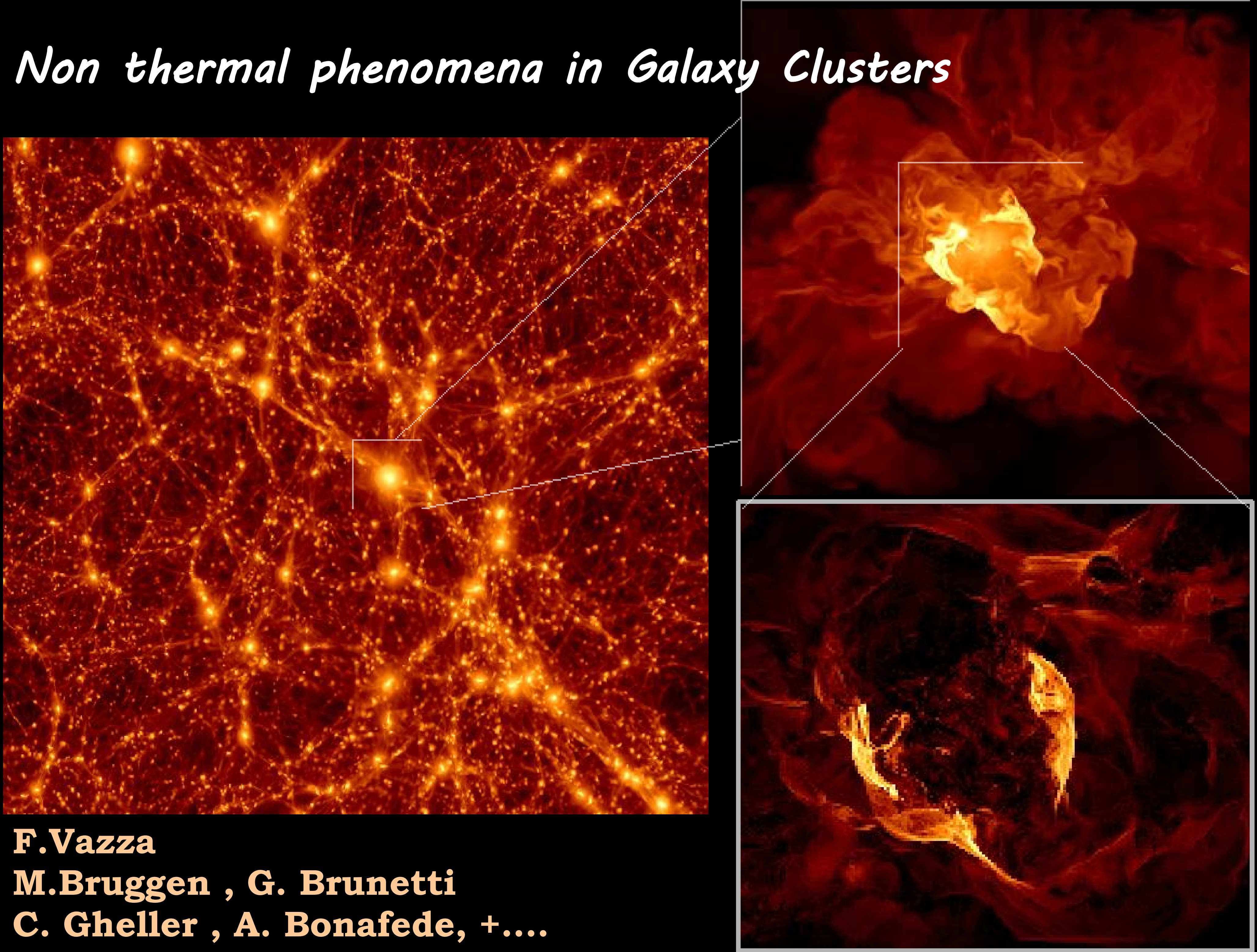
# Non thermal phenomena in Galaxy Clusters



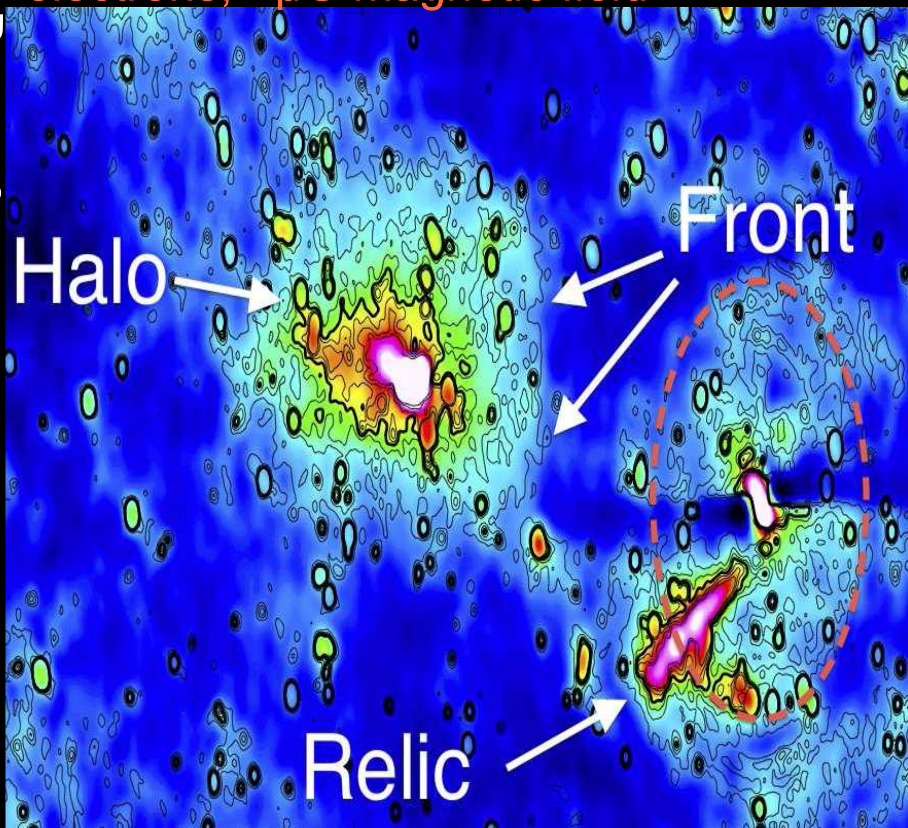
**F.Vazza**
**M.Bruggen , G. Brunetti**
**C. Gheller , A. Bonafede, +....**

# Summary:

- Cosmic rays protons from shocks and AGNs in simulated clusters
- (spatial location of) Radio relics
- Work in progress

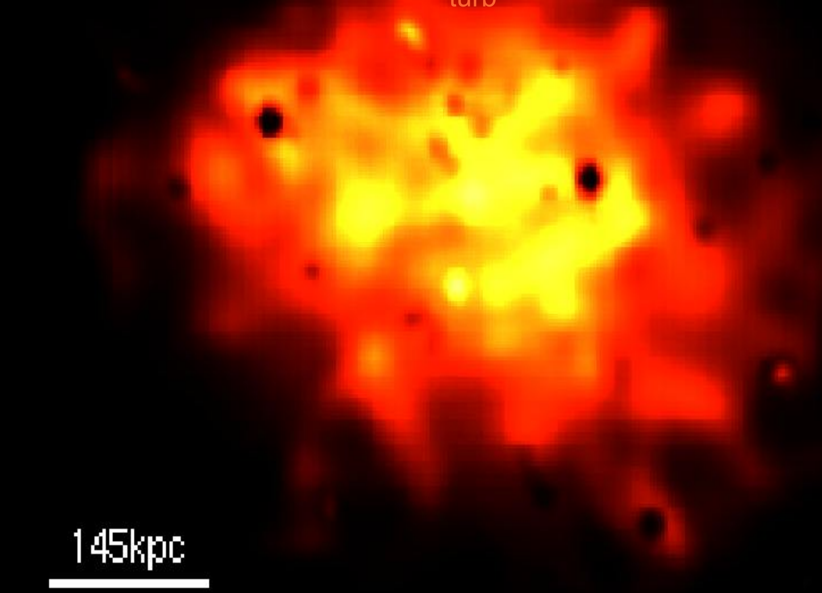
# EVIDENCE OF NT ENERGY <u>IN COMA</u>

Radio halo and relic → relativistic electrons, ~μG magnetic field



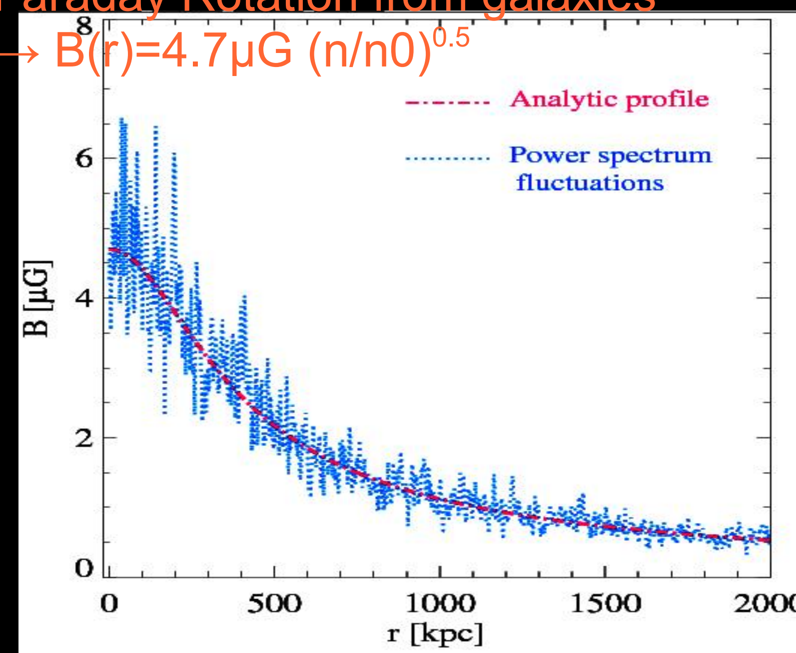

Brown & Rudnick 2010 (WSRT)

Pseudo-pressure fluctuations → turbulence with $P_{turb}/nKT$~0.2-0.3




Schuecker et al.2004 (XMM)

Faraday Rotation from galaxies → $B(r)=4.7\mu G\ (n/n0)^{0.5}$




Bonafede et al.2010 (VLA)

+ UPPER LIMIT ON GAMMA EMISSION by FERMI: $<10^{42}$erg/s
(Ackermann et al.2010)

+ INVERSE COMPTON EMISSION? very debated!
(FuscoFemiano+04, Vik+2010)

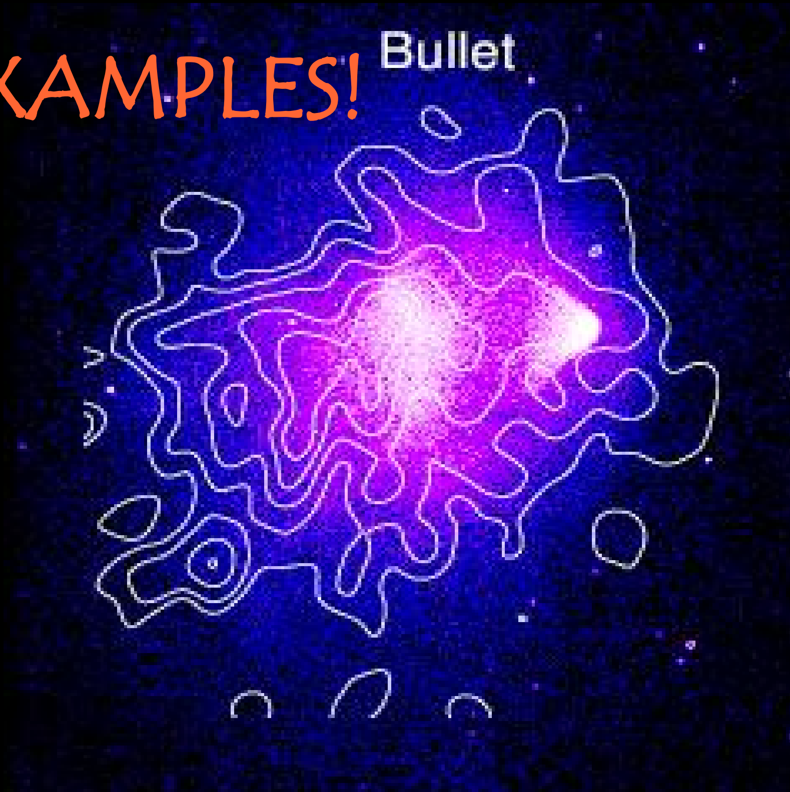
# MANY EXAMPLES!

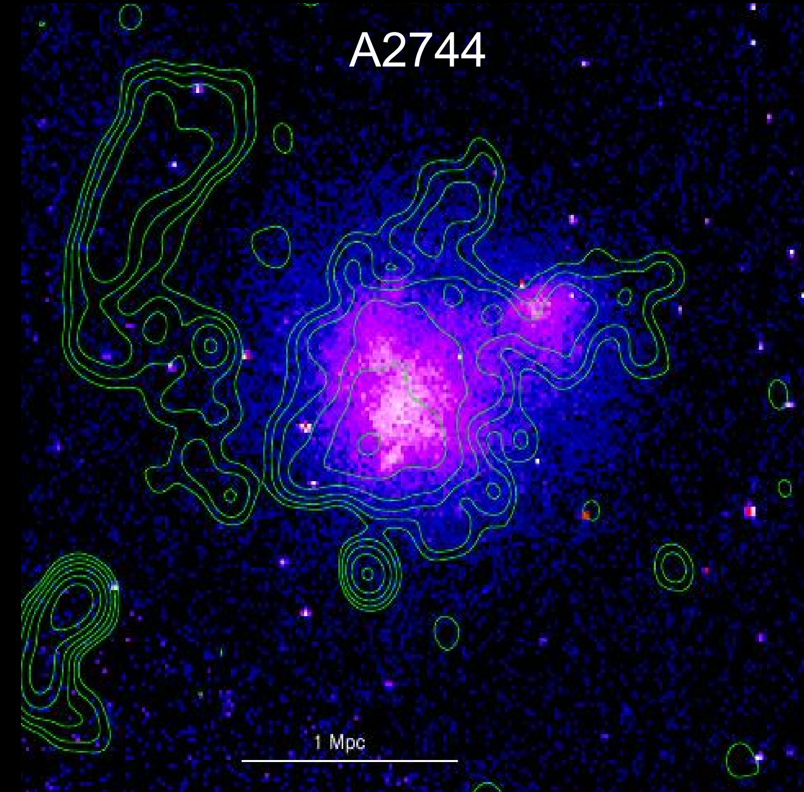
Colors:

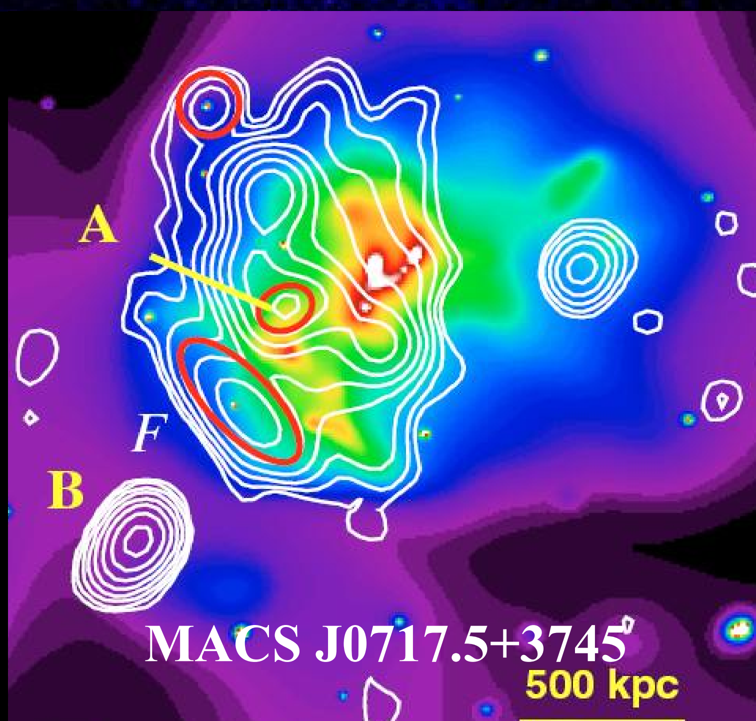
X-ray

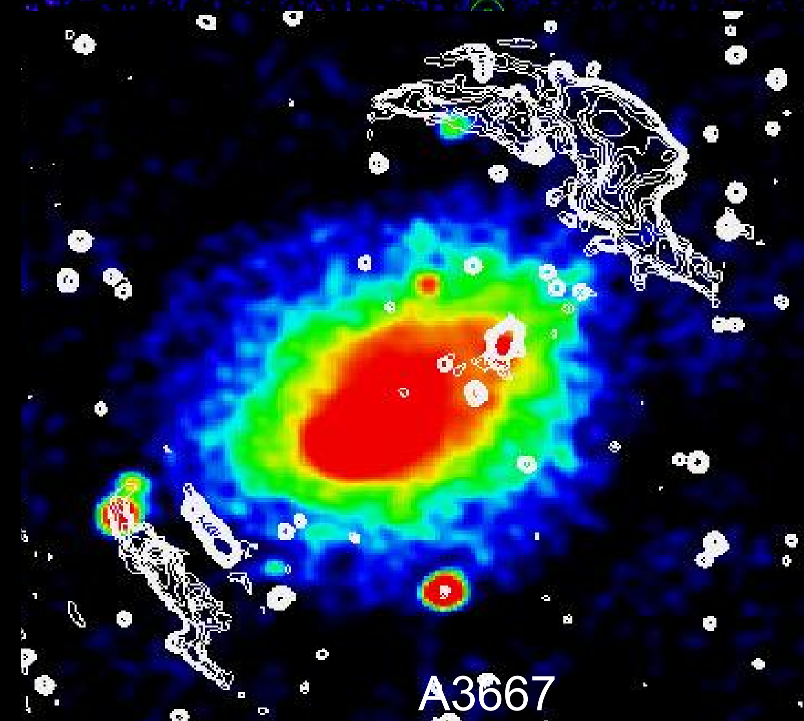
Contours:

radio



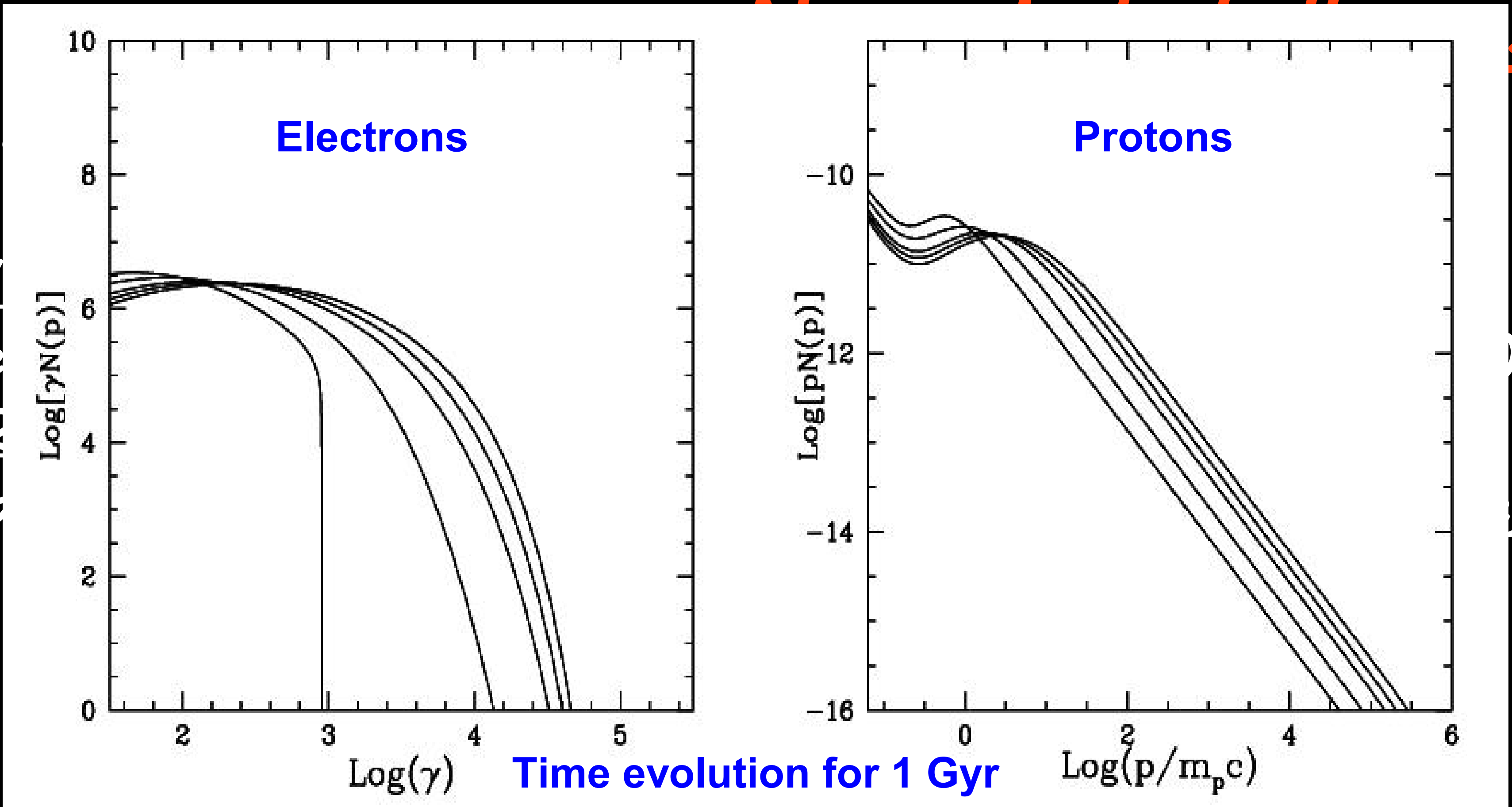
“Design an

Challenge 1

(→ turbule

Challenge 2

(→observat




“Methods

Challenge 3: ICM PHYSICS (run-time)

