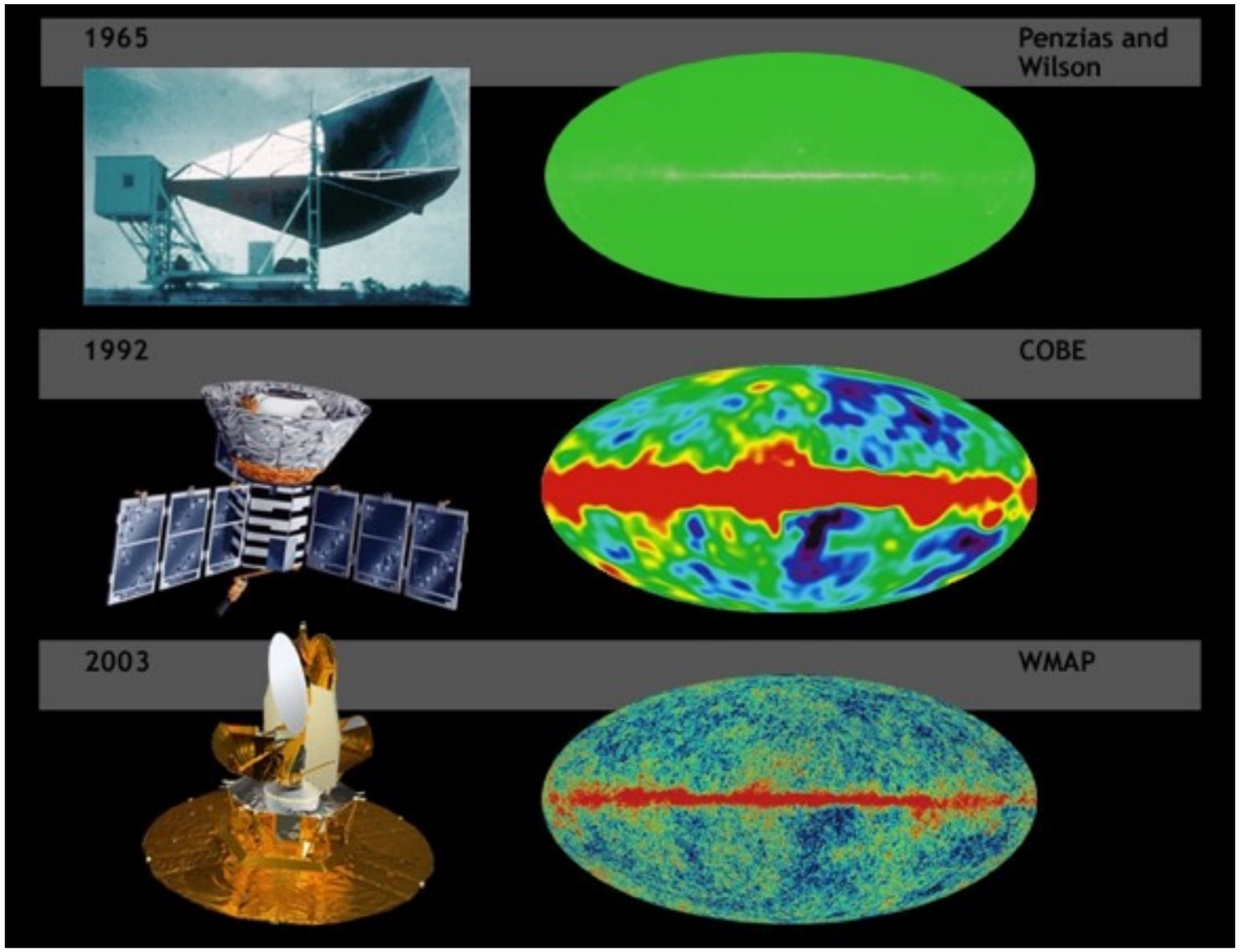
OBSERVATIONAL COSMOLOGY

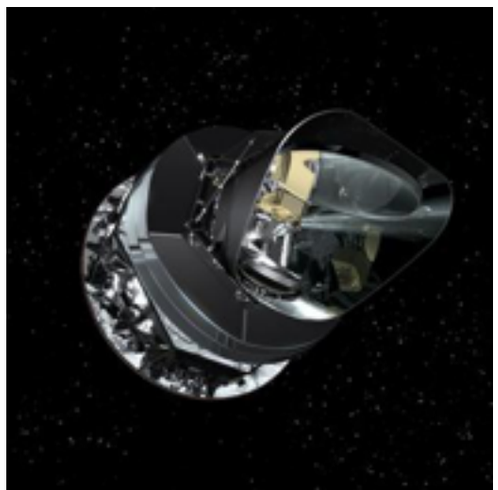
The Cosmic Microwave Background

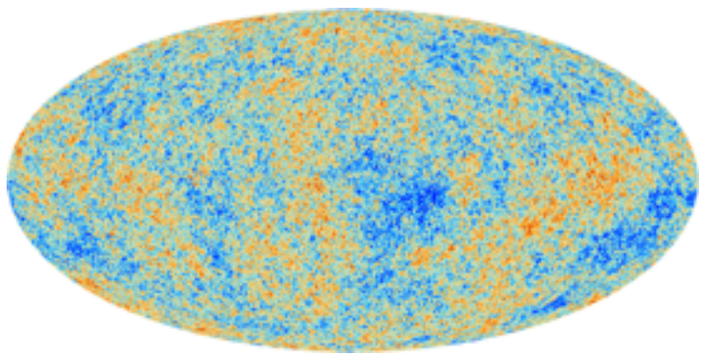
Cosmic Microwave Background (CMB)



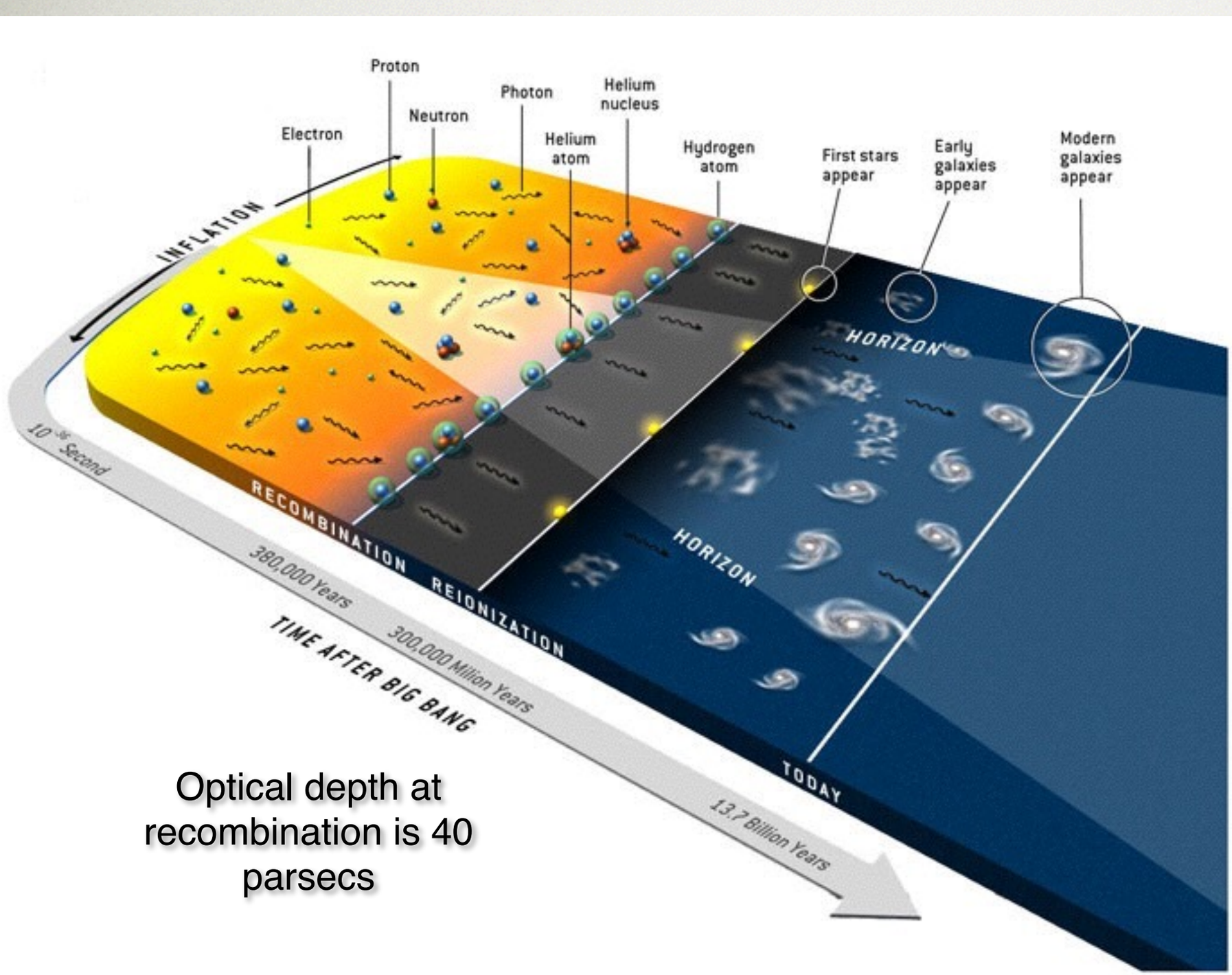
2009

Planck





The history of the Universe



Optical depth at recombination is 40 parsecs

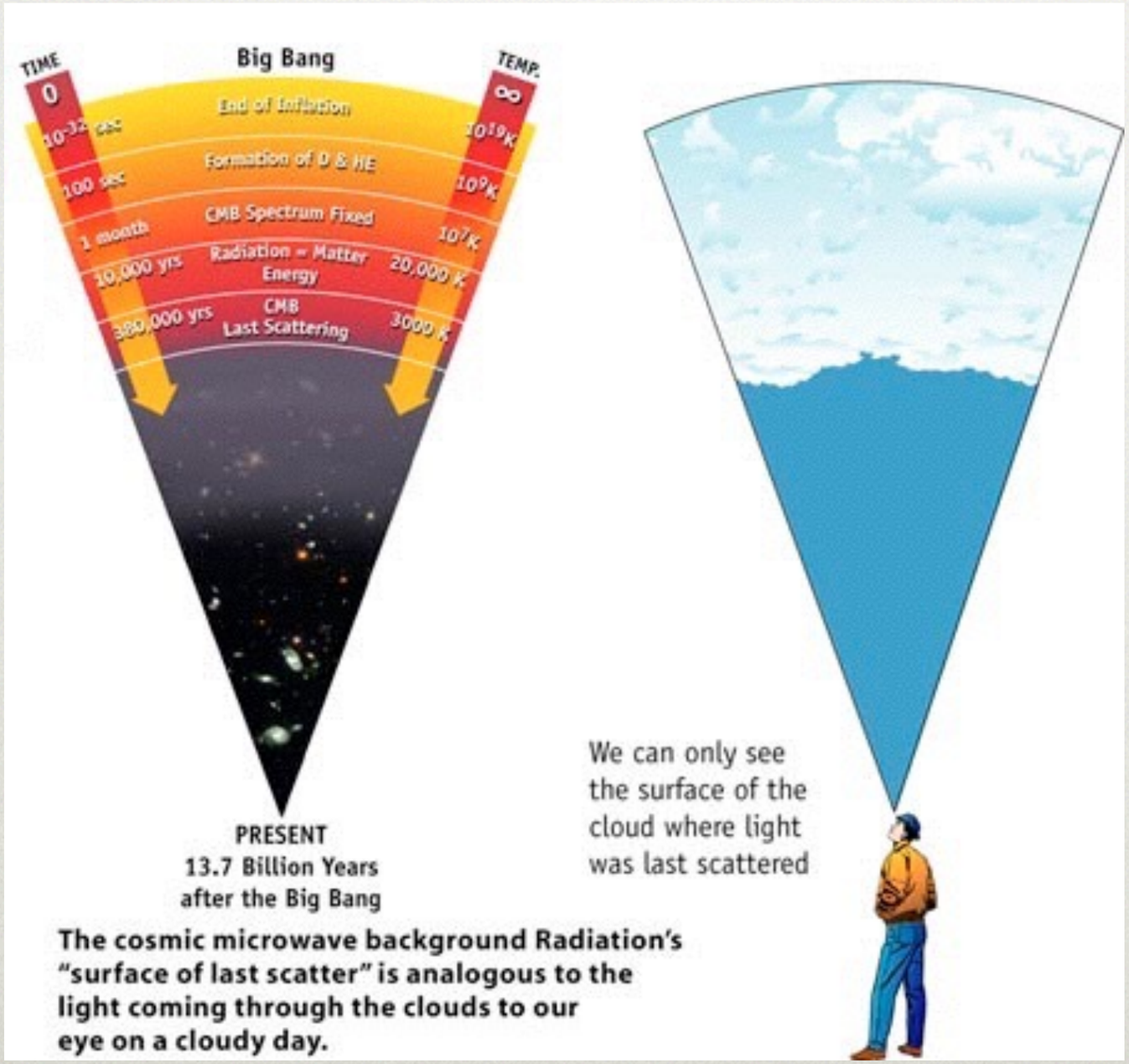
Universe is hot
Electrons are free
Light scatters off electrons

Until ~300,000 years after BB
CMB production

Universe is cooler
e^- and p^+ form hydrogen
Light travels freely

Hu & White 2004

Looking back in time



Optical depth at recombination is 40 parsecs

WMAP

Why Microwave?

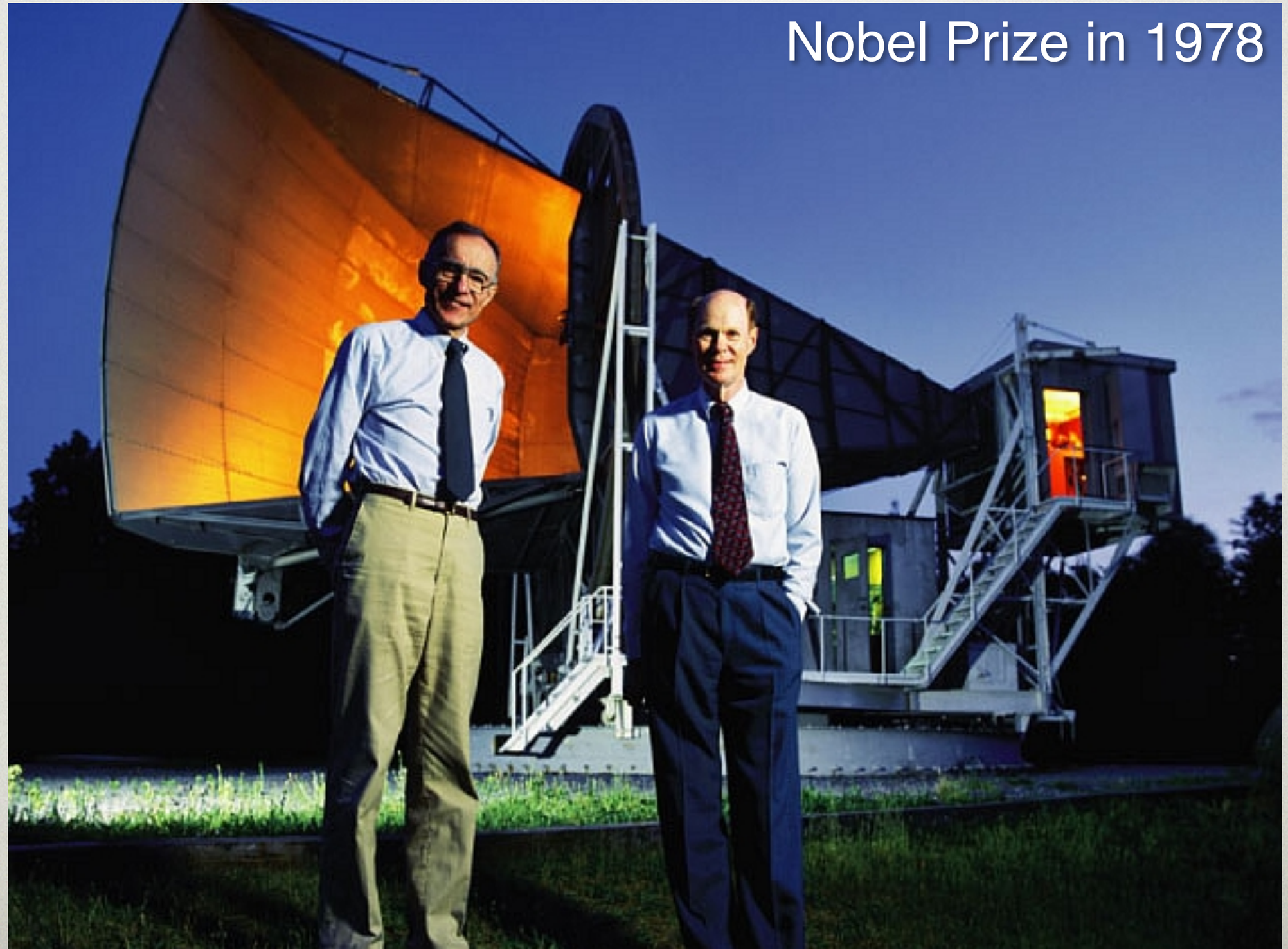
- Universe was ~ 3000° K at 380,000 yr
- Full of visible light (~μm)

- Universe is expanding
- Causes light to change wavelength

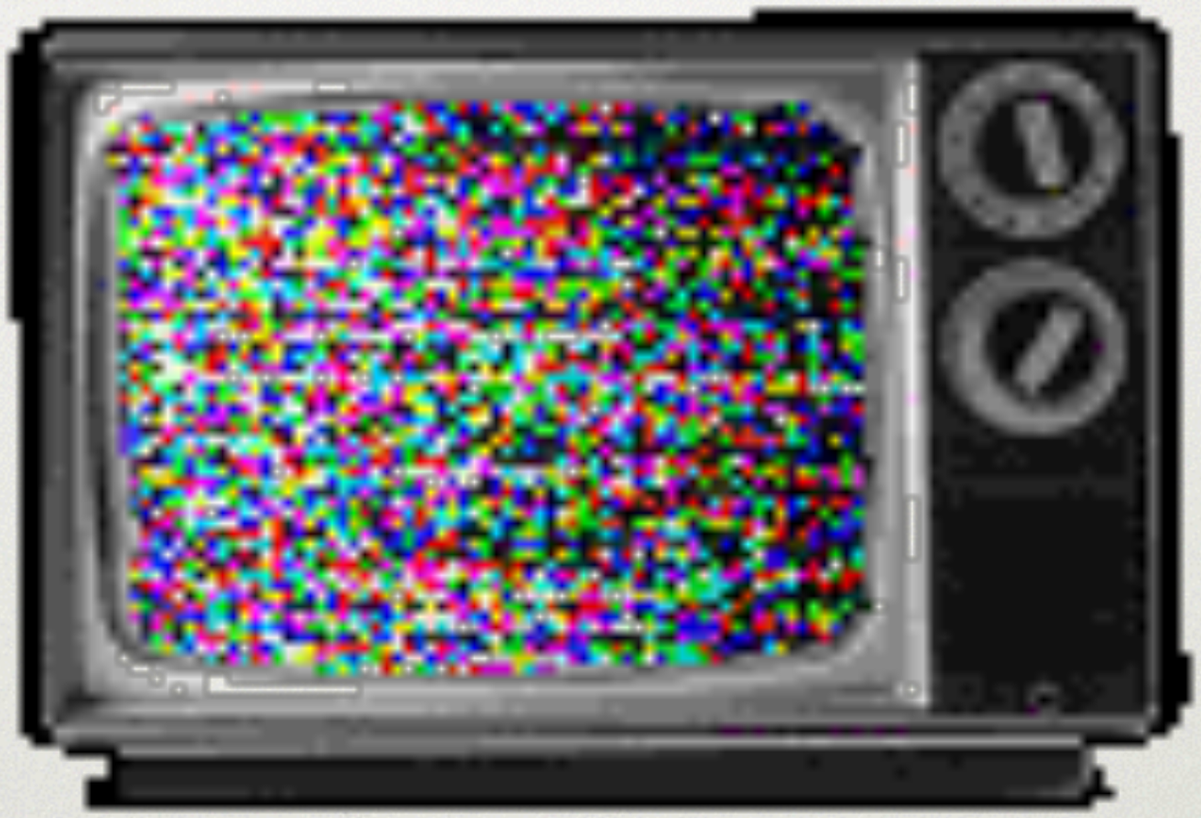
- Visible light becomes microwaves (~cm)

