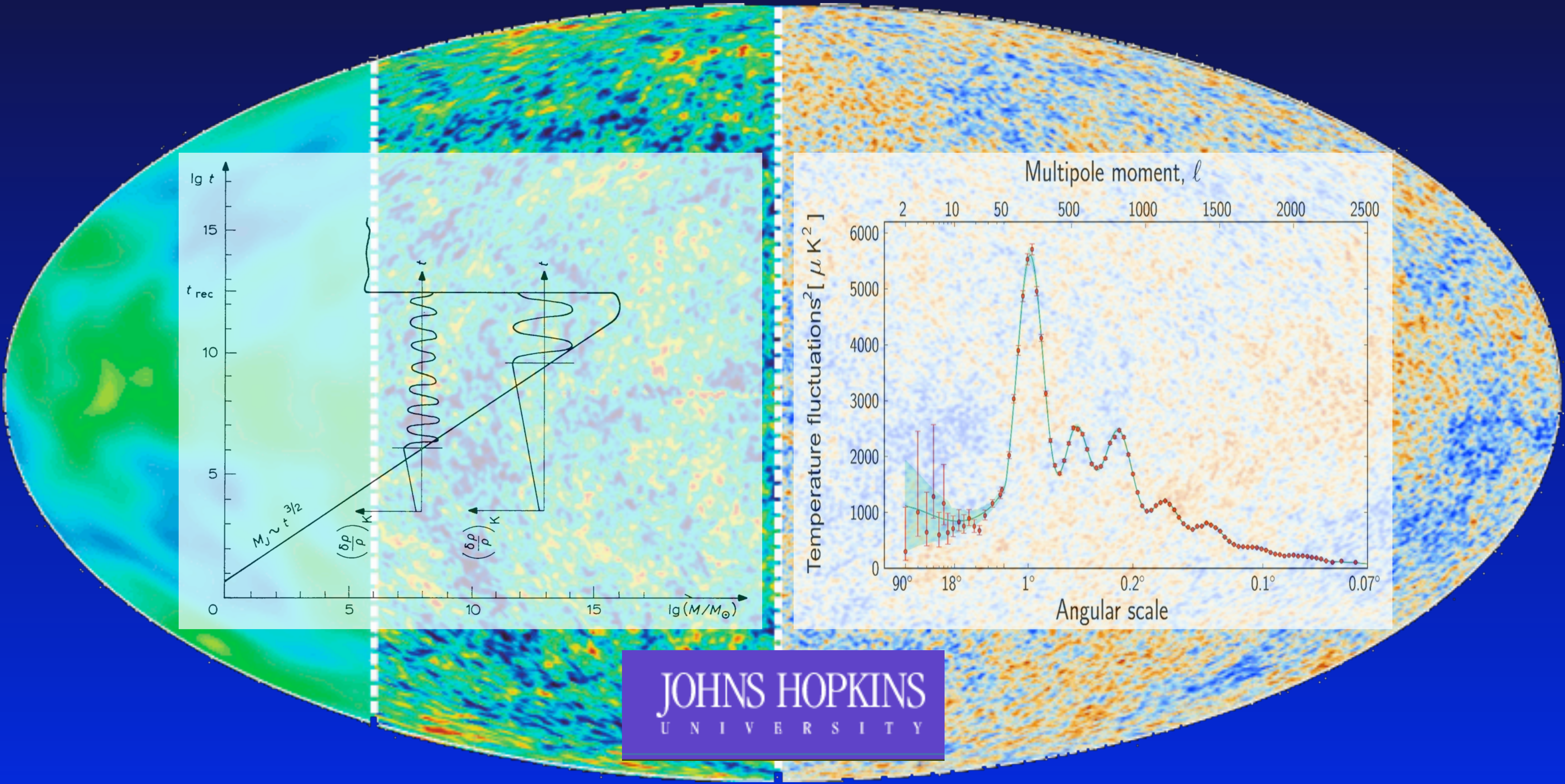
Physics of the Cosmic Microwave Background



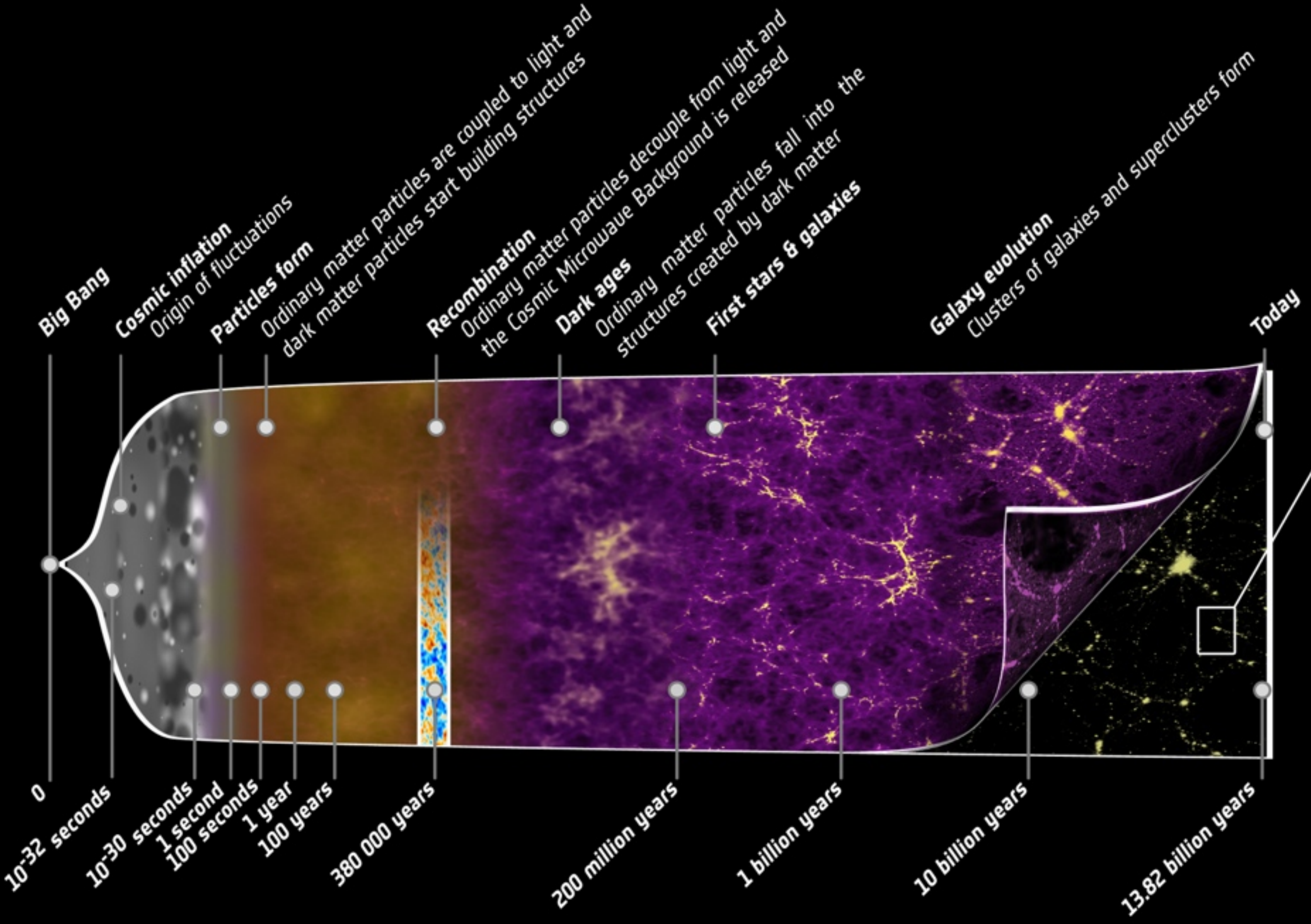
JOHNS HOPKINS
UNIVERSITY

Jens Chluba

School on Cosmological Tools

IFT, Madrid, Spain, Nov 12th - 15th, 2013

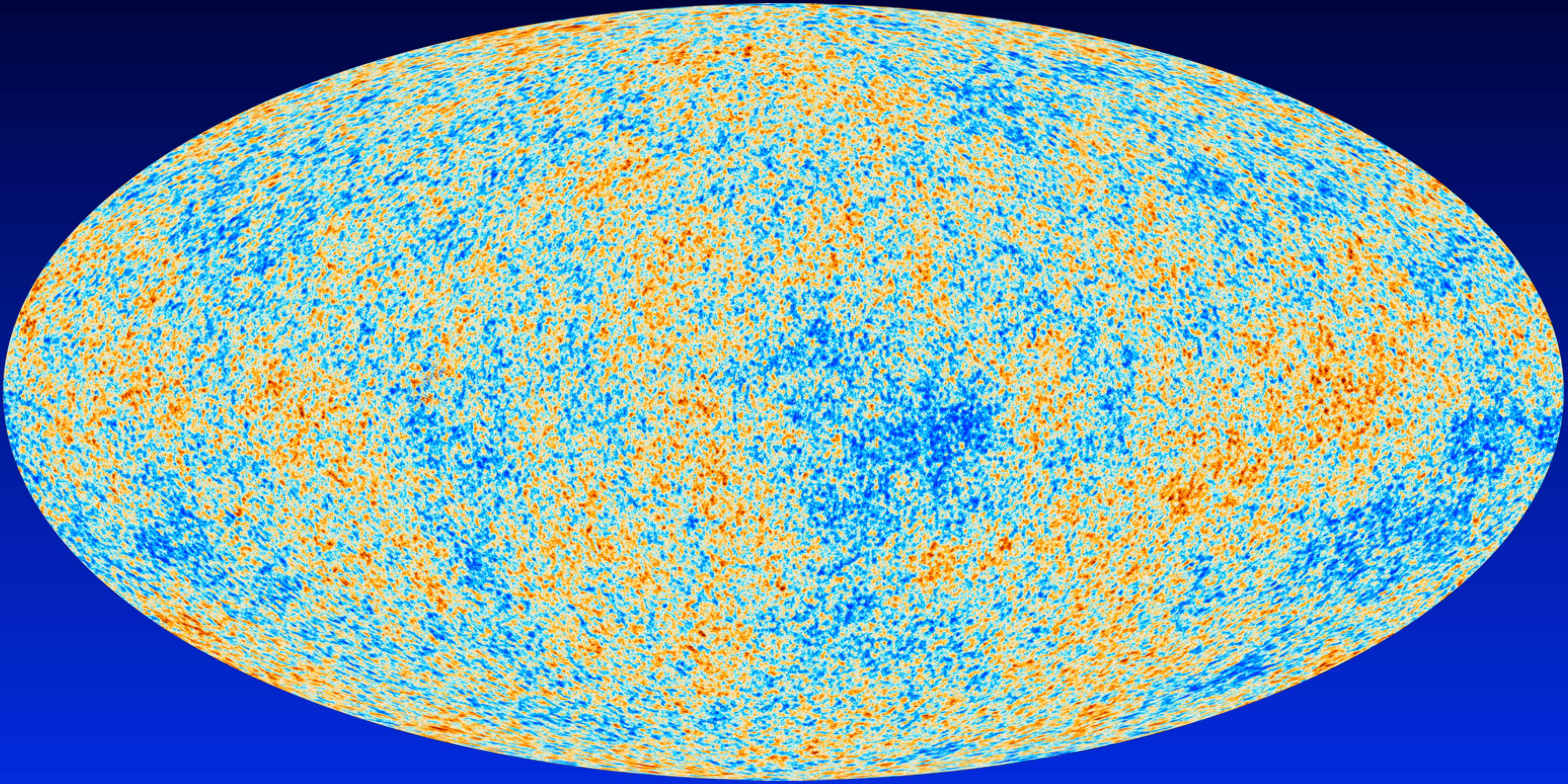
CITA
ICAT
Canadian Institute for
Theoretical Astrophysics
L'institut canadien
d'astrophysique theorique


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
0
10^{-32} seconds
10^{-30} seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

Some of the Big Questions of Cosmology

- What is the Universe made of?
- What are the initial conditions?
- Where do all the structures come from?
- Why do things look the way they do?
- Dark energy & dark matter?
- Gravitational Waves?
- Physics beyond the standard model?

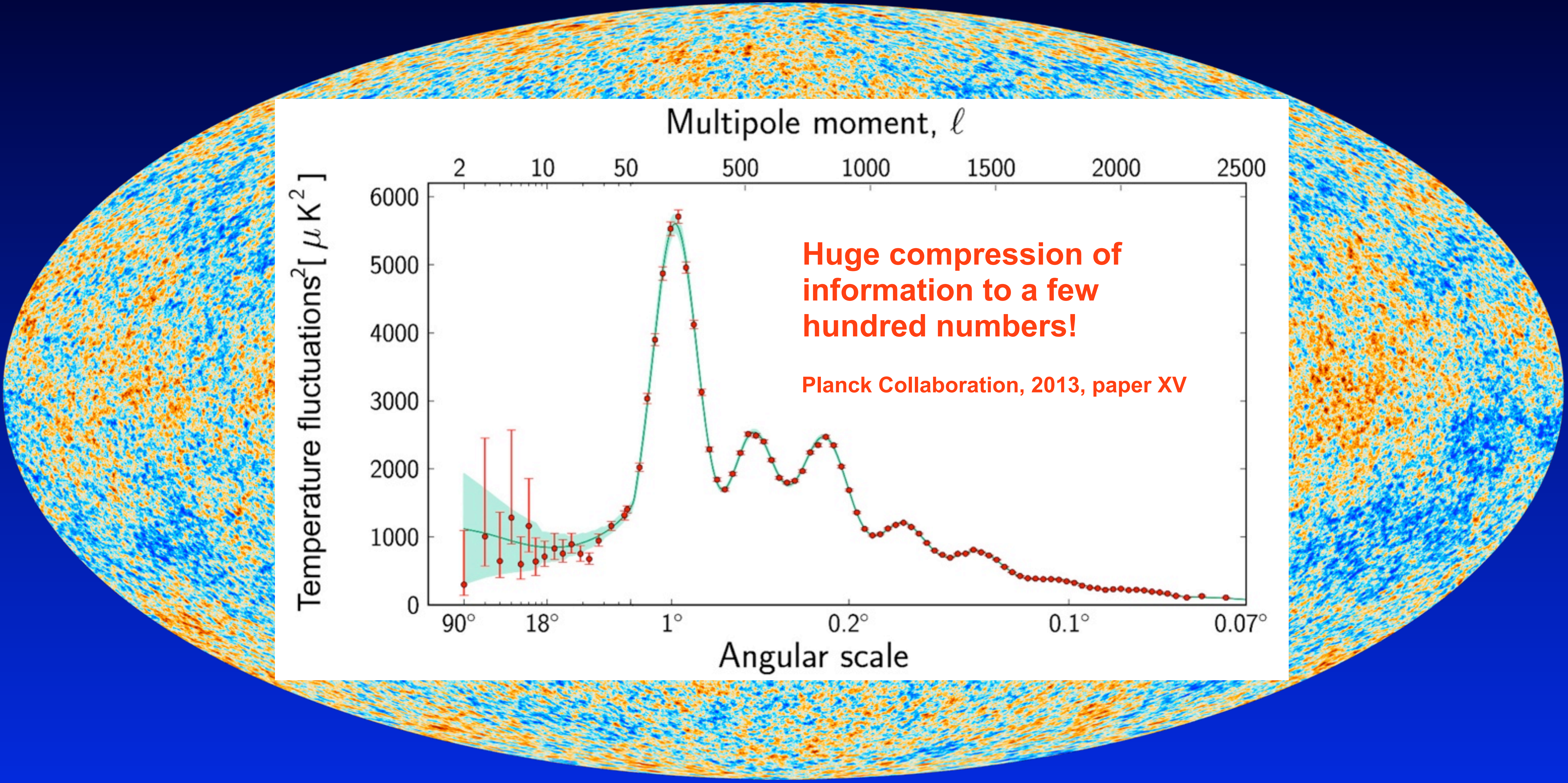
Cosmic Microwave Background Anisotropies help us to answer these questions!



Planck all sky map

- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

Cosmic Microwave Background Anisotropies help us to answer these questions!



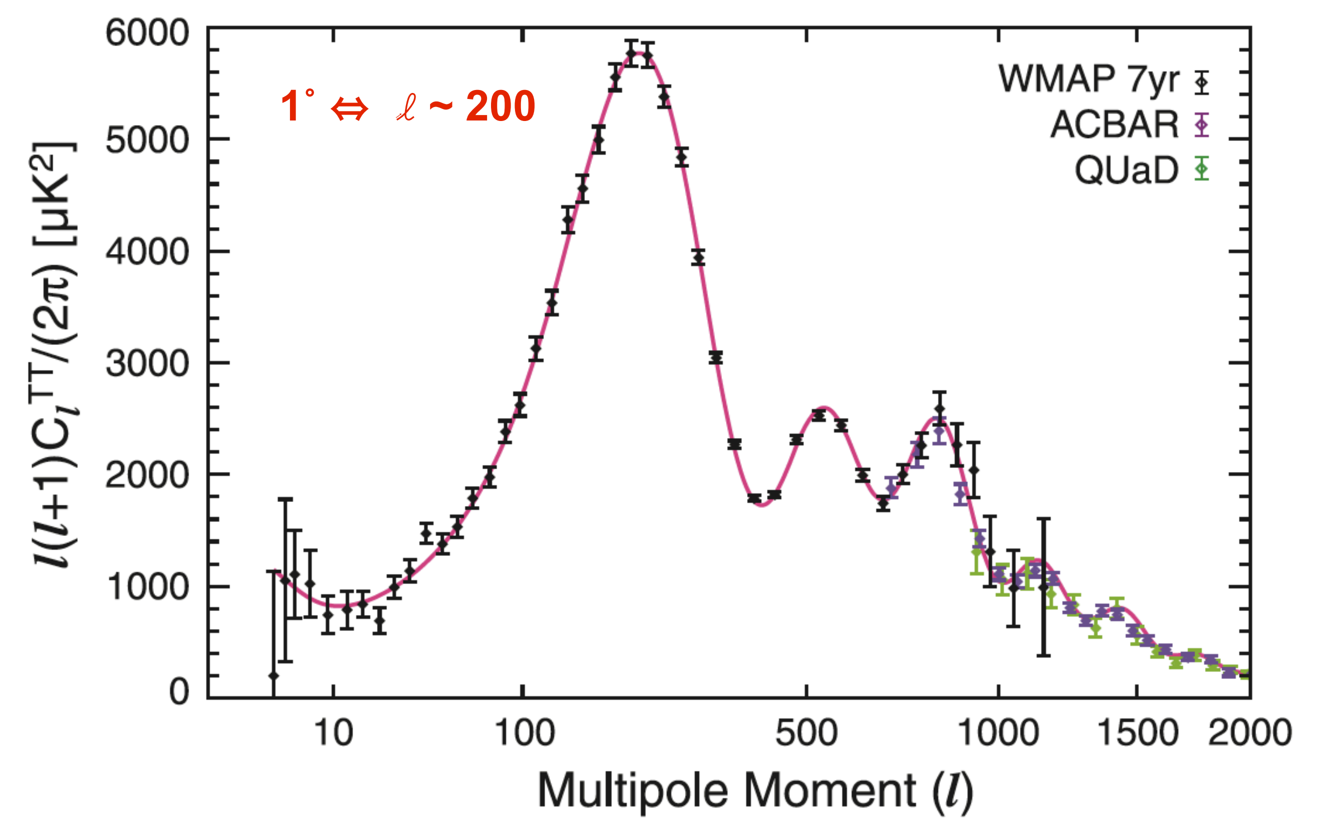
Huge compression of information to a few hundred numbers!

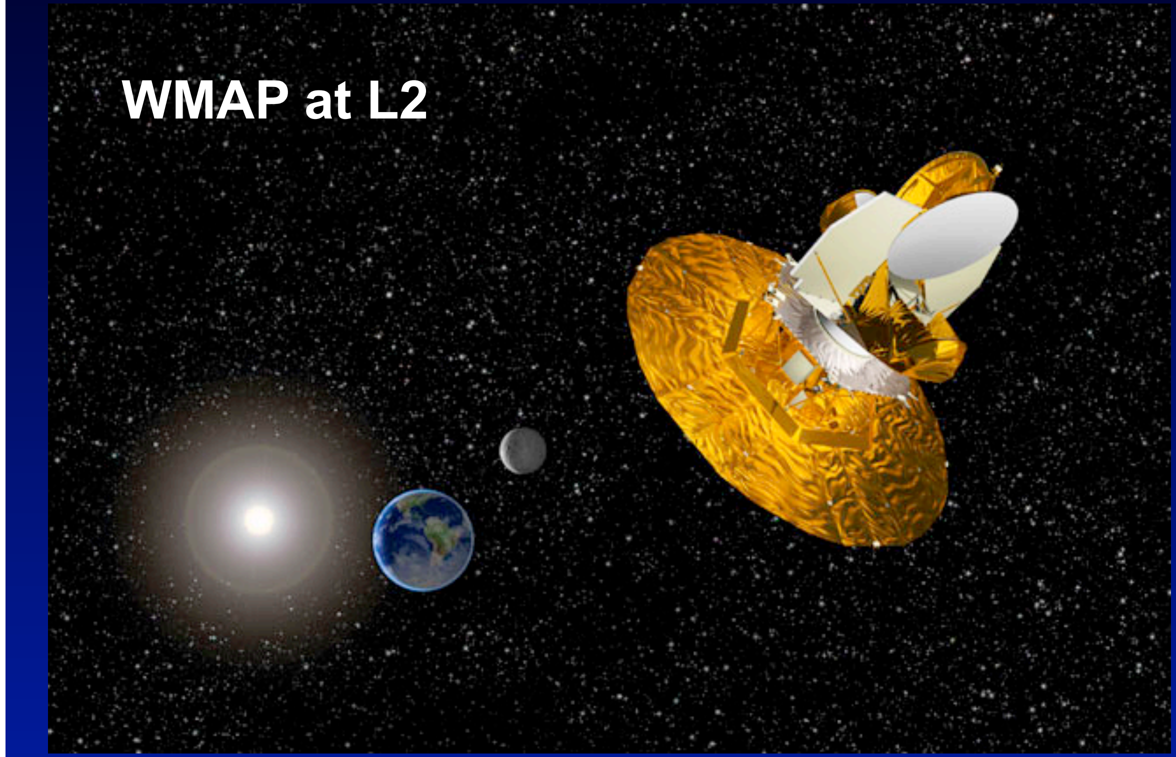
Planck Collaboration, 2013, paper XV

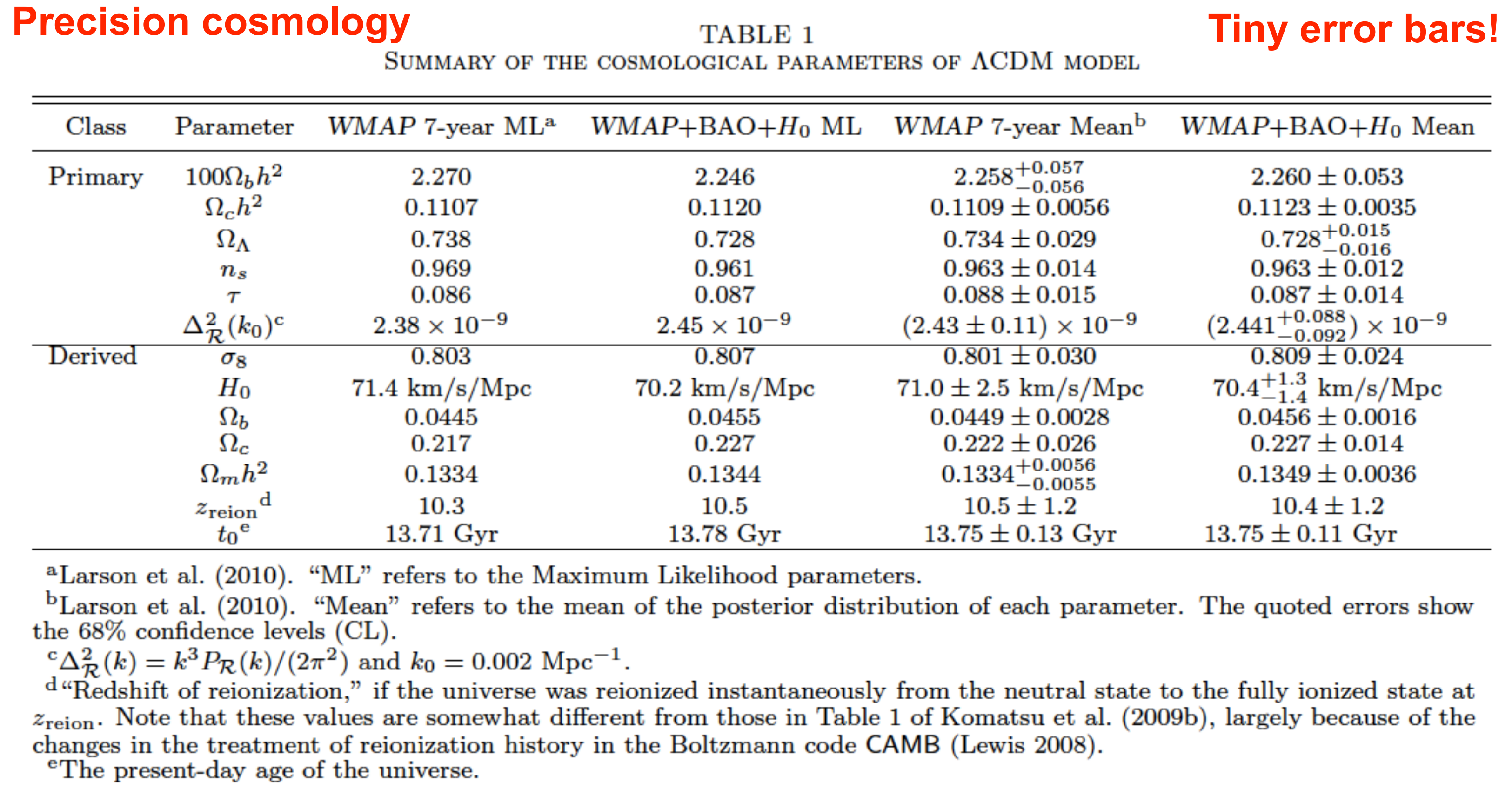
Planck all sky map

- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

CMB anisotropies clearly taught us a lot about the Universe we live in!







Precision cosmology

Tiny error bars!

TABLE 1
SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL

Class	Parameter	*WMAP* 7-year ML[a]	*WMAP*+BAO+H_0 ML	*WMAP* 7-year Mean[b]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.270	2.246	$2.258^{+0.057}_{-0.056}$	2.260 ± 0.053
	$\Omega_c h^2$	0.1107	0.1120	0.1109 ± 0.0056	0.1123 ± 0.0035
	Ω_Λ	0.738	0.728	0.734 ± 0.029	$0.728^{+0.015}_{-0.016}$
	n_s	0.969	0.961	0.963 ± 0.014	0.963 ± 0.012
	τ	0.086	0.087	0.088 ± 0.015	0.087 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[c]	2.38×10^{-9}	2.45×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.441^{+0.088}_{-0.092}) \times 10^{-9}$
Derived	σ_8	0.803	0.807	0.801 ± 0.030	0.809 ± 0.024
	H_0	71.4 km/s/Mpc	70.2 km/s/Mpc	71.0 ± 2.5 km/s/Mpc	$70.4^{+1.3}_{-1.4}$ km/s/Mpc
	Ω_b	0.0445	0.0455	0.0449 ± 0.0028	0.0456 ± 0.0016
	Ω_c	0.217	0.227	0.222 ± 0.026	0.227 ± 0.014
	$\Omega_m h^2$	0.1334	0.1344	$0.1334^{+0.0056}_{-0.0055}$	0.1349 ± 0.0036
	$z_{\rm reion}$[d]	10.3	10.5	10.5 ± 1.2	10.4 ± 1.2
	t_0[e]	13.71 Gyr	13.78 Gyr	13.75 ± 0.13 Gyr	13.75 ± 0.11 Gyr

[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.

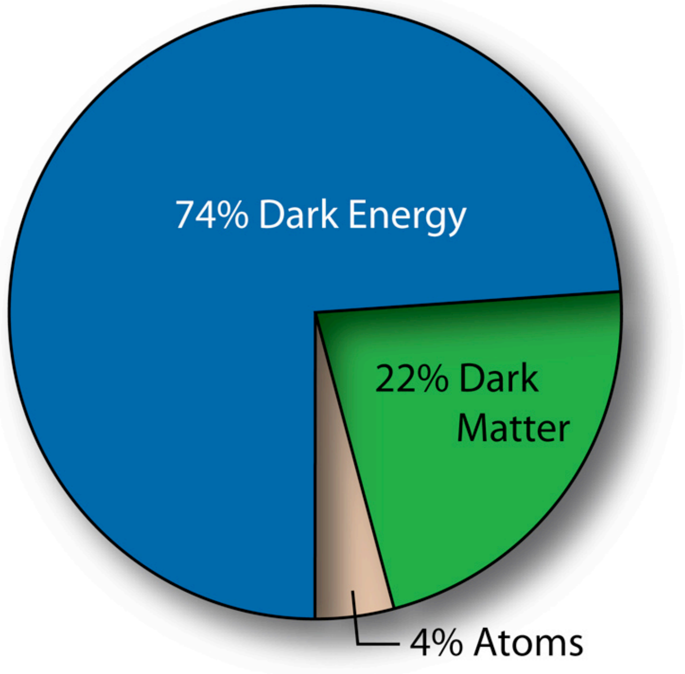
[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).

[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ Mpc^{-1}.

[d] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at $z_{\rm reion}$. Note that these values are somewhat different from those in Table 1 of Komatsu et al. (2009b), largely because of the changes in the treatment of reionization history in the Boltzmann code CAMB (Lewis 2008).

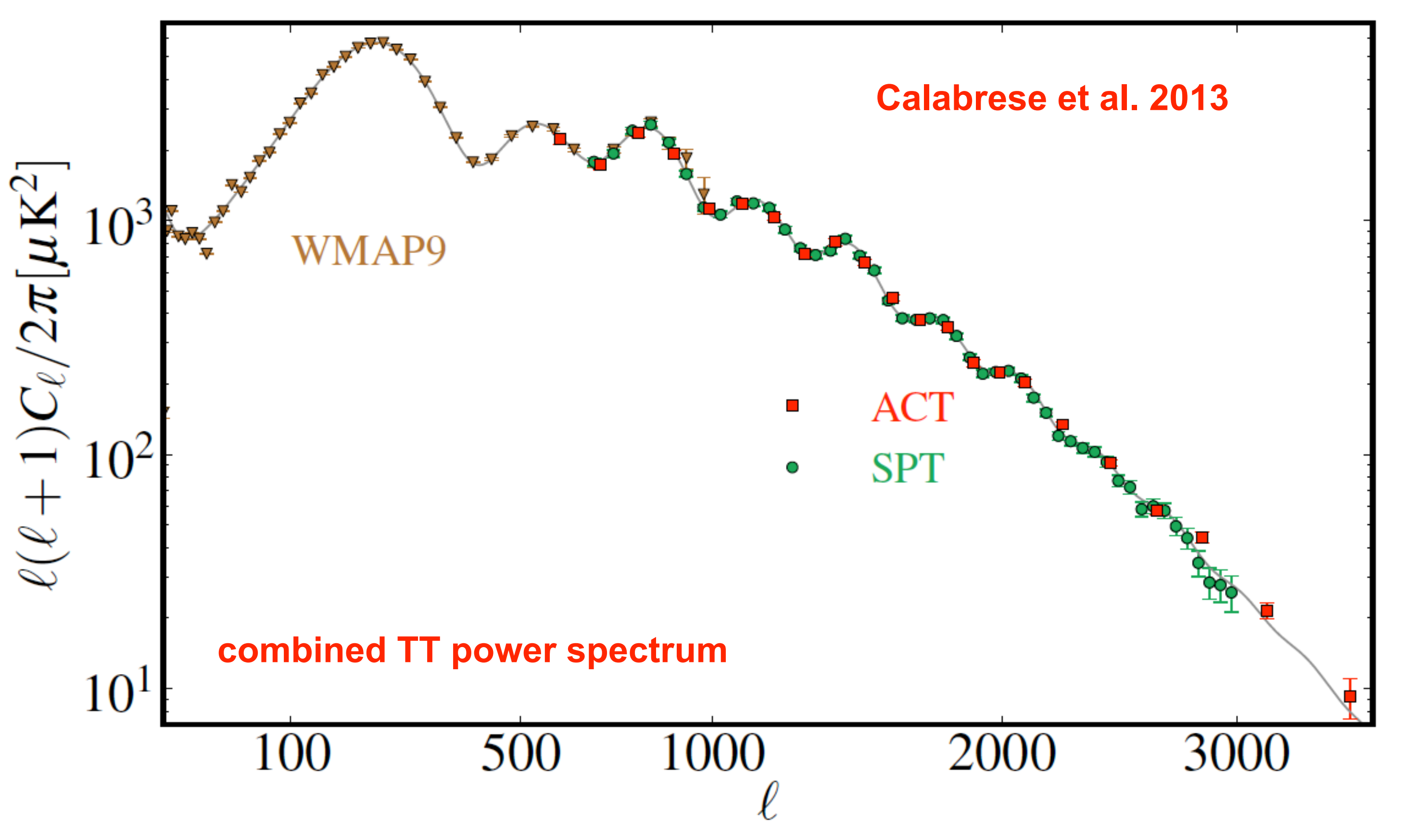
[e] The present-day age of the universe.

Pie-chart of the Universe



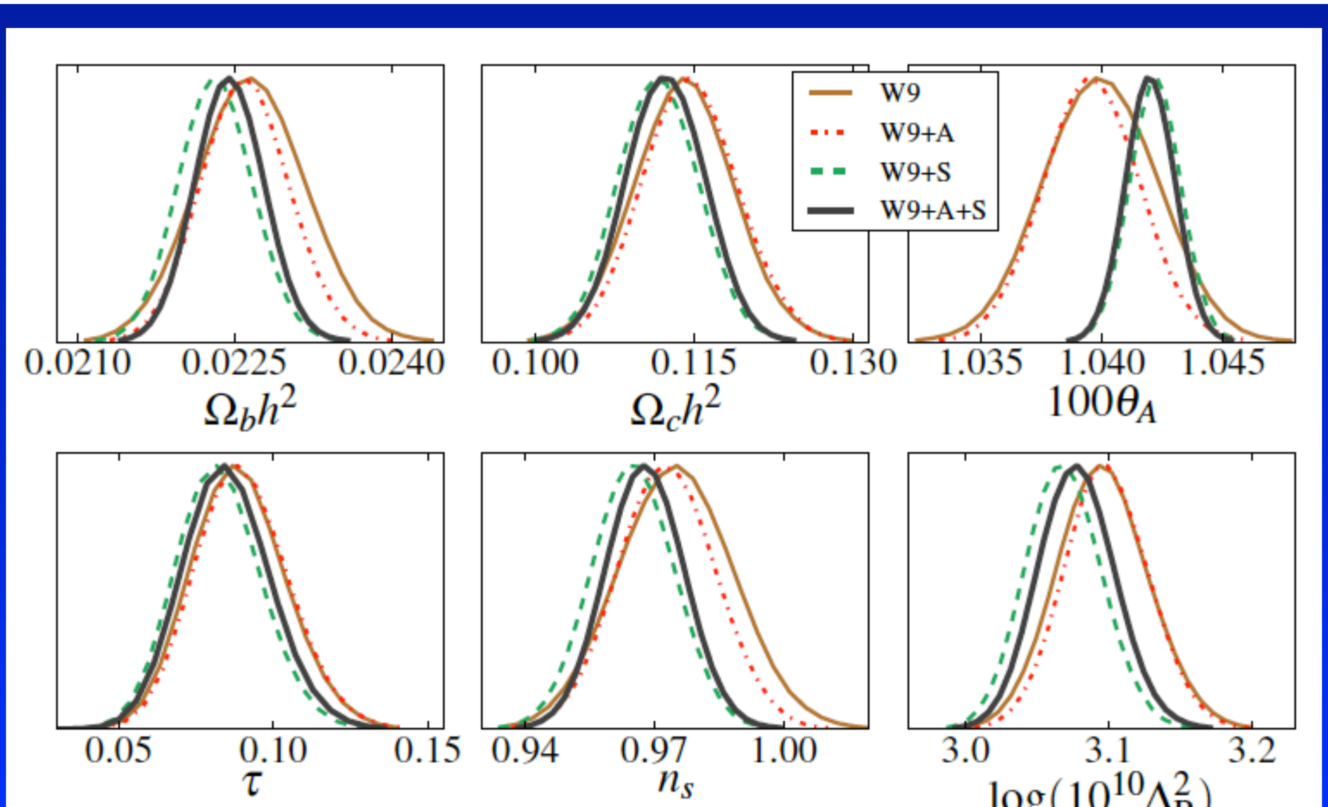
e.g. Komatsu et al., 2011, ApJ, arXiv:1001.4538
Dunkley et al., 2011, ApJ, arXiv:1009.0866

CMB anisotropies clearly taught us a lot about the Universe we live in!



Calabrese et al. 2013

combined TT power spectrum



Amazing consistency between different experiments!

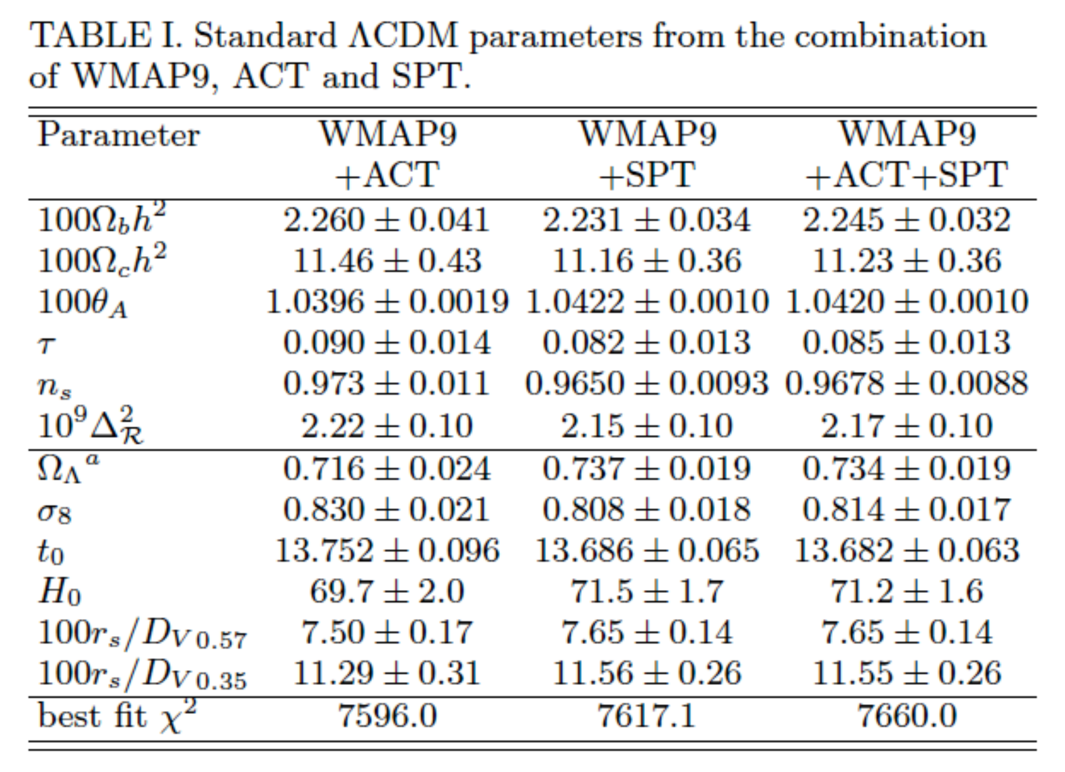
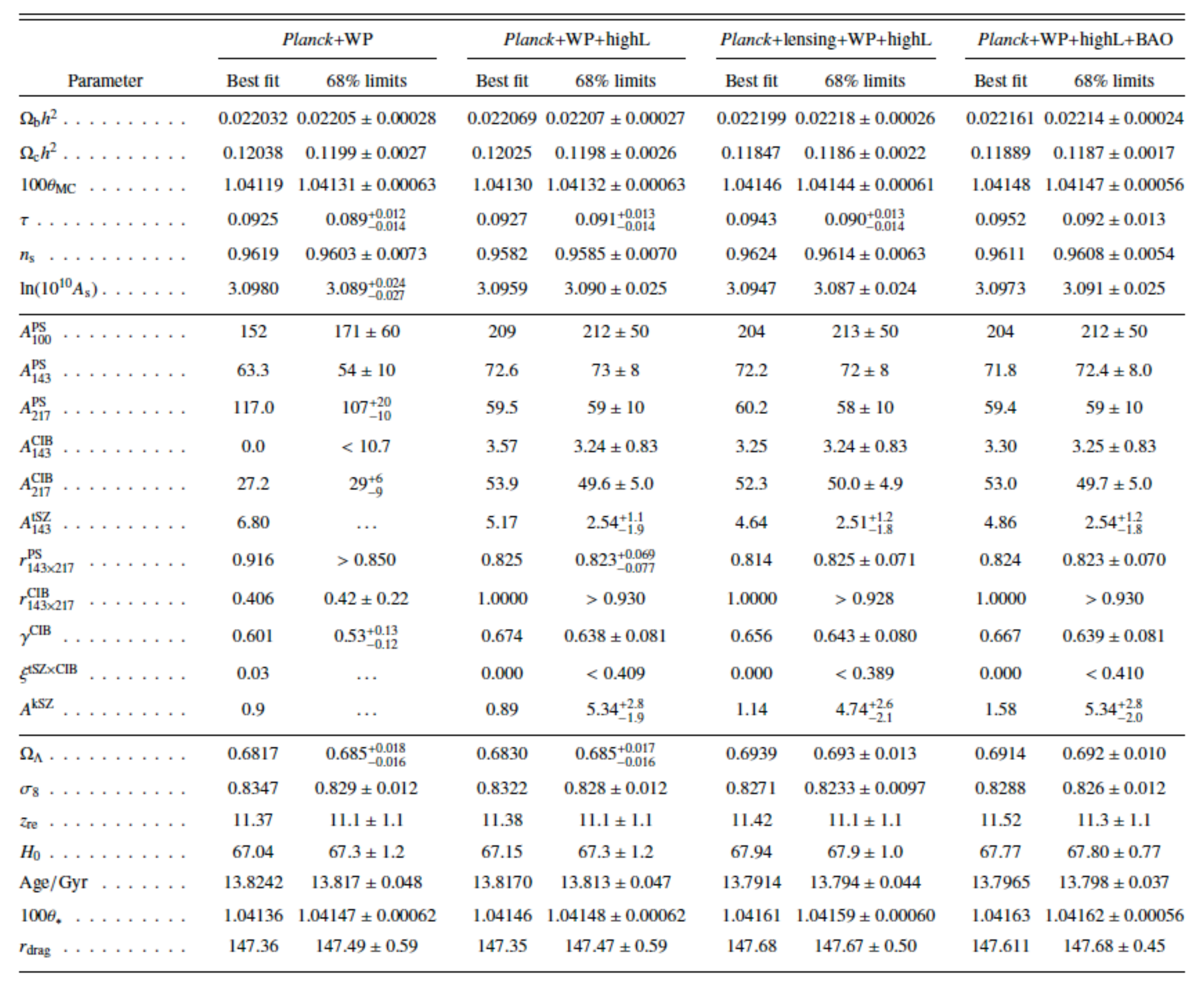


TABLE I. Standard ΛCDM parameters from the combination of WMAP9, ACT and SPT.

