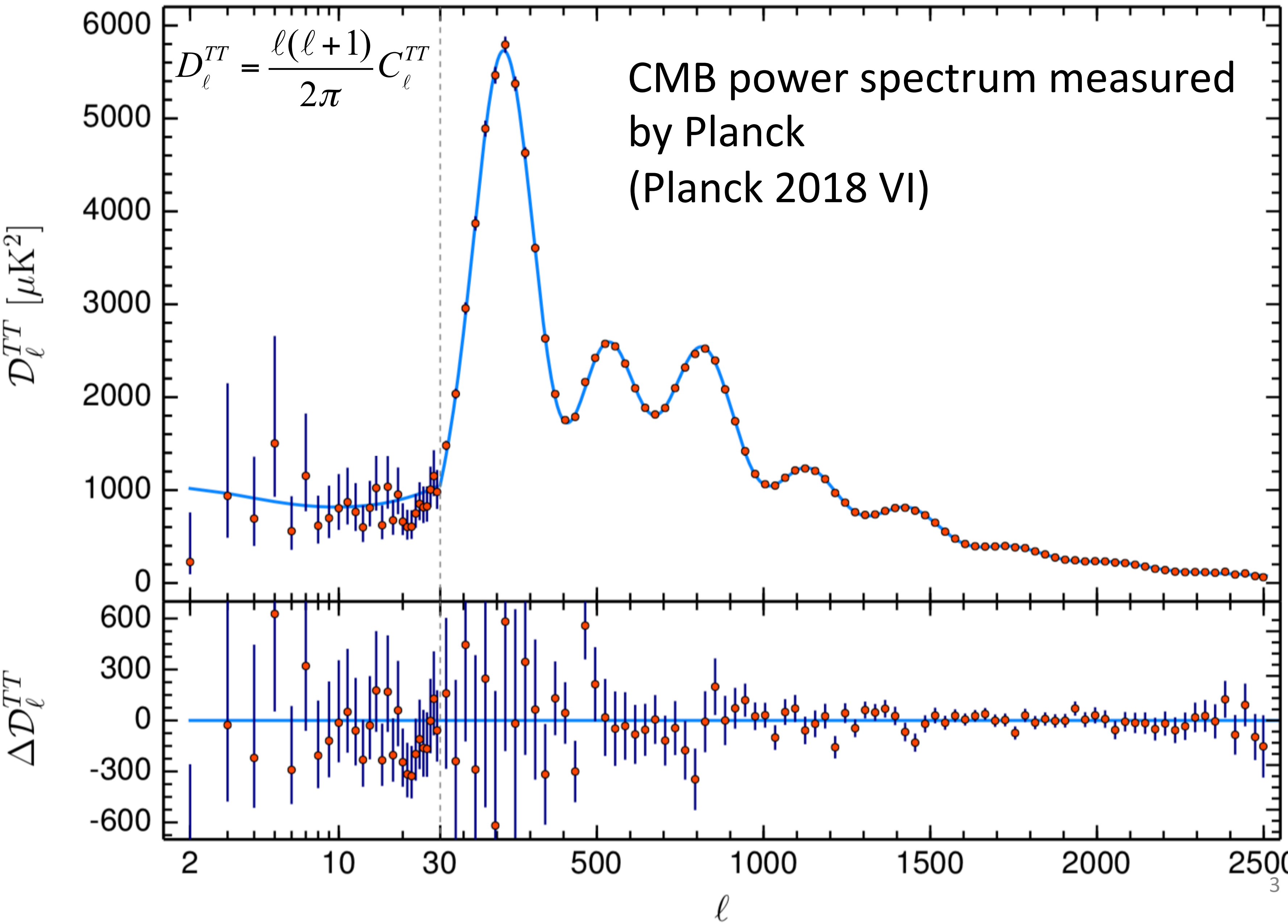
Supplement to Lecture XII: Cosmic Microwave Background

(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)
$\mathcal{D}_\ell^{TT}$ [μK^2]
$\Delta\mathcal{D}_\ell^{TT}$
ℓ
6000
5000
4000
3000
2000
1000
0
600
300
0
-300
-600
60
30
0
-30
-60
2
10
30
500
1000
1500
2000
2500

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 [$\mathrm{km\,s^{-1}Mpc^{-1}}$]	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

Linear perturbation theory

$$\Psi = -\frac{4\pi G a^2}{k^2}\left(\delta\rho + \frac{3\mathcal{H}J}{k}\right); \quad \dot{\Psi} + \mathcal{H}\Phi = \frac{4\pi G a^2}{k}J; \quad \Phi - \Psi = \frac{8\pi G a^2\hat{\Sigma}}{k^2}. \tag{8.147}$$

(One of these is redundant in the sense that it is implied by energy-momentum conservation.) The CDM evolution equations are

$$\dot{\delta}_c = -kv_c + 3\dot{\Psi}; \quad \dot{v}_c = -\mathcal{H}v_c + k\Phi. \tag{8.148}$$

For the baryons,

$$\dot{\delta}_b = -kv_b + 3\dot{\Psi}; \quad \dot{v}_b = -\mathcal{H}v_b + c_s^2 k\delta\rho_b + k\Phi + \frac{4\bar{\rho}_\gamma}{3\bar{\rho}_b}|\dot{\kappa}|(\Theta_{I,1}^{(m)} - v_b^{(m)}). \tag{8.149}$$

For the scalar fields,

$$\delta\ddot{\phi} = -2\mathcal{H}\delta\dot{\phi} - (k^2 + a^2V'')\delta\phi + (\dot{\Phi} + 3\Psi)\dot{\phi} - 2a^2V'\Phi. \tag{8.150}$$

For the massive neutrinos,

$$\delta\dot{f}_l = \frac{k\mathsf{q}}{a\mathcal{E}}\left(\frac{l}{2l-1}\delta f_{l-1} - \frac{l+1}{2l+3}\delta f_{l+1}\right) - \frac{df_0}{d\ln\mathsf{q}}\left(\dot{\Psi}\delta_{l,0} + k\Phi\frac{\mathsf{q}}{a\mathcal{E}}\delta_{l,1}\right); \tag{8.151}$$

for the photons,

$$\begin{aligned}
\dot{\Theta}_{I,l} &= k\left(\frac{l}{2l-1}\Theta_{I,l-1} - \frac{l+1}{2l+3}\Theta_{I,l+1}\right) + \dot{\Psi}\delta_{l,0} + k\Phi\delta_{l,1} \\
&\quad + |\dot{\kappa}|\left(\delta_{l,1}v_b - \Theta_{I,l} + \delta_{l,0}\Theta_{I,0} + \delta_{l,2}\frac{\Theta_{I,2} - \sqrt{6}\Theta_{E,2}}{10}\right); \\
\dot{\Theta}_{E,l} &= k\left(\frac{\sqrt{l^2-4}}{2l-1}\Theta_{E,l-1} - \frac{\sqrt{(l-1)(l+3)}}{2l+3}\Theta_{E,l+1}\right) + |\dot{\kappa}|\left(-\Theta_{E,l} + \delta_{l,2}\frac{6\Theta_{E,2} - \sqrt{6}\Theta_{I,2}}{10}\right)
\end{aligned} \tag{8.152}$$

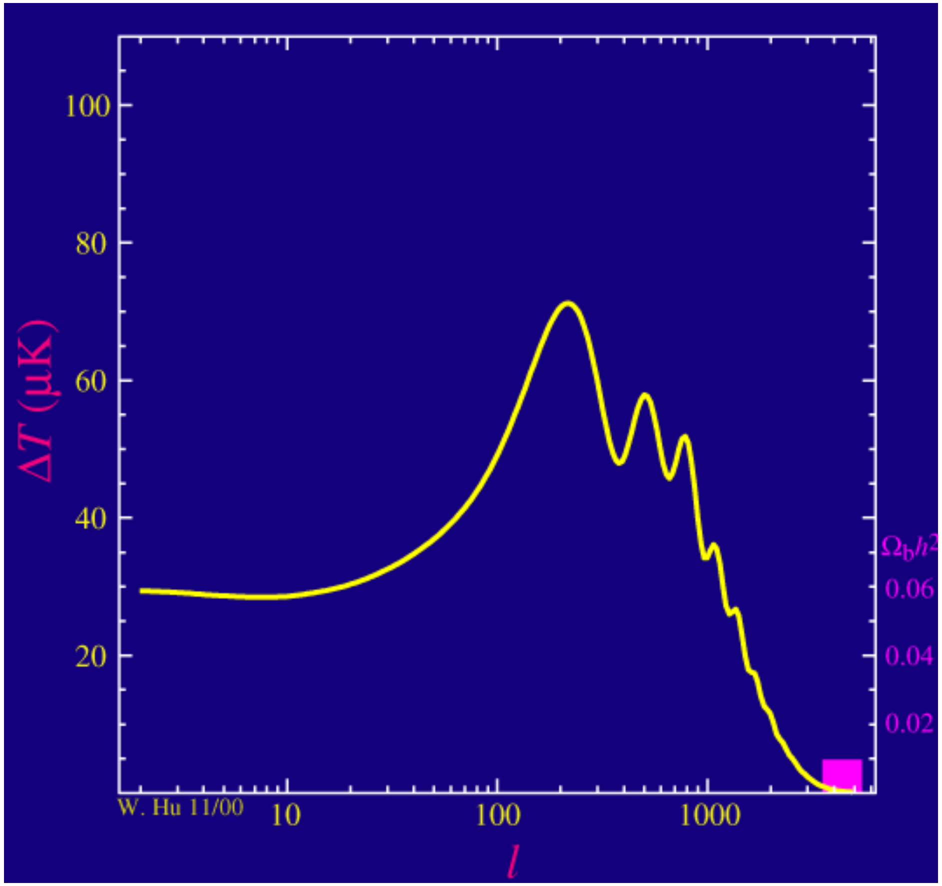
and again $\Theta_{B,l} = \Theta_{V,l} = 0$. The metric sources are