(e.g. CR, magnetic field, AGN, star formation, etc…)

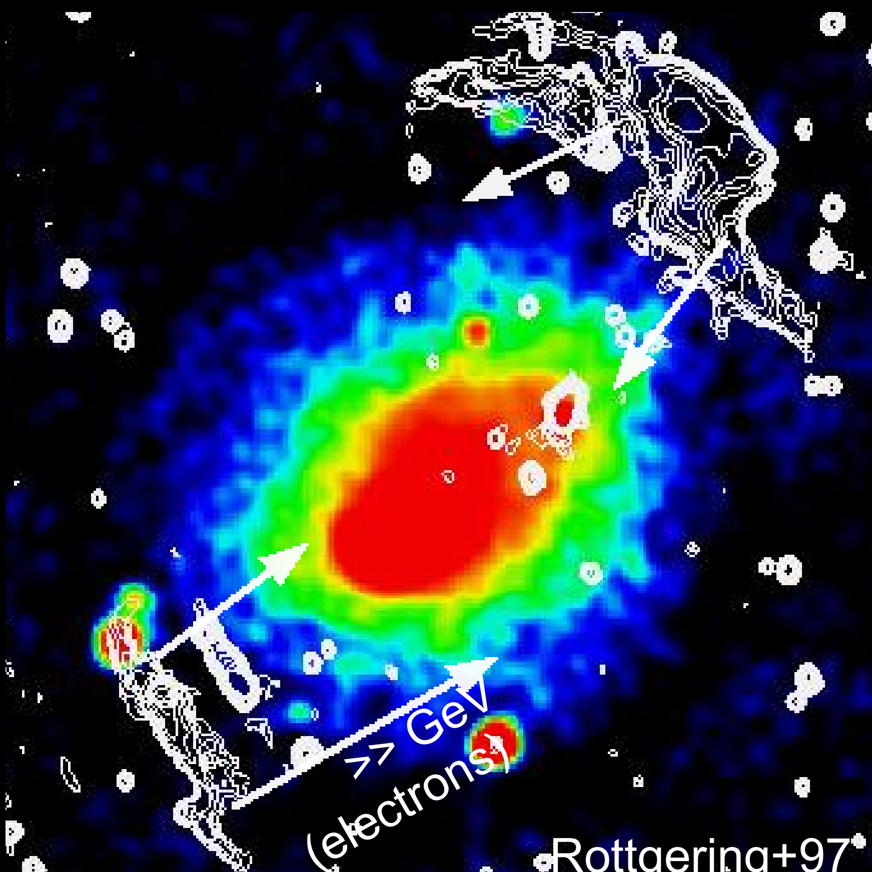
Challenge 4: CR PROTONS PHYSICS (run-time)

(e.g. Coulomb losses, Fermi I & II, t_loss >> $\Delta$t)

Challenge 5: CR ELECTRONS PHYSICS

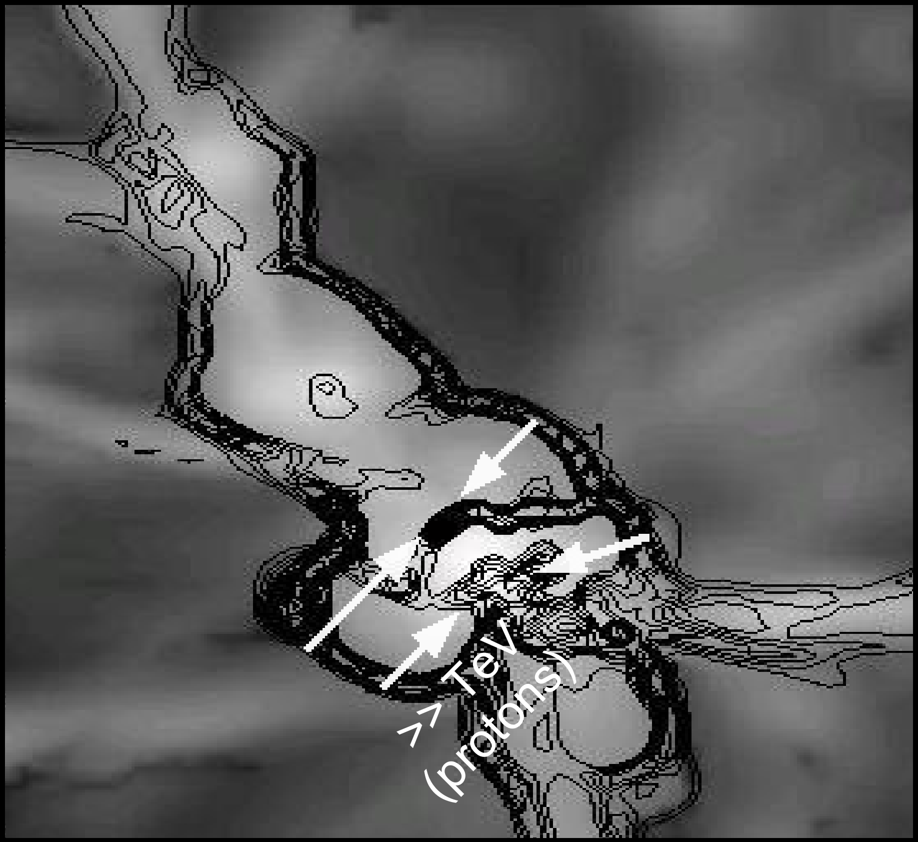
(post-proc.most probably fine : t_loss < $\Delta$t → Fokker Planck)

## Observations:




*RADIO RELICS provide evidence for relativistic ELECTRONS acceleration at shocks*
*→ much more PROTONS should be accelerated according to DSA*

## Theory & simulations:




Miniati+02
(see also Ryu+03, Pfrommer+06)

*STRUCTURE FORMATION SHOCKS can inject CR protons with high efficiency*
*(10-50% of thermal pool)*

**Modelling injection and feedback of Cosmic Rays in grid-based cosmological simulations: effects on cluster outskirts.**

F. Vazza[1,2*], M.Brüggen[1], C.Gheller[3], G. Brunetti[2]

Two-fluid model
Dorfi 1984; Bell 1987; Jones & Kang 1990; etc...

In cosmology:
•Miniati 2003 (fixed grid)
•Pfrommer et al 2006 & Ensslin et al.2007 (SPH)

$$\frac{d\rho}{dt} + \rho\nabla\cdot\boldsymbol{u} = 0\,,$$

$$\frac{d\boldsymbol{u}}{dt} = -\frac{1}{\rho}\nabla(P_g + \boxed{P_c})\,,$$

$$\frac{de}{dt} = -\frac{1}{\rho}\nabla\cdot[(P_g + \boxed{P_c})\boldsymbol{u}] + \frac{1}{\rho}\boxed{P_c}\nabla\cdot\boldsymbol{u} - \frac{\boxed{S}}{\rho}\,,$$

$$\frac{d\boxed{E_c}}{dt} = \boxed{-\gamma_c E_c}(\nabla\cdot\boldsymbol{u}) + \cancel{\nabla\cdot(\kappa\nabla \boxed{E_c})} + \boxed{S}\,.$$

Ingredients:

-Cosmic rays pressure

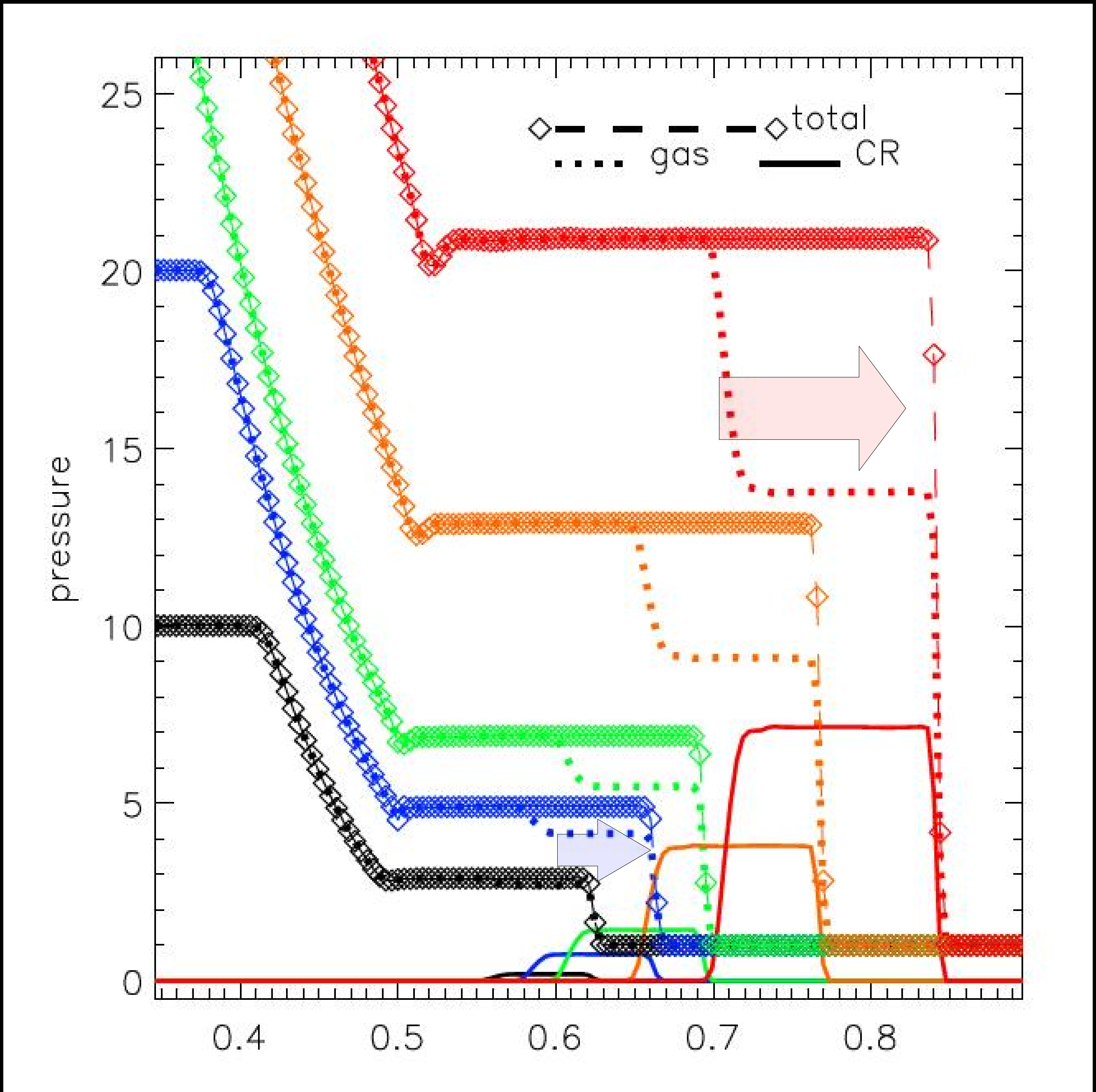
- Source term (e.g. shocks)

- Equation of state $P_c=(\gamma_c-1)E_c$ with $\gamma_c=4/3$

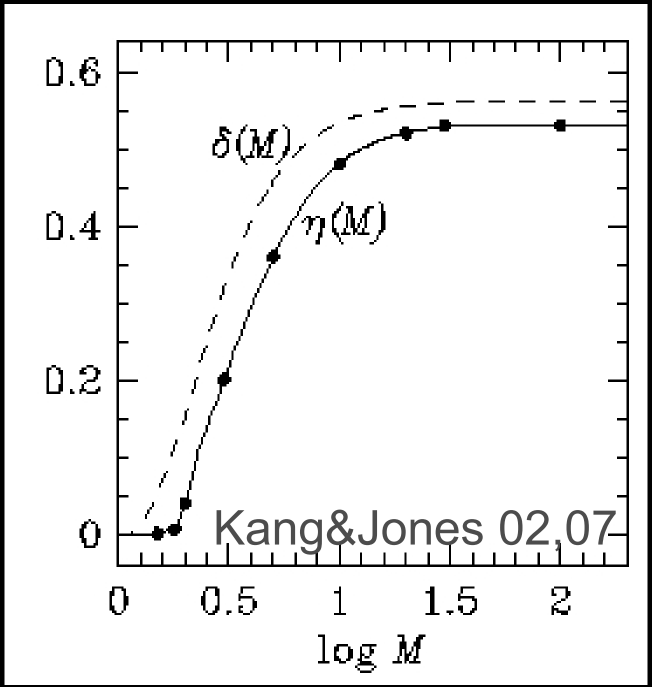
- ~~Cosmic rays diffusion~~

# 1-D tests for validation: from M=1.5 to M=5

Injection of CR for increasing Mach

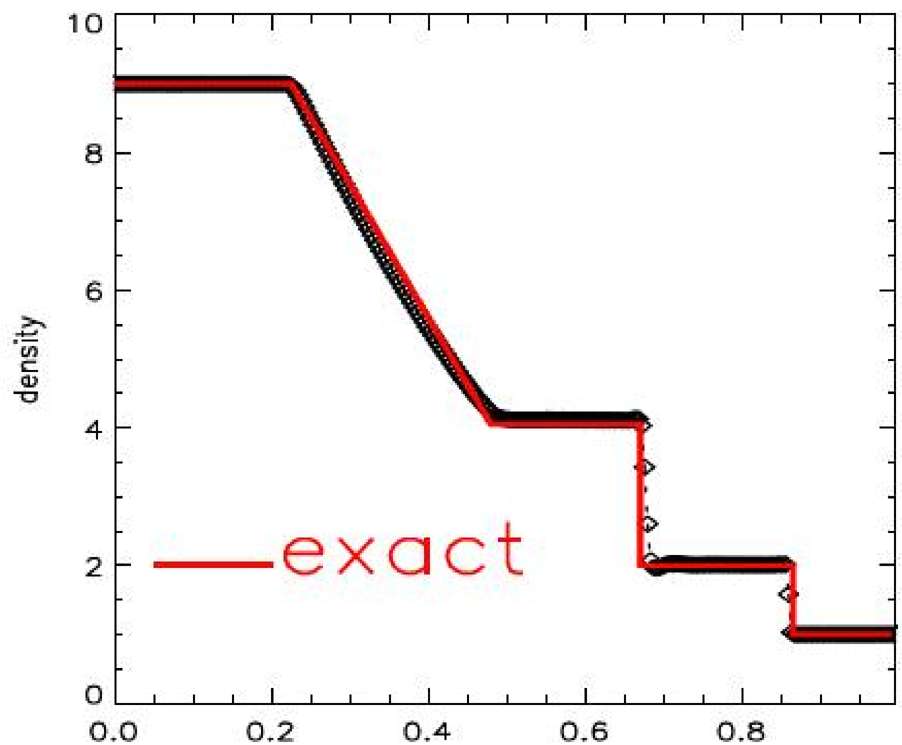


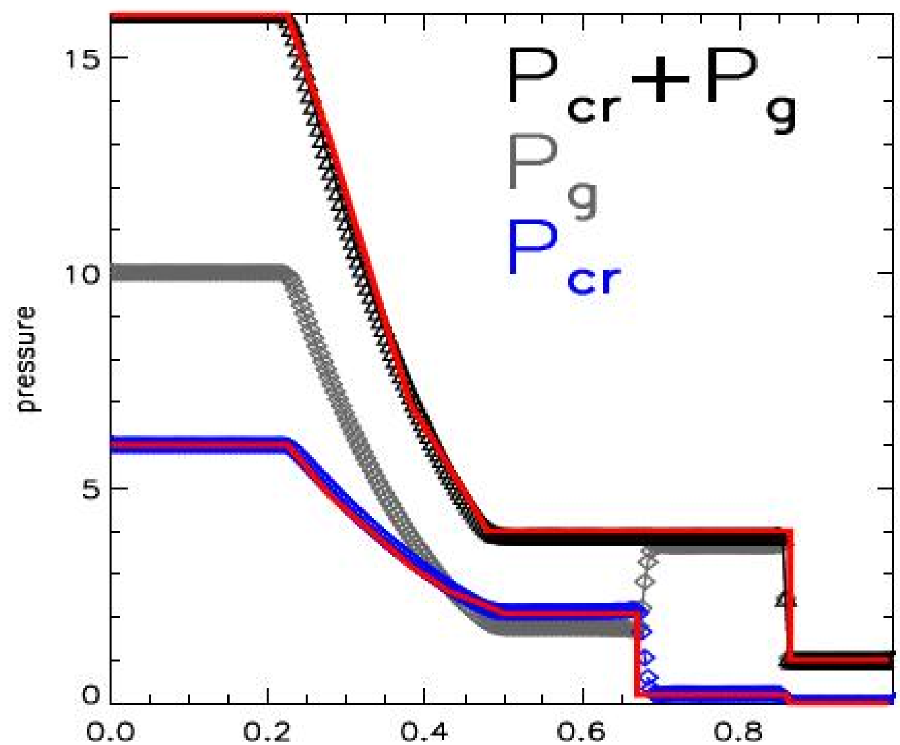

Efficiency from theoretical works

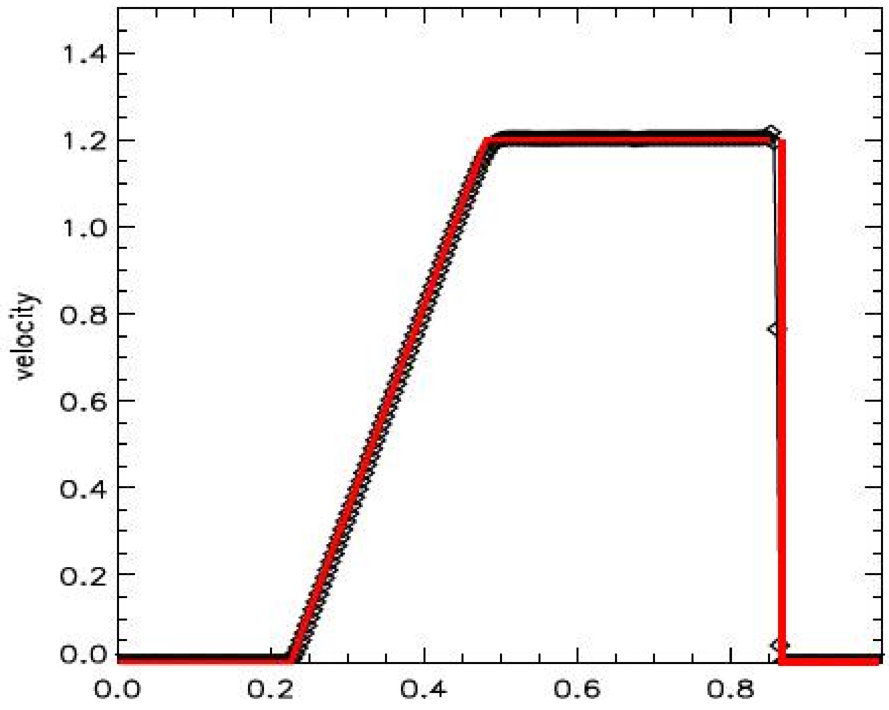



Diffusive shock accleration ~works in supernovae

# 1-D tests for validation : SHOCK TUBE



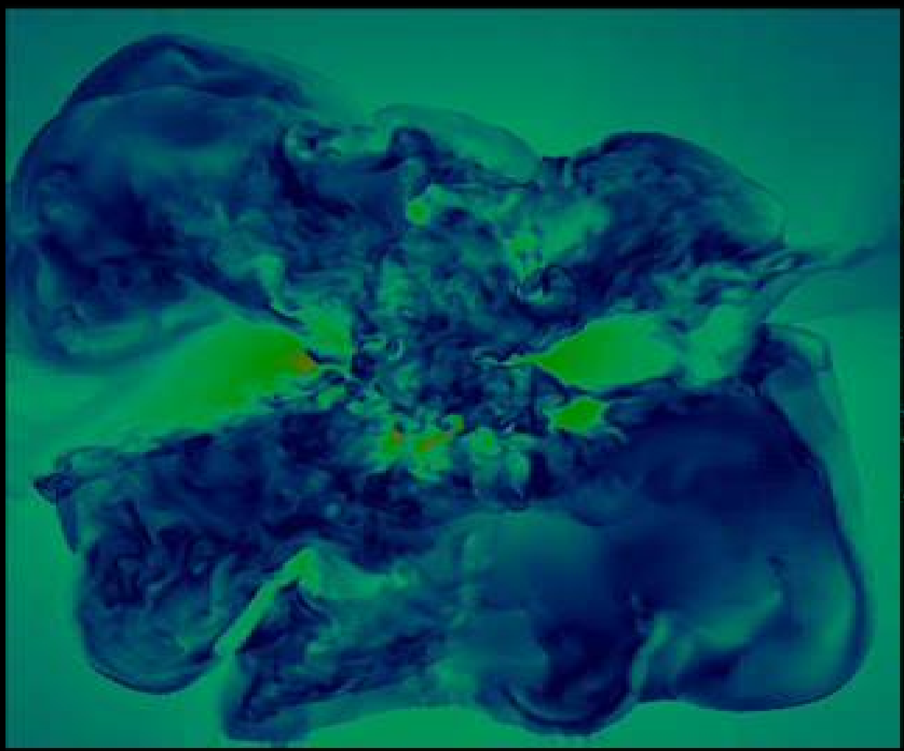

Initial conditions:

