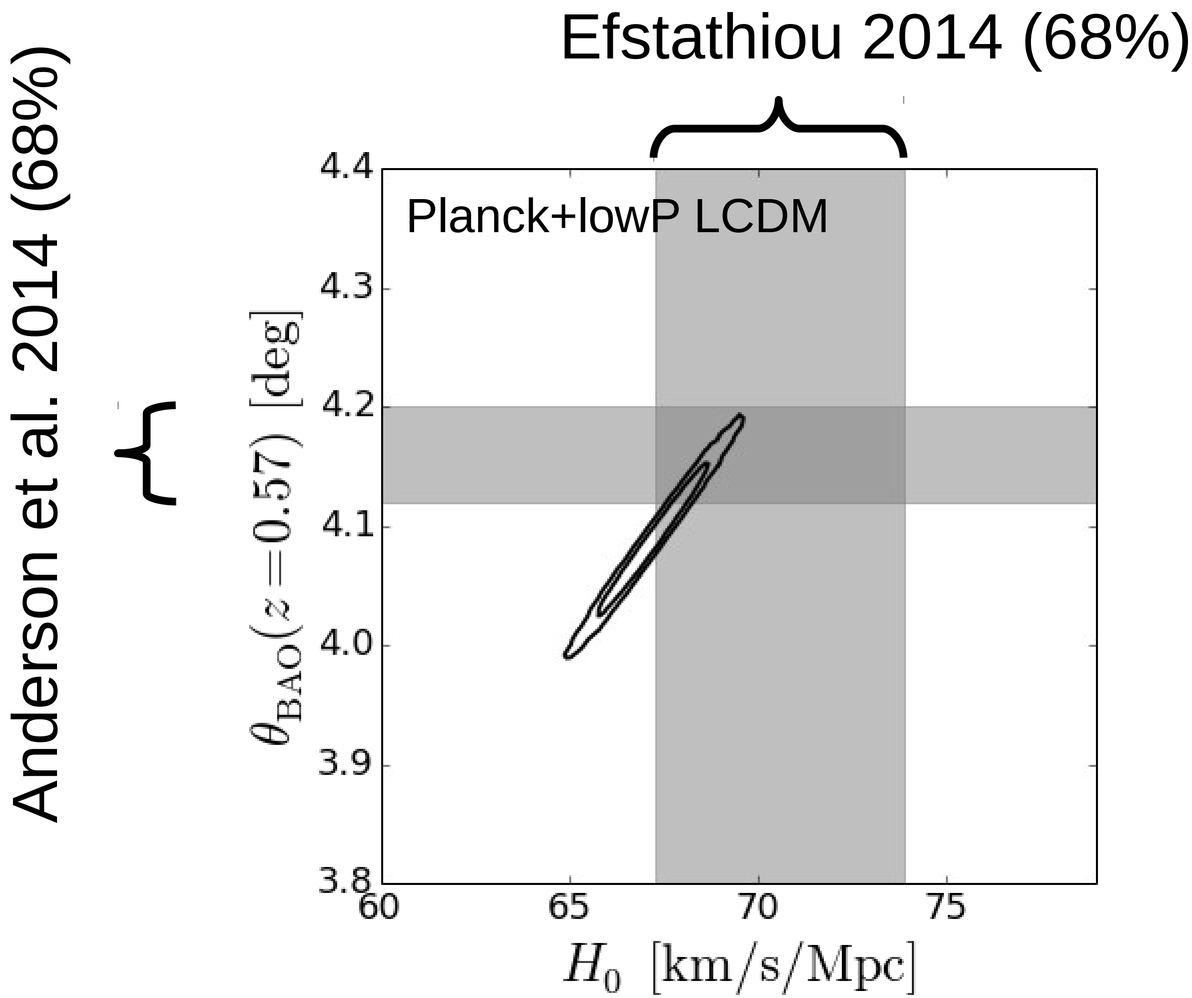
BOSS BAO, Riess et al. (2011) H_0 and Planck

- Update to 2014

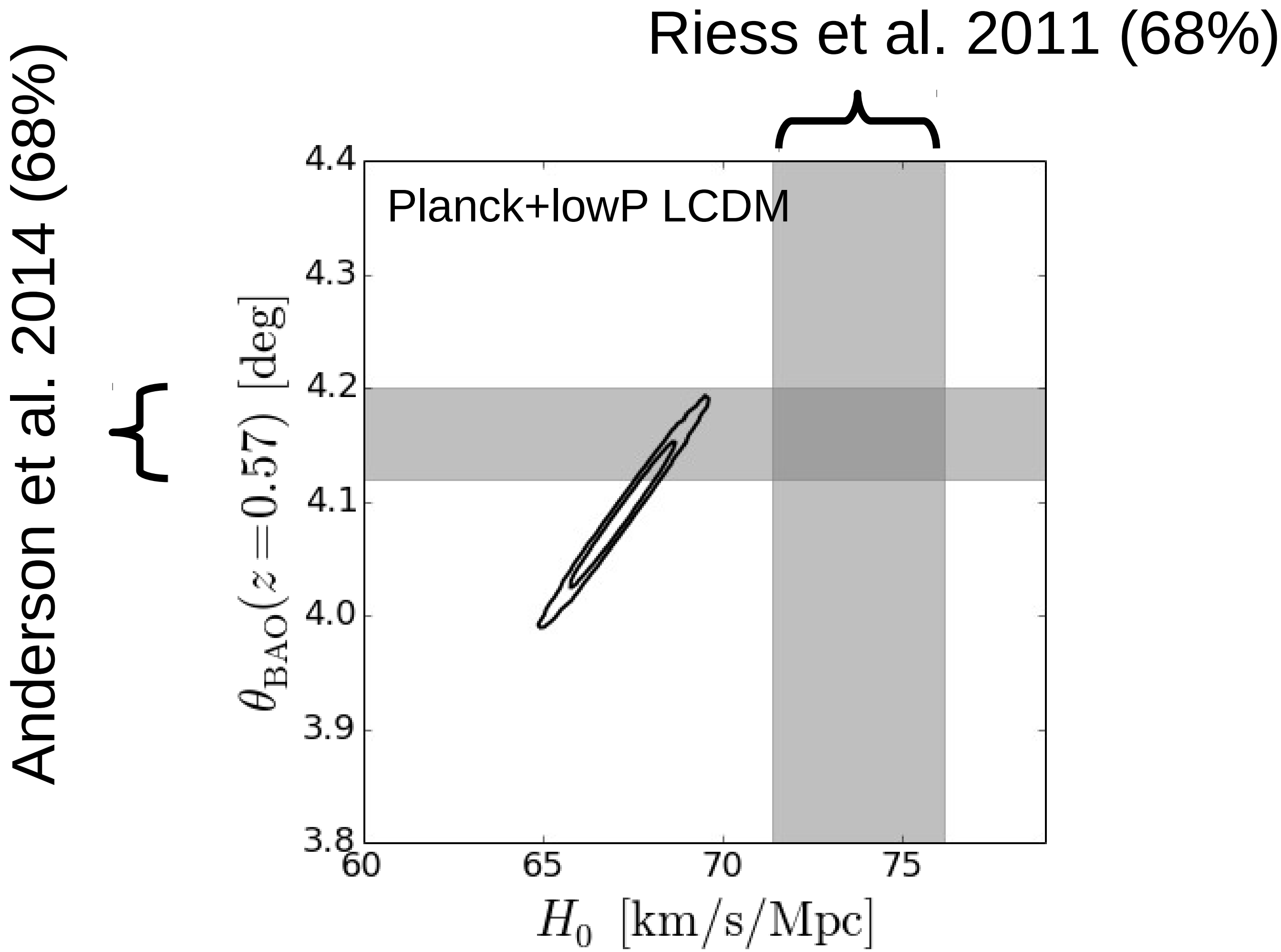


BOSS BAO, Riess et al. (2011) H_0 and Planck

- More conservative Hubble prior?



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



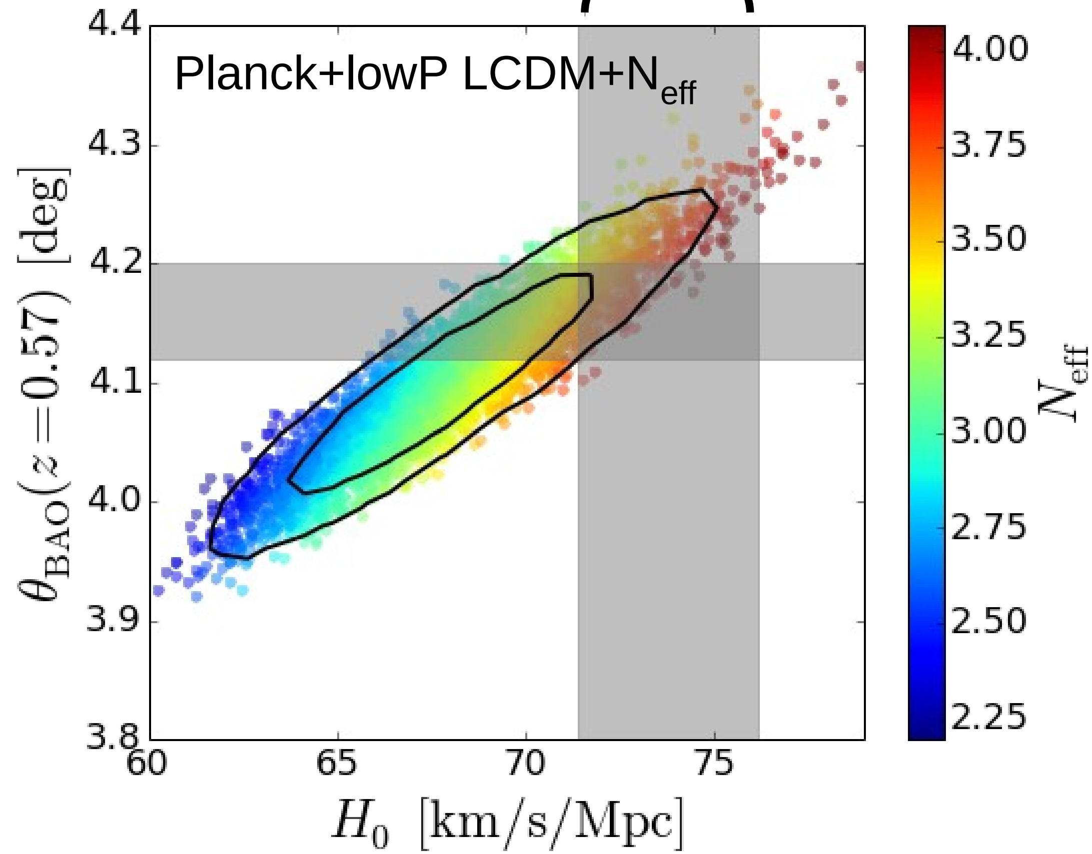
BOSS BAO, Riess et al. (2011) H_0 and Planck

$$\rho_{\rm rad} = \rho_\gamma + \rho_\nu = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma$$

LCDM:
$$N_{\rm eff} = 3.046$$

Riess et al. 2011 (68%)

Anderson et al. 2014 (68%)



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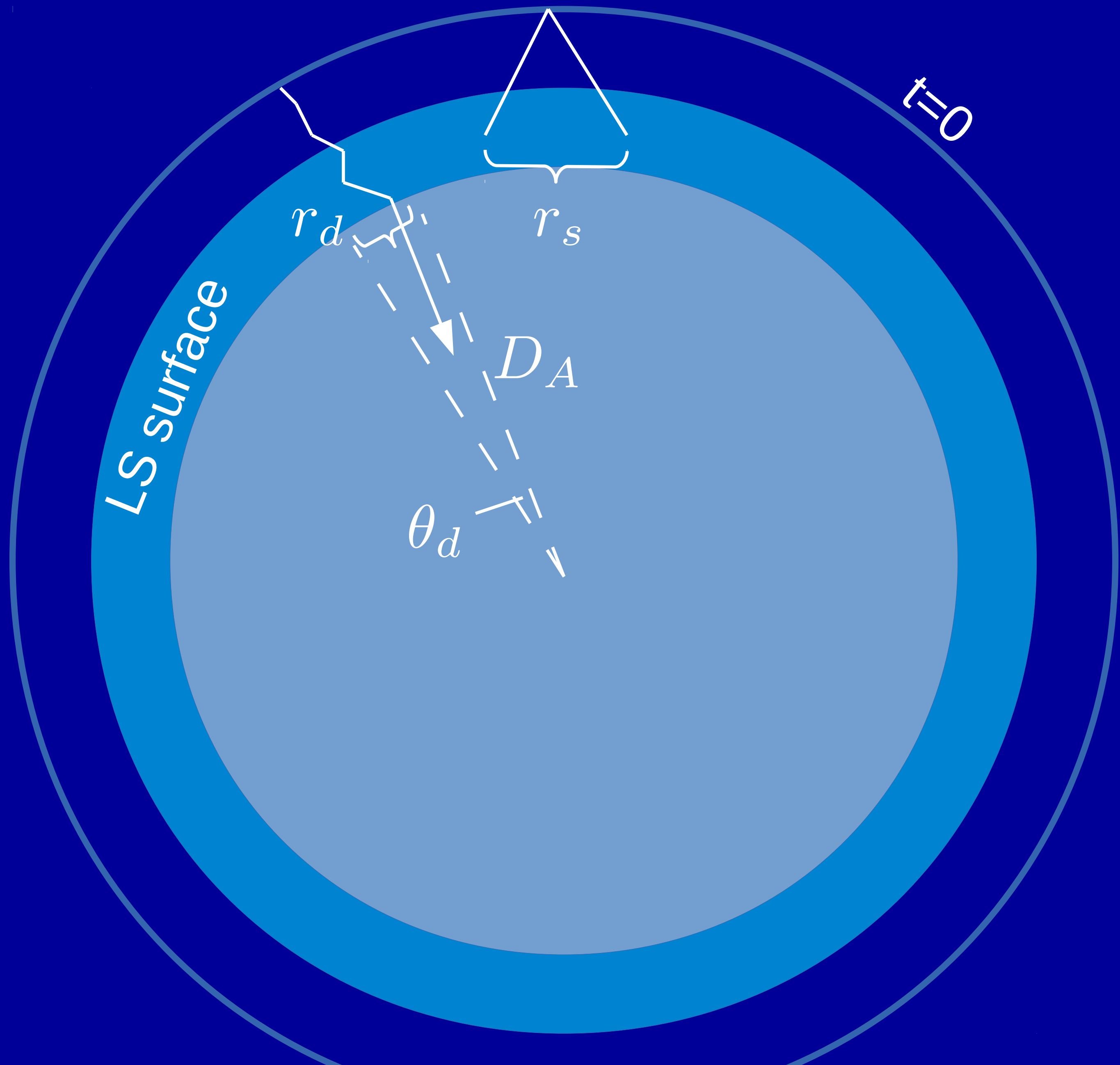

t=0
LS surface
r_d
r_s
D_A
θ_d

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)

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$$\theta_s = \frac{r_s}{D_A}$$

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

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

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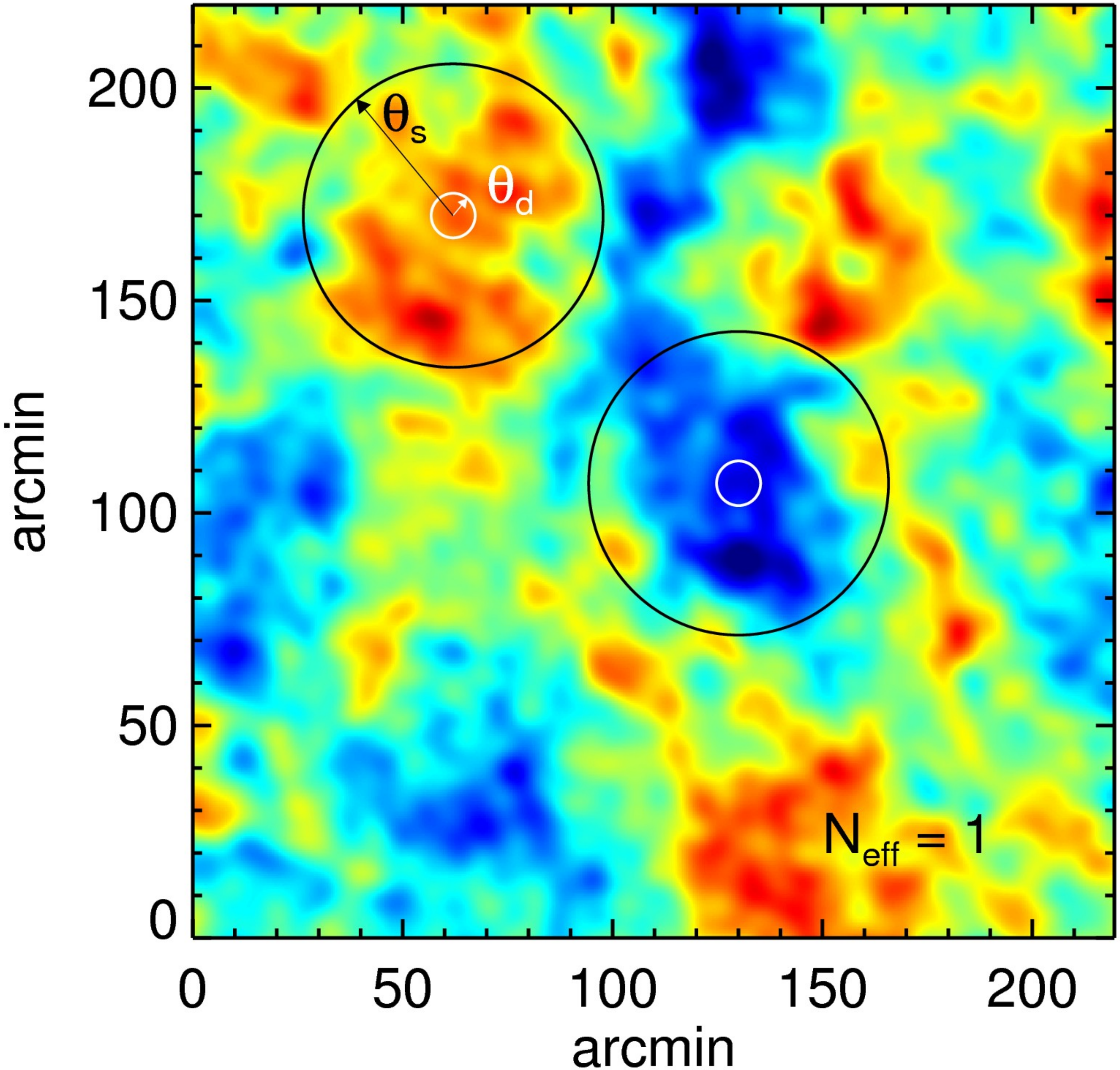
$$\frac{\theta_s}{\theta_d} = \frac{r_s}{r_d} \sim \frac{1}{\sqrt{H(a)}} \sim \frac{1}{N_{\mathrm{eff}}^{1/4}}$$

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

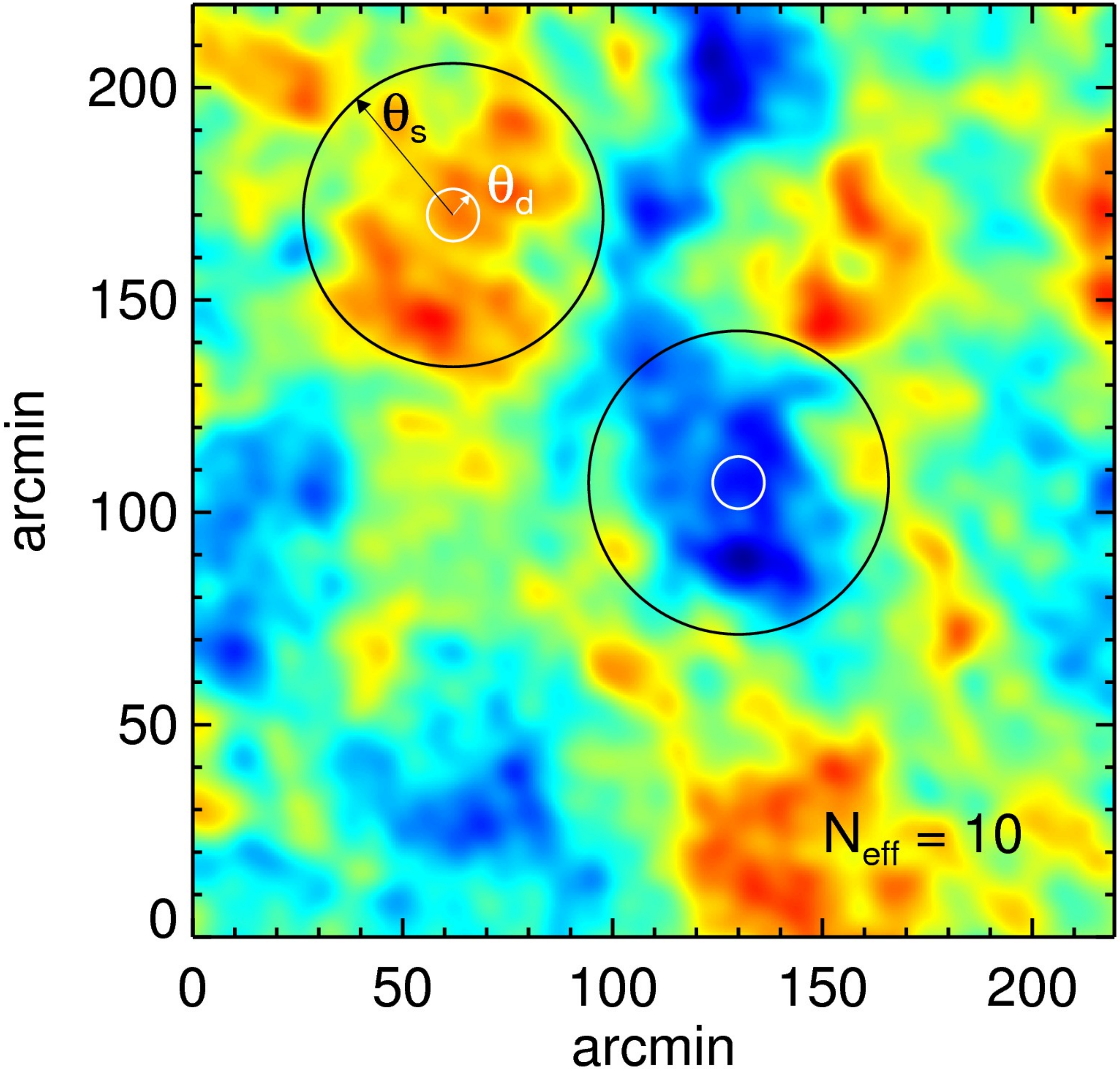
Neff affects the ratio of sound horizon to diffusion scale



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

To scale

Neff affects the ratio of sound horizon to diffusion scale



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

To scale

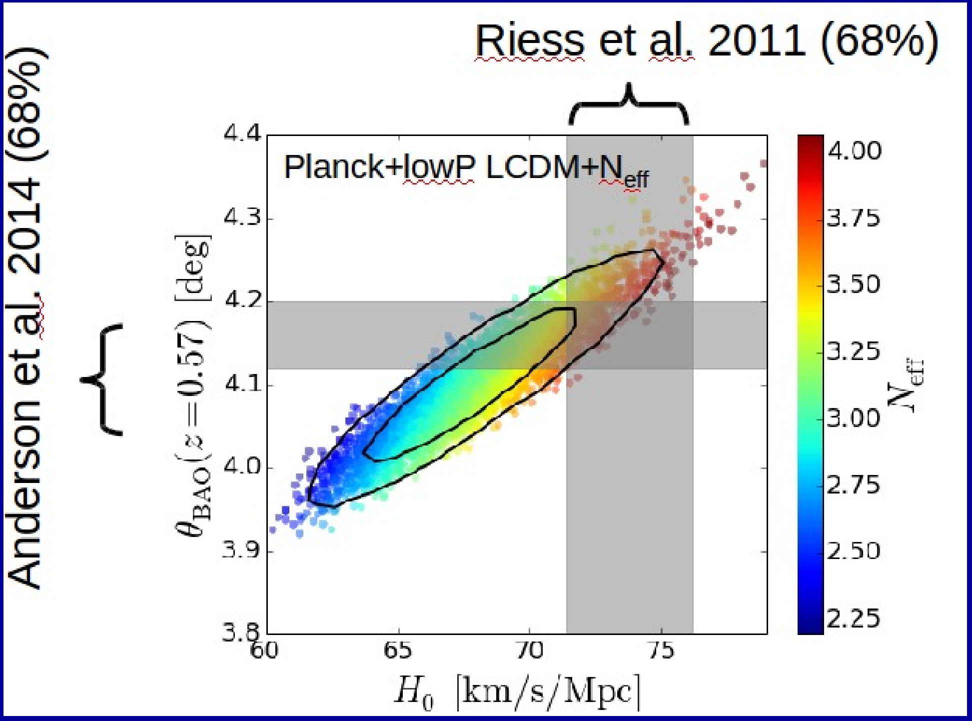
Light Degrees of Freedom

$$N_{\mathrm{eff}} = 3.13 \pm 0.32 \quad (\textit{Planck}\ \mathrm{TT{+}lowP})$$

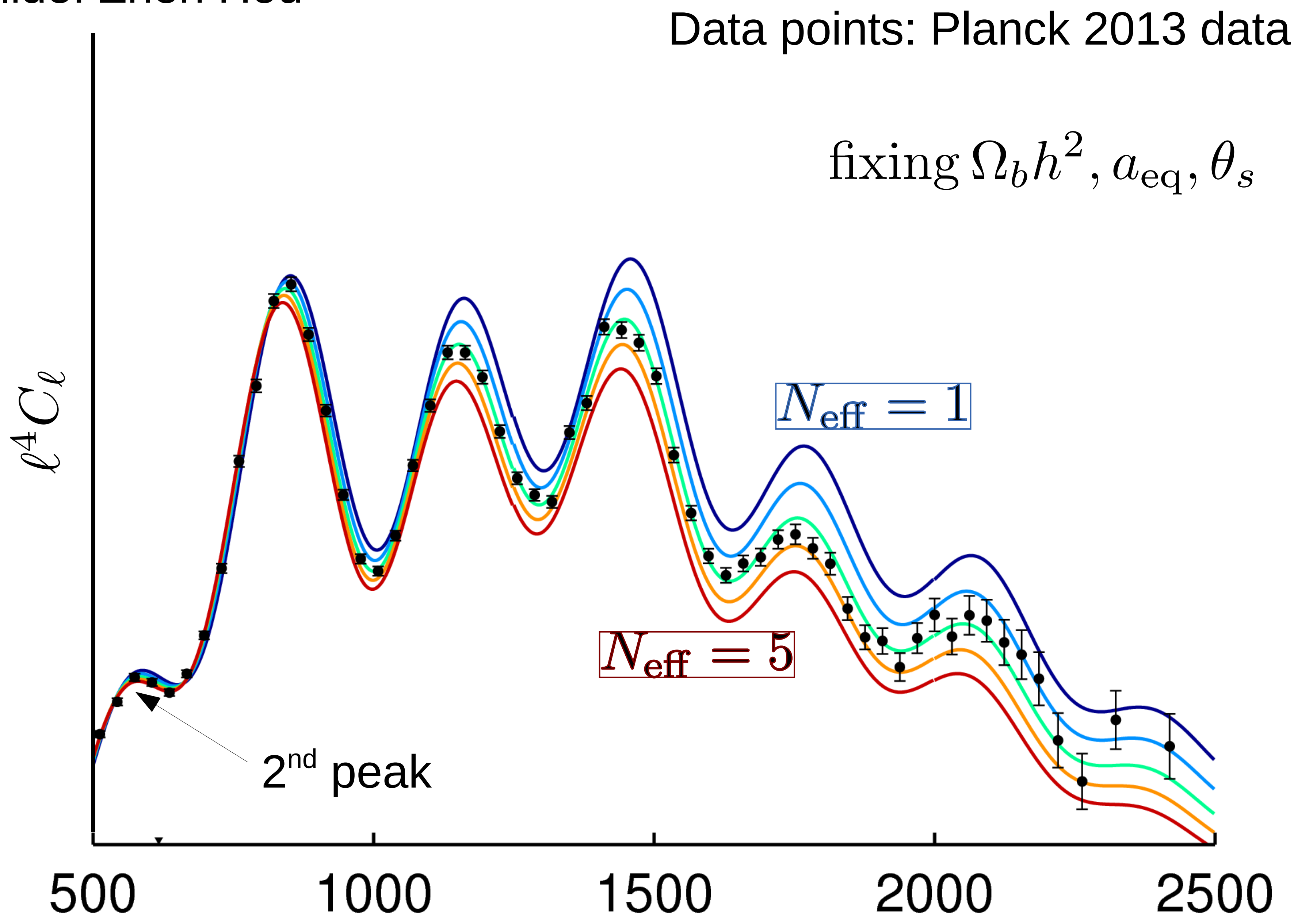
$$\boxed{N_{\mathrm{eff}} = 3.15 \pm 0.23} \quad (\textit{Planck}\ \mathrm{TT{+}lowP{+}\ BAO})$$

with high-l polarisation
$$\left\{\begin{array}{l} N_{\mathrm{eff}} = 2.98 \pm 0.20 \quad (\textit{Planck}\ \mathrm{TT,TE,EE{+}lowP}) \\ N_{\mathrm{eff}} = 3.04 \pm 0.18 \quad (\textit{Planck}\ \mathrm{TT,TE,EE{+}lowP{+}BAO}) \end{array}\right.$$

but …

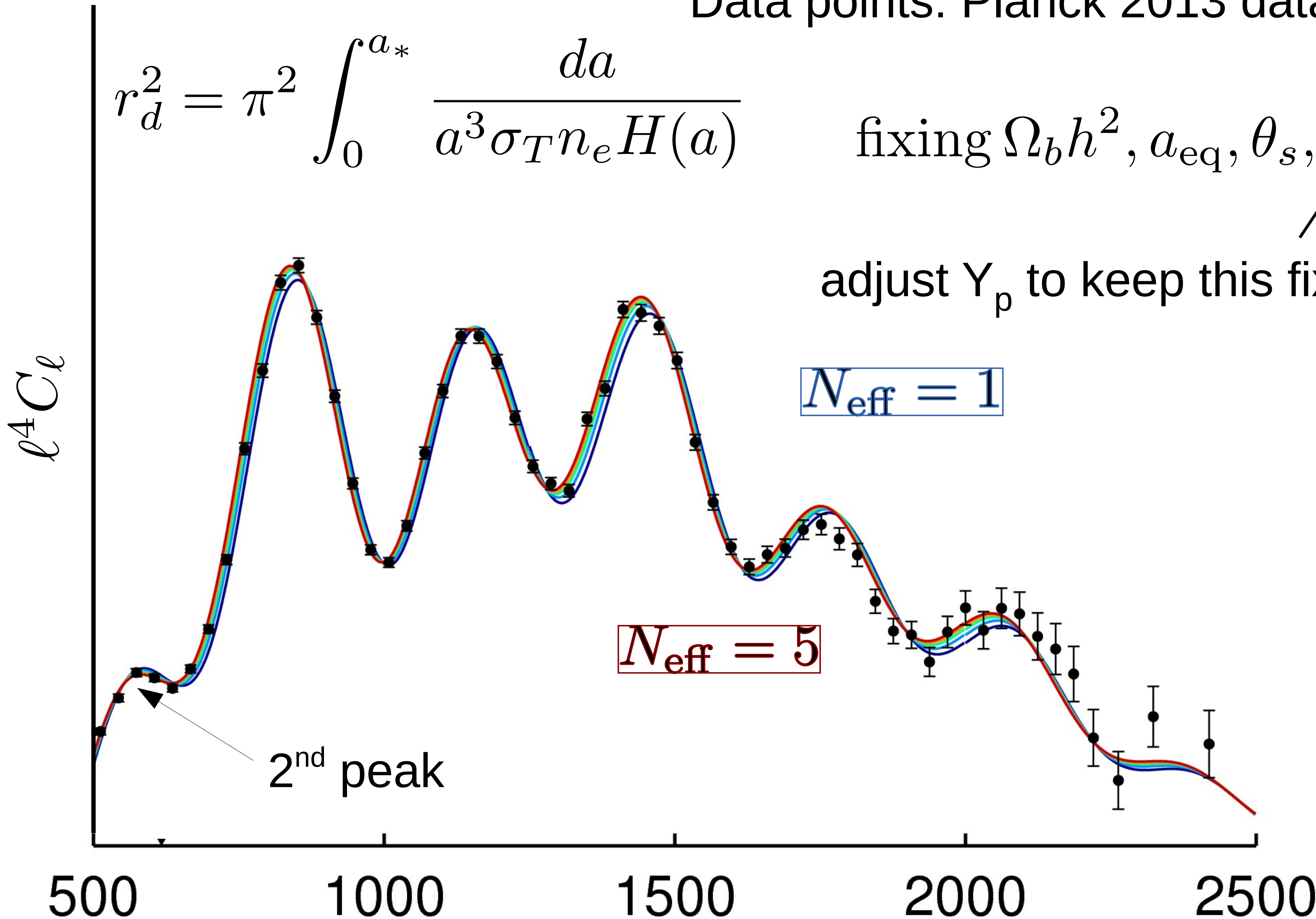


Slide: Zhen Hou

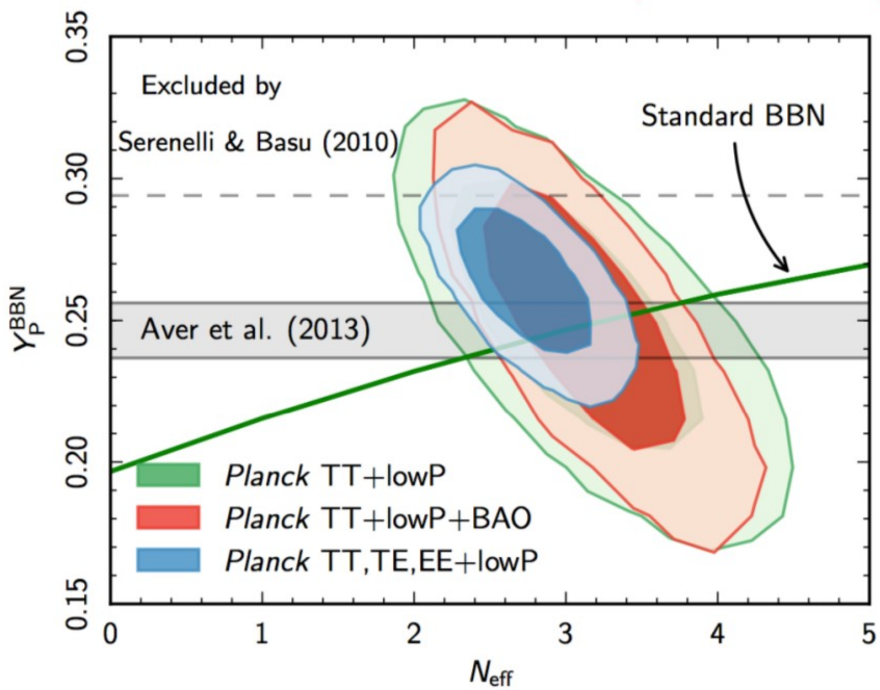


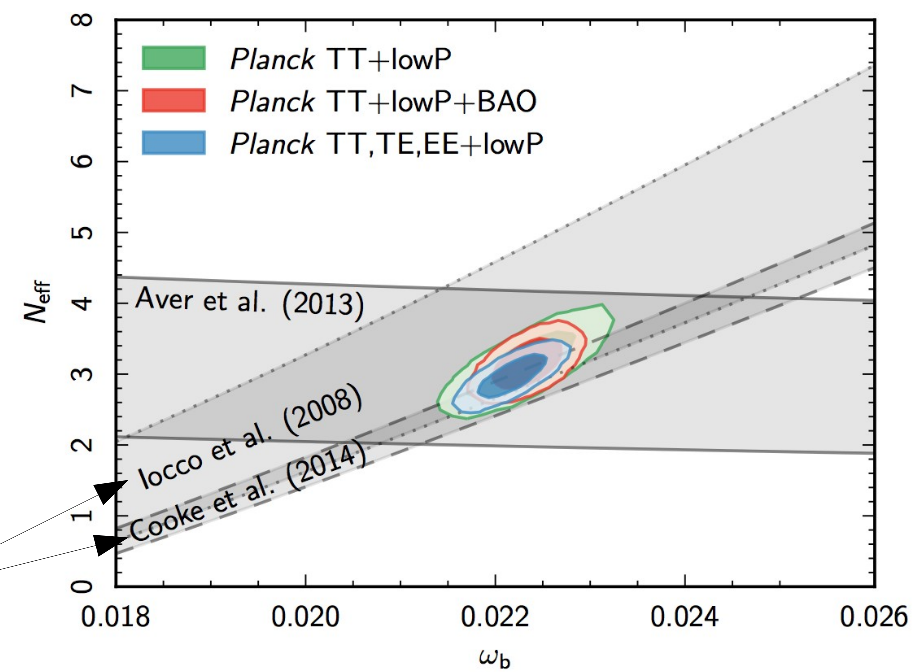
Slide: Zhen Hou

Data points: Planck 2013 data



CMB & BBN in great agreement





D/H measurements

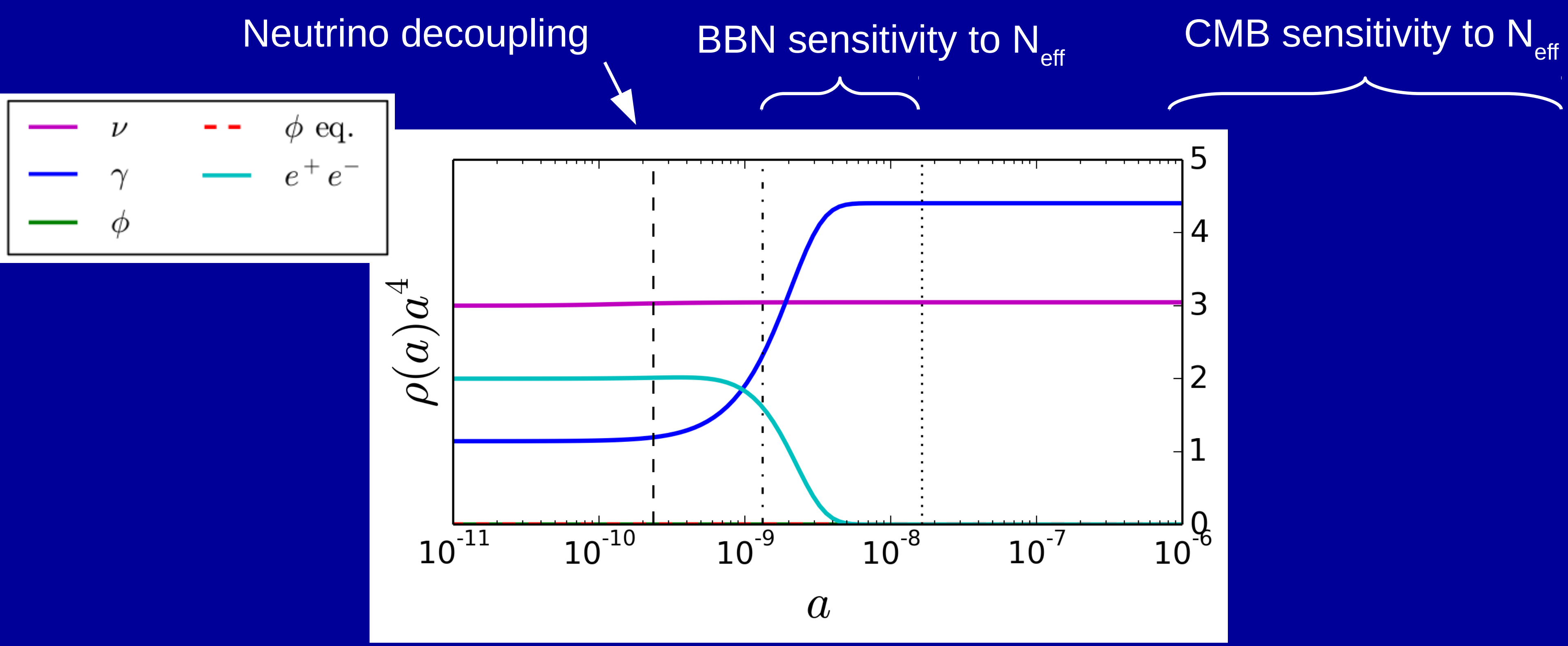
Outline

- Planck
- Number of neutrino-like species N_{eff}
  - BAO and H_0
  - Damping and acoustic oscillation phase shifts
  - Constraints on axions and axion-like particles (ALPs)
- Sum of neutrino masses Σm_ν
  - Gravitational lensing

Constraints on axions and ALPs

(Millea, Knox, and Fields 2014, in prep)

- The CMB and BBN can jointly probe scenarios where particles decay in between the two epochs.
- We consider a generic particle, called an axion-like particle (ALP) which can decay to two photons.



