The Cosmic Microwave Background : *Extracting Cosmological Information from Acoustic Oscillations*

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Outline

- A cosmology primer

- A CMB primer:
  - The microwave sky
  - Baryon acoustic oscillations in the sky...
  - ... at multiple redshifts.

- Guiding question:
  - How can we measure cosmological parameters with acoustic oscillations?

Useful References

- **Reference books:**
  - Scott Dodelson, *Modern Cosmology*
  - James Peebles, Lyman Page, Bruce Partridge, *Finding the Big Bang*
  - Durrer, *The Cosmic Microwave Background*
  - Bruce Partridge*, 3K: The Cosmic Microwave Background*
- **Many online resources:**
  - Wayne Hu's CMB tutorial
  - Matias Zaldarriaga CMB lectures
  - CMBSimple by Baumann and Pajer
  - Lecture notes by Daniel Baumann
- **Codes:**
  - CAMB, CLASS, CosmoMC, HEALPix
- **Data:**
  - WMAP, Planck data and data products are all public as well as associated softwares

Cosmological Parameters

- Universe content: Ω_b, Ω_{DM}, f_ν, Ω_Λ, $w(z)$
- Universe dynamics: H_0
- Initial perturbations (clumpiness): A_s , σ_8, $n_s(k)$
- Primordial gravity waves: $r=A_t/A_s$, A_t, n_t
- When the first stars formed: z_{re} , τ
- Other: WDM, isocurvature, non-Gaussianity...

$$\mathcal{P}_{\mathcal{R}}(k) = A_s \left(\frac{k}{k_0}\right)^{n_s - 1 + (1/2)(dn_s/d\ln k)\ln(k/k_0)}$$

$$\mathcal{P}_t(k) = A_t \left(\frac{k}{k_0}\right)^{n_t}$$

Parameter	Prior range	Baseline	Definition
$\omega_b \equiv \Omega_b h^2$	[0.005, 0.1]	...	Baryon density today
$\omega_c \equiv \Omega_c h^2$	[0.001, 0.99]	...	Cold dark matter density today
$100\theta_{MC}$	[0.5, 10.0]	...	$100 \times$ approximation to r_*/D_A (CosmoMC)
τ	[0.01, 0.8]	...	Thomson scattering optical depth due to reionization
Ω_K	[−0.3, 0.3]	0	Curvature parameter today with $\Omega_{tot} = 1 - \Omega_K$
$\sum m_\nu$	[0, 5]	0.06	The sum of neutrino masses in eV
$m^{eff}_{\nu,\,sterile}$	[0, 3]	0	Effective mass of sterile neutrino in eV
w_0	[−3.0, −0.3]	−1	Dark energy equation of state[a], $w(a) = w_0 + (1-a)w_a$
w_a	[−2, 2]	0	As above (perturbations modelled using PPF)
N_{eff}	[0.05, 10.0]	3.046	Effective number of neutrino-like relativistic degrees of freedom (see text)
Y_P	[0.1, 0.5]	BBN	Fraction of baryonic mass in helium
A_L	[0, 10]	1	Amplitude of the lensing power relative to the physical value
n_s	[0.9, 1.1]	...	Scalar spectrum power-law index ($k_0 = 0.05\mathrm{Mpc}^{-1}$)
n_t	$n_t = -r_{0.05}/8$	Inflation	Tensor spectrum power-law index ($k_0 = 0.05\mathrm{Mpc}^{-1}$)
$dn_s/d\ln k$	[−1, 1]	0	Running of the spectral index
$\ln(10^{10}A_s)$	[2.7, 4.0]	...	Log power of the primordial curvature perturbations ($k_0 = 0.05\,\mathrm{Mpc}^{-1}$)
$r_{0.05}$	[0, 2]	0	Ratio of tensor primordial power to curvature power at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
Ω_Λ		...	Dark energy density divided by the critical density today
t_0		...	Age of the Universe today (in Gyr)
Ω_m		...	Matter density (inc. massive neutrinos) today divided by the critical density
σ_8		...	RMS matter fluctuations today in linear theory
z_{re}		...	Redshift at which Universe is half reionized
H_0	[20,100]	...	Current expansion rate in $\mathrm{km\,s^{-1}Mpc^{-1}}$
$r_{0.002}$		0	Ratio of tensor primordial power to curvature power at $k_0 = 0.002\,\mathrm{Mpc}^{-1}$
$10^9 A_s$		...	$10^9 \times$ dimensionless curvature power spectrum at $k_0 = 0.05\,\mathrm{Mpc}^{-1}$
$\omega_m \equiv \Omega_m h^2$		...	Total matter density today (inc. massive neutrinos)
z_*		...	Redshift for which the optical depth equals unity (see text)
$r_* = r_s(z_*)$		...	Comoving size of the sound horizon at $z = z_*$
$100\theta_*$		...	$100 \times$ angular size of sound horizon at $z = z_*$ (r_*/D_A)
z_{drag}		...	Redshift at which baryon-drag optical depth equals unity (see text)
$r_{drag} = r_s(z_{drag})$		...	Comoving size of the sound horizon at $z = z_{drag}$
k_D		...	Characteristic damping comoving wavenumber (Mpc^{-1})
$100\theta_D$		...	$100 \times$ angular extent of photon diffusion at last scattering (see text)
z_{eq}		...	Redshift of matter-radiation equality (massless neutrinos)
$100\theta_{eq}$		...	$100 \times$ angular size of the comoving horizon at matter-radiation equality
$r_{drag}/D_V(0.57)$		...	BAO distance ratio at $z = 0.57$ (see Sect. 5.2)

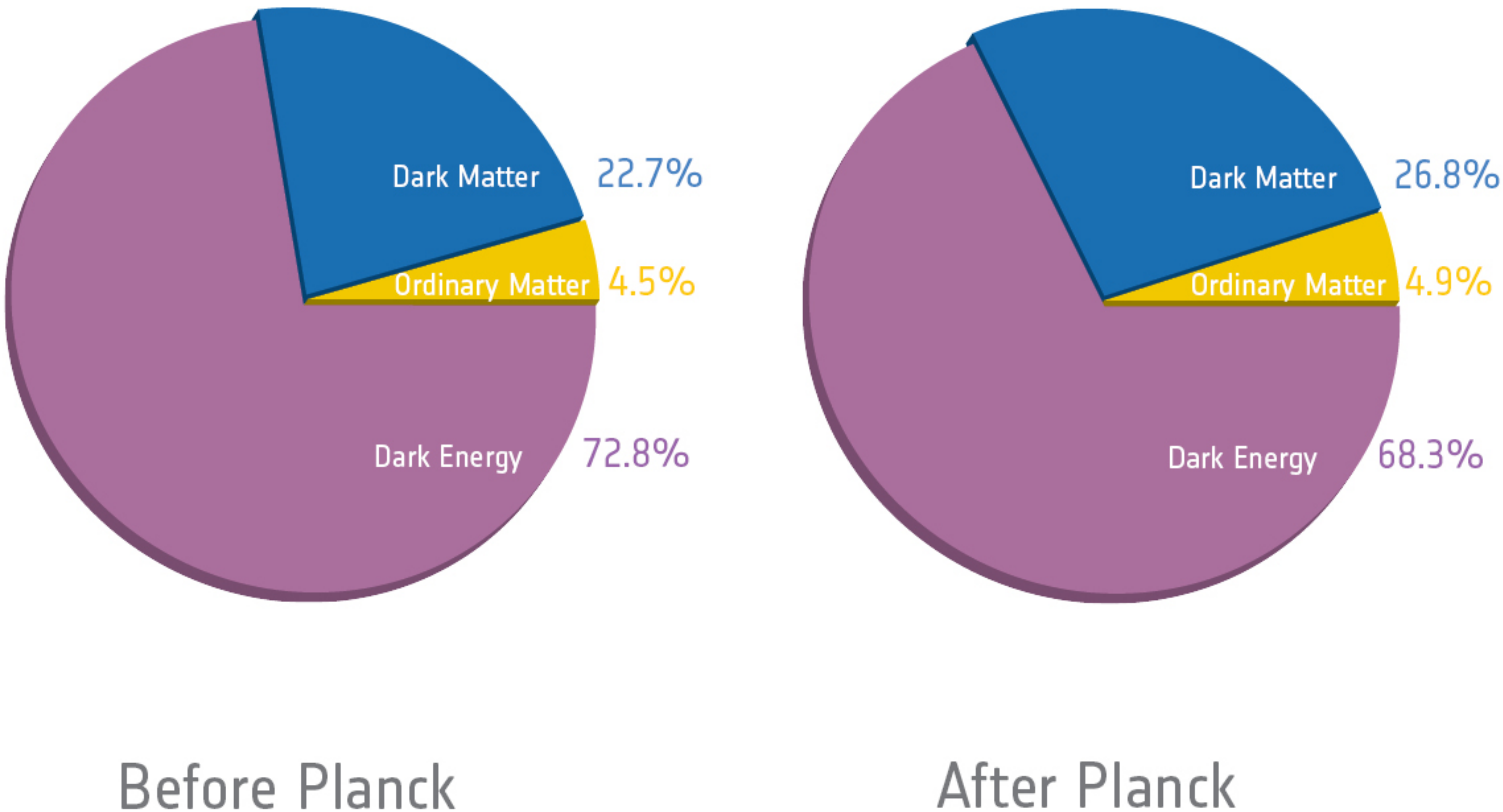
[a] For dynamical dark energy models with constant equation of state, we denote the equation of state by w and adopt the same prior as for w_0.

Varied

Derived

e.g., Planck 2013. XVI. Cosmological Parameters

Cosmic Camembert *



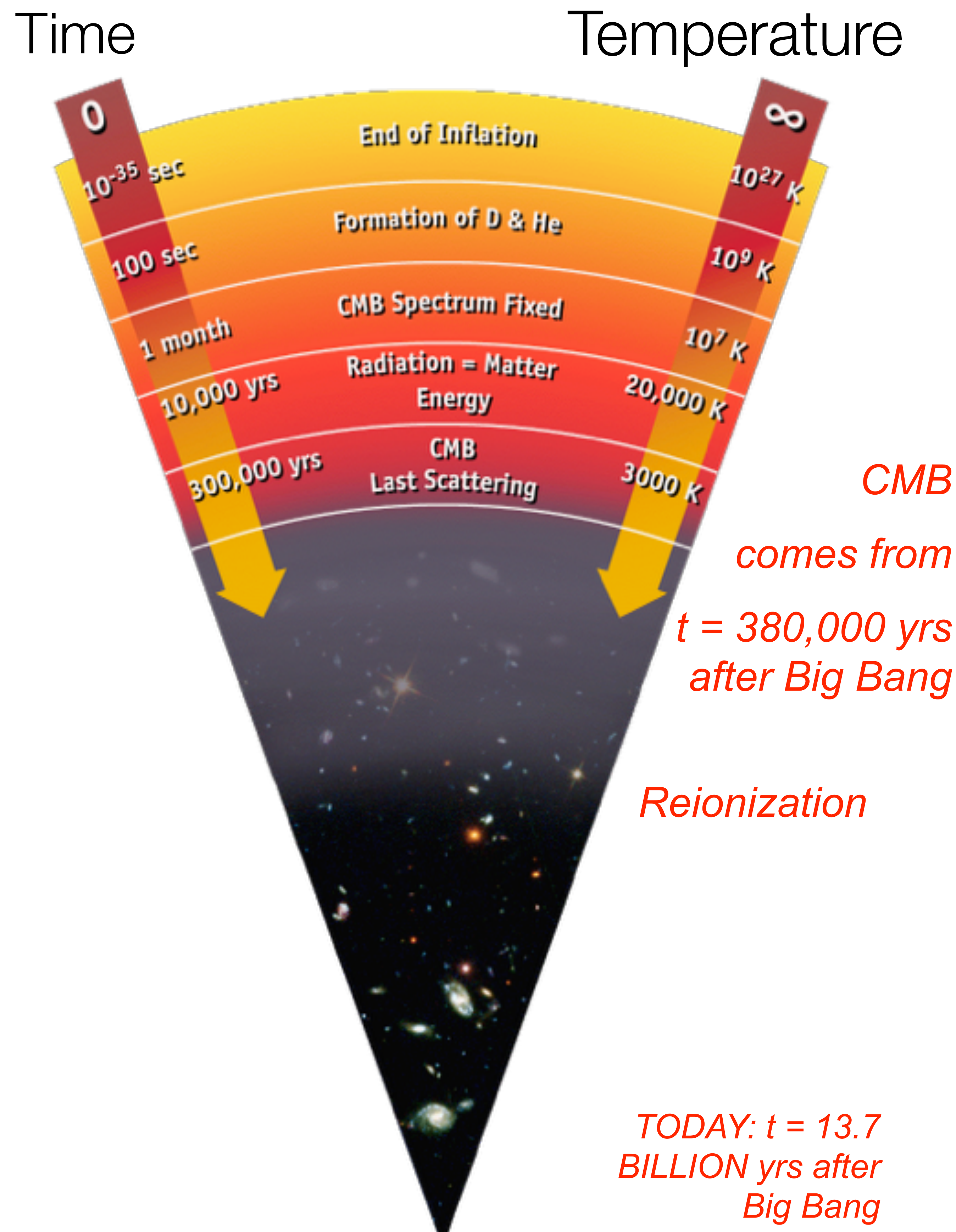
* J. Lesgourgues

CMB is a leftover from when the Universe was 380,000 yrs old

- The Universe is expanding and cooling

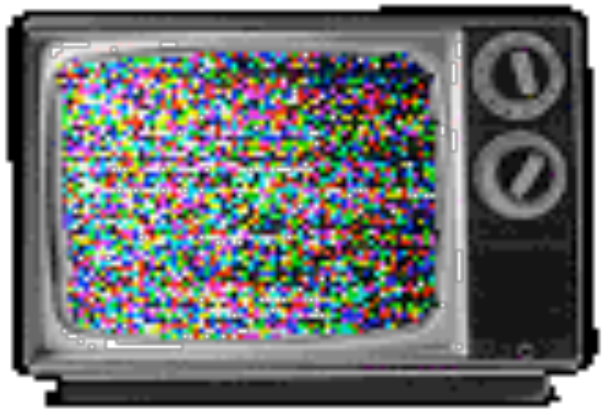
- Once it is cool enough for Hydrogen to form, (T~3000K, t~3.8 10^5 yrs), the photons start to propagate freely *(the Thomson mean free path is greater than the horizon scale)*

- This radiation has the imprint of the small anisotropies that grew by gravitational instability into the large structures we see today



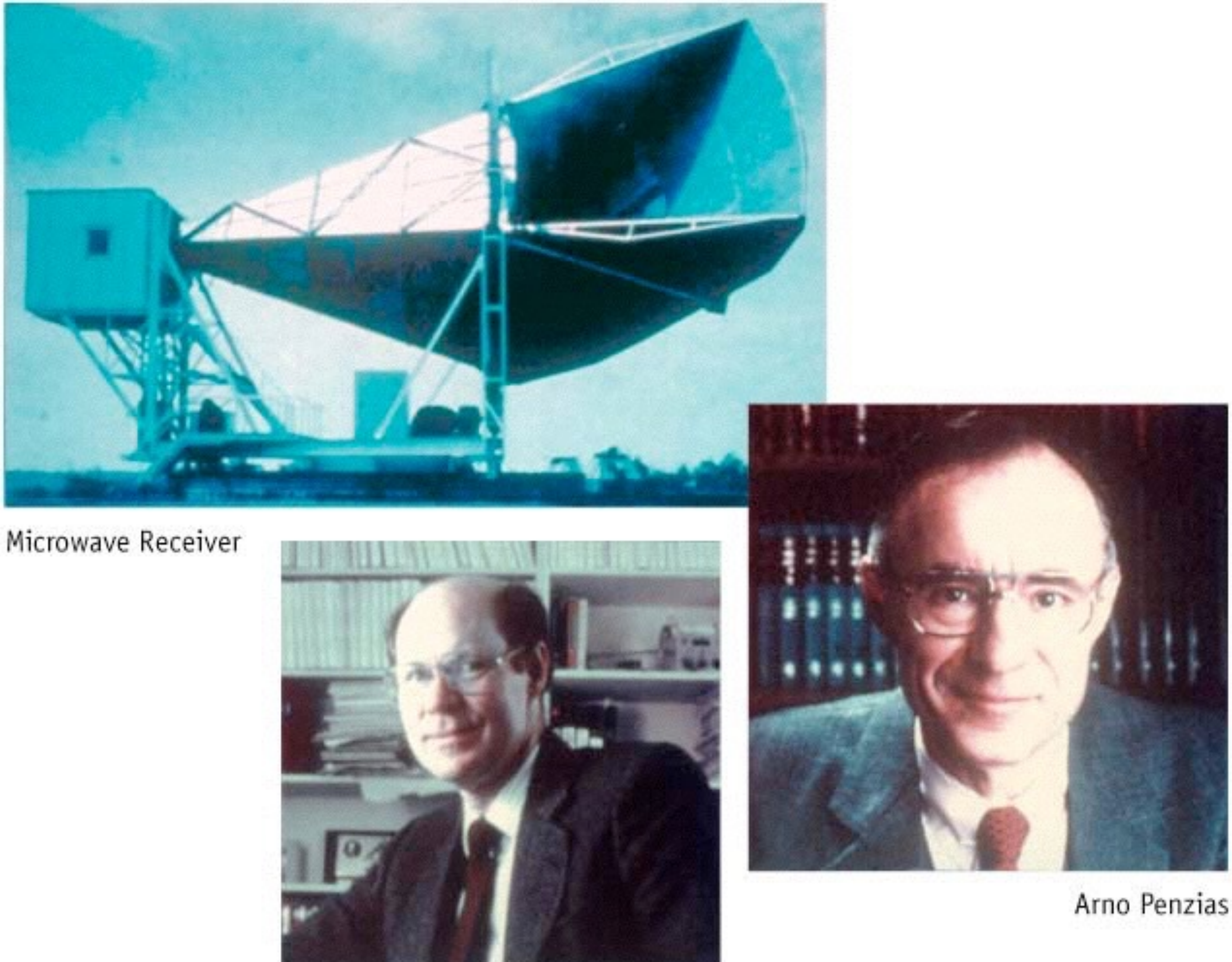
CMB Fun Facts

- Universe was ~ 3000° K at 380,000 yr
- Full of visible light (~1μm)
- Universe is expanding:
  - Causes light to change wavelength.
  - Visible light becomes microwaves (~1cm).



- 400 photons per cubic cm today.
- Universe in equilibrium ⇒ Black body.
  - Observe perfect black body at 2.73K
  - Can relate present day # photons, protons, 13.6eV to get $T_{\text{recombimation}}$.
  - From T_{CMB} today, we get $z_{\text{recombination}}$

