Cosmology with the Cosmic Microwave Background

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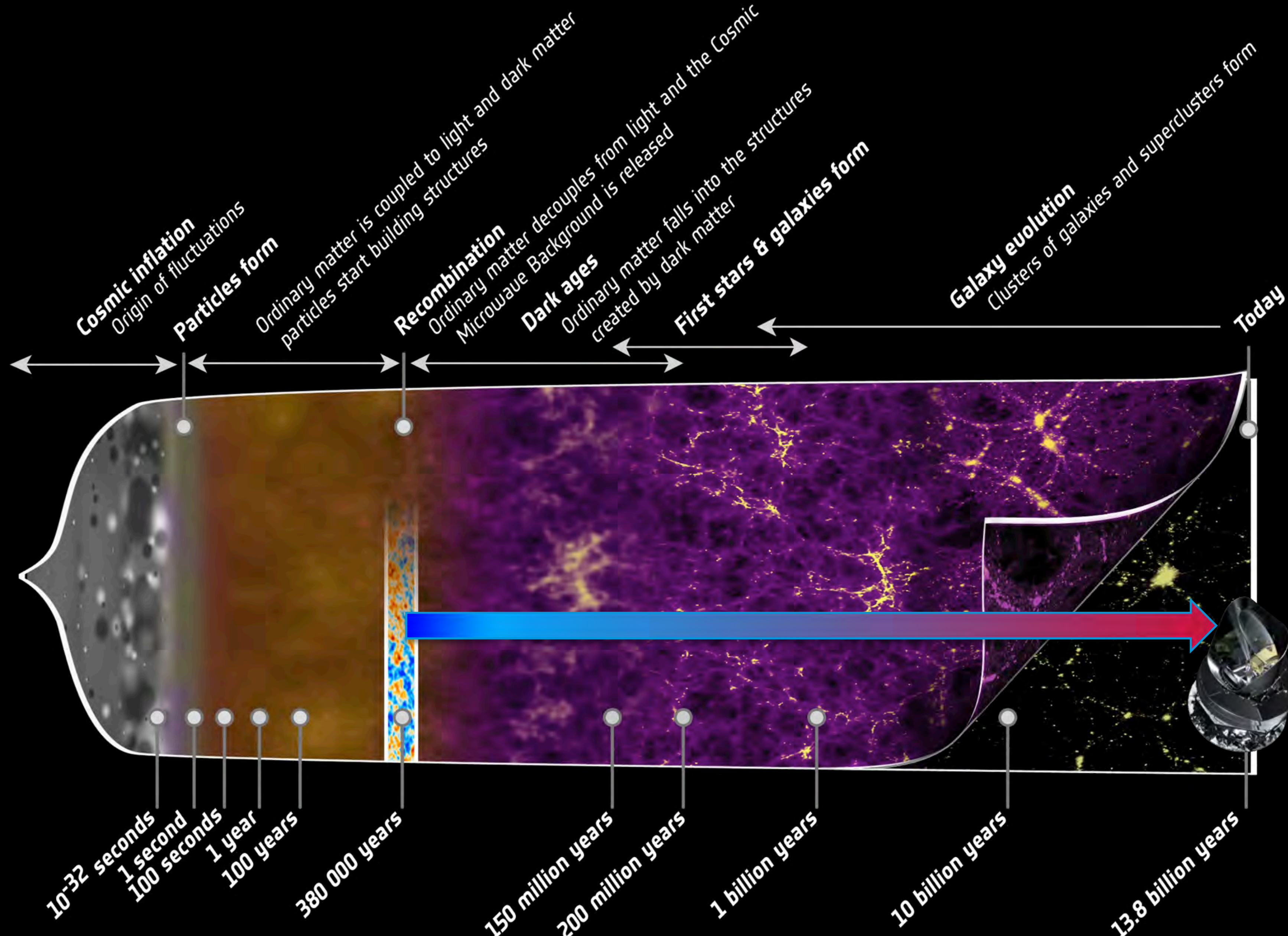
European Space Agency

Contents

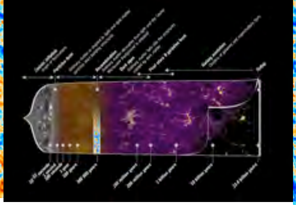
1. The Cosmic Microwave Background
2. Current state of CMB cosmology
3. Future directions

Most of this talk is based on the Planck Legacy paper (Planck Coll I 2018) downloadable from

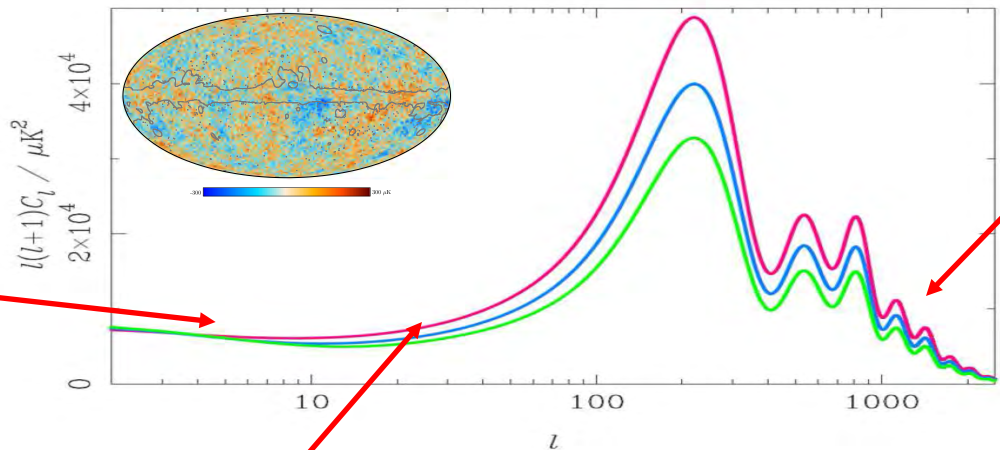
http://www.cosmos.esa.int/web/planck/publications


Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter is coupled to light and dark matter particles start building structures
Recombination
Ordinary matter decouples from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter falls into the structures created by dark matter
First stars & galaxies form
Galaxy evolution
Clusters of galaxies and superclusters form
Today
10-32 seconds
1 second
100 seconds
1 year
100 years
380 000 years
150 million years
200 million years
1 billion years
10 billion years
13.8 billion years

Physics at the time of recombination

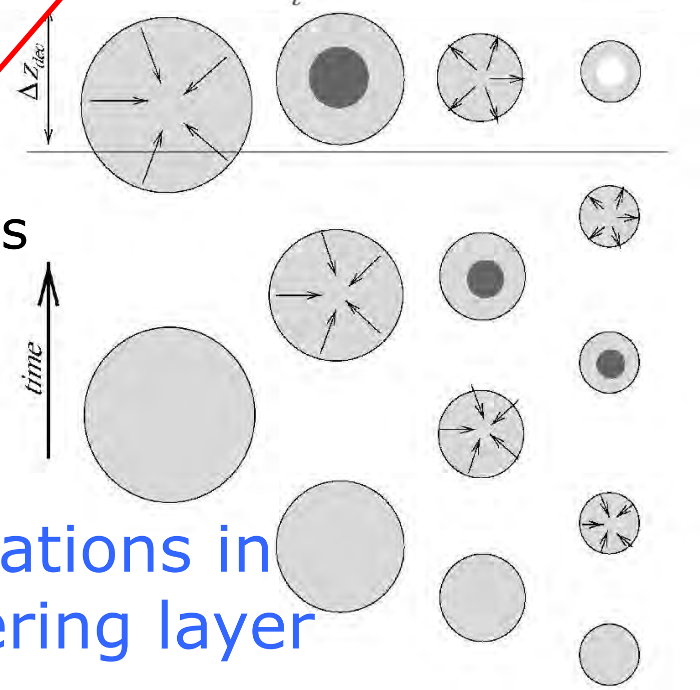


At the largest angular scales, the spectrum of primordial fluctuations is preserved

