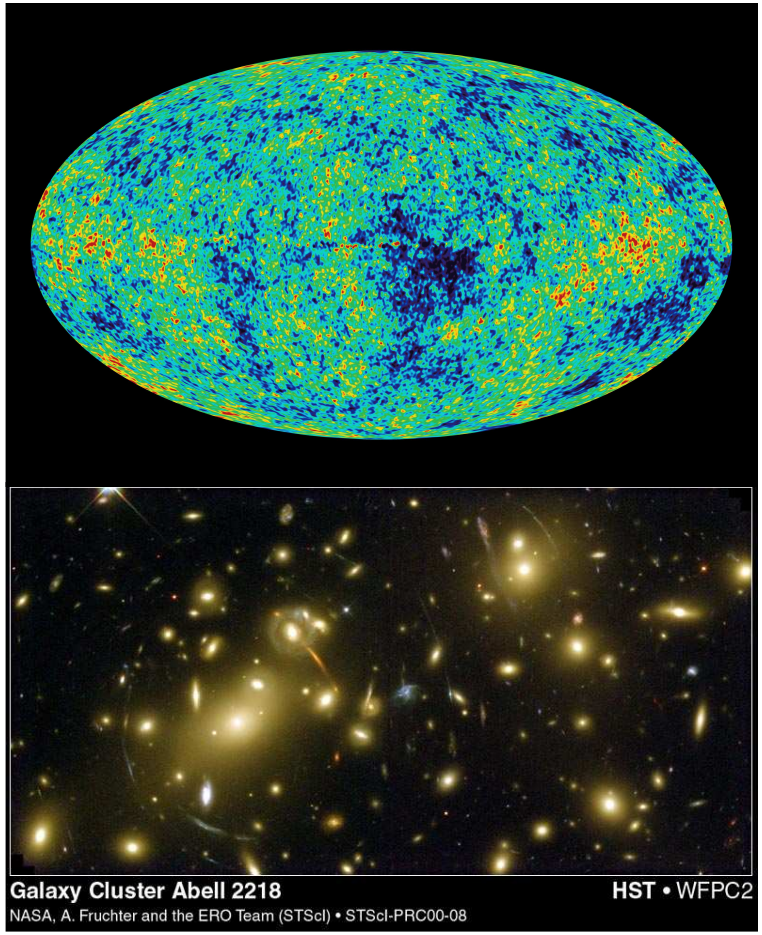
June 23, 2008

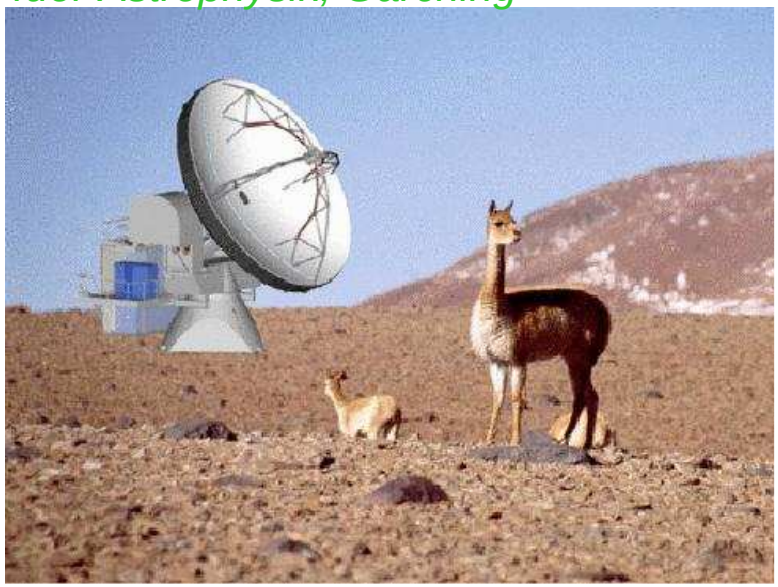
Landau100
Chernogolovka

Cosmic Microwave Background Radiation,
Clusters of Galaxies,
and
COSMOLOGY

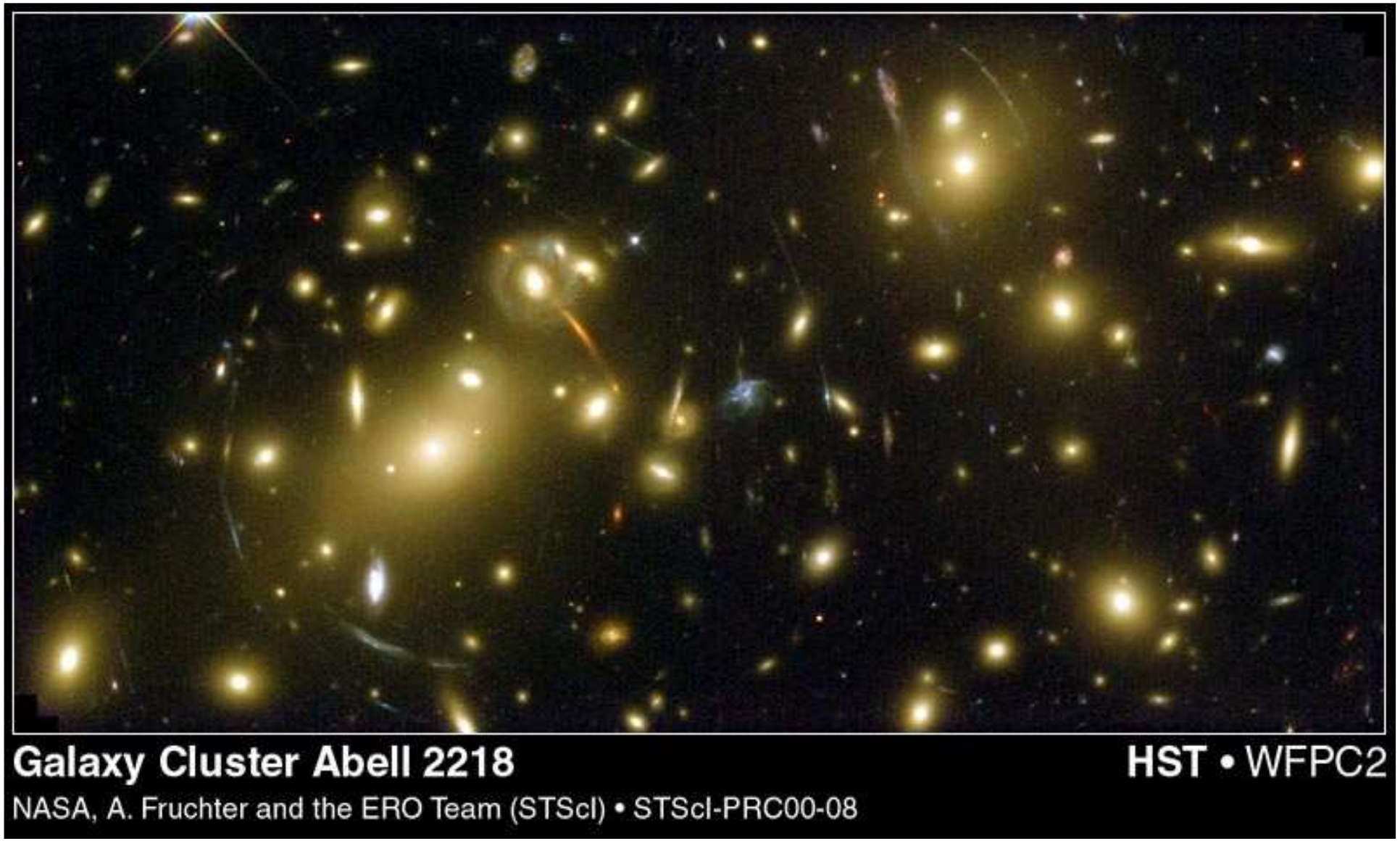


Rashid Sunyaev

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



CLUSTERS OF GALAXIES

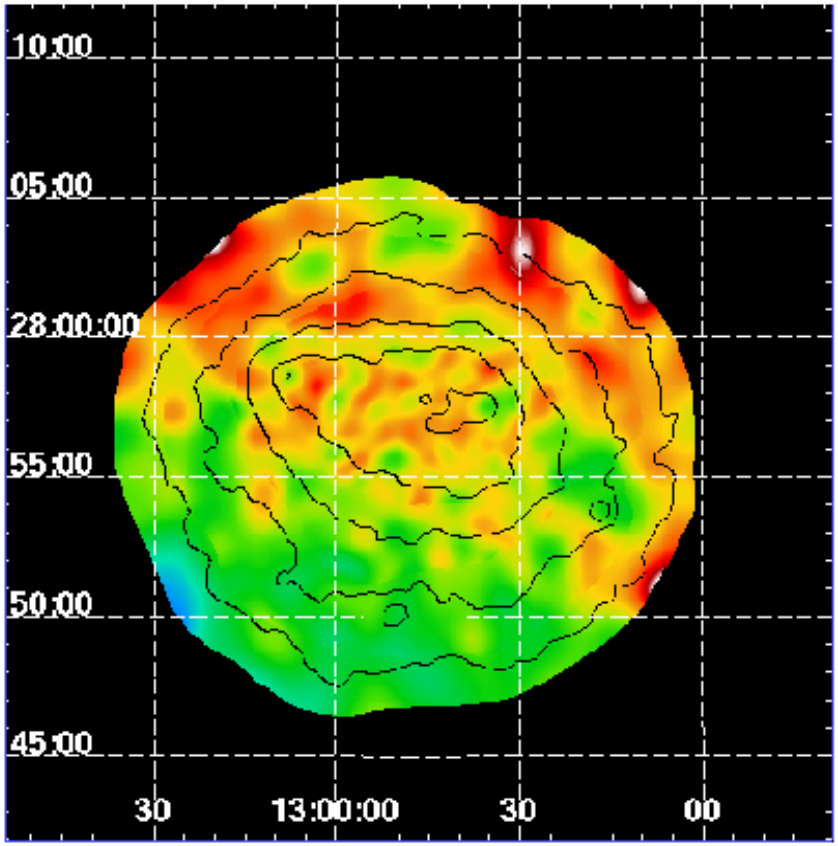


Thousands of galaxies with v ~ 1000 km/s
Hot **intergalactic gas** with Te ~ 3 – 10 KeV

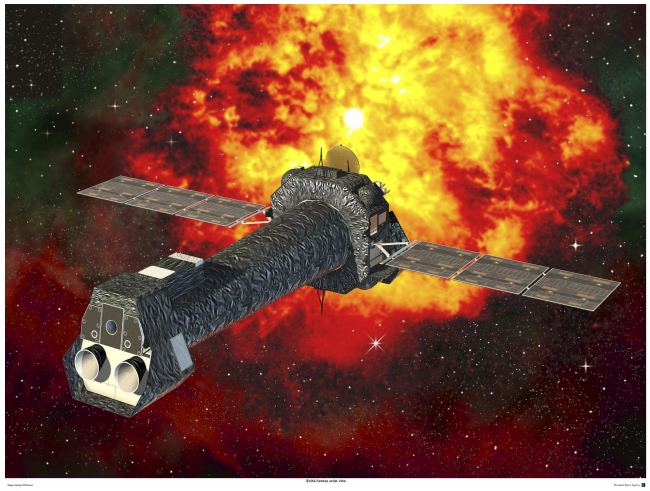
Gravitational potential defined by invisible ***dark matter***

Much *more distant* galaxies are gravitationally ***lensed*** by A 2218

X-RAY EMISSION FROM CLUSTERS OF GALAXIES



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



Electron temperature ~ 9 KeV

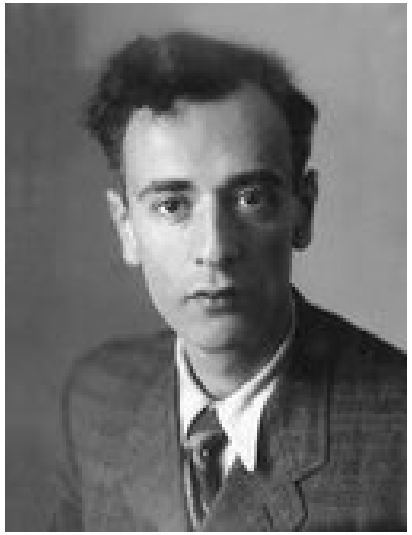
Electron density ~ 0.03 cm -3

Dark matter mass –
up to 10^15 Msun

Msun = 2 10^33 g

Sound velocity of gas is close to velocities of galaxies

Why we should loose time for clusters during Landau100 conference?