Discovery of the Cosmic Microwave Background



Microwave Receiver

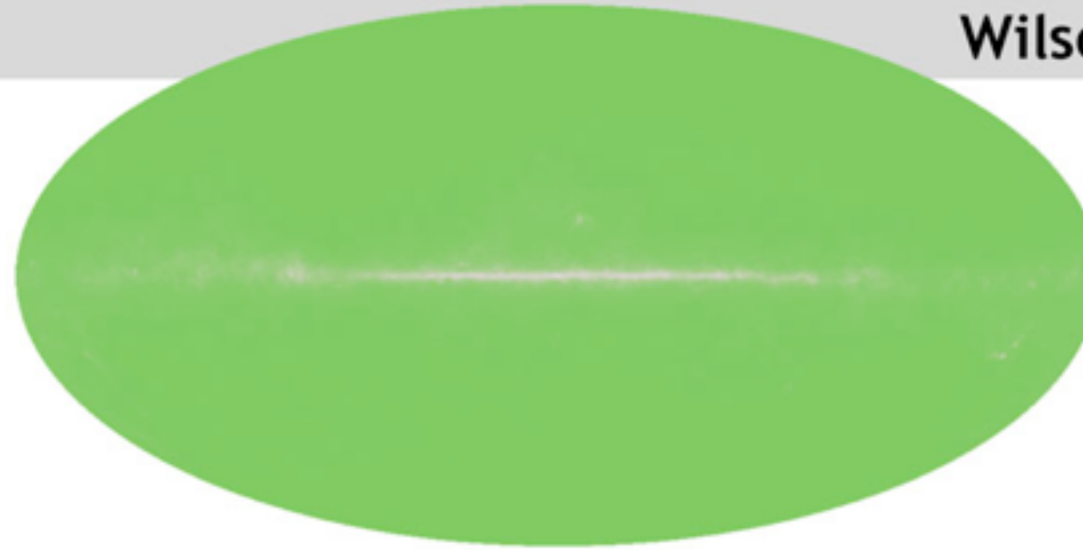
Robert Wilson

Arno Penzias

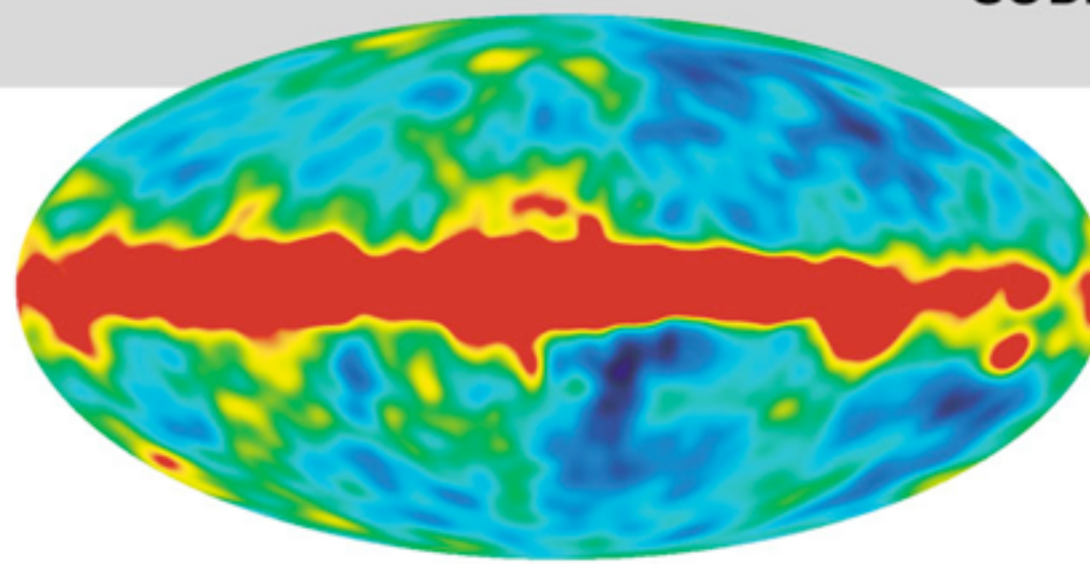
MAP990045

Penzias & Wilson 1965
Nobel Prize in Physics 1978

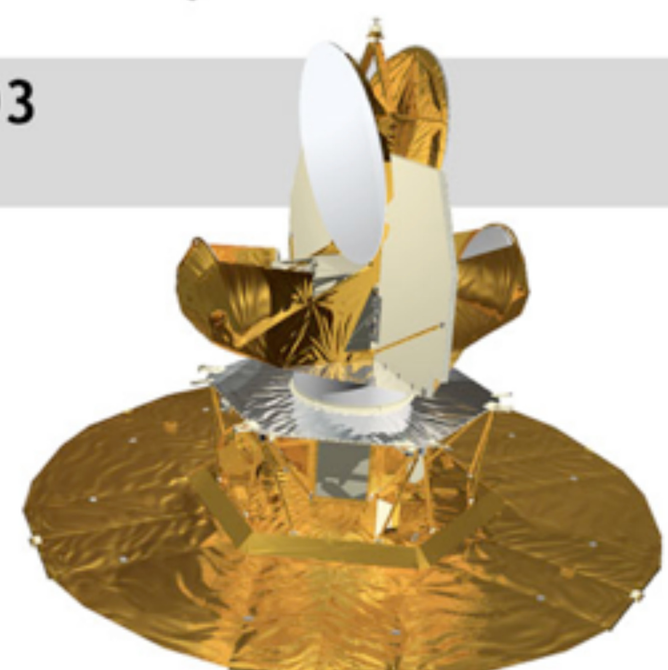
1965 Penzias and Wilson

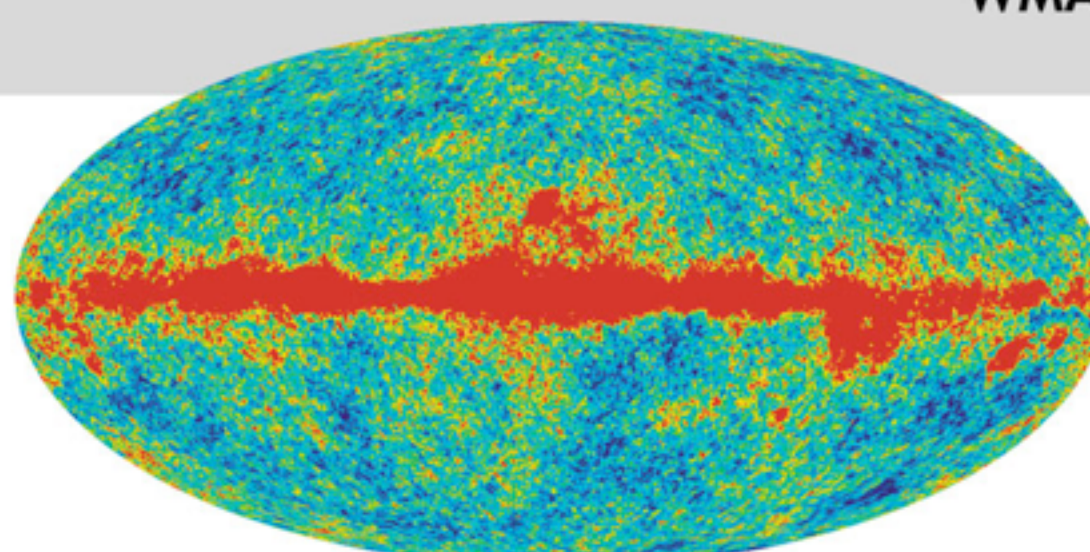


1992 COBE



2003 WMAP





Units

- Spectra in the microwave band is measured in several ways.
- Spectral intensity I_ν (units: MJy/sr)
- Blackbody temperature or thermodynamic temperature $T_B(\nu)$ (units: K)

$$I_\nu = \frac{2h\nu^3}{c^2}\frac{1}{\exp[h\nu/kT_B(\nu)]-1}$$

- Antenna temperature or brightness temperature $T_A(\nu)$ (units: K)

$$I_\nu = \frac{2k\nu^2}{c^2}T_A(\nu)$$

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Slides from Chris Hirata

Units, Part II

- All three functions – I_ν, $T_B(\nu)$, and $T_A(\nu)$ – contain the same information.
- Identities:
  – For a blackbody, $T_B(\nu)$=constant. Blackbody temperature is most useful for CMB.
  – At low frequencies, $h\nu \ll kT$, $T_B(\nu)=T_A(\nu)$. Since $T_A(\nu)$ is proportional to I_ν, antenna temperature is most useful for foreground studies.
- From now on, we'll use blackbody temperature and its perturbation $\Delta T_B(\nu)$.

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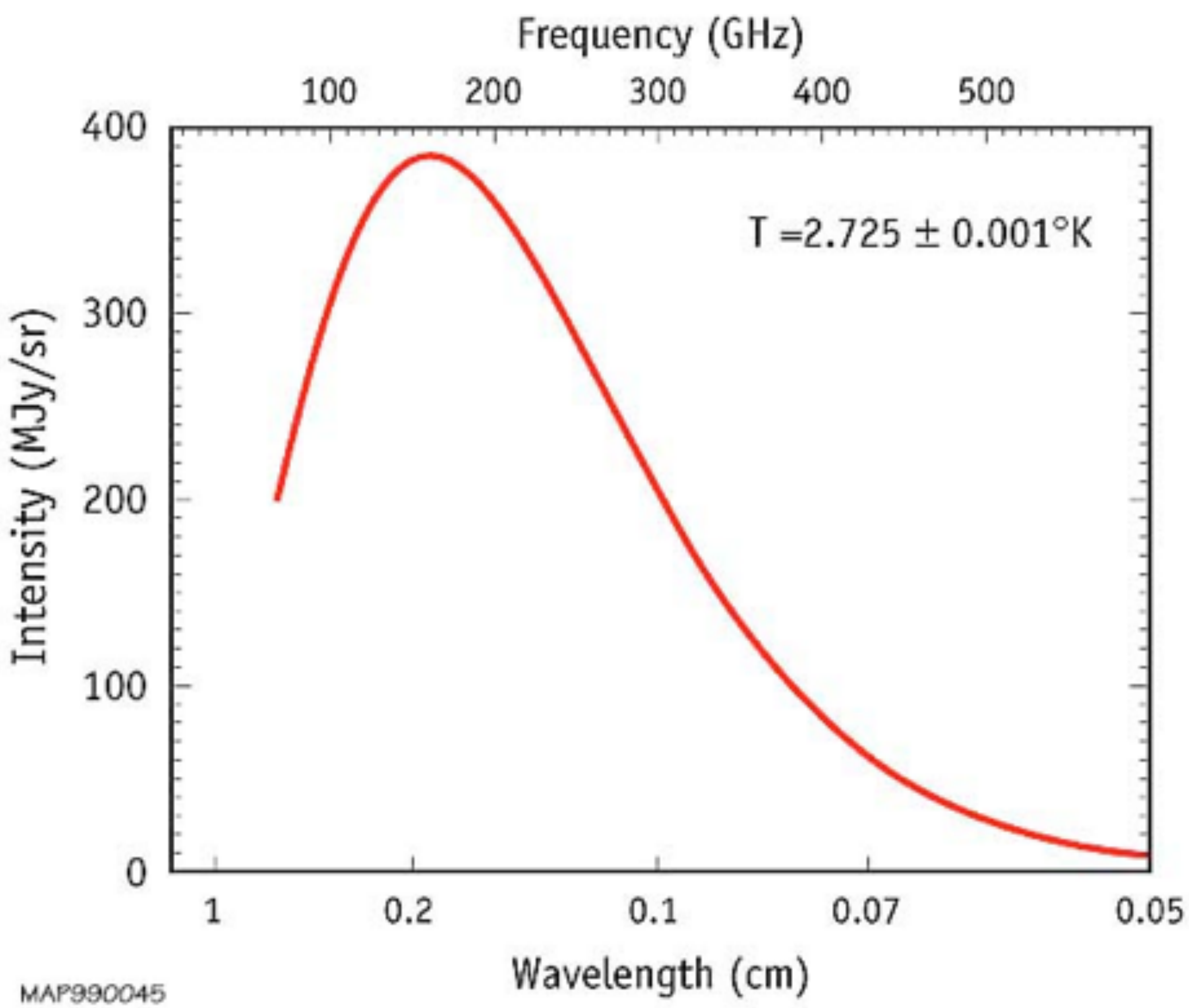
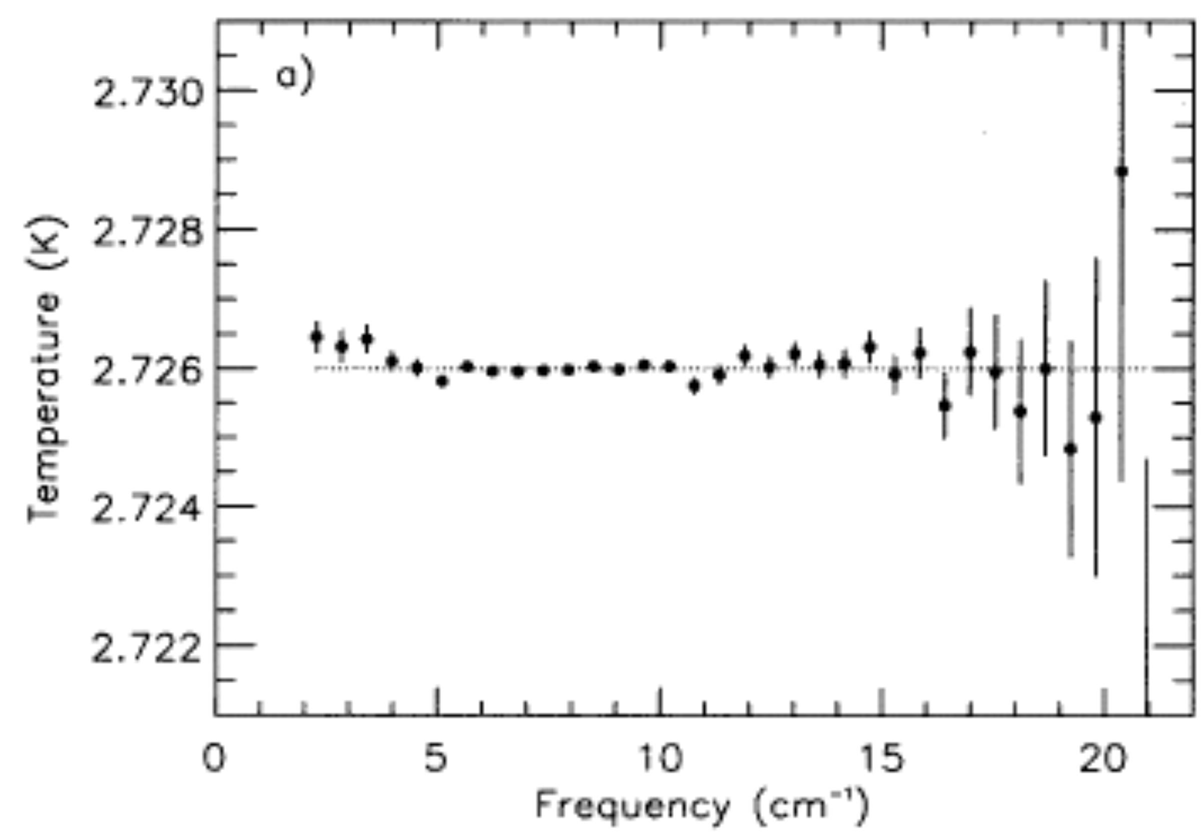
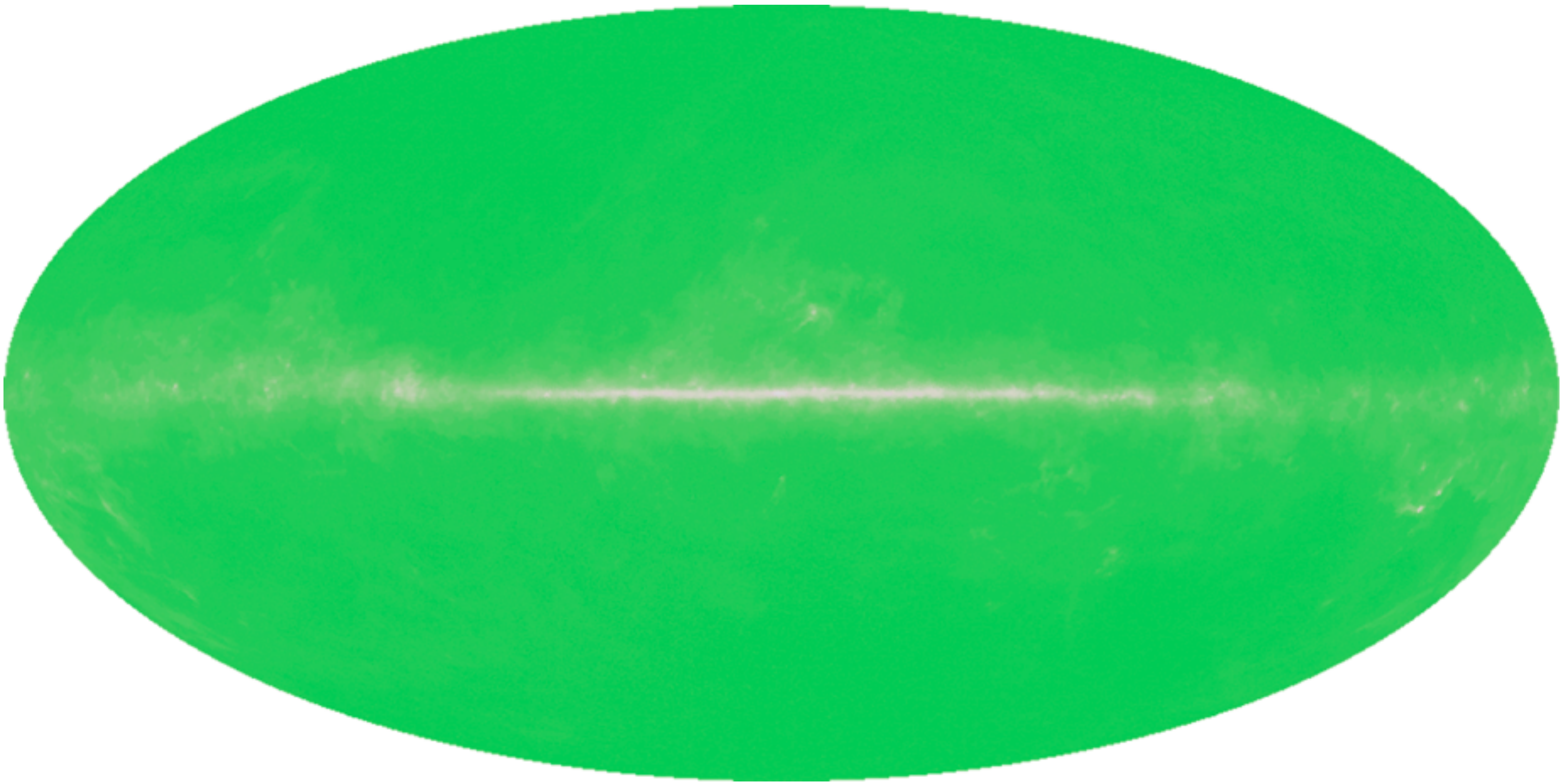
CMB Frequency Spectrum





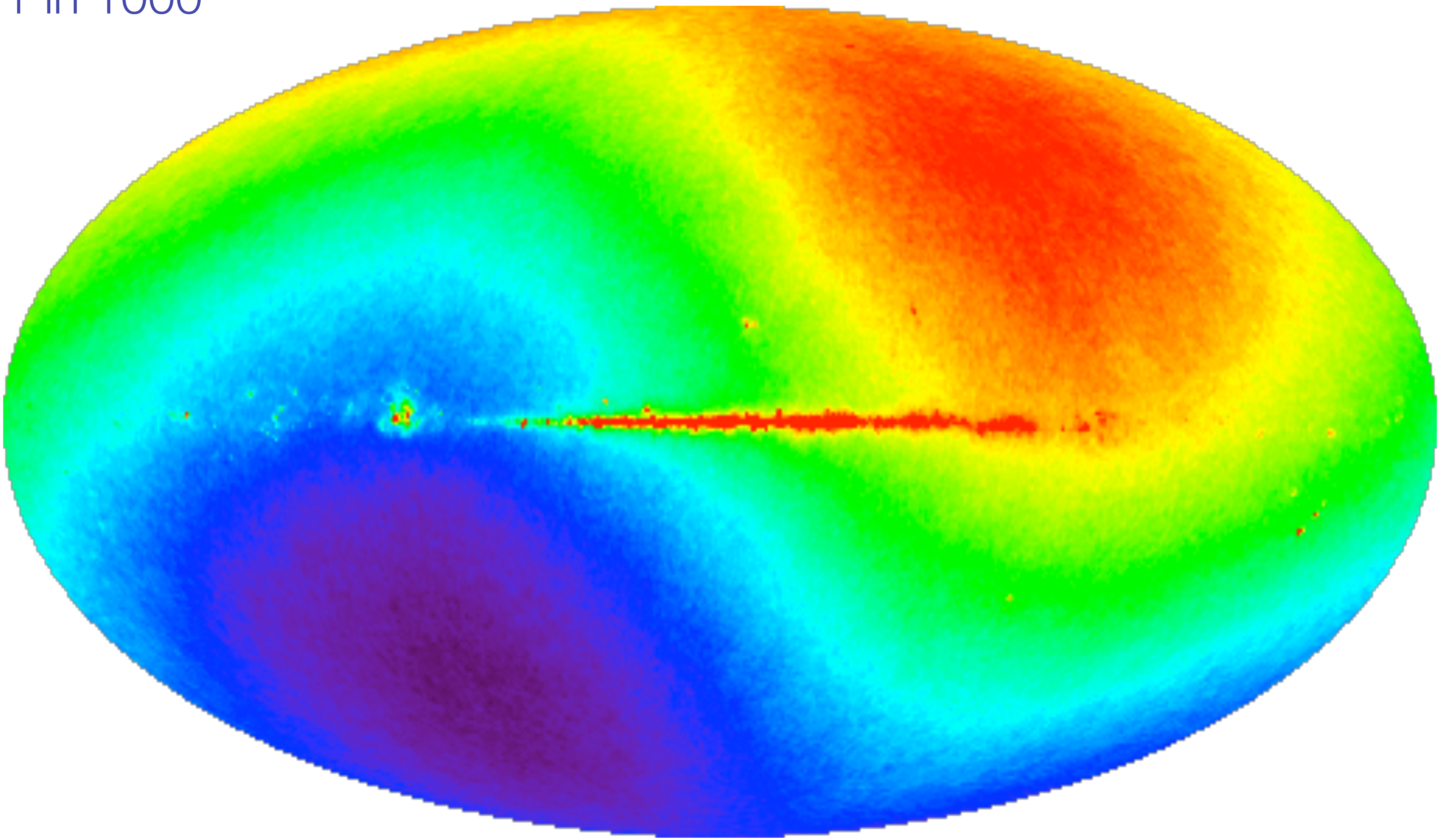
COBE FIRAS, Maher++94
Nobel Prize in Physics 2006

