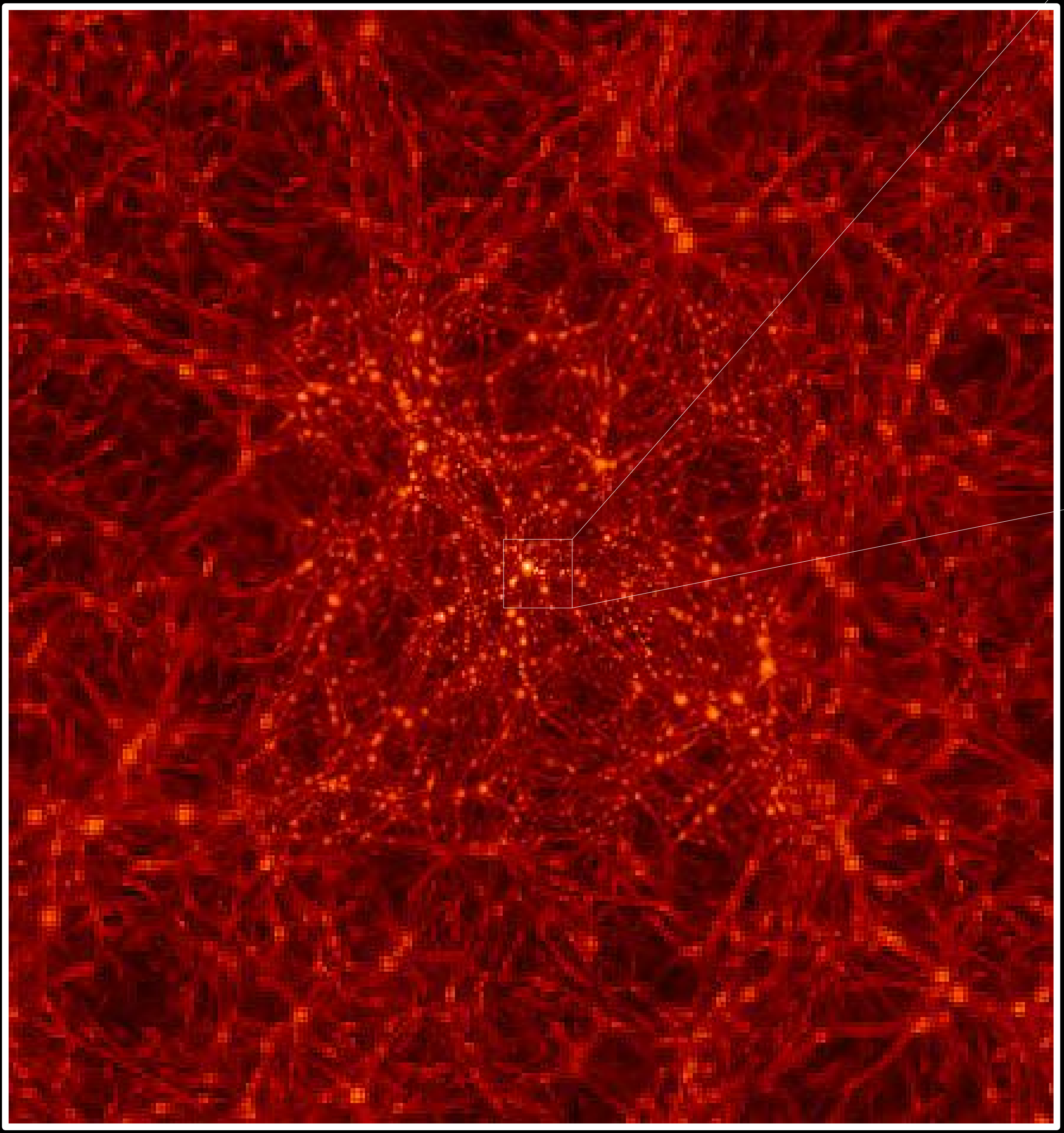
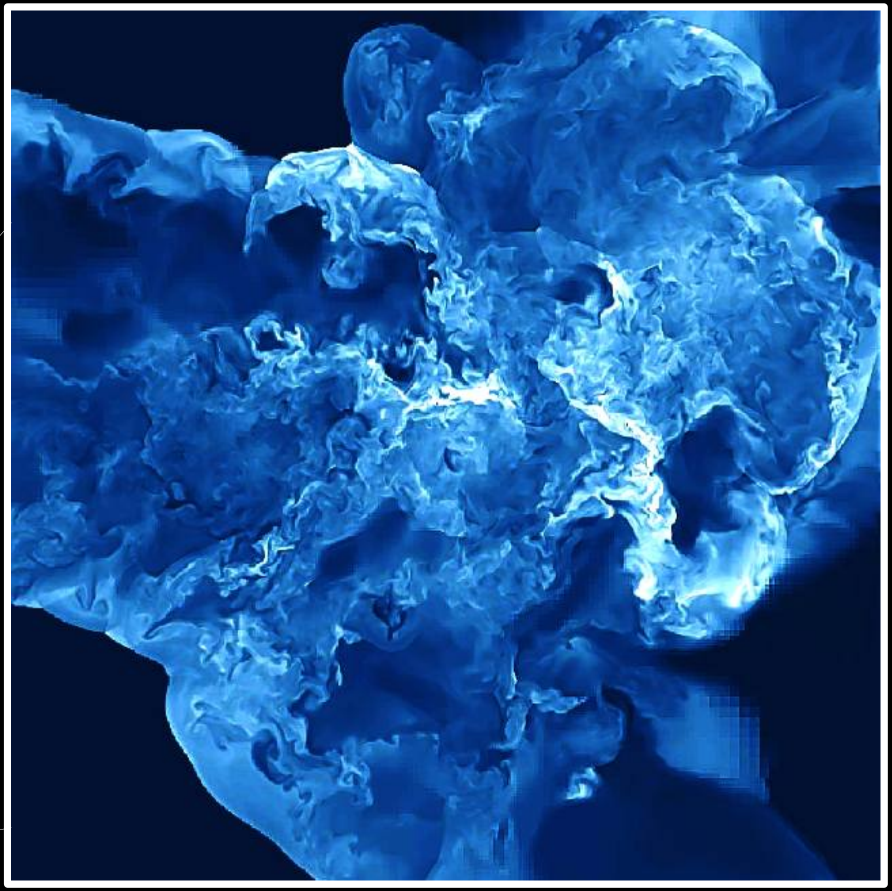
Majestic & Refined:
Shocks and turbulence in simulated massive galaxy clusters





- F.Vazza (Jacobs + IRA)
- G.Brunetti (IRA-Bologna)
- C.Gheller, R.Brunino (Cineca-Bologna)
- M.Brüggen (Jacobs)
- A.Bonafede (Jacobs)

Irsee, 05 Oct. 2010

Scientific cases:

MAIN:

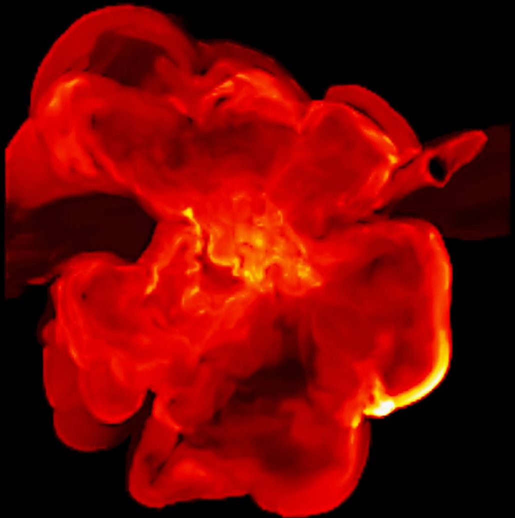
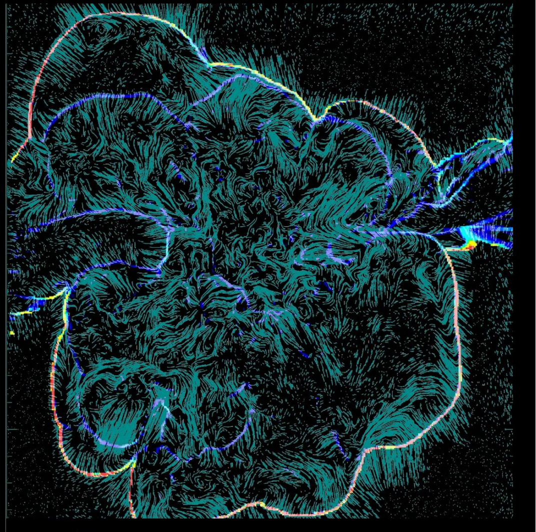
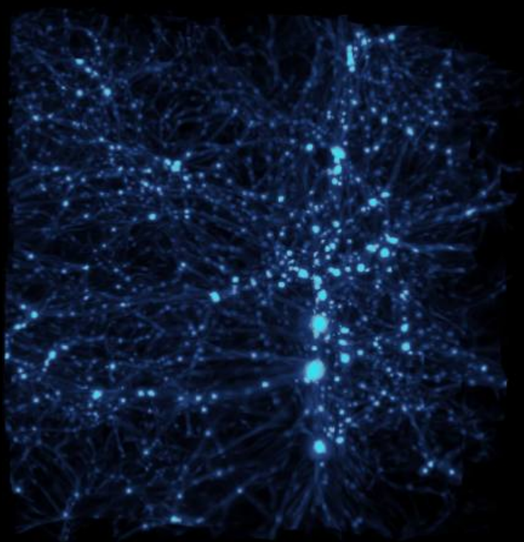
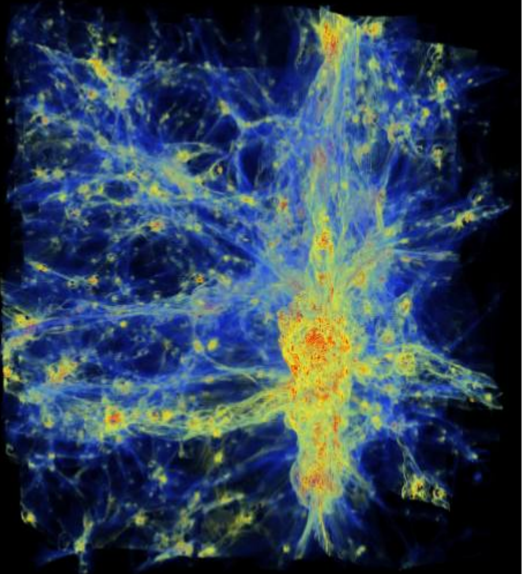
- SHOCK, TURBULENCE, MIXING MECHANISMS IN GALAXY CLUSTERS

- ACCELERATION OF RELATIVISTIC PARTICLES

- NON THERMAL EMISSION(S)

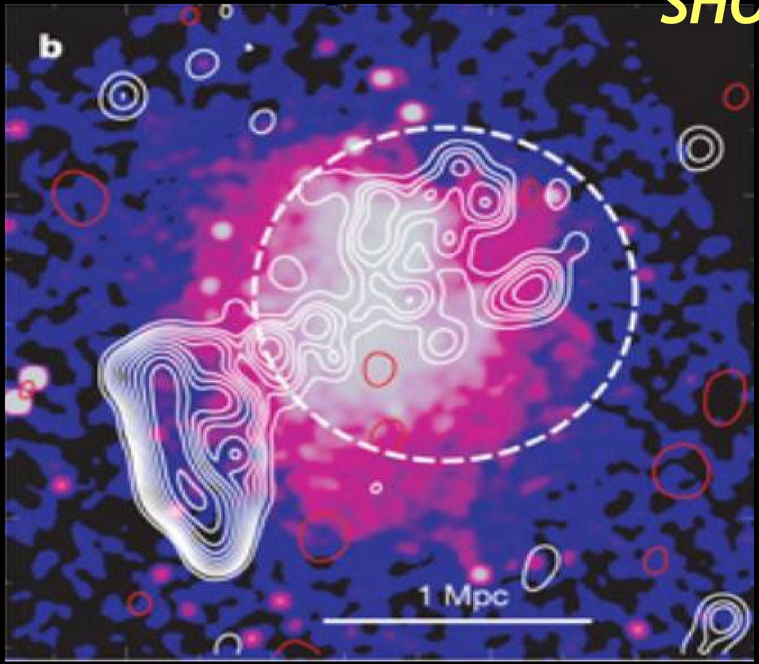
SPIN-OFFS:

- Metal enrichment in the ICM
- AGN feedback
- Jets - ICM interactions

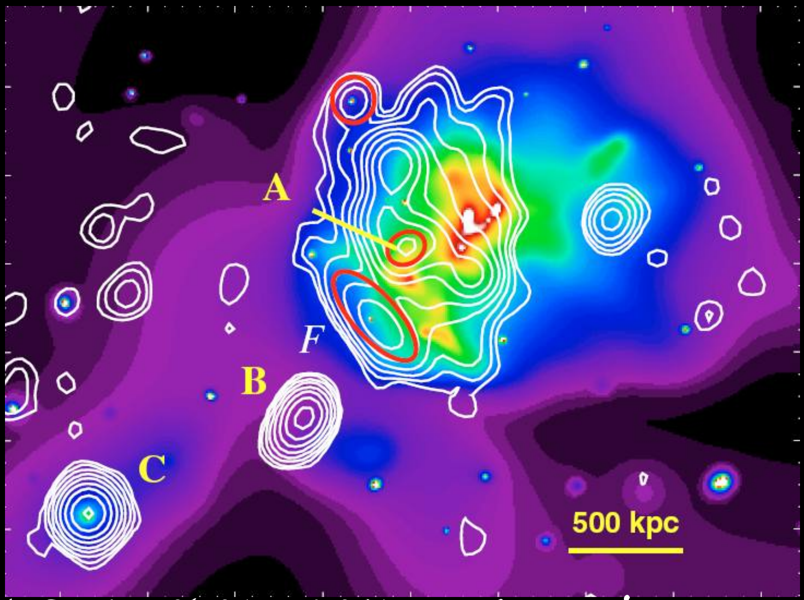





Why bothering?

NT emission are likely powered by SHOCKS and TURBULENCE (30% of clusters)

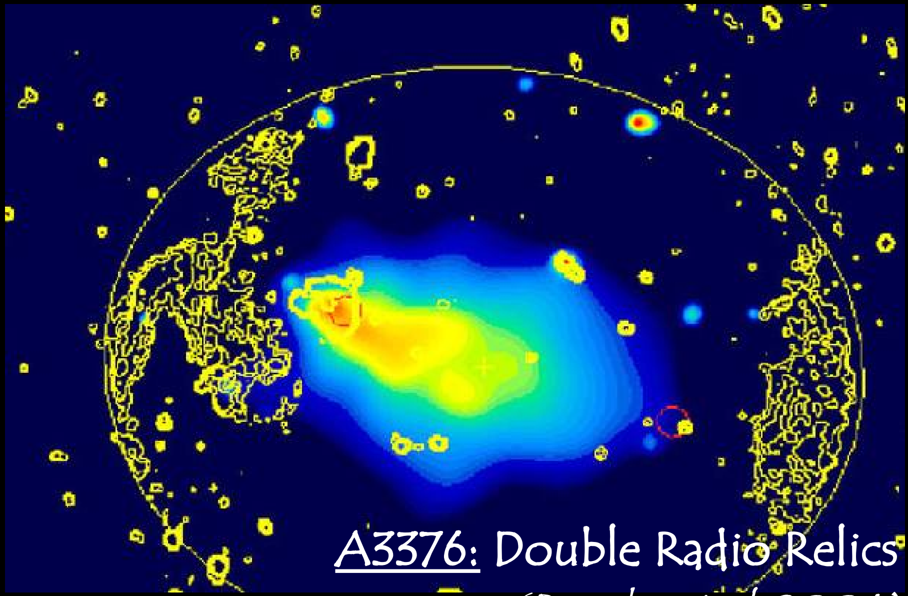


A521: Relic+Halo
(Giacintucci+al07, Brunetti+al08)



MACS J0717.5+3745: Radio Halo at z=0.55
(Bonafede et al.2009)

~30 radio halos
~20 radio relics
The main ingredients:
Relativistic particles, magnetic fields, chaotic motions
*(see talks by **Ensslin, Bonafede, Bruggen, Hoeft, Dolag**...)*



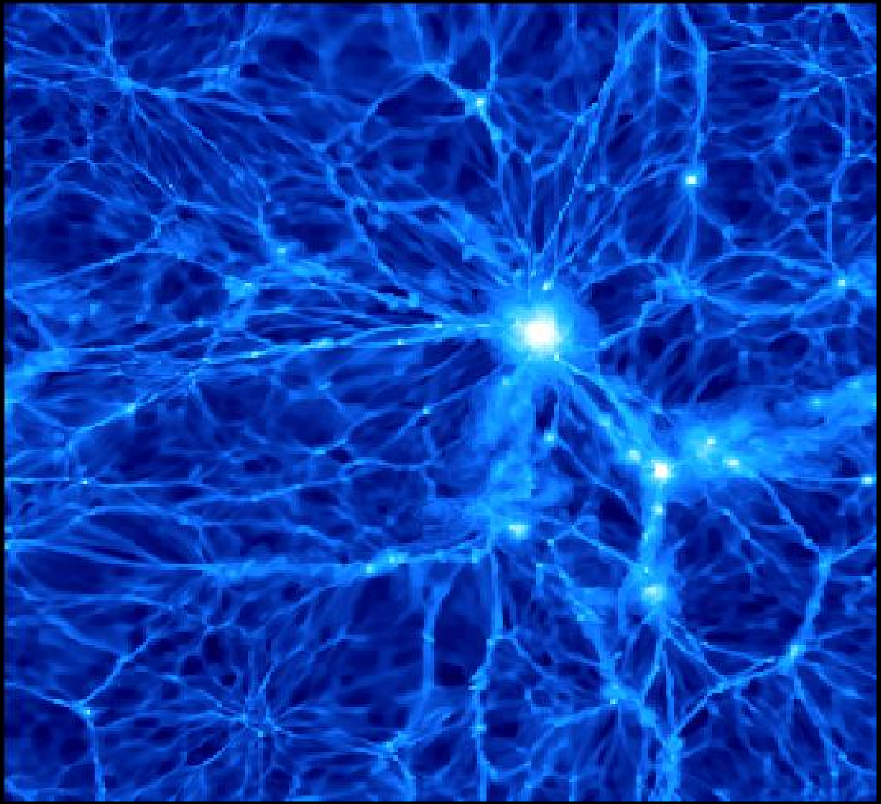
A3376: Double Radio Relics
(Bacghi et al.2006)

