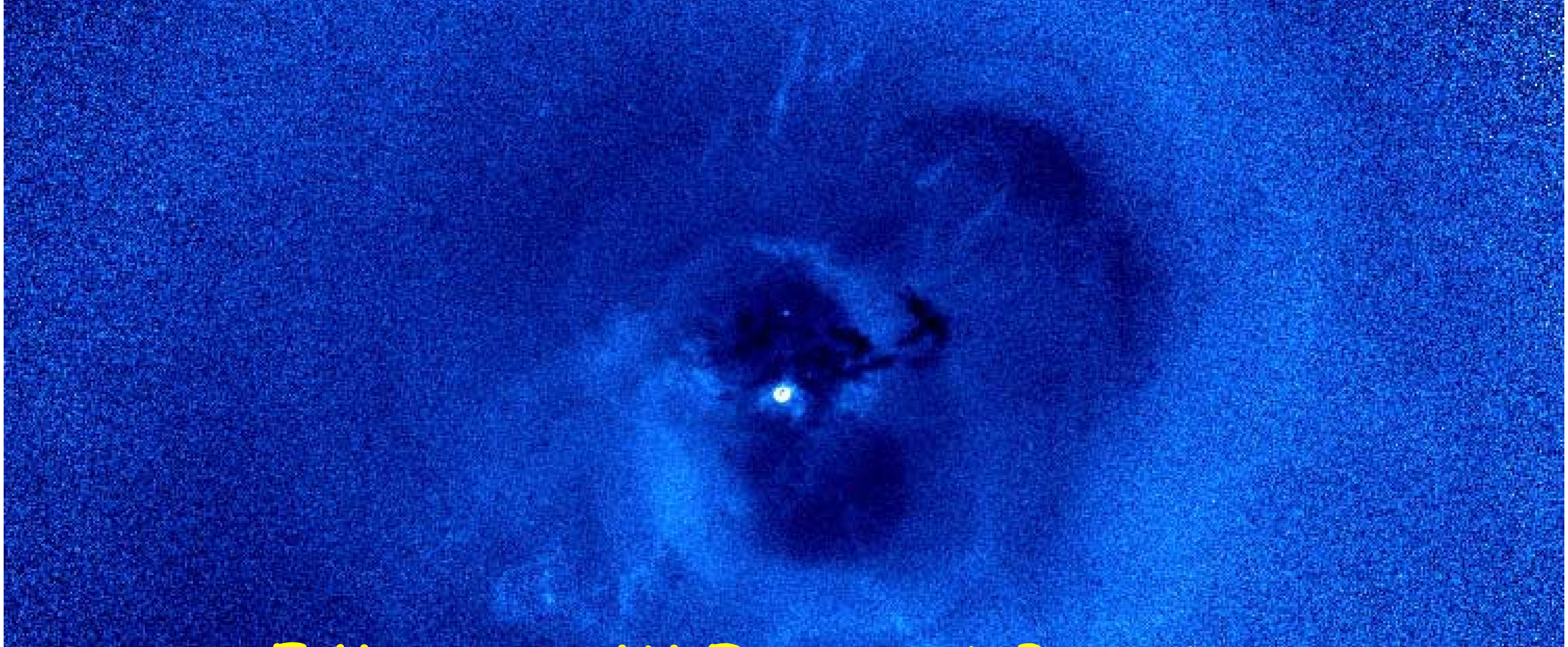
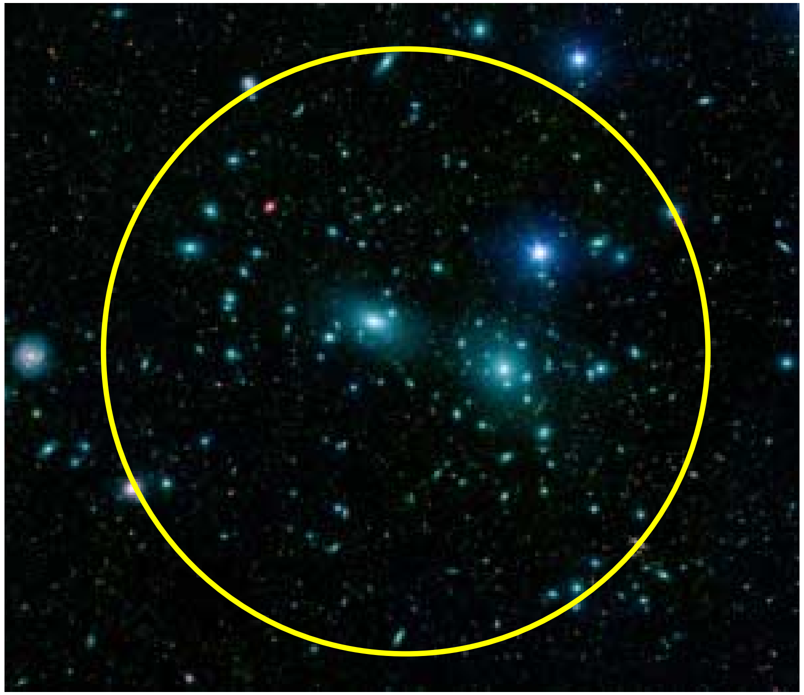
Скопления галактик и сверхмассивные черные дыры



Е.Чуразов, W.Forman, А.Вихлинин,
Р.Сюняев, S.Tremaine, C.Jones,
H.Boehringer, С.Сазонов, M.Brueggen,
C.Kaiser, S.Heinz, O.Gerhard


Coma cluster, SDSS

Clusters and Dark Matter



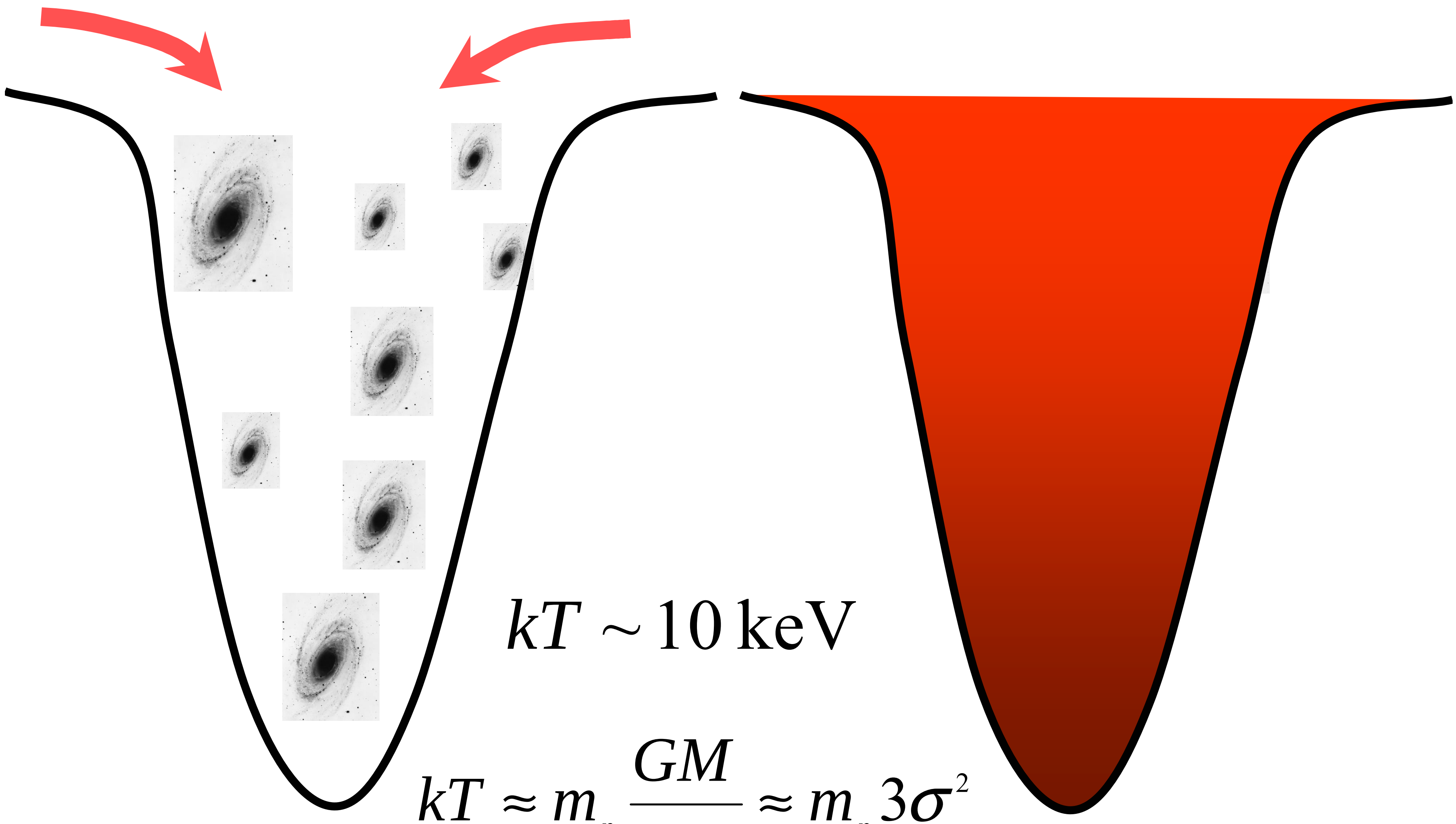
$$R \sim 1\,\text{Mpc}, \quad \sigma \sim 1000\,\text{km/s}$$

$$T = -\frac{1}{2}U$$

$$\frac{GM}{R} \approx \langle \text{v} \rangle^2 = 3\sigma^2$$

While examining the Coma galaxy cluster in 1933, **Zwicky** was the first to use the virial theorem to infer the existence of unseen matter, what is now called dark matter. He obtained a cluster mass about 160 times greater than expected from galaxies luminosity, and proposed that most of the matter was dark.

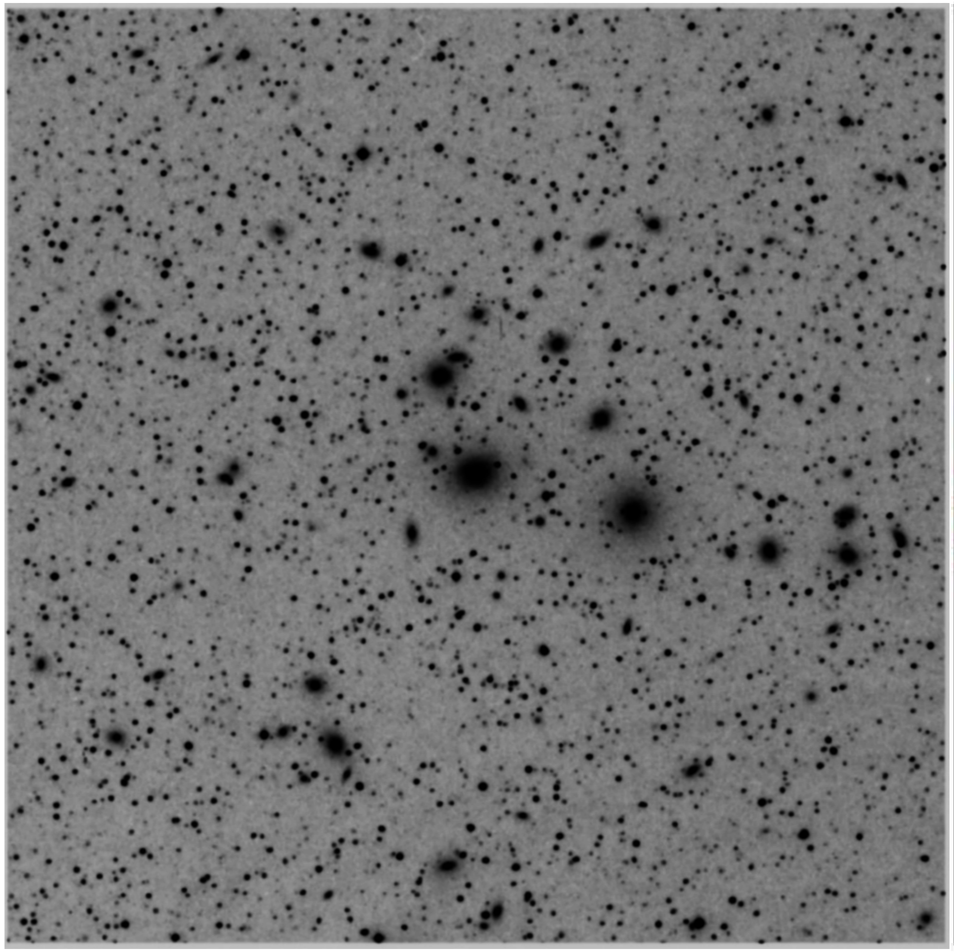
(DM) Potential Well + Gas (baryons)



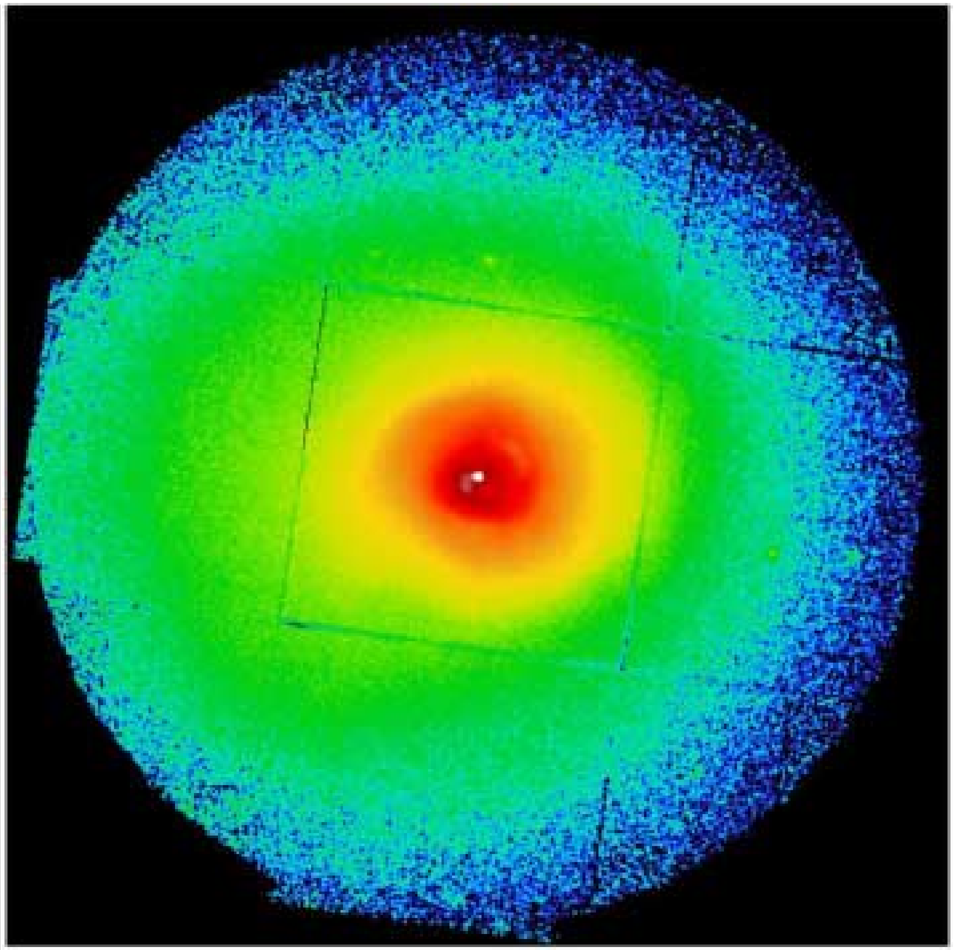
$$kT \sim 10\,\mathrm{keV}$$

$$kT \approx m_p \frac{GM}{R} \approx m_p 3\sigma^2$$

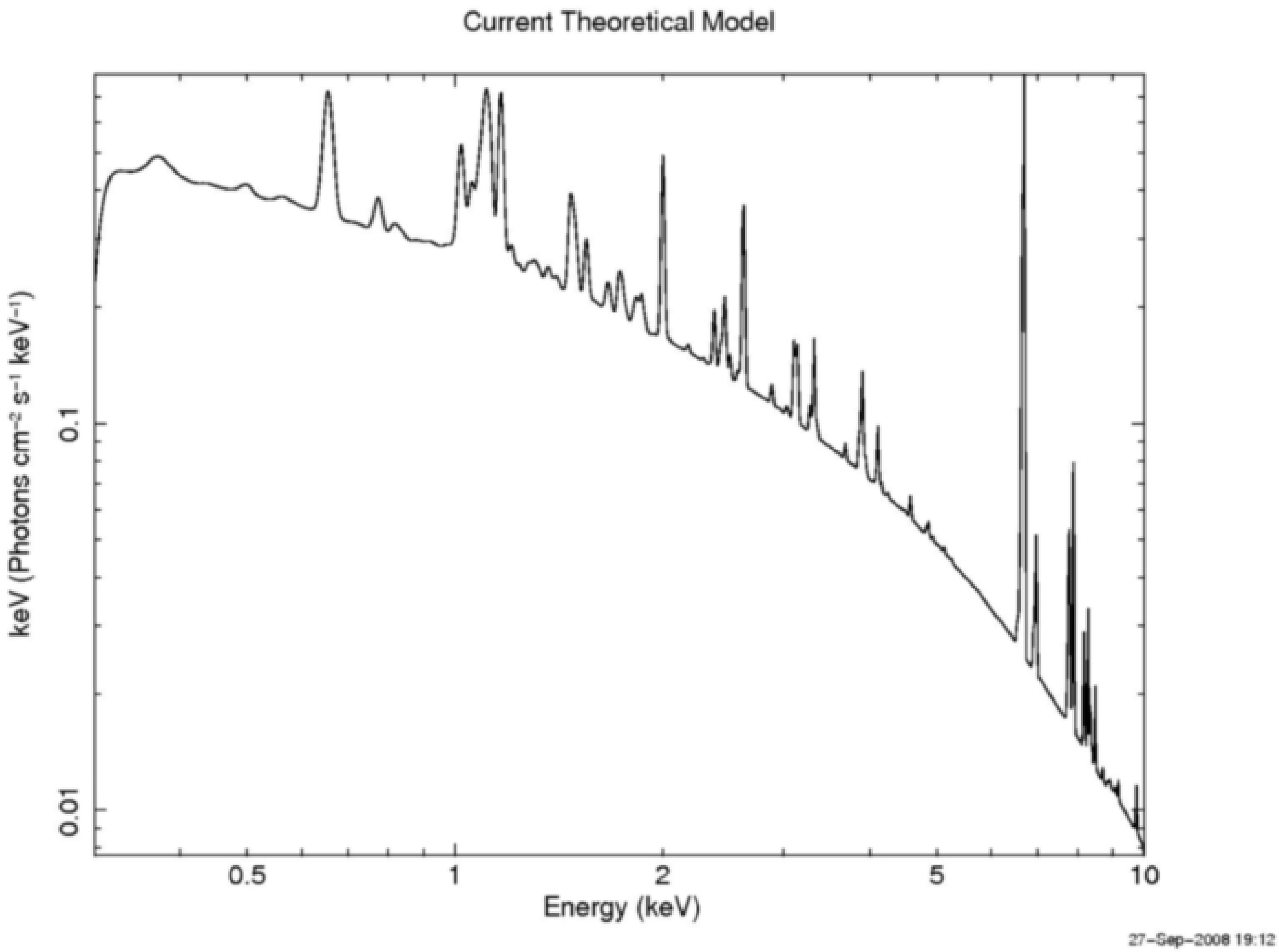
Optical



X-rays

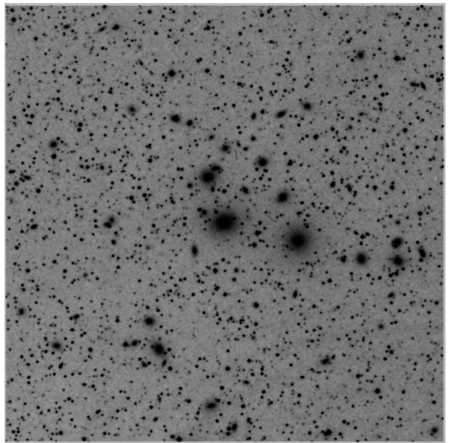


Typical X- ray spectrum of a cluster

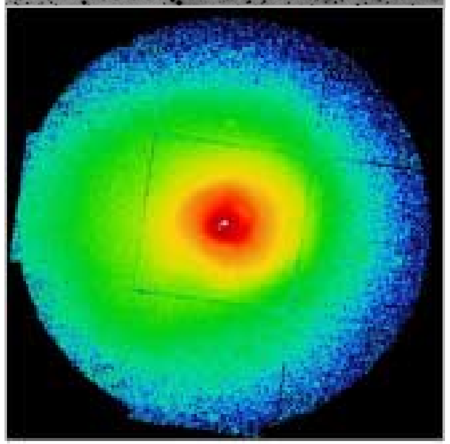


Bremsstrahlung + emission lines of ions (like He-like Fe)