Isaak Khalatnikov. Recent book of reminescences.

↓

Lev Landau was involved into Soviet program of atomic and hydrogen bomb.

Kompaneets, 1956, JETP paper: Lev Landau, Israil Gelfand, Sergey Dyakov are mentioned. They were helping Yakov Zeldovich group to solve Kompaneets equation and to find an upper limit for the temperature of gas during explosion.

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

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****.*

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

Kompaneets equation was published in 1956 because it occured ***useless*** for weapon research

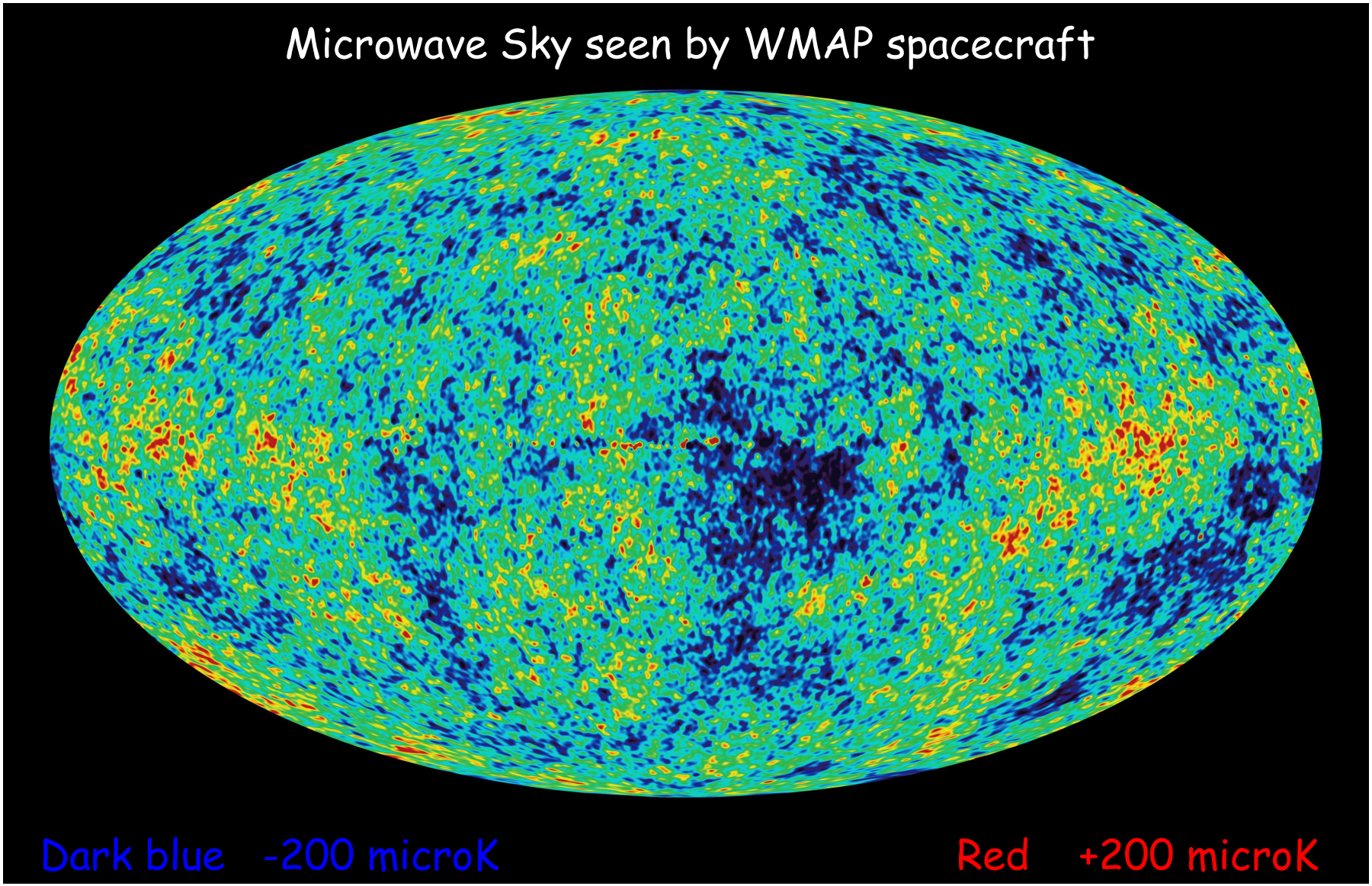
However !!! Comptonization process described by this equation defines

a) the radiation spectra of accretion disks around black holes

b) the interaction of matter and radiation in the early universe

c) the diminution of Cosmic Microwave Background Radiation brightness toward **clusters of galaxies with hot gas**

Great applications in modern cosmology and high energy astrophysics !!!



CMB (Cosmic Microwave Background) - practically isotropic and has a black spectrum Tiny !!! primordial angular fluctuations are of interest

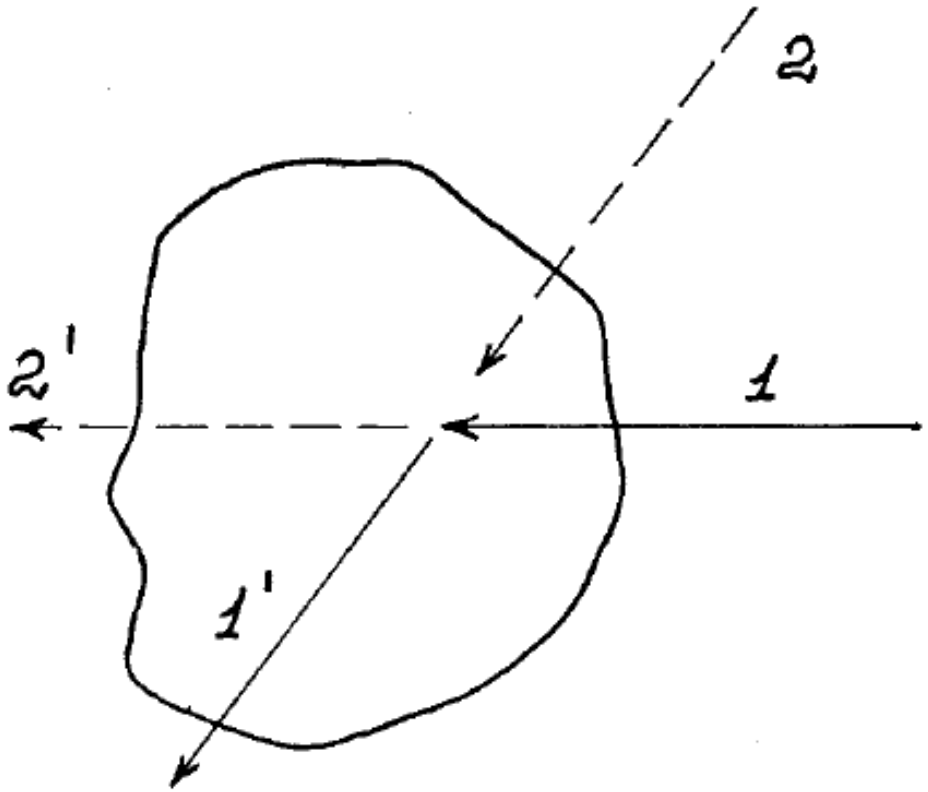
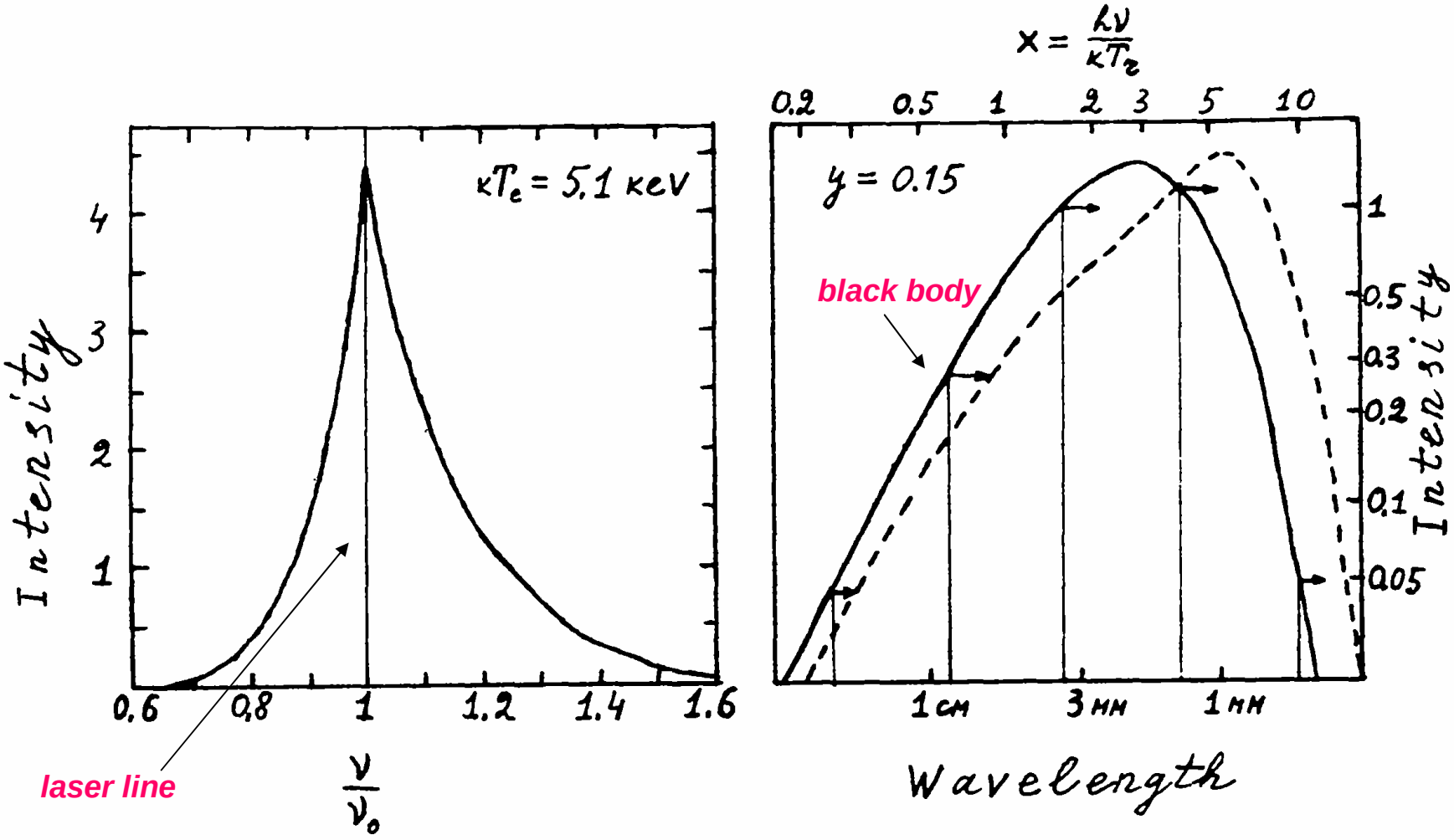


FIG. 2. The scattering of isotropic radiation field by the cloud of electrons.

