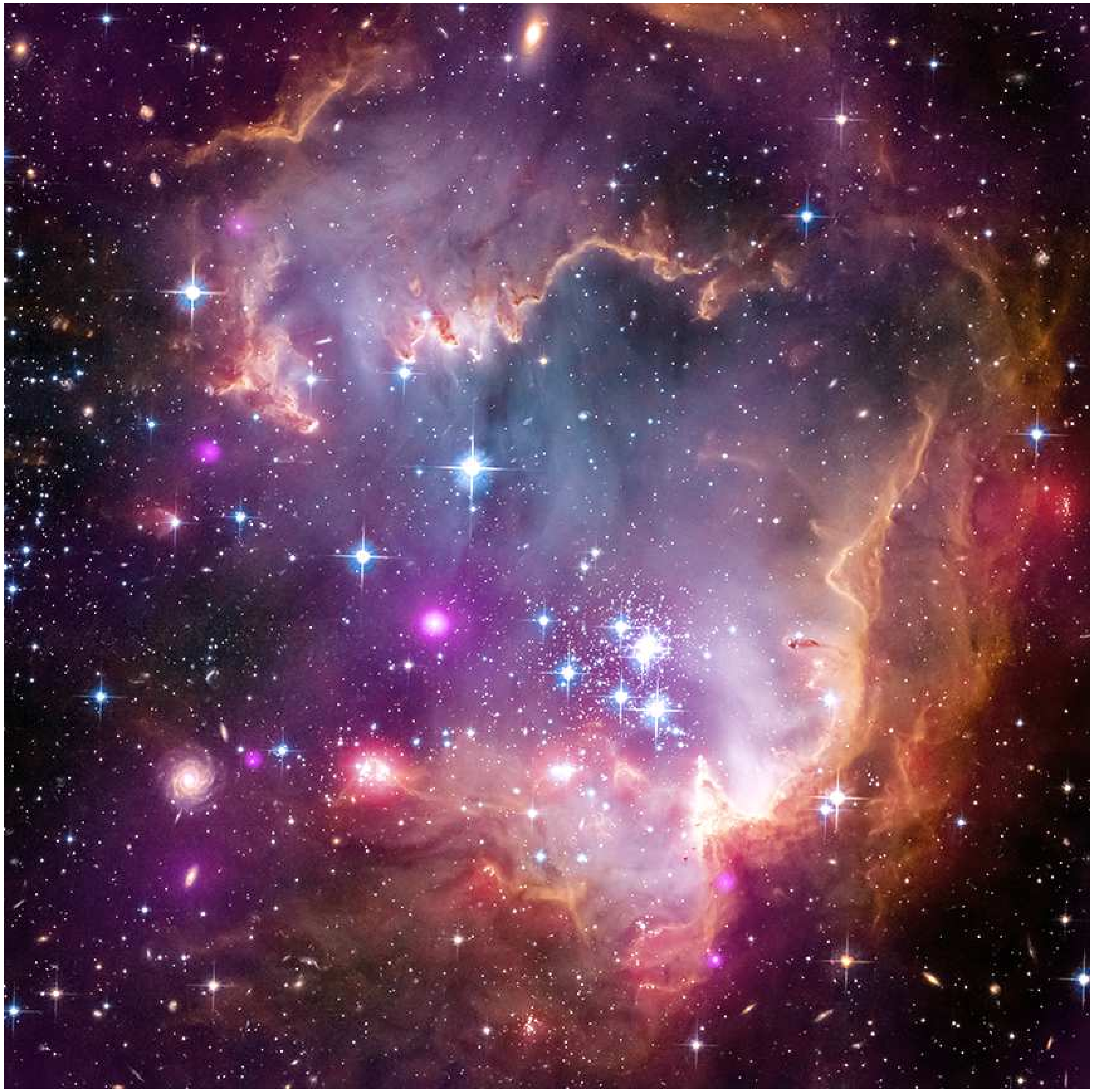
The X-Ray Universe



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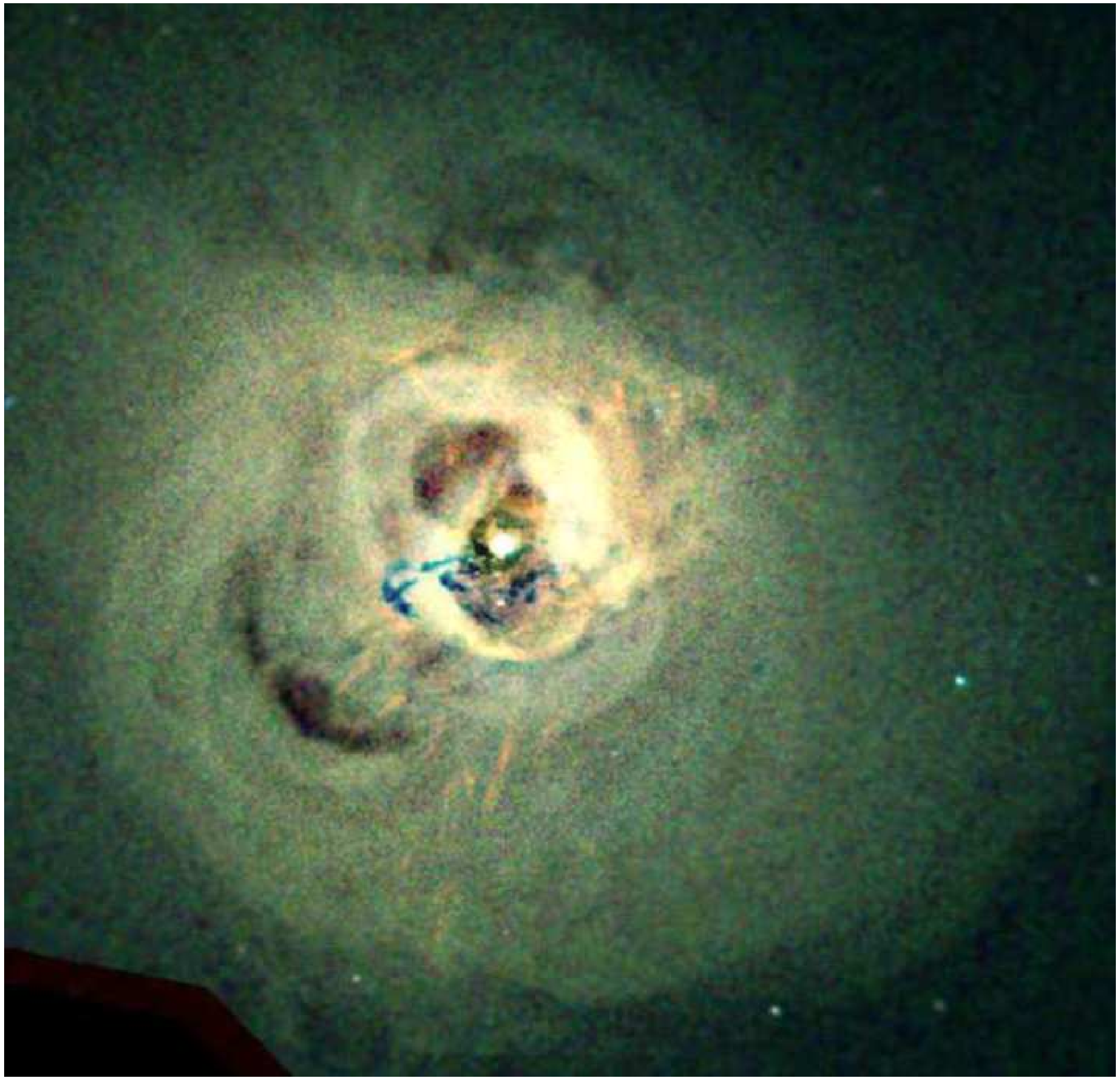
~lida/vorlesungXRAYSo17.html

Chandra X-ray, HST optical, Spitzer IR
NGC602 in the SMC
d=60pc

Clusters of galaxies



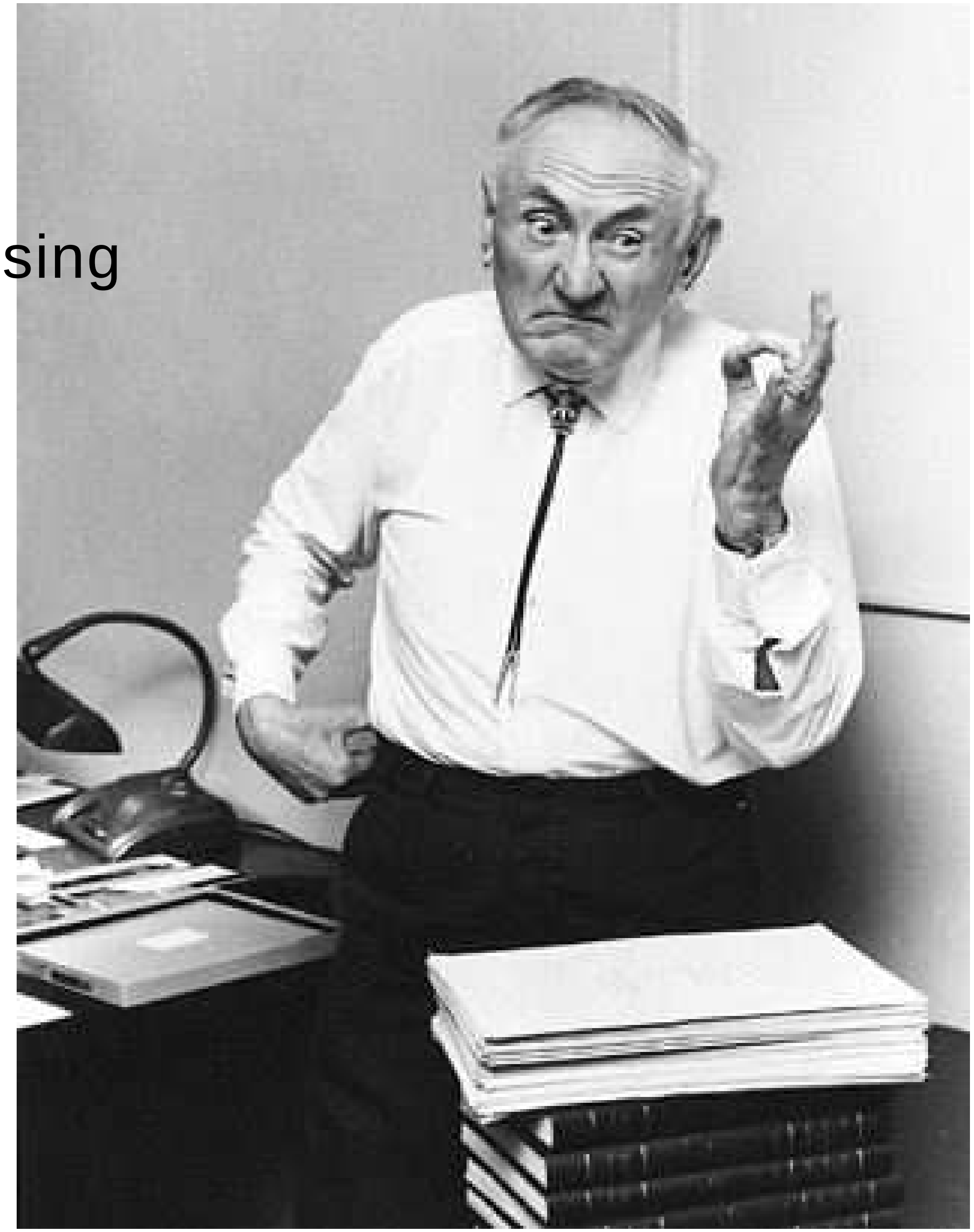
http://chandra.harvard.edu/

Galaxy clusters

HST Coma cluster z=0.023

- Total masses of 10^{14} to 10^{15} solar masses.
- Largest gravitationaly bound objects in the Universe
- Diameter from 2 to 10 Mpc
- They contain 50 to 1000 galaxies, Intra Cluster Matter (ICM) and dark matter
- The MW belongs to the Local Group: over 35 galaxies. The MW is the most massive and second largest in the Local Group,

Dark matter
Supernovae
Cosmic rays
Gravitational lensing



Fritz Zwicky (1898-1974)

Zwicki: Dark matter in Coma Cluster

- **$2E_K+E_P=0$ → from temperature of a gravitationaly bound object → its mass**
- Velocity dispersion of the galaxies Zwicki 1937

$$\overline{v^2} = \overline{v_x^2} + \overline{v_y^2} + \overline{v_z^2} = 3\overline{v_{pj}^2} \;\rightarrow T = \frac{1}{2}\sum_i m_i \overline{\vec{v}_i^2} = \frac{3}{2} M \overline{v_{pj}^2}$$

$$E_P = \frac{GM^2}{R} \rightarrow \quad M = \frac{3}{G}\overline{v_{pj}^2} R$$, where R is mean separation

- Zwicky: calculate the total mass of the Coma Cluster from his measured galactic velocities
- Measured the total light output of all the cluster's galaxies.
- The light output per unit mass for the cluster smaller by a factor > 400 compared to normal star systems.
- Zwicki "Coma Cluster must contain a large amount of matter not accounted for by the light of the stars." He called it **"dark matter."**

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Nature 555, pages 629632 (29 March 2018)

Gas temperature

- Itracluster medium is filled with gas. What is it temperature?

