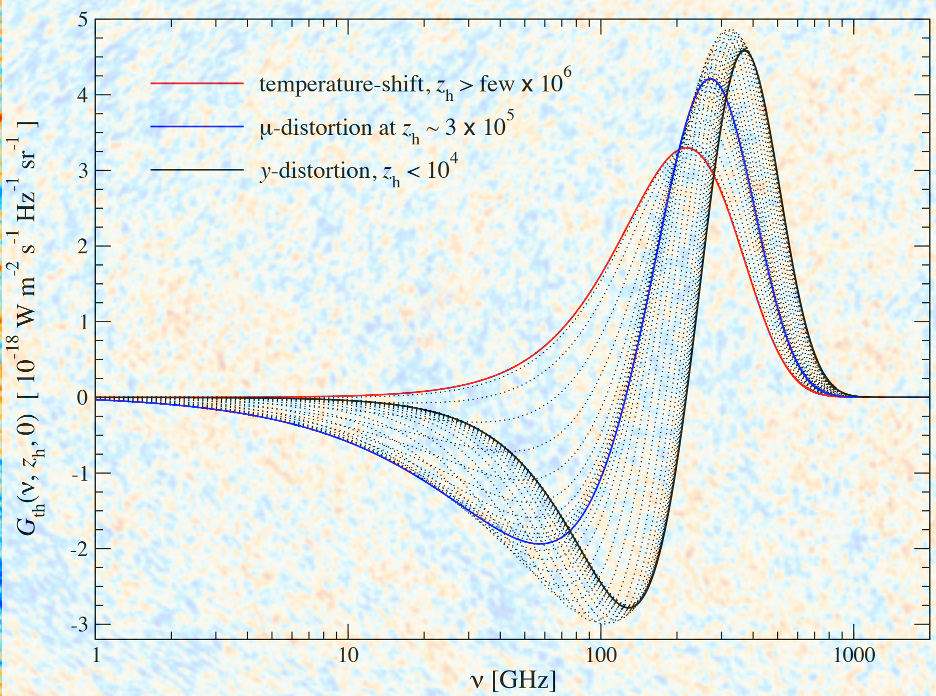
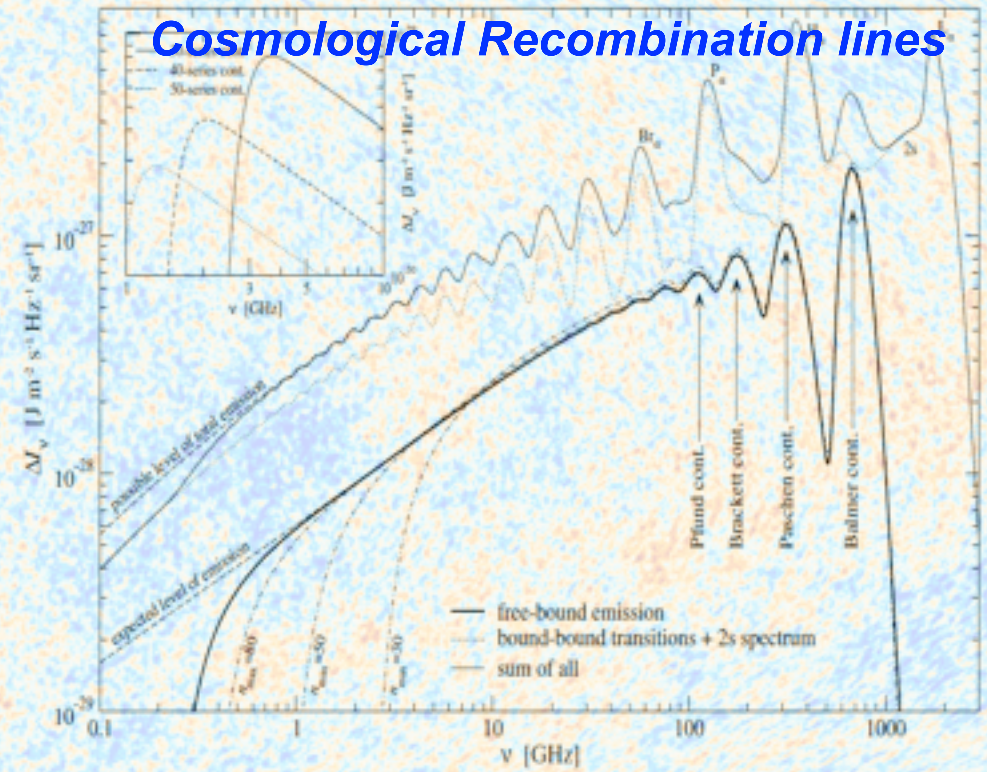
Science with Spectral Distortions of the CMB - I

Primordial Distortions



Cosmological Recombination lines



JOHNS HOPKINS UNIVERSITY

Jens Chluba

CUSO Doctoral Program in Physics

Lausanne, October 16^{th}, 2014

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

Main Goals of my Lectures

- Convince you that future CMB distortions science will be *extremely* exciting!
- Explain in detail how distortions evolve and thermalize
- Definition of different types of distortions
- Computations of spectral distortions *(you should be able to do this yourself afterwards!)*
- Provide an overview for different sources of primordial distortions
- Show you why the CMB spectrum provides a *complementary* probe of inflation and particle physics

Structure of the Lectures *(at least in theory)*

Lecture I:

- Overview and motivation
- Simple blackbody radiation warm-ups
- Formulation of the thermalization problem

Structure of the Lectures *(at least in theory)*

Lecture I:

- Overview and motivation
- Simple blackbody radiation warm-ups
- Formulation of the thermalization problem

Lecture II:

- Analytic description of the distortions
- Distortion visibility function
- Fast computation of the distortions

Structure of the Lectures (cont.)

Lecture III:

- Overview of different sources of distortions
- Dissipation of acoustic modes
- Decaying particles

Structure of the Lectures (cont.)

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- Overview of different sources of distortions
- Dissipation of acoustic modes
- Decaying particles

Lecture IV:

- Recombination physics and why it is important
- The cosmological recombination radiation
- Sunyaev-Zeldovich effect and what the signals could tell us

References for the Theory of Spectral Distortions

- Original works
  - Zeldovich & Sunyaev, 1969, Ap&SS, 4, 301
  - Sunyaev & Zeldovich, 1970, Ap&SS, 7, 20
  - Illarionov & Sunyaev, 1975, Sov. Astr., 18, 413

Yakov Zeldovich

Rashid Sunyaev

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  - Illarionov & Sunyaev, 1975, Sov. Astr., 18, 413
- Additional milestones
  - Danese & de Zotti, 1982, A&A, 107, 39
  - Burigana, Danese & de Zotti, 1991, ApJ, 379, 1
  - Hu & Silk, 1993, Phys. Rev. D, 48, 485
  - Hu, 1995, PhD thesis

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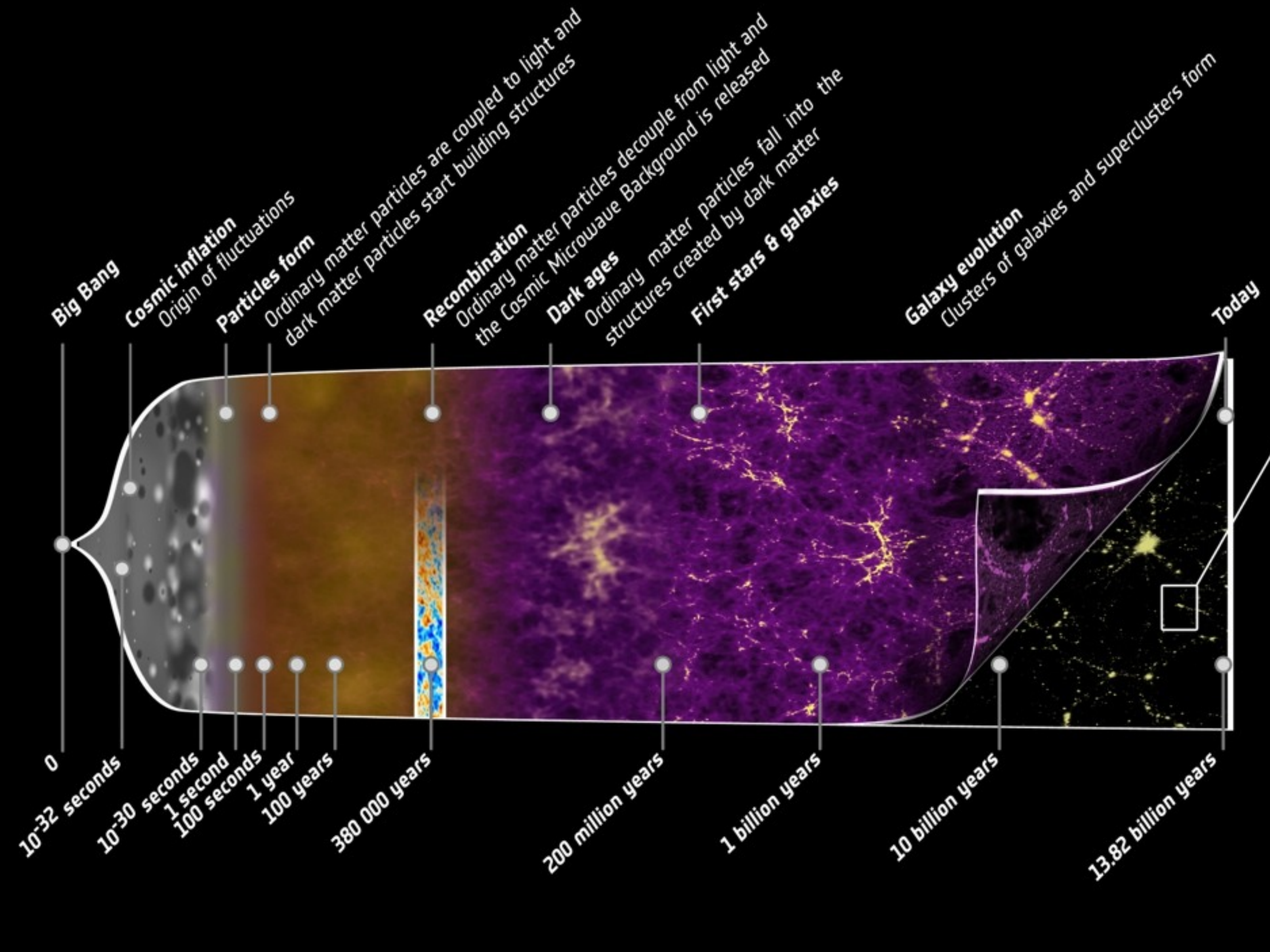
  - Burigana, Danese & de Zotti, 1991, ApJ, 379, 1
  - Hu & Silk, 1993, Phys. Rev. D, 48, 485
  - Hu, 1995, PhD thesis
- More recent overviews
  - Sunyaev & JC, 2009, AN, 330, 657
  - JC & Sunyaev, 2012, MNRAS, 419, 1294
  - JC, MNRAS, 436, 2232 & ArXiv:1405.6938

Overview and Motivation

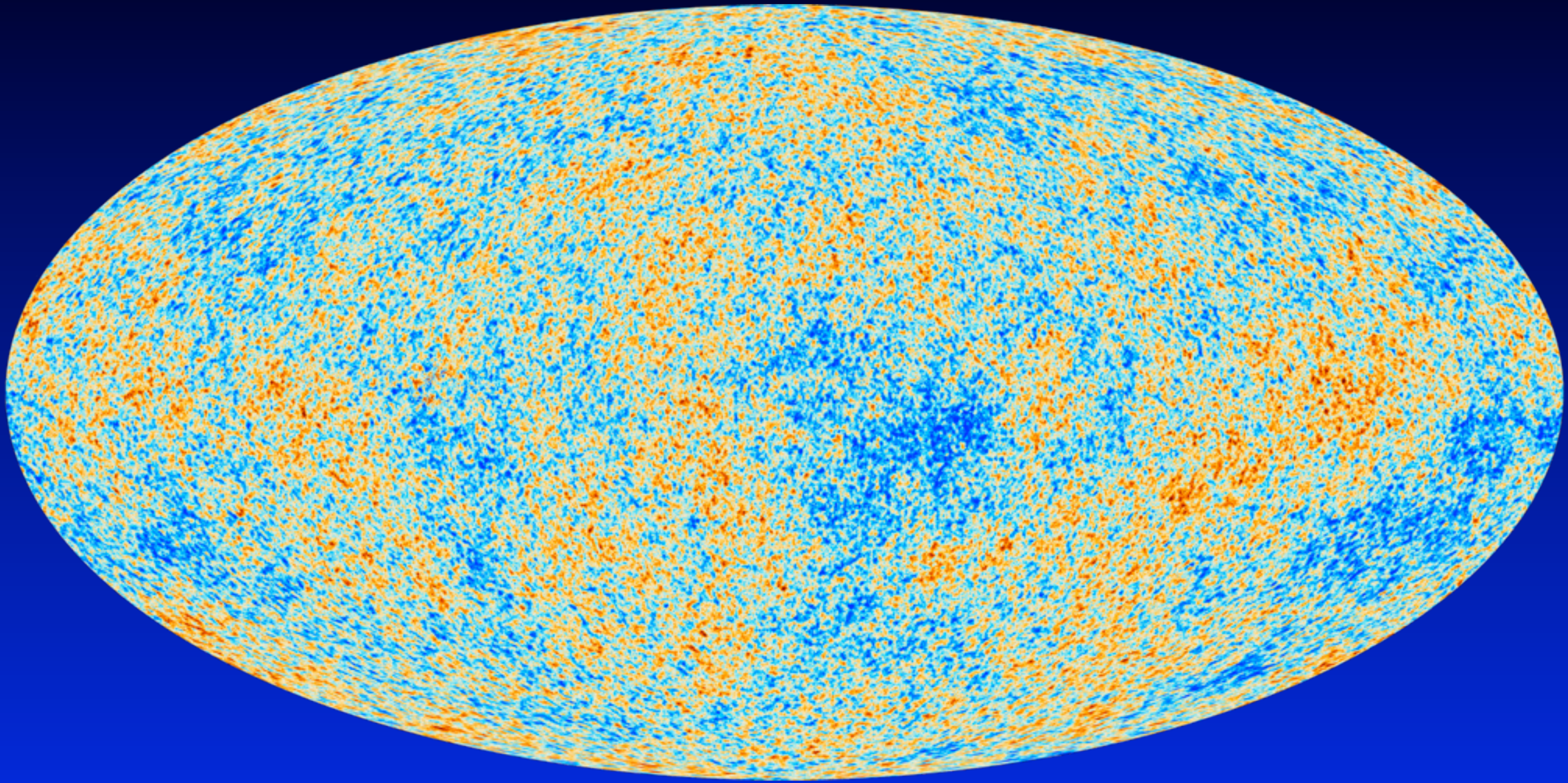


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles 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 helped us to answer these questions!



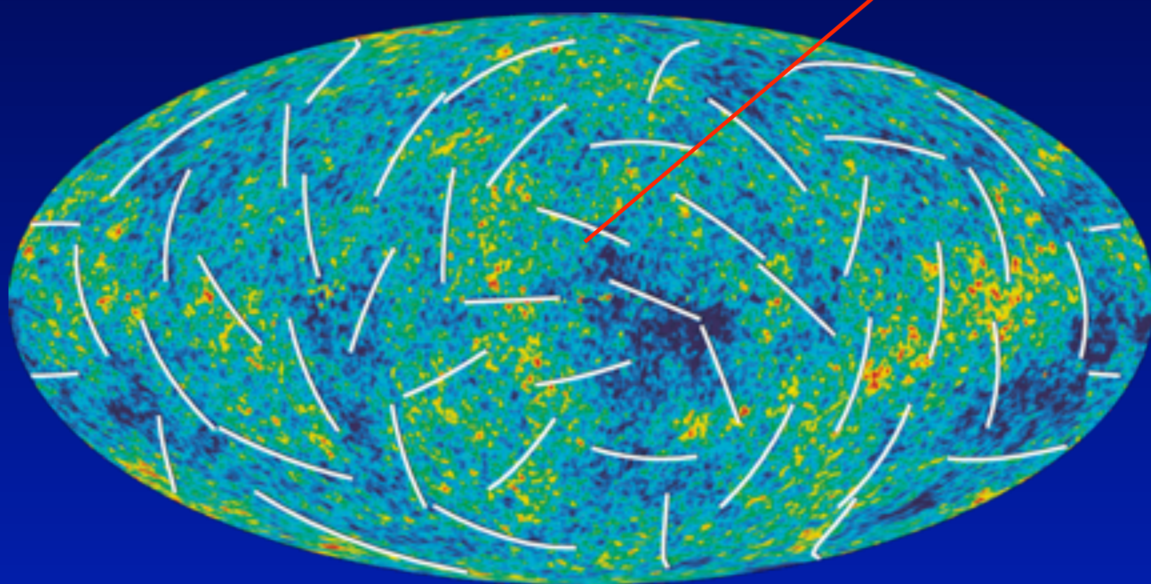
Planck all sky map

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

CMB Sky → Cosmology

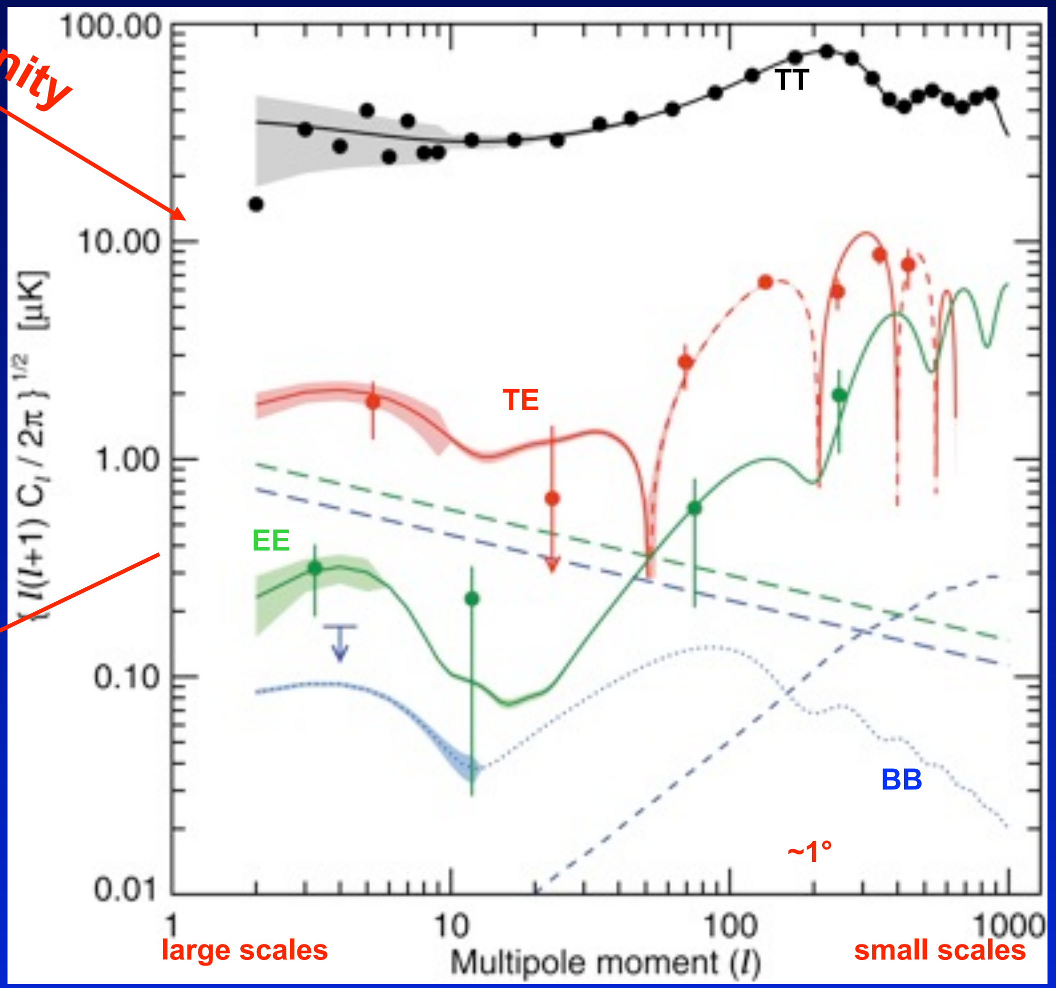
a_{lm}

WMAP CMB Sky



Gaussianity

Power spectra



(Joint) analysis

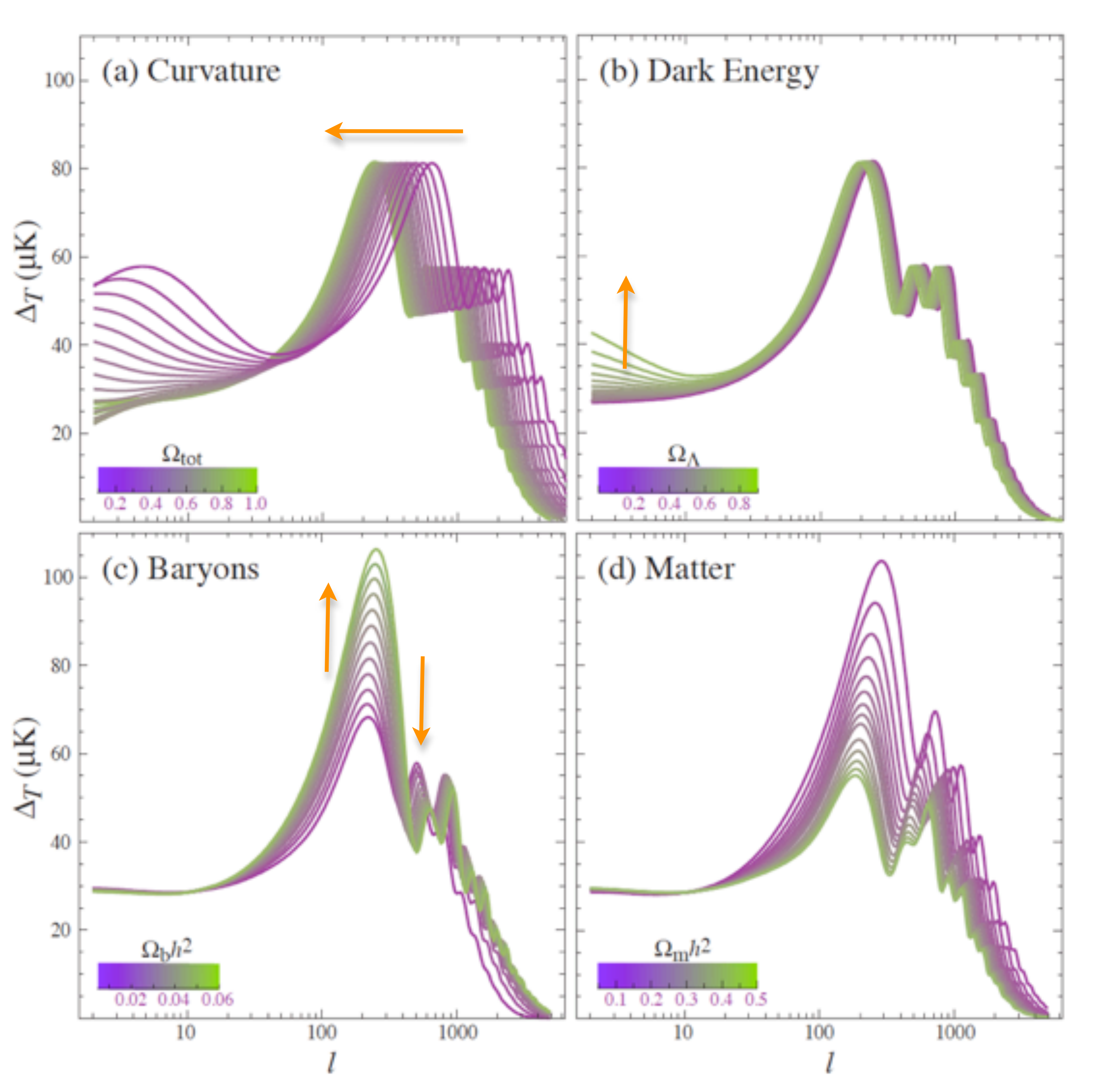
Cosmological Parameters

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, ...

Dependence of the Power Spectrum on the Main Cosmological Parameters



- Total density (curvature) → positions of peaks
- dark energy → ISW at large scales
- Baryon density → damping tail / ratio of peaks
- dark matter → gravitational driving / enhancement of third peak over second
- spectral index n_S → tilt of the overall power spectrum
- Thomson optical depth τ → large scale E-mode polarization → damping tail

Hu & Dodelson, 2002, ARAA

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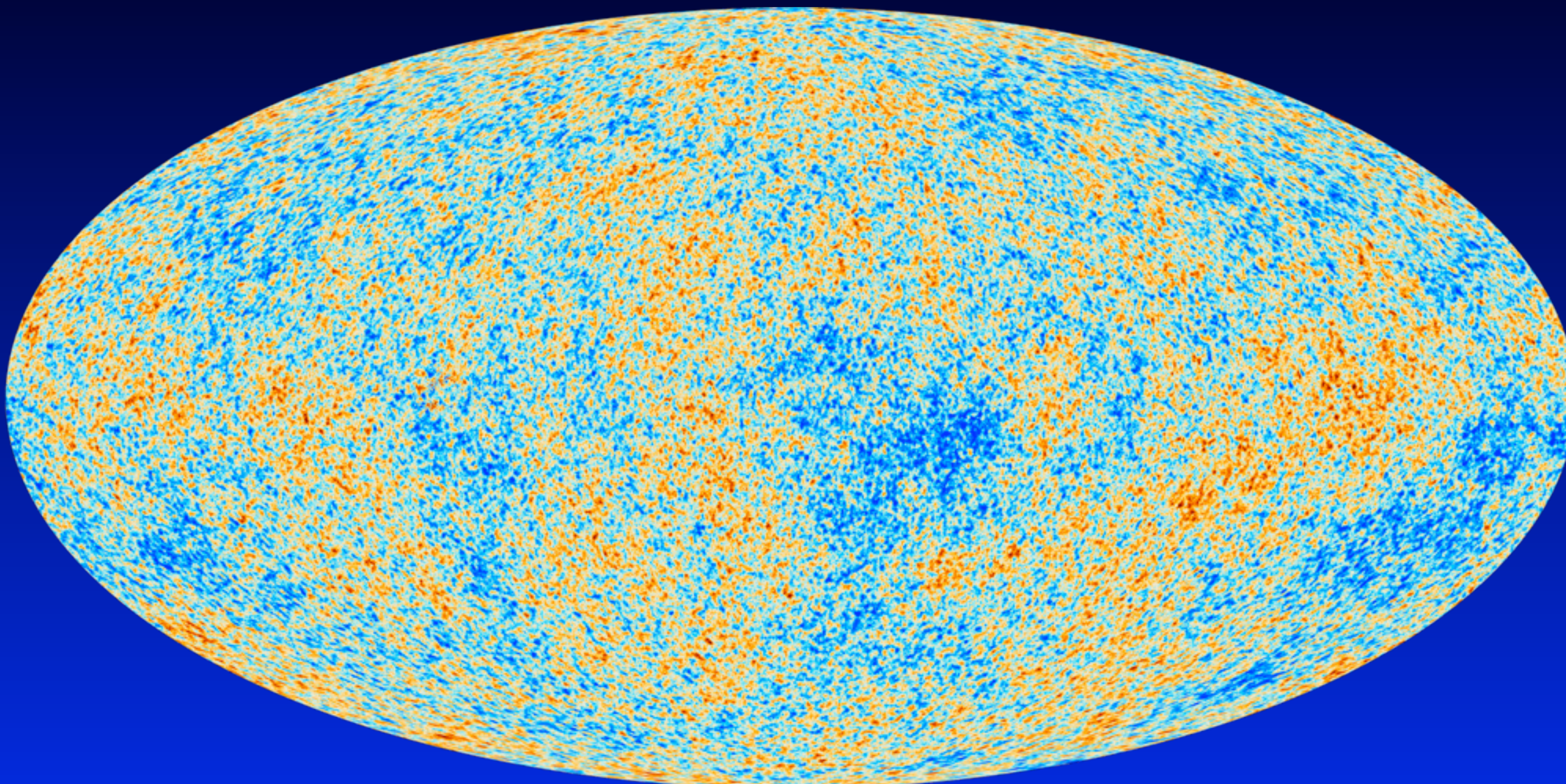