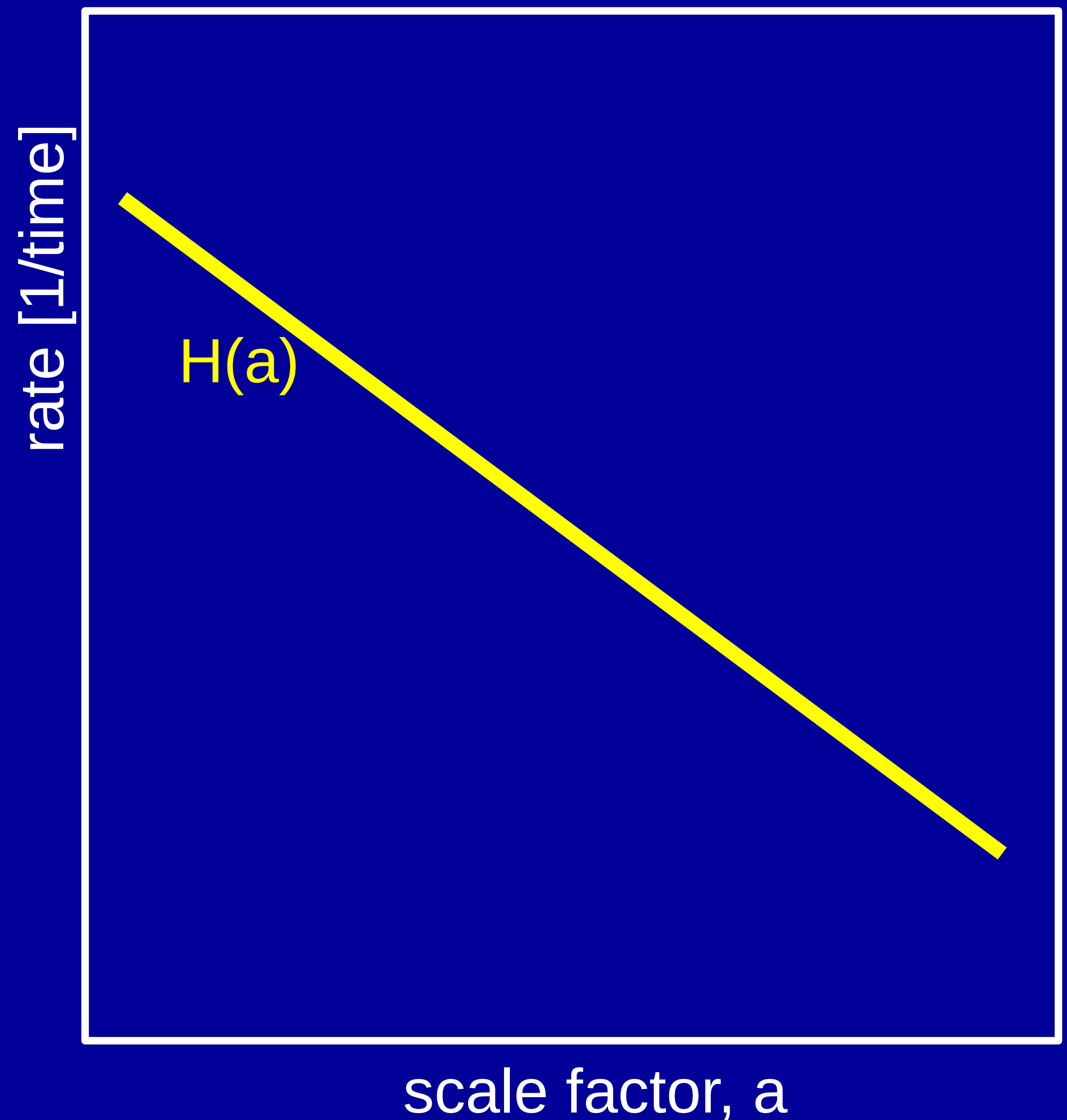
Axions and axion-like particles (ALPs)

- ALPs are a general class of particles with two free parameters: m_ϕ and $\tau_{\phi\gamma}$
  - Typical in theories with SSBs, e.g. string axiverse, etc..

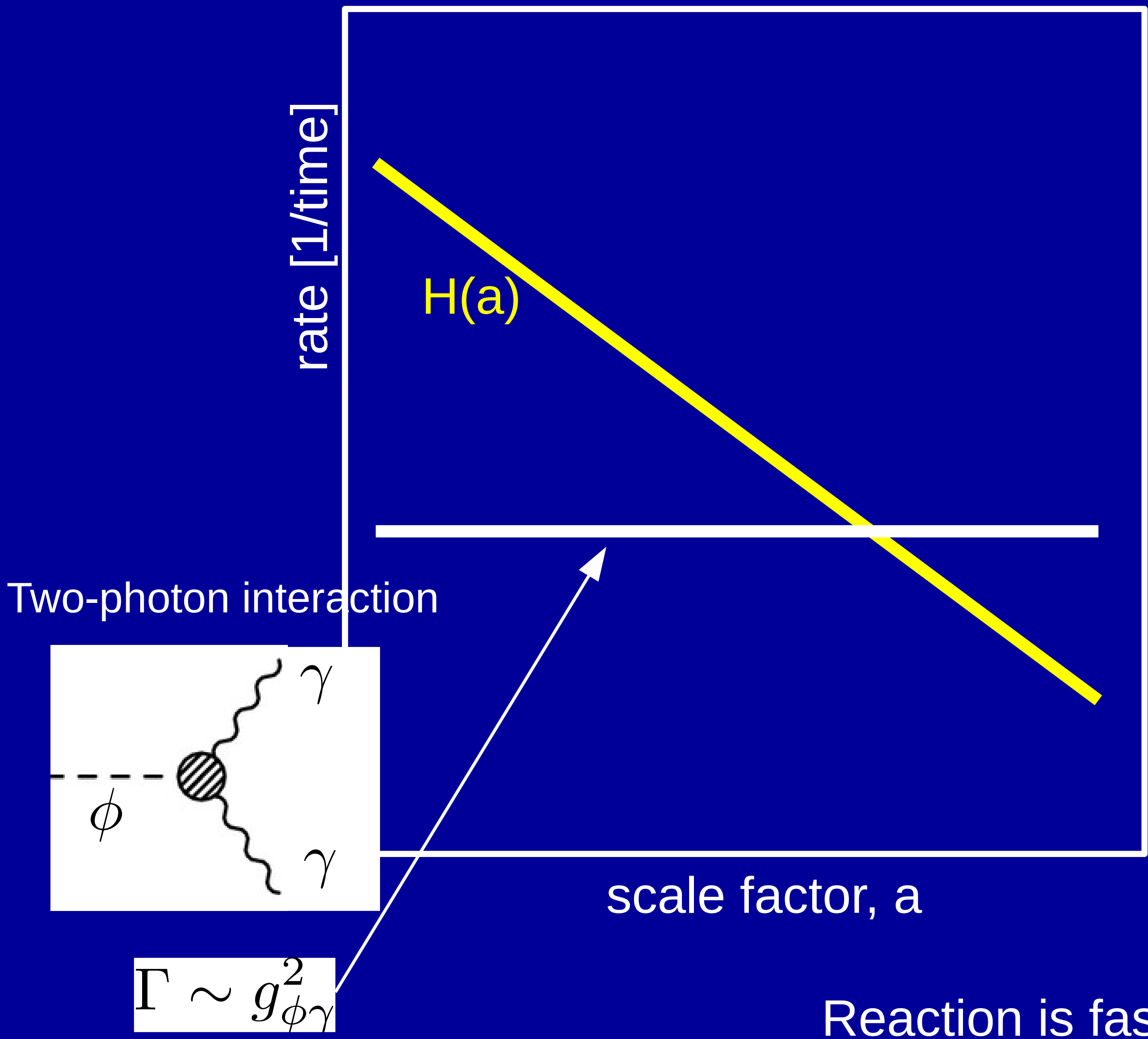
$$\mathcal{L} = \frac{1}{2} m_\phi^2 \phi^2 + \frac{g_{\phi\gamma}}{4} \phi F \tilde{F}$$

$$\tau_{\phi\gamma} = \frac{64\pi}{m_\phi^3 g_{\phi\gamma}^2}$$

- Axions are a type of ALPs where $g_{\phi\gamma}$ and m_ϕ are related
  - Well motivated theoretically to solve the strong CP problem.
- Relevant axions and ALPs here are heavy compared to "invisible" axion models
  - $m_\phi \sim 1\ \mathrm{MeV}$
  - $\tau_{\phi\gamma} \sim 1\ \mathrm{sec}$



Reaction is fast when $\Gamma > H$



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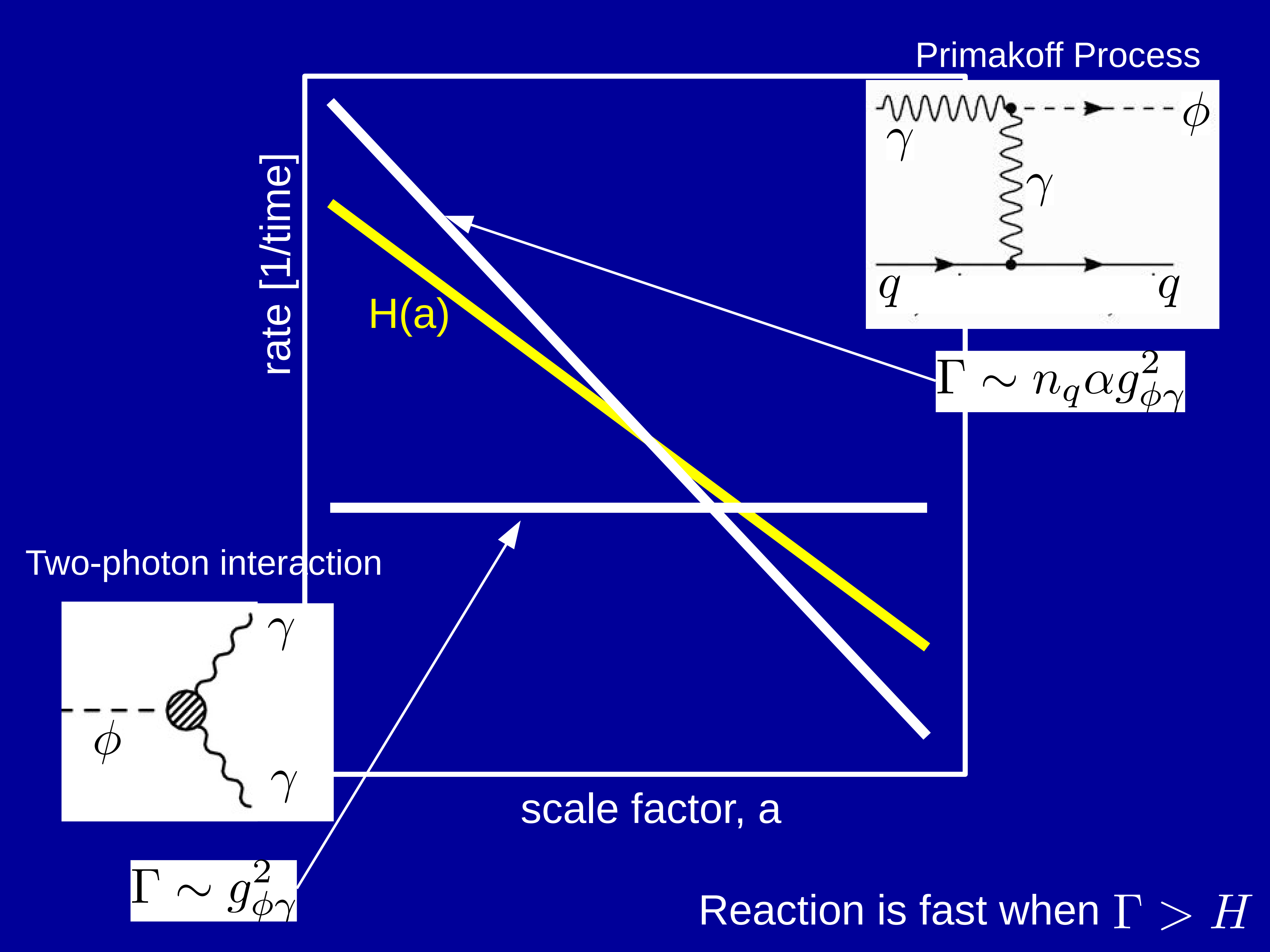


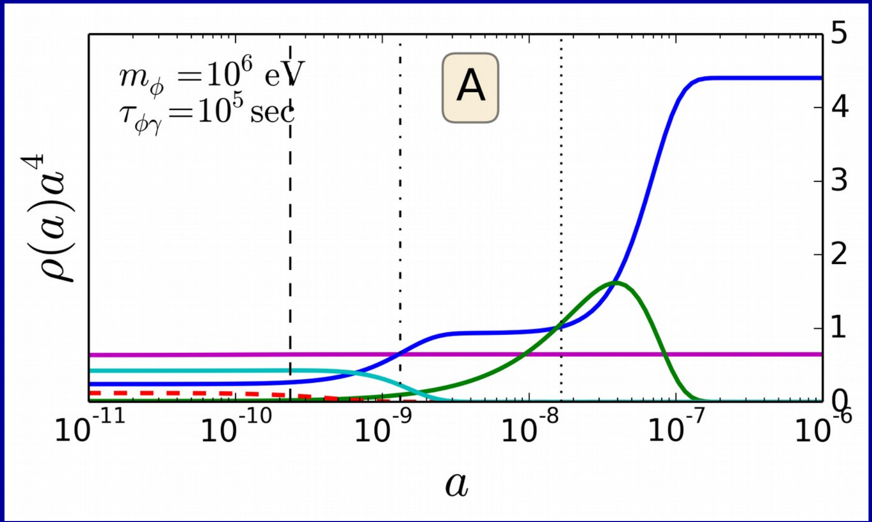
Primakoff Process
γ
ϕ
γ
q
q
rate [1/time]
H(a)
$\Gamma \sim n_q \alpha g_{\phi\gamma}^2$
Two-photon interaction
γ
ϕ
γ
scale factor, a
$\Gamma \sim g_{\phi\gamma}^2$
Reaction is fast when $\Gamma > H$

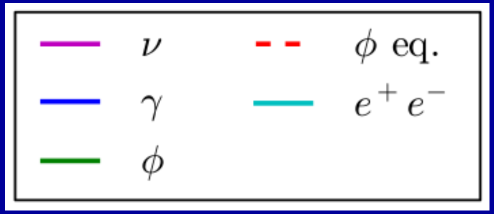
Primakoff fast

Decoupled

Two-photon fast

Out-of-equilibrium decay:

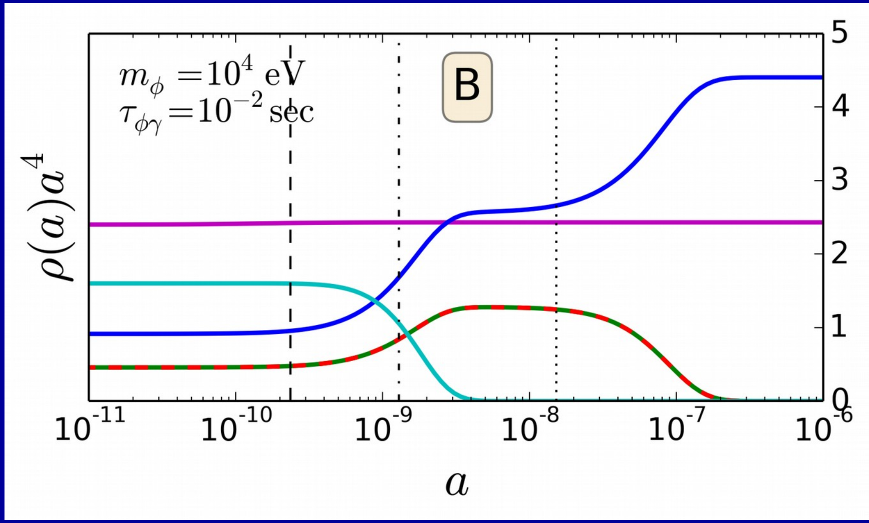


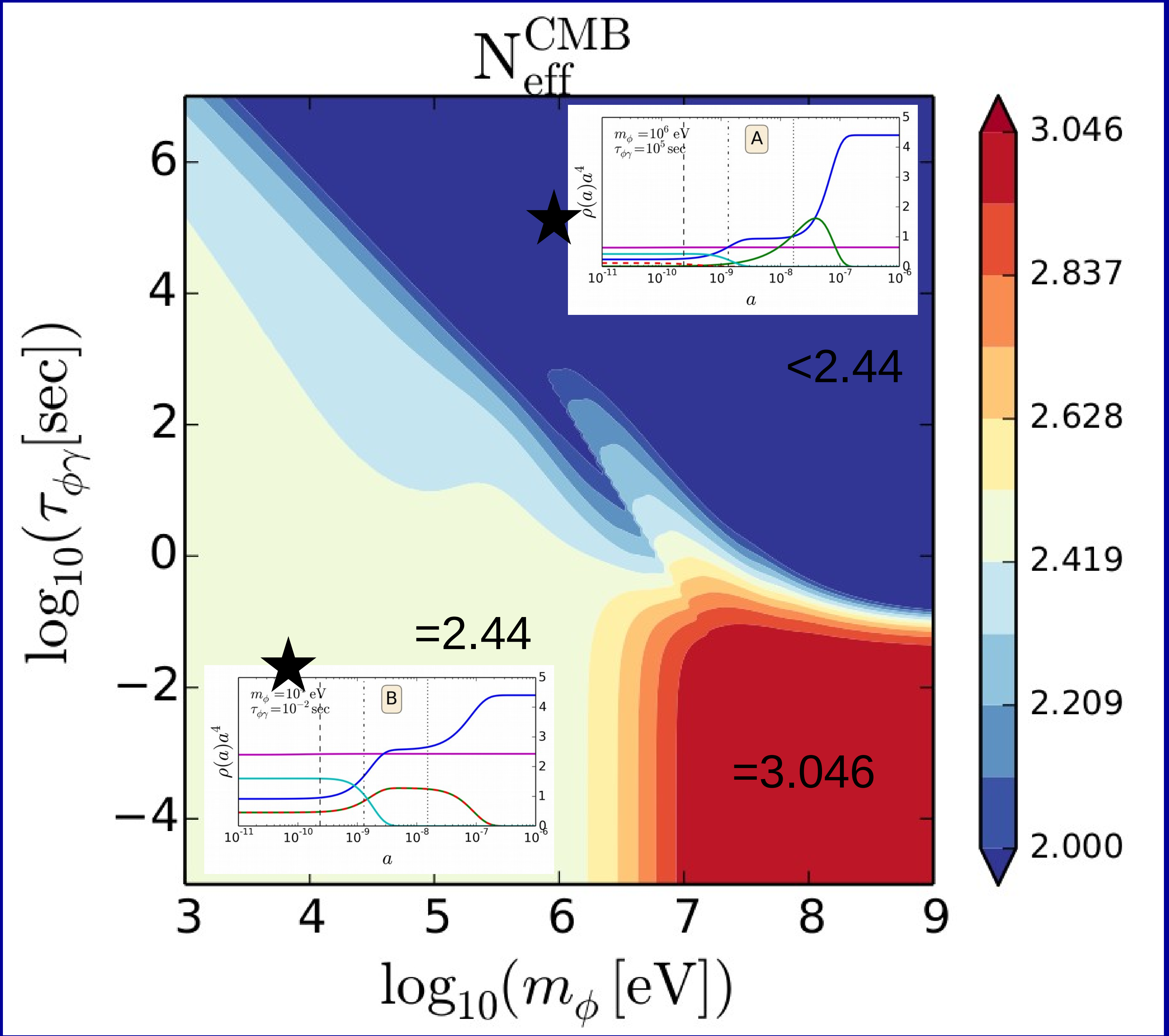


Two-photon fast

Primakoff fast

In-equilibrium decay:



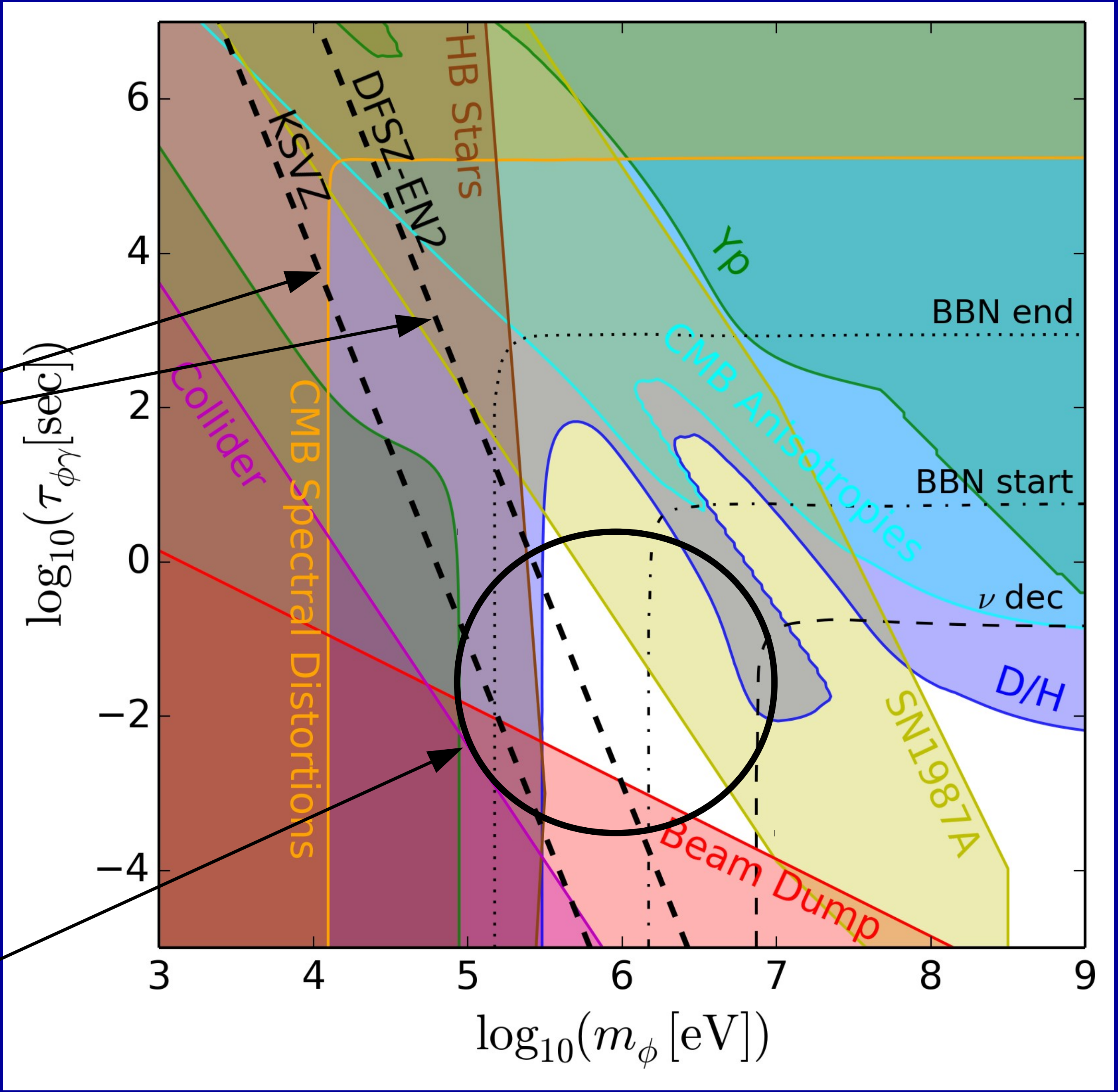


$N_{\rm eff}^{\rm CMB}$
$\log_{10}(\tau_{\phi\gamma}[\rm sec])$
$\log_{10}(m_\phi\,[\rm eV])$
<2.44
=2.44
=3.046
3.046
2.837
2.628
2.419
2.209
2.000
$m_\phi = 10^6$ eV
$\tau_{\phi\gamma} = 10^5$ sec
A
$\rho(a)a^4$
a
B
$\tau_{\phi\gamma} = 10^{-2}$ sec

Previous cosmological constraints from Cadamuro & Redondo (2012) + collider + beam dump

Two axion models

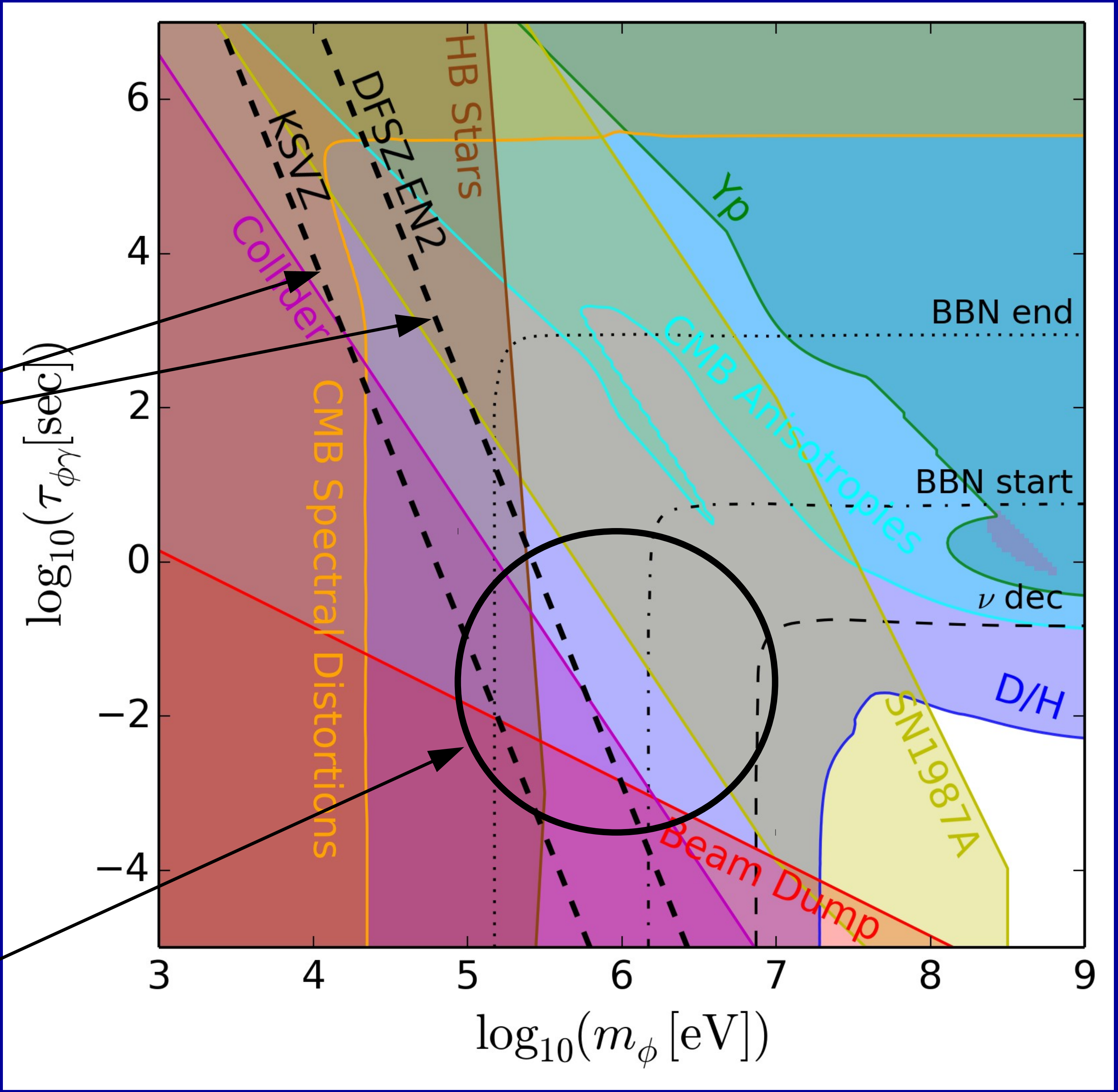
"MeV-ALP window"



Updates:

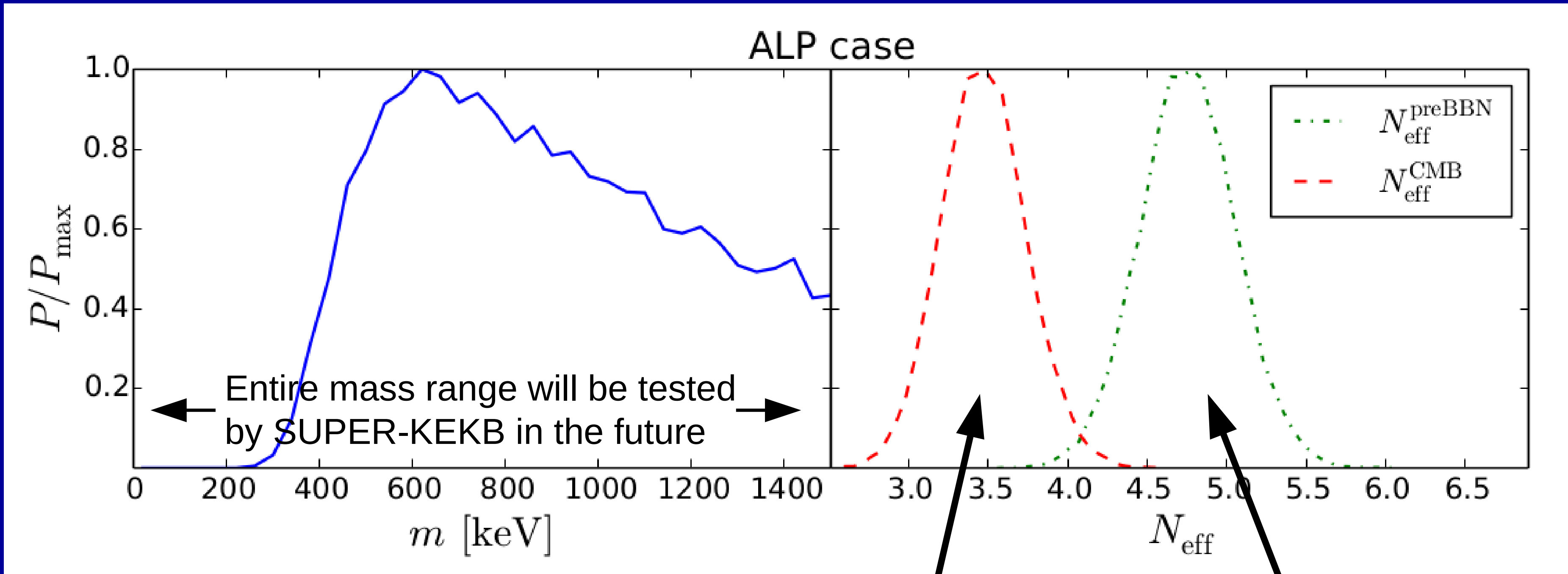
- Planck 2013
- Cooke et al. 2014 D/H
- Aver et al. 2013 Yp
- KEKB collider
- More accurate spectral distorition calculation

Two axion models



“MeV-ALP window”
No more...

Unless...

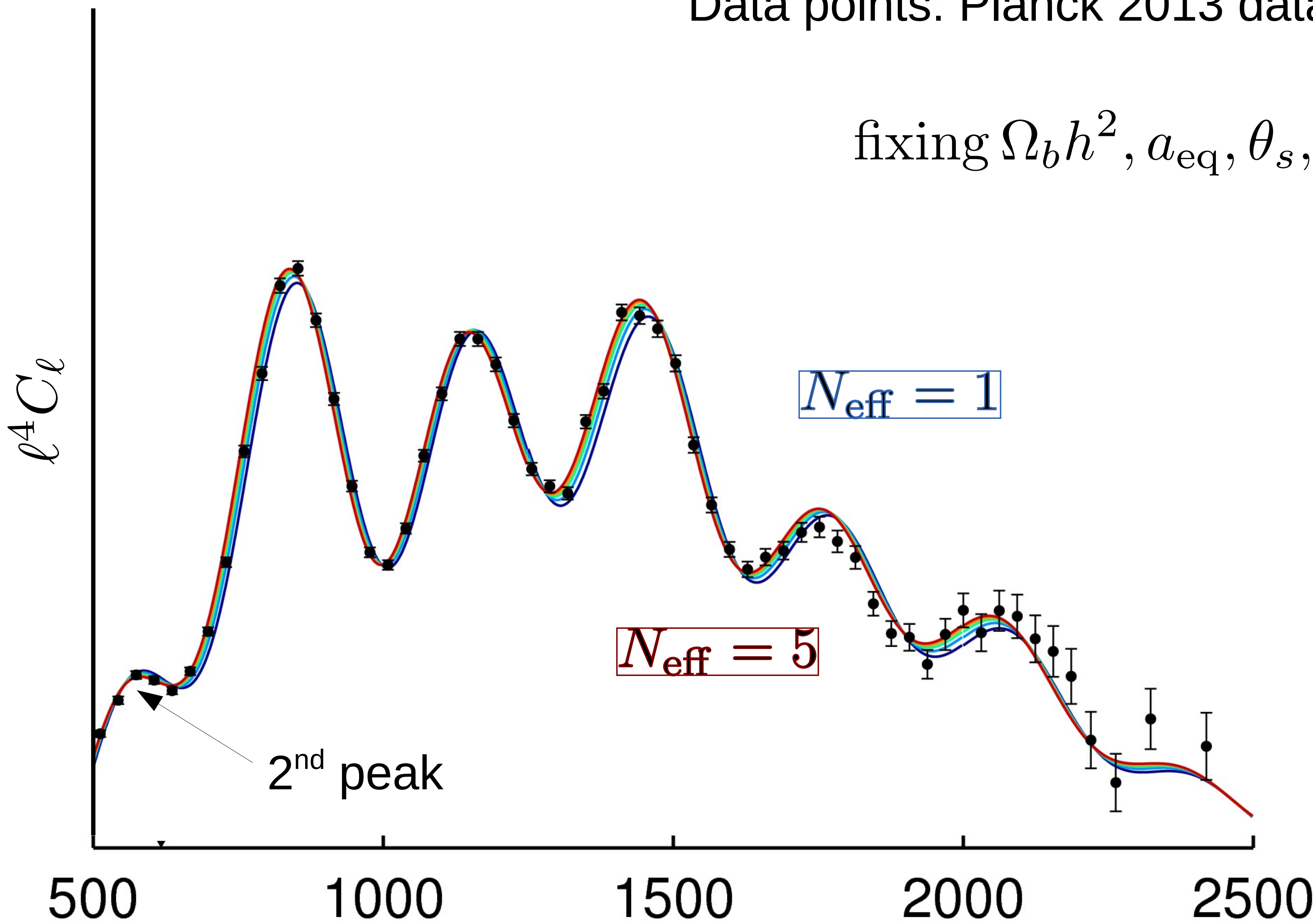


Can have 4 or 5 neutrino-like species initially

Diluted down to ~3 by CMB epoch

Slide: Zhen Hou

Data points: Planck 2013 data



Slide: Zhen Hou

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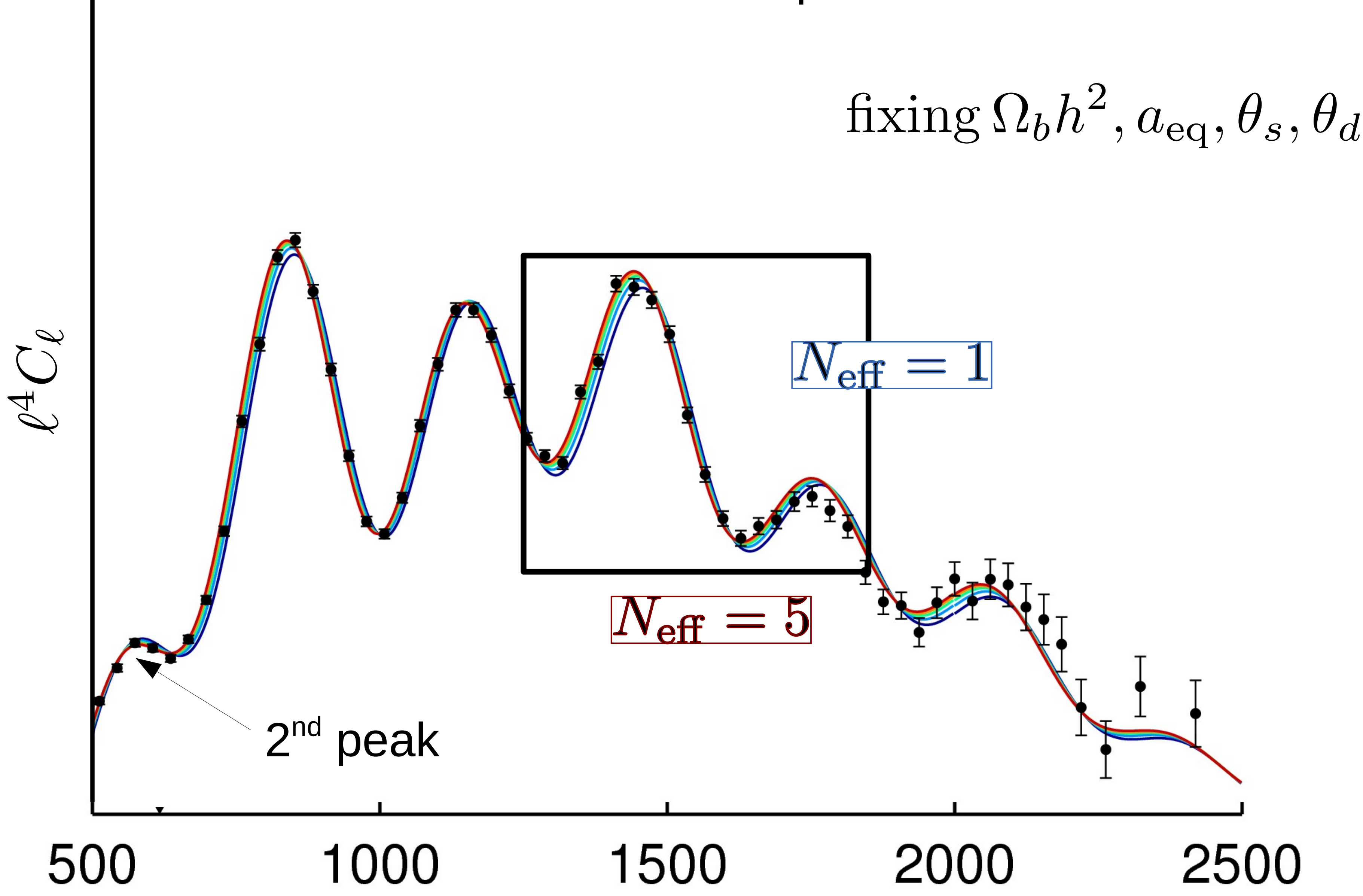
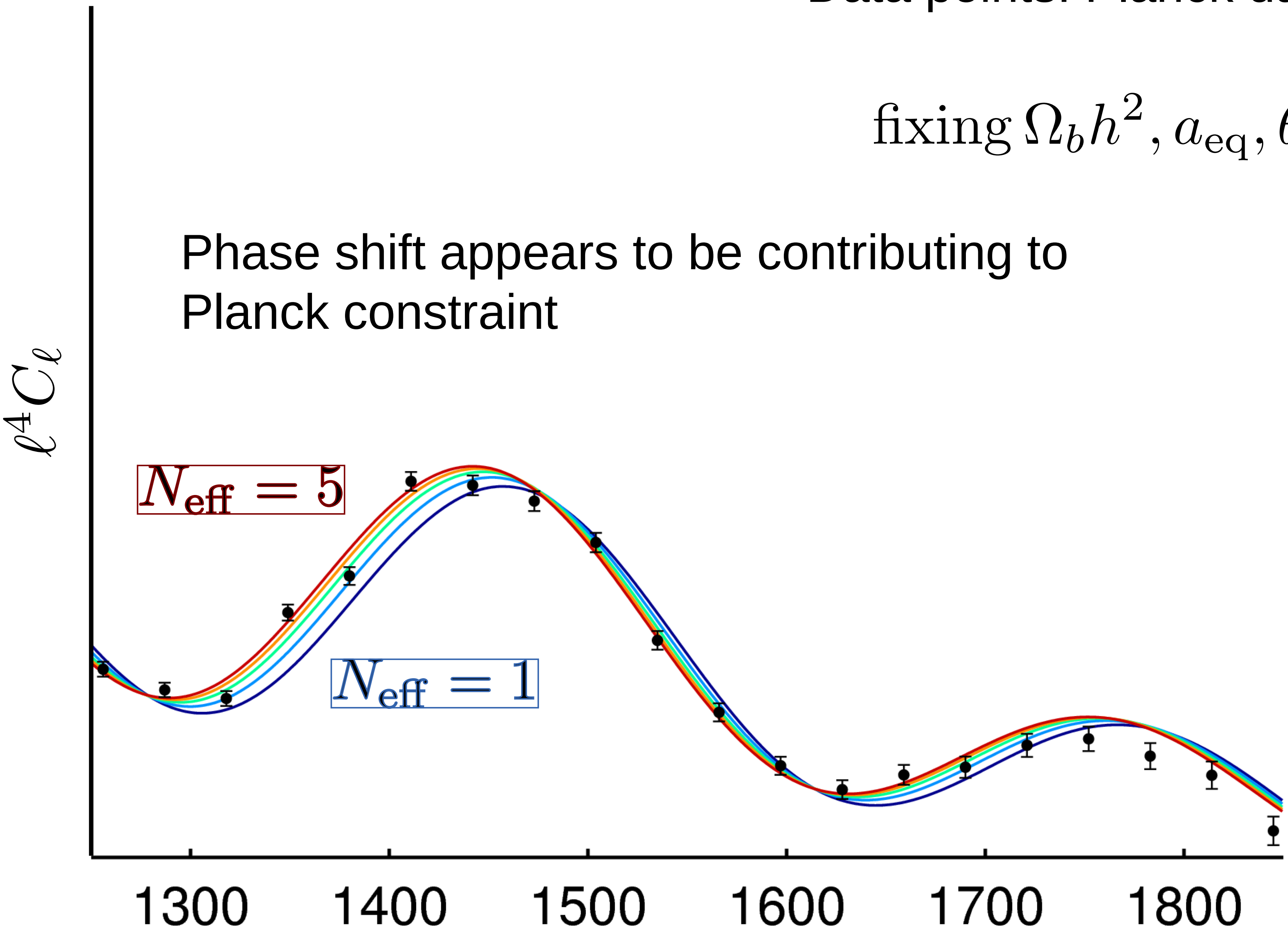