What Planck saw



Zooming the color scale…

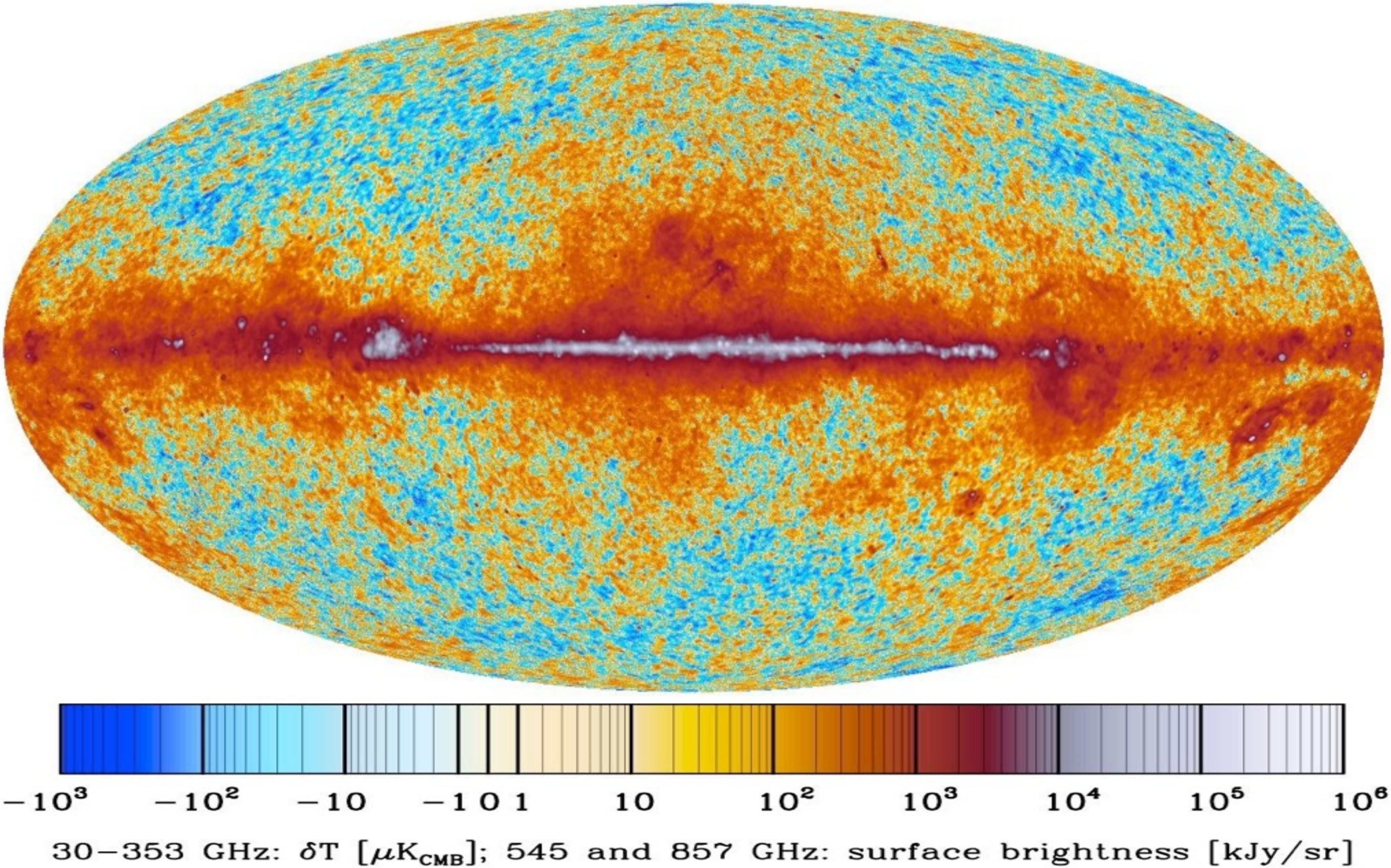
1 in 1000



Conventional explanation due to our motion with v/c = 0.0012 in direction of the constellation Crater

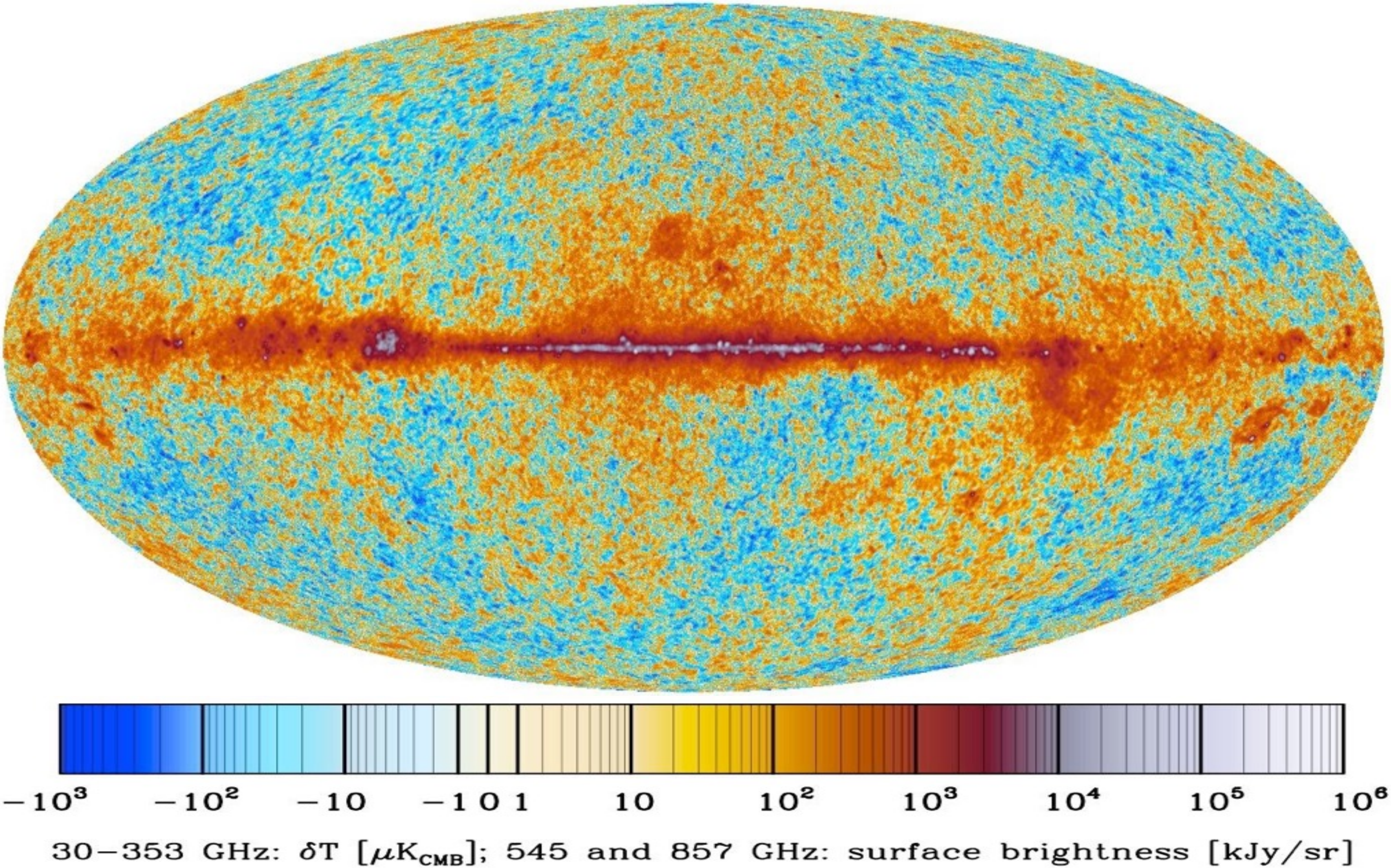
$$T(\hat{n}) = T'(\hat{n})(1 + \hat{n} \cdot \vec{v}/c)$$

30 GHz

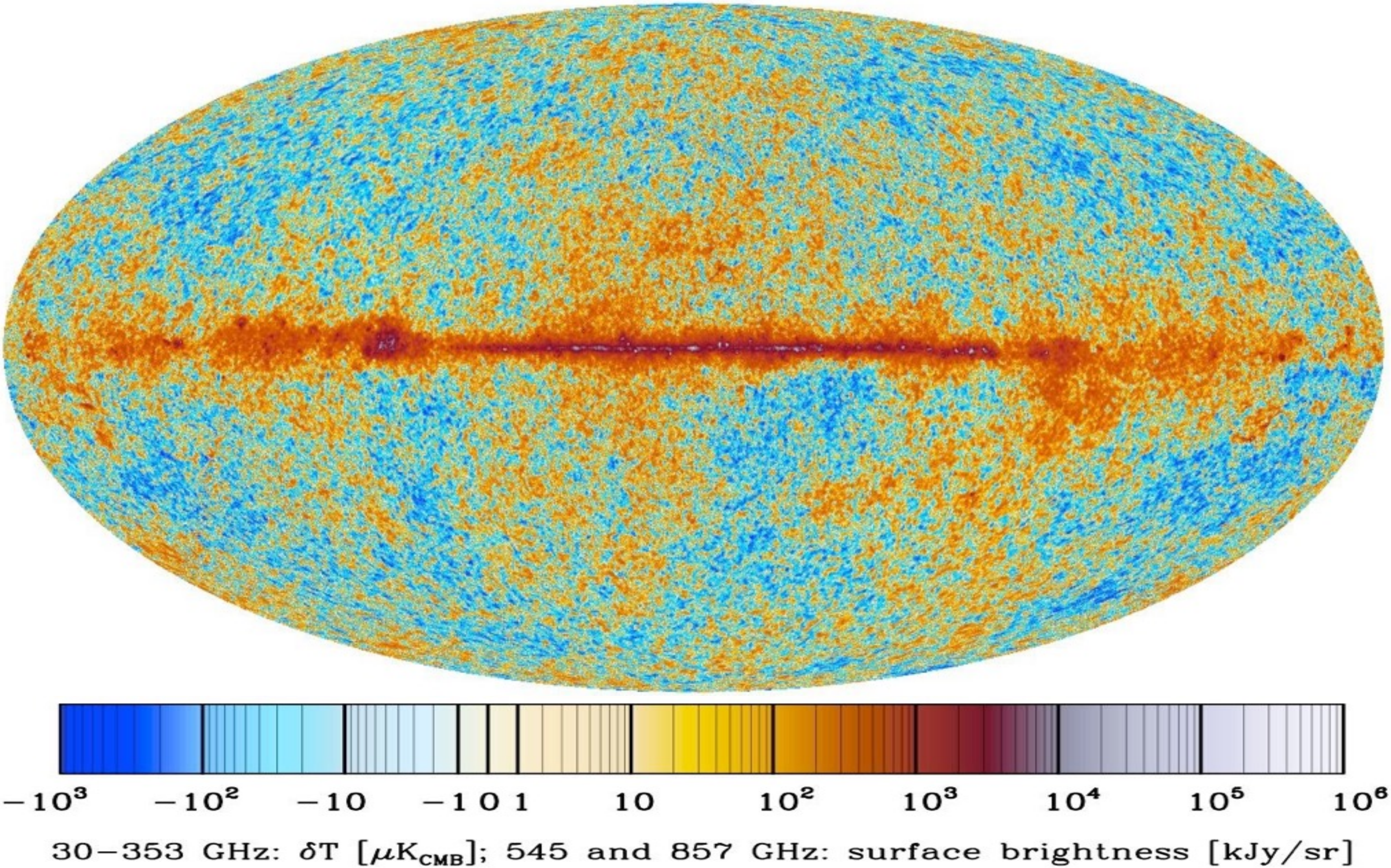


-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

44 GHz

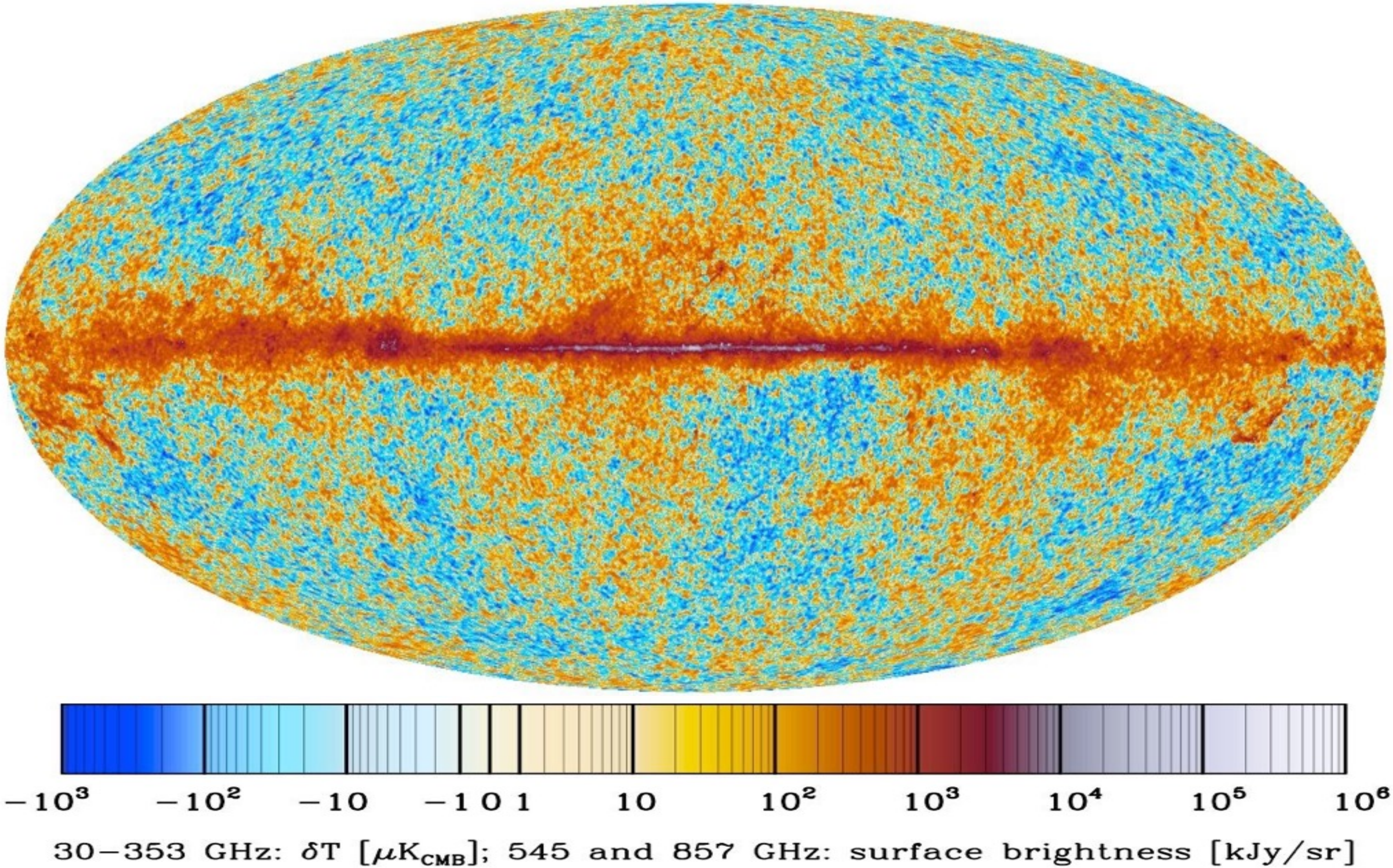

-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

70 GHz



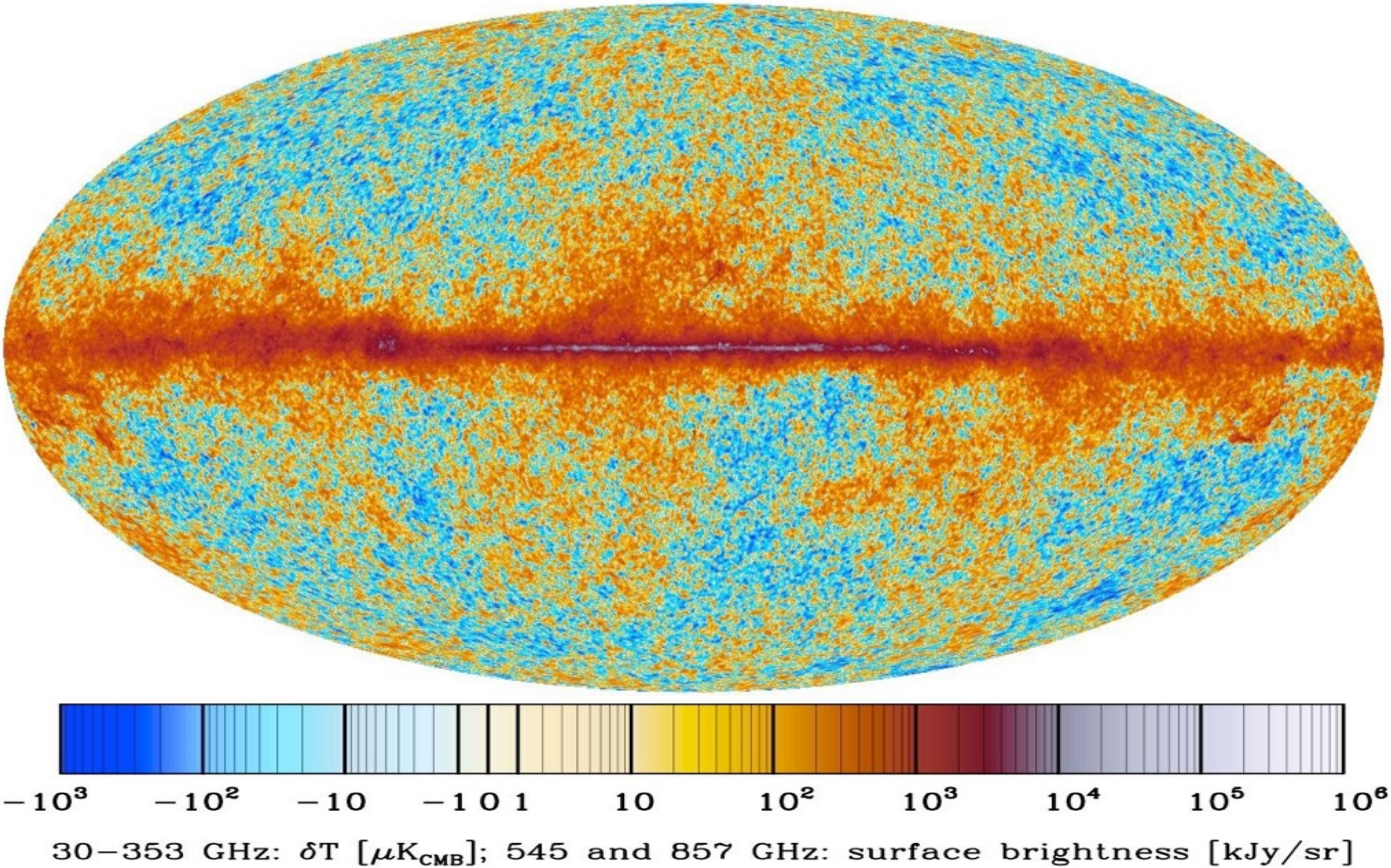
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

100 GHz



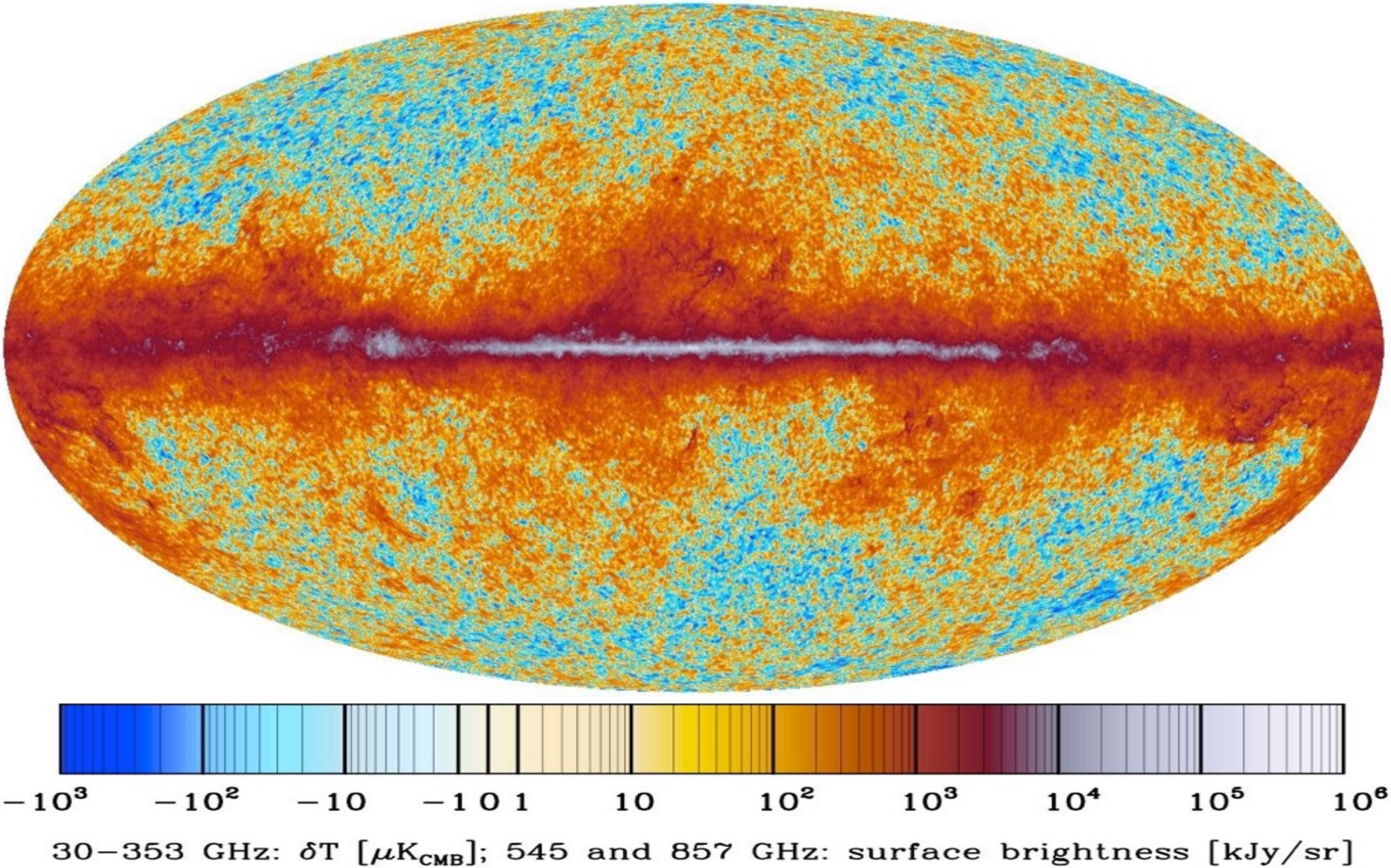
-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

