Cluster, jet simulations & radio observations

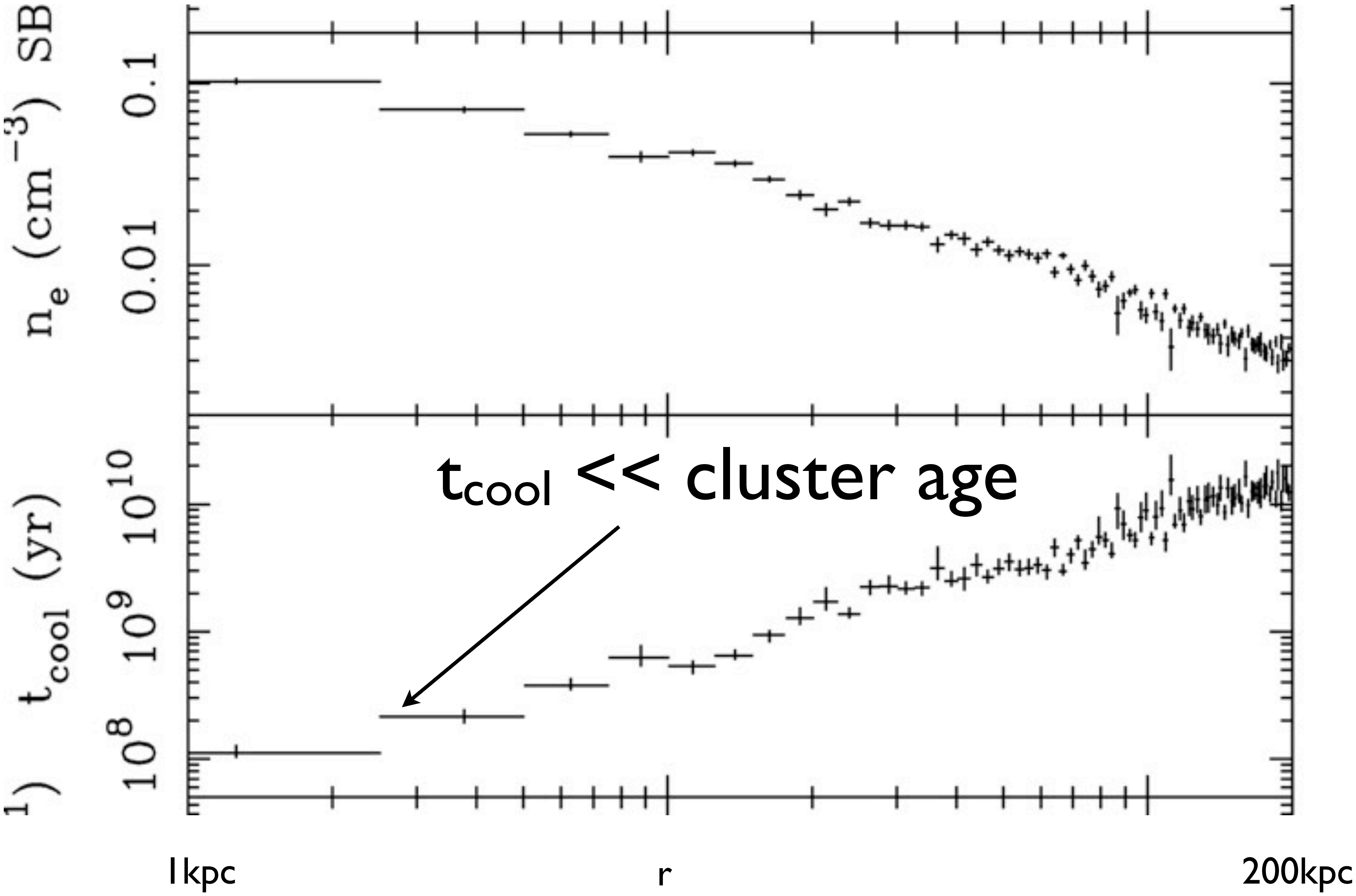
Prateek Sharma, IISc
Continuum science with SKA, 25/01/2016

Outline

- radio feedback from AGN, minihalos
- radio halos & mergers: turbulent acceleration
- radio relics: head on major mergers
- accretion/virial shock
- role of SKA

Cooling flow problem

[Johnstone et al. 2002]

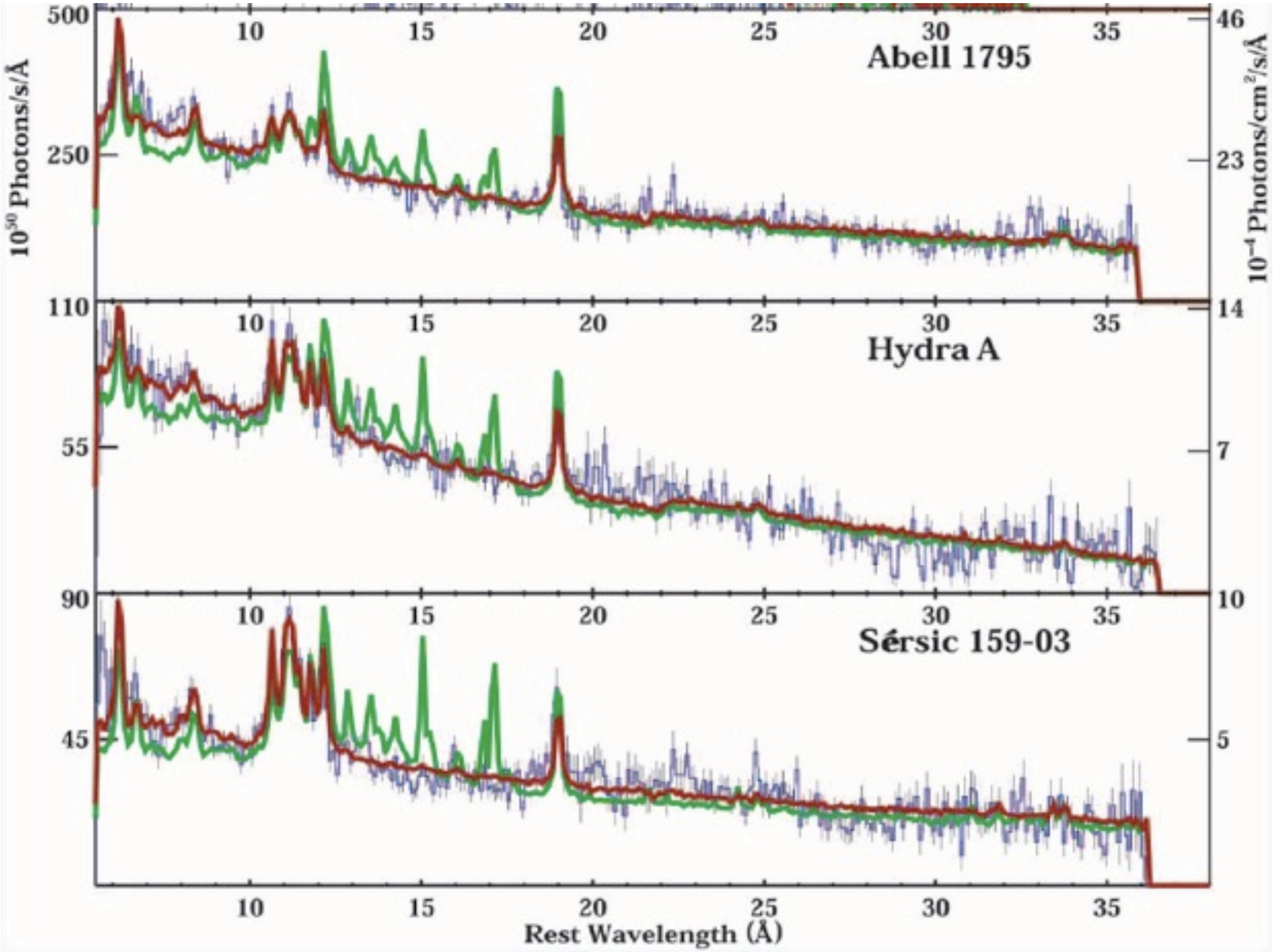


t_{cool} << cluster age

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

Cooling absent!

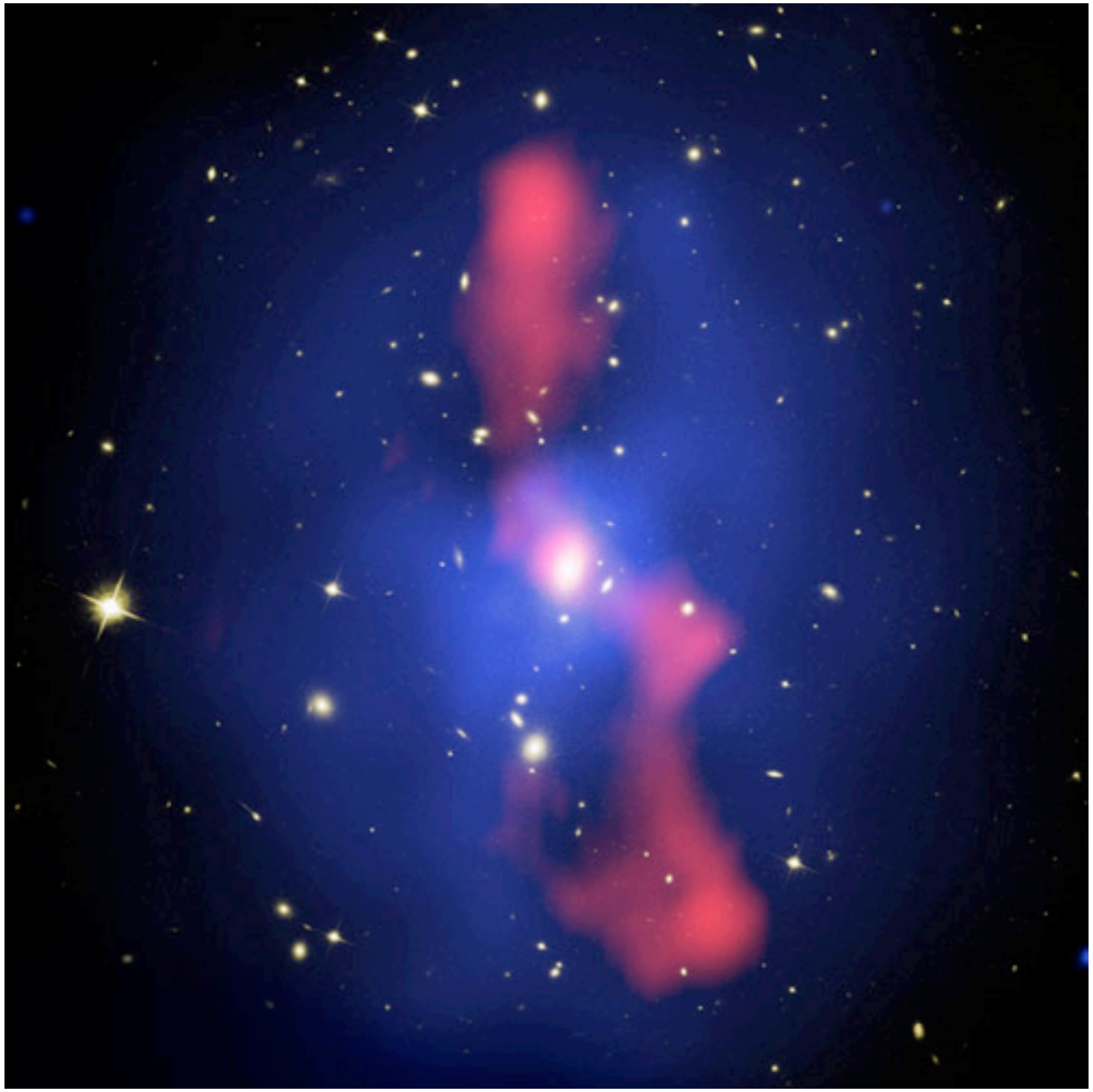
[Peterson et al. 2003]



soft X-ray lines missing! X-ray observations kicked off this field SKA is future

AGN feedback

[McNamara & Nulsen 2007]



cooling ICM can power SMBH
which launches jets

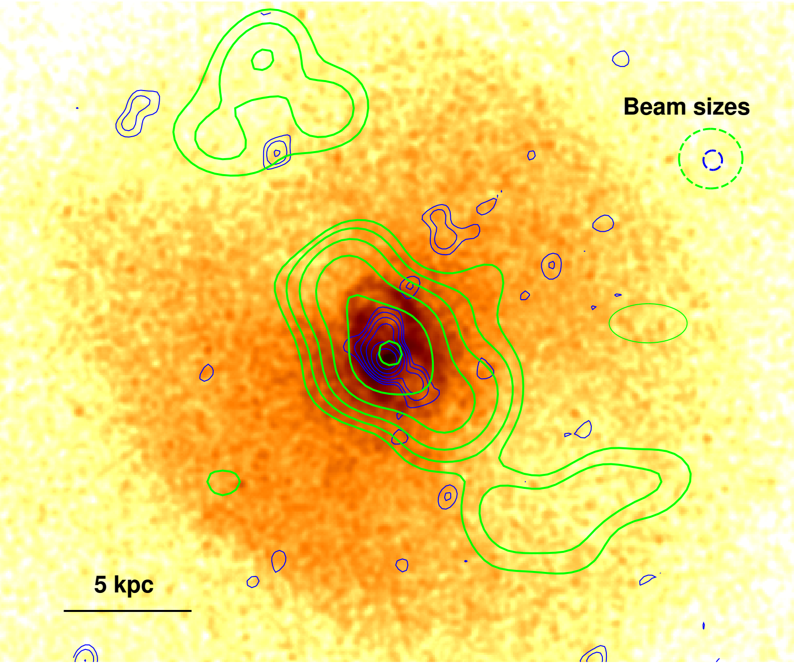
radio bubbles/X-ray cavities: FRI & FRII

