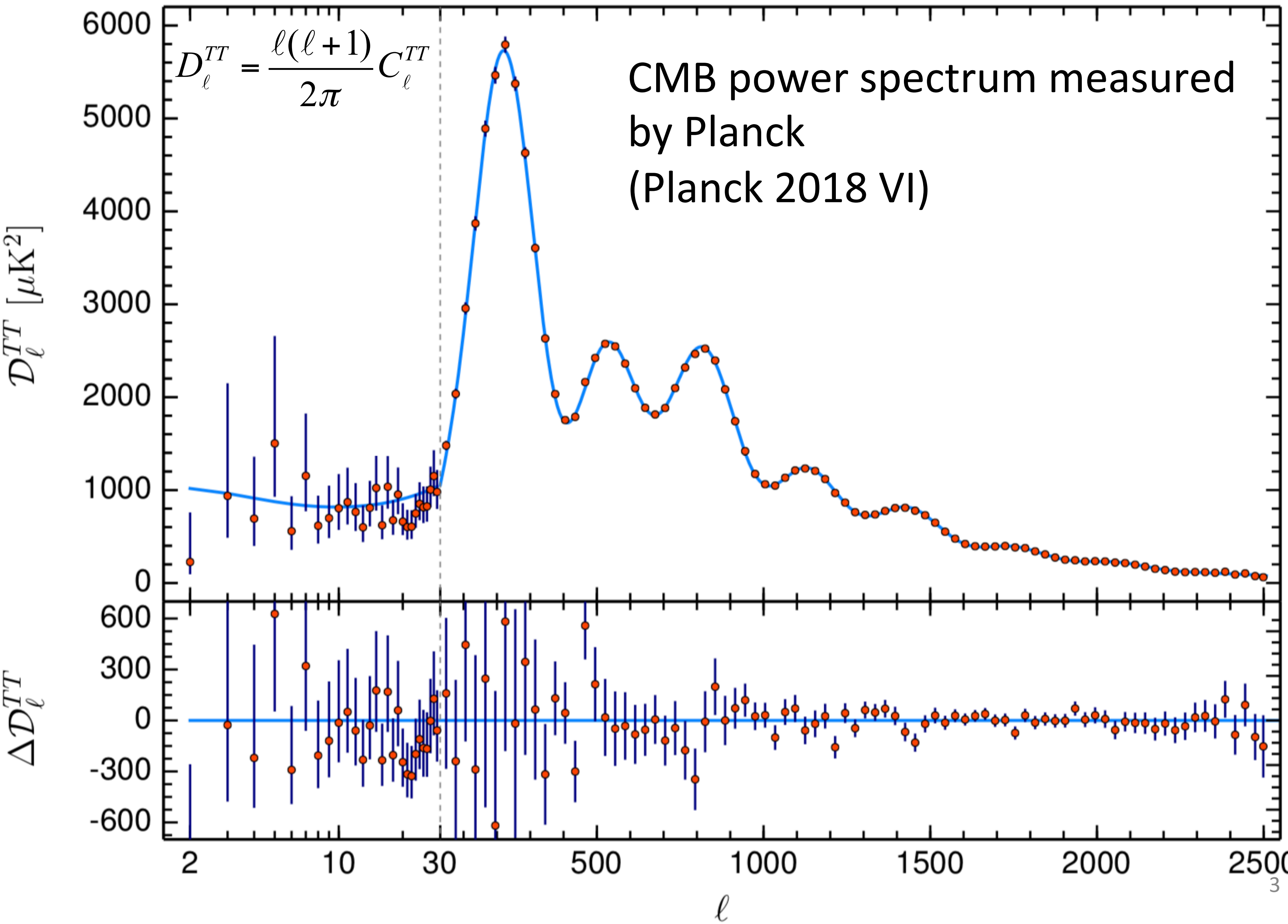
Supplement to Lecture XII: Cosmic Microwave Background

(Planck-centric since this is current)

Contents

1. How to use CMB anisotropies to measure cosmology

2. Observational aspects



$D_\ell^{TT} = \frac{\ell(\ell+1)}{2\pi} C_\ell^{TT}$
CMB power spectrum measured by Planck
(Planck 2018 VI)
$\mathcal{D}_\ell^{TT}\ [\mu\mathrm{K}^2]$
6000
5000
4000
3000
2000
1000
0
$\Delta\mathcal{D}_\ell^{TT}$
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500
ℓ

Planck 2018 Cosmological Parameters

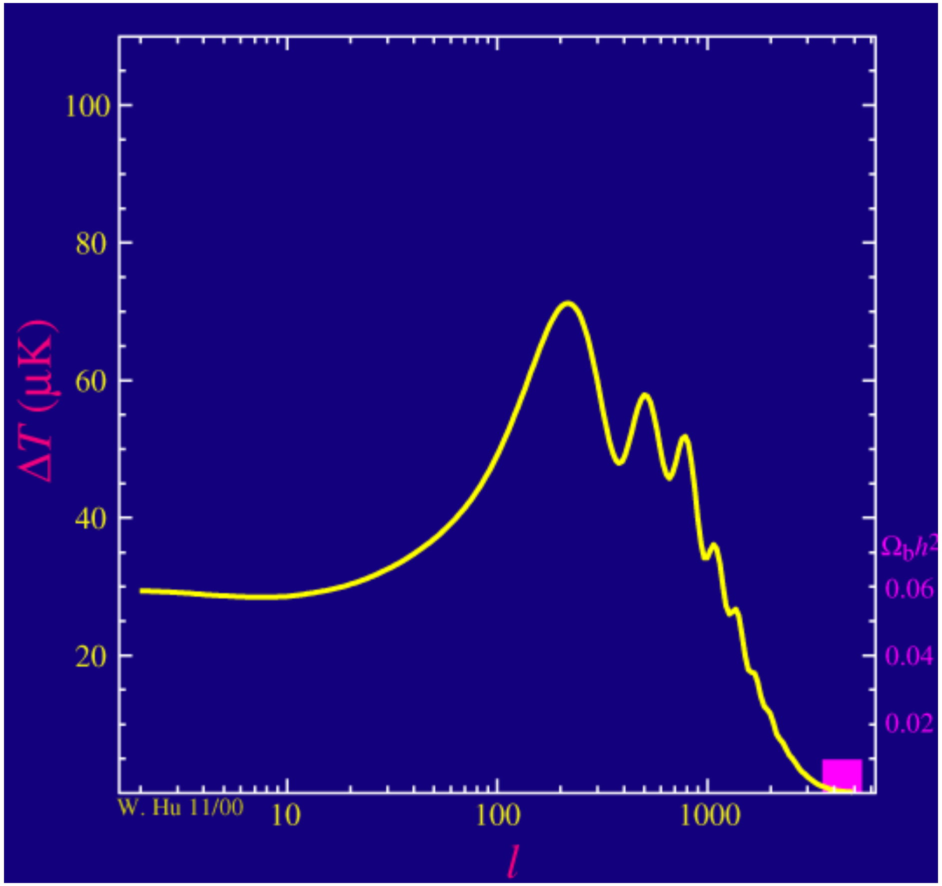
(ΛCDM model, fit with temperature + polarization + lensing of CMB)

Parameter	`Plik` best fit	`Plik` [1]
$\Omega_b h^2$	0.022383	0.02237 ± 0.00015
$\Omega_c h^2$	0.12011	0.1200 ± 0.0012
$100\theta_{MC}$	1.040909	1.04092 ± 0.00031
τ	0.0543	0.0544 ± 0.0073
$\ln(10^{10} A_s)$	3.0448	3.044 ± 0.014
n_s	0.96605	0.9649 ± 0.0042
$\Omega_m h^2$	0.14314	0.1430 ± 0.0011
H_0 [km s^{-1}Mpc^{-1}] . . .	67.32	67.36 ± 0.54
Ω_m	0.3158	0.3153 ± 0.0073
Age [Gyr]	13.7971	13.797 ± 0.023
σ_8	0.8120	0.8111 ± 0.0060
$S_8 \equiv \sigma_8(\Omega_m/0.3)^{0.5}$ . .	0.8331	0.832 ± 0.013
z_{re}	7.68	7.67 ± 0.73
$100\theta_*$	1.041085	1.04110 ± 0.00031
r_{drag} [Mpc]	147.049	147.09 ± 0.26