143 GHz

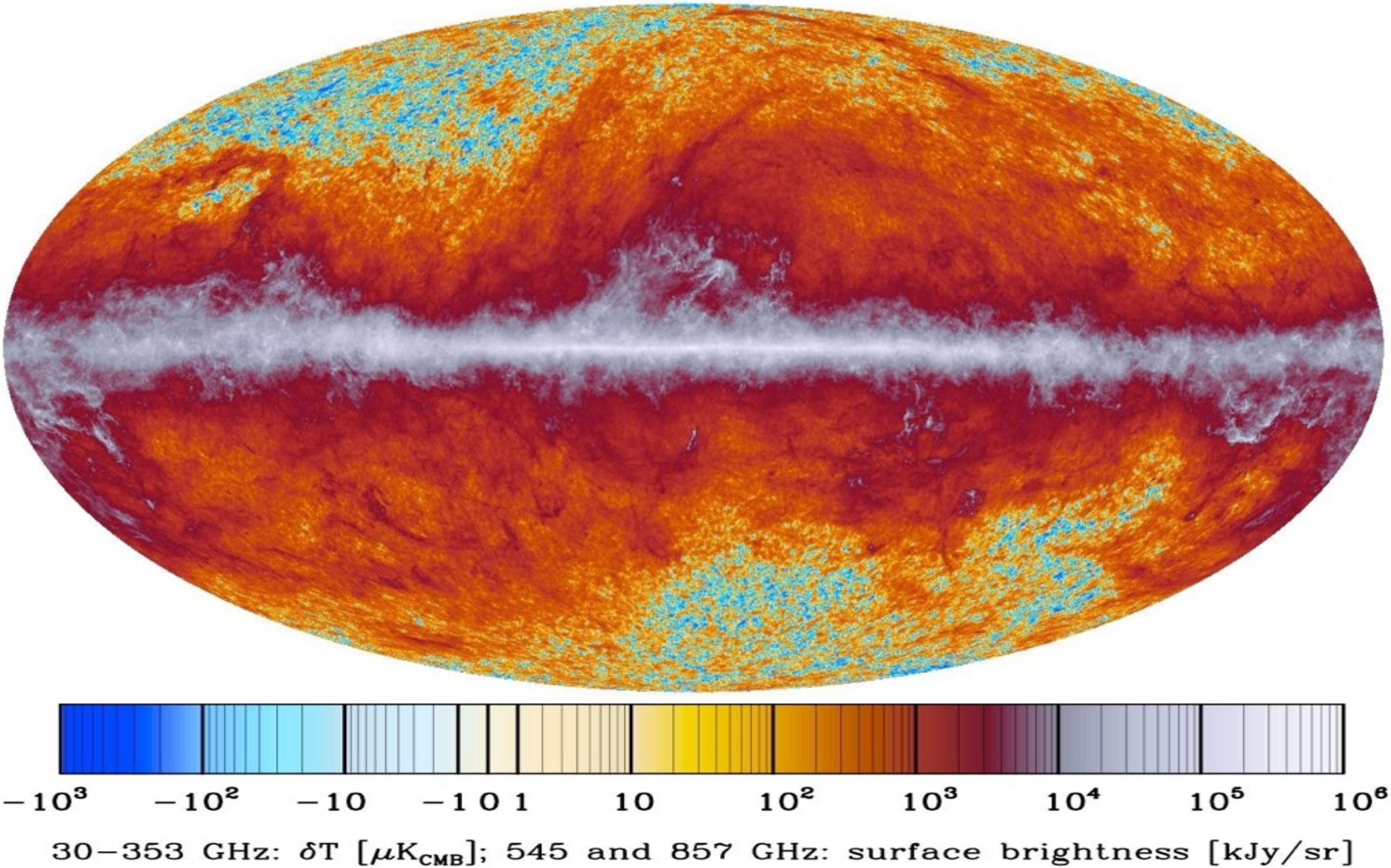


-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

217 GHz

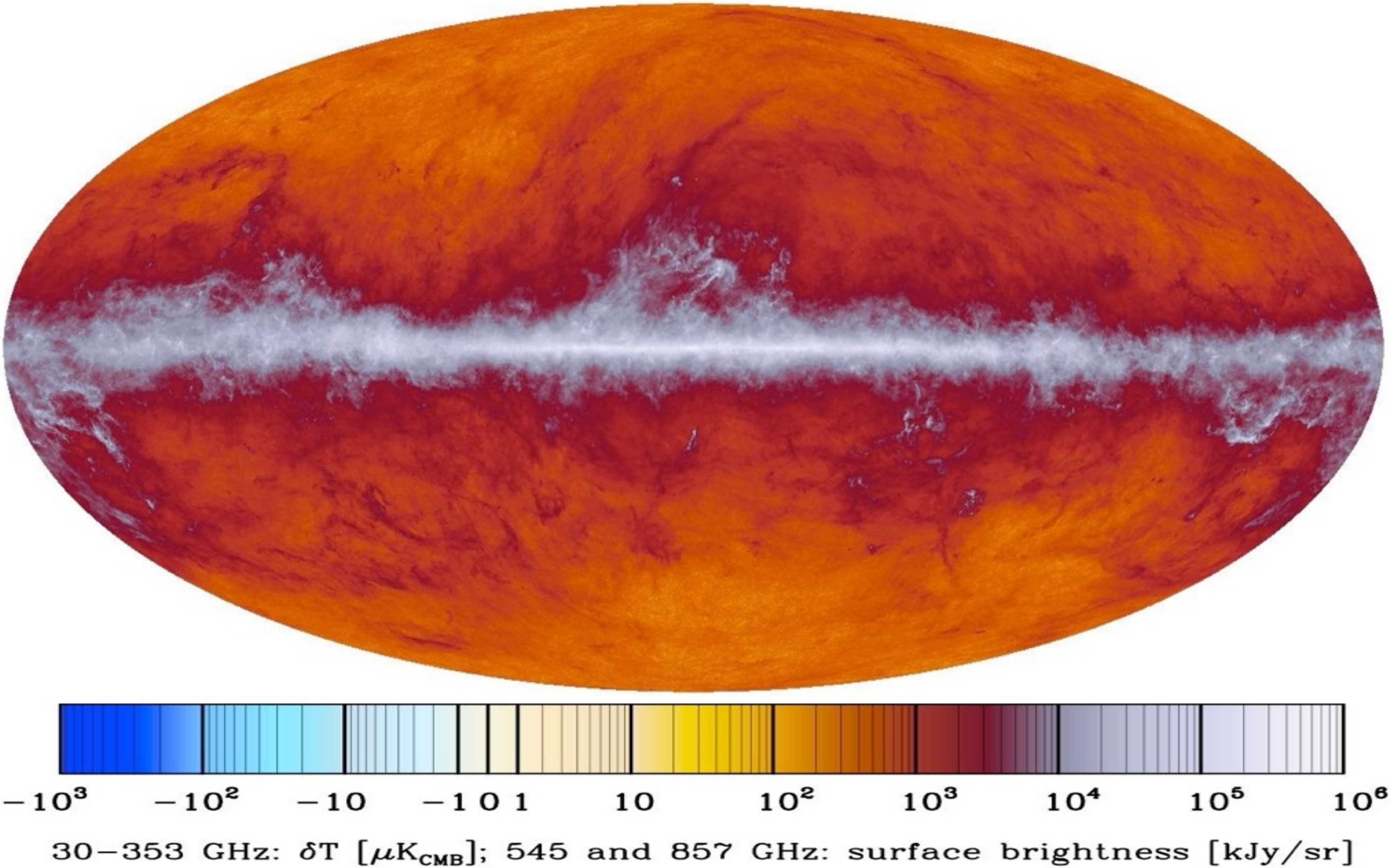

-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30–353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

353 GHz



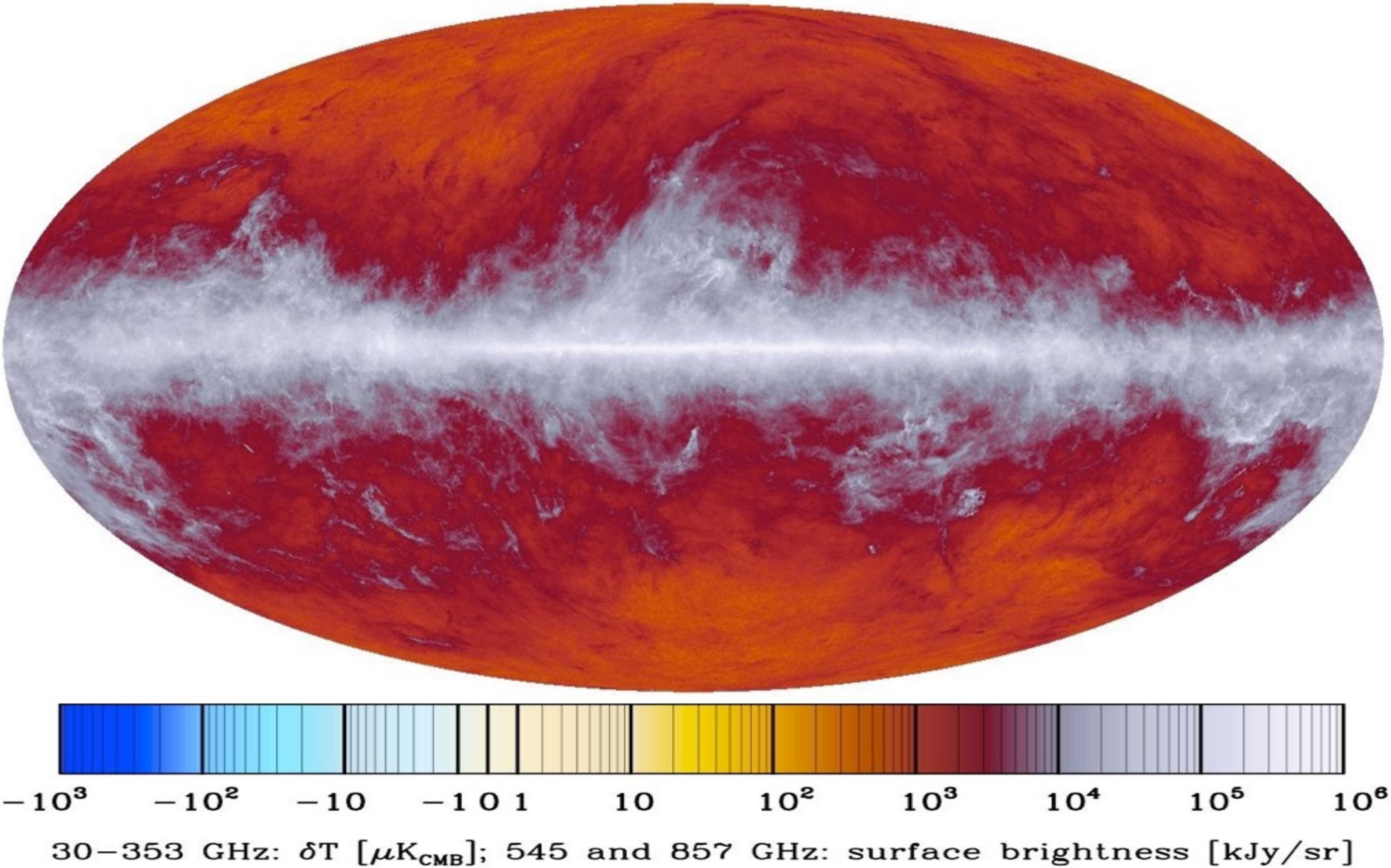
−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

545 GHz

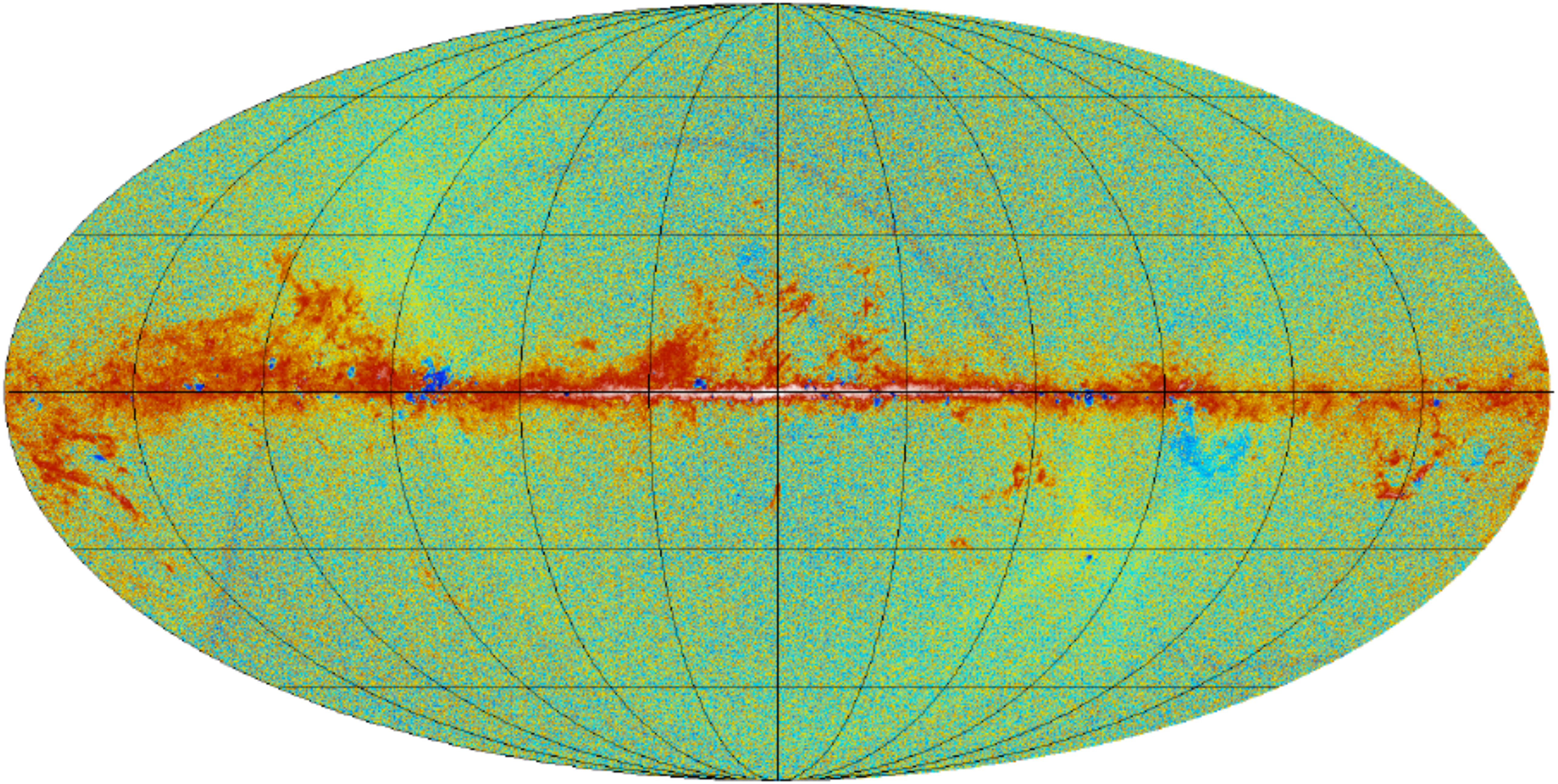


-10^3 -10^2 -10 -1 0 1 10 10^2 10^3 10^4 10^5 10^6
30−353 GHz: δT [μK_{CMB}]; 545 and 857 GHz: surface brightness [kJy/sr]

857 GHz

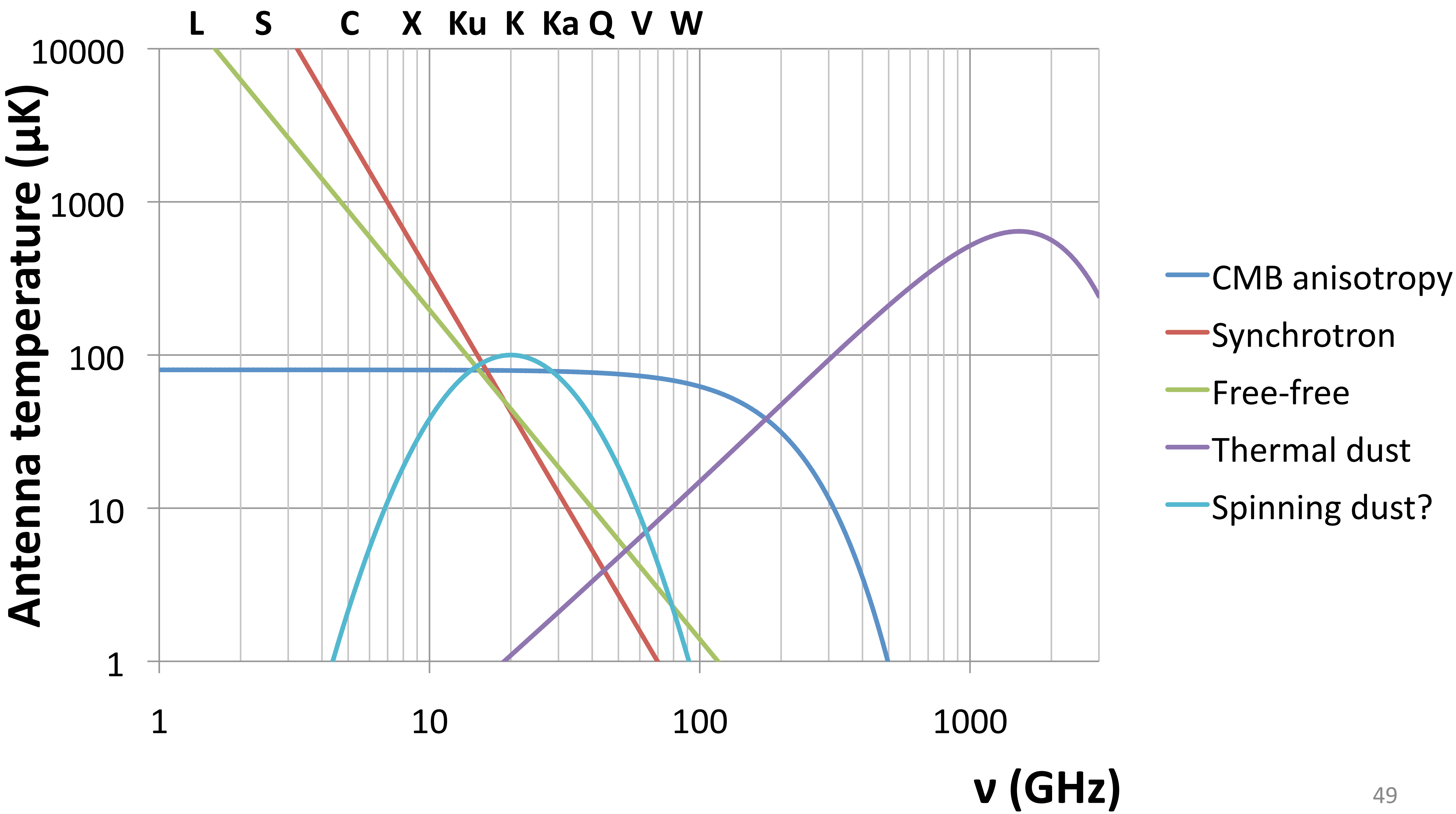

−10³ −10² −10 −1 0 1 10 10² 10³ 10⁴ 10⁵ 10⁶
30−353 GHz: δT [μK_CMB]; 545 and 857 GHz: surface brightness [kJy/sr]

Consistency between instruments: 100GHz – 70GHz



Galactic Emission, Part VI

[Schematic representation of medium-latitude sky. There may be other models that work!]



