Resolving and modelling the turbulent flow in galaxy clusters outskirts

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Overview

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

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

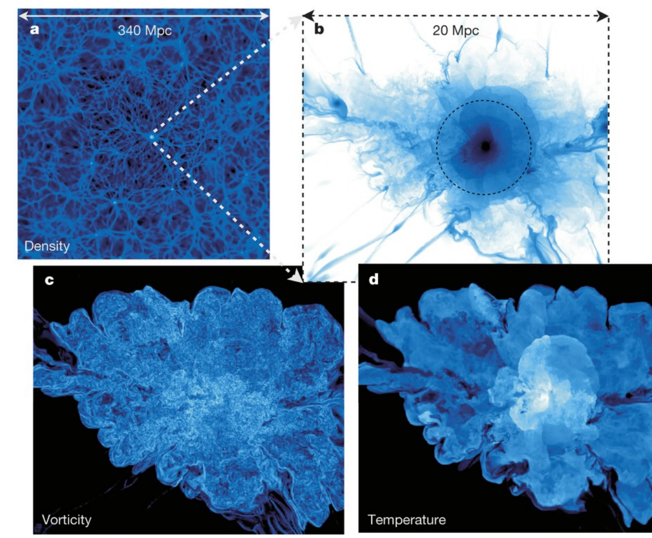
Properties of the flow on different length scales, in the framework of turbulence induced by cluster mergers

From the flow in the outskirts to *diffuse radio emission*: a few ideas

* : the simulations presented here have been performed using ENZO 2.3 as infrastructure, analysed with the **yt** toolkit (Turk+ 2011) and made possible by the computational facilities at the Leibniz Supercomputing Centre.

Role of turbulence in the cluster physics

- Injection of turbulence in the cosmic flow as a natural consequence of the *formation of the large-scale structure*.
- Energy content: kinetic energy associated with turbulent gas motions can be a significant component of the cluster energy budget.
- Turbulent pressure support → mass estimates
- Turbulence in clusters as a key for understanding. diffuse radio emission (halos and relics).
- Turbulence driving and features from different stirring mechanisms in the large-scale structure:



↑ Miniati & Beresniak 2015

Minor mergers (*VI* & Niemeyer 2008; *VI*+ 2008; Maier, *VI*+ 2009)

Major mergers (Paul, *VI*+ 2011, *VI, Federrath & Klessen* in prep.)

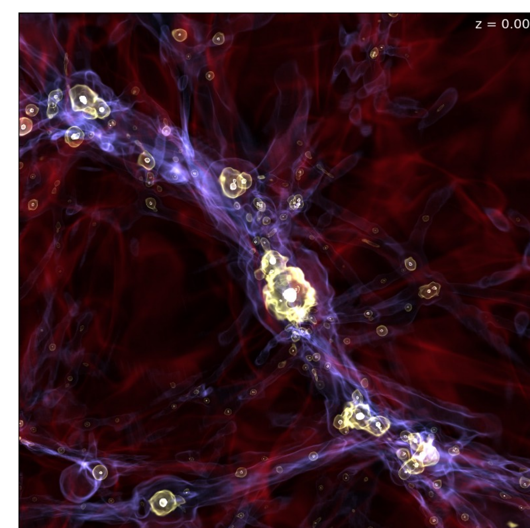
Production of vorticity at shocks (*VI* & Brüggen 2012)

Filaments (Zinger+ 2015)

