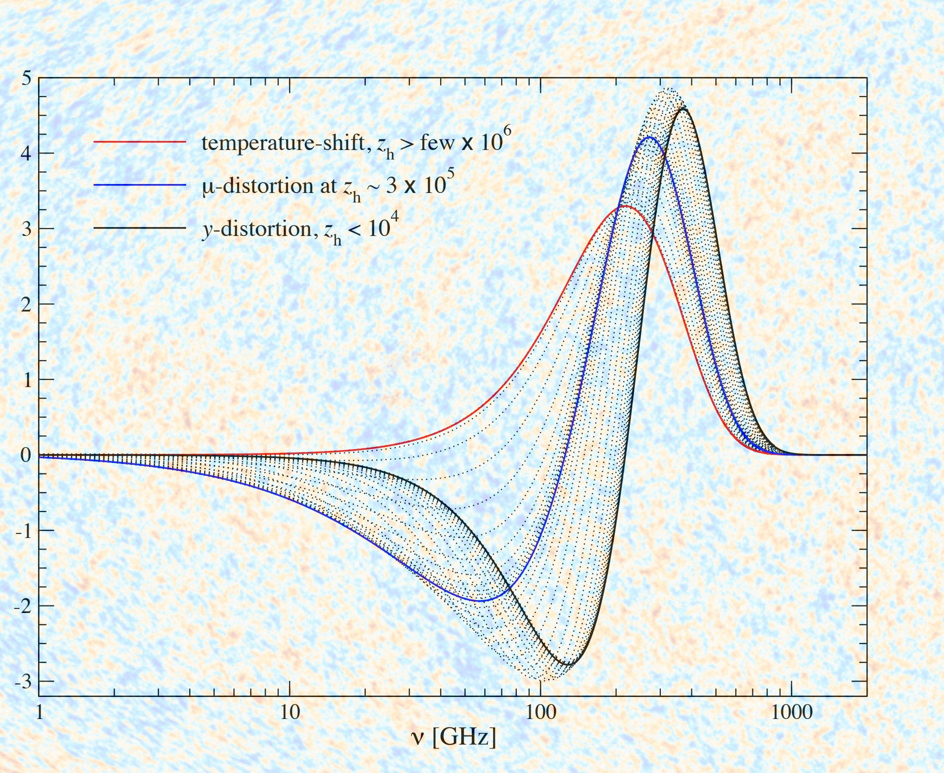
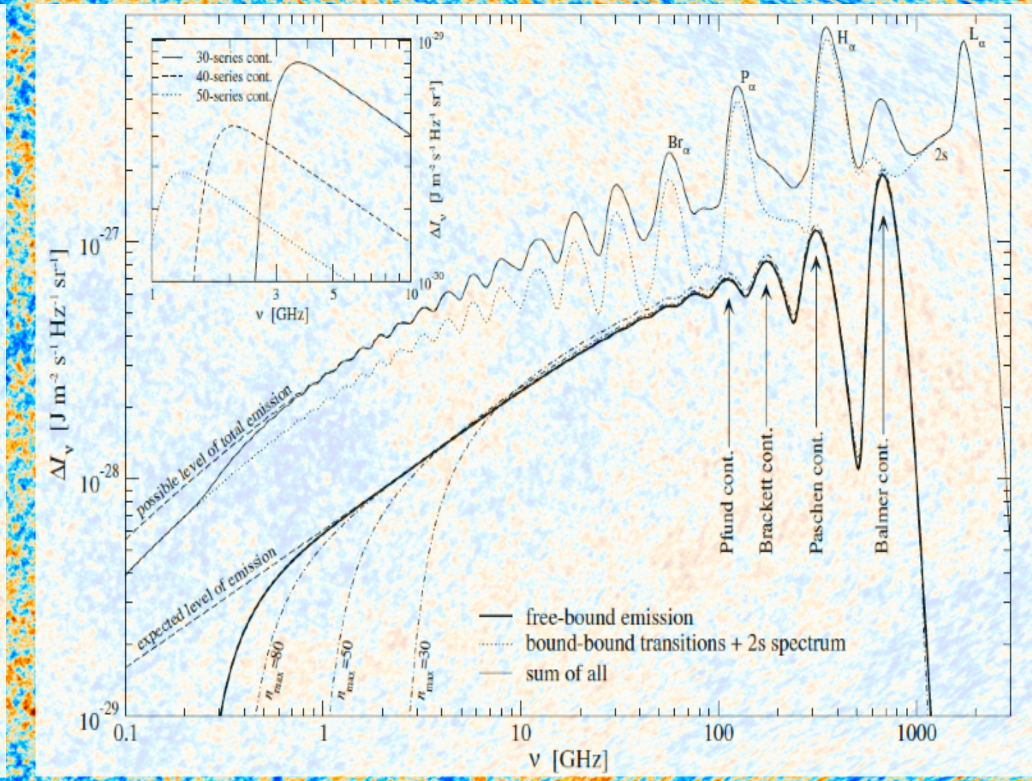
Cosmic Microwave Background and Spectral Distortions I:

CMB anisotropies and motivation for CMB spectral distortions*


Primordial Distortions


Cosmological Recombination lines

MANCHESTER
1824
The University of Manchester

Jens Chluba

ICCUB School: "Hot Topics in Cosmology"

Barcelona, Spain, Oct. 23rd-26th, 2017

erc

THE ROYAL SOCIETY

* *CMB ≙ Cosmic Microwave Background*

Main Goals of my Lectures

- Convince you that future CMB distortions science will be *extremely* exciting and lots of fun!
- Explain in detail how distortions evolve and thermalize
- Definition of different types of distortions (μ, y and r-type)
- Computations of spectral distortions
- Provide an overview for different sources of primordial distortions and what we might learn from them
- Show you why CMB spectral distortions provide a *complementary* probe of inflation and particle physics

References for the Theory of Spectral Distortions

- Early 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

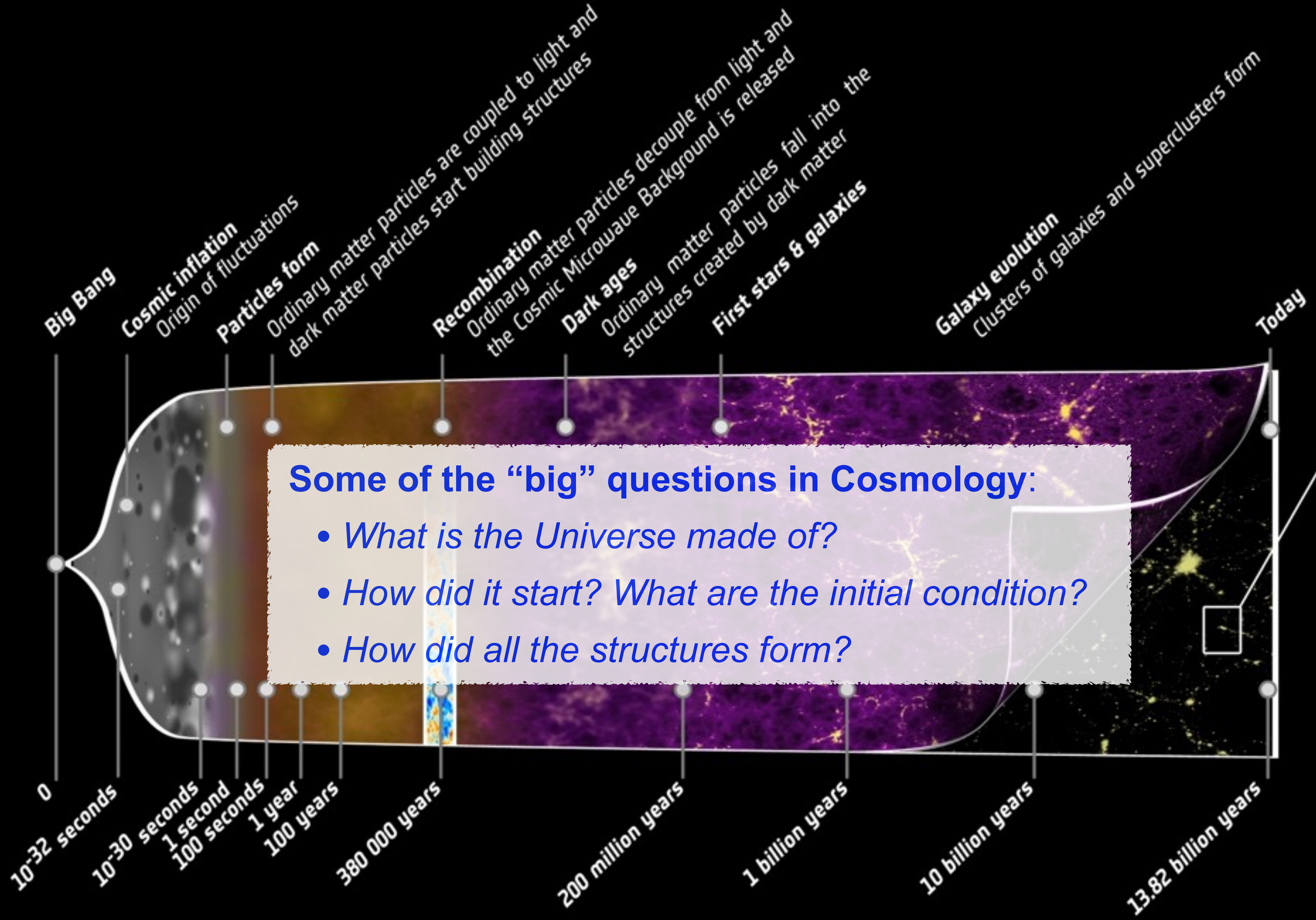
References for the Theory of Spectral Distortions

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

see also, CUSO *Lecture* notes at:
`www.Chluba.de/Science`

- More recent overviews
  - Sunyaev & JC, 2009, AN, 330, 657
  - JC & Sunyaev, 2012, MNRAS, 419, 1294
  - JC, 2013, MNRAS, 436, 2232 & ArXiv:1405.6938

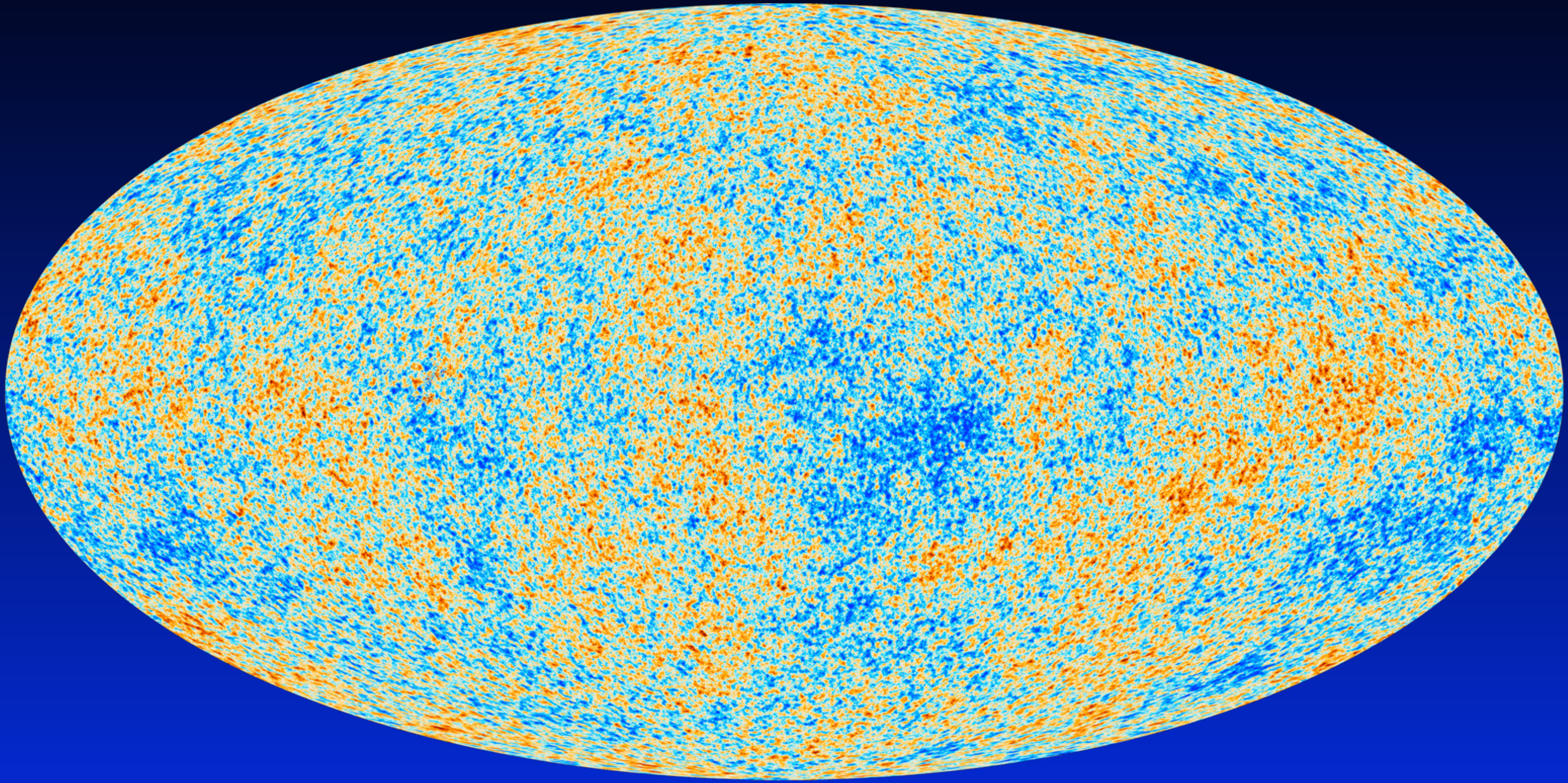
Part I: CMB anisotropies and motivation for CMB spectral distortions



Some of the "big" questions in Cosmology:

- *What is the Universe made of?*
- *How did it start? What are the initial condition?*
- *How did all the structures form?*

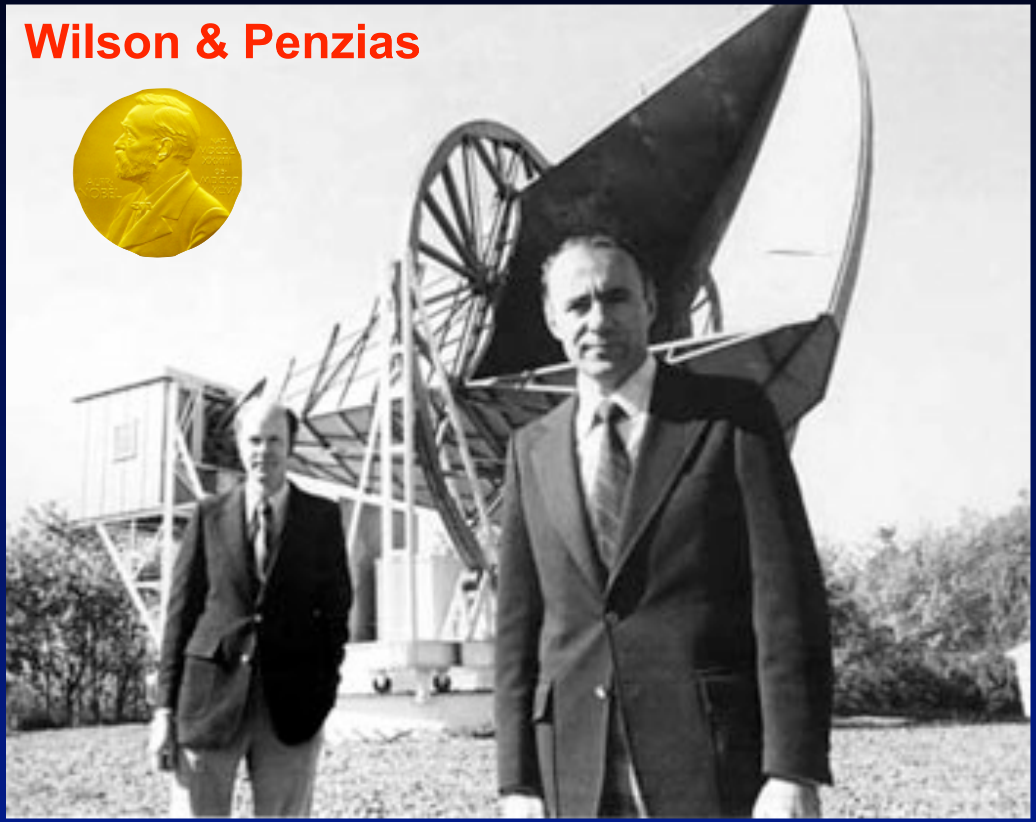
Cosmic Microwave Background Anisotropies

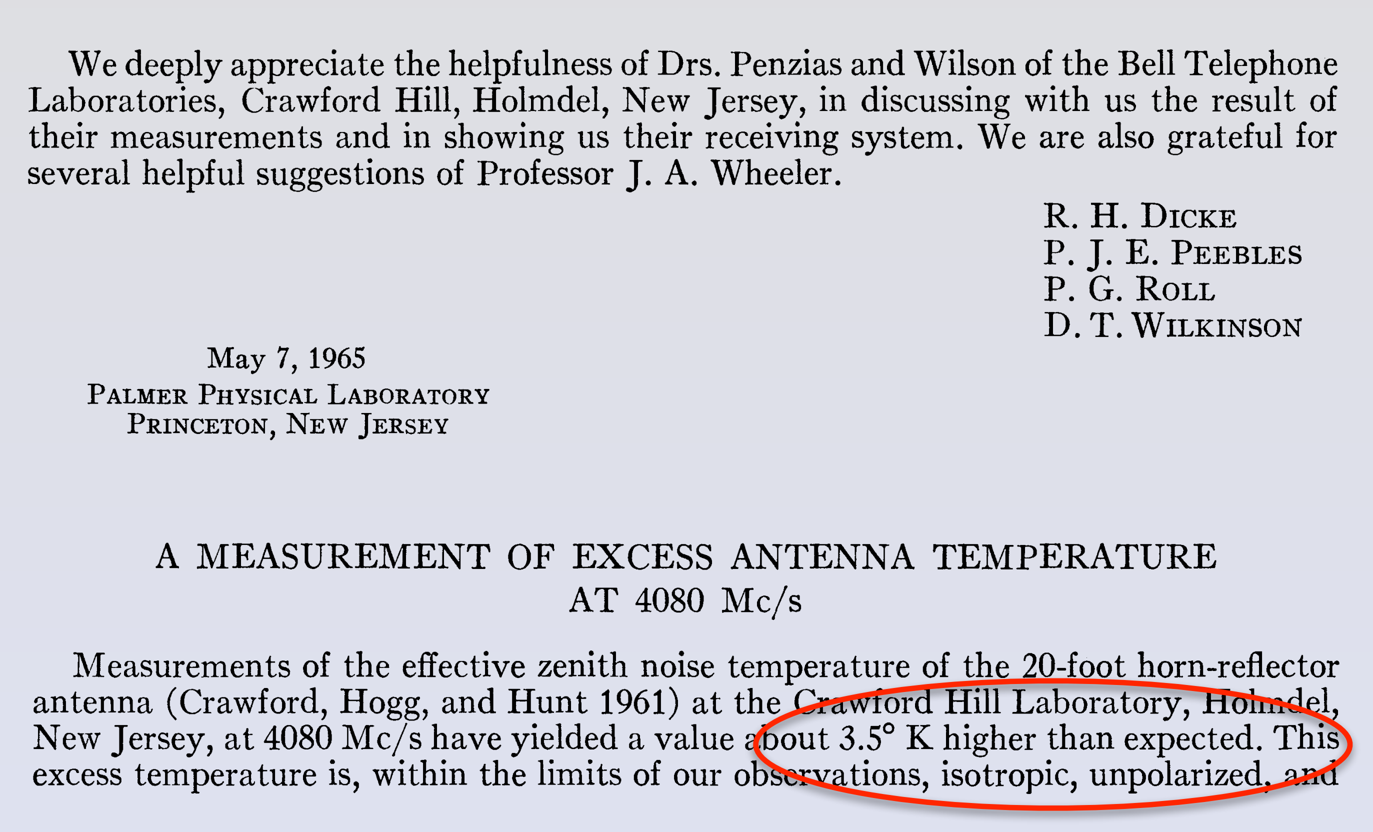


Planck all-sky temperature map

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

Discovery of Cosmic Microwave Background in 1965





We deeply appreciate the helpfulness of Drs. Penzias and Wilson of the Bell Telephone Laboratories, Crawford Hill, Holmdel, New Jersey, in discussing with us the result of their measurements and in showing us their receiving system. We are also grateful for several helpful suggestions of Professor J. A. Wheeler.

R. H. Dicke
P. J. E. Peebles
P. G. Roll
D. T. Wilkinson

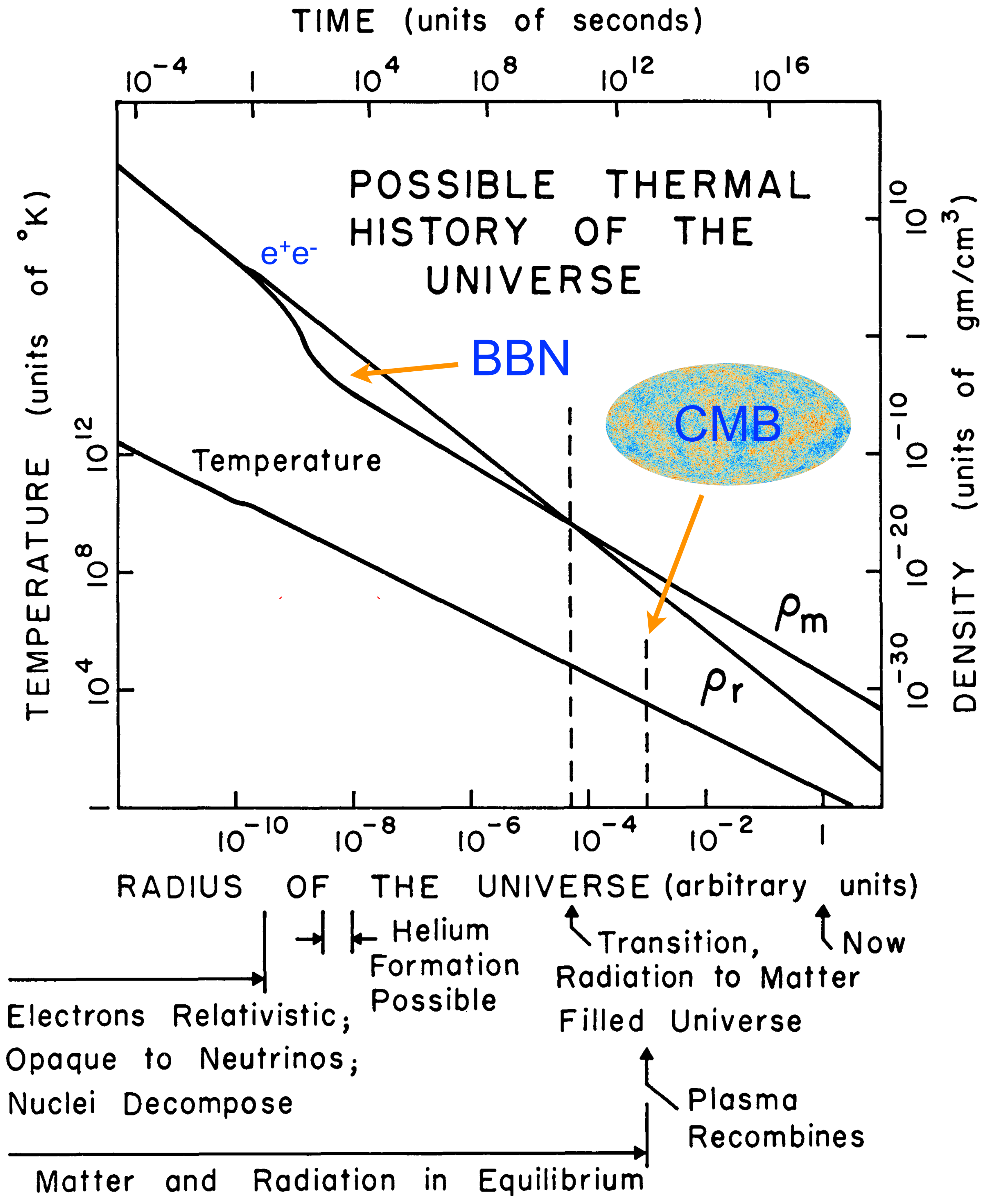
May 7, 1965
Palmer Physical Laboratory
Princeton, New Jersey

A MEASUREMENT OF EXCESS ANTENNA TEMPERATURE
AT 4080 Mc/s

Measurements of the effective zenith noise temperature of the 20-foot horn-reflector antenna (Crawford, Hogg, and Hunt 1961) at the Crawford Hill Laboratory, Holmdel, New Jersey, at 4080 Mc/s have yielded a value about 3.5° K higher than expected. This excess temperature is, within the limits of our observations, isotropic, unpolarized, and

- Anticipated *theoretically* (Gamow, Alpher & Herman, Dicke, etc)
- Dicke, Peebles and Wilkinson were actively looking for the CMB
- Experimentally *discovered* in 1964/65 by Penzias & Wilson (Nobel Prize 1978)
- Horn antenna (~6m) at Bell Labs (New Jersey)
- *Interpretation* as CMB by Dicke, Peebles, Roll & Wilkinson 1965
  (article directly preceding Penzias' & Wilson's ~1.2 page letter)
- Fixed the energy scale for the CMB and strongly supports the *hot Big Bang picture* of the Universe

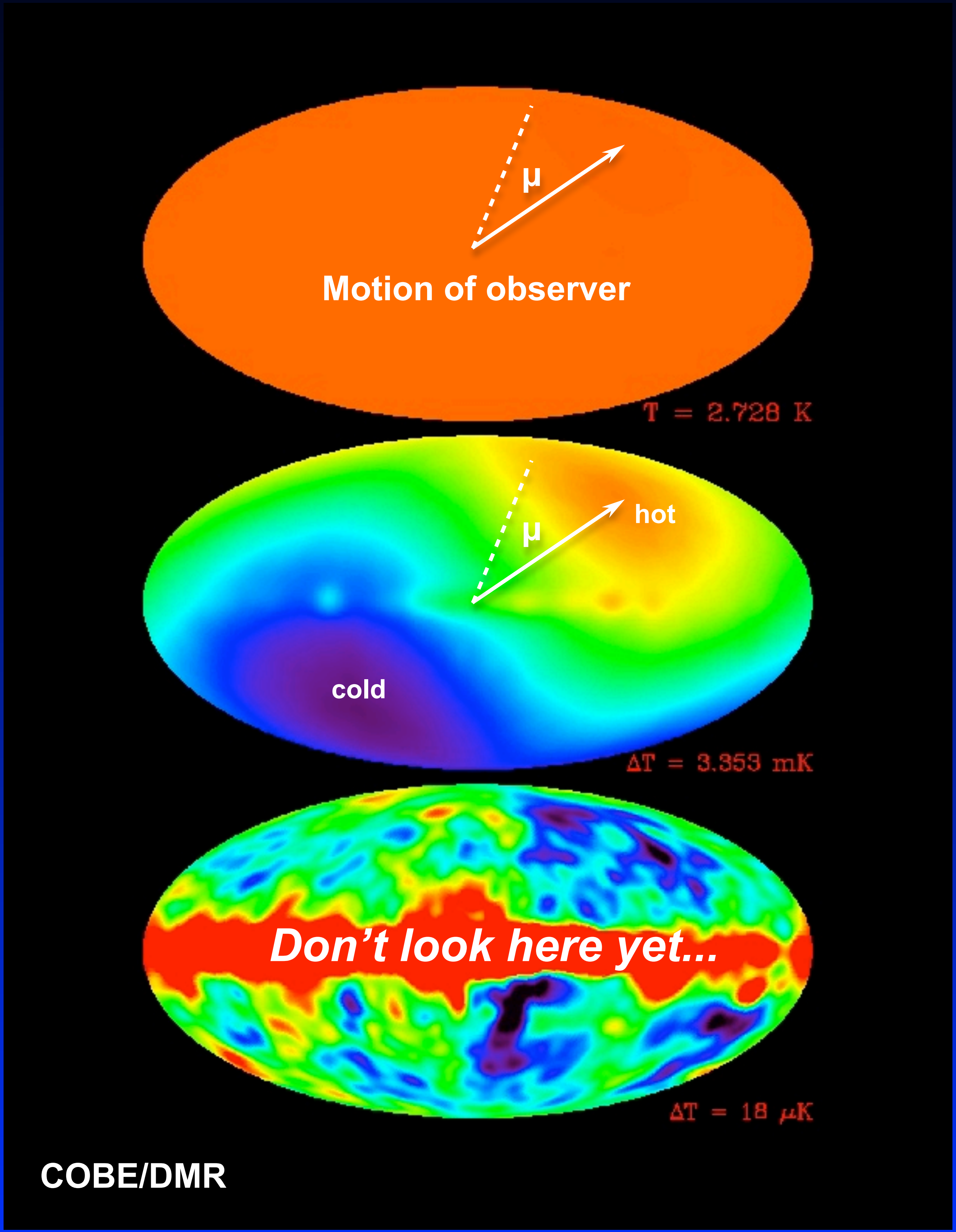
First sketch of the thermal history



- Hot big bang picture
  (as opposed to steady state)
- $T_m \sim T_\gamma$ until recombination
  (actually until z~150)
- e^+e^- annihilation around $T \sim 10^{10}$ K ~ 1 MeV
- Mention that this is also when nuclei are forming
- Say that this model would mainly produce helium
  (…no heavy elements)
- Mention puzzle about baryon-asymmetry