Parameter	WMAP9 +ACT	WMAP9 +SPT	WMAP9 +ACT+SPT
$100\Omega_b h^2$	2.260 ± 0.041	2.231 ± 0.034	2.245 ± 0.032
$100\Omega_c h^2$	11.46 ± 0.43	11.16 ± 0.36	11.23 ± 0.36
$100\theta_A$	1.0396 ± 0.0019	1.0422 ± 0.0010	1.0420 ± 0.0010
τ	0.090 ± 0.014	0.082 ± 0.013	0.085 ± 0.013
n_s	0.973 ± 0.011	0.9650 ± 0.0093	0.9678 ± 0.0088
$10^9\Delta^2_{\mathcal{R}}$	2.22 ± 0.10	2.15 ± 0.10	2.17 ± 0.10
$\Omega_\Lambda{}^a$	0.716 ± 0.024	0.737 ± 0.019	0.734 ± 0.019
σ_8	0.830 ± 0.021	0.808 ± 0.018	0.814 ± 0.017
t_0	13.752 ± 0.096	13.686 ± 0.065	13.682 ± 0.063
H_0	69.7 ± 2.0	71.5 ± 1.7	71.2 ± 1.6
$100r_s/D_{V\,0.57}$	7.50 ± 0.17	7.65 ± 0.14	7.65 ± 0.14
$100r_s/D_{V\,0.35}$	11.29 ± 0.31	11.56 ± 0.26	11.55 ± 0.26
best fit χ^2	7596.0	7617.1	7660.0

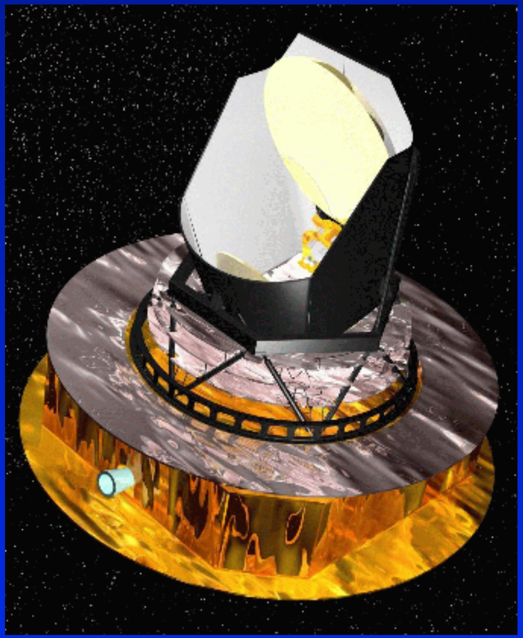
Precision Cosmology with Planck



		Planck+WP		*Planck*+WP+highL		*Planck*+lensing+WP+highL		*Planck*+WP+highL+BAO	
	Parameter	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits	Best fit	68% limits
Standard parameters	$\Omega_b h^2$	0.022032	0.02205 ± 0.00028	0.022069	0.02207 ± 0.00027	0.022199	0.02218 ± 0.00026	0.022161	0.02214 ± 0.00024
	$\Omega_c h^2$	0.12038	0.1199 ± 0.0027	0.12025	0.1198 ± 0.0026	0.11847	0.1186 ± 0.0022	0.11889	0.1187 ± 0.0017
	$100\theta_{MC}$	1.04119	1.04131 ± 0.00063	1.04130	1.04132 ± 0.00063	1.04146	1.04144 ± 0.00061	1.04148	1.04147 ± 0.00056
	τ	0.0925	$0.089^{+0.012}_{-0.014}$	0.0927	$0.091^{+0.013}_{-0.014}$	0.0943	$0.090^{+0.013}_{-0.014}$	0.0952	0.092 ± 0.013
	n_s	0.9619	0.9603 ± 0.0073	0.9582	0.9585 ± 0.0070	0.9624	0.9614 ± 0.0063	0.9611	0.9608 ± 0.0054
	$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$	3.0959	3.090 ± 0.025	3.0947	3.087 ± 0.024	3.0973	3.091 ± 0.025
Foregrounds and secondaries	A^{PS}_{100}	152	171 ± 60	209	212 ± 50	204	213 ± 50	204	212 ± 50
	A^{PS}_{143}	63.3	54 ± 10	72.6	73 ± 8	72.2	72 ± 8	71.8	72.4 ± 8.0
	A^{PS}_{217}	117.0	107^{+20}_{-10}	59.5	59 ± 10	60.2	58 ± 10	59.4	59 ± 10
	A^{CIB}_{143}	0.0	< 10.7	3.57	3.24 ± 0.83	3.25	3.24 ± 0.83	3.30	3.25 ± 0.83
	A^{CIB}_{217}	27.2	29^{+6}_{-9}	53.9	49.6 ± 5.0	52.3	50.0 ± 4.9	53.0	49.7 ± 5.0
	A^{tSZ}_{143}	6.80	...	5.17	$2.54^{+1.1}_{-1.9}$	4.64	$2.51^{+1.2}_{-1.8}$	4.86	$2.54^{+1.2}_{-1.8}$
	$r^{PS}_{143\times217}$	0.916	> 0.850	0.825	$0.823^{+0.069}_{-0.077}$	0.814	0.825 ± 0.071	0.824	0.823 ± 0.070
	$r^{CIB}_{143\times217}$	0.406	0.42 ± 0.22	1.0000	> 0.930	1.0000	> 0.928	1.0000	> 0.930
	γ^{CIB}	0.601	$0.53^{+0.13}_{-0.12}$	0.674	0.638 ± 0.081	0.656	0.643 ± 0.080	0.667	0.639 ± 0.081
	$\xi^{tSZ\times CIB}$	0.03	...	0.000	< 0.409	0.000	< 0.389	0.000	< 0.410
	A^{kSZ}	0.9	...	0.89	$5.34^{+2.8}_{-1.9}$	1.14	$4.74^{+2.6}_{-2.1}$	1.58	$5.34^{+2.8}_{-2.0}$
Derived parameters	Ω_Λ	0.6817	$0.685^{+0.018}_{-0.016}$	0.6830	$0.685^{+0.017}_{-0.016}$	0.6939	0.693 ± 0.013	0.6914	0.692 ± 0.010
	σ_8	0.8347	0.829 ± 0.012	0.8322	0.828 ± 0.012	0.8271	0.8233 ± 0.0097	0.8288	0.826 ± 0.012
	z_{re}	11.37	11.1 ± 1.1	11.38	11.1 ± 1.1	11.42	11.1 ± 1.1	11.52	11.3 ± 1.1
	H_0	67.04	67.3 ± 1.2	67.15	67.3 ± 1.2	67.94	67.9 ± 1.0	67.77	67.80 ± 0.77
	Age/Gyr	13.8242	13.817 ± 0.048	13.8170	13.813 ± 0.047	13.7914	13.794 ± 0.044	13.7965	13.798 ± 0.037
	$100\theta_*$	1.04136	1.04147 ± 0.00062	1.04146	1.04148 ± 0.00062	1.04161	1.04159 ± 0.00060	1.04163	1.04162 ± 0.00056
	r_{drag}	147.36	147.49 ± 0.59	147.35	147.47 ± 0.59	147.68	147.67 ± 0.50	147.611	147.68 ± 0.45

Planck Collaboration, 2013, paper XV

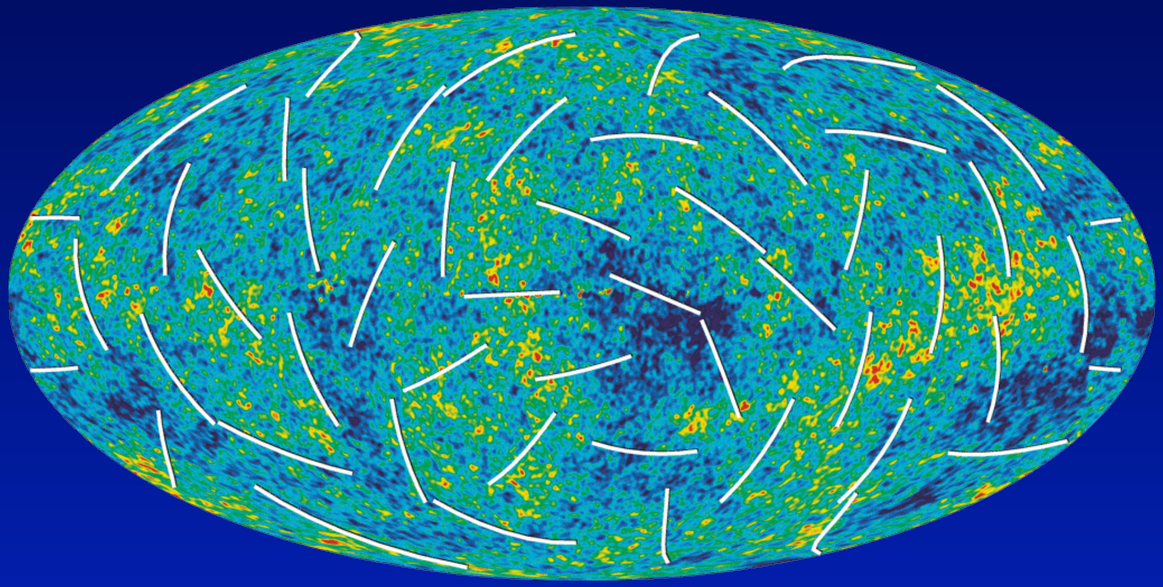
- Massive amount of information! (close to 30 Planck papers in March 2013)
- Impressive consistency between different experiments!
- Amazing confirmation of ΛCDM



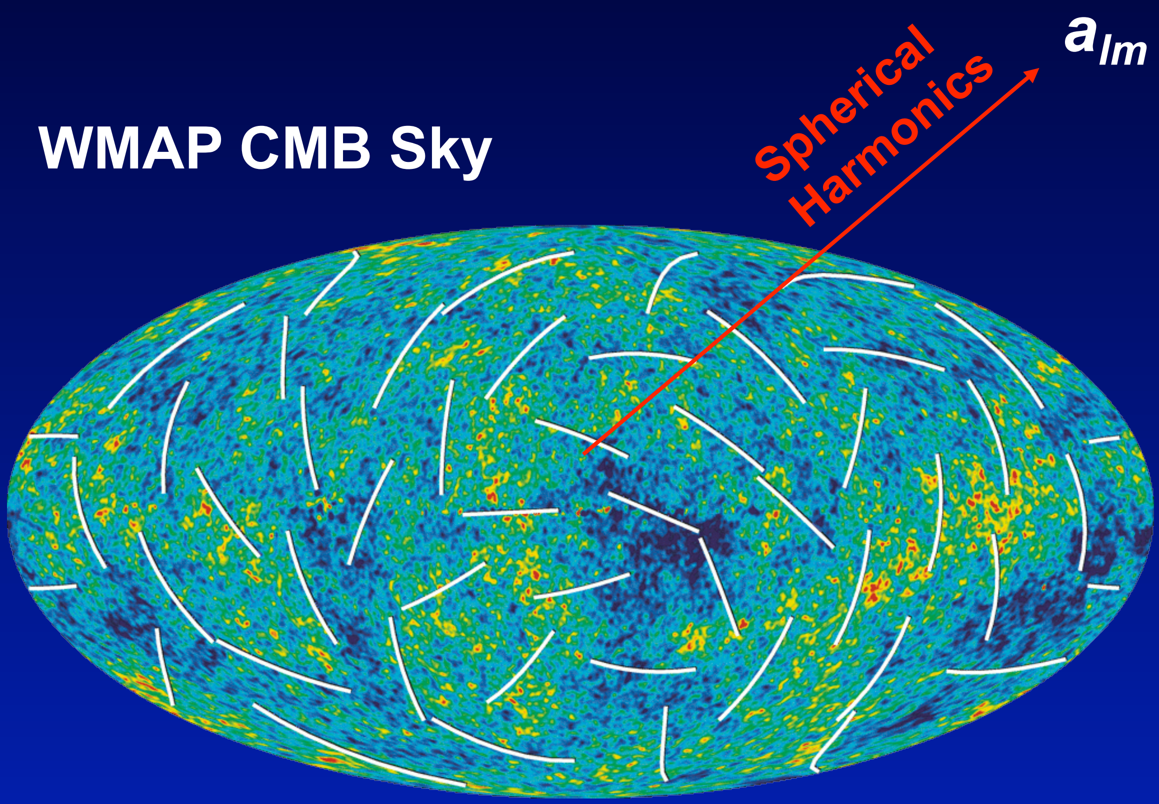
Planck Satellite

CMB Sky → Cosmology

WMAP CMB Sky



CMB Sky → Cosmology



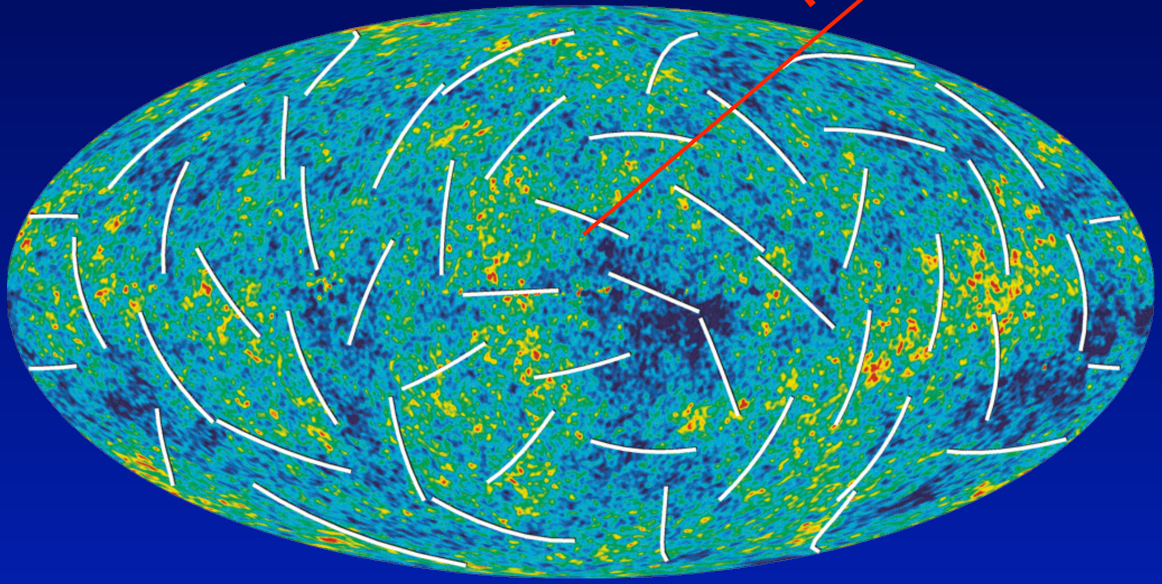
WMAP CMB Sky

Spherical Harmonics

a_{lm}

CMB Sky → Cosmology

WMAP CMB Sky

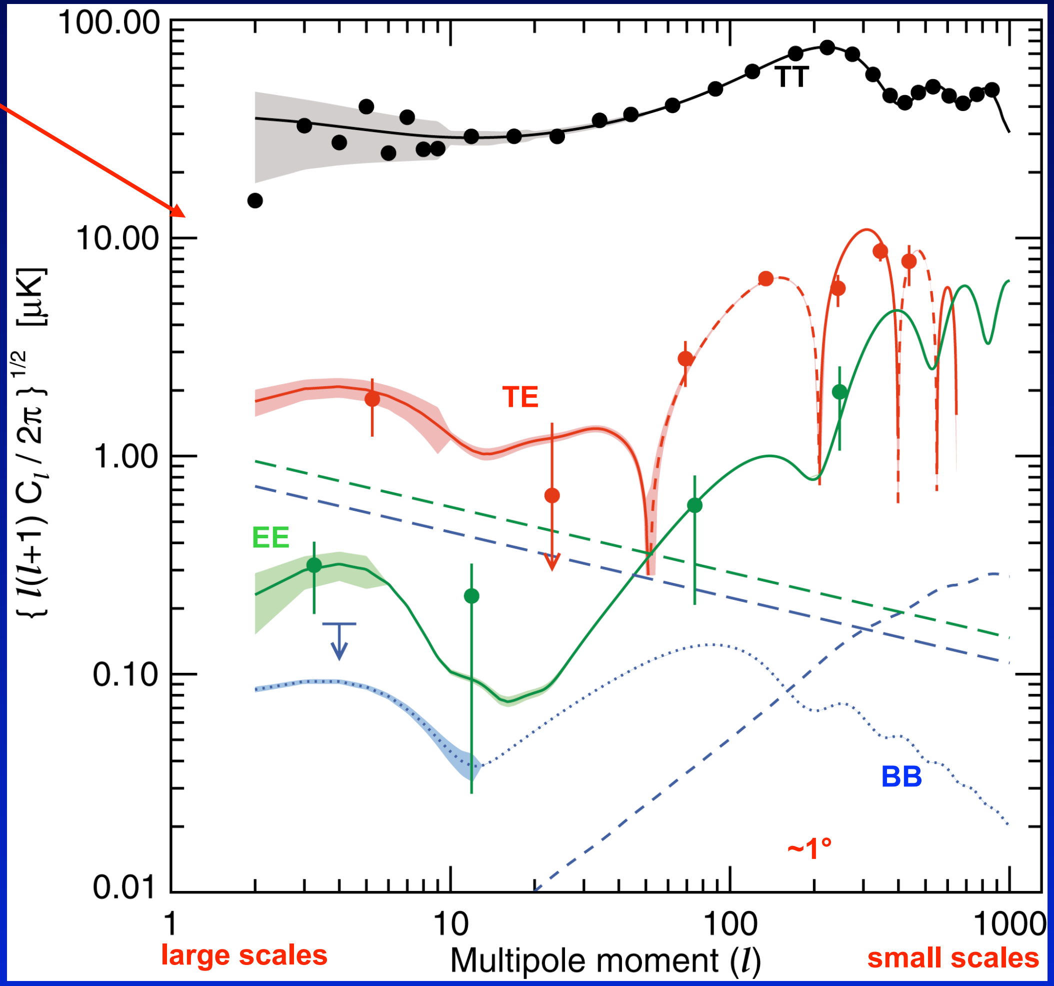


Spherical Harmonics

a_{lm}

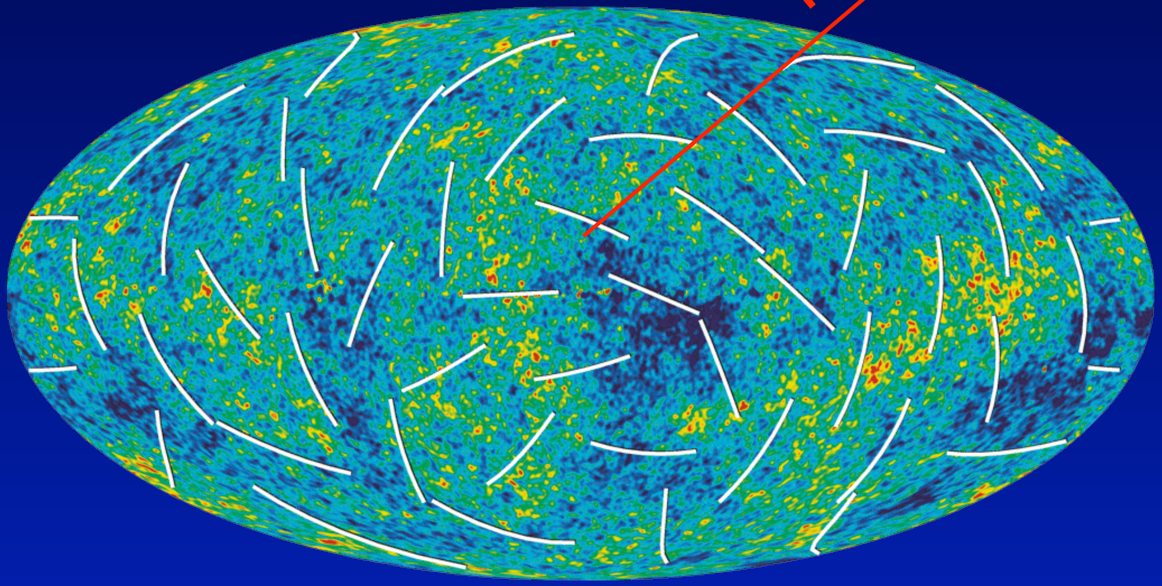
Gaussianity

Power spectra



CMB Sky → Cosmology

WMAP CMB Sky

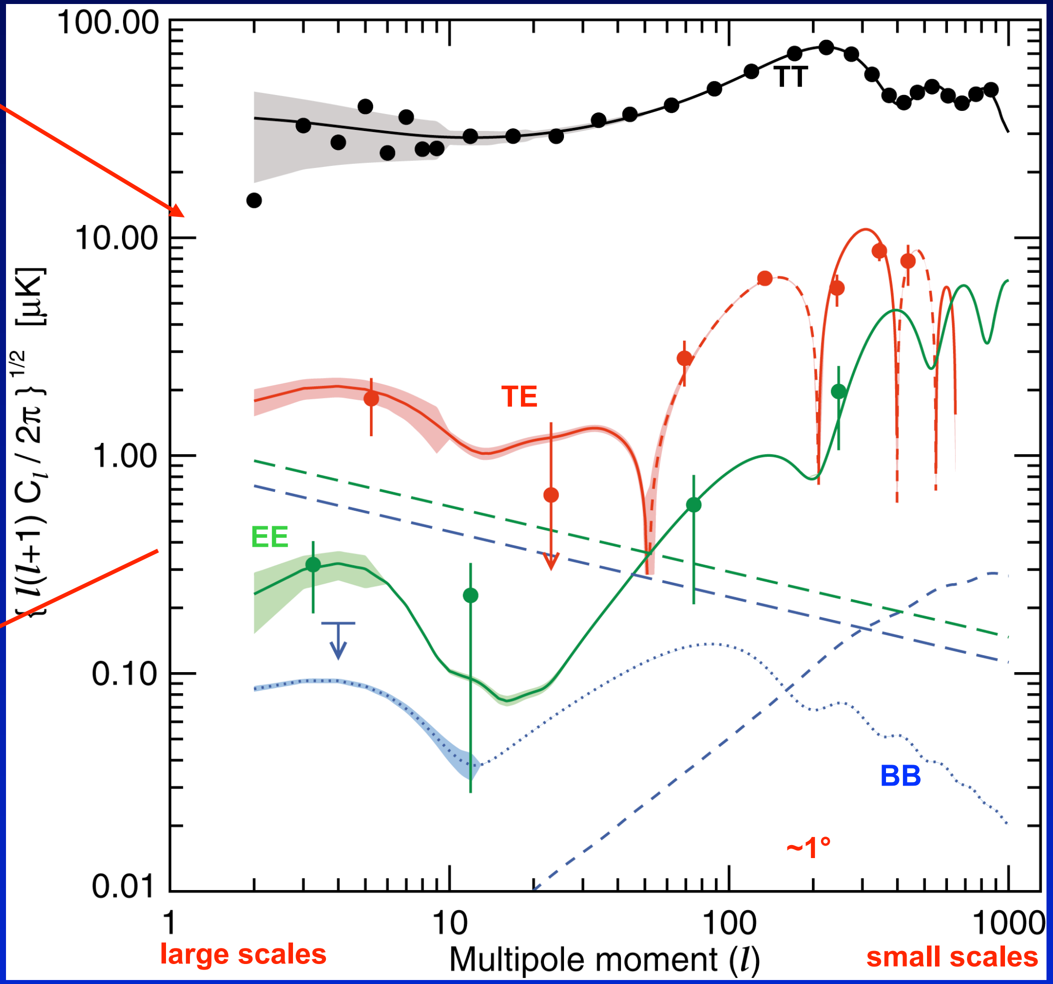


Spherical Harmonics

a_{lm}

Gaussianity

Power spectra



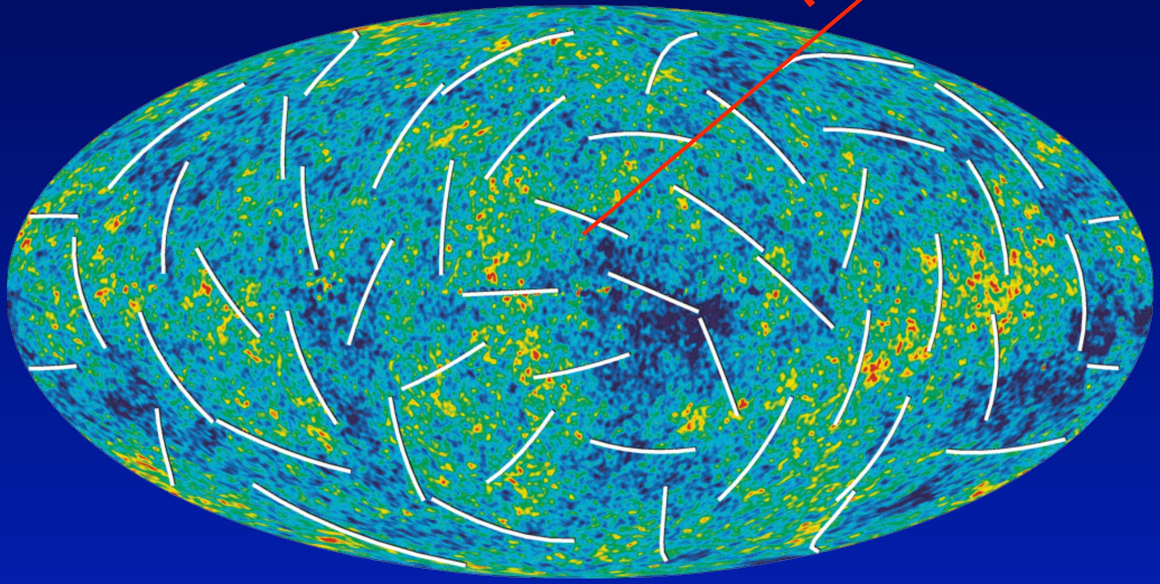
(Joint) analysis

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

CMB Sky → Cosmology

WMAP CMB Sky

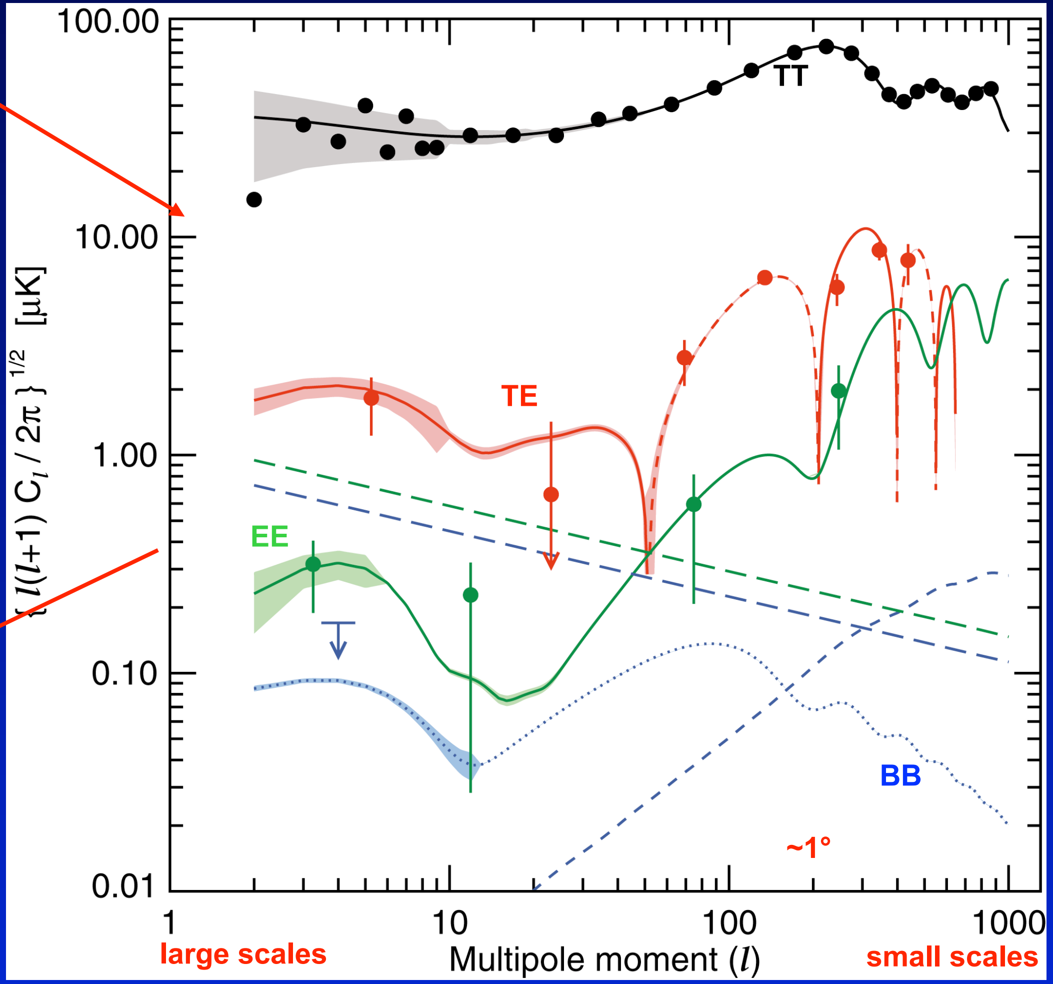


Spherical Harmonics

a_{lm}

Gaussianity

Power spectra



(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

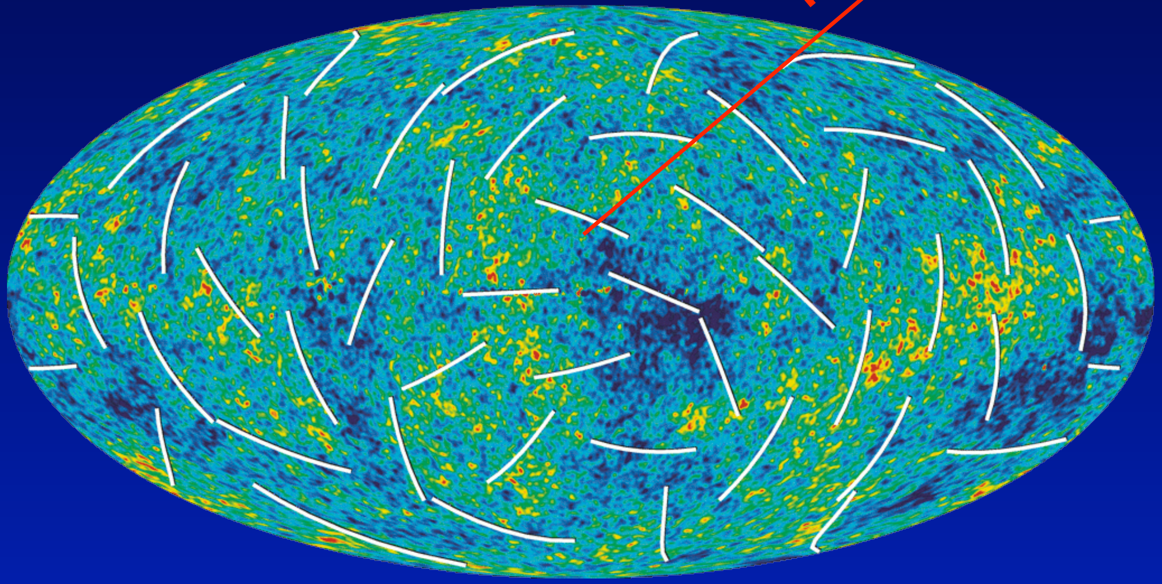
Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

CMB Sky → Cosmology

HealPix

WMAP CMB Sky

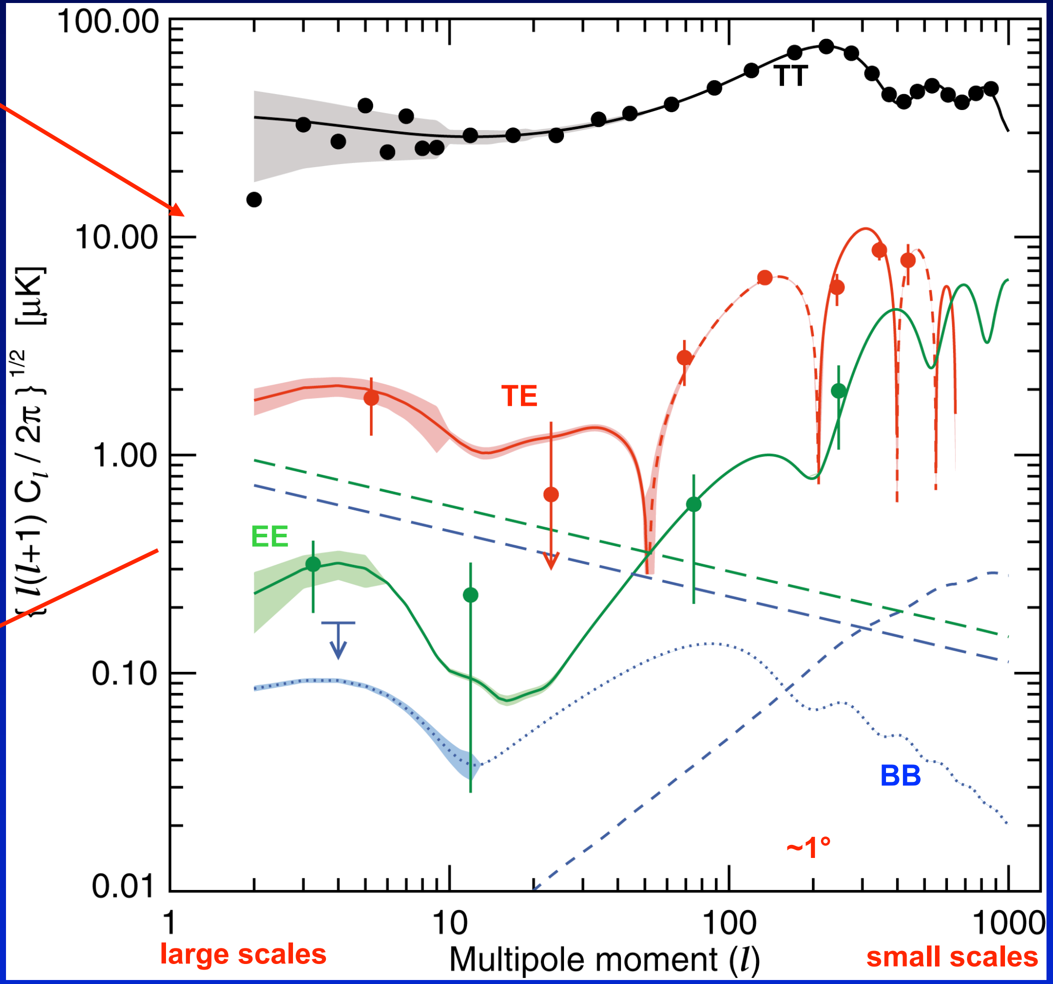


Spherical Harmonics

a_{lm}

Gaussianity

Power spectra



(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ, h, τ, n_s,...

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

CMB Sky → Cosmology

HealPix

CAMB/CMBfast

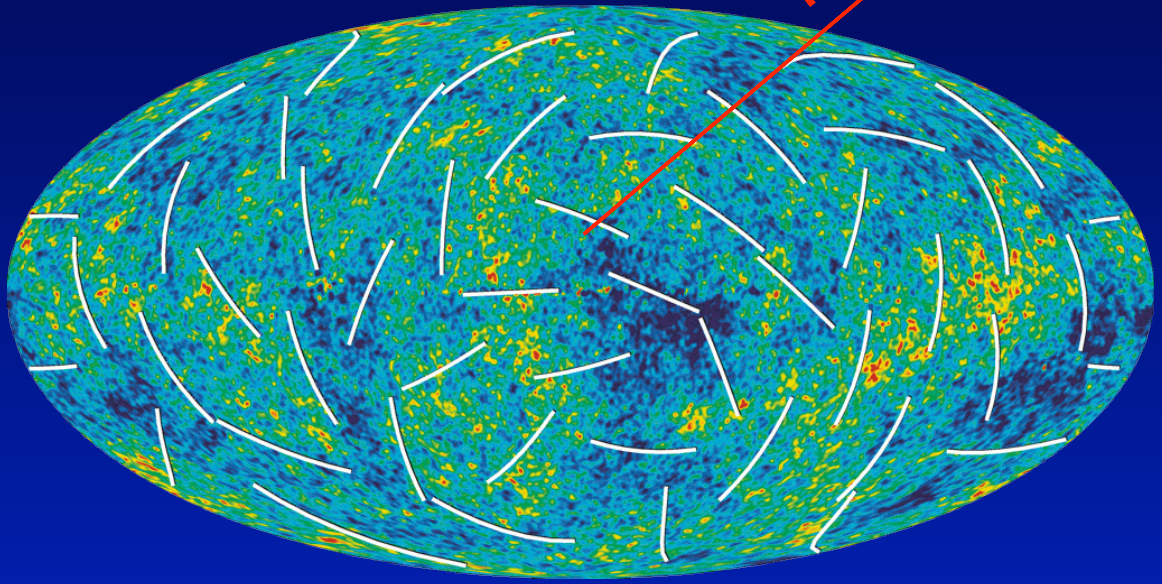
a_{lm}

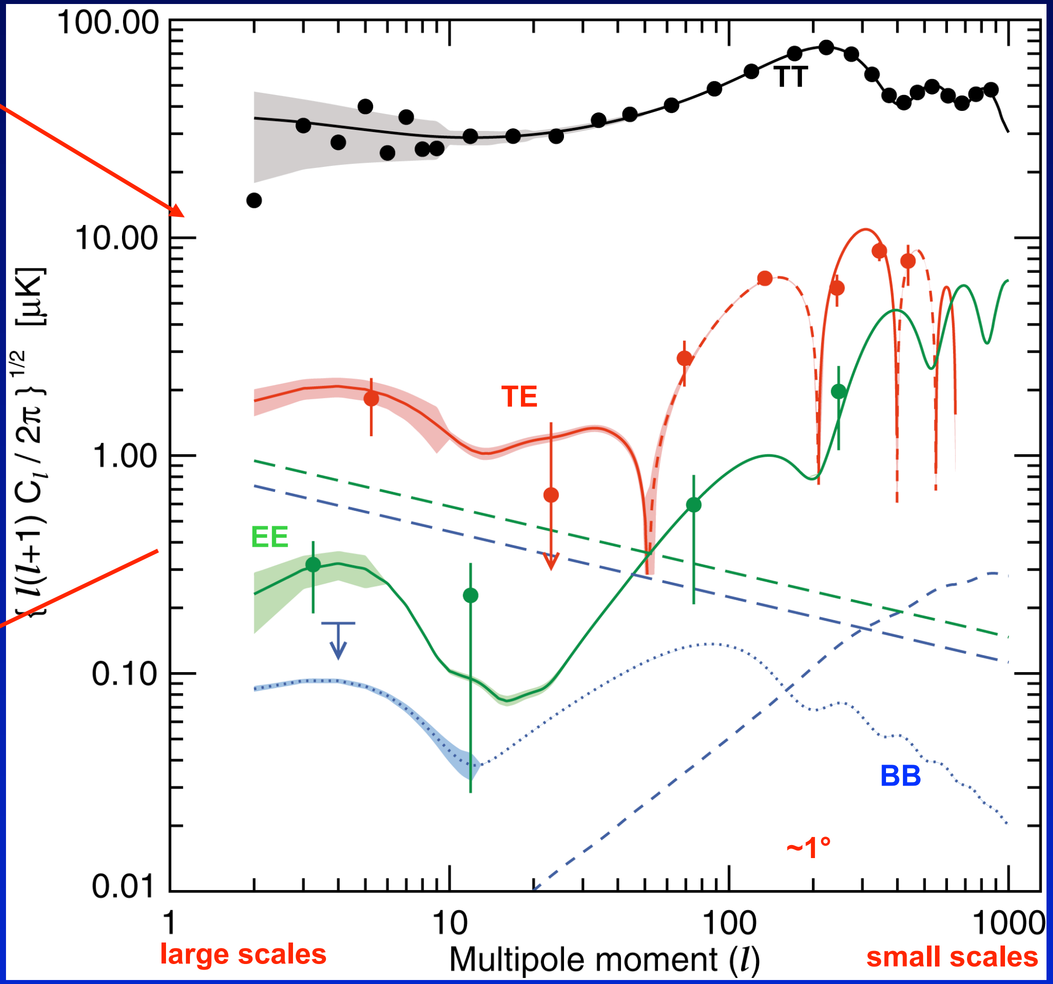
Spherical Harmonics

Gaussianity

Power spectra

WMAP CMB Sky





(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

CMB Sky → Cosmology

HealPix

CAMB/CMBfast

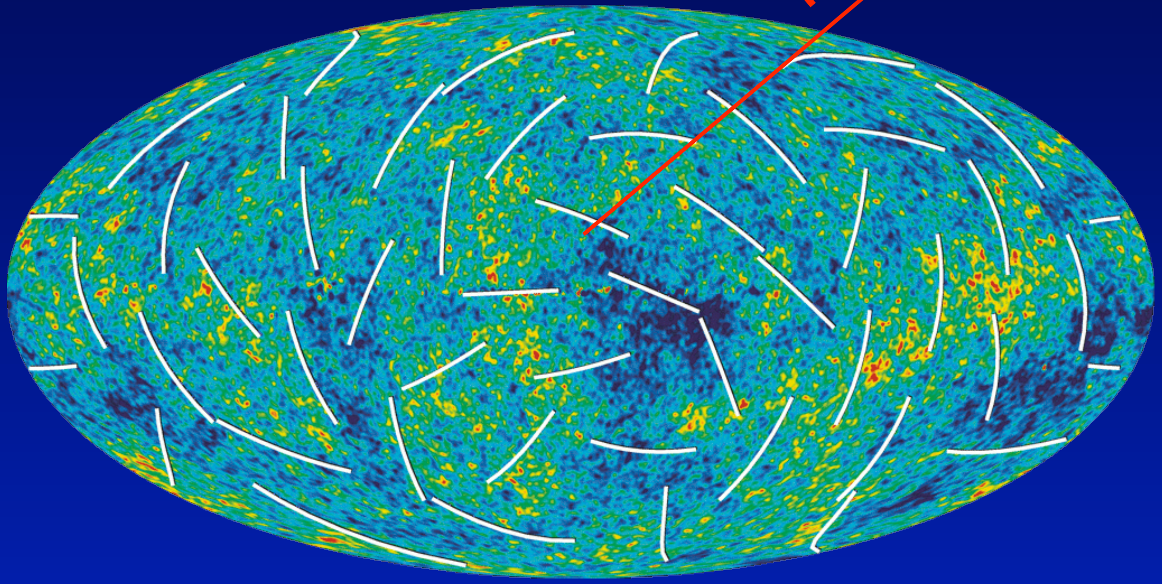
Recfast/CosmoRec/HyRec

a_{lm}

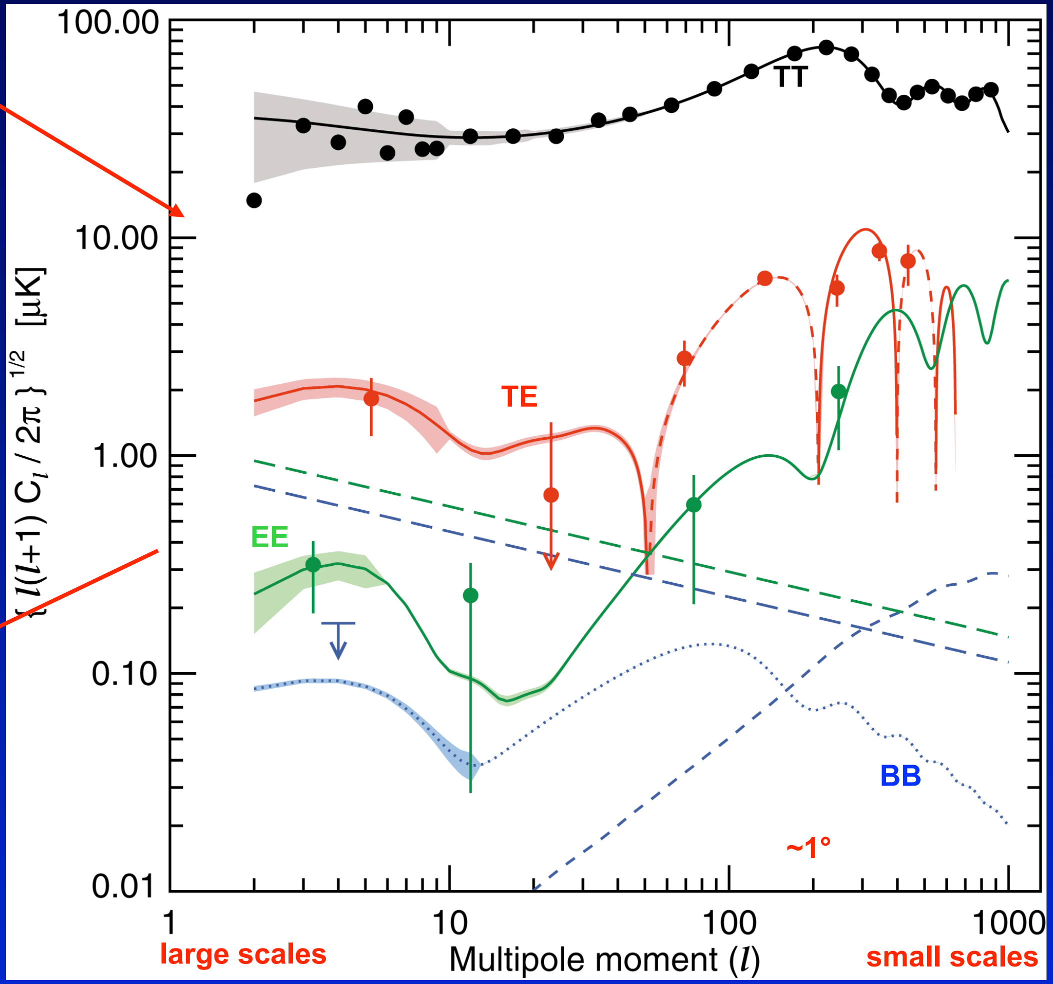
Spherical Harmonics

Gaussianity

WMAP CMB Sky



Power spectra



(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ, h, τ, n_s,...