LEFT: Pgas=10, Pcr=6, dens=9

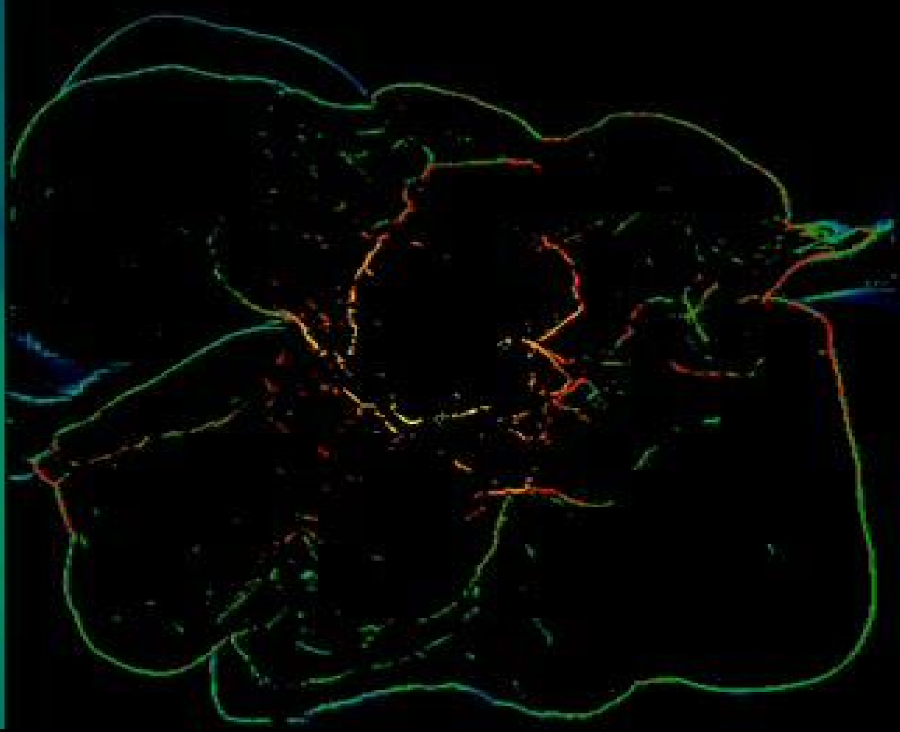
RIGHT:Pgas=1,Pcr=0,dens=1

Acceleration efficiency $\eta$ at shocks ~ 0.5%

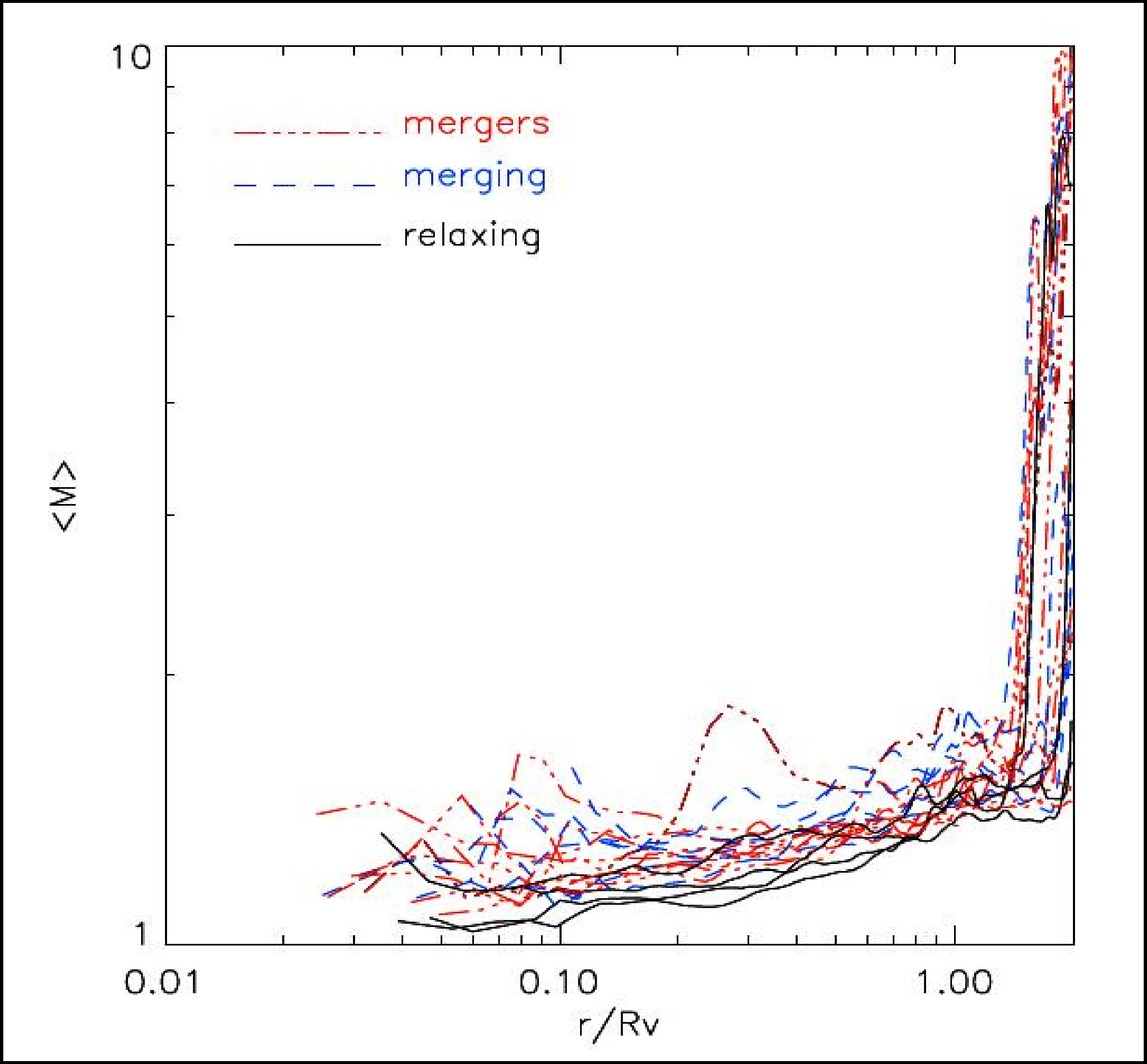
- We monitor the injection of energy across shocks at run time (velocity-jump or pressure-jump algorithm)



Temperature



shocks energy flux



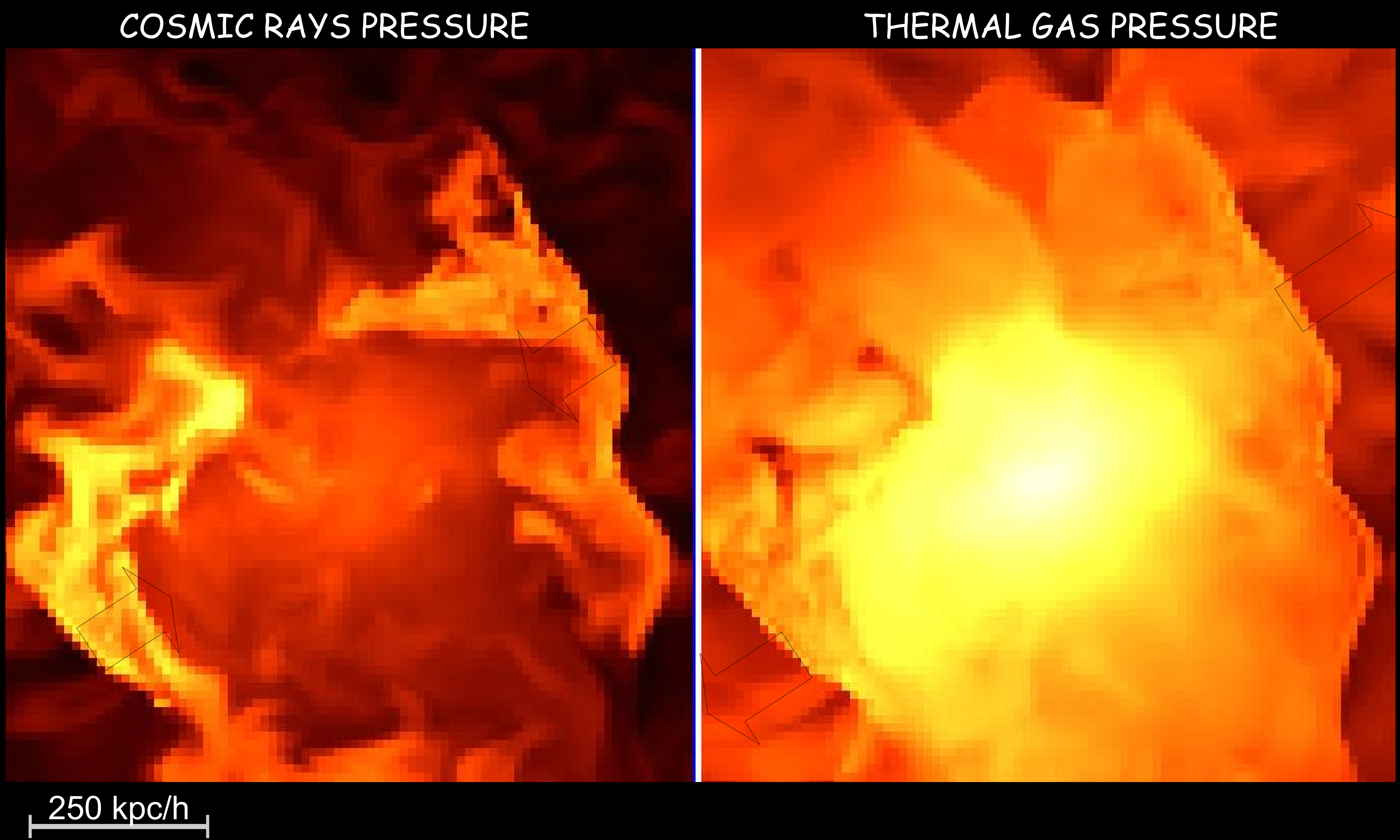

*Average radial profiles of Mach number*

THERMAL GAS PRESSURE


Same IC as in Vazza+10
Max res= 25kpc

Run at Juropa / SP6-Cineca
10-20 % longer CPU time - 10% more data

COSMIC RAYS PRESSURE




See movie (injection from z=0.6 on)

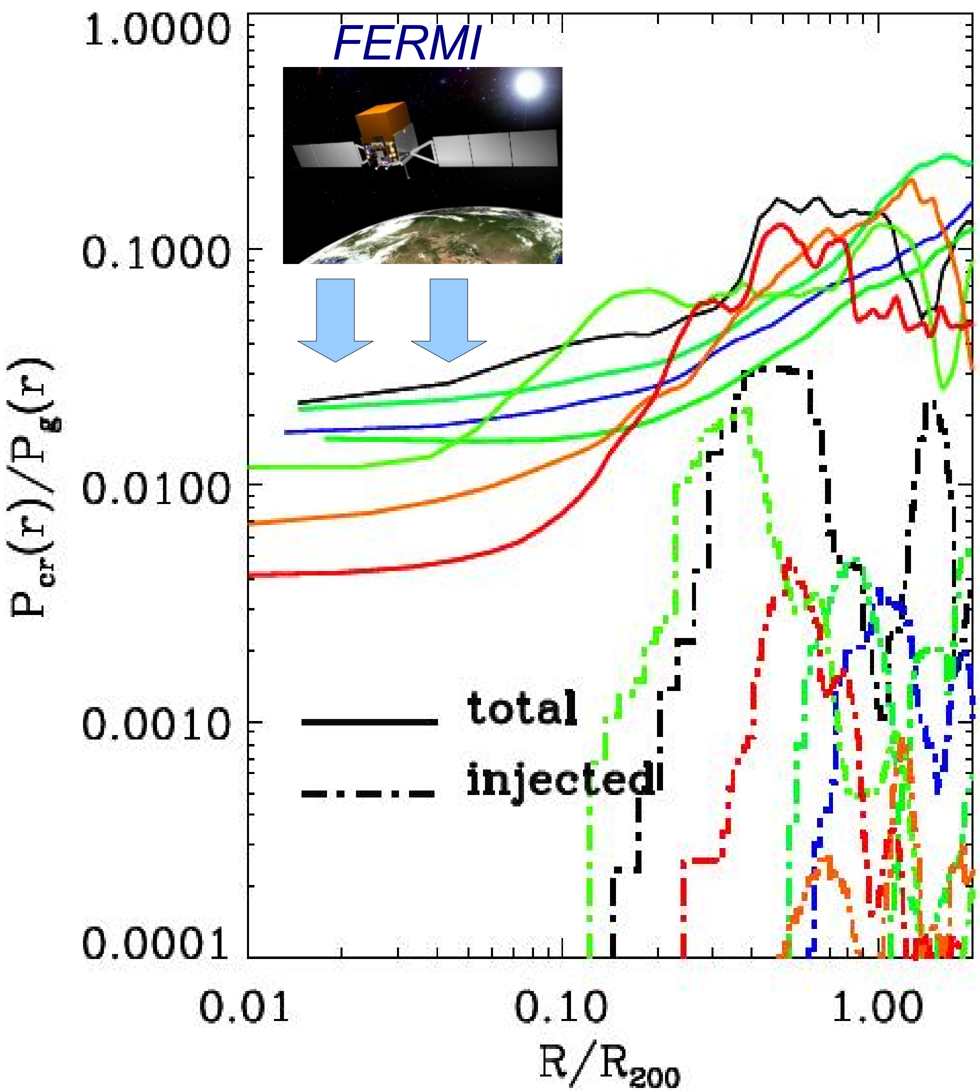
## Non radiative clusters:

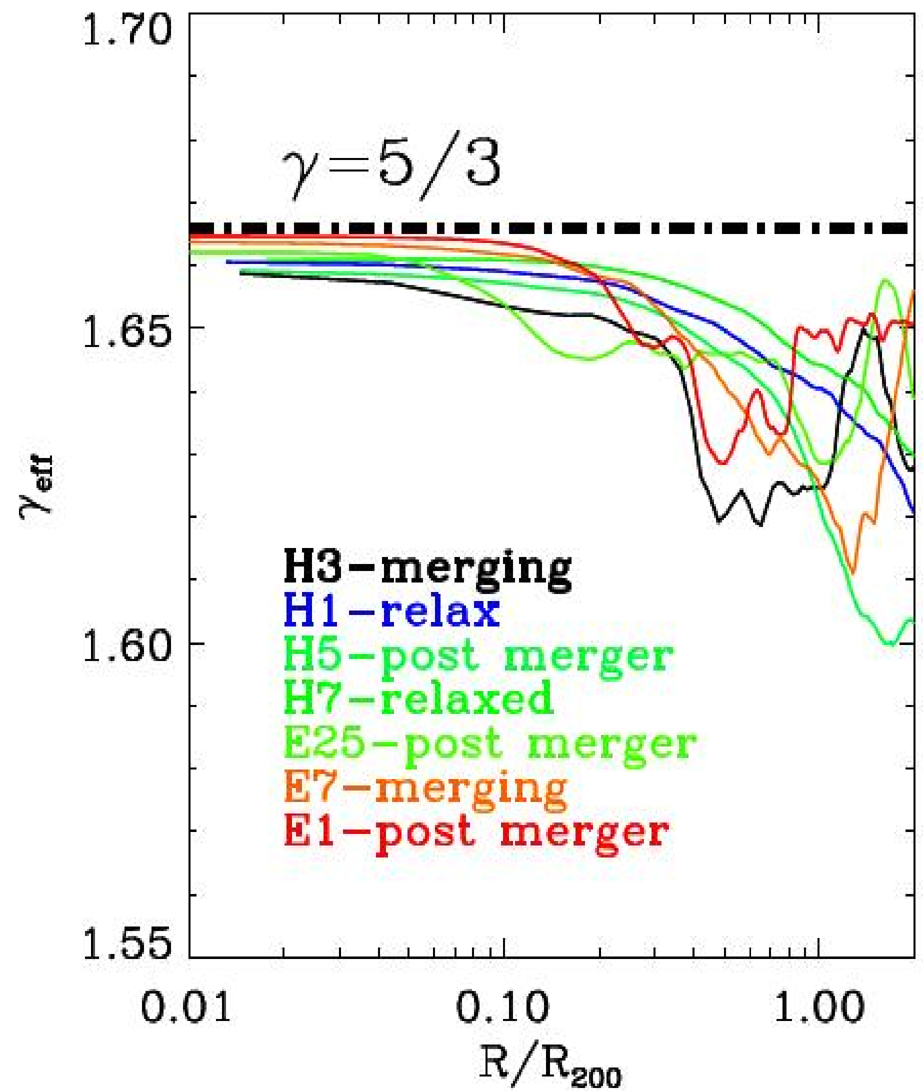
Pcr/ nkT <5% (core)  Pcr/ nkT<10% ($R_{200}$)

Largest effects at  $R_{200}$

$$\left(\gamma_{\rm eff} = \frac{(\gamma P_{\rm g}+\gamma_{\rm cr} P_{\rm c})}{P_{\rm g}+P_{\rm c}}\right)$$

