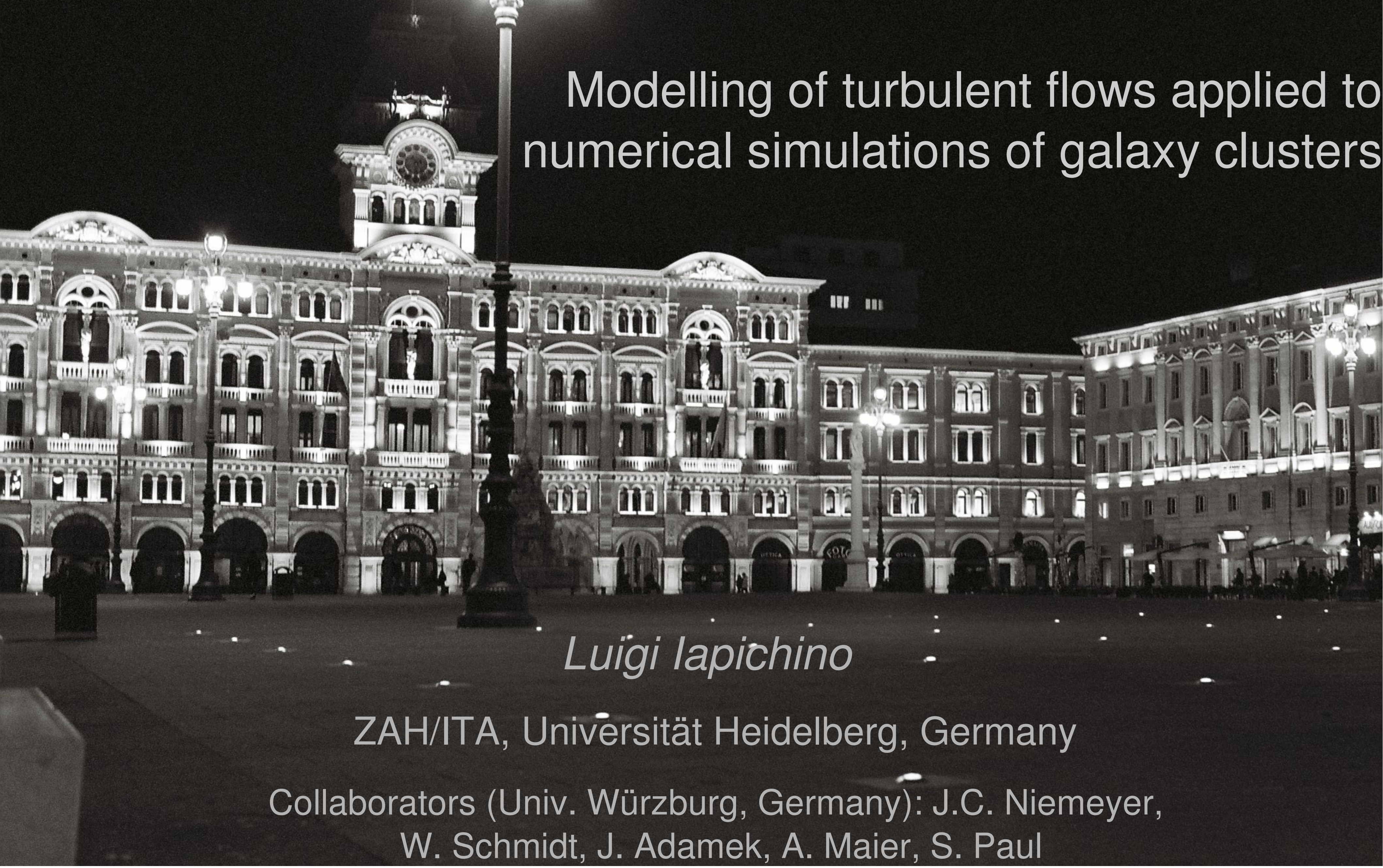

Modelling of turbulent flows applied to numerical simulations of galaxy clusters

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Overview

- Role of turbulence in the physics of galaxy clusters, and its numerical treatment

- Grid-based, adaptive mesh refinement (AMR) simulations * and efficient resolution of turbulent flows: definition of suitable refinement criteria

- Going further: Large Eddy Simulations and the *FEARLESS*** approach

- Application: galaxy cluster simulations

* : the simulations presented here have been performed using the ENZO code, v. 1.0

** : Fluid mEchanics with Adaptively Refined Large Eddy SimulationS

Turbulence and the physics of galaxy clusters

- CDM cosmology and hierarchical model of cluster evolution by merging
- X-ray observations of cluster substructures
- Simulations of merging clusters predict large-scale motions (e.g., Norman & Bryan 1999: bulk motions ~ 300 – 600 km/s, eddy scales 100 – 500 kpc)

Is the intra-cluster medium (ICM) turbulent?

Control parameter for the turbulent feature of a flow:
(Reynolds number » 1 = turbulence)

$$\mathrm{Re} = \frac{LU}{\nu}$$

- Direct detection via X-ray spectroscopy ☹
- Indirect evidences: observations interpreted as turbulence signatures

  Faraday rotation measures (Vogt & Enßlin 2005); pressure fluctuations in Coma pressure maps (Schuecker et al. 2004); lack of resonant scattering in the 6.7 keV Fe line implying the presence of gas motions in the core of Perseus (Churazov et al. 2004); broadening of abundance peaks in cluster cores (Rebusco et al. 2005)

- BUT: some observations and theoretical arguments call for a weakly suppressed, or unsuppressed, viscosity

Open questions about turbulence and the clusters physics

- Energy content and cluster features:
  Kinetic energy associated with turbulent gas motions can be a significant component to the cluster energy budget.
  Influence on temperature – density – entropy profiles?
  Turbulent pressure support → cluster mass estimates.

