

# ACCELERATING & TRANSPORTING COSMIC RAYS IN THE ICM: EULERIAN VS SPH

## OUTLINE (& CONCLUSIONS):

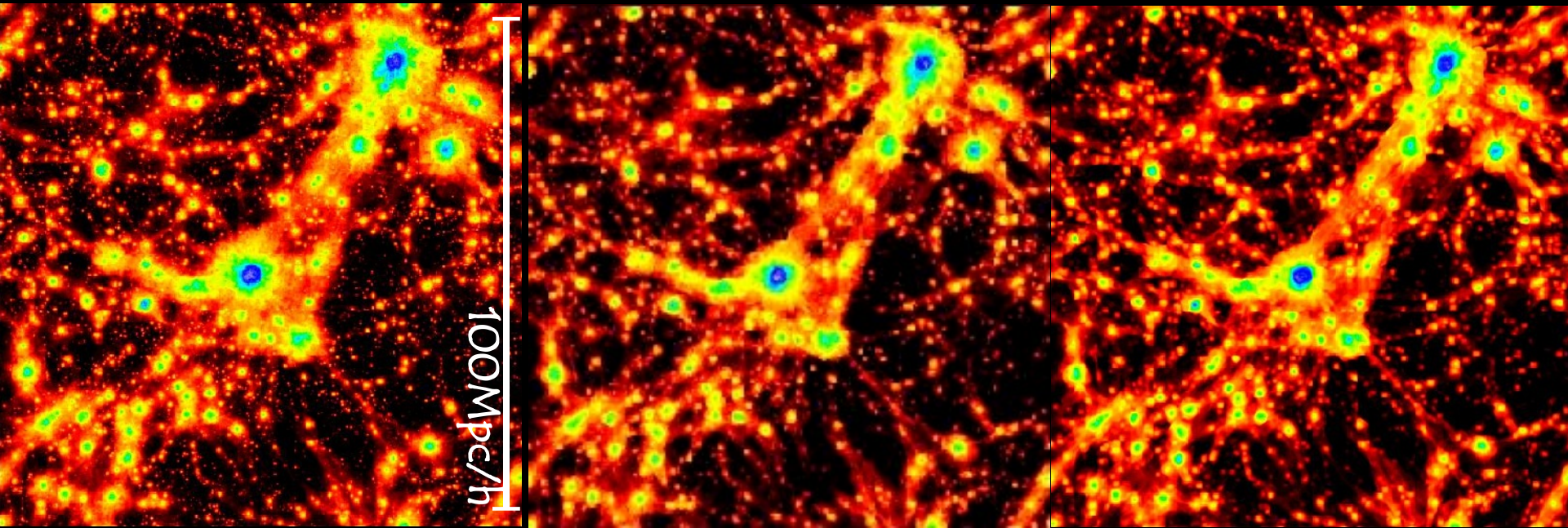
### 1. COMPARISON OF COSMOLOGICAL CODES

- CLUSTERS THERMAL PROPERTIES **CONVERGE** WITHIN  $\sim 10\%$
- **DIFFERENT** ACCRETION REGIONS & SHOCKS IN GRID vs SPH

### 2. HIGH RESOLUTION ENZO AMR SIMULATIONS

- MORPHOLOGICAL & SPECTRAL SIGNATURES OF **TURBULENCE**
- CR ENERGY IS  $\sim 5-10\%$  THERMAL ENERGY INSIDE CLUSTERS

# Comparison Project



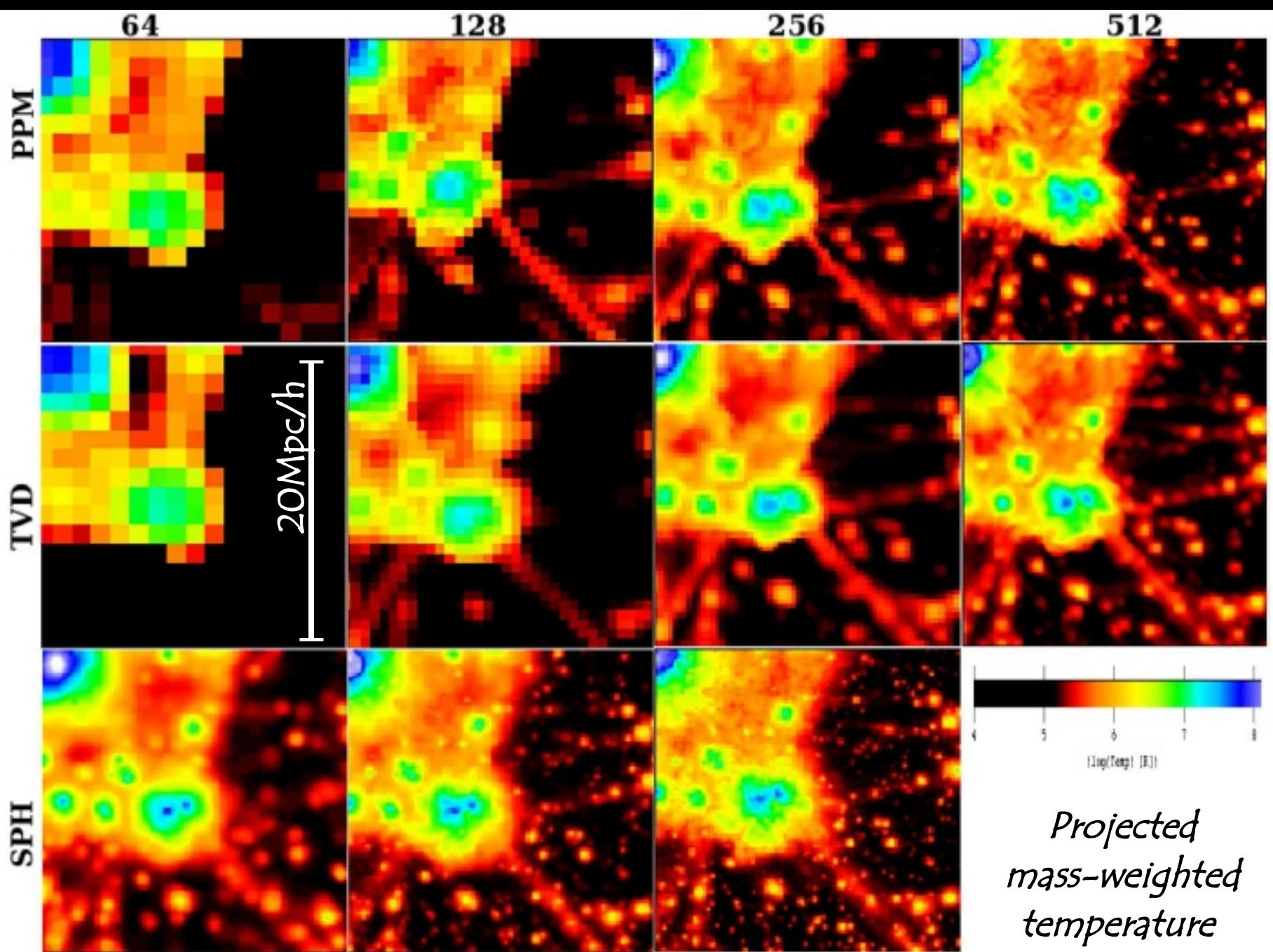
GADGET2 (Springel 2005)  
run by K.Dolag