Dicke, Peebles, Roll & Wilkinson, 1965

CMB dipole



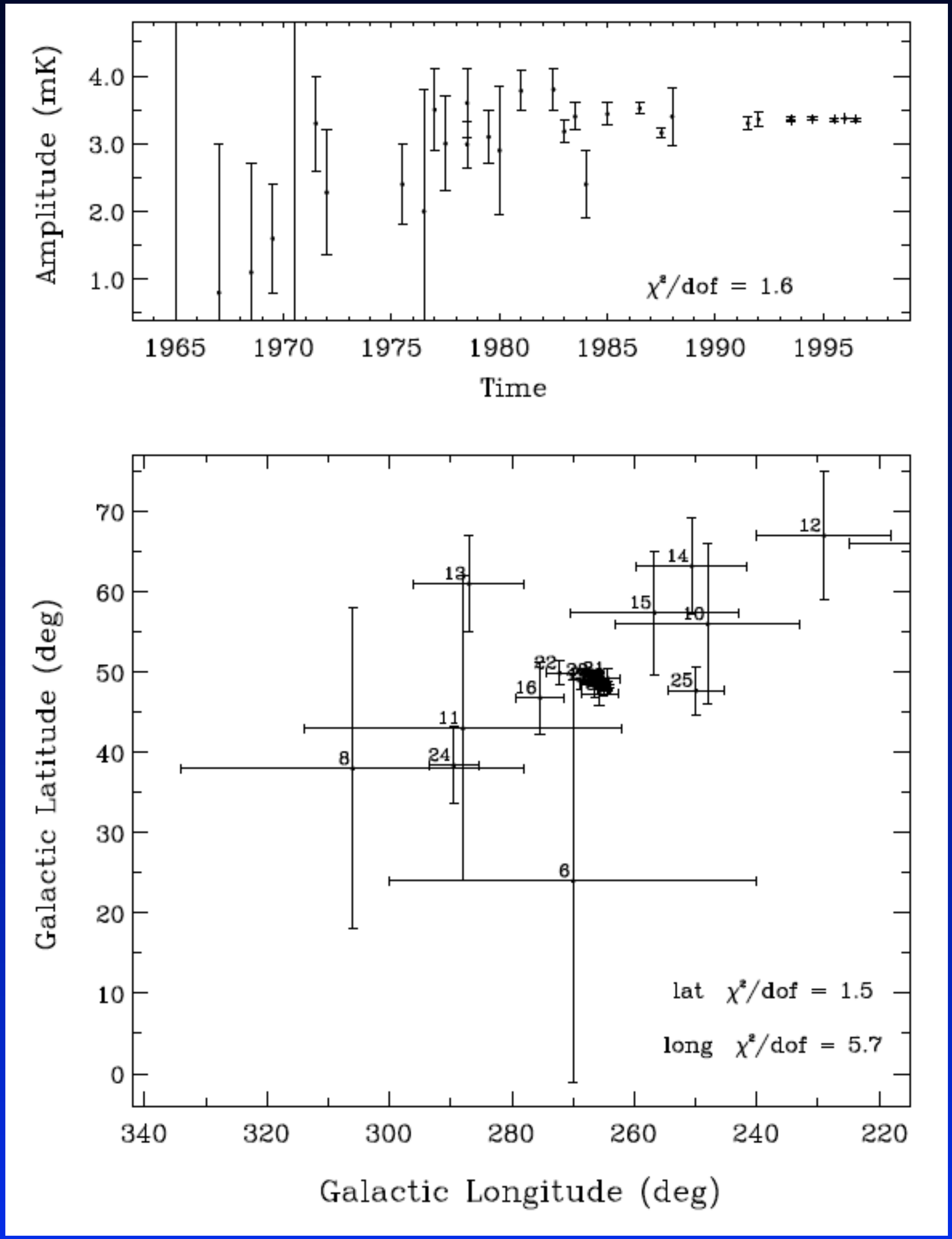
- Lowest order v/c effect caused by observers motion (simple Lorentz-trafo of average CMB blackbody into observer frame)

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

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

- Probably understood by contemporary folks but dipole was *first explicitly shown* 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 $\beta \implies$ motion-induced monopole & quadrupole and y-distortion monopole & quadrupole (e.g., JC & Sunyaev, 2004)

Measurements of CMB dipole



Lineweaver, astro-ph/9609034v1

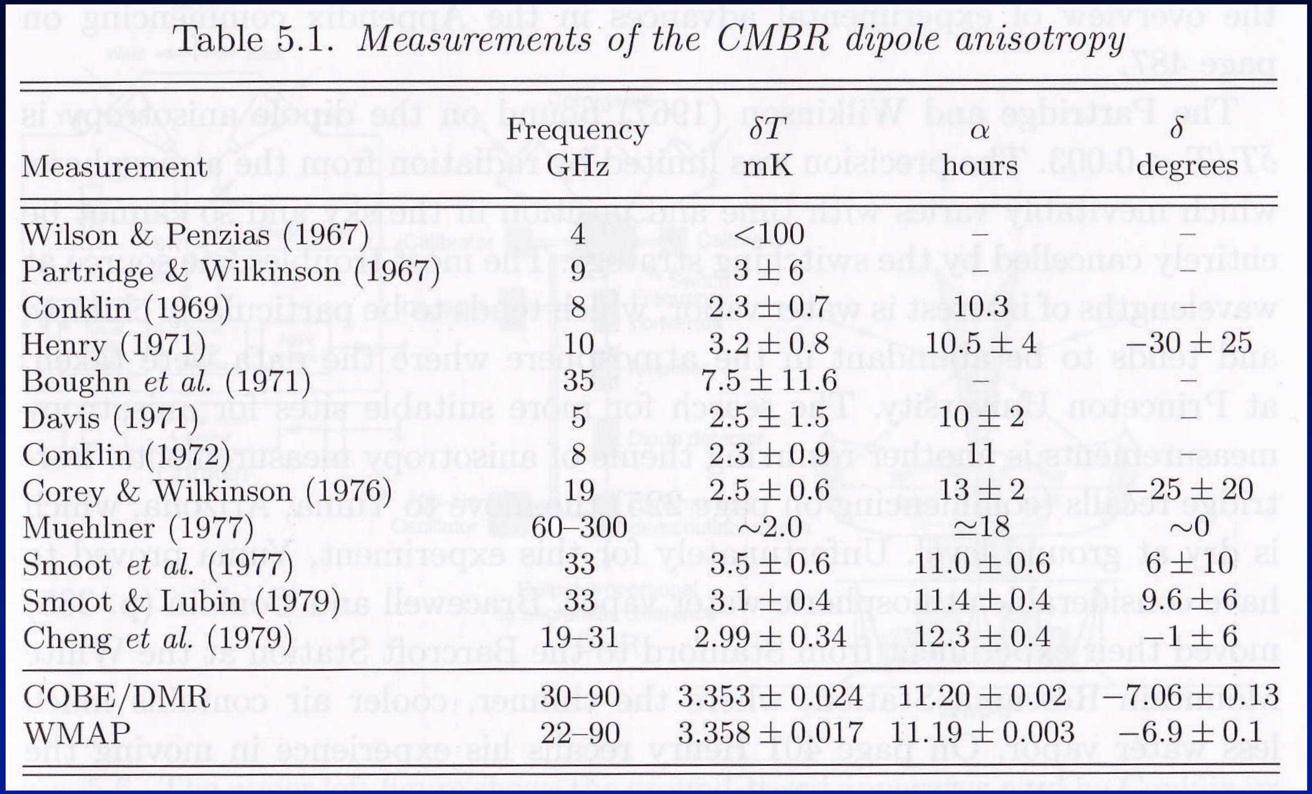


Table 5.1. *Measurements of the CMBR dipole anisotropy*

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	≃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!

Early Predictions of CMB anisotropies

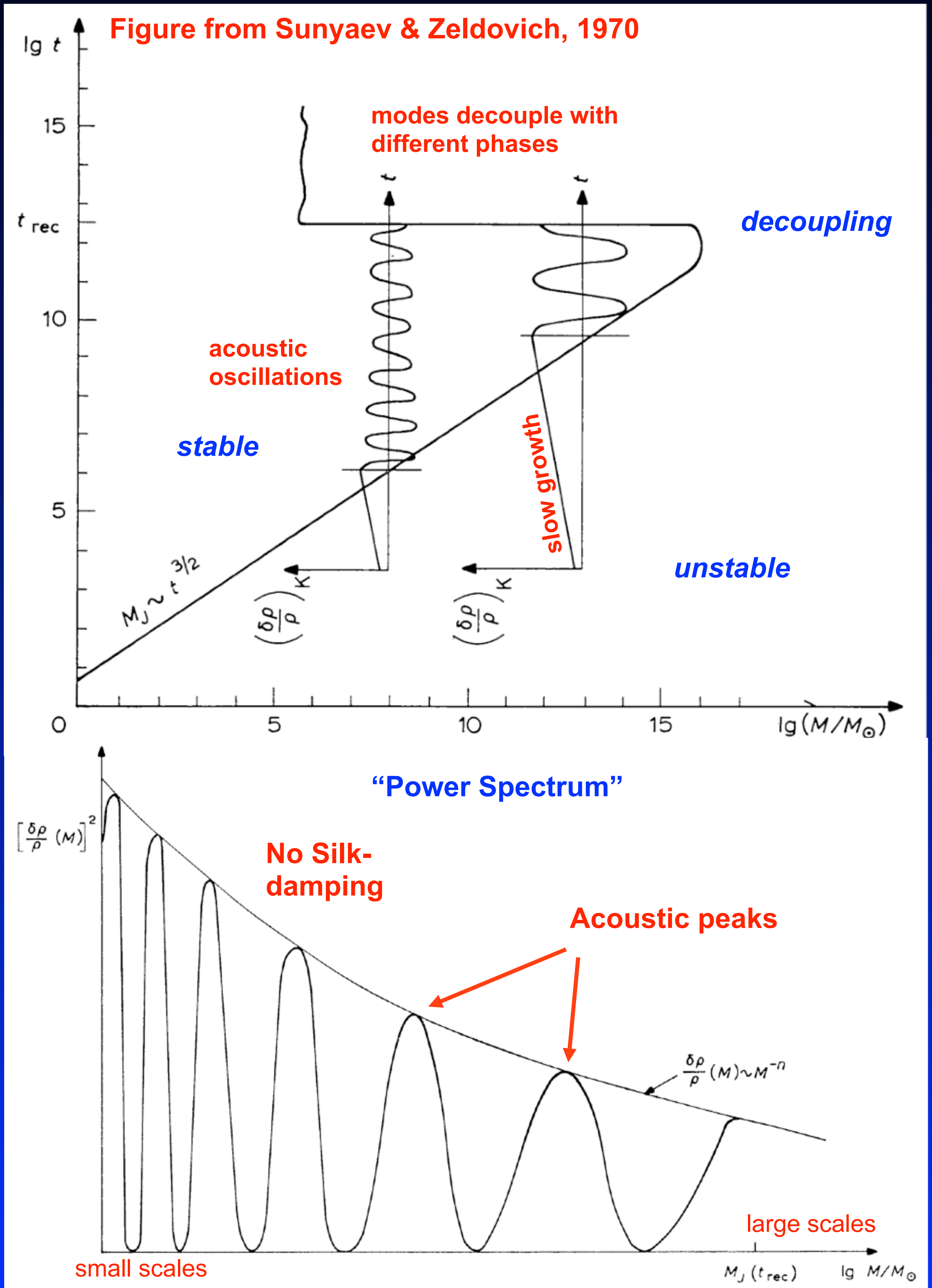


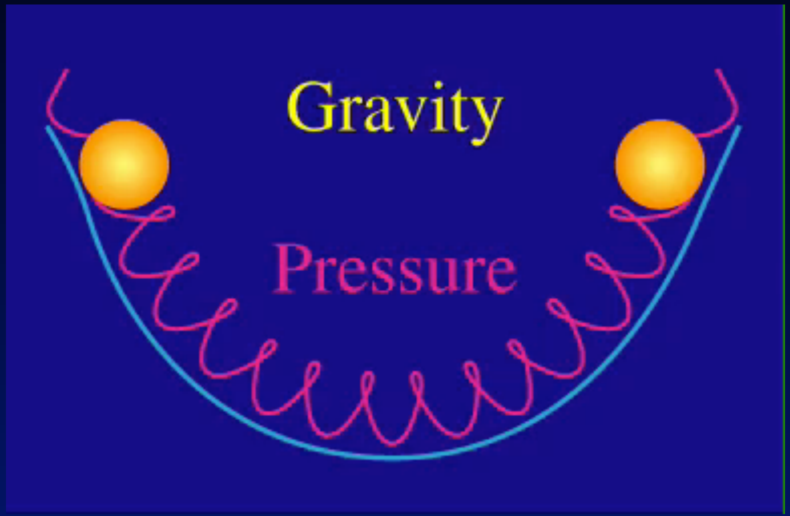
Figure from Sunyaev & Zeldovich, 1970

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

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

- *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

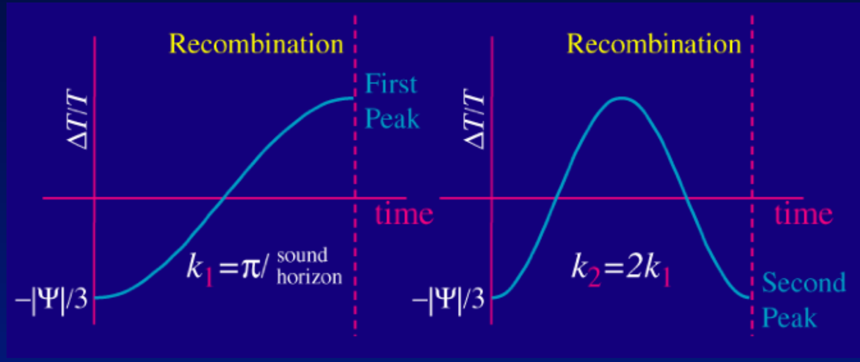
$$c_{\mathrm{s}} = \frac{c}{\sqrt{3(1+R)}}$$

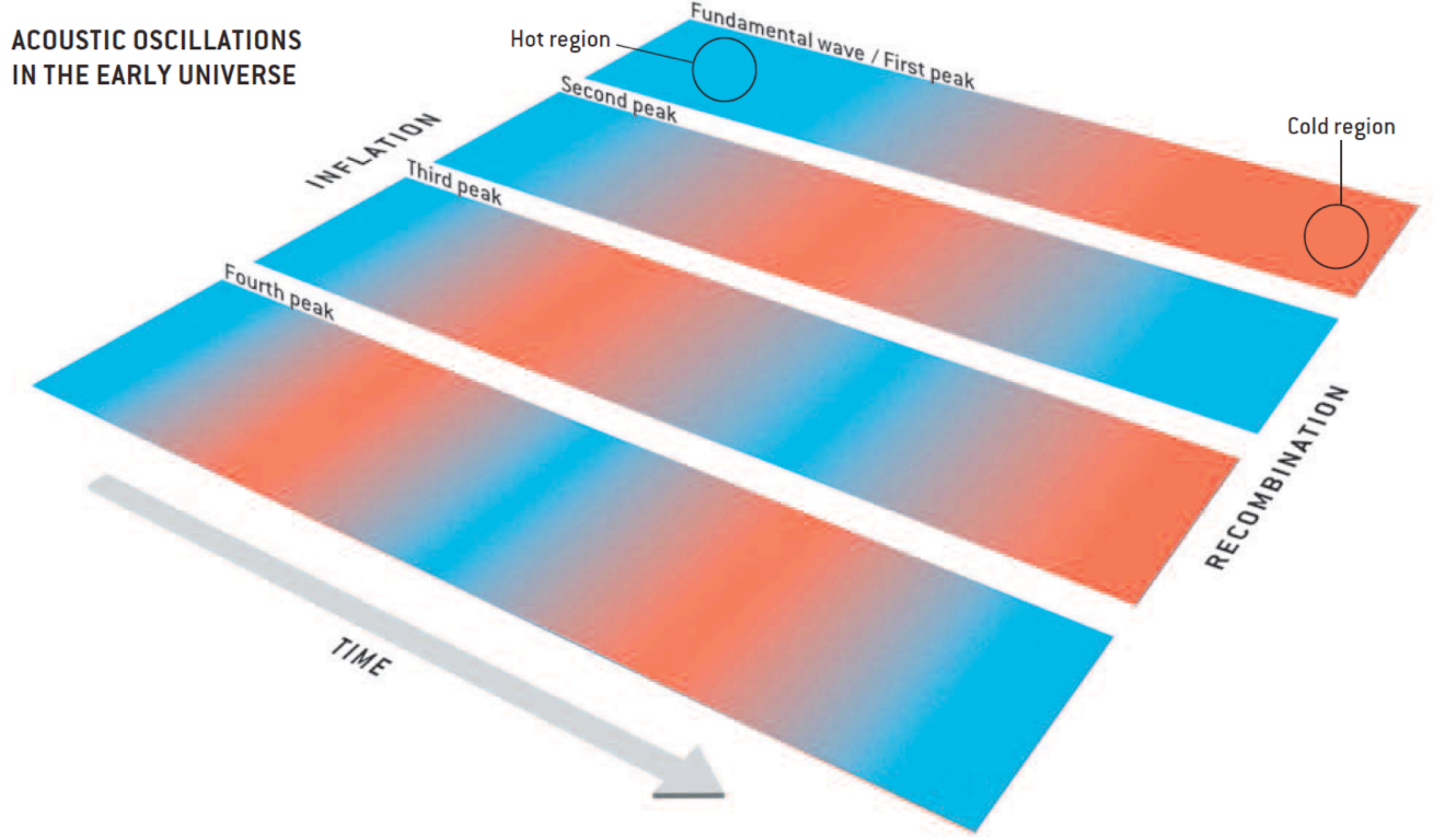
Baryon loading

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

Sound horizon

$$r_{\mathrm{s}} = \int \frac{c_{\mathrm{s}}\,\mathrm{d}t}{a}$$

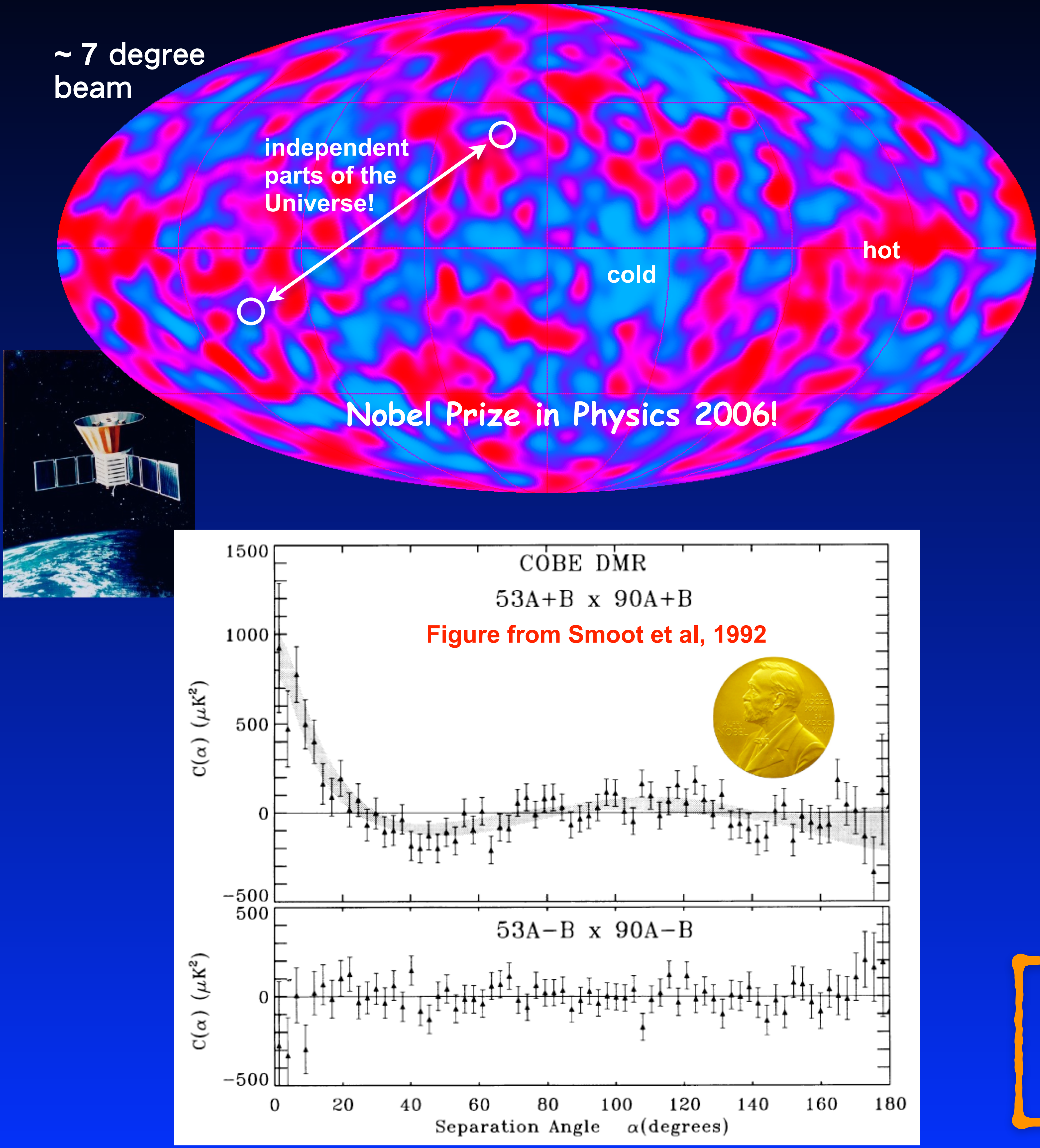




- position of first peak related to scale of *sound horizon* at recombination
- other peaks are *higher harmonics* of sound horizon scale

Hu & White, 2004

Discovery of CMB anisotropies by COBE/DMR



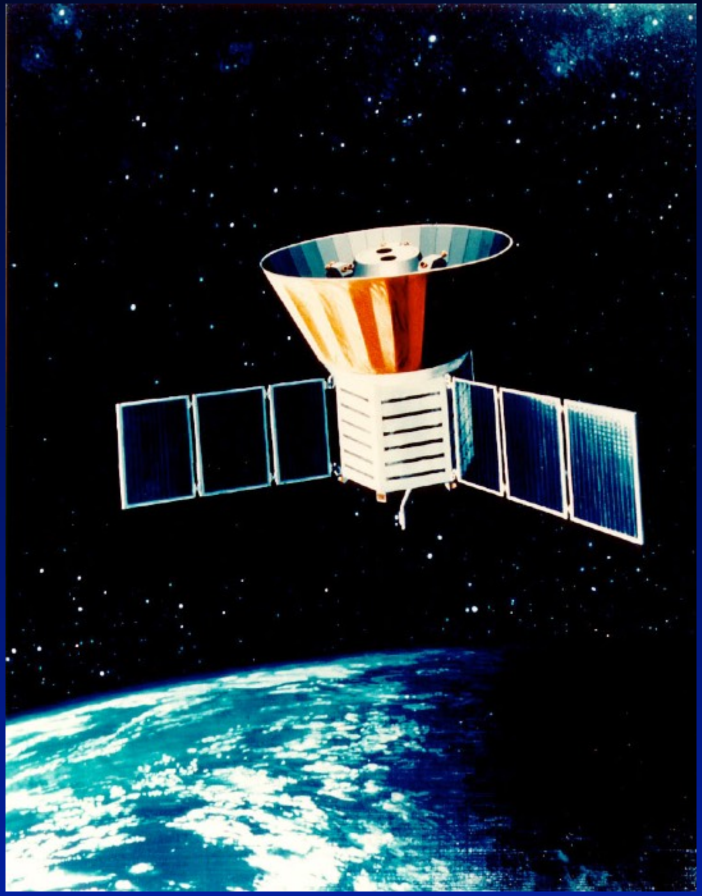
Nobel Prize in Physics 2006!

Figure from Smoot et al, 1992

- first measurement of large scale two-point correlation function (C_l's used later)
- consistent with a 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_{rec} $\Longrightarrow$ determined by *initial conditions* and *gravity* (*Sachs-Wolfe effect & ISW*)
- *hot spot* $\Longleftrightarrow$ *under density!*

Uniformity of CMB strong indication for Inflation!

