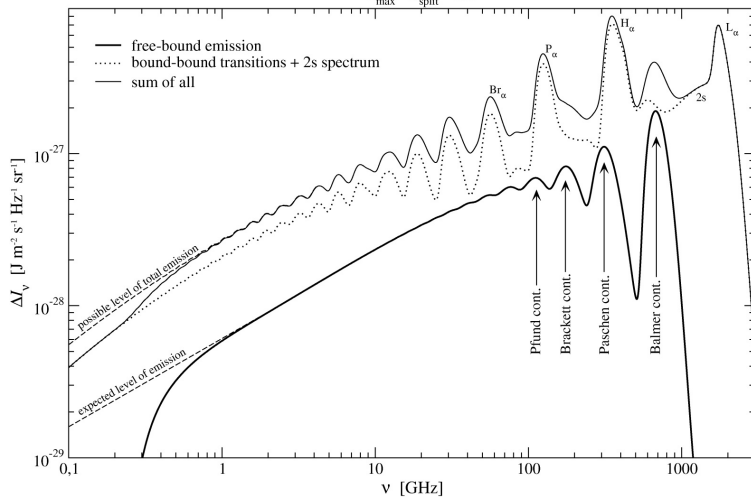PLANCK
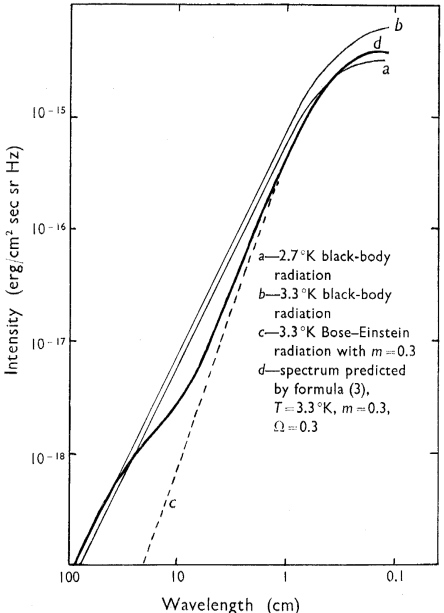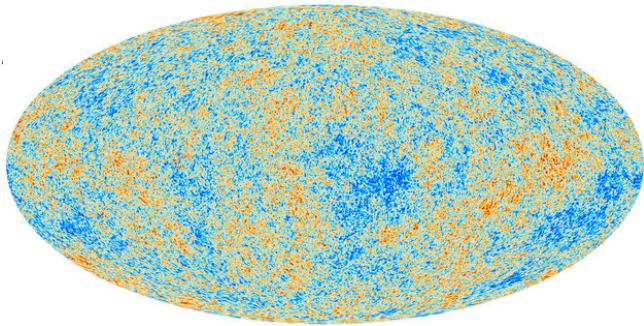
**Texas Symposium on
Relativistic Astrophysics
Geneva**
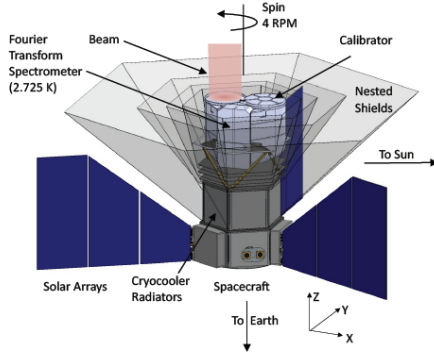
December 14, 2015

CMB spectral distortions

(Two milestones in the life of the Universe.
Last Scattering Surface and
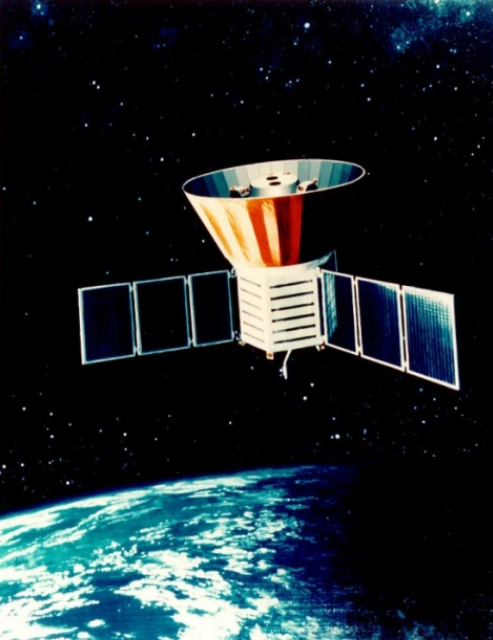## Black Body Photosphere)

Rashid Sunyaev

Max-Planck Institut fuer Astrophysik, Garching
Space Research Institute, RAS, Moscow

with Rishi Khatri (Mumbai) & Jens Chluba (Cambridge)

Adiabatic expansion of the Universe preserves the blackbody spectrum established at early times (for example during electron-positron annihilation) (In general $x = \nu/T$ is invariant w.r.t. expansion of the Universe.)

Cosmic Microwave Background (CMB): The most precise black body known: $T = 2.725K \pm 1mK$
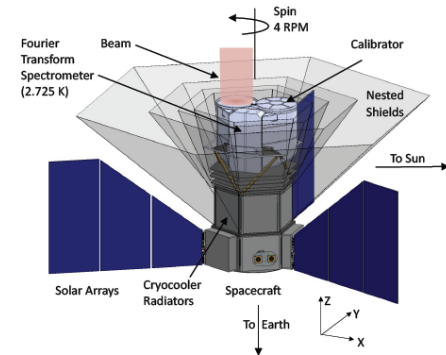
No spectral deviations are detected by COBE/FIRAS !

This was 25 years ago

Now:

Great progress in the technology of experiments and especially of detectors and cryogenics

PIXIE proposal: up to 100 or even thousand times more sensitive !

THERE ARE MANY THEORETICAL MODELS PREDICTING SIGNIFICANT ENERGY RELEASE IN THE EARLY UNIVERSE and *CMB spectral distortions:*

y and μ

are two main types

I WILL SPEAK TODAY ONLY ABOUT UNAVOIDABLE SPECTRAL FEATURES,
WHICH ARE PREDICTED WITHIN STANDARD COSMOLOGICAL MODEL

Black body photosphere of the Universe

In the spring of 1966 Yakov Zeldovich asked me to review on the group seminar the preprints of Layzer (Harvard) and Burbidges (Caltech) stating that CMB spectrum is just the stellar light thermalized by the dust.

I decided to check in addition the usual mechanism responsible for black body spectrum production inside hot stars: **the Rosseland free-free optical depth of the Universe for CMB – it was negligibly small up to the time of positron-electron annihilation.**
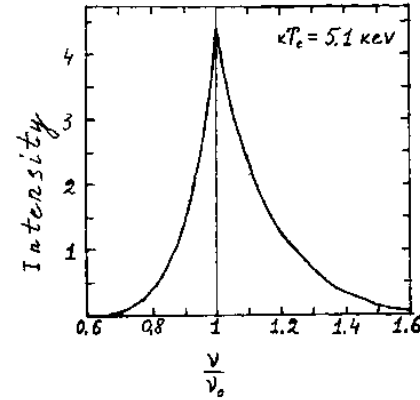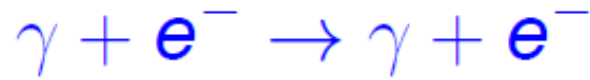
$$\tau_{\text{free-free}} \sim \int_0^{t(z)} dt\, n_e^2 \sigma_T c \frac{\alpha_{\text{fs}}}{(24\pi^3)^{1/2}} \left(\frac{k_B T_e}{m_e c^2}\right)^{-7/2} \left(\frac{h}{m_e c x_e}\right)^3 (1 - e^{-x_e})$$

$$\sim 4 \times 10^{-5} \left(\frac{1+z}{10^8}\right)^{1/2},$$

but Thomson optical depth was huge.

$$\tau_{\text{Thomson}} = \int_0^{t(z)} n_e \sigma_T c\, dt \overset{z \gg z_{\text{eq}}}{\approx} 0.21(1+z) \ \sim 2\ 10\text{^}7\ (z/10\text{^}8)$$

Optical depth – probability for the photon to be absorbed or scattered

Comptonization

$$\gamma + e^- \rightarrow \gamma + e^-$$

$kT_e = 5.1\ keV$

$\text{Doppler}: \dfrac{\delta\nu}{\nu} \sim \dfrac{v_e}{c} \sim \left(\dfrac{kT_e}{m_e c^2}\right)^{1/2}$

$\text{2ndorderDoppler}: \left(\dfrac{\delta\nu}{\nu}\right)_{\text{rms}} \sim 4\left(\dfrac{kT_e}{m_e c^2}\right)$

$\text{Recoil}: \dfrac{\delta\nu}{\nu} = -\dfrac{h\nu}{m_e c^2}(1 - \cos\theta)$

==

y: Amplitude of distortion

$$y = \int dt\, c\, \sigma_T n_e \dfrac{k_B\left(T_e - T_\gamma\right)}{m_e c^2}$$

Fokker-Planck expansion of the kinetic equation with induced scattering term yields

$$\frac{\partial n}{\partial y} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(n + n^2 + \frac{\partial n}{\partial x}\right)$$

Kompaneets (1956)

$$n = c^2 I_\nu / 8\pi h\nu^3$$

- occupation number , *I* – radiation intensity

$$x = h\nu/kT_e$$

$$y = \frac{kT_e}{m_e c^2}\sigma_T N_e ct = \frac{kT_e}{m_e c^2}u$$

- photon frequency,

time and number of scatterings

Kompaneets equation describes interaction of ***a radiation field*** with free ***hot maxwellian electrons*** due to **Compton scattering**. *The **energy exchange** due to **Doppler effect** and **recoil**.* **Thomson cross-section limit.**

Beautiful physics behind the term ~ n^2 *describing induced Compton scattering*

Efficiency of energy exchange between electrons and photons

Recoil:

$$y_\gamma = \int dt\, c\sigma_T n_e \frac{k_B T_\gamma}{m_e c^2}, \qquad T_\gamma = 2.725(1+z)$$

Doppler effect:

$$y_e = \int dt\, c\sigma_T n_e \frac{k_B T_e}{m_e c^2}$$

In early Universe $y_\gamma \approx y_e$

y: Amplitude of distortion

$$y = \int dt\, c\sigma_T n_e \frac{k_B (T_e - T_\gamma)}{m_e c^2}$$

Efficiency of energy exchange between electrons and photons

Recoil:

$$y_\gamma = \int \mathrm{d}t \, c\sigma_T n_e \frac{k_B T_\gamma}{m_e c^2}, \qquad T_\gamma = 2.725(1+z)$$

No. of scatterings

Doppler effect:

$$y_e = \int \mathrm{d}t \, c\sigma_T n_e \frac{k_B T_e}{m_e c^2}$$

In early Universe $y_\gamma \approx y_e$

y: Amplitude of distortion

$$y = \int \mathrm{d}t \, c\sigma_T n_e \frac{k_B \left(T_e - T_\gamma\right)}{m_e c^2}$$

Fokker-Planck expansion of the kinetic equation with induced scattering term yields

$$\frac{\partial n}{\partial y} = \frac{1}{x^2}\frac{\partial}{\partial x} x^4 \left(n + n^2 + \frac{\partial n}{\partial x} \right)$$

$$n = c^2 I_\nu / 8\pi h \nu^3$$

- occupation number , I – radiation intensity

$$x = h\nu/kT_e$$

$$y = \frac{kT_e}{m_e c^2} \sigma_T N_e c t = \frac{kT_e}{m_e c^2} u$$

- photon frequency,

time and number of scatterings

Kompaneets equation describes interaction of **a radiation field** with free **hot maxwellian electrons** due to **Compton scattering**. *The **energy exchange** due to **Doppler effect** and **recoil**. **Thomson cross-section limit.***

Beautiful physics behind the term ~ n^2 *describing* induced *Compton scattering*
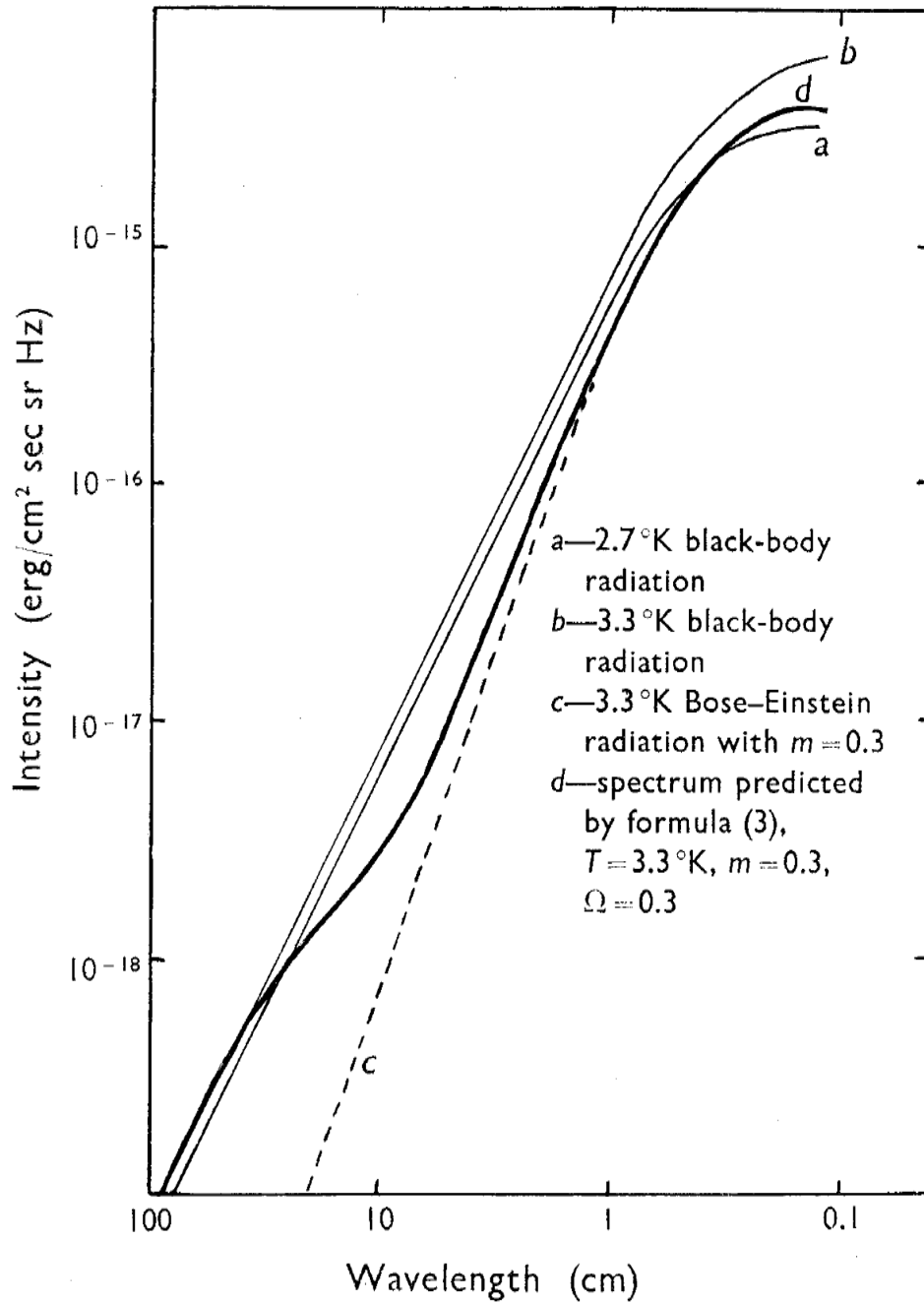
Bose-Einstein spectrum- Chemical potential (μ)

Stationary solution of Kompaneets equation **at y >> 1**

$$n(x) = \frac{1}{e^{x+\mu} - 1}$$

Given two constraints, energy density (E) and number density (N) of photons, T, μ uniquely determined.

Thomson scattering does not change amount of photons
(photon number conservation in Kompaneets equation)

a—2.7 °K black-body radiation
b—3.3 °K black-body radiation
c—3.3 °K Bose–Einstein radiation with $m = 0.3$
d—spectrum predicted by formula (3), $T = 3.3$ °K, $m = 0.3$, $\Omega = 0.3$

myu-type CMB distortions due to energy release in the early Universe $10^5 < z < 2 \cdot 10^6$

Sunyaev, Zeldovich, 1970

Bose-Einstein spectrum

$$n_{\mathrm{BE}} = \frac{1}{e^{\frac{h\nu}{k_{\mathrm{B}}T_{\mathrm{BE}}}+\mu} - 1}$$

$$= \frac{1}{e^{x-0.456\mu x+\mu} - 1}$$

$$\approx n_{\mathrm{pl}}(x) + \frac{\mu e^x}{(e^x - 1)^2}\left(\frac{x}{2.19} - 1\right),$$

We call this type of spectral distortions as a μ

distortion

At small y << 1, tau << 1
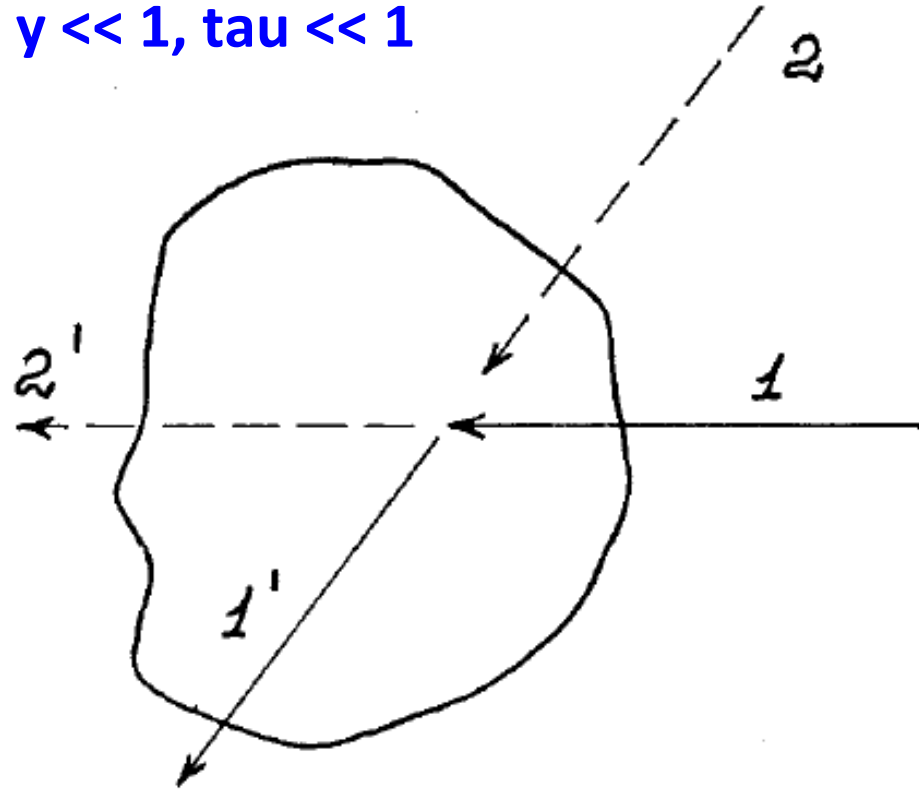
FIG. 2. The scattering of isotropic radiation field by the cloud of electrons.

Cloud is invisible in CMB radiation field
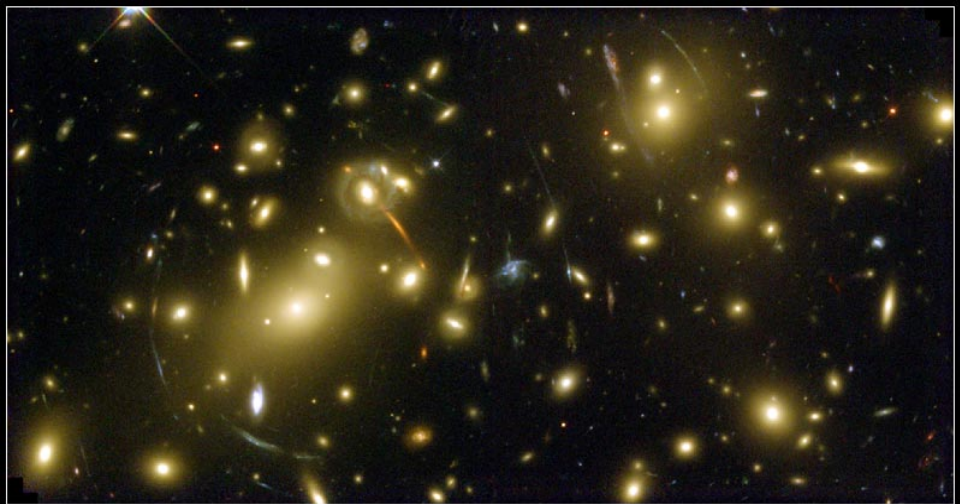
Galaxy Cluster Abell 2218
HST • WFPC2
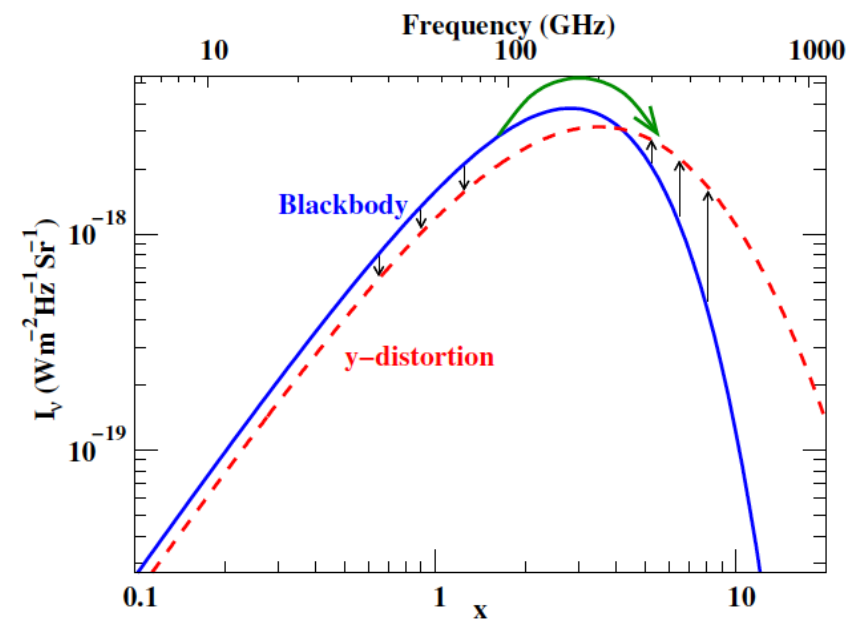NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08
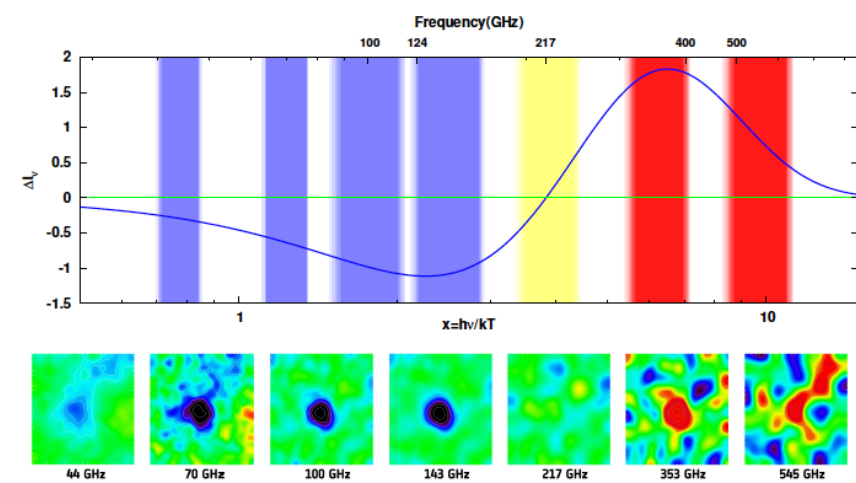
Image credit: ESA / HFI & LFI Consortia

$$n_{SZ} = y \; T^4 \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial n_{Pl}}{\partial T}$$

$$= y \; \frac{xe^x}{(e^x-1)^2} \left(x \frac{e^x+1}{e^x-1} - 4 \right)$$

$$\Delta I_{sz} = I_{sz} - I_{planck} = \frac{2h\nu^3}{c^2} n_{sz}$$

(Zeldovich and Sunyaev 1969)
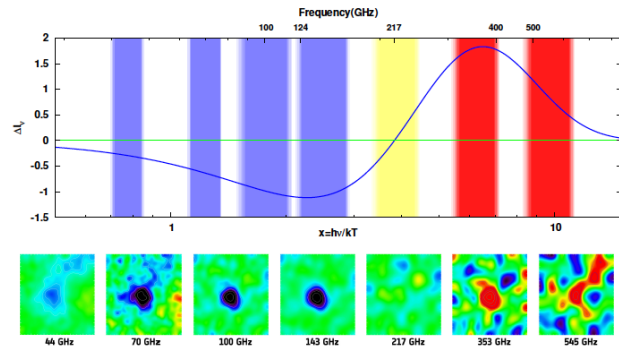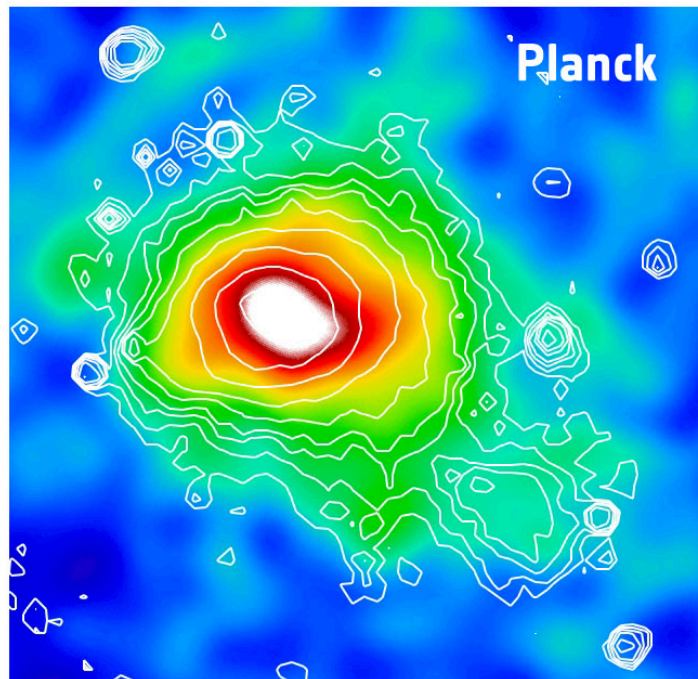COBE-FIRAS limit (95%): $y \lesssim 1.5 \times 10^{-5}$ *(Fixsen et al. 1996)*

Blackbody

y–distortion

PLANCK

Frequency (GHz)

Image credit: ESA / HFI & LFI Consortia

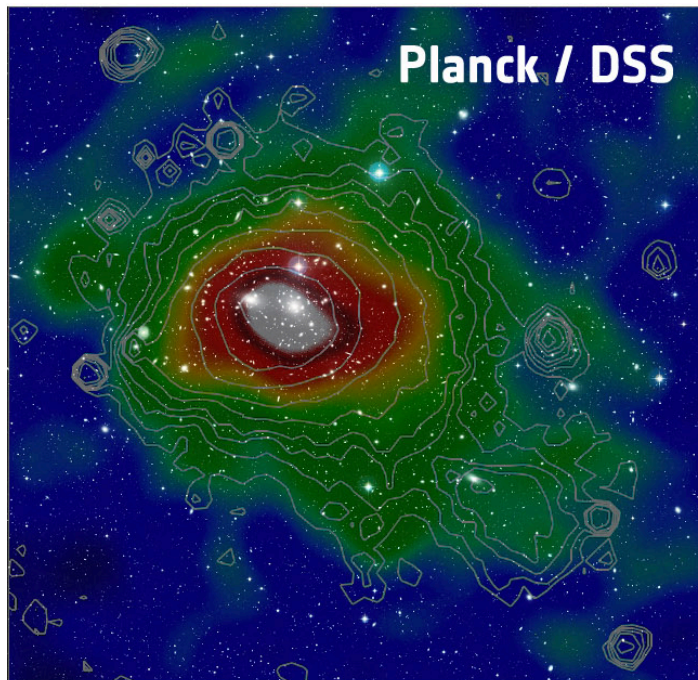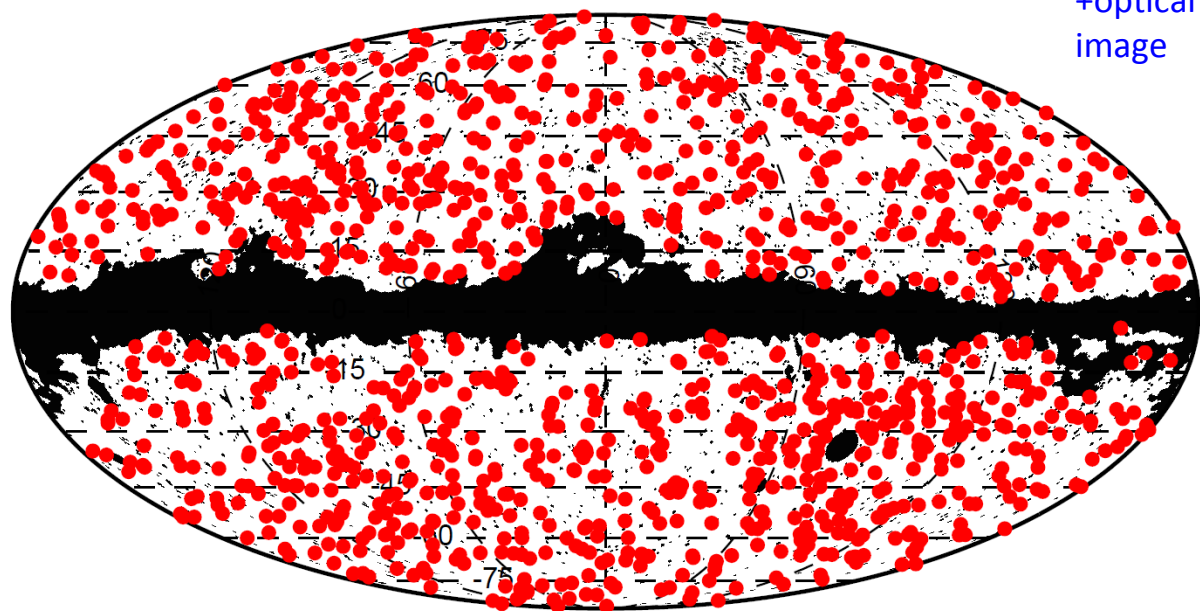44 GHz   70 GHz   100 GHz   143 GHz   217 GHz   353 GHz   545 GHz