Our simulations
2005-2010: @Bologna
2010 - ... @Jacobs

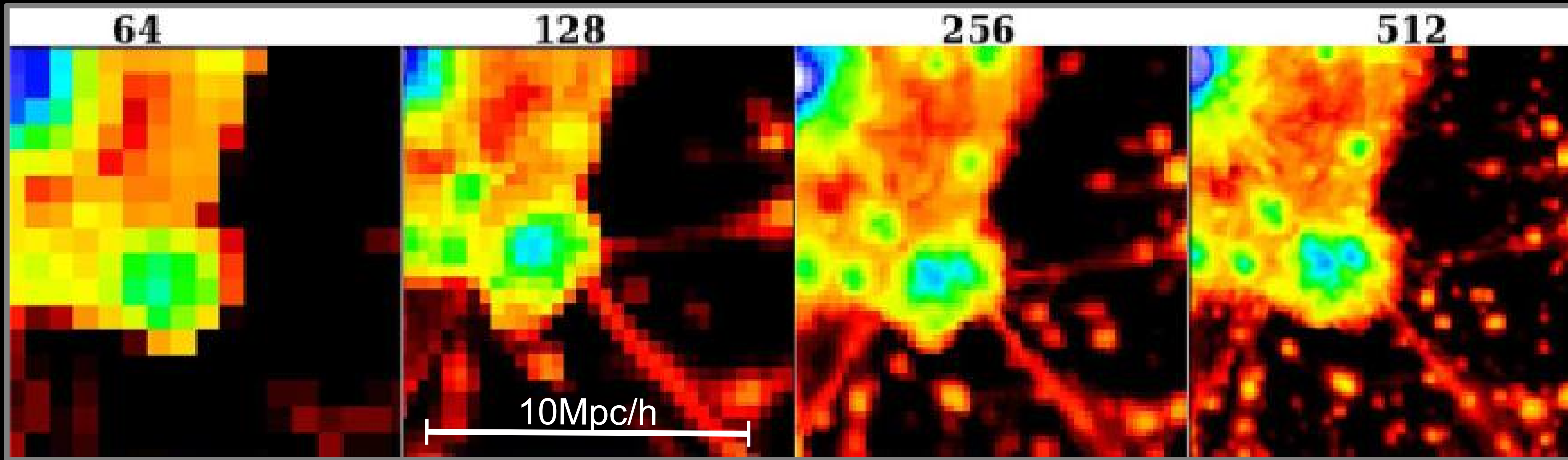
- *are done with the <u>grid code ENZO</u> (Bryan et al. 1995) + customization*

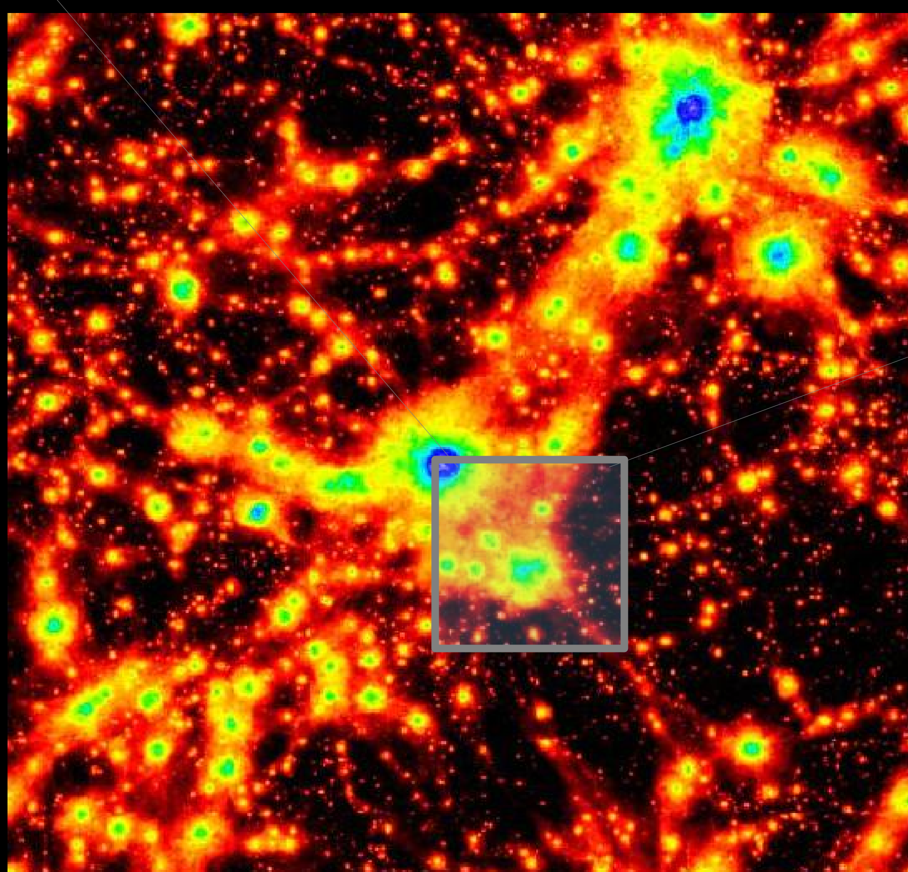
- *are fully <u>cosmological</u>*

- *do not contain fancy extra-physics (no star formation, no B field, no Cosmic Rays, no conduction, ...)*



- *At present, they likely provide the <u>most spatially resolved representation</u> of fluid-dynamical processes in the “standard” Intra Cluster Medium*

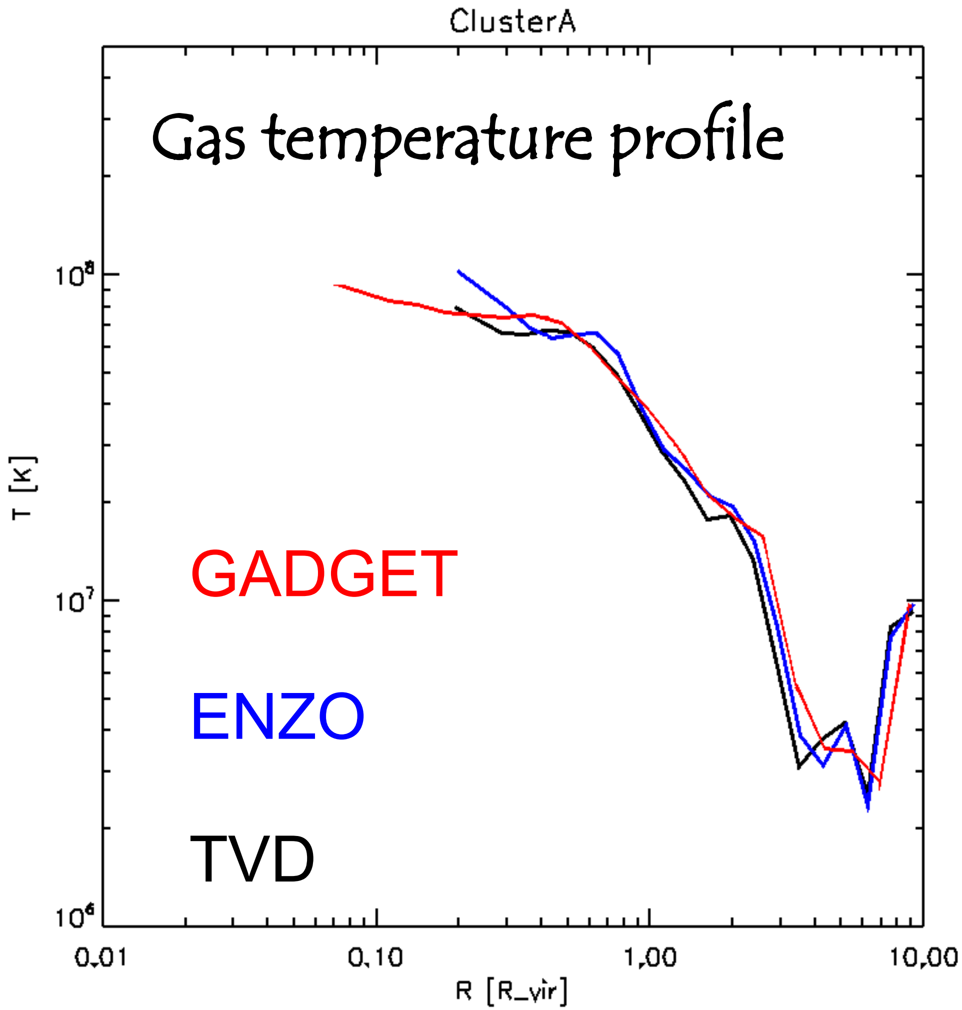


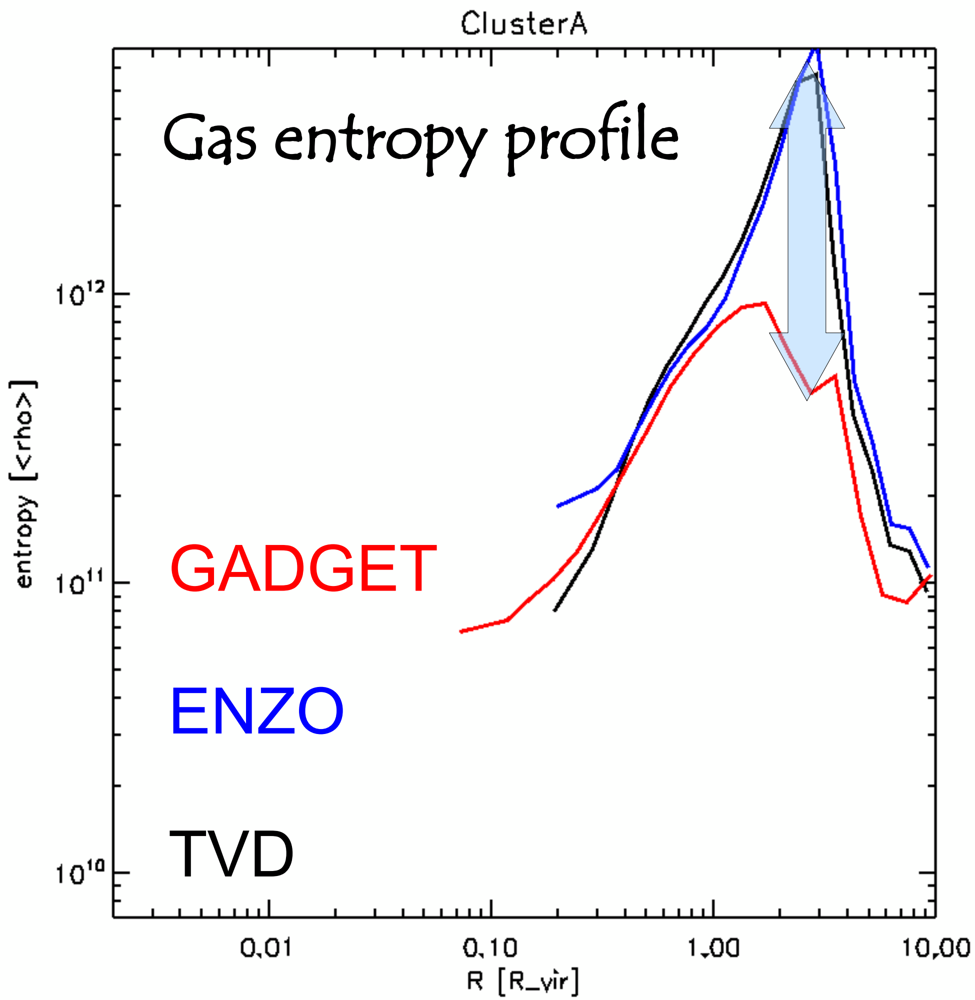


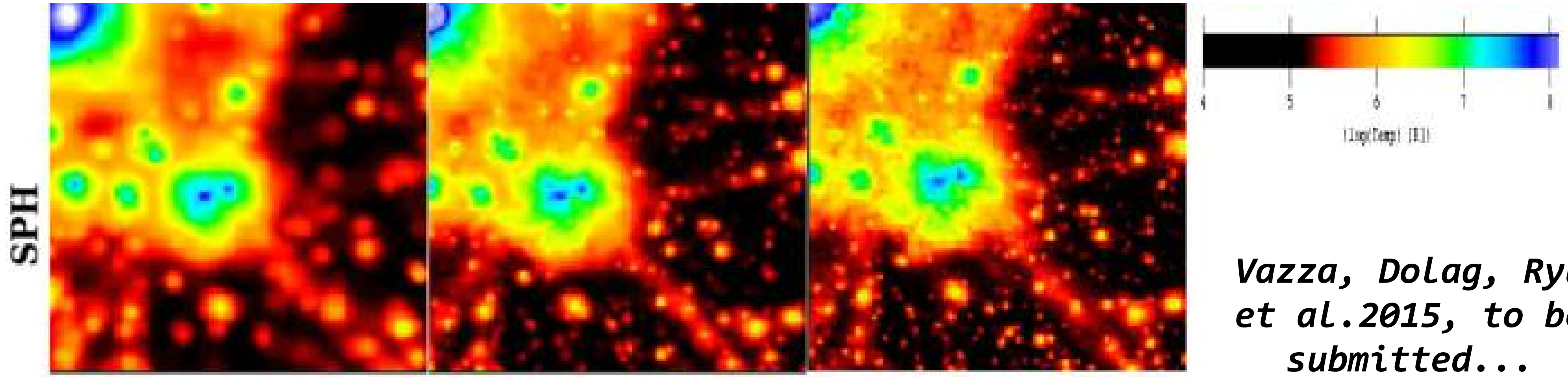
100Mpc/h
Projected
temperature

Yet, not a trivial issue, because the modelization of the ICM is not always convergent with resolution and against different numerical methods

(e.g. Grid vs Smoothed Particle Hydr,



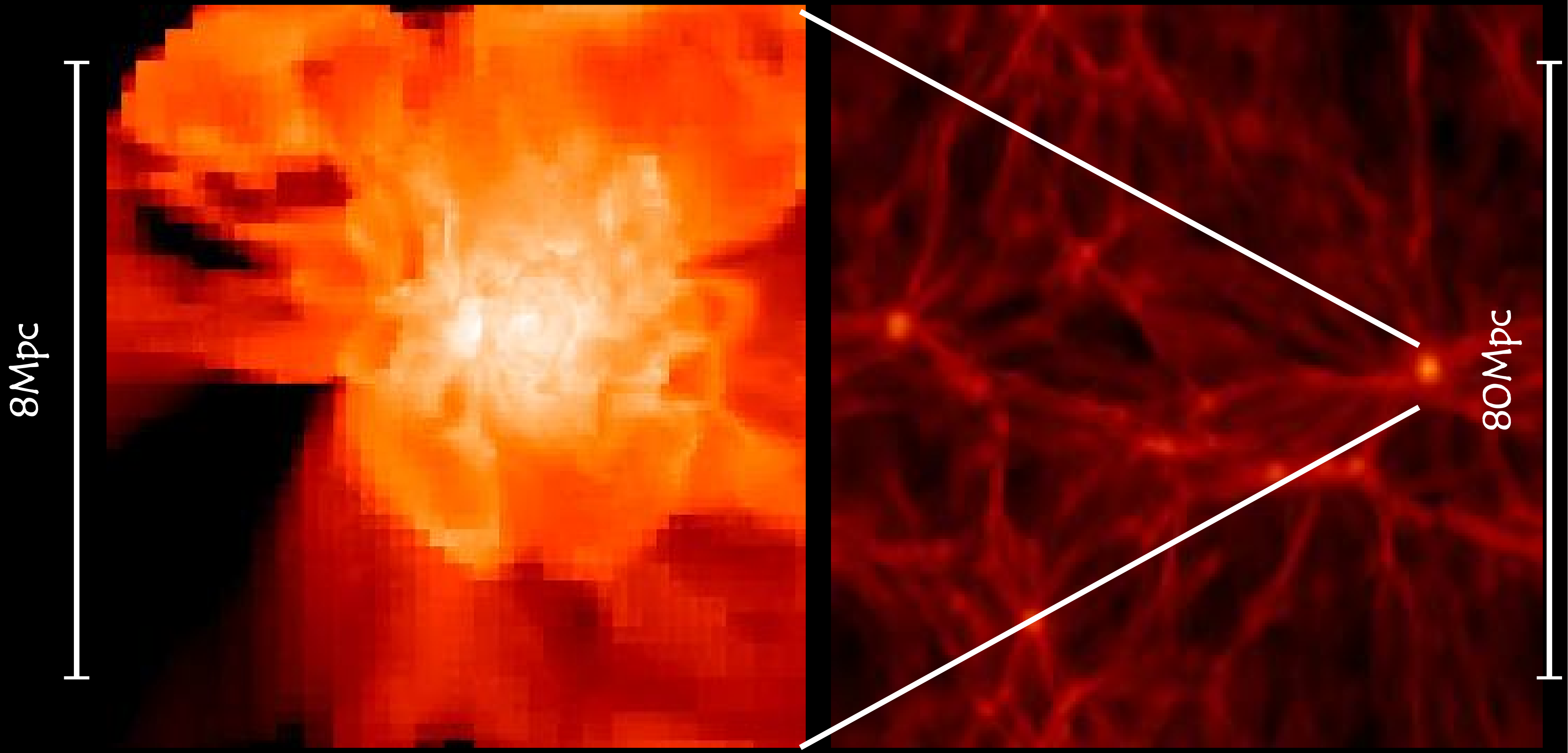




Vazza, Dolag, Ryu et al.2015, to be submitted...

WHAT IS THE BEST REFINEMENT FOR SHOCKS?

REFINEMENT ON GAS DENSITY

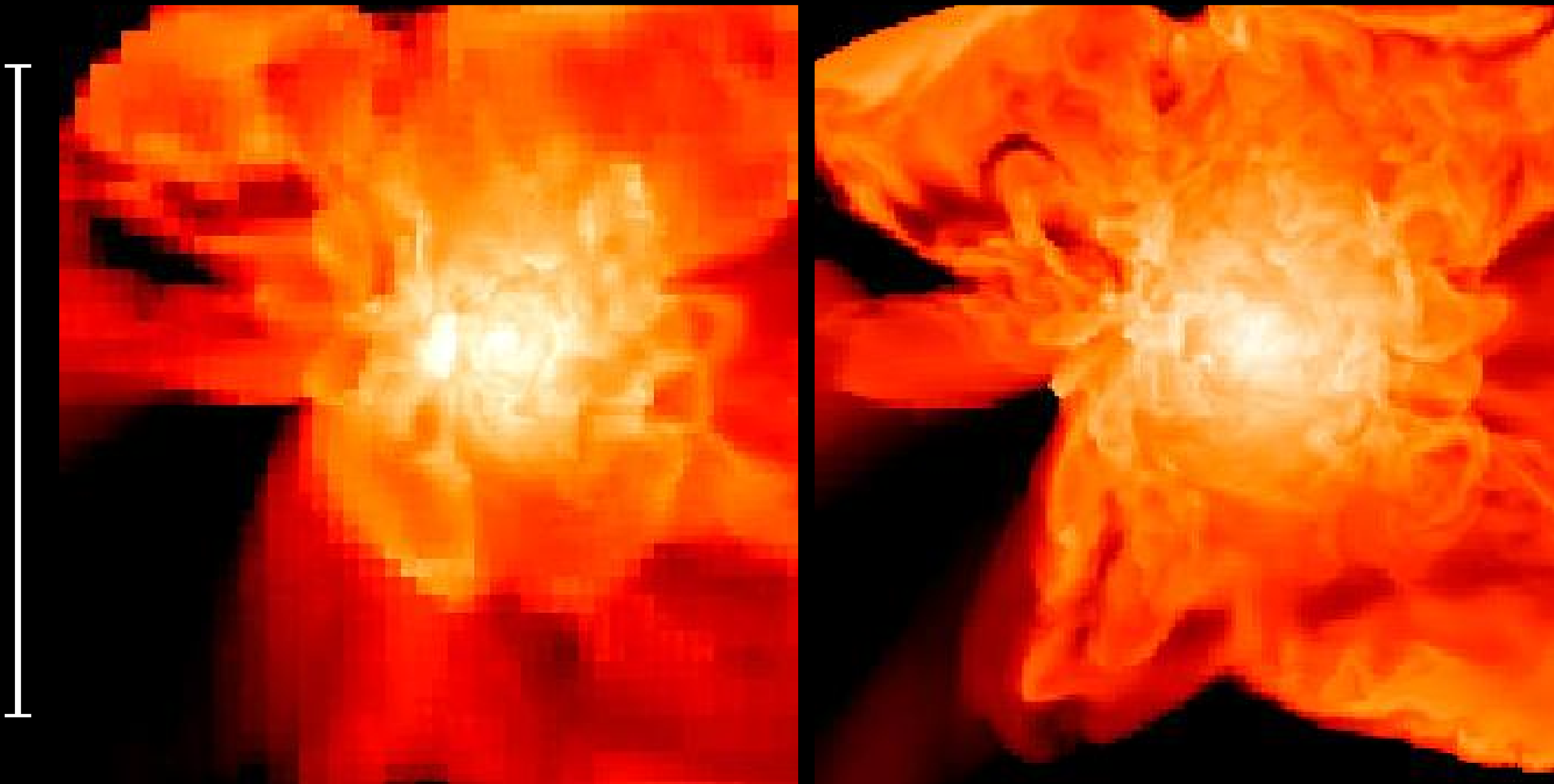


DM mass resolution $m_{dm} = 6.7 \cdot 10^8 M_o/h$

Peak resolution = 12kpc/h

WHAT IS THE BEST REFINEMENT FOR SHOCKS?

