Modelling of turbulent flows applied to simulations of the cosmological large-scale structure

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Overview

The problem: role of turbulent gas flows in the physics of the cosmological large-scale structure, and stirring mechanisms

The tools: grid based cosmological simulations*, including mesh refinement criteria suitable for turbulent flows, and a subgrid scale (SGS) model for modelling unresolved turbulence: the *FEARLESS*** approach

Recent results and *some technical details*

* : the simulations presented here have been performed using the Enzo code as infrastructure, analysed with the **yt** toolkit (Turk et al. 2011) and made possible by the computational facilities at the Leibniz Supercomputing Centre (project *pr95he*)

** : Fluid mEchanics with Adaptively Refined Large Eddy SimulationS

Turbulence in galaxy clusters: role and open questions

- There are several lines of evidence (theoretical, observational, and coming from simulations) pointing towards the onset of turbulent gas flows in the cosmic structure formation
- Although direct detection of small-scale turbulent flows is still awaited, there is a number of indirect evidences of turbulence in the ICM, e.g.:

  Pressure (Schuecker et al. 2004) and density (Churazov et al. 2012) fluctuations in Coma pressure maps ;

  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, de Plaa et al. 2012);

  Broadening of metal abundance peaks in cluster cool cores (e.g. Rebusco et al. 2005);

  Upper limits from *XMM-Newton* X-ray spectra of cool cores (Sanders et al. 2010, 2011, 2012).

- Energy content: kinetic energy associated with turbulent gas motions can be a significant component (5 – 15% of e_{therm}) of the cluster energy budget (e.g., Vazza et al. 2009, 2011)
- Turbulence in clusters as a key for understanding diffuse radio emission (halos and relics)

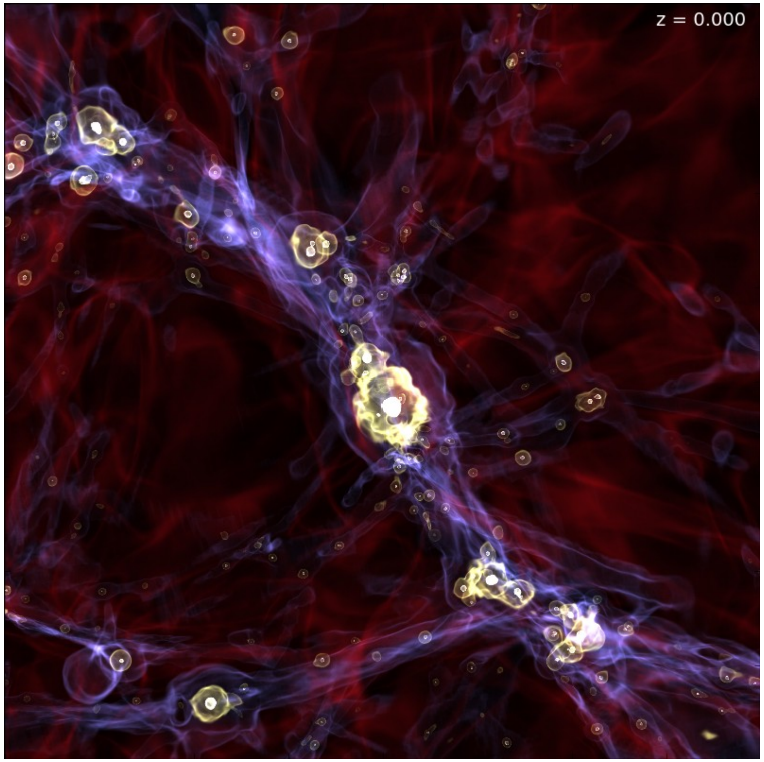
Stirring mechanisms

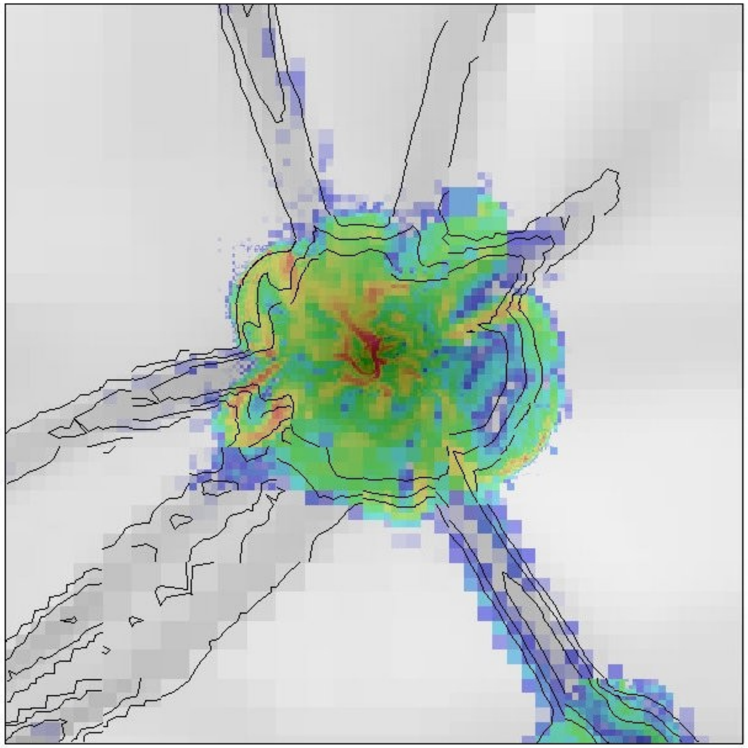
Turbulence at cluster scales is driven by several different mechanisms, related to the hierarchical structure formation, as shown in the movie:

- Minor mergers (*LI* & Niemeyer 2008; *LI* et al. 2008; Maier, *LI* et al. 2009)
- Major mergers (Paul, *LI* et al. 2011, *LI* et al. in prep.)
- Production of vorticity at shocks (*LI* & Brüggen 2012)

- AGN outflows
- Motion of cluster galaxies

These stirring agents will not be addressed in the following.
The second one, in general, has not been taken into account in cluster simulations in a satisfying way.