Planck

SZ shadow,
**Coma cluster
of galaxies**
*y-parameter map,
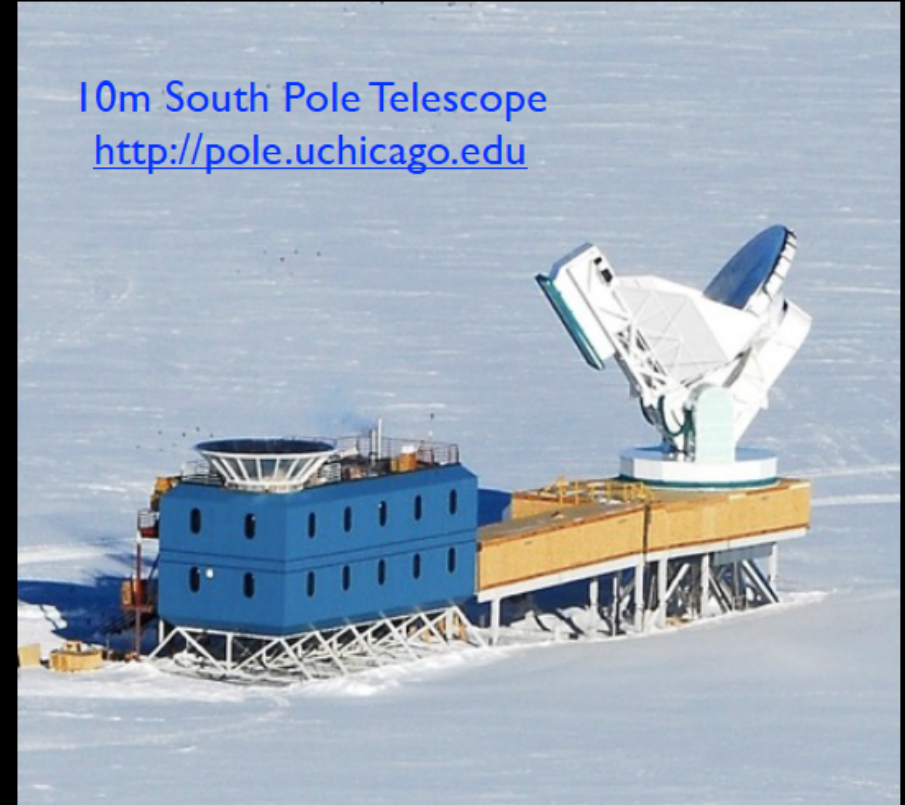based on
100-857 GHz data*

~ 900 clusters confirmed by X-Ray
or optical observations

Planck
+optical
image

Planck / DSS

ACT and SPT

Dedicated Telescopes for measurement of
CMB polarization and fine angular scale temperature anisotropy

6m Atacama Cosmology Telescope
http://www.physics.princeton.edu/act/

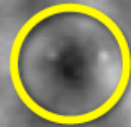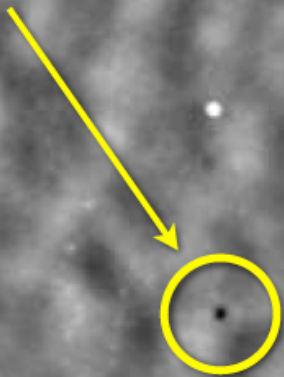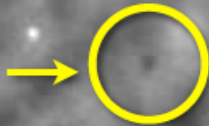10m South Pole Telescope
http://pole.uchicago.edu

- Exceptional high and dry sites for dedicated CMB observations.

- Exploiting ongoing revolution in low-noise bolometer cameras

SPT 150 GHz 50 deg²

Clusters of Galaxies

"Shadows" in the microwave background from clusters of galaxies

Lower limit on $\langle y \rangle$ from Planck and SPT detected clusters

Sum the $\langle y \rangle$ from Planck clusters at $z < 0.3$ and SPT clusters at $z > 0.3$
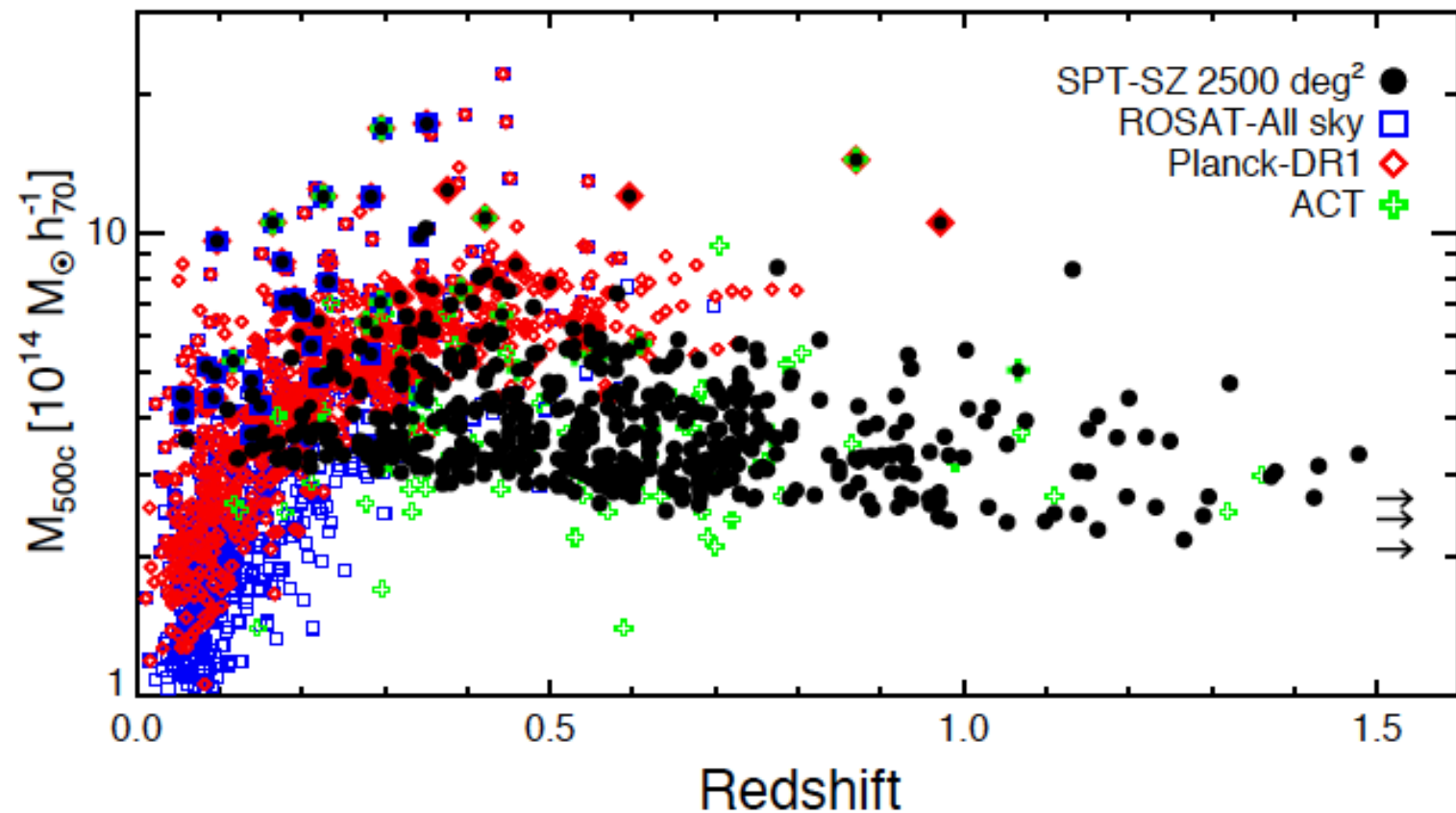

Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850

Lower limit on $\langle y \rangle$ from Planck and SPT detected clusters

Observed clusters $\Rightarrow$ Minimum average y-distortion in the CMB
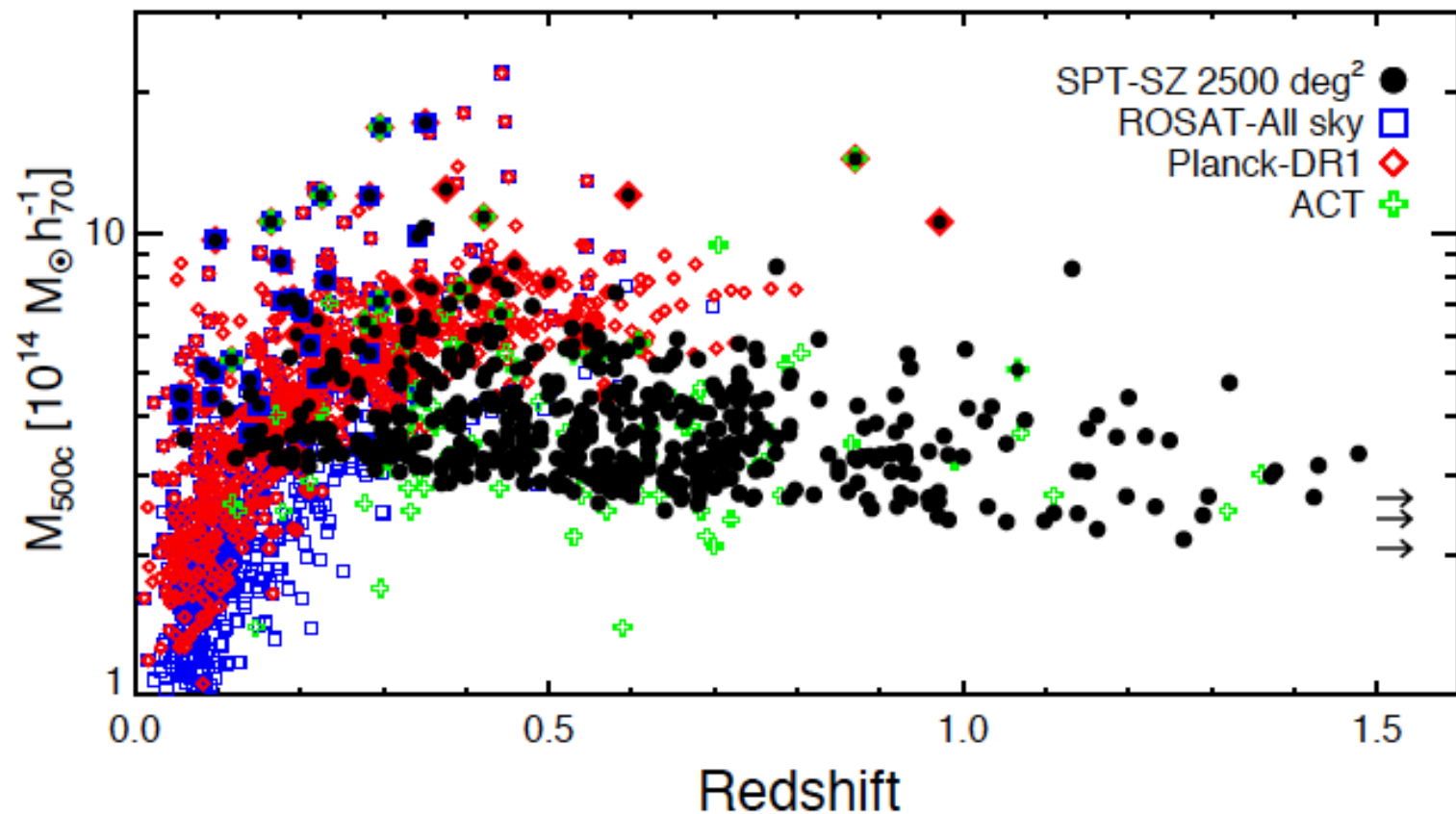$\langle y \rangle > 5.4 \times 10^{-8}$ (*Khatri & Sunyaev 2015*)

Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850

New upper limit on $\langle y \rangle$ from y-map created by combining Planck HFI channels

y−distortion map,10 arcmin

Khatri (2015) arXiv:1505.00778

−25.0   25.0 x 1e−6

fsky=51%

LIL
noise(LIL)
LIL,clusters masked

Khatri, Sunyaev, 2015

P(y) for the Planck y-map of the whole sky (Khatri, 2015)
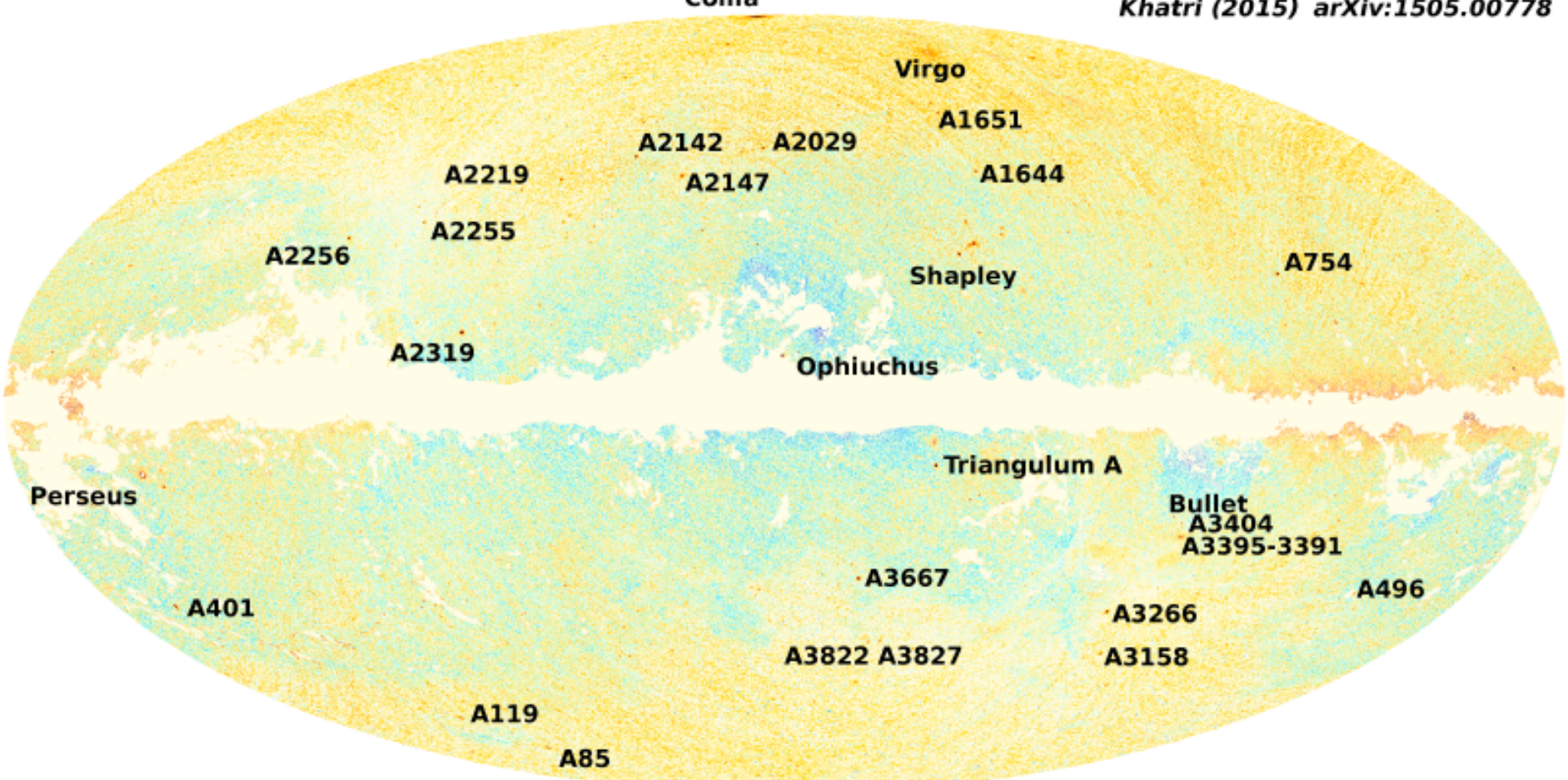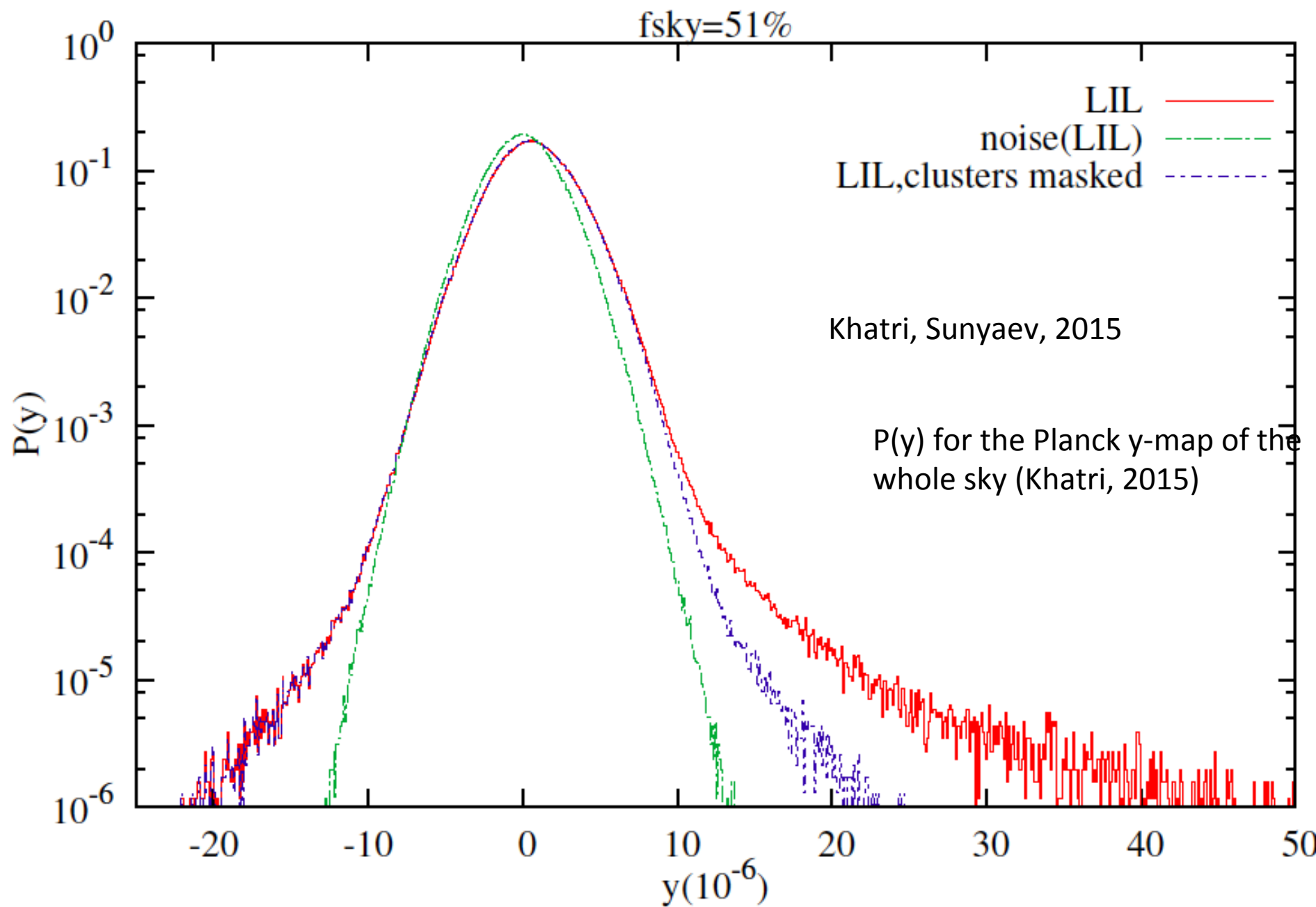
New upper limit on $\langle y \rangle$ from y-map created by combining Planck HFI channels

A simple conservative approach:

- ▶ Take all the positive pixels in the map (excluding contaminated regions)

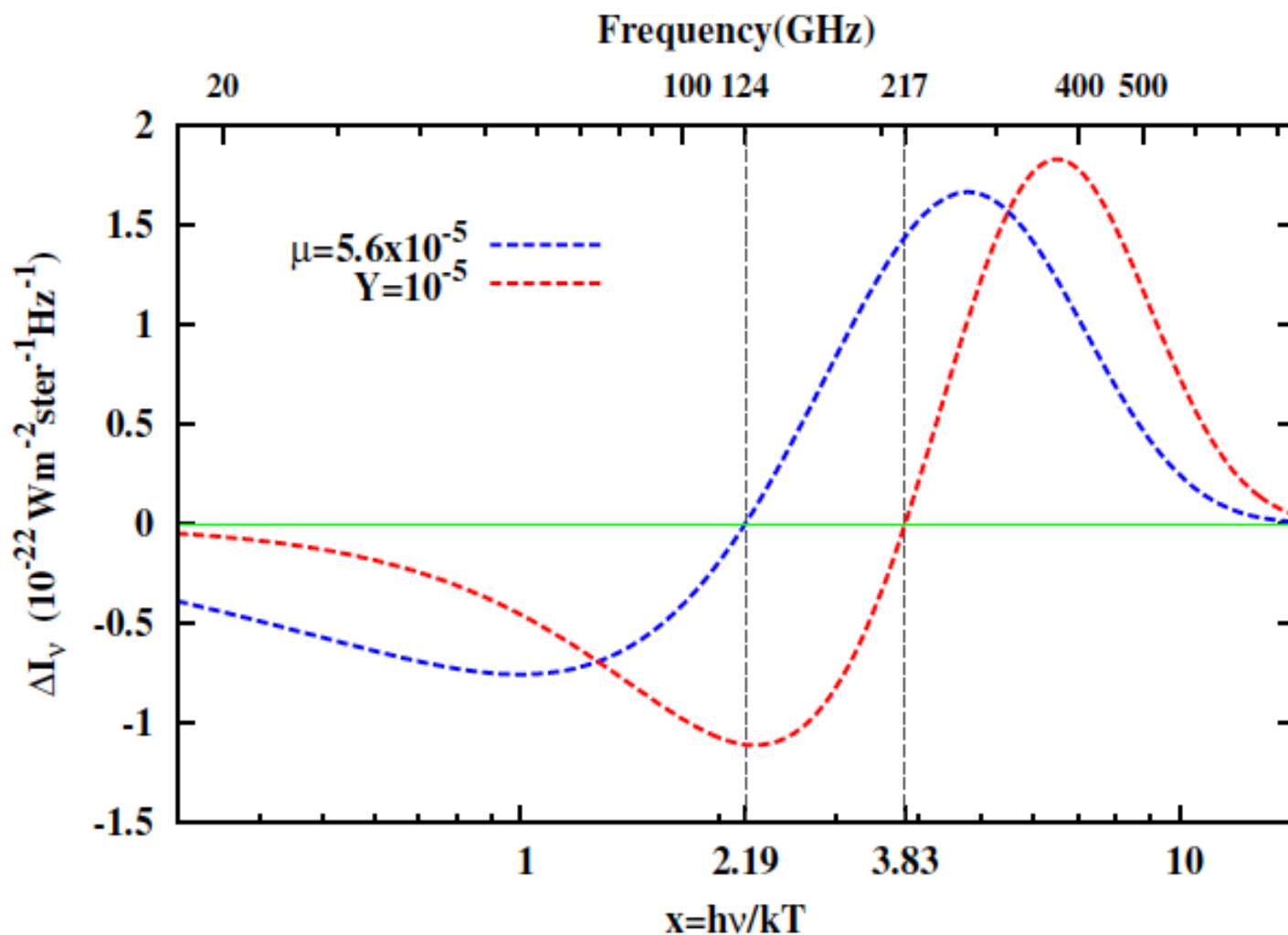- ▶ Average the y-distortion in the pixels (All pixels have equal area)

Result: $\langle y \rangle < 2.2 \times 10^{-6}$ *(Khatri & Sunyaev 2015)*

6.8 times stronger compared to the COBE-FIRAS upper limit:
$\langle y \rangle < 15 \times 10^{-6}$ *(Fixsen et al. 1996)*

μ-distortion: Bose-Einstein spectrum, $y_\gamma \gg 1$

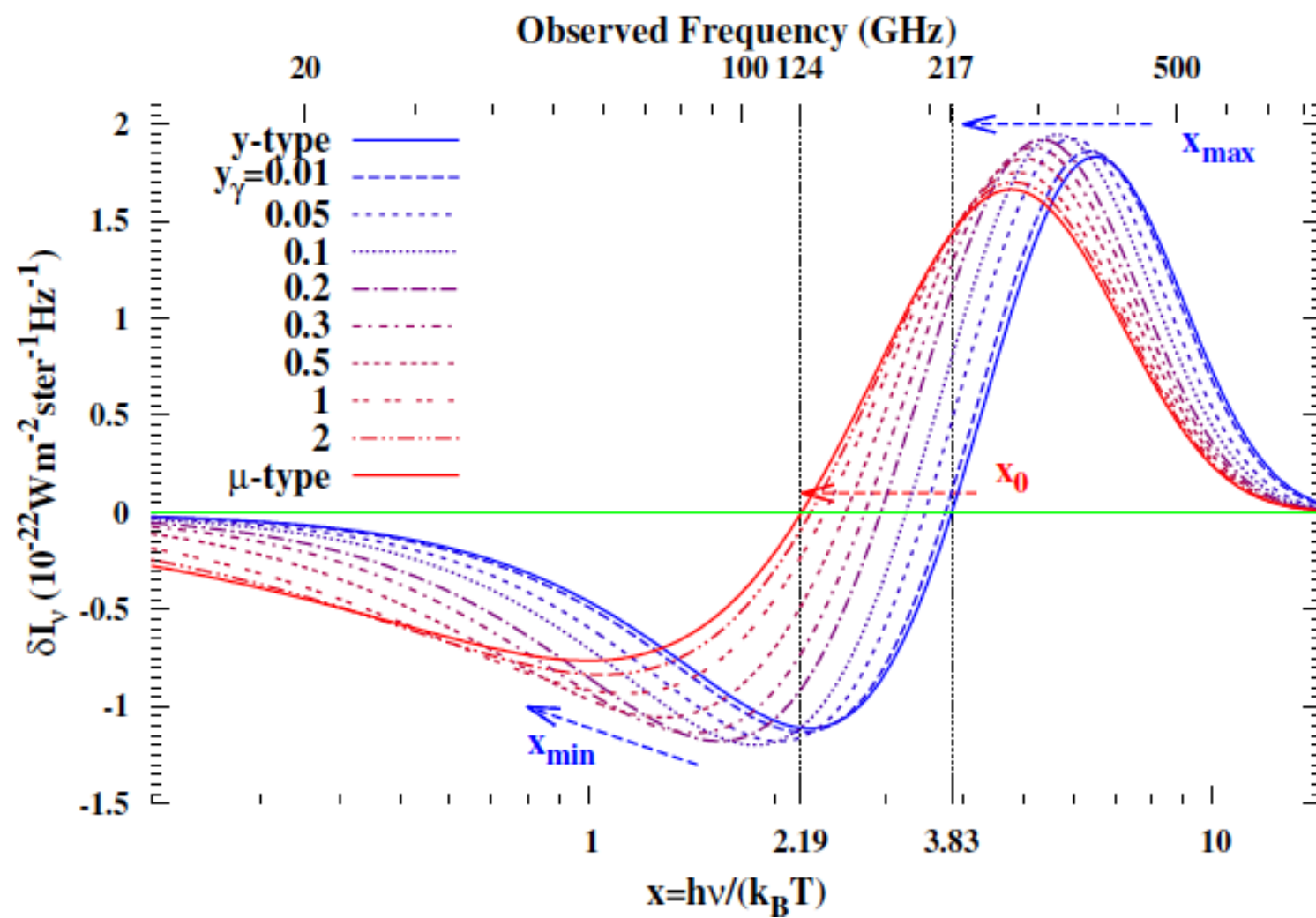COBE-FIRAS limit (95%): $\mu \lesssim 9 \times 10^{-5}$ *(Fixsen et al. 1996)*