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

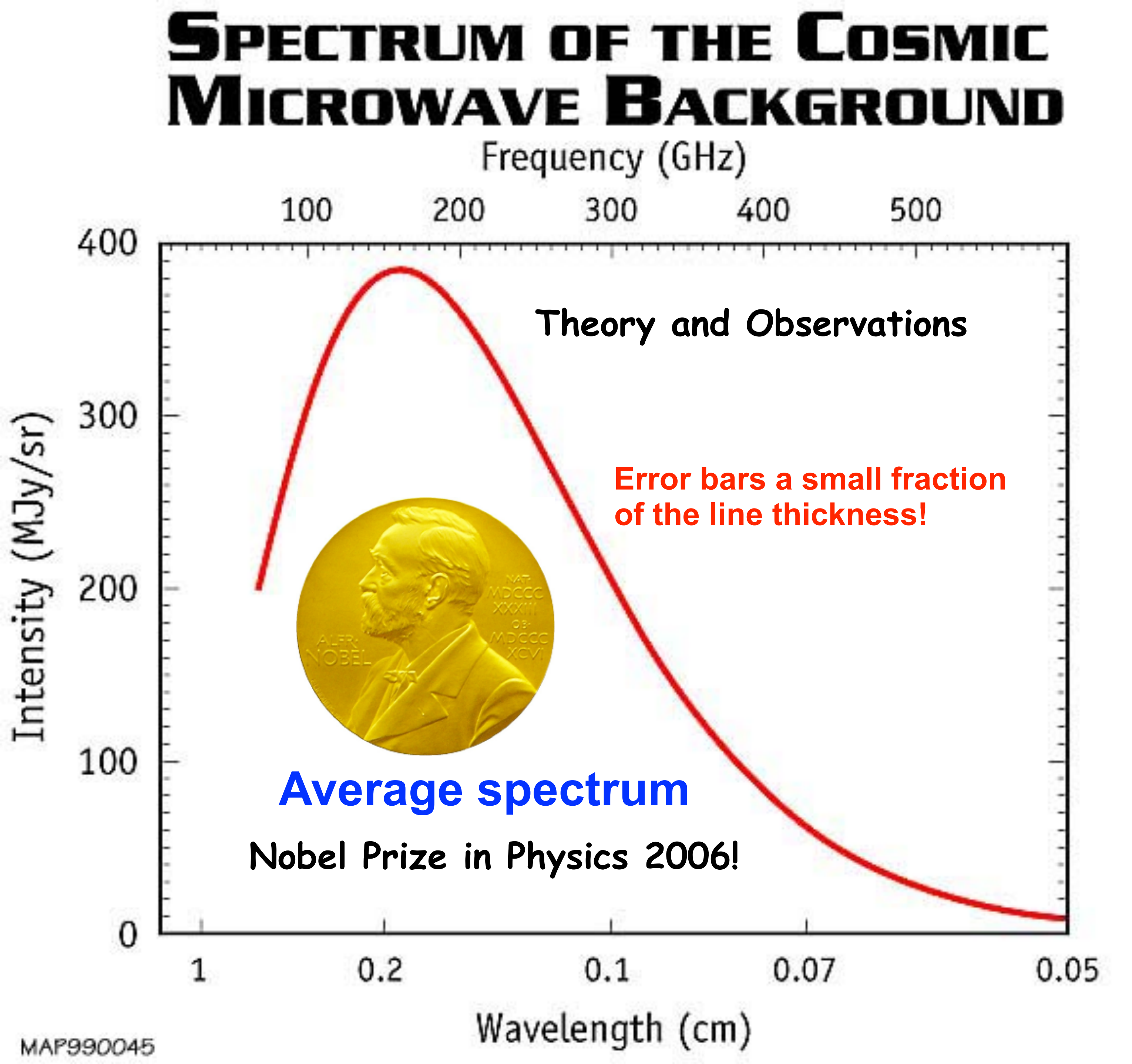


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

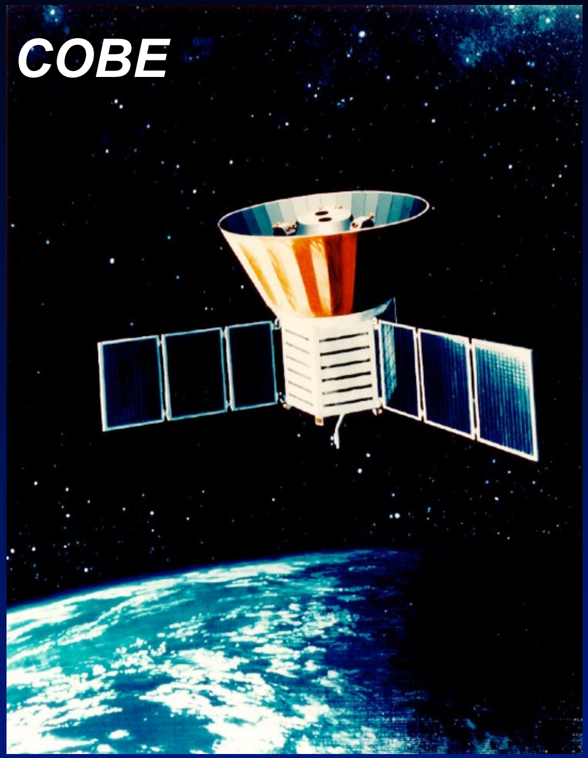
$$|\mu| \leq 9\times10^{-5}$$

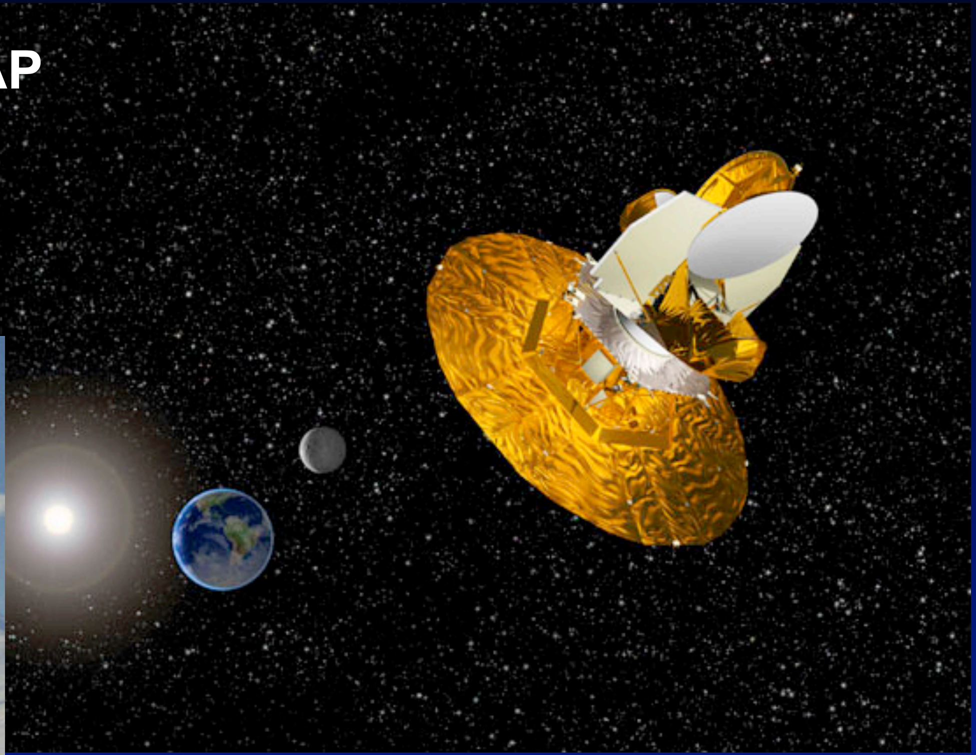
Mather et al., 1994, ApJ, 420, 439
Fixsen et al., 1996, ApJ, 473, 576
Fixsen et al., 2003, ApJ, 594, 67

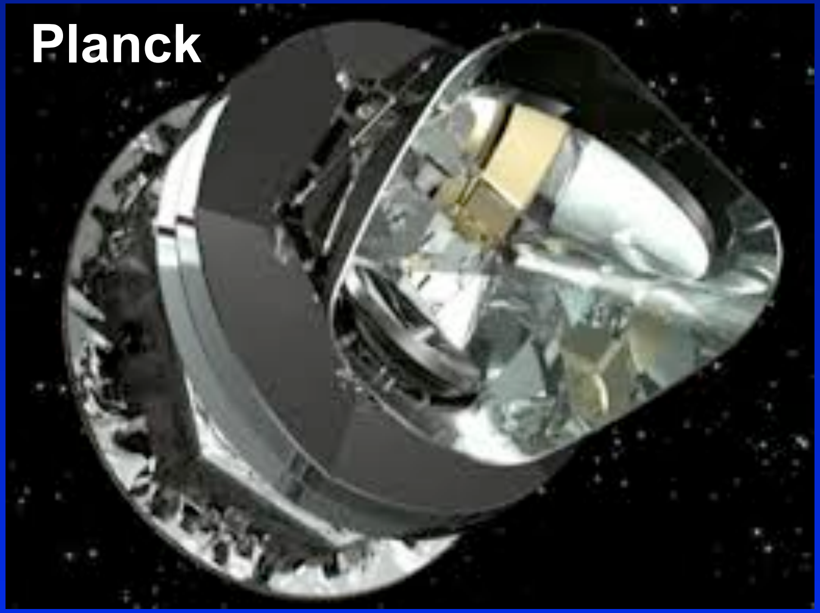


Blackbody spectrum strongly supports Big Bang picture

Lots of amazing progress over the past decades!







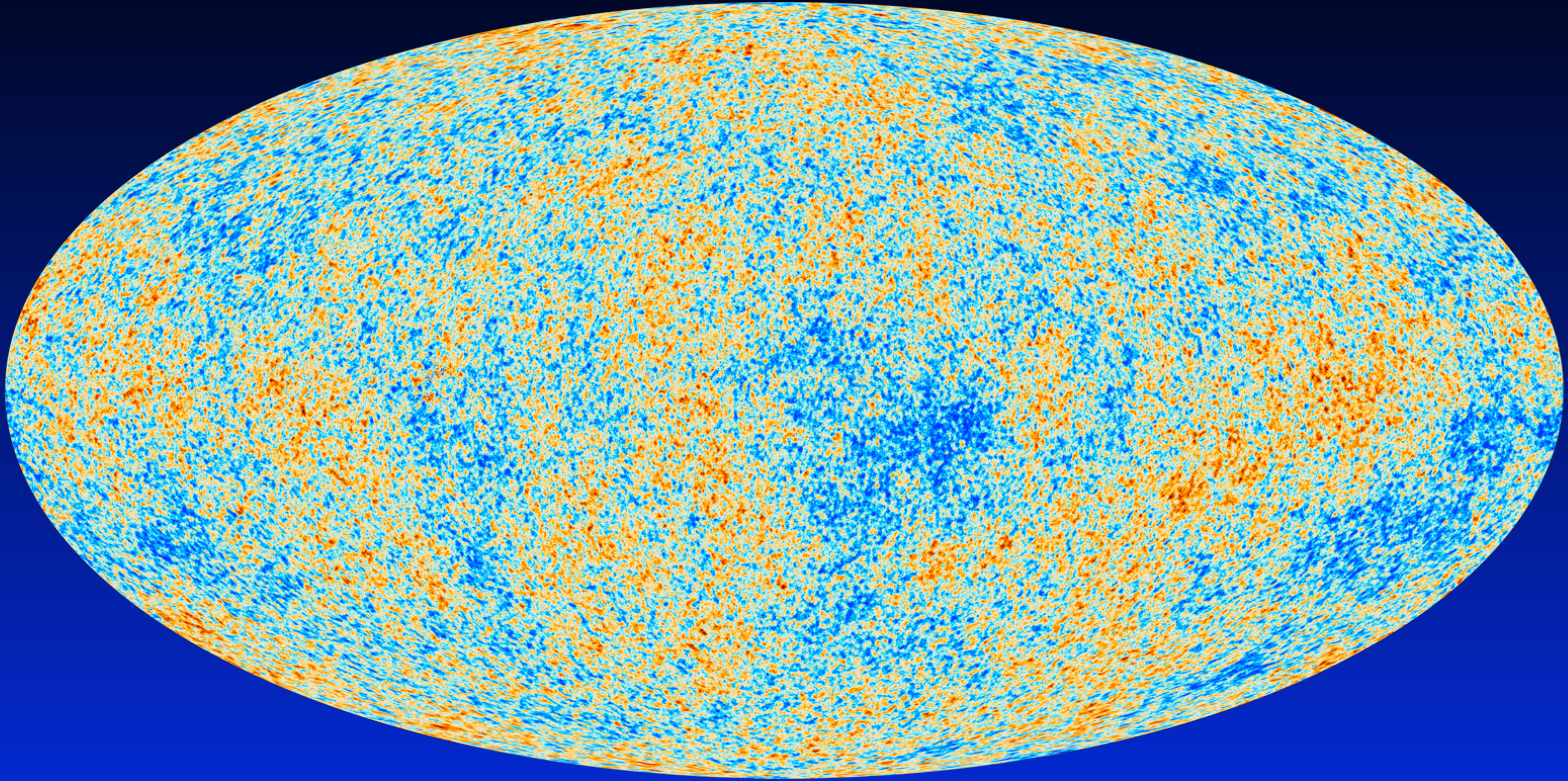
VSA, DESI, MAXIMA,

Keck Array, BICEP,

Polarbear, EBEX,

and many more...

Cosmic Microwave Background Anisotropies



Planck all-sky temperature map

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

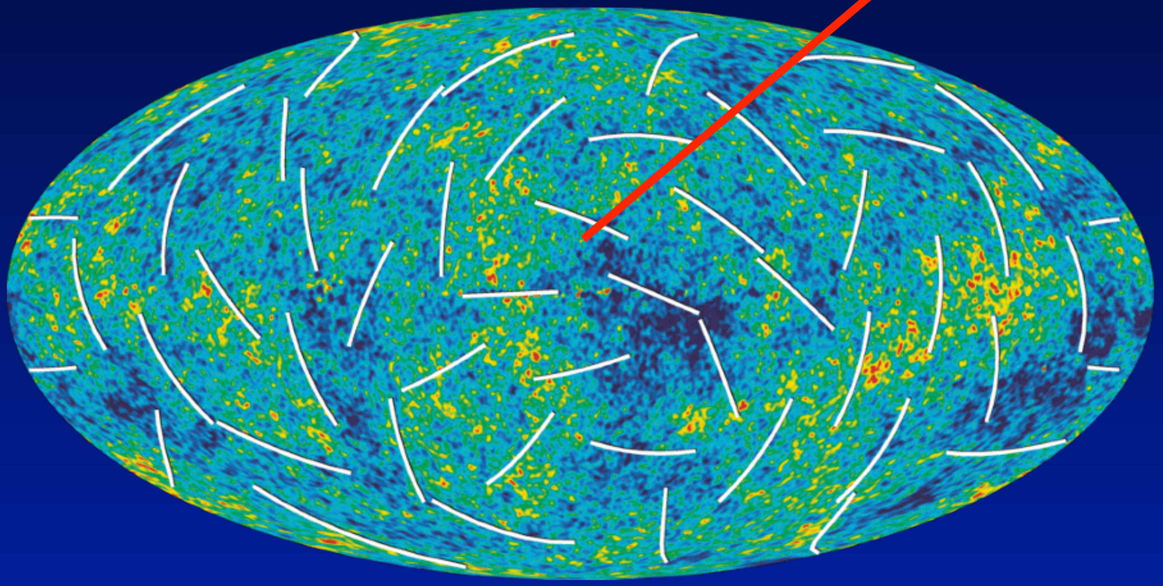
CMB Sky → Cosmology

$N_e(z)$ is an important input

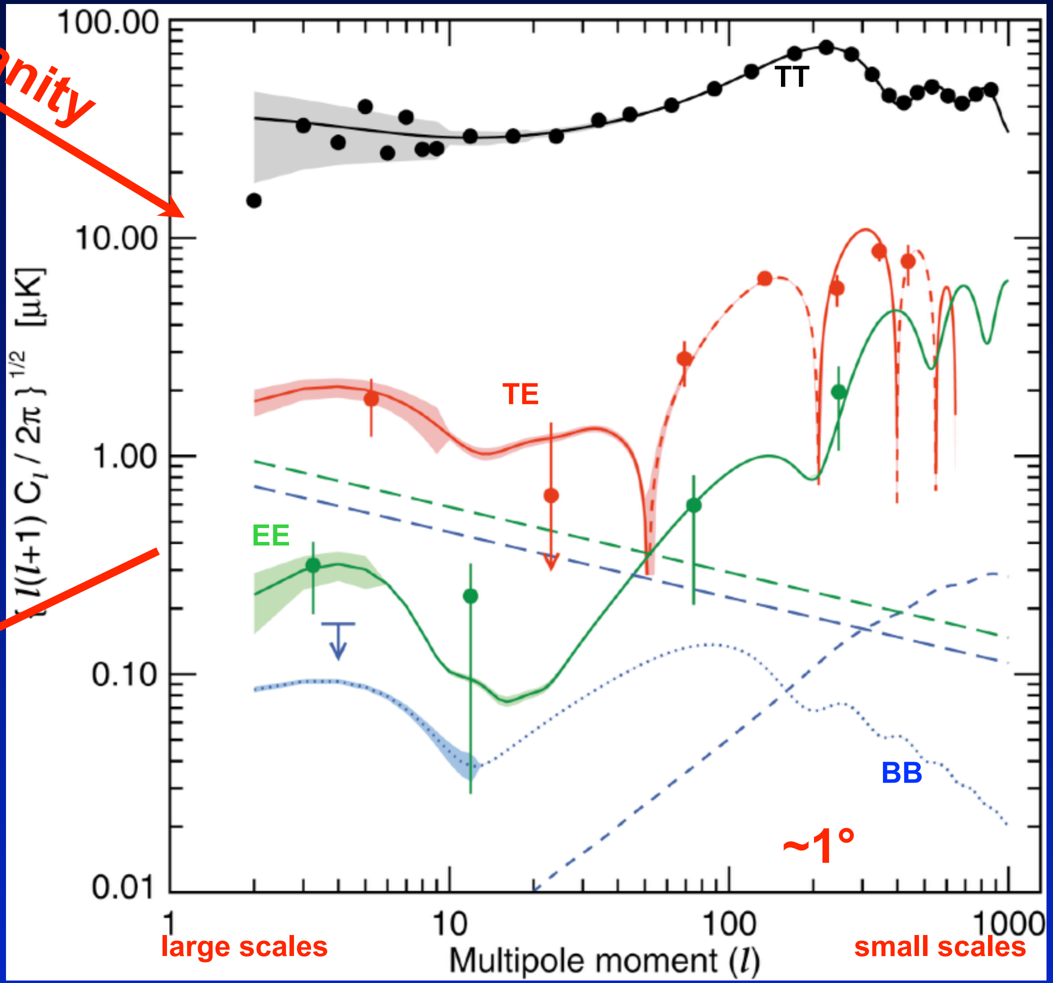
Power spectra

a_{lm}

CMB Sky
(temperature & polarization)



Gaussianity



(Joint) analysis

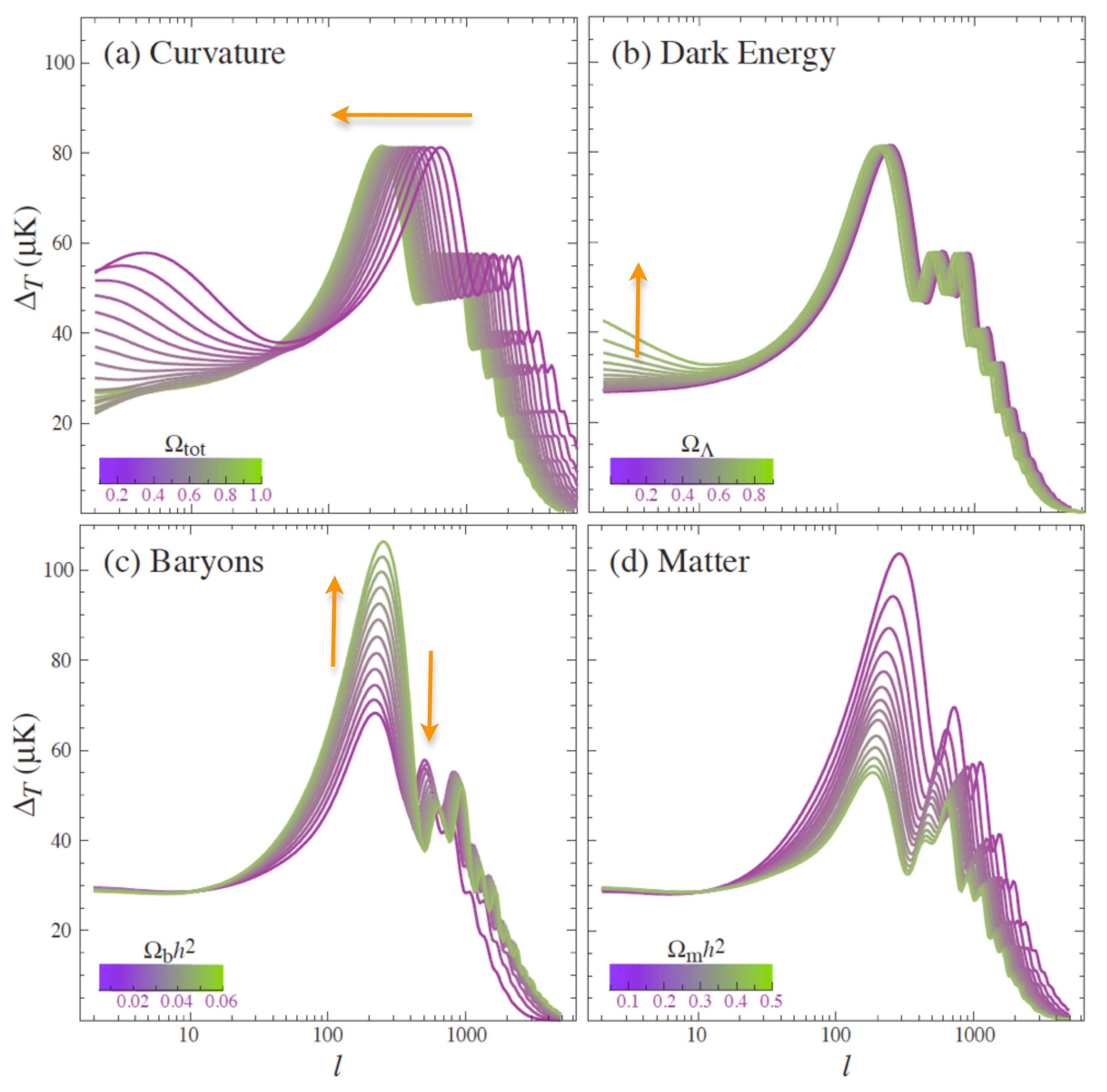
Cosmological Parameters

Ω_{tot}, Ω_m, Ω_b, Ω_Λ,
h, τ, n_s,...

Other cosmological Datasets:

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

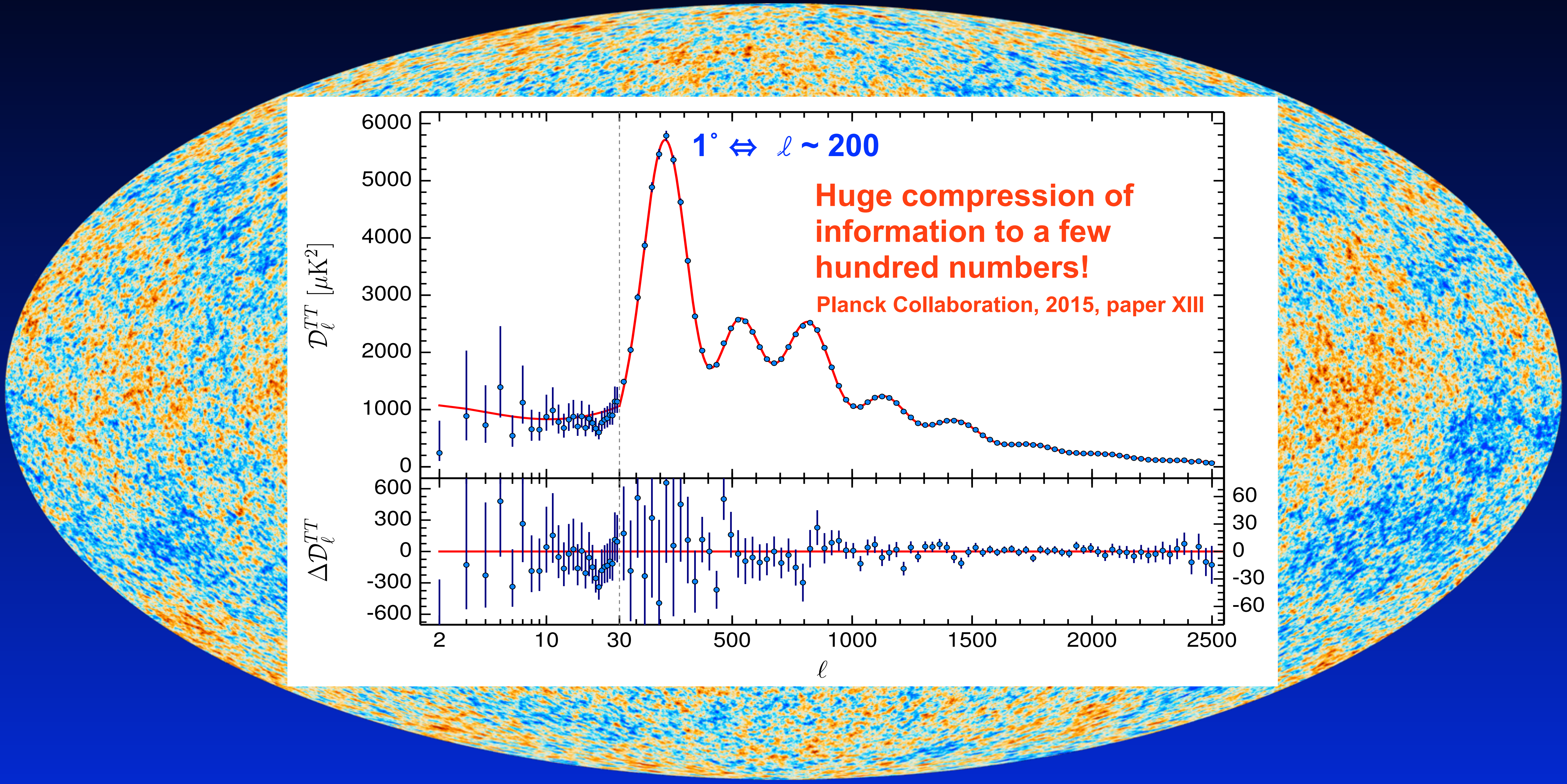
Dependence of the Power Spectrum on the Main Cosmological Parameters



Hu & Dodelson, 2002, ARAA

- **Total density (curvature)**
  → positions of peaks
- **dark energy**
  → ISW at large scales
- **Baryon density**
  → damping tail / peak heights and ratios
- **dark matter**
  → gravitational driving
  → enhancement of third over second peak
- **spectral index n_S and A_S**
  → overall tilt and amplitude of power spectrum
- **Thomson optical depth τ**
  → large scale E-modes
  → damping tail

Cosmic Microwave Background Anisotropies



1° ⇔ ℓ ~ 200

Huge compression of information to a few hundred numbers!

Planck Collaboration, 2015, paper XIII

Planck all-sky temperature map

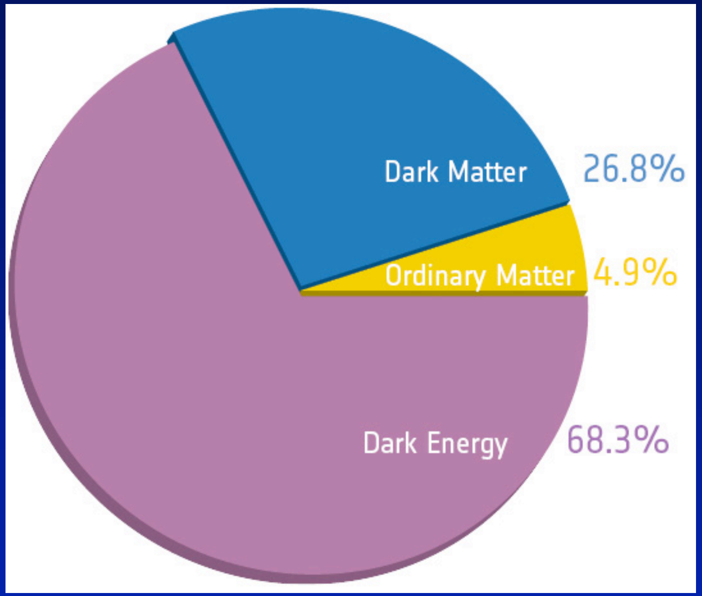
- CMB has a blackbody spectrum in every direction
- tiny variations of the CMB temperature $\Delta T/T \sim 10^{-5}$

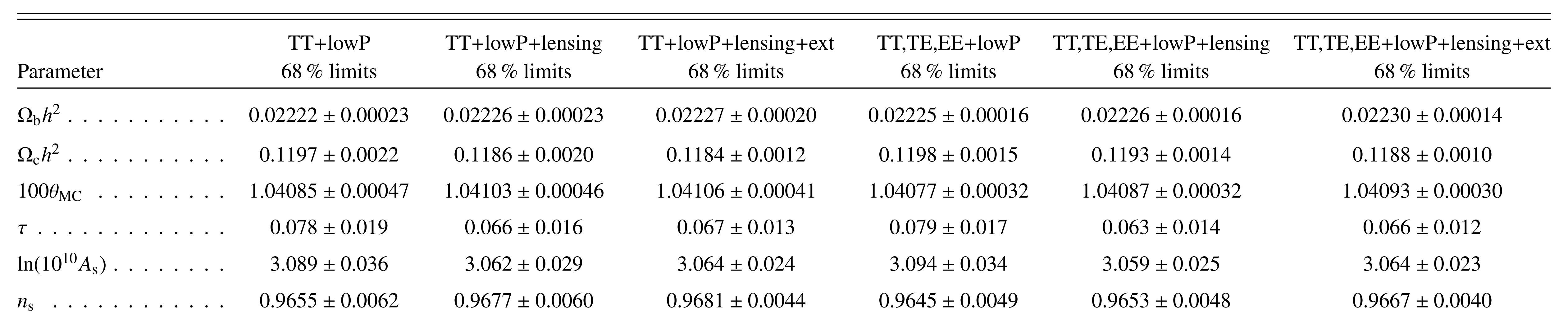
CMB anisotropies (with SN, LSS, etc...) clearly taught us a lot about the Universe we live in!