Slide: Zhen Hou

Data points: Planck data

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

Phase shift appears to be contributing to Planck constraint



(Follin, Knox, Millea, and Pan 2014, in prep)

Gravitational potentials

$$\ddot{\tilde{\delta}} + k^2 c_s^2 \tilde{\delta} = F(\Phi, \Psi)$$

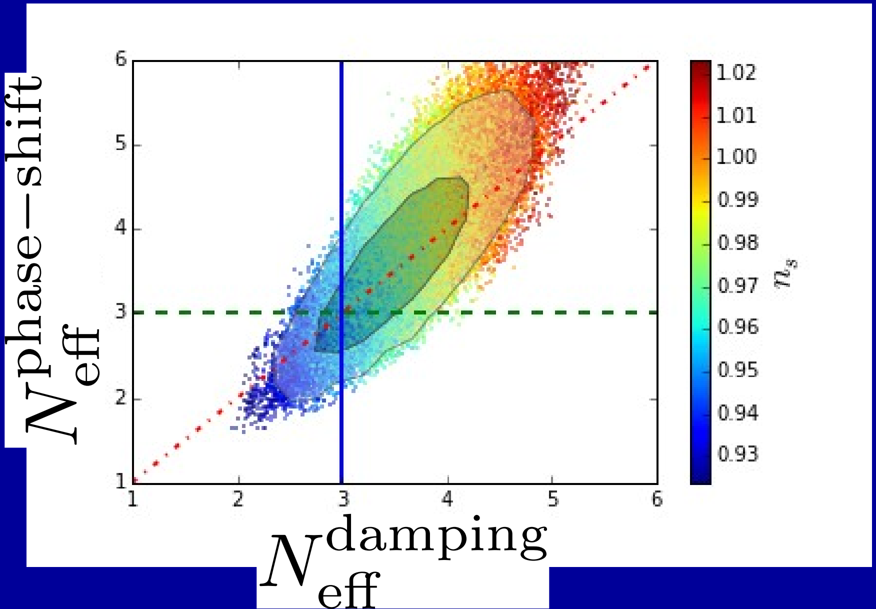
Neutrinos → potentials → photons

- Neutrino perturbations propagate at a different speed, which cause a phase shift in the acoustic oscillations.

$$C_\ell \to C_{\ell+\delta\ell}$$

$$\delta\ell = A(N_{\rm eff}, N_{\rm eff}^{\rm fid}) f_\ell$$

For the first time, we directly measure this phase shift:



(A similar test of neutrino perturbations as constraints on c_{vis} and c_{eff})

Outline

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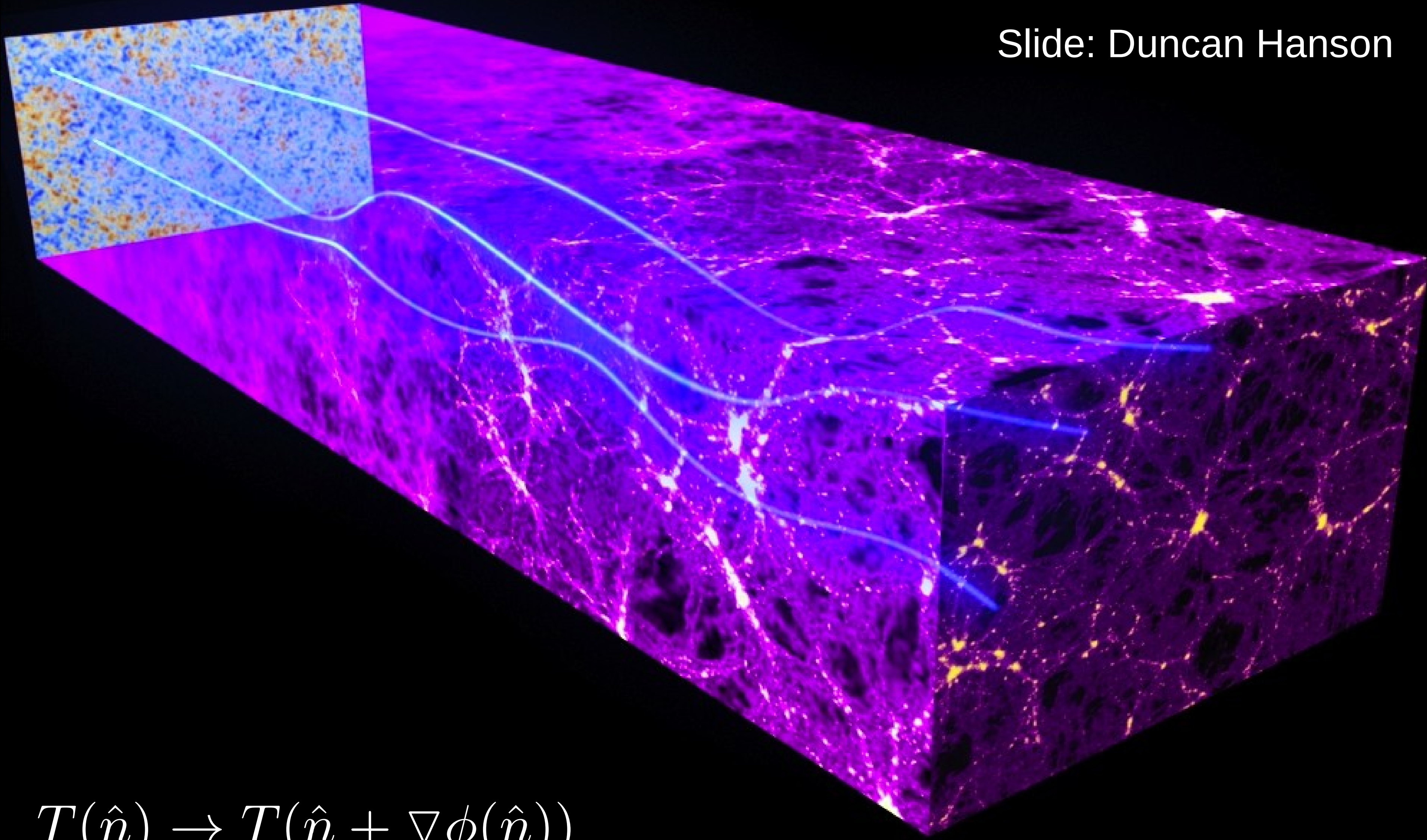
Slide: Duncan Hanson

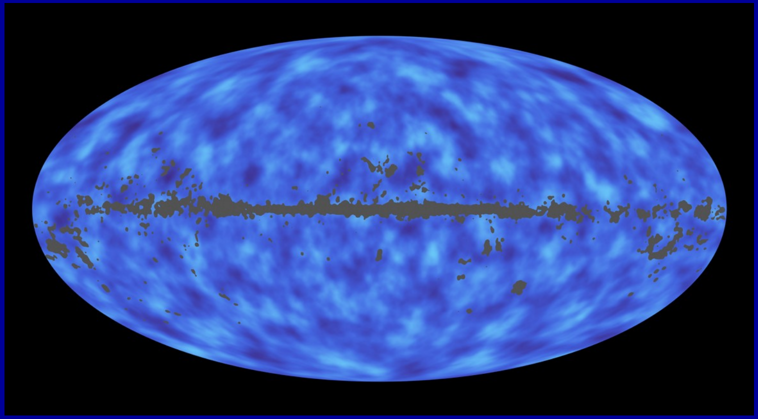


$$T(\hat{n}) \to T(\hat{n} + \nabla\phi(\hat{n}))$$

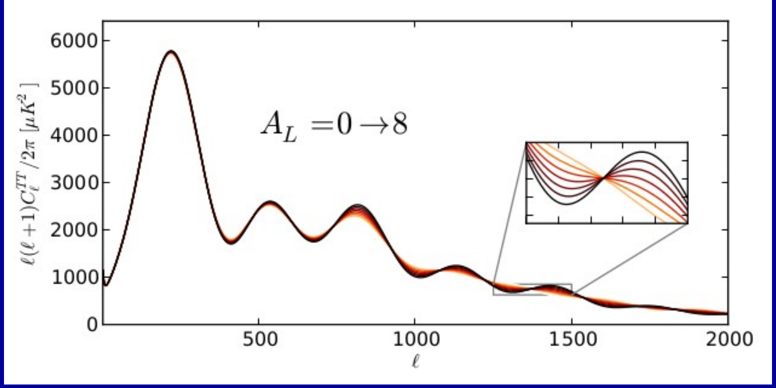
$$\phi(\hat{n}) = -2\int_0^{\chi_*} d\chi \frac{f_K(\chi_* - \chi)}{f_K(\chi_*) f_K(\chi)} \Psi(\chi\hat{n}; \eta_0 - \chi)$$

Two ways to analyze lensing with Planck

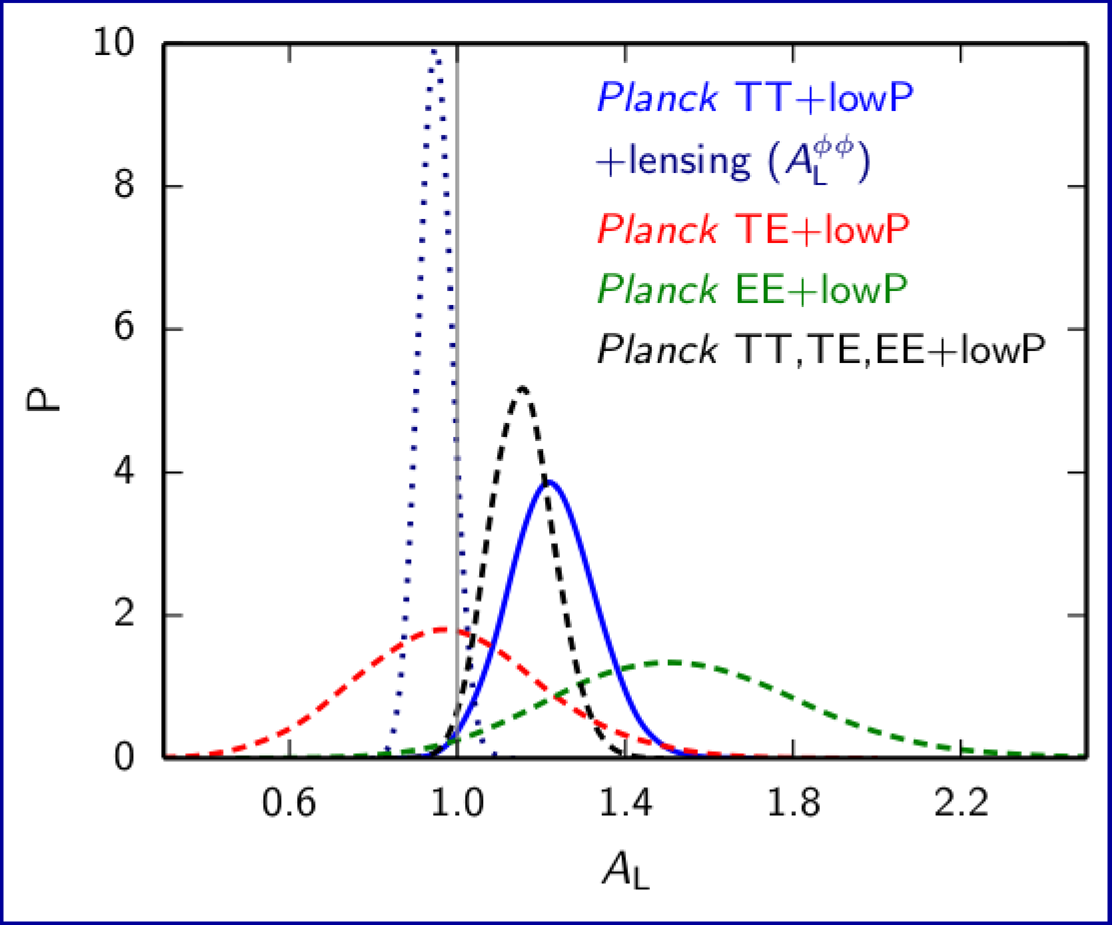
- Beginning with the Planck 2013 results, we inferred neutrino mass dominantly through their effect on lensing



Lensing potential reconstruction

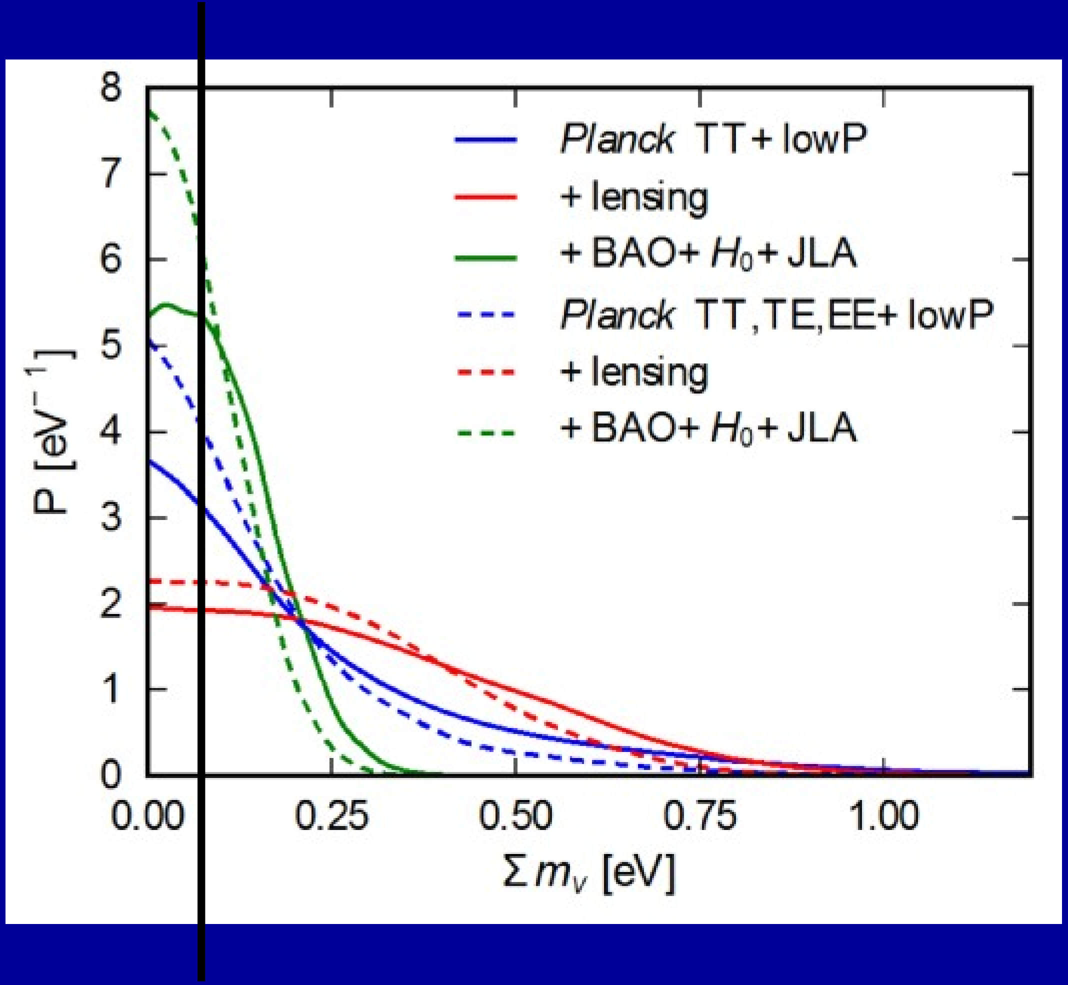


The smoothness of the temperature power spectrum



Tension persists in 2014 between the amount of lensing measured the two.

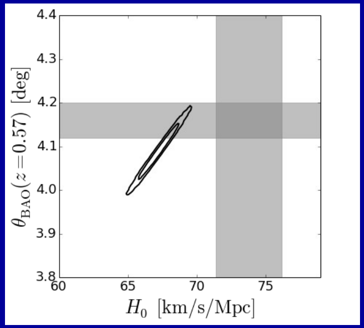
Minimum from neutrino oscillations



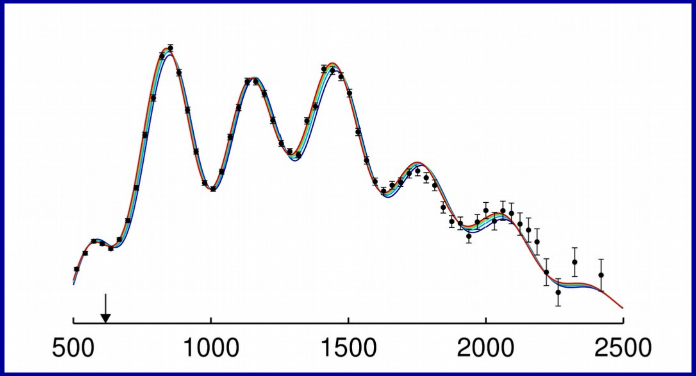
This manifests as a loosening of neutrino mass constraints upon addition of lensing reconstruction data.

Conclusion

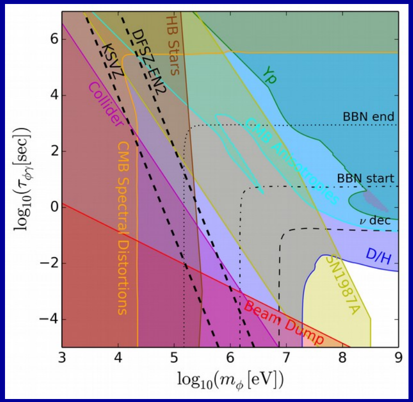
LCDM survives Planck 2014. Some hints of extensions in combination with other probes.



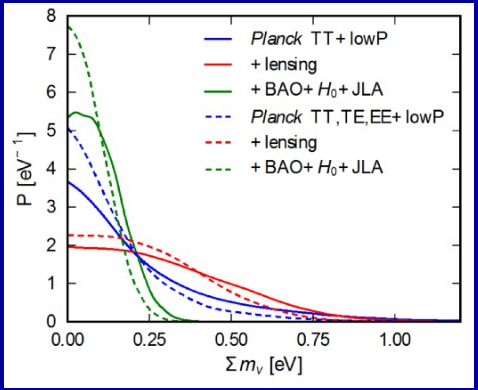
Neutrino number constraints from damping and phase shifts.



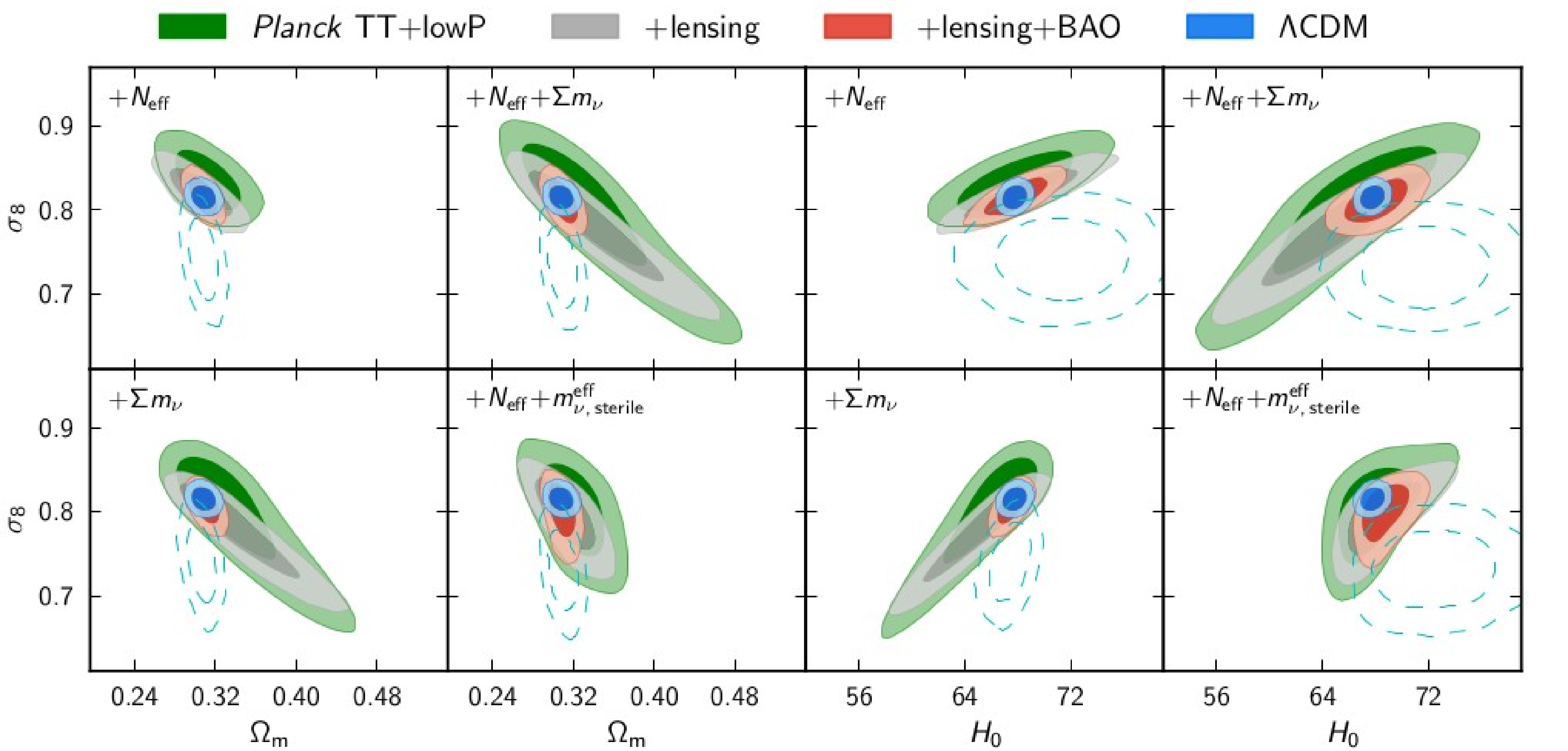
MeV axion ruled out, or maybe plays a role in a more speculative scenario?



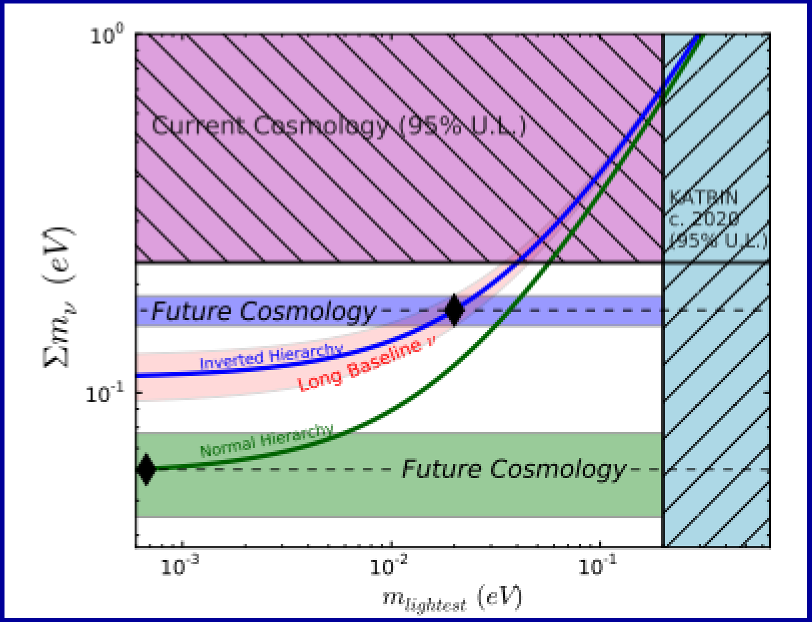
Neutrino mass constraints from lensing.

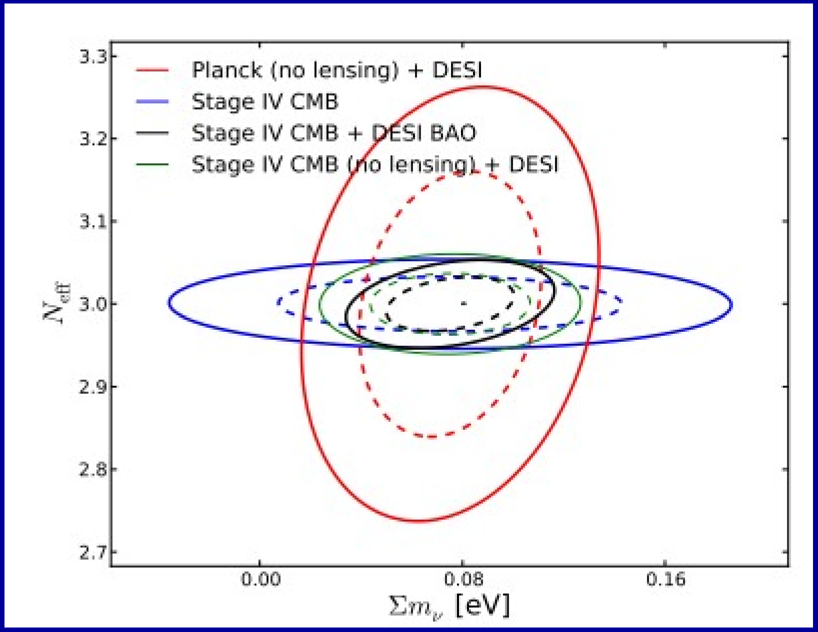


Extra slides


Planck TT+lowP
+lensing
+lensing+BAO
ΛCDM
$+N_{\rm eff}$
$+N_{\rm eff}+\Sigma m_\nu$
$+N_{\rm eff}$
$+N_{\rm eff}+\Sigma m_\nu$
$+\Sigma m_\nu$
$+N_{\rm eff}+m^{\rm eff}_{\nu,\,\rm sterile}$
$+\Sigma m_\nu$
$+N_{\rm eff}+m^{\rm eff}_{\nu,\,\rm sterile}$
σ_8
0.9
0.8
0.7
0.24
0.32
0.40
0.48
$\Omega_{\rm m}$
56
64
72
H_0

Forecast from SNOWMASS





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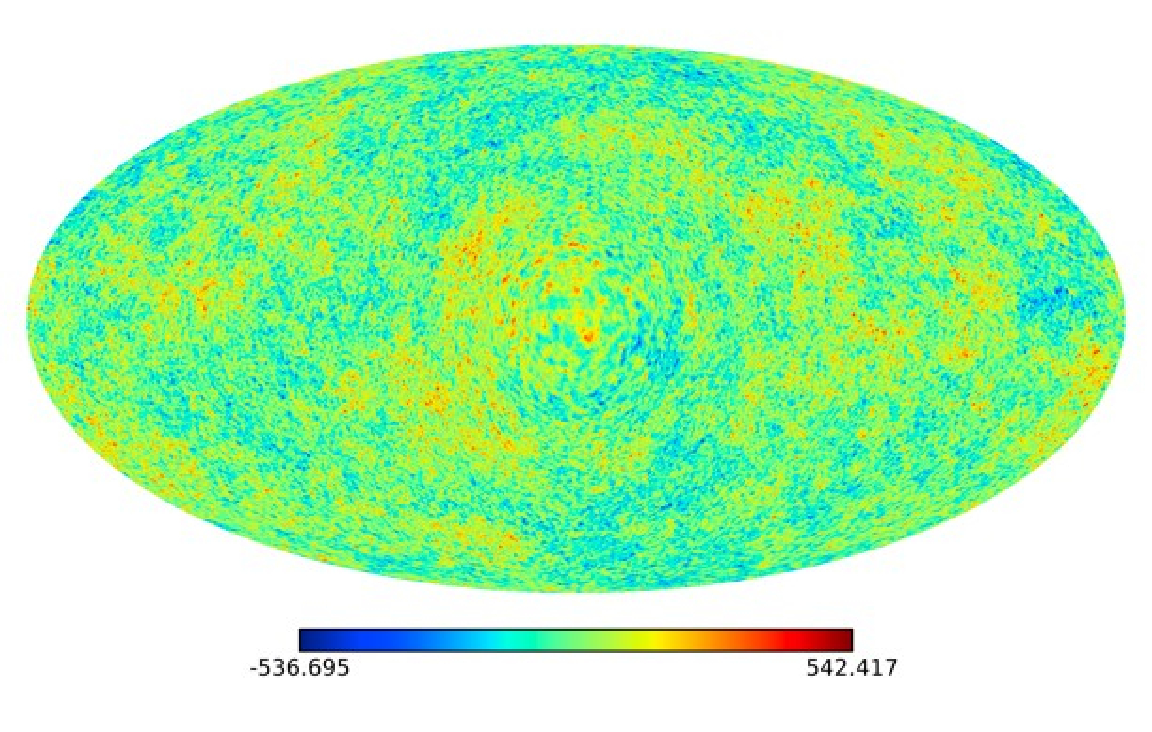
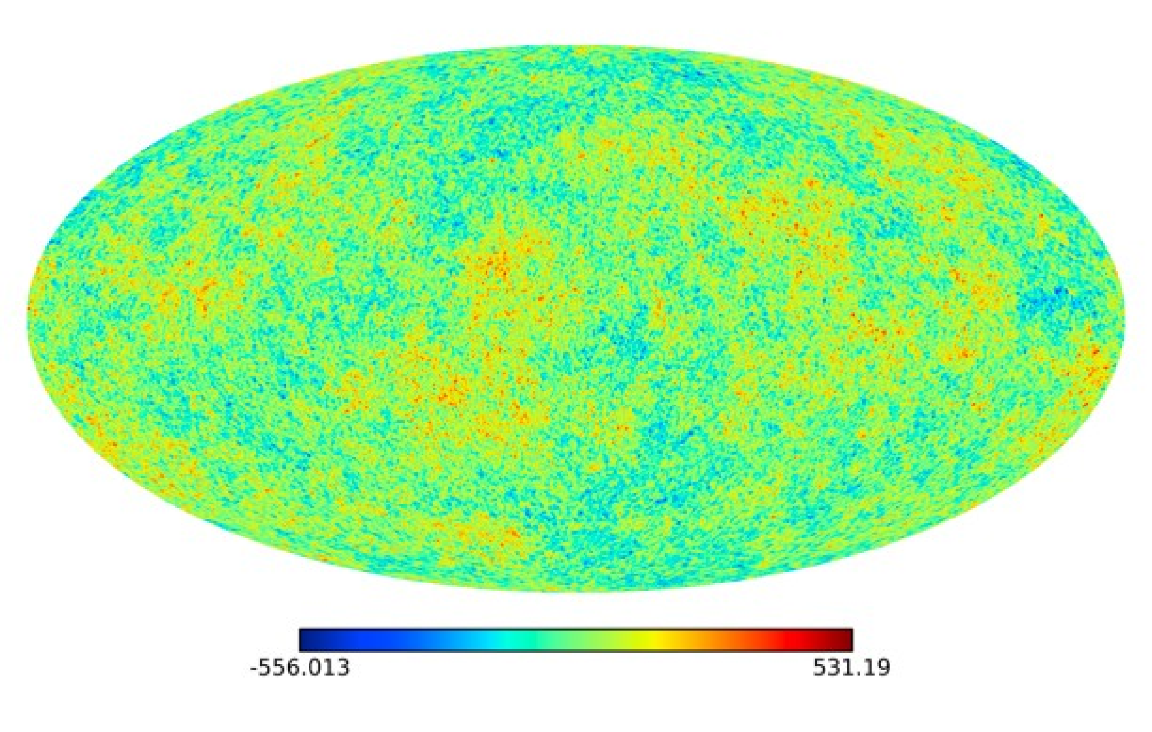
Gravitational Lensing

