Galaxy clusters: an overview

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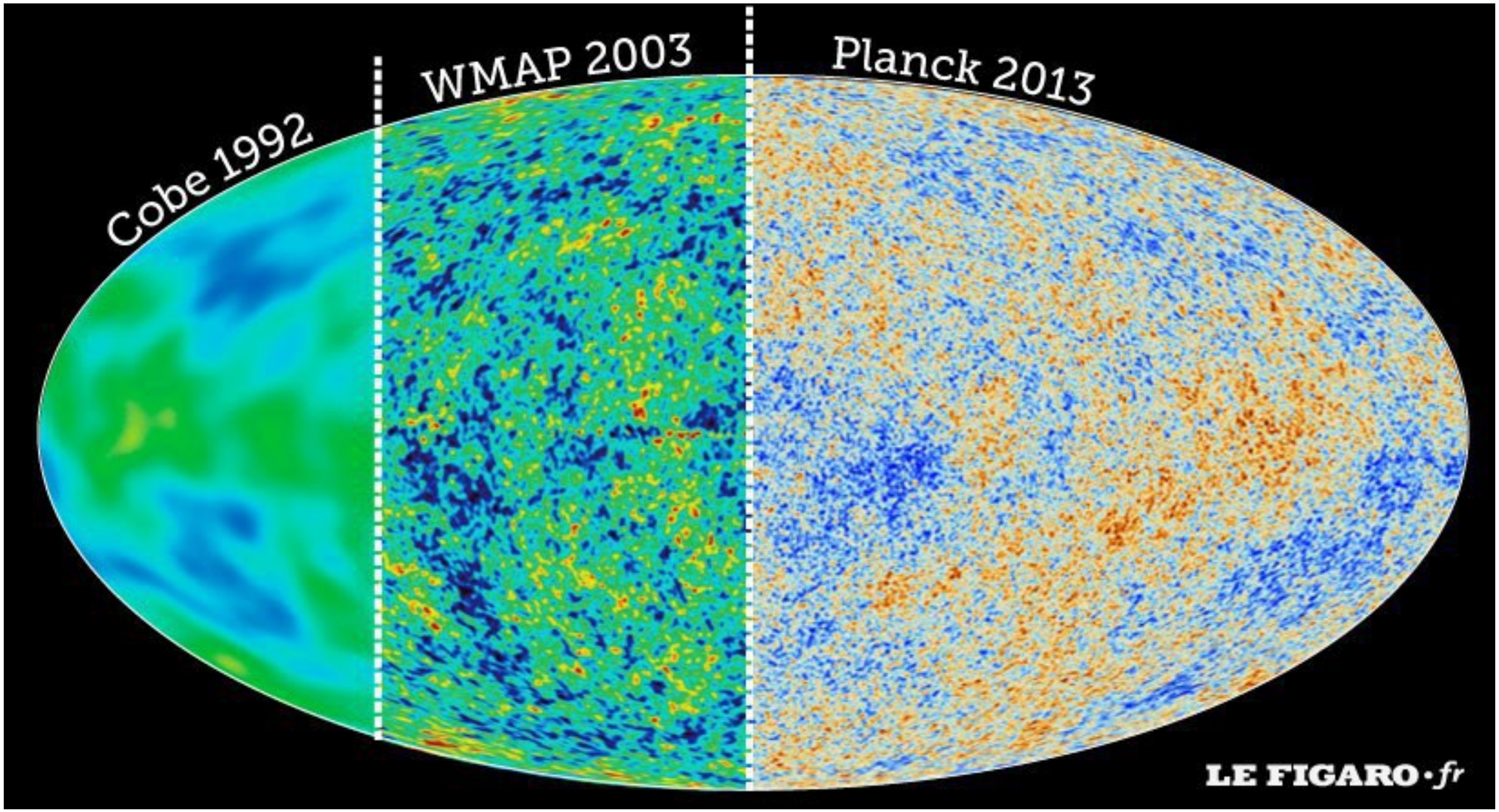
In the beginning



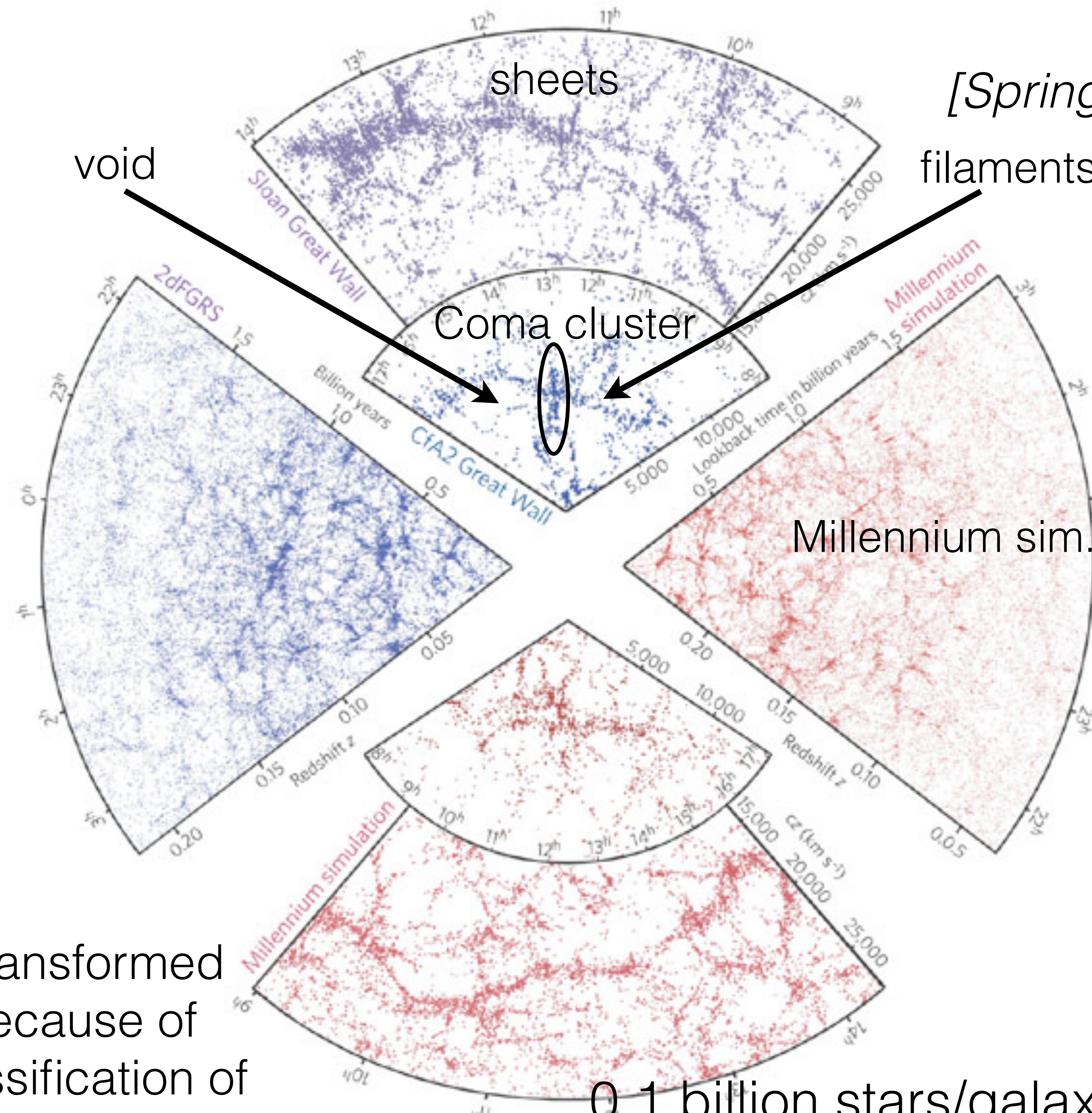
small temperature anisotropies: ~ 10^{-5}

small density perturbations seed the gravitational instability that leads to the formation of galaxies in an expanding universe

Large scale structure

[Springel et al.]

the spongy distribution of nearby galaxies

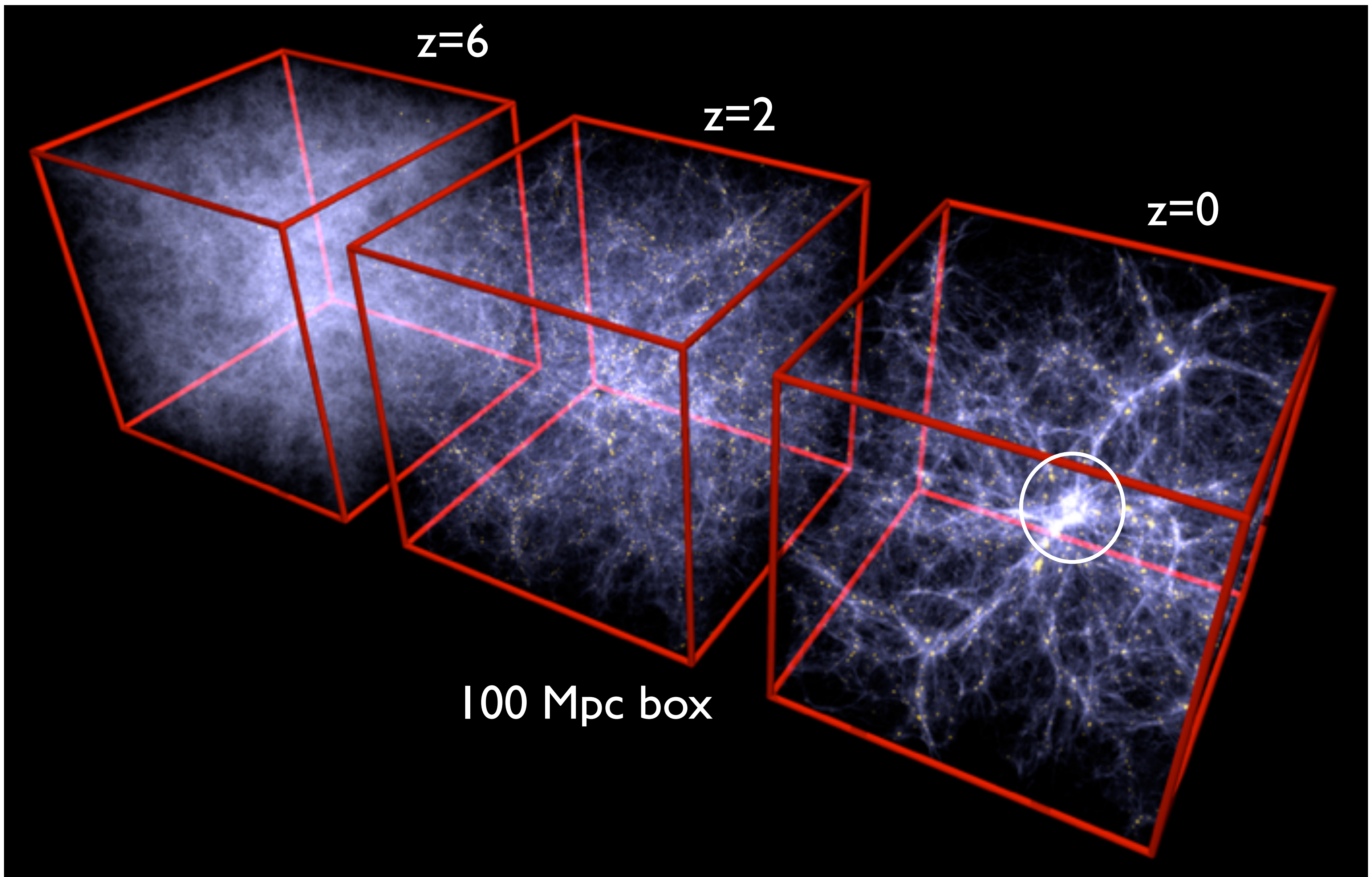


last 2 decades have transformed studies of galaxies because of automated surveys/classification of galaxies: SDSS, galaxy ZOO

0.1 billion stars/galaxies/AGN
millions of spectra!

Nonlinear evolution

[Springel et al. 2005]

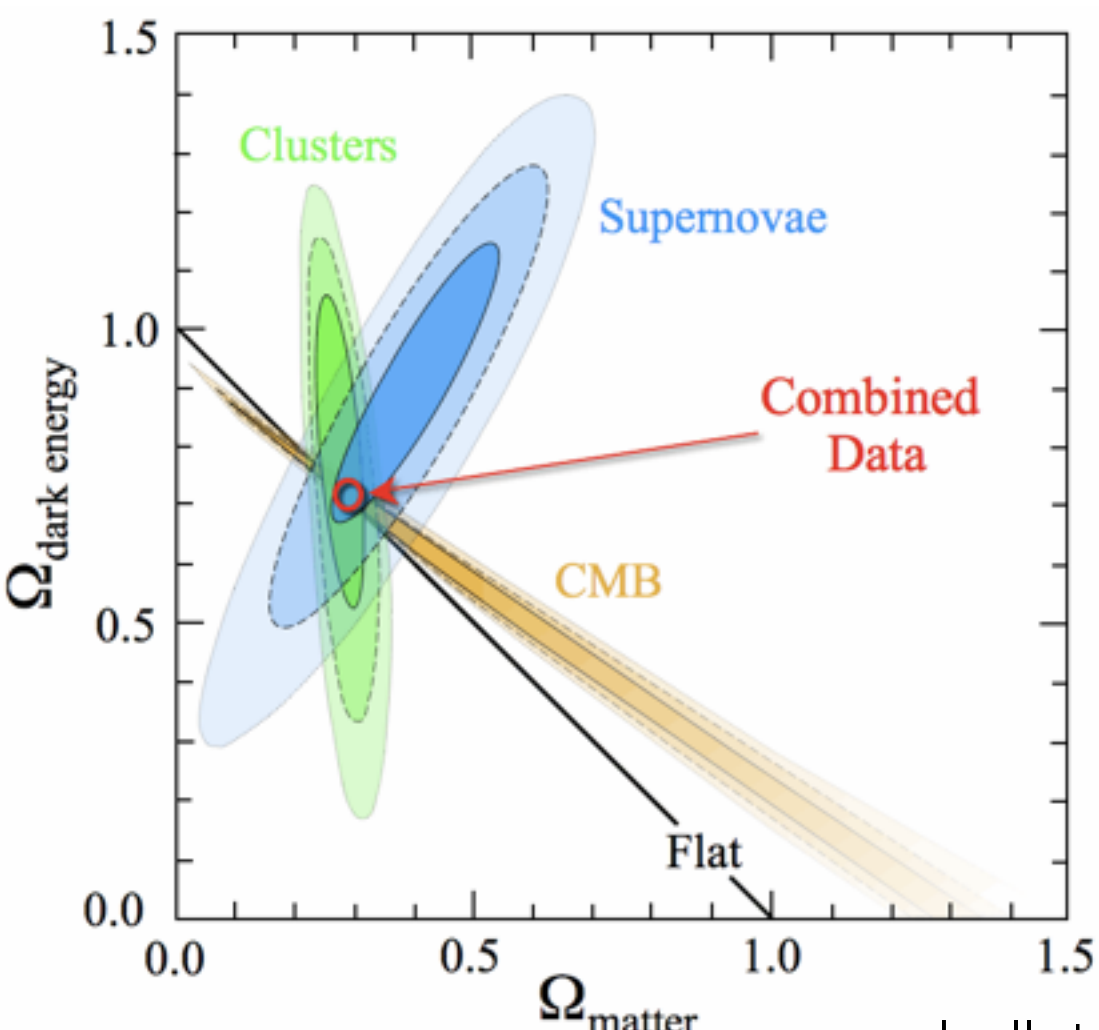


only limited progress with linear analysis

need nonlinear sims. to study structure formations

GCs: Crossroads of Cosmology & Astrophysics

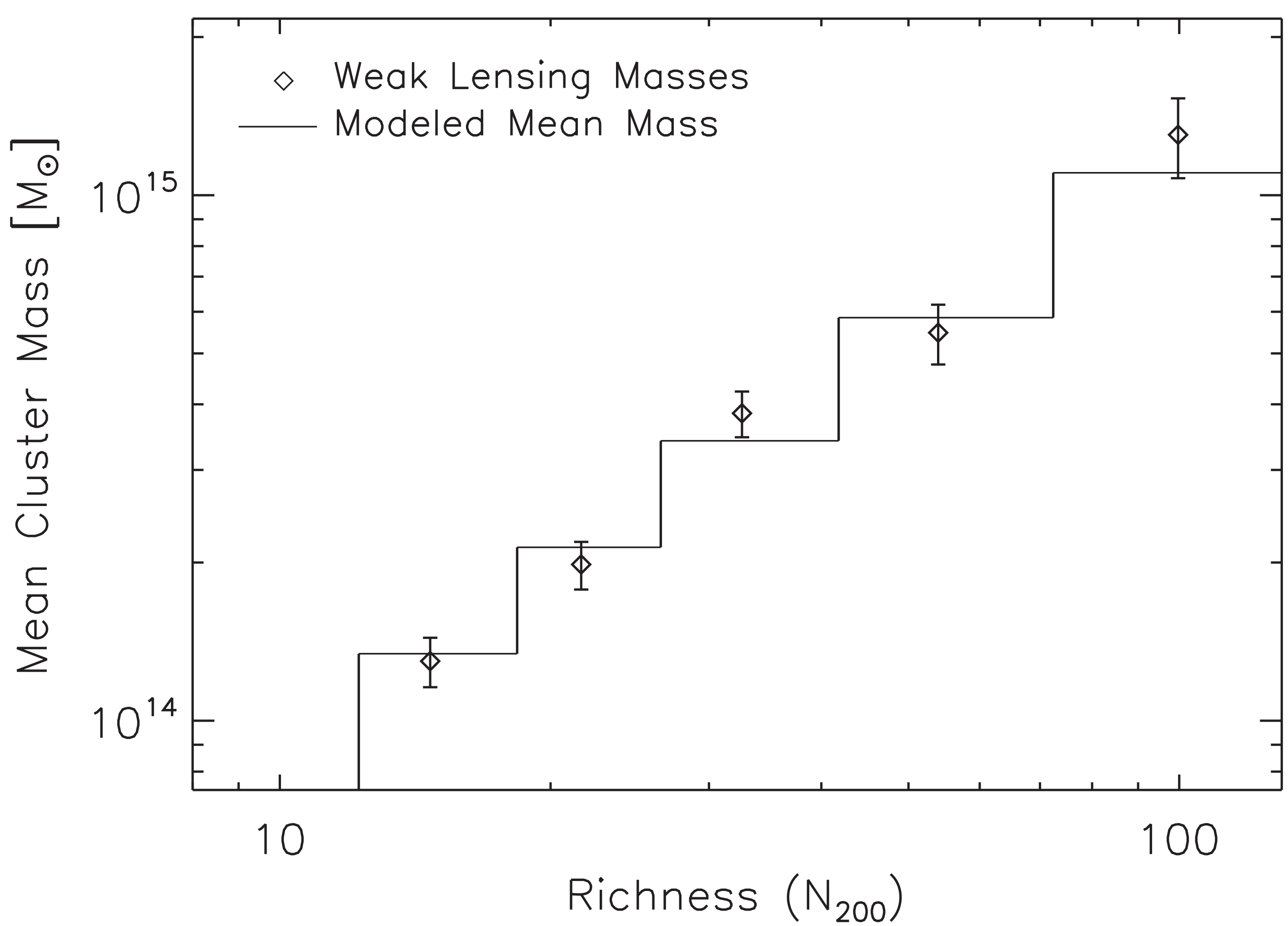
cosmology & messy astrophysics



bullet cluster: pink-Xrays vs. blue-dark matter via lensing
DM is non-interacting so pass through but gas is dissipative & shocks
rules out MOND

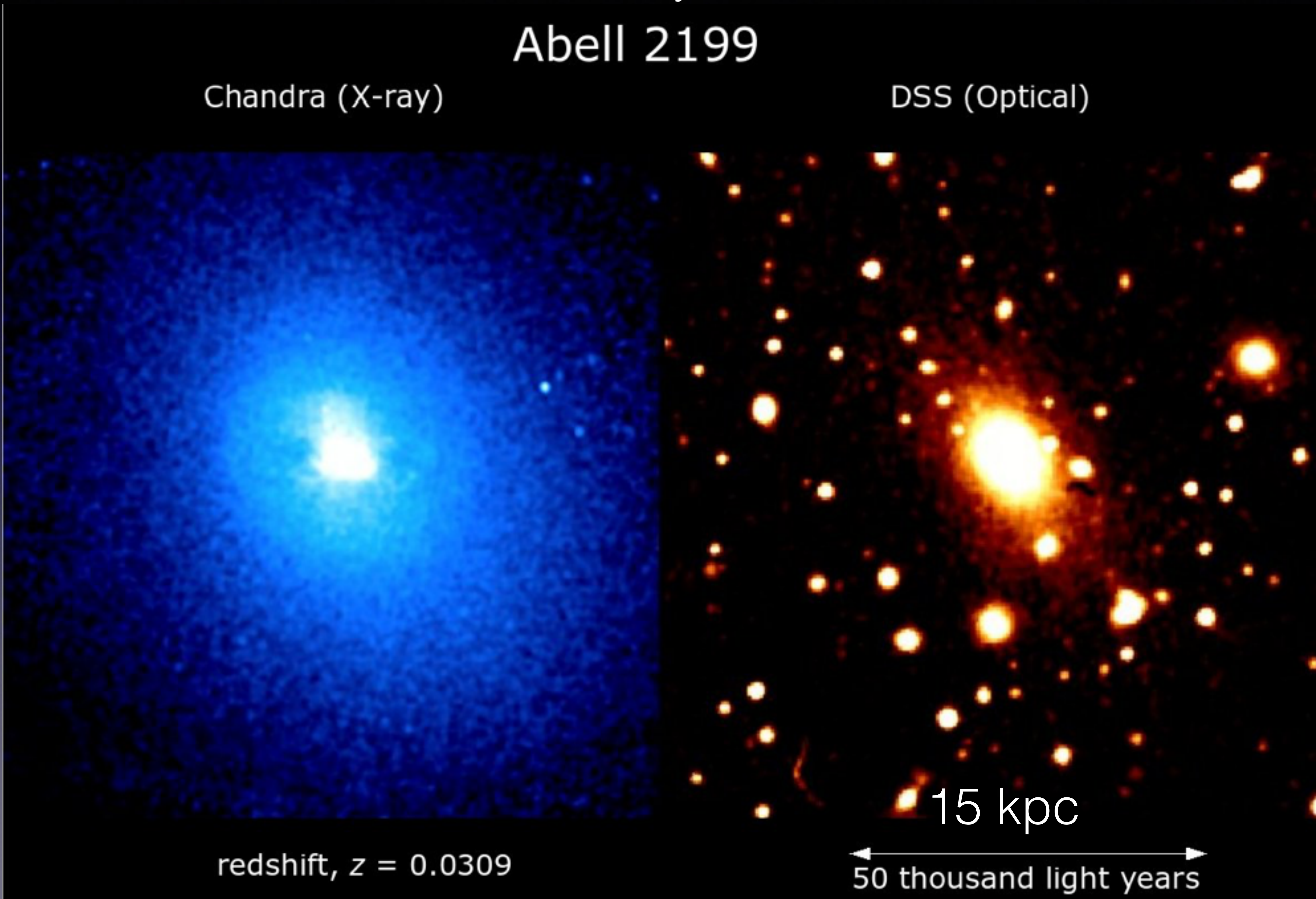
Optical

[Rozo et al. 2010]



