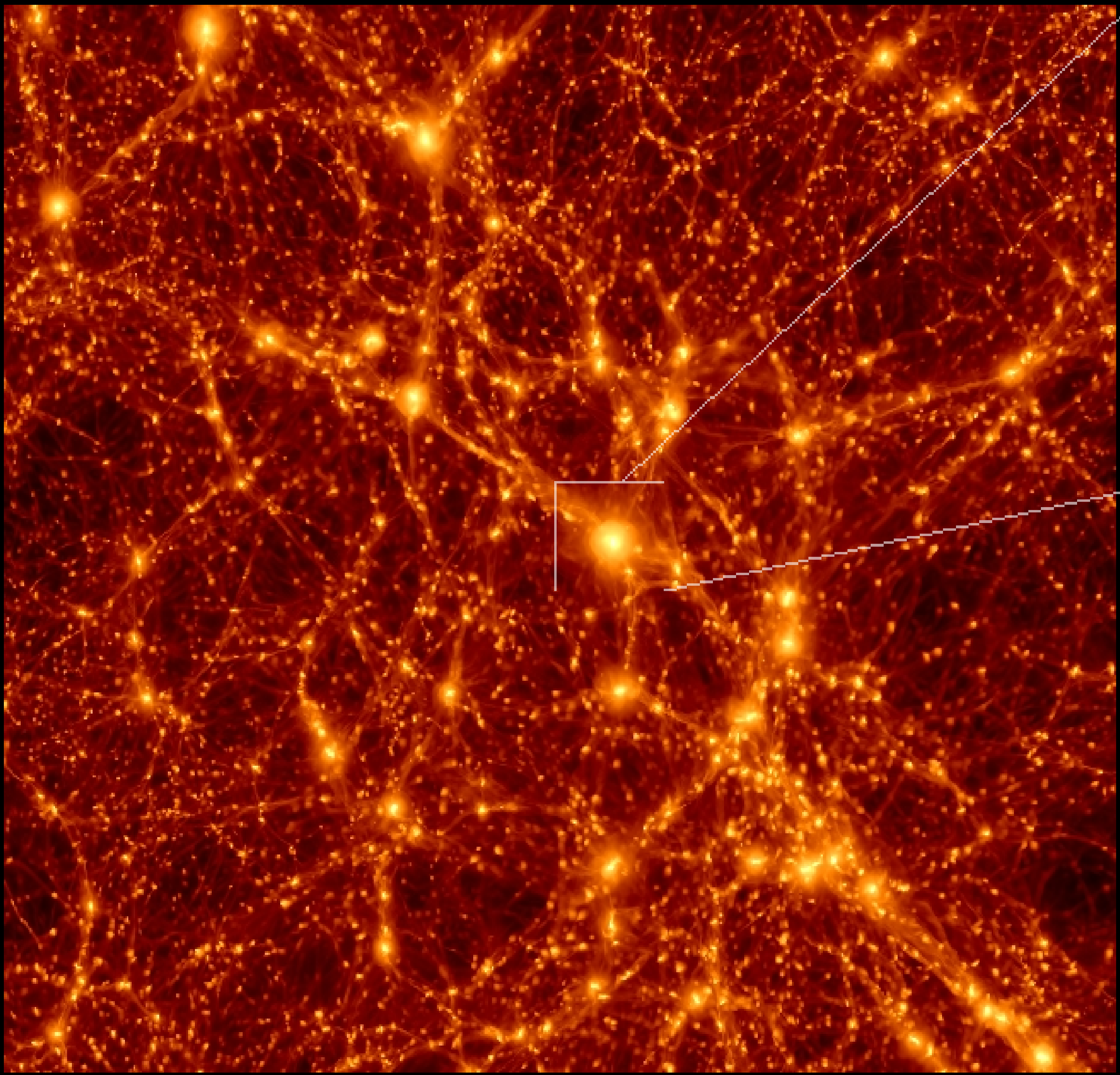
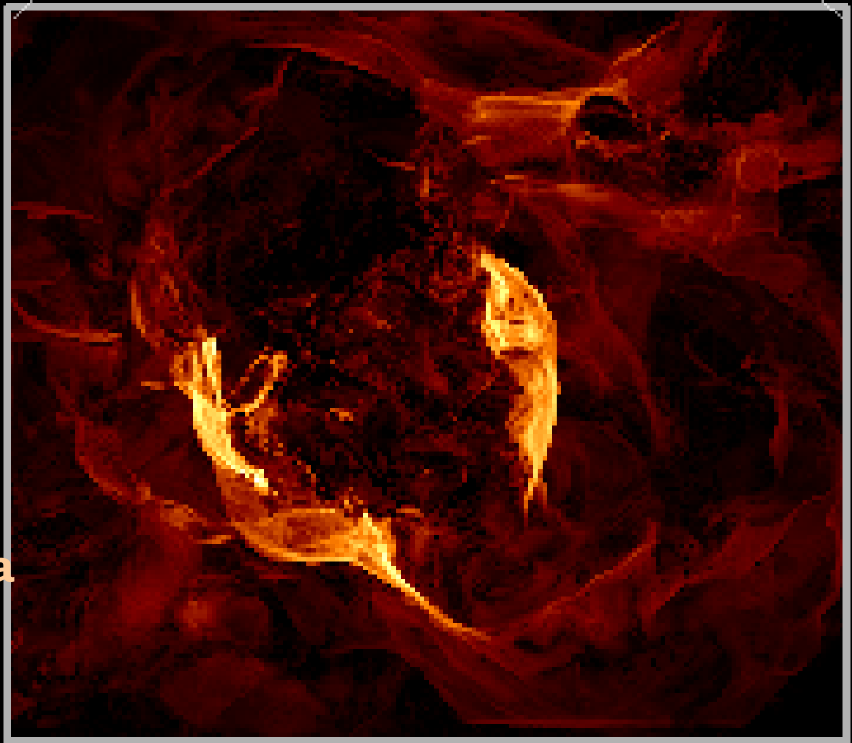
The injection and evolution of cosmic ray hadrons in cosmological simulations





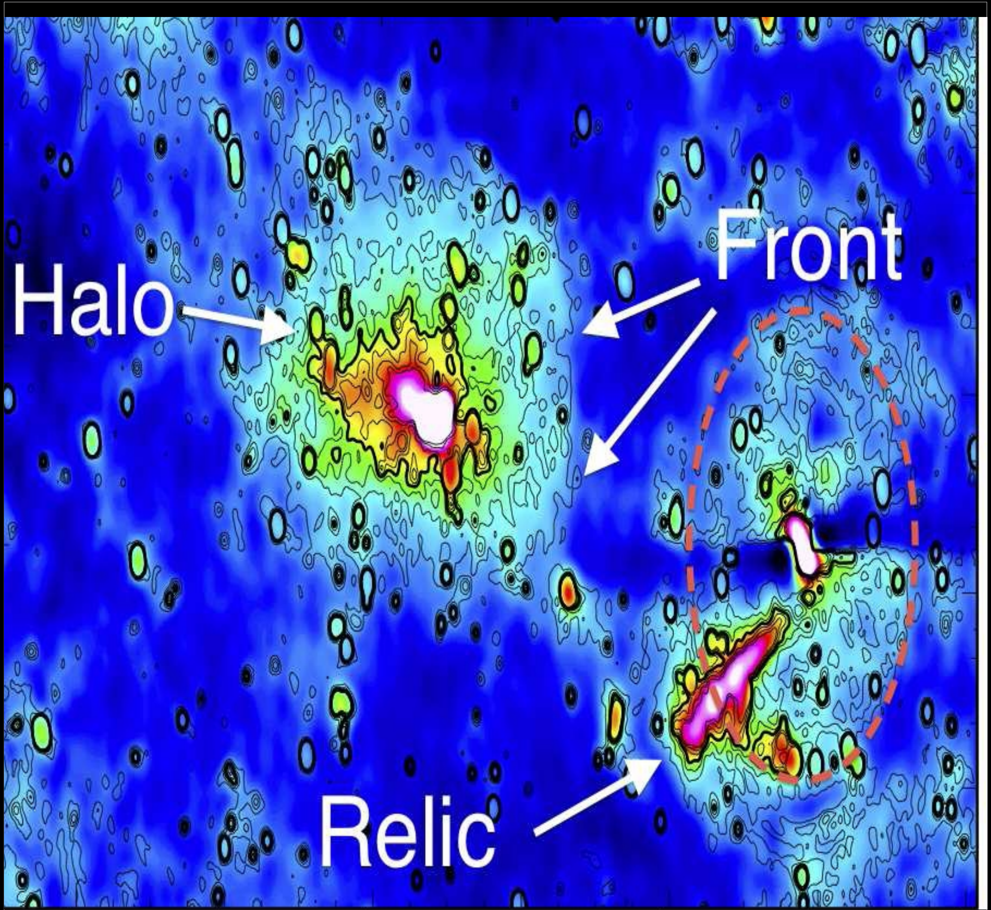
F.Vazza – Hamburg Obs. & Radio Inst.Bologna
M.Bruggen (HS) , G. Brunetti(IRA),
C. Gheller (CSCS) , A.Bonafede (HS)

Scientific case:

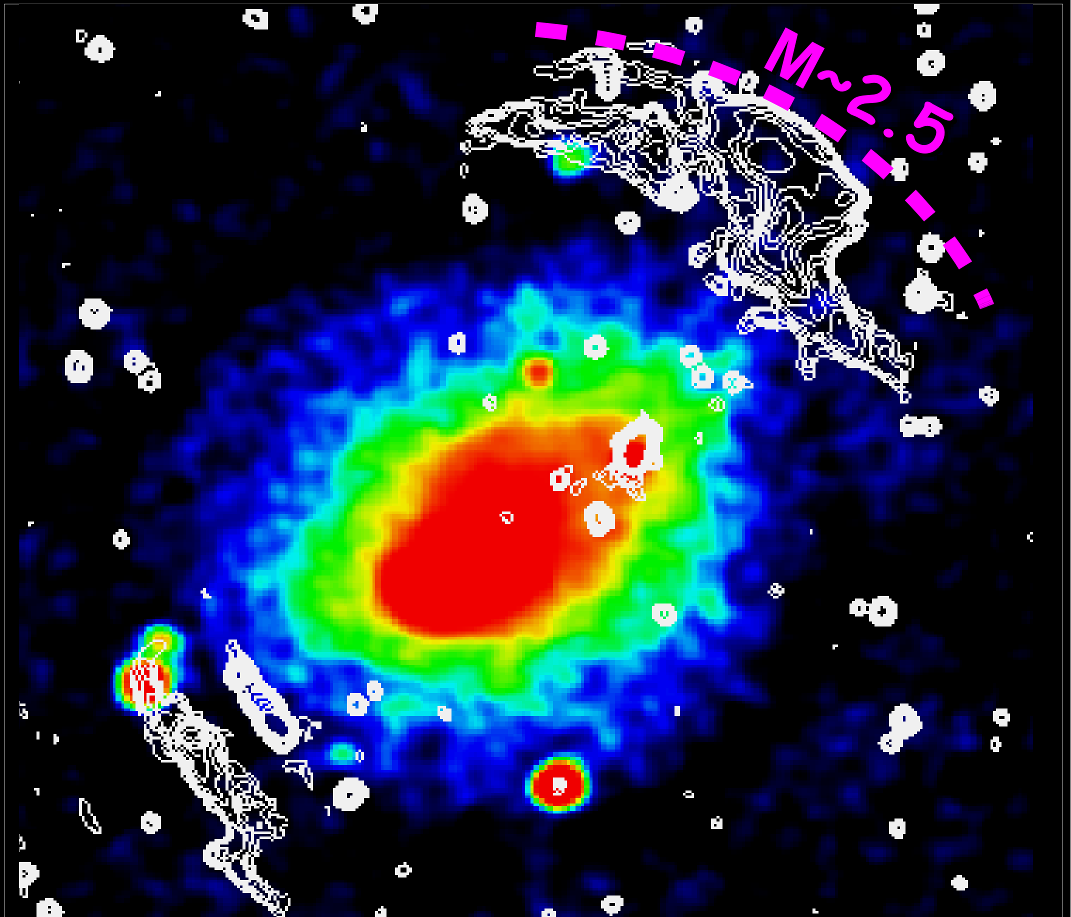
- Observed clusters show evidence of magnetic field, turbulence, shocks and CR (electrons) acceleration

  → need for improvement in cosmological simulations and methods for shocks and cosmic rays physics

shock:Akamatsu+12



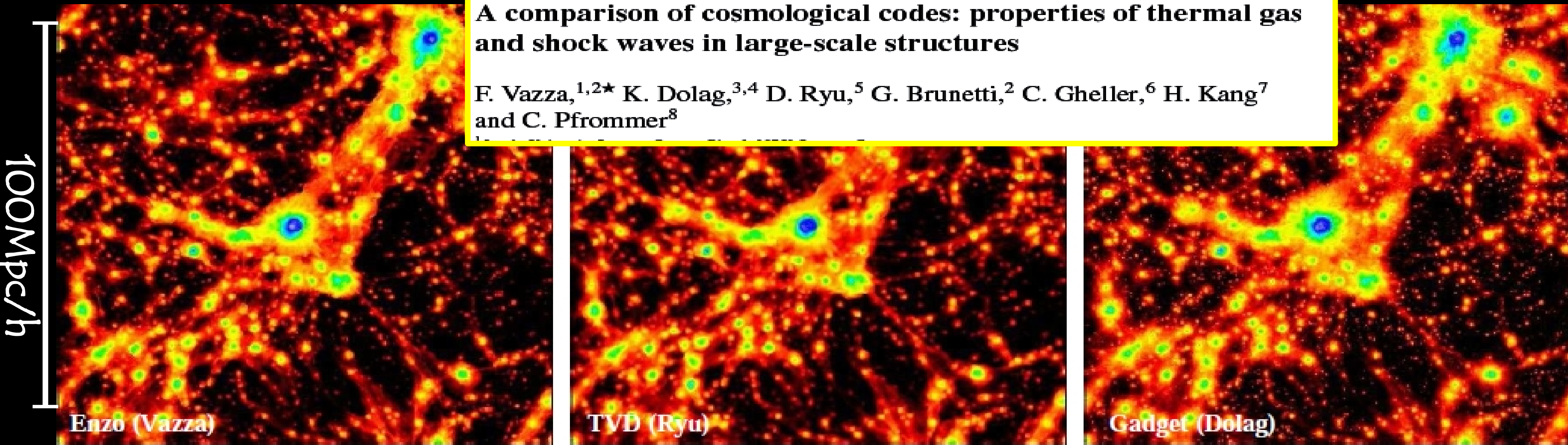
COMA Brown et al.2011



A3667 Rottgering et al.1998

A comparison of cosmological codes: properties of thermal gas and shock waves in large-scale structures

F. Vazza,[1,2★] K. Dolag,[3,4] D. Ryu,[5] G. Brunetti,[2] C. Gheller,[6] H. Kang[7] and C. Pfrommer[8]

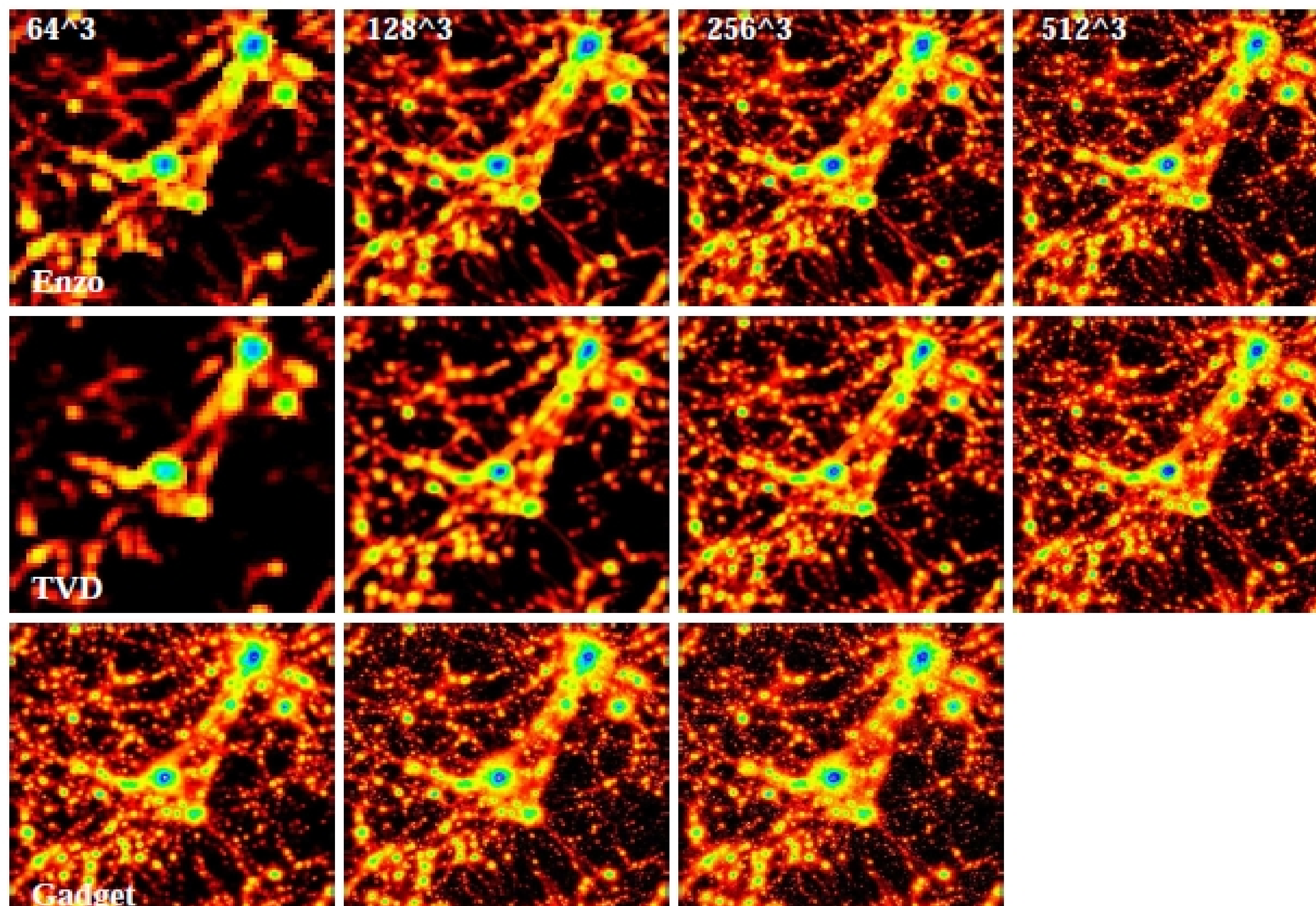


GRID CODES:

- **ES-TVD** (Ryu+93)
- **ENZO-PPM 1.5** (Bryan+95)