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

CMB Sky → Cosmology

HealPix

CAMB/CMBfast

Recfast/CosmoRec/HyRec

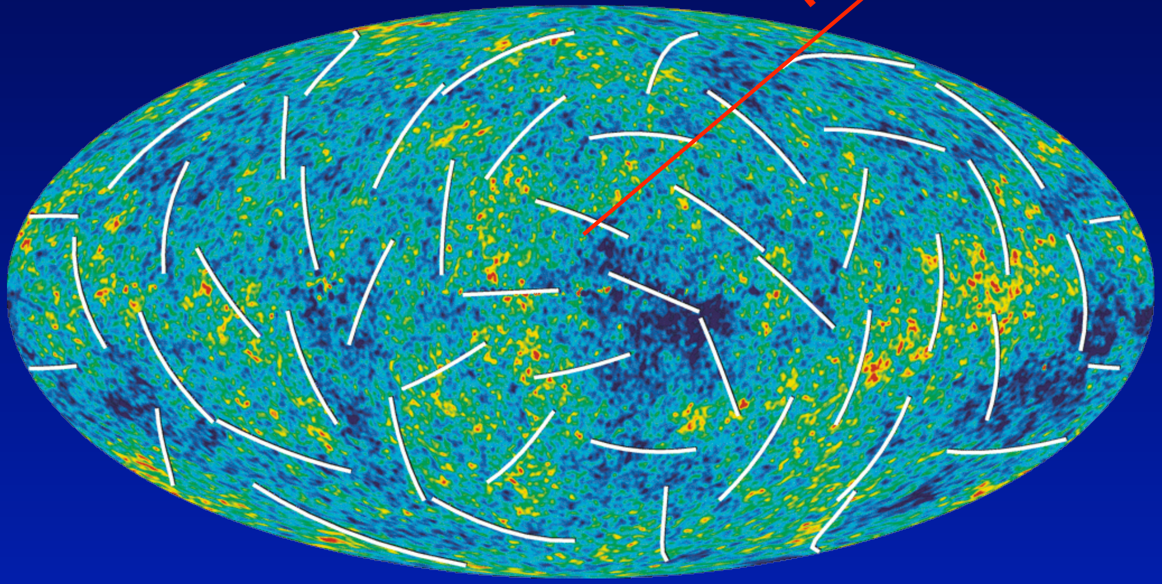
WMAP CMB Sky

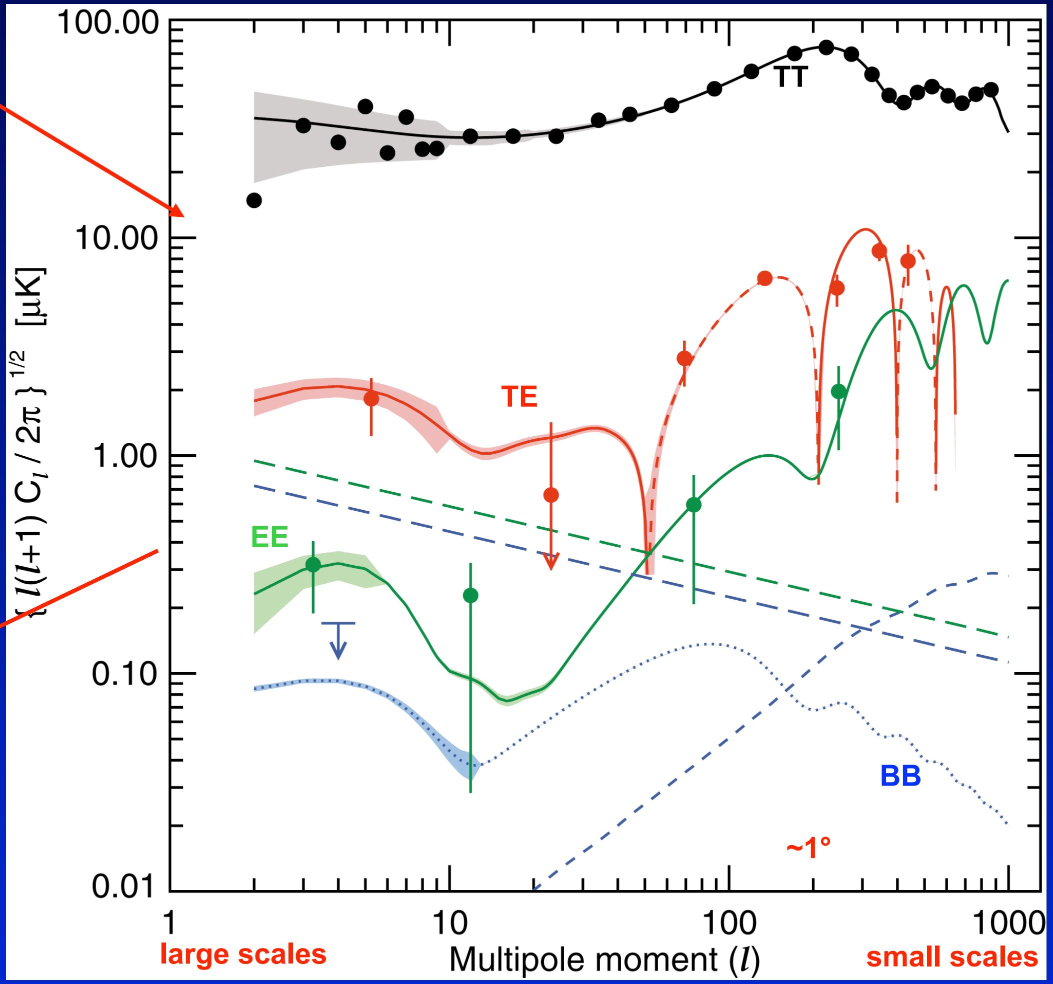
Spherical Harmonics

a_{lm}

Gaussianity

Power spectra





(Joint) analysis

Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ, h, τ, n_s,...

CosmoMC

Other cosmological Dataset:

small-scale CMB, Supernovae, large-scale structure/ BAO, Lyman-α forest, lensing, ...

References for the Theory of CMB anisotropies

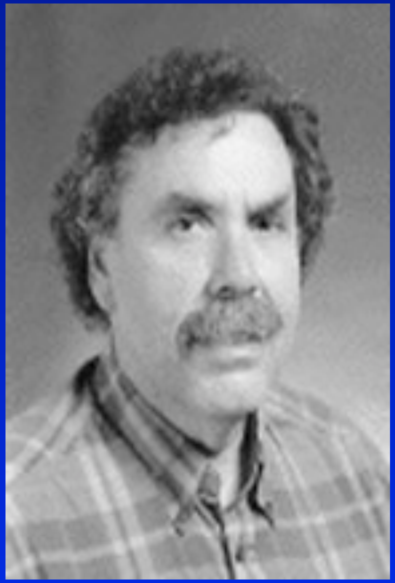
- Early works
  - Sachs & Wolfe, 1967, ApJ, 147, 73
  - Silk, 1968, ApJ, 151, 459
  - Peebles & Yu, 1970, Ap&SS, 4, 301
  - Sunyaev & Zeldovich, 1970, Ap&SS, 7, 3

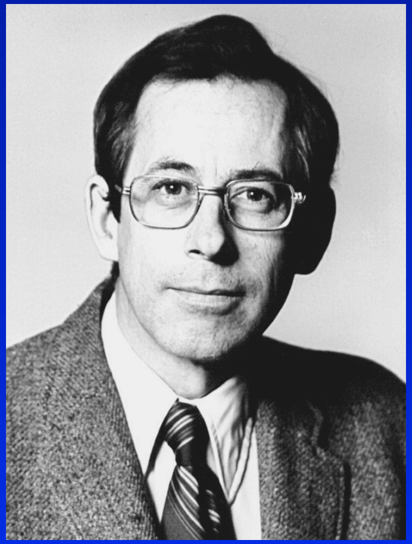

Joe Silk


Yakov Zeldovich


Rashid Sunyaev


Rainer Sachs


Arthur Wolfe


Jim Peebles

References for the Theory of CMB anisotropies

- Early works
  - Sachs & Wolfe, 1967, ApJ, 147, 73
  - Silk, 1968, ApJ, 151, 459
  - Peebles & Yu, 1970, Ap&SS, 4, 301
  - Sunyaev & Zeldovich, 1970, Ap&SS, 7, 3
- Nice Lectures and Reviews
  - Hu & White, 1996, ApJ, 471, 30
  - Hu & Dodelson, 2002, ARAA, 40, 171
  - Hu, 2008, arXiv:0802.3688
  - Challinor & Peiris, 2009, AIP Conf. Proc., 1132, 86

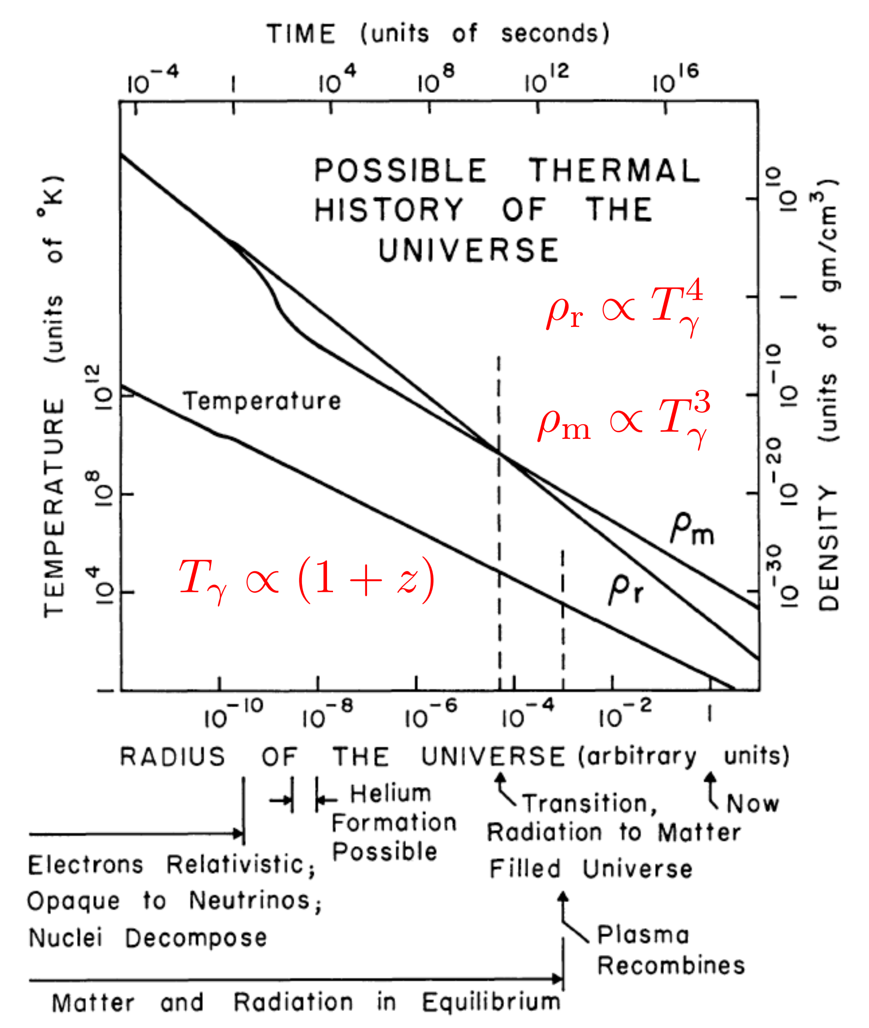
References for the Theory of CMB anisotropies

- Early works
  - Sachs & Wolfe, 1967, ApJ, 147, 73
  - Silk, 1968, ApJ, 151, 459
  - Peebles & Yu, 1970, Ap&SS, 4, 301
  - Sunyaev & Zeldovich, 1970, Ap&SS, 7, 3
- Nice Lectures and Reviews
  - Hu & White, 1996, ApJ, 471, 30
  - Hu & Dodelson, 2002, ARAA, 40, 171
  - Hu, 2008, arXiv:0802.3688
  - Challinor & Peiris, 2009, AIP Conf. Proc., 1132, 86
- Many great animations and illustrations for this lecture from Wayne Hu (http://background.uchicago.edu/~whu/)

Physics behind the CMB anisotropies

Early CMB History & Physics

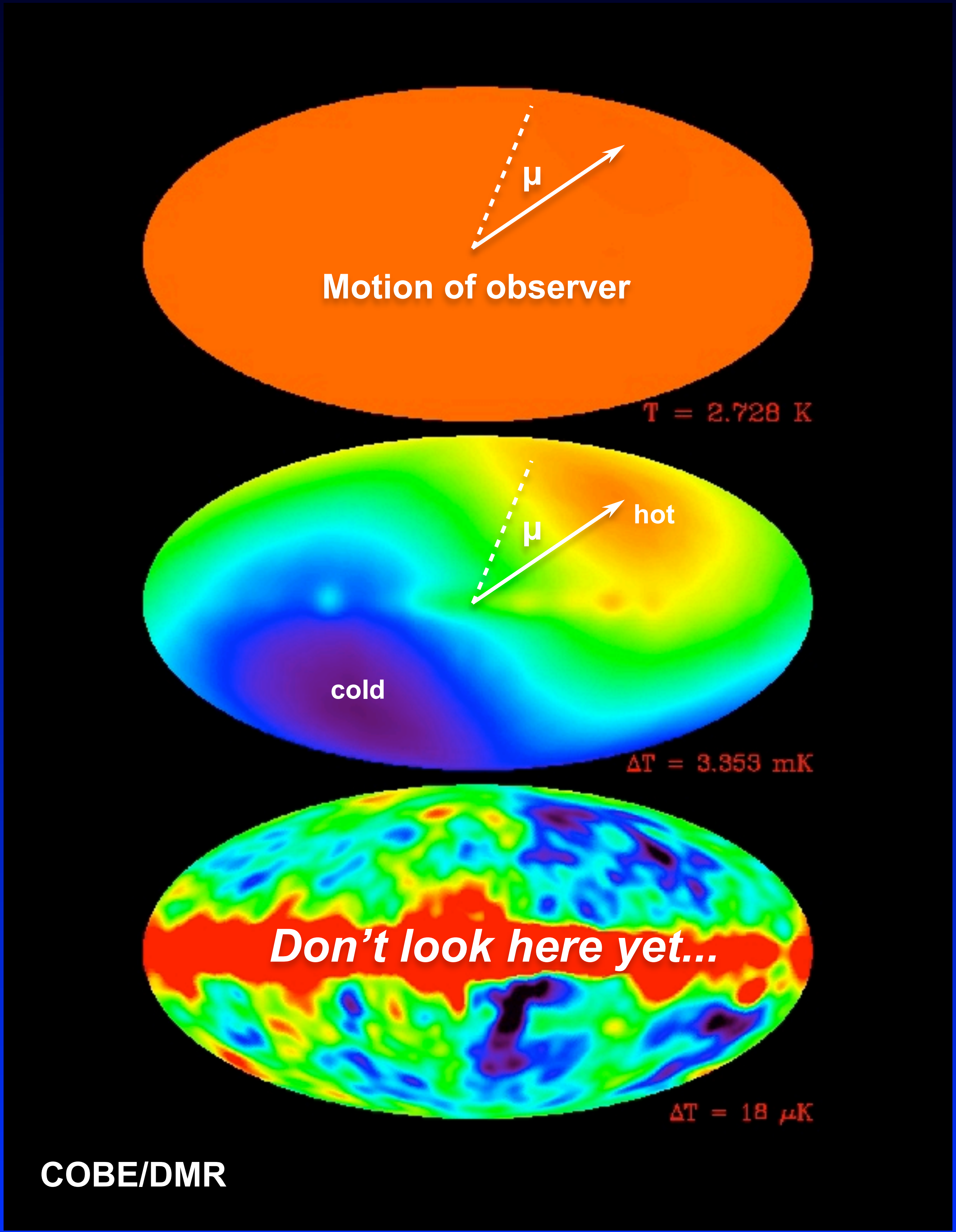
- Natural consequence of a Big-Bang Model (hence it is often referred to as one of the *pillars* of the Big-Bang Model)
- *Discussed* and *invoked* by Gamov, Alpher & Herman in 1946/1948 to understand the production of light elements in the early Universe
- Alpher & Herman 1948 *(at JHU at that time!)* the first to give an pretty good *estimate* of the CMB temperature *T*~5K (later revised it to *T*~28K)



From Dicke, Peebles, Roll & Wilkinson, 1965

- Experimentally *discovered* in 1964/65 by Penzias & Wilson (Nobel Prize 1978)
- *Interpretation* as CMB by Dicke, Peebles, Roll & Wilkinson 1965

CMB dipole



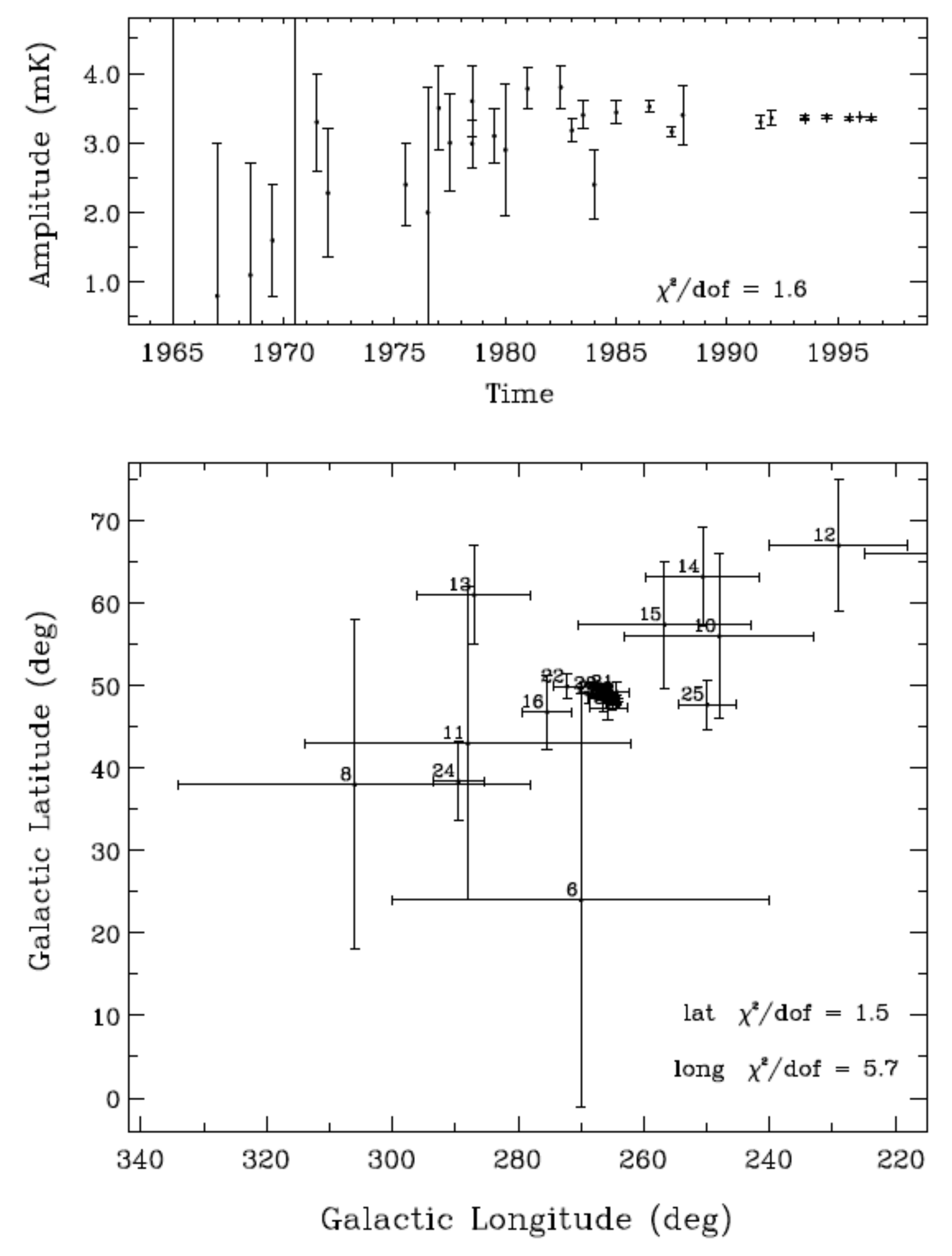
- Lowest order v/c effect caused by observers motion (simple Lorentz-trafo of average CMB blackbody into observer frame)

$$T' = \frac{T_0}{\gamma(1-\beta\mu)} \approx T_0[1+\beta\mu+\mathcal{O}(\beta^2)]$$

direction cosine $\mu = \hat{\gamma}\cdot\hat{\beta}$

- Probably understood by contemporary folks but dipole was *first explicitly mentioned* by *Peebles & Wilkinson*, 1968 and *Bracewell & Conklin*, 1968
- possibility to *measure our velocity* with respect to the CMB rest frame
- *earliest mentioning* by *Condon & Harwit*, 1967 (but they got the transformation law wrong...)
- much larger than expected *primordial dipole* for standard cosmology (today)
- second order in β $\Longrightarrow$ motion-induced monopole & quadrupole and y-distortion monopole & quadrupole (e.g., JC & Sunyaev, 2004)

Measurements of CMB dipole



Lineweaver, astro-ph/9609034v1

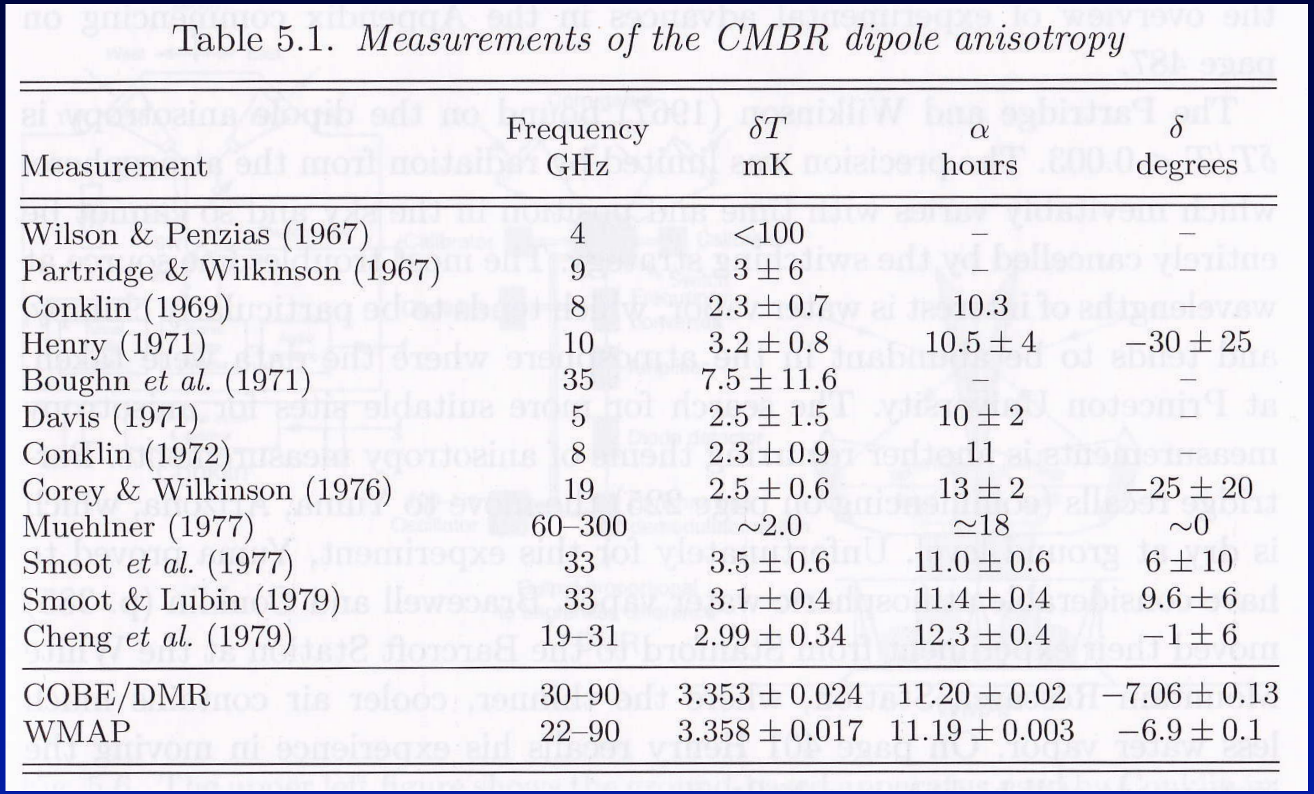


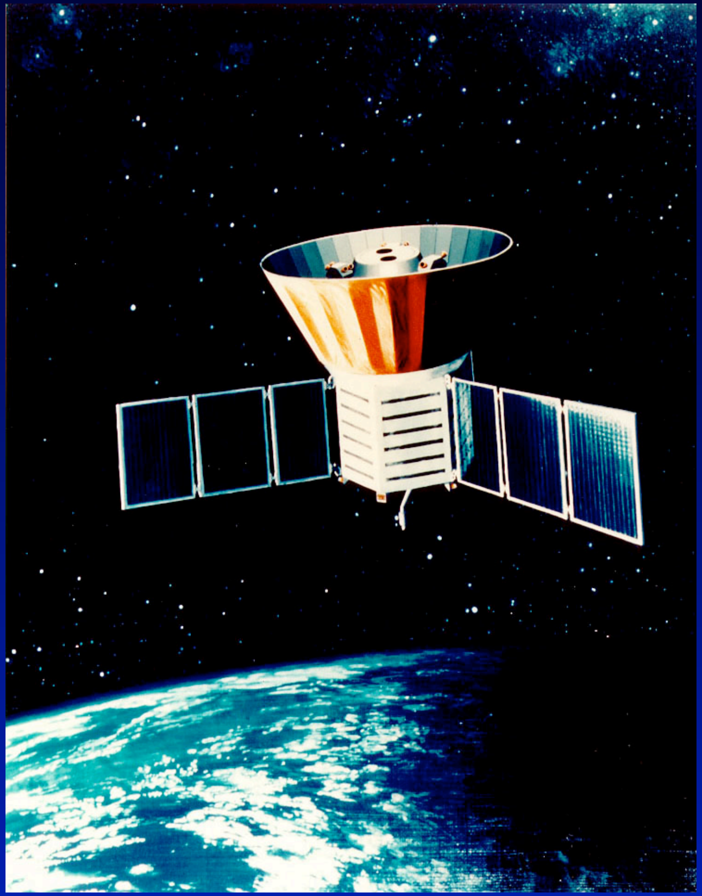
Table 5.1. *Measurements of the CMBR dipole anisotropy*

Measurement	Frequency GHz	δT mK	α hours	δ degrees
Wilson & Penzias (1967)	4	<100	–	–
Partridge & Wilkinson (1967)	9	3 ± 6	–	–
Conklin (1969)	8	2.3 ± 0.7	10.3	–
Henry (1971)	10	3.2 ± 0.8	10.5 ± 4	-30 ± 25
Boughn *et al.* (1971)	35	7.5 ± 11.6	–	–
Davis (1971)	5	2.5 ± 1.5	10 ± 2	–
Conklin (1972)	8	2.3 ± 0.9	11	–
Corey & Wilkinson (1976)	19	2.5 ± 0.6	13 ± 2	-25 ± 20
Muehlner (1977)	60–300	~ 2.0	$\simeq 18$	~ 0
Smoot *et al.* (1977)	33	3.5 ± 0.6	11.0 ± 0.6	6 ± 10
Smoot & Lubin (1979)	33	3.1 ± 0.4	11.4 ± 0.4	9.6 ± 6
Cheng *et al.* (1979)	19–31	2.99 ± 0.34	12.3 ± 0.4	-1 ± 6
COBE/DMR	30–90	3.353 ± 0.024	11.20 ± 0.02	-7.06 ± 0.13
WMAP	22–90	3.358 ± 0.017	11.19 ± 0.003	-6.9 ± 0.1

From Book of Peebles, Page & Partridge, “Finding the Big Bang”

- First marginal detection of CMB dipole amplitude: Conklin 1969
- ~6σ measurement Smoot et al. 1977
- dipole today still used for calibration purposes!

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

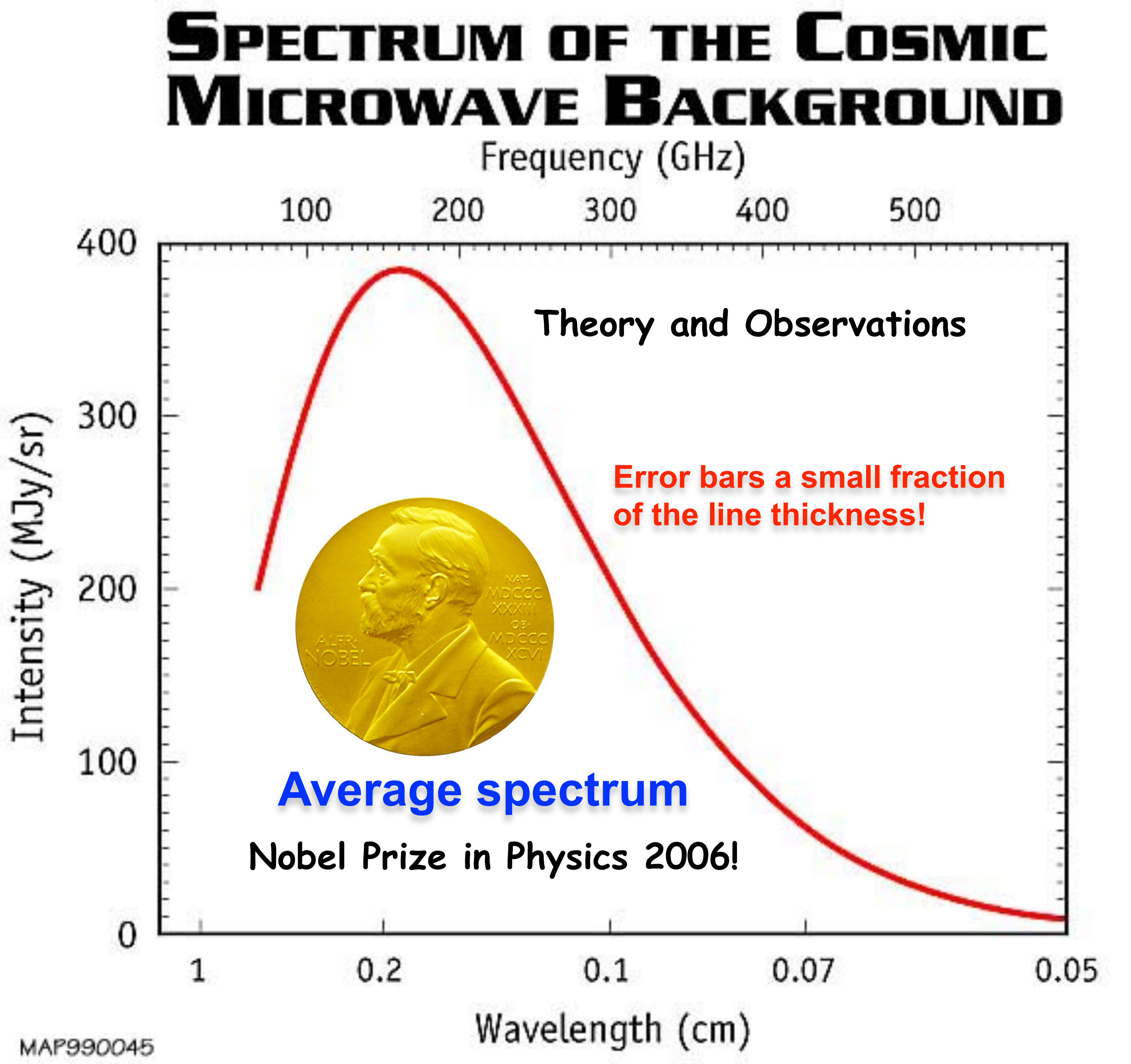


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

$$|\,y\,| \leq 1.5\times10^{-5}$$

$$|\,\mu\,| \leq 9\times10^{-5}$$

Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen et al., 2003, ApJ, 594, 67



Theory and Observations

Error bars a small fraction of the line thickness!

Average spectrum

Nobel Prize in Physics 2006!

Only very small distortions of CMB spectrum are still allowed!

Physical mechanisms that lead to spectral distortions

- *Cooling by adiabatically expanding ordinary matter*: $T_\gamma \sim (1+z) \leftrightarrow T_m \sim (1+z)^2$

  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
  - continuous *cooling* of photons until redshift $z \sim 150$ via Compton scattering
  - due to huge heat capacity of photon field distortion very small ($\Delta\rho/\rho \sim 10^{-10}$-$10^{-9}$)

Standard sources of distortions

- Heating by *decaying* or *annihilating* relic particles
  - How is energy transferred to the medium?
  - lifetimes, decay channels, neutrino fraction, (at low redshifts: environments), ...
- *Evaporation of primordial black holes & superconducting strings*

  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012)
  - rather fast, quasi-instantaneous but also extended energy release
- *Dissipation of primordial acoustic modes & magnetic fields*

  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; Jedamzik et al. 2000)
- *Cosmological recombination*

pre-recombination epoch

„high“ redshifts

„low“ redshifts

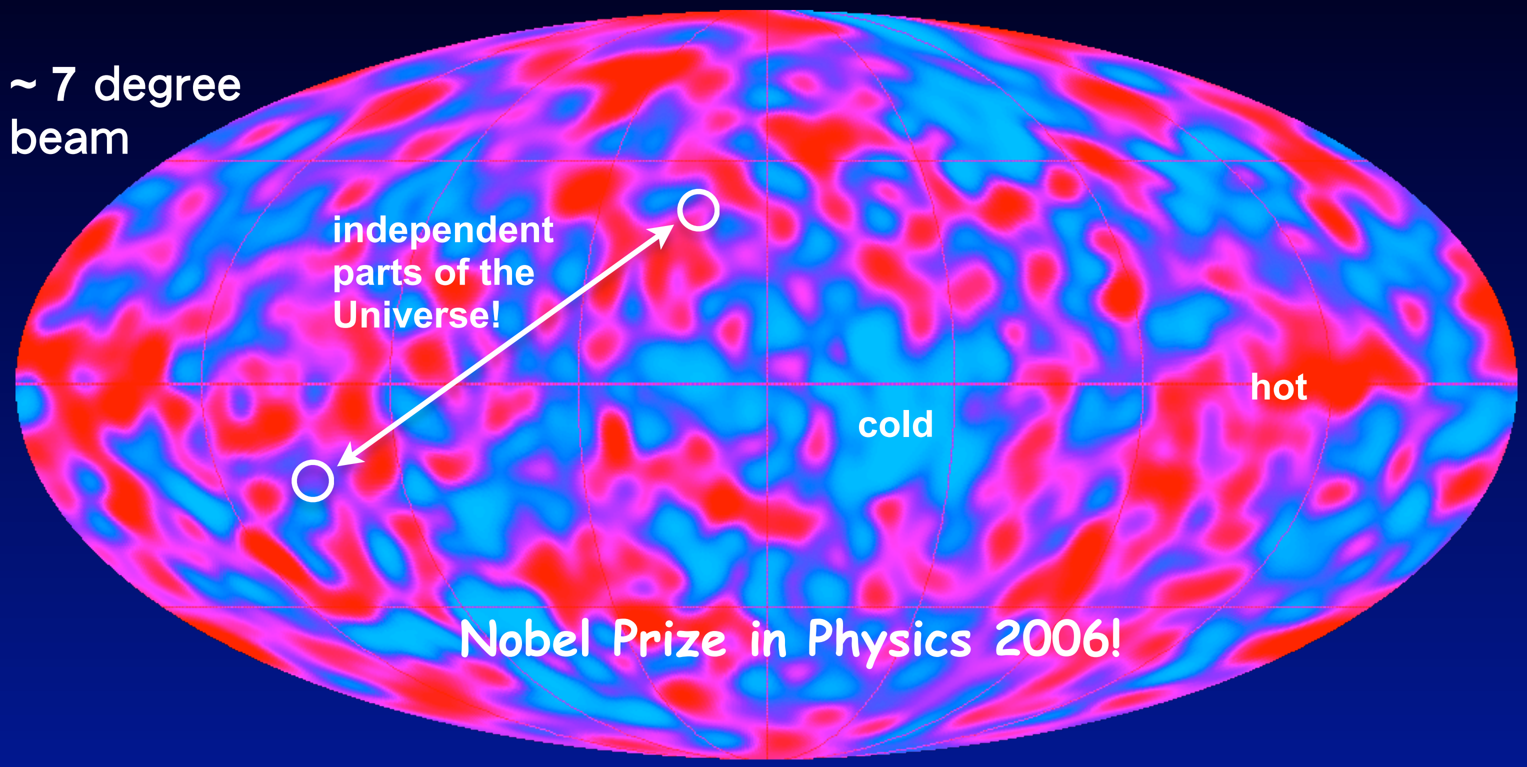
- Signatures due to first supernovae and their remnants

  (Oh, Cooray & Kamionkowski, 2003)
- Shock waves arising due to large-scale structure formation

  (Sunyaev & Zeldovich, 1972; Cen & Ostriker, 1999)
- SZ-effect from clusters; effects of reionization (Heating of medium by X-Rays, Cosmic Rays, etc)

post-recombination

Discovery of CMB anisotropies by COBE/DMR



Nobel Prize in Physics 2006!