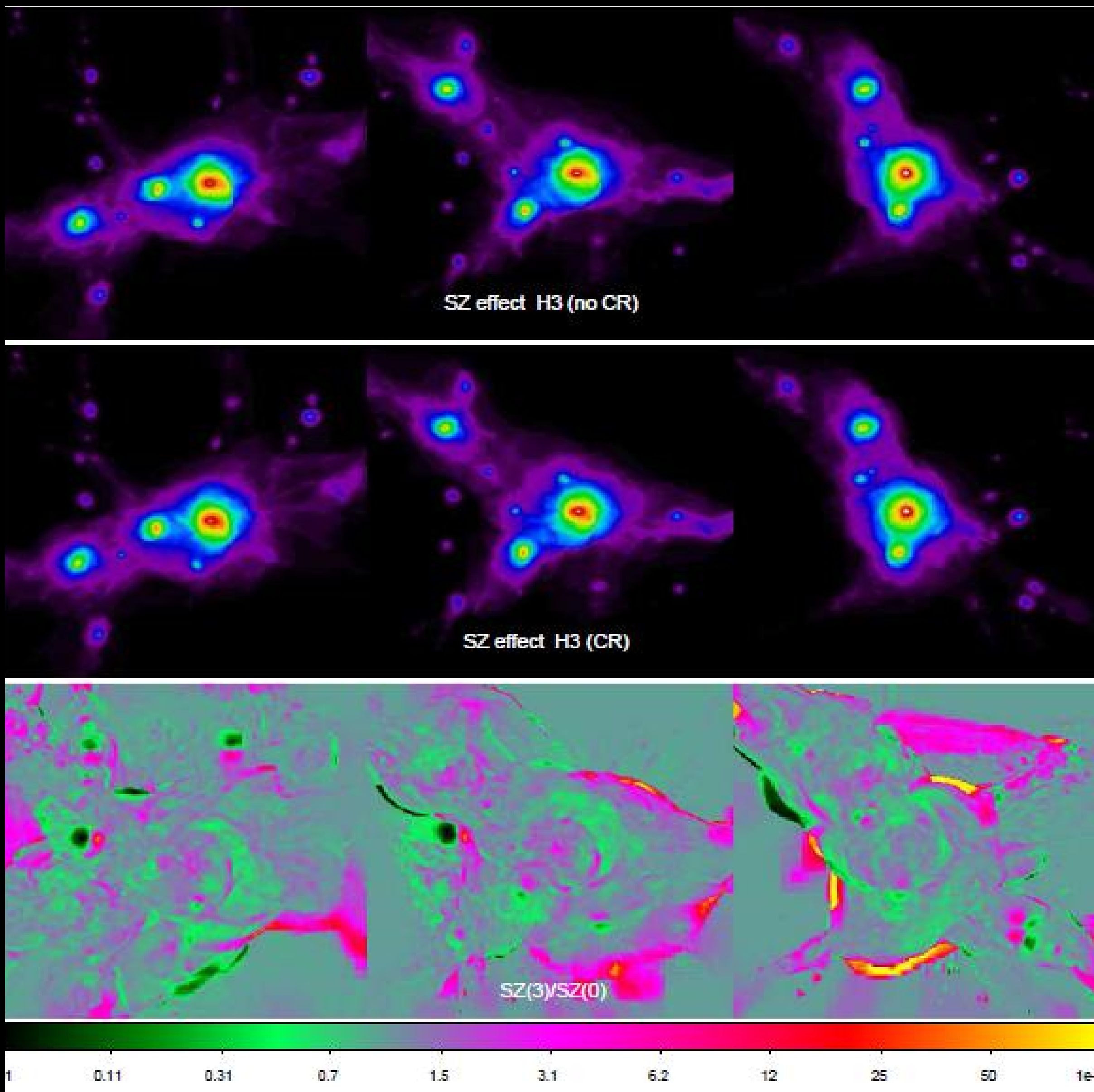
**Profile of CR to thermal pressure**

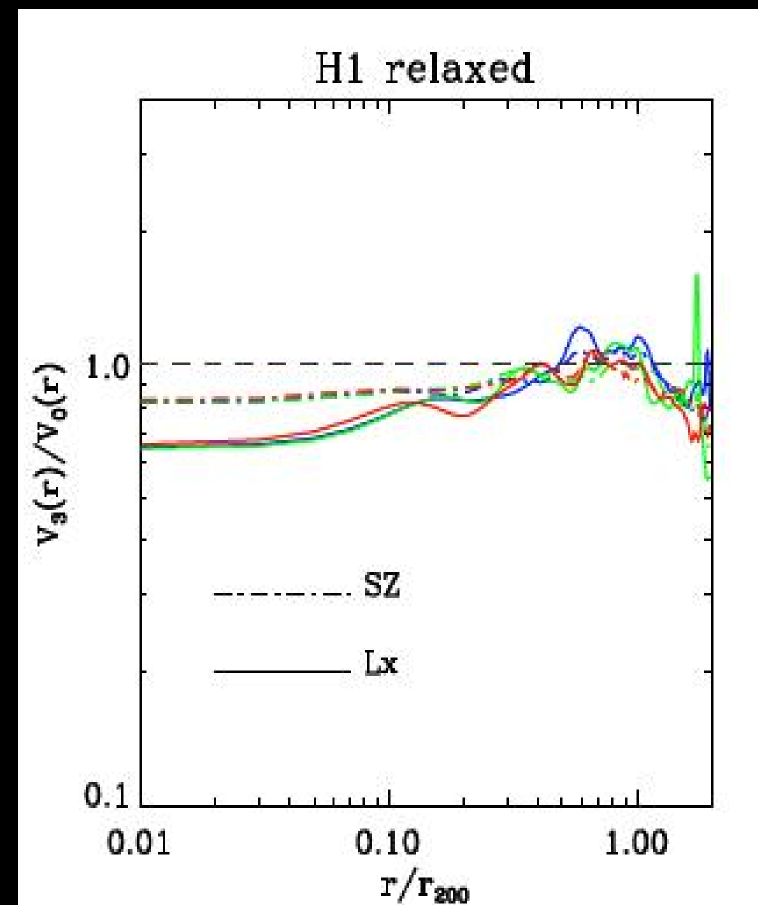


*Cosmic rays enhance compressibility of the ICM at $R_{200}$*

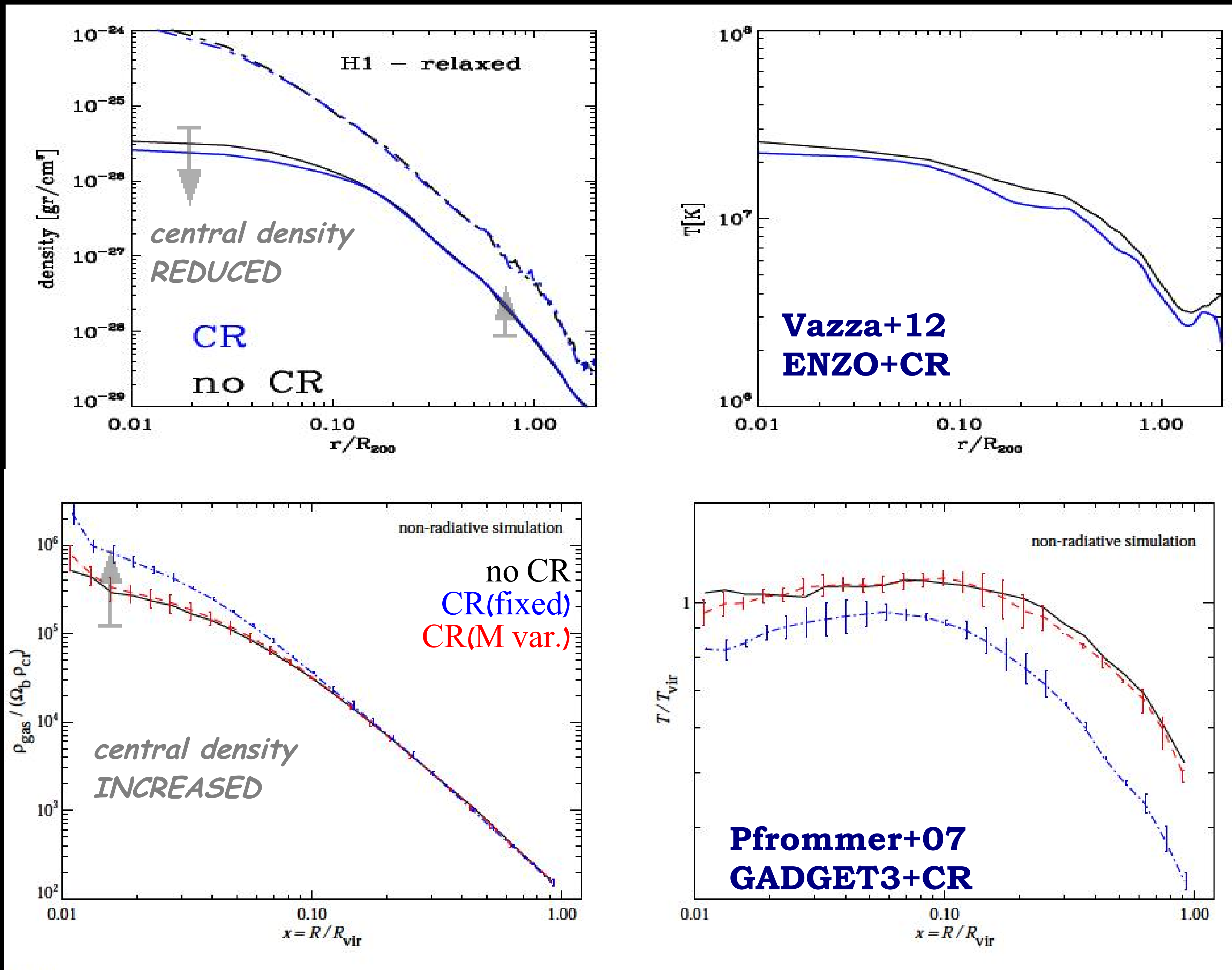
*X-ray lum. and SZ are affected by 10-20%*




Profile of the ratio between Lx and SZ with and without CR effects

# (small but) opposite trends in density and pressure for our implementation of CR in ENZO and SPH results



**Thermal and non-thermal traces of AGN feedback: results from cosmological AMR simulations**

F. Vazza[1,2,3⋆], M. Brüggen[1,2], C. Gheller[4]

submitted

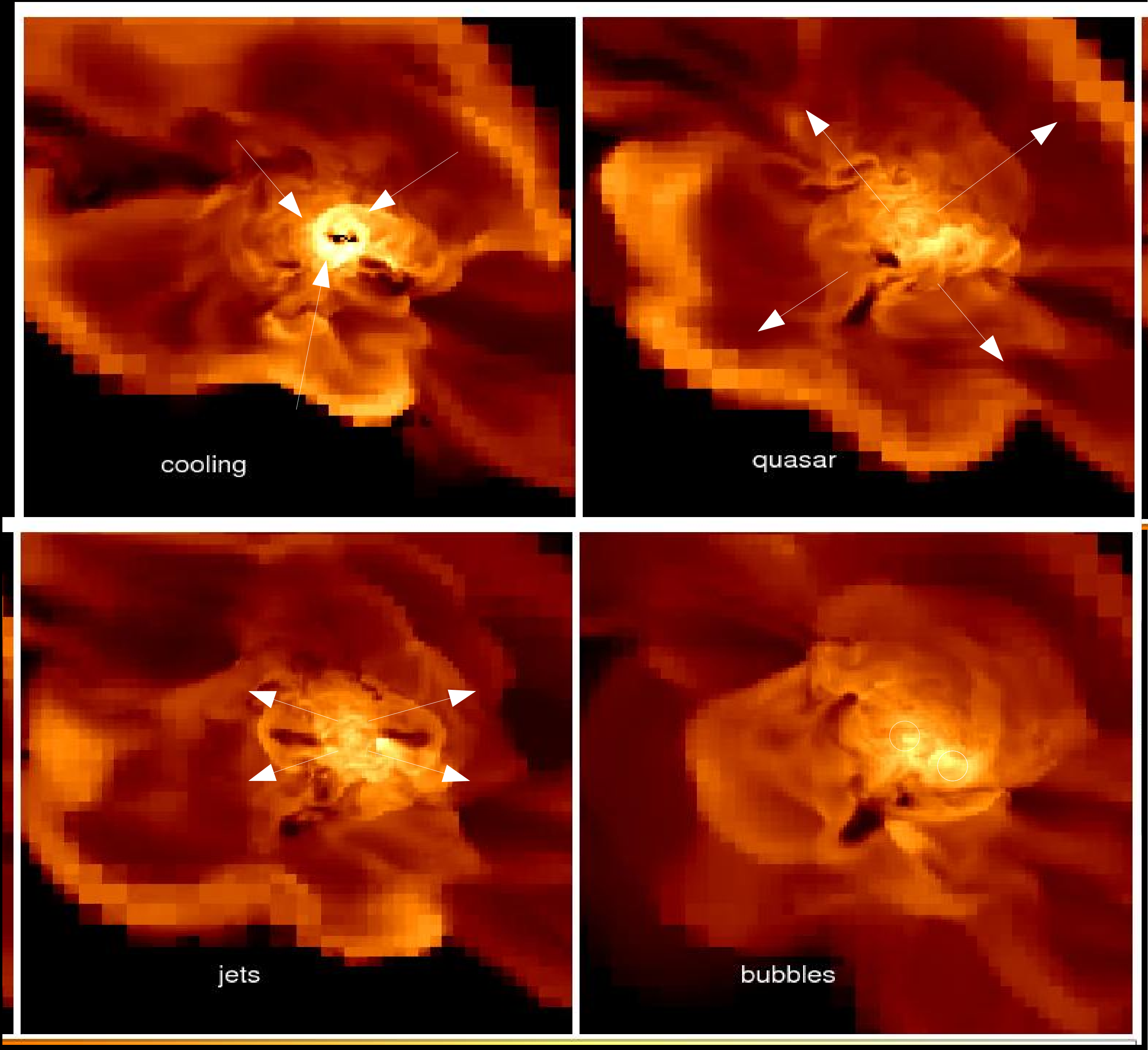
Baseline model of CR from shocks

+

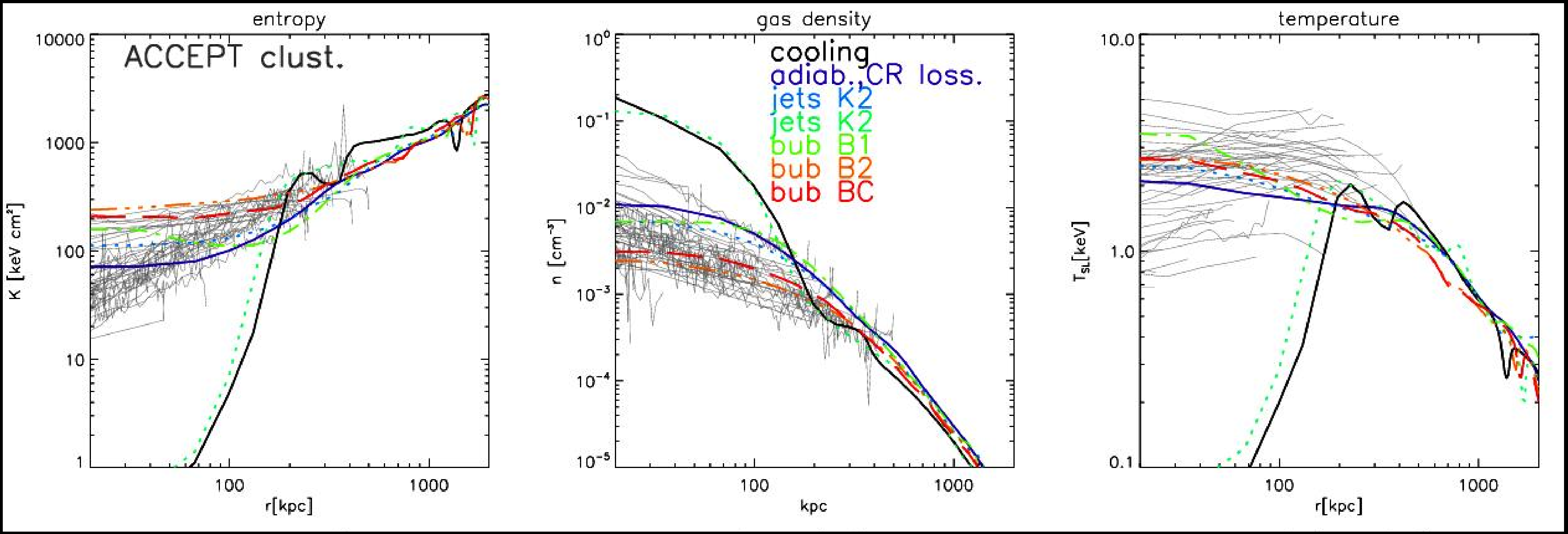
New features:

• cooling
• Shock-reacc.
• Coulomb & hadronic losses

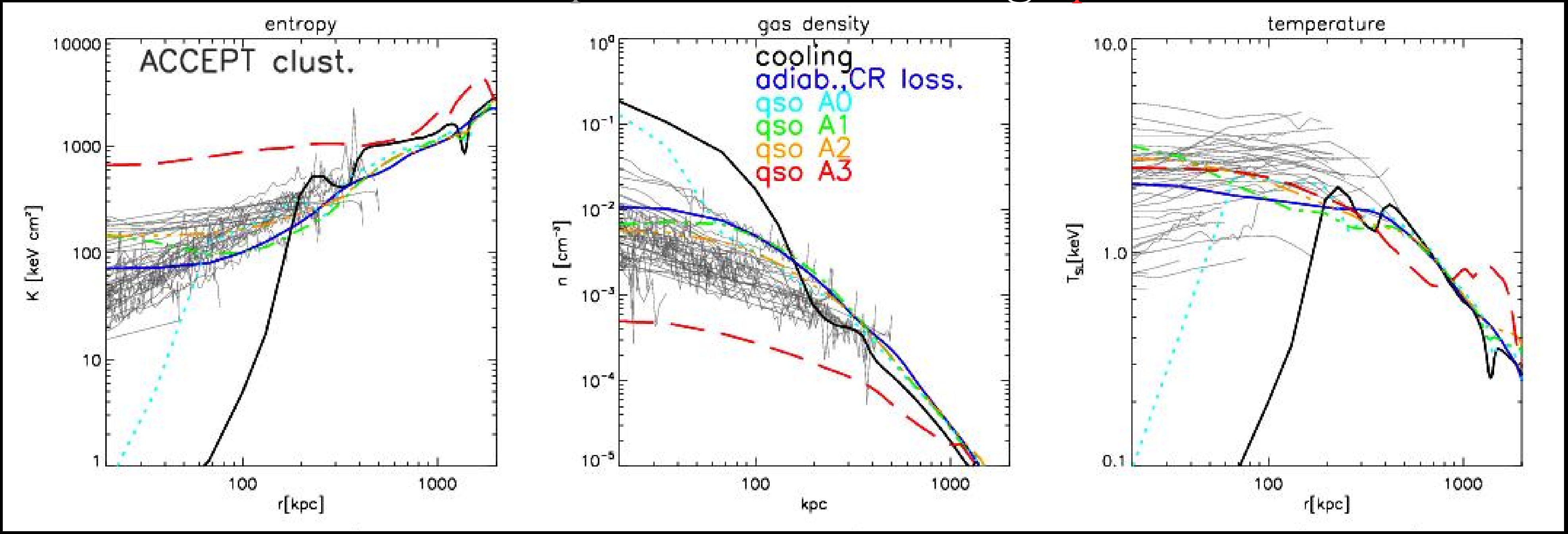
•AGN feedback:
jets (kinetic)
quasar (therm.)
bubbles(buoy.)



## Observed CHANDRA profiles vs cooling/jet/bubbles runs

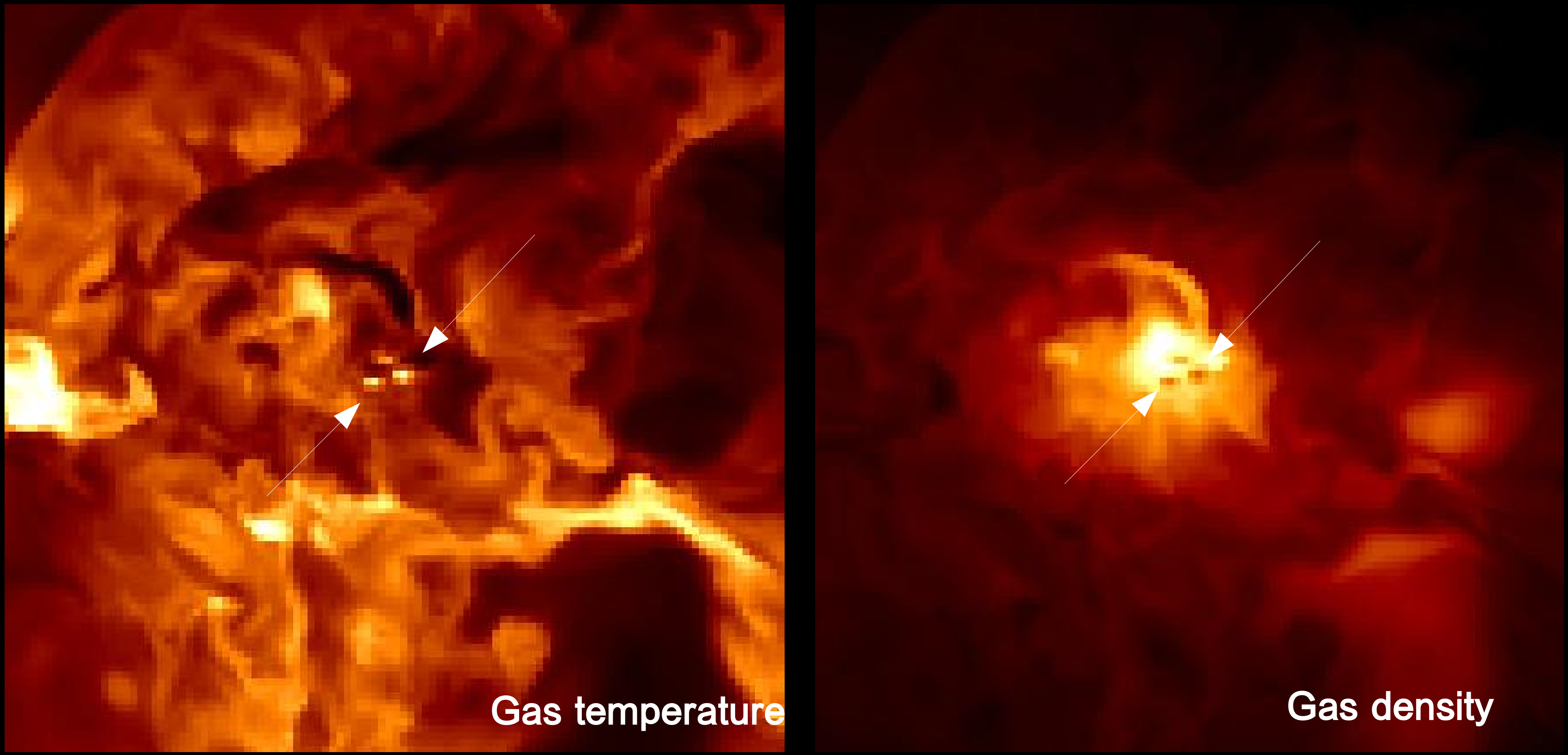



## Observed CHANDRA profiles vs cooling/quasar runs



# "Best" models: bubbles – feedback:

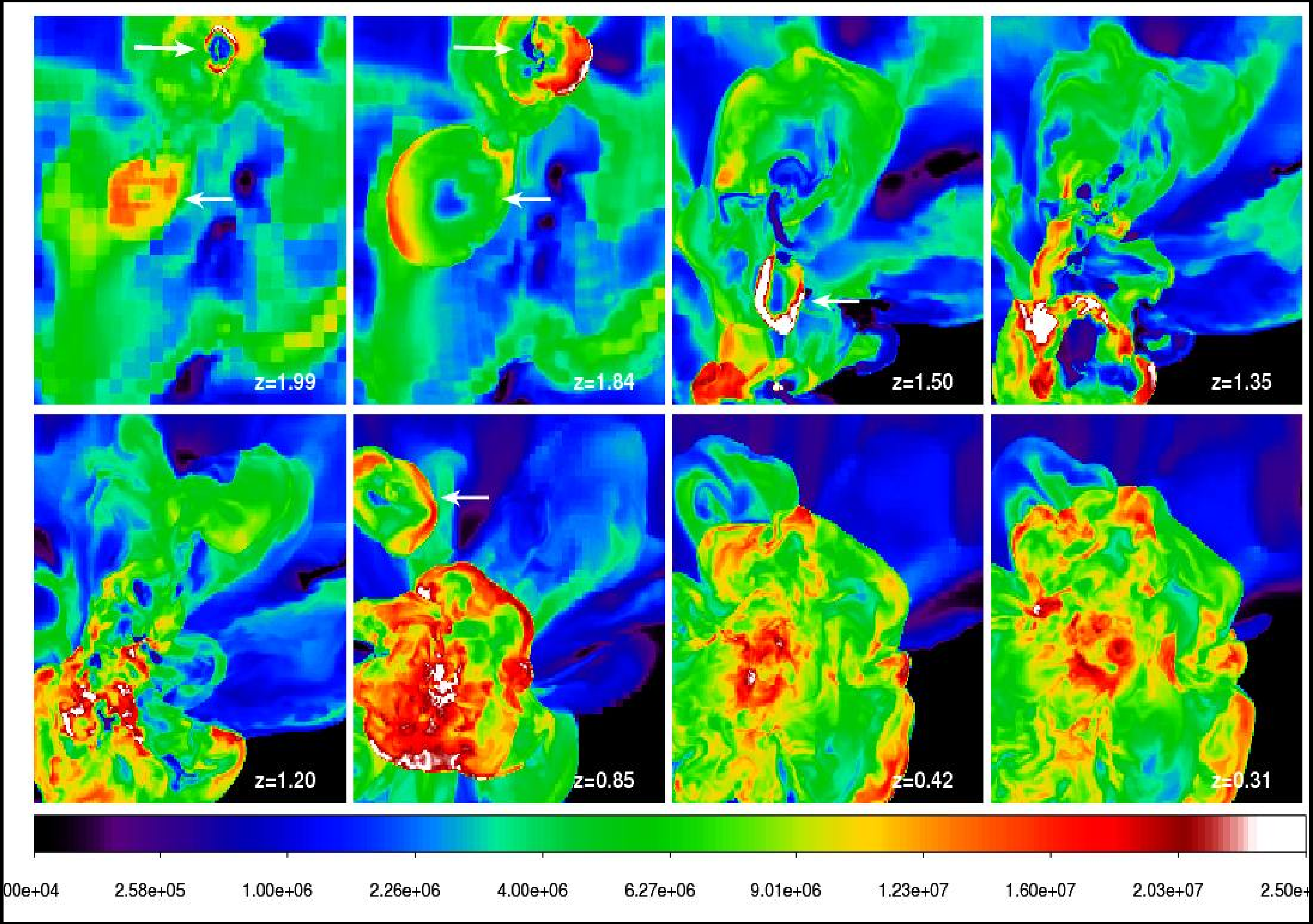
- are created as evacuated blobs in pressure equilibrium
- filled with gas ($\Gamma$=5/3) or a mixture with CR ($\Gamma_{cr}$ = 4/3)
- Initial radius $r_b$=25kpc/h
- Injected energy 3/2 PV ~ $10^{59}$ erg per event




see also:Bruggen et al. 2005; Sijacki et al.2008 (many others!)