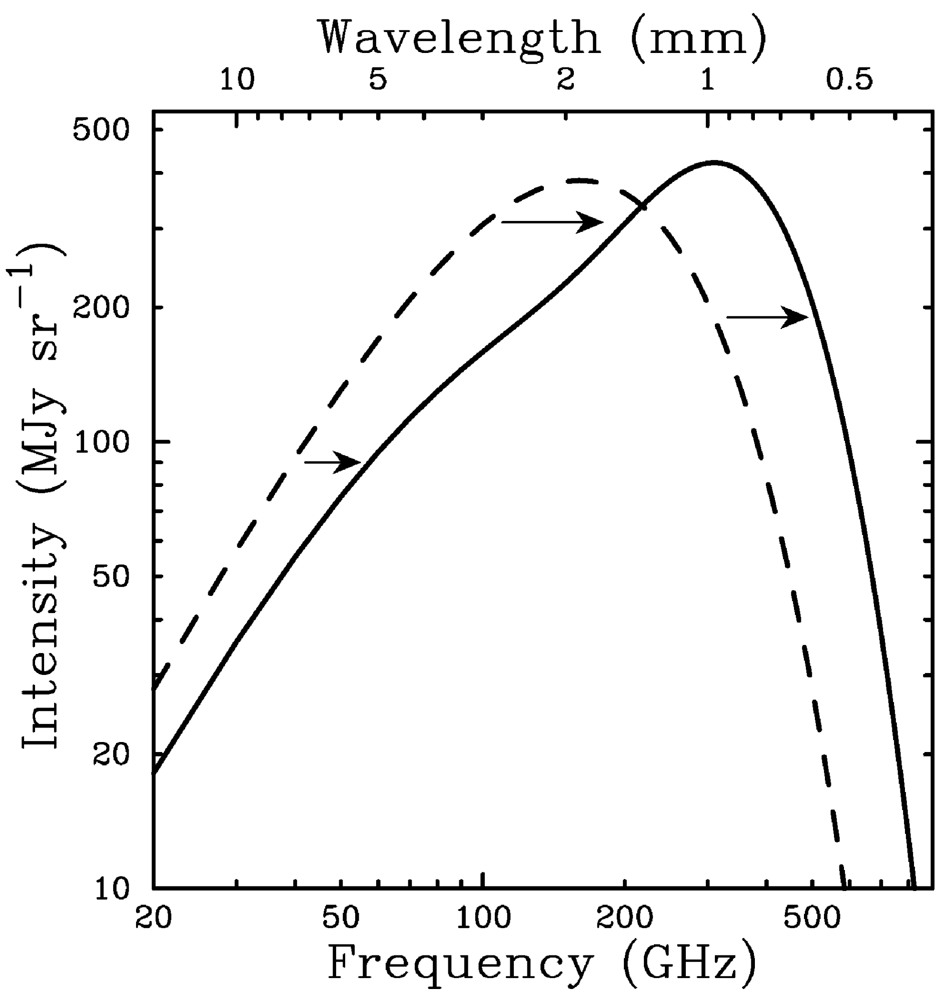
gravitational lensing of background galaxies helps to measure cluster masses

X-ray

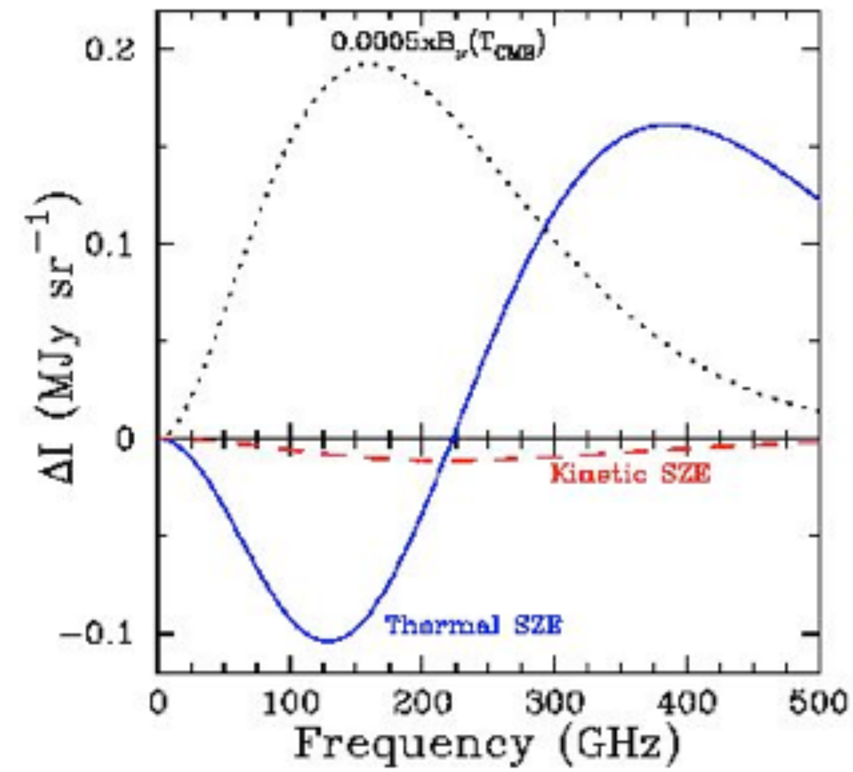

Abell 2199
Chandra (X-ray)
DSS (Optical)
redshift, z = 0.0309
15 kpc
50 thousand light years

SZ effect

hot cluster plasma upscatters the CMB (mm)



[Carlstrom 2002]



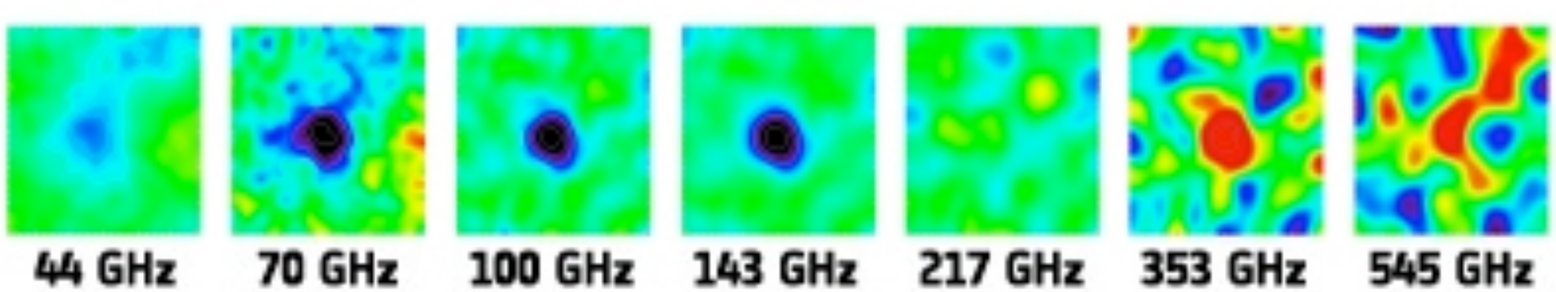
$$x \equiv \frac{h\nu}{k_B T_{CMB}}$$

$$\Delta I_{SZE} = g(x) I_0 y$$

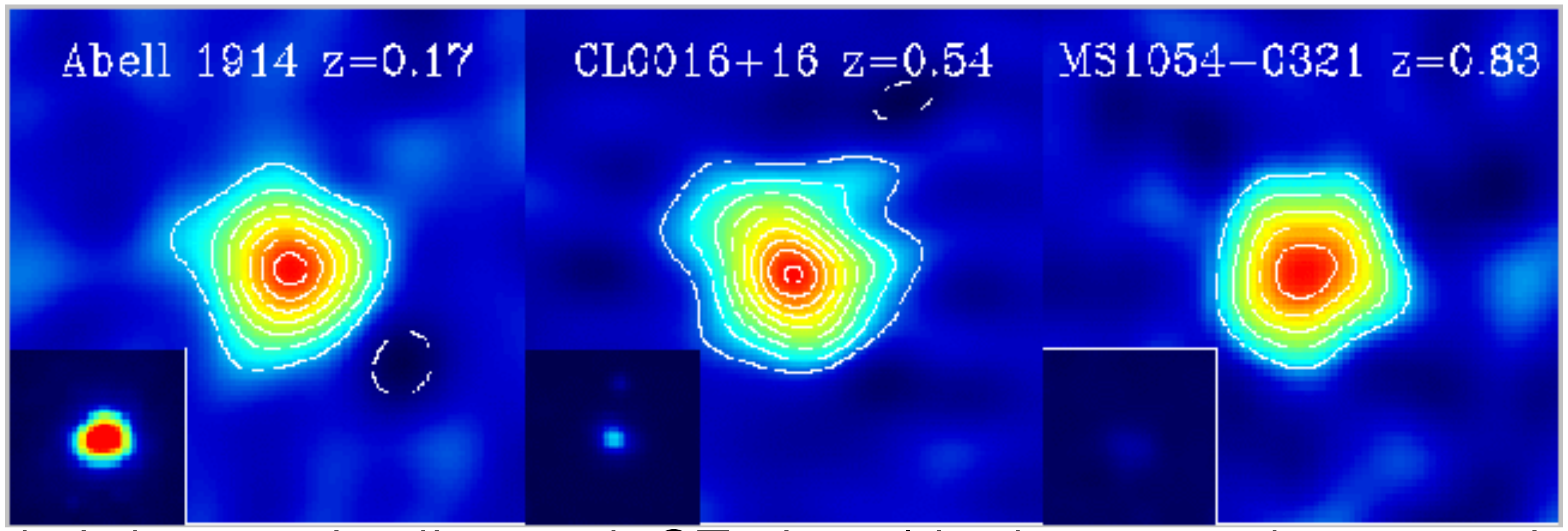
$$g(x) = \frac{x^4 e^x}{(e^x - 1)^2}\left(x\frac{e^x + 1}{e^x - 1} - 4\right)$$

$$y = \int n_e \frac{k_B T}{m_e c^2} \sigma_T dl$$

[Abell 2319 by Planck]



SZ clusters



while X-ray brightness is dimmed, SZ signal is the same because its based on scattering/absorption (same principle as quasar absorption line studies)

can obtain a huge sample of GCs at higher redshifts! => great for precision cosmology

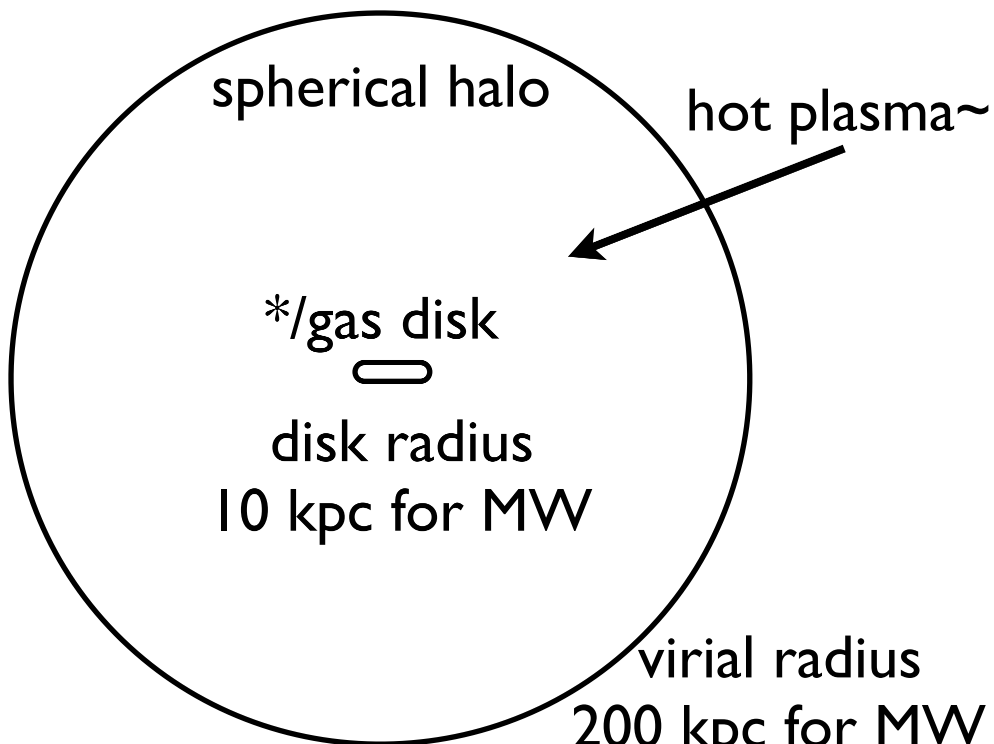
global Y parameter: $Y = \int n_e \frac{k_B T}{m_e c^2} \sigma_T dV = \int y dA \propto \int p dV \propto pV \propto M^{5/3}$

but need to understand systematics in observable (Y_{SZ})-halo mass relation

ground based mm telescopes: ACT, SPT ; space based Planck

Dark matter gravity

gas cools and condenses into central galaxy
leaving behind hot gas with long cooling time



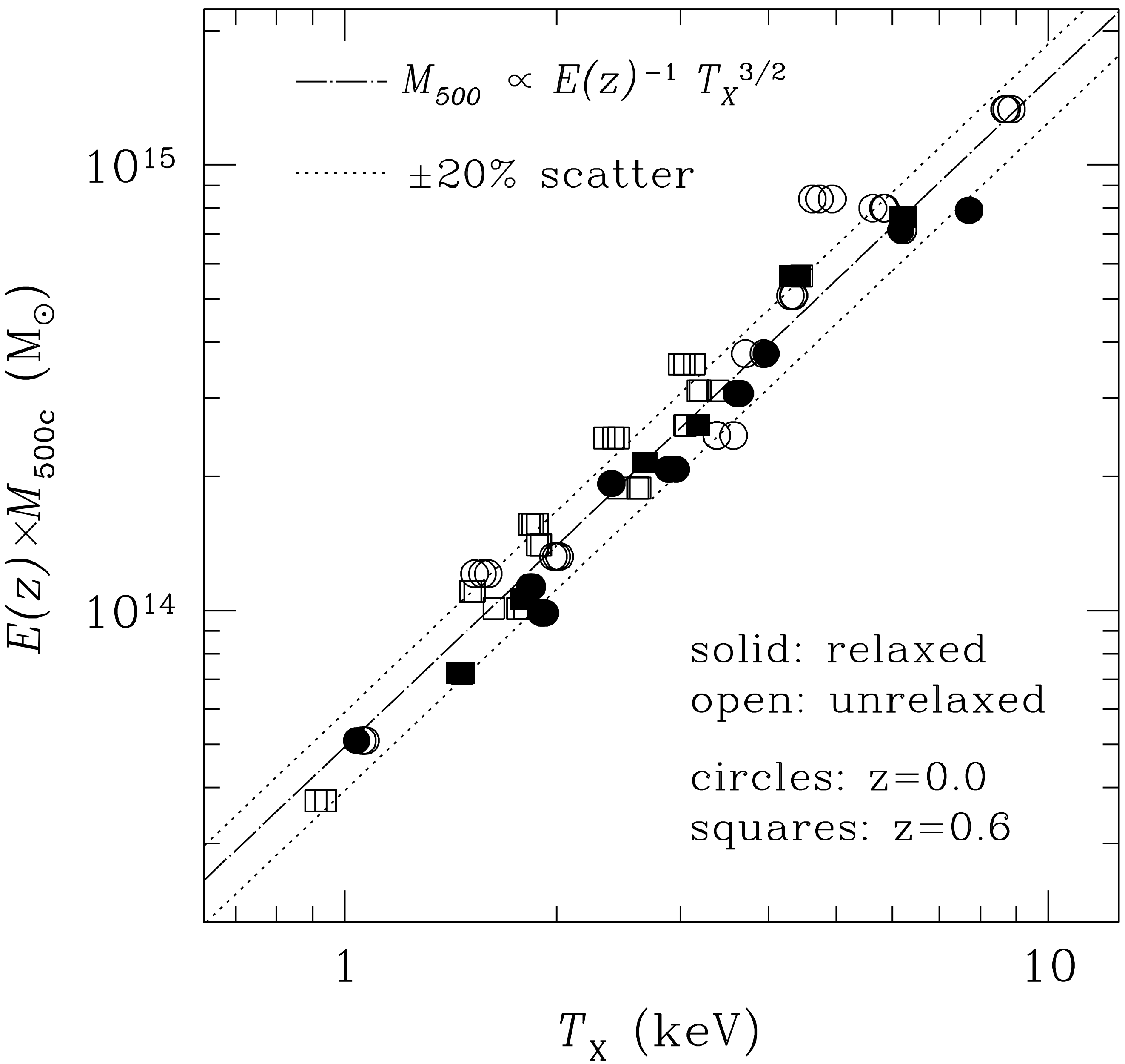
DM halo & hot gas extends much farther out compared to the visible disk

How does the distribution of baryons depend on the halo mass?
fraction of mass in stars, hot gas, cold gas, ...

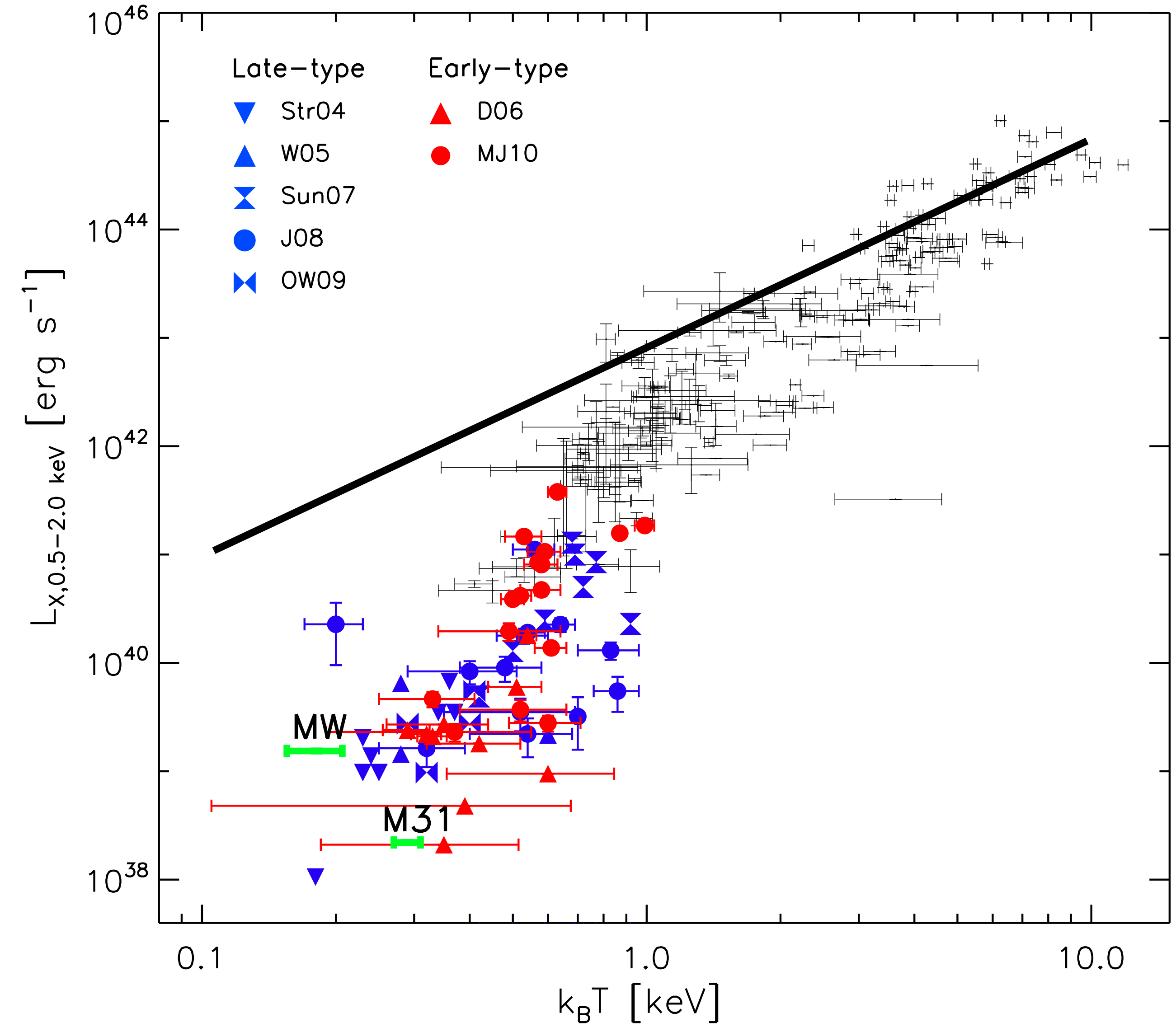
structure of hot gas, disk as a function of halo mass

Mass proxies

[Kravtsov et al. 2006]



[Crain et al. 2010]



self-similarity breaks down at small T.
How do we explain this?