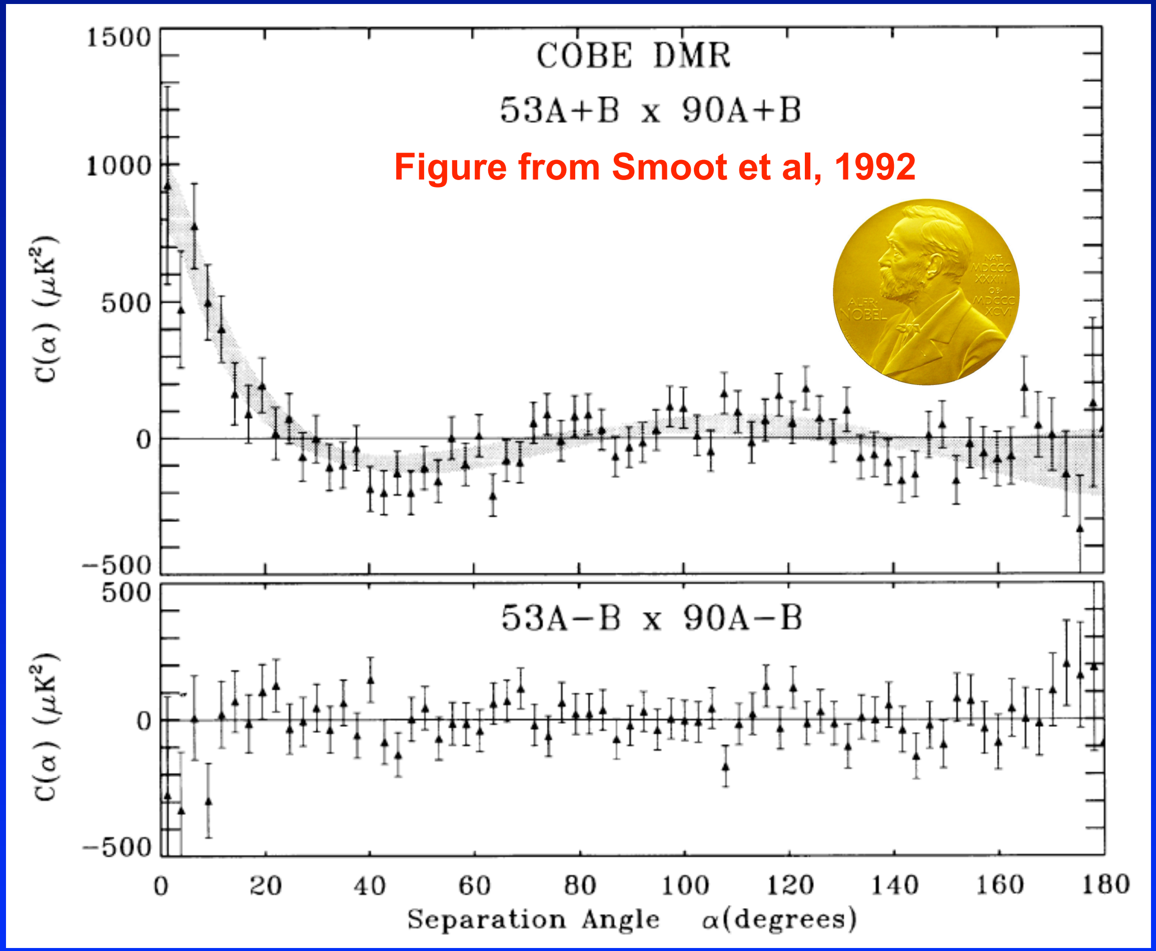
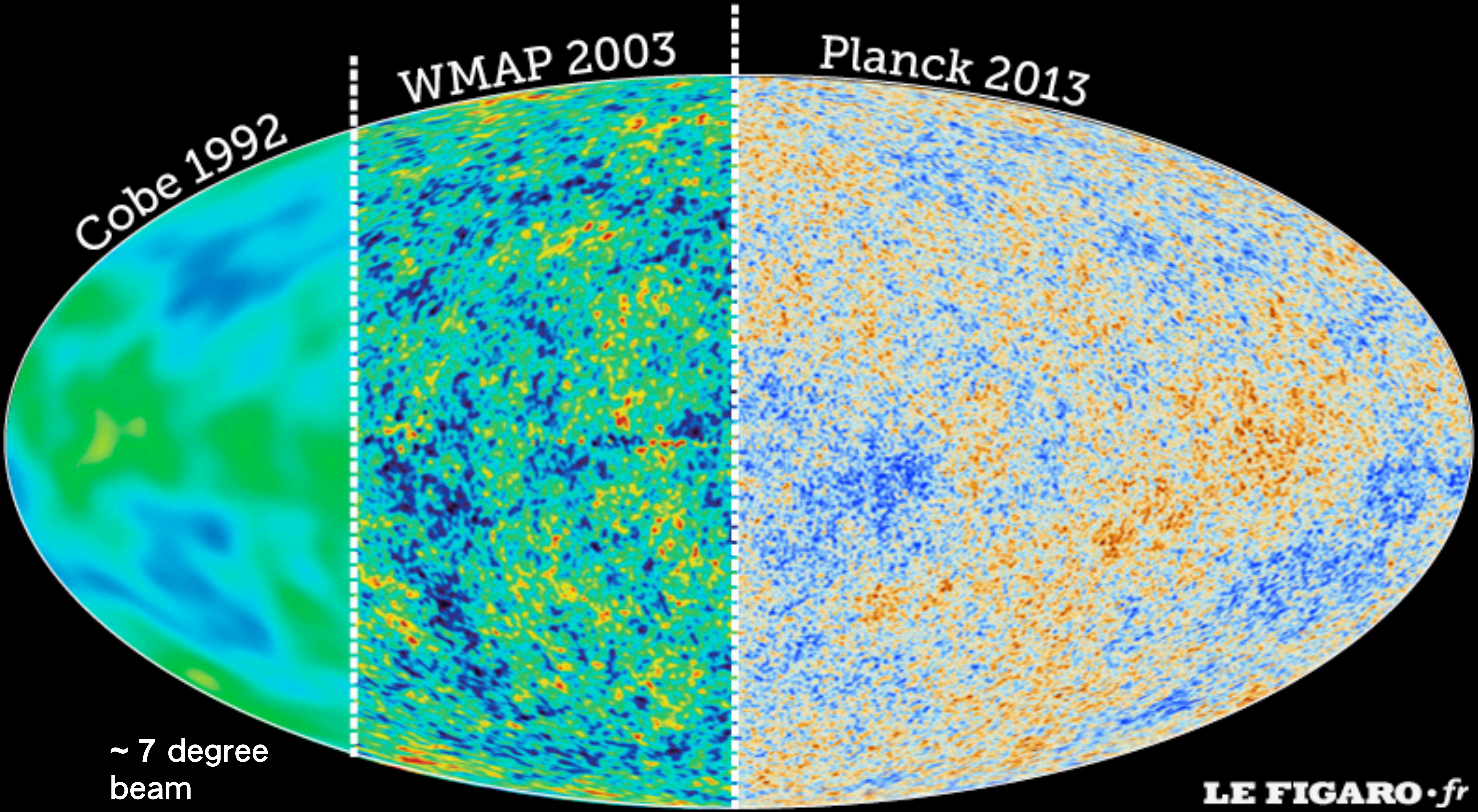


Figure from Smoot et al, 1992

- first measurement of large scale two-point correlation function
- consistent with scale invariant power spectrum (*Harrison-Zeldovich power spectrum*)
- observed perturbation amplitude pretty low $\Longrightarrow$ *dark matter* needed to explain structures
- fluctuations on super-horizon scales at $z_{\rm rec}$ $\Longrightarrow$ determined by *initial conditions* and *gravity* (*Sachs-Wolfe effect & ISW*)
- *hot spot* $\Longleftrightarrow$ *under density!*

Dramatic improvements in angular resolution and sensitivity over the past decades!

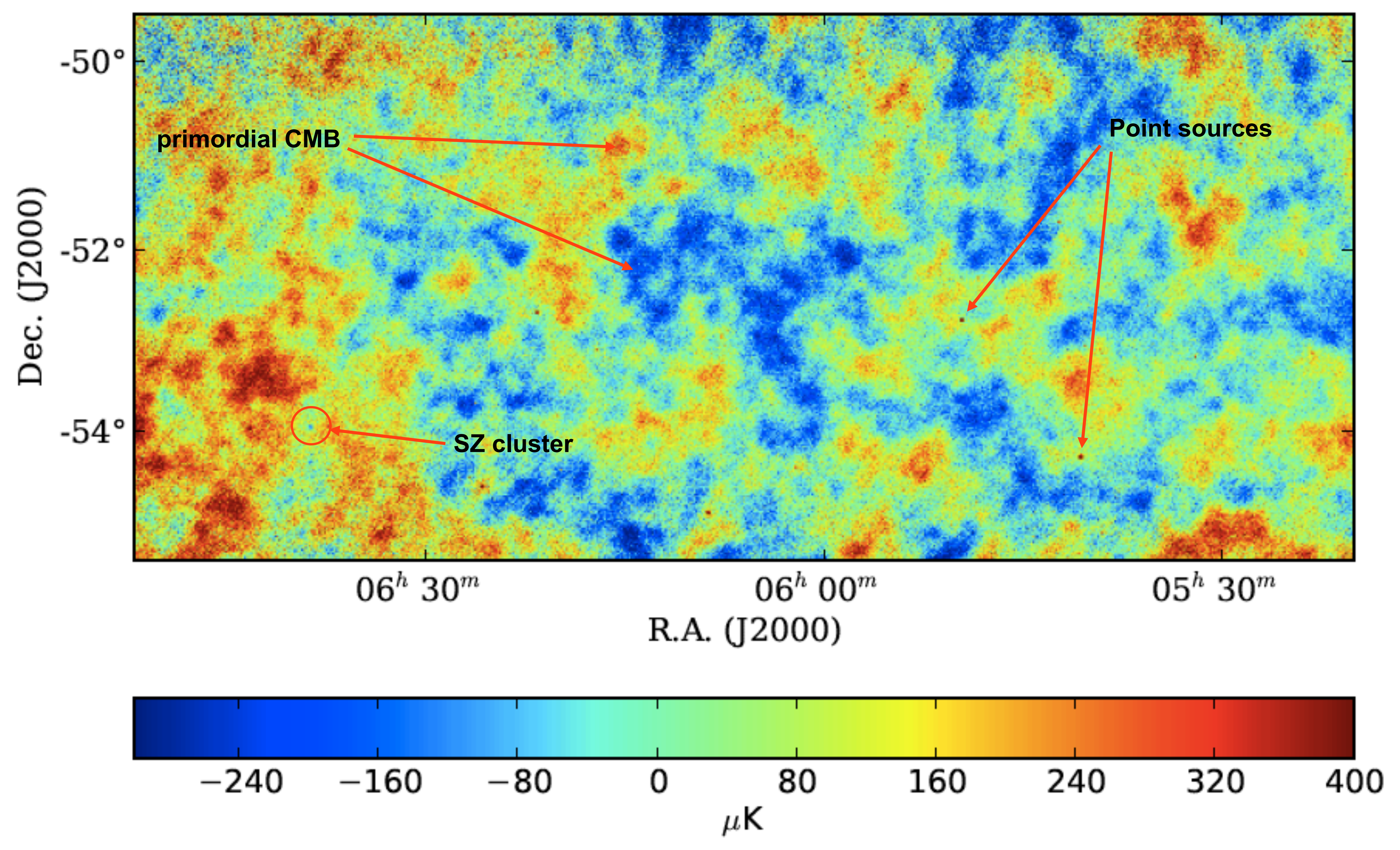


~ 7 degree beam

~ 0.3 degree beam

~ 0.08 degree beam

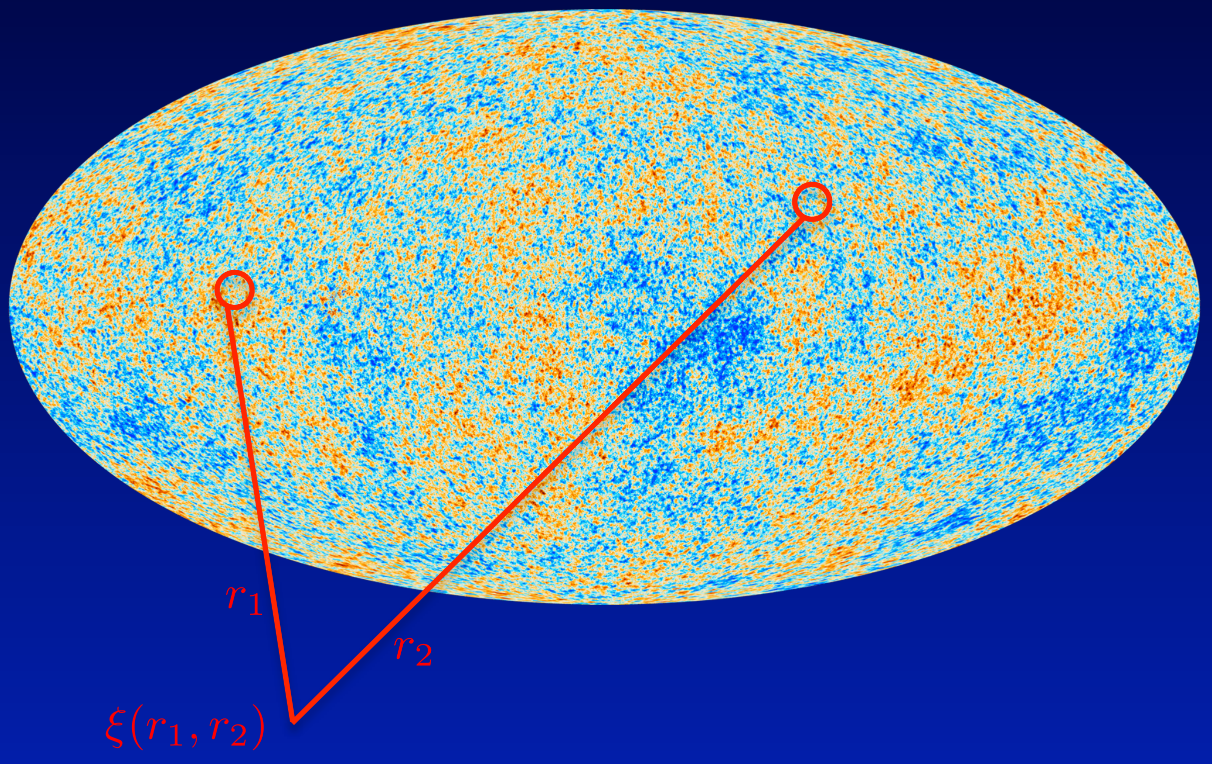
Cosmic Microwave Background Anisotropies with ACT

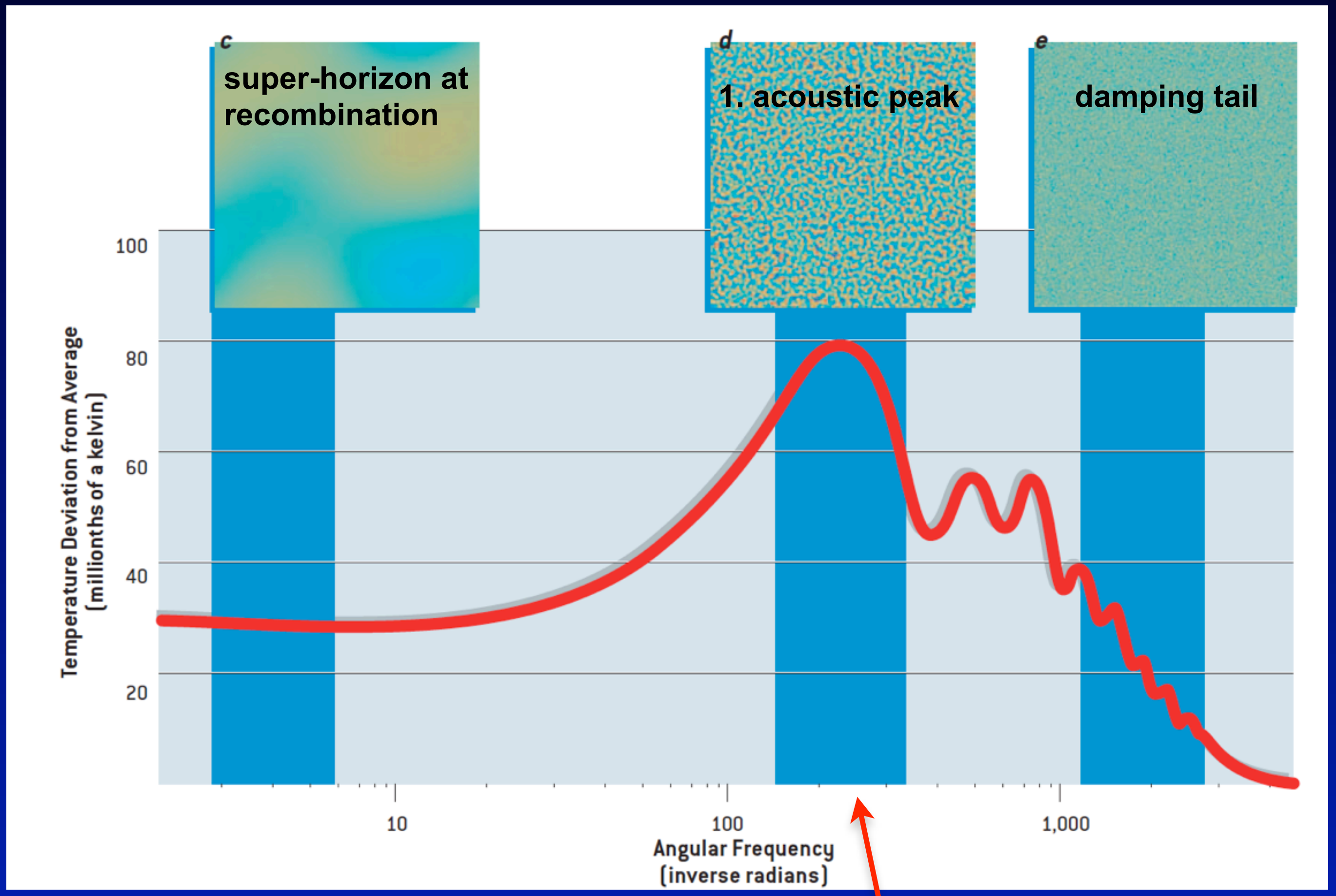


ACT - collaboration, 148 GHz Map, Hajian et al. 2010

~ 0.02 degree beam!

Interpretation of power spectrum in a nutshell

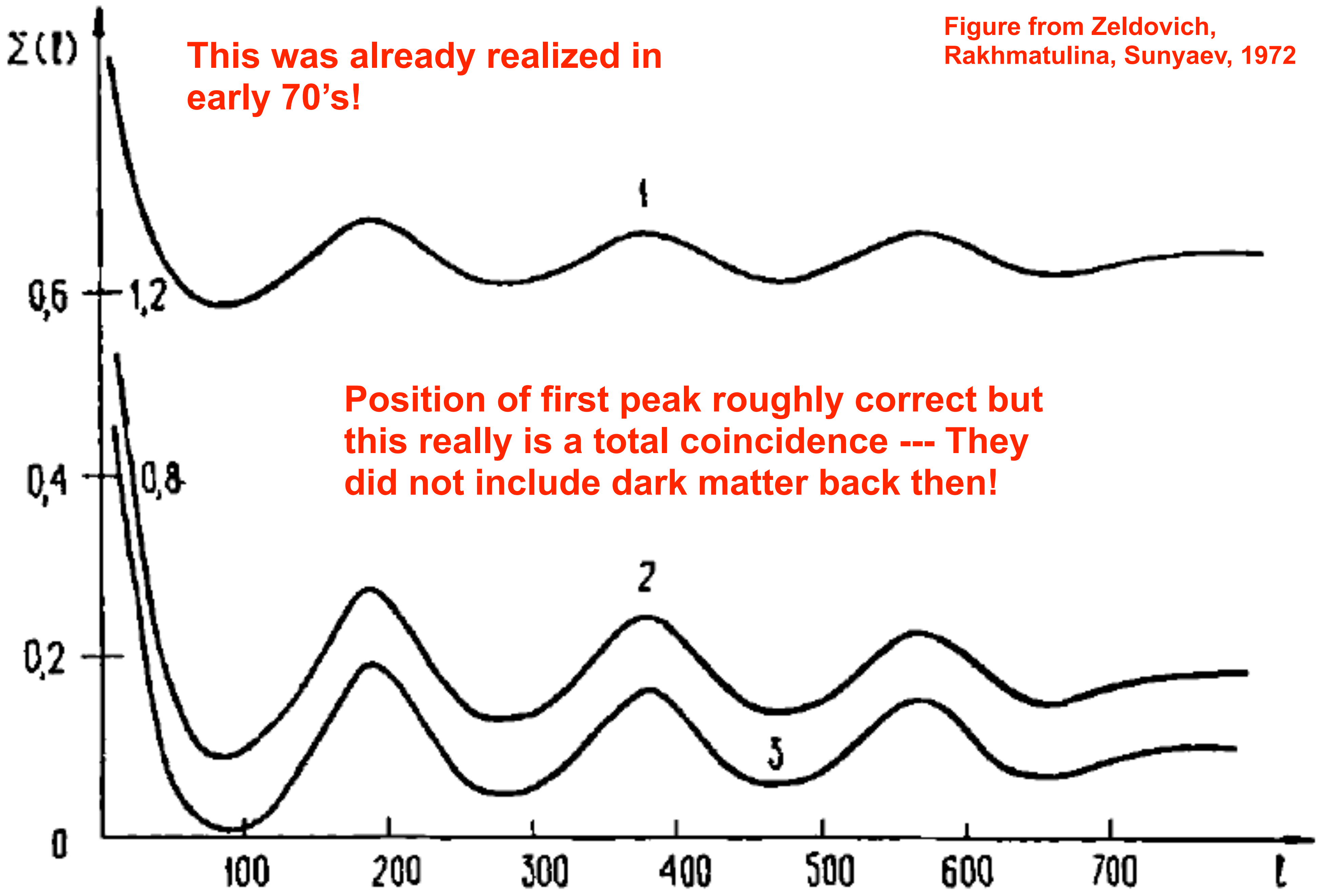




~ 1 degree or ~ twice diameter of moon!

- Fourier-transform of the two-point correlation function
- power spectrum describes the two-point statistics of a map
- Characterizes the *full statistics* (all *n*-point function) of a map for a Gaussian random field (odd *n*-point functions vanish)
- Homogeneity & isotropy of Universe $\Longrightarrow$ fluctuations only depend on scale but not specific directions (*other cases can be probed with BiPosh*)

Power spectrum is a really convenient way to talk about CMB maps and compress all its information!



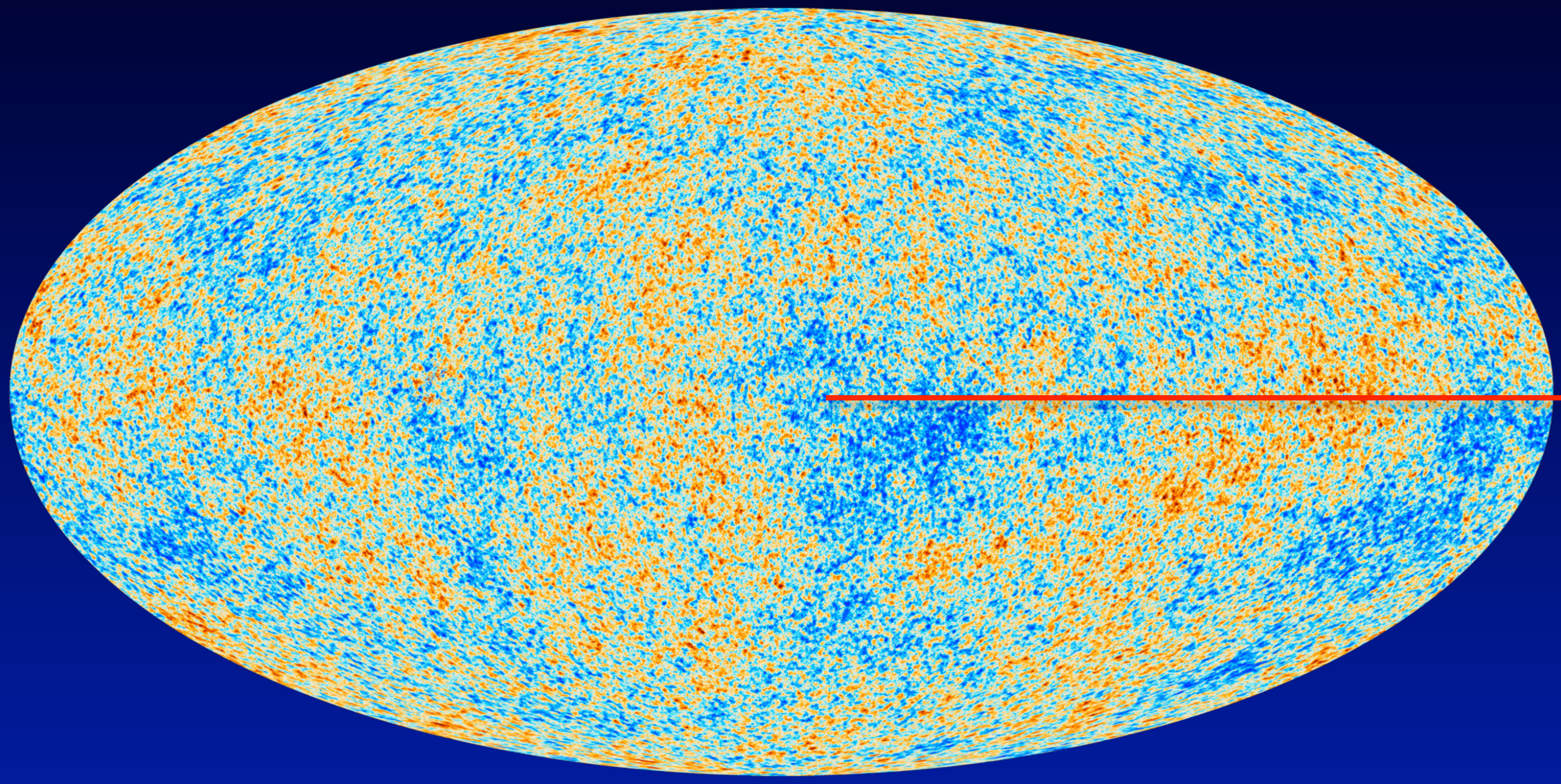
This was already realized in early 70’s!

Figure from Zeldovich, Rakhmatulina, Sunyaev, 1972

Position of first peak roughly correct but this really is a total coincidence --- They did not include dark matter back then!

Multipole

Cosmic Variance



$$a_{lm} = \int Y^*_{lm}(\theta,\phi)\frac{\Delta T(\theta,\phi)}{T}\,\mathrm{d}\Omega$$

$$\frac{\Delta T}{T} = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi)$$

Spherical harmonic expansion

- power spectrum describes intrinsic properties of the CMB for an ensemble of Universes (many realizations of the same field)
- determines variance of the harmonic coefficients
- We measure the CMB for *one* specific *realization*

$$\langle a_{lm}\rangle = 0$$

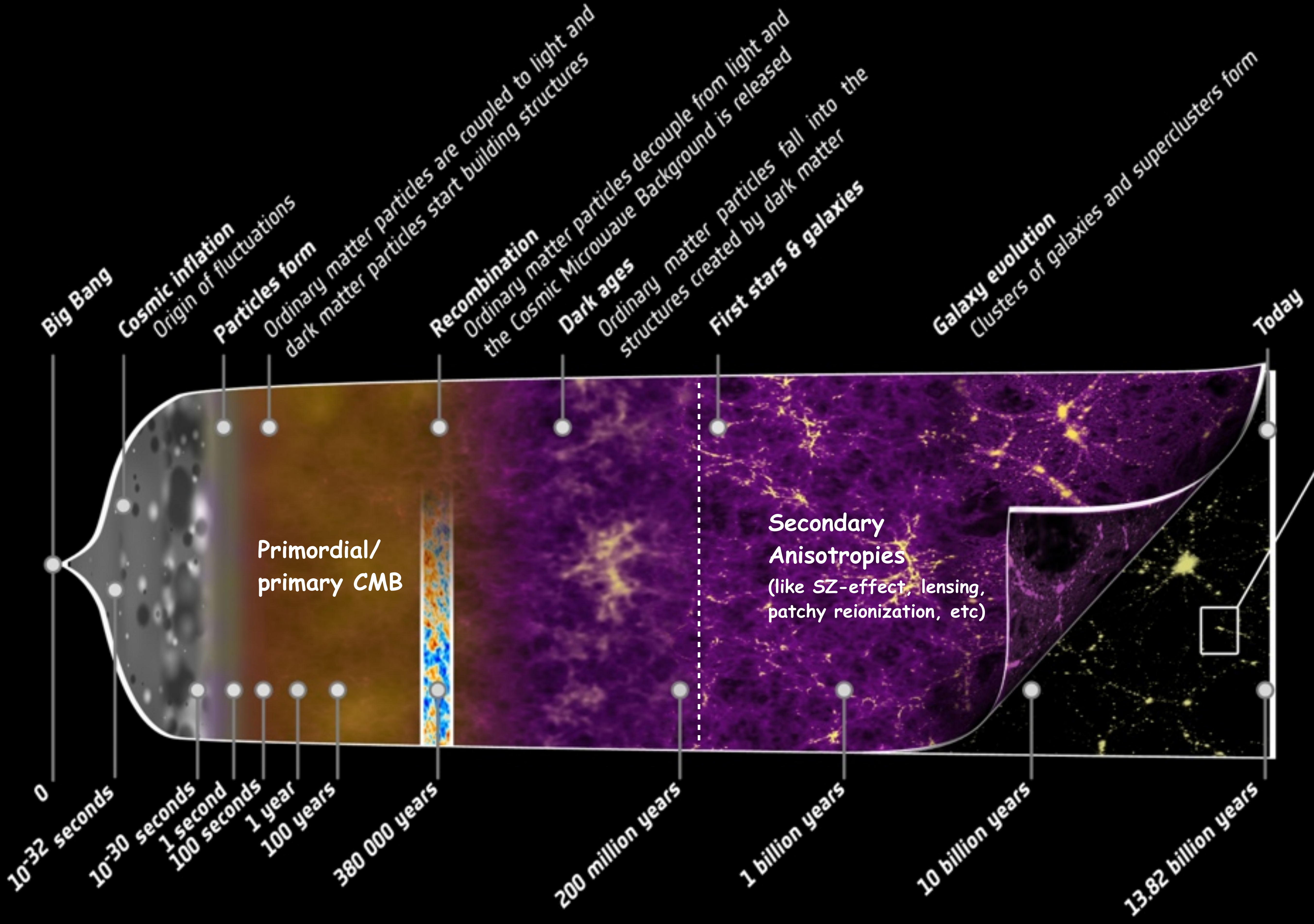
$$\langle a_{lm} a^*_{l'm'}\rangle = \delta_{ll'}\delta_{mm'}C_l$$

- Our measurement of one realization does not directly reflect the ensemble average / expectation value $\Longrightarrow$ *cosmic variance*
- Unavoidable noise/uncertainty!
- depends on the number of modes that are available

$$\Delta C_l / C_l = \sqrt{\frac{2}{2l+1}}$$

2 because field is real!

Primordial CMB anisotropies



Primordial/
primary CMB

Secondary
Anisotropies
(like SZ-effect, lensing,
patchy reionization, etc)

Early Predictions of CMB anisotropies

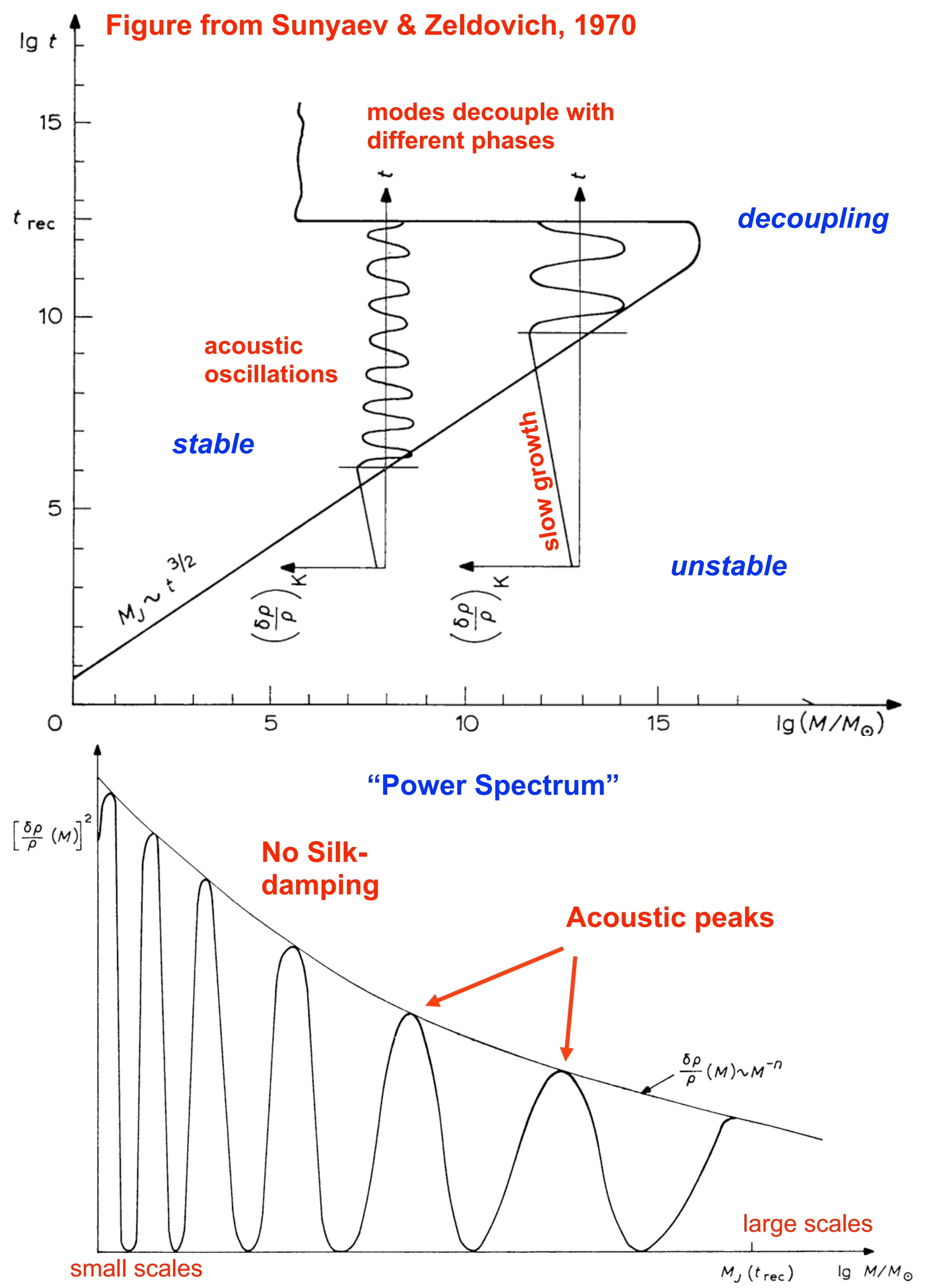


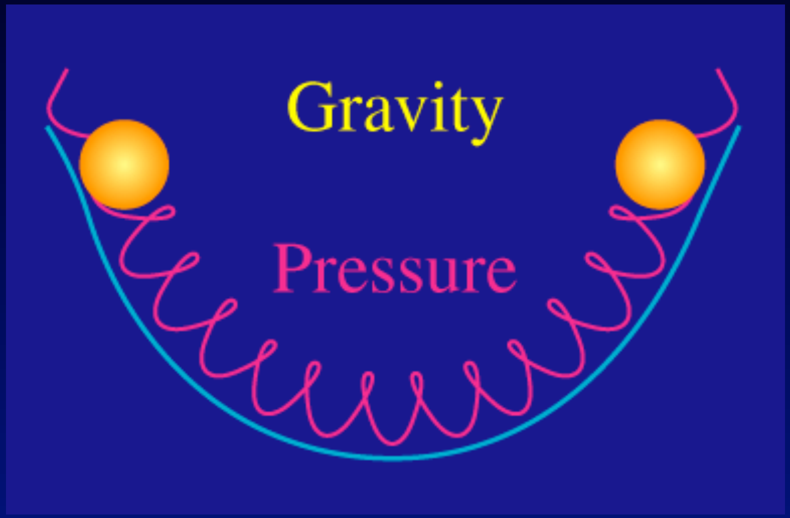
Figure from Sunyaev & Zeldovich, 1970

- Medium with photon & baryon (*dark matter not part of standard model back in the days!*)
- Some process (like inflation) set up *small* initial *perturbations* in the medium (*Harrison-Zeldovich power spectrum*)
- initial perturbations *adiabatic* (*isentropic*)

$$\frac{\delta\rho_{\rm m}}{\rho_{\rm m}} \approx \frac{3}{4}\frac{\delta\rho_\gamma}{\rho_\gamma}$$

- *pressure + gravity* determine evolution $\Longrightarrow$ gravitational collapse / growth for masses larger than Jeans mass
- Key features:
  - growth logarithmic early on (*super-horizon*)
  - acoustic oscillations before recombination
  - modes in different phases at decoupling
  - *Acoustic* peaks and *sound waves*!
- no CDM $\Longrightarrow$ expected perturbations large: $\Delta T/T \sim 10^{-3}$ -10^{-2}

