Impact of the Hydrodynamical Scheme on modeling Subsonic Turbulence

Turbulence with Meshless Finite Mass (MFM)

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Cosmic Magnetism in Voids and Filaments
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Motivation

- Turbulence plays an important role in the ICM
  - Provides additional pressure contribution
  - Turbulent dynamo
- In galaxy clusters subsonic turbulence excited after mergers, then decays

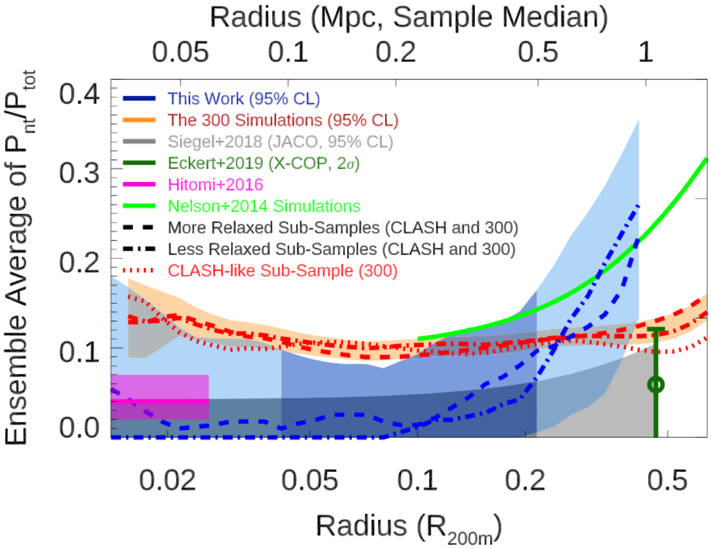
  e.g. Schuecker+2004, Subramanian+2006
- Many hydro-methods have problems with the description of subsonic turbulence

  Padoan+2007, Bauer&Springel2012

  Can be resolved partly by numerical improvements

  Price2012

Turbulence in Galaxy Clusters – Simulations vs Observations



- Disagreement between simulations and observations.
- Need to properly capture turbulent cascade.

Sayers et al. (2021)

MFM – Introduction

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(V_i U_i\right) + \sum_{j \in Ngb} \left(F_{ij} \cdot A_{ij}^{\mathrm{eff}}\right) = S_i V_i \tag{1}$$

$$\text{field } U = \begin{pmatrix} \rho \\ \rho v \\ \rho e \end{pmatrix} \tag{2}$$

$$\text{flux } F \tag{3}$$

$$\text{source } S \tag{4}$$

Combination of moving mesh and SPH:

- Flux calculation as for a moving mesh
- Neighbor finding + kernel weighting as for SPH

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Combination of moving mesh and SPH:

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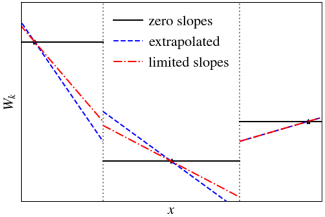
Numerically:

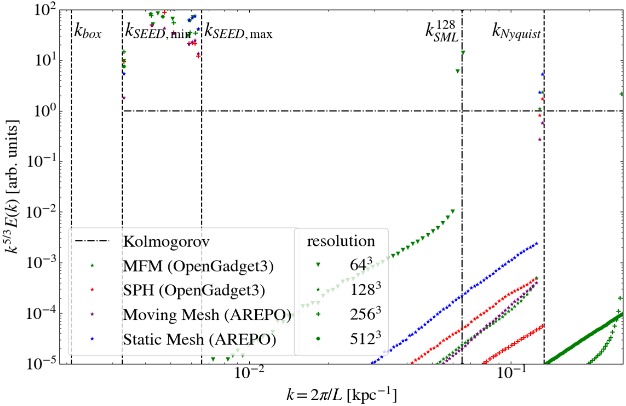
- Gradient interpolation
- Slope limiting
- Flux calculation