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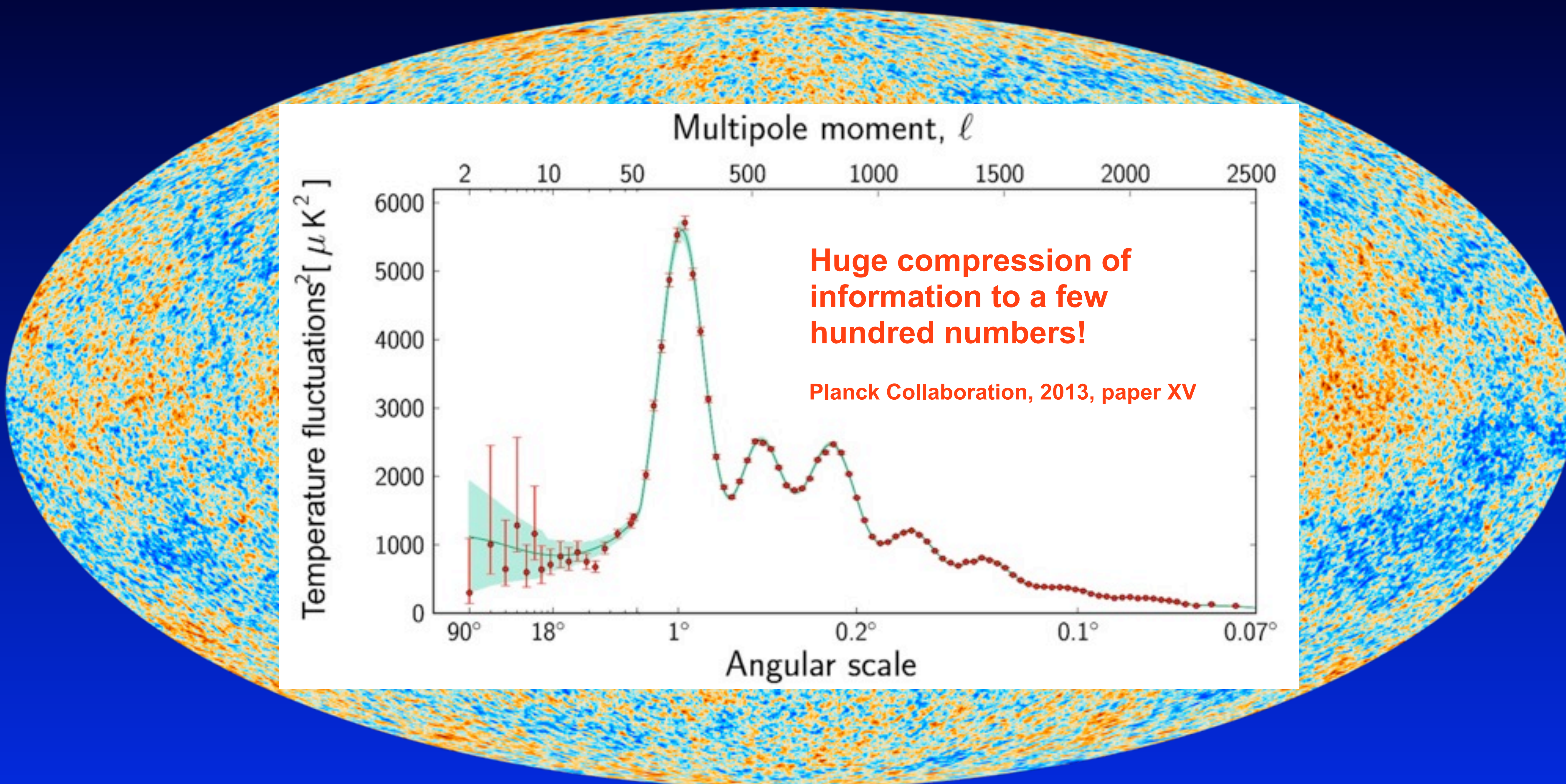

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- CMB has a blackbody spectrum in every direction
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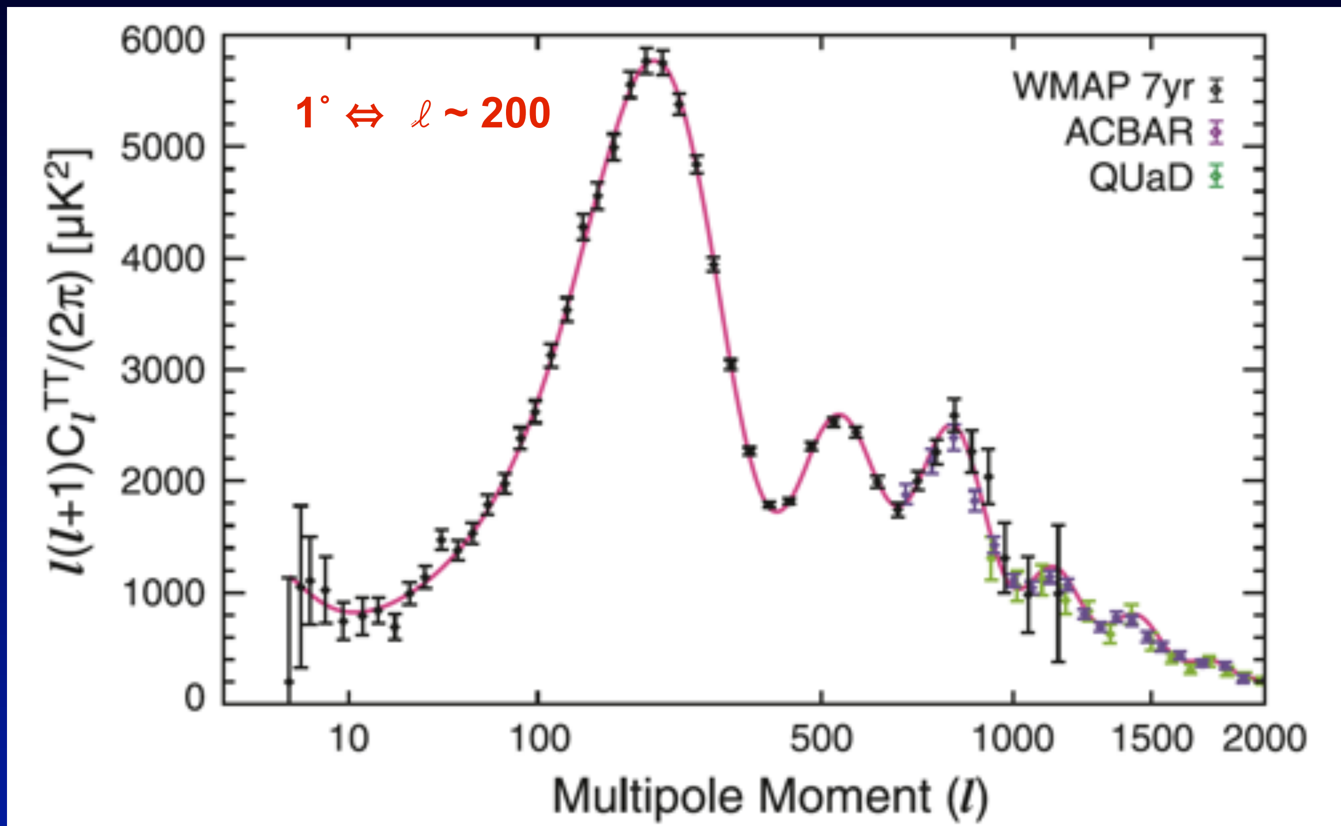
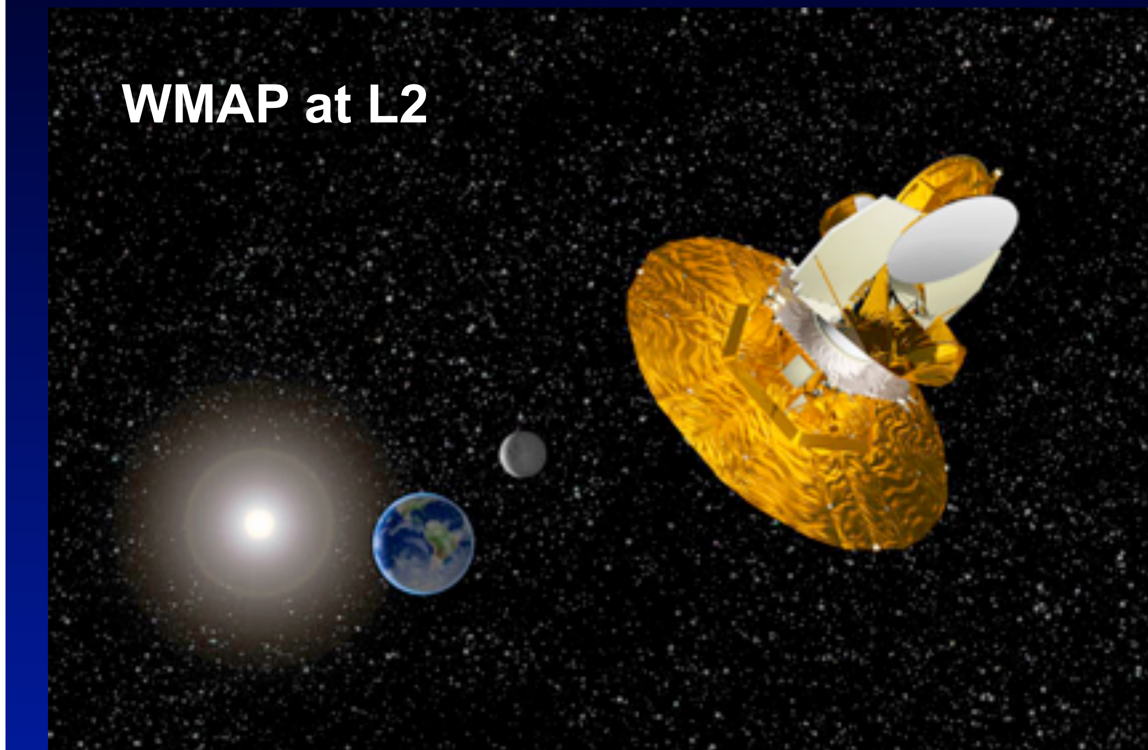
CMB anisotropies clearly taught us a lot about the Universe we live in!





Precision cosmology

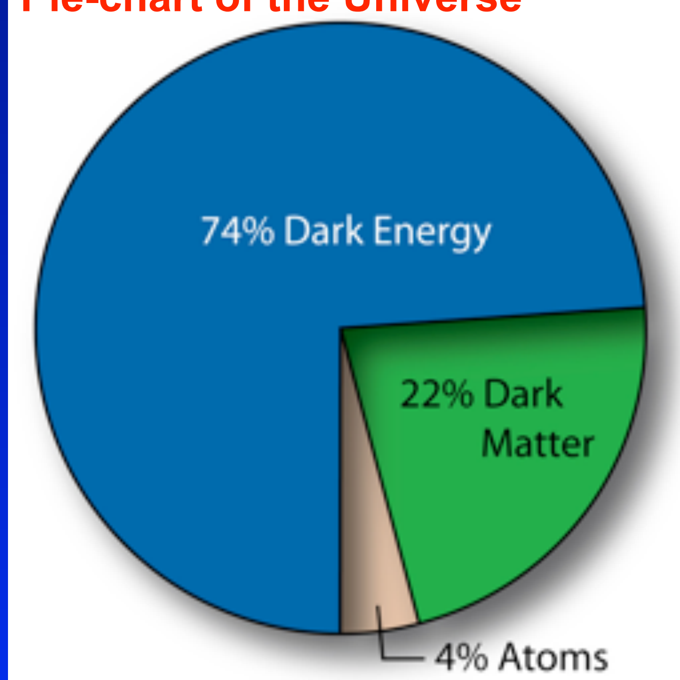
Tiny error bars!

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

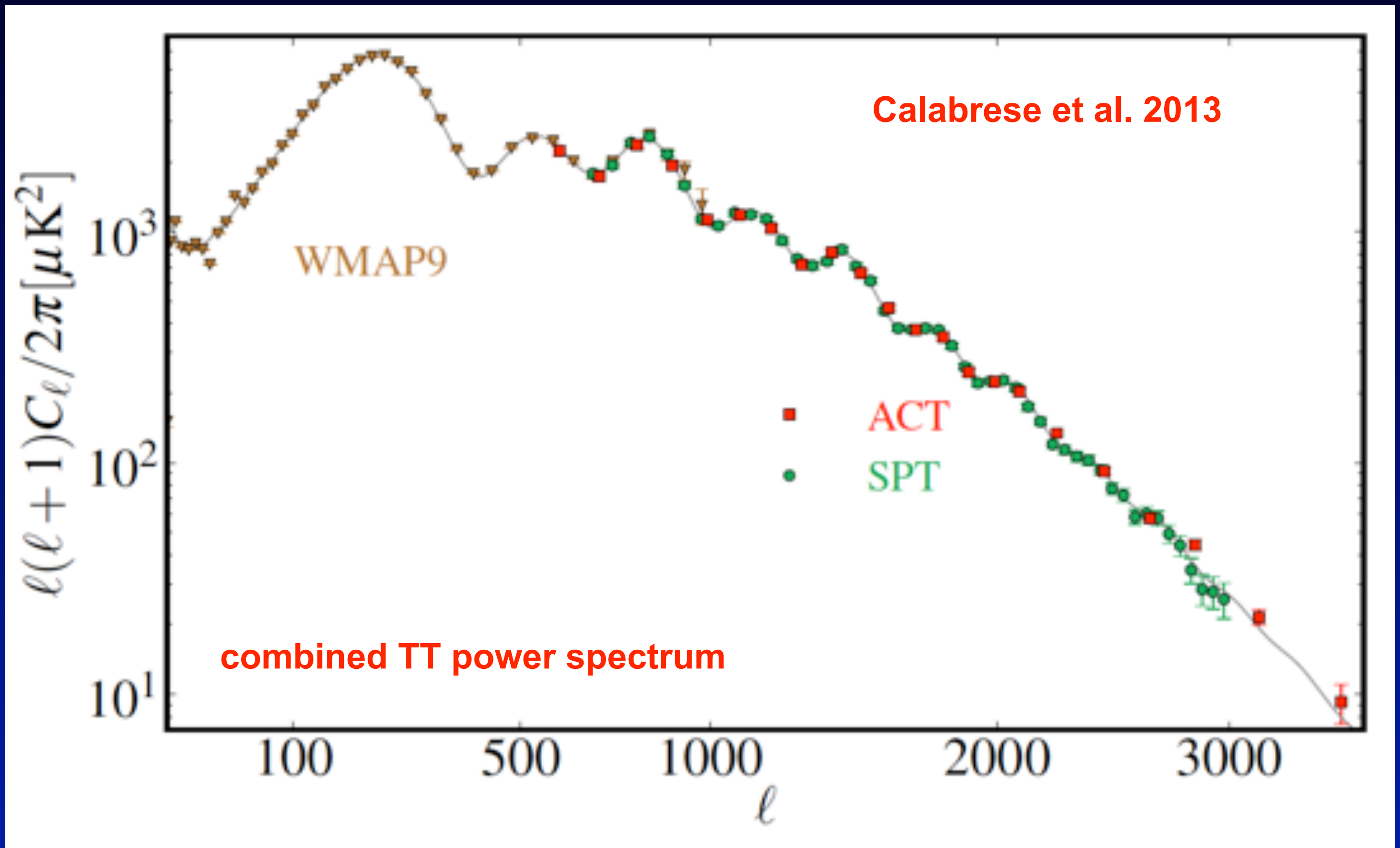
[a] Larson et al. (2010). "ML" refers to the Maximum Likelihood parameters.
[b] Larson et al. (2010). "Mean" refers to the mean of the posterior distribution of each parameter. The quoted errors show the 68% confidence levels (CL).
[c] $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ and $k_0 = 0.002$ 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!



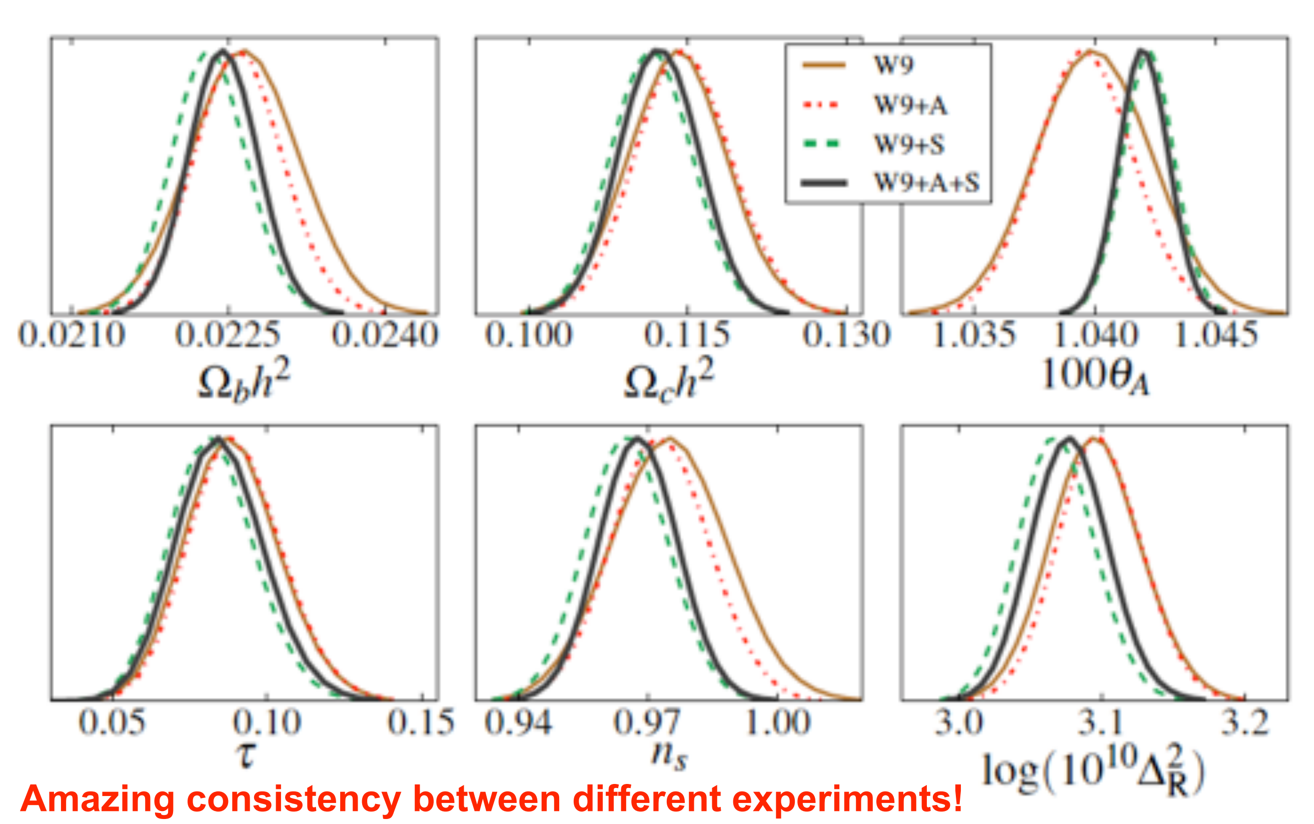


TABLE I. Standard ΛCDM parameters from the combination of WMAP9, ACT and SPT.

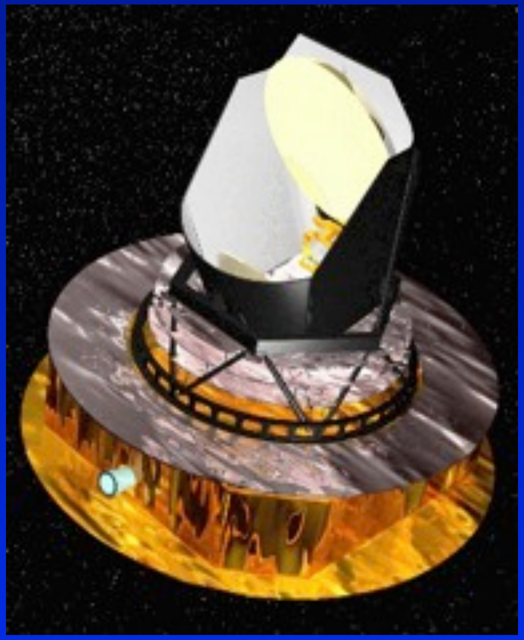
Parameter	WMAP9 +ACT	WMAP9 +SPT	WMAP9 +ACT+SPT
$100\Omega_b h^2$	2.260 ± 0.041	2.231 ± 0.034	2.245 ± 0.032
$100\Omega_c h^2$	11.46 ± 0.43	11.16 ± 0.36	11.23 ± 0.36
$100\theta_A$	1.0396 ± 0.0019	1.0422 ± 0.0010	1.0420 ± 0.0010
τ	0.090 ± 0.014	0.082 ± 0.013	0.085 ± 0.013
n_s	0.973 ± 0.011	0.9650 ± 0.0093	0.9678 ± 0.0088
$10^9 \Delta^2_{\mathcal{R}}$	2.22 ± 0.10	2.15 ± 0.10	2.17 ± 0.10
Ω_Λ [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

	Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits	*Planck*+WP+highL Best fit	*Planck*+WP+highL 68% limits	*Planck*+lensing+WP+highL Best fit	*Planck*+lensing+WP+highL 68% limits	*Planck*+WP+highL+BAO Best fit	*Planck*+WP+highL+BAO 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

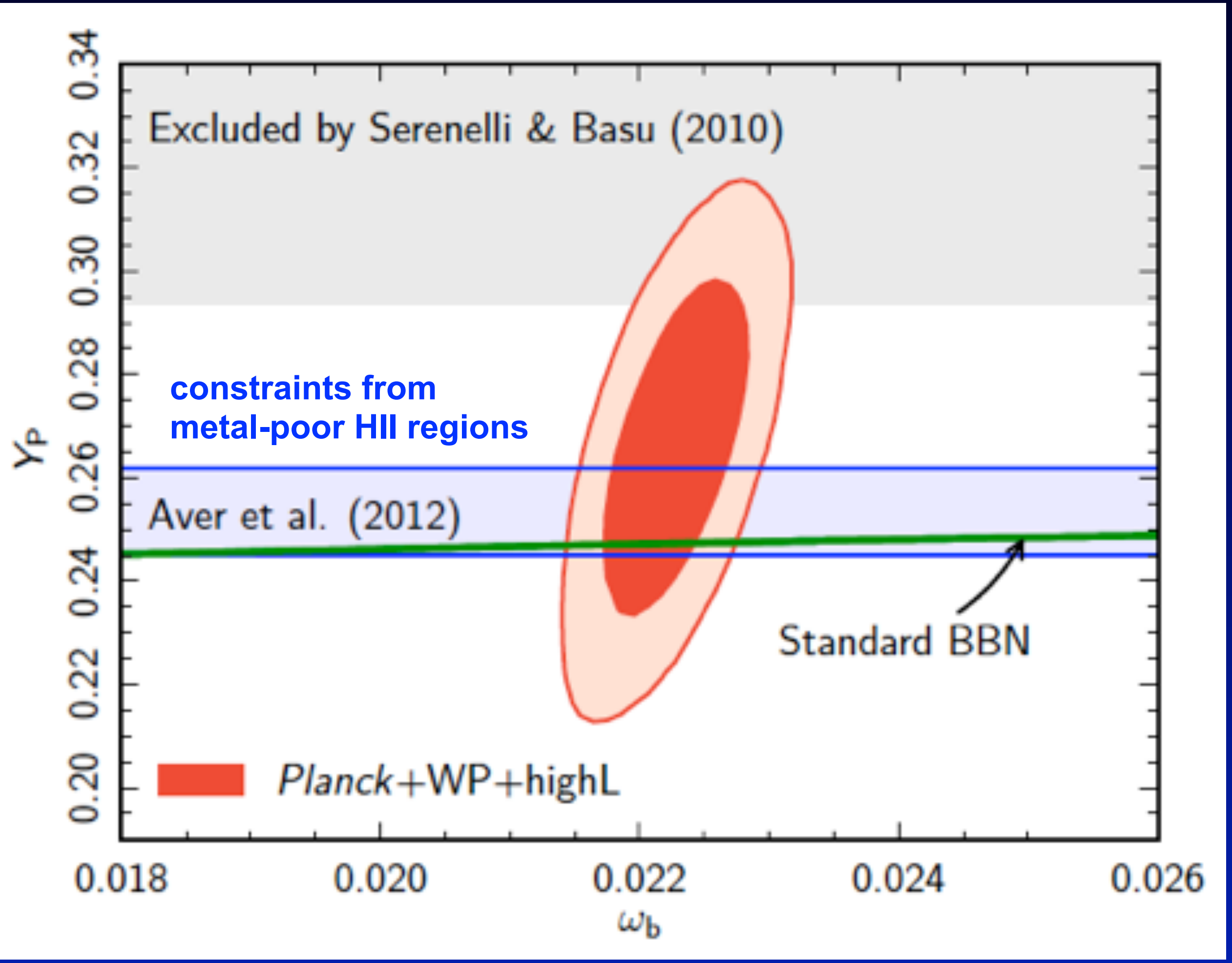
Planck Collaboration, 2013, paper XV

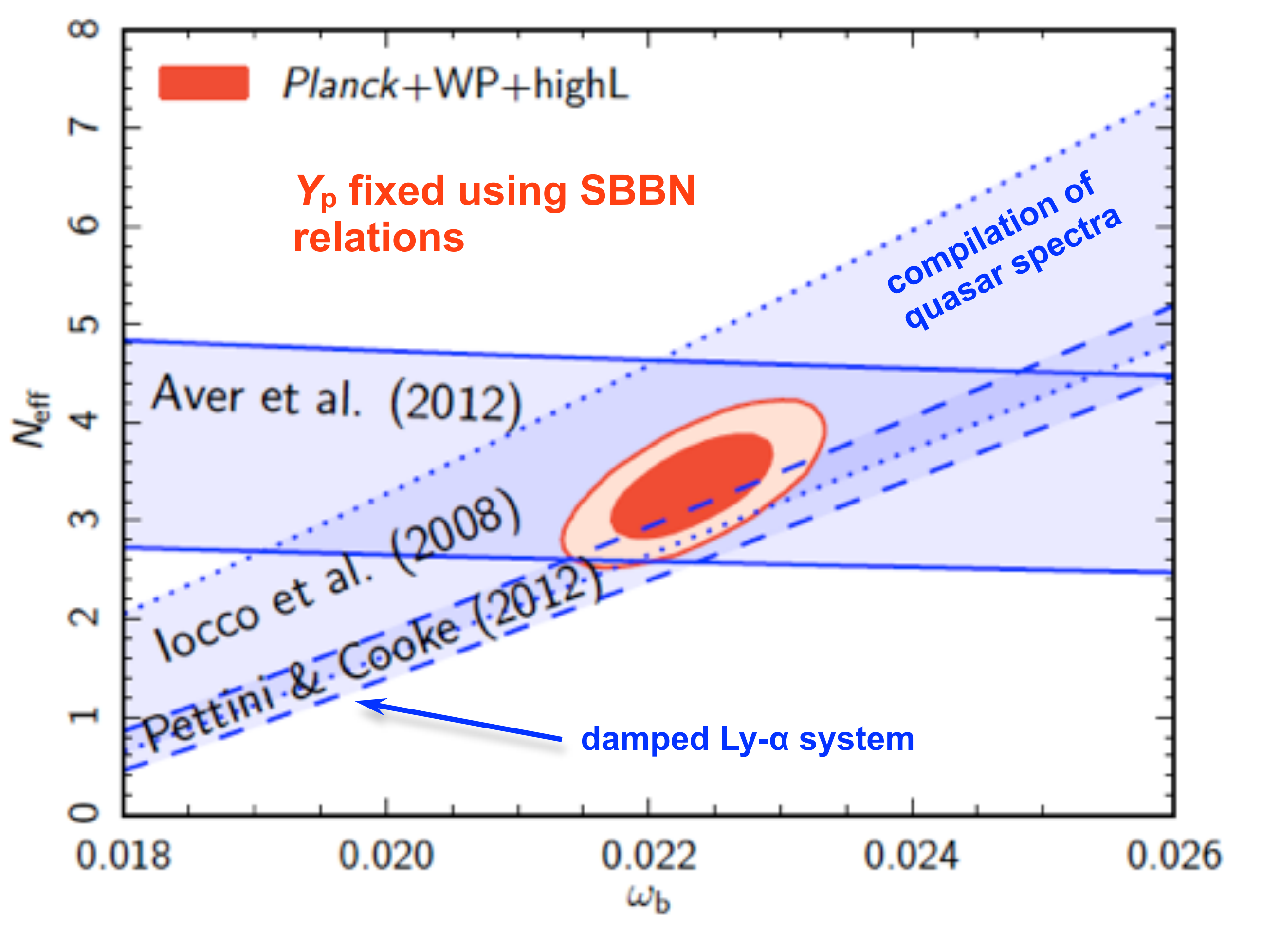
- Massive amount of information! (close to 30 Planck papers in March 2013)
- Impressive consistency between different experiments!
- Amazing confirmation of ΛCDM