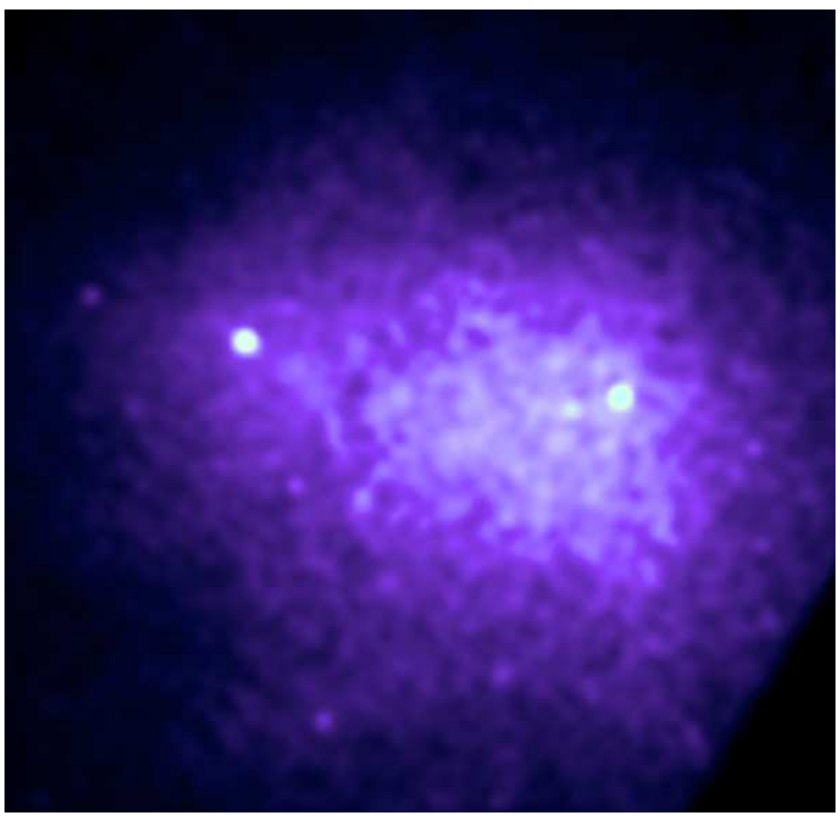
- $2E_K + E_G = 0$, E_K is the internal energy of ideal gas
- $E_K = C_V \langle T \rangle M$, $C_V = 3R/2\mu$ (monoatomic), $R = 8.310^7$ erg/K mol, $\mu = 0.5$ g/mol → $\langle T \rangle = \frac{GM}{R}\frac{\mu}{3\mathcal{R}}$ → $\langle M \rangle = \mathrm{const}\ \langle T \rangle\ R$
- $M_{\mathrm{cl}} \sim \times 10^{14} M_{\odot}$, $R_{\mathrm{cl}} \sim$ Mpc

- Gas in hydrostatic equilibrium within a cluster's gravitational potential has electron temperature T_e:
  - $kT_e \approx \frac{GMm_p}{2R} \approx 7\frac{m}{r}$ keV, where $m = M/M_{cl}$, $r = R/R_{cl}$

- The expected temperature 10^7 K. **Galaxy clusters shall be X-ray sources**

Coma cluster HST: 9 arcmin wide

Coma cluster CXO: 17 arcmin wide

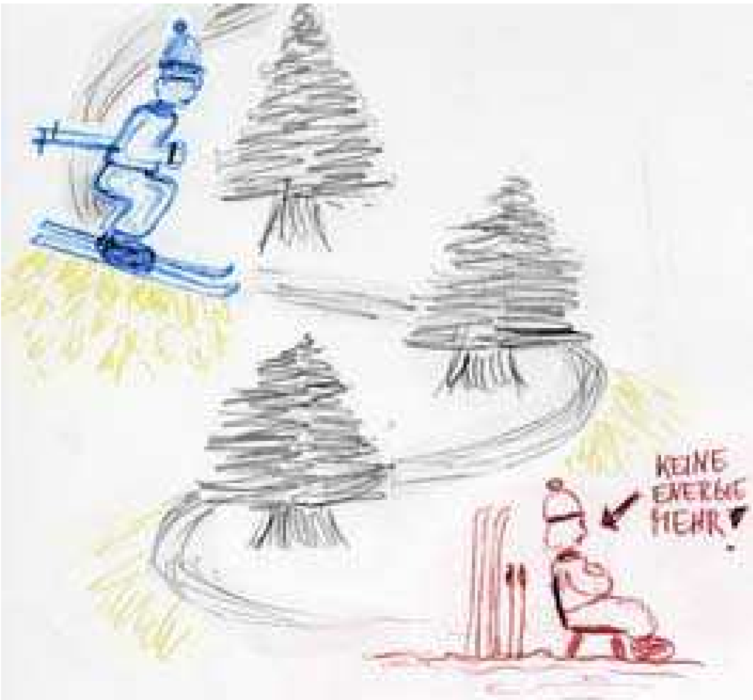


NASA/CXC/SAO/A.Vikhlinin et al.

07 X-rays from Clusters of Galaxies

- Clusters of galaxies are self-gravitating accumulations of dark matter which have trapped barions: ICM and galaxies.
- Most of the baryons are in the hot ICM plasma - only 10-20% are in the galaxies.
- The baryons in the ICM thermalize to $> 10^7$ K making clusters strong X-ray sources.
- Lets rememeber what is bremsstrahlung

Thermal Bremssshtrahlung



http://www.desy.de

Bremssshtrahlung calculations

Find spectrum from single encounter of electron and ion with given impact parameter

Integrate over all possible impact paraemters

Integrate over distribution of electron velocities (in this case Maxwellian)

Important when temperatures are very high:10...100 MK

The dominant emission from cluster of galaxies

The total bremsstrahlung emission:

$$\frac{dP_{\mathrm{B}}}{dV} = 2.4 \times 10^{-27} \sqrt{T} N_{\mathrm{e}}^{2} \quad [\mathrm{erg\ cm^{-3} s^{-1}}]$$

Note that electron distribution can be non-thermal,

$J(E)=J_0 E^{-s}$ [erg cm^{-2} s^{-1} erg^{-1}] →

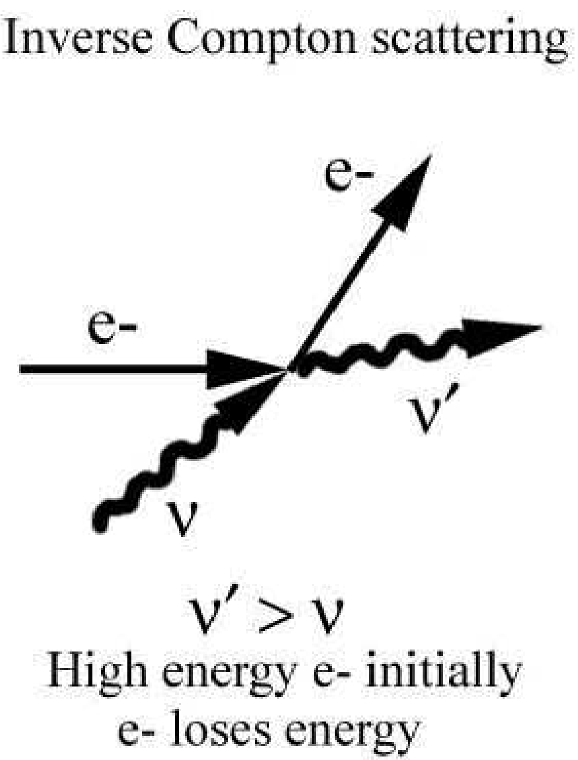
spectral shape depends on the elesctron spectrum

Sunyaev-Zeldovich effect (1970)

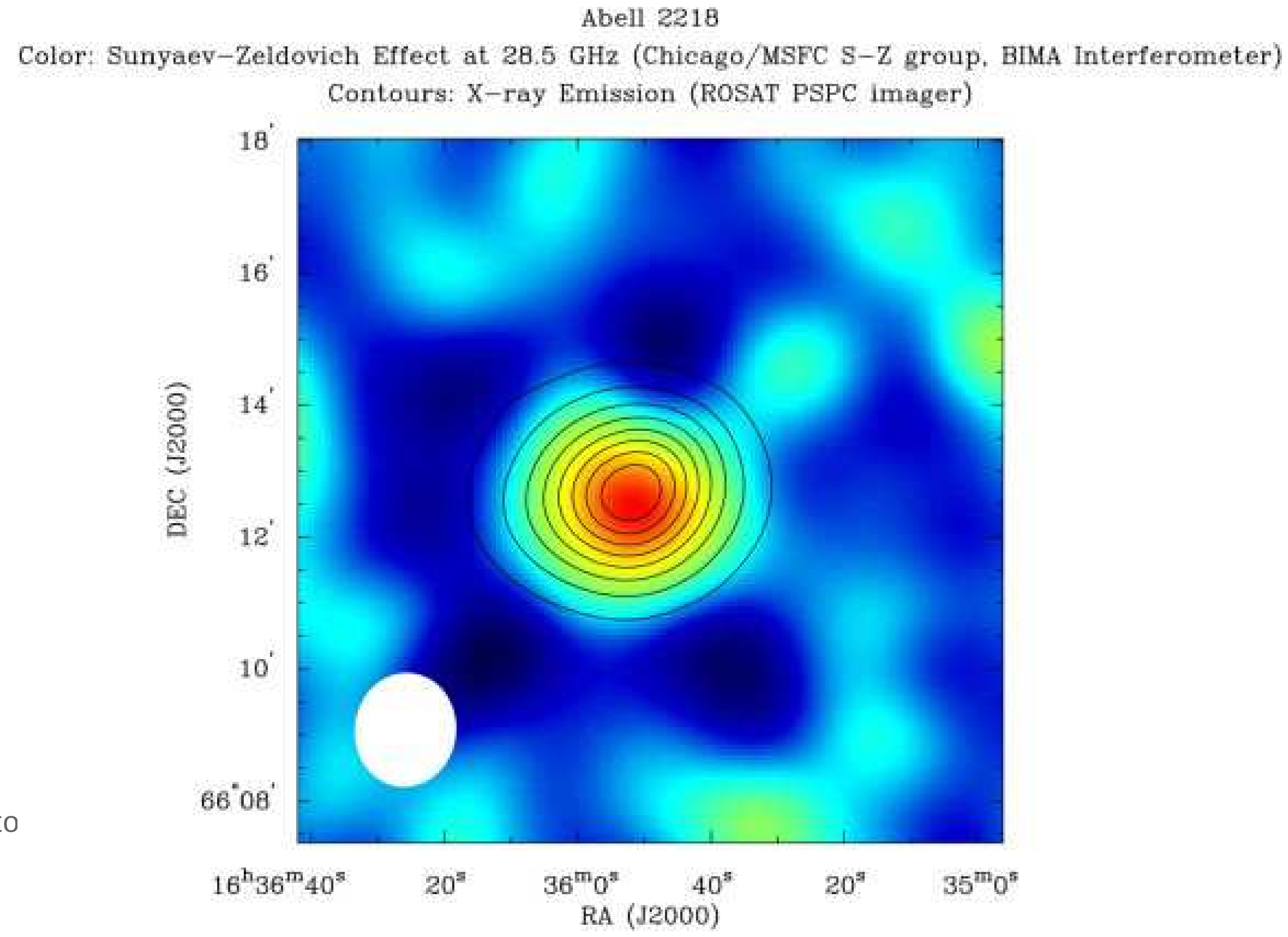
- Interaction between Cosmic Microwave Background Radiation (CMB) (z~1100, T =2.725(1+z)K) and hot gas in the galaxy clusters (z~0-3).
- CMB photons passing through the hot ICM have a ~1 per cent chance of inverse Compton scattering off the energetic electrons → a small (~1 mK) distortion of the CMB spectrum: the SZ effect.
- The rate of change of of the photon occupation number of an isotropic radiation field is described by Kompaneets (1957) equation.
- When the velocity distribution of the electrons is isotropic, the spectral shift is proportional to T_e. The radiation gains energy through scattering by the much hotter IC gas.
- The temperature and the density of of the gas is determined from X-ray observations.