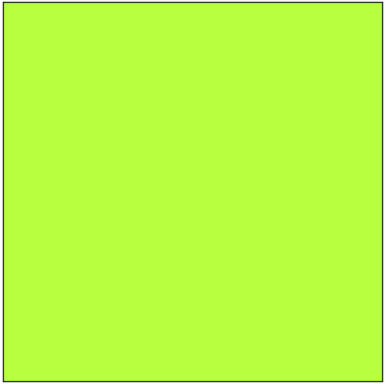
Groth et al. (2023),
submitted to MNRAS
arXiv:2301.03612

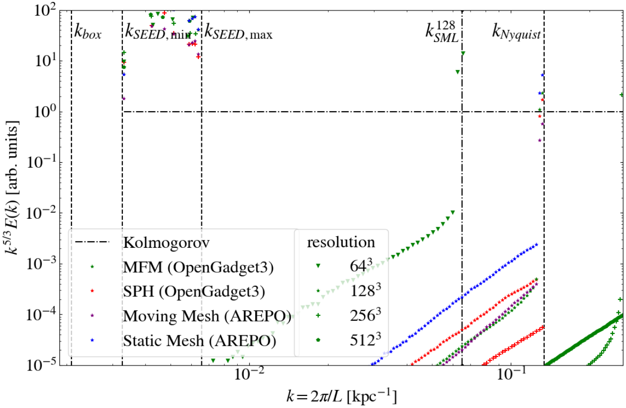
Turbulent Power Spectrum – Setup

- 300 kpc box
- Constant density $\rho = 1.6 \cdot 10^{-6}$
- Seed energy at a ≈ 70 large scale modes
- Initial turbulent energy fraction $X_i = 0.3$
- Energy cascades down
- Turbulent power spectrum builds up
- Use different hydro-methods, resolution and initial turbulent energy fraction



Turbulent Power Spectrum – Evolution





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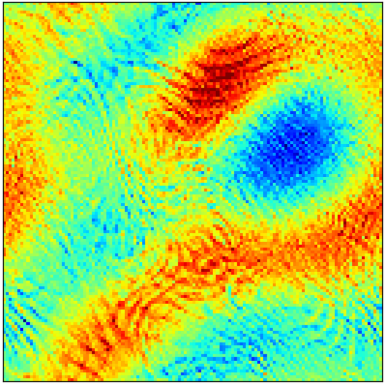

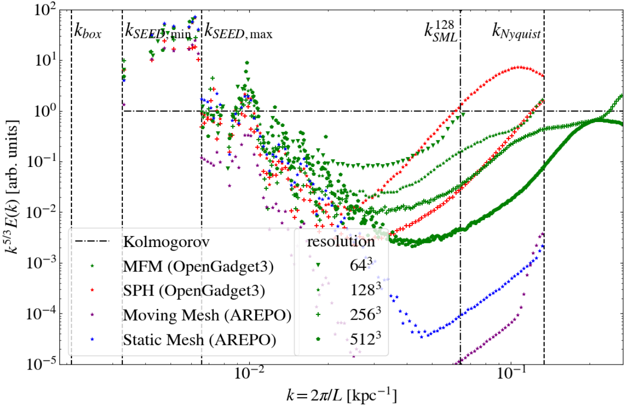

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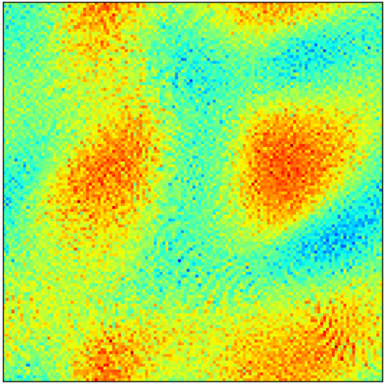