Planck Satellite

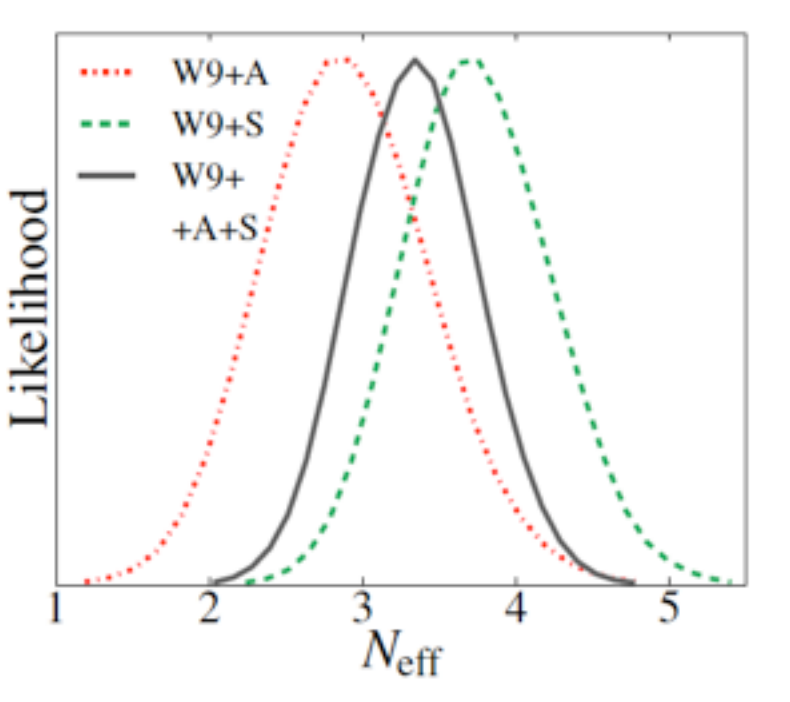
CMB constraints on N_{eff} and Y_p





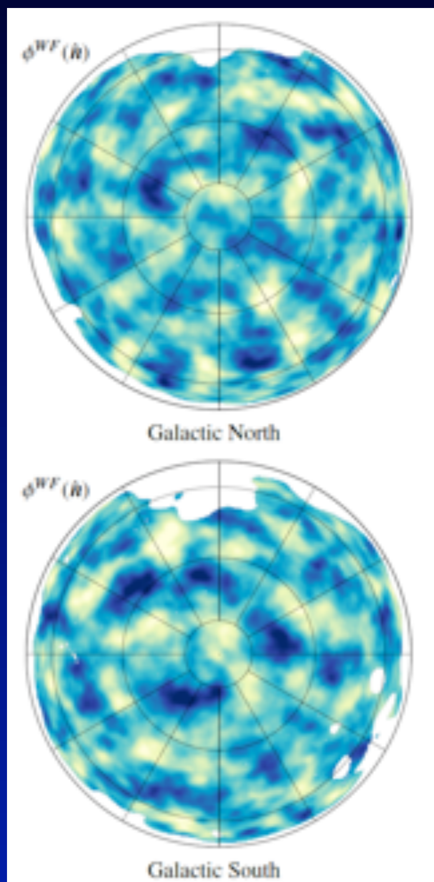
Planck Collaboration, 2013, paper XV

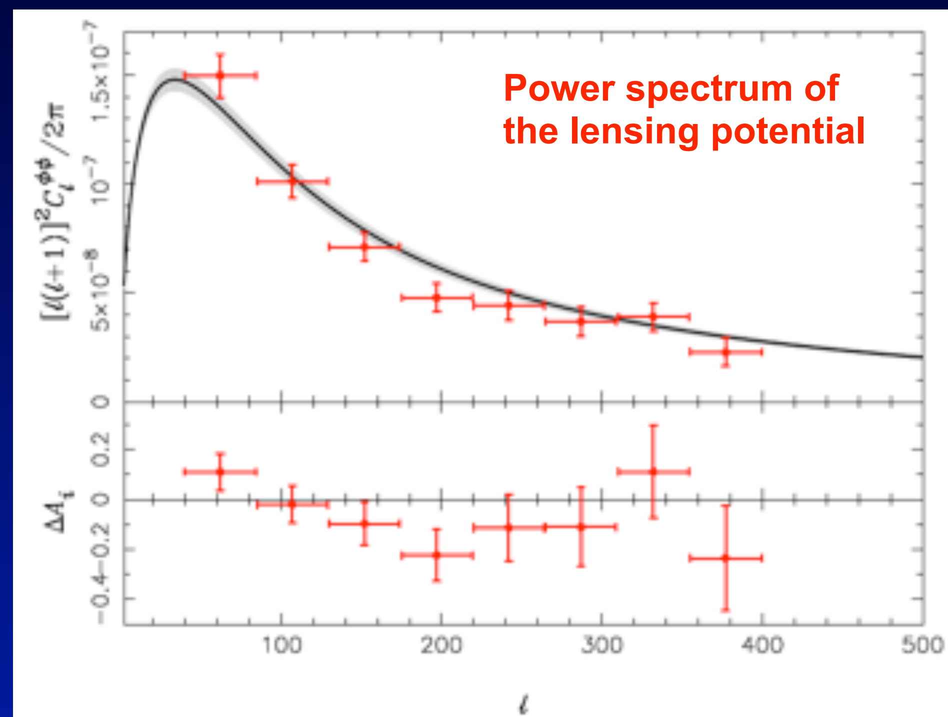
- *Helium determination from CMB consistent with SBNN prediction*
- *CMB constraint on N_{eff} competitive!*
- *Partial degeneracy with Y_p and running*
- *Some tension between different data sets*



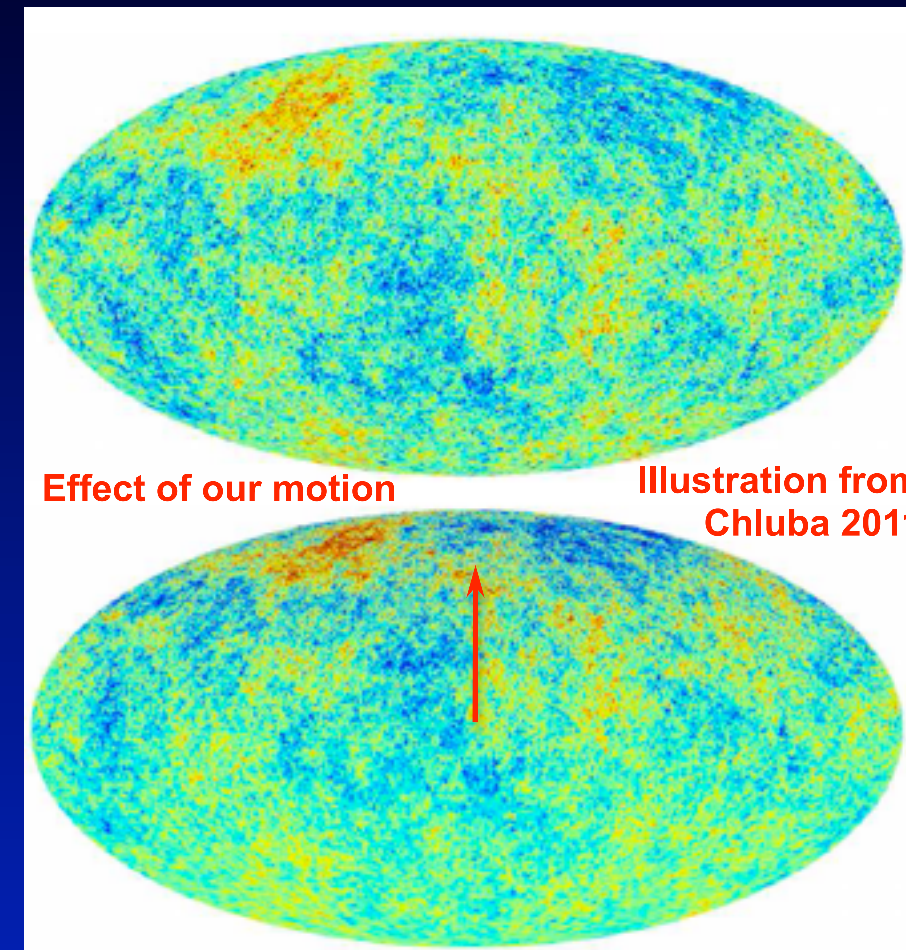
Calabrese et al. 2013

All kind of fun new science with the CMB anisotropies!



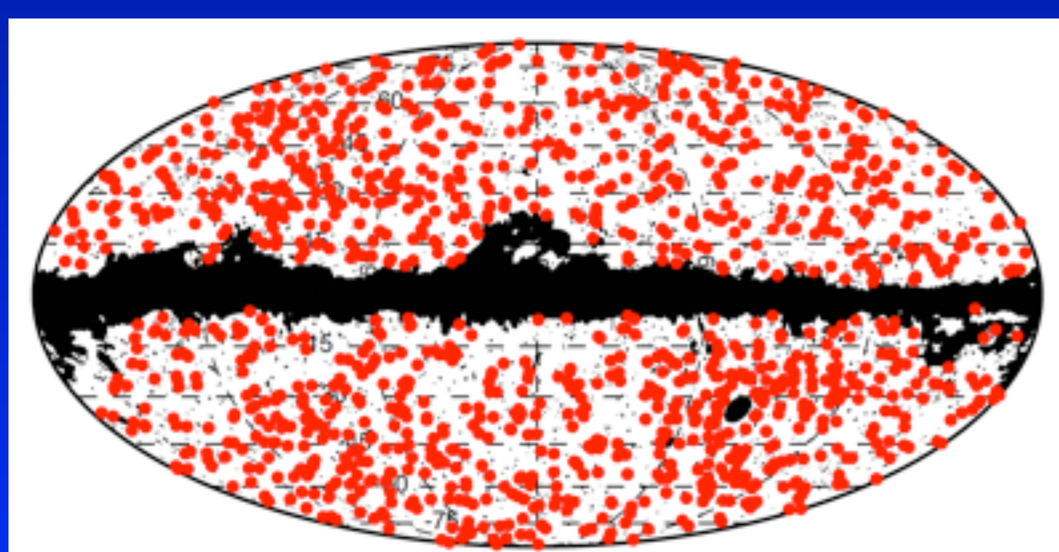


Planck Collaboration, 2013, paper XVII



Planck Collaboration, 2013, paper XXVII

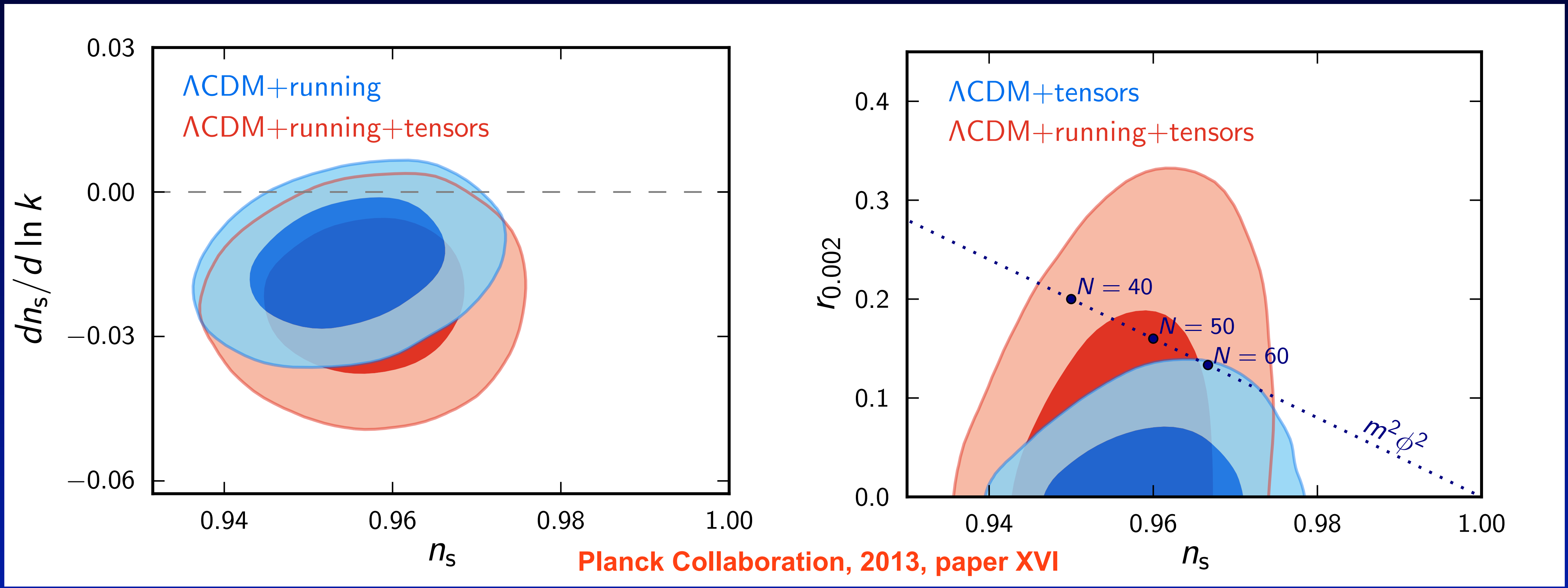
SZ clusters on the sky



Planck Collaboration, 2013, paper XXIV

- *Non-Gaussianity* (test of inflation models)
- *Topology*
- *CMB anomalies*
- *CIB* and *Galactic science*

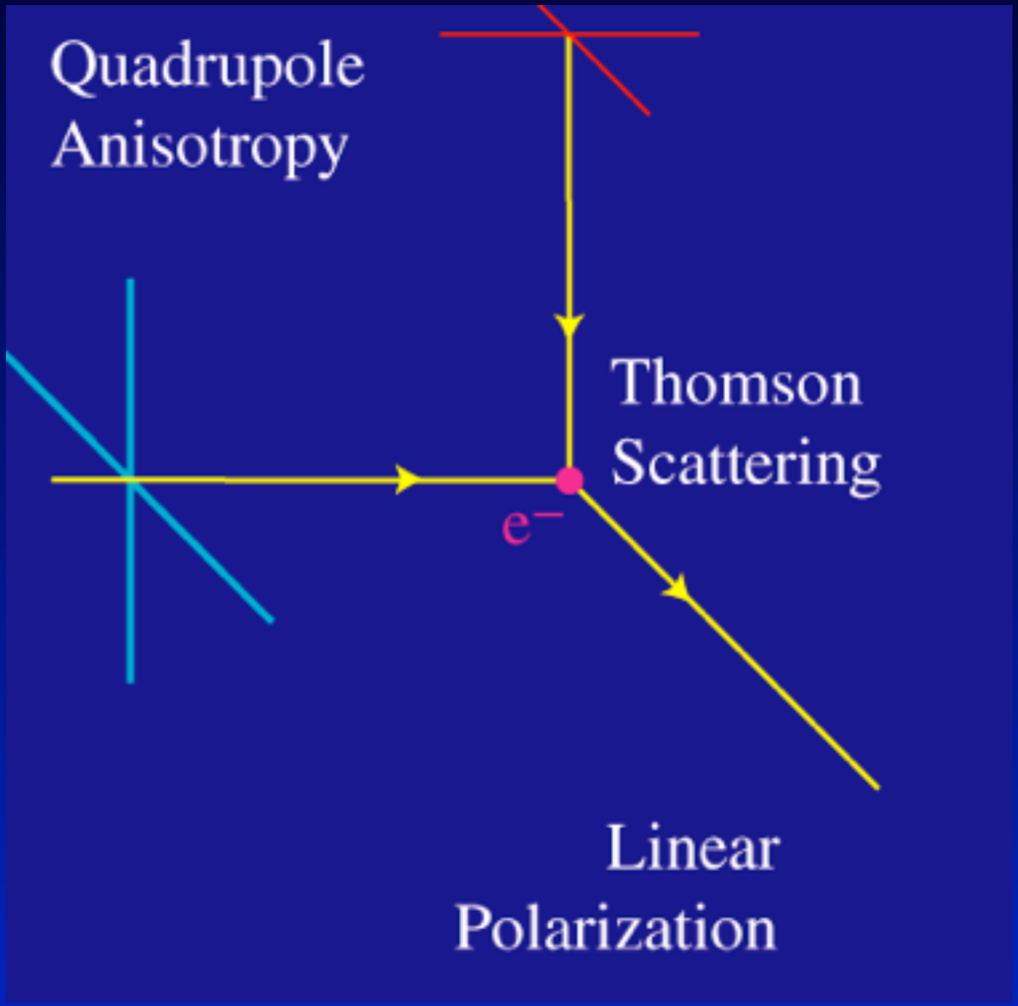
CMB anisotropies as probe of Inflation



- *Big goal/hope:* detection of B-polarization
- Plenty of progress over the next few years:

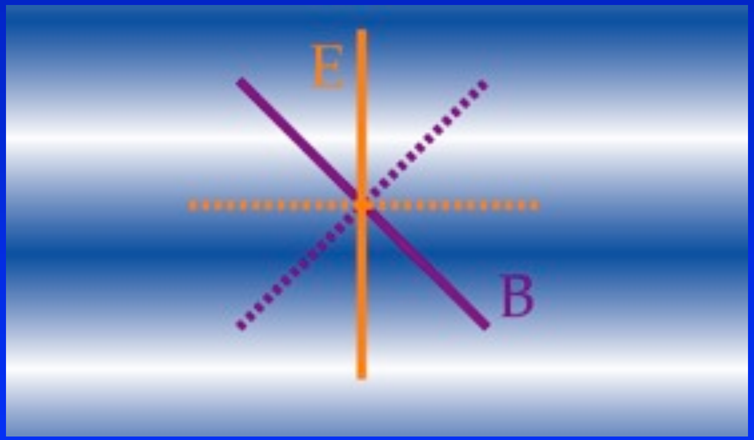
  ground/balloon: BICEP2, SPTpol, ACTpol, Spider, ...
  space: Planck, LiteBIRD, PIXIE, COrE+, ...?

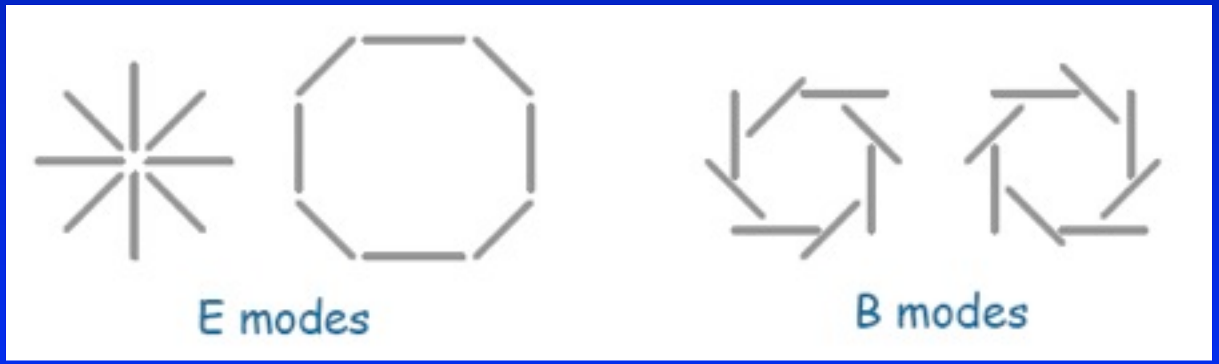
Polarization from Thomson scattering



- 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*

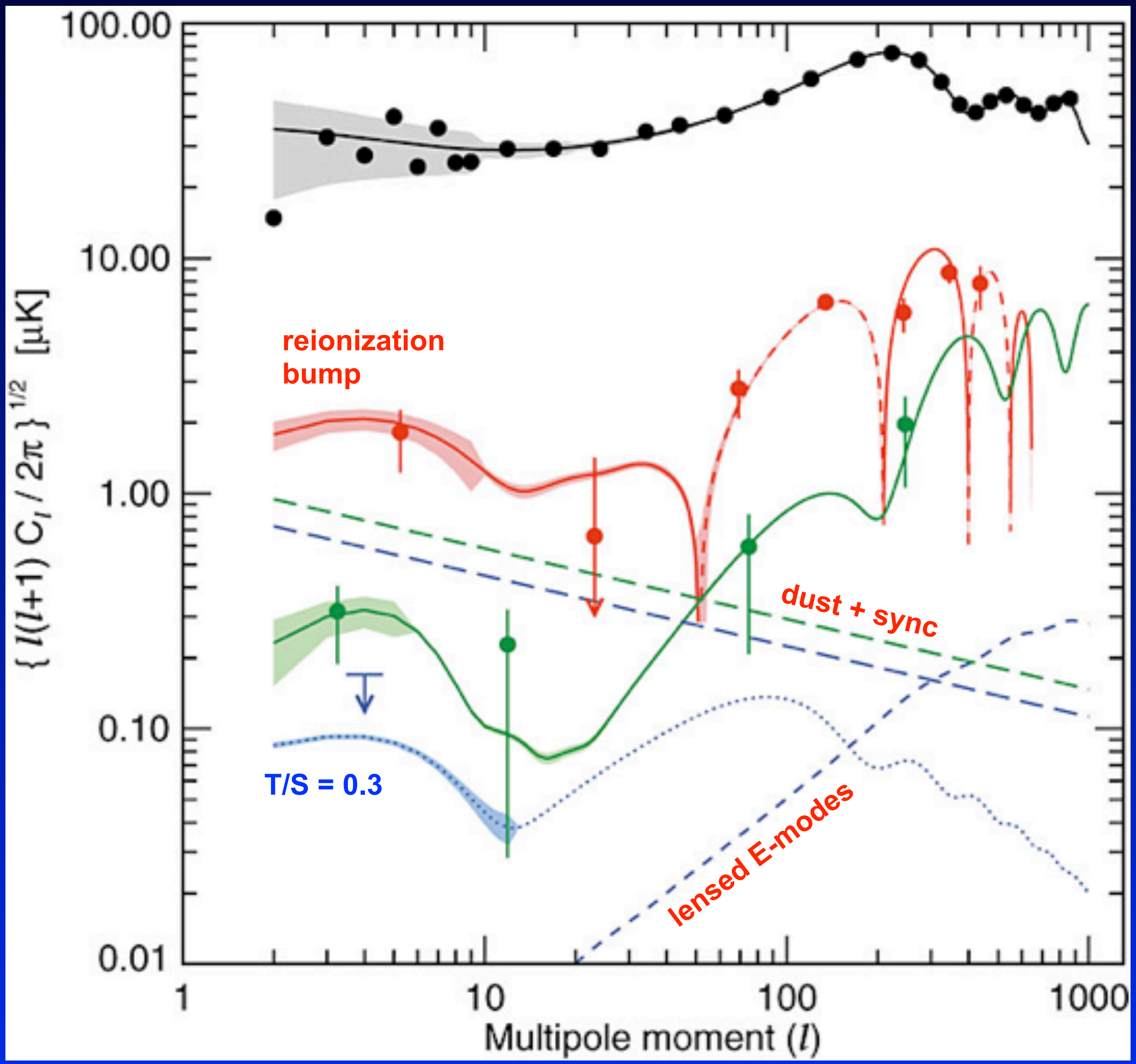
Temperature perturbation





"Divergence free" "Curl free"

WMAP Polarization Measurements



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

  ⟹ limits tensor to scalar ratio

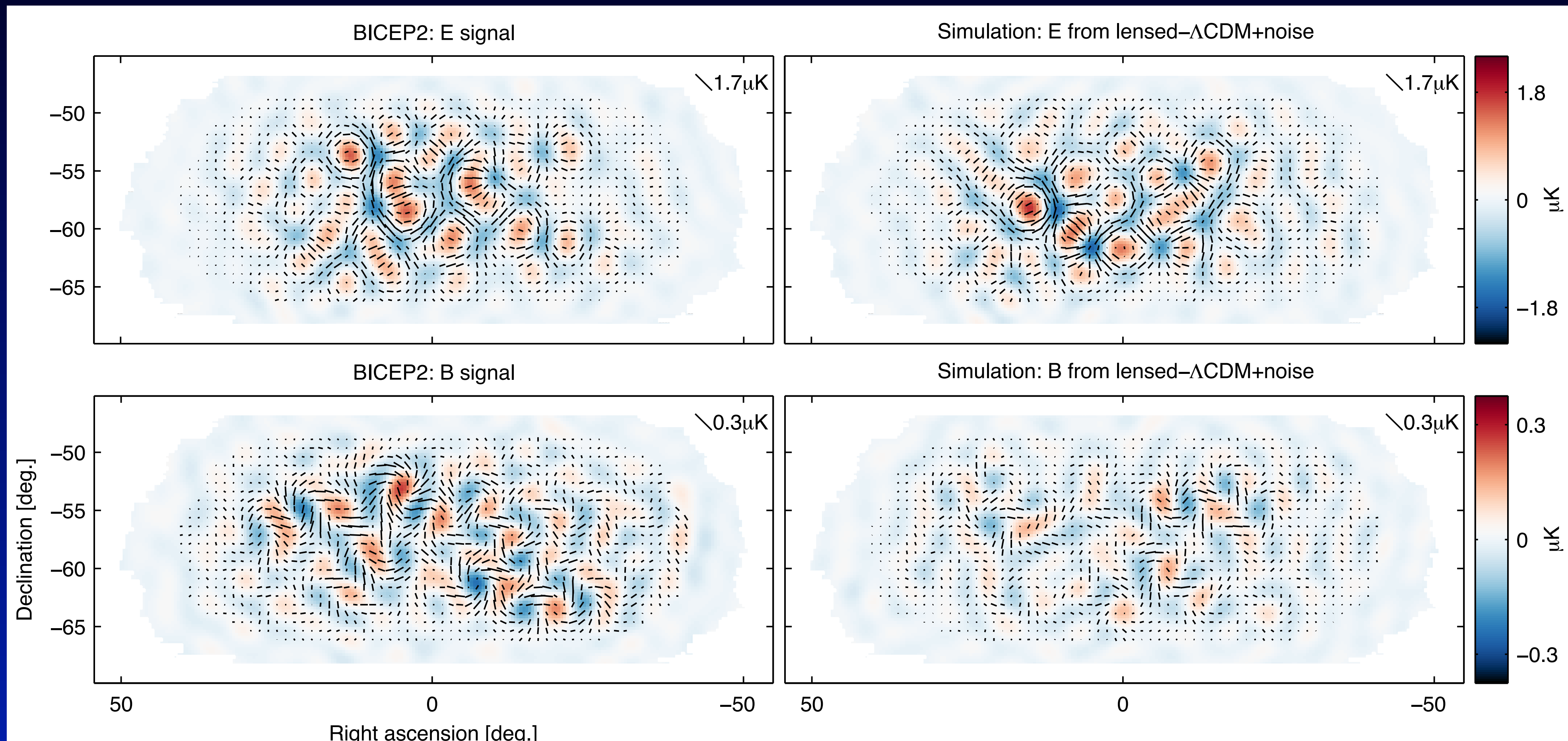
  ⟹ energy-scale of inflation

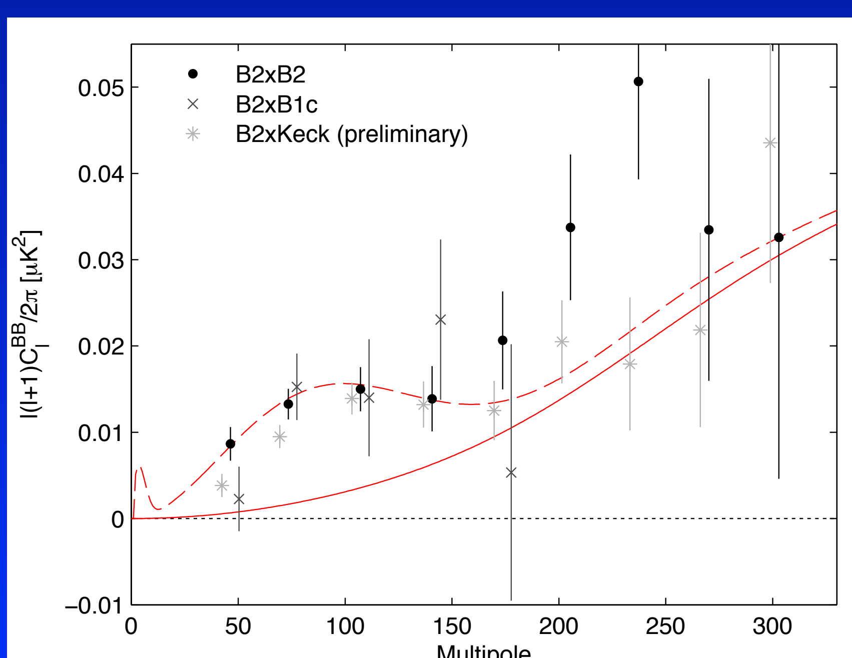
  ⟹ gravity waves
- Lots of experiments are trying to go for this:

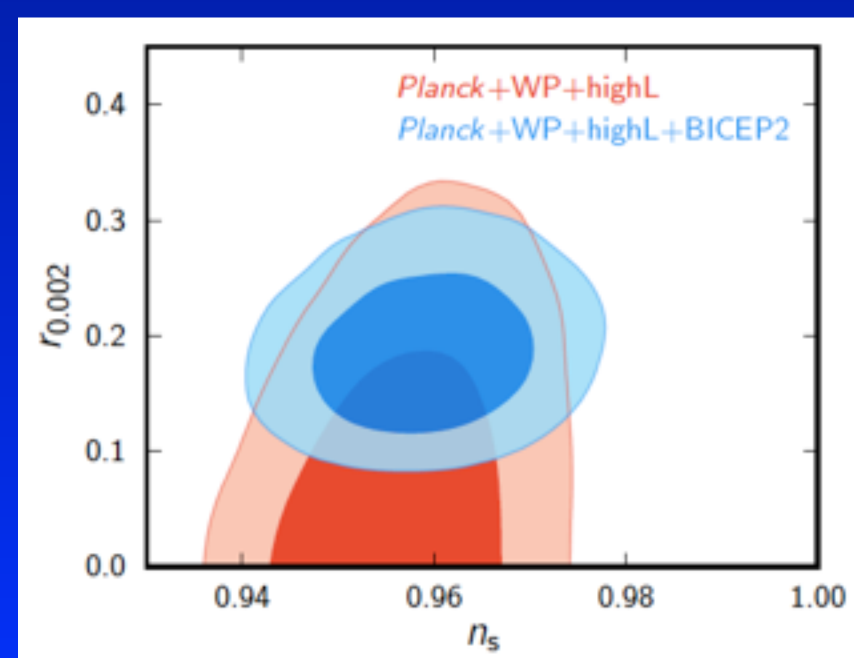
  PLANCK, LITEBIRD, SPIDER, CLASS, BICEP2, KECKarray, PIXIE, COrE+, Stage IV-CMB

WMAP 3yr, Page et al., 2007

“To dust or not to dust?”