History of CMB observations

1964:



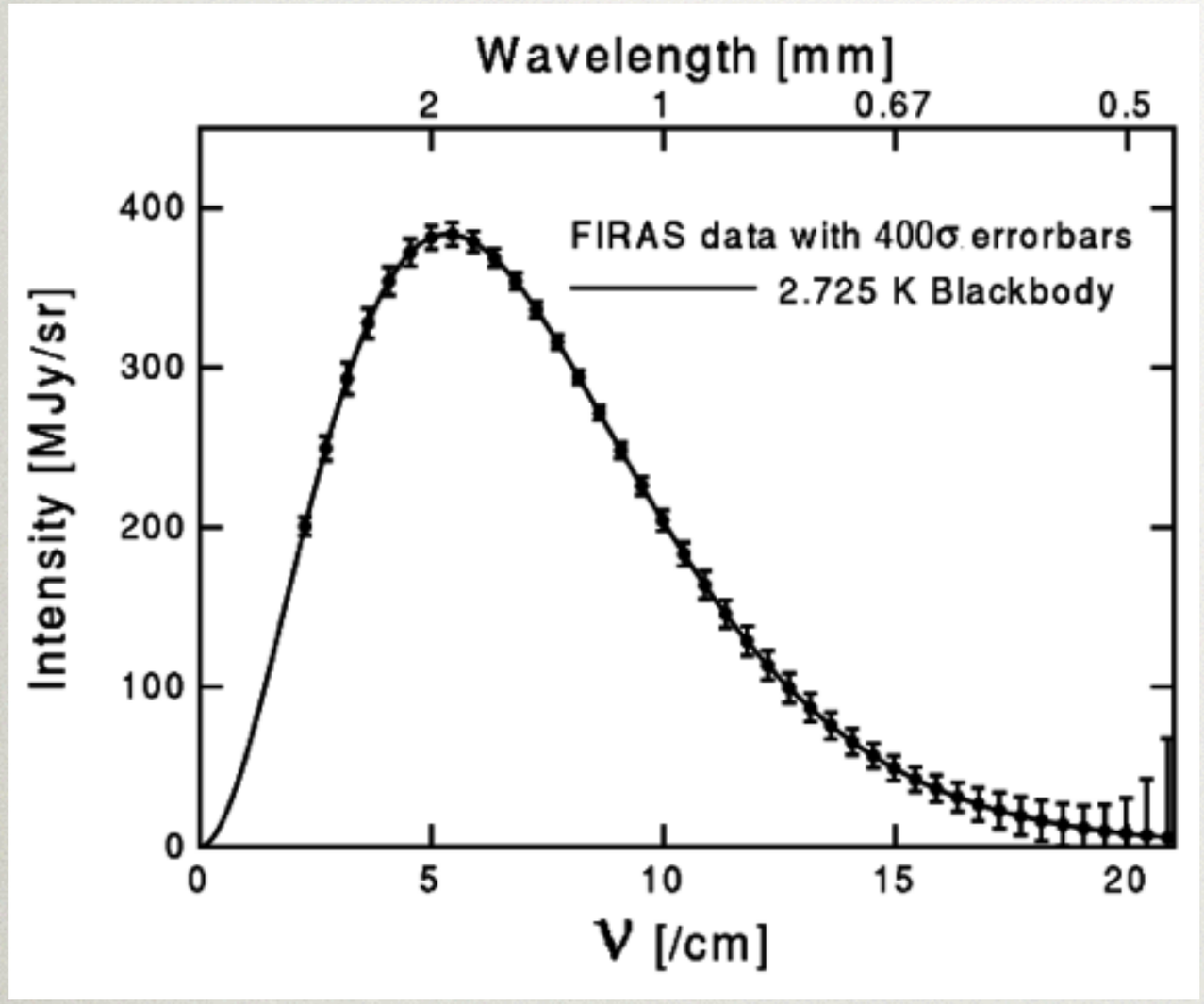
History of CMB observations



- 400 photons per cubic cm !

from Wayne Hu, http://background.uchicago.edu/~whu/beginners/introduction.html

The frequency spectrum

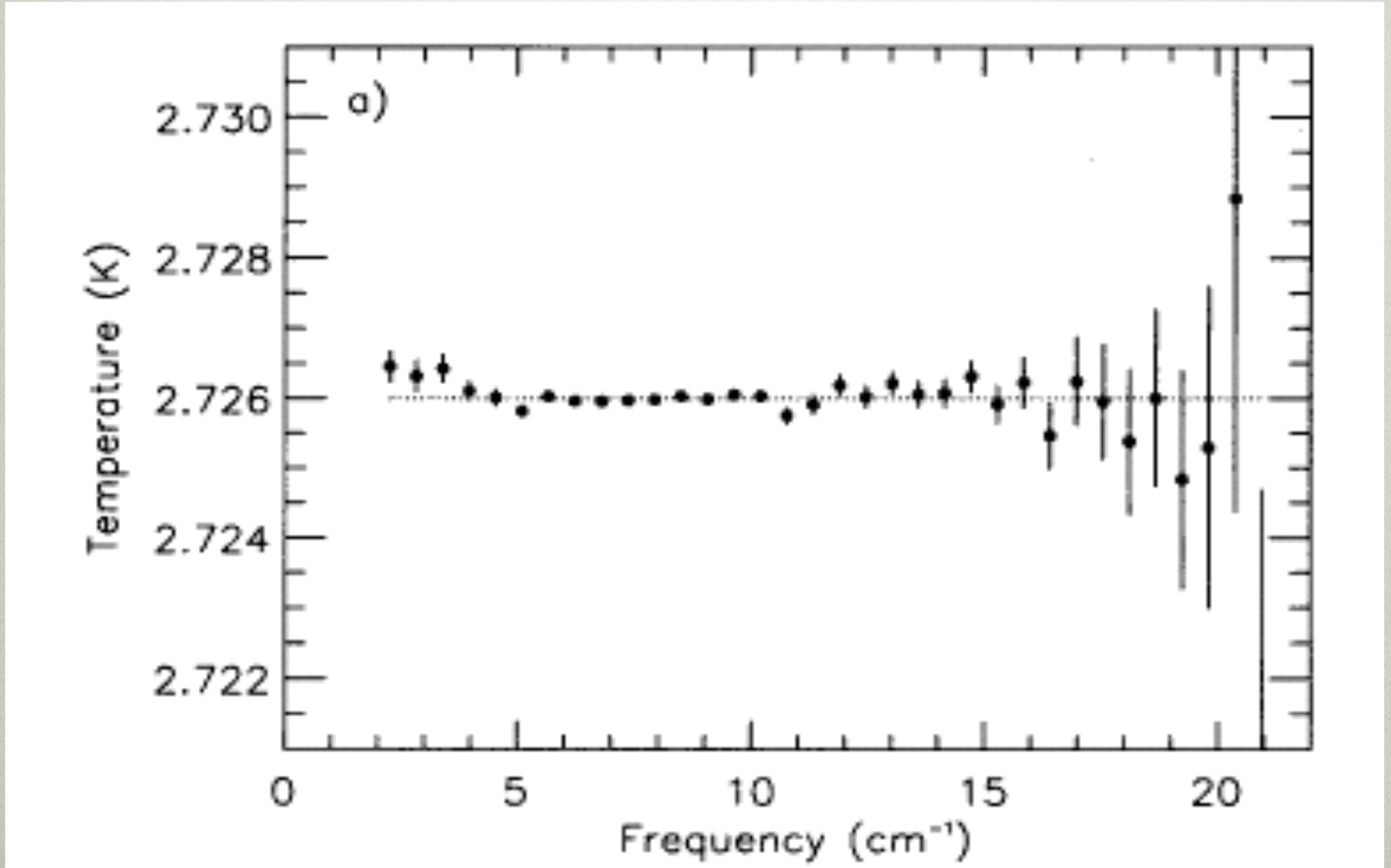


Cosmic Background Explorer (COBE)

Universe in equilibrium -> Black body

Observe perfect black body at 2.73K

COBE residuals

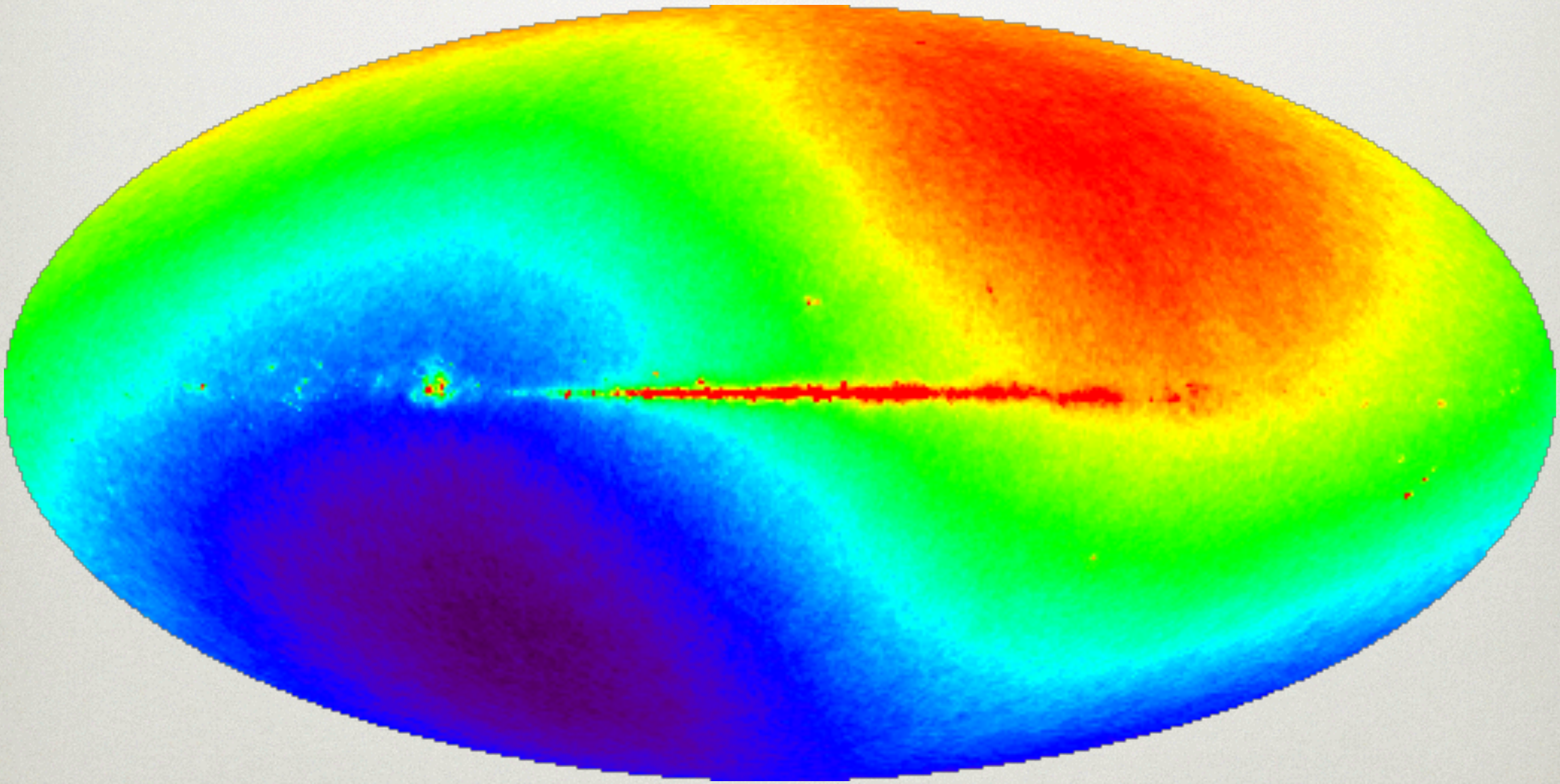


Mather et al (1994)