ES-TVD (Ryu+1993)  
run by D.Ryu

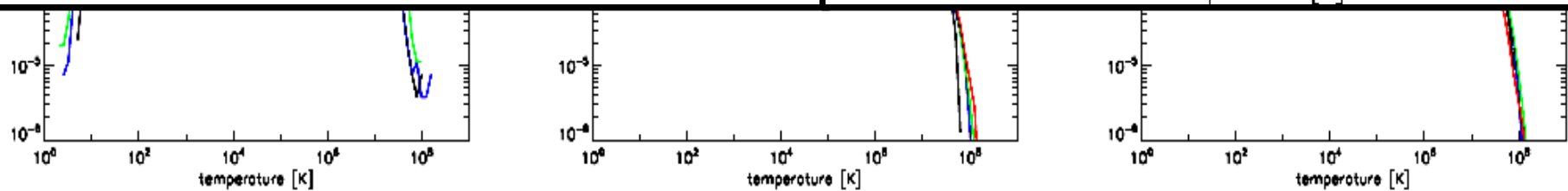
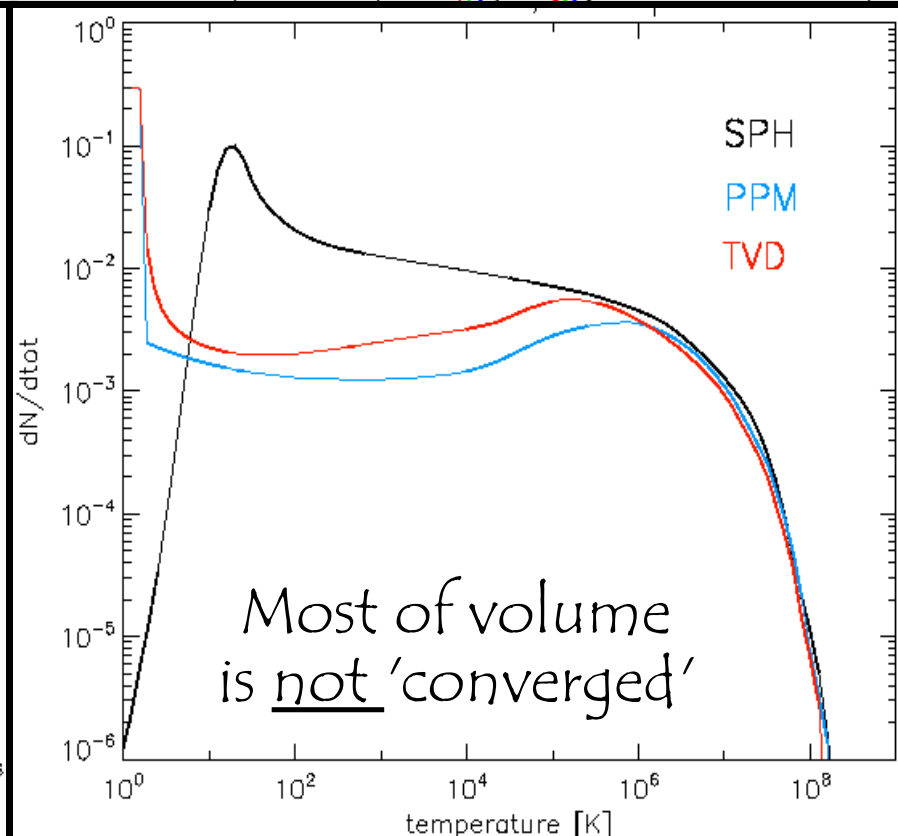
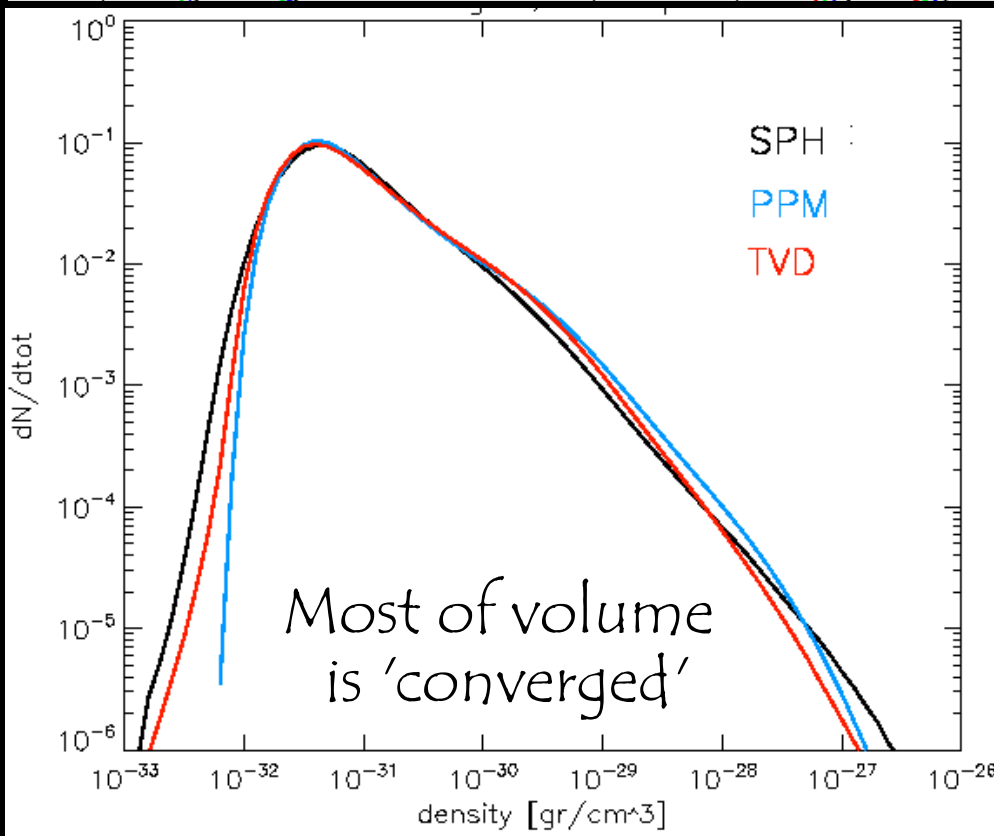
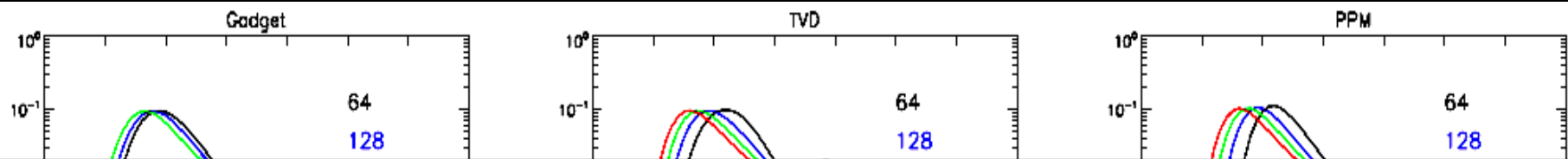
ENZO (Bryan&Norman 1995)  
run by F.Vazza

- Shared initial conditions:  $100\text{Mpc}/h, \sigma_8 = 1.2$
- Non-radiative physics, no reionization
- Different shock detecting schemes
- Resolution studies:  $64^3 - 128^3 - 256^3 - 512^3$

Vazza, Dolag, Ryu, Brunetti, Gheller, Kang & Pfrommer in prep.

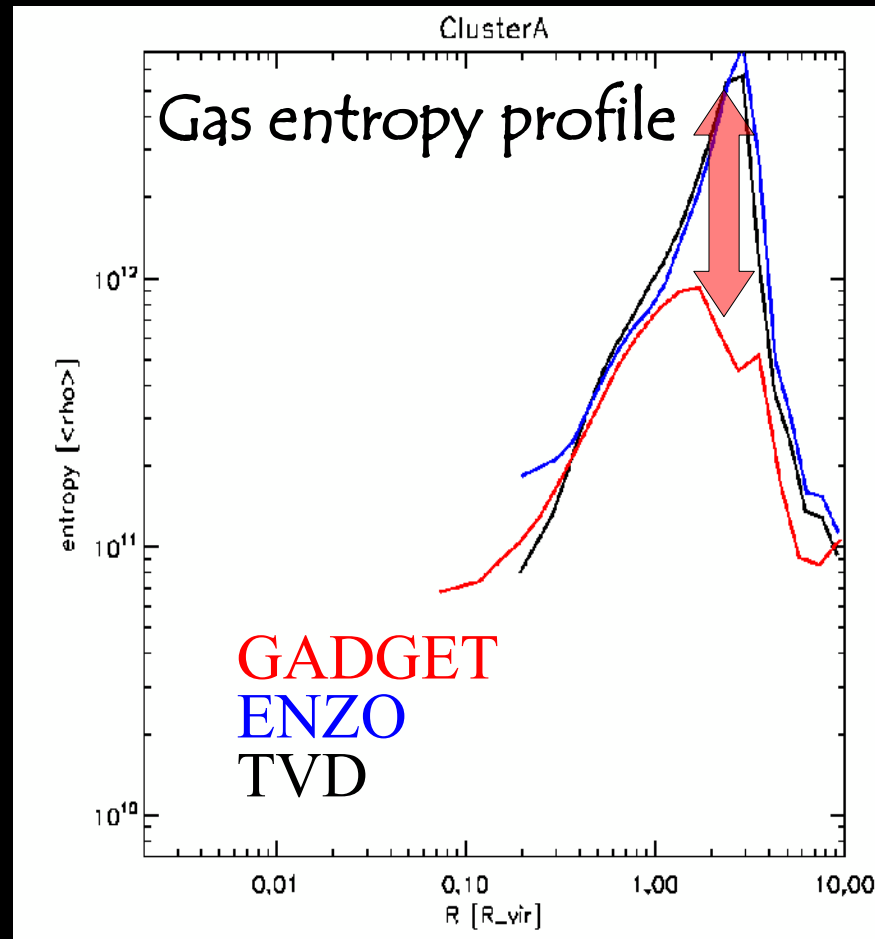
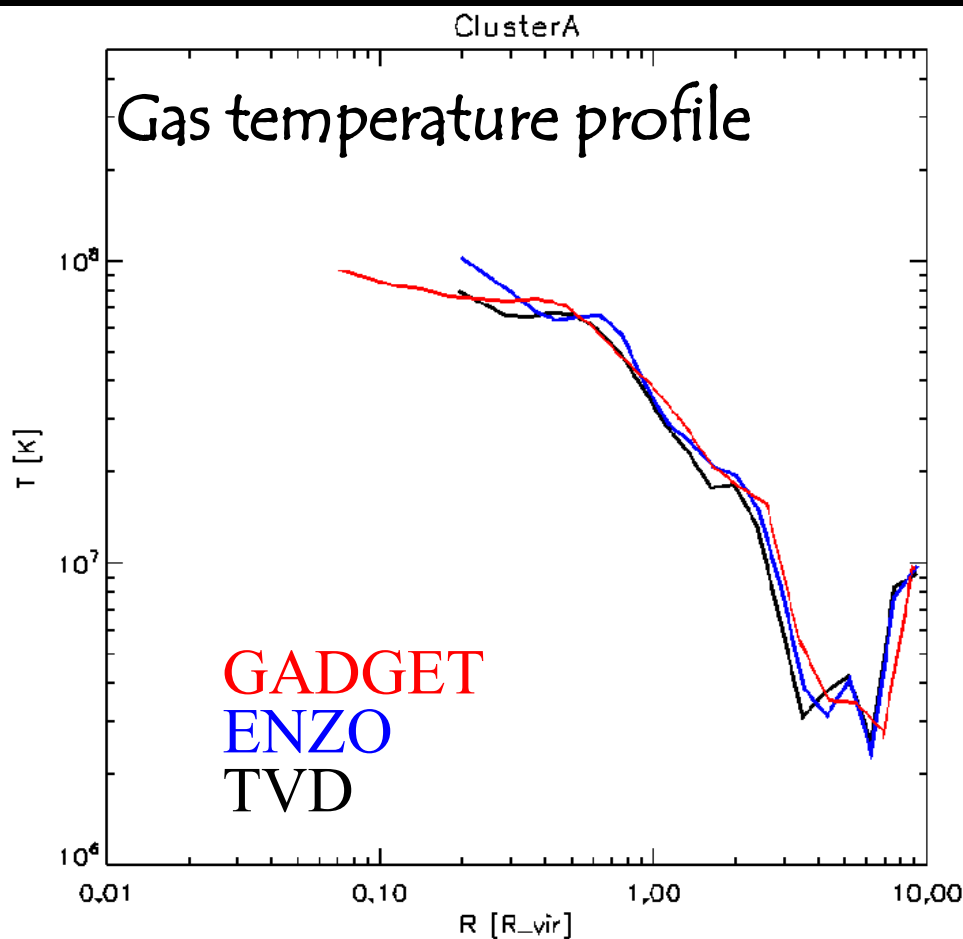
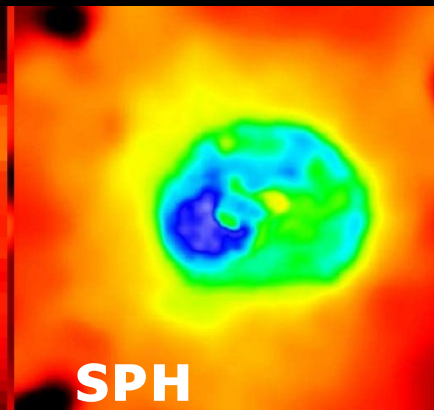
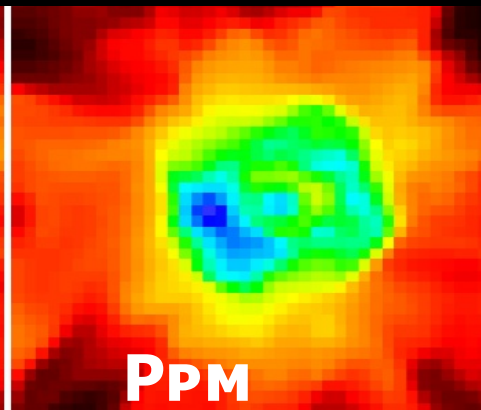
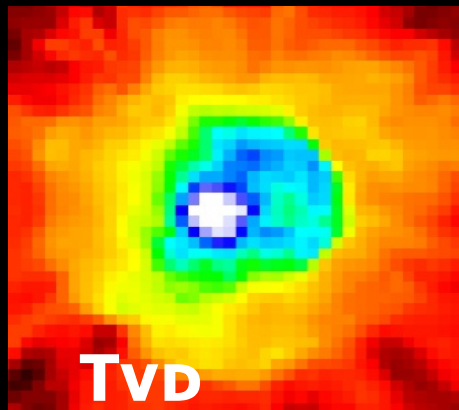