What's underneath the χ^2 fit

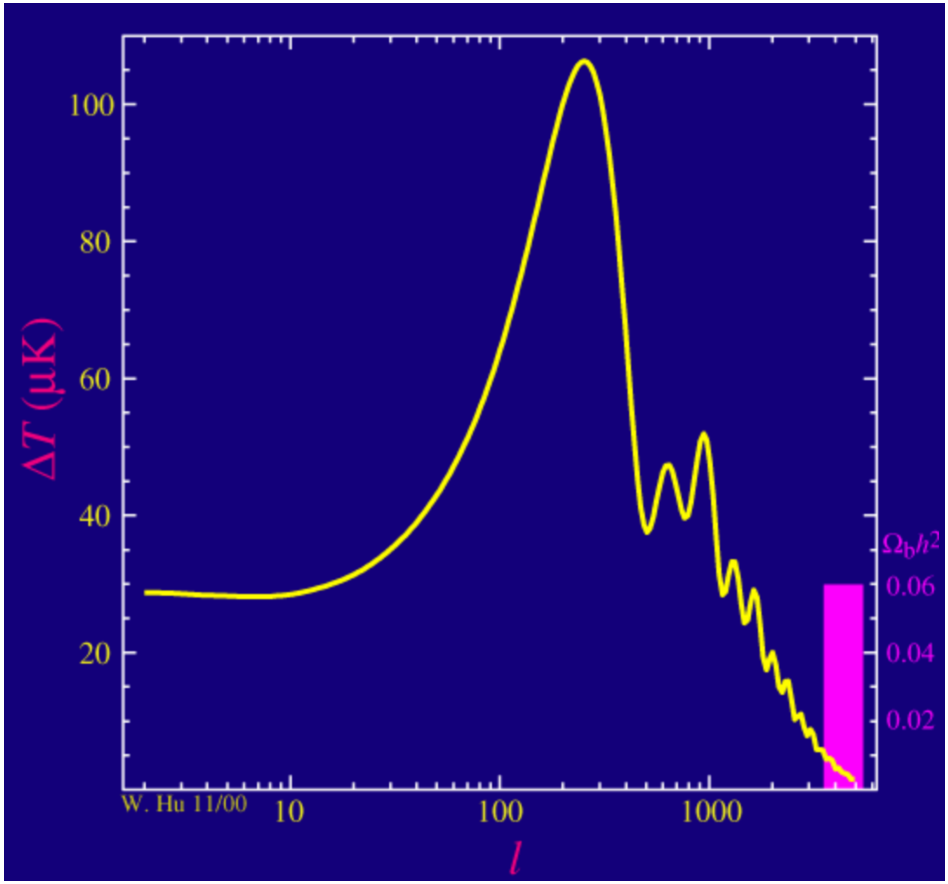
pictures from Wayne Hu's CMB tutorial – http://background.uchicago.edu/~whu/intermediate/

Low $\Omega_b h^2$



Weak odd-even effect in peaks

High $\Omega_b h^2$

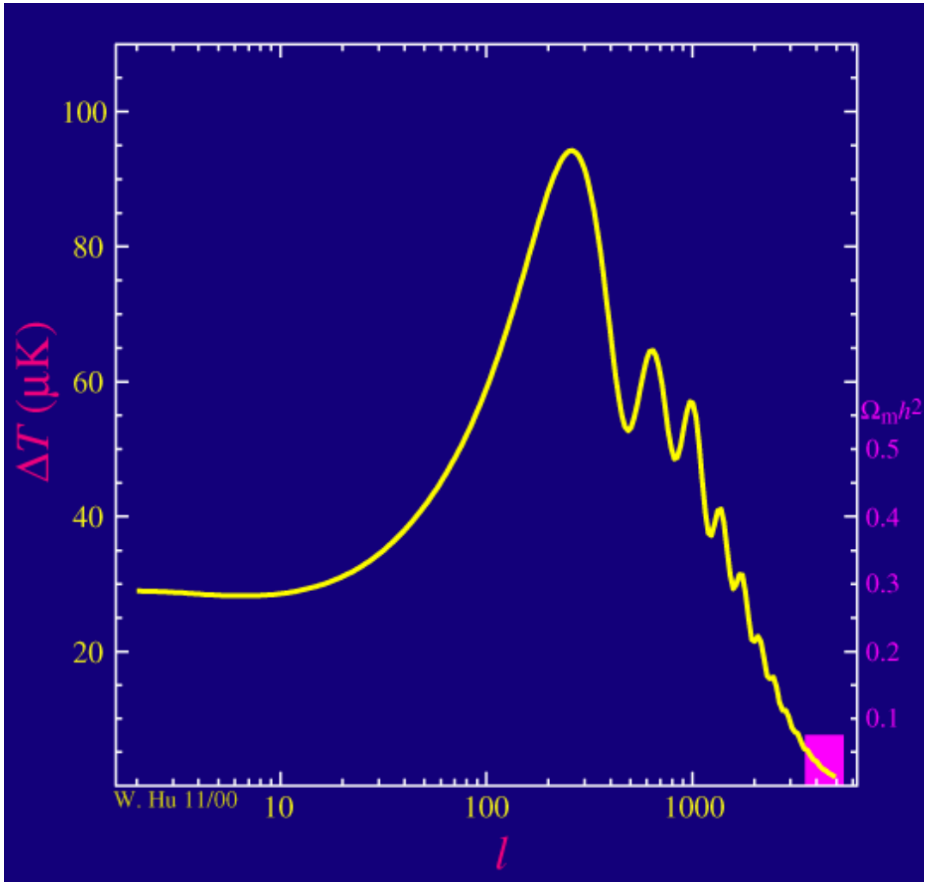


Strong odd-even effect in peaks

What's underneath the χ^2 fit

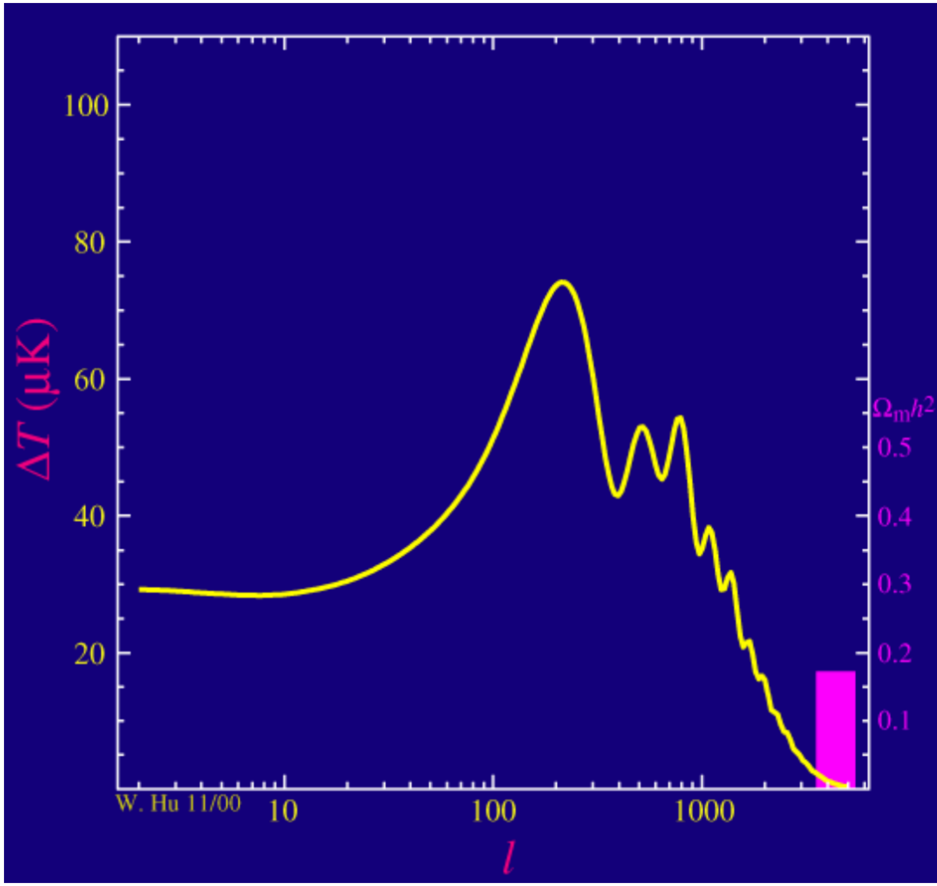
pictures from Wayne Hu's CMB tutorial – http://background.uchicago.edu/~whu/intermediate/