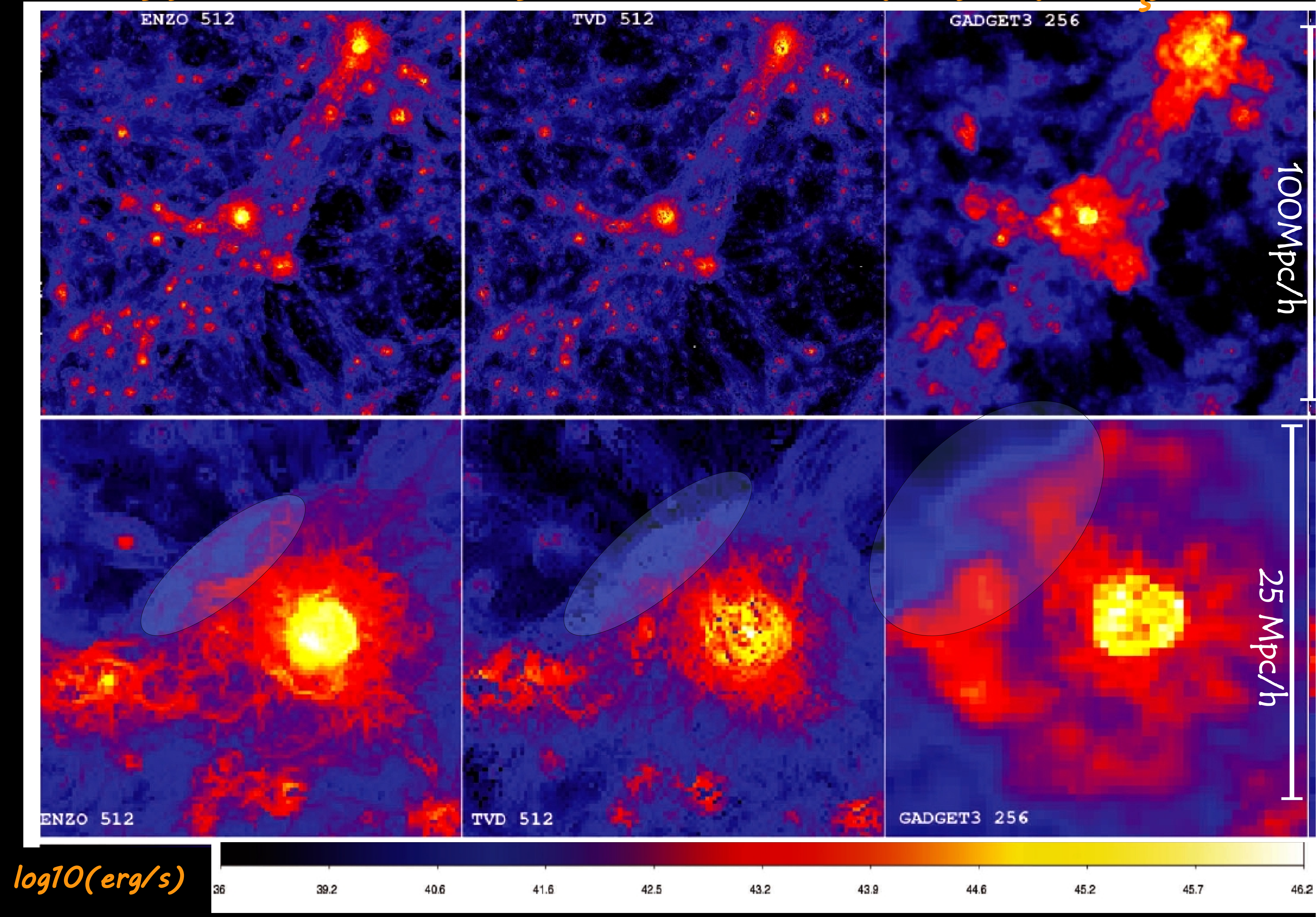
SPH CODE:

- **GADGET3** (Springel05)

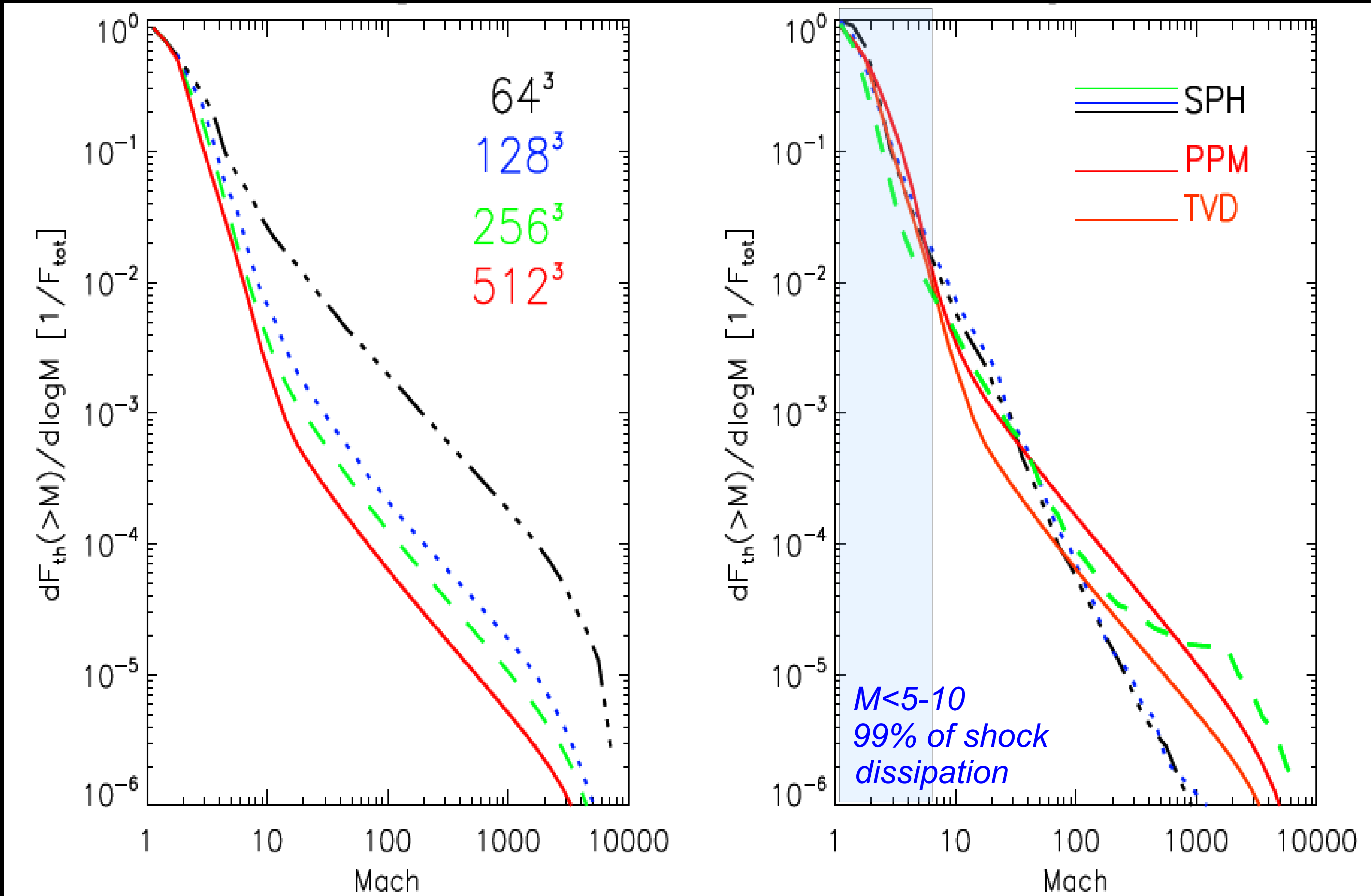


- Shared initial conditions: 100Mpc/h, σ_8=1.2
- Non-radiative physics, no reionization
- Different shock detecting schemes
- Resolutions: 64^3-128^3-256^3-512^3

Energy flux through shocks ~$\delta(M)\rho(Mc_s)^3/2$



Energy flux through shocks $\Phi=\delta(M)\rho(Mc_s)^3/2$



Convergence with resolution

comparison between codes

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...

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

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

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

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

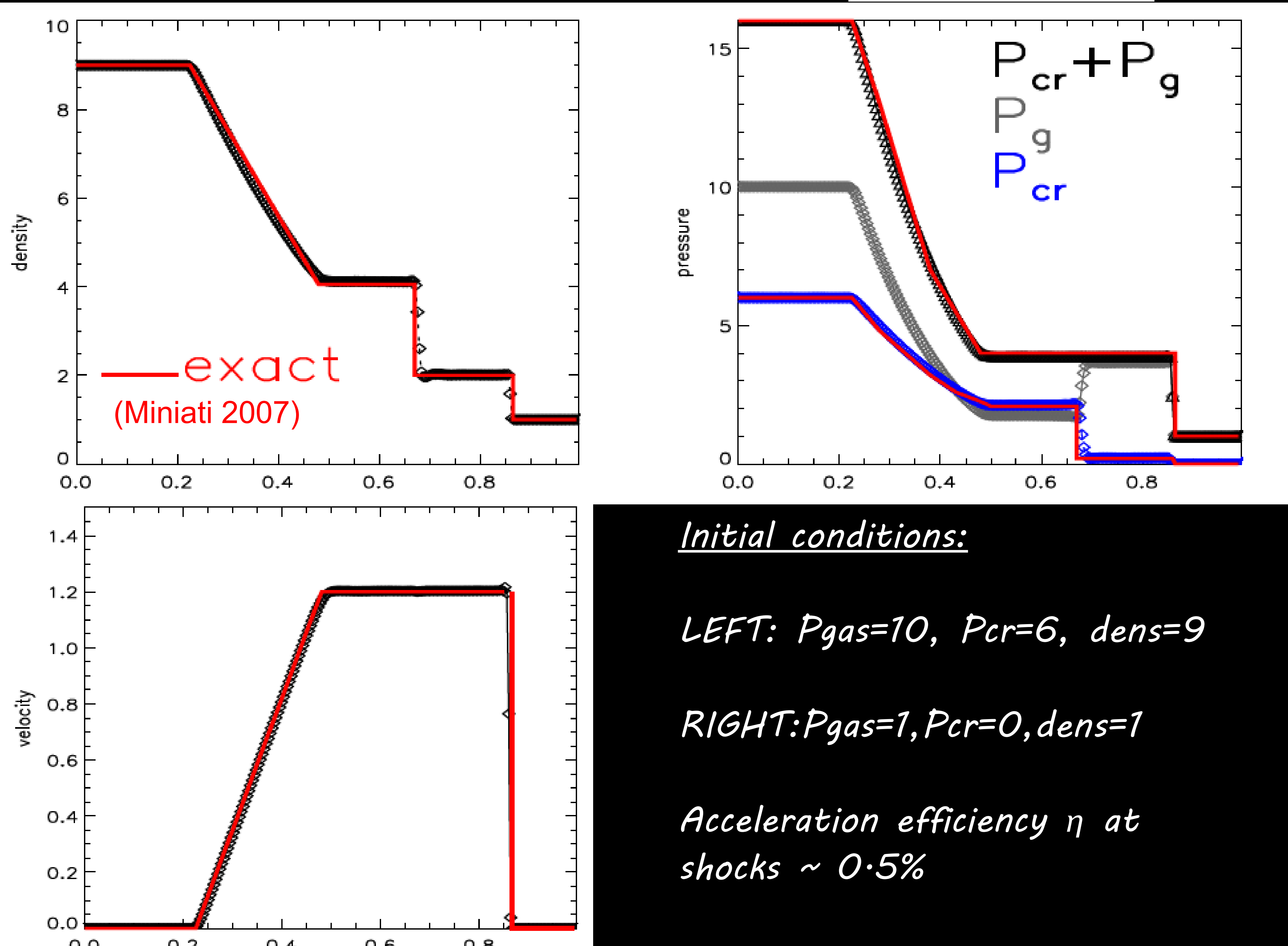
In cosmology:

- Miniati 2003 (fixed grid)
- Pfrommer et al 2006 & Ensslin et al.2007 (SPH)

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~~ (>10kpc)

1-D tests for validation : SHOCK TUBE



Initial conditions:

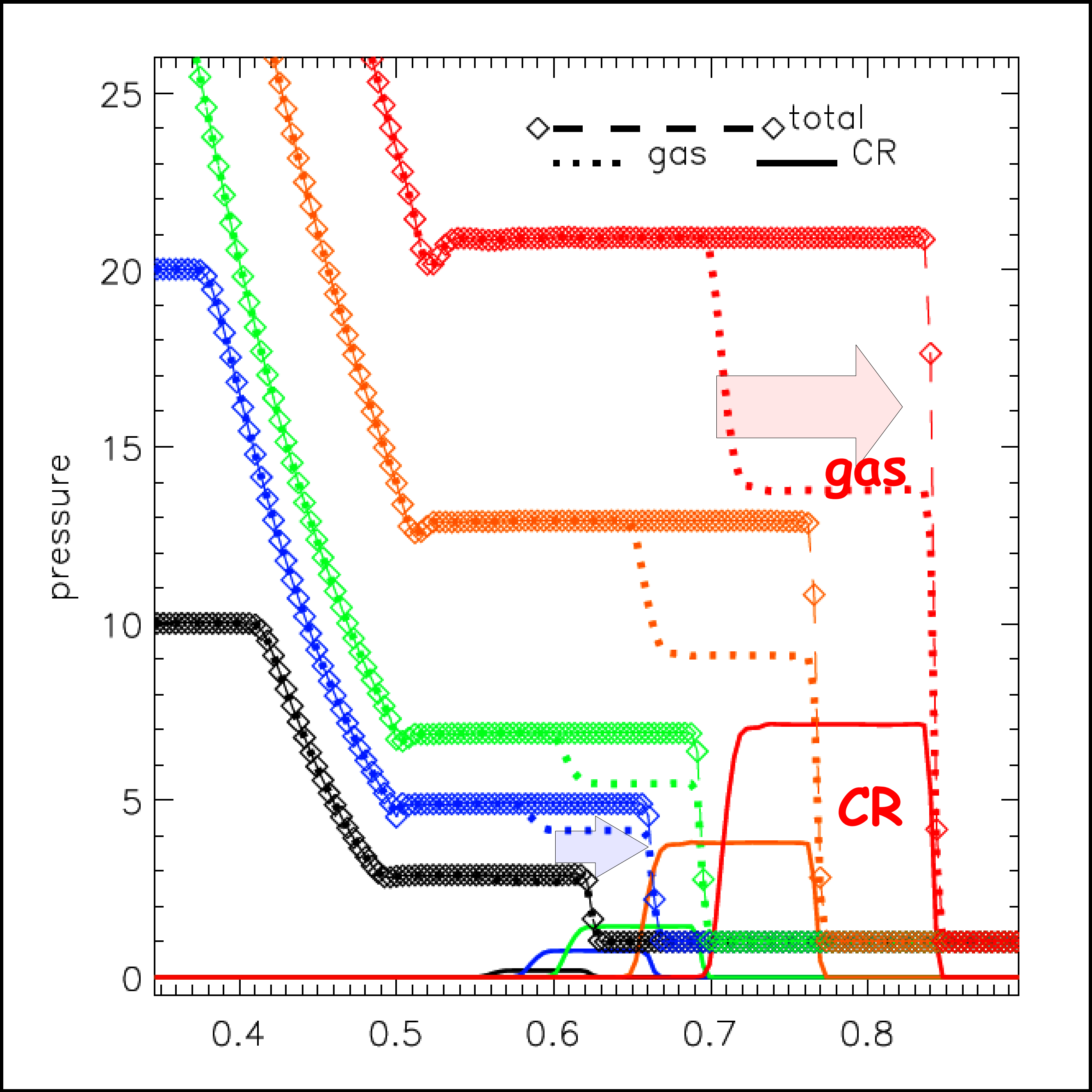
LEFT: Pgas=10, Pcr=6, dens=9

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

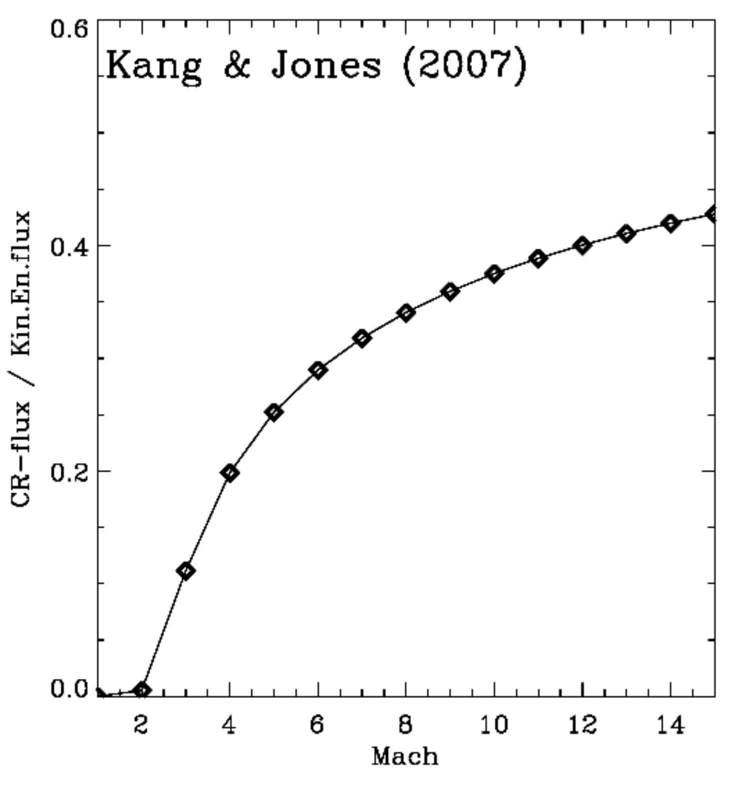
Acceleration efficiency η at shocks ~ 0.5%

