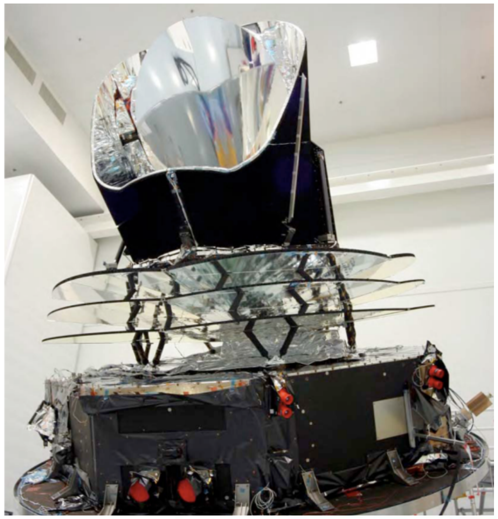
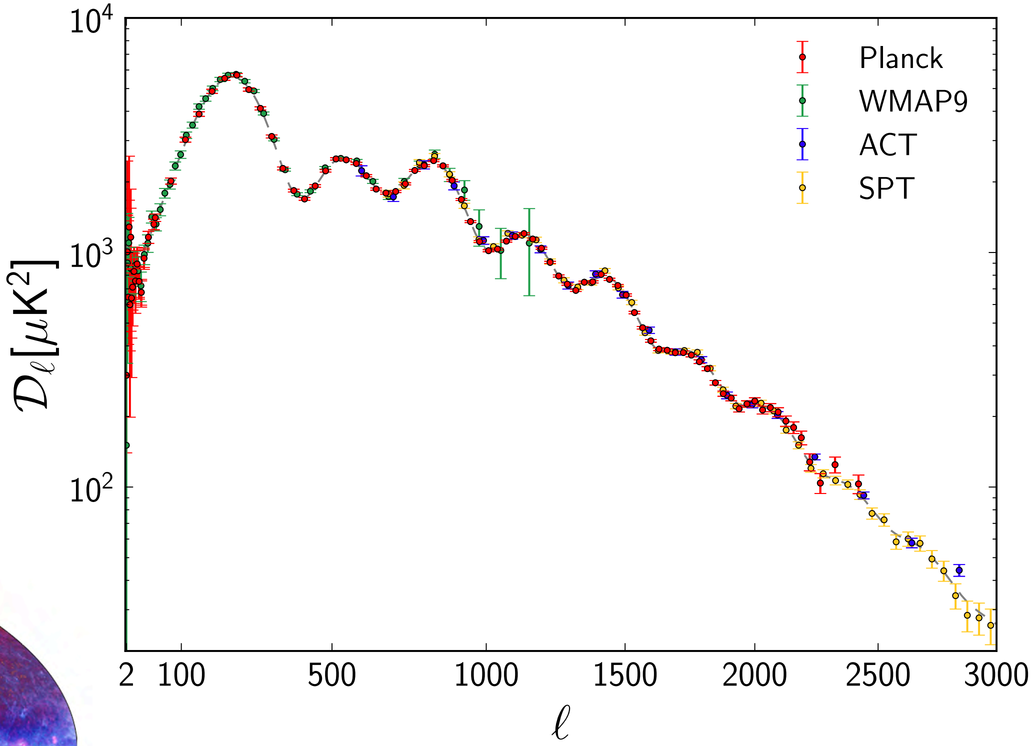
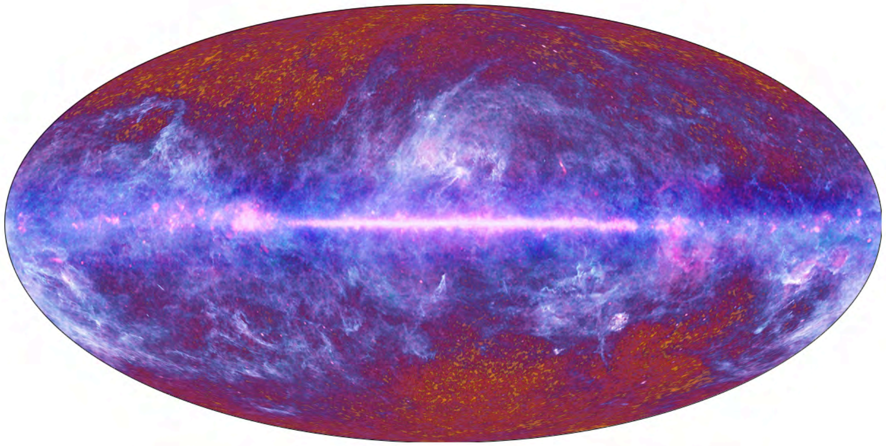
Recent Results from the Planck Satellite



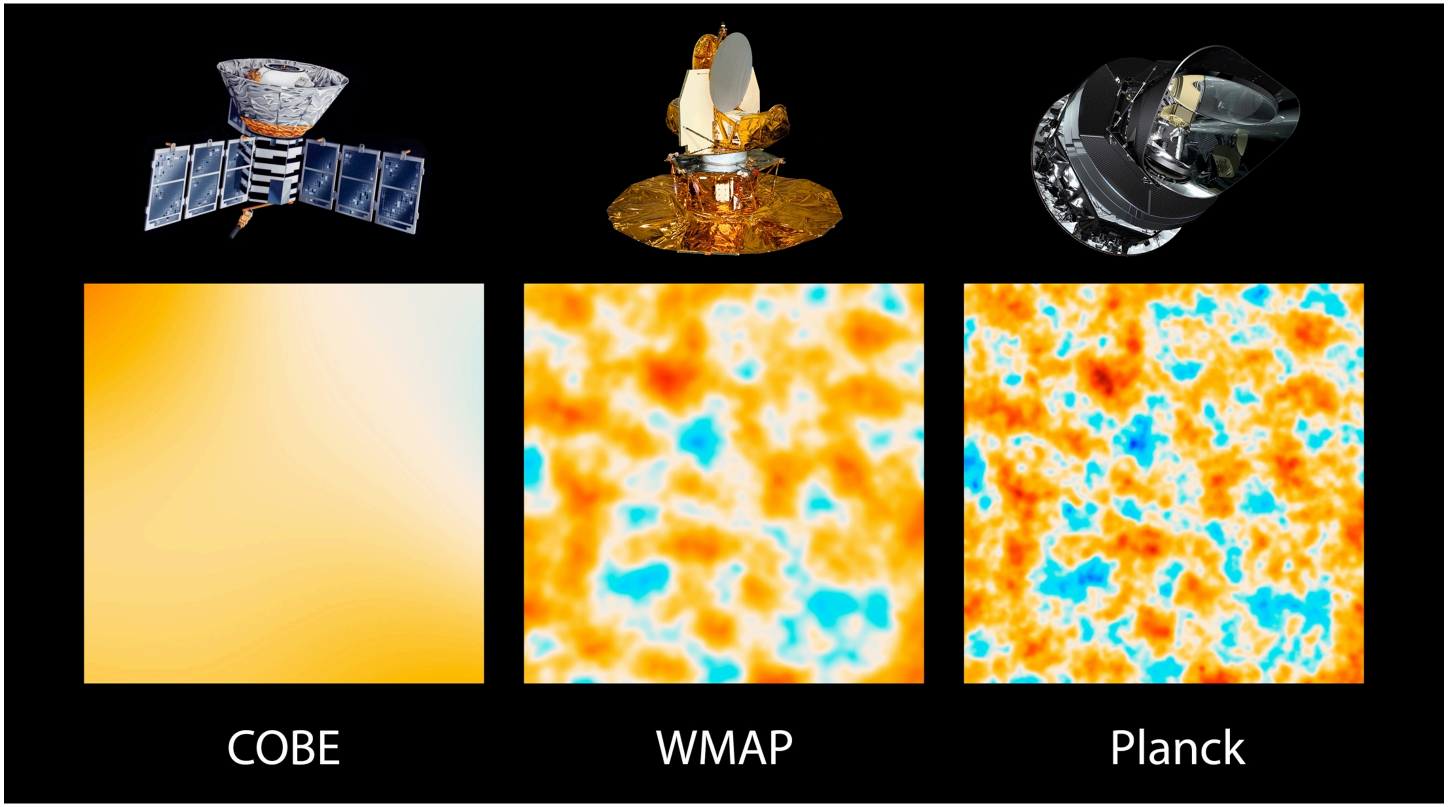




Sarah Church

KIPAC, Stanford University

Planck – 3rd generation CMB satellite

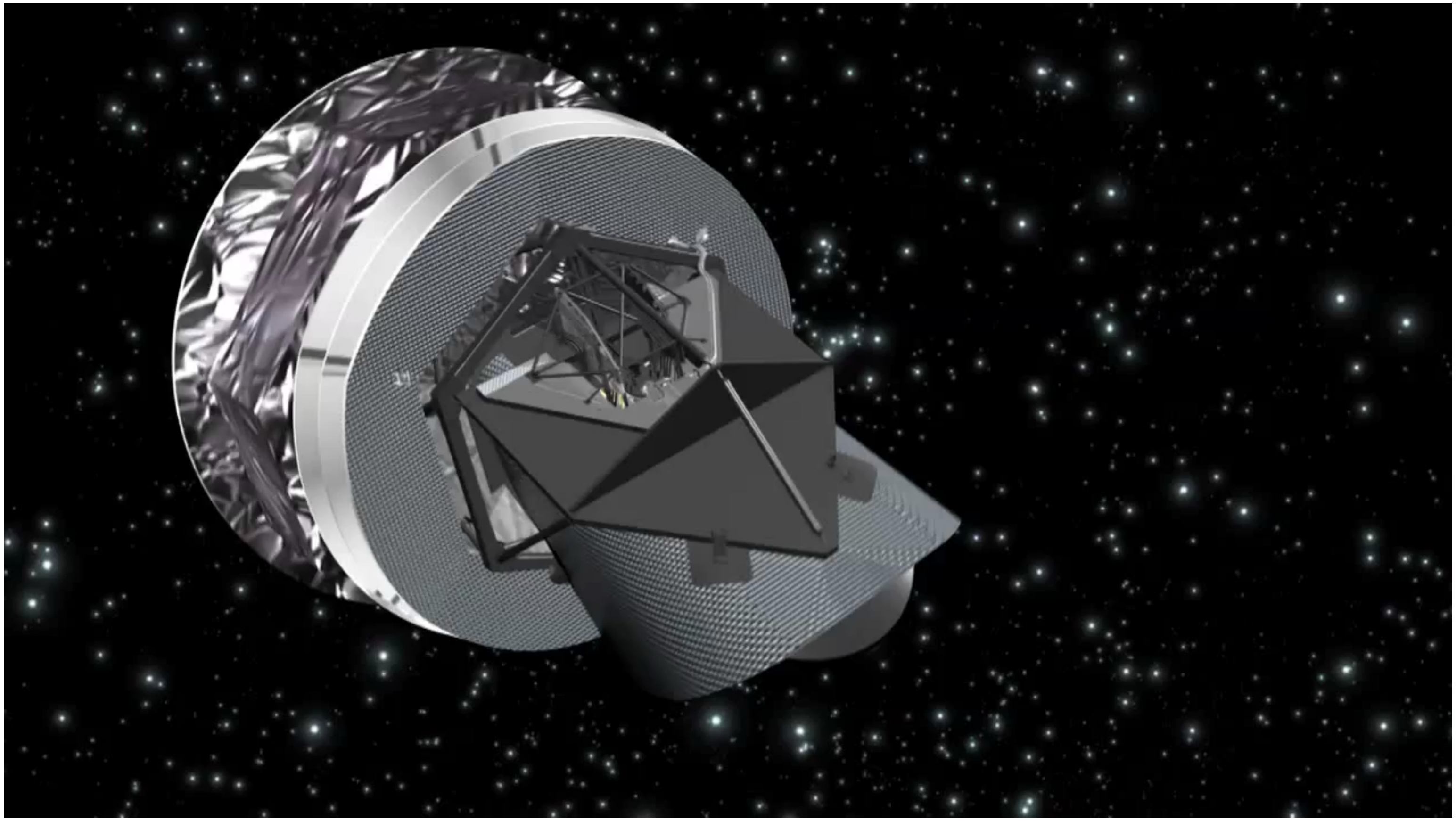


Planck compared to WMAP:

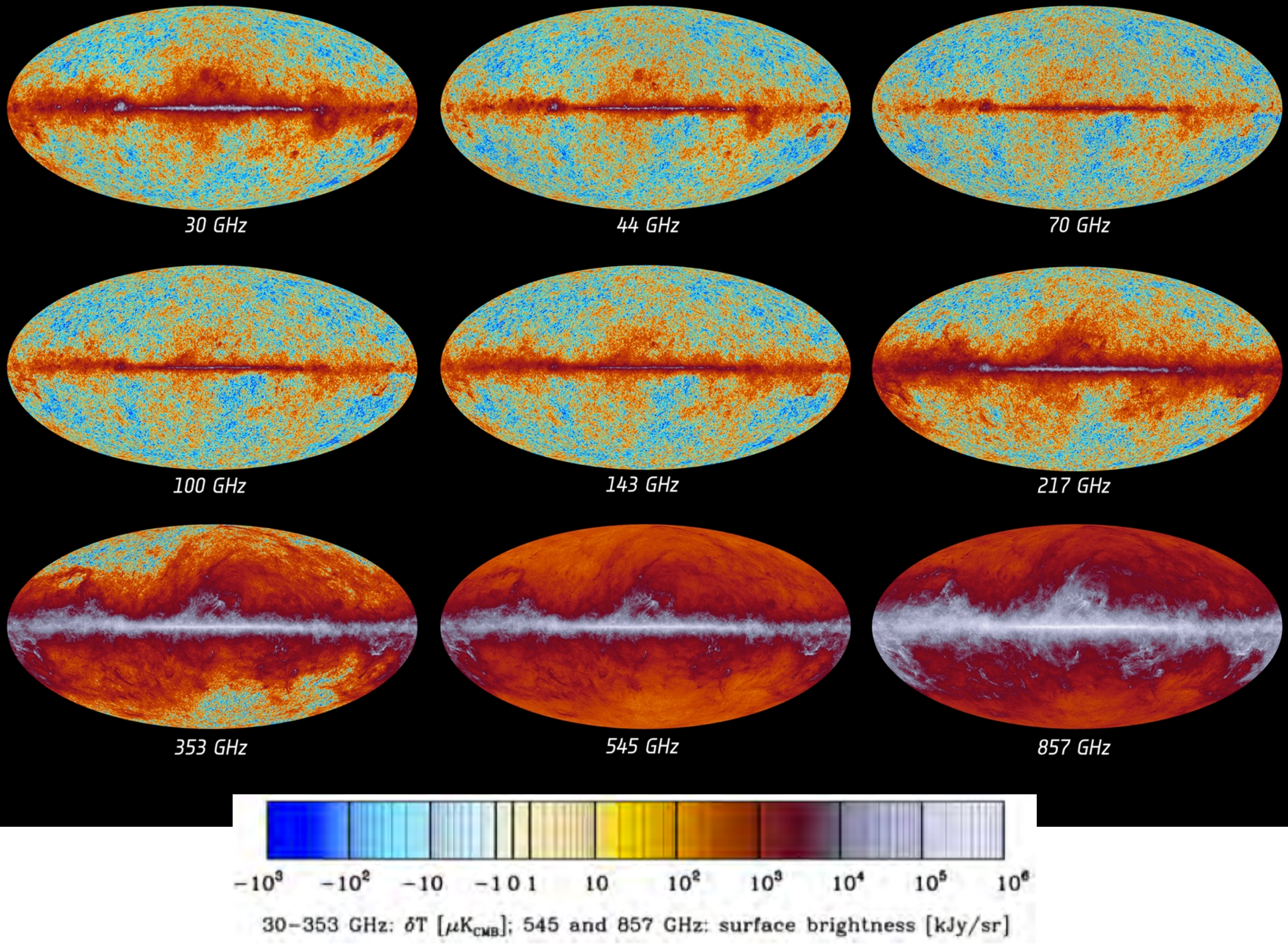
- 3x the angular resolution
- 25x the sensitivity,
- broader frequency coverage

The Planck Satellite

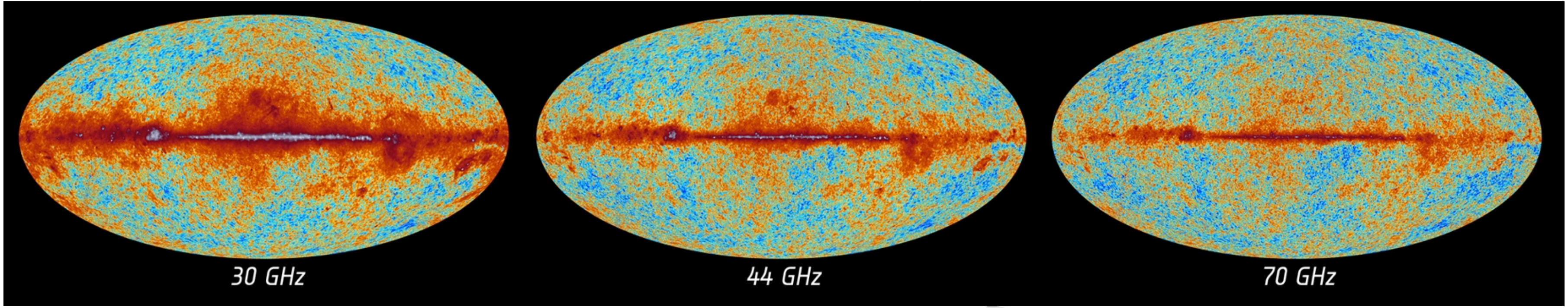
- Launched May 2009
- Full-sky maps at ~25 to ~1000 GHz
- March 2013 data release covers 15.5 months data