Baryons in gps./clusters

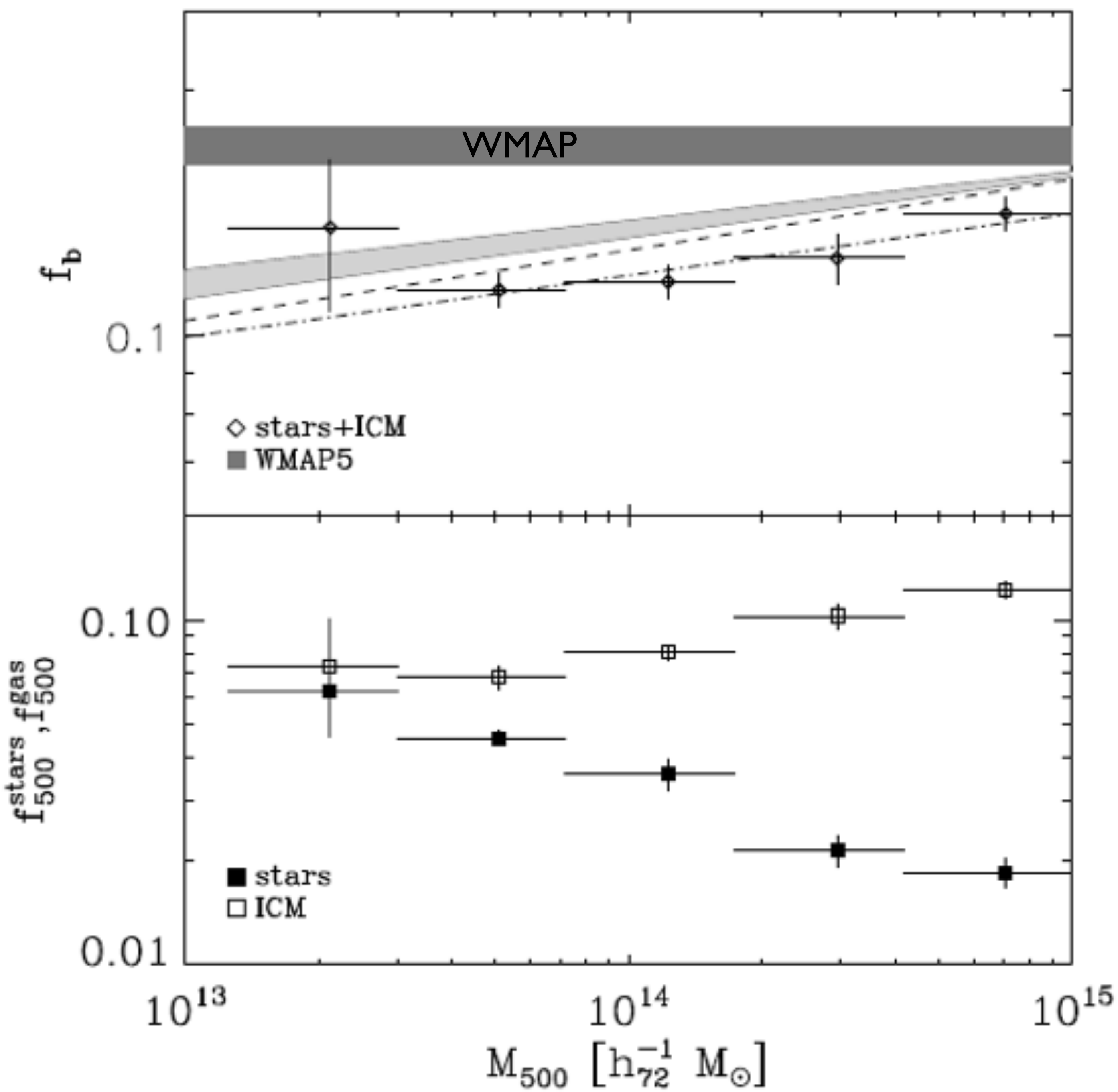
[Giodini et al. 2009]

most mass in clusters: DM

f_b~ 0.17 in baryons

most baryons in hot gas (ICM)

clusters are roughly closed boxes because of a deep potential well



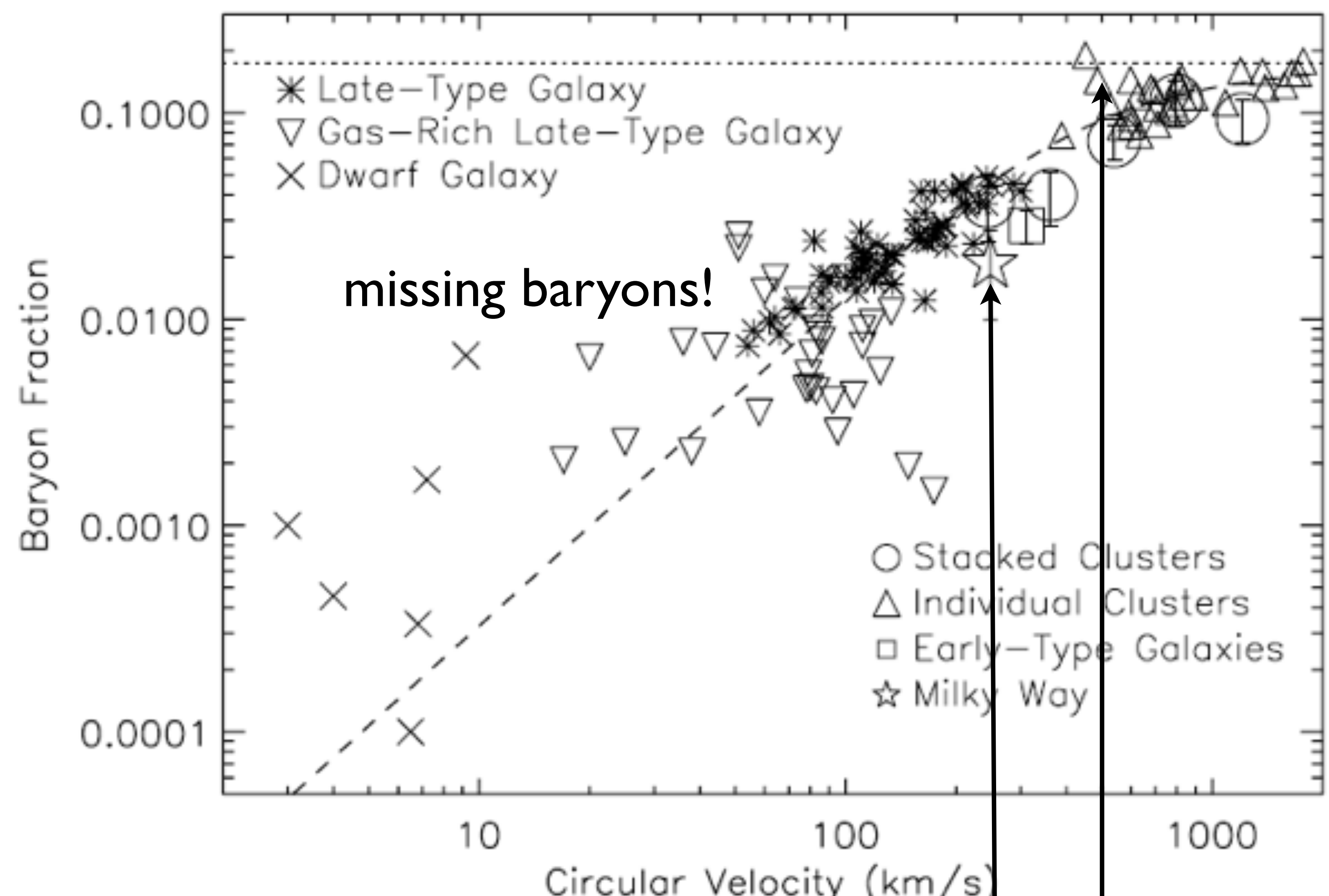
Smaller halos?

[Dai et al. 2010]

baryon fraction: a fn. of halo mass irresp. of SF/AGN activity in central galaxy

halos become baryon poor below ~10^{13} Msun

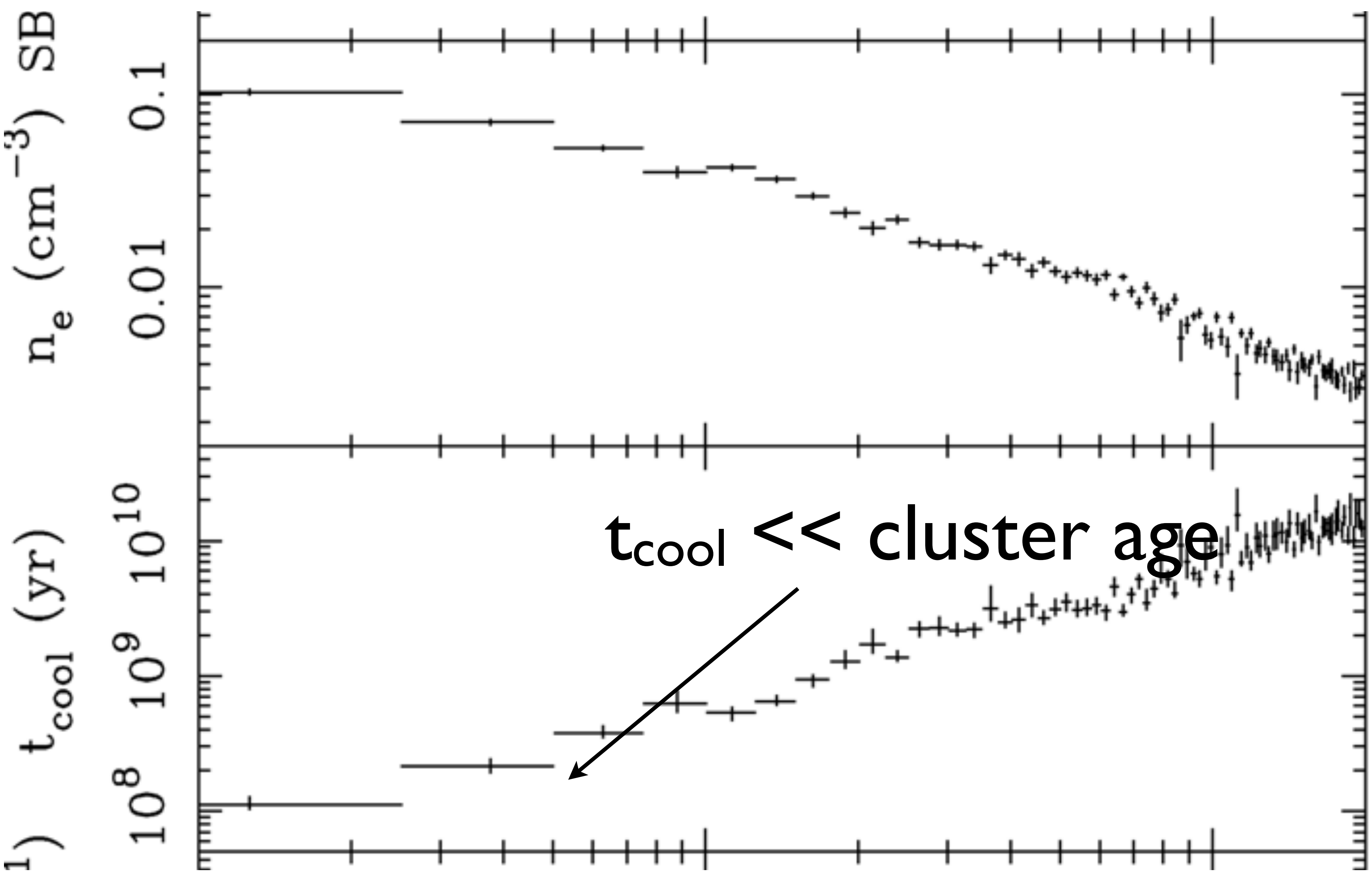
majority of baryons missing!



most gas is in the hot, difficult to observe, diffuse phase
cold molecular/atomic gas must be replenished

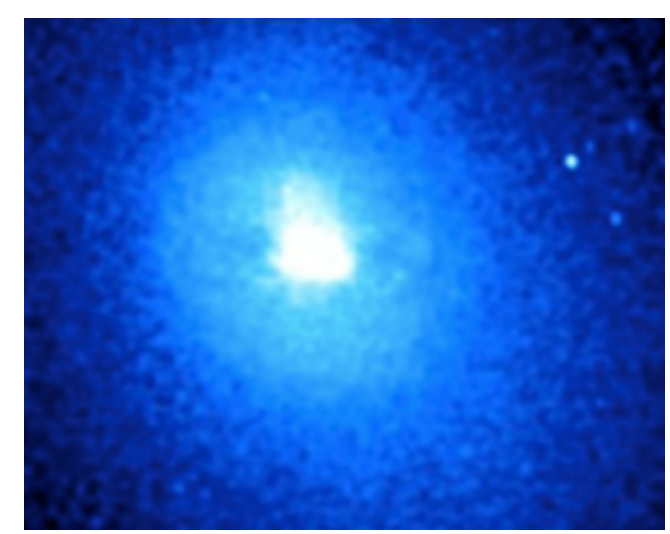
Cooling flow problem

[Johnstone et al. 2002]



1kpc 200kpc

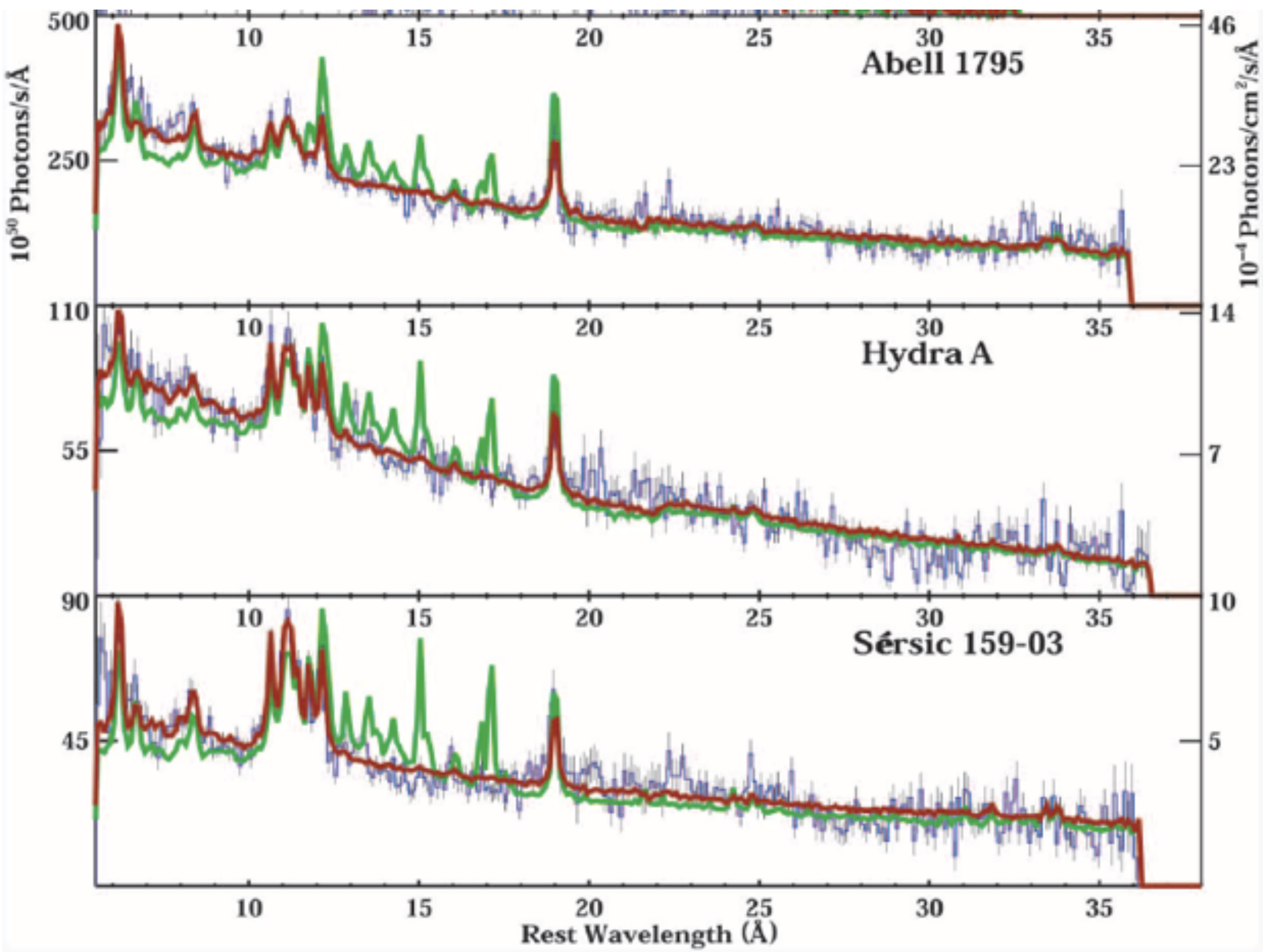
coming back to clusters, where hot gas is best observed



$t_{cool} \sim nkT/n^2\Lambda$ << their age yet no signs of cooling

Cooling absent!

[Peterson et al. 2003]



$$L_X \approx \frac{N k_B T}{t_{\rm cool}}$$

$$\dot{M} = \frac{\mu m_p N}{t_{\rm cool}}$$

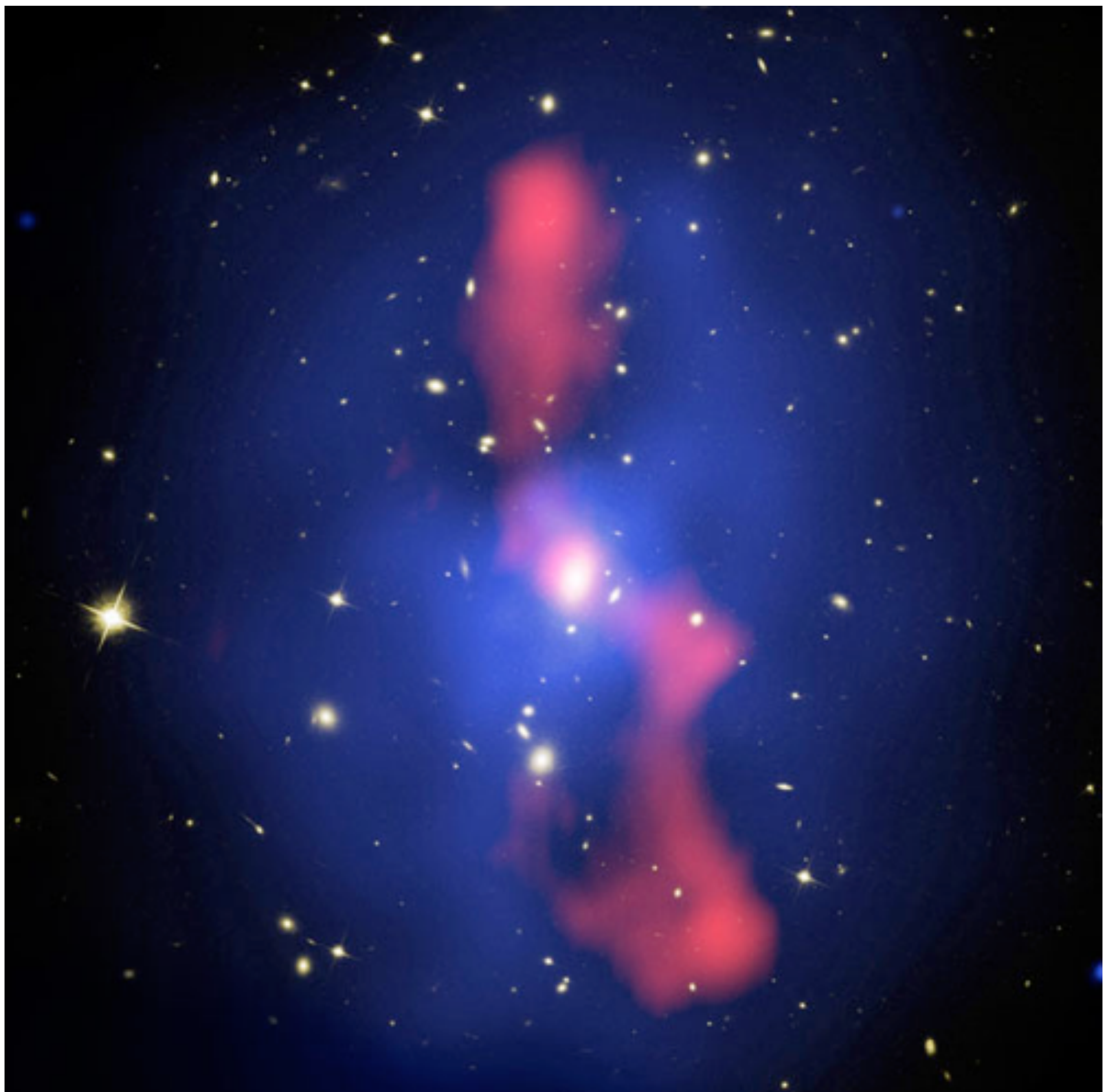
$$L_X = \frac{5}{2} \frac{\dot{M} k_B T}{\mu m_p}$$

observed Mdot is ~ 10 or smaller than above

soft X-ray lines missing!

AGN Heating?