Cloud is invisible

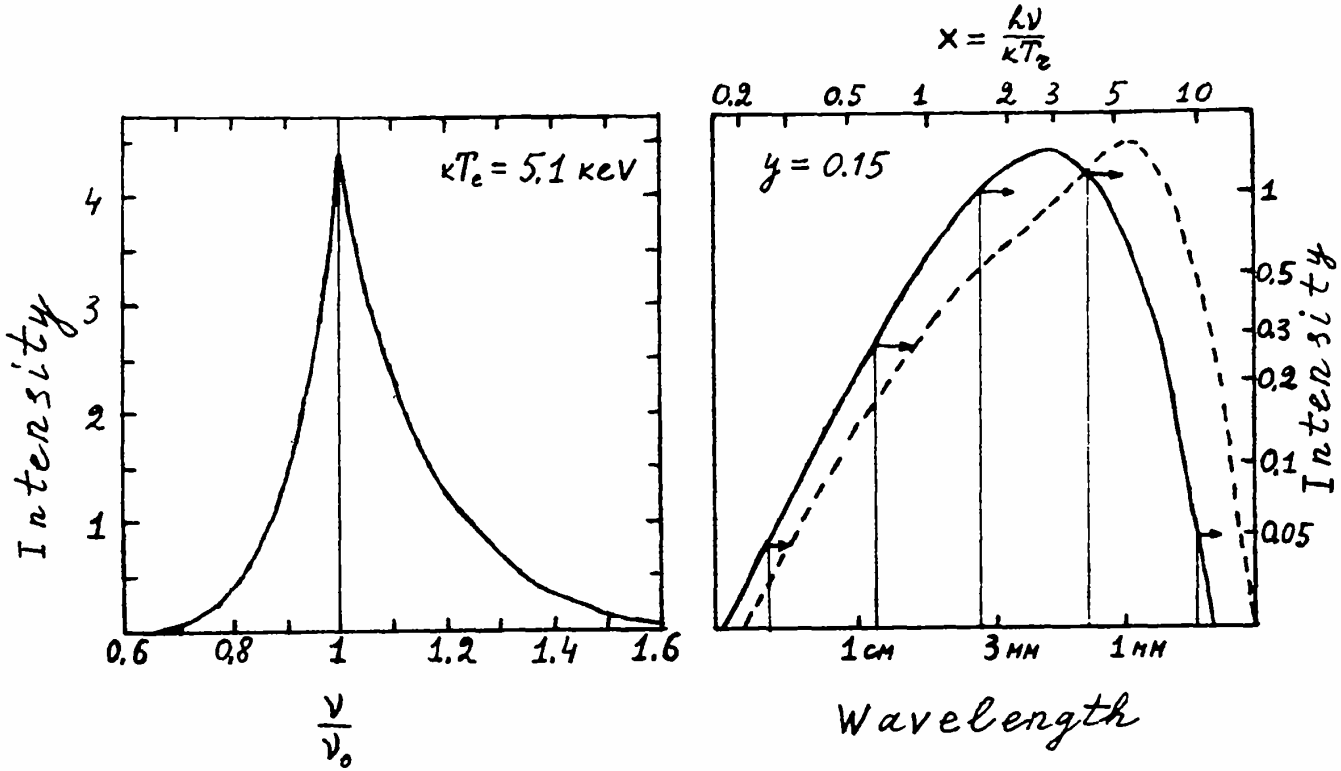
SCATTERING OF RADIATION BY HOT MAXWELLIAN ELECTRONS

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

Initial photons have low frequency, electrons are very hot,
only Doppler effect is of importance

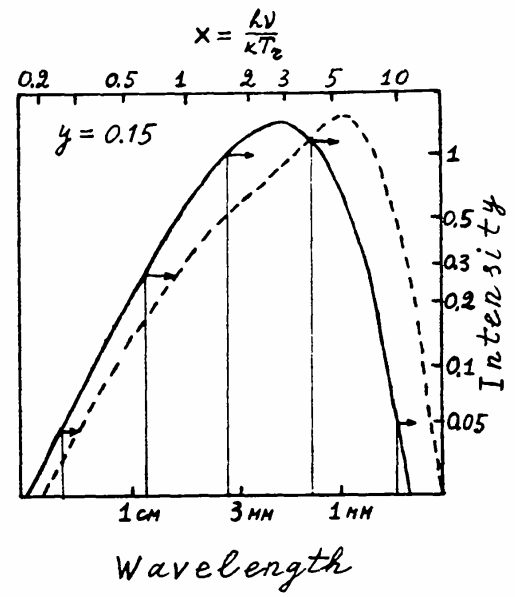


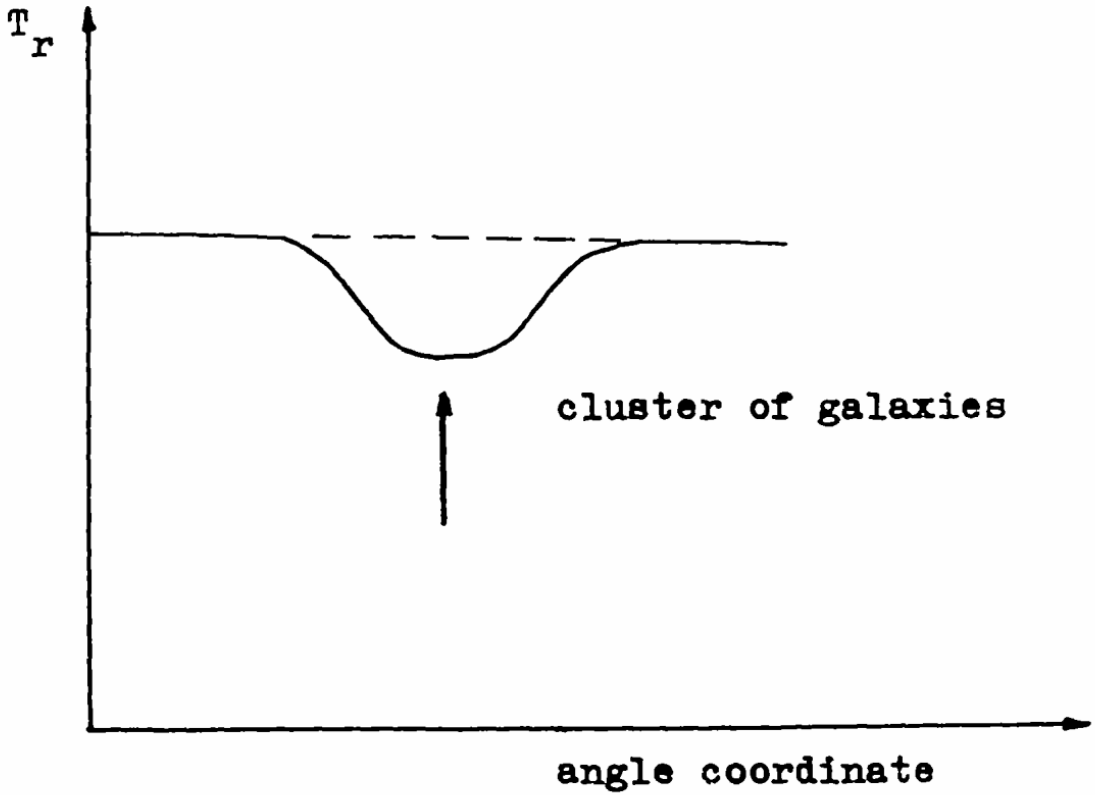
high frequency wing of the line after scattering is stronger than the low frequency one !
Cusp due to scatterings to small angles !
This is the kernel of Integral kinetic equation.

See exact formula in Sunyaev, 1980 and in Sunyaev, Zeldovich, 1980, Annual Review for Astronomy and Astrophysics, 18, 537

Every photon in the black body spectrum with Tr<<Te also moves towards higher frequencies

As a result – *intensity* ***drops*** *in the* ***Rayleigh-Jeans*** *part of the spectrum and* ***increases*** *in the* ***Wien*** *part* ***!!!***
(Sunyaev, Zeldovich, 1970, 1972)



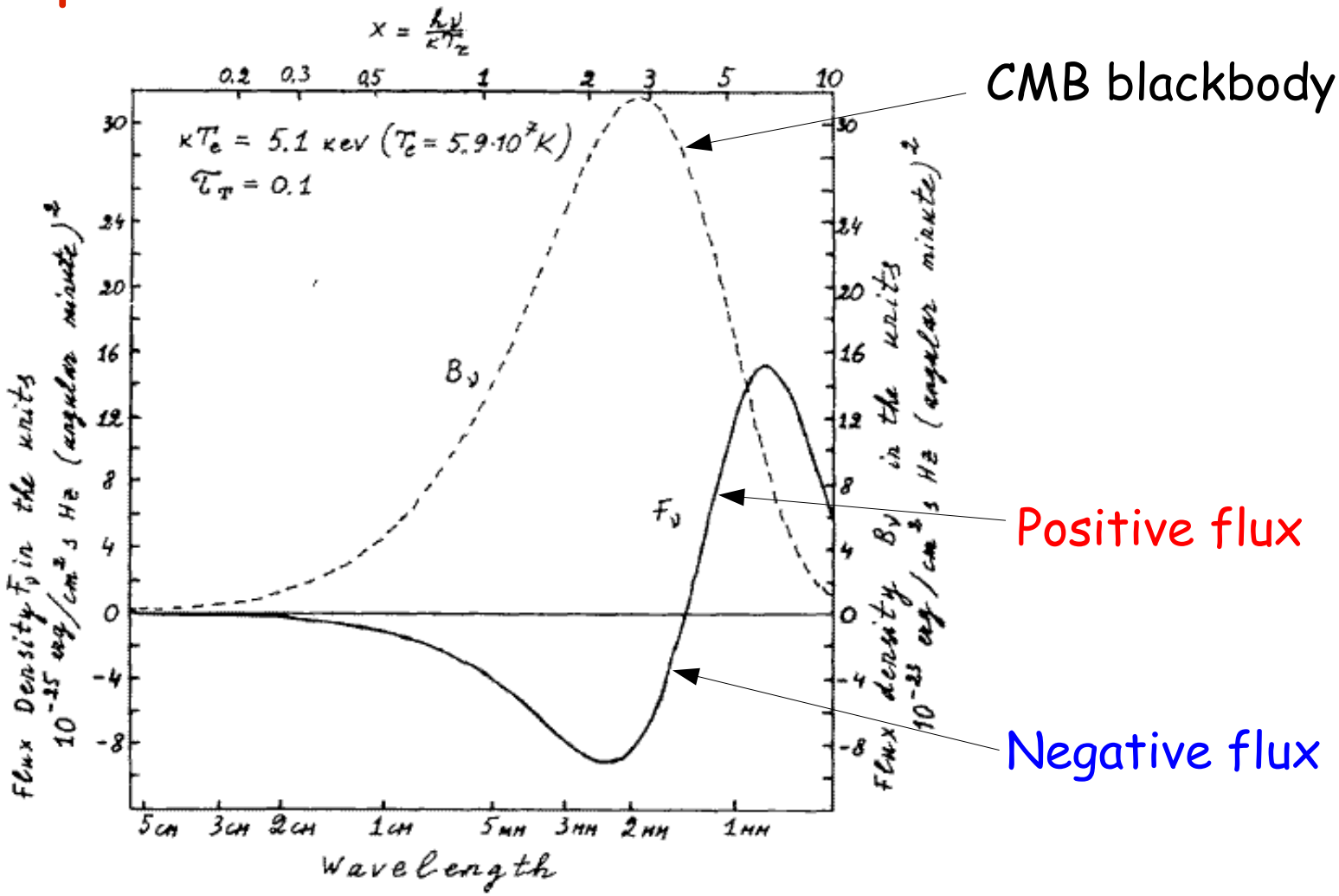


*In centimeter spectral band clusters should be observed as a **holes** in the sky average brightness defined by CMB intensity*