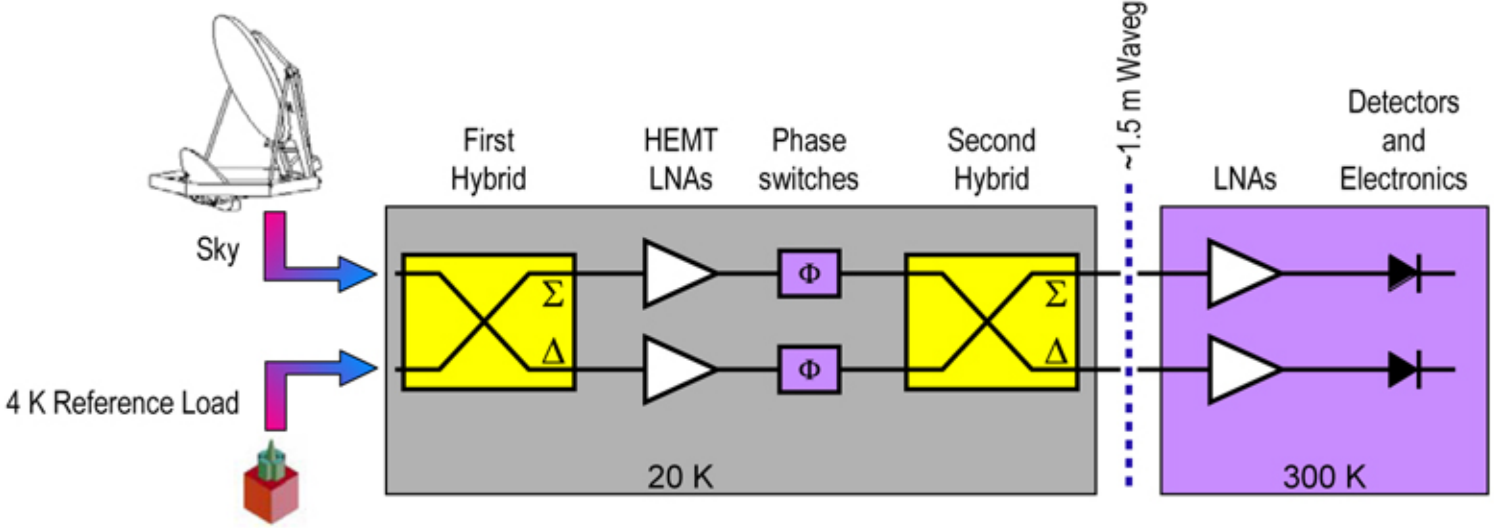


The sky as seen by Planck

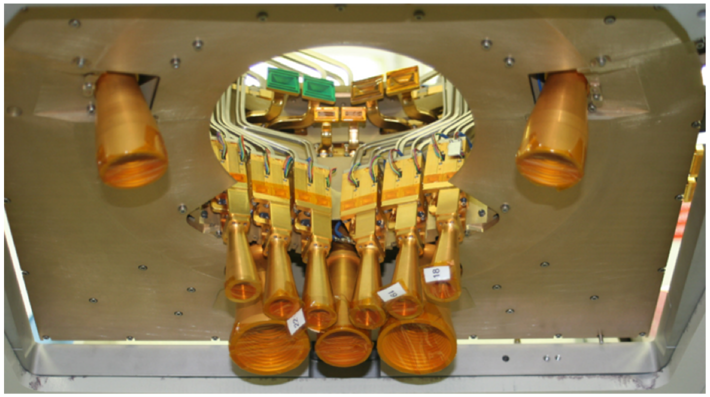


Planck Low Frequency Instrument



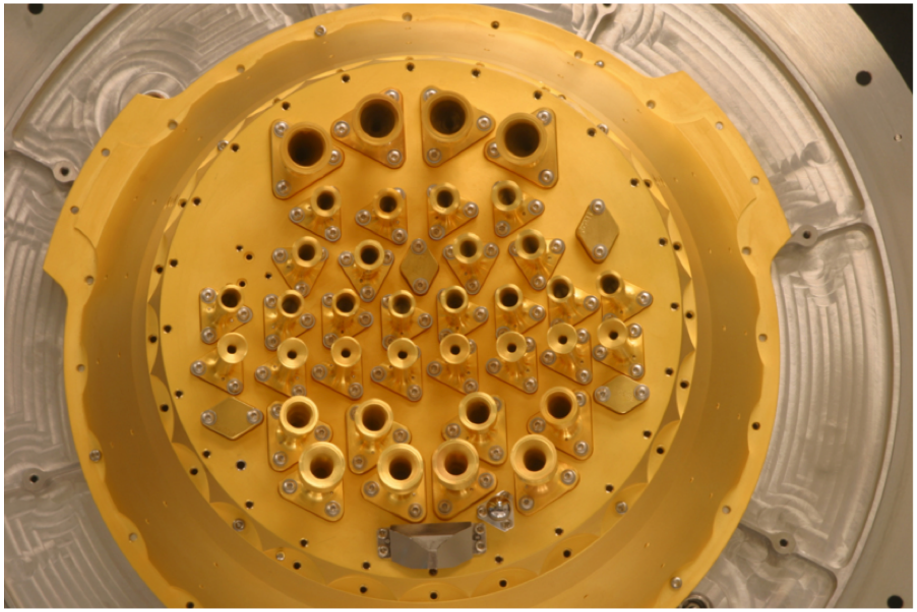


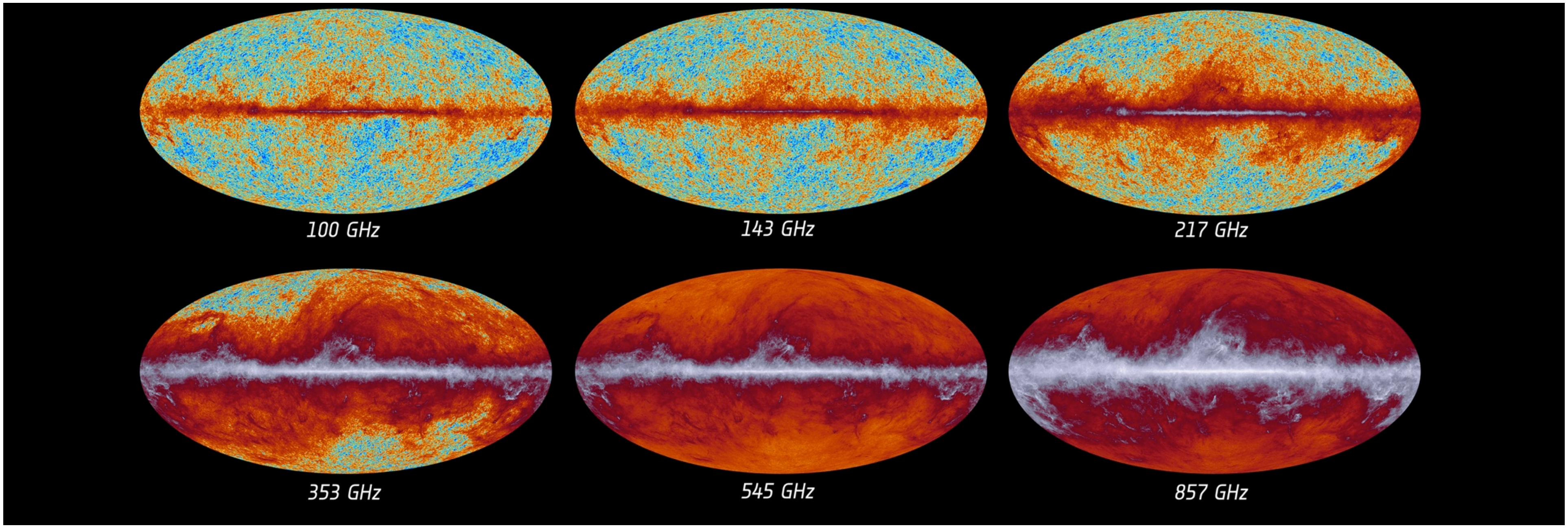
- pseudo-correlation radiometers, based on HEMT low noise amplifiers