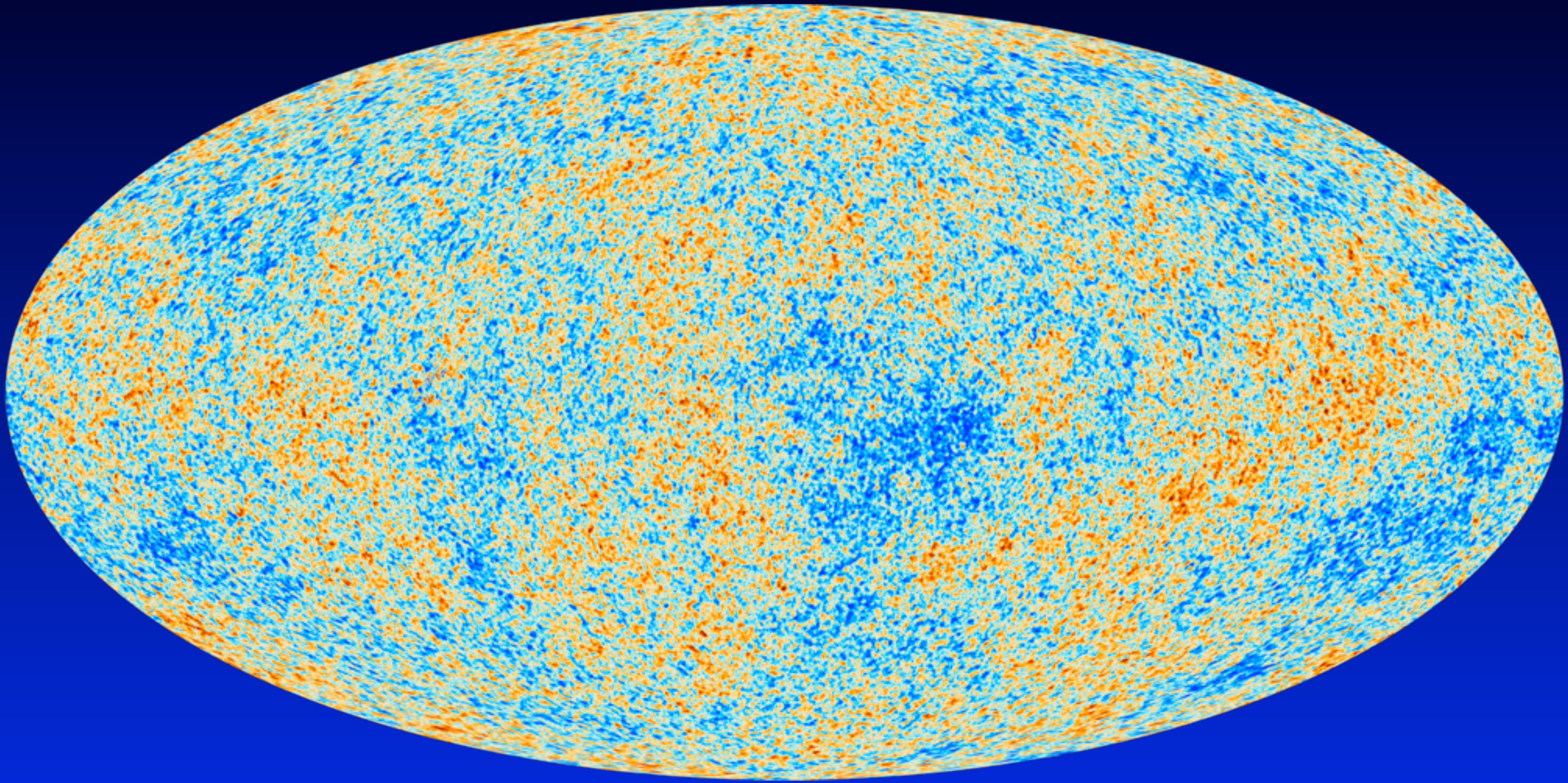




BICEP2 collaboration, 2014

$$r = 0.2^{+0.07}_{-0.05}$$

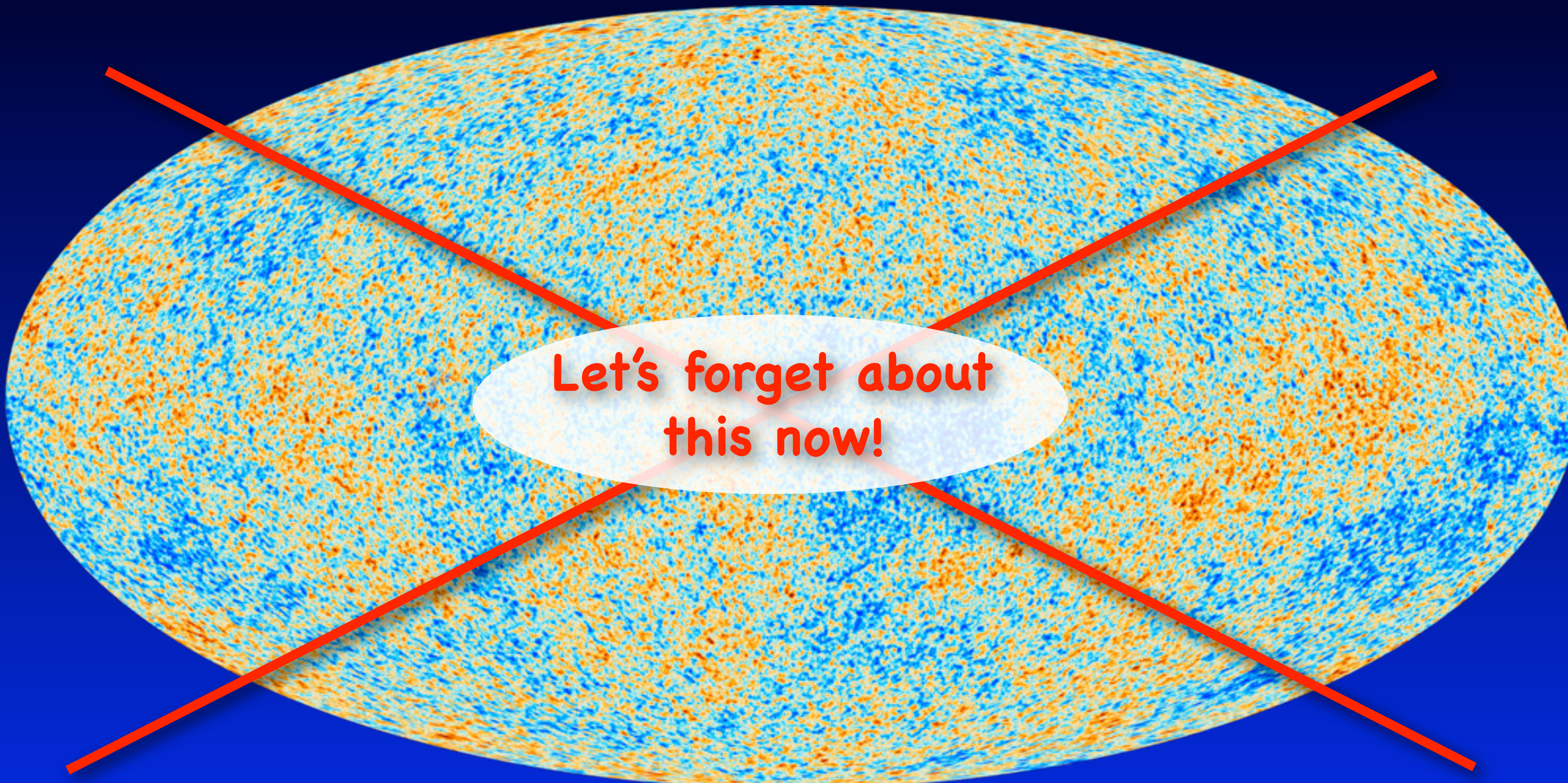
Cosmic Microwave Background Anisotropies



Planck all-sky temperature 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



Planck all-sky temperature map

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

CMB provides another independent piece of information!

COBE/FIRAS

$$T_0 = (2.726 \pm 0.001)\,\mathrm{K}$$

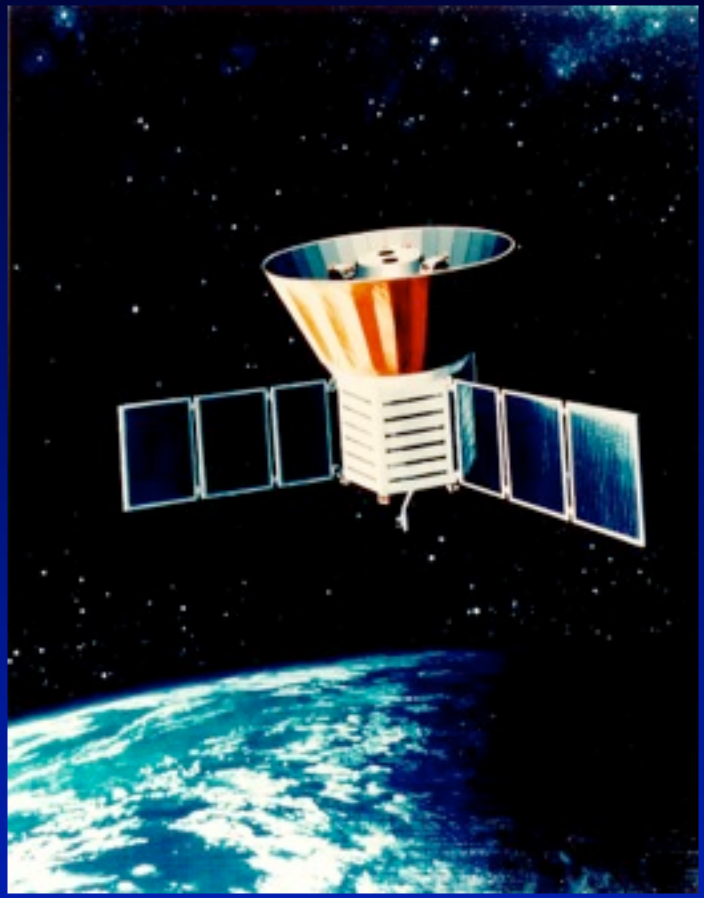
Absolute measurement required!

One has to go to space...

Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen, 2003, ApJ, 594, 67
Fixsen, 2009, ApJ, 707, 916

- CMB monopole is 10000 - 100000 times larger than the fluctuations

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

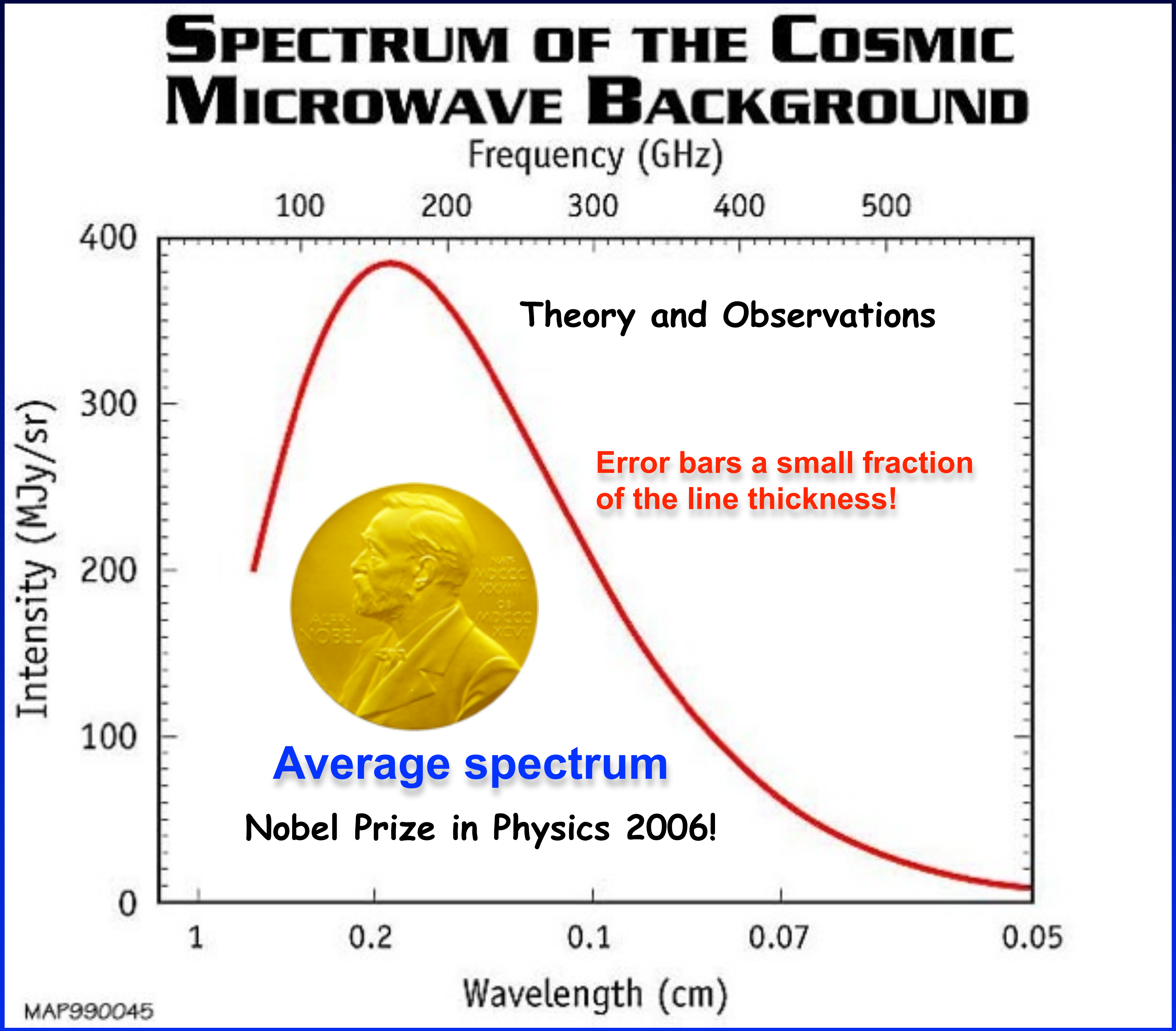


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

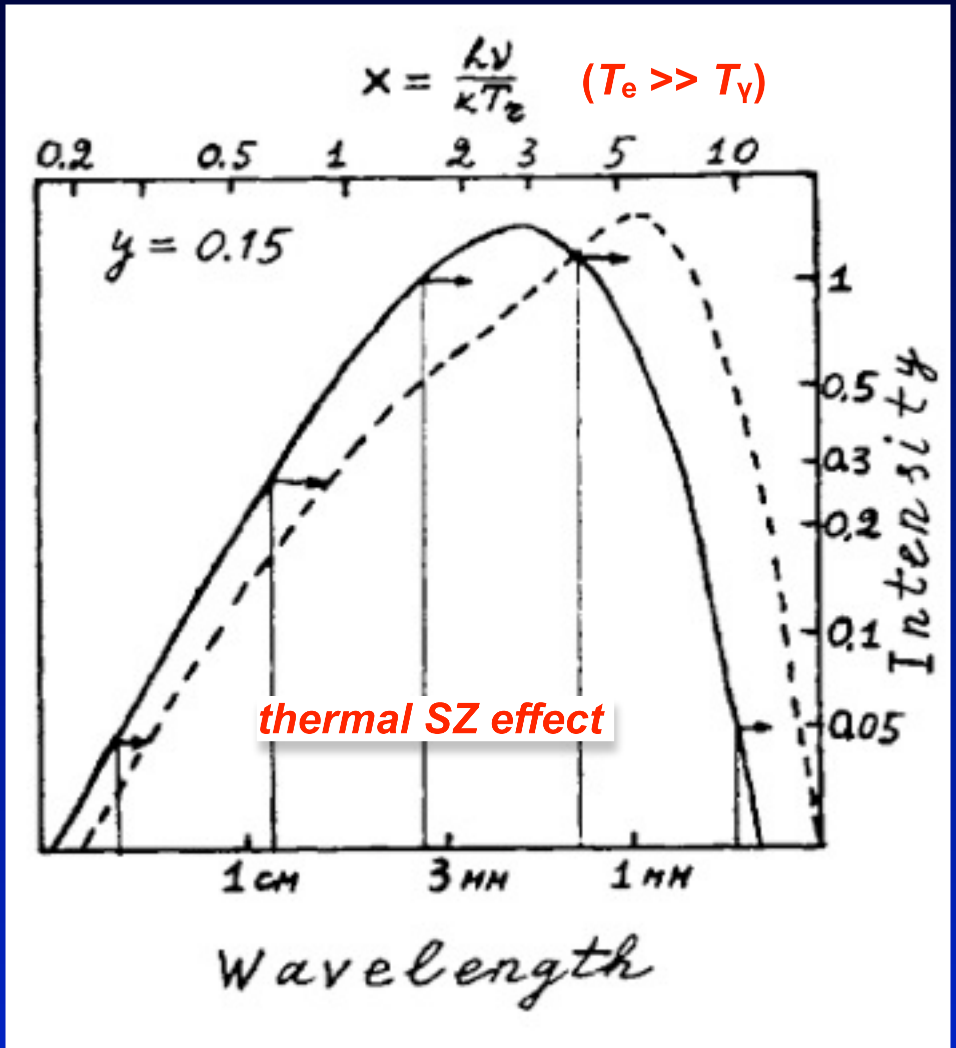
$$|\mu| \leq 9\times10^{-5}$$

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



Standard types of primordial CMB distortions

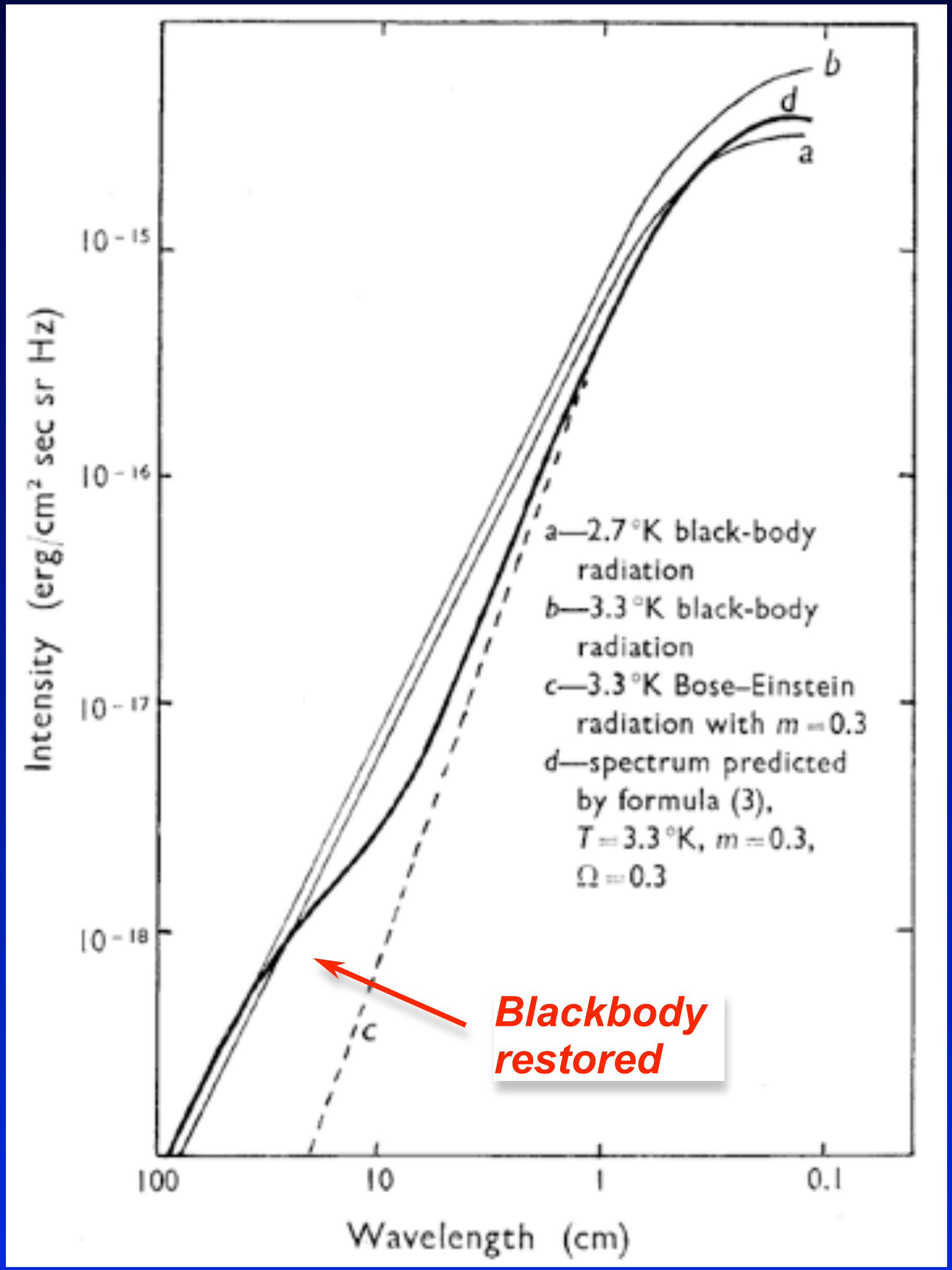
Compton y-distortion



Sunyaev & Zeldovich, 1980, ARAA, 18, 537

- also known from thSZ effect
- up-scattering of CMB photon
- important at late times (z<50000)
- scattering inefficient

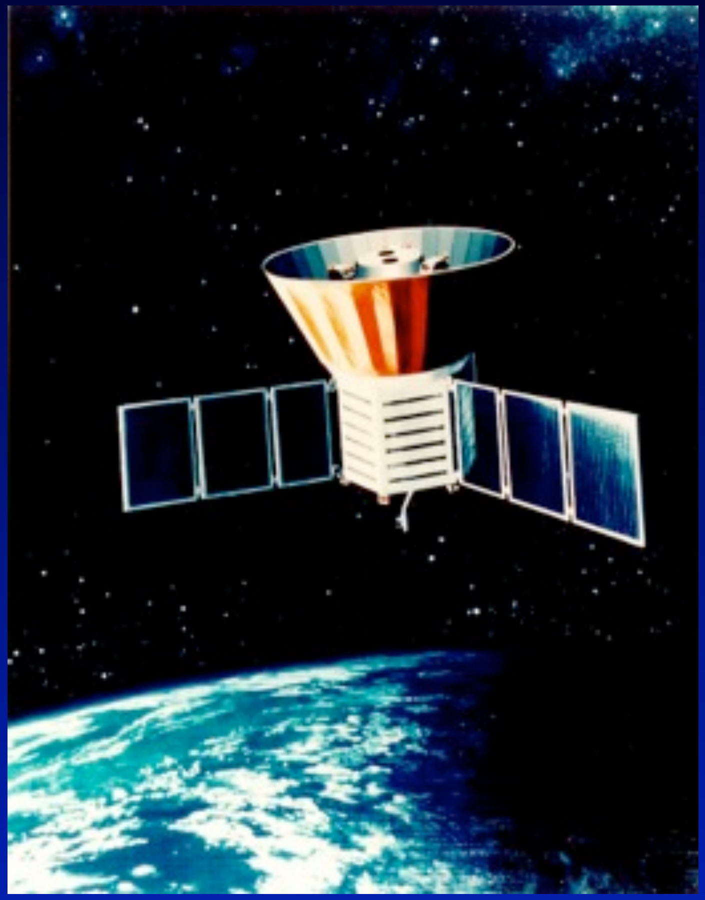
Chemical potential μ-distortion



Sunyaev & Zeldovich, 1970, ApSS, 2, 66

- important at very times (z>50000)
- scattering very efficient

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)



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

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$$|\mu| \le 9\times10^{-5}$$

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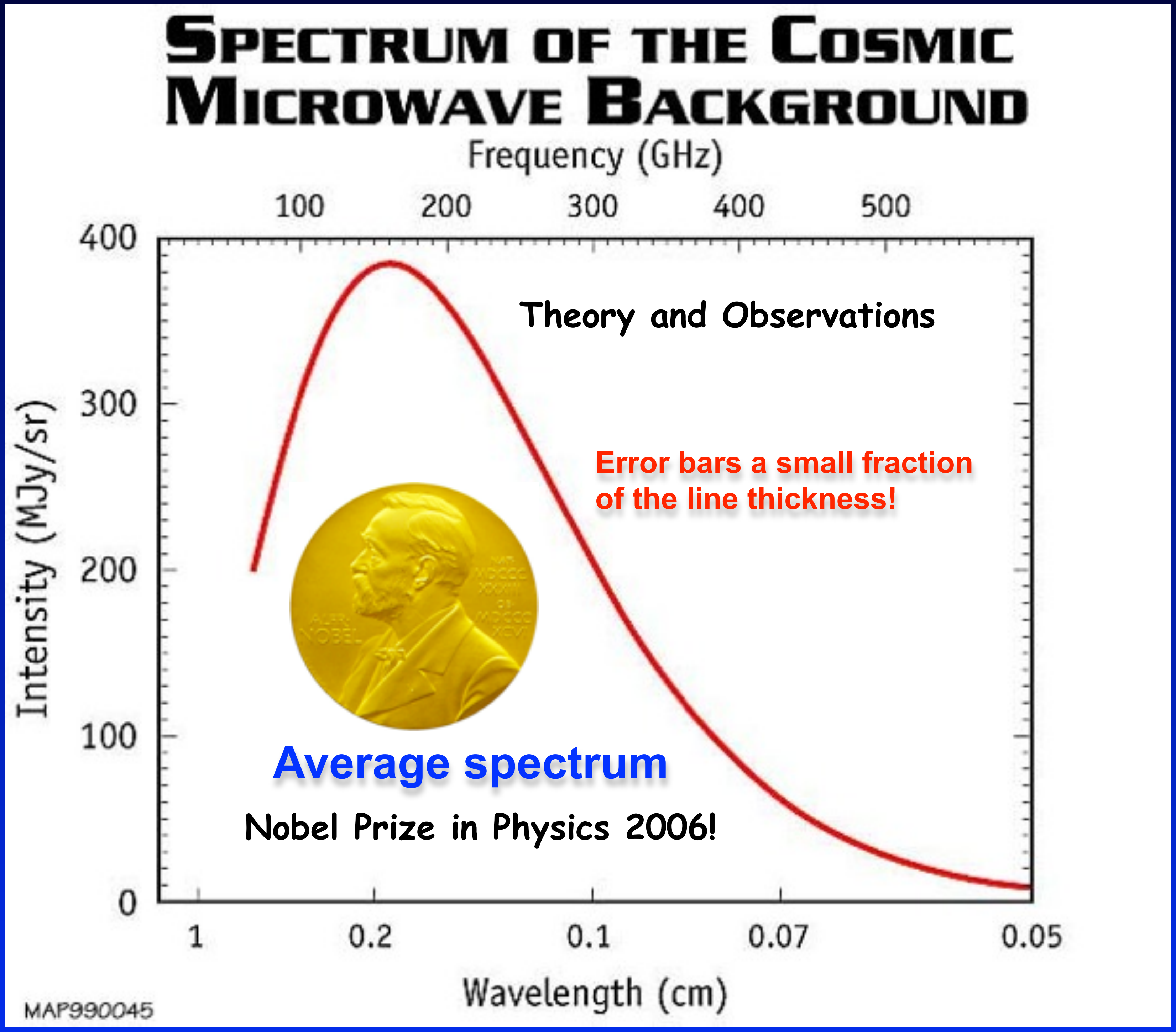
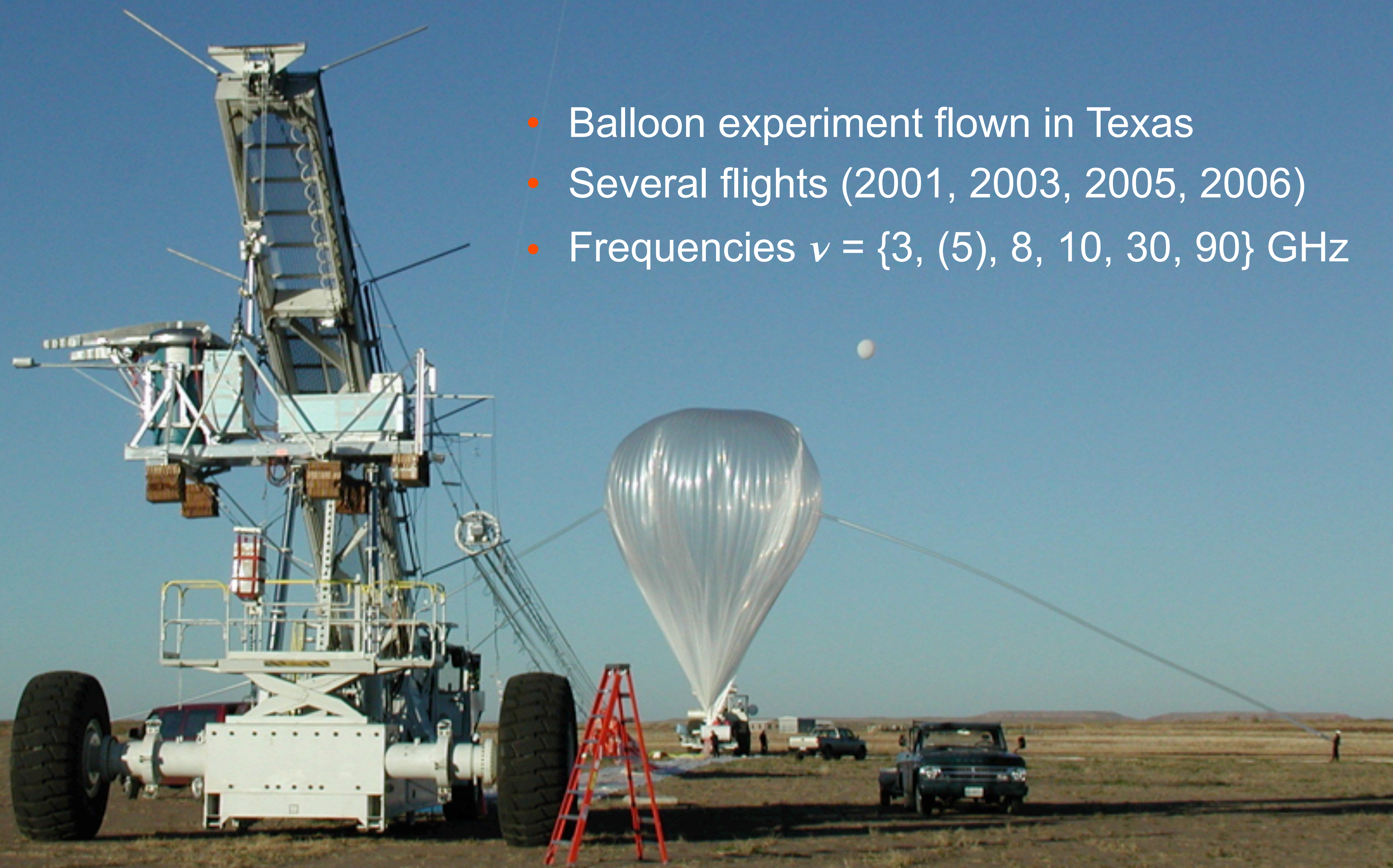


Only very small distortions of CMB spectrum are still allowed!