"Best" models: Quasar - feedback:

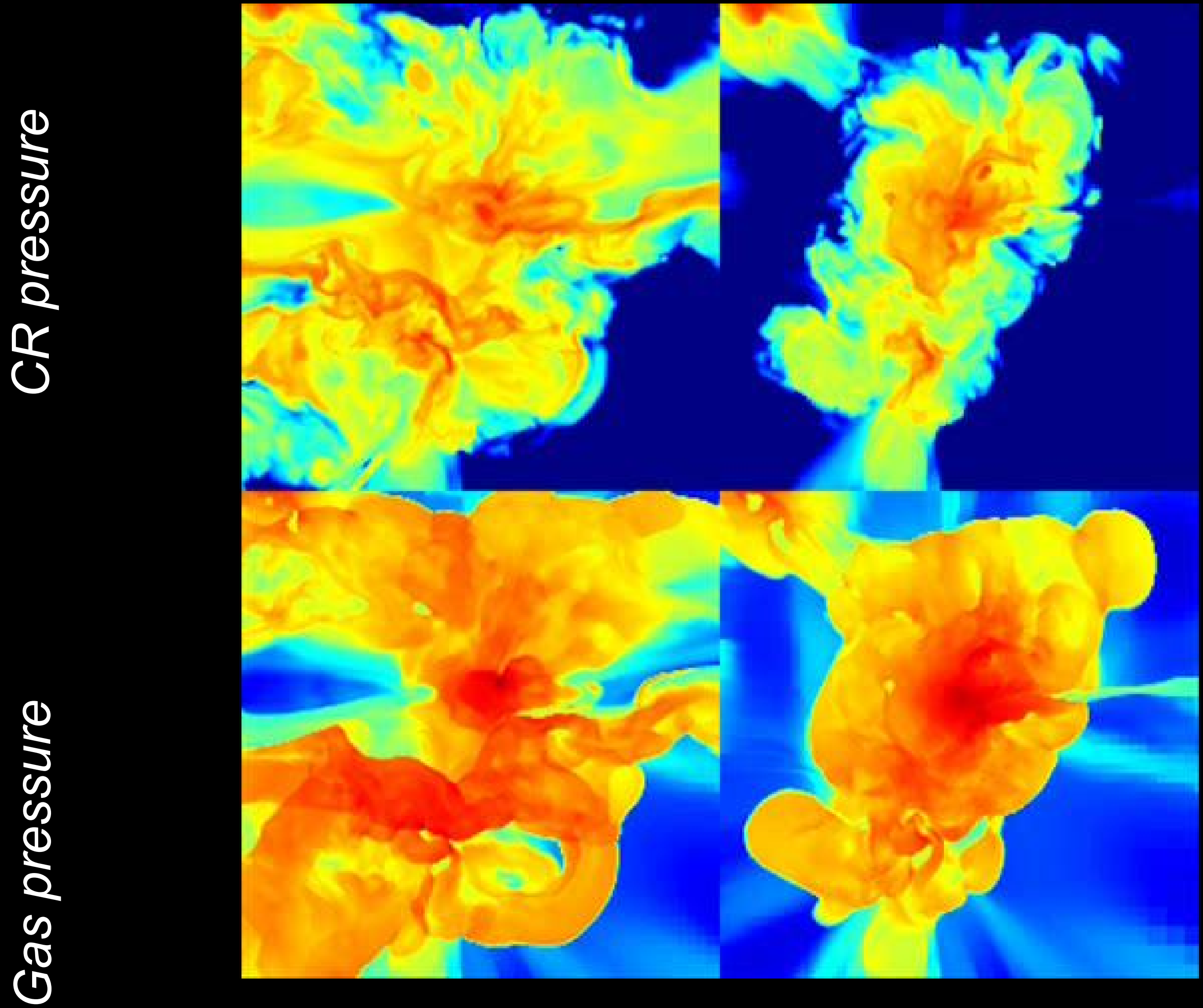
- Thermal energy output drives a blast wave
- Mach number ~5-10
- Injected energy ~ $10^{59}$-$10^{60}$ erg per event




see also: McCarthy+ 04, Sijacki+ 07, Teyssier+ 10 (many others!)

"Best" models: Jets – feedback:

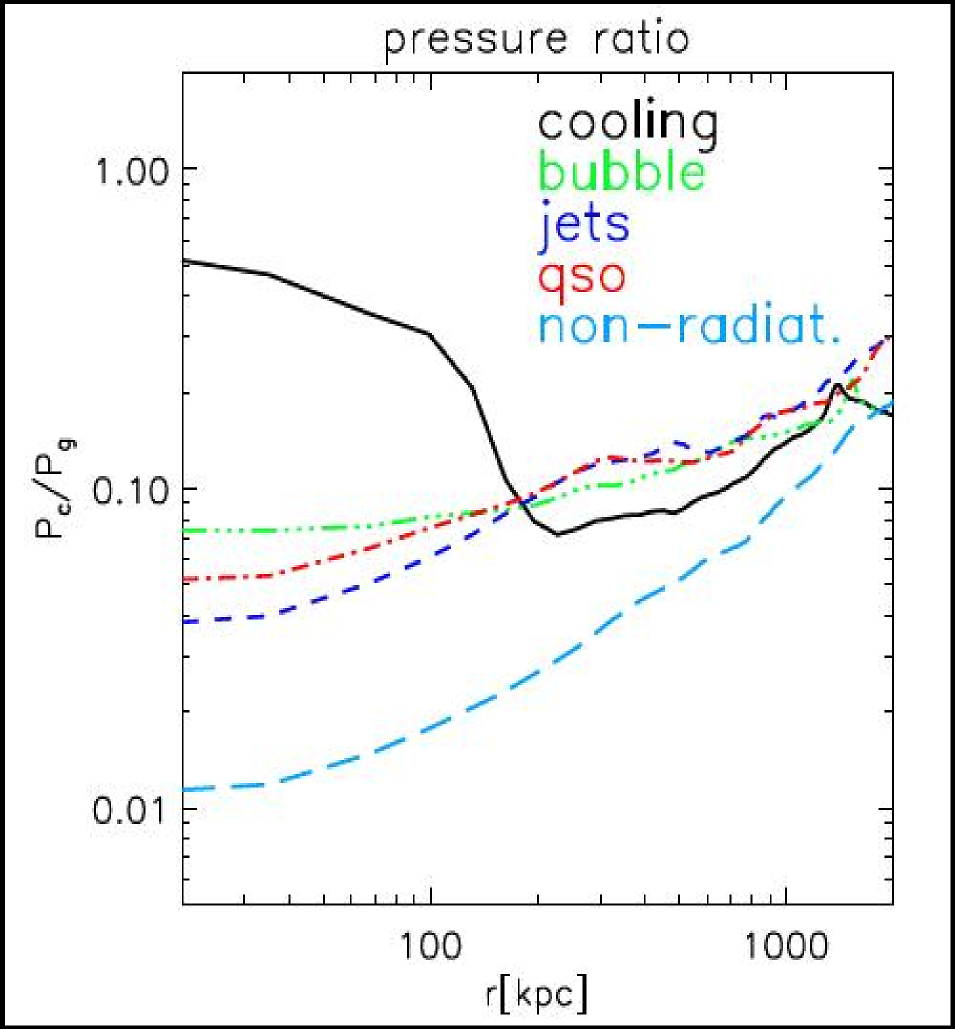
- Kinetic energy output from bipolar jets
- Jet velocity ~ 600-800 km/s at 50kpc/h
- Injected energy ~ $10^{59}$ erg per event




see also: Gaspari+ 11, Dubois + 11 (+ many others!)

## What is the CR output of each feedback mode?

Profile of CR pressure to thermal pressure in different modes




- pure cooling produces Pcr ~ nkT
- AGN feedback increases Pcr/nkT with respect to non-radiative

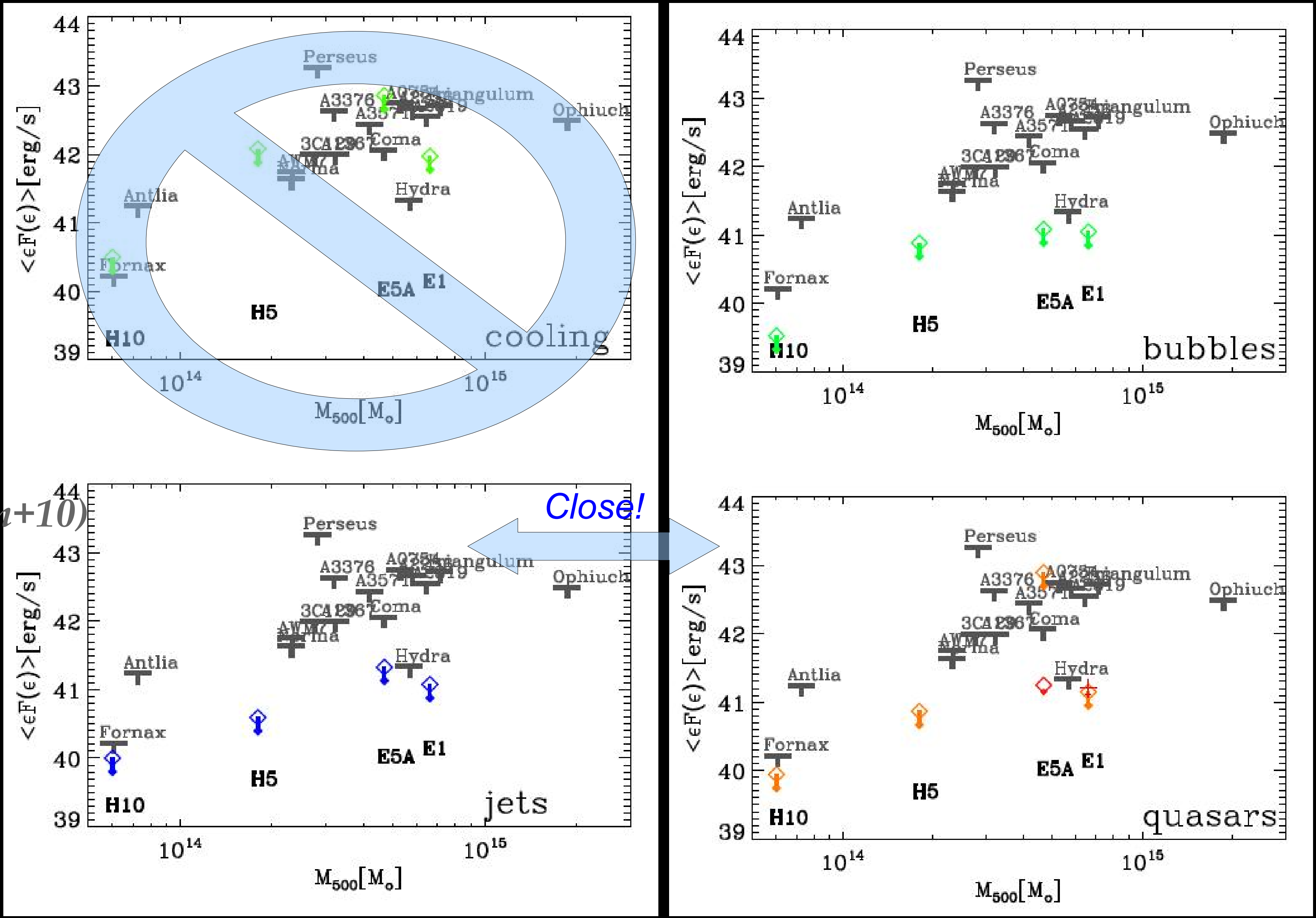
# What is the CR output of each feedback mode?

$$L_\gamma \propto \rho_{IGM}^2 M T \langle \frac{\epsilon_{CR}}{\epsilon_{th}} \rangle$$

Hadronic collision → γ-flux (Pfrommer&Ensslin04)

the proton spectrum must be assumed: α~2.5 (M~3)

*FERMI Limits [1-10]GeV (Ackermann+10)*



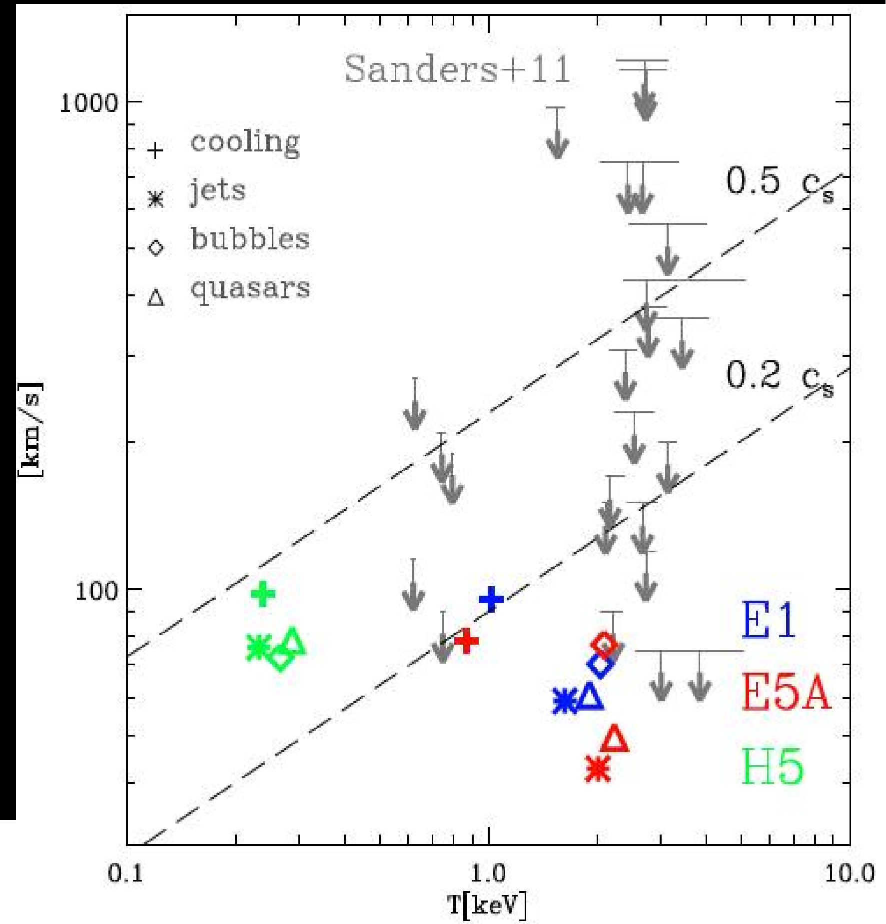

See also: Miniati03;Pinzke&Pfrommer10;Donnert+ 10

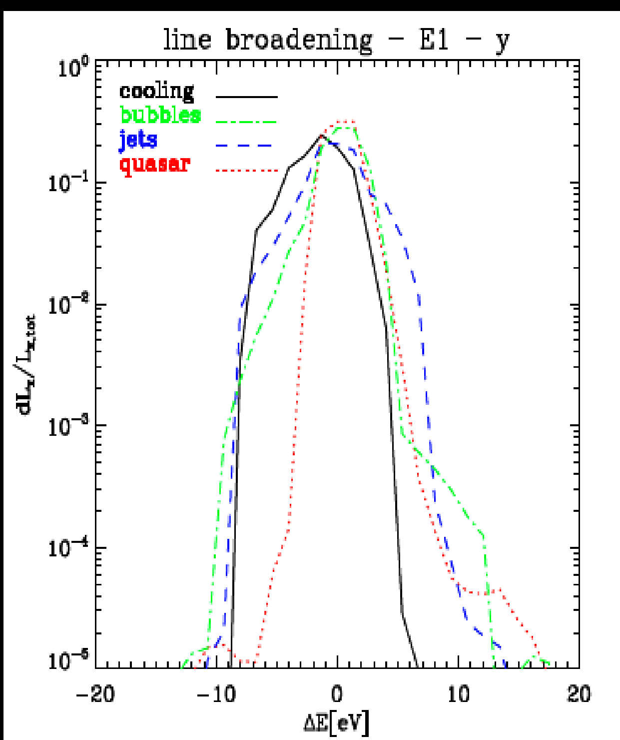
• How much turbulence does each mechanism generate?

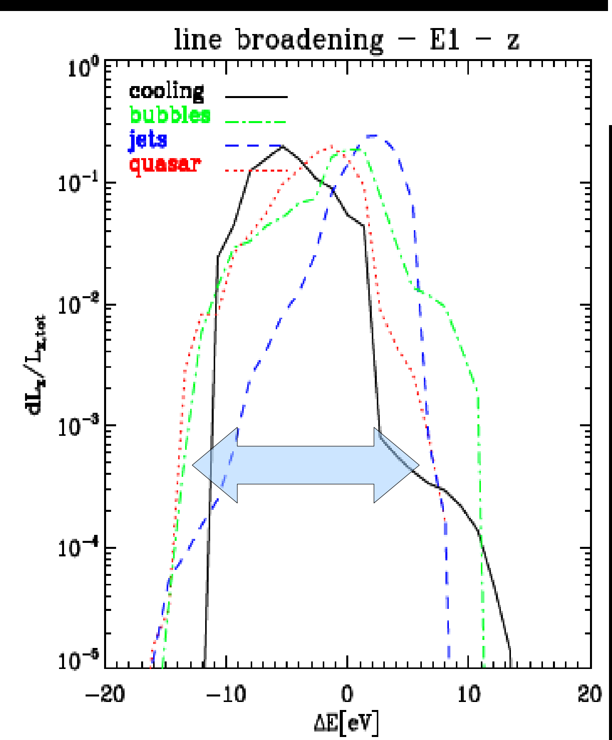
We compare with upper limits from Sanders et al.10 (XMM)

The volumetric turbulence from mergers is dominant

jets/AGN/bubbles → within core




jets/AGN
→300km/s intermittent

bubbles
→ 70 km/s continuous

jets → anisotropy

Cosmic ray (protons) from accretion, merger and AGN driven shocks:

→ various "modes" of AGN feedback seem to solve the "cooling flow" problem

→ the different modes can produce nearly identical X-ray (thermal properties), but quite different NT-ones.