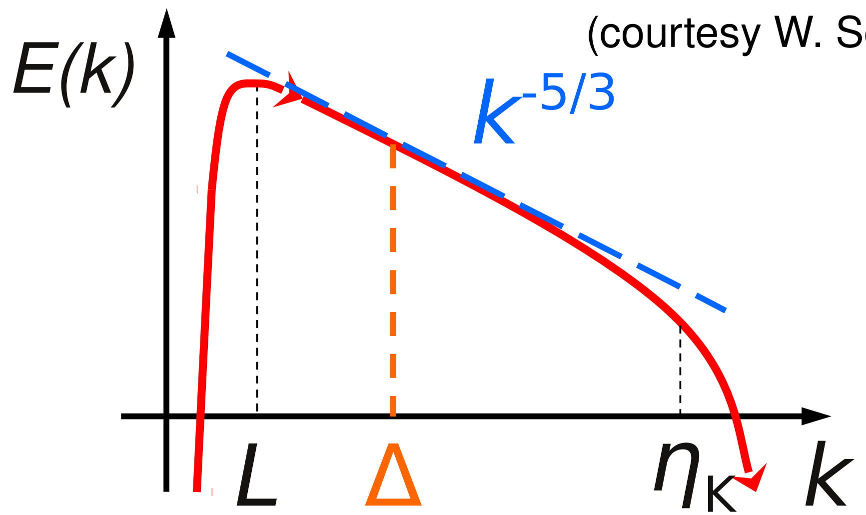
(from Paul, *LI* et al. 2011)

Cosmological simulations and turbulence

Evolution of complex, nonlinear and asymmetric objects: hydrodynamical simulations as the main investigation tool for the physics of the ICM. Can we resolve turbulent motions?

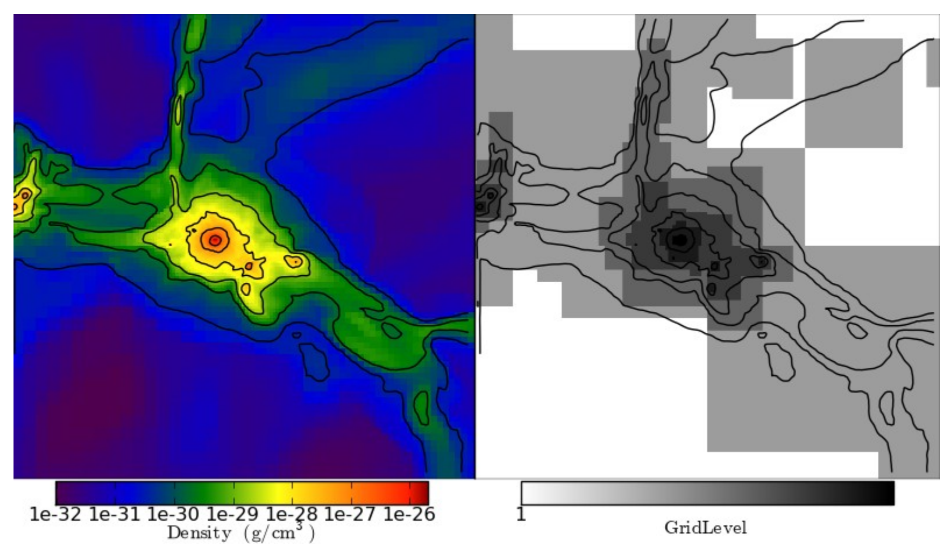
In most cases, the full spatial resolution of the turbulent cascade implies a dynamical range well beyond the available computational resources.

(courtesy W. Schmidt)



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

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



Cluster simulation at $z = 0$, *LI* & Niemeyer 2008

Resolving turbulent flows with AMR

Regional variability of structural invariants of the flow

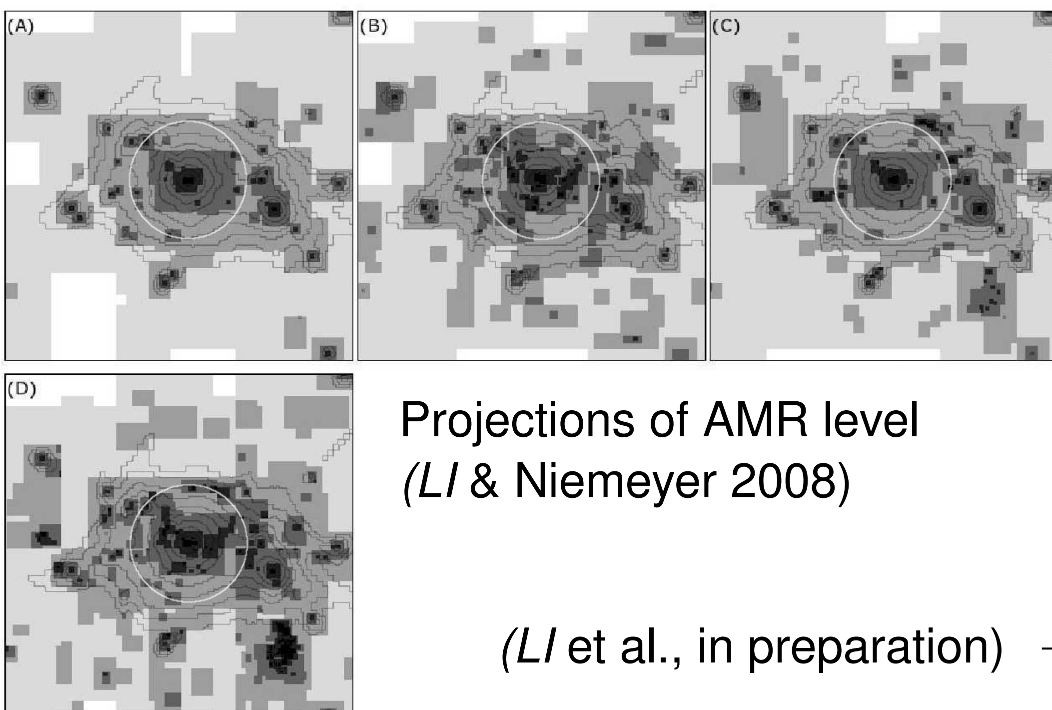
(Schmidt et al. 2009)