- Turbulence generation and development (major – minor mergers), volume filling vs. area covering factor (Subramanian et al., MNRAS 2006)

- Metal diffusion in the ICM, amplification of magnetic fields, CR acceleration and non-thermal emission...

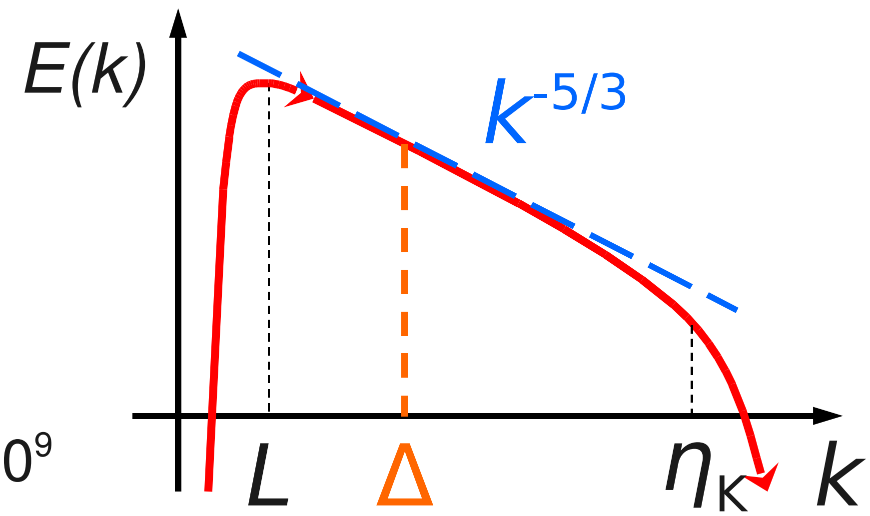
- Stirring agents: in the following I will not deal with AGN outflows and galactic wakes

Resolving turbulence in cosmological simulations (with grid-based hydrocodes)

Number of degrees of freedom:

$$N = \left(\frac{L}{\eta_K}\right)^3 = \mathrm{Re}^{9/4}$$

Supercomputers manage up to $N \sim 10^9$



(courtesy W. Schmidt)

Two approaches for the resolution of turbulent flows in strongly clumped media:

- Adaptive mesh refinement (AMR)
- Large Eddy Simulations

Resolving turbulent flows with AMR

Regional variability of structural invariants of the flow
(W. Schmidt et al., A&A submitted, arXiv:0809.1321).

- Given the variable $q(\boldsymbol{x},t)$, AMR is triggered if:

$$q(\boldsymbol{x},t)-\langle q\rangle_i(t)\geqslant\alpha\lambda_i(t)$$

$\langle q\rangle_i$: average of q in the grid patch i;
λ_i: max($\langle q\rangle_i$, standard deviation of q in i);
α : threshold parameter.

- Control variables: related to the velocity gradients. Examples: <u>enstrophy</u> and <u>rate of compression</u>.

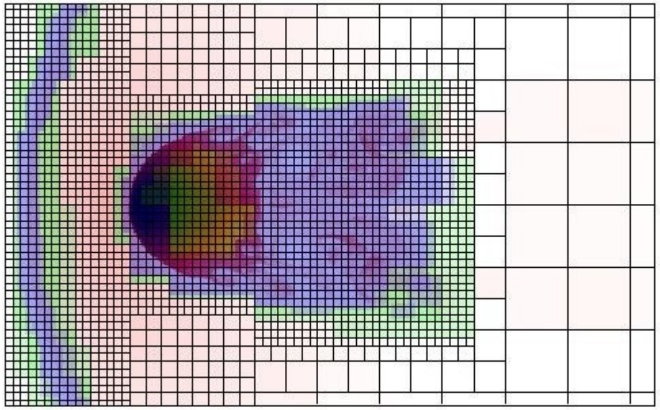
- Particular care is also taken in setting the overdensity criteria in cosmological simulations. According to them, a cell at level l is refined if

$$\rho_i > f_i \rho_0 \Omega_i N^l$$

i: baryons or DM; ρ_0: critical density; Ω_i: fractions of critical density; $N = 2$: refinement factor

Application #1: substructure in a wind

(*LI*, J. Adamek, W. Schmidt, J.C. Niemeyer: 2008, MNRAS **388**, 1079)



← The standard AMR is not able to refine the turbulent wake.