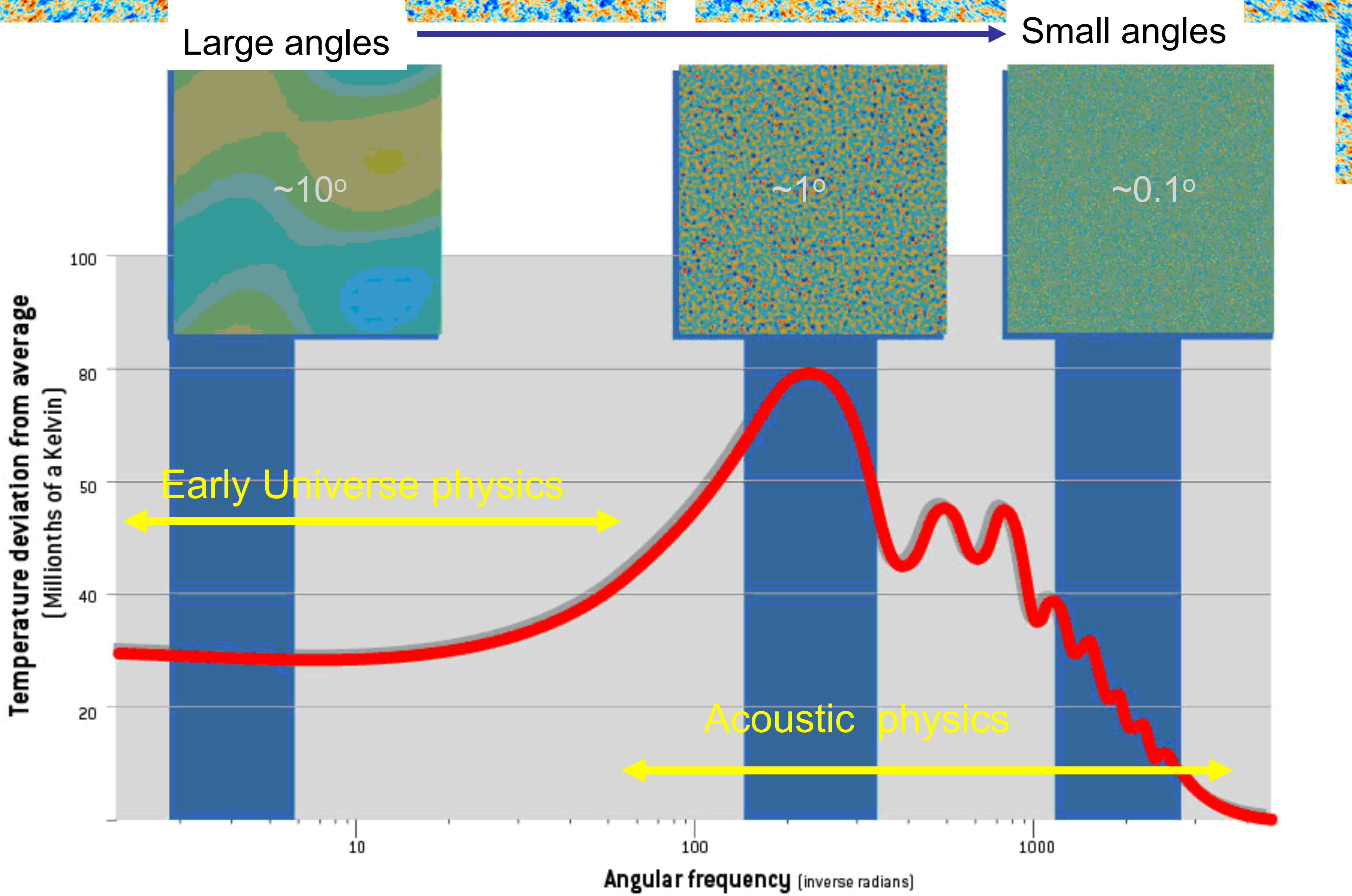


Photon diffusion damps the signal amplitudes at small angular scales

Reionisation increases the optical depth

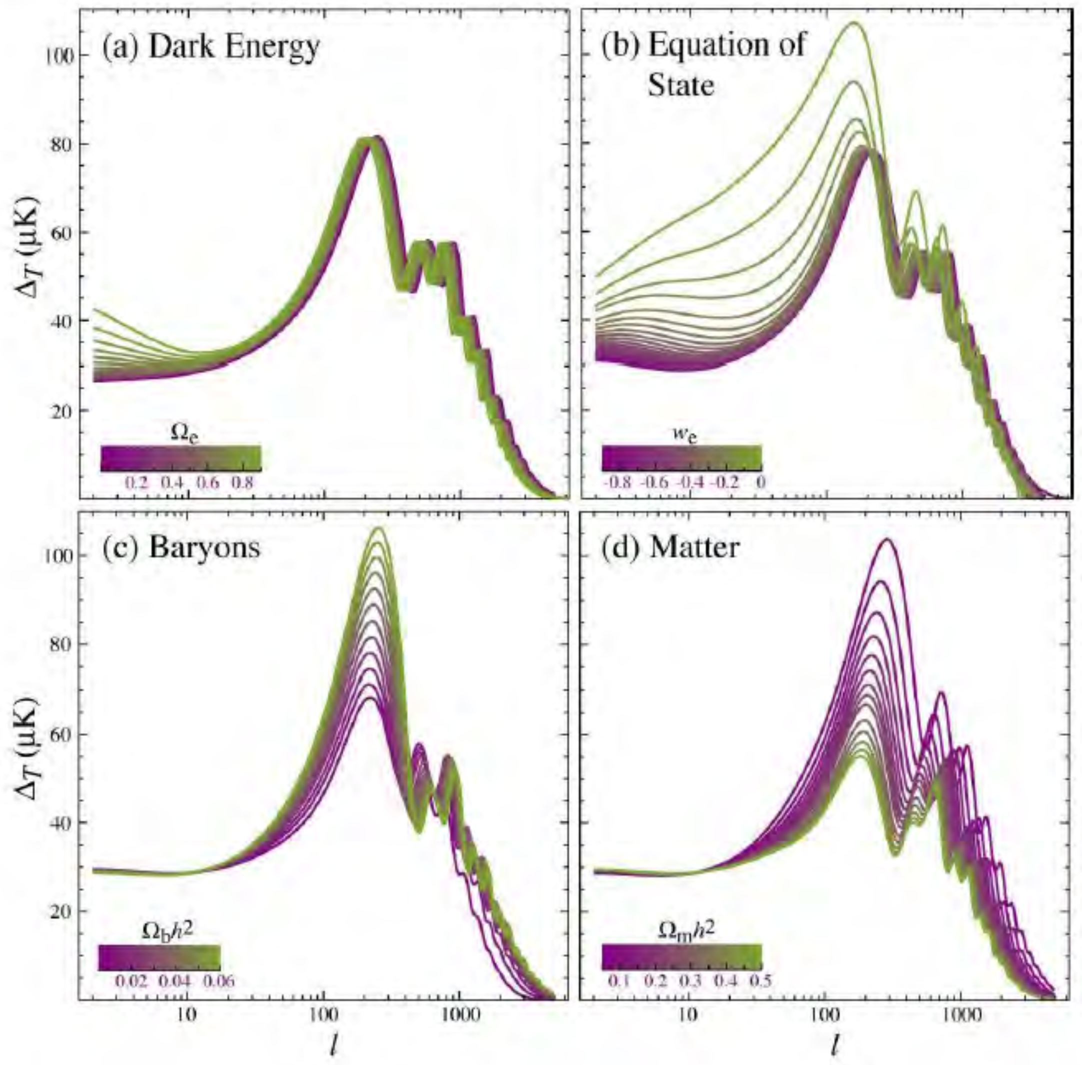


Acoustic oscillations in the last scattering layer



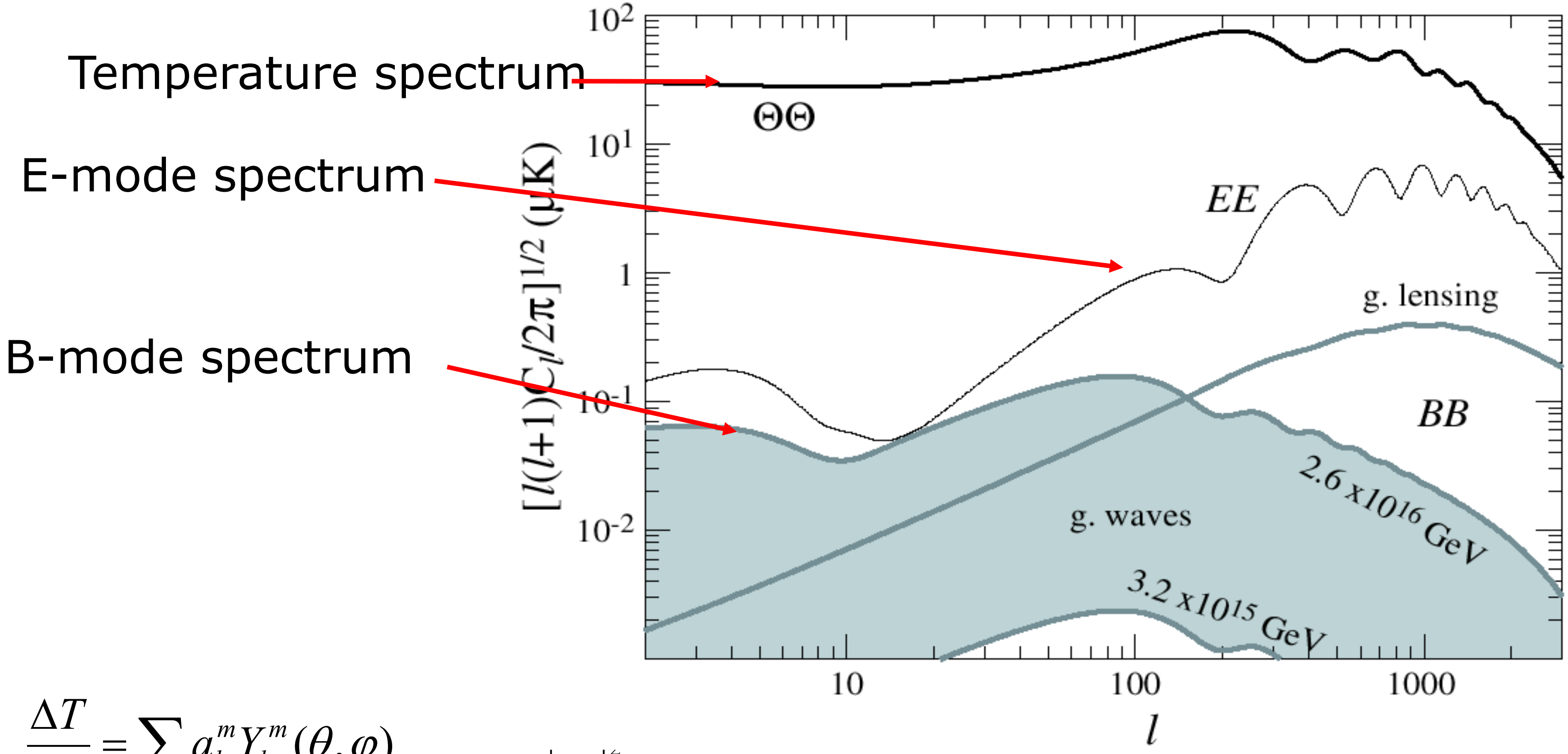
The angular power spectrum of the temperature and polarisation anisotropies can be used to extract the value of fundamental cosmological parameters

The shape of the power spectrum depends sensitively on the value of cosmological parameters

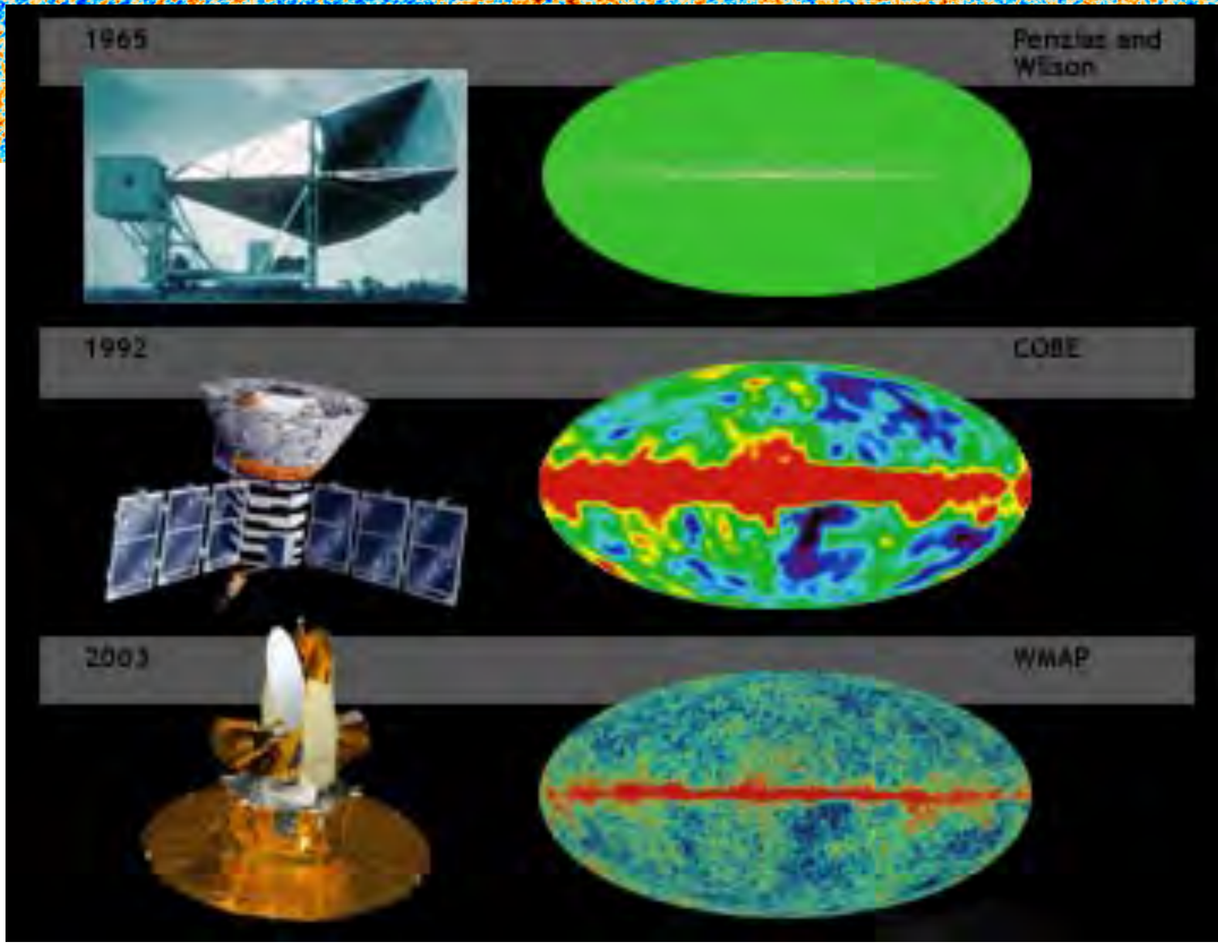


Hu 2002

Theoretical angular power spectrum of the polarised CMB



$$\frac{\Delta T}{T} = \sum_{l,m} a_l^m Y_l^m(\theta,\varphi) \qquad C_l = \langle |a_l^m|^2 \rangle$$

