The impact of shock-accelerated Cosmic Rays in Large Scale Structures

Franco Vazza
Jacobs Univ. Bremen

+M.Brüggen
+G.Brunetti
+C.Gheller

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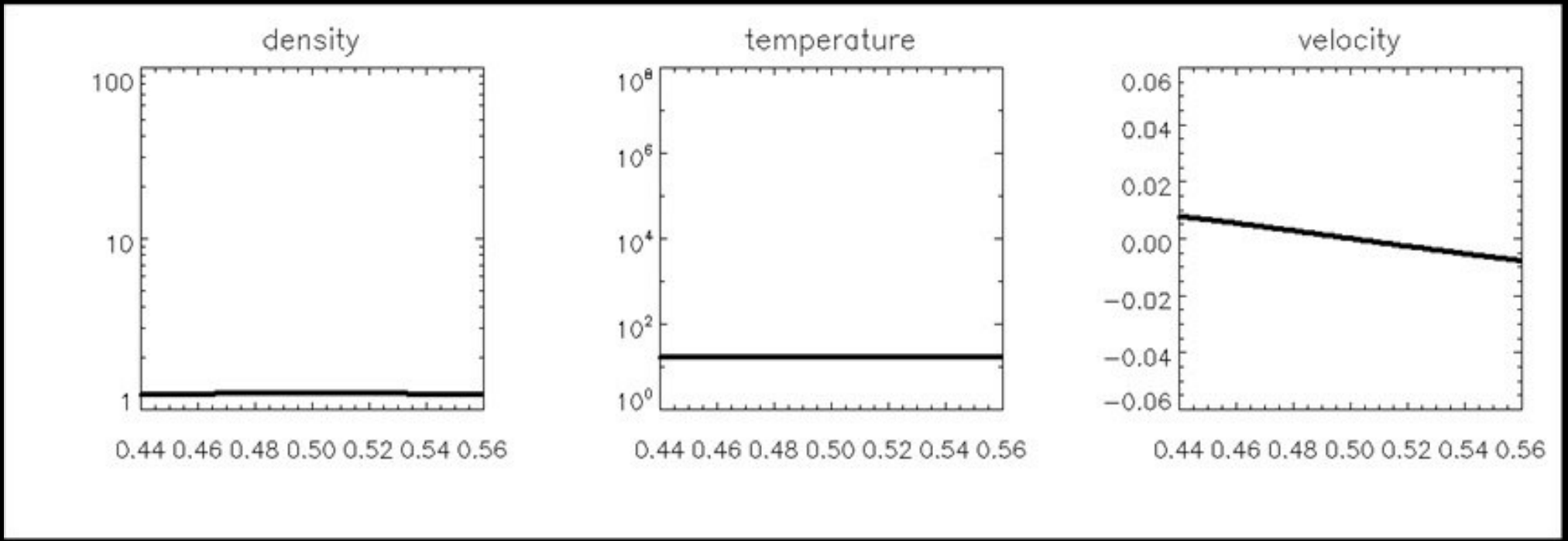


Zeldovich 1970; Sunyaev & Zeldovich 1972

"Such calculations, in 3D and with random initial conditions, promise to be tedious.Therefore an approximate method [...] is of interest." *Ya.B.Zeldovich 1970*

Run-time injection and dynamical feedback of CR protons (injected at shocks, or else)

Two-fluid model

Dorfi 1984; Bell 1987; Jones & Kang 1990; etc...

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

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

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

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

In cosmology:

- Miniati 2003 (fixed grid)
- Pfrommer et al 2006 & Ensslin et al.2007 (SPH) (see also Hansz+ 2004)

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.

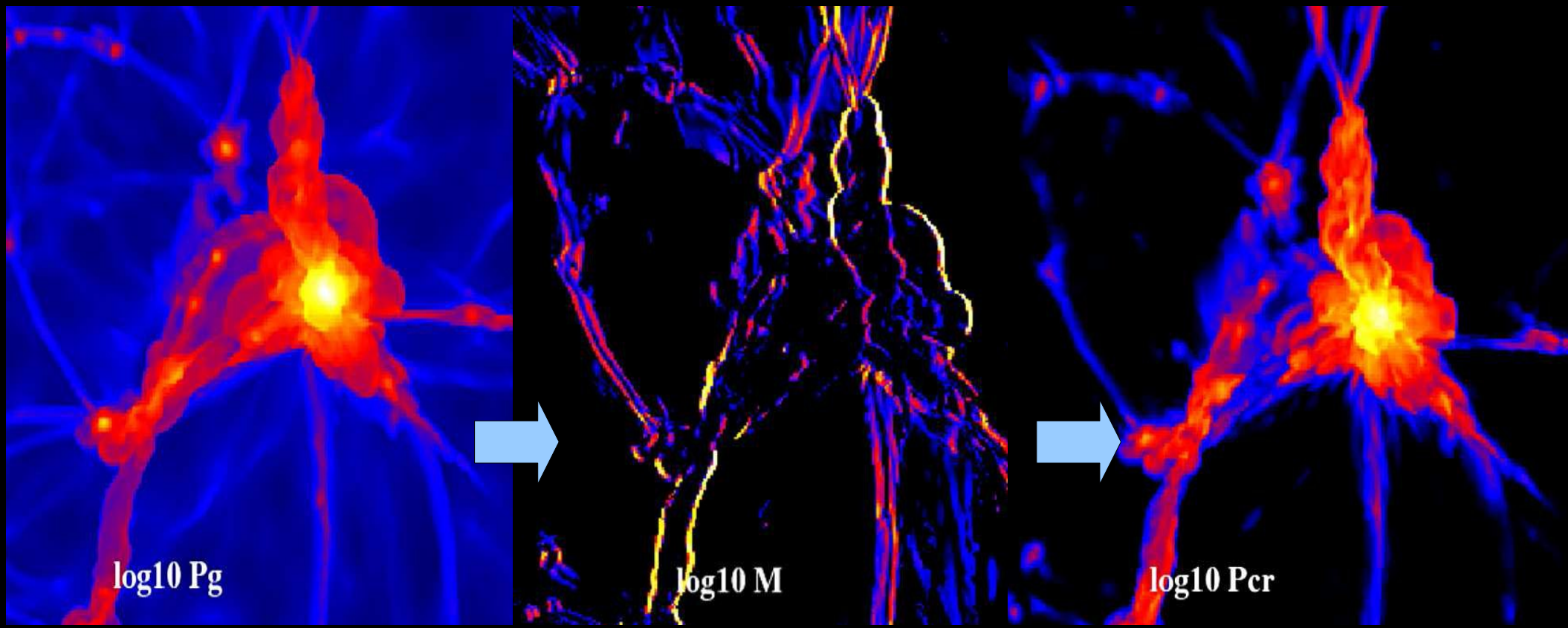
Identify shocks (pressure or Velocity based)

2.