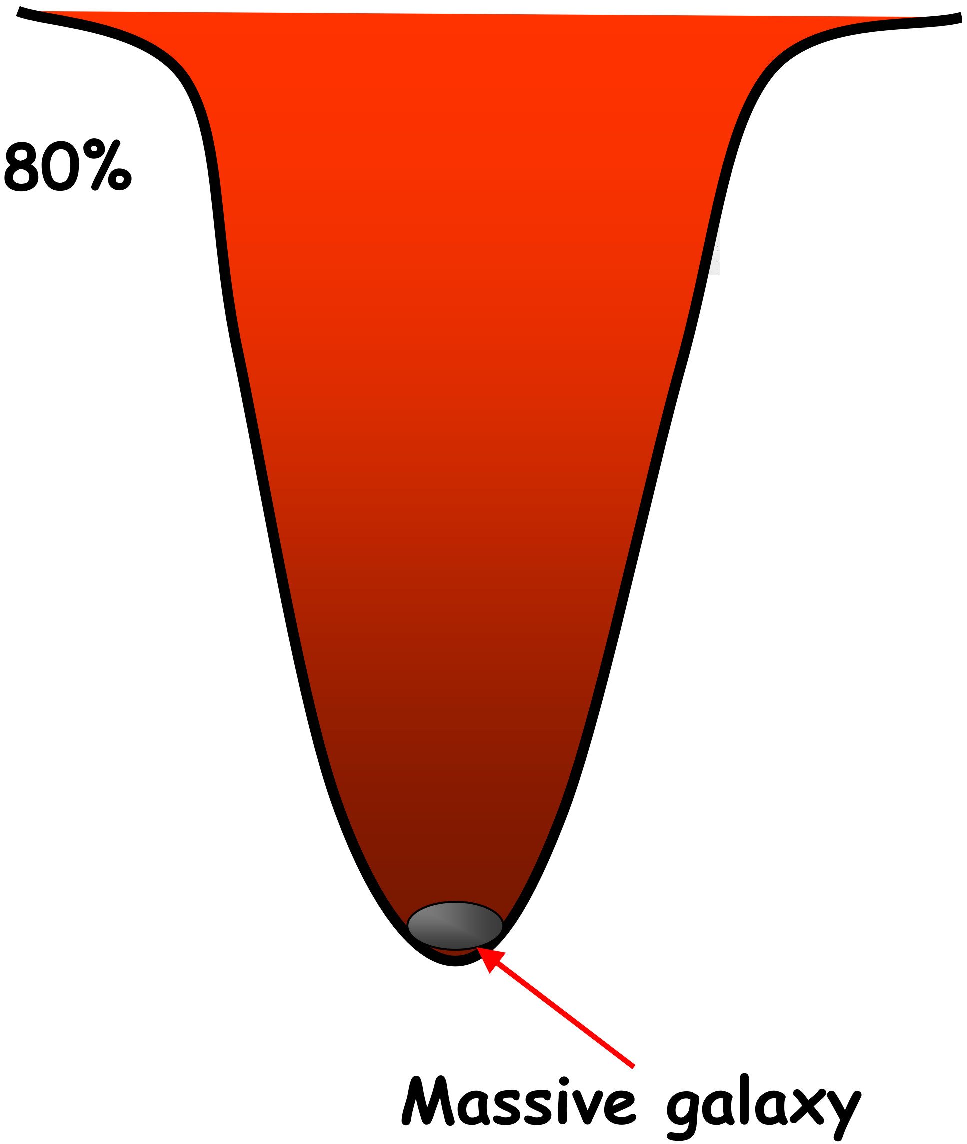
Dark matter ~80%



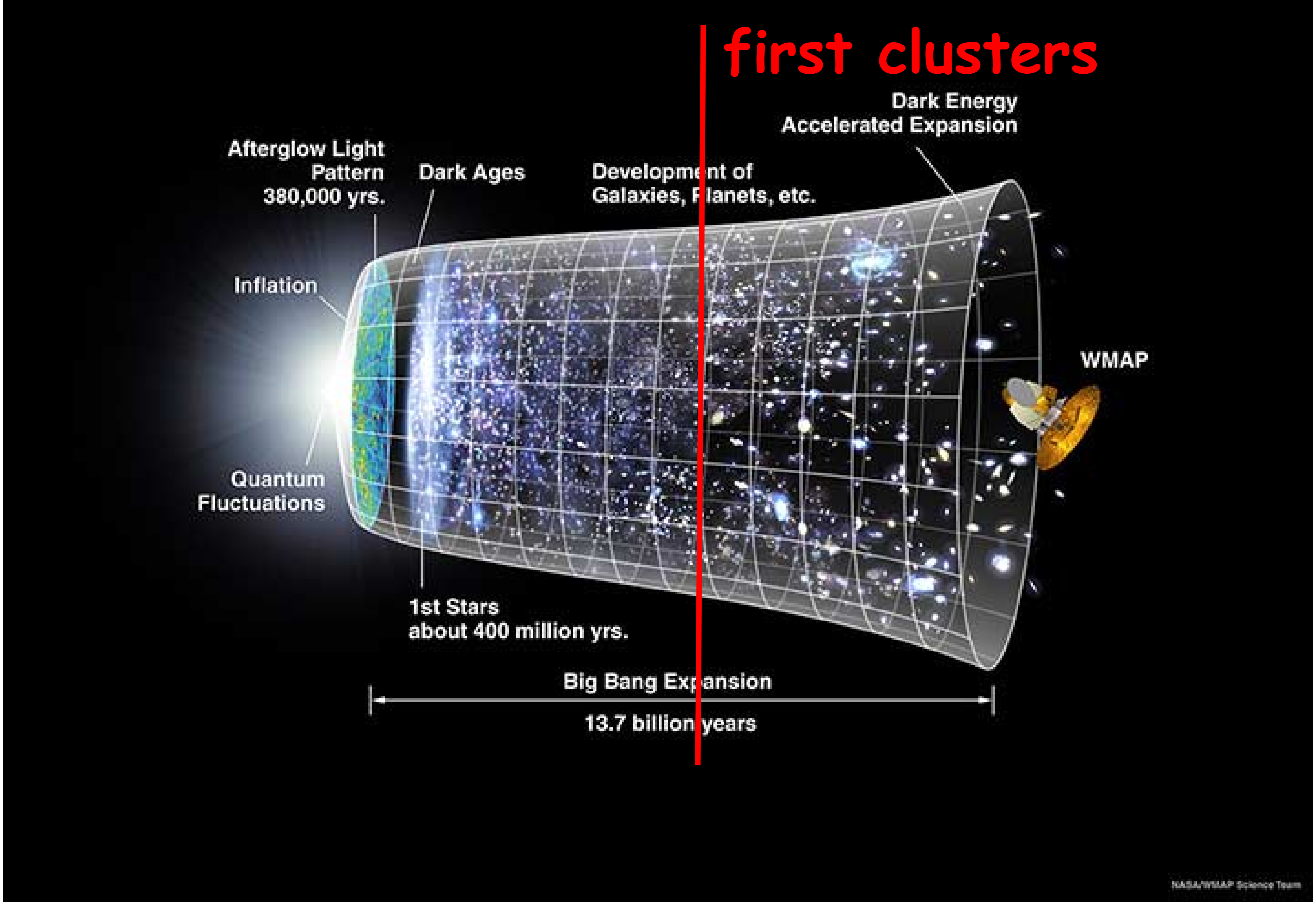
Stars, few %



Gas,~15%



Clusters of galaxies and Dark Energy



Clusters of galaxies and Dark Energy

$$\Omega_M, \quad \Omega_\Lambda$$

$$p_X = w\rho_X$$

$$w = w_0 + w_a(1-a)$$

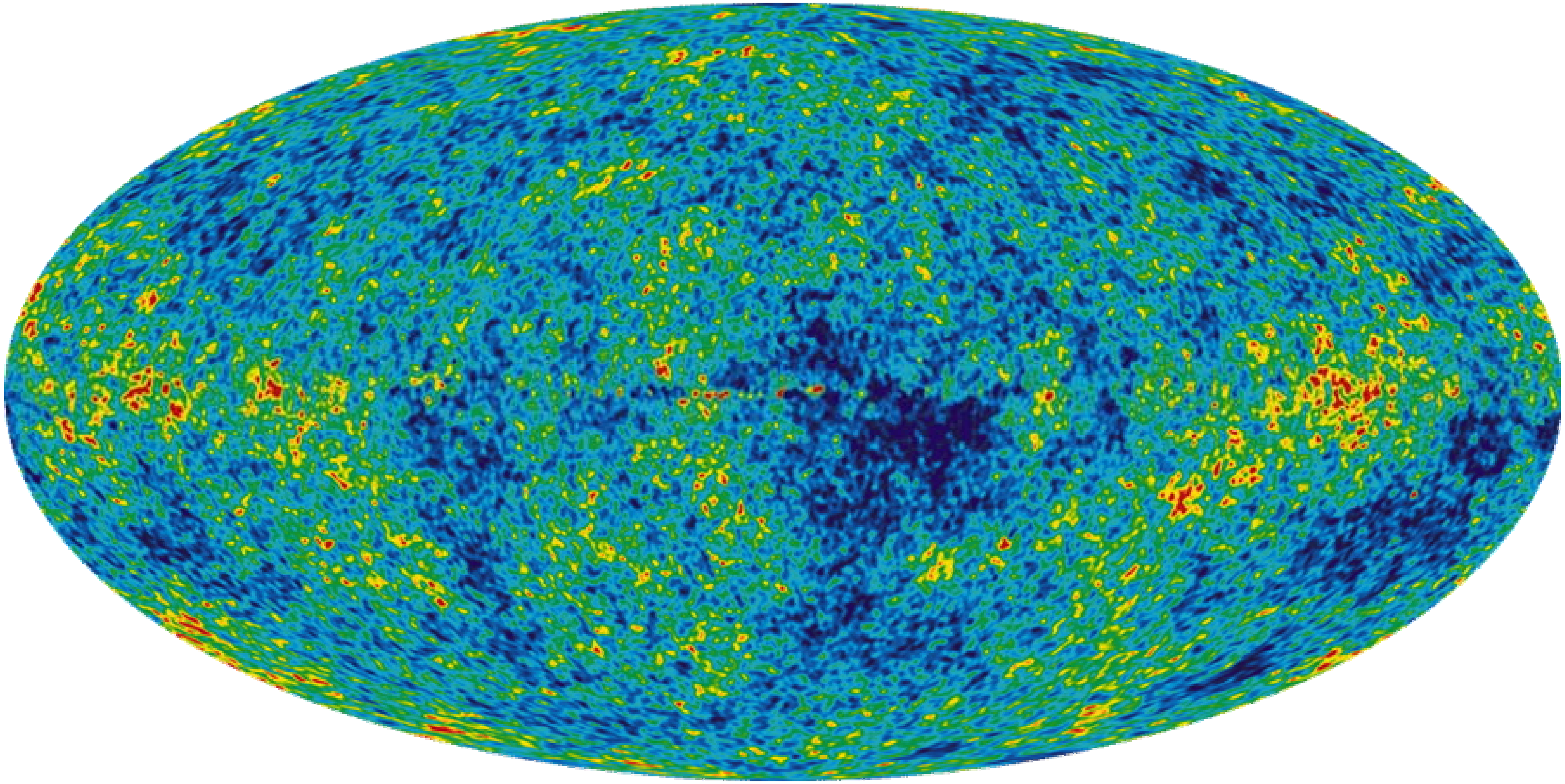
$$w \equiv -1 \ \text{Cosmological Constant}$$

$$\Omega_\Lambda \approx 0.75 \ \text{at } z = 0, \quad \Omega_\Lambda \approx 0.1 \ \text{at } z = 2$$

How to measure DE properties (equation of state)?

Standard candle - SNIa
Standard rules – baryonic oscillations (clusters, galaxies,….)
Growth of perturbations – number of clusters (clusters, lensing)

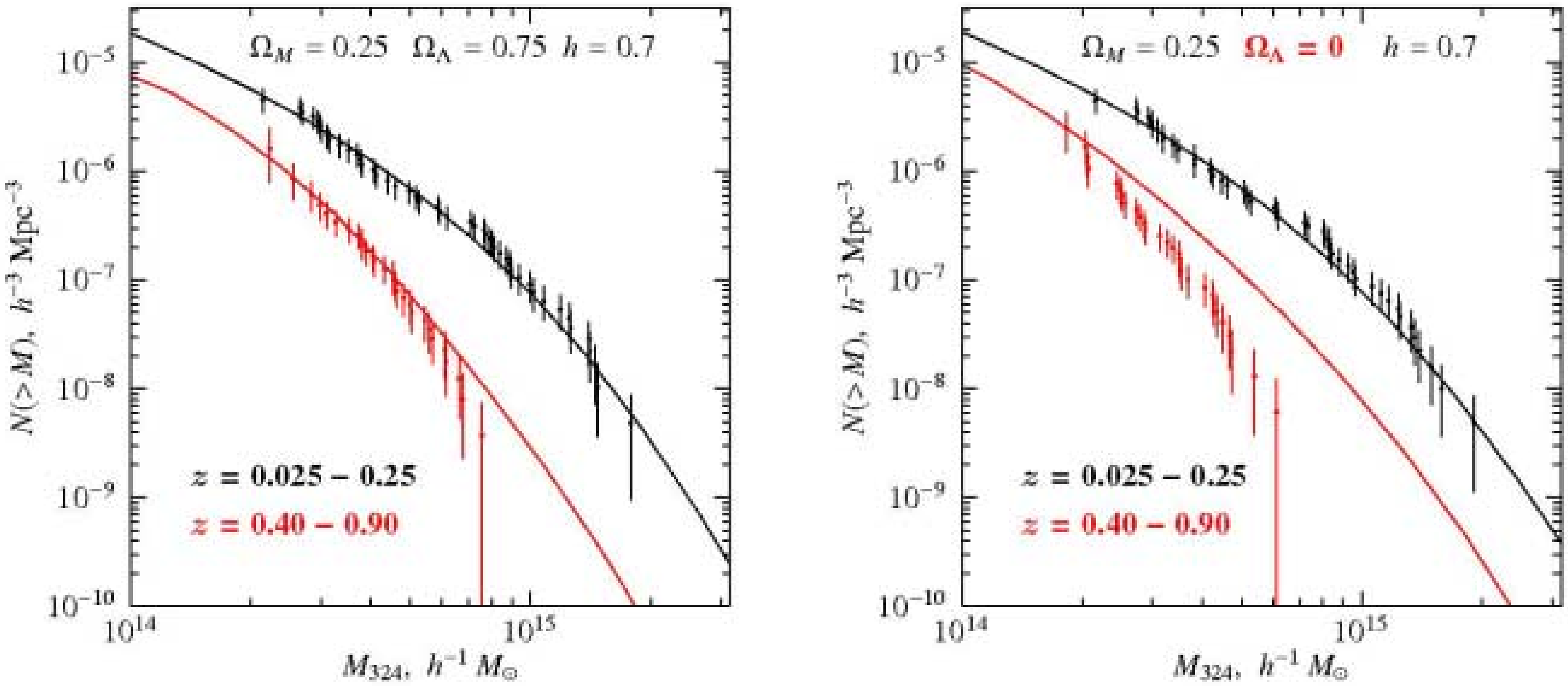
WMAP: Temperature fluctuations ~10^{-5}



Use theory + observations (e.g. CMB) as initial conditions

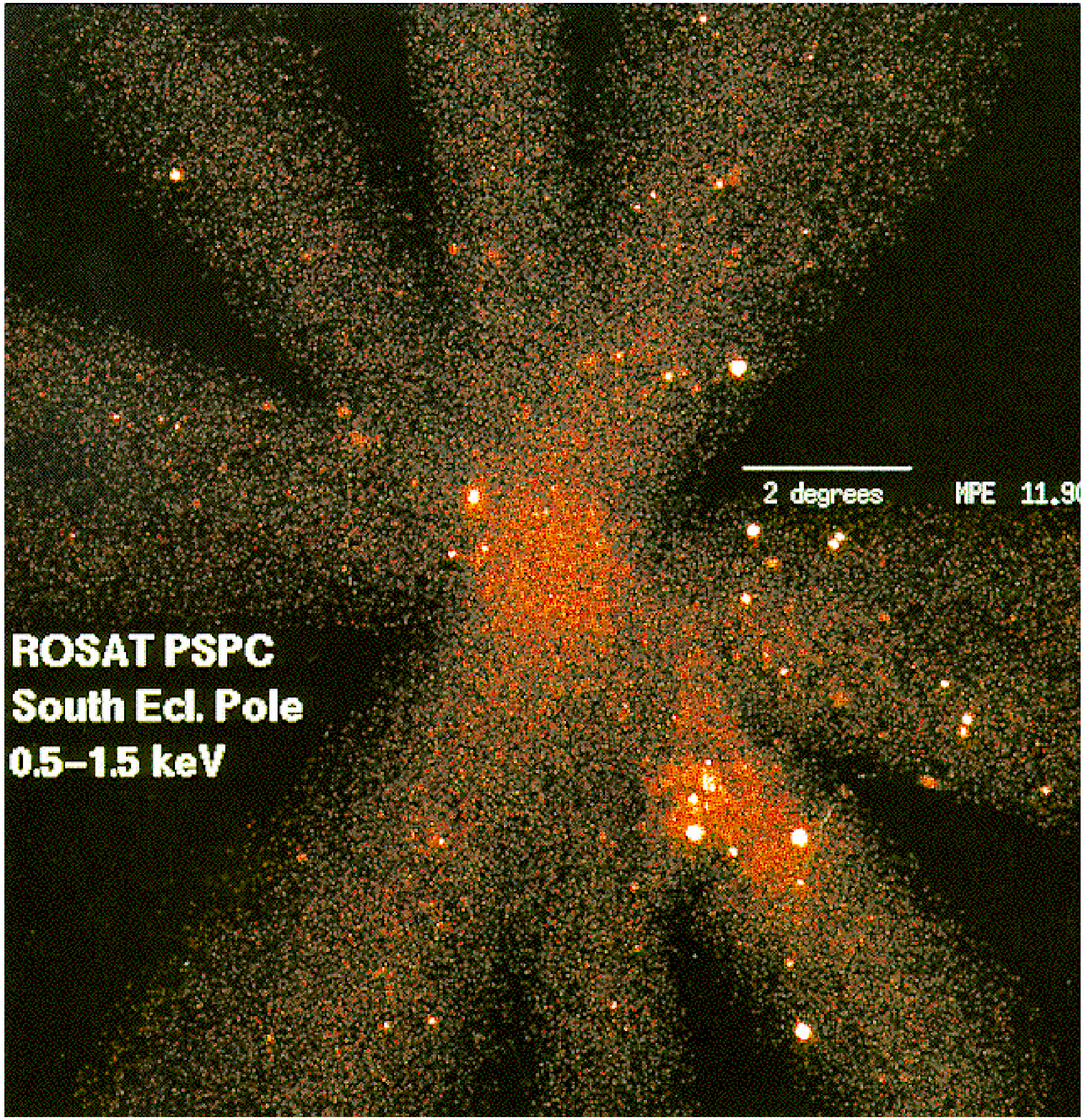
[redacted]

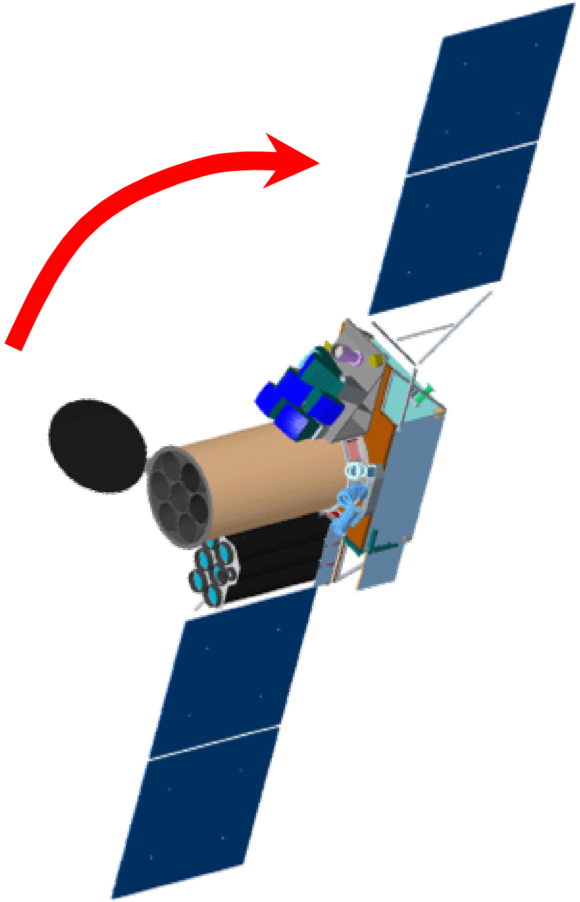
Clusters mass function at different redshifts



Vikhlinin et al., 2006, 2008
Burenin et al., 2007

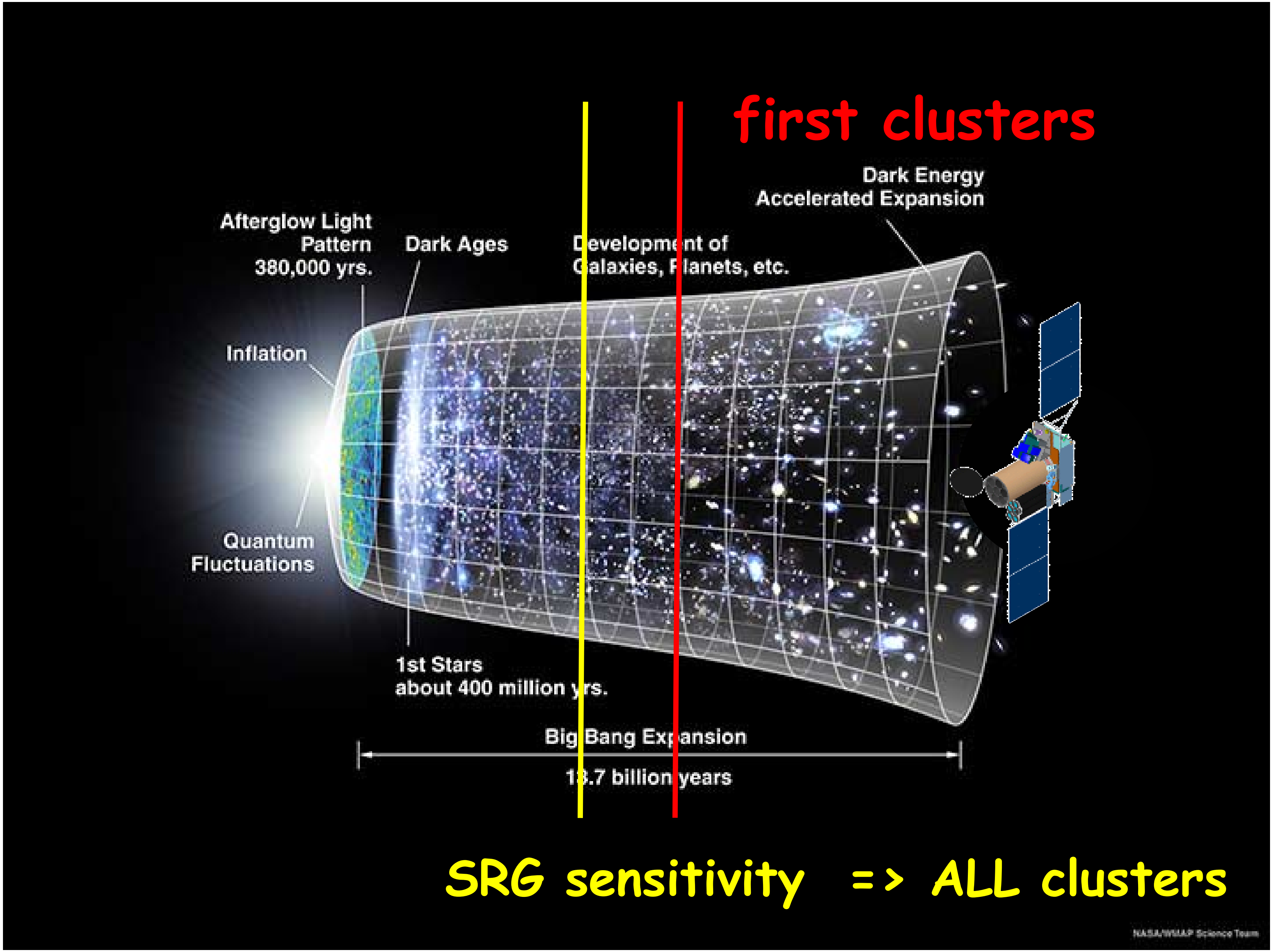
Spectrum-RG All-Sky Survey (2011-2015)