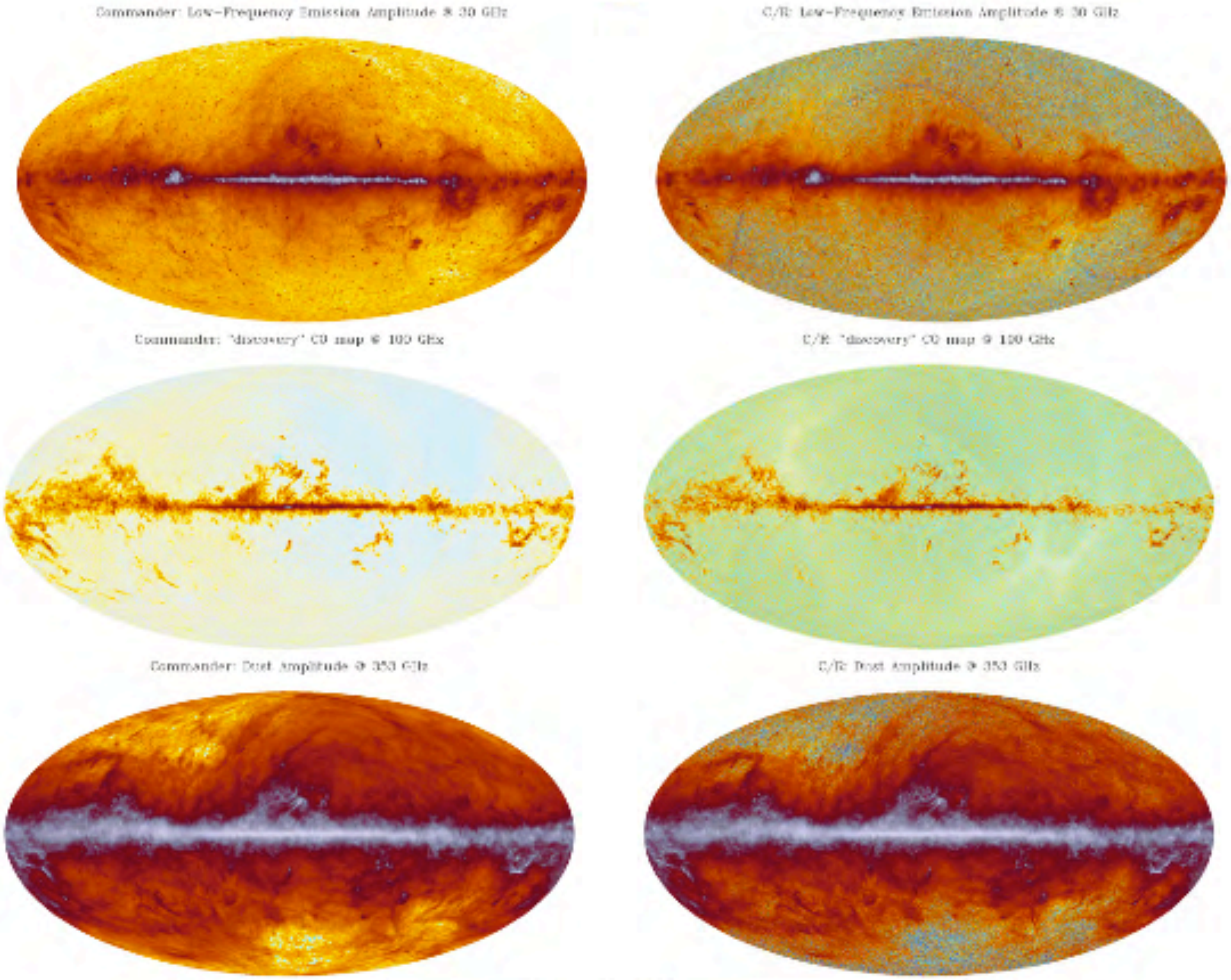
High Frequency Instrument

- NTD-Germanium bolometric detectors





Broad Frequency Coverage Allows Foreground Removal



Low frequency

Carbon Monoxide

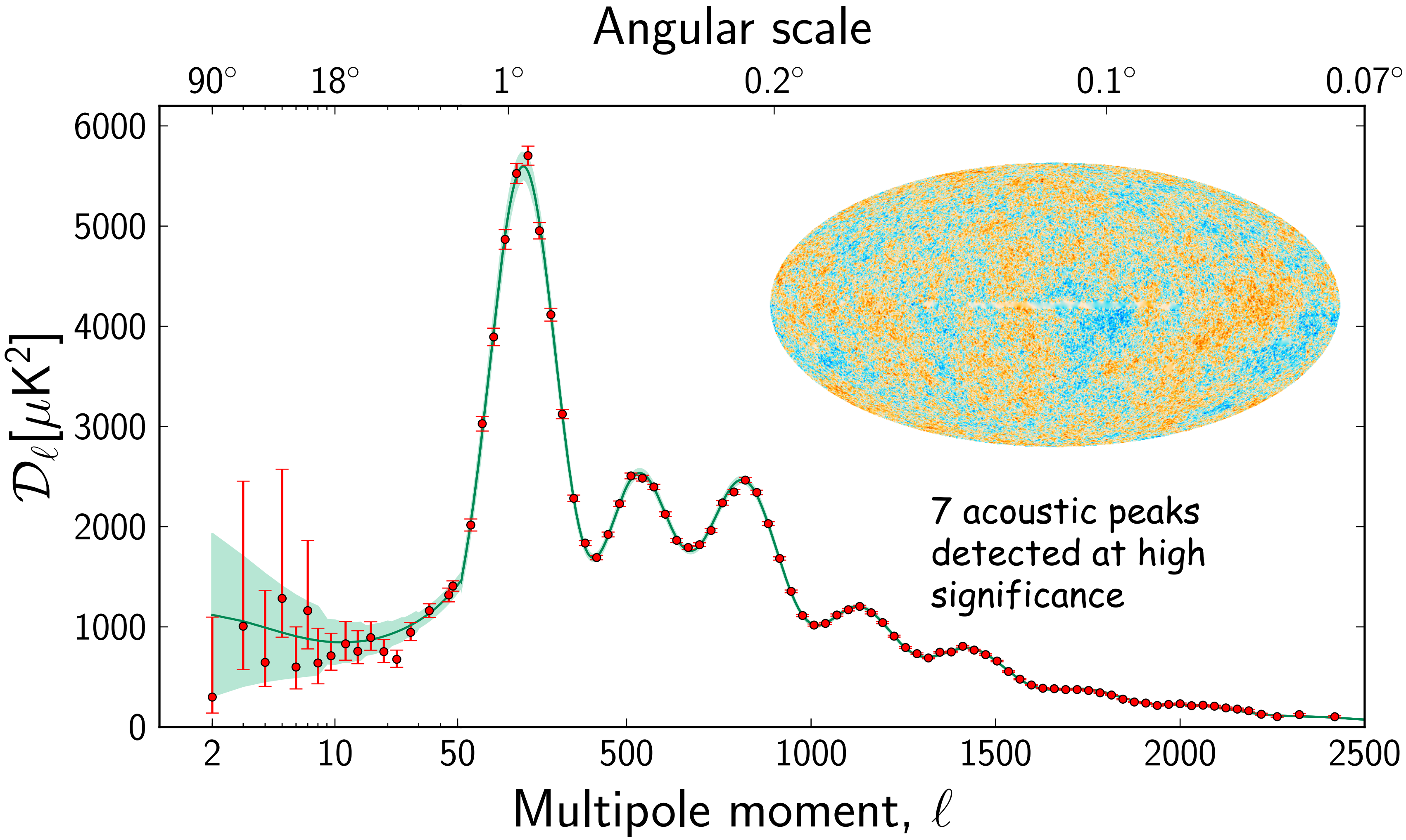
Dust

1 degree

7′

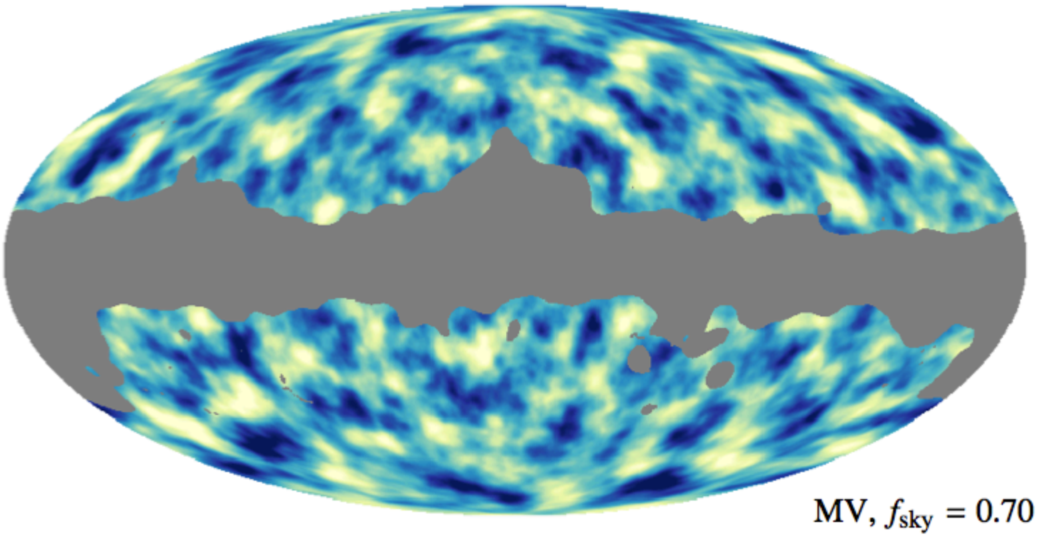
Selected Planck Data Products

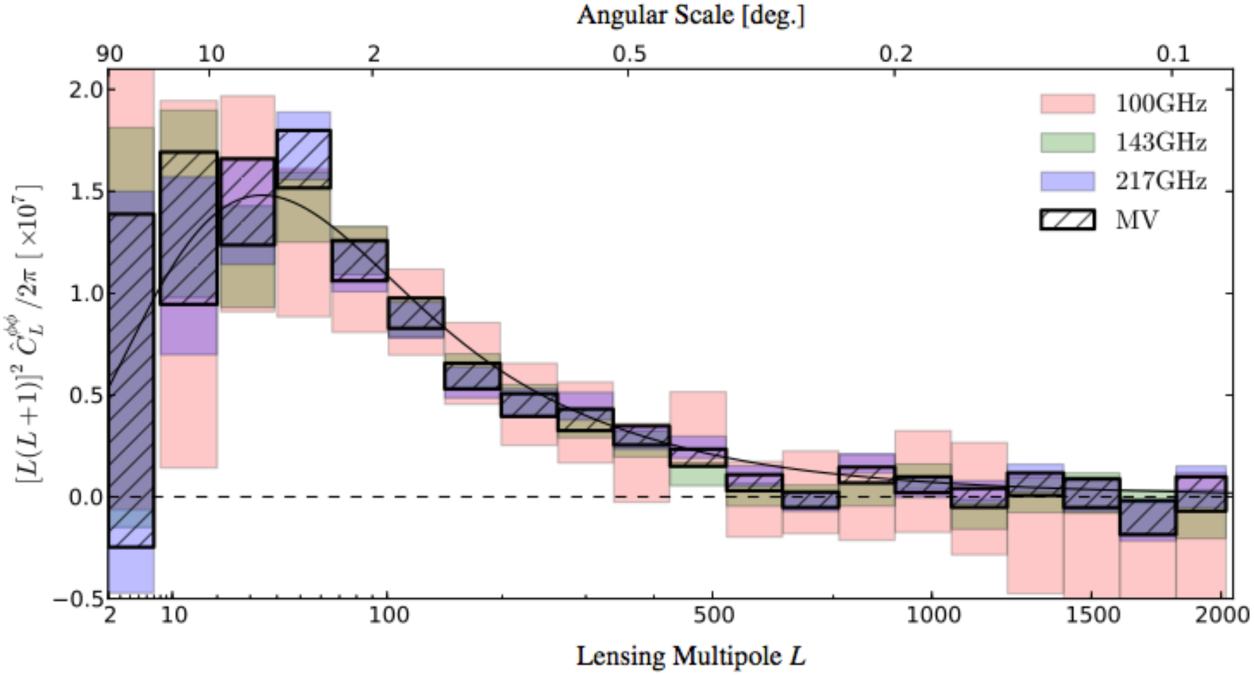
CMB Map and Power Spectrum

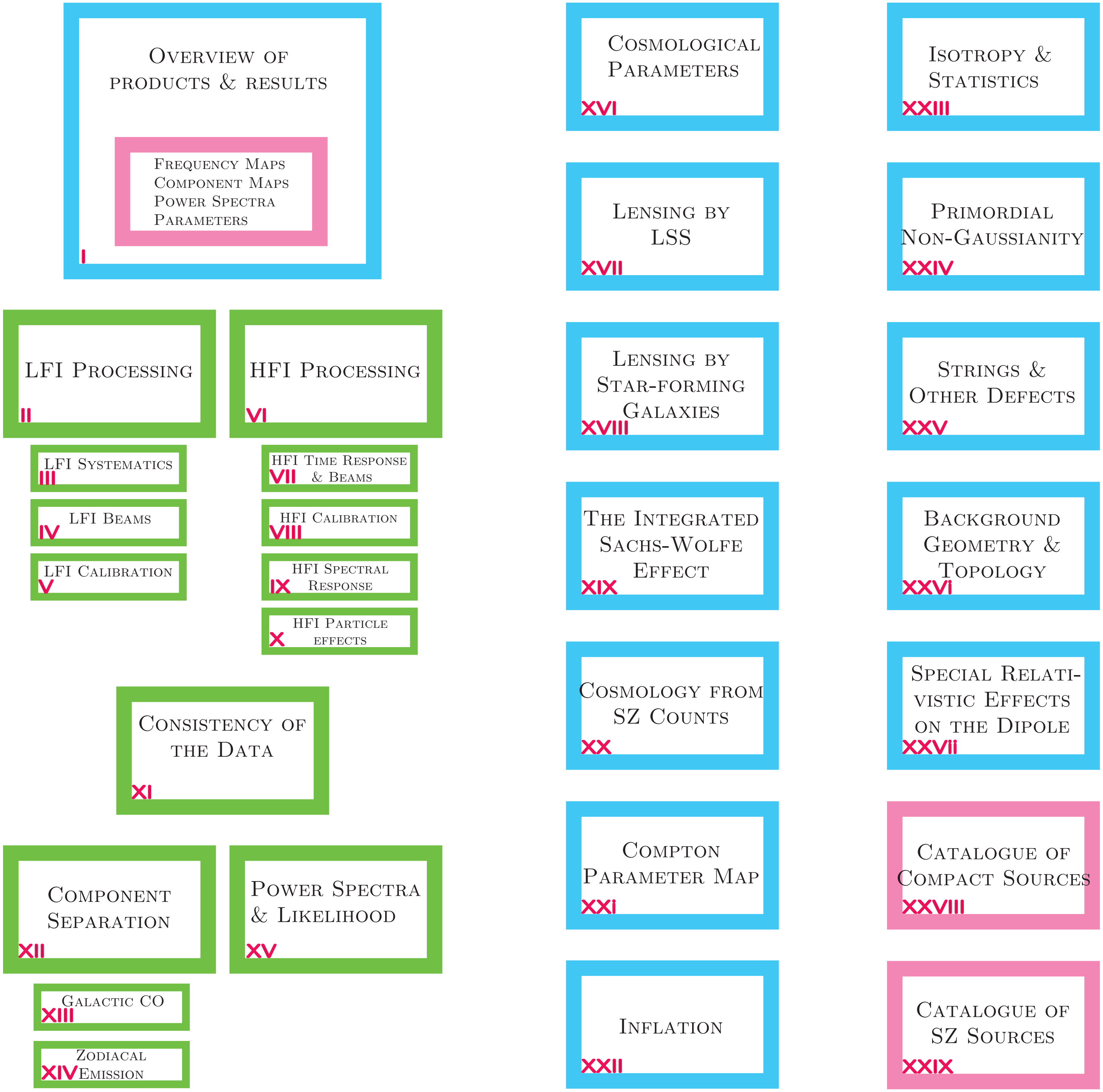


7 acoustic peaks detected at high significance

Gravitational potential of matter between us and last scattering reconstructed from lensing of CMB fluctuations


MV, $f_{\rm sky}$ = 0.70




OVERVIEW OF PRODUCTS & RESULTS
FREQUENCY MAPS
COMPONENT MAPS
POWER SPECTRA
PARAMETERS
I
LFI PROCESSING
II
LFI SYSTEMATICS
III
LFI BEAMS
IV
LFI CALIBRATION
V
HFI PROCESSING
VI
HFI TIME RESPONSE & BEAMS
VII
HFI CALIBRATION
VIII
HFI SPECTRAL RESPONSE
IX
HFI PARTICLE EFFECTS
X
CONSISTENCY OF THE DATA
XI
COMPONENT SEPARATION
XII
GALACTIC CO
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ZODIACAL EMISSION
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COSMOLOGICAL PARAMETERS
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CATALOGUE OF COMPACT SOURCES
XXVIII
CATALOGUE OF SZ SOURCES
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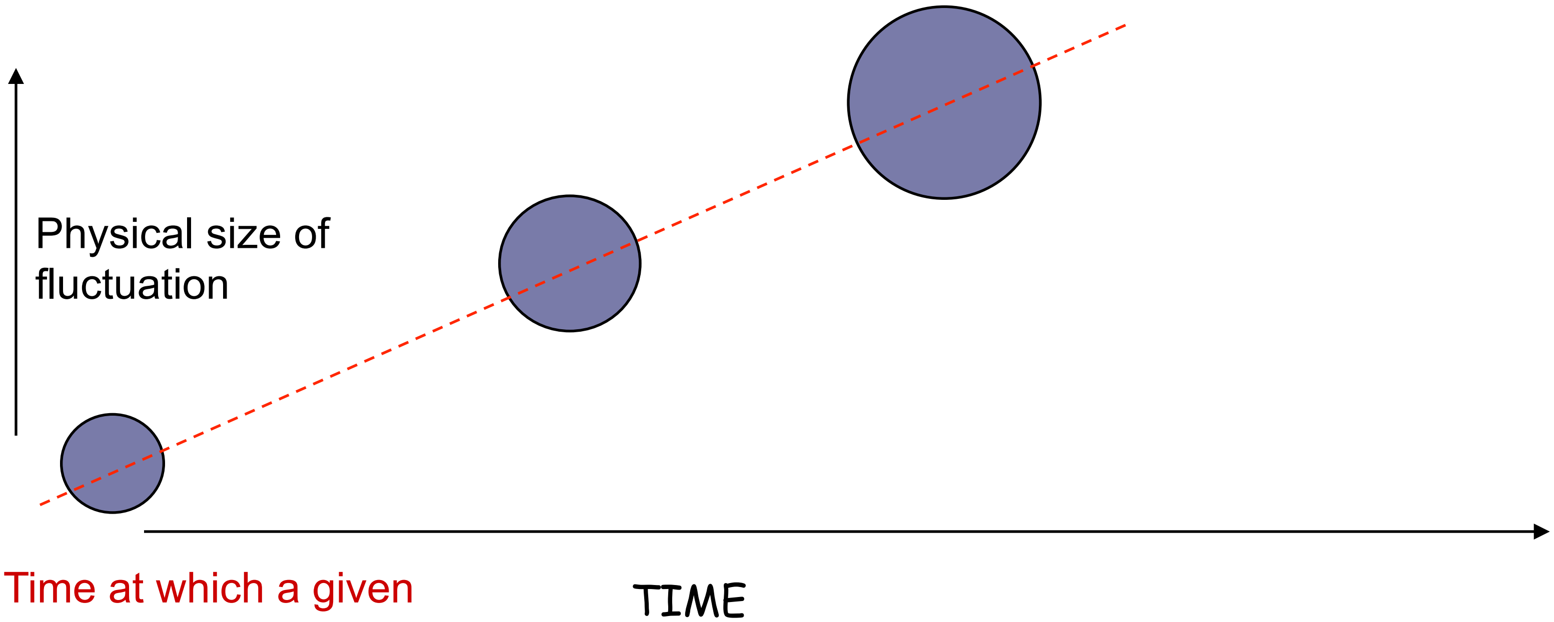
Science Highlights that I'll Discuss

- Powerful test of ΛCDM
  - Standard theory of particle physics + 6 parameter model gives excellent fit to Planck data
  - Some tension in best fit parameter values compared to other data sets, e.g. high Ω_m, low H_0
- Extensions to the model
  - Neutrino Constraints
  - Inflationary Parameters

The physics of CMB fluctuations are straightforward

- Initial power spectrum of scalar modes and tensor modes (arise naturally from quantum fluctuations stretched out by inflation)
- Matter fluctuations begin to collapse as they enter the horizon



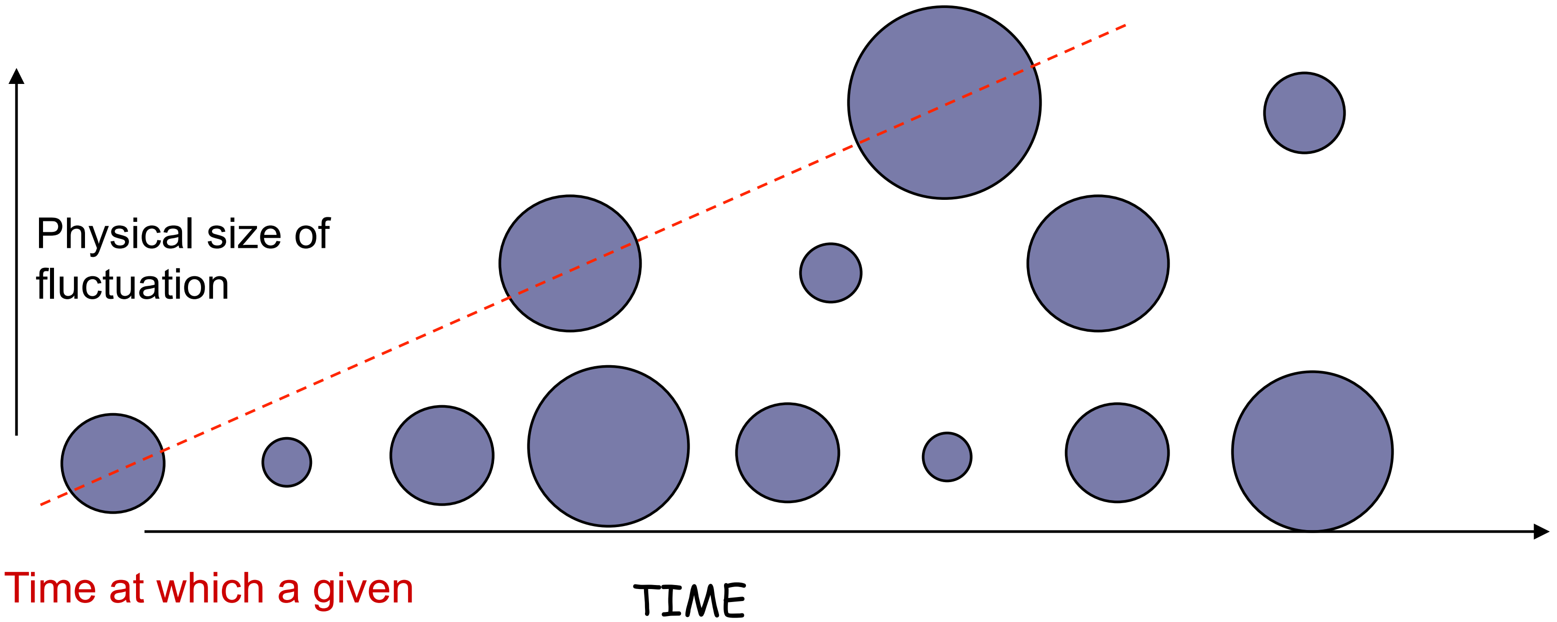
Physical size of fluctuation

TIME

Time at which a given fluctuation enters the horizon

The physics of CMB fluctuations are straightforward

- Initial power spectrum of scalar modes and tensor modes (arise naturally from quantum fluctuations stretched out by inflation)
- Matter fluctuations begin to collapse as they enter the horizon
- Gravity + radiation pressure couple the baryons and the photon background ⇒ oscillations in the photon-baryon fluid