# Gas density distribution functions

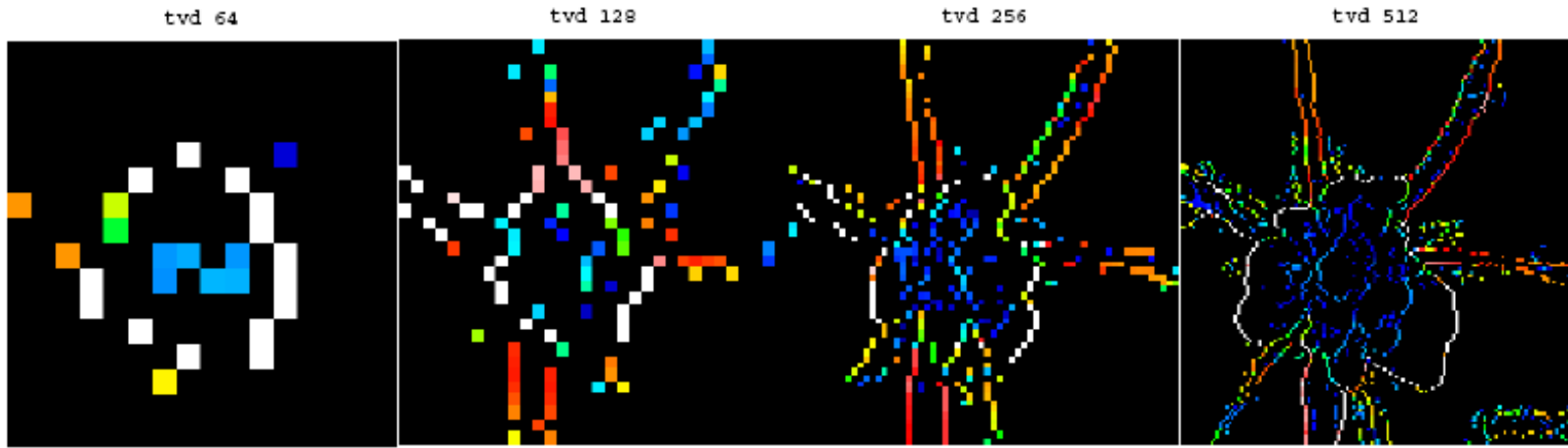


# Gas temperature distribution functions

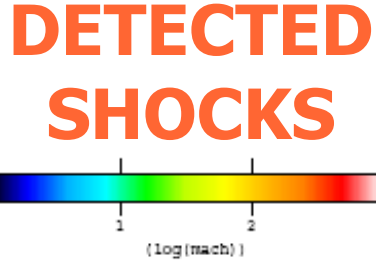
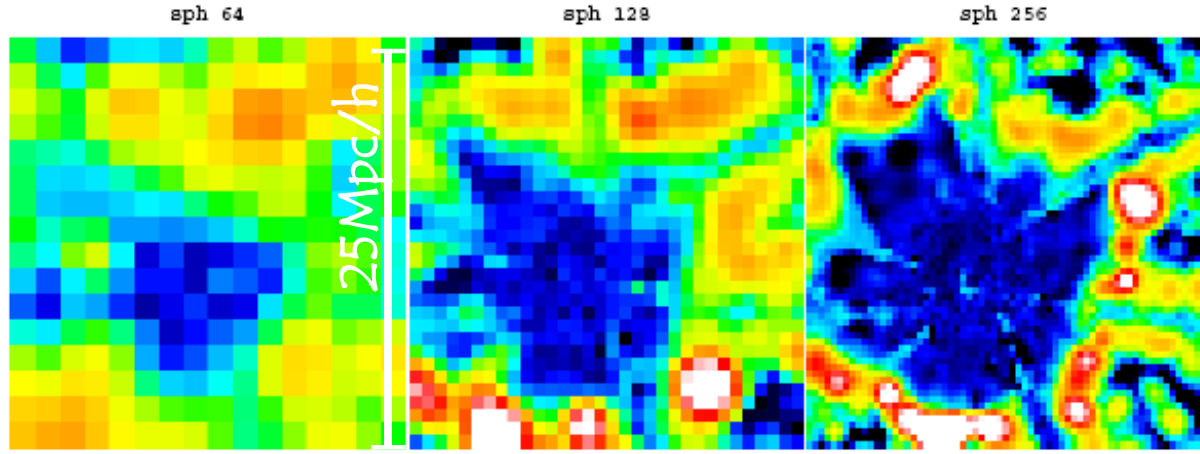
Convergence  
for galaxy  
clusters



Mach from temperature jumps  
(Ryu+03; Kang+07)

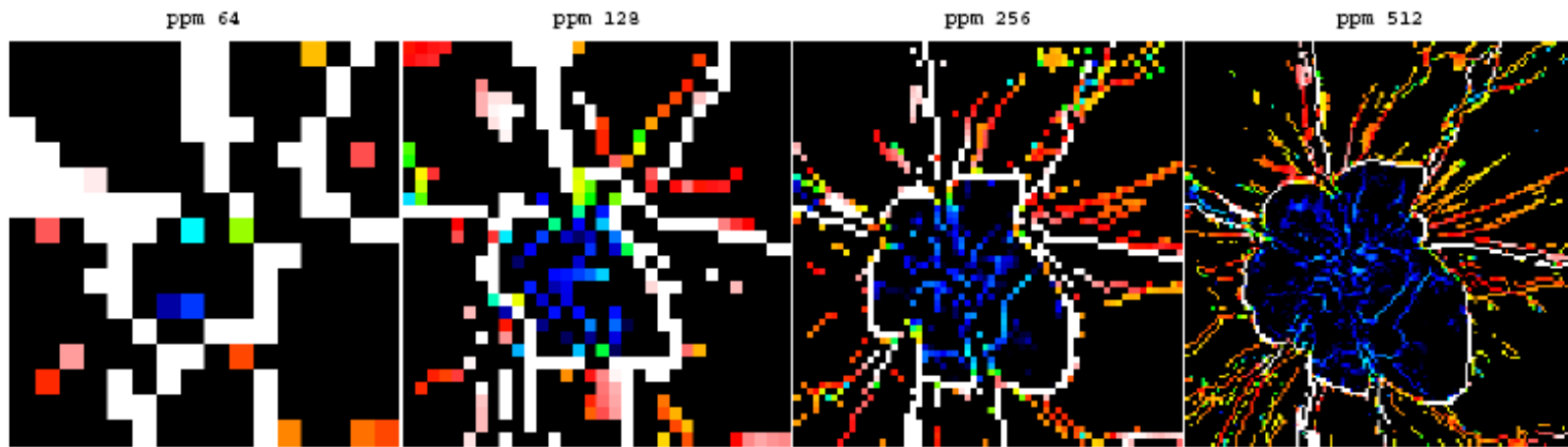


Mach from entropy jumps  
(on the fly)  
(Pfrommer+06,07)