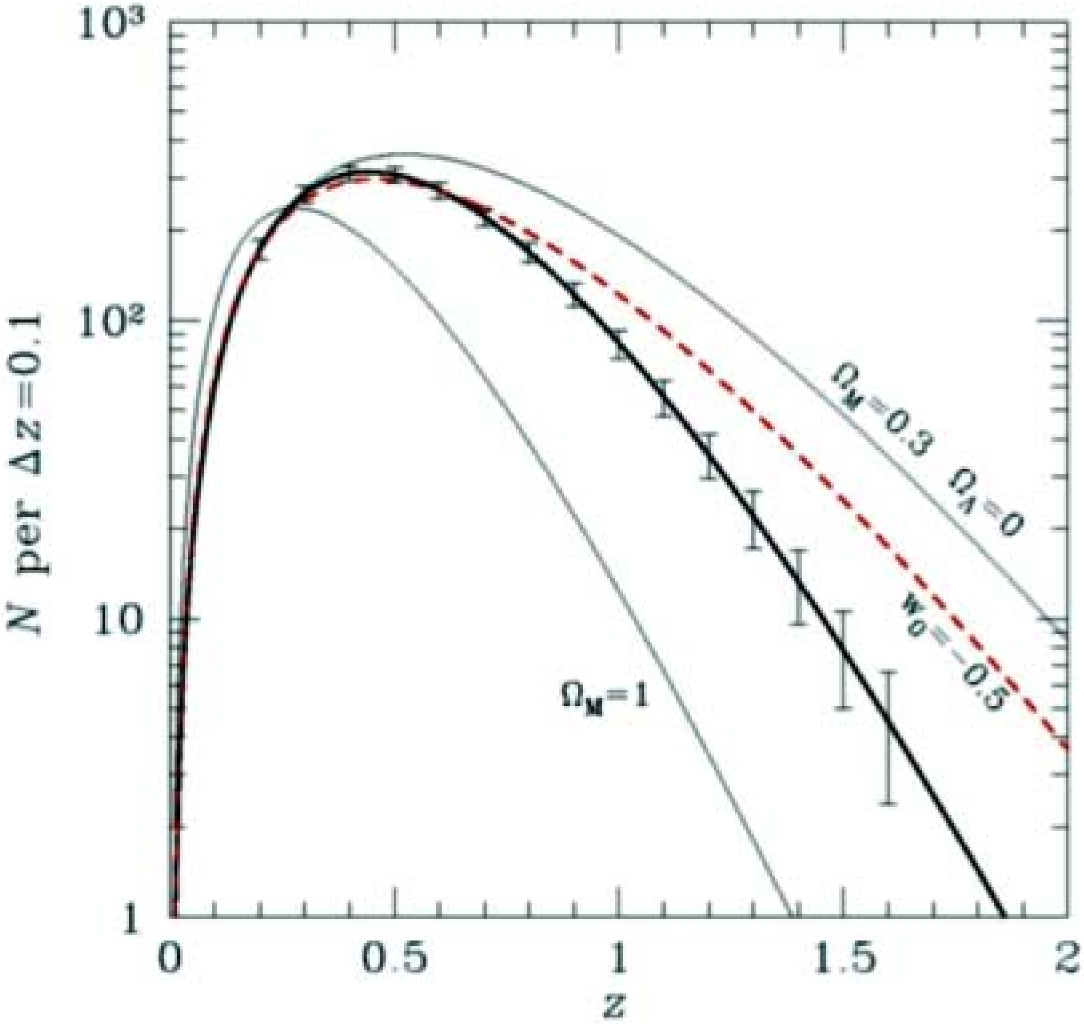
Spectrum-RG All-Sky Survey

Area covered	**41 253 deg^2**
Duration	**4 years**
Mean exposure per field	**1315 c**
Sensitivity (0.5-2 keV)	**4×10^{-14} erg cm^{-2} s^{-1}**
Expected number of clusters	**~100000**


first clusters
Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
380,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
SRG sensitivity => ALL clusters
NASA/WMAP Science Team

Number of clusters as a function of redshift

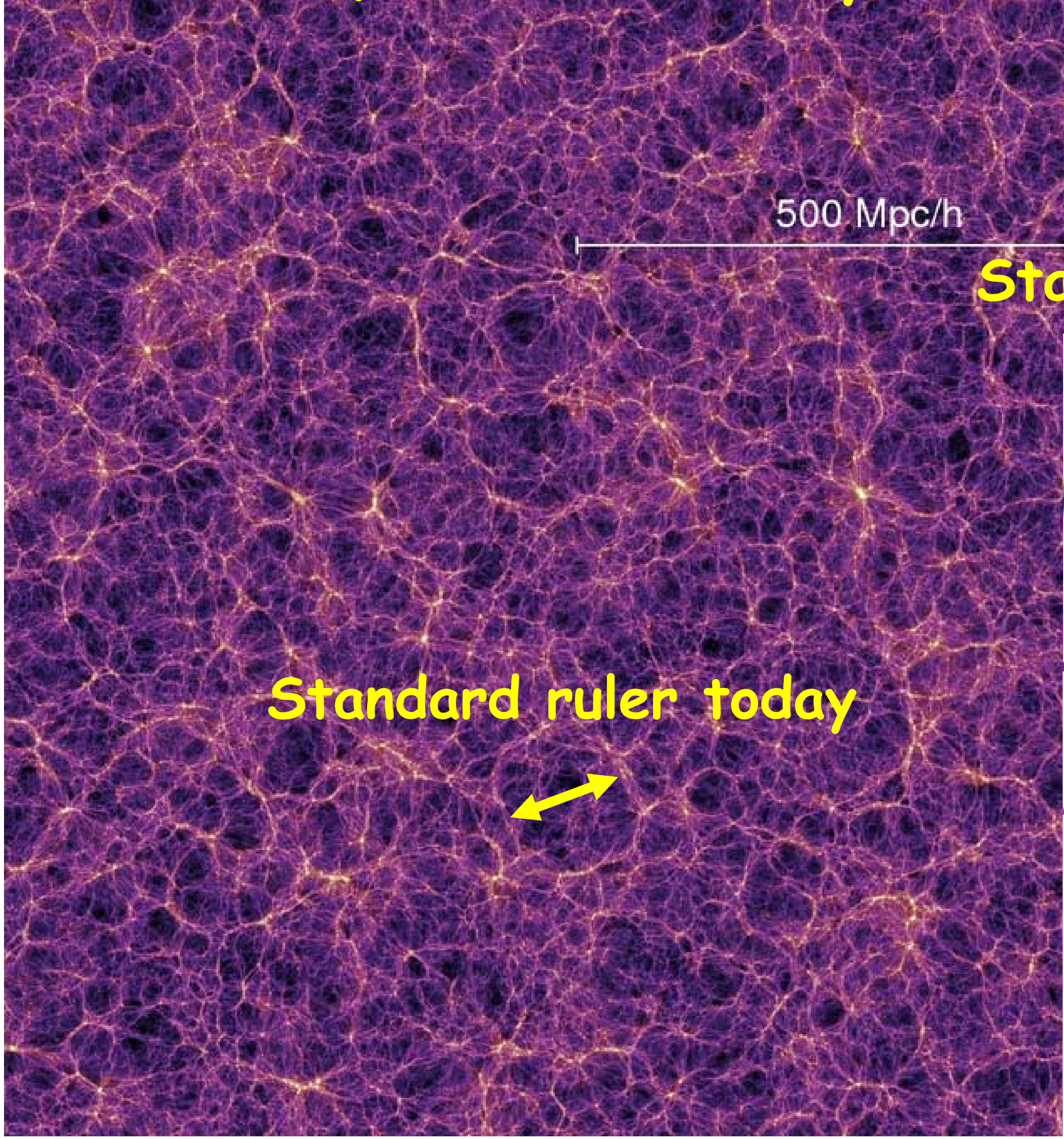
Concordance model: $\Omega_M=0.3$, $\Omega_\Lambda=0.7$, h=0.73
Normalization at z=0.2 (σ_8)

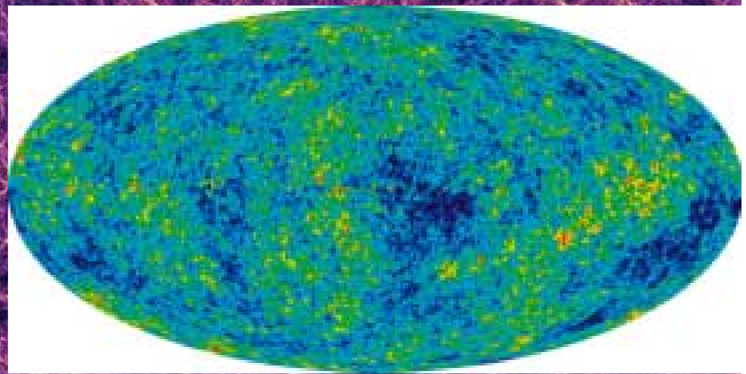


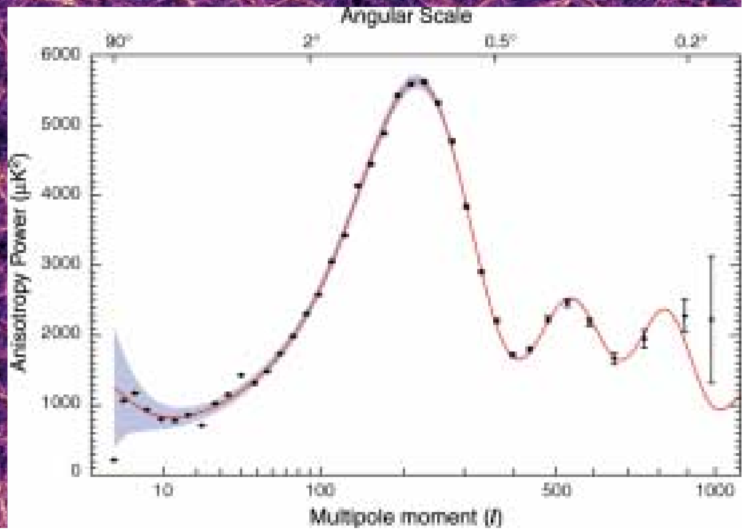
~2000 clusters from Spectrum-RG survey

[redacted]

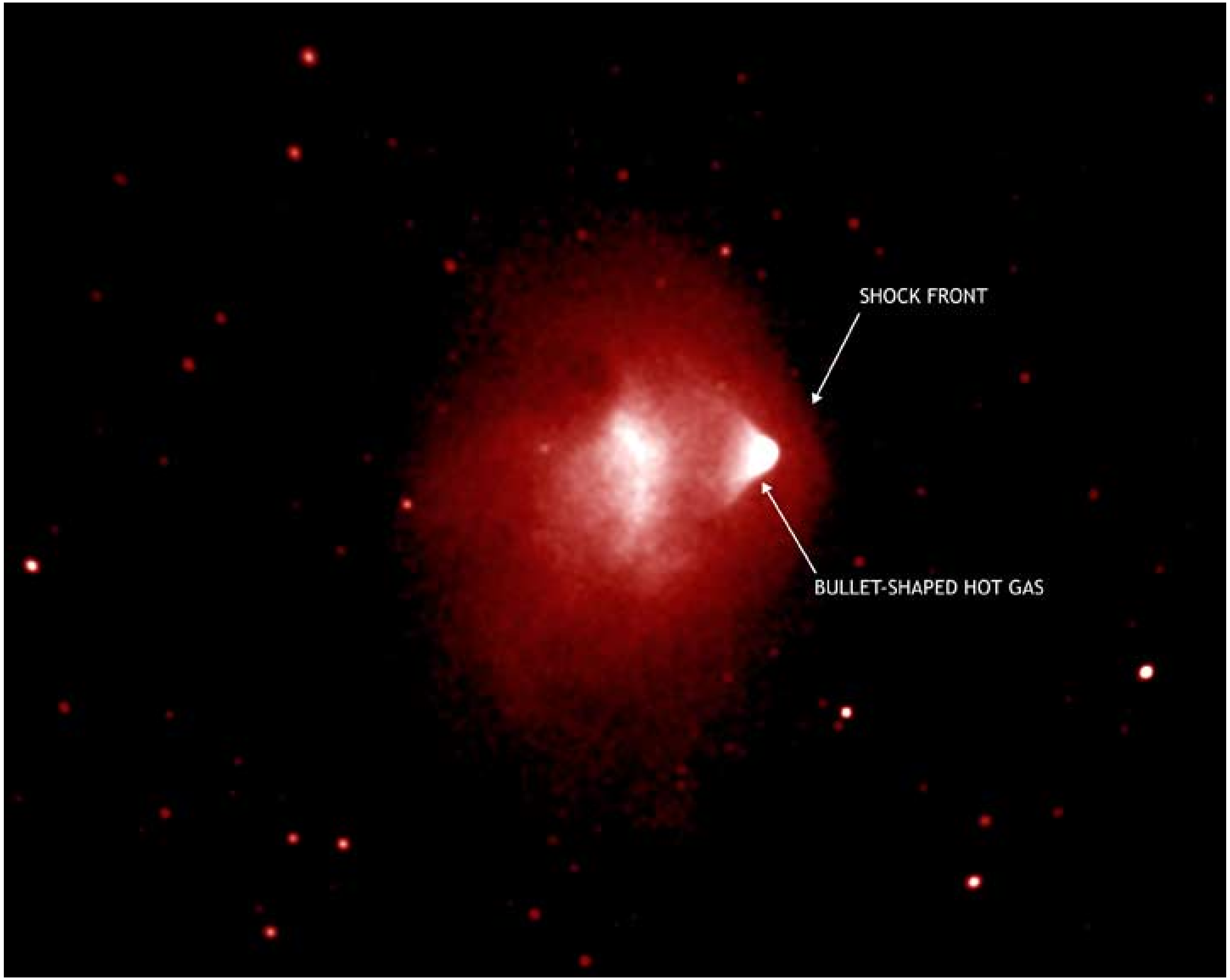
Baryonic oscillations (Zeldovich, Sunyaev, Peebles, Yu)



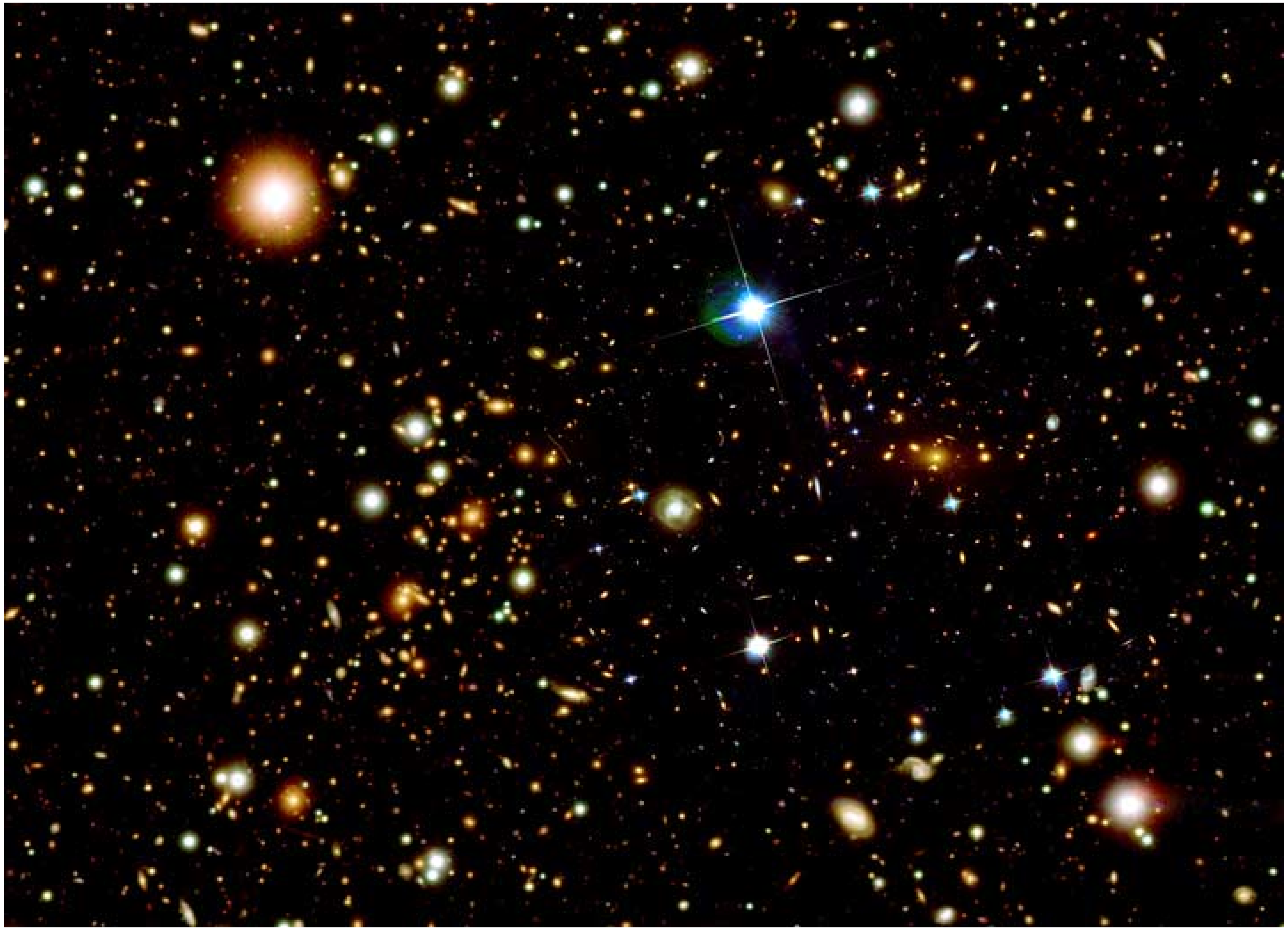




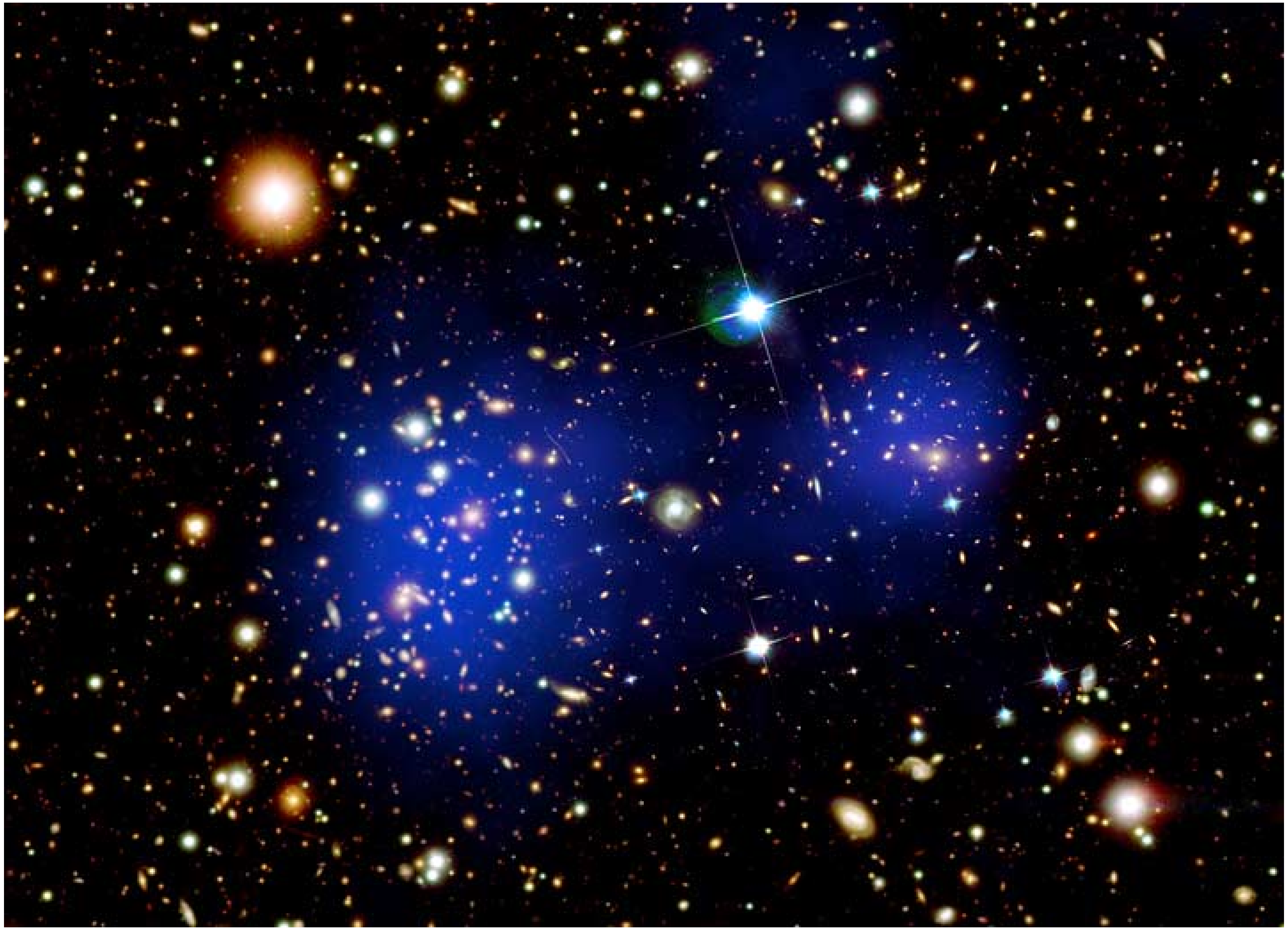
Back to Dark Matter – direct empirical evidence



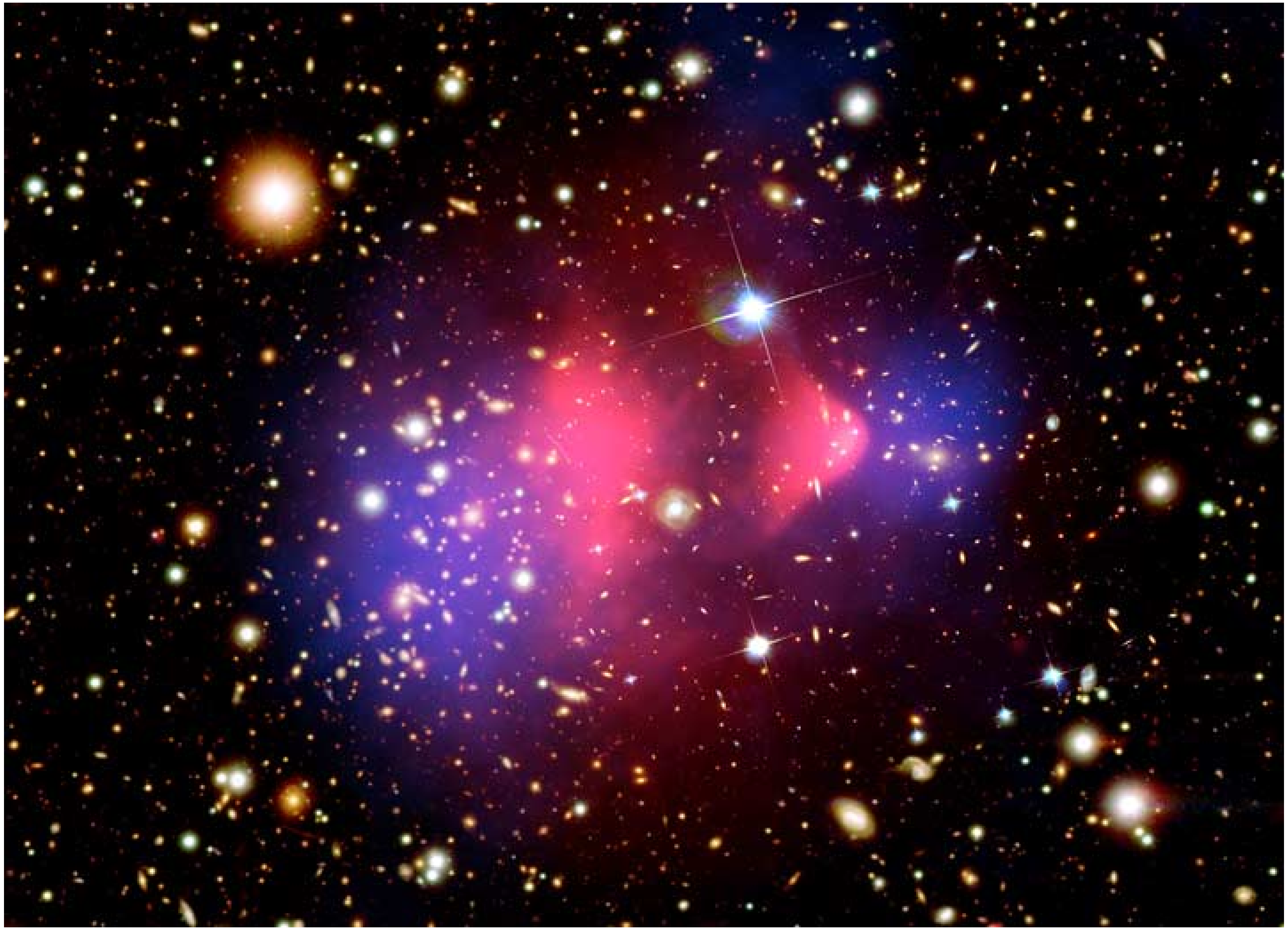
Bullet cluster, X-ray image (Markevitch et al.)