ARCADE

(Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission)

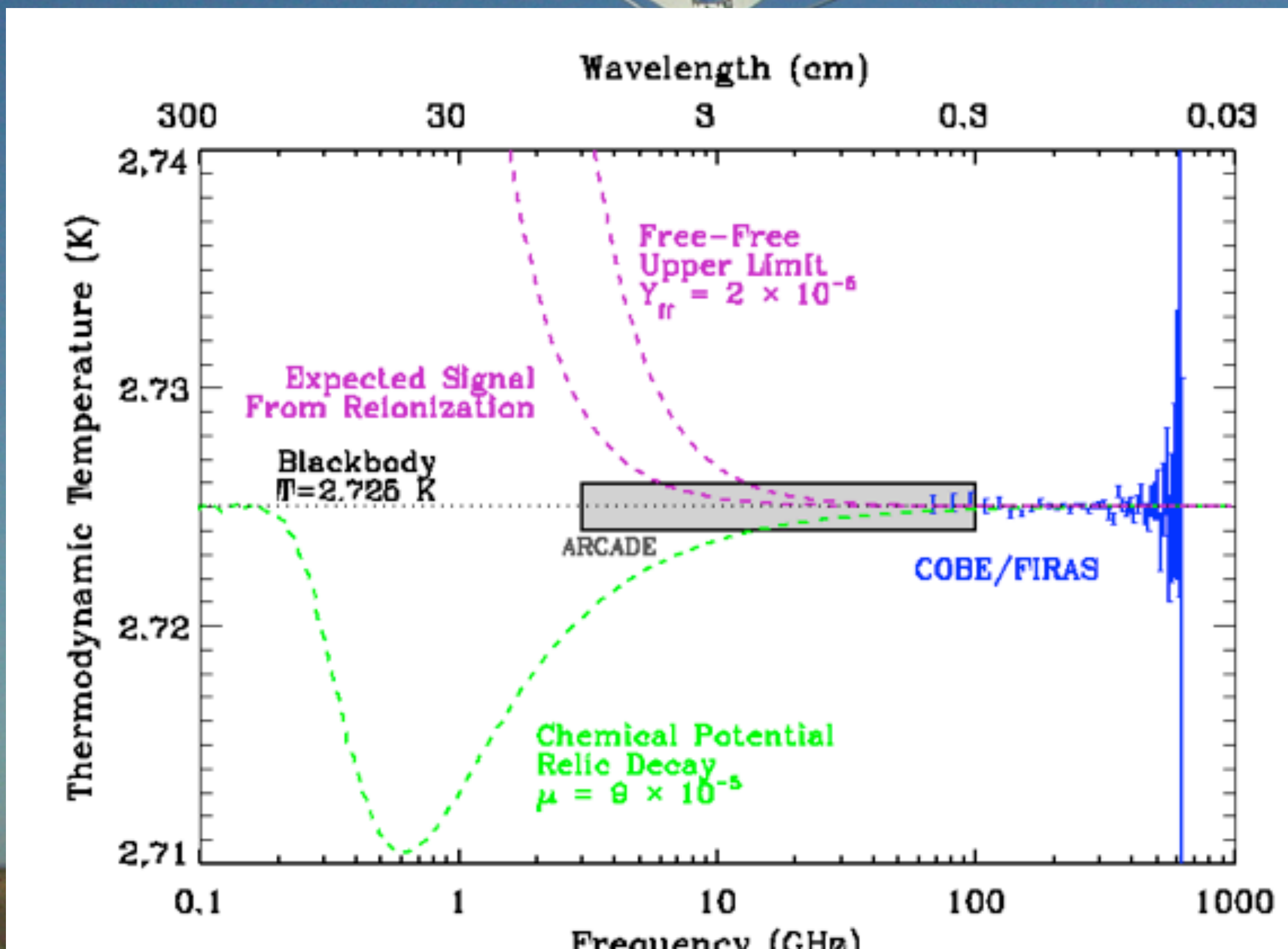
- Balloon experiment flown in Texas
- Several flights (2001, 2003, 2005, 2006)
- Frequencies ν = {3, (5), 8, 10, 30, 90} GHz



Kogut et al. 2006, New Astronomy Rev., 50, 925
Kogut et al., 2011, ApJ, 734, 9
Fixsen et al., 2011, ApJ, 734, 11
Seiffert et al., 2011, ApJ, 734, 8

ARCADE

(Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission)



- Distortion constraints:

  $|\mu| < 6 \times 10^{-4}$

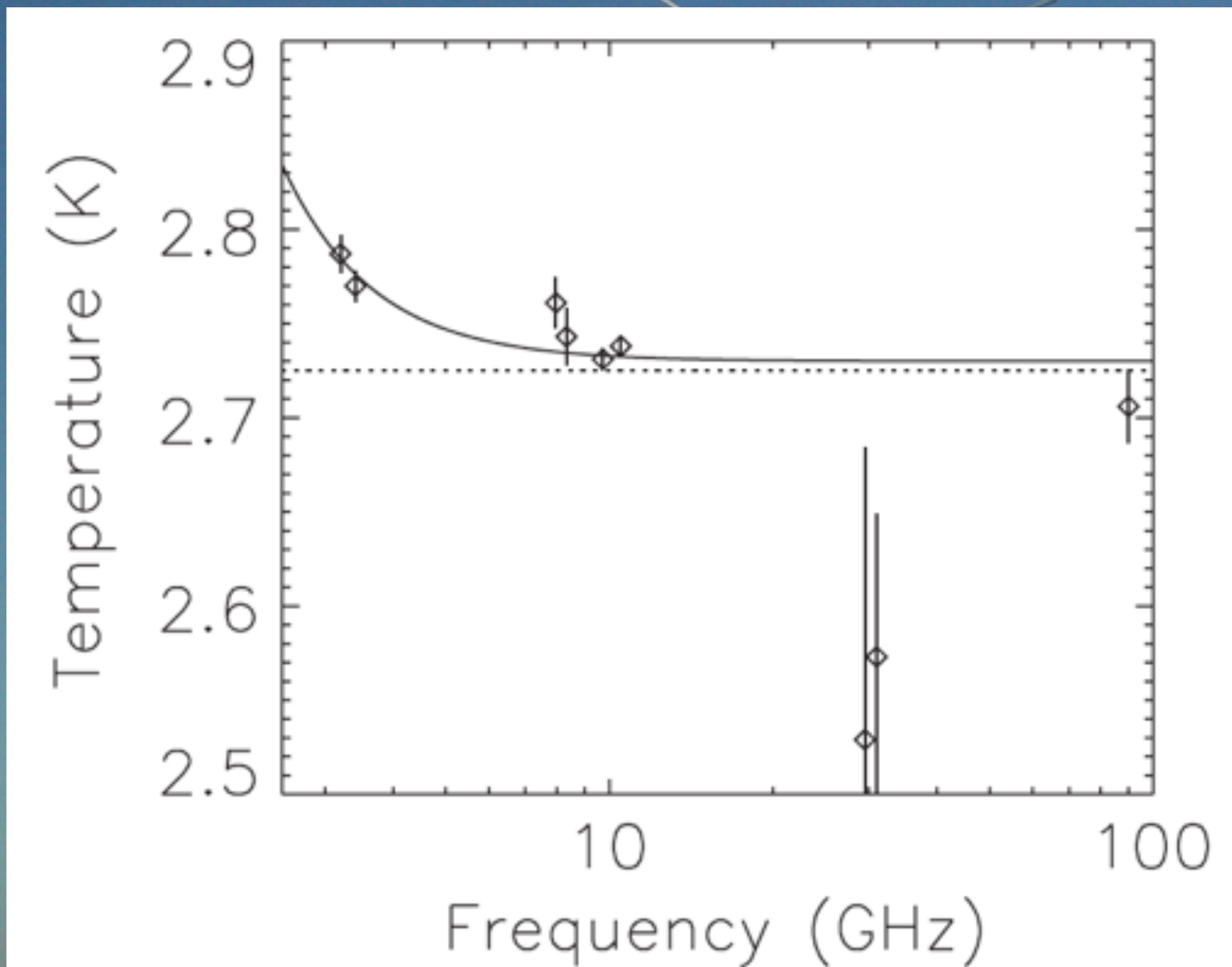
  $|Y_{\rm ff}| < 10^{-4}$

- No limit on y-parameter

Kogut et al. 2006, New Astronomy Rev., 50, 925
Kogut et al., 2011, ApJ, 734, 9
Fixsen et al., 2011, ApJ, 734, 11
Seiffert et al., 2011, ApJ, 734, 8

ARCADE

(Absolute Radiometer for Cosmology, Astrophysics and Diffuse Emission)



- Found some low frequency excess
- Spectrum:

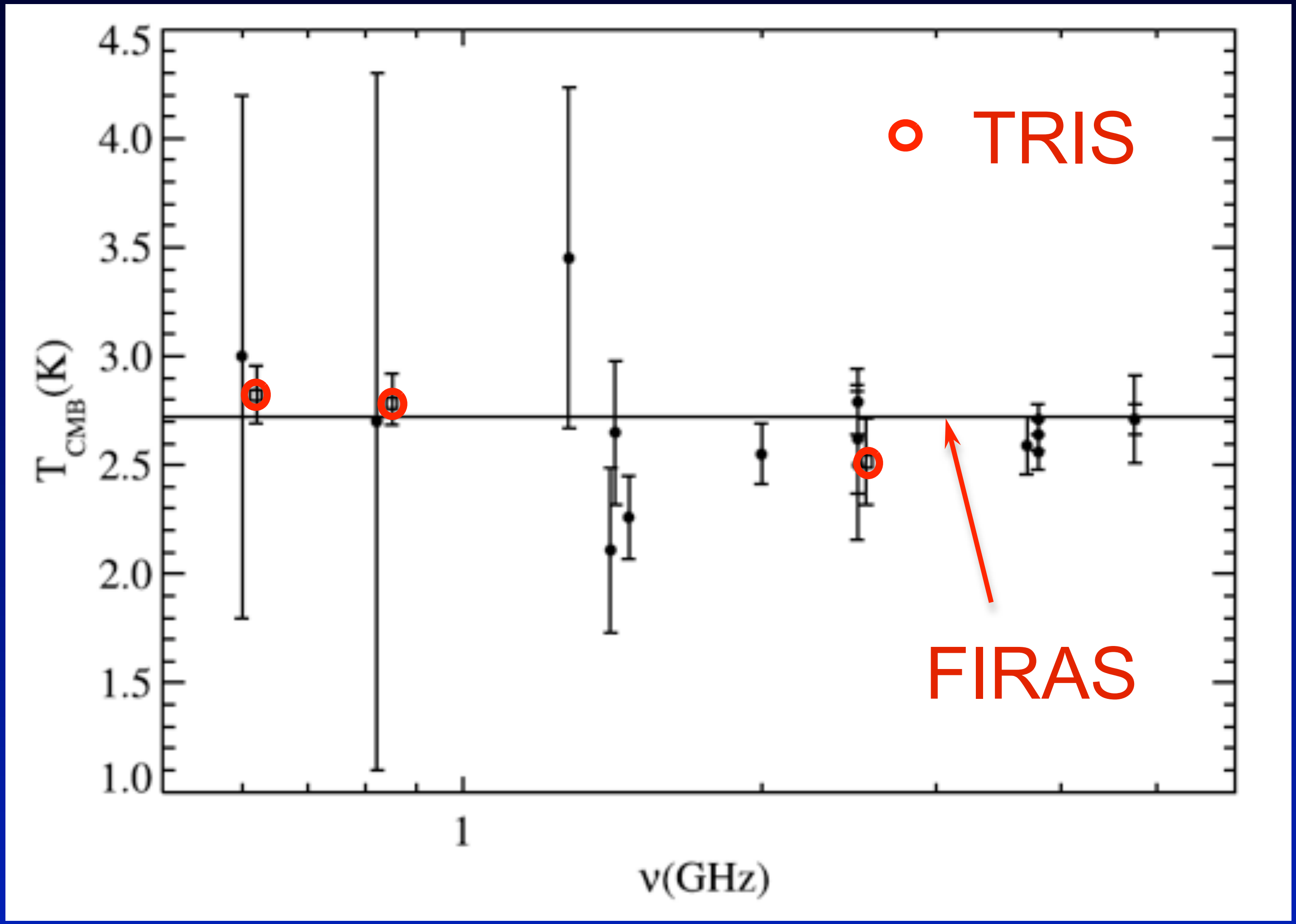
$$T(\nu) = (24.1 \pm 2.1)\mathrm{K}(\nu/\nu_0)^{-2.599\pm0.036}$$

$$\nu_0 = 310\,\mathrm{MHz}$$

- Origin of excess *unclear*
- New population of radio sources?
- Systematic effect?
- In tension with TRIS results? (next slide)

Kogut et al. 2006, New Astronomy Rev., 50, 925
Kogut et al., 2011, ApJ, 734, 9
Fixsen et al., 2011, ApJ, 734, 11
Seiffert et al., 2011, ApJ, 734, 8

TRIS and Other Low Frequency Measurements



- Ground-based radio antenna
- Grand Sasso Lab, Italy
- Frequencies ν = {0.6, 0.82, 2.5} GHz

TABLE 1

A Summary of Low-Frequency CMB Absolute Temperature Measurements Collected Starting from the 1980s

λ (cm)	ν (GHz)	T_{CMB} (K)	References
50.0	0.60	3.0 ± 1.2	1
36.6	0.82	2.7 ± 1.6	2
23.4	1.28	3.45 ± 0.78	3
21.3	1.41	2.11 ± 0.38	4
21.05	1.425	$2.65^{+0.33}_{-0.30}$	5
20.4	1.47	2.26 ± 0.19	6
15.0	2.0	2.55 ± 0.14	7
12.0	2.5	2.62 ± 0.25	8
12.0	2.5	2.79 ± 0.15	9
12.0	2.5	2.50 ± 0.34	2
8.1	3.7	2.59 ± 0.13	10
7.9	3.8	2.56 ± 0.08	11
7.9	3.8	2.71 ± 0.07	11
7.9	3.8	2.64 ± 0.07	12
6.3	4.75	2.71 ± 0.20	13
6.3	4.75	2.70 ± 0.07	14

References.—(1) Sironi et al. 1990; (2) Sironi et al. 1991; (3) Raghunathan & Subrahmanyan 2000; (4) Levin et al. 1988; (5) Staggs et al. 1996; (6) Bensadoun et al. 1993; (7) Bersanelli et al. 1994; (8) Sironi et al. 1984; (9) Sironi & Bonelli 1986; (10) De Amici et al. 1988; (11) De Amici et al. 1990; (12) De Amici et al. 1991; (13) Mandolesi et al. 1984; (14) Mandolesi et al. 1986.

- Distortion constraints:

$$|\mu| < 6 \times 10^{-5}$$ (30% improvement over FIRAS)

$$-6.3 \times 10^{-6} < Y_{\rm ff} < 1.3 \times 10^{-5}$$

- No new limit on y-parameter (too low ν)

Zannoni et al. 2008, ApJ, 688, 12
Gervasi et al., 2008, ApJ, 688, 24
Tartari et al., 2008, ApJ, 688, 32

No primordial distortion found so far!? Why are we at all talking about this then?

Physical mechanisms that lead to spectral distortions

Standard sources of distortions

- *Cooling by adiabatically expanding ordinary matter*
  (JC, 2005; JC & Sunyaev 2011; Khatri, Sunyaev & JC, 2011)
- Heating by *decaying* or *annihilating* relic particles
  (Kawasaki et al., 1987; Hu & Silk, 1993; McDonald et al., 2001; JC, 2005; JC & Sunyaev, 2011; JC, 2013; JC & Jeong, 2013)
- *Evaporation of primordial black holes & superconducting strings*
  (Carr et al. 2010; Ostriker & Thompson, 1987; Tashiro et al. 2012; Pani & Loeb, 2013)
- *Dissipation of primordial acoustic modes & magnetic fields*
  (Sunyaev & Zeldovich, 1970; Daly 1991; Hu et al. 1994; JC & Sunyaev, 2011; JC et al. 2012 - Jedamzik et al. 2000; Kunze & Komatsu, 2013)
- *Cosmological recombination radiation*
  (Zeldovich et al., 1968; Peebles, 1968; Dubrovich, 1977; Rubino-Martin et al., 2006; JC & Sunyaev, 2006; Sunyaev & JC, 2009)

pre-recombination epoch

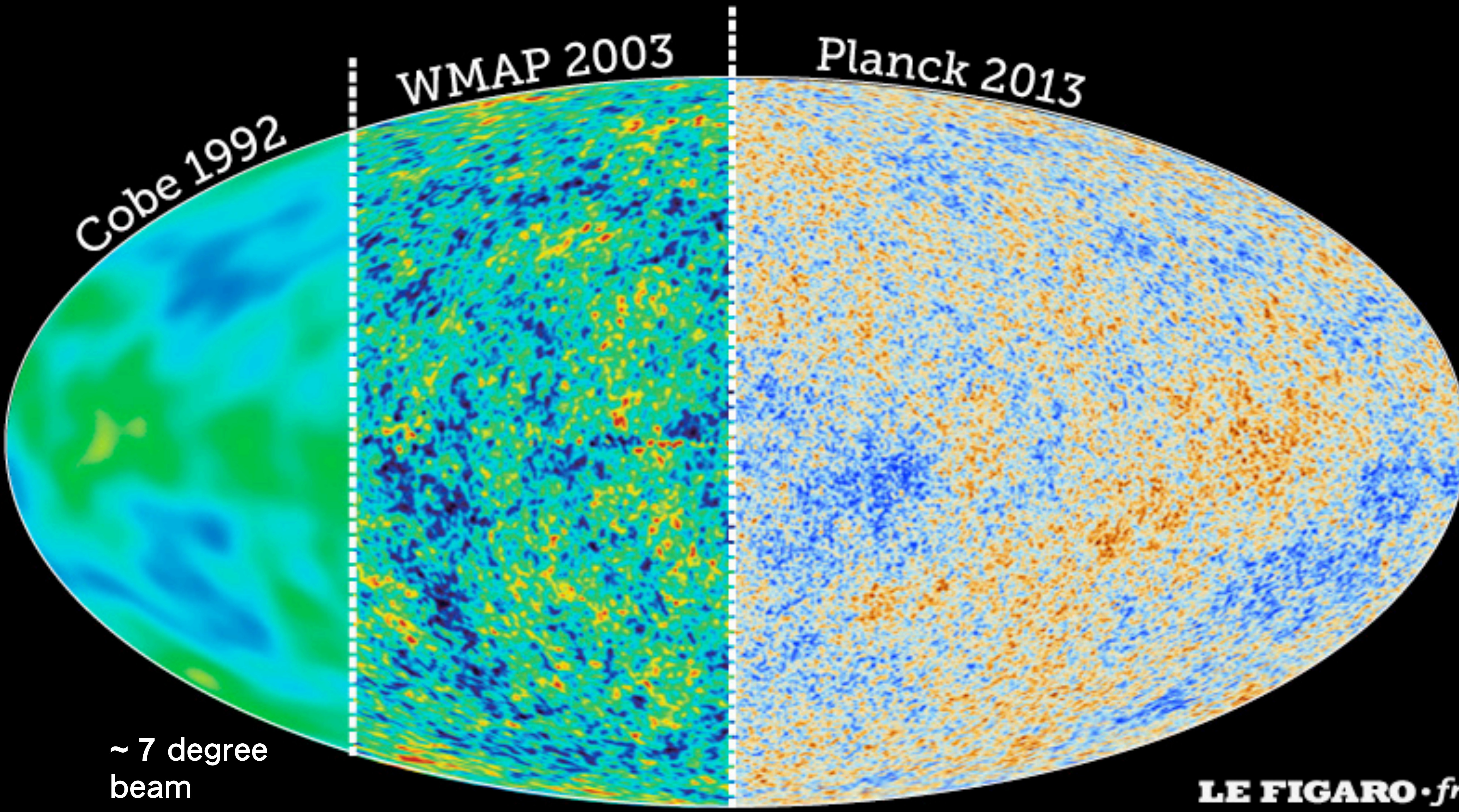
„high“ redshifts

„low“ redshifts

post-recombination

- 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
  (Refregier et al., 2003; Zhang et al. 2004; Trac et al. 2008)
- more exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

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

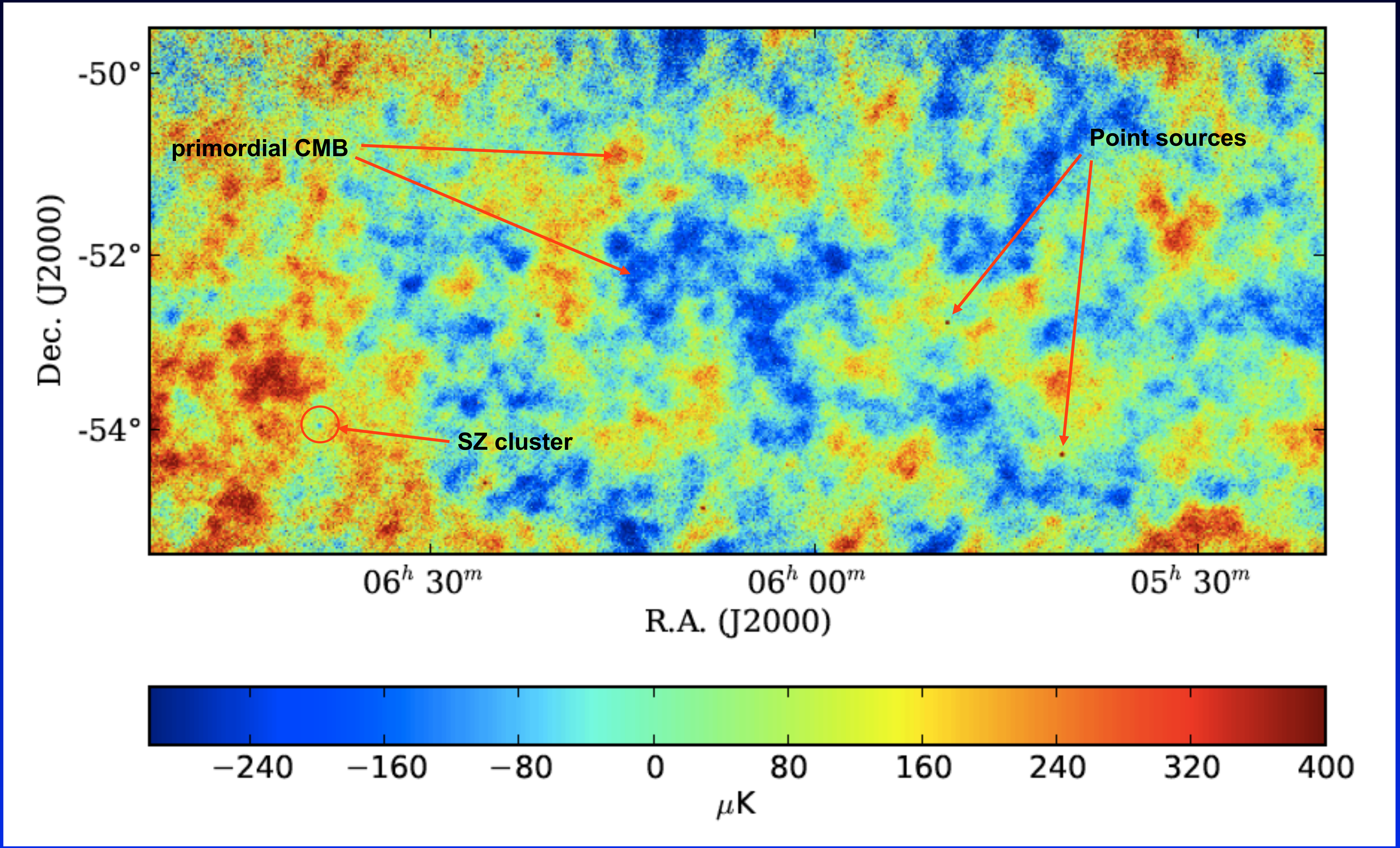


~ 7 degree beam

~ 0.3 degree beam

~ 0.08 degree beam

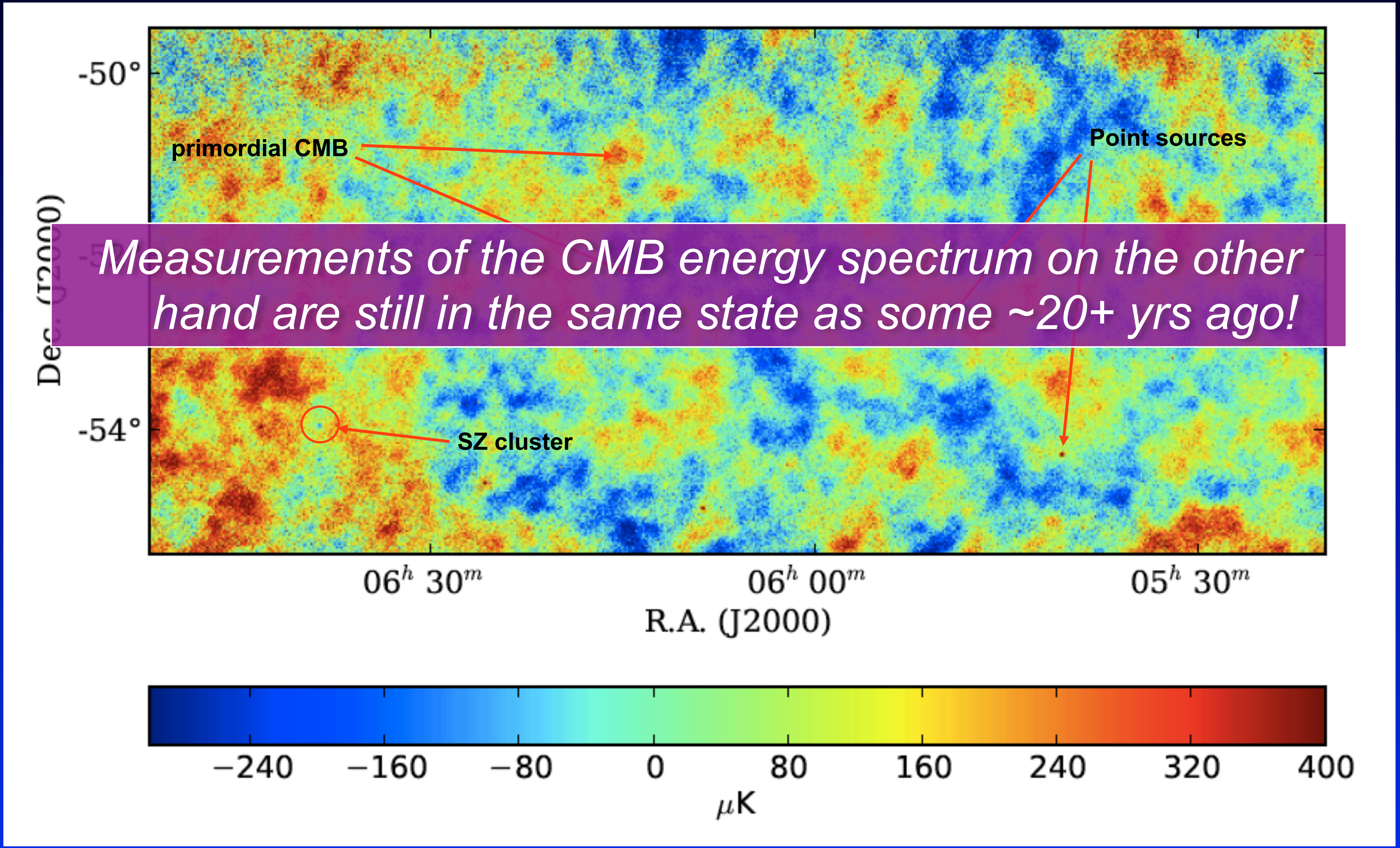
Cosmic Microwave Background Anisotropies with ACT



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

~ **0.02** degree beam!