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

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

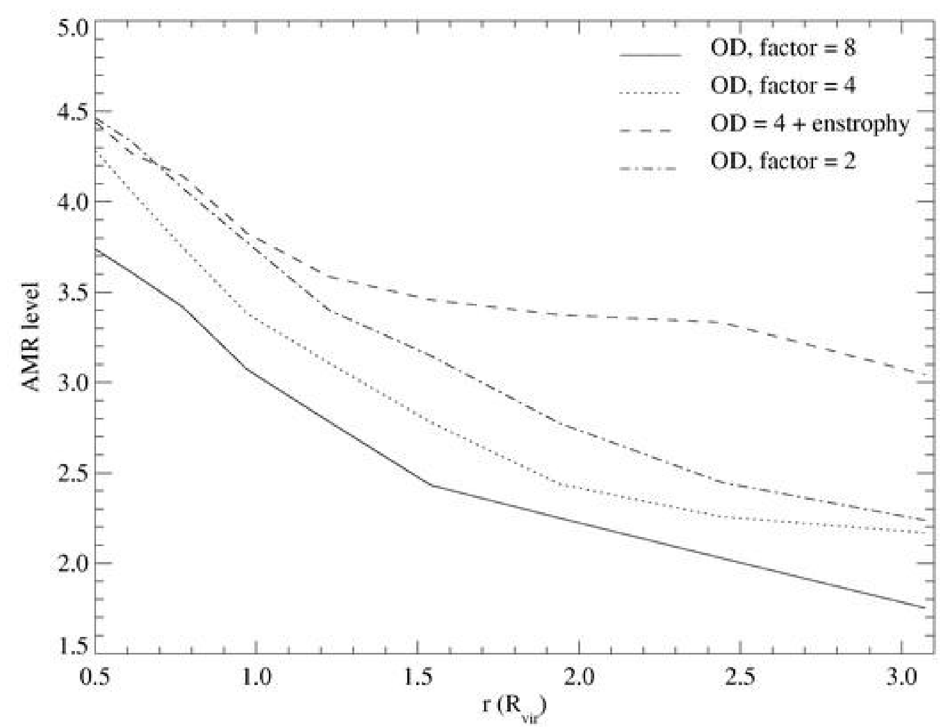
$\langle q\rangle_i$: average of q in the grid patch i;
λ_i: max($\langle q\rangle_i$, standard deviation of q in i);
α: threshold parameter.

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

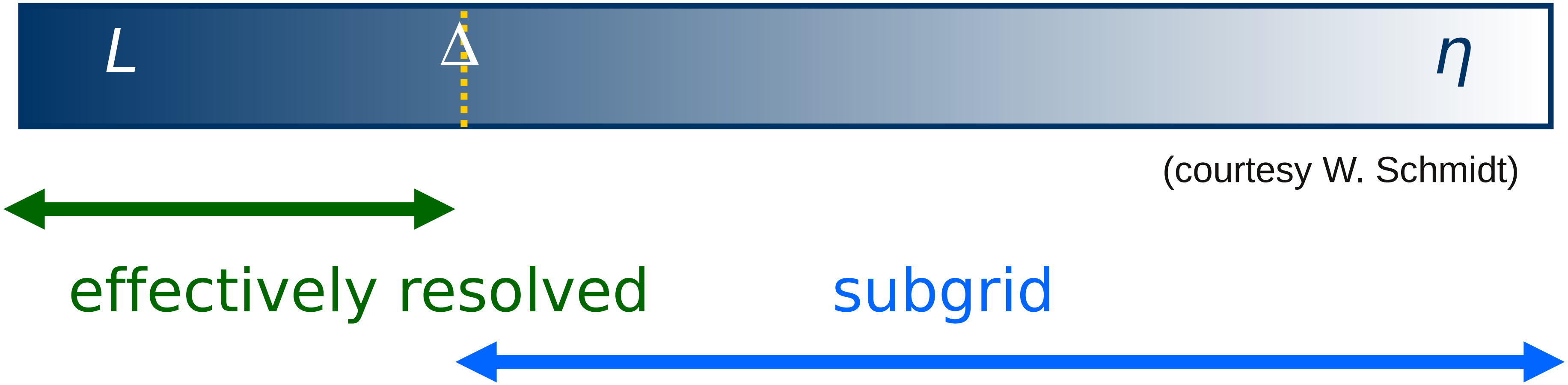


Projections of AMR level
(*LI* & Niemeyer 2008)