$$\begin{aligned}
\delta\rho &= \bar{\rho}_c\delta_c + \bar{\rho}_b\delta_b + \frac{\dot{\phi}\delta\dot{\phi} - A\dot{\phi}^2}{a^2} + V'\delta\phi + \frac{4\pi g_\nu}{a^3}\int \mathsf{q}^2\mathcal{E}\delta f_0\, d\mathsf{q} + 4\bar{\rho}_\gamma\Theta_{I,0}; \\
J &= \rho_c v_c + \rho_b v_b + \frac{k\dot{\phi}\delta\phi}{a^2} + \frac{4\pi g_\nu}{3a^3}\int \mathsf{q}^3\delta f_1\, d\mathsf{q} + \frac{4}{3}\bar{\rho}_\gamma\Theta_{I,1}; \\
\hat{\Sigma} &= \frac{4\pi g_\nu}{5a^5}\int \frac{\mathsf{q}^4}{\mathcal{E}}\delta f_2\, d\mathsf{q} + \frac{4}{5}\bar{\rho}_\gamma\Theta_{I,2}.
\end{aligned} \tag{8.153}$$

What's underneath the χ^2 fit

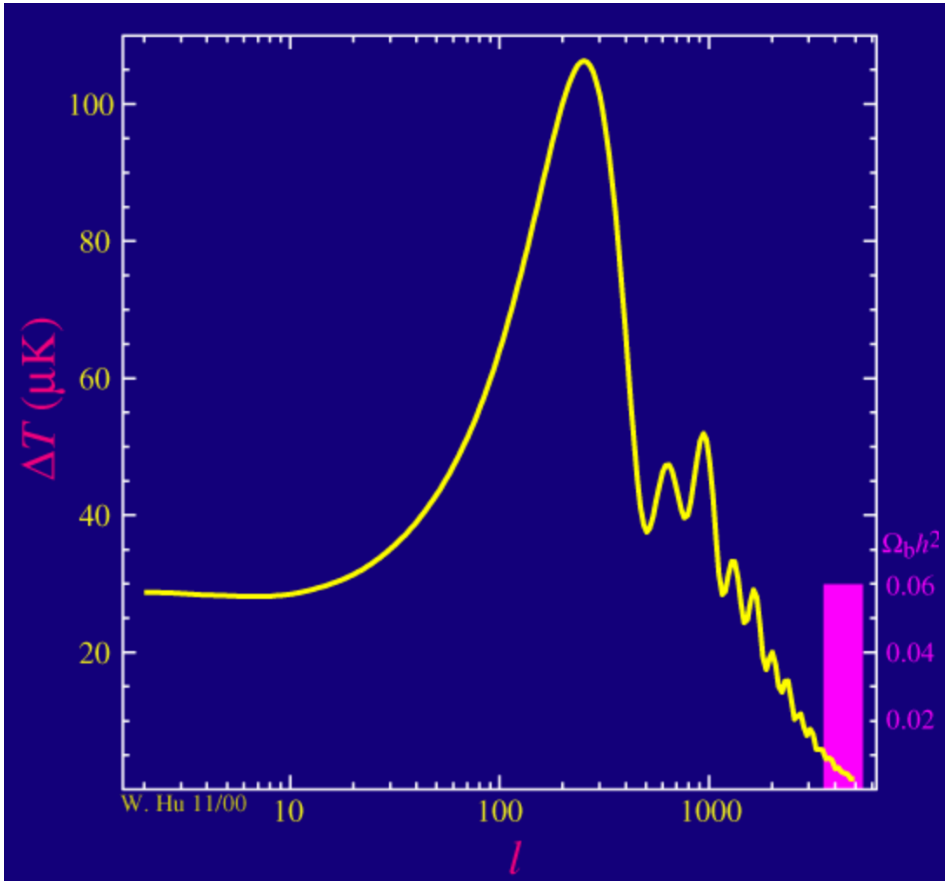
pictures from Wayne Hu's CMB tutorial – http://background.uchicago.edu/~whu/intermediate/

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

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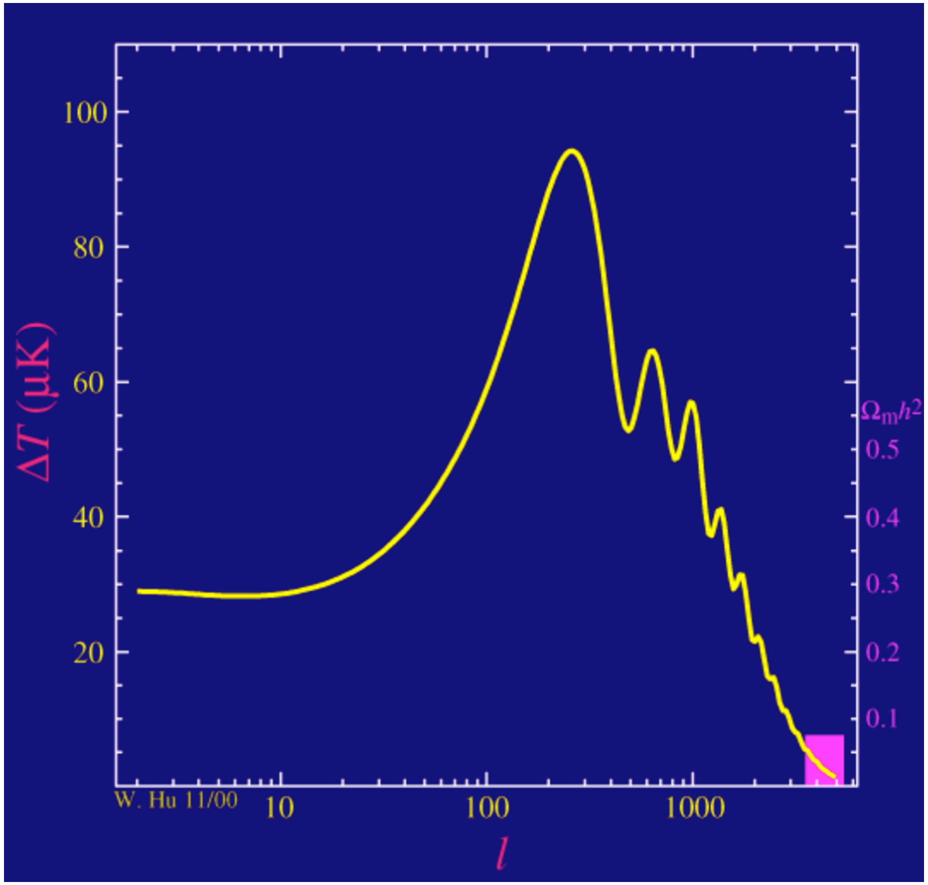
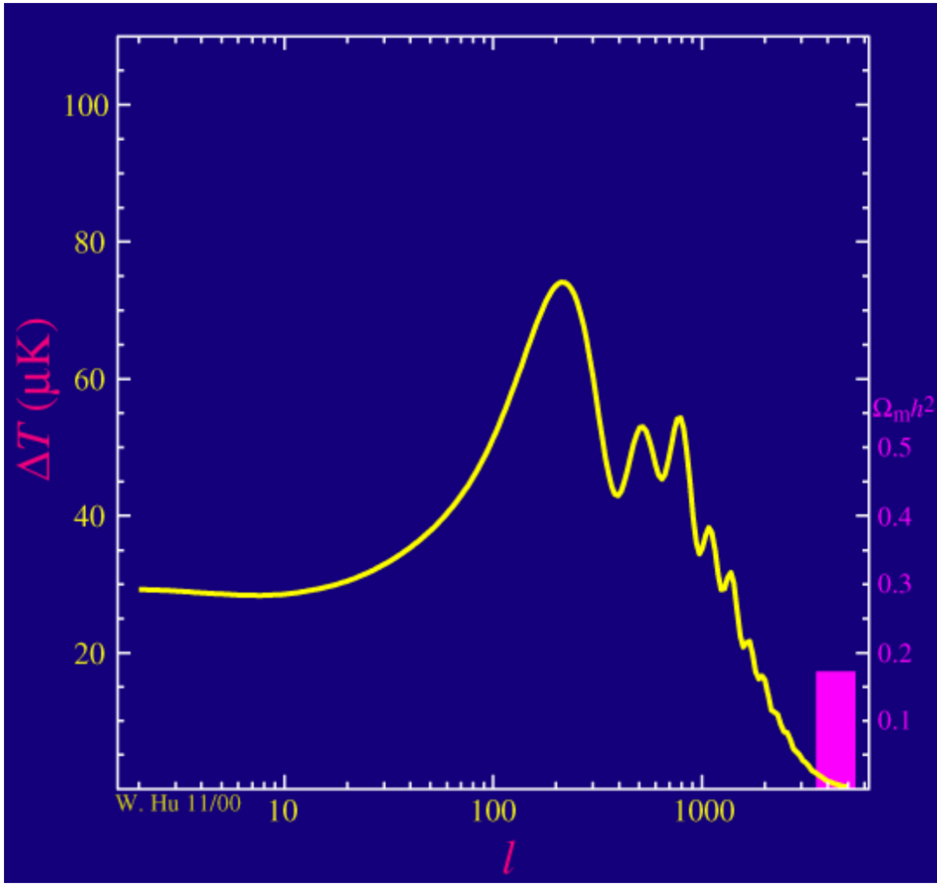
Low $\Omega_m h^2$