Low $\Omega_m h^2$



Small 3rd:1st peak ratio

High $\Omega_m h^2$



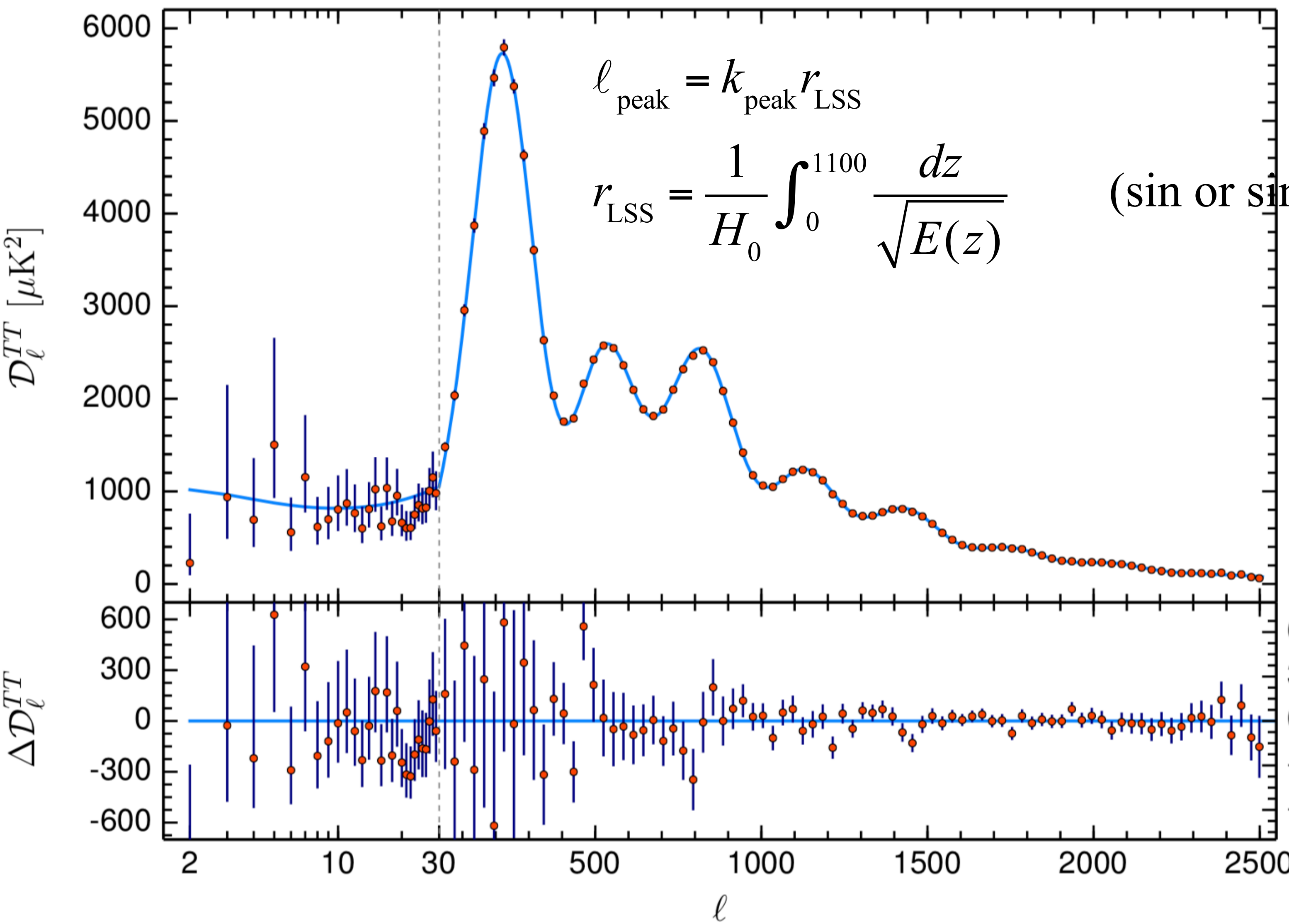
Large 3rd:1st peak ratio

CMB peak position

$$\ell_{\text{peak}} = k_{\text{peak}} r_{\text{LSS}}$$

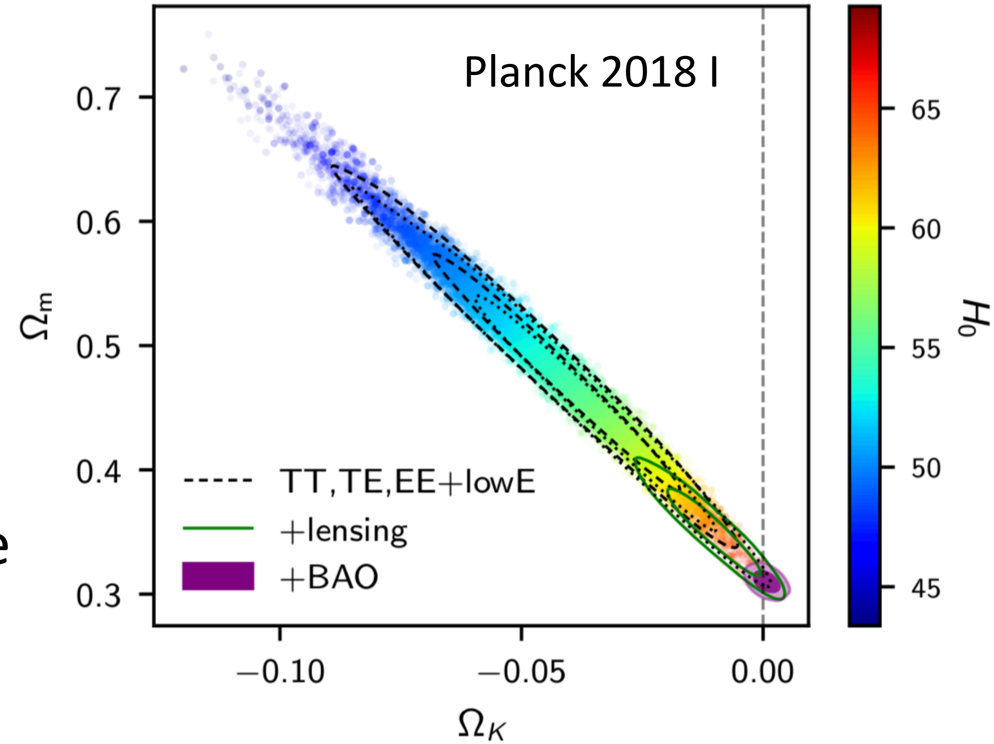
$$r_{\text{LSS}} = \frac{1}{H_0} \int_0^{1100} \frac{dz}{\sqrt{E(z)}}$$

(sin or sinh if curved)