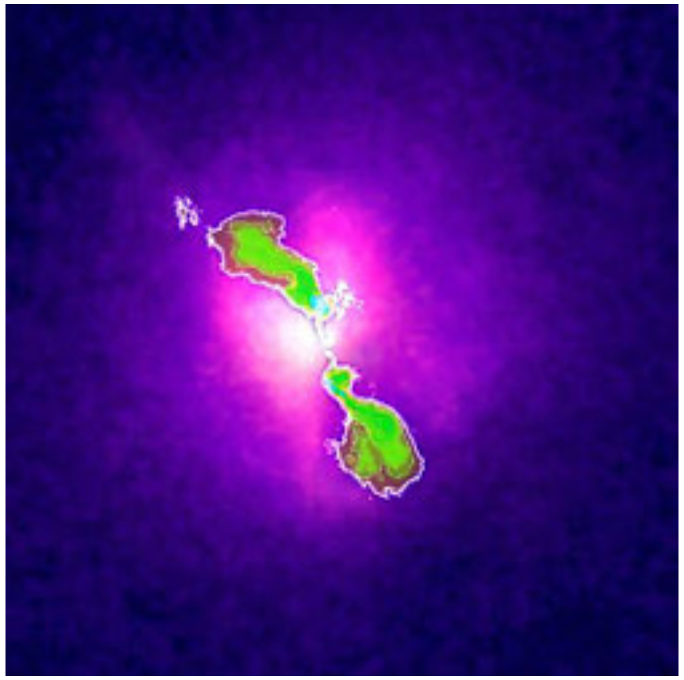
negative feedback loop prevents
catastrophic cooling

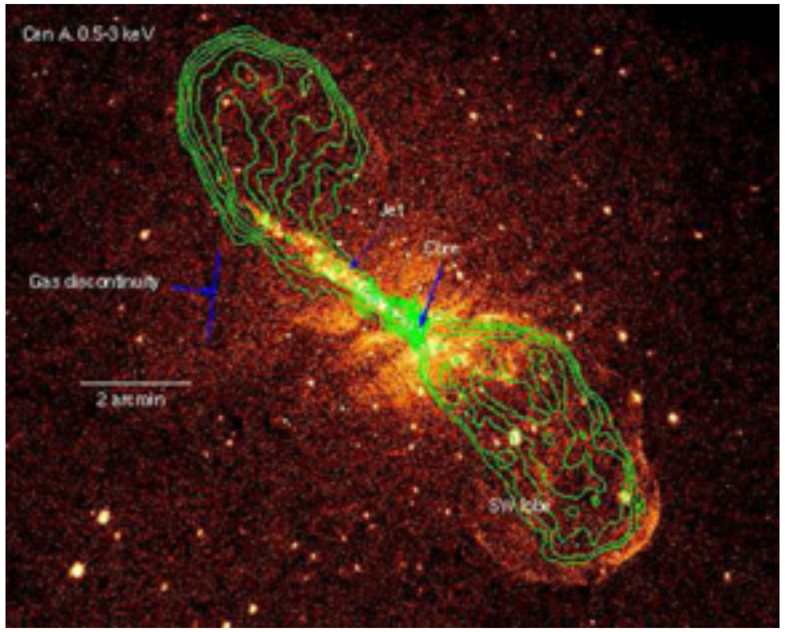
jet/cavity power ~ X-ray luminosity
& lack of cooling