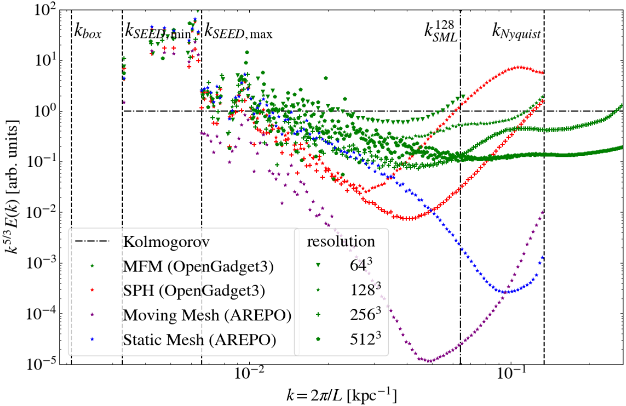

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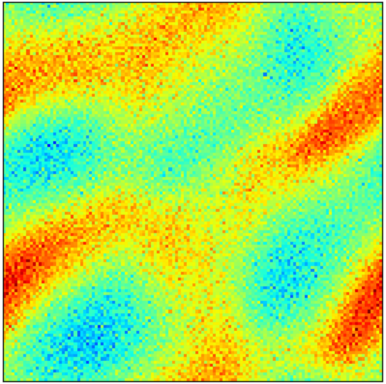

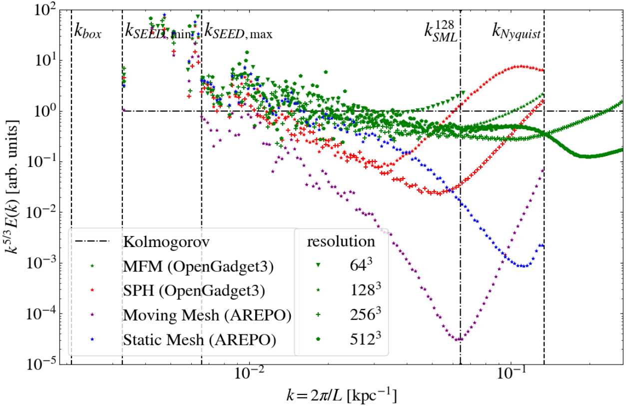

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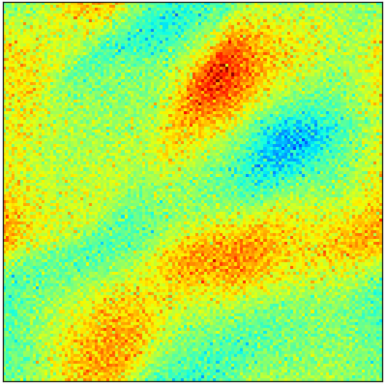

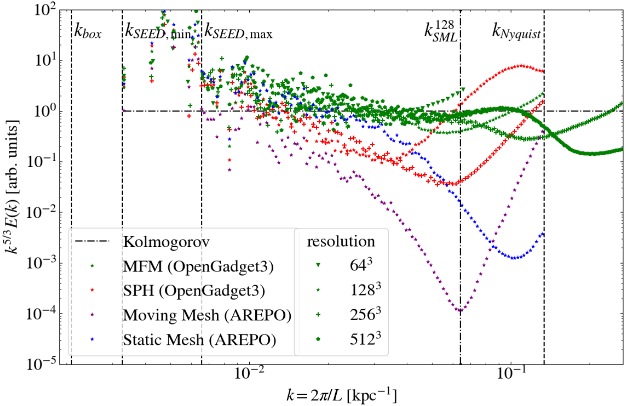

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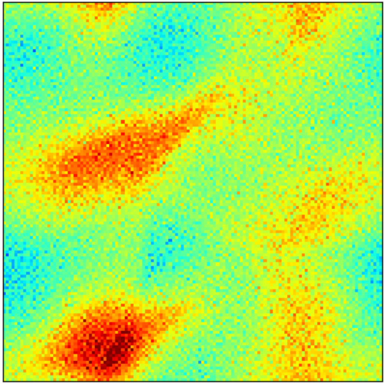