Deviations from isotropy

1 in 1000

3.343 +-0.016 mK



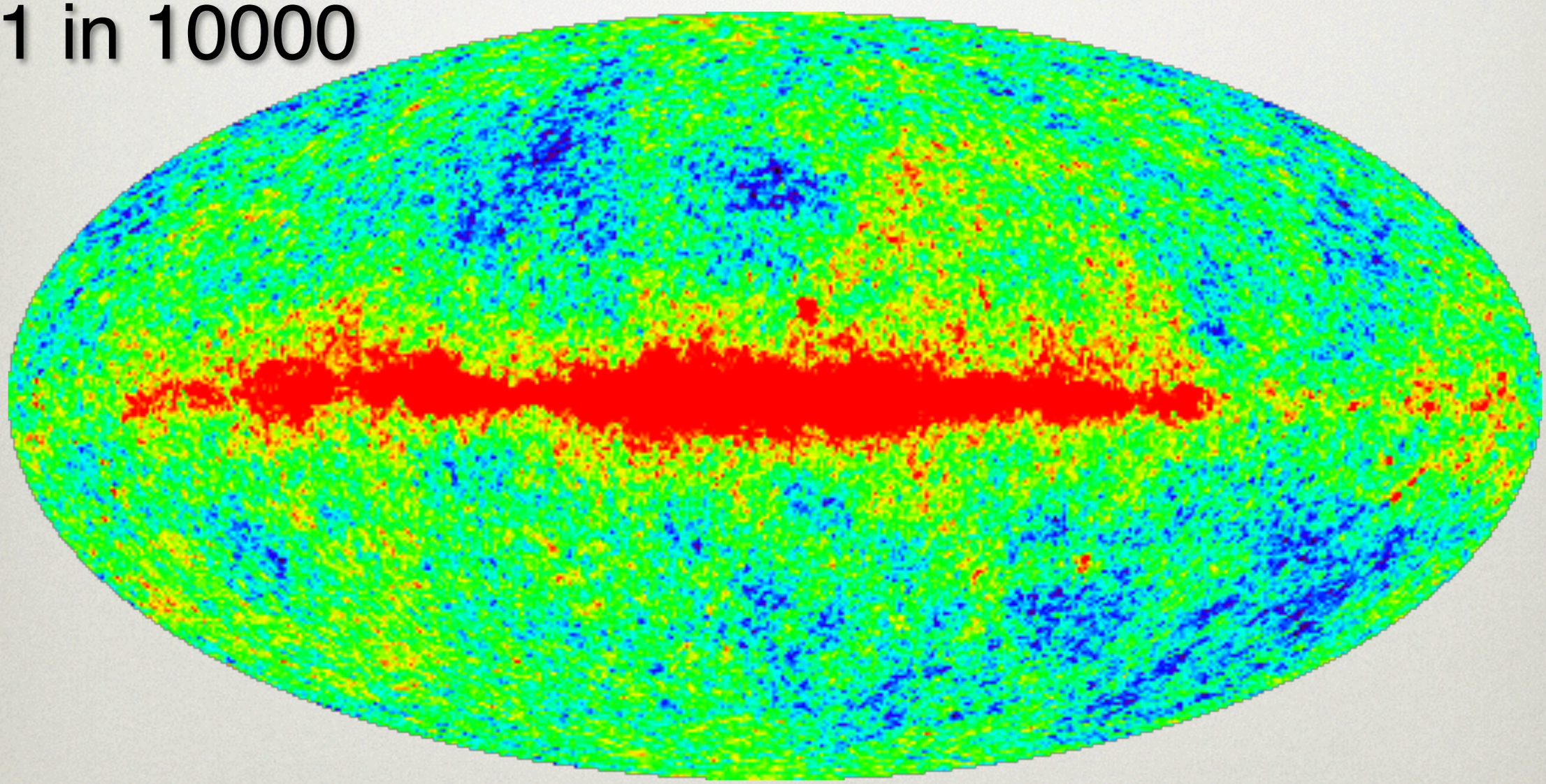
Direction (l,b): 264.4, 48.5 degrees

Our combined motion relative to CMB ~360km/s

WMAP

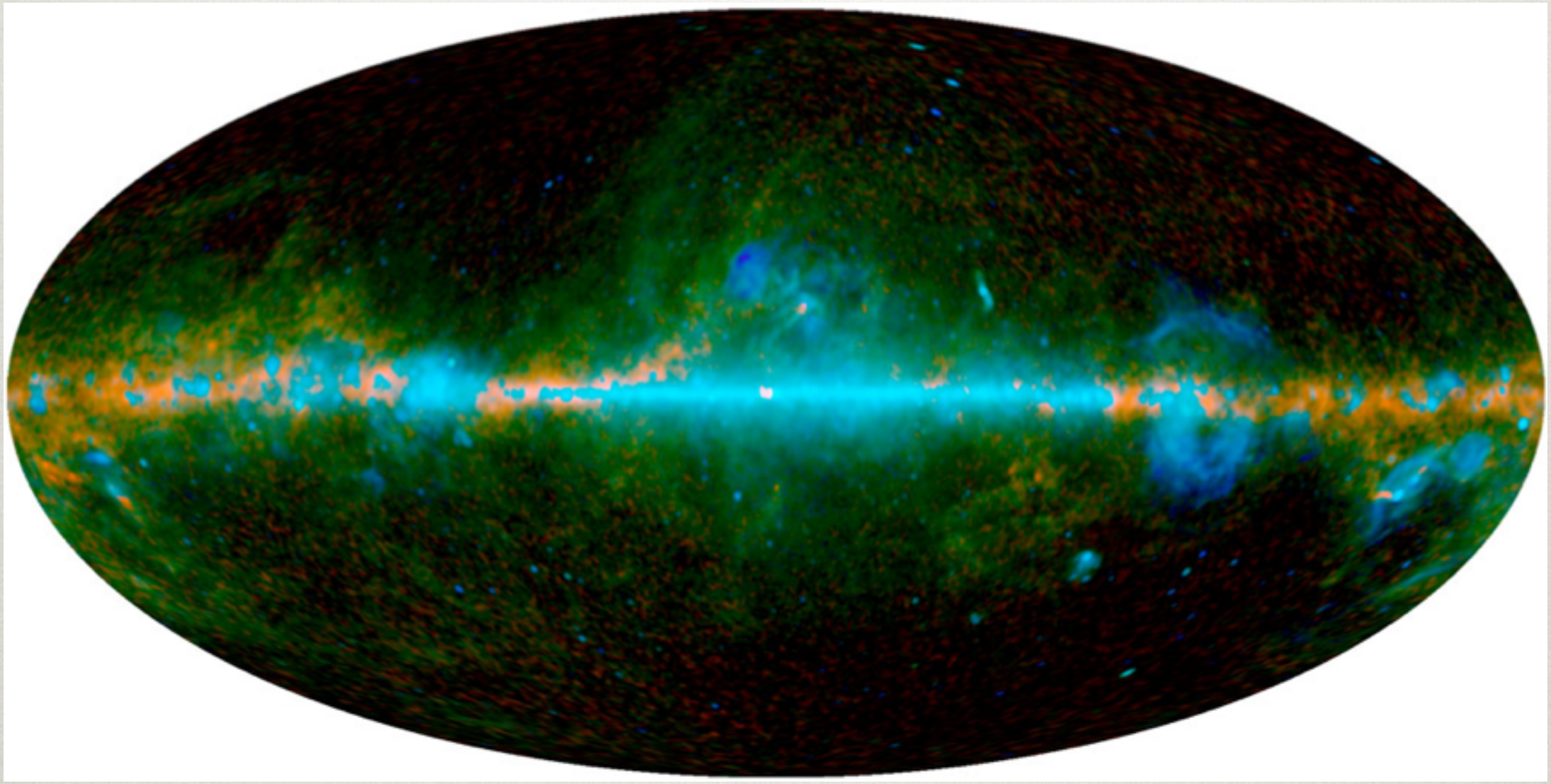
Dipole removed

1 in 10000



WMAP

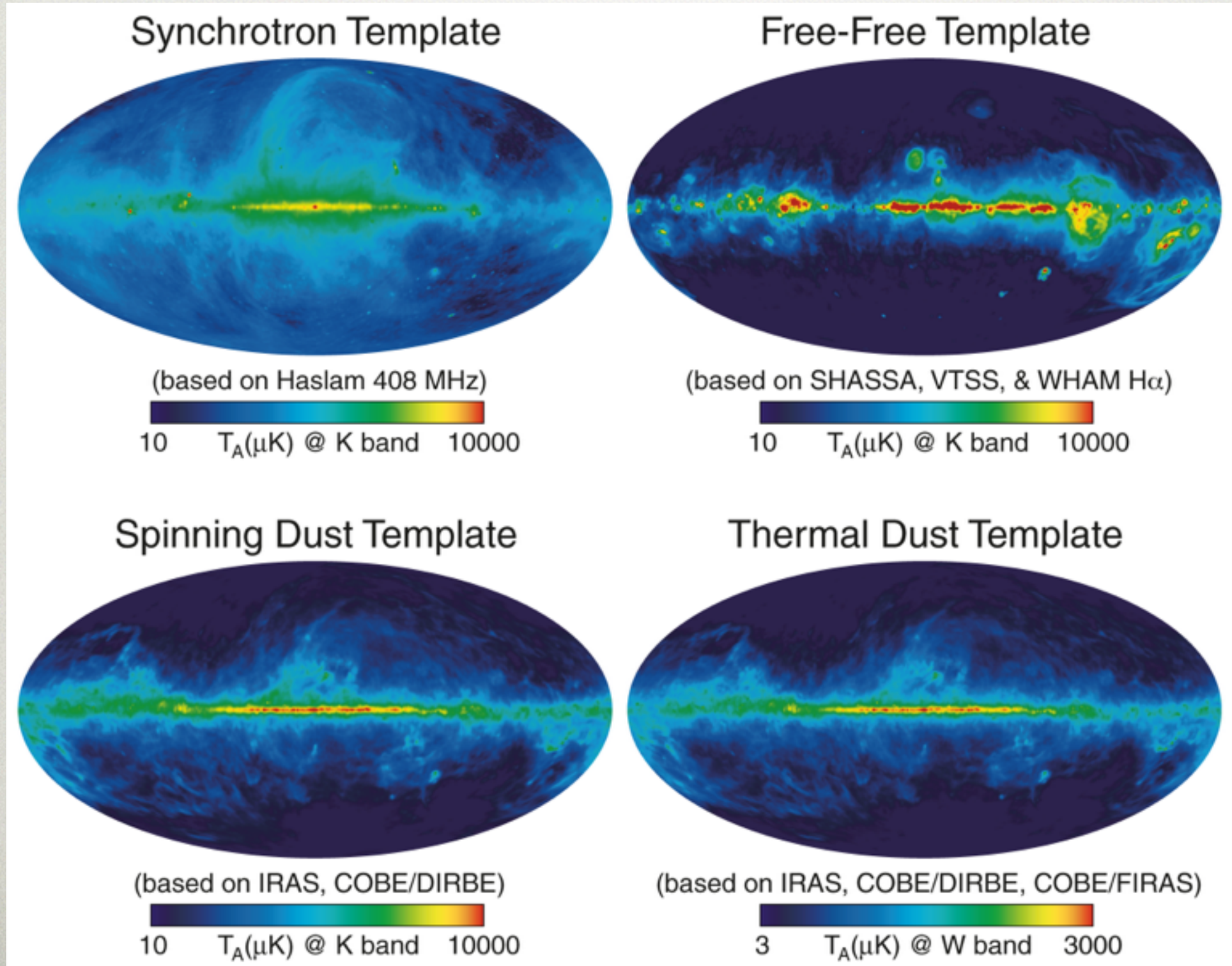
Lots of foregrounds that need modelling



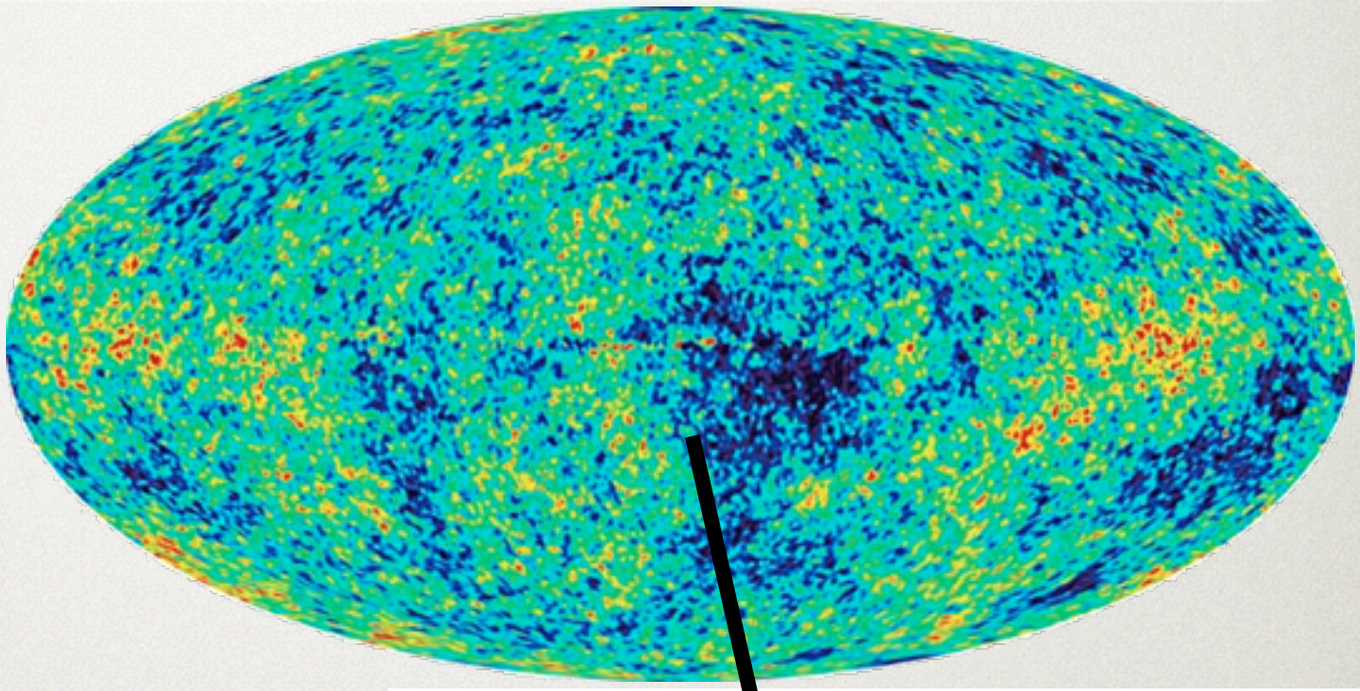
Red (W-V) highlights regions where thermal emission from dust is highest. Blue (Q-W) is dominated by free-free emission. Green ((K-Ka)- 1.7(Q-W)) illustrates contributions from synchrotron and spinning dust.

WMAP

Combined with other data



Statistical analysis

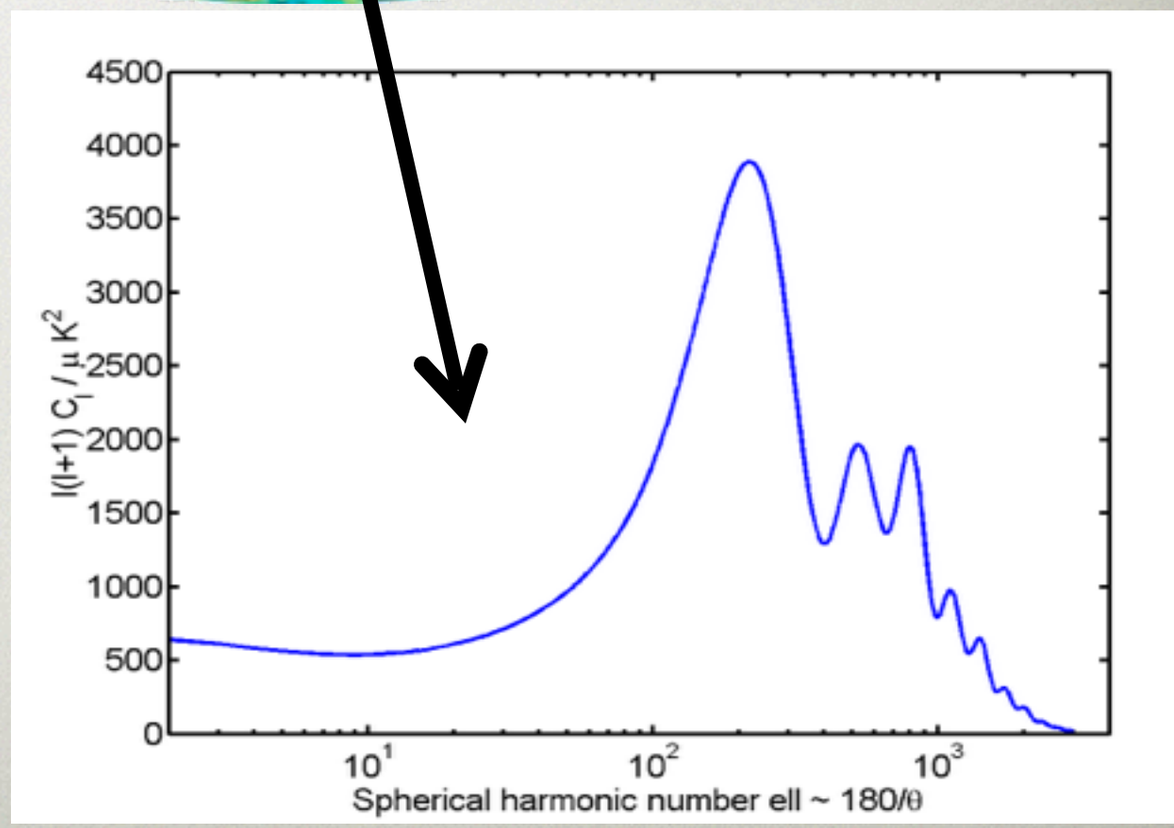


$$\frac{\Delta T}{T} = \Theta(\theta,\varphi) = \sum_{l,m} a_{lm} Y_{lm}(\theta,\varphi)$$

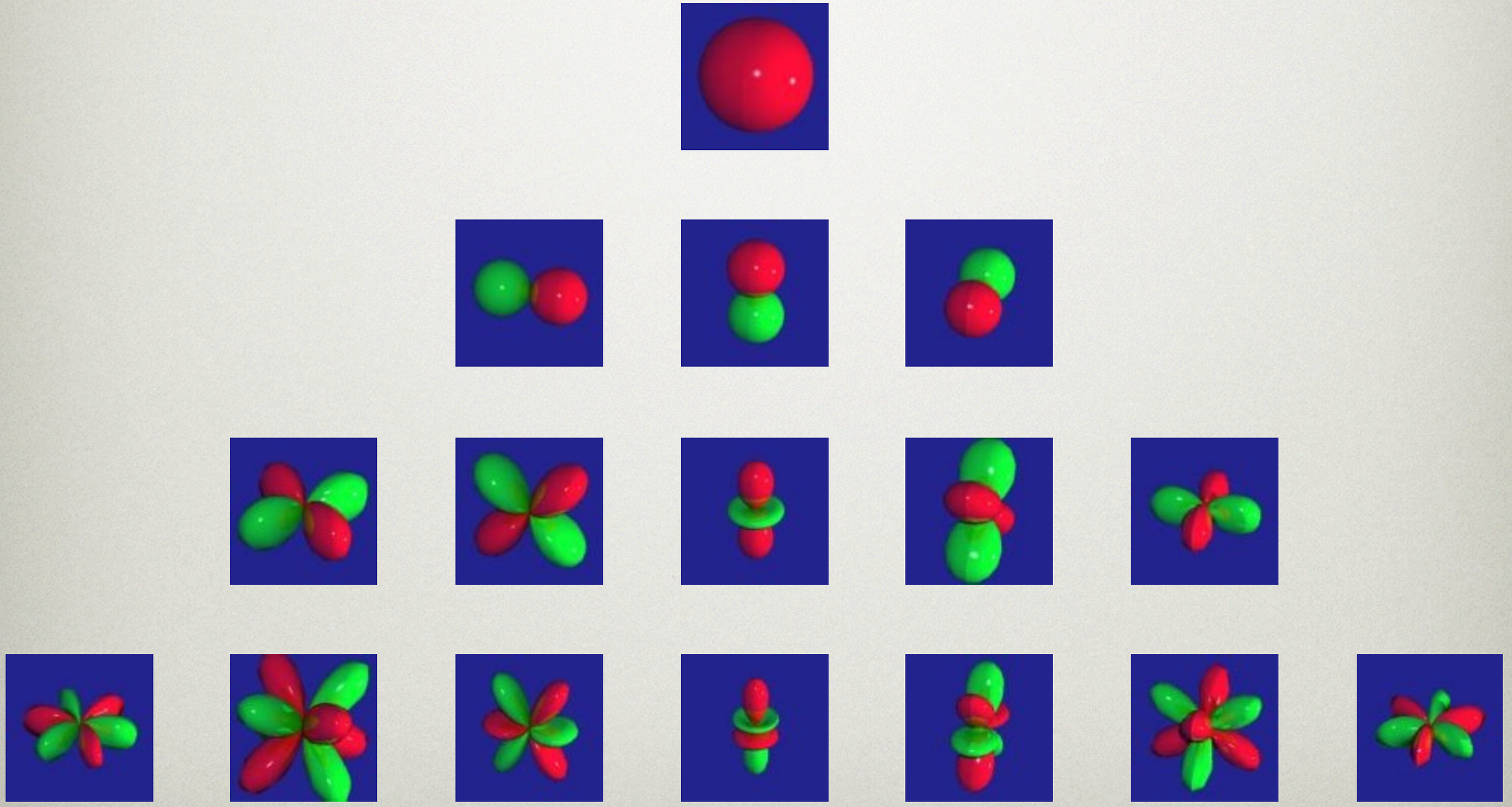
where: $a_{lm} = \int Y^{*}_{lm}(\theta,\varphi)\ \Theta(\theta,\varphi)\ d\Omega$

and $\left\langle a^{*}_{lm} a_{l'm'} \right\rangle = C_l \delta_{ll'} \delta_{mm'}$ (spher. symmetry)

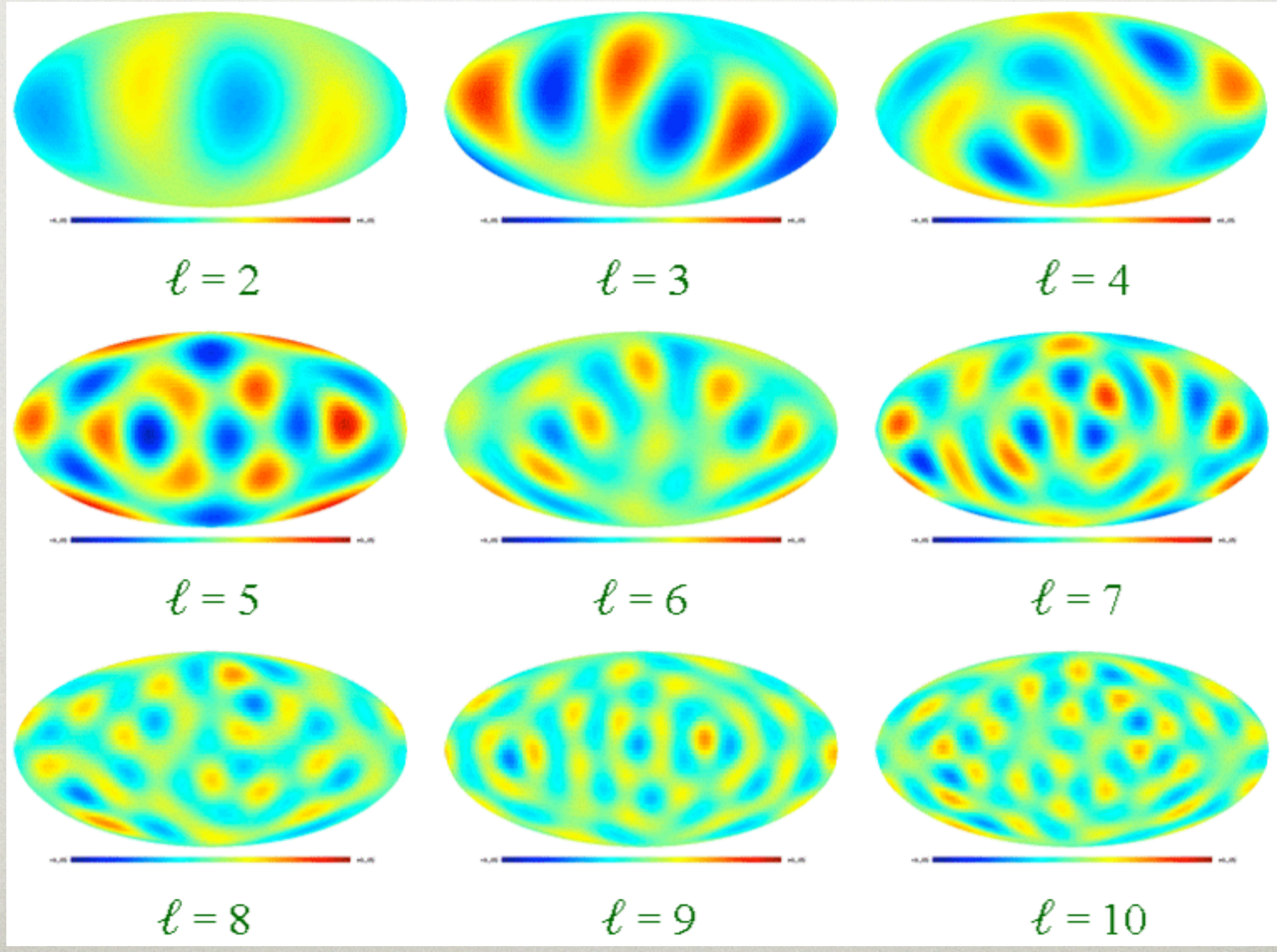
$Y_{lm}(\theta,\varphi)$ are the sperical harmonics