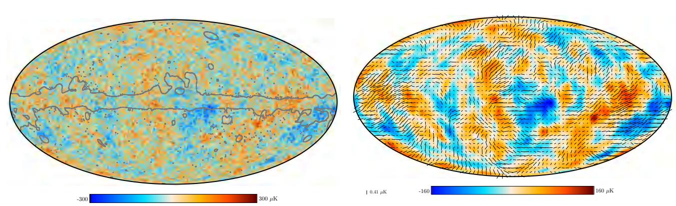


Penzias & Wilson

COBE

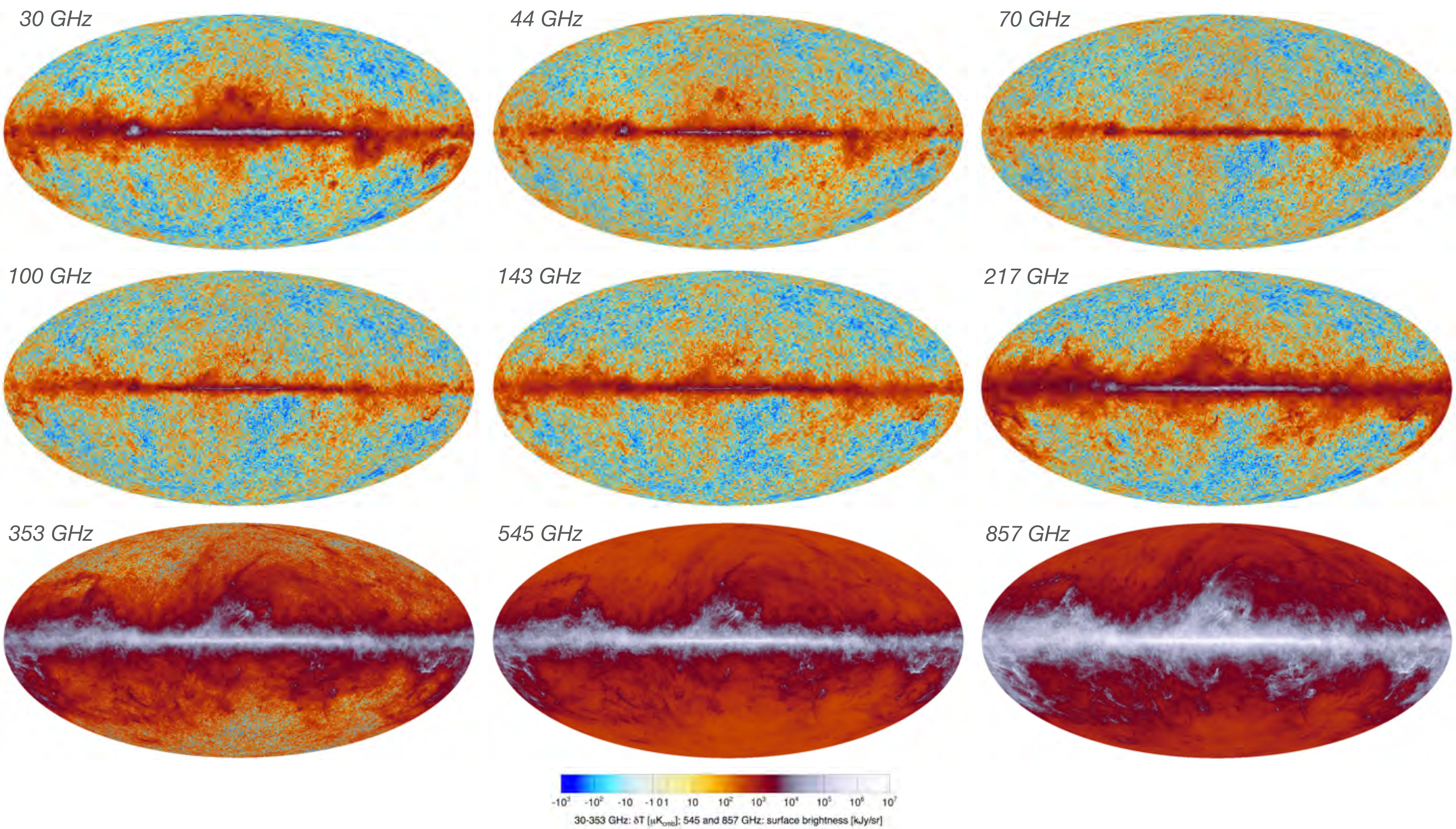
WMAP

2009



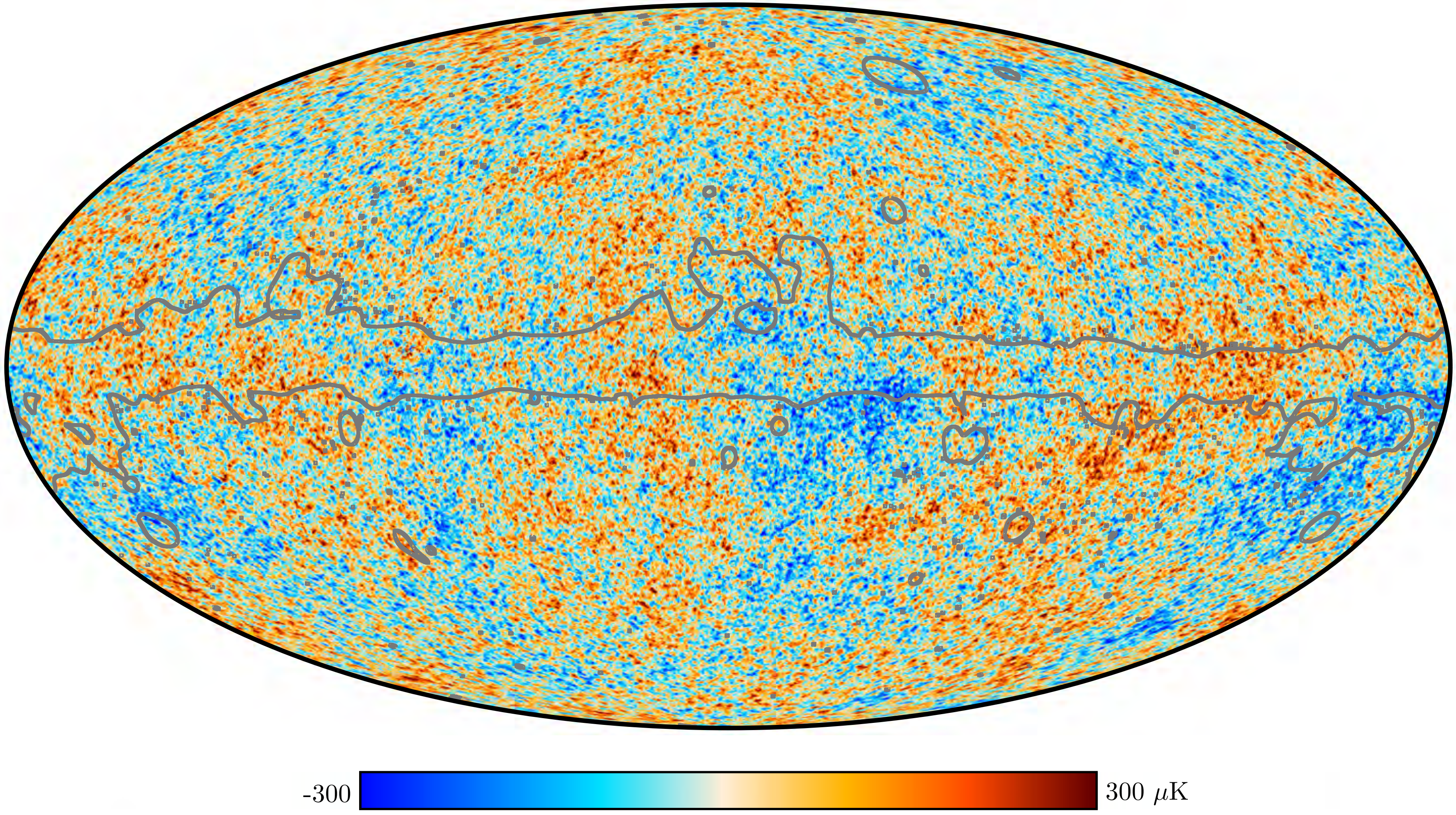
Planck

2018 Planck maps



The temperature fluctuations of the CMB

planck



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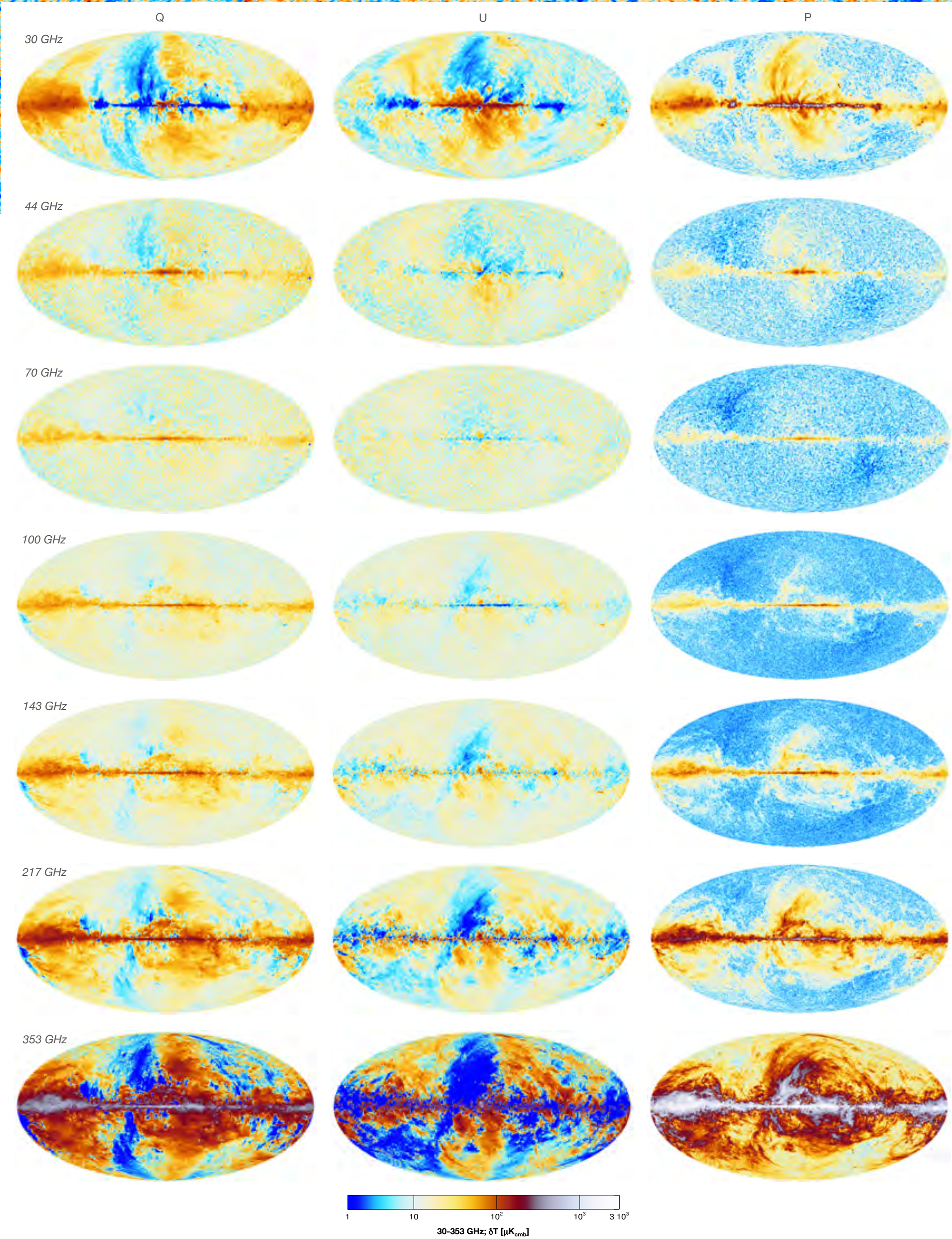
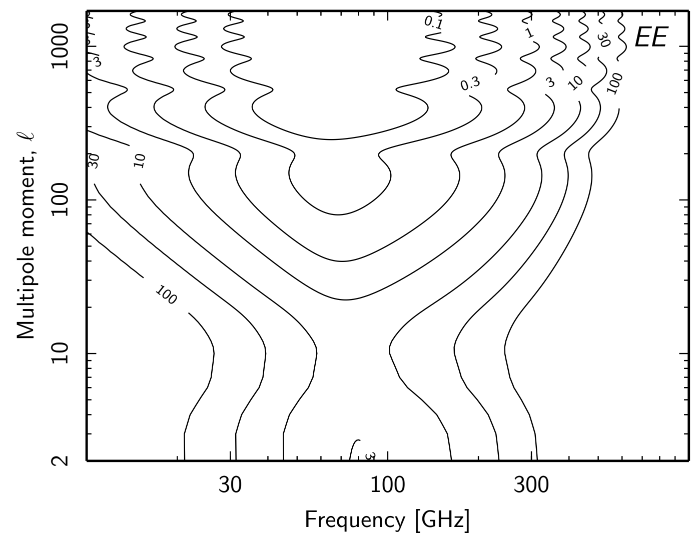
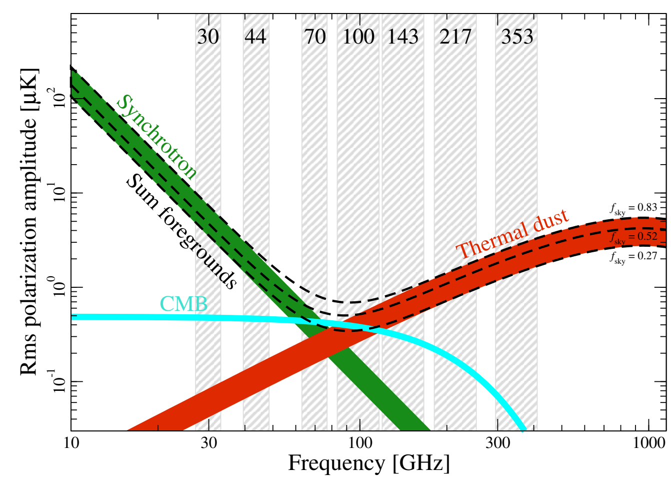
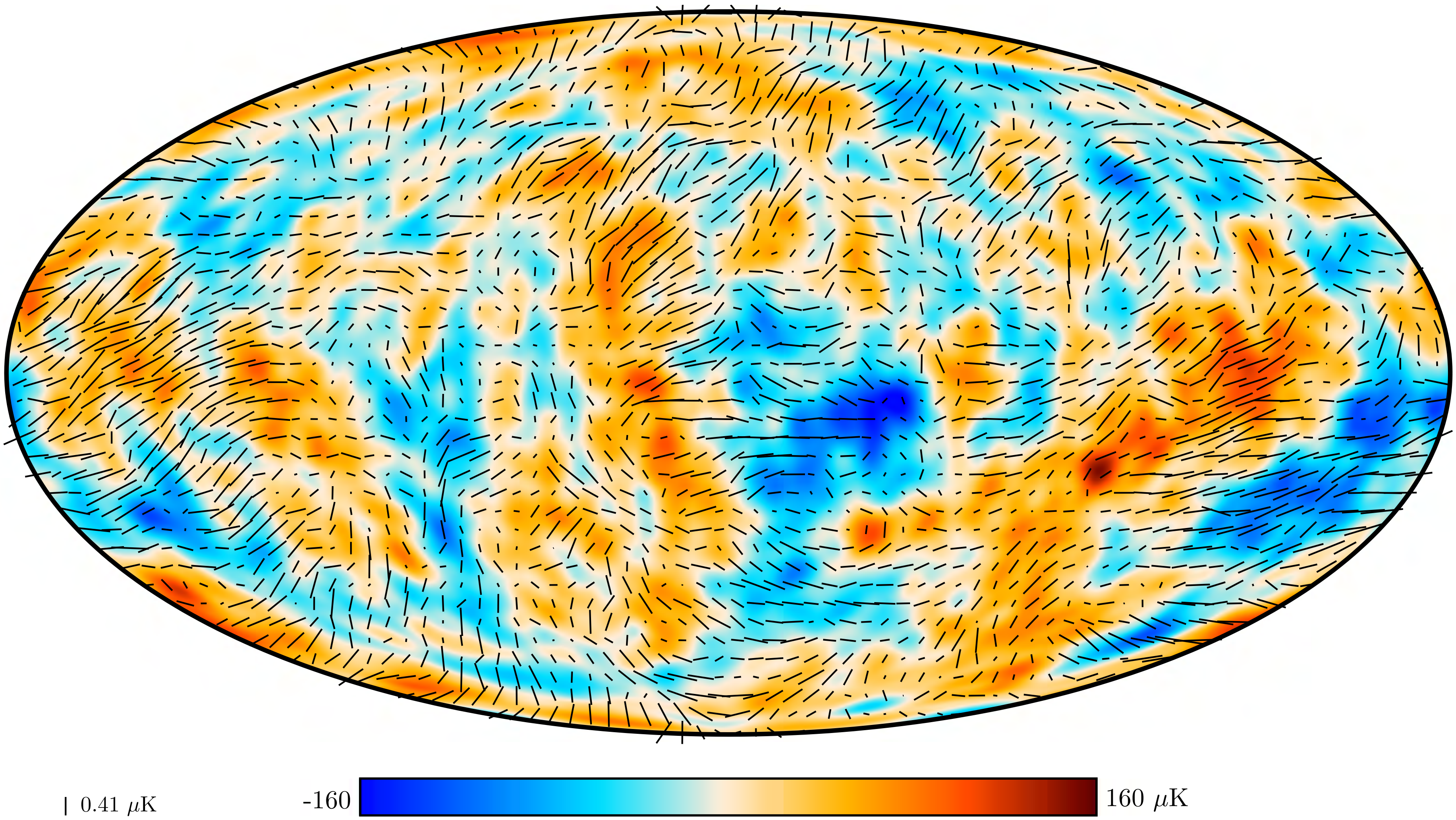
2018 polarized maps