AGN outflows

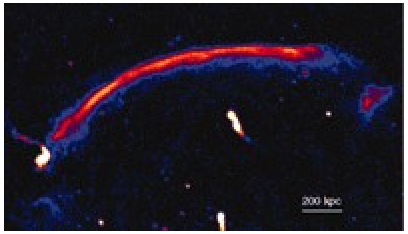
Motion of cluster galaxies

} These stirring agents will not be addressed in the following



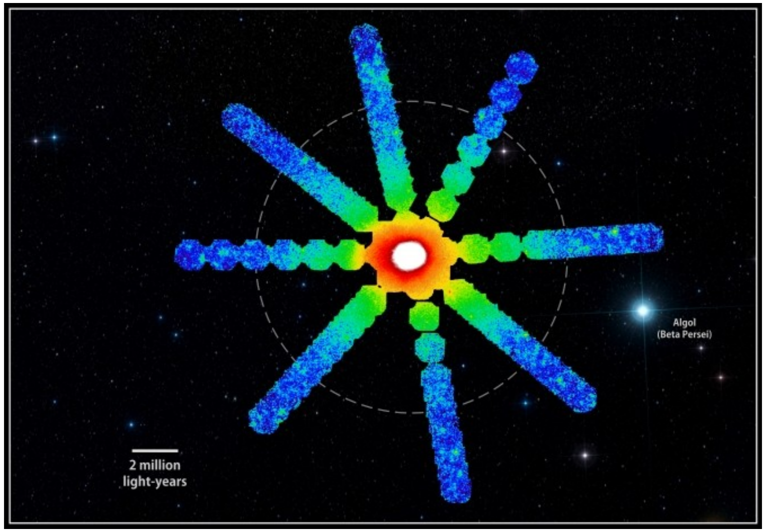
The cluster outer regions

- Only in the last decade these regions have been observed in X rays. Findings for the physical conditions somewhat controversial (entropy profiles...).
- Diffuse radio emission: relics, related to merger shock propagation and powered by DSA.
- Recent ideas (Pinzke+ 2013, Shimwell+ 2015, Fujita+ 2015) draw the attention on the pre-shock medium.

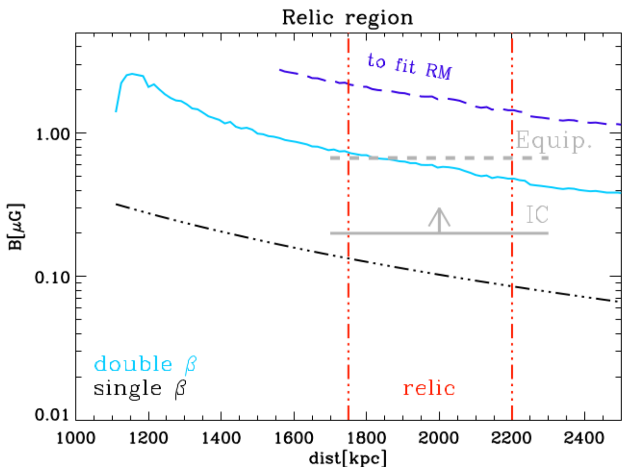


Sausage relic CIZA J2242.8+5301, van Weeren+ 2010

- Magnetic fields: implied by previous point, with values up to the μG level.
- Turbulent flow in the outskirts: regions not settled in hydrostatic equilibrium. Computationally: not trivial to resolve them.