Subcluster mass ~ 10^{14} Msun

Core radius = 250 kpc

Temperature: 3.65 keV (subcluster), 8.0 keV (background)

Wind velocity = 1.1 c_s

Baryons: beta profile, β = 0.6

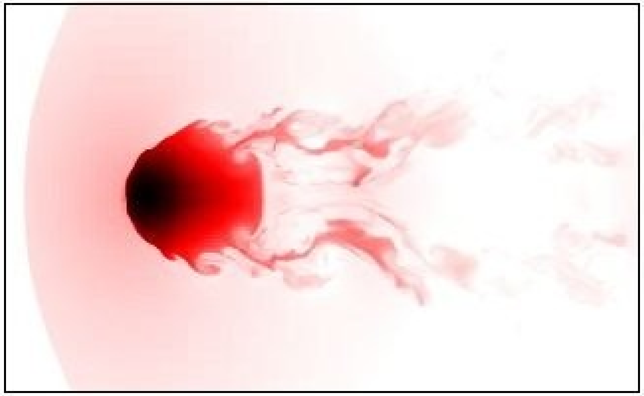
Gravity: as given by a static King profile

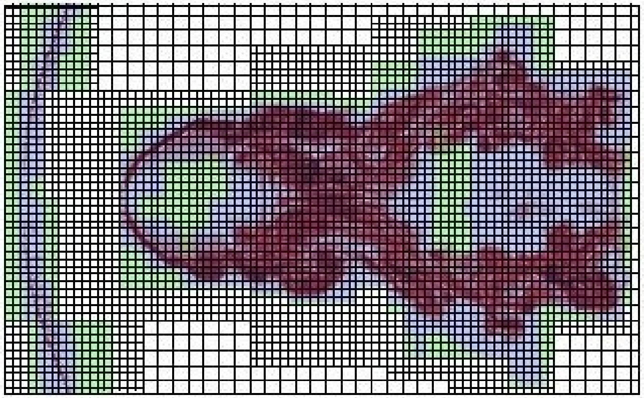
Resolution: 16^3 + 5 AMR levels = 512^3 effective (spatial effective: 7.8 kpc)

The new AMR allows a better resolution of the flow past the subcluster. The onset of the shear instability, the evolution of the turbulent wake and the subsequent back-reaction on the subcluster core morphology are effectively followed. ↓

Results:

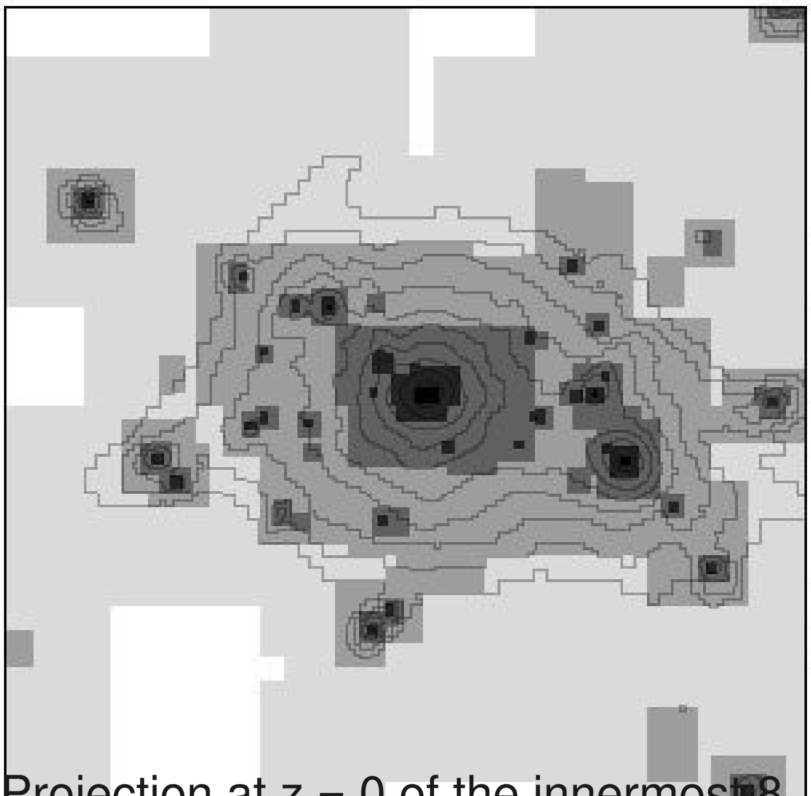
- Back-reaction of the wake on the core: relevance for the physics of the cold fronts.
- Effectiveness in resolving turbulence: rms velocity (at length scale 400 kpc) ~ 500 km/s (similar to 512^3 static run, twice as large as with standard AMR)





Application #2: galaxy cluster simulations (*LI* & J.C. Niemeyer: 2008, MNRAS **388**, 1089)

- Study of the turbulent gas flows in the ICM of a galaxy cluster
- Several simulations were performed, with the same parameters and starting from the same initial conditions, but with different AMR criteria.



Projection at $z = 0$ of the innermost 8 Mpc/h, showing the mesh structure and the density contours.