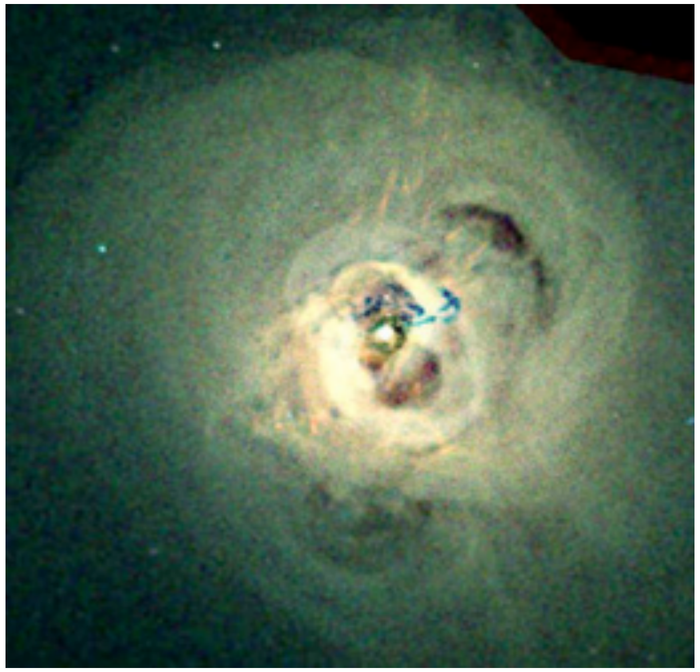
=> rough thermal balance

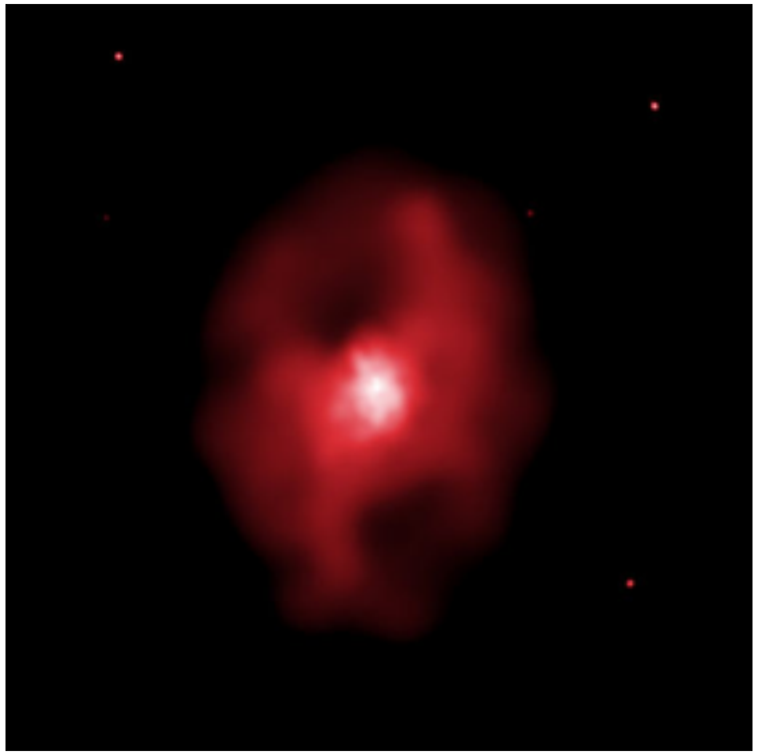
Rogues' gallery









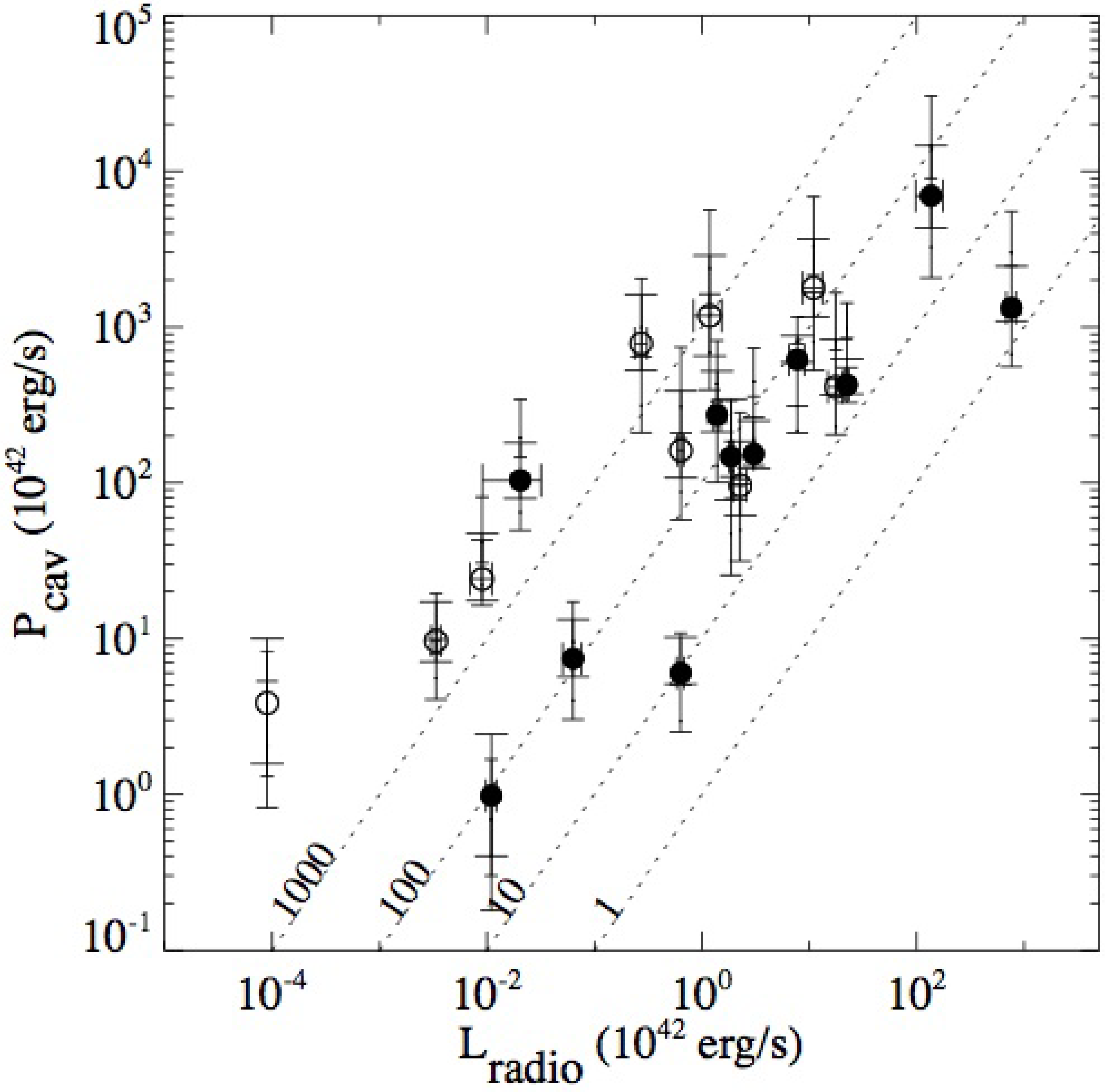


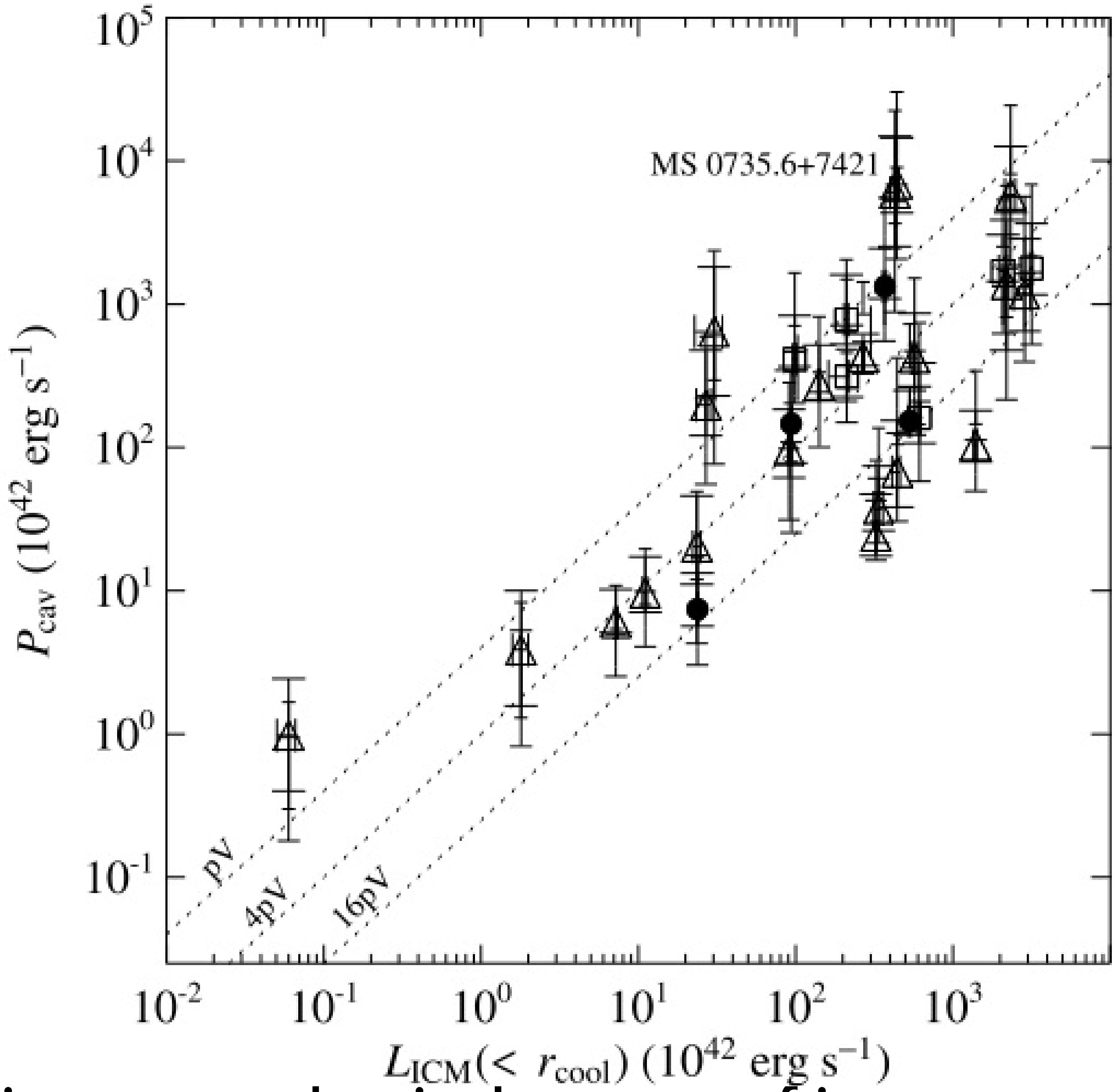
roughly 10s of kpc
small scale radio bubbles

with its higher sensitivity SKA can detect dimmer radio bubbles out to high z

L_{radio}, P_{cav}, L_X

[McNamara & Nulsen 2012]





radio power subdominant relative to mechanical power of jets

reasonable estimates of P_{cav} can balance radiative losses!

How does radio-mode feedback evolve at high z? spectral index maps, high resolution images, etc. => jet-ICM coupling in different environments

AGN jet-ICM sims.

$$\boxed{\begin{aligned} \frac{\partial \rho}{\partial t} + \nabla \cdot \rho \mathbf{v} &= S_\rho \\ \rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) &= -\nabla p - \rho \nabla \Phi + S_\rho v_{\rm jet} \hat{\mathbf{r}} \\ \frac{p}{\gamma - 1} \frac{d}{dt} \ln(p/\rho^\gamma) &= -n^2 \Lambda \end{aligned}}$$

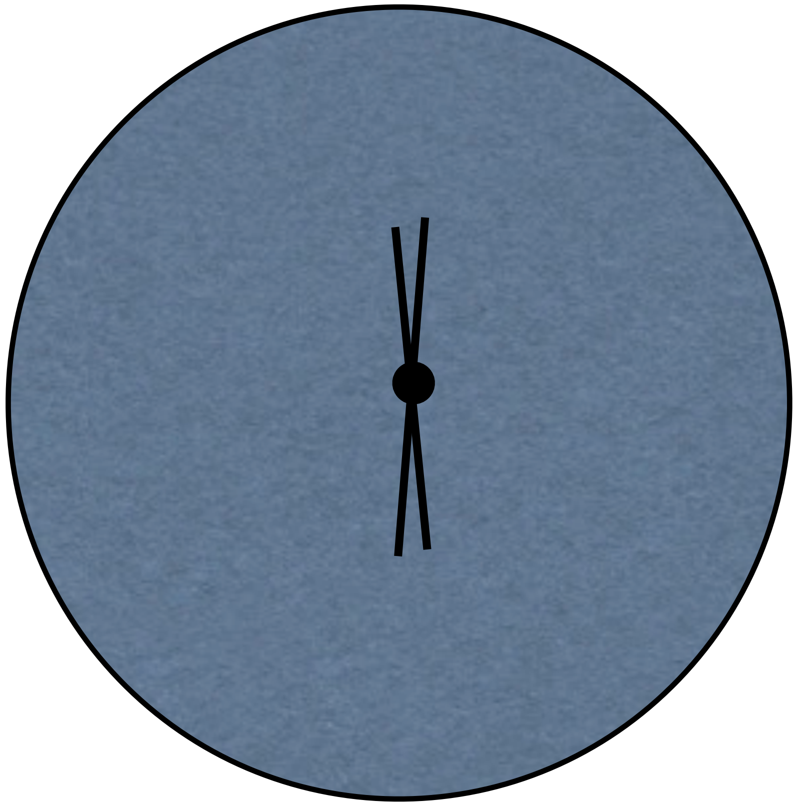
mass

momentum

source terms

to mimic injection by

feedback AGN jets



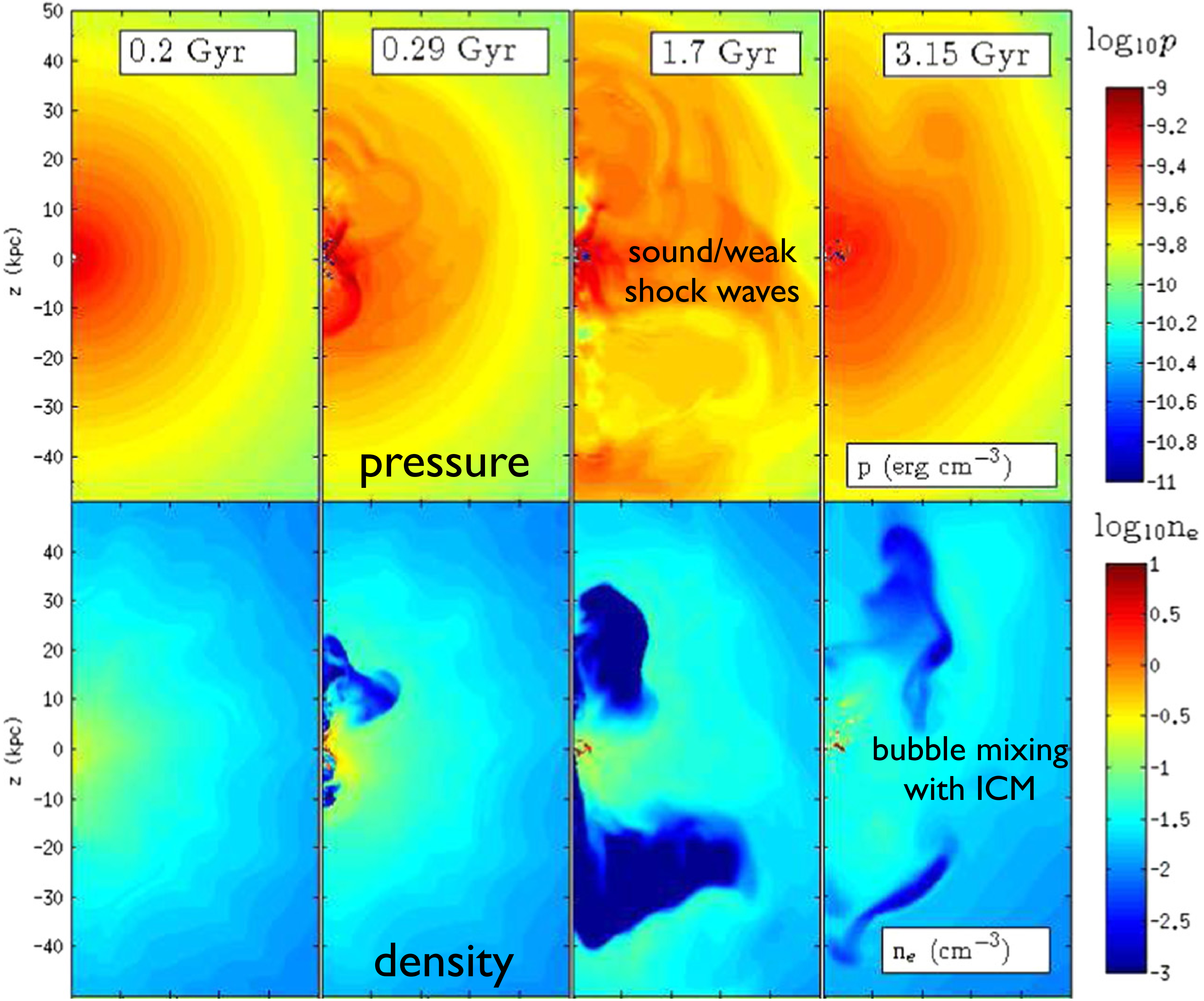
source term applied in a small bipolar cone at the center: opening angle of 30^0, 3 kpc

$$\boxed{\frac{\dot{M}_{\rm jet} v_{\rm jet}^2}{2} = \epsilon \dot{M}_{\rm acc} c^2}$$

$v_{\rm jet}=0.1c$

jets & buoyant bubbles

[Prasad et al. 2015]