[McNamara & Nulsen 2007]



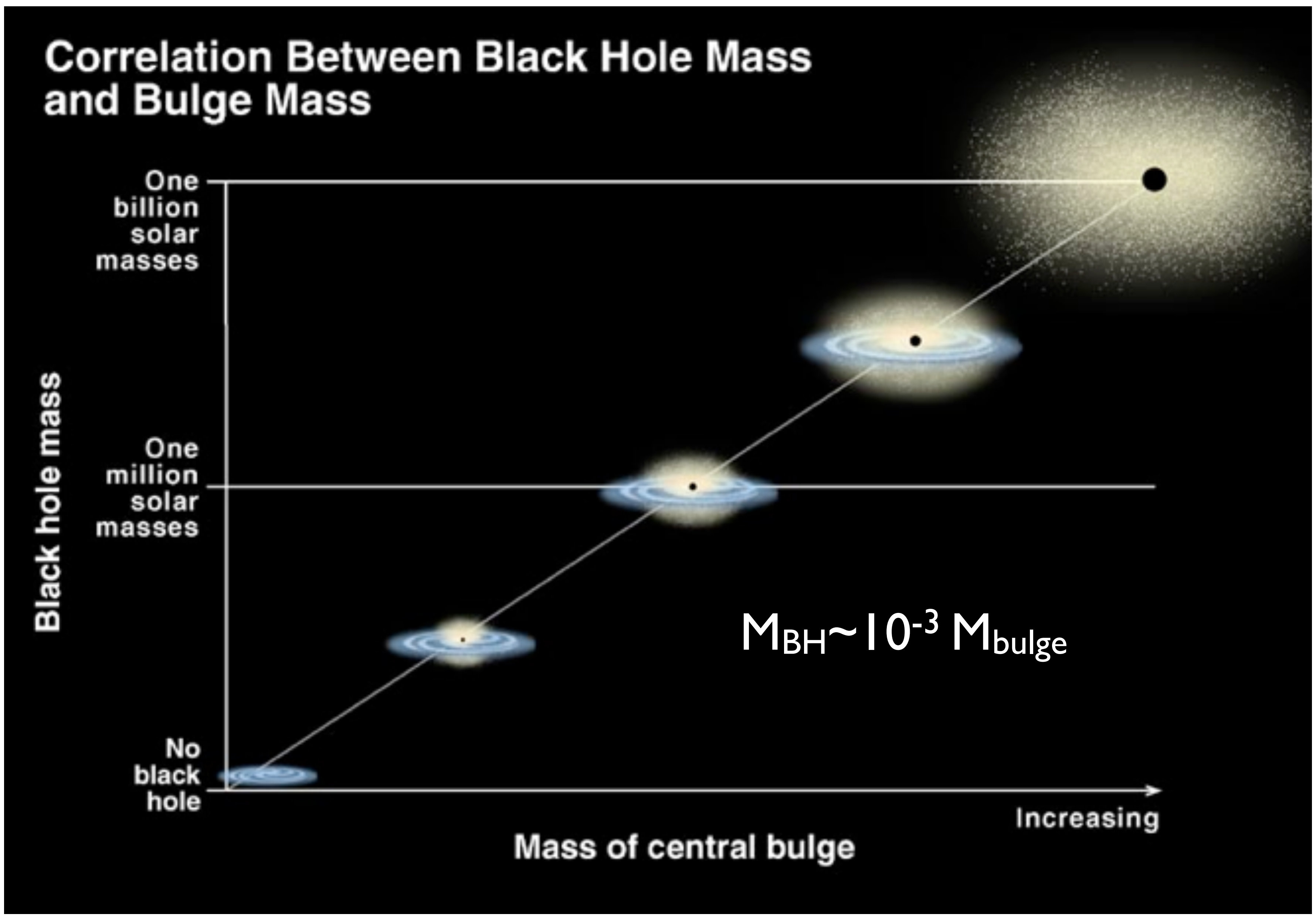
cooling ICM can power AGN
negative feedback loop
prevents catastrophic cooling

jet/cavity power ~ X-ray luminosity
& lack of cooling

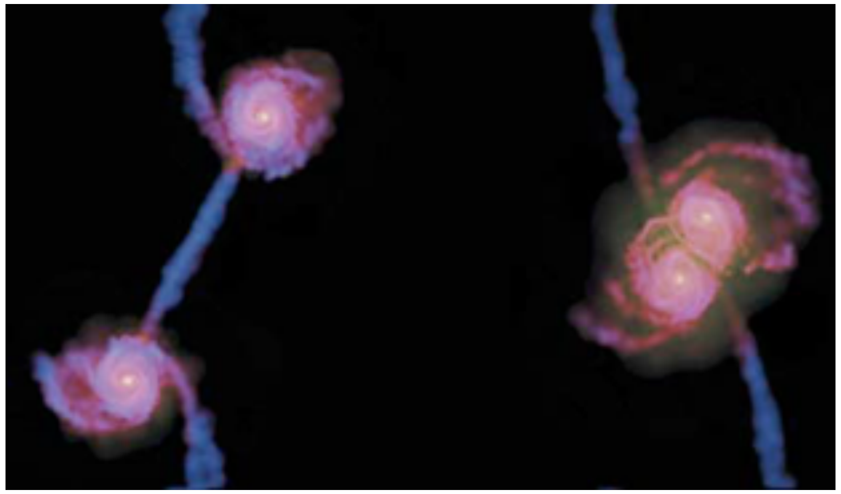
=> rough thermal balance

BH-bulge correlations

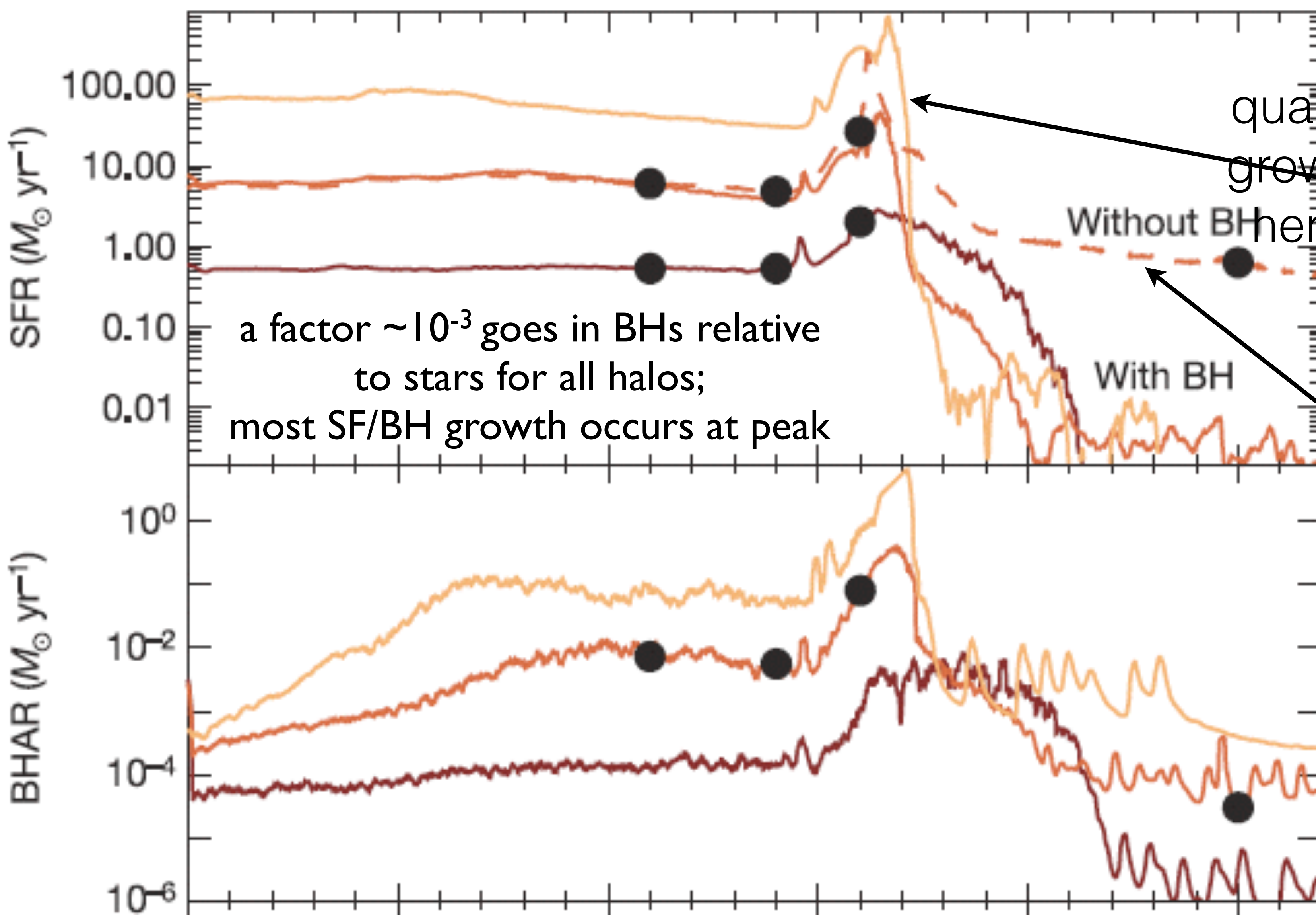
bulge >> BH sphere of influence & yet is correlated w. BH => BH affects star-formation in bulge



BHs affects galaxy formation at large scales!



[Di Matteo et al. 2005]



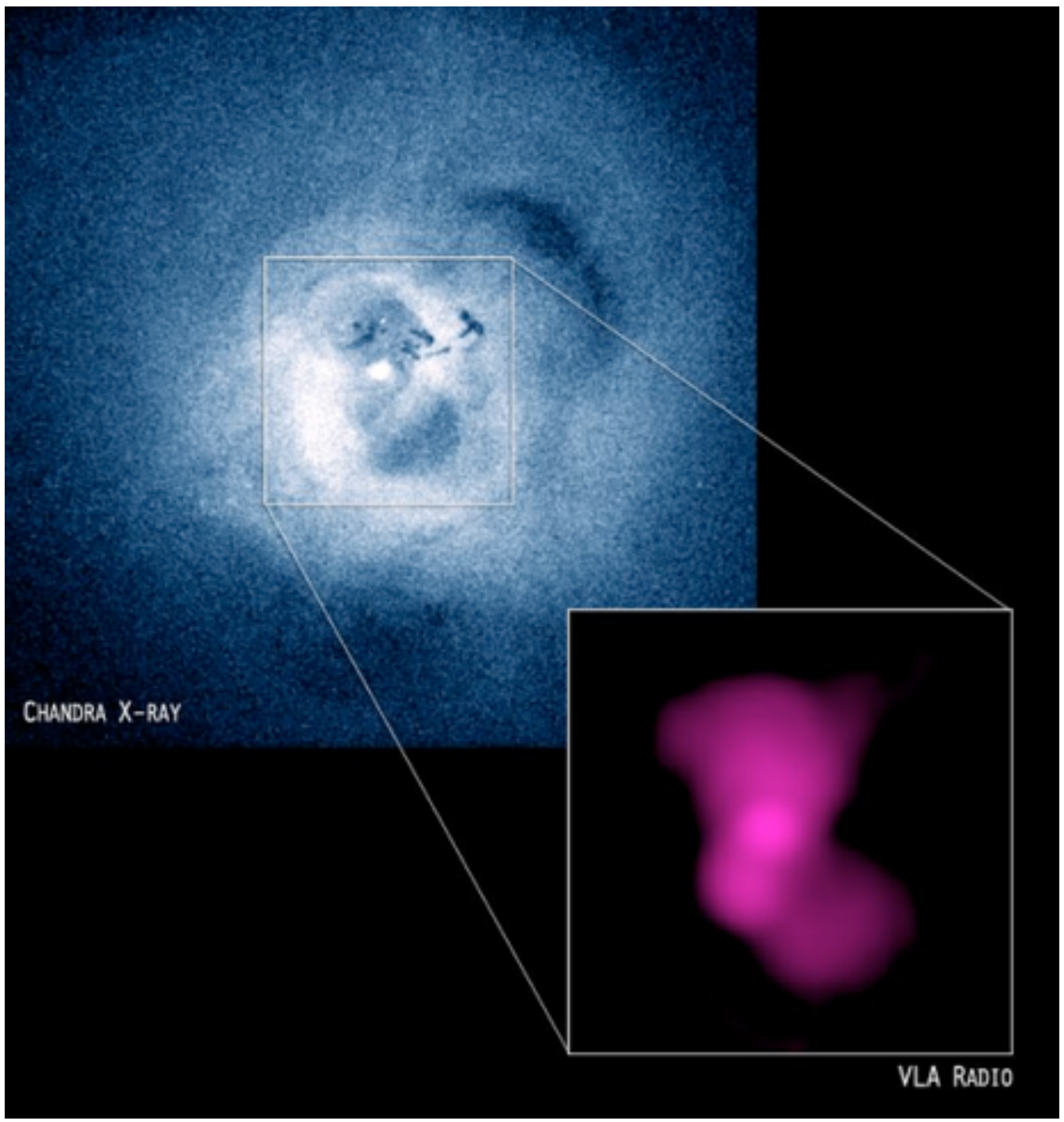
time from 0 to 2.5 Gyr

quasar feedback quenches SF & BH growth, producing massive ellipticals where growth is triggered by merger

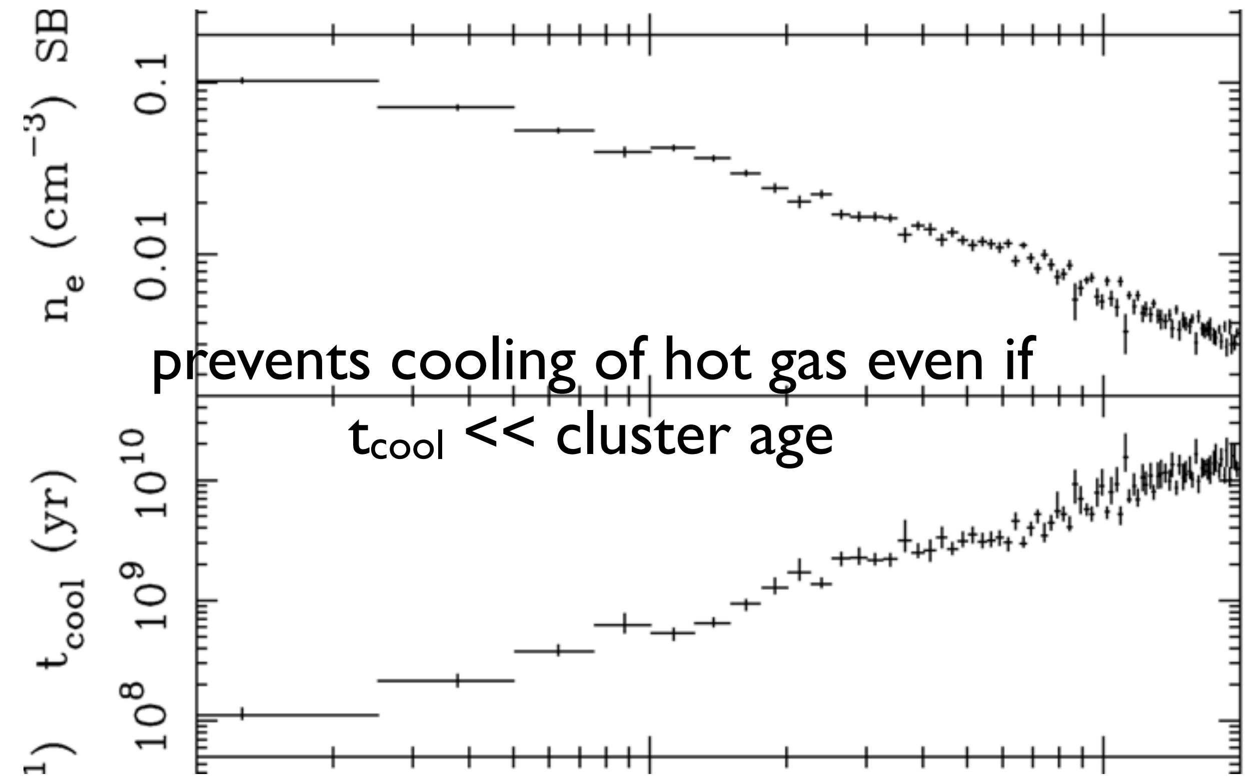
maintenance/radio mode FB: still reqd. to prevent hot gas from cooling & preventing SF

Kinetic FB

best observed in galaxy clusters,
home to biggest BHs and galaxies



[Johnstone et al. 2002]

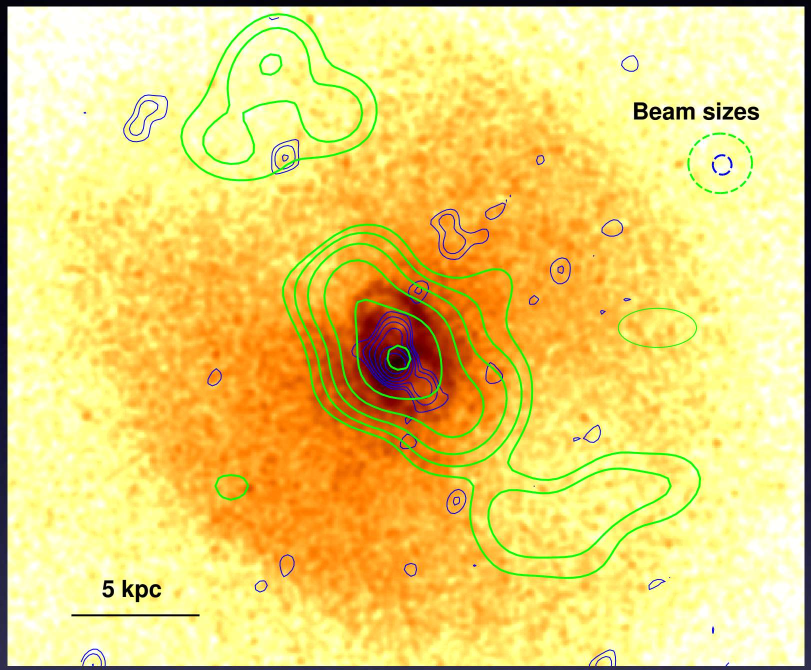


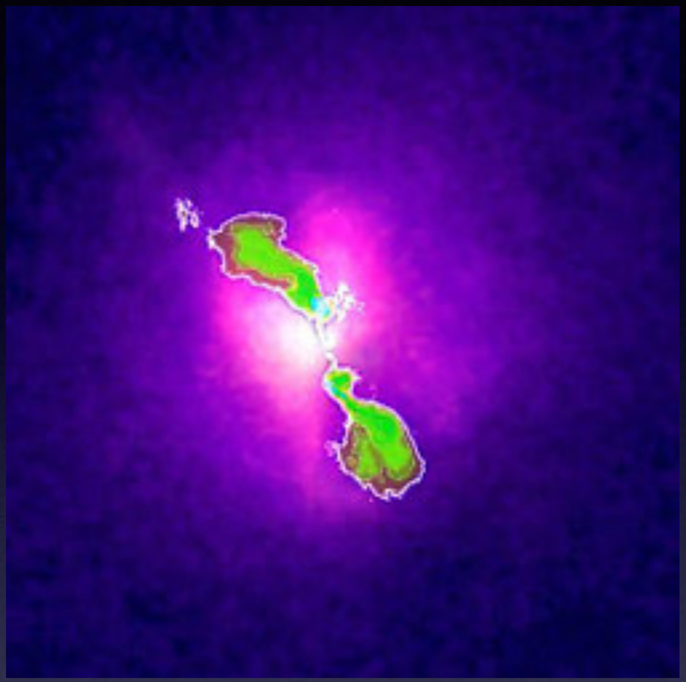
prevents cooling of hot gas even if
t_{cool} << cluster age

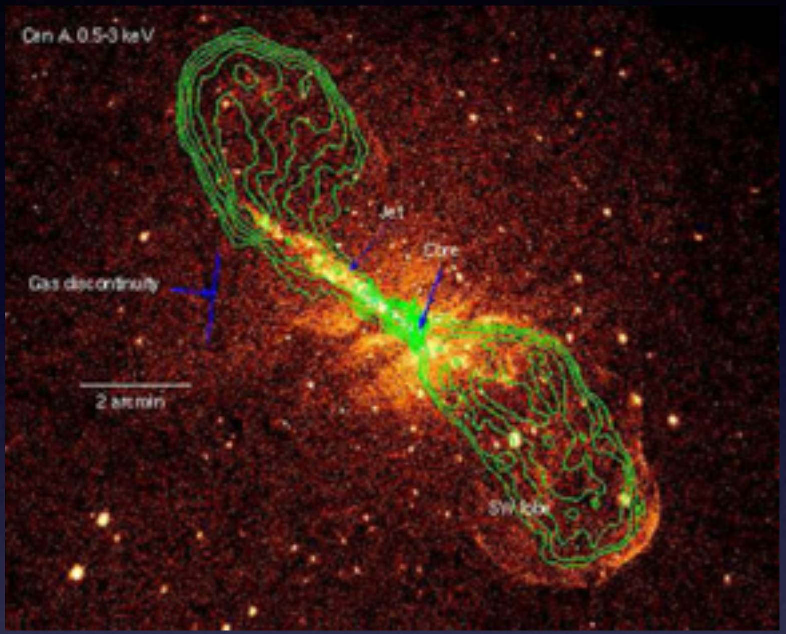
1kpc 200kpc

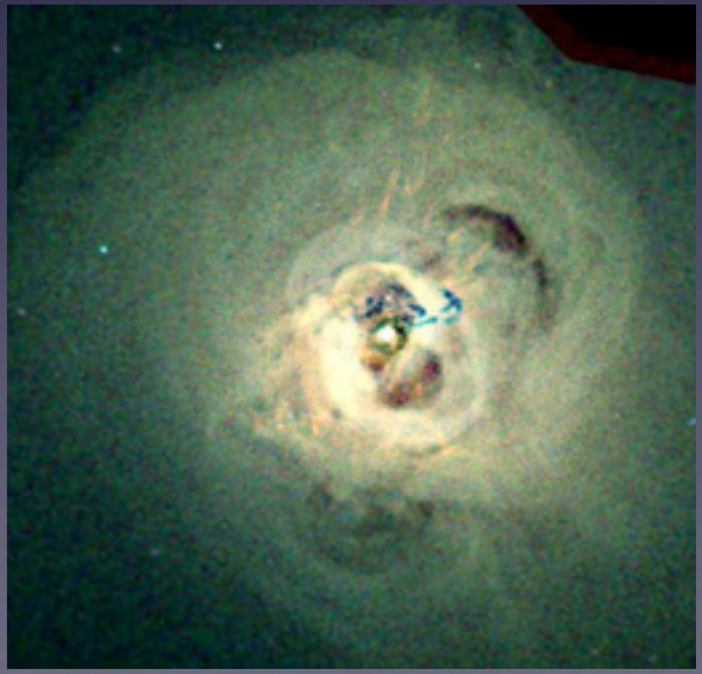
jet/cavity power ~ core-luminosity
=> cooling losses balanced by AGN heating
& thermal eqbn.