Intermediate-type distortions *(Khatri and Sunyaev 2012b)*

Solve Kompaneets equation with initial condition of $y-$type solution.
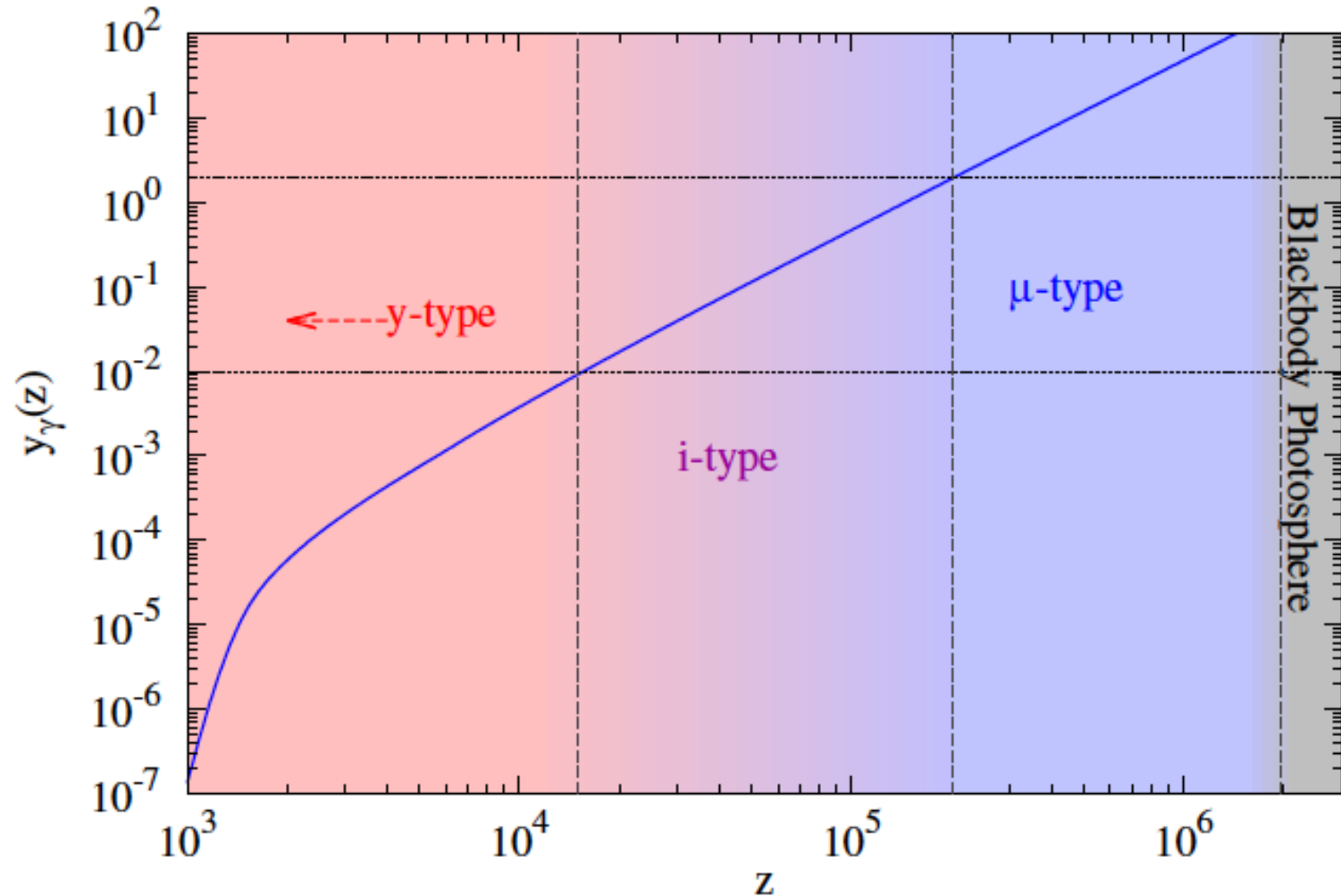
$$\frac{\partial n}{\partial y_\gamma} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(n+n^2+\frac{T_e}{T}\frac{\partial n}{\partial x}\right), \quad \frac{T_e}{T} = \frac{\int(n+n^2)x^4dx}{4\int nx^3dx}$$

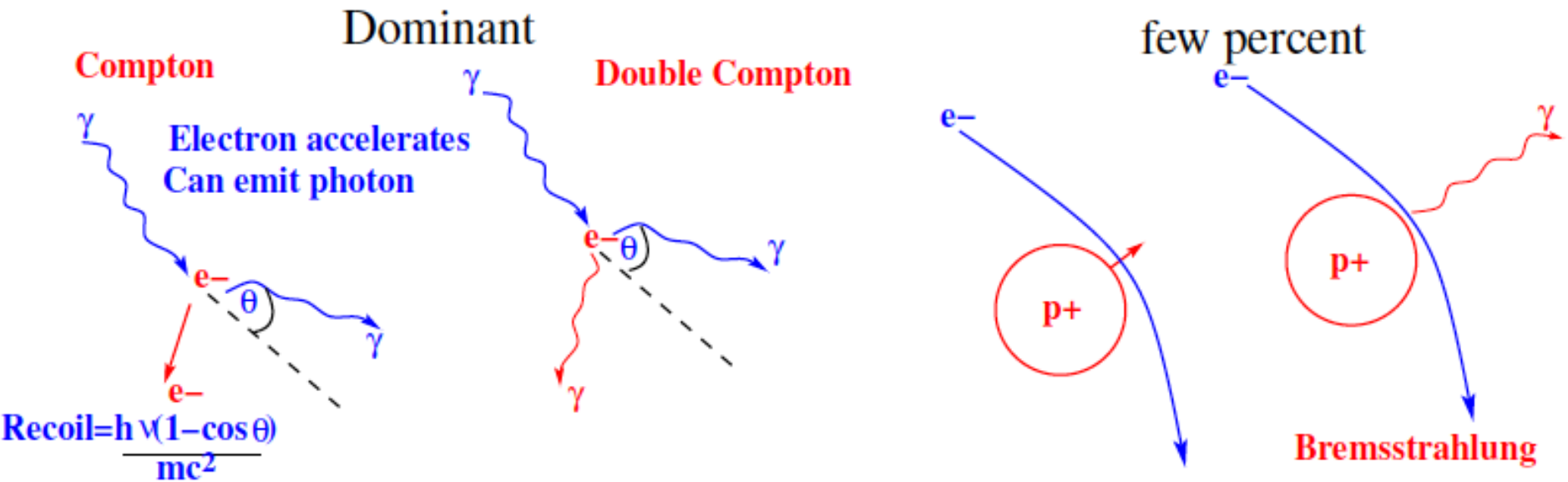# For $y_\gamma \gg 1$ equilibrium is established.

T_e and T_γ converge to common value

The photon spectrum relaxes to equilibrium Bose-Einstein distribution

Processes responsible for creation of CMB spectrum

Dominant

few percent

Compton

γ

Electron accelerates
Can emit photon

e−

θ

γ

e−

Recoil=$\dfrac{h\nu(1-\cos\theta)}{mc^2}$

Double Compton

γ

e− θ

γ

γ

e−

γ

e−

p+

p+

Bremsstrahlung

- ► Double Compton and bremsstrahlung create/absorb photons ($\propto 1/x^2$)
- ► Compton scattering distributes them over the whole spectrum

Creation of CMB Planck spectrum

Double Compton+bremsstrahlung create Planck spectrum

Departure from blackbody prompts double Compton and bremsstrahlung to create photons

Planck

Bose-Einstein

Compton scattering redistributes photons creating Bose-Einstein spectrum with $\mu \to 0$

Competition between Compton scattering and double Compton+bremsstrahlung

$x^3 n(x) \propto$ Intensity

x
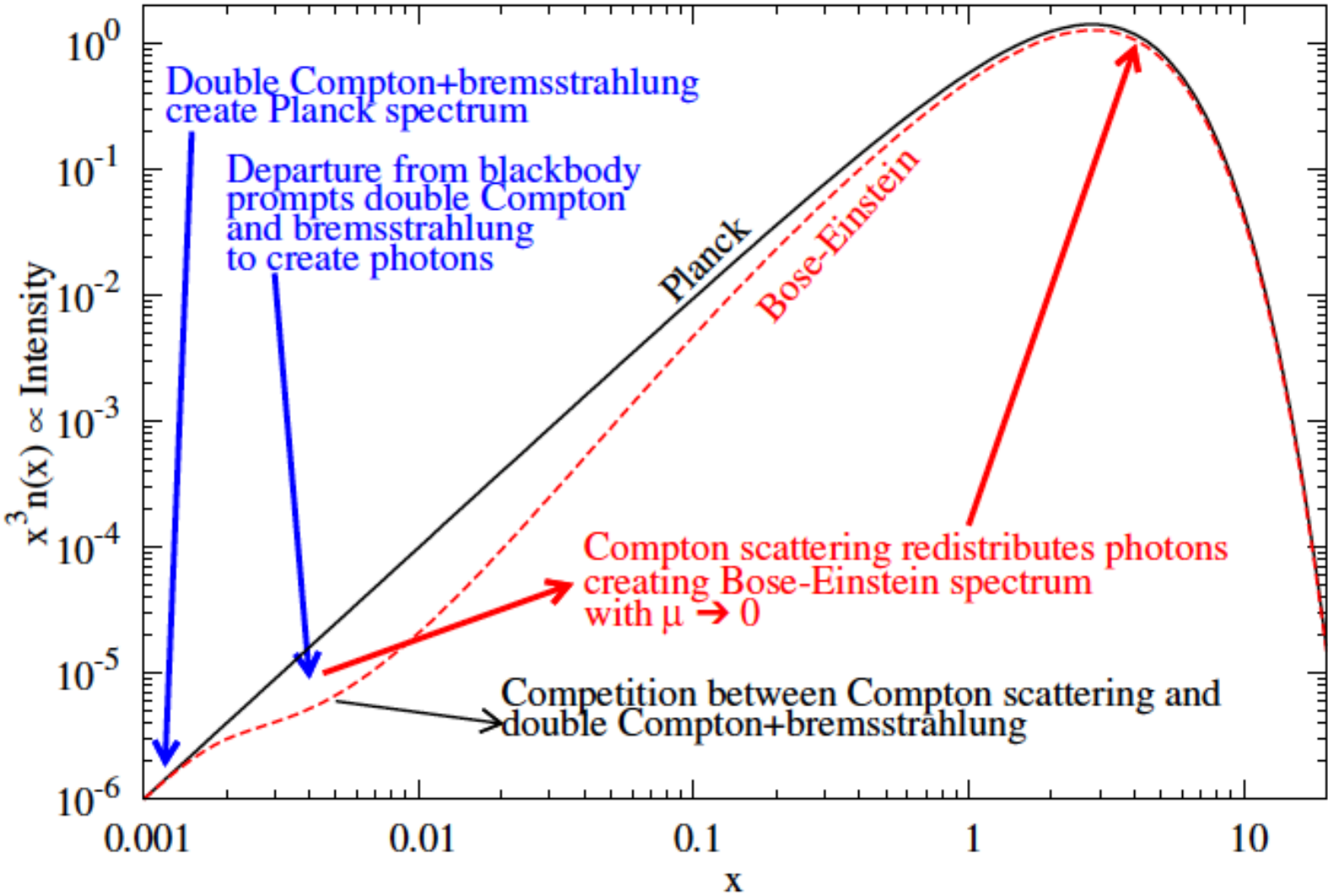
Analitical solution(Sunyaev, Zeldovich, 1970

$$\mu = \mu(t_0) \, e^{-2\sqrt{(ak)}(t-t_0)}$$

Where a and k are scattering (Comptonisation) and real absorption coefficients correspondently

In the case of Double Compton (emission of second photon during scattering) spectral deviations decrease with time

$$\frac{\mu^{final}}{\mu^{initial}} \approx e^{-(z_i/z_{dc})^{5/2}}$$

Danese, de Zotti, 1984

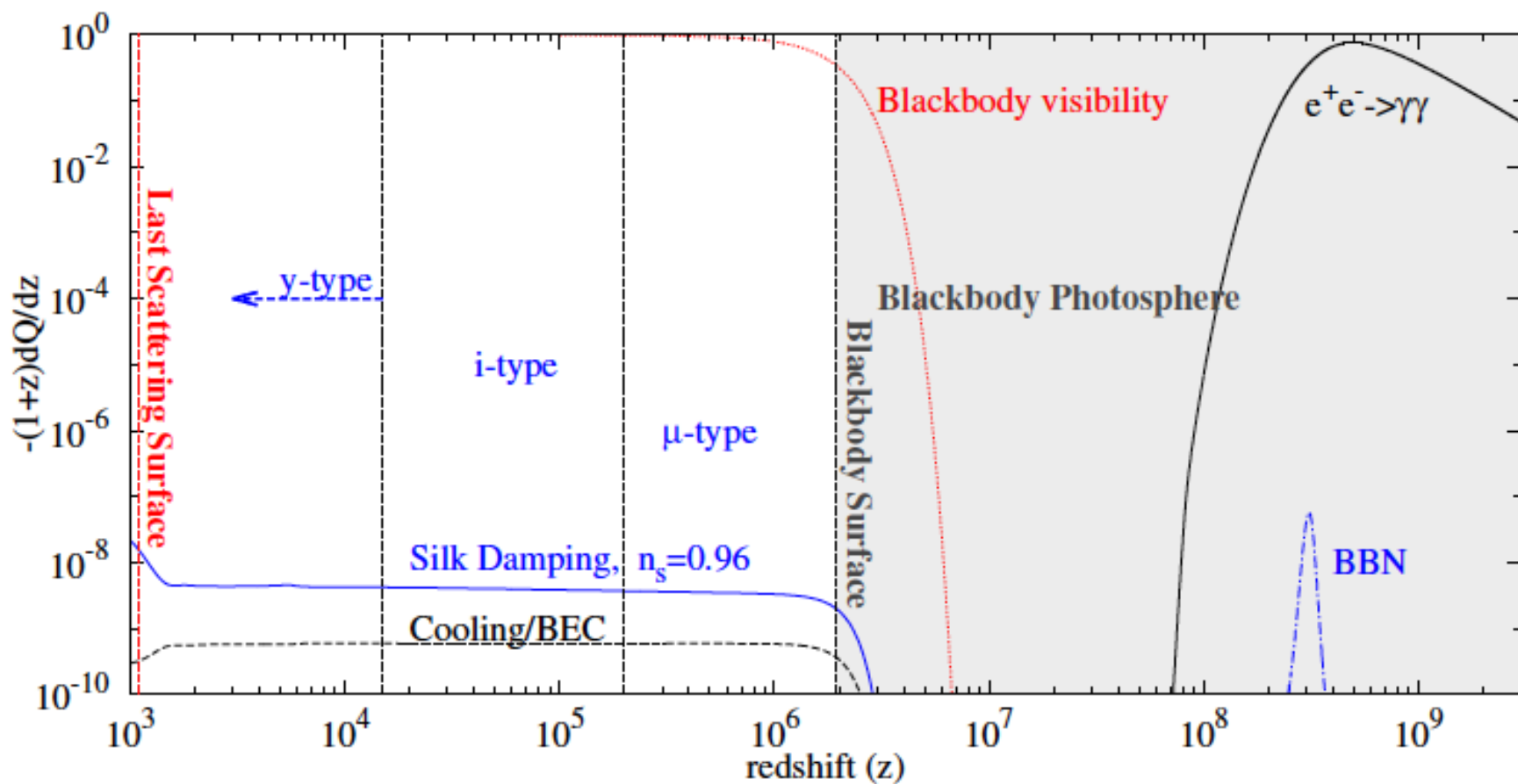# Bose-Einstein spectrum- Chemical potential (μ)

$$n(x) = \frac{1}{e^{x+\mu} - 1}$$

Given two constraints, energy density (E) and number density (N) of photons, T, μ uniquely determined.
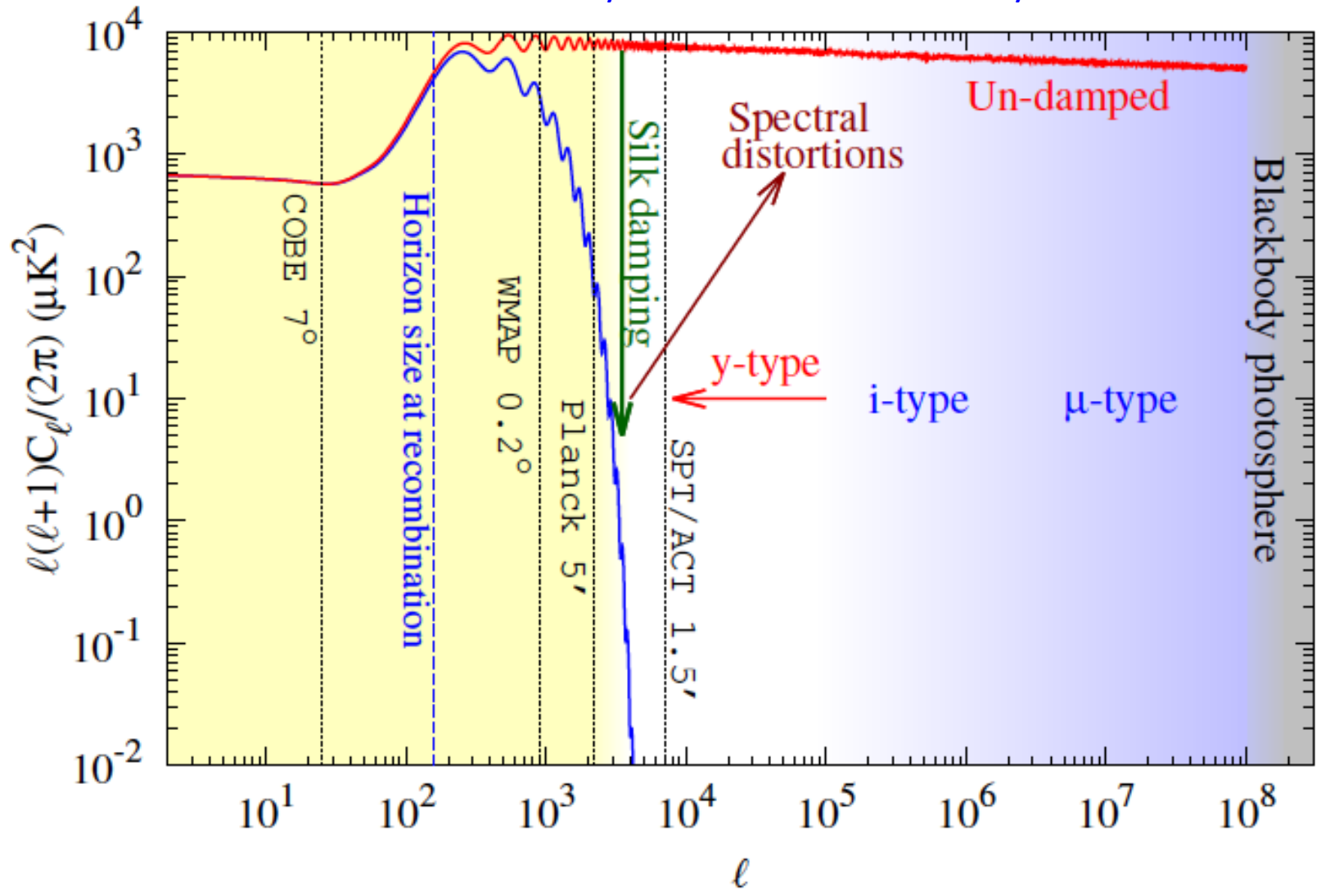
Idea behind analytic solutions:

If we know rate of production of photons and energy injection rate, we can calculate the evolution/production of μ (and T)
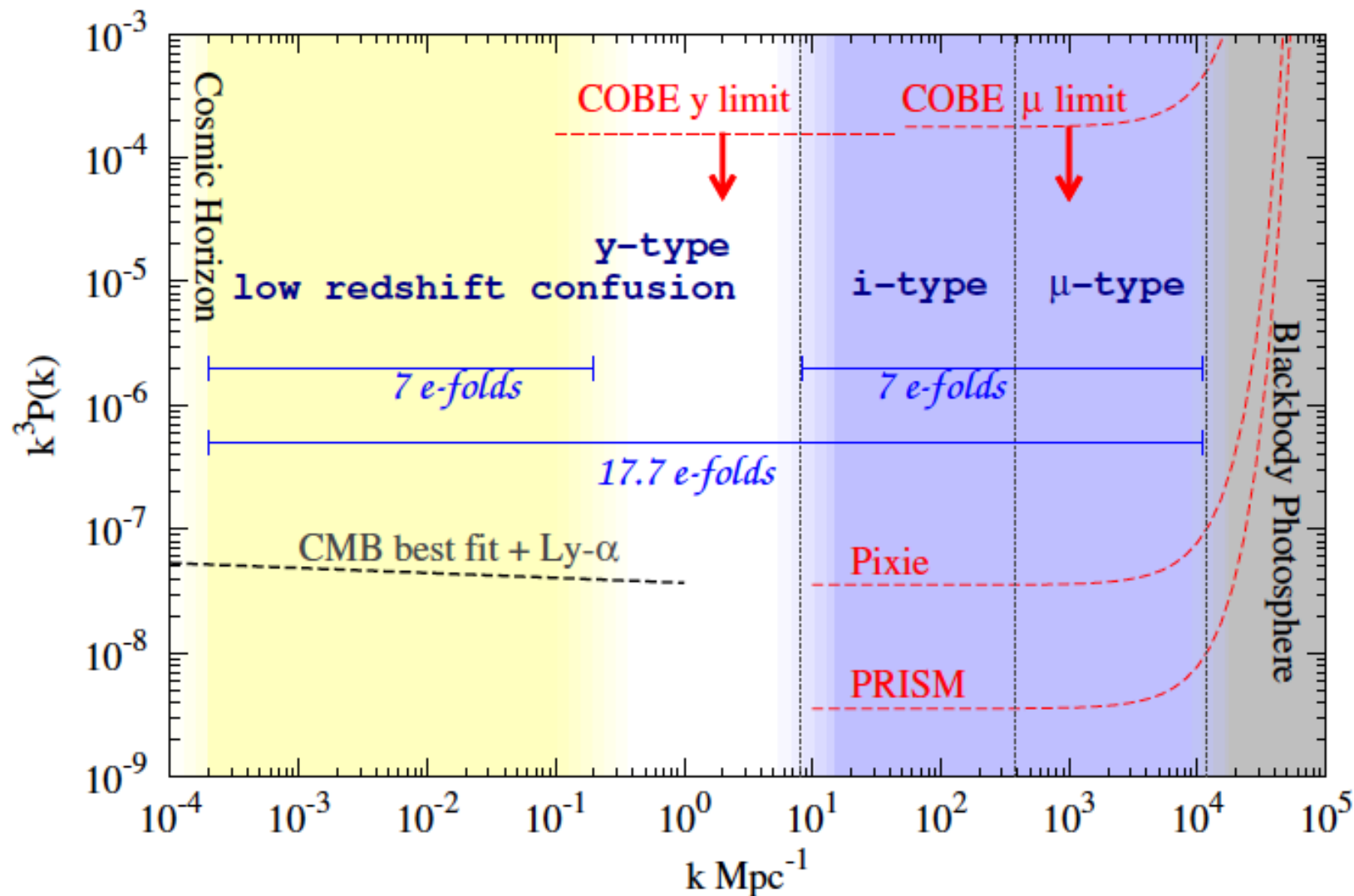
The general picture

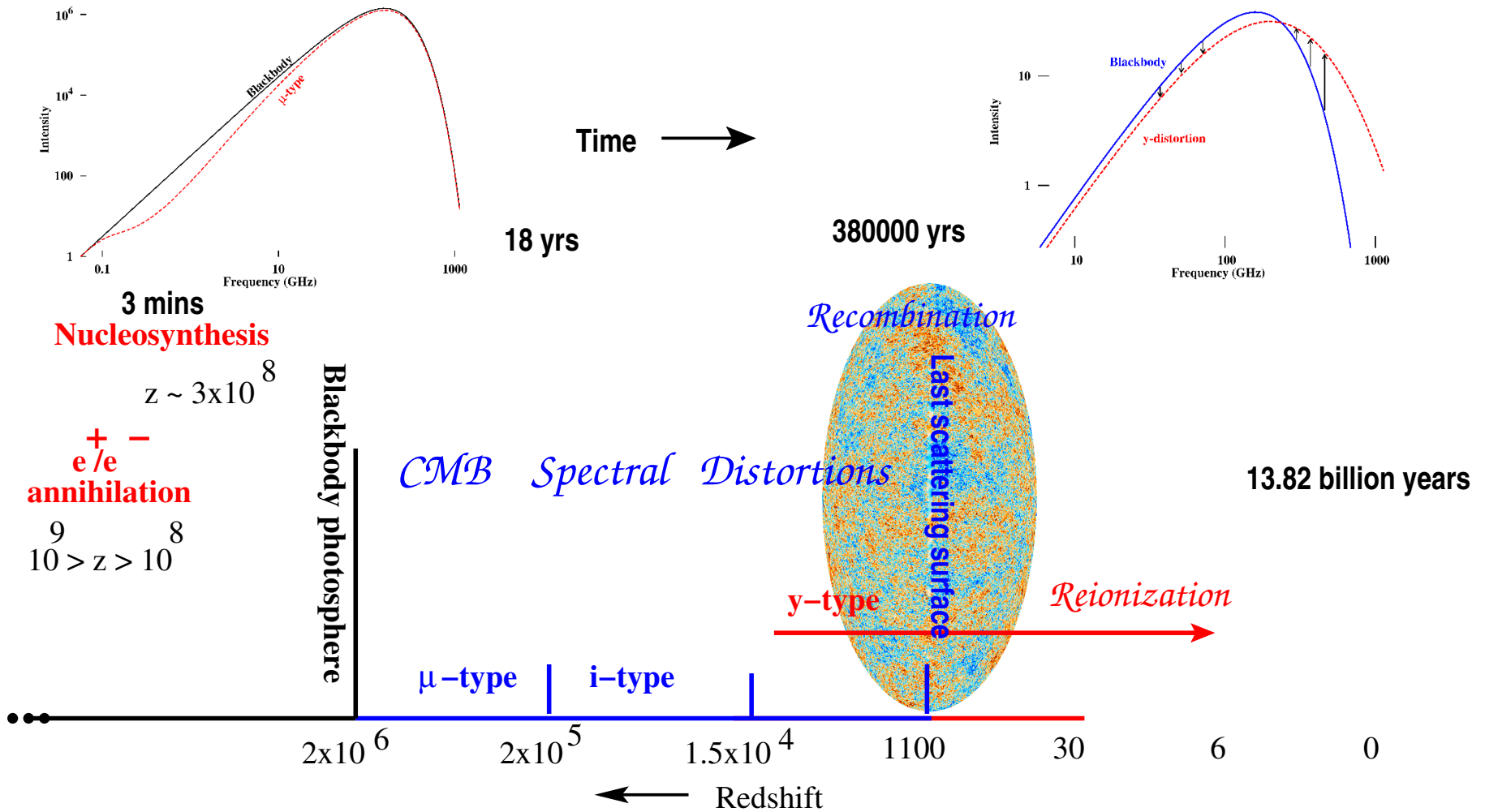# We have reached the resolution limit for CMB anisotropies