depth ~200kpc

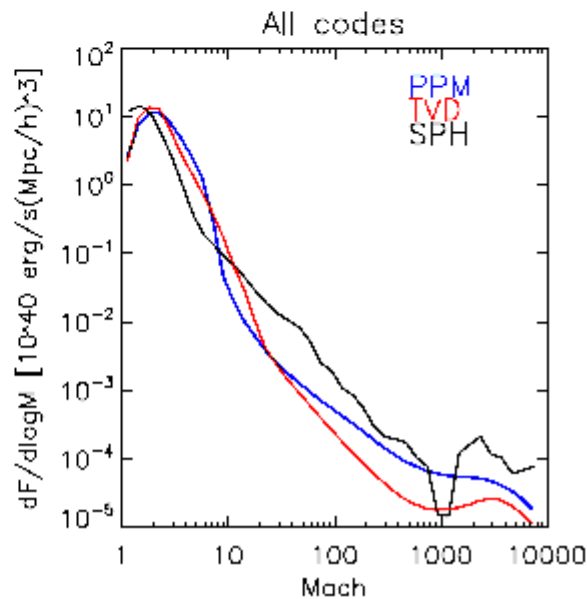
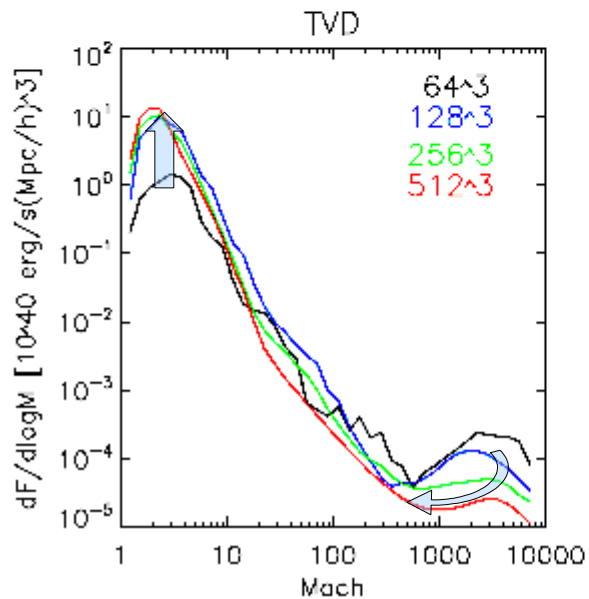
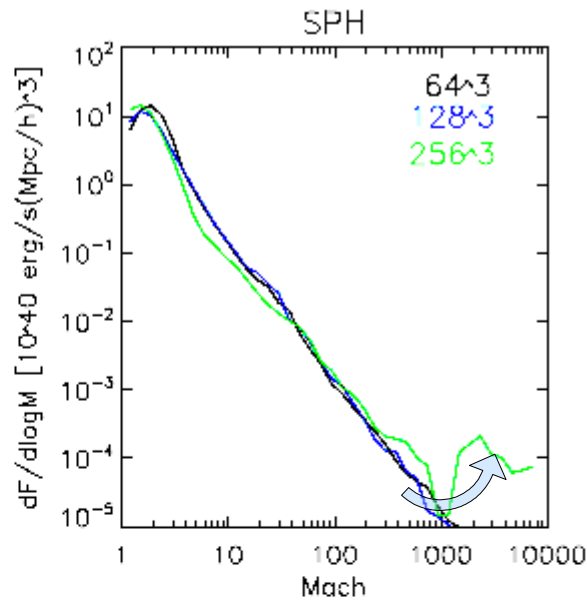
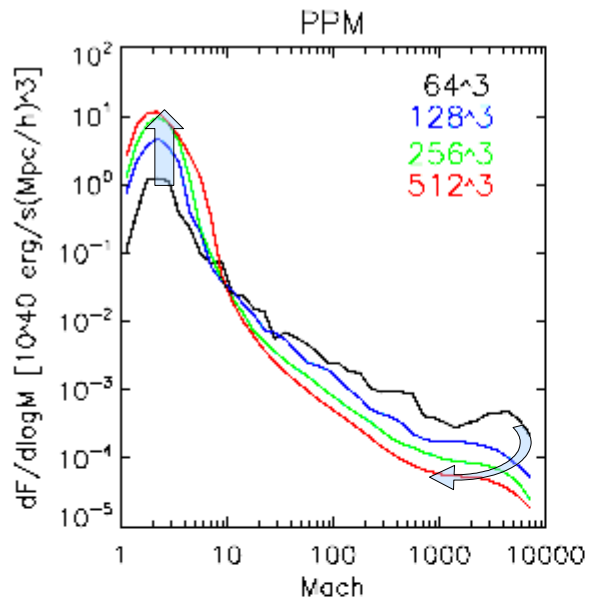
Mach from velocity jumps  
(Vazza+09)



# Shocks Energy Flux vs Resolution

## ALL codes:

- Bulk of energy flux at  $M \sim 2$
- steep flux distribution  
 $d \log F / d \log M \sim -2$



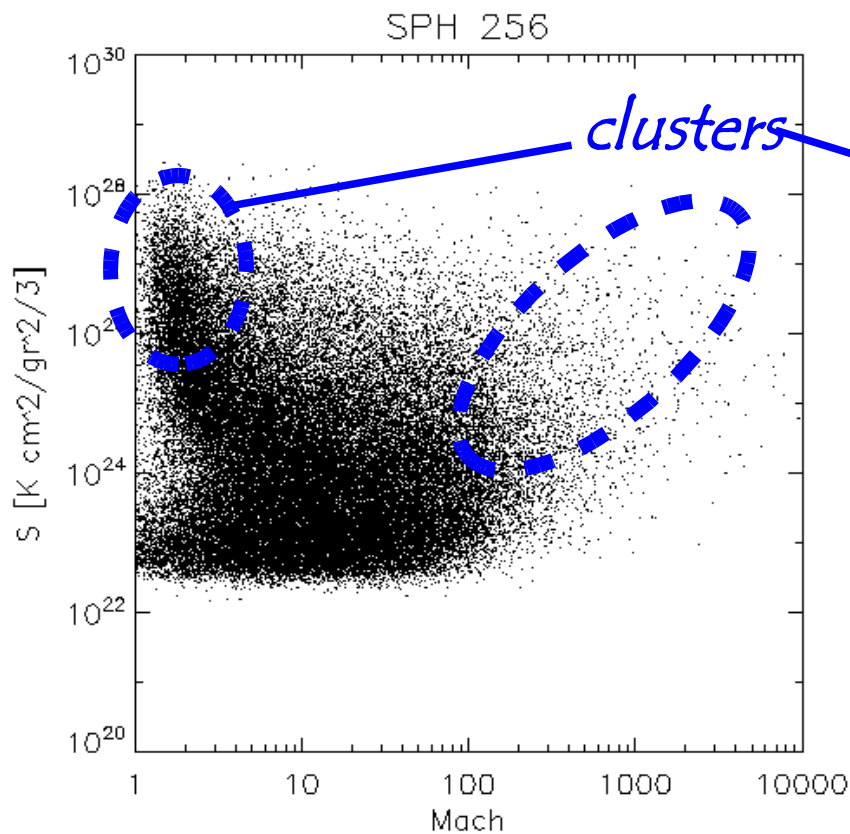
## Differences:

- SPH shows the most converged results
- grid codes and SPH shows convergence to different distributions

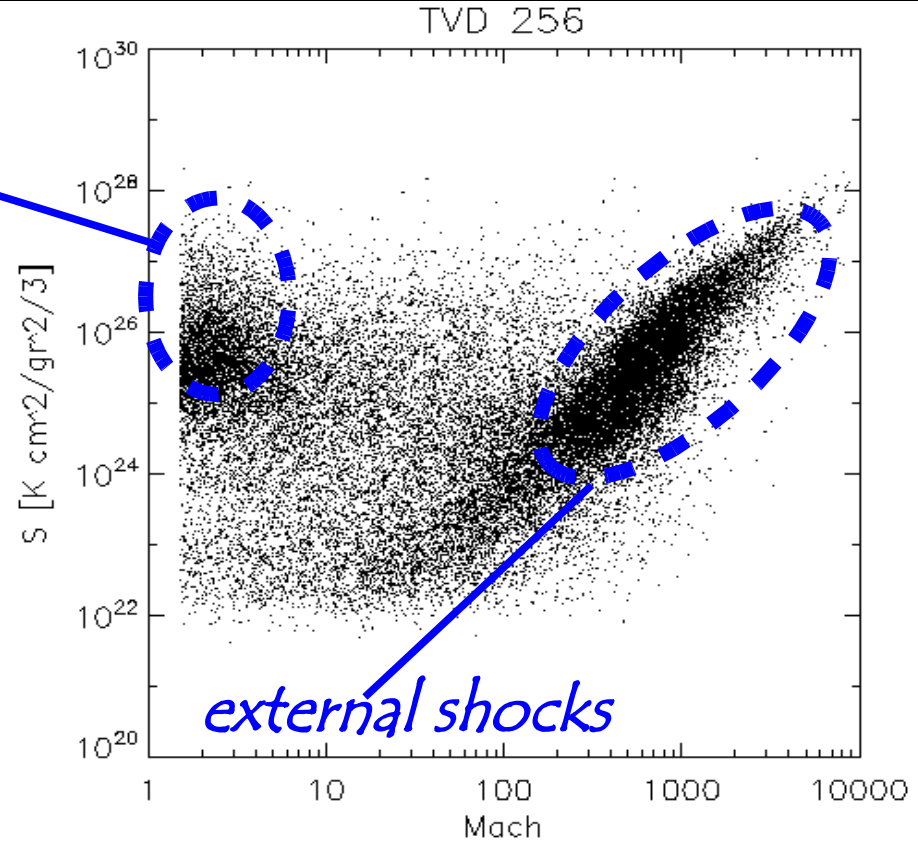
Different behaviour at increasing resolution?