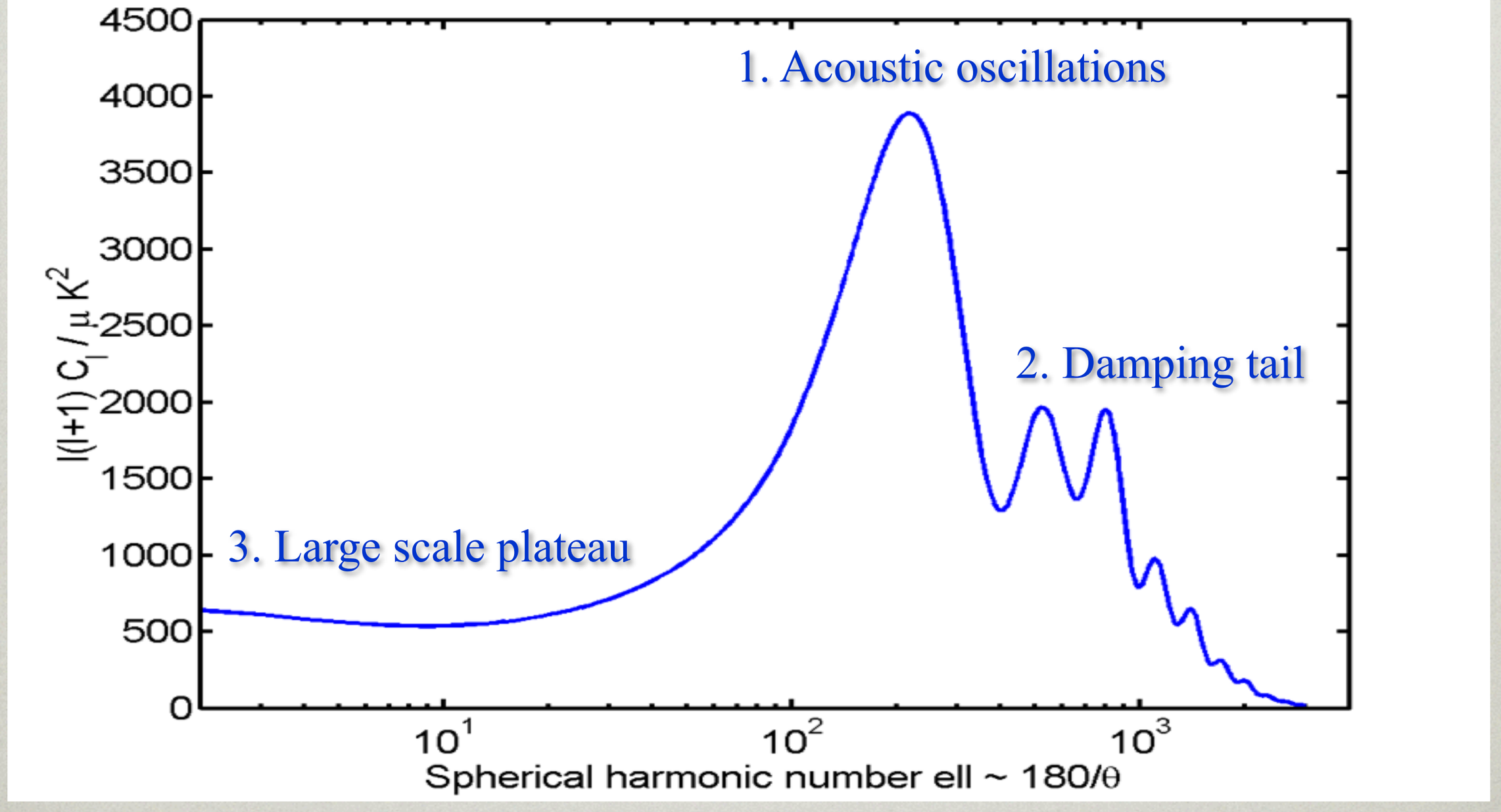
Spherical Harmonics



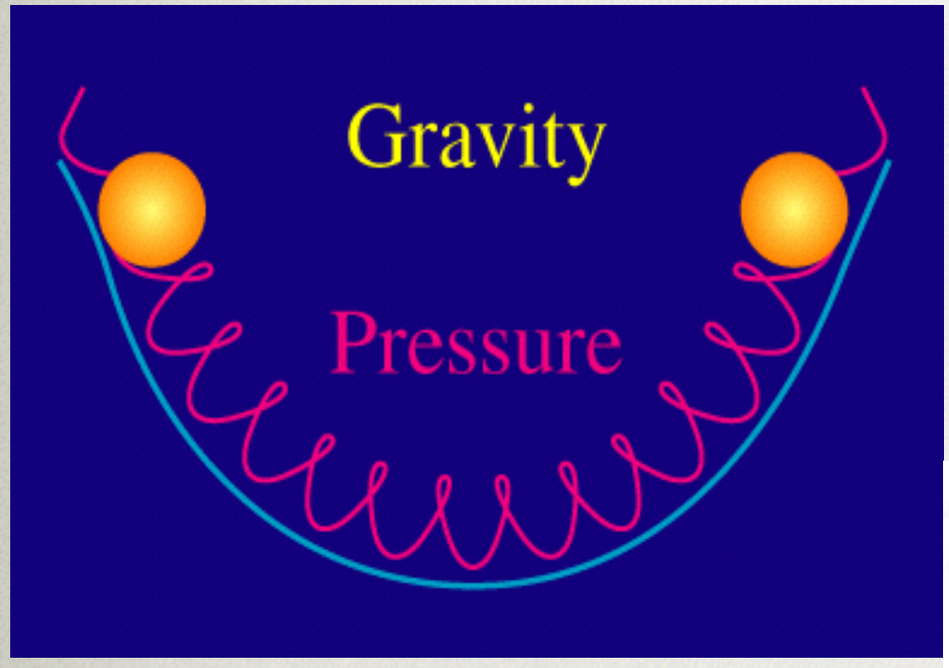
First 10 modes of the map



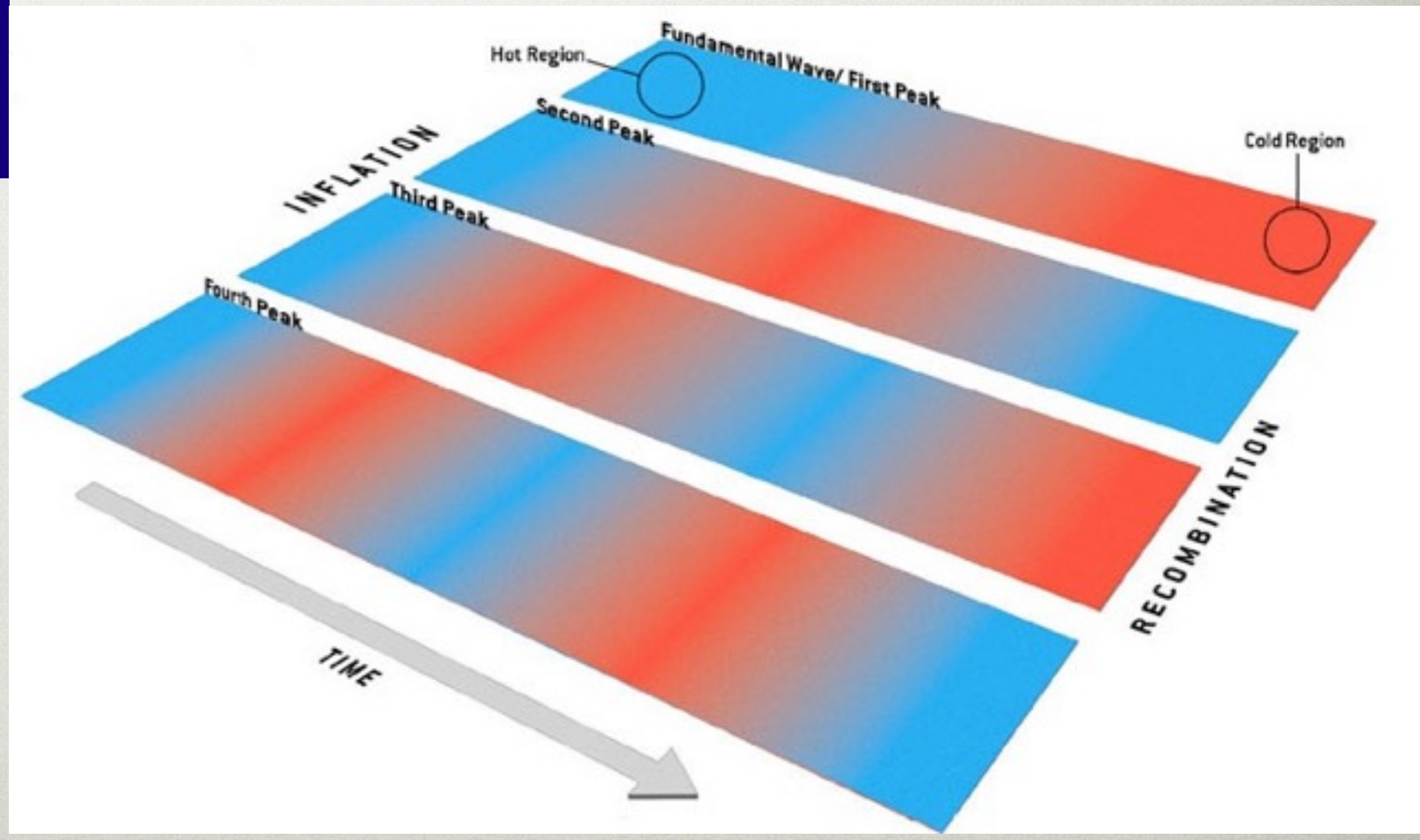
REGIMES OF CMB POWER



1. Acoustic Oscillations



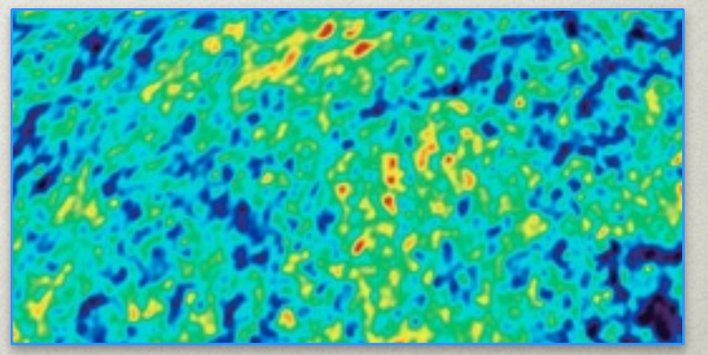
Amplitude depends on dark matter density



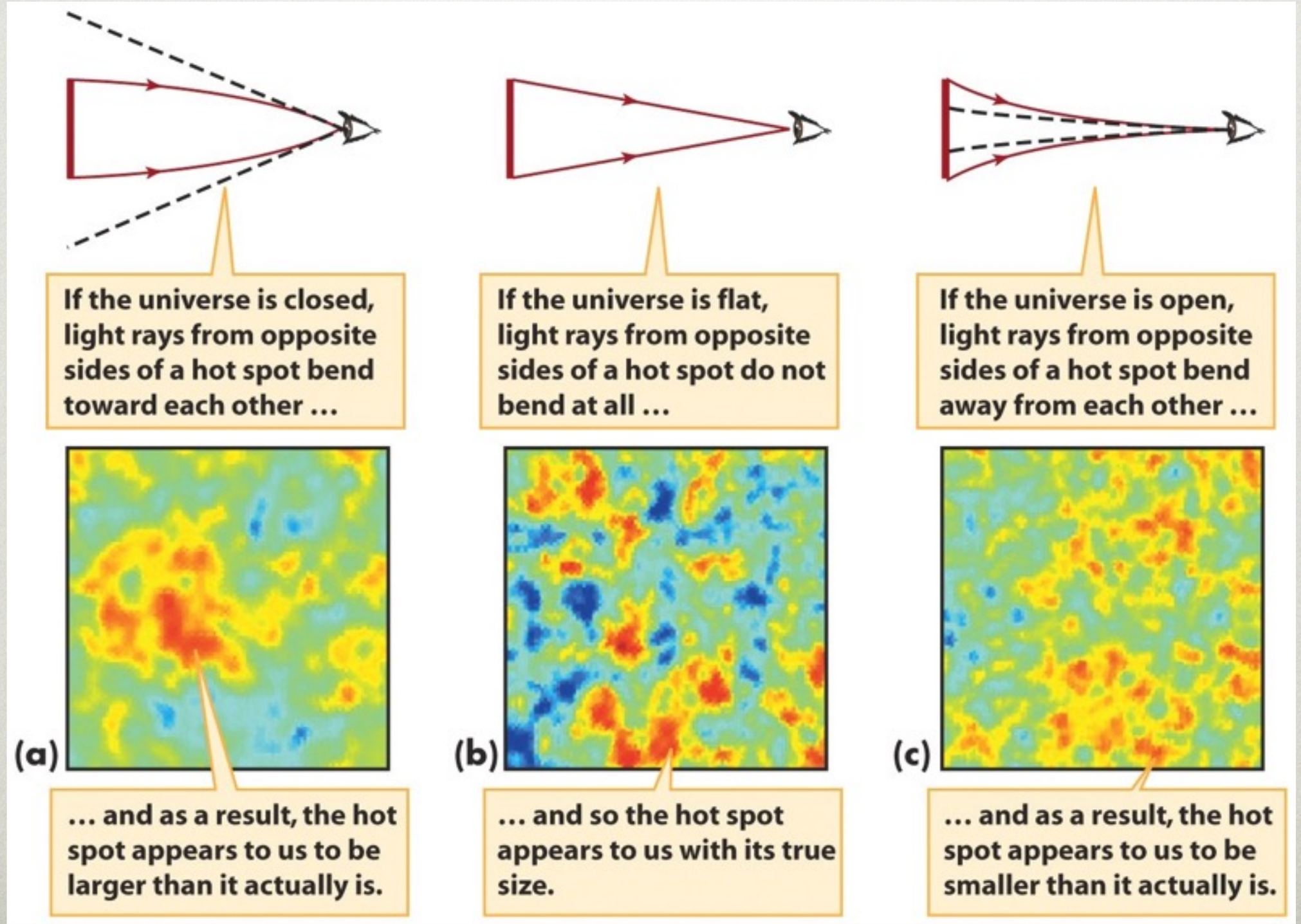
Wayne Hu

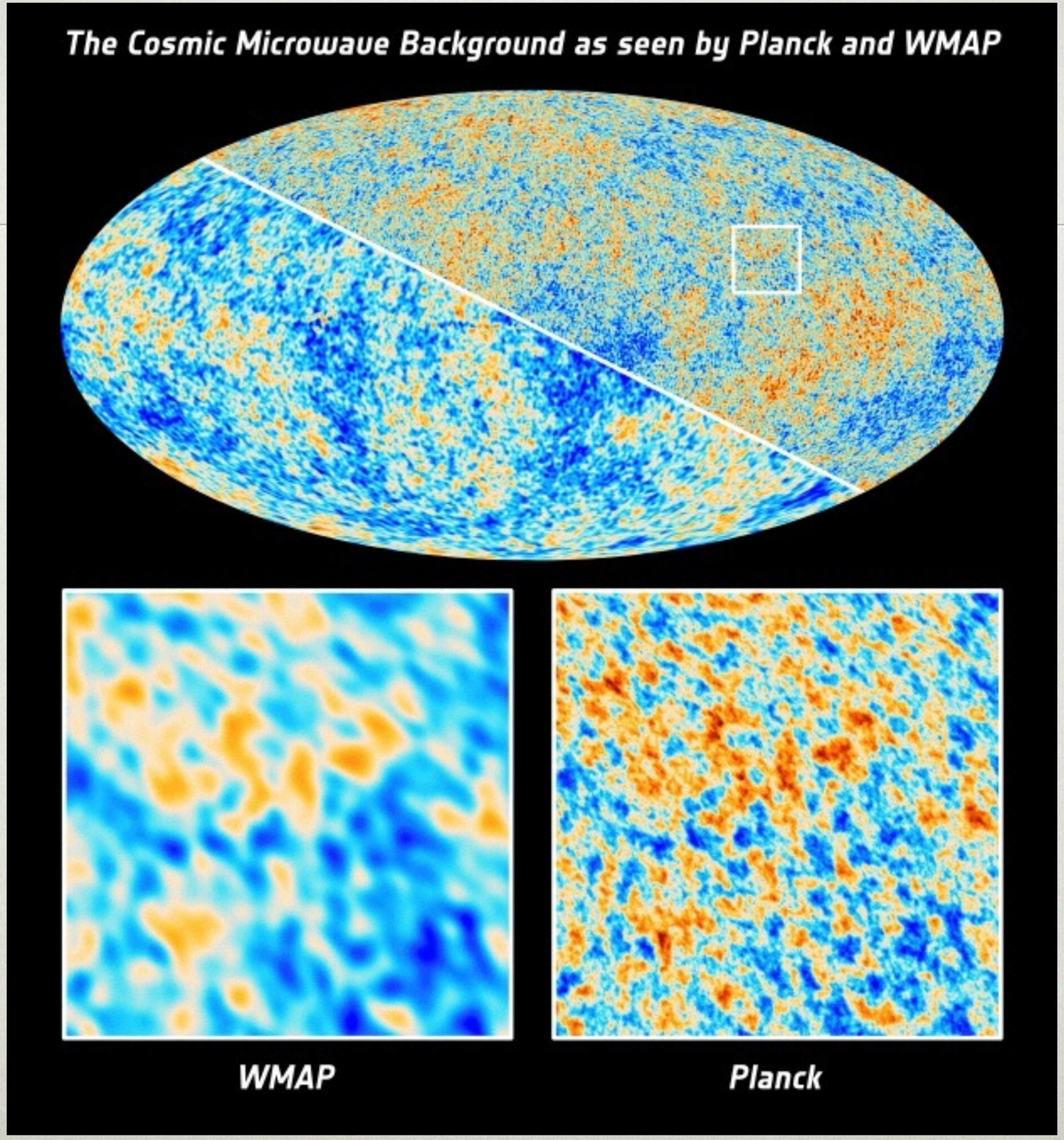
Primary CMB feature: peak locations

- Consider scale which had time only to collapse under gravity since big-bang
- it is at maximum T => hot-spot
- Scale = collapse speed × time allowed
- ~ sound speed × age of universe at z~1000
- ~ million light years at z~1000
- ~ 1 degree