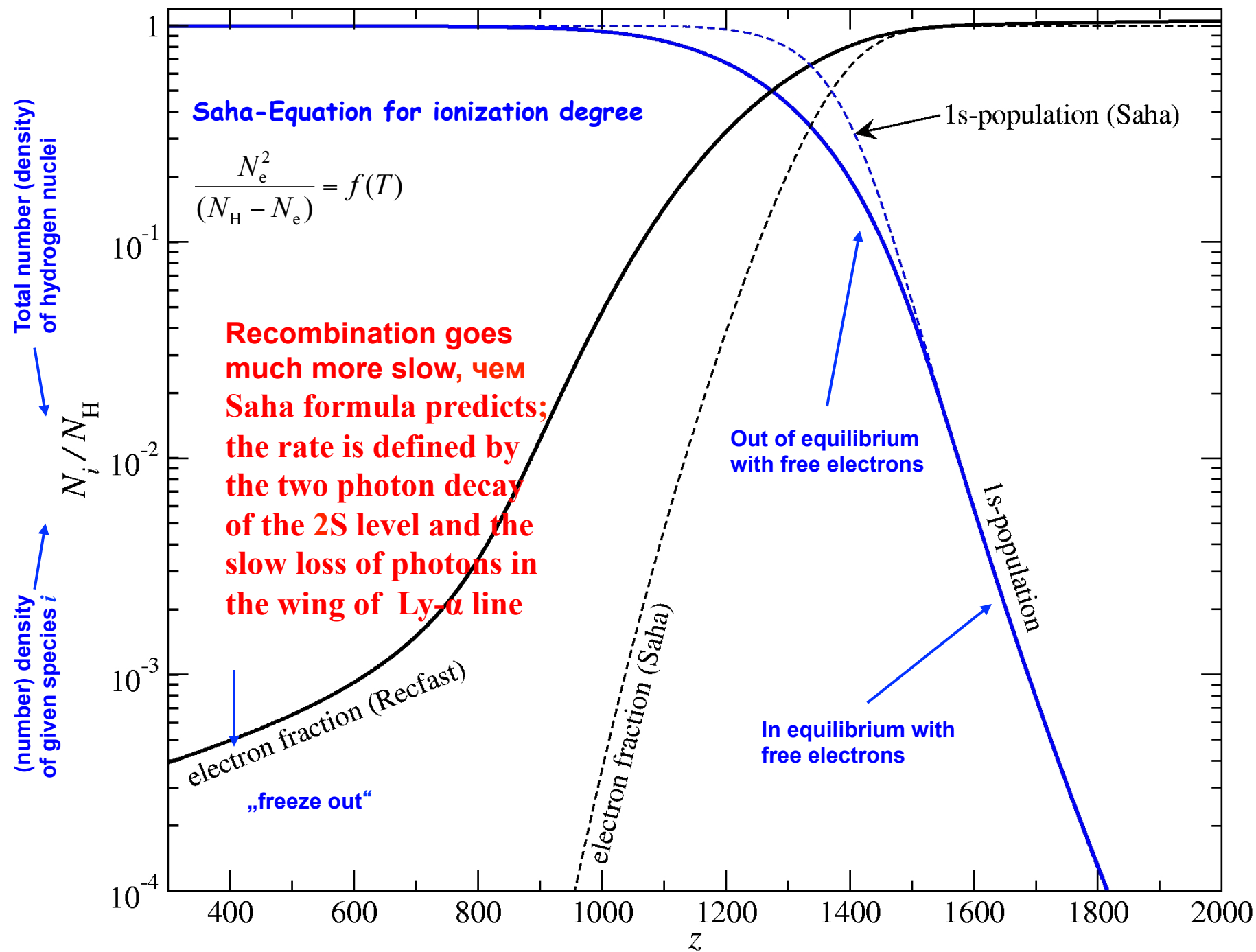Silk damping of standing sound waves due to radiative viscosity and thermal conductivity

Going from 7 to 17 e-folds of inflation

Two milestones in the life of the Universe:
Last Scattering Surface and
Black Body Photosphere

Time →

18 yrs

380000 yrs

3 mins
Nucleosynthesis

$z \sim 3 \times 10^8$

e^+/e^- annihilation

$10^9 > z > 10^8$

Recombination

Blackbody photosphere

CMB Spectral Distortions

Last scattering surface

13.82 billion years

y−type

Reionization

μ −type   i−type

2×10^6 2×10^5 1.5×10^4 1100   30   6   0

← Redshift

with Rishi Khatri and Jens Chluba

Saha-Equation for ionization degree

$$\frac{N_e^2}{(N_H - N_e)} = f(T)$$

Recombination goes much more slow, чем Saha formula predicts; the rate is defined by the two photon decay of the 2S level and the slow loss of photons in the wing of Ly-α line

1s-population (Saha)

Out of equilibrium with free electrons

In equilibrium with free electrons

1s-population

electron fraction (Recfast)

electron fraction (Saha)

„freeze out"

Total number (density) of hydrogen nuclei

(number) density of given species i

N_i / N_H

z

from Chluba, Sunyaev, 2009

Zeldovich, Kurt, Sunyaev,1968; Peebles, 1968
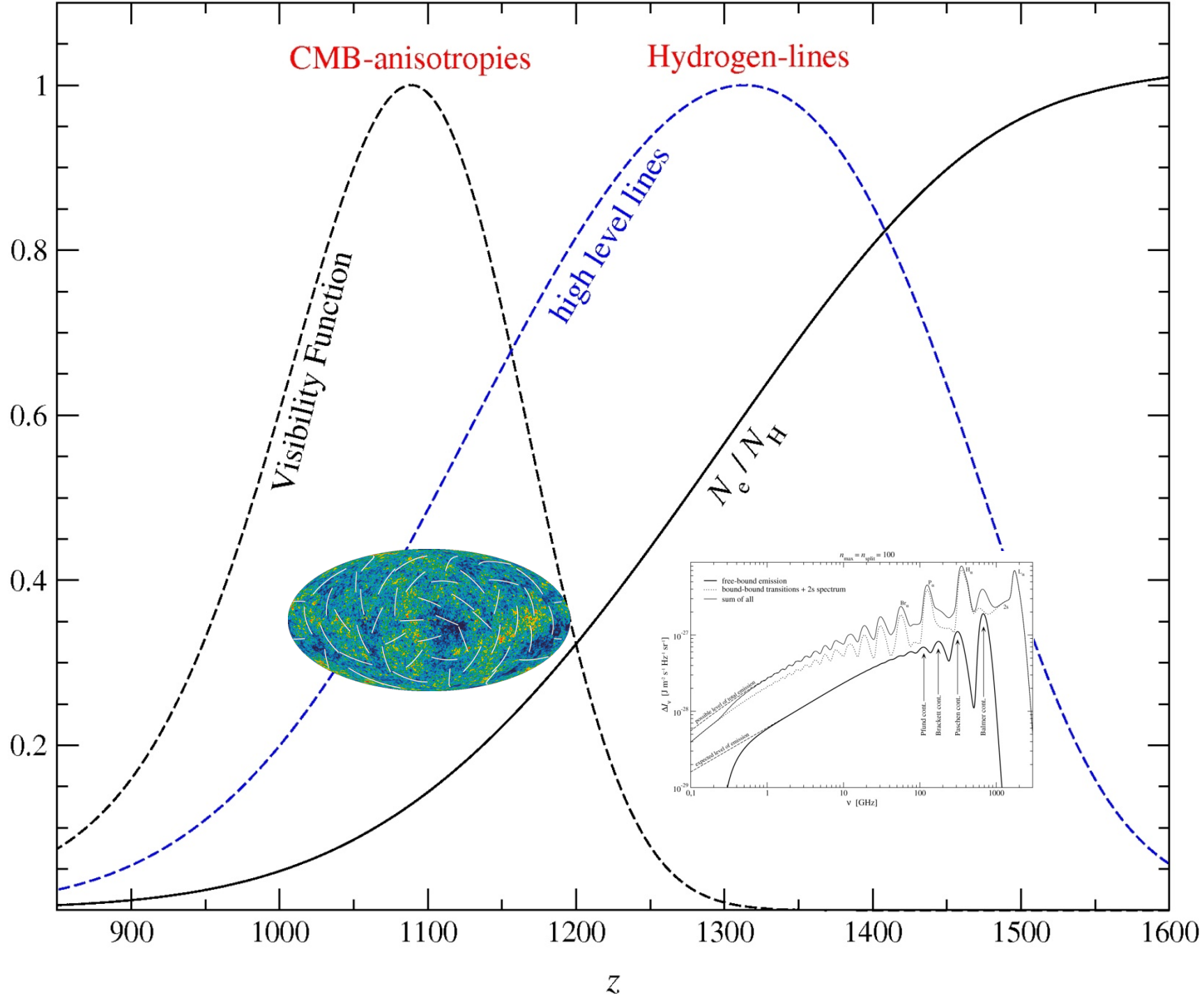
Visibility function

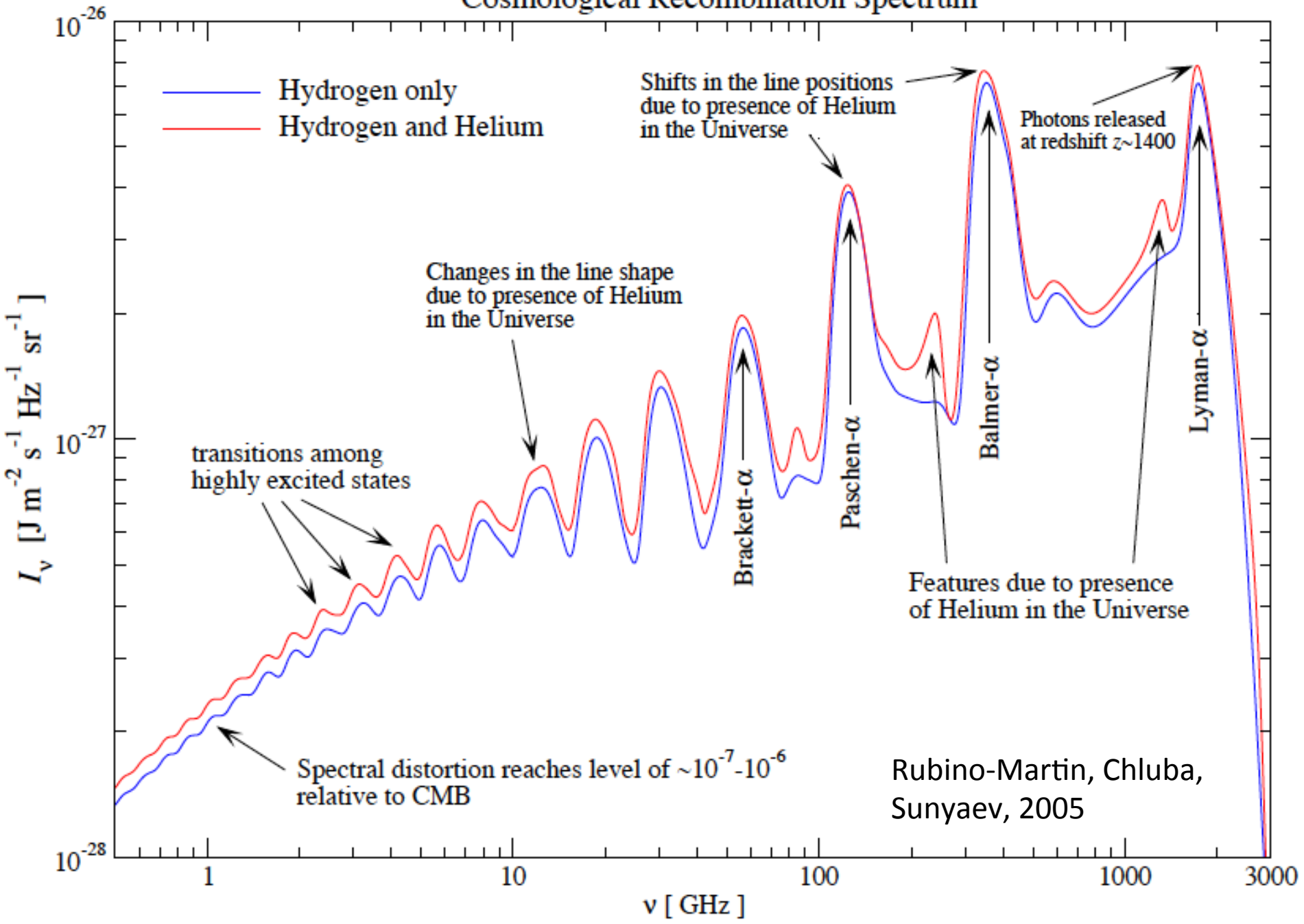*Last scattering surface*

Below we will need the function

$$e^{-\tau} \frac{d\tau}{dz} = \sigma_T n_c c H_0^{-1} A z^{-1/2} \exp\left\{ - a z^{3/2} e^{-B/z} - \frac{B}{z} - \tau_0 \right\}, \qquad (6)$$

which in agreement with (3) has a sharp maximum for $z_{max} = 1055$ ($(e^{-\tau}(d\tau/dz))_{z=z[max]} = 3.32 \times 10^{-3}$) and exponentially decreases in both directions, the value of the function decreasing to half its maximum value for $z_3 = 960$ and $z_4 = 1135$. It will be convenient in what follows to approximate this function by a Gaussian function with dispersion $\sigma_z = 75$ whose integral equals 1.

The redshift and the width of this function were very well confirmed by WMAP and recently PLANCK

CMB-anisotropies

Hydrogen-lines

Visibility Function

high level lines

N_e / N_H

$n_{max} = n_{split} = 100$

- free-bound emission
- bound-bound transitions + 2s spectrum
- sum of all

ΔI_ν [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]

possible level of total emission

expected level of emission

Br$_\alpha$

P$_\alpha$

H$_\alpha$

L$_\alpha$

2s

Pfund cont.

Brackett cont.

Paschen cont.

Balmer cont.

ν [GHz]

z

Cosmological Recombination Spectrum

- Hydrogen only
- Hydrogen and Helium

Shifts in the line positions due to presence of Helium in the Universe

Photons released at redshift $z\sim1400$

Changes in the line shape due to presence of Helium in the Universe

transitions among highly excited states

Features due to presence of Helium in the Universe

Brackett-α

Paschen-α

Balmer-α

Lyman-α

Spectral distortion reaches level of $\sim10^{-7}$-10^{-6} relative to CMB

I_ν [J m^{-2} s^{-1} Hz^{-1} sr^{-1}]

ν [GHz]

Rubino-Martin, Chluba, Sunyaev, 2005

the blurring of primordial fluctuations. Thomson tau = 0.85 (WMAP)

full analogy with Gunn-Peterson effect, but Tr inhomogeneities on the sky are playing the role of quasars and submm lines are used instead Ly-alpha.
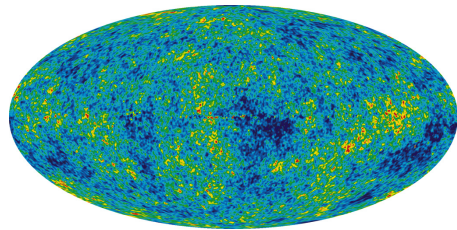
Hot and cold spots

zero effect for monopole, polarization from quadrupole

Basu, Hernandez-Monteagudo, Sunyaev, 2004
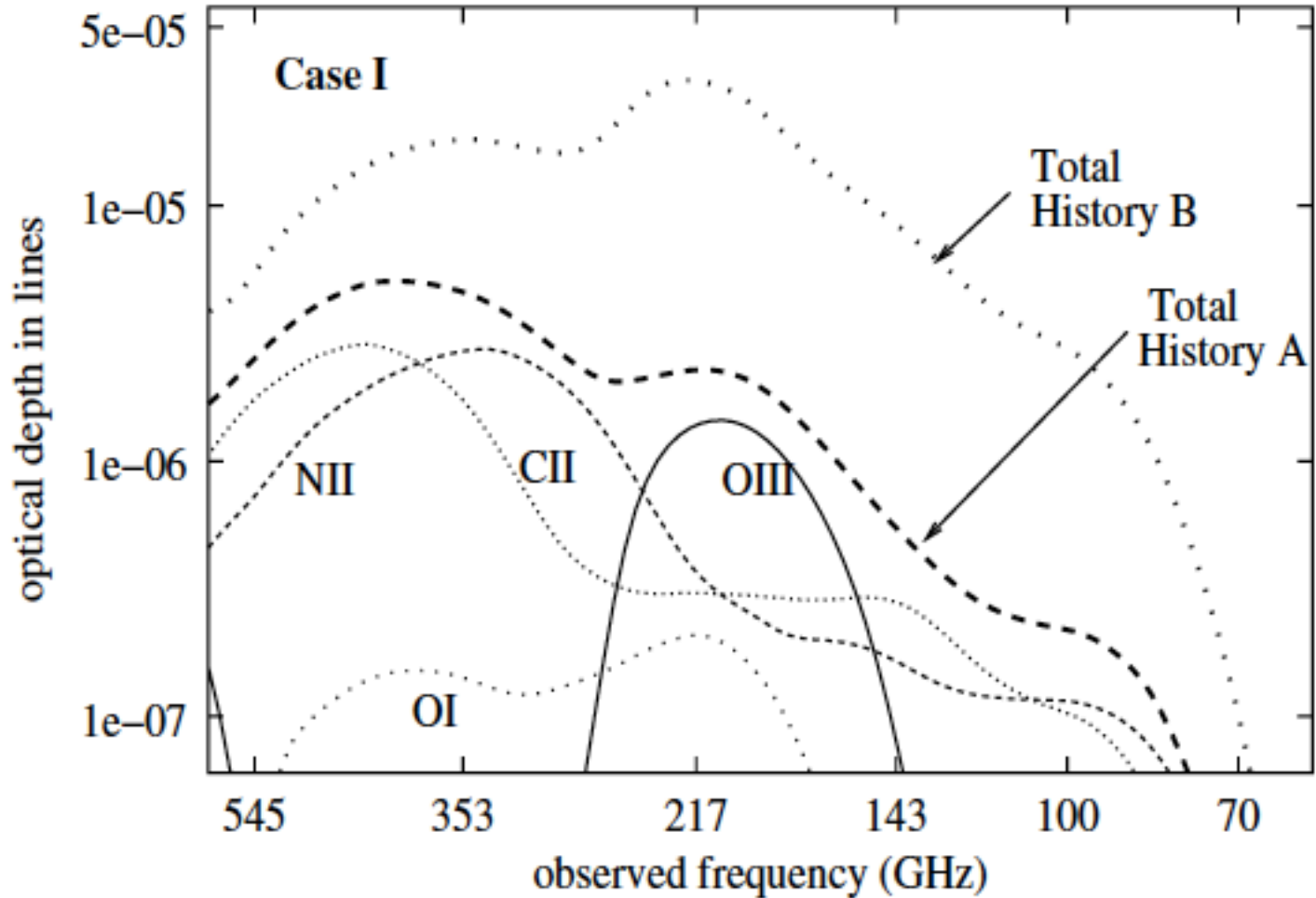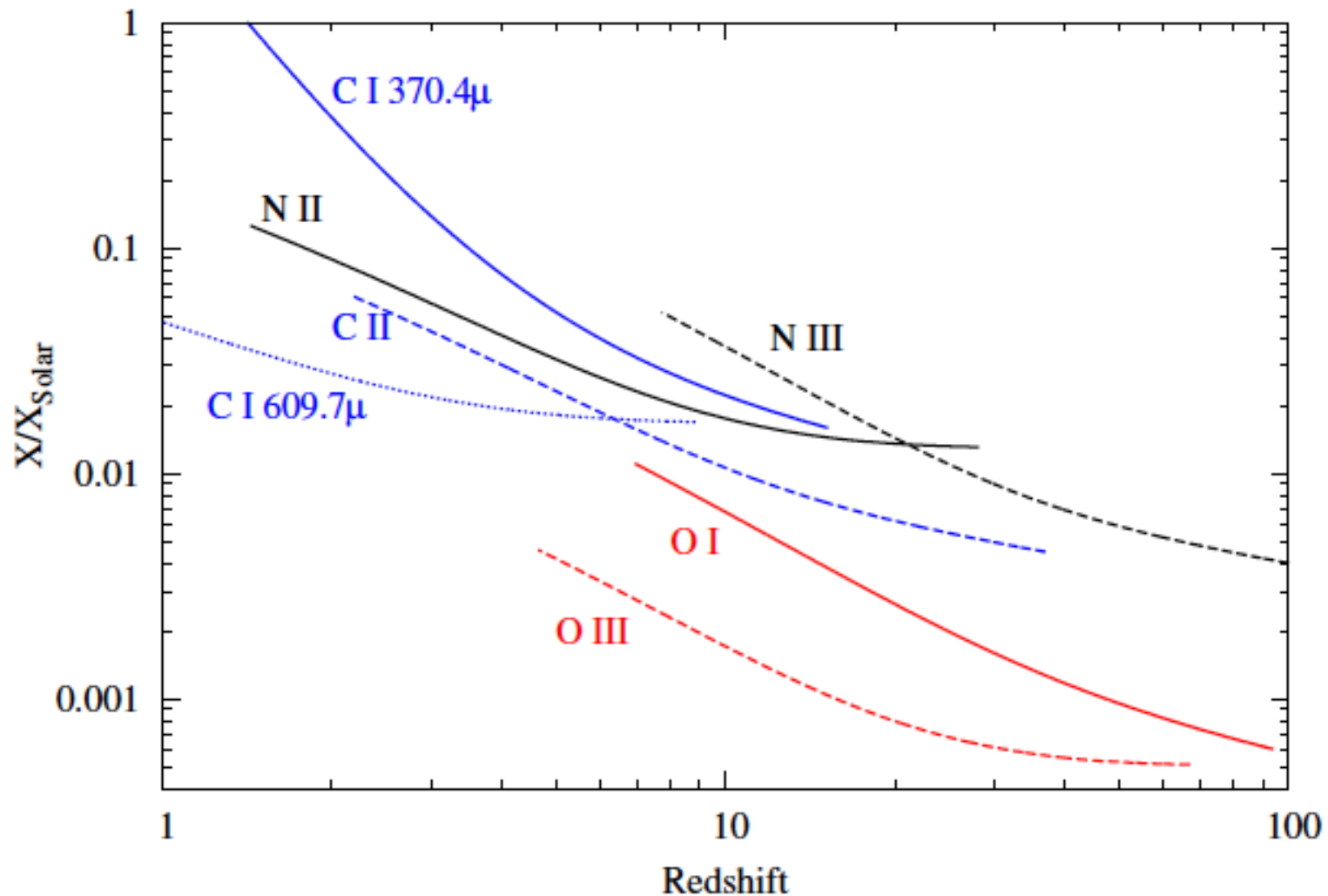
Figure 47. Projected constraints on abundance of C,N,O atoms and ions from 50-600 GHz channels of PRISM assuming it will have the inter-channel calibration accuracy of 0.001% to be able to measure the difference in the optical depth (to the last scattering surface) seen by different channels of $\tau_{LSS} = 10^{-5}$. The highest and lowest redshifts at the endpoints of the each curve correspond to 50 GHz and 600 GHz observed frequency respectively. The constraints as a fraction of solar abundance are plotted, with the reference solar abundances taken to be photosphere abundances in [399].

PRISM proposal

Frequency dependence — $\Delta\nu/\nu_{obs}=10^{-3}$

CO 1−0
CO 2−1
CO 3−2
CO 4−3
CO 5−4
CO 6−5
CO 7−6
CO sum

RADIO

DUST

CII 158

$C_\ell^{line}/C_\ell^{prim}$ ($\ell^*=2000$)

Observing frequency [GHz]
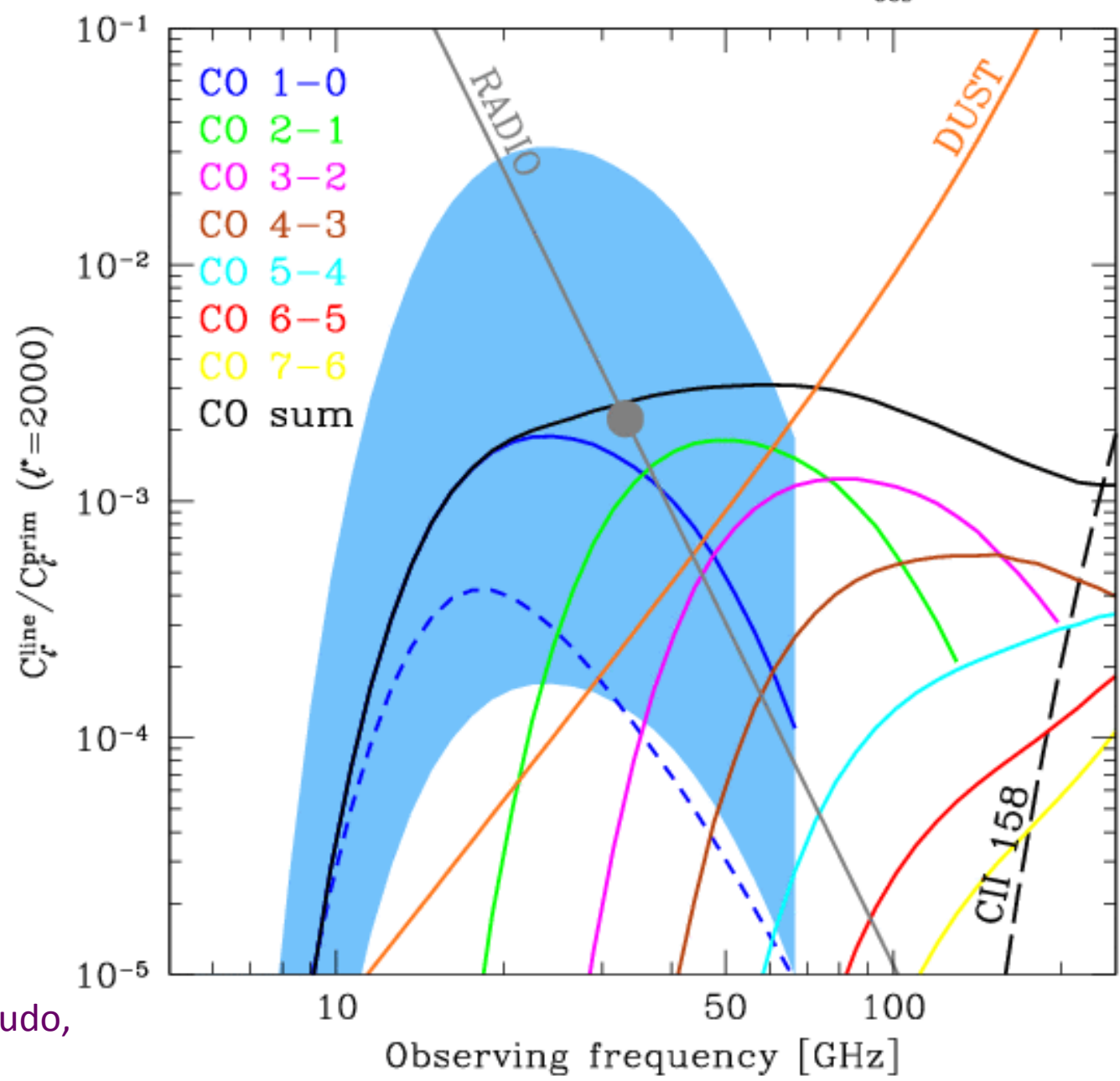
Righi, Hernandez-Monteagudo, Sunyaev, 2008

Experiments of the type of COBE/FIRAS are possible not much often than once in 25 years

The goal, theorists are dreaming:

a sensitivity necessary to detect

a) myu-type distortions on the level of 10^-9 (we do not expect signal below few times 10^-9, but who knows?). However any upper limit will be useful.
b) such a sensitivity will permit to study recombinational lines of hydrogen and helium coming from redshifts ~ 1500 , 2400 and 6000
c) It will be possible to separate y distortions produced before recombination from generated much later (they will distort the recombinational spectrum)

Summary

- The shape of the μ and intermediate type distortions is rich in information

- With spectral distortions we can extend our 'view' of inflation from 6-7 e-folds at present to 17 e-folds

- Spectral distortions take us a little nearer to the end of inflation

- μ-type and intermediate type distortions can be calculated very fast using analytic and pre-calculated cosmology-independent high precision numerical solutions (Green's functions). This allows us to explore the rich multidimensional parameter space

- i-type distortions are quite powerful in removing degeneracies between power spectrum parameters. The extra information comes from the shape of the i-type distortion

THANK YOU !!!