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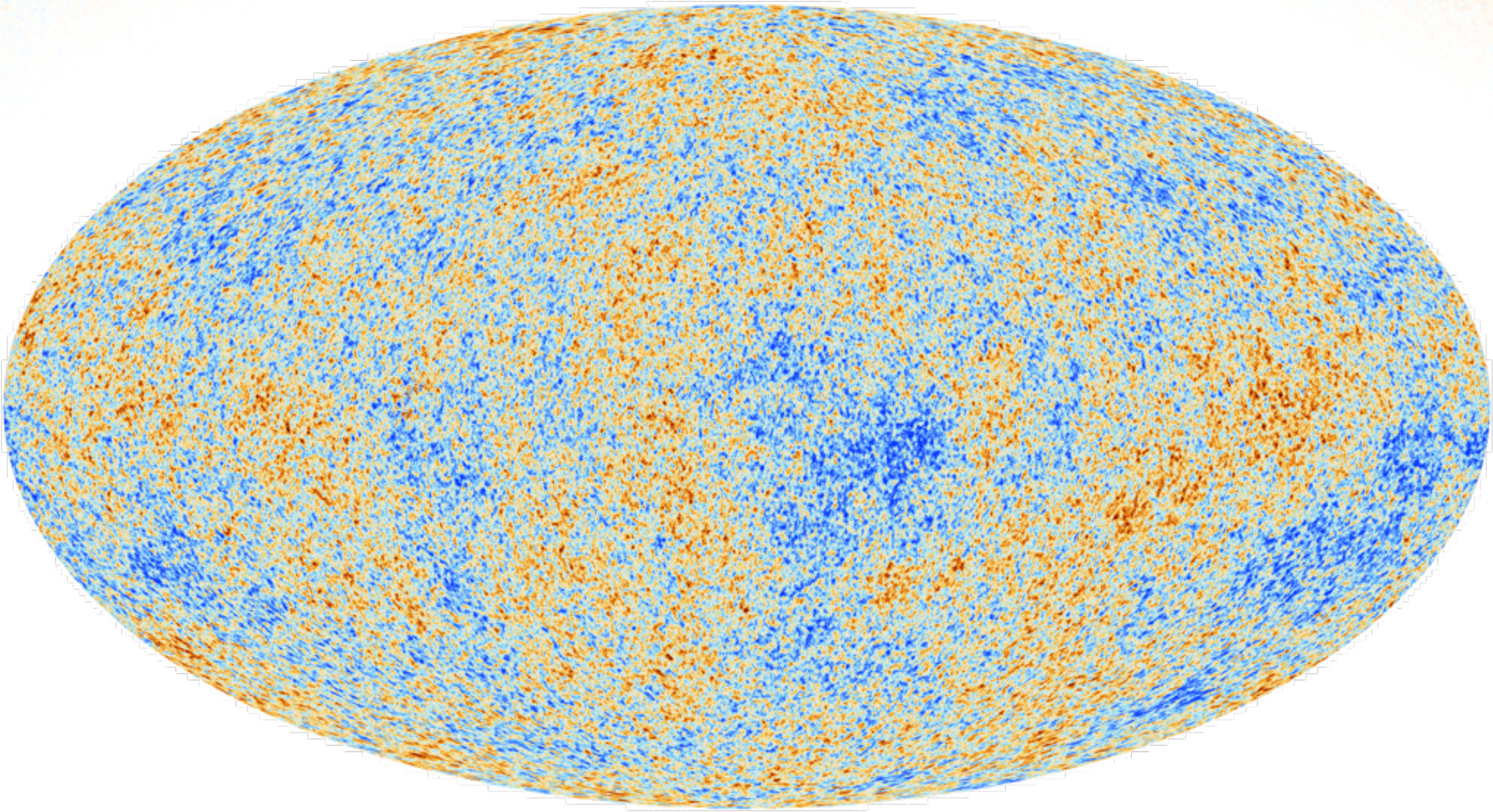
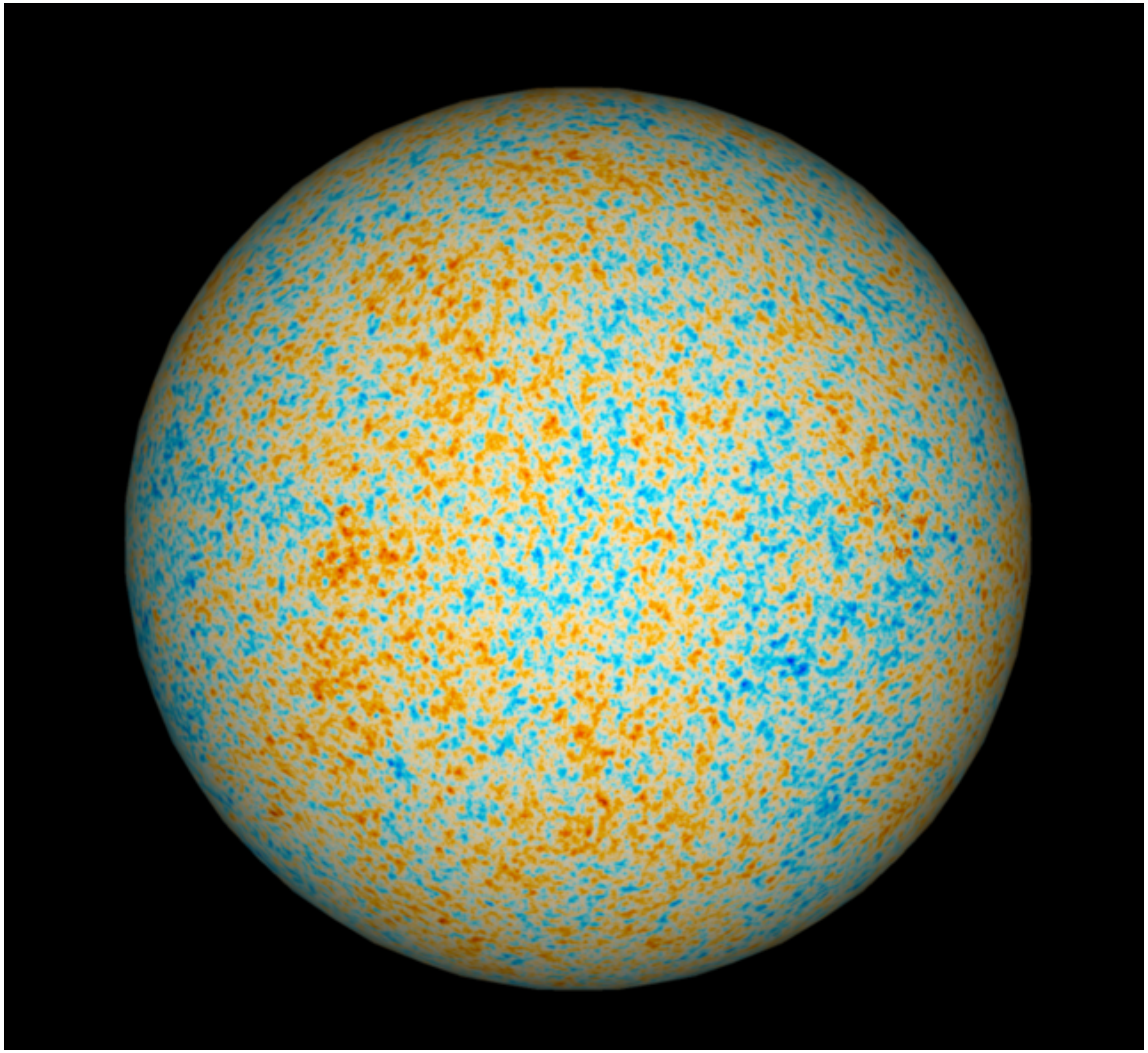
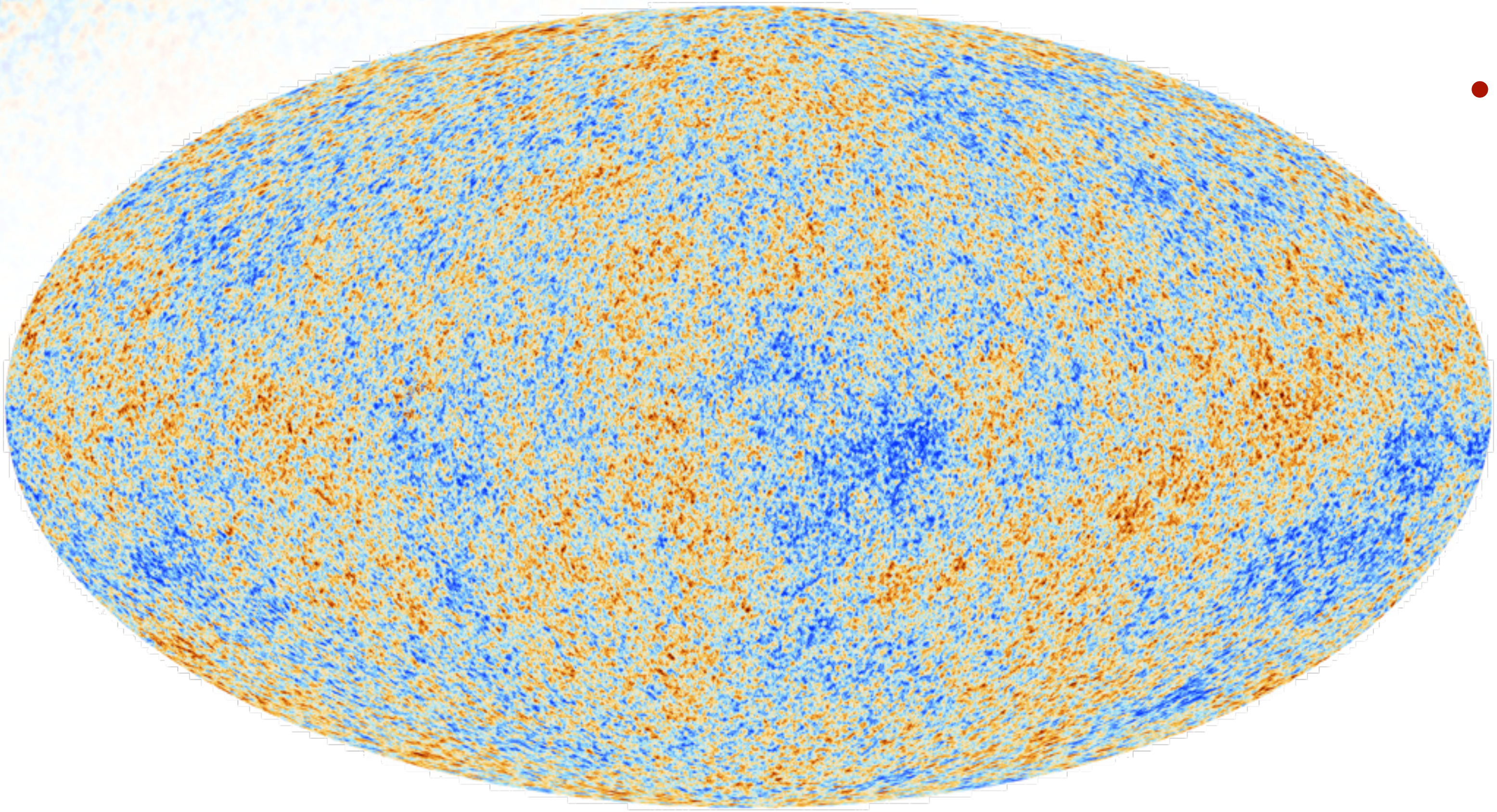
Cosmic Microwave Background



The Same, but Fancier...



Planck Cosmic Microwave Background



- Summary:
  - Color codes temperature (intensity), here ±100μK
  - Temperature traces gravitational potential at the time of recombination, when the Universe was 372 000 ±14000 years old
  - Planck has improved over WMAP by a factor of 10 in sensitivity and 2.5 in angular resolution
  - The statistical analysis of this map entails detailed cosmological information

- Several remarks come to mind:
  - Clearly random
  - But not white, i.e., you clearly see a distinctive scale
  - Looks statistically isotropic, e.g., the same characteristic size is visible everywhere
  - All these statements needs to be quantified but are highly non-trivial and have important consequences!

Statistics

- CMB anisotropy is a statistical field and one can define correlation functions and power spectra on it.
- This is similar to the density field case except that CMB anisotropy lives on the unit sphere.
- The correlation function is:

$$C(\theta) = \left\langle \Delta T(\hat{\mathbf{n}}) \Delta T(\hat{\mathbf{n}}') \right\rangle, \qquad \hat{\mathbf{n}} \cdot \hat{\mathbf{n}}' = \cos\theta$$

  (Depends on angular separation θ.)
- To define the power spectrum, we need to go to "Fourier" (i.e. spherical harmonic) space.

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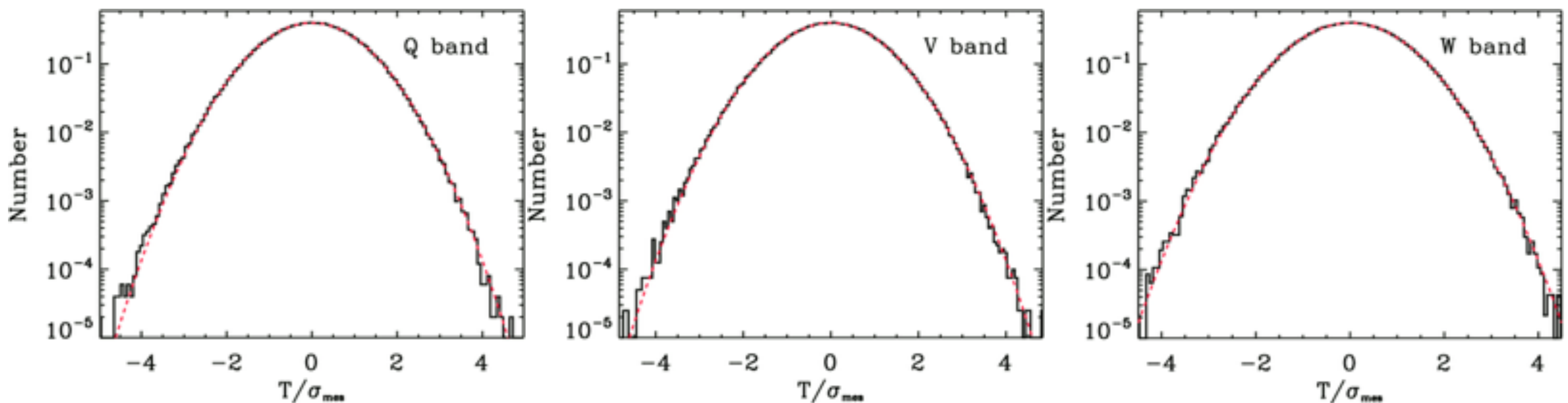
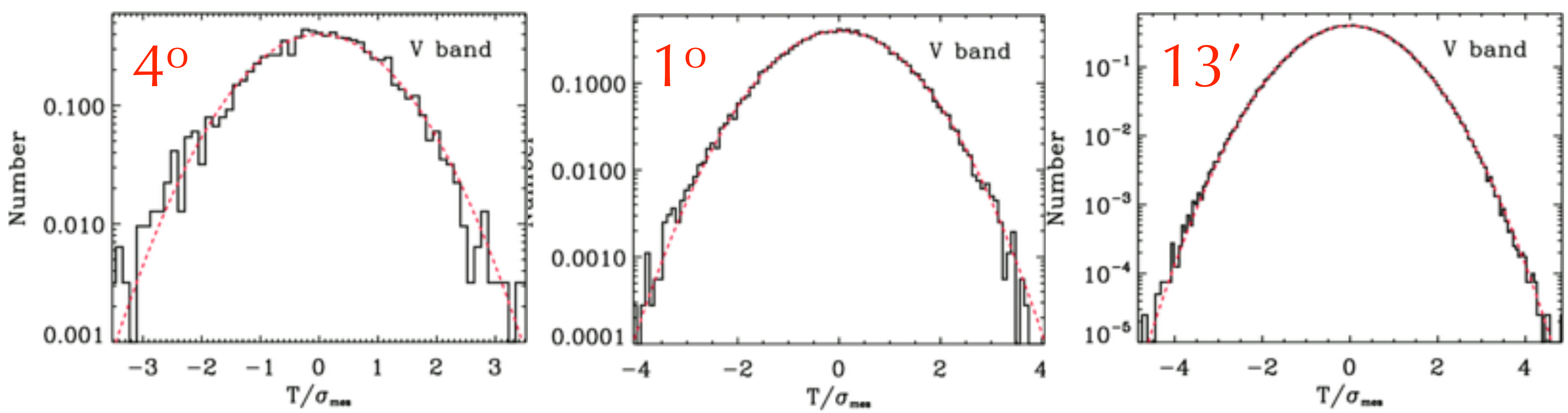
PDF of a Noise Normalized Map (WMAP V band)

Various bands



V band at various resolution



- Very Gaussian
- The CMB follow a multi-variate Gaussian distribution (up to 0.025% in power)

Angular Power Spectrum

$$T_{\rm CMB} = 2.726K$$

$$\Delta T(\theta,\phi) = T(\theta,\phi) - T_{\rm CMB}$$

$$a_{\ell m} \quad = \quad \int \frac{\Delta T(\theta,\phi)}{\mathrm{T}_{\rm CMB}}\, Y_{\ell m}(\theta,\phi)\ \mathrm{d}\Omega \qquad\qquad C_\ell \quad = \quad \langle |a_{\ell m}|^2 \rangle$$

$$\langle T(\hat{n}_1)T(\hat{n}_2)\rangle = \sum \frac{2\ell+1}{4\pi} C_\ell P_\ell(\cos\theta_{12}) B_\ell^2$$

- For a Gaussian random field, all statistical information is contained in the power spectrum, i.e., no information in phase.
- Isotropy implies no *m* dependence
- The angular power spectrum C_l is thus the right place to confront theory and measurements.

Cosmic Variance

- Limitation: since there are only 2*l*+1 multipoles a_{lm} for each *l*, can only measure their variance with accuracy

$$\frac{\sigma(C_l)}{C_l} = \sqrt{\frac{2}{2l+1}}$$

even with a perfect instrument.

- This limitation is known as cosmic variance.
- WMAP is at/near cosmic variance limitation at *l*<530. Frontier has moved to high *l* and polarization.

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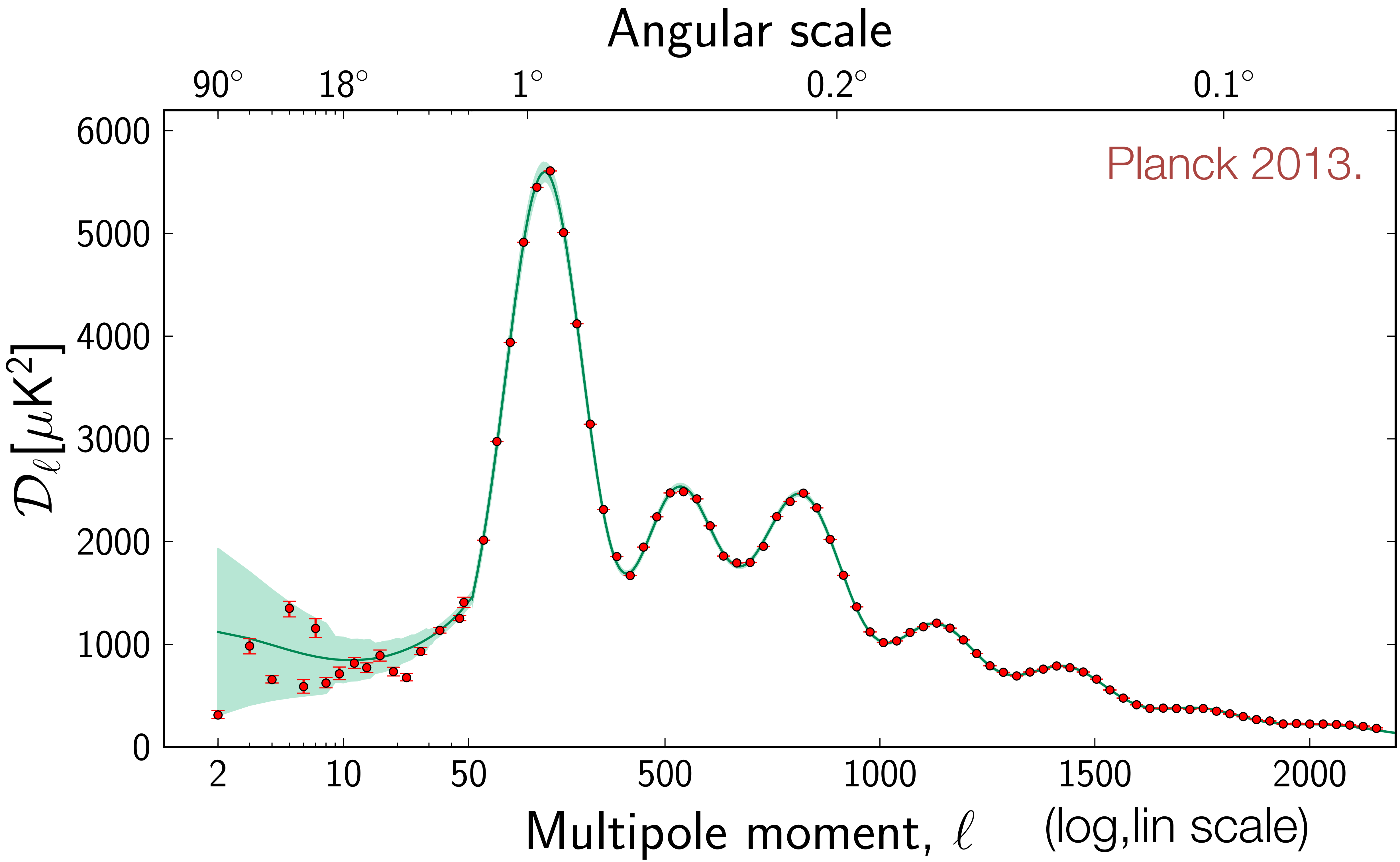
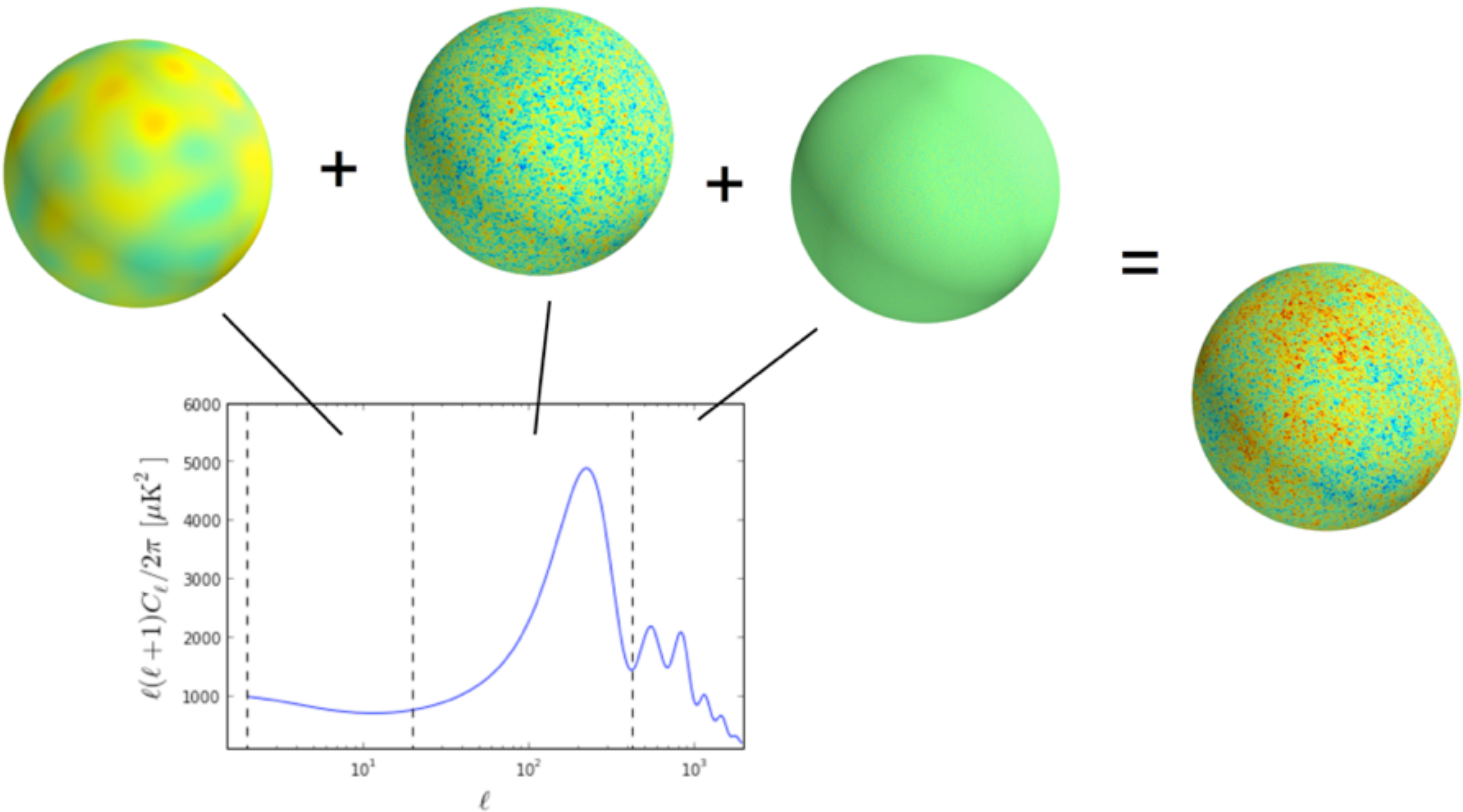
Planck CMB Angular Power Spectrum