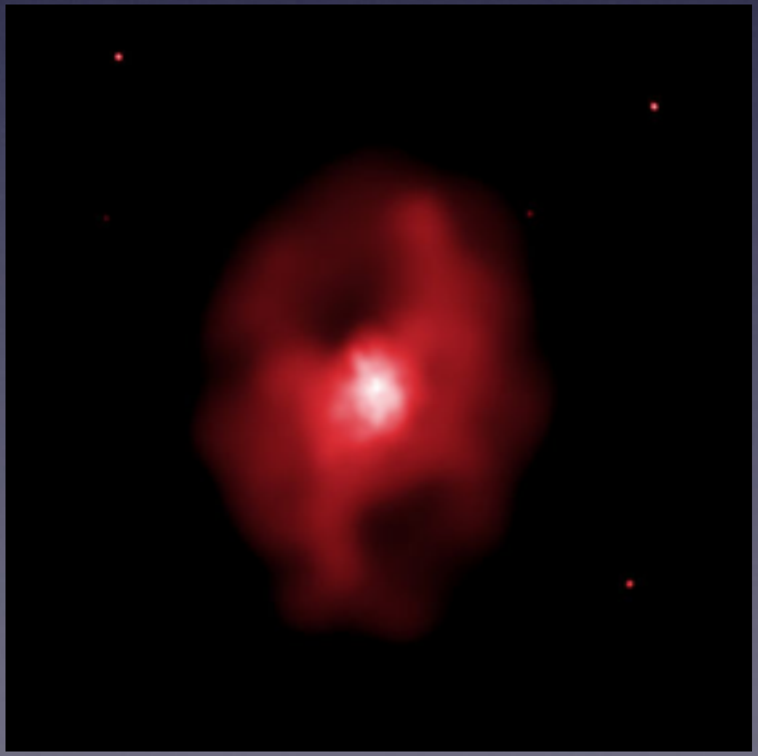
Rogues' gallery







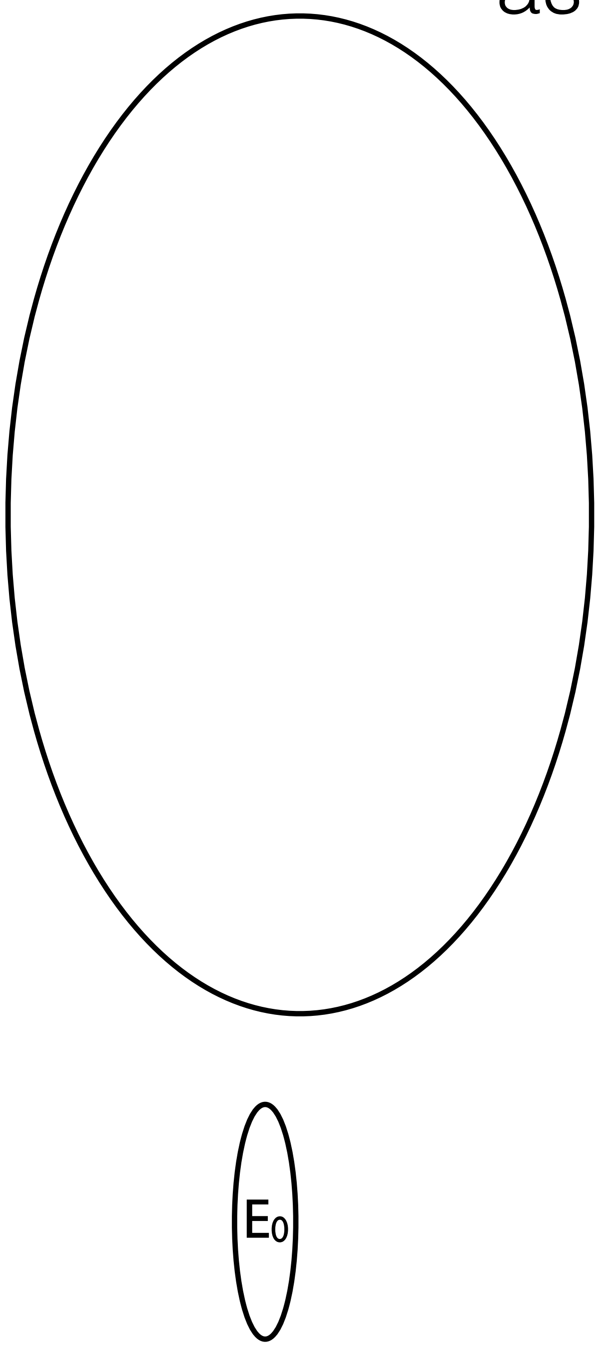




roughly 10s of kpc

Jet Power

[Churazov et al. 2002] as bubble/cavity expands it does PdV work on the ICM
a fraction of it converts to irreversible heating



$$E_0 = \gamma/(\gamma - 1)PV$$

initial bubble energy
energy stored+pdV work

$$\Delta E = -\int V\rho \frac{\mathrm{d}\phi}{\mathrm{d}r}\mathrm{d}r = E_0 - \frac{\gamma}{\gamma - 1}PV$$

$$= E_0\left[1 - \left(\frac{P}{P_0}\right)^{1-1/\gamma}\right],$$

energy dissipated=work
done by buoyancy force

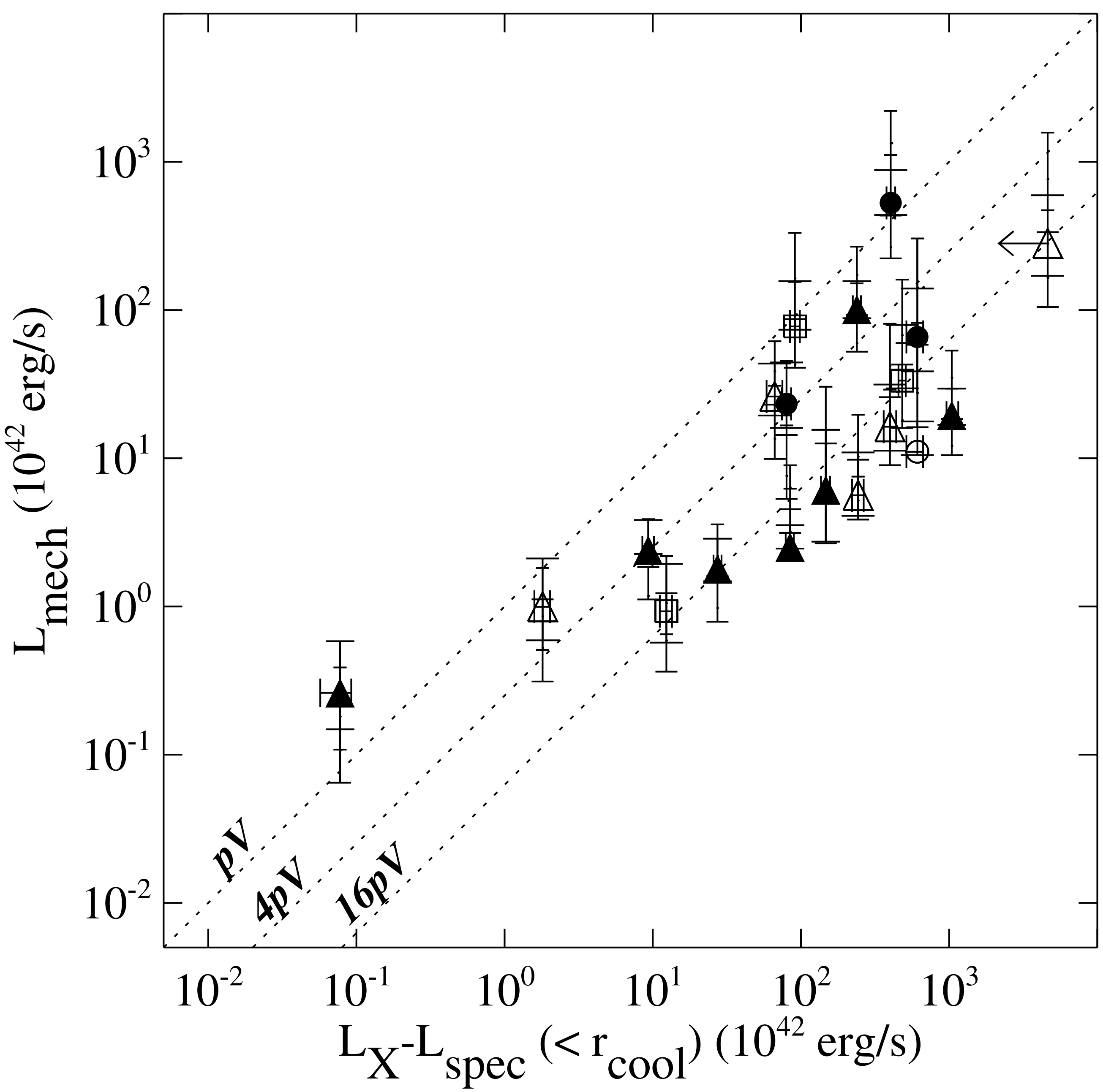
$$\Delta W = \frac{\gamma}{\gamma - 1}(p_0 V_0 - p_1 V_1) = H_0 - H_1$$

$$P = \Delta W/\tau$$

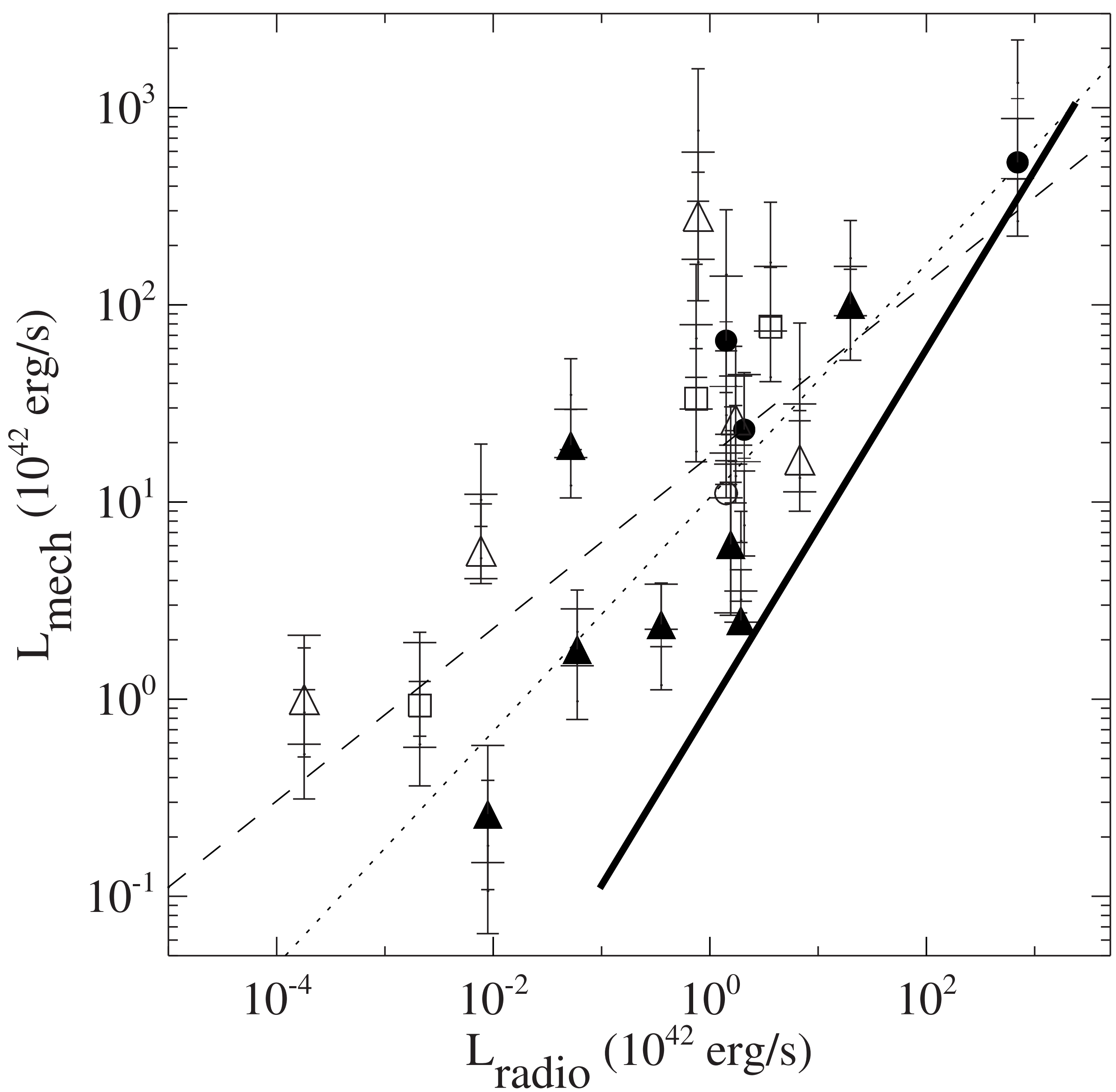
timescale given by rise time~dynamical time~sound-crossing time

Cavity power vs. core cooling

[Birzan et al. 2004]

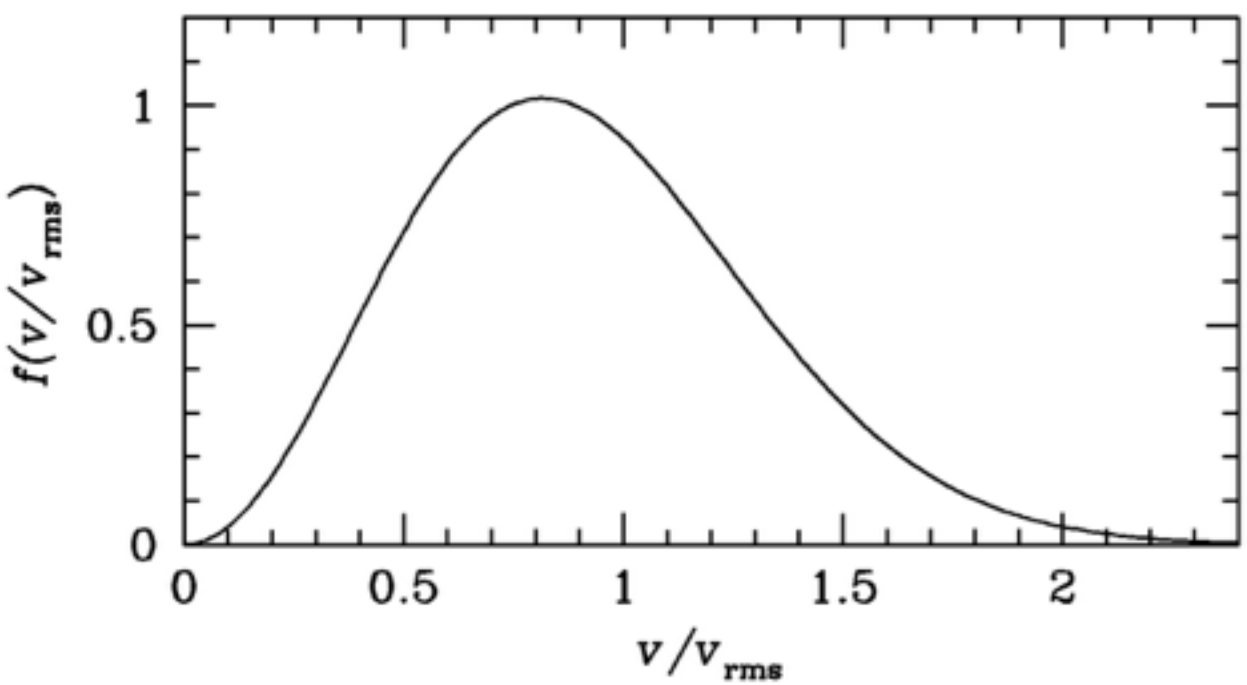


jets are radiatively inefficient!

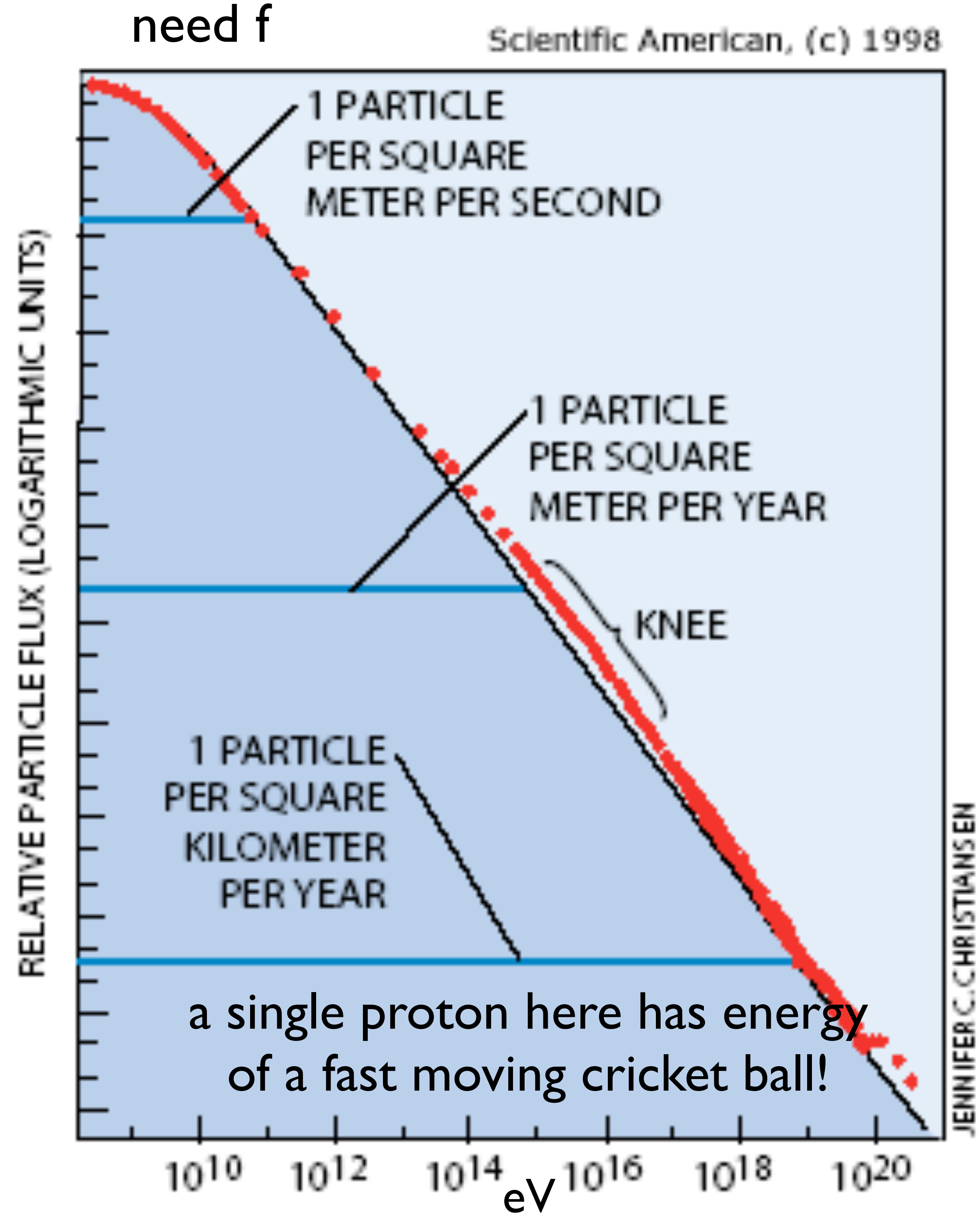


Thermal vs. Nonthermal

MHD ok



need f

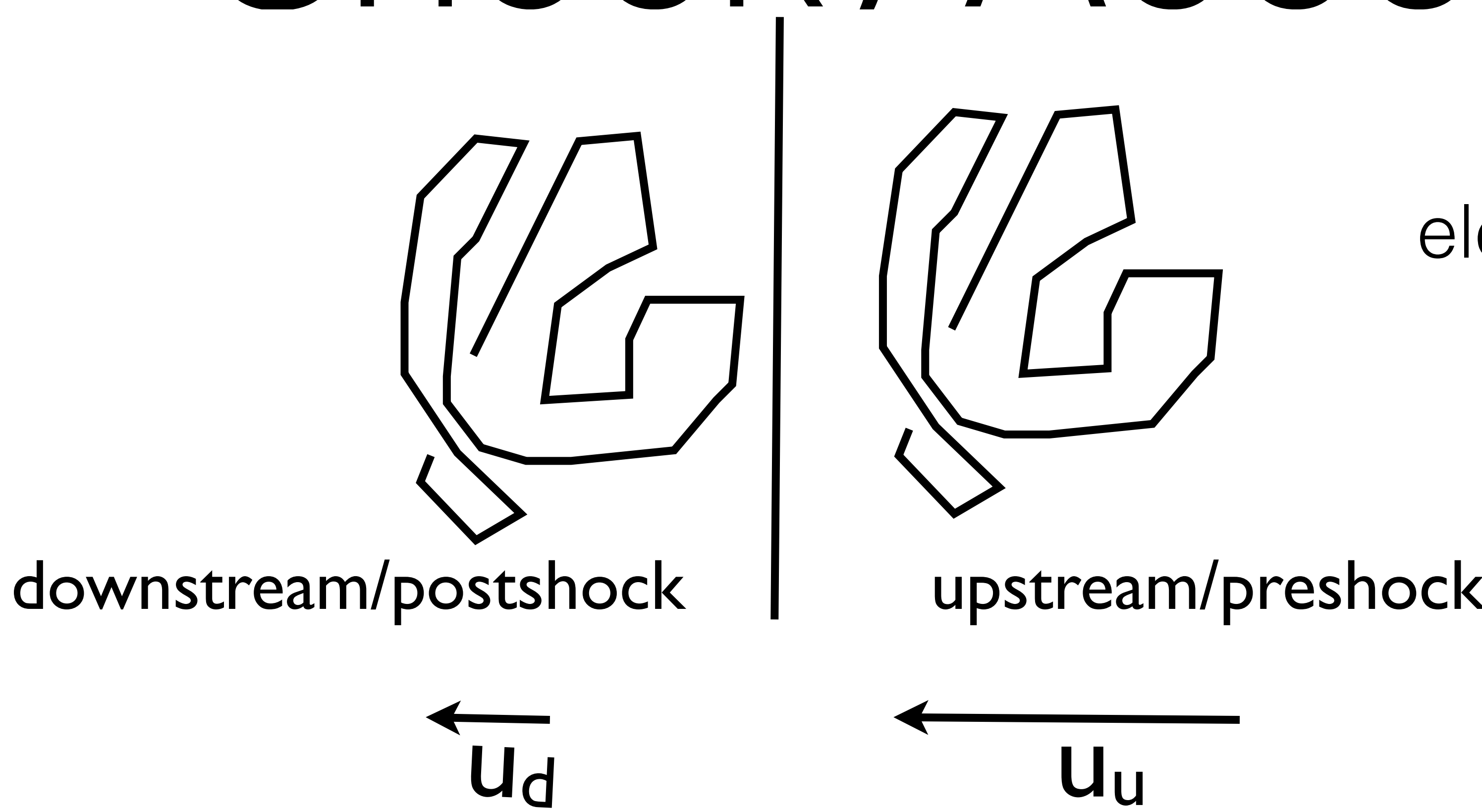


plasma physics consequences for both thermal and nonthermal phenomena in astrophysics

Relativistic Particles?