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

Injection of CR for increasing Mach



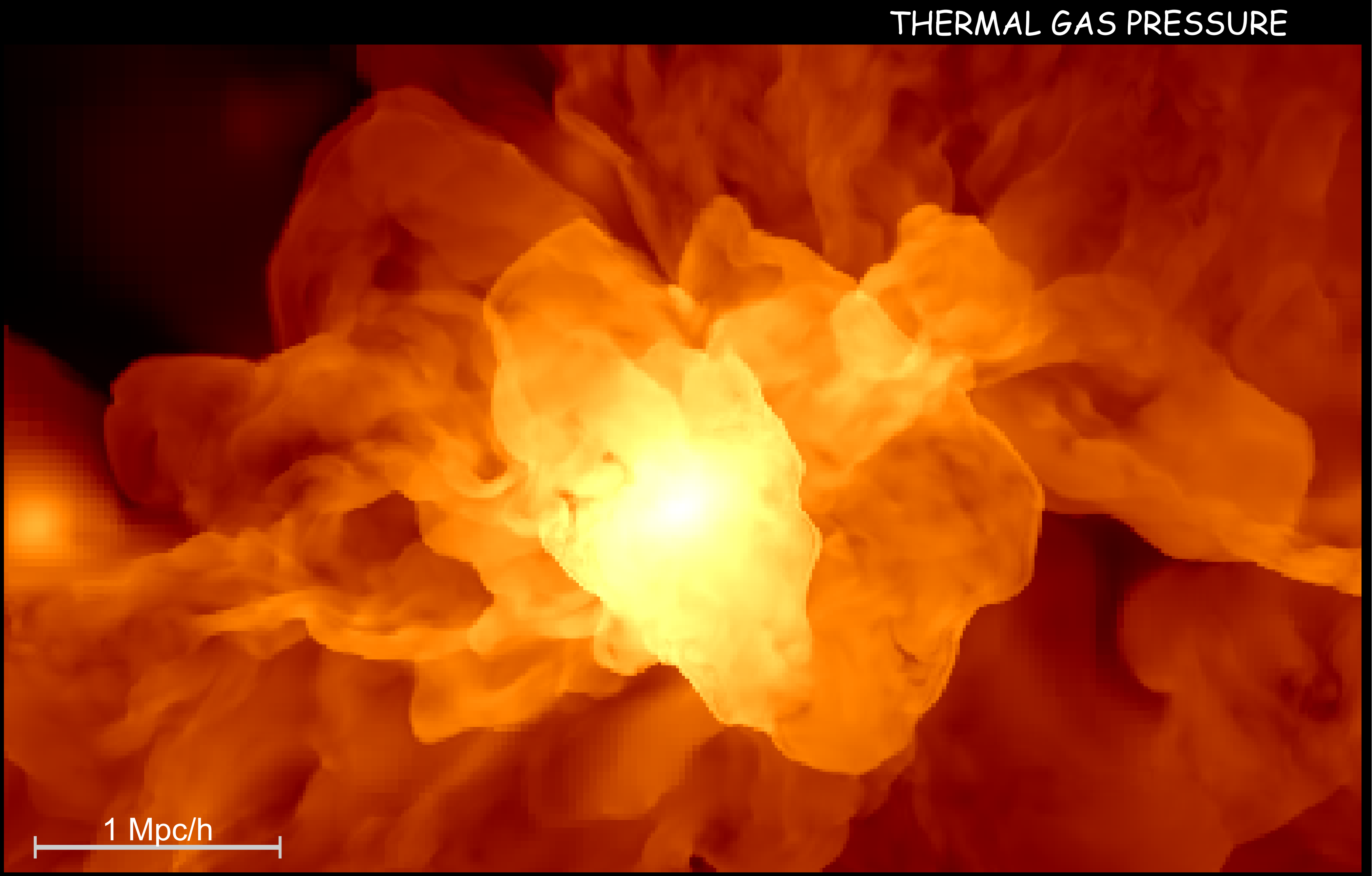
Efficiency from theoretical works



Diffusive shock accleration

~ tested with SNR M>10

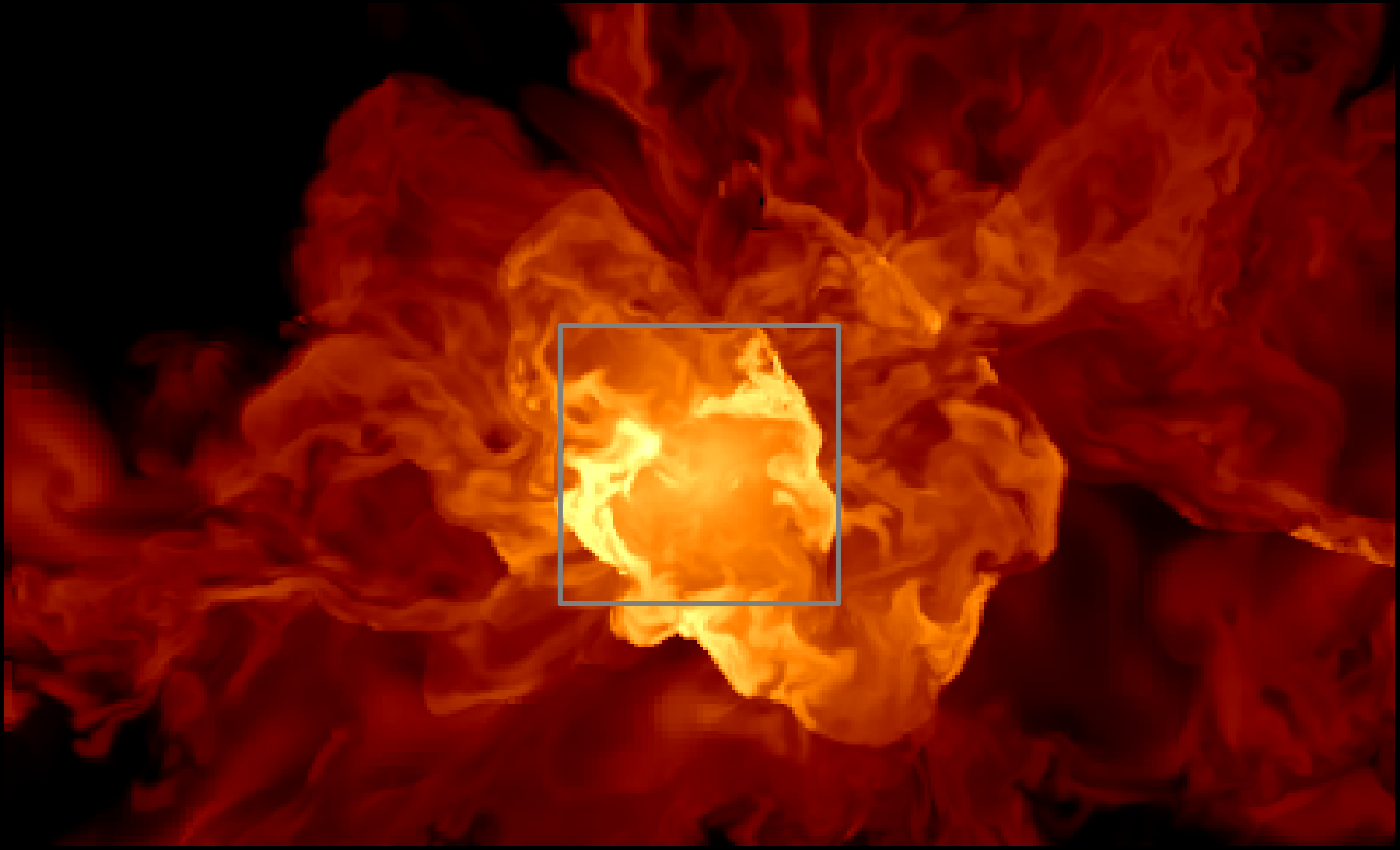
AMR-cosmological nested IC simulations

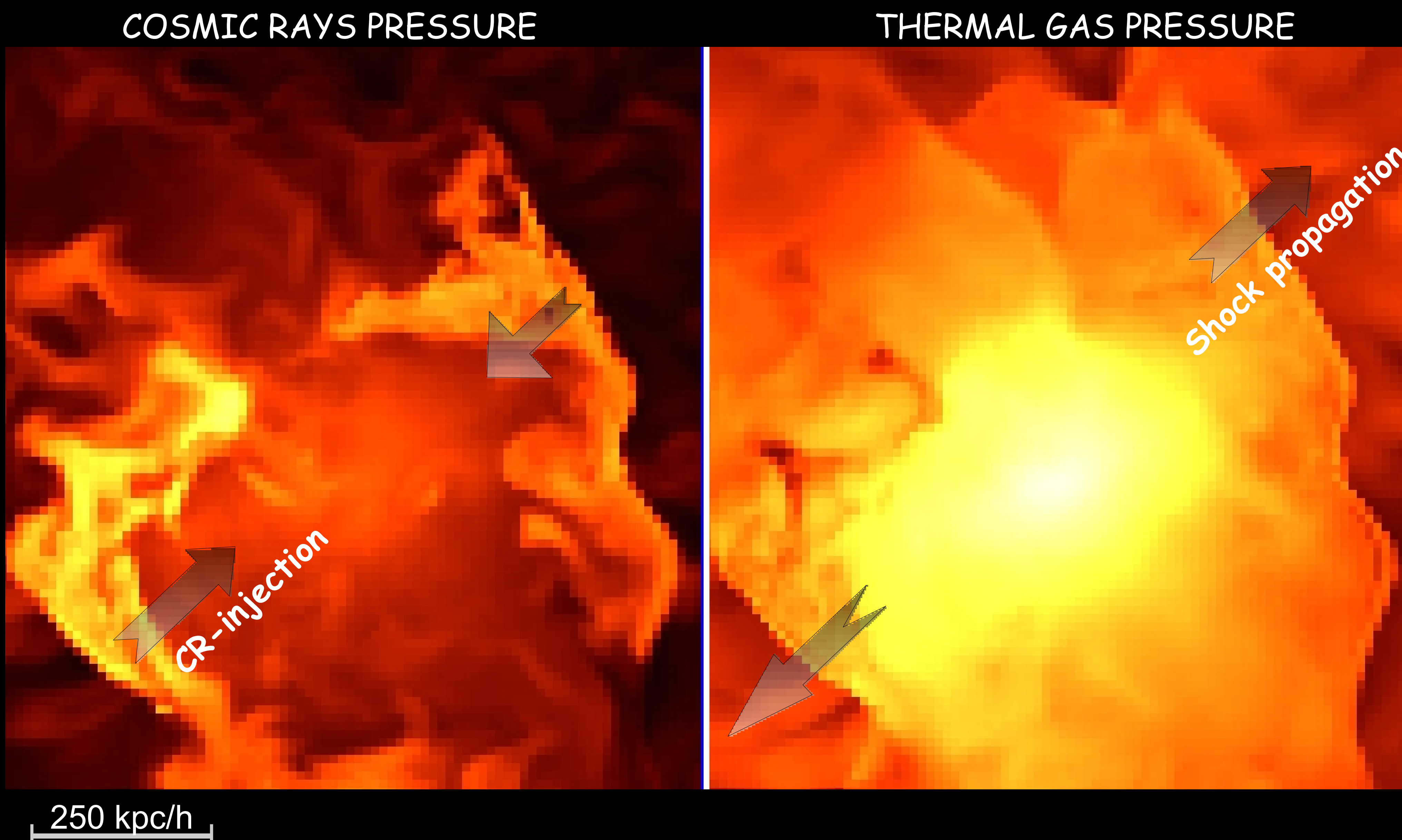


Same IC as in Vazza+10
Max res= 25kpc

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

COSMIC RAYS PRESSURE





Inside cluster cores: CR pressure~0.5-5% Thermal

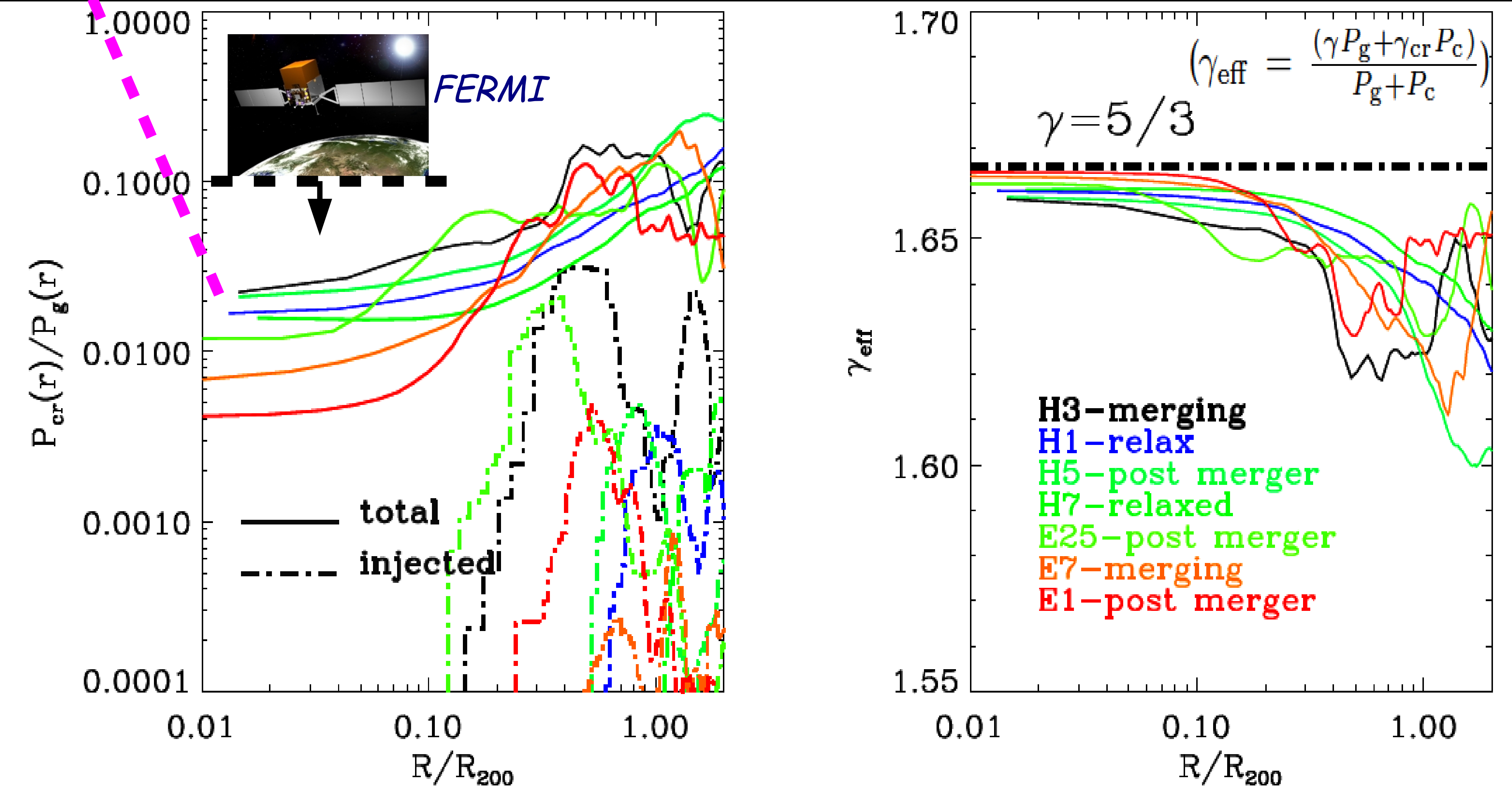
Inside cluster volume: " ~10-20% "

LIMITS ON THE ENERGY BUDGET OF CR-PROTONS

γ-ray emission from hadronic collsions in the ICM

CRp + p → π^0 → γ [1-100GeV] (→ EGRET, MAGIC, FERMI...)

