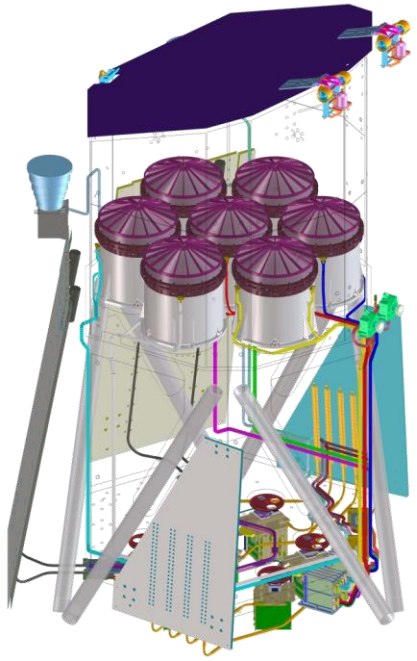
Towards a next probe for CMB observations

CERN, Geneva

May 17, 2016

eRosita



Galaxy clusters + synergy with eRosita

2319 seen by Planck

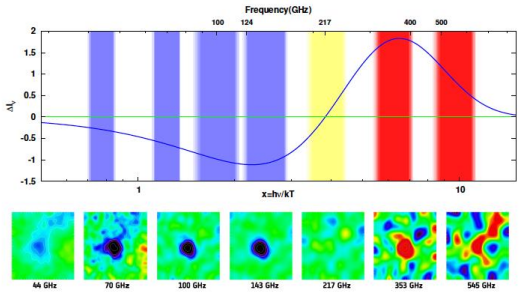
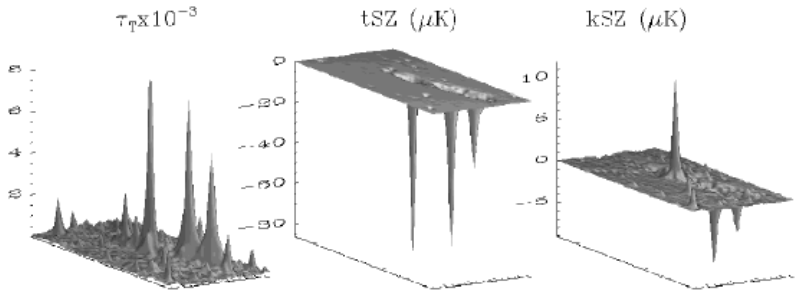
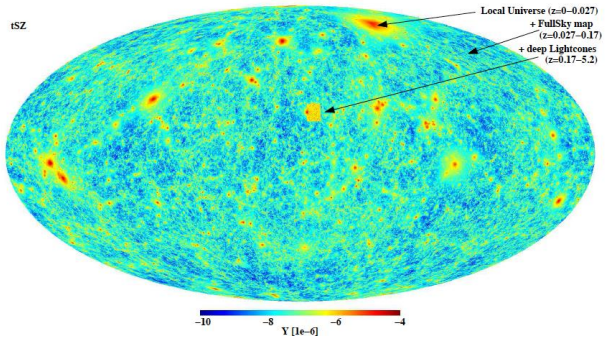


Image credit: ESA / HFI & LFI Consortia

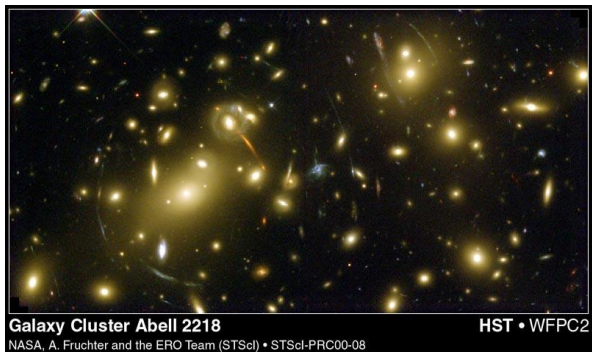


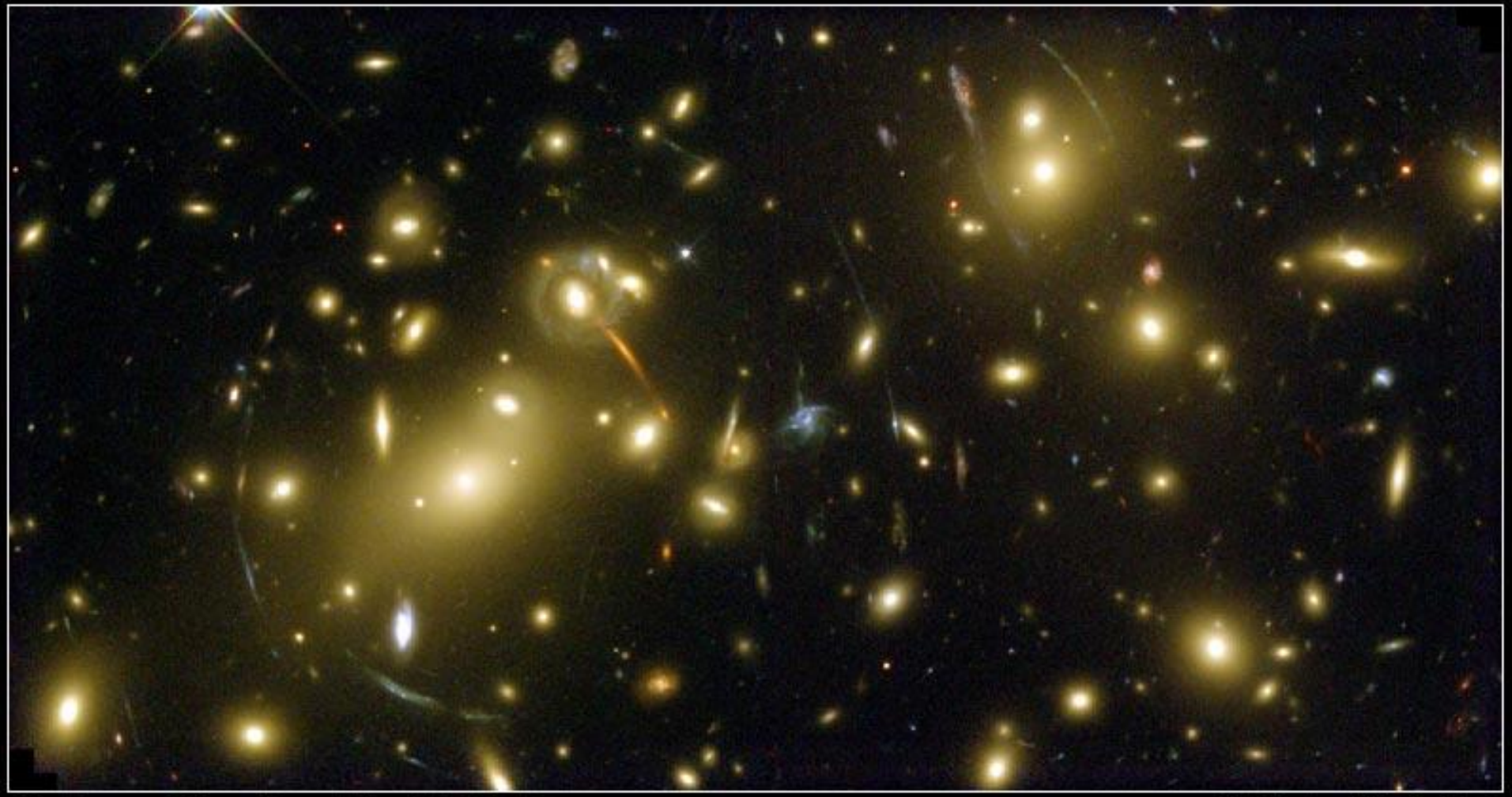
K. Dolag, E. Komatsu, R. Sunyaev



Rashid Sunyaev

Max-Planck Institut fuer Astrophysik
Space Research Institute, Moscow



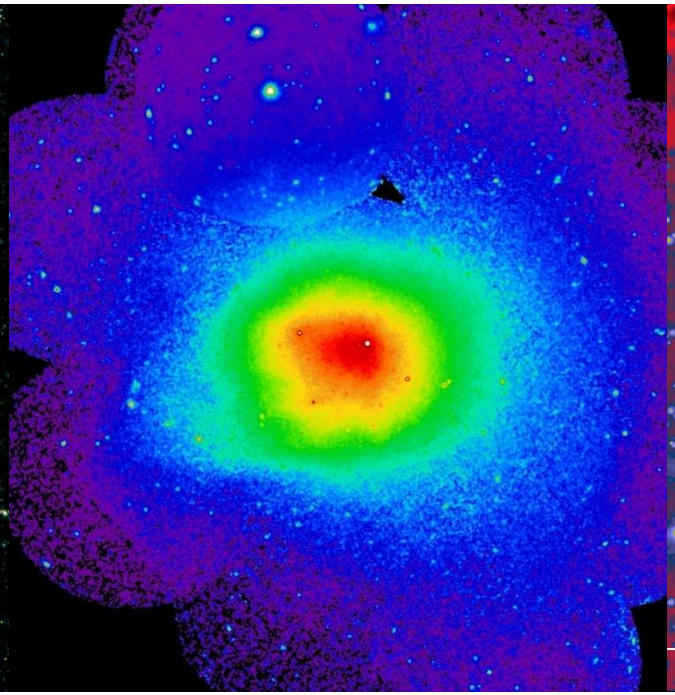
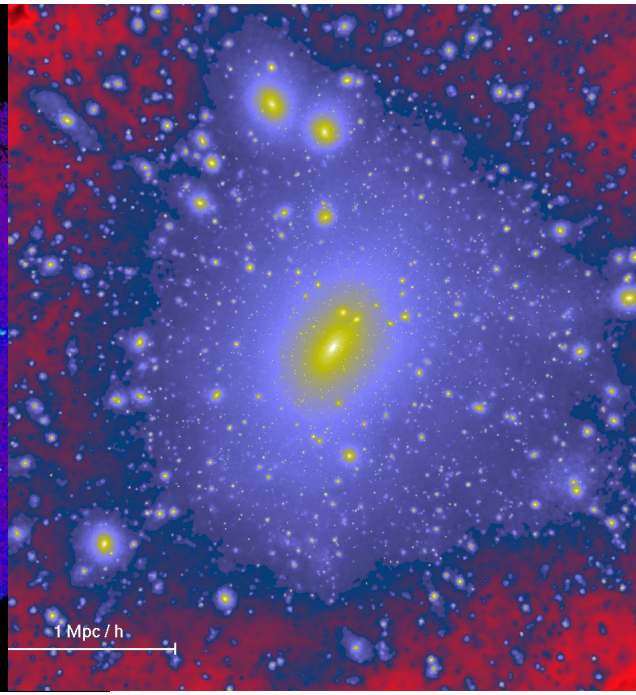


Thousands of galaxies with v ~ 1000 km/s
Hot **intergalactic gas** with Te ~ 3 – 10 KeV

Gravitational potential defined by invisible ***dark matter***

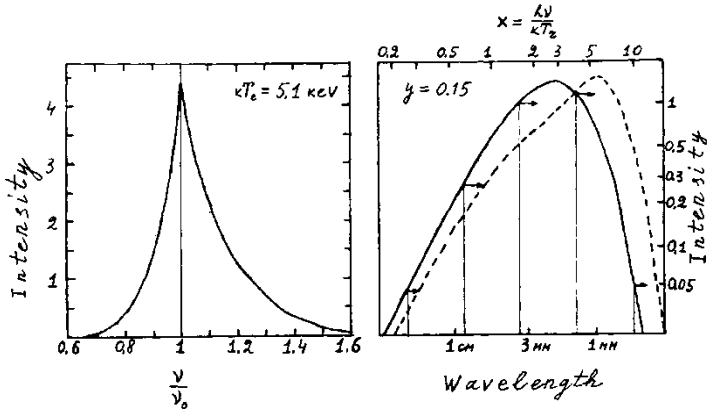
Distant galaxies are gravitationally ***lensed*** by A 2218

Major components of a galaxy cluster

Stars	Hot gas	Dark matter
		
few % of total mass	15 %	80 %
Optical	X-rays, CMB	Indirect

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)

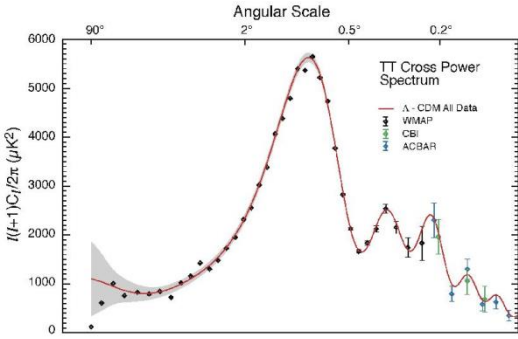
$$\frac{\Delta T}{T_r} = -\frac{v_r}{c}\tau_T$$

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

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

(see Sunyaev, Zeldovich, 1981)



Comptonization

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

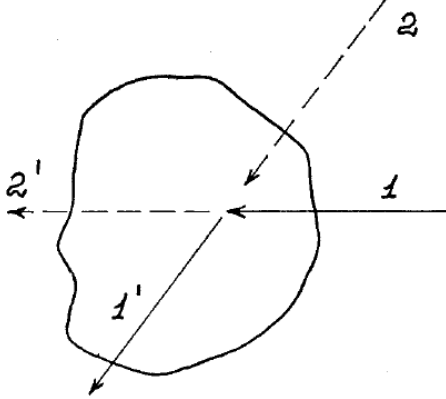


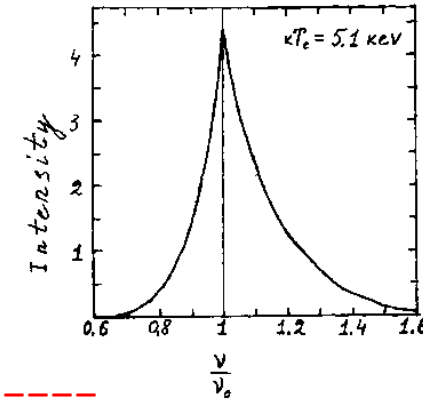
FIG. 2. The scattering of isotropic radiation field by the clo

Cloud is invisible

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

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

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



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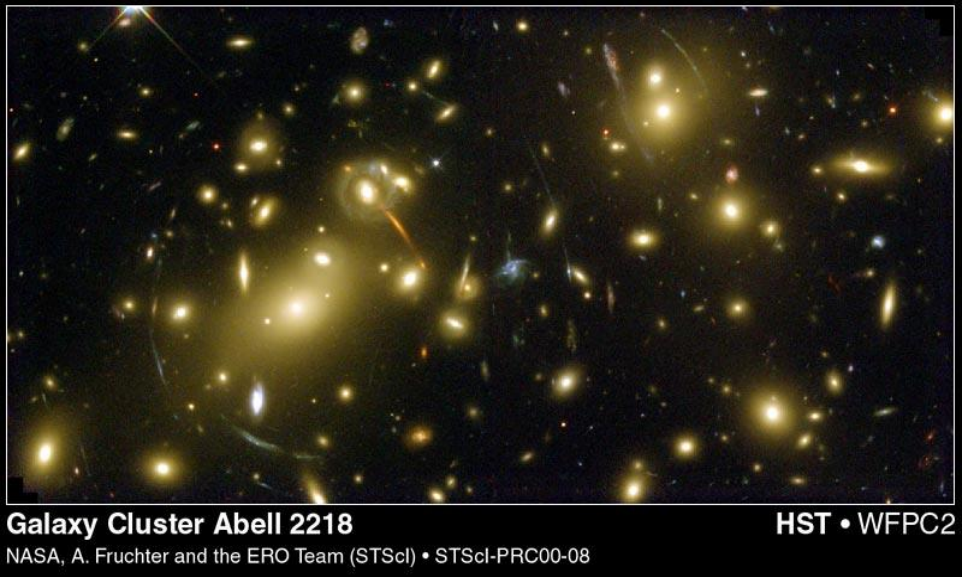
y: Amplitude of distortion

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



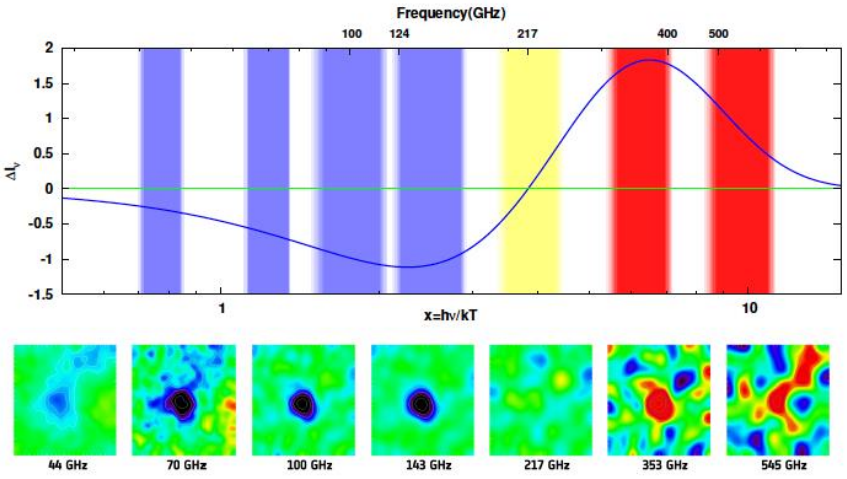


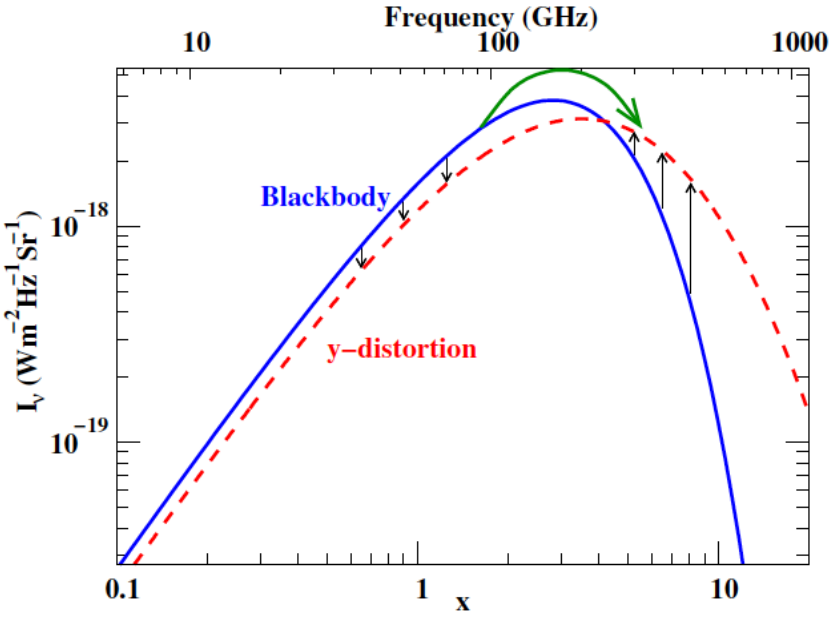
Image credit: ESA / HFI & LFI Consortia

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

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

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

(Zeldovich and Sunyaev 1969)
COBE-FIRAS limit (95%): $y \lesssim 1.5\times10^{-5}$ *(Fixsen et al. 1996)*



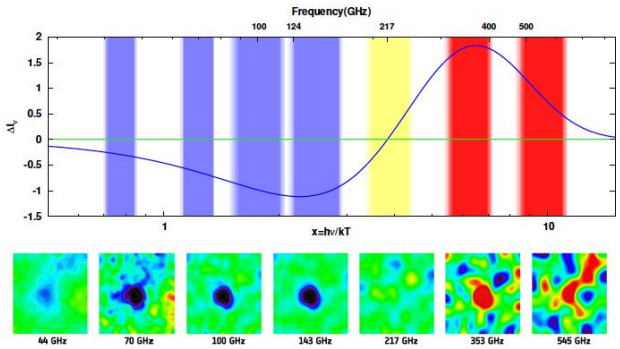
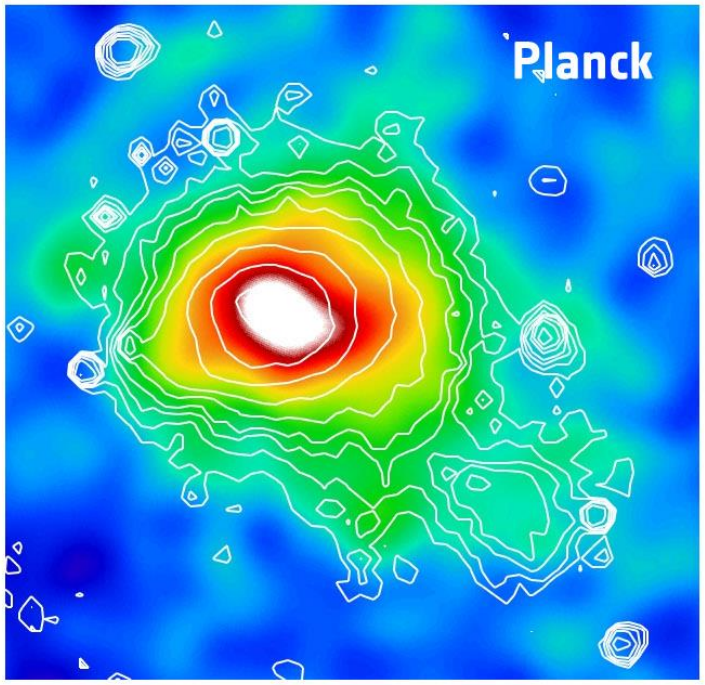
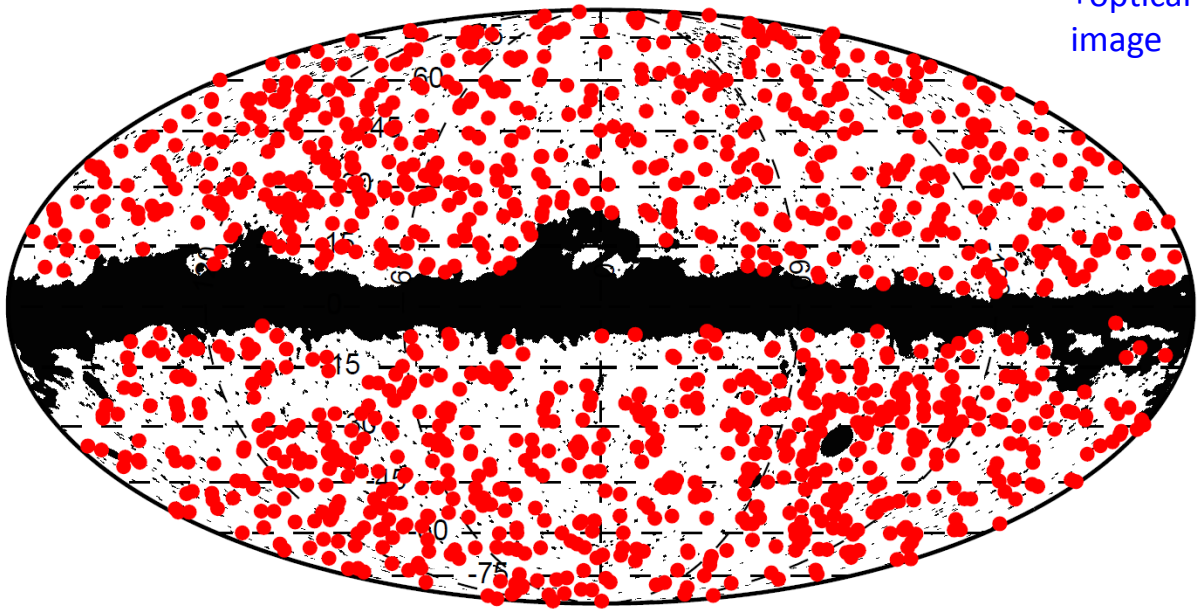