Initial redshift: $z = 60$
Comoving box size: 128 Mpc/h (h = 0.7)
Root grid resolution: 128^3 cells + 128^3 N-Body particles
1 static grid (64 Mpc/h size, 128^3 cells + 128^3 particles)
6 additional AMR levels, effective resolution 7.8 kpc/h

- The static grid and the refined volume are nested around the place of formation of a galaxy cluster
- Virial mass: 5.8×10^{14} M_{sol} / h
- Virial radius: 1.35 Mpc / h
- The cluster is remarkably relaxed and show no signs of recent major merger, thus it is an optimal case for the study of <u>turbulence generation by minor mergers.</u>

Resolving turbulence in the ICM and in the cluster core with AMR

Results from the cluster simulations, with respect to standard AMR runs:

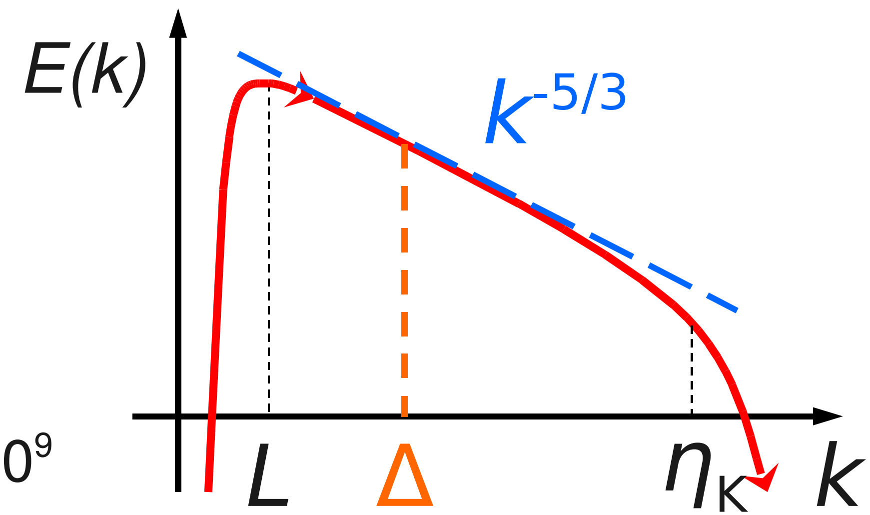
- Increased volume filling (up to 30%) and area covering factor (~ total) of turbulent flows in the ICM: in substantial agreement with the theoretical predictions by Subramanian et al. 2006.
- Larger rms velocity in the cluster core, up to ~ 300 km/s (+ 40%) on length scales 128 kpc/h = 0.1 R_{200}.
- P_{turb} / P_{tot} doubles (~ 2.7%) → contribution of the turbulent pressure support to the HSE.
- T increases (5 %) → enhanced dissipation of kinetic to internal energy.
- Entropy increases (~ 10 %) → more effective mixing.

Resolving turbulence in cosmological simulations (with grid-based hydrocodes)

Number of degrees of freedom:

$$N = \left(\frac{L}{\eta_K}\right)^{٣} = \mathrm{Re}^{٩/٤}$$

Supercomputers manage up to $N \sim 10^9$



(courtesy W. Schmidt)

Two approaches for the resolution of turbulent flows in strongly clumped media:

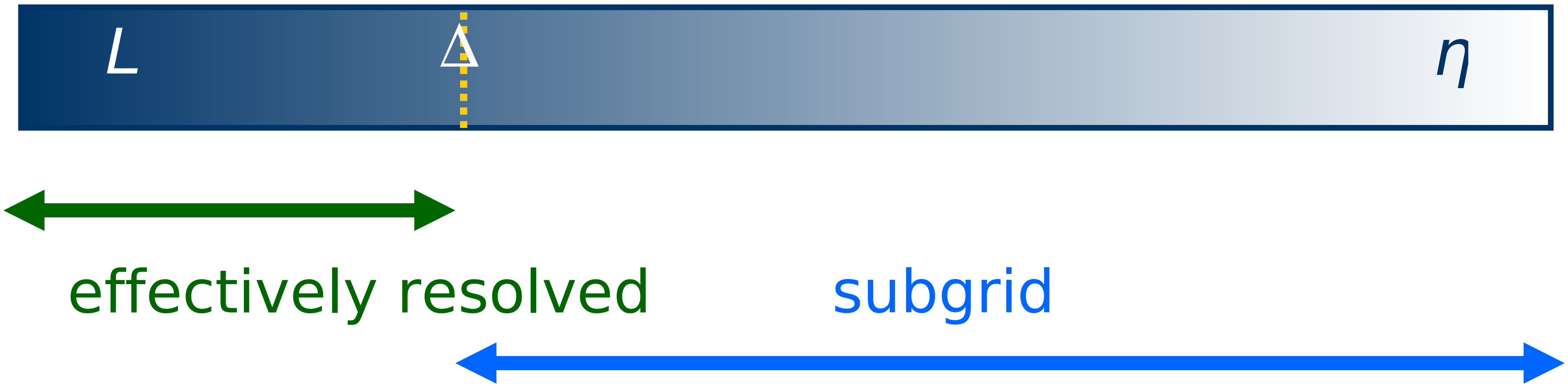
- Adaptive mesh refinement (AMR)
- Large Eddy Simulations (LES)