- Standard 6* parameter concordance cosmology with parameters known to percent level precision

* T_0 also parameter

- Gaussian-distributed adiabatic fluctuations with nearly scale-invariant power spectrum over a wide range of scales
- cold dark matter (“CDM”)
- accelerated expansion today (“Λ”)
- Standard BBN scenario → $N_{\rm eff}$ and $Y_{\rm p}$
- Standard ionization history → $N_{\rm e}(z)$

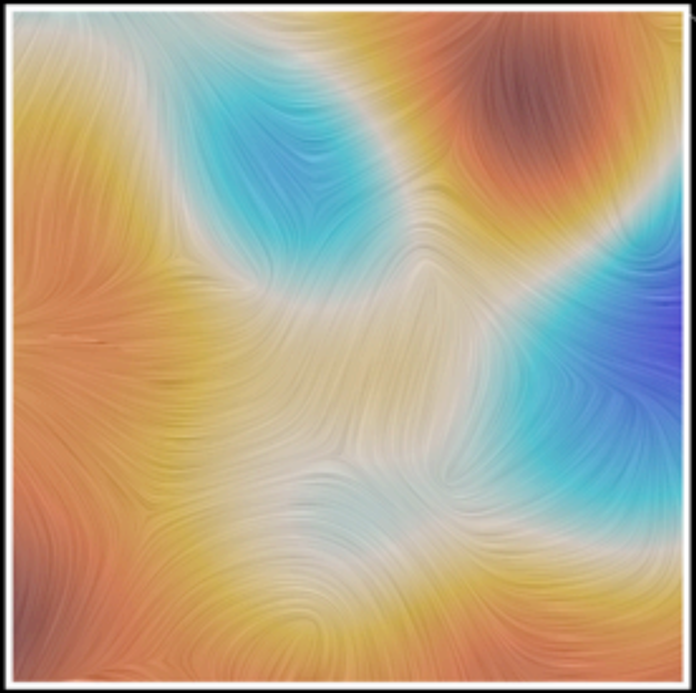


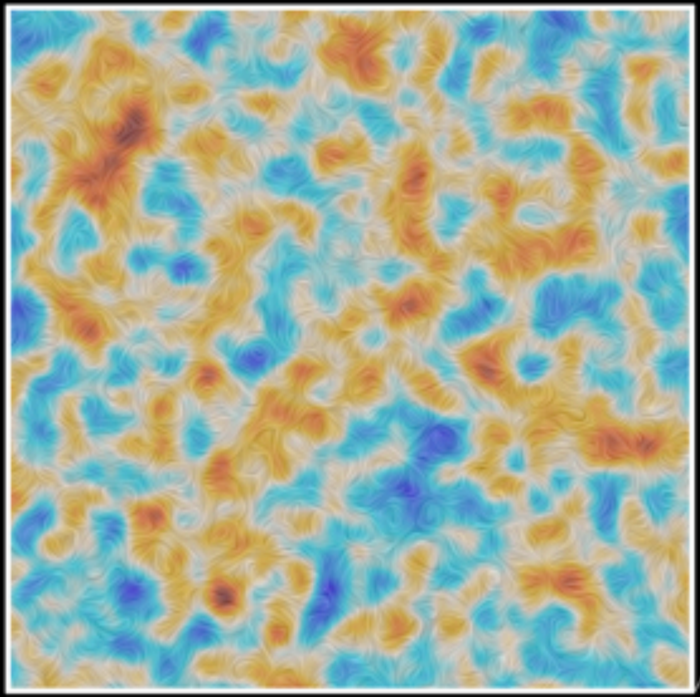


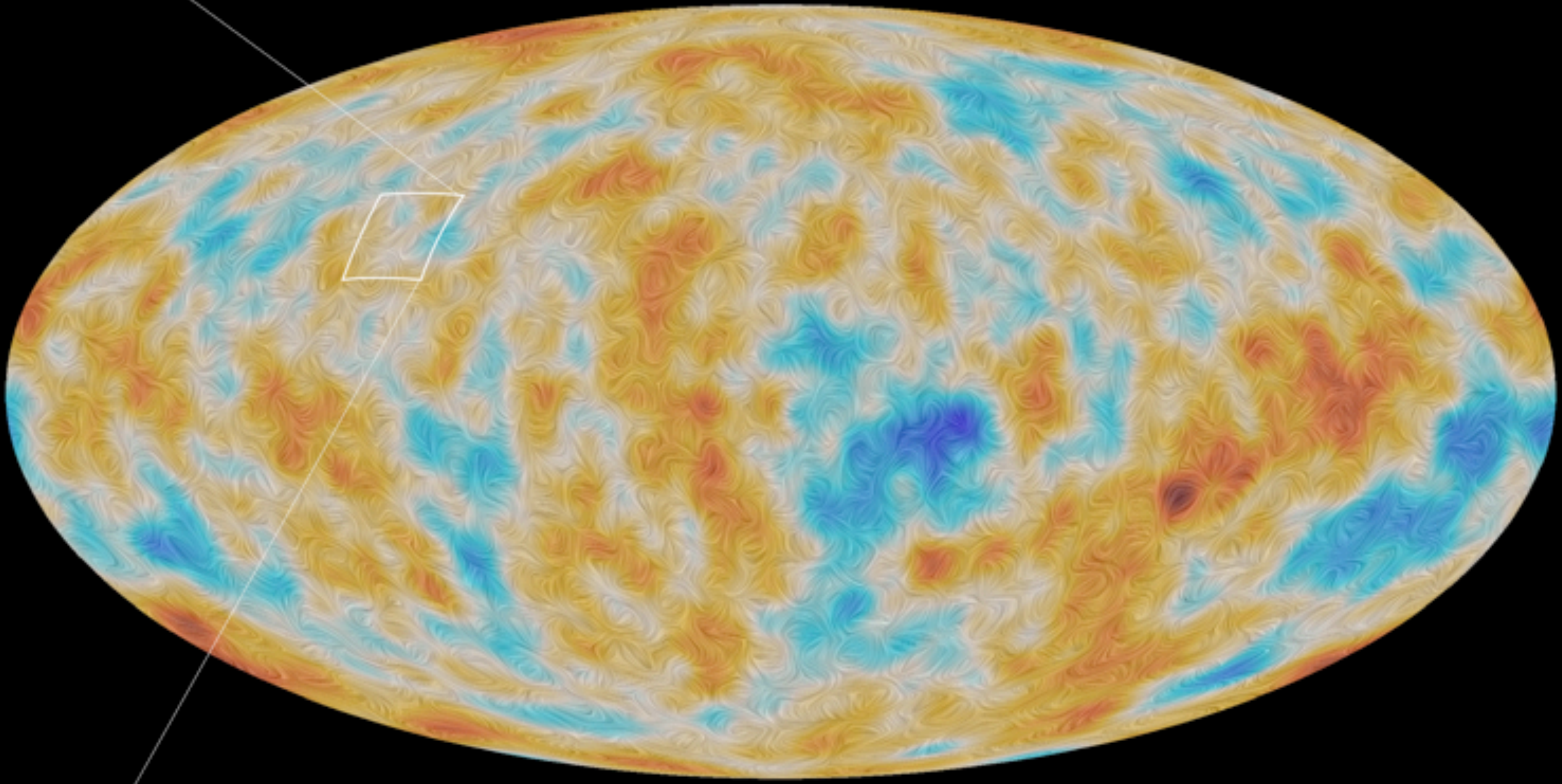
Parameter	TT+lowP 68 % limits	TT+lowP+lensing 68 % limits	TT+lowP+lensing+ext 68 % limits	TT,TE,EE+lowP 68 % limits	TT,TE,EE+lowP+lensing 68 % limits	TT,TE,EE+lowP+lensing+ext 68 % limits
$\Omega_{\rm b}h^2$	0.02222 ± 0.00023	0.02226 ± 0.00023	0.02227 ± 0.00020	0.02225 ± 0.00016	0.02226 ± 0.00016	0.02230 ± 0.00014
$\Omega_{\rm c}h^2$	0.1197 ± 0.0022	0.1186 ± 0.0020	0.1184 ± 0.0012	0.1198 ± 0.0015	0.1193 ± 0.0014	0.1188 ± 0.0010
$100\theta_{\rm MC}$	1.04085 ± 0.00047	1.04103 ± 0.00046	1.04106 ± 0.00041	1.04077 ± 0.00032	1.04087 ± 0.00032	1.04093 ± 0.00030
τ	0.078 ± 0.019	0.066 ± 0.016	0.067 ± 0.013	0.079 ± 0.017	0.063 ± 0.014	0.066 ± 0.012
$\ln(10^{10}A_{\rm s})$	3.089 ± 0.036	3.062 ± 0.029	3.064 ± 0.024	3.094 ± 0.034	3.059 ± 0.025	3.064 ± 0.023
$n_{\rm s}$	0.9655 ± 0.0062	0.9677 ± 0.0060	0.9681 ± 0.0044	0.9645 ± 0.0049	0.9653 ± 0.0048	0.9667 ± 0.0040

Planck Collaboration, 2015, paper XIII

→ PLANCK'S POLARISATION OF THE COSMIC MICROWAVE BACKGROUND

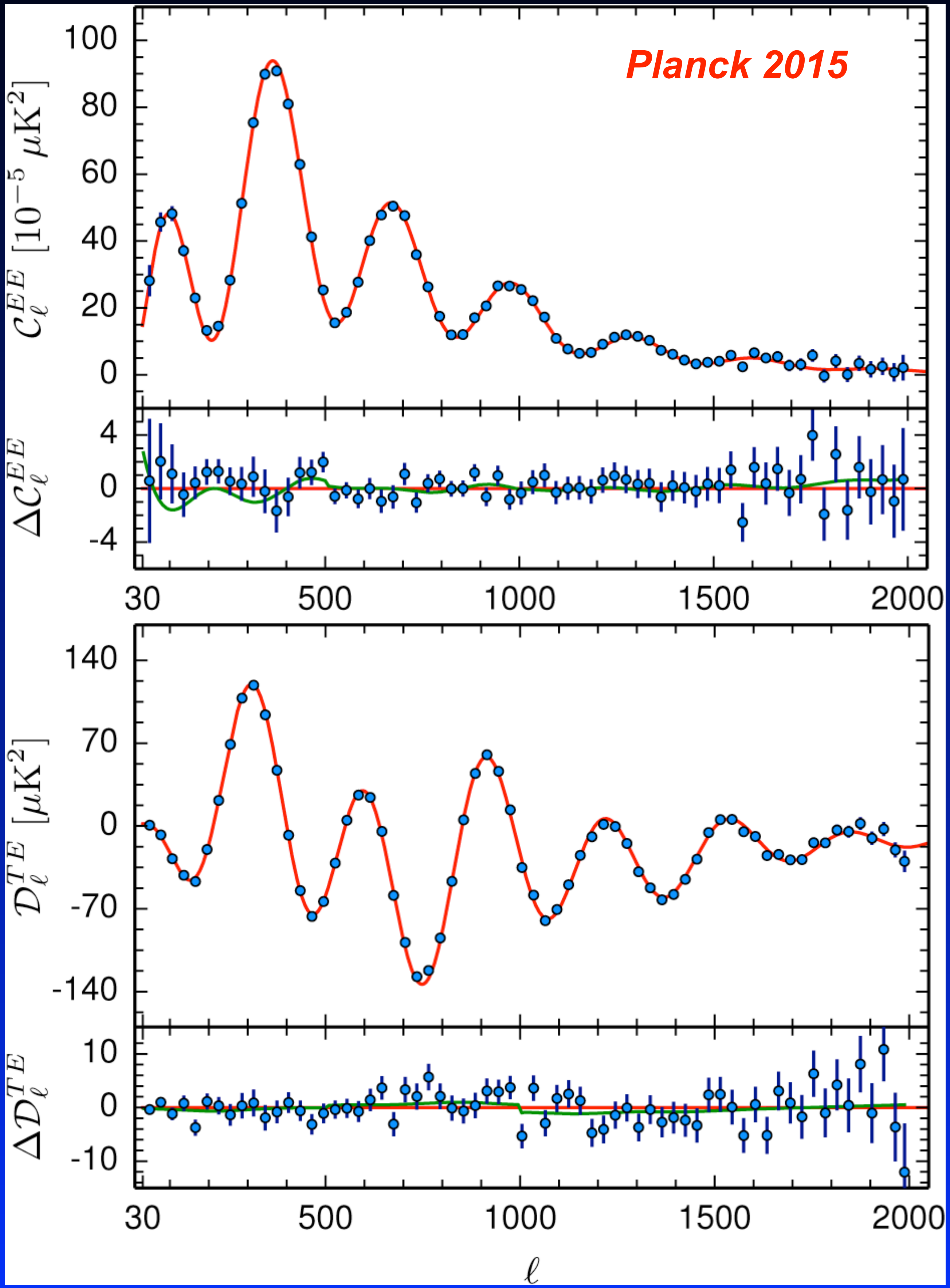

Filtered at 5 degrees

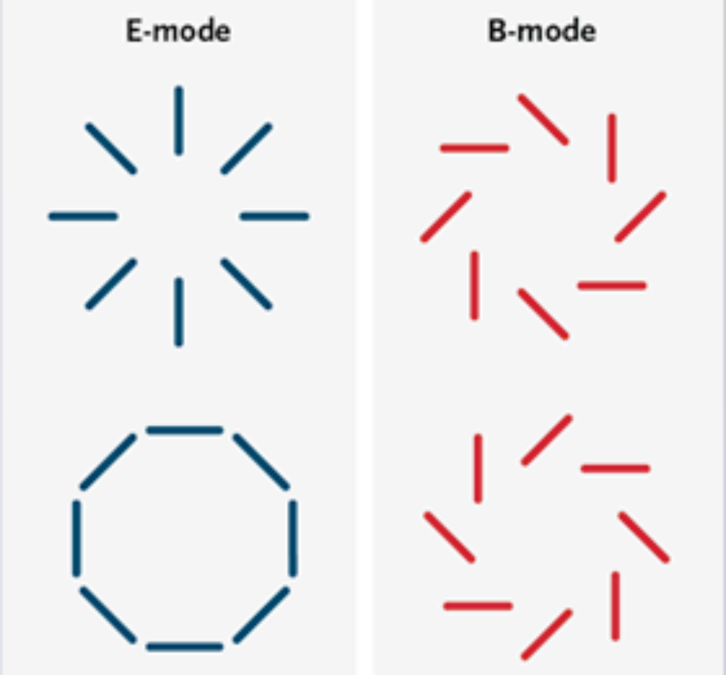

Filtered at 20 arcminutes


Full sky map

Filtered at 5 degrees

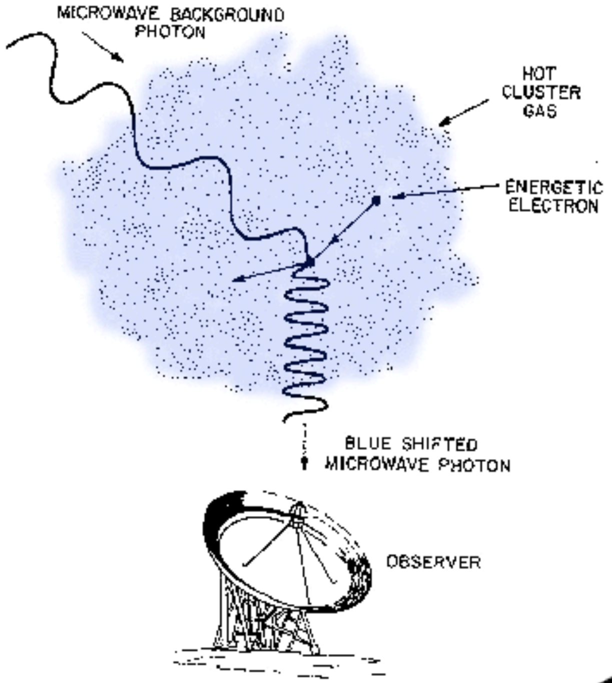
Beautiful measurements of CMB E-modes!

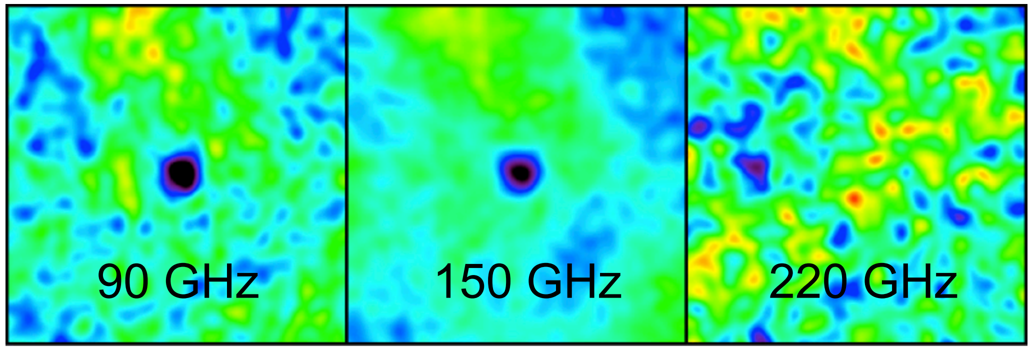




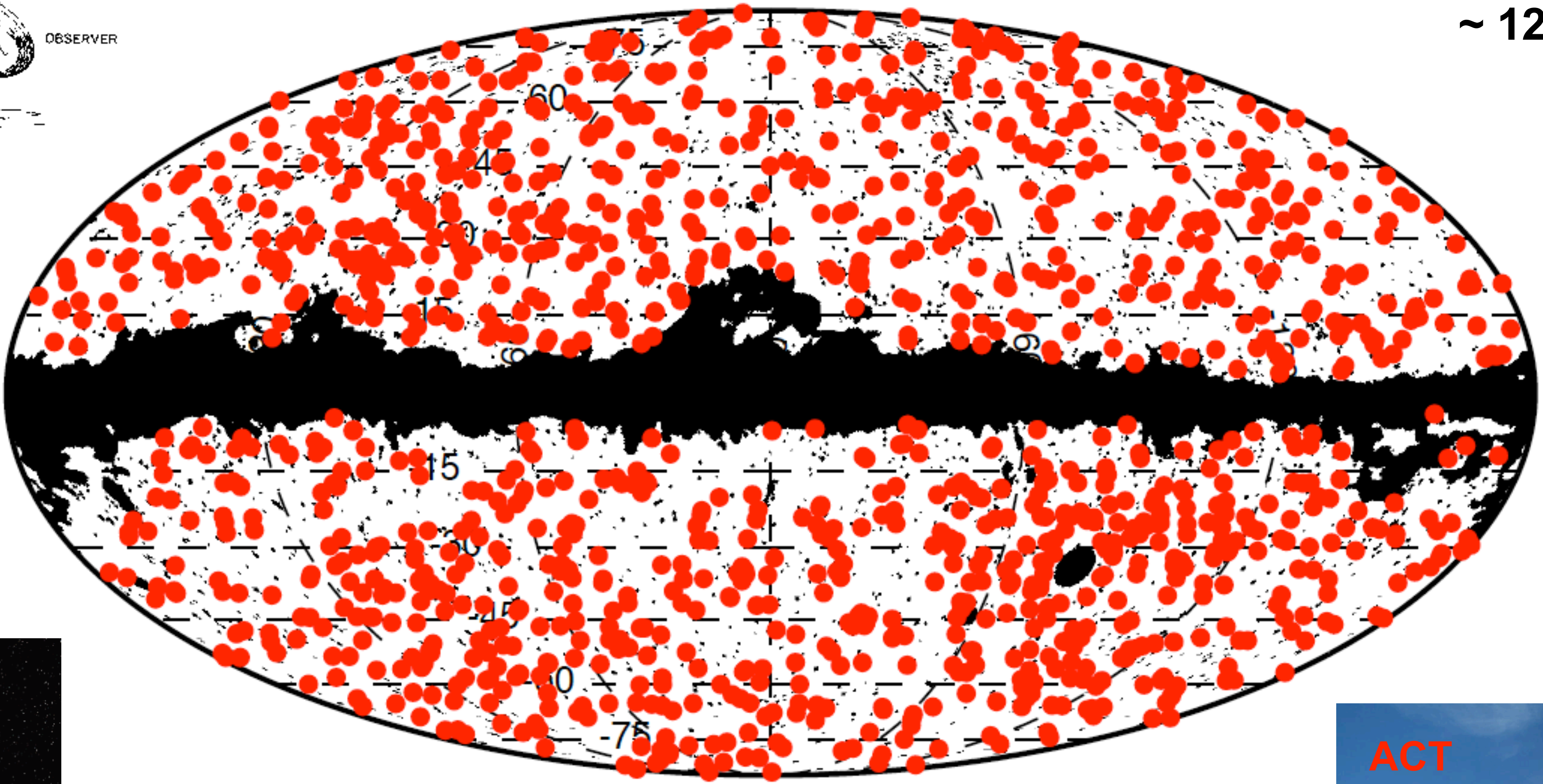
- E-modes generated by scalar perturbations
- B-modes sourced by tensors
  ⇒ *gravitational waves / inflation*
- observed E-modes match model predicted from best-fit temperature power spectrum!

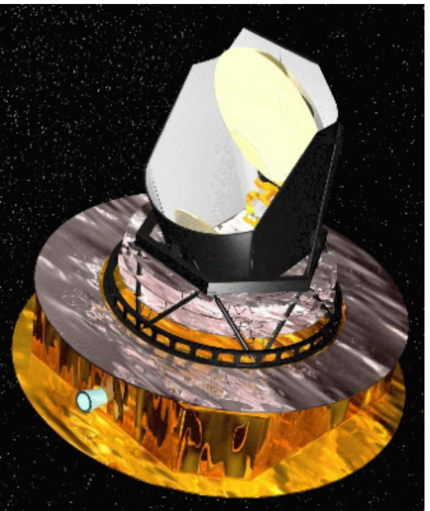
Thermal SZ effect is now routinely observed!