# Entropy vs Mach Number diagram:

## GADGET



## EULERIAN CODES



- a whole "family" of shocks in the  $(S, M)$  phase diagram is missing in GADGET runs at  $z=0$
- external accretion shocks show similar properties in Eulerian codes, regardless of codes and detect. methods

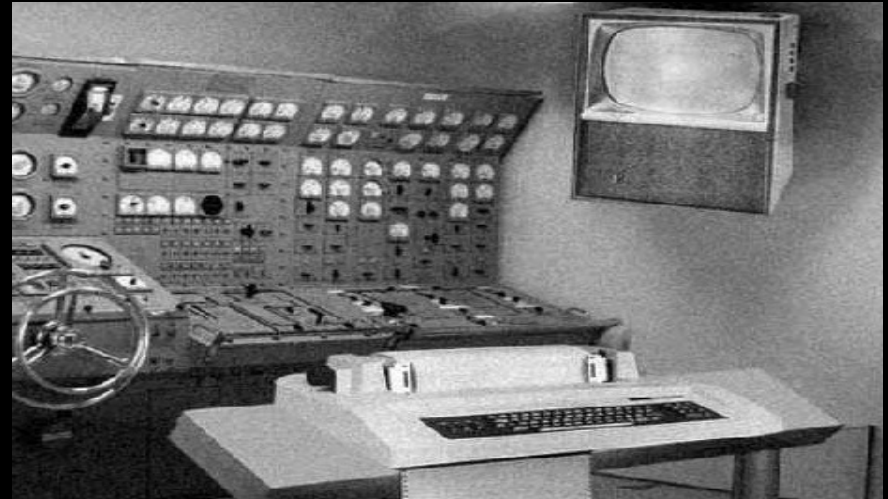


First (exciting) solution:



*PARALLEL UNIVERSES!*

Second possible solution:



**JUST BORING NUMERICS**

similar and complementary by products of fundamental differences among SPH and GRID codes, that were reported in several recent works:

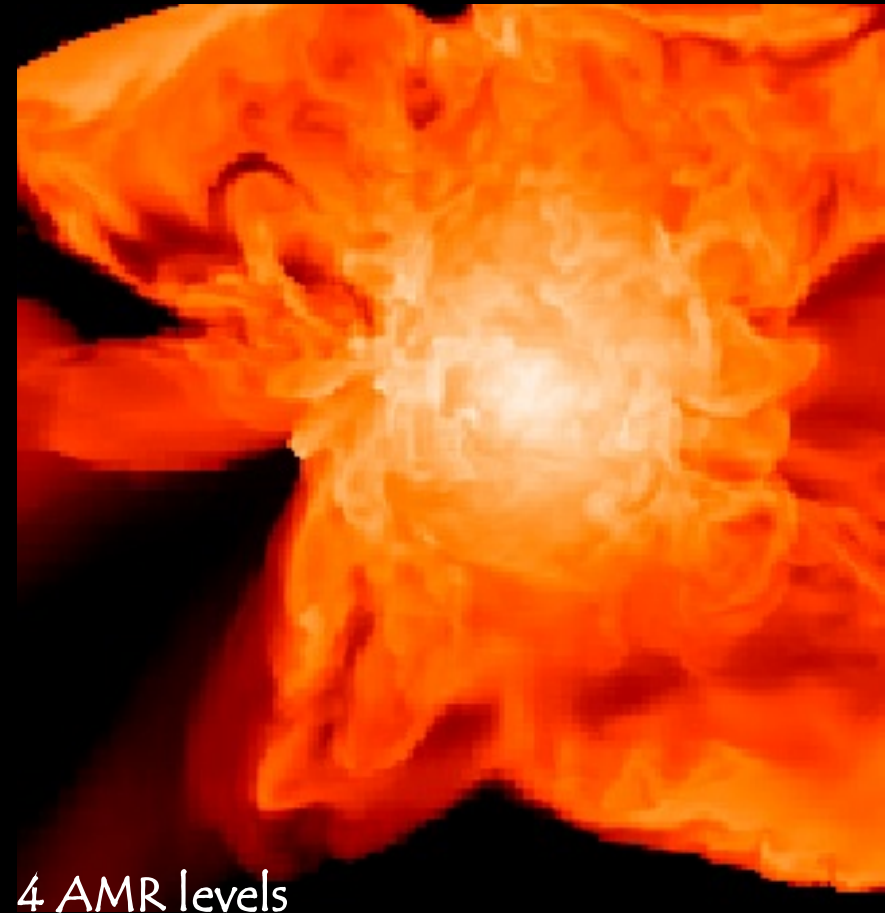
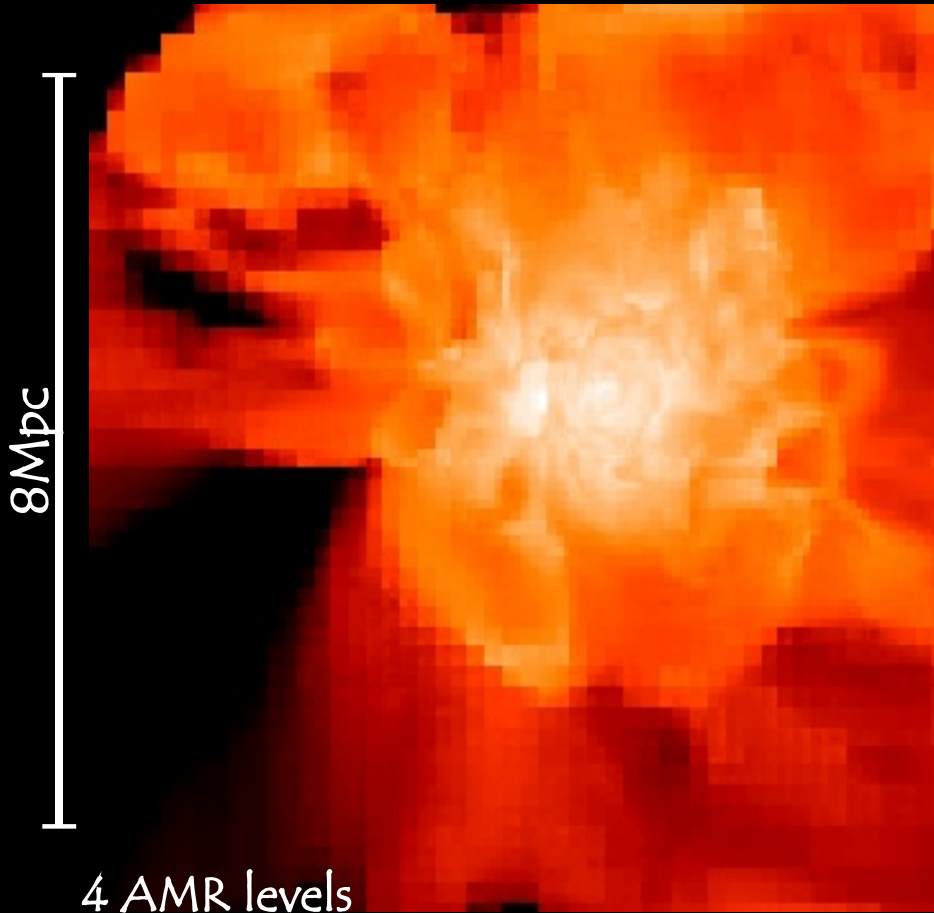
*Agertz et al.2006*