LES and FEARLESS

Large scales: computation of flow dynamics

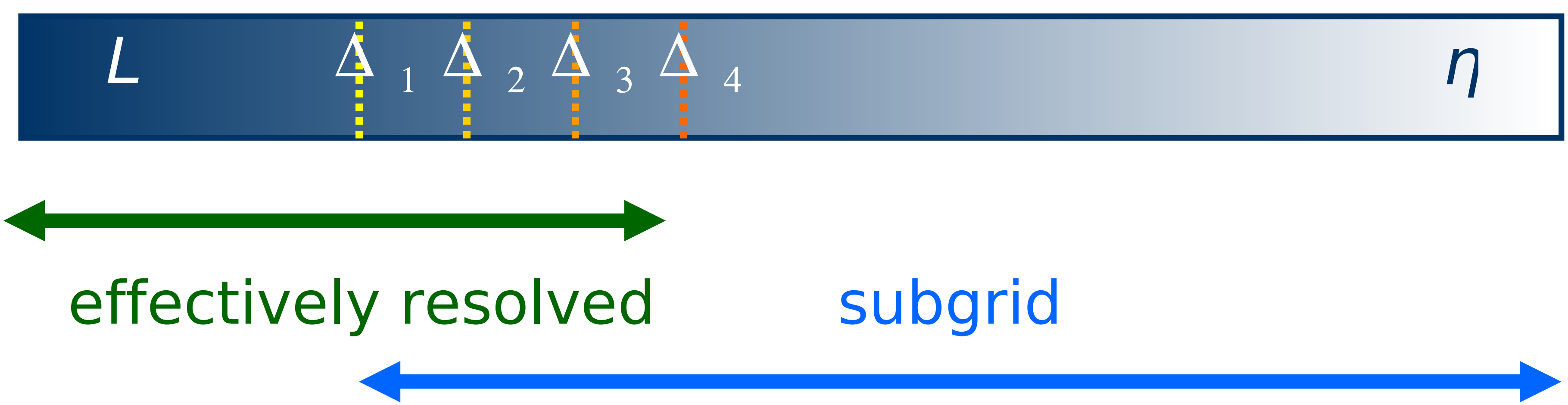
Small scales: subgrid scale model

(courtesy W. Schmidt)



AMR: useful for clumpy flows, but impossible down to η
SGS: assumes homogeneous, isotropic flow

} AMR + LES = FEARLESS



Basics of the subgrid scale (SGS) model

Turbulence: velocity fluctuations at all (i.e., resolved and unresolved, to η) scales

Total kinetic energy = resolved kinetic energy + unresolved, subgrid scale turbulent energy

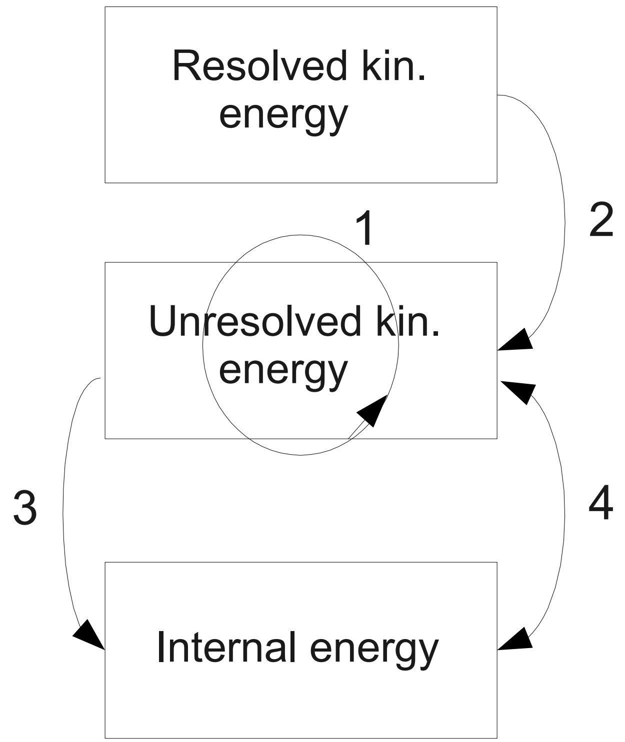
The energy budget can be represented in this way:

1: turbulent diffusion term

2: turbulent production term

3: viscous dissipation term

4: pressure dilatation term

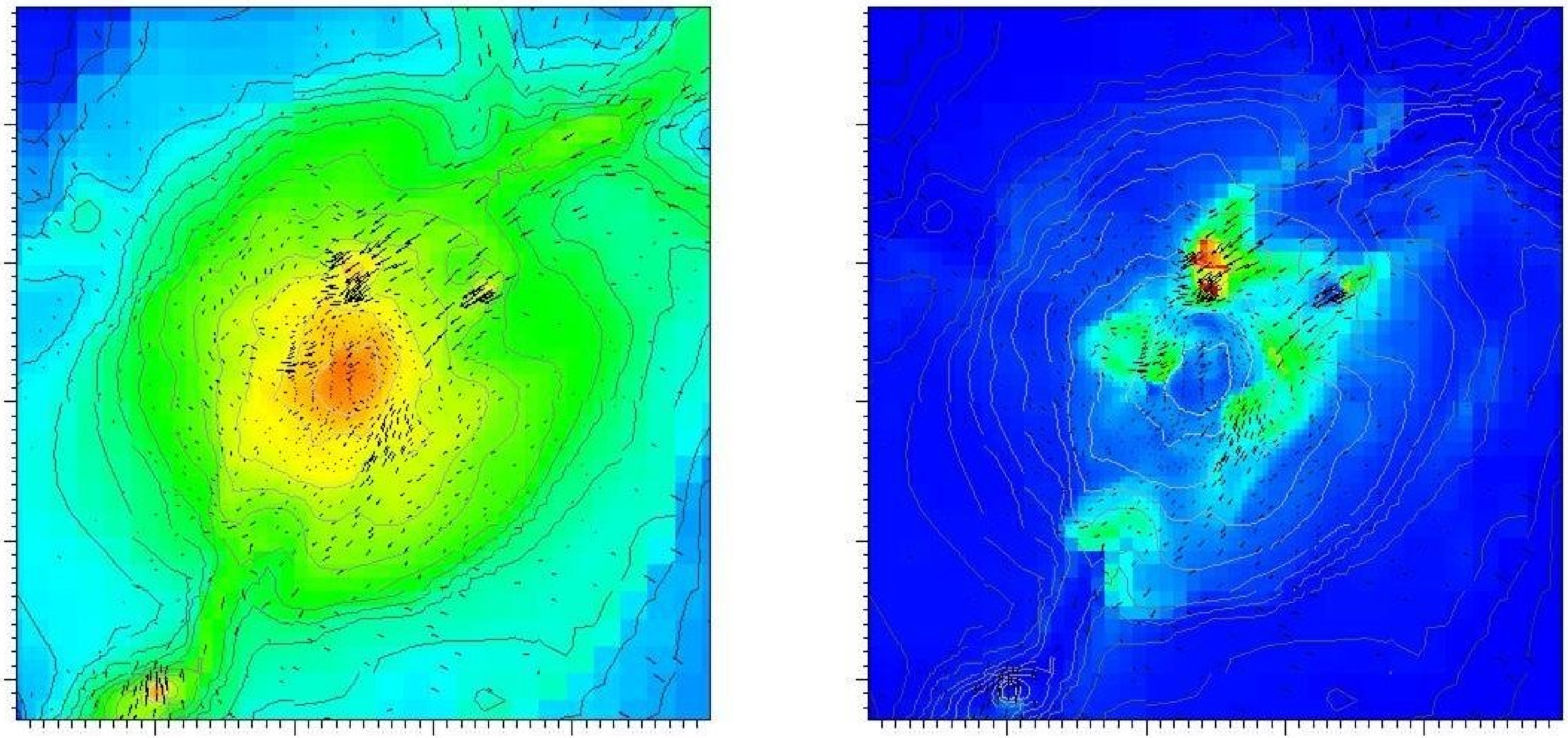


Benefits from using *FEARLESS*

- Study of turbulence in strongly clumped media: resolution only when and where needed (use of refinement criteria based on rate of turbulence generation)
- Turbulent kinetic energy and related quantities: computed by the model, no need of post-processing tricks
- Energy budget and contribution of turbulent pressure evaluated consistently
- SGS model: Schmidt, Niemeyer & Hillebrandt 2006, A&A

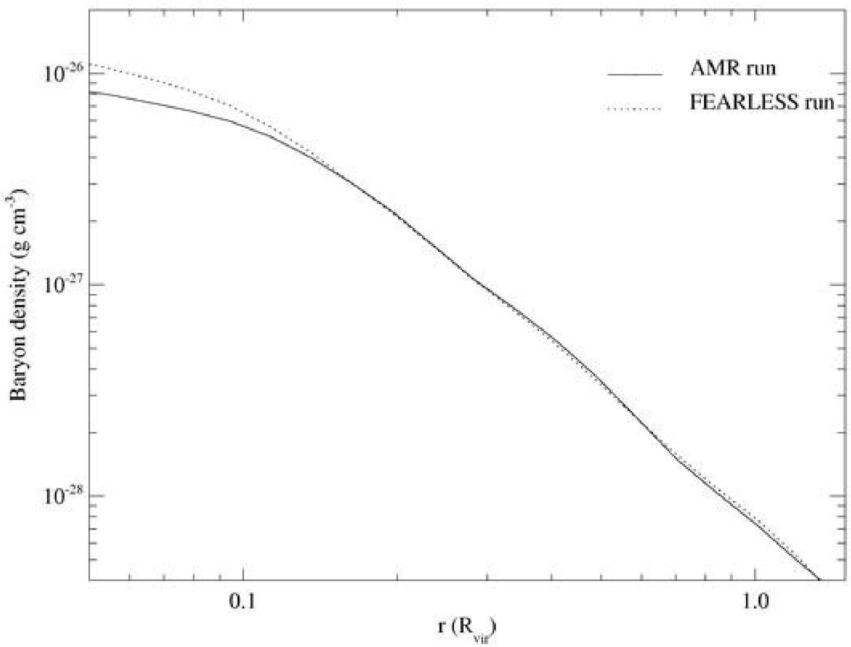
FEARLESS cluster simulations: first results (A. Maier, *LI*, W. Schmidt & J.C. Niemeyer, in preparation)