Perseus with Suzaku, Urban+ 2014



B profile in Coma, Bonafede+ 2013

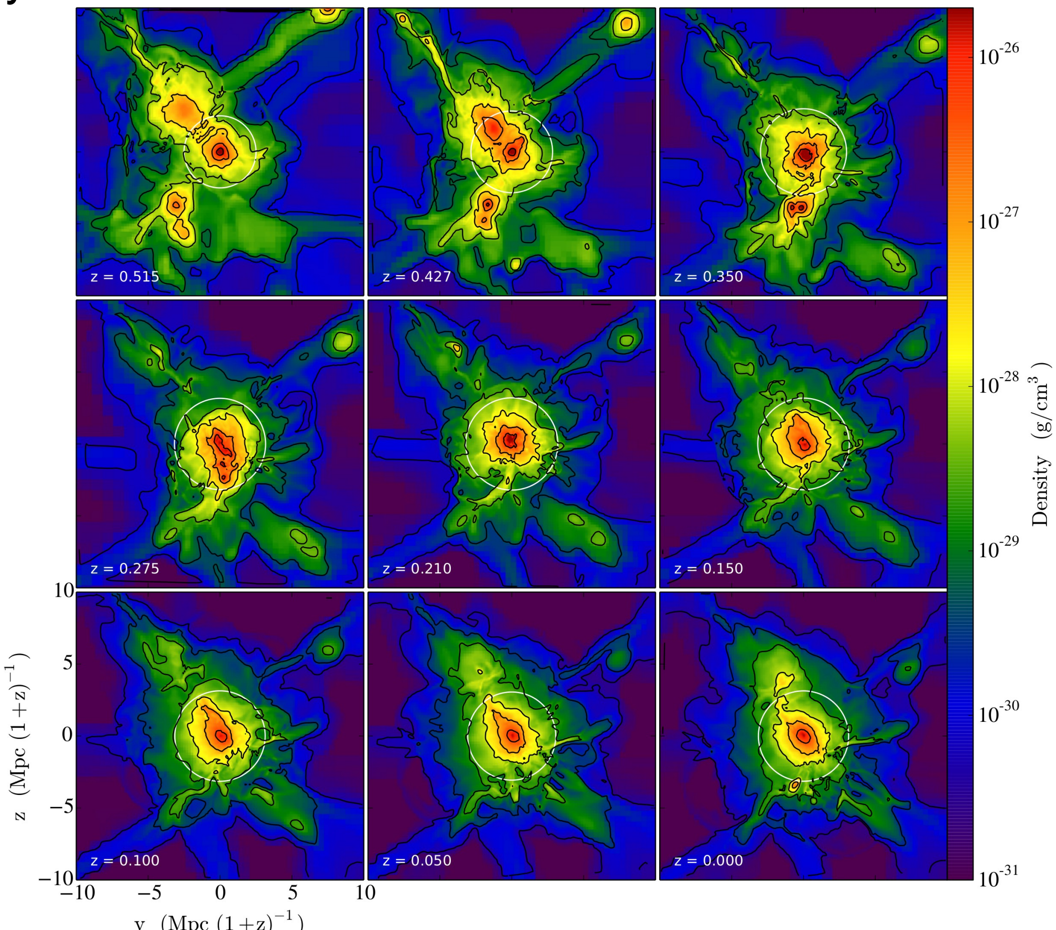
These simulations

Study of the turbulent gas flows in the ICM and the outskirts of a cluster undergoing a major merger at z ~ 