Reminder: Inverse Compton effect

Occurs when electron cannot be considered at rest



http://venables.asu.edu/quant/proj/compto



The energy is transferred from the e to the ph

SZE and galaxy clusters

Scattering optical depth $\tau = n_e \sigma_T R_{cl}$ $\delta\nu/\nu \approx kT_e/m_e c^2 \approx 0.01$

The change in the intensity 10^{-4}. A signal which is about ten times larger than the cosmological signal in the microwave background radiation detected by COBE. (Planck is 1000 times more sensitve)

The primordial and SZE effects can be distinguished. SZE are localized: they are seen towards clusters of galaxies. Primordial structures in the CMB are non-localized: they are not associated with structures at other wavebands: distributed at random over the sky.

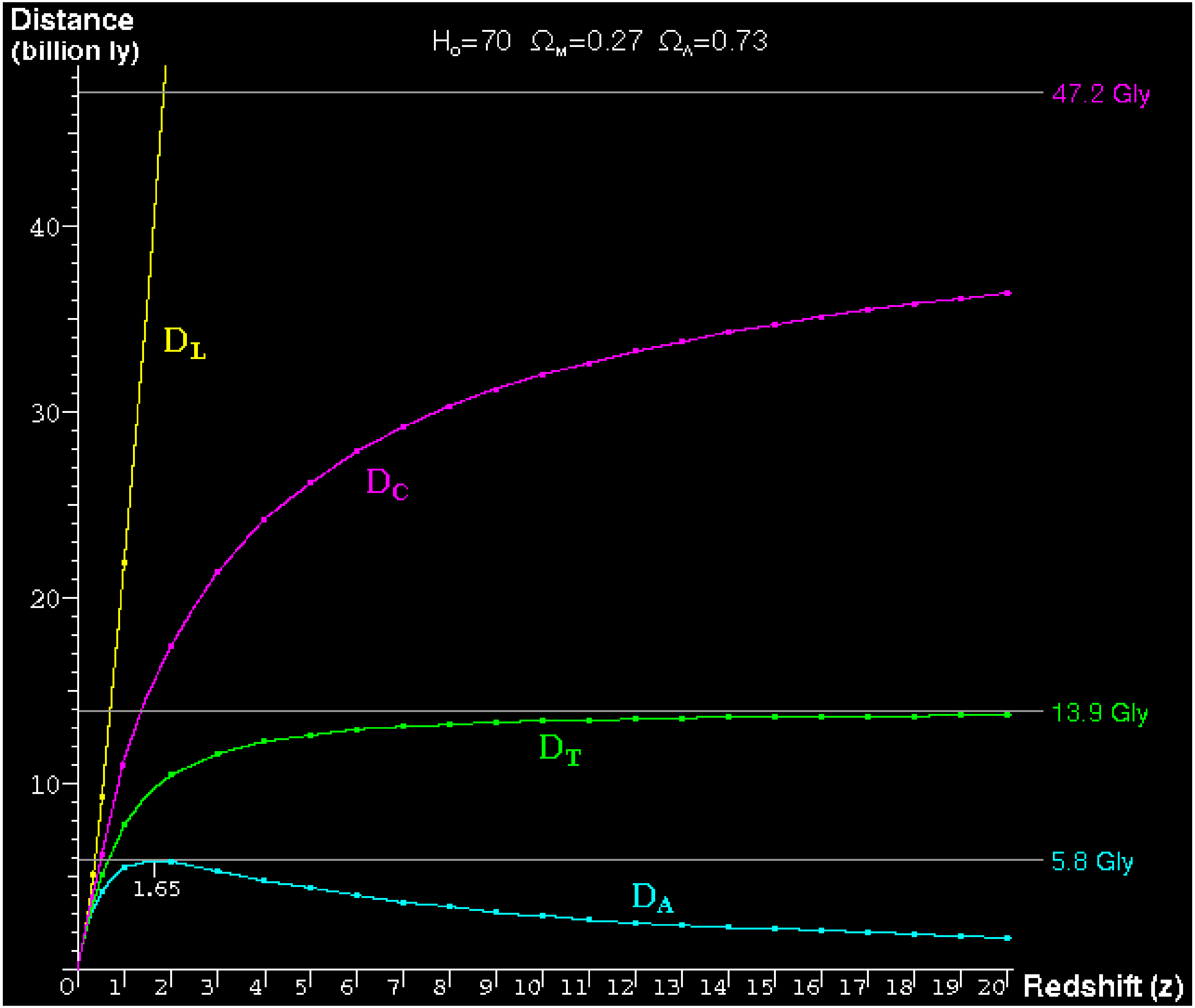
SZ effect as cosmology probe: a comparison of the emission and absorption of radiation from gas: the surface brightness of the gas in emission $E \sim \int N_e^2 dl$

The absorption of some background source of radiation is proportional to the optical depth: $A \sim \int N_e dl$

If the structure of the gas is known, and its angular size, can be measured, then the angular diameter distance of the gas can be estimated.

Reminder: The Distance Scale of the Universe

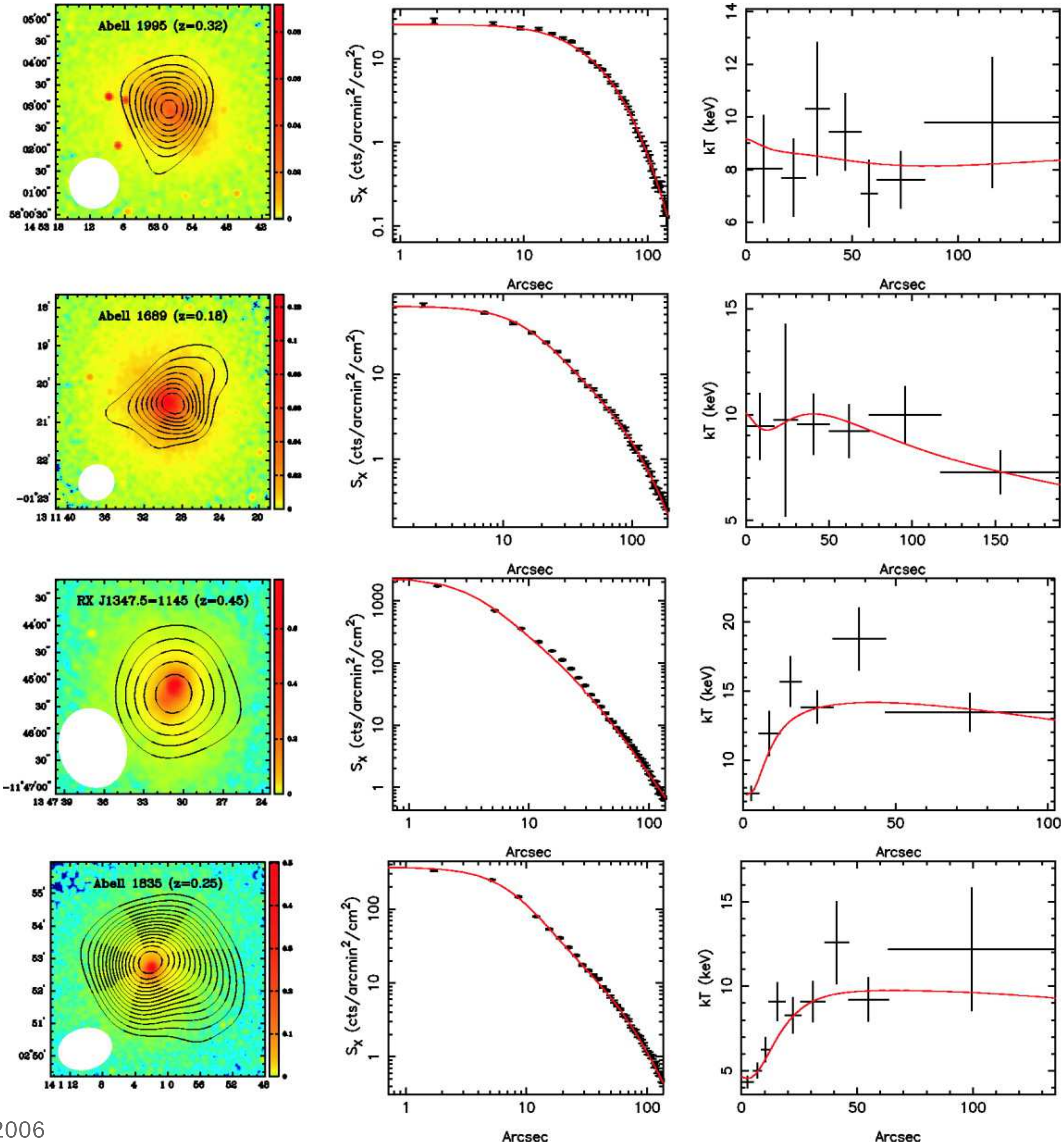
- Luminosity Distance - D_L Distant galaxies are much dimmer: the photons are spread out over a wide area. The most distant galaxies appear as if they are about 350 billion lyr away.
- Angular Diameter Distance - D_A We see the galaxies when they were very young (~14 byr ago), because light took 14 byr to reach us. At that time the galaxies were much closer to us. Depends on the curvature of the Universe. Very distant galaxies look much larger and fainter than now.
- Comoving Distance - D_C. The distance scale that expands with the Universe. The opposite of the Angular Diameter Distance it tells us where galaxies are now rather than where they were when they emitted the light.
- Light Travel Time Distance - D_T. The time taken for the light from distant galaxies to reach us. The visible universe has a radius of 14 billion lyr. A measure of time as well as measure of distance.