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

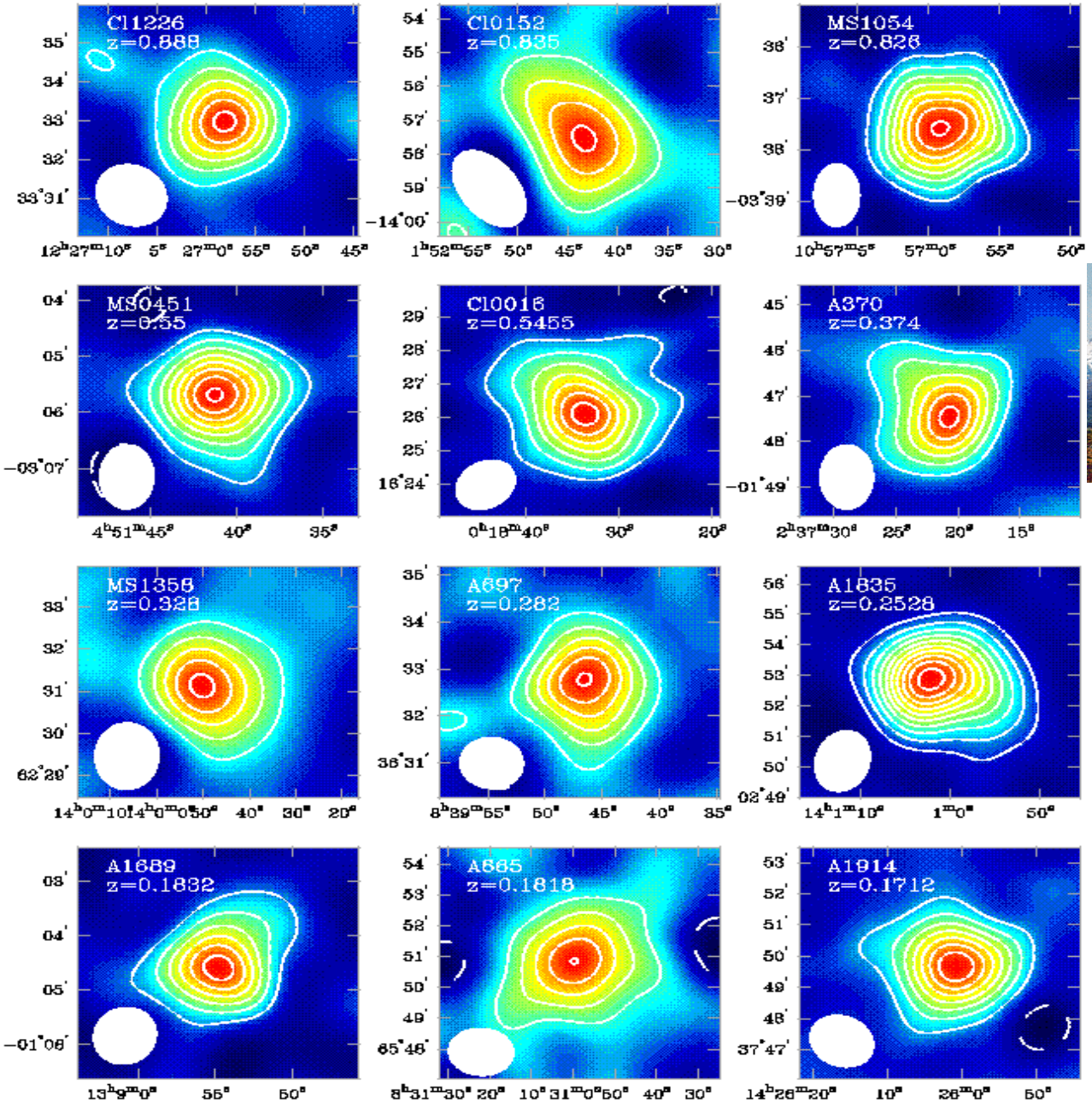
It depends only on temperature of the electrons and optical depth of the cluster

The spectrum of clusters due to thermal effect



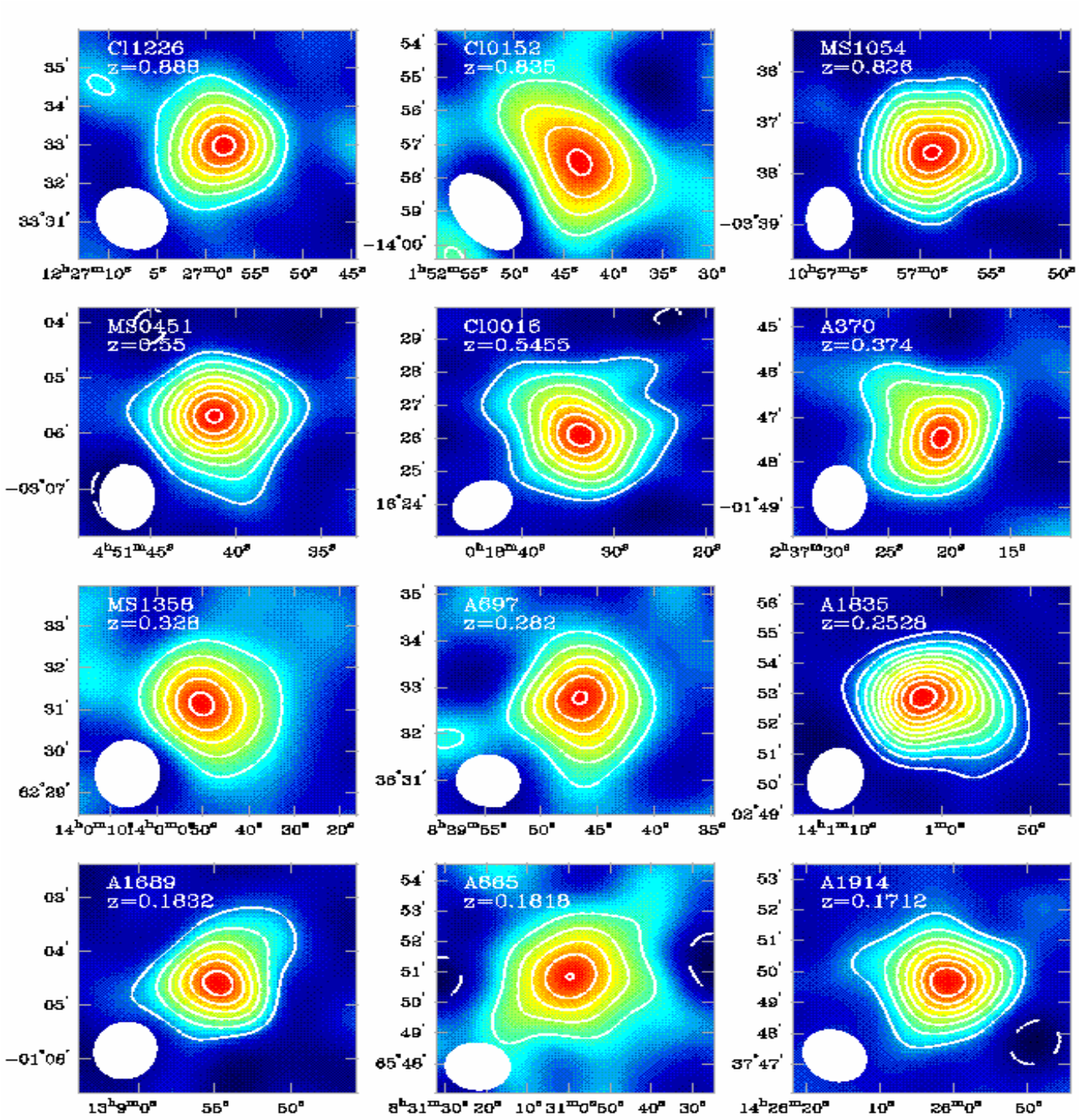
The microwave spectrum of the cluster depends only on

$x = h\nu/kT_r$ and is independent on redshift z of the cluster because both nominator and denominator of x are proportional to (1 + z)



Interferometric observations of clusters

Carlstrom et al.



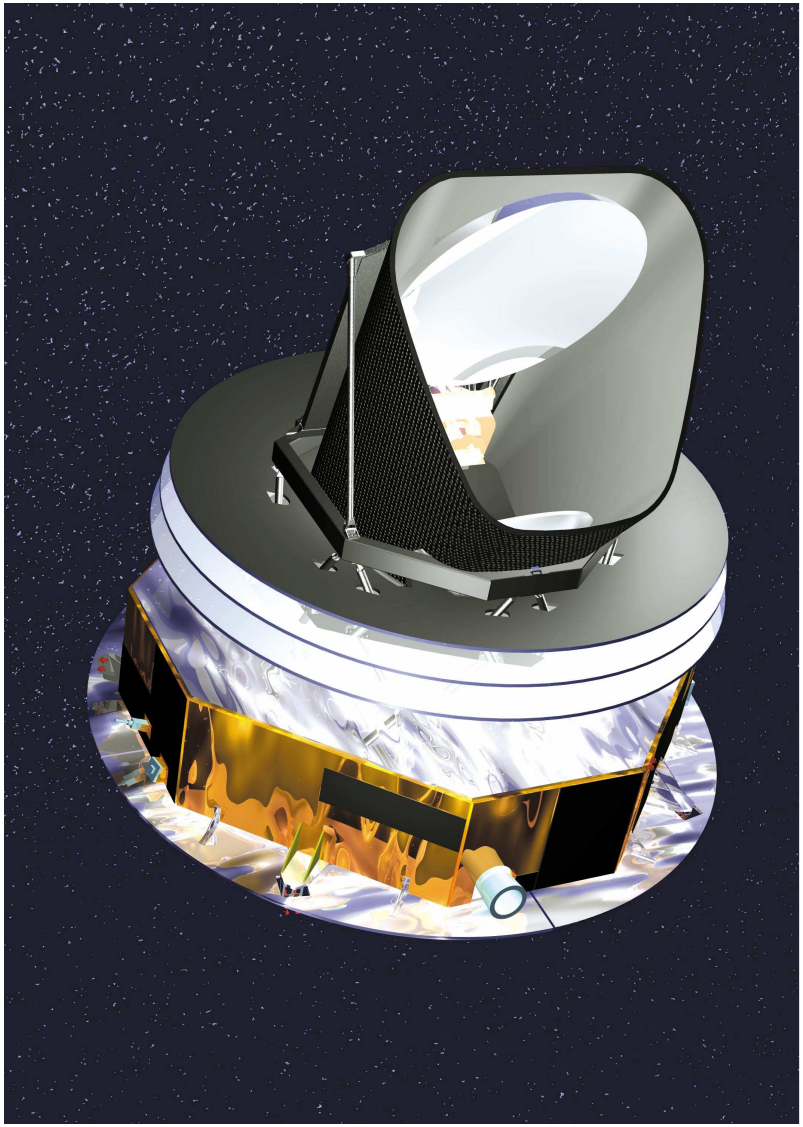
X-Ray brightness of clusters decreases with redshift as (1+z)^4

SZ-brightness does not depend on redshift !

Cluster at z = 0.888 is as bright as cluster at z=0.17

We are able to observe all existing clusters in the whole Universe

PLANCK Surveyor spacecraft

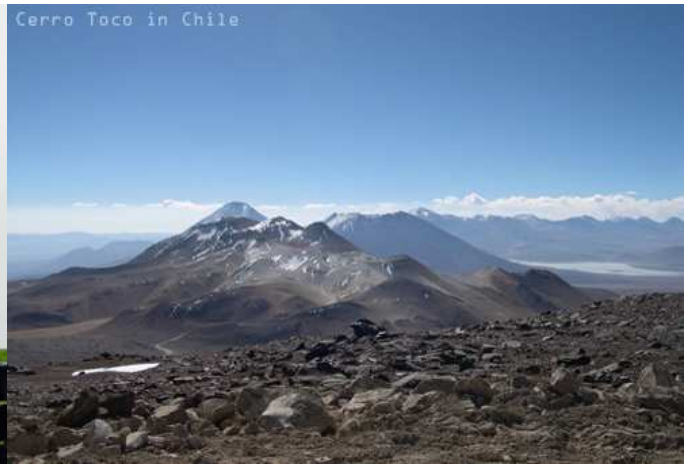


New spacesraft (PLANCK Surveyor) and
groundbased telescopes are going to observe
CMB brightness diminution
in the directions towards
rich clusters of galxies and
to look for them on the blanck sky

Main goal – to check what was
the growth rate of clusters of galaxies
(how their density was increasing with time)
and the search for barionic oscillations
in their spatial distribution