Time at which a given fluctuation enters the horizon

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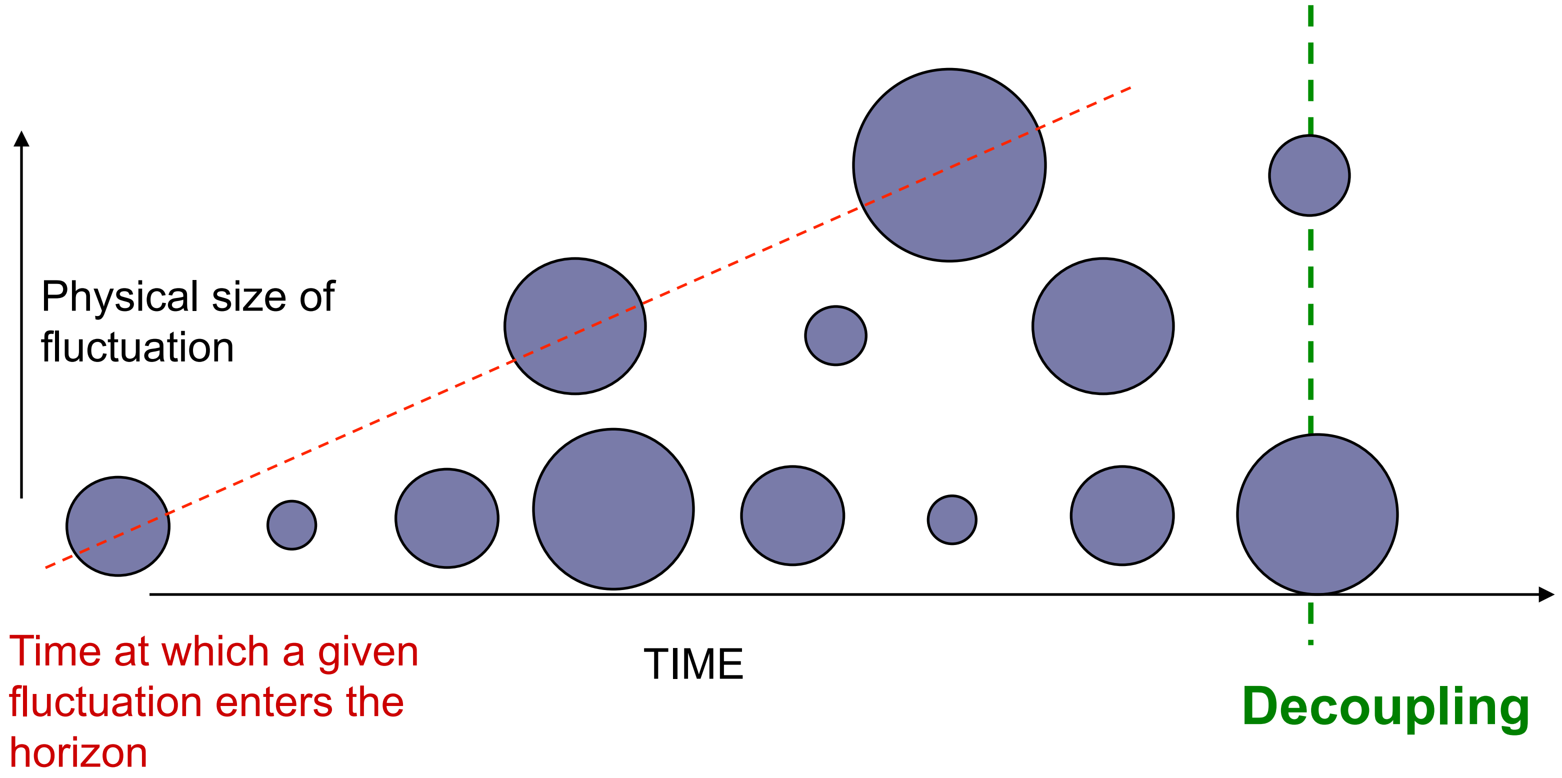
- Initial power spectrum of scalar modes and tensor modes (arise naturally from quantum fluctuations stretched out by inflation)
- Matter fluctuations begin to collapse as they enter the horizon
- Gravity + radiation pressure couple the baryons and the photon background $\Rightarrow$ oscillations in the photon-baryon fluid
- Decoupling removes radiation support; matter fluctuations are frozen into the CMB



The physics of CMB fluctuations are straightforward

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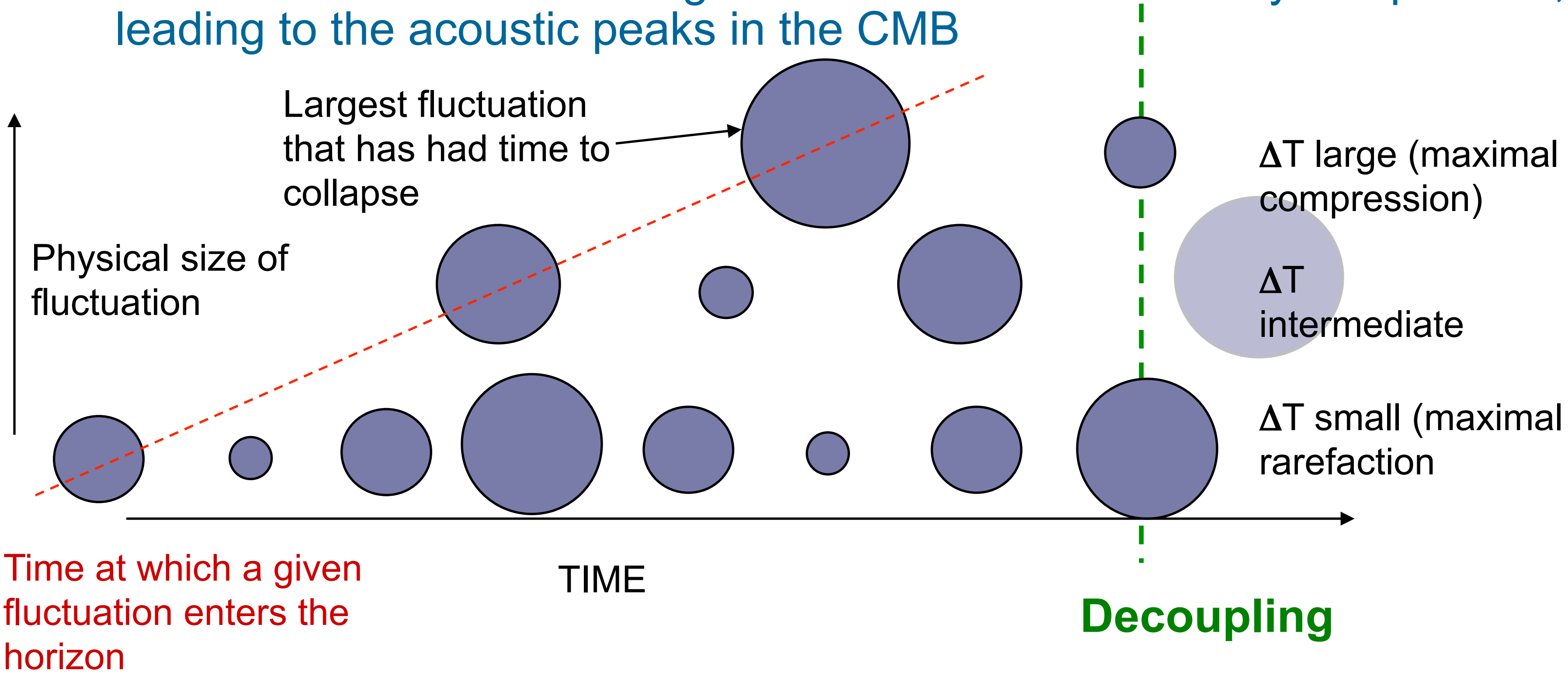
- Gravity + radiation pressure couple the baryons and the photon background ⇒ oscillations in the photon-baryon fluid
- Decoupling removes radiation support; matter fluctuations are frozen into the CMB
- Scalar modes on certain angular scales are enhanced by this process, leading to the acoustic peaks in the CMB



Largest fluctuation that has had time to collapse

ΔT large (maximal compression)

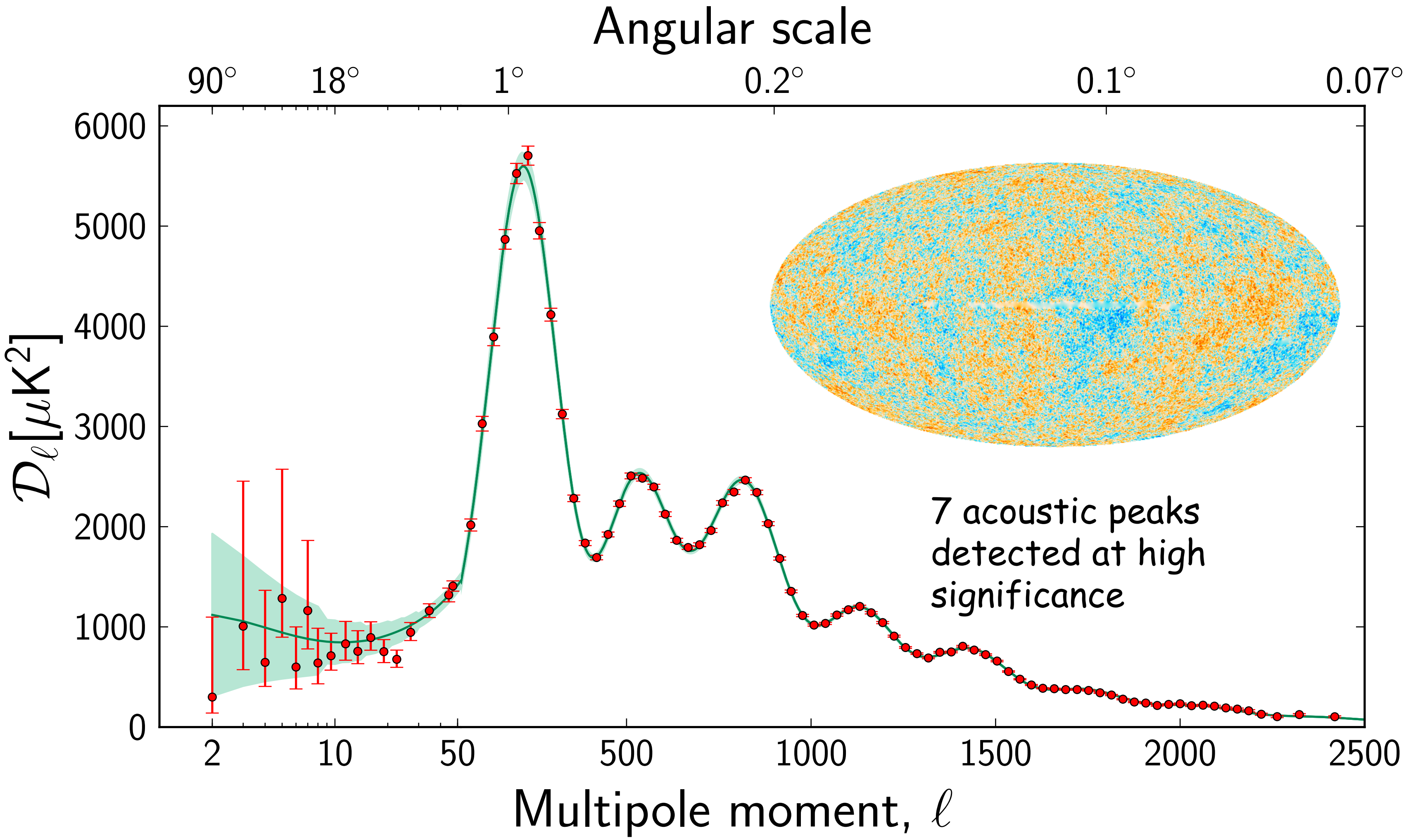
ΔT intermediate

ΔT small (maximal rarefaction

Time at which a given fluctuation enters the horizon

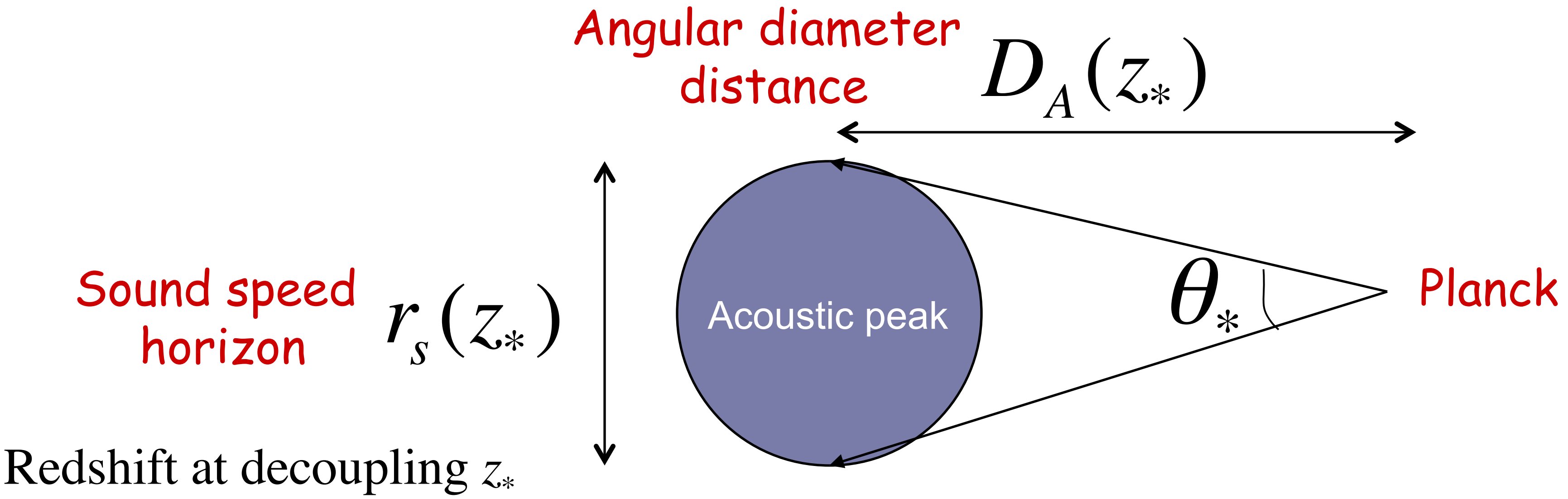
Decoupling

See as acoustic peaks in the power spectrum



7 acoustic peaks detected at high significance

Relation to parameters



Angular diameter distance $D_A(z_*)$

Sound speed horizon $r_s(z_*)$

Acoustic peak

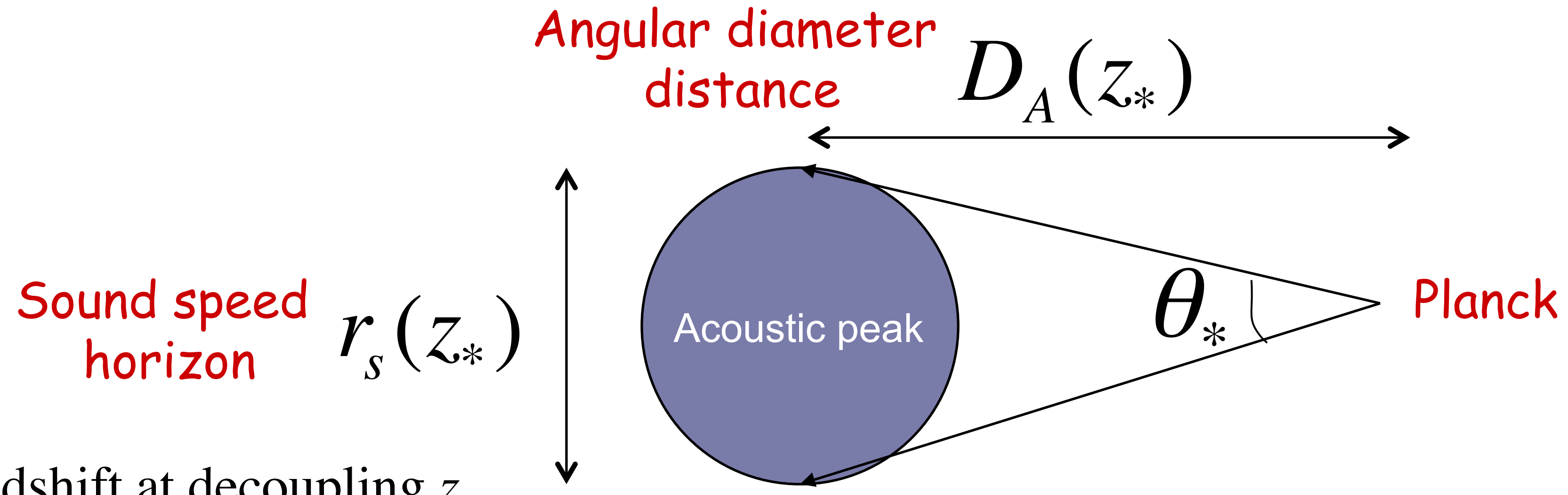
θ_*

Planck

Redshift at decoupling z_*

- Physics of peaks depend only on baryon/photon ratio, and non-relativistic to relativistic energy density (total matter to photons + neutrinos) → determines r_s
- Distance depends on geometry and late time effects on the expansion rate.