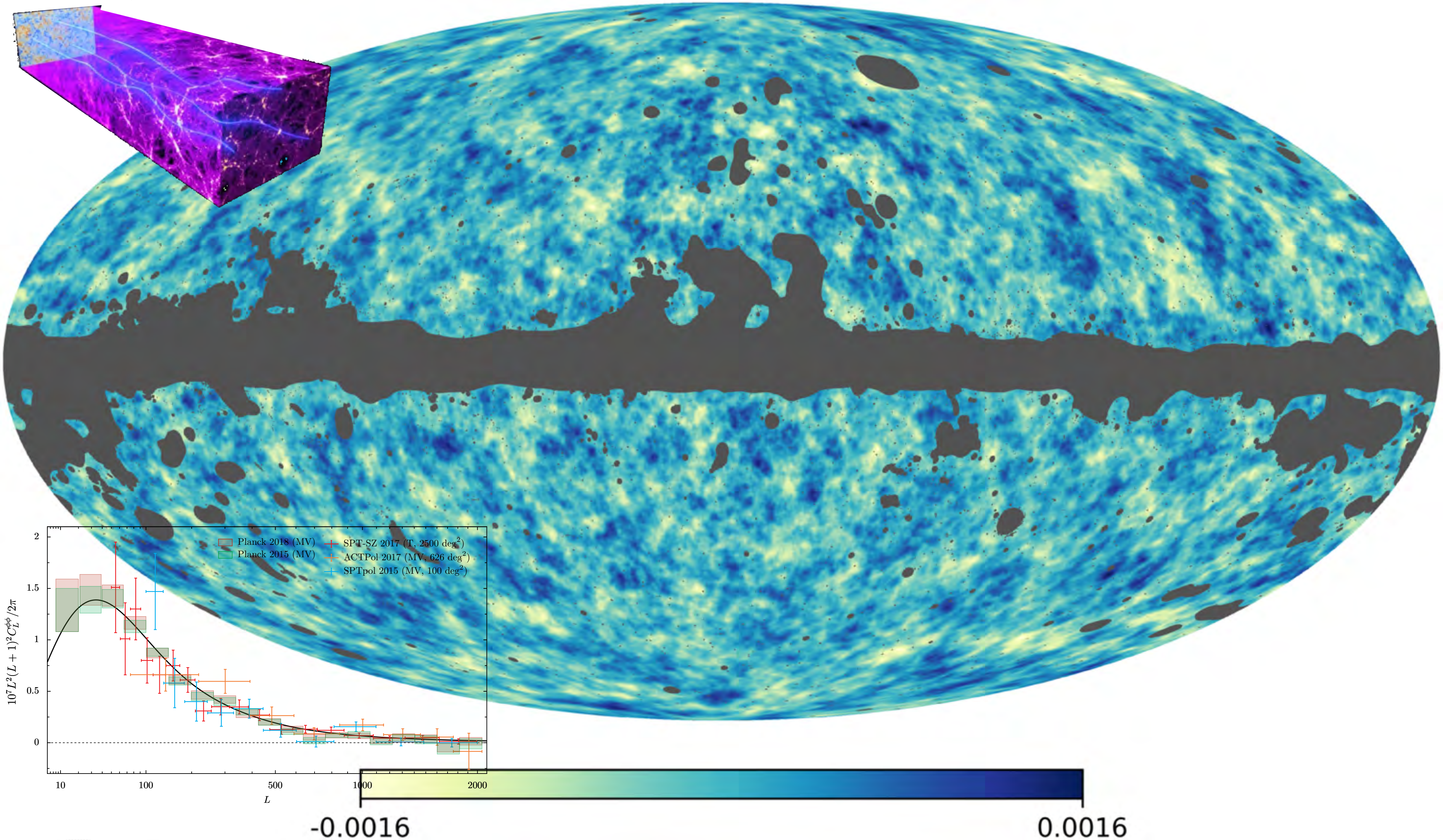




The polarized CMB



Lensing of the CMB

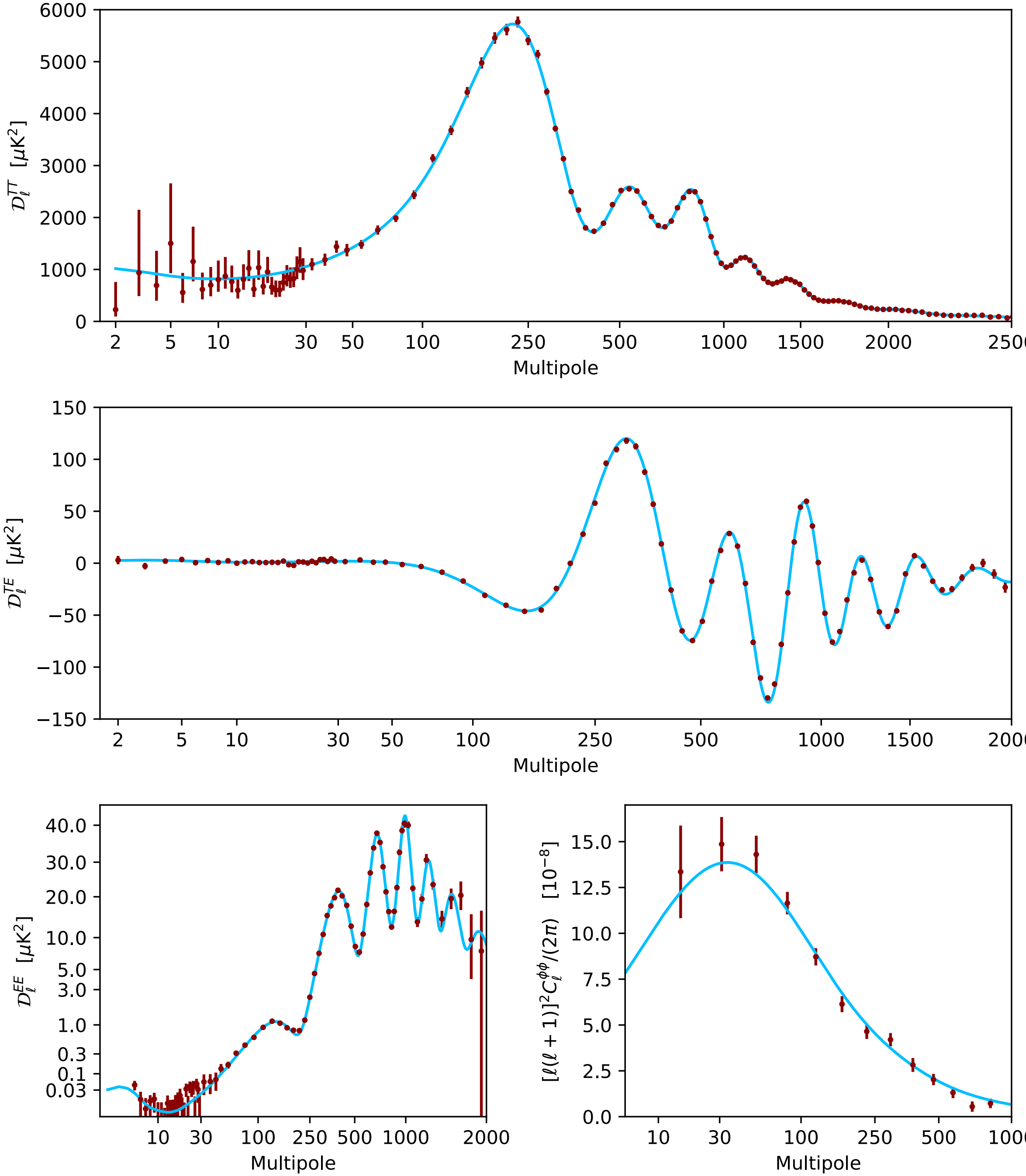


The ΛCDM base model

1. General assumptions: GR, homogeneity, isotropy, …
2. Close-to-zero curvature and simple topology
3. Contents of the Universe
   a. photons
   b. Baryons
   c. Dark matter
   d. Dark energy that behaves like a cosmological constant
   e. Sub-dominant levels of relativistic particles (low-mass neutrinos)
4. Initial density variations are gaussian, adiabatic, nearly-scale-invariant (inflation)

Best ΛCDM fit to TT, TE, EE+lowE+lensing

Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
$k_{eq}[\mathrm{Mpc}^{-1}]$	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

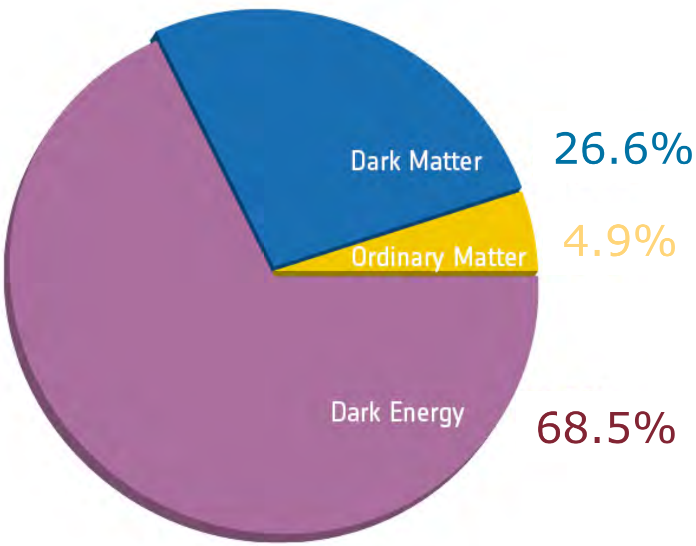


Jan Tauber, Astroparticle p

Precision concordance cosmology

Parameter	*Planck* alone
$\Omega_b h^2$	0.02237 ± 0.00015
$\Omega_c h^2$	0.1200 ± 0.0012
$100\theta_{MC}$	1.04092 ± 0.00031
τ	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.044 ± 0.014
n_s	0.9649 ± 0.0042

Age of the Universe: 13.8 Gyr
Hubble constant: 67.4 km s^{-1}/Mpc
Reionization redshift: $z_{re} \sim 7.7$



- Percent accuracies except for τ
- Consistency between temperature and polarization
- Consistency with other tracers of cosmology

Extensions to ΛCDM

Extensions to ΛCDM allow to

- Test assumptions
- Constrain theoretical parameters, e.g. set upper limits

Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
$N_{\rm eff}$	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

$$f_{NL} = 2.5 \pm 5.7$$

- Departures from flatness
- Neutrino masses
- Number of relativistic species
- spatial non-gaussianity
- tensor modes (primordial gravitational waves)
- Deviations from scalar invariance
- Dark energy equation of state
- Deviations from isotropy
- Strange topologies
- Non-adiabaticity
- …

Inflationary scorecard

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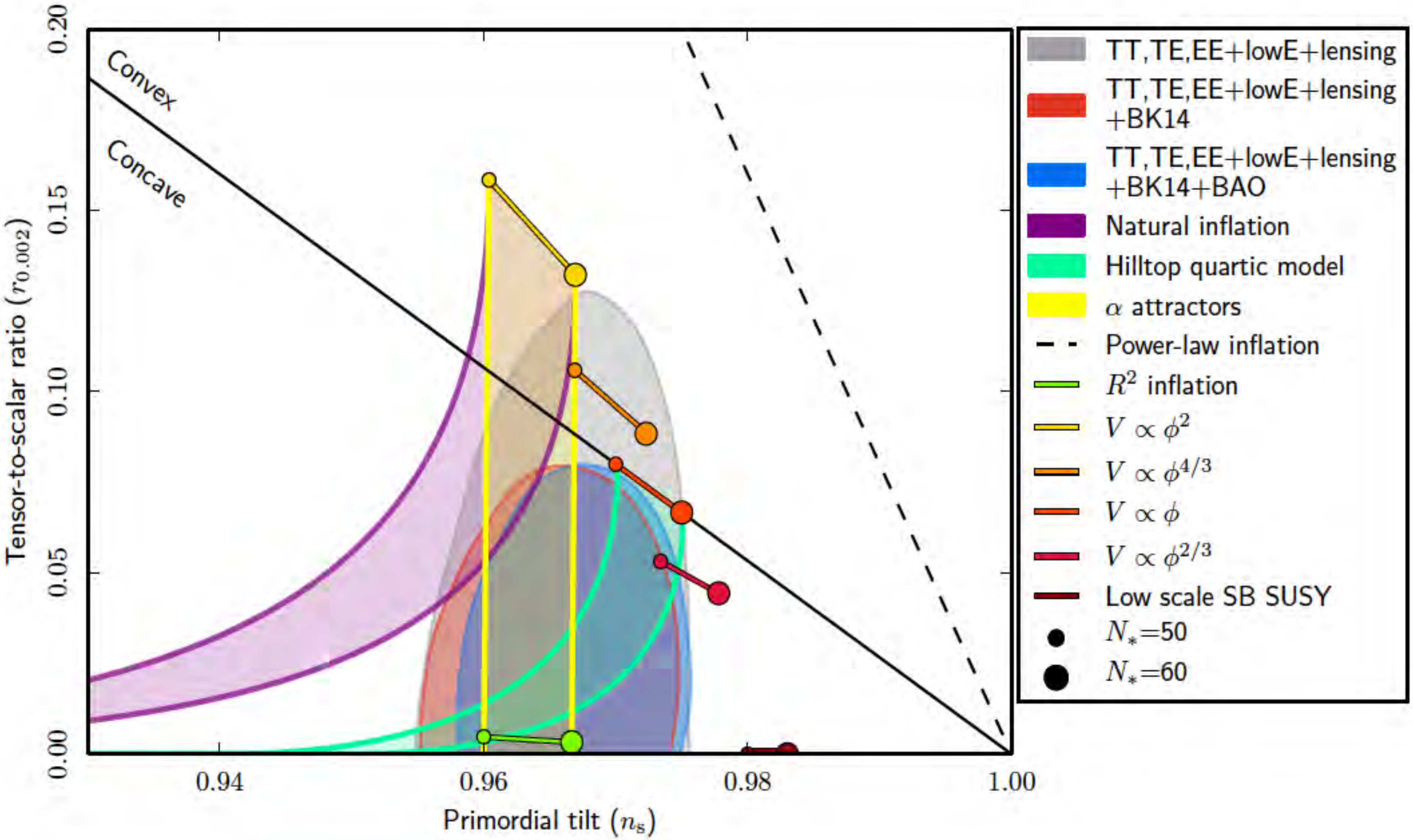
Prediction	Measurement
A spatially flat universe	$\Omega_K = 0.0007 \pm 0.0019$
with a *nearly* scale-invariant (red)	
spectrum of density perturbations,	$n_s = 0.967 \pm 0.004$
which is almost a power law,	$dn/d\ln k = -0.0042 \pm 0.0067$
dominated by scalar perturbations,	$r_{0.002} < 0.07$
which are Gaussian	$f_{NL} = 2.5 \pm 5.7$
and adiabatic,	$\alpha_{-1} = 0.00013 \pm 0.00037$
with negligible topological defects	$f < 0.01$