μ-type distortions
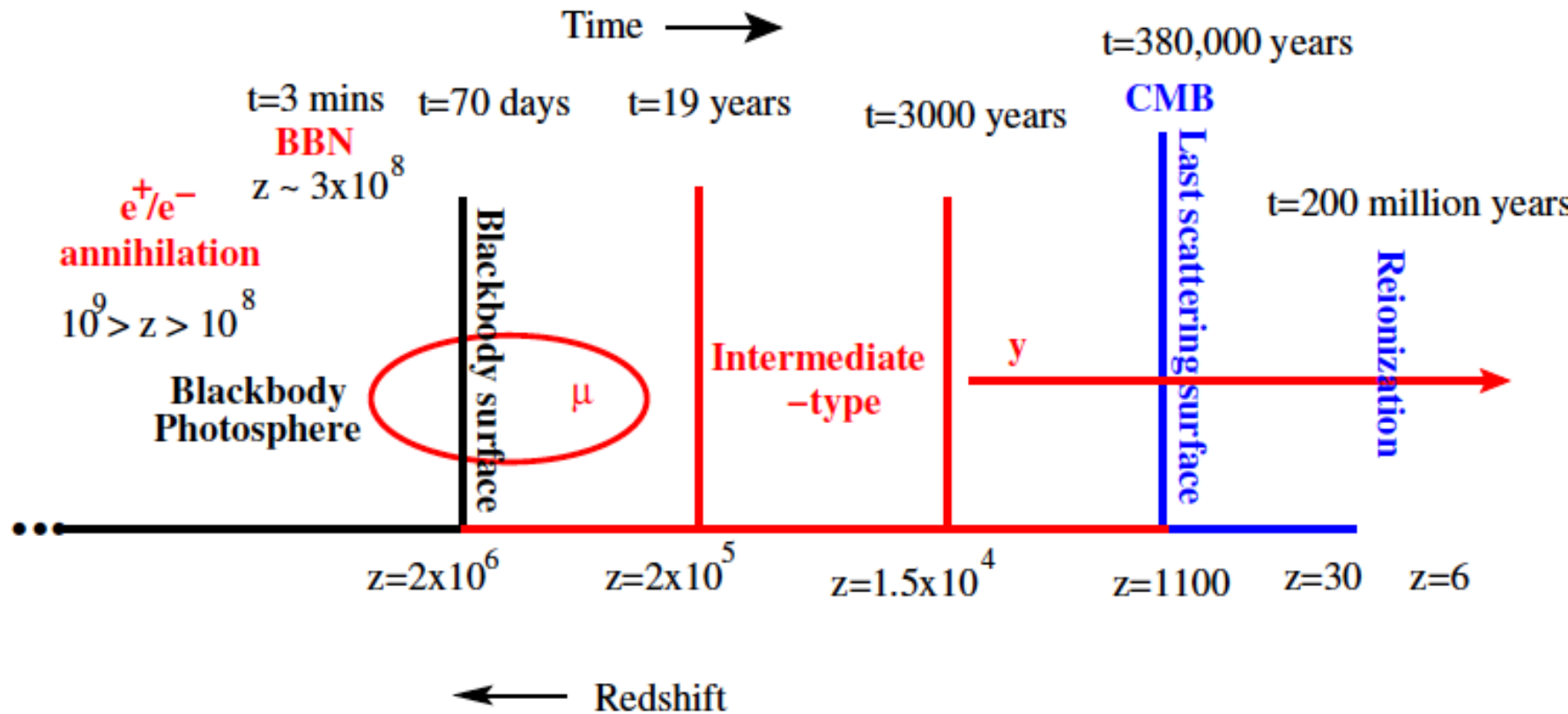
Compton + double Compton + bremsstrahlung
Analytic solution: $\mu = 1.4 \int \frac{dQ}{dz} e^{-\mathscr{T}(z)} dz$
(Sunyaev and Zeldovich 1970)
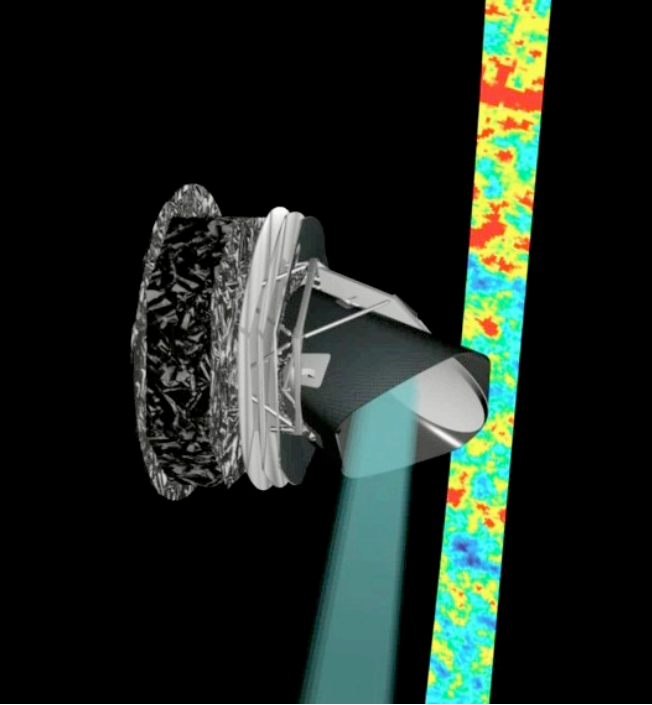
PLANCK spacecraft scans the sky

From paper Sunyaev, Zeldovich 1970
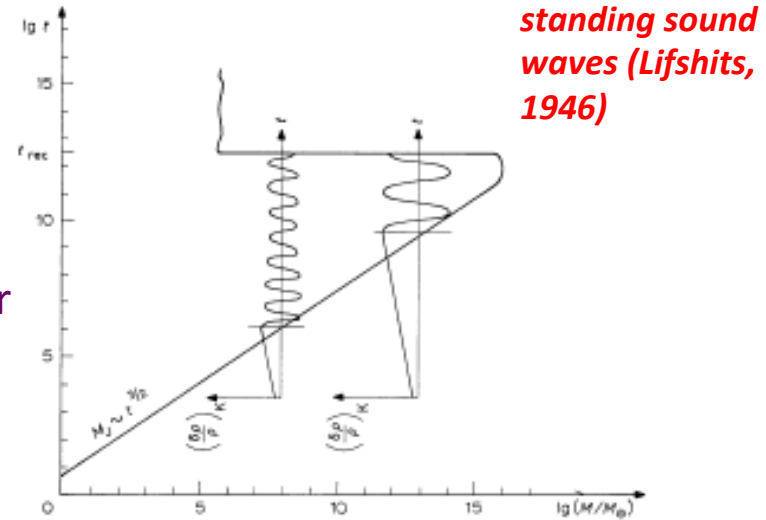
standing sound waves (Lifshits, 1946)

Fig. 1a. Diagram of gravitational instability in the 'big-bang' model. The region of instability is located to the right of the line $M_J(t)$; the region of stability to the left. The two additional lines of the graph demonstrate the temporal evolution of density perturbations of matter: growth until the moment when the considered mass is smaller than the Jeans mass and oscillations thereafter. It is apparent that at the moment of recombination perturbations corresponding to different masses correspond to different phases.

Planck Collaboration: The *Planck* mission

Angular scale
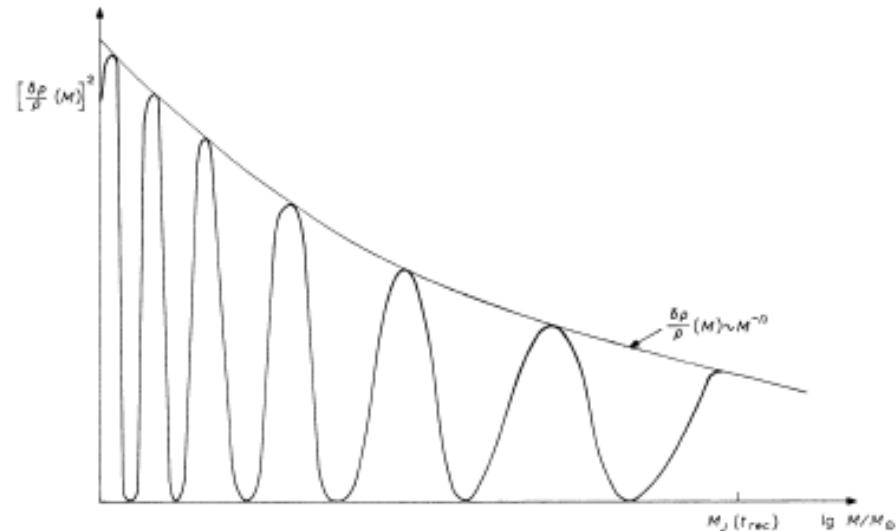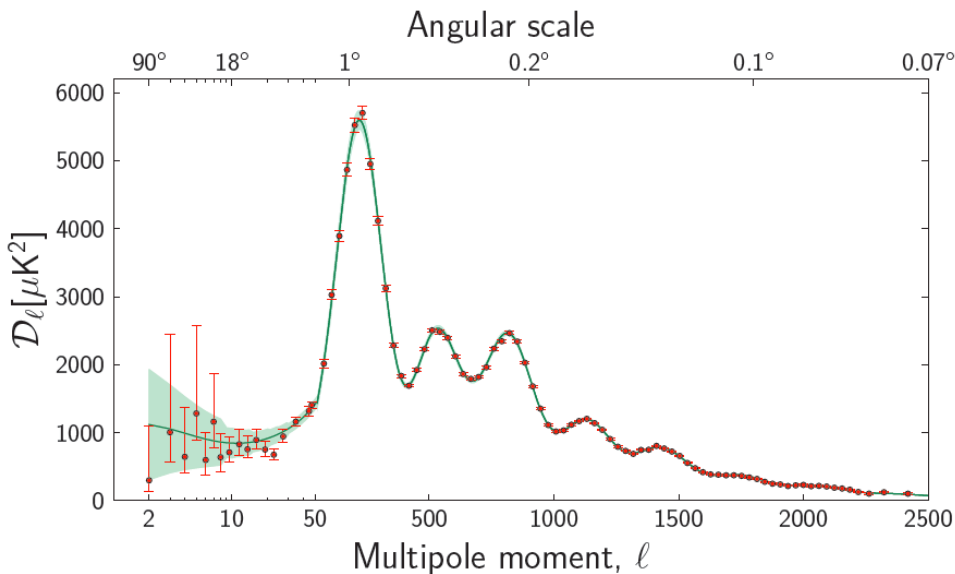
Fig. 1b. The dependence of the square of the amplitude of density perturbations of matter on scale. The fine line designates the usually assumed dependence $(\delta \varrho/\varrho)_M \sim M^{-\alpha}$. It is apparent that fluctuations of relic radiation should depend on scale in a similar manner.
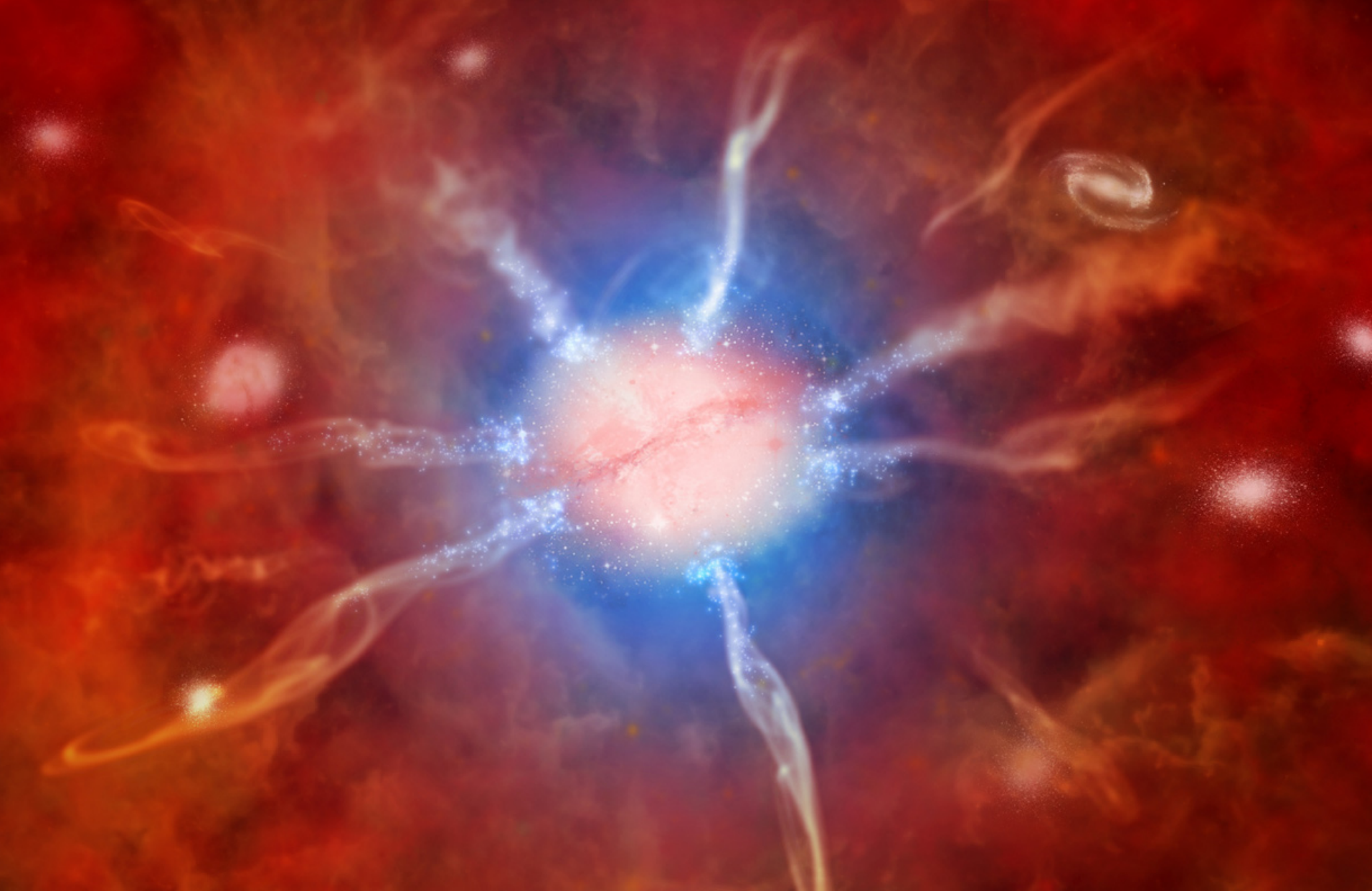
Fenix cluster of galaxies discovered by SPT at z=0.596 and observed by CHANDRA, GALEX and Magellan: star burst – 800 solar masses a year, luminosity 8 10^45 erg/s, cooling flow ~ 3000 Solar masses a year. Black hole in the center accretes 60 solar masses a year.

Summary continued

With intermediate-type distortions we can distinguish between different mechanisms of energy injection which have different redshift dependence

There is more....

- ▶ Cosmological recombination spectrum gives measurement of primordial helium

    Kurt, Zeldovich, Sunyaev, Peebles, Dubrovich, Chluba, Rubino-Martin

- ▶ Resonant scattering on C,N,O and other ions during and after reionization makes the optical depth to the last scattering surface frequency dependent

    Basu, Hernandez-Monteagudo, and Sunyaev 2004

- ▶ Sunyaev-Zeldovich effect from hot electrons during reionization/WHIM can give a measurement of average electron temperature, find missing baryons

    Zeldovich & Sunyaev 1969, Hu, Scott, Silk 1994, Cen and Ostriker 1999,2006,

- ▶ Primordial non-gaussianity on extremely small scales
    Pajer and Zaldarriaga 2012, Ganc and Komatsu 2012

Summary continued

- Silk damping: $\frac{dQ}{dz} \propto (1+z)^{(3n_s-5)/2}$
  (Chluba, Khatri and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012)

- Adiabatic cooling: Opposite sign to Silk damping with $n_s = 1$
  (Chluba and Sunyaev 2012, Khatri, Sunyaev and Chluba 2012b)

- Particle decay: $\frac{dQ}{dz} \propto \dfrac{e^{-\left(\frac{1+z_{\text{decay}}}{1+z}\right)^2}}{(1+z)^4}$
  (Hu and Silk 1993, Chluba and Sunyaev 2012, Khatri and Sunyaev 2012a, 2012b)

- Cosmic strings: $\frac{dQ}{dz} \propto$ constant
  Tashiro, Sabancilar, Vachaspati 2012

- Primordial magnetic fields : $\propto (1+z)^{(3n+7)/2}$, n is the spectral index of magnetic field power spectrum *(Jedamzik, Katalinic, and Olinto 2000)*

- Black holes: Depends on the mass function
  Tashiro and Sugiyama 2008, Carr et al. 2010

- Quantum wave function collapse: $\frac{dQ}{dz} \propto (1+z)^{-4}$
  Lochan, Das and Bassi 2012

There is still a long road ahead for CMB cosmology

CMB spectrum is very rich in information about the early Universe, late time Universe and fundamental physics

This information is accessible and within reach of experiments in not too far future: Pixie, PRISM

Thank you !!!

clusters/reionization

$$y_\gamma \ll 1 \ , \ T_e \sim 10^4$$

$$y = (\tau_{\text{reionization}}) \frac{k_B T_e}{m_e c^2} \sim (0.1)(1.6 \times 10^{-6}) \sim 10^{-7}$$
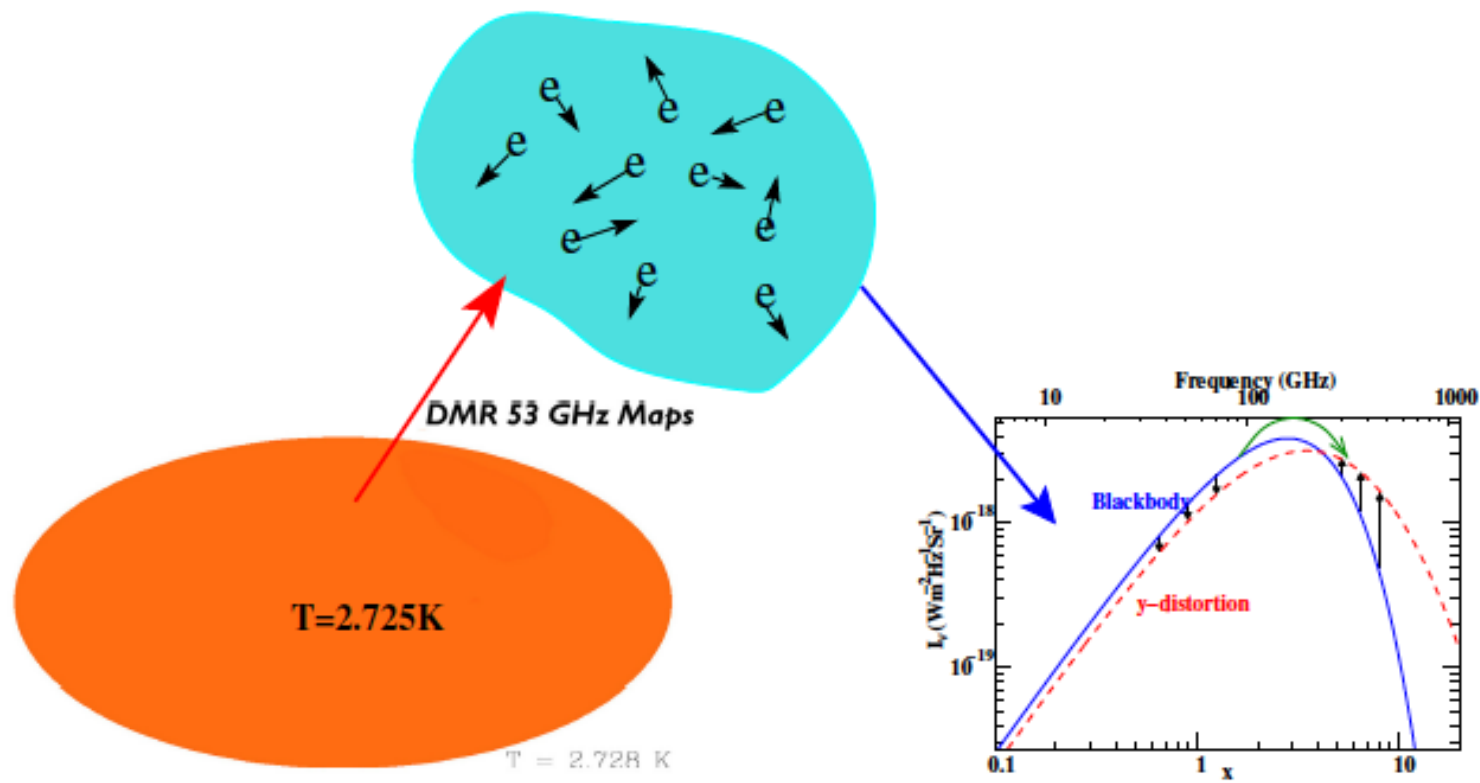
DMR 53 GHz Maps

T=2.725K

T = 2.728 K

Efficiency of energy exchange between electrons and photons

Recoil:

$$y_\gamma = \int dt\, c\, \sigma_T n_e \frac{k_B T_\gamma}{m_e c^2}, \qquad T_\gamma = 2.725(1+z)$$

No. of scatterings   Energy transfer per scattering

Doppler effect:

$$y_e = \int dt\, c\, \sigma_T n_e \frac{k_B T_e}{m_e c^2}$$

In early Universe $y_\gamma \approx y_e$

y: Amplitude of distortion

$$y = \int dt\, c\, \sigma_T n_e \frac{k_B (T_e - T_\gamma)}{m_e c^2}$$

Pivot point $k_0 = 42 \text{ Mpc}^{-1}$

Power spectrum of initial density perturbations

$$P_\zeta = (A_\zeta 2\pi^2/k^3)(k/k_0)^{n_s - 1 + \frac{1}{2}\mathrm{d}n_s/\mathrm{d}\ln k(\ln k/k_0)}$$
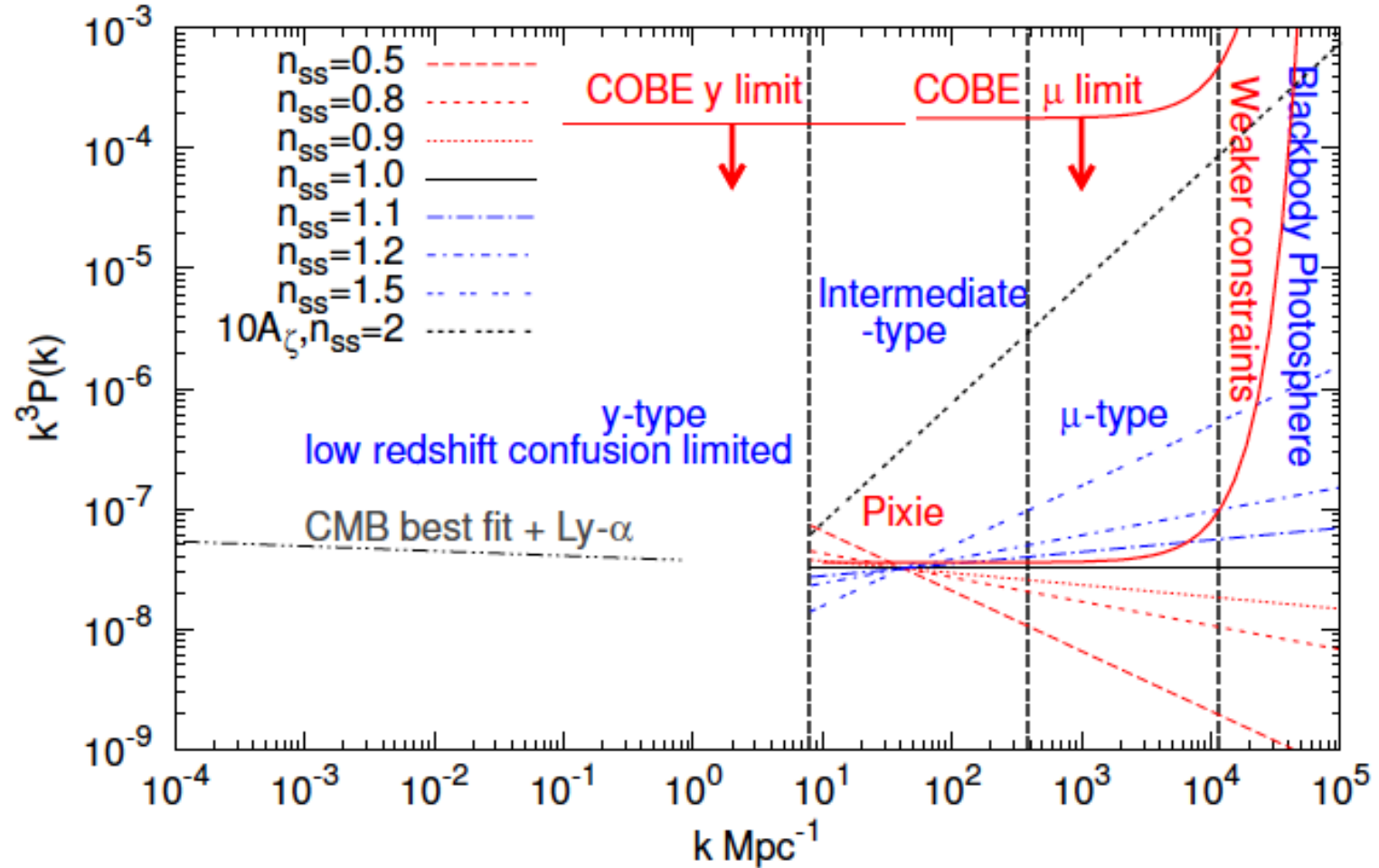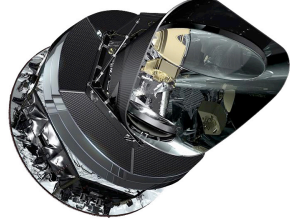
black body spectrum

Tr = 2.725 (1+z)K

COBE-Firas:

practically isotropic
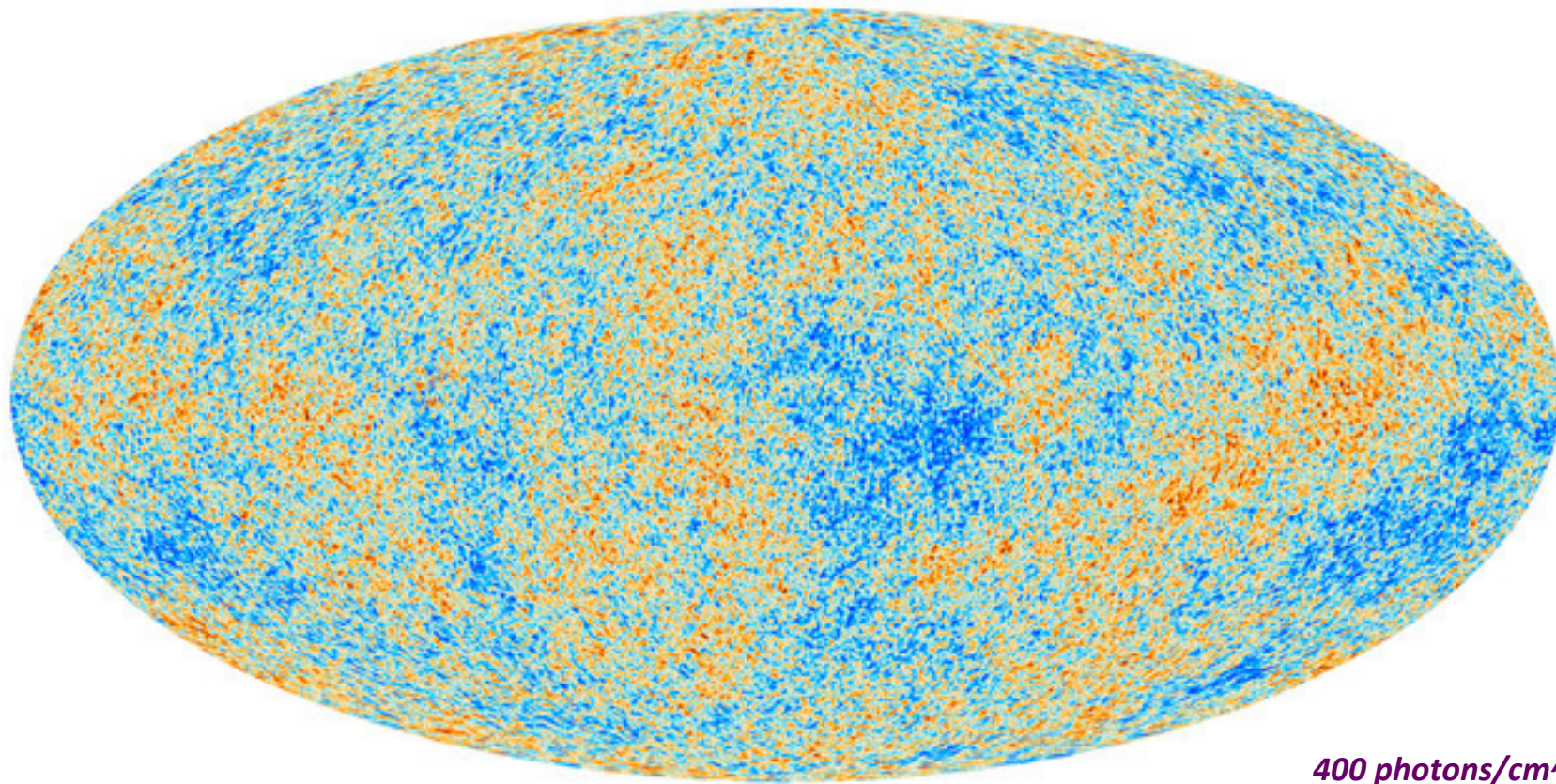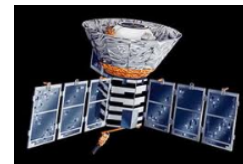
400 photons/cm^3

dark blue - 200 microK

red +200 microK
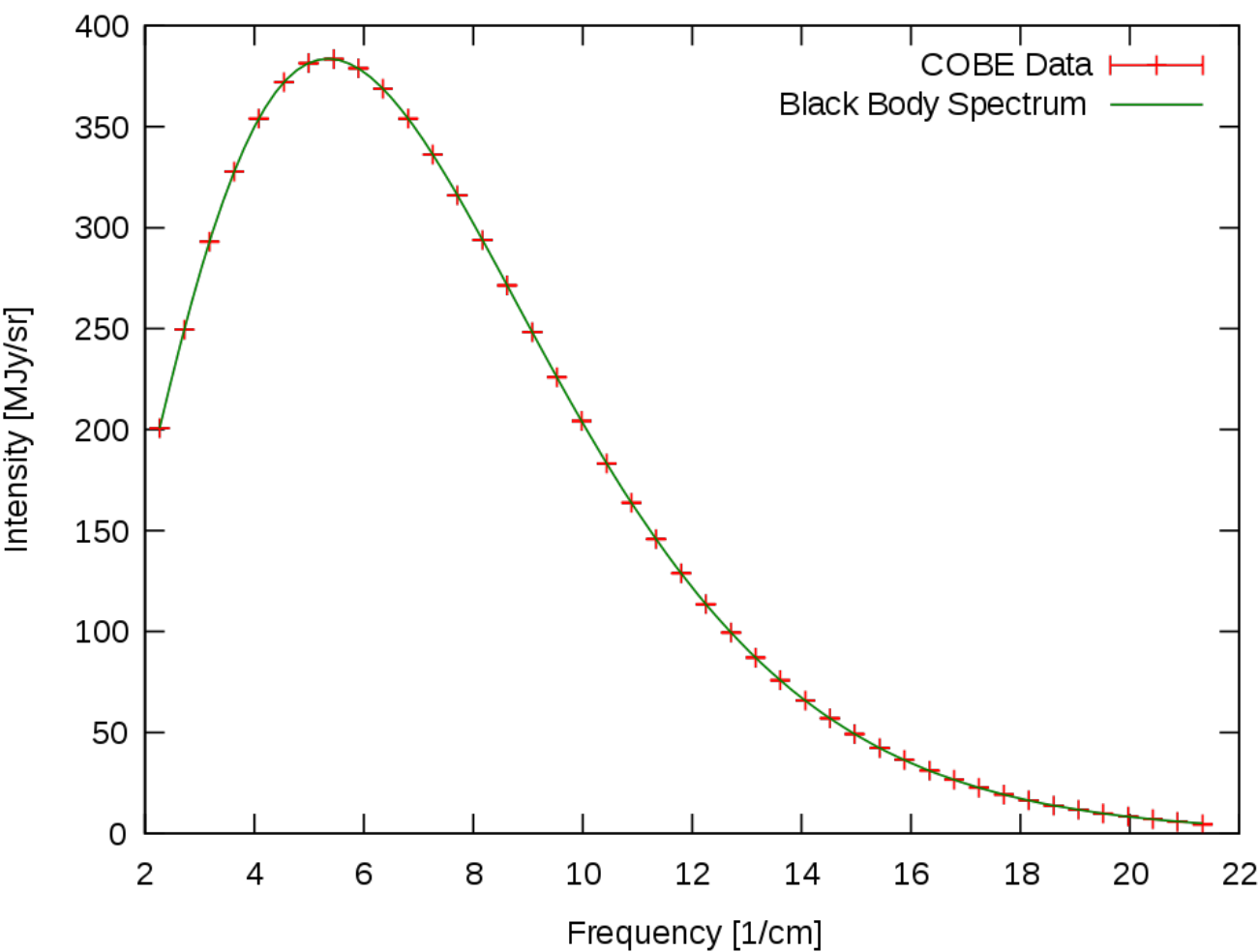
Max Planck 1858-1947

Cosmic Microwave Background (CMB): The most precise black body known: $T = 2.725K \pm 1mK$

No spectral deviations are detected !!!