www.atlasoftheuniverse.com/redshift.html

Back to clusters

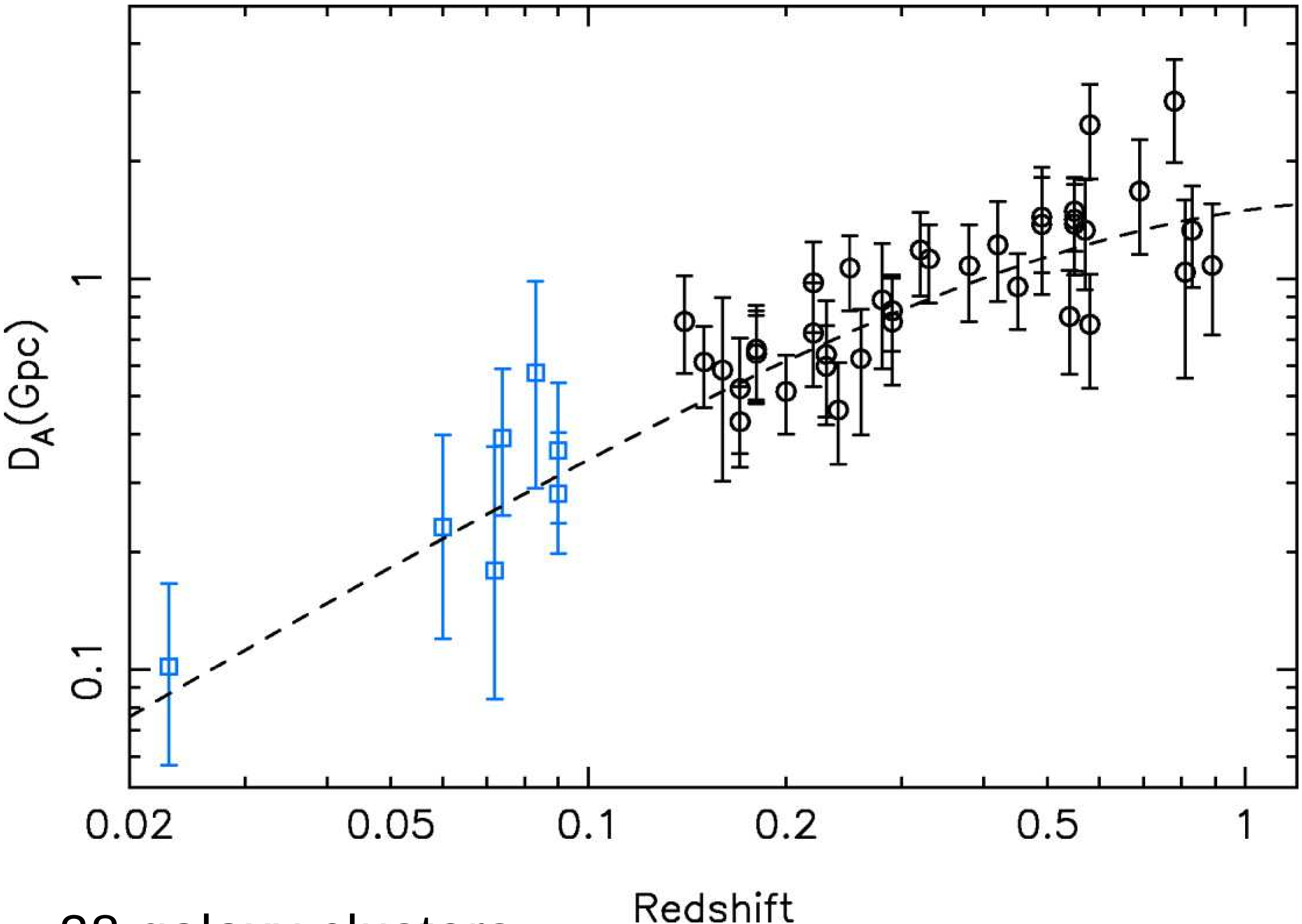
- The X-ray surface brightness $S_X \propto \int n_e^2 \Lambda(T_e) D_A d\theta$
- The temperature decrement $\Delta T_{\mathrm{CMB}} \propto \int n_e T_e D_A d\theta$
- The cluster angular diameter distance $D_A = dl/d\theta$. θ is the line-of-sight angular size. Usually, spherical geometry for a cluster is adopted, therefore θ=measured angular size.
- $D_A \propto \frac{\Delta T_{\mathrm{CMB}}^2 \Lambda(T_e)}{S_X T_e^2}$ Right part from data.
- The angular diameter distance D_A is a function of the cluster redshift z, the mass density Ω_M, the dark energy density Ω_Λ, a nd the Hubble constant H_0
- Adopting Ω_M and Ω_Λ → H_0 from combining radio and X-ray mesurments.



Bonamente etal. 2006

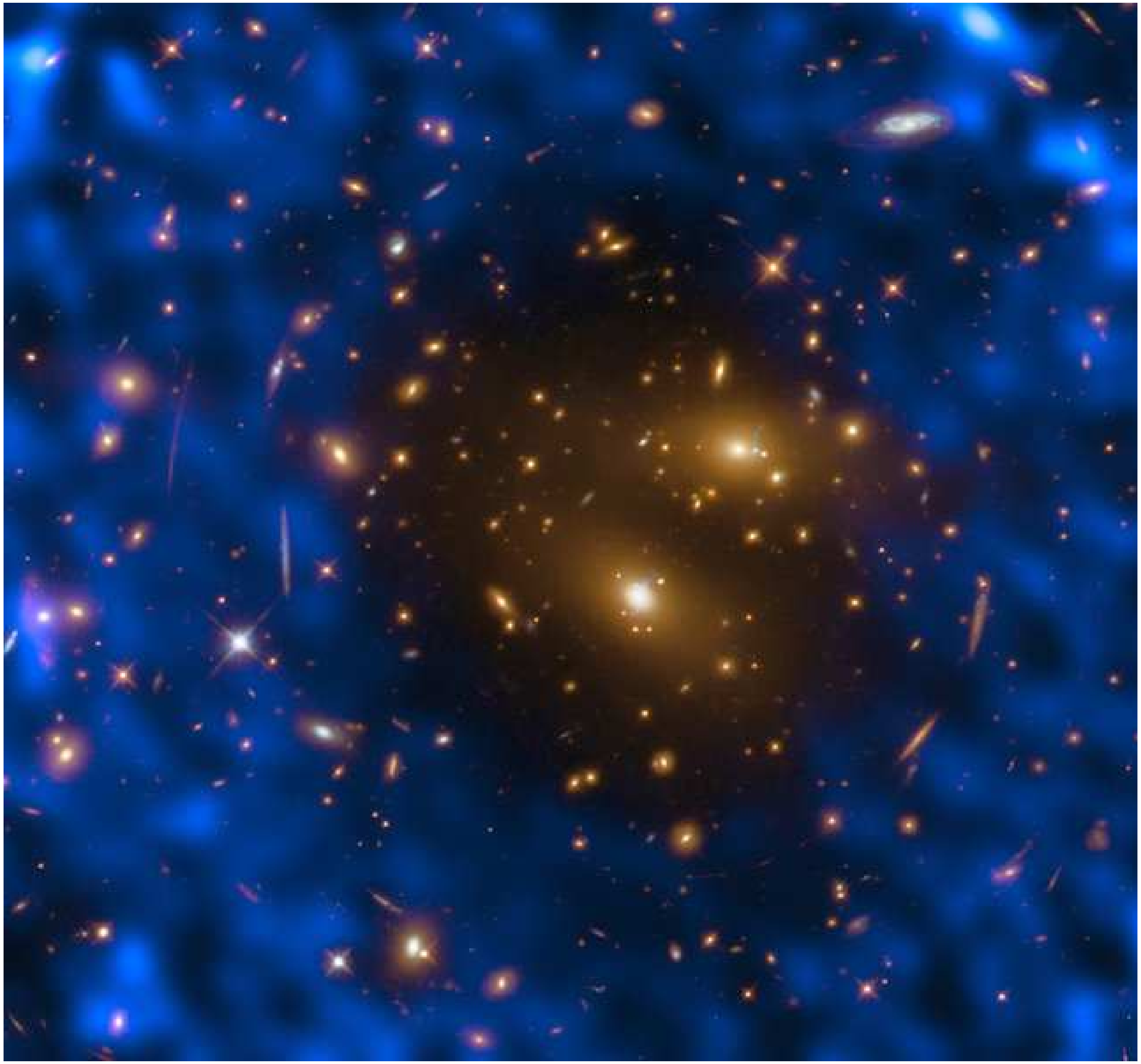
16 Cosmology with SZE

Bonamente etal. ApJ 647, 25



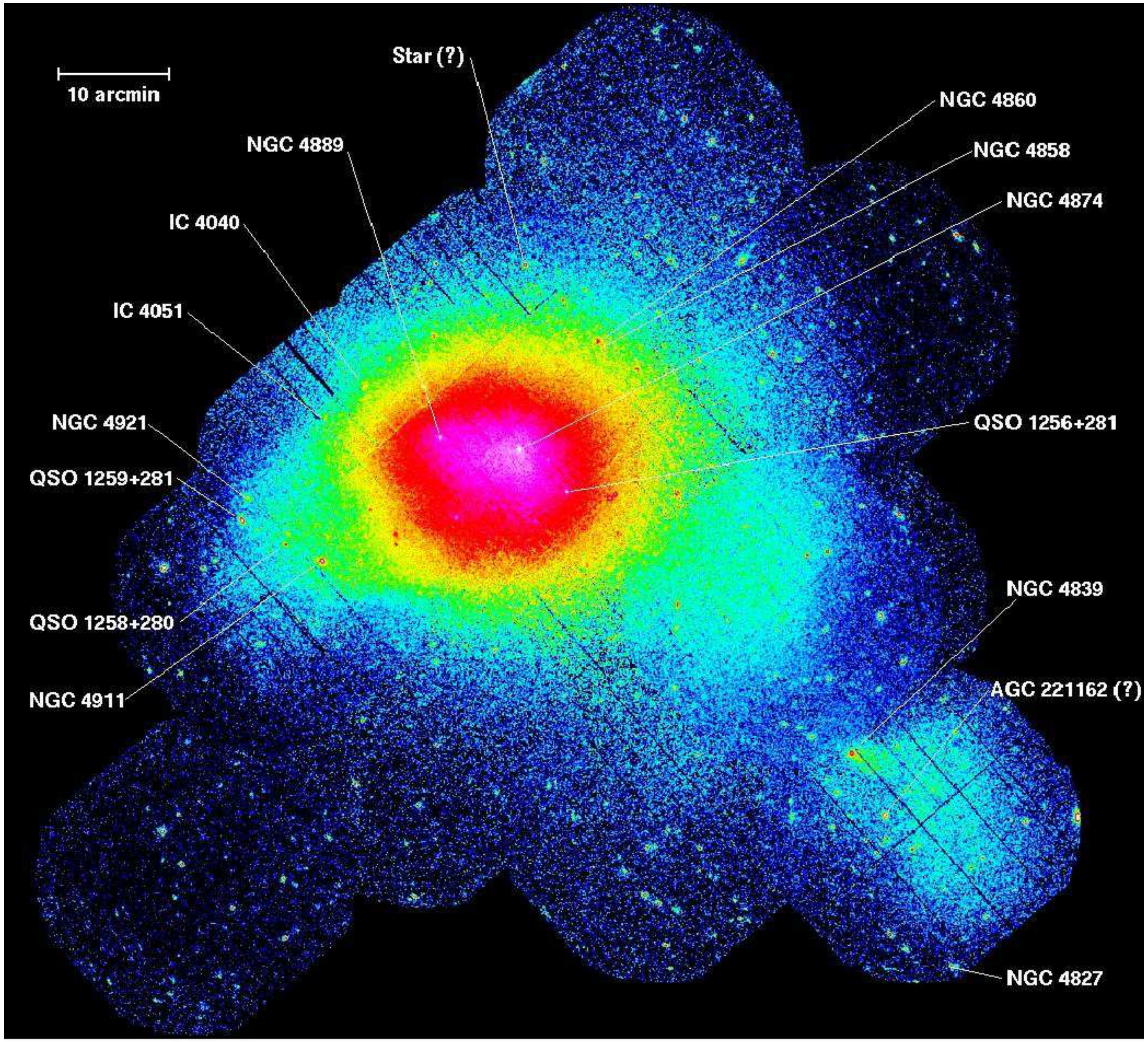
-- 38 galaxy clusters

-- H_0=76.9 km s^{-1} Mpc^{-1}, Ω_M=0.3, Ω_Λ=0.7



SZ effect in the cluster RX J1347.5-1145 taken with ALMA (blue). The background image was taken by the HST. A hole in ALMA im is the SZ effect.