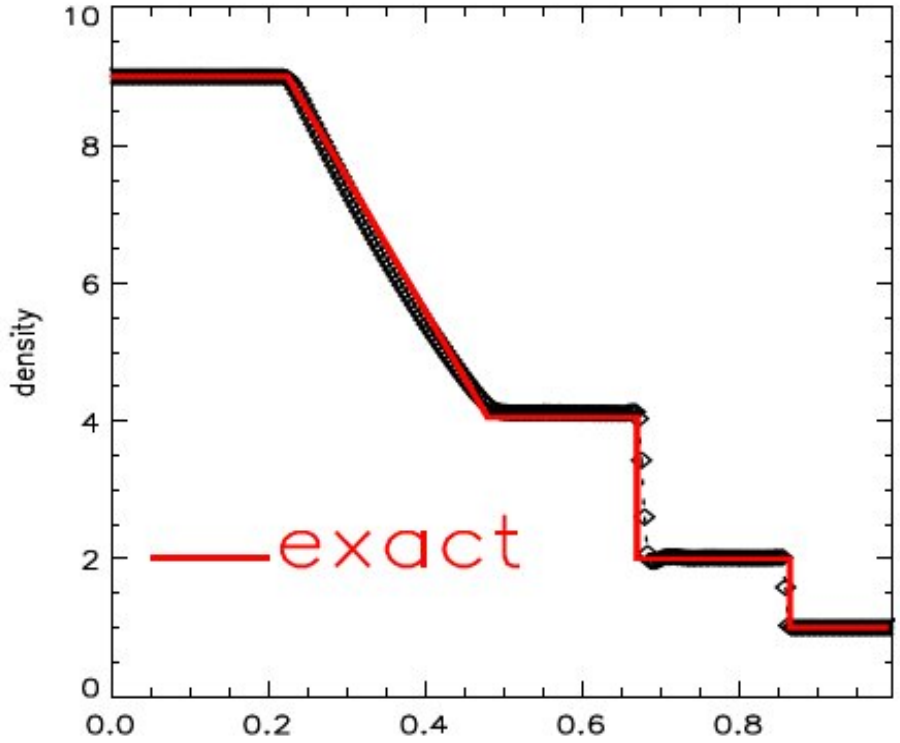
- compute CR flux
- reduce post-shock gas energy

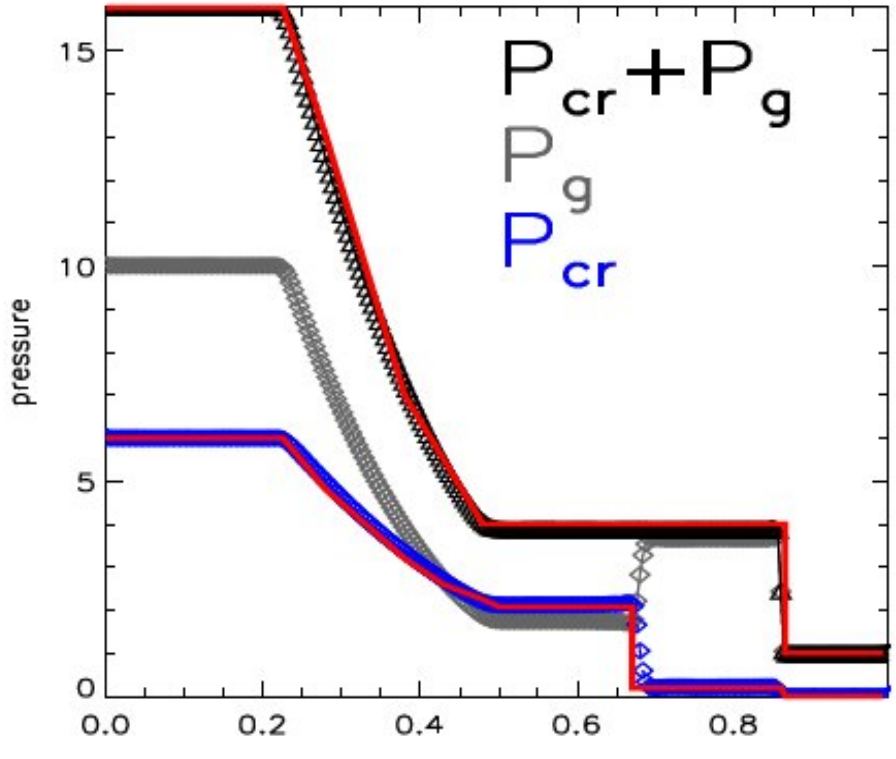
3.

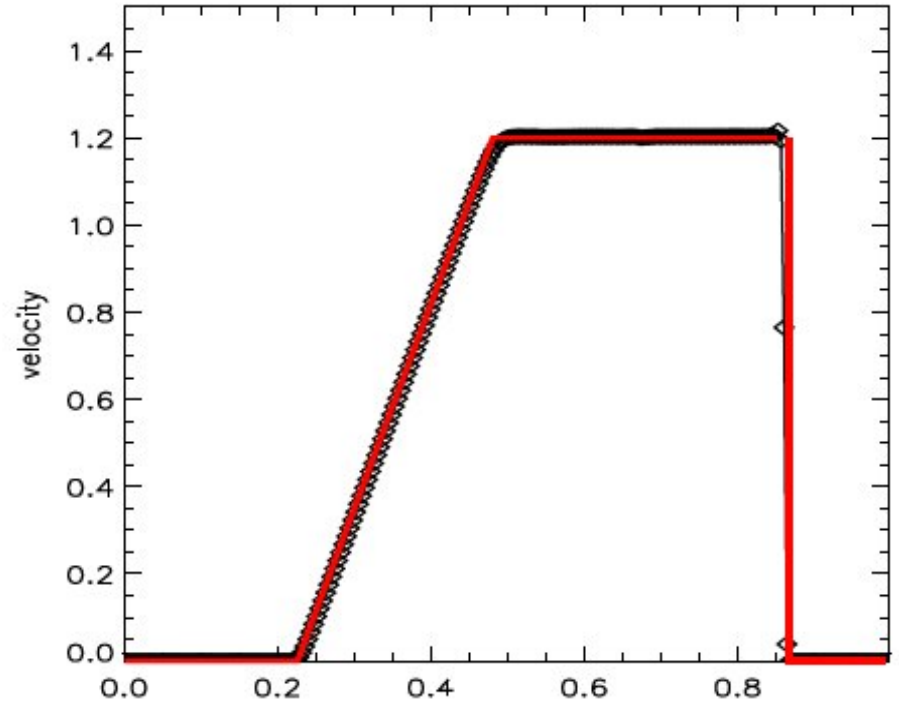
- advect CR energy
- compute total Dynamic pressure (Pgas+Pcr)