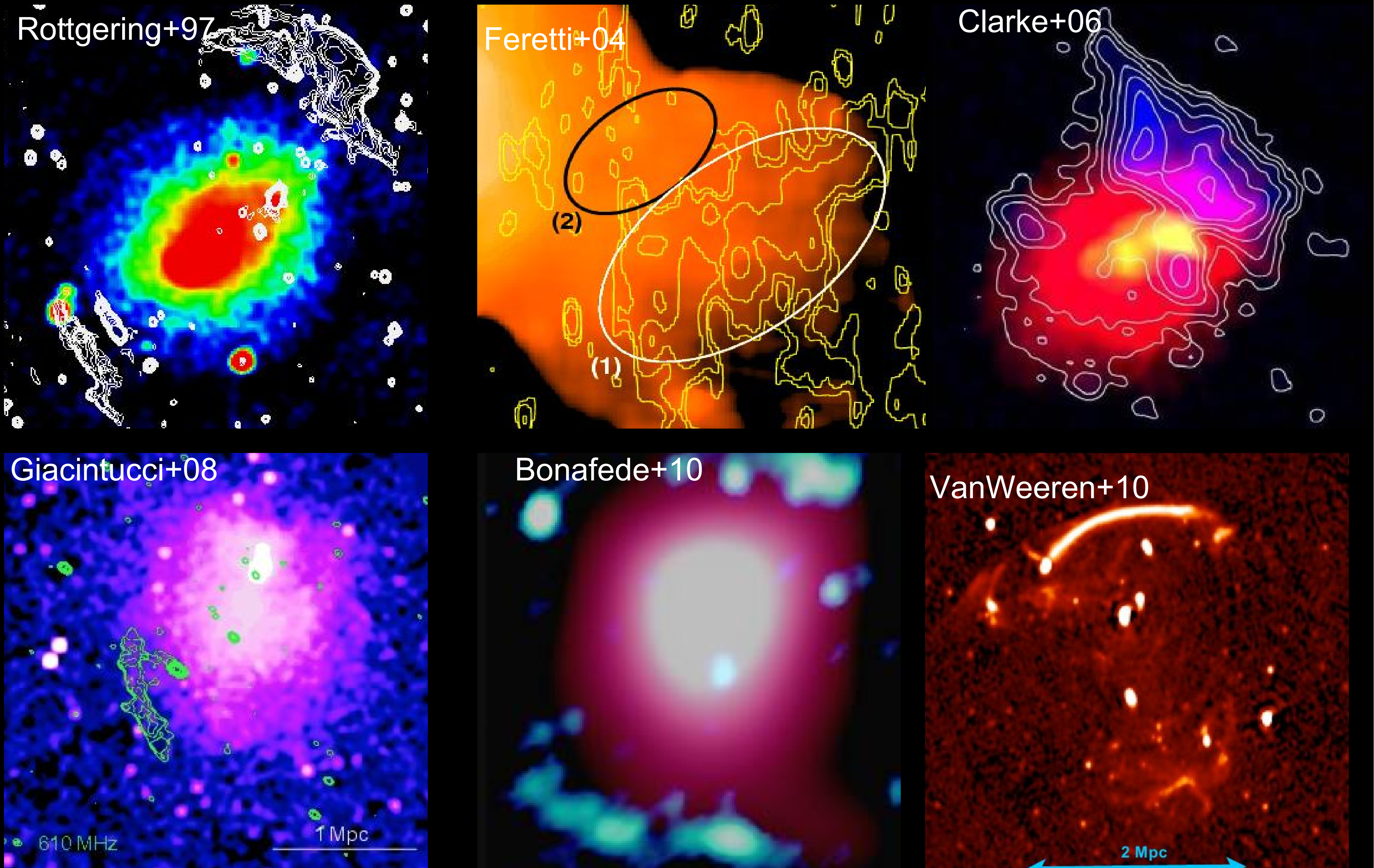
→ cooling-flow models are ALWAYS rejected

→ 3 times lower FERMI limits for $\gamma$-flux will limit power/duty cycle of jets/quasar mode

→ upper limits for turbulence <100km/s will limit bubbles density contrast

# Why are central radio relics so rare?

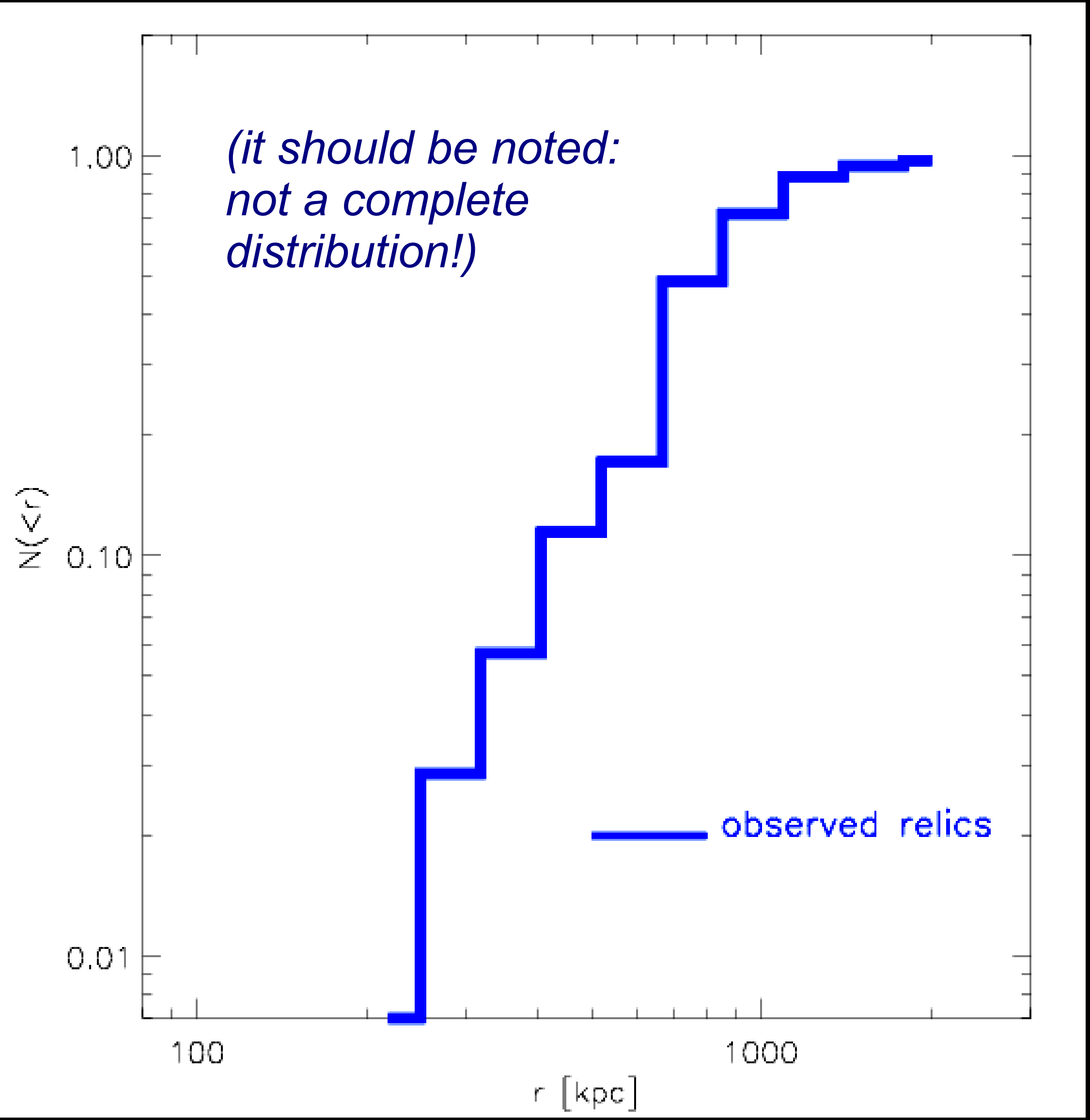
F. Vazza[1,2⋆], M. Brüggen[1], R. van Weeren[3], A. Bonafede[1], K. Dolag[4], G. Brunetti[2]



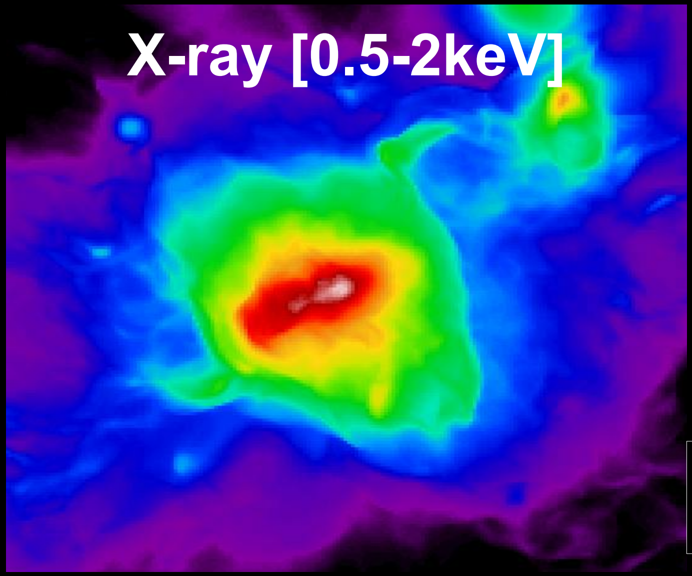
| name | z | r[kpc] |
|---|---|---|
| Coma cluster | 0.023 | 2008 |
| Abell 548b | 0.042 | 693 |
| Abell 548b* | 0.042 | 456 |
| Abell 3376 E | 0.0456 | 845 |
| Abell 3376 W | 0.0456 | 1008 |
| Abell 3667 E | 0.055 | 1459 |
| Abell 3667 W | 0.055 | 1887 |
| Abell 2256 | 0.059 | 470 |
| CIZA J0649.3+1801 | 0.064 | 802 |
| RXC J1053.7+5452 | 0.07 | 981 |
| Abell 2061 | 0.078 | 1558 |
| Abell 2255 | 0.0806 | 1065 |
| Abell 3365 E | 0.093 | 1079 |
| Abell 3365 W | 0.093 | 777 |
| ZwCl 0008.8+5215 E | 0.104 | 798 |
| ZwCl 0008.8+5215 W | 0.104 | 808 |
| Abell 1664* | 0.128 | 895 |
| Abell 1240 S | 0.159 | 982 |
| Abell 1240 N | 0.159 | 924 |
| Abell 2345 E | 0.177 | 1431 |
| Abell 2345 W | 0.177 | 857 |
| Abell 1612 | 0.179 | 894 |
| CIZA J2242.8+5301 N | 0.192 | 1565 |
| CIZA J2242.8+5301 S | 0.192 | 1062 |
| Abell 115 | 0.197 | 998 |
| Abell 2163 | 0.203 | 1405 |
| Abell 746 | 0.232 | 1606 |
| RXC J1314.4-2515 W | 0.244 | 577 |
| RXC J1314.4-2515 E | 0.244 | 937 |
| Abell 521 | 0.247 | 692 |
| ZwCL 2341.1+0000 N* | 0.27 | 1198 |
| ZwCL 2341.1+0000 S | 0.27 | 767 |
| Abell 2744 | 0.308 | 1501 |
| MACSJ0717.5+3745* | 0.555 | 298 |

34 clusters    $0 \leq z \leq 0.3$

# Cumulative radial distribution of observed radio relics from the clusters centre




NO relics inside 200 kpc!



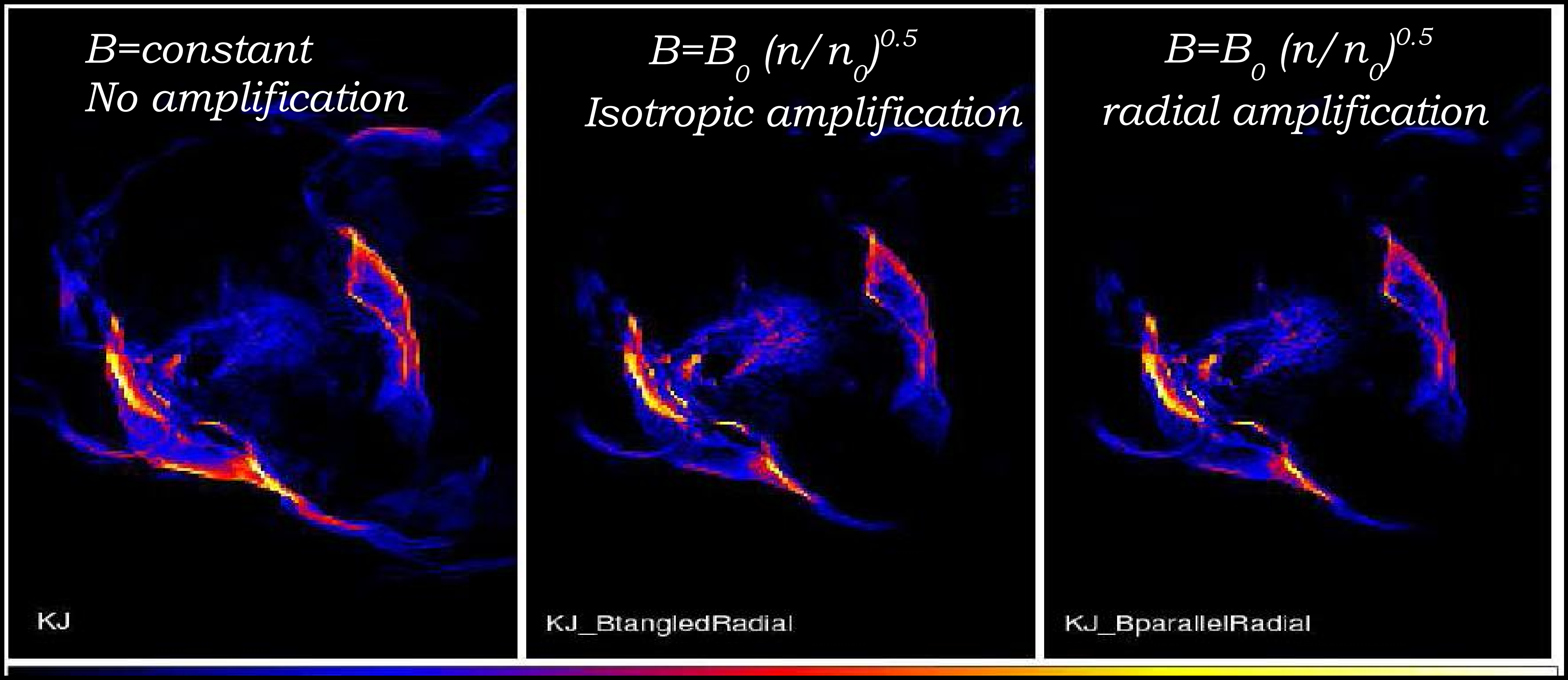

- We measure Mach numbers in the 3D
- Flux of kinetic energy across the shock:

$$F_{\rm KE} = \frac{\rho_{\rm u} v_{\rm s}^3}{2} \Delta S,$$

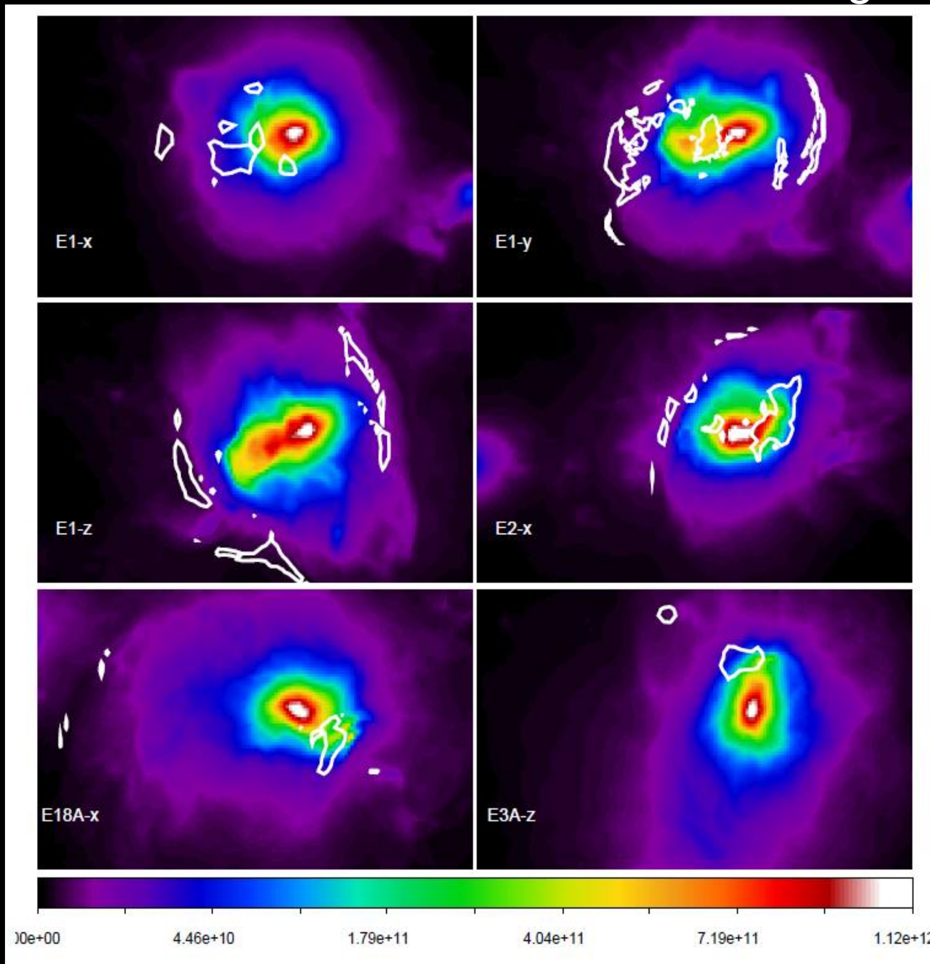
- Injection efficiency $\eta(M)$
- Different magnetic field profiles B(n)
- Compression factor R(n)