Optical image of the same cluster



Mass distribution (from lensing)



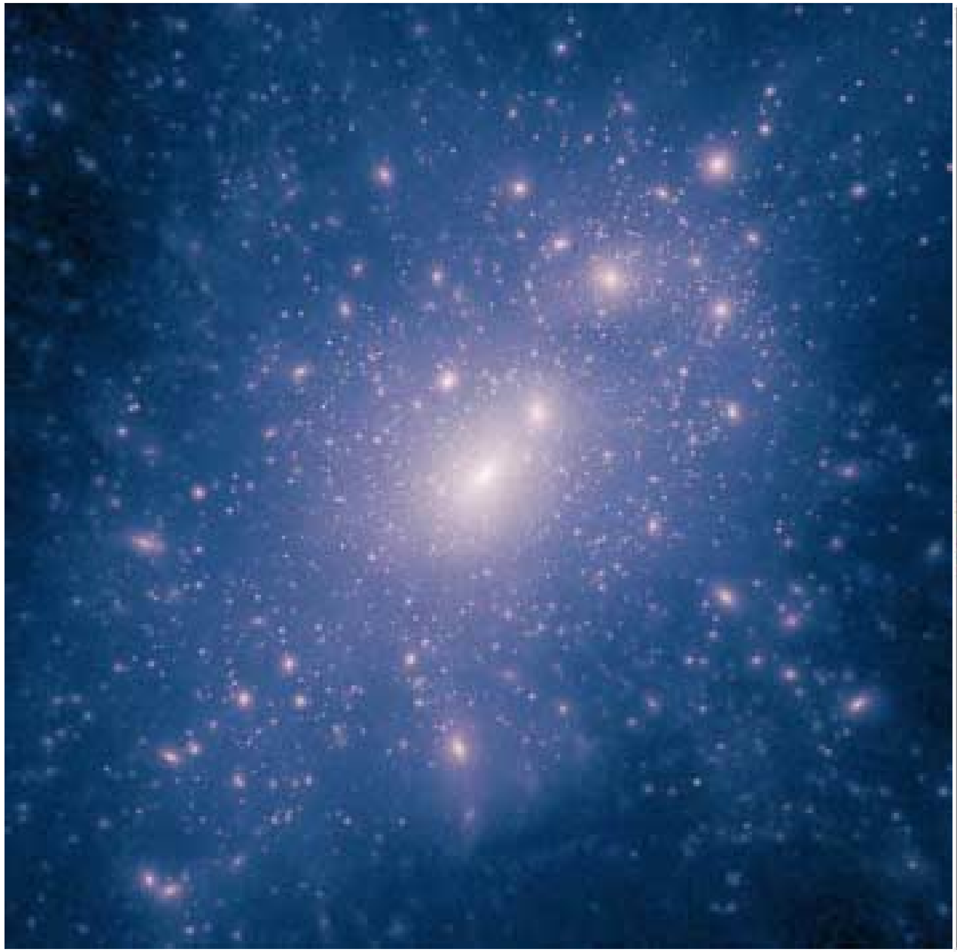
Optical, Mass, X-rays

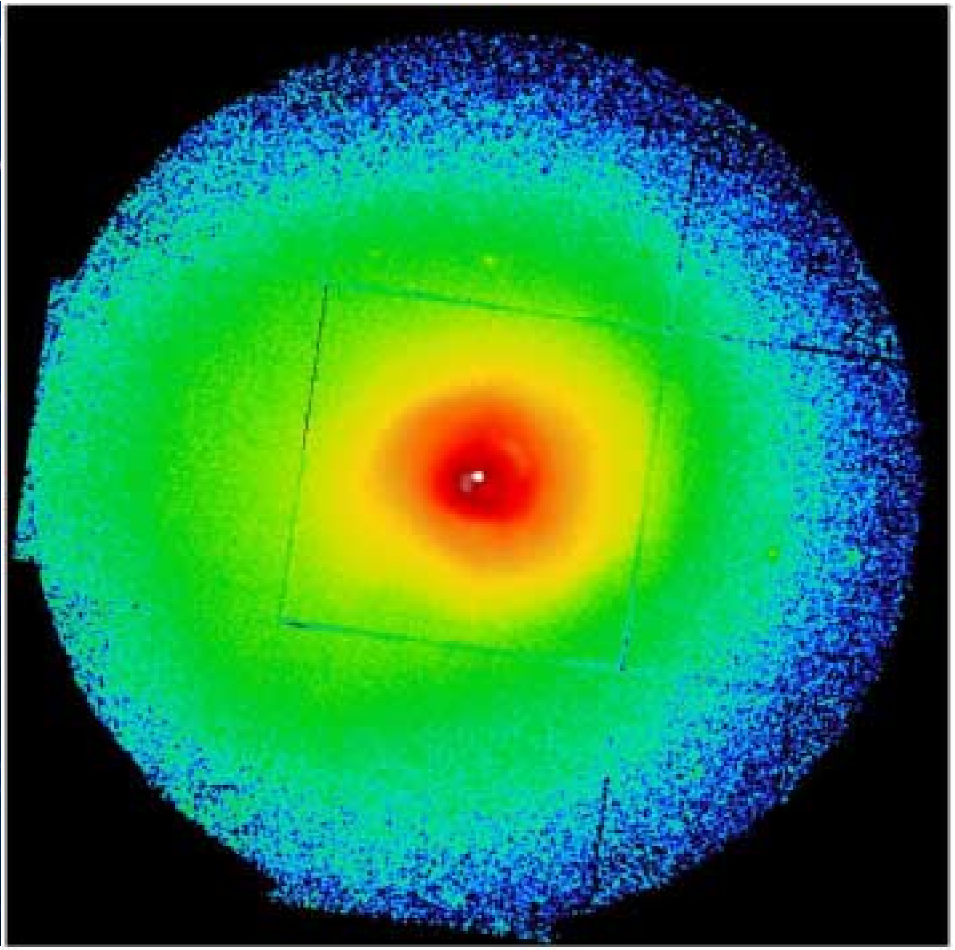
Clusters of Galaxies are extremely useful objects for Cosmology (Dark Matter and Dark Energy)

Clusters and Supermassive black holes

Dark Matter (Sim)

X-rays





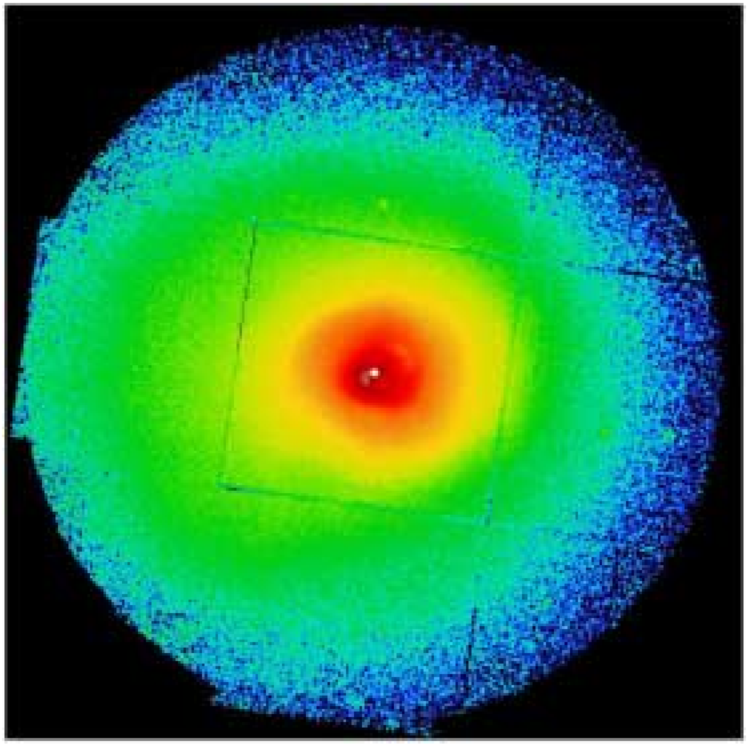
DM does not radiate energy
=> does not cool

Gas loses energy => cools

Cooling flows

Cooling time

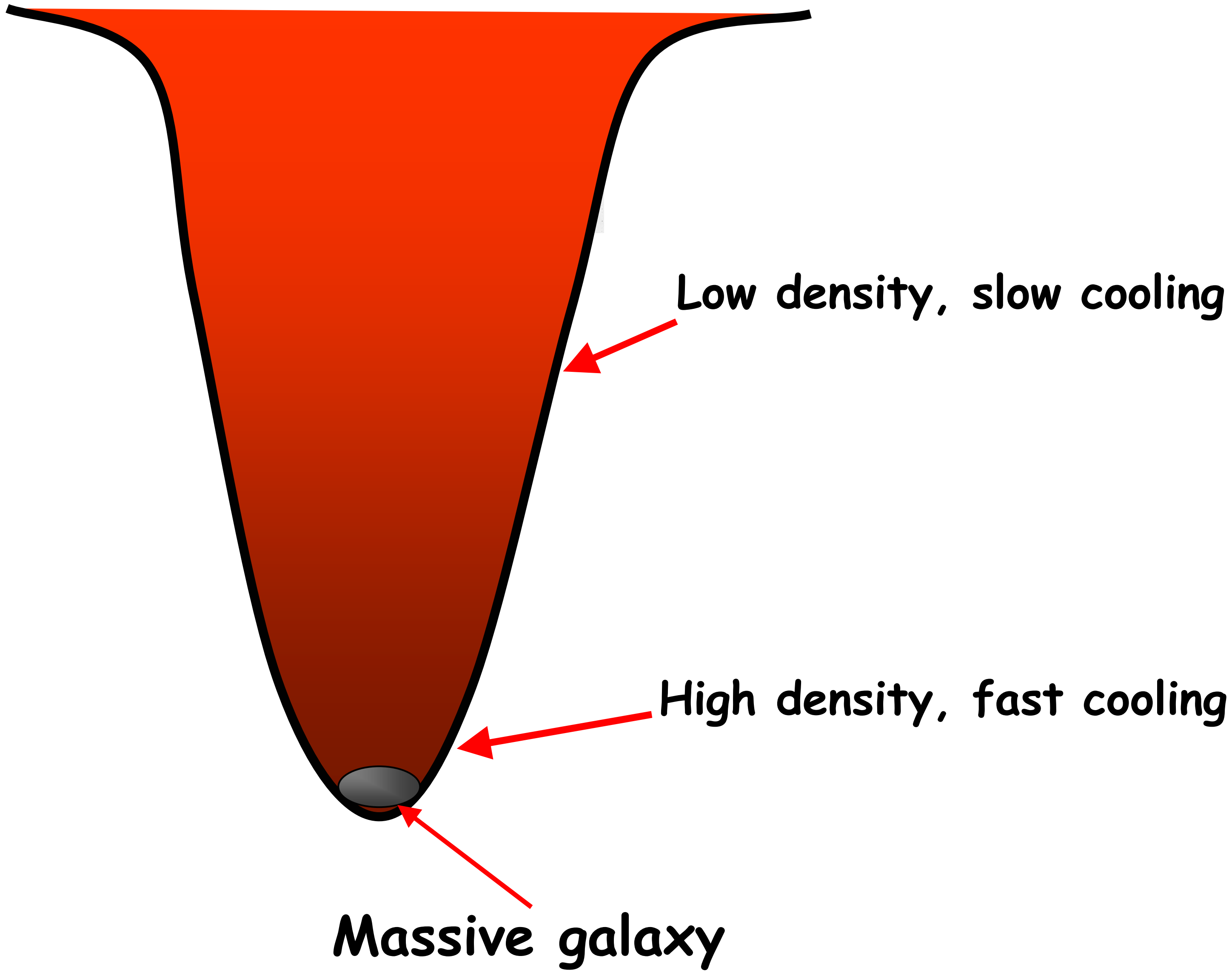
$$t_{cool} = \frac{\frac{3}{2} nkT}{n^2 \Lambda(T)} \approx 5\,10^8 \text{ years}$$



Cooling rate

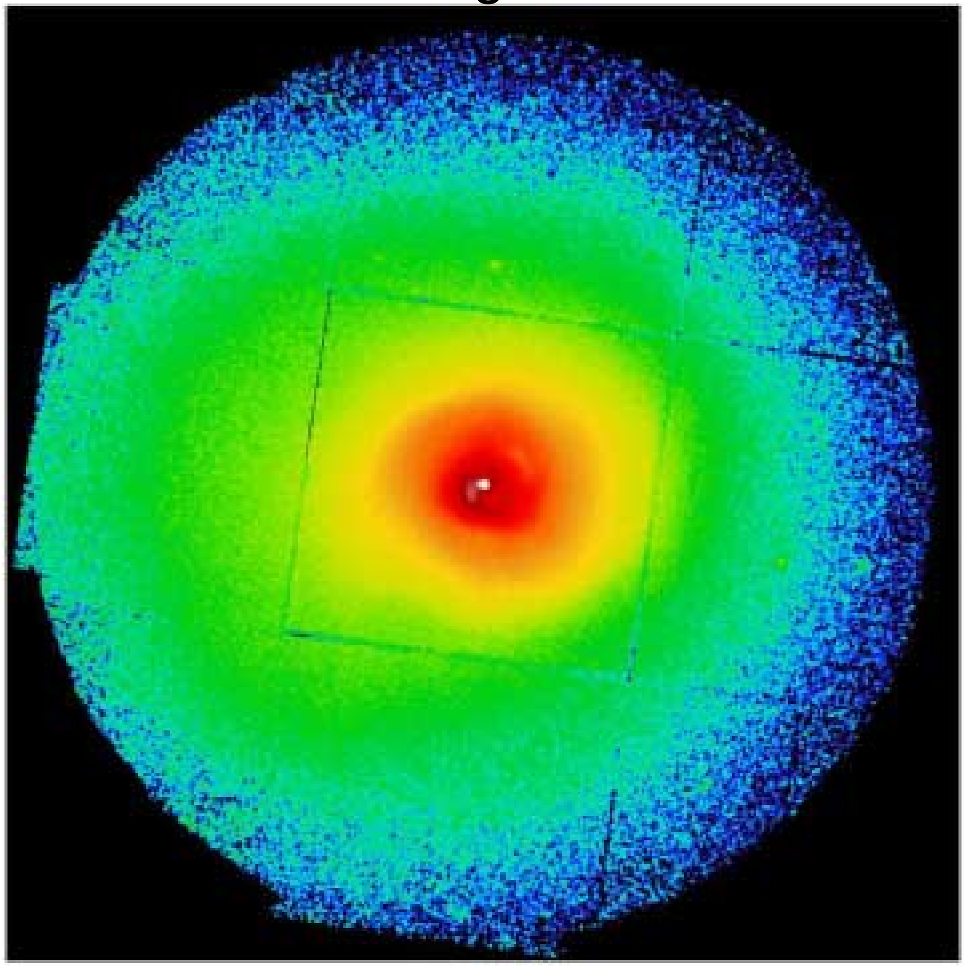
$$\dot{M} = \frac{L_X}{\frac{5}{2}kT} \times \mu m_p \approx 600\ M_\Theta\ \text{yr}^{-1} \qquad (L_X = 10^{45}\ \text{erg/s})$$

[see Fabian, 1994 for review]

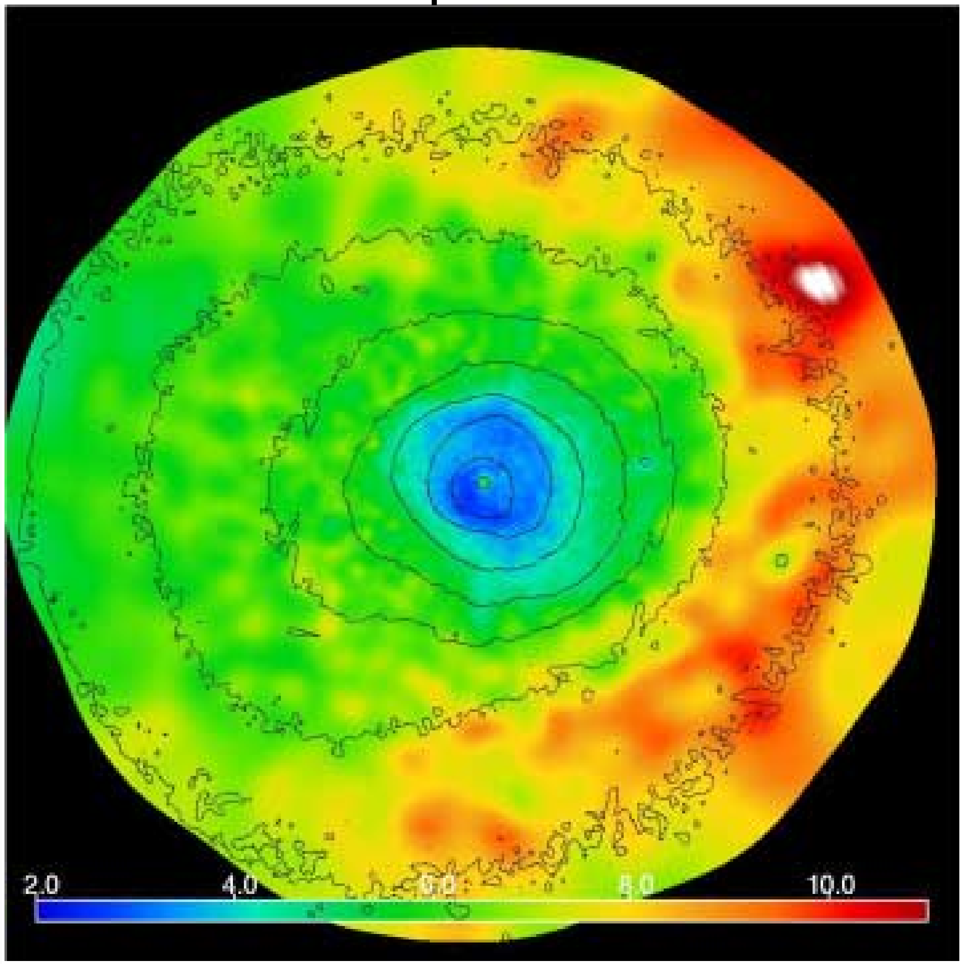

Low density, slow cooling
High density, fast cooling
Massive galaxy

Gas temperature

Surface brightness

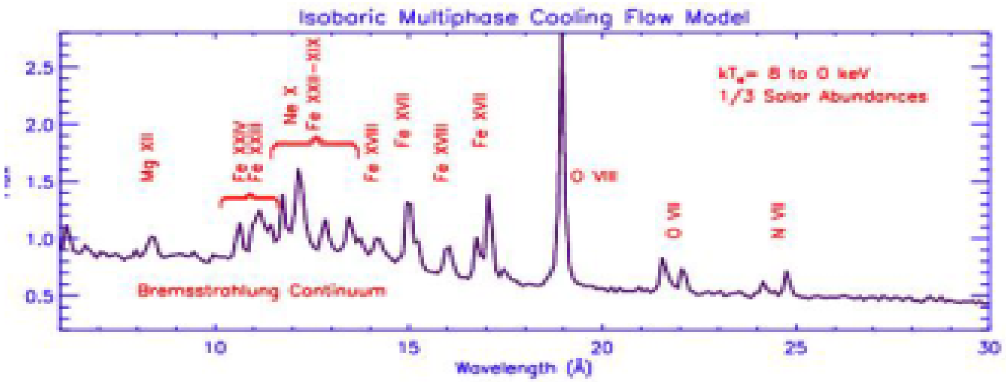


Temperature

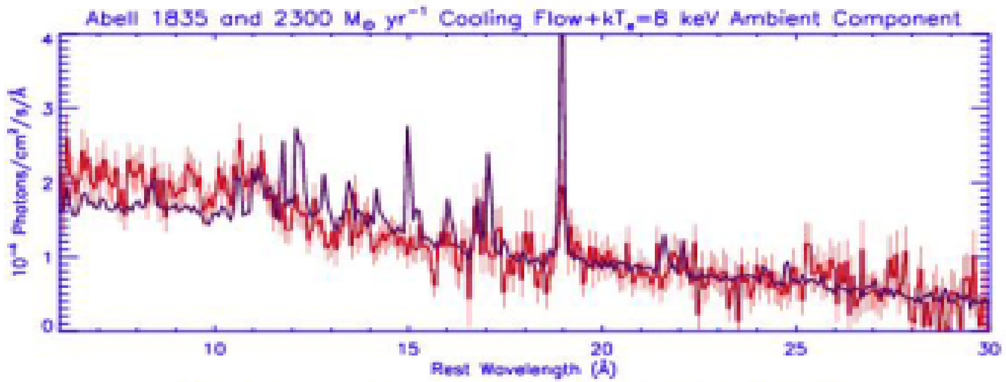


Cooling flows – emission lines?