1-D tests for validation : M=1·5 shock







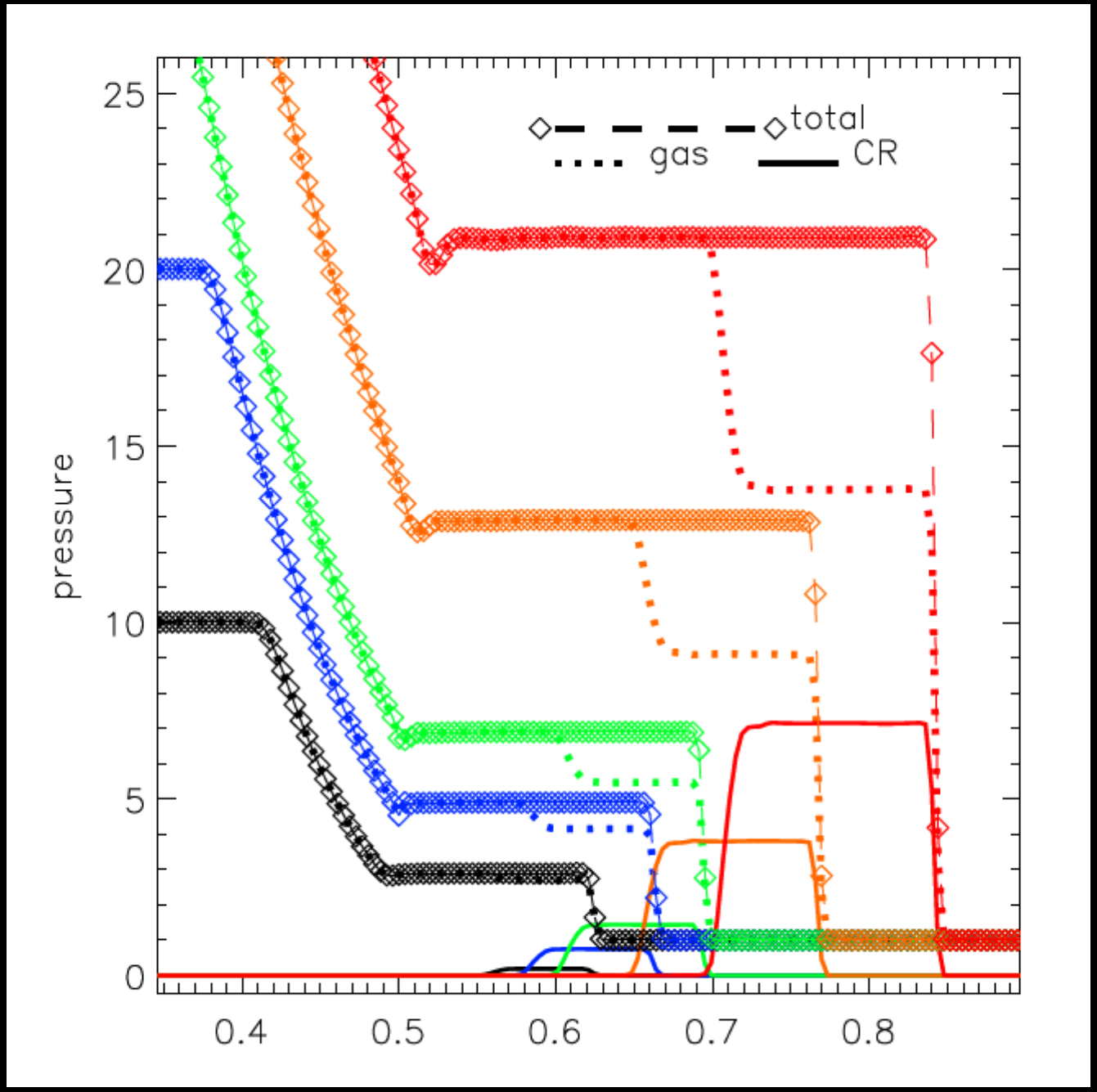
Initial conditions:

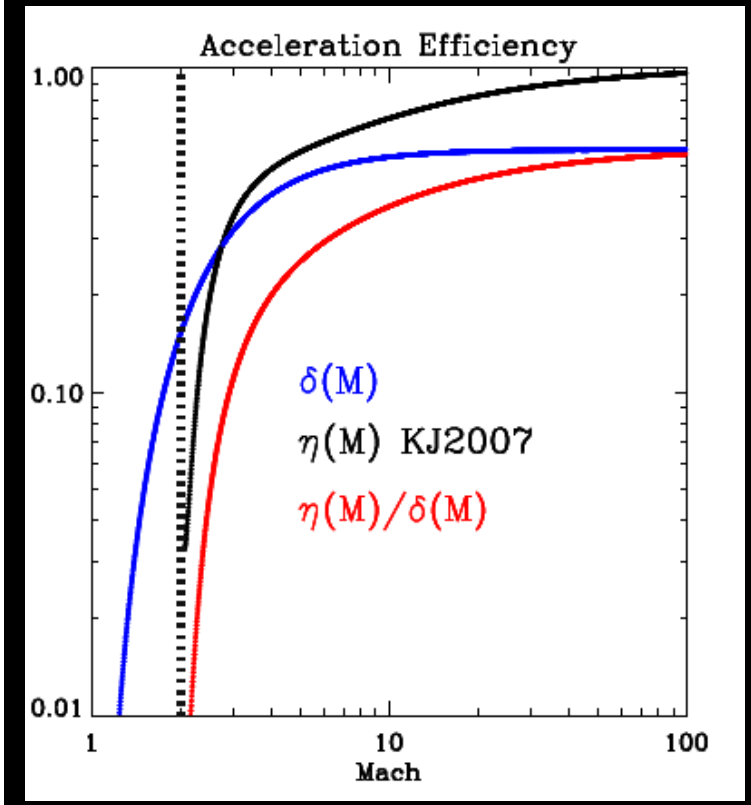
LEFT: Pgas=10, Pcr=6, dens=9

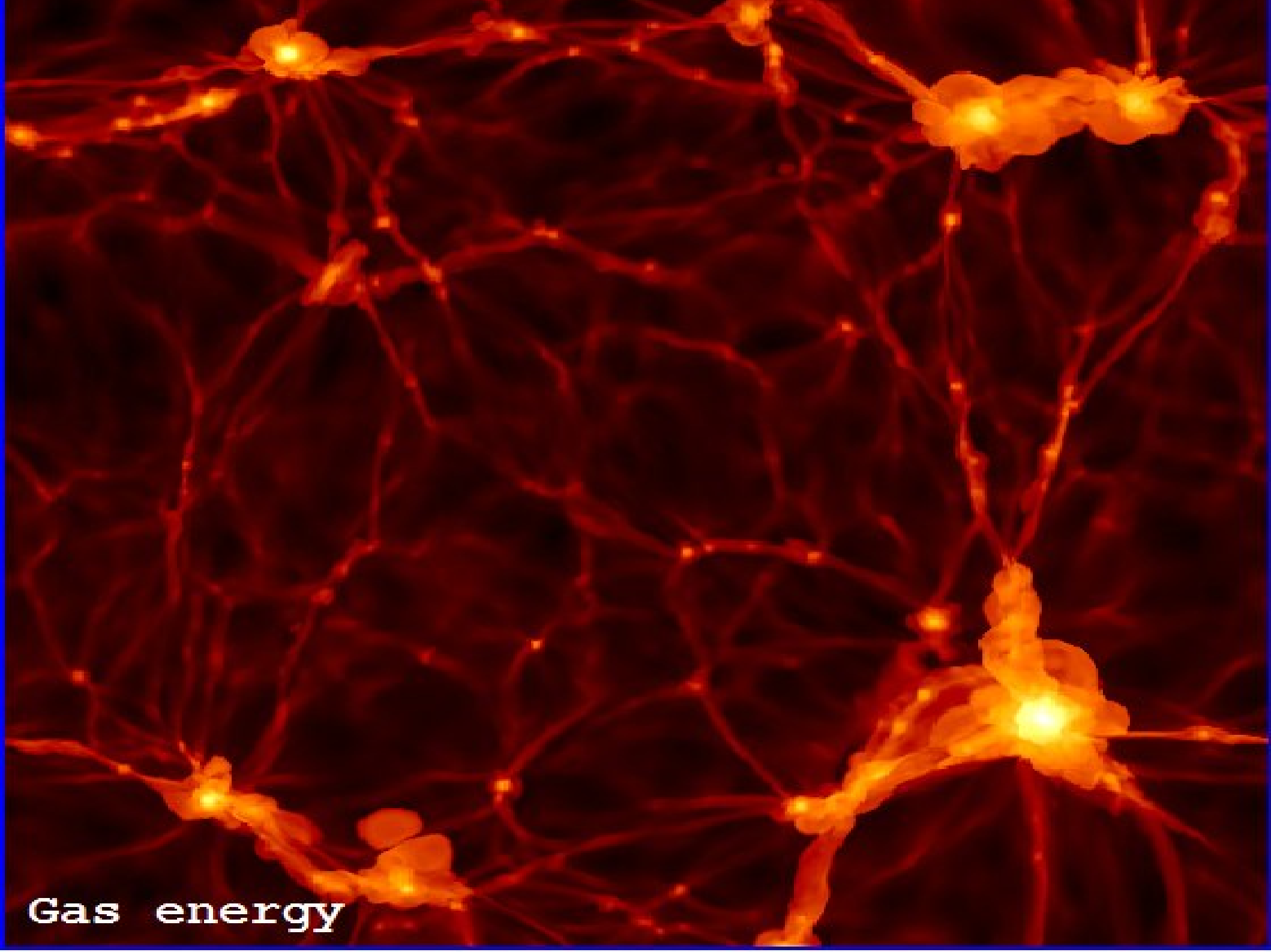
RIGHT:Pgas=1,Pcr=0,dens=1

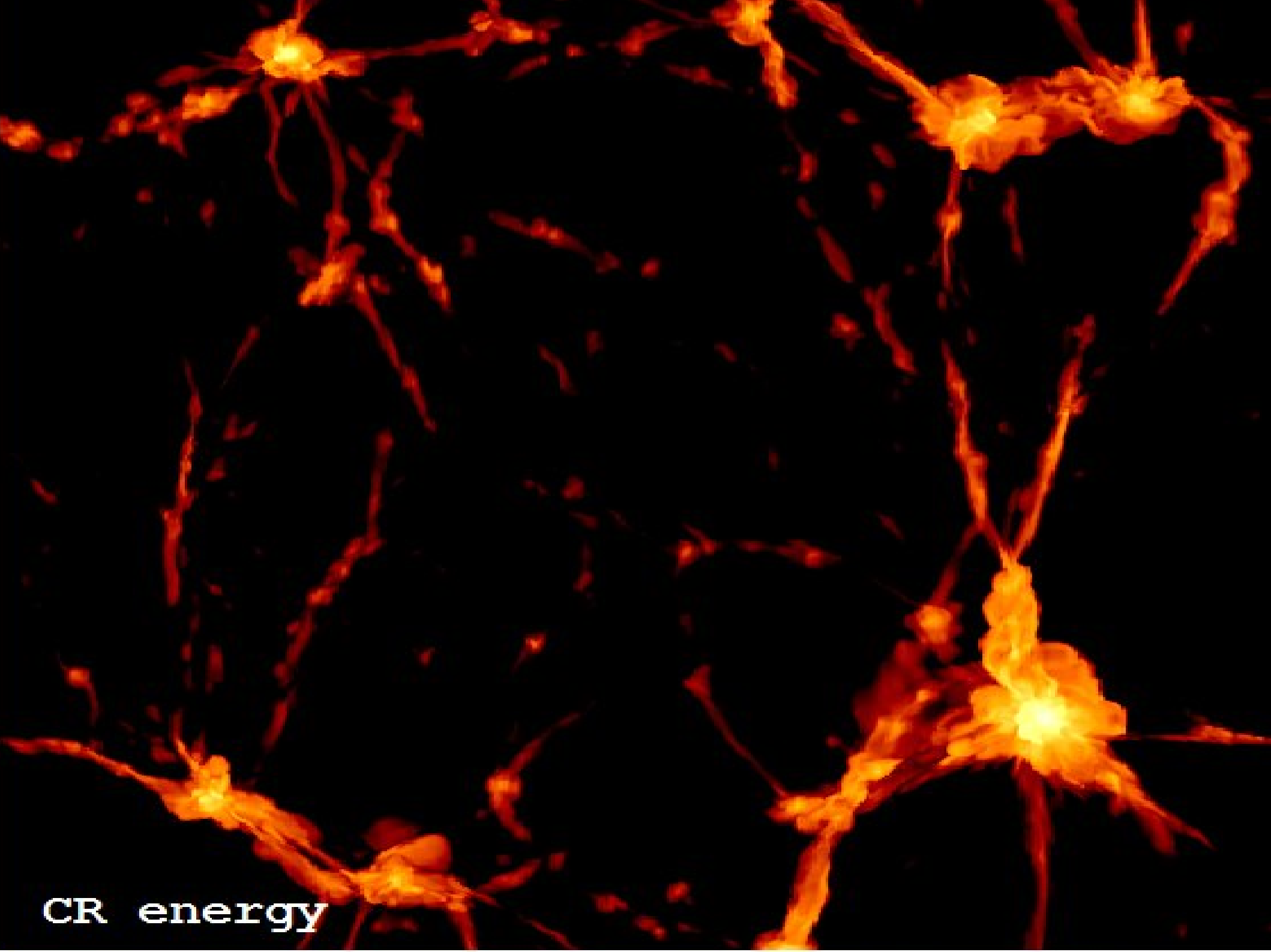
Acceleration efficiency η at shocks ~ 0·5%