Image credit: ESA / HFI & LFI Consortia

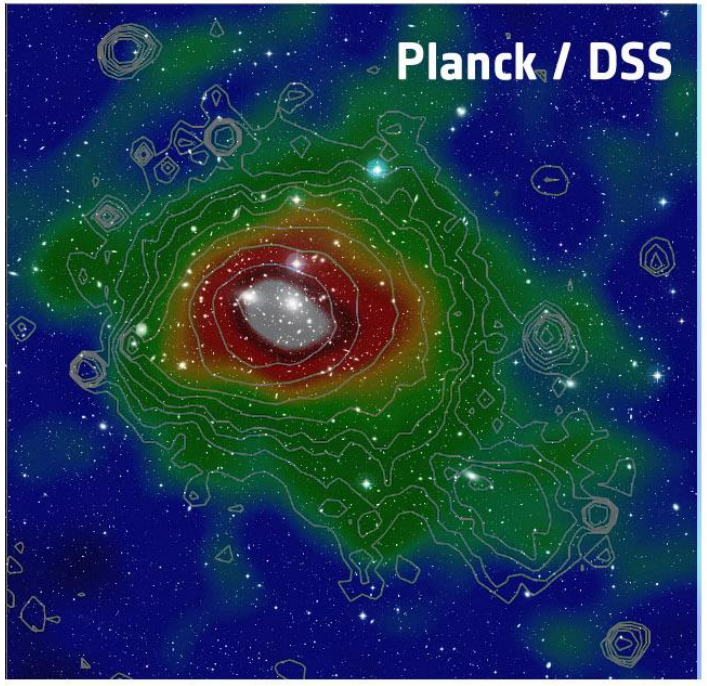


SZ shadow,
Coma cluster
of galaxies
y-parameter map,
based on
100-857 GHz data

~ 900 clusters confirmed by X-Ray
or optical observations

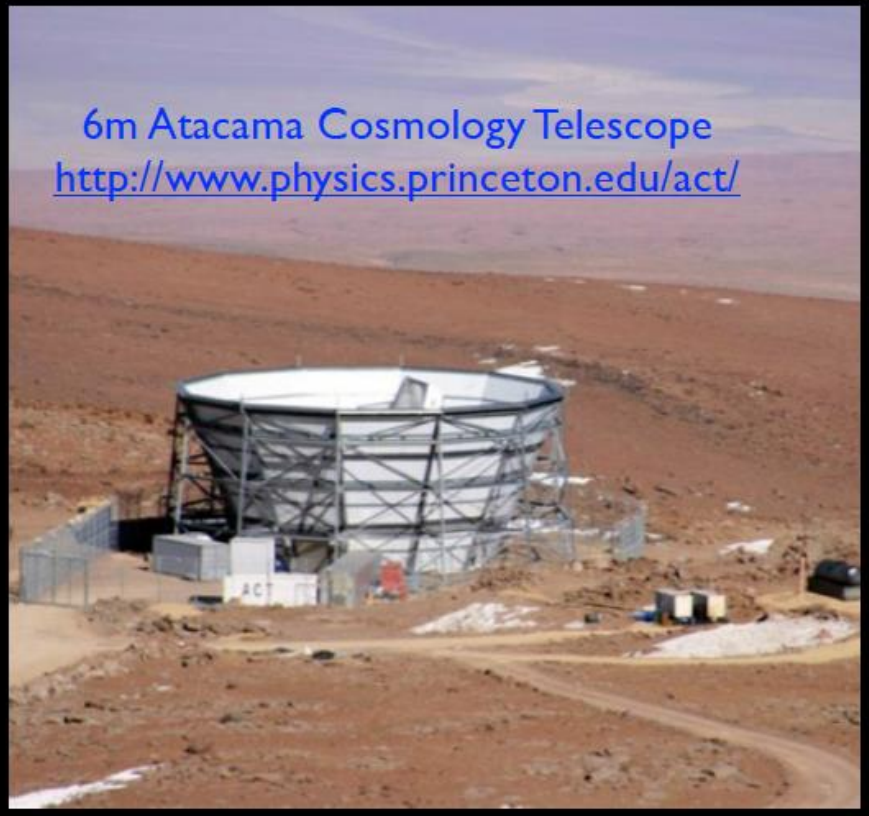


Planck
+optical
image



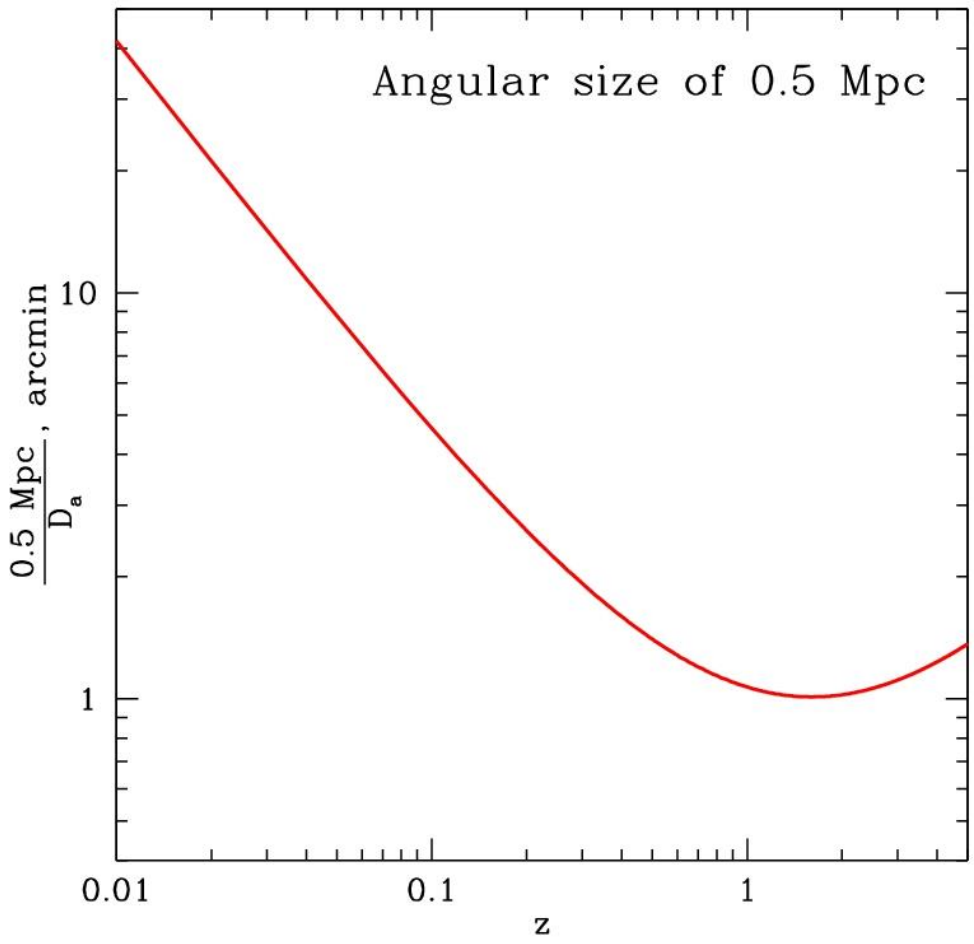
ACT and SPT

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



- Exceptional high and dry sites for dedicated CMB observations.
- Exploiting ongoing revolution in low-noise bolometer cameras

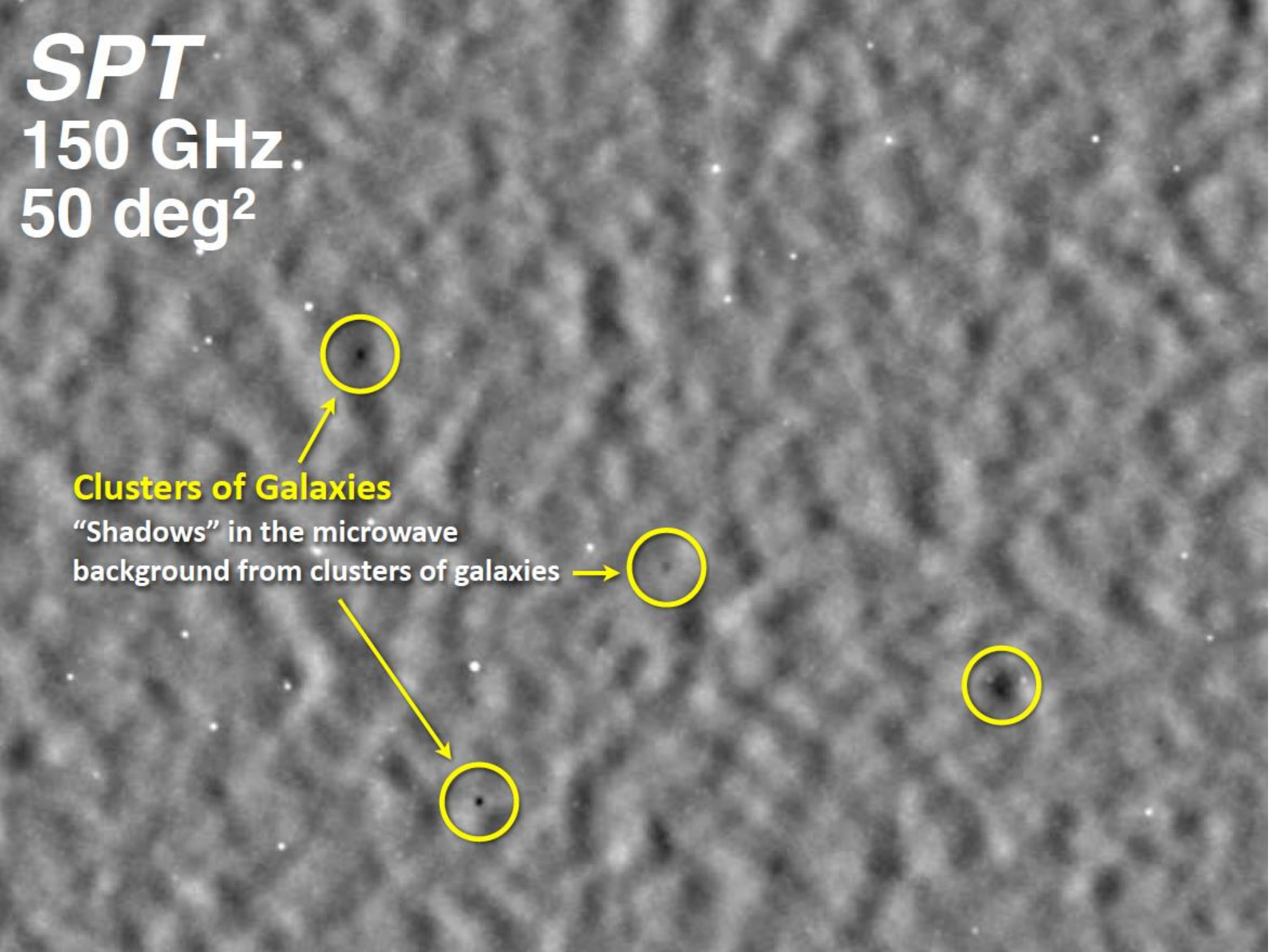
Angular size as a function of z

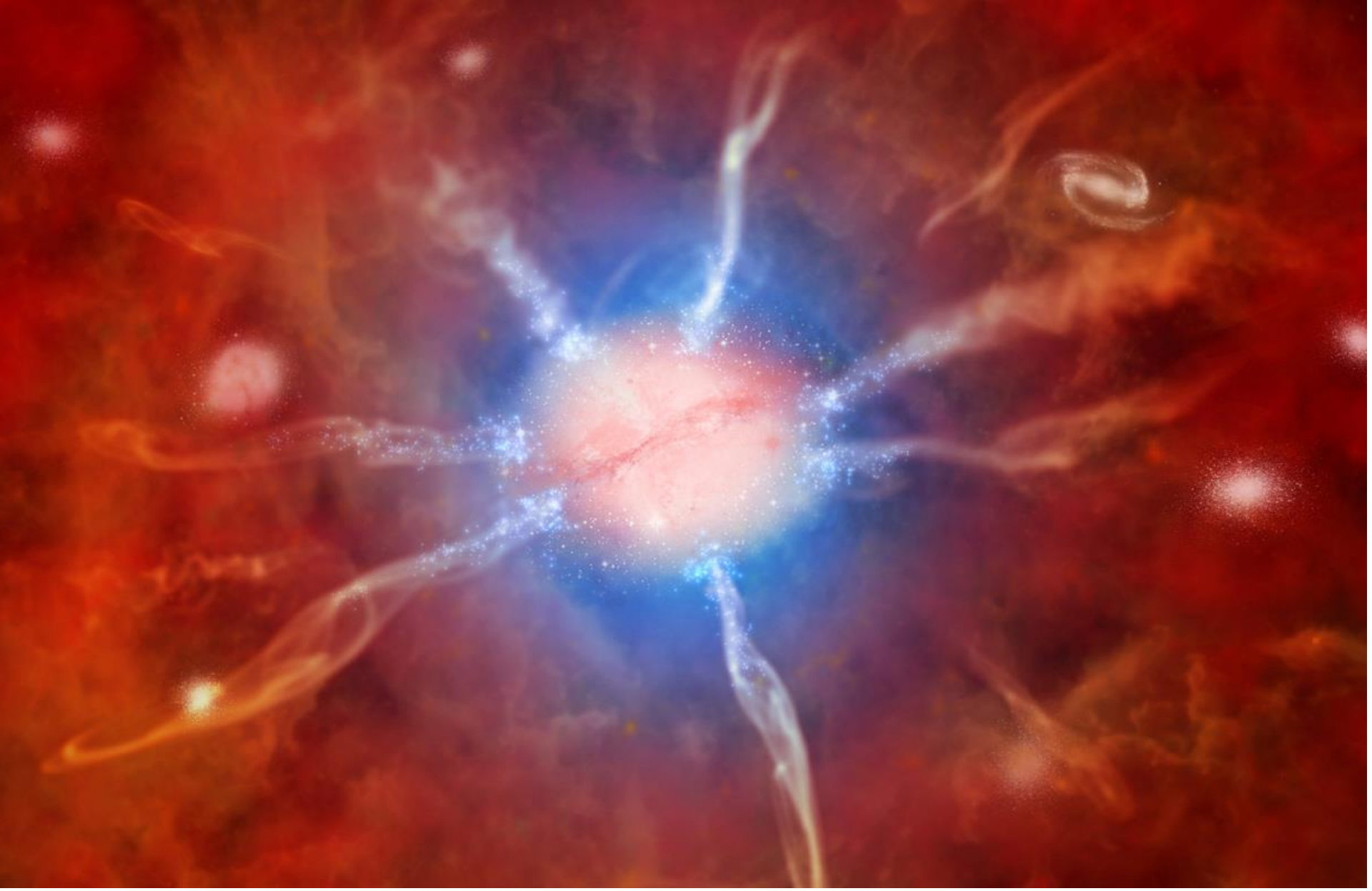


For distant clusters their angular size does not depend on redshift!

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


SPT
150 GHz
50 deg²
Clusters of Galaxies
"Shadows" in the microwave
background from clusters of galaxies



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.

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 $z > 0.3$

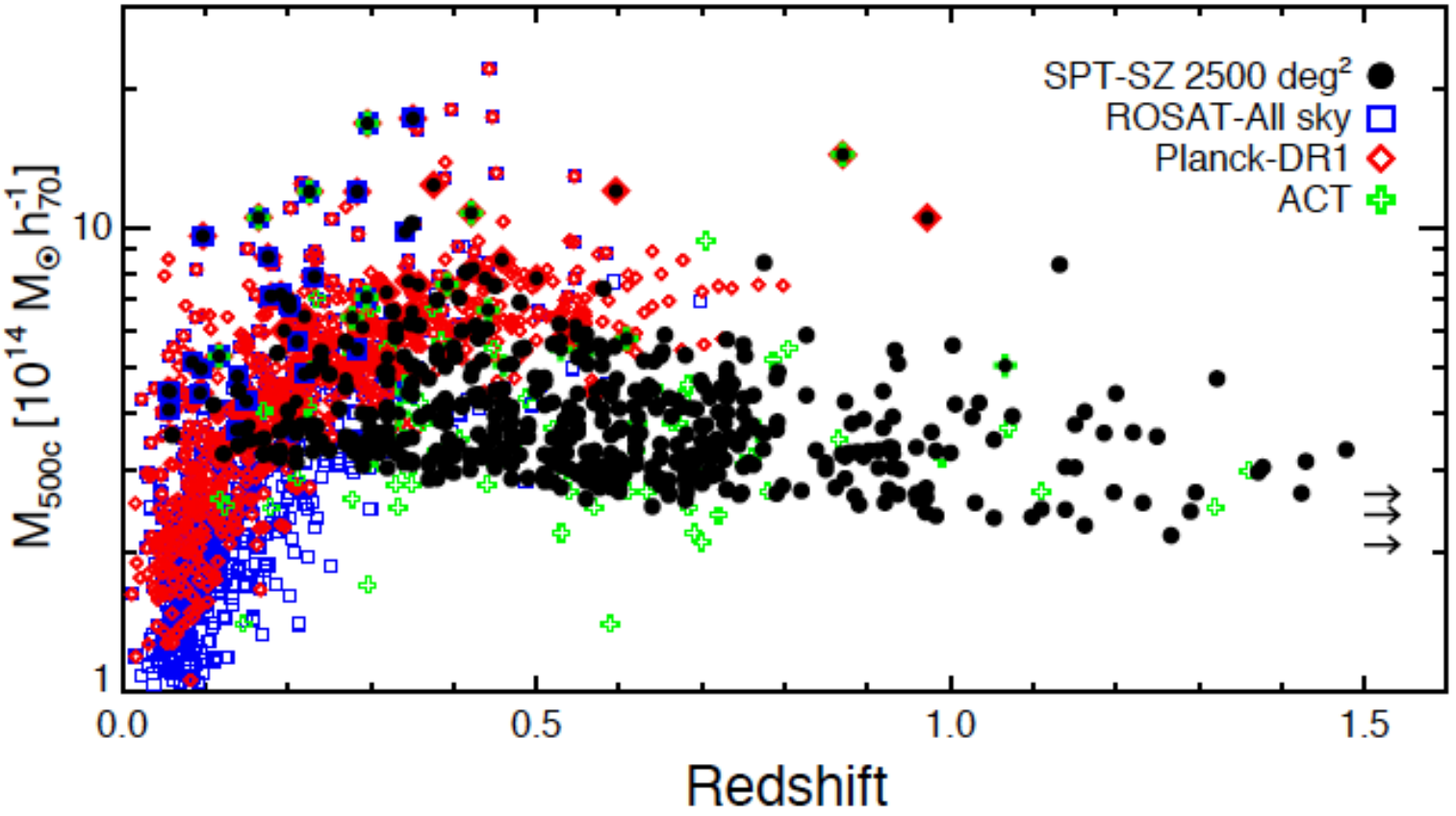


Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850

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*)