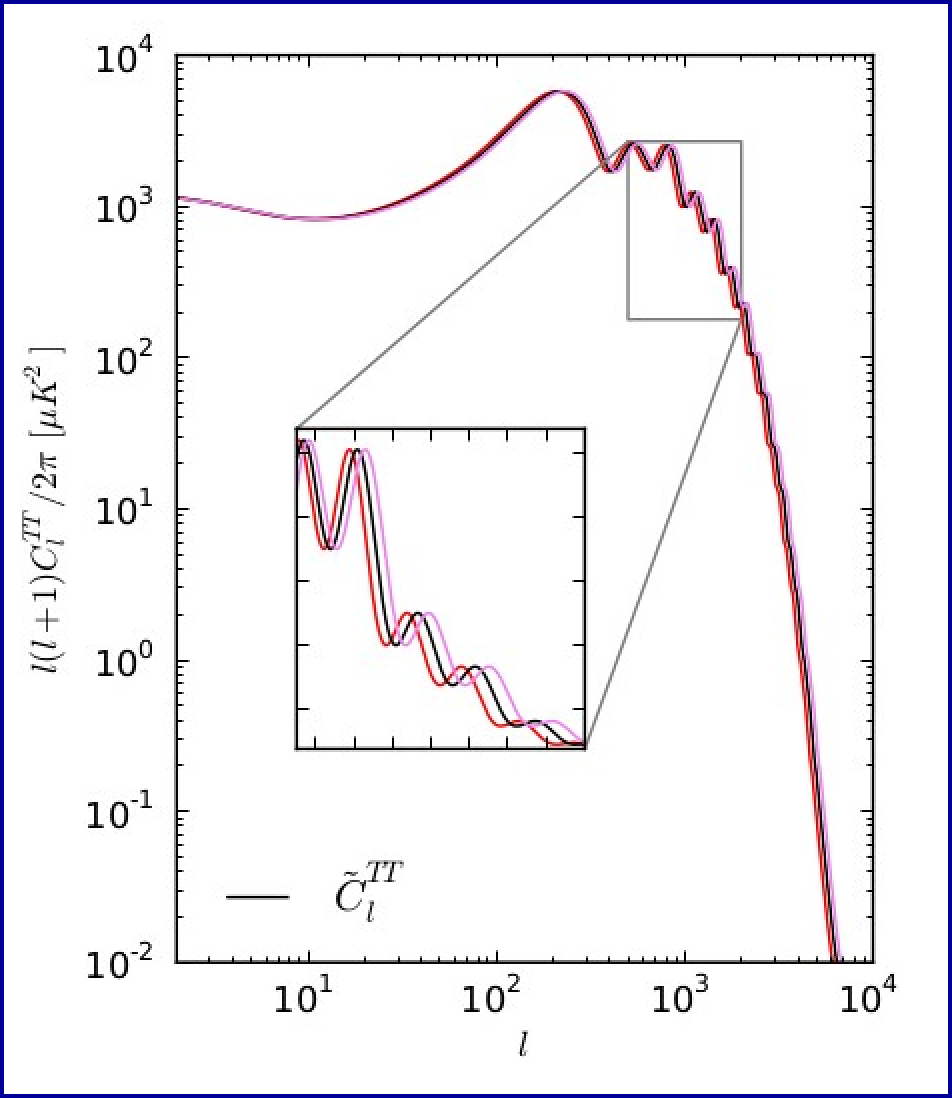


Slide: Duncan Hanson

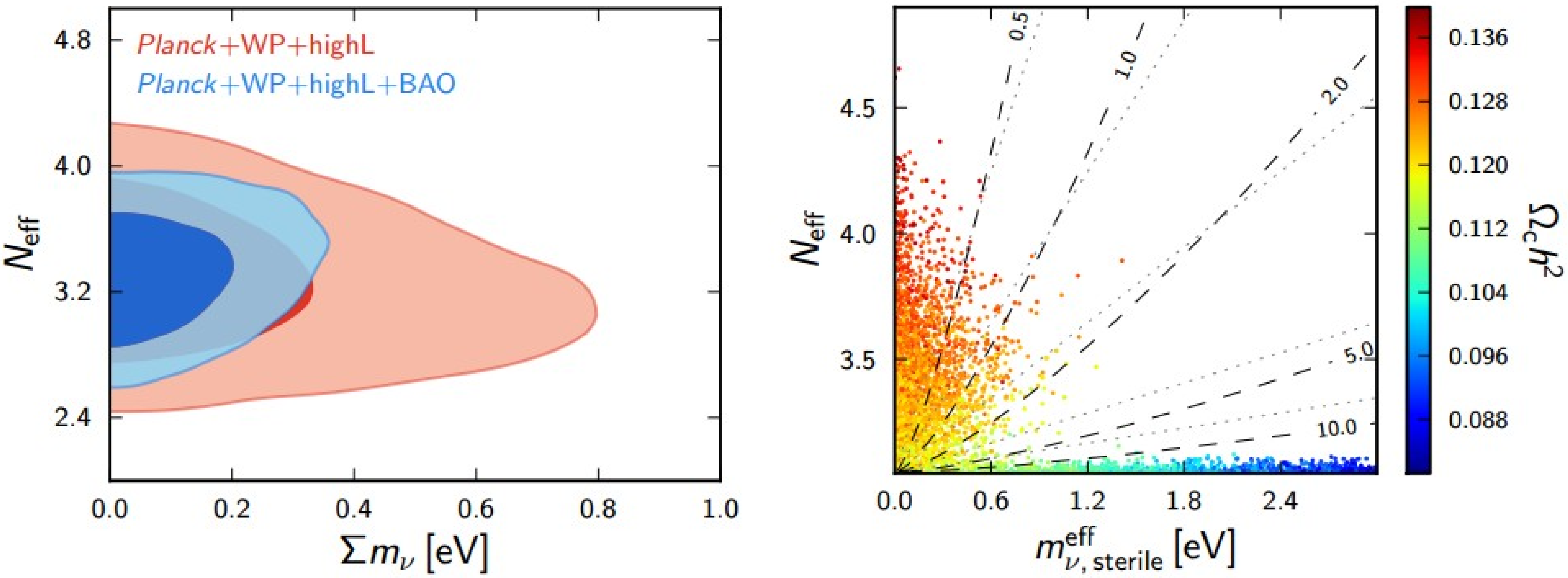
Gravitational Lensing



Slide: Duncan Hanson

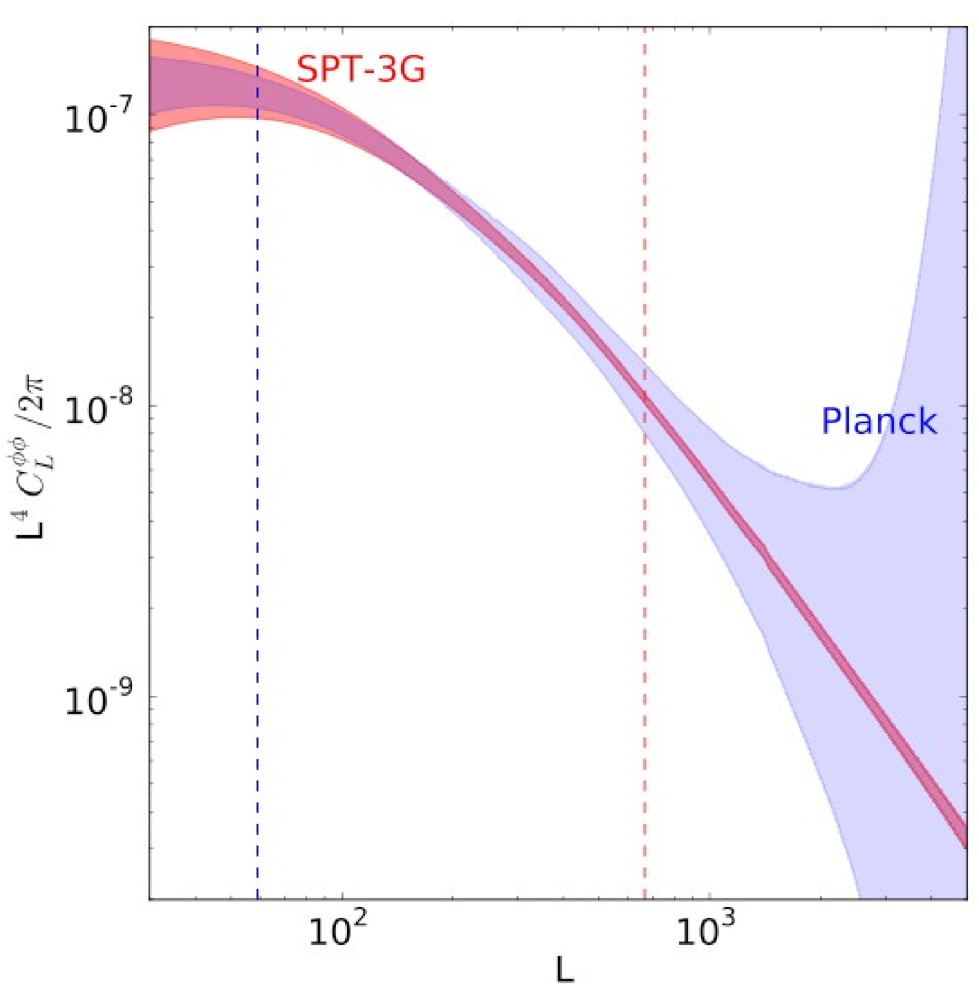


Neff and mnu



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
$m^{\mathrm{eff}}_{\nu,\,\mathrm{sterile}}$ [eV]
0.136
0.128
0.120
0.112
0.104
0.096
0.088
$\Omega_c h^2$

CMB Polarization and Lensing Reconstruction

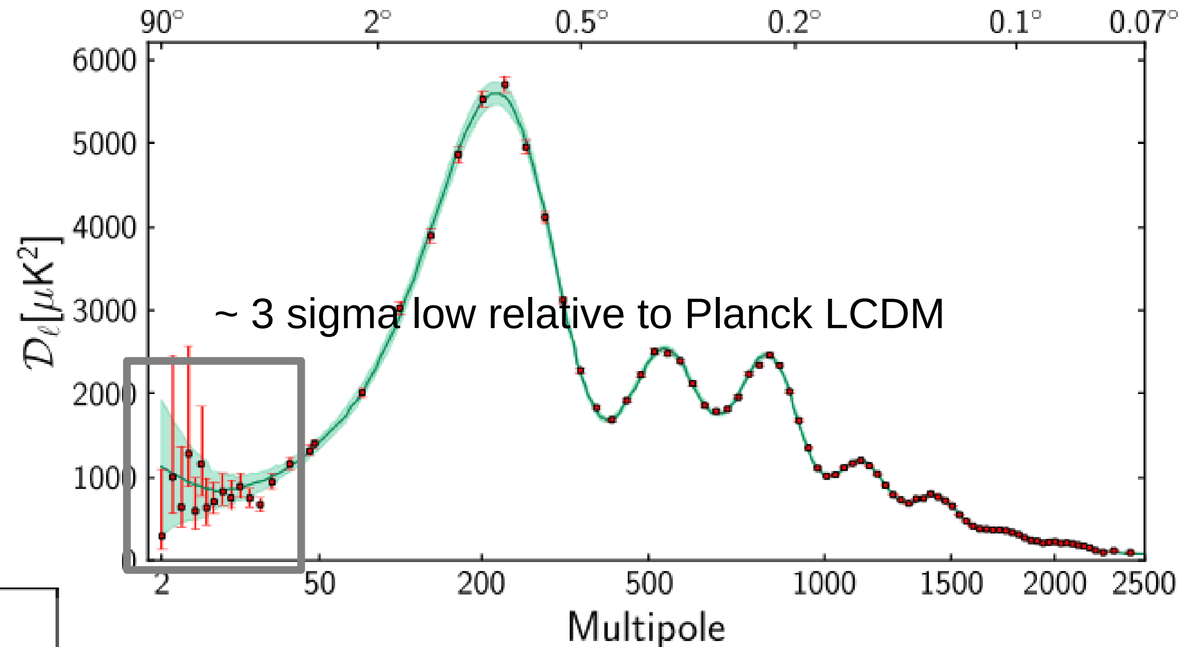


SPT-3G: A proposed 2500 sq. deg. Survey with a 3rd-generation polarization-sensitive focal plane.

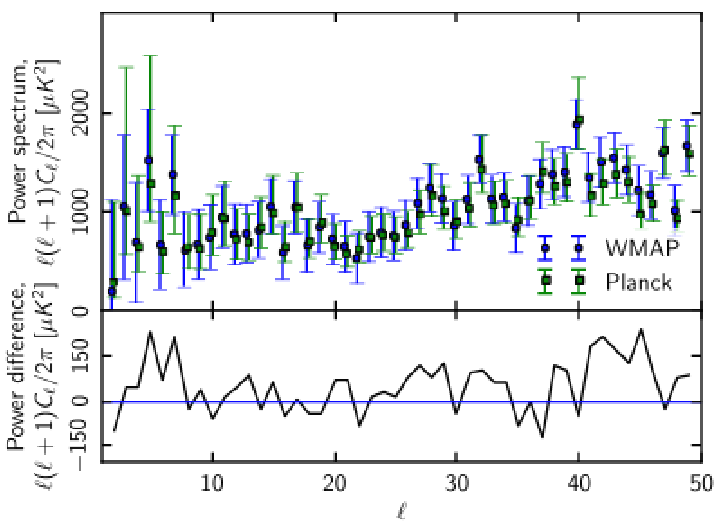
Enabling a deflection angle power spectrum measurement as forecasted here and

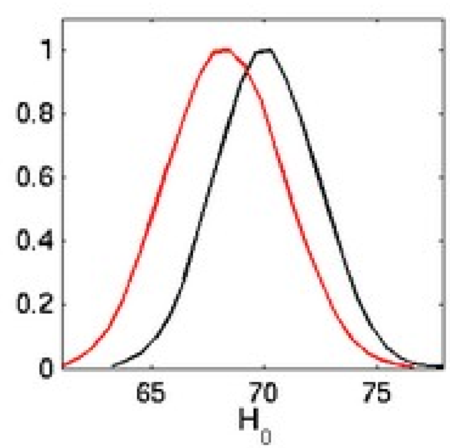
$\sigma(\Sigma m_\nu) = 0.06$ eV

A curiosity: Low-L tension with LCDM



Planck and WMAP in the
2<L<50 region

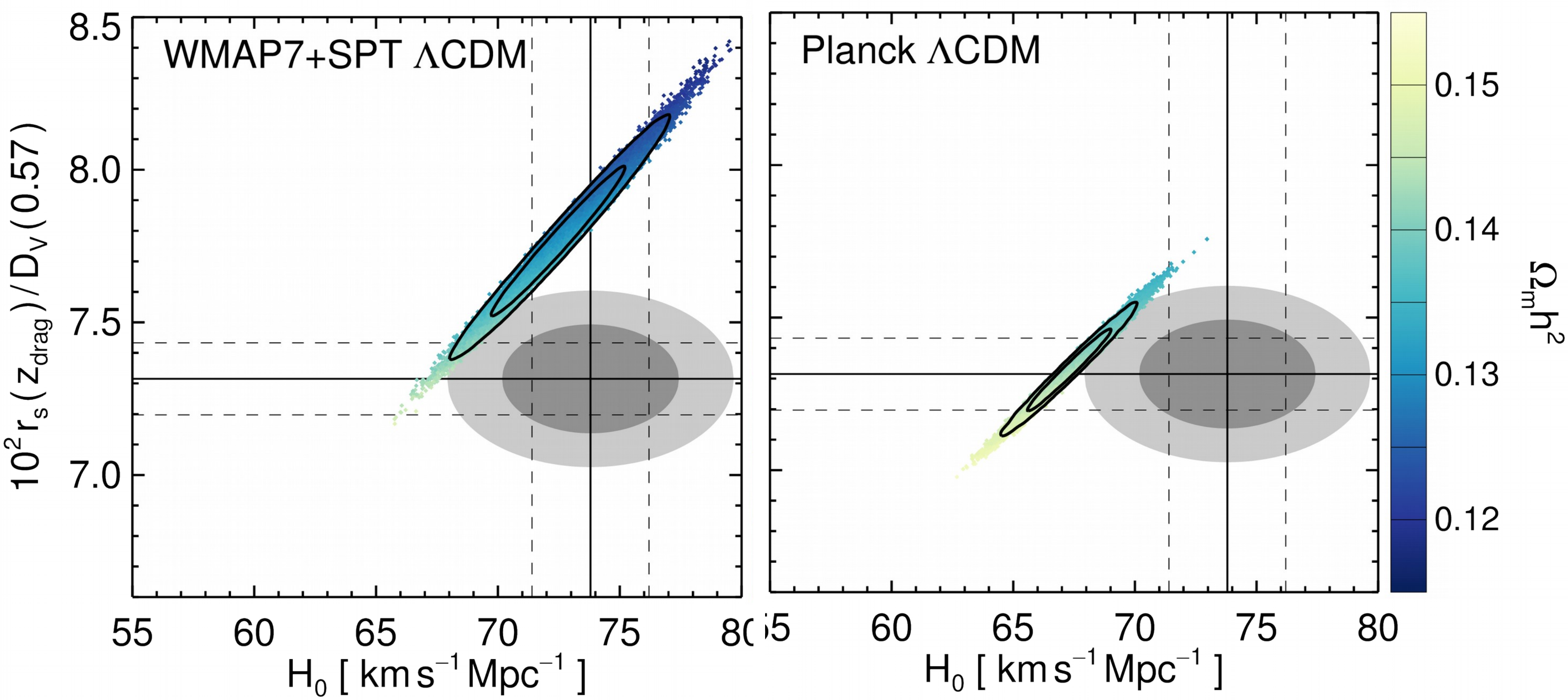


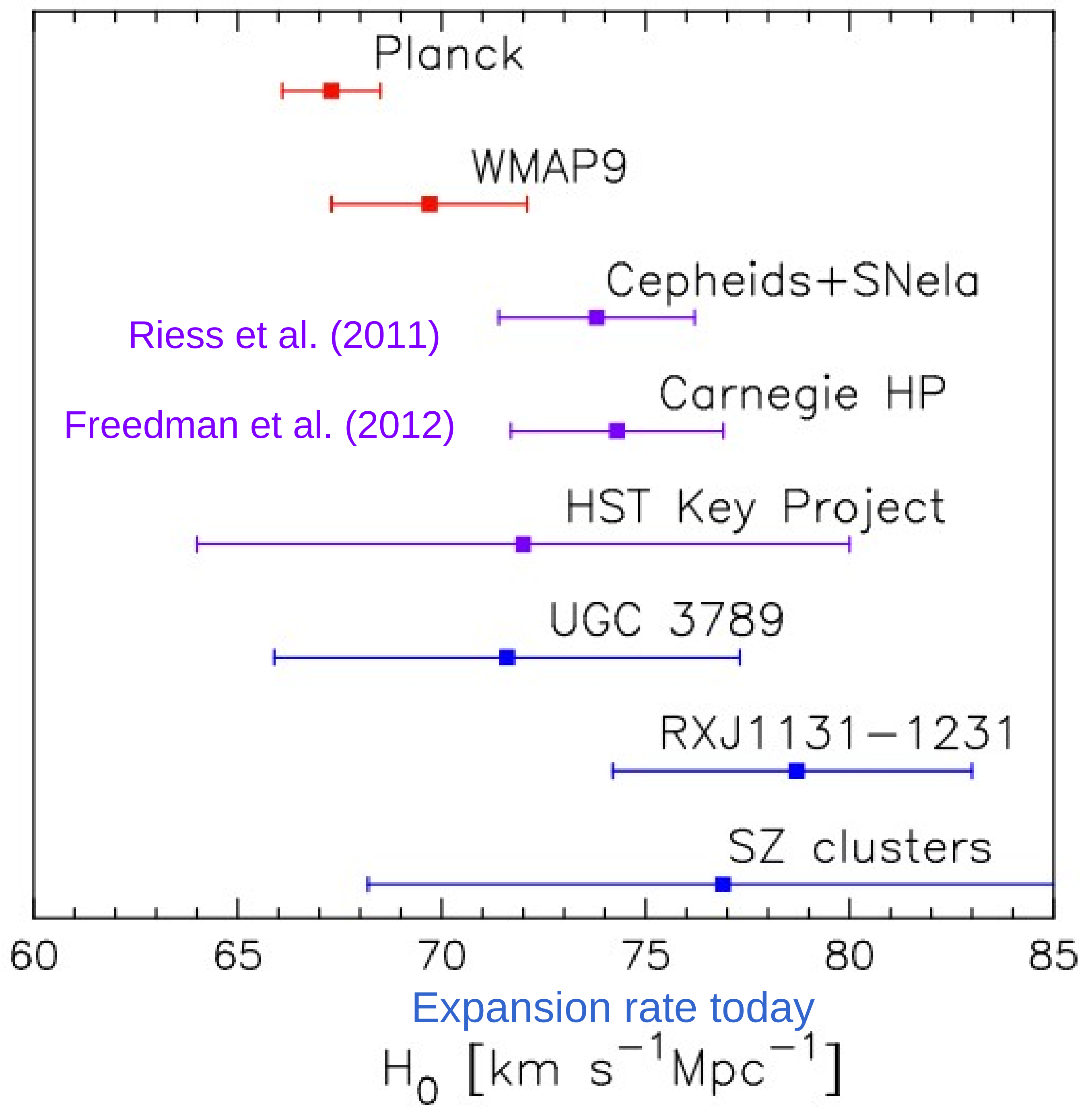


WMAP
WMAP+(no L<30 TT)

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

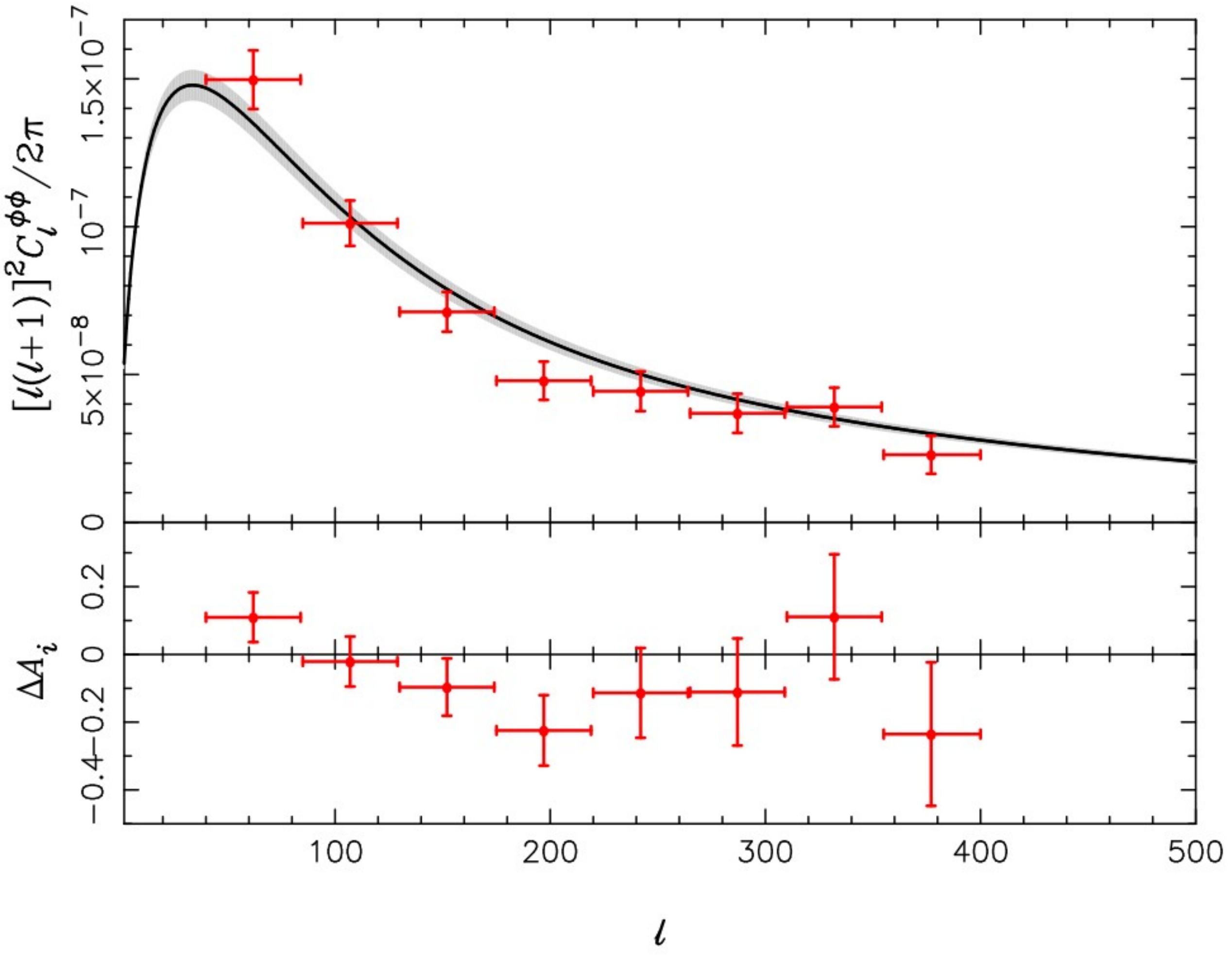
- Planck is in excellent agreement with BAO measurement, discrepant with Riess et al. H_0

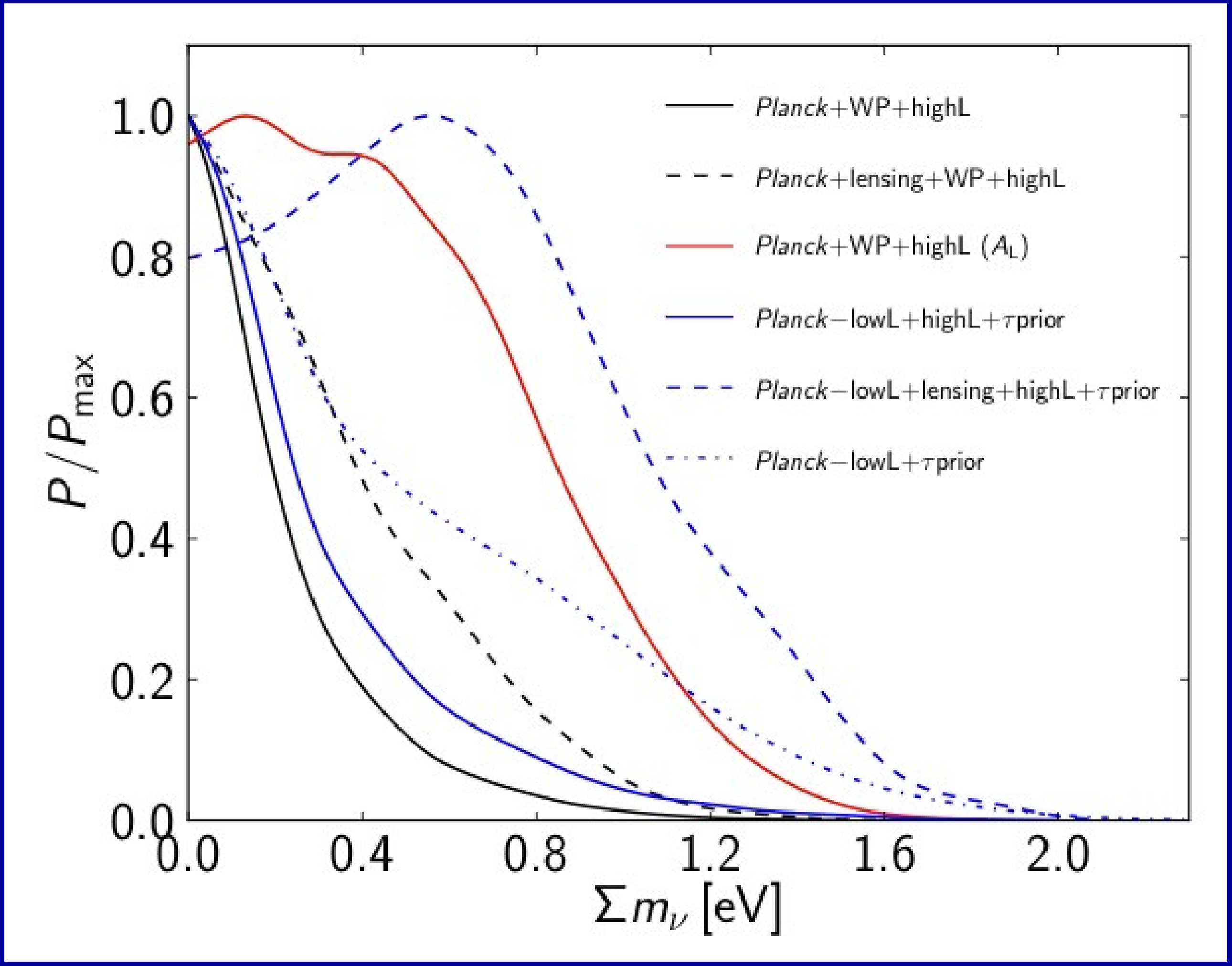




Planck
WMAP9
Cepheids+SNeIa
Riess et al. (2011)
Carnegie HP
Freedman et al. (2012)
HST Key Project
UGC 3789
RXJ1131−1231
SZ clusters
60
65
70
75
80
85
Expansion rate today
H0 [km s−1Mpc−1]

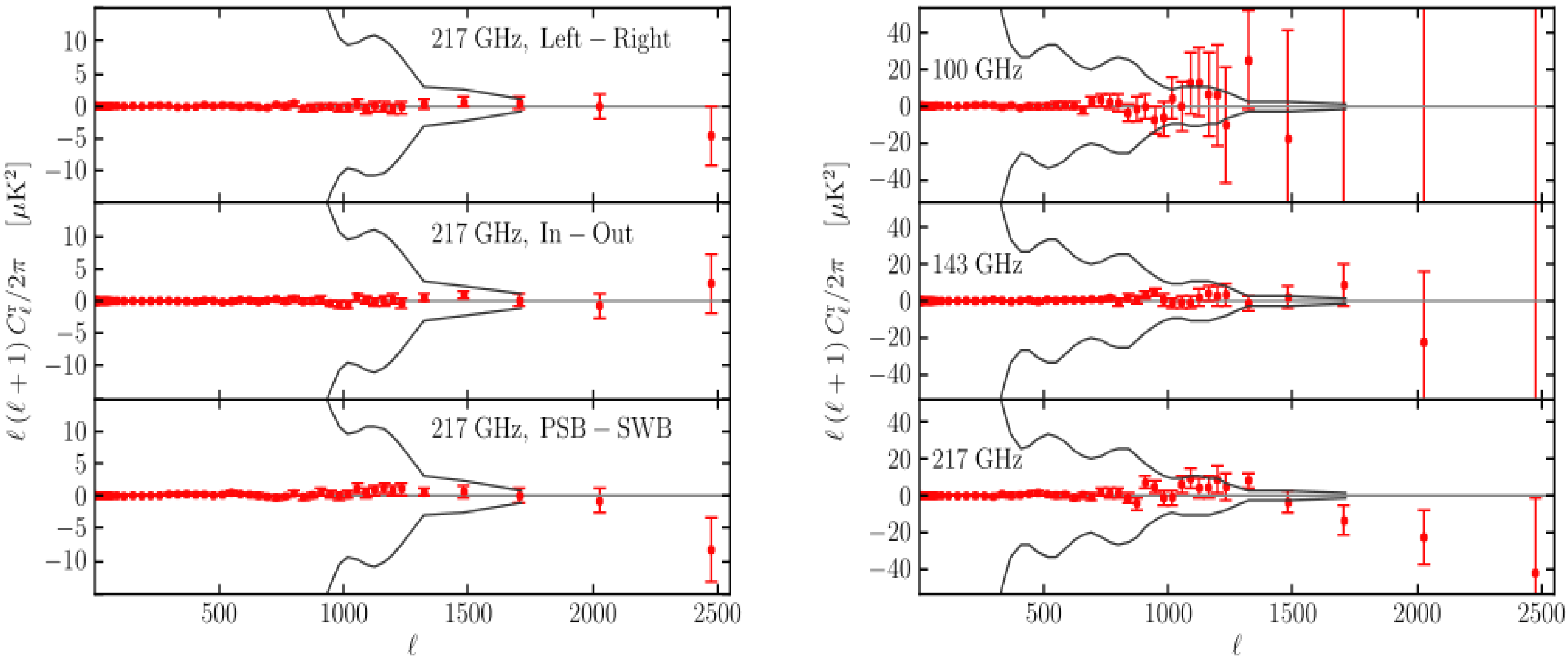
The deflection angle power spectrum





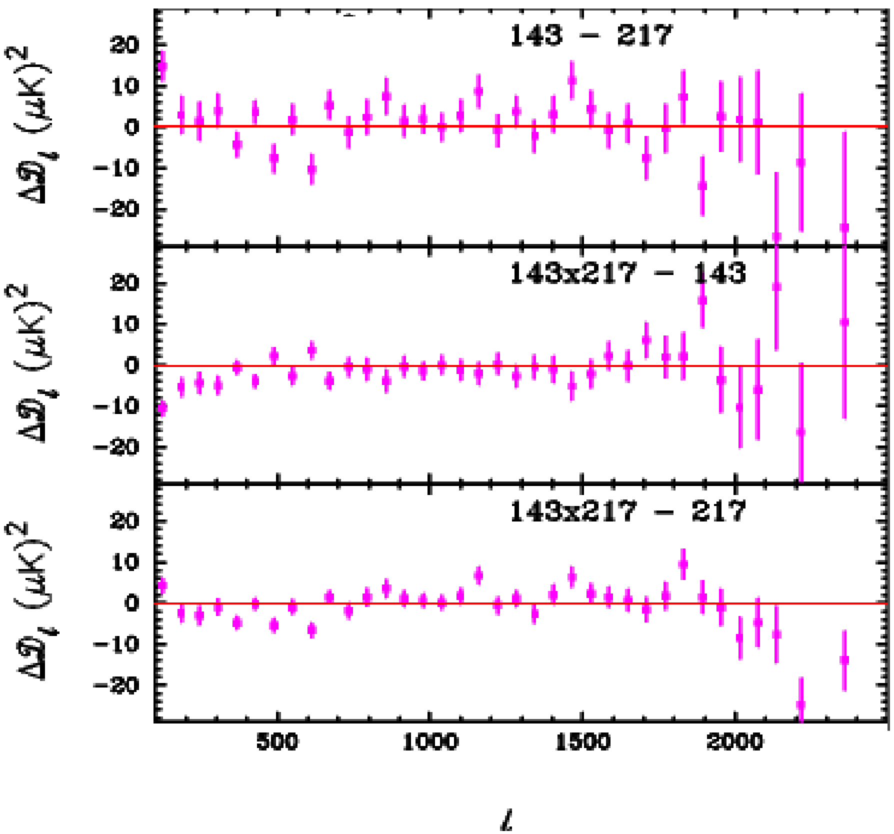
Planck+WP+highL
Planck+lensing+WP+highL
Planck+WP+highL (A_L)
Planck−lowL+highL+τprior
Planck−lowL+lensing+highL+τprior
Planck−lowL+τprior
P/P_{max}
Σm_ν [eV]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.4
0.8
1.2
1.6
2.0

Consistency Tests Within Same Frequency

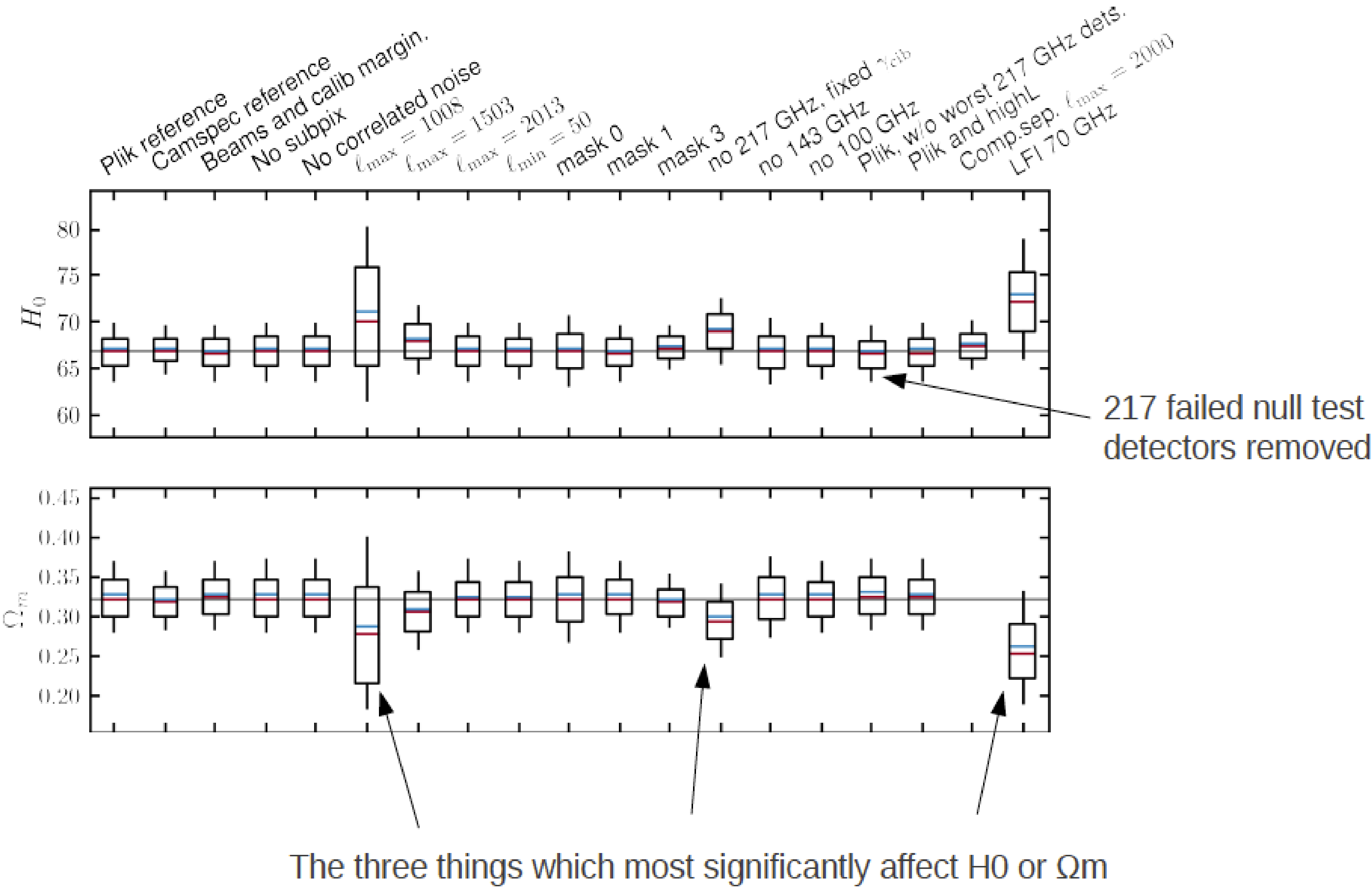


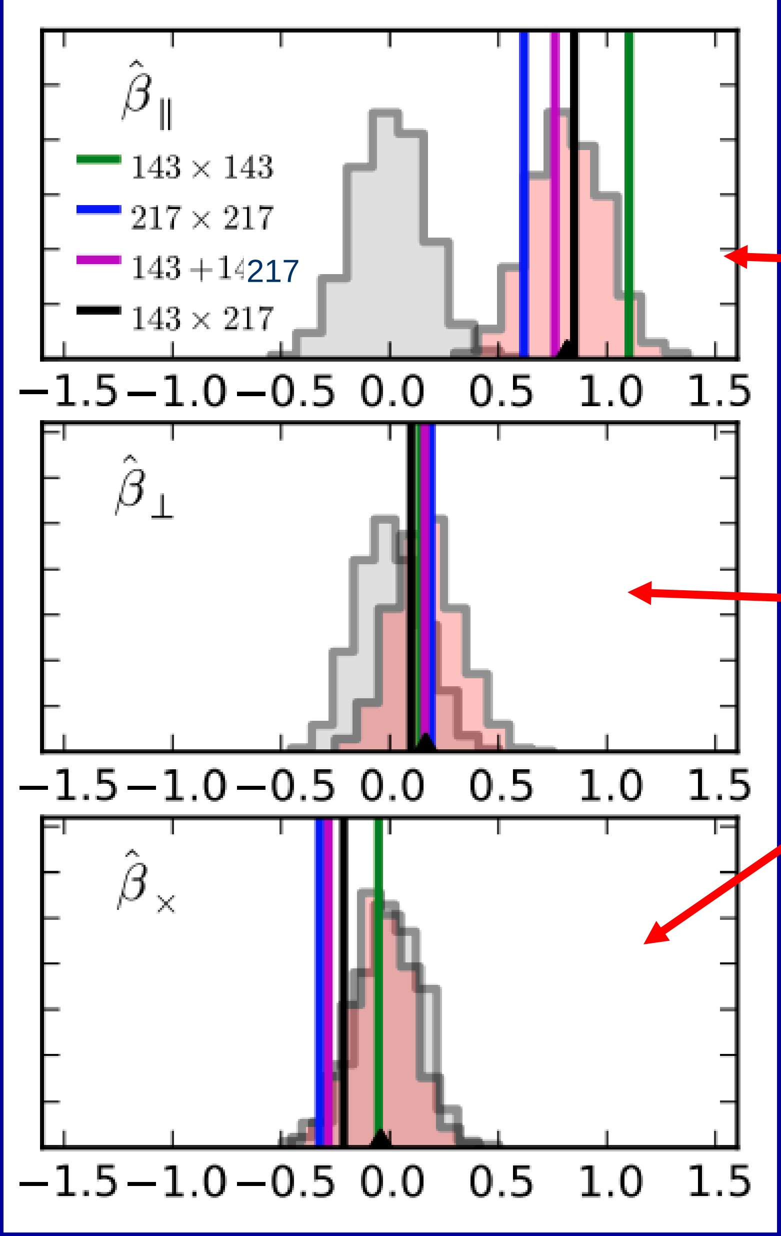
Consistency Tests Between Different Frequencies

- 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





β/β^{dipole}

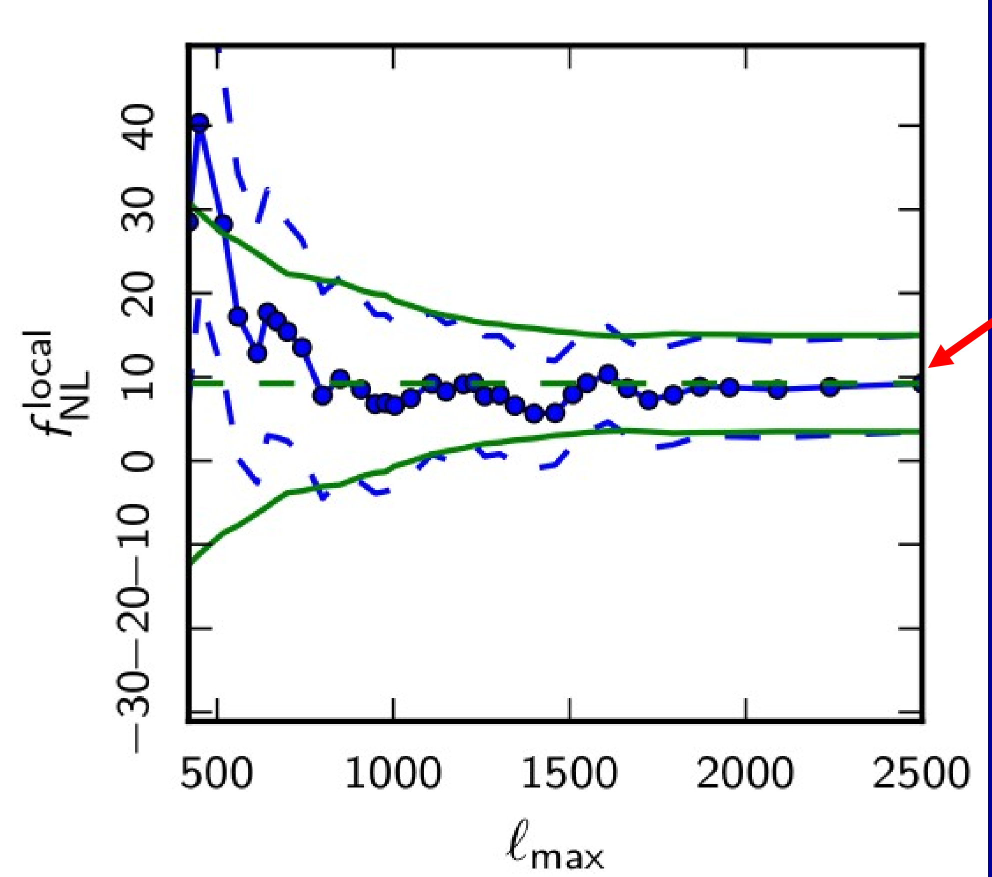
Component along dipole direction

Components along two directions perpendicular to the dipole direction

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



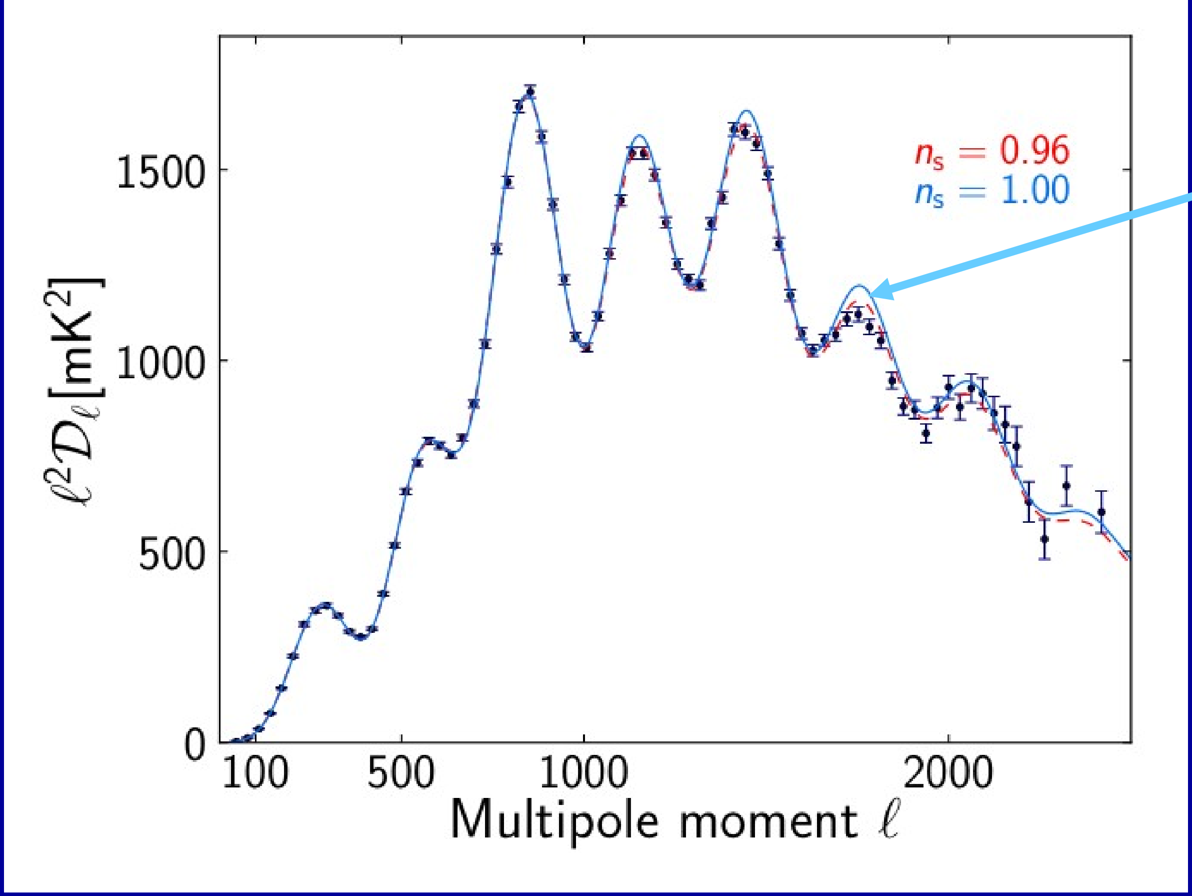
Non-zero!