Parameters from CMB anisotropies

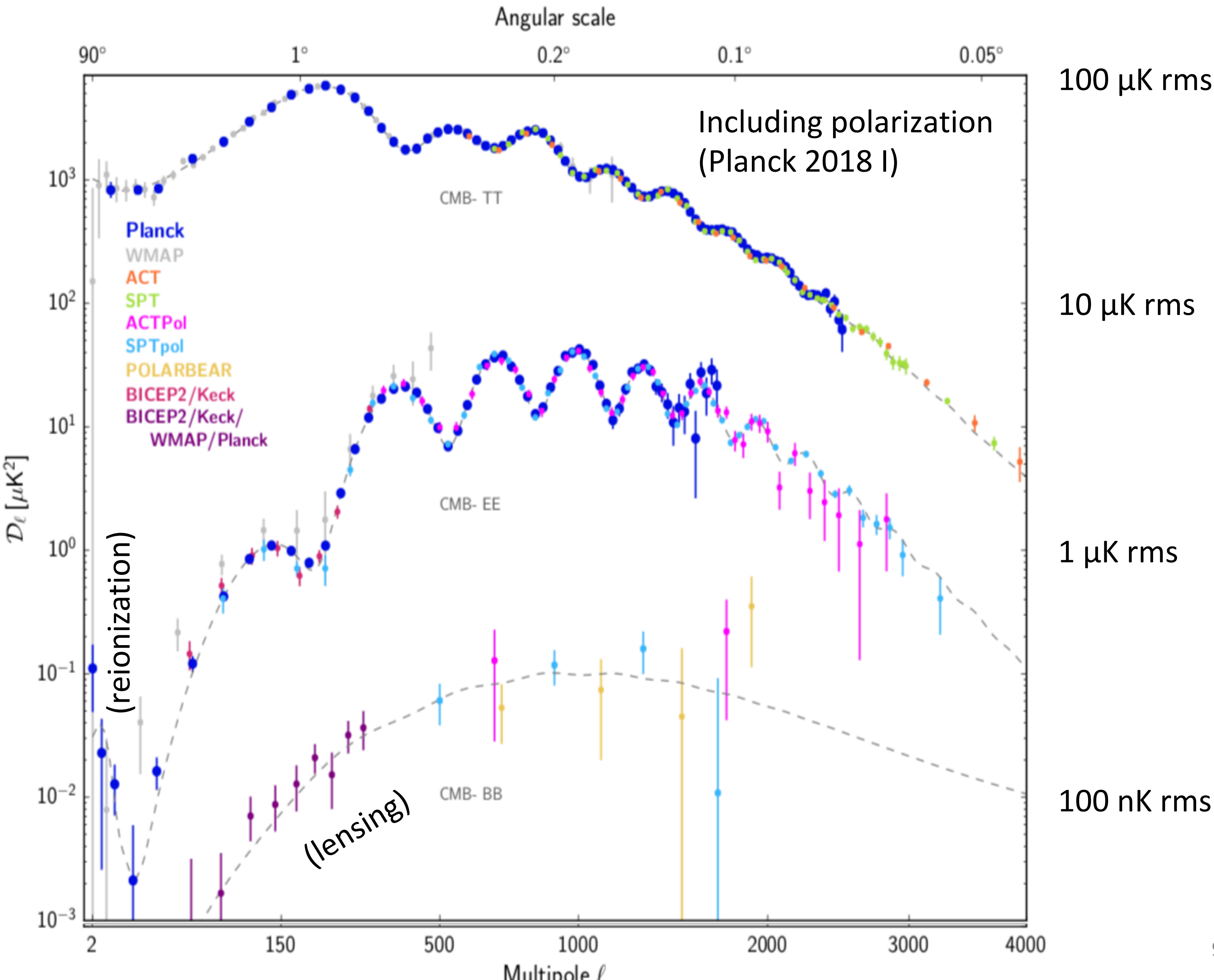
- Peak structure → $\Omega_b h^2$, $\Omega_m h^2$
- Broadband → A_s, n_s
- Peak position → r_{LSS} (z=1100)



In ΛCDM, this gives expansion history of the Universe since there is 1 unknown ($\Omega_\Lambda h^2$) that is constrained by r_{LSS}.

➢ H_0 is a derived quantity since $\Omega_b h^2 + \Omega_m h^2 + \Omega_\Lambda h^2 = h^2$.

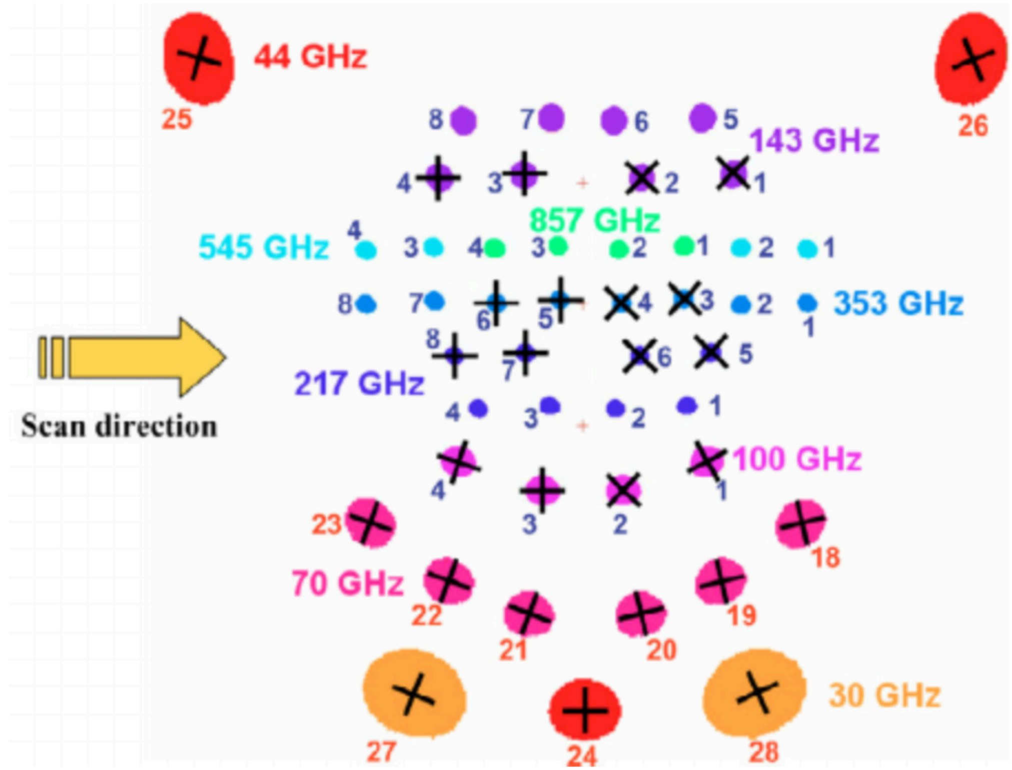
In extended models (e.g. ΛCDM + curvature), need more information.



Angular scale
90°
1°
0.2°
0.1°
0.05°
100 μK rms
Including polarization
(Planck 2018 I)
CMB- TT
Planck
WMAP
ACT
SPT
ACTPol
SPTpol
POLARBEAR
BICEP2/Keck
BICEP2/Keck/
WMAP/Planck
10 μK rms
CMB- EE
1 μK rms
(reionization)
CMB- BB
(lensing)
100 nK rms
$\mathcal{D}_\ell\ [\mu K^2]$
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
2
150
500
1000
2000
3000
4000
Multipole ℓ