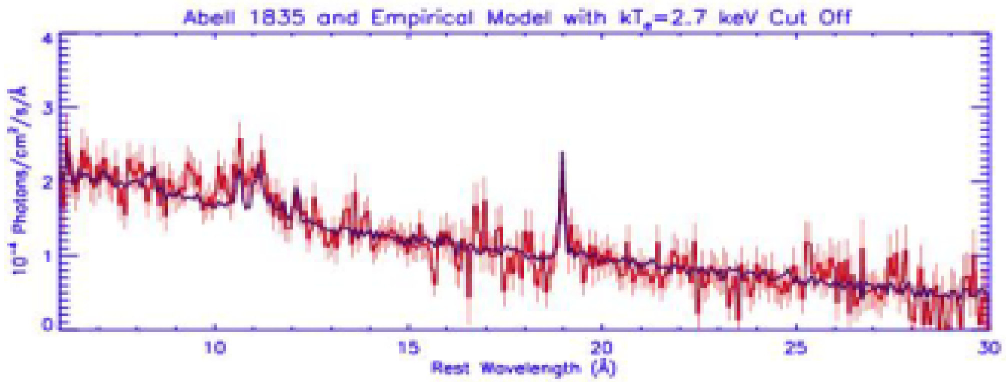
$$S_\nu = \frac{5}{2}\frac{\dot{M}}{\mu m_p}\int_{T_{\min}}^{T_{\max}} \frac{\varepsilon_\nu(T)}{\Lambda(T)}dT$$



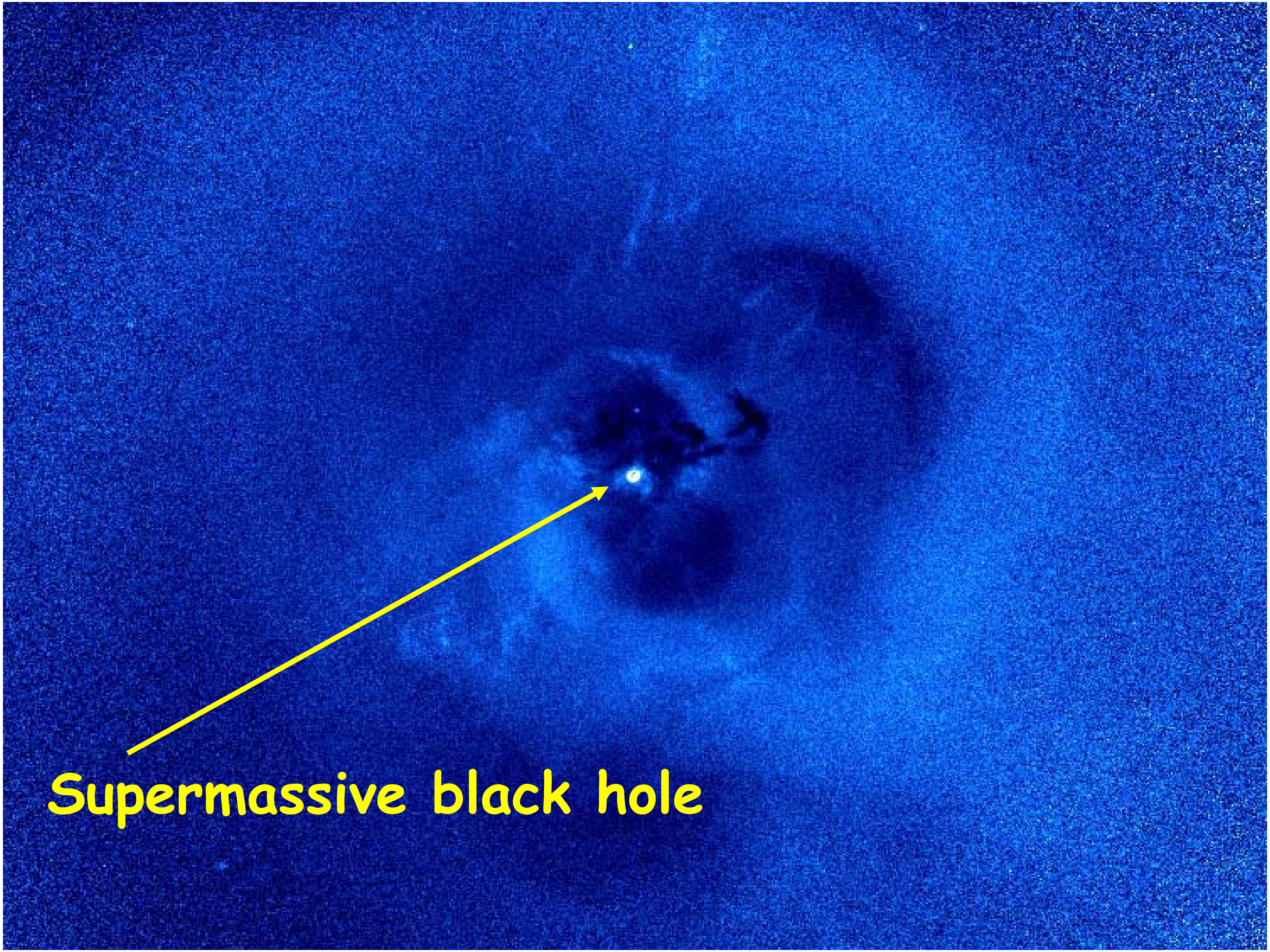
$$T_{\max} = 8\,\mathrm{keV}; \quad T_{\min} = 0$$

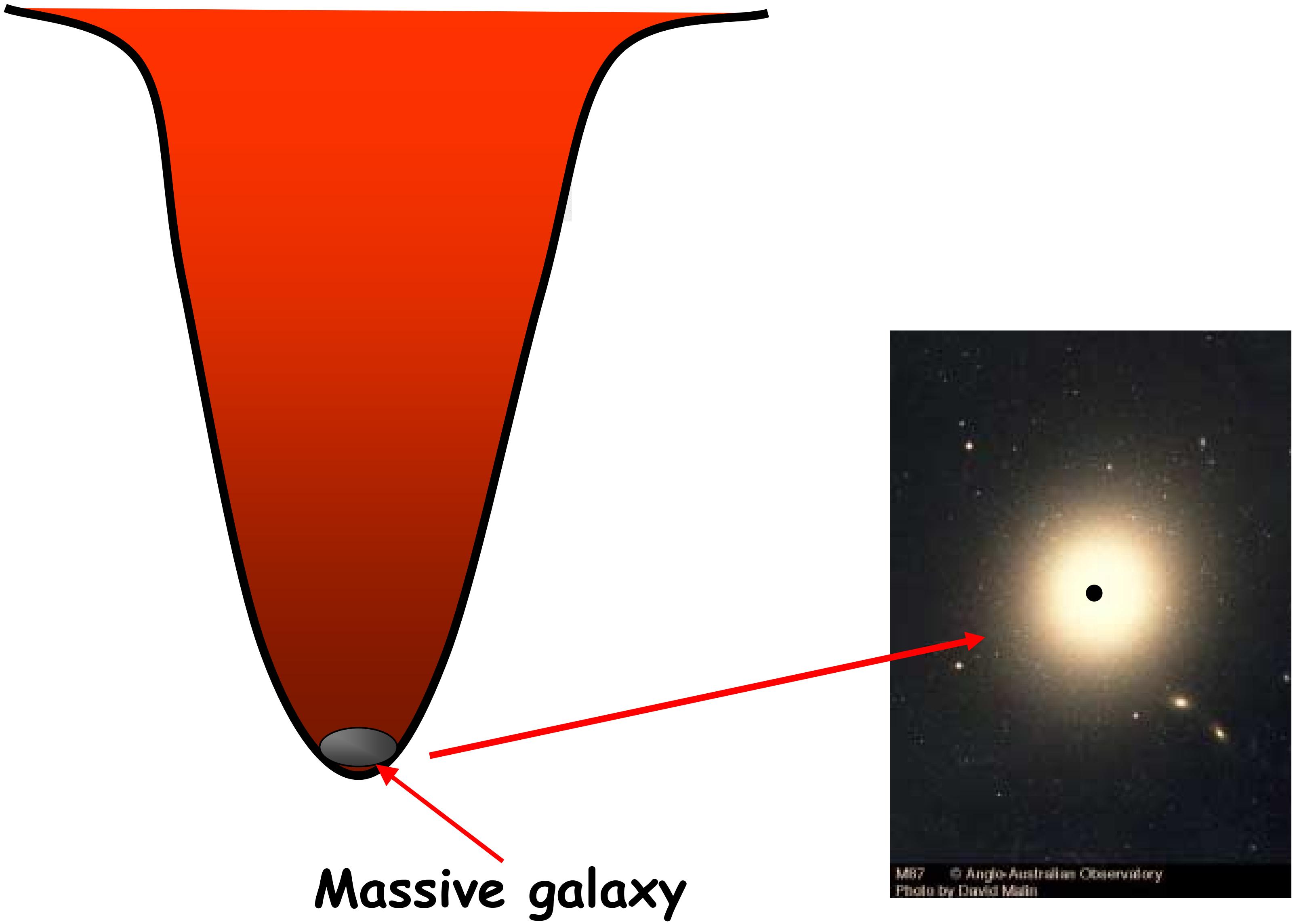


$$T_{\max} = 8\,\mathrm{keV}; \quad T_{\min} = 3$$

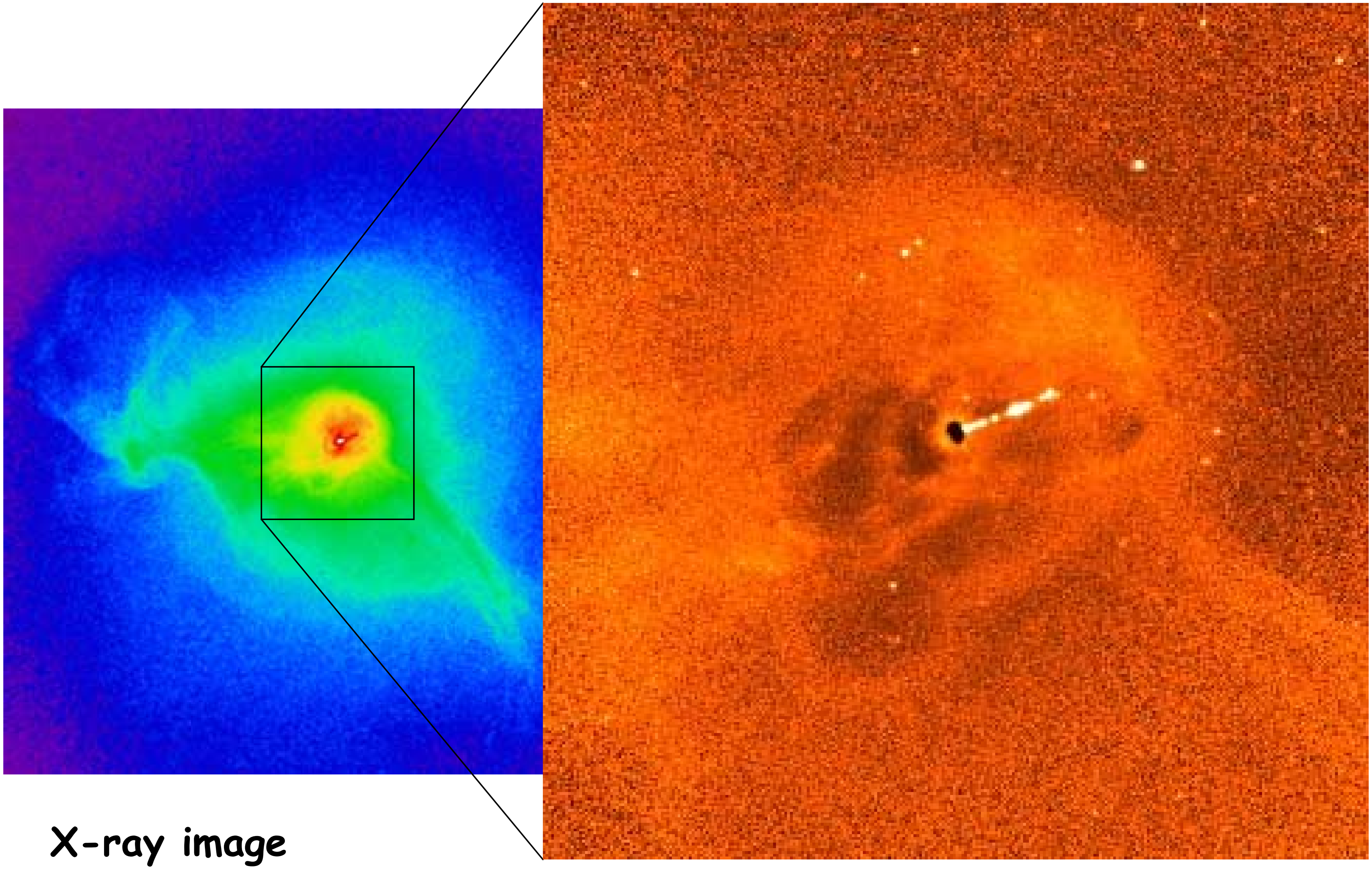


Why the gas does not cool? **We need 10^{43}-10^{45} erg/s!!!!!**


Supermassive black hole

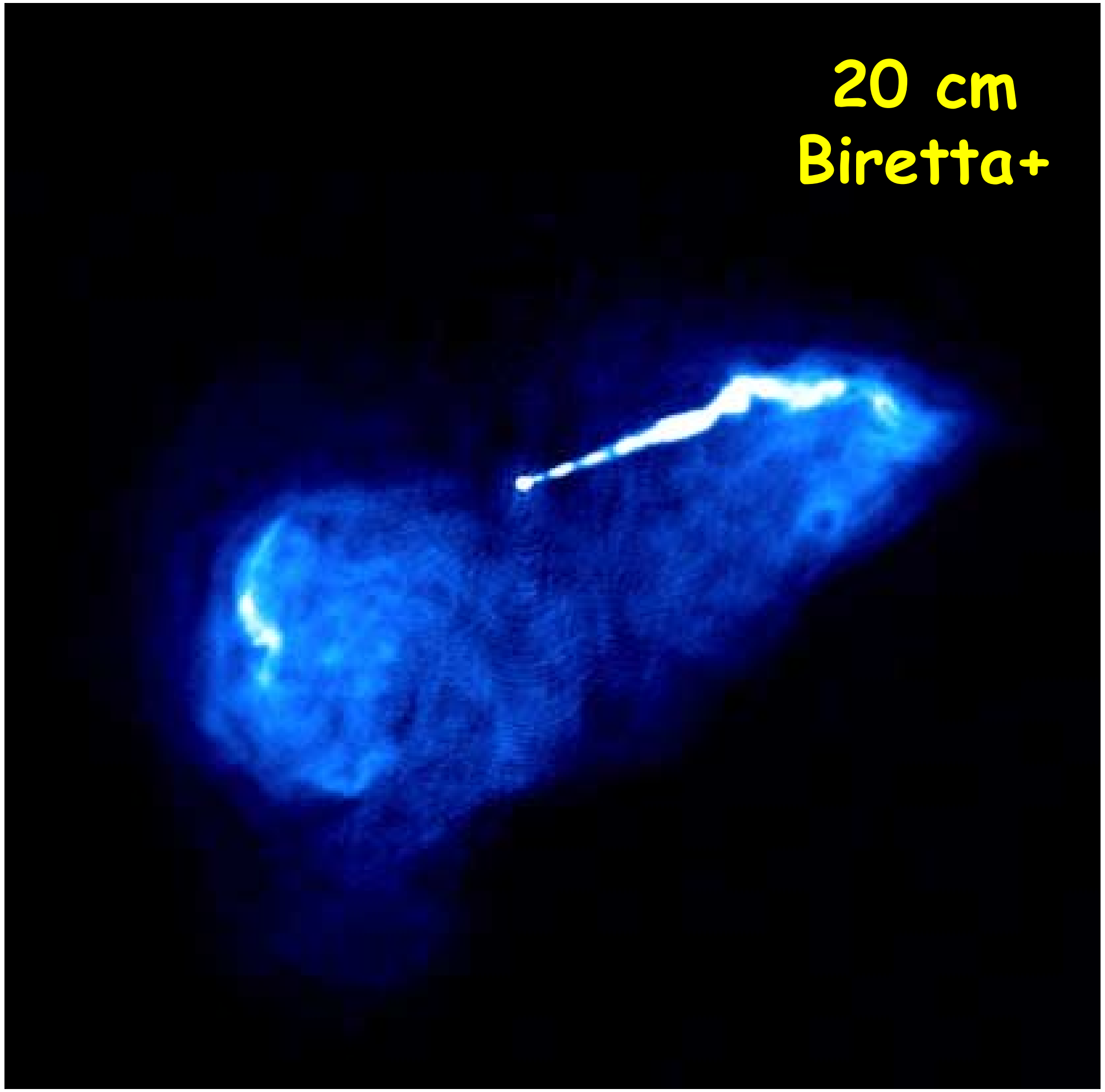

Massive galaxy
M87 © Anglo-Australian Observatory
Photo by David Malin

M87 (gas looses 10^{43} erg/s)



X-ray image

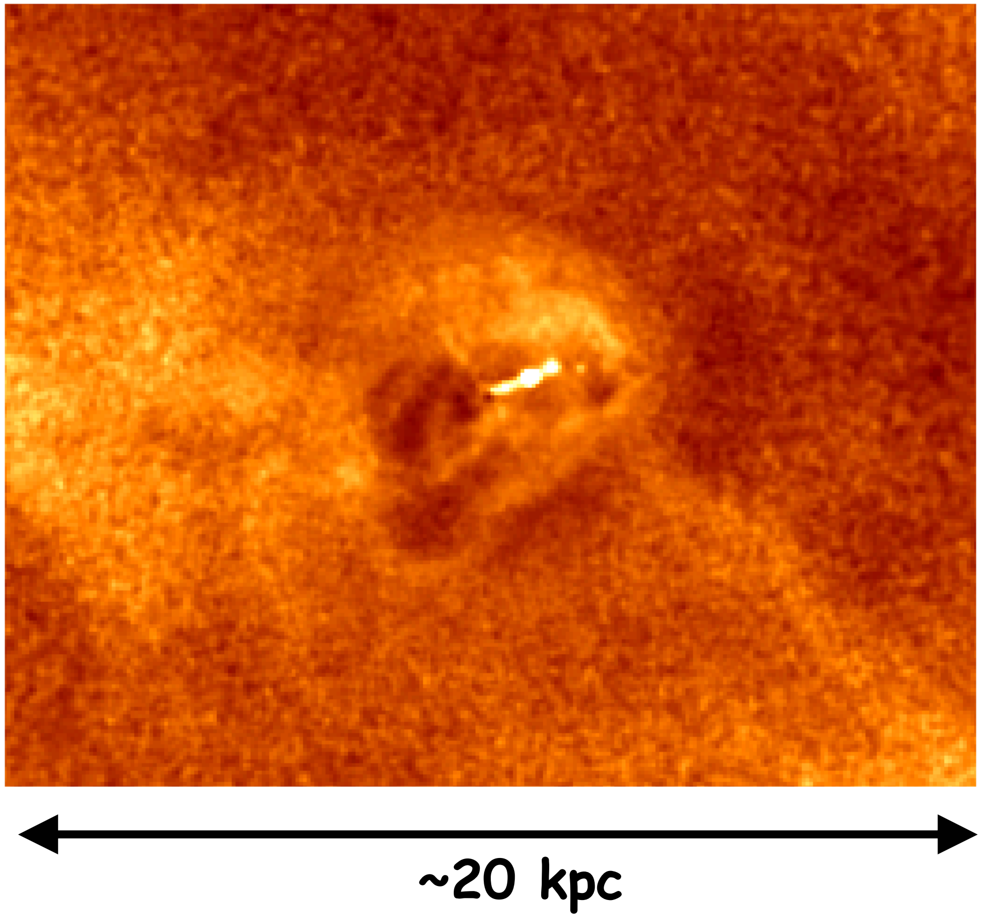
Radio (synchrotron radiation)
Relativistic plasma