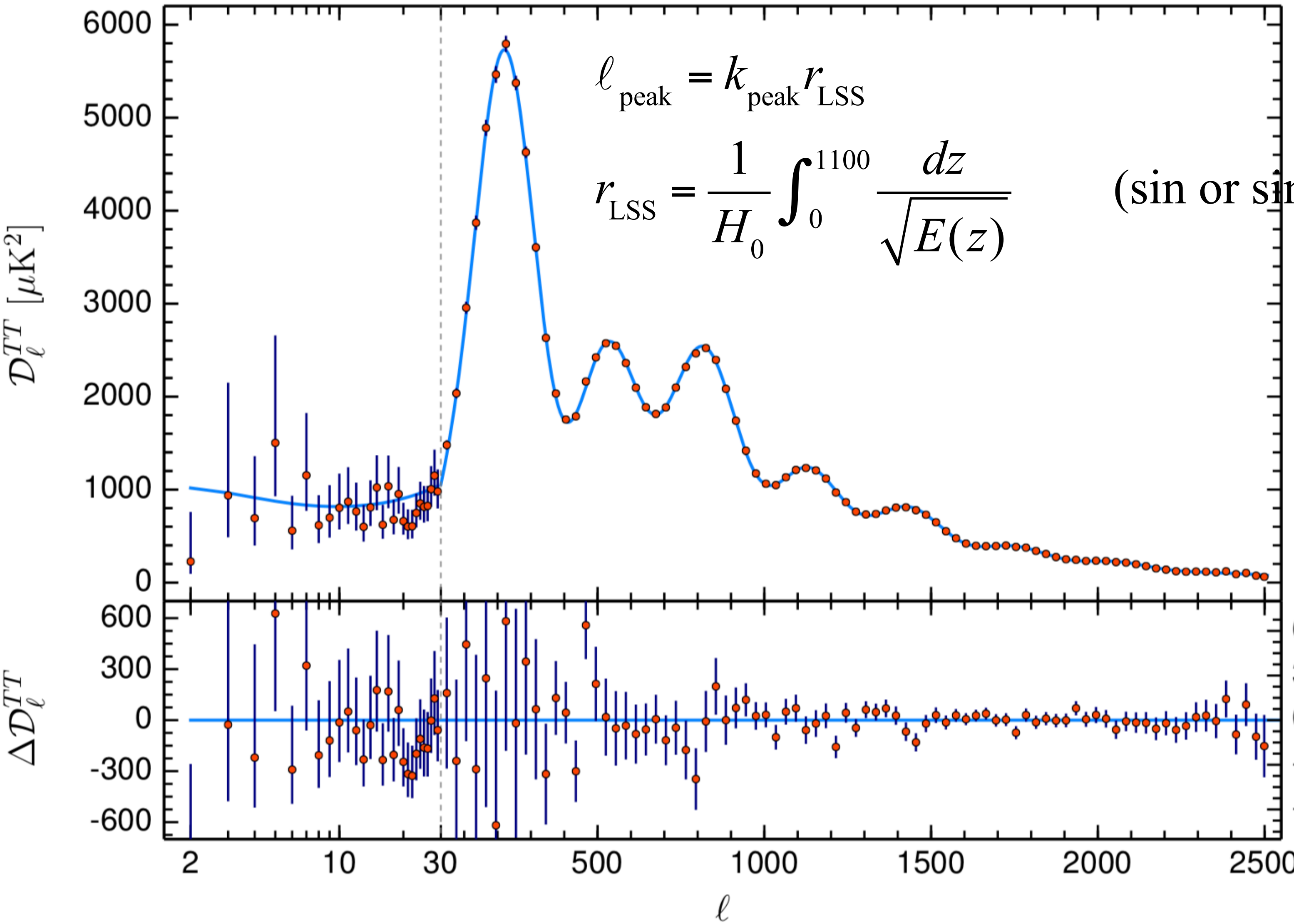
Small 3rd:1st peak ratio

High $\Omega_m h^2$



Large 3rd:1st peak ratio

CMB peak position



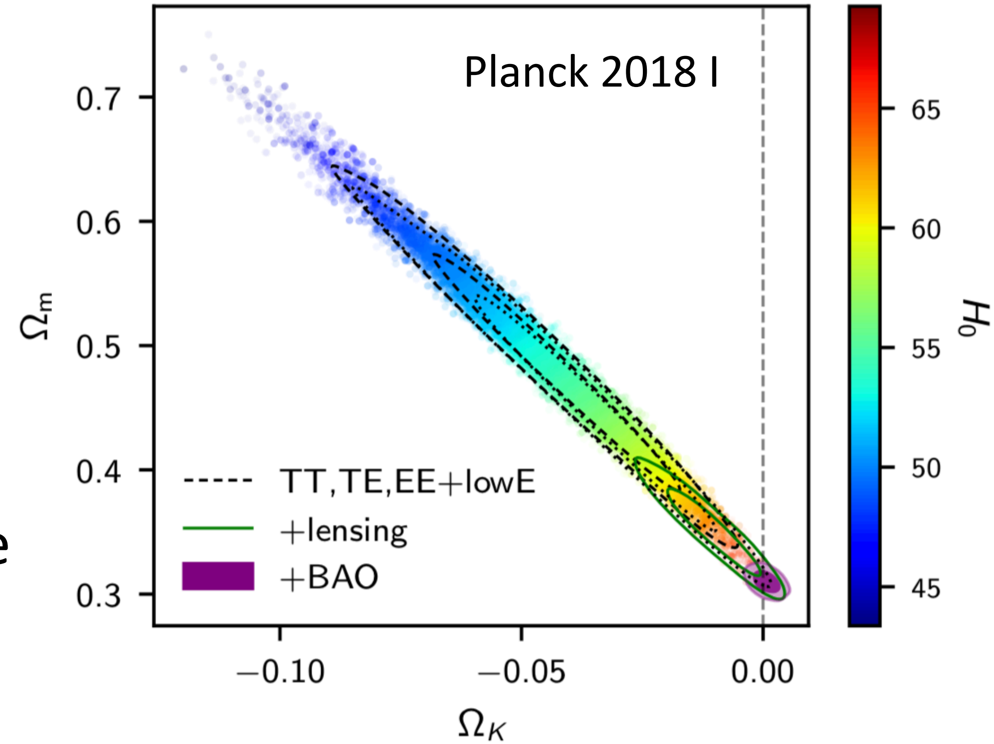
$$\ell_{\text{peak}} = k_{\text{peak}} r_{\text{LSS}}$$

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

(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)