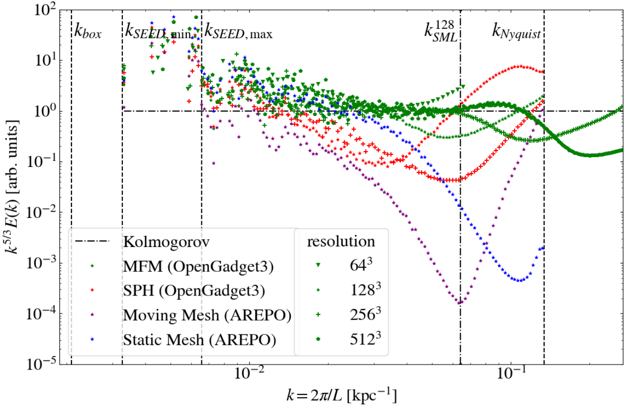

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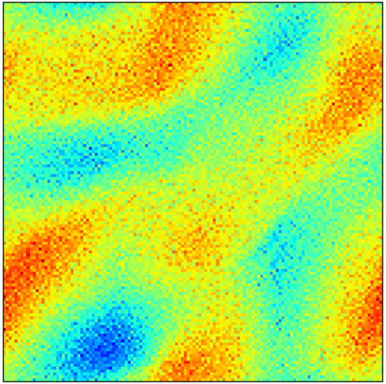

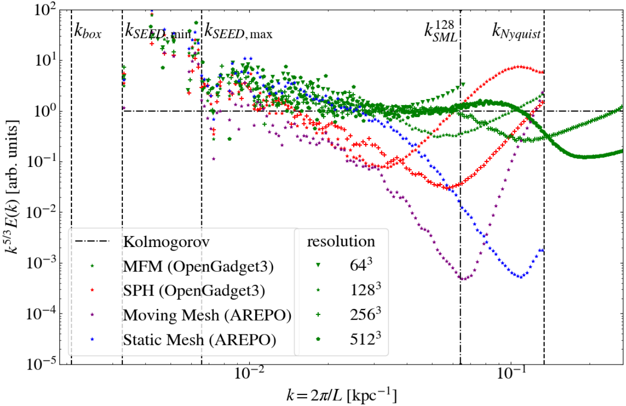

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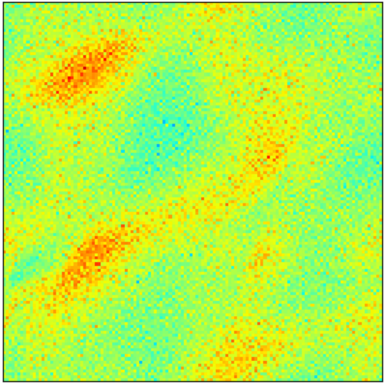