(*LI* et al., in preparation) →

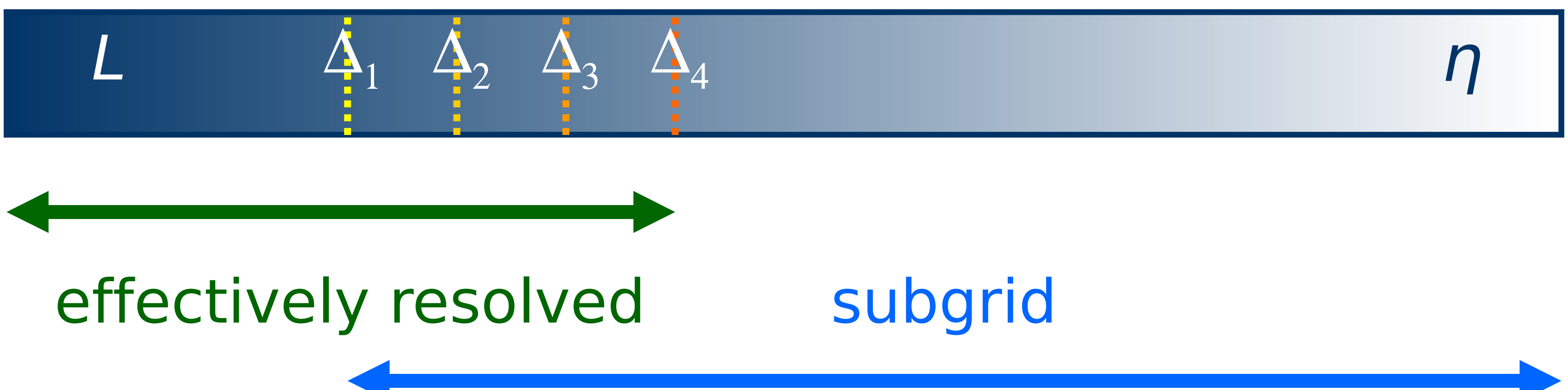


Large Eddy Simulations and *FEARLESS*



Large scales: computation of flow dynamics
Small scales: subgrid scale model
Grid refinement and energy adjustments

} AMR + LES = *FEARLESS*



In the movie we will see how the production of turbulence energy (right panel, projection) is linked to the cluster evolution (left panel, volume rendering).

Some computational details

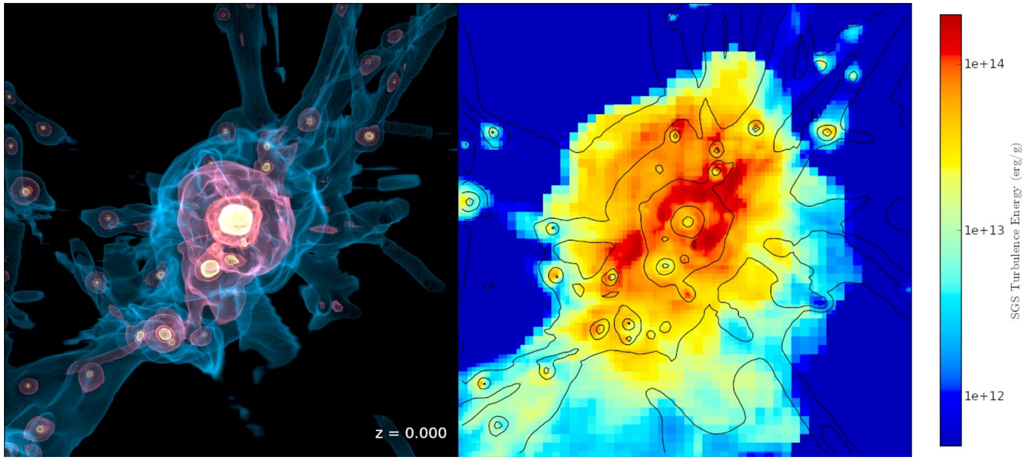
- Enzo is a hybrid (N-Body + hydro) AMR code, parallelised with MPI, and using the HDF5 structured data format for the output.
- Grid setup: 128^3 + 2 static grids + 6 additional AMR levels (volume at $l = 8$: ~ 10^{-5} of total).
- Main issue in simulations with aggressive AMR is memory. Some of the most demanding runs have been performed on the fat node island (former SuperMIG).
- Interestingly, with growing computational resources, there is again some trend towards adding only static subgrids or even performing monolithic-grid runs.

Of special interest was the production of the two shown movies:

- more than 500 datadumps from the simulation (about 0.5 TB of data, 1.5 million files);
- analysis with **yt** (Python-based toolkit for analysis and visualisation of AMR data);
- embarrassingly parallel strategy, for performing the volume rendering on 220 cores.

Future directions in developing Enzo:

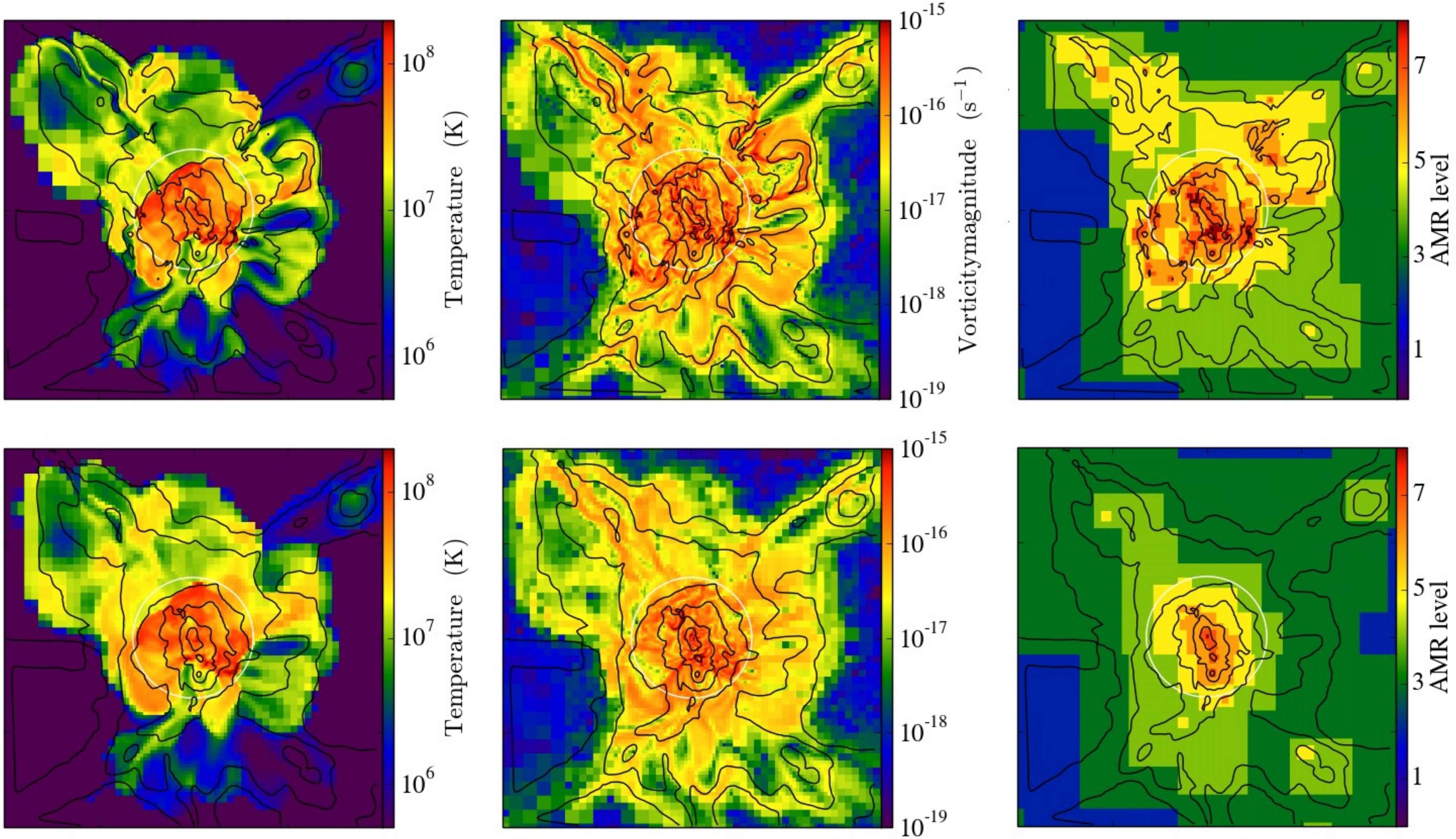
- experimental CUDA support;
- Python-embedded inline analysis.



Recent results: a major merger with FEARLESS

(*LI* et al., in preparation)

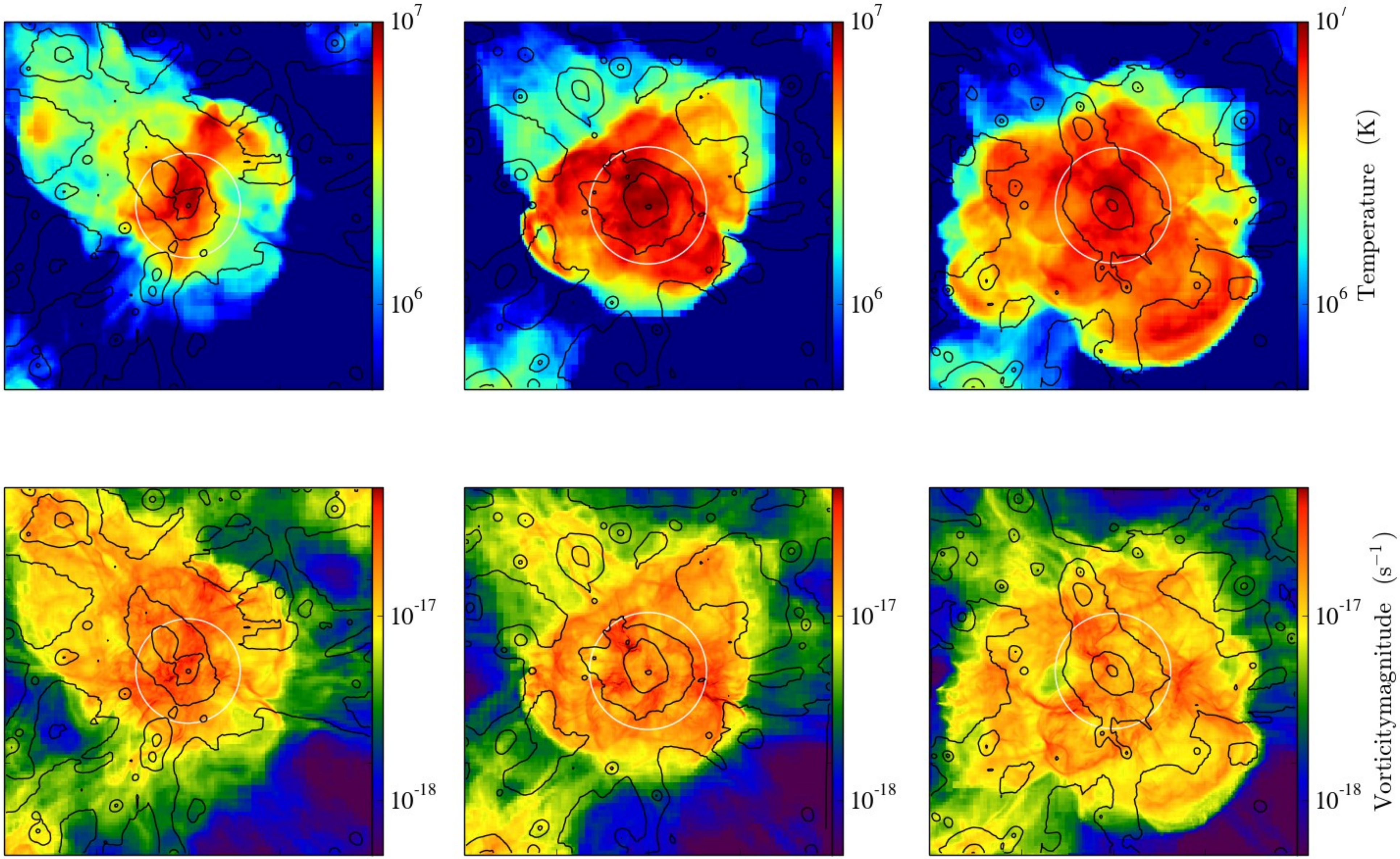
AMR on overdensity + vorticity, slices right after a major merger



AMR on overdensity only

Time evolution

(Projections)



Summary and outlook

- (Mesh based) hydrodynamical simulations: the main theoretical tool in the study of the intra-cluster medium.