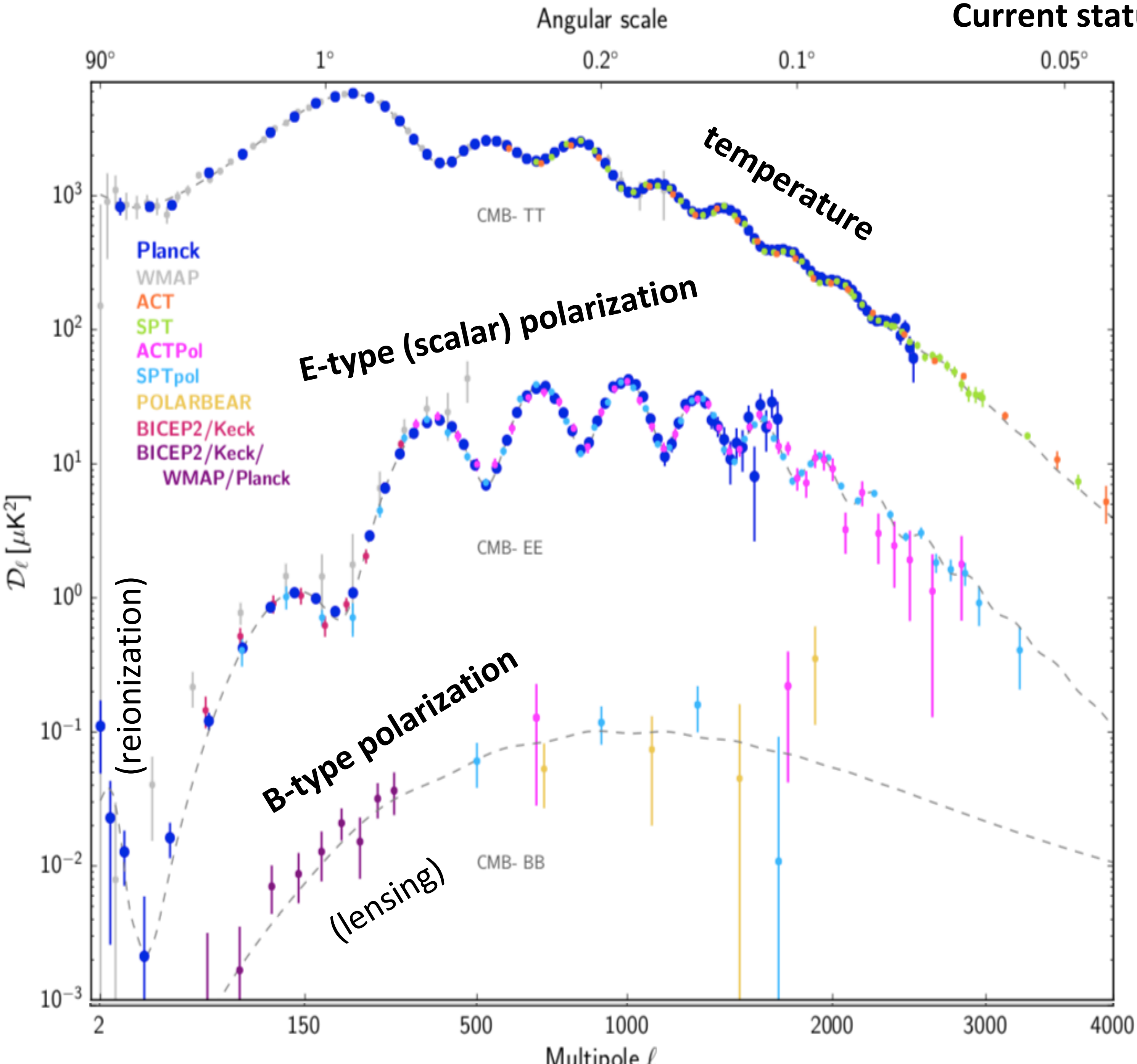


In ΛCDM, this gives expansion history of the Universe since there is 1 unknown ($\Omega_\Lambda h^2$) that is constrained by r_{LSS}.

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

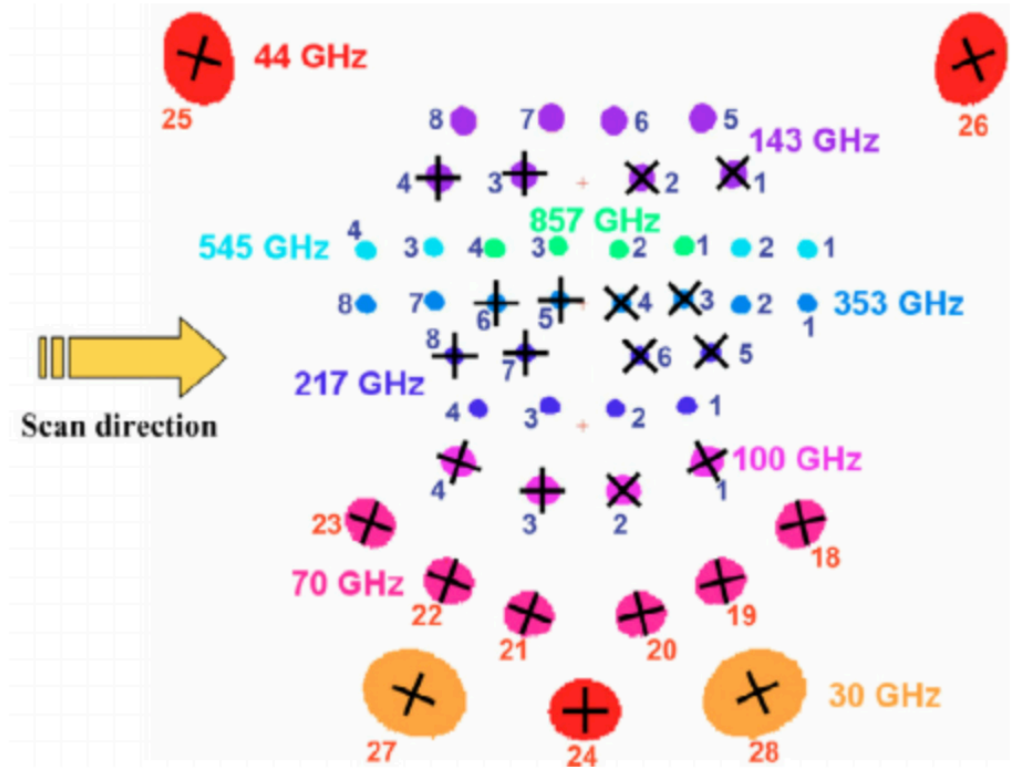
In extended models (e.g. ΛCDM + curvature), need more information.

Current status (Planck 2018 I)



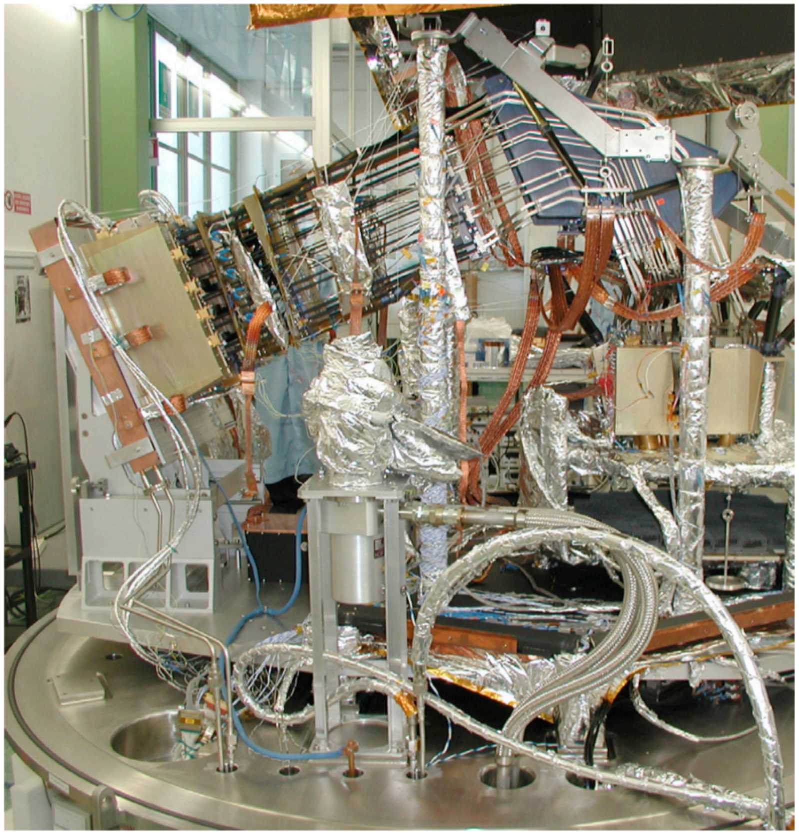
Planck – launched 2009

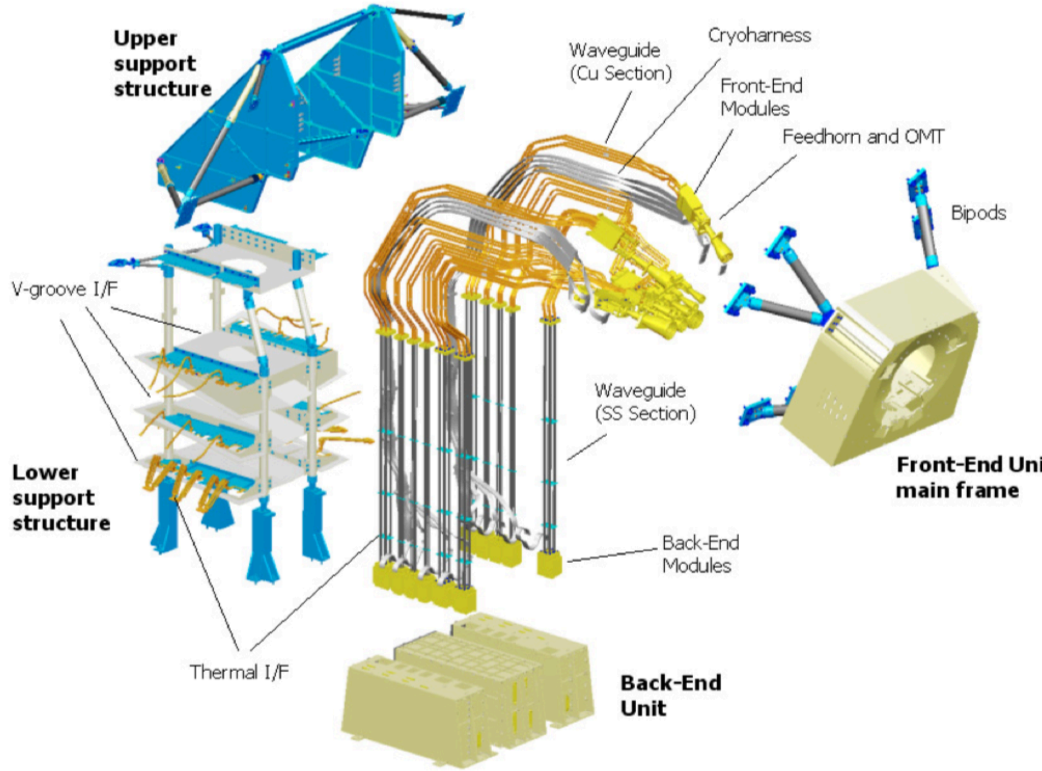
Planck at launch site
(ESA)