Profiles of CR to thermal pressure



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]

ENZO

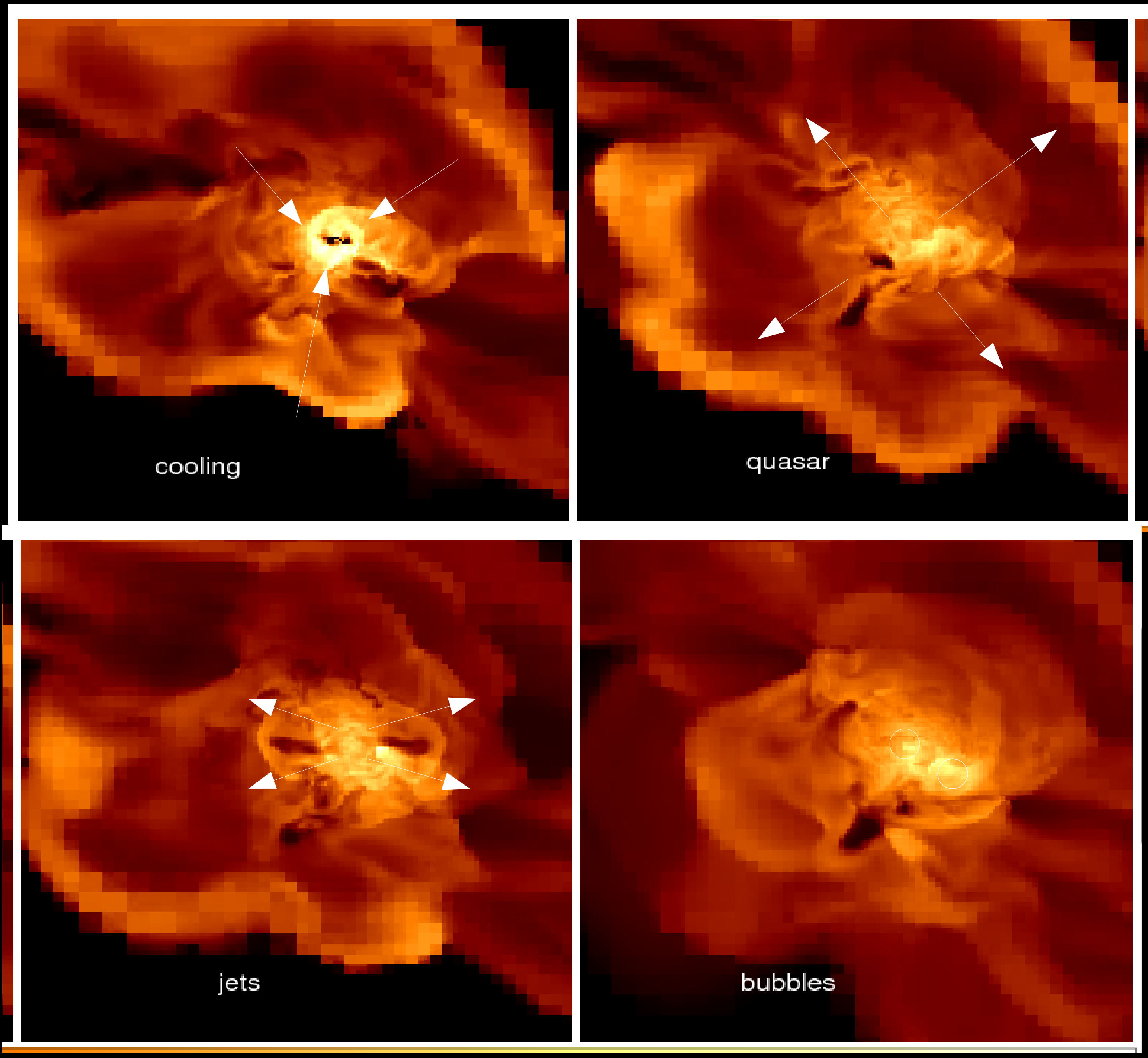
+

Our baseline model for CR from shocks

+

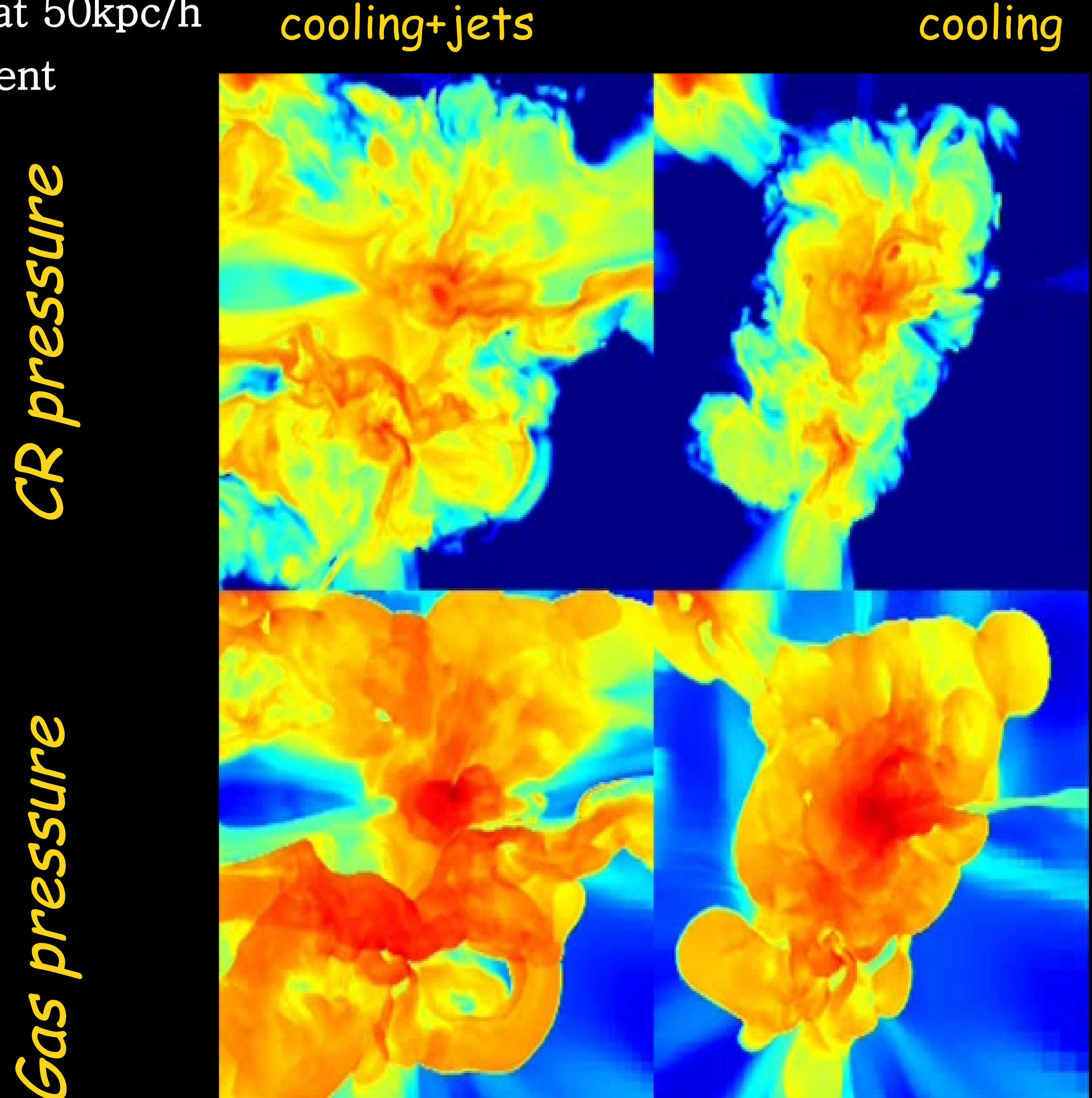
New features:

- cooling
- Shock-reacc.
- Coulomb & hadronic losses
- AGN feedback: jets (kinetic) quasar (therm.) bubbles(buoy.)



Example: Jets – feedback:

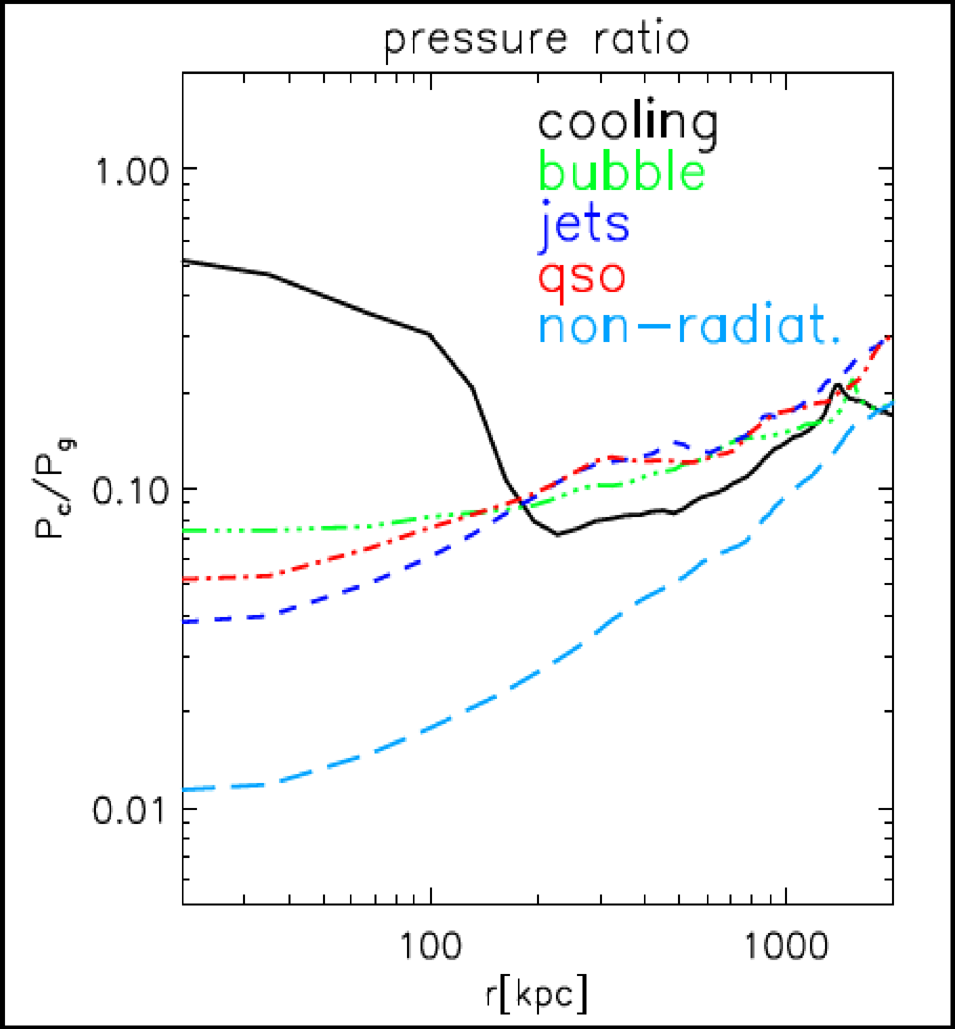
- V_J ~700 km/s at 50kpc/h
- E_J~10^{59} erg/event