- Approach combining LES and AMR in the simulation of astrophysical flows: *FEARLESS.*

- First results on cluster simulations: better refinement in the outskirts, effect of major mergers up to large distances from cluster cores.

- Future developments: machines like SuperMUC and its successors can only been exploited through a deep re-thinking of code designs and data analysis strategies. A closer link between code developers, users, and experts of scientific computing should be established.

Partnership Initiative Astrophysics Lab

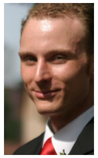
- LRZ initiative for stronger scientific community outreach

- Current Application Labs
  - Astro Lab
  - Geo Lab
  - Environment Lab
  - Life Science Lab

- The team

Vasileios Karakasis

Luigi Iapichino



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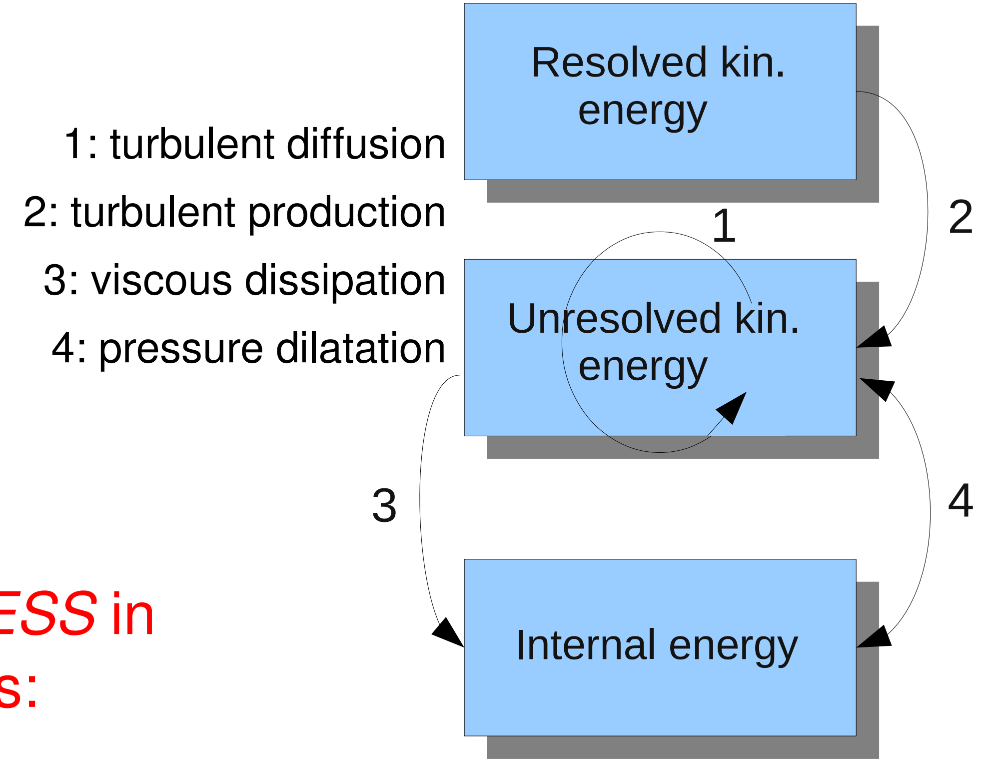
Partnership Initiative Astrophysics Lab

- Background ideas
  - Topical HPC experts solely for Astrophysics community.
  - Collaboration for high level HPC supports.
  - Stronger orientation towards serving the needs and wishes of the Astrophysics community

- Looking forward to
  - Feedback from scientific community
  - Wishlists for the future challenges

- Every discretisation introduces a scale separation: with the SGS model we account for the effect of the unresolved scales on the resolved ones.
- Total kinetic energy = resolved kinetic energy + unresolved, subgrid scale turbulence energy.



Benefits from using *FEARLESS* in simulations of turbulent flows:

- Study of turbulence in strongly clumped media: resolution only when and where needed (use of refinement criteria based on turbulence diagnostics)
- Turbulent kinetic energy and related quantities: computed by the model, no need of post-processing tricks
- The injection of energy at larger scales is imprinted on the SGS turbulent energy because of the energy transport through the turbulent cascade
- Energy budget and contribution of turbulent pressure evaluated consistently

More mathematical details? Maier, *LI*, Schmidt & Niemeyer, *ApJ* 707 (2009) 40; Schmidt & Federrath, *A&A* 528 (2011) A106; *LI*, Schmidt, Niemeyer & Merklein, *MNRAS* 414 (2011) 2297.