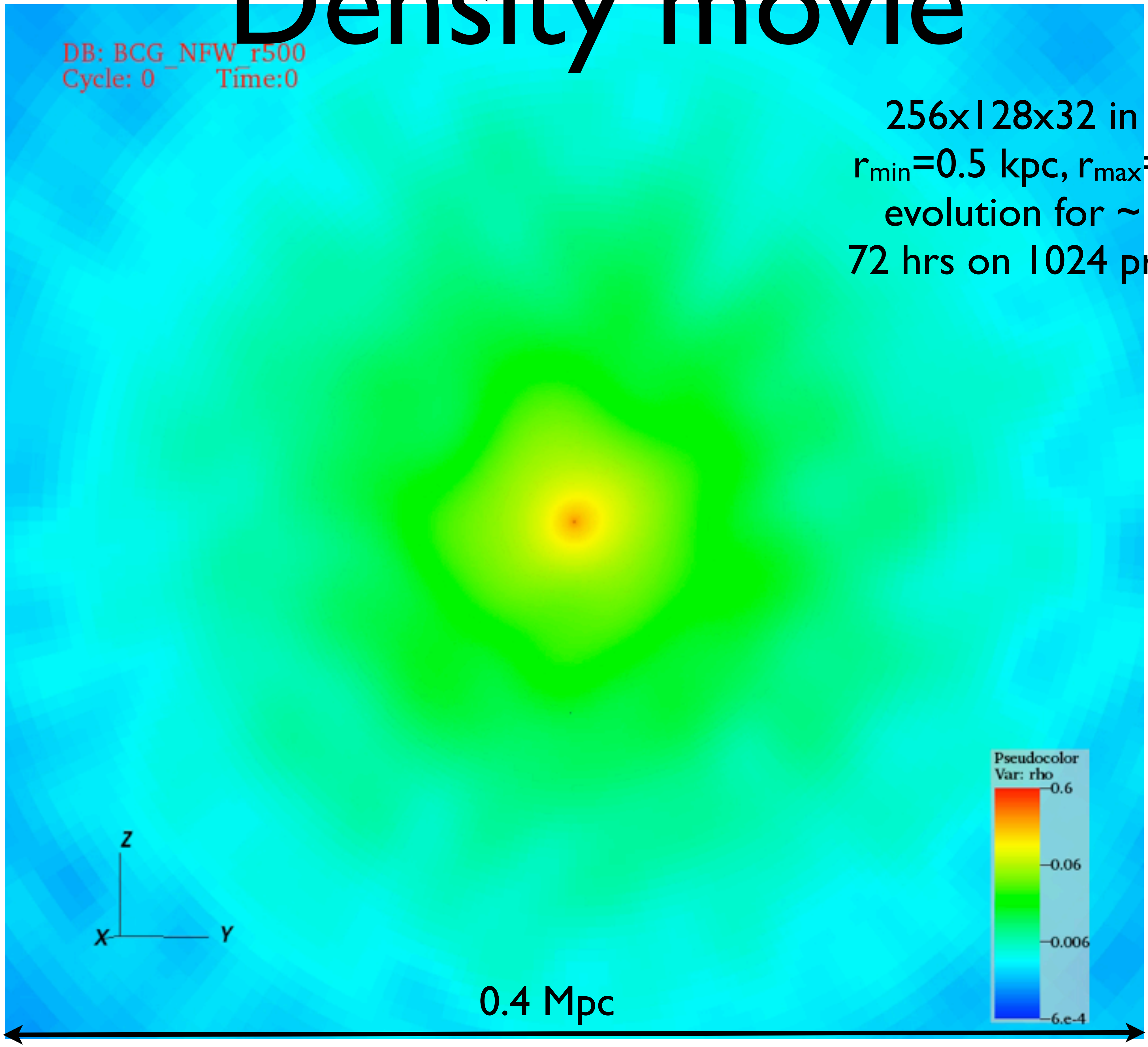
pressure

sound/weak shock waves

density

bubble mixing with ICM

Density movie



256x128x32 in (r,θ,φ)
r_{min}=0.5 kpc, r_{max}=0.5 Mpc
evolution for ~1.2 Gyr
72 hrs on 1024 processors

0.4 Mpc

Radio minihalos

steep spectrum radio sources associated with strong cool-cores

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

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

likely emission beyond cooling break

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

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

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

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

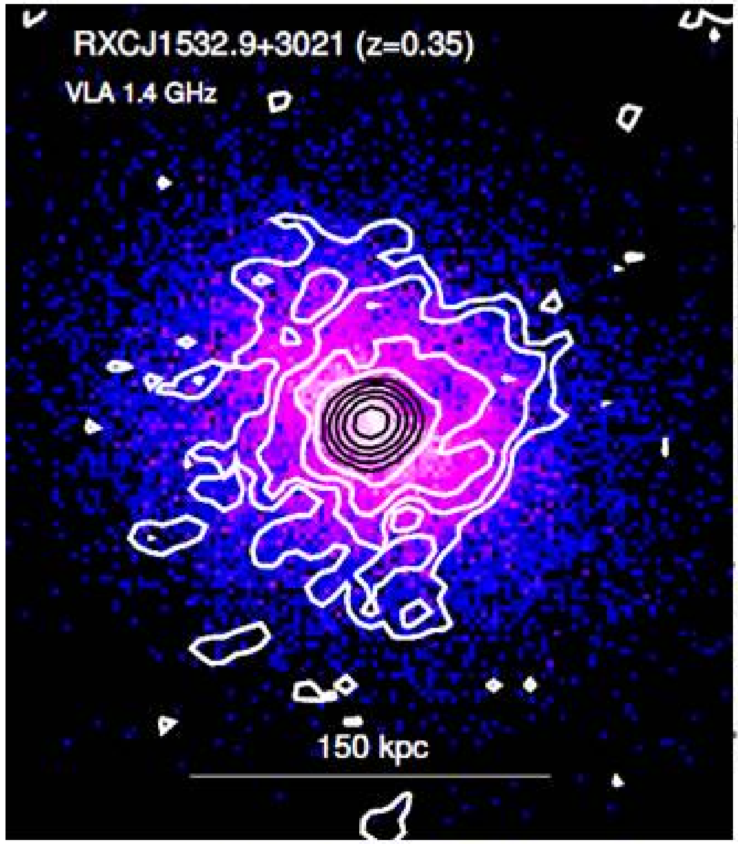
$$t_{\rm diff} \approx 0.1 \ {\rm Gyr} (r/100 \ {\rm kpc})^2 (D/3 \times 10^{31} \ {\rm cm}^2 {\rm s}^{-1})^{-1}$$

~100 kpc low SB diffuse radio emission associated with massive CC clusters

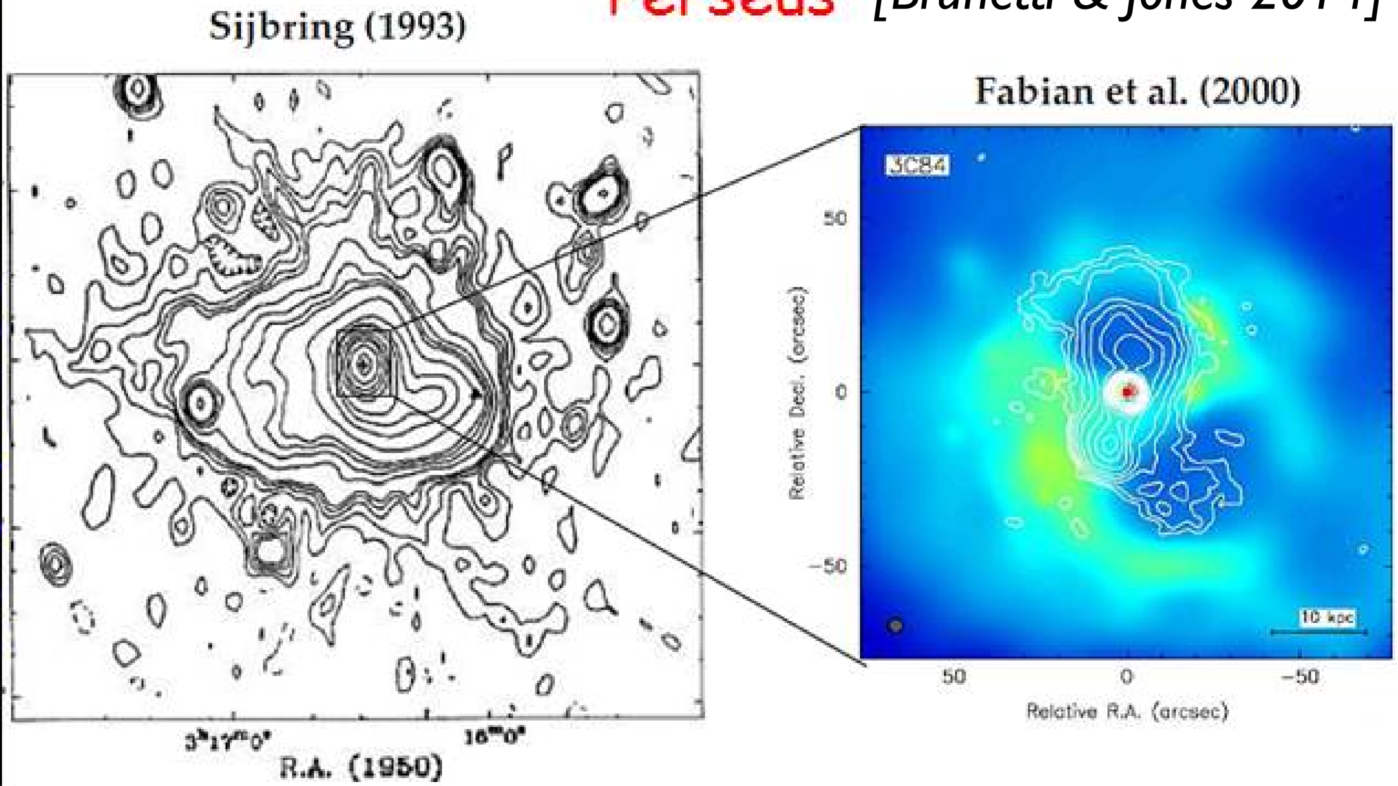
AGN/sloshing driven turbulence reaccelerated e^-s? secondaries from pp?

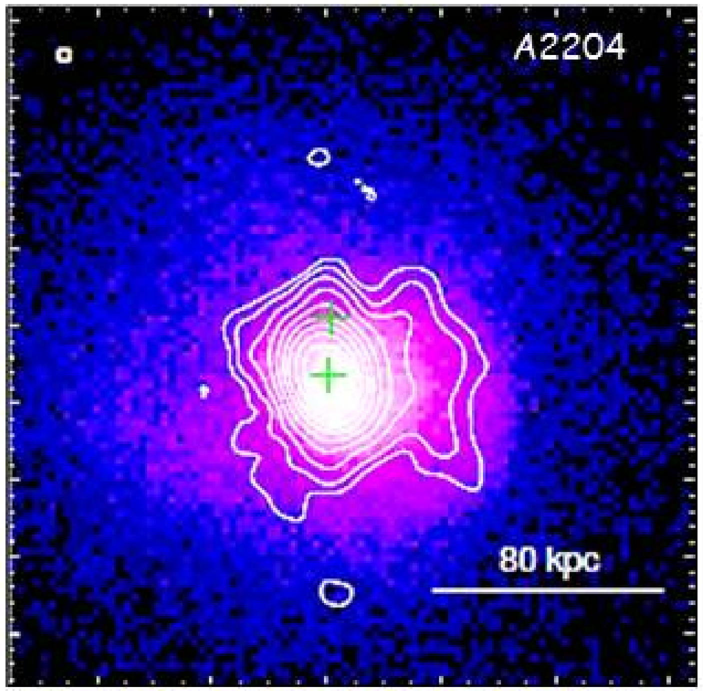
a large D required for CR transport => in-situ acceleration