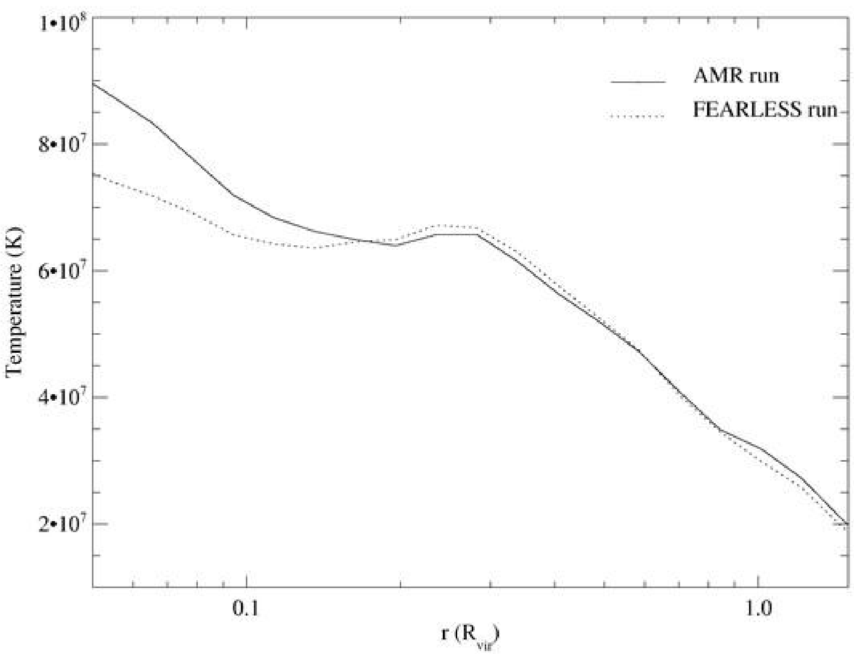
Numerical setup: same as Iapichino & Niemeyer 2008 (a relaxed cluster, M = 5.8 x 10^{14} M_{sun} h^{-1}, R_{vir} = 1.35 Mpc h^{-1}), spatial resolution 15 kpc h^{-1} (2 x coarser).



Slices at z = 0.05, size 6.4 Mpc h^{-1} on a side

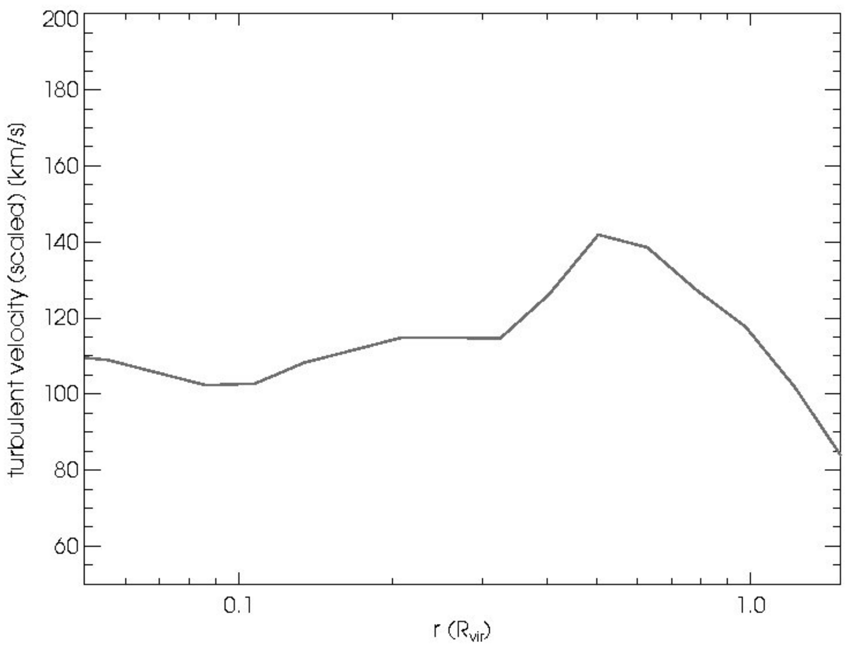
Radial profiles

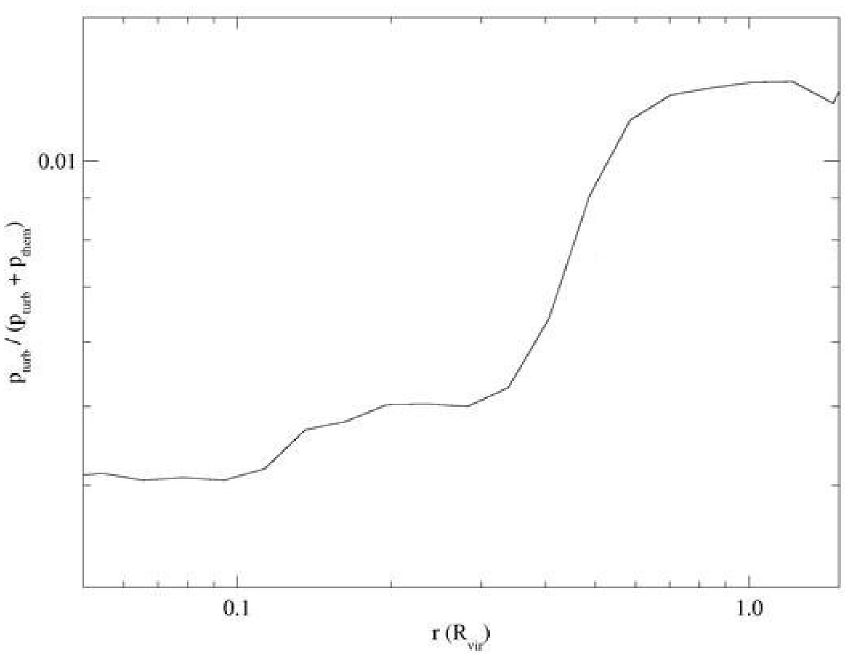




- Cluster core: lower T, therefore denser.
- But $E_{int} >> E_{turb}$!
- On the other hand, total mass and energy within R_{vir} are conserved
- Possible interpretation: *turbulent diffusion*