Cosmic Microwave Background Anisotropies with ACT

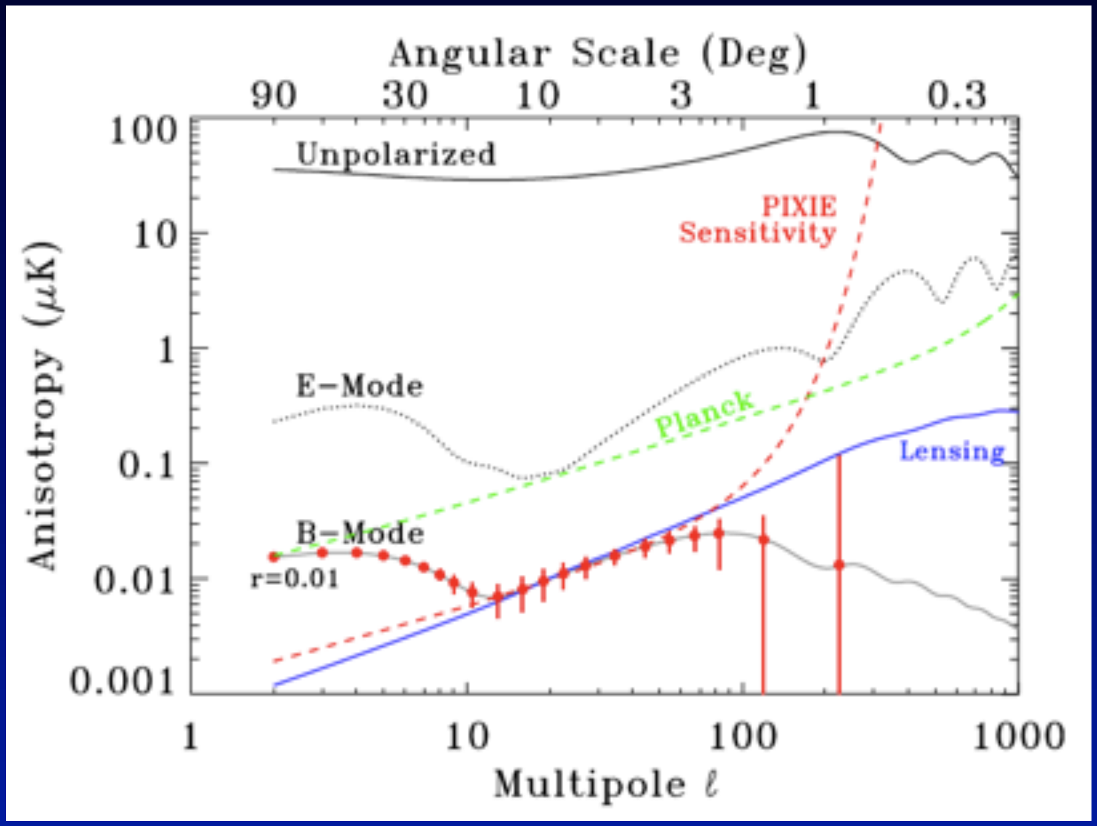


Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ yrs ago!

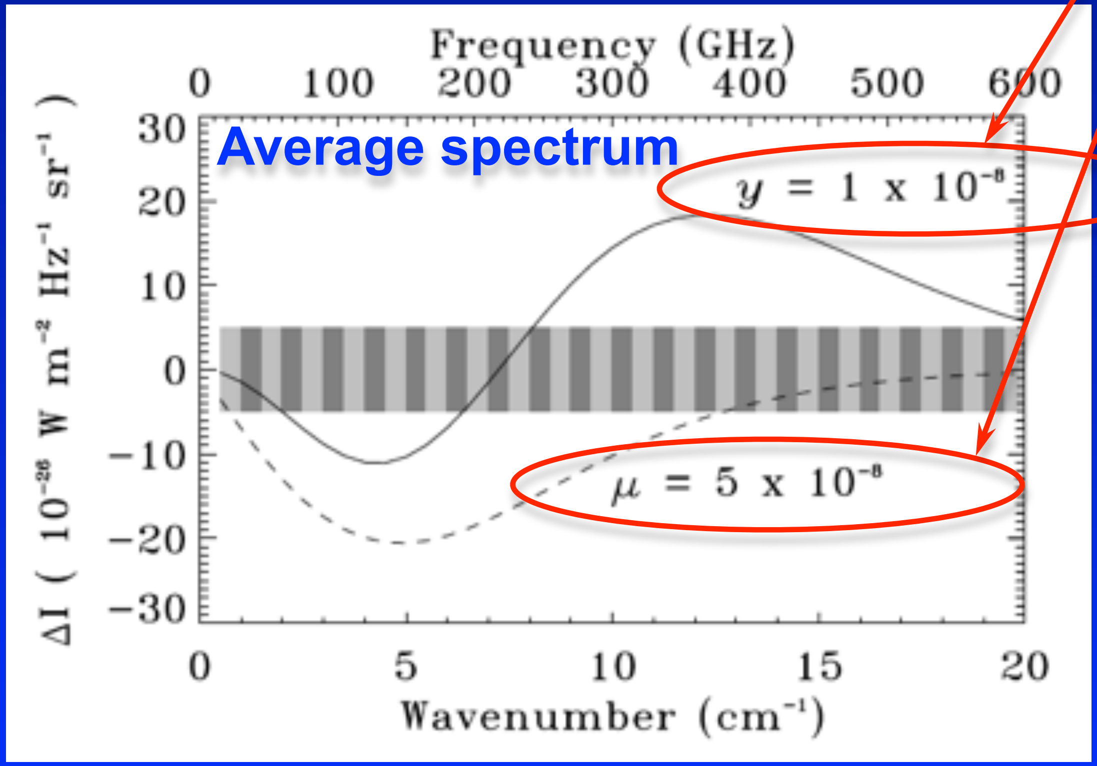
ACT - collaboration, 148 GHz Map, Hajian et al. 2010

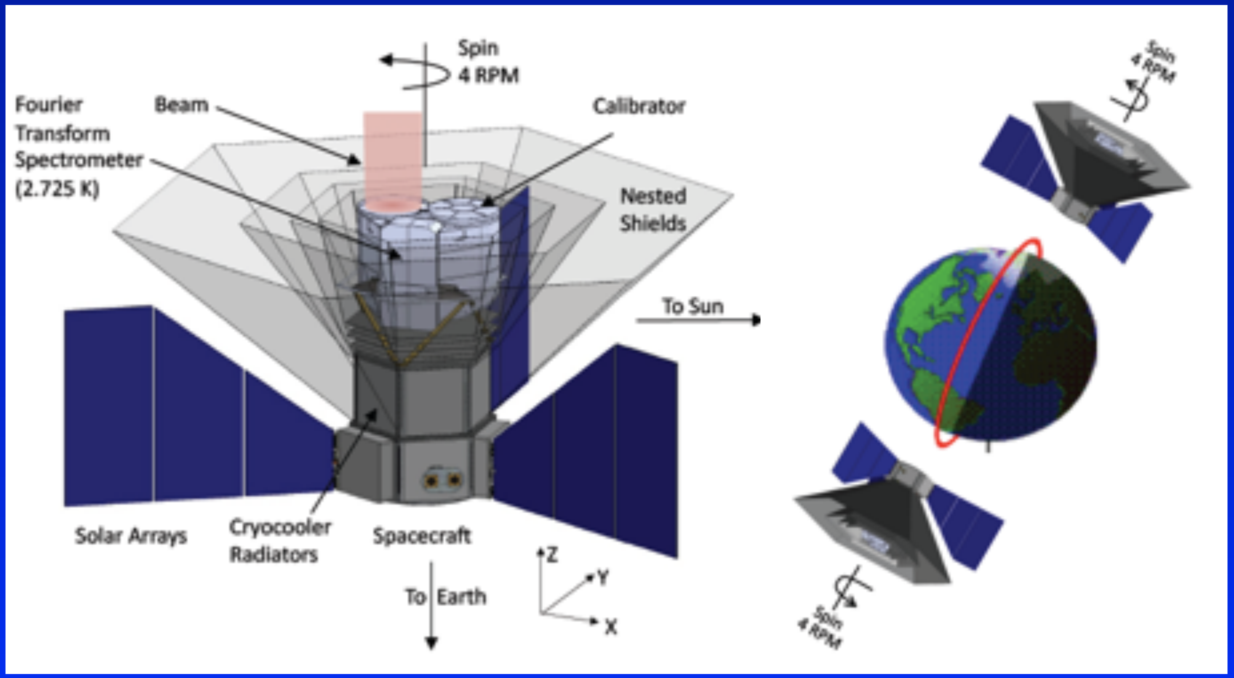
~ 0.02 degree beam!

PIXIE: Primordial Inflation Explorer

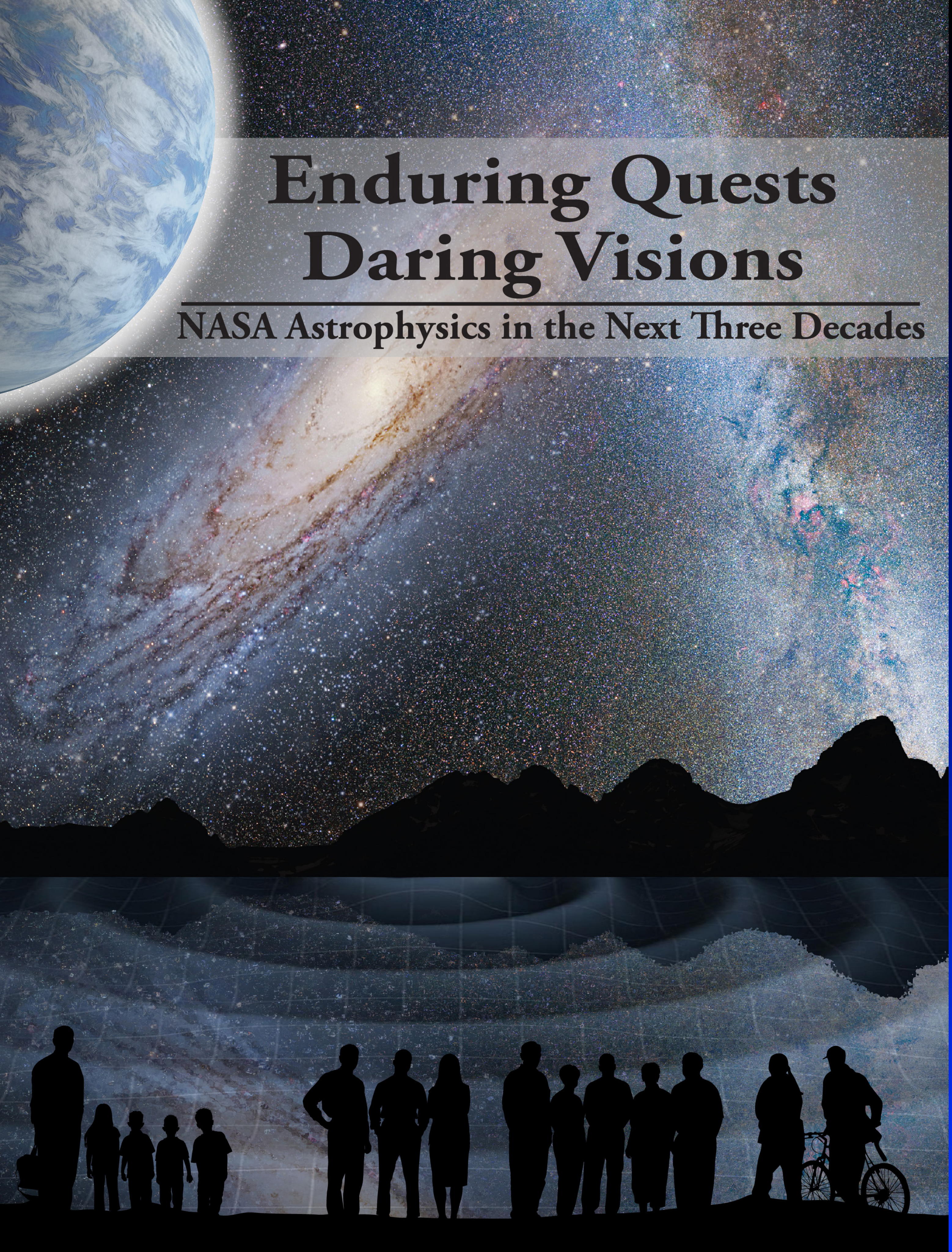


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



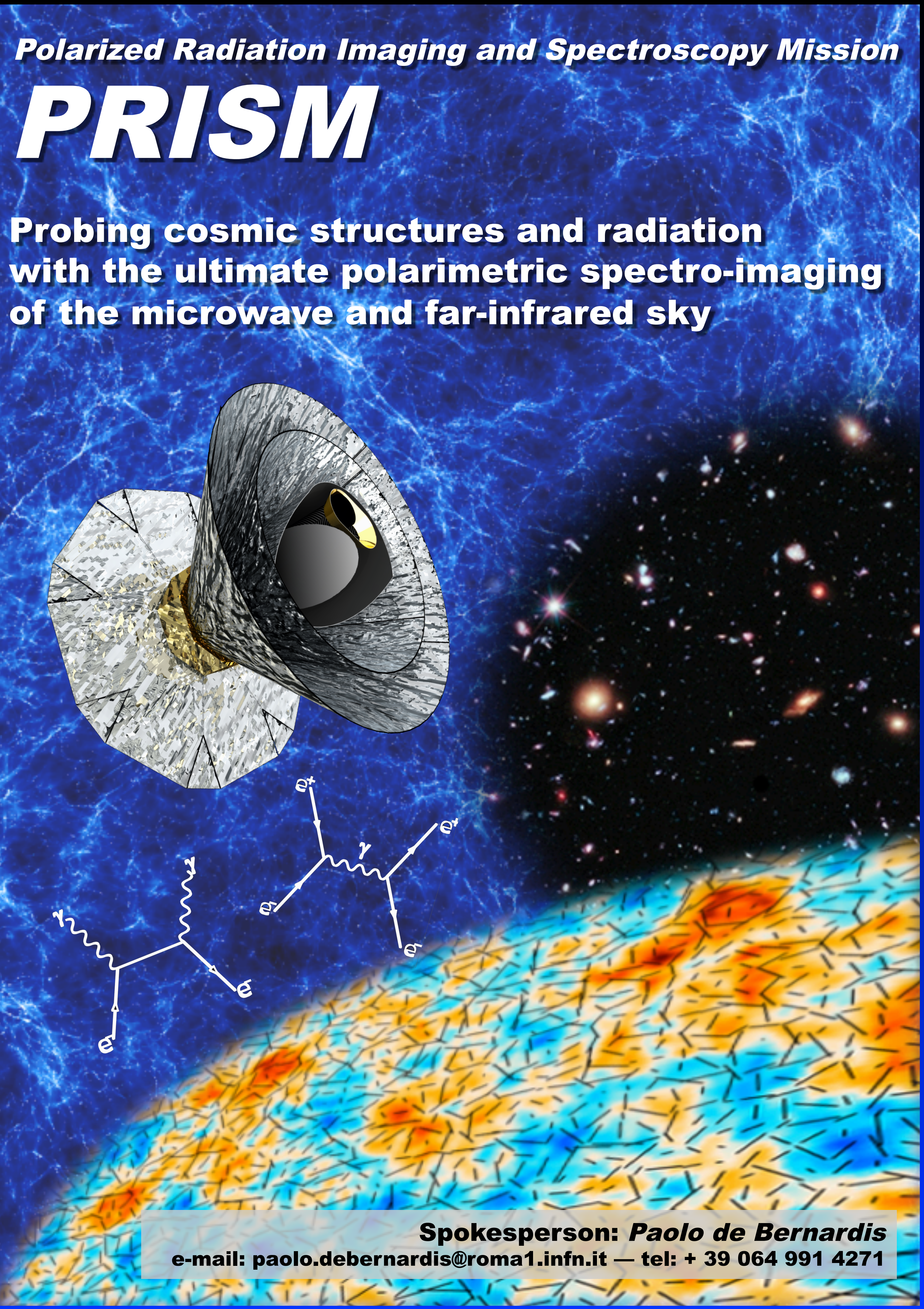
NASA 30-yr Roadmap Study

(published Dec 2013)

How does the Universe work?

"Measure the spectrum of the CMB with precision several orders of magnitude higher than COBE FIRAS, from a moderate-scale mission or an instrument on CMB Polarization Surveyor."

New call from NASA expected ~2-3 years from now



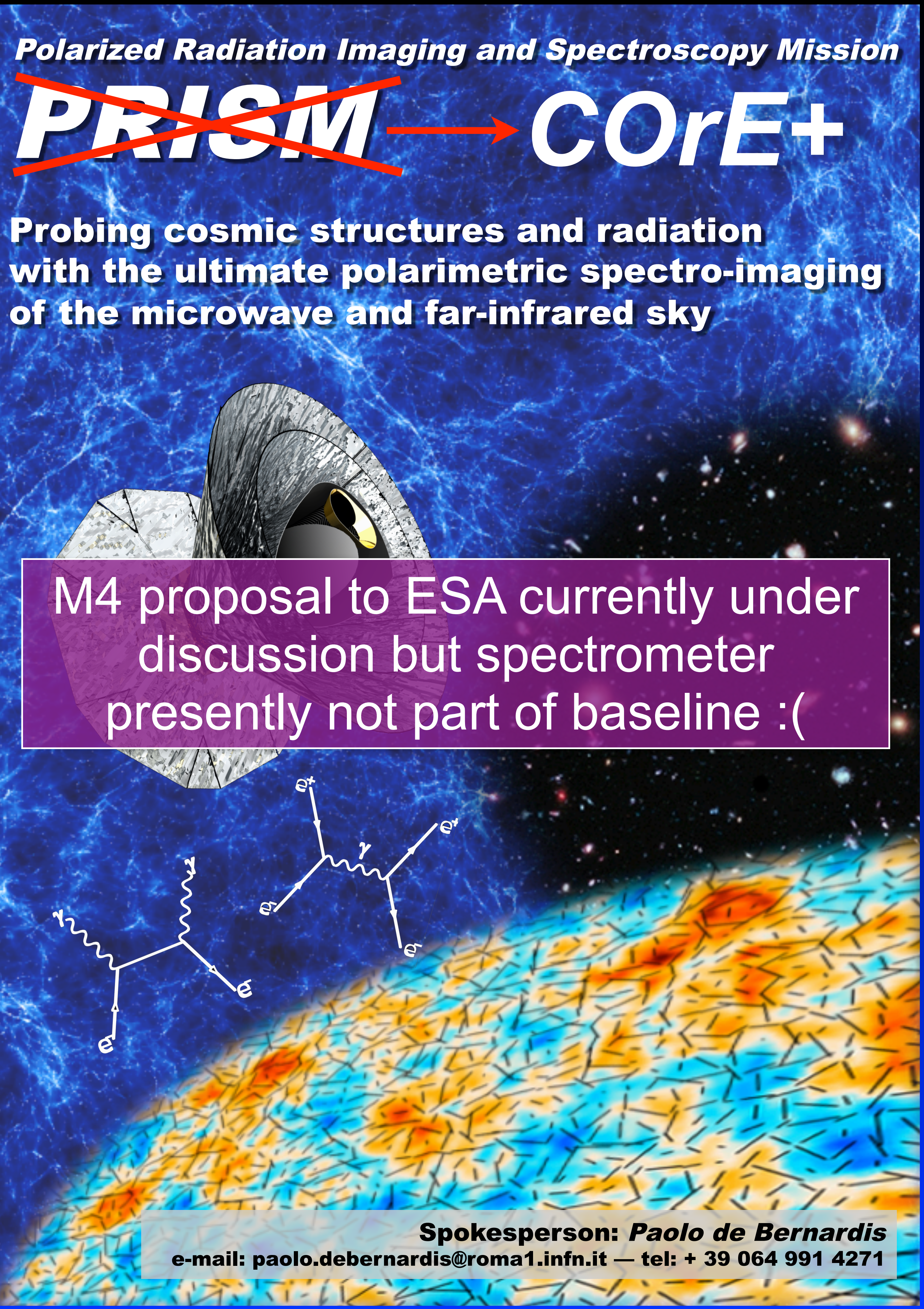
Instruments:

- L-class ESA mission
- White paper, May 24th, 2013
- Imager:
  - polarization sensitive
  - 3.5m telescope [arcmin resolution at highest frequencies]
  - 30GHz-6THz [30 broad (Δv/v~25%) and 300 narrow (Δv/v~2.5%) bands]
- Spectrometer:
  - FTS similar to PIXIE
  - 30GHz-6THz (Δv~15 & 0.5 GHz)

Some of the science goals:

- B-mode polarization from inflation ($r \approx 5 \times 10^{-4}$)
- count all SZ clusters $>10^{14}$ M_{sun}
- CIB/large scale structure
- Galactic science
- *CMB spectral distortions*

More info at:
http://www.prism-mission.org/



M4 proposal to ESA currently under discussion but spectrometer presently not part of baseline :(

Instruments:

- L-class ESA mission
- White paper, May 24th, 2013
- Imager:
  - polarization sensitive
  - 3.5m telescope [arcmin resolution at highest frequencies]
  - 30GHz-6THz [30 broad ($\Delta\nu/\nu \sim 25\%$) and 300 narrow ($\Delta\nu/\nu \sim 2.5\%$) bands]
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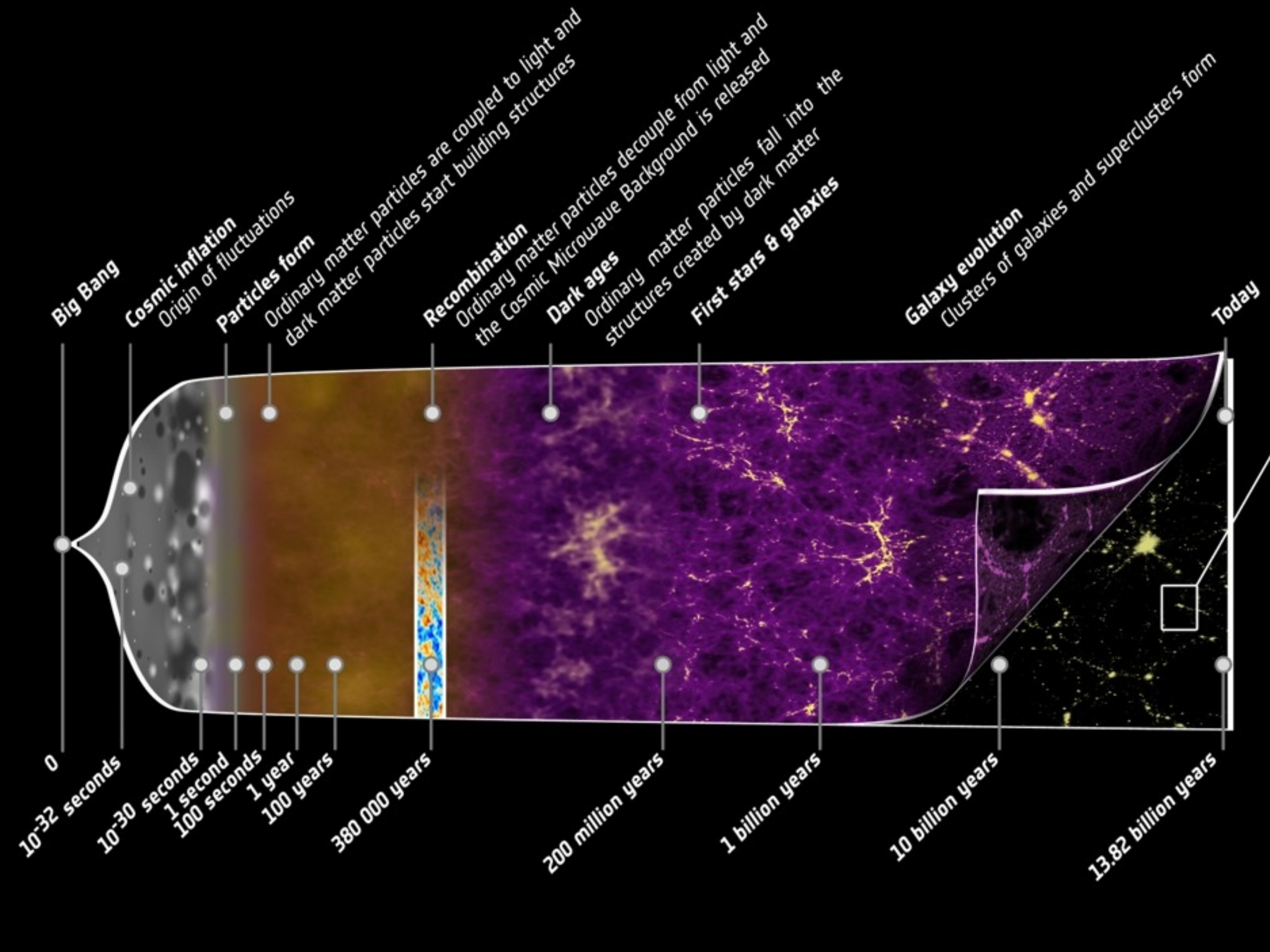
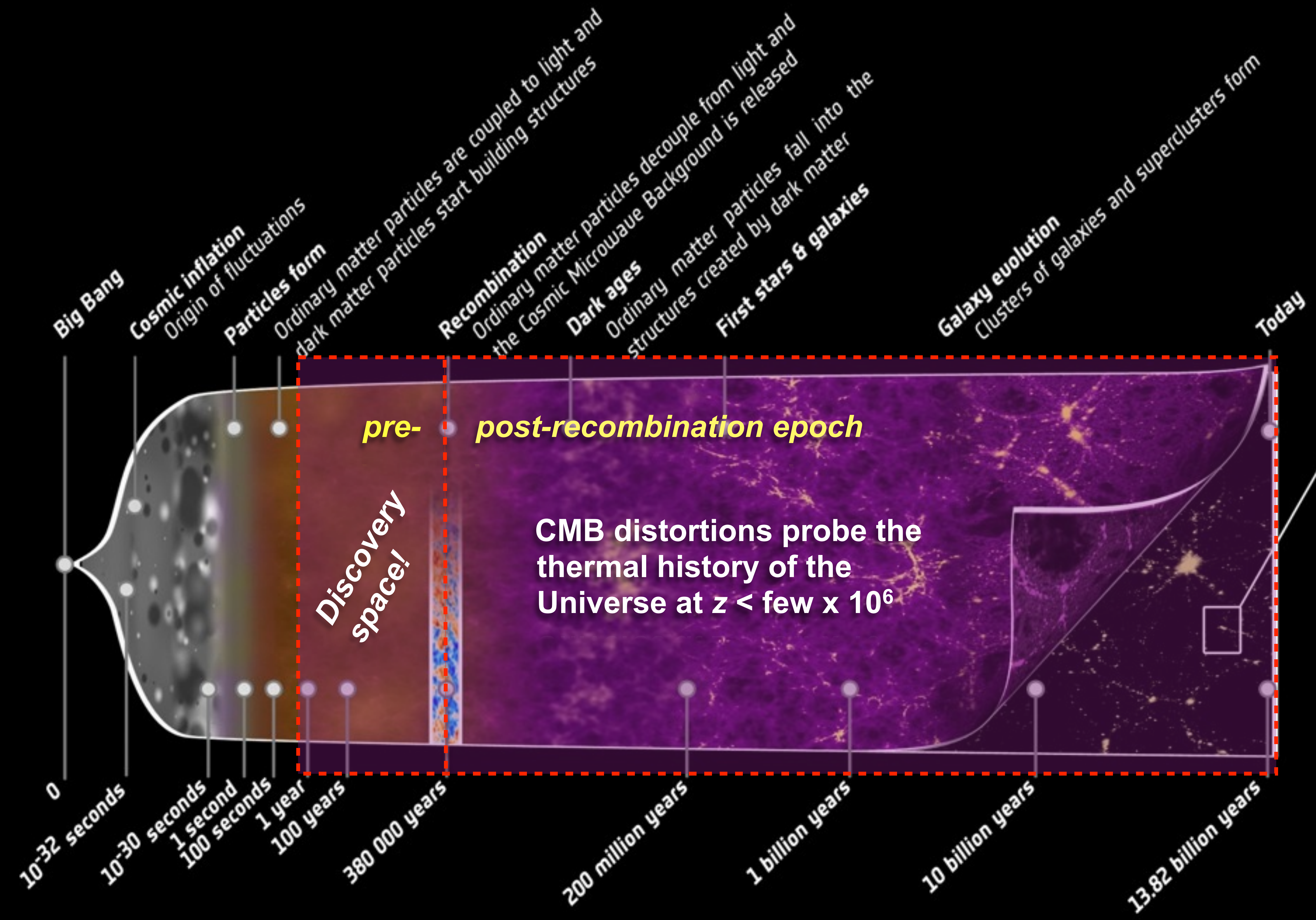