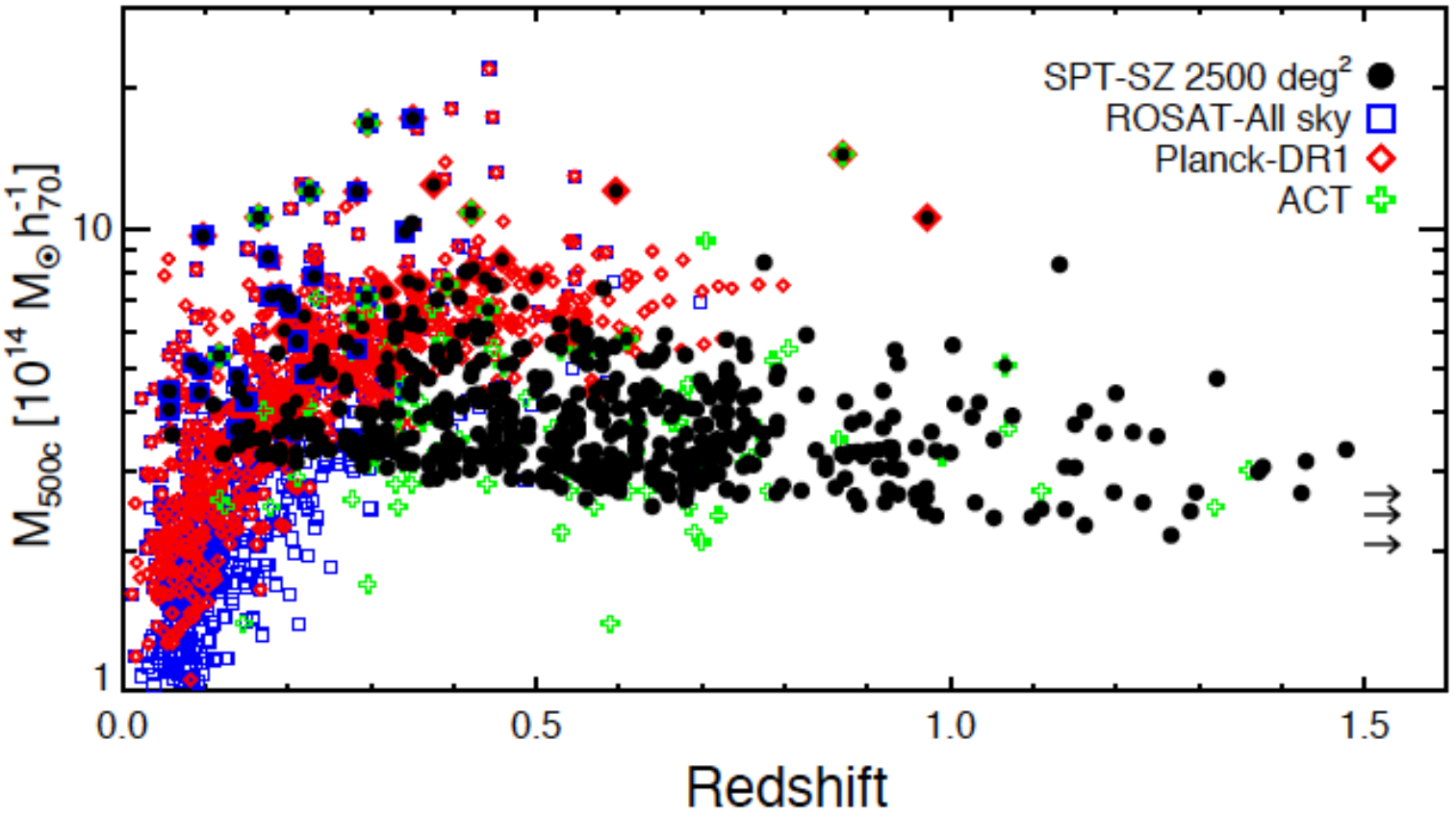


Fig. from Bleem et al. 2015 (SPT) arXiv:1409.0850

Dolag et al, 2014

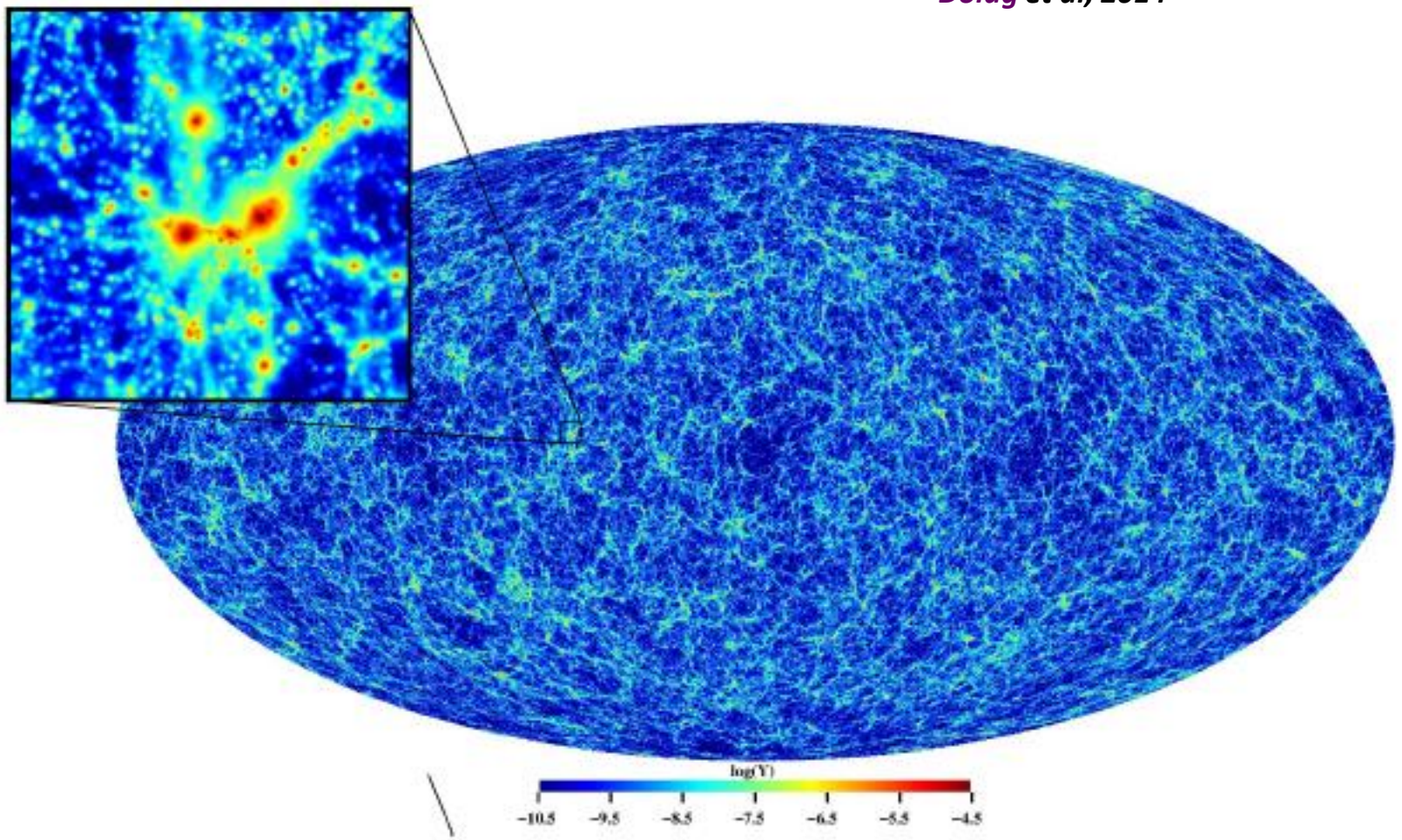


Figure 34. Map of simulated y-distortion taken from [207]. The y-type signal from the post-reionization epoch is dominated by the collapsed objects and filaments in the large scale structure.

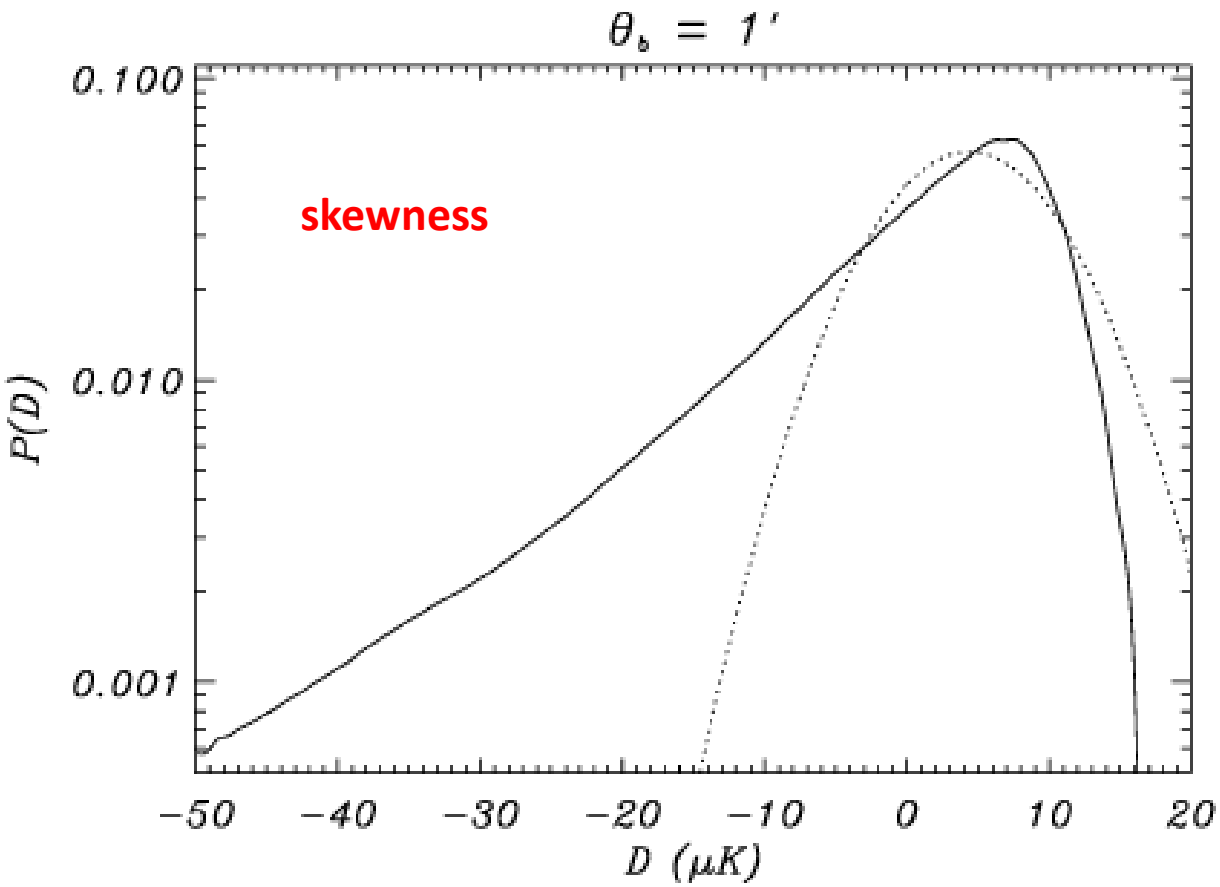
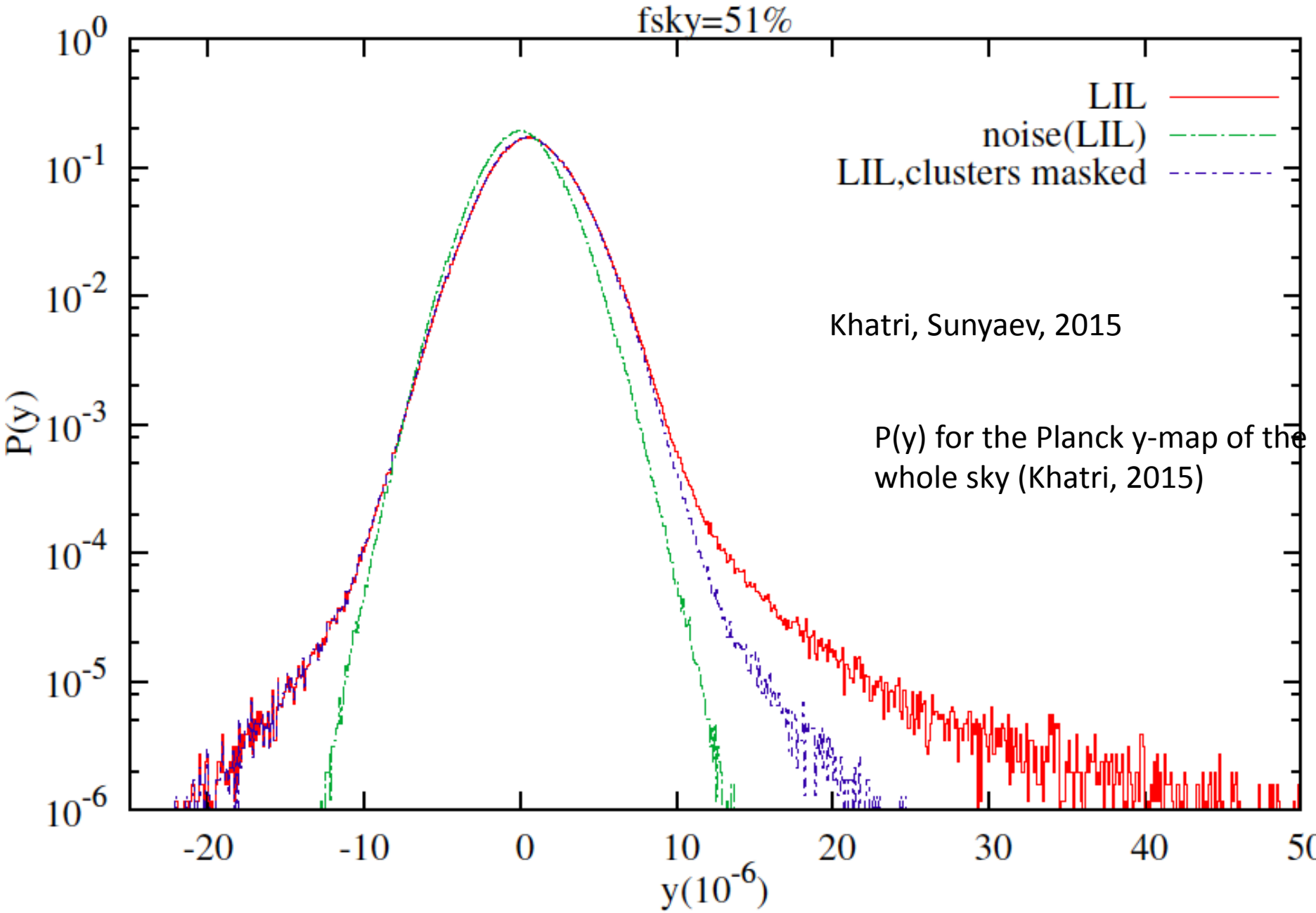


Figure 2. Example of the strong non-Gaussianity of the $P(D)$ function for SZ clusters. We present the $P(D)$ function for a SZ map in the Rayleigh–Jeans region of the spectrum, where clusters are 'negative' sources. For comparison, we also show the best Gaussian fit to this $P(D)$ curve (σ = 6.1 μK). This curve will be explained in detail in Section 7.

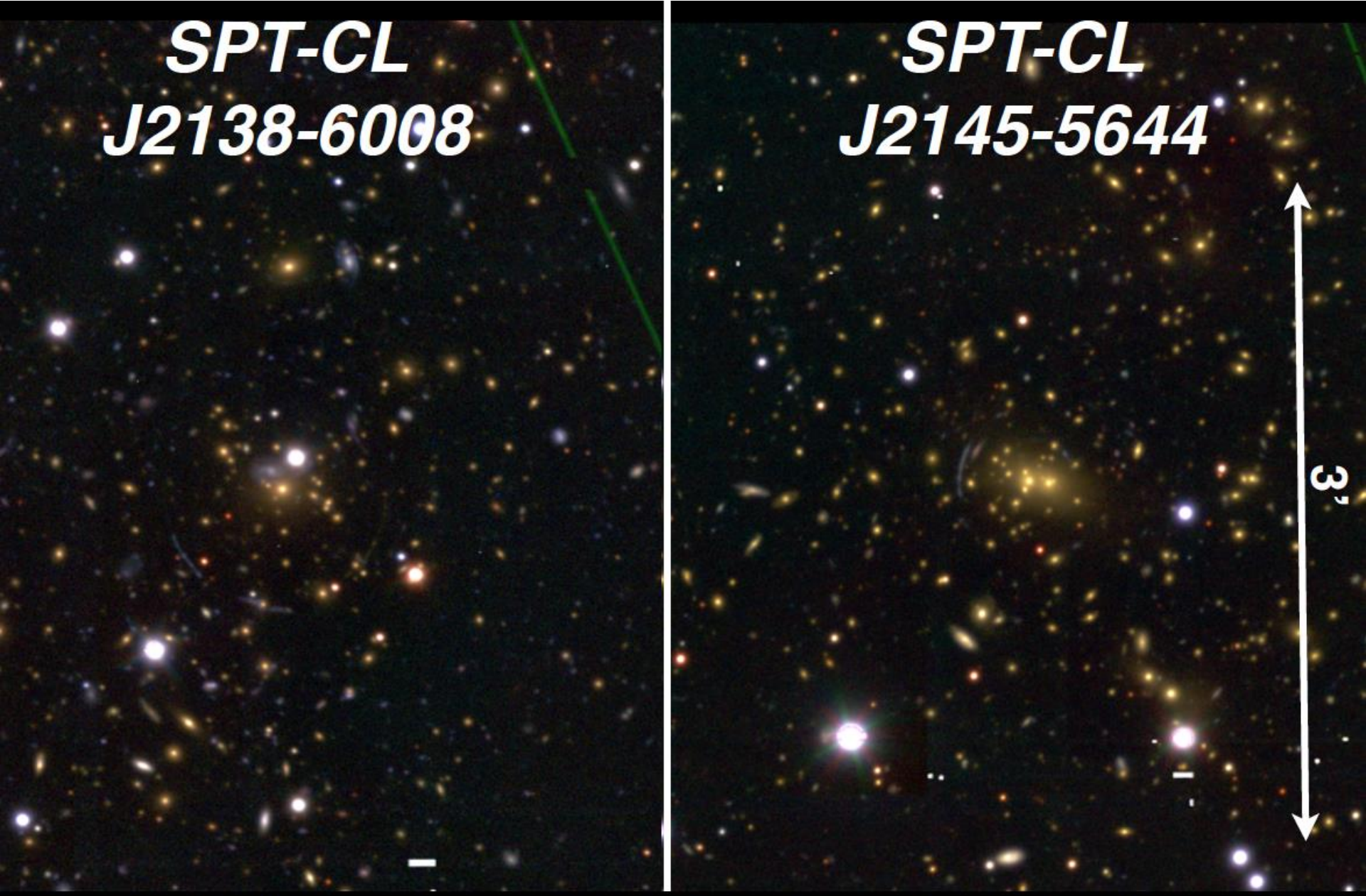
J. A. Rubiño-Martín and R. A. Sunyaev , 2003

D - deviation



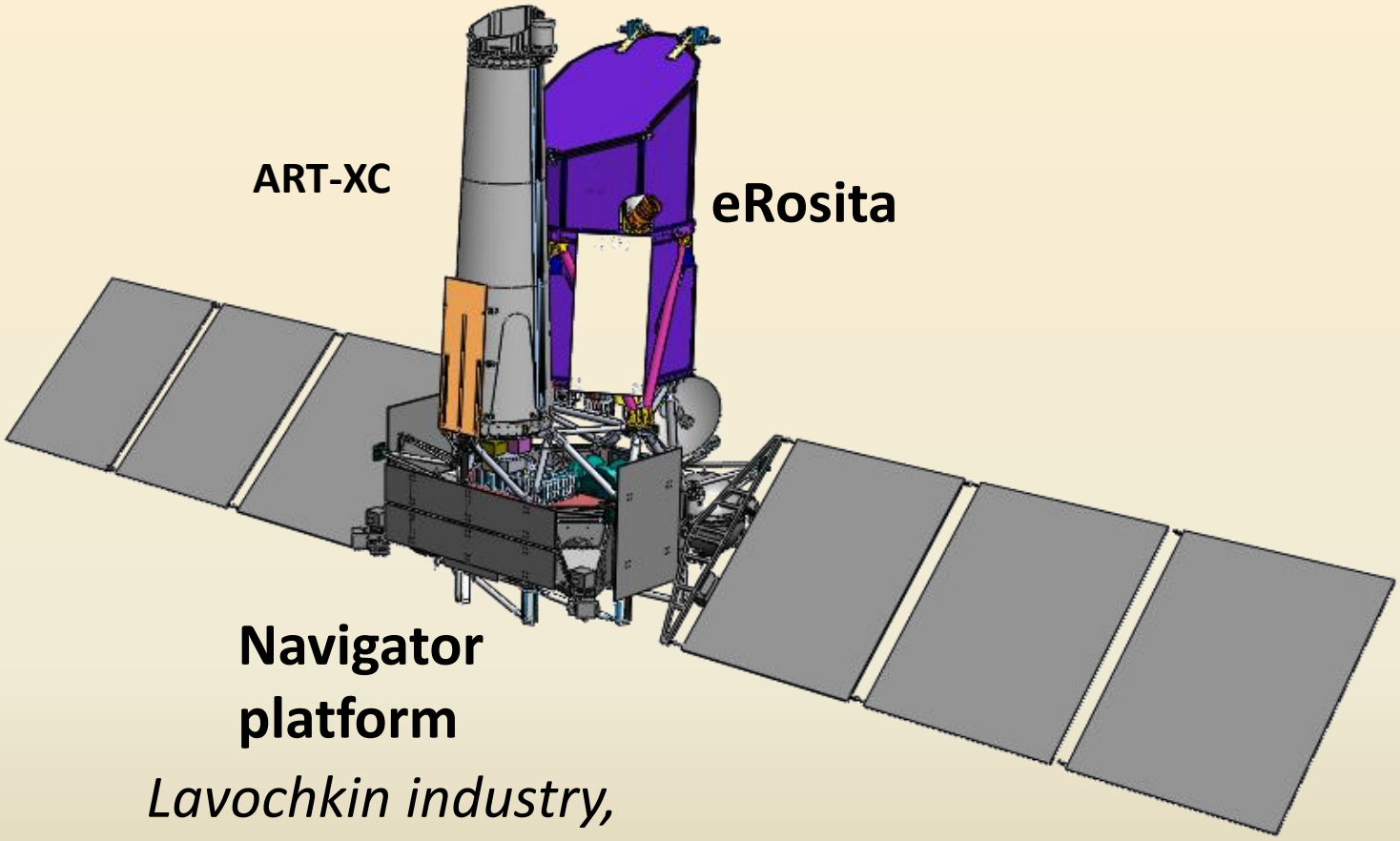
Khatri, Sunyaev, 2015

P(y) for the Planck y-map of the whole sky (Khatri, 2015)



Optical follow-up; redshifts, lensing, dynamical masses

Spectrum-Roentgen-Gamma (SRG)