A clear characteristic angular scale

Power Spectrum Review

$$\langle a^*_{lm} a_{lm} \rangle = C_l$$



The Use of Standard Ruler in Cosmology

- Suppose we had an object whose length is known (in meters) and we knew it as a function of cosmic epoch

- By measuring the angle (θ) subtended by this ruler (r=ΔD) as a function of redshift we map out the angular diameter distance D_A

$$\Theta = \frac{r}{D_A(z)} \qquad D_A(z) = \frac{D_L}{(1+z)^2} \propto \int_0^z \frac{dz'}{H(z')}$$

- By measuring the redshift interval (Δz) associated with this distance, we map out the Hubble parameter H(z)

$$\mathrm{c}\Delta z = H(z)\Delta D$$

- Measuring D_A allows to probe the constituents of the Universe using the Friedmann's equation

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

The CMB as a Cosmological Standard Ruler

- At early times, the Universe was hot, dense and ionized. Photons and baryons were tightly coupled by Thomson scattering.
- The mean free path of photons is much smaller than the horizon and allows fluid approximation

- Initial fluctuations in density and gravitational potential drive acoustic waves in the fluid: compressions and rarefactions with $\delta_{photons} \propto \delta_b$
- These perturbations show up at temperature fluctuations in the CMB

- Since $\rho \propto T^4$ a harmonic wave will be for one comoving mode k

$$\Delta T \simeq \delta\rho_\gamma^{1/4} \simeq A(k) cos(kc_s t)$$

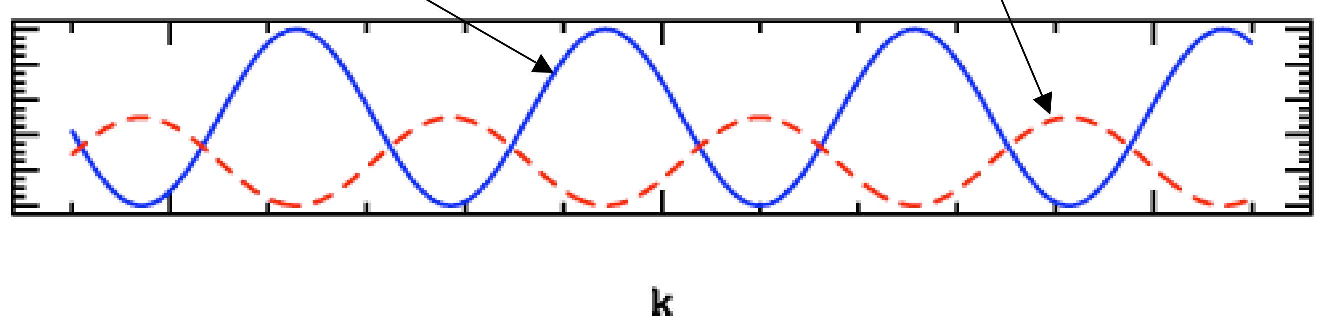
- Plus a component due to the velocity of the fluid (Doppler effect)

Courtesy M. White

The CMB as a Standard Ruler

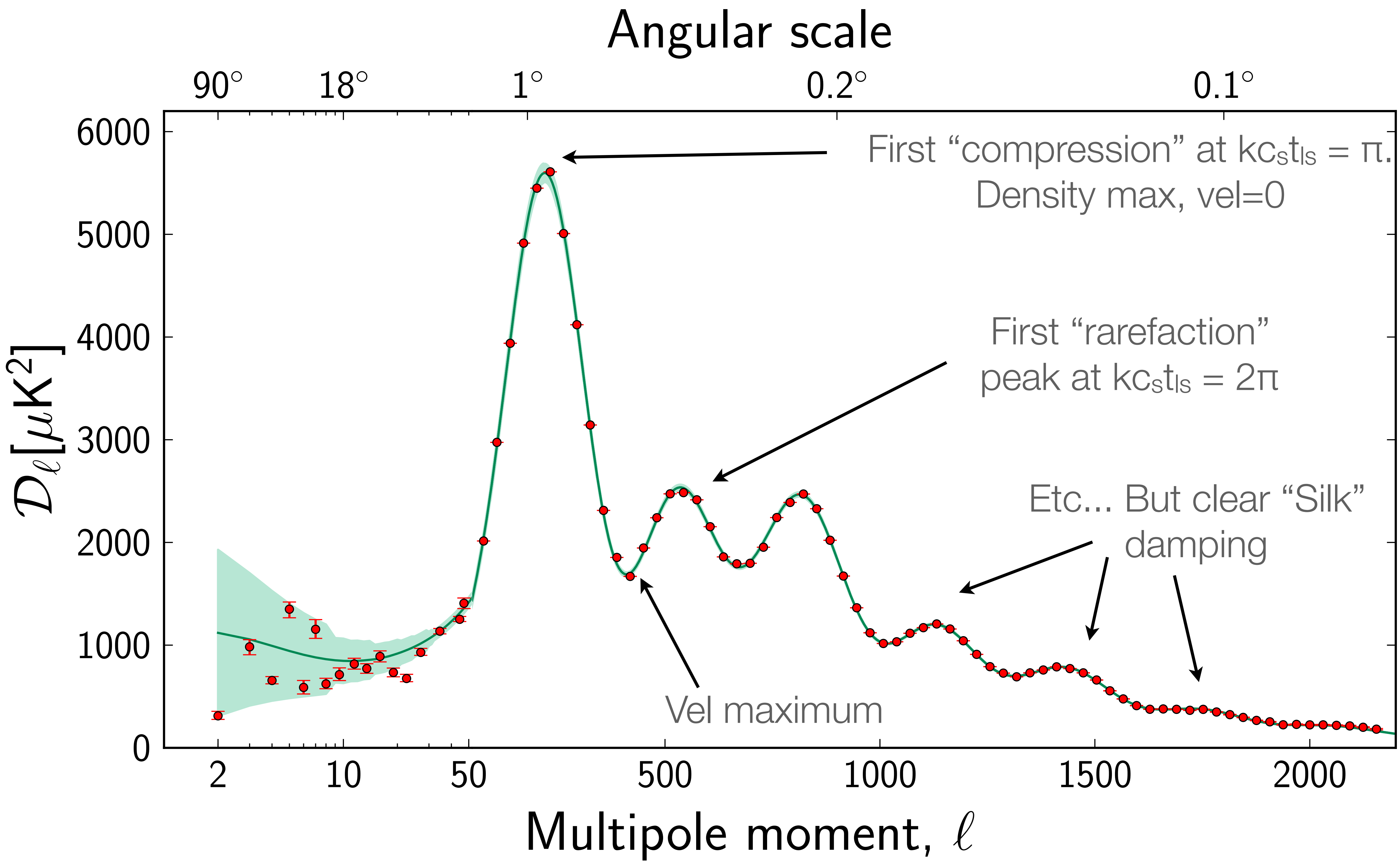
- A sudden recombination decouples the radiation and matter giving us a snapshot of the fluid at last scattering

$$(\Delta T)^2_{\mathrm{ls}} \sim \cos^2(kc_s t_{\mathrm{ls}}) + \text{velocity terms}$$



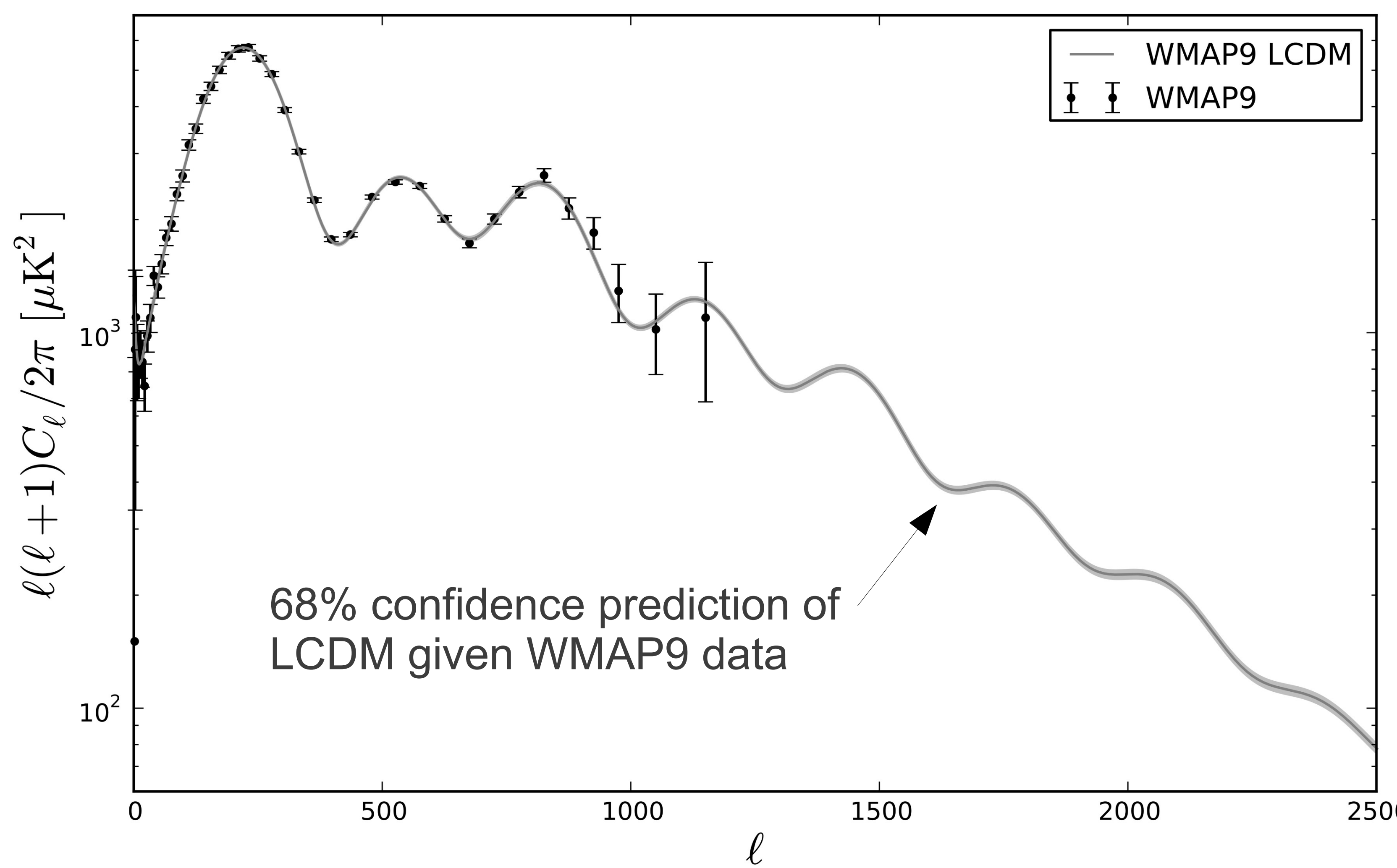
- The fluctuations are projected on the sky as $\lambda{\sim}D_A(l_{sound})\theta$ or $l{\sim}k_{recombination}\, l_{sound}$