~8 kpc

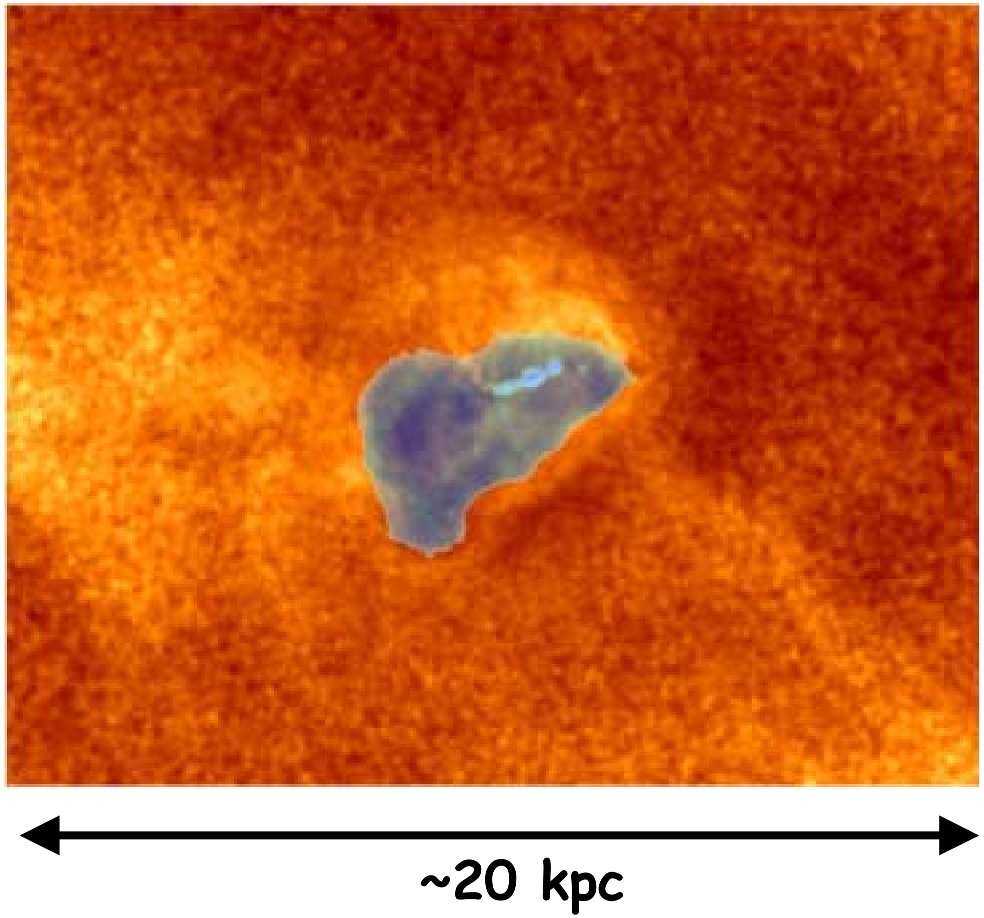
Radio
Relativistic plasma

X-rays
Thermal plasma



Radio
Relativistic plasma

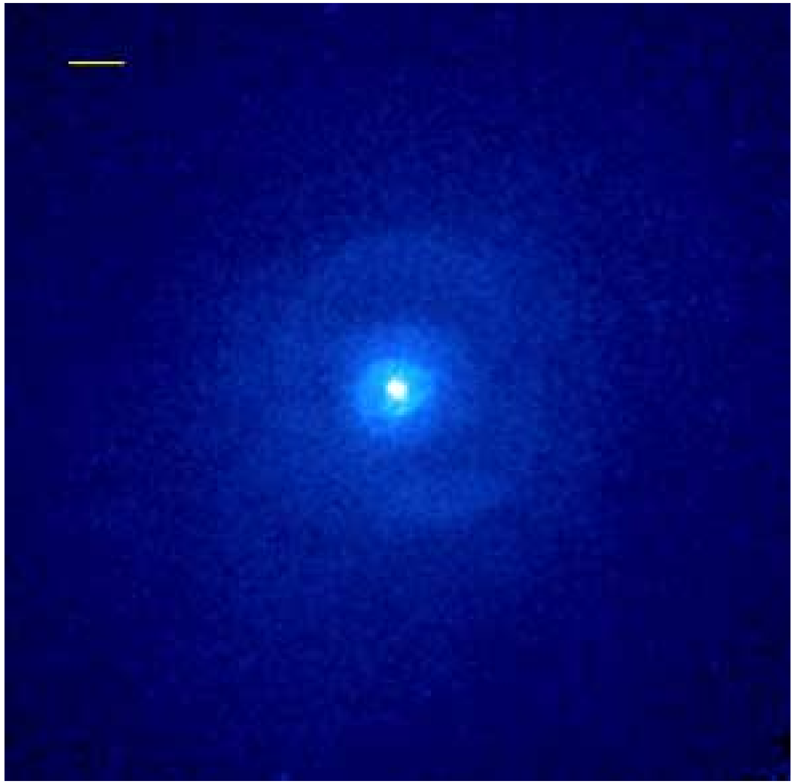
X-rays
Thermal plasma



Shock wave in M87

Simulations

Observations

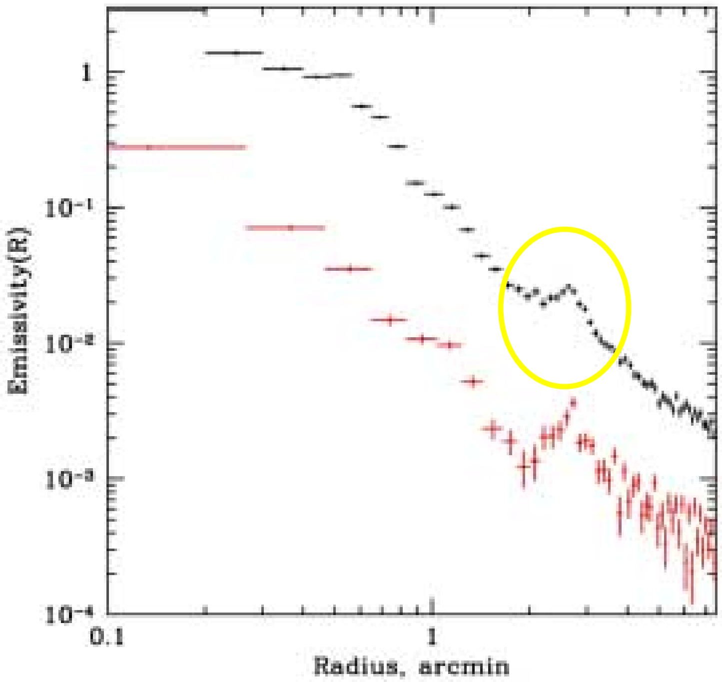


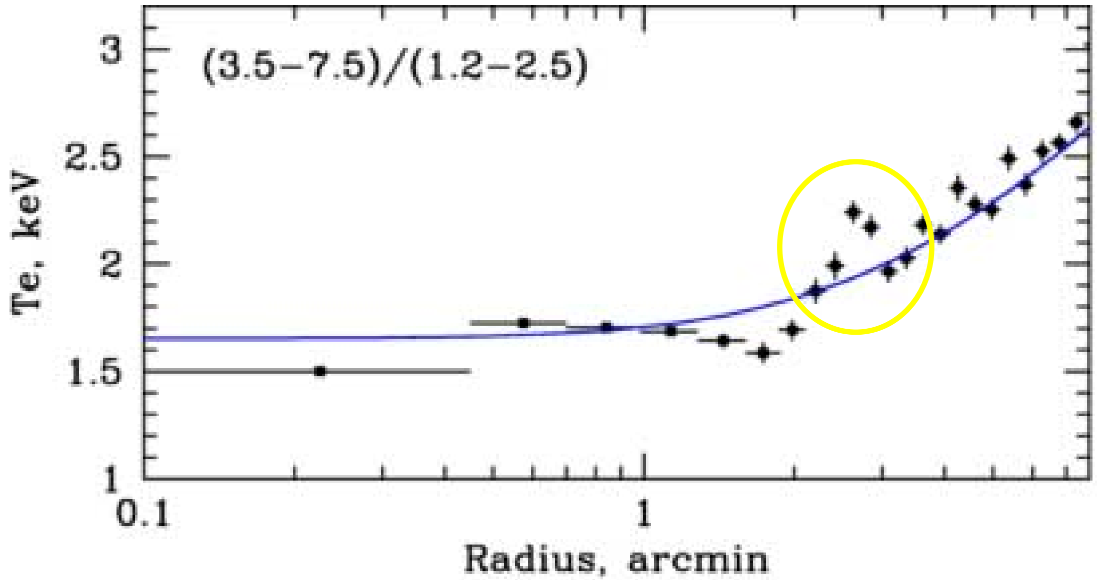
Forman+, 07

Ruszkowski+, 04

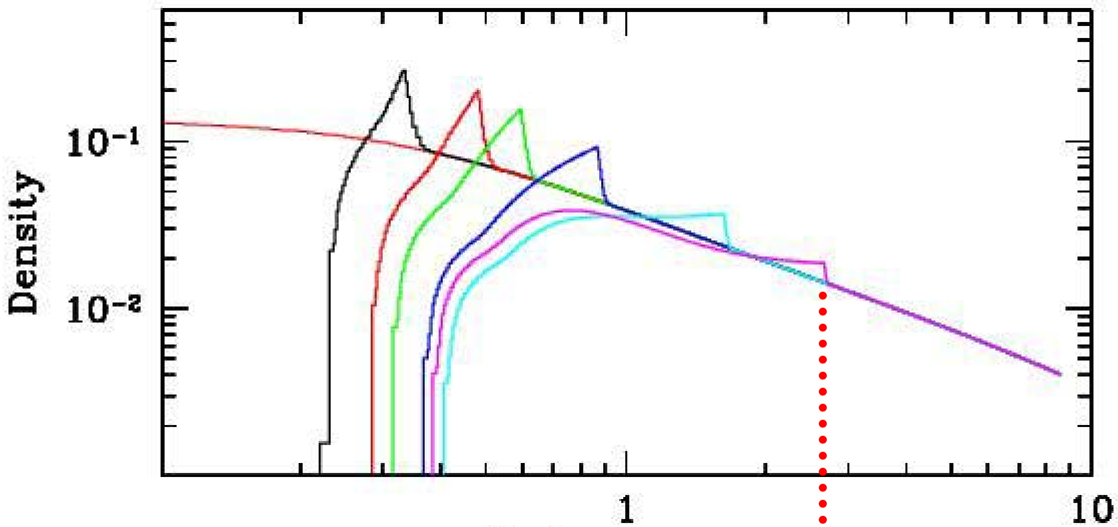
Sedov Taylor problem?

Shock wave in M87





$$E = 5\ 10^{57}\ \text{ergs}$$

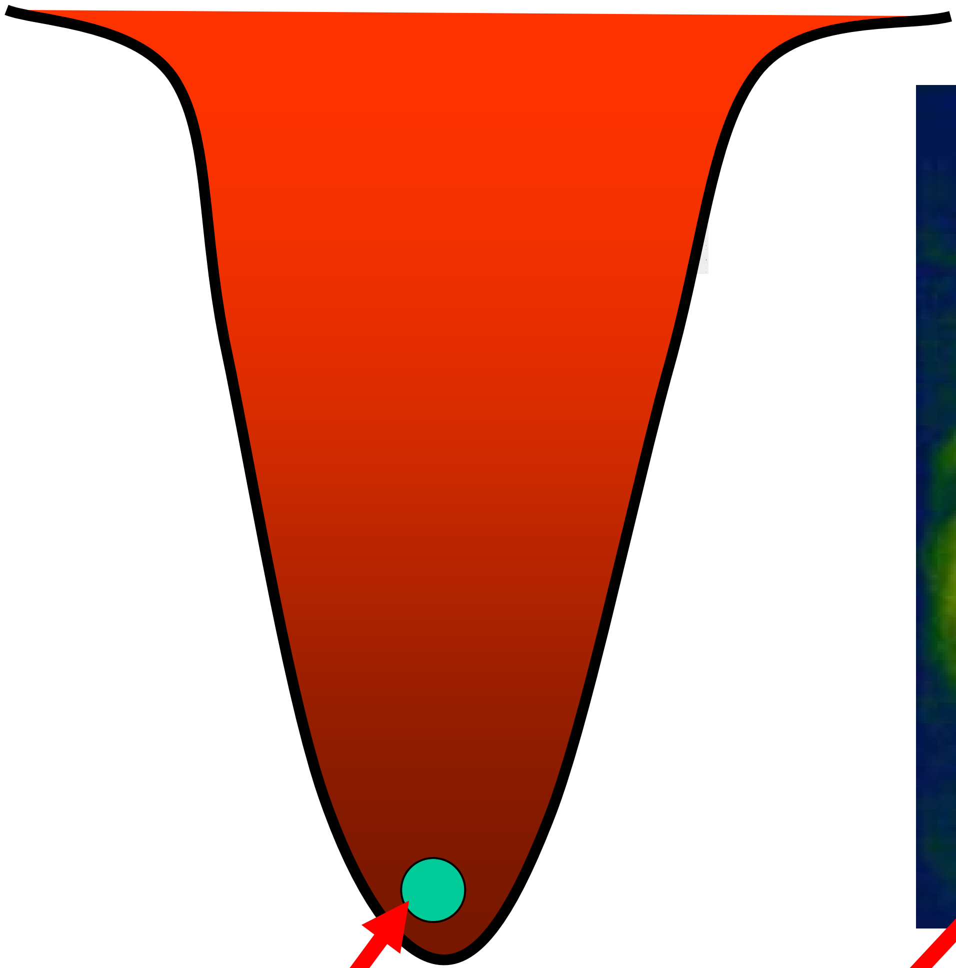


Numerical solution

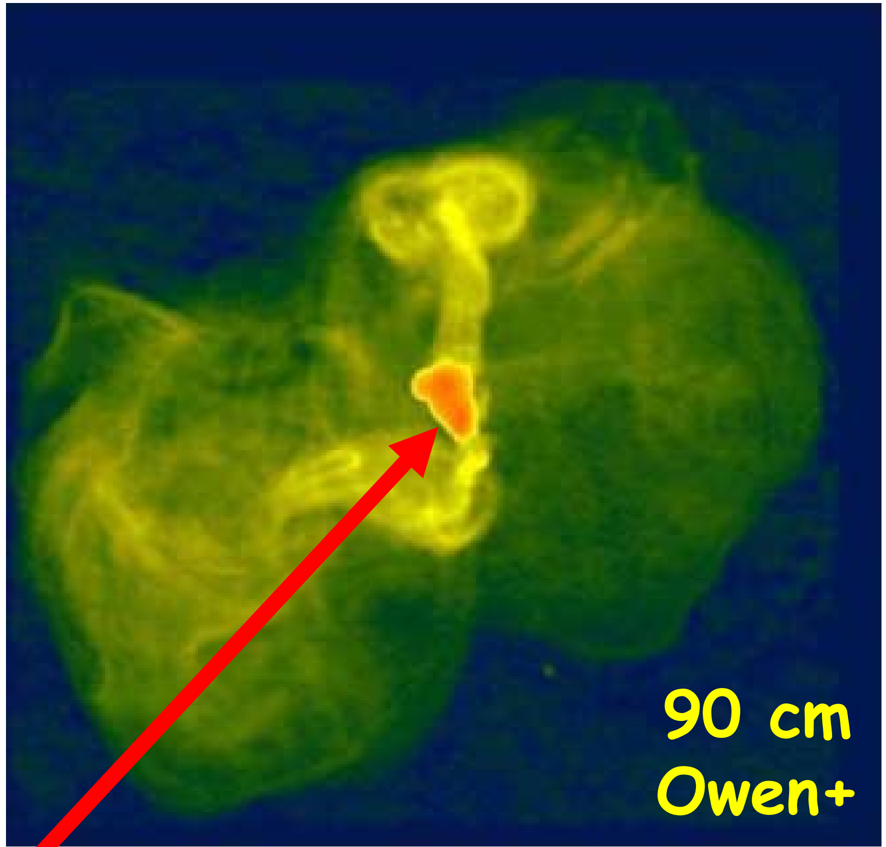
$E \sim 5\ 10^{57}$ erg; $\Delta t \sim 2$ Myr; $t \sim 12$ Myr

$$\text{Power} = \frac{5 10^{57}\ \text{erg}}{1.2 10^{7}\ \text{yr}} \approx 10^{43}\ \text{erg/s}$$

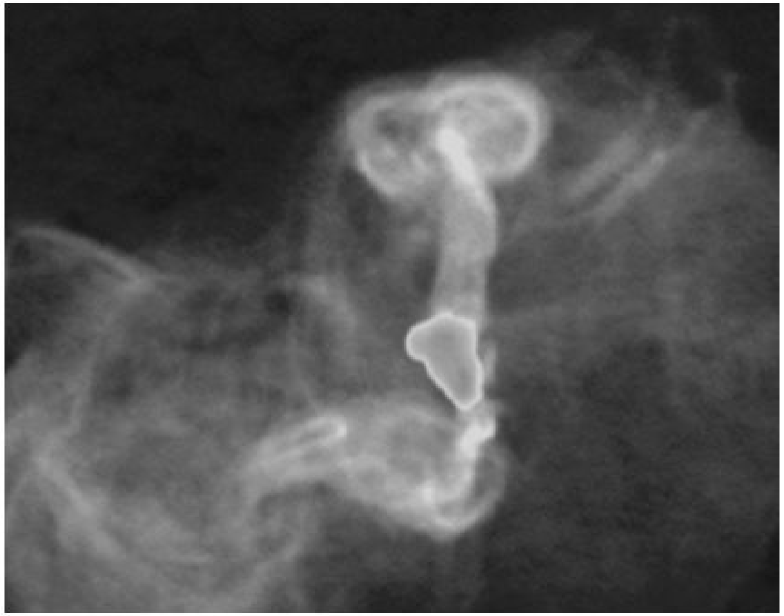
Can we estimate jet power over longer period?

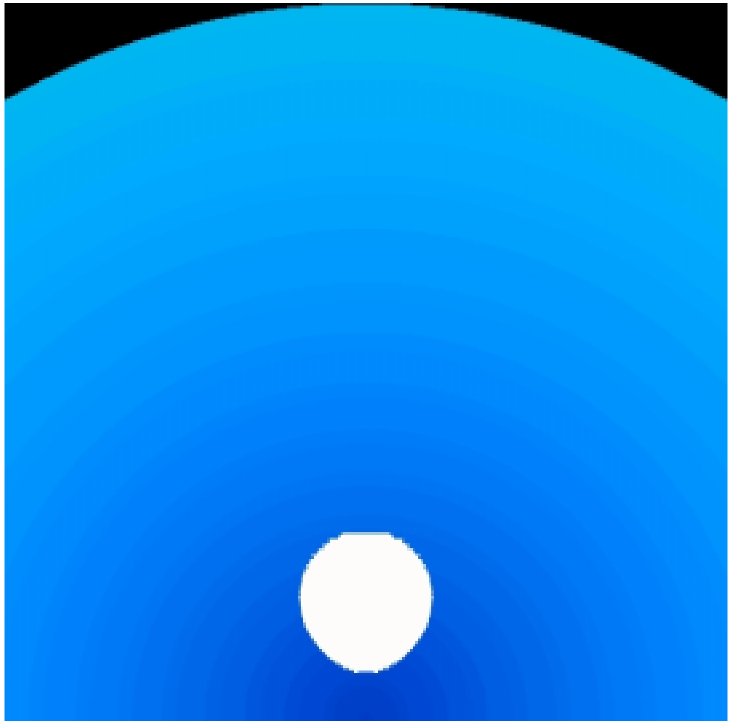


M87 in radio band (90 cm)



Bubble of relativistic plasma





Churazov et al., 2001

Measuring jet power with bubbles

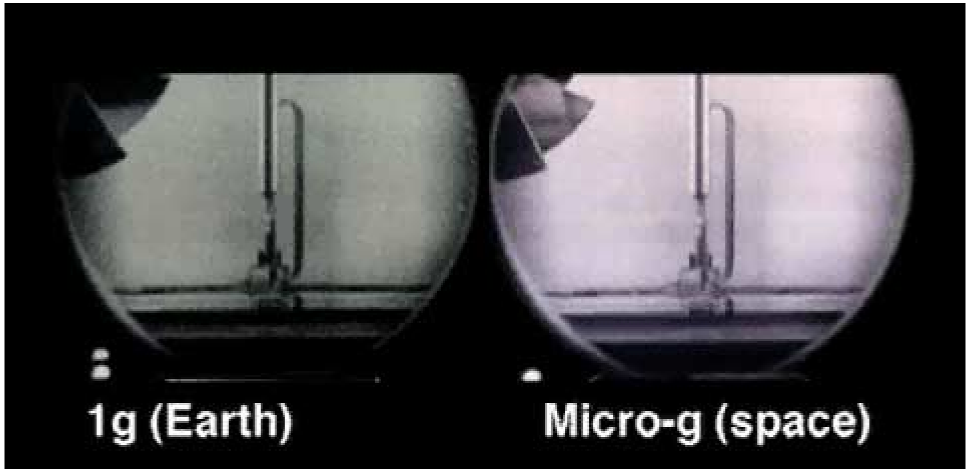
Expansion versus buoyancy

expansion velocity $v_{exp} : L_j \times t \approx PV$

rise velocity $v_{rise} : v_K \sqrt{\frac{r}{R}} \approx f\, c_s$

$v_{exp} \approx v_{rise}$

$L_j \approx \text{few } 10^{43} - 10^{44} \text{ erg/s}$



$$L \approx \text{few } 10^{43} - 10^{44} \text{ erg/s}$$

Directly observed

$$\text{X - ray cooling}: L_X \approx 10^{43}\ \text{erg/s [over 100 Myr]}$$

Derived from AGN/gas interaction

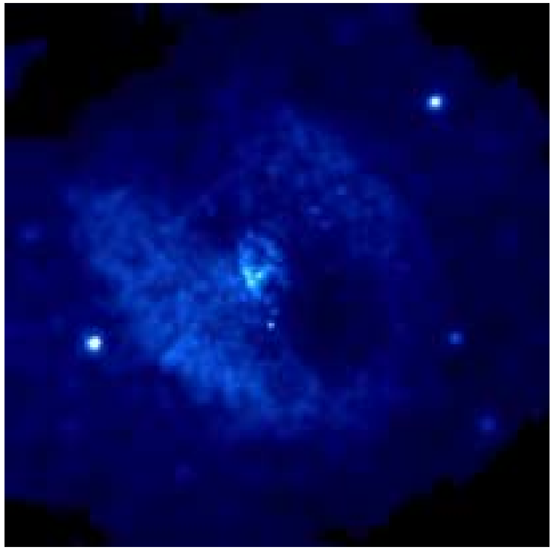
$$\text{From shock}: L_{Jet} \approx 10^{43}\ \text{erg/s [over 10 Myr]}$$

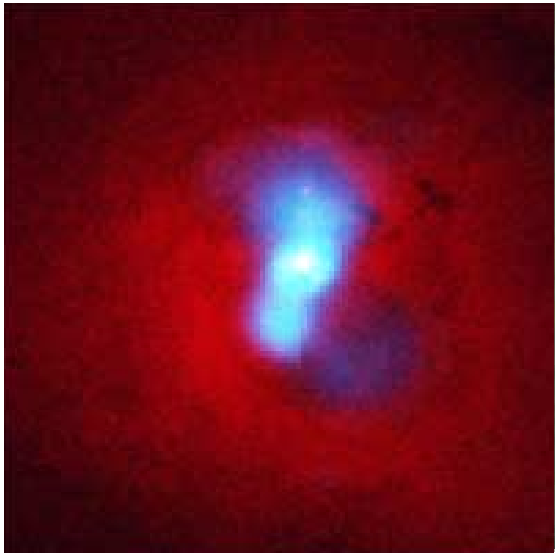
$$\text{From bubbles}: L_{Jet} \approx \text{few } 10^{43}\ \text{erg/s [over 100 Myr]}$$

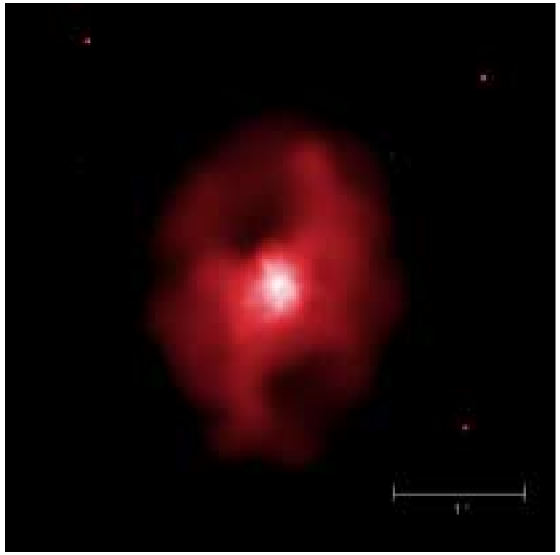
$$L_{Jet} \approx L_X \quad \Rightarrow \quad \text{Enough energy to stop cooling}$$

$$L_{Jet} >> L_{bol} \quad \Rightarrow \quad \text{Radiatively inefficient accretion}$$

Do we see similar structures in other objects?