$$P_{radio} = F_{KE} \cdot \eta(M) \cdot B(n) \cdot R(M)$$

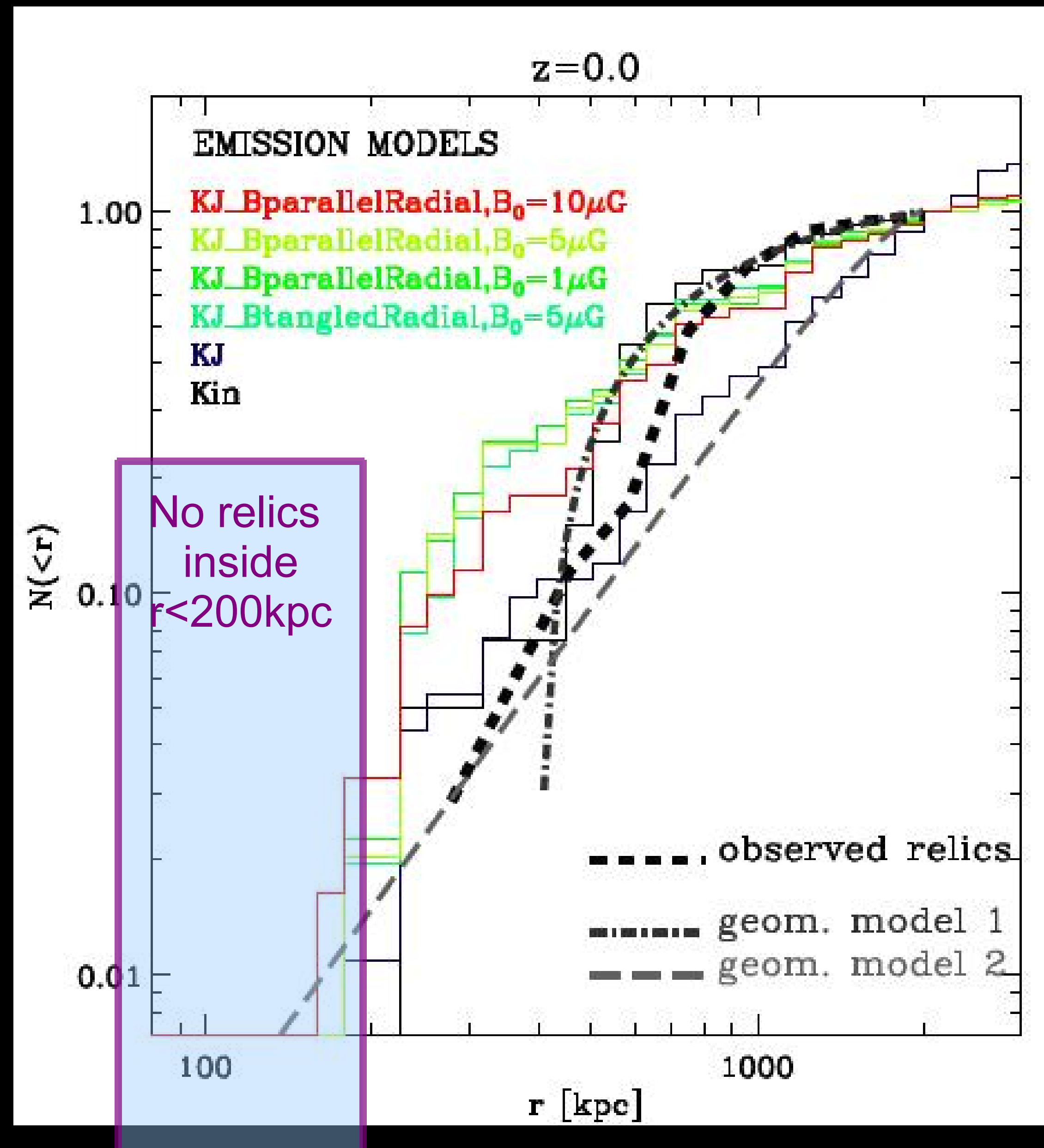
*(Pfrommer+07,Hoeft+08,Skillmann+10)*



"Detectable" radio relics → relics catalogue



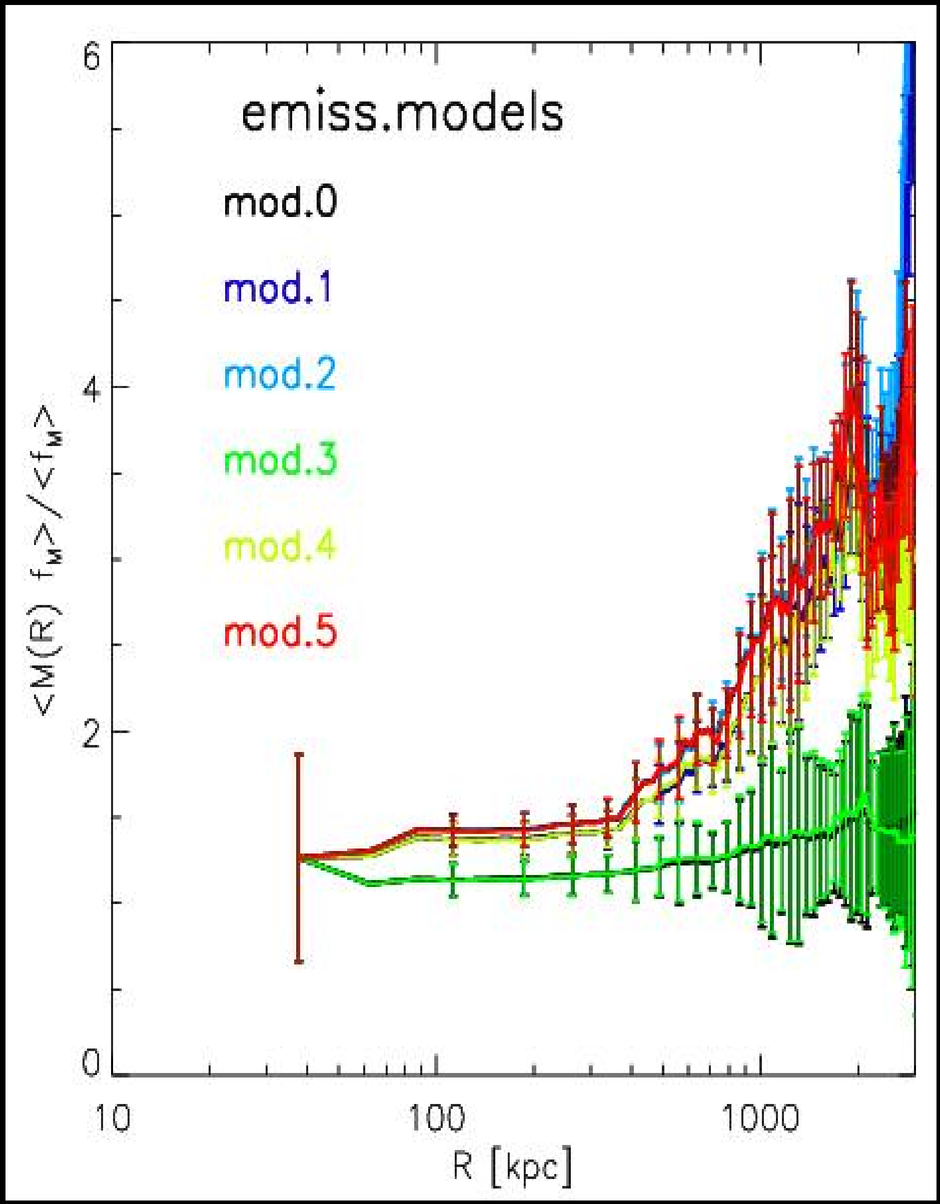

# Radial distribution functions for Simulated radio relics (5 models)

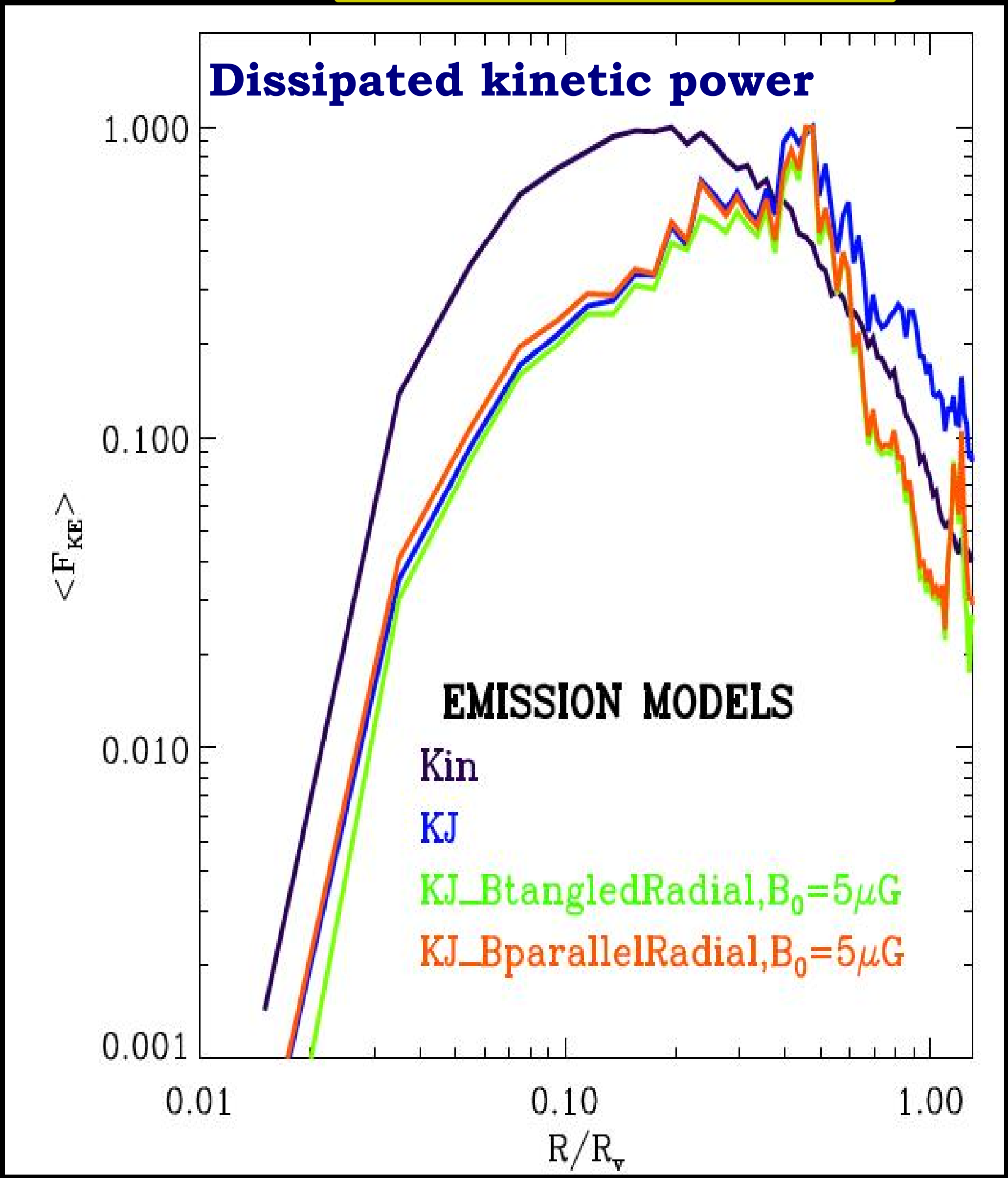



~Regardless of the assumed model for B(n) and amplification the lack of central relics is naturally explained if they originate from shocks

3D profiles of average Mach number (weighted by all models)

3D profiles of energy flux across shocks (all models)



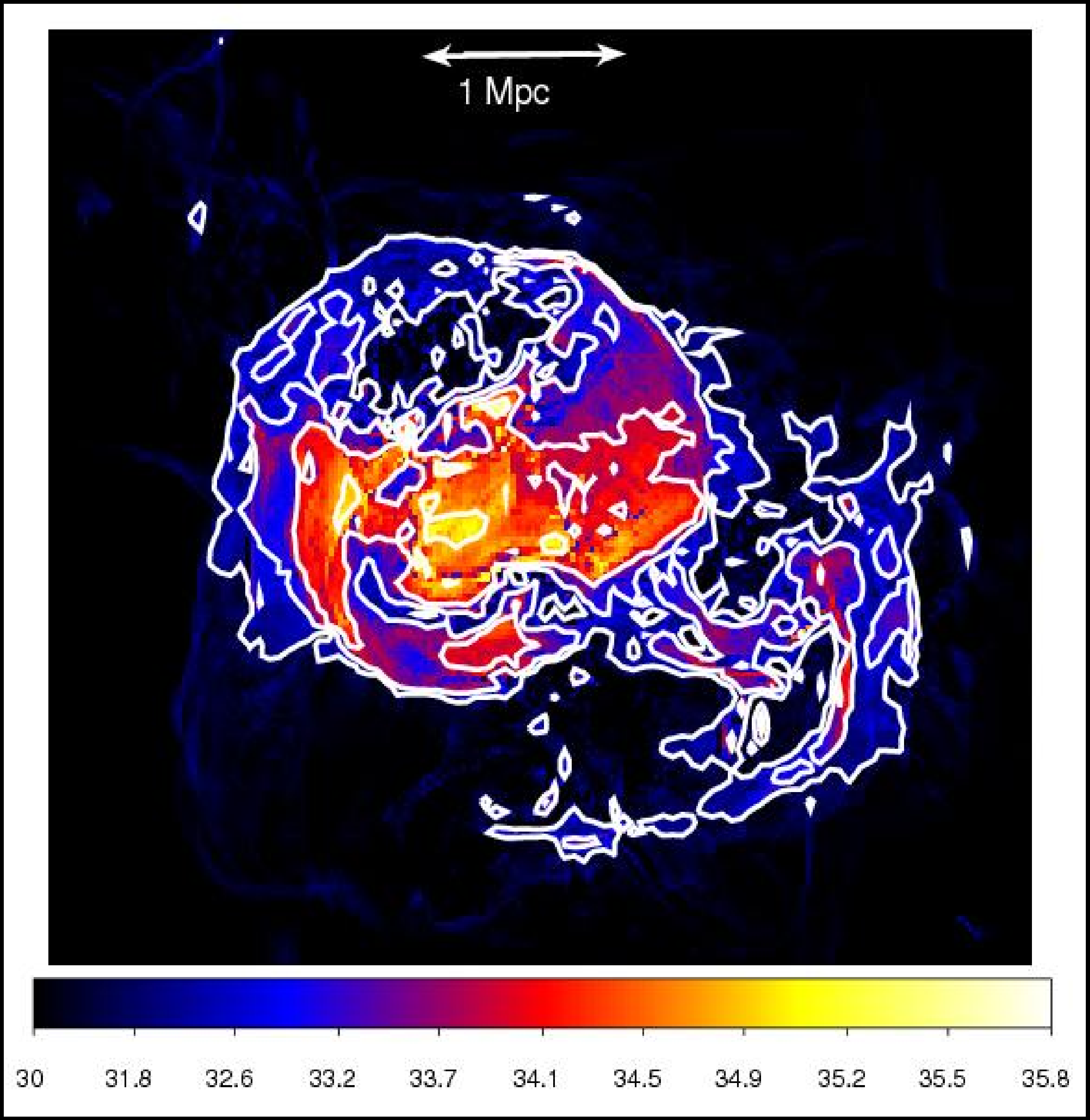



# Radio-halos CANNOT be face-on relic (from shocks)

- We studied projection effects for each cluster

- If the relics is seen face-one, we would need a dynamical range of ~100 in radio images to detect emission

- The emission would have a very “flat” spectrum $\alpha \approx -1$



# Why are central radio relics so rare?

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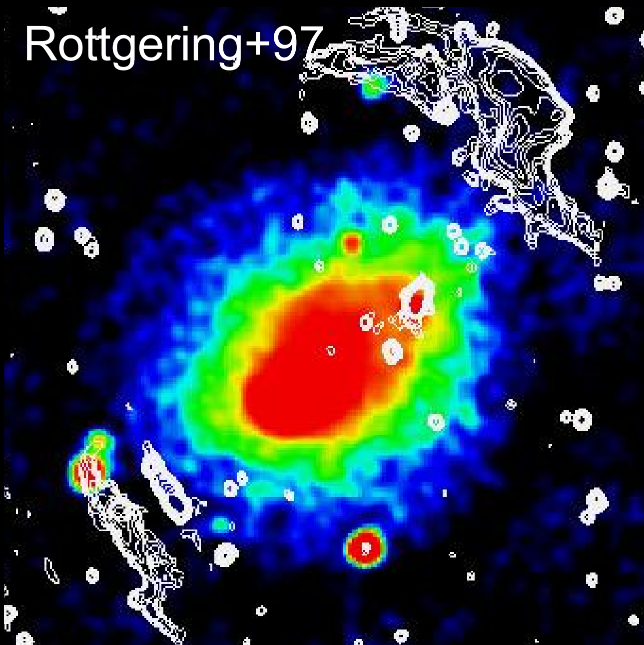
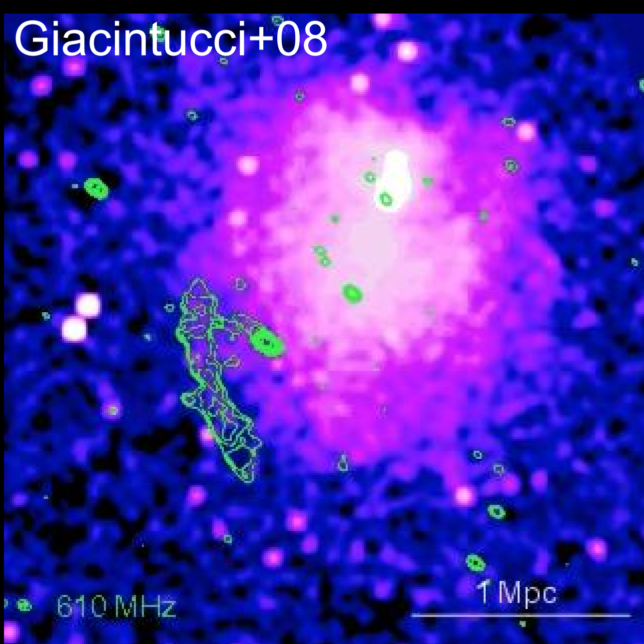



We suggest that:

1) shocks in the ICM dissipate most of the kinetic energy at R>0.2Rvir

2) geometry makes the probability of seeing a relics *projected* onto the centre very small, <1%

3) a relic seen face-on is too dim to be detected ($Flux_{face\text{-}on}$ < 0.01-01 $Flux_{edge\text{-}on}$)

## Work in progress: VLA observation of Abell1497 (z=0.11)
(FV, Bonafede, Bruggen in prep..)

**A1497:**

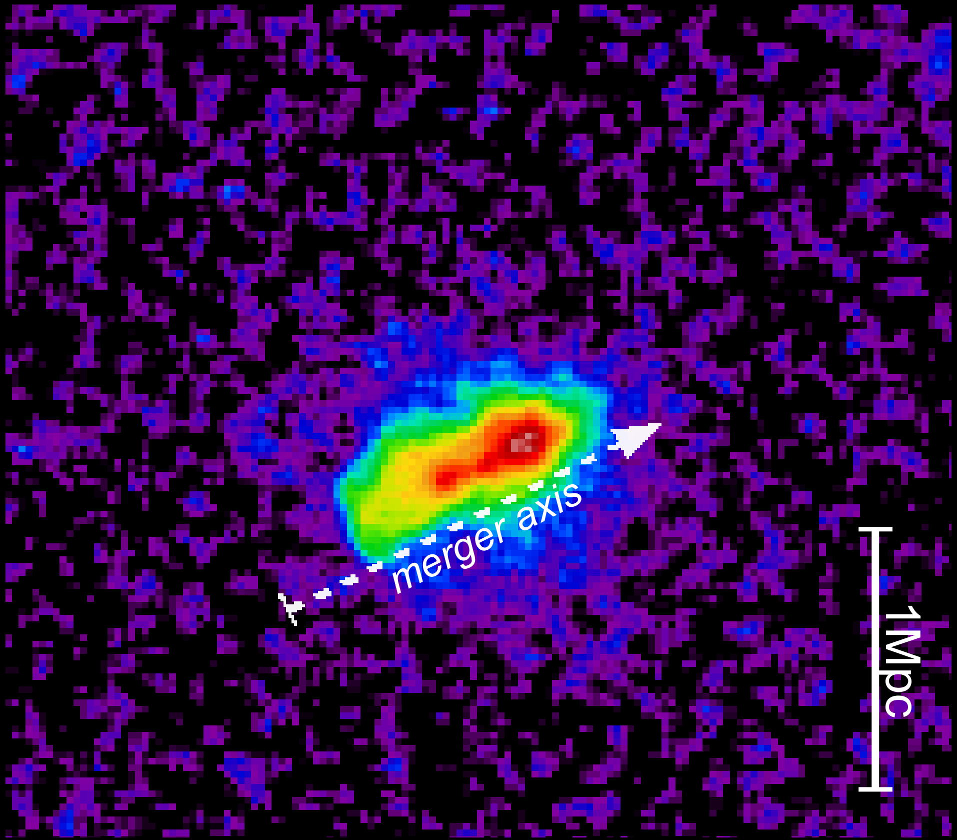
*z=0.11*

*Lx ~3 $10^{44}$ erg/s*

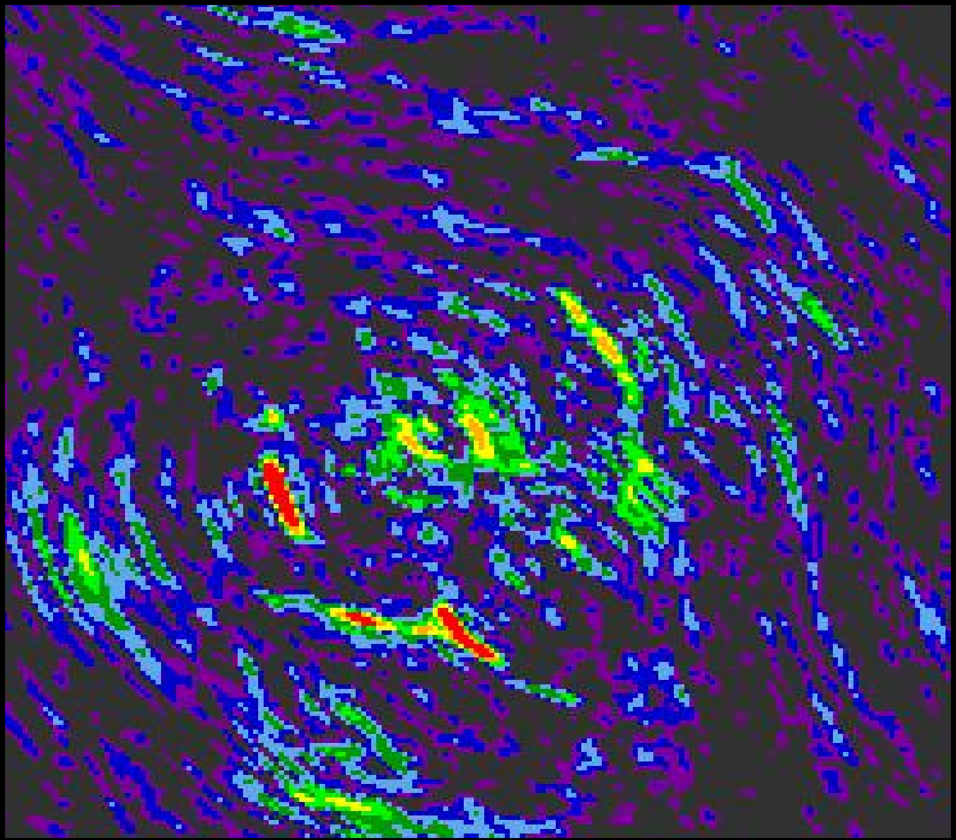
**Radio observation:**

*VLA Array D*

*Observing time = 10 hr*




A1497 with Chandra



(dirty image)

## Work in progress: VLA observation of Abell1497 (z=0.11)

(FV, Bonafede, Bruggen in prep..)