REFINEMENT ON GAS DENSITY + VELOCITY JUMPS

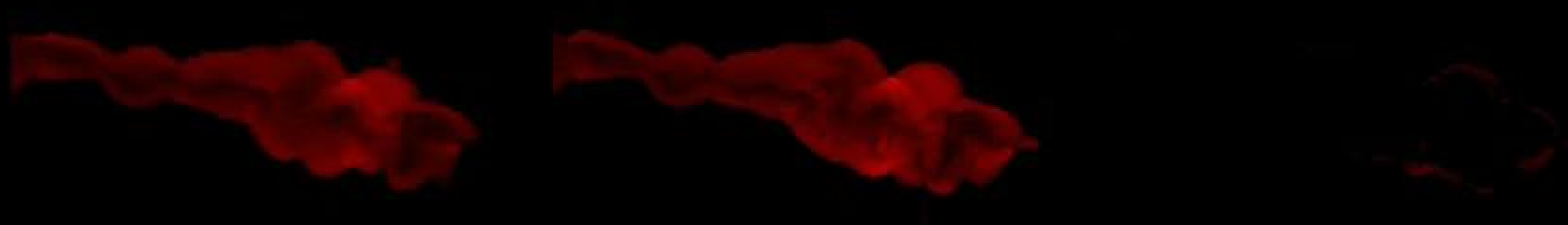


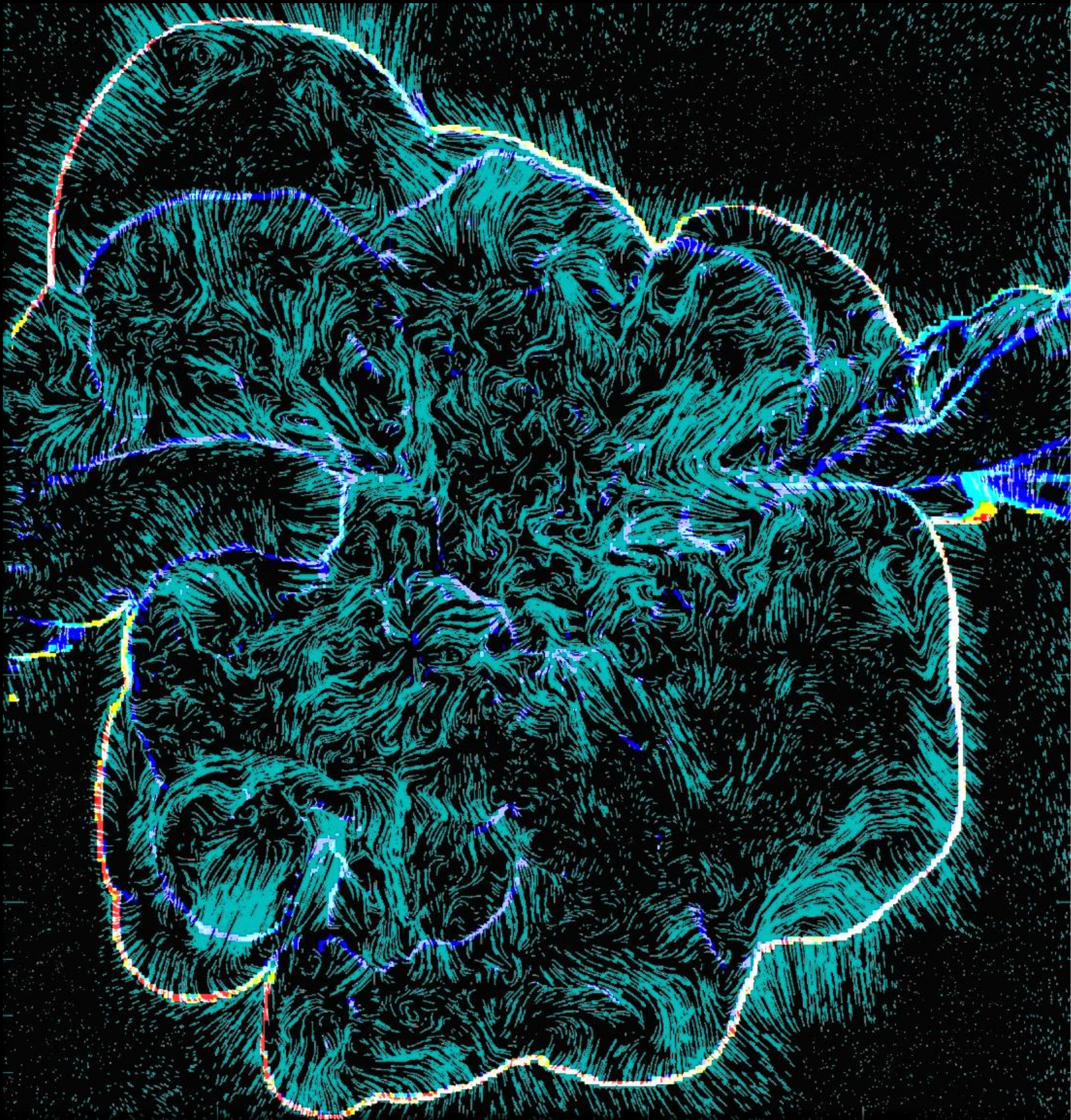
Shocks and gas/DM clumps are refined up to 12kpc/h even
When located at clusters outskirts

→ *Vazza, Brunetti, Kritsuk, Gheller, Wagner & Norman 2009*

“Dance” of a formig cluster (temperature)

“standard AMR” “new” AMR difference

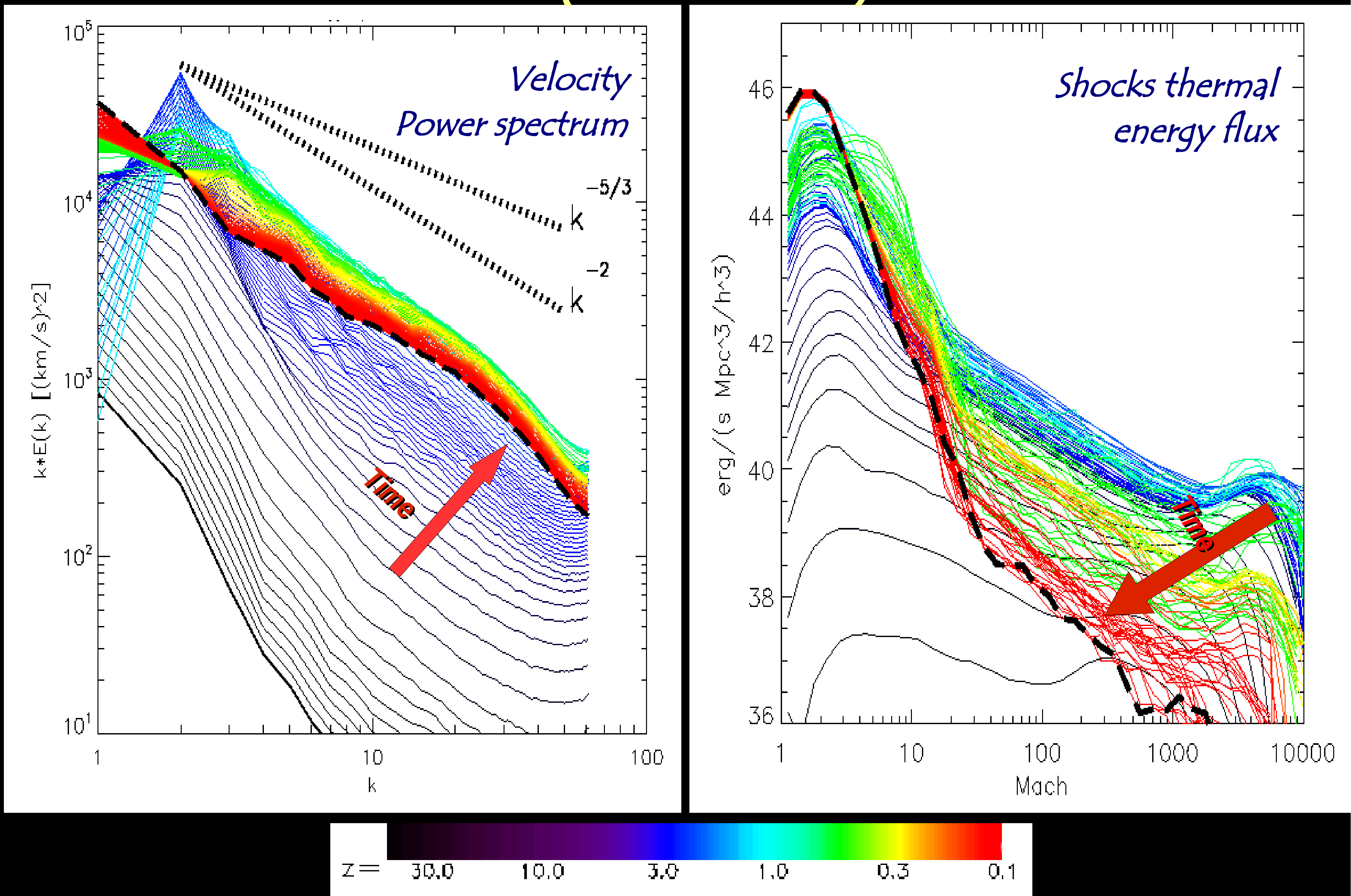




Streamlines:
turbulent velocity field

Colors:
shocks

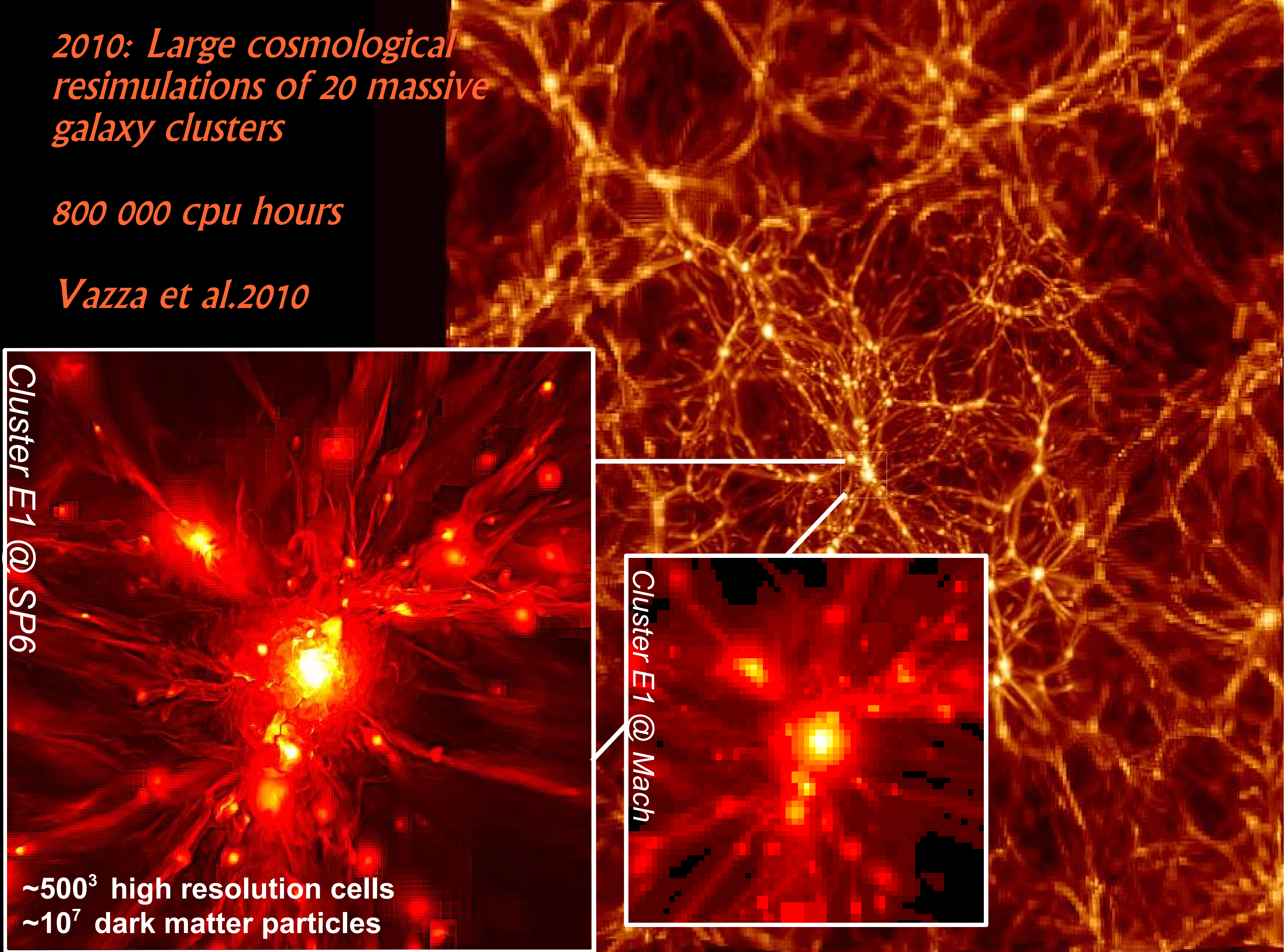
Example: The shock-turbulence connection (time evolution)



2010: Large cosmological resimulations of 20 massive galaxy clusters

800 000 cpu hours

Vazza et al.2010



The final sample:
20 clusters

<u>dynamical state:</u>
- *4 "relaxed"*
- *6 "merging"*
- *10 "post-merger"*

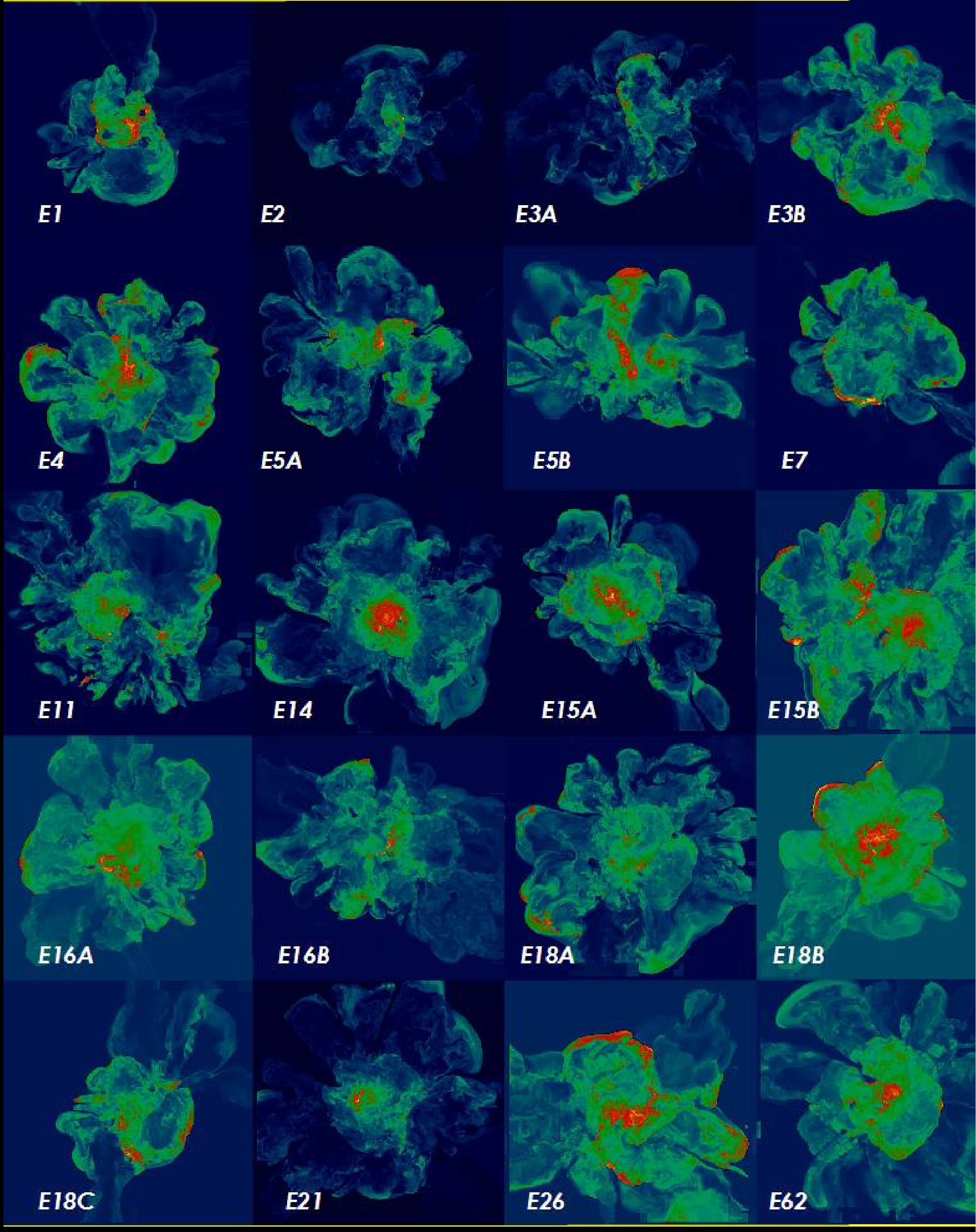
<u>masses:</u>
$7 \cdot 10^{14}\ M_{sol} < M < 3 \cdot 10^{15}\ M_{sol}$