See also:
Dubois+ 10,11
Gaspari+ 11,12

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

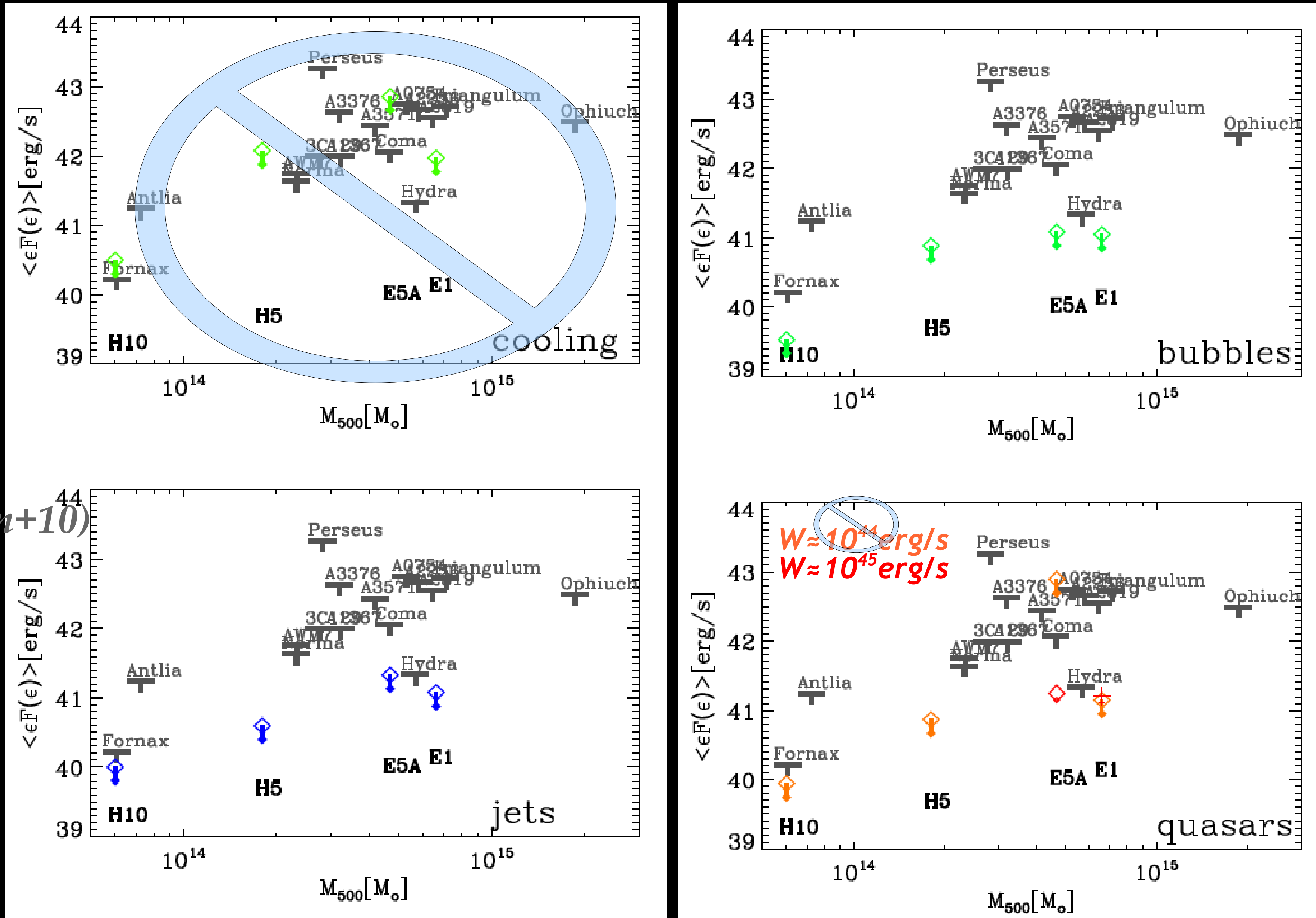
What is the CR output of each feedback mode?

Hadronic collision → γ-flux (Pfrommer&Ensslin04)

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

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

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



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

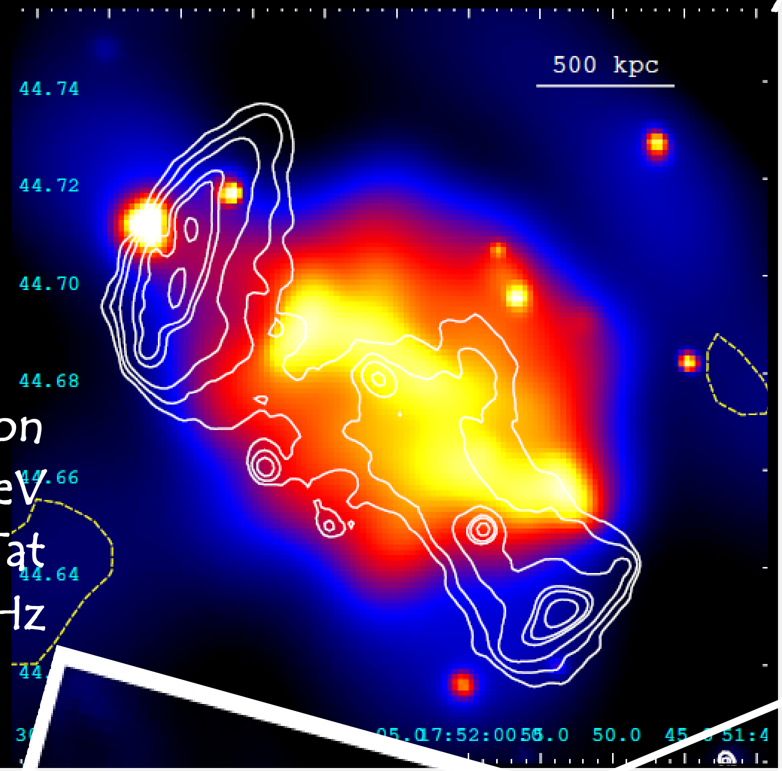
Some non-trivial match with observations : X-ray and Radio!