0.5, launching a shock with Mach number ~ 6.

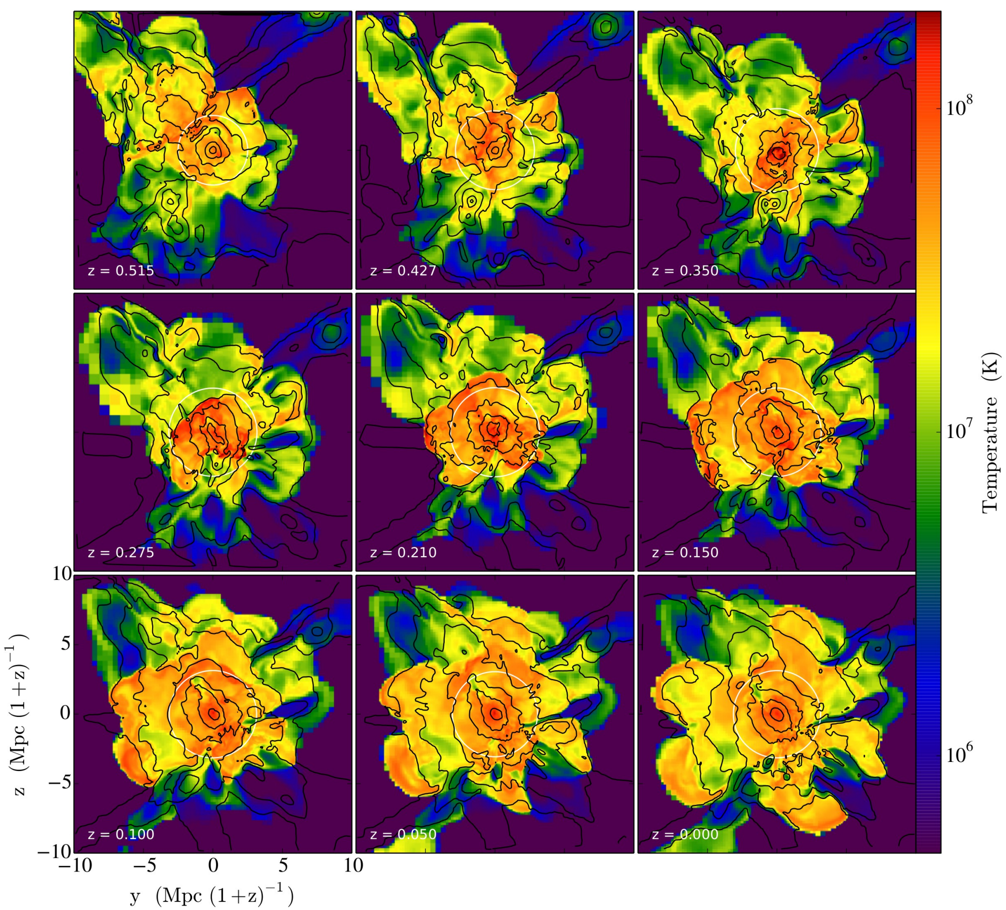
The static grids and the refined volume are nested around the place of formation of a cluster, previously identified in a low resolution DM-only run.