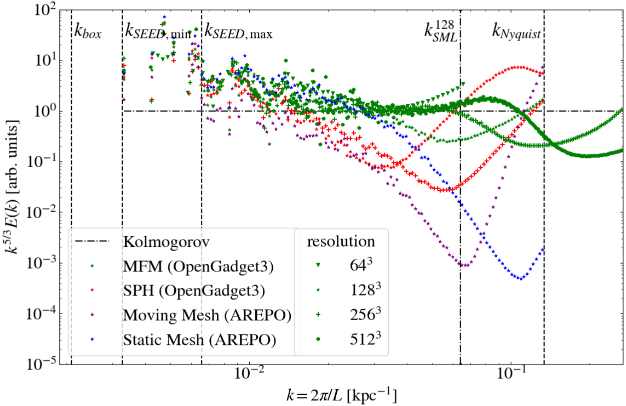

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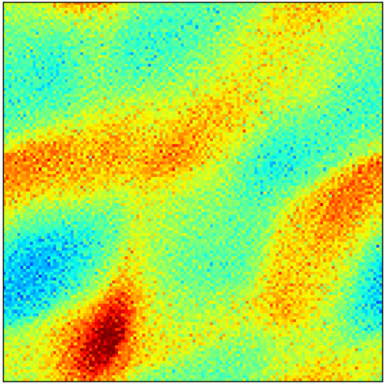
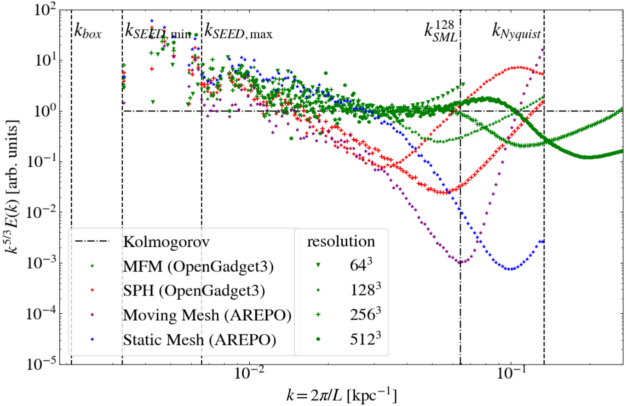
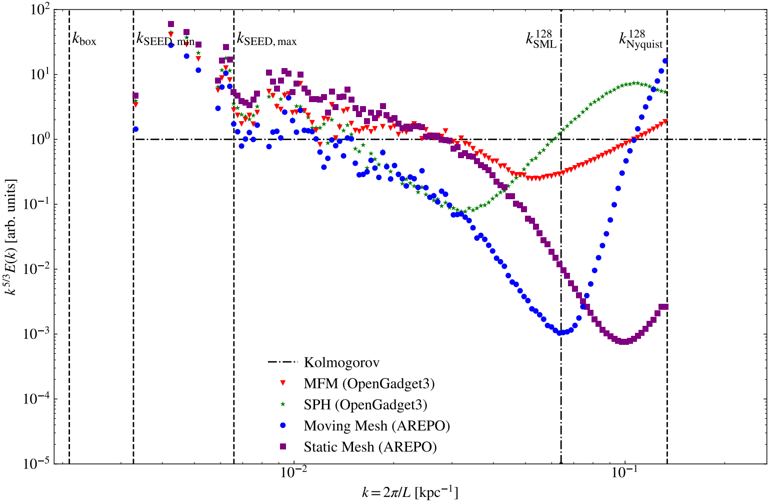


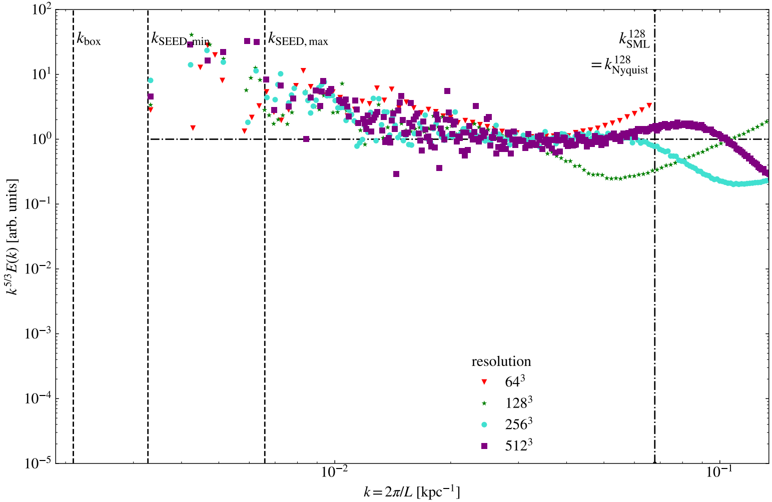


Turbulent Power Spectrum – Method Comparison



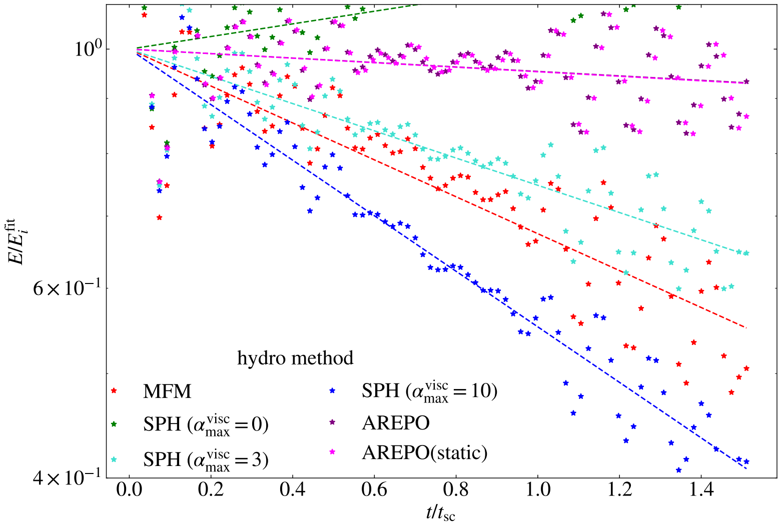
- All methods agree at large scales.
- Lack energy present at intermediate to small scales compared to expected Kolmogorow spectrum.
- MFM shows the shallowest dip in energy, located close to the resolution limit.