~ 1230 objects

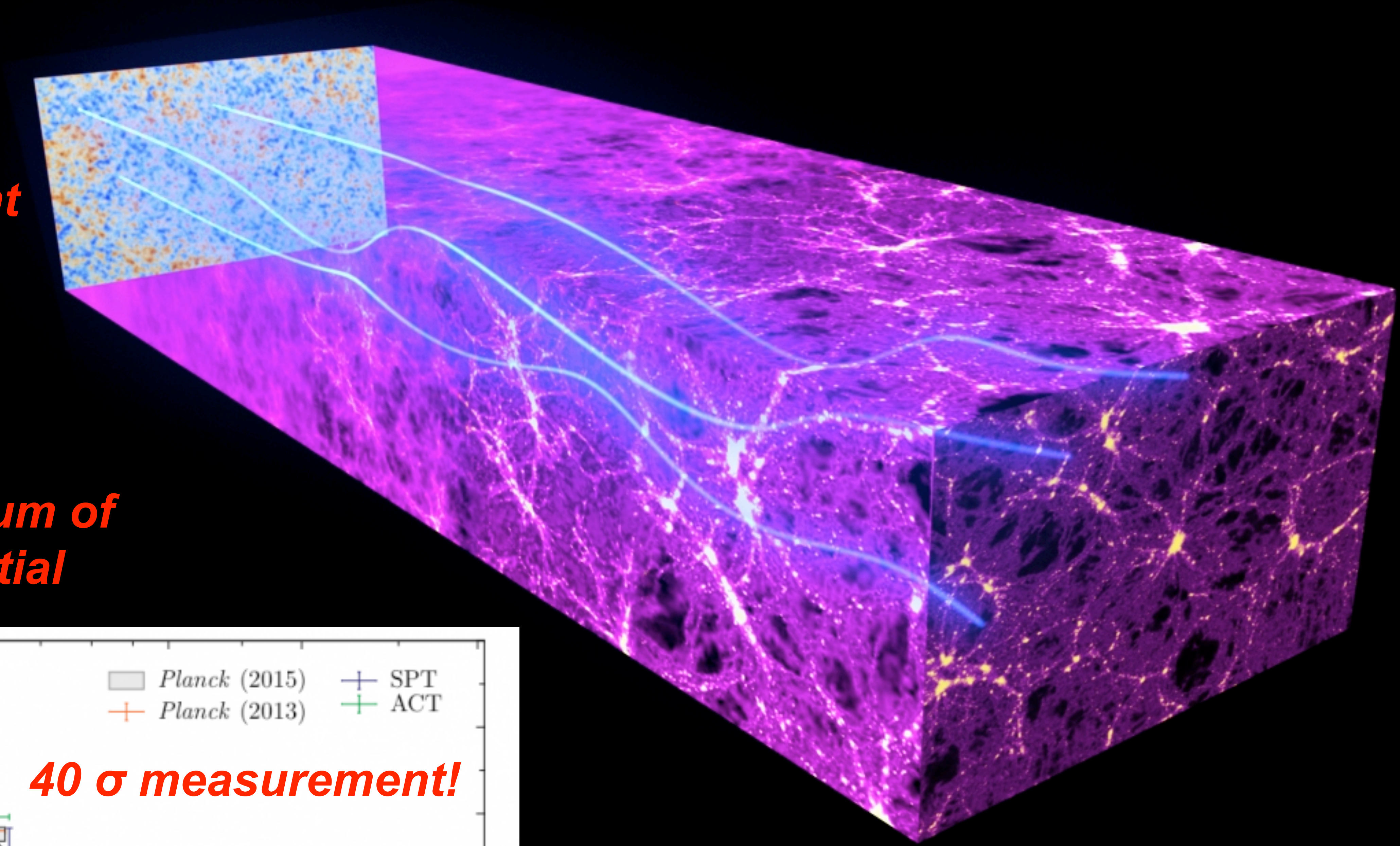




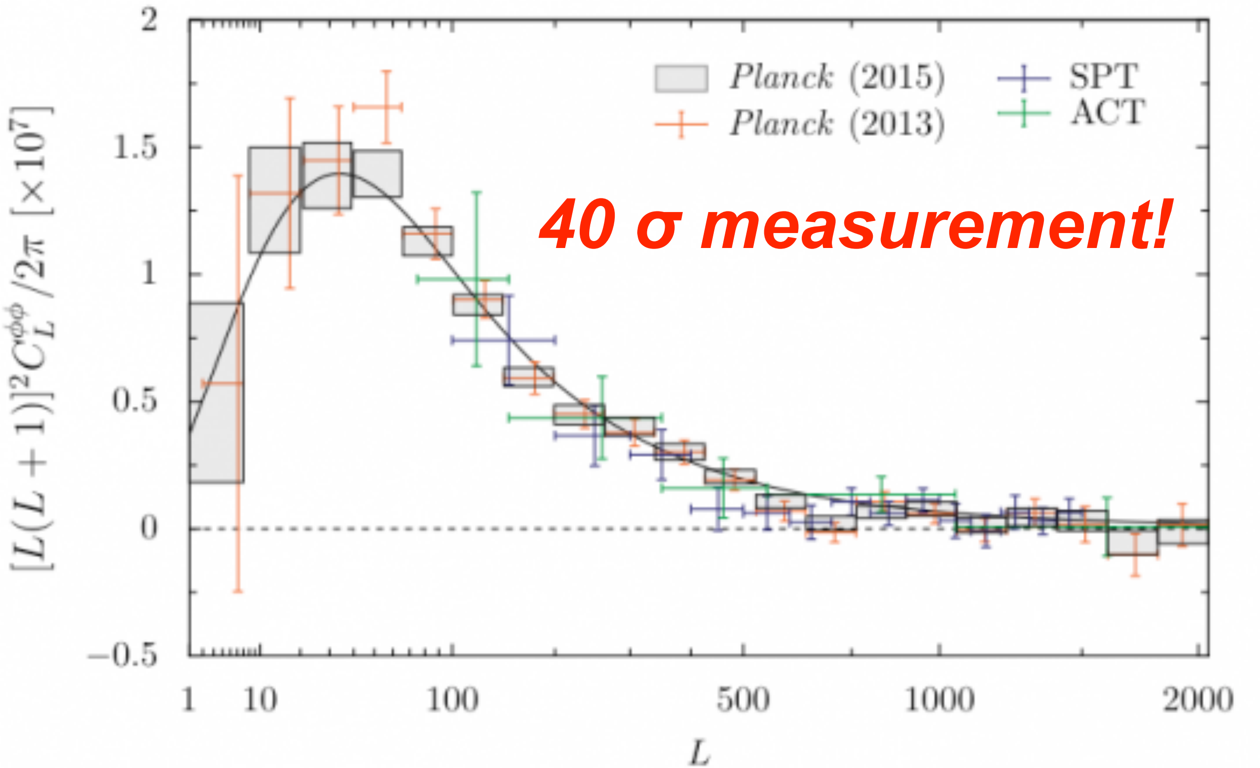
Planck Collaboration, 2013, paper XXIV

CMB lensing

CMB serves as background light



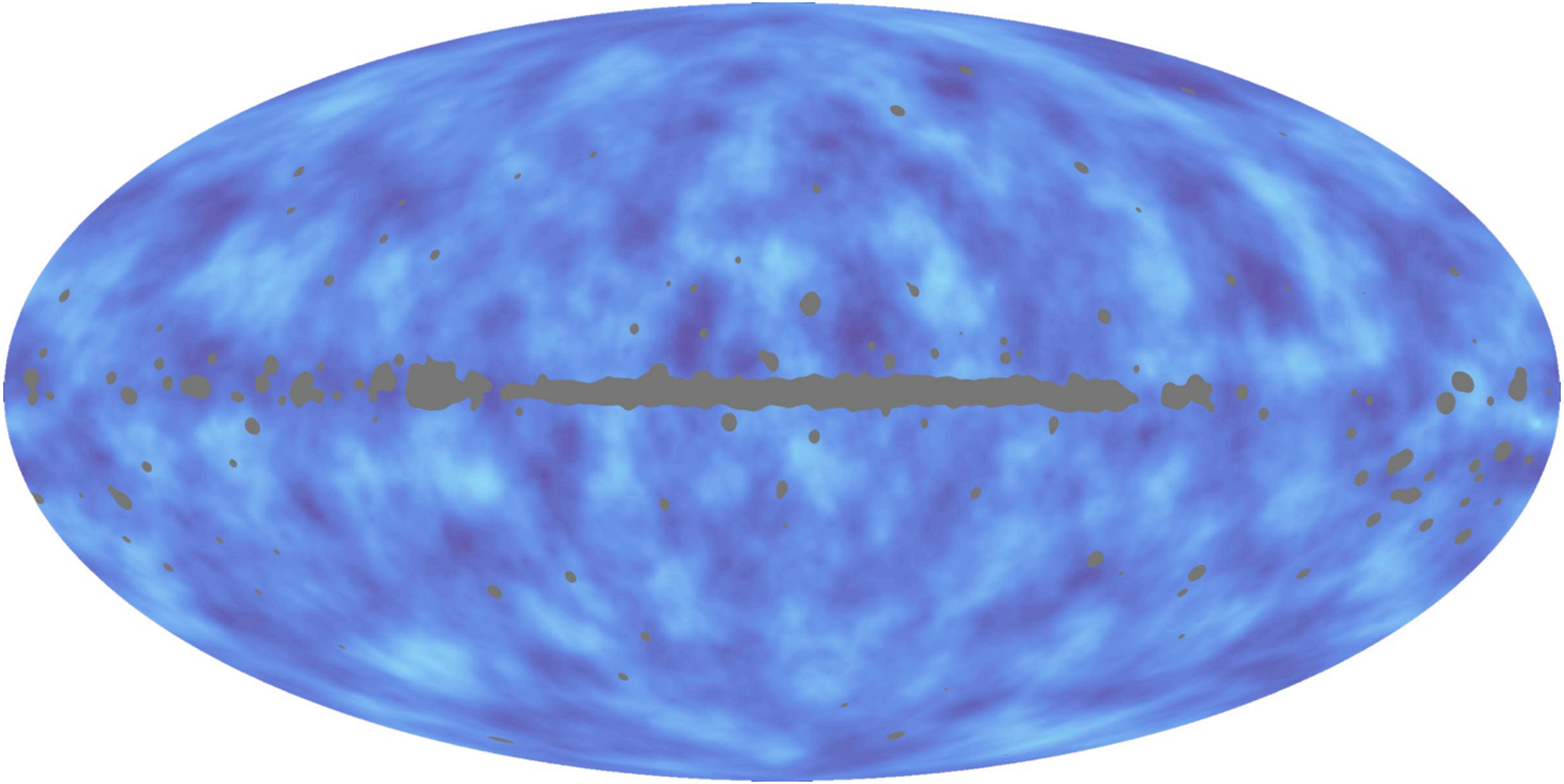
Power spectrum of lensing potential



40 σ measurement!

Higher order statistics of CMB reveal presence of lenses

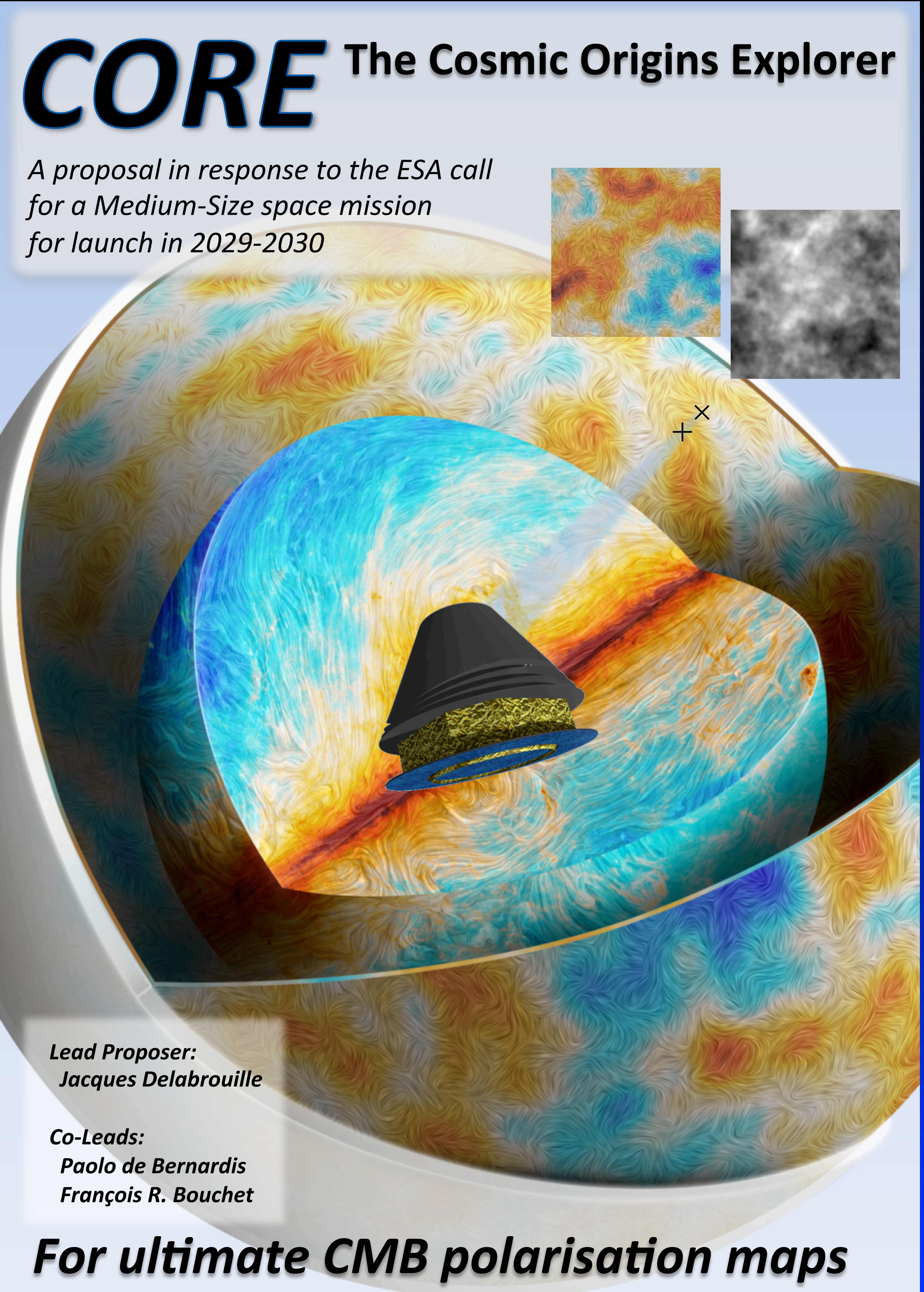
First real map of the lensing potential!



Distribution of mass in the Universe at large scales

Planck Collaboration, 2015, paper XV

What are the next steps for CMB anisotropies?



CORE The Cosmic Origins Explorer

A proposal in response to the ESA call
for a Medium-Size space mission
for launch in 2029-2030

Lead Proposer:
Jacques Delabrouille

Co-Leads:
Paolo de Bernardis
François R. Bouchet

For ultimate CMB polarisation maps

- M-class ESA mission (M5 call)
- Proposal in 2016 (not selected)
- L2 orbit
- Large European collaboration
- Possible collaboration with JAXA (→ *Litebird*) was discussed
- ~550 MEuro + ~150MEuro

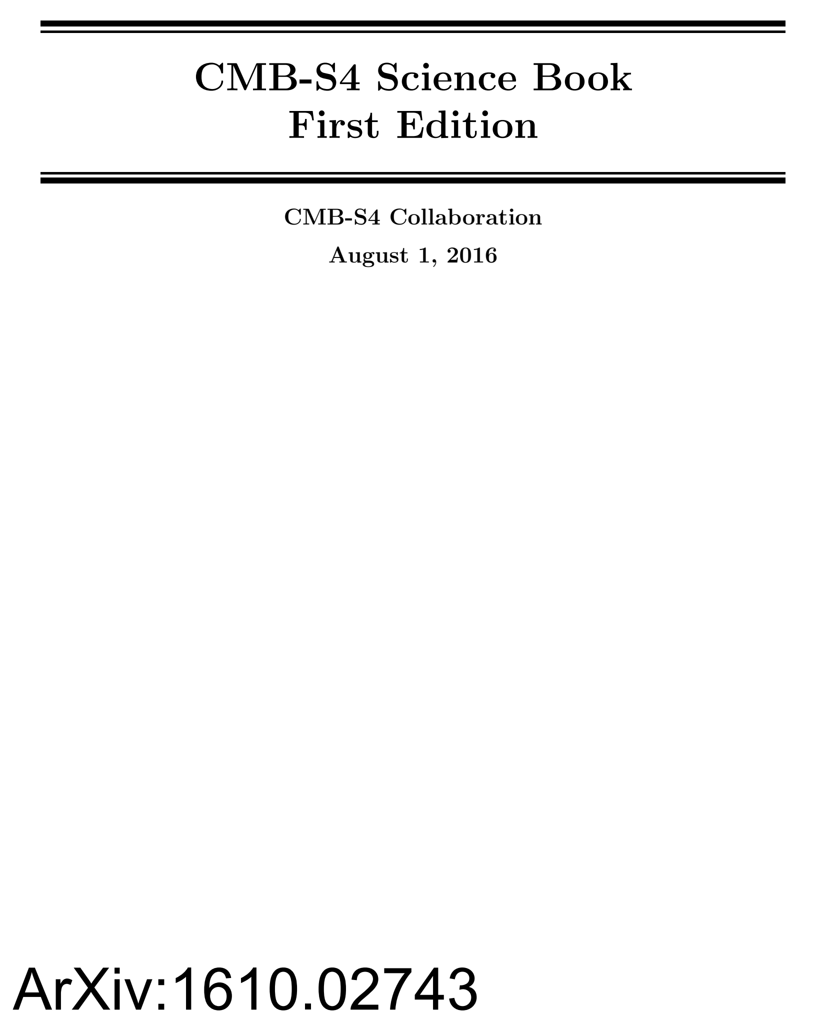
Some of the science goals:

- B-mode polarization from inflation ($r \approx 10^{-3}$)
- SZ clusters
- CIB/large-scale structure
- CMB lensing
- Galactic science

Other space missions on the horizon

➡ *PIXIE*
➡ *Litebird*

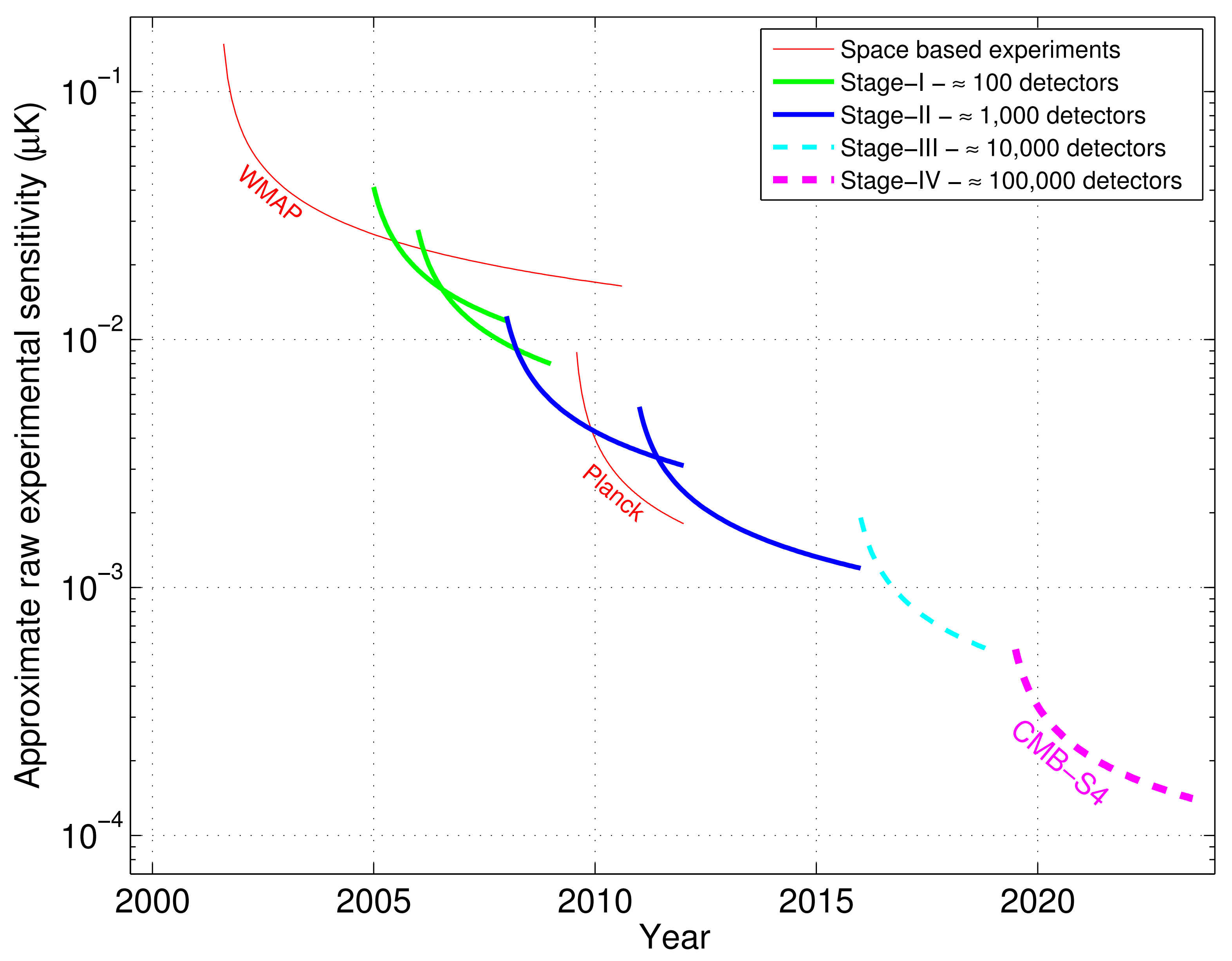
Stage IV CMB



CMB-S4 Science Book
First Edition

CMB-S4 Collaboration
August 1, 2016

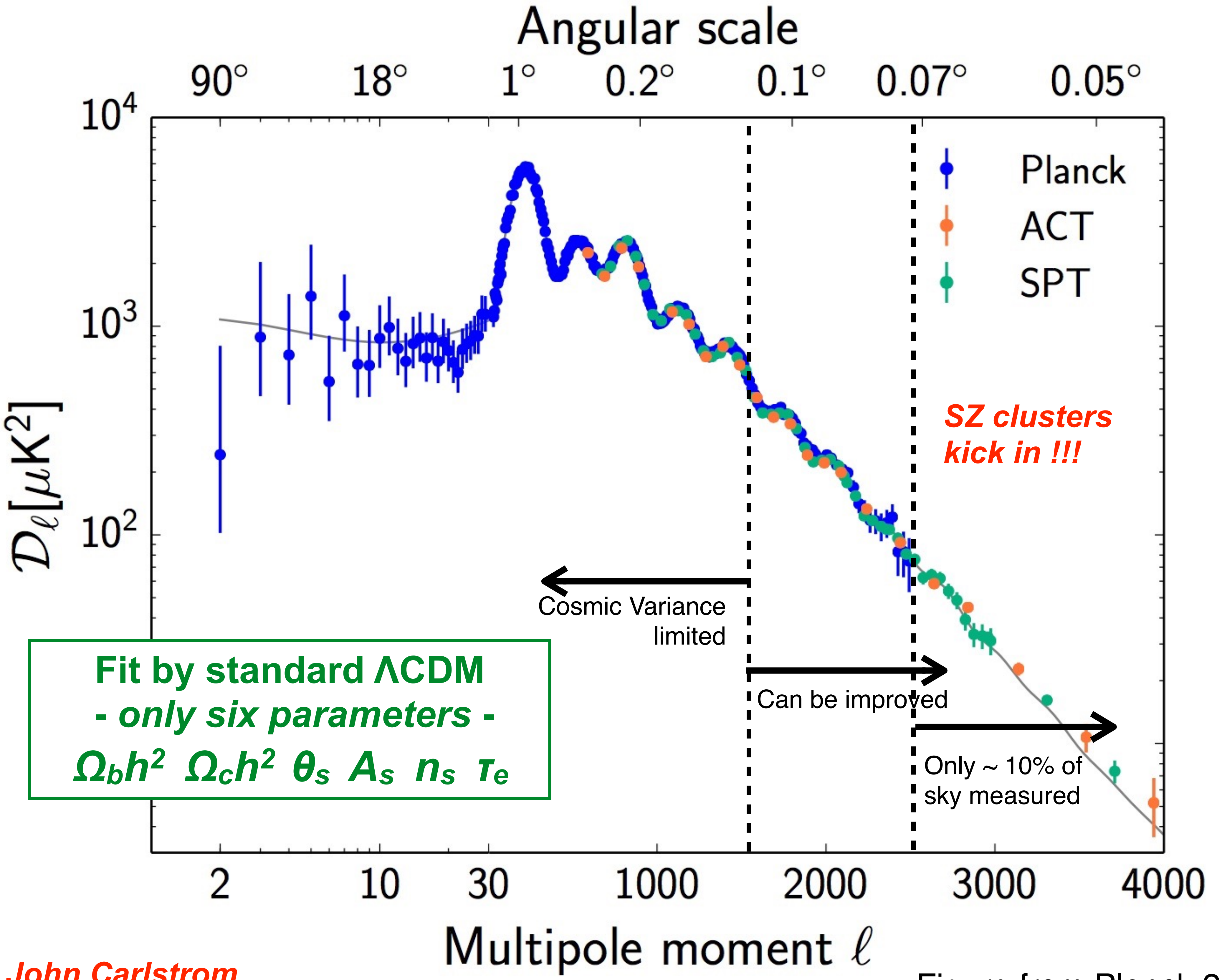
ArXiv:1610.02743



What are the *main* next targets for CMB anisotropies?

- CMB temperature power spectrum kind of finished...

Status of primary CMB TT measurements



SZ clusters kick in !!!

Cosmic Variance
limited

Can be improved

Only ~ 10% of
sky measured

Fit by standard ΛCDM
- only six parameters -
$\Omega_b h^2$ $\Omega_c h^2$ θ_s A_s n_s τ_e

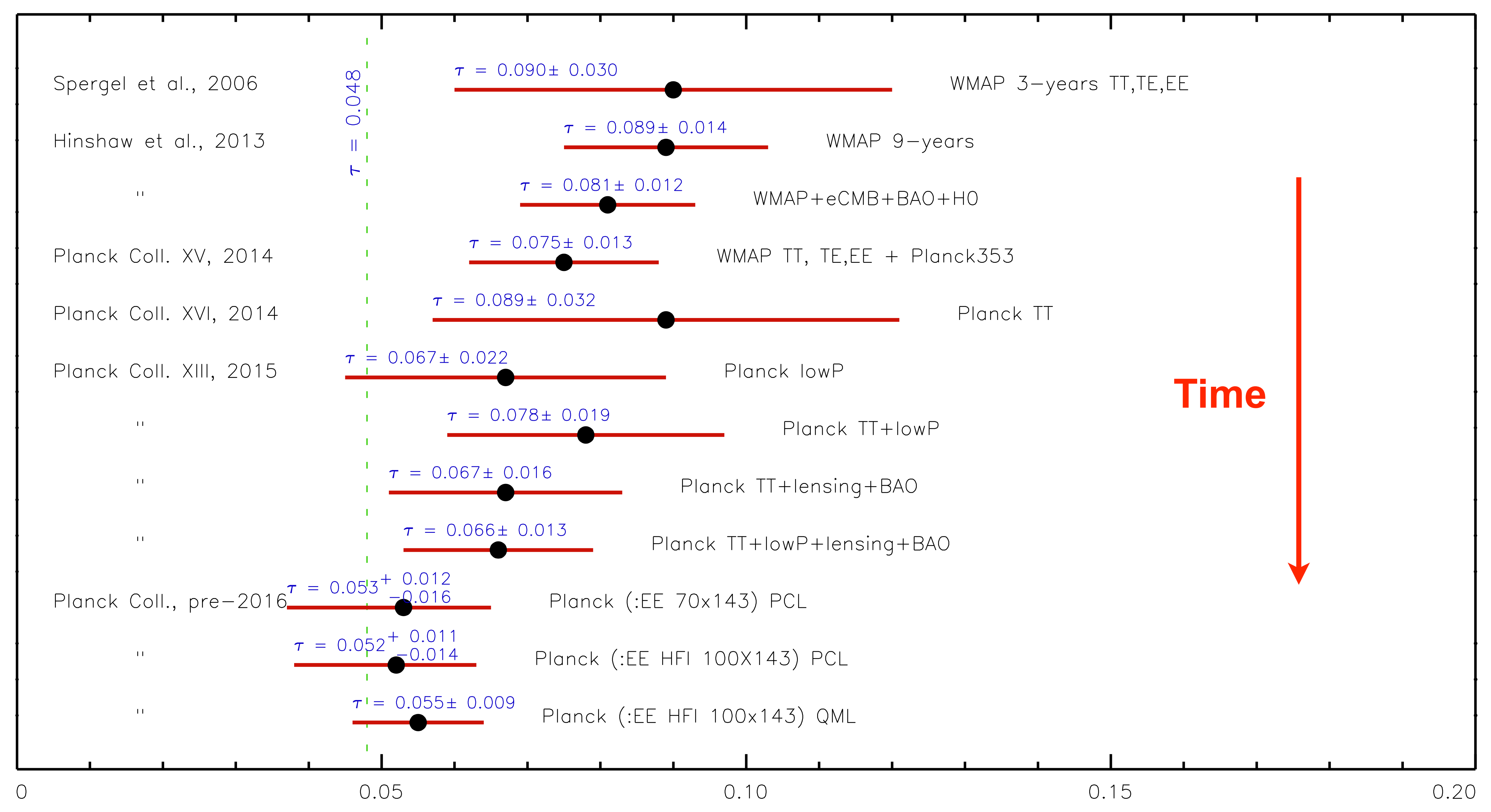
Courtesy John Carlstrom

Figure from Planck 2015 Results XI

What are the *main* next targets for CMB anisotropies?

- CMB temperature power spectrum kind of finished...
- E modes cosmic variance limited to high-l
  - better constraint on τ from large-scale E modes
  - refined CMB damping tail science from small-scale E modes
  - CMB lensing and de-lensing of primordial B-modes

Constraints on the Thomson optical depth

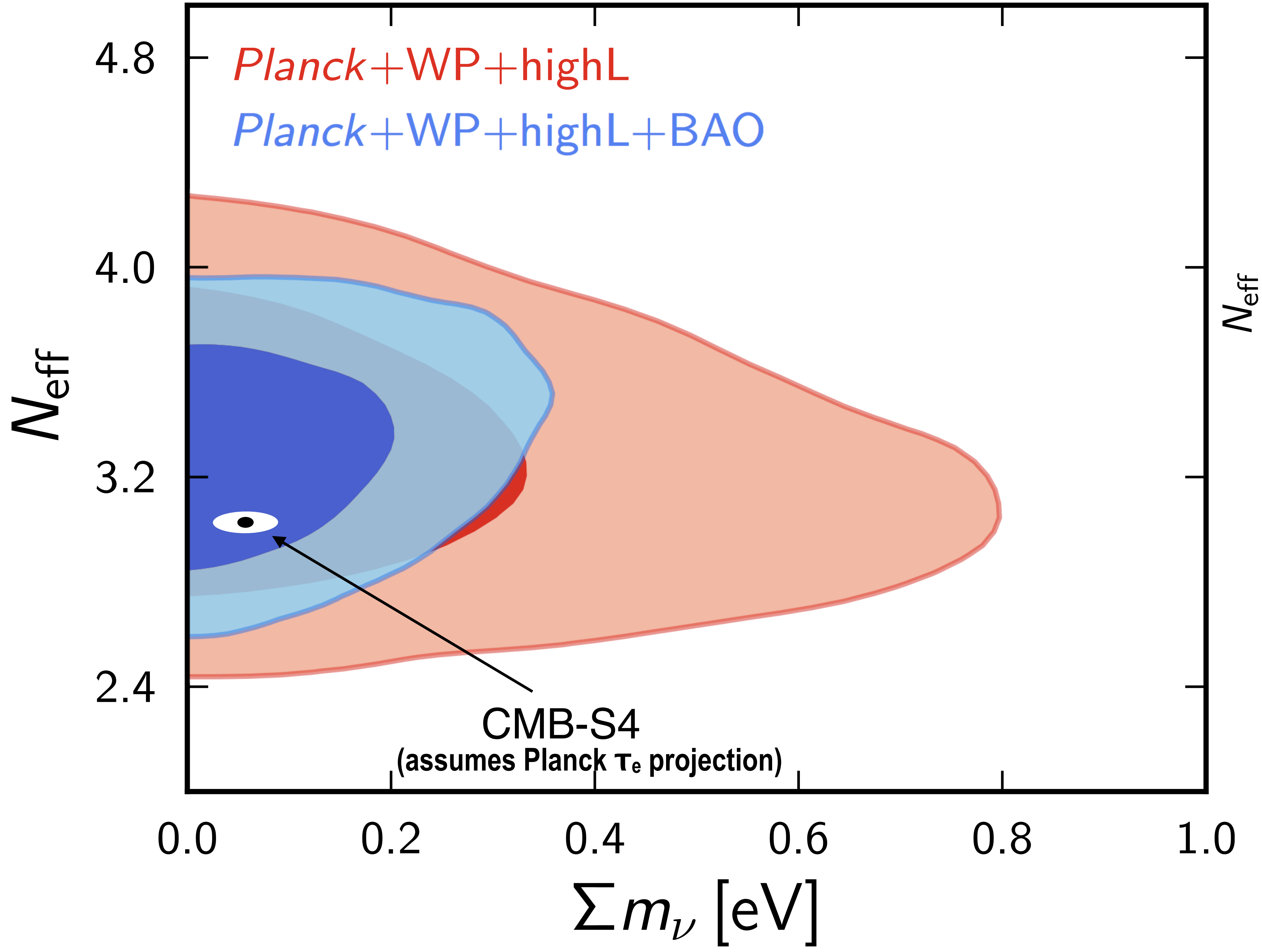


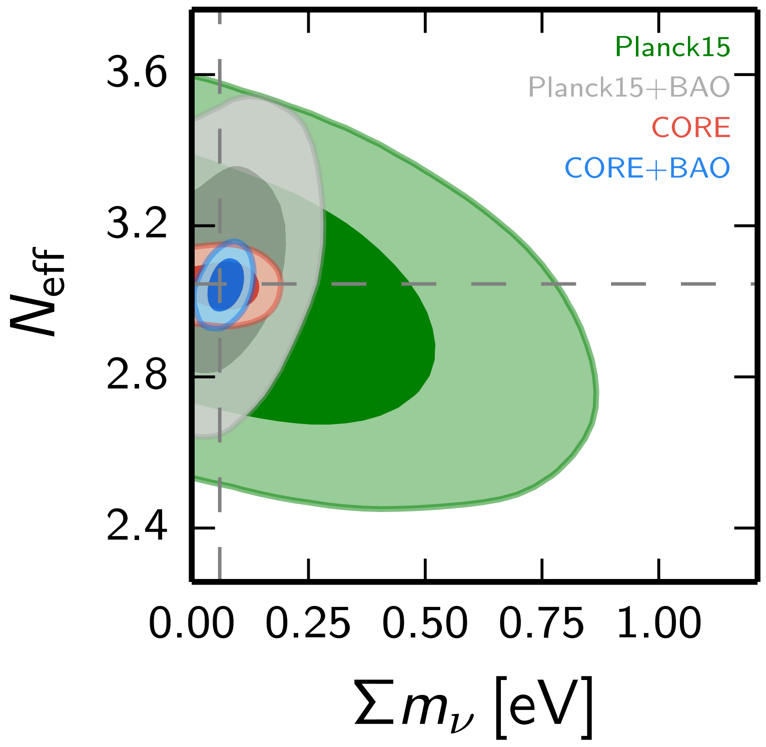
Planck Collaboration, 2016, paper XLVI

Clear sign of remaining systematics....