Energy density of Planck spectrum

$$E_\nu = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

$$E = a_R T^4$$

CMB lensing is taking off

**Large-Scale
Structure
Lenses the CMB**

- RMS deflection of ~2.5'
- Lensing efficiency peaks at $z \sim 2$
- Coherent on ~degree
  (~300 Mpc) scales
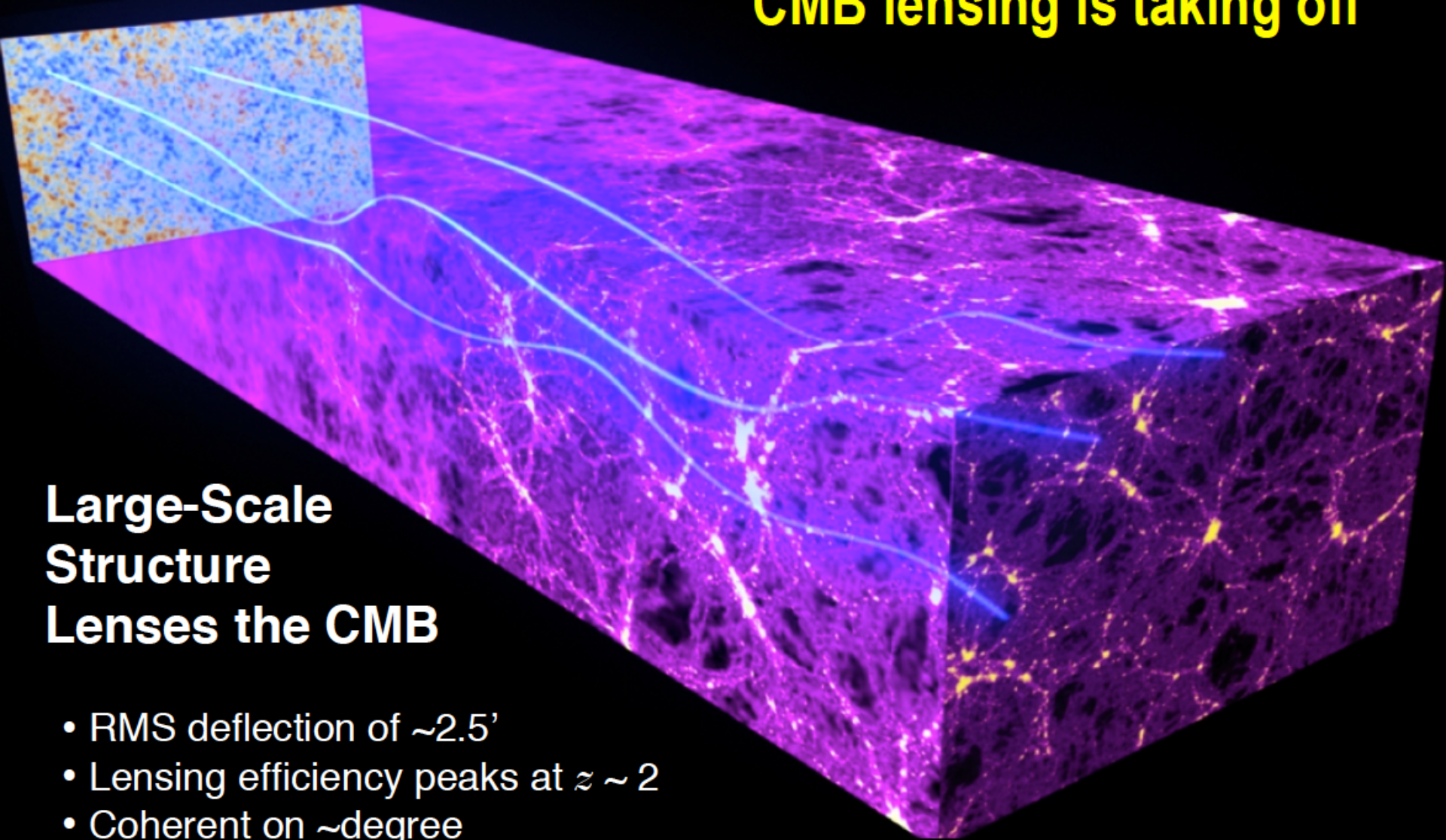
graphic from ESA Website

$$n_{SZ} = y \ T^4 \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial n_{\text{Pl}}}{\partial T}$$

$$= y \ \frac{xe^x}{(e^x - 1)^2} \left(x\frac{e^x + 1}{e^x - 1} - 4 \right)$$

$$\Delta I_{sz} = I_{sz} - I_{planck} = \frac{2h\nu^3}{c^2} n_{sz}$$

(Zeldovich and Sunyaev 1969)
COBE-FIRAS limit (95%): $y \lesssim 1.5 \times 10^{-5}$ *(Fixsen et al. 1996)*

Coma, *optical image,* central part
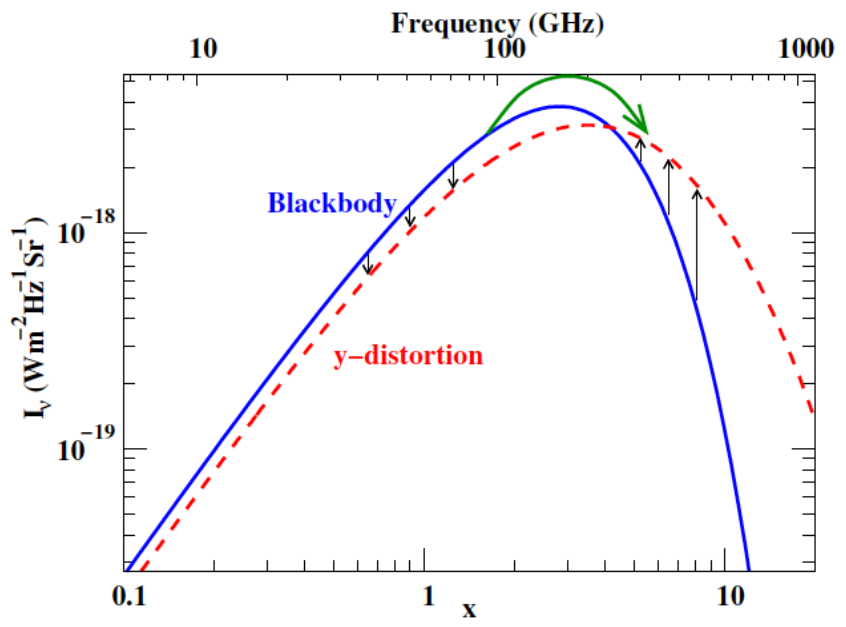
143 GHz

Coma cluster of galaxies (SZ-image)
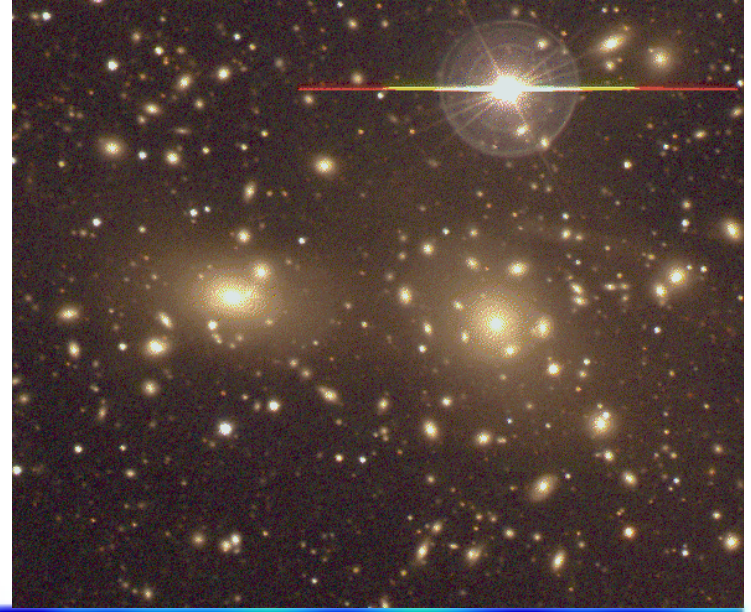
$$n_{SZ} = y \; T^4 \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial n_{\mathrm{Pl}}}{\partial T}$$

$$= y \; \frac{x e^x}{(e^x - 1)^2} \left(x \frac{e^x + 1}{e^x - 1} - 4 \right)$$

$$\Delta I_{sz} = I_{sz} - I_{planck} = \frac{2h\nu^3}{c^2} n_{sz}$$
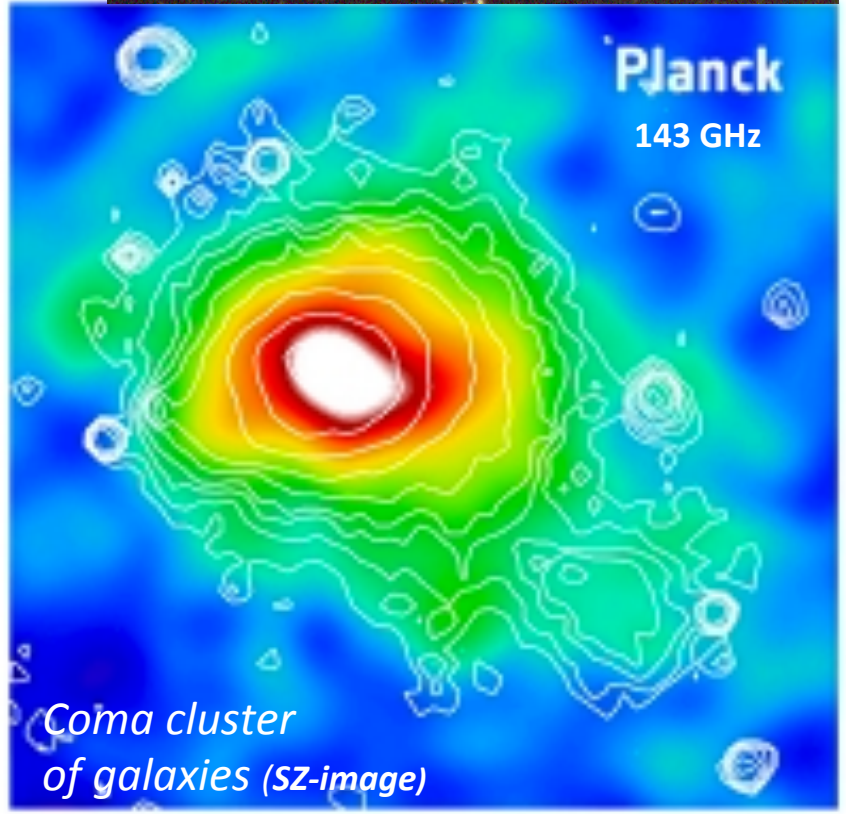
PLANCK/HFI

Coma, optical image central part
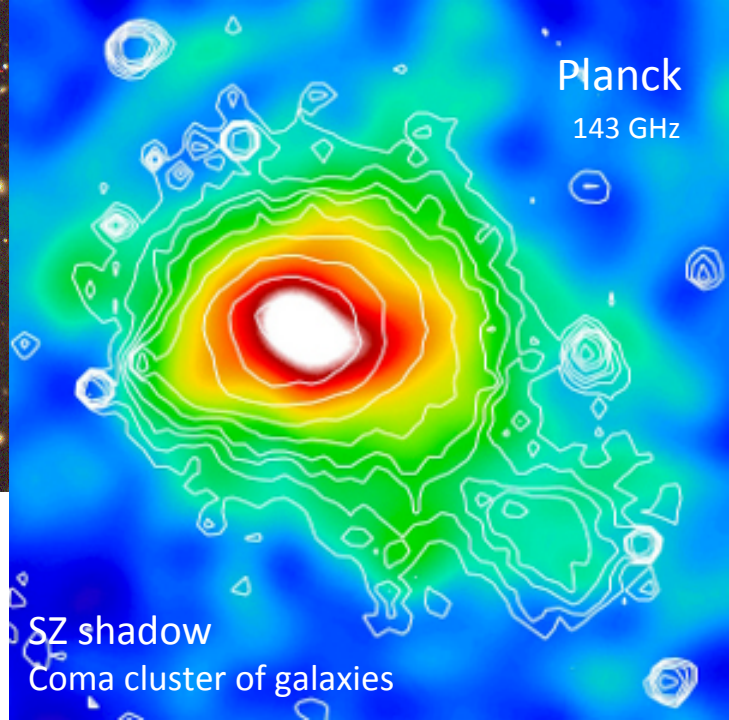
Planck
143 GHz

SZ shadow
Coma cluster of galaxies

~ 900 clusters confirmed by X-Ray
or optical observations
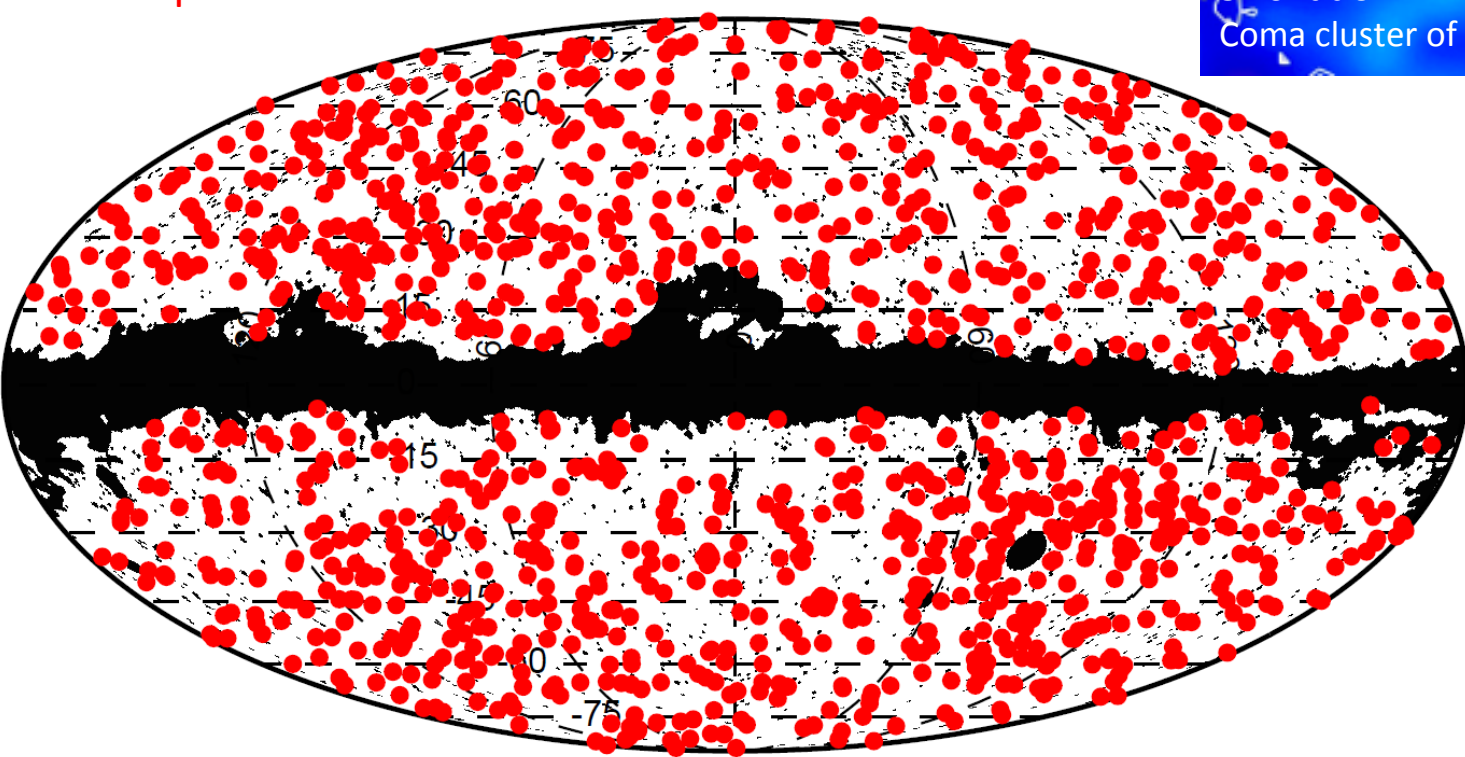
PLANCK/HFI

Coma, optical image central part
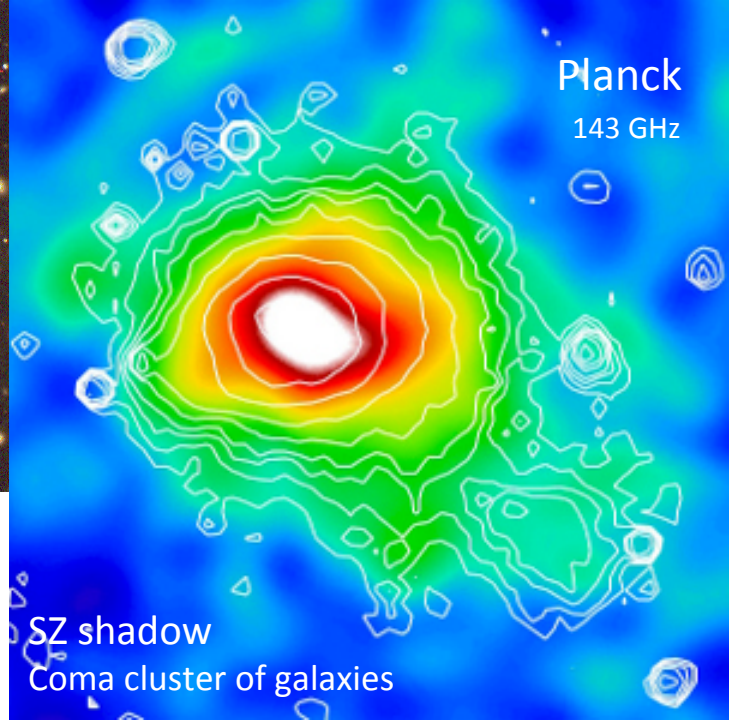
Planck
143 GHz

SZ shadow
Coma cluster of galaxies

~ 900 clusters confirmed by X-Ray
or optical observations
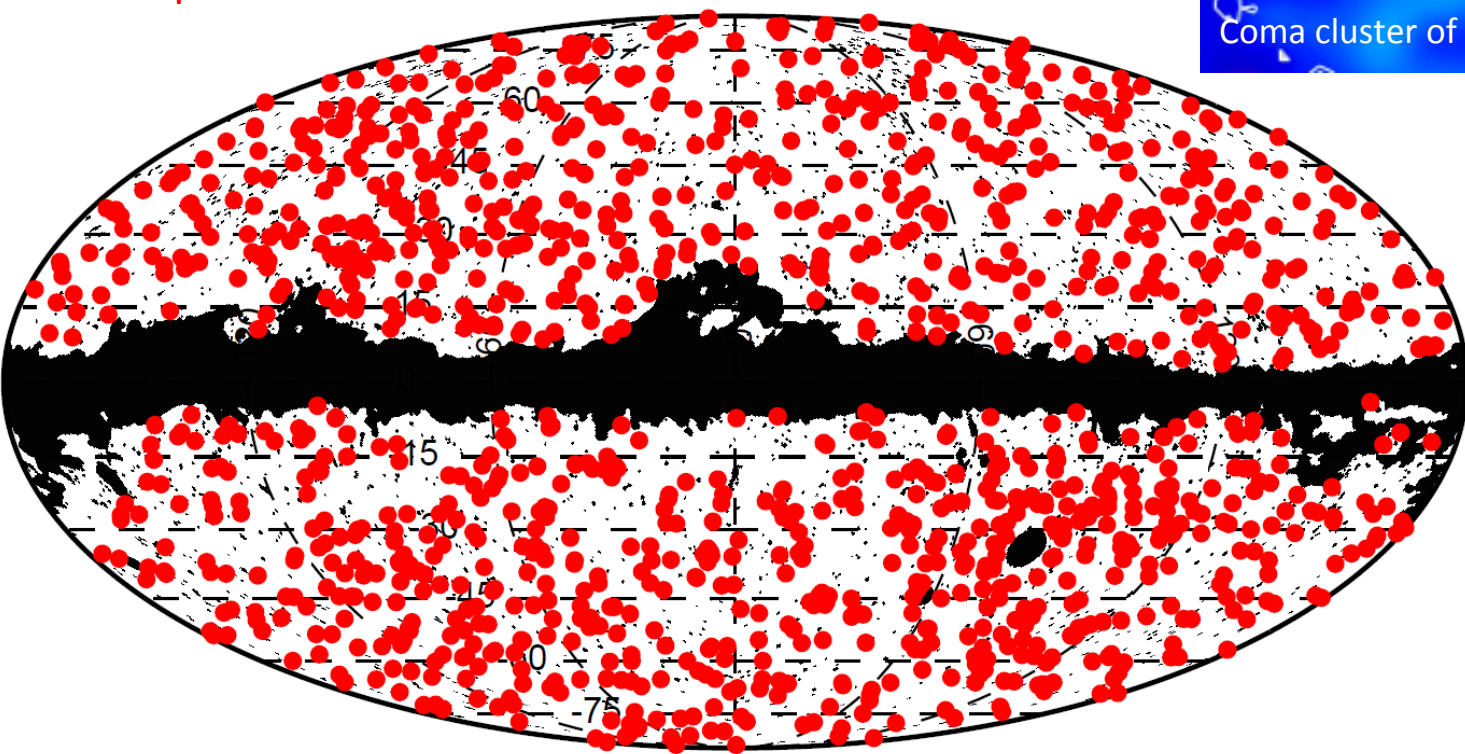
Planck
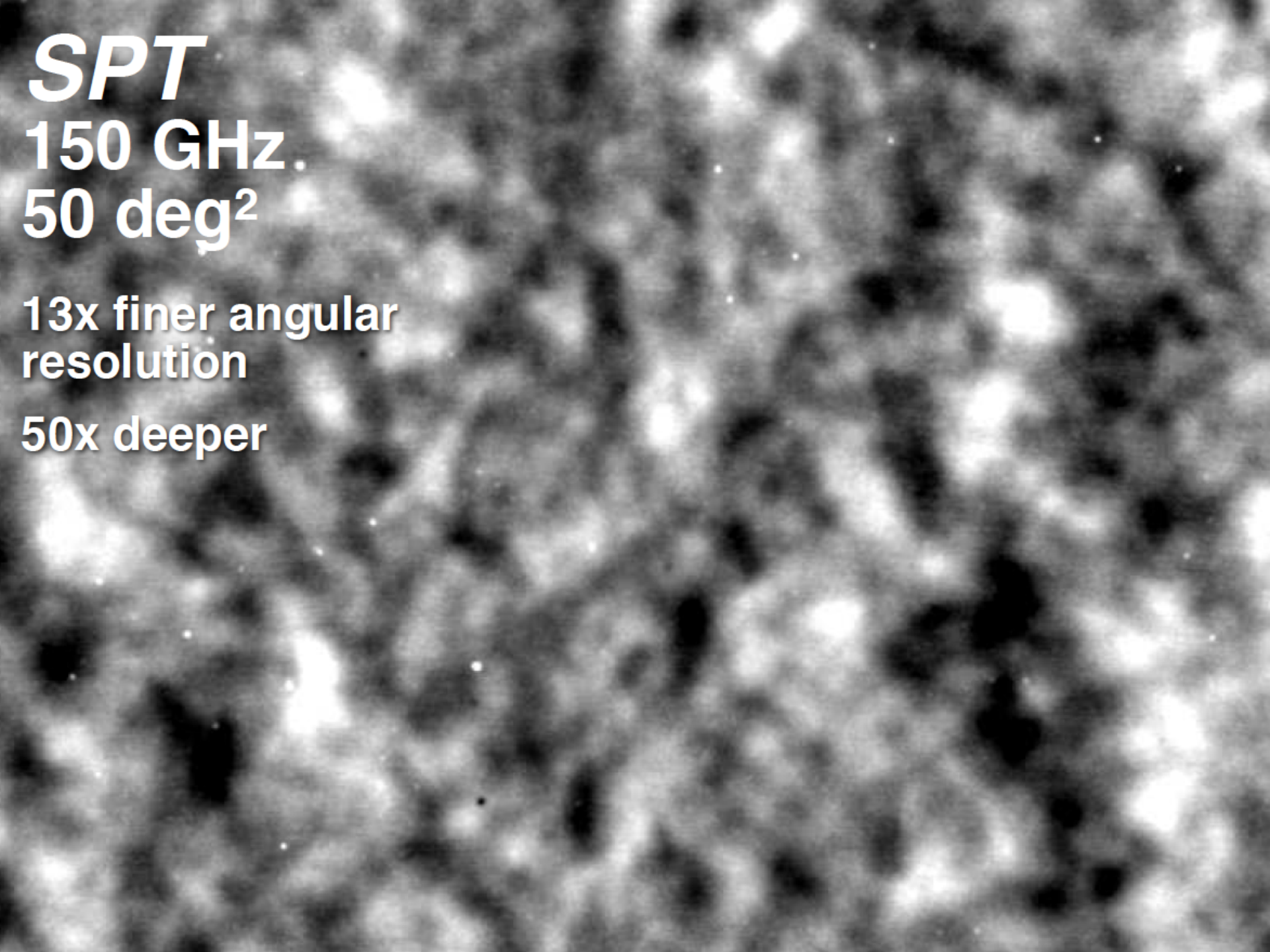143 GHz
50 deg²