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

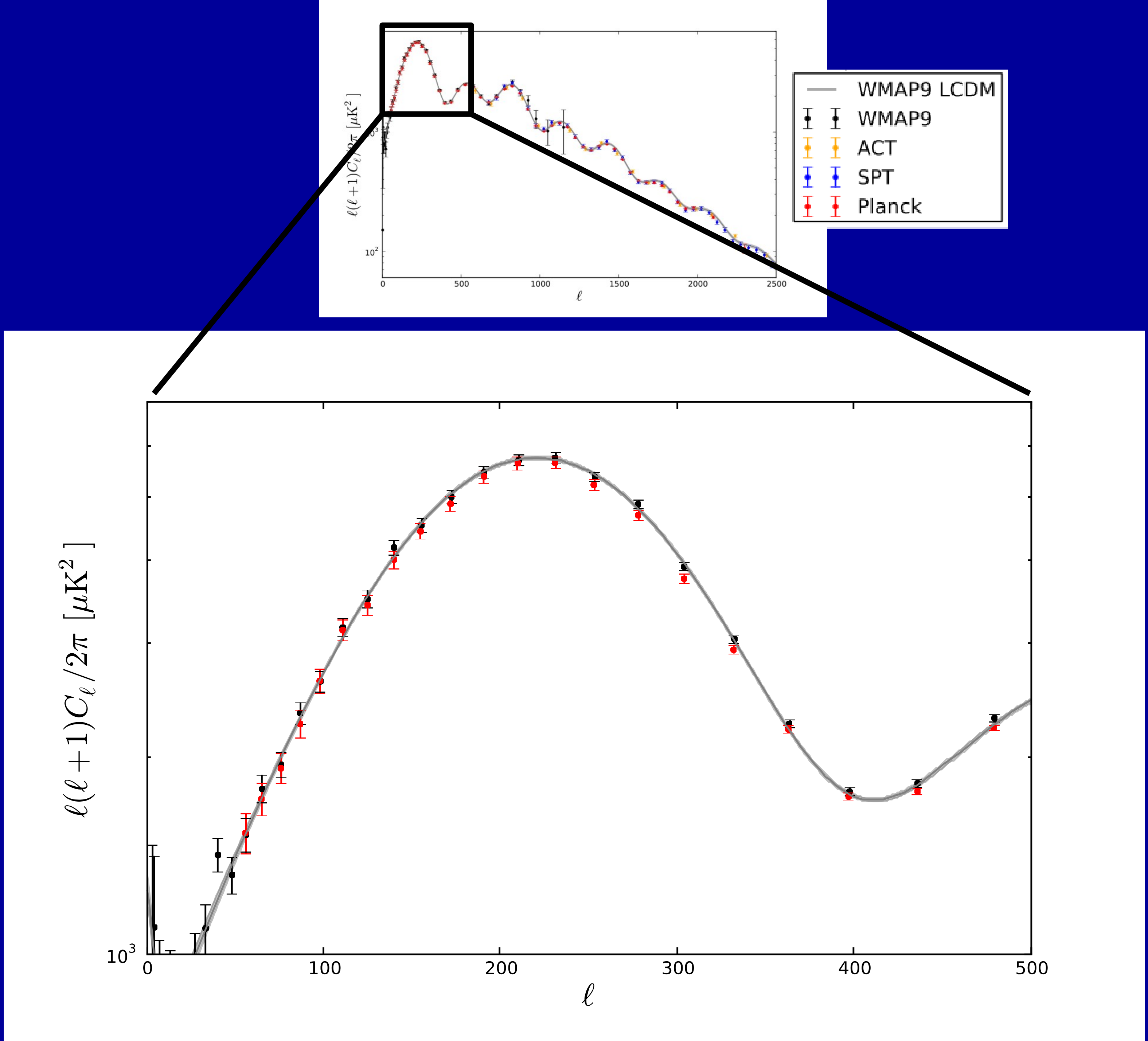
After subtraction of late-time effect:

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

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

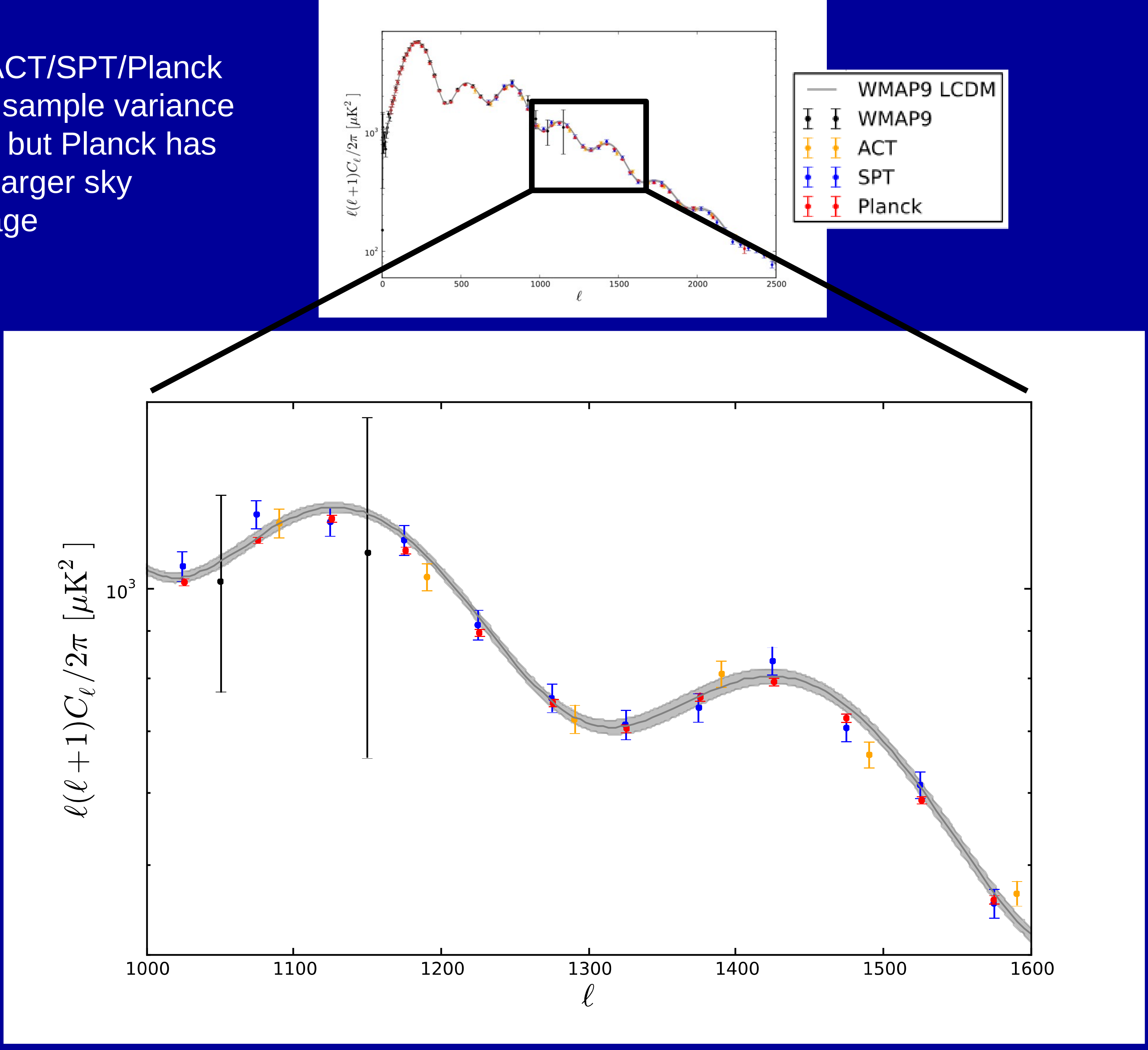


Best-fit scale-invariant (n_s =1) model

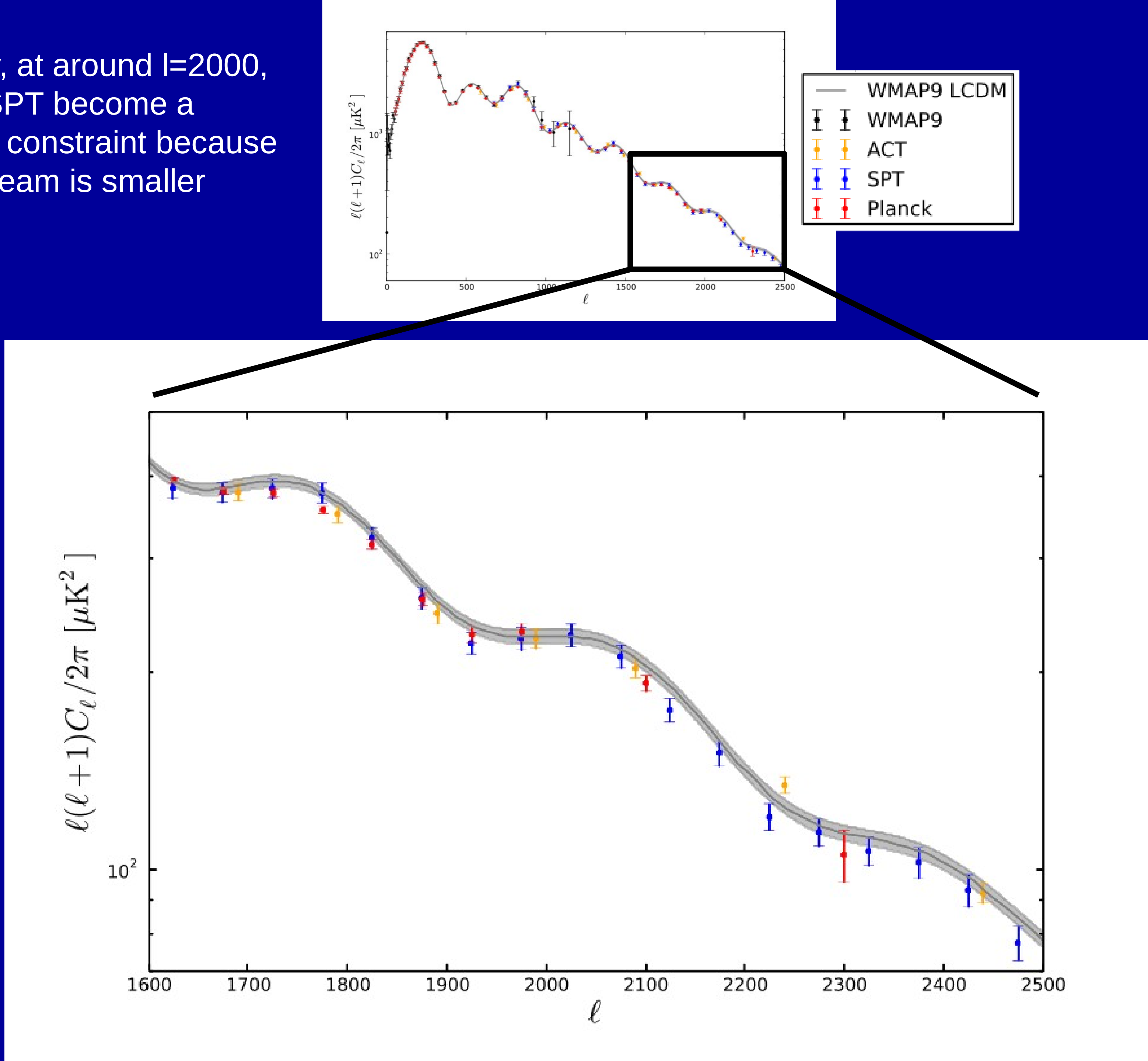


WMAP9 LCDM
WMAP9
ACT
SPT
Planck
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
ℓ
10^3
0
100
200
300
400
500

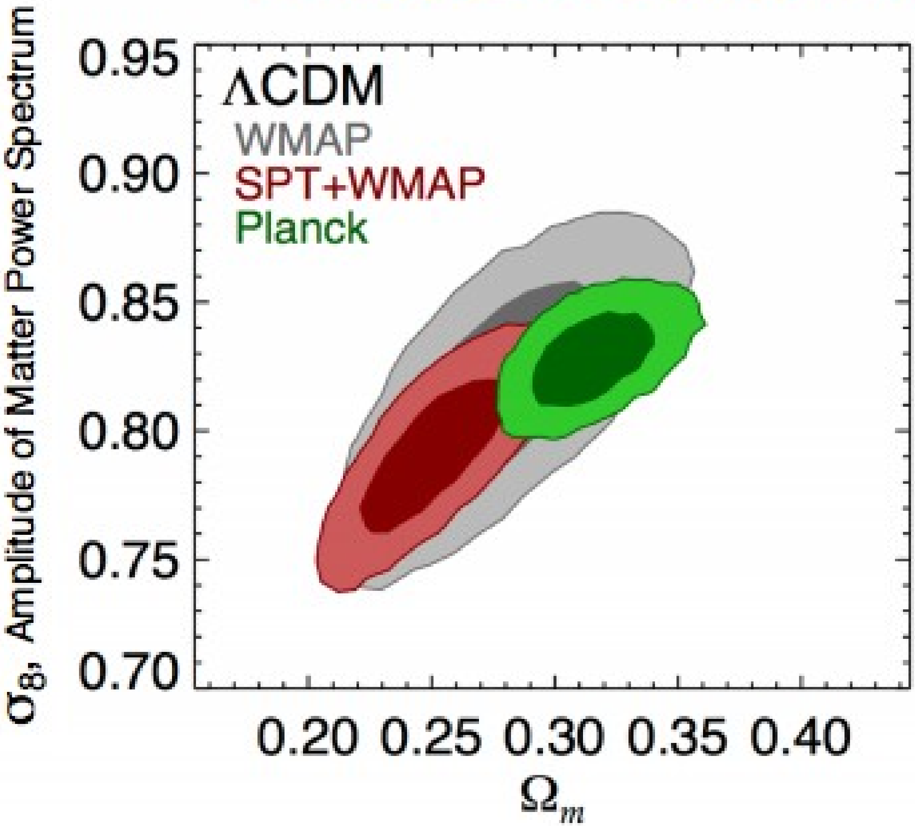
Here ACT/SPT/Planck are all sample variance limited but Planck has much larger sky coverage



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



CMB Constraints on σ_8, Ω_m



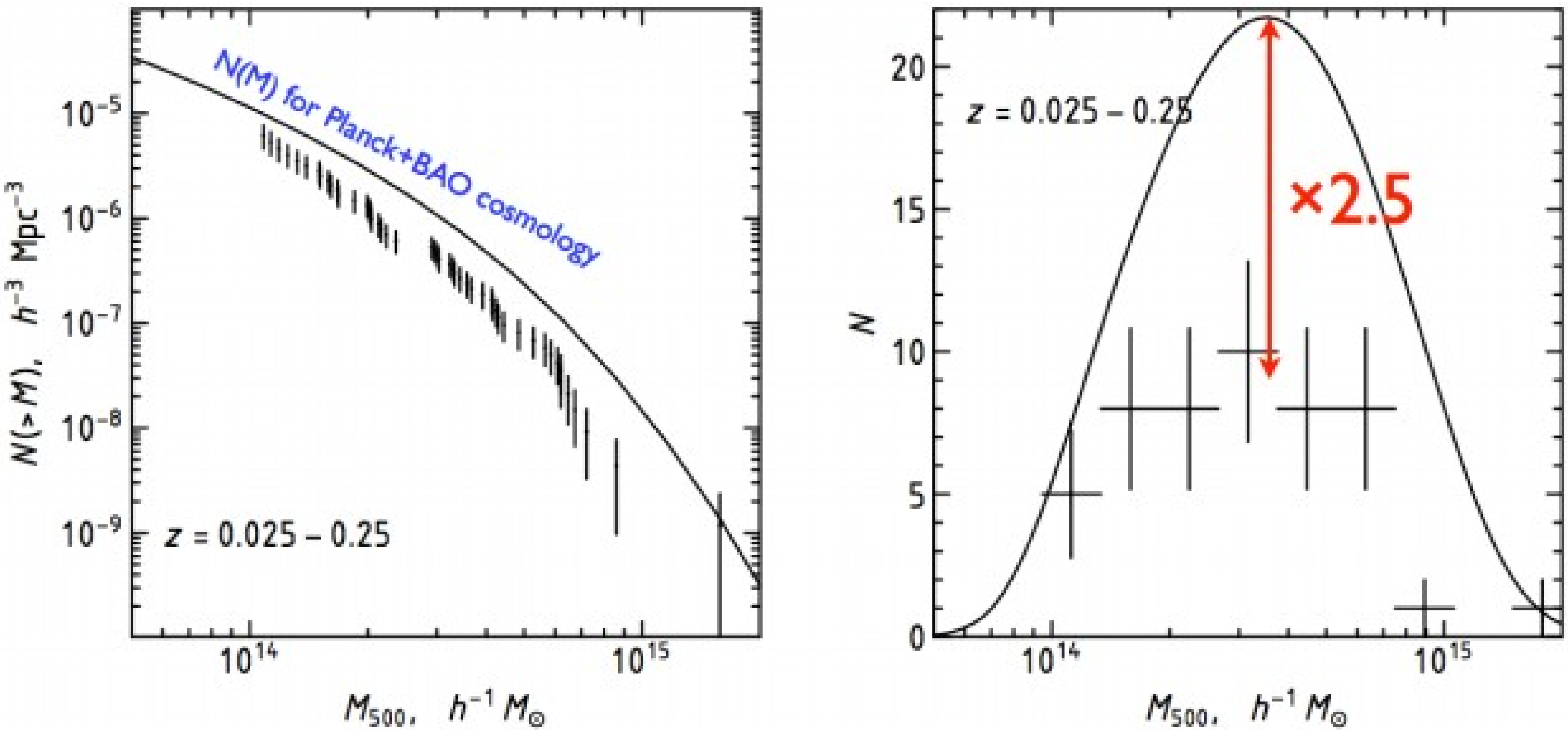
Planck measurements favor a shift in σ_8 and Ω_m Driven by:

- 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

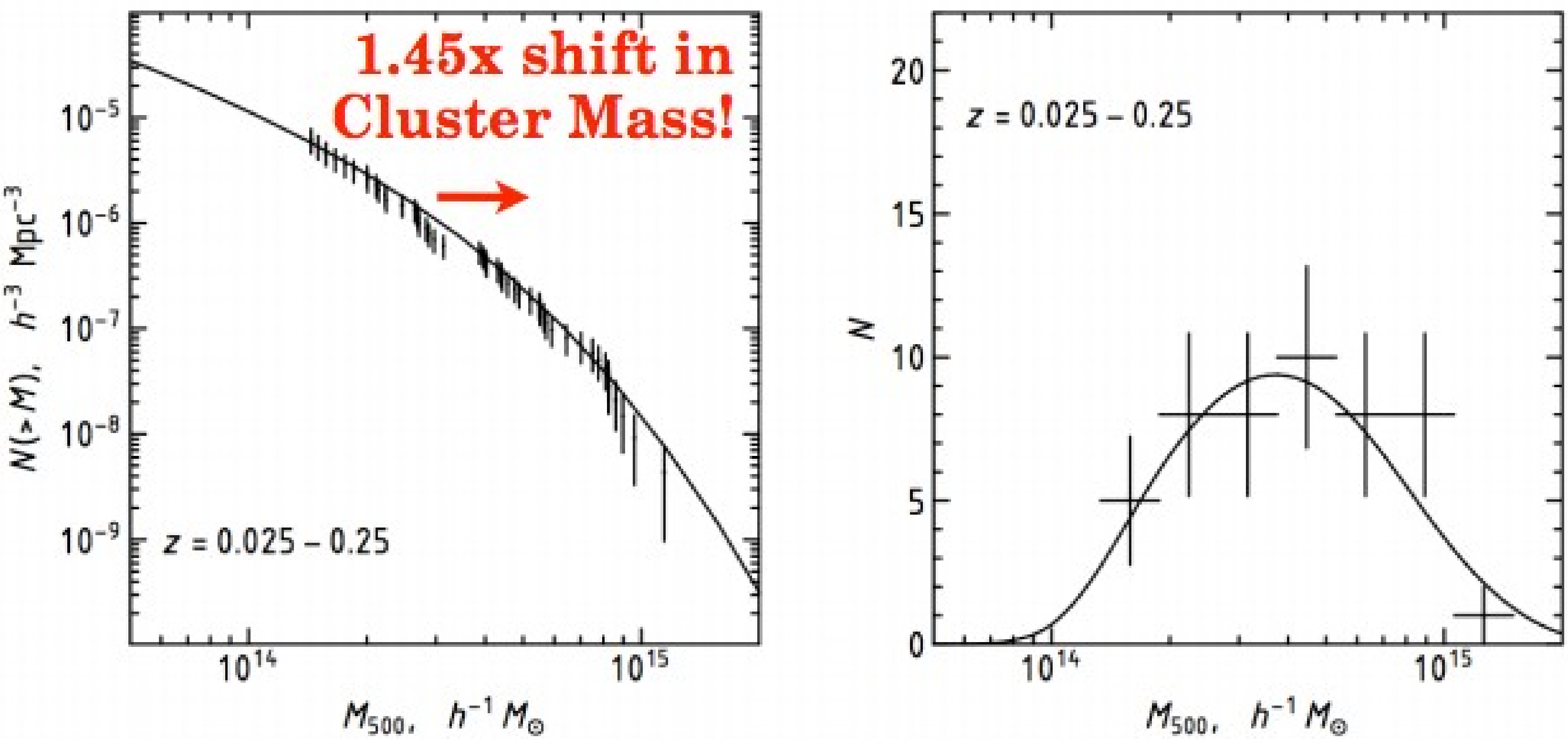
Planck Cosmology has ***profound*** mismatch with Cluster Abundance



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

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

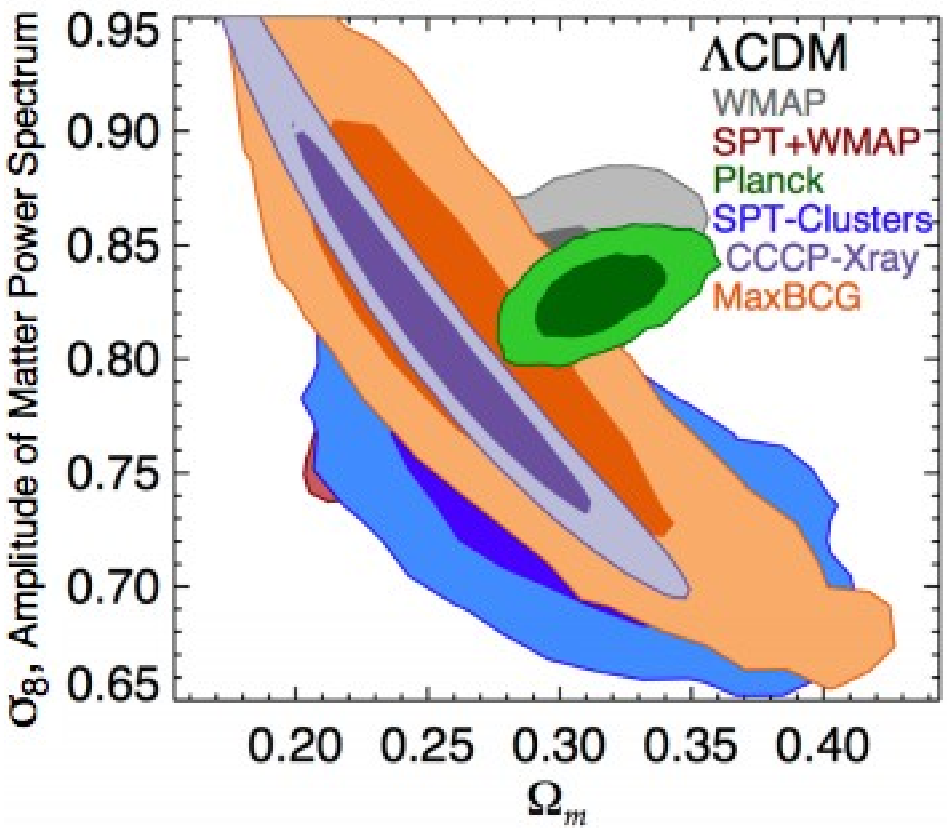
Planck Cosmology has ***profound*** mismatch with Cluster Abundance



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

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

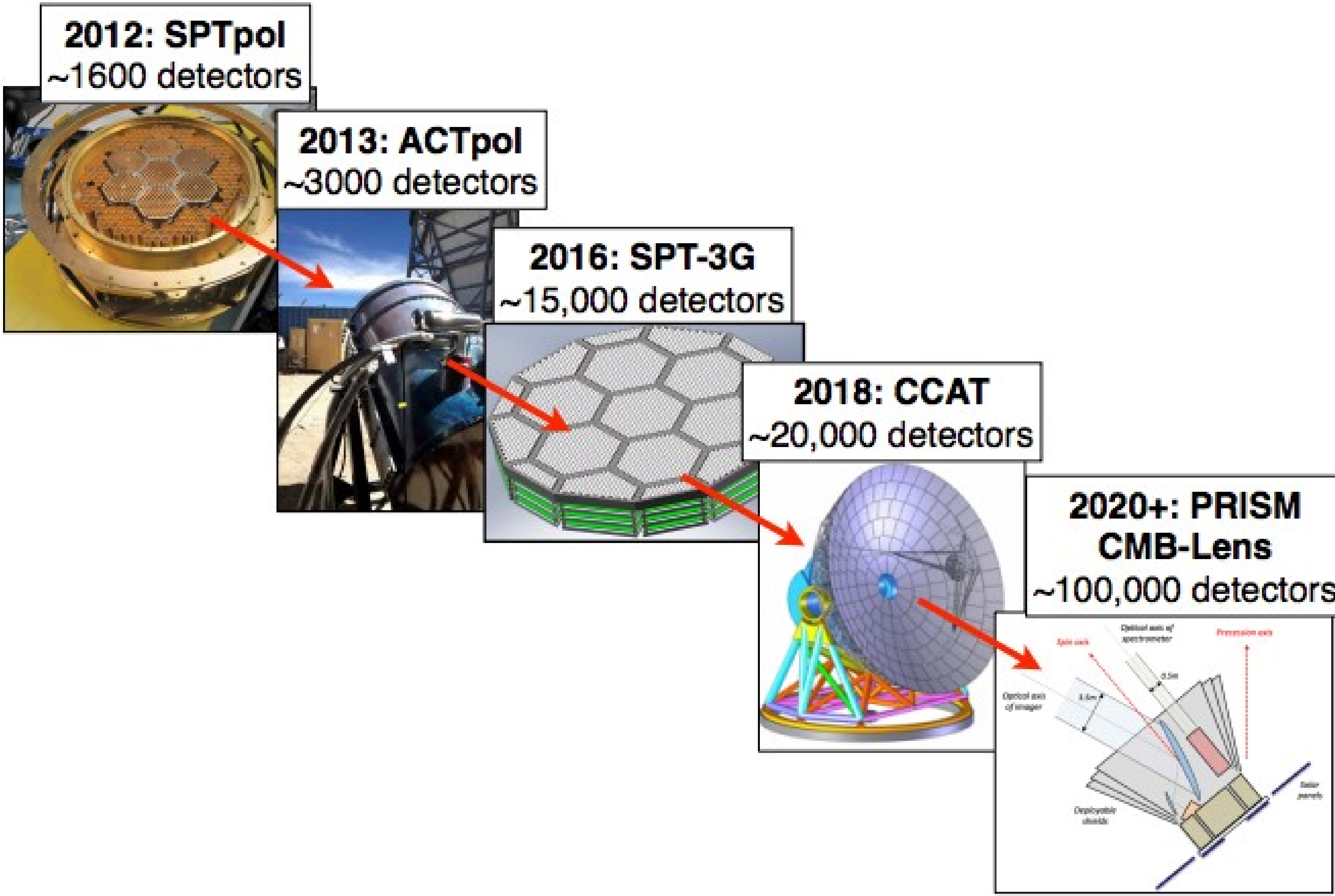
Tension exists for ***SZ, X-ray, Optical*** cluster surveys and other probes of structure



- ***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



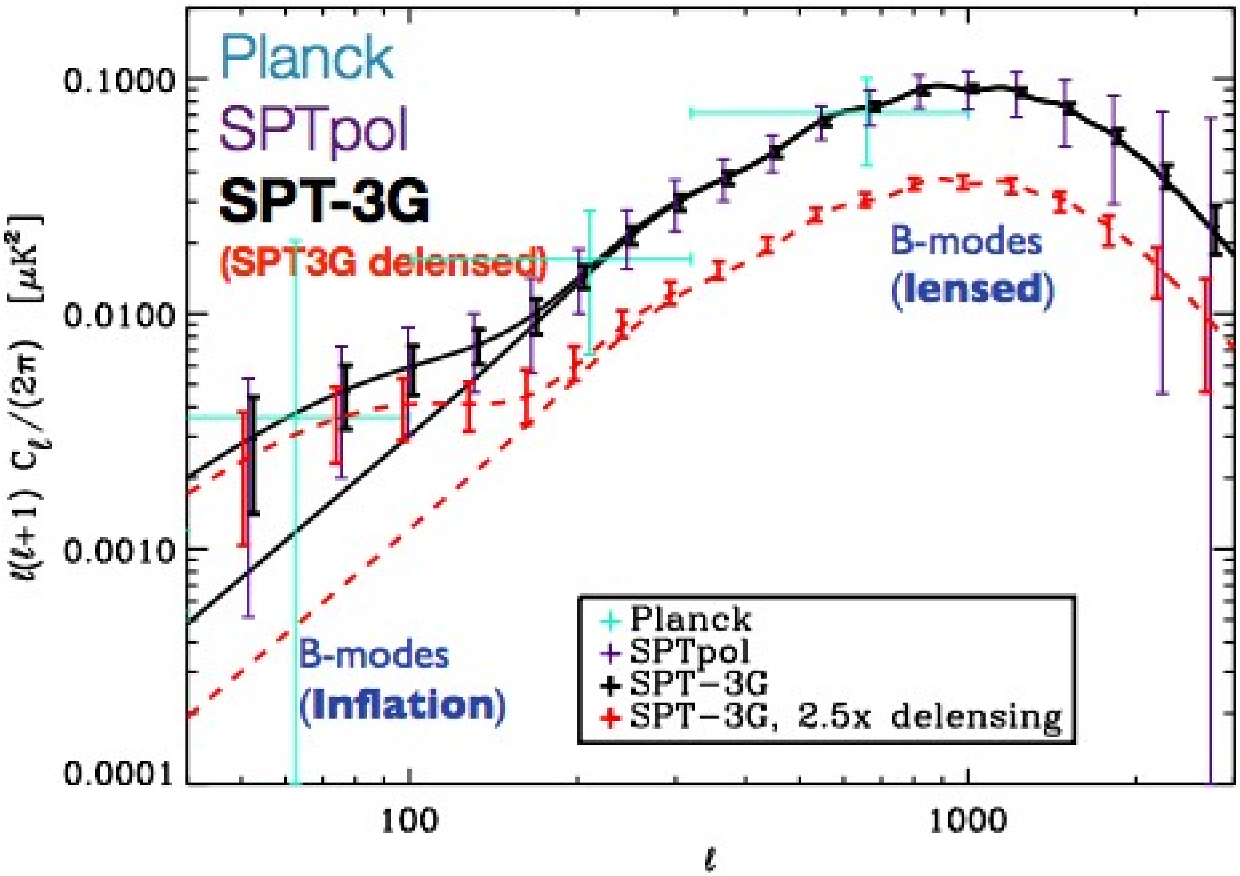
Current and Future SZ Surveys

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**

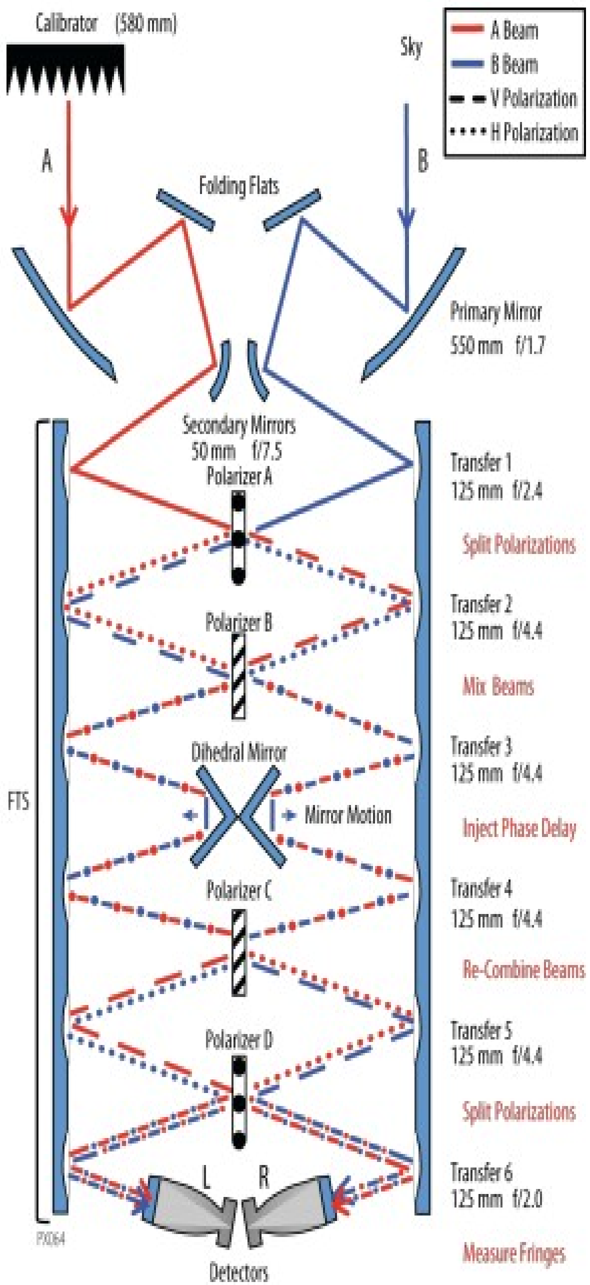
SPT-3G:
Projected B-mode Power Spectrum



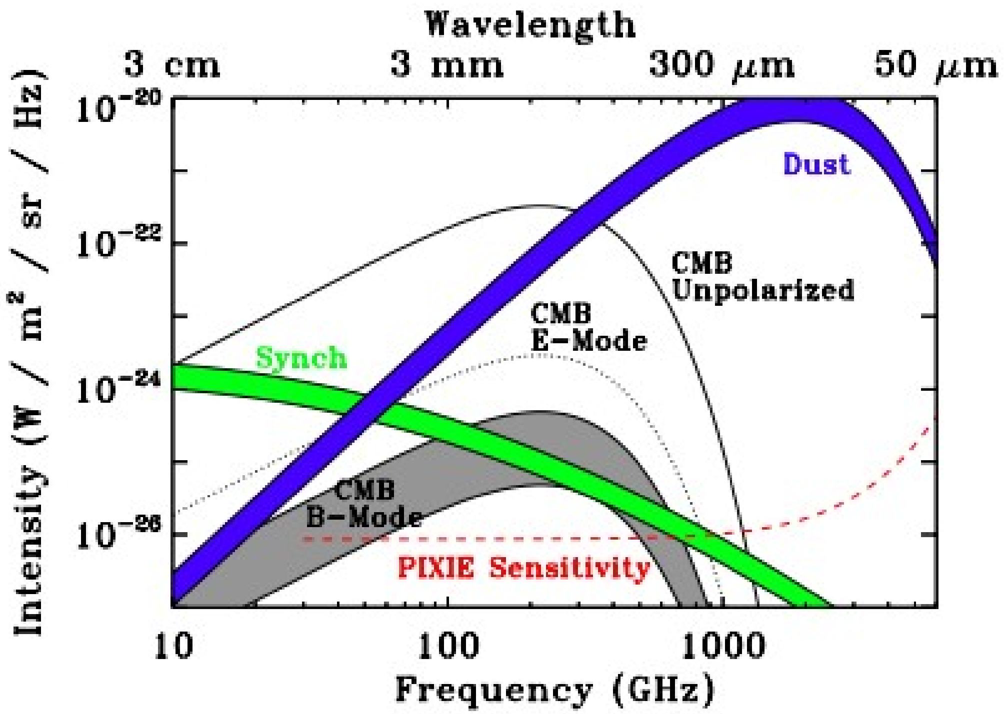
- Neutrino Constraints:
  - ***$\delta(N_{eff}) = 0.06$***
  - ***$\delta(\Sigma m\nu) = 0.06$ eV***
- "De-lens" the CMB at large-angular scales and improve "***r***" Inflation constraint
  - ***$\delta(r) = 0.01$***