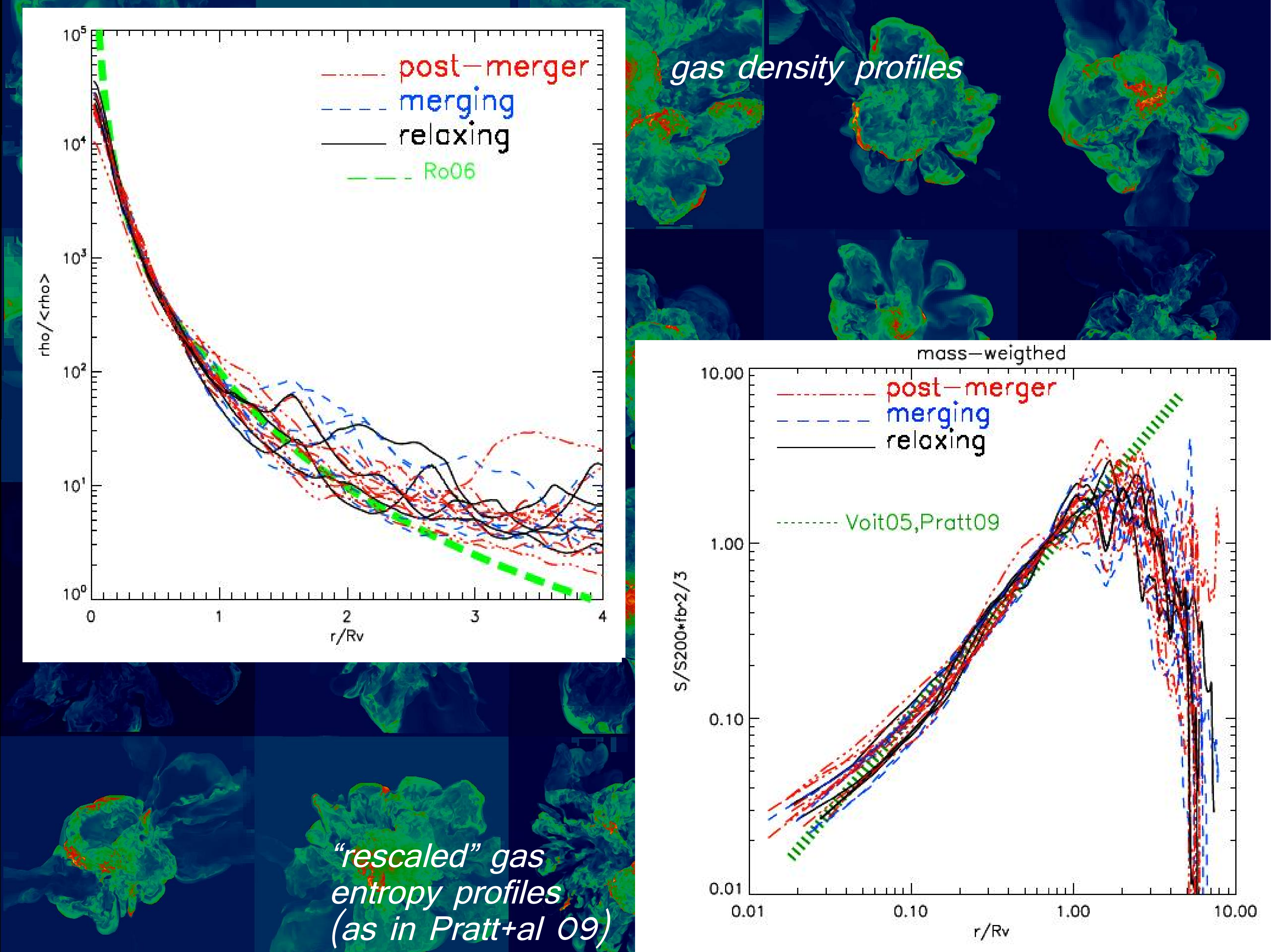
<u># of Dark M. particles</u>:
$N \sim 10^{6} - 10^{7}$

<u># of high resolution cells:</u>
$N_g \sim 550^3 \sim 10^8$

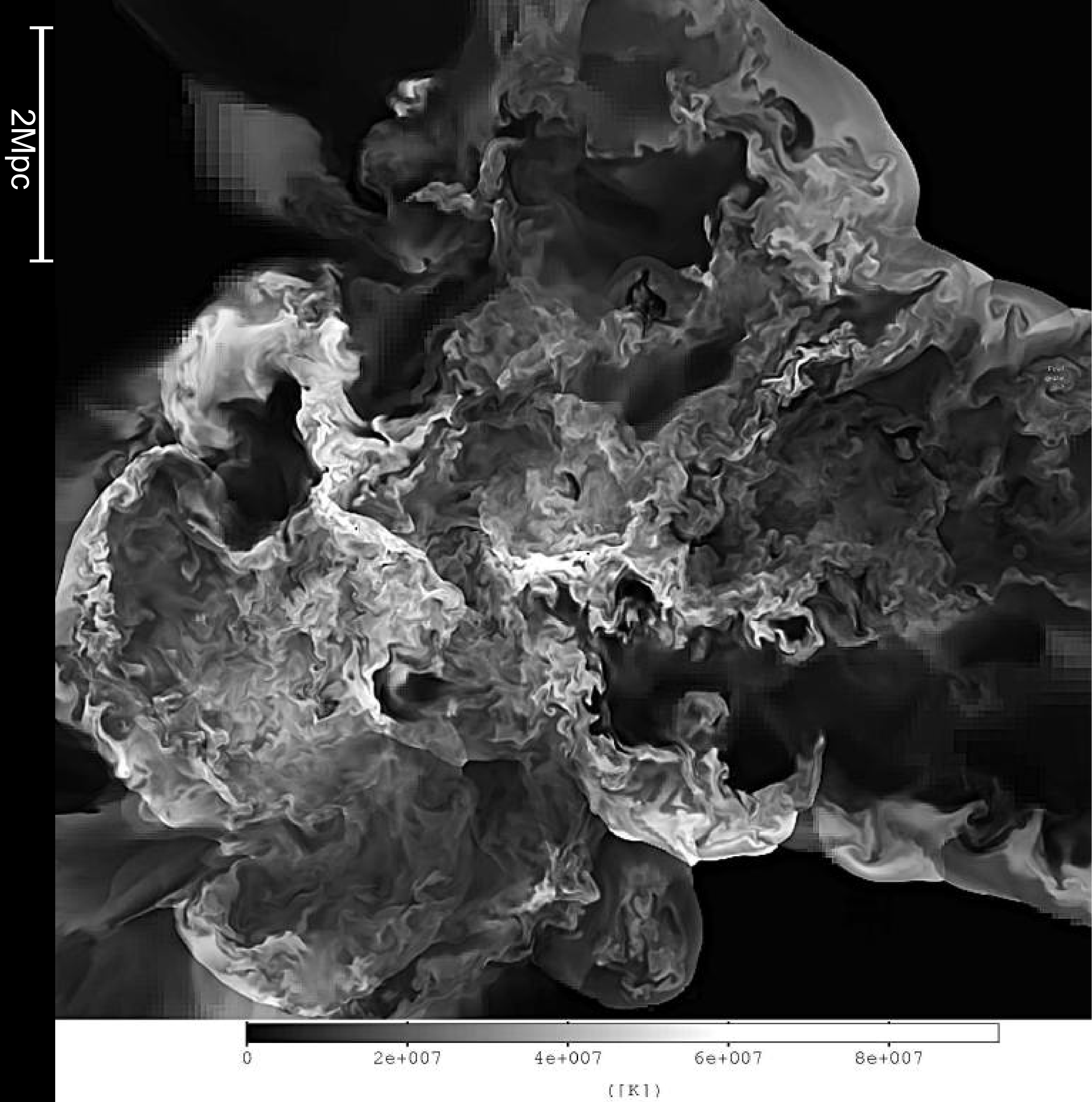
every run ~ 30 000 hours

http://data.cineca.it/




gas density profiles
post−merger
merging
relaxing
Ro06
rho/<rho>
r/Rv
mass−weigthed
post−merger
merging
relaxing
Voit05,Pratt09
S/S200*fb^2/3
r/Rv
"rescaled" gas
entropy profiles
(as in Pratt+al 09)

How they look like.....

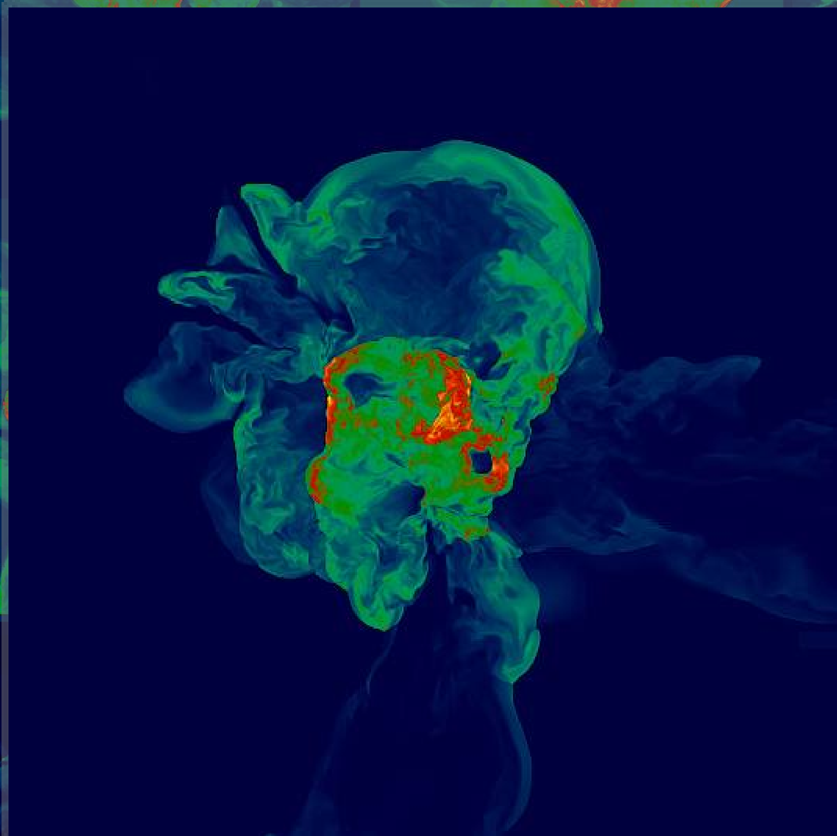


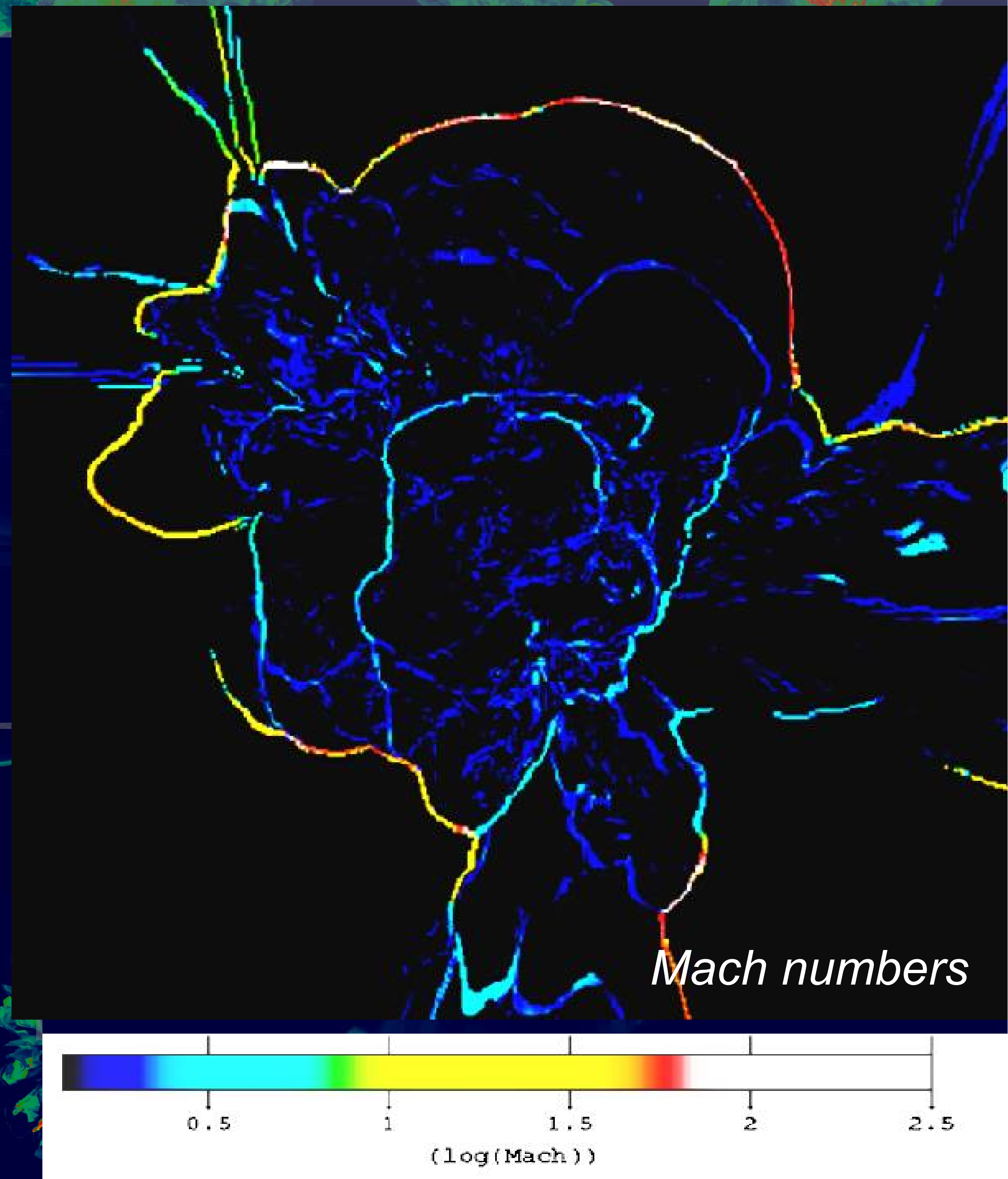
A cluster merger at z=0.6

(N ~ 550^3 grid points)

Trip to E1

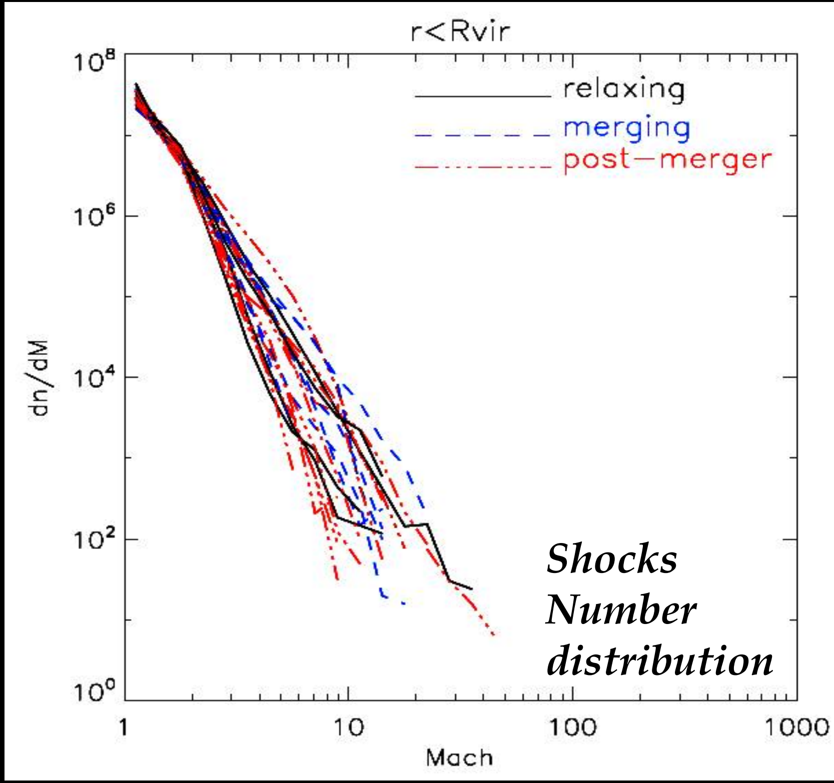
SHOCKS → unprecedented statistics and spatial detail at the same time

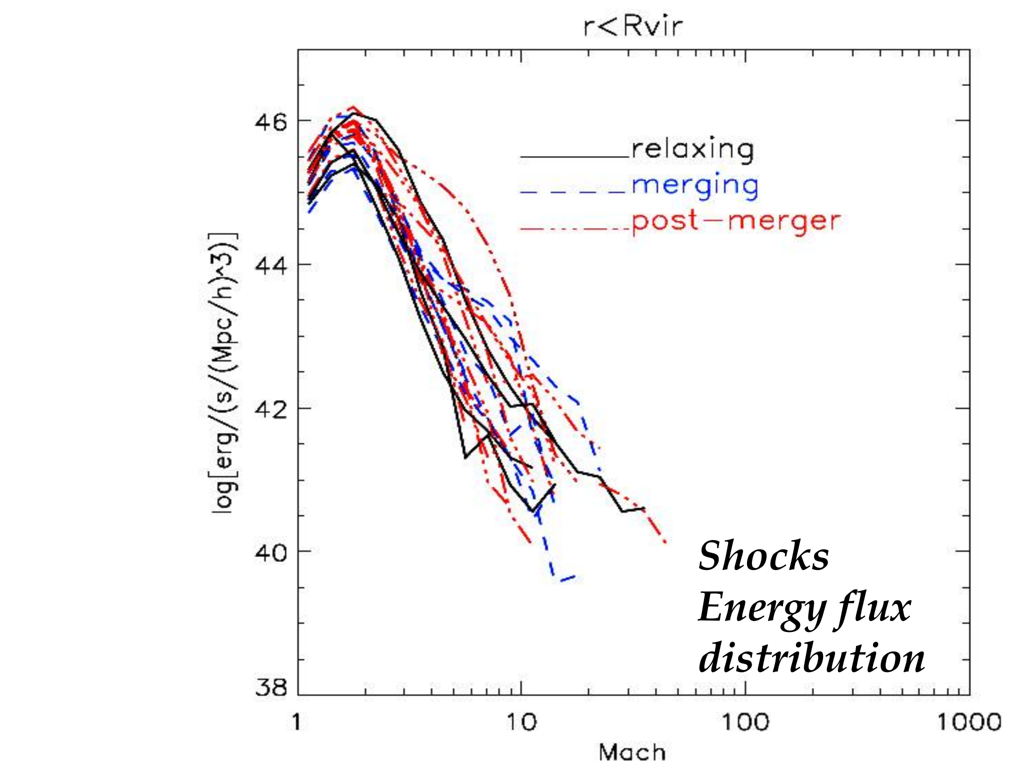




$$\Delta v = \frac{3}{4} v_s \frac{1 - M^2}{M^2}$$

(see Vazza, Brunetti & Gheller 2009 MNRAS)



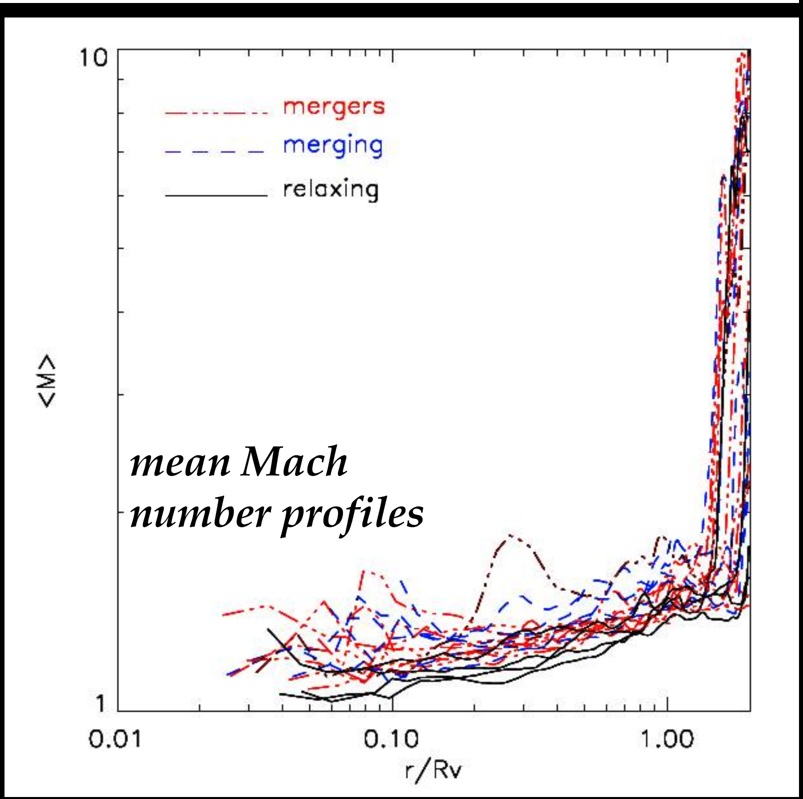


- >90% of shocks in clusters is weak ($\mathcal{M}$<2)

- Peak of energy dissipation at $\mathcal{M}$~2

- Very steep injection spectra of Cosmic Rays ***$N(p) \sim p^{-\delta}$ $\delta > 3$***

(cfr. with Ryu, Pfrommer ...)