Acoustic Scales Seen in the CMB

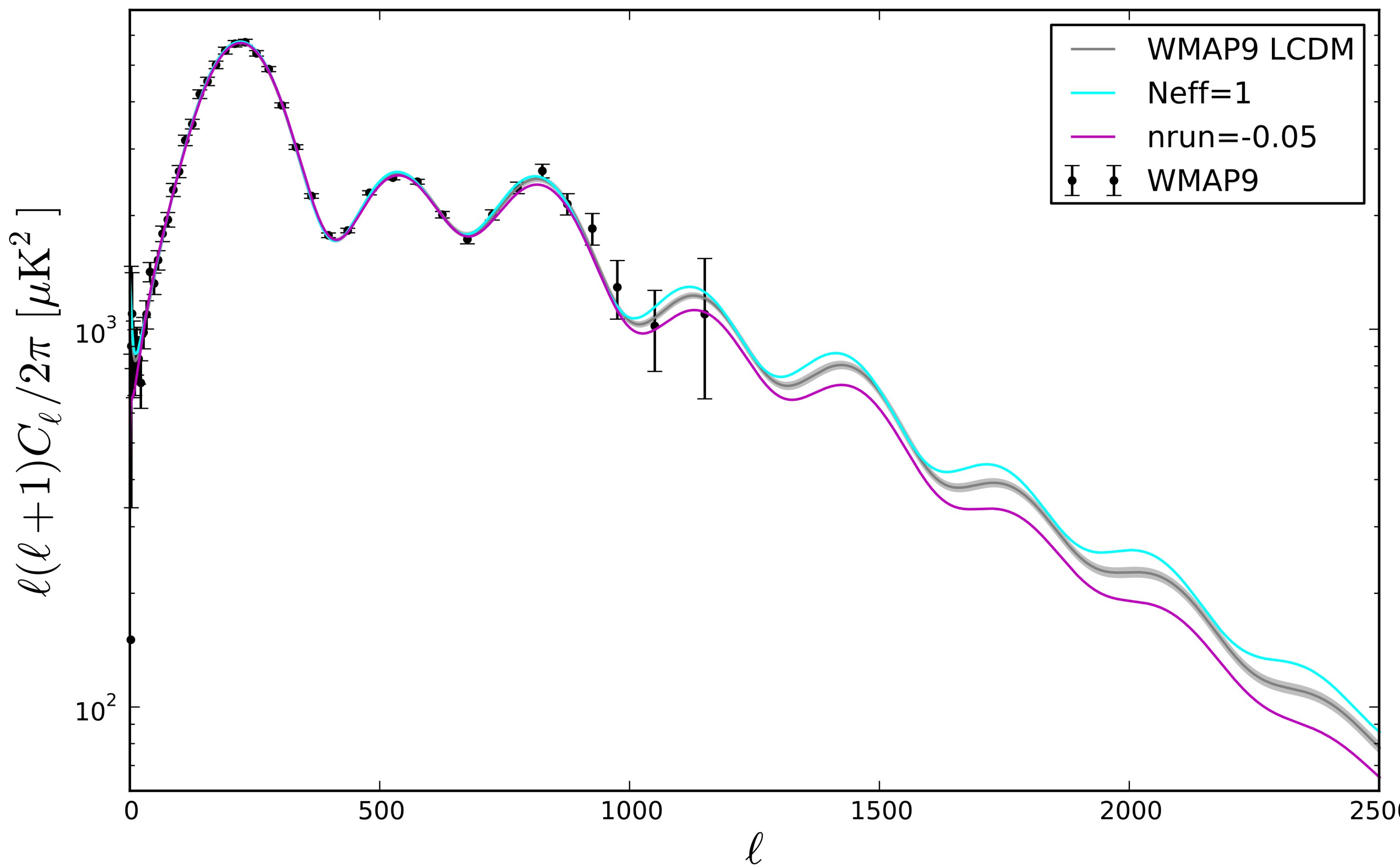


Acoustic scale is set by the sound horizon at last scattering, $s = c_s t_{ls}$

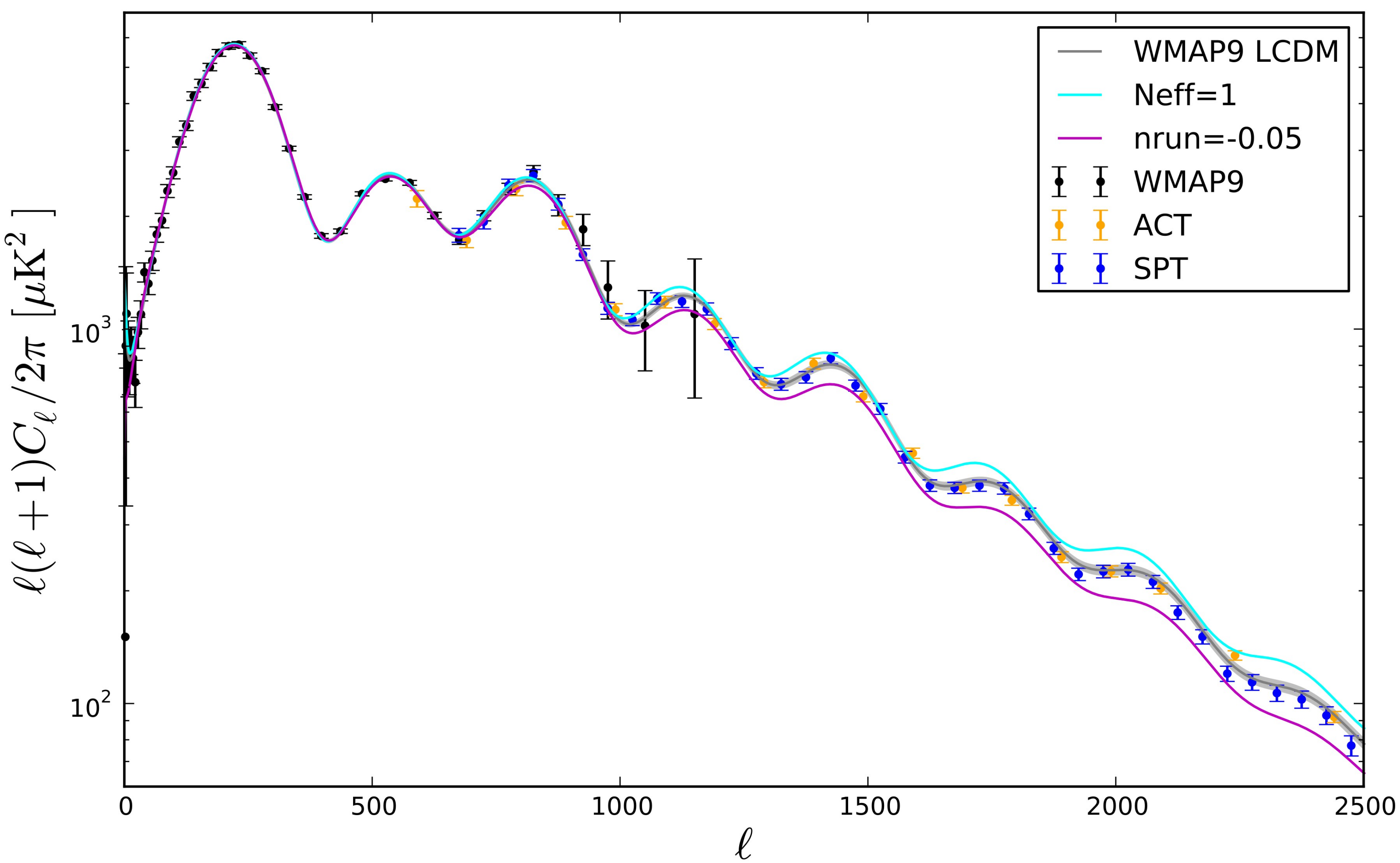
LCDM Predictions are VERY Accurate



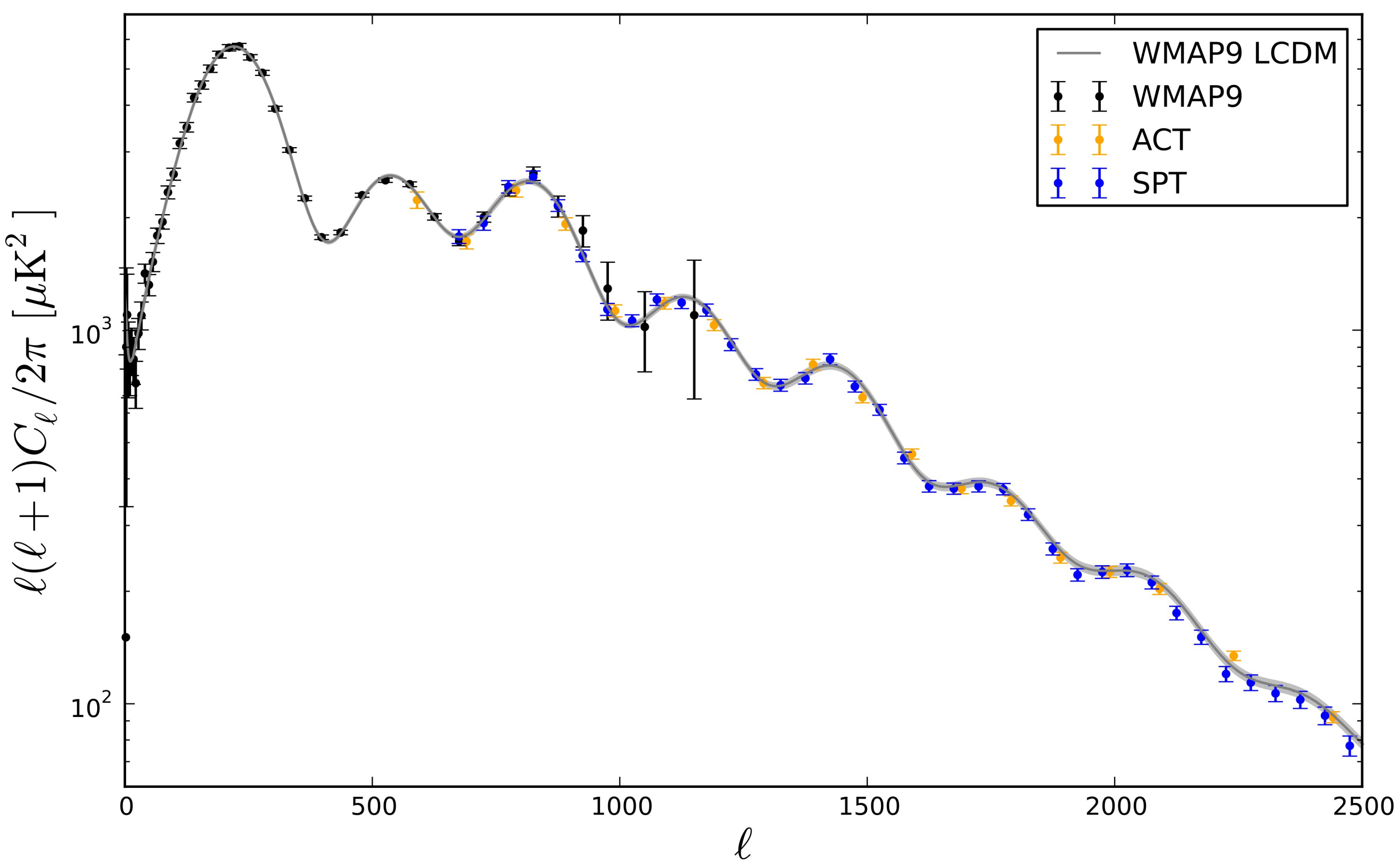
LCDM Predictions are VERY Accurate



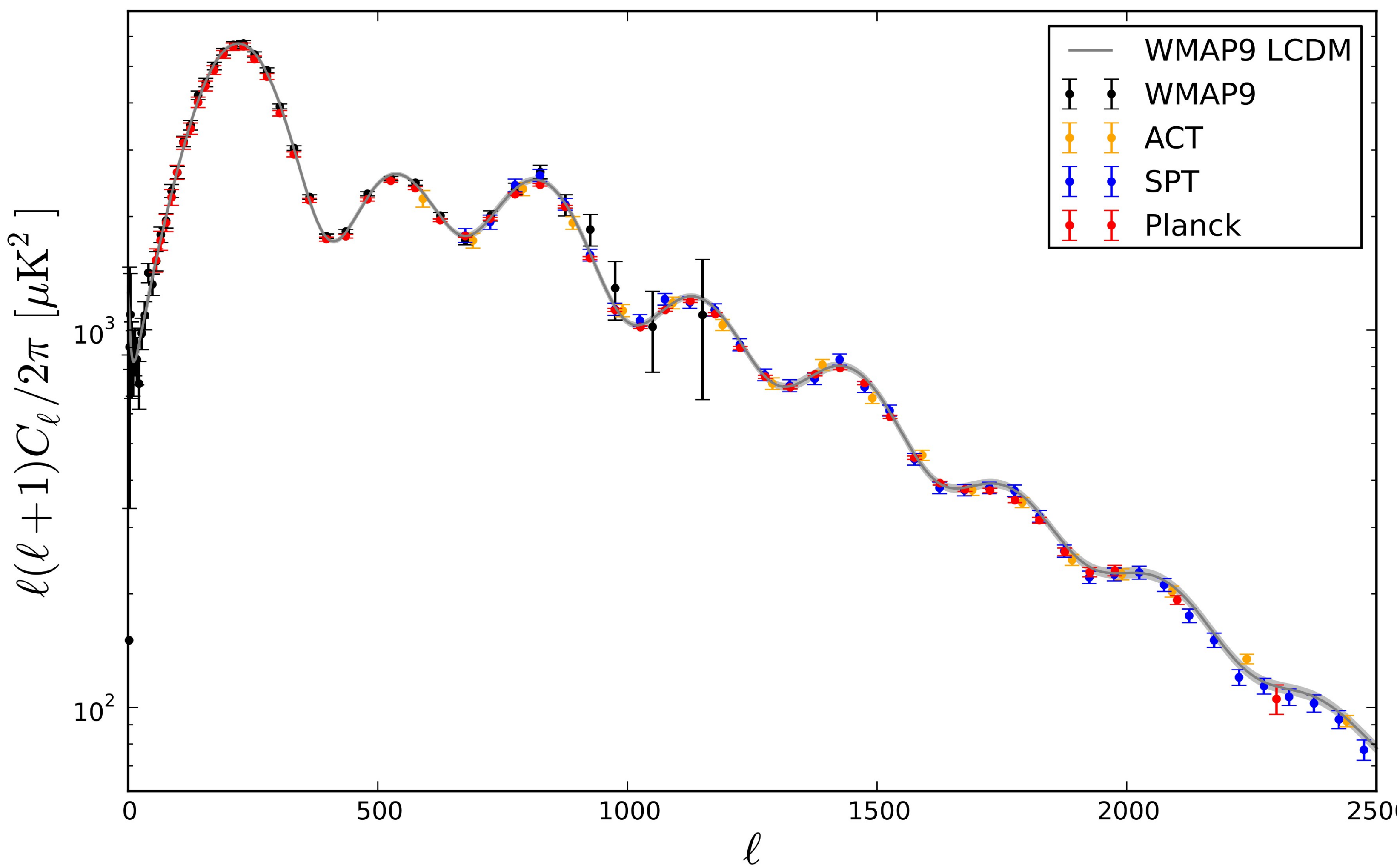
LCDM Predictions are VERY Accurate



LCDM Predictions are VERY Accurate

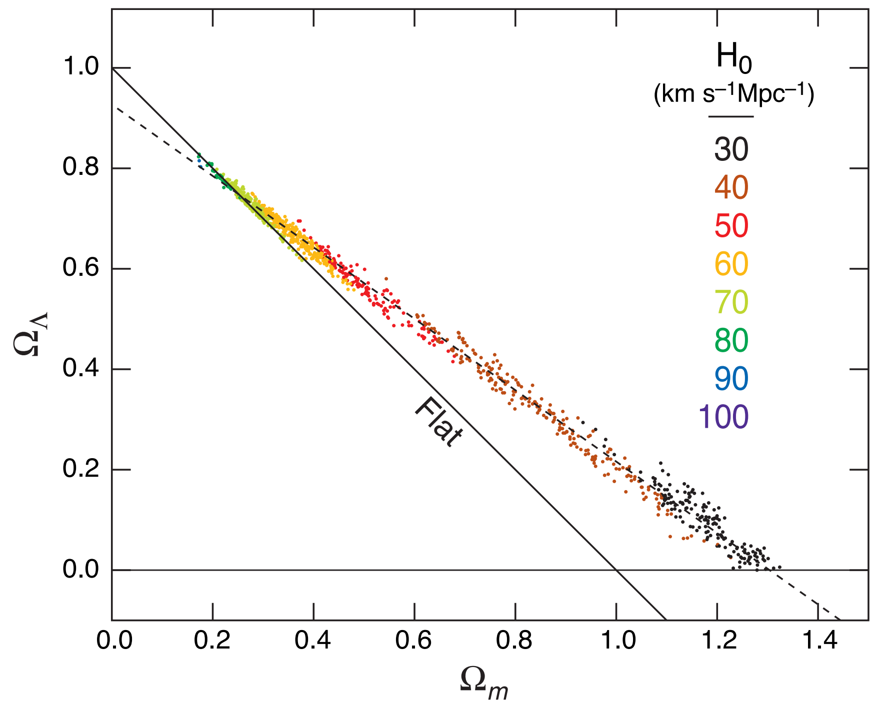


LCDM Predictions are VERY Accurate

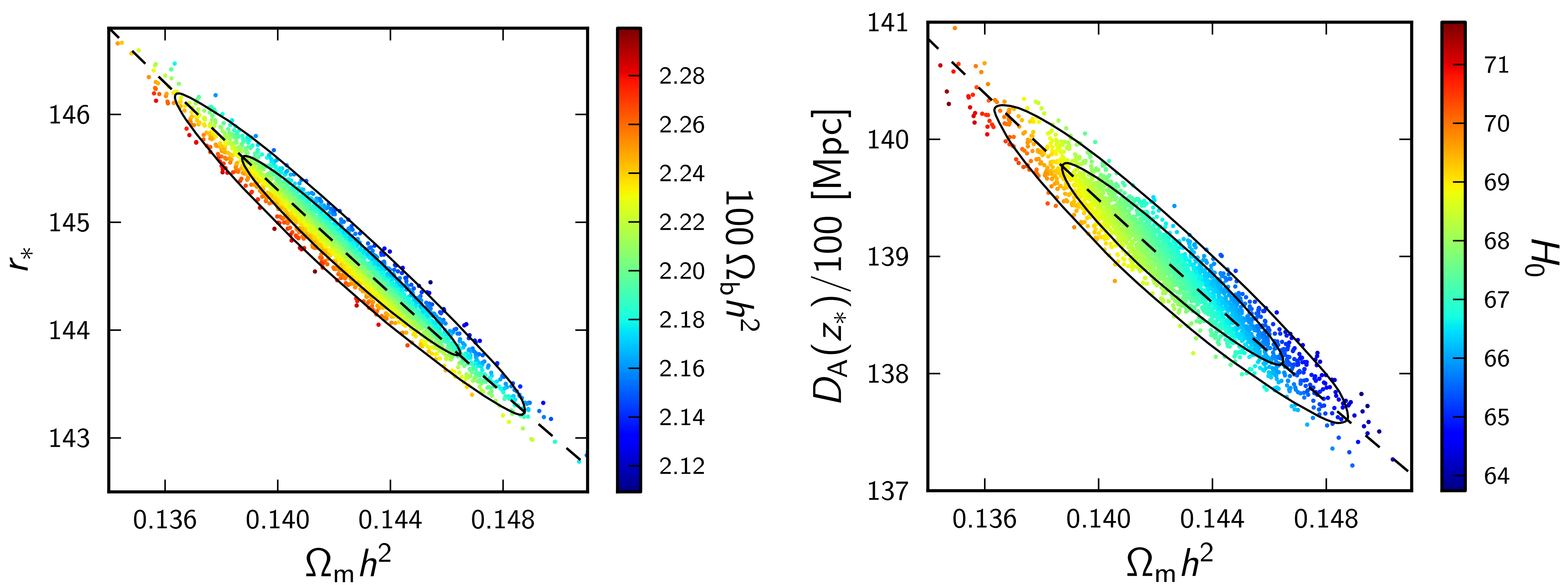


This accuracy demonstrates the power of CMB where accurate linear predictions are possible

The Angular Diameter Degeneracy



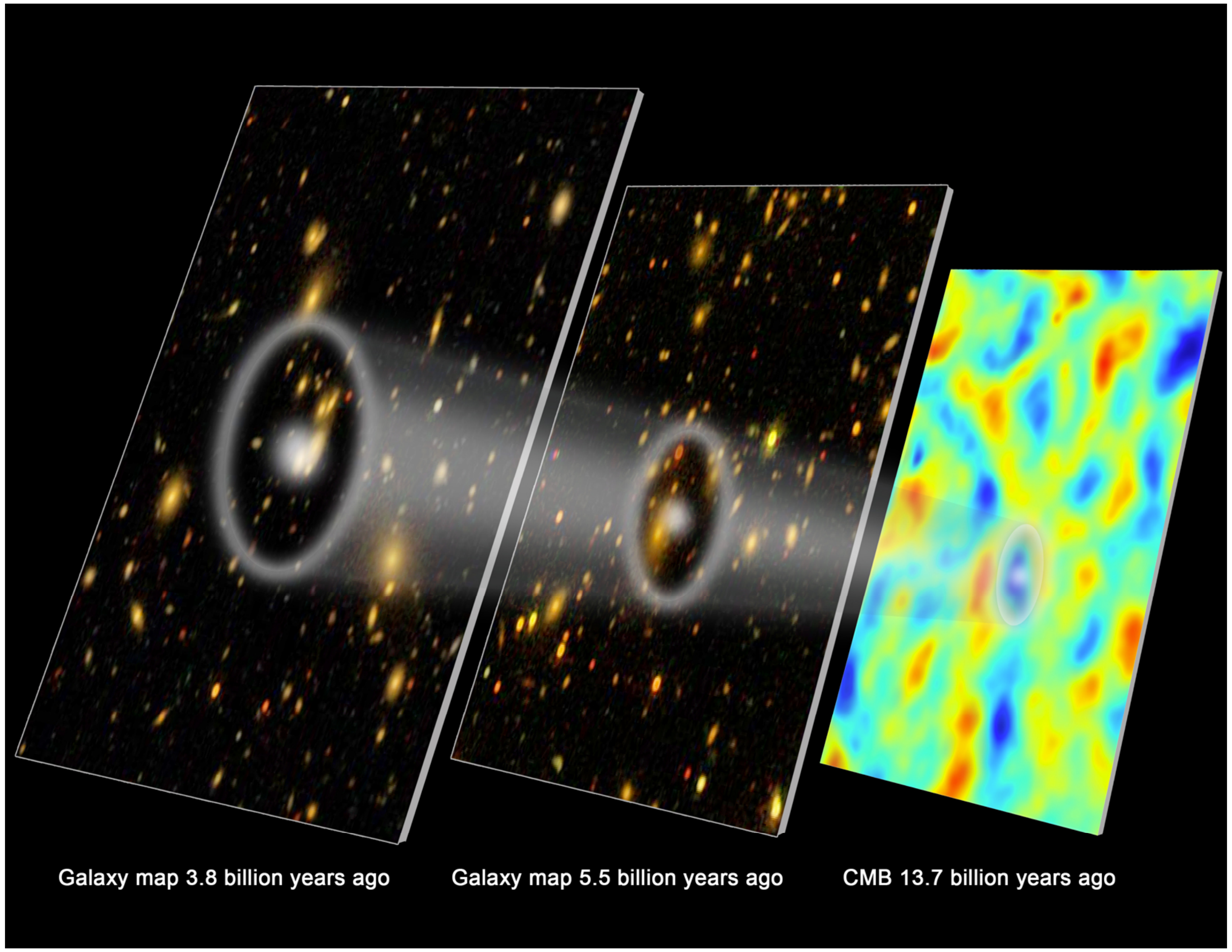
WMAP 3 yrs



Planck 2013. XVI. Cosmological Parameters

The Key Number

- Not coincidentally, the sound horizon is extremely well determined by the structure of the acoustic peaks in the CMB



- Planck: $\theta_s(a=9.166 \times 10\text{-}4) = (0.59672 \pm 0.00038)$ deg (0.1% at 1σ!)
- SDSS-BOSS: $\theta_s(a=0.64) = (4.19 \pm 0.07)$ deg (1.7%)

Courtesy M. White

Planck + Baryon Acoustic Oscillations

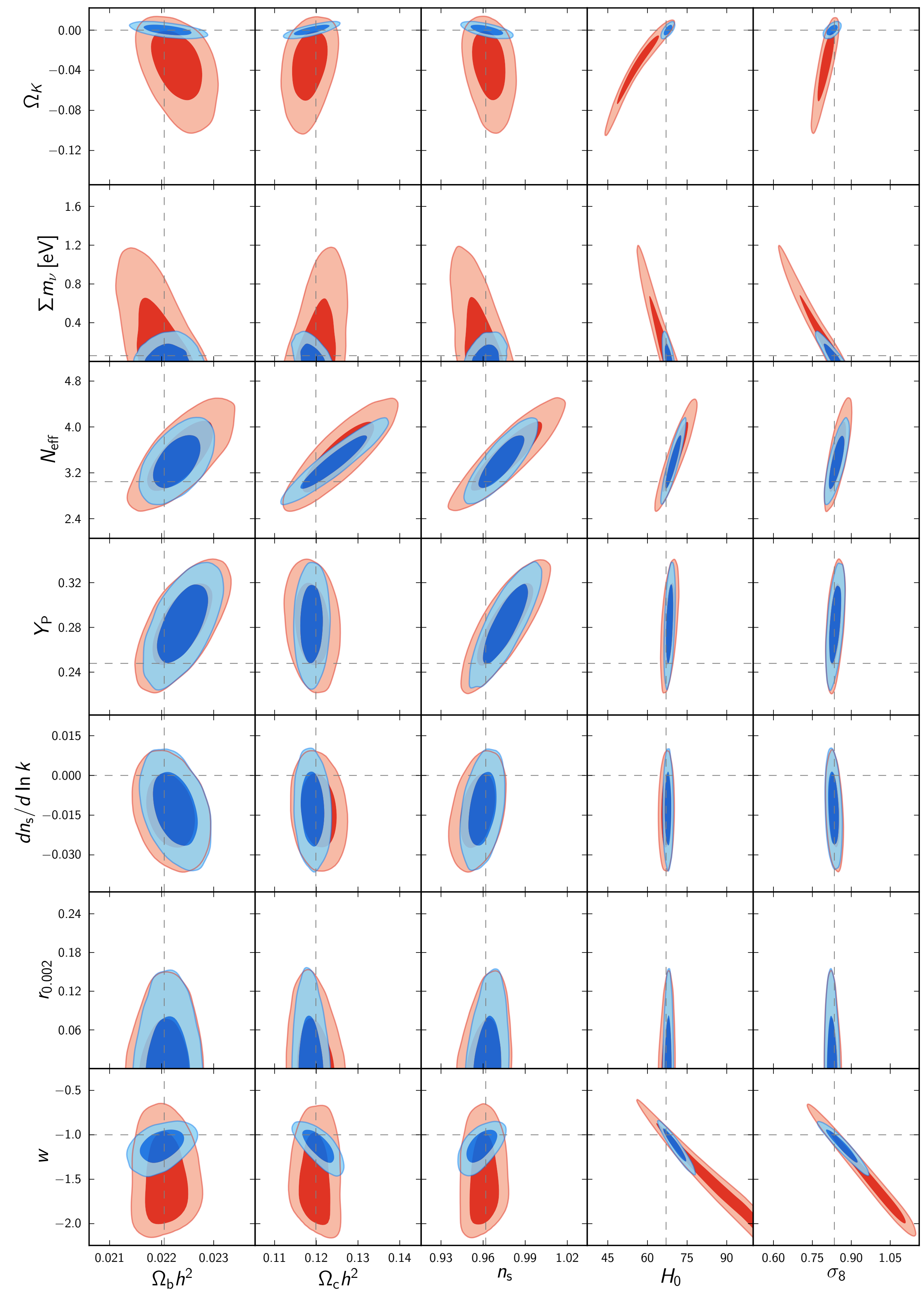
- Measuring explicitly D_a as a function of z allows to break the intrinsic "D_a-degeneracy"

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

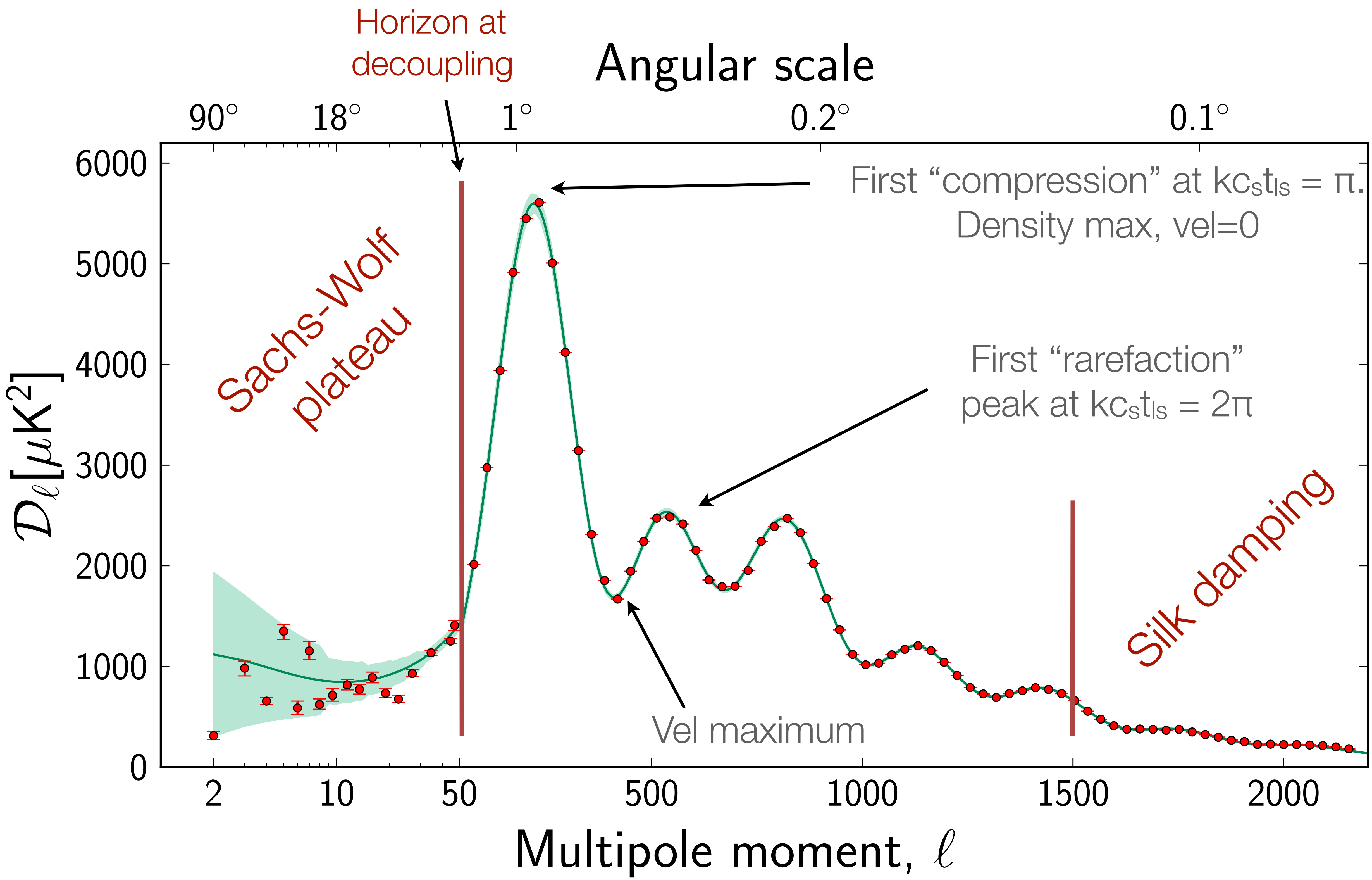
- Here, constraining single parameter extension of LCDM model
- The use a compilation of current BAO data illustrates clearly the power of this combination.