2x finer angular
resolution

7x deeper
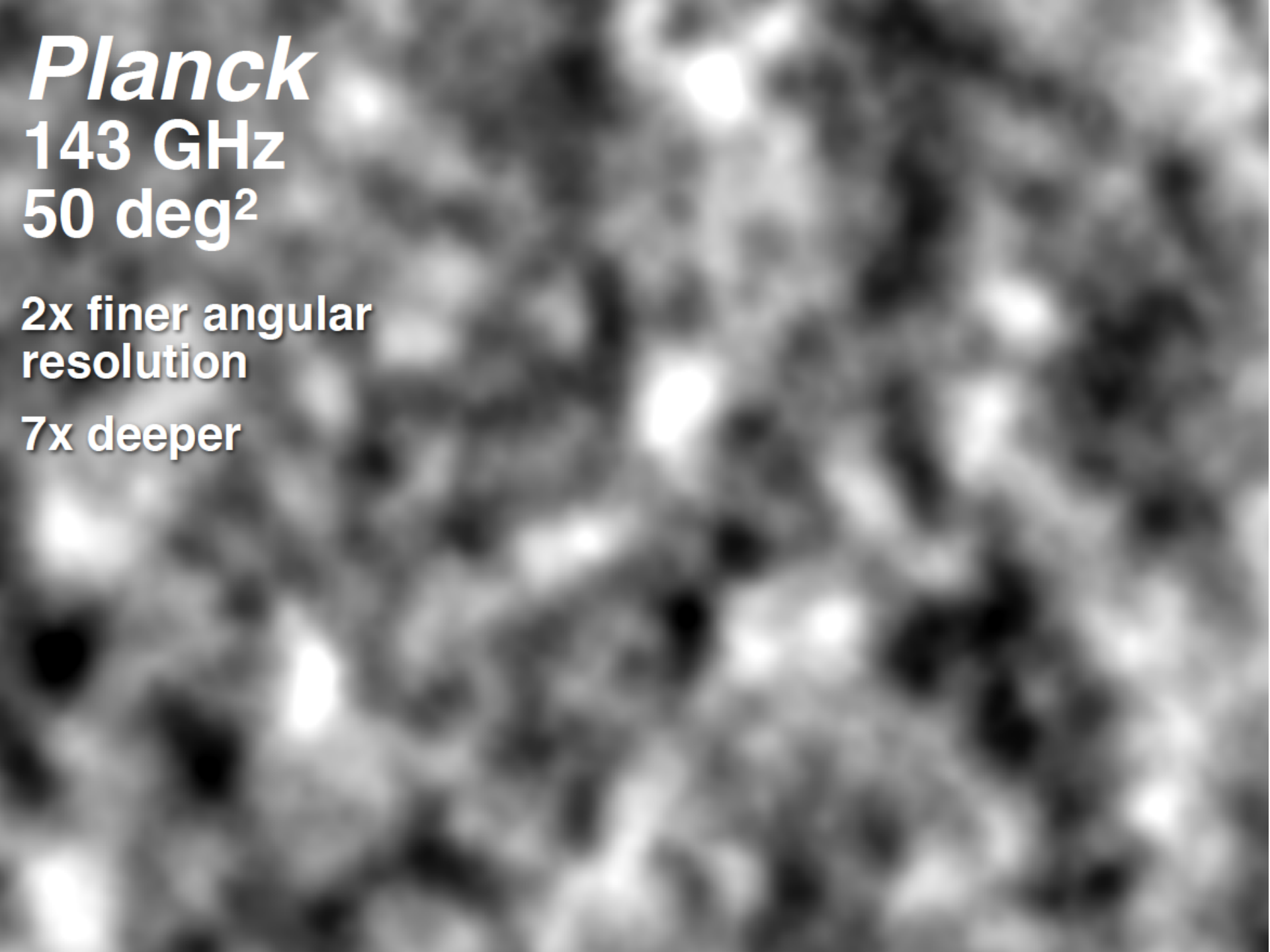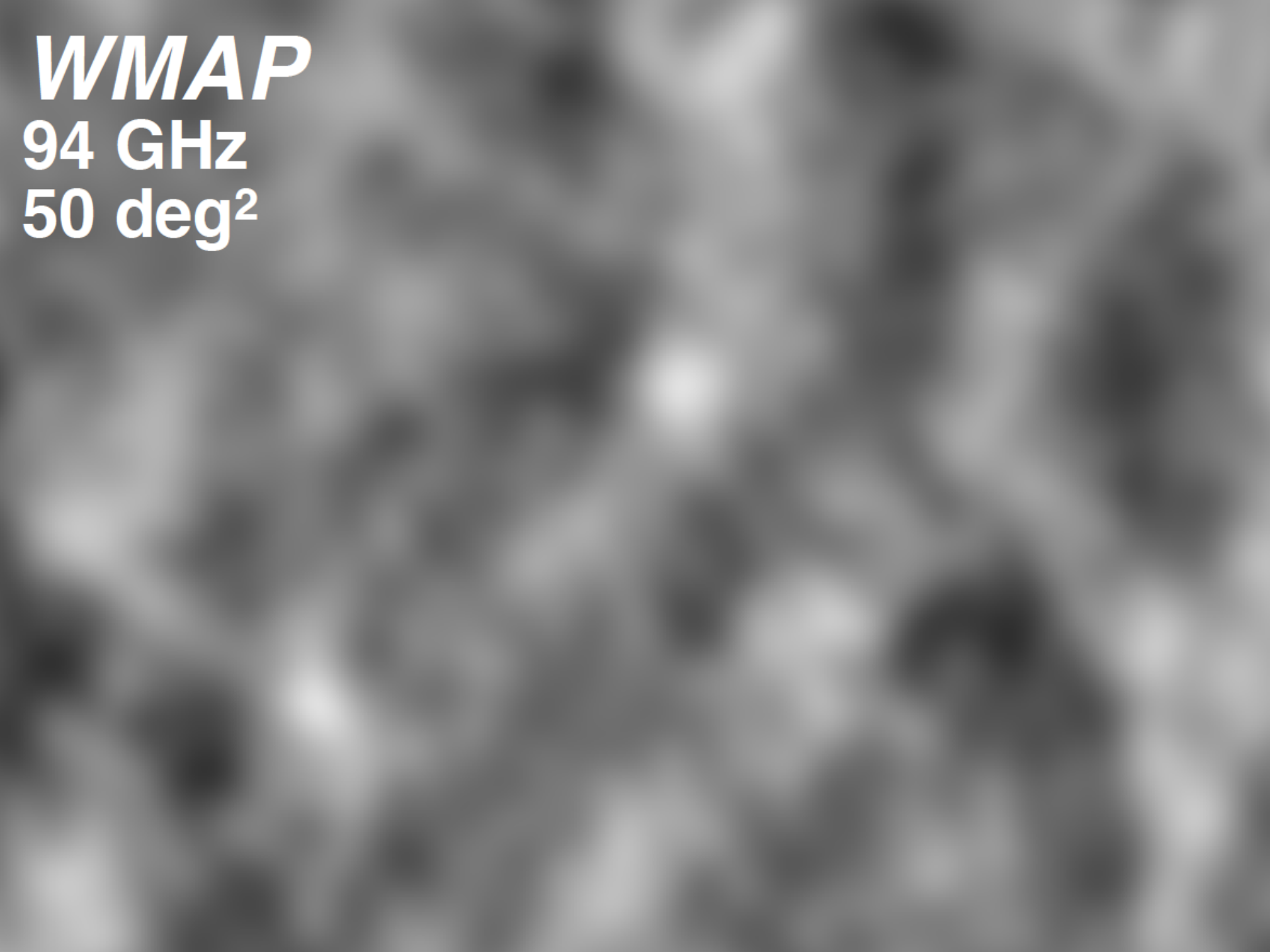
SPT
150 GHz
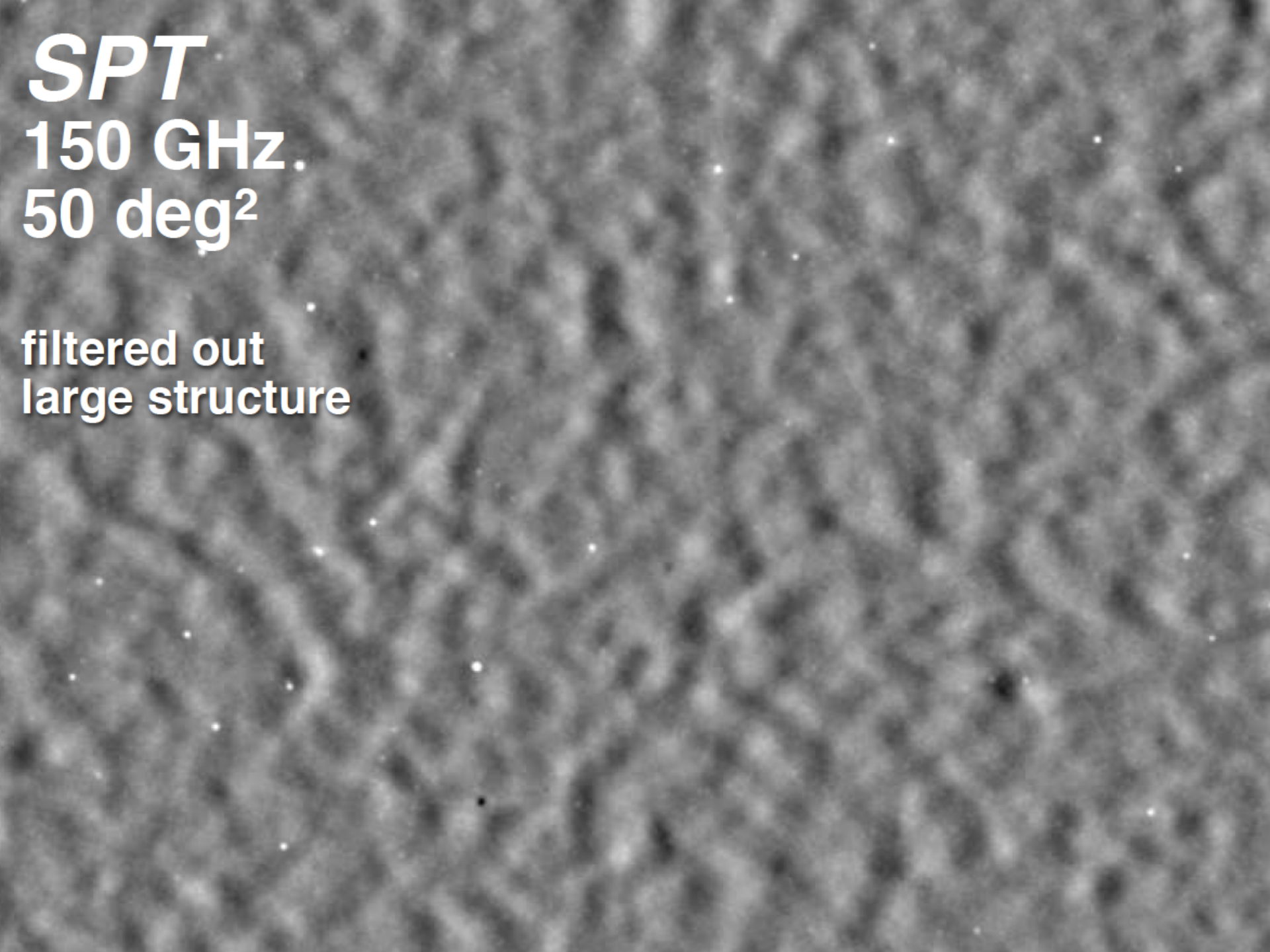**50 deg²**

13x finer angular resolution

50x deeper
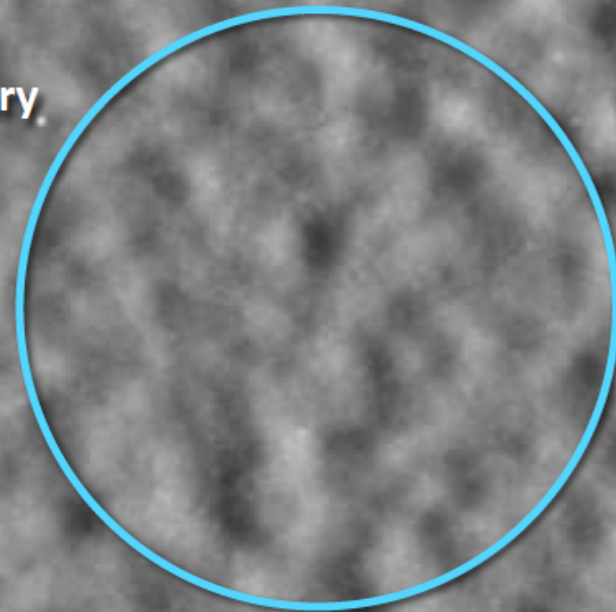
SPT
150 GHz
50 deg²

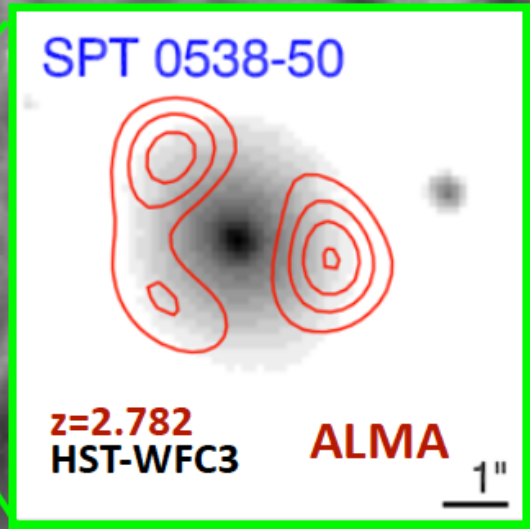filtered out
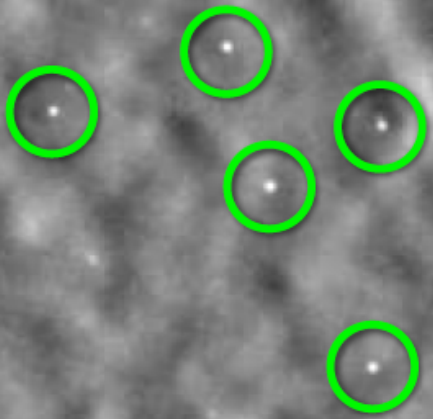large structure

SPT
150 GHz
50 deg²

CMB Anisotropy
Primordial and secondary
anisotropy in the CMB

SPT
150 GHz
50 deg²

Point Sources
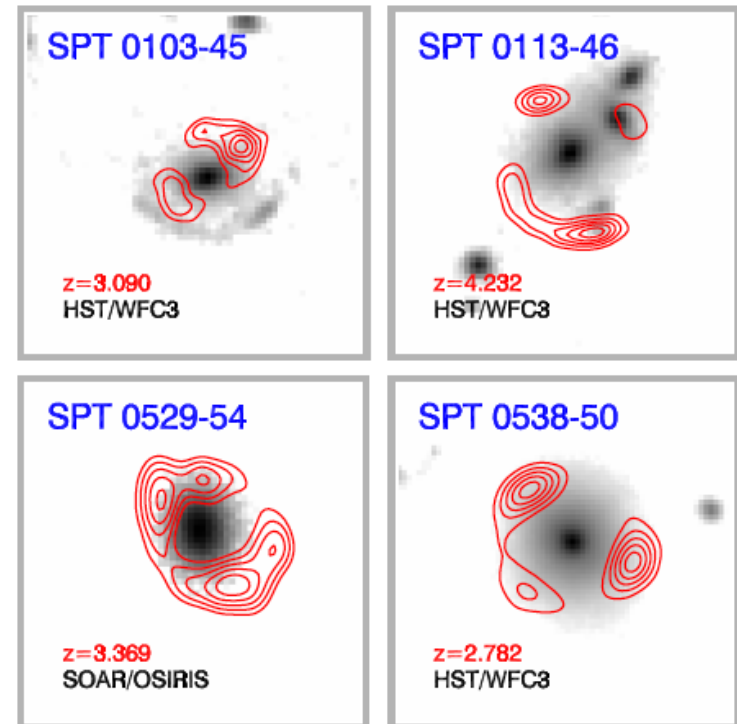Active galactic nuclei, and the most distant, star-forming galaxies

SPT 0538-50

z=2.782
HST-WFC3   ALMA

1"

SPT-SZ: *Lensed Sources in SPT-SZ Survey*

mm-wavelength Source Number Counts
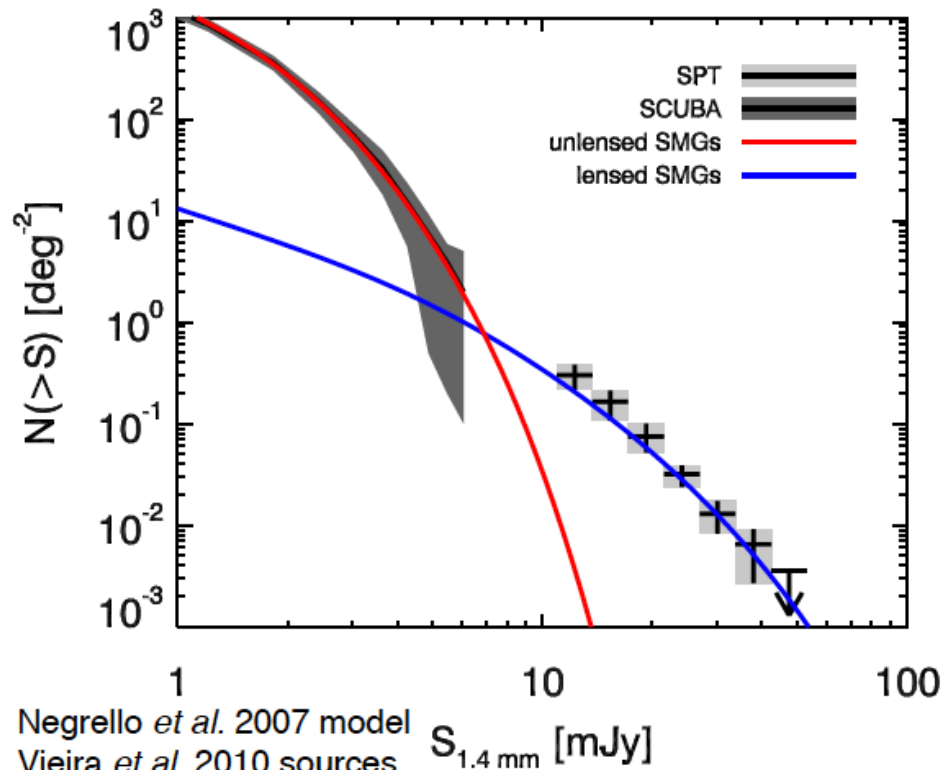
SPT lensed high-z ($2 < z < 6$) galaxies resolved by ALMA

Negrello *et al.* 2007 model
Vieira *et al.* 2010 sources

Vieira *et al.* 2013 Nature
Hezevah et al. 2013

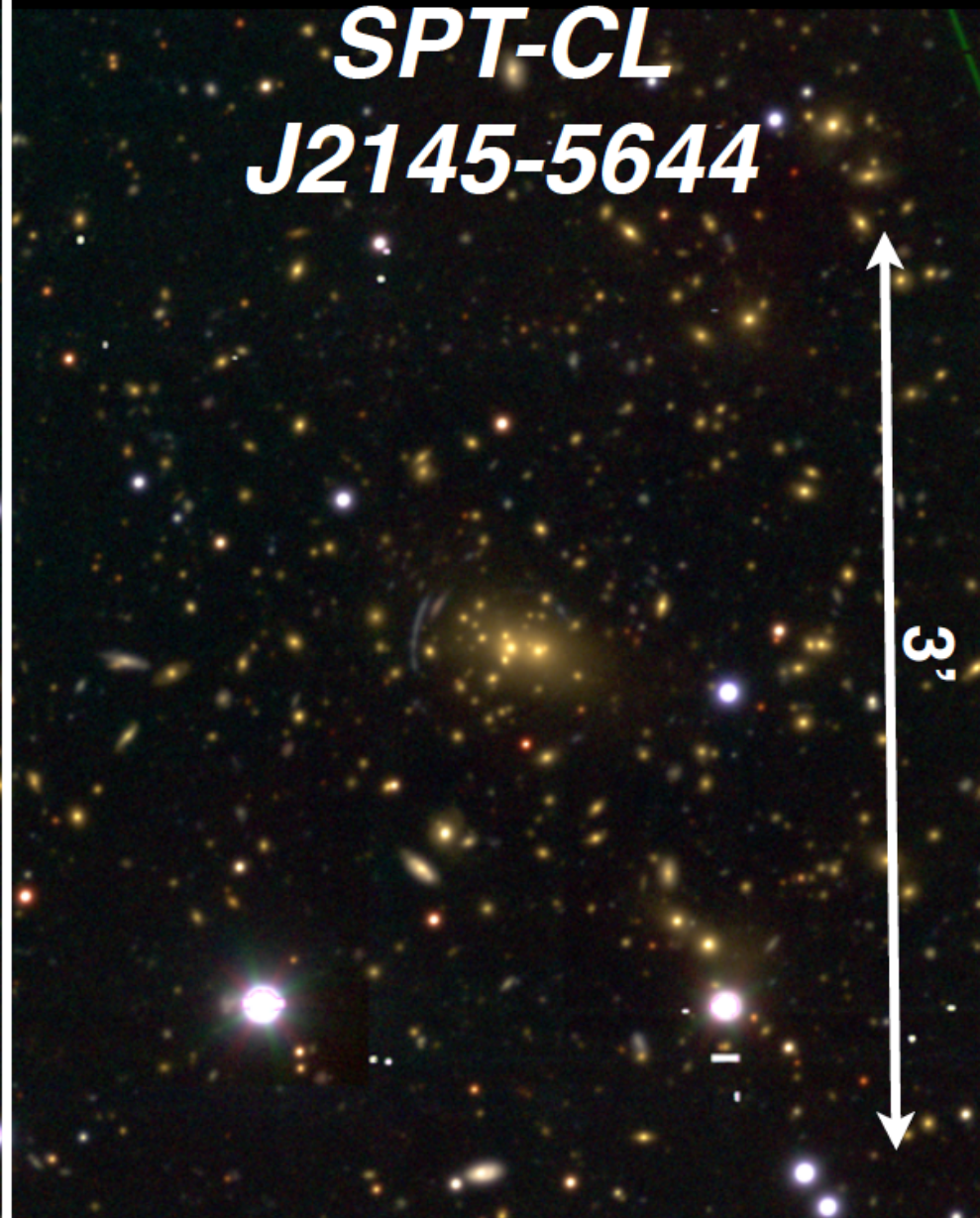**Next use exquisite resolution and sensitive of ALMA ALMA to image dark matter subhalos of the lens**

Brief history

Time →

| 3 mins | 19 yrs | 380000 yrs | 13.82 billion years |

70 days   3000 yrs   200 million yrs

BBN
$z \sim 3 \times 10^8$

Recombination

e⁺/e⁻ annihilation
$10^9 > z > 10^8$

Blackbody Photosphere

Blackbody surface

Spectral Distortions

Last scattering surface

y–type   *Reionization*

μ–type   i–type

| 1.98×10^6 | 2.06×10^5 | 1.57×10^4 | 1100 | 30 | 6 | 1 | 0 |
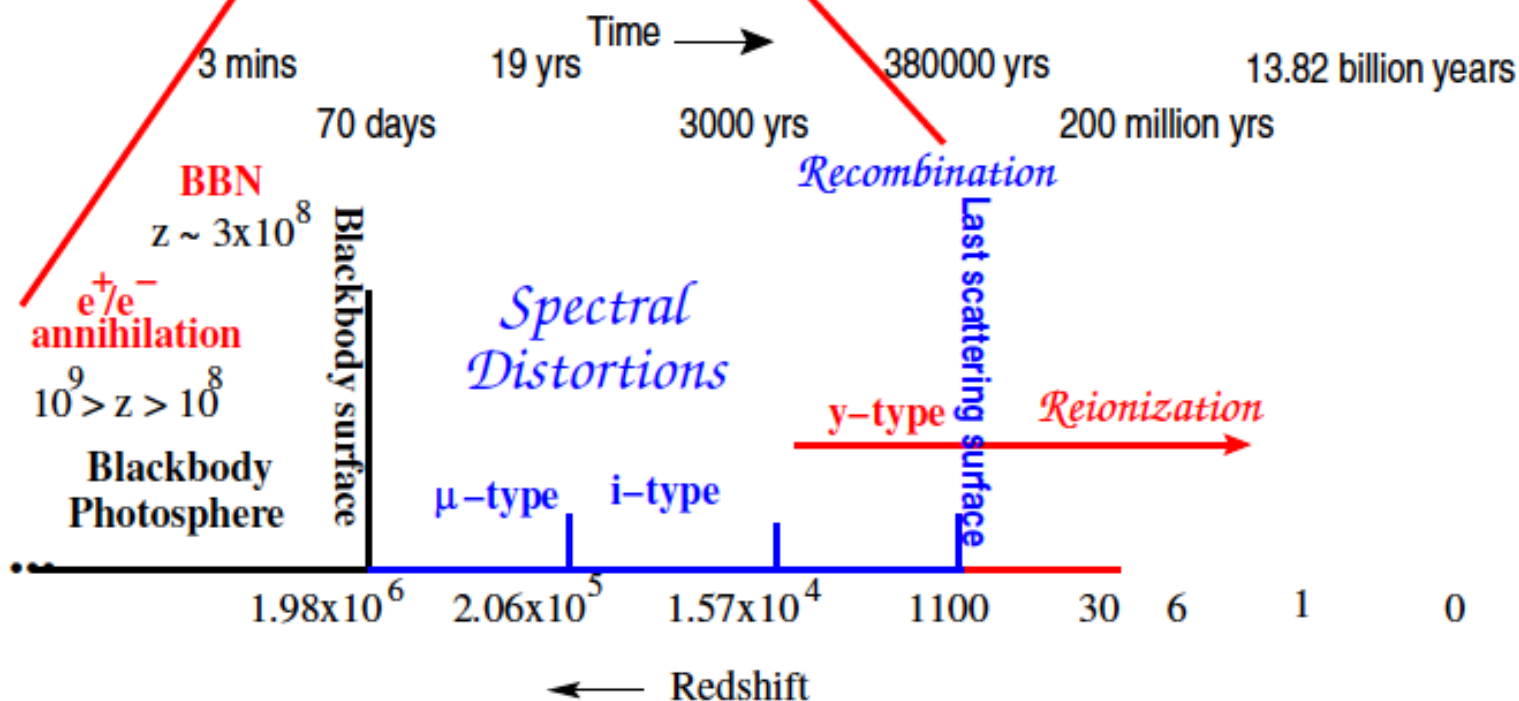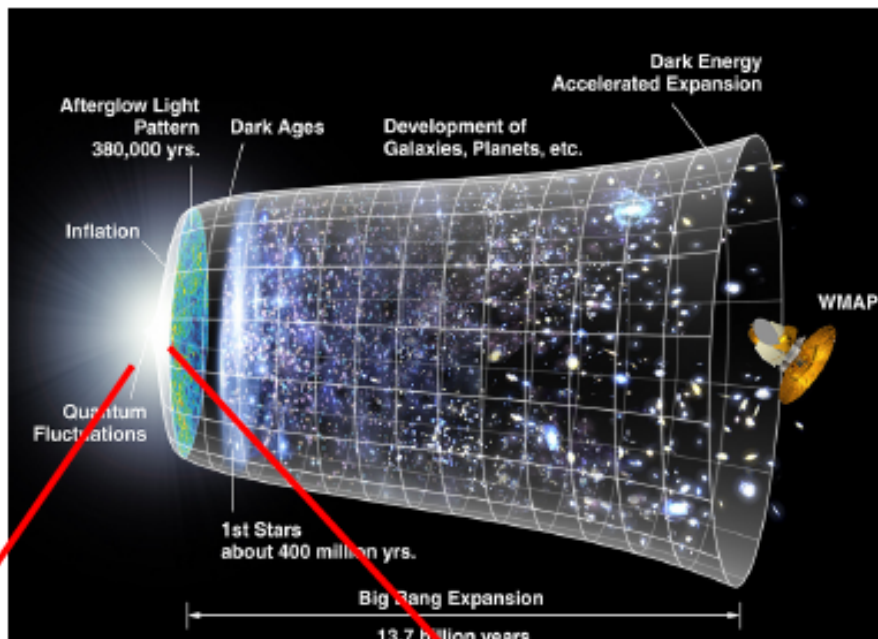
← Redshift

SPT-CL J2138-6008

SPT-CL J2145-5644

3'

Optical follow-up; redshifts, lensing, dynamical masses

Entropy is conserved in thermodynamic equilibrium

Entropy per baryon of radiation + baryons

$$\sigma = \frac{4a_R T^3}{3n_B} + Nk_B \ln\left(\frac{T^{3/2}}{n_B C}\right)$$

baryon density
$$n_B \propto (1 + z)^3$$

Constant entropy

$$T_{\text{radiation}} \propto 1 + z \qquad T_{\text{baryons}} \propto (1 + z)^2$$
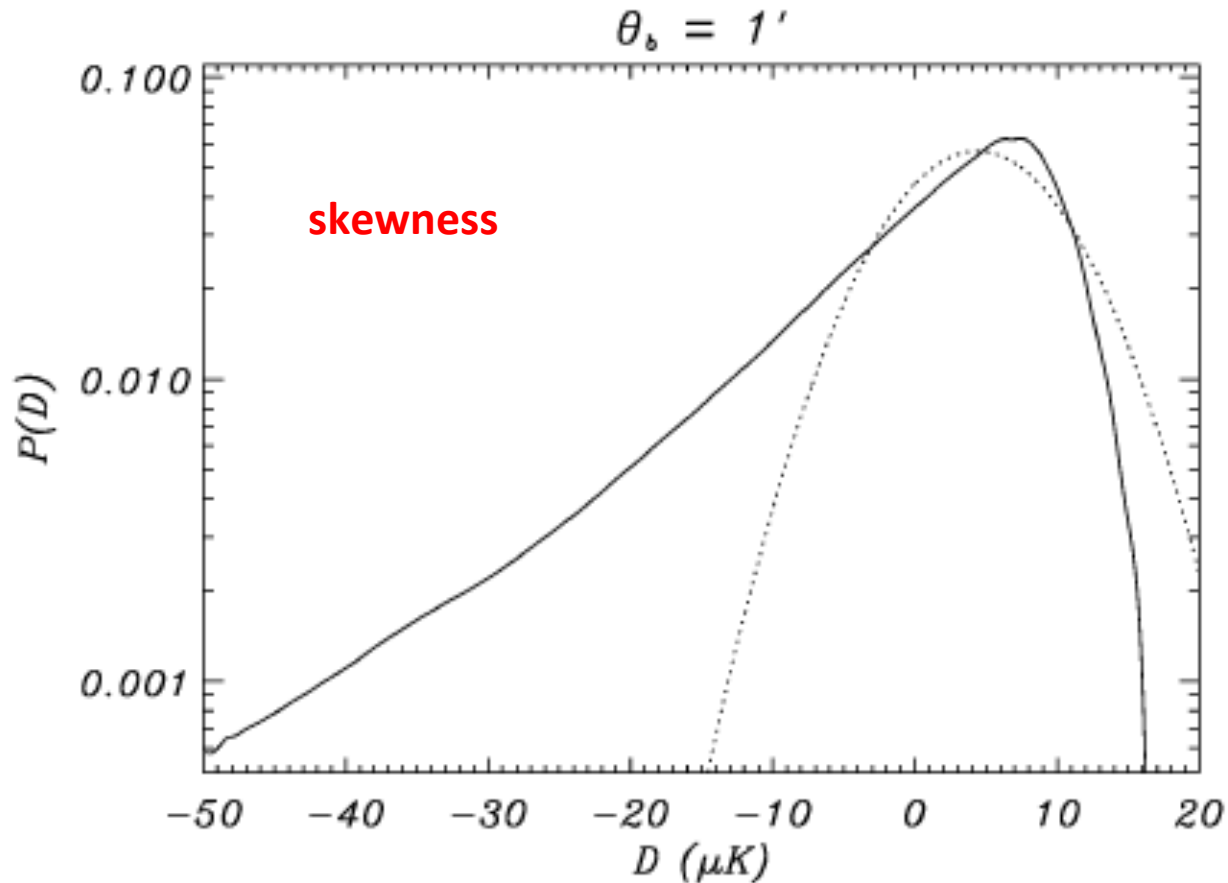
Figure 2. Example of the strong non-Gaussianity of the $P(D)$ function for SZ clusters. We present the $P(D)$ function for a SZ map in the Rayleigh–Jeans region of the spectrum, where clusters are 'negative' sources. For comparison, we also show the best Gaussian fit to this $P(D)$ curve ($\sigma = 6.1 \ \mu K$). This curve will be explained in detail in Section 7.