CMB-S4
Next Generation CMB Experiment

Projected CMB-S4 N_{eff} - Σm_ν constraints





CORE forecast....

Constraint on optical depth crucial !!!
⇒ space

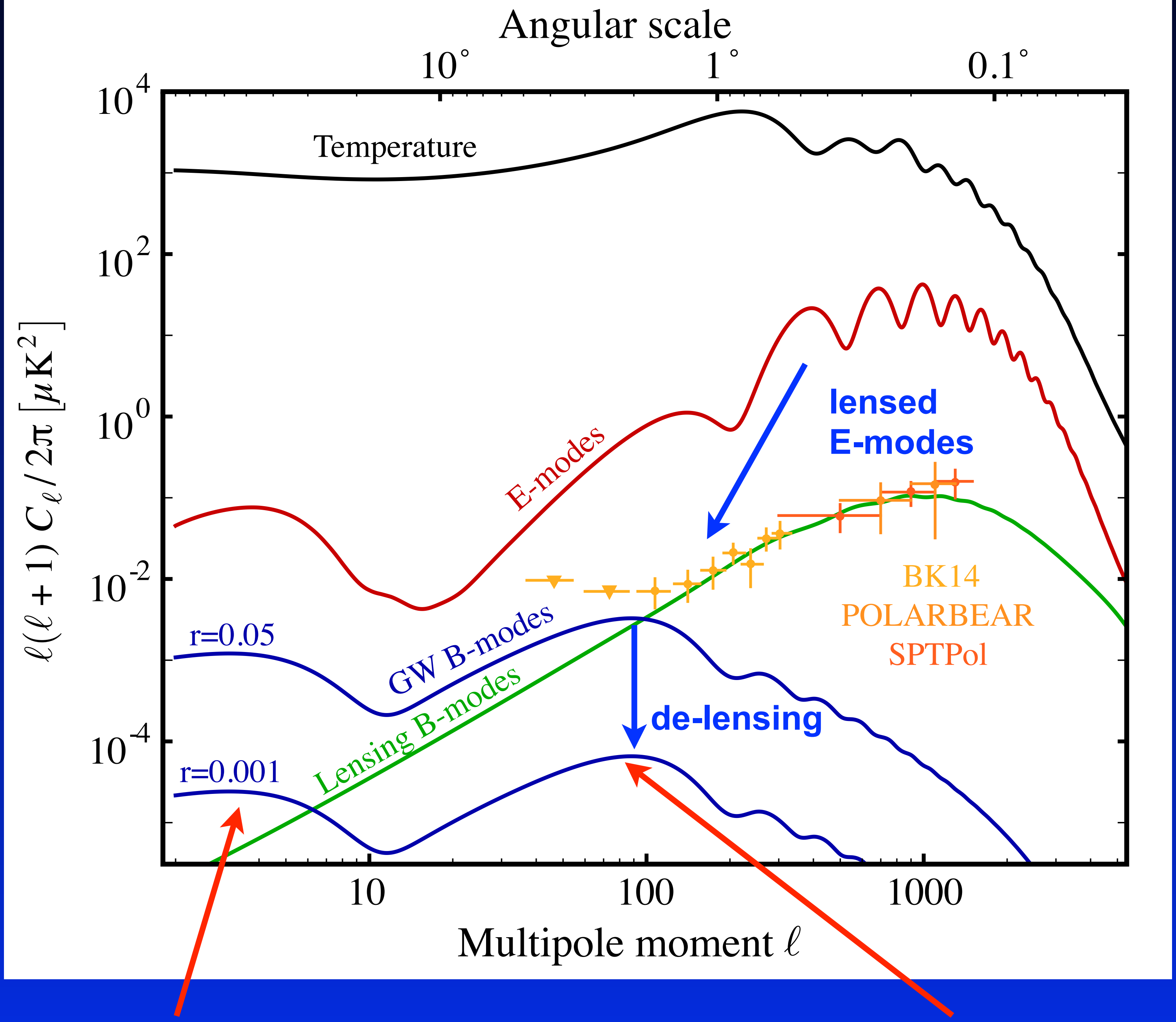
CMB-S4 forecast: arXiv:1309.5383; see also Wu et al, ApJ 788,138 (2014)*

Courtesy John Carlstrom

What are the *main* next targets for CMB anisotropies?

- CMB temperature power spectrum kind of finished...
- E modes cosmic variance limited to high-l
  - better constraint on τ from large scale E modes
  - refined CMB damping tail science from small-scale E modes
  - CMB lensing and de-lensing of primordial B-modes
- primordial B modes
  - detection of $r \sim 10^{-3}$ *(energy scale of inflation)*
  - upper limit on $n_T < O(0.1)$ as additional ‘proof of inflation’

E and B mode signals and targets



- *no clear target* for B-mode amplitude!
- foreground challenge is extreme
- to obtain constraints on n_T recombination bump is needed
- Still quite a long way to go to reach primordial B-modes

Reionization bump targeted by *CLASS, PIXIE, Litebird*

Recombination bump target of *Stage-IV CMB*

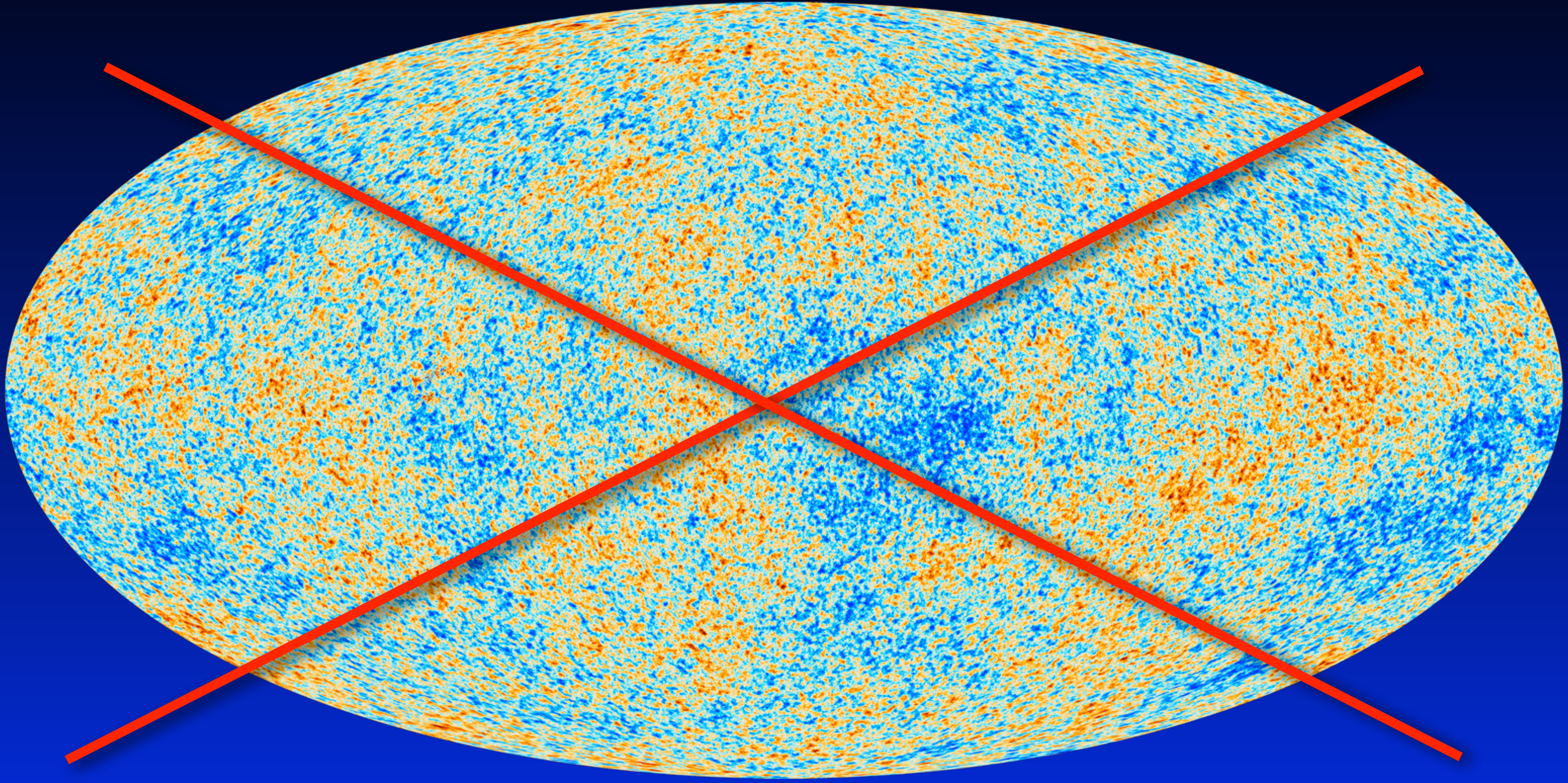
What are the *main* next targets for CMB anisotropies?

- CMB temperature power spectrum kind of finished...
- E modes cosmic variance limited to high-l
  - better constraint on τ from large scale E modes
  - refined CMB damping tail science from small-scale E modes
  - CMB lensing and de-lensing of primordial B-modes
- primordial B modes
  - detection of $r \sim 10^{-3}$ *(energy scale of inflation)*
  - upper limit on $n_T < O(0.1)$ as additional ‘proof of inflation’
- CMB anomalies
  - stationarity of E and B-modes, lensing potential, etc across the sky
- SZ cluster science
  - large cluster samples and (individual) high-res cluster measurements

➡ *CORE*
➡ *PIXIE*
➡ *Litebird*
➡ *CMB S4*

A bright and exciting future with lots of competition!

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

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

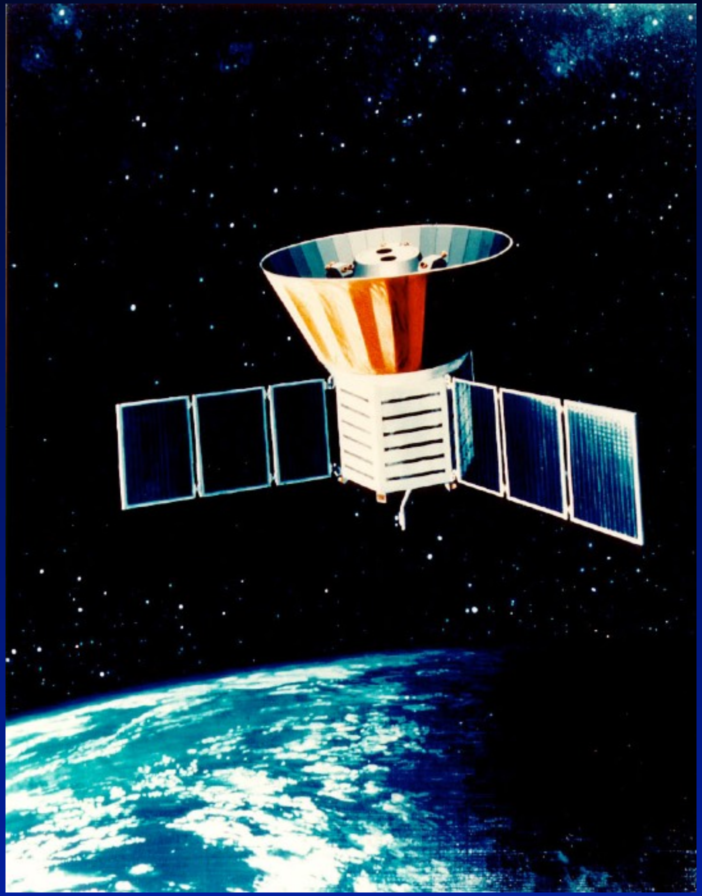
Absolute measurement required!

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)

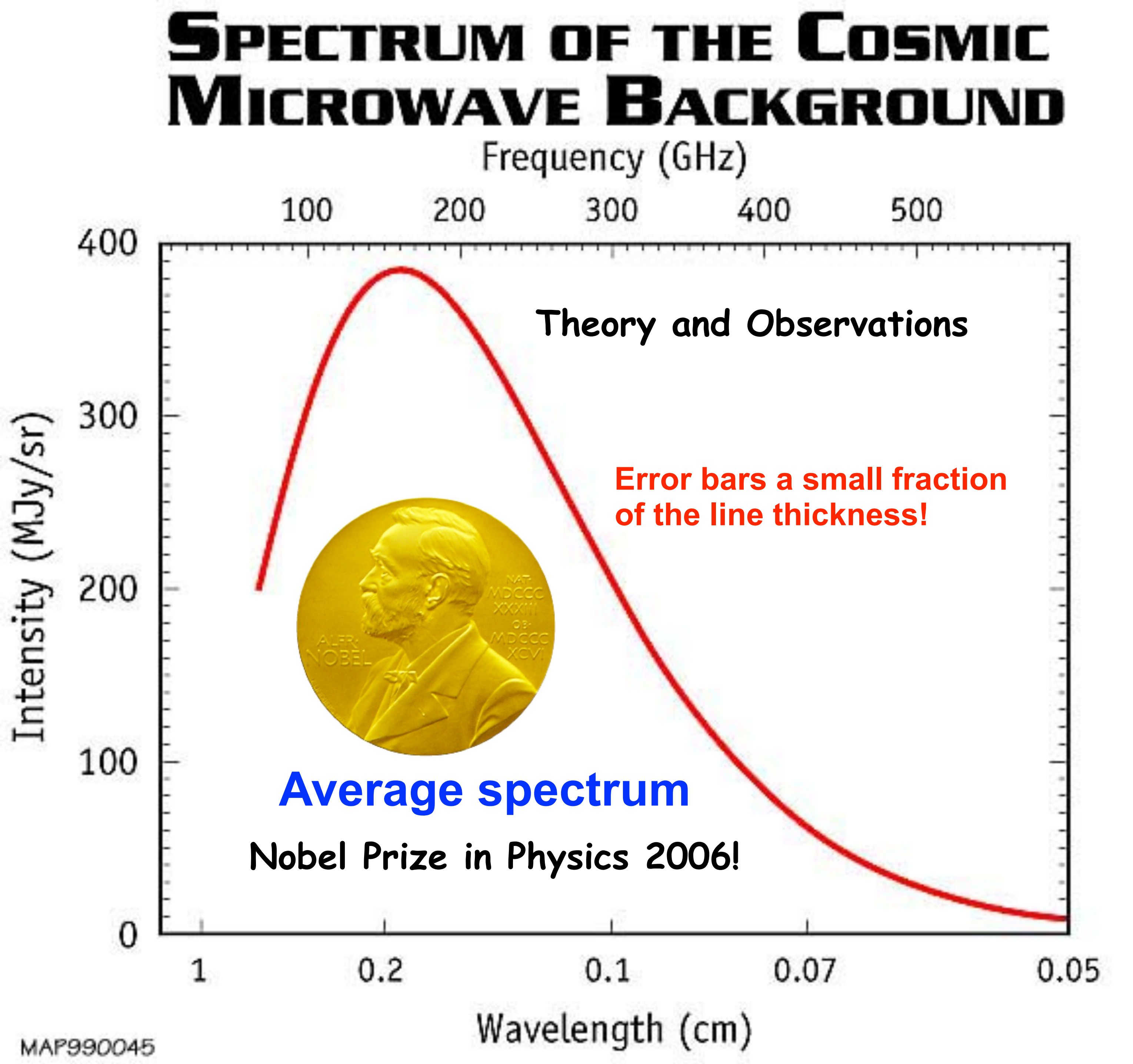


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

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

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



SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND

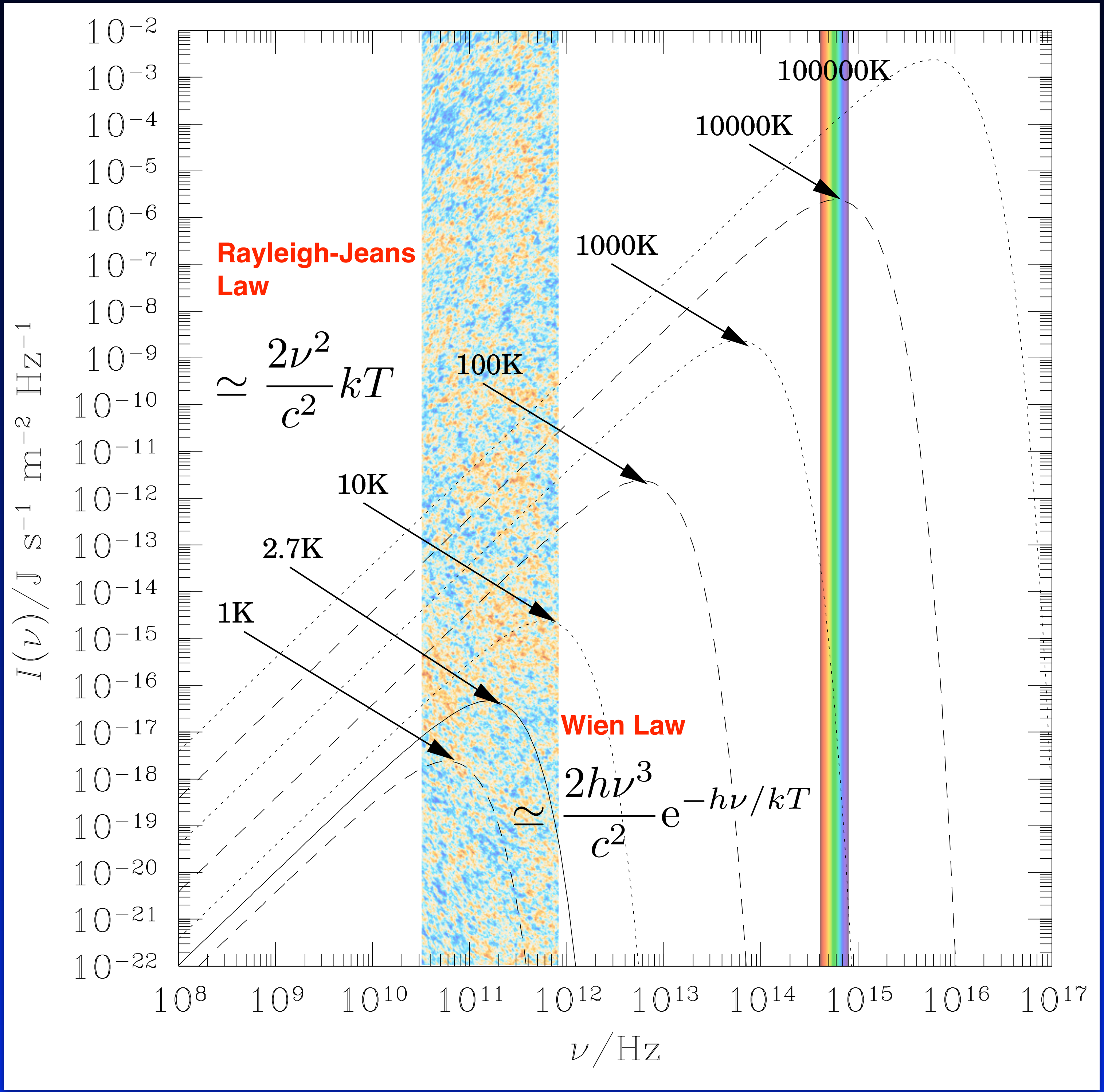
Theory and Observations

Error bars a small fraction of the line thickness!

Average spectrum

Nobel Prize in Physics 2006!

Simple Blackbody Properties



Photon occupation number

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\, n_\nu(T)$$
$$= \frac{2h}{c^2}\,\frac{\nu^3}{\mathrm{e}^{h\nu/kT}-1}$$
$$= I_o\,\frac{x^3}{\mathrm{e}^x-1}$$

$$I_o = \frac{2h}{c^2}\left(\frac{kT}{h}\right)^3$$
$$\approx 270\,\mathrm{MJy\,sr^{-1}}\left[\frac{T}{2.725\mathrm{K}}\right]^3$$

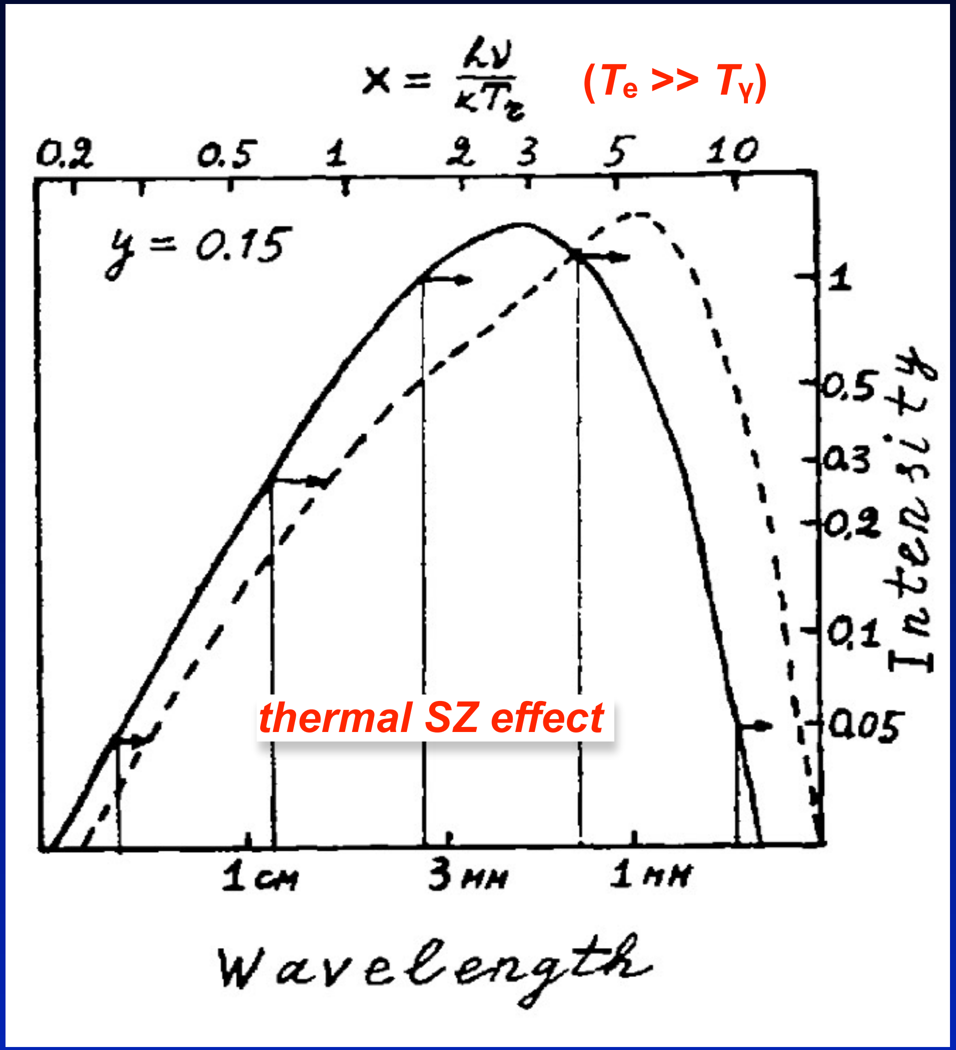
(1 Jy = 10^{-26} J $\mathrm{s^{-1}}$ $\mathrm{m^{-2}}$ $\mathrm{Hz^{-1}}$)

$$x = \frac{h\nu}{kT}$$ (Independent of redshift)

$$\nu_{\max} \approx 58.8\,\mathrm{GHz\,K^{-1}}\,T \approx 160\,\mathrm{GHz}\left[\frac{T}{2.725\,\mathrm{K}}\right] \leftrightarrow x_{\max} \approx 2.821$$

Standard types of primordial CMB distortions

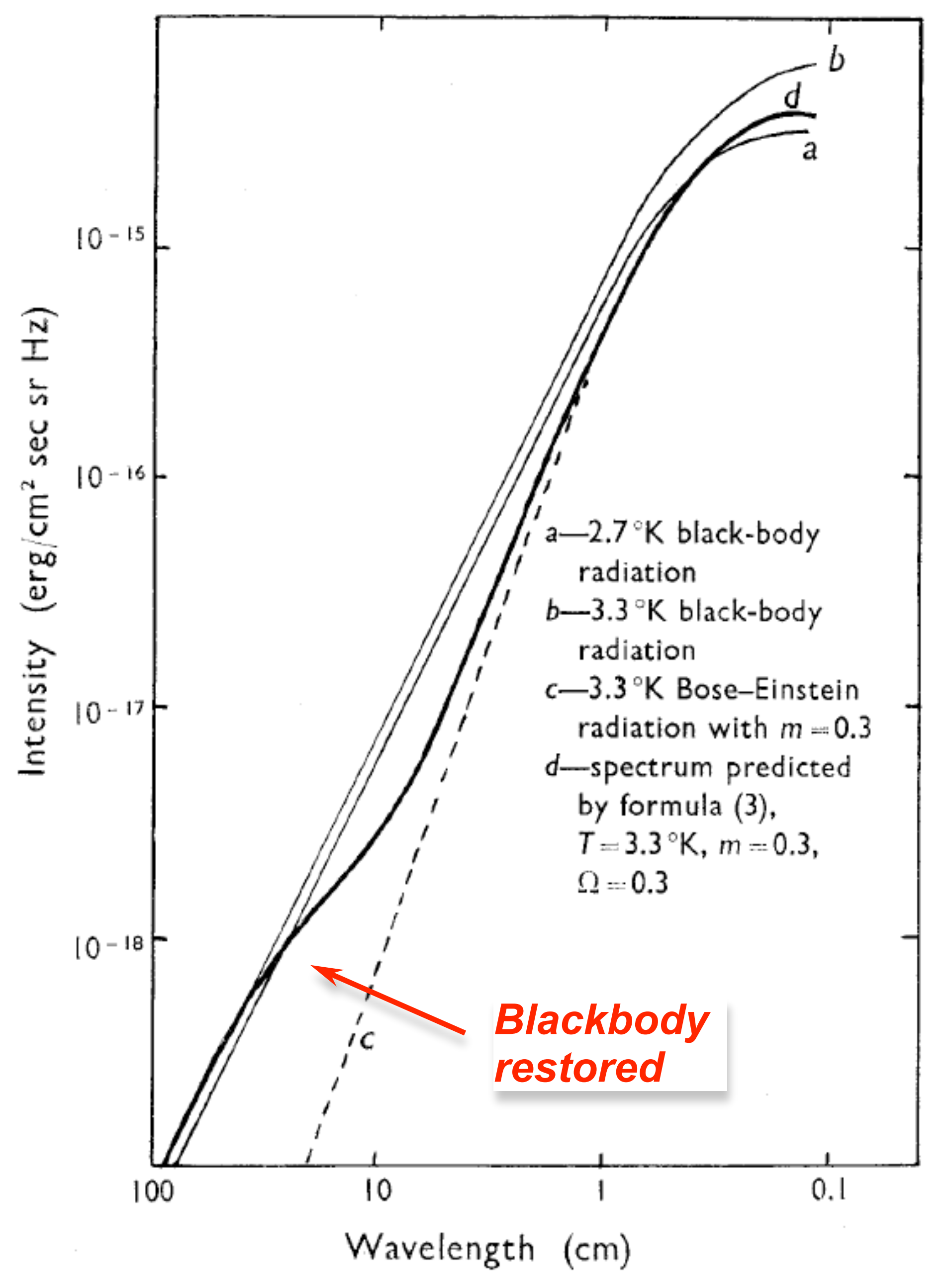
Compton y-distortion



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'

Why should one expect some spectral distortion?