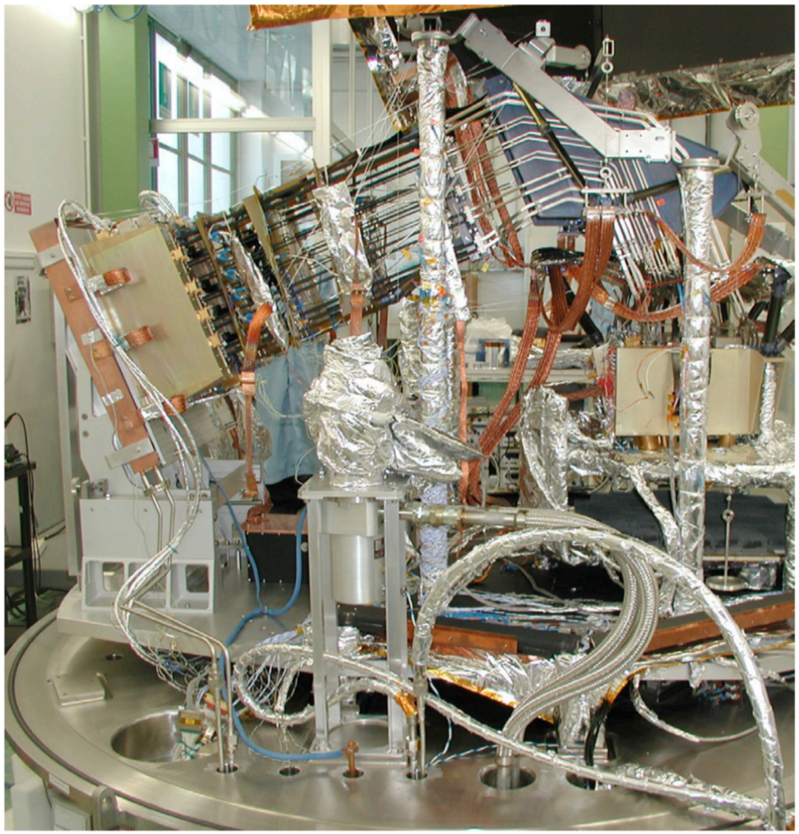
Planck – launched 2009

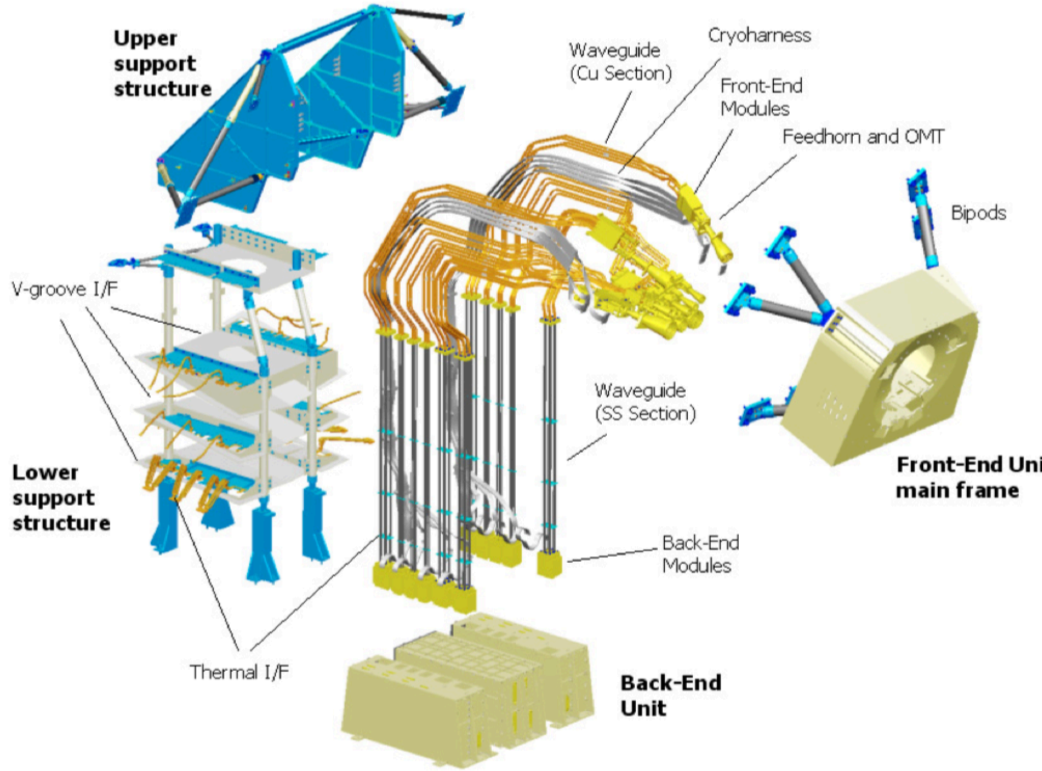
Planck at launch site
(ESA)



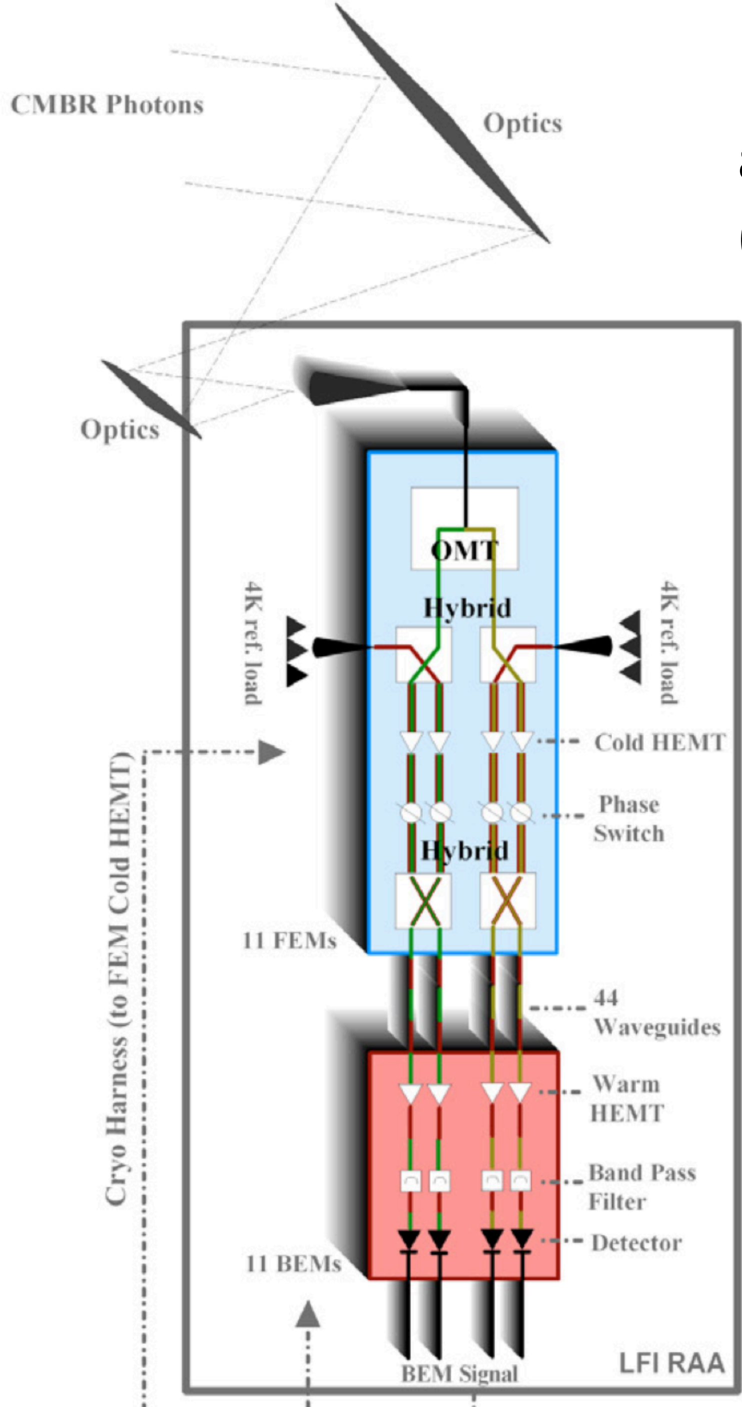
Focal plane layout
(Planck early results XIV)
"+" indicates polarized detectors

Low Frequency Instrument





Bersanelli et al., A&A 520, A4 (2010)