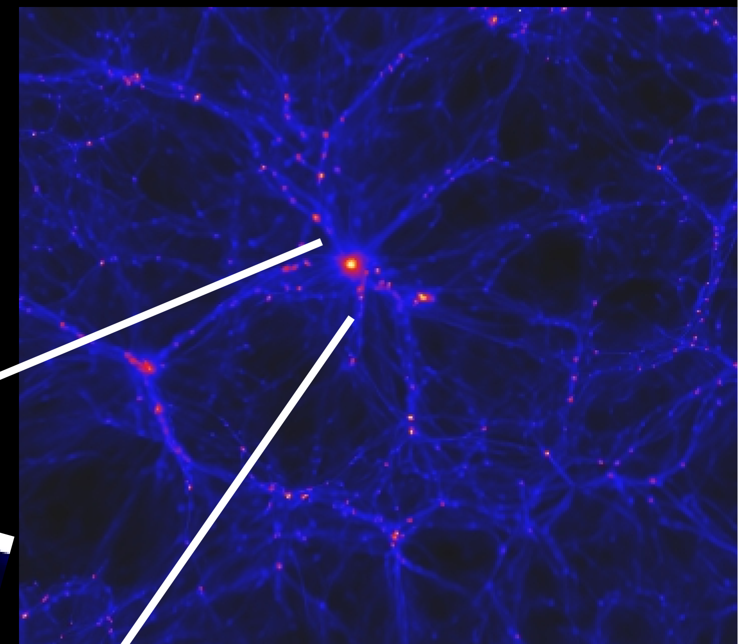
MACSJ1752.0+4440

Bonafede et al.2012

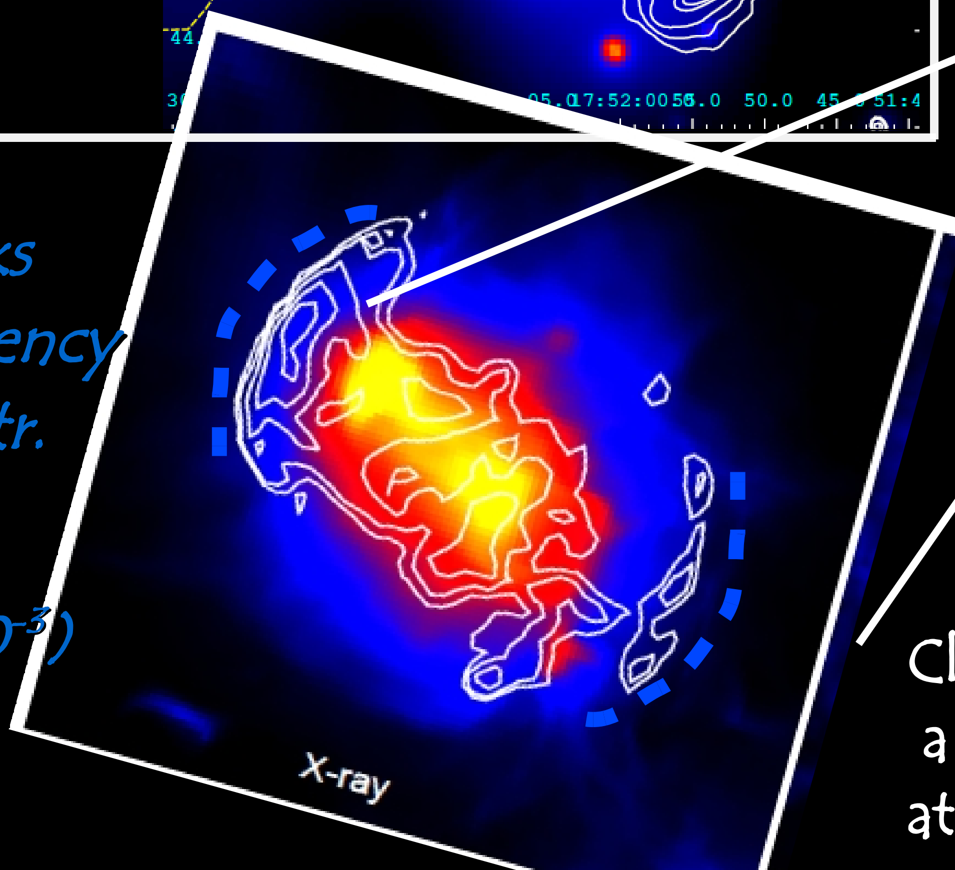
-Colors: XMM-Newton [0.5-2]keV

-Contours: GMRTat 300MHz





Sample of Vazza et al.2010
Volume ~$(400\mathrm{Mpc})^3$



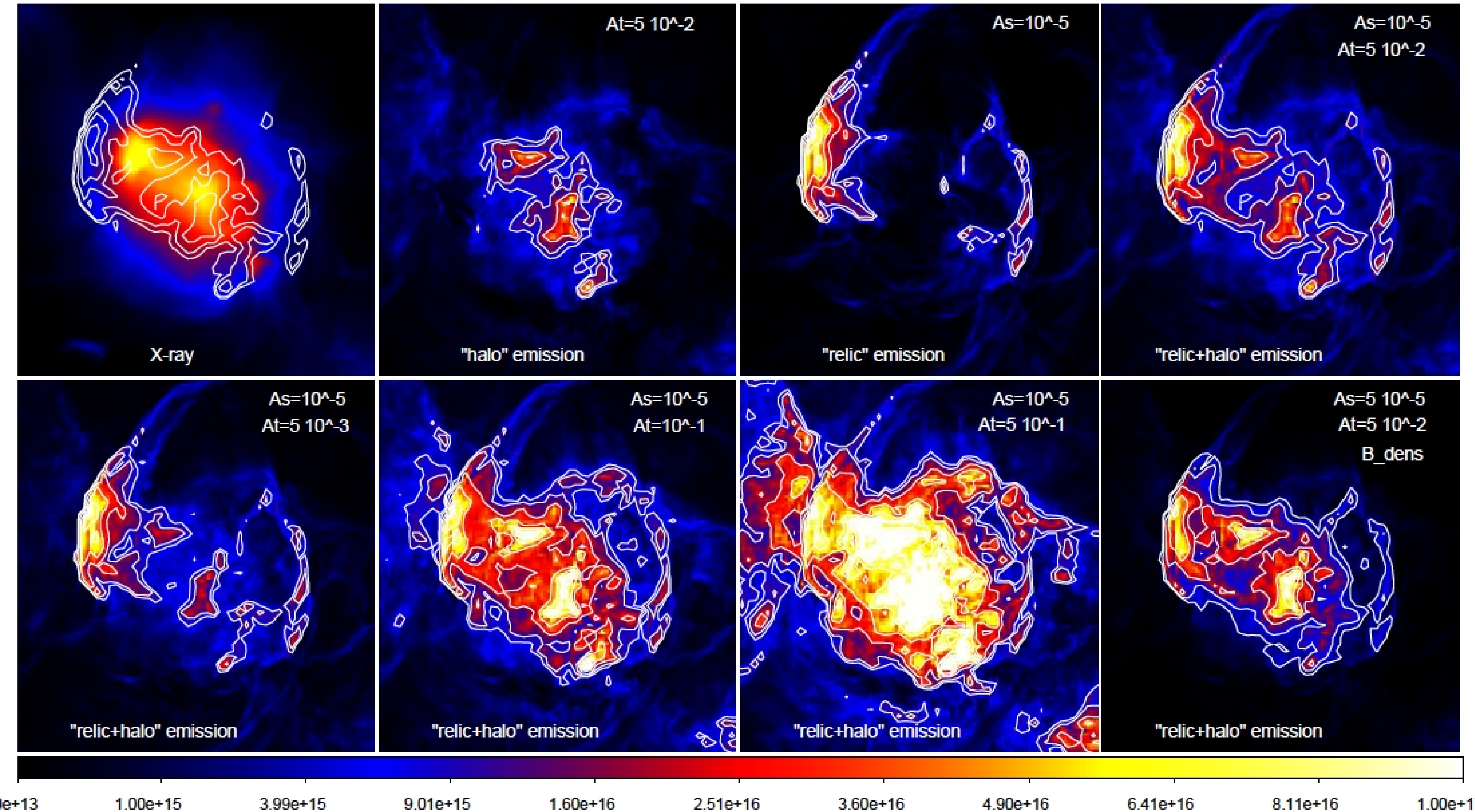
M≈5 shocks
accel.efficiency of CR electr.
$\xi \sim 10^{-5}$
$(Re/p = 5\ 10^{-3})$

Cluster of $6\ 10^{14}$ Msol
a major merger
at z~0.1

From the simulations : kinetic energy in shocks and turbulence

$$P_{RADIO} \approx \xi \, \Phi_{SHOCK}$$

(assumptions: B=1μG, no re-accel, $I(\nu)\sim\nu^{-1}$)



by matchig the observed emission →EFFICIENCIES OFACCELERATION of CR-electrons by SHOCKS ($\xi\sim10^{-5}$) and by TURBULENCE ($\xi\sim0.05$)

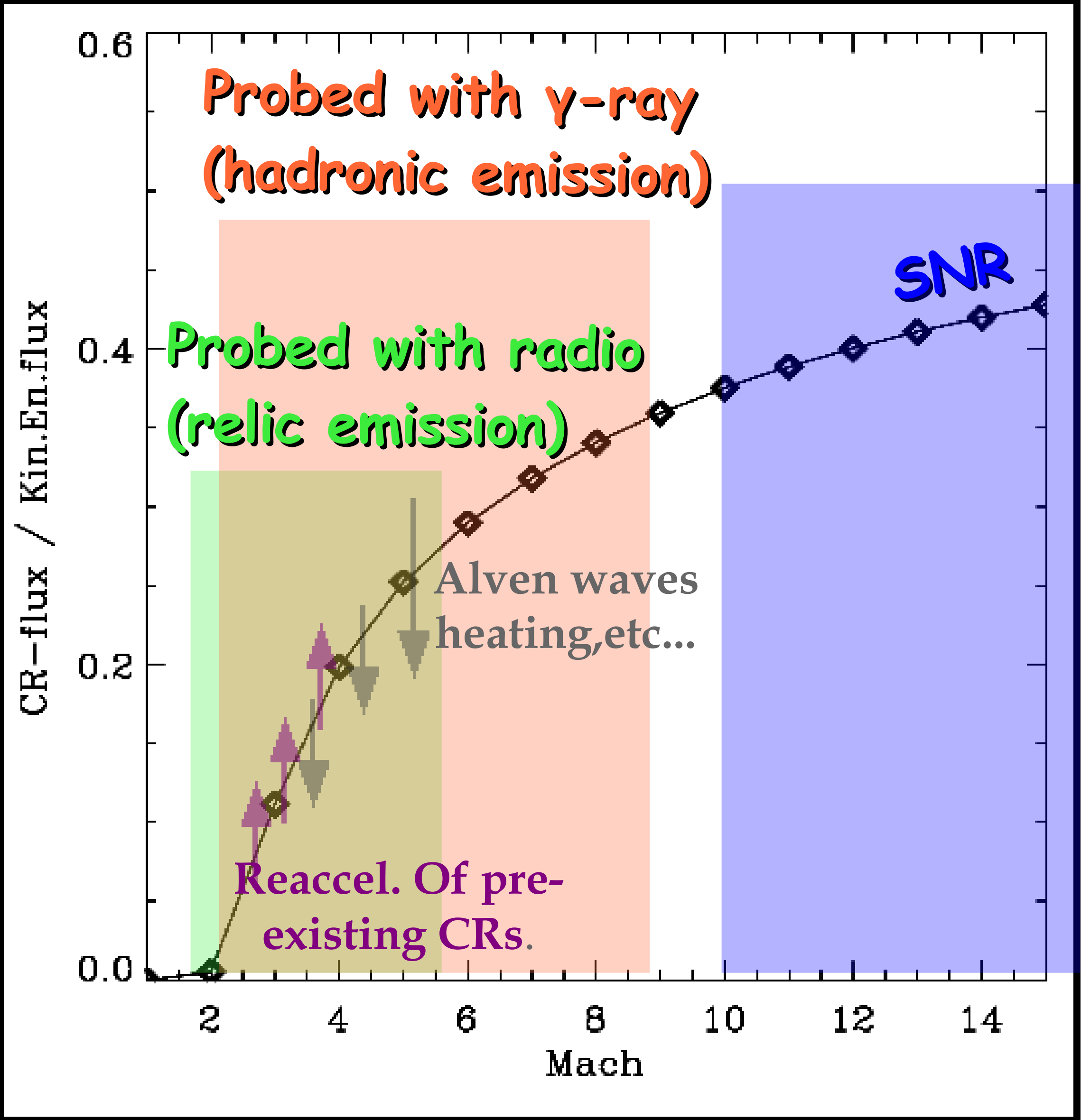
Conclusions

1) NON-THERMAL EMISSION FROM CLUSTERS TO STUDY CR IN THE ICM

2) SHOCKS IN THE ICM ARE WEAK, ACCEL·EFFICIENCY DIFFICULT TO CONSTRAIN

3) CR PROTONS: PROBED THROUGH γ-RAY, THEY TELL US ABOUT M<10 SHOCKS

4) CR ELECTRONS: PROBED BY RADIO RELICS, THEY TELL US ABOUT 2<M<5 ACCELERATION ($\xi \sim 10^{-5}$)



End, thanks!