Turbulent Power Spectrum – Convergence Behavior



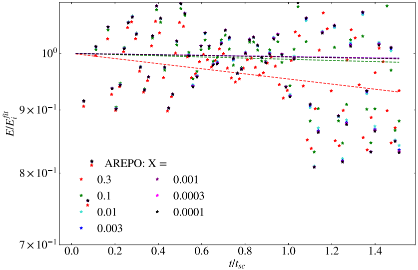
- Dip moves to smaller scales as the resolution increases.
- For highest resolution, almost perfectly resembles expected Kolmogorov slope over wide range of scales.
- Overall, MFM converges well with resolution.

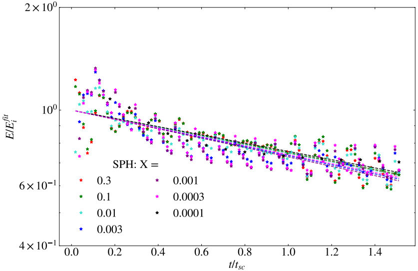
Decay of Turbulent Energy – Method Comparison

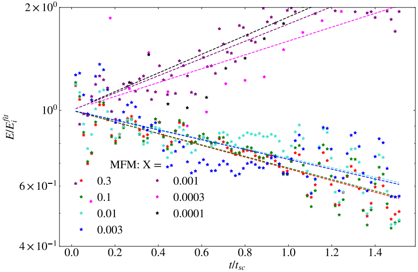


- Total energy conserved
- Turbulent energy transformed into internal energy
- Comparable decay between MFM and SPH

Decay of Turbulent Energy

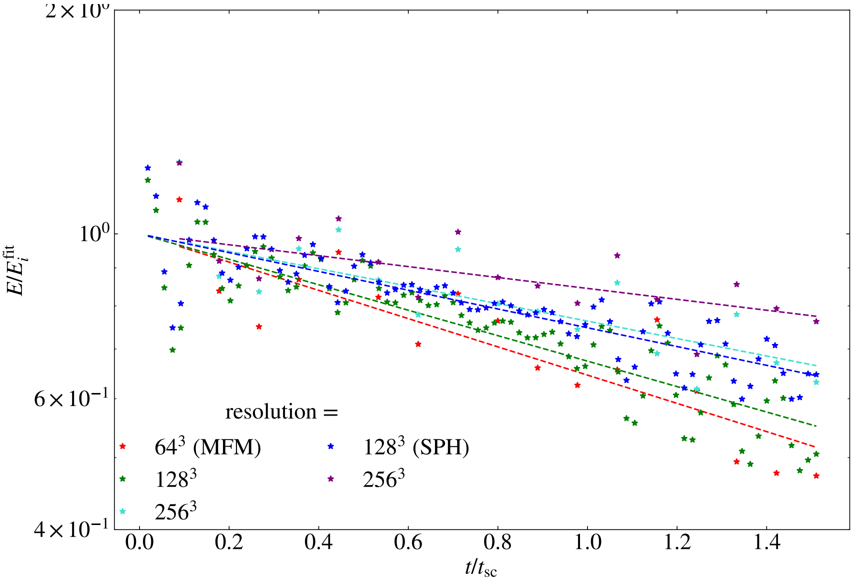






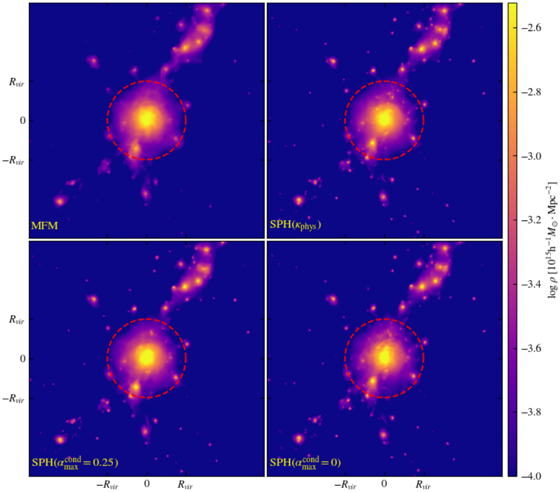
- Decay independent of X_i for SPH and Arepo
- Breaks down for MFM only at $X_i < 0.003$, corresponding to $\mathcal{M} < 0.007$