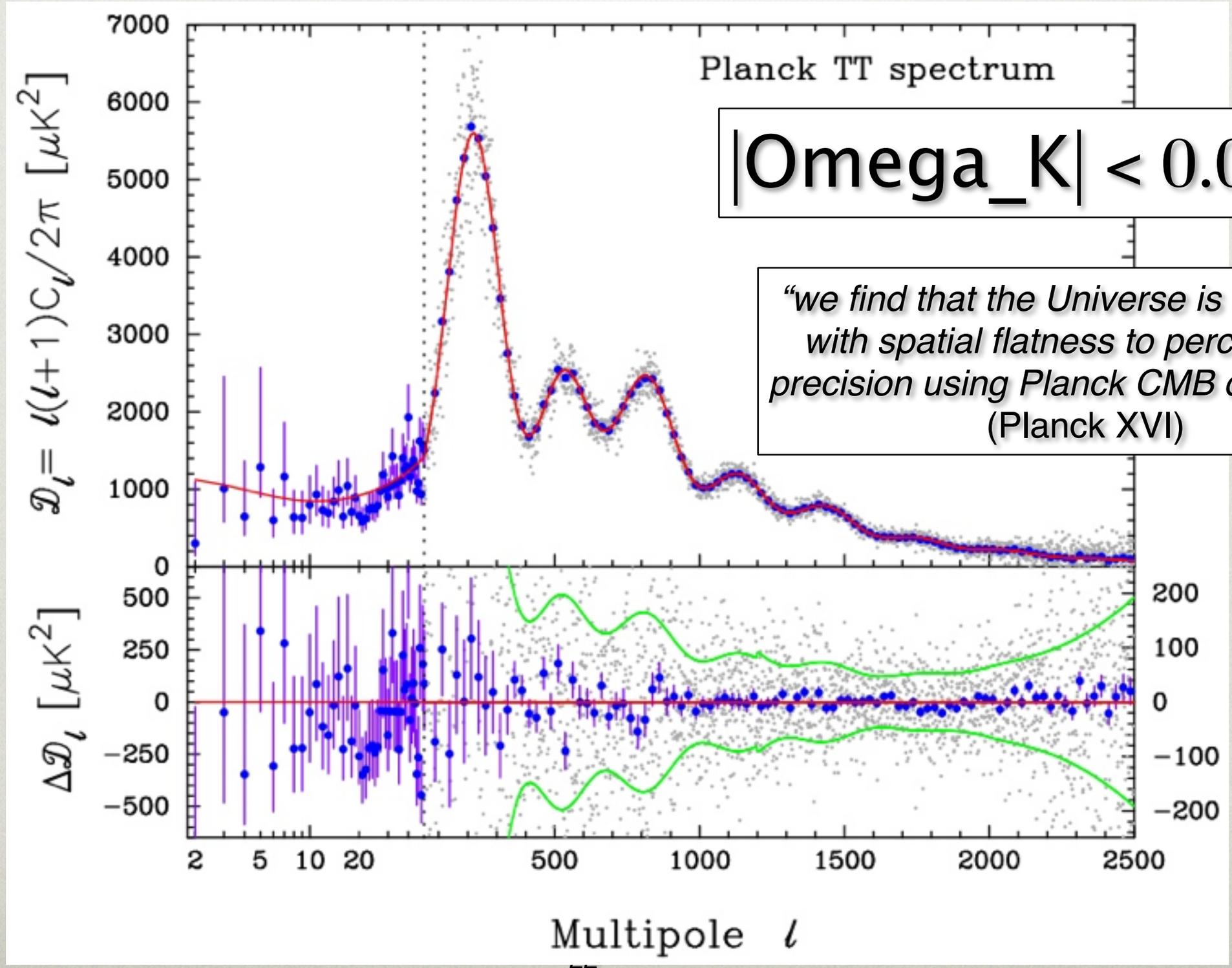


Flatness to 0.5%



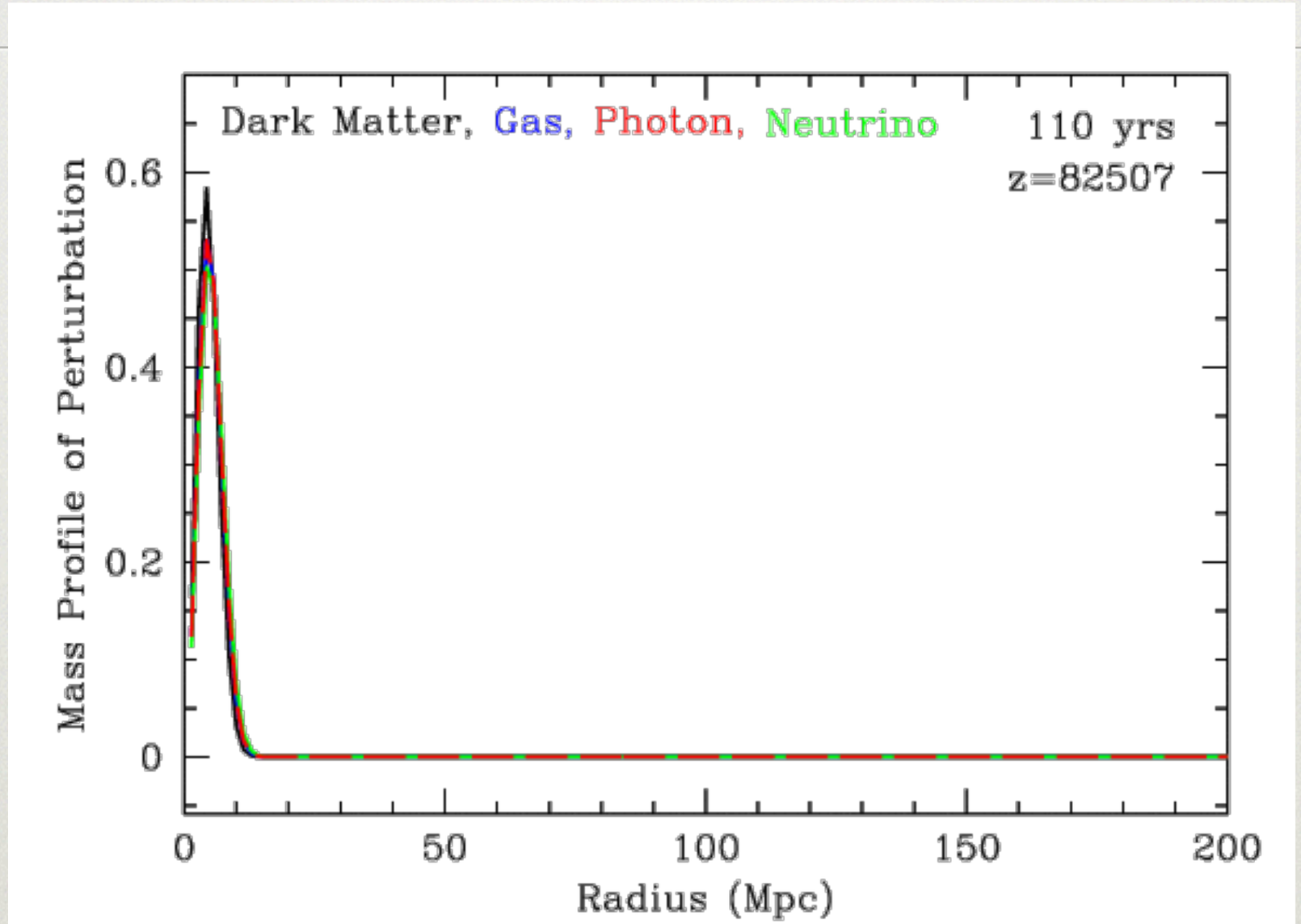

The Cosmic Microwave Background as seen by Planck and WMAP
WMAP
Planck

Planck TT Power Spectrum

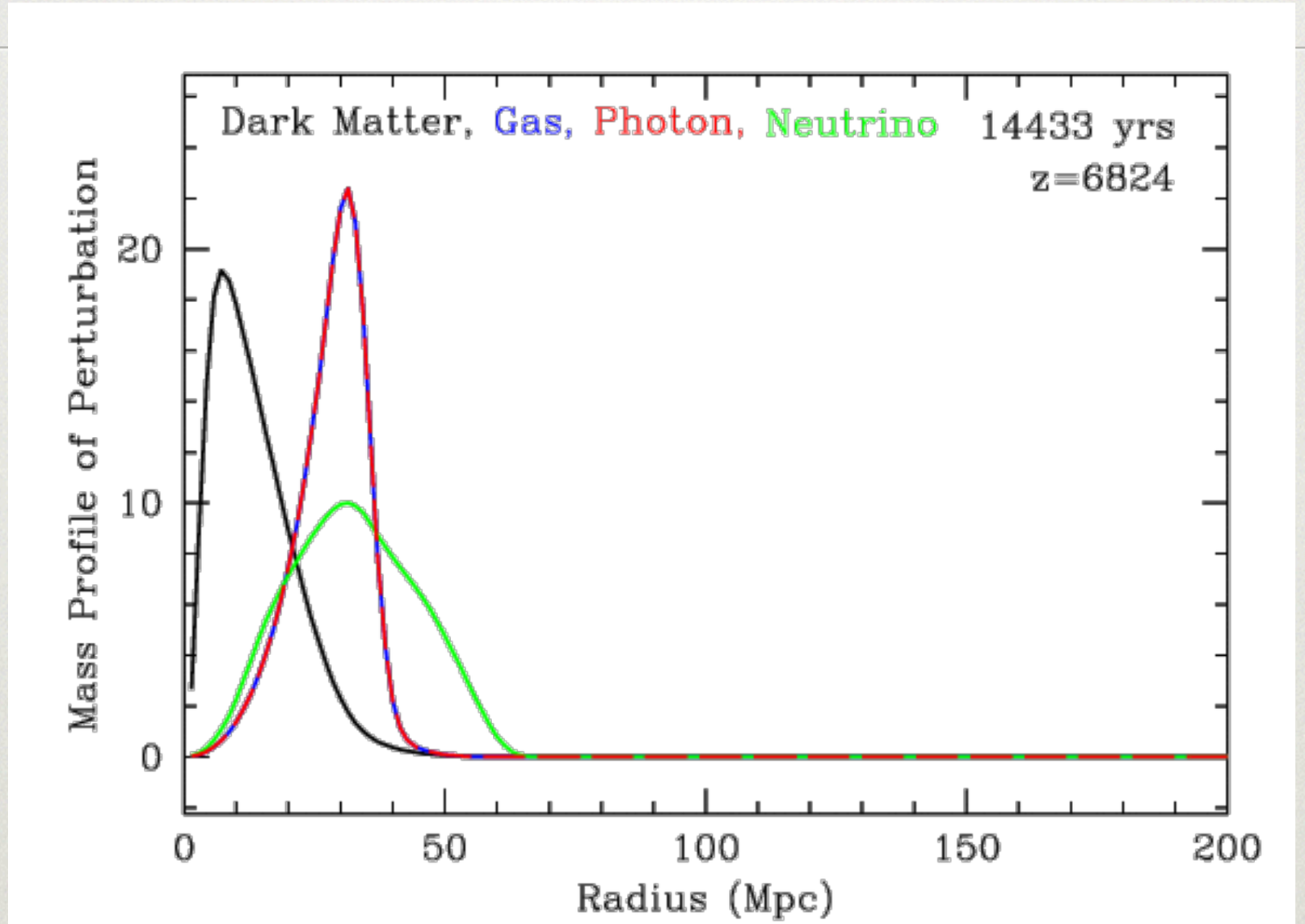


$$|\Omega_K| < 0.005$$

"we find that the Universe is consistent with spatial flatness to percent-level precision using Planck CMB data alone" (Planck XVI)



Plots by Eisenstein



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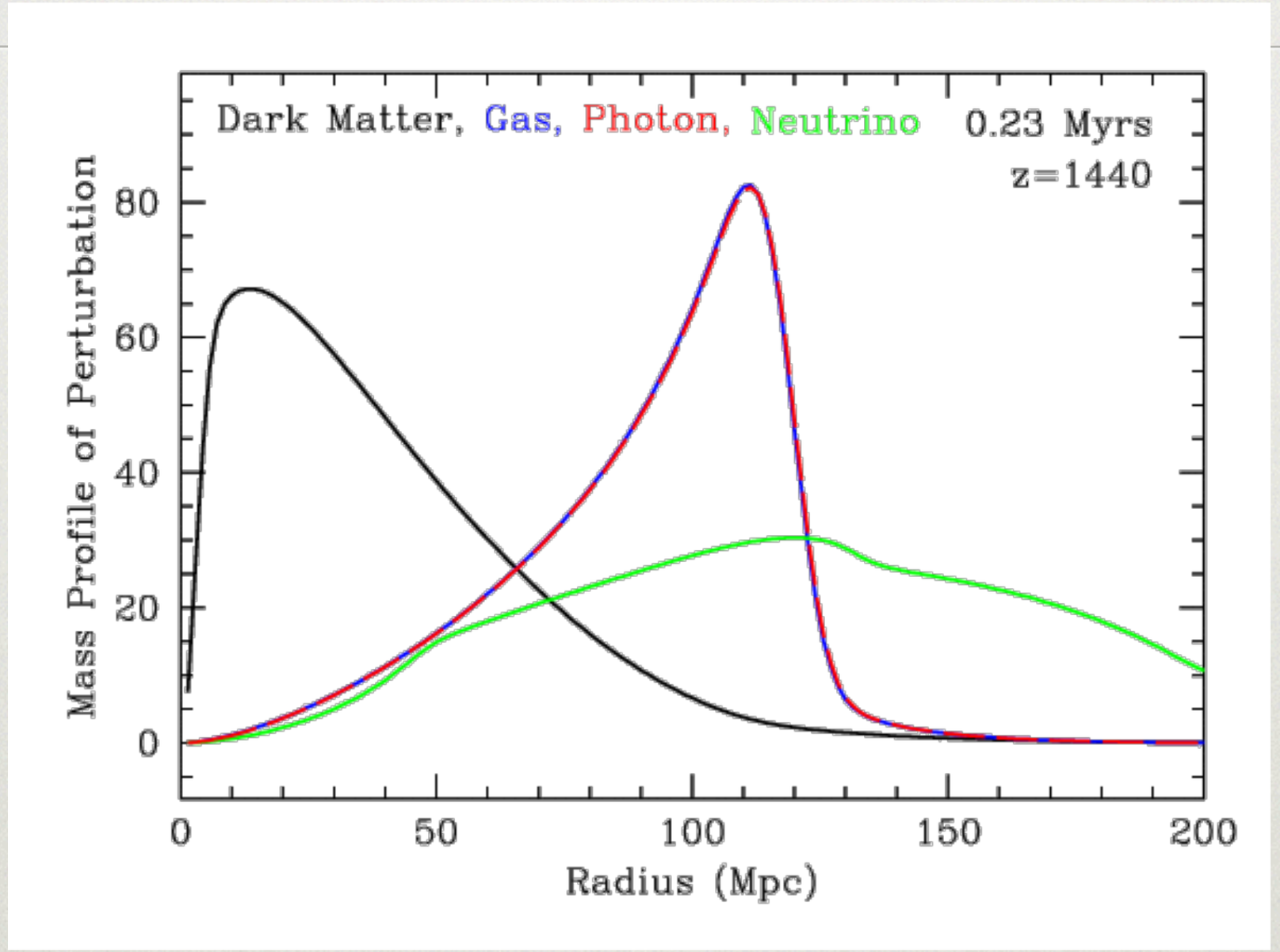

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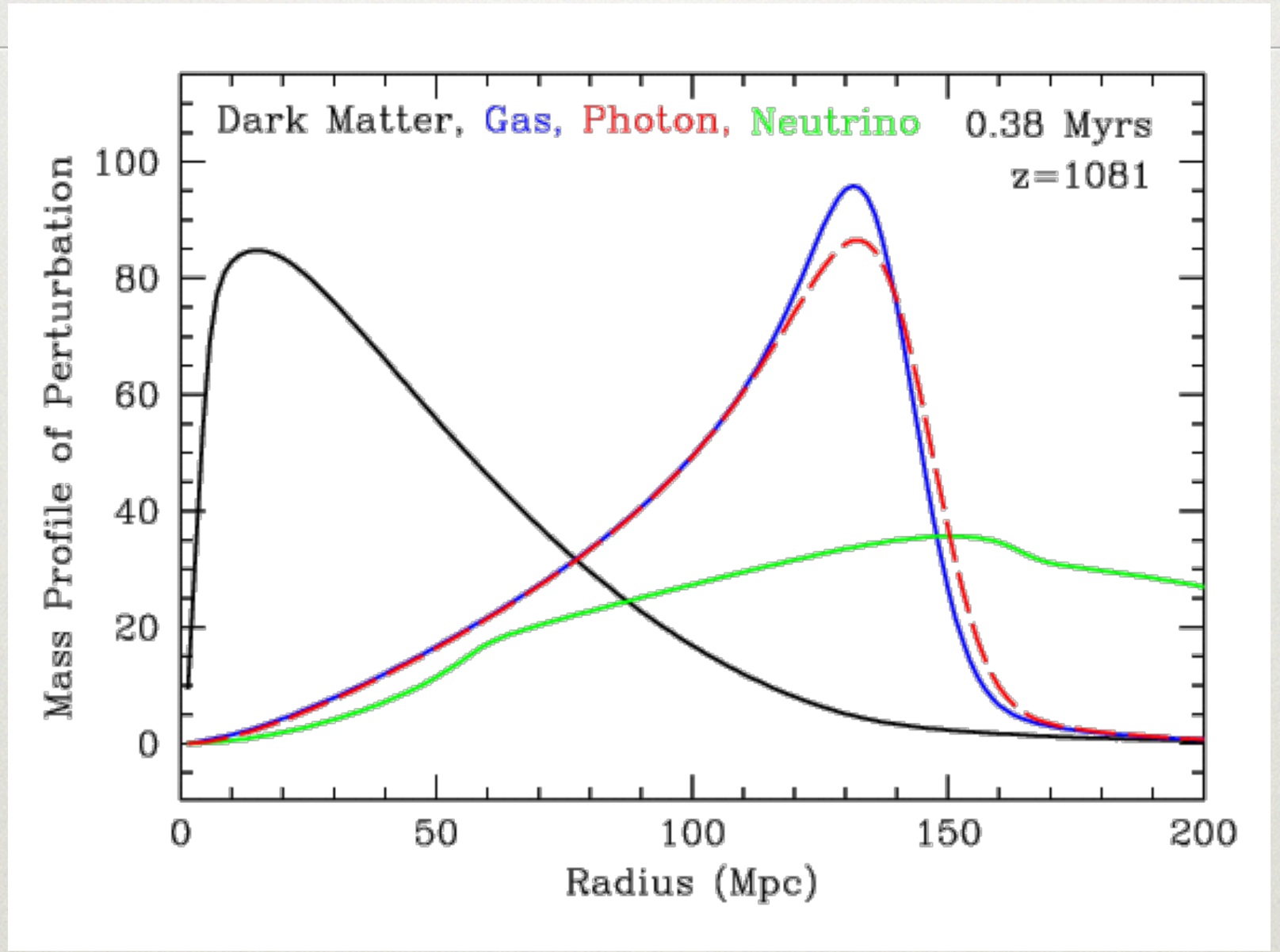

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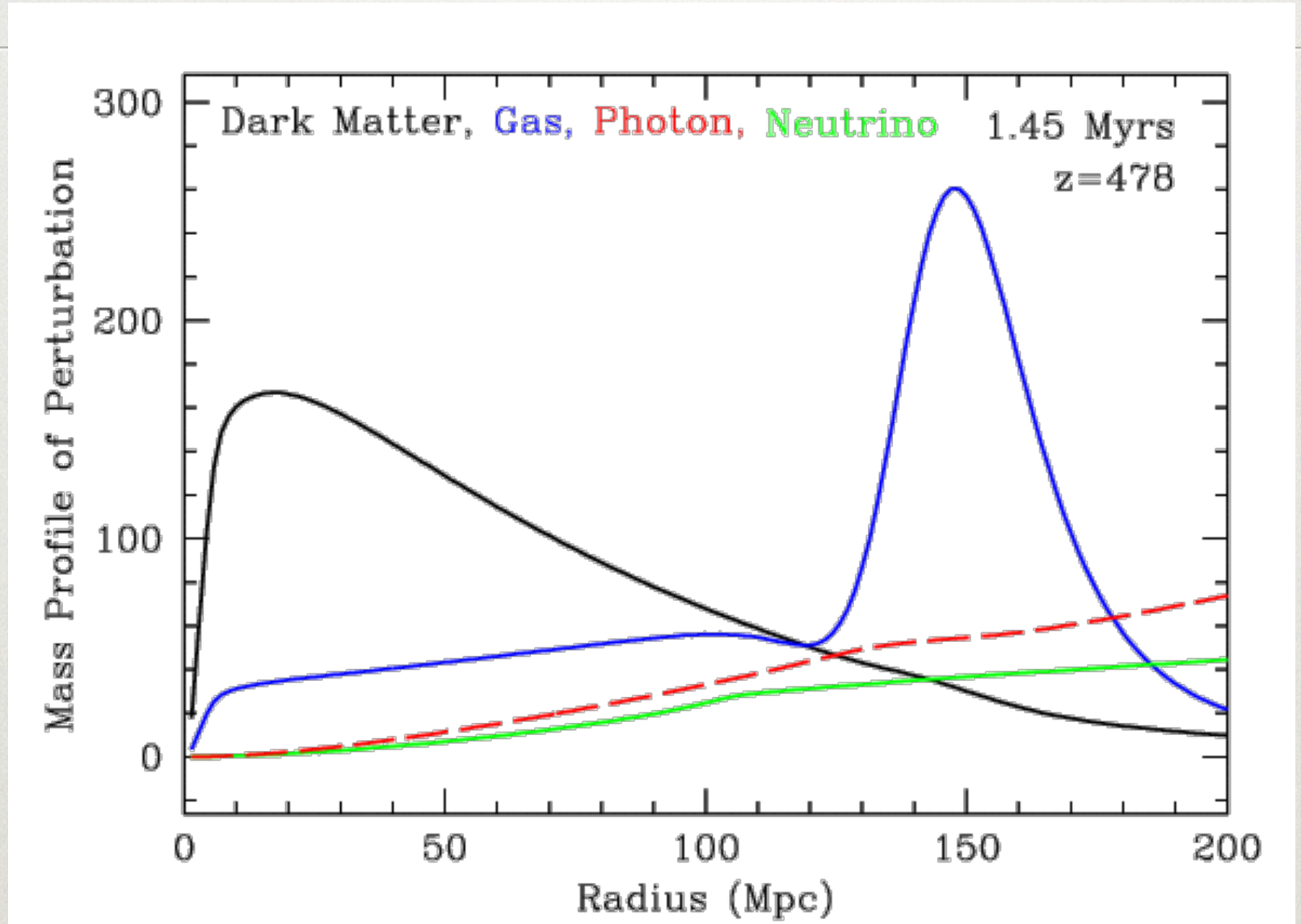