Credit: T. Crawford

PIXIE

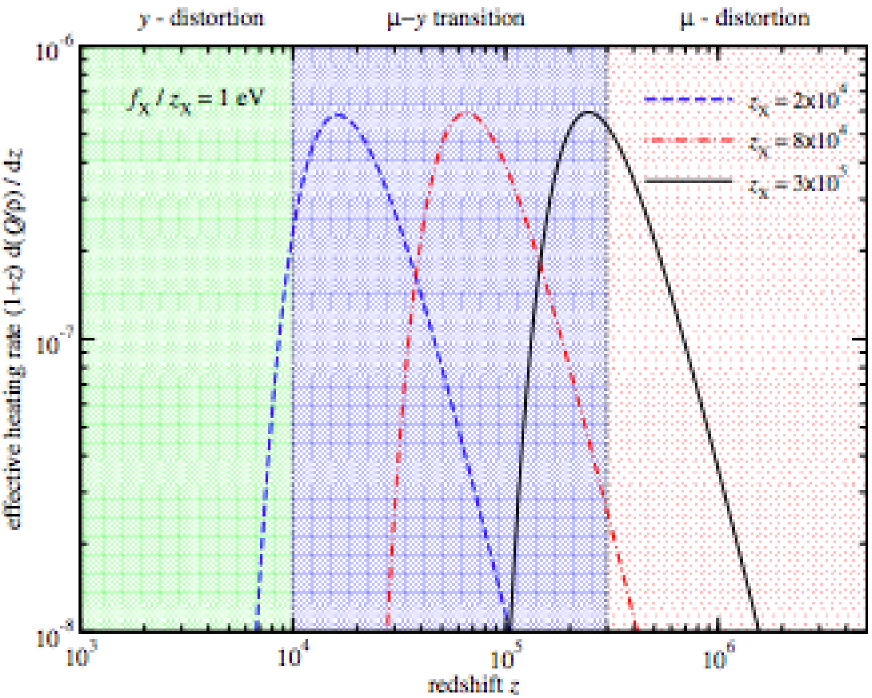


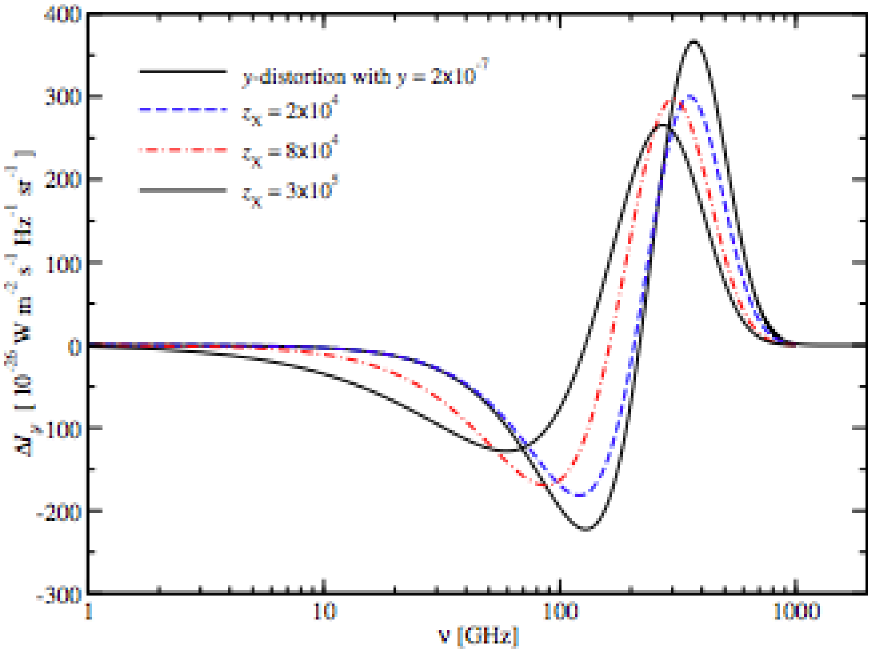
Calibrator (580 mm)
Sky
A Beam
B Beam
V Polarization
H Polarization
A
B
Folding Flats
Primary Mirror
550 mm f/1.7
Secondary Mirrors
50 mm f/7.5
Polarizer A
Transfer 1
125 mm f/2.4
Split Polarizations
Polarizer B
Transfer 2
125 mm f/4.4
Mix Beams
Dihedral Mirror
Transfer 3
125 mm f/4.4
FTS
Mirror Motion
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
Detectors
Measure Fringes



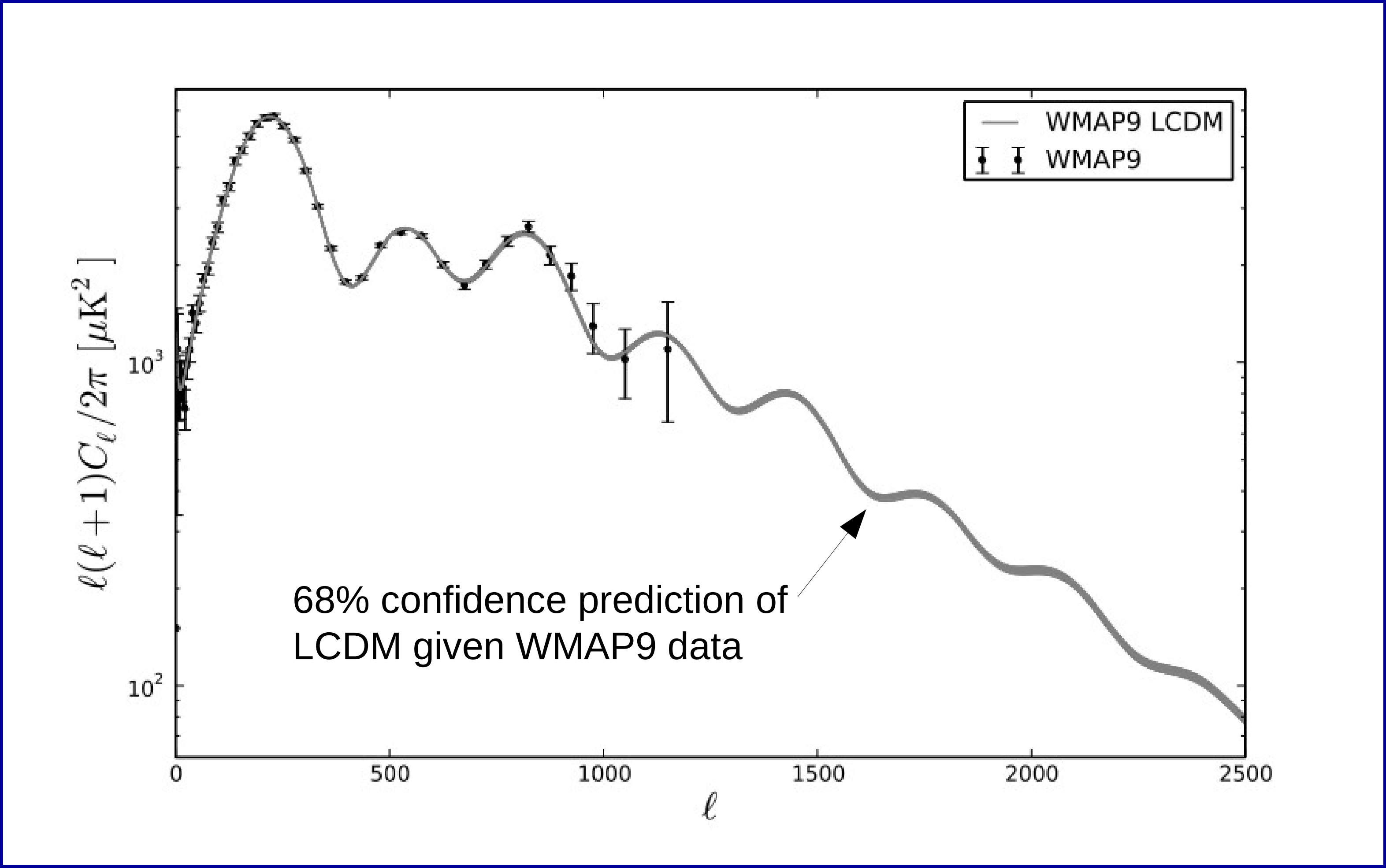
Wavelength
3 cm
3 mm
300 μm
50 μm
10^{-20}
10^{-22}
10^{-24}
10^{-26}
Intensity (W / m^2 / sr / Hz)
Dust
CMB Unpolarized
CMB E-Mode
Synch
CMB B-Mode
PIXIE Sensitivity
10
100
1000
Frequency (GHz)

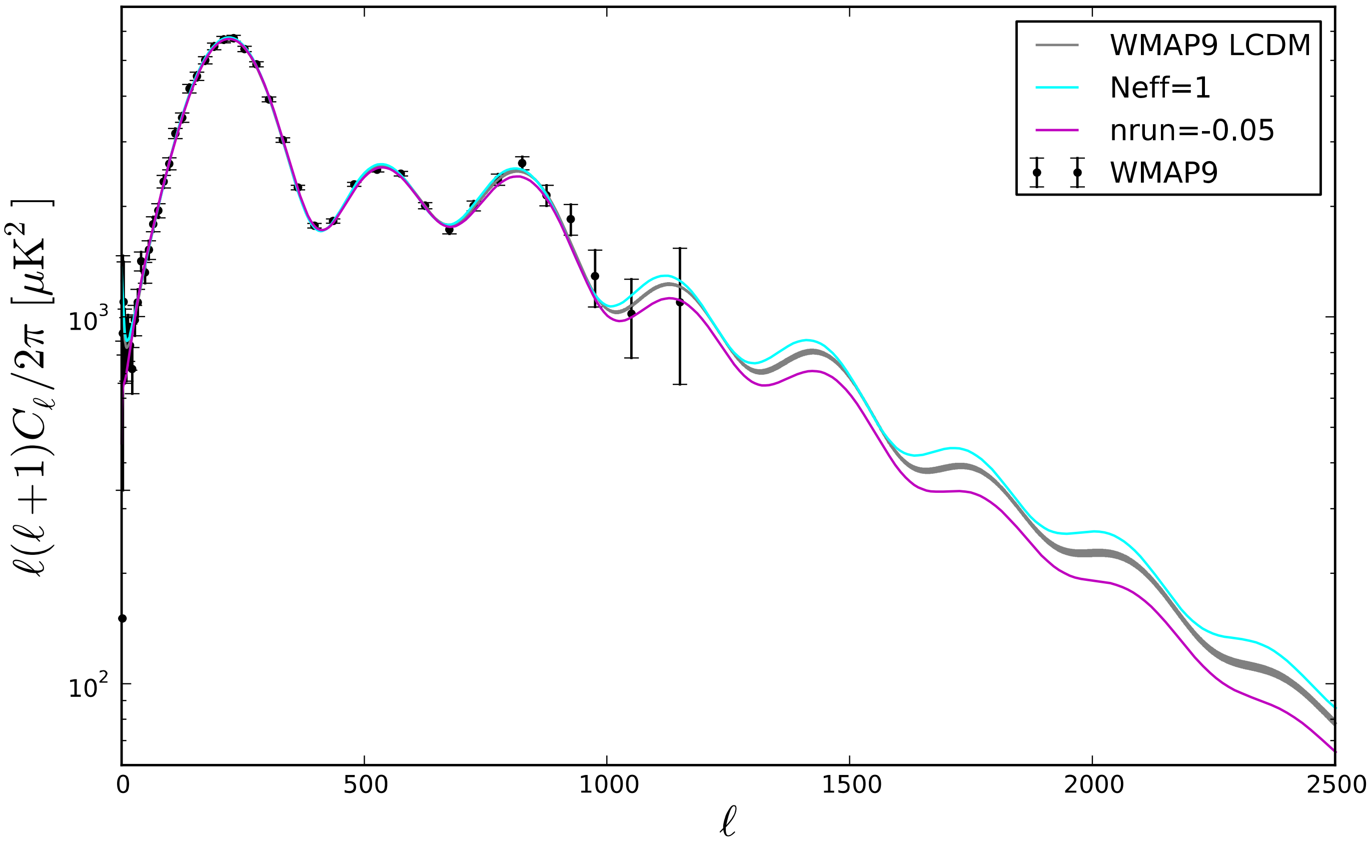
Spectral Distortions

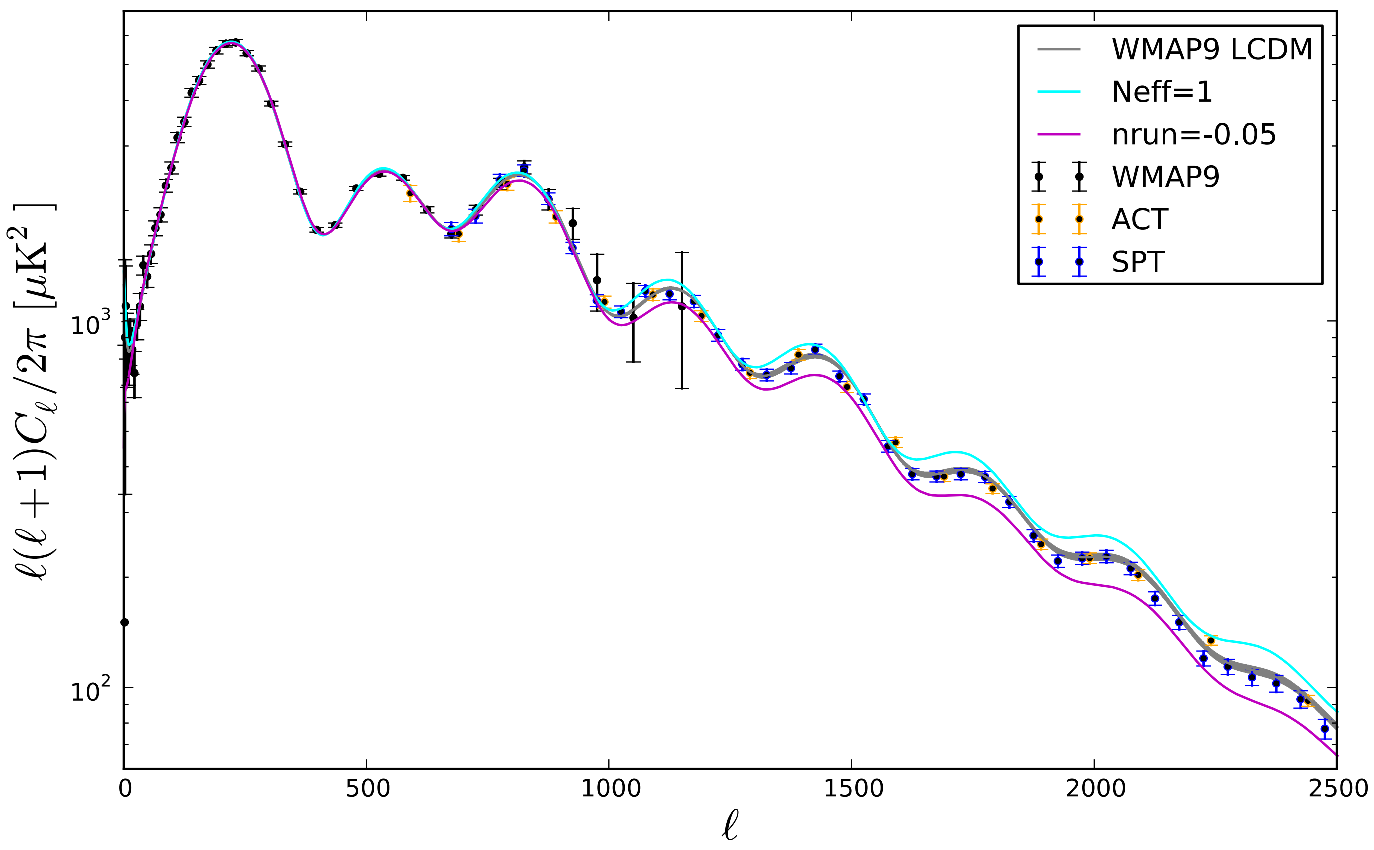




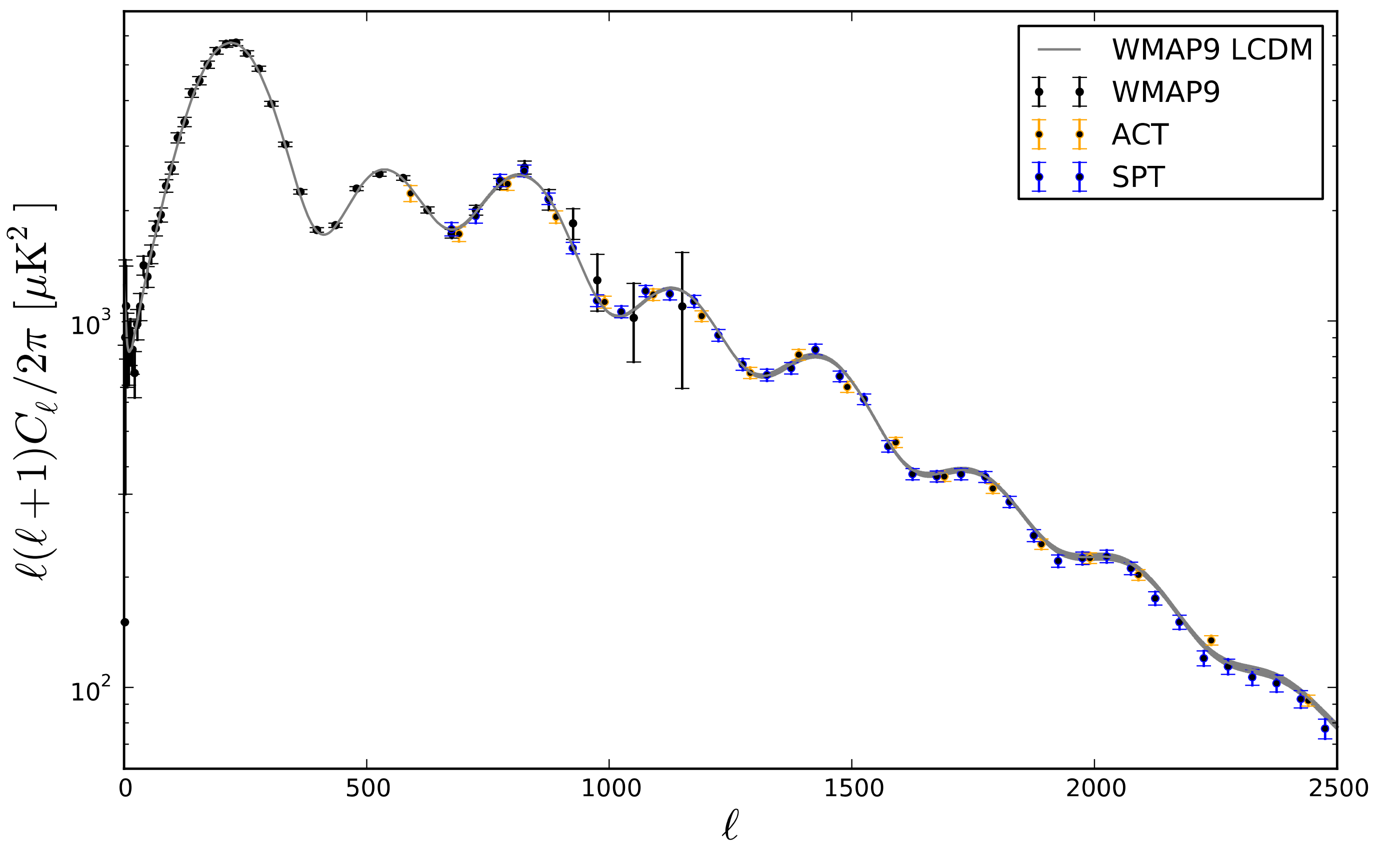
LCDM makes a very precise prediction



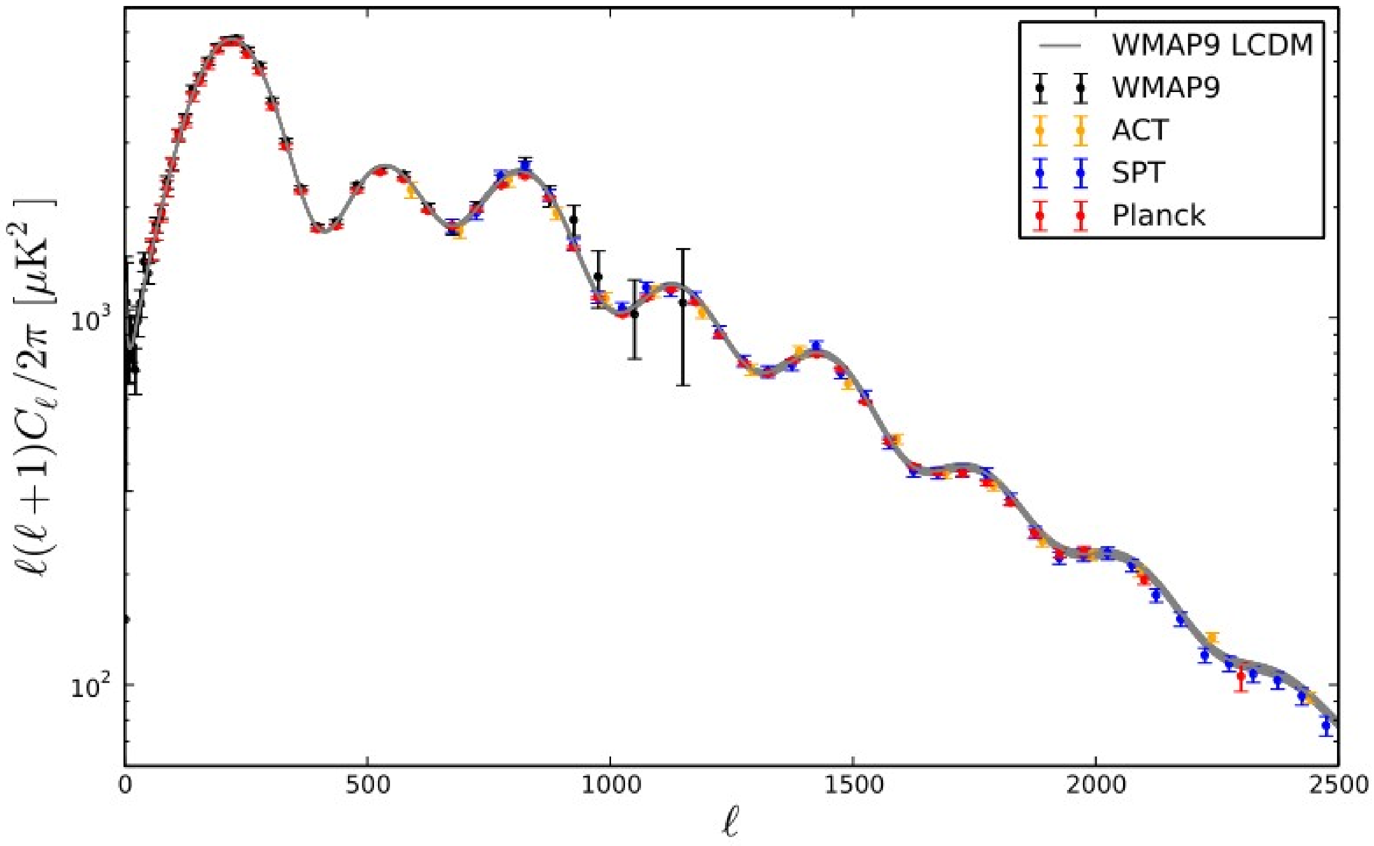

WMAP9 LCDM
Neff=1
nrun=-0.05
WMAP9
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ



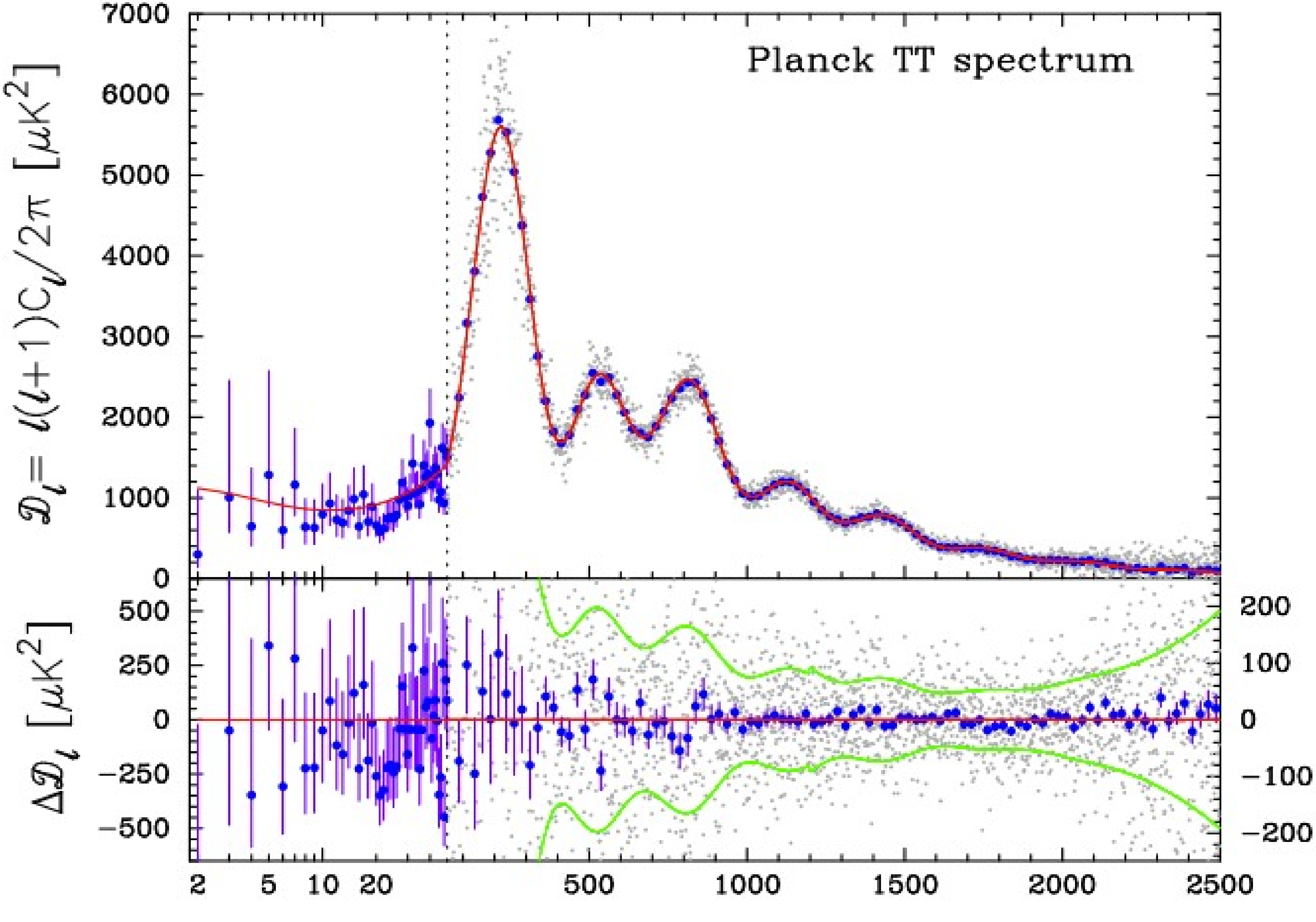
WMAP9 LCDM
Neff=1
nrun=-0.05
WMAP9
ACT
SPT
$\ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ



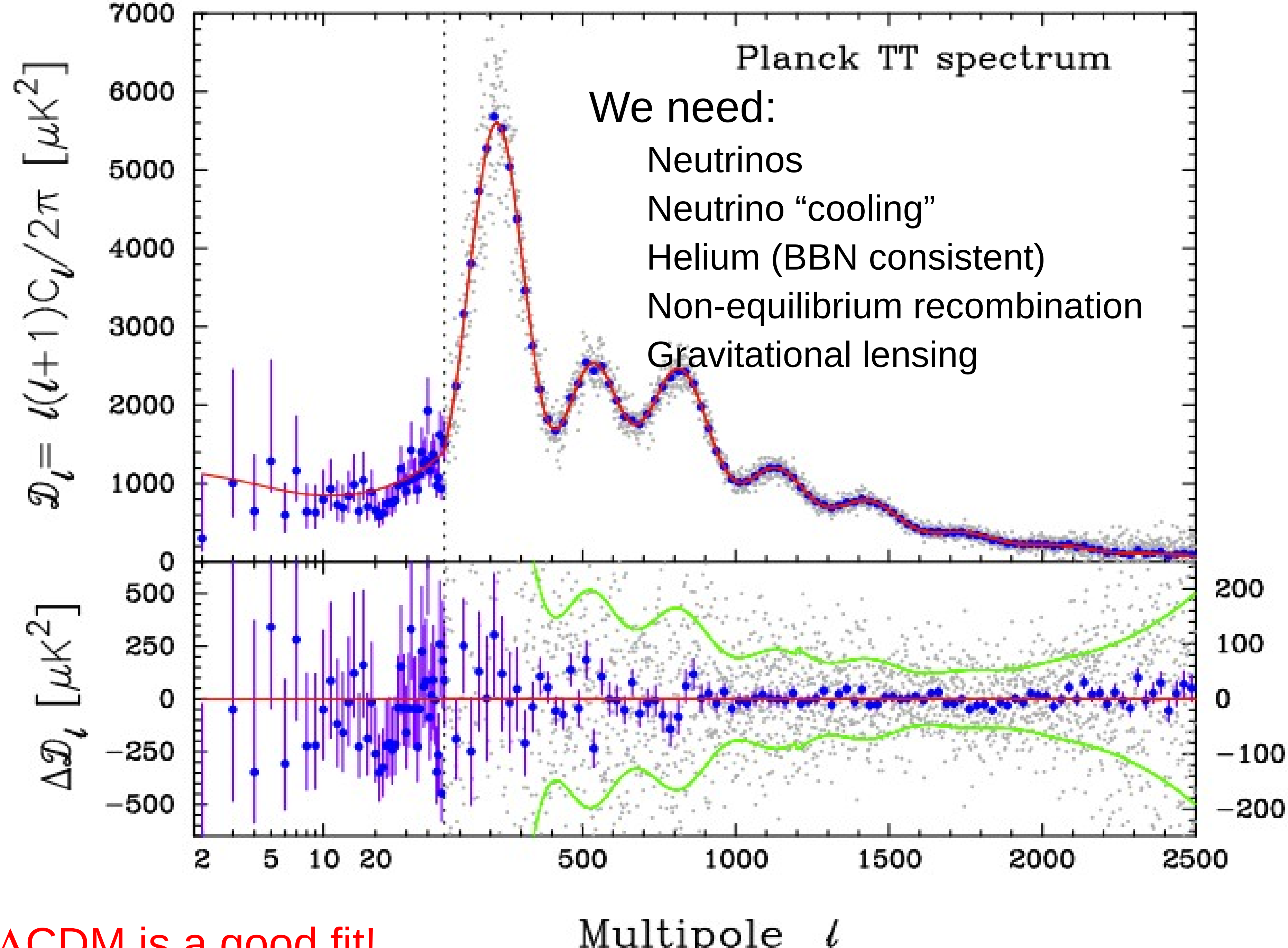
WMAP9 LCDM
WMAP9
ACT
SPT
$\ell(\ell+1)C_\ell/2\pi\ [\mu\mathrm{K}^2]$
10^3
10^2
0
500
1000
1500
2000
2500
ℓ



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



ΛCDM is a good fit!



We need:

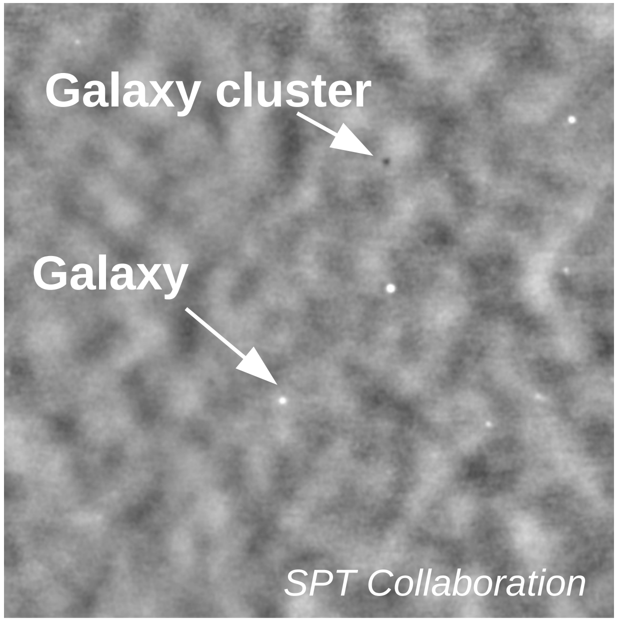
- Neutrinos
- Neutrino "cooling"
- Helium (BBN consistent)
- Non-equilibrium recombination
- Gravitational lensing

ΛCDM is a good fit!