Simulated Radio Relics from ENZO clusters
(Vazza, Brunetti, Bonafede, Bruggen et al., in prep.)

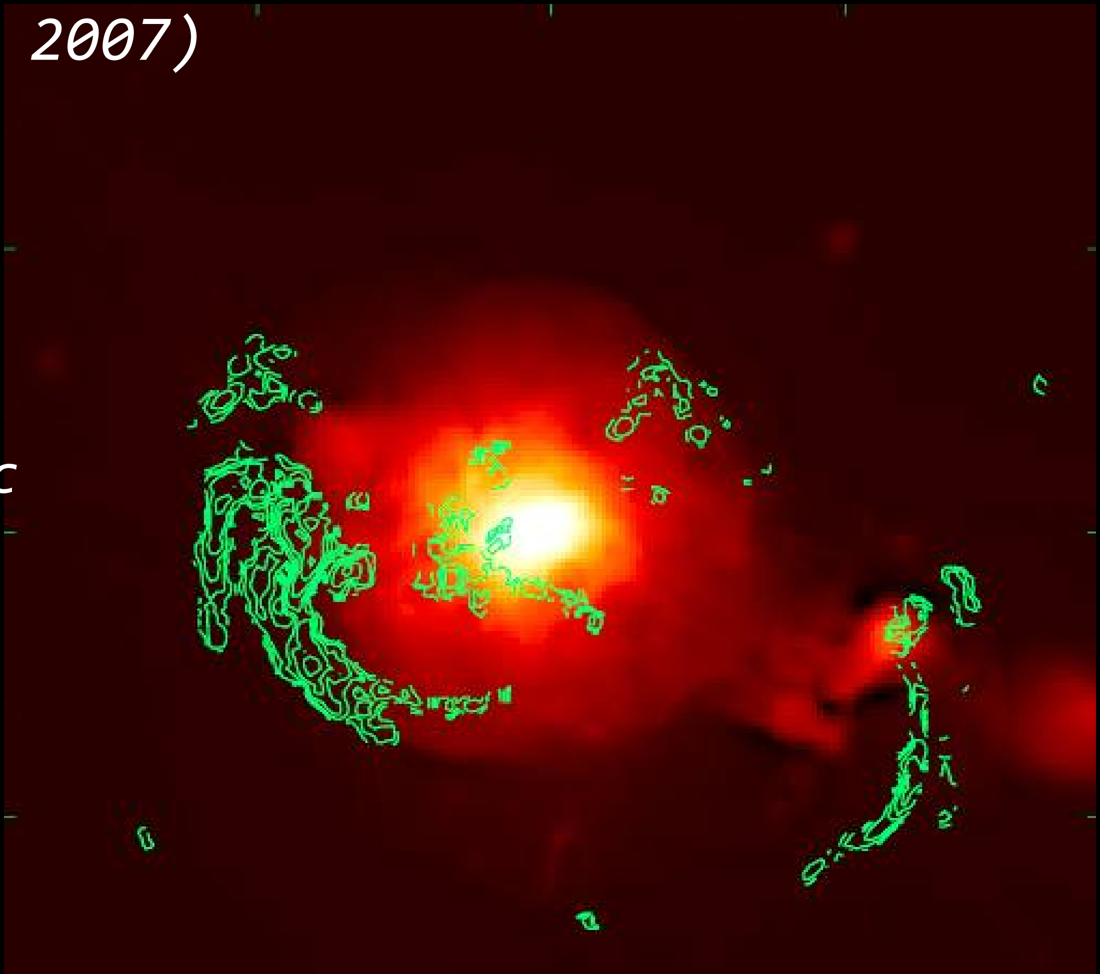
- *Estimated Cosmic Rays injection from Diffusive Shock Acceleration theory (as in Kang & Jones 2002, 2007)*

- *Extension of syncrothron emission model from <u>Hoeft & Bruggen 2007</u>*

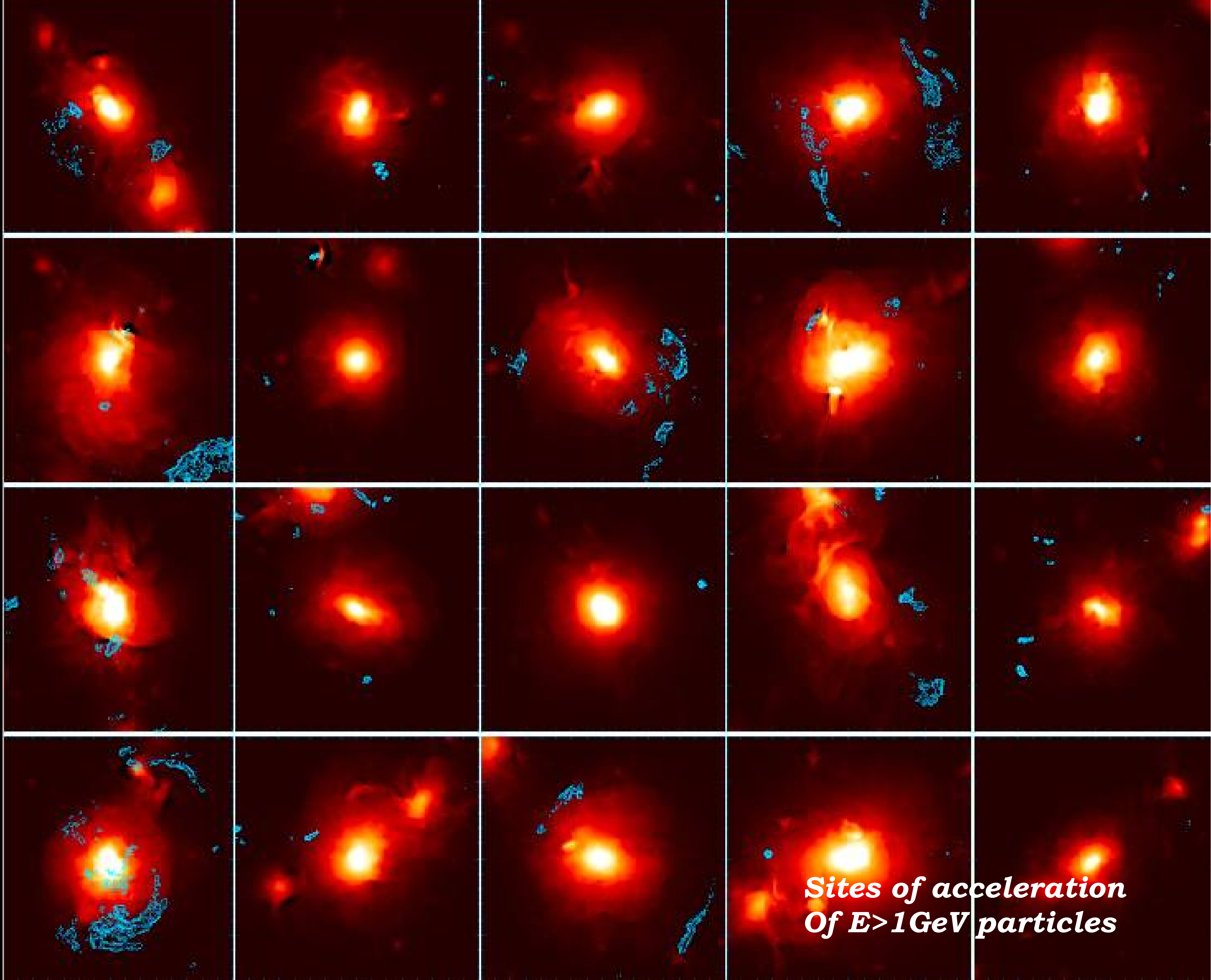
- *Various (passive) magnetic field models*

- $\xi_p^e = 0.01$

- *convolution for VLA (D-array) senstivities & resolution*

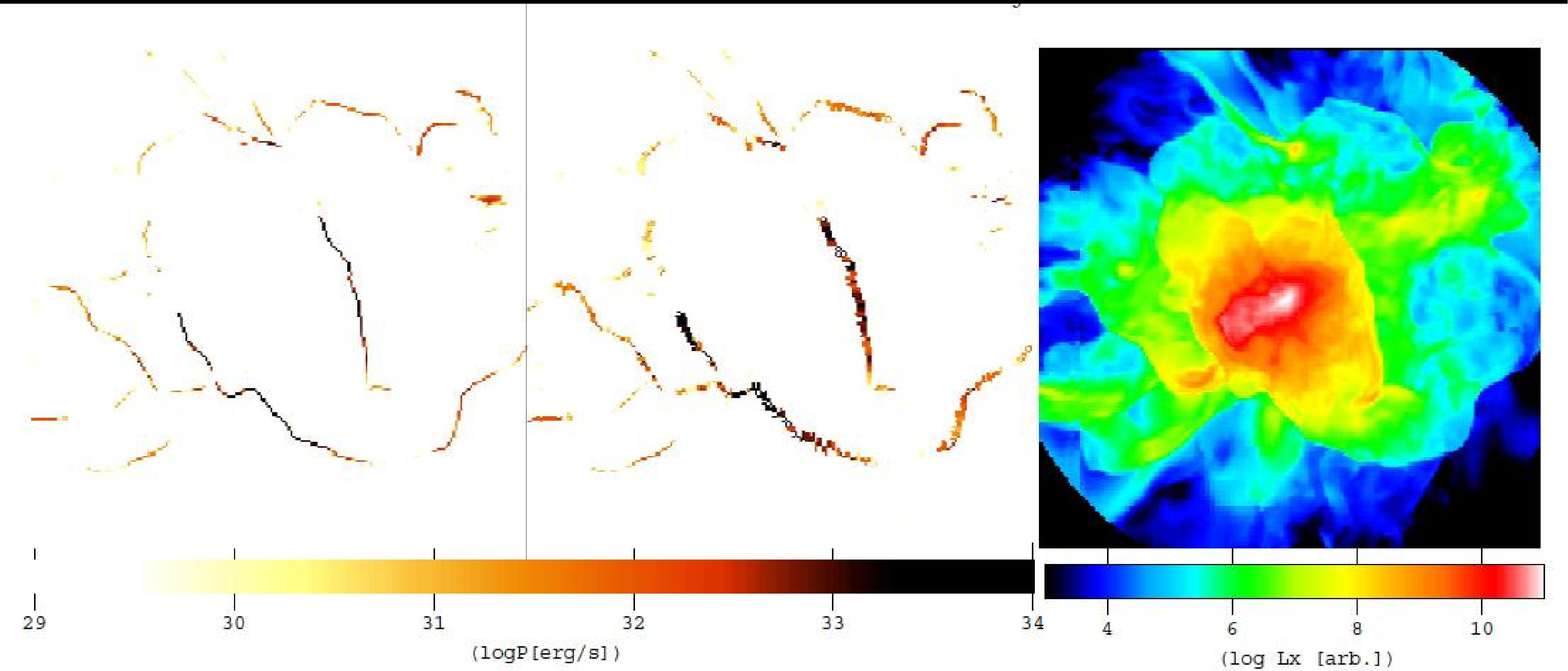


"sites" of particle acceleration for E>1GeV


Sites of acceleration
Of E>1GeV particles

Radio emission from a thin layer = 25kpc

No broadening — *with broadening* — *X-ray luminosity*

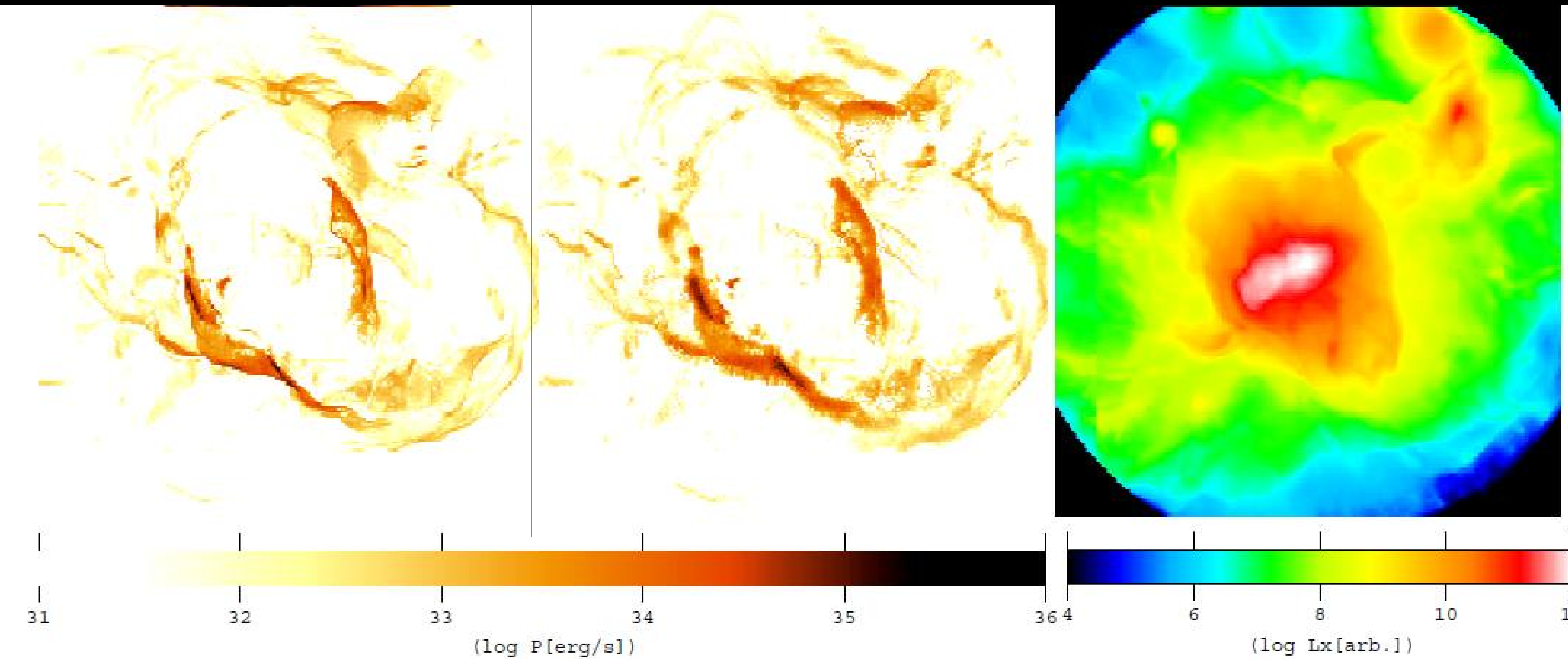


Size of the downstream emitting region (e.g. Hoeft & Bruggen 07)

$$y_c = 135kpc \cdot \frac{V_{dw}}{100km/s} \cdot \frac{B_{\mu G}^{1/2}}{B_{\mu G}^2 + B_{CMB}^2} \cdot \left(\frac{\nu_{obs}}{1.4Ghz}\right)^{-1/2},$$

Radio emission from the whole cluster = 8Mpc

No broadening *with broadening* *X-ray luminosity*



$$y_c = 135kpc \cdot \frac{V_{dw}}{100km/s} \cdot \frac{B_{\mu G}^{1/2}}{B_{\mu G}^2 + B_{CMB}^2} \cdot \left(\frac{\nu_{obs}}{1.4Ghz}\right)^{-1/2},$$

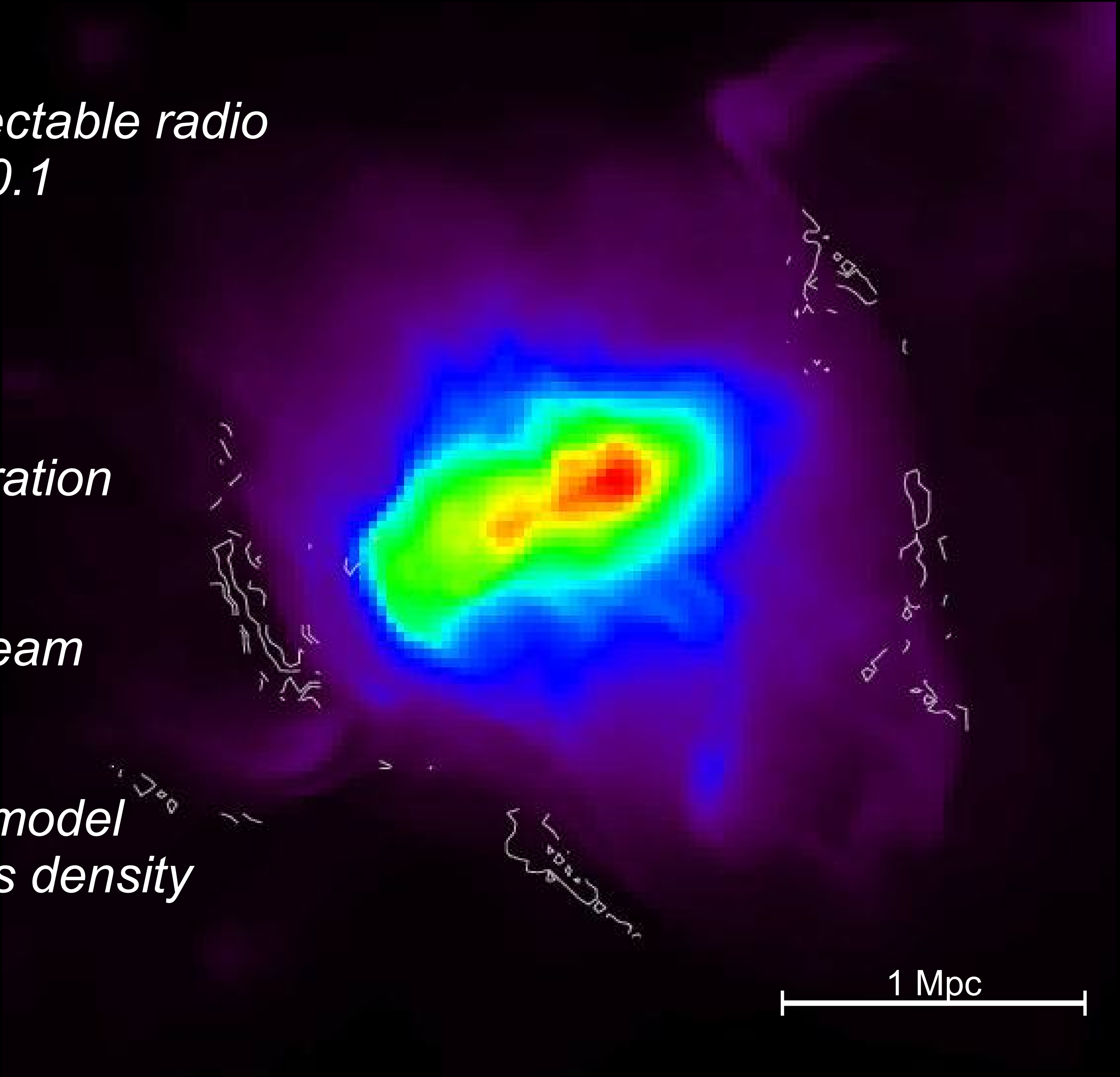
Potentially detectable radio emission at z=0.1