Comoving box size: 256 Mpc / *h* (*h* = 0.678)
Root grid resolution: 128^3 cells + 128^3 N-Body particles
2 nested static grids (128 and 64 Mpc / *h* size, 128^3 cells + 128^3 particles each)
6 additional AMR levels, effective resolution 7.8 kpc / *h*

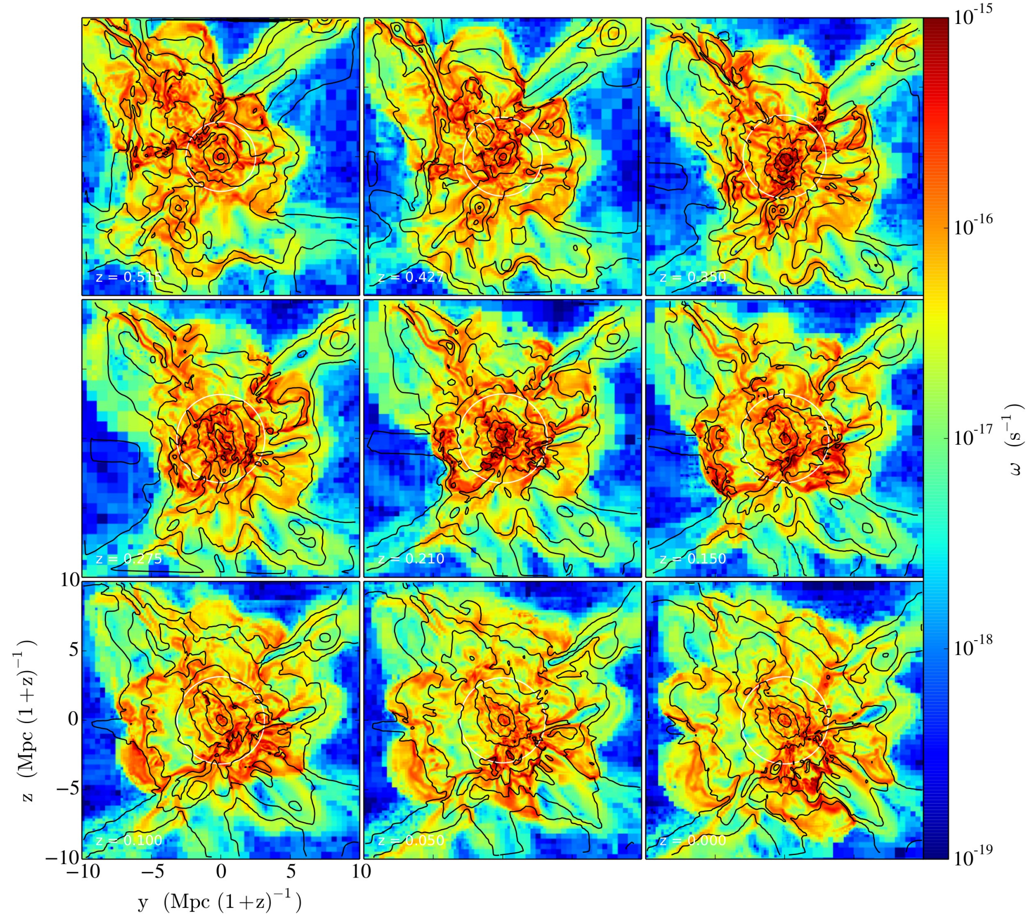
- Besides the turbulence SGS model, the runs make use of “adiabatic” physics.
- Virial mass at z = 0: 0.95 x 10^{15} $M_\odot$ / *h* ; virial radius: 2.13 Mpc / *h.*
- Four simulations from the same ICs, with different AMR strategies.