Inflationary models



The linear matter power spectrum (z~0)

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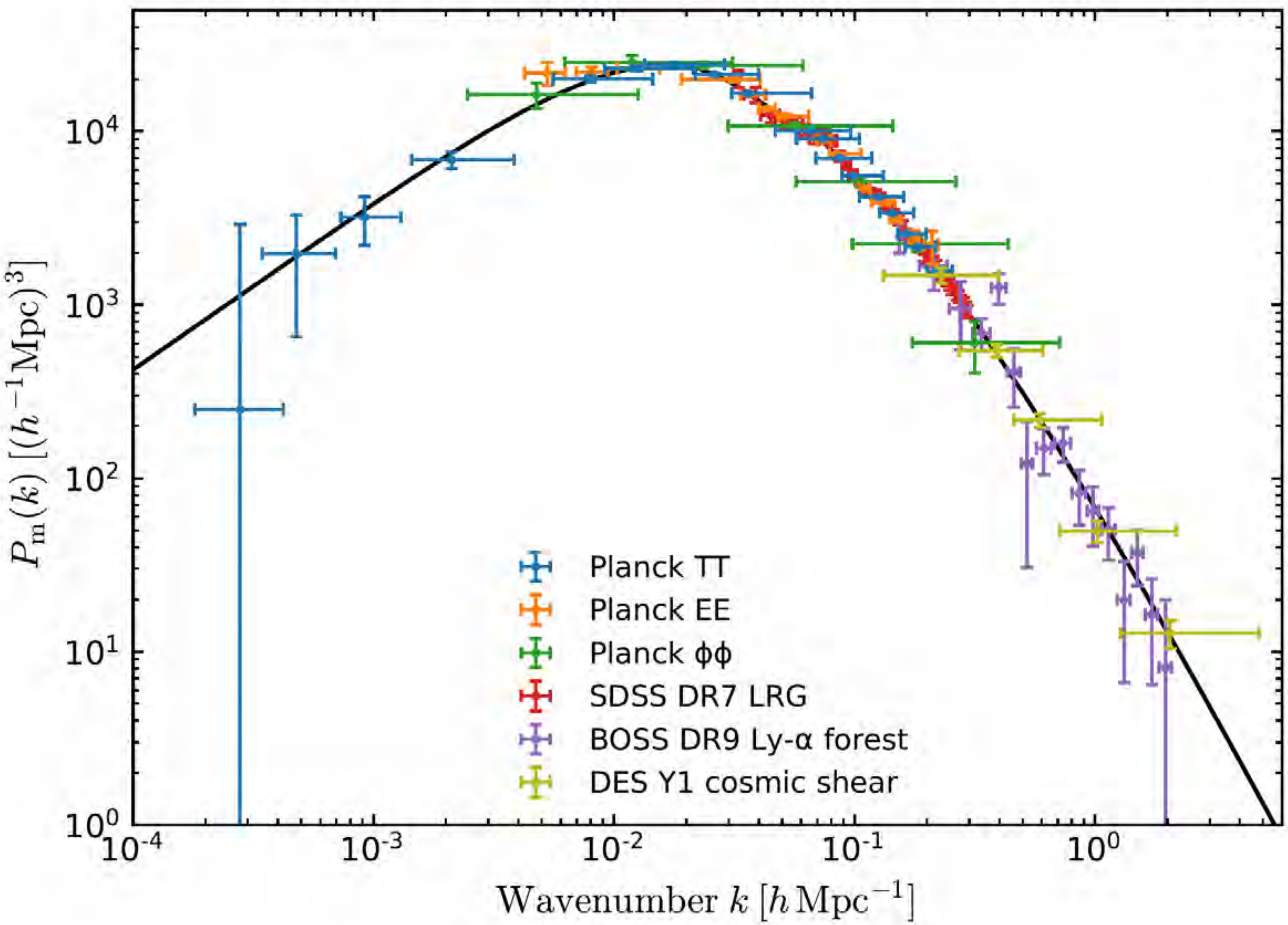
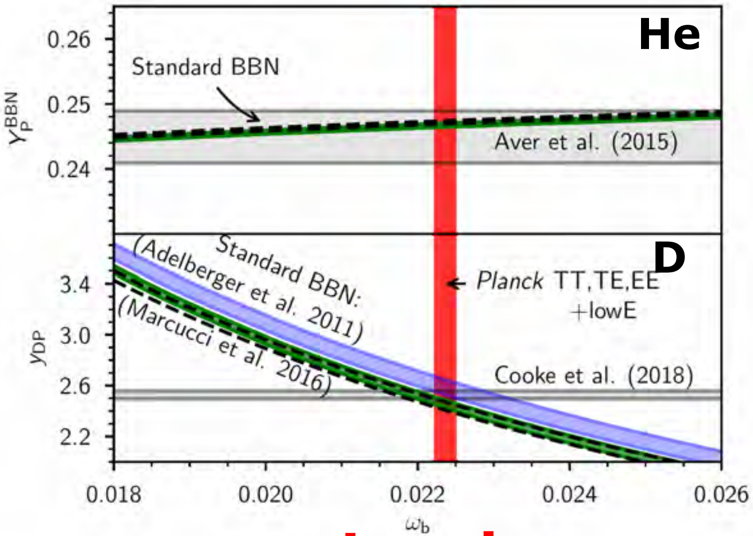
from different probes spanning 14Gyr in time and >3 decades in scale