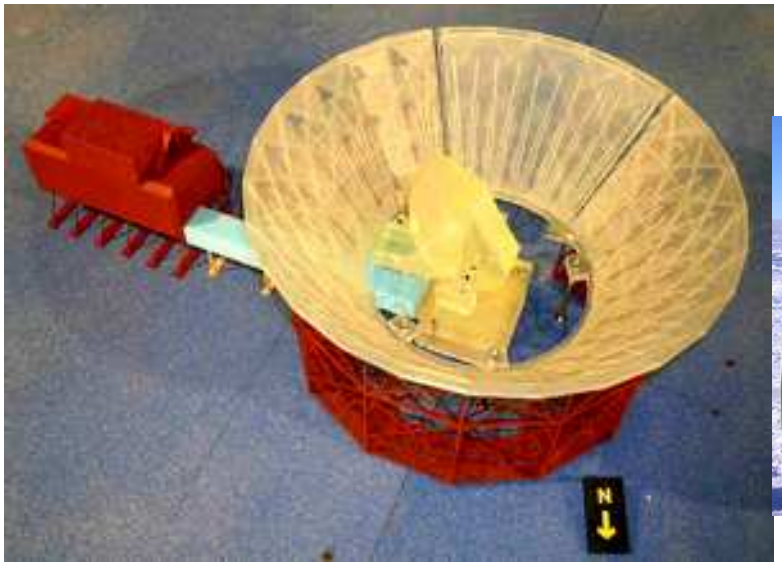
These experiments should open
new way to estimate
key cosmological parameters
including the equation of state
of the **dark energy**

up to 10 thousand clusters of galaxies on the whole sky



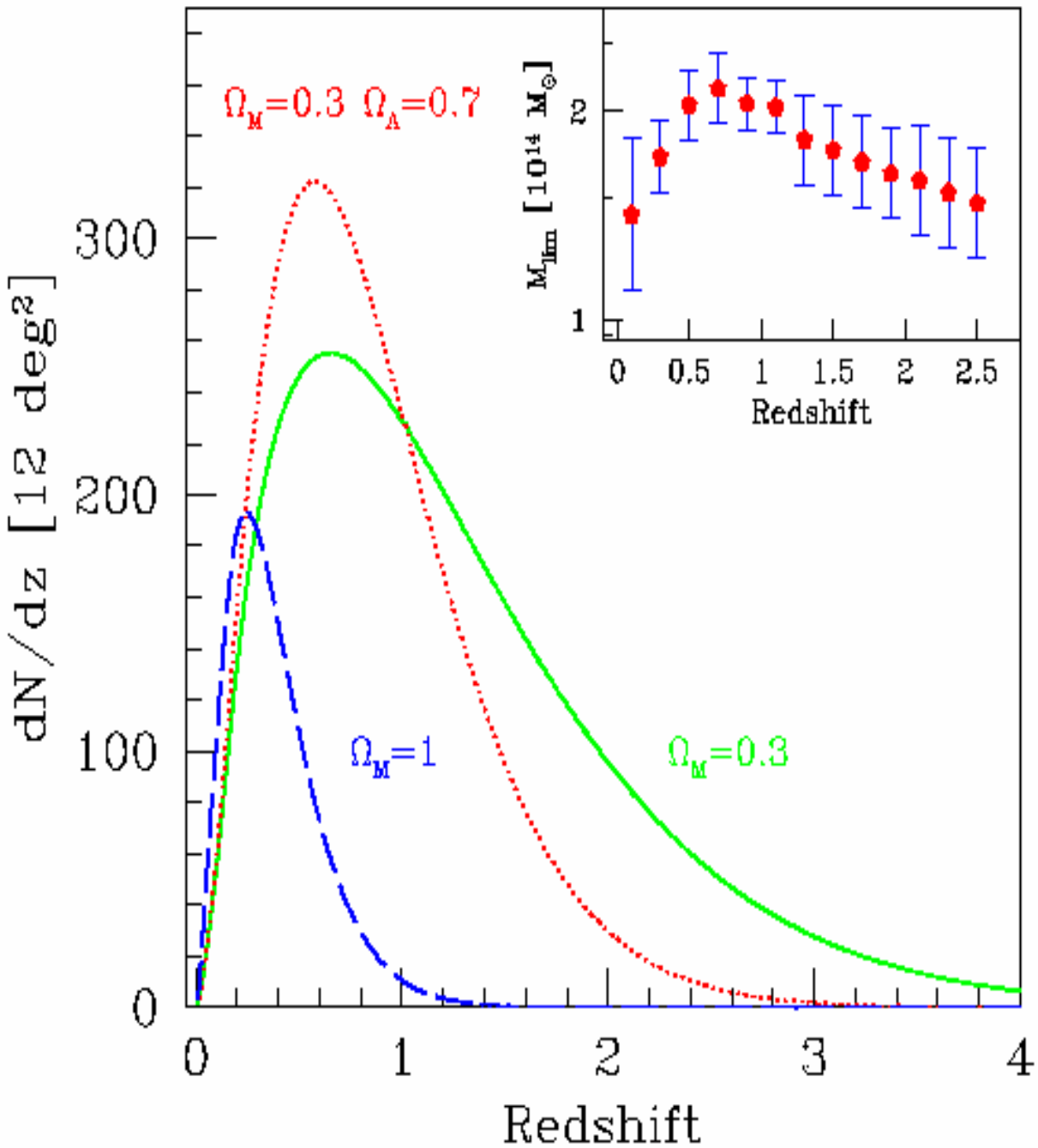
Atacama Cosmology Telescope,
5200 m height, 3024 bolometers,

AMI, Cambridge



Site of South Pole Telescope
Now 10m telescope is staying there
2800 m altitutde
980 bolometers

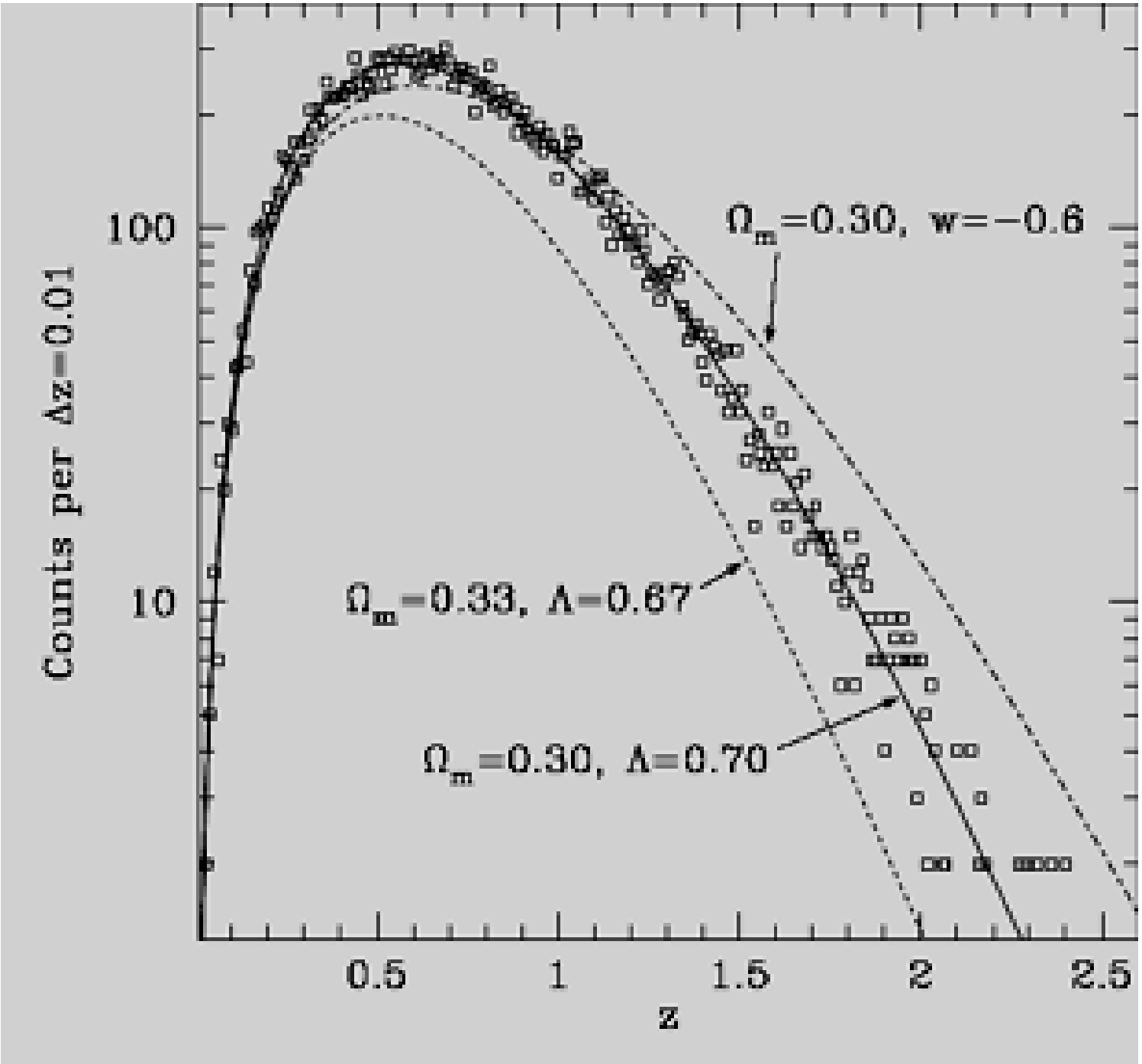
SZ Array, California



Deep counts of galaxy clusters using thermal SZ-effect

Additional way to get information about dark matter, dark energy and other parameters of the Universe

Hundred fifty thousand clusters on the whole sky



Predicted **source counts** of clusters ***as function of z*** for **South Pole Telescope** (Mohr et al) will demonstrate ***growth curve of clusters***

New way to investigate properties of ***dark energy*** including its ***equation of state***

CMB is isotropic only in one reference frame

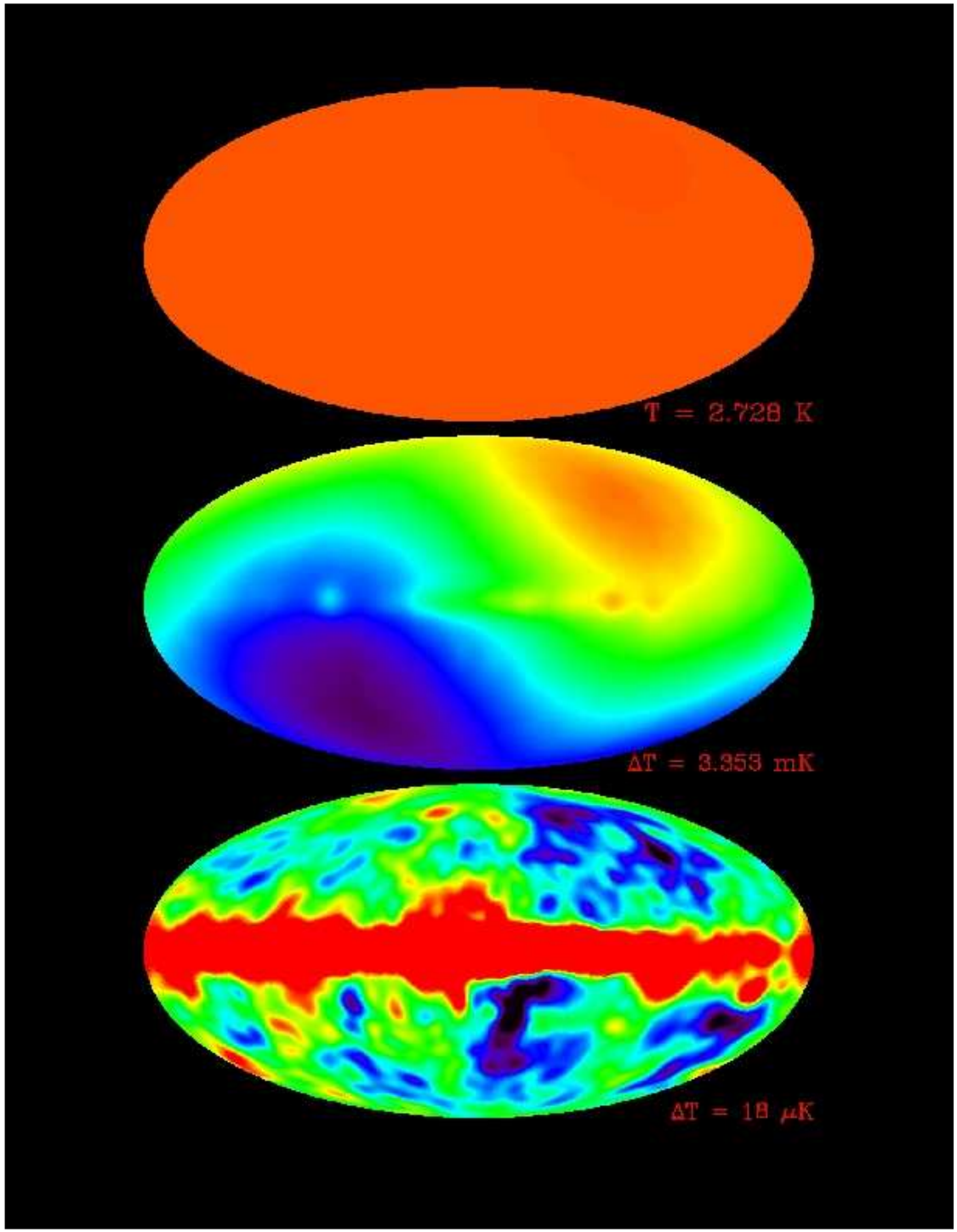
Motion of Solar System leads
to the DIPOLE COMPONENT
in the CMB brightness distribution
over the SKY