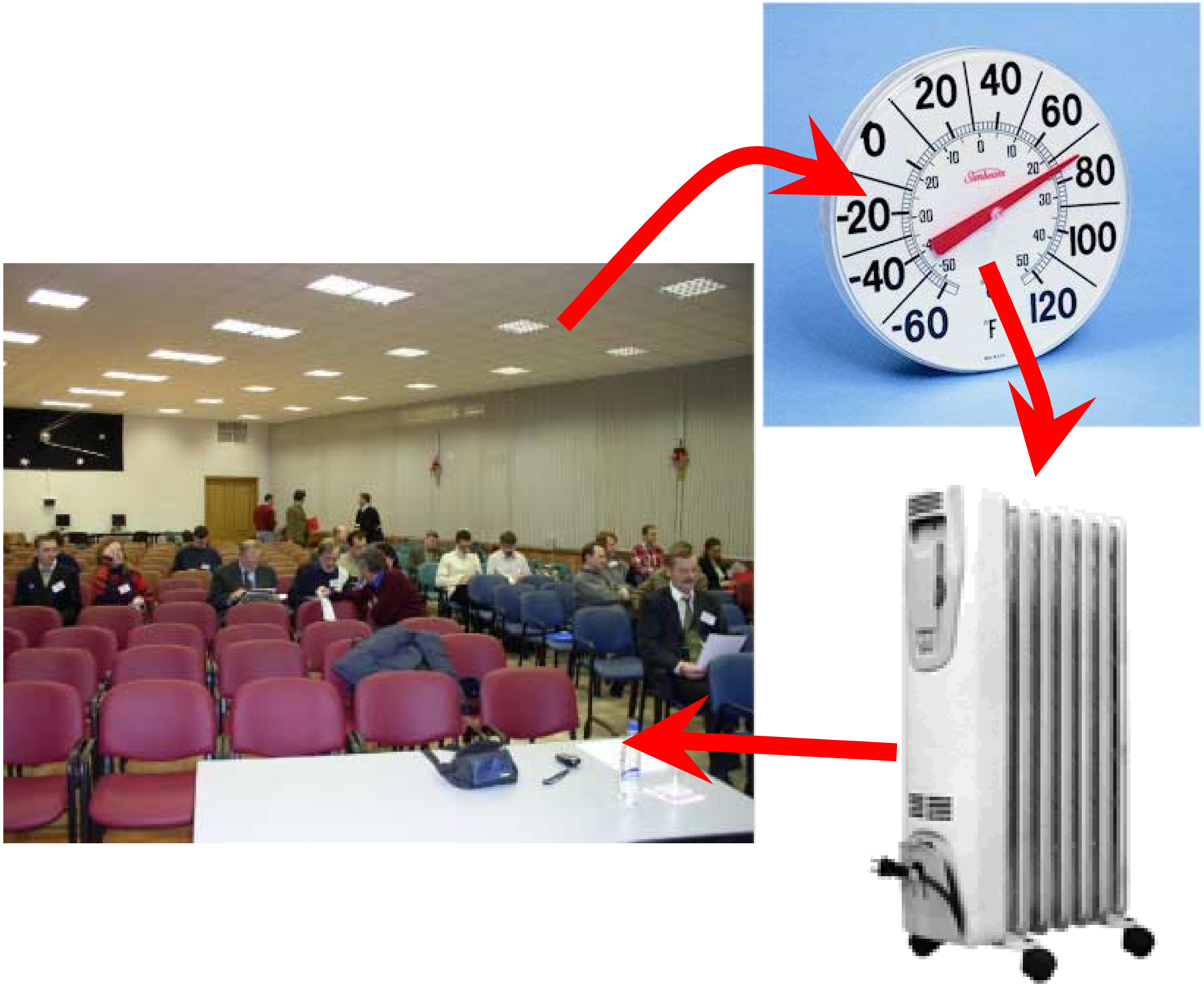


1 kpc
10^{56} erg
10^{42} erg/s

10 kpc
10^{59} erg
10^{45} erg/s

100 kpc
10^{62} erg
10^{46} erg/s

In each object the power provided by SMBH is about right!
How SMBH knows the right power?


20
40
60
0
80
-20
100
-40
120
-60
°F

Self-regulation of AGN power

$$L_{cooling}$$

$$L_{jet} \propto \dot{M}_{Bondi} = 4\pi\lambda(GM_{BH})^2 \rho / c_s^3 \propto s^{-3/2}$$

$$L_{jet} > L_{cooling} \Rightarrow s\text{ - increases} \Rightarrow L_{jet}\text{ - decreases}$$

$$L_{jet} < L_{cooling} \Rightarrow s\text{ - decreases} \Rightarrow L_{jet}\text{ - increases}$$

1. System with negative feedback (self regulated)
2. Stable equilibrium is possible

AGN feedback keeps the gas in cluster's cores hot!

Similar AGN feedback is now believed to be a crucial ingredient in evolution of galaxies

Plasma in clusters

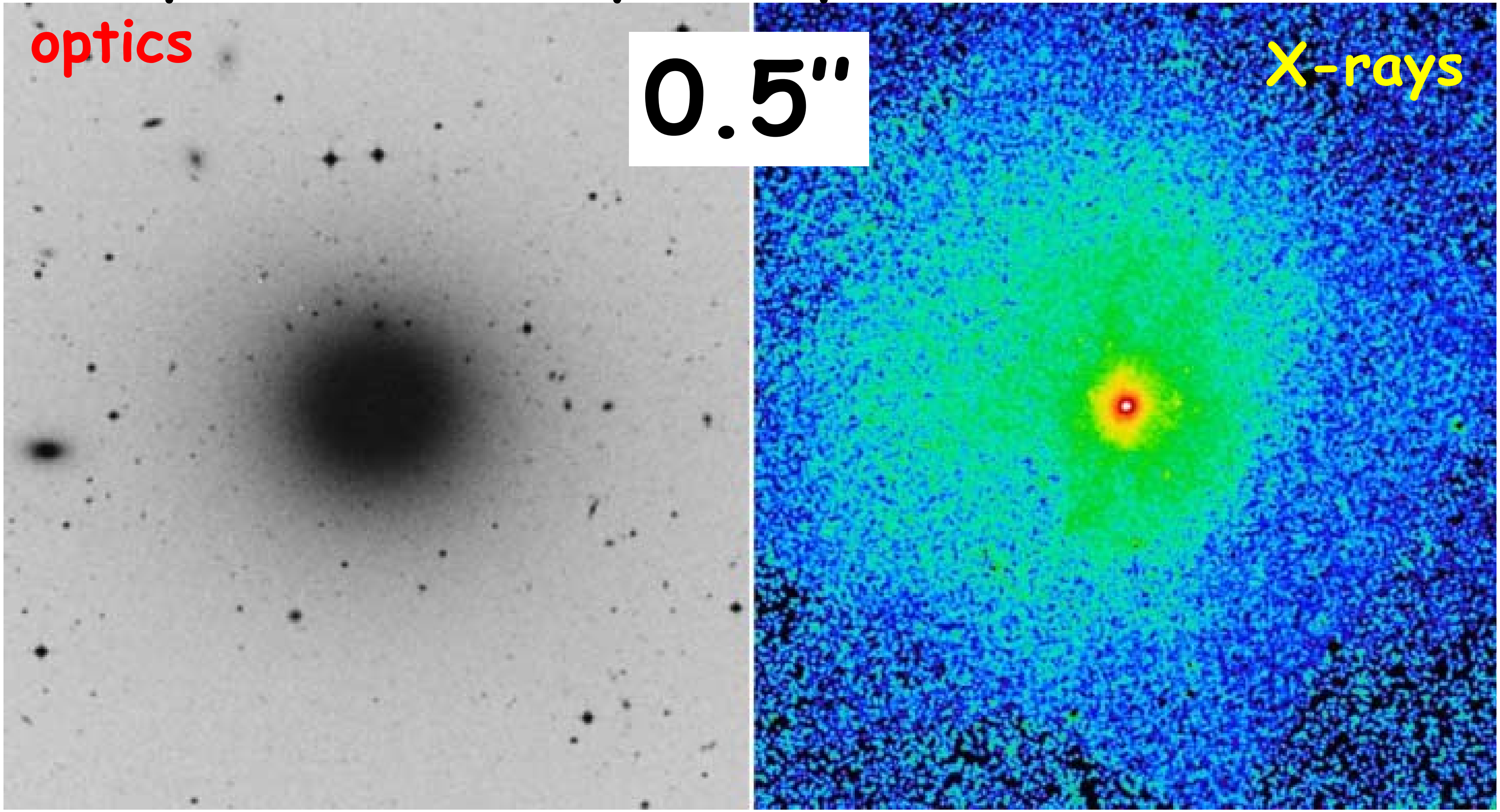
What we know for sure?

Electron density $\sim 10^{-1} - 10^{-4}$ cm^{-3}

Electron temperature $\sim 2 - 15$ keV

Magnetic fields?
Viscosity?
Thermal conduction?
Cosmic rays?

Comparison of X-ray and optical data for cores



Stars:gravity

Gas: gravity, magnetic fields, cosmic rays, turbulence

$$\frac{1}{n}\frac{dn\sigma^2}{dr} = -\frac{d\varphi}{dr}$$

Jeans equation (isotropic)

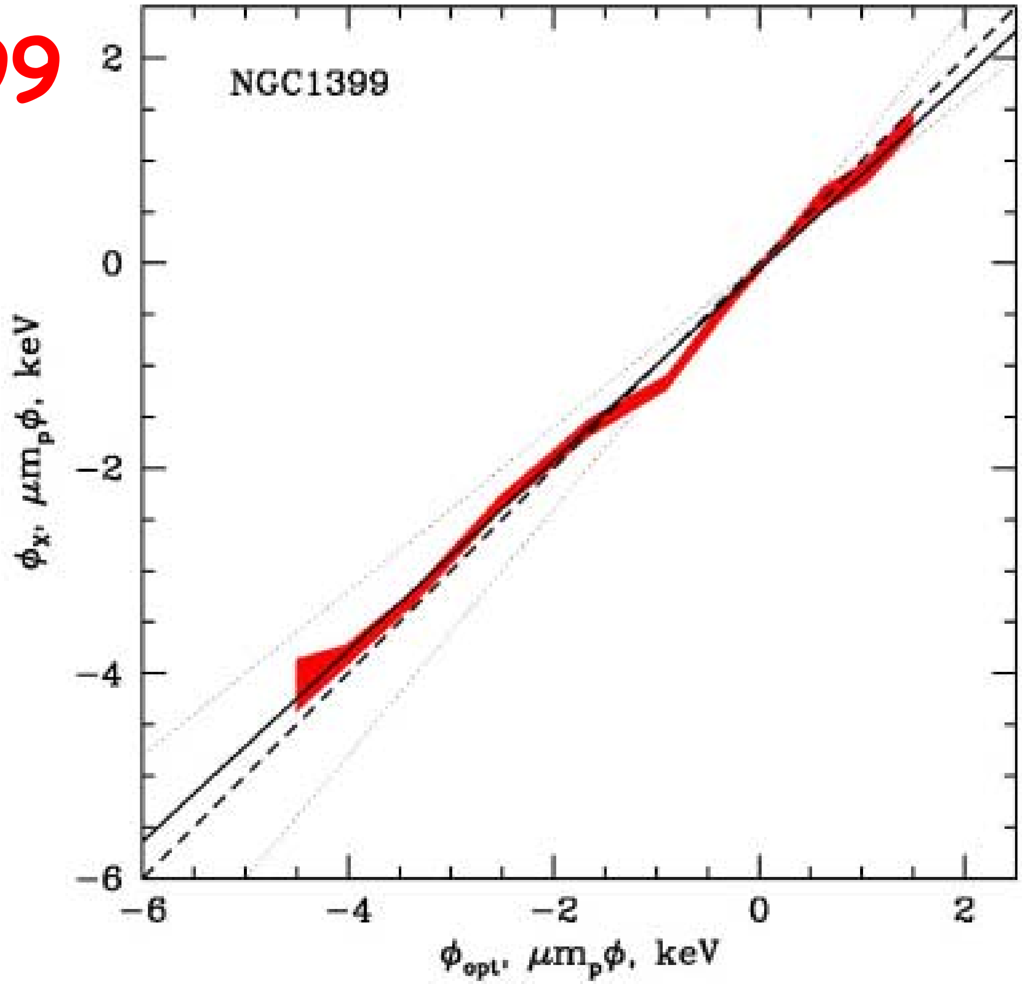
$$\frac{1}{\rho}\frac{dP}{dr} = -\frac{d\varphi}{dr}$$

Hydrostatic equilibrium

$$P = nkT + \frac{B^2}{8\pi} + P_{CR} + P_{turb}$$

$$\varphi_X(r) \approx \alpha\,\varphi_{true}(r), \qquad \alpha \leq 1$$

NGC1399



$$\varphi_X(r) \approx 0.93\,\varphi_{opt}(r) + C$$

$$U_{CR} + \frac{H^2}{8\pi} + U_{turb} = 0.07\,U_{thermal}$$

Churazov et al., 2008

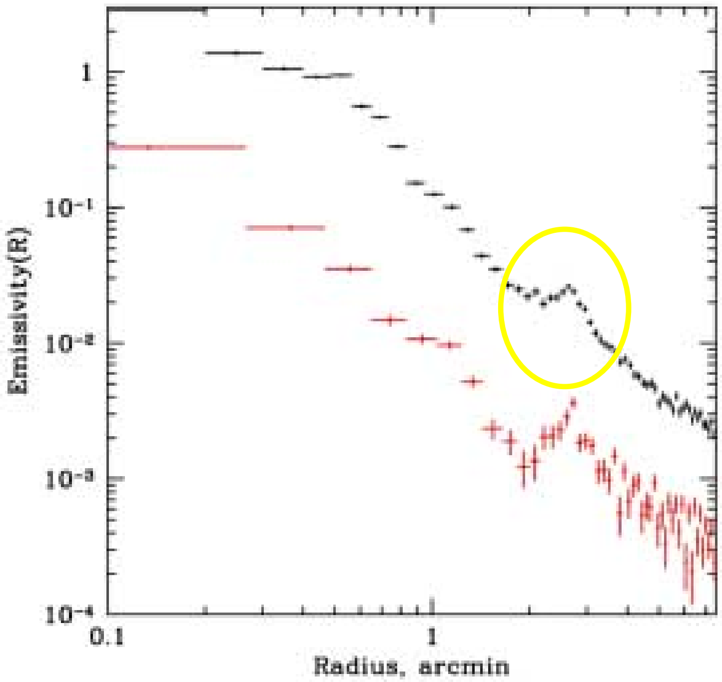
$$\frac{P_{gas}}{P_{mag}} \geq 15; \quad H \leq 10\ \mu G$$

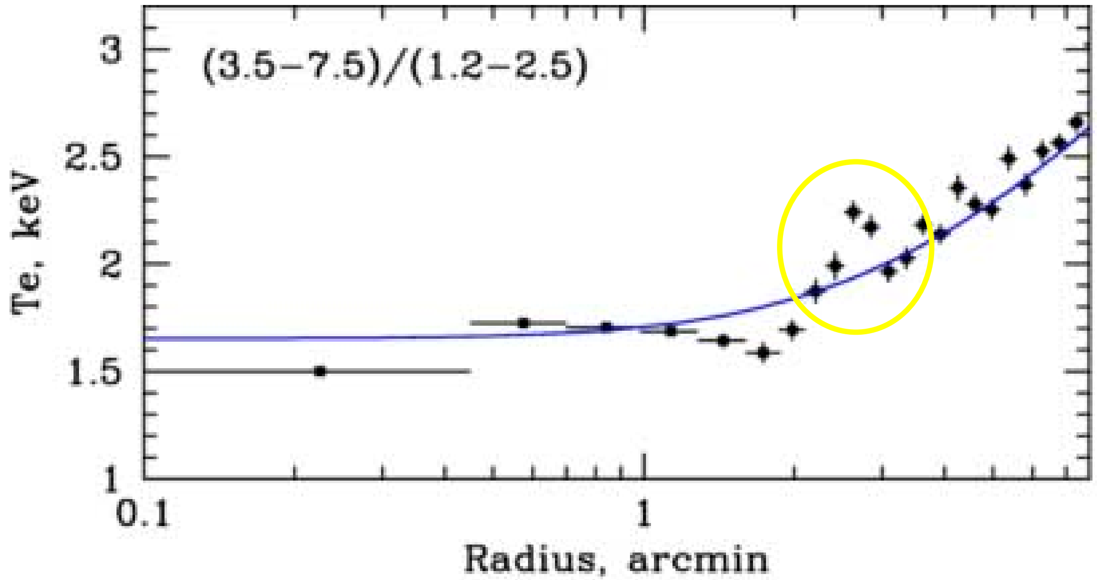
$$r_l \approx \gamma \times 10^{-10} \left(\frac{B}{10\mu G}\right)^{-1} \text{ kpc}$$

$$\lambda_e = \lambda_i = 2\left(\frac{T}{10^8\ \mathrm{K}}\right)^2 \left(\frac{n_e}{10^{-2}\ \mathrm{cm}^{-3}}\right)^{-1} \text{ kpc}$$

$$k = 4.6\times 10^{13}\left(\frac{T}{10^8 K}\right)^{5/2}\left(\frac{\Lambda}{40}\right)^{-1} \text{ erg cm}^{-1}\text{ s}^{-1}\text{ K}^{-1}$$

Jump condition, Mach number, adiabatic index





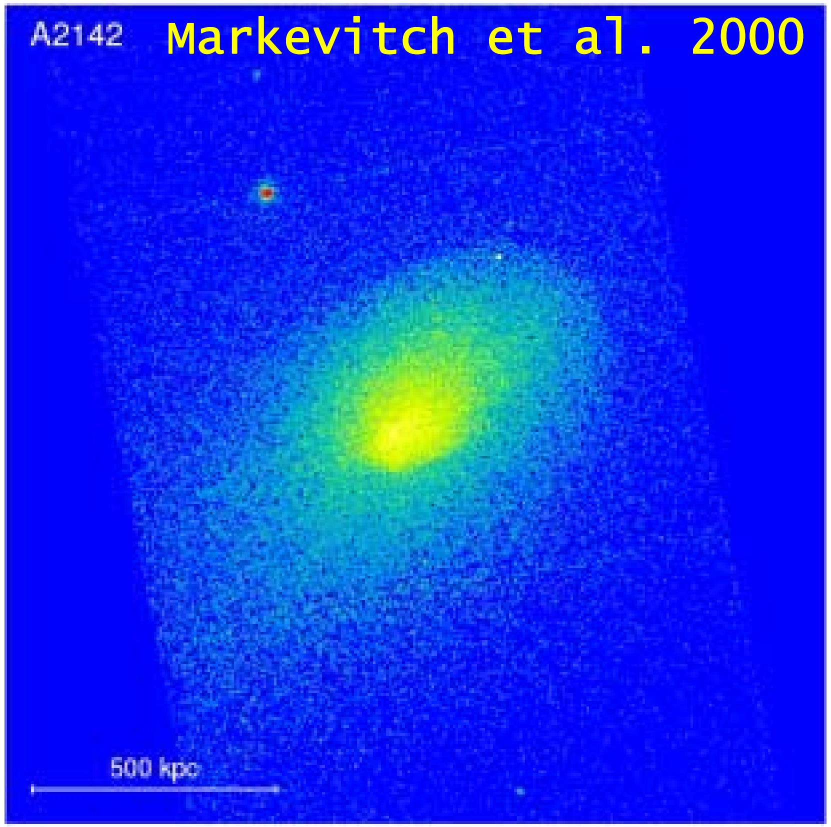
$$\frac{T_2}{T_1} = 1.2; \quad \frac{T_2}{T_1} = \frac{\left[(\gamma+1)+2\gamma(M^2-1)\right]\left[(\gamma+1)+(\gamma-1)(M^2-1)\right]}{(\gamma+1)^2 M}; \quad M = 1.24$$

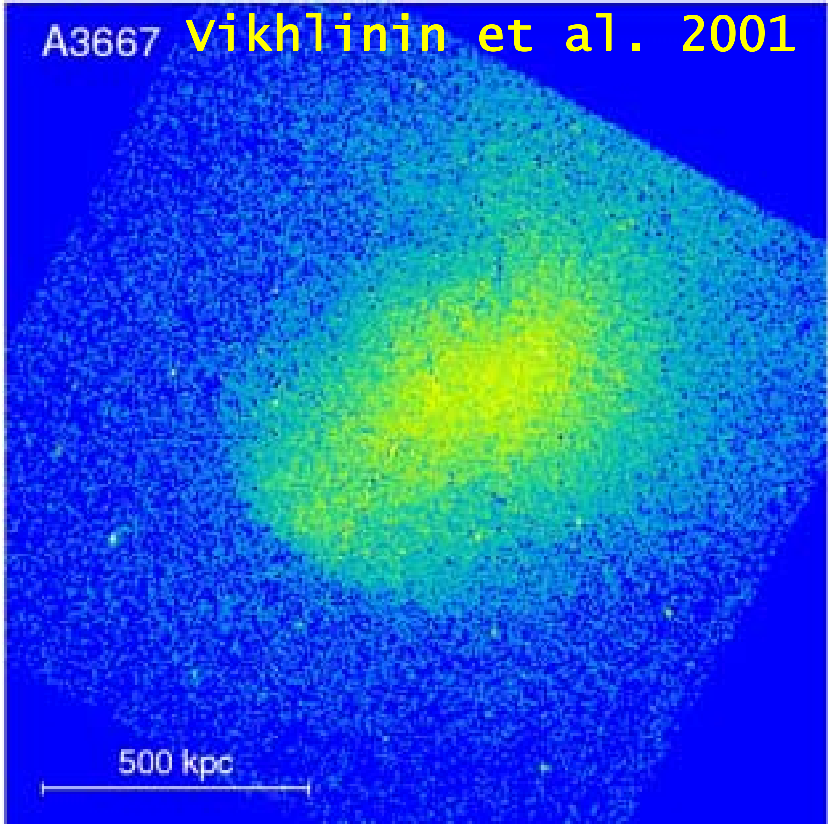
$$\frac{\rho_2}{\rho_1} = 1.34; \quad \frac{\rho_2}{\rho_1} = \frac{(\gamma+1)M^2}{(\gamma+1)+(\gamma-1)(M^2-1)}; \quad M = 1.21$$

$$\gamma \approx 5/3$$

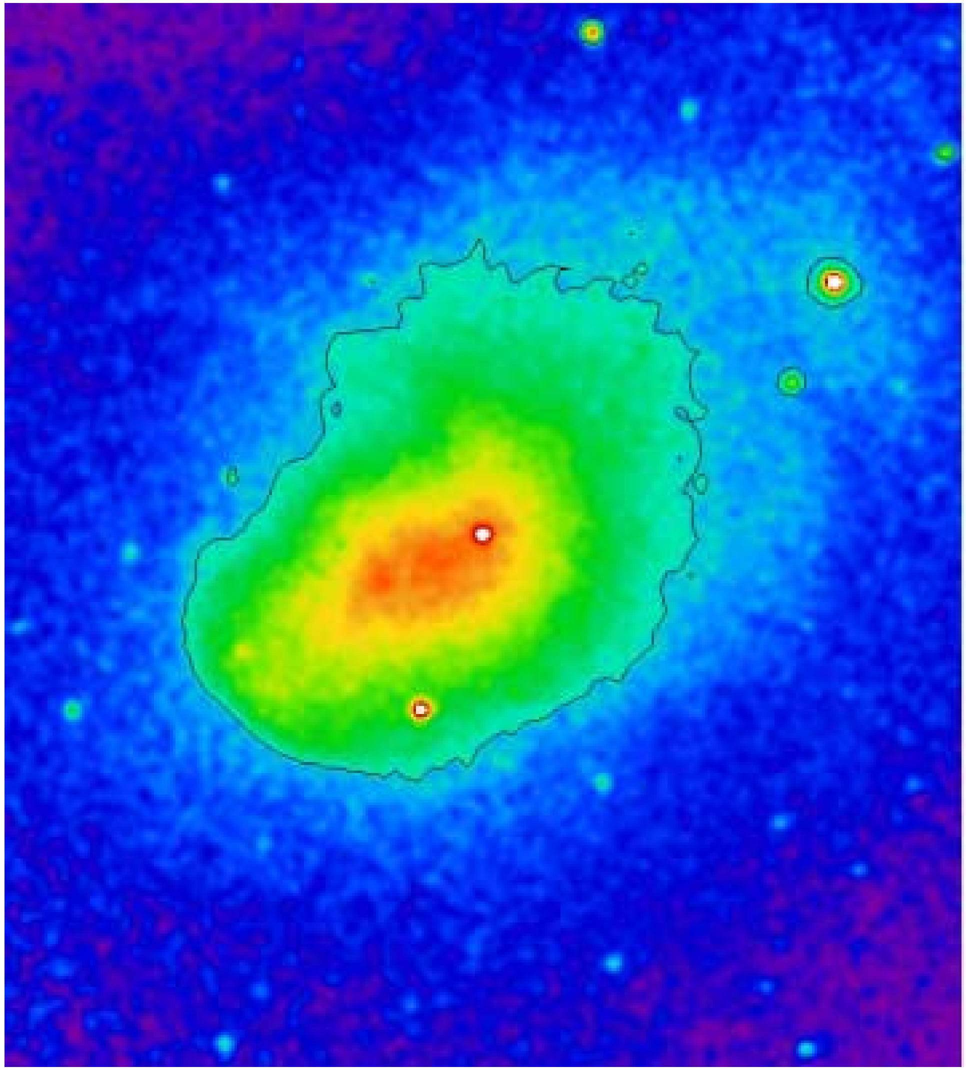
$$v \approx 0.5\, c_s$$

Sharp edges in the surface brightness
(shock waves?)