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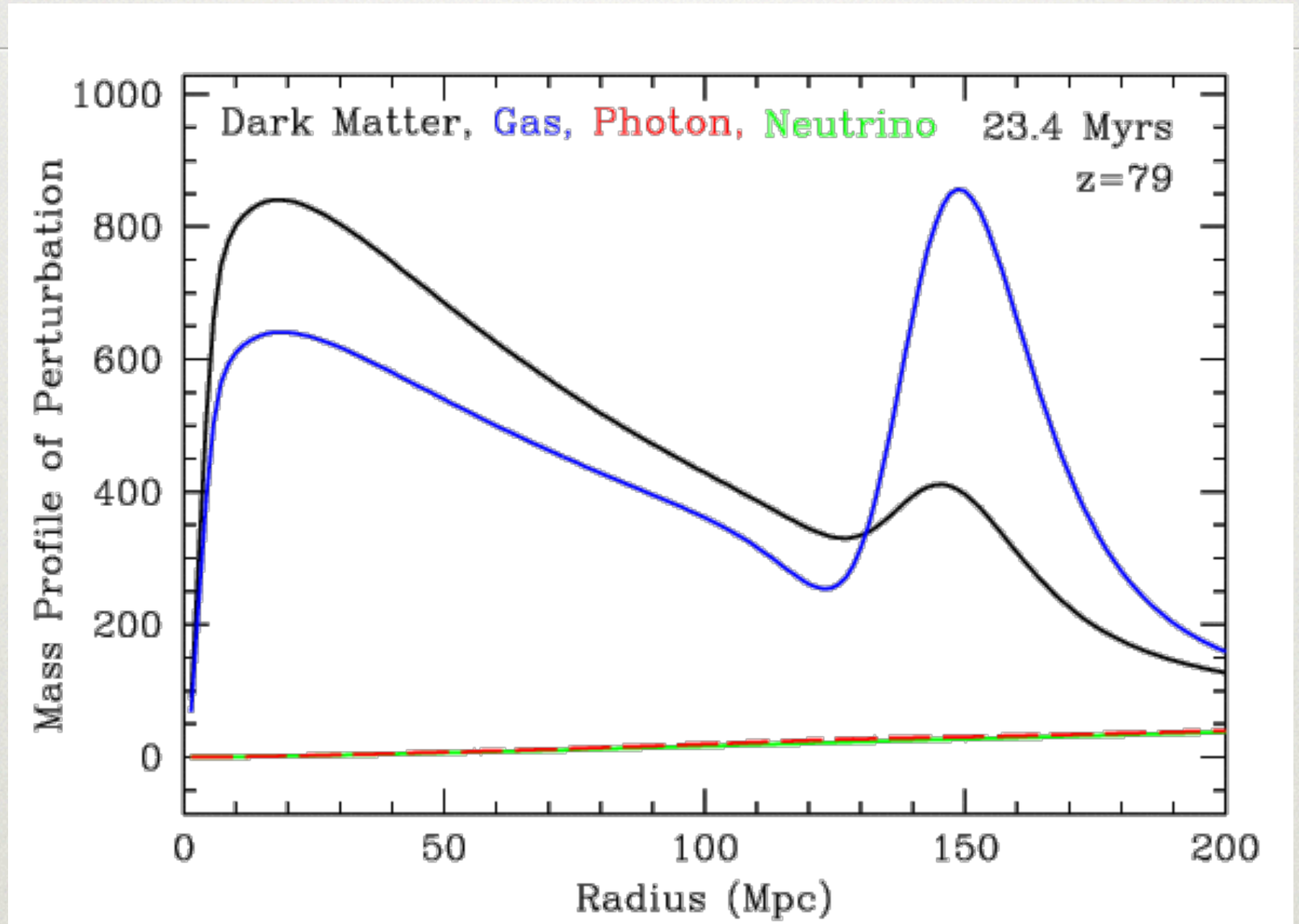
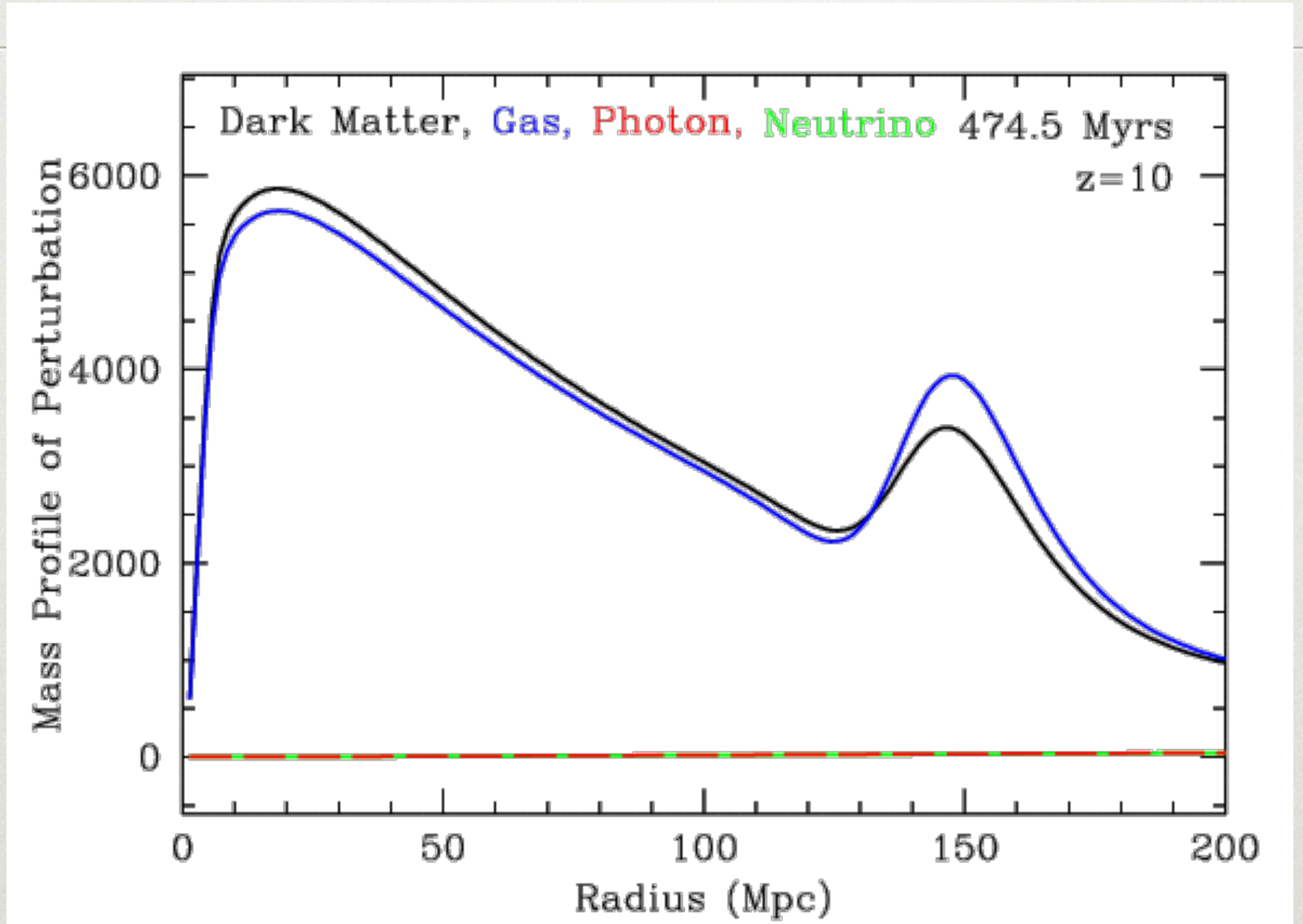
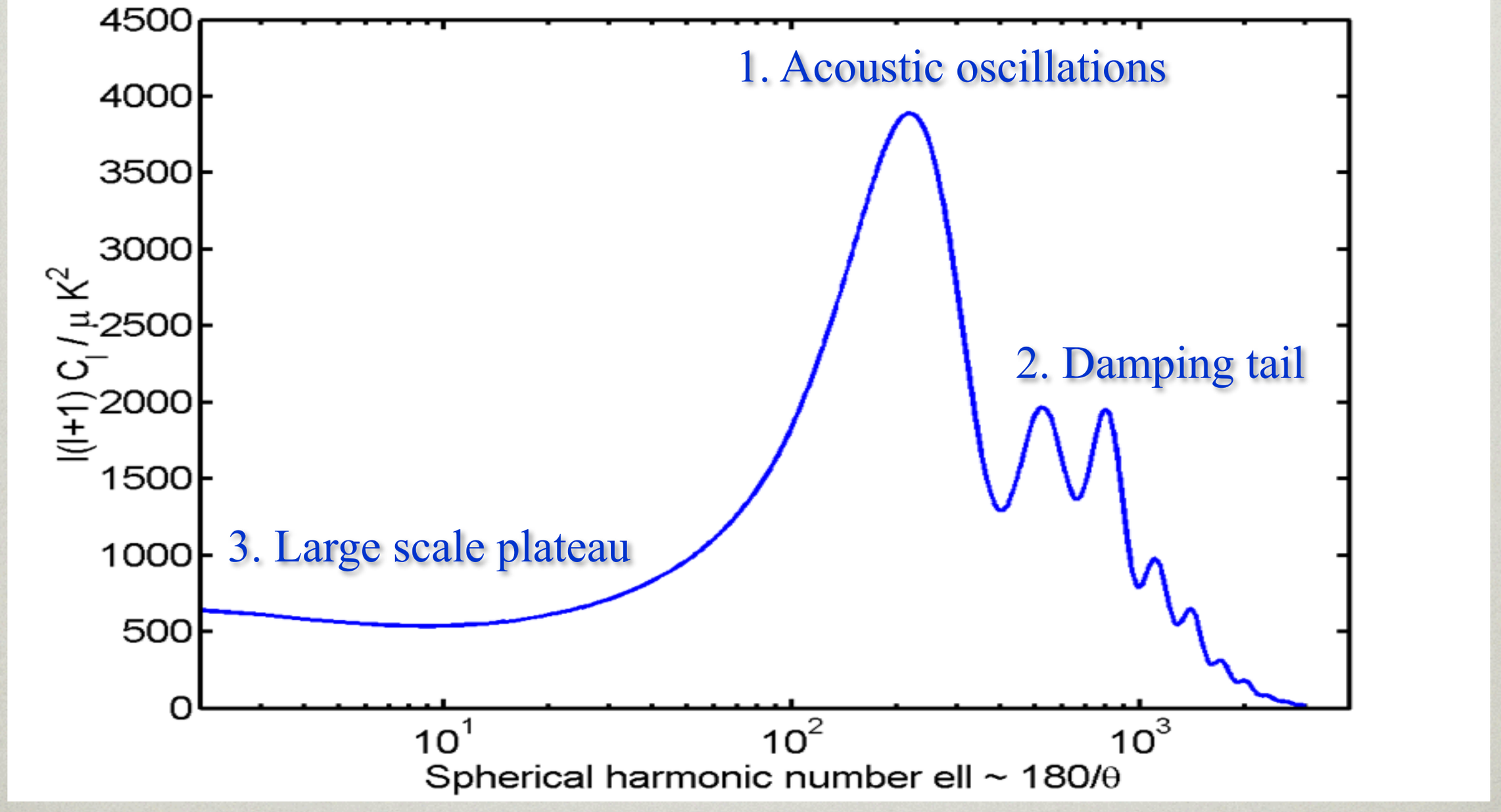


Plots by Eisenstein



Plots by Eisenstein

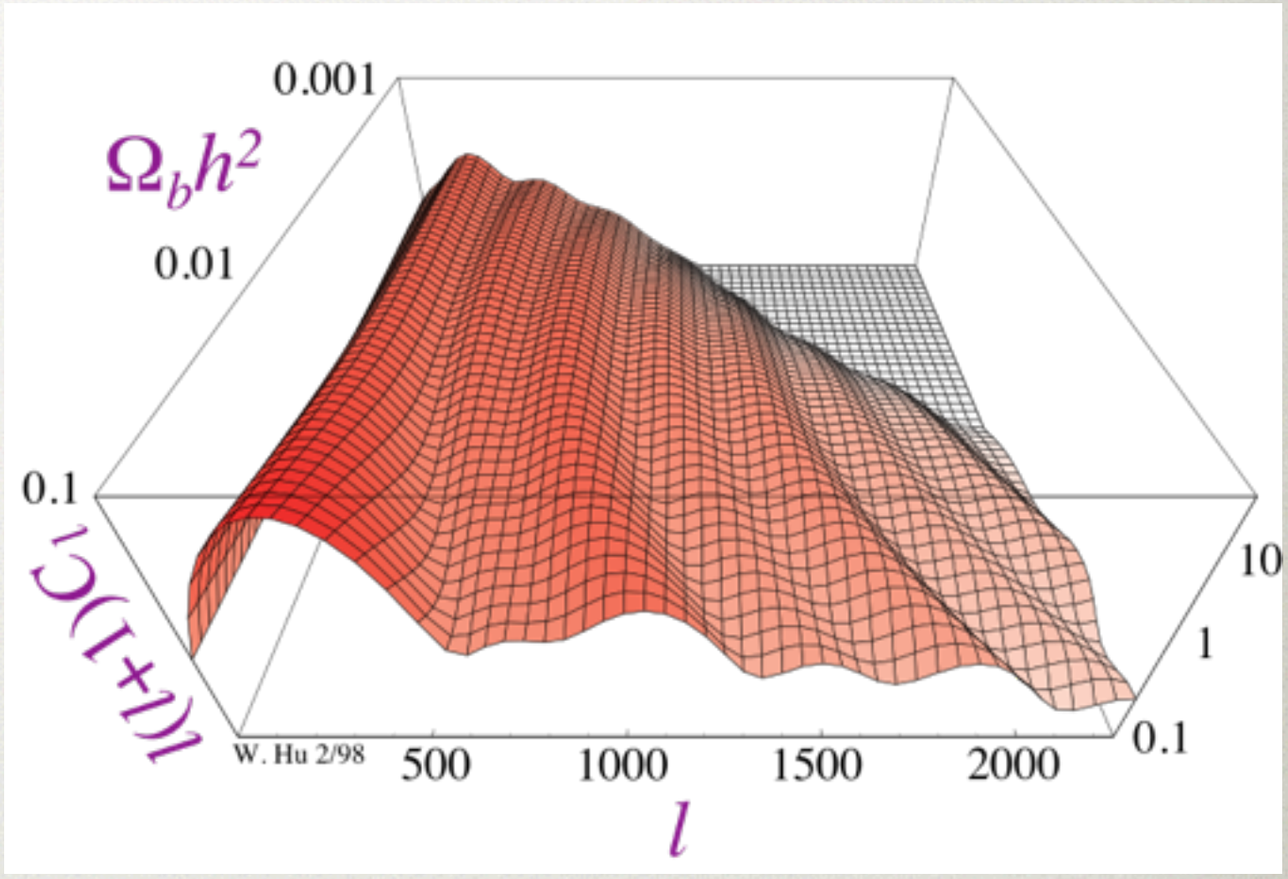
REGIMES OF CMB POWER



2. Damping tail (effect of baryons)

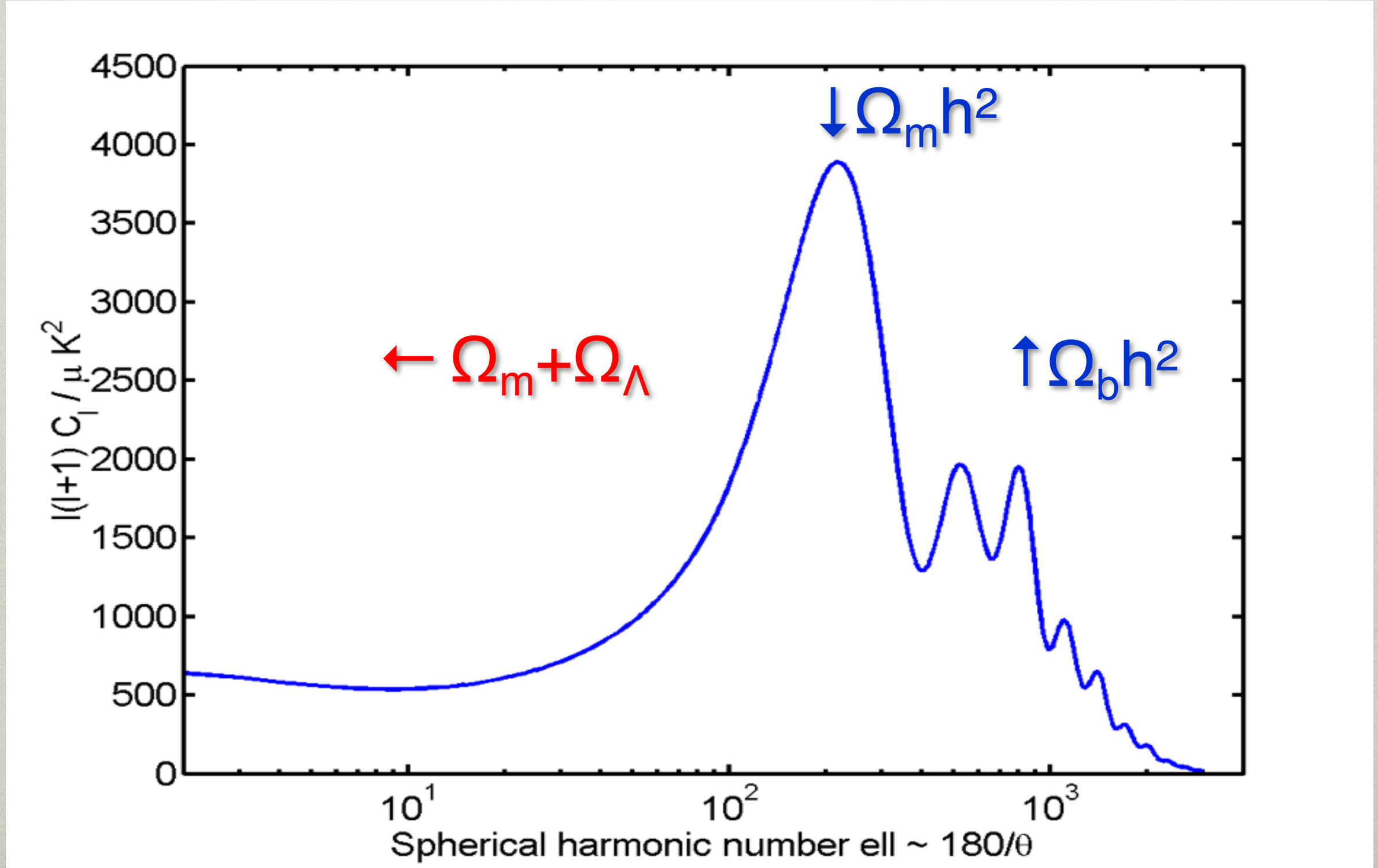
- Baryons are heavy and act to slow down the oscillations, moving them to larger k

- Baryons increase offset of over and under-densities because of gravity of baryons