- Acceleration at shocks - 1st order Fermi
- Magnetic reconnection
- random magnetic clouds (e.g., MHD turbulence) - 2nd order Fermi

Fermi (Diffusive-Shock) Acceleration



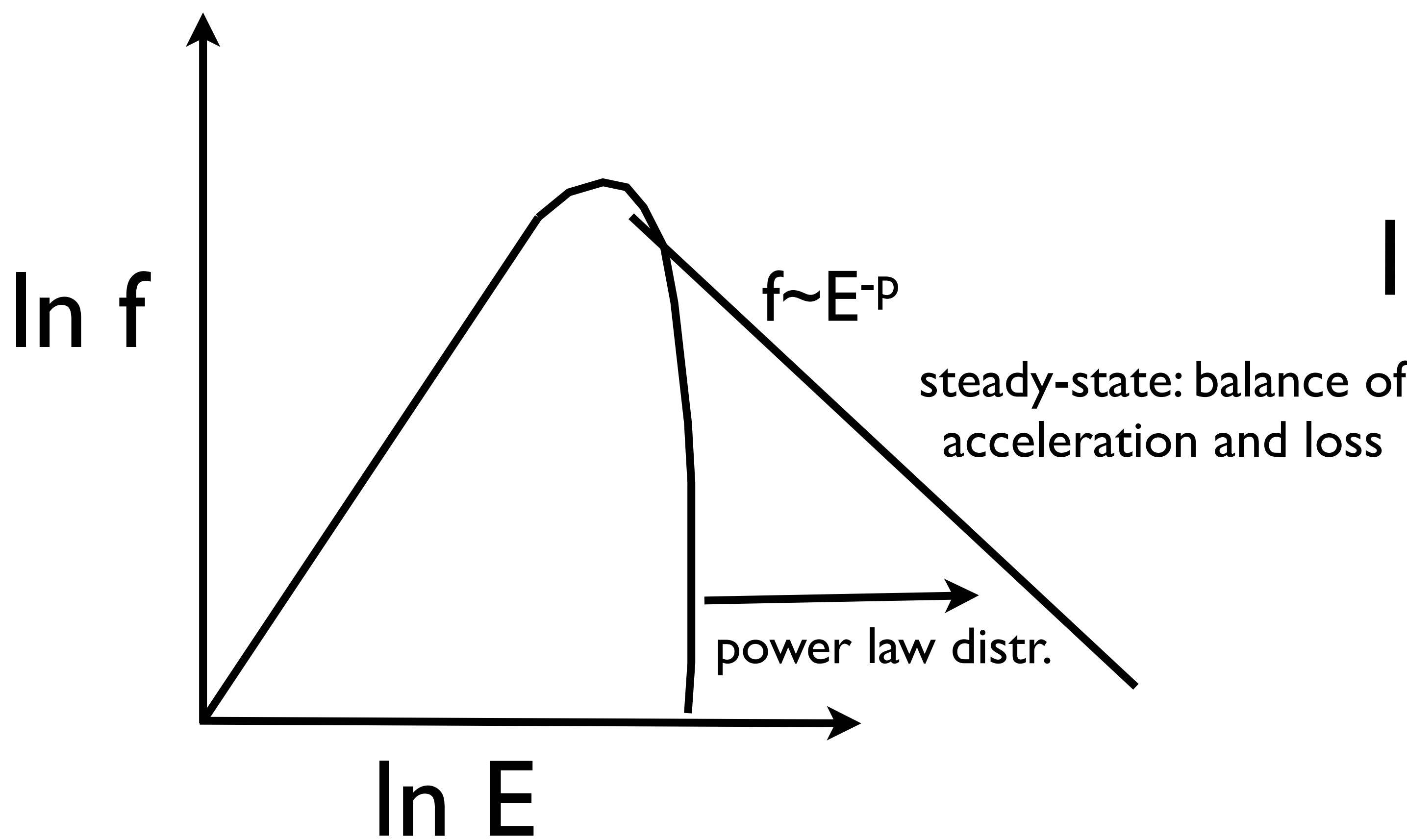
electrons scattered both upstream and downstream of shock

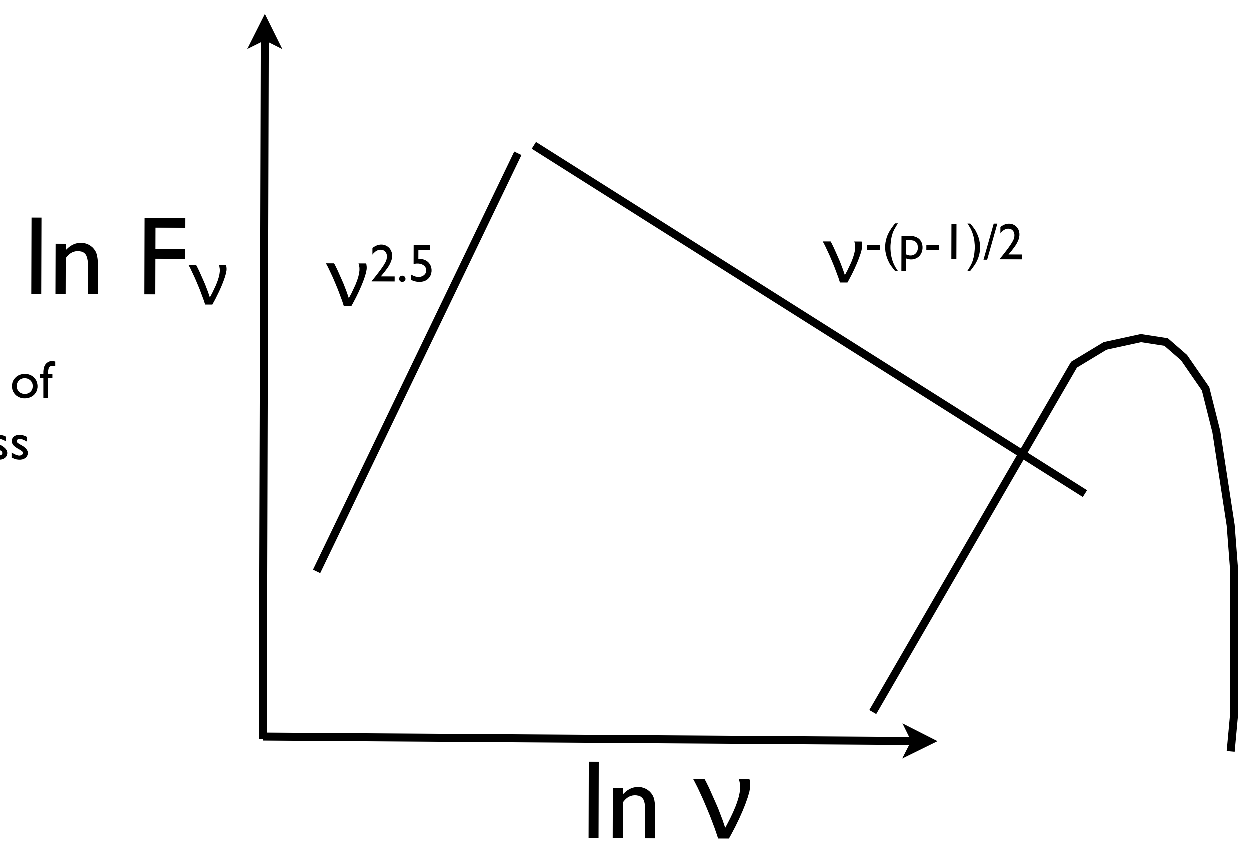
particle gains (loses) $2mvu_u$ ($2mvu_d$) in each scattering
total energy gained after N scatterings: $(1+2[u_u-u_d]/v)^N$
particle loss from down-stream => SS power-law spectrum

$f \sim E^{-\alpha}$; where α just depends on Mach #!

Fermi Accn.

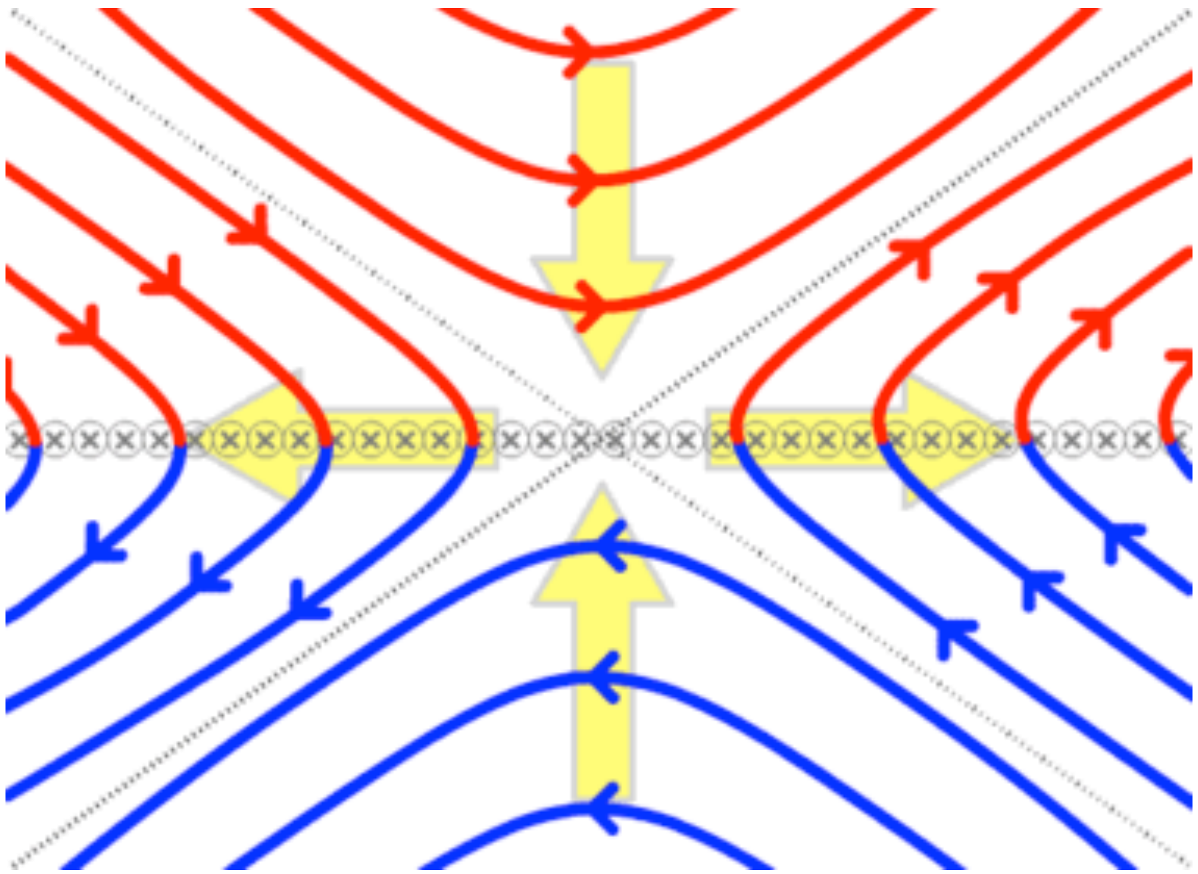
high energy relativistic e-s give synchrotron/Compton radiation

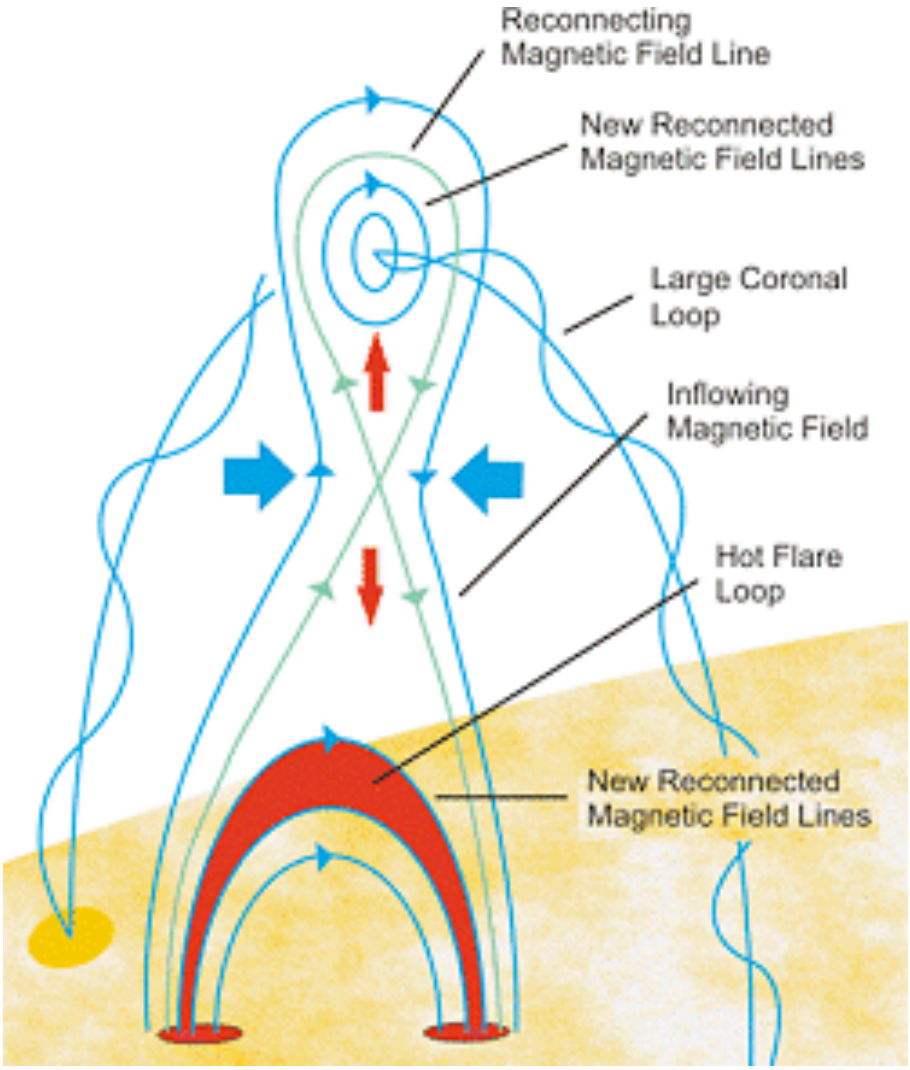




Magnetic Reconnection

magnetic energy explosively converted into relativistic & thermal plasma energy





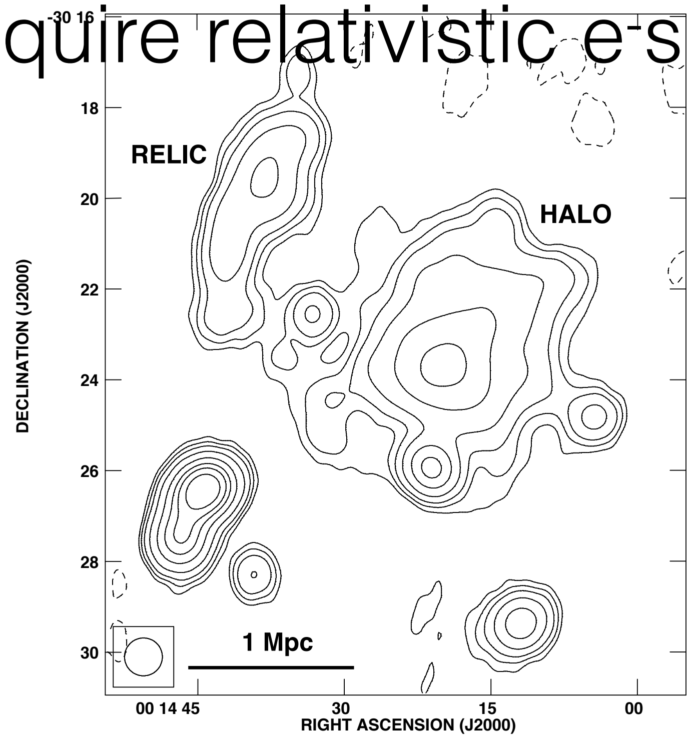
Radio Relics, Halos, Minihalos. Jets/

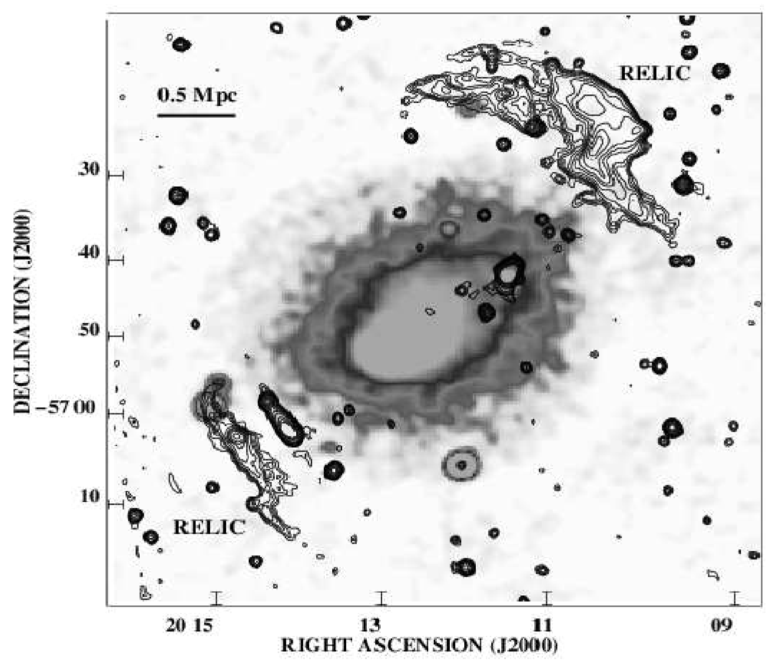
sync. emission

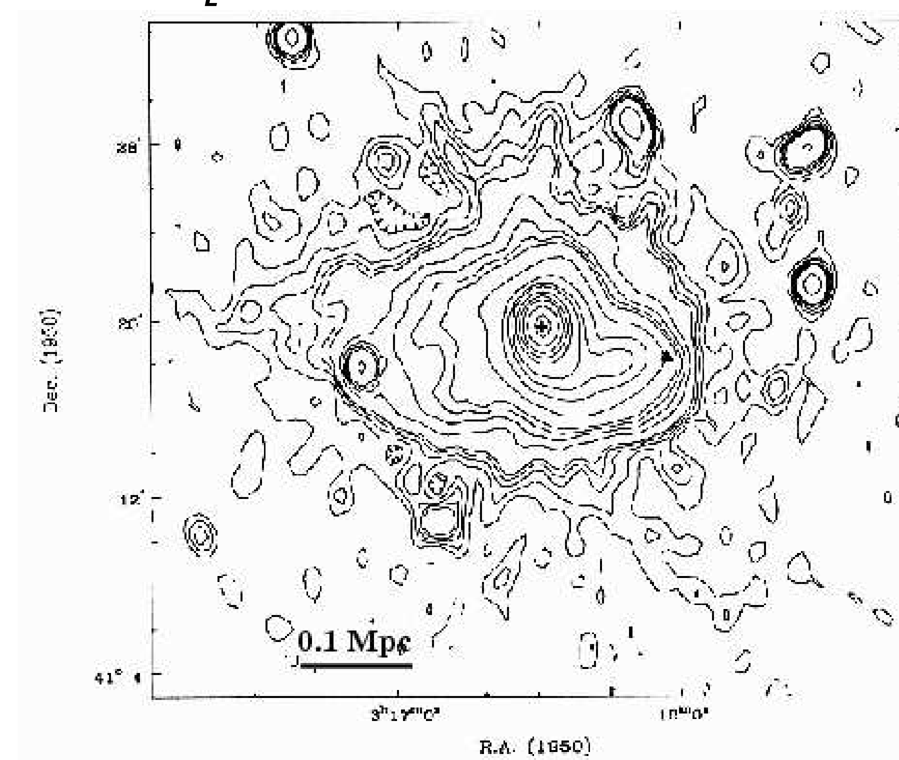
require relativistic e-s &B

B~0.1-10μG

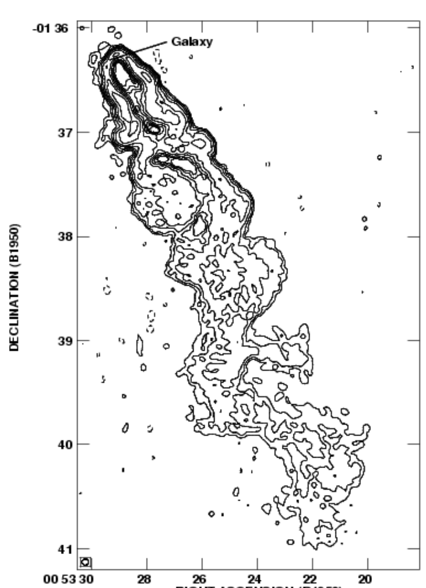
[Feretti & Giovannini 2008]

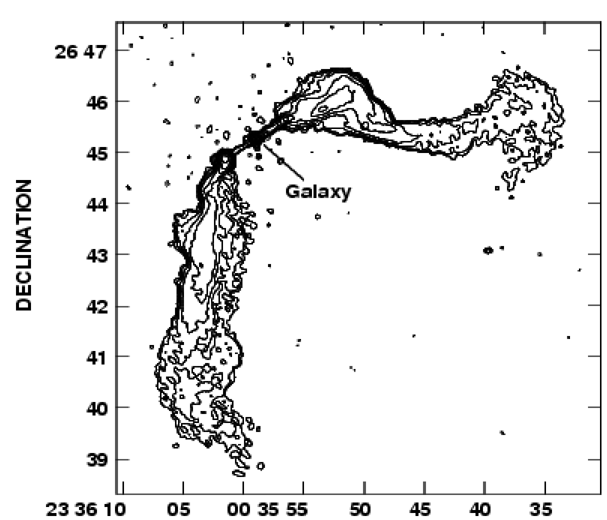


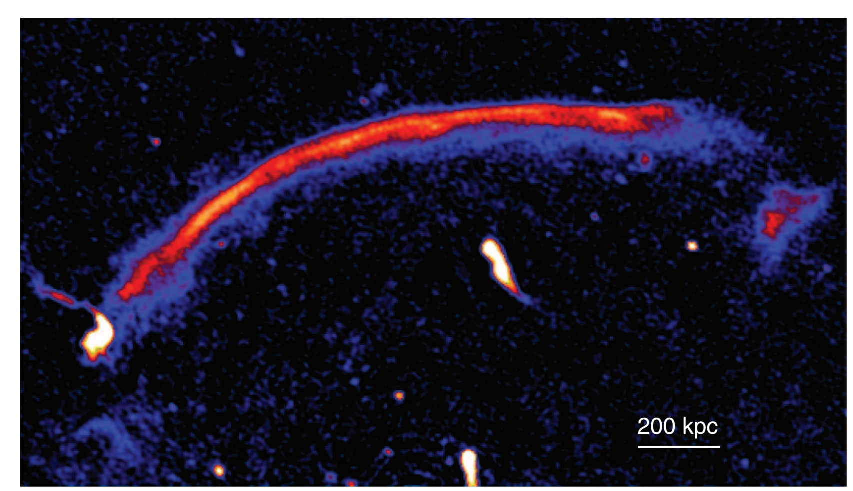




[van Weeren et al. 2010]