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

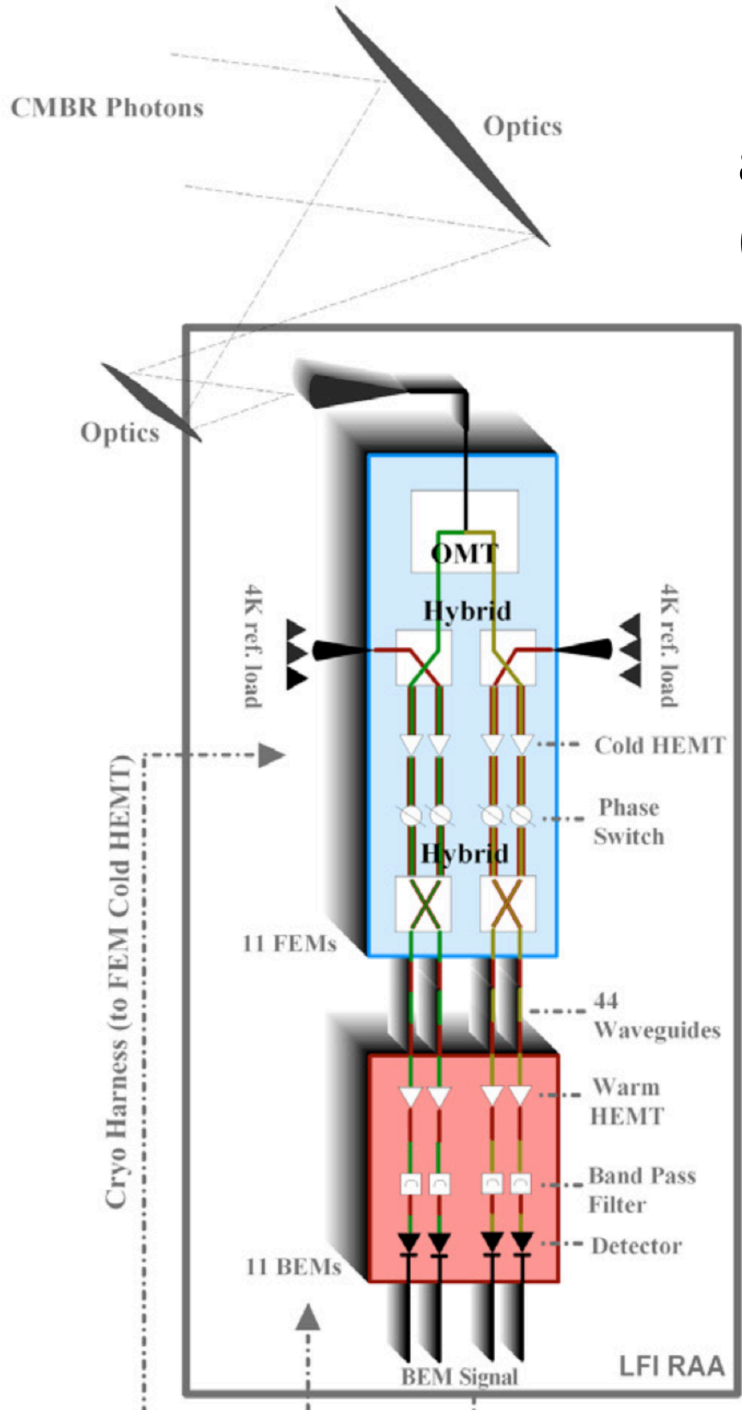
Low Frequency Instrument





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

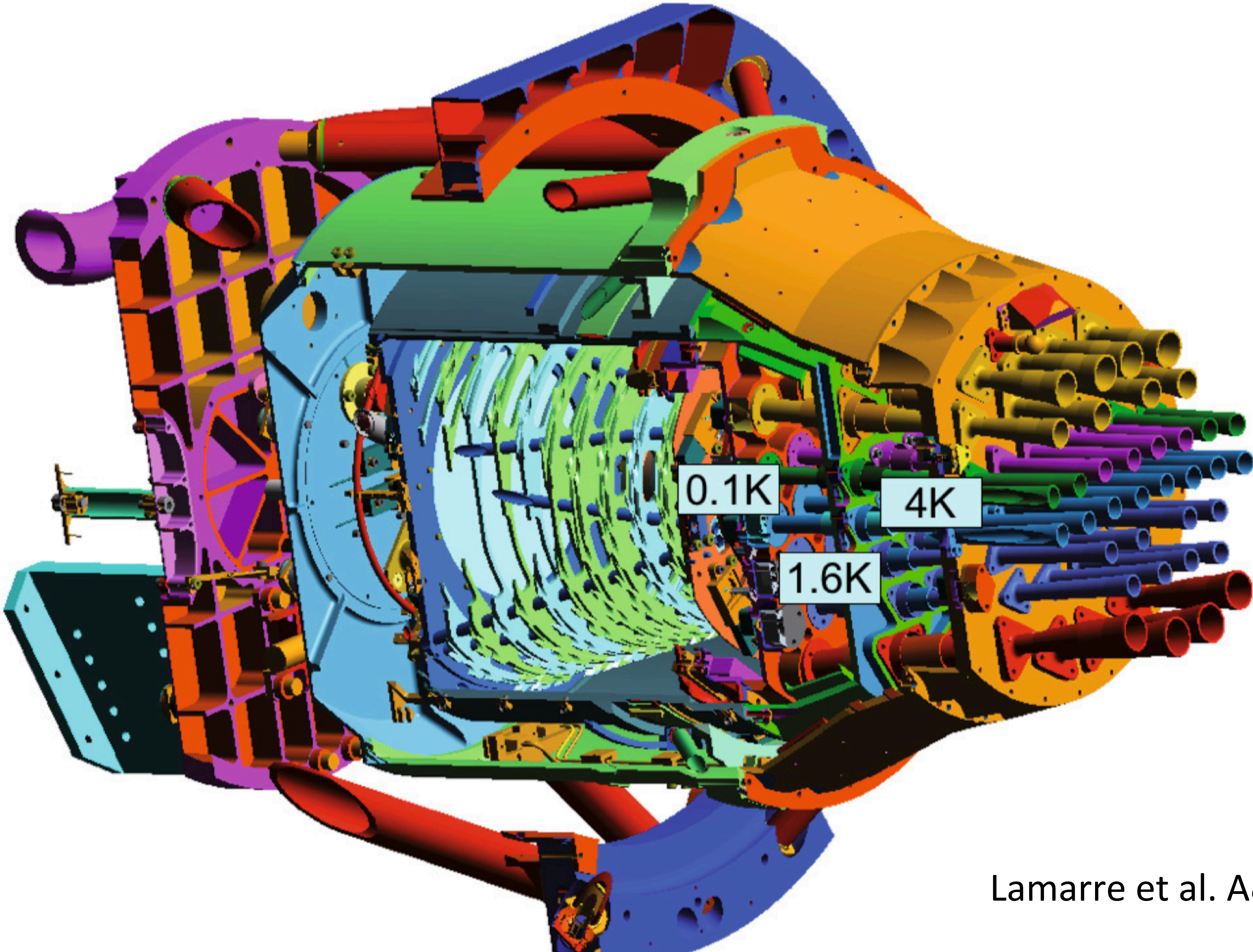
High electron mobility transistor amplifier technology (WMAP, Planck Low Frequency Instrument)