Acoustic oscillations until recombination



Sound speed

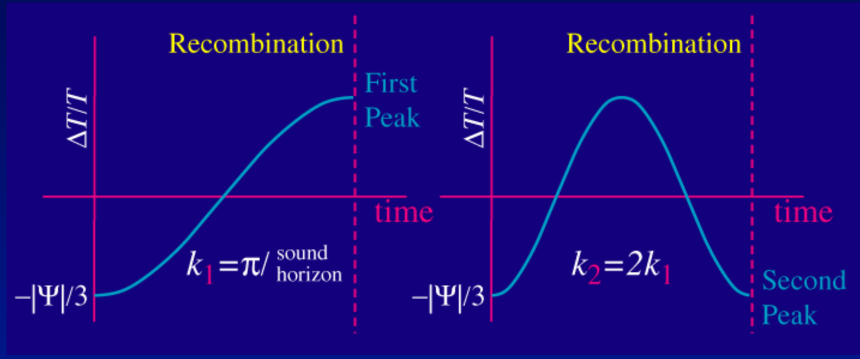
$$c_s = \frac{c}{\sqrt{3(1+R)}}$$

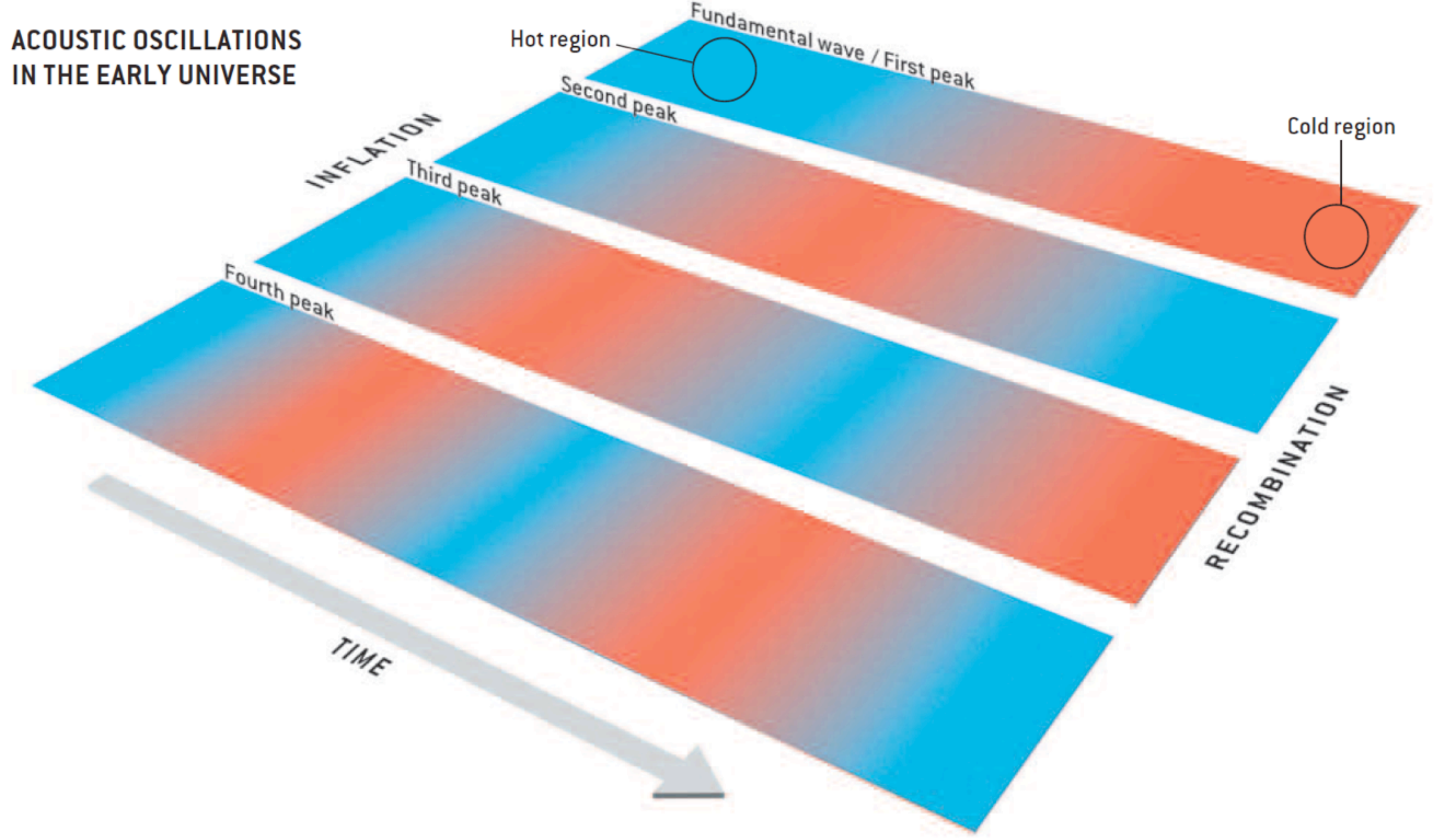
Baryon loading

$$R = \frac{3}{4}\frac{\rho_b}{\rho_\gamma} \approx \frac{673}{1+z}$$

Sound horizon

$$r_s = \int \frac{c_s \, dt}{a}$$

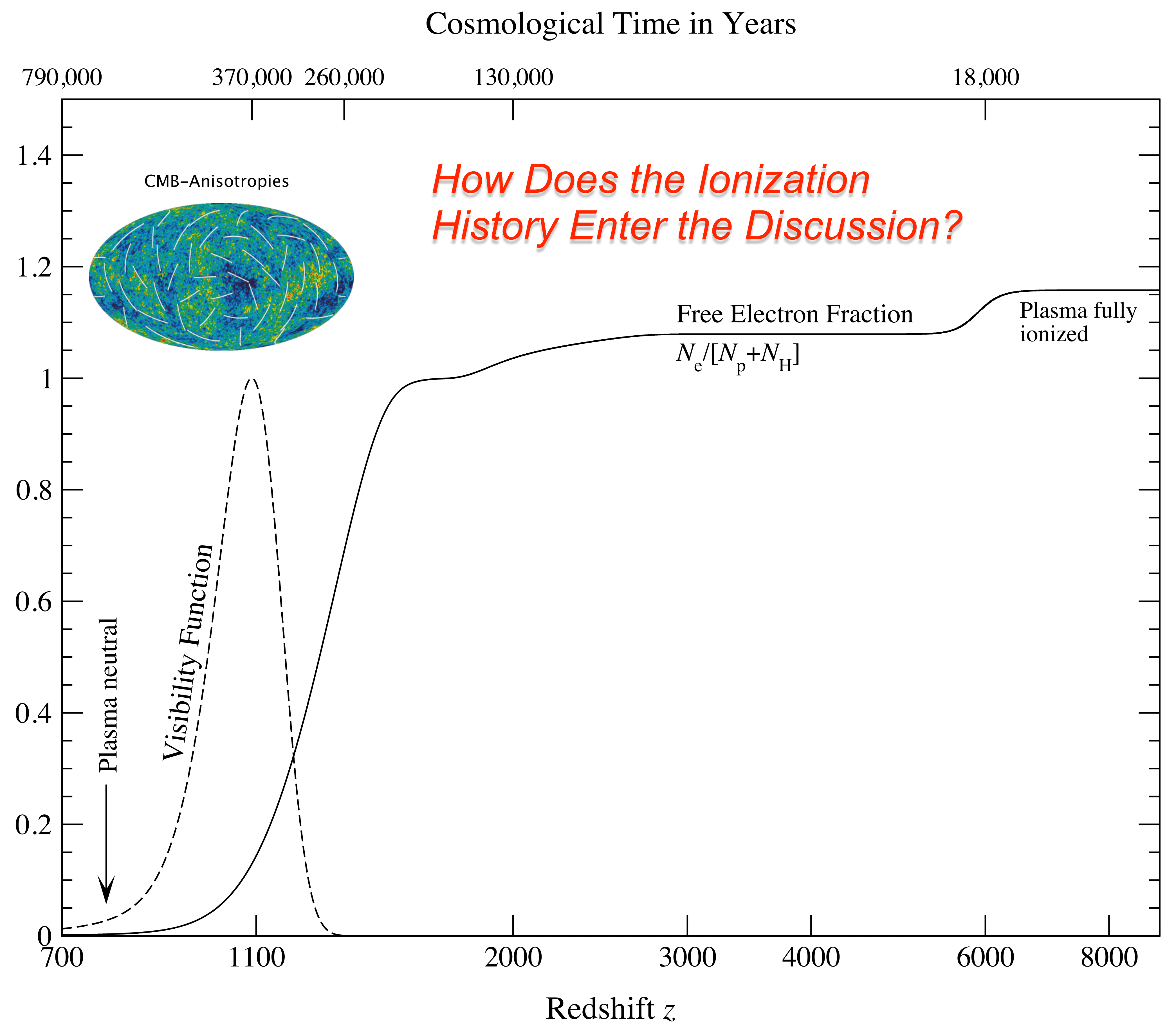




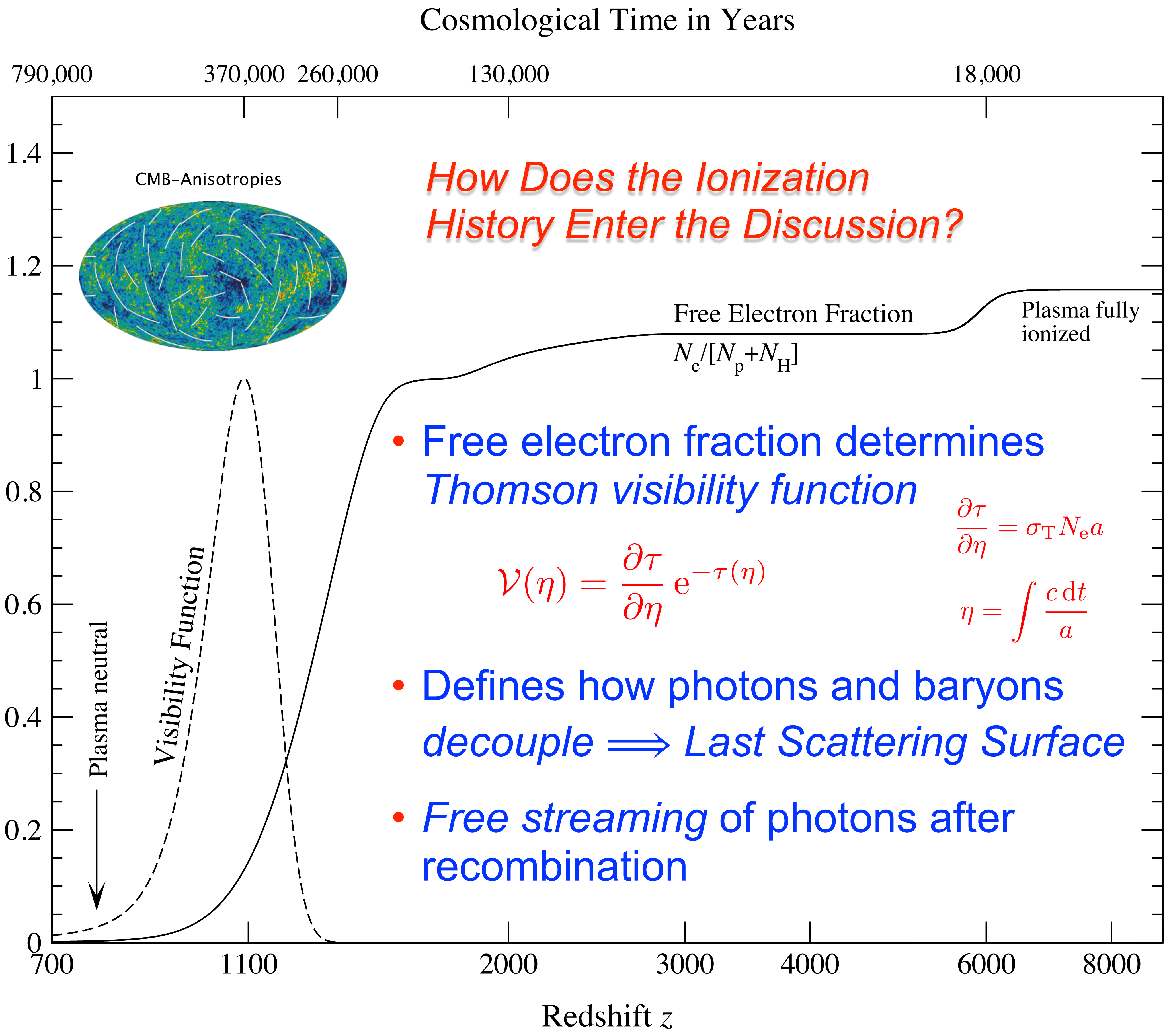
- position of first peak related to scale of *sound horizon* at recombination
- other peaks are *higher harmonics* of sound horizon scale

Hu & White, 2004

How Does the Ionization History Enter the Discussion?



How Does the Ionization History Enter the Discussion?



- Free electron fraction determines *Thomson visibility function*

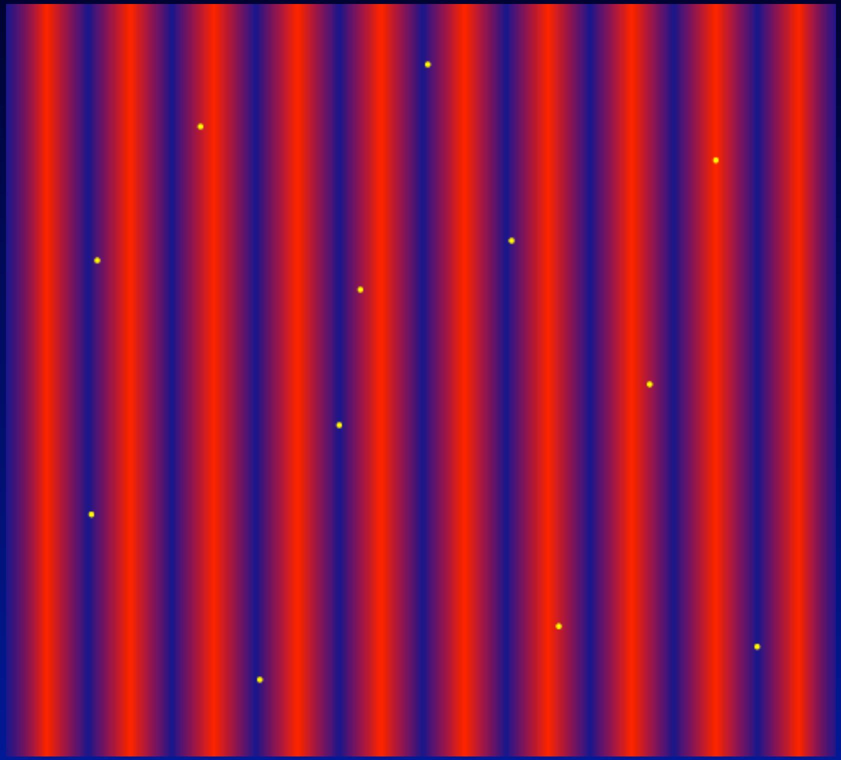
$$\frac{\partial\tau}{\partial\eta} = \sigma_{\rm T} N_{\rm e} a$$

$$\mathcal{V}(\eta) = \frac{\partial\tau}{\partial\eta}\,{\rm e}^{-\tau(\eta)}$$

$$\eta = \int \frac{c\,{\rm d}t}{a}$$

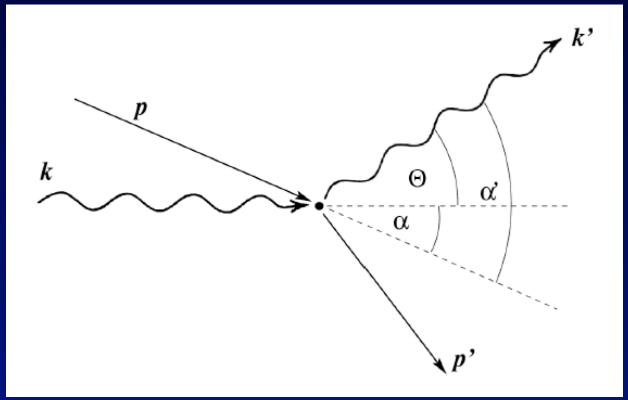
- Defines how photons and baryons *decouple* $\Longrightarrow$ *Last Scattering Surface*
- *Free streaming* of photons after recombination

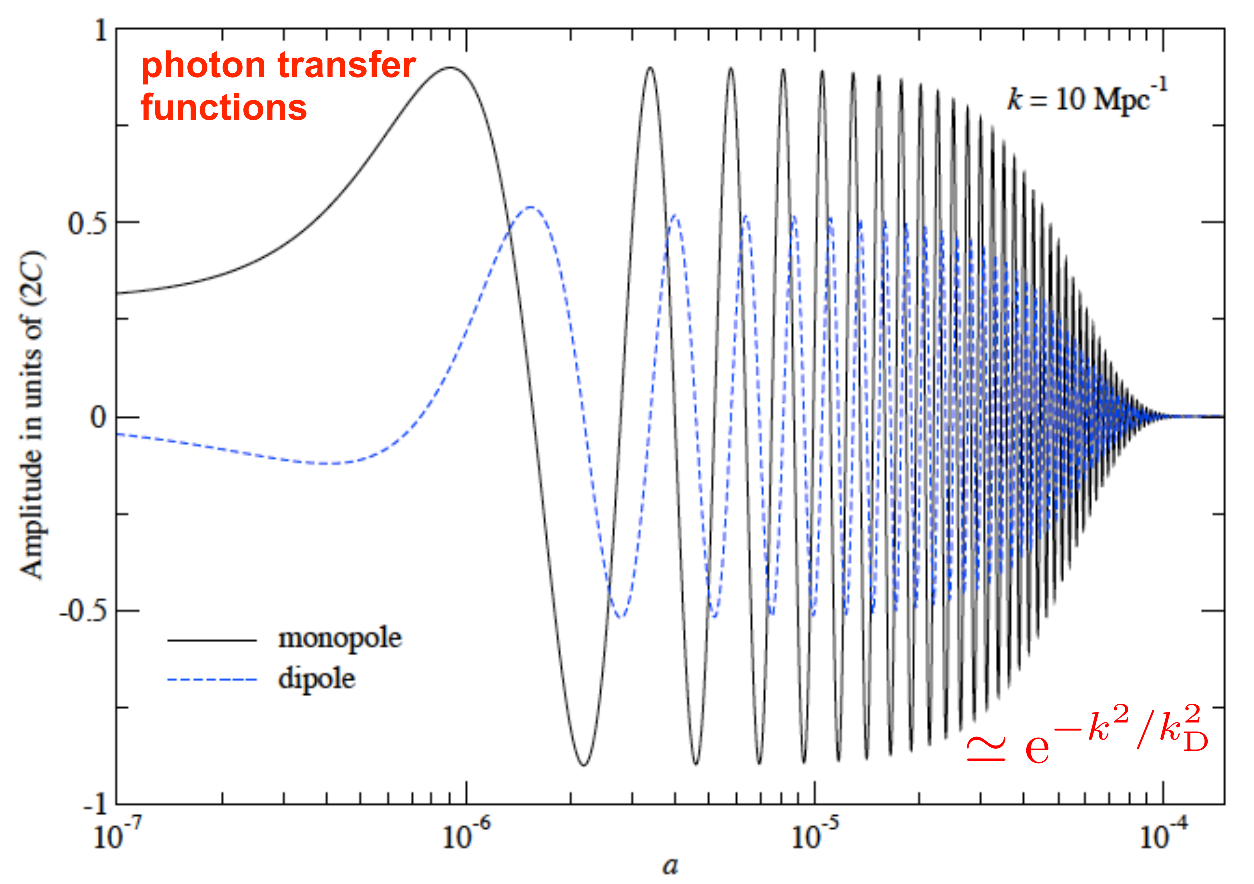
Thomson scattering and Silk damping



Thomson scattering cross section

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega} = \frac{3\sigma_\mathrm{T}}{16\pi}\left[1 + (\hat{\gamma}\cdot\hat{\gamma}')^2\right]$$





- couples to monopole & quadrupole
- helps to *isotropize* the radiation field
- *erases* anisotropies below the diffusion damping scale, k_D

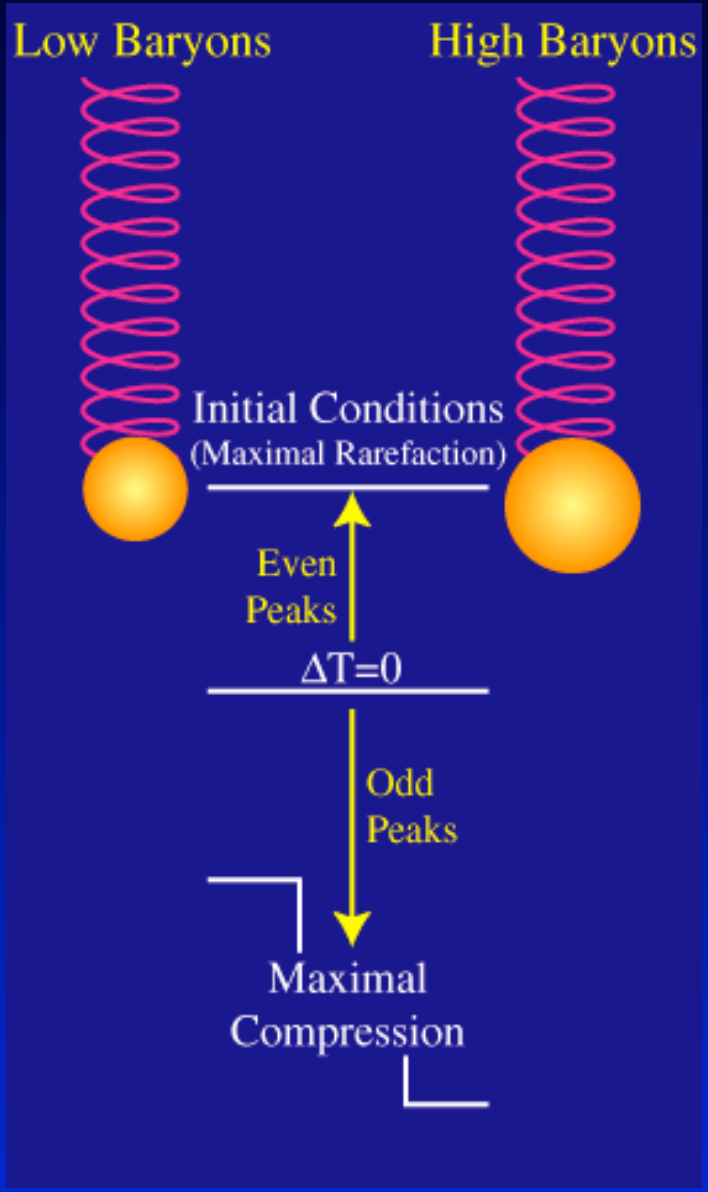
$$\frac{1}{k_\mathrm{D}^2} \simeq \frac{8}{45}\int \frac{\mathrm{d}\eta}{a\sigma_\mathrm{T}N_\mathrm{e}}$$

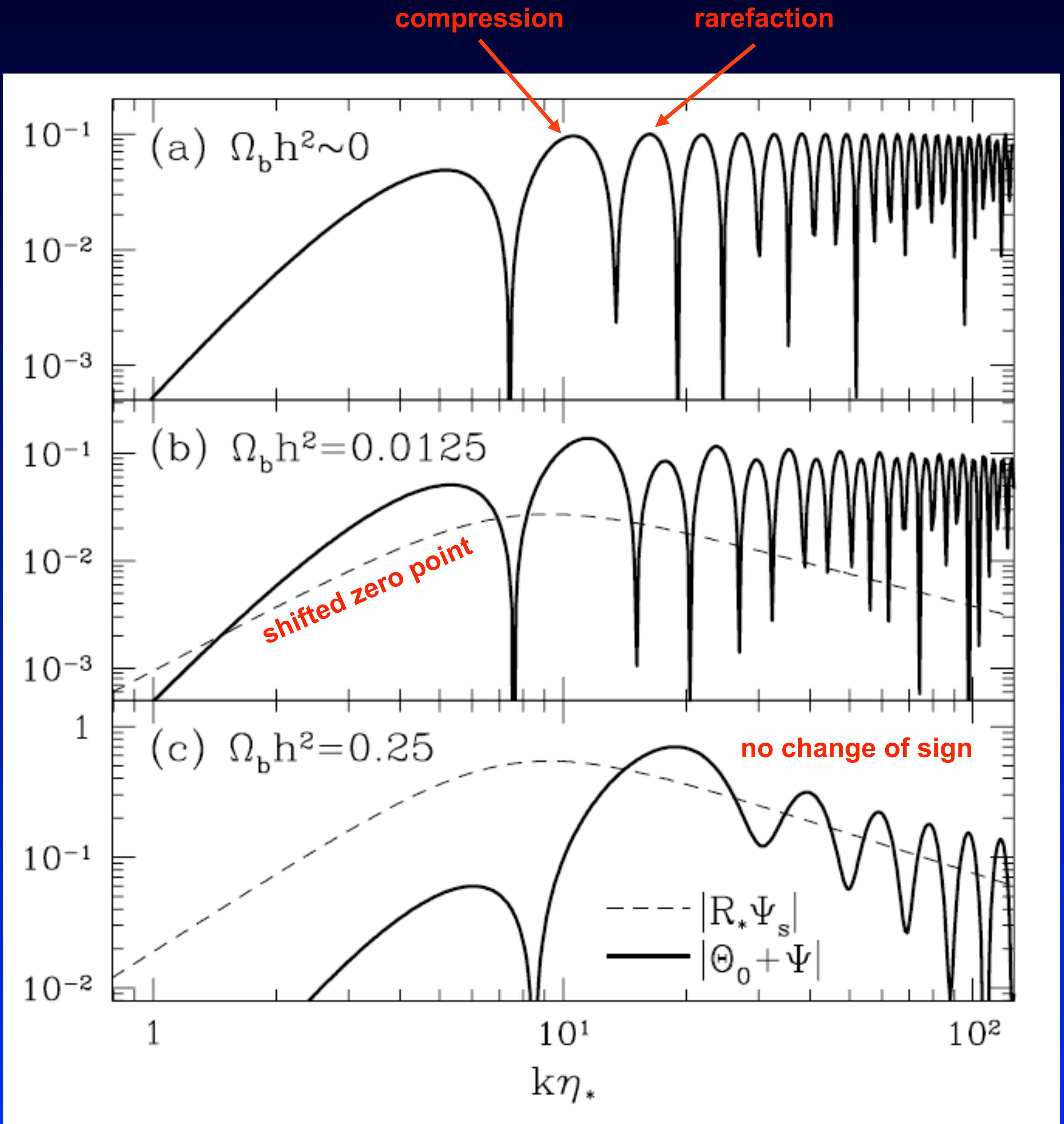
(radiation-domination)

$$k_\mathrm{D} \simeq 4\times 10^{-6}(1+z)^{3/2}\mathrm{Mpc}^{-1}$$

- mixing of blackbodies
  $\Longrightarrow$ CMB spectral distortions

Effect of Baryon loading on local monopole





compression

rarefaction

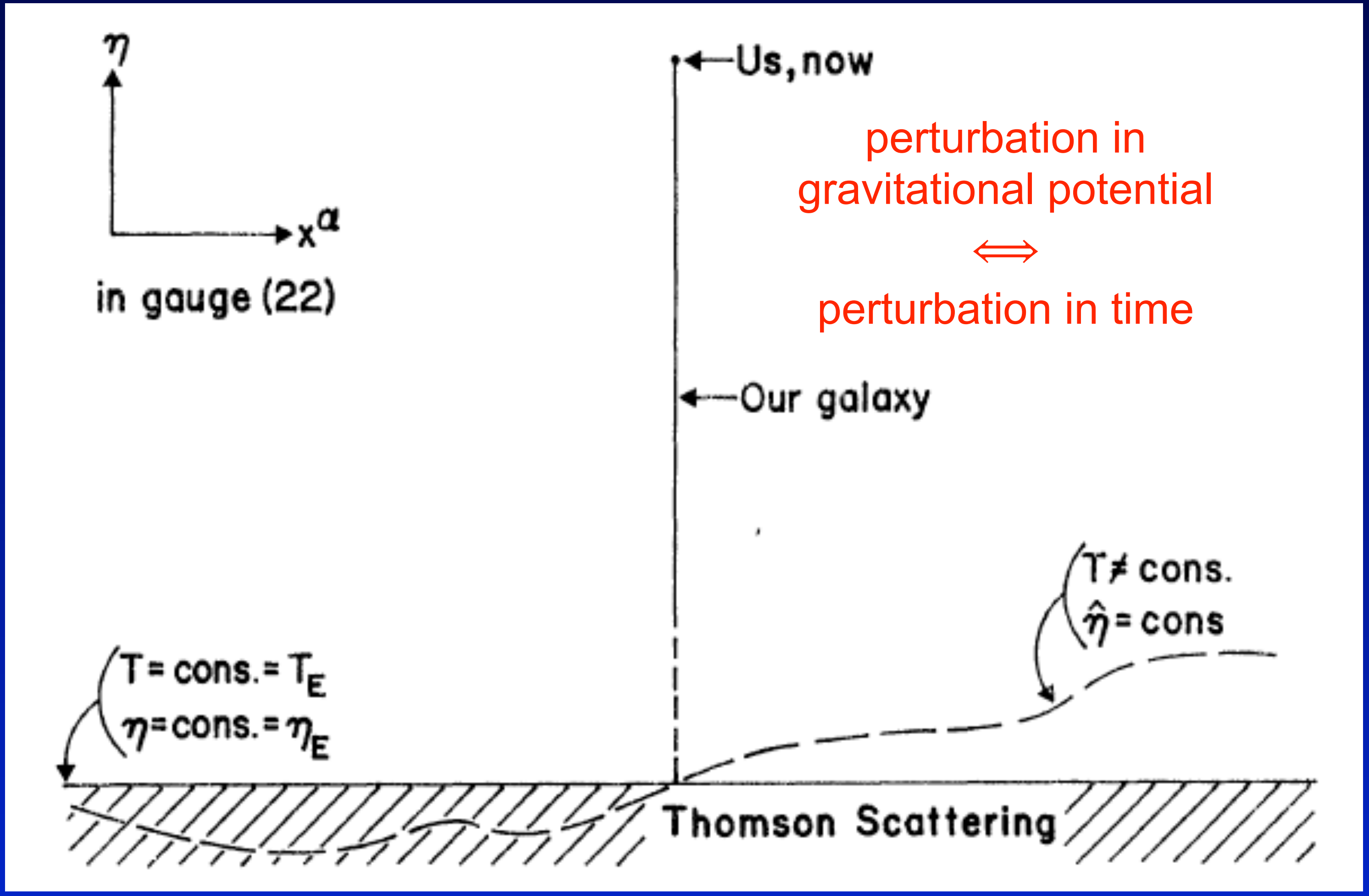
shifted zero point

no change of sign

Figure from Hu & White, 1996

- shifts the zero point of oscillation (need dark matter!)
- compression peaks have larger amplitude

Sachs-Wolfe Effect



perturbation in gravitational potential

⟺

perturbation in time

Figure from Sachs & Wolfe, 1967

- related to difference in the gravitational potential between us and recombination
- gravitational redshifting
- important at large scales (super-horizon)
- hot spots ⟺ under dense regions

$$\left.\frac{\Delta T}{T}\right|_{\rm obs} \simeq \left.\frac{\Delta T}{T}\right|_{\rm prim} + \Phi_{\rm rec} - \Phi_{\rm obs} \approx -\frac{\Phi}{3}$$

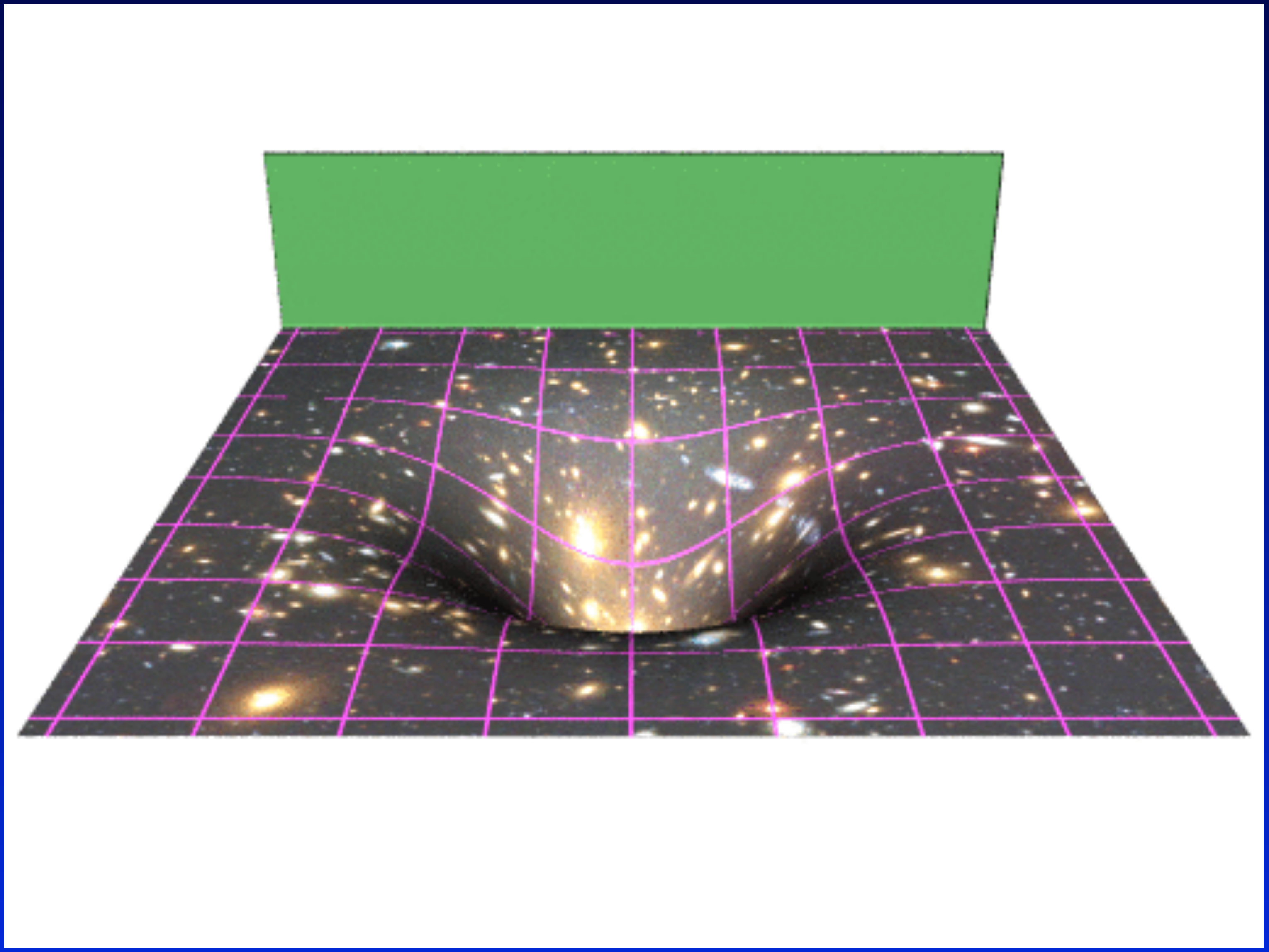
Integrated Sachs-Wolfe Effect (ISW)

- evolution (decay) of potential
- gravitational blue and redshifting do not cancel (photon hotter)
- only when Universe is not matter dominated
  - ➡ dark energy era (*now*)
  - ➡ early ISW around matter radiation equality but also during recombination
- ISW is both primordial and secondary source of anisotropies

Movie from Neyrinck & Szapudi

$$\left.\frac{\Delta T}{T}\right|_{\rm ISW} \simeq \int (\dot{\Phi} + \dot{\Psi})\, \mathrm{d}\eta$$

Integrated Sachs-Wolfe Effect (ISW)



Movie from Neyrinck & Szapudi

- evolution (decay) of potential
- gravitational blue and redshifting do not cancel (photon hotter)
- only when Universe is not matter dominated
  - ➡ dark energy era (*now*)
  - ➡ early ISW around matter radiation equality but also during recombination
- ISW is both primordial and secondary source of anisotropies

$$\left.\frac{\Delta T}{T}\right|_{\mathrm{ISW}} \simeq \int (\dot{\Phi} + \dot{\Psi})\, \mathrm{d}\eta$$

Doppler effect

- gas volumes in motion at recombination
- in tight-coupling regime (before recombination)

$\Longrightarrow$ photon monopole & dipole $\pi/2$ shifted

$\Longrightarrow$ coherent addition == 0

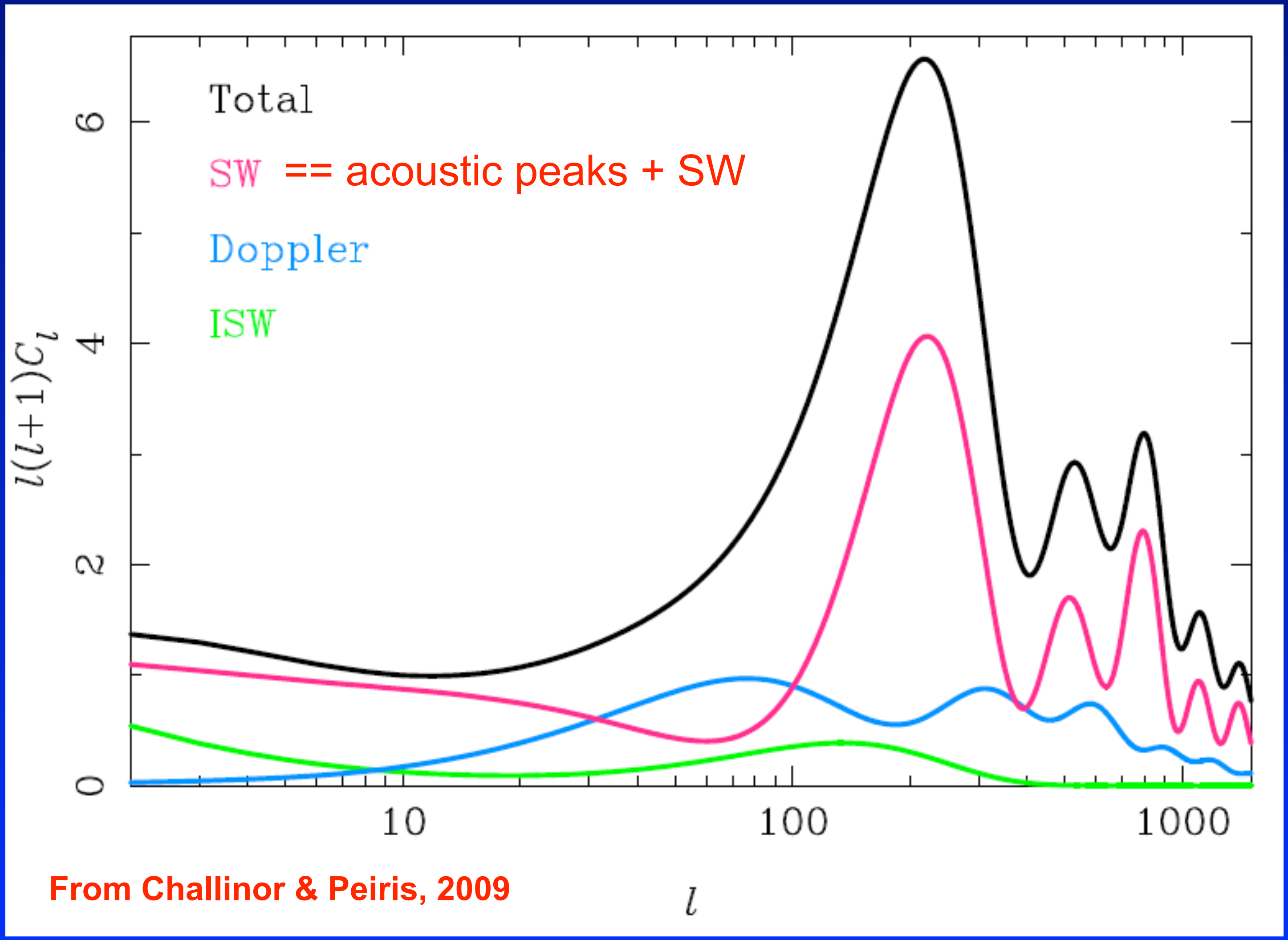
$$\left.\frac{\Delta T}{T}\right|_{\mathrm{Doppler}} \simeq \beta \cdot \hat{\gamma}$$

- projection effects and R>0 render Doppler terms weaker so that acoustic peaks remain intact

Doppler effect

- gas volumes in motion at recombination
- in tight-coupling regime (before recombination)
  - $\Longrightarrow$ photon monopole & dipole $\pi/2$ shifted
  - $\Longrightarrow$ coherent addition == 0
- projection effects and R>0 render Doppler terms weaker so that acoustic peaks remain intact

$$\left.\frac{\Delta T}{T}\right|_{\mathrm{Doppler}} \simeq \beta \cdot \hat{\gamma}$$



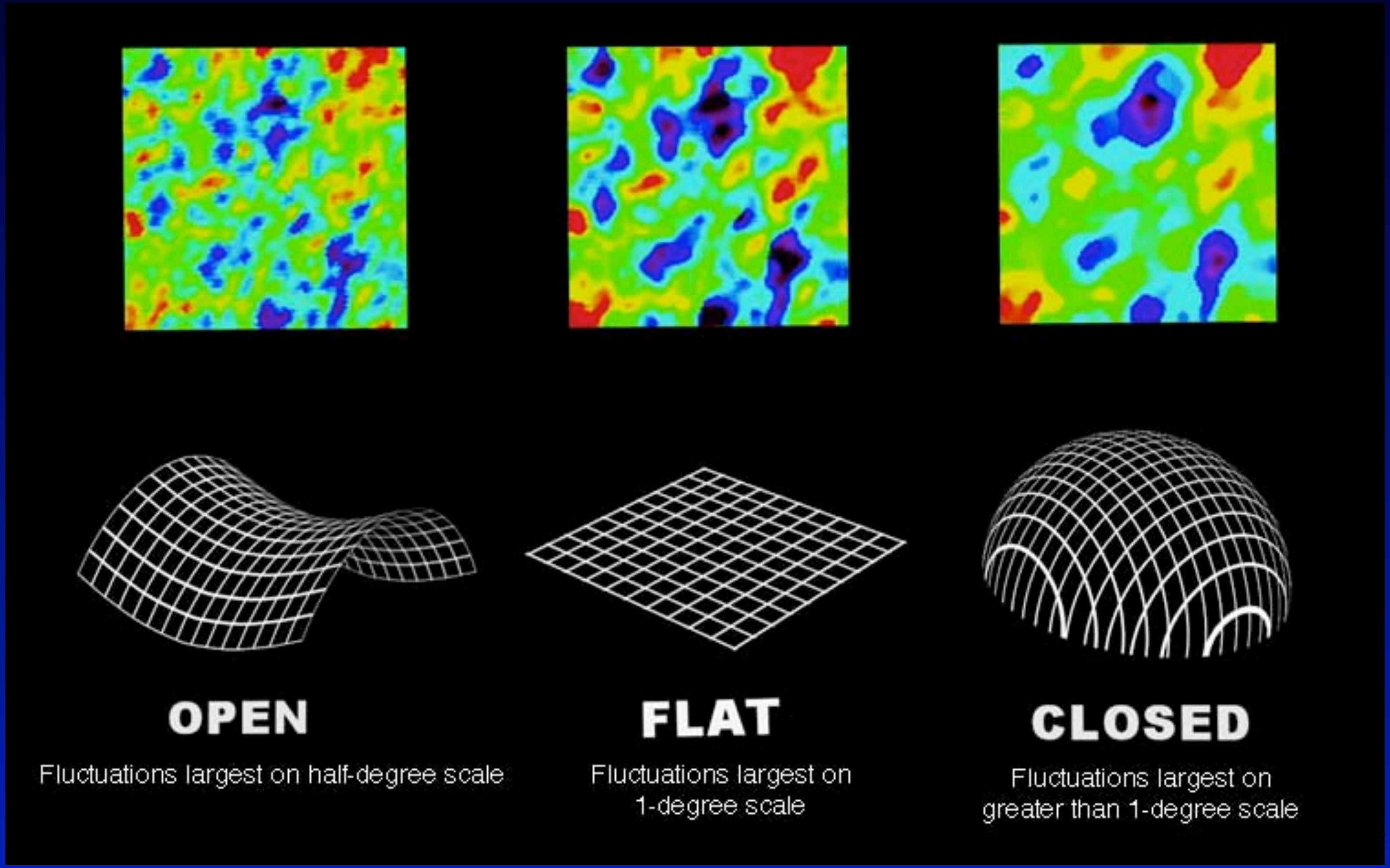
From Challinor & Peiris, 2009

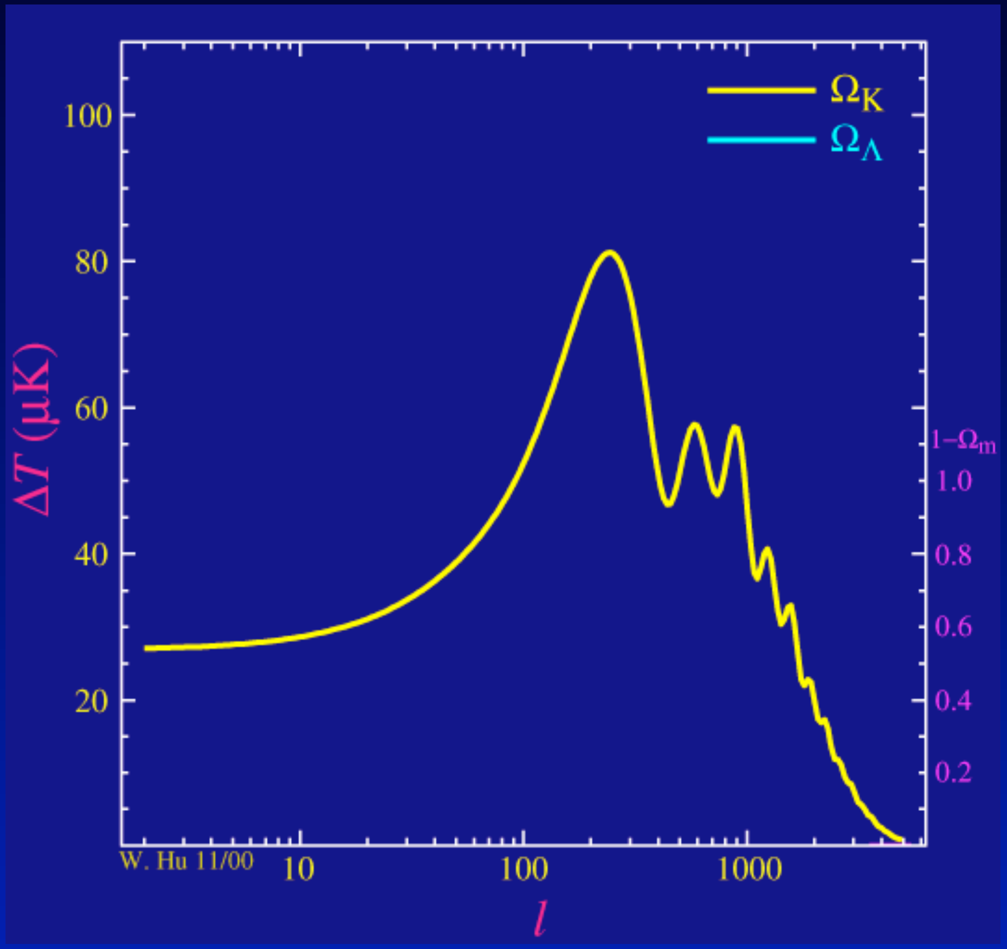
Sum of Effects

- acoustic peaks + SW dominant
- late ISW at large scales
- early ISW around first peak
- Doppler terms out of phase with acoustic peaks