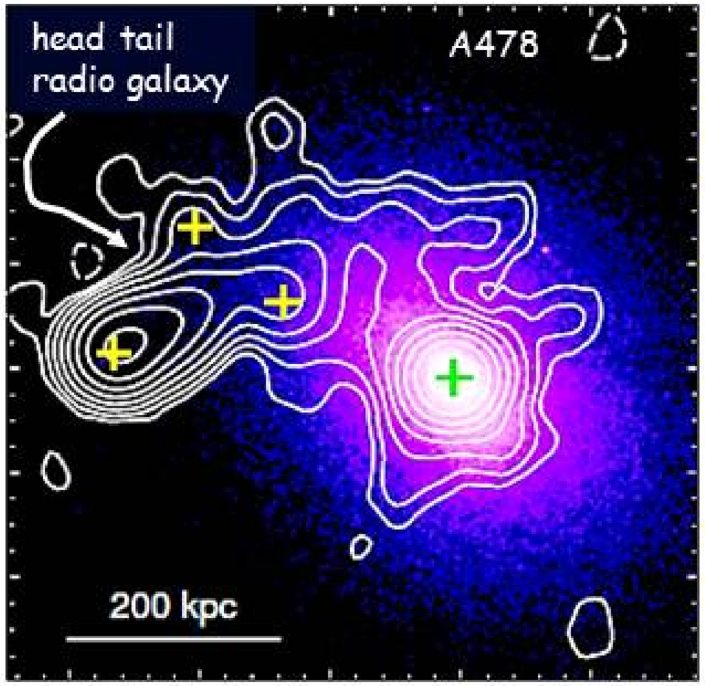
Minihalo examples

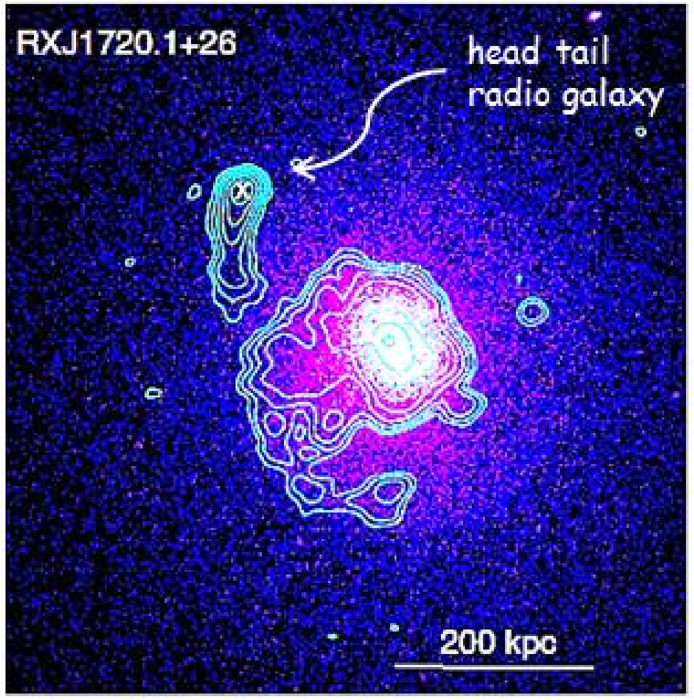


Perseus *[Brunetti & Jones 2014]*





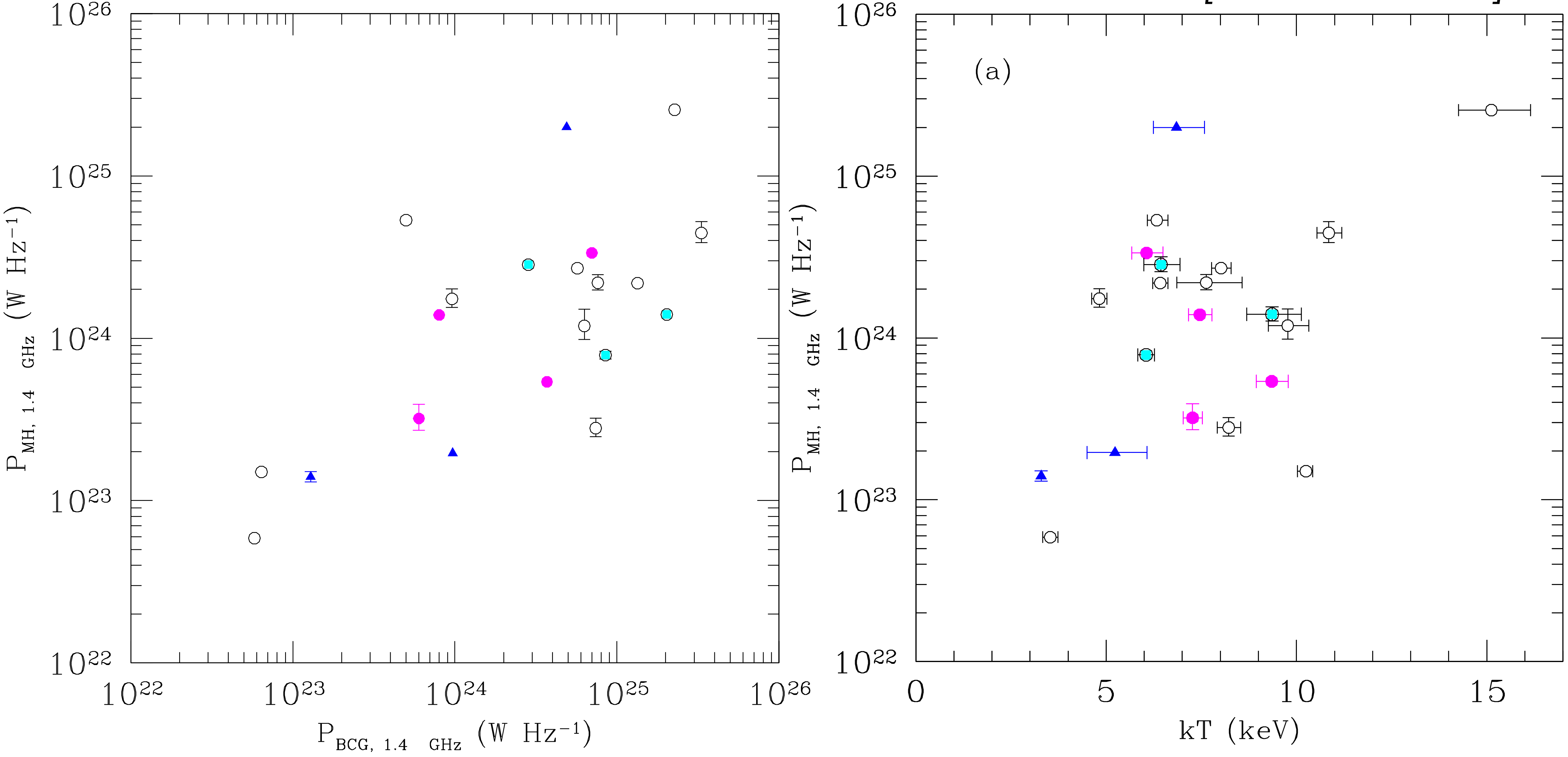




confined within cold fronts (contact discontinuities) observed in X-rays

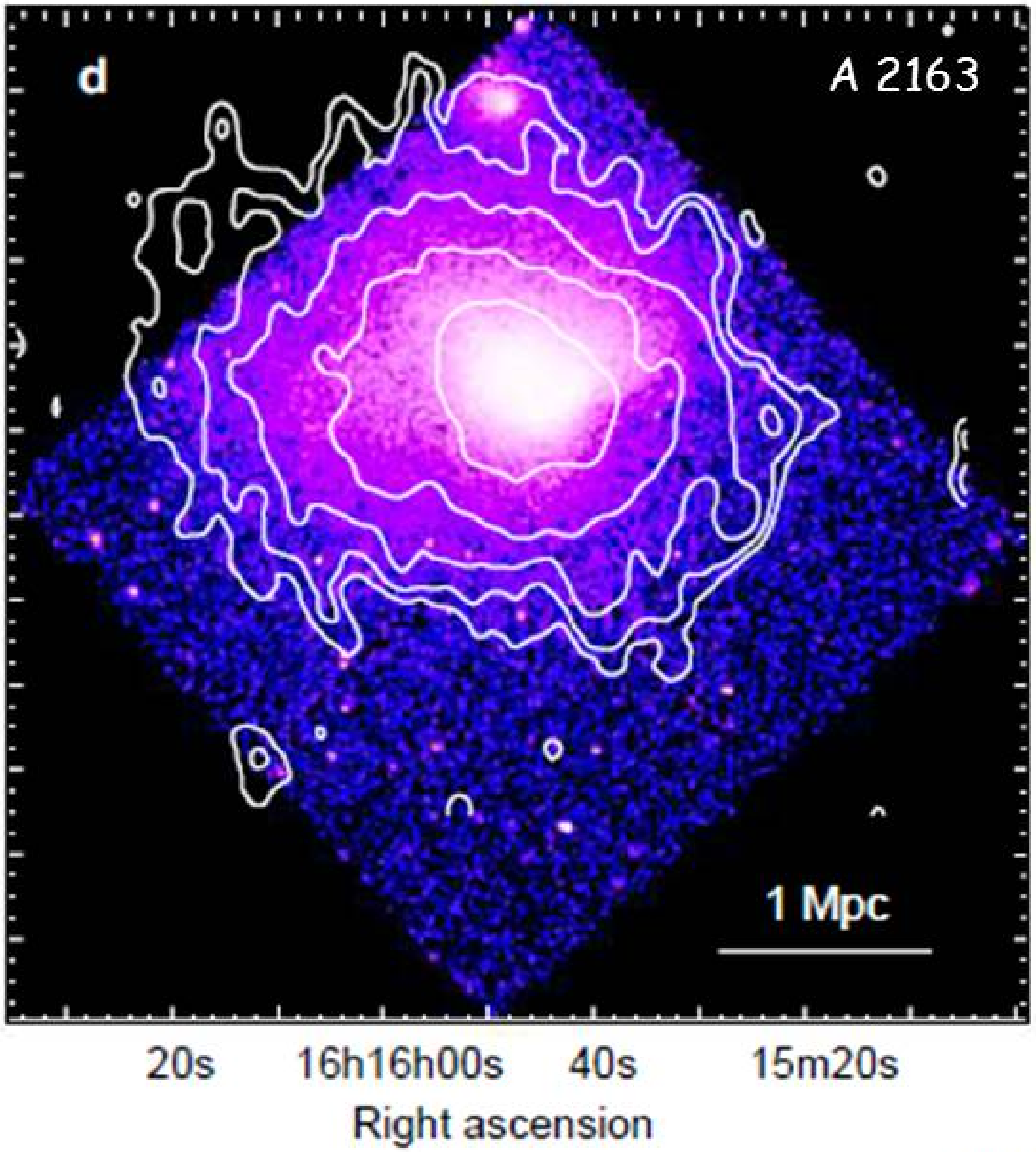
MH & BCG radio correlated

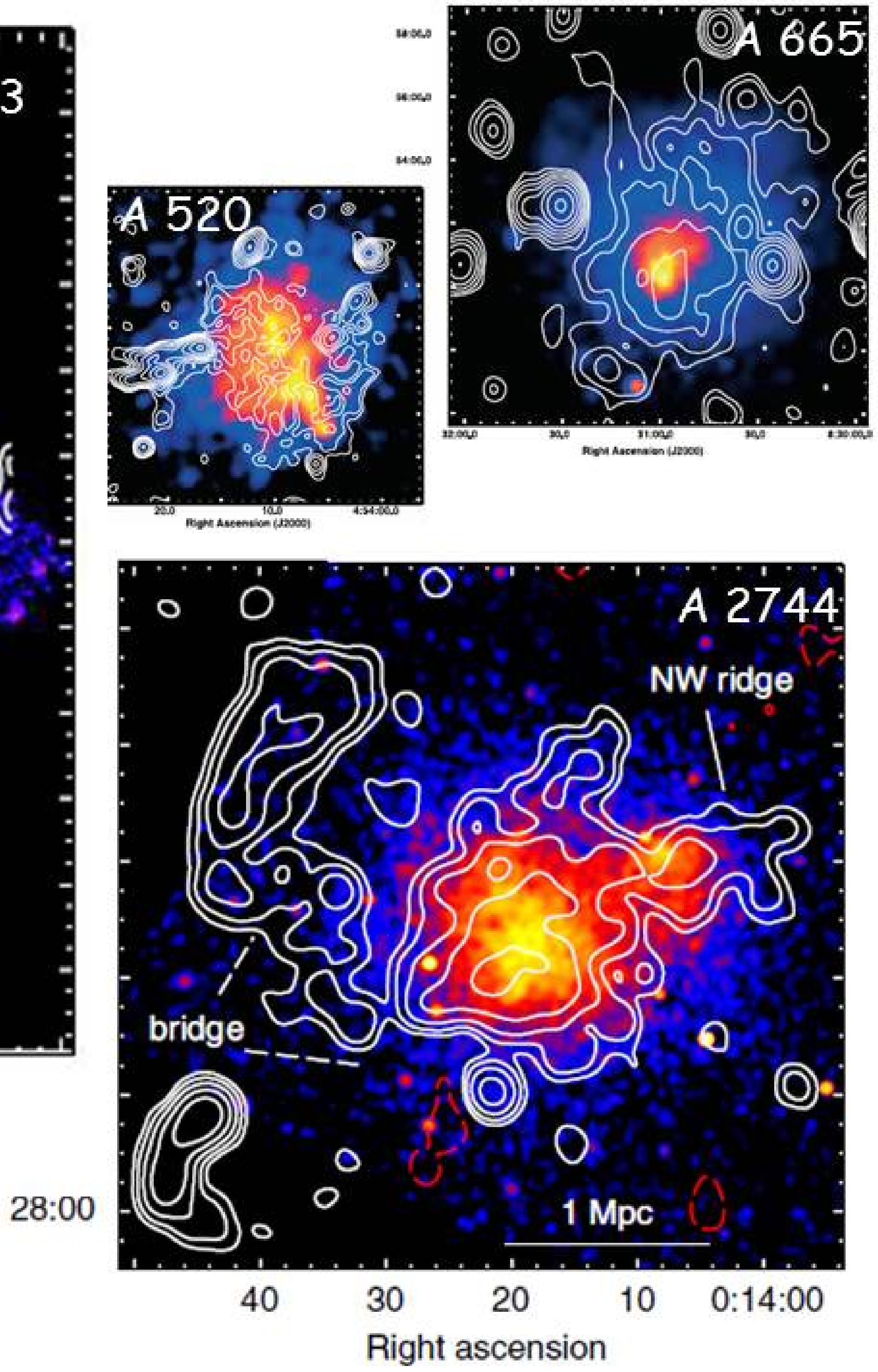
[Giacintucci et al. 2014]



BCG radio jets powered by cold gas condensing in cores
do MHs also have something to do with it?