Possible contamination affecting damping: unresolved foregrounds

To scale

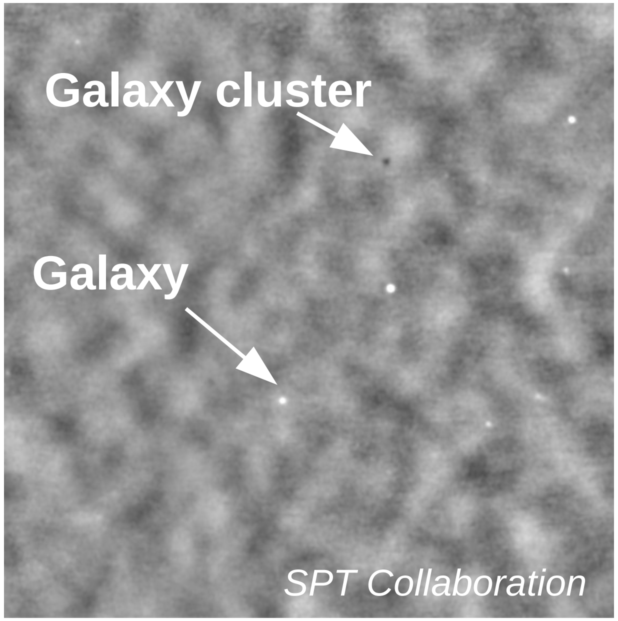
Resolved foregrounds:



Possible contamination affecting damping: unresolved foregrounds

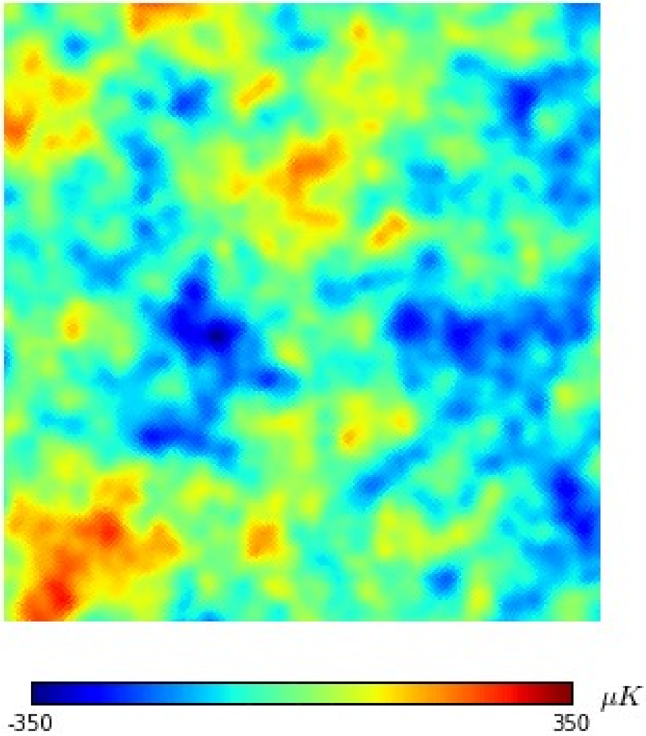
To scale

Resolved foregrounds:



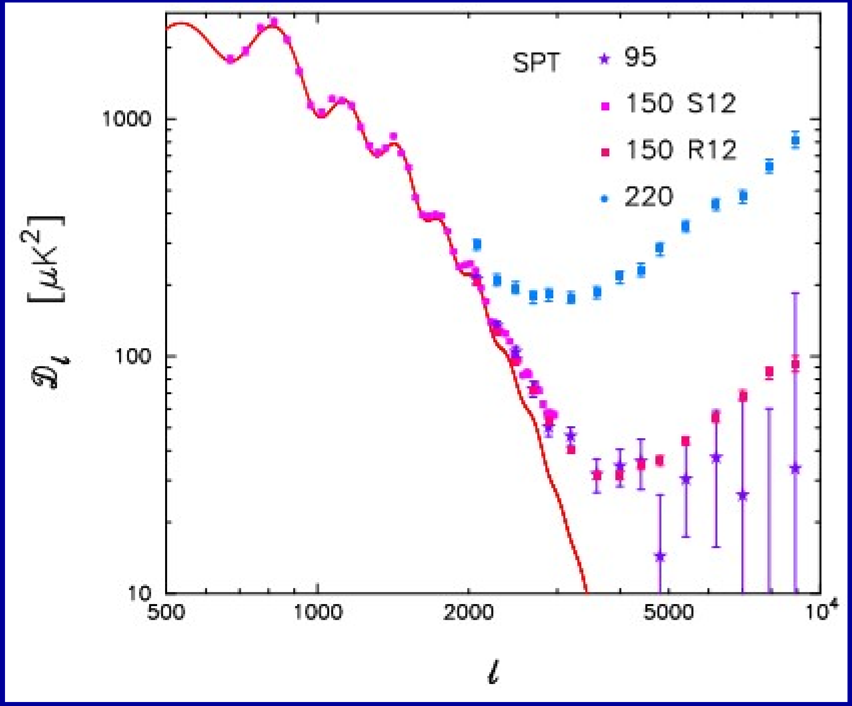
Unresolved foregrounds:

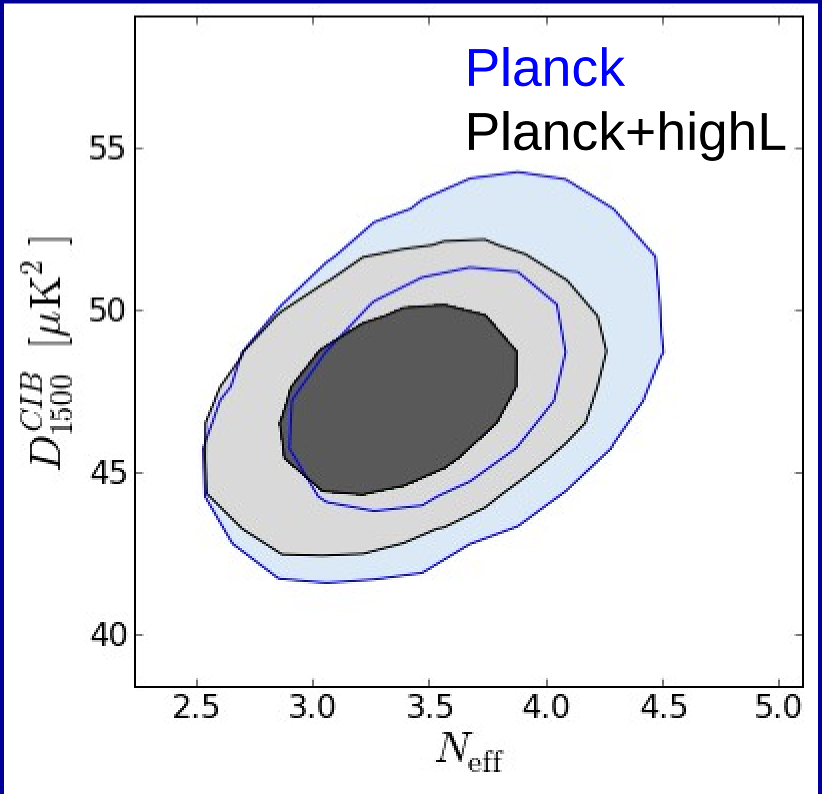
(Noise-free simulation)



Adding “highL” to help constrain foregrounds

SPT highL





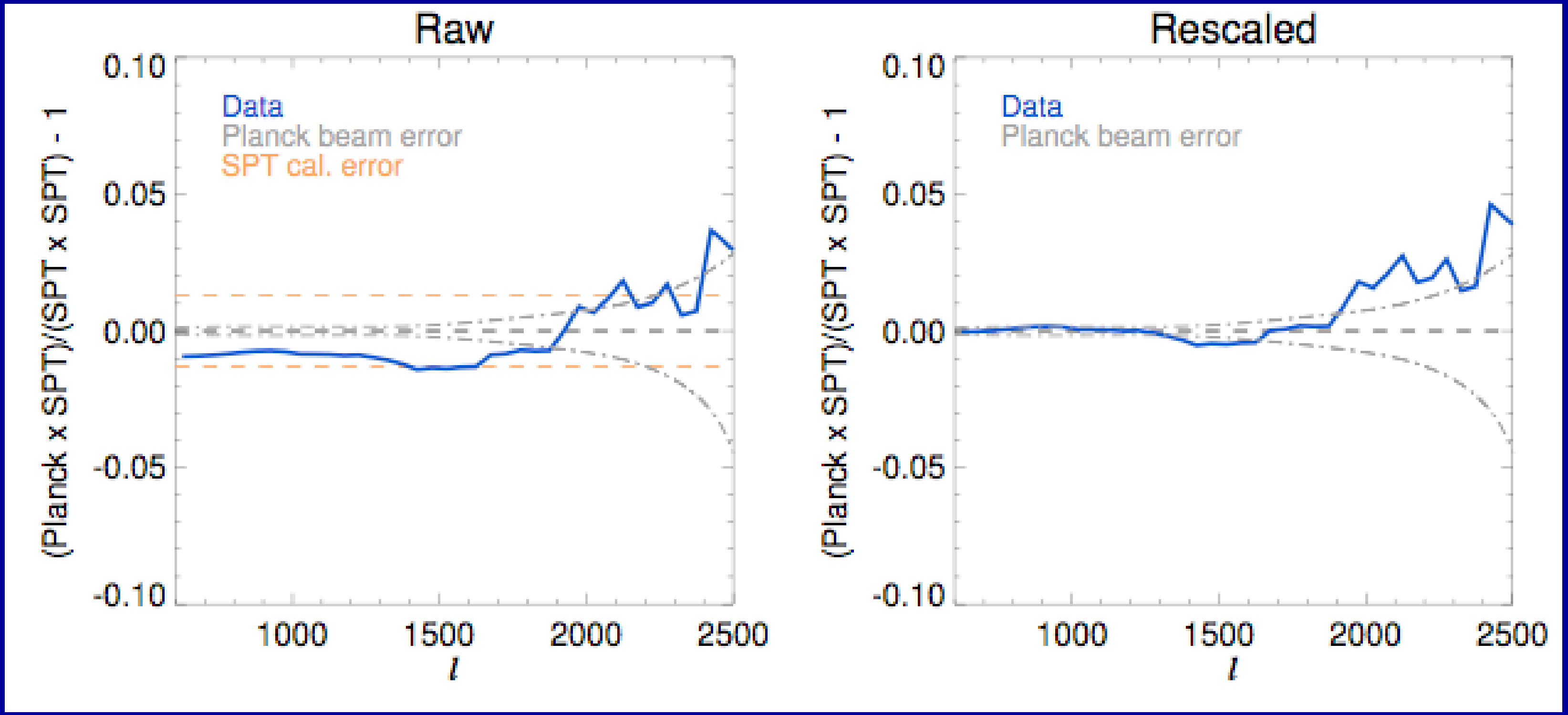
correlation coefficient ~ .5

potential for 25% tighter sigma

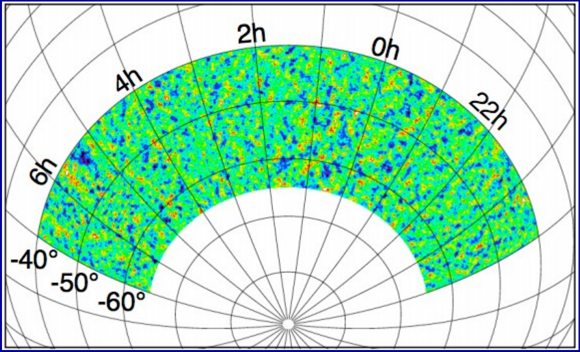
Consistency with other CMB experiments

- 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.

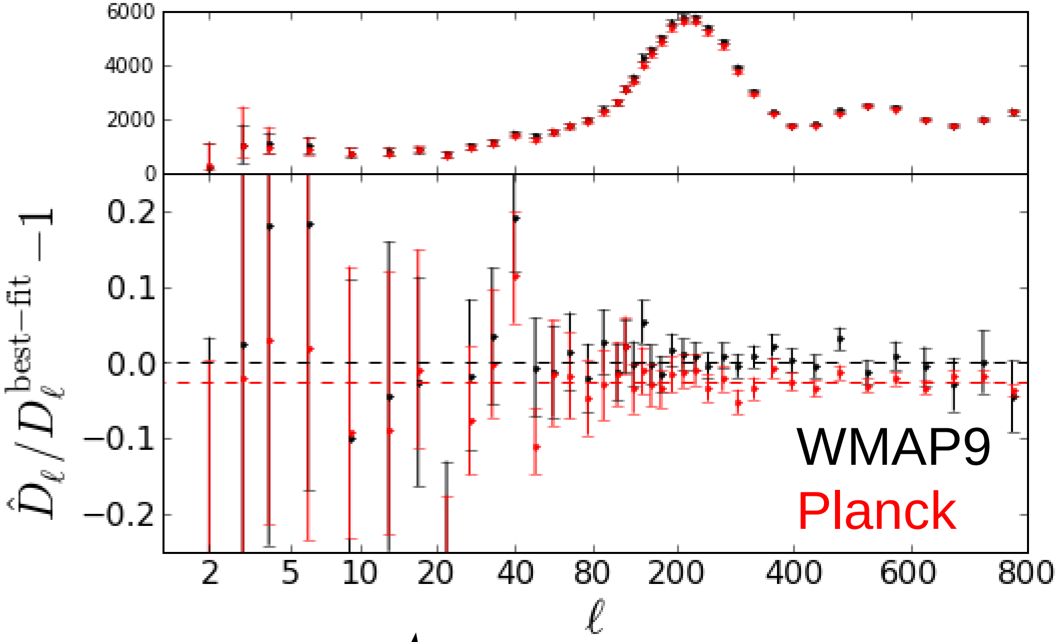
Planck-SPT consistency



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

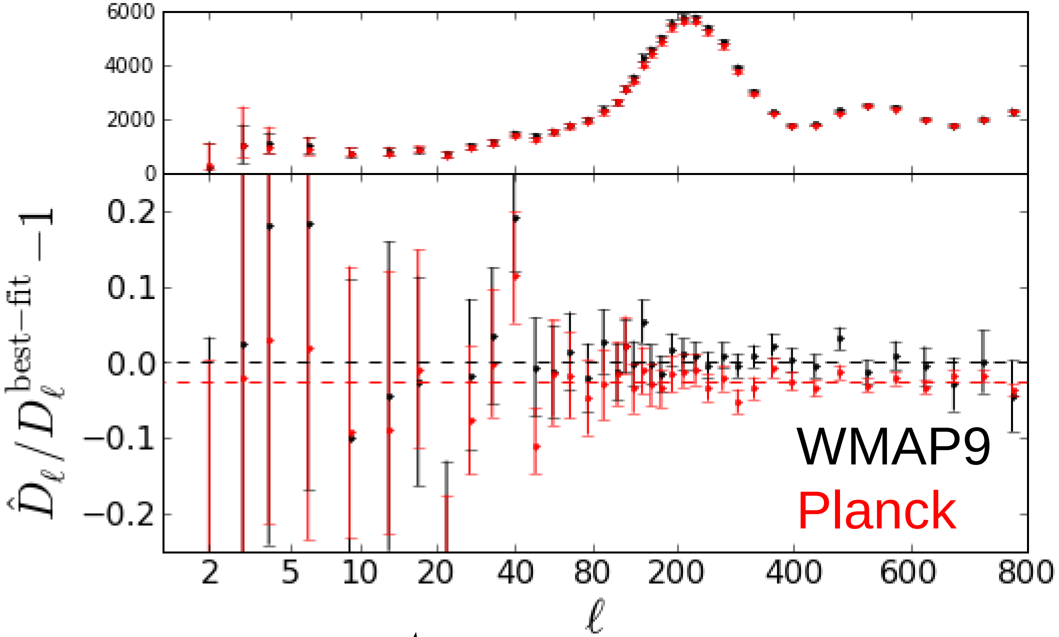


Planck-WMAP consistency



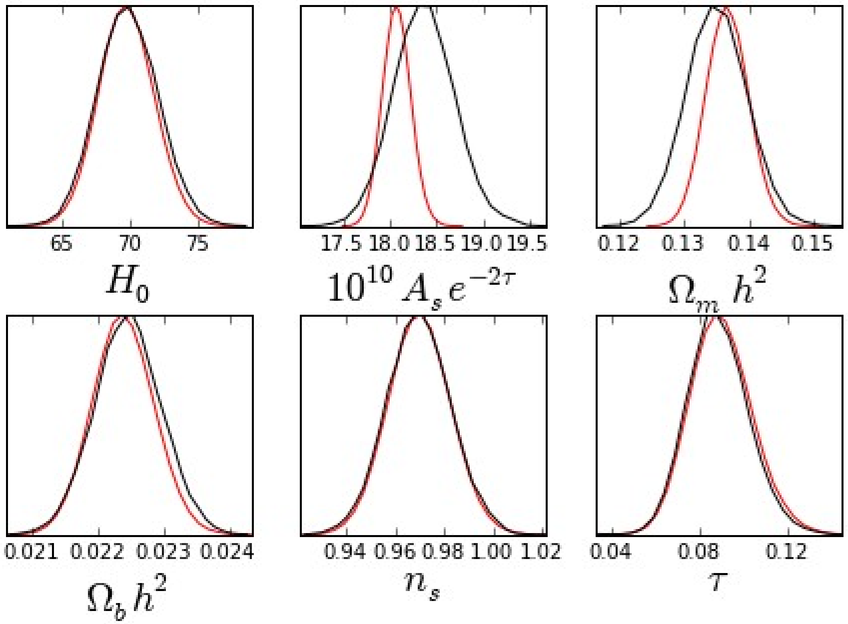
There are differences between Planck and WMAP that look something like a 2.5% rescaling

Planck-WMAP consistency



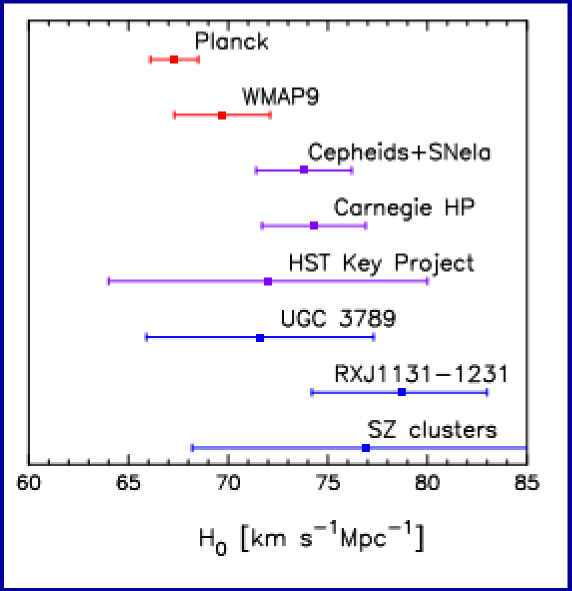
There are differences between Planck and WMAP that look something like a 2.5% rescaling

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?

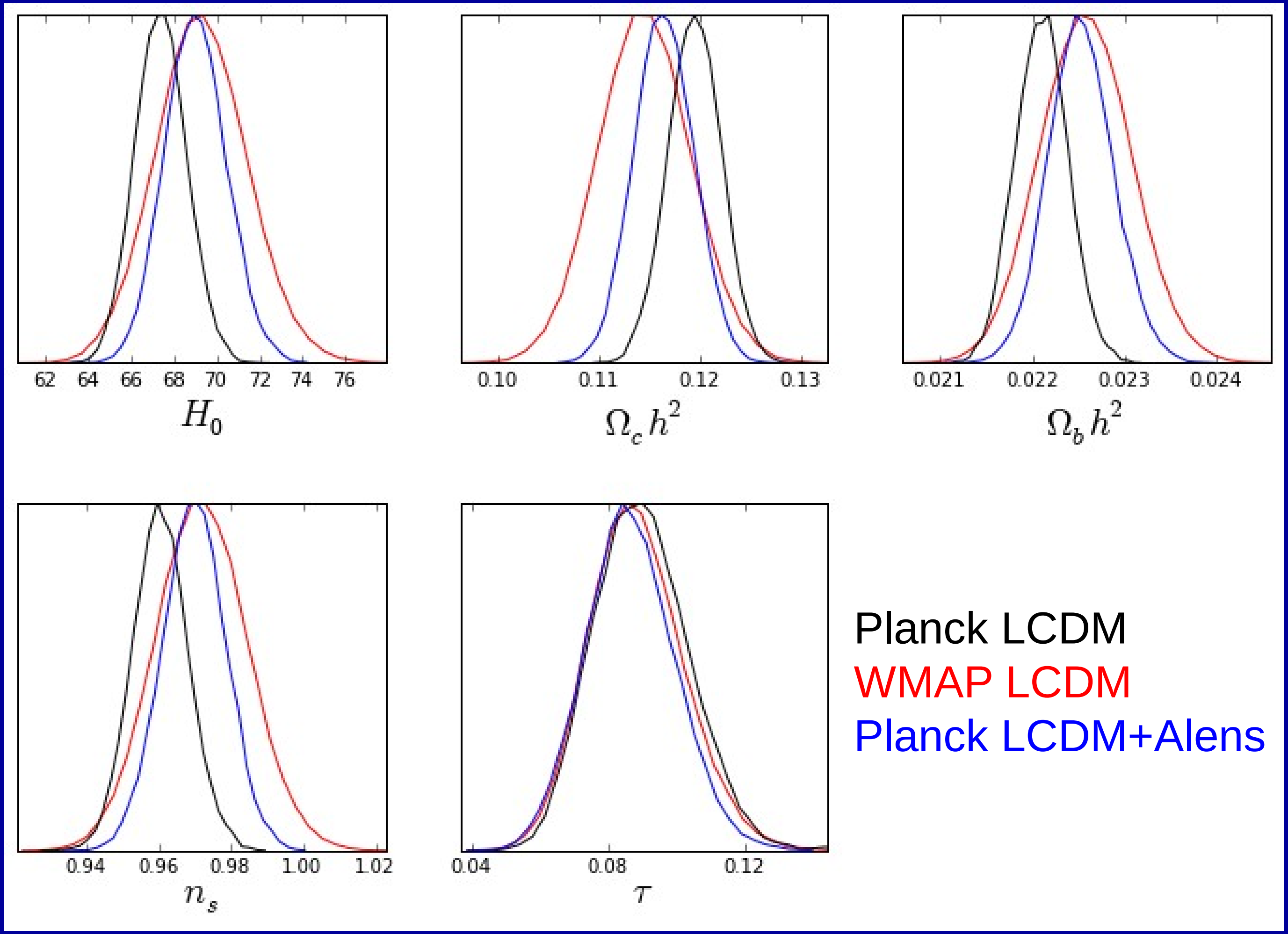


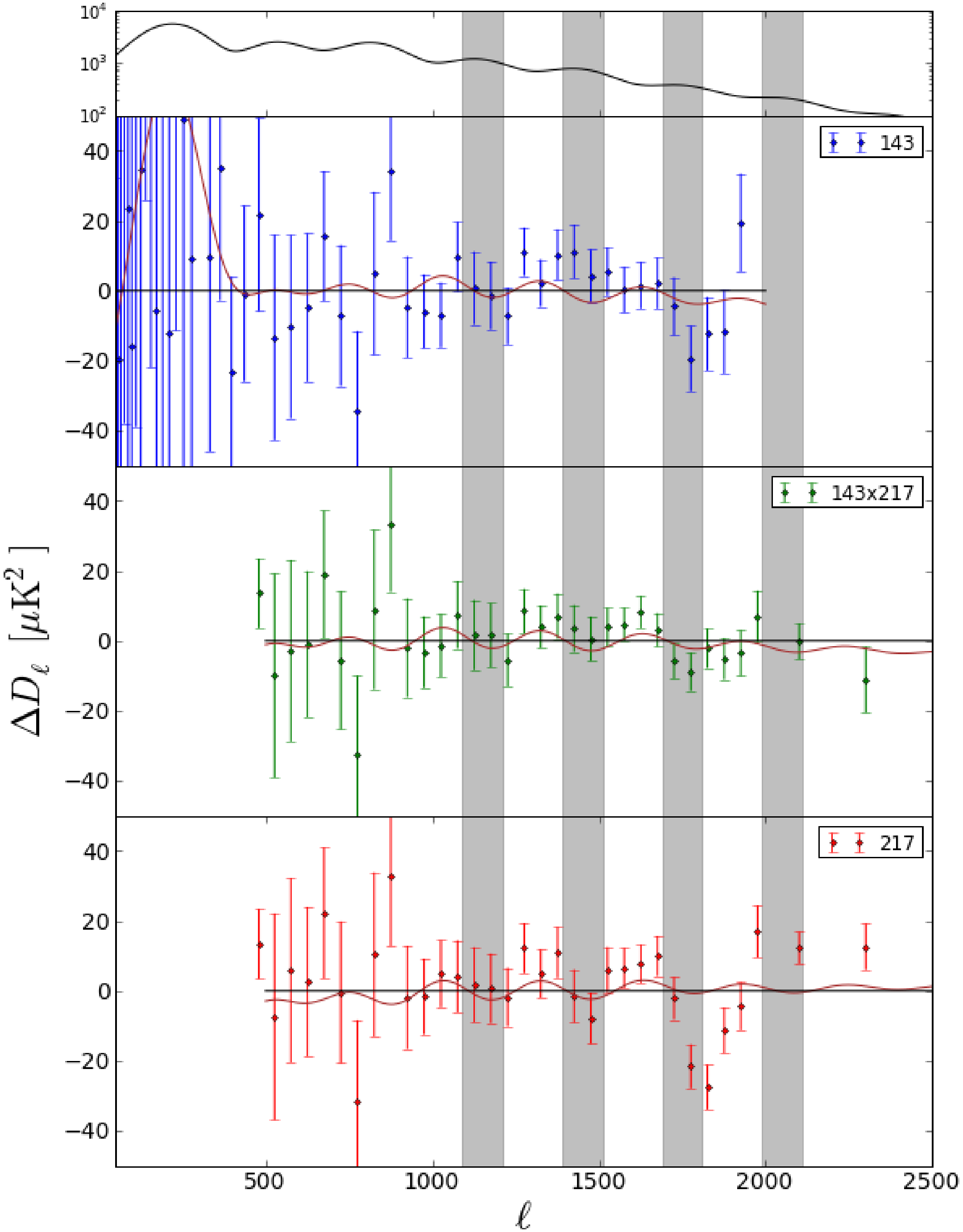
- Its lensing
- This is going to be very important for the Σm_ν constraint

Outline

- 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

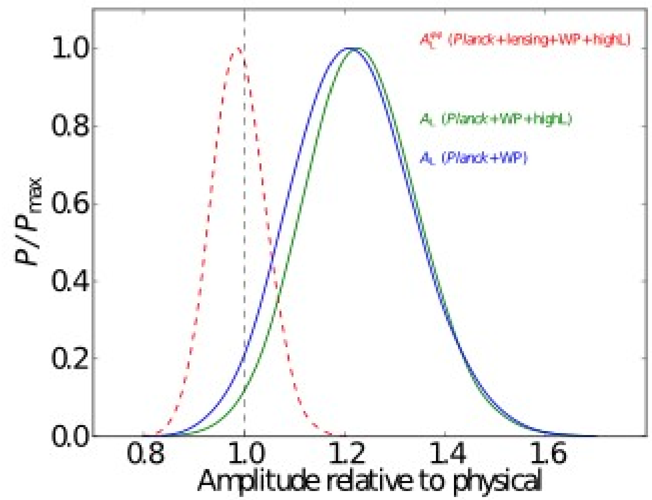
Removing lensing information send Planck parameters back to WMAP

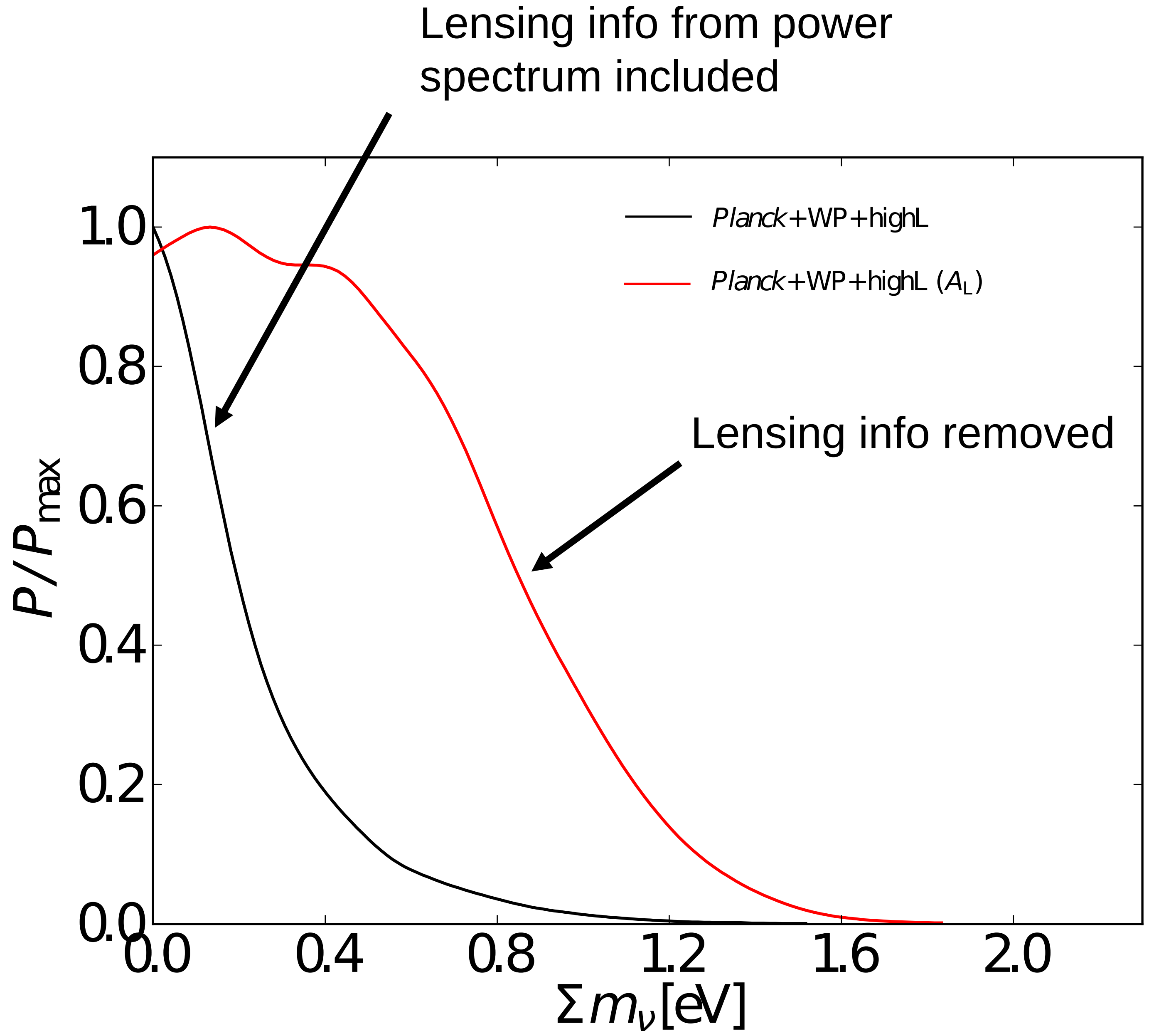




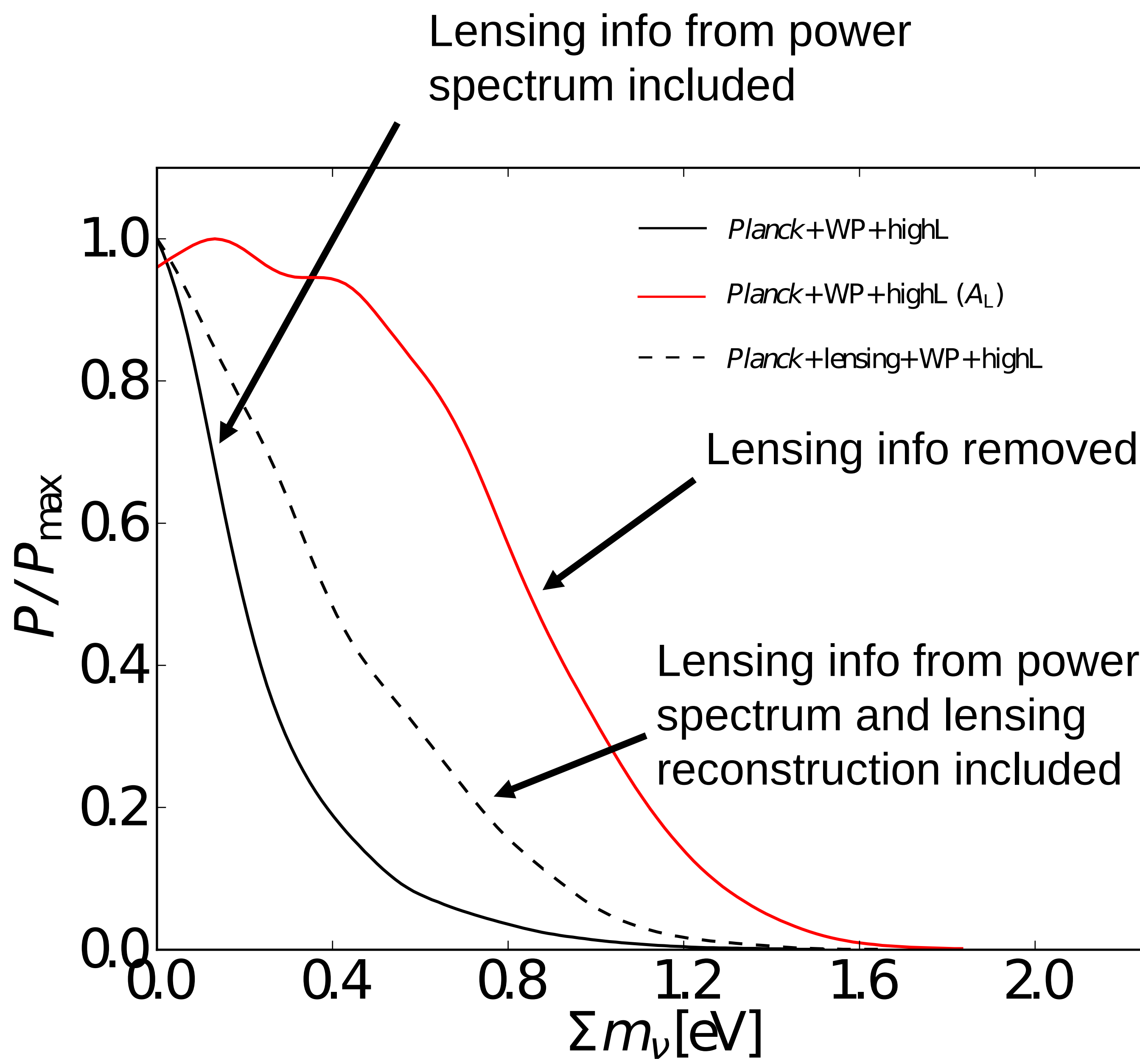
Planck+WP LCDM best-fit

Planck+WP LCDM+Alens best-fit



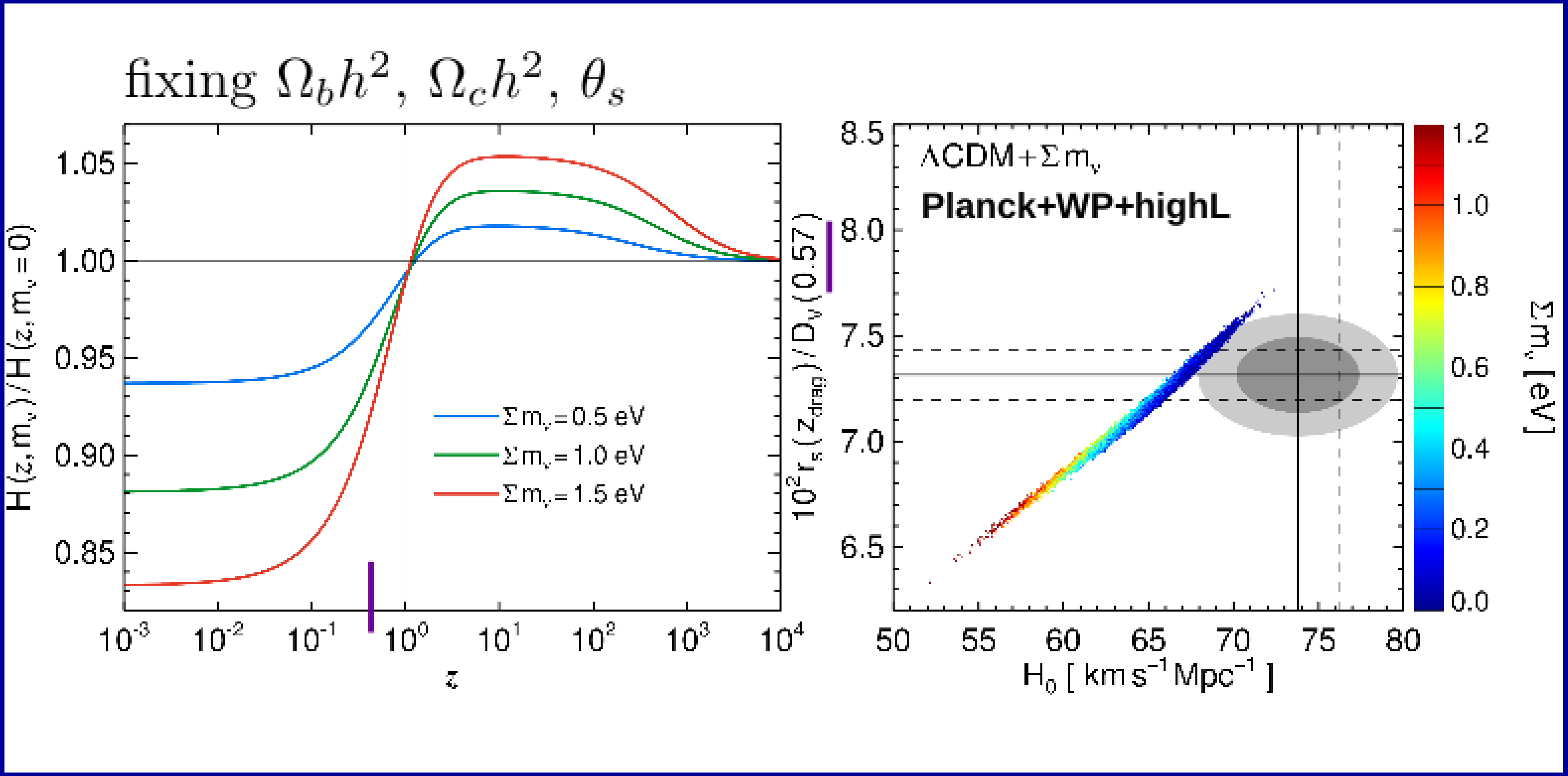


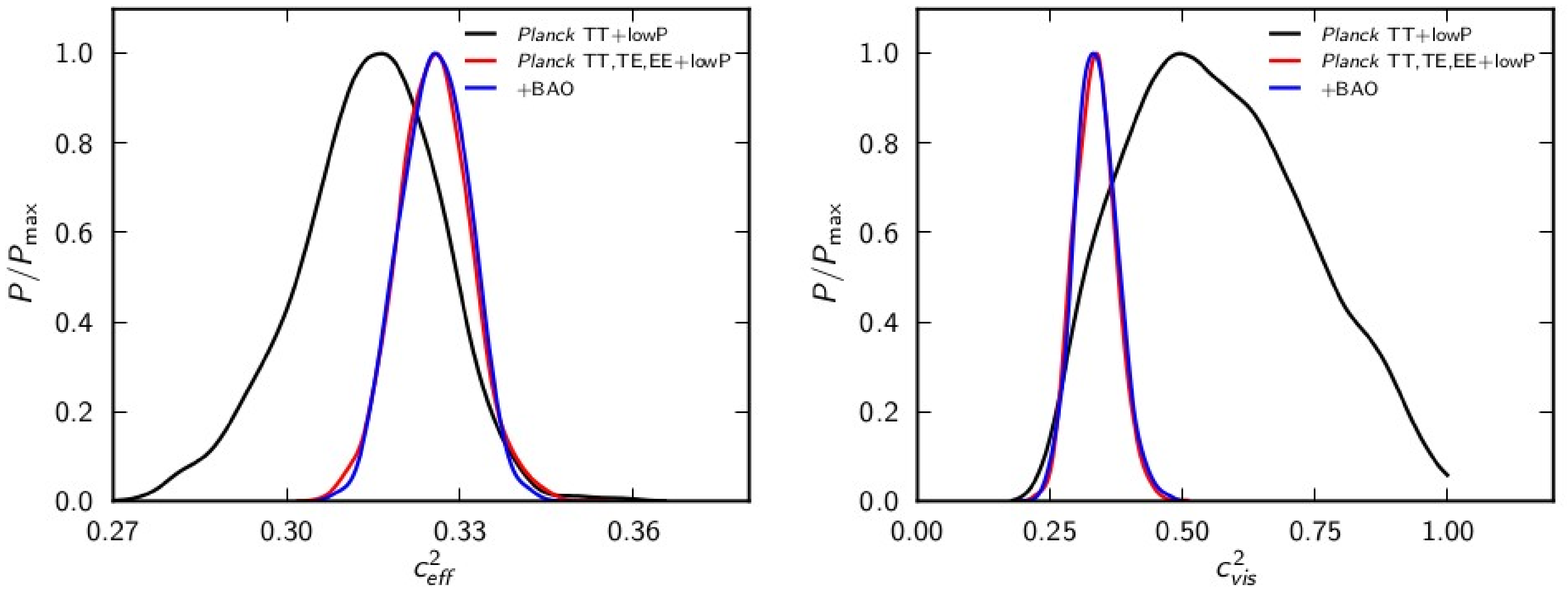
Lensing info from power spectrum included
Lensing info removed
Planck+WP+highL
Planck+WP+highL (A_L)
P/P_{max}
Σm_ν[eV]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.4
0.8
1.2
1.6
2.0



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]
0.0
0.2
0.4
0.6
0.8
1.0
0.0
0.4
0.8
1.2
1.6
2.0

Massive neutrino impact on BAO-H_0-CMB



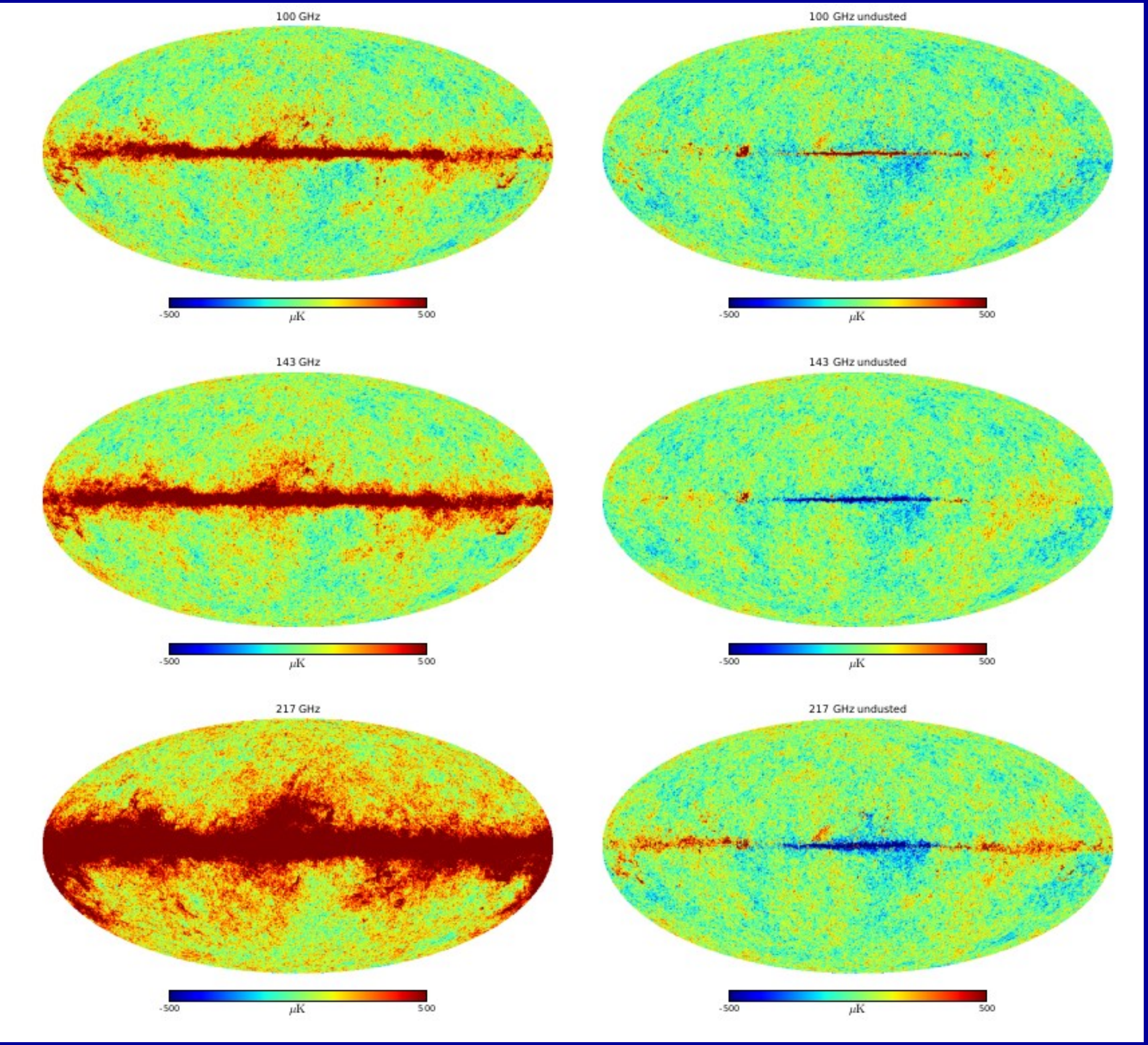


Planck TT+lowP
Planck TT,TE,EE+lowP
+BAO
P/P_{max}
0.0
0.2
0.4
0.6
0.8
1.0
0.27
0.30
0.33
0.36
c^2_{eff}
Planck TT+lowP
Planck TT,TE,EE+lowP
+BAO
P/P_{max}
0.0
0.2
0.4
0.6
0.8
1.0
0.00
0.25
0.50
0.75
1.00
c^2_{vis}