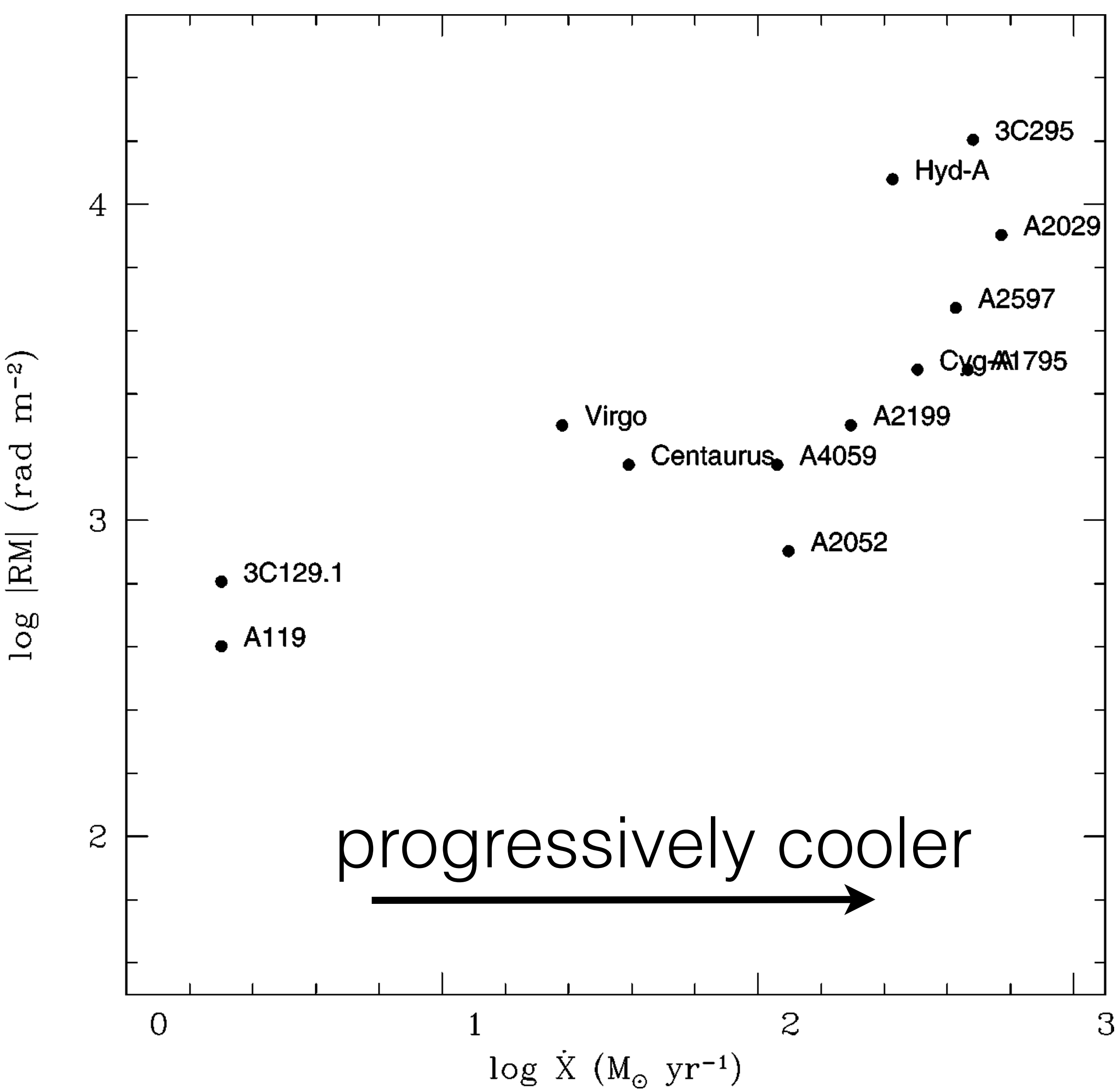


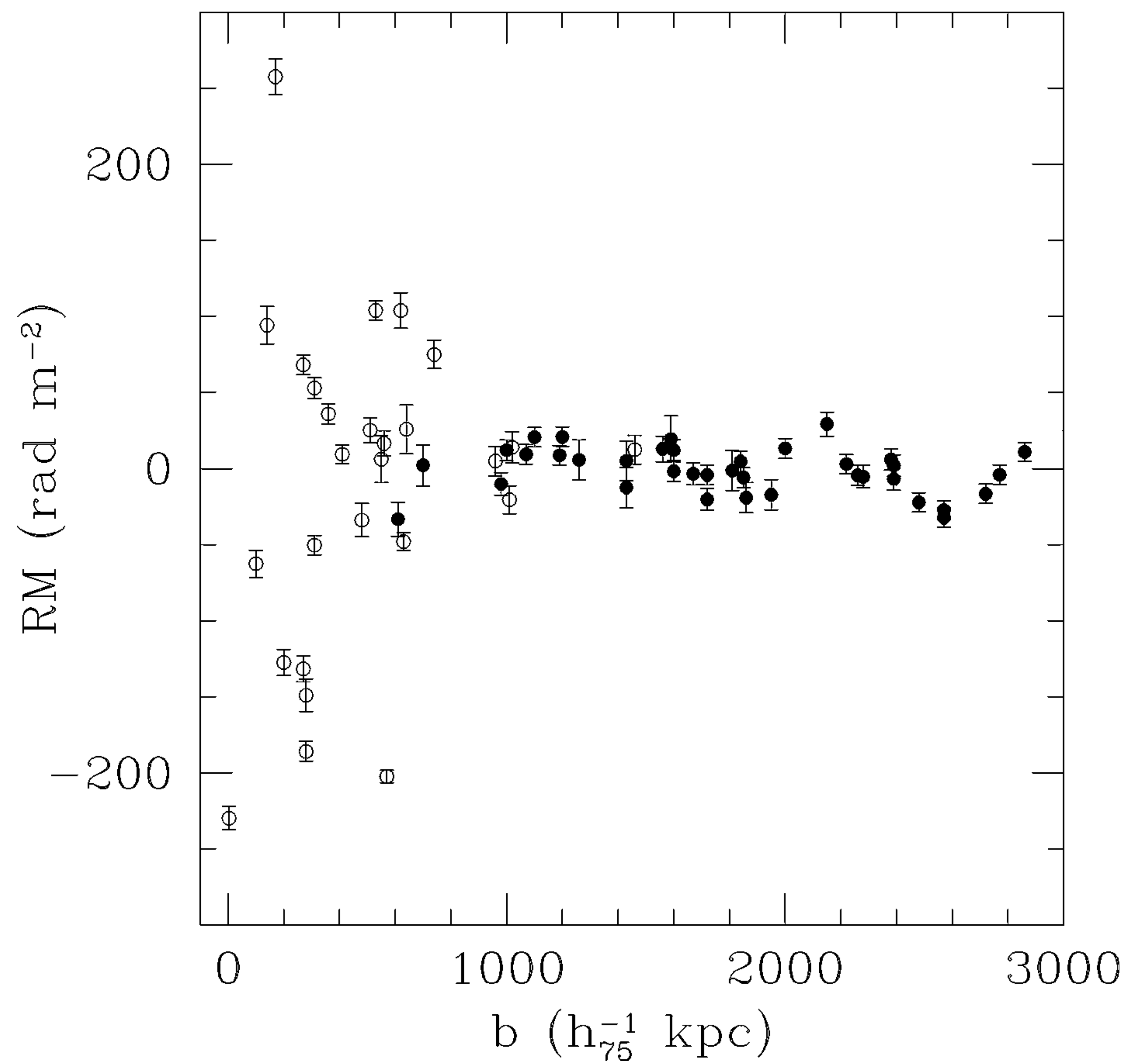


B fields in GCs

$$n_{L,R} = \left(1 - \frac{\omega_p^2}{\omega^2 \pm \omega\Omega_e}\right)^{1/2} \quad \mathrm{RM} = 812 \int_0^L n_\mathrm{e}\mathbf{B}\cdot d\mathbf{l}\,\mathrm{radians\,m}^{-2}, \quad \Delta\chi = \mathrm{RM}\,\lambda^2$$

[Carili & Taylor 2002]





Radio halos

steep spectrum radio sources associated with strong cool-cores

$S_\nu \propto \nu^{-1}$ or steeper

$L_\nu \propto \nu^{(1-p)/2} B^{(1+p)/2}$ => $p \geq 3$ for $dn/d\gamma \propto \gamma^{-p}$

$$\Omega_c = eB/m_e c \approx 170(B/10\mu\text{G})\ \text{s}^{-1}$$

$$\nu = \gamma^2 \nu_0 \propto \gamma^2 B$$

$$B_{\text{CMB}} \approx 3(1+z)^2\ \mu\text{G}$$

$$\gamma \approx 3 \times 10^3 (B/10\mu\text{G})^{-1/2} (\nu/1.4\ \text{GHz})^{1/2}$$

$$t_{\text{sync}} \approx 0.1\ \text{Gyr}(B/10\mu\text{G})^{-3/2} (\nu/1.4\ \text{GHz})^{-1/2}$$

$$t_{\text{diff}} \approx 0.1\ \text{Gyr}(r/100\ \text{kpc})^2 (D/3 \times 10^{31}\ \text{cm}^2\text{s}^{-1})^{-1}$$

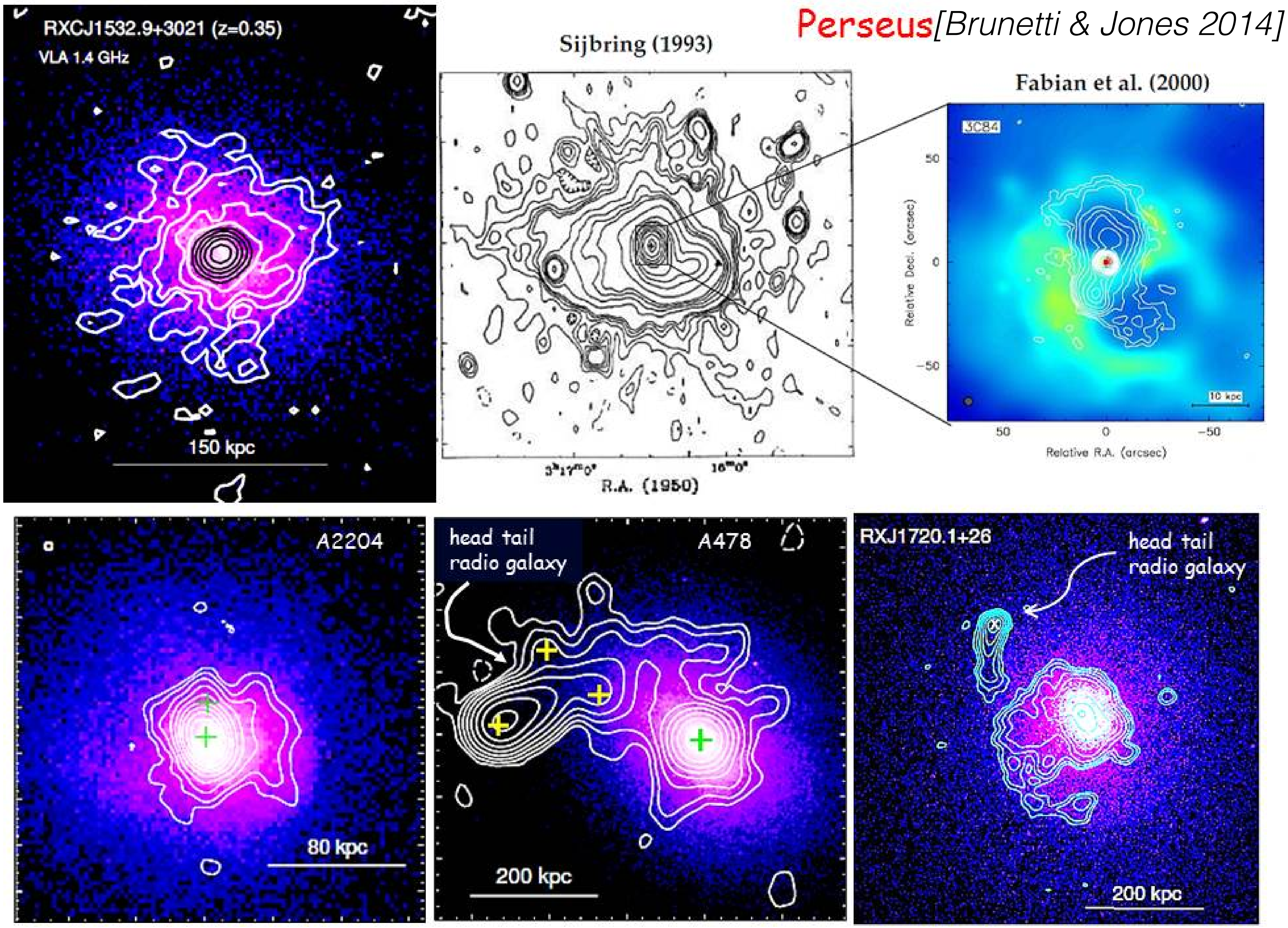
100 kpc low SB diffuse radio emission associated with massive CC cluster

~Mpc scale giant radio halos

AGN/sloshing driven turbulence reaccelerated e^-s? secondaries from pp?

a large D required for CR transport => in-situ acceleration

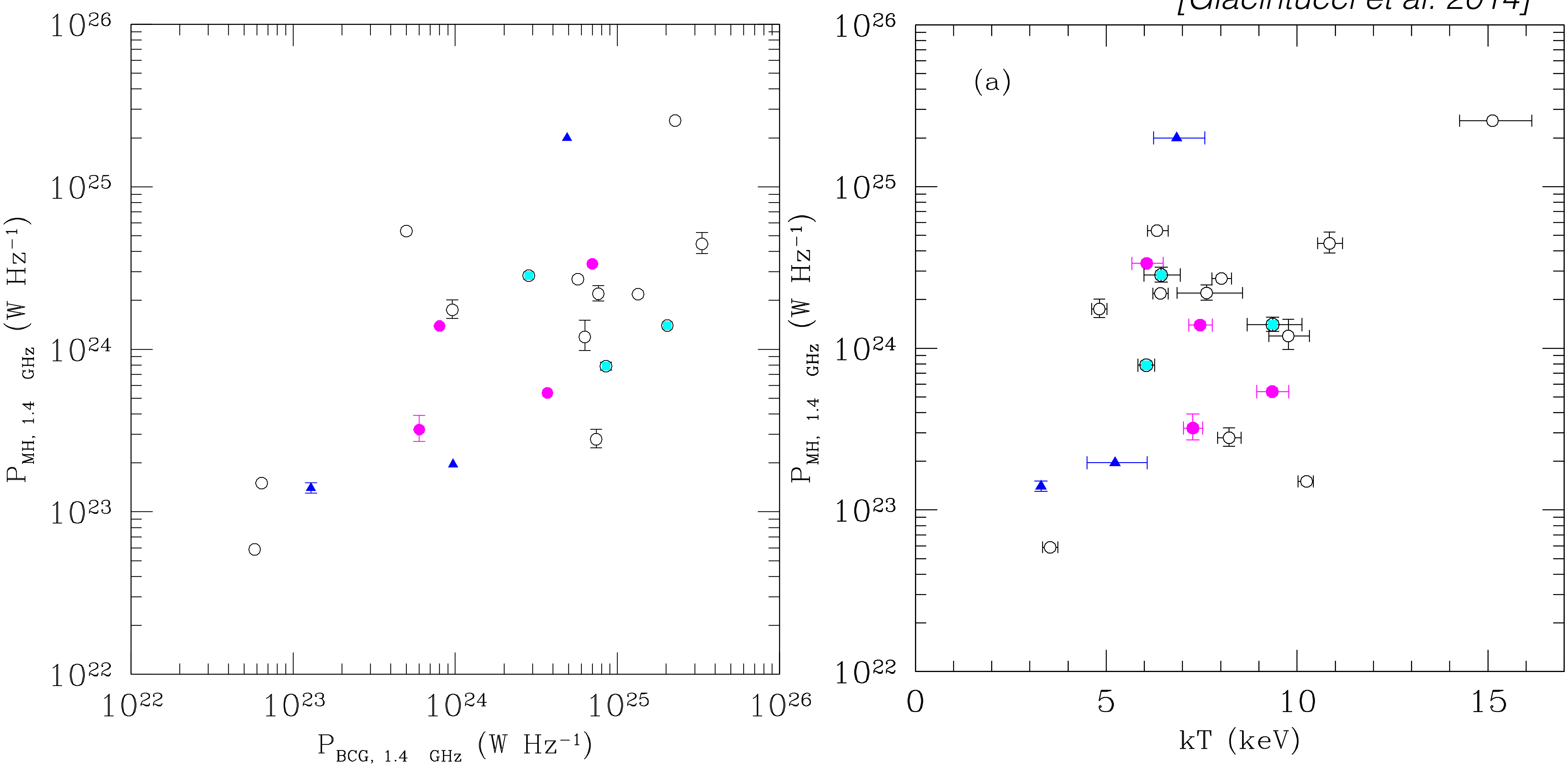
Minihalo examples



confined within cold fronts (contact discontinuities) observed in X-rays associated with cool cores

MH & BCG radio correlated

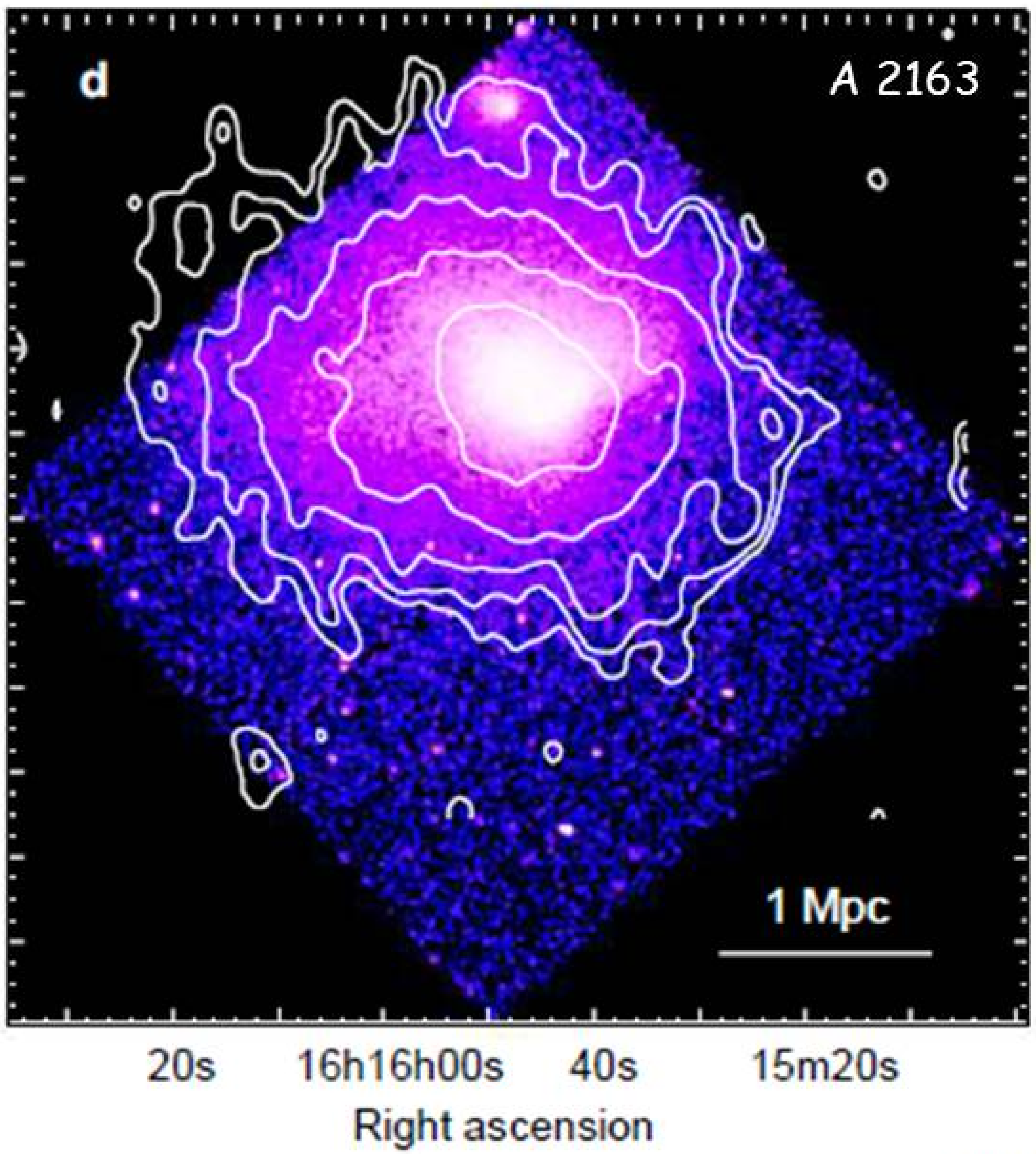
[Giacintucci et al. 2014]



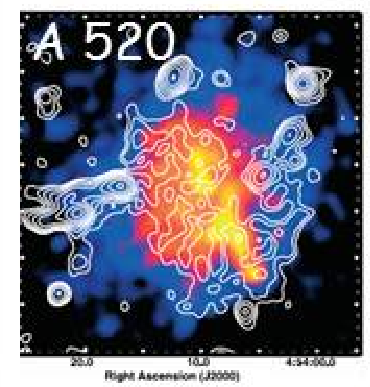
BCG radio jets powered by cold gas condensing in cores

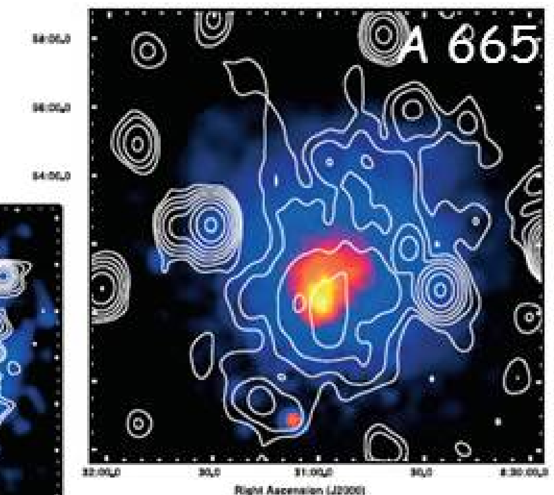
do MHs also have something to do with BCG jets?