Sky is 0.1% brighter in the direction of our motion

327 km/s

and is less bright in opposite direction

This is the brightest anisotropy on CMB sky – thousands times
stronger than primordial fluctuations
main calibrator for CMB experiments

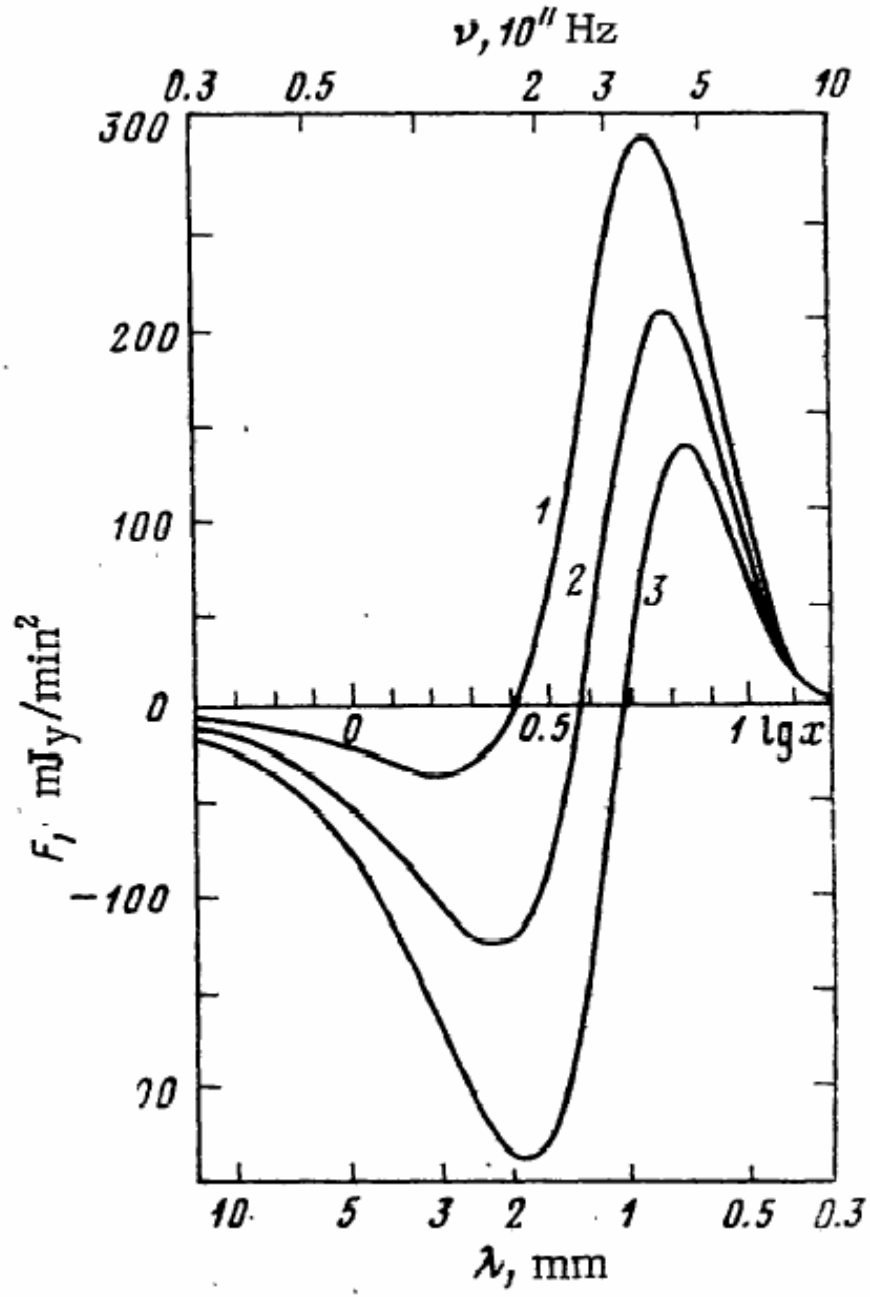


CMB is isotropic only in one coordinate frame

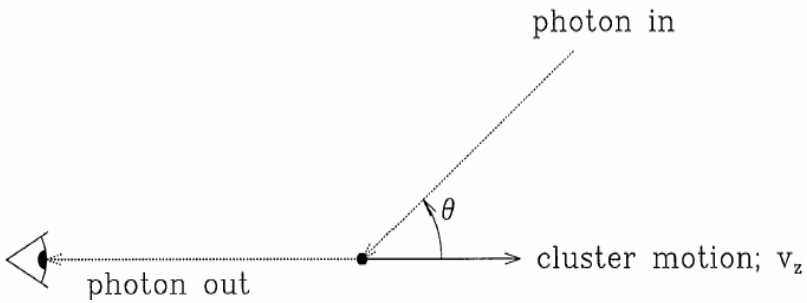
Solar system is moving relative to this frame

we see anisotropy of CMB and measure our velocity

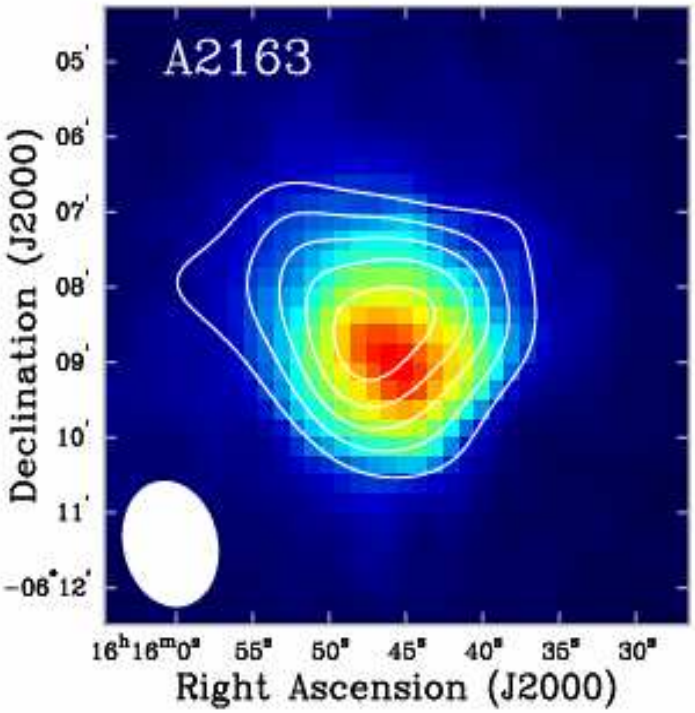
370 km/sec

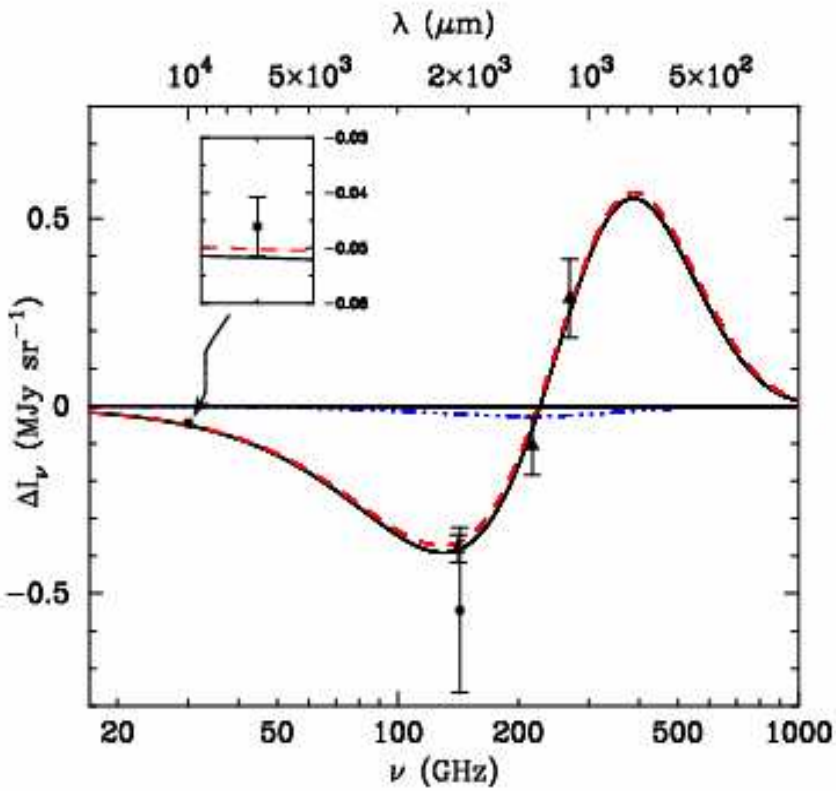


Kinetic SZ-effect



$$\frac{\Delta T_{\rm rad}}{T_{\rm rad}} \approx -\tau_{\rm e}\frac{v_z}{c}$$



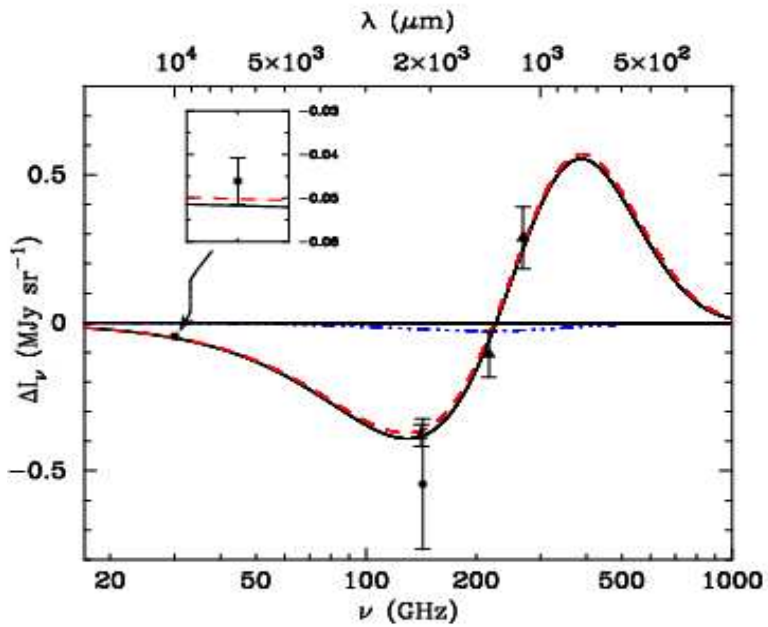


Perculiar velocity
V= 415 +920/-760 km/s

Cluster MS1054 at redshift z=0.826

moving from us due to Universe expansion

with a velocity 54 % of speed of light (162 000 km/s).