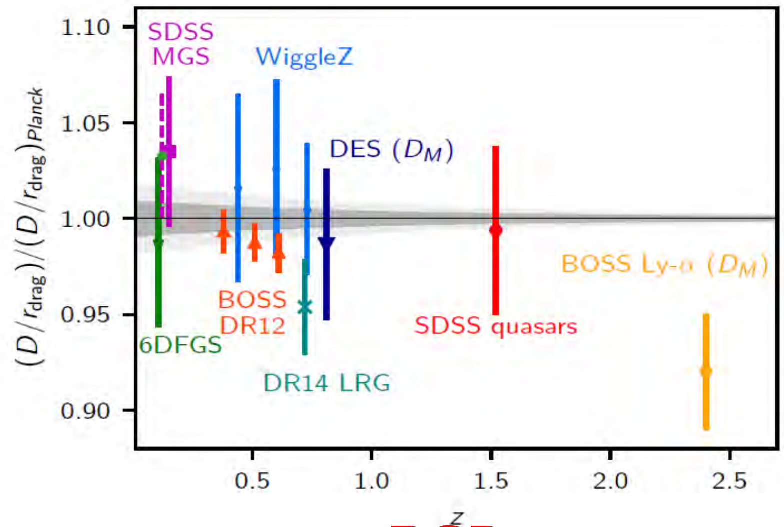


Concordance cosmology

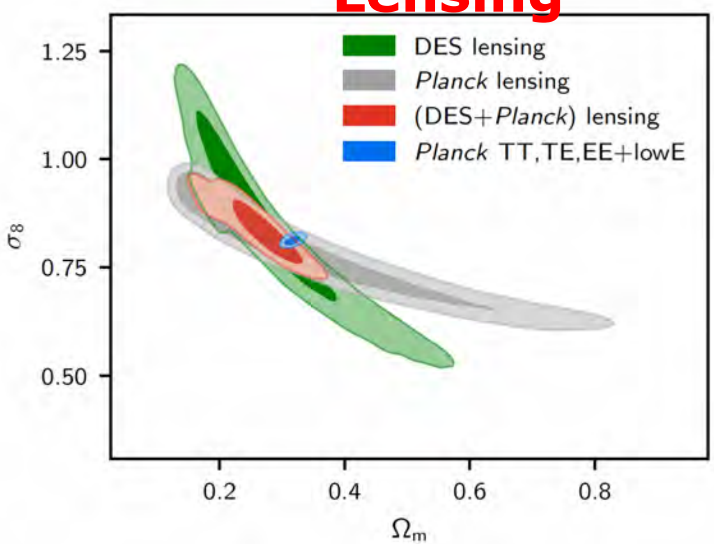
BBN



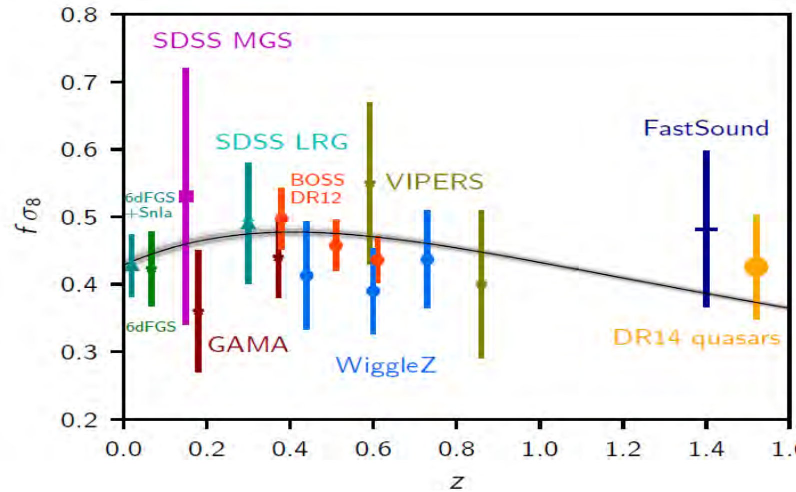
BAO



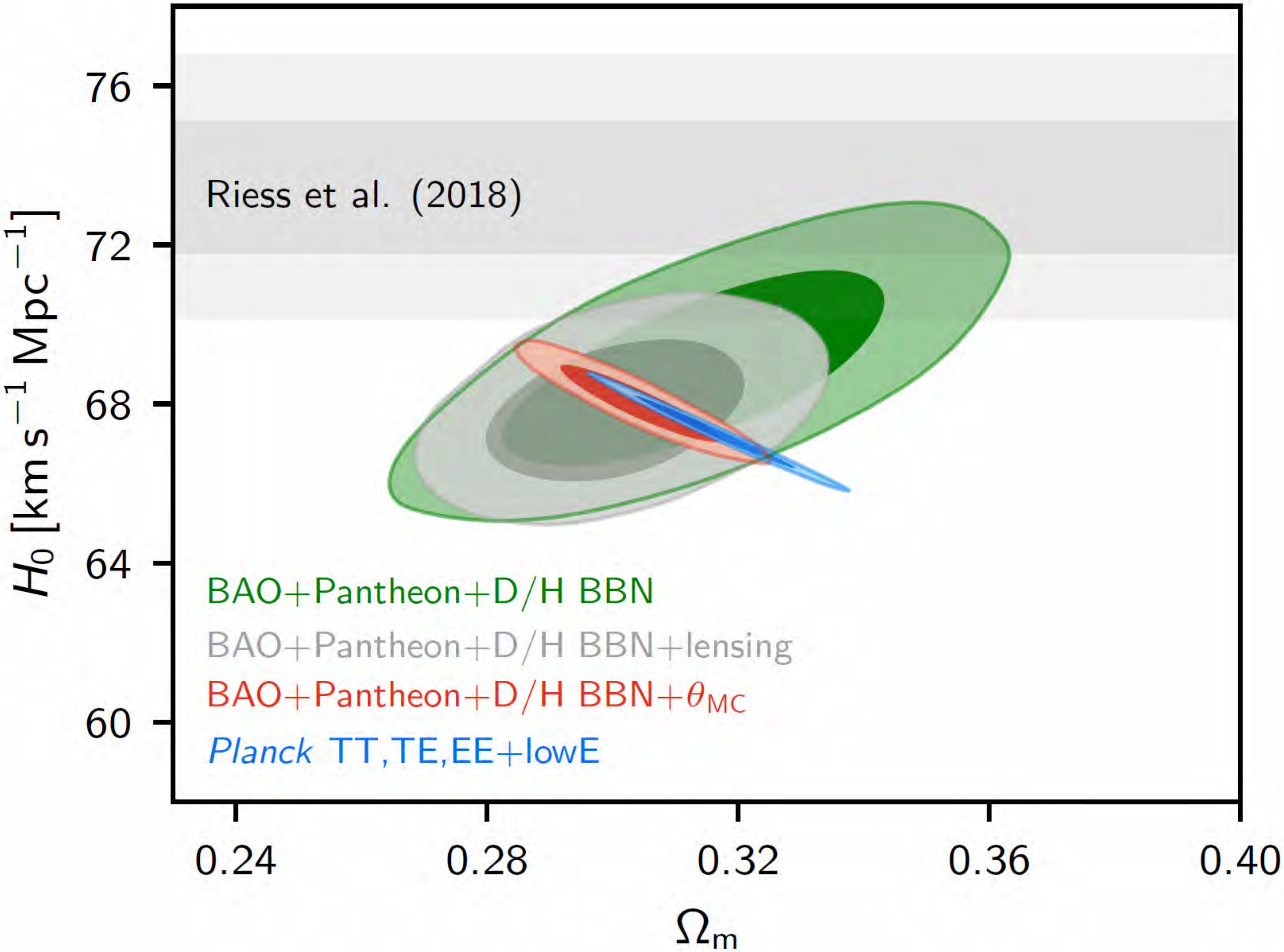
Lensing

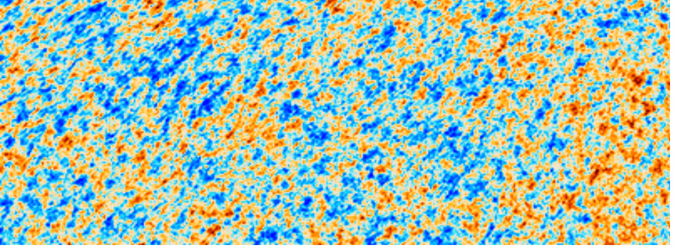


RSD

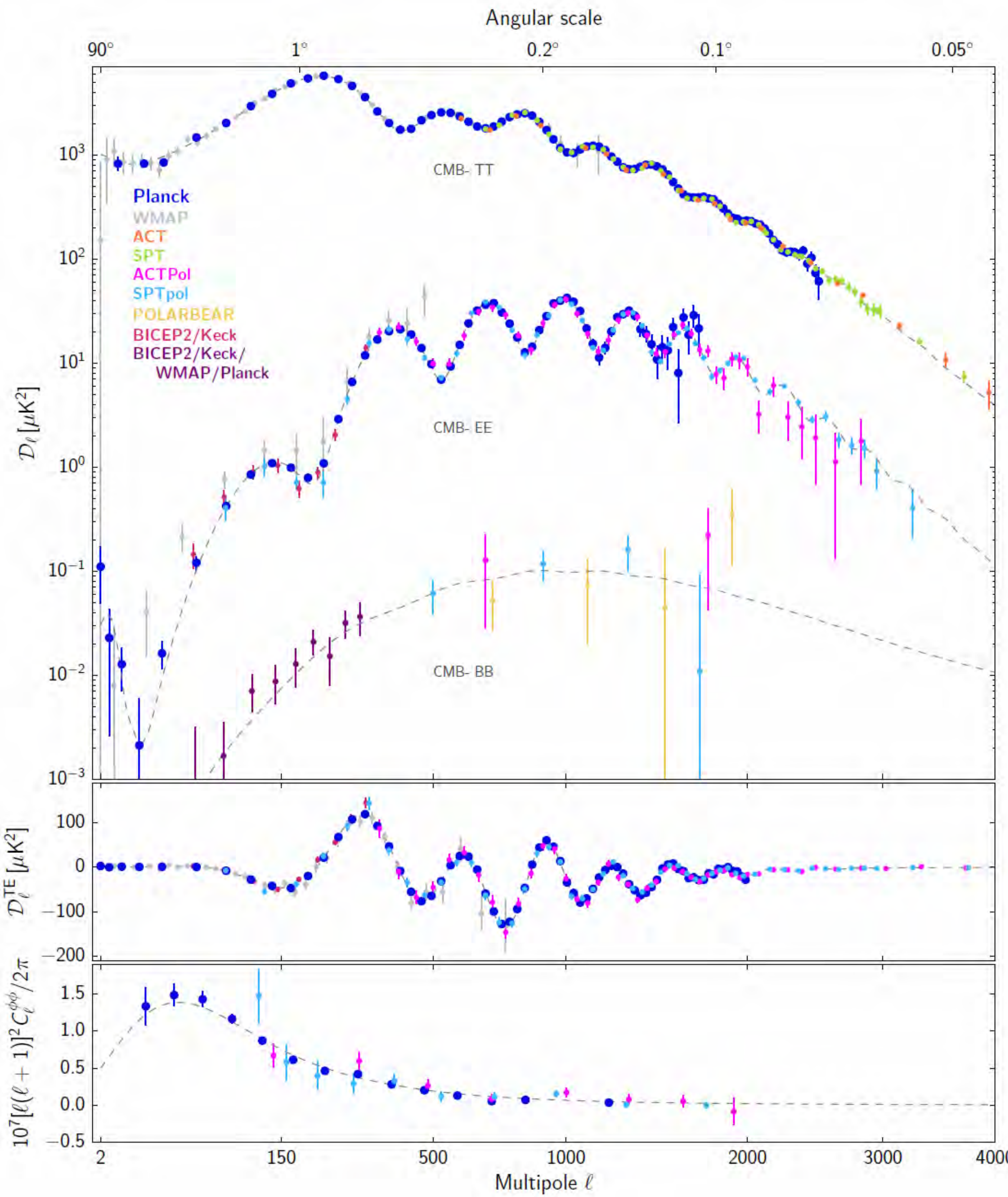