- 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

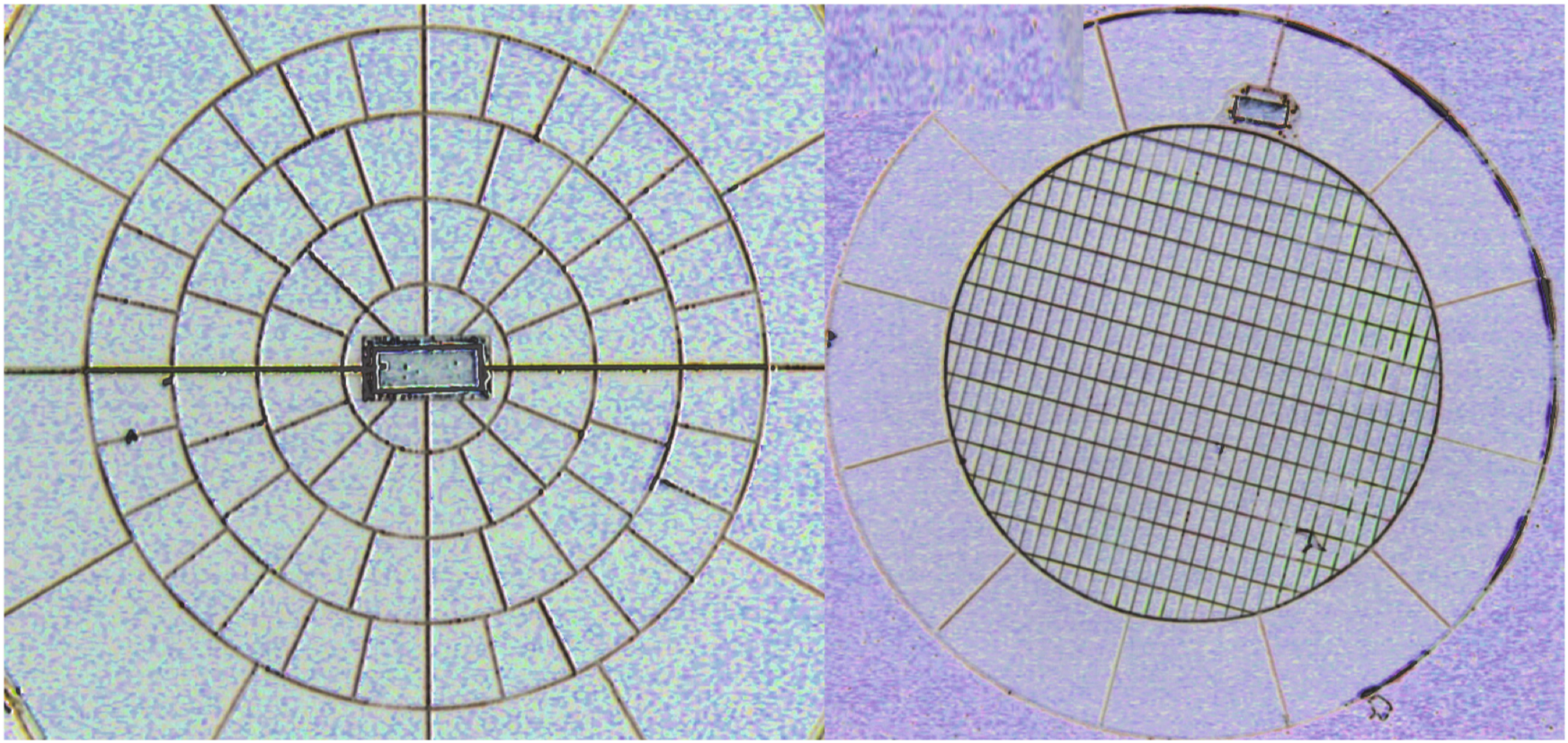
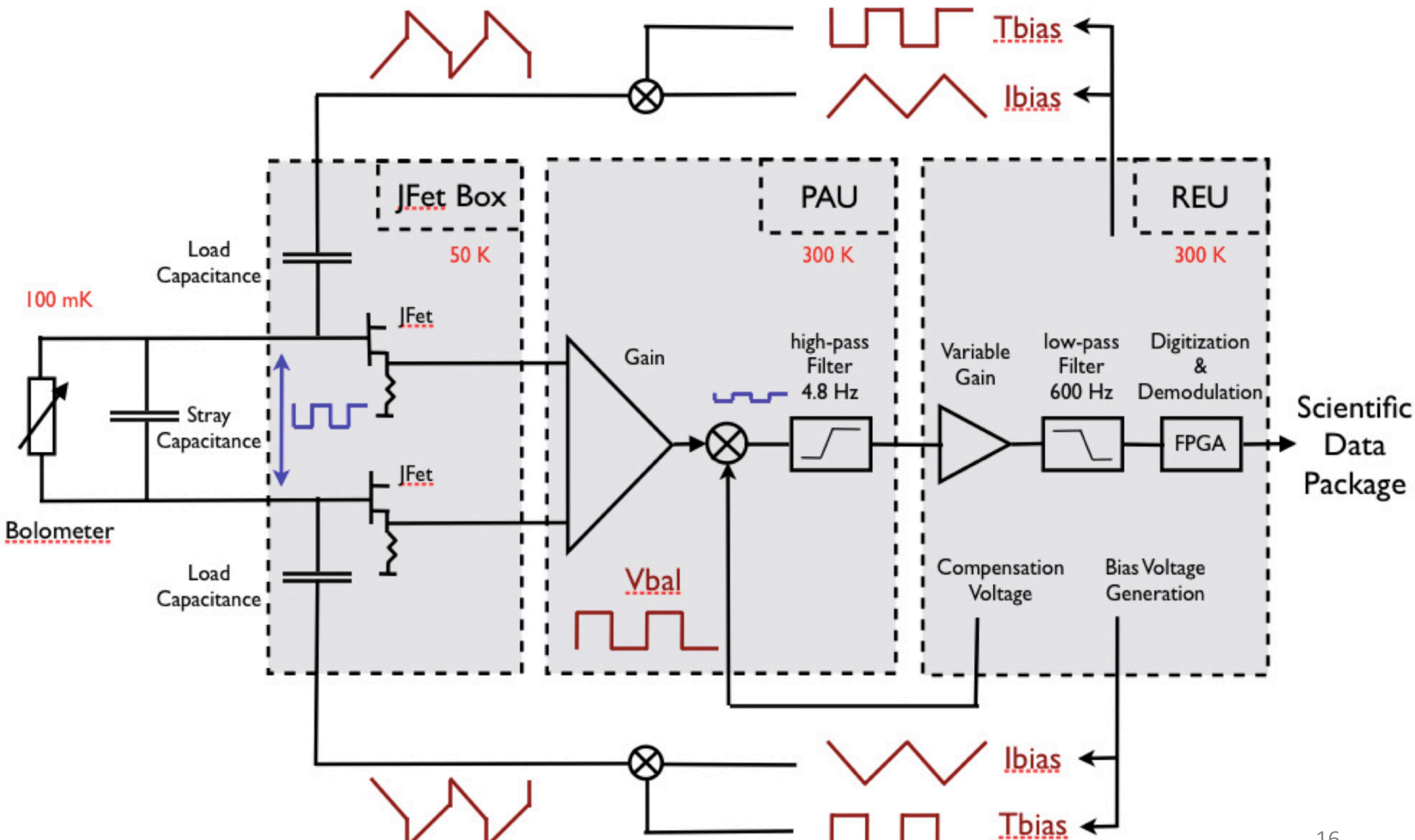


Fig. 7. Picture of a 143 GHz spider web bolometer (*left*) and of a 217 GHz polarisation-sensitive bolometer (*right*). One can see the temperature sensor at the centre of the SWB and at the upper edge of the PSB.