Relation to parameters



Angular diameter distance $D_A(z_*)$

Sound speed horizon $r_s(z_*)$

Acoustic peak

θ_*

Planck

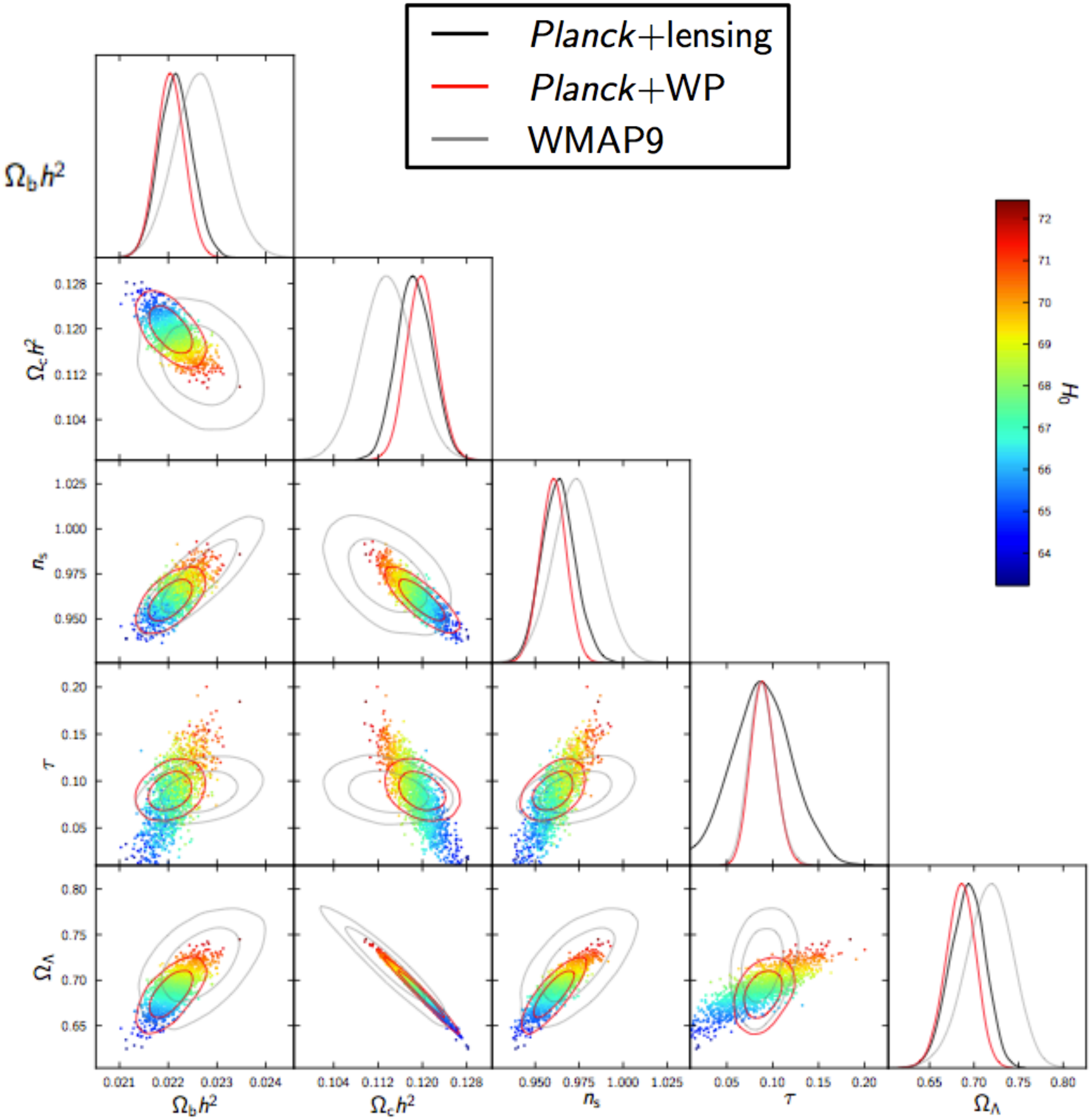
Redshift at decoupling z_*

- Angular size measured to 0.1% precision from Planck

$$\theta_* = (1.04148 \pm 0.00066) \times 10^{-2} = 0.596724^\circ \pm 0.00038^\circ.$$

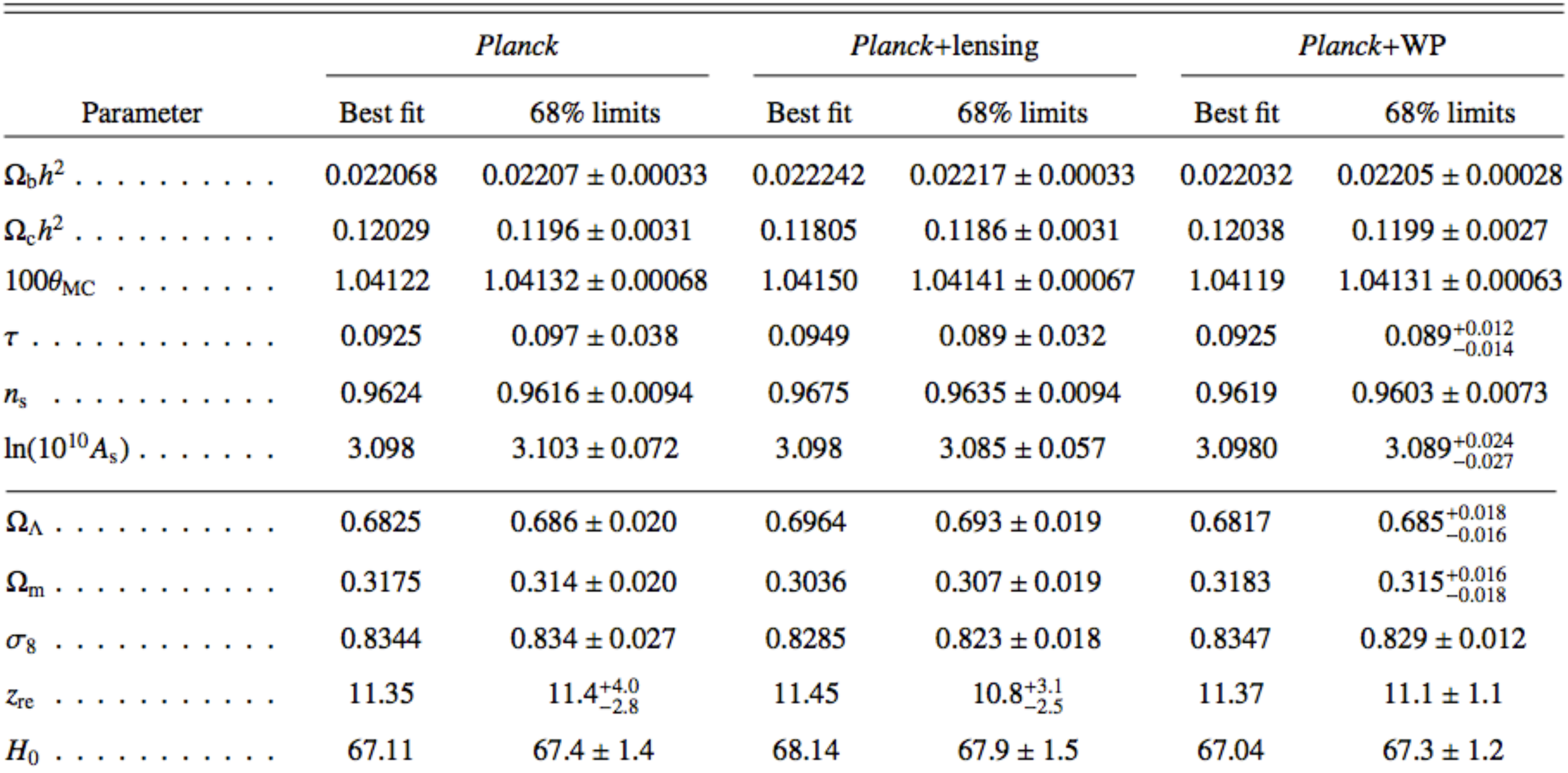
Data are fit with the “Standard Model” of Cosmology

- Standard model of particle physics…..
- + general relativity…..
- + ΛCDM in its simplest form
  - spatially-flat
  - parameters – $\Omega_b h^2$, $\Omega_m h^2$, Ω_Λ, τ
  - a power-law spectrum of adiabatic scalar perturbations -- n_s, A
- If curvature is included, spatial flatness is implied to percent level precision using Planck CMB data alone.



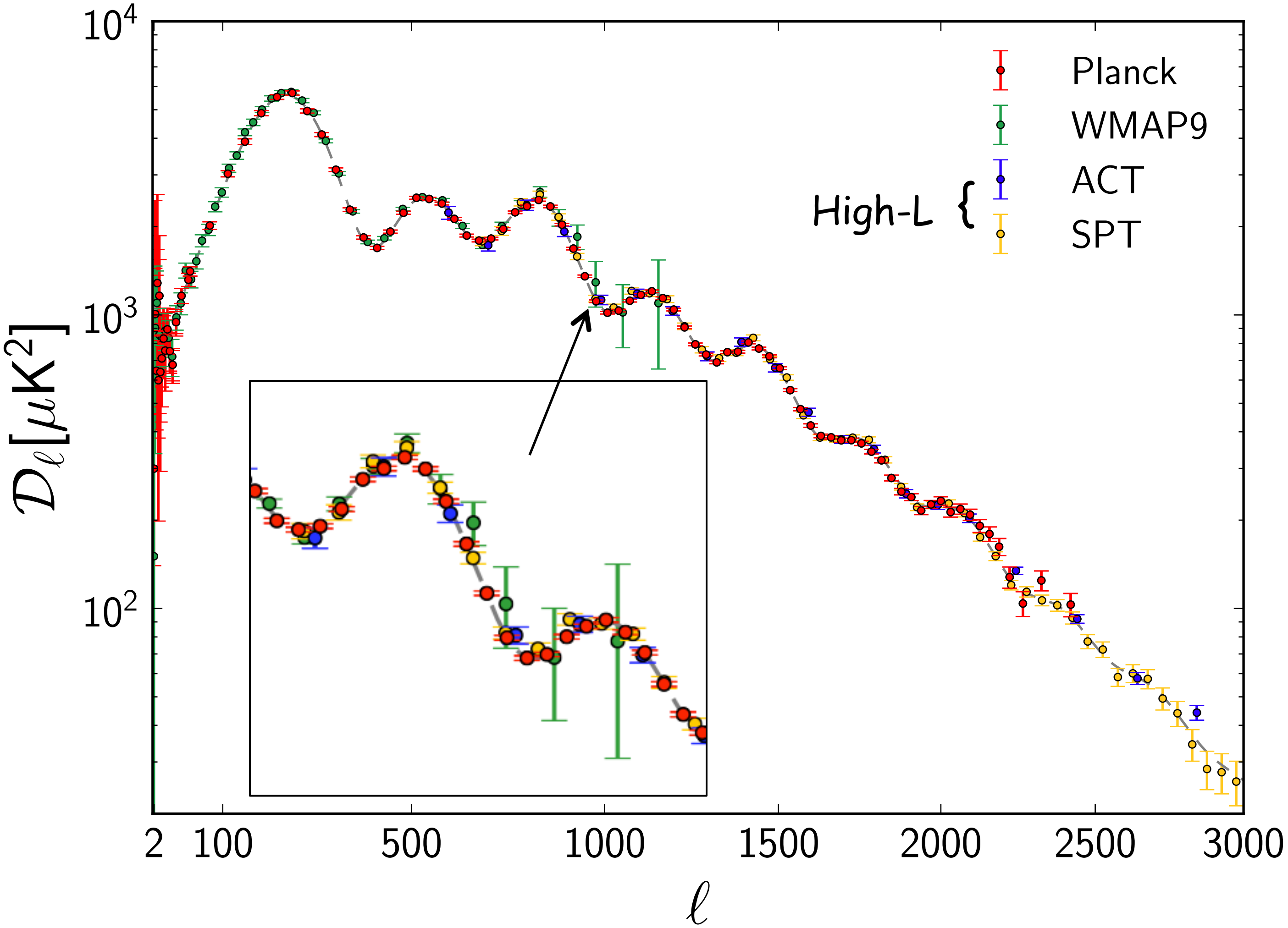
Planck+lensing
Planck+WP
WMAP9
$\Omega_b h^2$
$\Omega_c h^2$
n_s
τ
Ω_Λ
H_0
64
65
66
67
68
69
70
71
72
0.104
0.112
0.120
0.128
0.950
0.975
1.000
1.025
0.05
0.10
0.15
0.20
0.65
0.70
0.75
0.80
0.021
0.022
0.023
0.024

Parameters



Parameter	*Planck*		*Planck*+lensing		*Planck*+WP	
	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
$\Omega_b h^2$	0.022068	0.02207 ± 0.00033	0.022242	0.02217 ± 0.00033	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12029	0.1196 ± 0.0031	0.11805	0.1186 ± 0.0031	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04122	1.04132 ± 0.00068	1.04150	1.04141 ± 0.00067	1.04119	1.04131 ± 0.00063
τ	0.0925	0.097 ± 0.038	0.0949	0.089 ± 0.032	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9624	0.9616 ± 0.0094	0.9675	0.9635 ± 0.0094	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.098	3.103 ± 0.072	3.098	3.085 ± 0.057	3.0980	$3.089^{+0.024}_{-0.027}$
Ω_Λ	0.6825	0.686 ± 0.020	0.6964	0.693 ± 0.019	0.6817	$0.685^{+0.018}_{-0.016}$
Ω_m	0.3175	0.314 ± 0.020	0.3036	0.307 ± 0.019	0.3183	$0.315^{+0.016}_{-0.018}$
σ_8	0.8344	0.834 ± 0.027	0.8285	0.823 ± 0.018	0.8347	0.829 ± 0.012
z_{re}	11.35	$11.4^{+4.0}_{-2.8}$	11.45	$10.8^{+3.1}_{-2.5}$	11.37	11.1 ± 1.1
H_0	67.11	67.4 ± 1.4	68.14	67.9 ± 1.5	67.04	67.3 ± 1.2

Comparison with other data sets



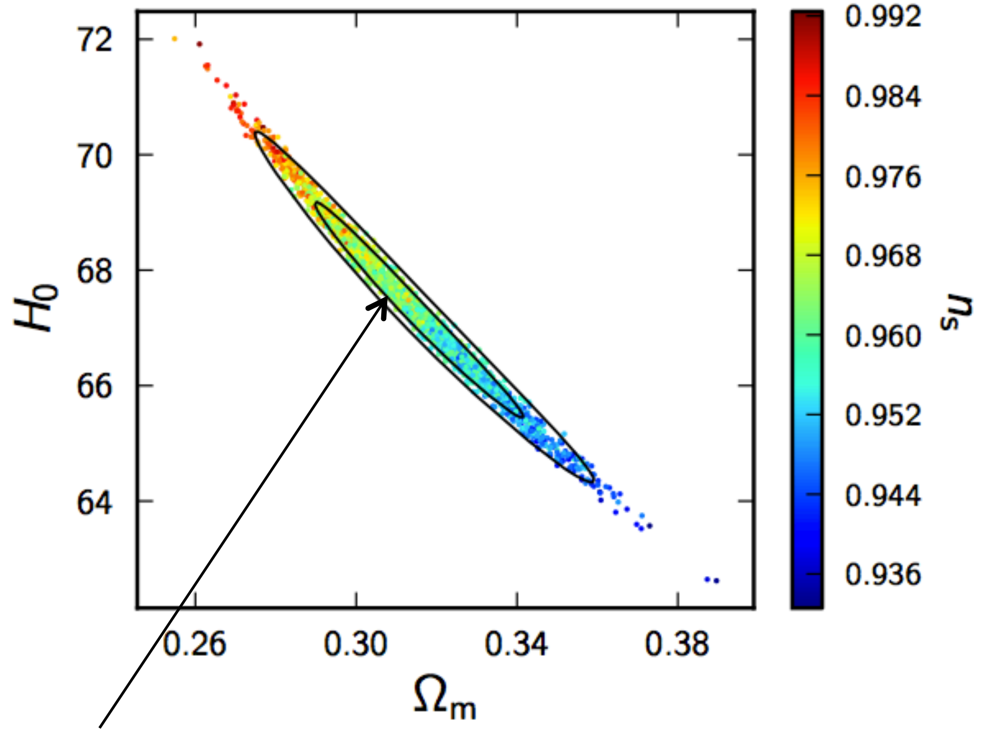
High l data constrain foreground signals that are not well resolved by Planck. Consistency check on parameters

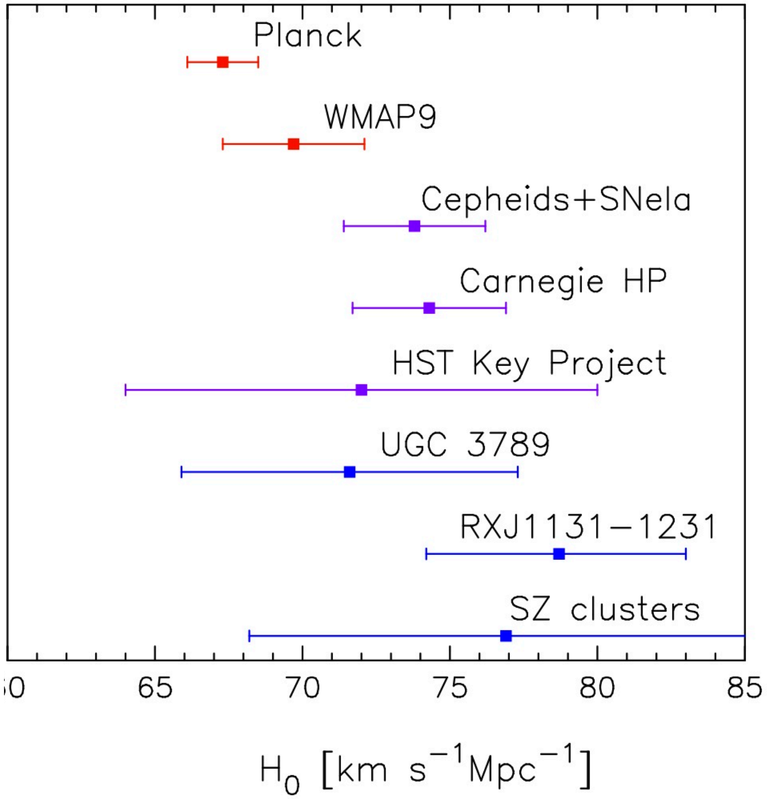
Some tension with low-*z* measurements of H_0

- From Planck alone:

$H_0 = 67.4 \pm 1.4$ km s^{-1} Mpc^{-1}

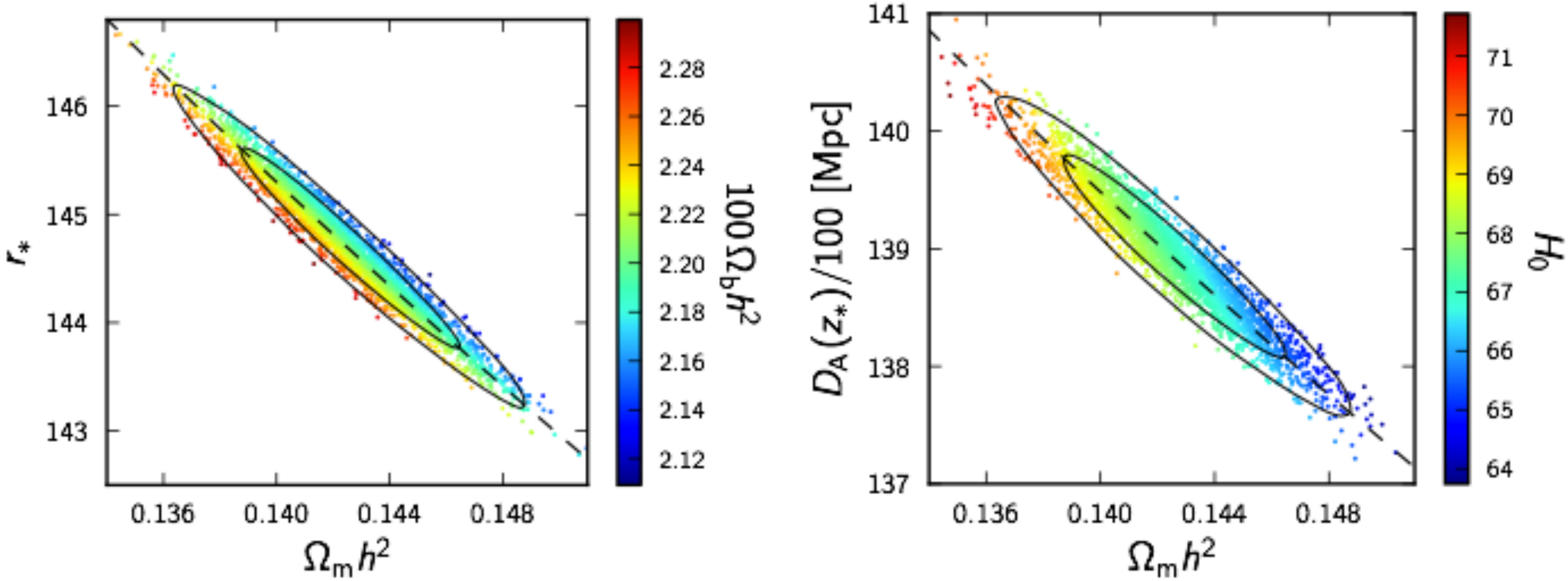
$\Omega_m = 0.315 \pm 0.017$.