Full thermodynamic equilibrium (certainly valid at very high redshift)

- CMB has a blackbody spectrum at every time (not affected by expansion)
- Photon number density and energy density determined by temperature T_γ

$$T_\gamma \sim 2.726\,(1+z)\ \mathrm{K}$$

$$N_\gamma \sim 411\ \mathrm{cm}^{-3}\,(1+z)^3 \sim 2\times10^9\, N_\mathrm{b}$$ (*entropy density dominated by photons*)

$$\rho_\gamma \sim 5.1\times10^{-7}\, m_\mathrm{e}c^2\ \mathrm{cm}^{-3}\,(1+z)^4 \sim \rho_\mathrm{b} \times (1+z) / 925 \sim 0.26\ \mathrm{eV\ cm}^{-3}\,(1+z)^4$$

Perturbing full equilibrium by

- Energy injection (interaction *matter* ←→ *photons*)
- Production of (energetic) photons and/or particles (i.e. change of entropy)

→ CMB spectrum deviates from a pure blackbody

→ thermalization process (partially) erases distortions

(Compton scattering, double Compton and Bremsstrahlung in the expanding Universe)

Measurements of CMB spectrum place very tight limits on the thermal history of our Universe!

Some simple statements about distortions

- Start with blackbody: $T_\gamma,\ N_\gamma^{\rm bb}(T_\gamma) \propto T_\gamma^3,\ \text{and}\ \rho_\gamma^{\rm bb}(T_\gamma) \propto T_\gamma^4$
- Inject photons (isotropic): $\Delta N_\nu,\ \Delta N_\gamma = (4\pi/c) \int \Delta N_\nu \, {\rm d}\nu > 0$

$$\Delta \rho_\gamma = (4\pi/c) \int h\nu \, \Delta N_\nu \, {\rm d}\nu > 0$$

- Effective temperatures: $T_N^* = \left(\frac{h^3 c^3 N_\gamma}{16\pi k^3 \zeta(3)} \right)^{1/3} \approx T_\gamma \left(1 + \frac{1}{3} \frac{\Delta N_\gamma}{N_\gamma^{\rm bb}} \right) > T_\gamma$

$$\begin{aligned} N_\gamma &\equiv N_\gamma^{\rm bb}(T_N^*) \\ \rho_\gamma &\equiv \rho_\gamma^{\rm bb}(T_\rho^*) \end{aligned} \quad \Longrightarrow \quad T_\rho^* = \left(\frac{15 h^3 c^3 \rho_\gamma}{8\pi^5 k^4} \right)^{1/4} \approx T_\gamma \left(1 + \frac{1}{4} \frac{\Delta \rho_\gamma}{\rho_\gamma^{\rm bb}} \right) > T_\gamma .$$

- For blackbody: $T_N^* = T_\rho^* \quad \Longrightarrow \quad \boxed{\frac{\Delta \rho_\gamma}{\rho_\gamma^{\rm bb}} \approx \frac{4}{3} \frac{\Delta N_\gamma}{N_\gamma^{\rm bb}}}$
- This is a *necessary* condition if you do not want to distort the CMB!
- *Energy release alone inevitably* creates distortions (need additional photons)

Another simple example: *δ-function photon injection*

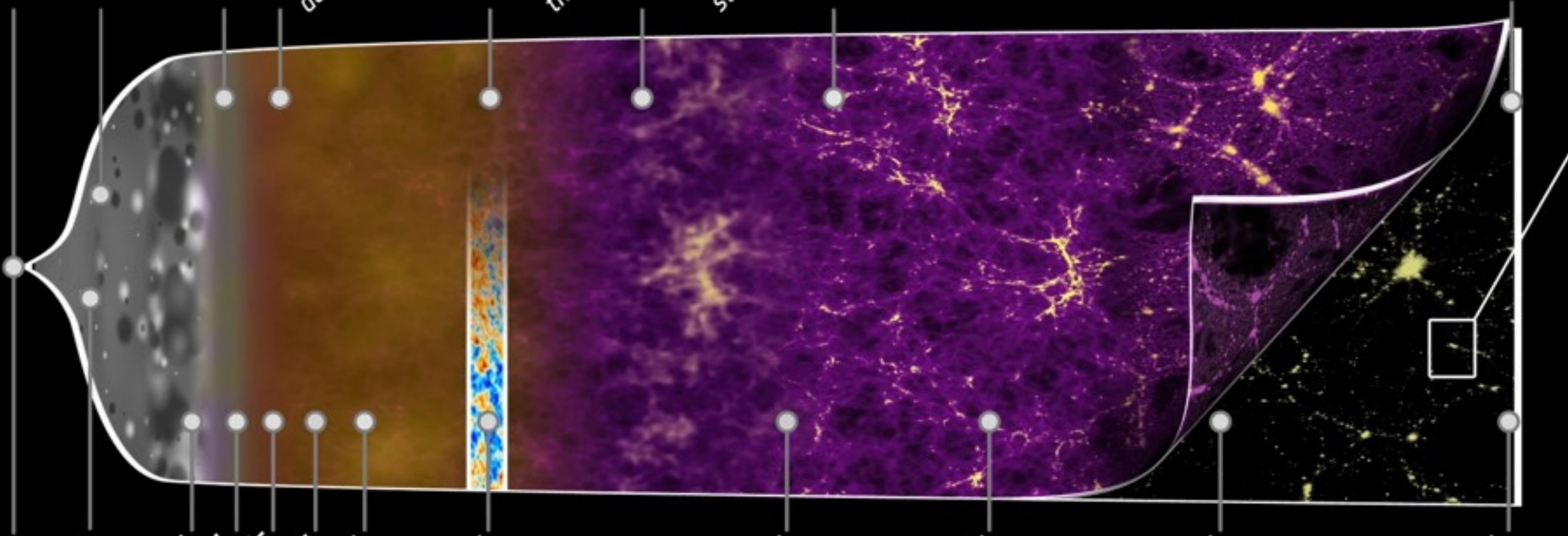
- Assume: $\Delta N_\nu = \frac{c\Delta N_\gamma}{4\pi}\,\delta(\nu - \nu_0) \quad \Longrightarrow \quad \Delta\rho_\gamma = h\nu_0\,\Delta N_\gamma$
- Then $\frac{\Delta\rho_\gamma}{\rho_\gamma^{\rm bb}} = h\nu_0 \frac{\Delta N_\gamma}{\rho_\gamma^{\rm bb}} = \frac{h\nu_0}{2.7kT_\gamma}\,\frac{\Delta N_\gamma}{N_\gamma^{\rm bb}} \equiv \frac{4}{3}\,\frac{\Delta N_\gamma}{N_\gamma^{\rm bb}} \quad \Longrightarrow \quad \frac{h\nu_{\rm c}}{kT_\gamma} \approx 3.6$

$$\nu_{\rm c} \simeq 3.6\,kT_\gamma/h \simeq 204.5\,(1+z)\,{\rm GHz}$$

- Injection at $\nu = \nu_{\rm c}$ $\Longrightarrow$ *only need to redistribute photons over energy*
- Injection at $\nu < \nu_{\rm c}$ $\Longrightarrow$ *need more energy / absorb photons*
- Injection at $\nu > \nu_{\rm c}$ $\Longrightarrow$ *need to add photon / cool photon field*

The thermalization problem really is about redistributing photons over energy and adjusting their number!

Question: Is there enough time to restore full equilibrium?



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

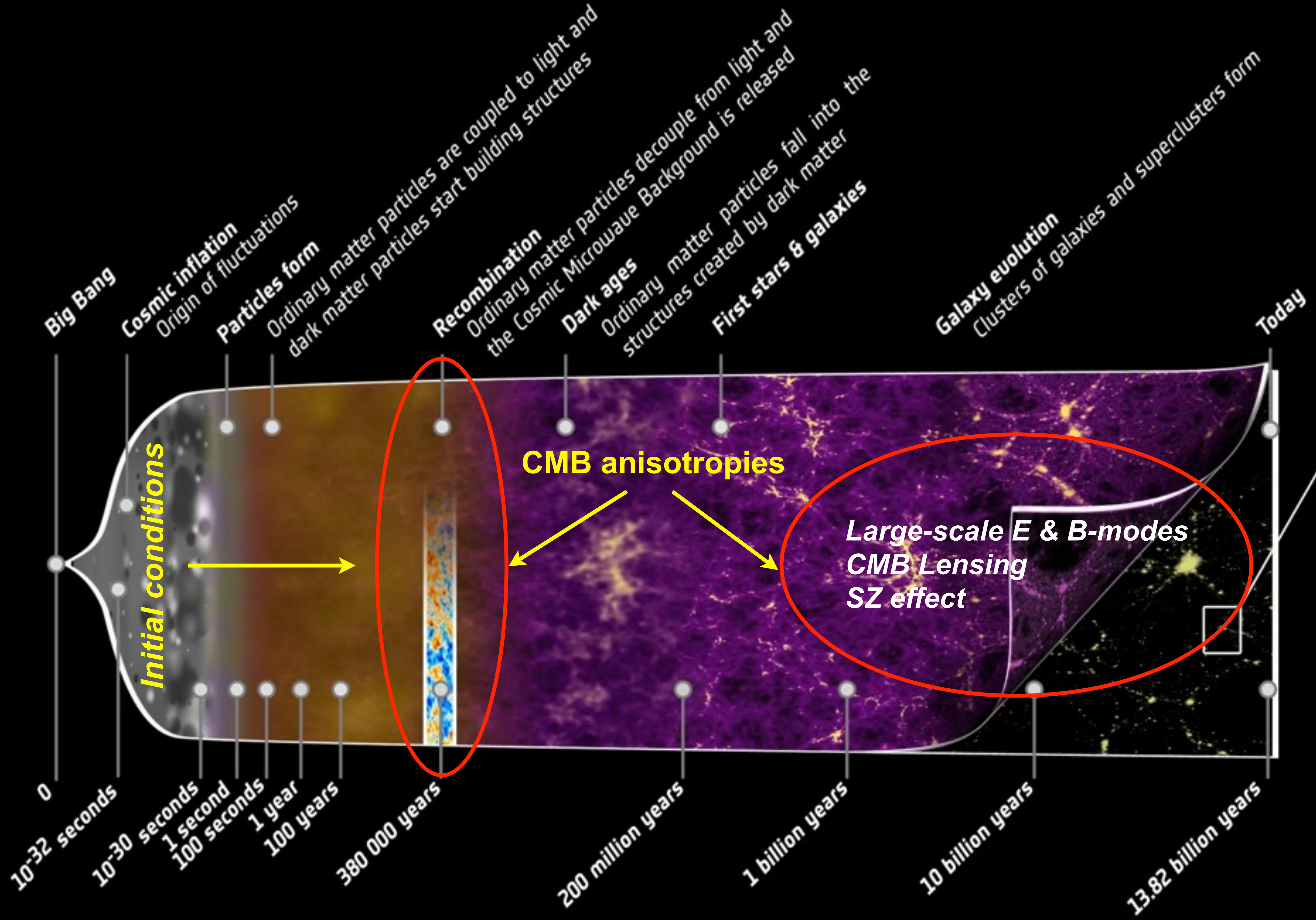
Dark ages
Ordinary matter particles fall into the structures created by dark matter

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

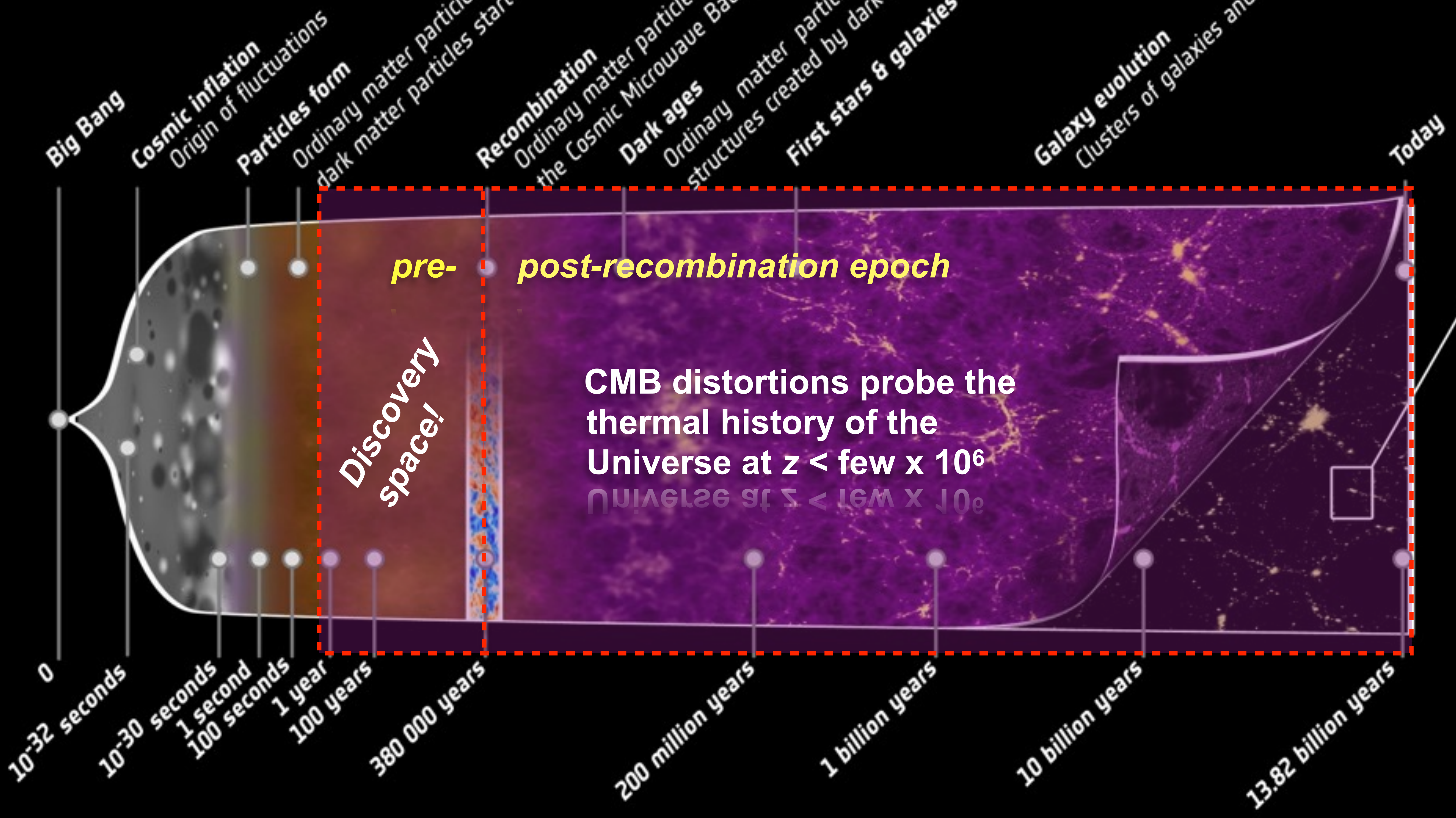


Initial conditions

CMB anisotropies

Large-scale E & B-modes
CMB Lensing
SZ effect

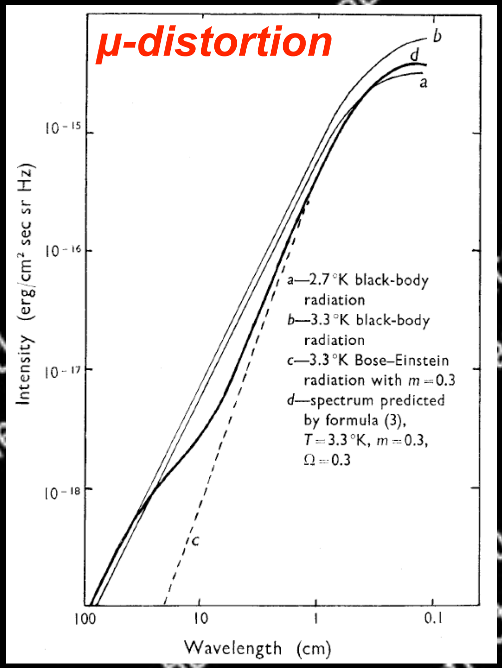
Measurements of CMB spectrum will open a new unexplored window to the early Universe!

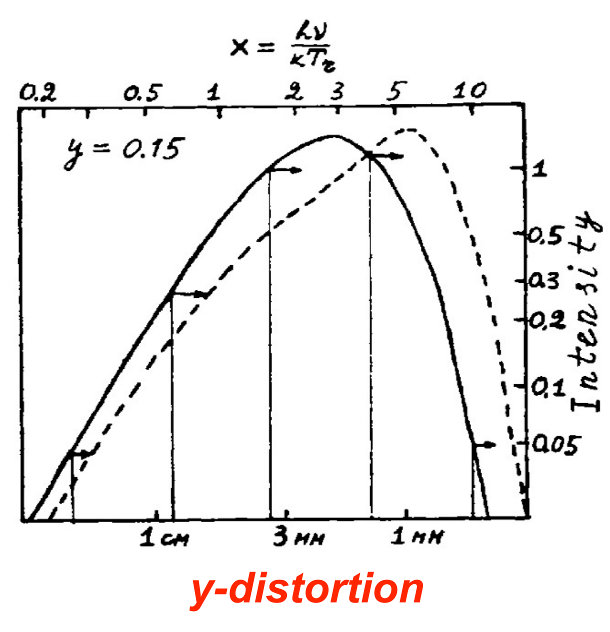


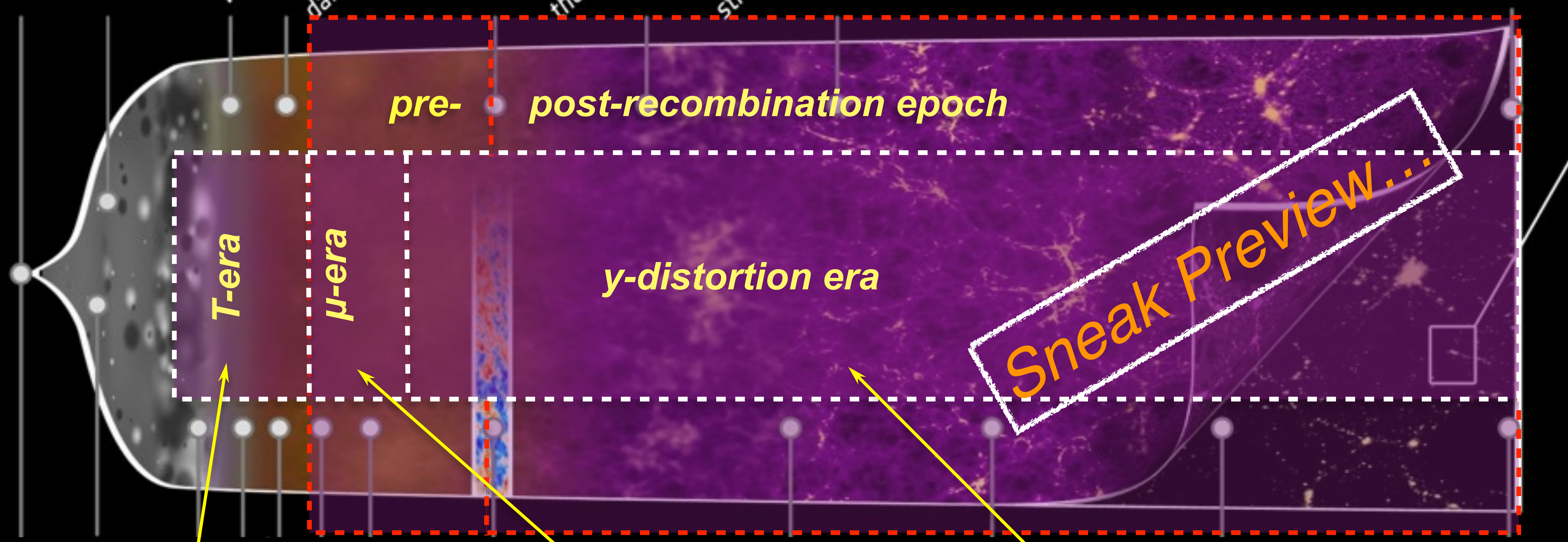
pre- *post-recombination epoch*

Discovery space!

CMB distortions probe the thermal history of the Universe at $z <$ few x 10^6







pre-

post-recombination epoch

T-era

μ-era

y-distortion era

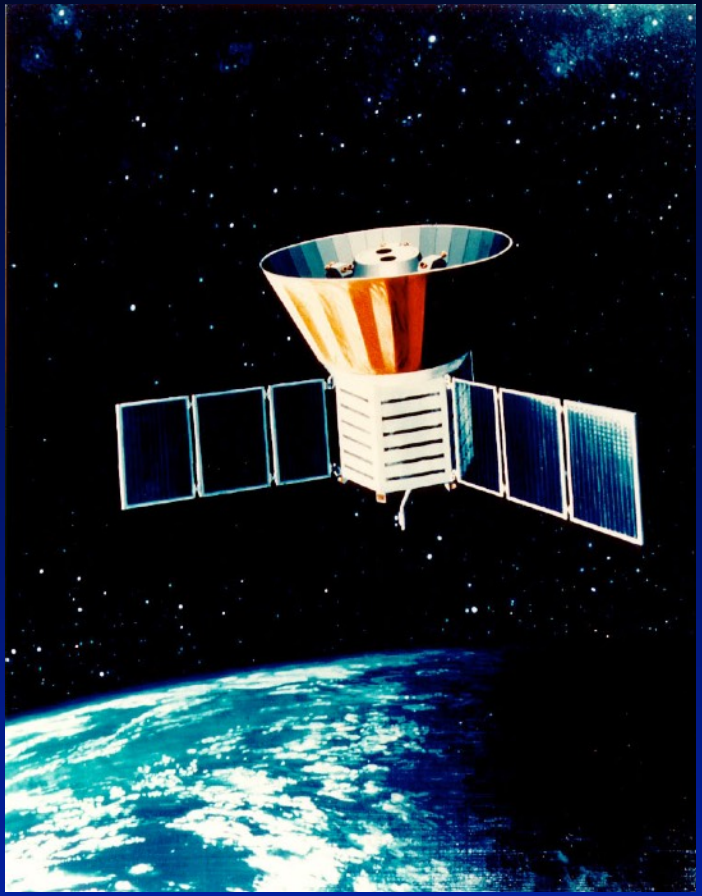
Sneak Preview…

$$\frac{\Delta T}{T} \simeq \frac{1}{4}\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_T$$

$$\mu \simeq 1.4\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_\mu$$

$$y \simeq \frac{1}{4}\left.\frac{\Delta\rho_\gamma}{\rho_\gamma}\right|_y$$

COBE / FIRAS (Far InfraRed Absolute Spectrophotometer)

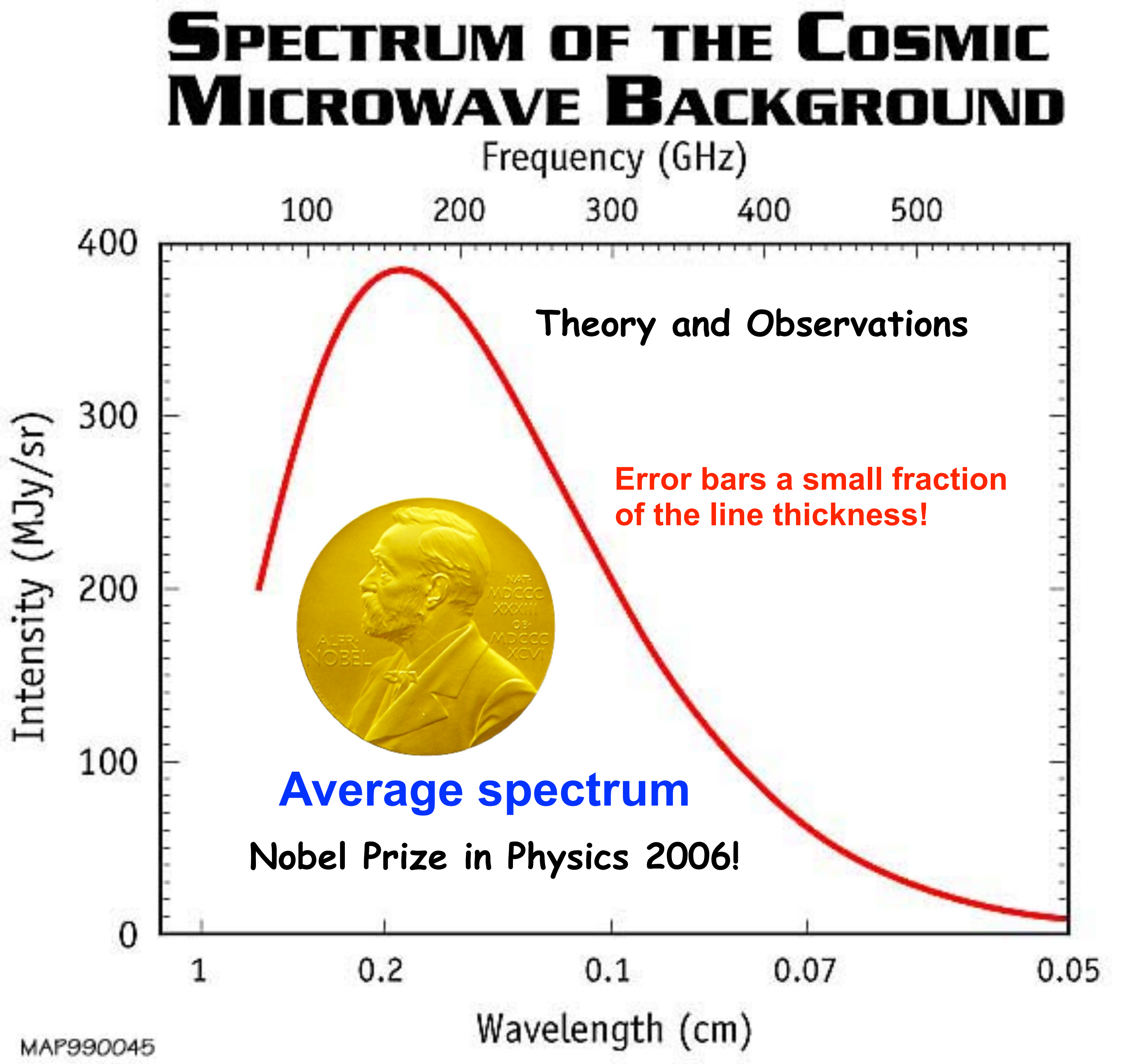


$$T_0 = 2.725 \pm 0.001\,\mathrm{K}$$

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

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

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



SPECTRUM OF THE COSMIC MICROWAVE BACKGROUND

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!