J. A. Rubiño-Martín and R. A. Sunyaev , 2003

D - deviation
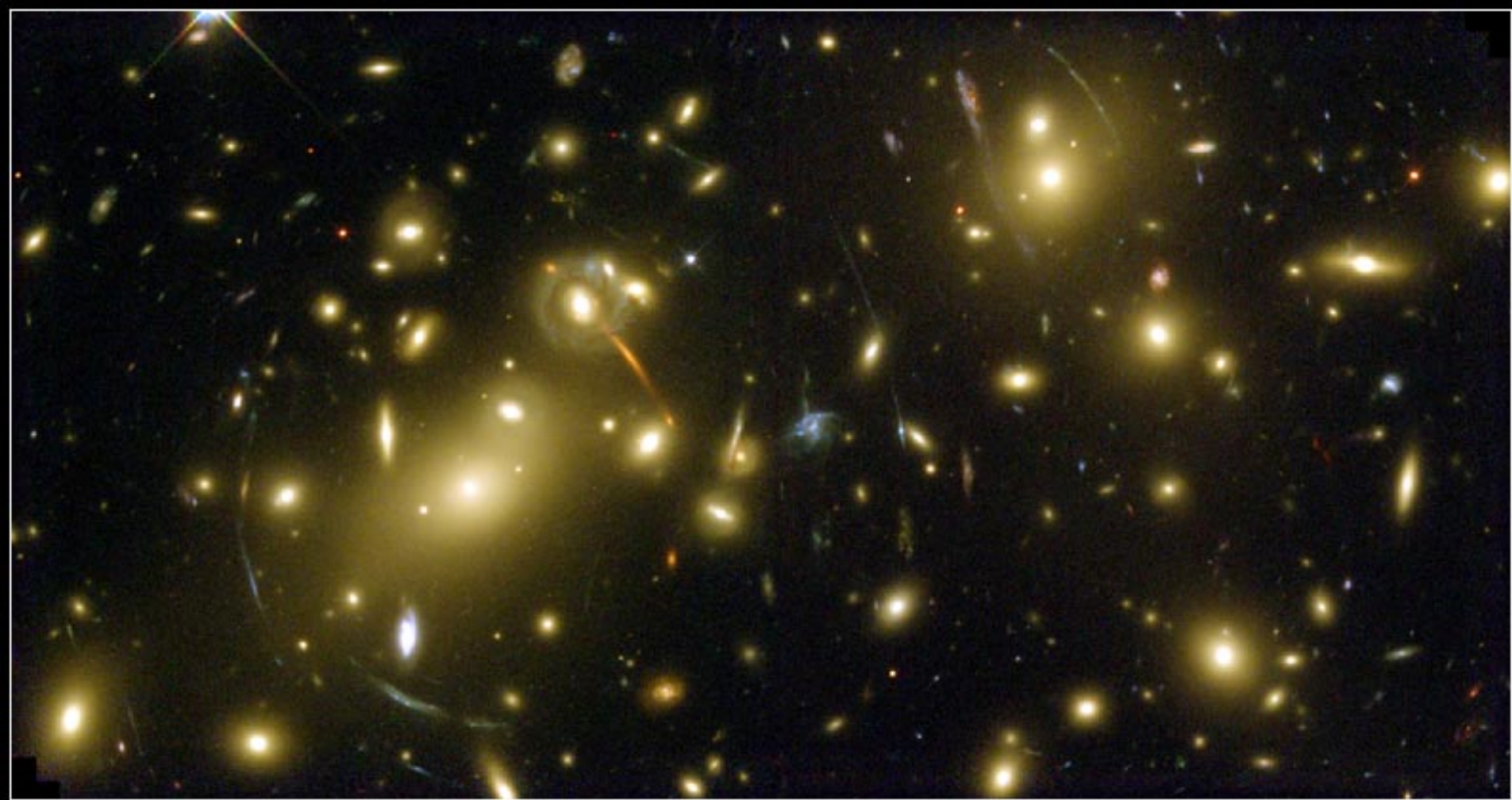
Galaxy Cluster Abell 2218 · HST • WFPC2
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08
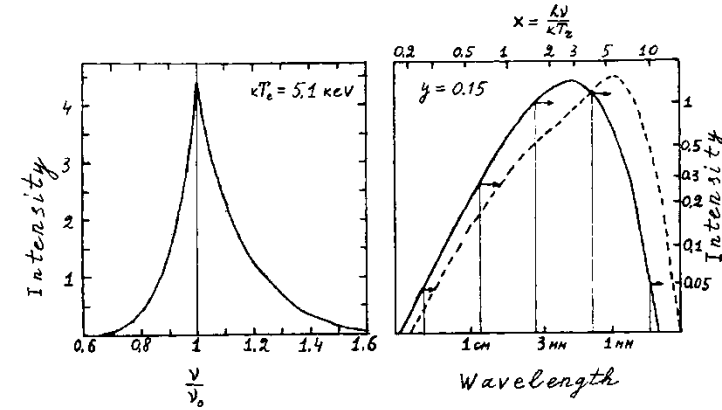
Thousands of galaxies with v ~ 1000 km/s
Hot **intergalactic gas** with Te ~ 3 – 10 KeV

Gravitational potential defined by invisible *dark matter*

Distant galaxies are gravitationally *lensed* by A 2218

There are three effects which make cloud visible:

1. **Thermal effect (change of the CMB spectrum in the direction to the cloud with hot gas)**

2. **Kinetic effect (moving cloud changes the spectrum of scattered CMB photons due to Doppler effect)**

$$\frac{\Delta T}{T_r} = -\frac{v_r}{c}\,\tau_T$$

Full analogy with the origin of the Dipole Component in the CMB angular distribution arising due to our motion relative to the reference frame where CMB is isotropic.
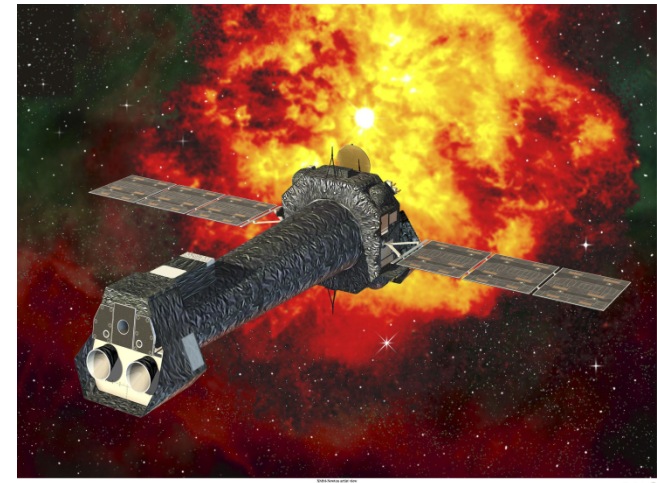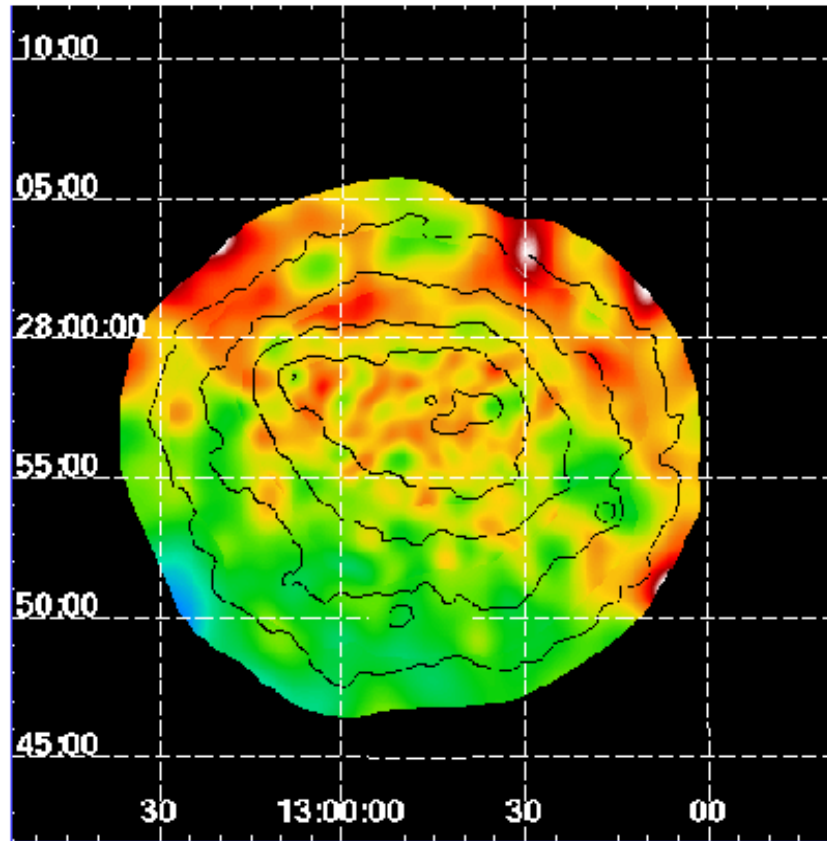
3. **Blurring effect (CMB in reality is not isotropic. There are angular fluctuations. Scattering in the cloud removes all anisotropies in the direction to the cloud except 10% of quadrupole at the position of a cloud**

$$\frac{\Delta I}{I_0} = \frac{I_1(\mu) - I(\mu)}{I_0} = -\tau_T$$
$$\times \left[a\mu + 0.9b\left(\mu^2 - \tfrac{1}{3}\right) + \sum_{n=3}^{\infty} C_n P_n(\mu) \right]$$

(see Sunyaev, Zeldovich, 1981)
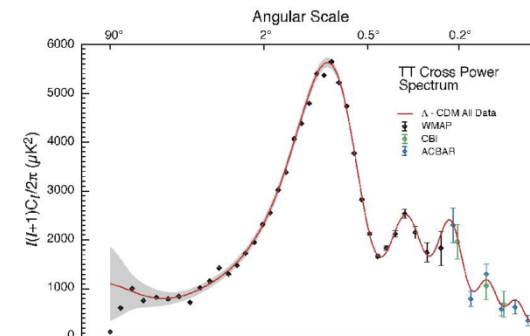
X-RAY EMISSION FROM CLUSTERS OF GALAXIES

COMA CLUSTER TEMPERATURE MAP (XMM-Newton)
(Briel et al. 2001, image by Churazov)

Electron temperature ~ 9 KeV

Electron density ~ 0.03 cm -3

Dark matter mass –
up to 10^15 Msun

Msun = 2 10^33 g

Sound velocity of gas is close to velocities of galaxies

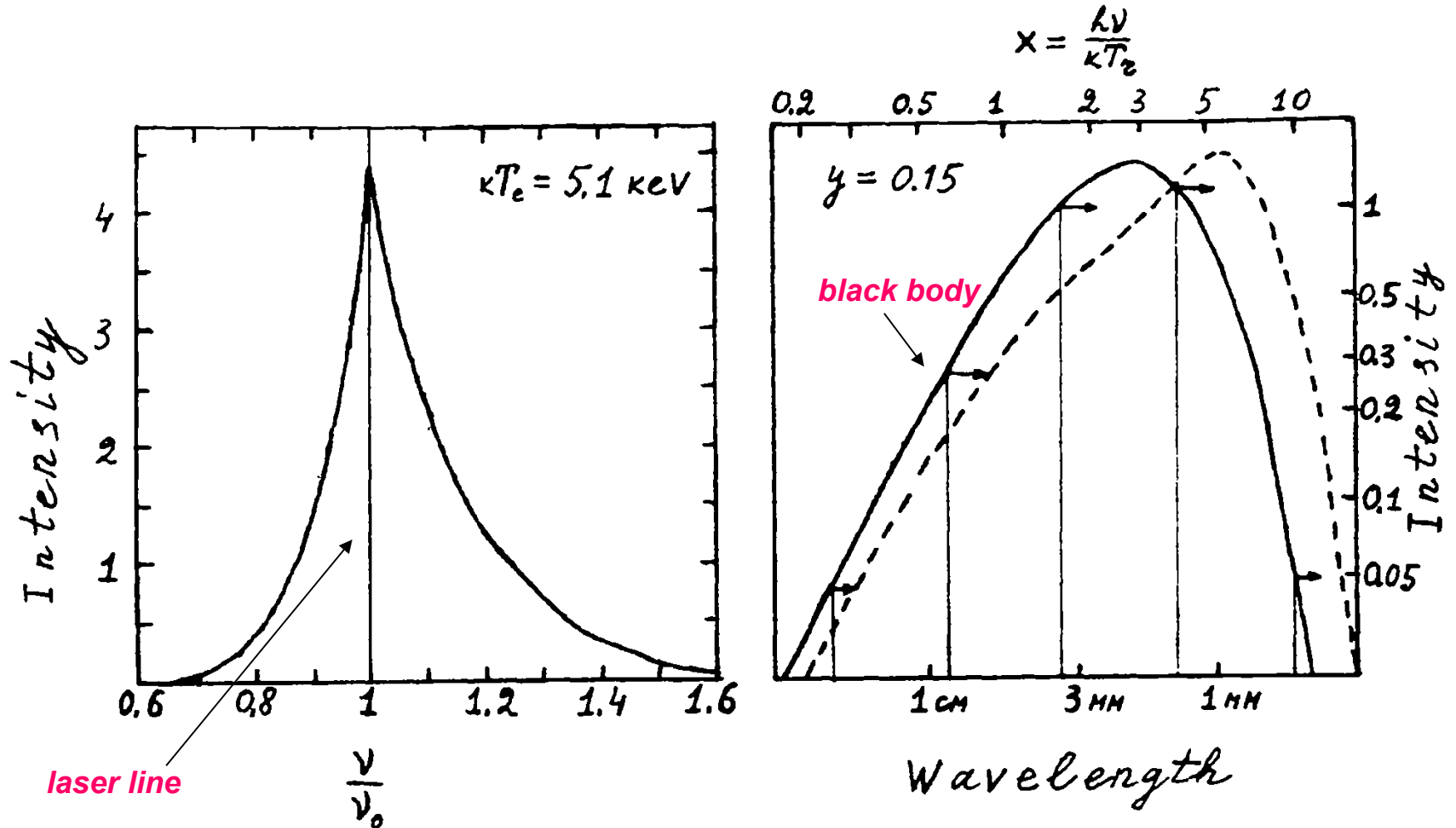SOUTH POLE TELESCOPE

PI: J.Carlstrom

10m dish; 95, 150, 220 GHz
1'

Photograph by: Glenn Grant
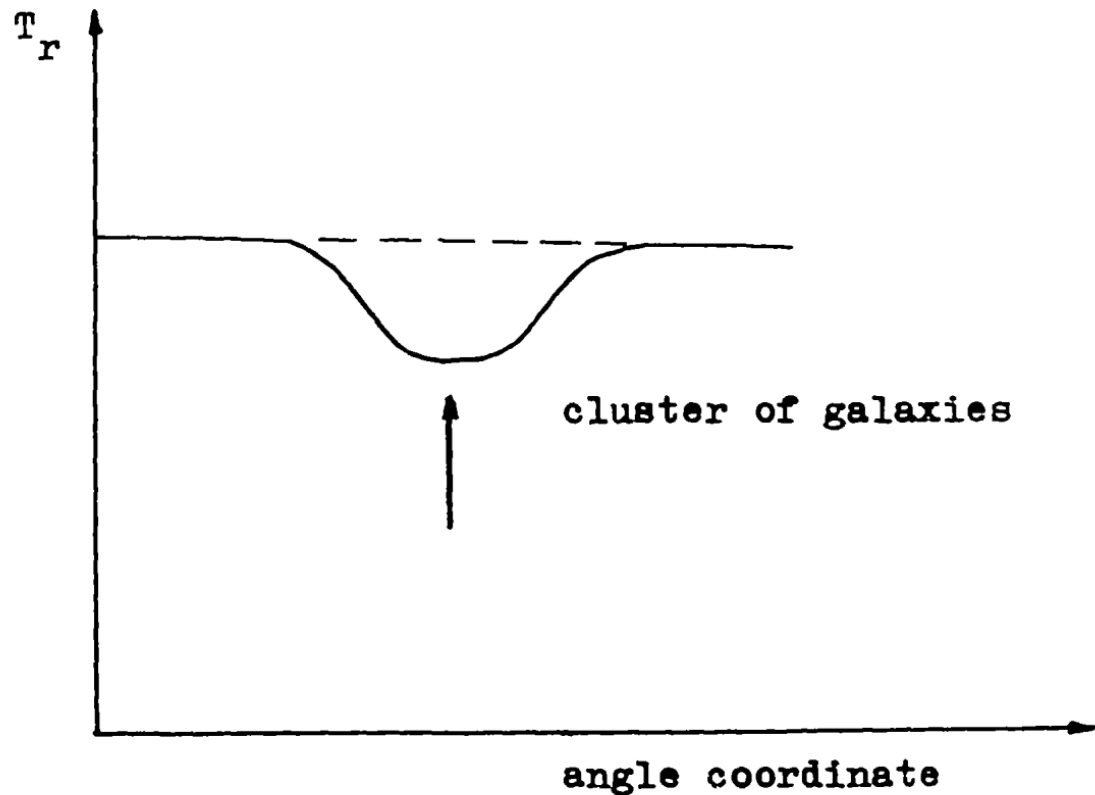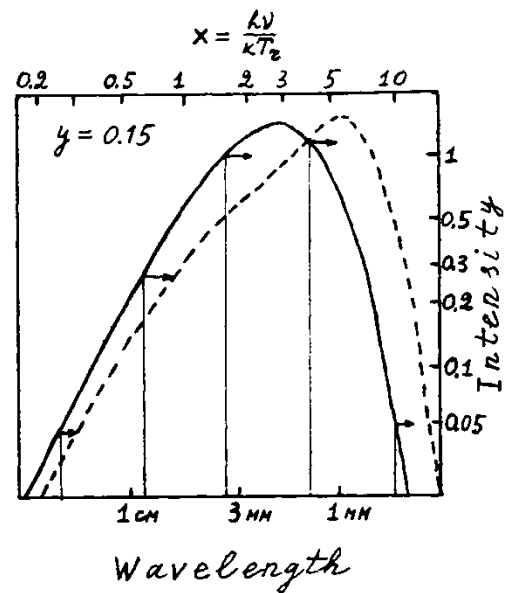National Science Foundation

SCATTERING OF RADIATION BY HOT MAXWELLIAN ELECTRONS

spectral changes due to doppler-effect on moving electrons
with kTe~ 5 KeV and average velocity of the order of 1/7 c

*Line is broadened and effectively shifted toward higher frequencies due to second order effects in v/c*

$x = \frac{h\nu}{kT_z}$

0.2 0.5 1 2 3 5 10

$y = 0.15$

Intensity

1 0.5 0.3 0.2 0.1 0.05

1 cm 3 мм 1 мм

Wavelength

T_r

cluster of galaxies

angle coordinate

$$y = \int \frac{\sigma_T}{m_e c^2} P_e dl$$

Pe = Ne kTe – electron thermal pressure

*In centimeter and mm spectral bands clusters should be observed as a **holes** in the sky average brightness defined by CMB intensity*

the depth of this hole does not depend on the redshift of the cluster of galaxies

It depends only on temperature of the electrons and optical depth of the cluster

Angular size as a function of z
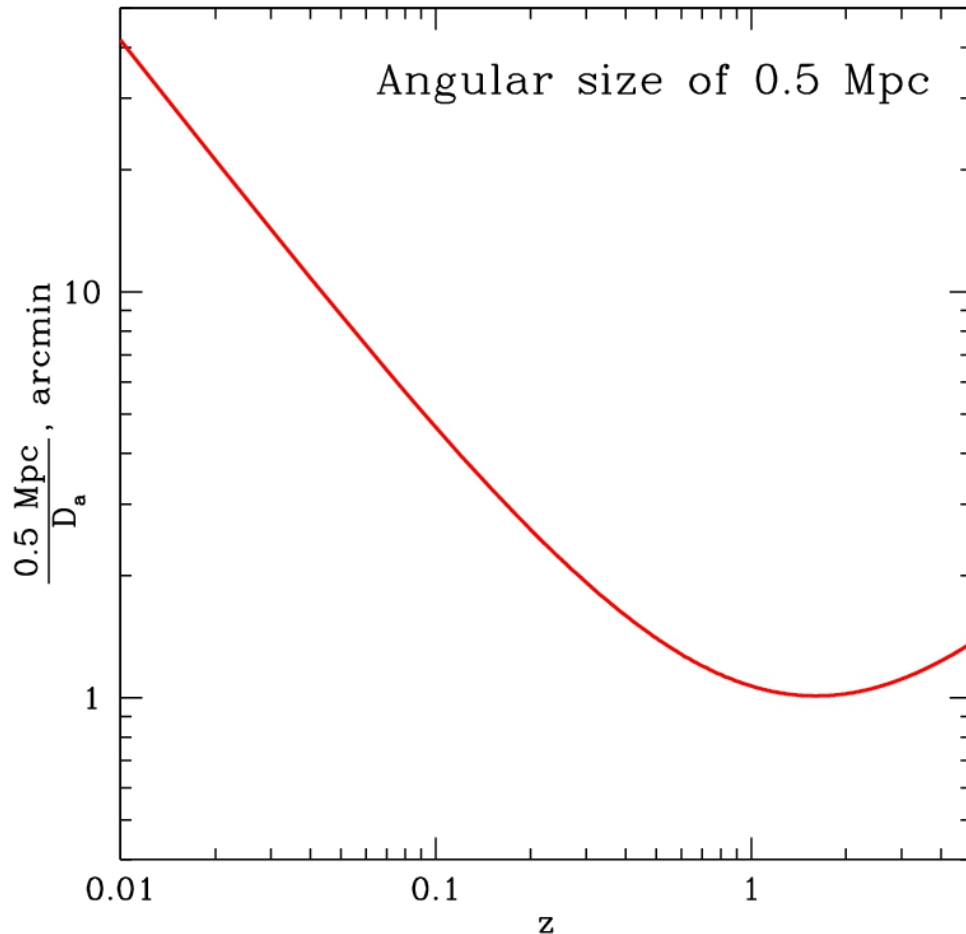
For distant clusters their angular size does not depend on redshift!

It is close to 1 arcmin

This means, that their total flux also does not depend on redshift for 0.5 < z < 2 (for similar clusters at different redshifts)
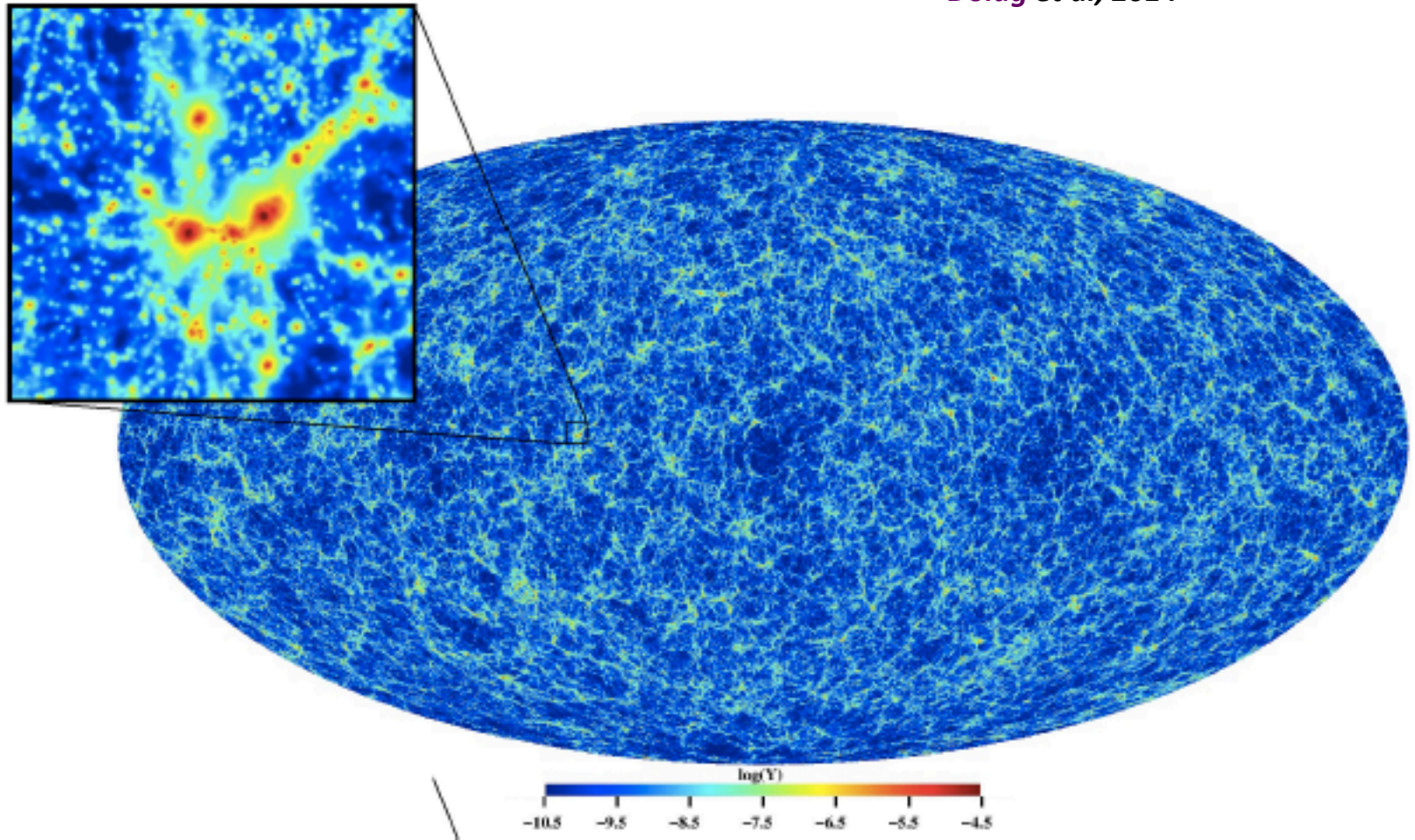**because observed surface brightness also does not depend on the redshift**

Dolag *et al, 2014*

Figure 34. Map of simulated *y*-distortion taken from [207]. The *y*-type signal from the post-reionization epoch is dominated by the collapsed objects and filaments in the large scale structure.