Galactic Cleaning Cross-Check

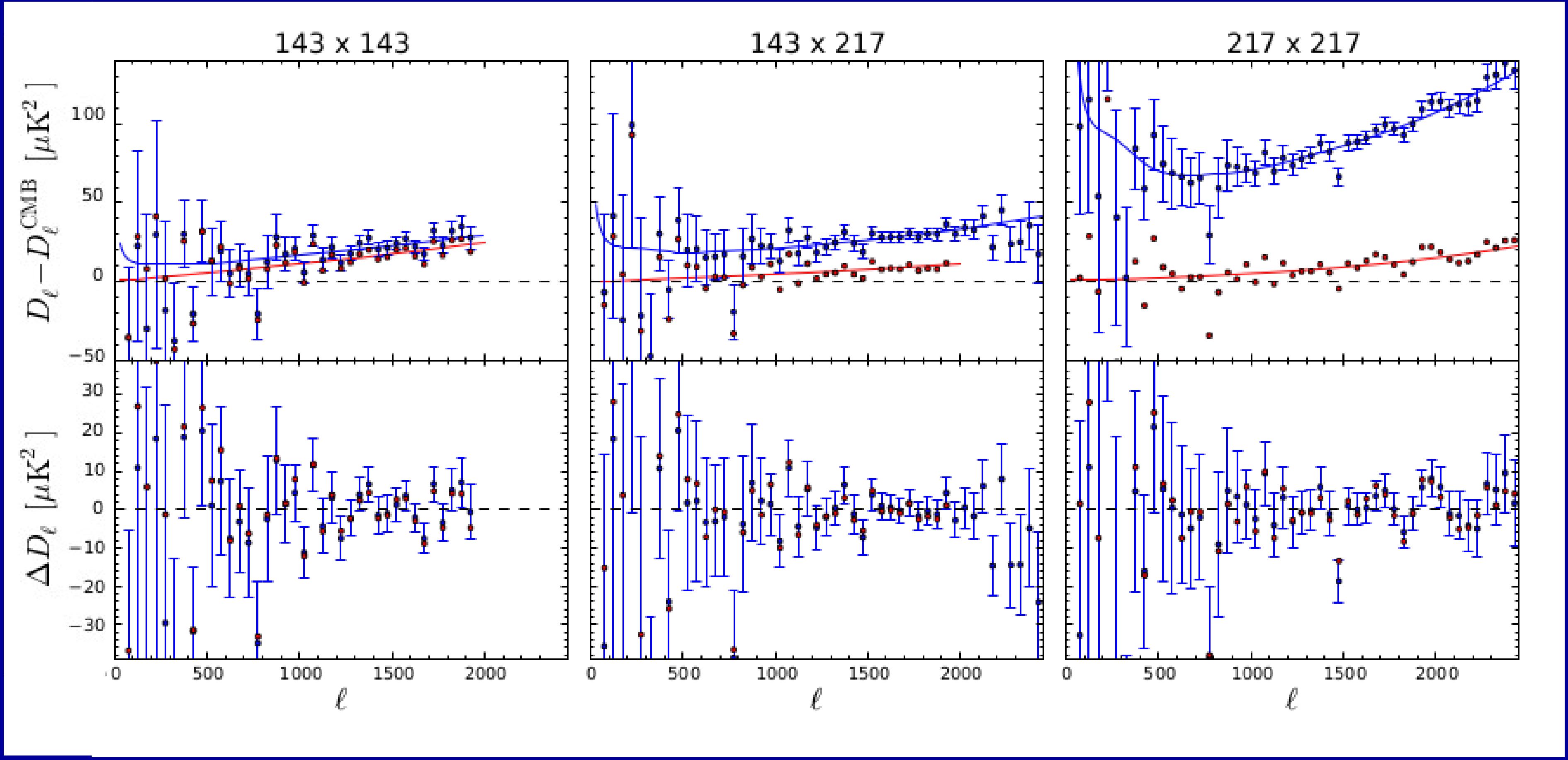
$$T^{\mathrm{clean}} = (T^{\mathrm{freq}} - x\,T^{545})/(1-x)$$

- For the power spectrum analysis we use frequency maps which we clean in two ways
  – Model the power spectrum of the galaxy and subtract it (2013, 2014 baseline)
  – Subtract a high frequency map (“Mspec", new in 2014 for cross check since we use more sky)



Top row: Difference between TT spectrum and CMB best-fit

Mspec (map cleaning)
Plik (2014 baseline)

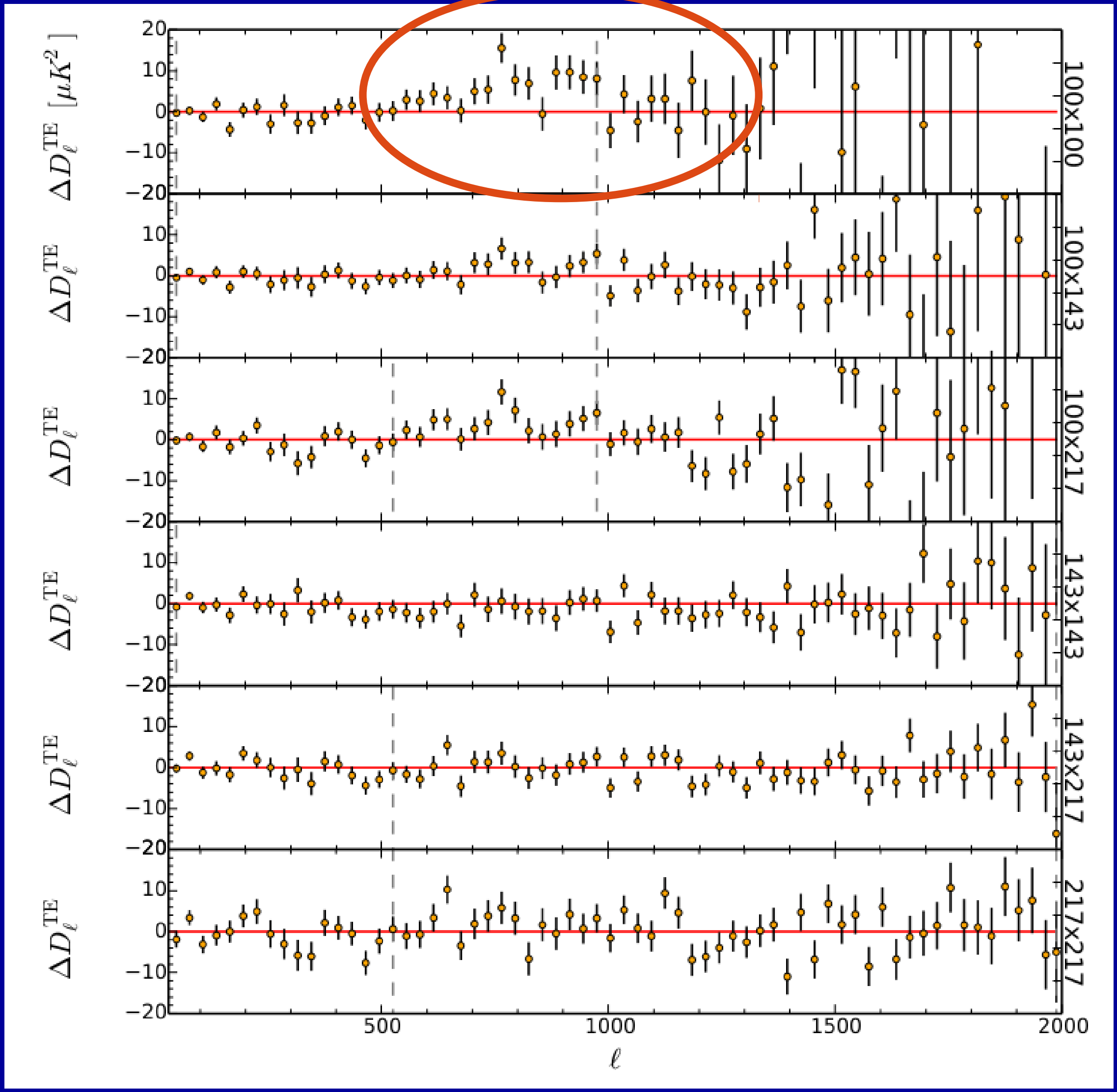


Bottom row: after subtracting the foreground spectrum as well

Excellent power spectrum (and also cosmological parameter) agreement.
=> Galactic dust cleaning is under very good control.

TE & EE systematics

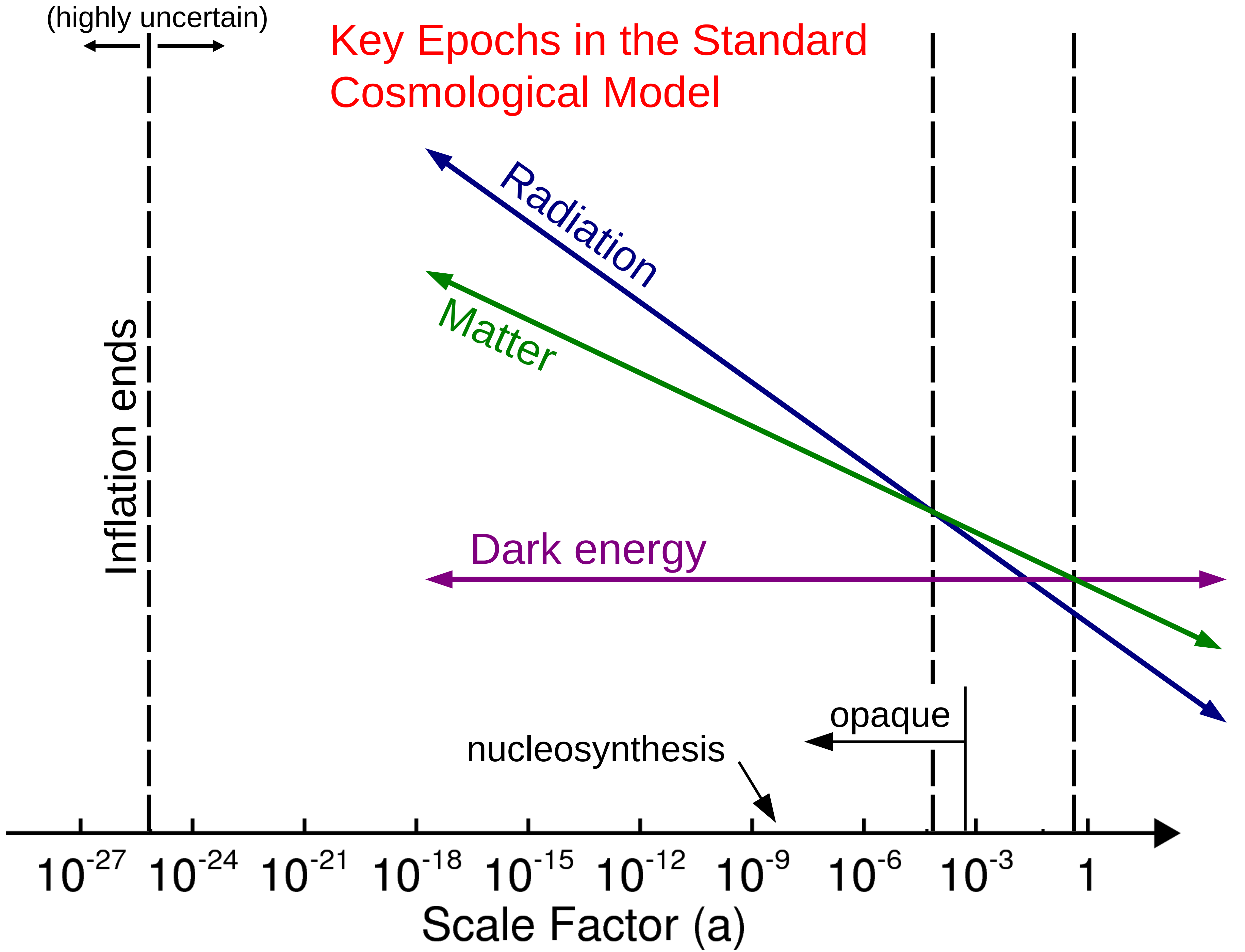
- The polarization power spectra are not yet sufficiently well tested to use in the main analysis.
- There are low-level systematics largely from to T->P leakage due to beam mismatch.
- This will be fixed for 2015



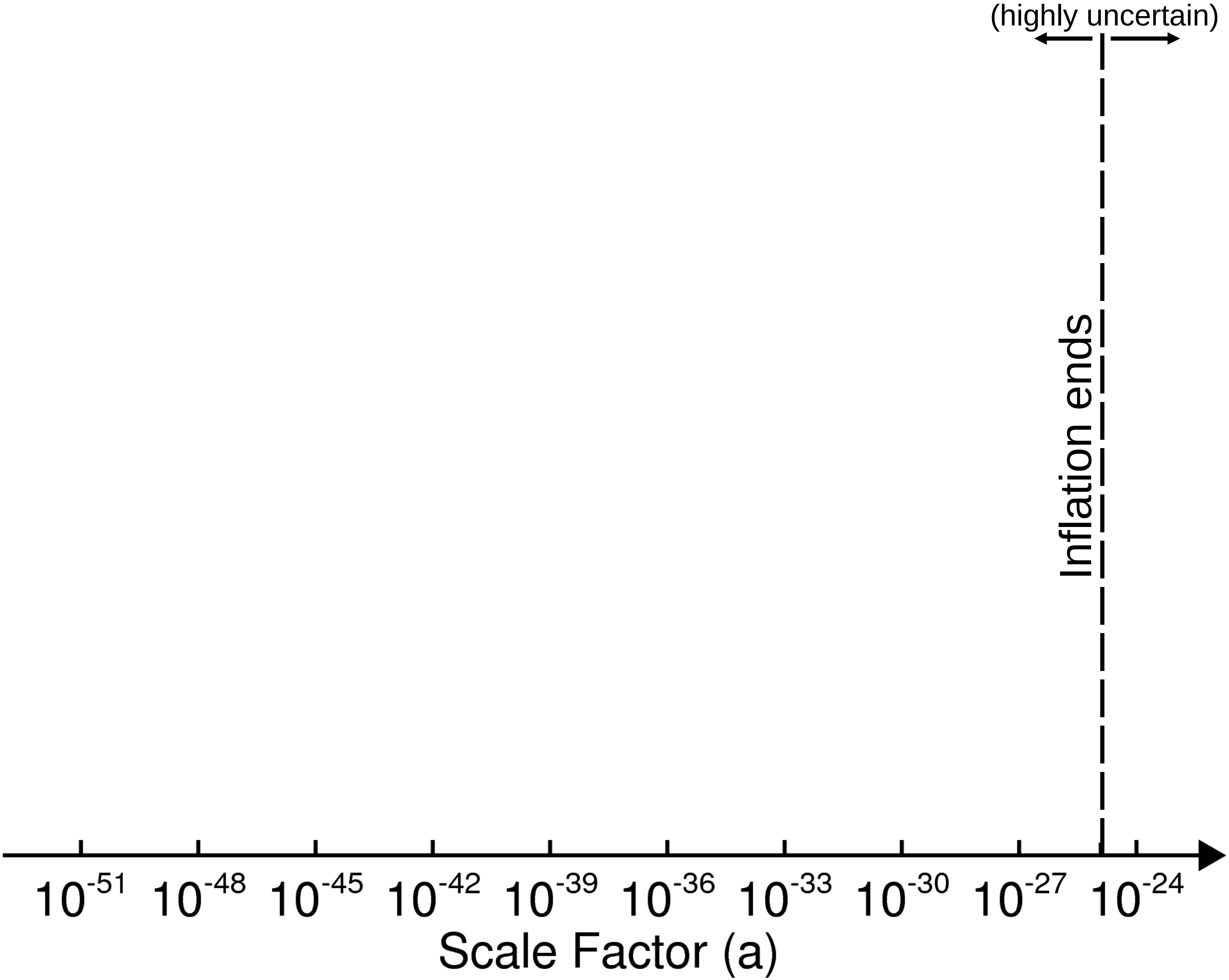
TE spectrum – best-fit CMB (from TT)

Outline

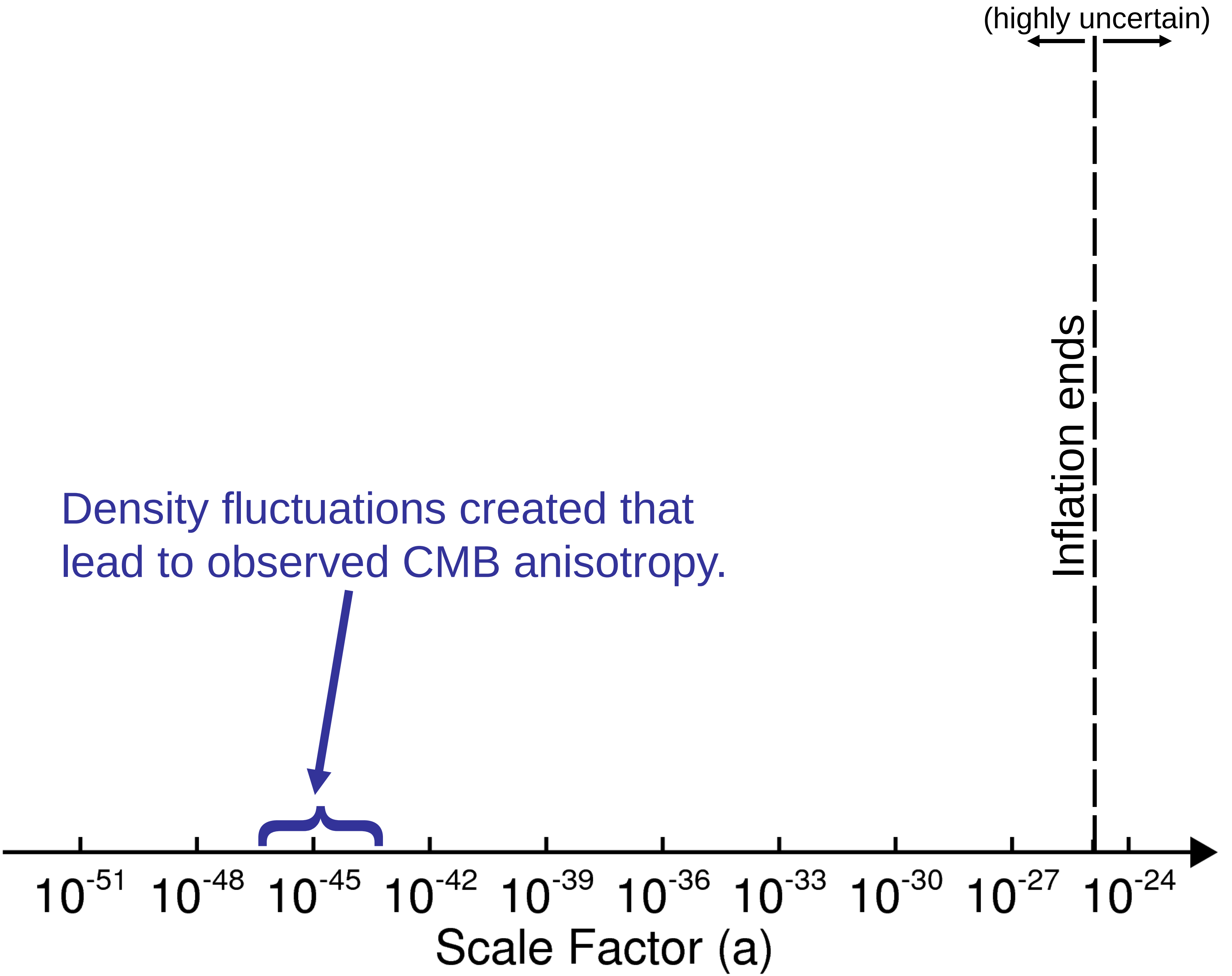
- Planck
- **ΛCDM, the standard model of cosmology, passes another precision test**
- Hands on with the Planck data
- Number of neutrino-like species N_{eff}
  - BAO and H_0
  - Damping and acoustic oscillation phase shifts
  - Constraints on axions and axion-like particles (ALPs)
- Sum of neutrino masses Σm_ν
  - Gravitational lensing

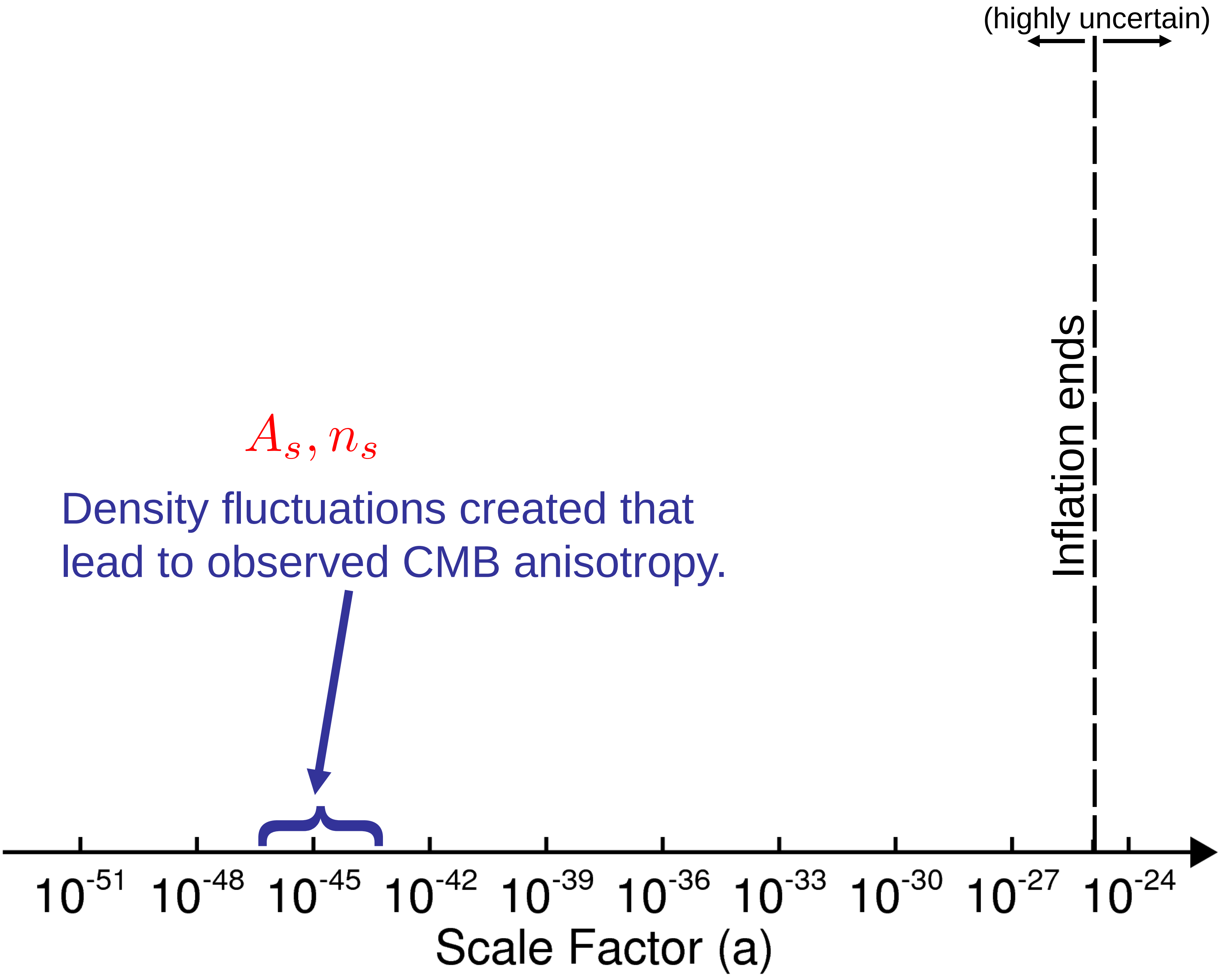


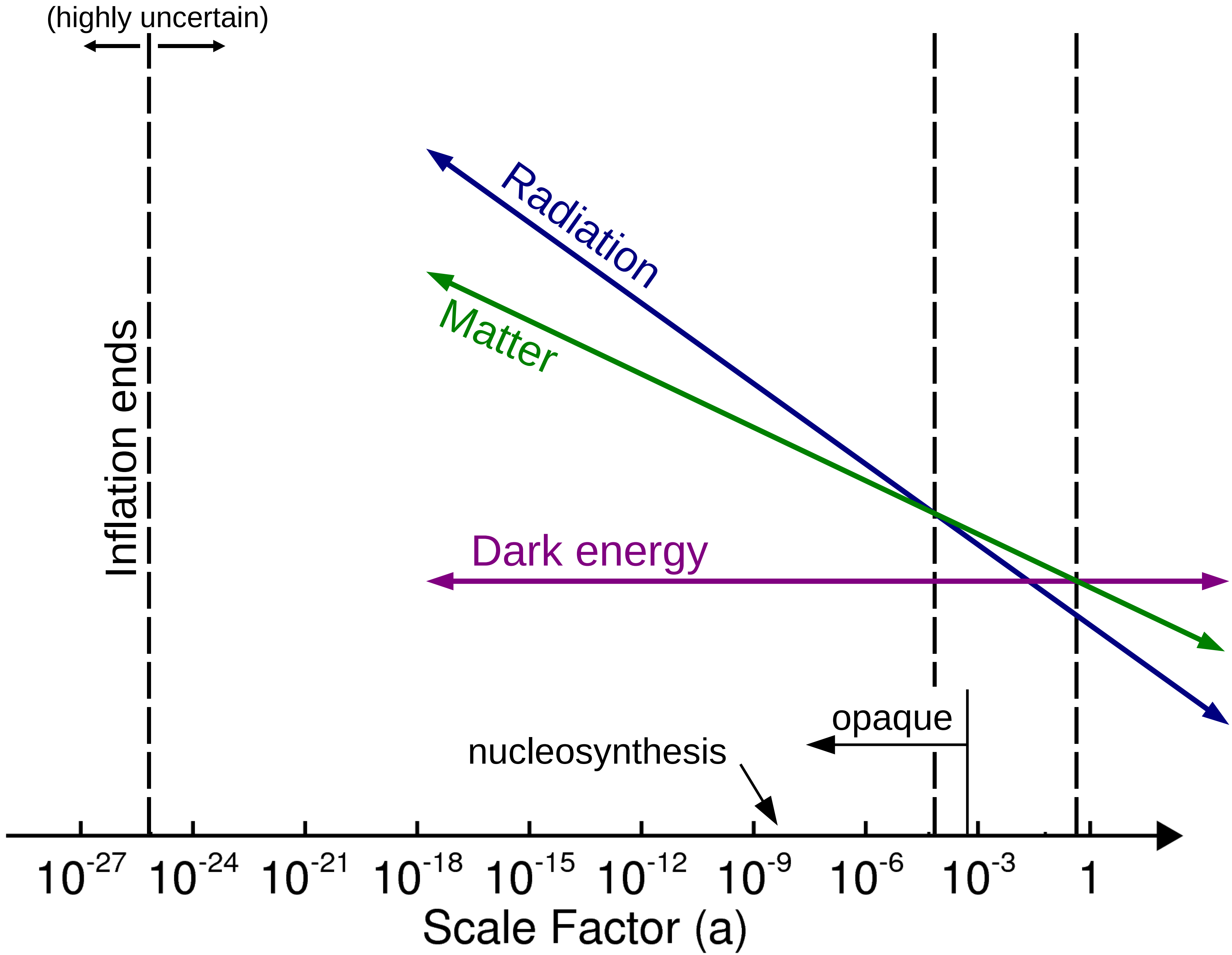
Key Epochs in the Standard Cosmological Model
(highly uncertain)
Inflation ends
Radiation
Matter
Dark energy
opaque
nucleosynthesis
10^{-27} 10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1
Scale Factor (a)



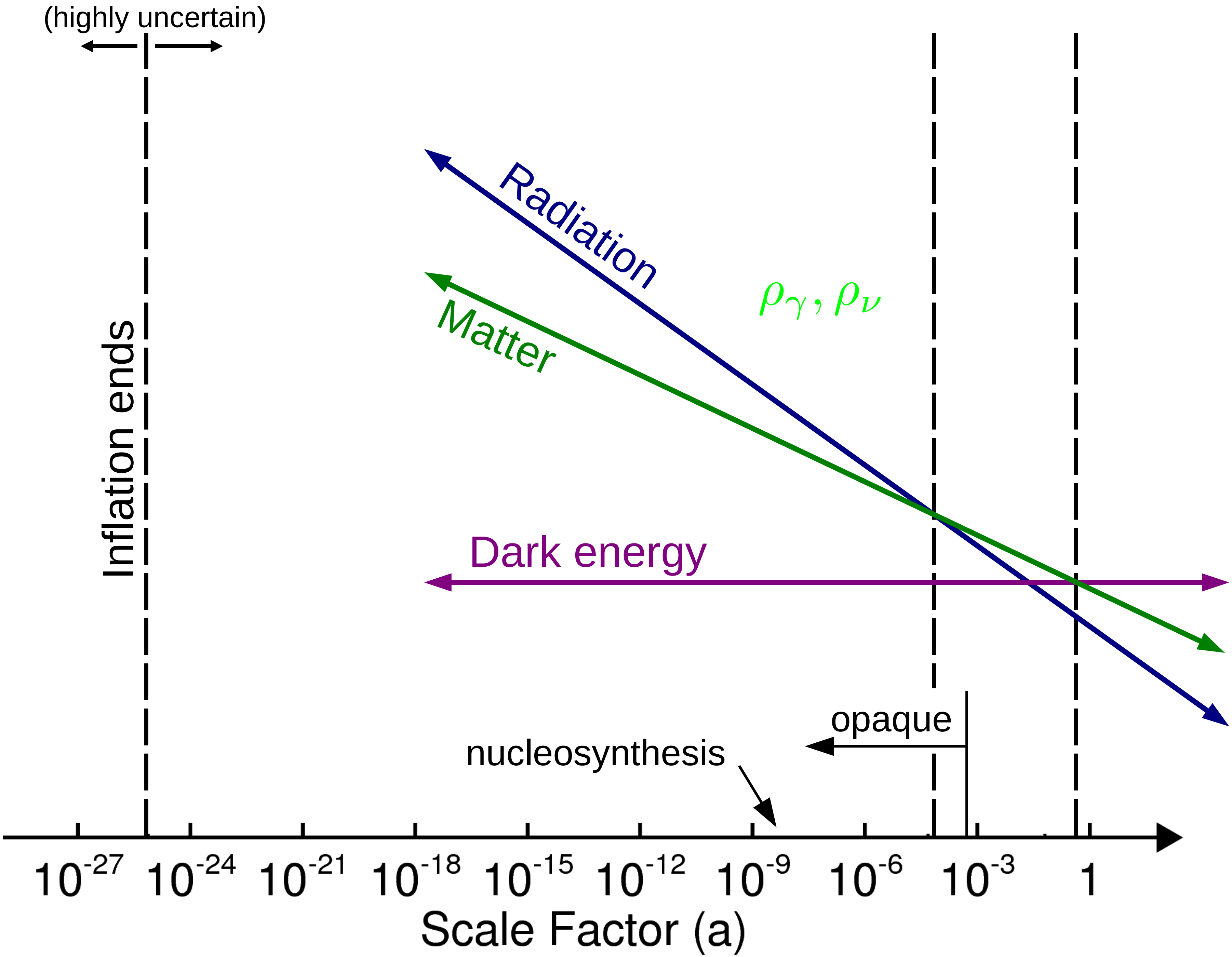
(highly uncertain)
Inflation ends
10^{-51} 10^{-48} 10^{-45} 10^{-42} 10^{-39} 10^{-36} 10^{-33} 10^{-30} 10^{-27} 10^{-24}
Scale Factor (a)


(highly uncertain)
Inflation ends
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)

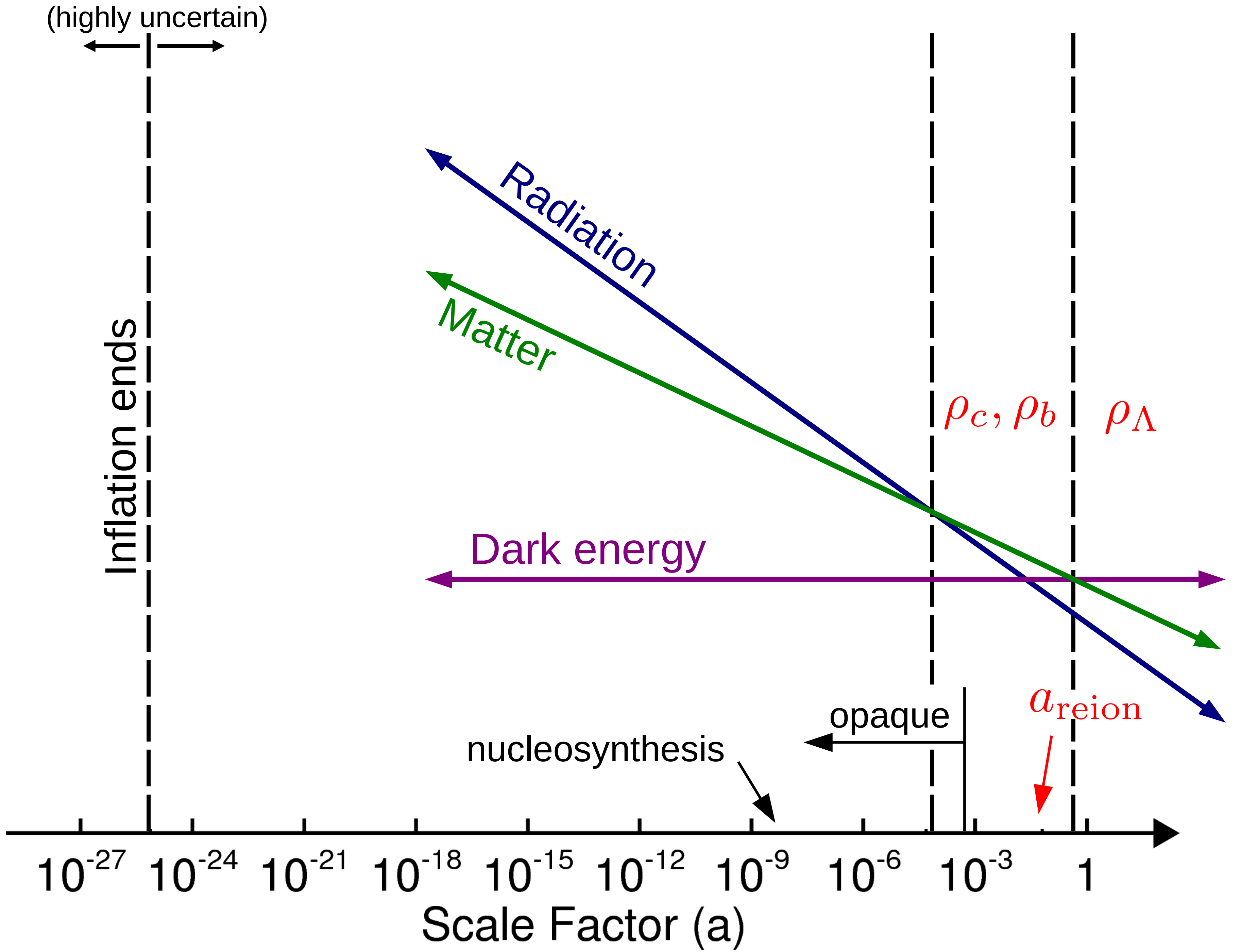

(highly uncertain)
Inflation ends
A_s, n_s
Density fluctuations created that
lead to observed CMB anisotropy.
10^{-51} 10^{-48} 10^{-45} 10^{-42} 10^{-39} 10^{-36} 10^{-33} 10^{-30} 10^{-27} 10^{-24}
Scale Factor (a)



(highly uncertain)
Inflation ends
Radiation
Matter
Dark energy
opaque
nucleosynthesis
10^{-27} 10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1
Scale Factor (a)



(highly uncertain)
Inflation ends
Radiation
Matter
ρ_γ, ρ_ν
Dark energy
opaque
nucleosynthesis
10^{-27} 10^{-24} 10^{-21} 10^{-18} 10^{-15} 10^{-12} 10^{-9} 10^{-6} 10^{-3} 1
Scale Factor (a)


(highly uncertain)
Inflation ends
Radiation
Matter
Dark energy
ρ_c, ρ_b
ρ_Λ
$a_{\rm reion}$
opaque
nucleosynthesis
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

Optical depth to reionization

$a_{\rm reion} \to \tau$

The six-parameter ΛCDM model

$$A_s, n_s$$

Governs Spectrum of
Primordial fluctuations

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

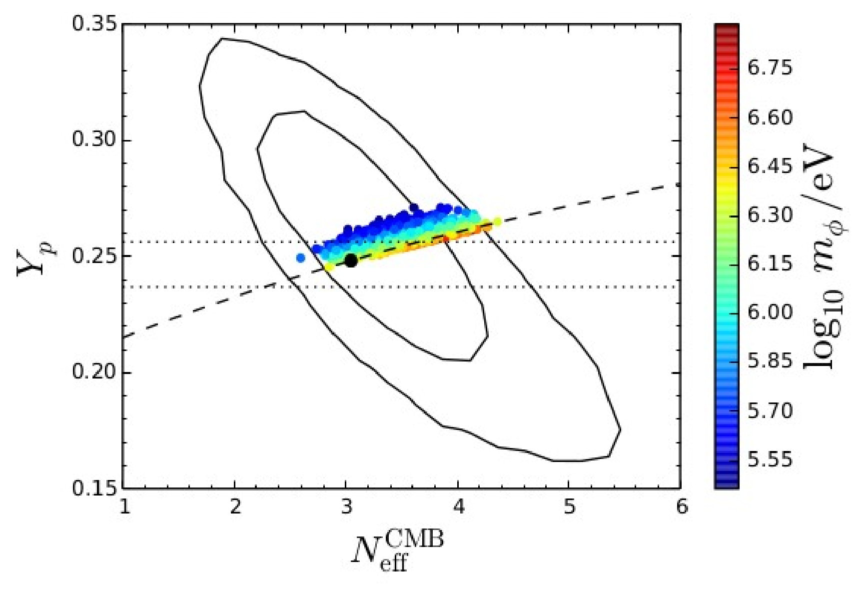
Matter Content

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

Extensions

Optical depth to
reionization

$$a_{\mathrm{reion}} \to \tau$$



0.35
0.30
0.25
0.20
0.15
Y_p
1
2
3
4
5
6
$N_{\rm eff}^{\rm CMB}$
6.75
6.60
6.45
6.30
6.15
6.00
5.85
5.70
5.55
$\log_{10}\, m_\phi/{\rm eV}$

The orbit

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