However its peculiar velocity

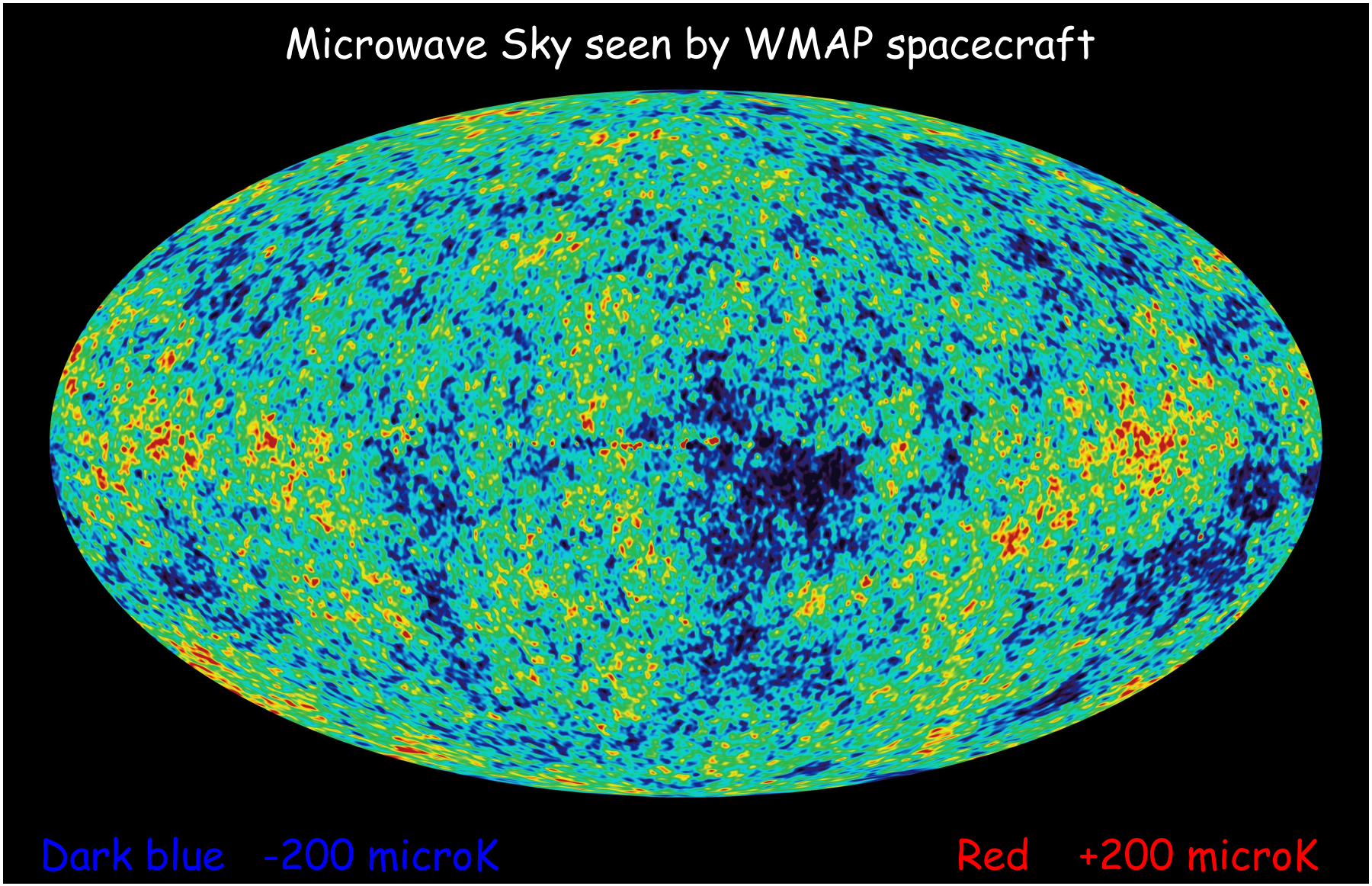
is less than 1000 km/s with respect to the reference frame in which the

cosmic background radiation is isotropic

ACOUSTIC PEAKS

and

their **ORIGIN**



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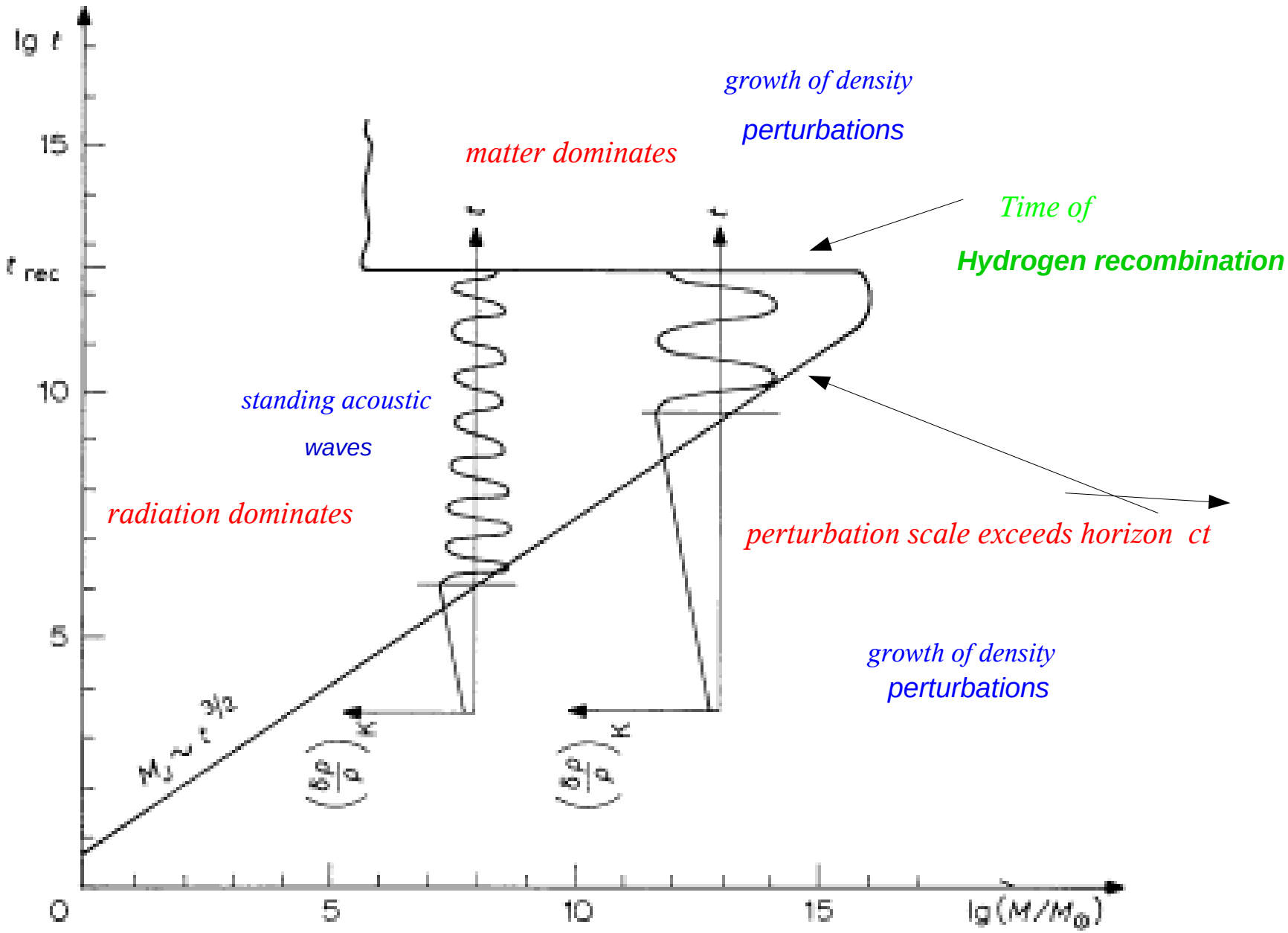
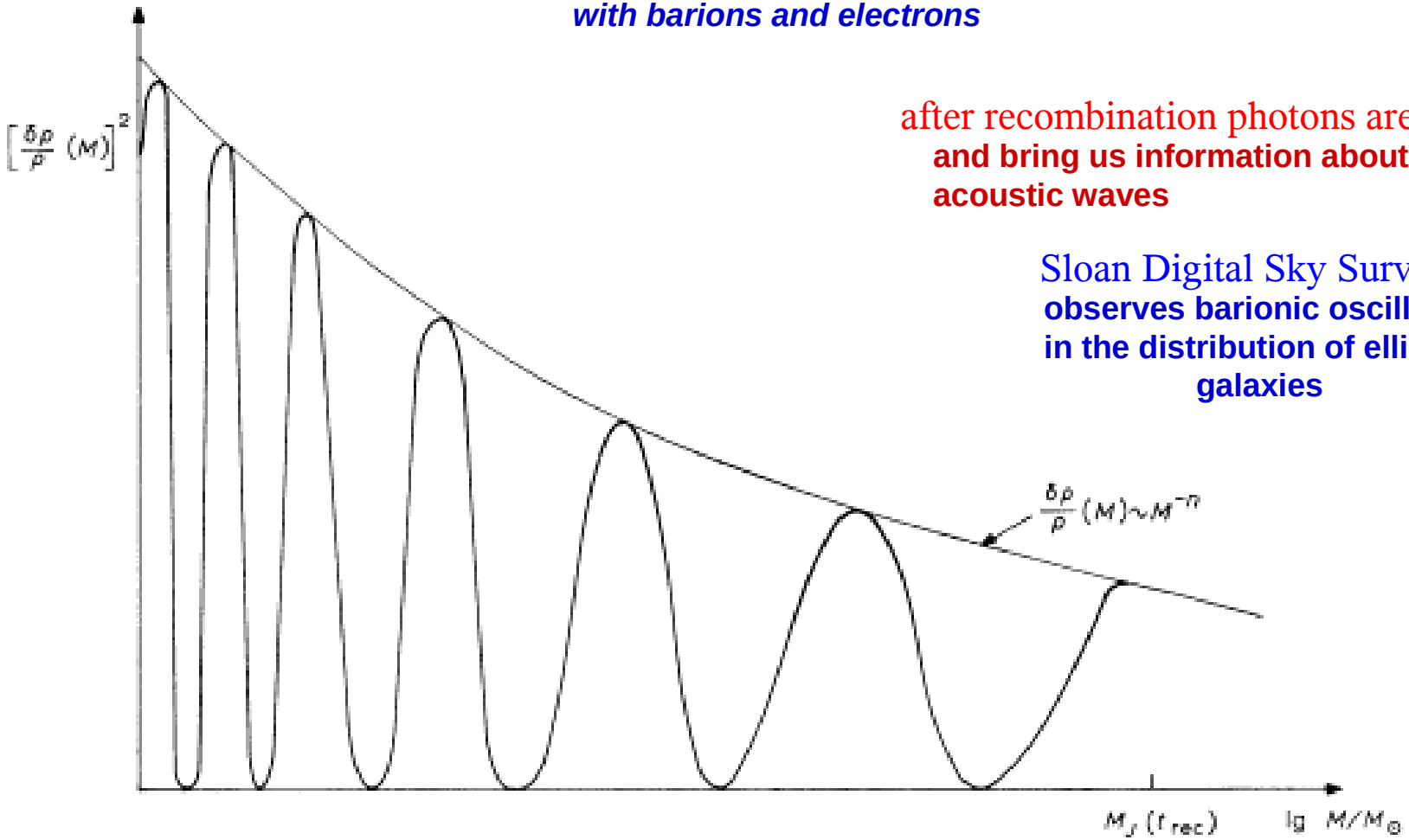


Evolution of density perturbations in the expanding Universe *(Sunyaev, Zeldovich, 1970)*