Giant radio halos



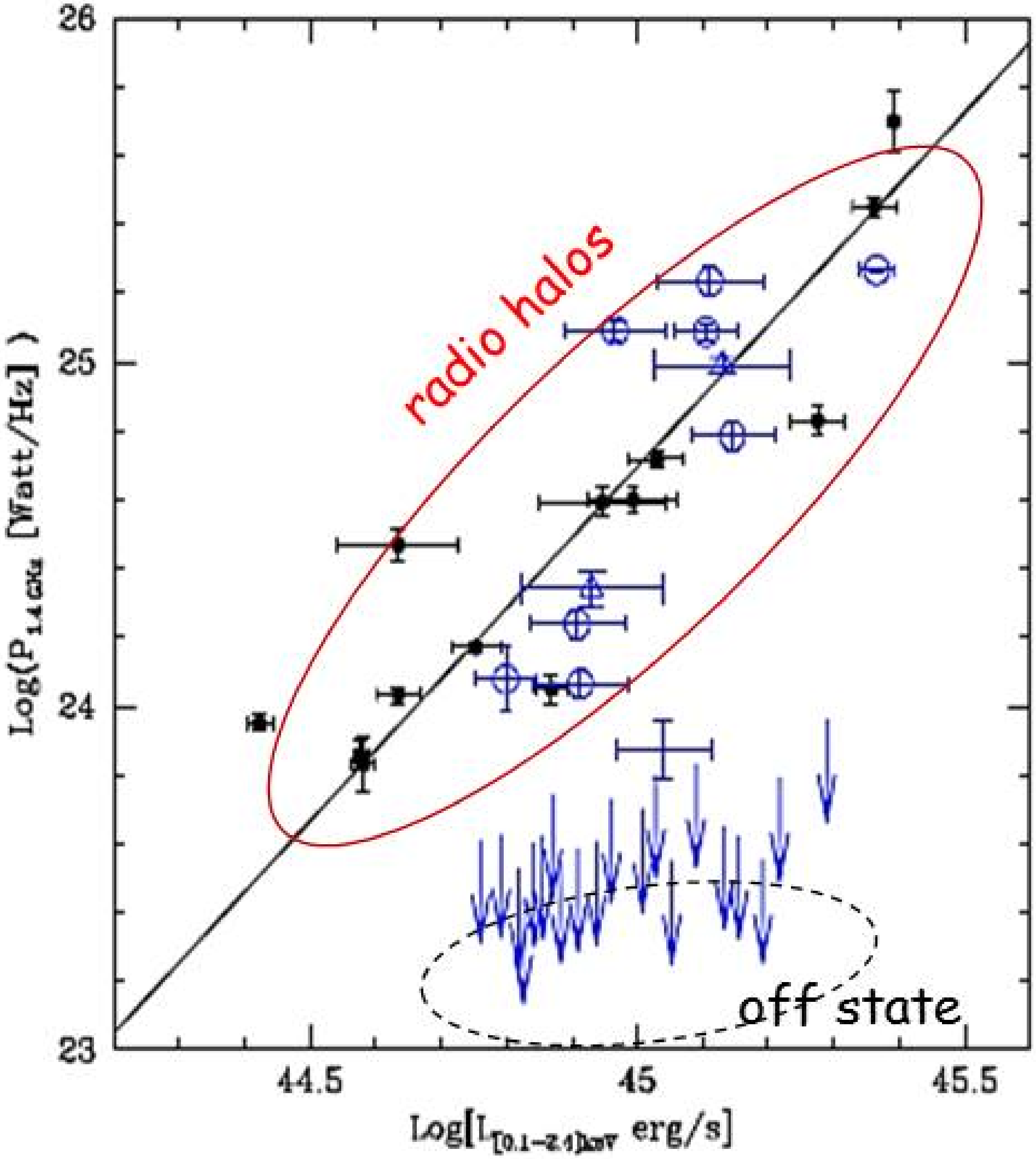


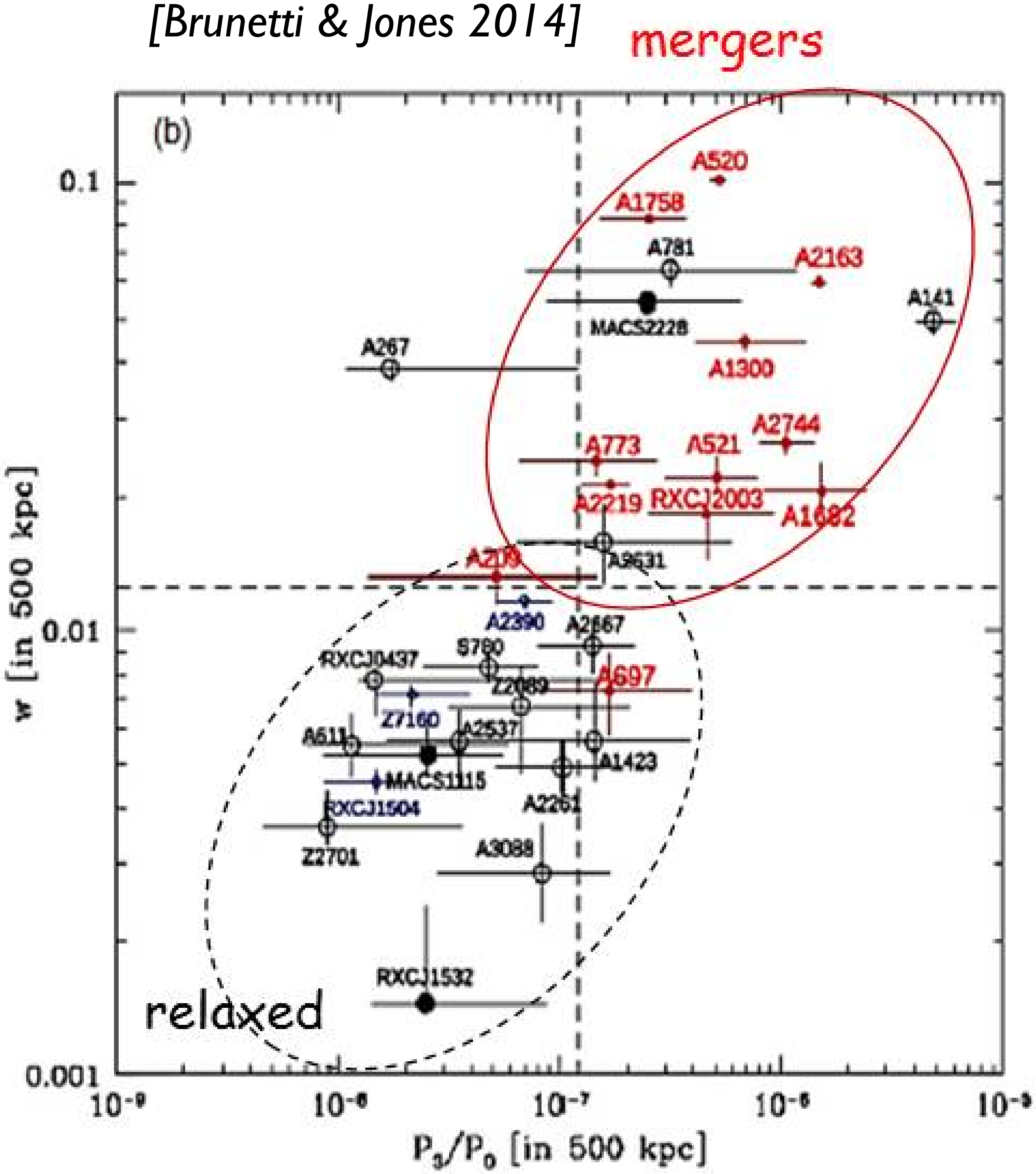
[Brunetti & Jones 2014]

mostly unpolarized

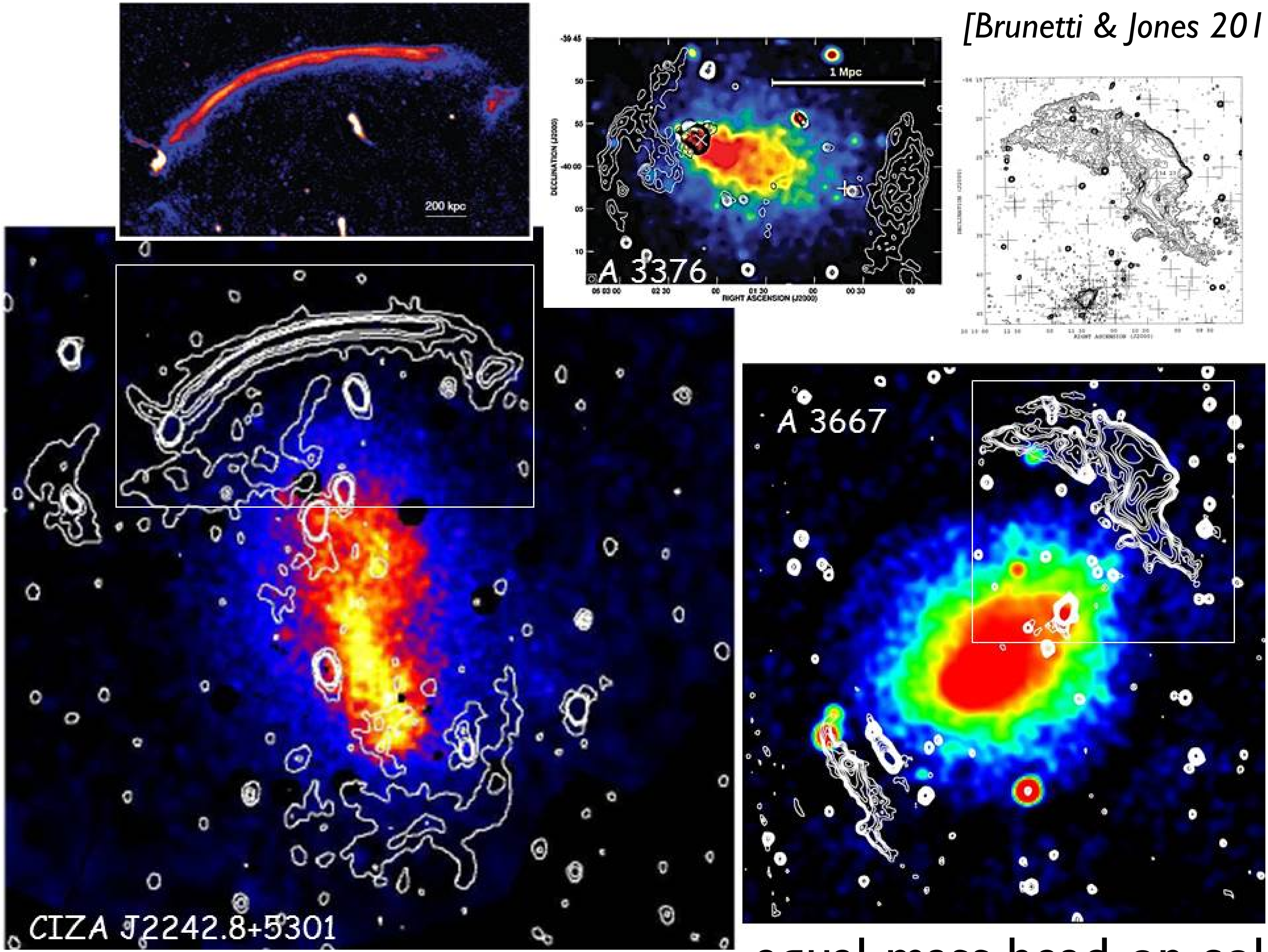
RHs are mergers

[Brunetti & Jones 2014]





Radio relics



[Brunetti & Jones 2014]

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

Simulating NT emission

- need B for synchrotron, U_{ph} for IC
- relativistic electrons, power-law, cut-offs
- turbulence, merger shocks, virial shock (1st & 2nd order Fermi)
- recipe for acceleration, escape, cooling
- radio, X-rays & gamma-rays
- hadronic (via secondary e^-s) vs. leptonic
- much more involved than thermal=>X-rays