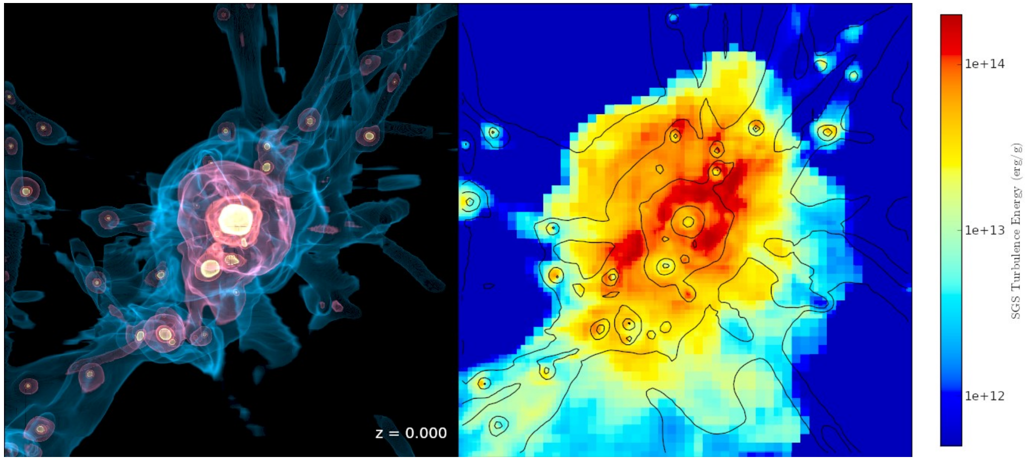
Turbulence modelling in cosmological simulations: minor mergers

(*LI* & Niemeyer 2008; Maier, *LI*, Schmidt & Niemeyer 2009)

Study of the turbulent gas flows in the ICM of a galaxy cluster.

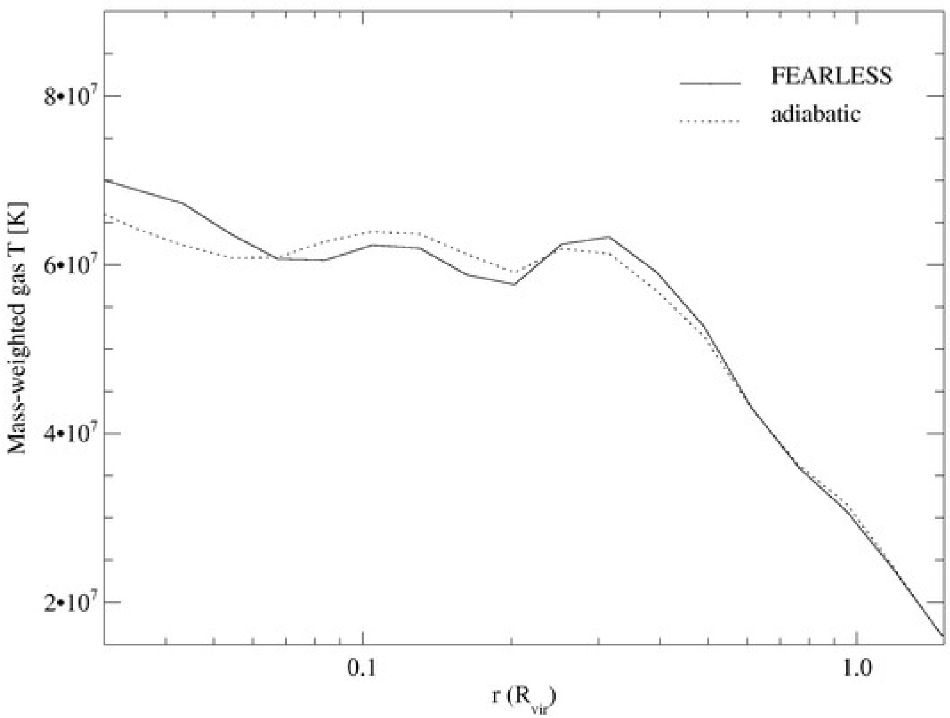
The static grid and the refined volume are nested around the place of formation of a cluster, previously identified in a low resolution DM-only run.

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



- The cluster is remarkably relaxed and show no signs of recent major merger, thus it is an optimal case for the study of turbulence generation by minor mergers.
- Virial mass: 5.8 x 10^{14} $M_\odot$ / h ; virial radius: 1.35 Mpc / h
- In the movie we will see how the production of turbulence energy (right panel, projection) is linked to the cluster evolution (left panel, volume rendering).

Main results from the cluster simulations



- Injection and dissipation of turbulent energy in minor mergers as a localised process. The turbulent dissipation heats the gas in the turbulent wake of mergers.

- Effect on global cluster features almost negligible: the unresolved turbulence is subsonic.

$$P_{turb} = \frac{2}{3} \rho e_{turb}$$

- SGS turbulence pressure support about 0.1%; resolved pressure support on scales of 100 kpc / *h* above 1% (rms velocity ~ 200 km/s).

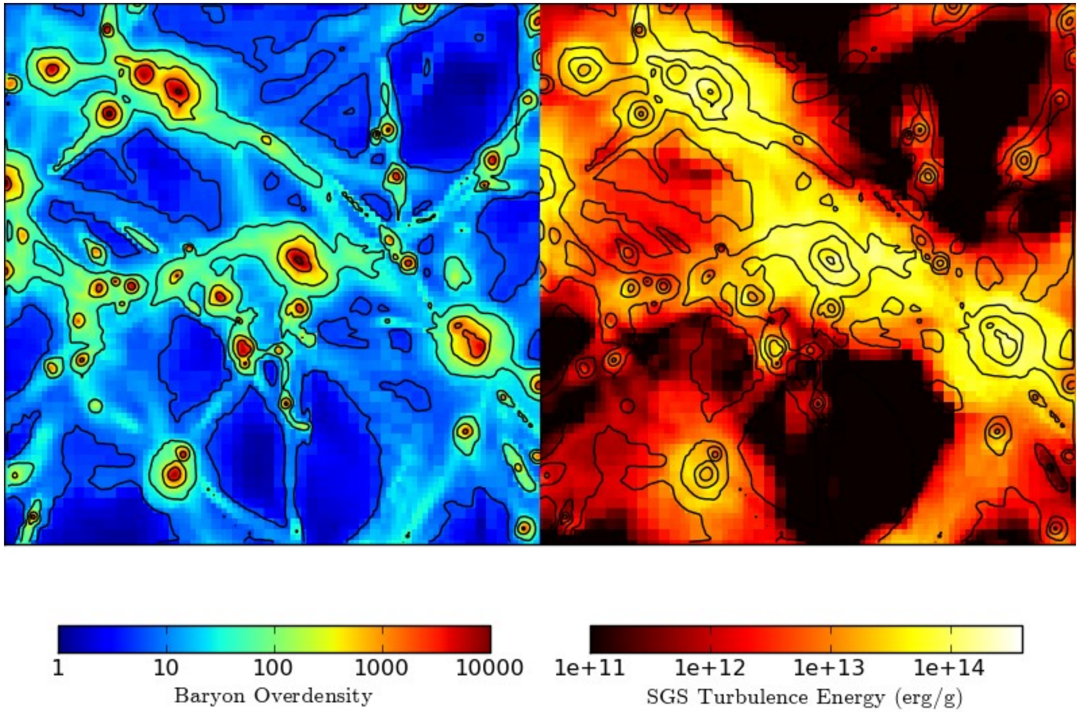
- Radial *T* profile: the effect is visible in the cluster core.