CMB angular distribution remembers these oscillations

in the radiation dominated fluid
with barions and electrons

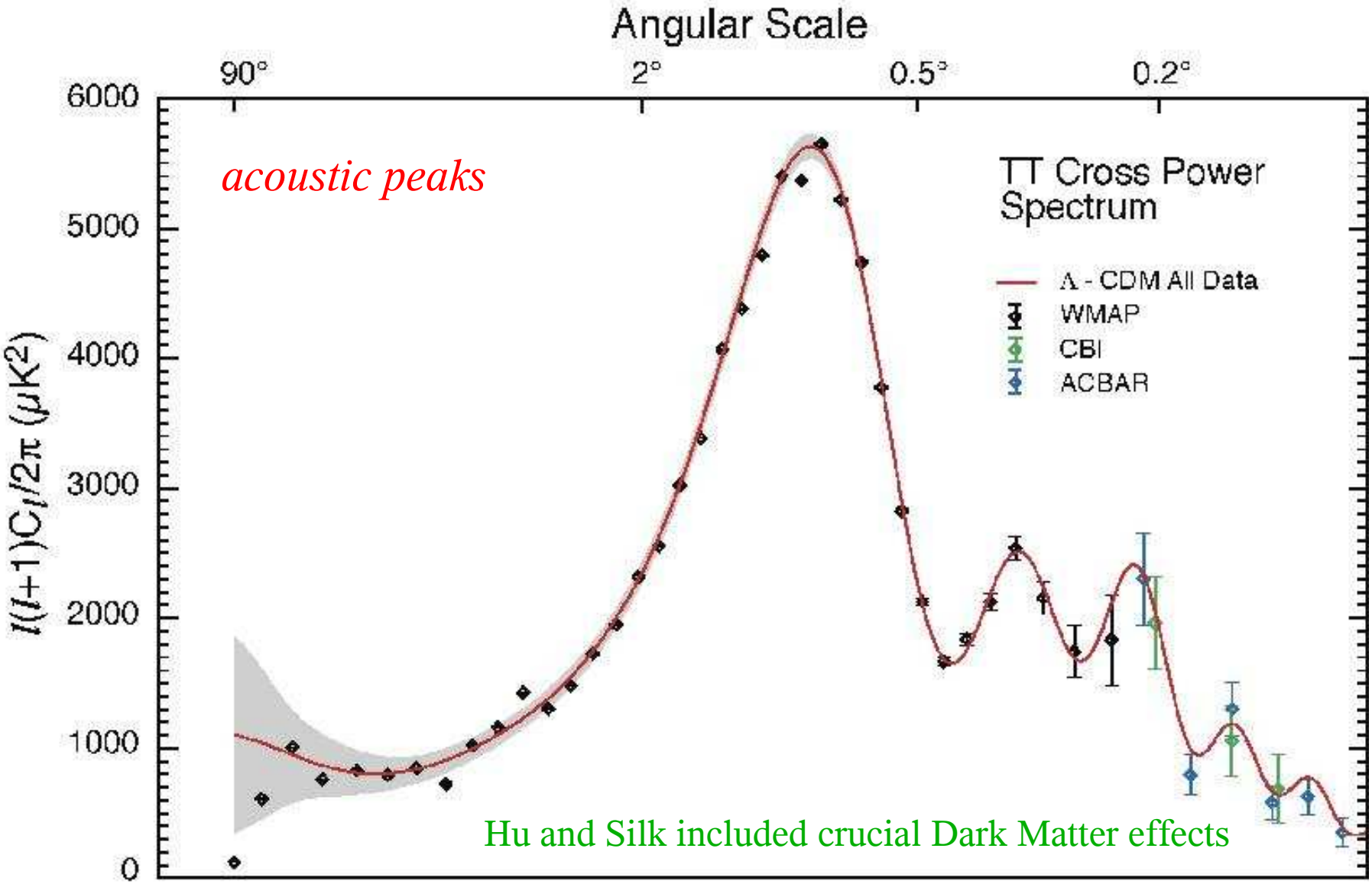


after recombination photons are free
and bring us information about these acoustic waves

Sloan Digital Sky Survey
observes barionic oscillations in the distribution of elliptical galaxies

Dependence of the amplitude of the density perturbations on the scale

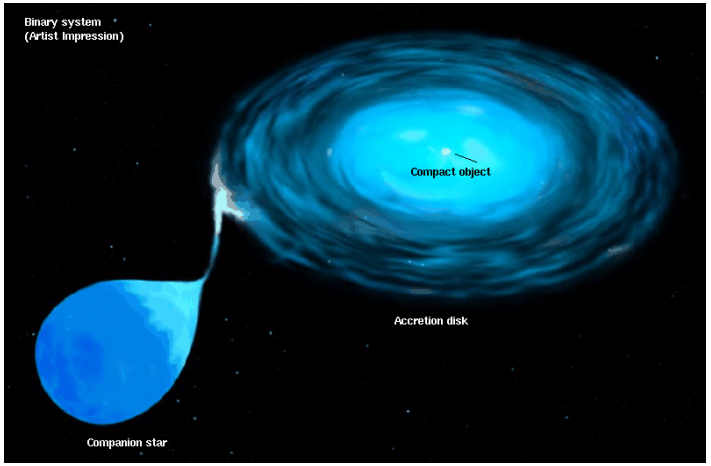
Sunyaev and Zeldovich, 1970



Sunyaev and Zeldovich, 1970; Peebles and Yu – prediction

Boomerang, Maxima, WMAP, ACBAR, VSA, CBI - Discovery

Accreting black holes and neutron stars

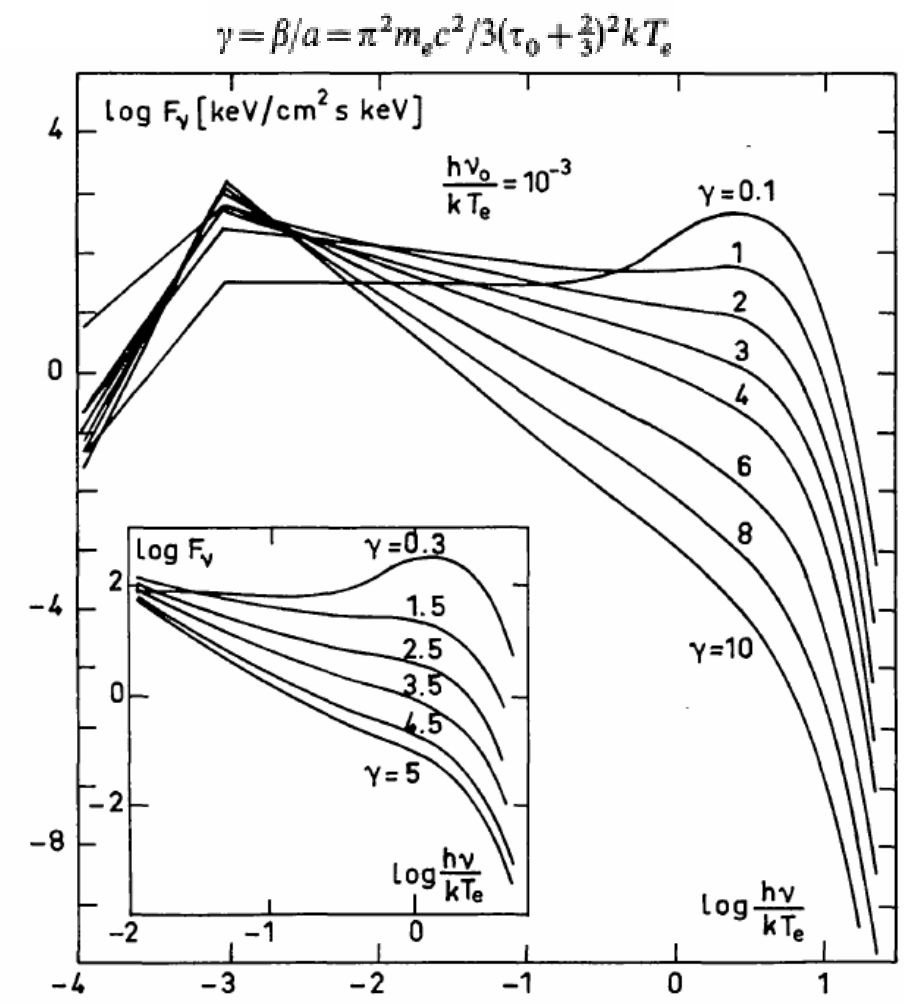


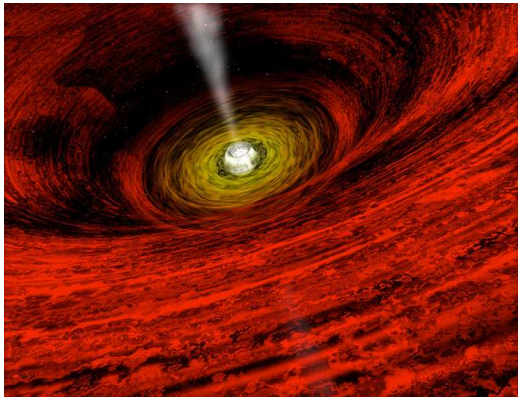
Gas in the accretion disks and boundary layer is very hot (kTe ~ 1 – 100 KeV) due to enormous gravitational energy release

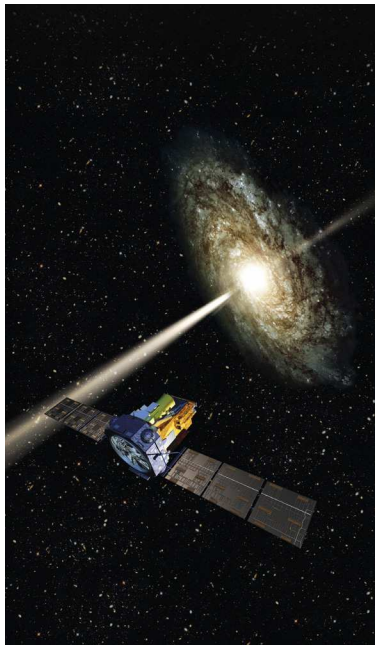
Main plasma cooling mechanisms is again comptonization – the scattering of low frequency seed photons on extremely hot electrons

Exact solution of Kompaneets equation in the plasma cloud (Sunyaev, Titarchuk, 1980) demonstrates how the observed power law X-Ray spectra with exponential high energy cutoff form in accretion disks.

Exact solution of Kompaneets equation in the plasma cloud (Sunyaev, Titarchuk, 1980) demonstrates how the *power law spectra with exponential high energy cutoff form* due to Comptonization..





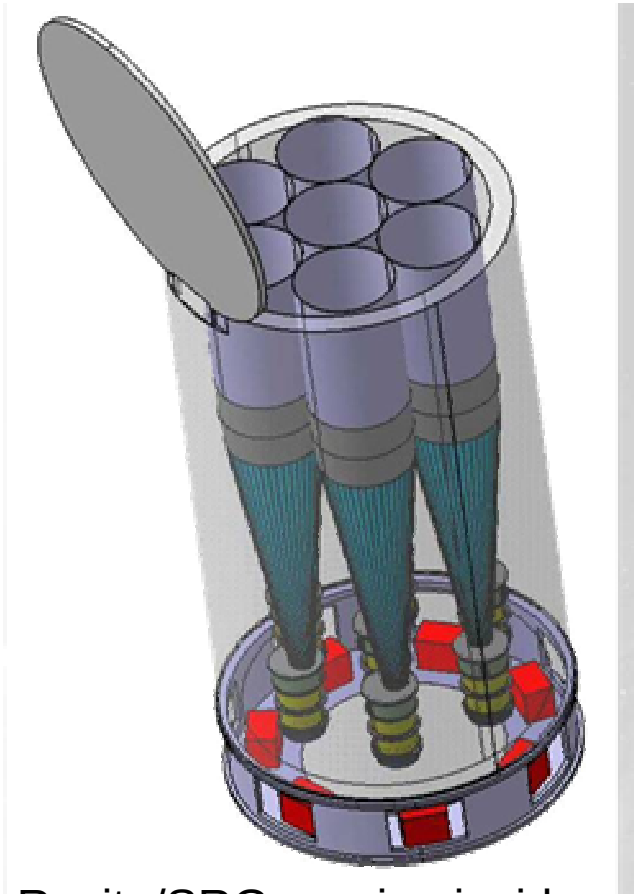


Such X-Ray spectra are observed now from ***hundreds of Galactic binary X-Ray sources*** – *accreting neutron and black holes* and from ***hundreds active galactic nuclei – supermassive black holes powered by accretion.***

In 2012 Russia is planning to launch SPECTRUM-X spacecraft (with telescopes designed in broad international cooperation) able to **map whole sky** and detect **all rich clusters of galaxies** in the observable Universe (~ 150 000) and 3 – 5 millions AGNs **(active galactic nuclei)** via their X-Ray emission.

Planned microwave and X-Ray observations of clusters of galaxies should give a lot of unique cosmological information about the properties of our Universe.

In all these objects **Comptonization** is playing crucial role. It was first considered in early 50ties by *Aleksandr Kompaneets, Yakov Zeldovich, Lev Landau and Israil Gelfand* for completely different applications.



eRosita/SRG grazing incidence X-Ray telescopes

MPE-DLR (Germany)