Big Bang
Cosmic inflation
Origin of fluctuations
Particles form
Ordinary matter particles are coupled to light and dark matter particles start building structures
Recombination
Ordinary matter particles decouple from light and the Cosmic Microwave Background is released
Dark ages
Ordinary matter particles 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



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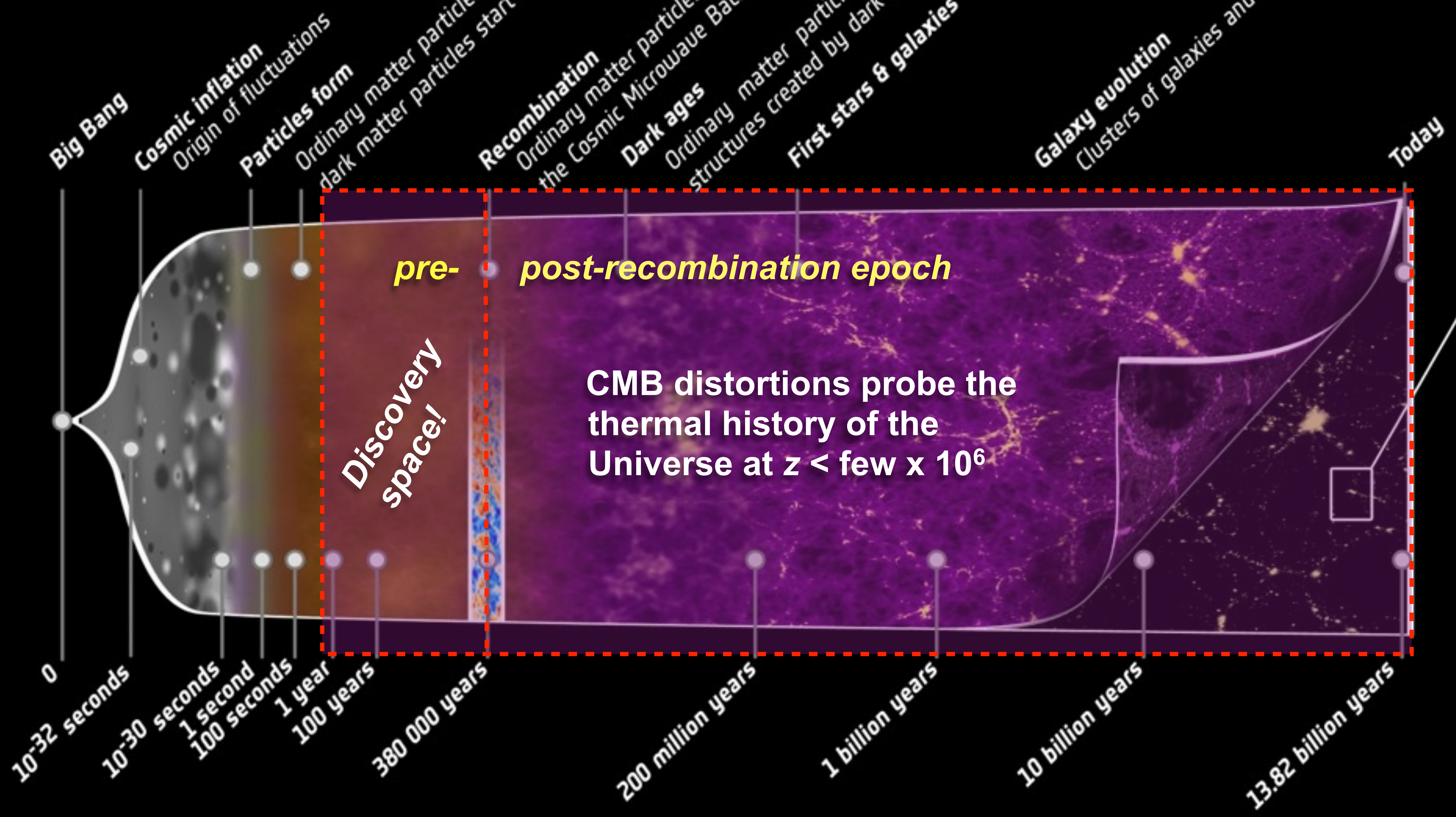
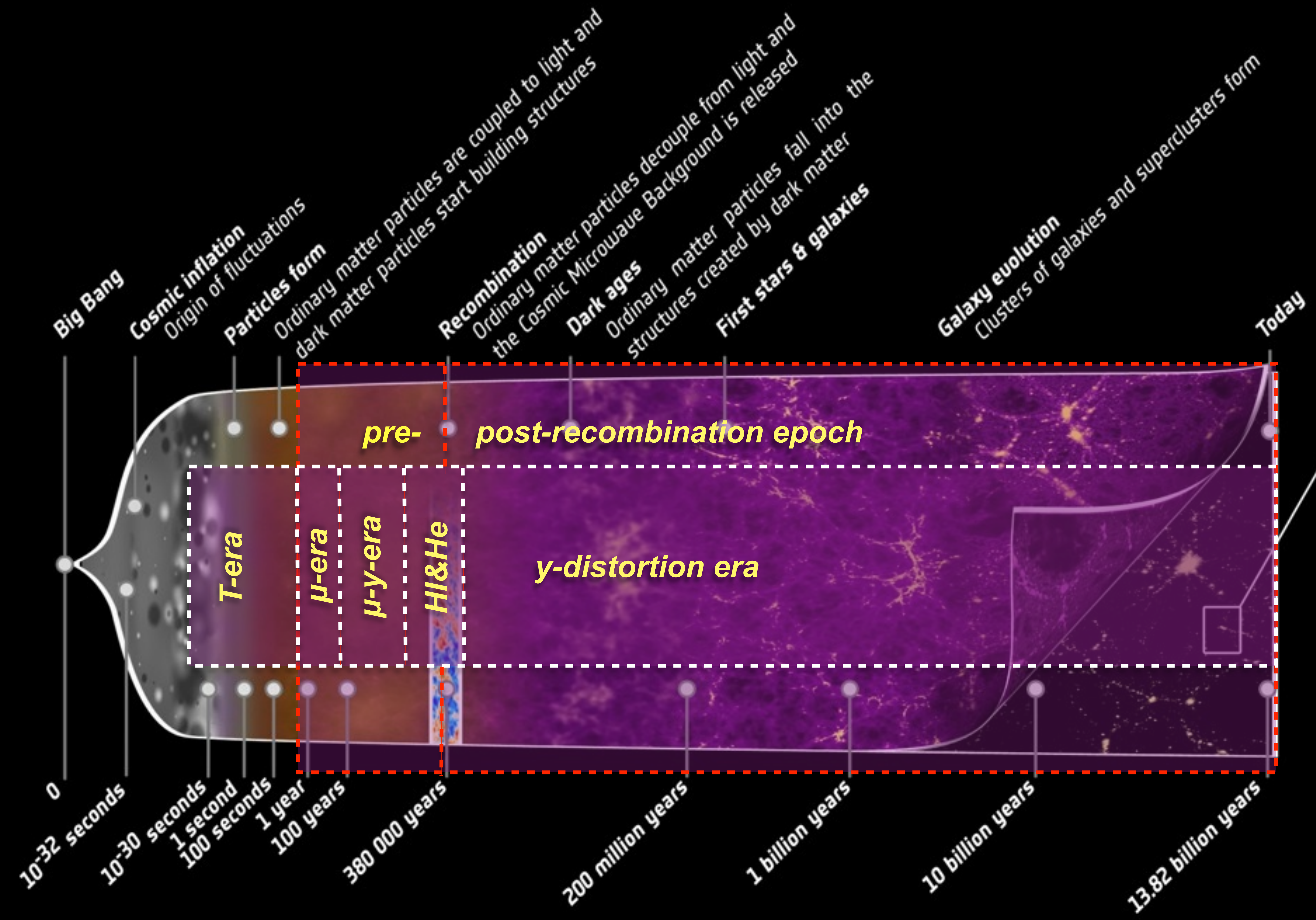
Ordinary matter particles fall into the structures created by dark matter
First stars & galaxies
Galaxy evolution
Clusters of galaxies and superclusters form
Today
pre-
post-recombination epoch
Discovery space!
CMB distortions probe the thermal history of the Universe at z < few x 10^6
0
10-32 seconds
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

Measurements of CMB spectrum will open a new unexplored window to the early Universe!





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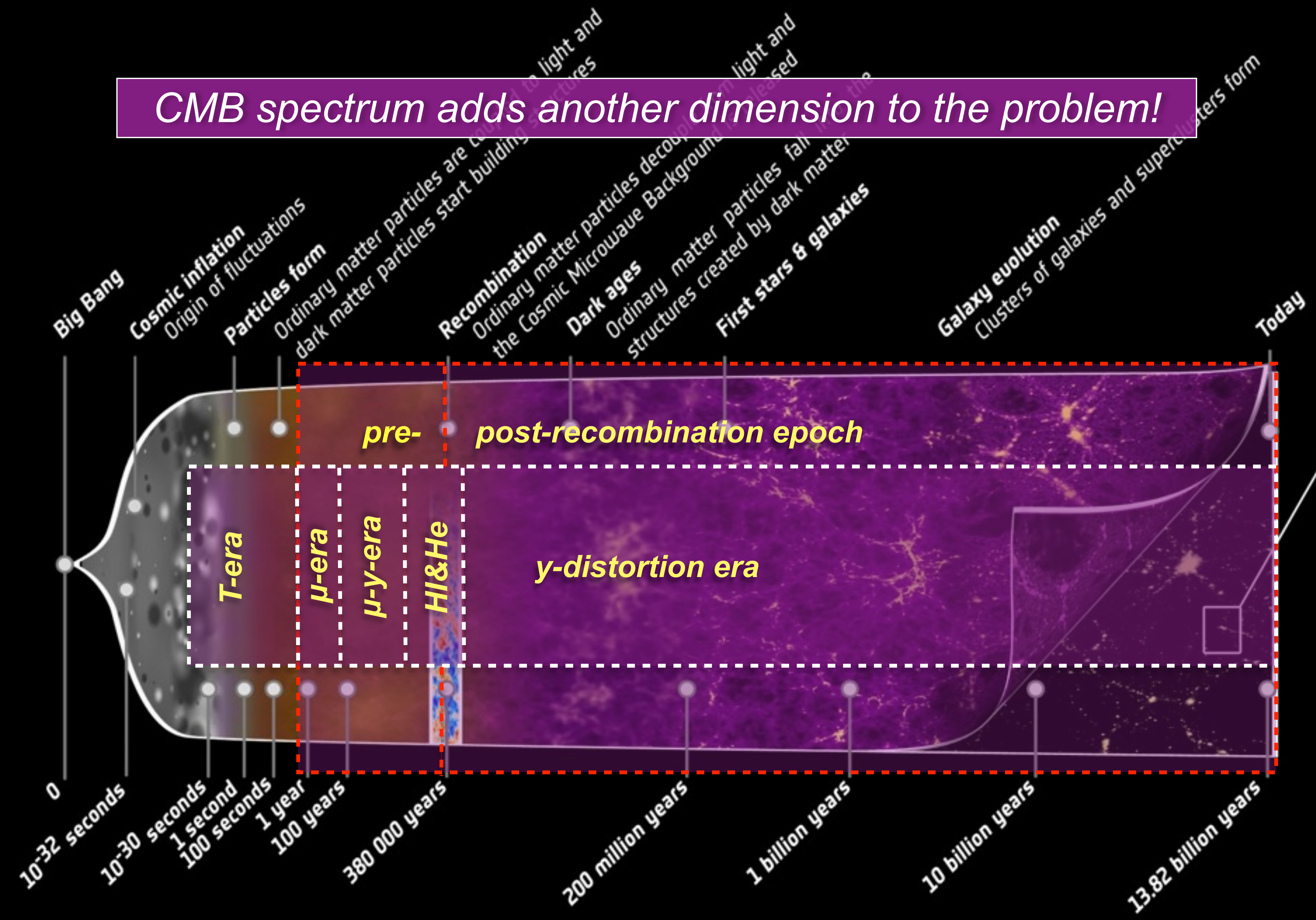
post-recombination epoch
T-era
μ-era
μ-y-era
HI&He
y-distortion era
0
10-32 seconds
10-30 seconds
1 second
100 seconds
1 year
100 years
380 000 years
200 million years
1 billion years
10 billion years
13.82 billion years

CMB spectrum adds another dimension to the problem!



Simple blackbody radiation warm-ups

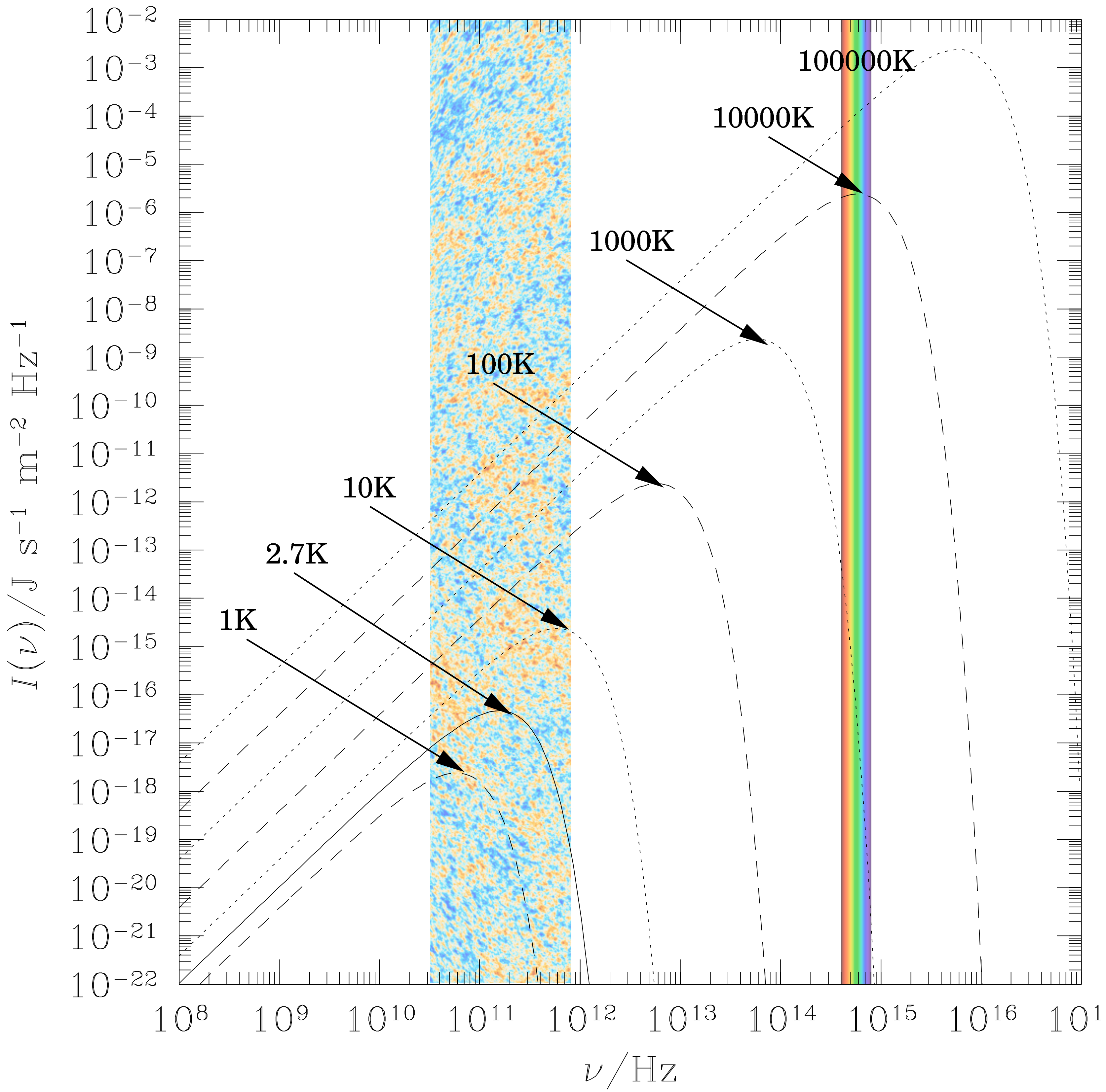


Figure 2.2: Blackbody spectrum for different temperatures. The intensity maximum is roughly at $\nu_{\max} \approx 58.8\,\mathrm{GHz\,K^{-1}}\,T$, which for the CMB blackbody today is $\nu_{\max} \simeq 160\,\mathrm{GHz}$ or at 2 mm wavelength. For $T \simeq 10^4\,\mathrm{K}$ the intensity maximum is in the visible part of the electromagnetic spectrum.

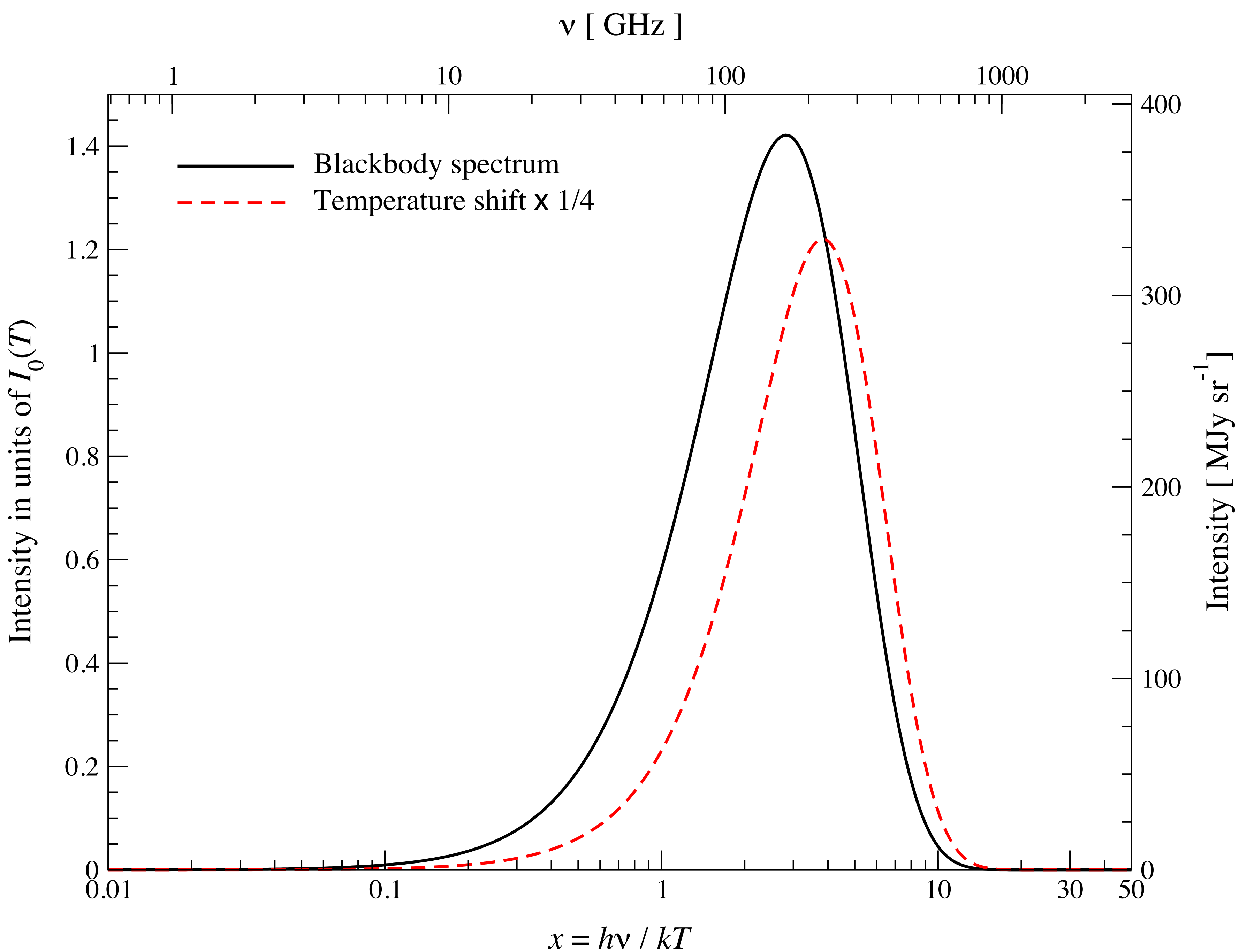


Figure 2.3: Blackbody spectrum and the spectrum of a temperature shift, $T\partial_T B_\nu = I_0(T)\, x^3 G(x) = -I_0(T)\, x^4 \partial_x n_{\rm Pl}(x)$. For convenience, we plot the spectrum as a function of $x = h\nu/kT$ and normalize the left y-axis by $I_0(T) = (2h/c^2)(kT/h)^3 \approx 270\,\text{MJy sr}^{-1}(T/2.725\text{K})^3$ [the shown curves are basically $x^3/(\mathrm{e}^x - 1)$ and $x^3 G(x)$]. The maximum of the blackbody is at $x \approx 2.821\,(\equiv 160\text{GHz})$, while the maximum of the temperature shift is at $x \simeq 3.830\,(\equiv 217\text{GHz})$. The upper x-axis and right y-axis also gives the corresponding frequency and spectral intensity for $T = 2.725\,\text{K}$.

Formulation of the thermalization problem

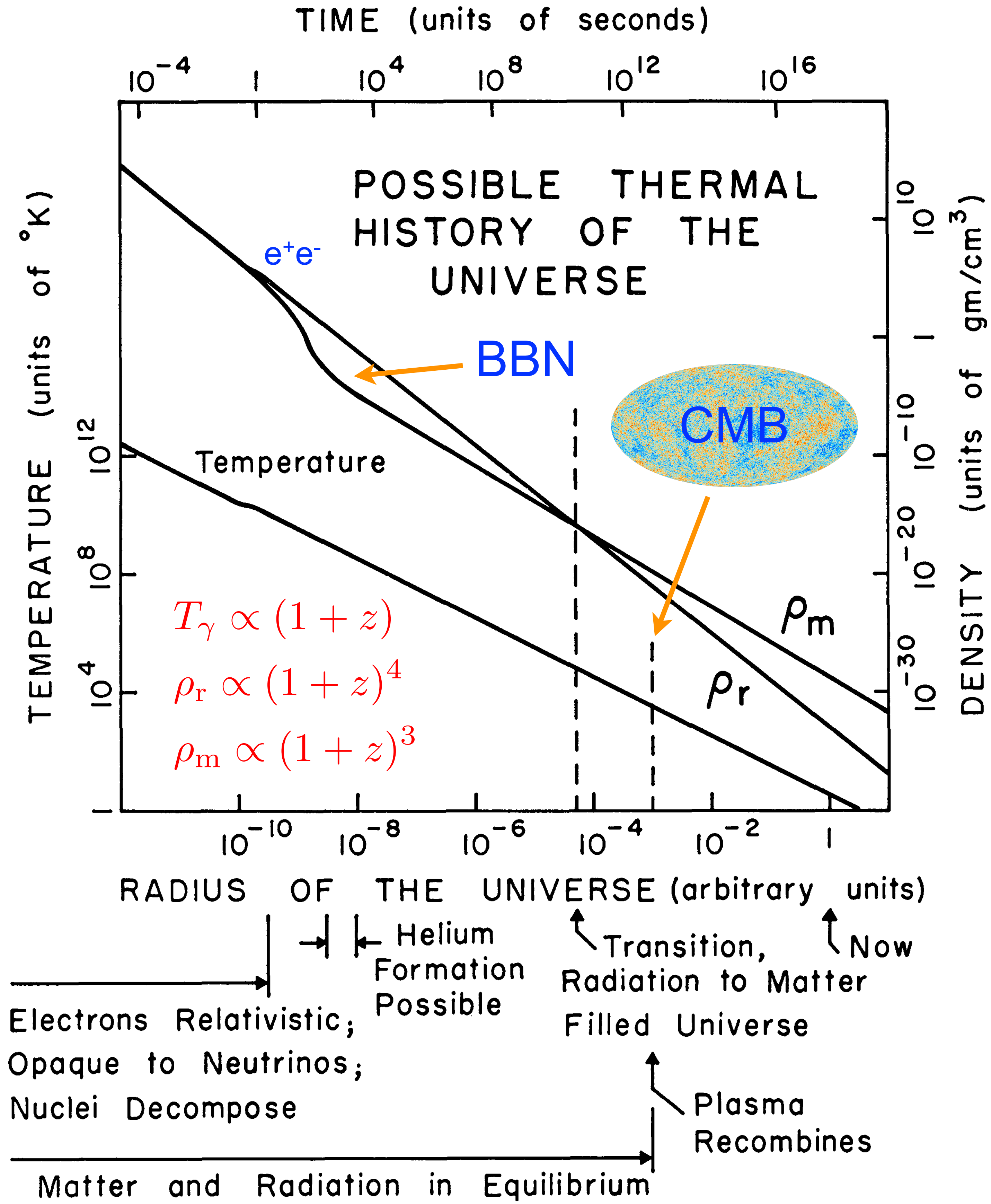
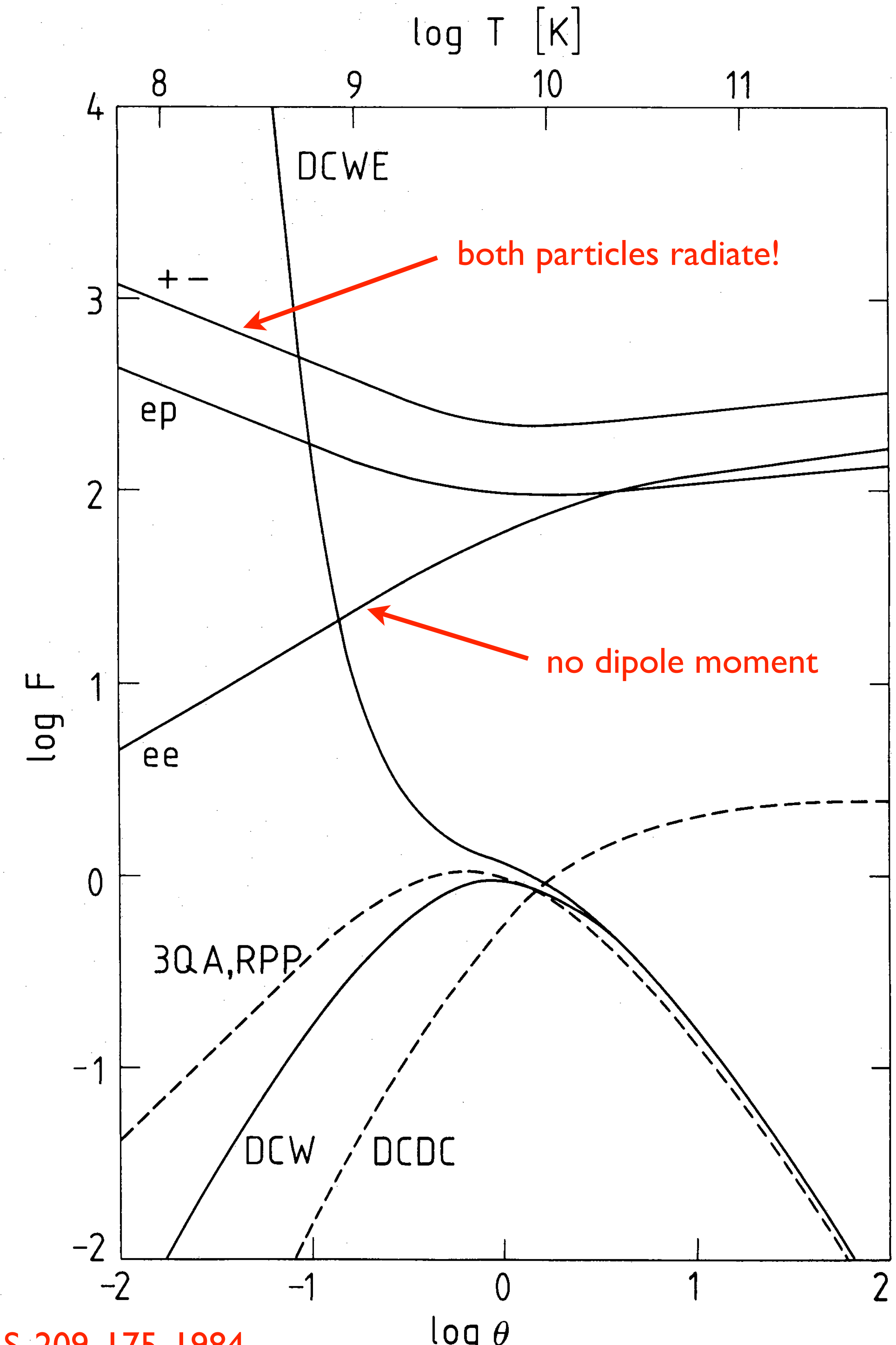
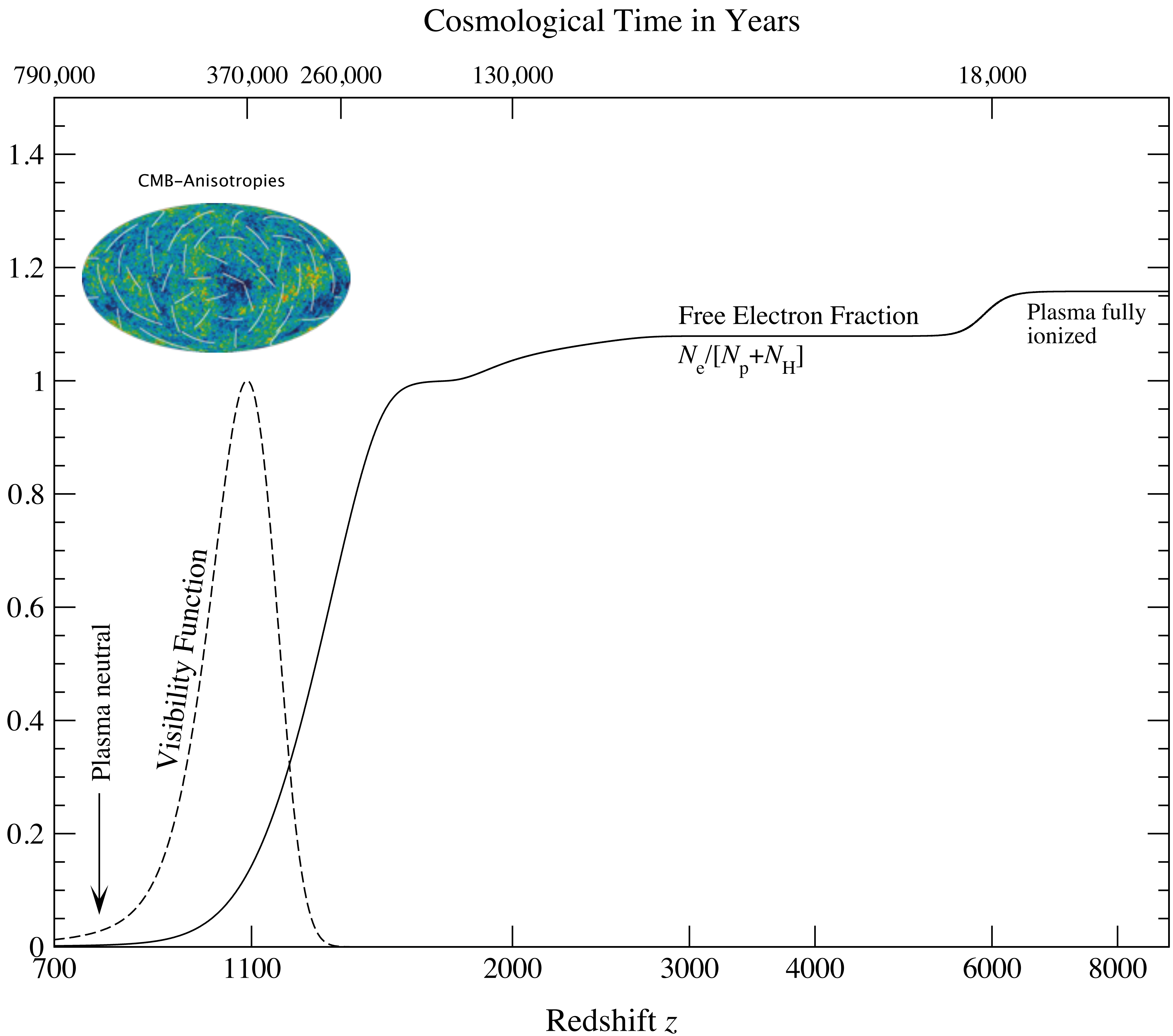