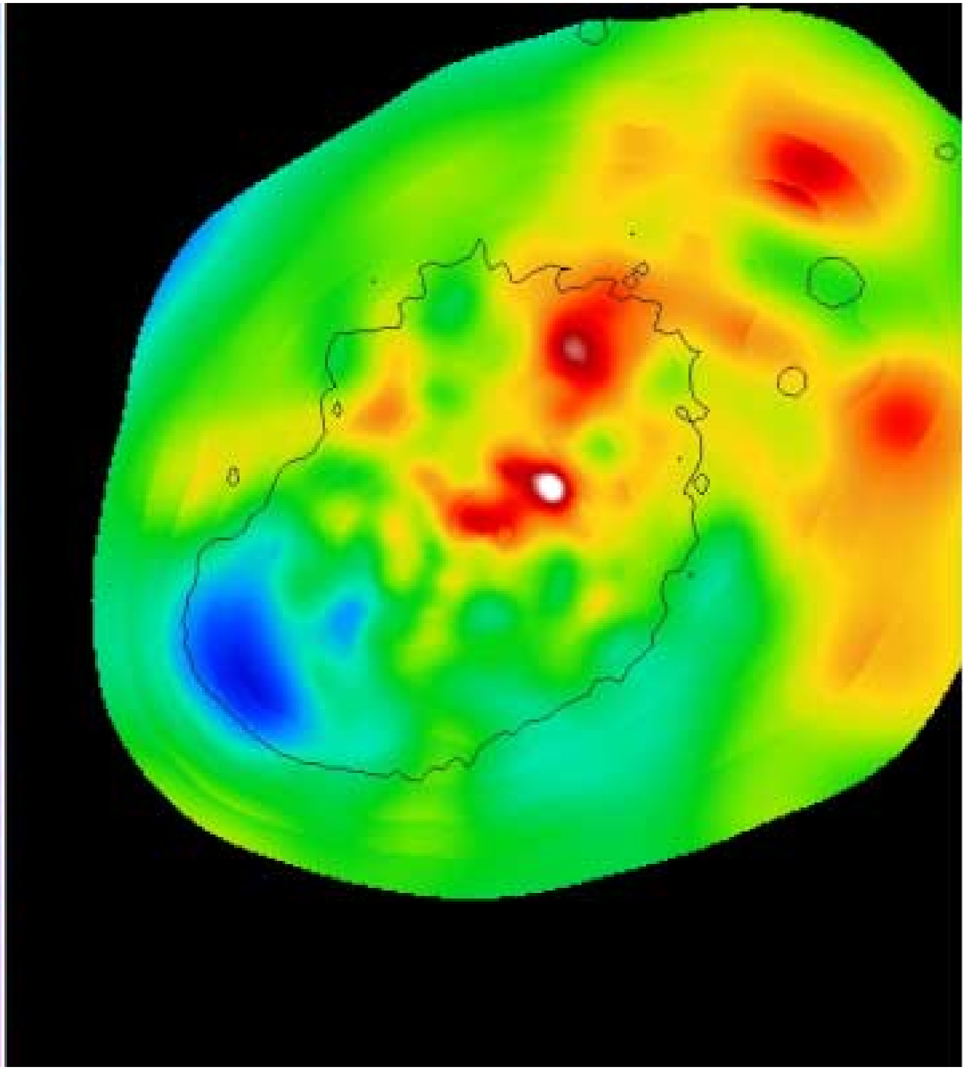




Surface brightness
(density)

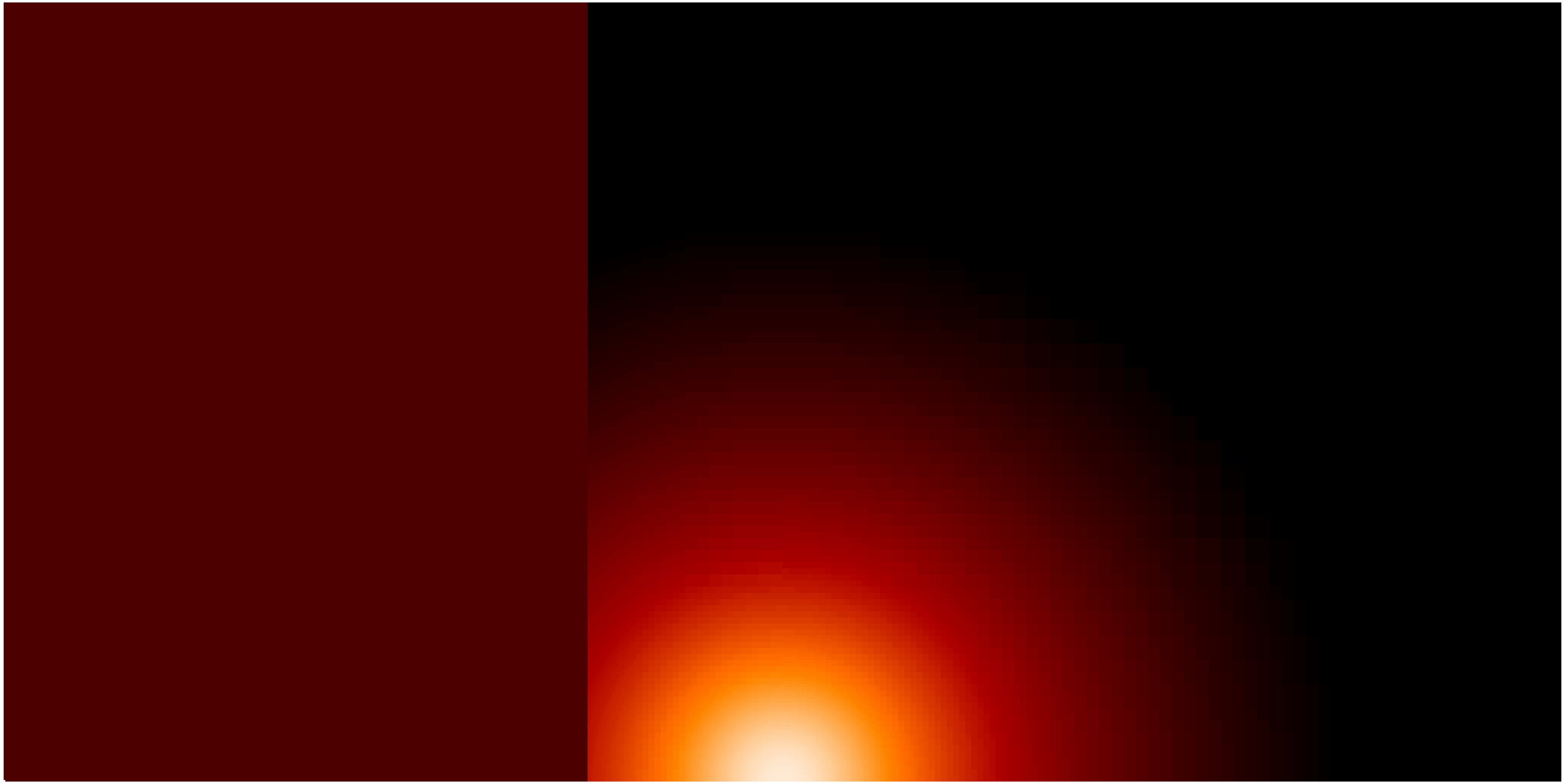


Gas temperature
(blue- cold)



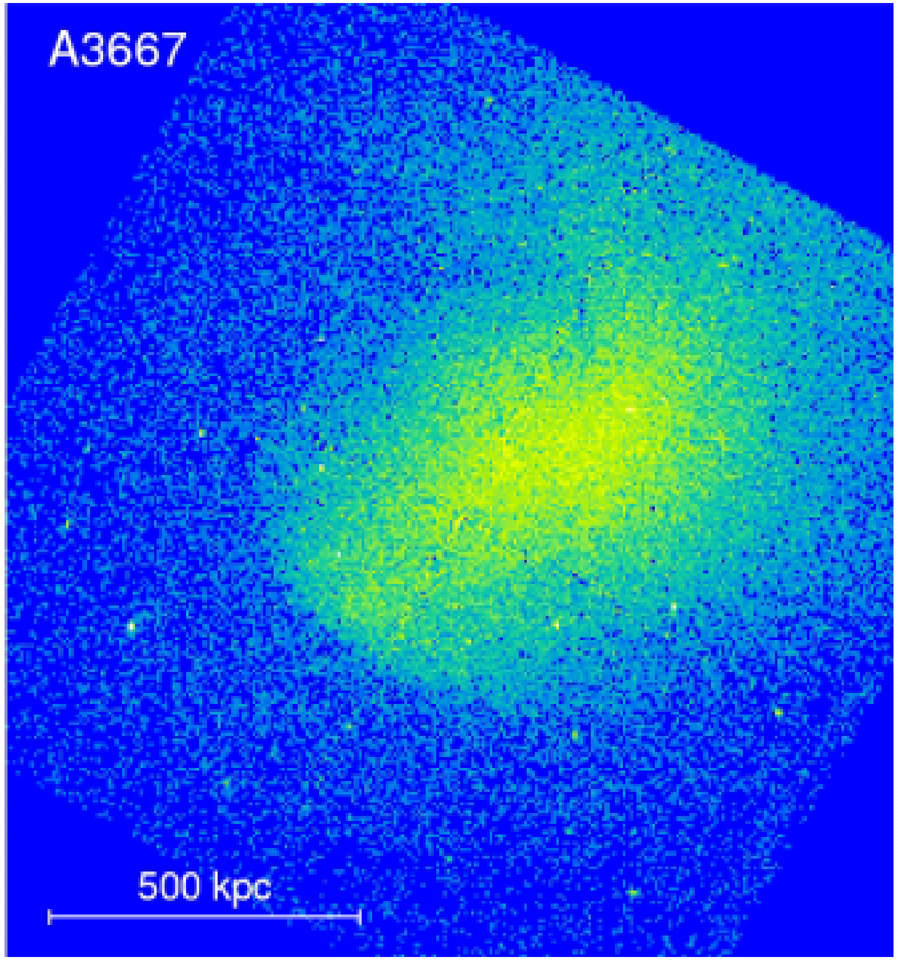
Contact discontinuity! – Cold front

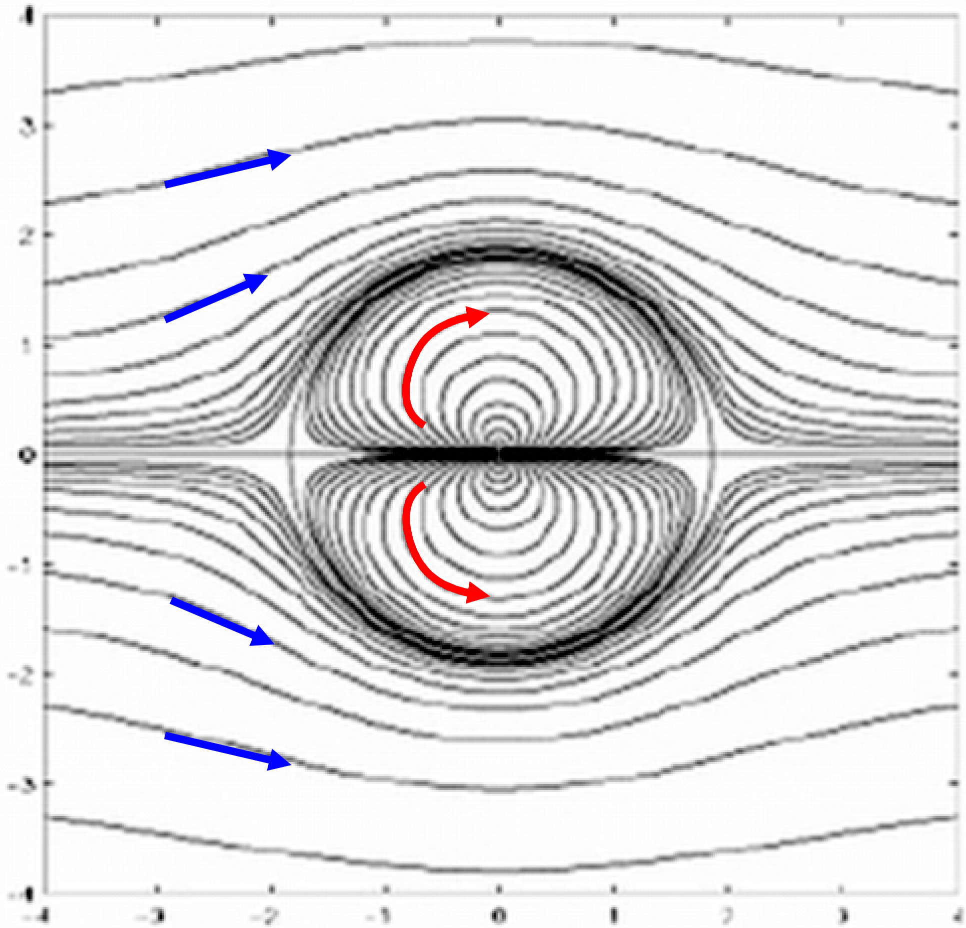
Cloud in the wind



Ram pressure "shaves" the cloud head, forming a sharp edge

Heinz et al., 2003

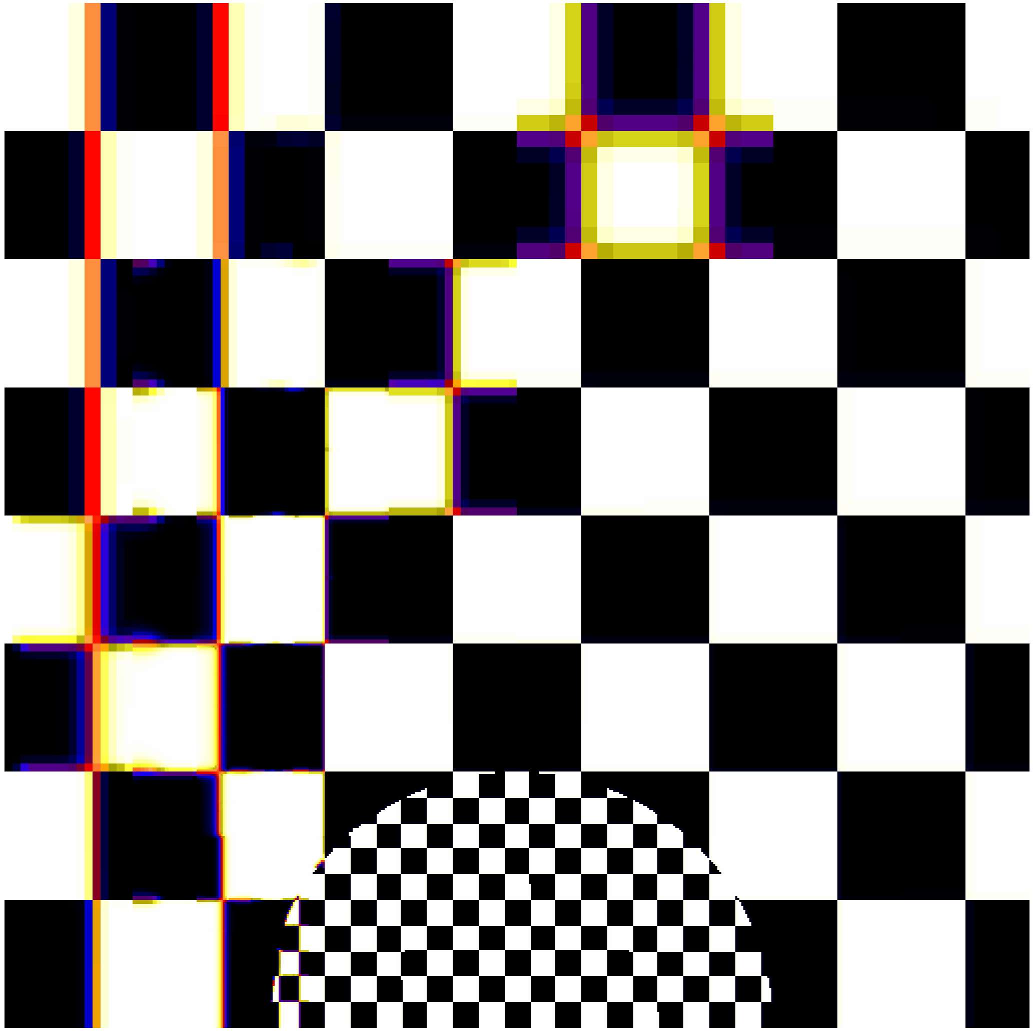




What suppresses Kelvin-Helmholtz instability
What suppresses thermal conductivity?

Magnetic field? (Vikhlinin et al, 2001)

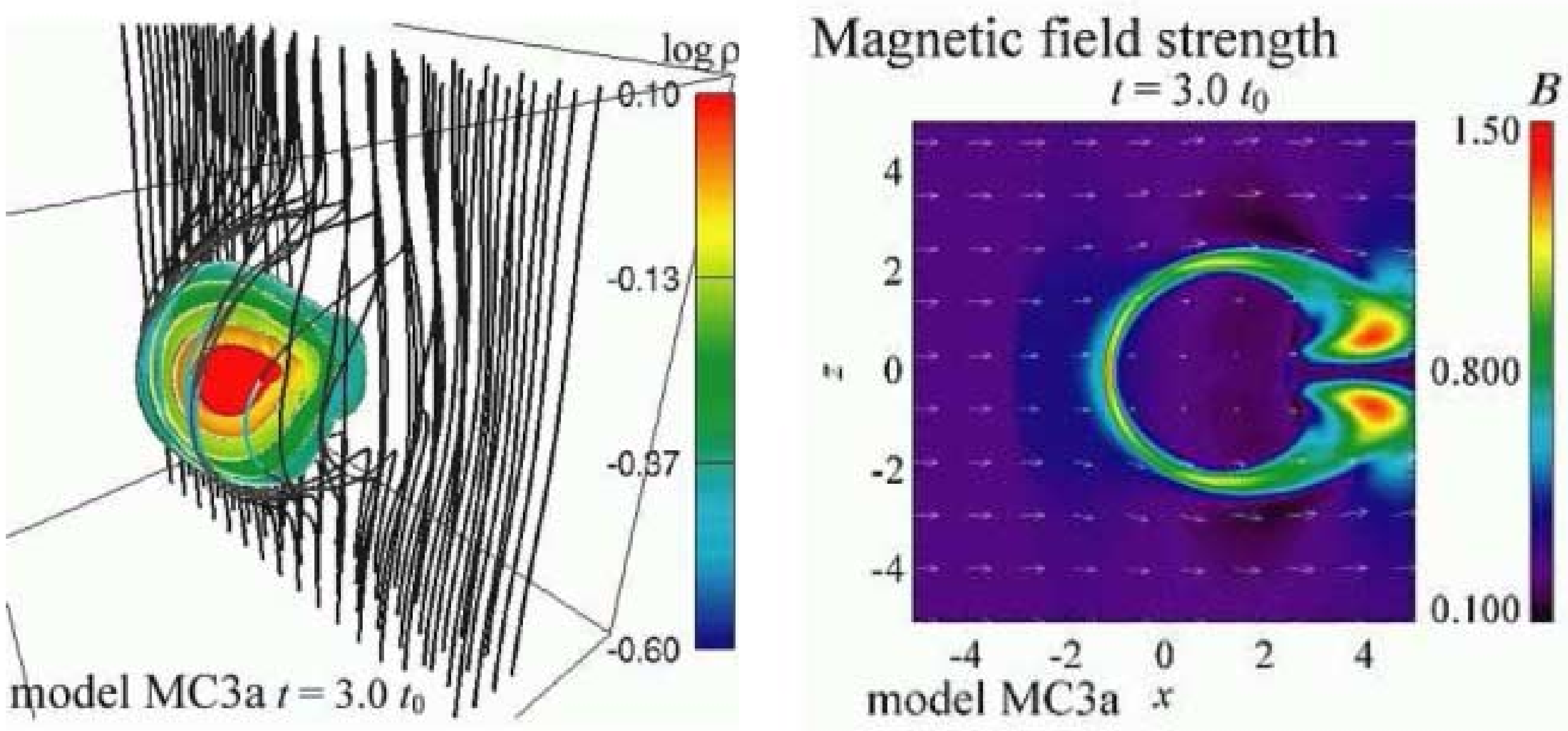
Gas motions inside the cloud



Contraction/stretching near stagnation point

Stretching/contraction (partly) suppresses instabilities
(Churazov & Inogamov, 2004)

Magnetic field enhancement



Asai et al, 2005

We do not know effective conduction and viscosity

We do not know topology and strength of B field

We do not know if the medium is turbulent or not

We learning and hope to learn more:

Velocity with X-ray spectroscopy => turbulence

Gamma-rays => Cosmic Rays (protons)

1. Clusters are useful objects for Cosmology

2. SMBHs keep the gas in the cores hot (same process operate in galaxies)

3. We starting to learn more on plasma in clusters (beyond just density and temperature)

Clusters have bright future ahead (next 10 years)!