ν_{obs} =1.4GHz

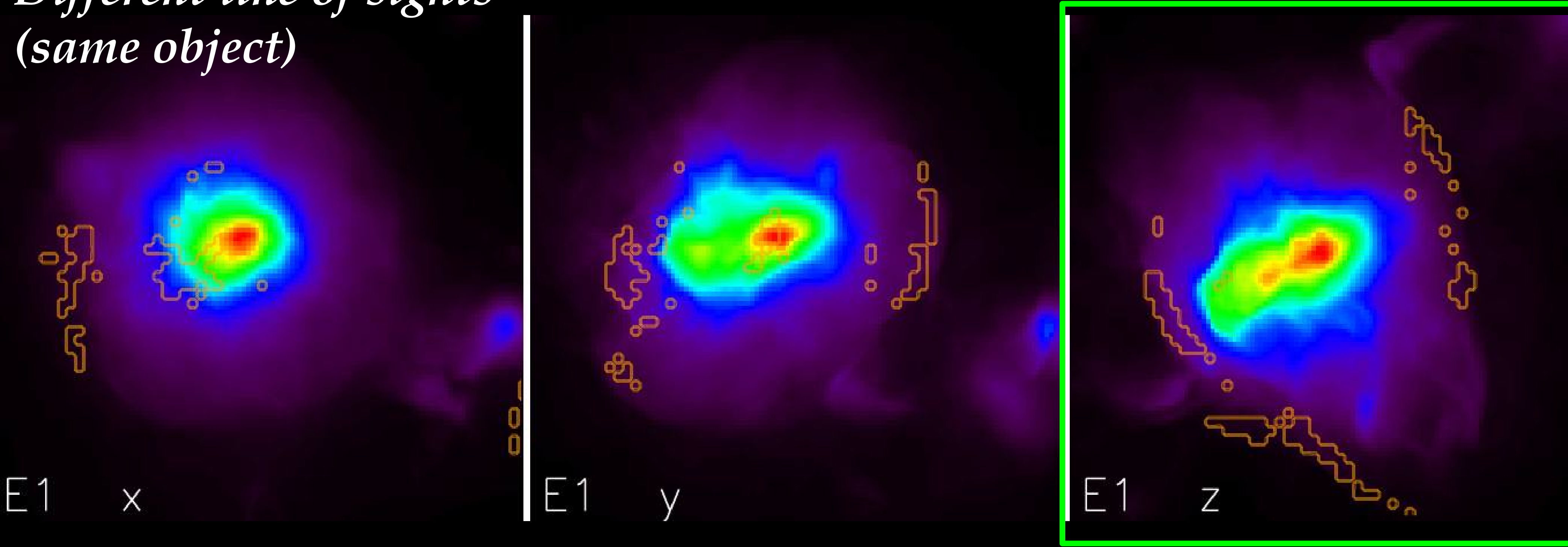
VLA D-configuration

>3σ = 90μJ / beam

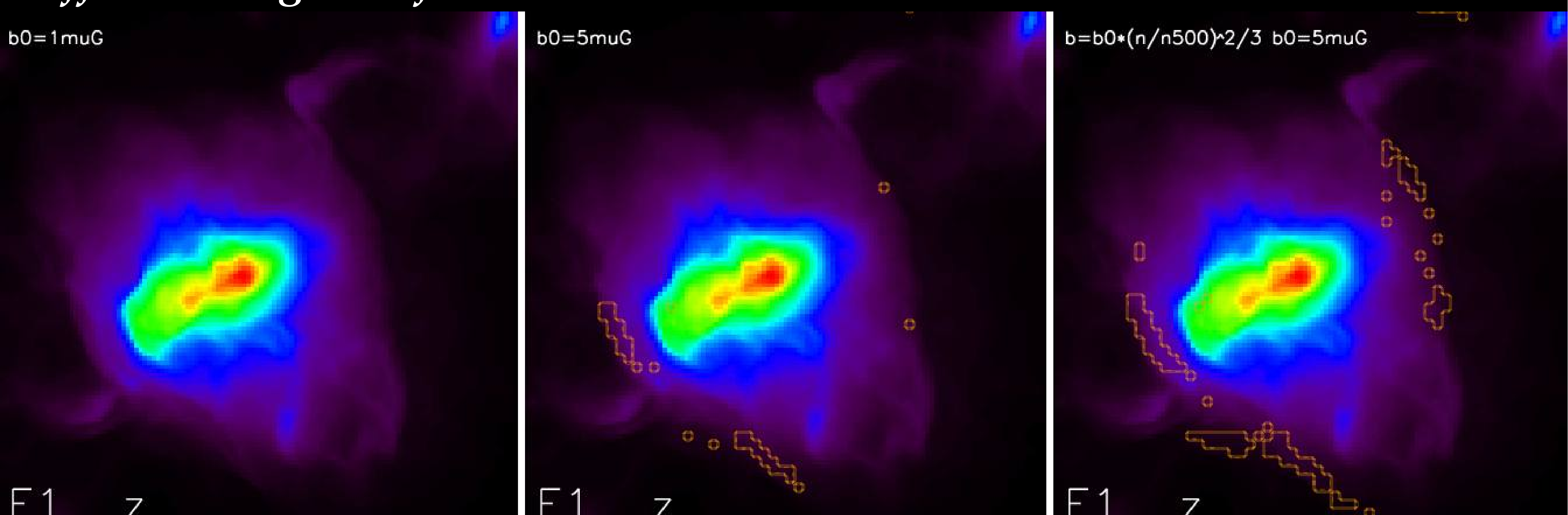
Magnetic field model scaling with gas density

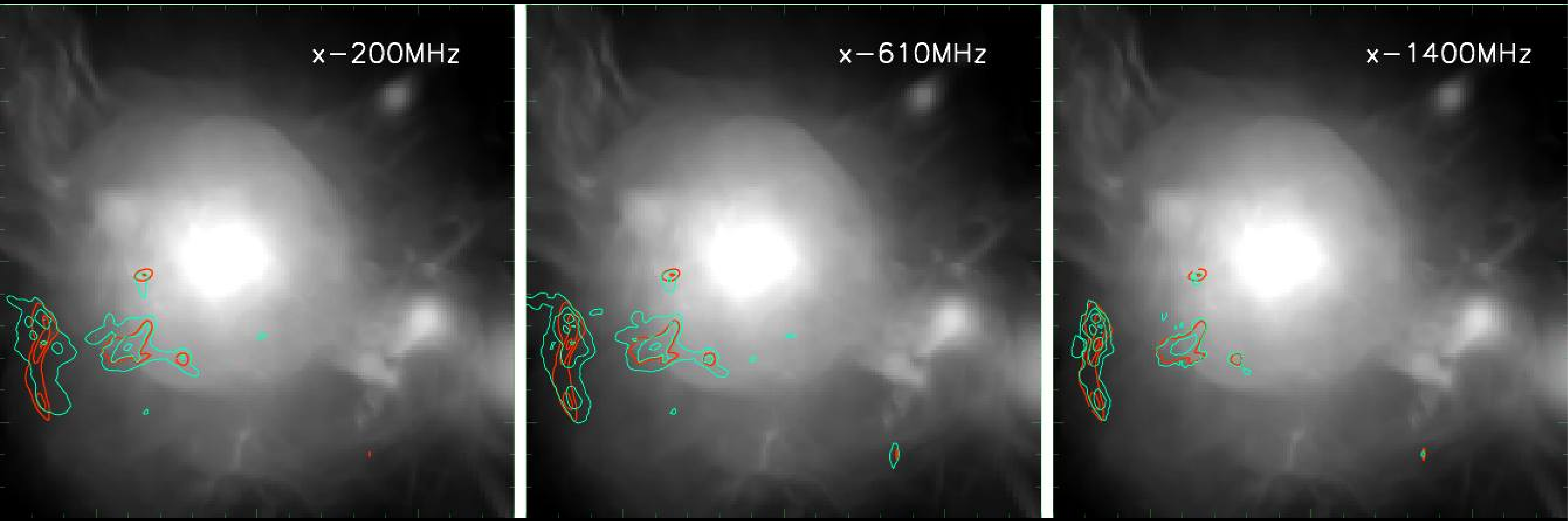


Different line of sights (same object)

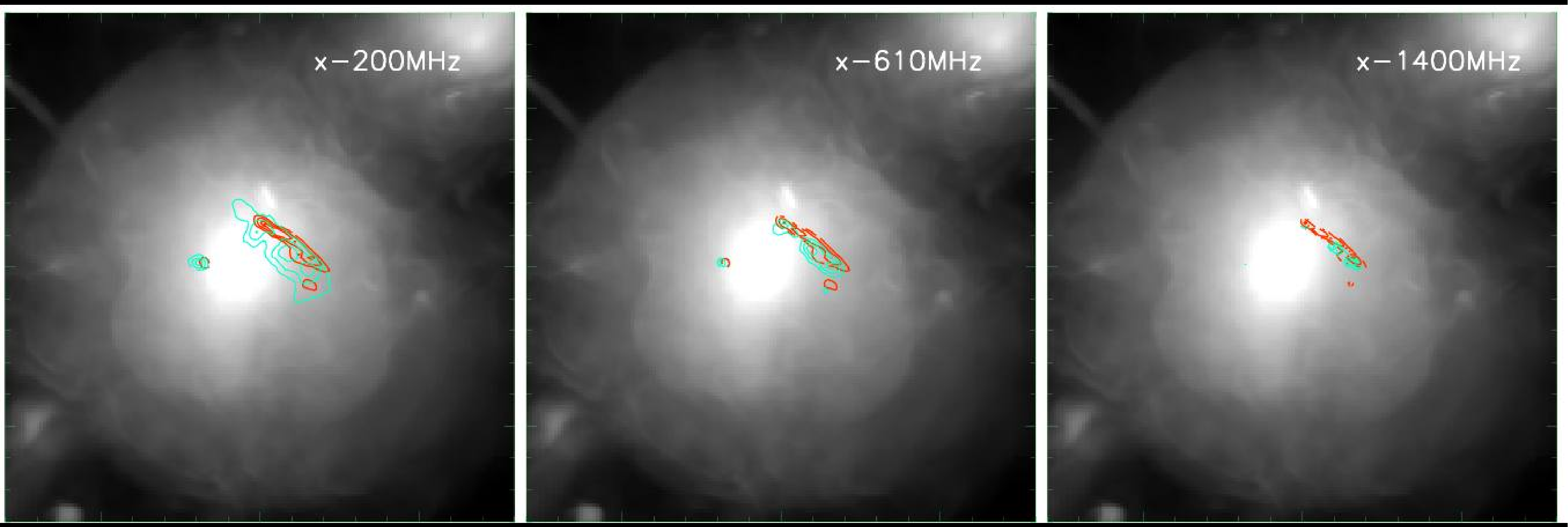


Different magnetic fields





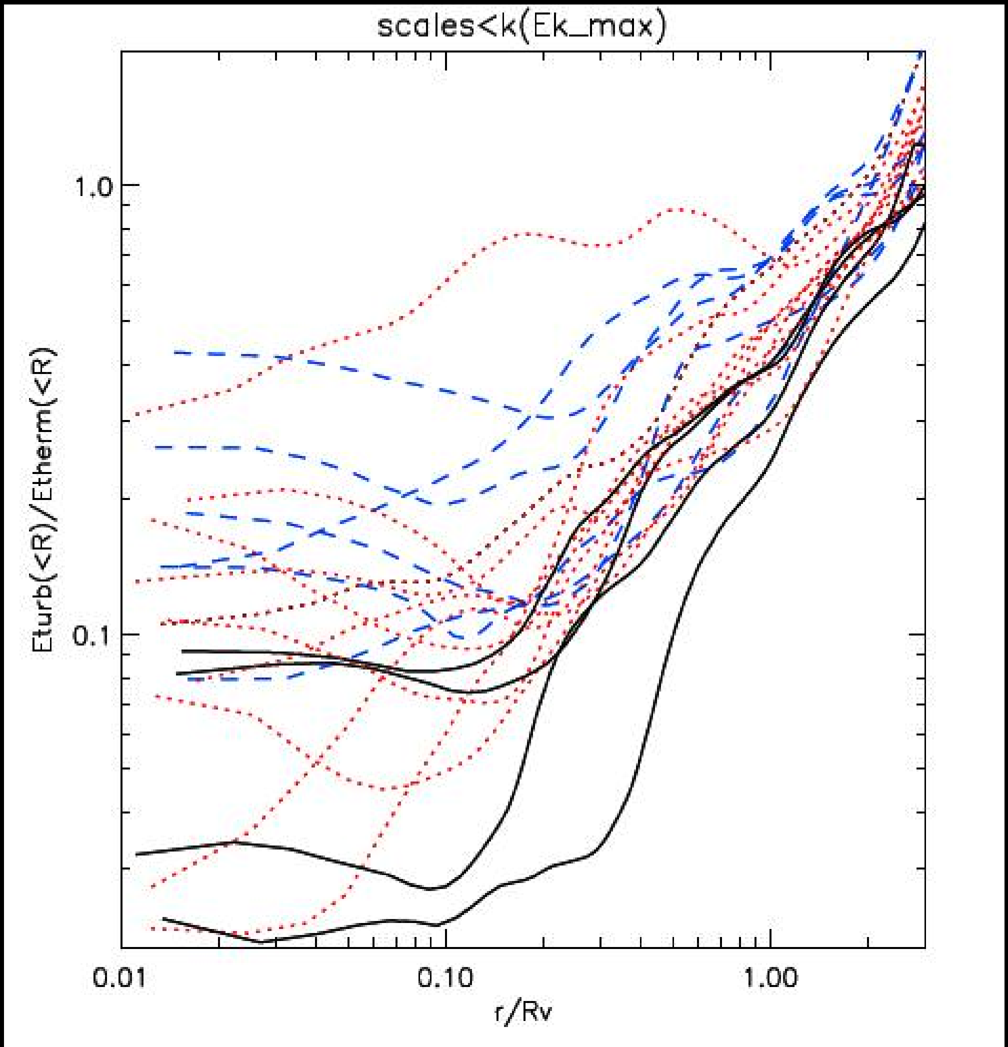
The broadening of the emission region is important at lower frequencies



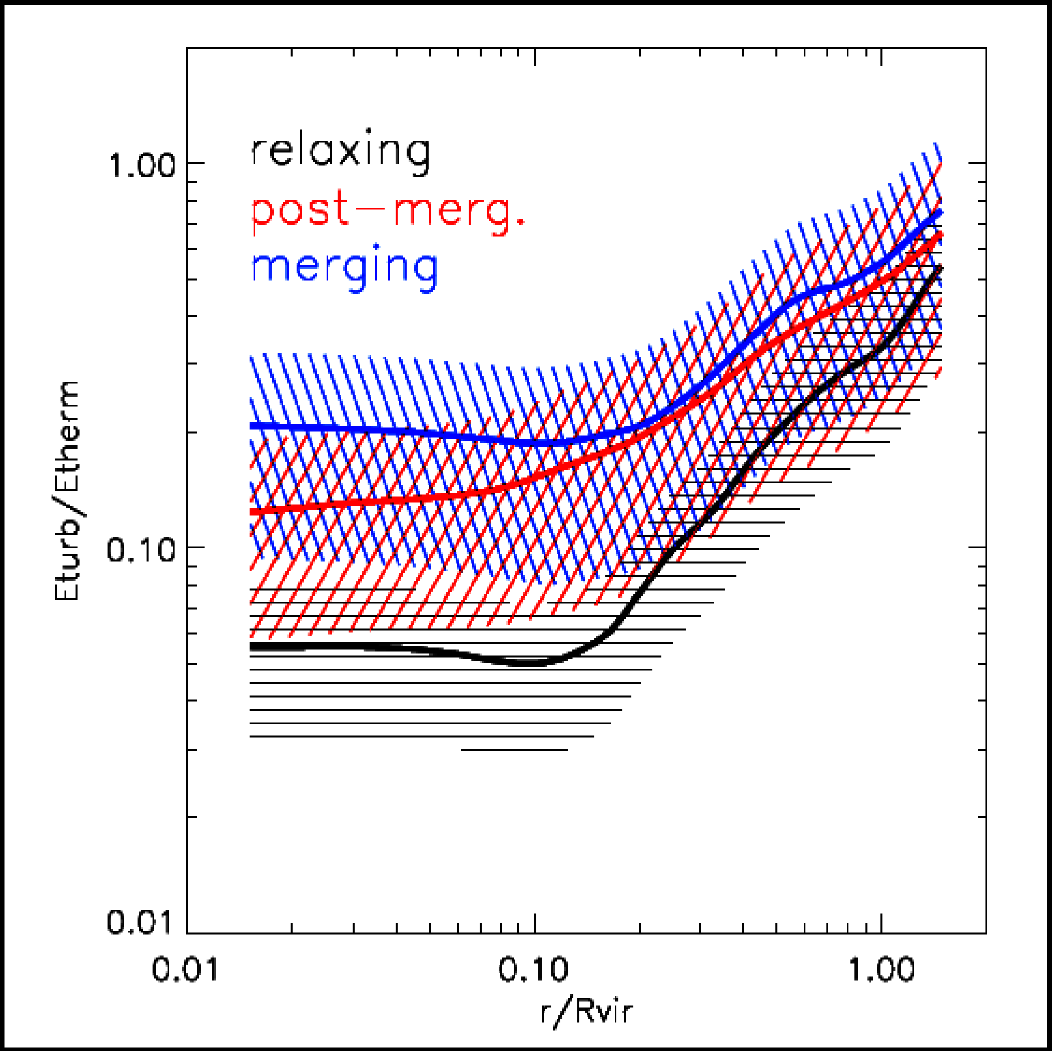
TURBULENCE → unprecedented statistics and large scale separation

Vazza, Brunetti, Gheller, Brunino & Bruggen to be submitted

Average profiles for the ratio between turbulent and thermal energy (turbulence = velocity struct. < 300kpc)

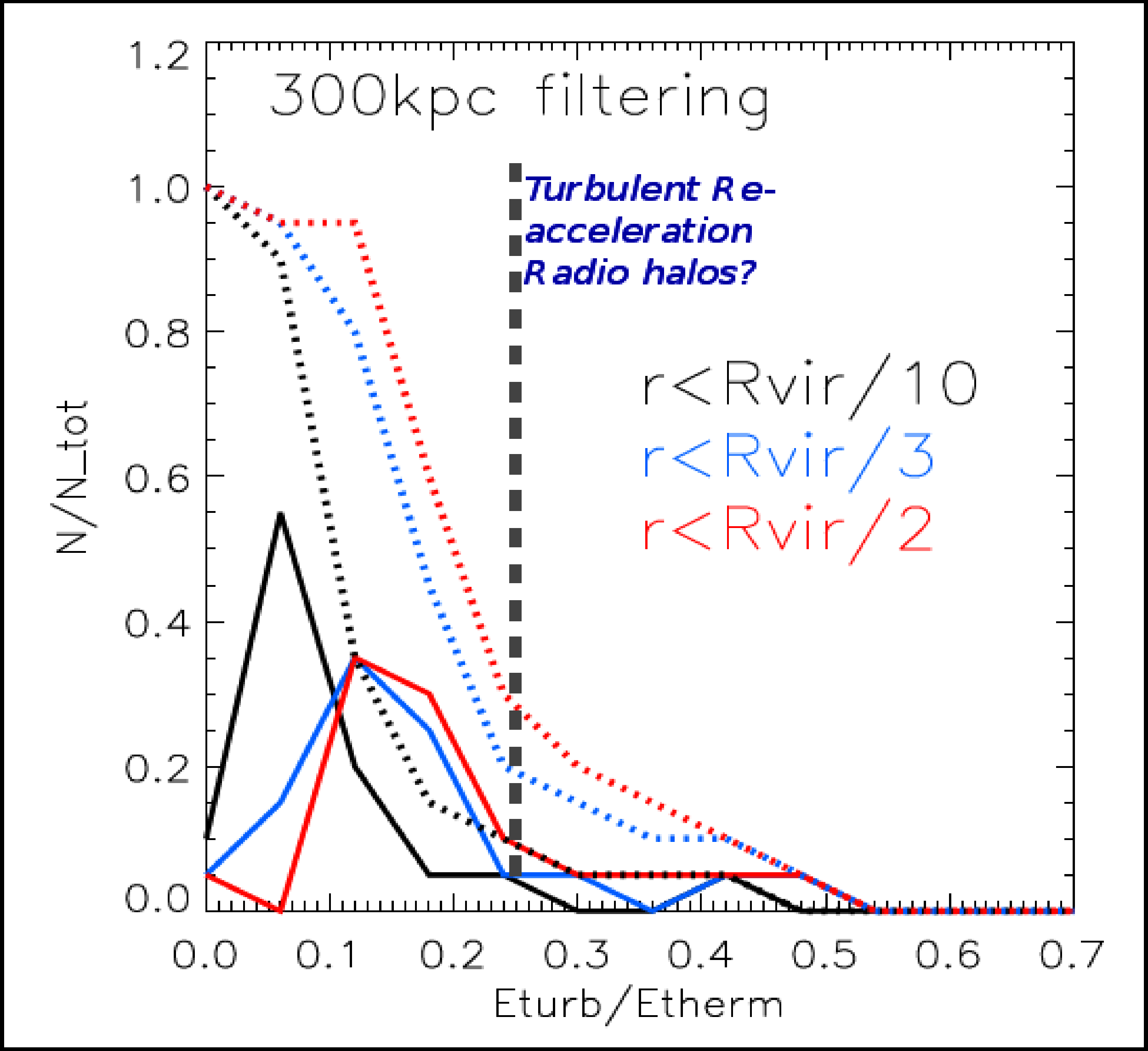


Individual profiles



Average profiles

How many clusters contain enough turbulence to power ~Mpc Radio Halos ?