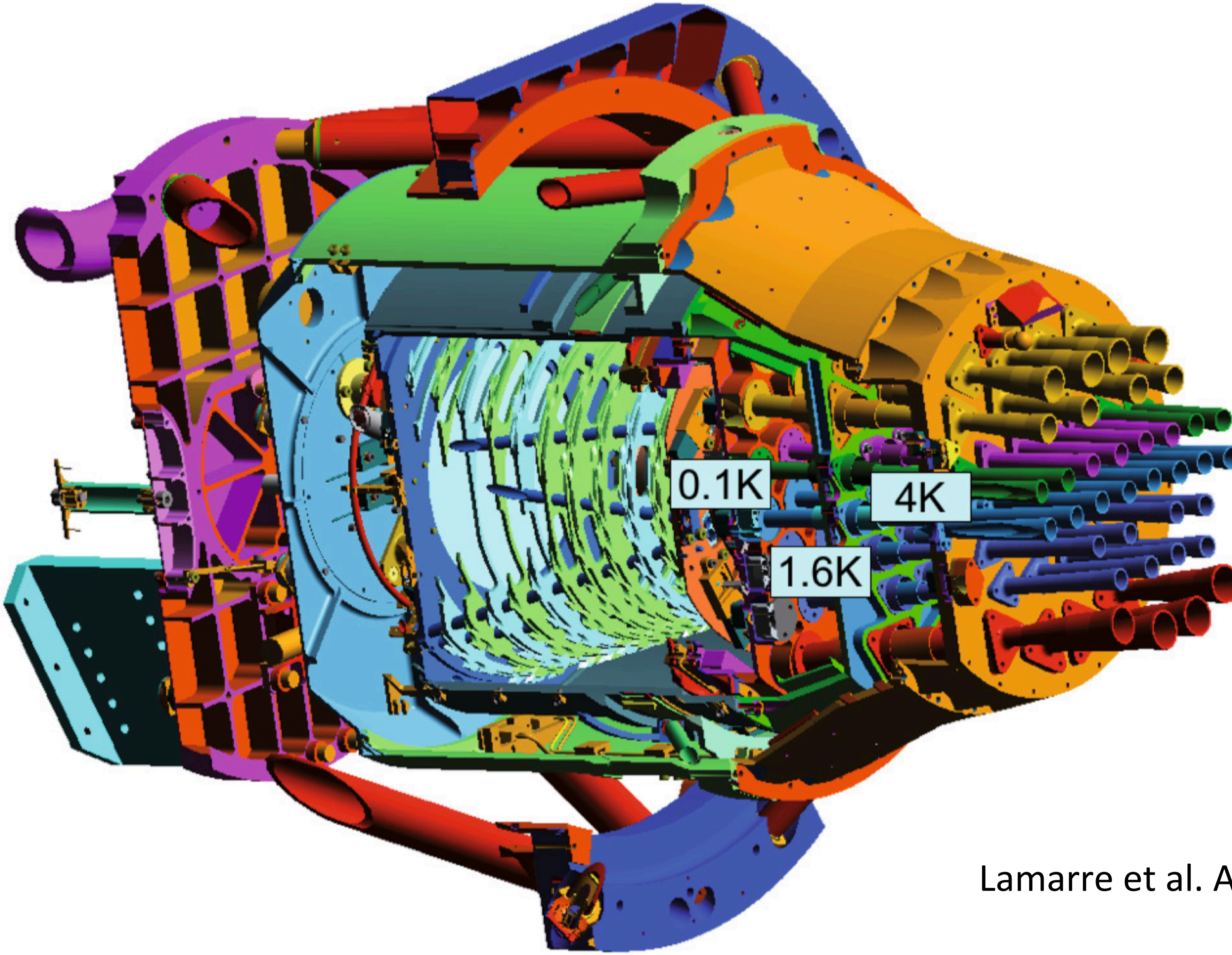


High electron mobility transistor amplifier technology (WMAP, Planck Low Frequency Instrument)

- Signals are coherently amplified (sense voltage, not total power)
- Hybrid couplers A, B → $(A \pm B)/\sqrt{2}$ used twice for robustness against cold amplifier gain fluctuations
- Phase switch to rapidly swap which output is signal and which is reference
- Reference may be internal load (Planck) or another patch of CMB sky (WMAP)
- “Cold” amplifiers = tens of Kelvin
- Amplifiers harder as you increase frequency!

Bersanelli et al., A&A 520, A4 (2010)

High Frequency Instrument



Lamarre et al. A&A 520, A9 (2010)

Bolometers

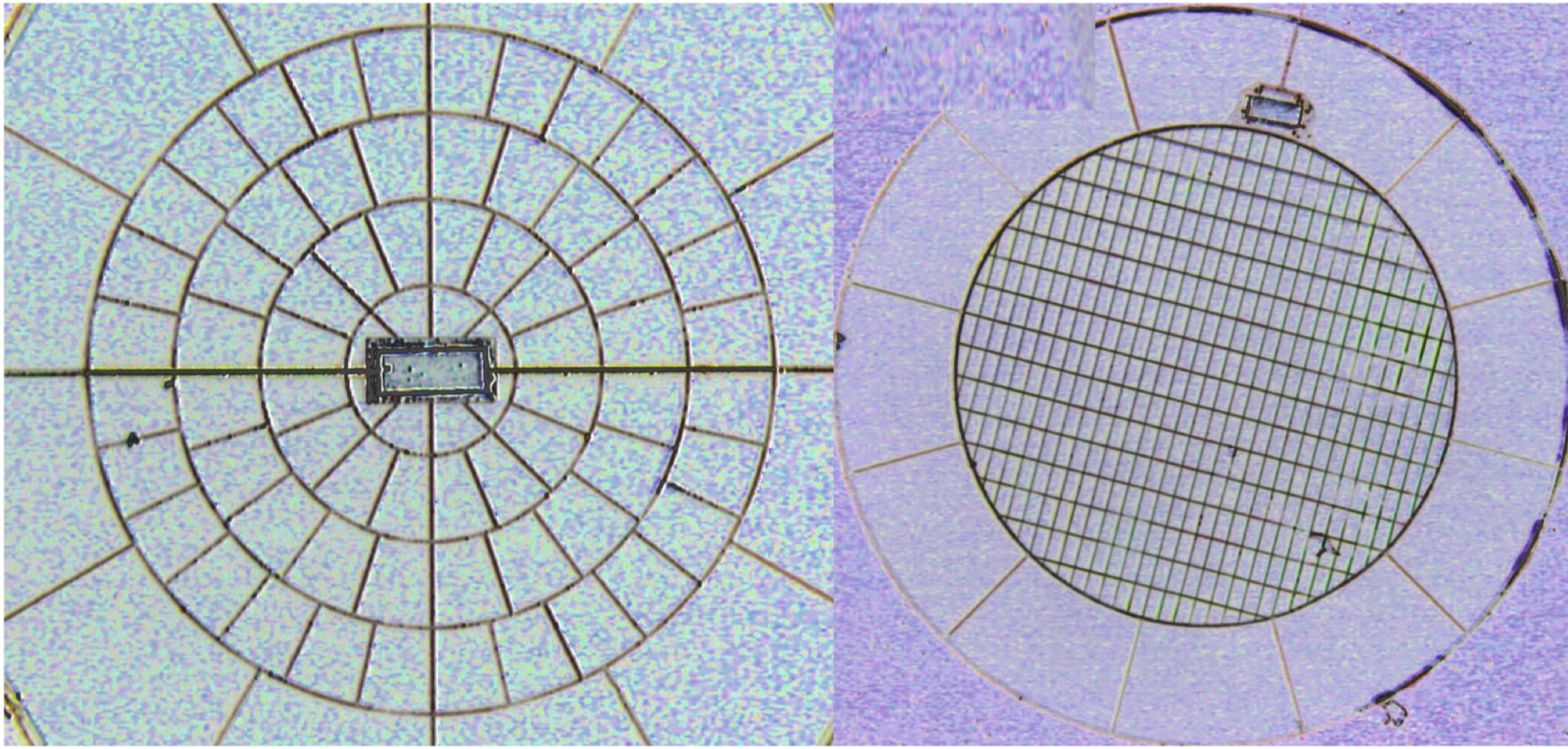
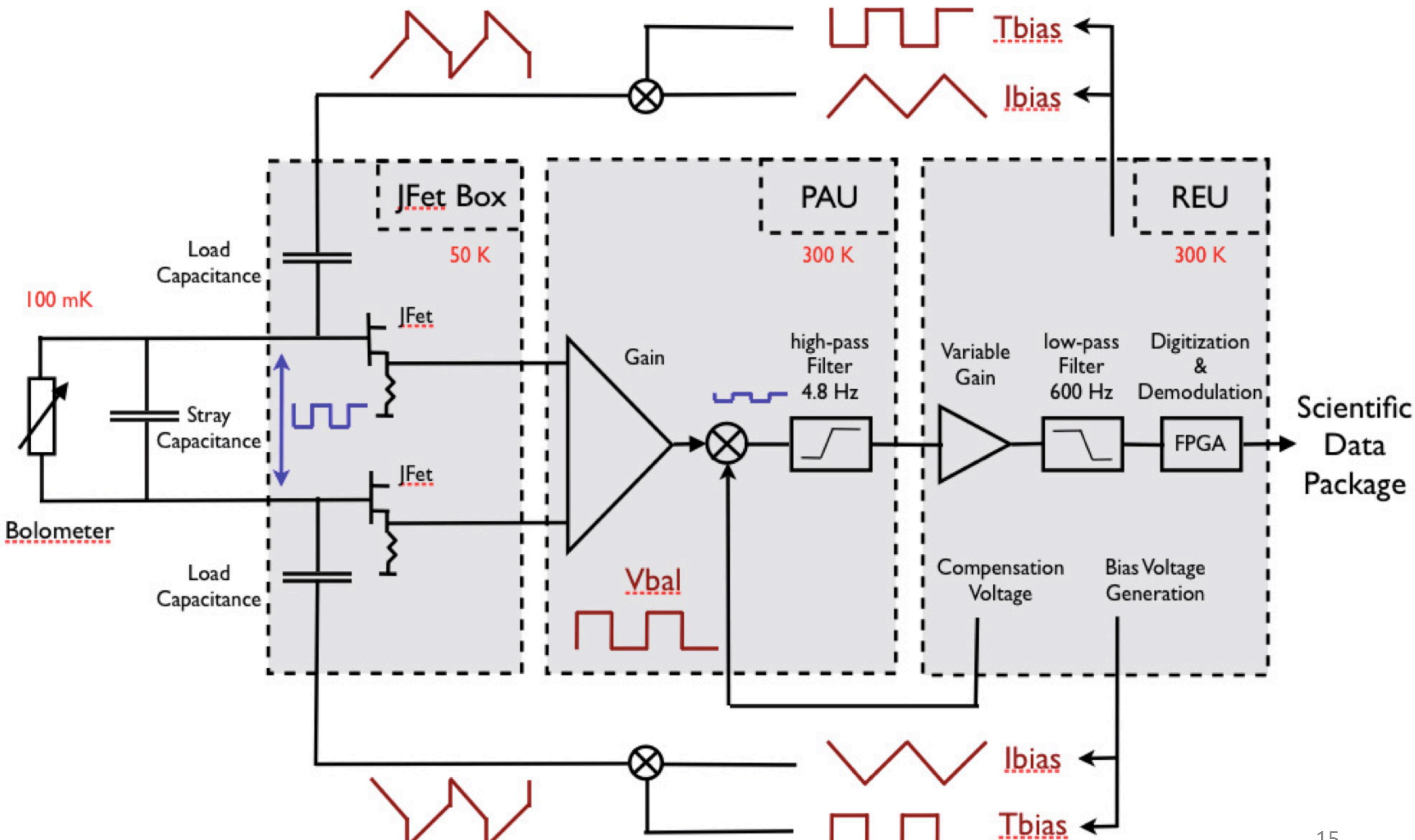