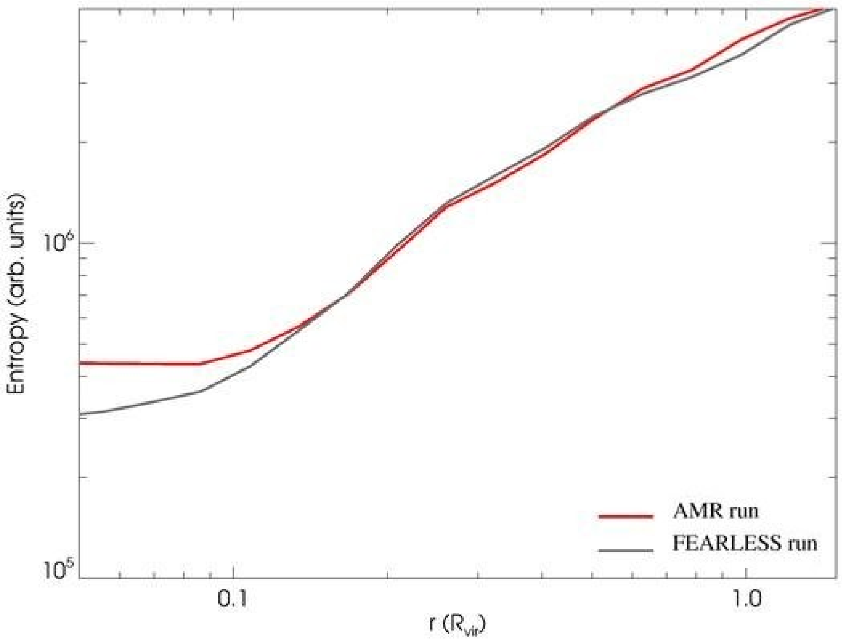
SGS turbulence in the ICM

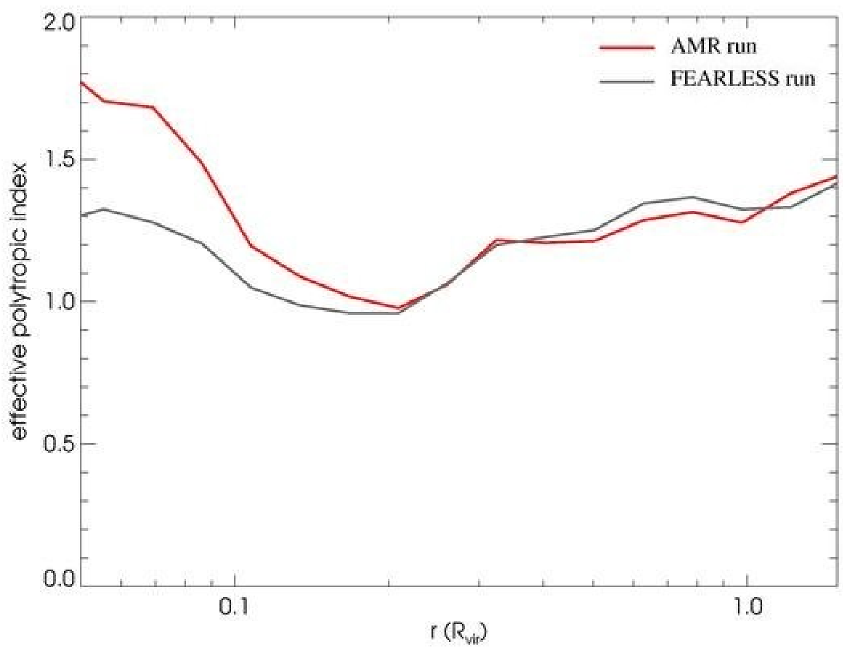




- Turbulent diffusion coefficient (Dennis & Chandran 2005): $D \sim 0.11\ v\ l$
- In our case, $D = 8 \times 10^{28}$ cm^2 s^{-1}
- Rebusco et al. 2005 and 2006 require *D* of the order of 10^{29} cm^2 s^{-1} for reproducing the iron abundance profile in cool core clusters.
- Nevertheless, the contribution of turbulent motions on the cluster energy budget is not prominent.
- On length scales ~ 120 kpc h^{-1}, the turbulent pressure contribution is about 2.3% in the cluster core.
- Beware: this is a very relaxed cluster...

Entropy and polytropic index





- Entropy is defined as $T / \rho^{2/3}$
- The FEARLESS profile is not trivially caused by mixing!
- The effective polytropic index:

$$n_{eff}(r) = \frac{d \ln(\rho)}{d \ln(T)} - 1$$

- Core of the AMR run: n_{eff} ~ 5/3 (adiabatic)
- Core of the FEARLESS run: n_{eff} ~ 1.3
- Average within R_{vir}: 1.27 vs 1.18
- Anything new about entropy profiles (grid vs. SPH)?

Summary and outlook

- Potential importance of turbulence in the cluster physics.

- Numerical tools: grid-based AMR cosmological simulations with ENZO.
  New AMR criteria (regional variability of structural invariants of the flow).
  Combined use of AMR and LES: FEARLESS

- Simulations of galaxy clusters: emphasis on turbulent diffusion. Energy (and pressure) contribution of turbulent motions at the percent level.

- AMR-only cluster simulations: better resolution of turbulent flows, but the results are more prone to numerics.

- In preparation: FEARLESS simulations of structure formation;
  study of magnetic field amplification by turbulent flows (cf. Ryu et al. 2008);
  ...