Main Dependencies on Parameters

CMB is sensitive to curvature of the Universe



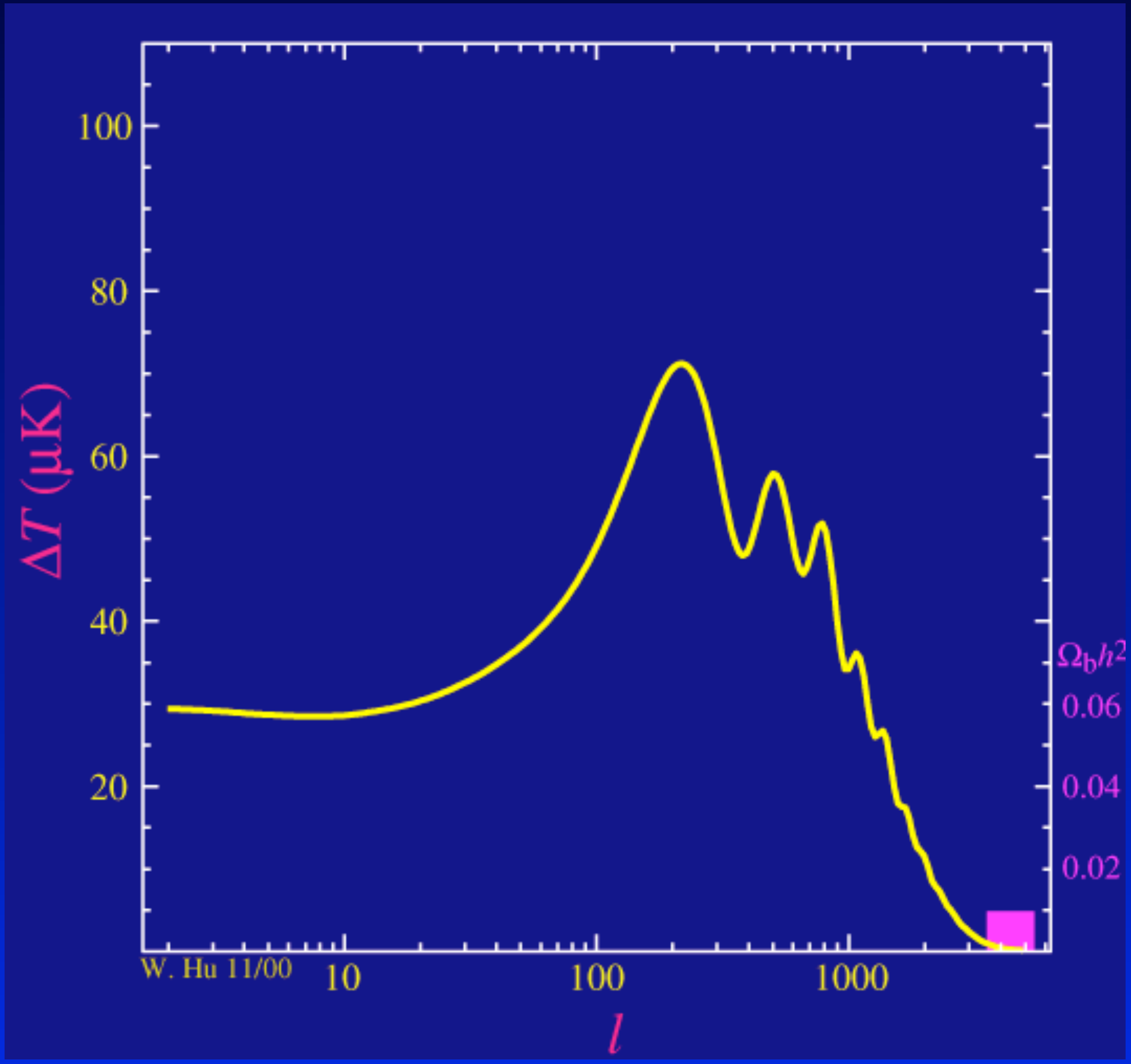


$$\Omega_k = 1 - \Omega_0$$

matter, dark energy, radiation, neutrinos, etc

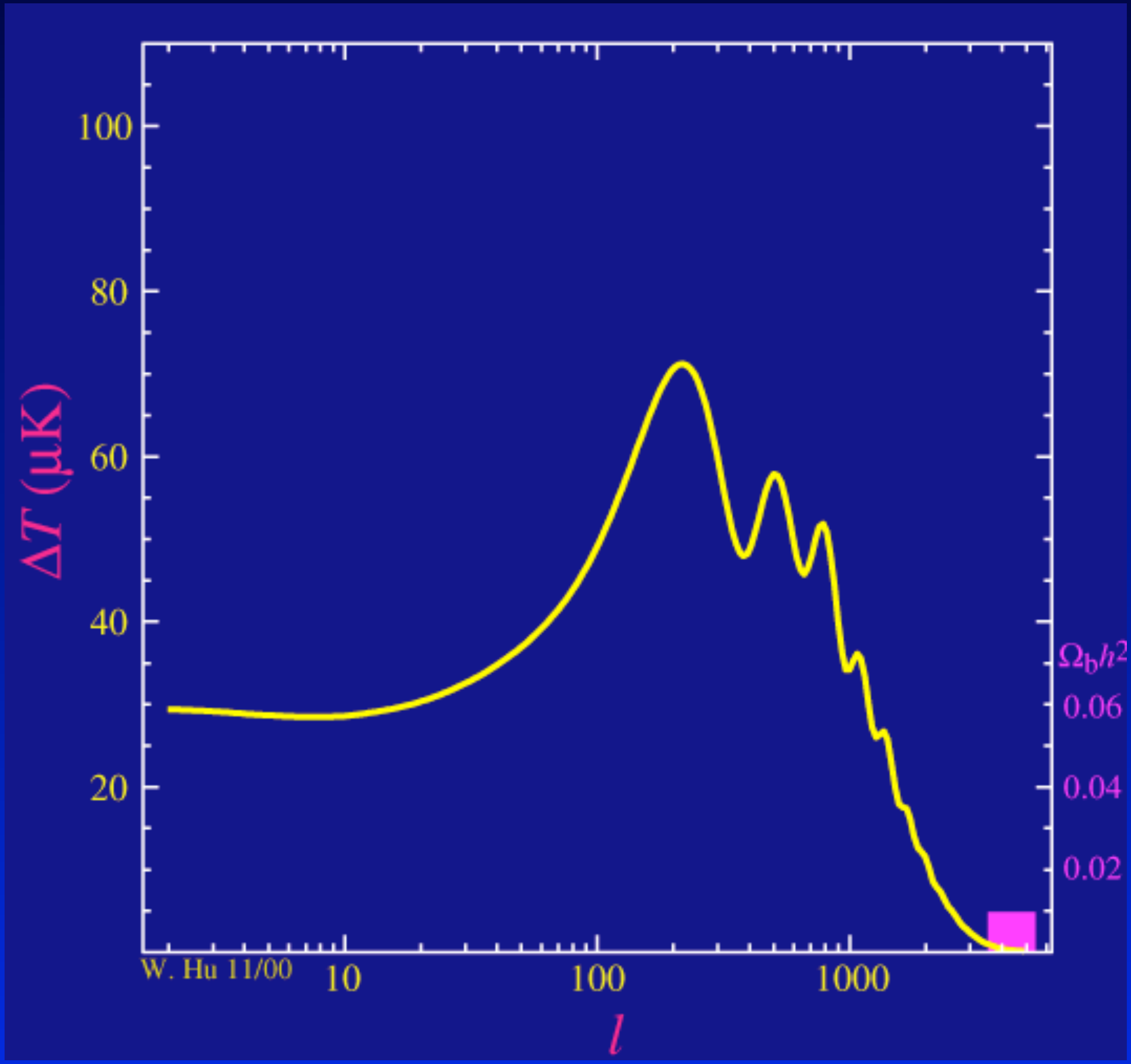
- acoustic peaks define *standard ruler* at last scattering
- the corresponding *observed* angular scale is directly related to the sound horizon scale by the angular diameter distance
- positions of acoustic peaks probe total curvature of the Universe
- Geometric degeneracy (has very similar effect dark energy)

Effect of Baryon density



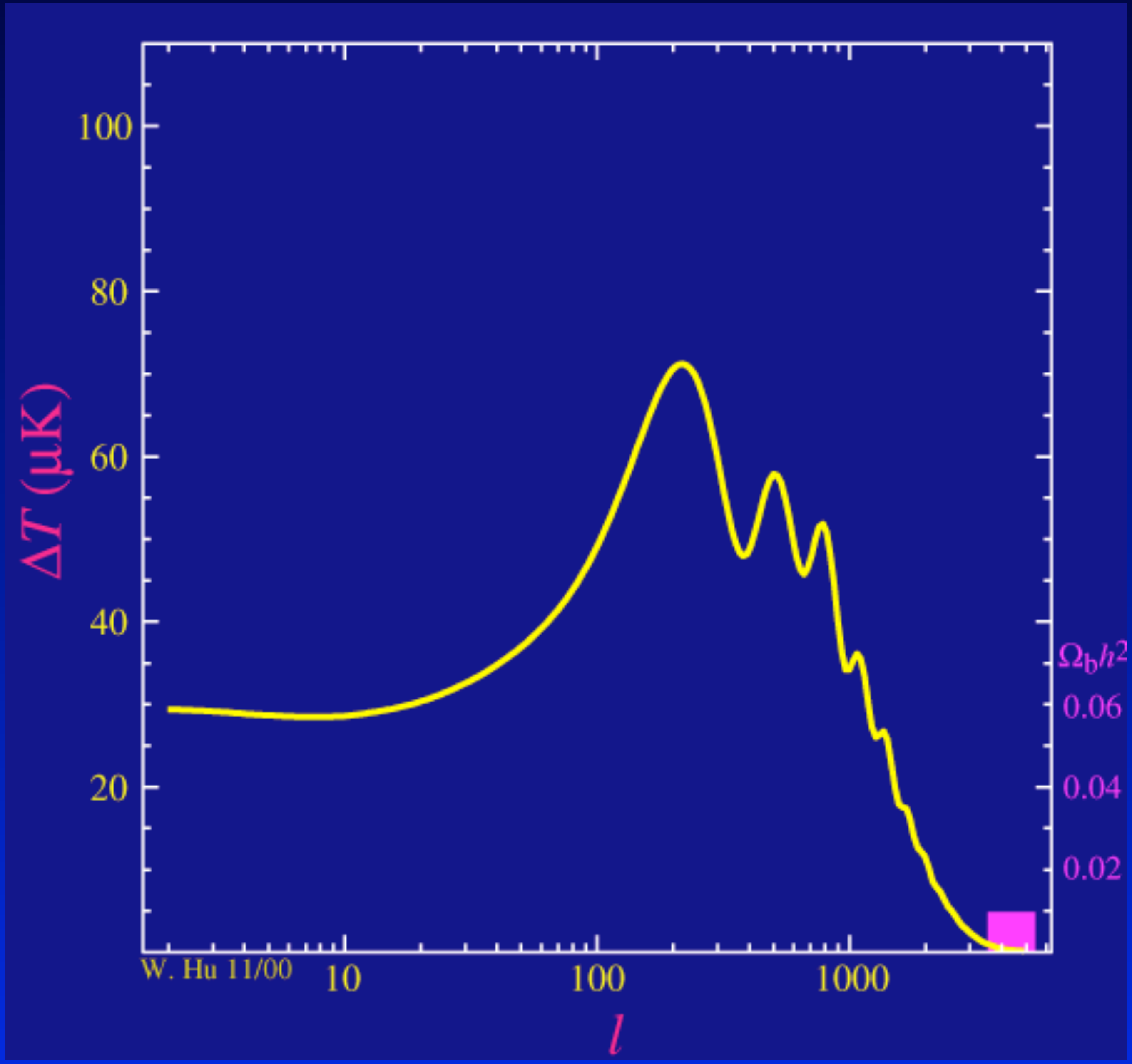
- Increasing $\Omega_\mathrm{b} h^2$
  - decreases sound speed
  - decreases sound horizon
  - *peak positions shift to smaller scales*

Effect of Baryon density



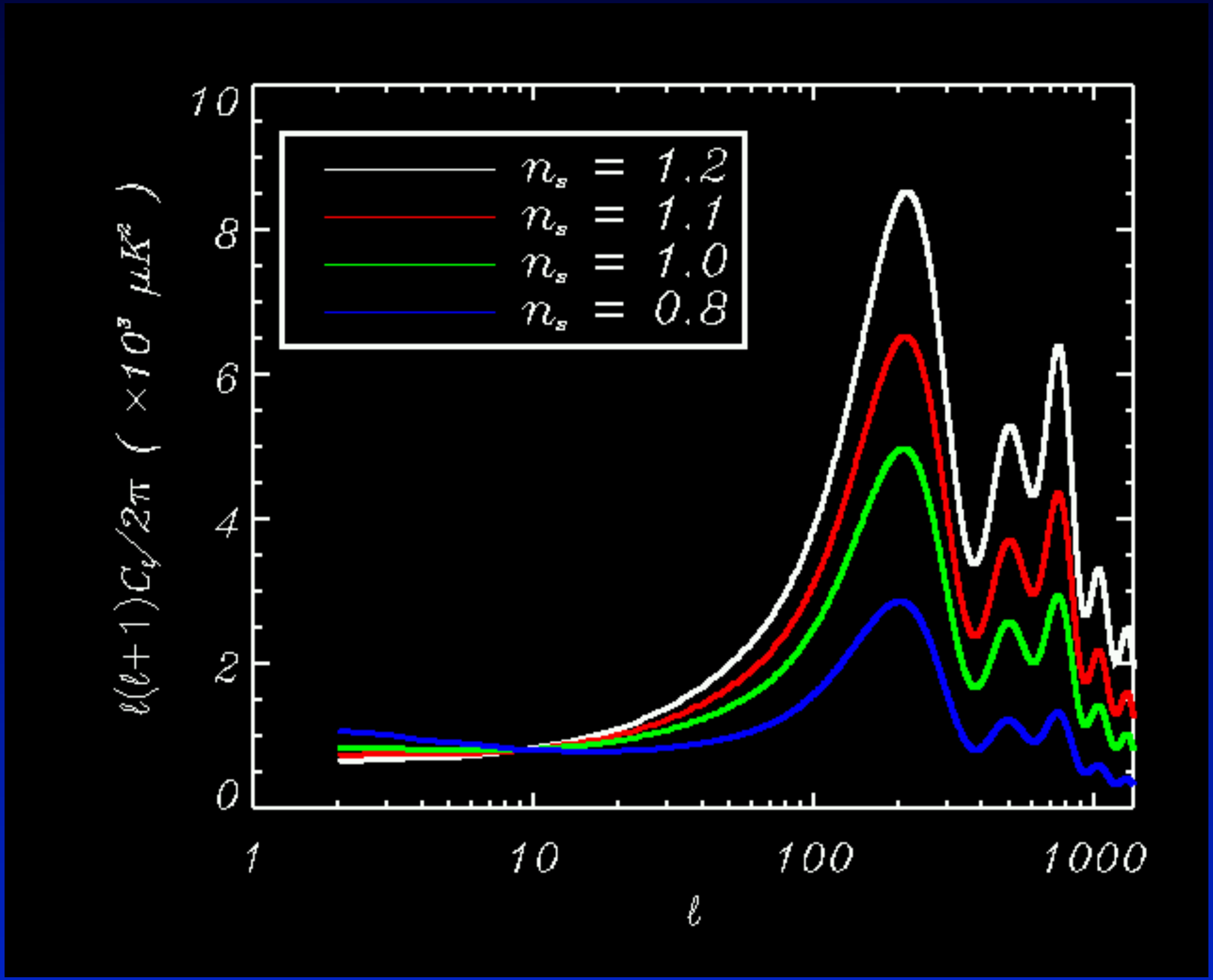
- Increasing $\Omega_{\mathrm{b}} h^2$
  - decreases sound speed
  - decreases sound horizon
  - *peak positions shift to smaller scales*
- Increasing $\Omega_{\mathrm{b}} h^2$
  - increases scattering rate
  - decreases damping scale
  - *more small scale power*

Effect of Baryon density



- Increasing $\Omega_\mathrm{b}h^2$
  - decreases sound speed
  - decreases sound horizon
  - *peak positions shift to smaller scales*
- Increasing $\Omega_\mathrm{b}h^2$
  - increases scattering rate
  - decreases damping scale
  - *more small scale power*
- Increasing $\Omega_\mathrm{b}h^2$
  - shift zero point of oscillations
  - *odd (compressional) peaks higher* (assuming dark matter is present)

Dependence on power spectrum parameters



- Dependence on overall power spectrum amplitude trivial
  - large scale part cosmic variance
  - degeneracy with ISW
- Spectral index determines overall tilt
  - pivot scale usually chosen to de-correlate parameter from amplitude (depends on exp.)
- running determines overall curvature of power spectrum
  - small in single field inflation

$$n_{\rm run} \simeq (n_{\rm S} - 1)^2$$

Standard parametrization of curvature power spectrum

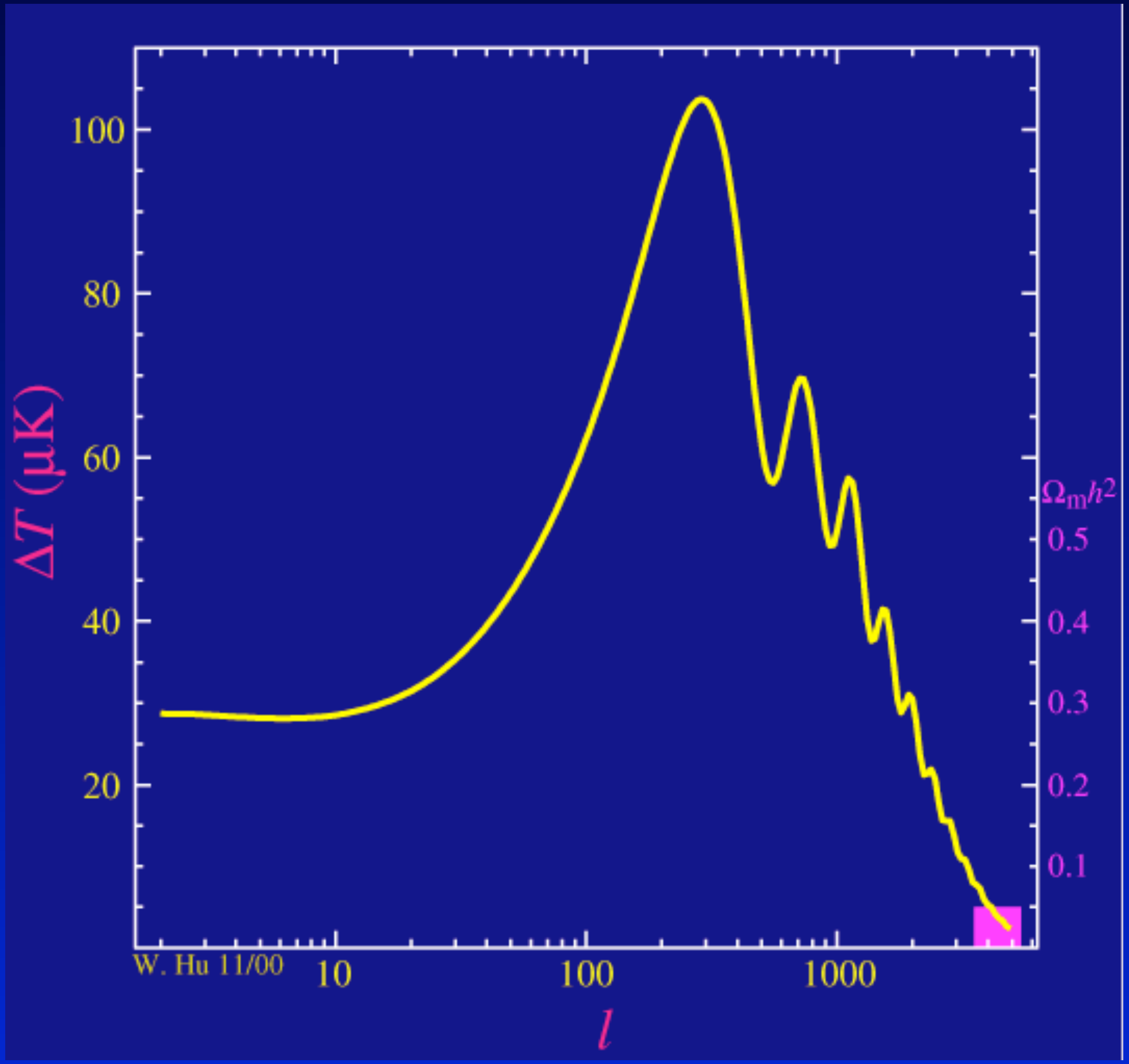
running

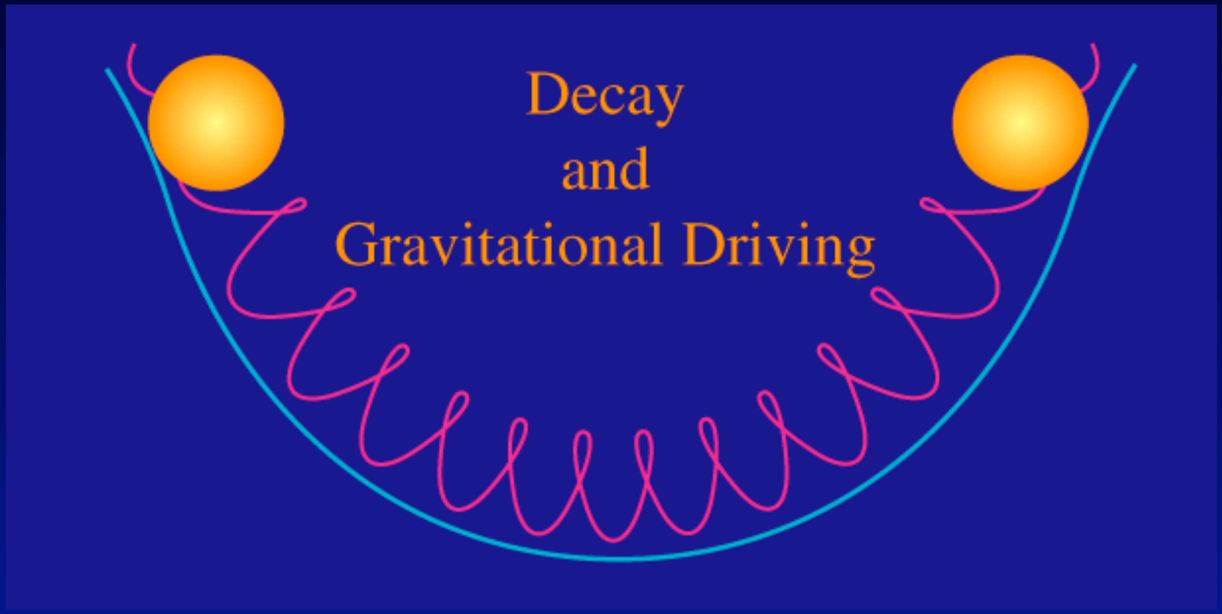
$$P_\zeta = 2\pi^2 A_\zeta k^{-3} (k/k_0)^{n_{\rm S} - 1 + \frac{1}{2} n_{\rm run} \ln(k/k_0)}$$

overall amplitude

spectral index

Effect of Dark Matter





- Increasing $\Omega_{\mathrm{cdm}} h^2$
  - matter-domination earlier
  - gravitational driving effect important for smaller scales
  - baryon loading becomes larger
  - age of Universe increases (*distance sound can travel increases*)
  - peaks move to larger scales

Isocurvature modes

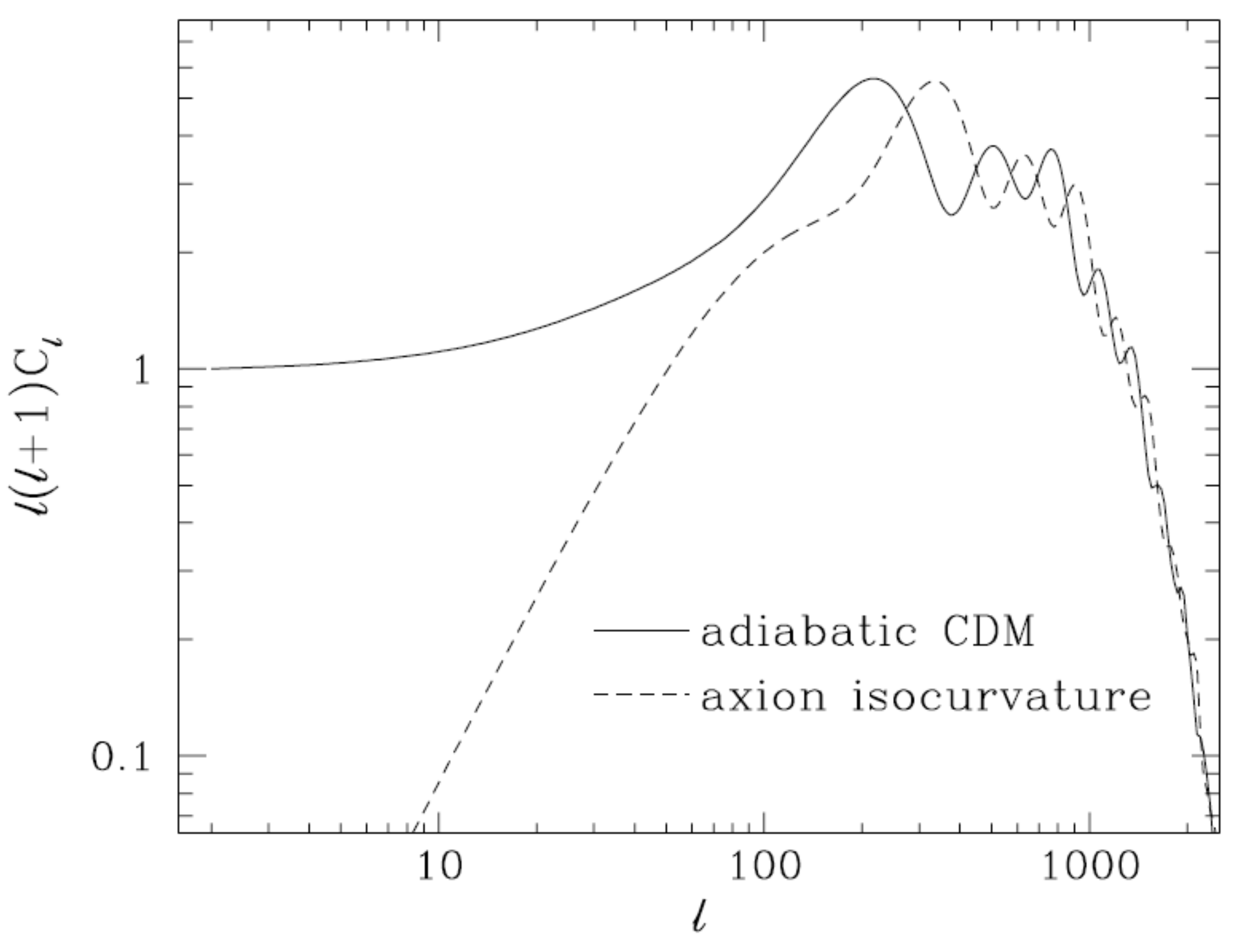


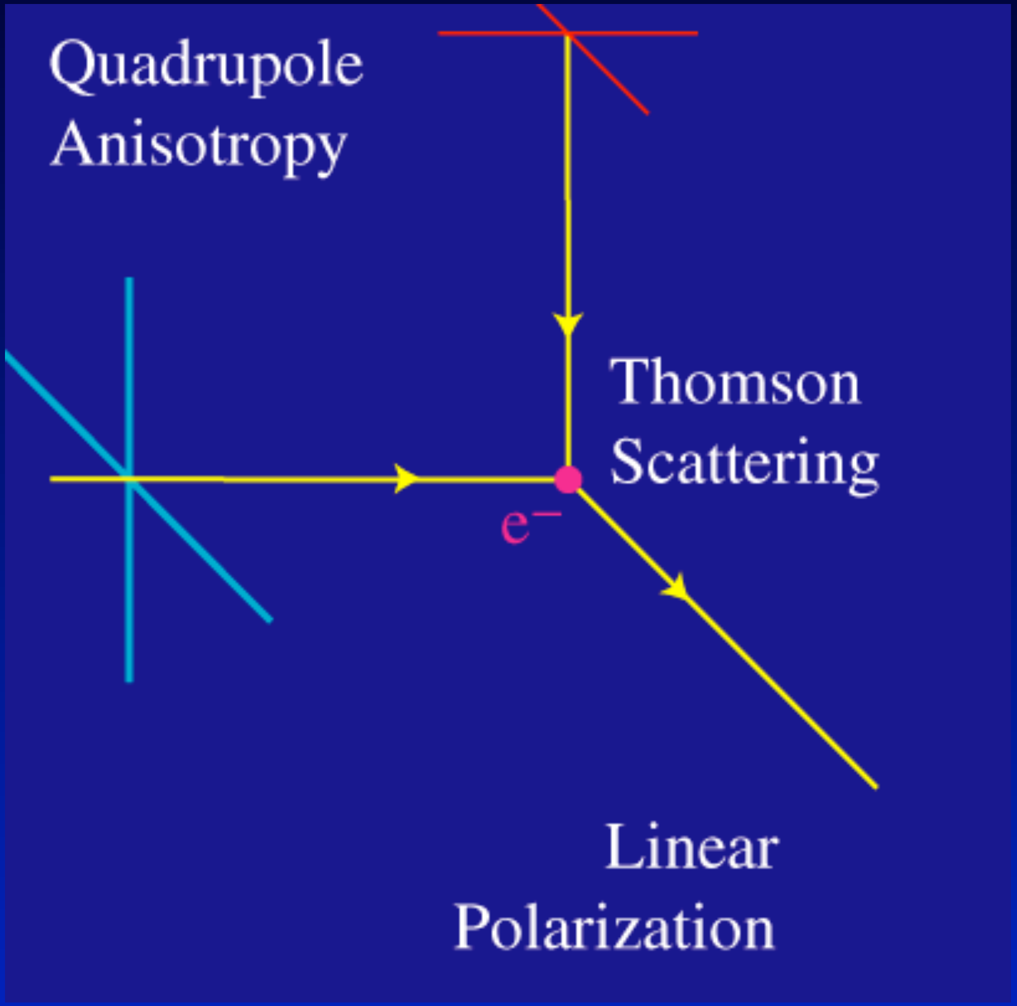
Figure from Hu & White, 1996

- initial perturbations in the *entropy/composition* of the medium
- different types (baryon/CDM/neutrino/compensated) of modes depending on what component is perturbed
- photon perturbations vanish at super-horizon scales
- peak positions shifted
- from observations we know that the contribution is small at CMB scales
- significant contribution at smaller scales not ruled out!

$\Longrightarrow$ CMB spectral distortions

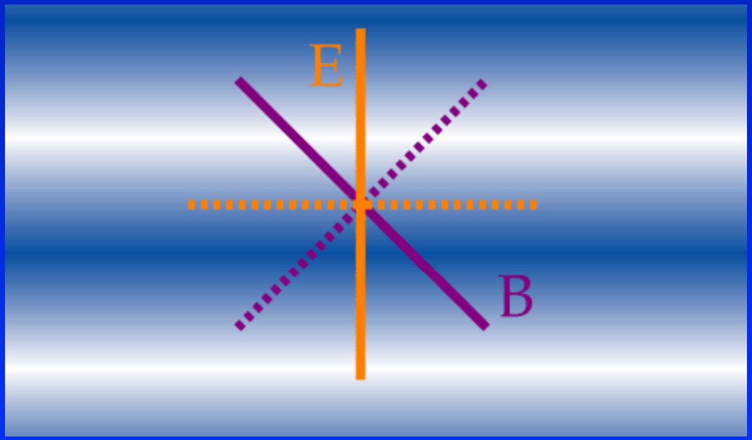
CMB polarization and Secondary Anisotropies

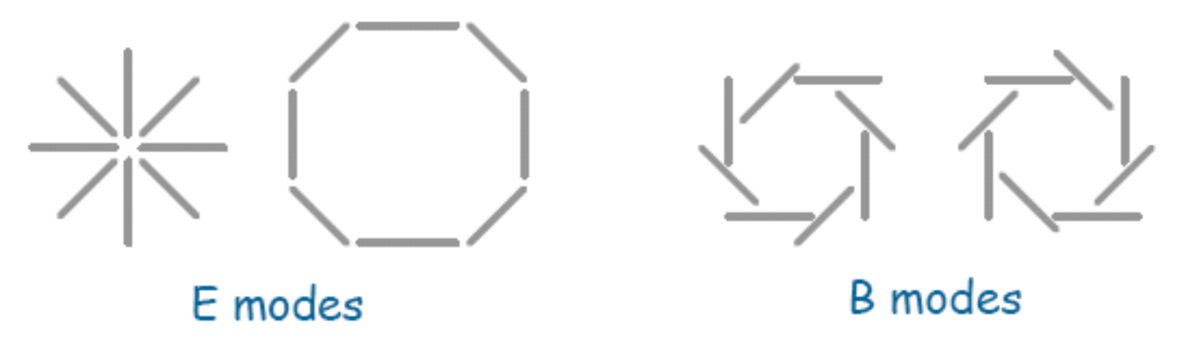
Polarization from Thomson scattering



- Thomson scattering of *anisotropic* radiation (quadrupole part) creates linear polarization signal
- signal is small, since quadrupole part of the radiation field is scattering with 1/10 *probability* of the monopole
- Thomson scattering only creates *E*-mode polarization at lowest order in perturbation theory
- generation of polarization at *recombination* & *reionization*

Temperature perturbation

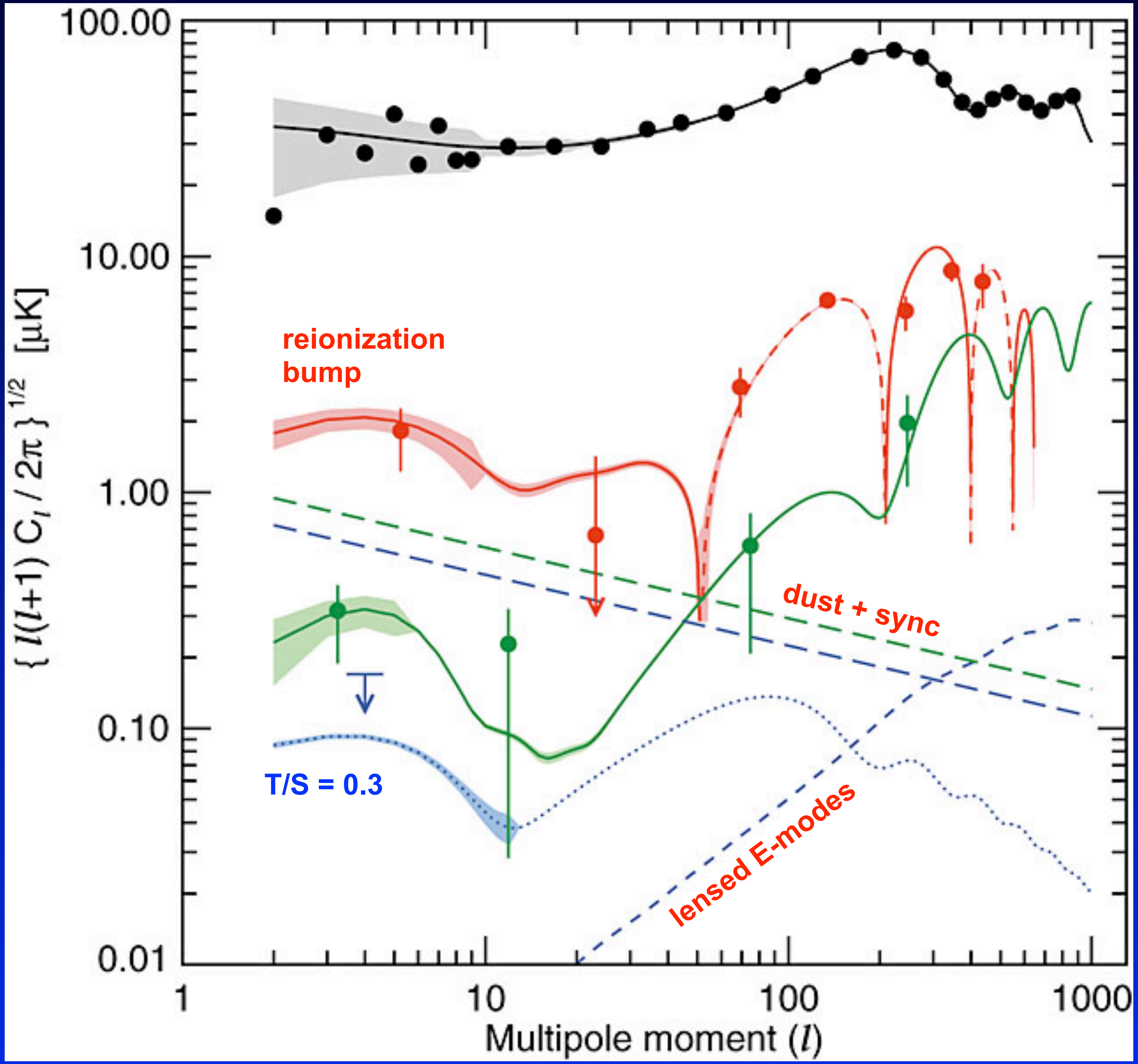




“Divergence free”

“Curl free”

WMAP Polarization Measurements



WMAP 3yr, Page et al., 2007

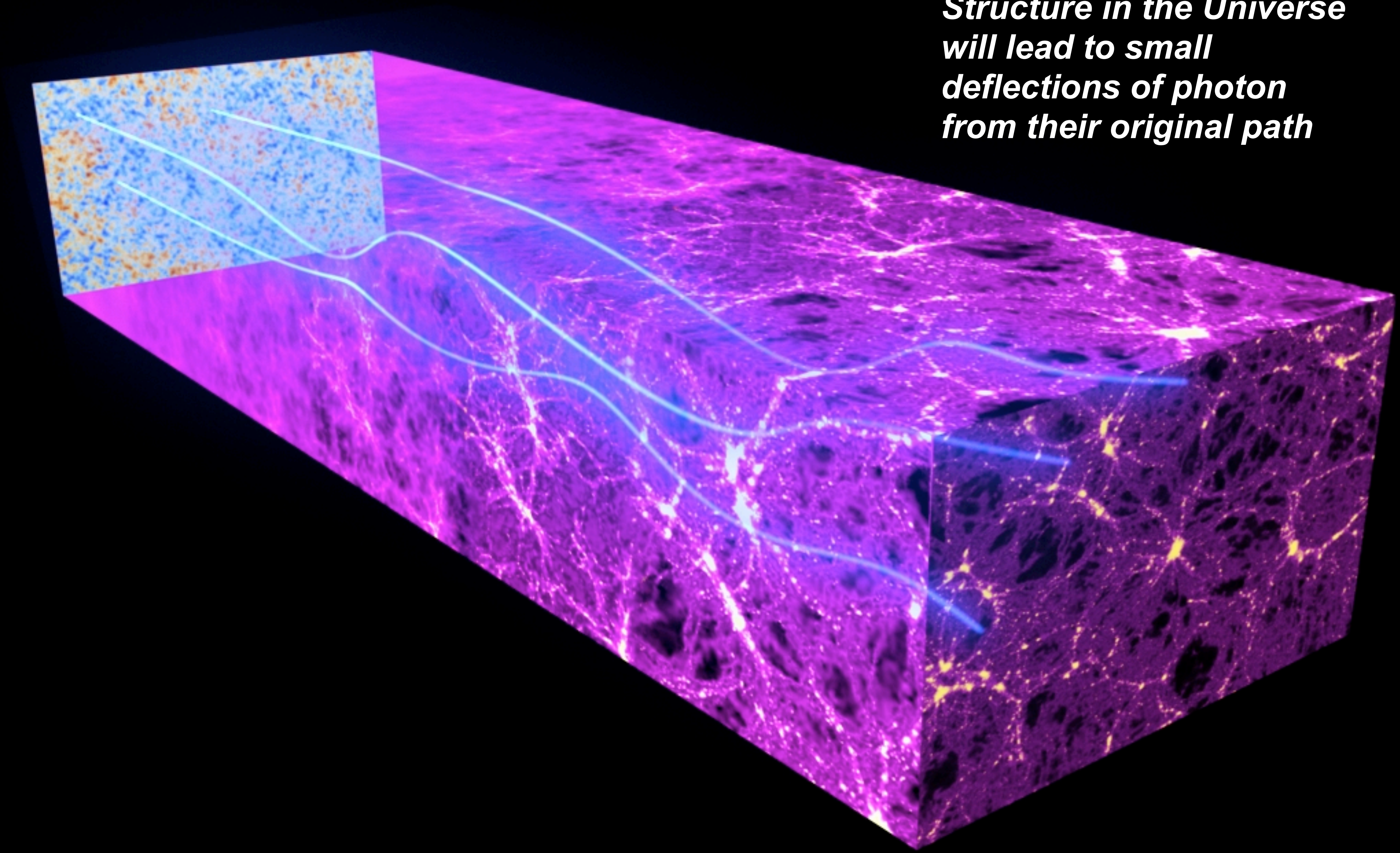
- From TE and EE power spectra constraint on Thomson optical depth τ~0.1 to reionization
- upper limit on B-mode polarization