Fig. 7. Picture of a 143 GHz spider web bolometer (*left*) and of a 217 GHz polarisation-sensitive bolometer (*right*). One can see the temperature sensor at the centre of the SWB and at the upper edge of the PSB.

Lamarre et al. A&A 520, A9 (2010)

"Temperature sensor" = R(T). Nominal ~ 10 MΩ

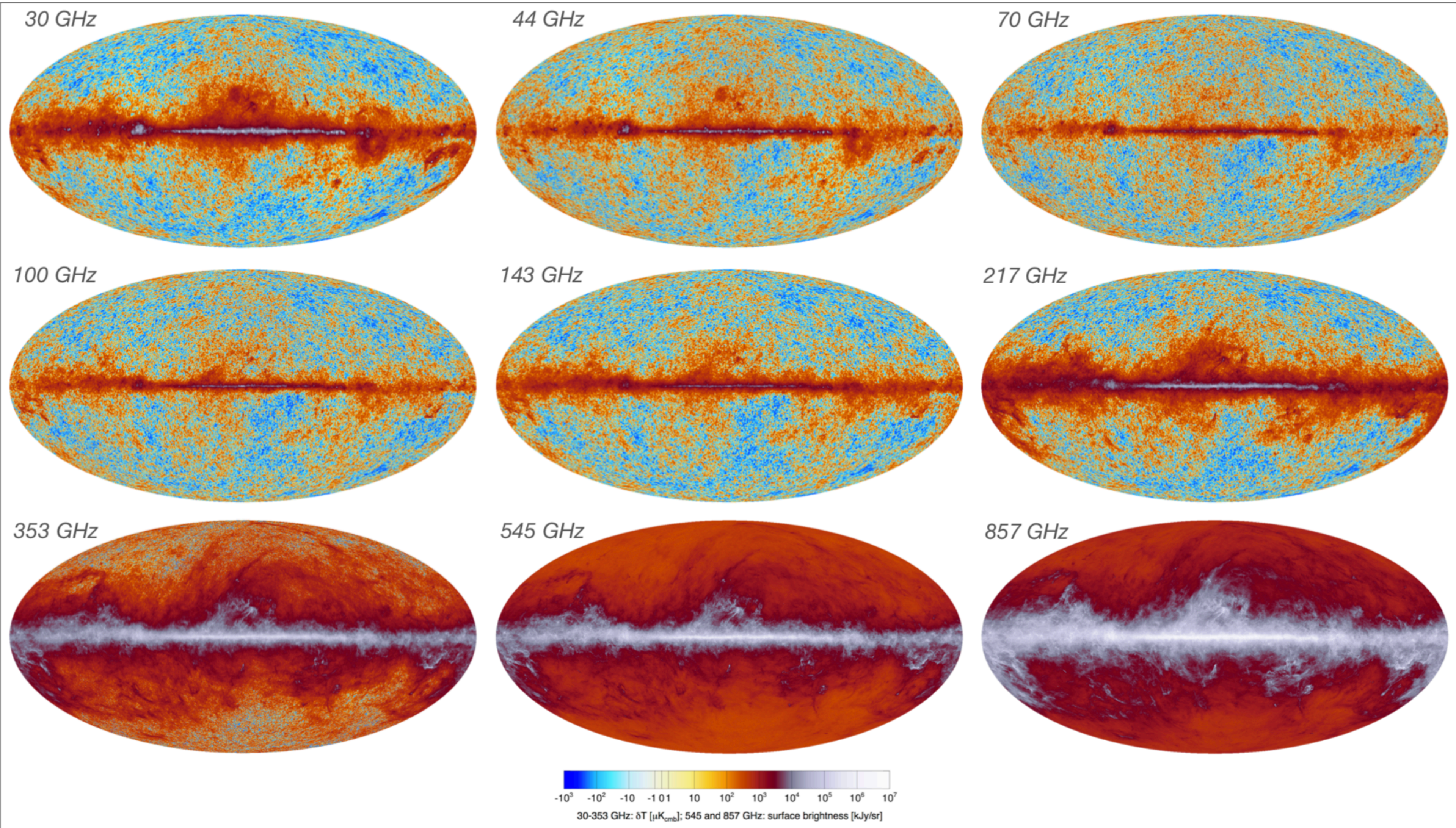
Readout



Lamarre et al. A&A 520, A9 (2010)

The Sky as seen by Planck

(CMB + synchrotron, free-free, dust …)