- Beware: this is a relaxed cluster!

Two modes of turbulence production in the IGM

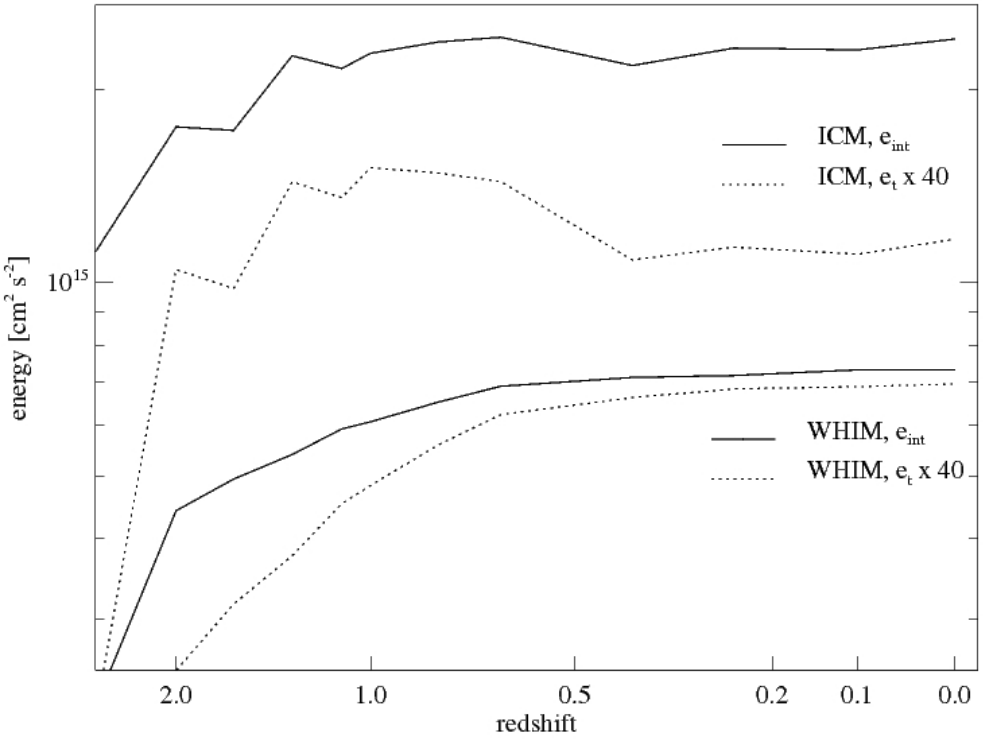
(*LI*, Schmidt, Niemeyer and Merklein 2011, *MNRAS* **414**, 2297)

- Analysis of turbulence features not only in clusters, but also in less dense (and less studied) environments.
- Astrophysical relevance: turbulence starts being observed in the LSS (e.g. quasar absorption spectra), and is expected in the cluster outskirts, but a theoretical framework of its injection and features is largely missing.
- Warm-Hot Intergalactic Medium (WHIM): $T > 10^5$ K and $\delta < 10^3$ (filaments and cluster outer parts). More than 50% of the baryons at low *z* are in this phase.
- Setup: *FEARLESS* simulation in a box of 100 Mpc/*h*, 128^3 root grid, 4 AMR levels (eff. resolution: 48.8 kpc/*h*)
- The use of *FEARLESS* is crucial for a setup where it is basically impossible to reach high resolution everywhere in the computational domain, and where the analysis will be sorted by temperature phases.



Projections of a cube of 20 Mpc/*h* at $z = 0$

Evolution of turbulence energy in different baryon phases



The features of turbulence are studied from the SGS turbulence energy e_{turb}.

The evolution of e_{turb} (dotted lines) is different in the two baryon phases.

We argue that the different evolution is caused by two distinct stirring mechanisms acting on ICM and WHIM.

Turbulence in the ICM: injected chiefly by merger-induced shear flows. The peak at z ~ 1.0-0.65 is consistent with the formation epoch (= major merger phase) of halos in the mass range 10^{13} $M_\odot < M < 10^{14}$ $M_\odot$ (e.g. Giocoli et al. 2007).

Turbulence in the WHIM: mainly by the baroclinic injection at curved accretion shocks. The evolution resembles the kinetic energy flux through external shocks (e.g. Miniati et al. 2000) and is expected in the theoretical analysis of the cluster outskirts by Cavaliere et al. 2010.

Furthermore, the different driving is dominated by solenoidal modes in the ICM, by compressional modes in the WHIM. Consequences for, e.g., magnetic field amplification have to be explored.