*Tasker et al.2008*

*Mitchell et al.2009*

# SHOCKS & TURBULENCE in ENZO AMR

*FV, Brunetti, Kritsuk, Wagner, Gheller & Norman 2009, Highlight of A&A 504*

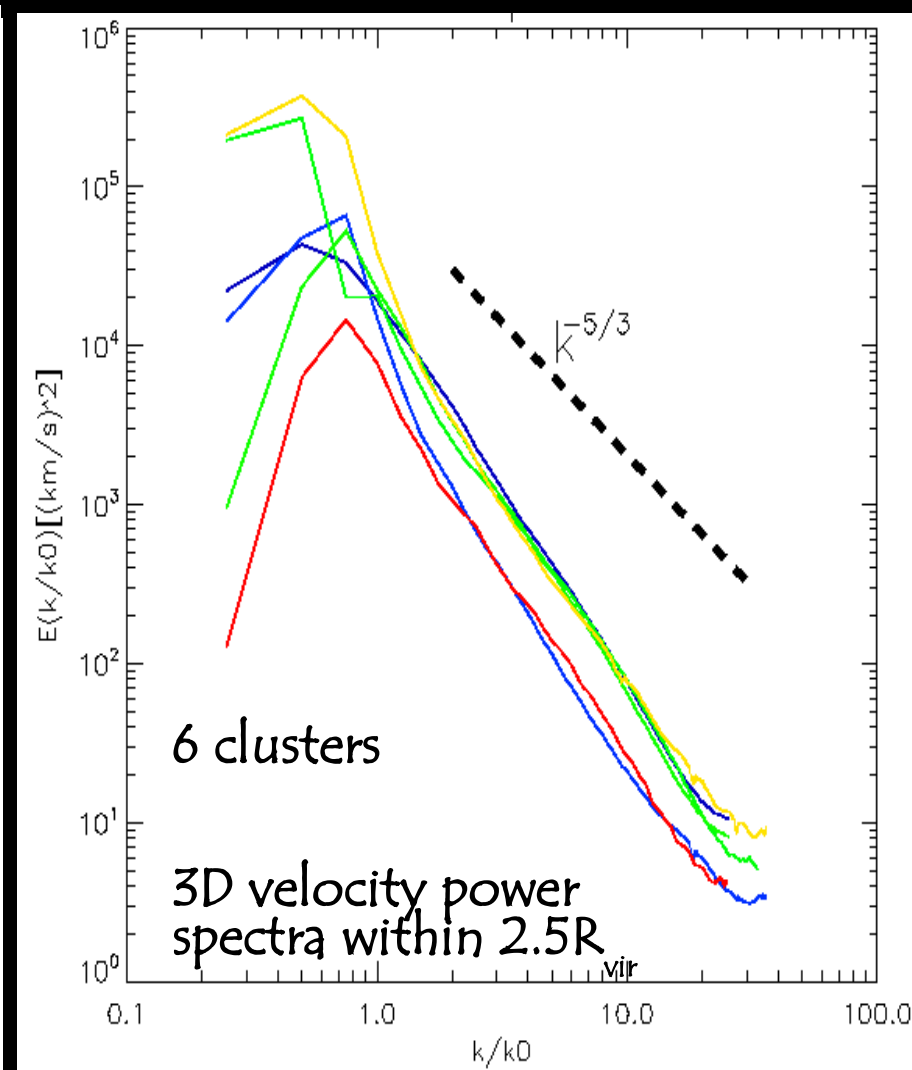
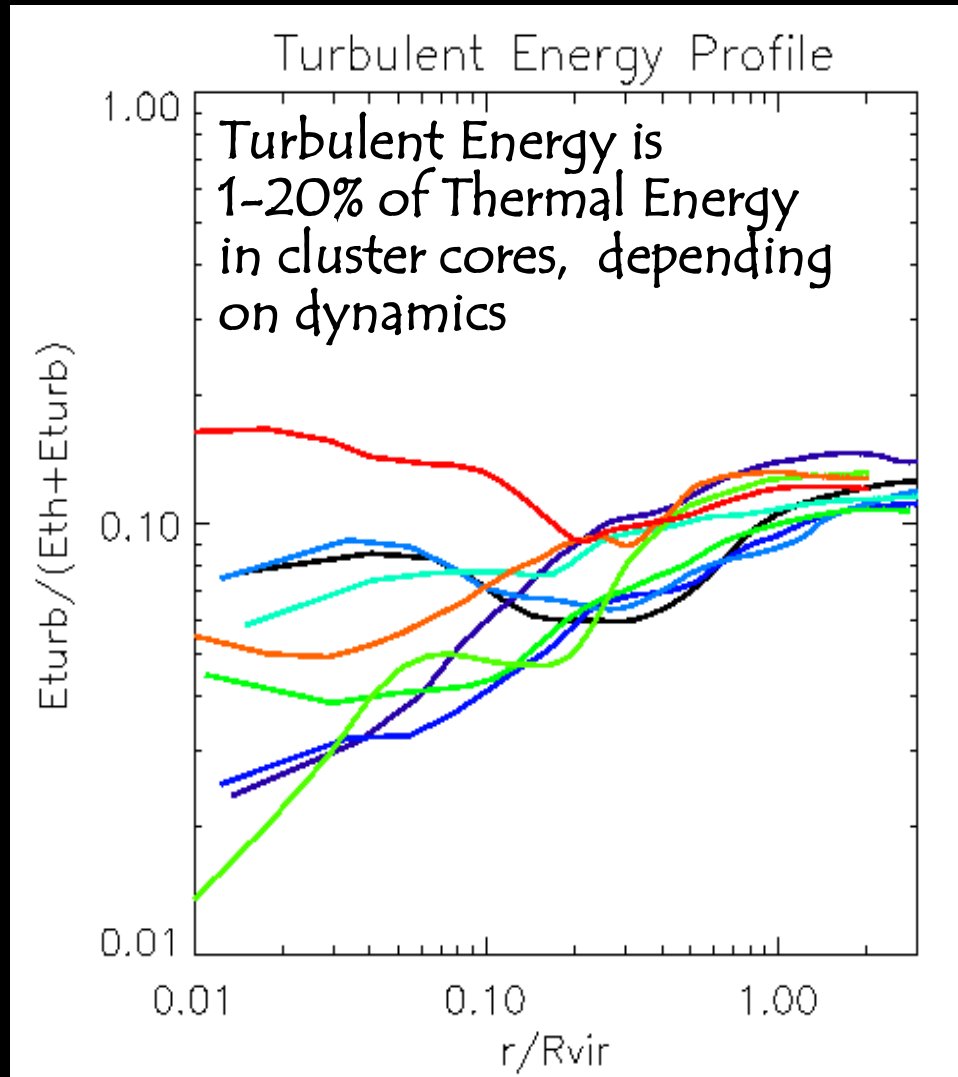


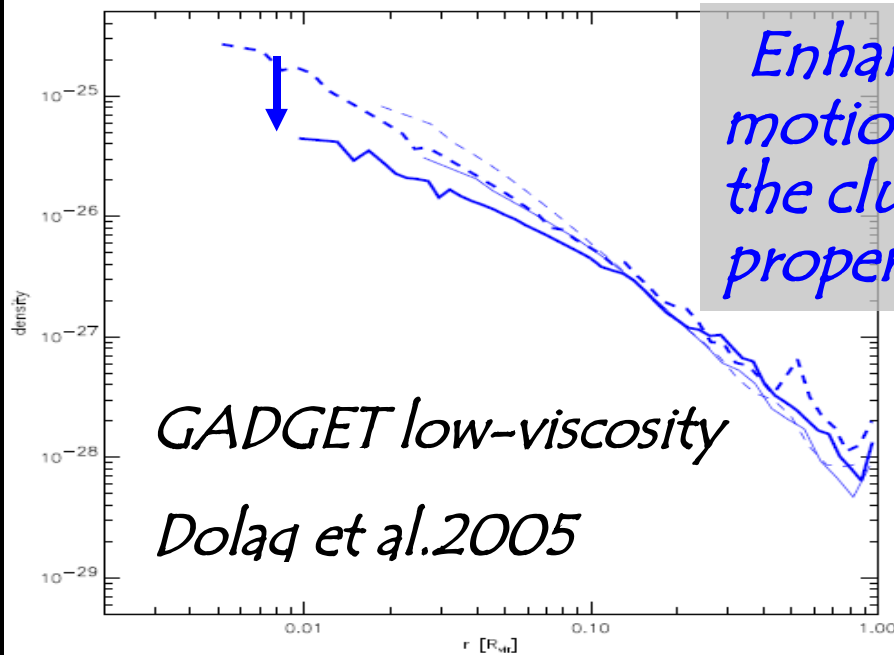
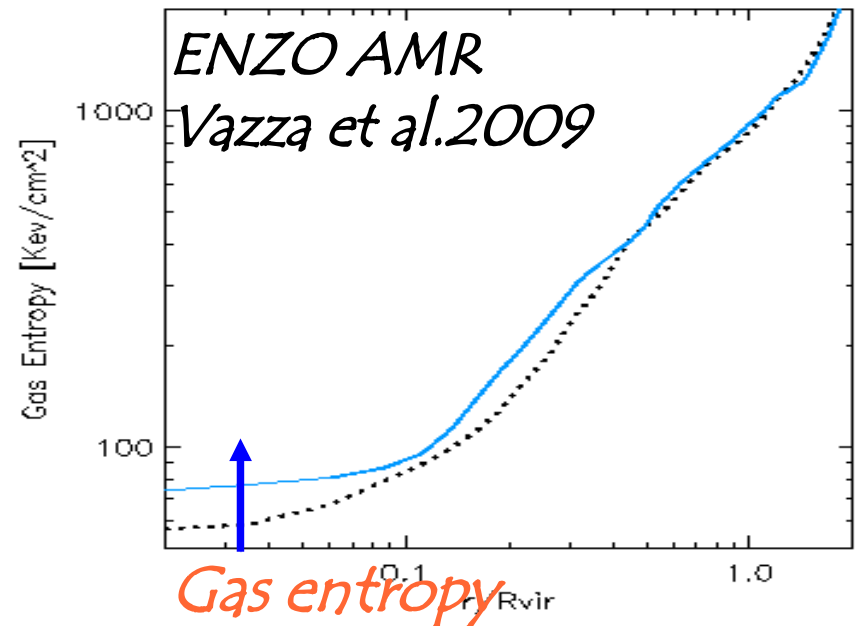
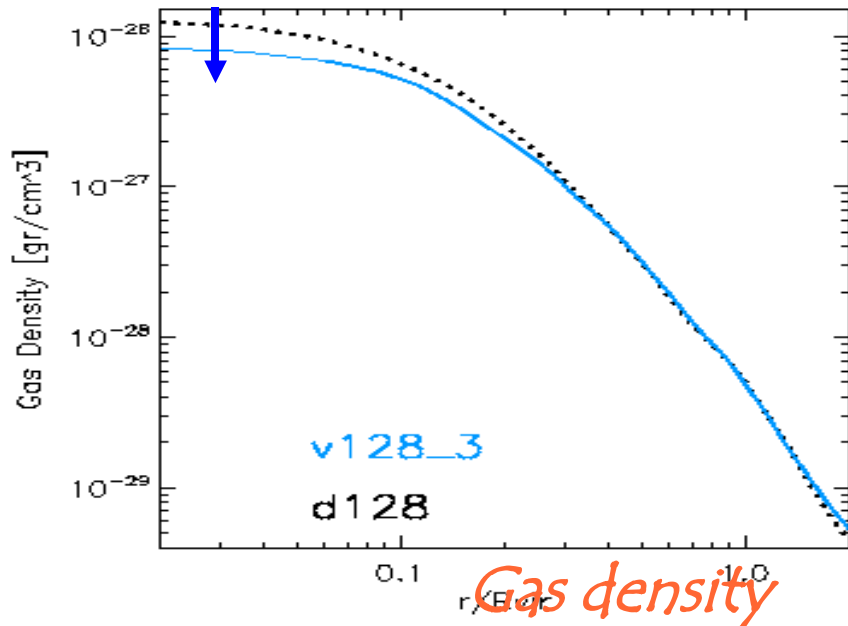
DM mass resolution  $m_{\text{dm}} = 6.7 \cdot 10^8 M_{\odot} / h$   
Peak resolution = 12kpc/h