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

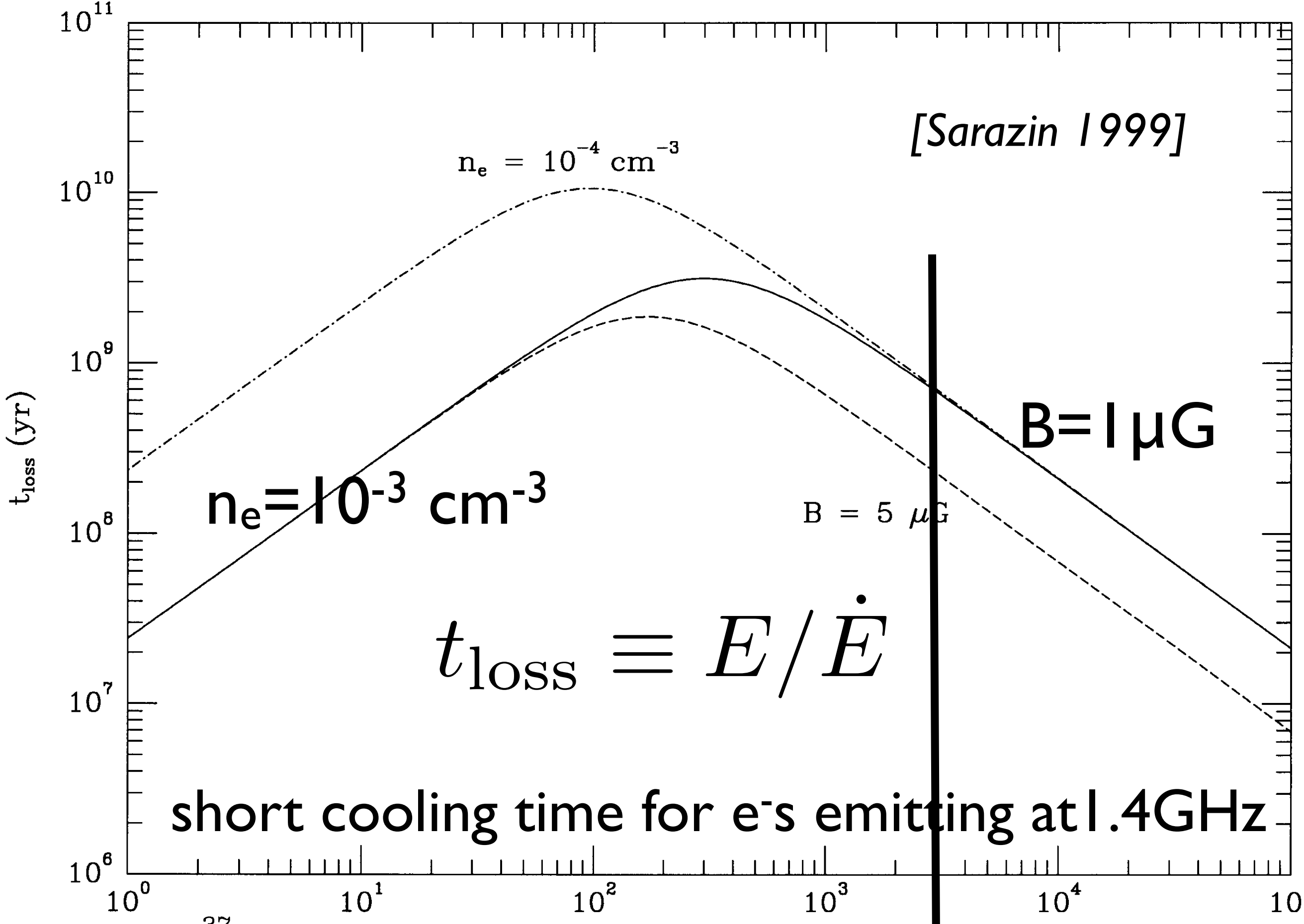
$$\left(\frac{dp}{dt}\right)_{\rm rad} = -4.8\times10^{-4}p^2\left[\left(\frac{B_{\mu G}}{B_{\rm CMB}}\right)^2\frac{\sin^2\theta}{2/3} + (1+z)^4\right]$$

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

Energy gains & losses



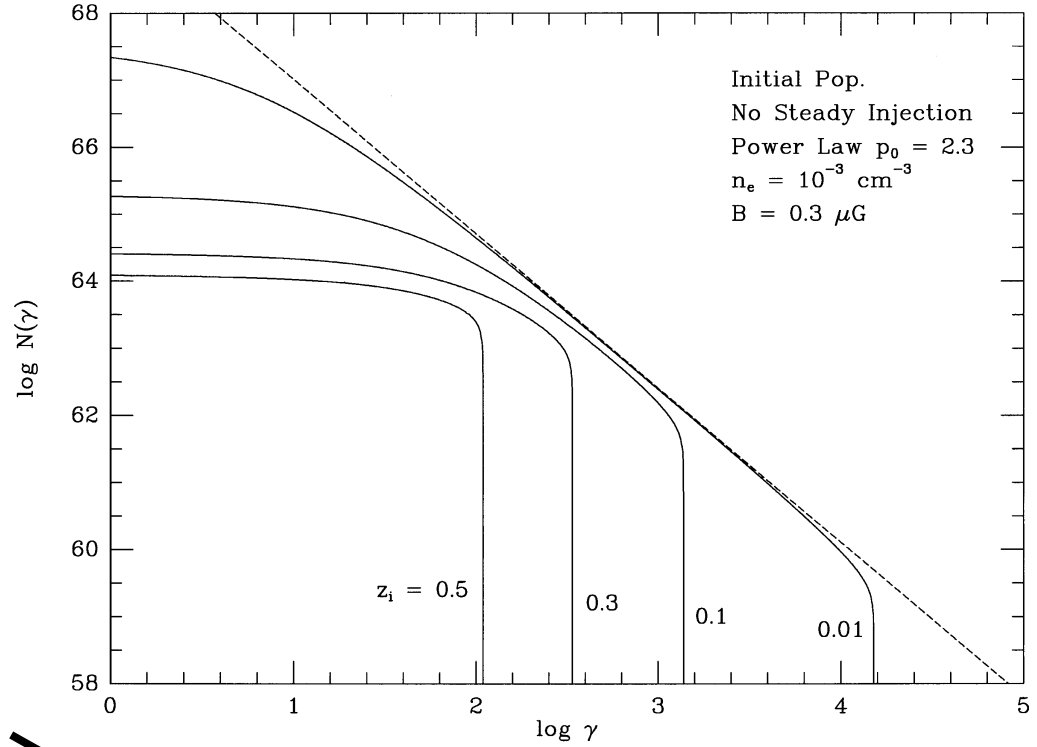
[Sarazin 1999]

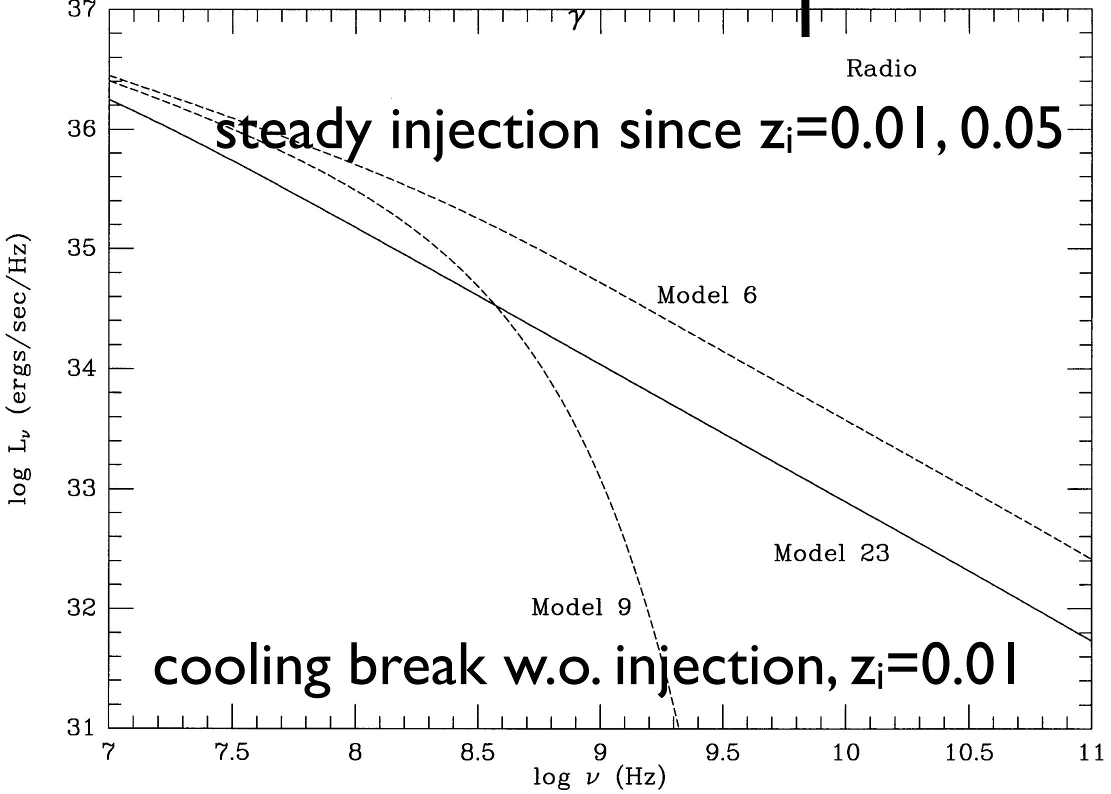
B=1μG

n_e=10^{-3} cm^{-3}

$$t_{\rm loss} \equiv E/\dot{E}$$

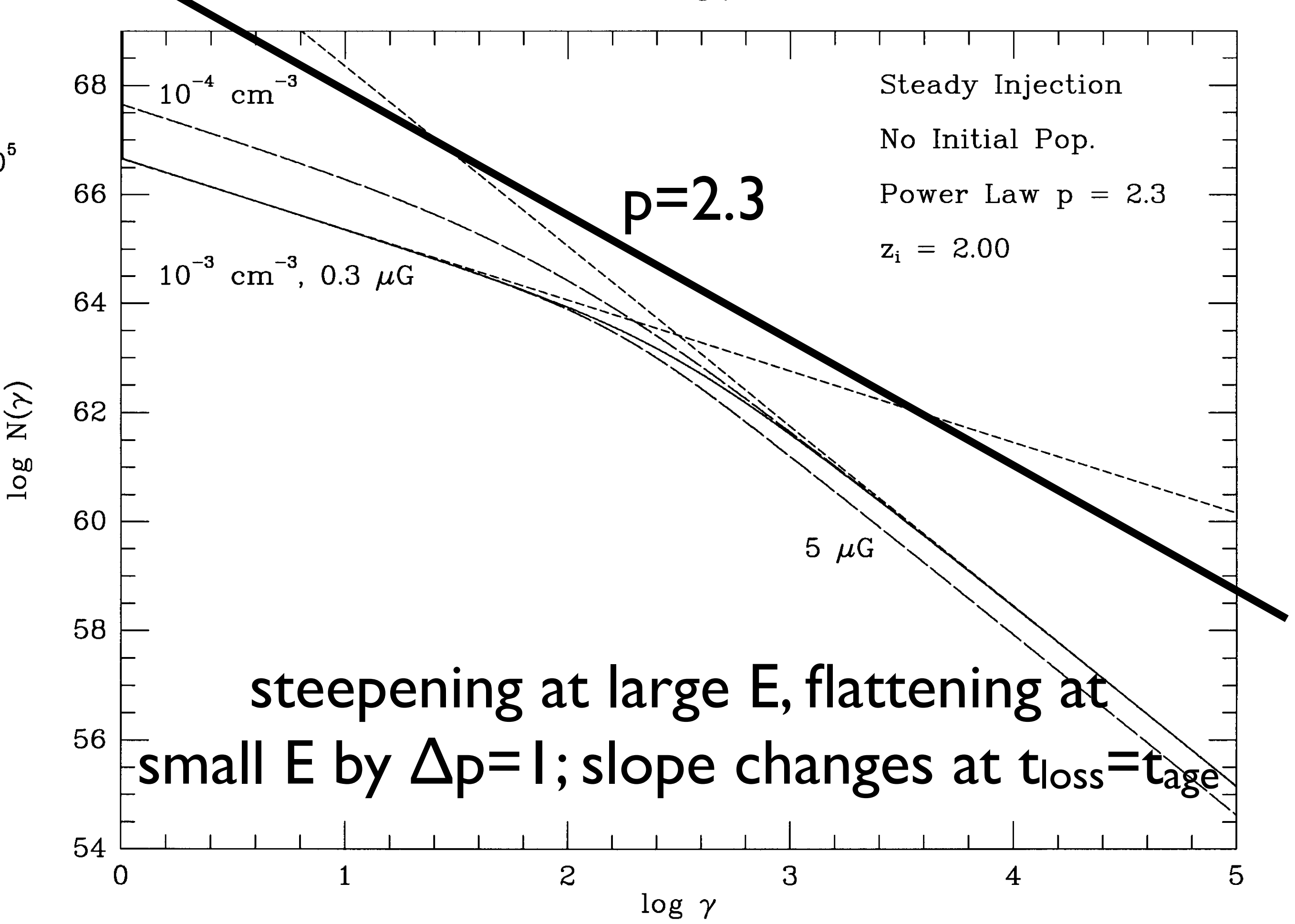
short cooling time for e$^-$s emitting at1.4GHz





steady injection since z_i=0.01, 0.05

cooling break w.o. injection, z_i=0.01



p=2.3

steepening at large E, flattening at small E by Δp=1; slope changes at $t_{\rm loss}$=$t_{\rm age}$