18 X-ray measurments



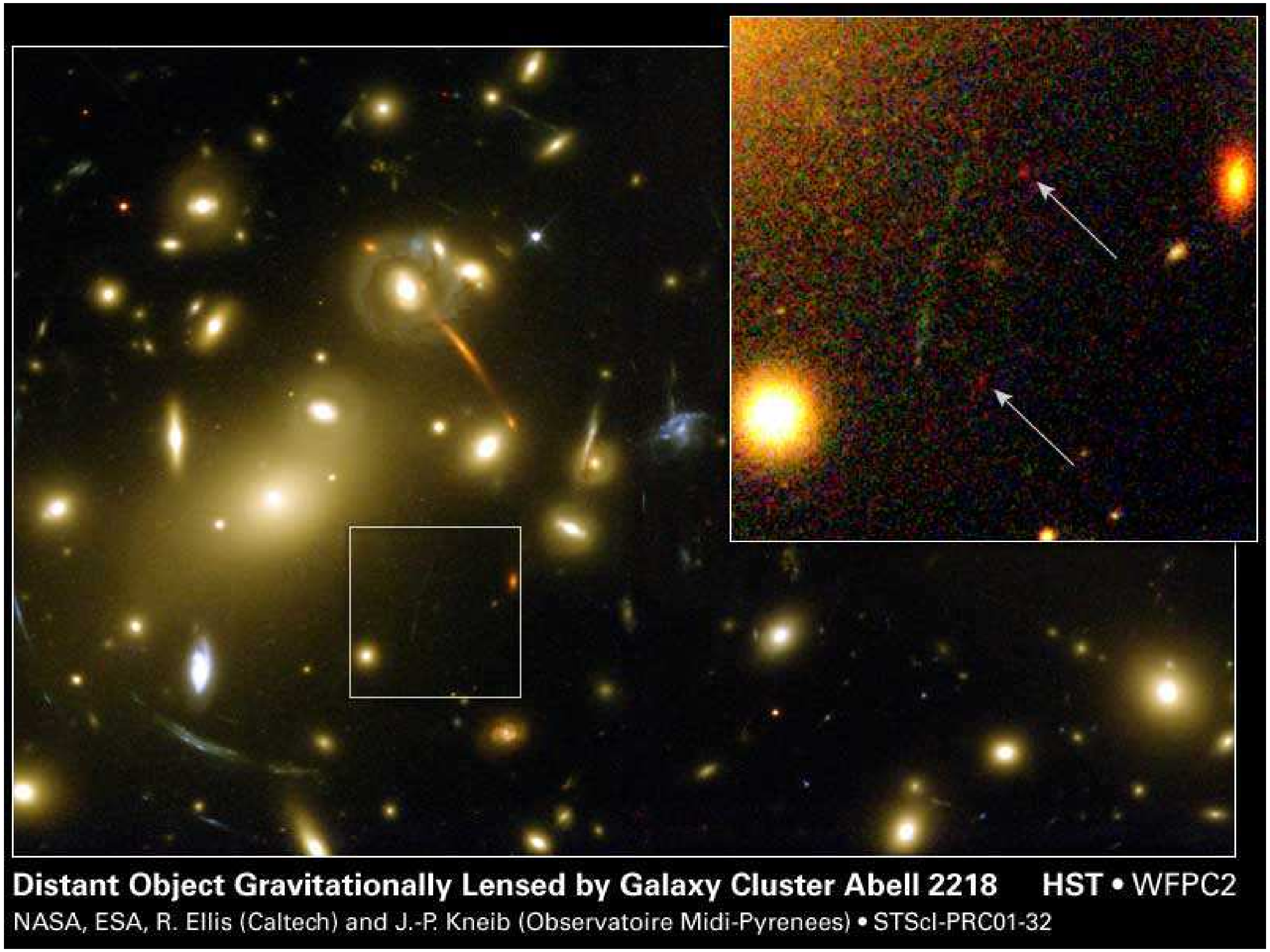
Coma Cluster of galaxies

Image courtesy of U. Briel, MPE Garching, Germany

European Space Agency

- From the spectrum we can measure a mean temperature, a redshift, and abundances of the most common elements (heavier than He).
- With good S/N we can determine whether the spectrum is consistent with a single temperature or is a sum of emission from plasma at different temperatures.
- Using symmetry assumptions the X-ray surface brightness can be converted to a measure of the ICM density.

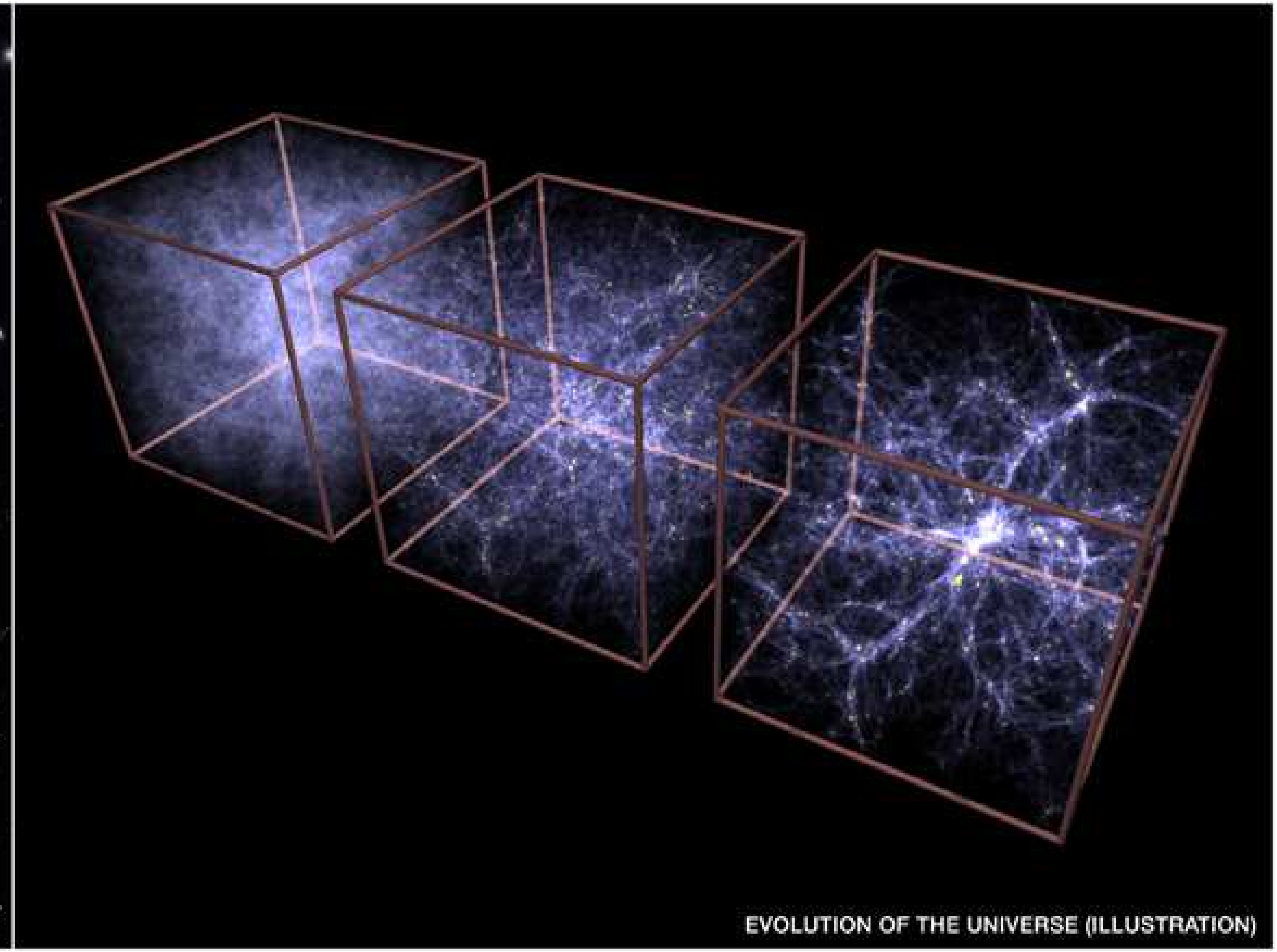
19 Other ways to detrmine cluster mass



-- The gravitational potential acts as a lens on light from background galaxies.

-- Solving lens equation yields the cluster mass

Galaxy clusters as cosmological probes



21 Standard Cosmological Model

- General Relativity
- Six Parameters Describing Matter & Energy
  - Present Hubble parameter H_0
  - Present density of matter Ω_M
  - Present density of baryons Ω_b
  - Present fluctuations of matter in 8 Mpc spheres σ_8
  - Optical depth to last scattering τ
  - Initial matter fluctuation power spectrum index n_s

Model describes well the structure in and evolution of the universe

If GR is correct and there are really only six parameters, we are nearly done.

All but τ are currently measured at 5 percent level

22 Goal is to test standard model,

- Is the dark energy density Ω_{Λ}=1-Ω_{m} ?
- Flat Universe?

- Is the dark energy a cosmological constant?
- Equation of state parameter w_0=-1 ?

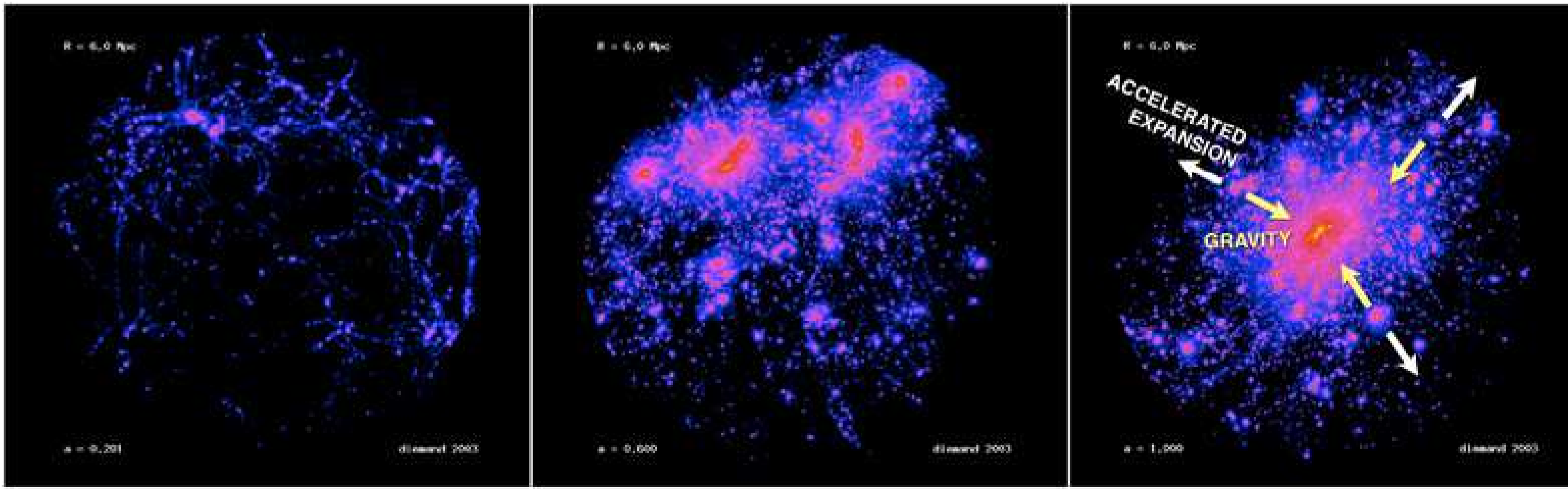
- Is dark energy only an artifact of General Relativity not being correct on Mpc scales?