Contours from adding WMAP polarization data

Higher values of H_0 are difficult to match with the standard ΛCDM model

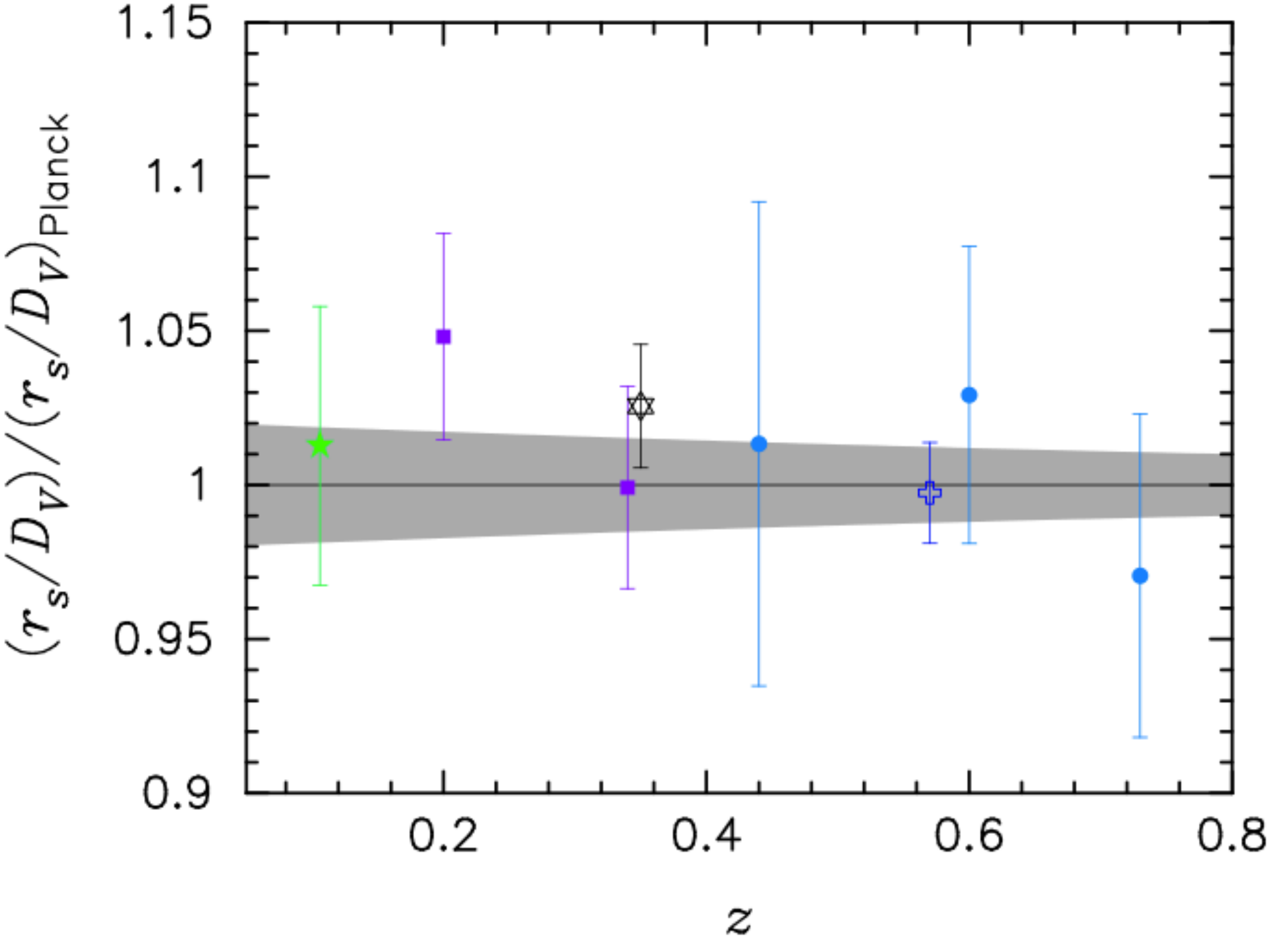


Well-constrained angular scale of acoustic peaks depends on

$$\frac{r_*}{D_A(z_*)}$$

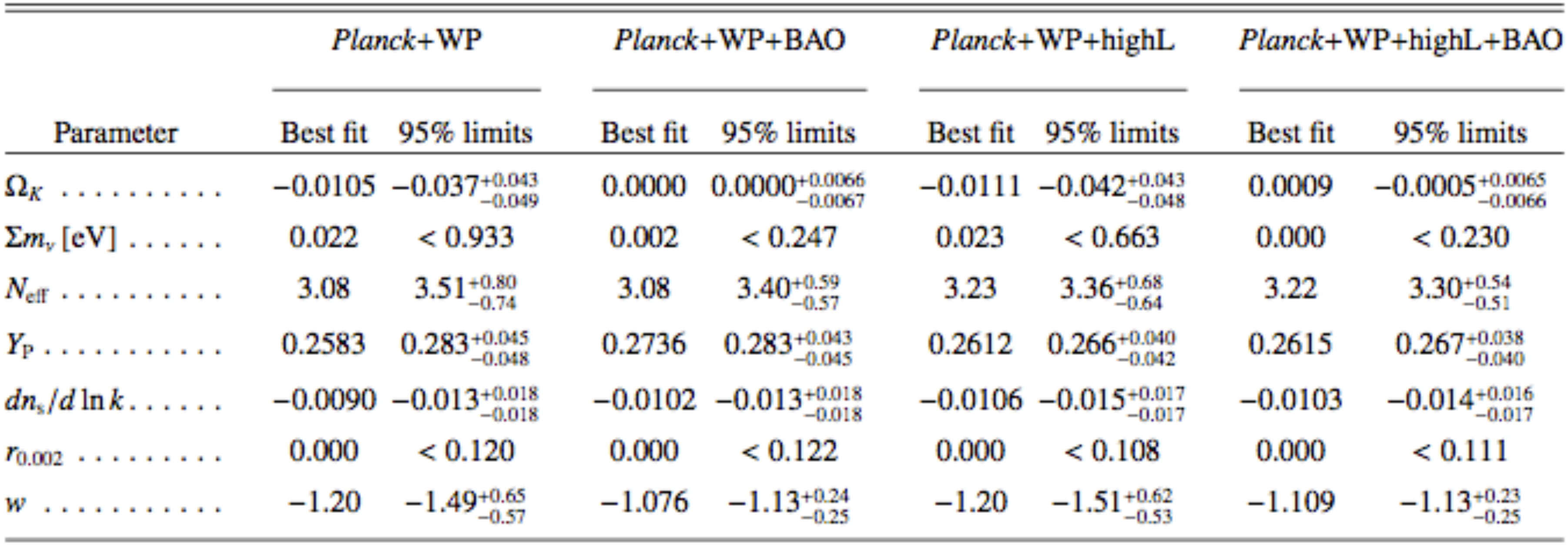
The addition of WMAP polarization data and high-l data limits the degeneracy

ΛCDM model predicts an acoustic scale for BAO measurements that agrees well with data



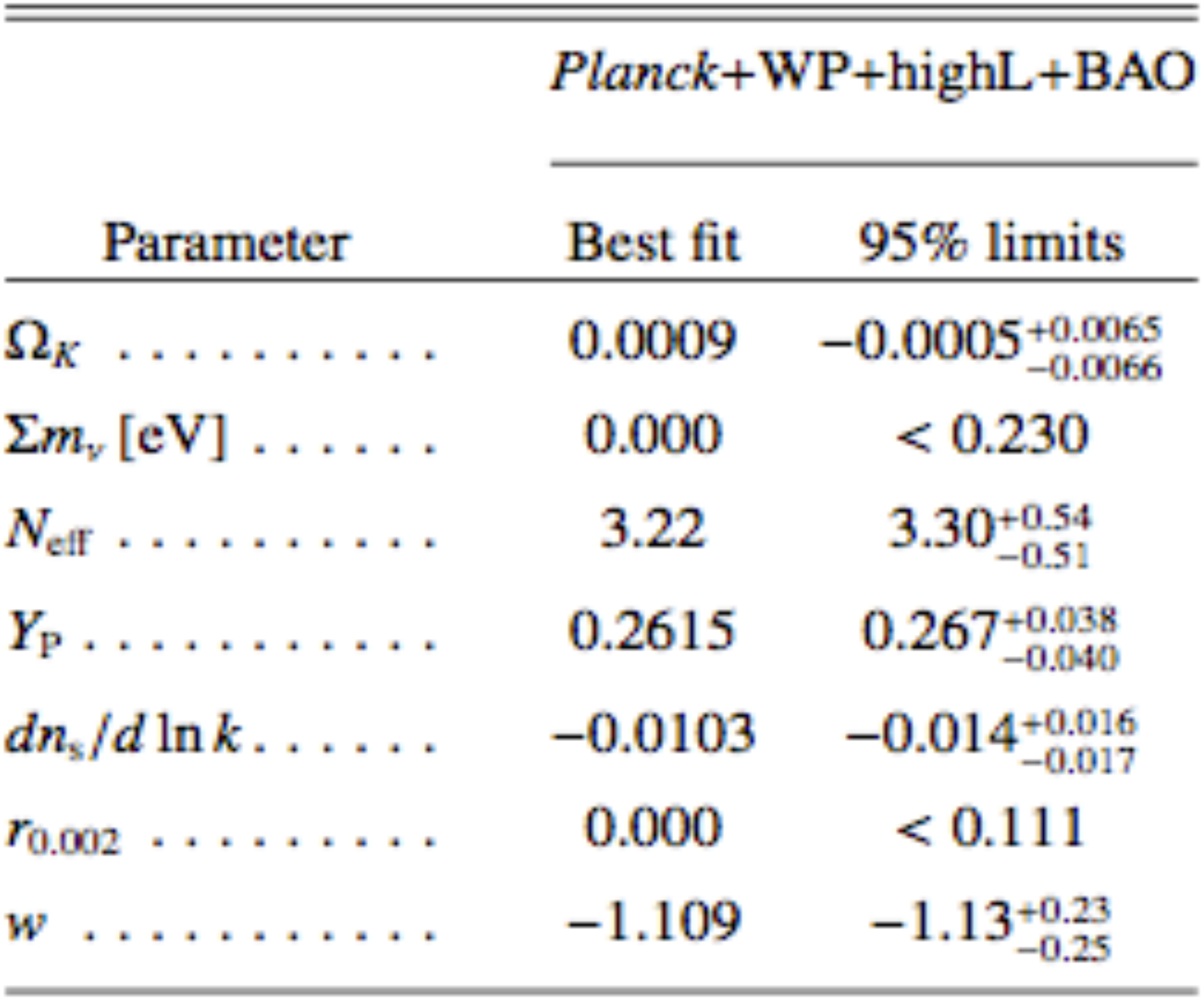
Consistency check for the H_0 measurements

Helps to set constraints on additional parameters above and beyond the 6-parameter model



	Planck+WP		*Planck*+WP+BAO		*Planck*+WP+highL		*Planck*+WP+highL+BAO	
Parameter	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits	Best fit	95% limits
Ω_K	-0.0105	$-0.037^{+0.043}_{-0.049}$	0.0000	$0.0000^{+0.0066}_{-0.0067}$	-0.0111	$-0.042^{+0.043}_{-0.048}$	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.022	< 0.933	0.002	< 0.247	0.023	< 0.663	0.000	< 0.230
N_{eff}	3.08	$3.51^{+0.80}_{-0.74}$	3.08	$3.40^{+0.59}_{-0.57}$	3.23	$3.36^{+0.68}_{-0.64}$	3.22	$3.30^{+0.54}_{-0.51}$
Y_{P}	0.2583	$0.283^{+0.045}_{-0.048}$	0.2736	$0.283^{+0.043}_{-0.045}$	0.2612	$0.266^{+0.040}_{-0.042}$	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\mathrm{s}}/d\ln k$	-0.0090	$-0.013^{+0.018}_{-0.018}$	-0.0102	$-0.013^{+0.018}_{-0.018}$	-0.0106	$-0.015^{+0.017}_{-0.017}$	-0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.120	0.000	< 0.122	0.000	< 0.108	0.000	< 0.111
w	-1.20	$-1.49^{+0.65}_{-0.57}$	-1.076	$-1.13^{+0.24}_{-0.25}$	-1.20	$-1.51^{+0.62}_{-0.53}$	-1.109	$-1.13^{+0.23}_{-0.25}$

Helps to set constraints on additional parameters above and beyond the 6-parameter model

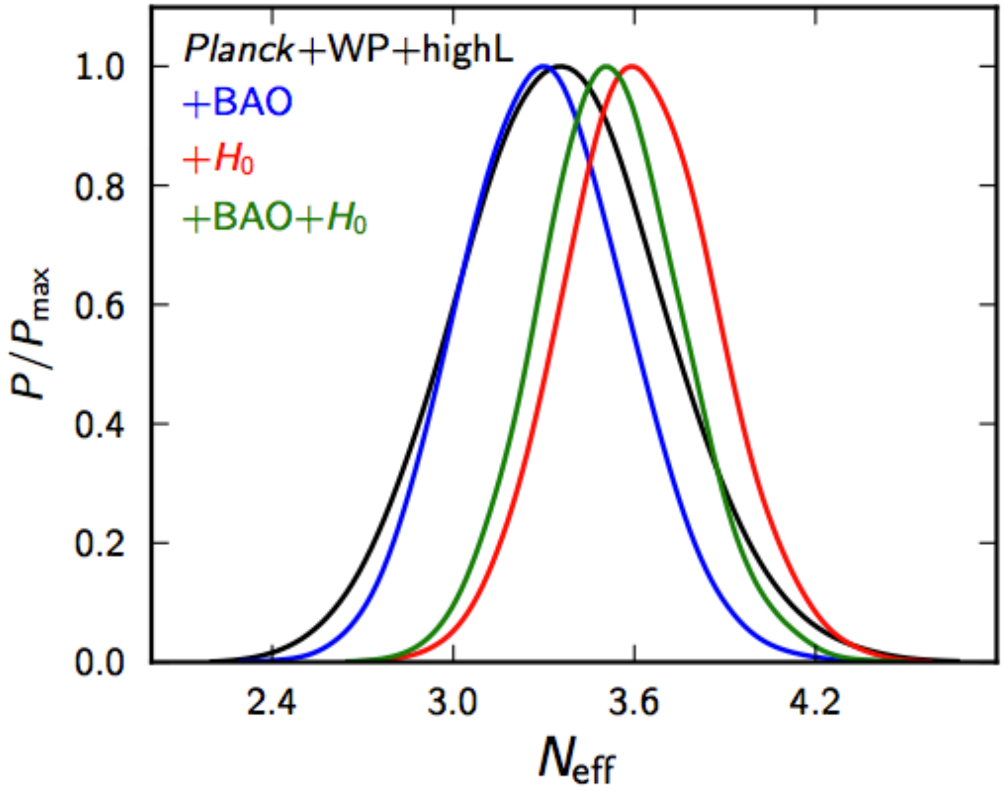


	Planck+WP+highL+BAO	
Parameter	Best fit	95% limits
Ω_K	0.0009	$-0.0005^{+0.0065}_{-0.0066}$
Σm_ν [eV]	0.000	< 0.230
N_{eff}	3.22	$3.30^{+0.54}_{-0.51}$
Y_{P}	0.2615	$0.267^{+0.038}_{-0.040}$
$dn_{\mathrm{s}}/d\ln k$	−0.0103	$-0.014^{+0.016}_{-0.017}$
$r_{0.002}$	0.000	< 0.111
w	−1.109	$-1.13^{+0.23}_{-0.25}$