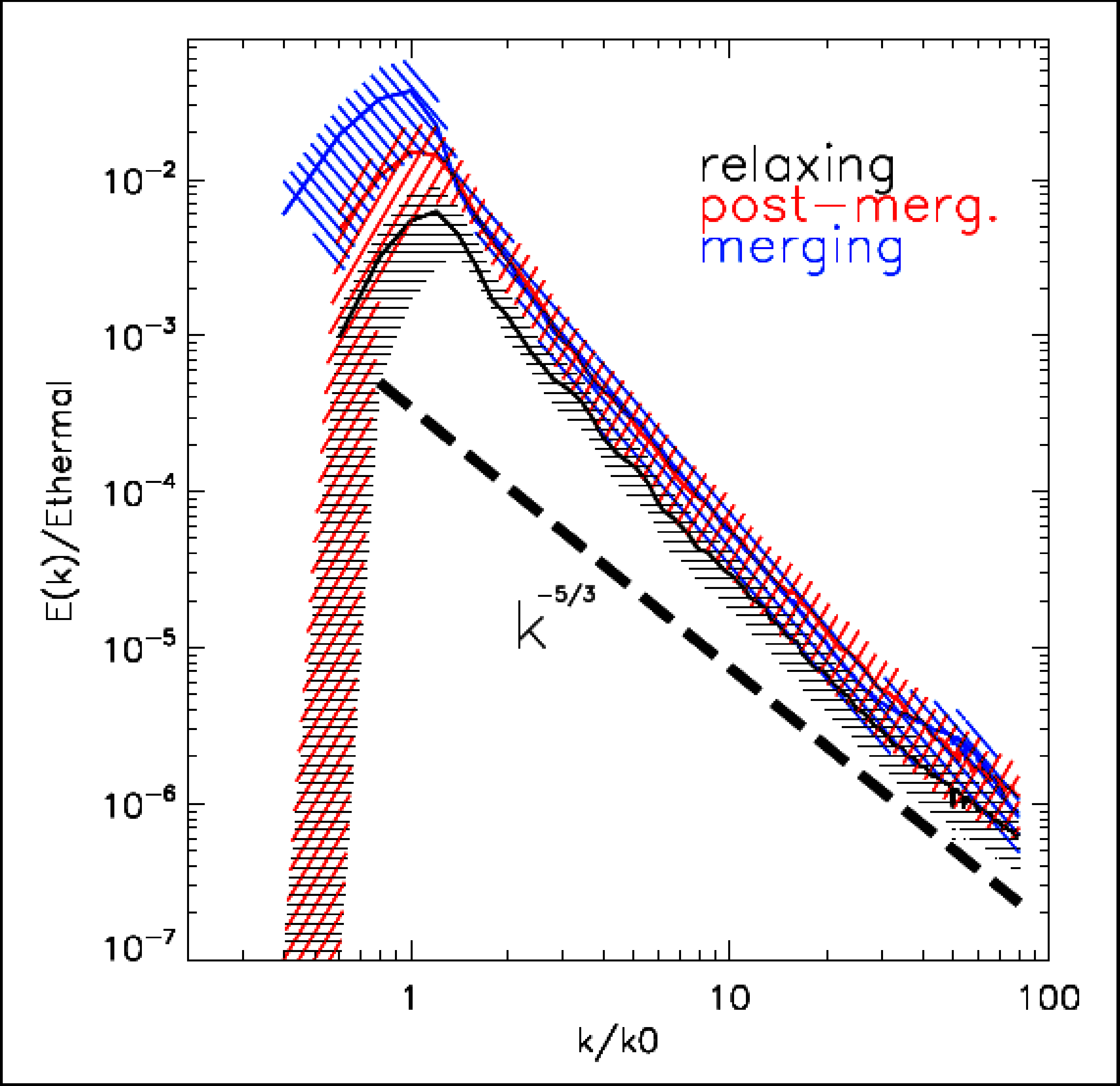


20-30% of clusters have an innermost turbulent region with E_turb > 0.25 E_therm

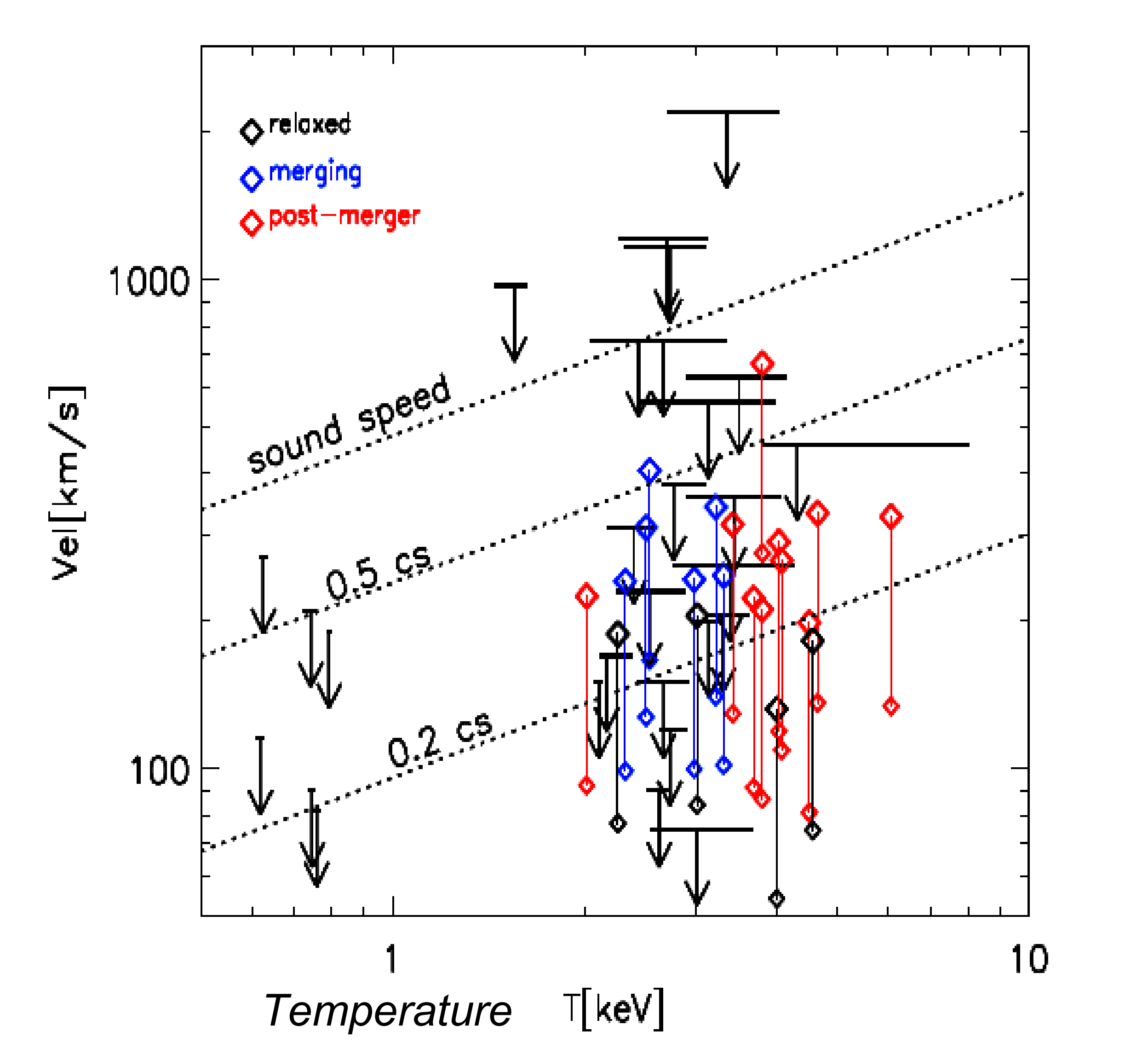
Average power spectra for the 3D velocity field

Other proxies of turbulence:

- *Structure functions*
- *Pair dispersion statistics (tracers)*
- *Iron Line broadening*



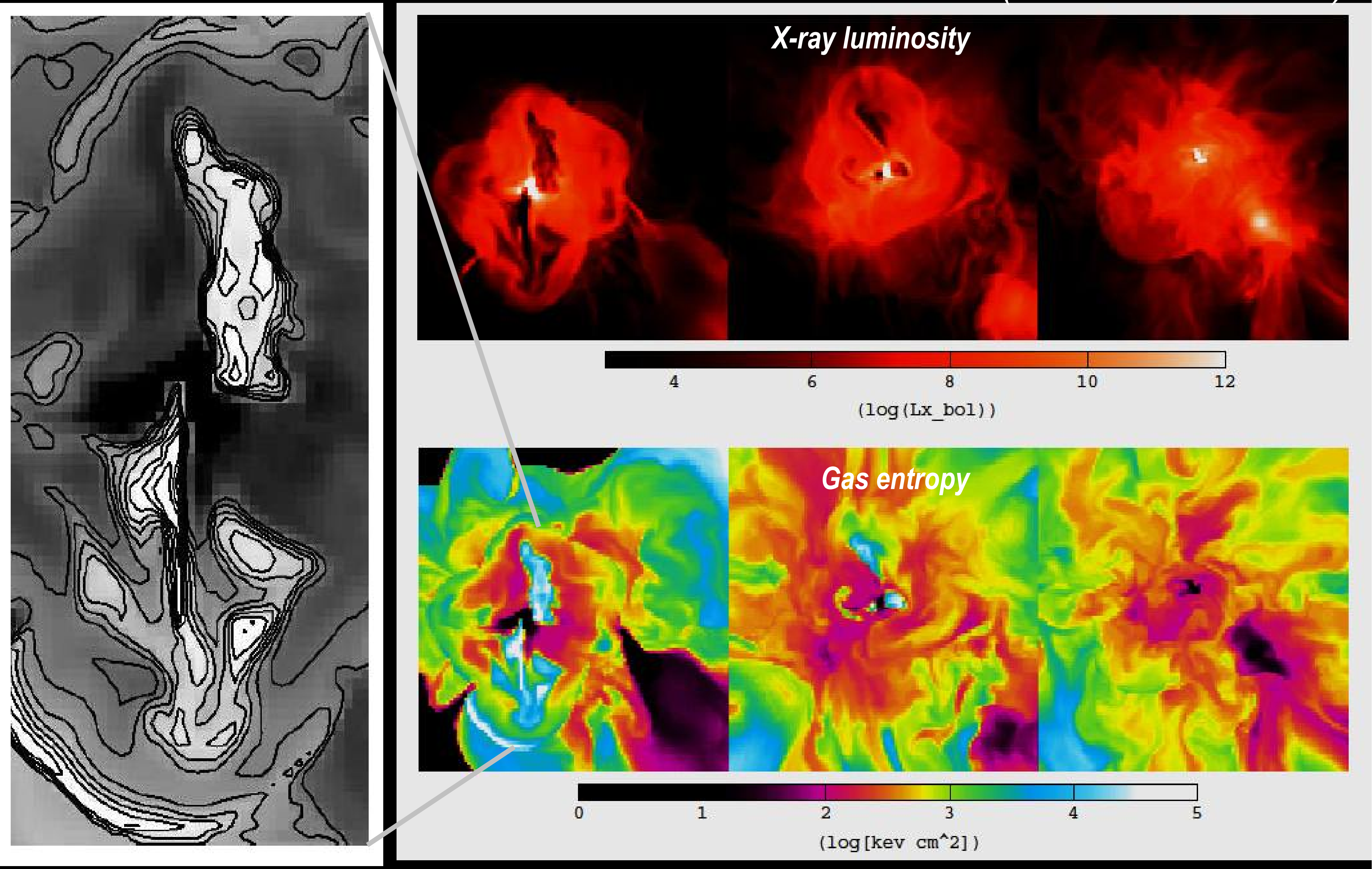
How do simulated turbulent fields compare with real cluster observations?



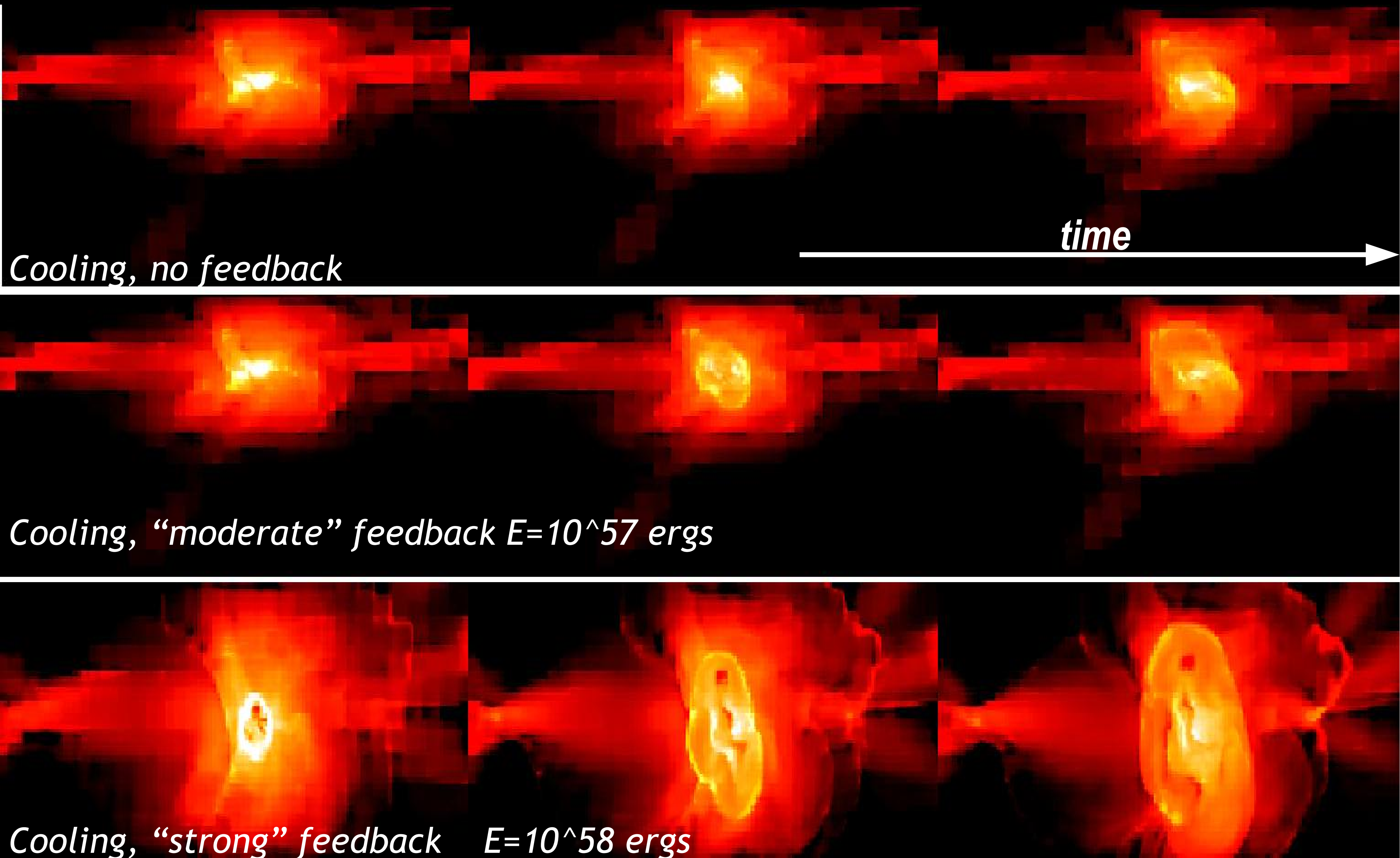
Upper limits: real XMM-Newton data from Sanders et al.2010 (note: FOV < 100kpc)

A numerical study of the entropy floor on cluster simulations, + first cosmological "experiments" with AGN feedback in ENZO simulations

(Vazza 2010 MNRAS)



Major merger + thermal feedback from AGN jets
...how much is needed to quench cooling?



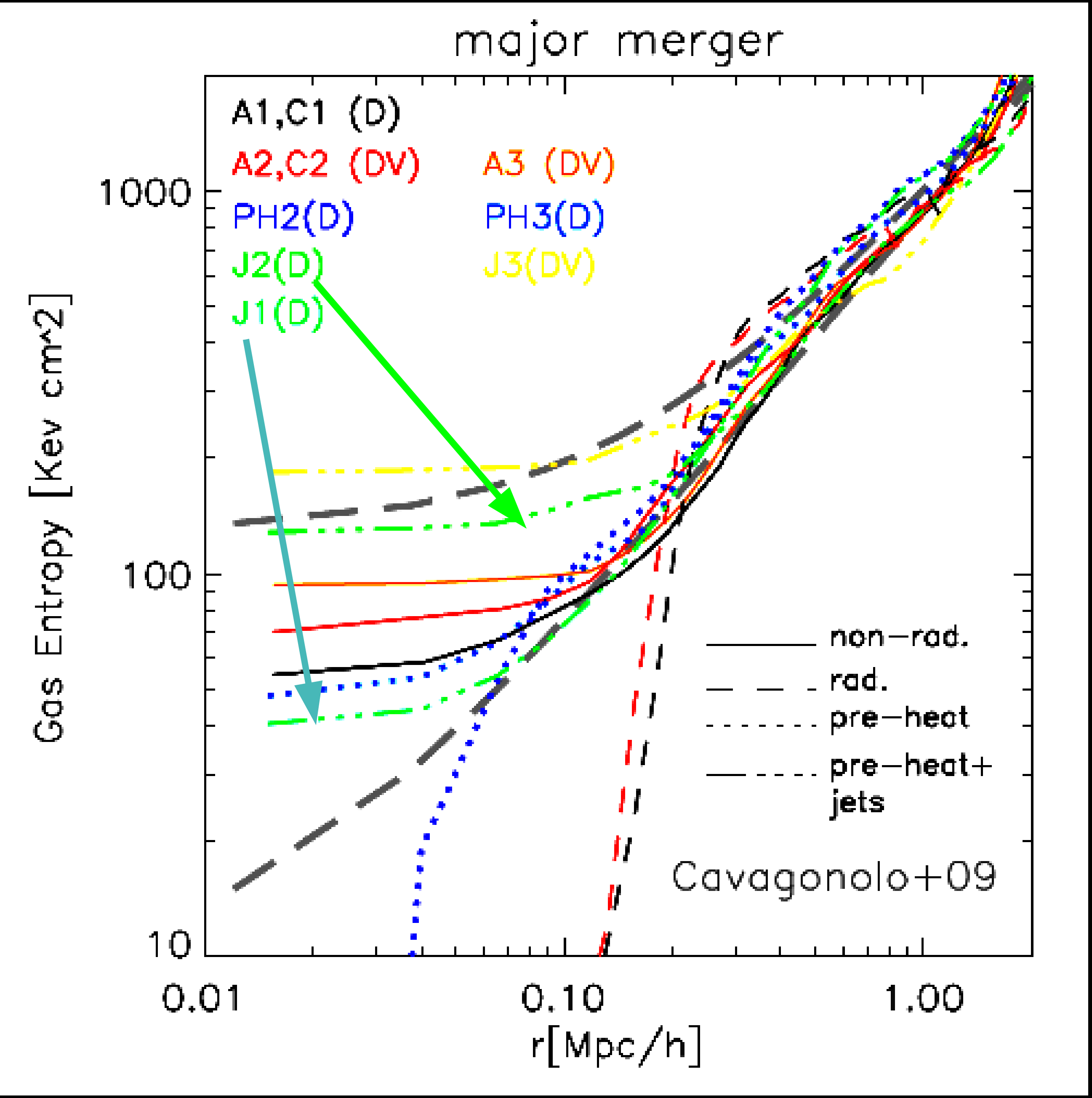
Energetically feasible, it can restore the entropy floor seen by CHANDRA.