MOVIE

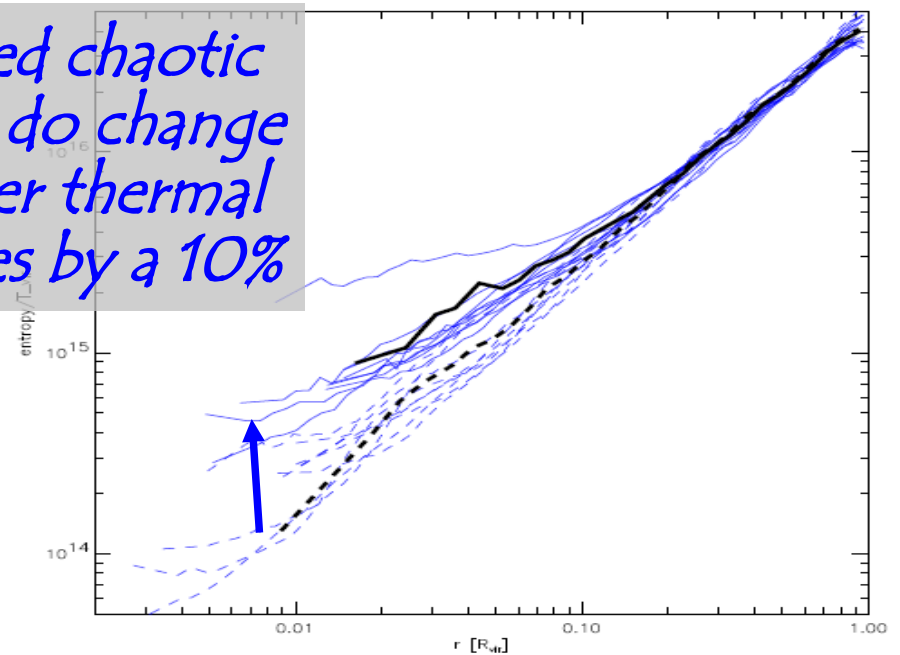
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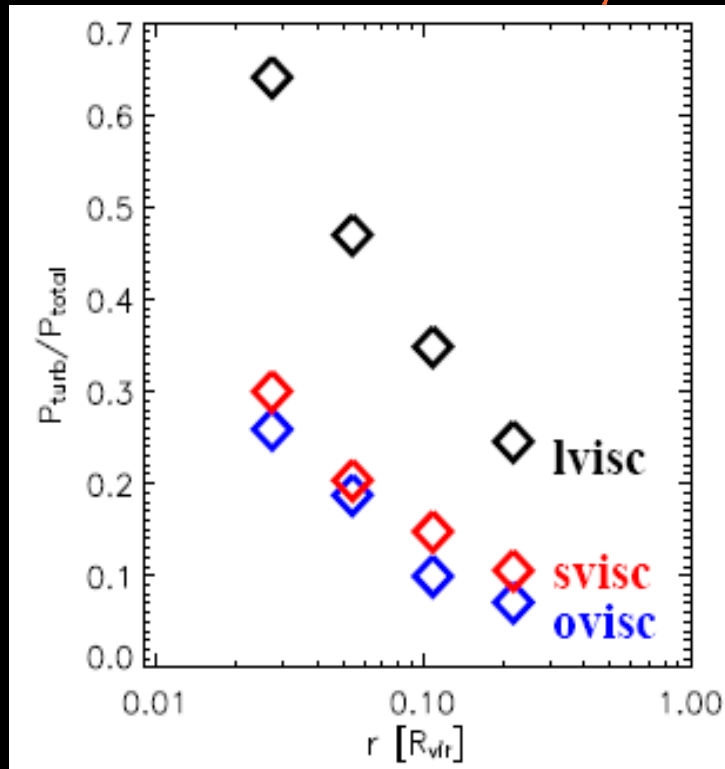


*Enhanced chaotic motions do change the cluster thermal properties by a 10%*



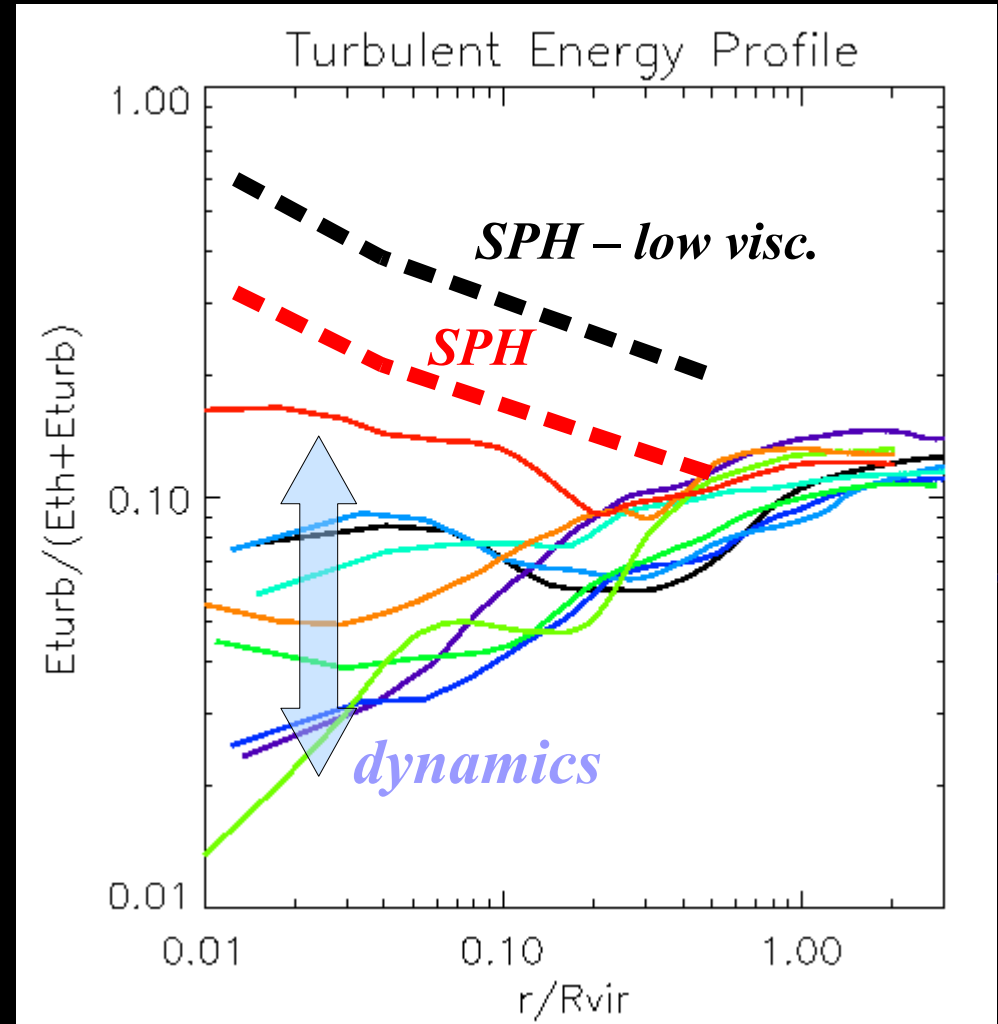
# Profiles of turbulent (<300kpc) to total pressure in simulated clusters:

Gadget 2  
+ reduced viscosity



Dolağ et al. 2005  
Vazza et al. 2006

ENZO + implemented AMR

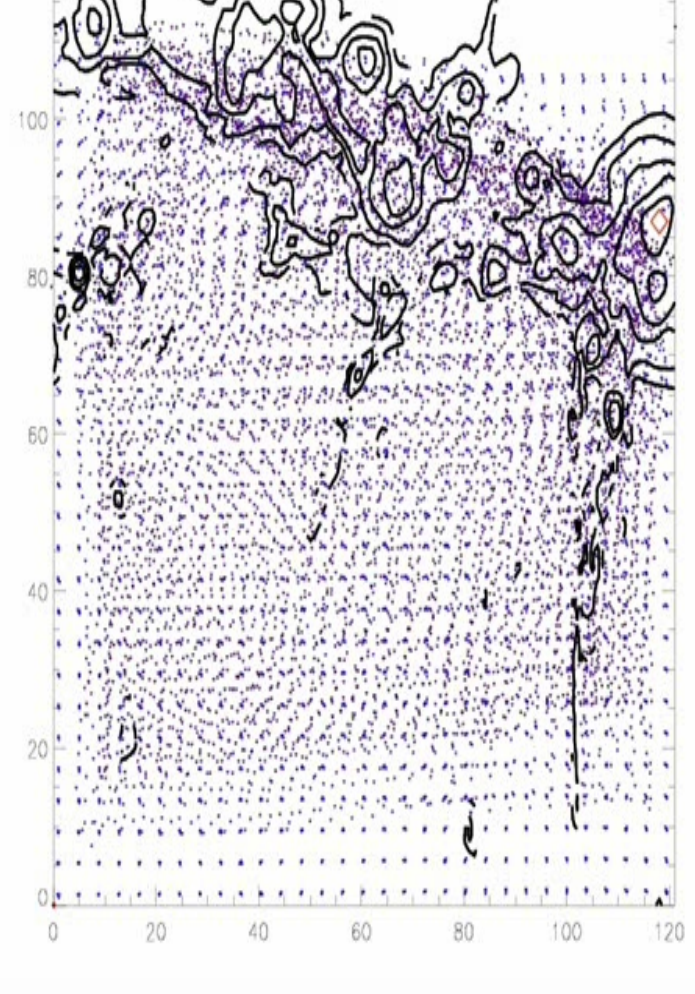


*INJECTION +  
ADVECTION  
of Cosmic Rays with  
tracers*

*- 10 generations of  $10^5$   
tracers*

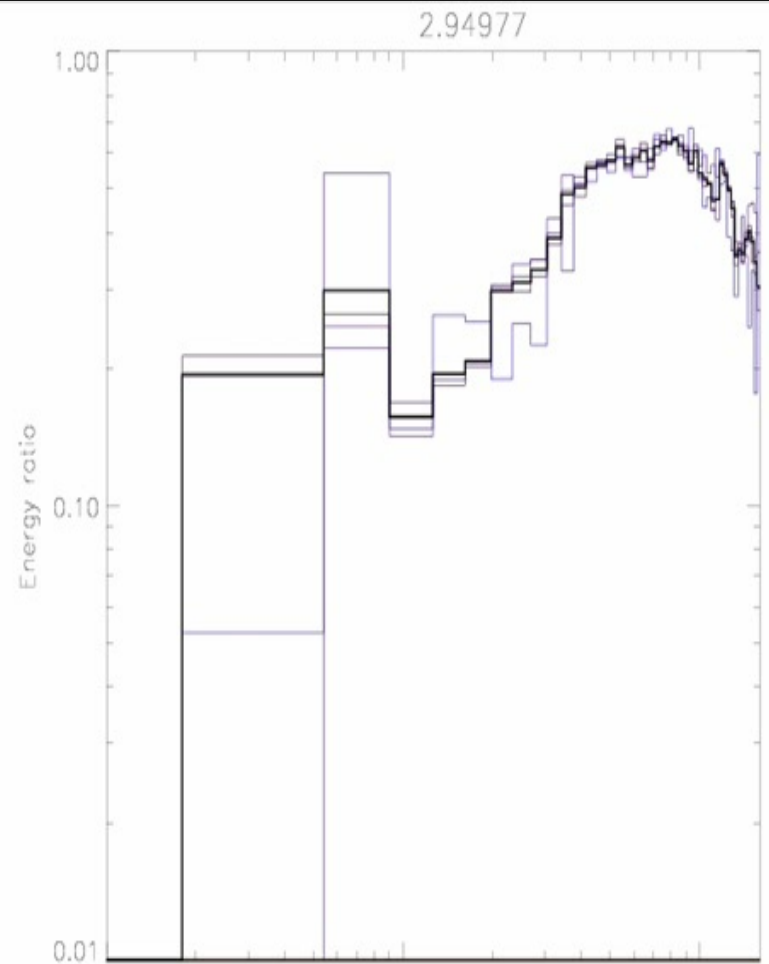
*- $\eta(M)$  injection efficiency at  
shocks from Kang & Jones  
2007*

*INJECTION + ADVECTION  
of Cosmic Rays with tracers*  
- 10 generations of  $10^5$  tracers  
-  $\eta(M)$  injection efficiency at  
shocks from Kang & Jones 2007



*Top: tracers &  
gas density*

*Right: profile of  
CR to thermal  
Energy*





Ongoing re-simulations:

target :  $M > 10^{15} M_{\odot}/h$  clusters

6-7 levels of refinement

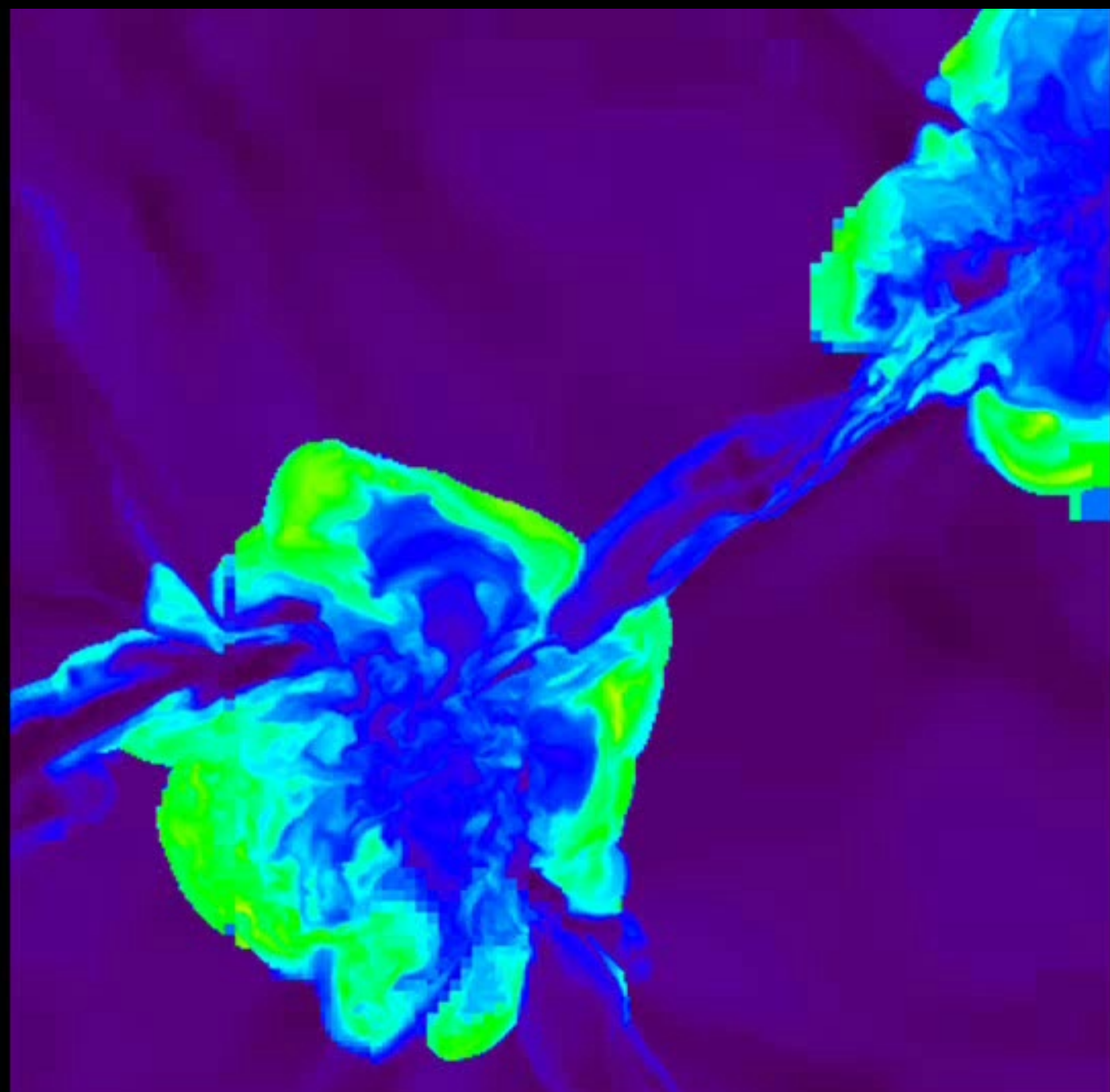
AMR region:  $4 \times 4 \times 4 R_{\text{vir}}$

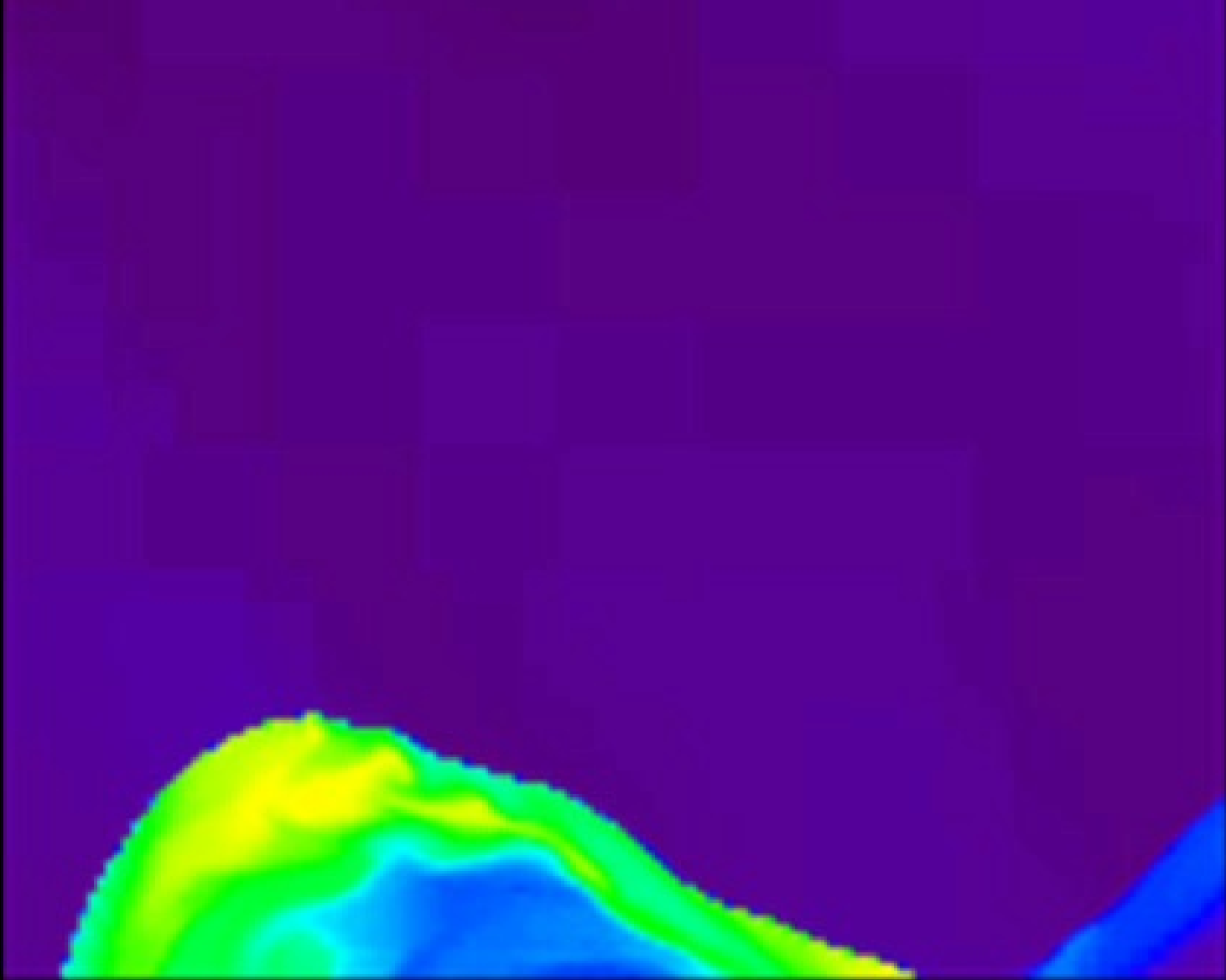
peak resolution of 12-24kpc/h

dynamical range  $\sim 500-1000$

DM mass resolution =  $6.7 \times 10^8 M_{\odot}/h$







감사합니다 !!