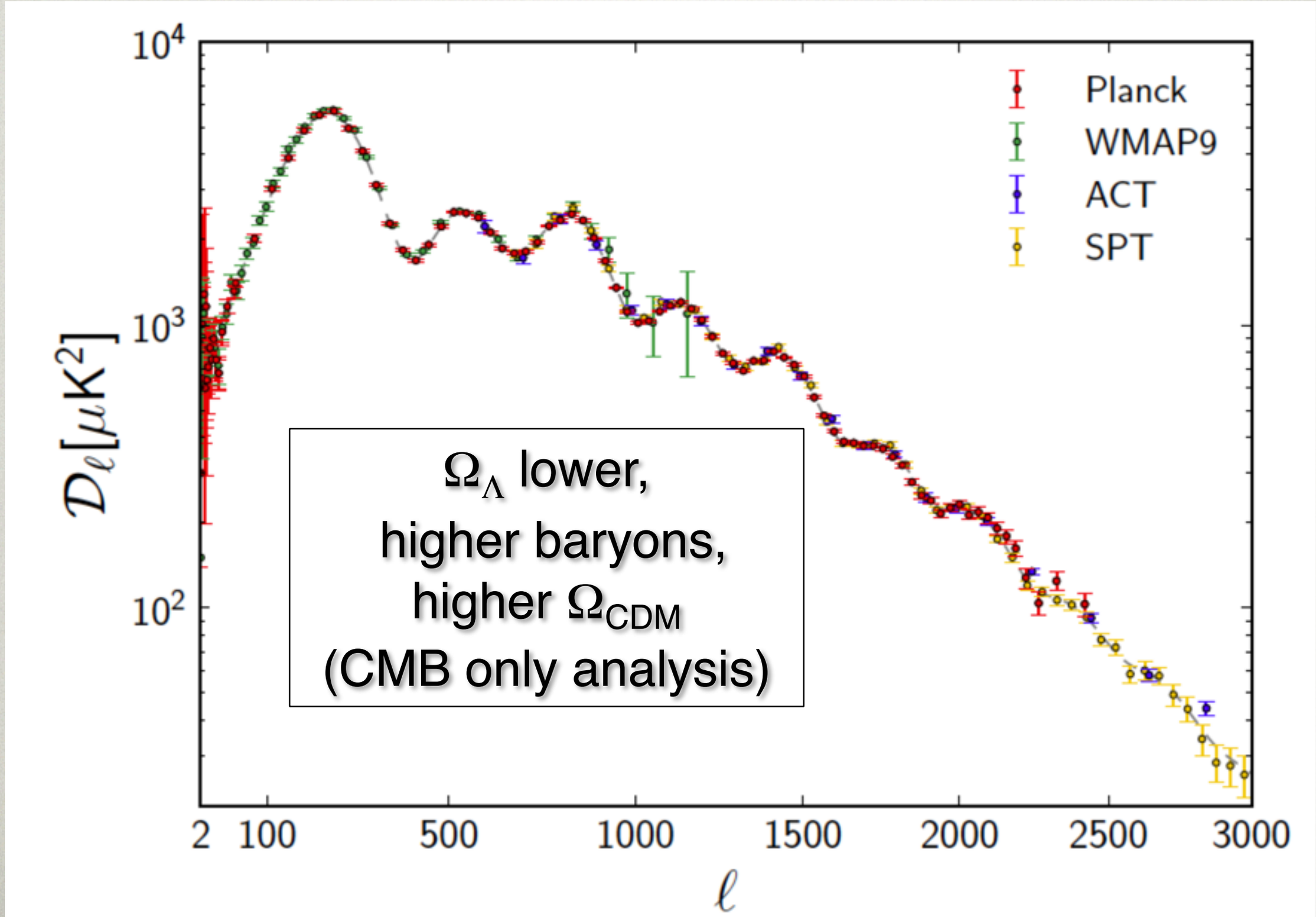


Wayne Hu

Rough guide to the CMB



Comparison with other CMB experiments



Cosmological Parameters

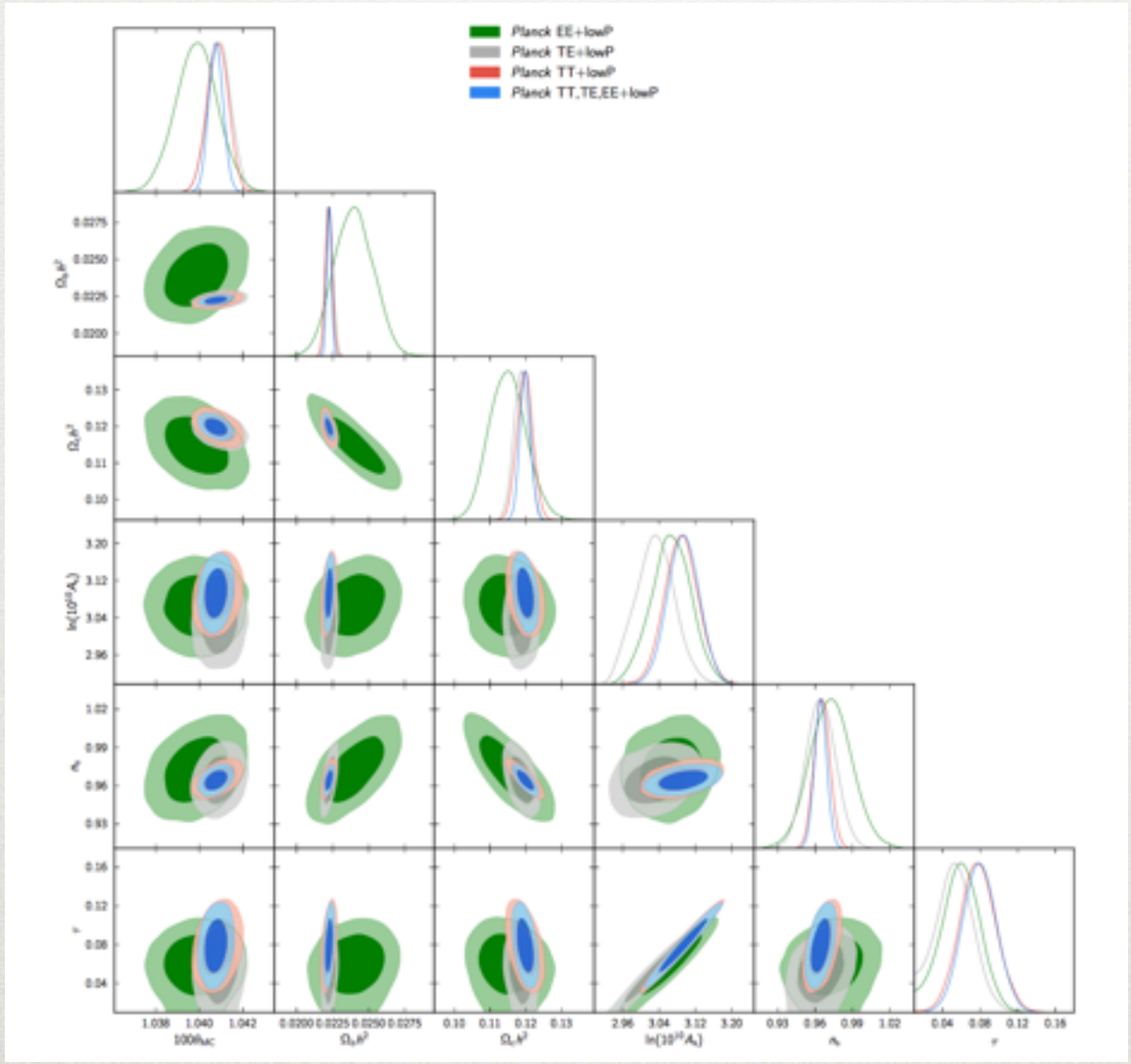
- Universe content: $\Omega_{\mathbf{b}}$, $\Omega_{\mathbf{DM}}$, $\Omega_{\mathbf{v}}$, $w(z)$
- Universe dynamics: $H_{\mathbf{0}}$
- Clumpiness: σ_8, $n_{\mathbf{s}}(k)$
- Primordial gravity waves: $A_{\mathbf{t}}$, $n_{\mathbf{t}}$
- When the first stars formed: $z_{\mathbf{re}}$
- Other: WDM, isocurvature, non-Gaussianity...

Each parameter has an effect on the CMB

Cosmological Parameters

- CMB can be predicted by numerically solving the Einstein-Boltzmann equations
- See Dodelson “Modern Cosmology” for a review

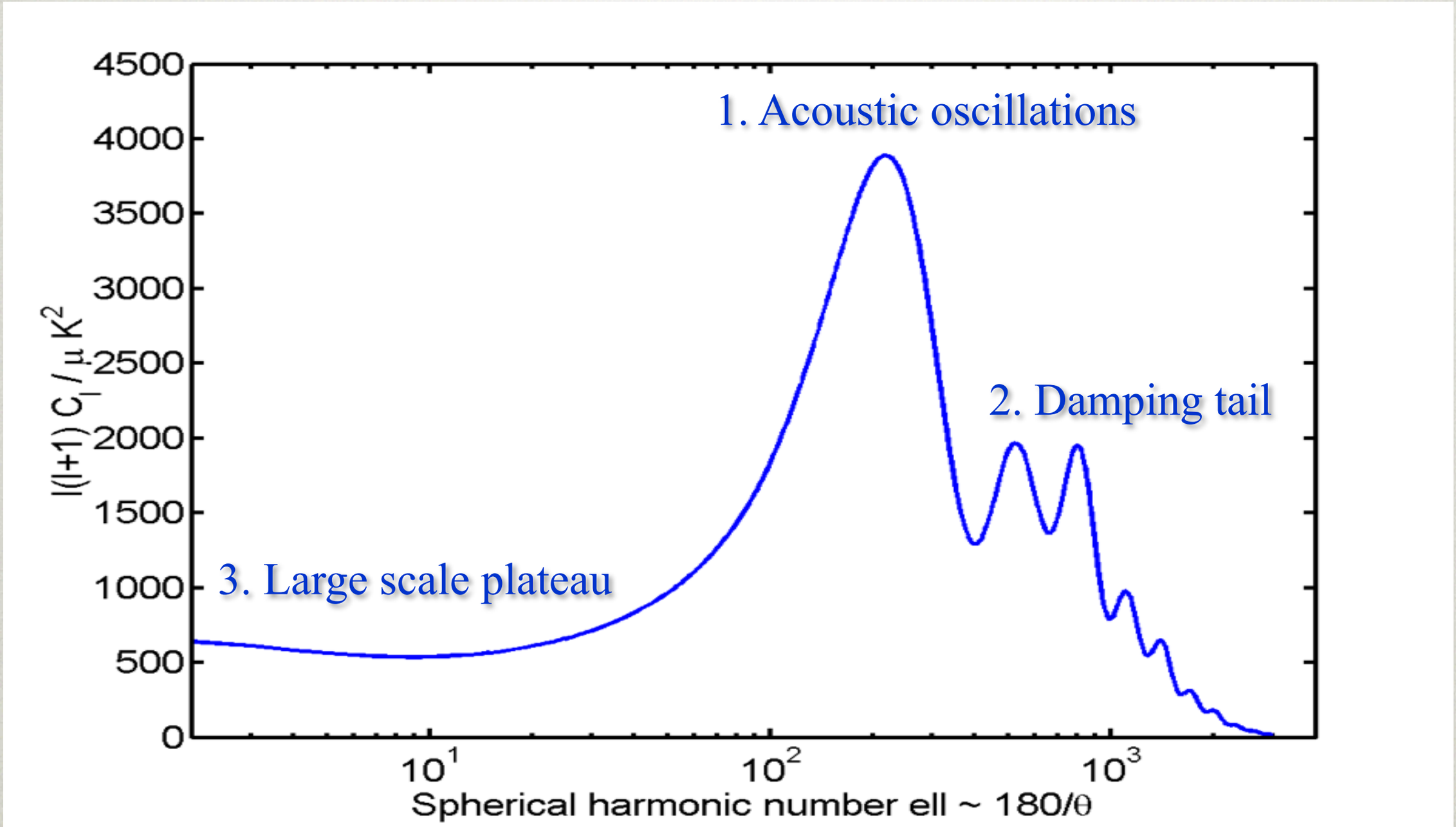
Cosmological parameters for Planck



Implications for Universe - dark matter, dark energy!

Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_c h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
n_s	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040
H_0	67.31 ± 0.96	67.81 ± 0.92	67.90 ± 0.55	67.27 ± 0.66	67.51 ± 0.64	67.74 ± 0.46
Ω_Λ	0.685 ± 0.013	0.692 ± 0.012	0.6935 ± 0.0072	0.6844 ± 0.0091	0.6879 ± 0.0087	0.6911 ± 0.0062
Ω_m	0.315 ± 0.013	0.308 ± 0.012	0.3065 ± 0.0072	0.3156 ± 0.0091	0.3121 ± 0.0087	0.3089 ± 0.0062
$\Omega_m h^2$	0.1426 ± 0.0020	0.1415 ± 0.0019	0.1413 ± 0.0011	0.1427 ± 0.0014	0.1422 ± 0.0013	0.14170 ± 0.00097
$\Omega_m h^3$	0.09597 ± 0.00045	0.09591 ± 0.00045	0.09593 ± 0.00045	0.09601 ± 0.00029	0.09596 ± 0.00030	0.09598 ± 0.00029
σ_8	0.829 ± 0.014	0.8149 ± 0.0093	0.8154 ± 0.0090	0.831 ± 0.013	0.8150 ± 0.0087	0.8159 ± 0.0086
$\sigma_8 \Omega_m^{0.5}$	0.466 ± 0.013	0.4521 ± 0.0088	0.4514 ± 0.0066	0.4668 ± 0.0098	0.4553 ± 0.0068	0.4535 ± 0.0059
$\sigma_8 \Omega_m^{0.25}$	0.621 ± 0.013	0.6069 ± 0.0076	0.6066 ± 0.0070	0.623 ± 0.011	0.6091 ± 0.0067	0.6083 ± 0.0066
z_{re}	$9.9^{+1.8}_{-1.6}$	$8.8^{+1.7}_{-1.4}$	$8.9^{+1.3}_{-1.2}$	$10.0^{+1.7}_{-1.5}$	$8.5^{+1.4}_{-1.2}$	$8.8^{+1.2}_{-1.1}$
$10^9 A_s$	$2.198^{+0.076}_{-0.085}$	2.139 ± 0.063	2.143 ± 0.051	2.207 ± 0.074	2.130 ± 0.053	2.142 ± 0.049
$10^9 A_s e^{-2\tau}$	1.880 ± 0.014	1.874 ± 0.013	1.873 ± 0.011	1.882 ± 0.012	1.878 ± 0.011	1.876 ± 0.011
Age/Gyr	13.813 ± 0.038	13.799 ± 0.038	13.796 ± 0.029	13.813 ± 0.026	13.807 ± 0.026	13.799 ± 0.021
z_*	1090.09 ± 0.42	1089.94 ± 0.42	1089.90 ± 0.30	1090.06 ± 0.30	1090.00 ± 0.29	1089.90 ± 0.23
r_*	144.61 ± 0.49	144.89 ± 0.44	144.93 ± 0.30	144.57 ± 0.32	144.71 ± 0.31	144.81 ± 0.24
$100\theta_*$	1.04105 ± 0.00046	1.04122 ± 0.00045	1.04126 ± 0.00041	1.04096 ± 0.00032	1.04106 ± 0.00031	1.04112 ± 0.00029
z_{drag}	1059.57 ± 0.46	1059.57 ± 0.47	1059.60 ± 0.44	1059.65 ± 0.31	1059.62 ± 0.31	1059.68 ± 0.29
r_{drag}	147.33 ± 0.49	147.60 ± 0.43	147.63 ± 0.32	147.27 ± 0.31	147.41 ± 0.30	147.50 ± 0.24
k_D	0.14050 ± 0.00052	0.14024 ± 0.00047	0.14022 ± 0.00042	0.14059 ± 0.00032	0.14044 ± 0.00032	0.14038 ± 0.00029
z_{eq}	3393 ± 49	3365 ± 44	3361 ± 27	3395 ± 33	3382 ± 32	3371 ± 23
k_{eq}	0.01035 ± 0.00015	0.01027 ± 0.00014	0.010258 ± 0.000083	0.01036 ± 0.00010	0.010322 ± 0.000096	0.010288 ± 0.000071
$100\theta_{s,eq}$	0.4502 ± 0.0047	0.4529 ± 0.0044	0.4533 ± 0.0026	0.4499 ± 0.0032	0.4512 ± 0.0031	0.4523 ± 0.0023
f_{2000}^{143}	29.9 ± 2.9	30.4 ± 2.9	30.3 ± 2.8	29.5 ± 2.7	30.2 ± 2.7	30.0 ± 2.7
$f_{2000}^{143\times217}$	32.4 ± 2.1	32.8 ± 2.1	32.7 ± 2.0	32.2 ± 1.9	32.8 ± 1.9	32.6 ± 1.9
f_{2000}^{217}	106.0 ± 2.0	106.3 ± 2.0	106.2 ± 2.0	105.8 ± 1.9	106.2 ± 1.9	106.1 ± 1.8

REGIMES OF CMB POWER



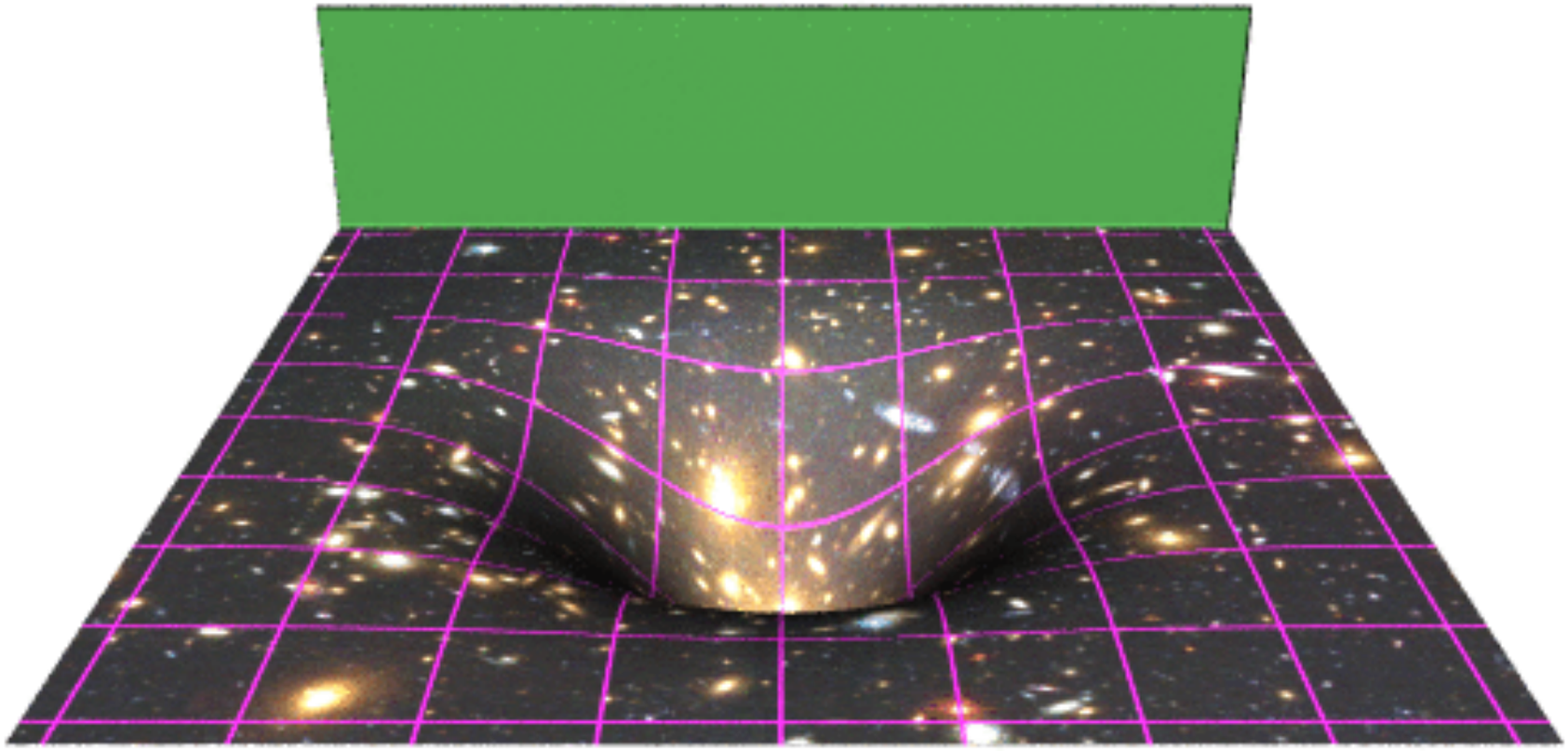
3. Large scale plateau

(*l*< *100*)

- At last-scattering surface, photons have to climb from potential wells (the *Sachs-Wolfe Effect*)
- Gravitational potential wells due to DM
- Happen at all scales, but most important at large scales (where causal effects are not important)

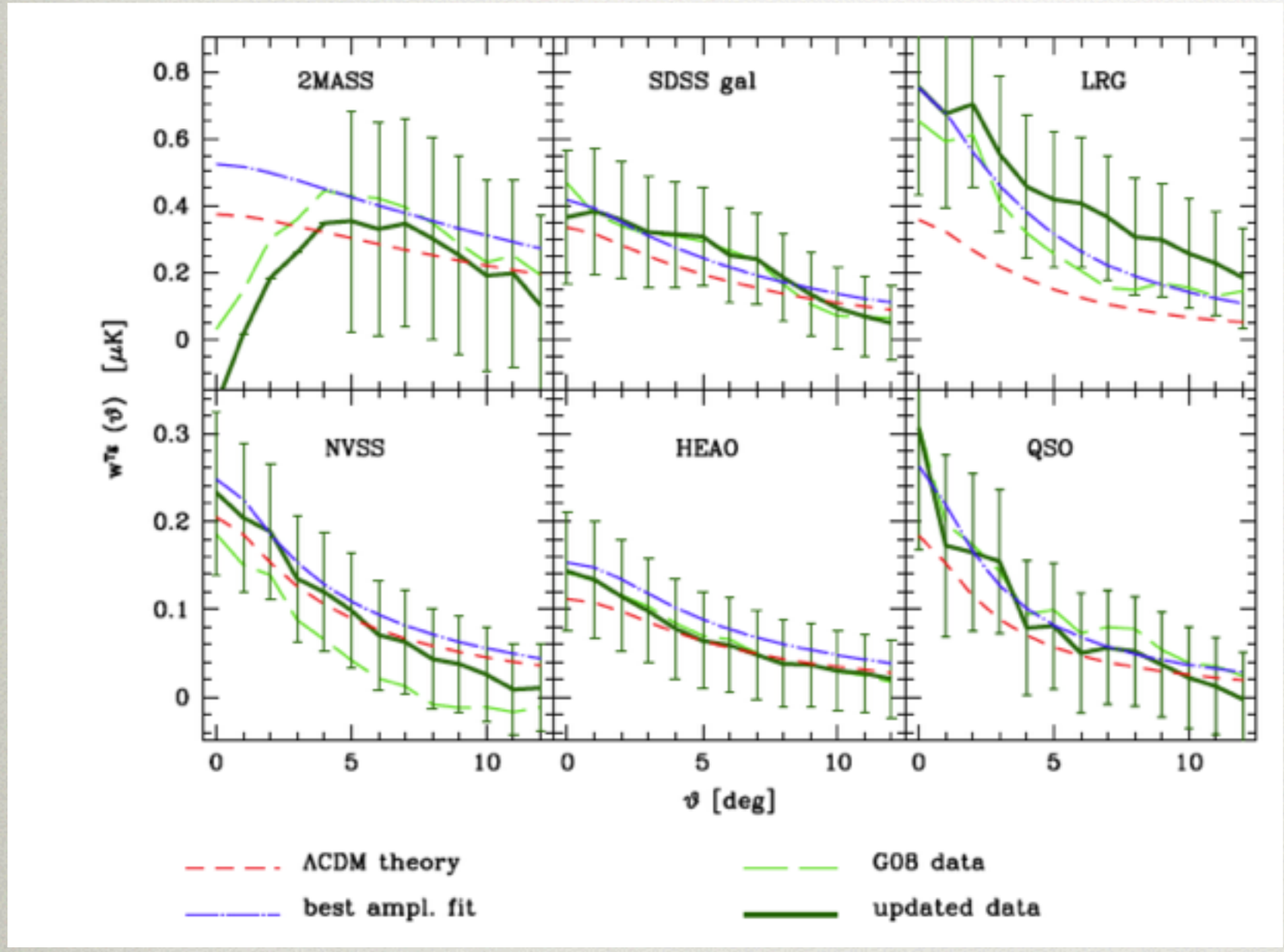
Integrated Sachs-Wolfe effect

$$\frac{\Delta T}{T}(\hat{\mathbf{n}}_2) = -2\int \mathrm{e}^{-\tau(z)}\,\frac{d\Phi}{dz}(\hat{\mathbf{n}}_2, z)dz$$