23 Tests are of two general types

- Growth of structure: measures D(z) i.e number of clusters in dependence on redshift n(z)

- Geometrical: measure cluster fraction of gas f_{gas}
  - The matter content of the largest clusters approx. fair sample of the matter content of the Universe.
  - The ratio of baryonic-to-total mass in clusters → ratio of the cosmological parameters Ω_b / Ω_m .
  - The baryonic mass in clusters: dominated by the X-ray emitting gas (by factor of 6).
  - Baryonic mass fraction in clusters from X-rays + determination of Ω_b from cosmic microwave background (CMB) data + big bang nucleosynthesis calculations + Hubble constant → Ω_m (Fabian 1991; White Frenk 1991).
  - Evolution of the f_{gas}(z) can also be used to probe the acceleration of the Universe

24 The growth of galaxy clusters



- Galaxy cluster growth is influenced by the expansion rate of the Universe
- Expansion rate: the competing effects of dark matter and dark energy and by the properties of gravity over large scale
- Observations of SNe Ia depend only on the expansion rate of the universe and are not sensitive to the properties of gravity.

25 Modified theories of gravity

Modified theories of gravity generally predict values of structure growth rate different from the general relativistic prediction.

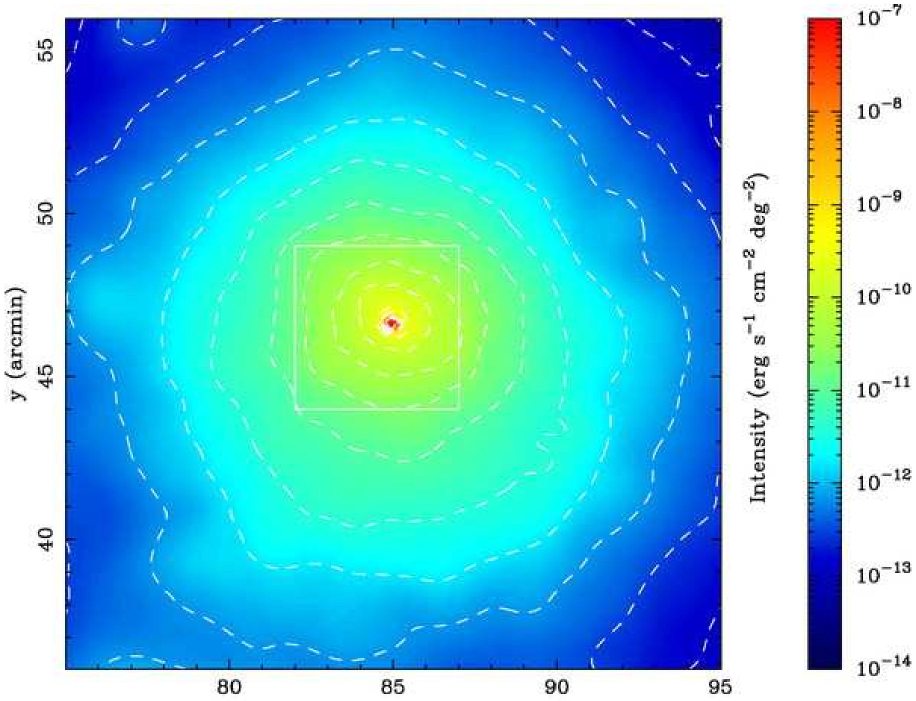
- f(R) gravity : a modification of the gravitational force. Mass estimates of galaxy clusters in the local universe were compared with model predictions for f(R) gravity.
  - GR: gravity = curvature of space and time. The source of this curvature are mass and energy. In the absence of any mass or energy spacetime can become completely flat.
  - f(R): spacetime to act as a source of its own curvature. Some curvature even if spacetime is completely empty and the energy is zero. As the universe expands and empties out, some curvature remains, resulting in cosmic acceleration.
  - f(R) an additional("5th") force is introduced. Galaxy clusters masses: compare predictions between GR and f(r): the range of this 5th force can be estimated.
- "DGP gravity" (Dvali-Gabadadze-Porrati): a slower rate of cluster growth than GR, because gravity is weakened on large scales as it leaks into an extra dimension.

26 Mass determination

- X-ray observations allow **two** mass determinations for a relaxed galaxy cluster
- Mass of gas is proportional to square root of X-rays emission, because the emission is thermal Bremsstrahlung.
- Total mass is proportional to the gas temperature, because this defines the cluster potential.
- Temperature profile can be used to constrain the cluster potential and find $\mathbf{f_{gas}=M_{gas}/M_{total}}$
- Eck (1998): the mean baryonic mass fraction b within the virial radius of a cluster is similar to the universal baryon fraction. Because R_{vir} separates the region where shells of material are infalling for the first time.
- From X-ray data gas fraction is only about 82% of average barion fraction → clusters loose some gas when they form, it decreases with z.

27 Mass determination

Simulation of X-Ray Emission



Fang et al.2003, 623, 612

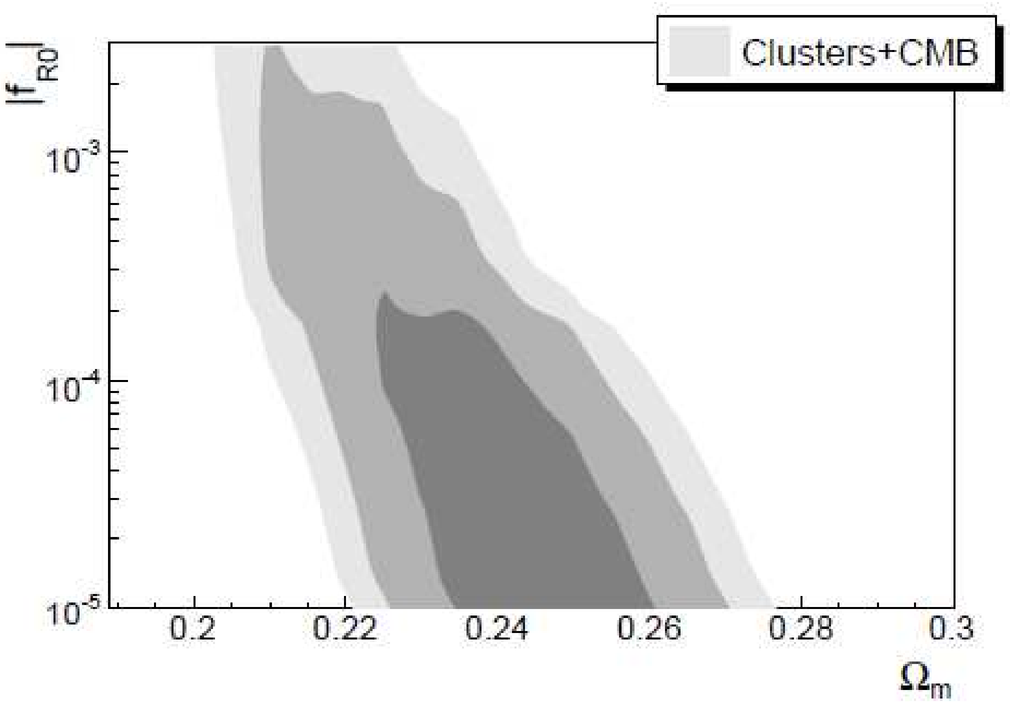
ICM: bremsstrahlung emission

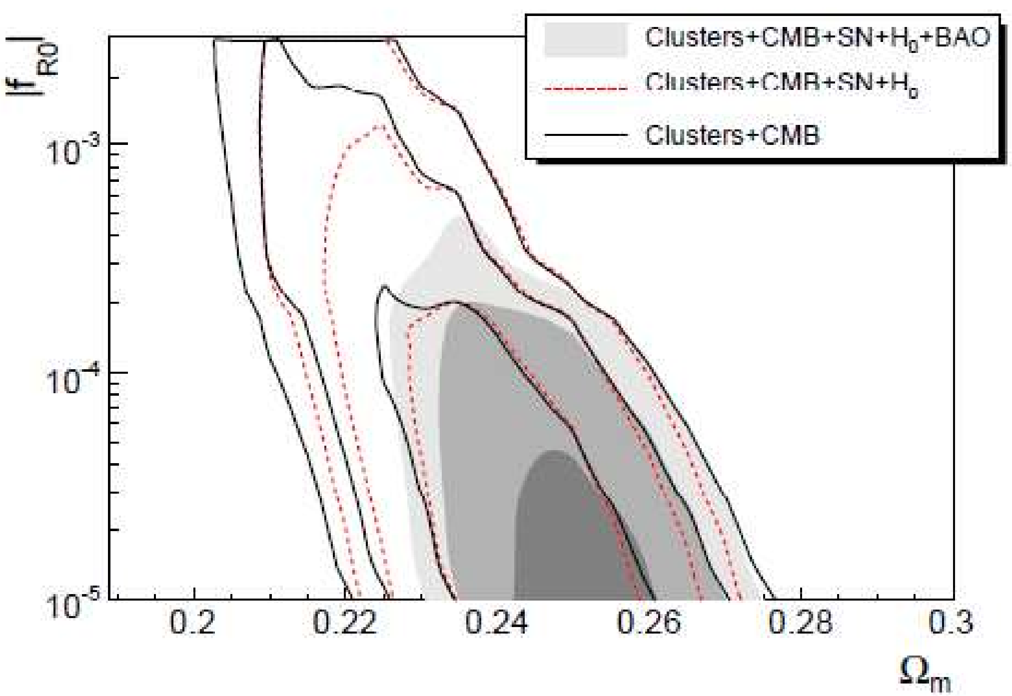
$$\epsilon(E) \propto \sqrt{\left(\frac{m_e}{kT}\right)} g N^2 \exp - E/kT$$

- If we can measure the temperature and density at different positions in the cluster then assuming the plasma is in hydrostatic equilibrium we can derive the gravitational potential and hence the amount and distribution of the dark matter. (e.g. Sarazin 1998)
  - $\nabla P = -\rho_{\rm gas} \nabla U = -\frac{GM}{r^2}\rho$, $P = \frac{\rho k T}{\mu m_{\rm H}}$
  - $\frac{dP}{dr} = \frac{k}{\mu m_{\rm H}}\left(T\frac{d\rho}{dr} + \rho\frac{dT}{dr}\right)$
  - $= \frac{\rho k T}{\mu m_{\rm H}}\left(\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right)$
  - $M = -\frac{kTr^2}{G\mu m_{\rm H}}\left(\frac{d\log\rho}{dr} + \frac{d\log T}{dr}\right)$