Navigator platform

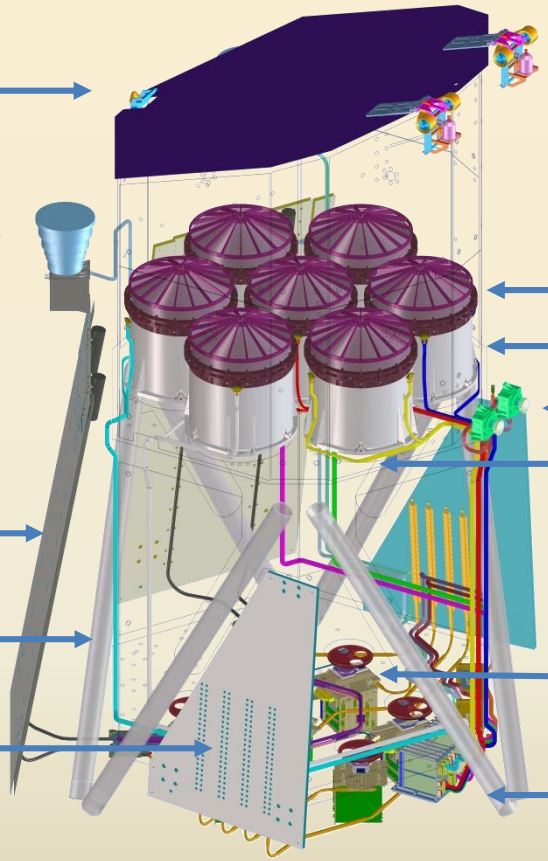
Lavochkin industry, Khimki near Moscow

Launch from Baikonur with Zenit-Fregat, September 2017

Scan of the whole sky from L2 like PLANCK, but in X-Rays, during 4 years

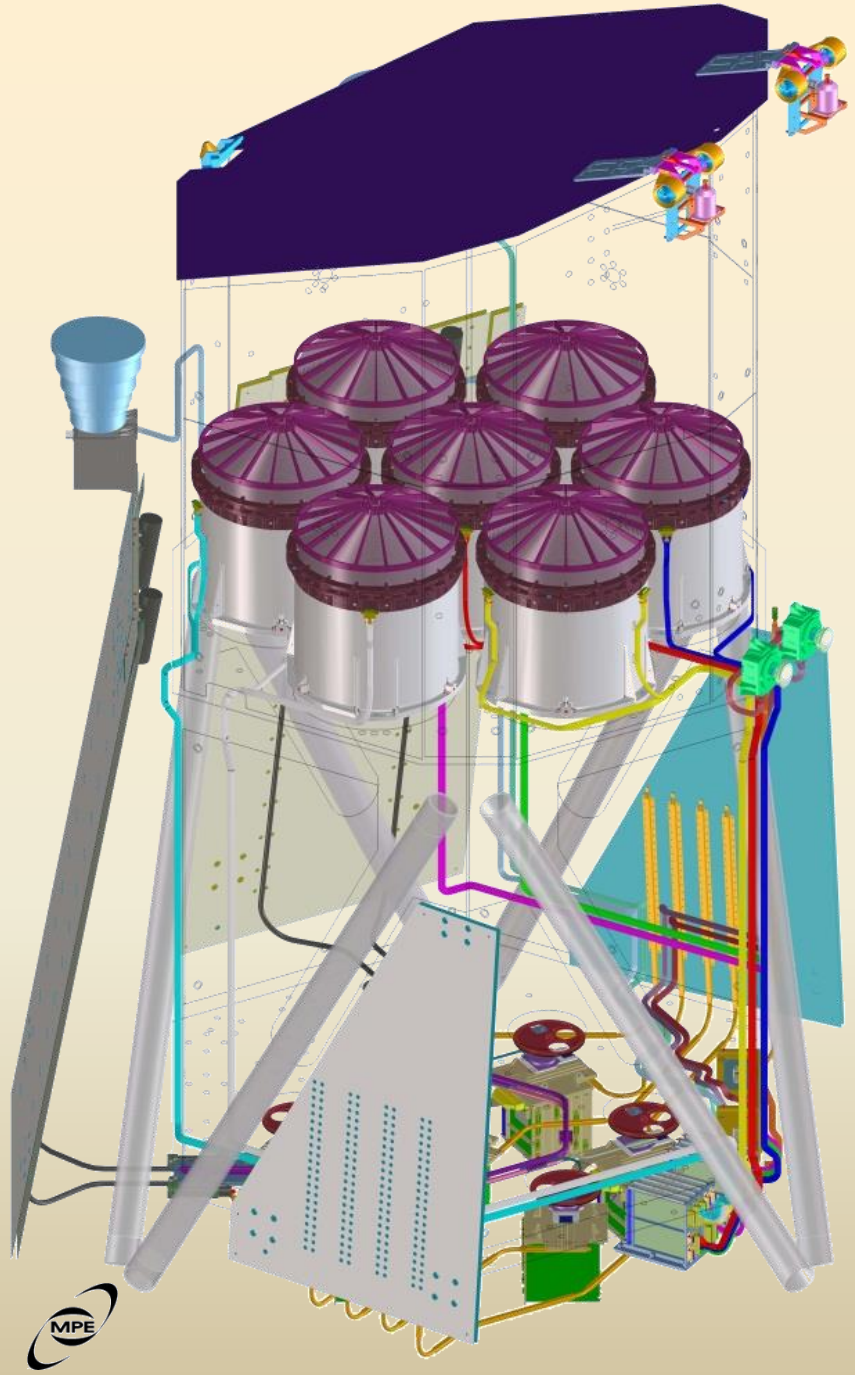
eRosita is an instrument designed to perform all sky 0.5 – 10 KeV surveys: Large Field of View, large effective area good resolution 15-25”

Instrument



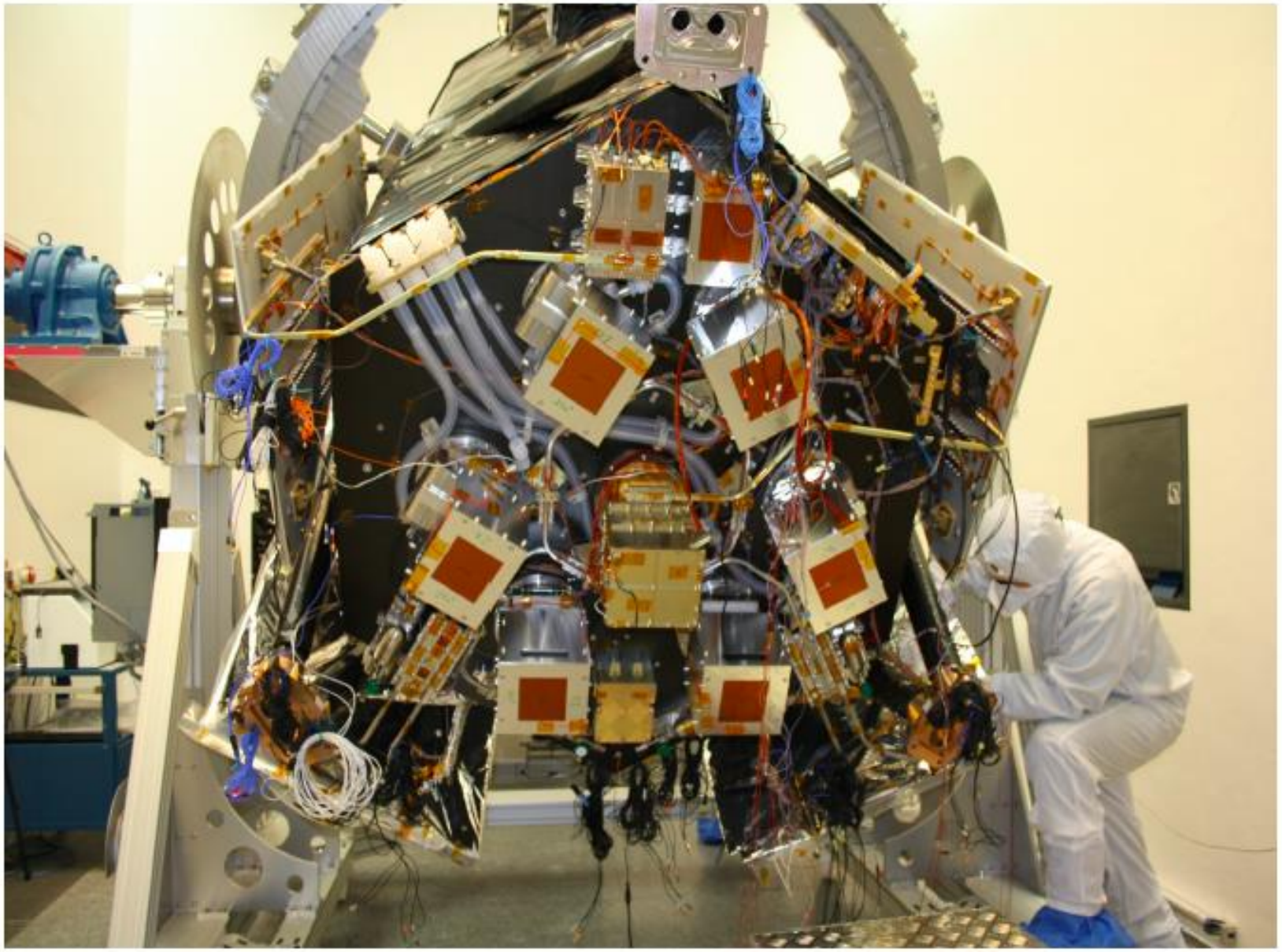
7 identical Mirror Modules	Field of View	1° Ø
54 nested Mirror Shells each	Angular Resolution	15 arcsec on-axis
7 identical pnCCD Cameras	Energy Range	~0,3 - 10 keV

MPE



Focal length - 1.6 m
Weight ~ 800 kg

Focal plane complexity

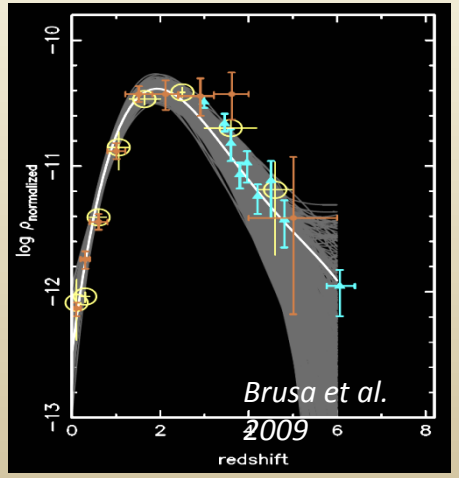


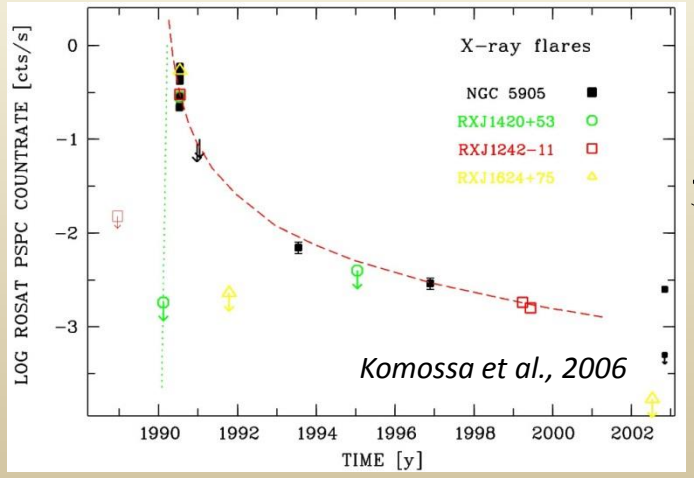
10 thousand star forming galaxies

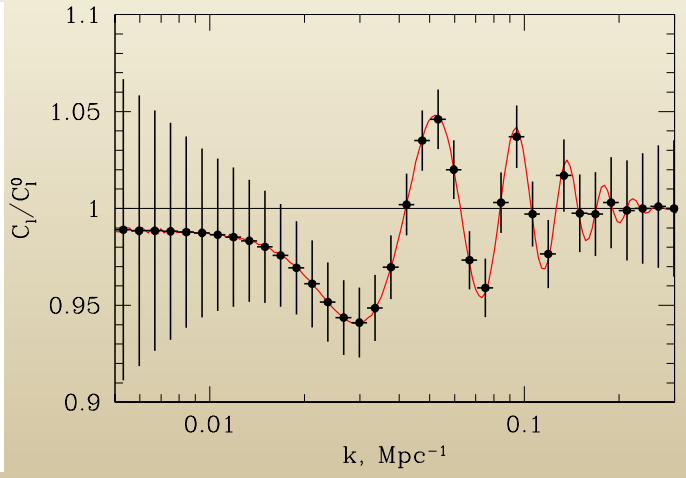
AGN

3 Mio. AGN

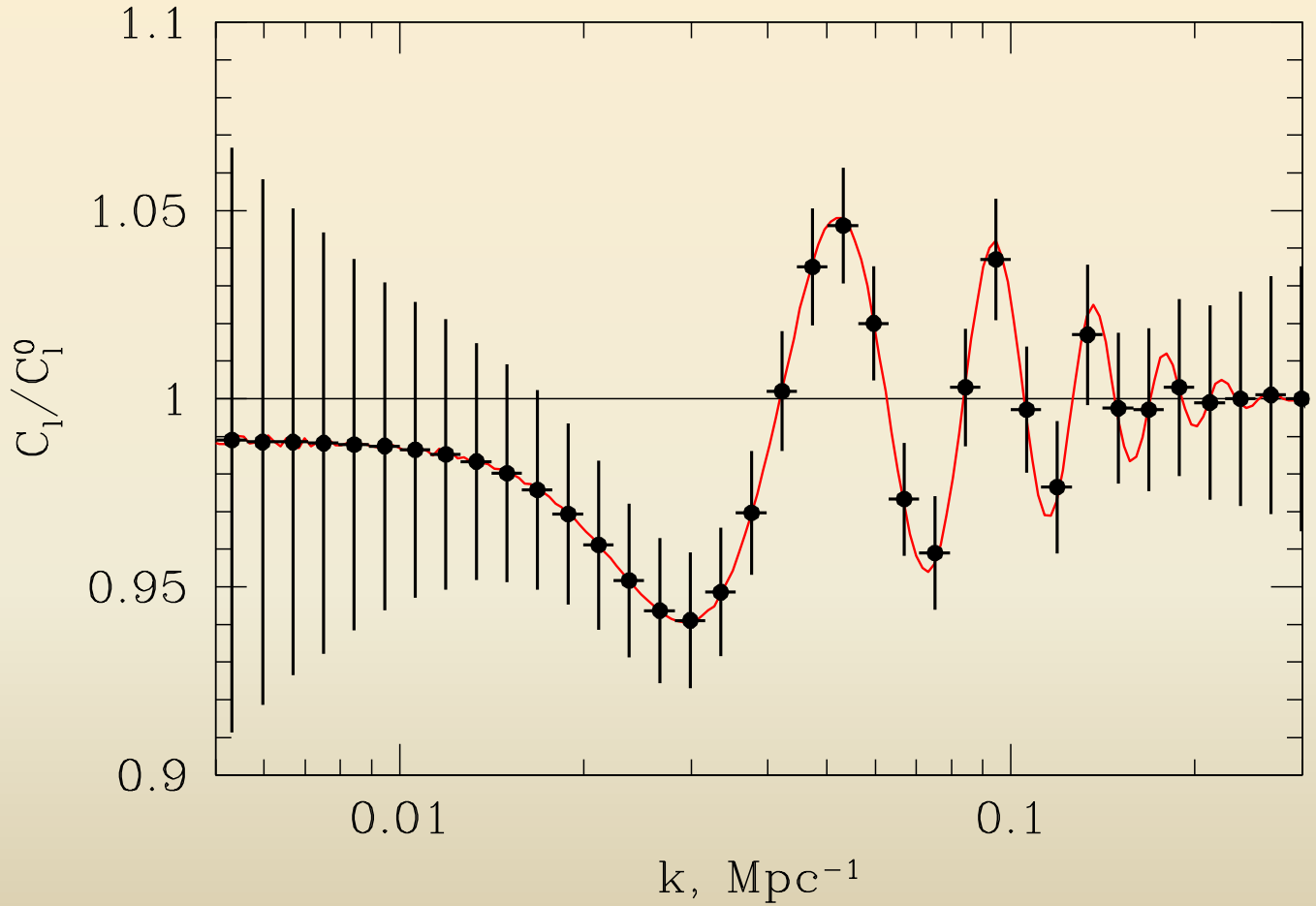
- Accretion History: XLF, obscured vs. unobscured
- LSS: AGN ACF, AGN/Galaxy CCF, AGN/Cluster CCF
- AGN host Galaxies: Morphology, SFR, Obscuration
- Sub-Populations:
  - High Redshift (z>6)
  - Extreme Luminosity
  - Compton thick AGN
- Spectra: Obscuration, Continuum, Soft Excess, Iron Lines
- Variability: Var. vs. L, L/L_{edd}, z, Tidal Disruptions
- BAOs: 10σ detection, but precise redshifts needed.







AGN Cosmology: BAO



~10σ detection using full sky data

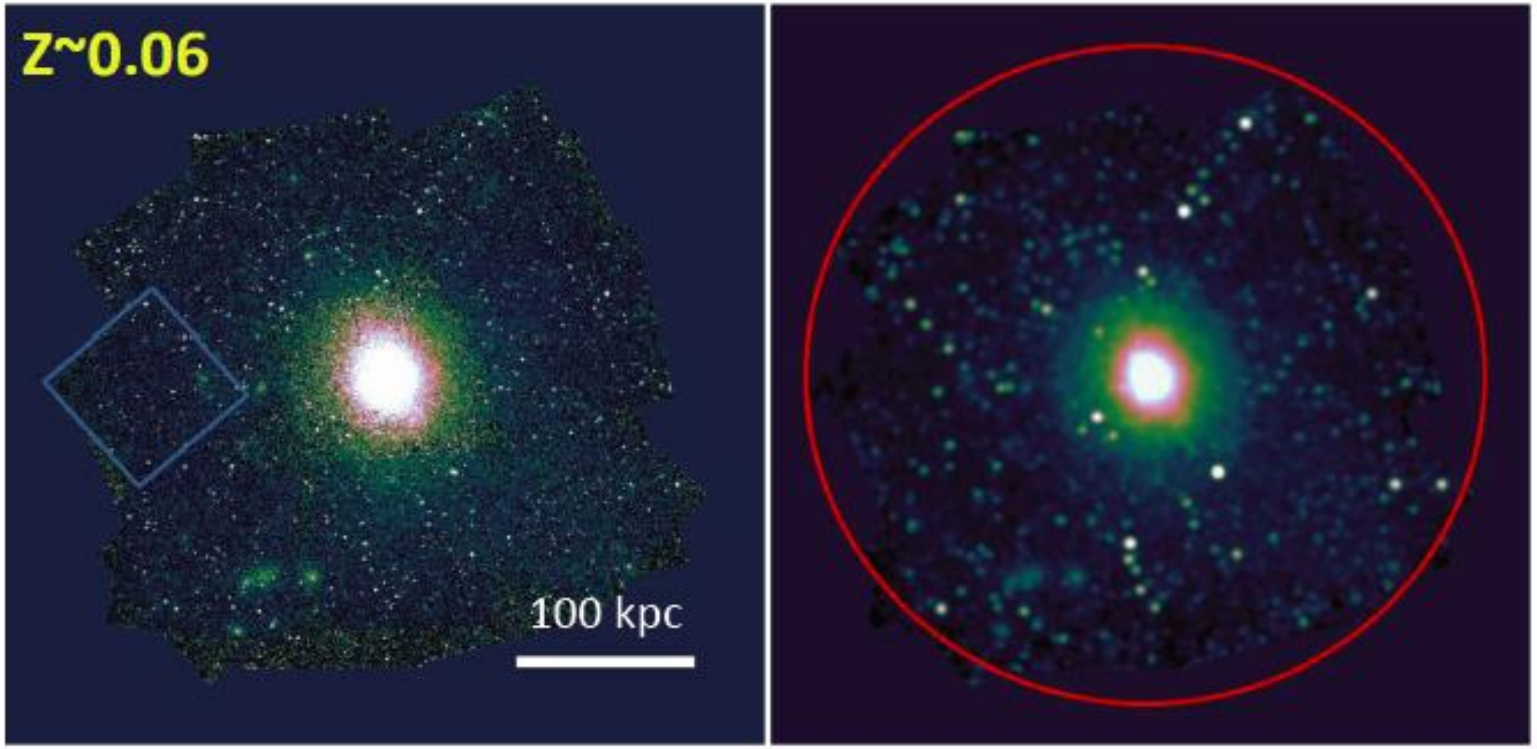
Δz~0.05 or better is required

Gilfanov

A fast survey machine

for clusters of galaxies

Chandra | **eRosita**

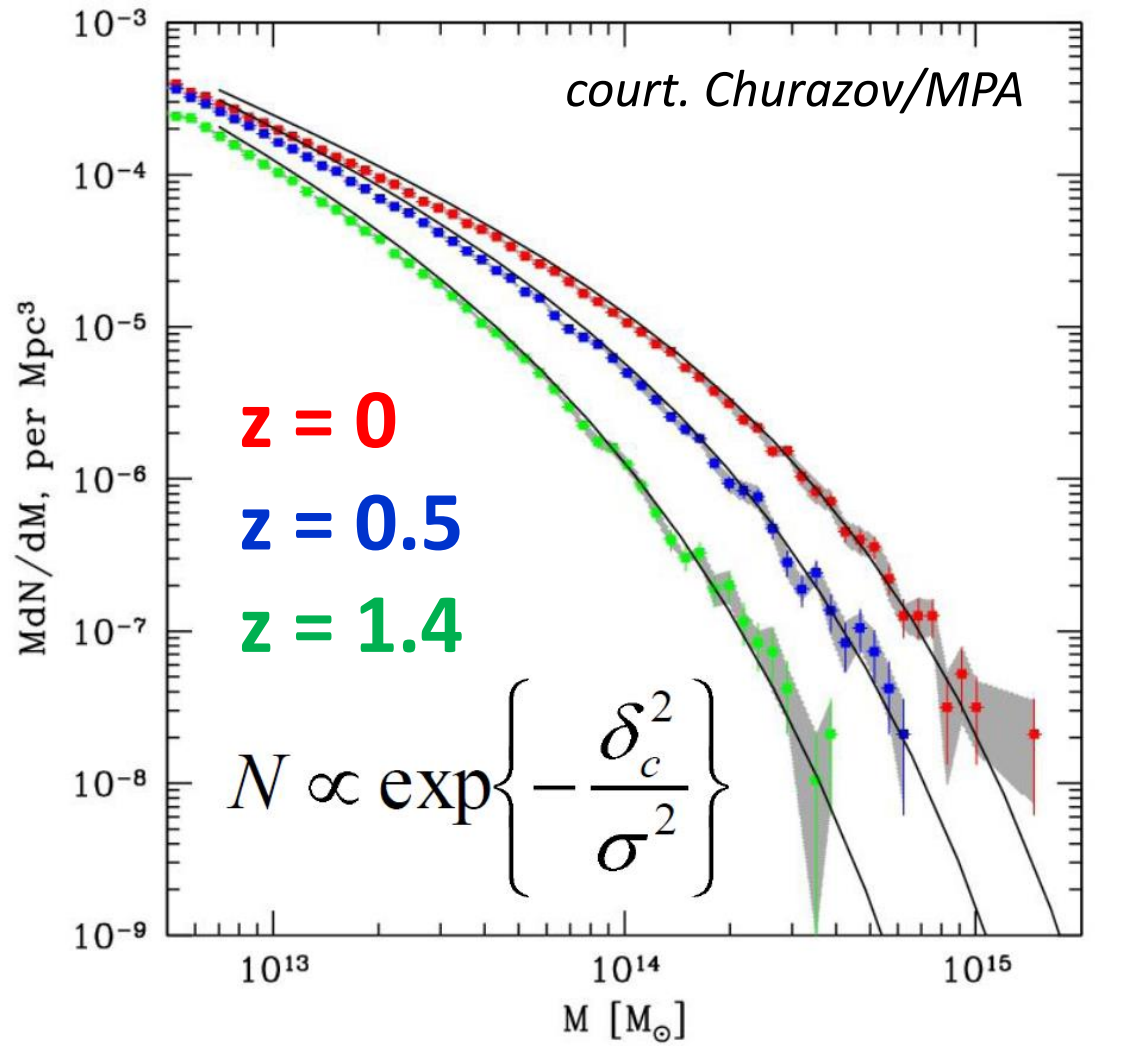


~30 pointings
~2 Msec
[0.5” HEW]