Planck Image Gallery

Other Signals

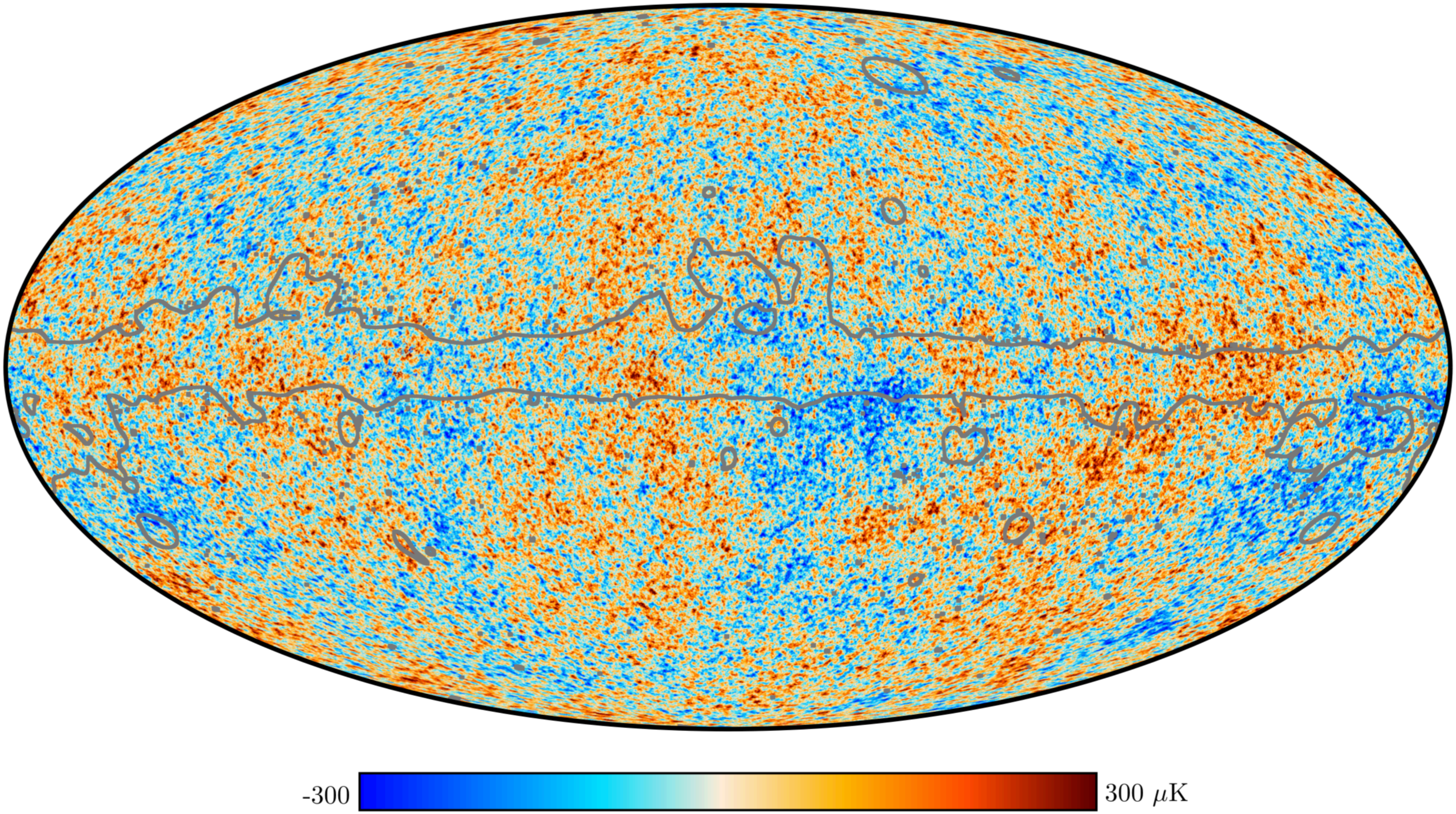
Our Galaxy

- Synchrotron radiation (relativistic electrons)
- Free-free radiation (ionized gas)
- Thermal dust (dominant at high frequencies)
- Anomalous dust (rotational or magnetic dipole emission?)

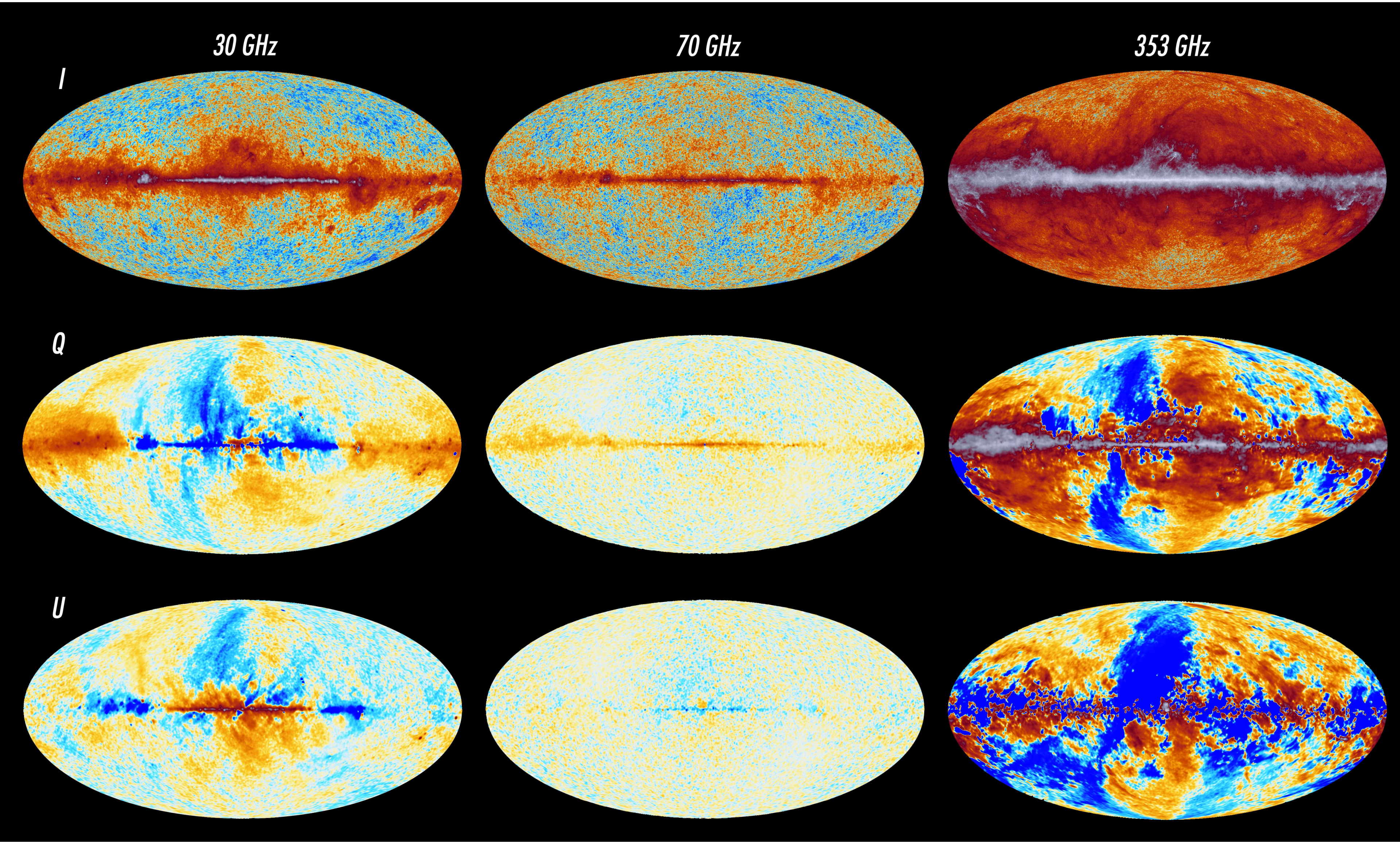
Extragalactic

- Active galactic nuclei (synchrotron sources − a few bright ones!)
- Dusty star-forming galaxies (fluctuating background from z~few)
- Sunyaev-Zel’dovich effect (hot gas in galaxy clusters)

“Foreground Cleaned” (SMICA)



Planck Image Gallery



Planck Image Gallery