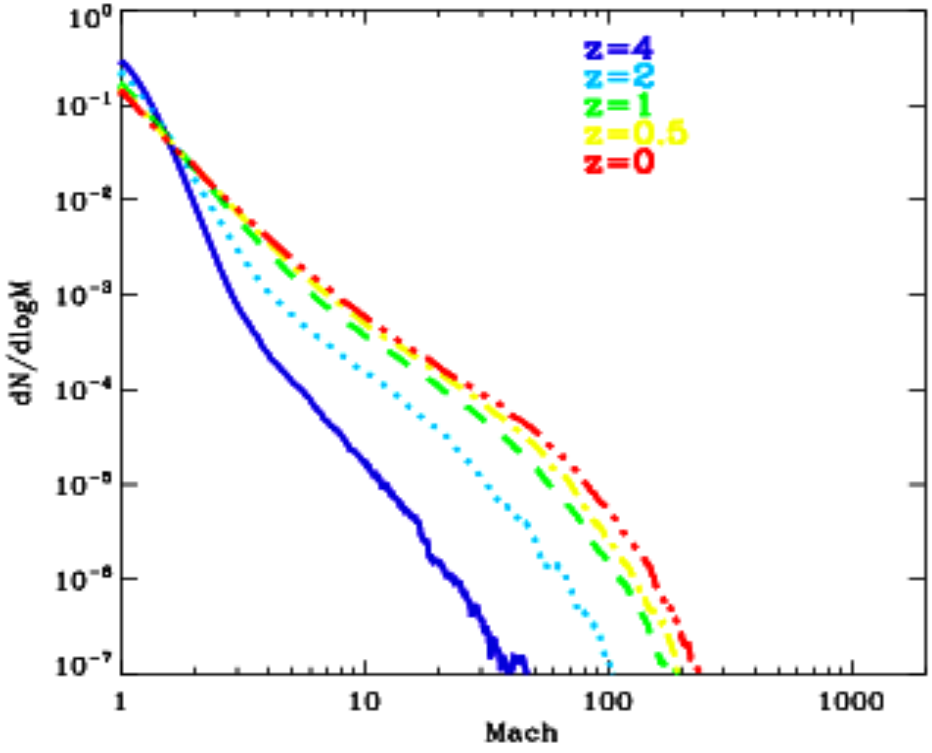
1-D tests for validation: from M=1·5 to M=5