MH simulations

TURBULENCE AND RADIO MINI-HALOS IN THE SLOSHING CORES OF GALAXY CLUSTERS

J. A. ZUHONE[1], M. MARKEVITCH[1], G. BRUNETTI[2], AND S. GIACINTUCCI[3]

MHD simulations w. prescription for test e$^-$ acceleration & losses
e$^-$s accelerated by turbulence driven by sloshing due to mergers

$$\frac{\partial N(p,t)}{\partial t} = \frac{\partial}{\partial p}\left[N(p,t)\left(\left|\frac{dp}{dt}\right|_{\rm rad} + \left|\frac{dp}{dt}\right|_{\rm coll} - \frac{4D_{pp}}{p}\right)\right] + \frac{\partial^2}{\partial p^2}[D_{pp}N(p,t)]$$

only compressive MHD modes accelerate
this physics is uncertain; Landau damping

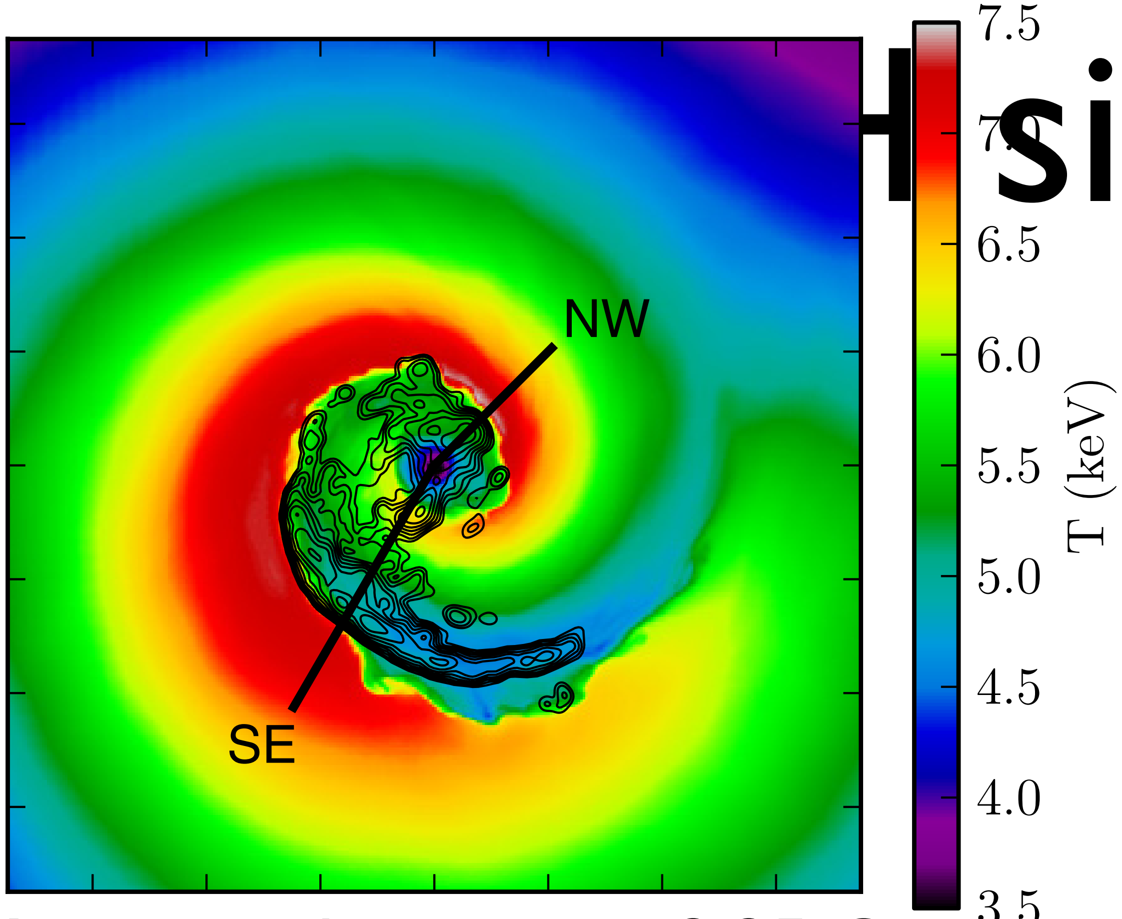
$$D_{\rm pp,TTD} \approx 1.5 \times 10^{-11}\langle k\rangle \left(\frac{f}{1.5}\right)\left(\frac{v_t^2}{v_z^2}\right)\left(\frac{R^c}{0.25}\right) {v_z}^2 p^2$$

$$D_{\rm pp,C} \approx 1.3 \times 10^{-12} k_{\rm mfp} \left(\frac{f}{1.5}\right)\left(\frac{v_t^2}{v_z^2}\right)\left(\frac{R^c}{0.25}\right) {v_z}^2 p^2$$

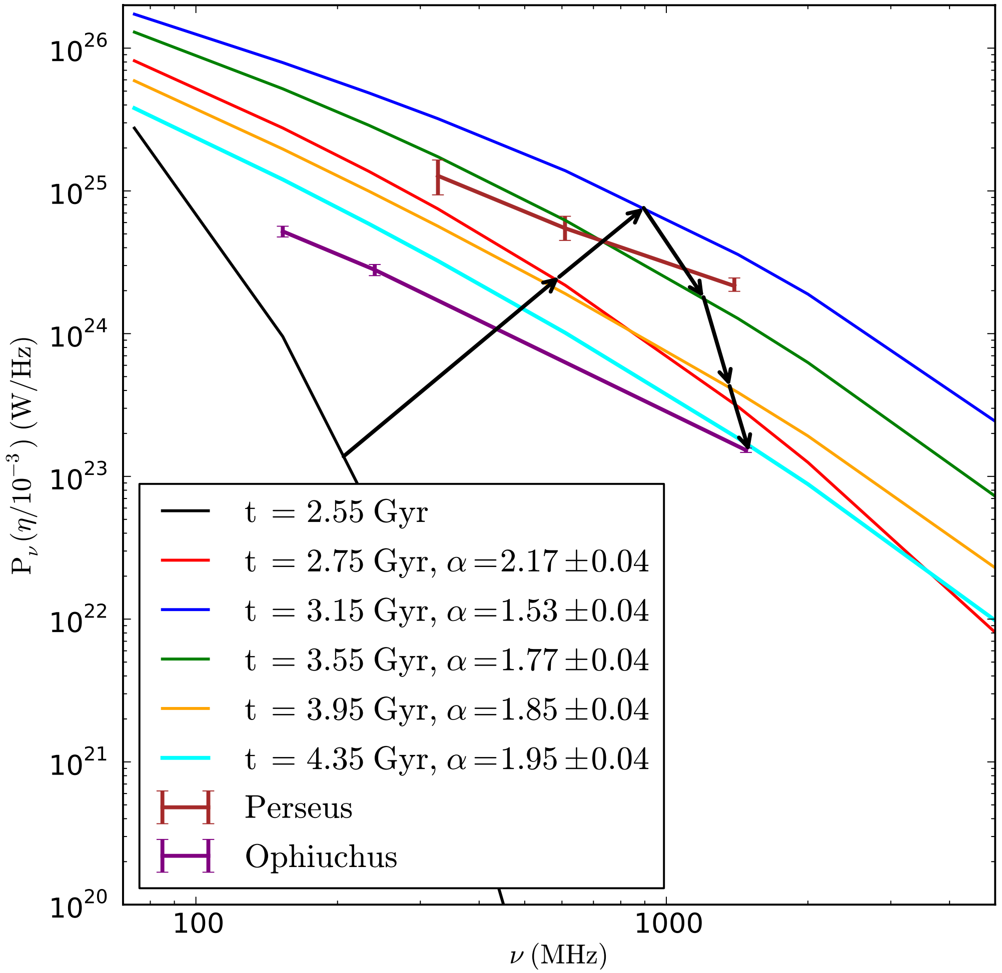
momentum diffusion due
to TTD & compression

Fokker-Planck equation for particle DF solved via a stochastic/Langevin equation
Monte Carlo approach, technically quite sophisticated

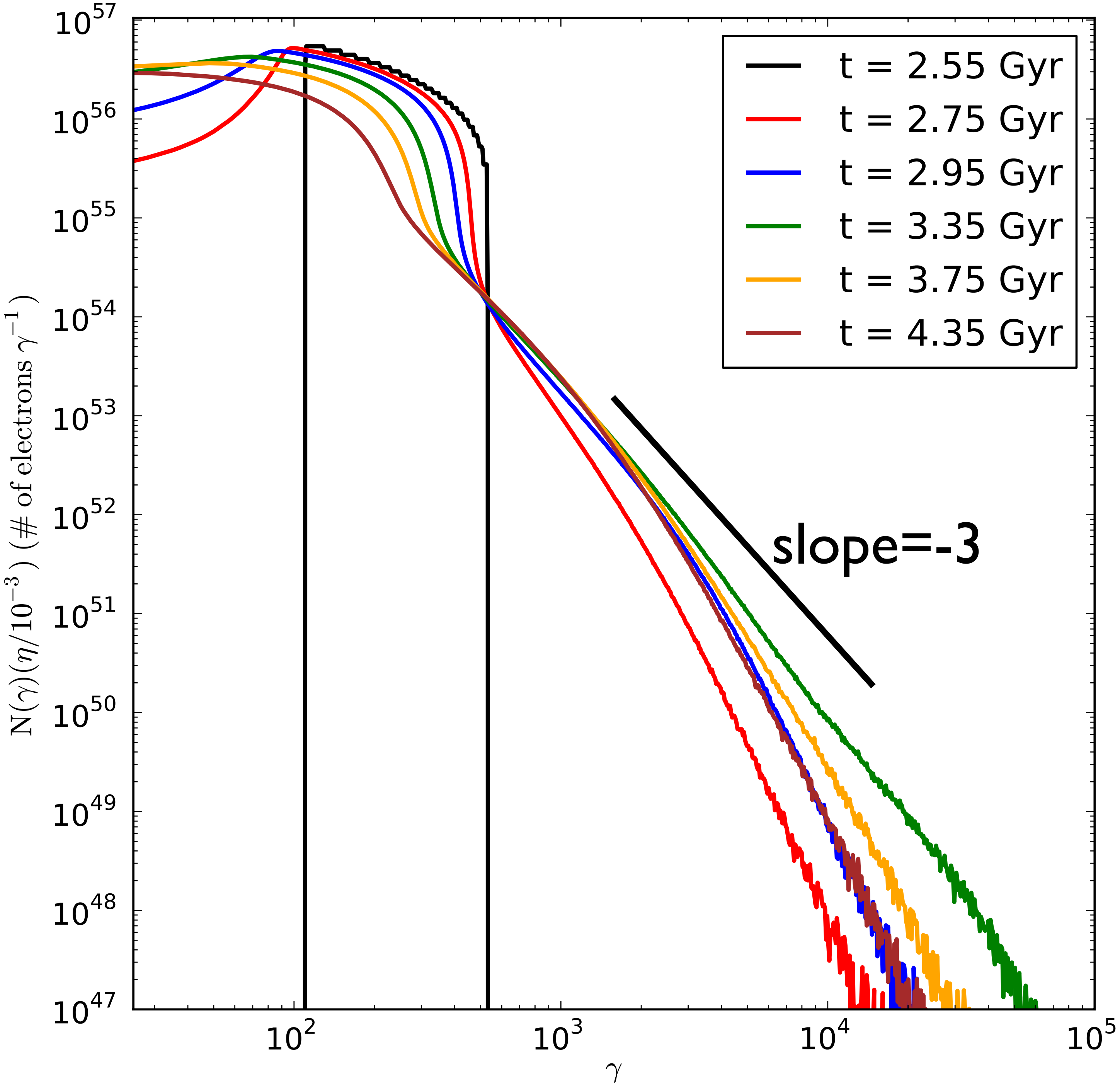
H simulations



X-ray & radio maps at 3.35 Gyr



particle spectra



predictive but some uncertain physics