~1 pointing
~80 ksec
[28” HEW (FoV avg)]

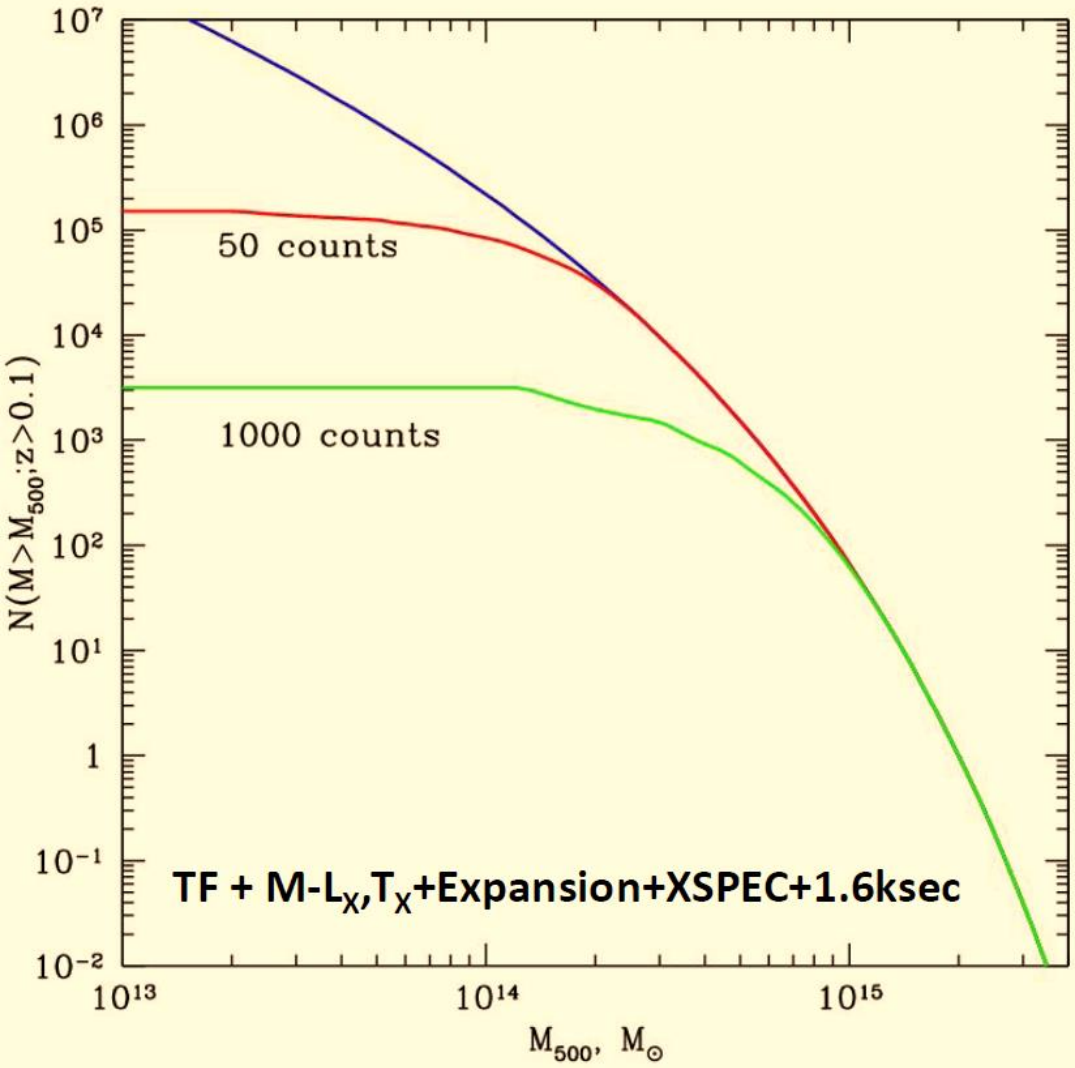
Churazov, IKI, MPA

Evolution of Cluster Mass Function



Number of most massive clusters is extremely sensitive to cosmology

Will eROSITA detect all Clusters?



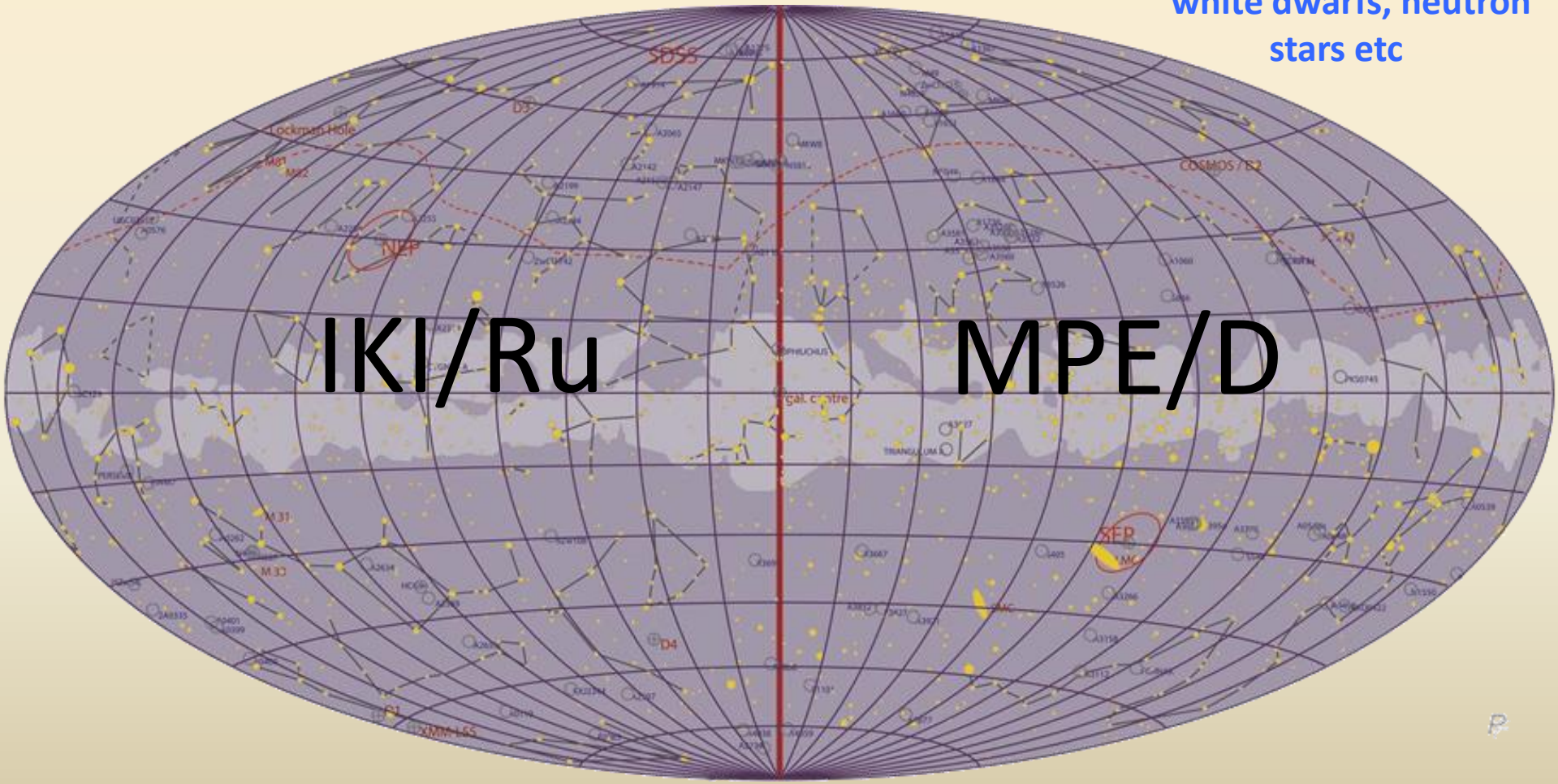
M	z	N	eRosita
10^{14}	~3	$8\ 10^4$	40%
$3\ 10^{14}$	~2	$8\ 10^3$	100%
10^{15}	~1	50	100%

Churazov/IKI,MPA: Yes!

Z_{max}~2, M~3 10^{14} M_{Sun}

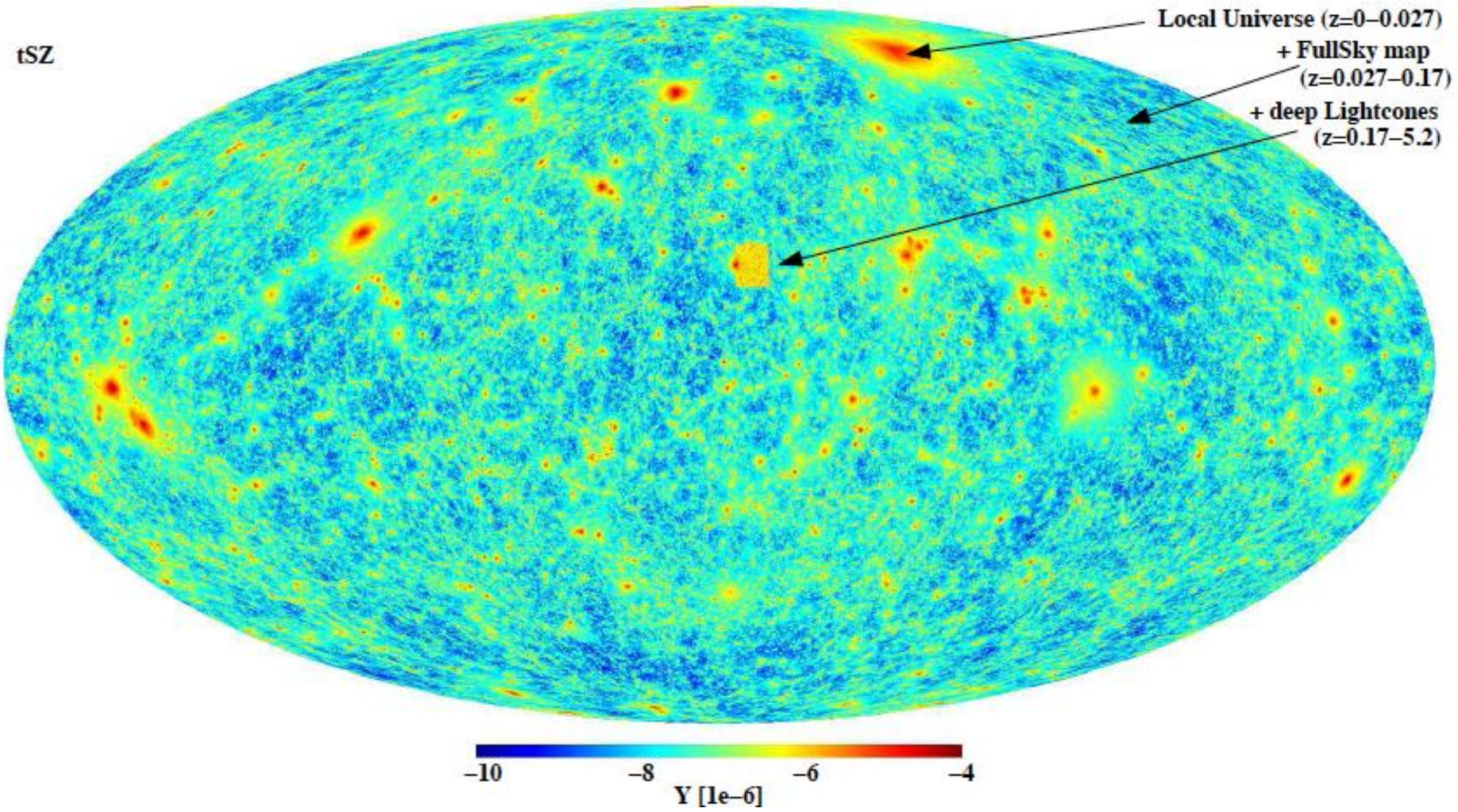
Sky Division

Hundreds of thousands Galactic X-Ray sources:
supernovae remnants, young stars and stars with active coronae, white dwarfs, neutron stars etc

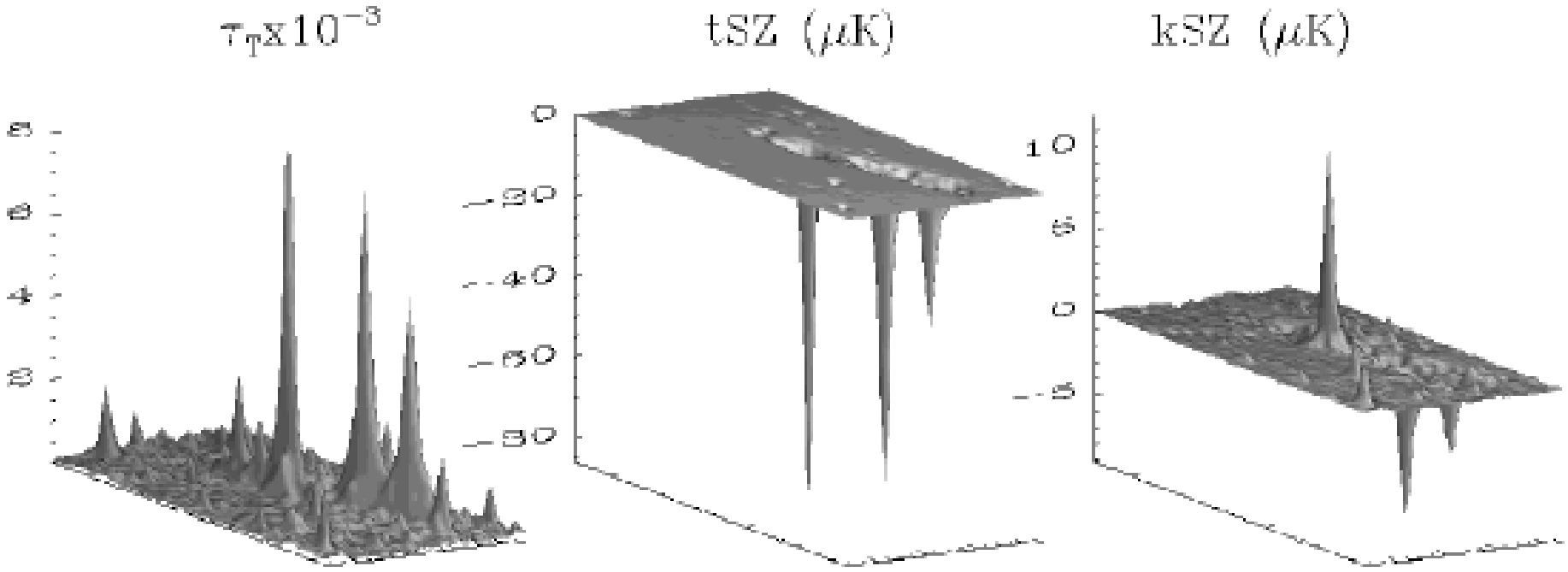


Galactic coordinates

K. Dolag, E. Komatsu, R. Sunyaev



It will be great to overlap eRosita map with 100 000 clusters and groups of galaxies onto high quality y-map from the future CMB spacecraft



Diarerio, Sunyaev, Nusser, 2003

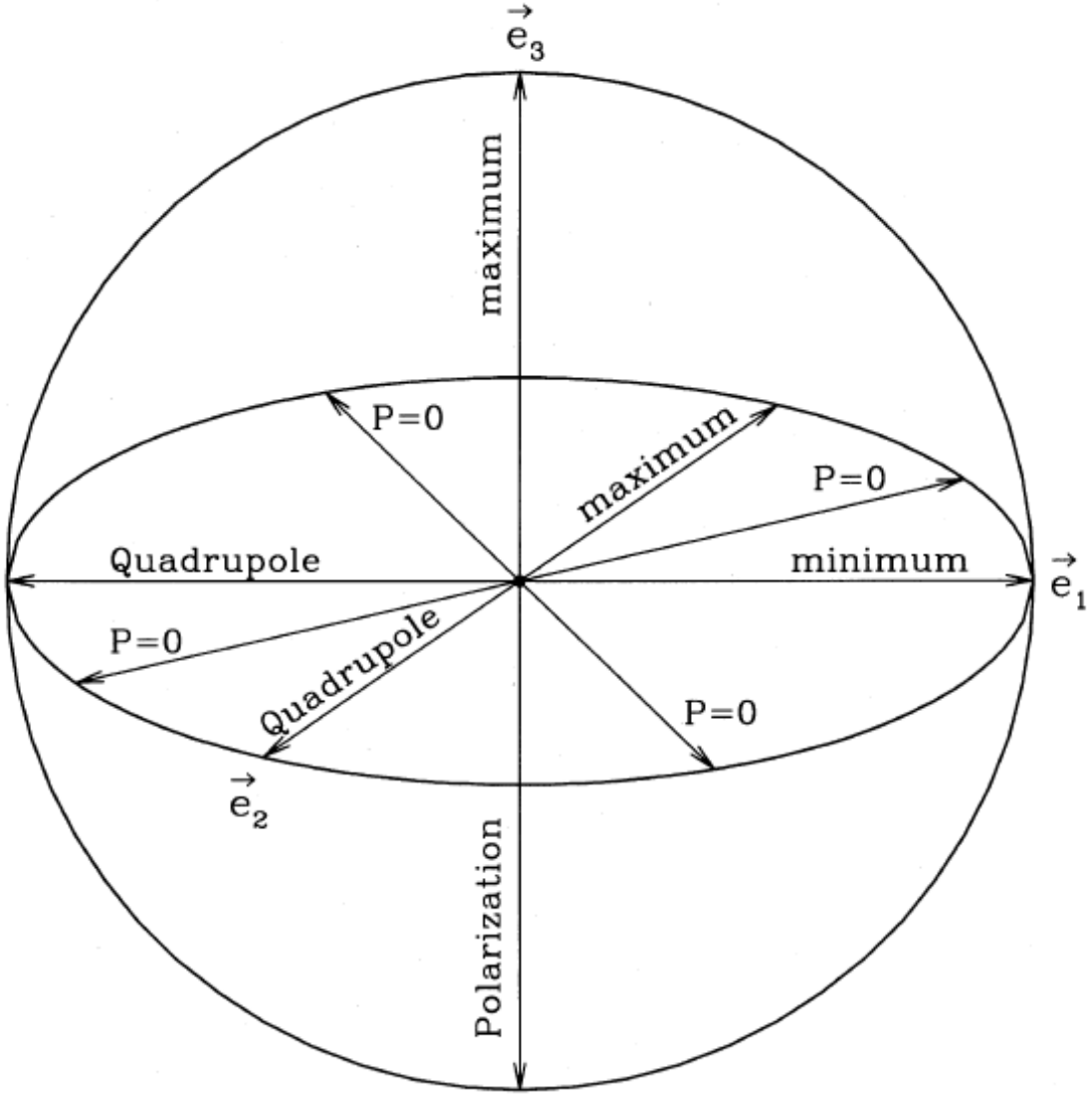


Figure 1. The geometry of the polarization effect induced by the CMB quadrupole. The vectors e_1, e_2 and e_3 define the eigensystem of the CMB quadrupole temperature anisotropy. The polarization effect has two broad maxima in the directions $\pm e_3$ orthogonal to the plane which contains the minima ($\pm e_1$) and maxima ($\pm e_2$) of the quadrupole. In the same plane there are four directions for which there is no polarization.

Archaeology with polarisation in clusters of galaxies

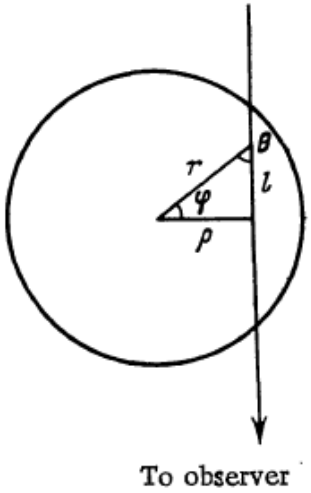


FIG. 1. Geometry of the problem of the scattering of the radio waves emitted by a central source in a cluster of galaxies.