Decay of Turbulent Energy – Convergence



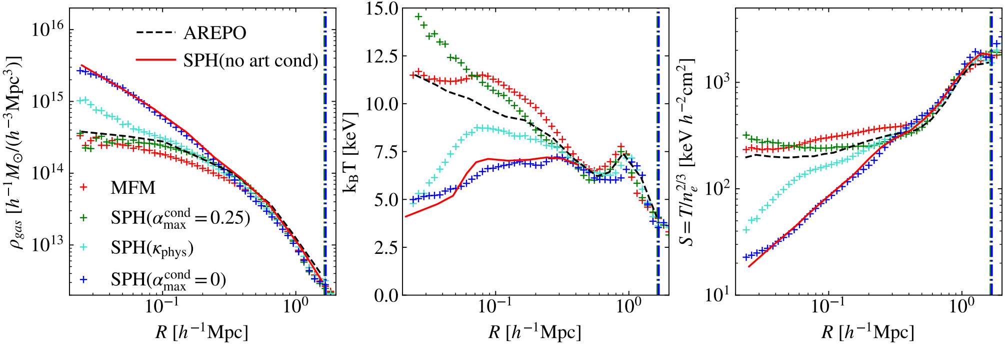
Decay time increases with resolution.

MFM for Calculations of Galaxy Clusters



- Similar large scale structure in all cases
- Structures more smeared out for MFM compared to SPH
- Depends on artificial conductivity for SPH

MFM for Calculations of Galaxy Clusters



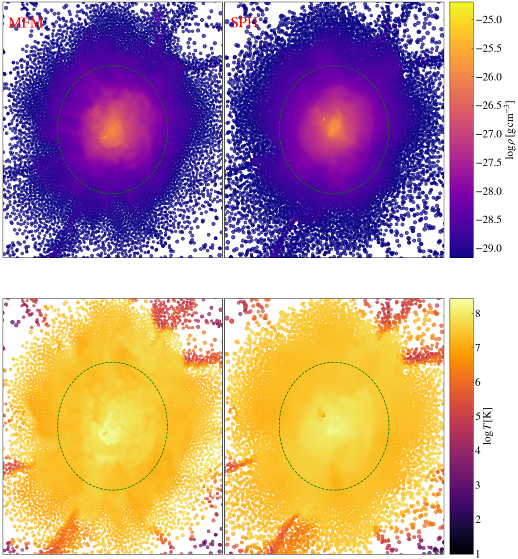
Reference lines from Sembolini+2016

Riemann solver in MFM allows mixing into the core

⇒ increased central entropy

⇒ lower central density

Turbulence in Galaxy Clusters – Effect of the Hydro-Scheme



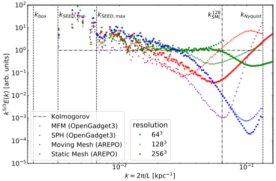
- Zoom-in simulation of a galaxy cluster at low resolution ($m_{\mathrm{gas}} = 1.6 \cdot 10^8 M_\odot$, $m_{\mathrm{DM}} = 10^9 M_\odot$)
- From the dianoga suite

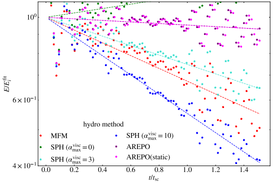
  Bonafede+2011

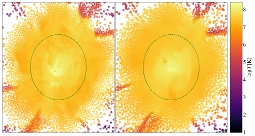
Preliminary results:

- Core is less dense for MFM
- More smaller structures, visible both in density and temperature
- Increased amount of turbulence at smaller scales for MFM

Summary







- New MFM implementation in OpenGadget3
- MFM performs very well when applied to decaying subsonic turbulence
- Power-spectrum captured most accurately compared to other methods
- Good convergence behavior
- Comparable decay in turbulent energy between MFM and SPH
- Works down to very small Mach numbers $\mathcal{M} < 0.007$
- Promising first results for simulations of galaxy clusters towards the modeling of turbulence in the ICM