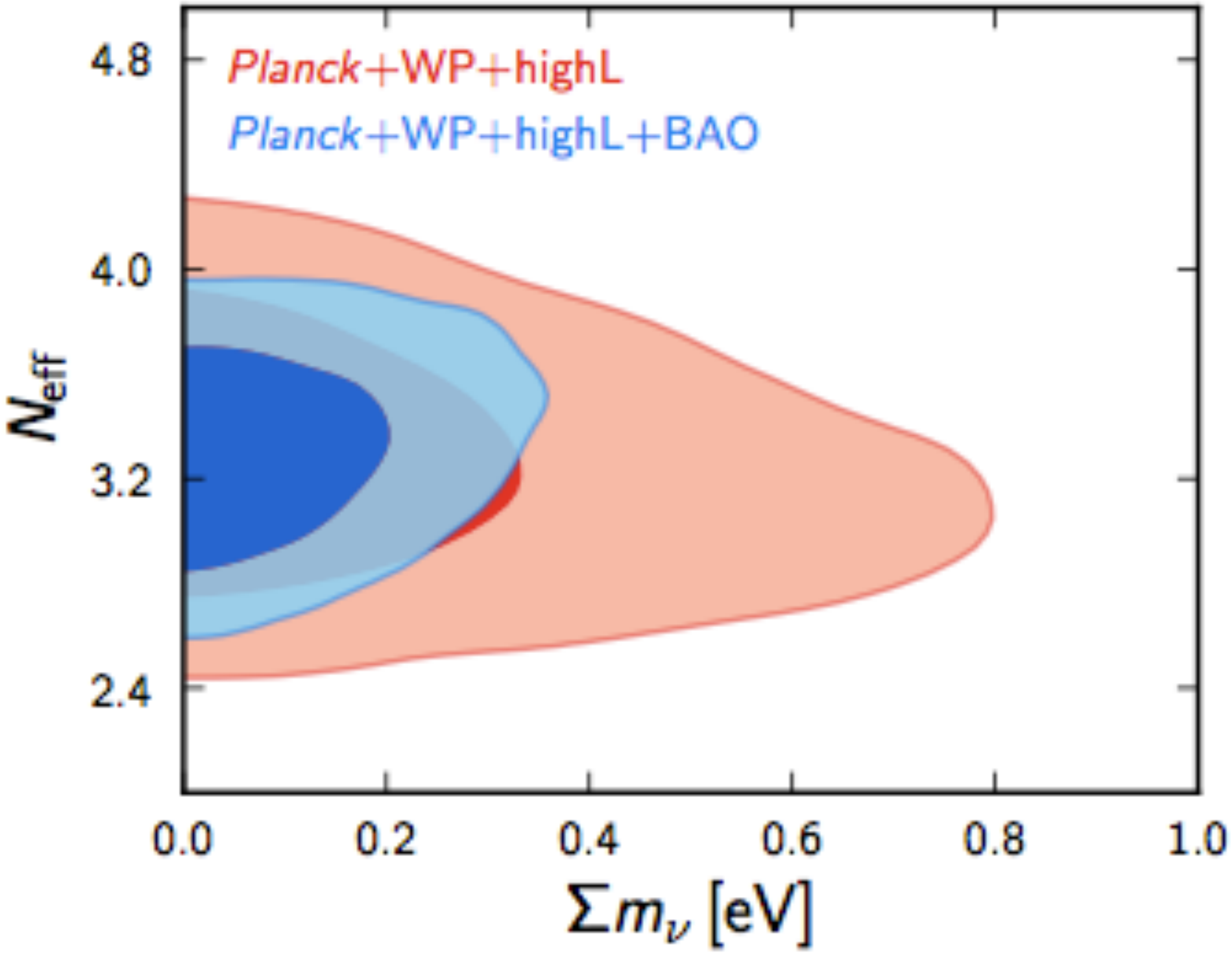
Neutrinos

- Effect of increasing radiation density via addition of neutrino families is to suppress small scale power in the CMB

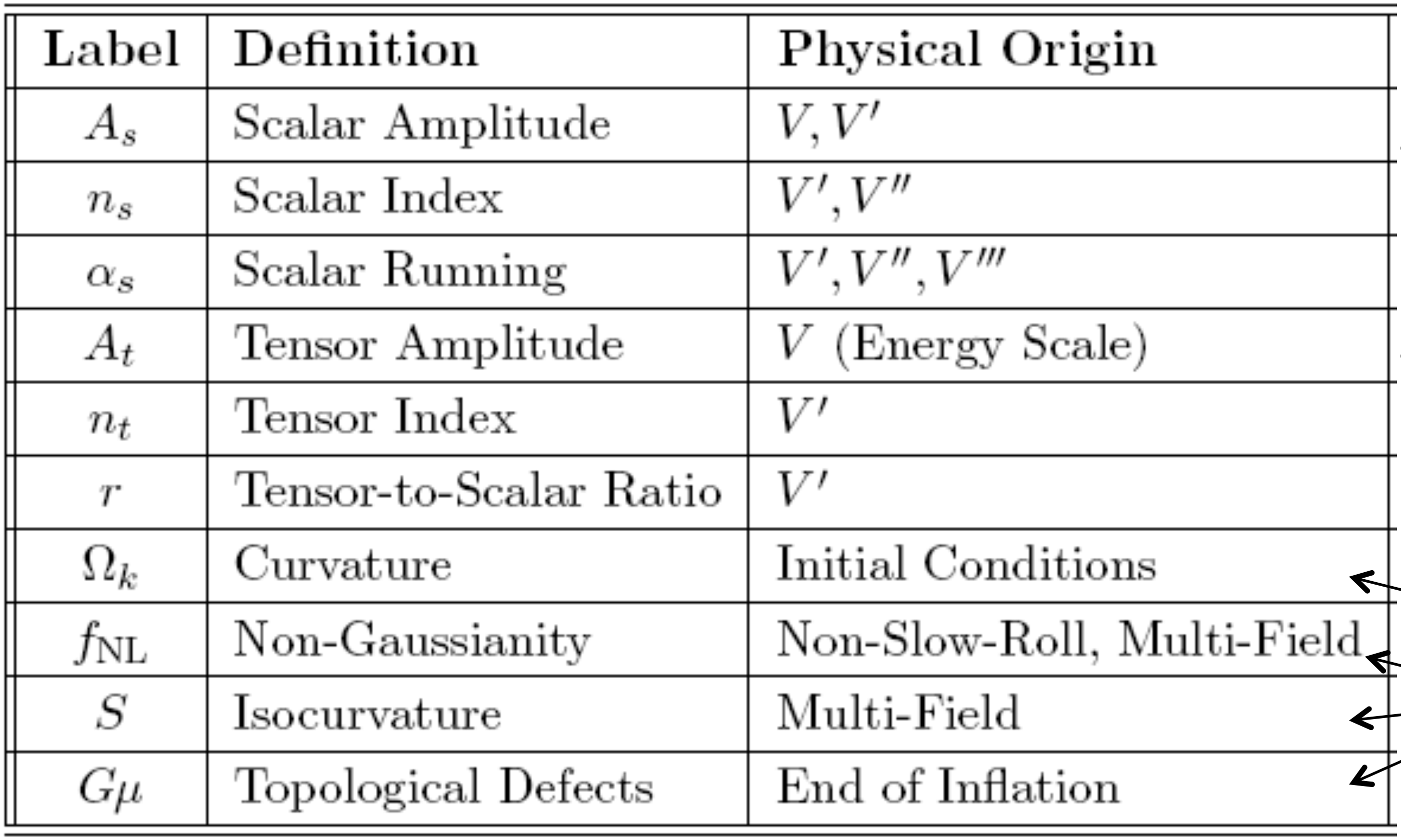
Low-z measurements of H_0 push N_{eff} to a higher value



CMB plus BAO also constrains the sum of the neutrino masses



Planck Probes Inflationary parameters



Label	Definition	Physical Origin
A_s	Scalar Amplitude	V, V'
n_s	Scalar Index	V', V''
α_s	Scalar Running	V', V'', V'''
A_t	Tensor Amplitude	V (Energy Scale)
n_t	Tensor Index	V'
r	Tensor-to-Scalar Ratio	V'
Ω_k	Curvature	Initial Conditions
$f_{\rm NL}$	Non-Gaussianity	Non-Slow-Roll, Multi-Field
S	Isocurvature	Multi-Field
$G\mu$	Topological Defects	End of Inflation

} Matter power spectrum

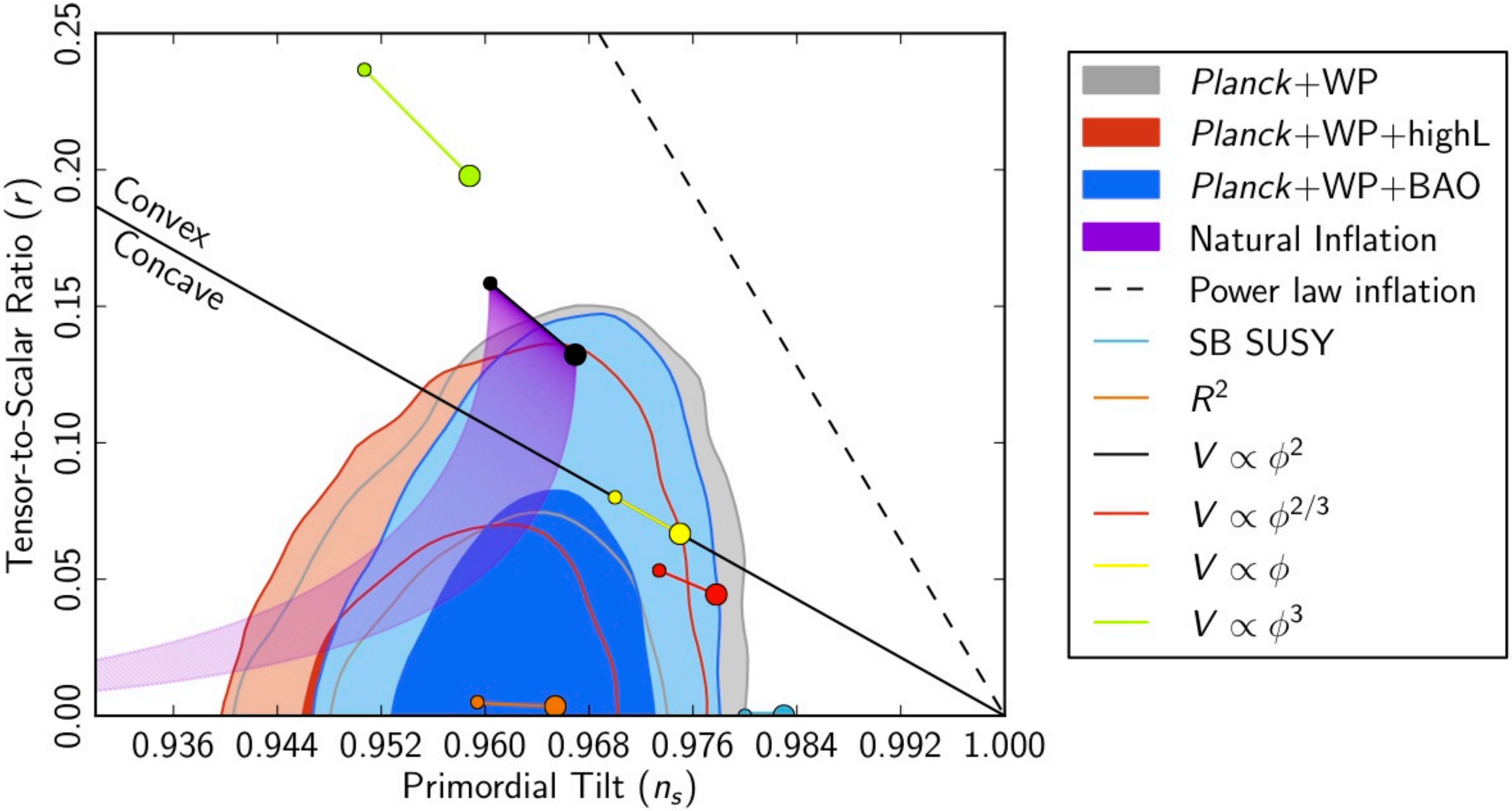
} Primordial Gravitational waves

Zero to 1%

Not detected

See review Baumann et al., arXiv:0811.3919

Implications for Inflation



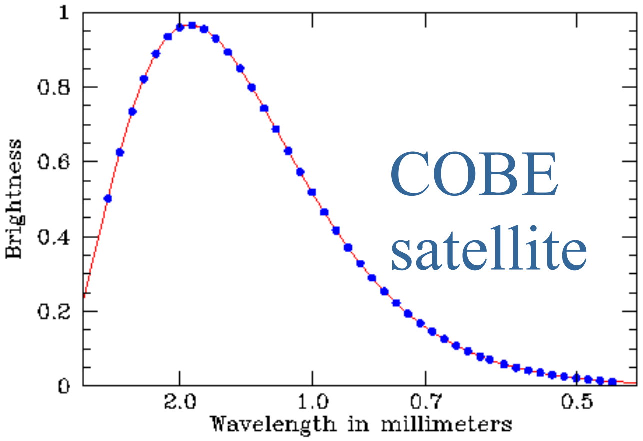
Consistent with single-field slow-roll inflation

Summary

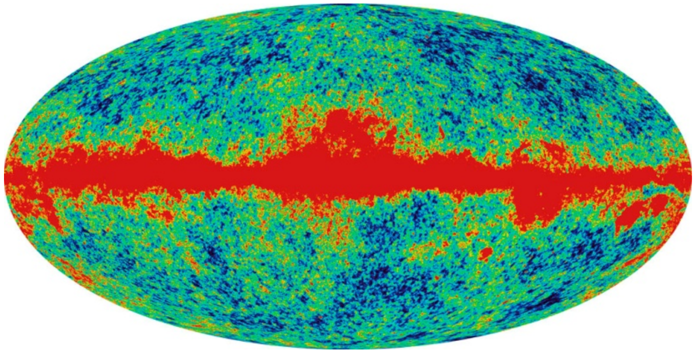
- A wealth of data from Planck has provided strong evidence for the standard ΛCDM.
- There are a vast number of science results that I didn’t have time to touch upon!
- There are some discrepancies with non-CMB data that the Planck team is working to resolve.
- 2014 will see another data release – more temperature data; polarization data.

Looking ahead – the CMB isn't done yet!

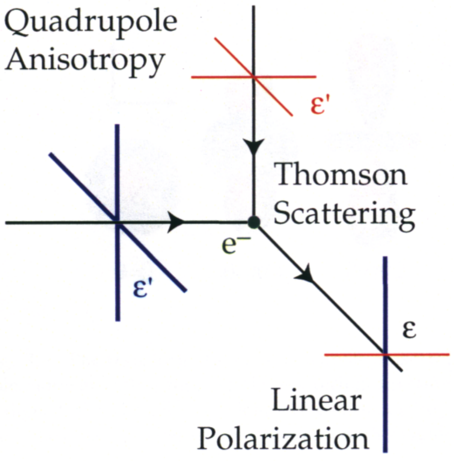
- Frequency spectrum



- Spatial temperature variations:



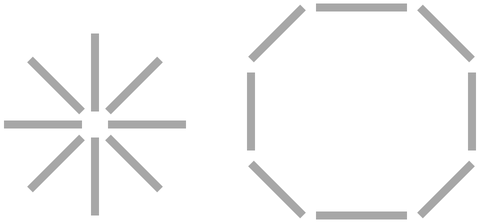
WMAP, Planck



Picture by W. Hu

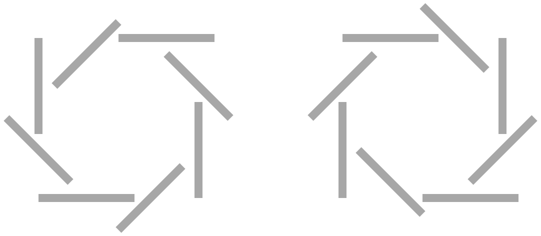
- Polarization generated by anisotropic Thomson scattering
- The polarization percentage is high (around 10%), but the signal is still very weak
- Once again the physics is well-understood
- Precision cosmology equally feasible using polarization

“E” and “B” modes

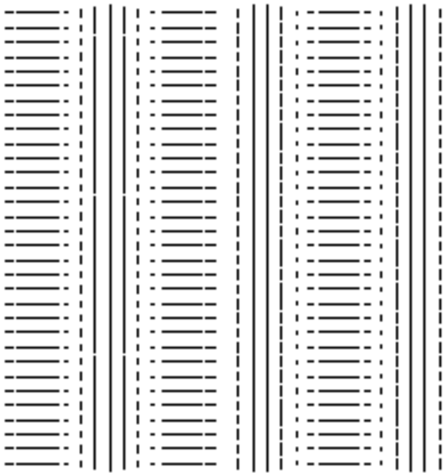


E modes

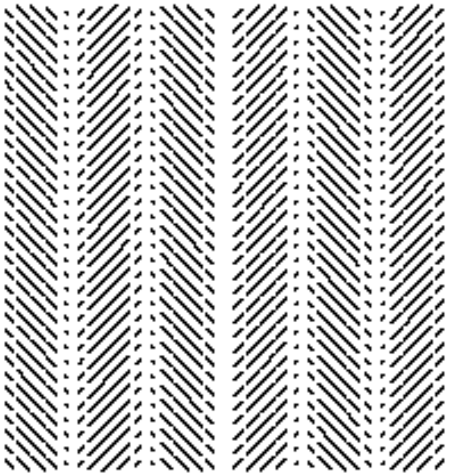
B modes



ONLY FROM TENSOR MODES
(gravitational waves)