Panels with side of 20 Mpc / *h* each

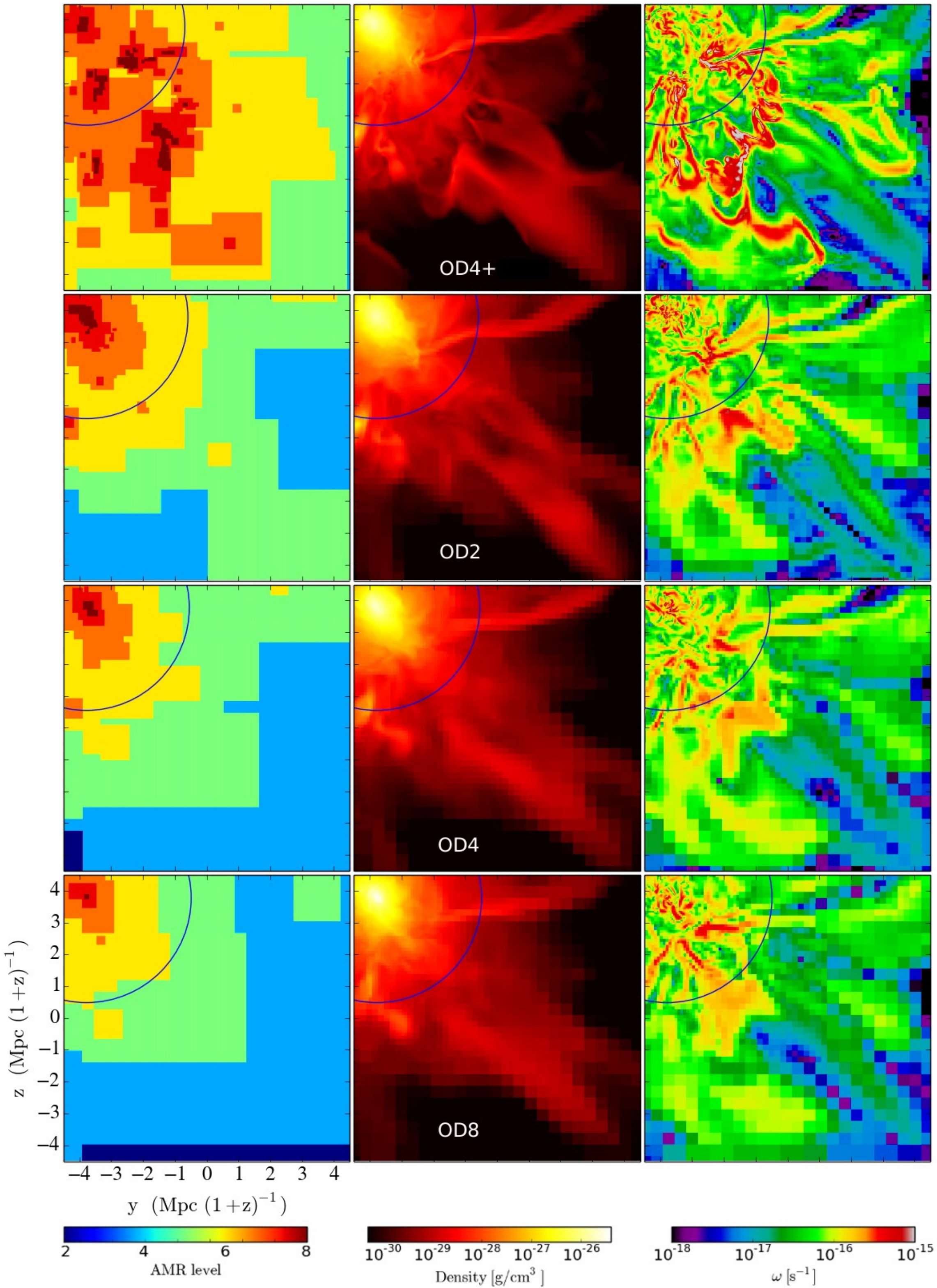


Temperature slices



Vorticity slices

Resolving turbulent flows with AMR



Refinement by overdensity (OD)

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

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

Regional variability of structural invariants of the flow

(Schmidt+ 2009)

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

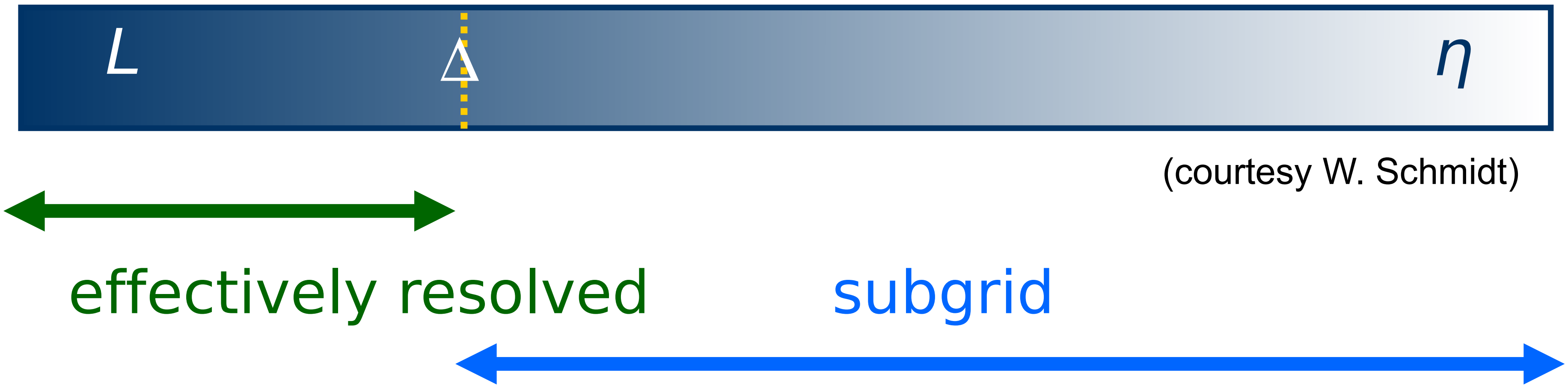
$$q(\boldsymbol{x},t) - \langle q \rangle_i(t) \geqslant \alpha \lambda_i(t)$$

$\langle q \rangle_i$: average of *q* in the grid patch *i*;

λ_i: max($\langle q \rangle_i$, standard deviation of *q* in *i*);

α: threshold parameter.