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

Physical mechanisms that lead to spectral 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)
- Additional exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

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

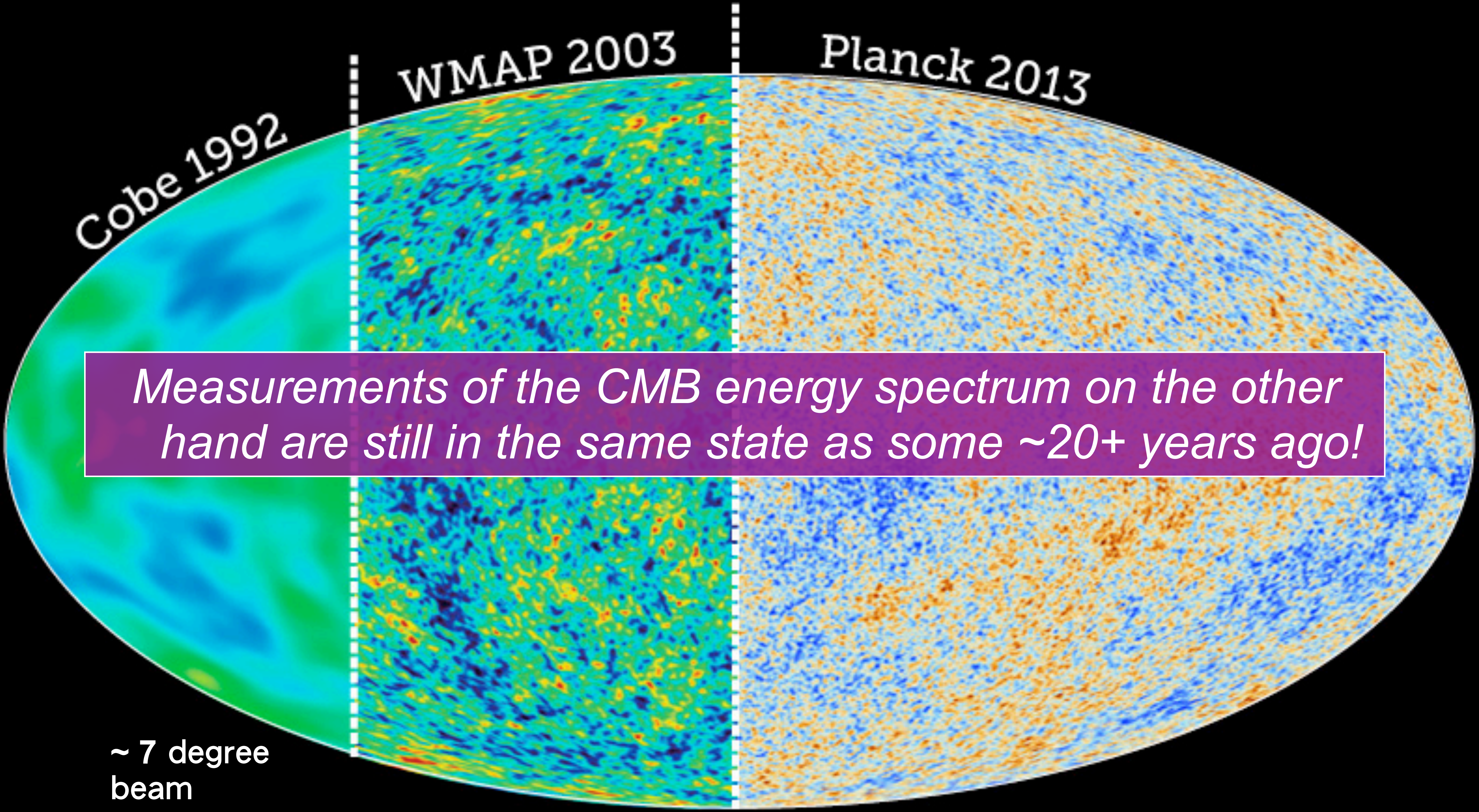
- -

„low“ redshifts

- 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)
- Additional exotic processes
  (Lochan et al. 2012; Bull & Kamionkowski, 2013; Brax et al., 2013; Tashiro et al. 2013)

post-recombination

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



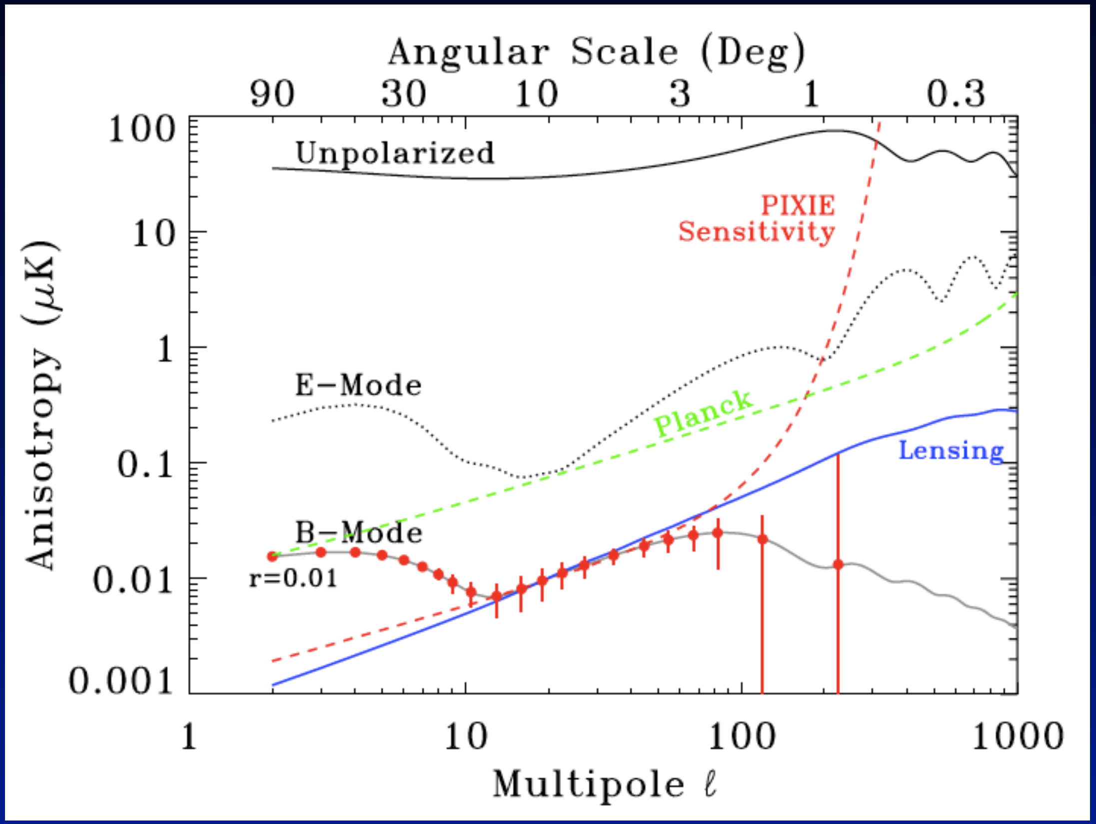
Measurements of the CMB energy spectrum on the other hand are still in the same state as some ~20+ years ago!

~ 7 degree beam

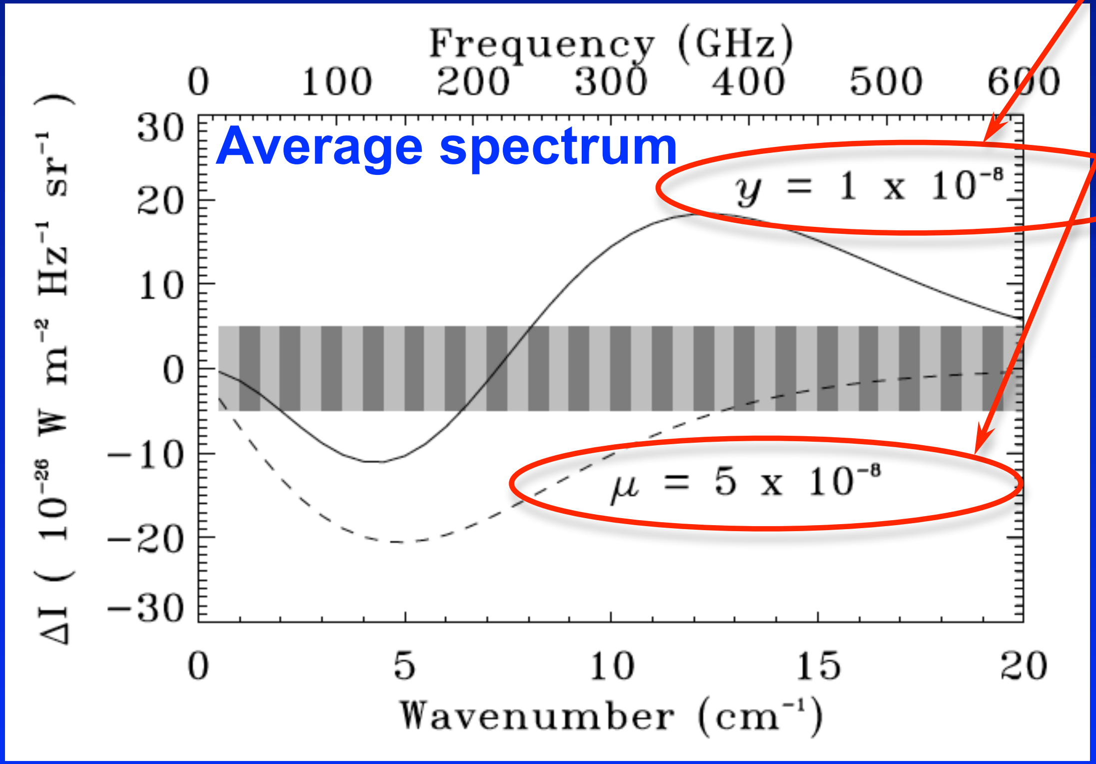
~ 0.3 degree beam

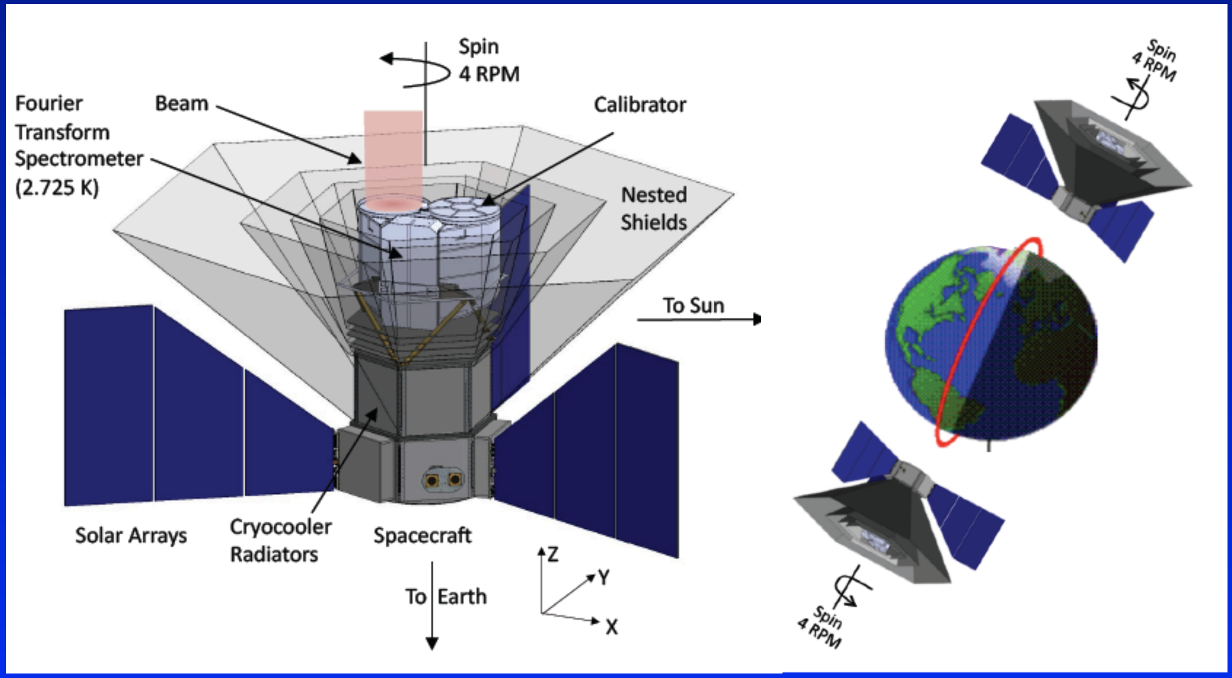
~ 0.08 degree beam

PIXIE: Primordial Inflation Explorer

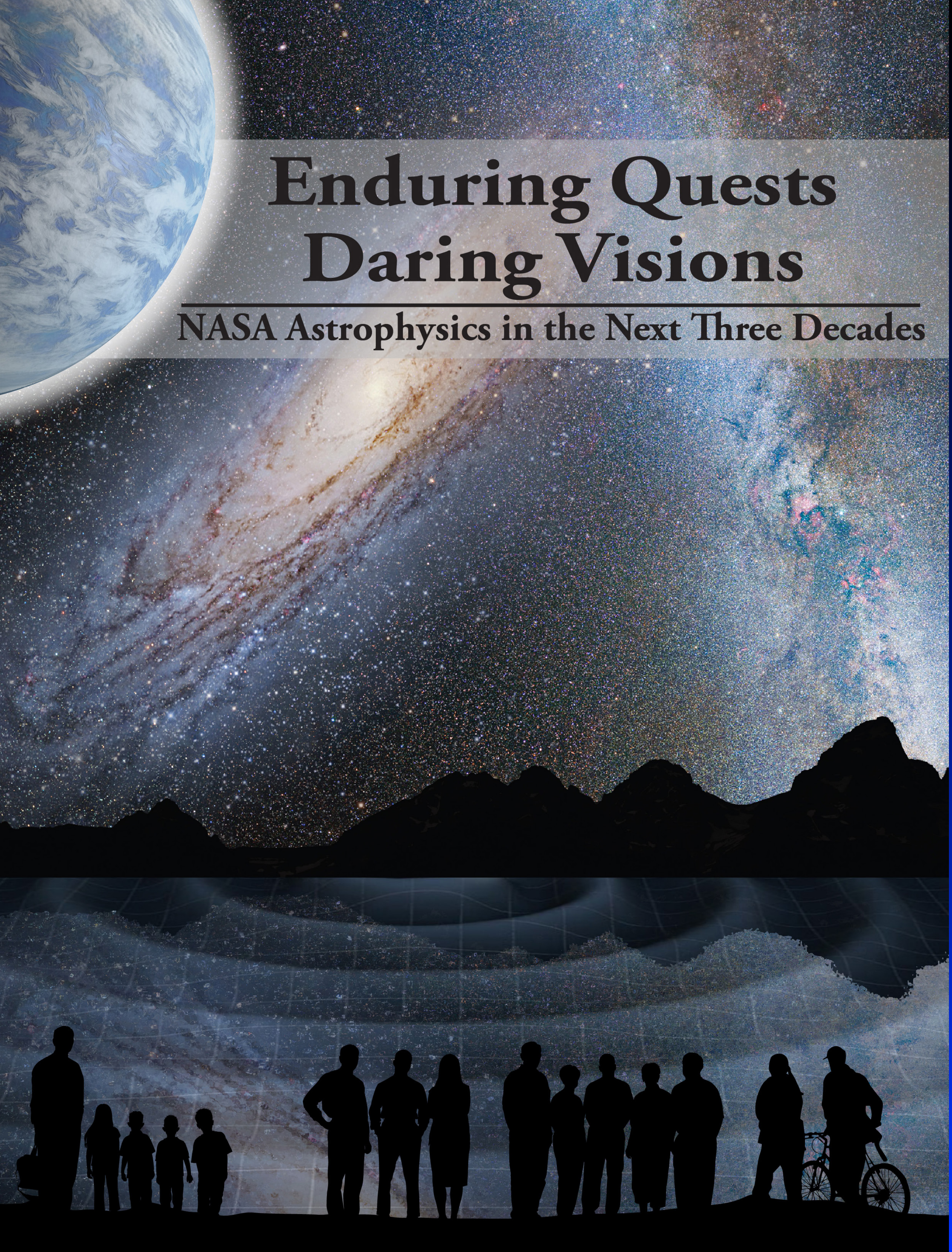


- 400 spectral channel in the frequency range 30 GHz and 6THz (Δv ~ 15GHz)
- about 1000 (!!!) times more sensitive than COBE/FIRAS
- B-mode polarization from inflation ($r \approx 10^{-3}$)
- improved limits on μ and y
- was proposed 2011 as NASA EX mission (i.e. cost ~ 200 M$)





Kogut et al, JCAP, 2011, arXiv:1105.2044



Enduring Quests
Daring Visions

NASA Astrophysics in the Next Three Decades

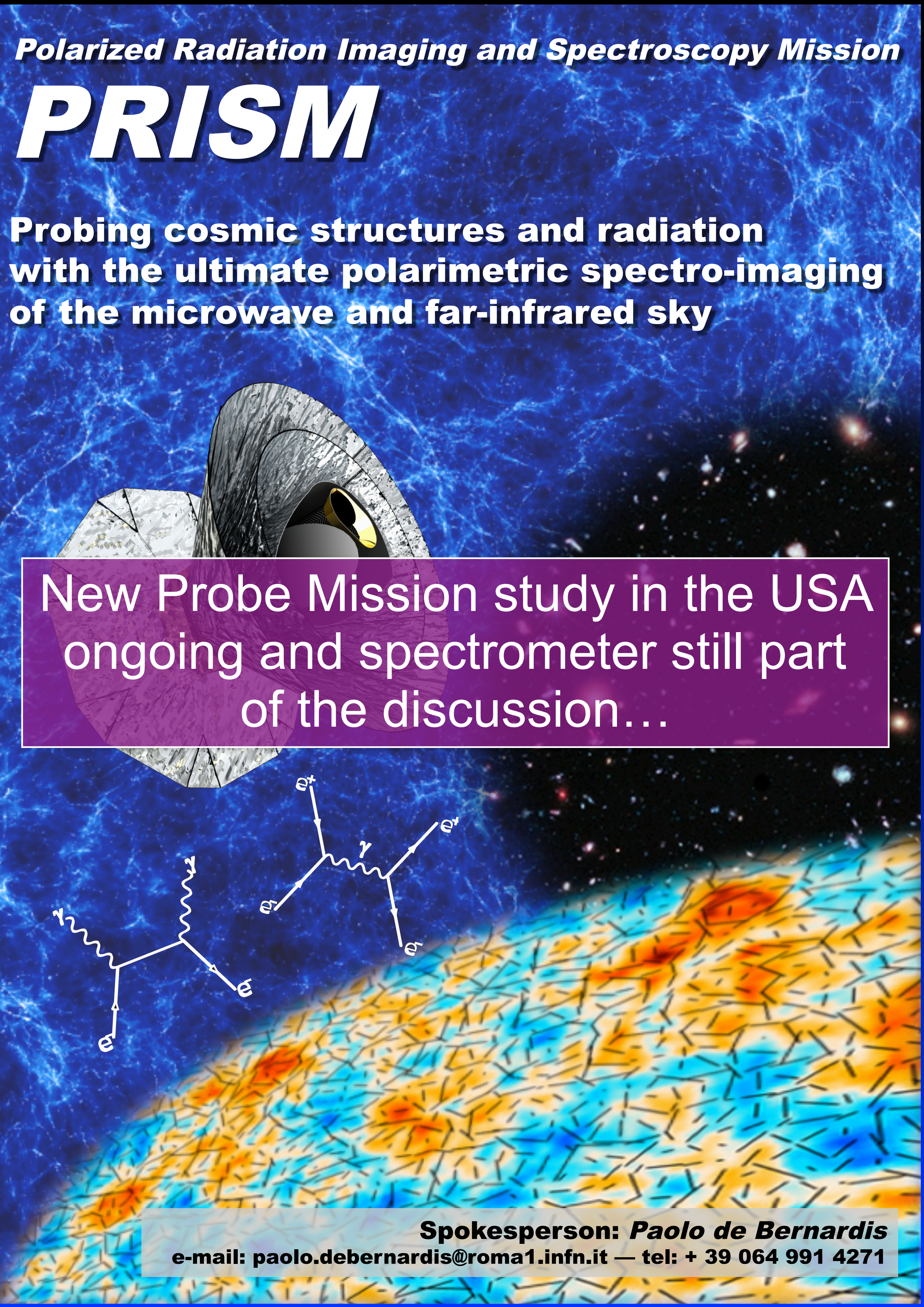
NASA 30-yr Roadmap Study

(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."

PIXIE was proposed to NASA in Dec 2016.
Sadly not selected :(:(



Polarized Radiation Imaging and Spectroscopy Mission

PRISM

Probing cosmic structures and radiation with the ultimate polarimetric spectro-imaging of the microwave and far-infrared sky

New Probe Mission study in the USA ongoing and spectrometer still part of the discussion…

Spokesperson: *Paolo de Bernardis*
e-mail: paolo.debernardis@roma1.infn.it — tel: + 39 064 991 4271

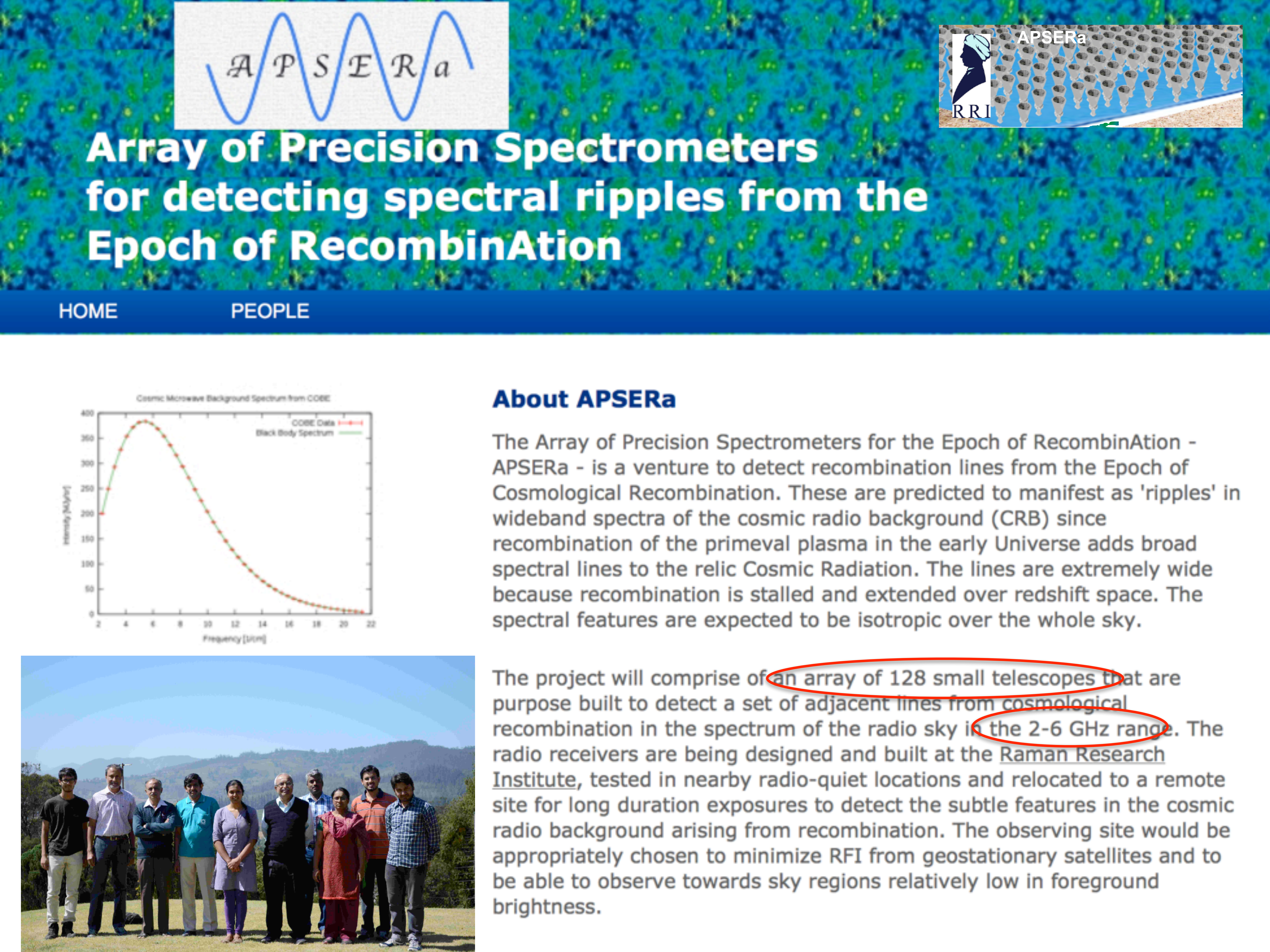
Instruments:

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

Some of the science goals:

- B-mode polarization from inflation ($r \approx 5\mathrm{x}10^{-4}$)
- 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/



Array of Precision Spectrometers for detecting spectral ripples from the Epoch of RecombinAtion

About APSERa

The Array of Precision Spectrometers for the Epoch of RecombinAtion - APSERa - is a venture to detect recombination lines from the Epoch of Cosmological Recombination. These are predicted to manifest as 'ripples' in wideband spectra of the cosmic radio background (CRB) since recombination of the primeval plasma in the early Universe adds broad spectral lines to the relic Cosmic Radiation. The lines are extremely wide because recombination is stalled and extended over redshift space. The spectral features are expected to be isotropic over the whole sky.

The project will comprise of an array of 128 small telescopes that are purpose built to detect a set of adjacent lines from cosmological recombination in the spectrum of the radio sky in the 2-6 GHz range. The radio receivers are being designed and built at the Raman Research Institute, tested in nearby radio-quiet locations and relocated to a remote site for long duration exposures to detect the subtle features in the cosmic radio background arising from recombination. The observing site would be appropriately chosen to minimize RFI from geostationary satellites and to be able to observe towards sky regions relatively low in foreground brightness.

COSMO at Dome C

COSmological Monopole Observer


Concordia station at Dome-C

SAPIENZA
UNIVERSITÀ DI ROMA

Taken from a talk by Elia Battistelli

SAPIENZA UNIVERSITÀ DI ROMA

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

CNR IFN Istituto di Fotonica e Nanotecnologie

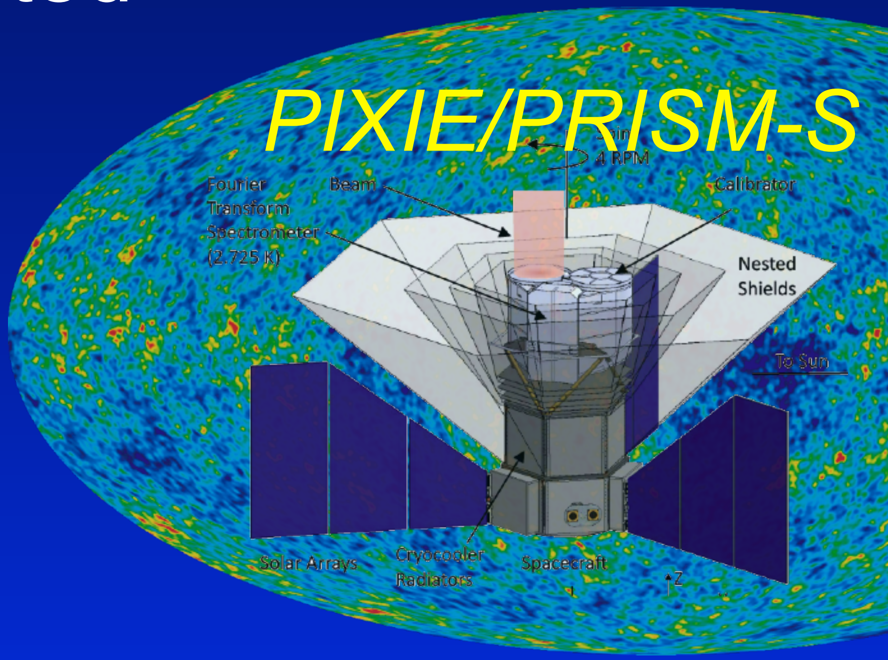
CARDIFF UNIVERSITY PRIFYSGOL CAERDYDD

ASU ARIZONA STATE UNIVERSITY

PROGRAMMA NAZIONALE DI RICERCHE IN ANTARTIDE
ITALIANTARTIDE

What can CMB spectral distortions add?

- Add a *new dimension* to CMB science
  - probe the thermal history at different stages of the Universe
- *Complementary* and *independent* information!
  - cosmological parameters from the recombination radiation
  - new/additional test of large-scale anomalies
- Several *guaranteed signals* are expected
  - y-distortion from low redshifts
  - damping signal & recombination radiation
- Test various *inflation* models
  - damping of the small-scale power spectrum
- *Discovery* potential
  - decaying particles and other exotic sources of distortions


PIXIE/PRISM-S

All this largely without any competition from the ground!!!

To be continued…