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

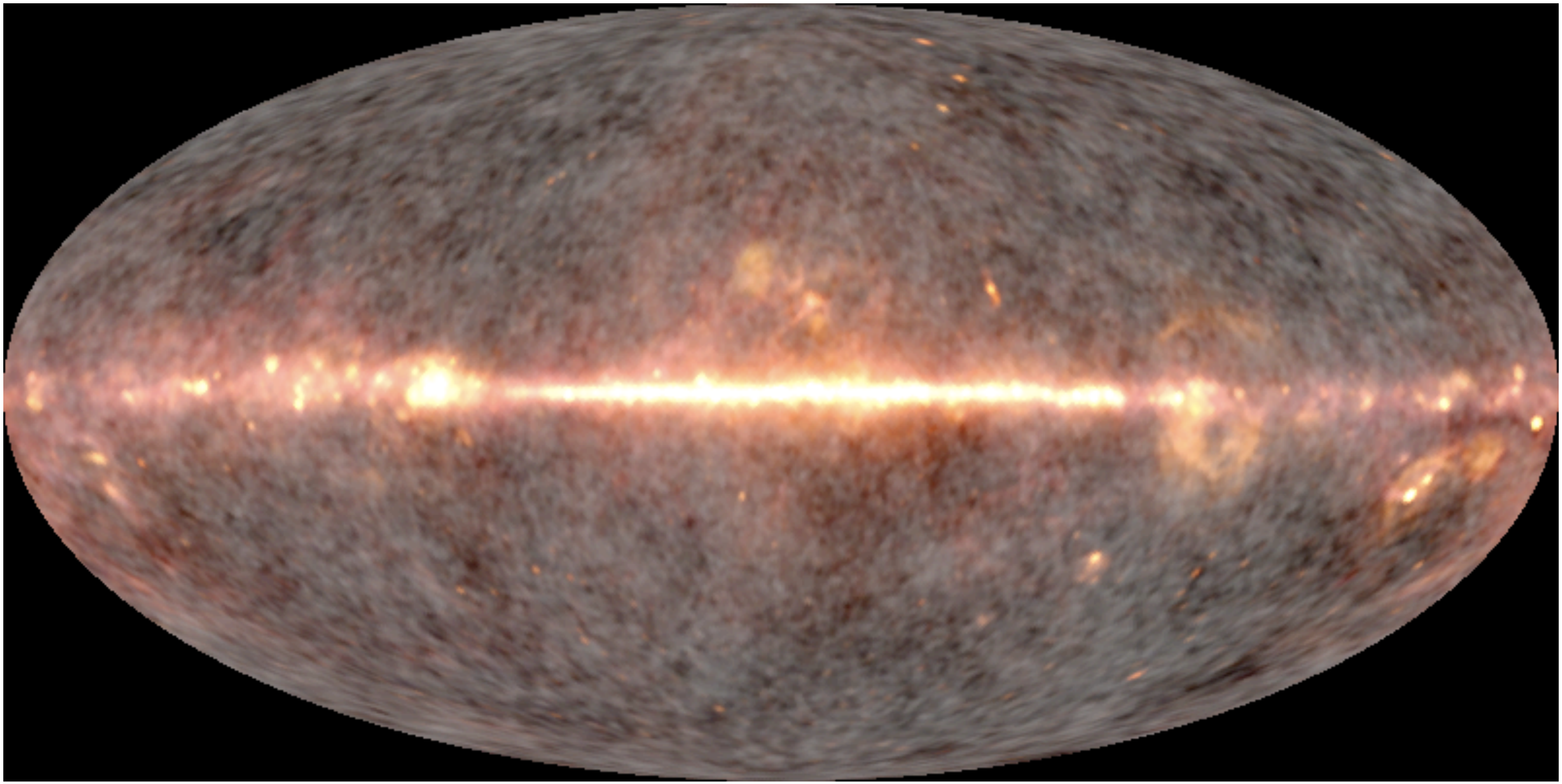
"Temperature sensor" = R(T). Nominal ~ 10 MΩ