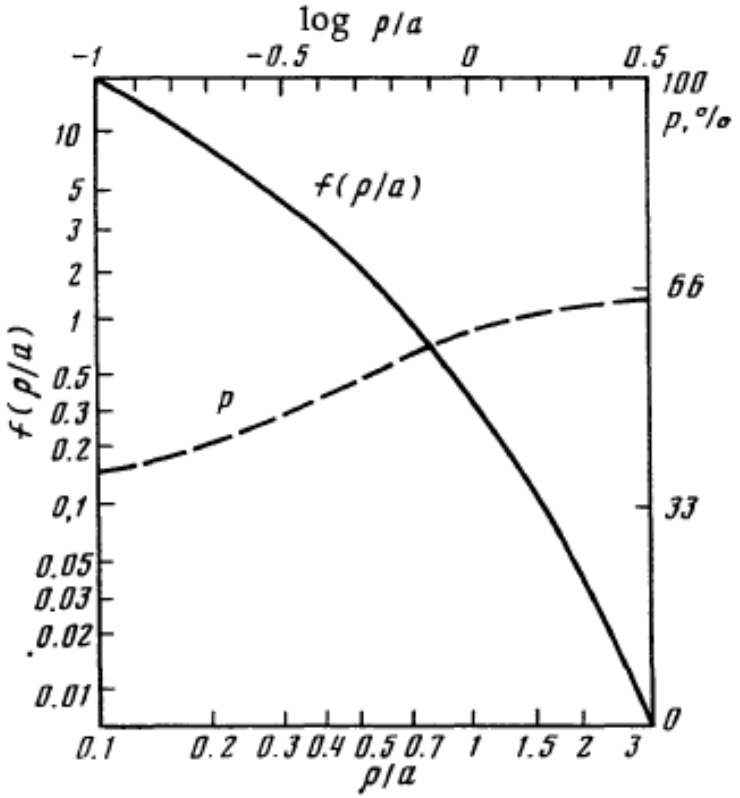


FIG. 2. Solid curve, the function f(ρ/a) describing the dependence of the diffuse scattered radiation intensity on the distance of the line of sight from the compact radio source at the center of a galaxy cluster of core radius *a*. Dashed curve, percentage polarization of the diffuse radiation as a function of ρ/a.

Quasars are variable, we can see the history of their activity in the reflected radiowaves (traces of the jets)

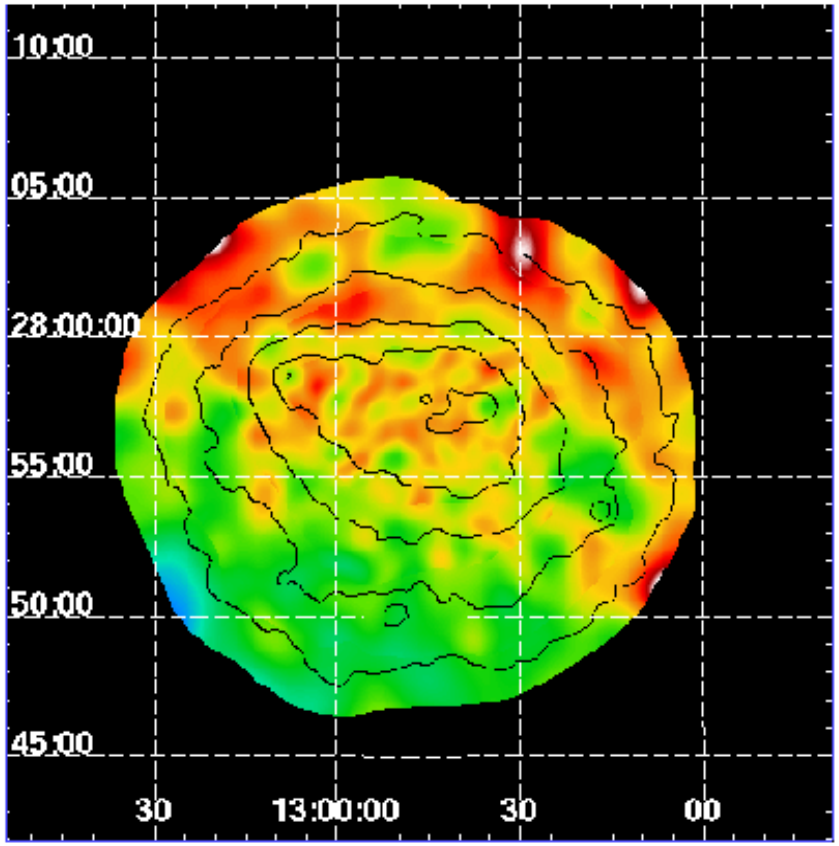
Sunyaev, 1982

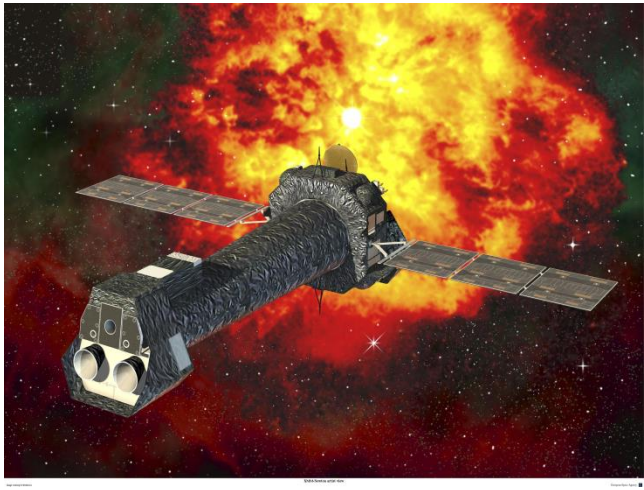
Thank you !!!

Bose-Einstein spectrum

$$
\begin{aligned}
n_{\mathrm{BE}} &= \frac{1}{e^{\frac{h\nu}{k_{\mathrm{B}}T_{\mathrm{BE}}}+\mu}-1} \\
&= \frac{1}{e^{x-0.456\mu x+\mu}-1} \\
&\approx n_{\mathrm{pl}}(x) + \frac{\mu e^x}{(e^x-1)^2}\left(\frac{x}{2.19}-1\right),
\end{aligned}
$$

X-RAY EMISSION FROM CLUSTERS OF GALAXIES





Electron temperature ~ 9 KeV

Electron density ~ 0.03 cm -3

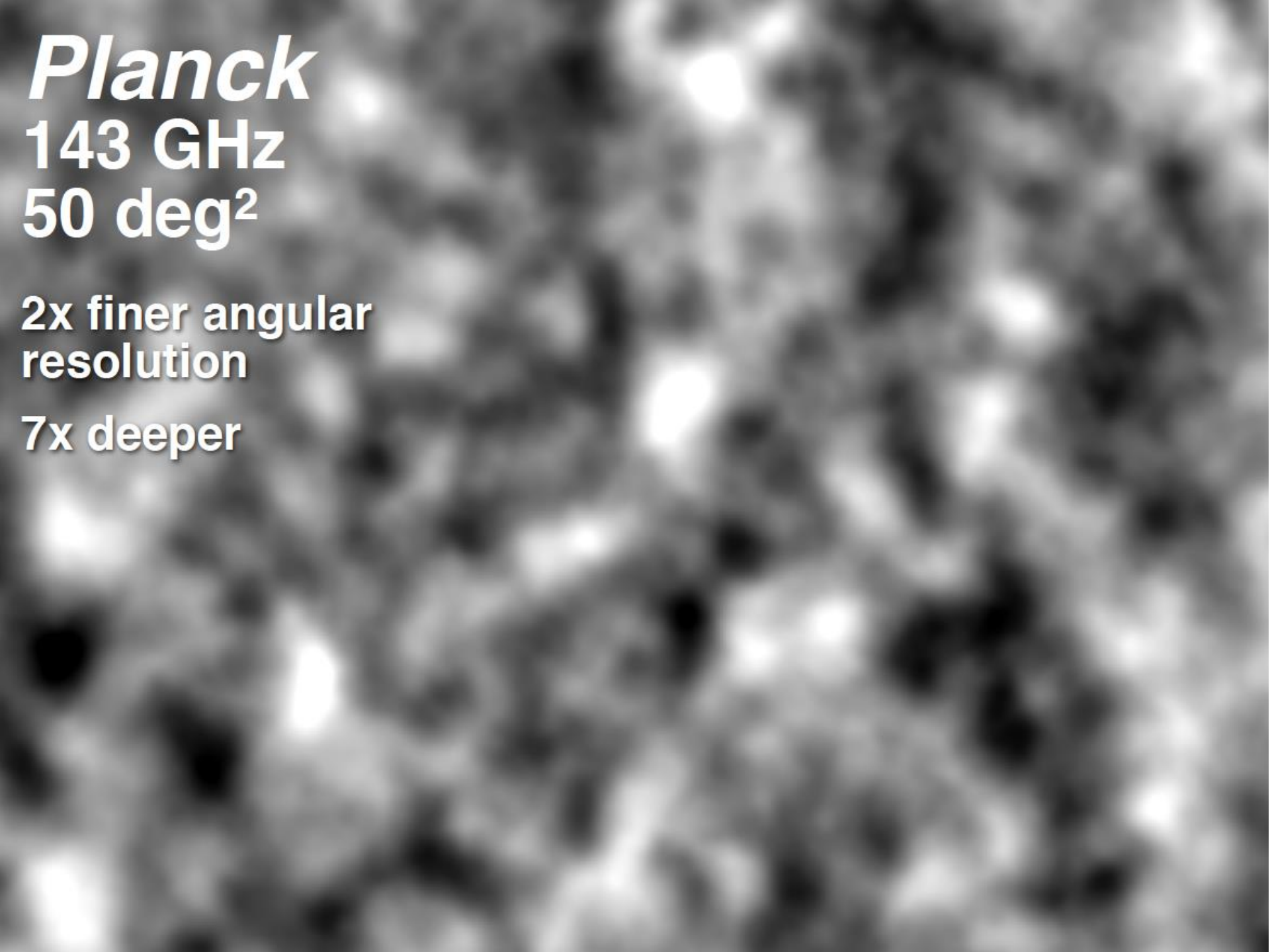
COMA CLUSTER TEMPERATURE MAP (XMM-Newton)

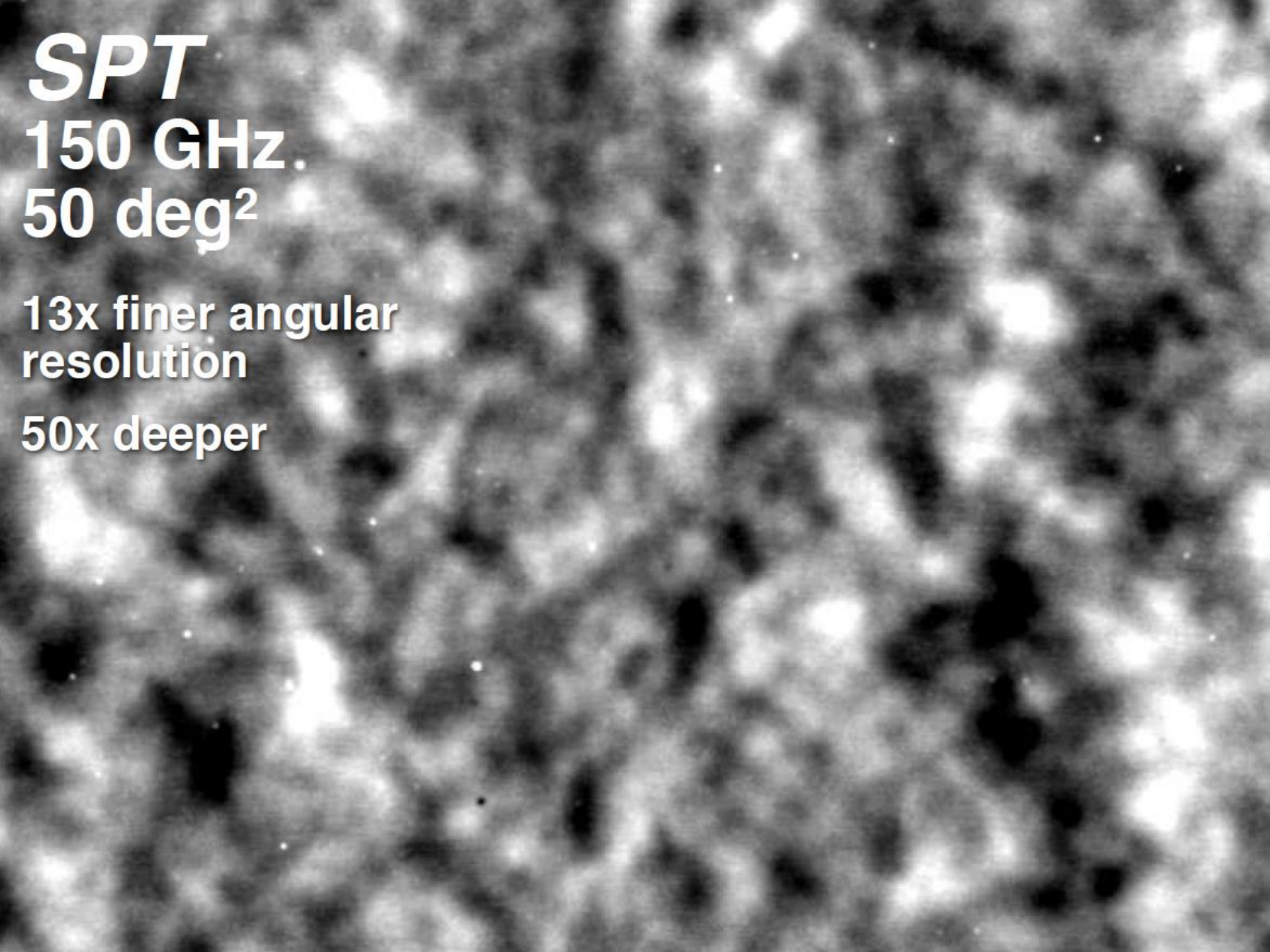
(Briel et al. 2001, image by Churazov)

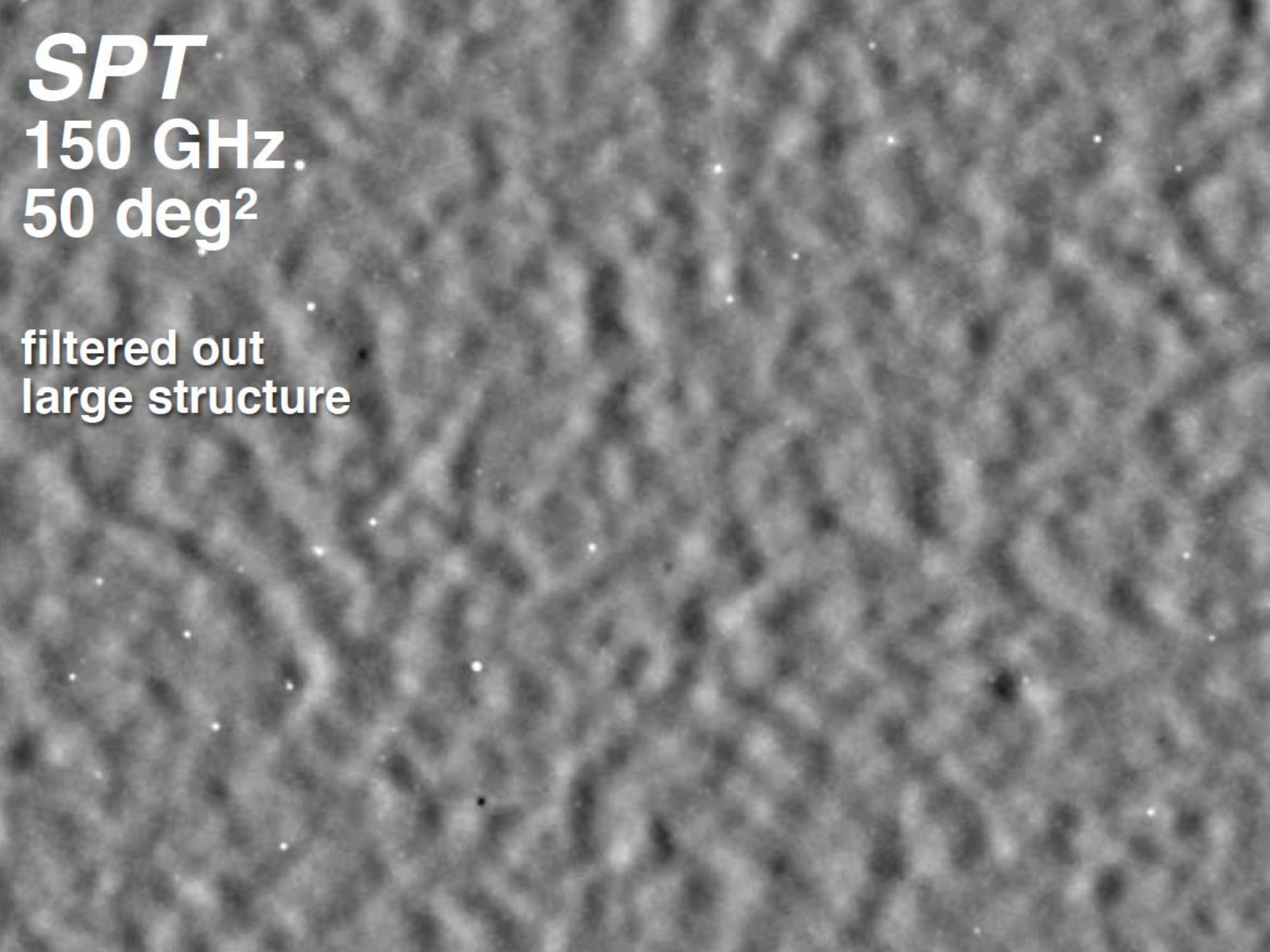
Dark matter mass –
up to 10^15 Msun

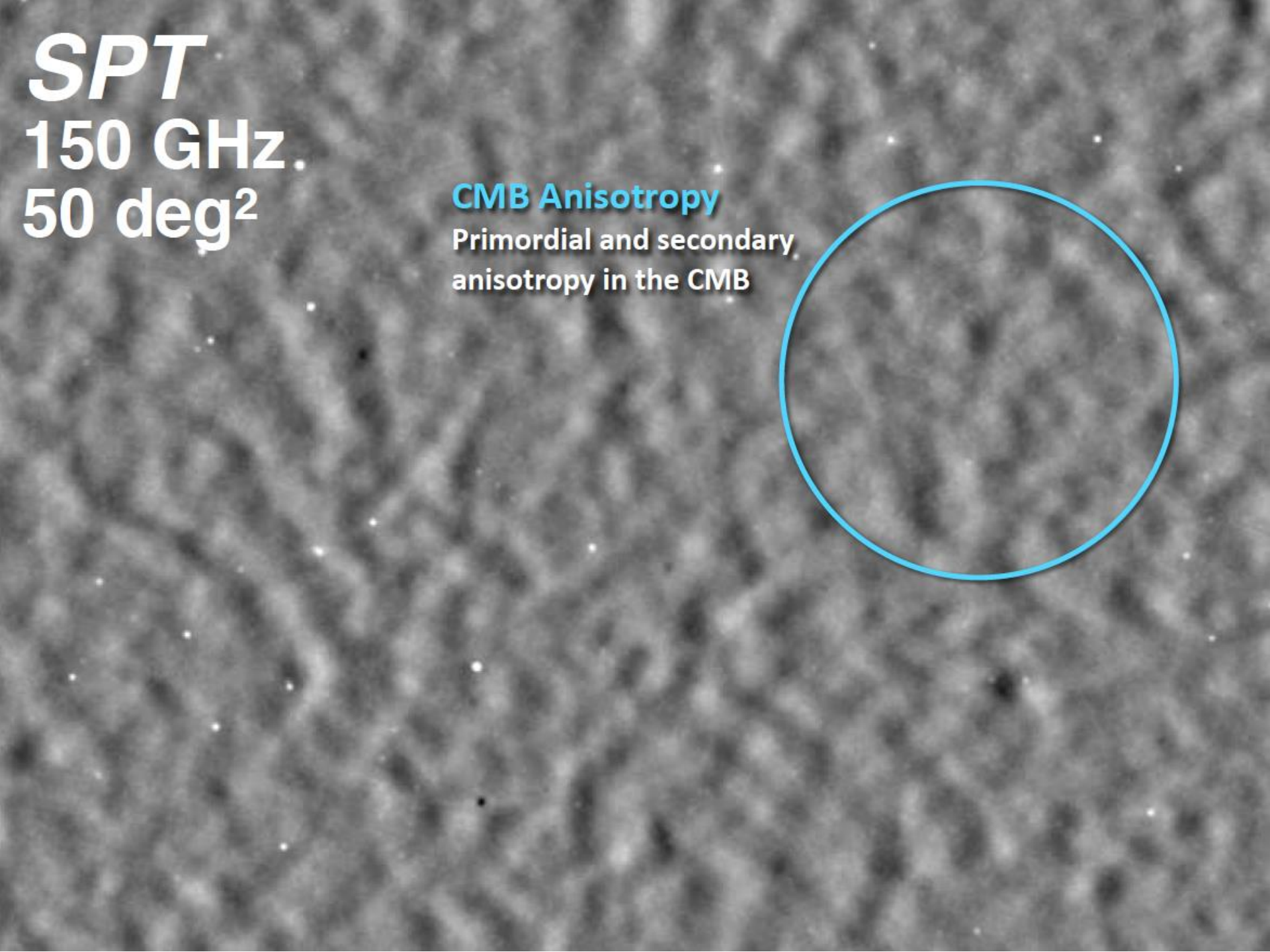
Msun = 2 10^33 g

Sound velocity of gas is close to velocities of galaxies


Planck
143 GHz
50 deg^2
2x finer angular resolution
7x deeper


SPT
150 GHz
50 deg²
13x finer angular resolution
50x deeper

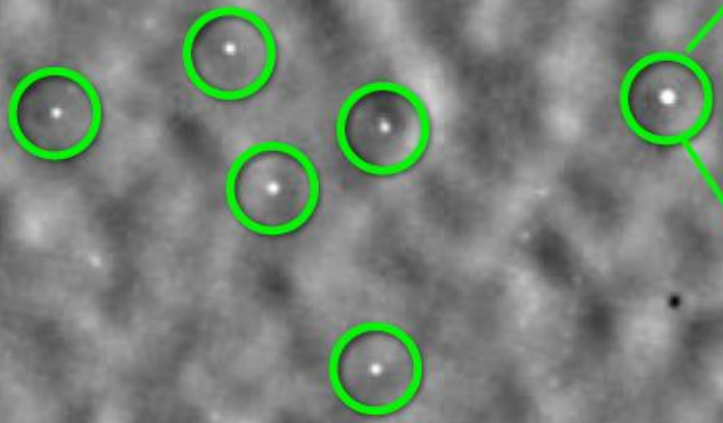

SPT
150 GHz
50 deg²
filtered out
large structure

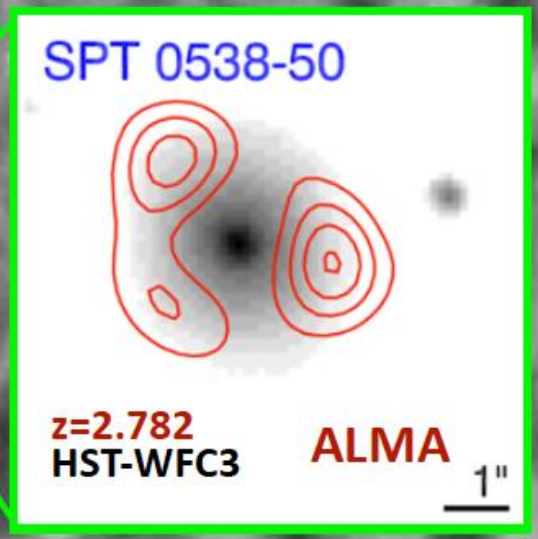

SPT
150 GHz
50 deg²
CMB Anisotropy
Primordial and secondary
anisotropy in the CMB