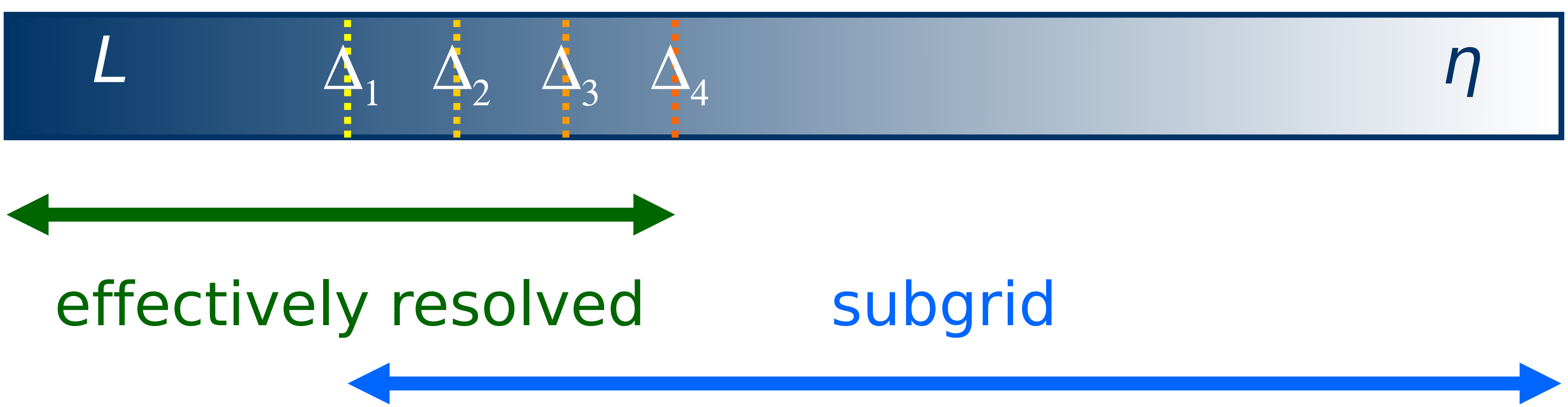
Large Eddy Simulations and *FEARLESS*



(courtesy W. Schmidt)

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

} AMR + LES = *FEARLESS*



Properties of turbulence on different scales

	v [km s^{-1}]	Δv [km s^{-1}]	v_t [km s^{-1}]	M_{turb}
core				
$z = 0$	658	819	39.7	0.65
$z = 0.350$	1151	1267	73.1	0.83
outskirts				
$z = 0$	990	1112	36.3	1.46
$z = 0.275$	1283	1117	82.2	1.15

- Analysis in cluster core ($r < 0.5\ R_{vir}$) and outer shell ($0.5 < r/R_{vir} < 2$).
- Diagnostic of large-scale flow: v (c.m. corrected).
- Further diagnostic on large scale: "AMR-filtered" velocity

$$\Delta v = v - v_{coarse}$$

where v_{coarse} refers to l = 500 kpc h^{-1}

- The flow is subsonic in the core, slightly supersonic in the outskirts.
- Velocities in the two regions are not very different at the time of maximum turbulence, but the thermal content is.
- Ratio of turbulent to thermal pressure (from Δv): 0.23 → 0.38 in the core, 1.18 → 0.73 in the outskirts.
- Time evolution in the outskirts is driven by the merger shock. Decay time of turbulence: ~ 2.5 Gyr, $t_{eddy} = L/v$ ~ 0.7 Gyr.

A few ideas for radio observers and modellers

Indications for models of radio halos:

- *Timescales*: turbulent re-acceleration theory for radio halos rely on short timescales for activation of radio emission (bimodality). Turbulence decay timescales too long! Hidden "switch" in the theory?
- *First phases of mergers* in the core dominated by shock propagation: analogy with radio relics? Detectable intrinsic polarisation in halos (SKA)?

Indications for models of radio relics:

- *Magnetic fields*: generated by compression of pre-shock, turbulence-amplified field. The large pre-shock non-thermal pressure supports this idea (analysis by *LI* & Brüggen 2012).
- *Volume filling factor* of regions with large vorticity: at any time > 60% with $\omega > 10\ H_0$ in the outskirts. Upstream flow inhomogeneities might therefore affect diffuse radio emission.
- These properties are especially interesting for theories of relic emission based on pre-existing conditions of any kind (CR population, magnetic field..., Pinzke+ 2013, Shimwell+ 2015, Fujita+ 2015).

Summary and outlook

- Simulations of a galaxy cluster merger, studied with a turbulence SGS model and different AMR strategies.
- AMR based on vorticity: suitable in the outskirts, refines underdense structures
- Turbulence SGS model: useful indicator of small-scale turbulence, complementary to other diagnostics.
- The evolution is dominated by the major merger, both in the cluster core *and* in the outskirts. Peak Mach numbers 0.8 / 1.5 in core / outskirts
- First step towards more detailed predictions for the non-thermal radio emission, and estimates of magnetic fields.
- To do: features of the flow during the merger (stirring modes etc...) Federrath, *LI* & Klessen, in preparation