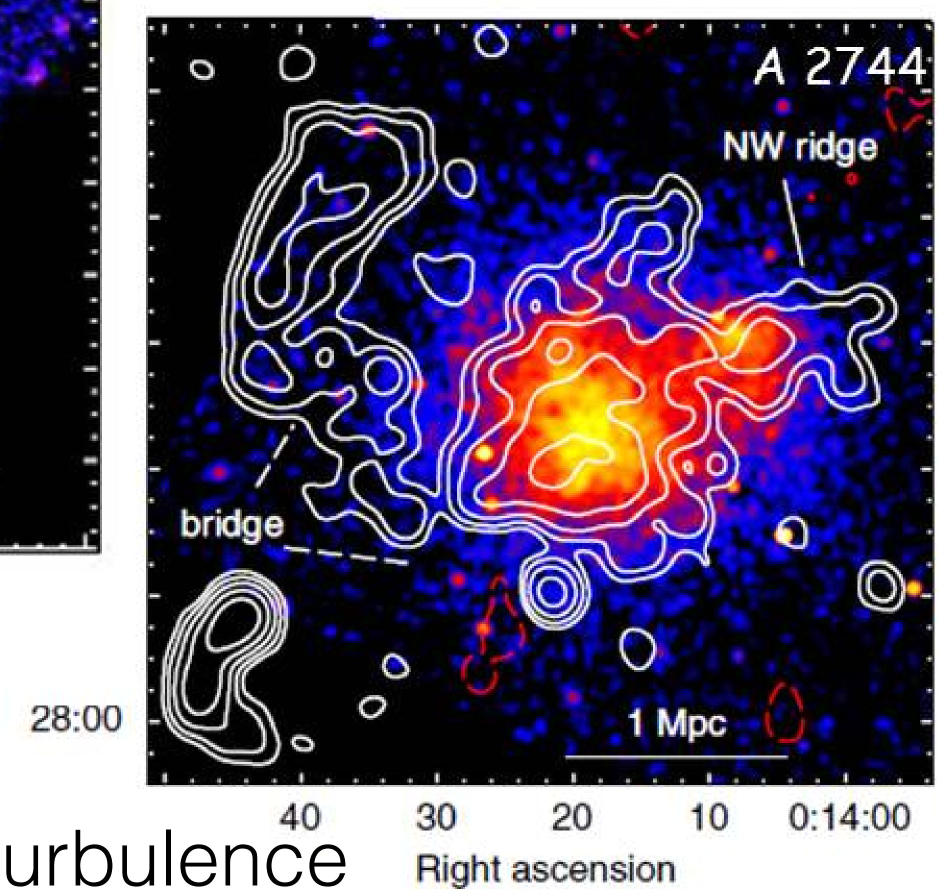
Giant radio halos



[Brunetti & Jones 2014]





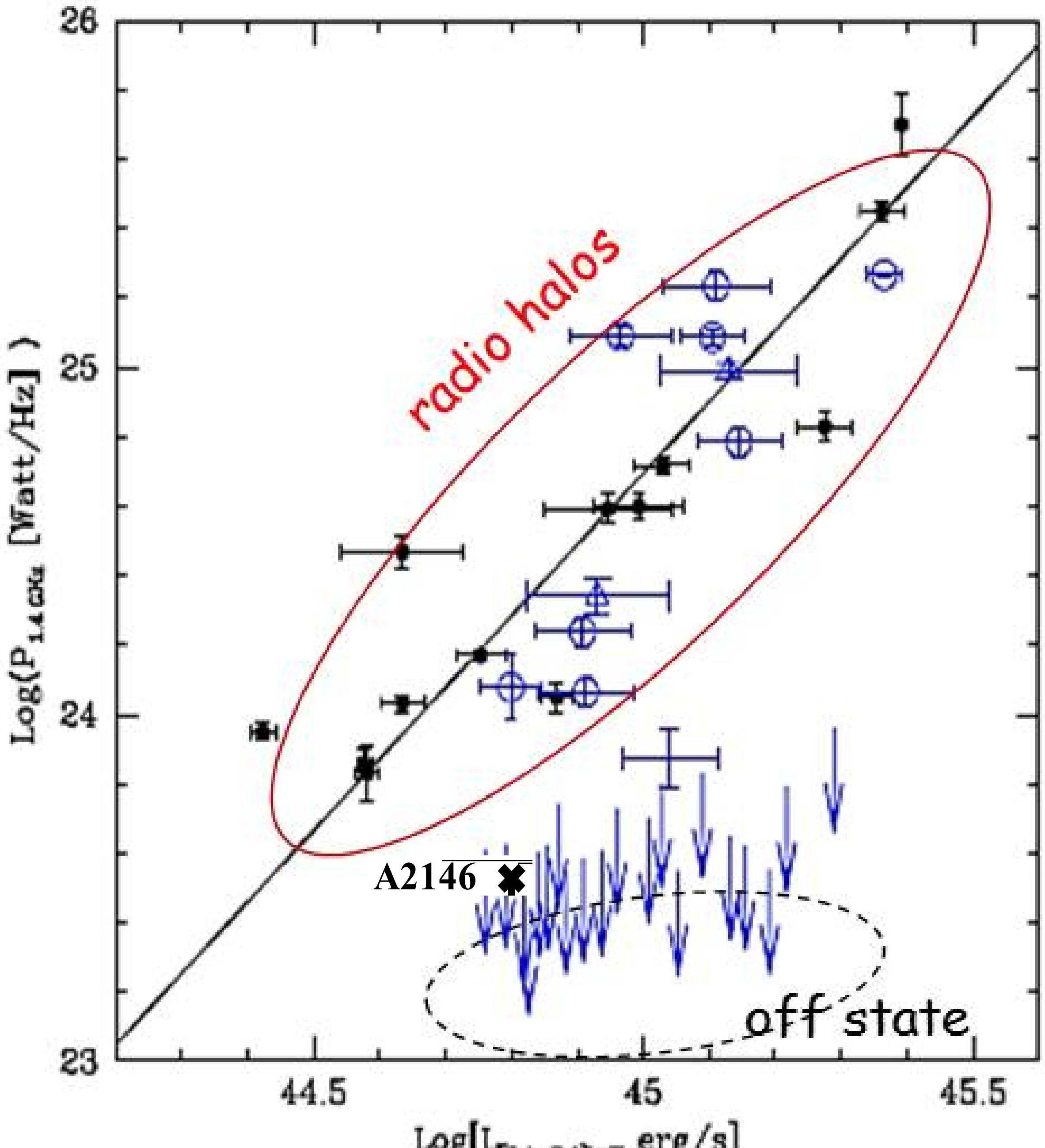


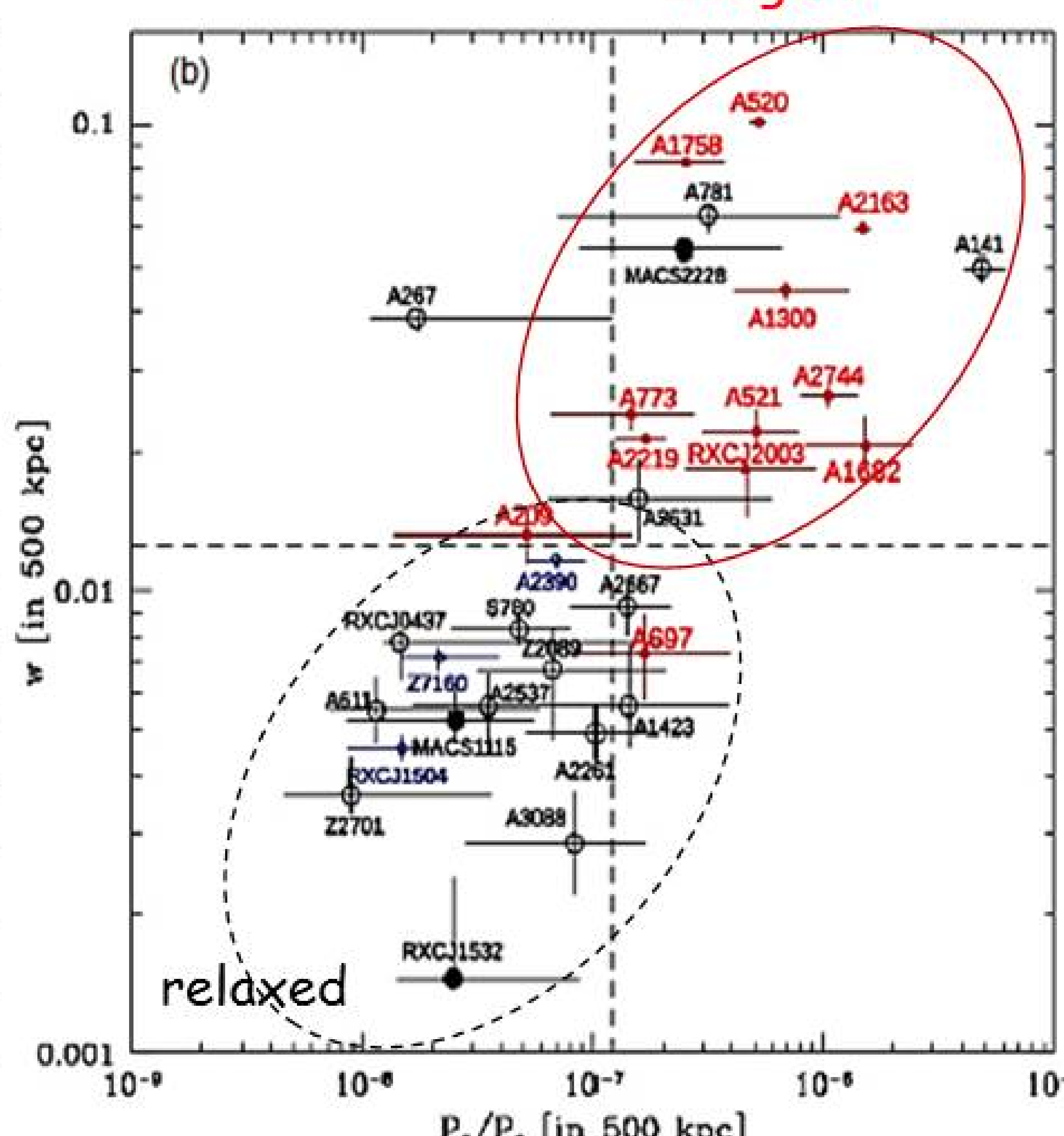
mostly unpolarized, merger generated turbulence

similar appearance as MHs but larger, lower emissivity

RHs are mergers

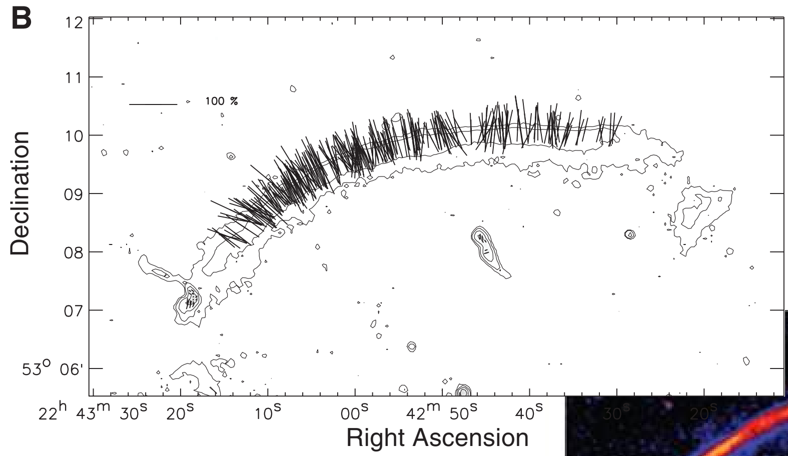
[Brunetti & Jones 2014]

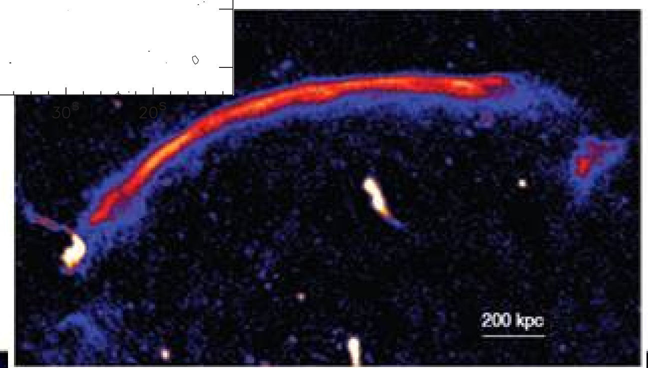


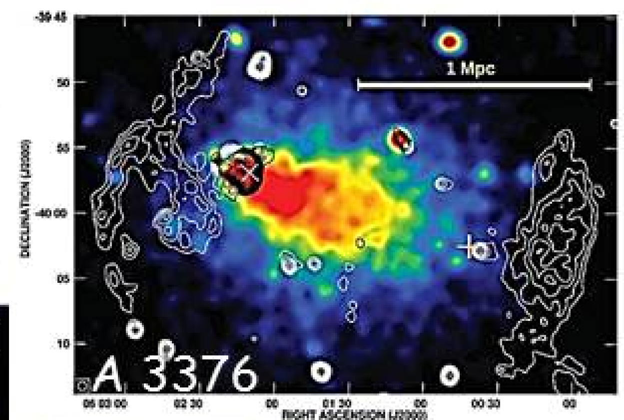


both axes measure disturbance in X-ray morphology

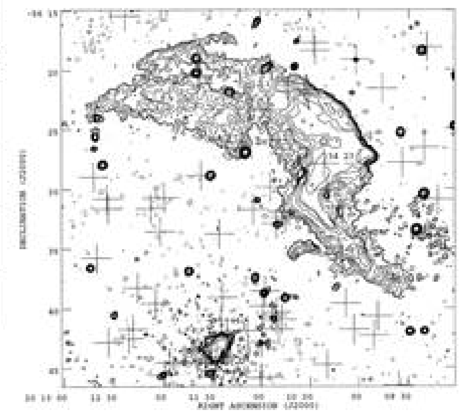
Radio relics



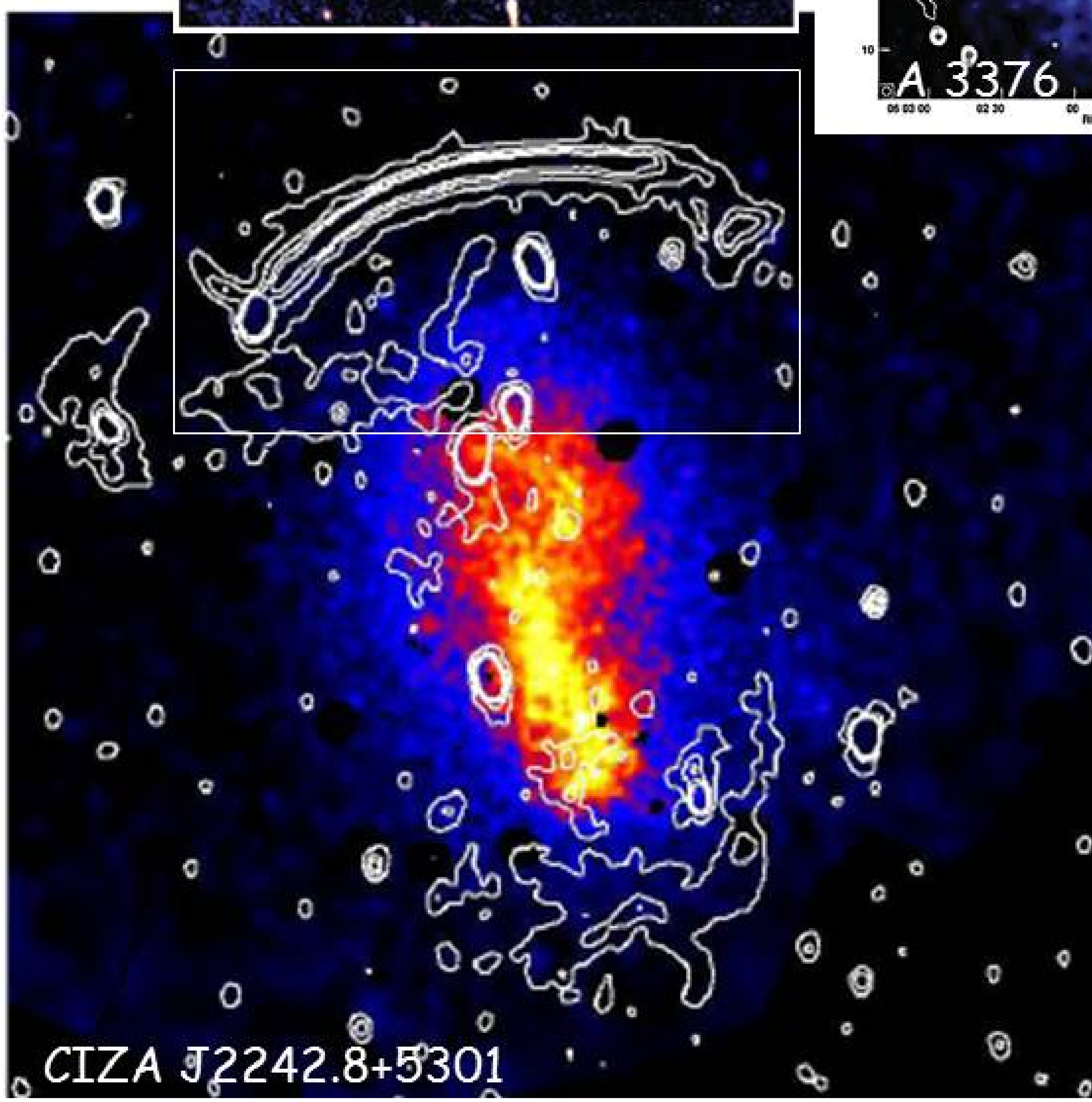


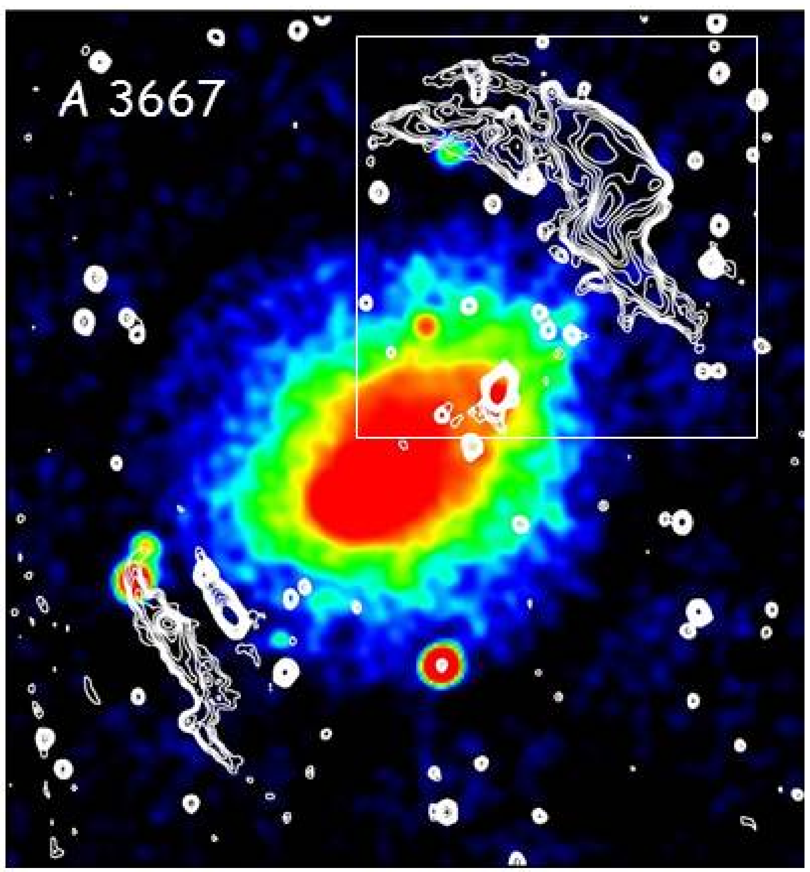


[Brunetti & Jones 2014]



head-on
collisions
~1:2
mergers





equal-mass head-on collisions?
high polarization => ordered B

Model for primary e^-s

diffusion-loss eq. for primary e^-s

$$\frac{dn(E)}{dt} = -n(E)\nabla \cdot \mathbf{v} + \nabla\cdot[D(E)\nabla n(E)] + \frac{\partial}{\partial E}[\dot{E}n(E)] + q(E)$$

$n(E)dE$ number density of e-s with energy [E,E+dE]; d/dt Lagrangian derivative

$$\frac{\partial N(E)}{\partial t} = \frac{\partial}{\partial E}[\dot{E}N(E)] + Q(E)$$

volume integrated 1-zone model; assuming confinement of e^-s

$$\left(\frac{dp}{dt}\right)_{\rm rad} = -4.8\times10^{-4}p^2\left[\left(\frac{B_{\mu G}}{B_{\rm CMB}}\right)^2\frac{\sin^2\theta}{2/3} + (1+z)^4\right]$$ sync./IC losses

$$\left(\frac{dp}{dt}\right)_{\rm coll} = -3.3\times10^{-29}n_{\rm th}\left[1+\frac{\ln(\gamma/n_{\rm th})}{75}\right]$$ Coulomb losses

Summary

- clusters very important for cosmology, galaxy formation, SMBH, feedback, lensing, dark matter
- multi-wavelength observations from radio to gamma rays
- have cosmic baryon fraction with most of them in diffuse plasma
- thermal & non-thermal physics of plasmas & radiation

Thank you for your attention!