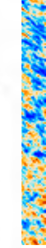
The Hubble constant



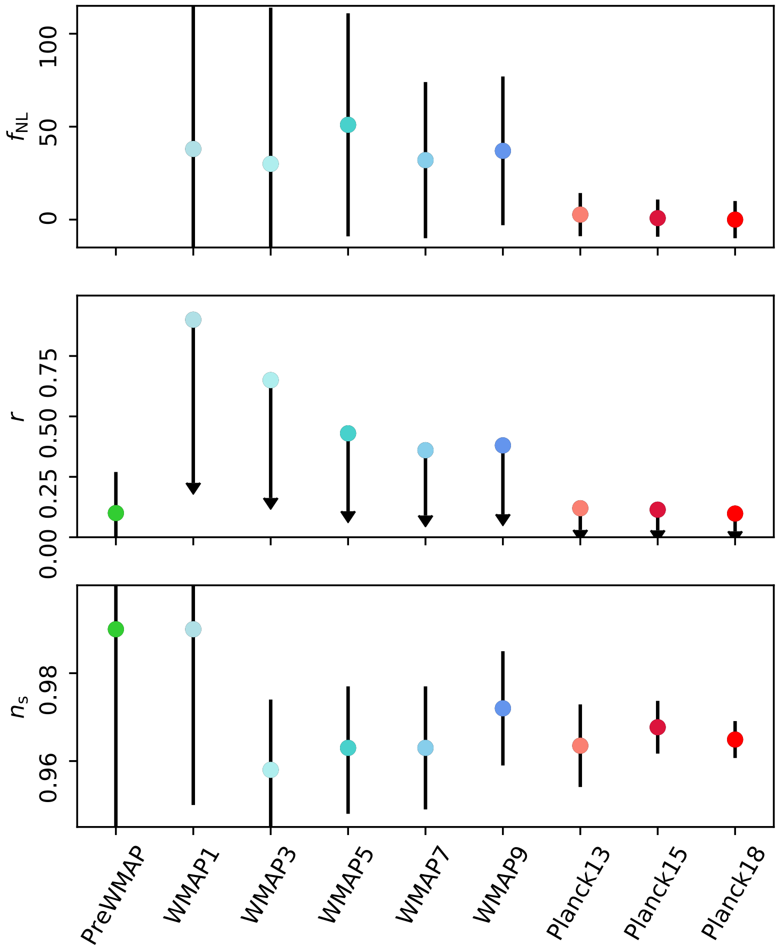


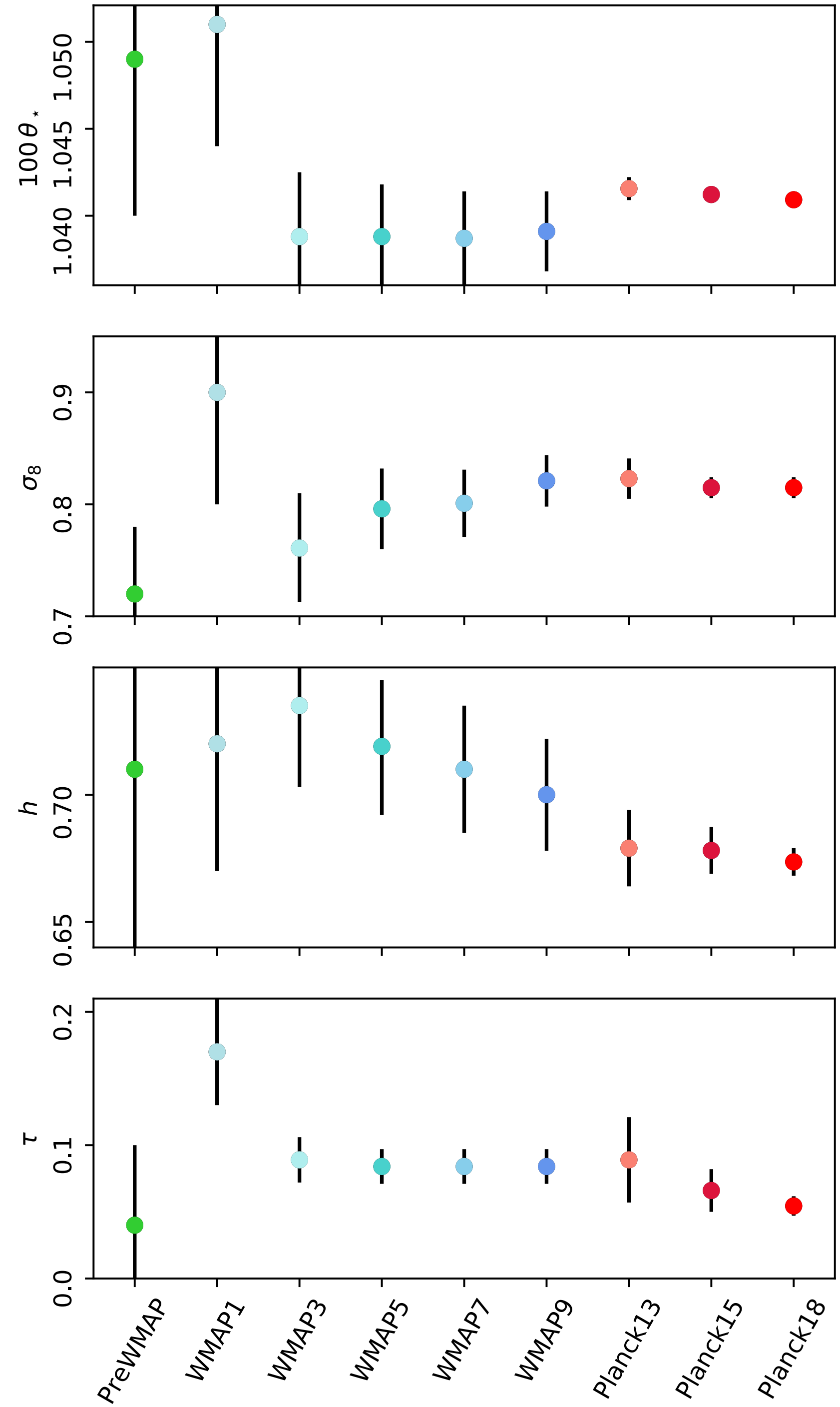
CMB measurements state of the art





Cosmological parameters over time





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What next ?