Red: Planck alone

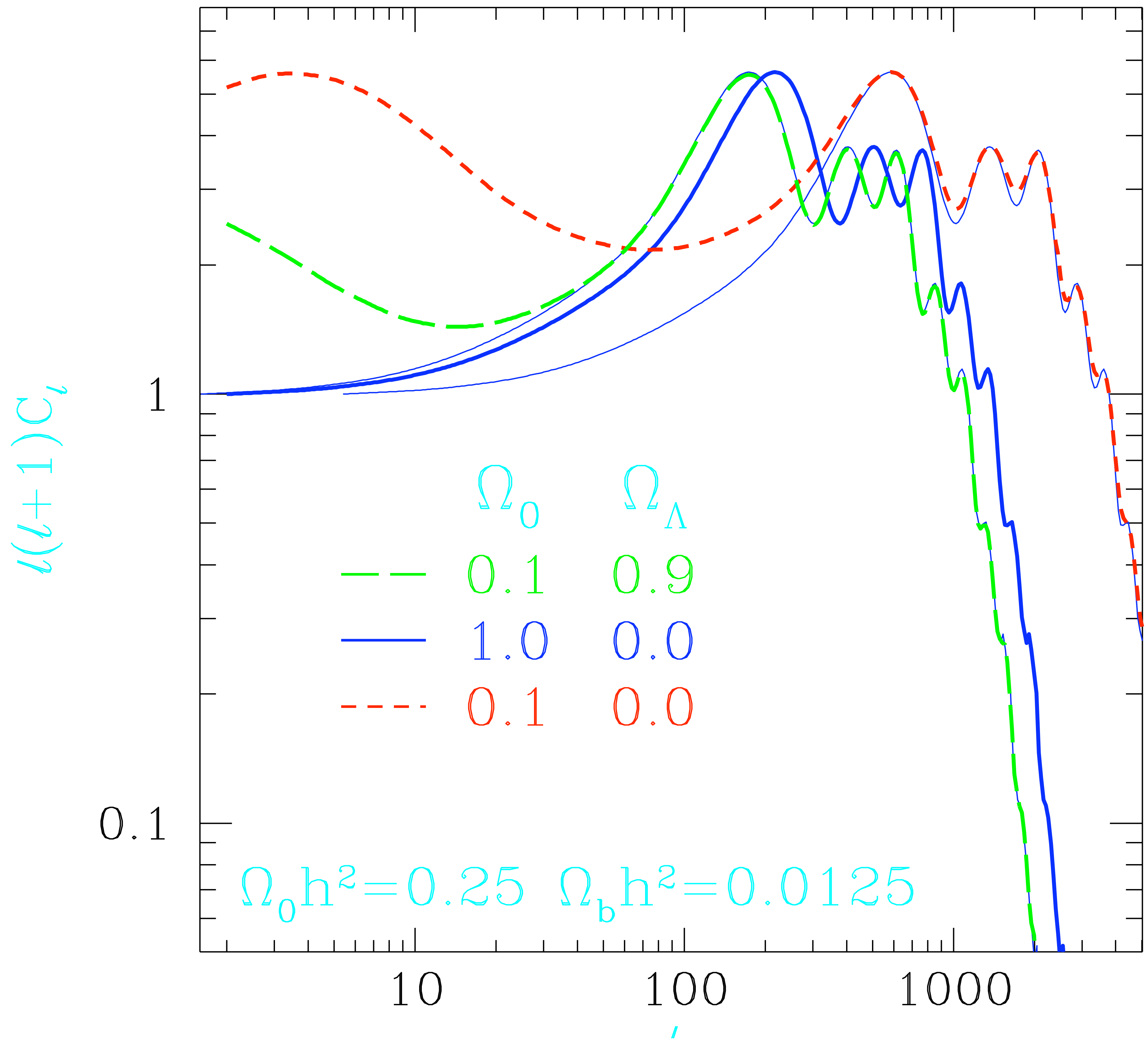
Blue: Planck + BAO



More than Acoustic Scales Seen in the CMB

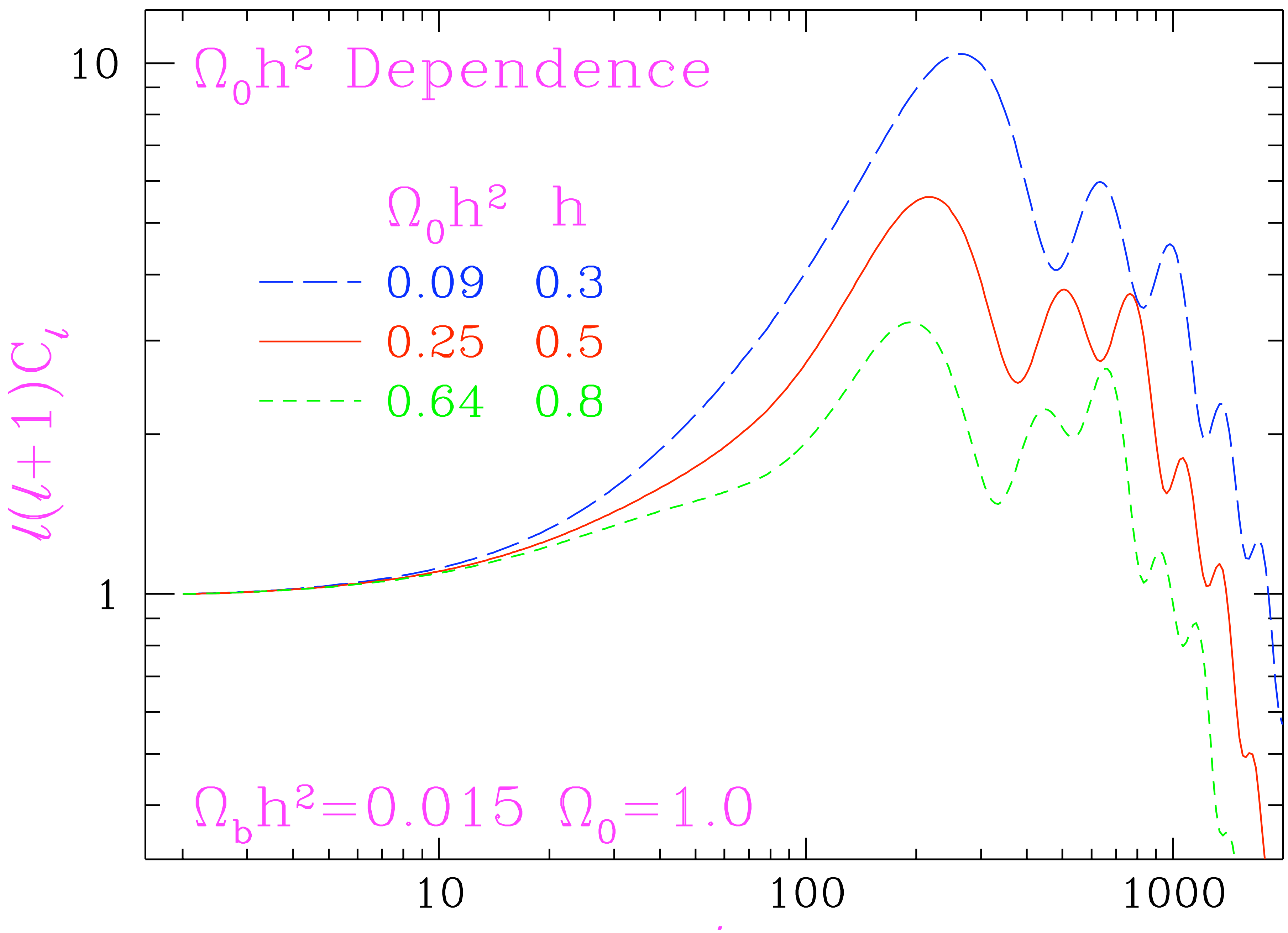


Flat → Open: Peak shifts to the right



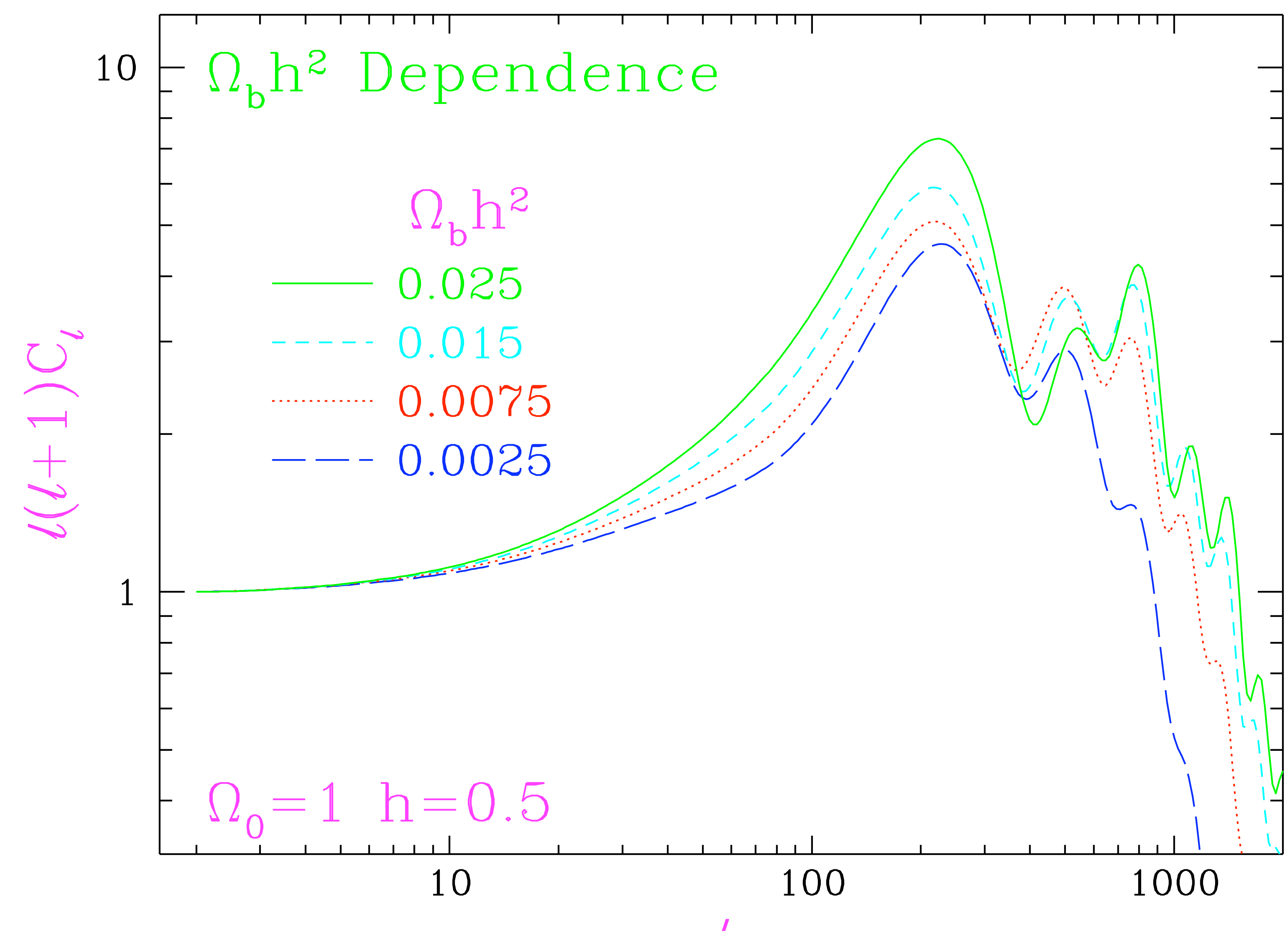
Wayne Hu's page

Varying Matter Density



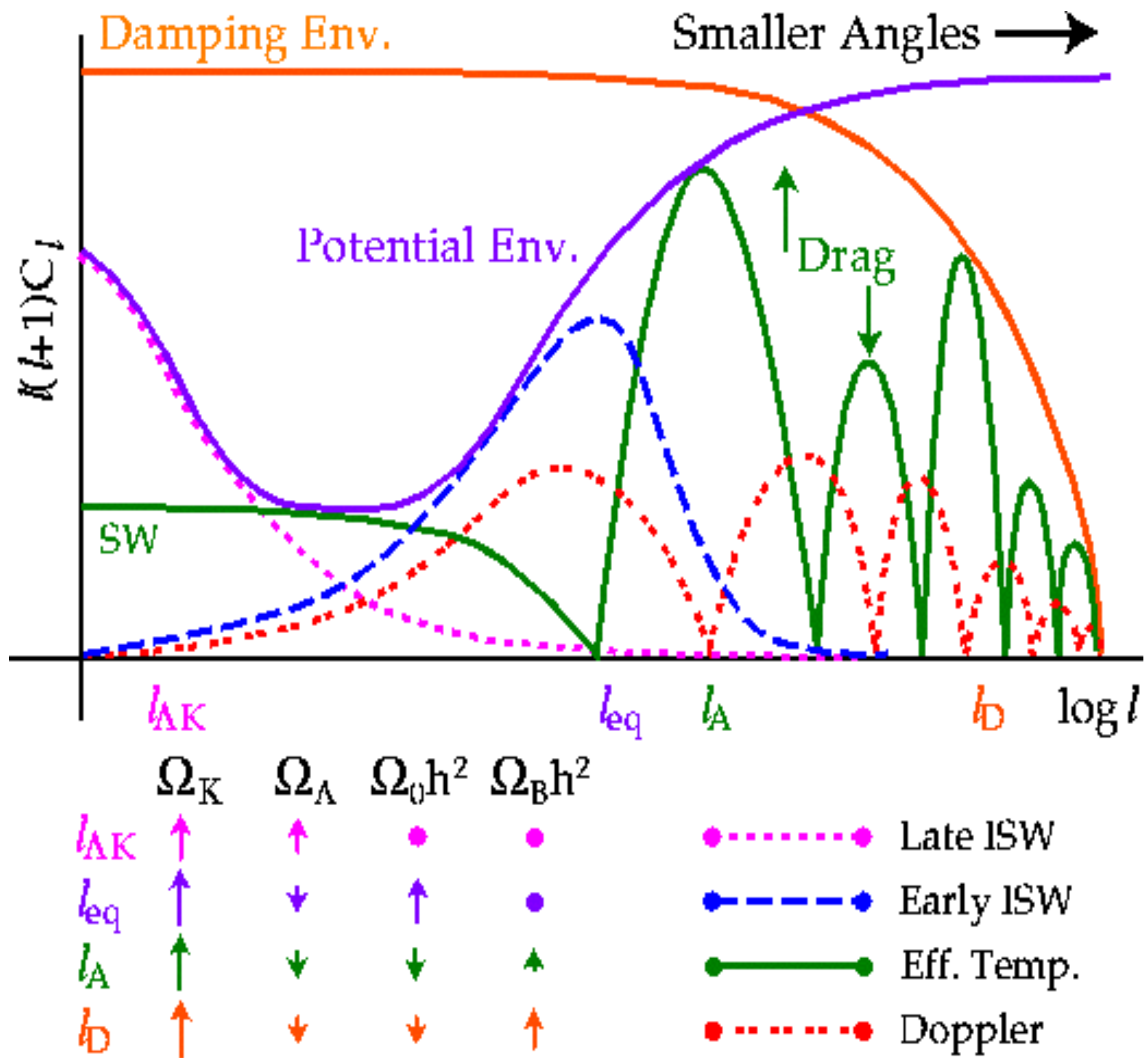
Wayne Hu's page

Varying Baryon Density

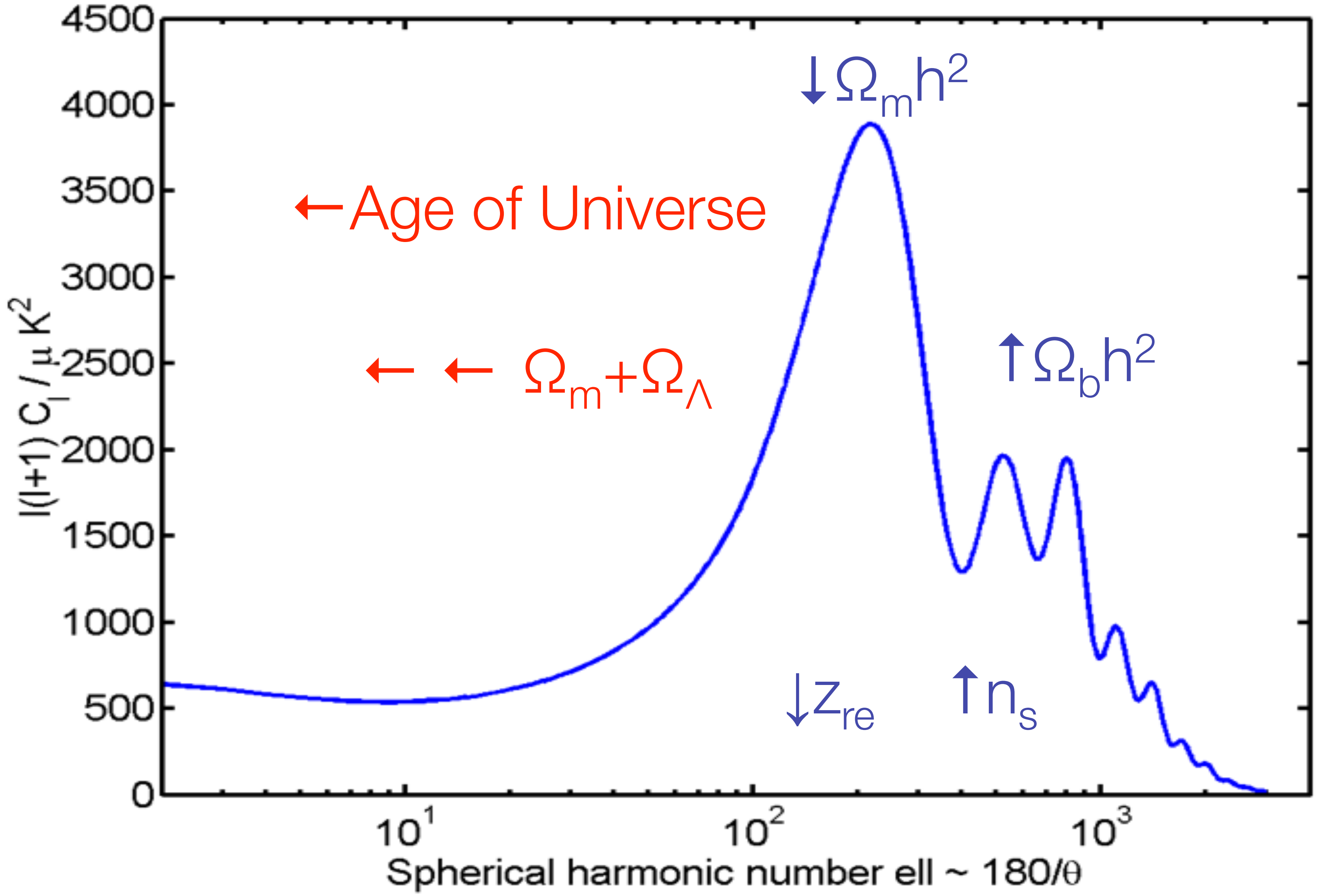


Wayne Hu's page

CMB Phenomenology



CMB Cheat Sheet



Conclusions

- Acoustic oscillations in the sky enable cosmological standard rulers across cosmic times.
- The linear physics at play at the time of recombination makes the CMB the perfect cosmological probe ("How can you study anything else?!", *C. Lawrence*).
- It points us towards a "standard" LCDM model
- And there is more to it:
  - The CMB is polarized
    - Probe of reionization *and* Inflation.
  - The CMB could be mildly non-Gaussian
    - Probe of Inflation *and* low-z Universe.
  - The microwave sky contains other cosmological signatures:
    - The Sunyaev-Zel'dovich signal.
    - The lensing of the CMB.
    - The potential mild CMB non-Gaussianity.
    - The Cosmic Infrared Background (tomorrow).
    - Anomalies (?)
    - What *you* will find!

FIN