T, N from X-ray spectra → mass

28 Cluster constraints on f(R) gravity

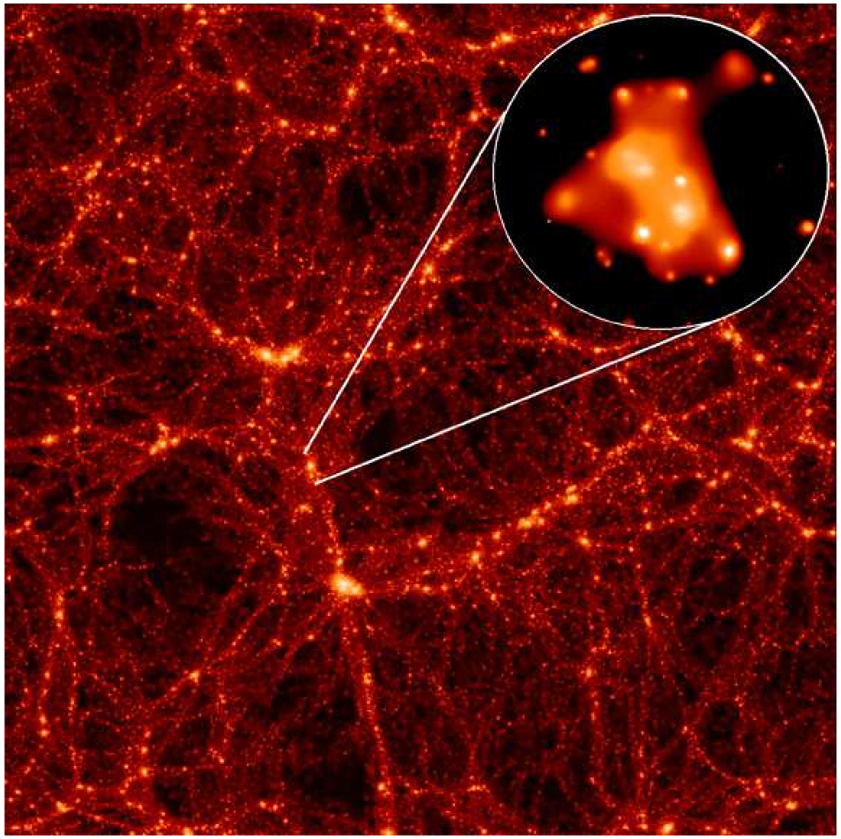




- Parameter f(R0) controls the strength and range of the force modification
- In order to be compatible with the Solar System GR tests, f(R0)<10^{-5}

Schmidt, F. etal 2009, PhRevD80h3505

29 Galaxy Clusters have a lot in common

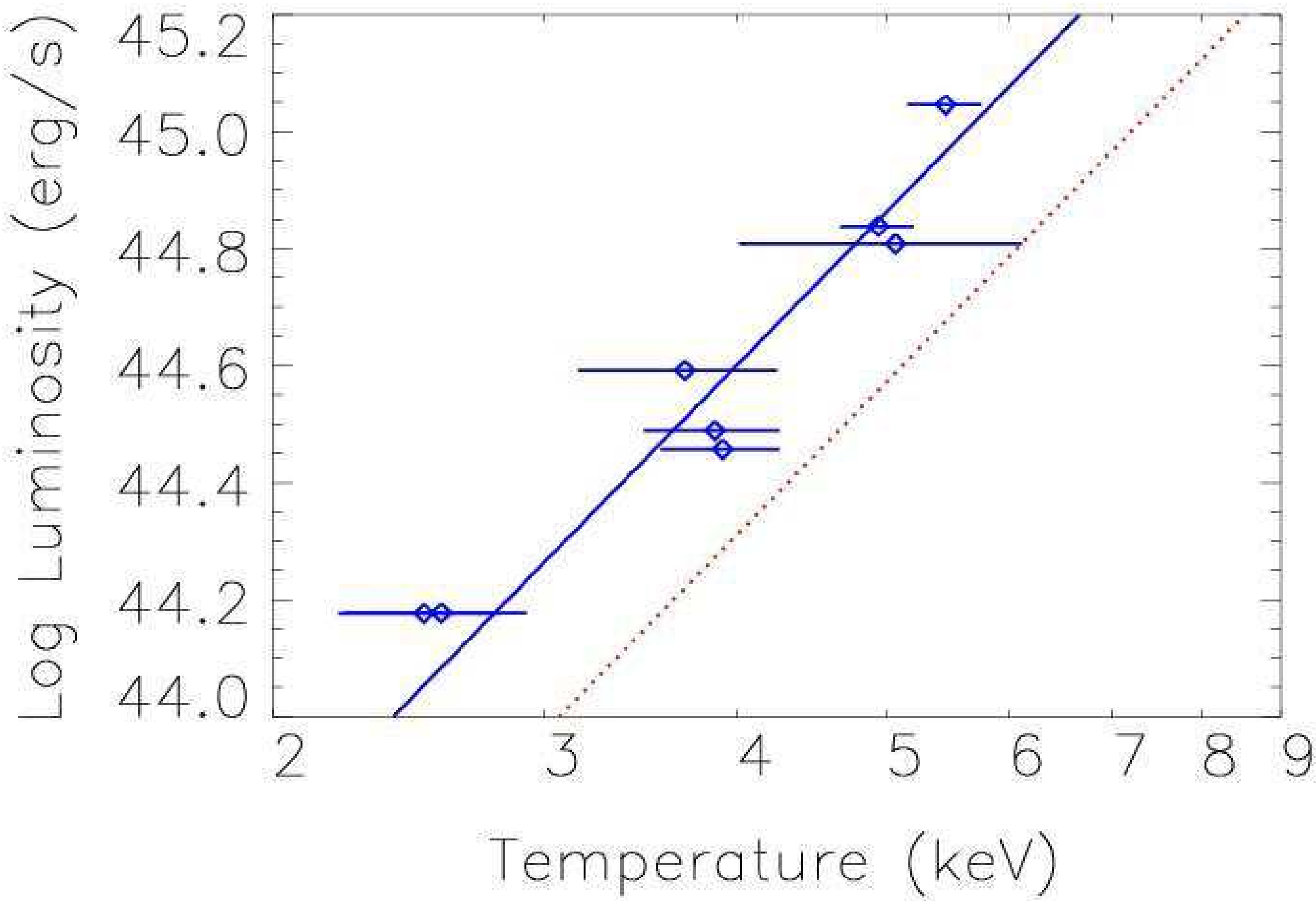


Virgo consortium; Jenkins et al. 1998

The observed M-T-L correlations → high-redshift clusters were denser than at present - hotter and more luminous for a given mass, as expected in a theory of the hierarchical self-similar formation. (in general..)

- Number of surveys with XMM and Chandra. E.g. z = 0.6-1.0 the Universe was half its present age.
- Icluding two merging clusters and an extremely massive "relaxed" cluster.
- **The galaxy clusters are weakly self-similar.**
- Vikhlinin et al. 2002, ApJ 578, 107 Correlations between X-ray temperature, luminosity, and gas mass: evolution in all three correlations between z>0.4 and the present epoch.
- Ω=0.3, Λ=0.7 cosmology: $L(T) \propto (1+z)^{1.5}$; $M_{gas}(L) \propto (1+z)^{-1.8}$ and $M_{gas}(T) \propto (1+z)^{-0.5}$

30 Redshift evolution of the L-T relation for clusters of galaxies



Redshift evolution of the lt relation for clusters of galaxies

Image courtesy of D. H. Lumb, J.G. Bartlett et al.,

European Space Agency

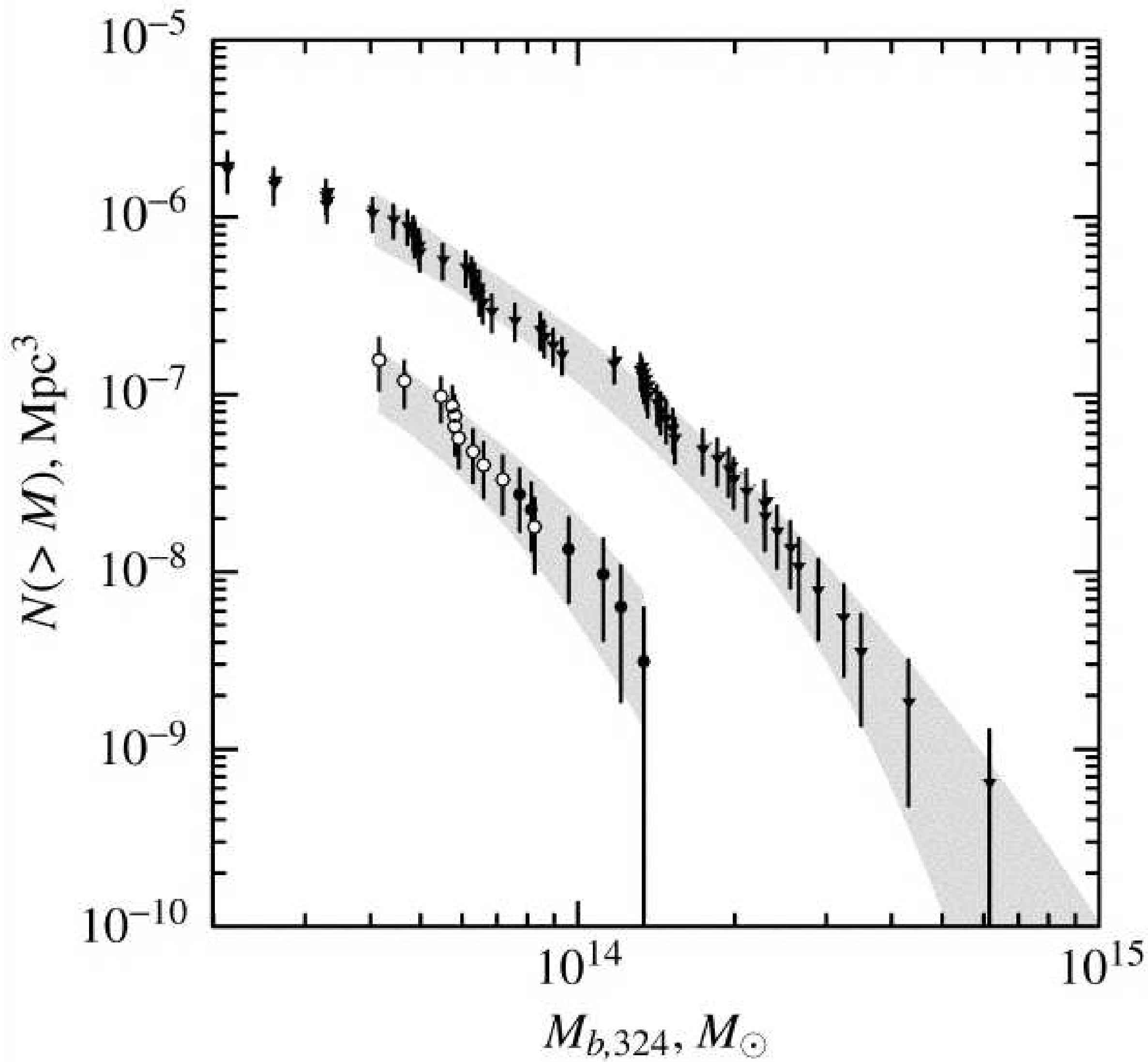
- galaxy clusters for a redshift range 0.45<z<0.62
- Low-Redshift clusters there is evolution with redshift

Cosmological simulations predict distributions of masses. If we want to use X-ray selected samples of clusters of galaxies to measure cosmological parameters then we must be able to relate the observables (X-ray luminosity and temperature) to the theoretical masses.