  $\Longrightarrow$ limits tensor to scalar ratio

  $\Longrightarrow$ energy-scale of inflation

  $\Longrightarrow$ gravity waves
- Lots of experiments are trying to go for this: PLANCK, LITEBIRD, SPIDER, PIXIE, PRISM, Stage IV-CMB

CMB lensing



Structure in the Universe will lead to small deflections of photon from their original path

CMB lensing

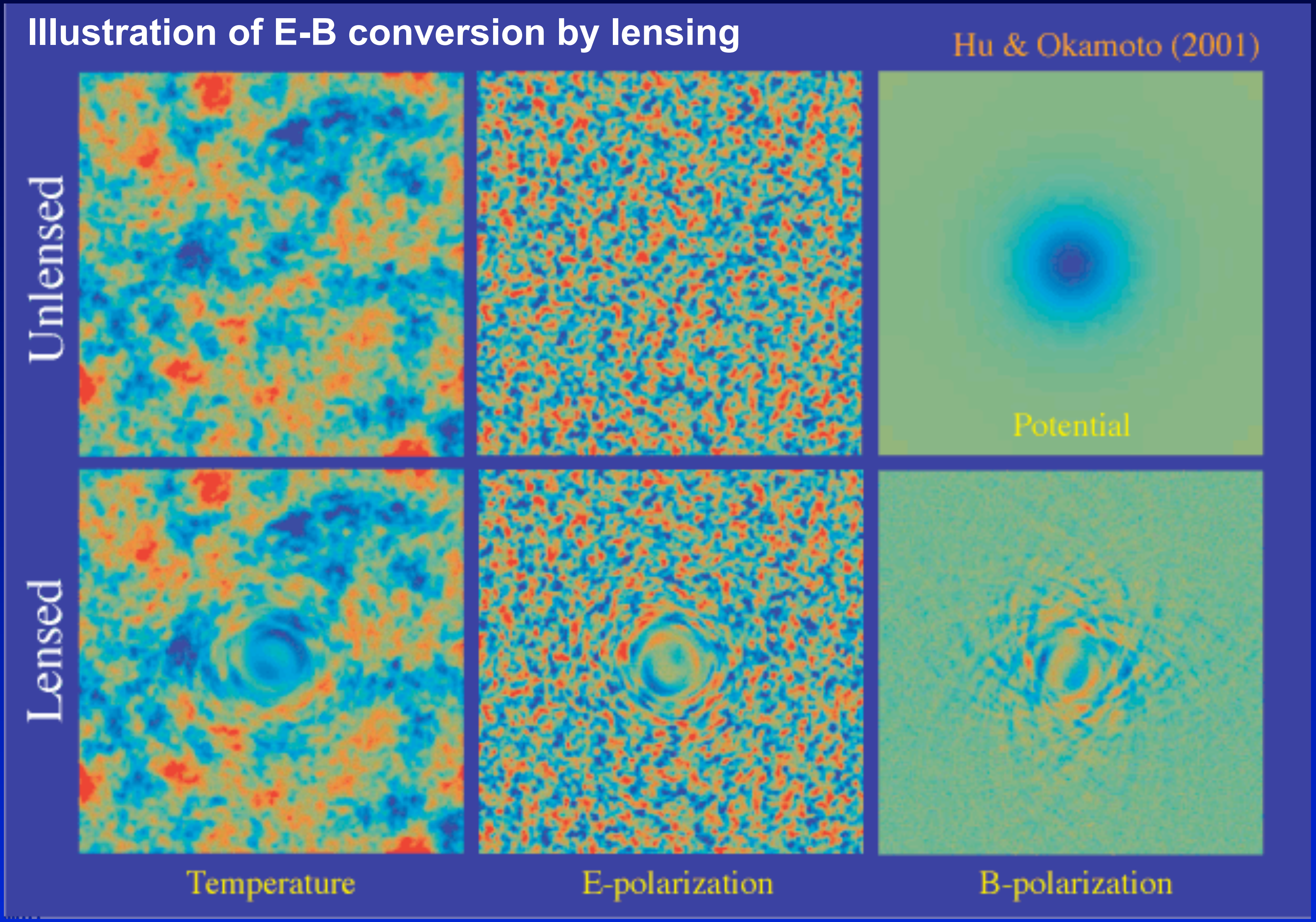
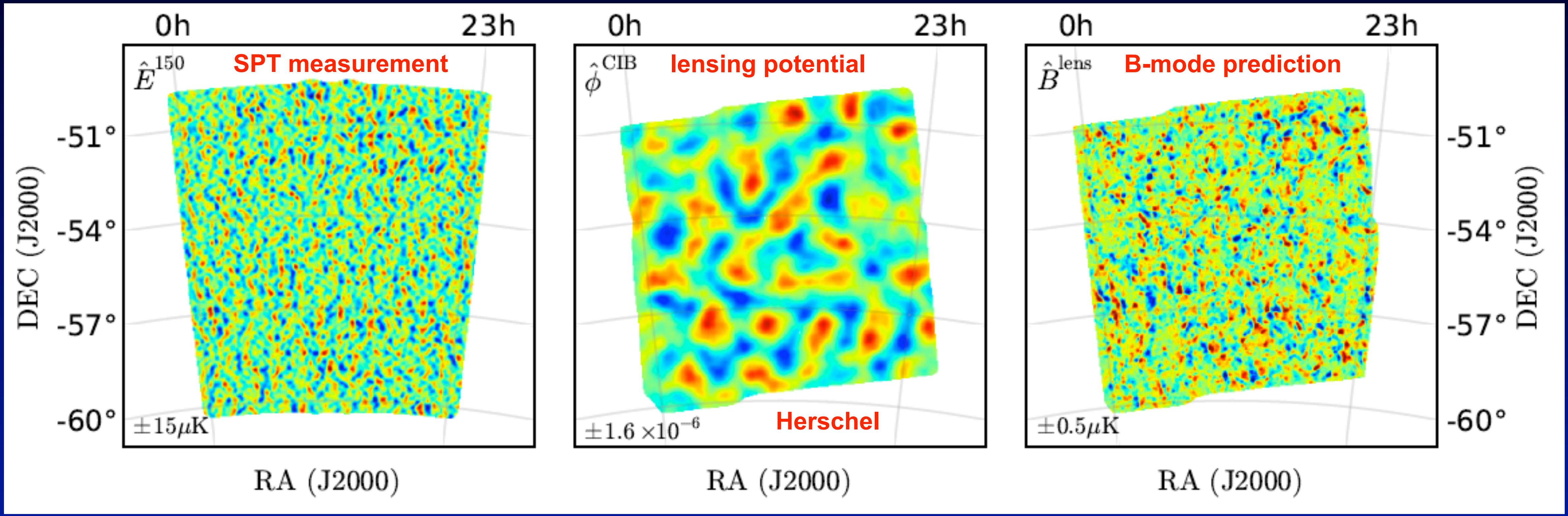


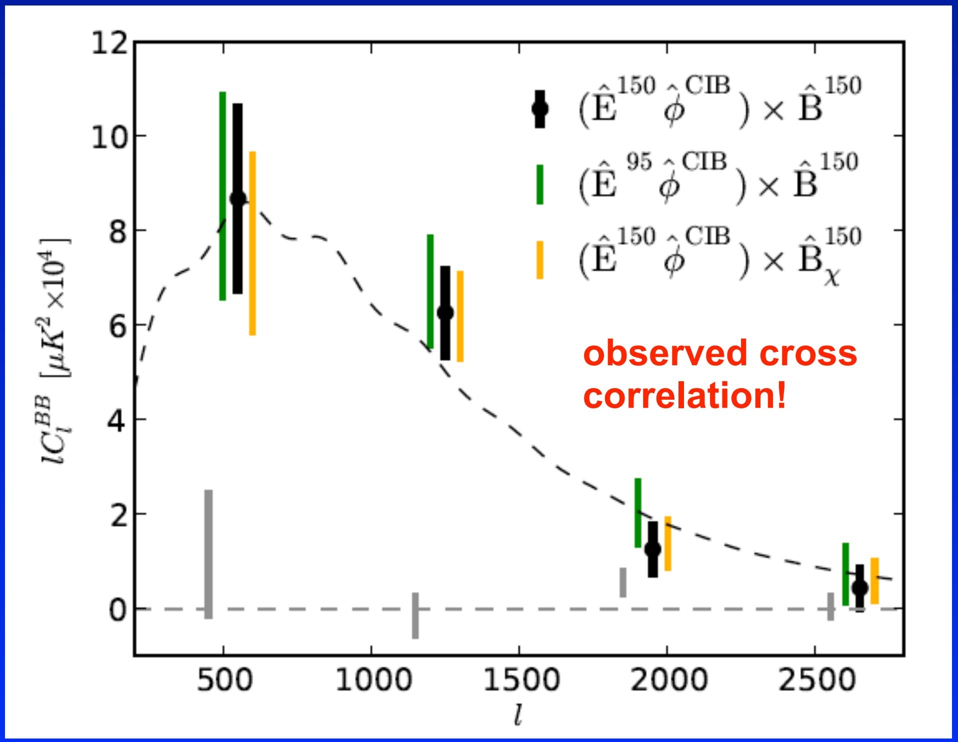
Illustration of E-B conversion by lensing

Hu & Okamoto (2001)

- conversion of E-modes to B-modes
- lensing also introduces small smearing of temperature power spectrum
- effect can be used to reconstruct the lensing potential of the intervening matter
- higher order statistics
- real effect much more subtile ...

First detection of lensed B-modes by SPT

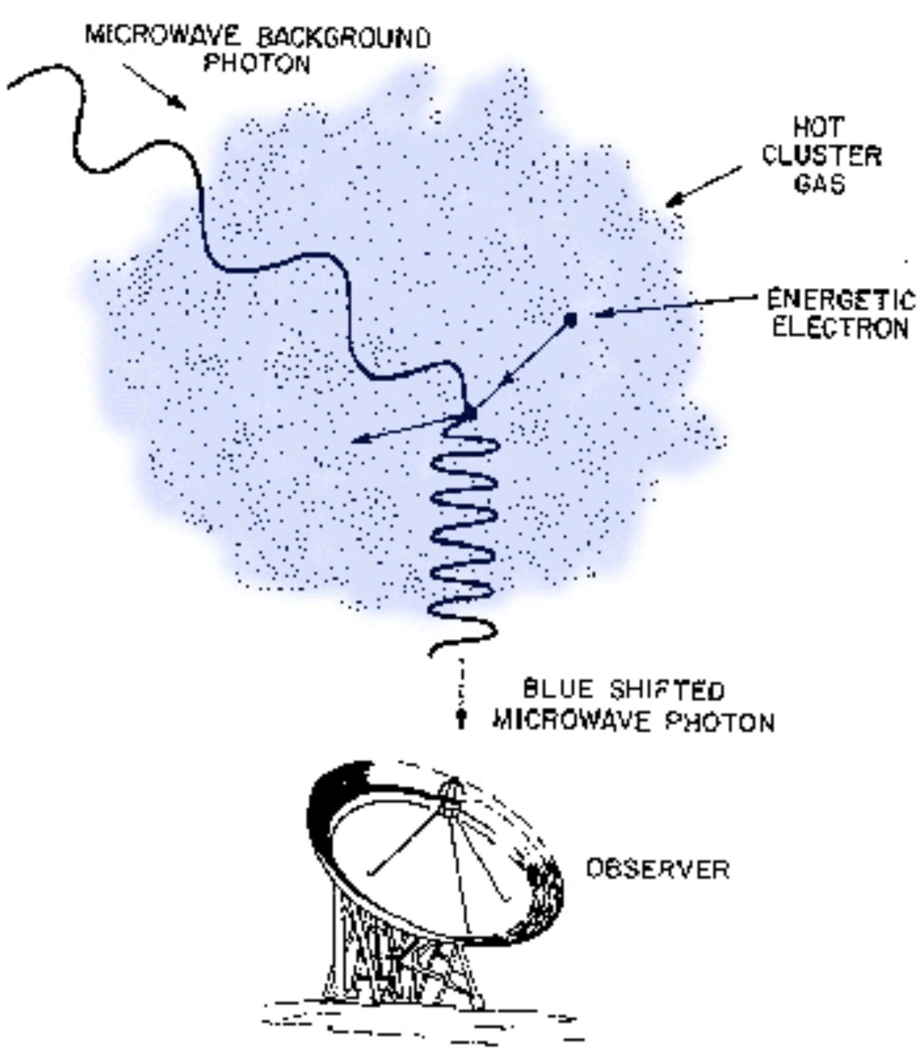




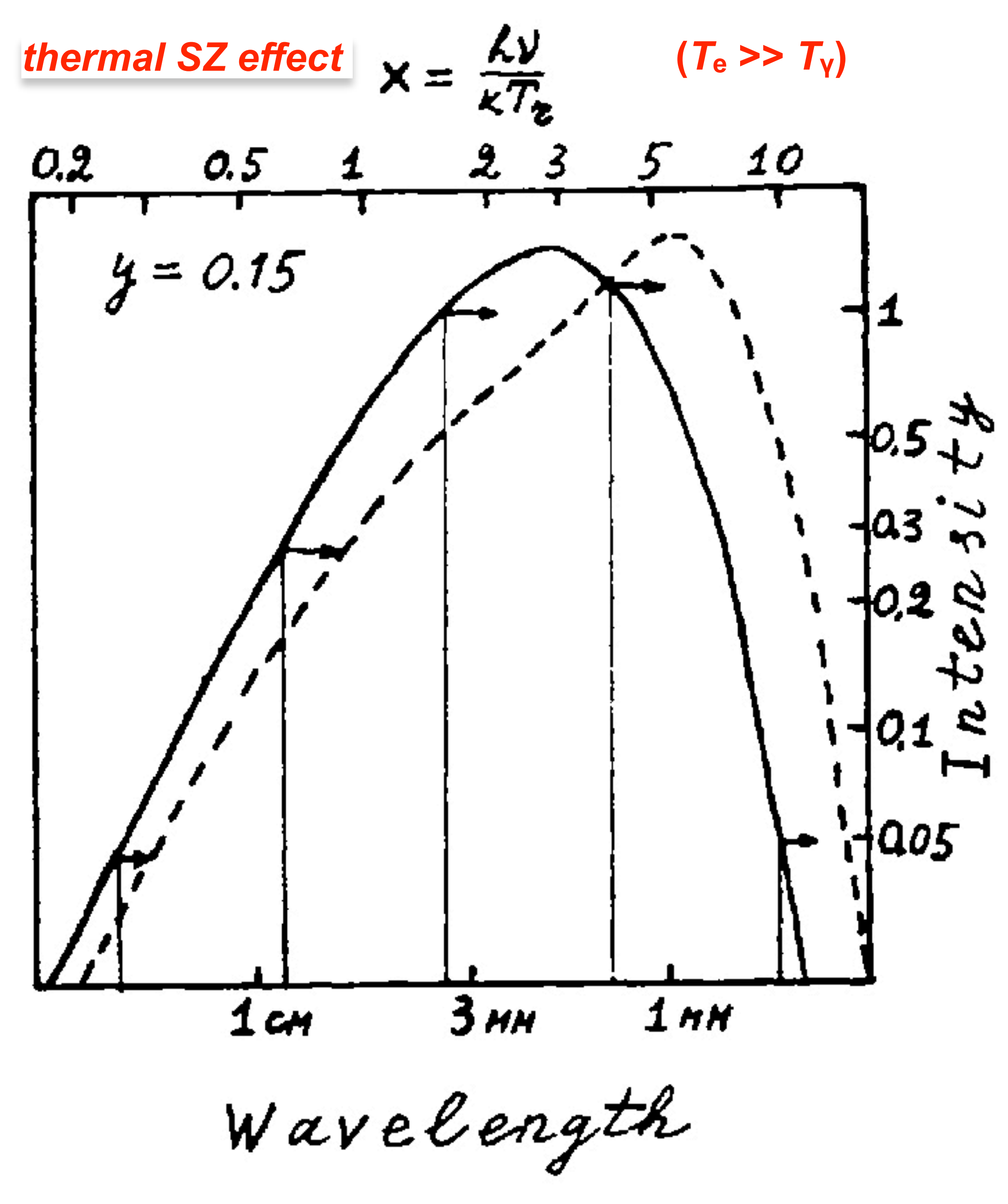
- effect really small....
- 7.7σ detection of the E-B conversion effect using cross correlation and Herschel data to estimate the lensing potential

Hanson et al., 2013

Thermal and kinematic SZ effect

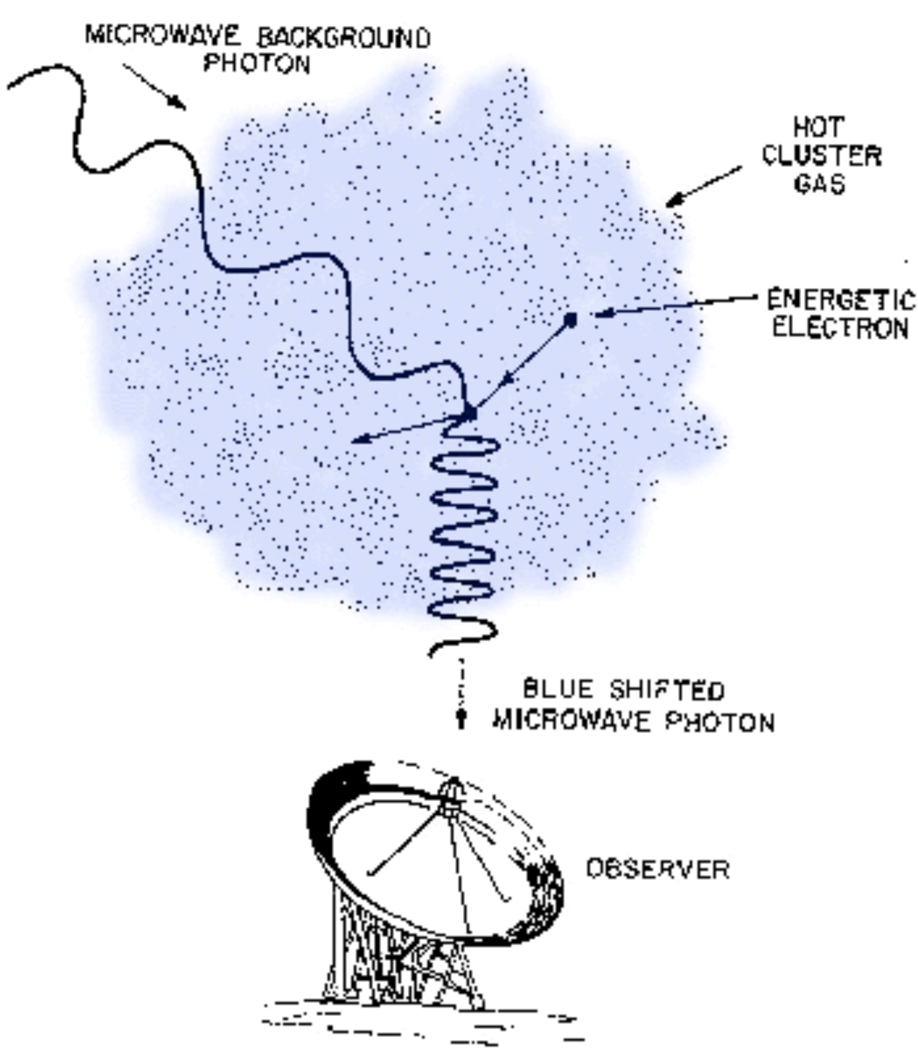


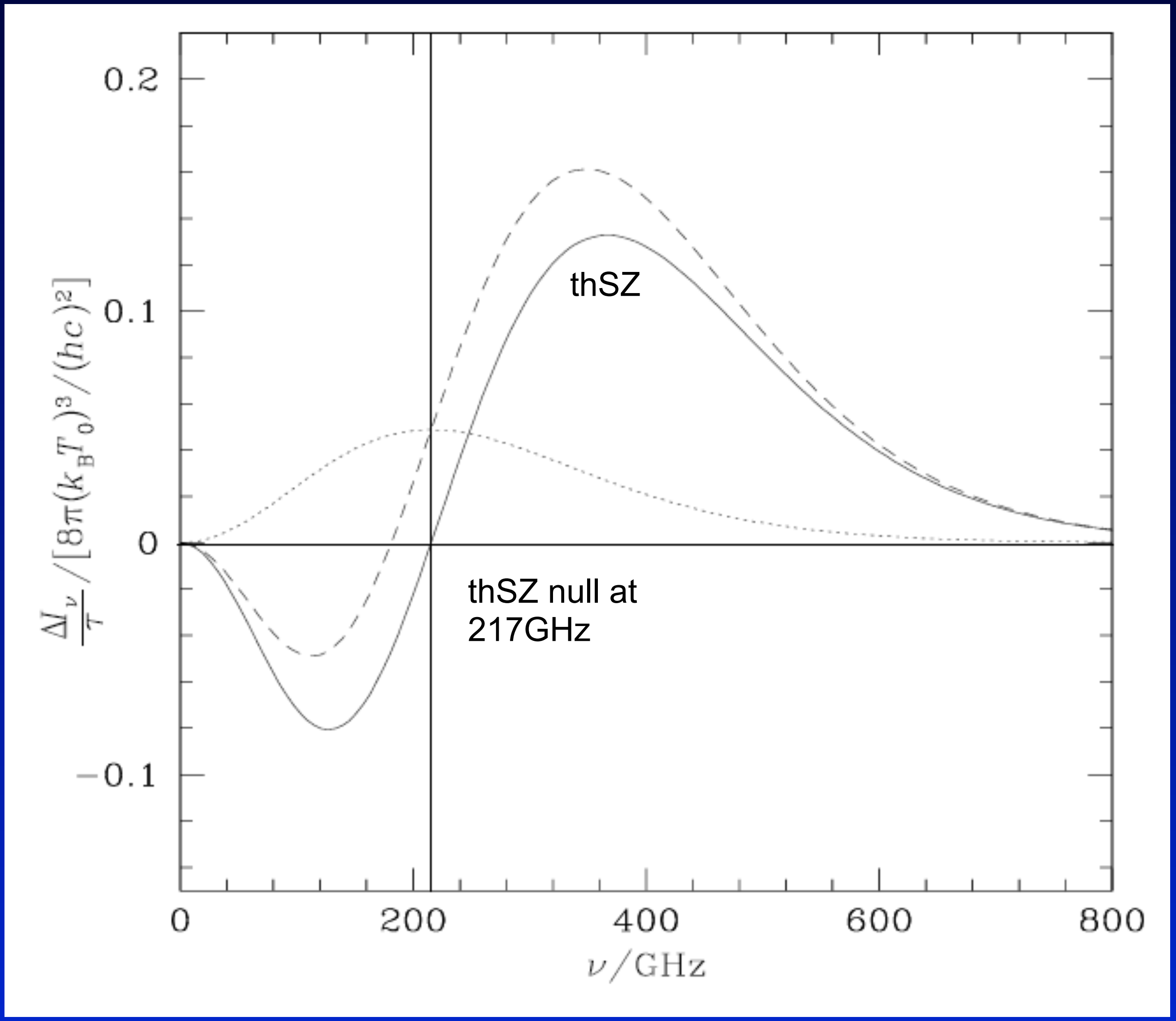
thermal SZ ⟺ Up-scattering of CMB photon by hot electrons in galaxy cluster



Sunyaev& Zeldovich, 1980, ARAA, 18, 537

Thermal and kinematic SZ effect



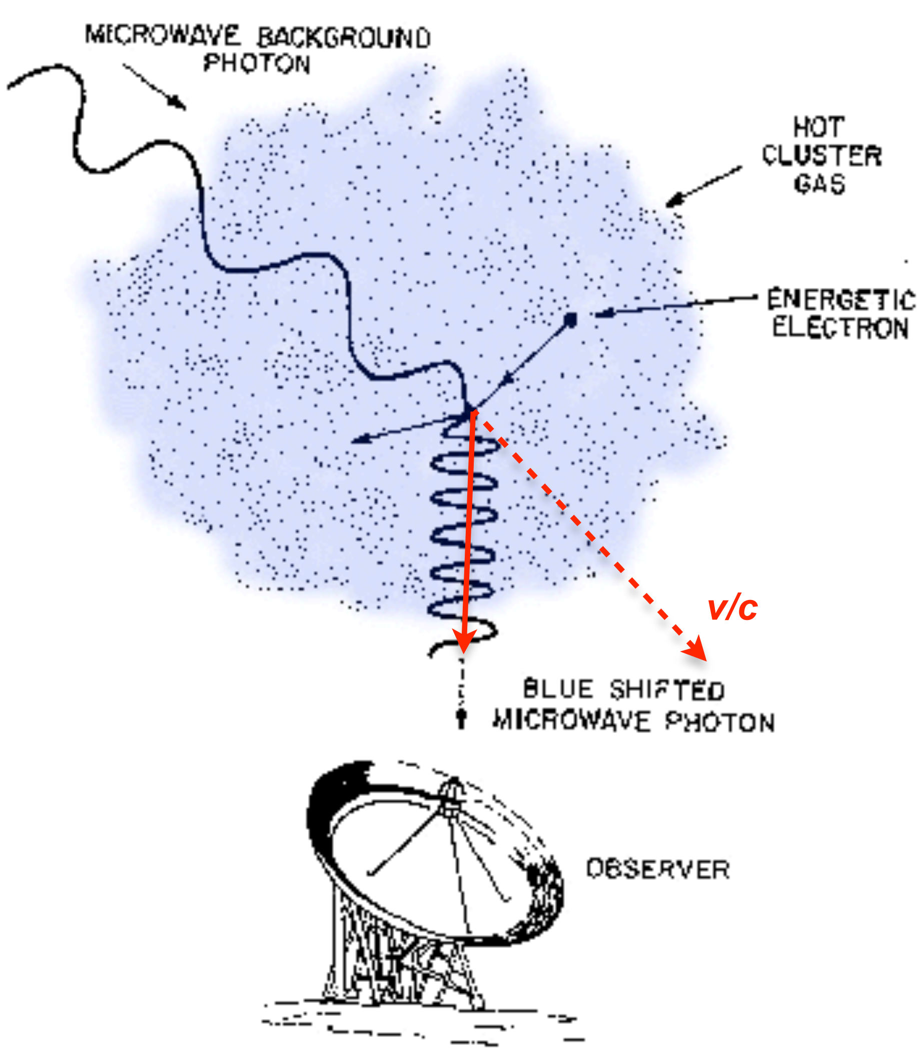


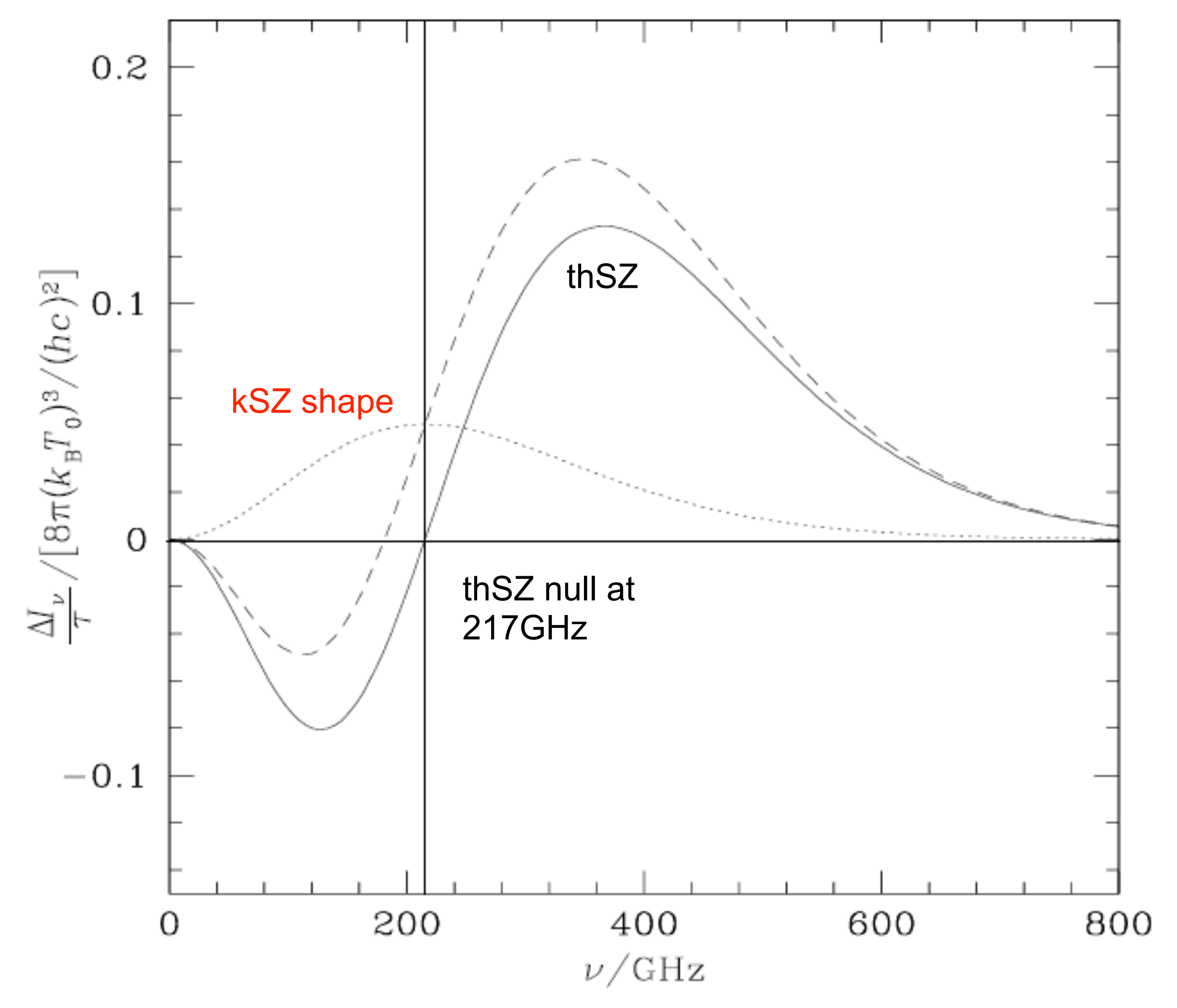
thSZ

thSZ null at 217GHz

thermal SZ $\Longleftrightarrow$ Up-scattering of CMB photon by hot electrons in galaxy cluster

Thermal and kinematic SZ effect

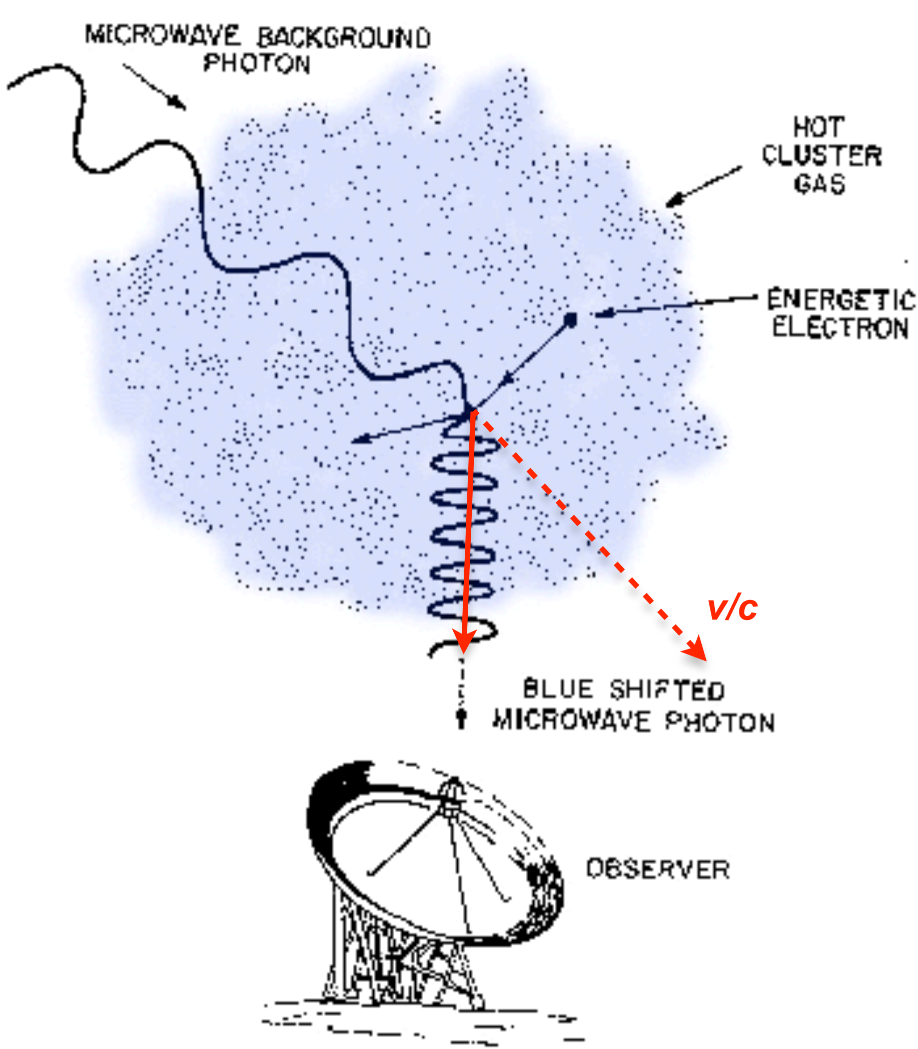


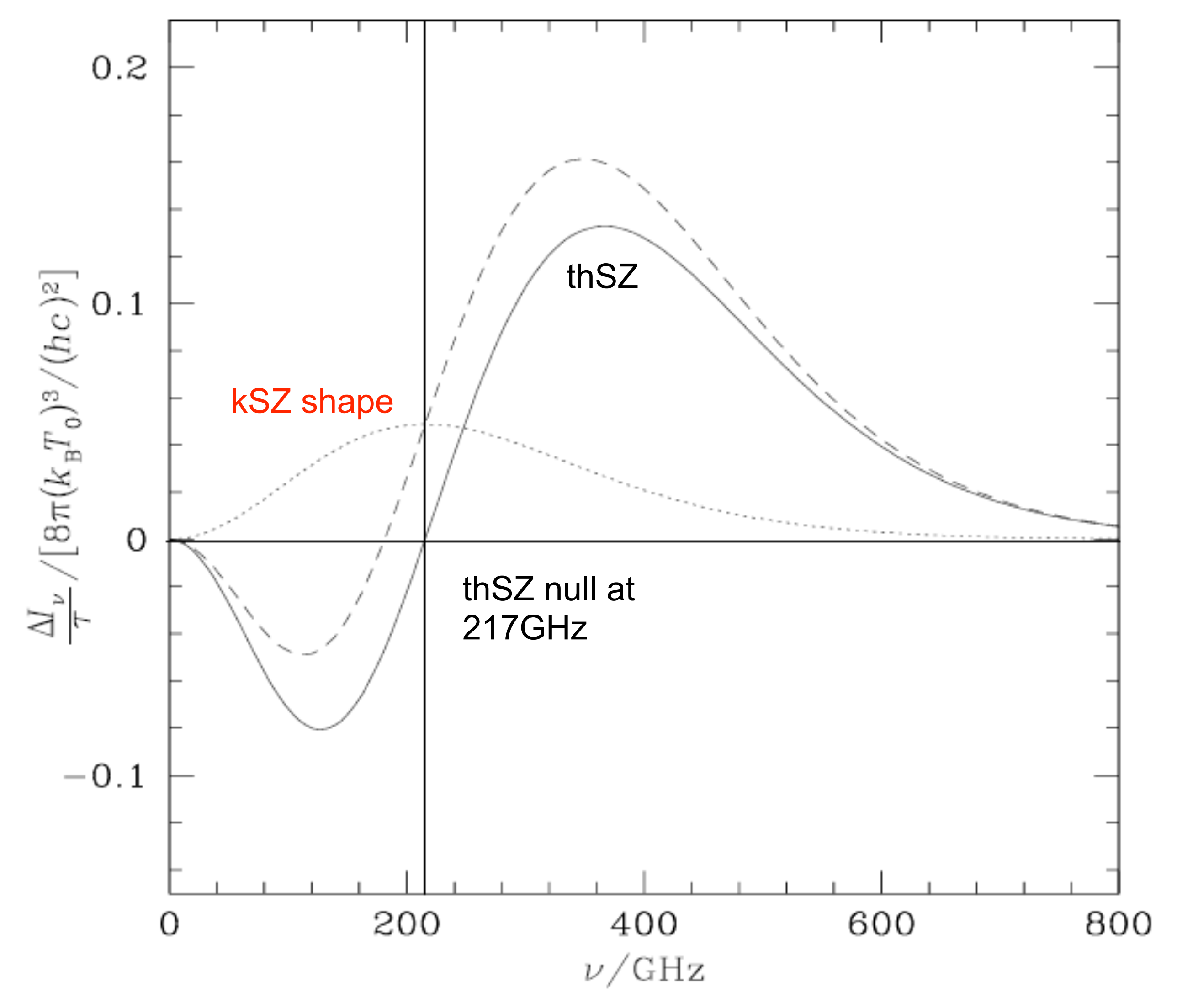


thermal SZ ⟺ Up-scattering of CMB photon by hot electrons in galaxy cluster

kinetic SZ ⟺ Doppler shift caused by bulk motion of the cluster

Thermal and kinematic SZ effect



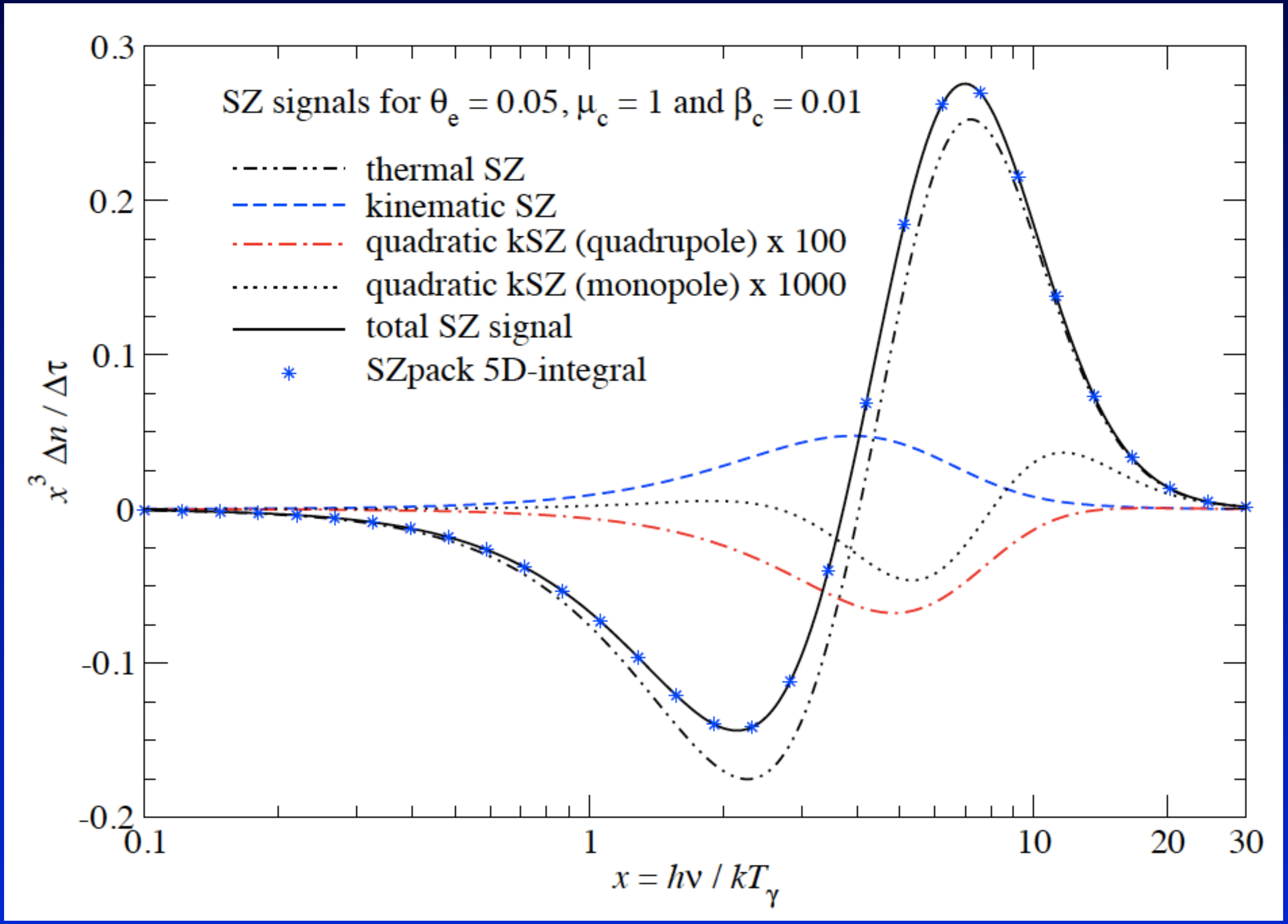


thermal SZ ⟺ Up-scattering of CMB photon by hot electrons in galaxy cluster

kinetic SZ ⟺ Doppler shift caused by bulk motion of the cluster

- Allows probing growth of structures and ‘gastrophysics’ of clusters
- depends on large-scale flows

Relativistic corrections to the SZ effect with SZpack



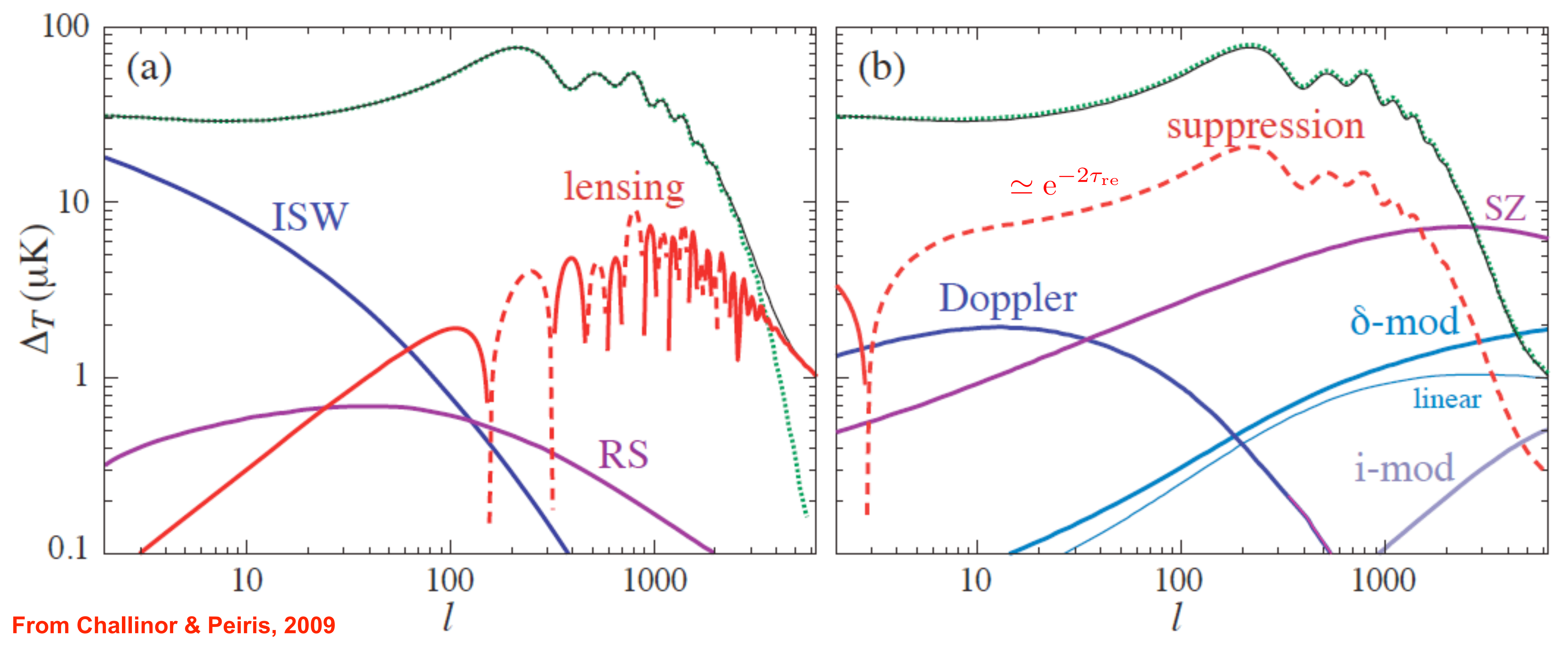
- *quasi-exact* computation of the SZ signal
- computation *very fast* (<~0.01 sec)
- allows including *line-of-sight variations* of the electron temperature
- *multiple scattering* contribution included
- will be useful for the analysis of *future high-resolution/high-sensitivity* SZ measurements (CCAT, CARMA, etc)
- *stacking analysis* with cluster samples!