**A1497:**

*z=0.11*

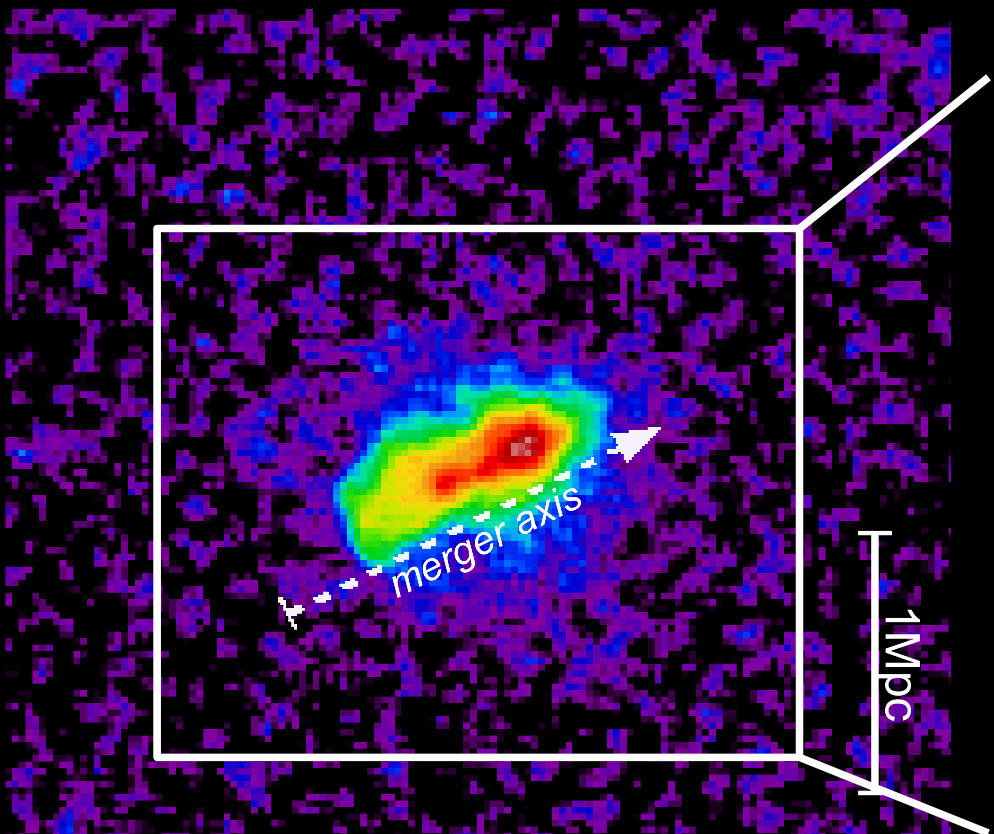
*Lx ~3 $10^{44}$ erg/s*

**Radio observation:**

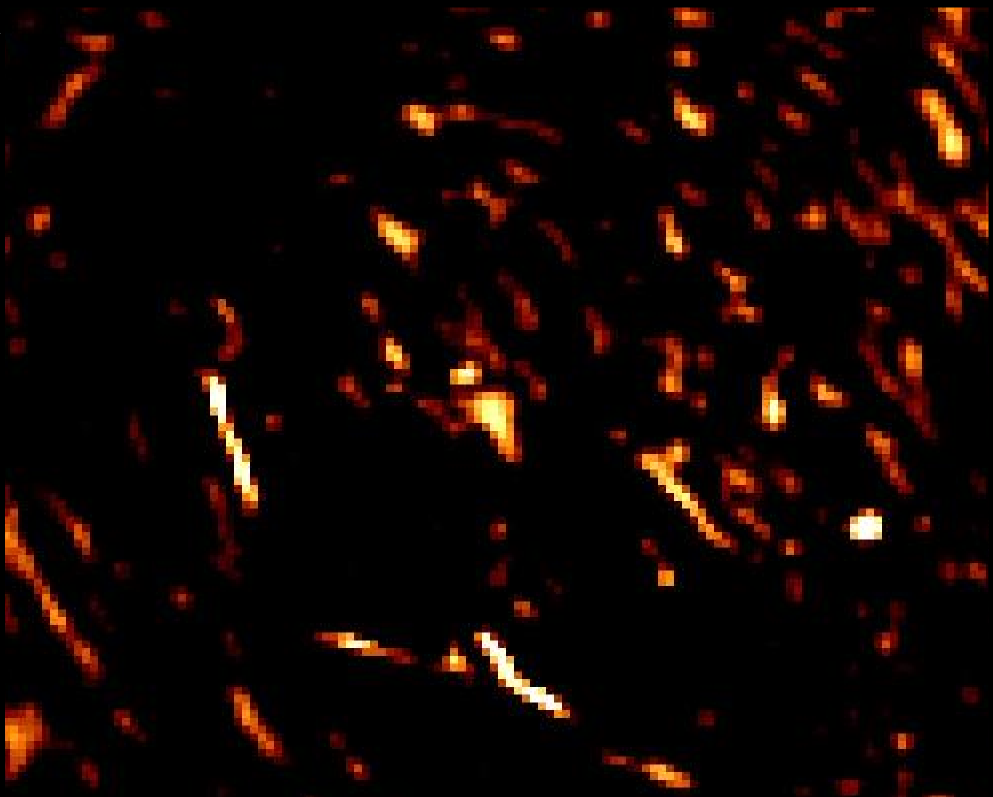
*VLA Array D*

*Observing time = 10 hr*

*Noise ~70μJ/beam*

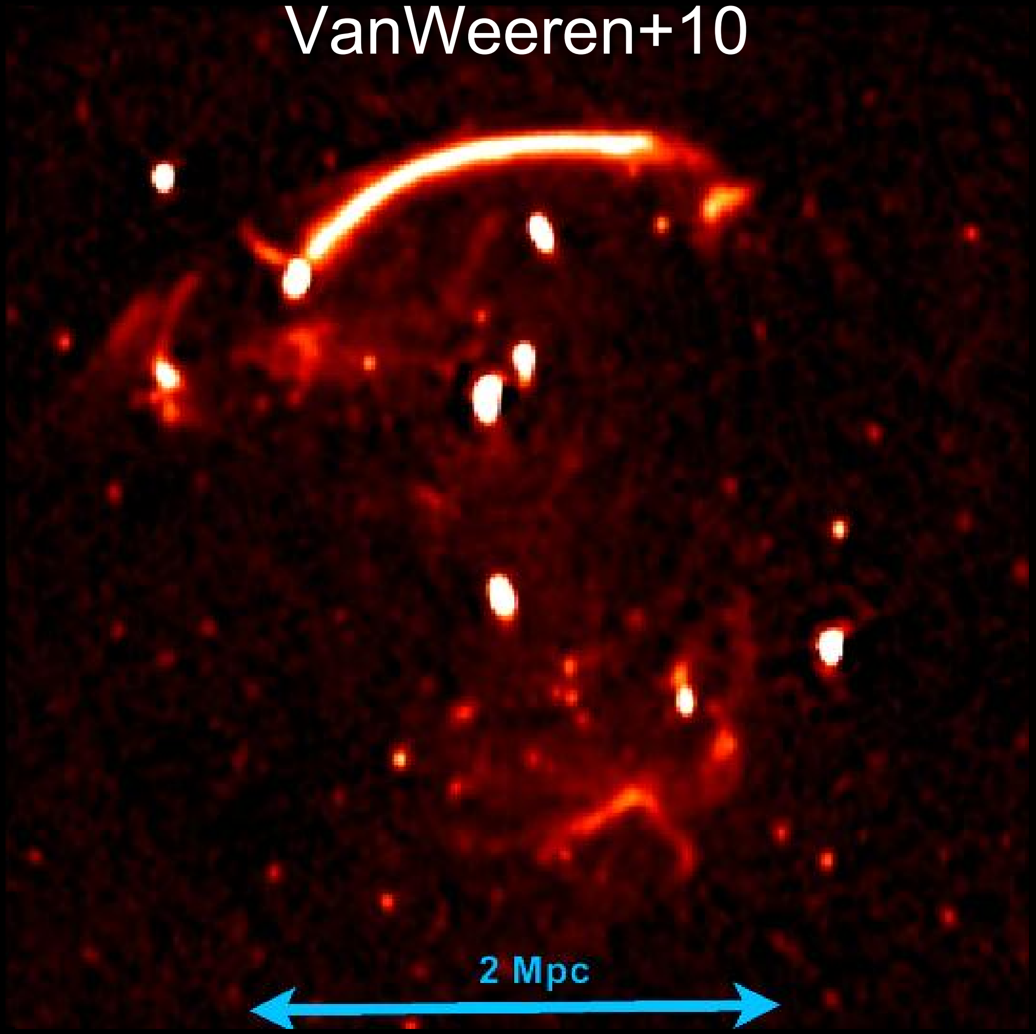



A1497 with Chandra



(image after cleaning...preliminary)

## Work in progress: VLA observation of Abell1497 (z=0.11)
(FV, Bonafede, Bruggen in prep..)

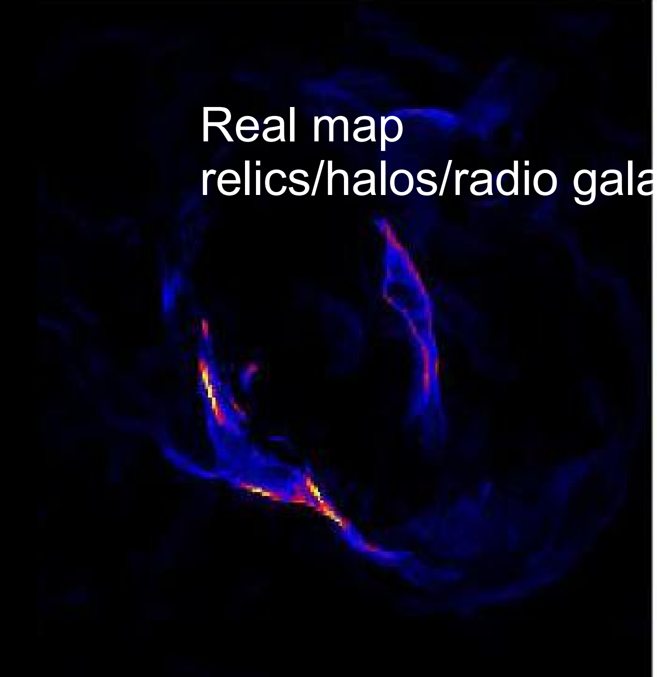


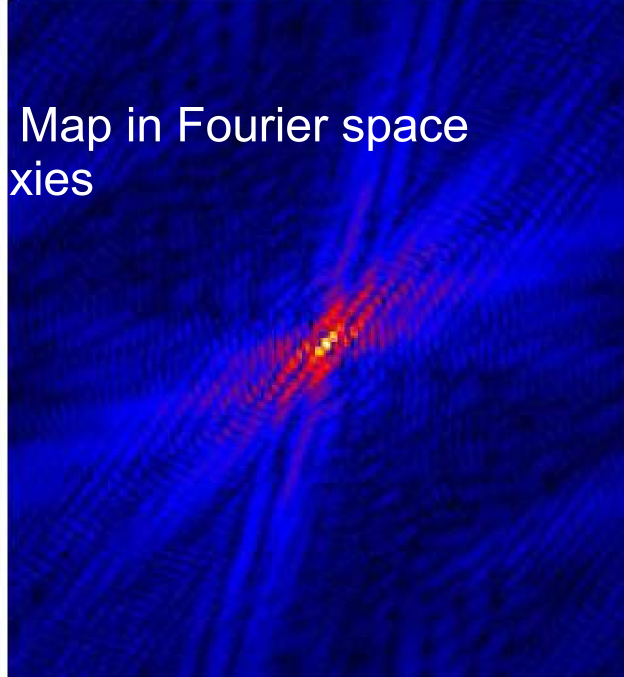

CIZA J2242.8+5301

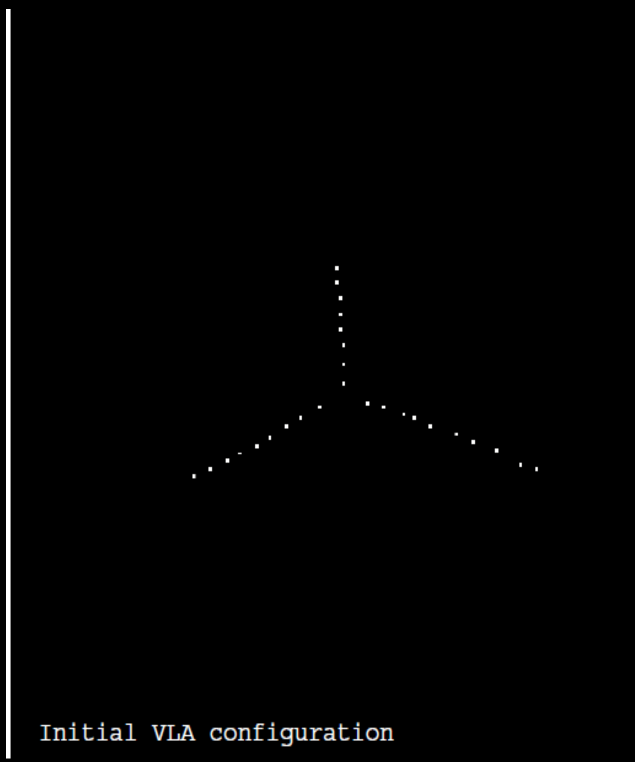
A1497

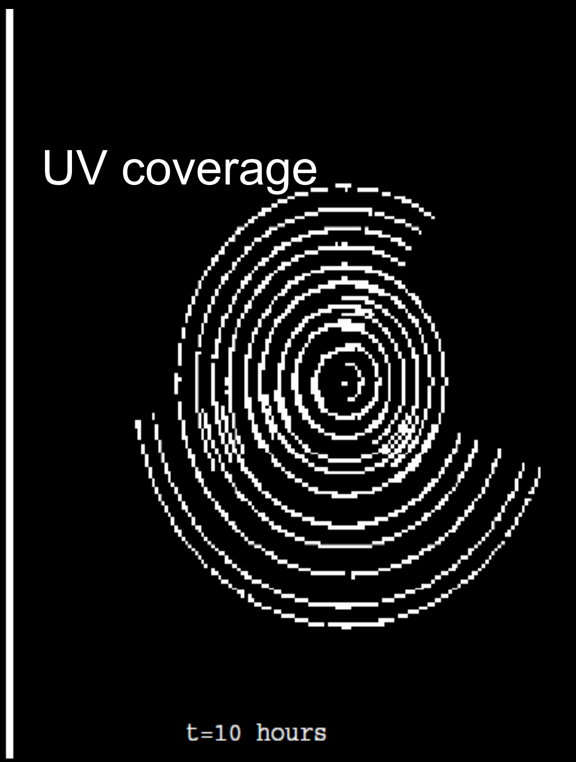
# SIMULATED RADIO

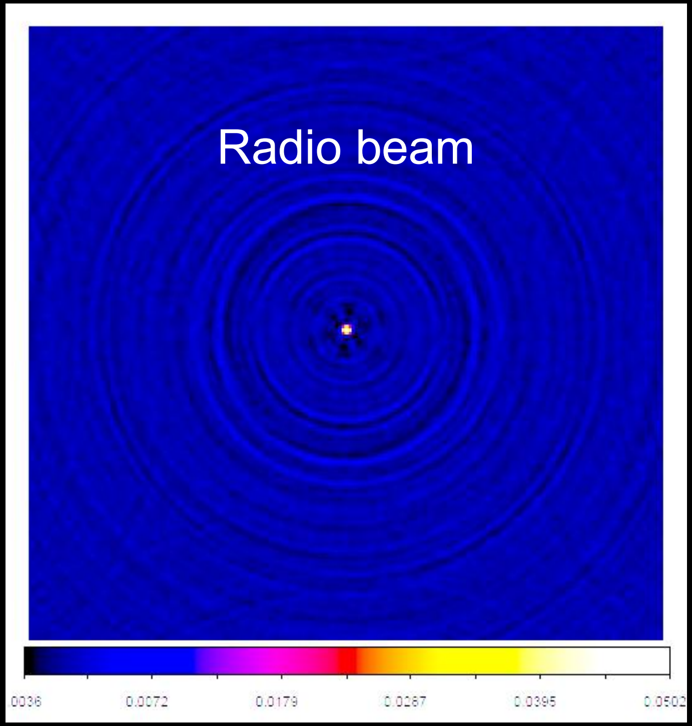
(IMAGES)



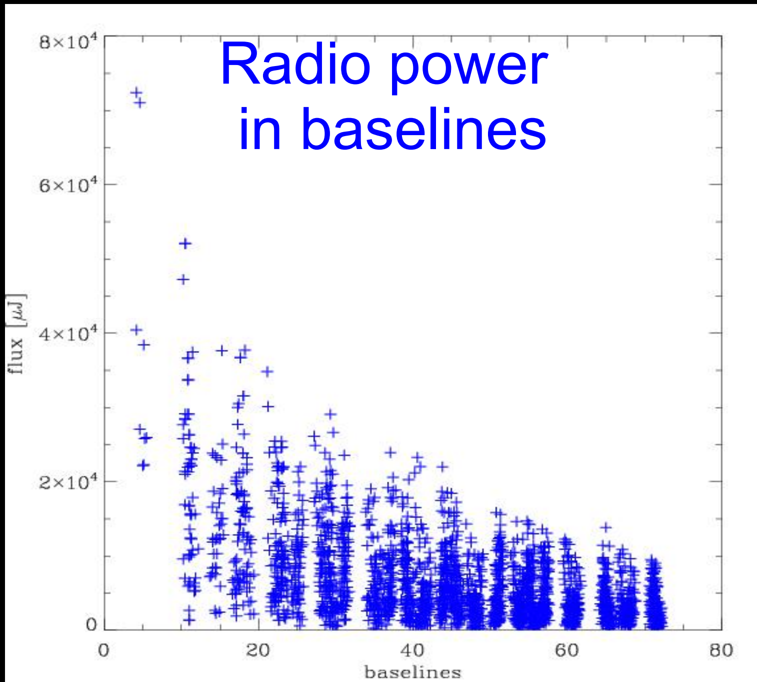



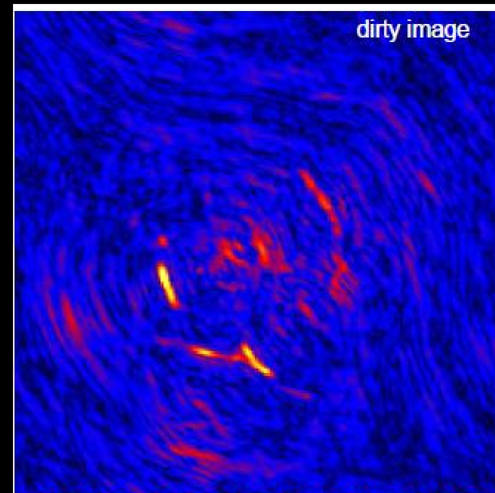



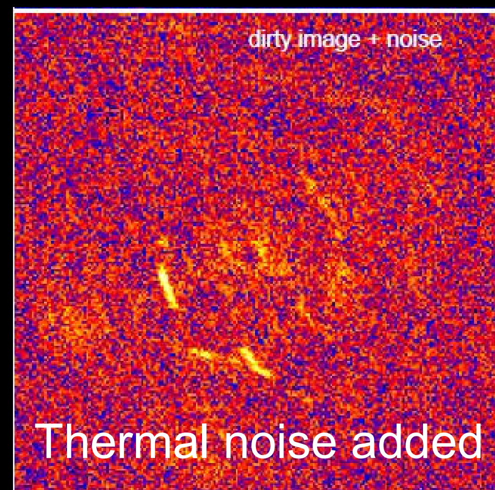



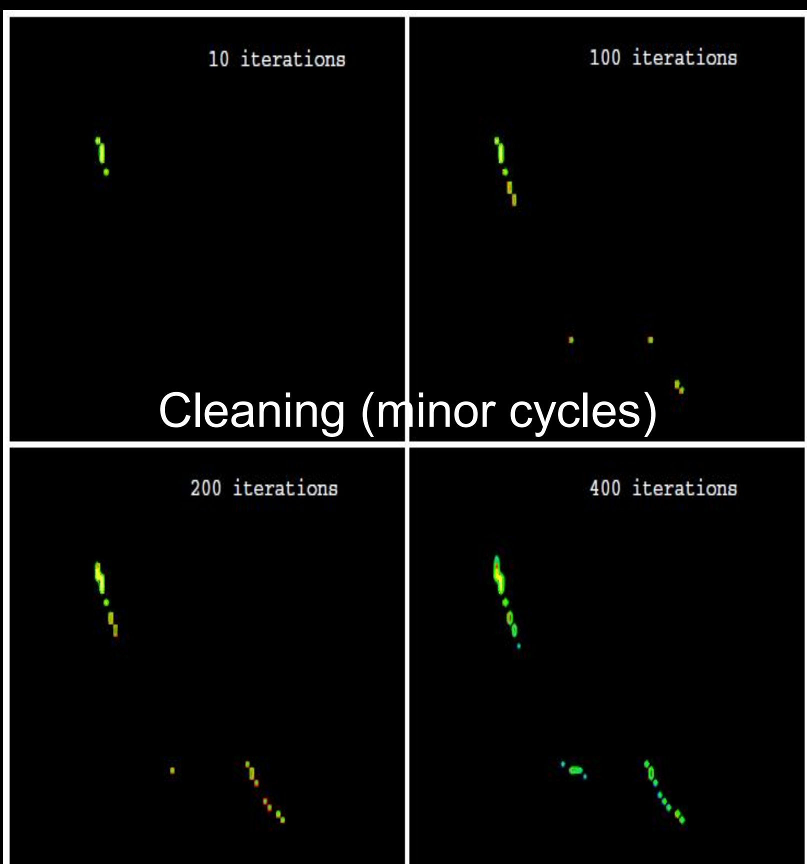
# SIMULATED RADIO

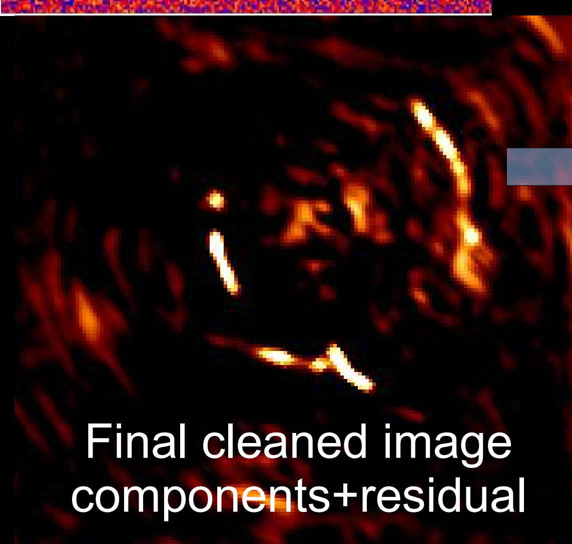
*(IMAGES)*



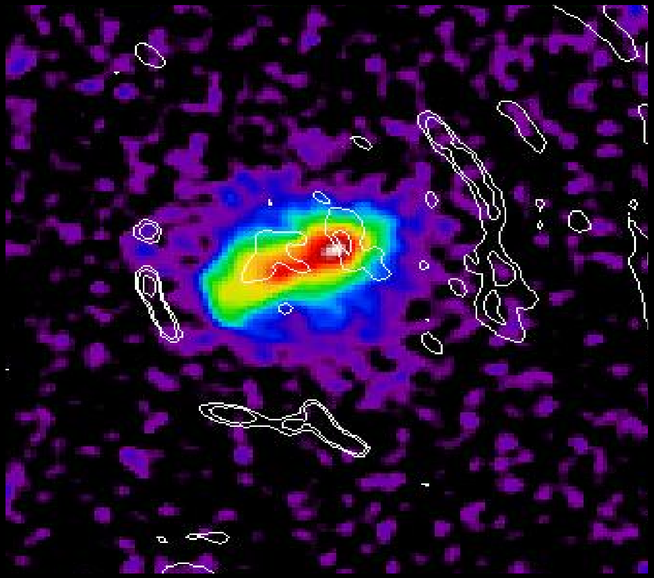




- R*ealistic* mock radio images (hopefully)
- Can process any 2D image from sim.
- Test models under realistic conditions
- Useful for proposal (hopefully)



**A1497:**


*danke!*