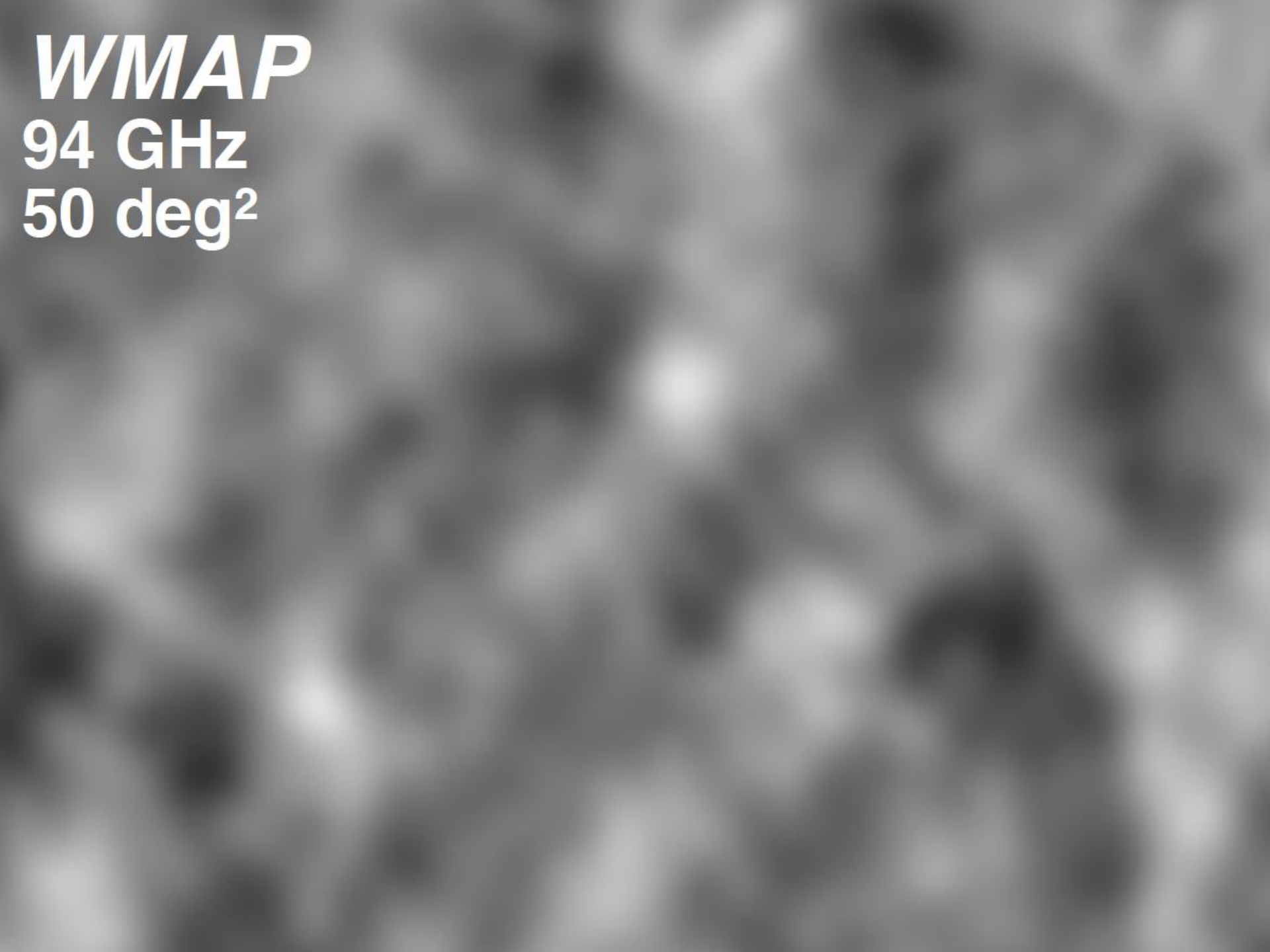
SPT
150 GHz
50 deg^2

Point Sources

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



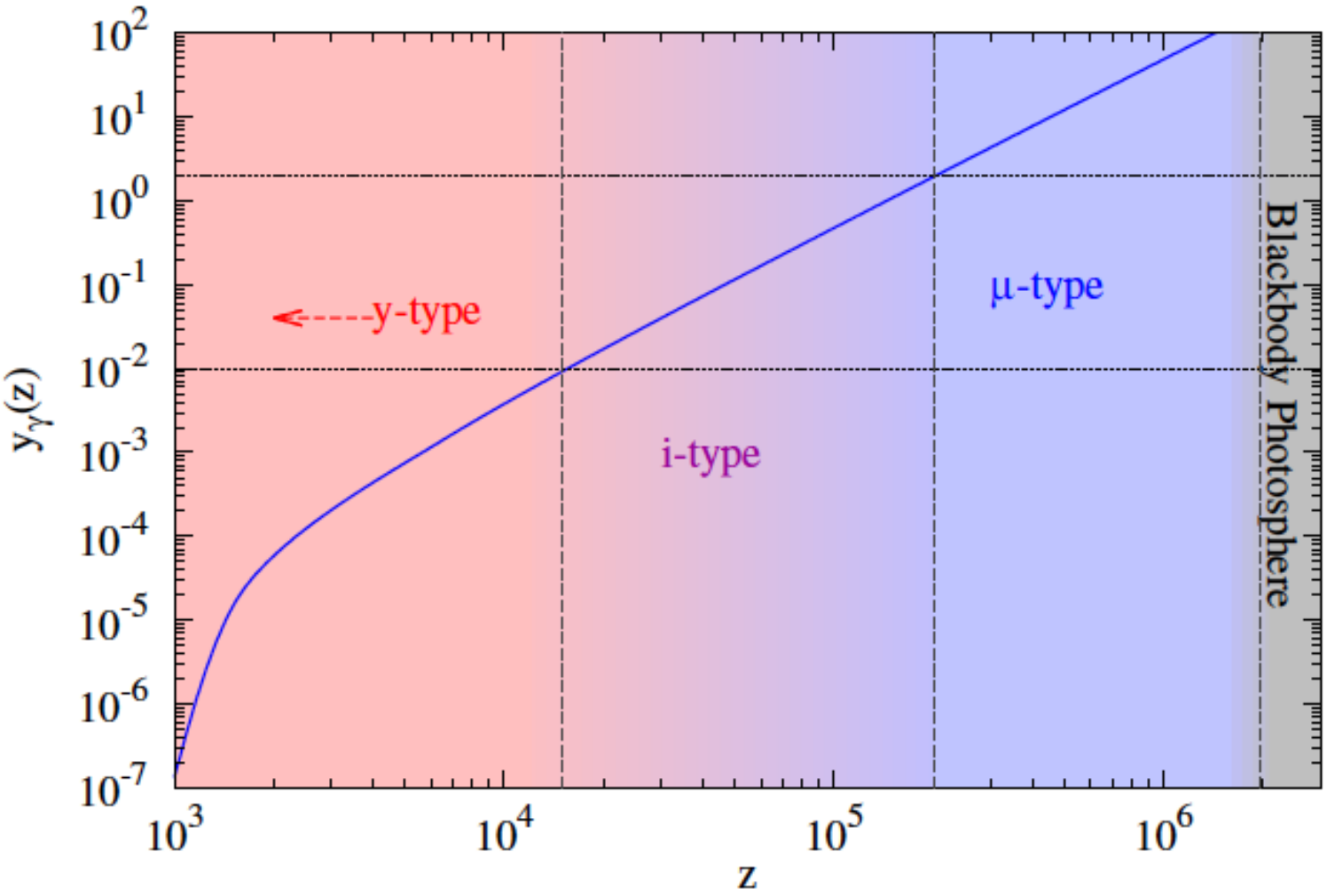



WMAP
94 GHz
50 deg²

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

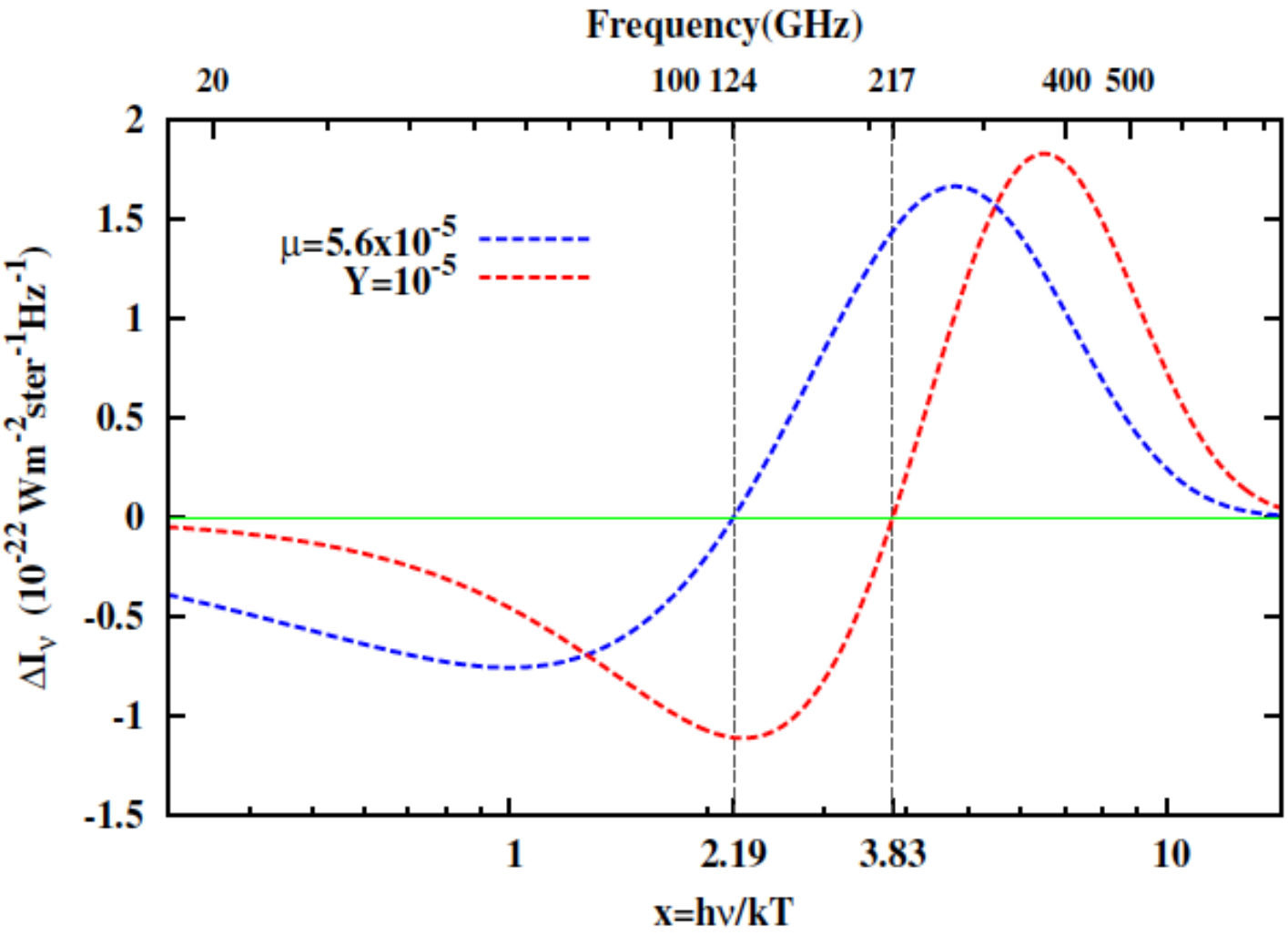
T_e and T_γ converge to common value

The photon spectrum relaxes to equilibrium Bose-Einstein distribution

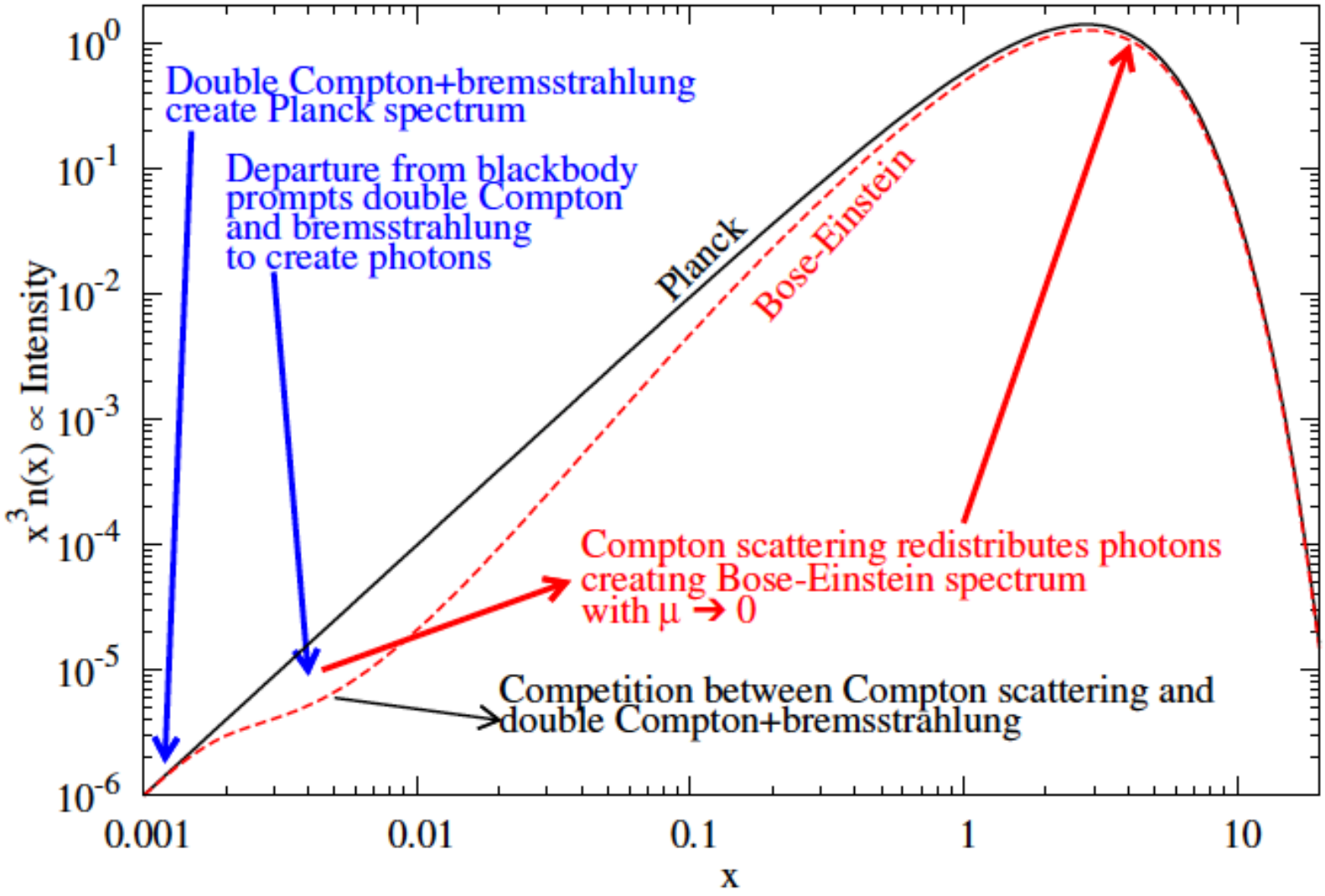


μ-distortion: Bose-Einstein spectrum, $y_\gamma \gg 1$

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



Creation of CMB Planck spectrum



Analitical solution(Sunyaev, Zeldovich, 1970

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

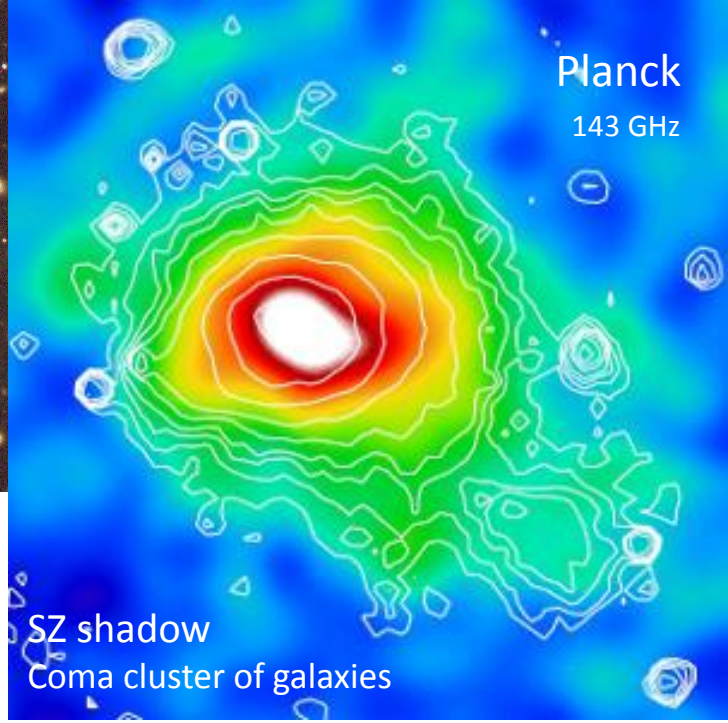
Where a and k are scattering (Comptonisation) and real absorption coefficients correspondently

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

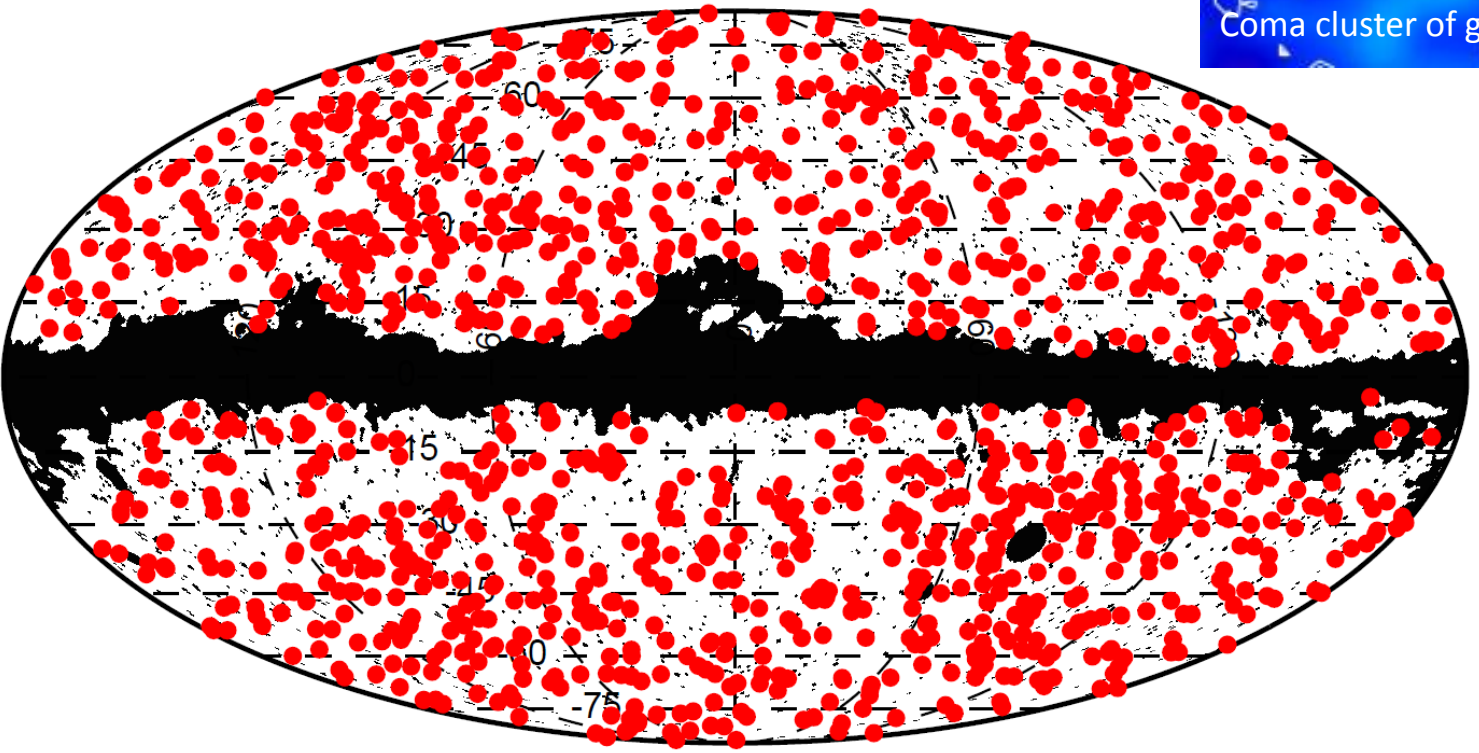
$$\frac{\mu^{\text{final}}}{\mu^{\text{initial}}} \approx e^{-(z_i/z_{dc})^{5/2}}$$