JC, Nagai, Sazonov & Nelson, 2012
JC, Switzer, Nagai, Nelson, 2012

SZpack available at:
www.Chluba.de/SZpack

Secondary CMB signals for temperature

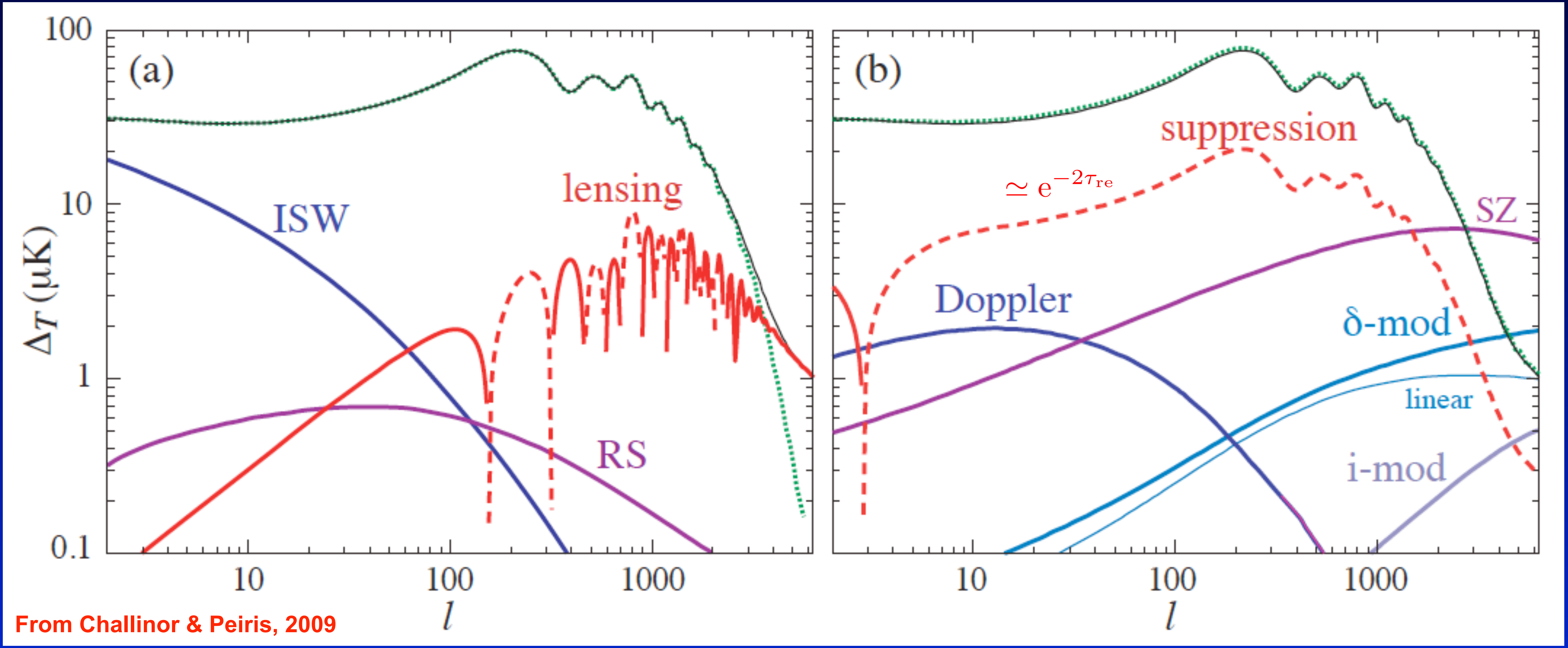
Gravitational effects **Scattering effects**



From Challinor & Peiris, 2009

Secondary CMB signals for temperature

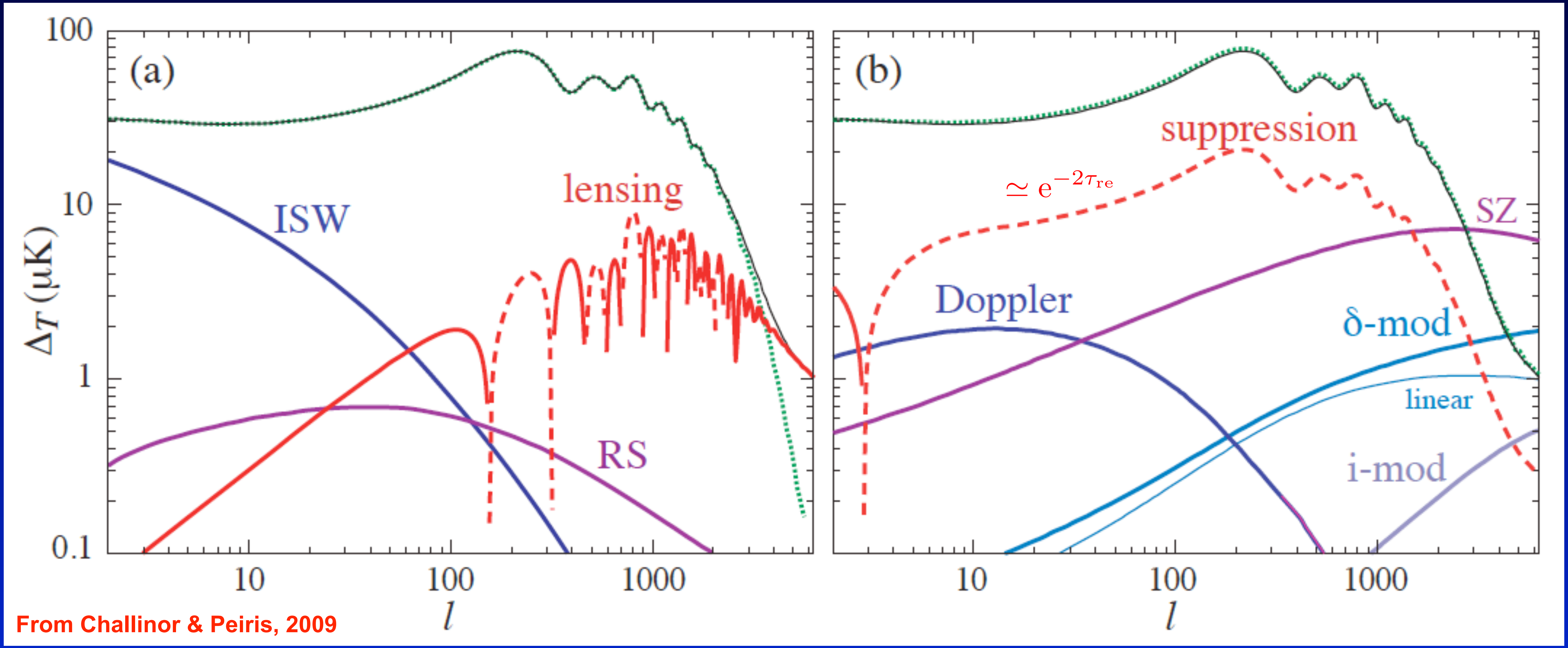
Gravitational effects **Scattering effects**



From Challinor & Peiris, 2009

- smearing by lensing important at small scales
- Rees-Sciama effect from non-linear growth of structures

Secondary CMB signals for temperature



Gravitational effects

Scattering effects

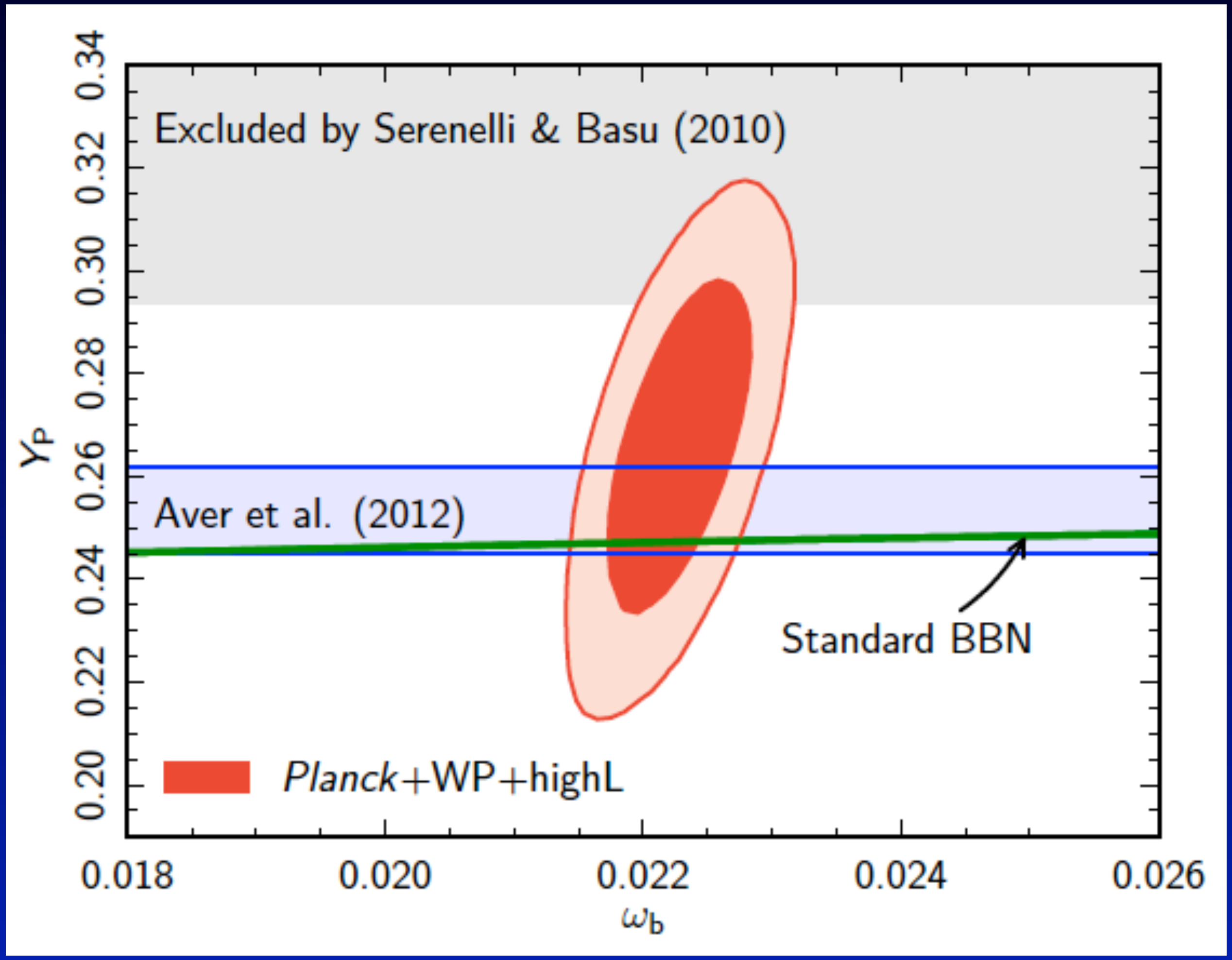
From Challinor & Peiris, 2009

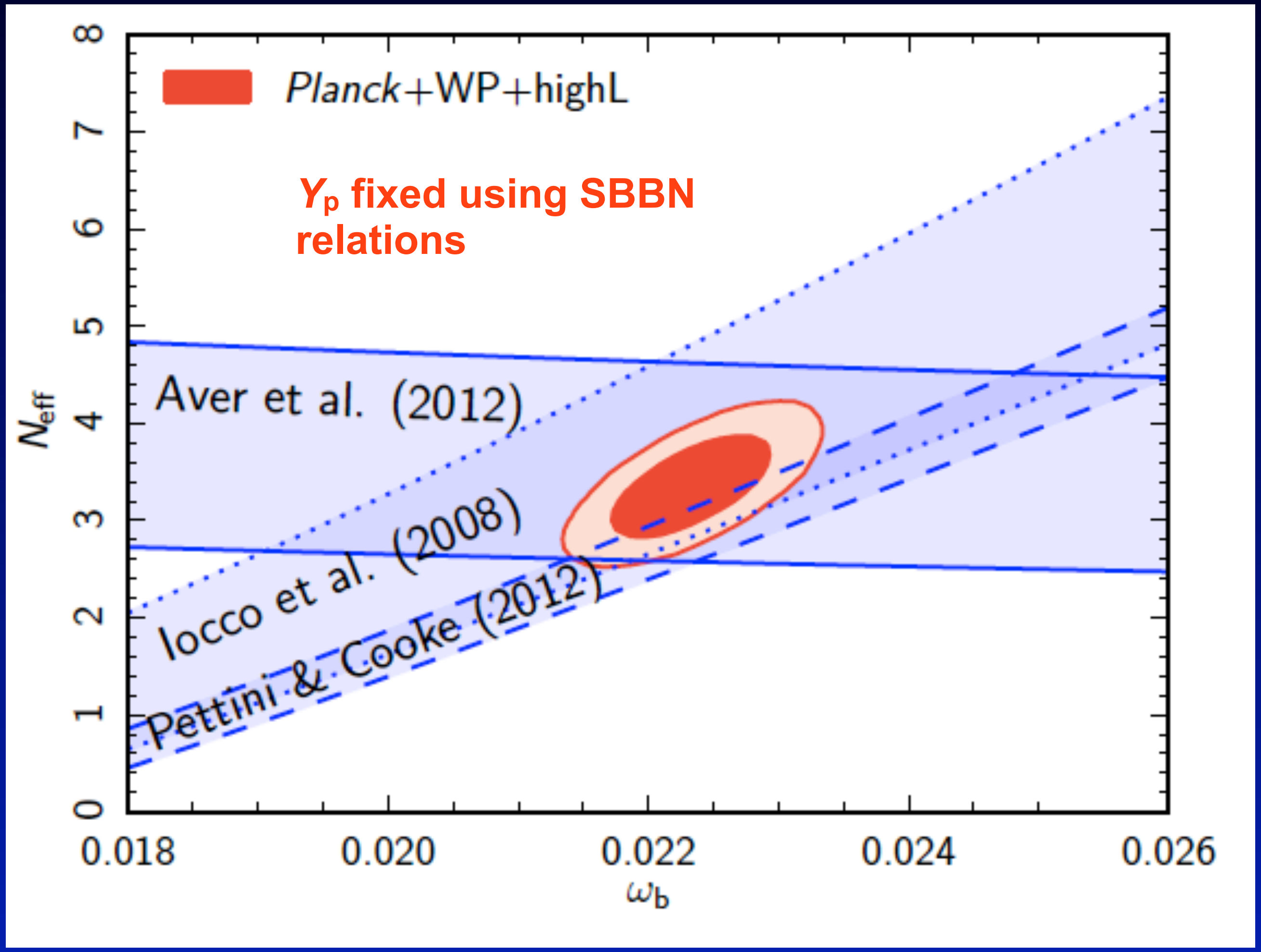
- smearing by lensing important at small scales
- Rees-Sciama effect from non-linear growth of structures

- thSZ dominant at small scales
- several effects from velocity and density fluctuations during reionization (*line of sight cancelations!*)

Some words about damping tail physics

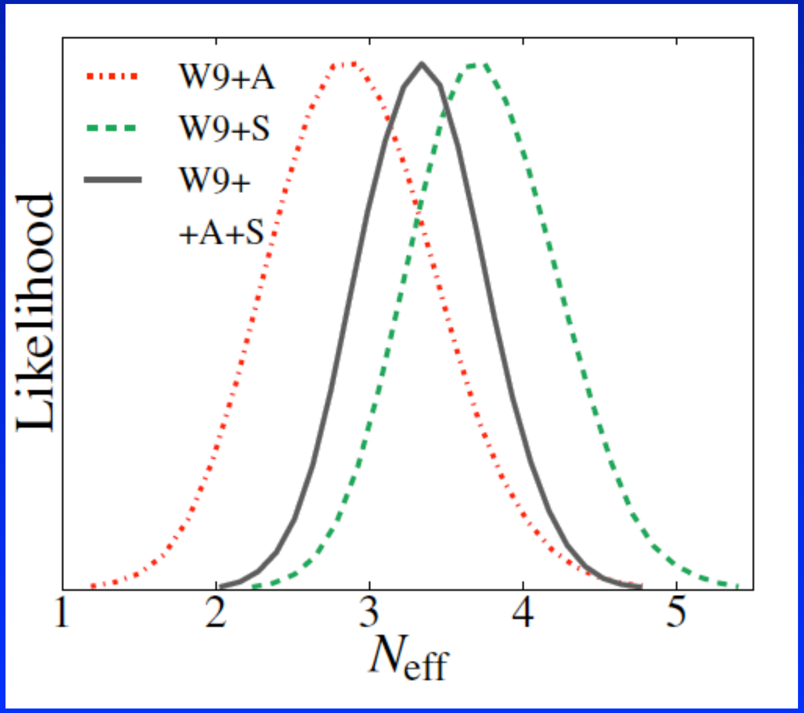
CMB constraints on N_{eff} and Y_{p}





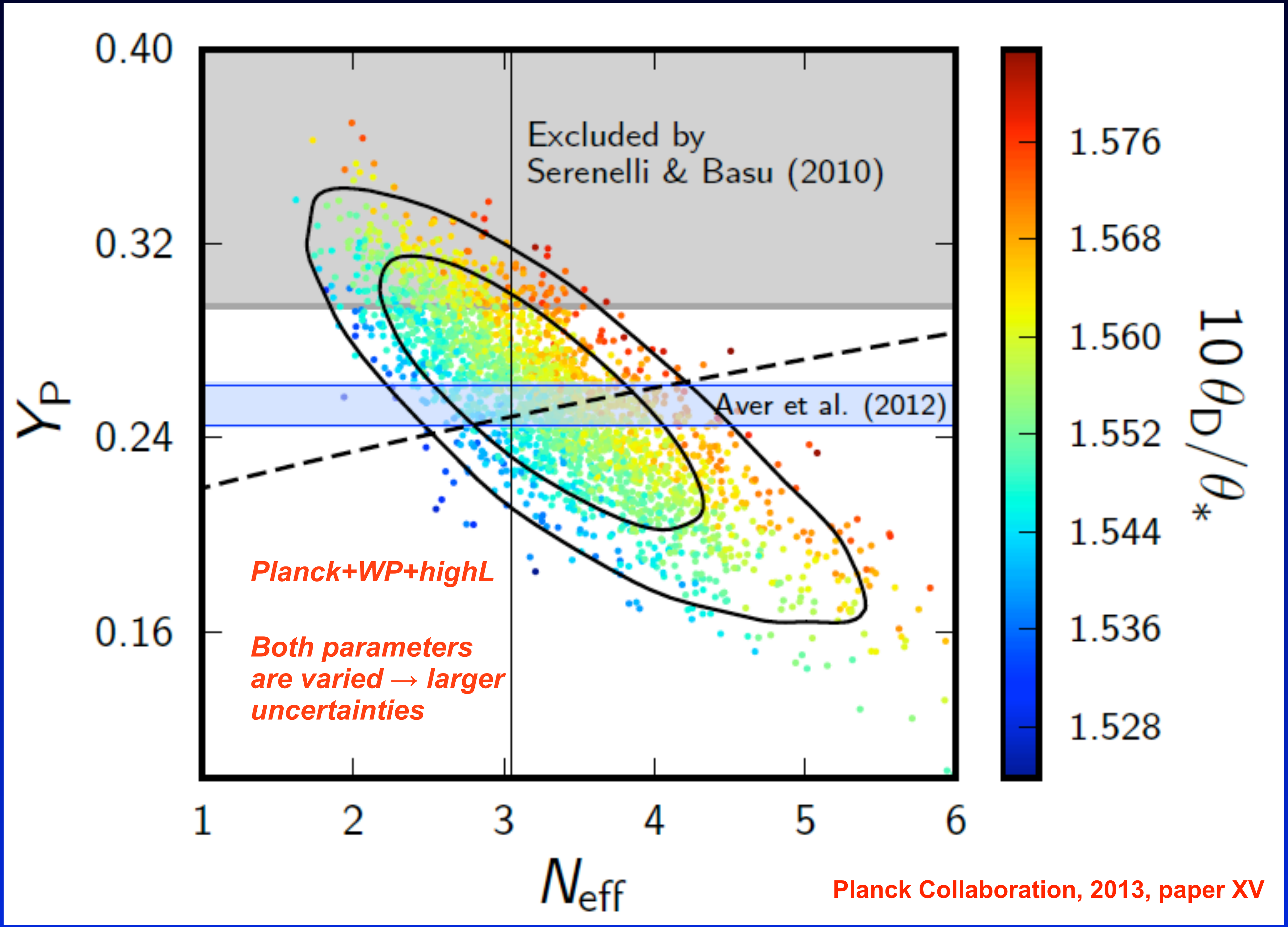
Planck Collaboration, 2013, paper XV

- *Helium determination from CMB consistent with SBNN prediction*
- *CMB constraint on N_{eff} competitive*
- *Partial degeneracy with Y_{p} and running*
- *Some tension between different data sets*



Calabrese et al. 2013

CMB constraints on N_{eff} and Y_p



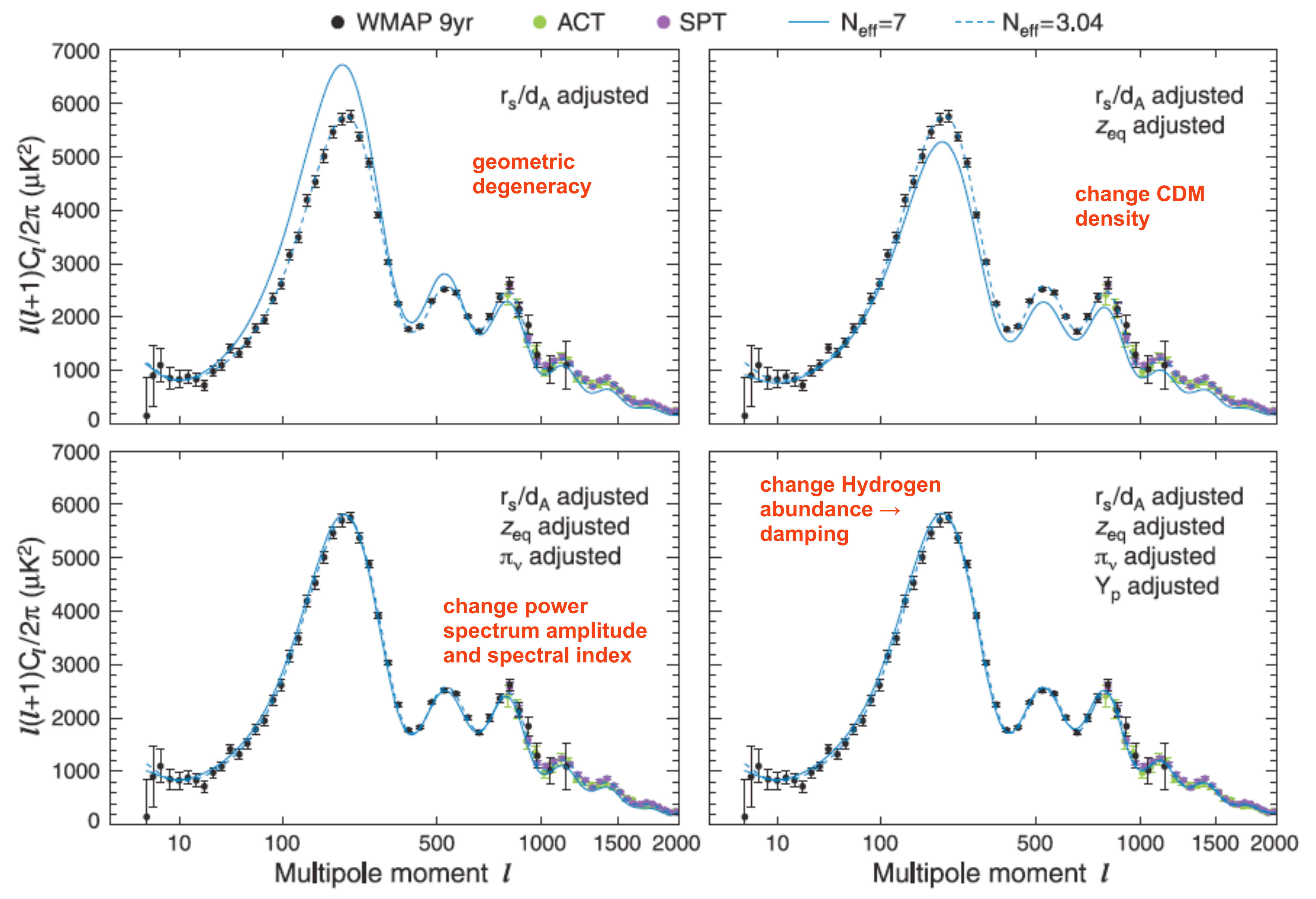
Planck+WP+highL

Both parameters are varied → larger uncertainties

Planck Collaboration, 2013, paper XV

- *Consistent with SBBN and standard value for N_{eff}*
- *Future CMB constraints (SPTPol & ACTPol) on Y_p will reach 1% level*

Interplay of N_{eff} and Y_{p} and other parameters



geometric degeneracy

change CDM density

change power spectrum amplitude and spectral index

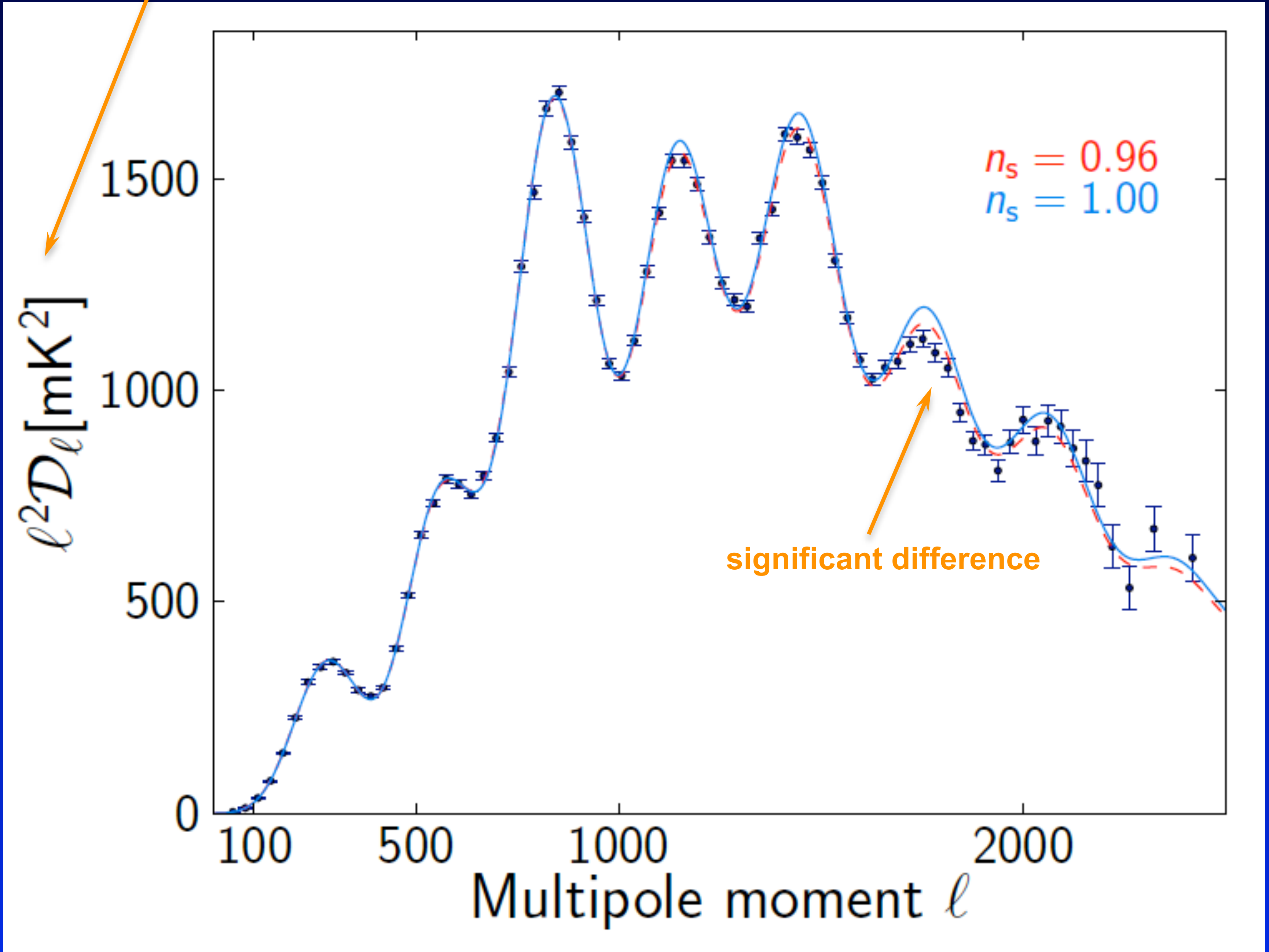
change Hydrogen abundance → damping

Hinshaw et al, 2012 (WMAP-9yr)

Bottom line: changes in the damping tail can be mimicked by combinations of many parameters

CMB anisotropies directly probe early-universe physics / inflation

Another way to plot small-scale power spectrum

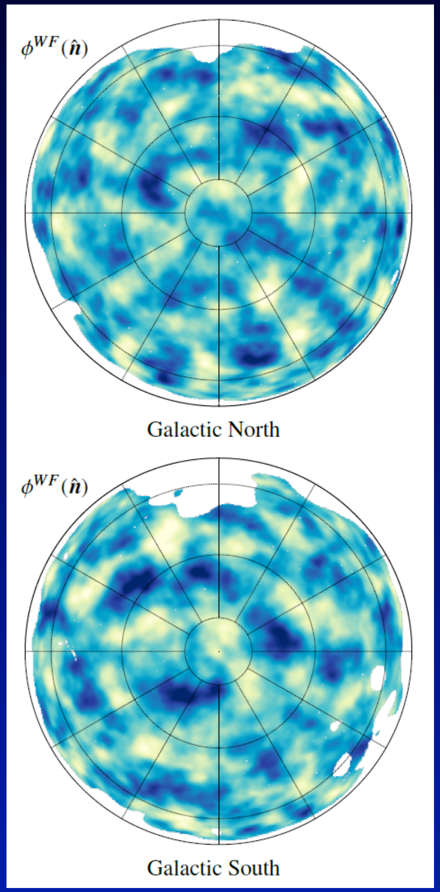


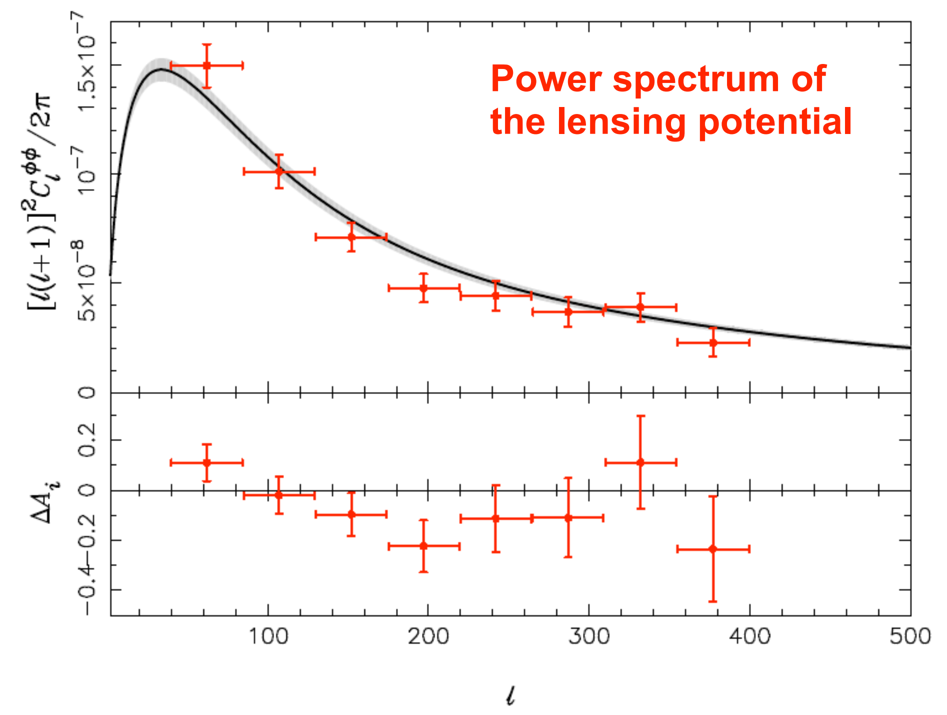
significant difference

Planck Collaboration, 2013, paper XV

- 6σ deviation from scale-invariance (previously ~ 3σ)
- single-field inflation predicts departure from scale-invariance (e.g., Mukhanov 2007)
- *Degeneracies* with, e.g., effective number of relativistic degrees of freedom, N_{eff}, Helium abundance, Y_p, and recombination physics!
- *The power spectrum at small scales thus directly links early-Universe, particle and recombination physics!*

All kind of fun science with the CMB (no time for this though)

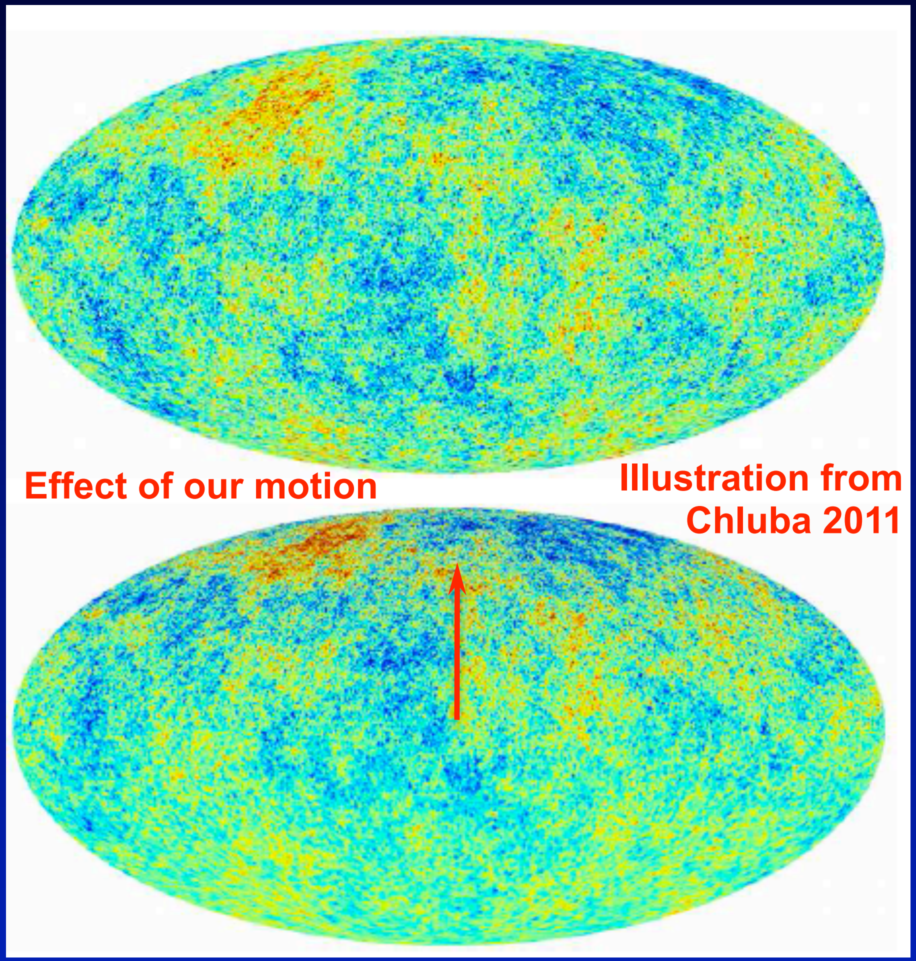




Power spectrum of the lensing potential

Planck Collaboration, 2013, paper XVII

CMB aberration

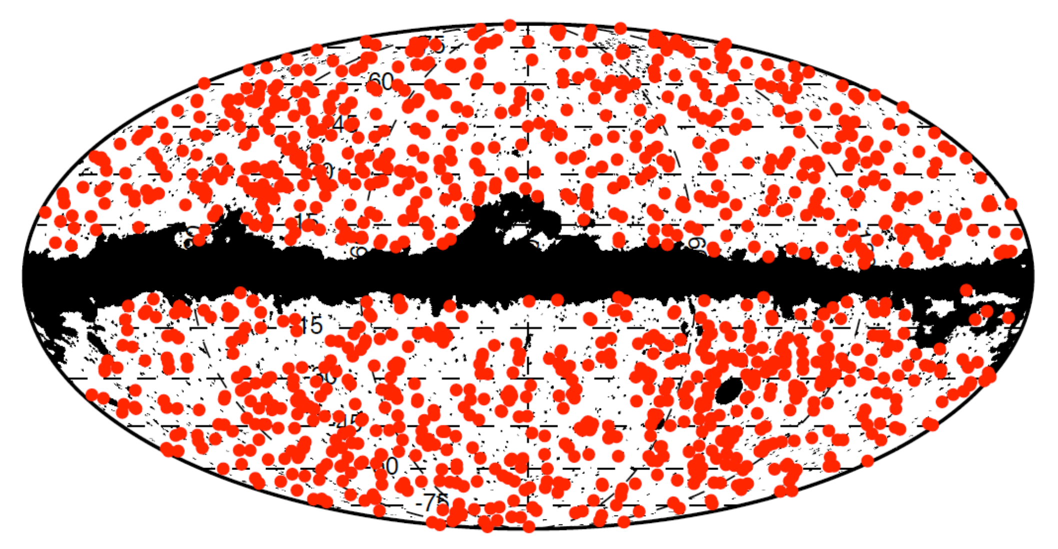


Effect of our motion

Illustration from Chluba 2011

Planck Collaboration, 2013, paper XXVII

lots of SZ clusters to play with!



Planck Collaboration, 2013, paper XXIV

- *Non-Gaussianity* (test of inflation models)
- *Topology*
- *CMB anomalies* *(power-asymmetry, low-l correlations, etc.)*
- *CIB* and *Galactic science*

Conclusions

- CMB physics is very rich but also very clean!
- CMB anisotropies so far provide an *outstanding confirmation* of ΛCDM cosmology
- The data has become so precise that one can start *testing non-standard extensions* of ΛCDM
- *The future of CMB is bright*: lots of new data from the ground and space
- New avenues (*polarization, spectral distortions, higher order statistics, cross-correlation with other data sets*) will open up!
- *Lots of interesting work ahead of you guys!*