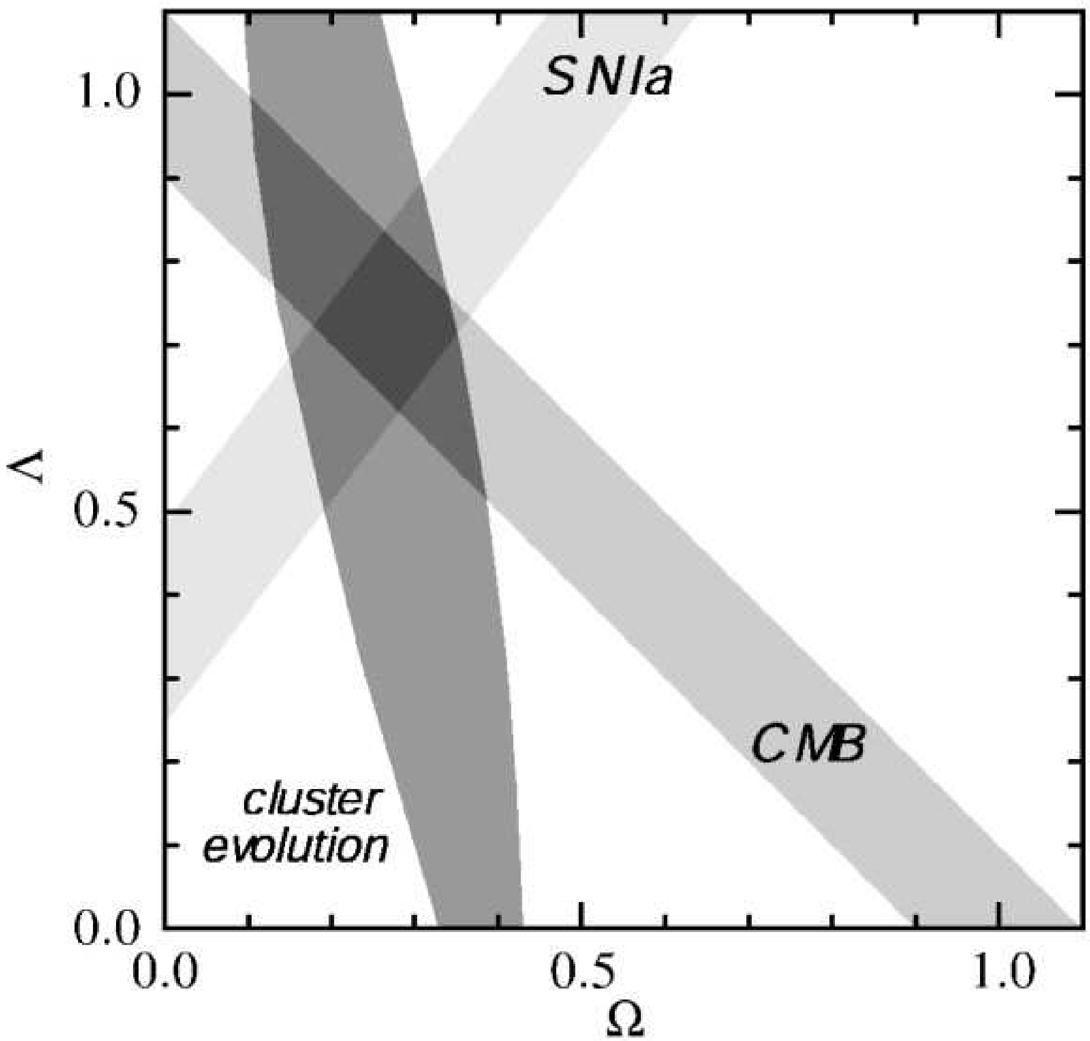
31 Cosmology from cluster evolution (Vikhlinin et al. 2003)

- Barion mass fraction from measuring T_X and L_X and used as a proxy for total M
- Cosmological simulations predict the cluster mass function at any redshift
- Constraining N of cluster of given mass with redshift constarins cosmological models.
- Most of the difficulties are on the observational side.

- Baryon mass function for the cluster survey with 0.4<z<0.8. measured by Chandra barion mass measurments: data points
- Grey: computed theoretical mass function (Ω_m=0.3, Λ=0.7) includng error bars.
- Upper curve: local Universe, cosmology independent



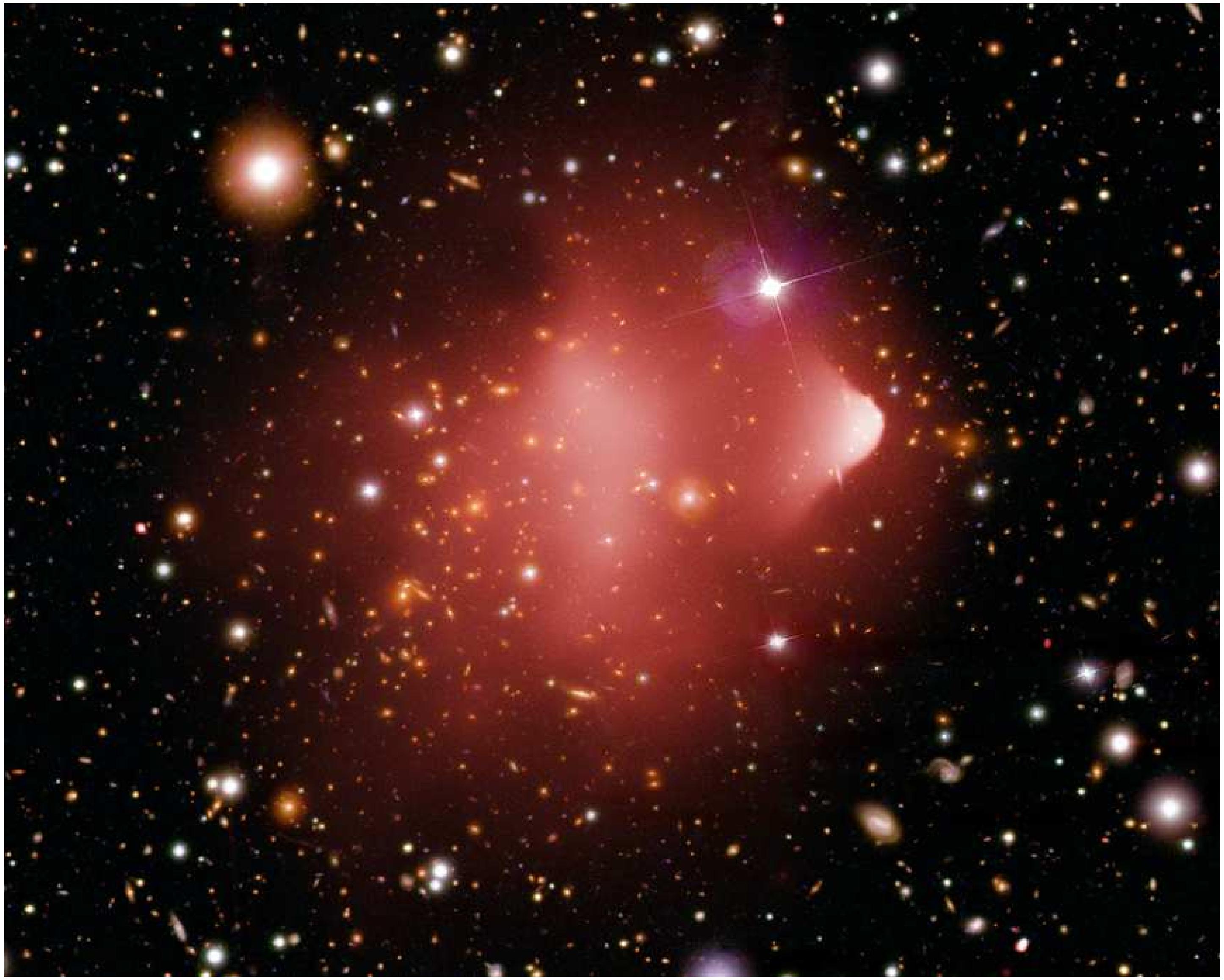
32 Cosmology from cluster evolution (Vikhlinin et al. 2003)



-- Independent on other methods

-- New surveys are underway

33 The Bullet Cluster (two interacting clusters)

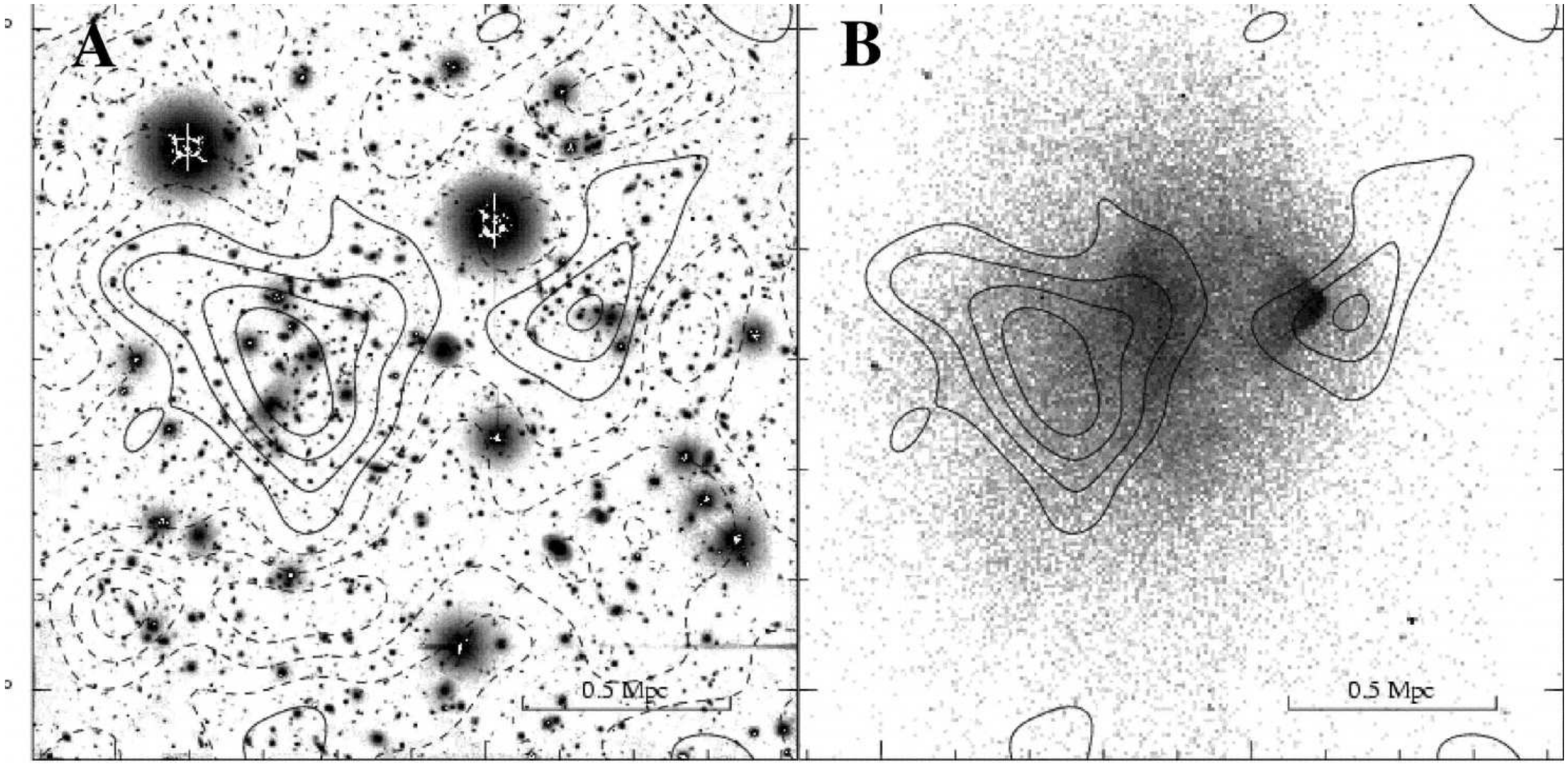


X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/D.Clowe et

- System has just undergone pass-through: the two clusters are now moving away from one another.
- no γ-rays, no antimatter!

34 Does gravitational potential trace barions?

Weak-lensing maps overlayed with X-ray image



Clowe et al. 2004 ApJ 604, 596

- Galaxies are collisionless particles in the pass-through
- There is agreement in position between the mass peak and galaxy overdensity
- The X-ray gas:the ram pressure of the interacting gas halos, it is slowed down during interaction
- There is offset between barionic density (X-ray) and mass density
- Bulk of the mass is collsionless as expected for the **dark matetr**