Danese, de Zotti, 1984

Coma, optical image
central part



~ 900 clusters confirmed by X-Ray
or optical observations

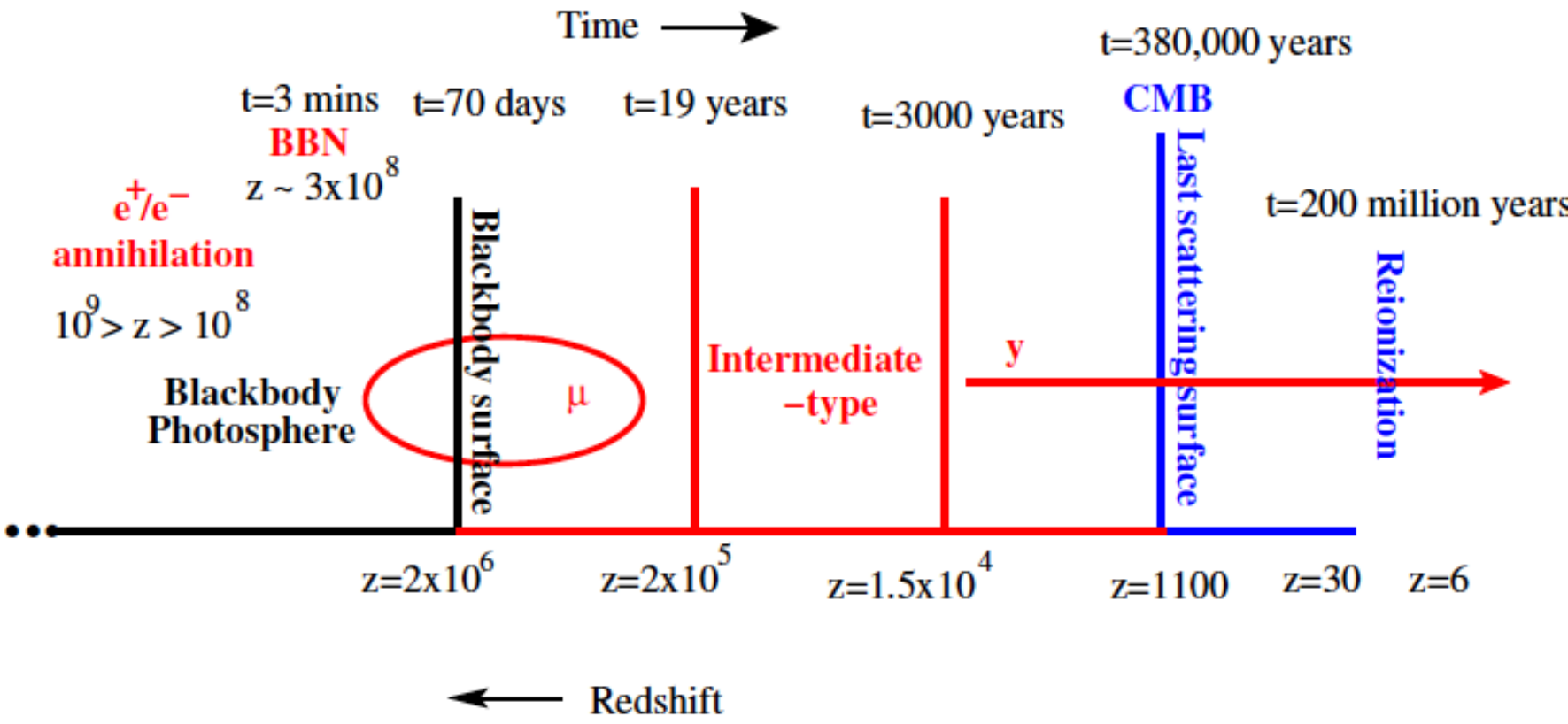


$$n_{SZ} = y \; T^4 \frac{\partial}{\partial T} \frac{1}{T^2} \frac{\partial n_{\mathrm{Pl}}}{\partial T}$$

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

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

μ-type distortions

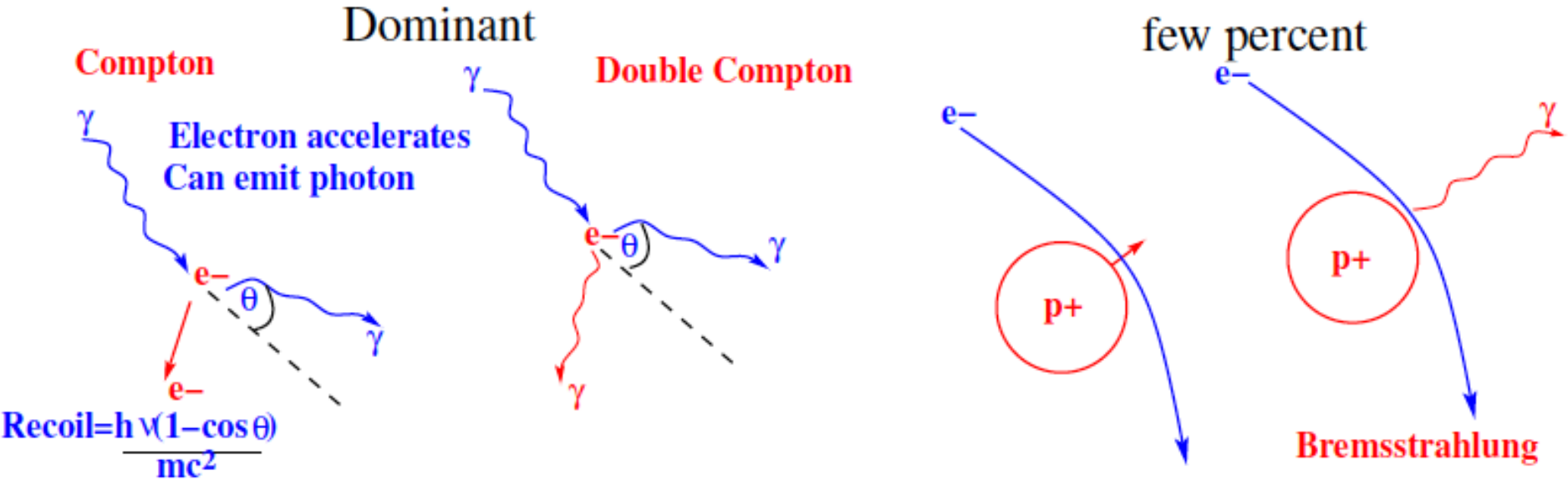


Compton + double Compton + bremsstrahlung

Analytic solution: $\mu = 1.4 \int \frac{dQ}{dz} e^{-\mathcal{J}(z)} dz$

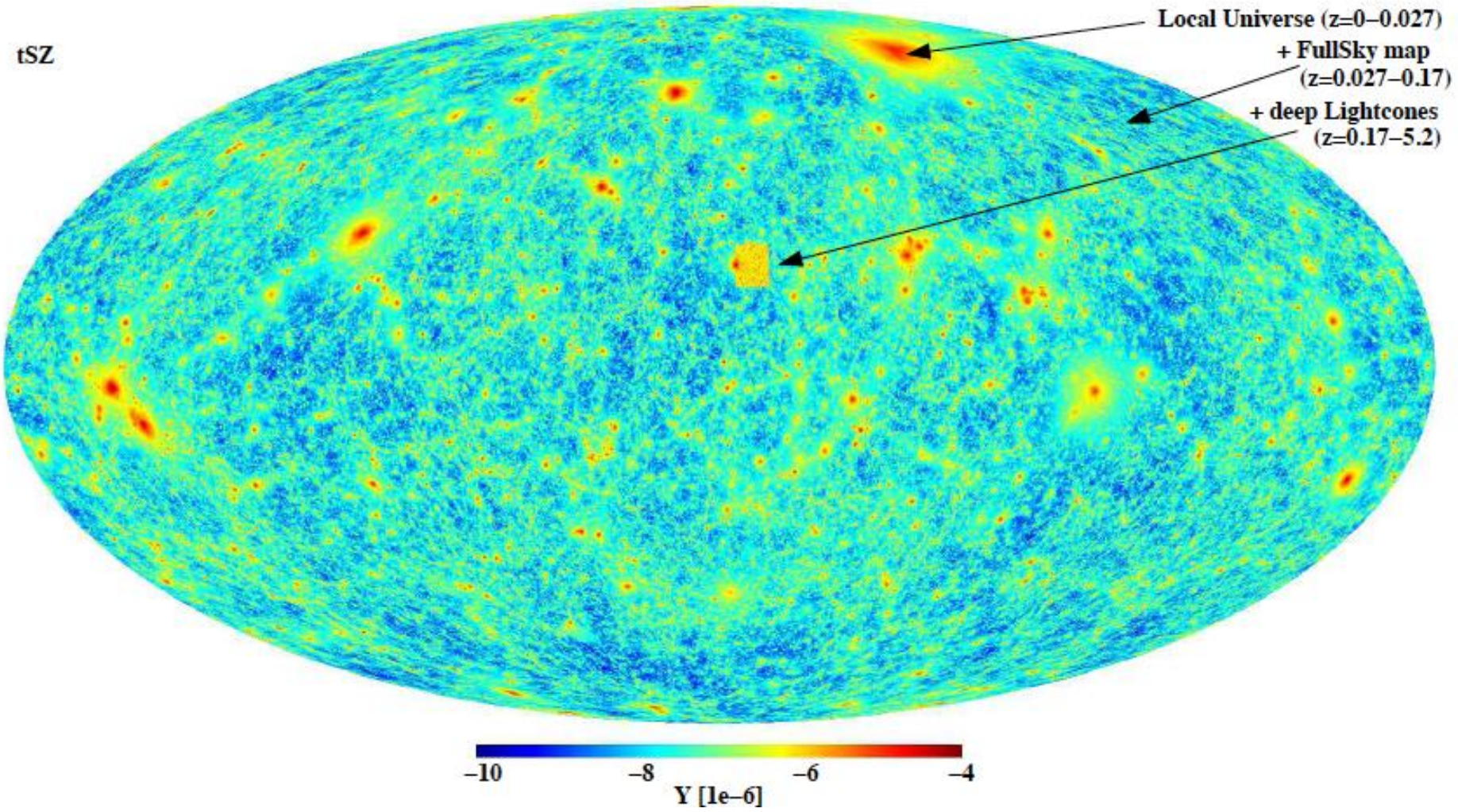
(Sunyaev and Zeldovich 1970)

Processes responsible for creation of CMB spectrum



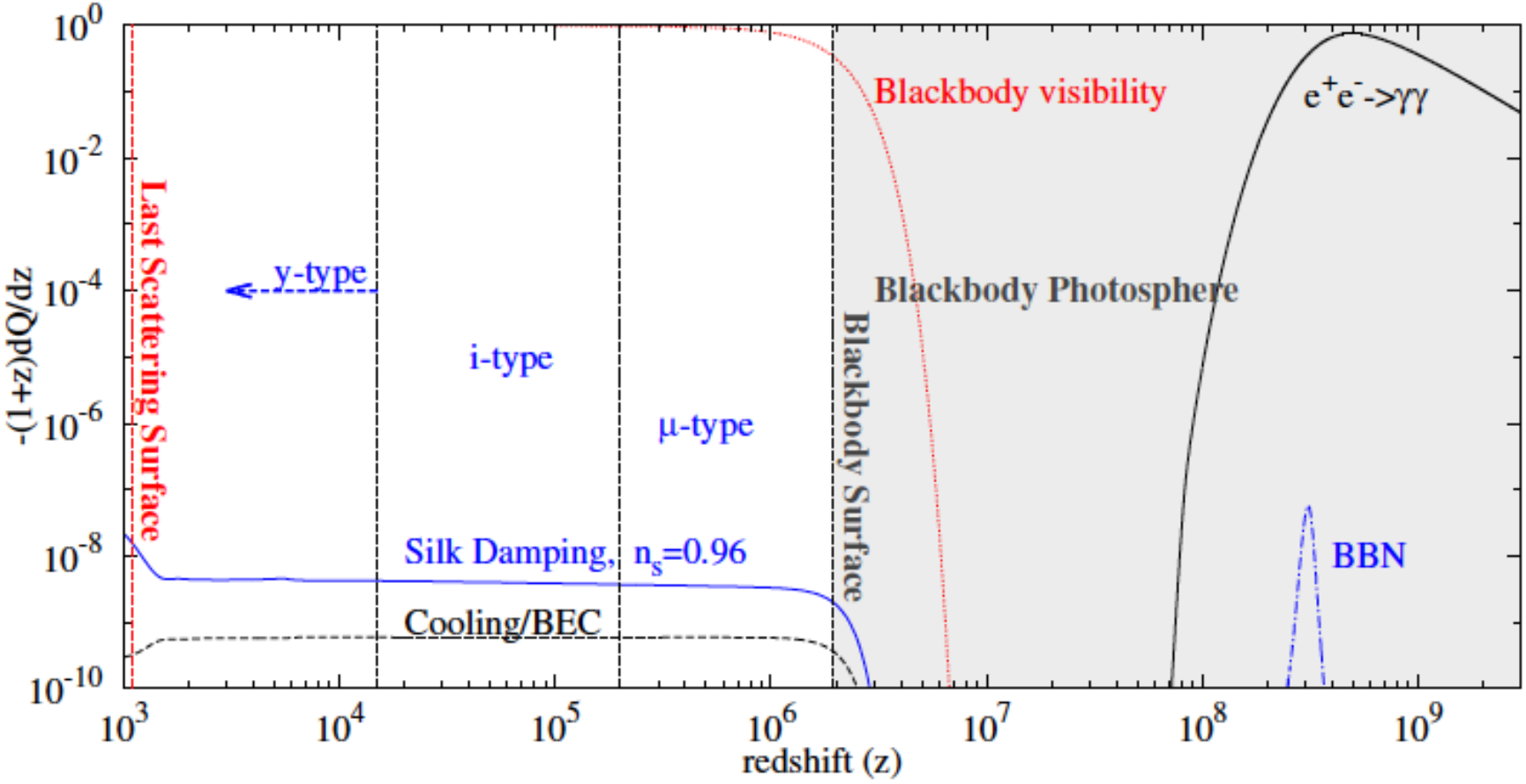
- Double Compton and bremsstrahlung create/absorb photons ($\propto 1/x^2$)
- Compton scattering distributes them over the whole spectrum

K. Dolag, E. Komatsu, R. Sunyaev



It will be great to overlap eRosita map with 100 000 clusters and groups of galaxies onto high quality y-map from the future CMB spacecraft

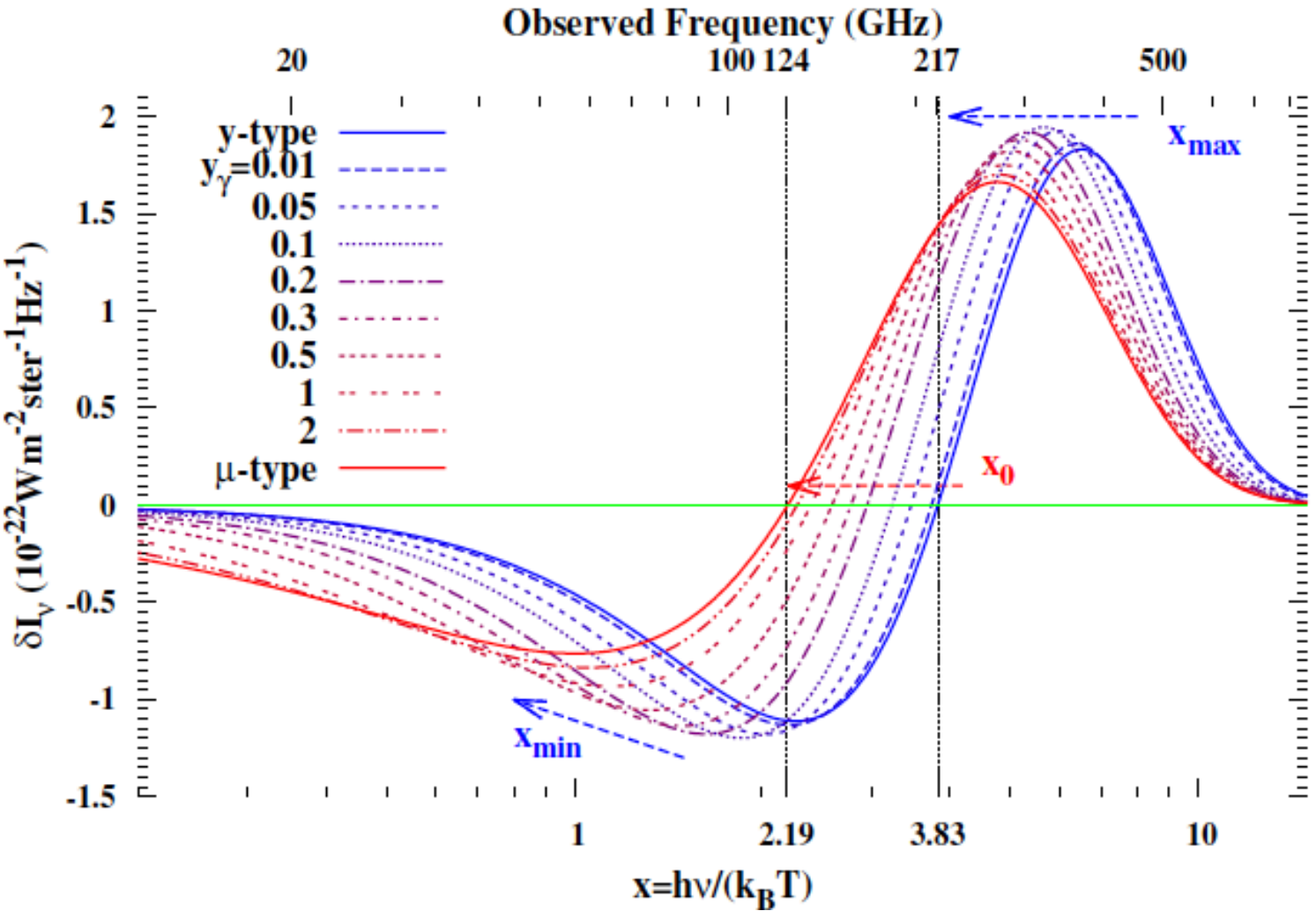
The general picture



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

Solve Kompaneets equation with initial condition of $y-$type solution.

$$\frac{\partial n}{\partial y_\gamma} = \frac{1}{x^2}\frac{\partial}{\partial x}x^4\left(n+n^2+\frac{T_e}{T}\frac{\partial n}{\partial x}\right), \quad \frac{T_e}{T} = \frac{\int (n+n^2)x^4dx}{4\int nx^3dx}$$



Bose-Einstein spectrum- Chemical potential (μ)

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

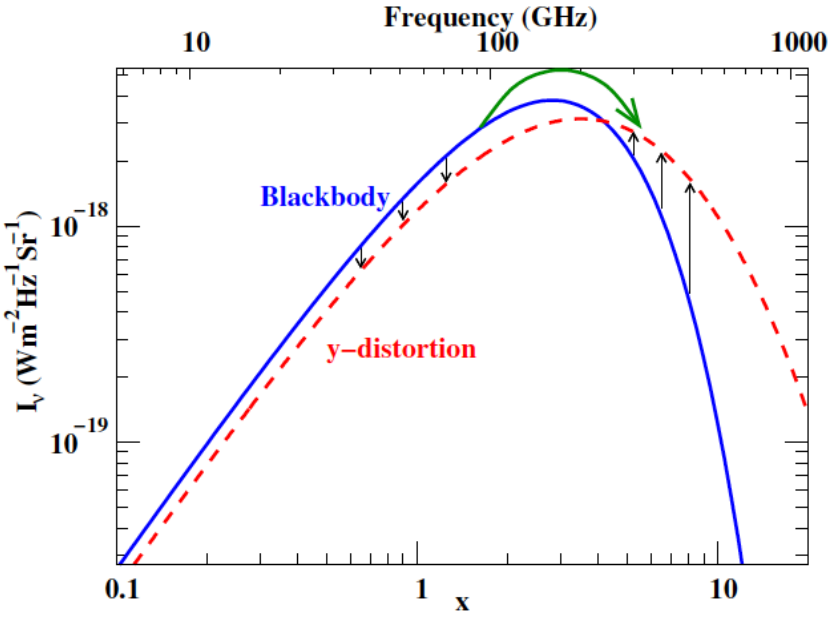
Given two constraints, energy density (E) and number density (N) of photons, T, μ uniquely determined.

Idea behind analytic solutions:

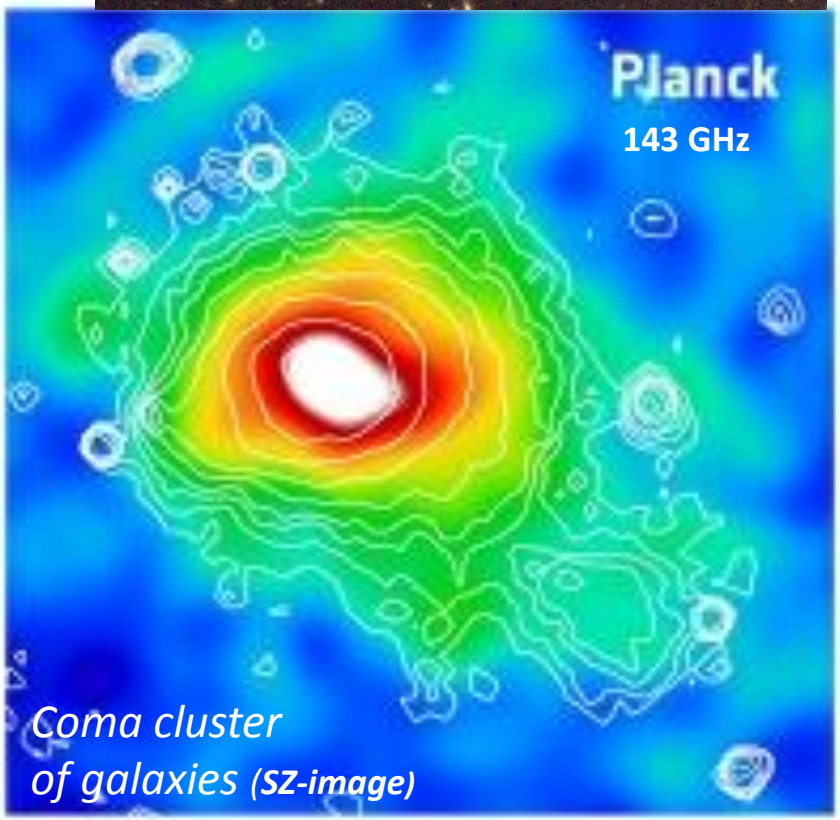
If we know rate of production of photons and energy injection rate, we can calculate the evolution/production of μ (and T)

(Zeldovich and Sunyaev 1969)

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



Coma, *optical image,* central part



Coma cluster of galaxies ***(SZ-image)***

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

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

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