Szapudi et al

ISW Effect



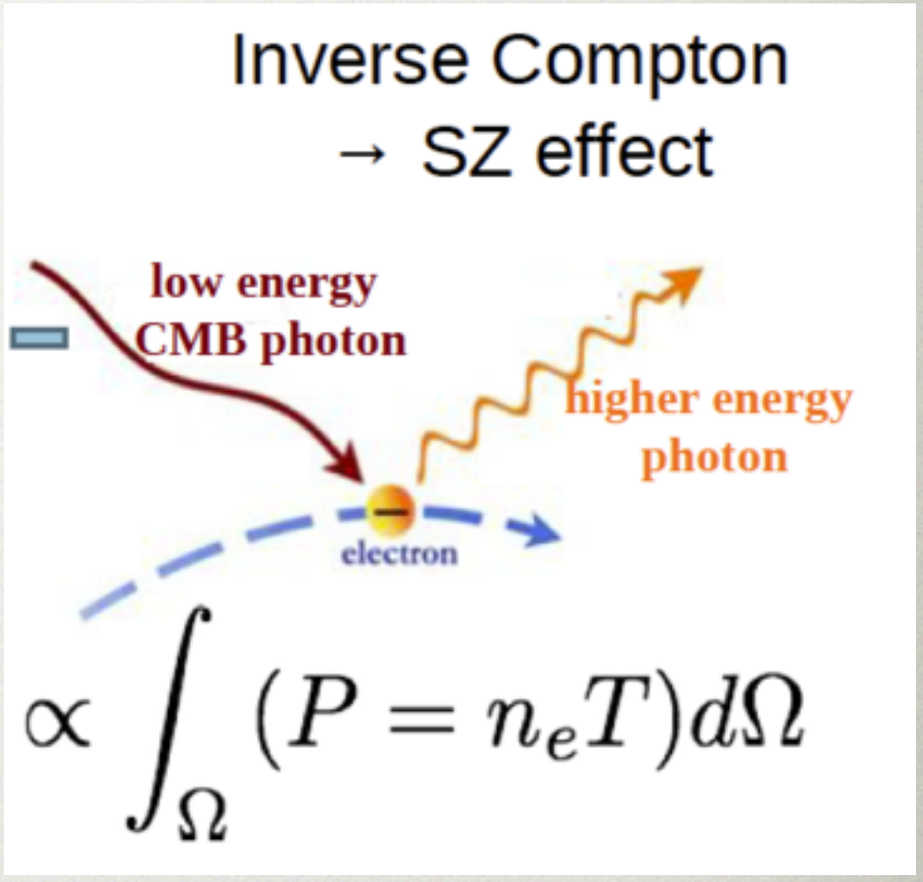
Achromatic
4.4+/-0.4 sigma

Giannantonio et al 2012

With no DE, we expect nothing!

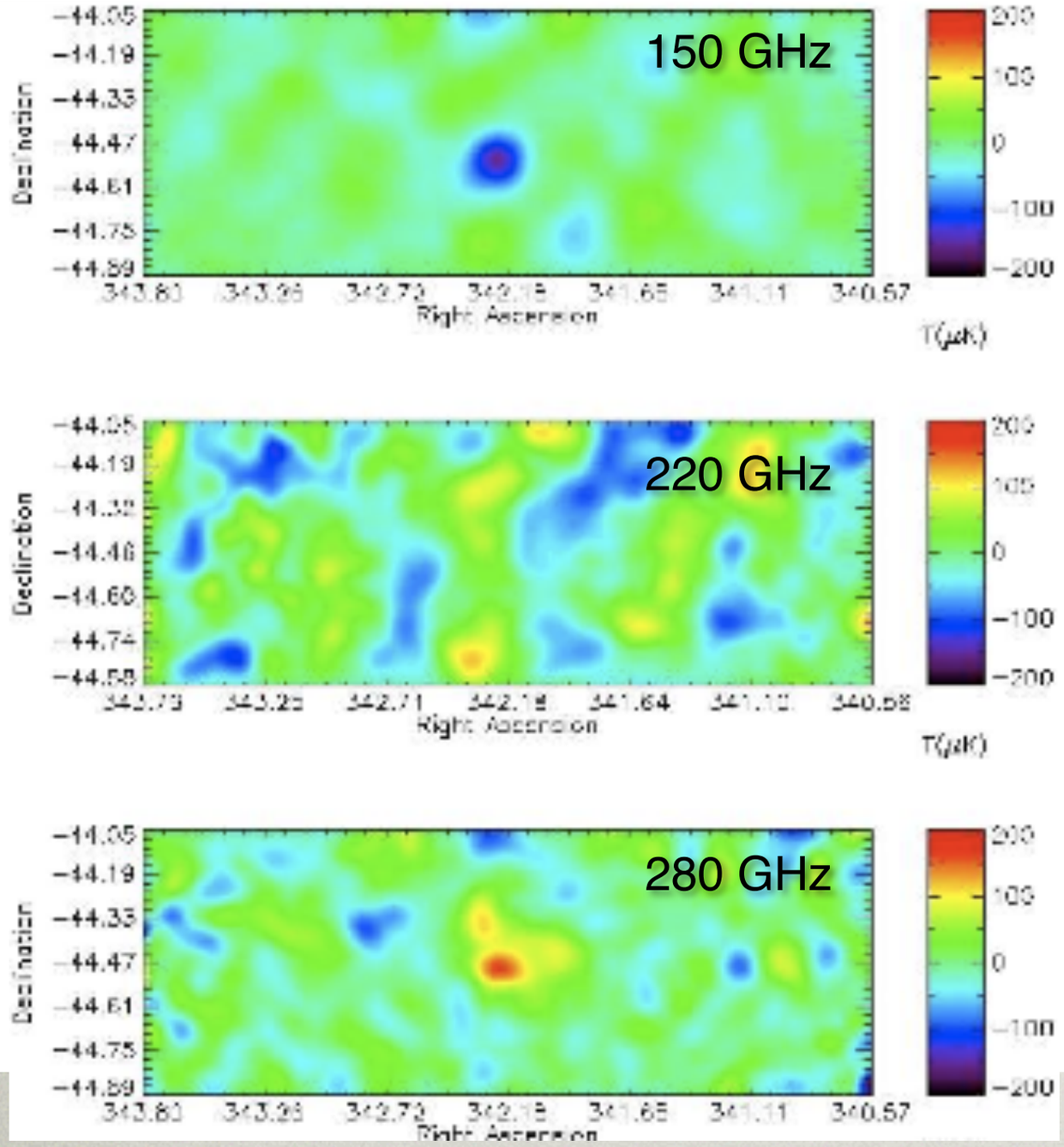
Sunyaev-Zel'dovich effect

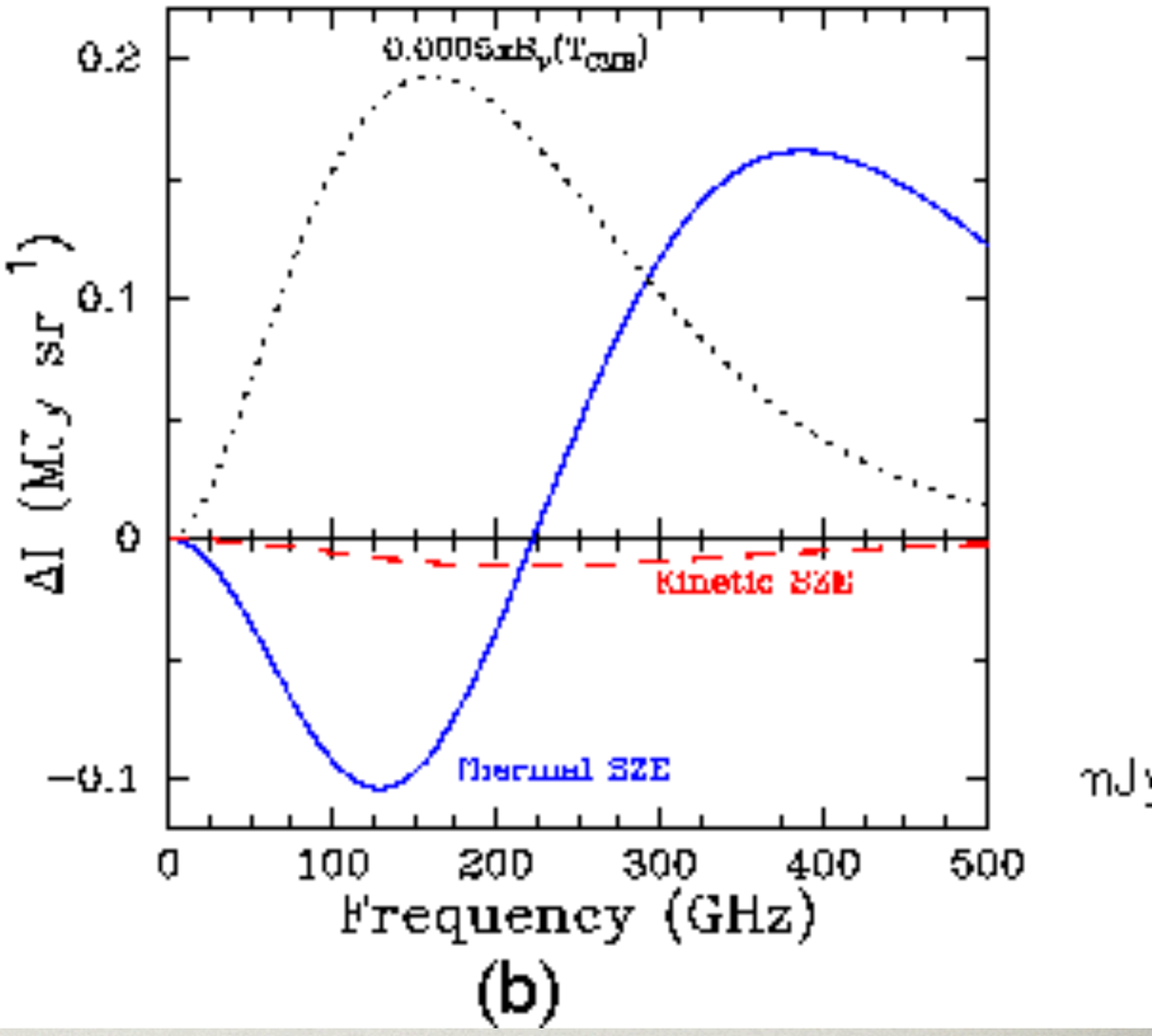
- high energy electrons (in the centres of clusters) inverse Compton scatter CMB photons; give energy to photons
- divided into
  - kinetic SZ effect (energy transfer due to motion of electrons)
  - thermal SZ effect (energy transfer due to temperature of electrons)



SZ

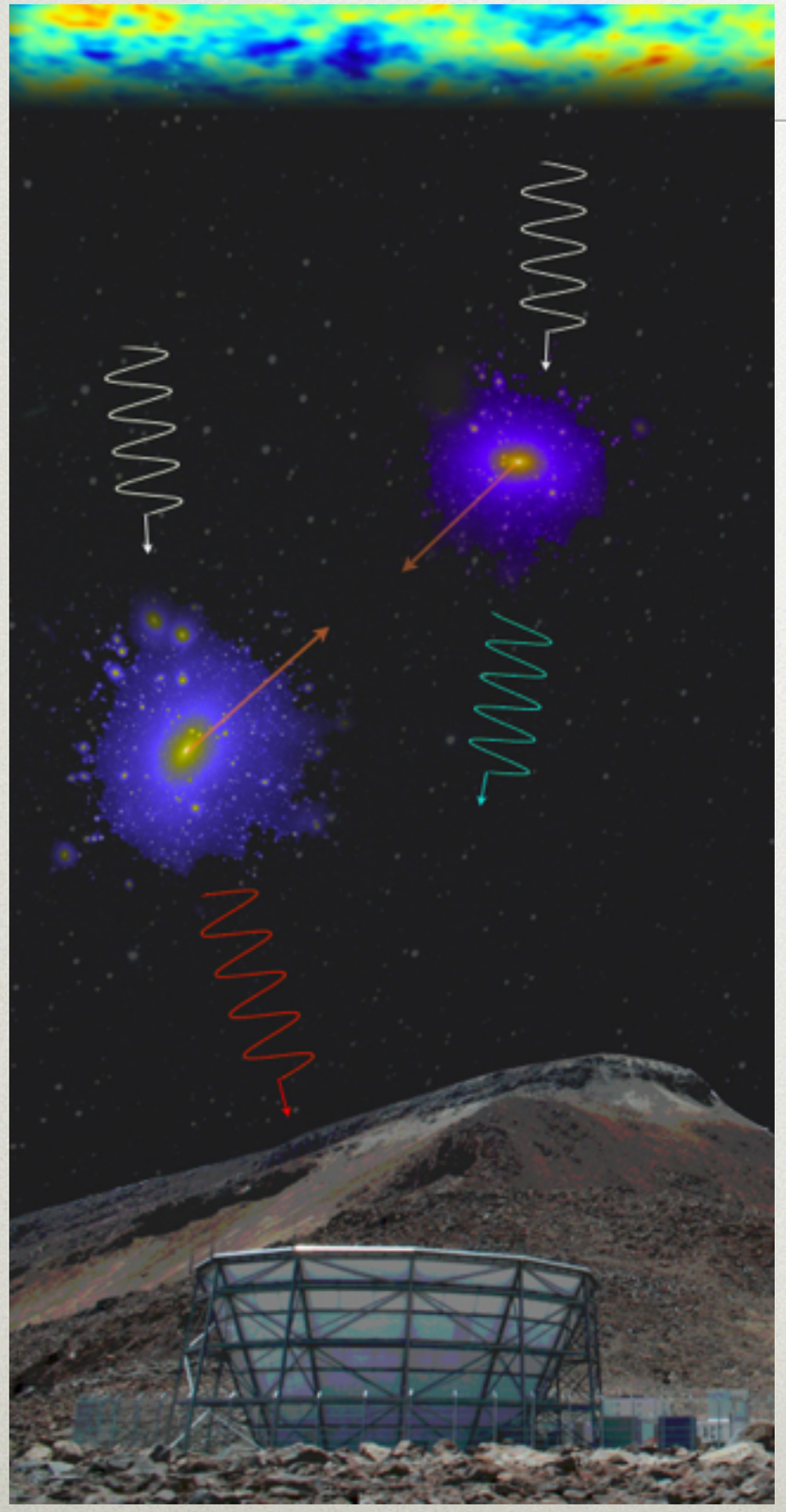
ACBAR cluster at z=0.35





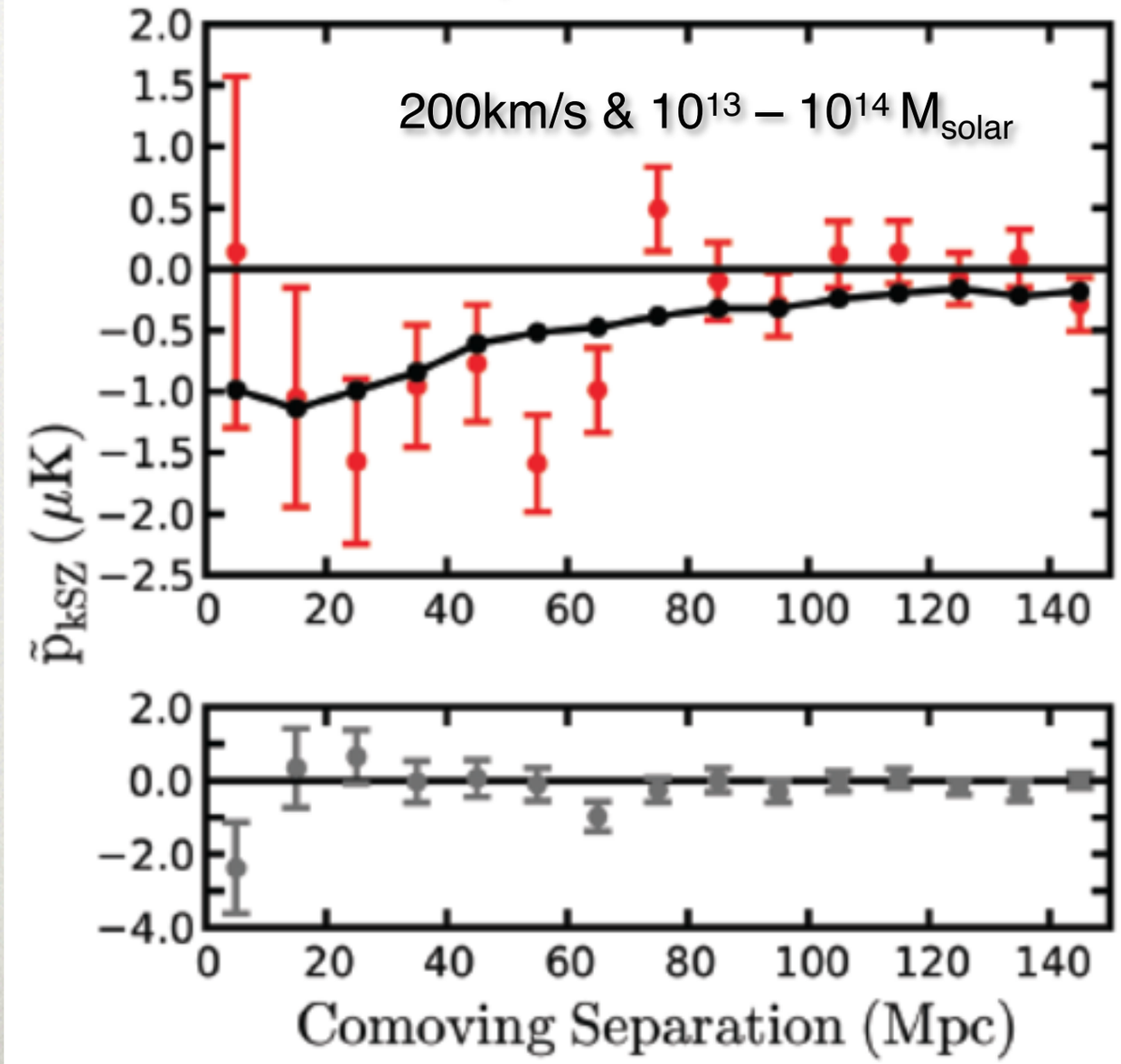
Conservation of photons

Kinetic SZ



$$\frac{\Delta T_{SZE}}{T_{CMB}} = -\tau_e \left(\frac{v_{pec}}{c} \right),$$

Hand et al. 2012 (ACT+BOSS cross-correlation)



Summary

The CMB features clearly show:

- we need more matter than mere baryons;

- we need more energy-density than mere matter.