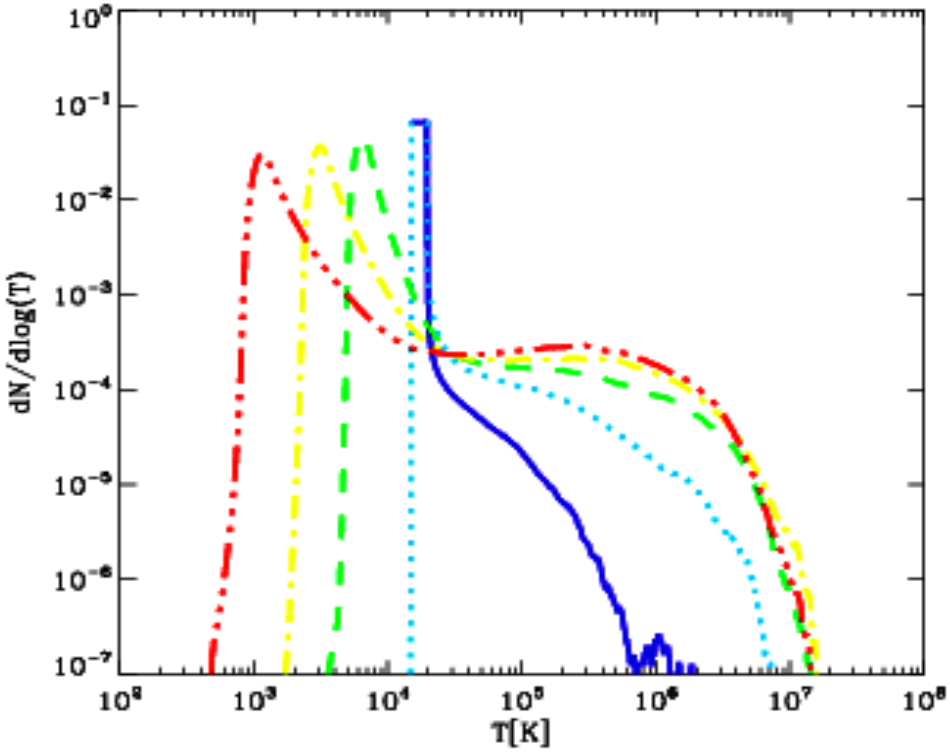




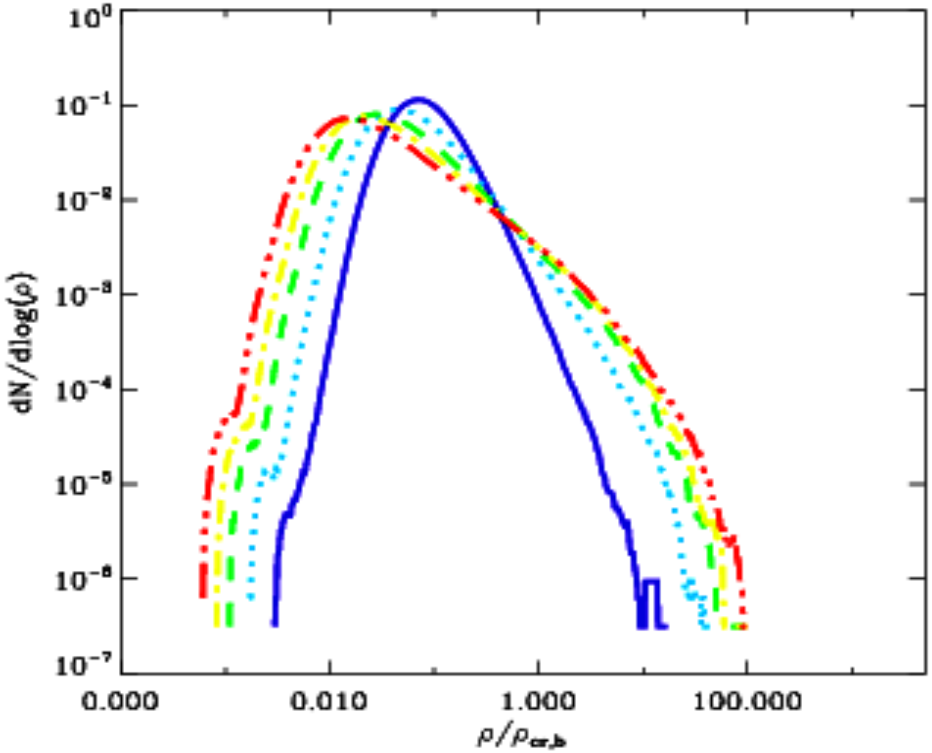

Gas energy

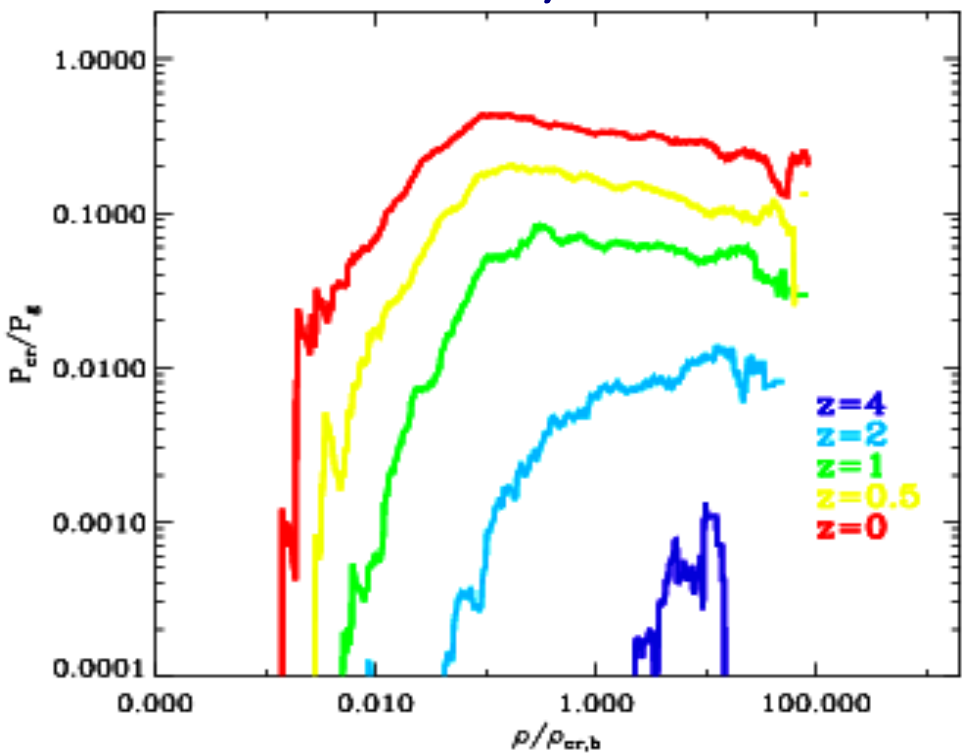

CR energy



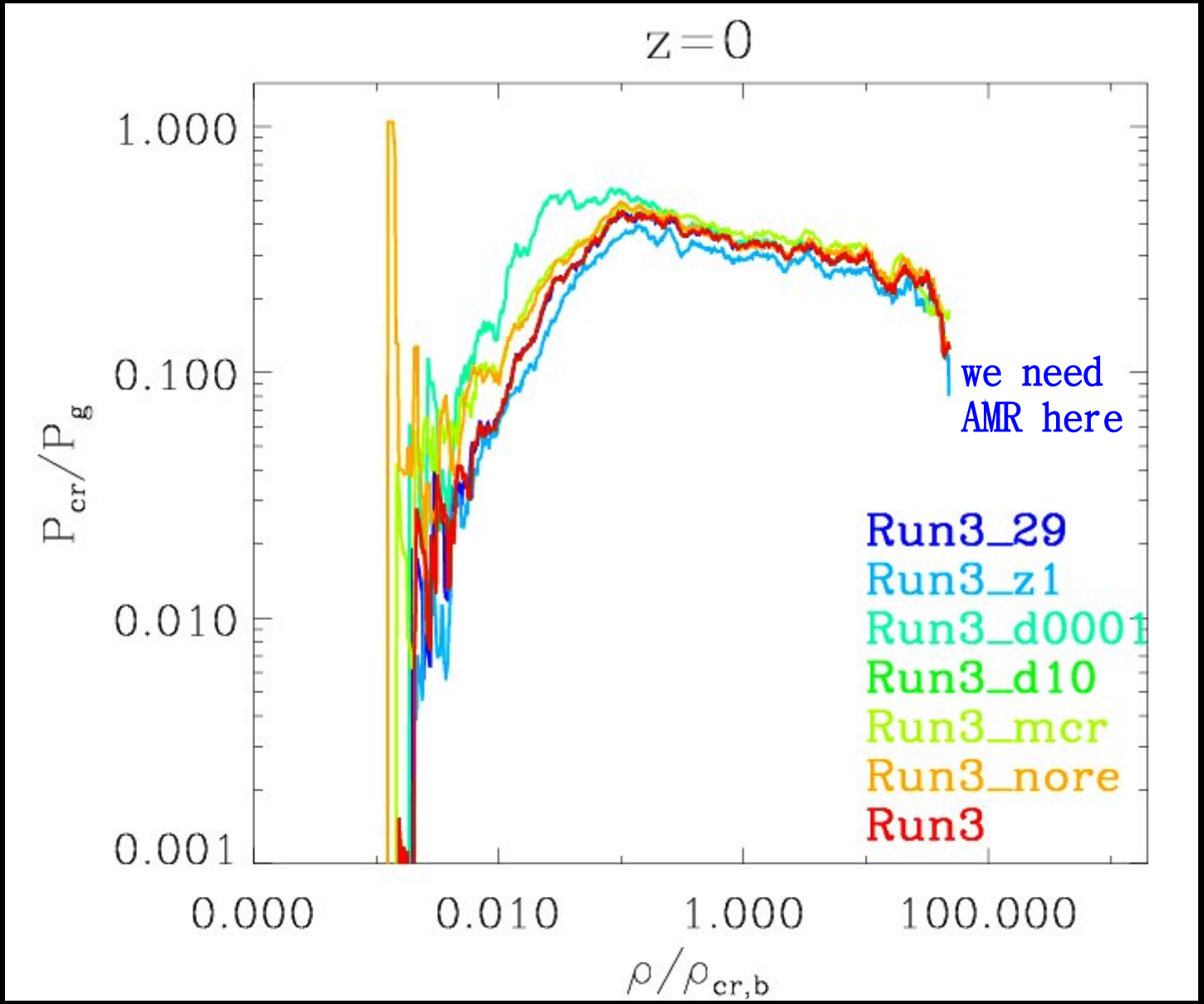


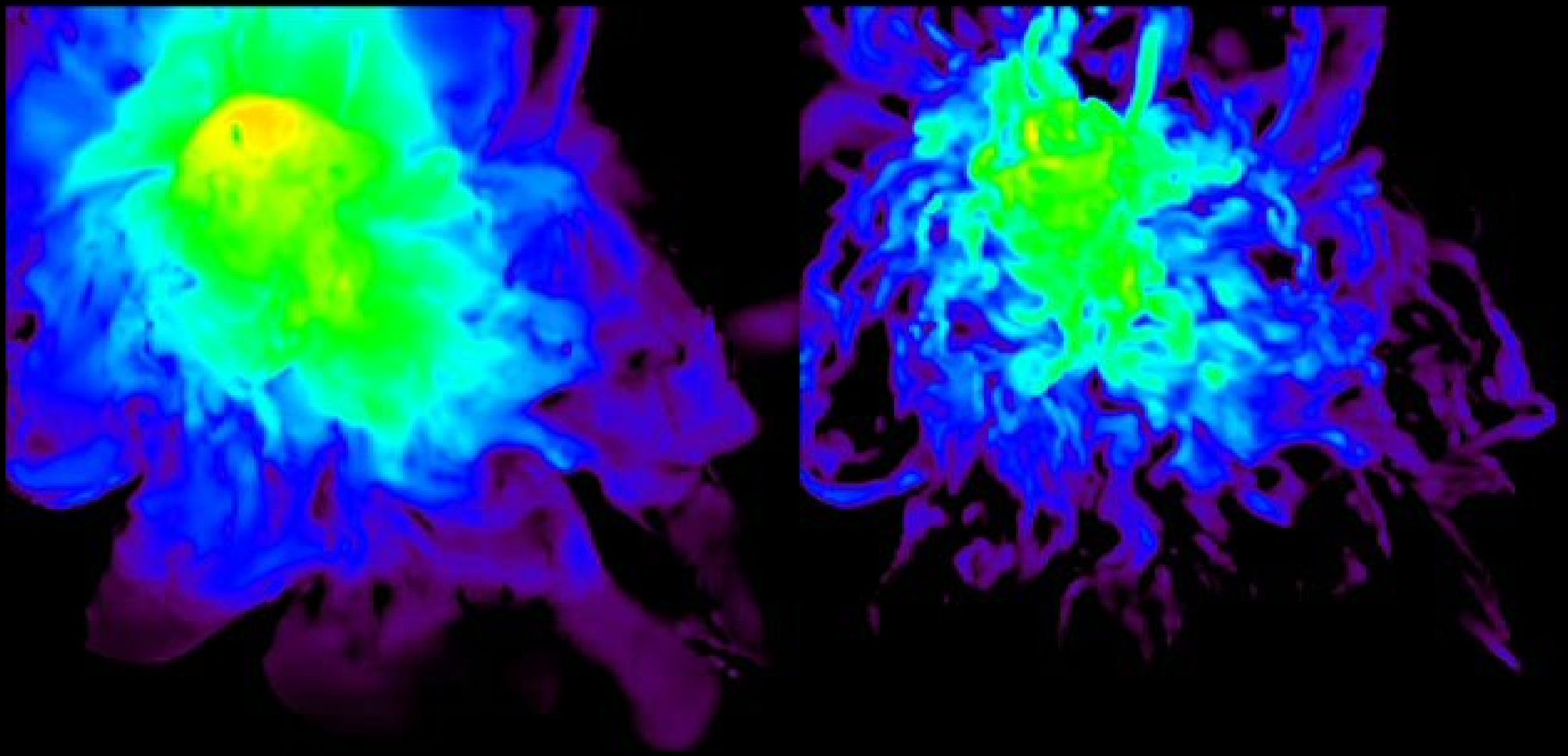
AVERAGE TIME EVOLUTION FOR 80Mpc^3

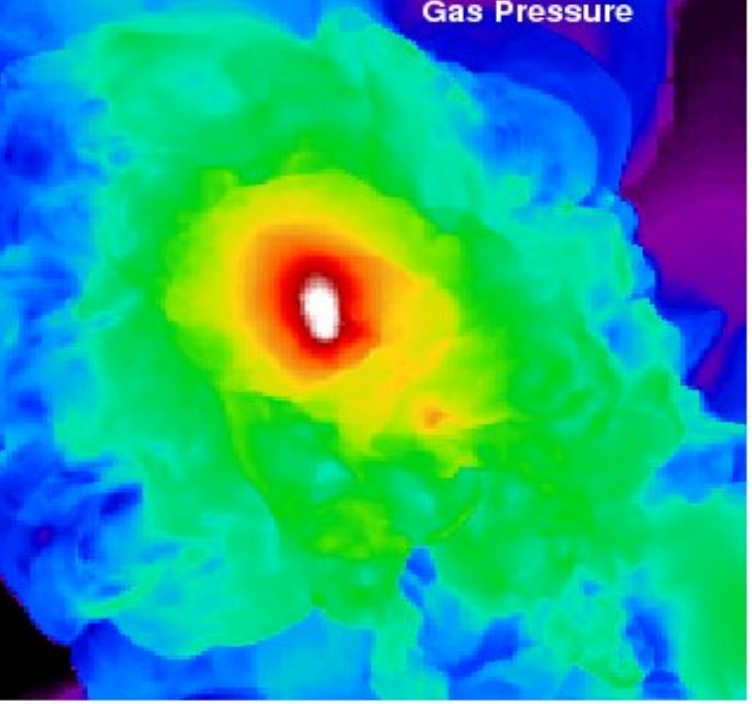


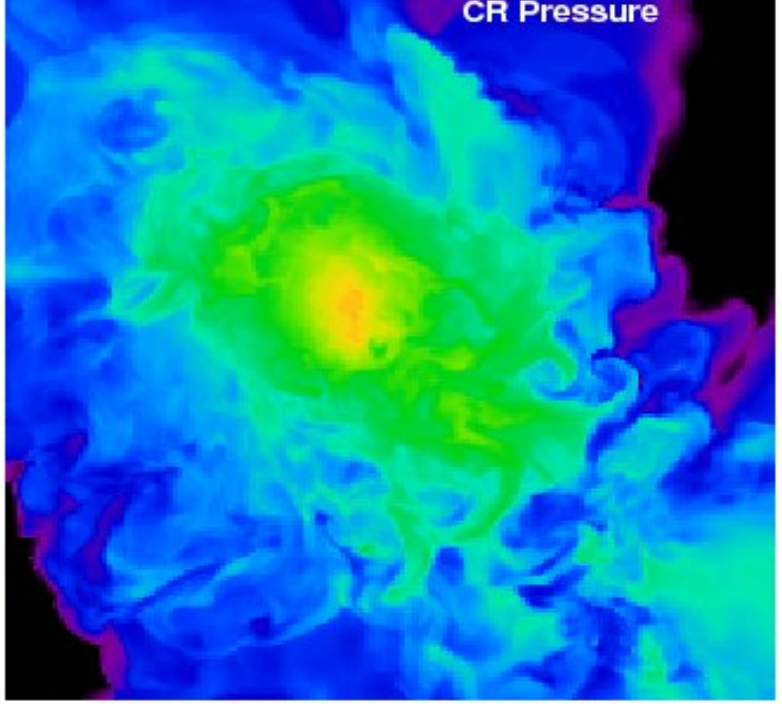


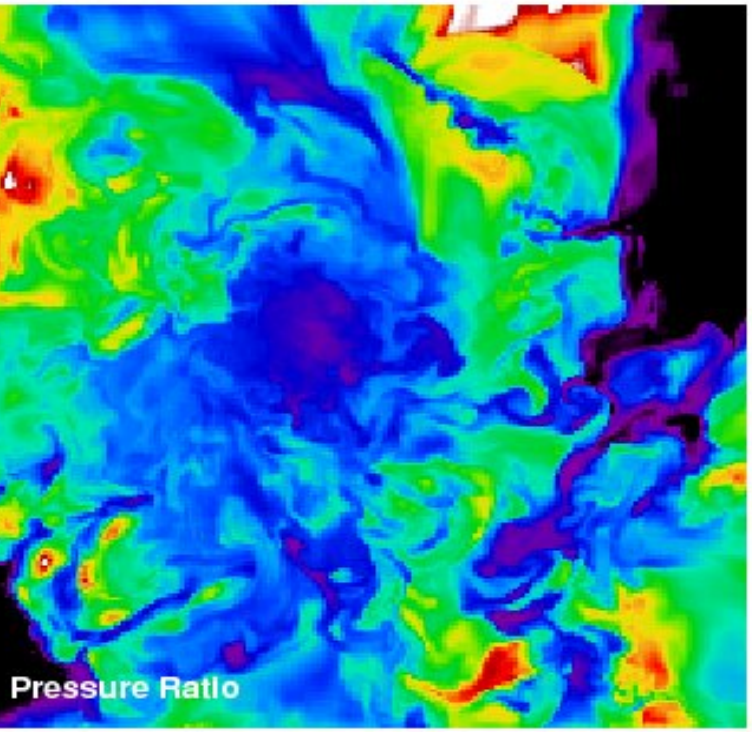
Dependence on "numerics" (i.e. details of injections etc…)

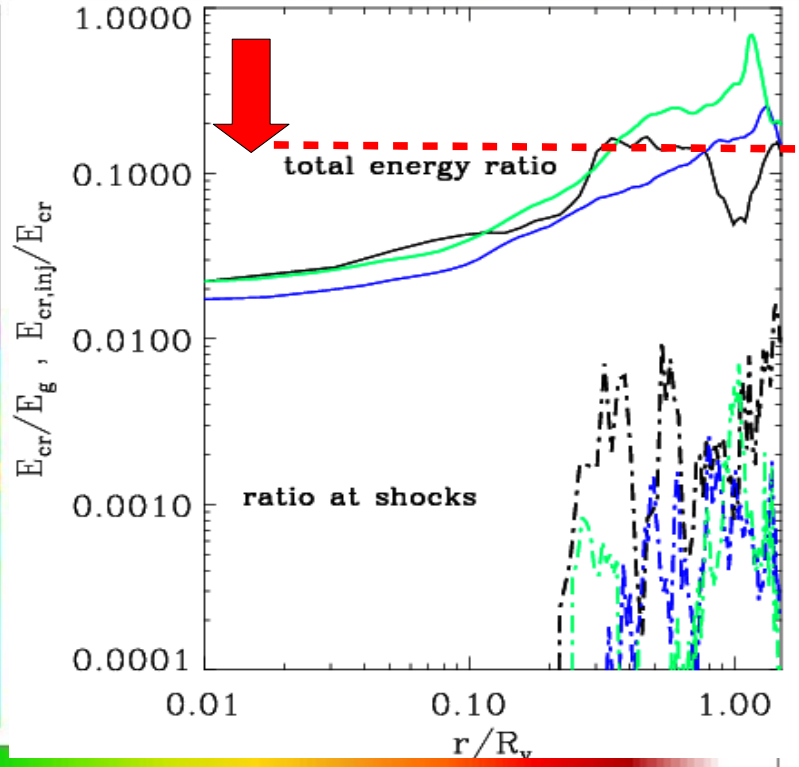












What is the energy ratio between CR and gas in clusters at z=0?

Upper limits from FERMI (now)

Future:

- Coulomb losses
- gamma-flux
- AGN injection
- B field

etc...

Conclusions

1) The incorporation of Diffusive Shock Acceleration and CR feedback (basics) in grid simulations are now doing production

2) CR energy density from structure formation inside clusters seems <10%; small effects on gas density and thermal properties <Rvir

NQP (never quoted people, maybe)

- Zeldovich 1970; Sunyaev & Zeldovich 1972
-G·Bryan, M·Norman,B·O'Shea & UCSD for the development and public release of the ENZO code
- paper on DSA: too many! (see talk by Bell)
- Miniati 2003, 2007 for DSA in TVD grid method;
- Pfrommer et al·2006,08; Ensslin et al·2007; Jubelgas et al· 2008 for CR physics in GADGET2;
- Hanasz et al·2004 for 2-fluid models in galaxy dynamo simulations;
- Kang & Jones 2002,07 for DSA in IGM & ICM;
- Ryu+03; Hoeft+08;Skillman+08 for shocks in simulated galaxy clusters

.....thanks