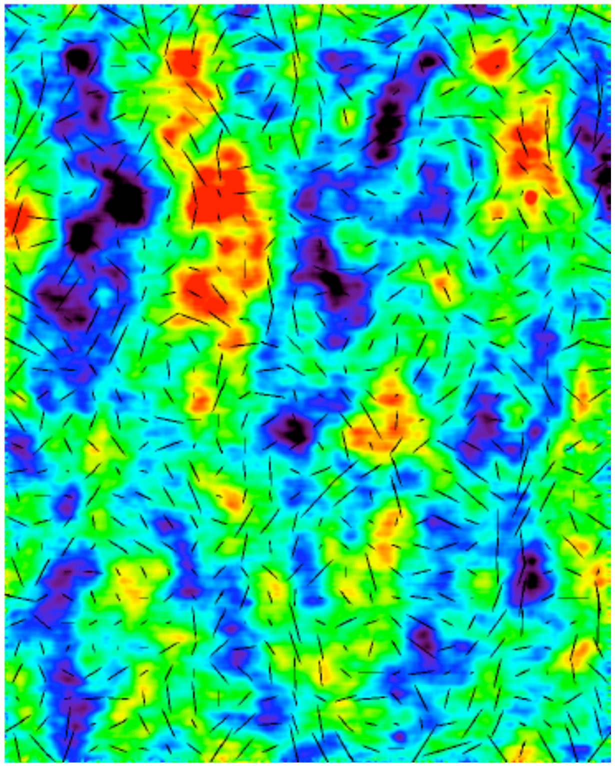


E Fourier mode



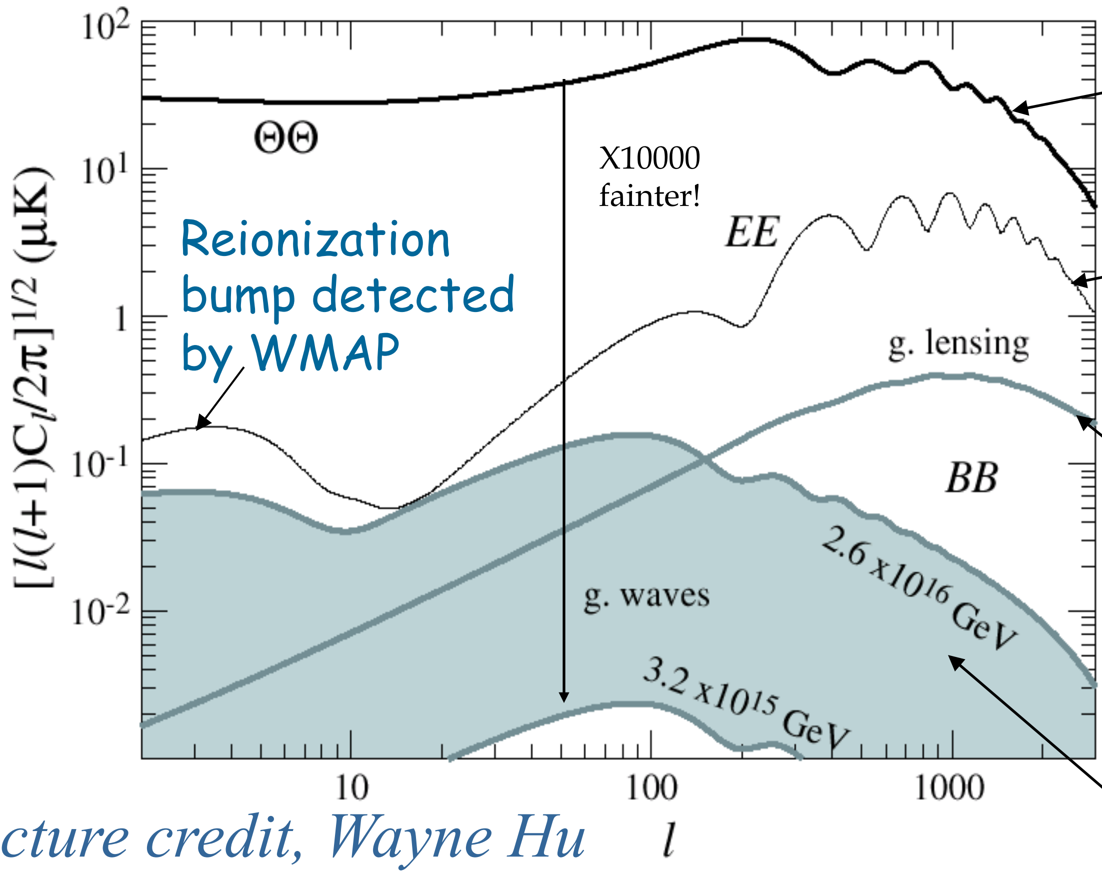
B Fourier mode

See, e.g. Bunn, 2005



QUaD Experiment (Brown et al. 2009)

Polarization measurements require greater sensitivity than temperature measurements...



Reionization bump detected by WMAP

Temperature spectrum mapped by Planck WMAP

Planck Polarization data release 2014

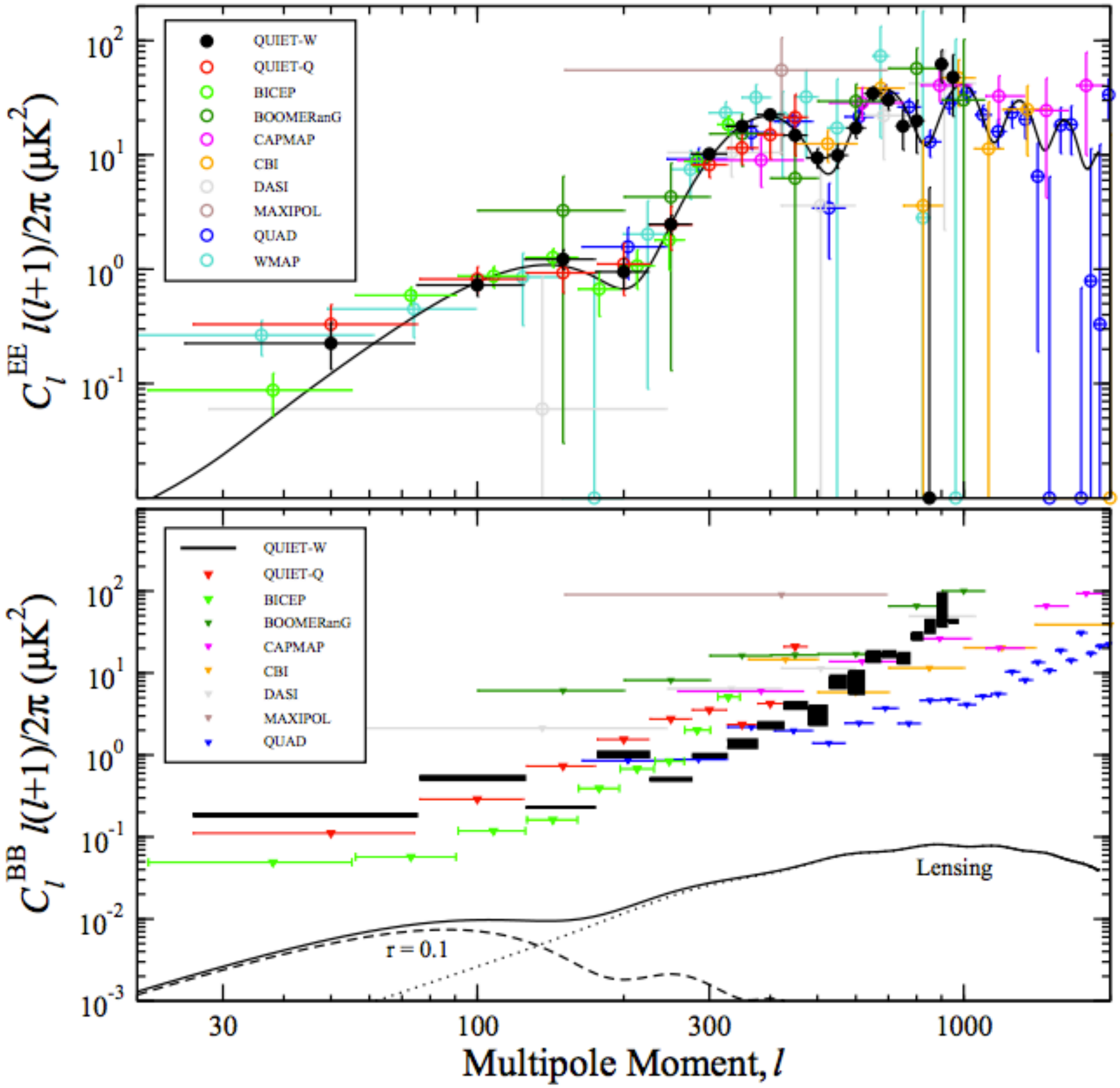
Gravitationally lensed E-modes probe large scale structure formation, neutrino mass, dark energy

Projected effect of a gravitational wave background

Picture credit, Wayne Hu

The range shown for the gravitational wave background spans the maximum allowable level pre-Planck, WMAP, and the minimum detectable from CMB measurements

Current status of field

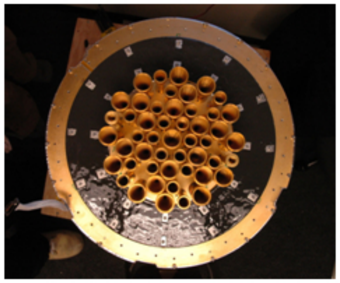


Planck data to come 2014

Looking ahead – the CMB isn’t done yet!

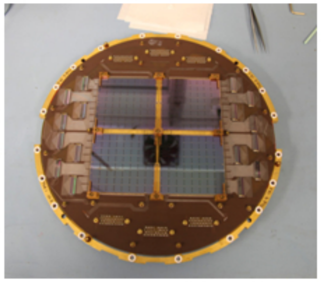
- The Planck data (polarization to come 2014) are honing in on cosmological parameters with ever greater precision
- However, significantly stronger limits on interesting new physics will require a new generation of CMB polarization experiments
  - Deep integrations on areas of clean sky with tens of thousands of polarization-sensitive detectors
  - Much stronger limits on neutrino and inflationary physics

Presentation by Chao-Lin Kuo at the Cosmic Frontier Workshop, SLAC, March 2013



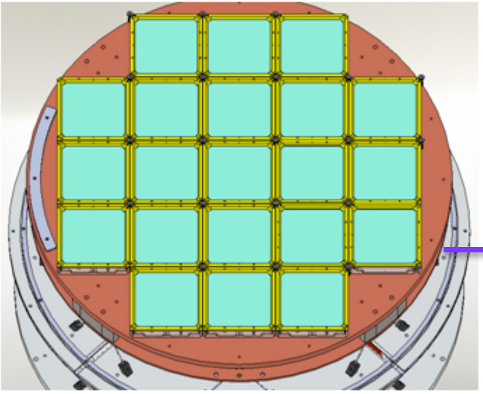
98 NTDs (95/150 GHz)

Stage I
Planck-style
QUaD, BICEP



512 TESs (150 GHz) per F.P.

Stage II
Fielded
Keck, SPT, Polarbear, ACT



>4,000 TESs (150GHz) per F.P.

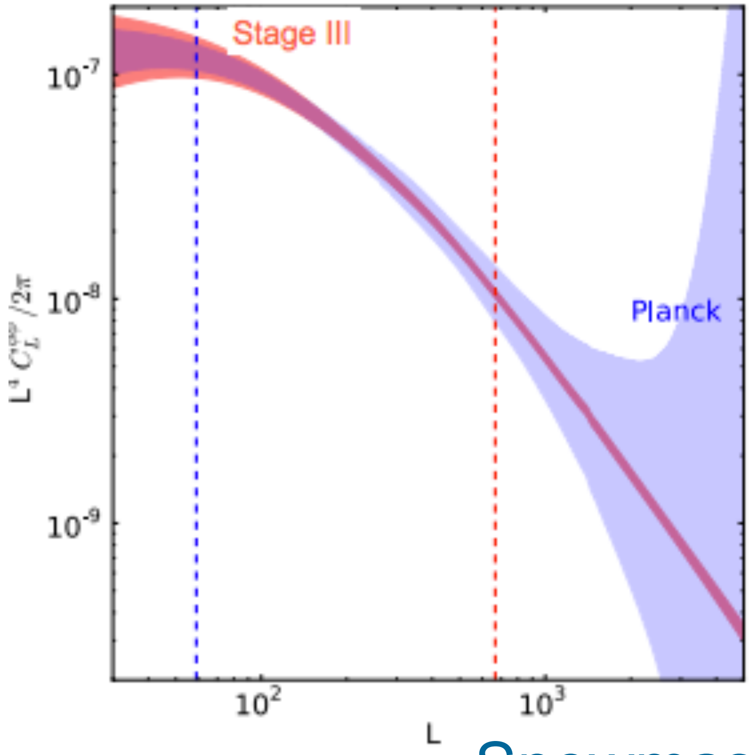
Stage III
Being built

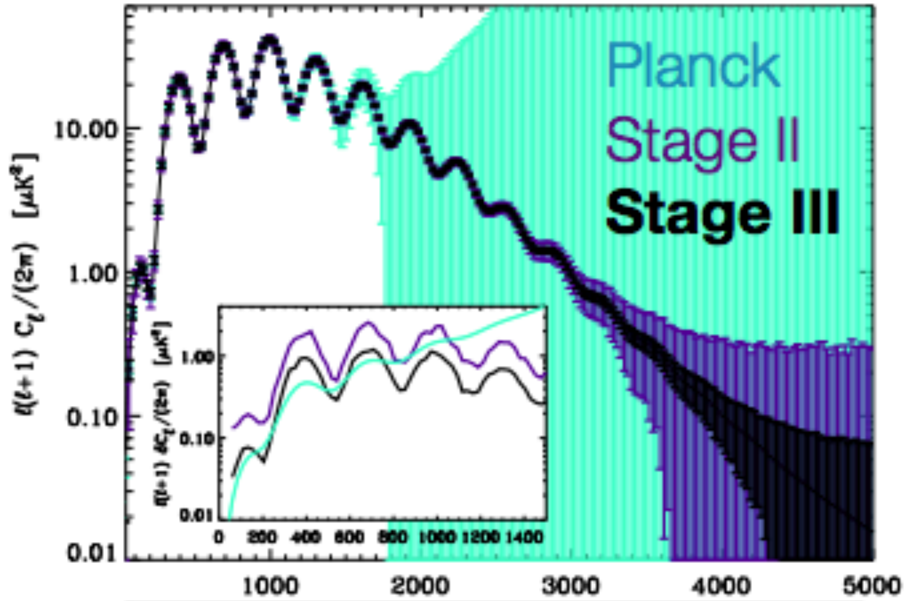
Stage-IV CMB
Duplicate (>10x)
Focal planes

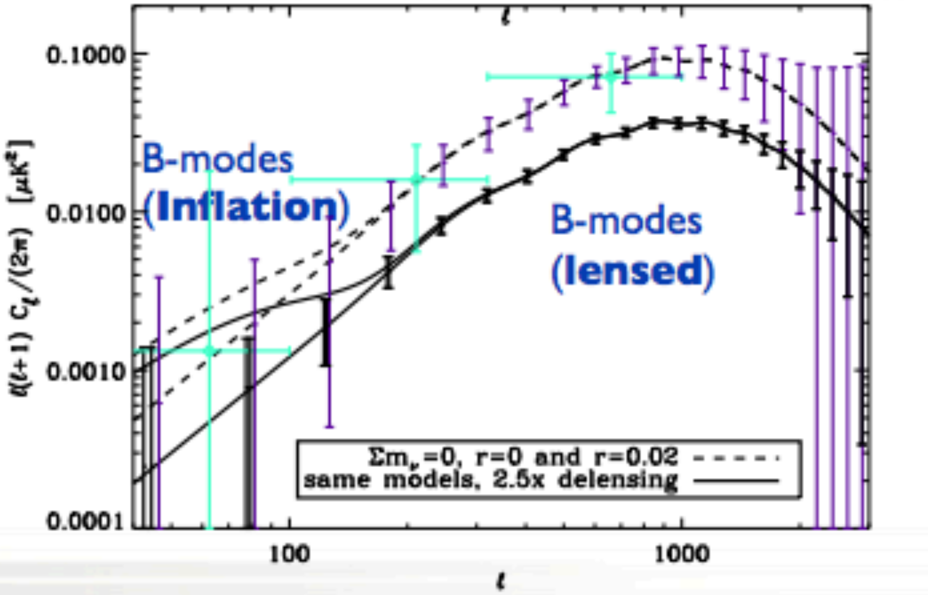
Presentation by Clarence Chang at the Cosmic Frontier Workshop, SLAC, March 2013

- Stage III ← Being built
  - σ(r) = 0.01
  - σ(Σm$_\nu$) = 60 meV

- Stage IV
  - 10x mapping speed over Stage III to map 10x the area to ~1 uK arcmin







Snowmass Working Group CF5