<u>However</u>

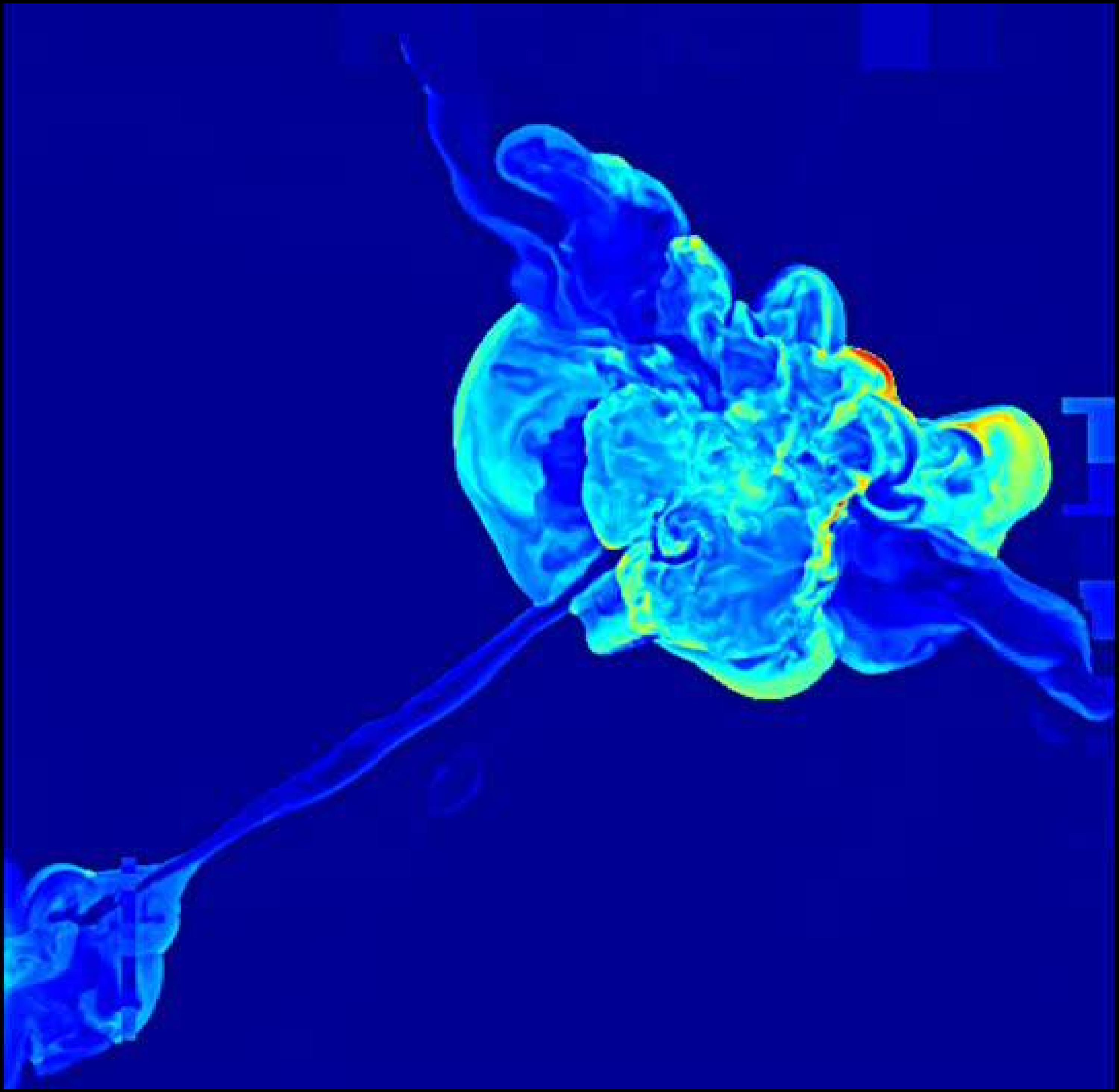
→ need of having self-consistent energy budget

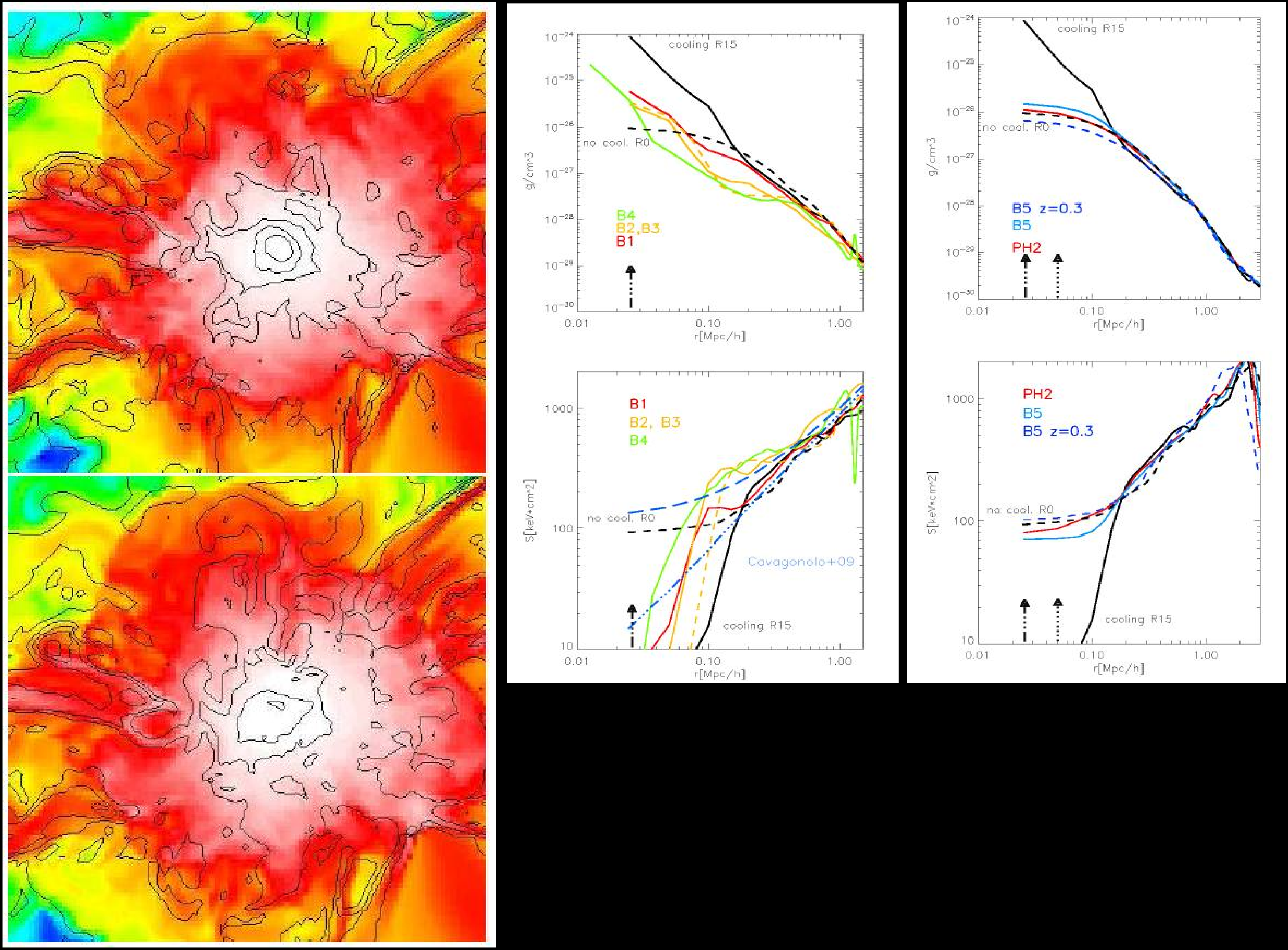
→ go to -10-100 higher resolutions to model jet-launching

...new simulations!

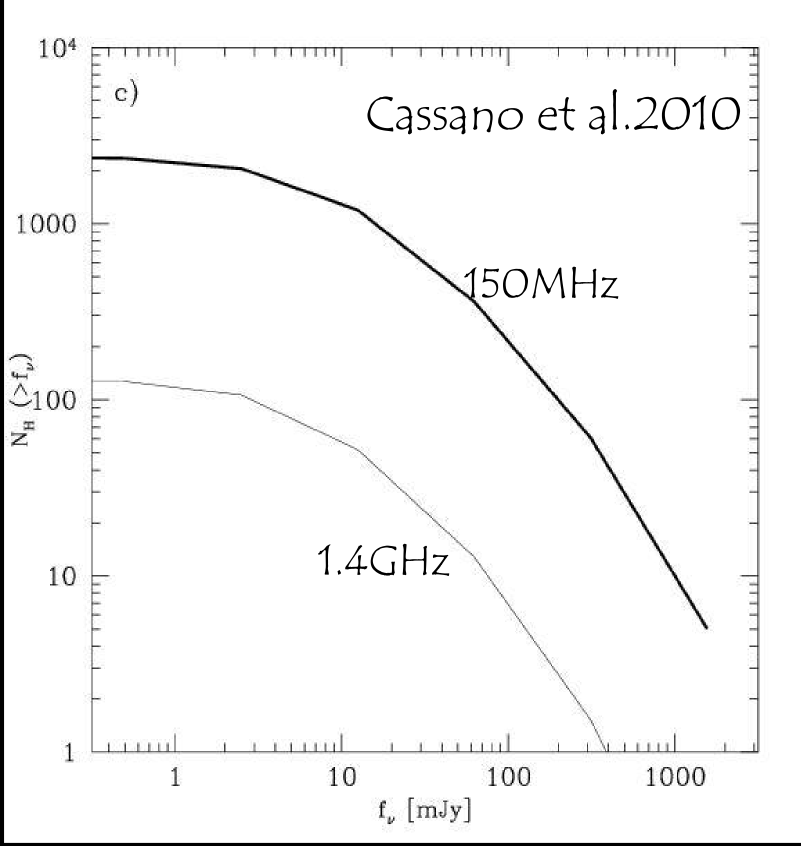


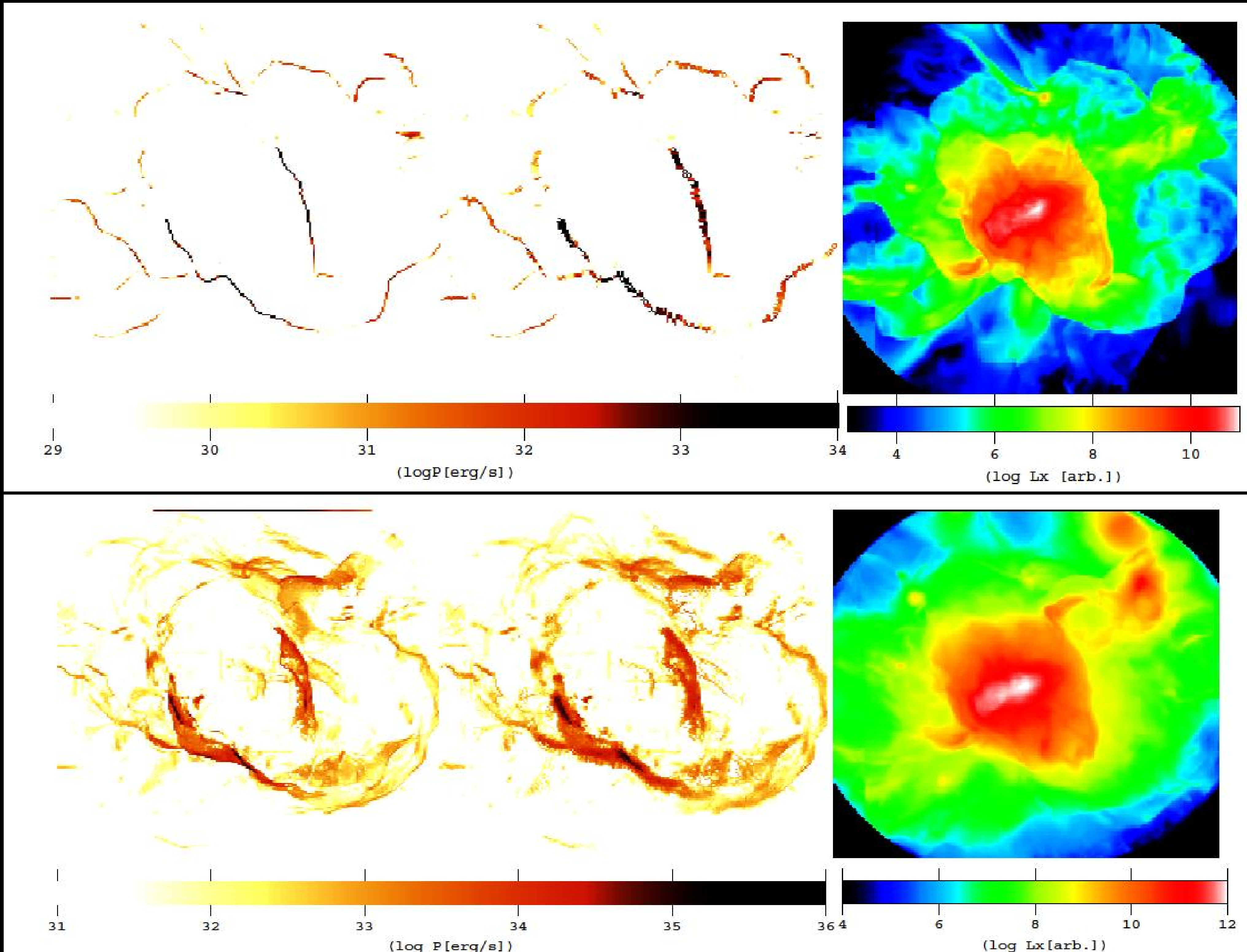
End, thanks



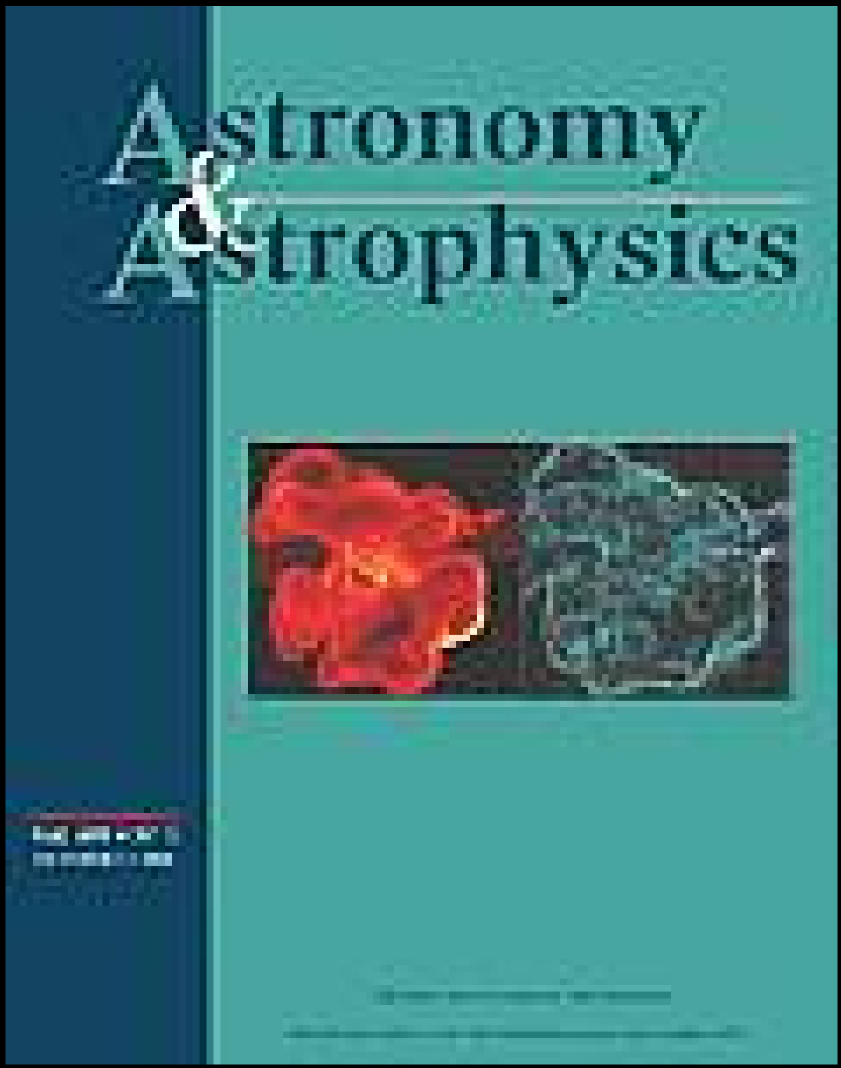

cooling R15
no cool. R0
B4
B2,B3
B1
g/cm^3
r[Mpc/h]
S[keV*cm^2]
B1
B2, B3
B4
Cavagnolo+09
B5 z=0.3
B5
PH2

Incoming Low-Frequency Radio tools: LOFAR & LWA will increase the number of radio halos by ~10-100 !
~ ALL radio halos in the UNIVERSE!




29
30
31
32
33
34
(logP[erg/s])
4
6
8
10
(log Lx [arb.])
31
32
33
34
35
36
(log P[erg/s])
4
6
8
10
12
(log Lx[arb.])

A new and more complete view of turbulence and shocks in evolving galaxy clusters



Temperature Map Evolution

Velocity Map Evolution

Curl of Velocity Map Evolution

Shocks Evolution

Tracers Evolution

Ref:

Vazza et al.2009 A&A

Vazza, Gheller & Brunetti 2010 A&A


1.0
Mpc
res=25kpc
SHOCK ACCELERATION
OF COSMIC RAYS
→ RADIO RELICS?
TURBULENCE INJECTION
AND EVOLUTION
→ RADIO HALOS