Figure 3.1: Sketch of the thermal history of our Universe from the paper of Dicke et al. [14], published in the same issue with the CMB discovery paper of Penzias & Wilson [30] in 1965. Parts of this picture were already worked out by Gamow, Alpher and Herman years earlier, but the value of $T_0 \simeq 3.5$ K fixed the energy scale for radiation. Neutrinos decoupled at a temperature $kT_\gamma \simeq 1.5$ MeV $-$ 2 MeV, while electron-positron annihilation finished around $kT_\gamma \simeq 0.5$ MeV. The light elements produced in the Big Bang Nucleosynthesis (BBN) era froze out at $kT_\gamma \lesssim 0.1$ MeV.



Svensson, MNRAS, 209, 175, 1984

The dimensionless emissivity $F(x=10^{-6}, \theta) \equiv \dot{n}(x, \theta)\, x/(n_1 n_2 c r_e^2 \alpha)$ in the soft photon limit ($x \ll \theta$). The process and $n_1 n_2$ for each curve are +−: e^+e^- bremsstrahlung, $n_+ n_-$; ep: ep bremsstrahlung, $(n_+ + n_-)n_p$; ee: $e^\pm e^\pm$ bremsstrahlung, $n_+^2 + n_-^2$; DCW: double Compton from a Wien distribution, $n_\gamma(n_+ + n_-)$; DCDC: double Compton from a double Compton distribution, $N_\gamma(n_+ + n_-)$; DCWE: double Compton in pair-dominated Wien equilibrium, n_+^2; 3QA: three quantum annihilation, $n_+ n_-$; RPP: radiative pair production in Wien equilibrium, $n_+ n_-$, respectively. $F(x, \theta)$ depends on x (logarithmically) for bremsstrahlung only. See Appendix A for definition of N_γ and further details.



Cosmological Time in Years
790,000
370,000
260,000
130,000
18,000
1.4
1.2
1
0.8
0.6
0.4
0.2
0
CMB-Anisotropies
Free Electron Fraction
$N_e/[N_p+N_H]$
Plasma fully ionized
Visibility Function
Plasma neutral
700
1100
2000
3000
4000
6000
8000
Redshift z

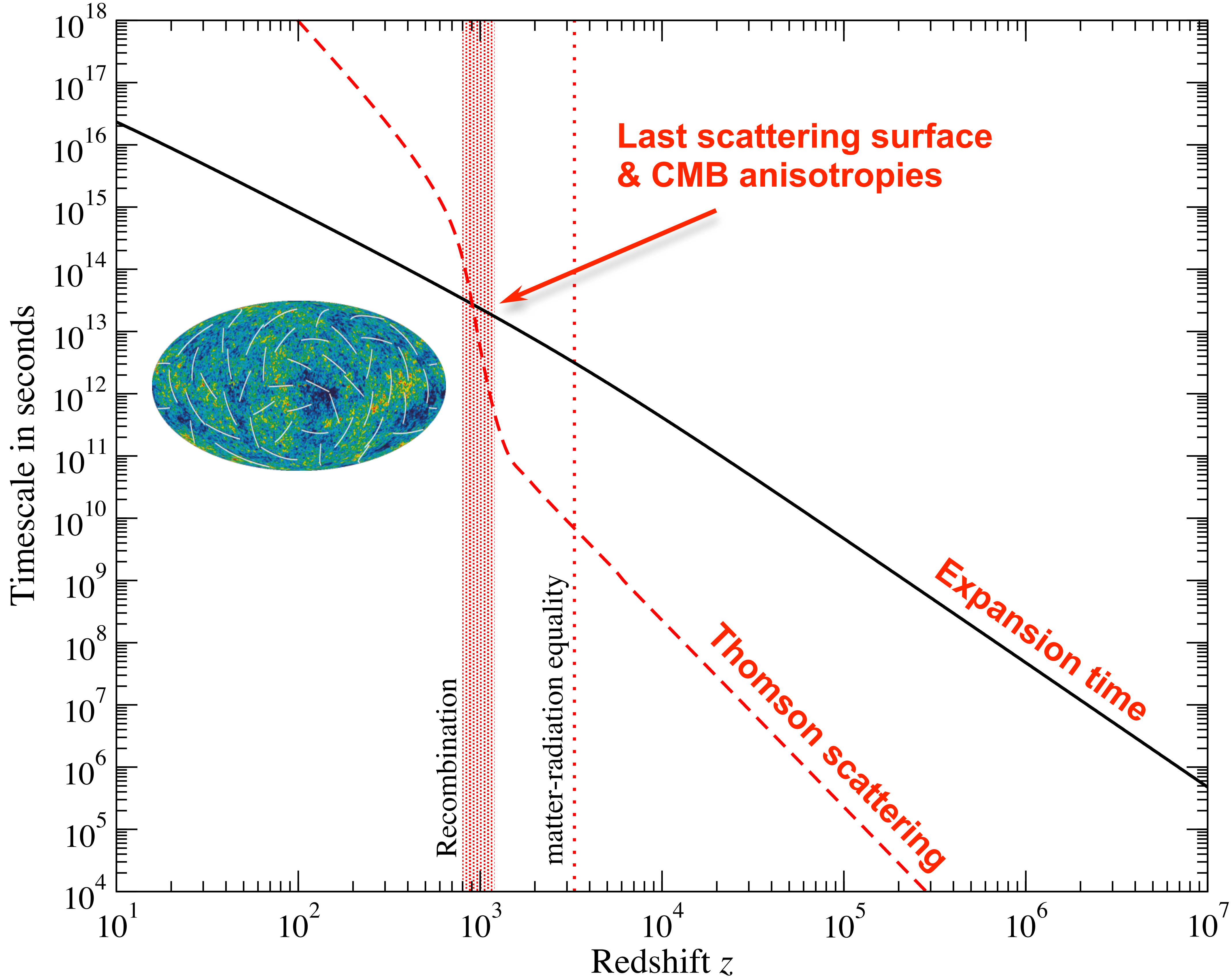
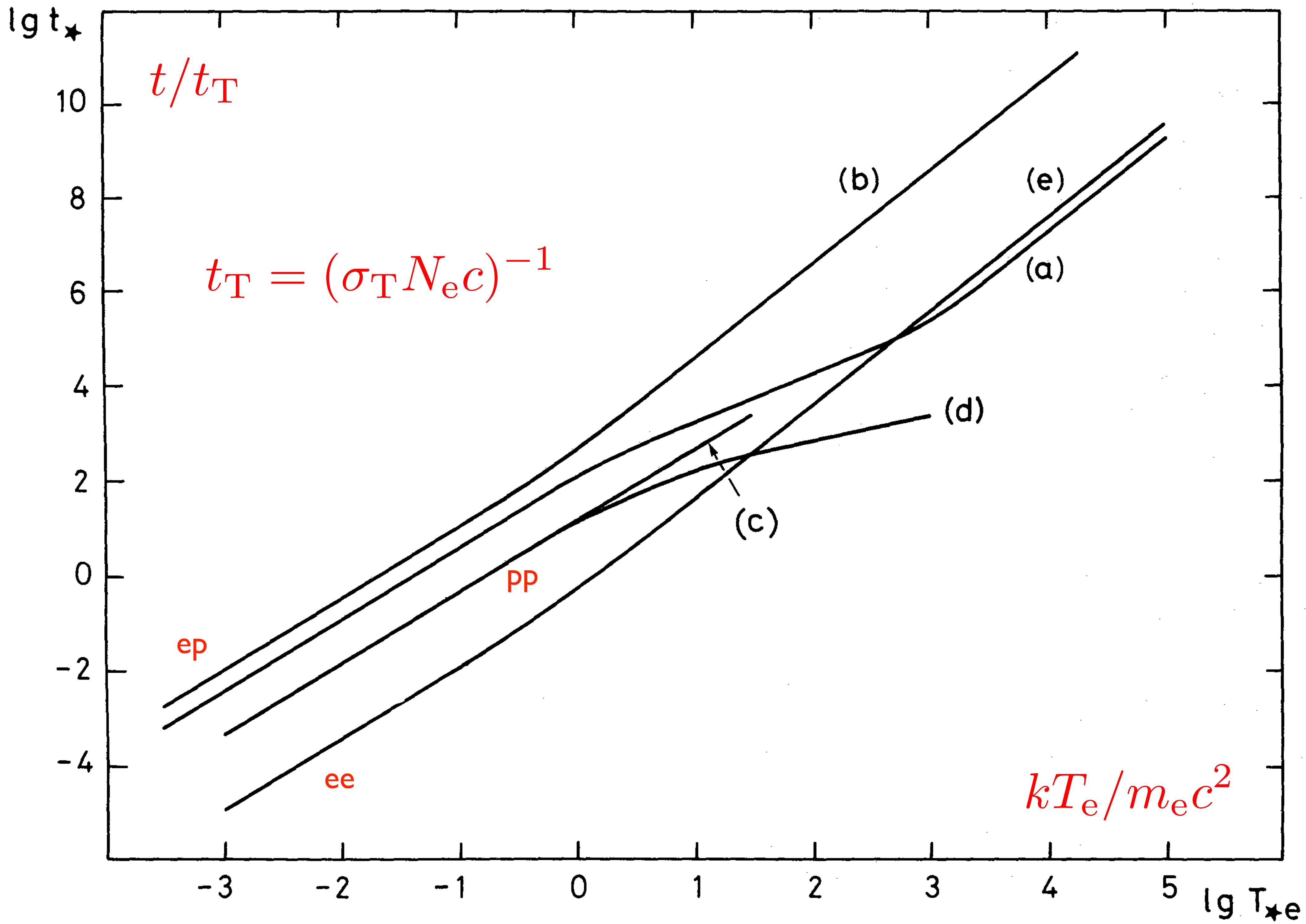


Figure 3.4: Comparison of the Thomson scattering time-scale with the Hubble expansion time-scale.

Stepney, MNRAS, 202, 467, 1983



Two-body relaxation time-scales (putting $N_e = N_p$, $\ln \Lambda = 20$). (a) Electron –proton relaxation, $T_p = T_e$. (b) Electron–proton relaxation, $T_p = m_p T_e/m_e$. (c) Pure Coulomb proton–proton relaxation. (d) Proton–proton relaxation including nuclear scattering. (e) Electron–electron relaxation.

Compton Kernel for different temperatures

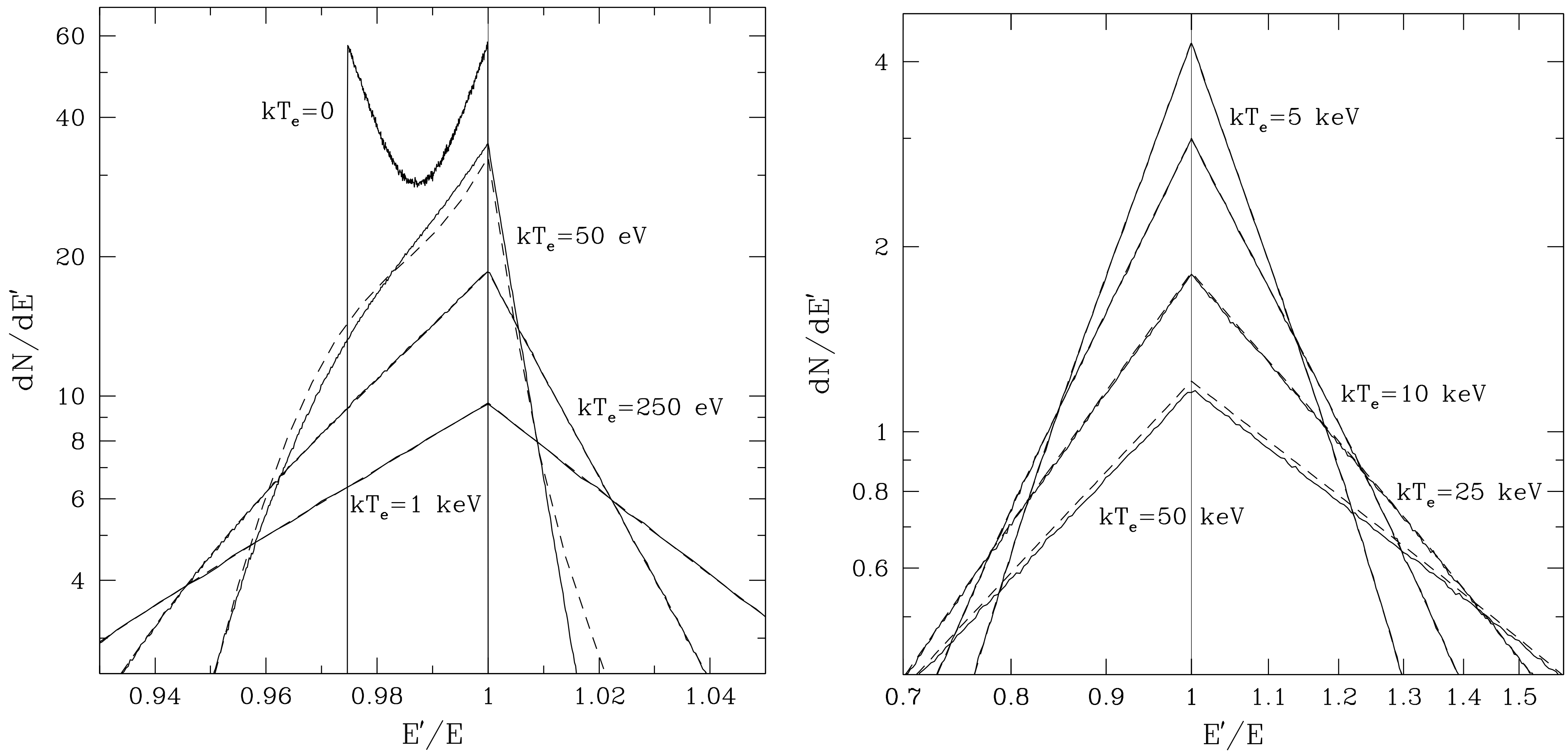


Figure 3.7: Compton scattering kernel for $E = h\nu = 6.7\,\text{keV}$ photons. The left panel shows cases for cold ($h\nu \gg kT_e$) electrons. In this case the redistribution process has significant contributions from recoil, although even for $kT_e \simeq 0.01h\nu$ the Doppler broadening already becomes important. The right panel shows examples for hot ($h\nu \ll kT_e$) electrons, where the redistribution is dominated by Doppler broadening and boosting. Dashed lines show analytic approximations for the kernel. The figure was taken from Sazonov & Sunyaev [36].

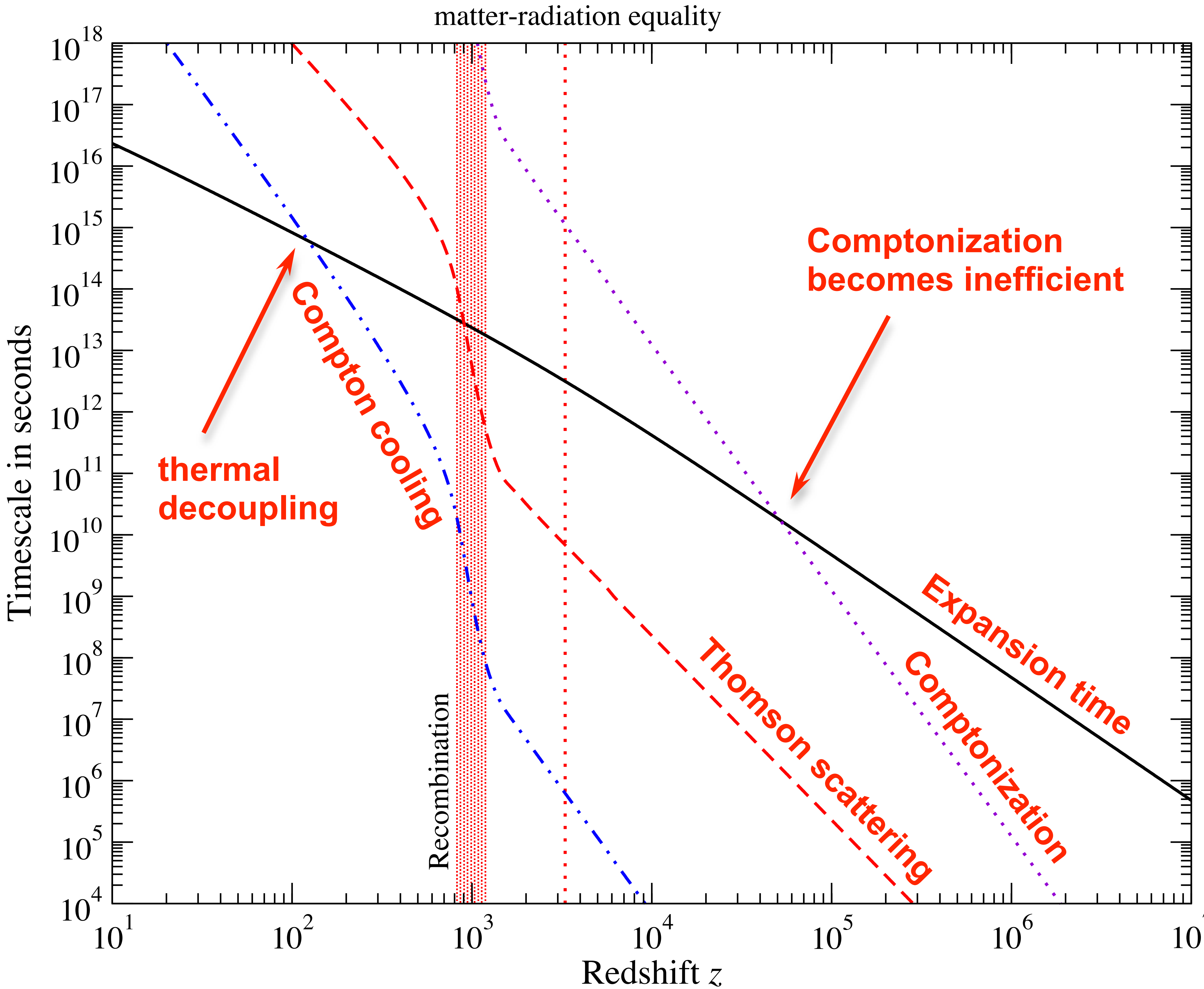


Figure 3.8: Comparison of the Comptonization and Compton cooling time-scale with the Hubble expansion time-scale.

Bremsstrahlung Gaunt factors (Itoh et al 2000)

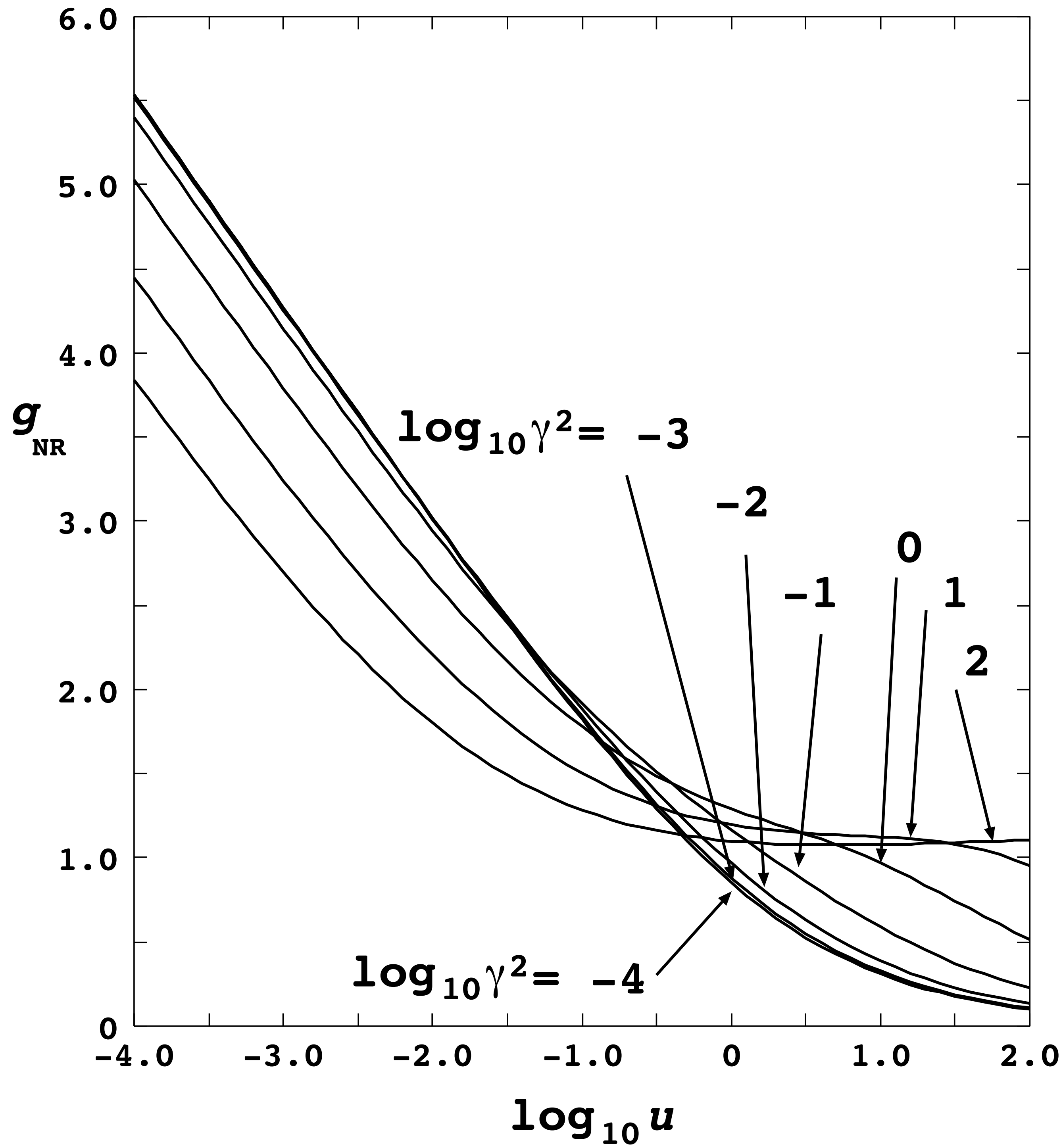


Figure 3.10: Thermally averaged Gaunt factor in the non-relativistic limit. Here, $u = \frac{h\nu}{kT_e}$ and $\gamma^2 = \frac{Z^2 1.579\times10^5\mathrm{K}}{T_e}$. The figure is taken from Itoh et al. [22] and a modern version of computations by Karzas & Latter [24].

Final Set of evolution equations (sneak preview)

$$\frac{\partial f}{\partial \tau} \approx \frac{\theta_{\rm e}}{x^2}\frac{\partial}{\partial x} x^4 \left[\frac{\partial}{\partial x} f + \frac{T_\gamma}{T_{\rm e}}\, f(1+f)\right] + \frac{K_{\rm BR}\,{\rm e}^{-x_{\rm e}}}{x_{\rm e}^3}[1 - f\,({\rm e}^{x_{\rm e}} - 1)] + \frac{K_{\rm DC}\,{\rm e}^{-2x}}{x^3}[1 - f\,({\rm e}^{x_{\rm e}} - 1)] + S(\tau, x)$$

$$K_{\rm BR} = \frac{\alpha}{2\pi}\frac{\lambda_{\rm e}^3}{\sqrt{6\pi}\,\theta_{\rm e}^{7/2}} \sum_i Z_i^2 N_i\, \bar{g}_{\rm ff}(Z_i, T_{\rm e}, T_\gamma, x_{\rm e}), \qquad K_{\rm DC} = \frac{4\alpha}{3\pi}\,\theta_\gamma^2\, I_{\rm dc}\, g_{\rm dc}(T_{\rm e}, T_\gamma, x)$$

$$\bar{g}_{\rm ff}(x_{\rm e}) \approx \begin{cases} \frac{\sqrt{3}}{\pi}\ln\left(\frac{2.25}{x_{\rm e}}\right) & \text{for} \quad x_{\rm e} \leq 0.37 \\ 1 & \text{otherwise} \end{cases}, \qquad g_{\rm dc} \approx \frac{1 + \frac{3}{2}x + \frac{29}{24}x^2 + \frac{11}{16}x^3 + \frac{5}{12}x^4}{1 + 19.739\theta_\gamma - 5.5797\theta_{\rm e}}.$$

$$\frac{{\rm d}\rho_{\rm e}}{{\rm d}\tau} = \frac{{\rm d}(T_{\rm e}/T_\gamma)}{{\rm d}\tau} = \frac{t_{\rm T}\dot{Q}}{\alpha_{\rm h}\theta_\gamma} + \frac{4\tilde{\rho}_\gamma}{\alpha_{\rm h}}[\rho_{\rm e}^{\rm eq} - \rho_{\rm e}] - \frac{4\tilde{\rho}_\gamma}{\alpha_{\rm h}}\mathcal{H}_{\rm DC,BR}(\rho_{\rm e}) - H\,t_{\rm T}\,\rho_{\rm e}.$$

$$k\alpha_{\rm h} = \frac{3}{2}k[N_{\rm e} + N_{\rm H} + N_{\rm He}] = \frac{3}{2}kN_{\rm H}[1 + f_{\rm He} + X_{\rm e}] \qquad \rho_{\rm e}^{\rm eq} = T_{\rm e}^{\rm eq}/T_\gamma$$

$$\tilde{\rho}_\gamma = \rho_\gamma/m_{\rm e}c^2$$