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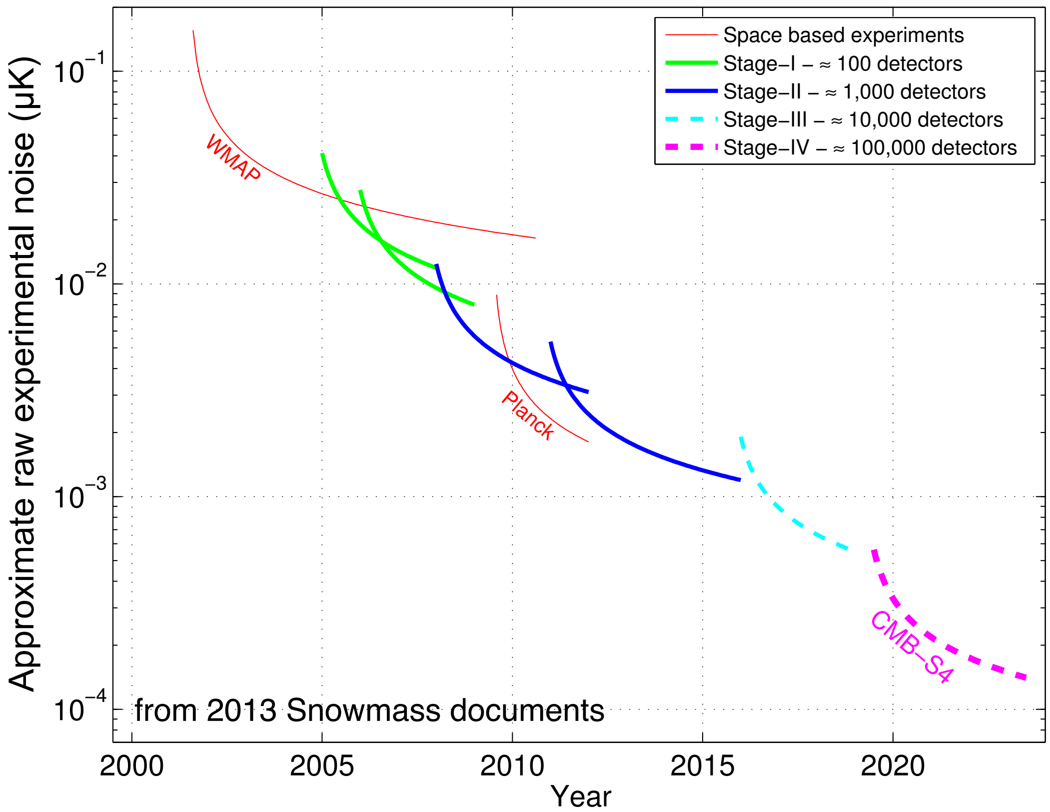
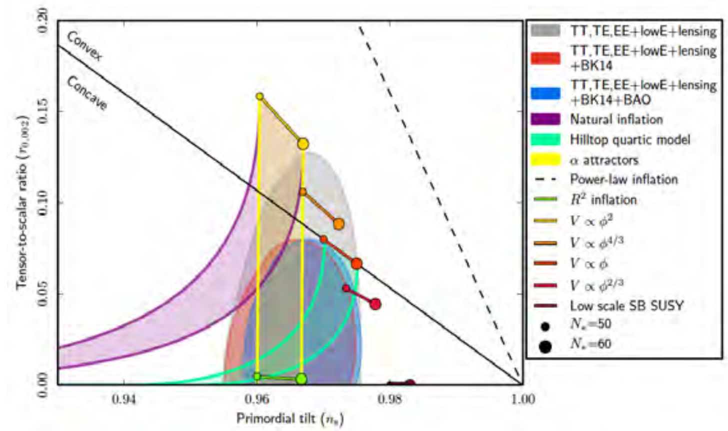
"Moore's Law" of CMB sensitivity



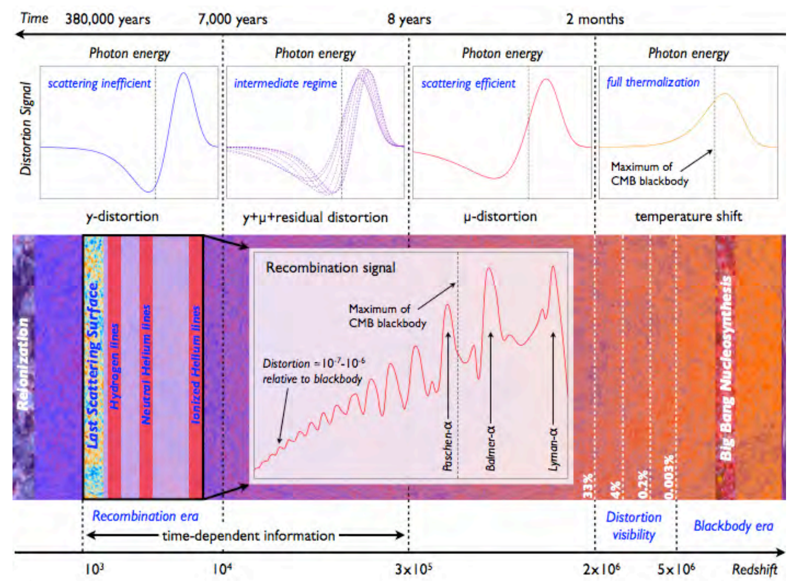
But need more than detectors...

What next ?

- CMB anisotropies + lensing
  - Primordial grav waves
  - Neutrino parameters
  - Cluster science
  - …



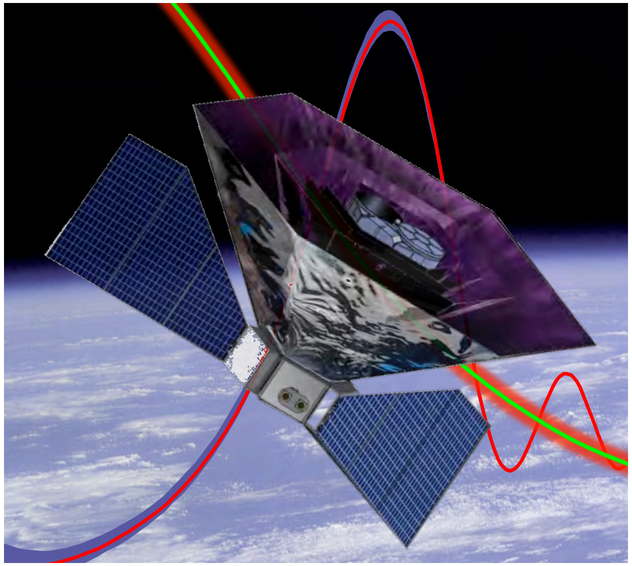
- CMB spectrum
  - Distortion signals
  - Recombination- and reionization-era lines
  - …



Potential future satellites

Litebird

Pixie

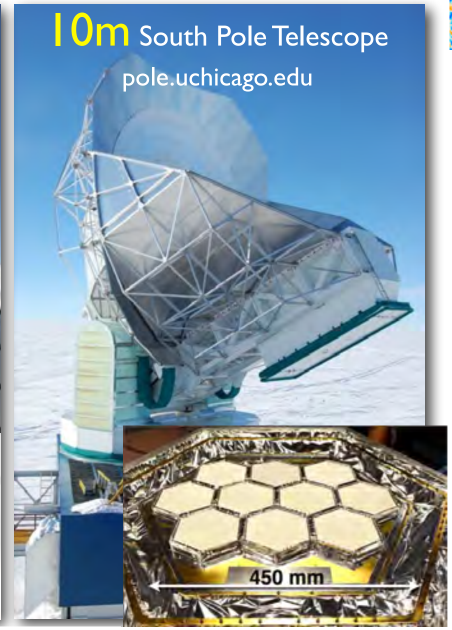


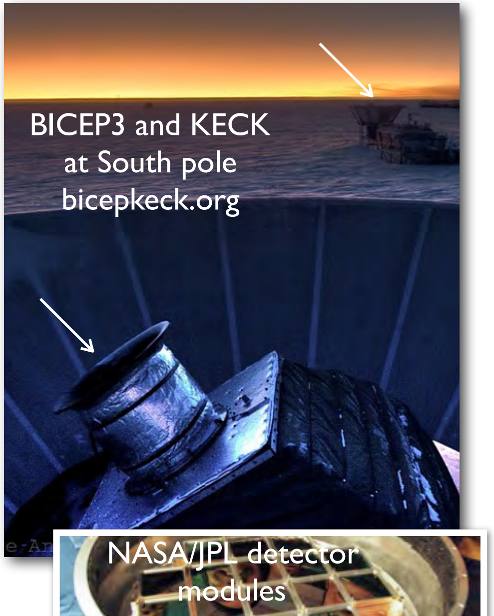
CORE

Sub-orbital


2.5m POLARBEAR
Huan Tran Telescope
bolo.berkeley.edu/polarbear


6m Atacama Cosmology Telescope
physics.princeton.edu/act/


10m South Pole Telescope
pole.uchicago.edu
450 mm


BICEP3 and KECK
at South pole
bicepkeck.org
NASA/JPL detector
modules


CLASS telescope #1
http://sites.krieger.jhu.edu/class/

Ground-based forecasts

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Years	Stage	Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015, 2016, 2017	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	0.15eV (Boss BAO prior)	~180 (DES+BOSS SPT clusters)
2018, 2019, 2020, 2021, 2022, 2023	Stage 3 10,000 detectors	10^{-6}	0.003	0.06	~0.06eV (Boss BAO prior)	~300-600 (DES + DESI SZ Clusters)
2024, 2025, 2026						
2027/34	CMB-S4	**10^{-8}**	**0.0005**	**0.03**	**0.015eV** (DESI BAO $+T_e$ prior)	**1250** (DESI +LSST S4 Clusters)

CMB cosmology

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- The Cosmic Microwave Background is at the origin of the Hot Big Bang scenario
- It remains one of the major contributors to the development of a standard concordance cosmology
- It tests fundamental assumptions and provides precision measures of model parameters
    - The challenge now is to achieve coherence between early and late Universe probes
- The CMB's impact has grown according to the instrumental capabilities
    - We can expect that it will continue to provide priceless cosmological information

Thank you