Readout



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

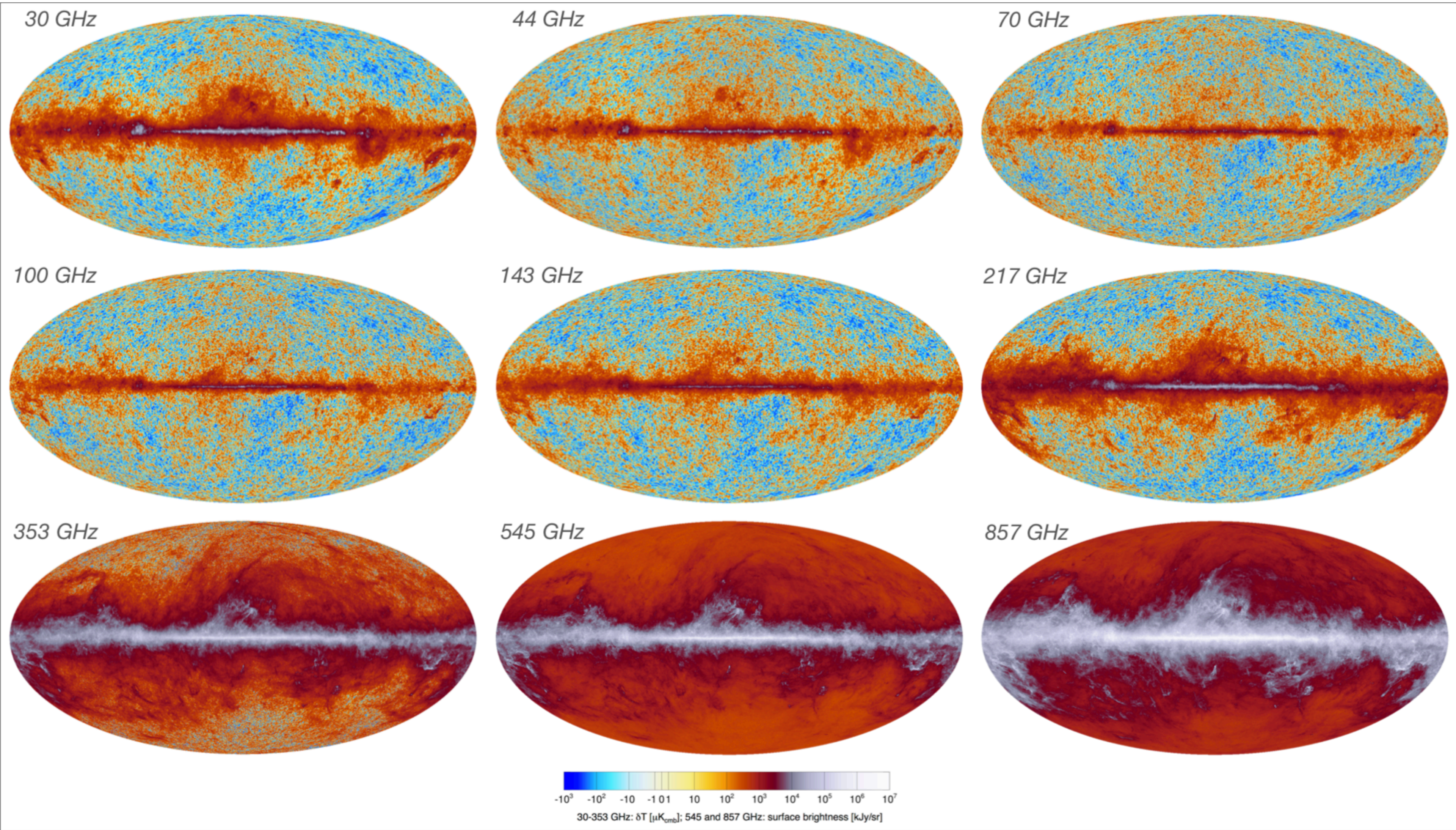
The Sky as Seen by WMAP



Composite of 22, 41, and 94 GHz sky maps from WMAP

The Sky as seen by Planck

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



Planck Image Gallery

Other Signals

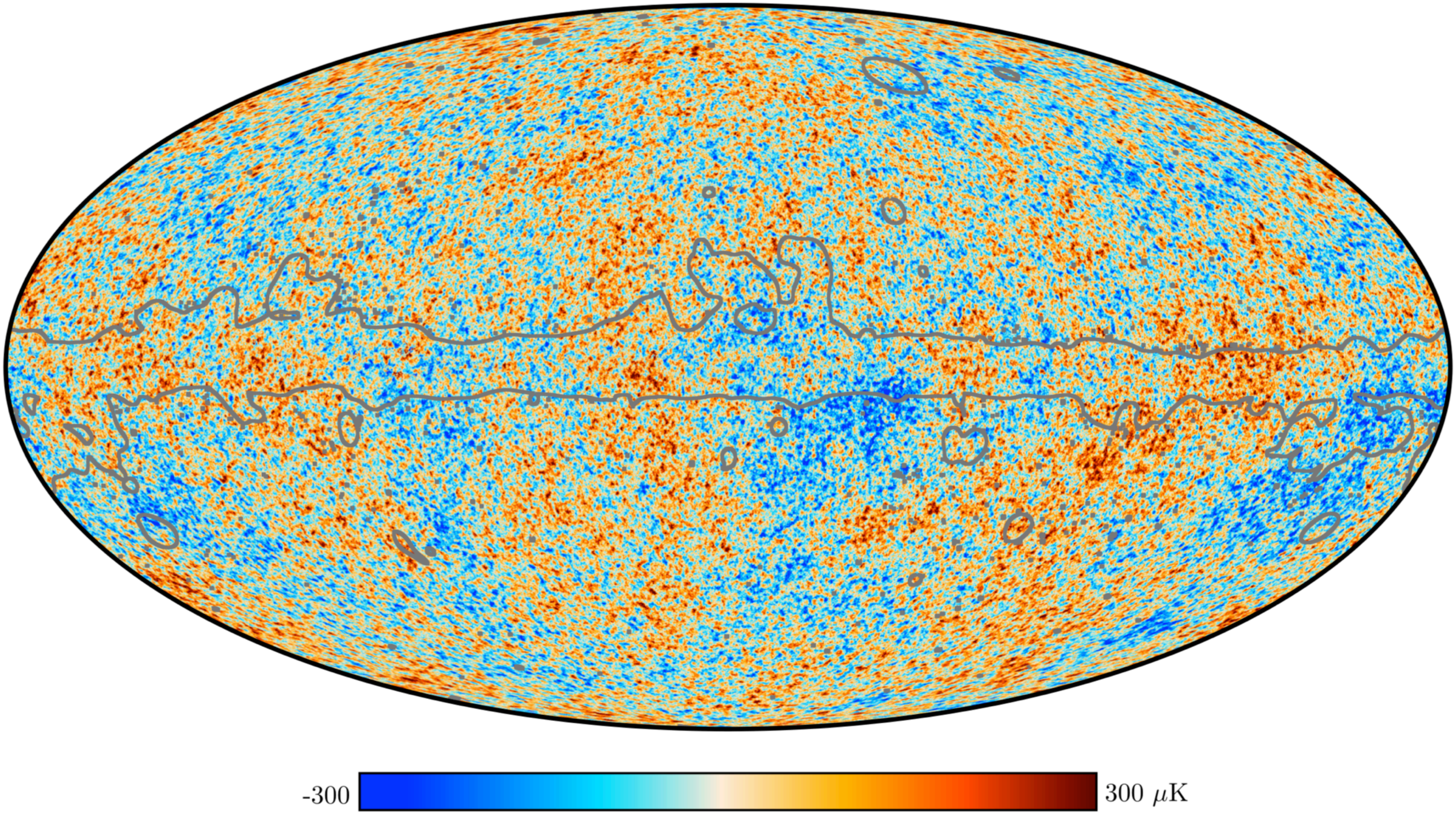
Our Galaxy

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

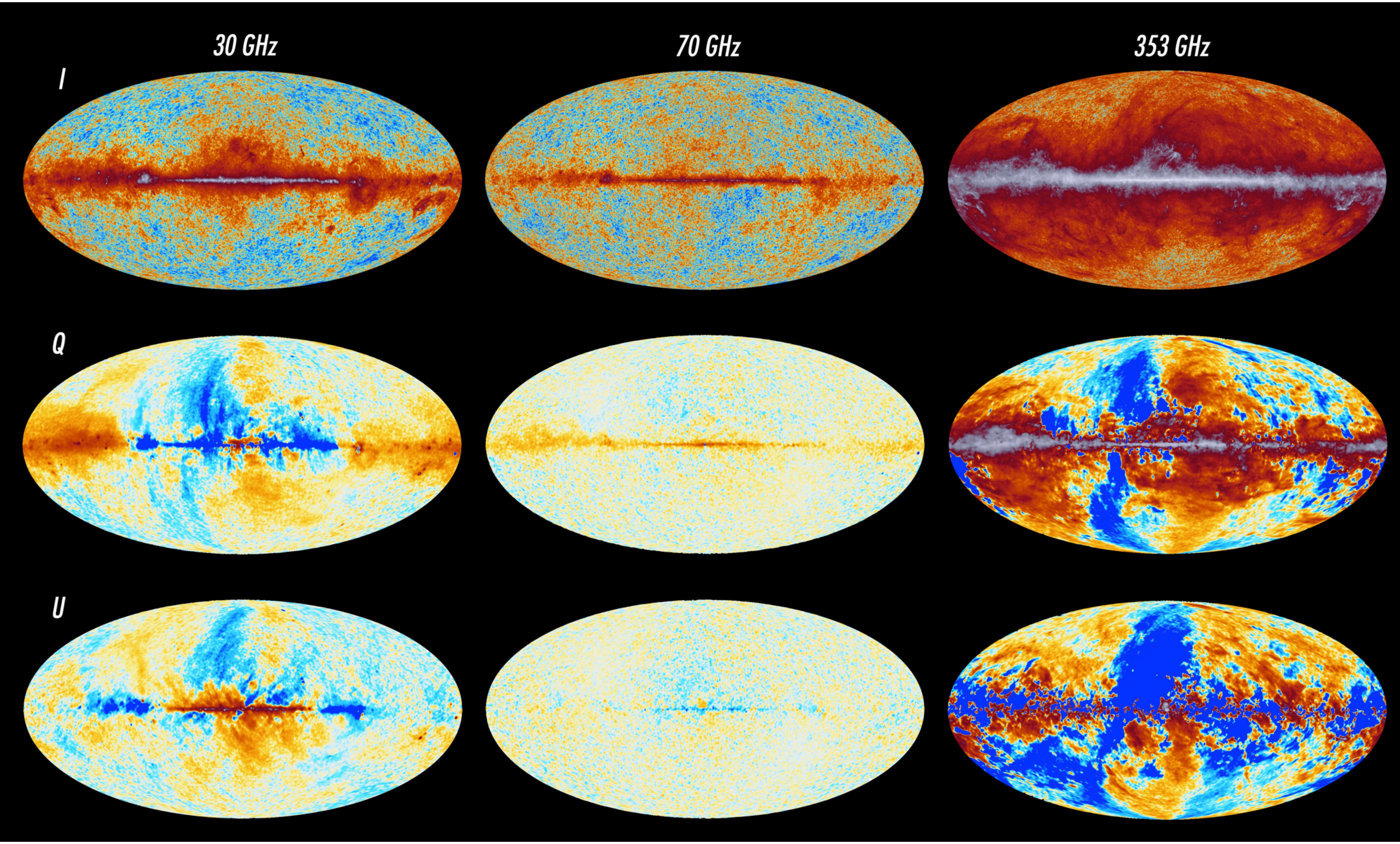
Extragalactic

- 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

Atacama Cosmology Telescope

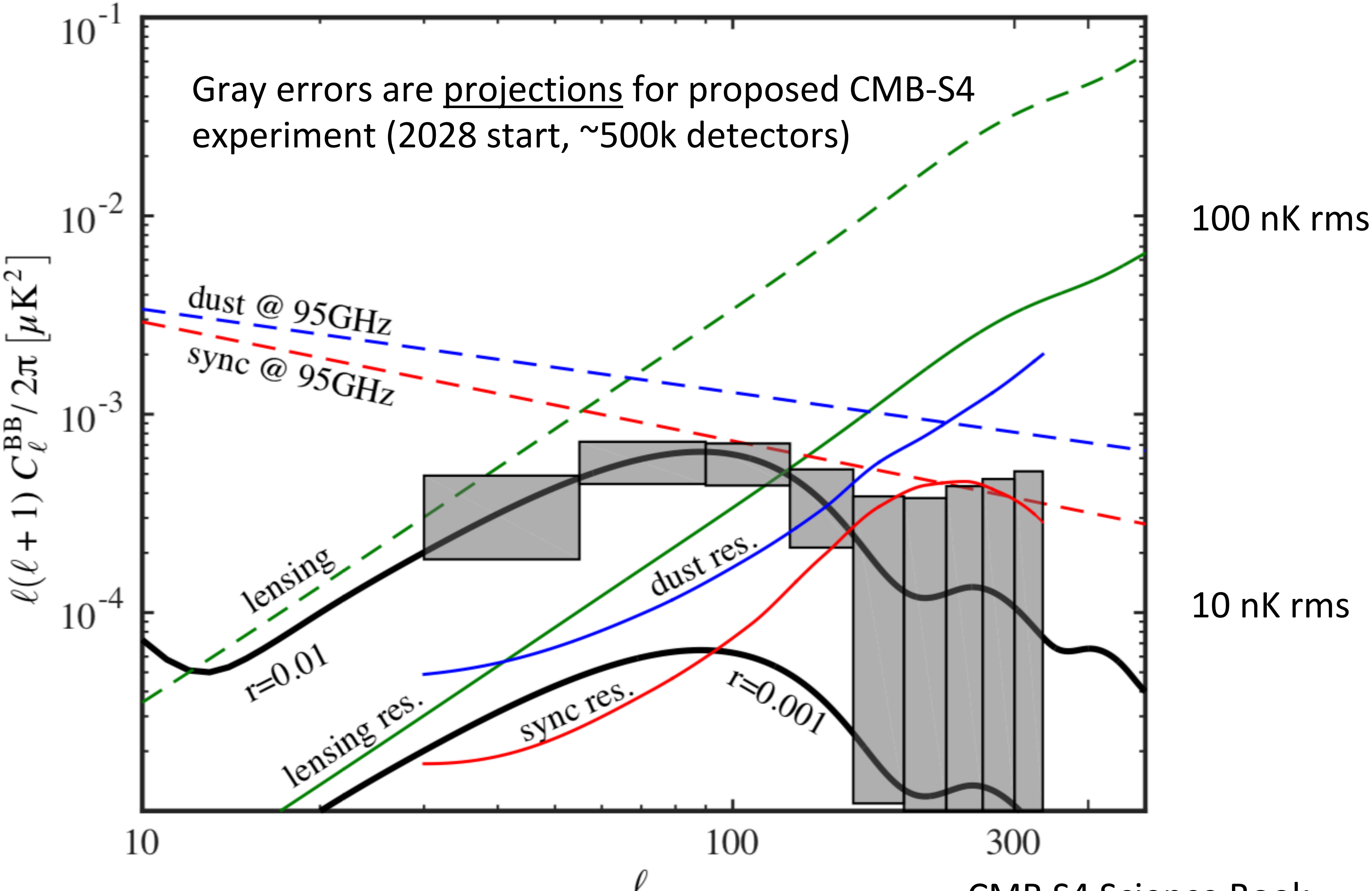
South Pole Telescope

Stephan Meyer

(both using bolometer technology − multiple generations of focal planes …)

The future: B polarization!

r = ratio of tensor / scalar initial power spectra



CMB S4 Science Book