The PICO-Cluster Project: cluster sample, magnetic field growth, and weakly collisional effects

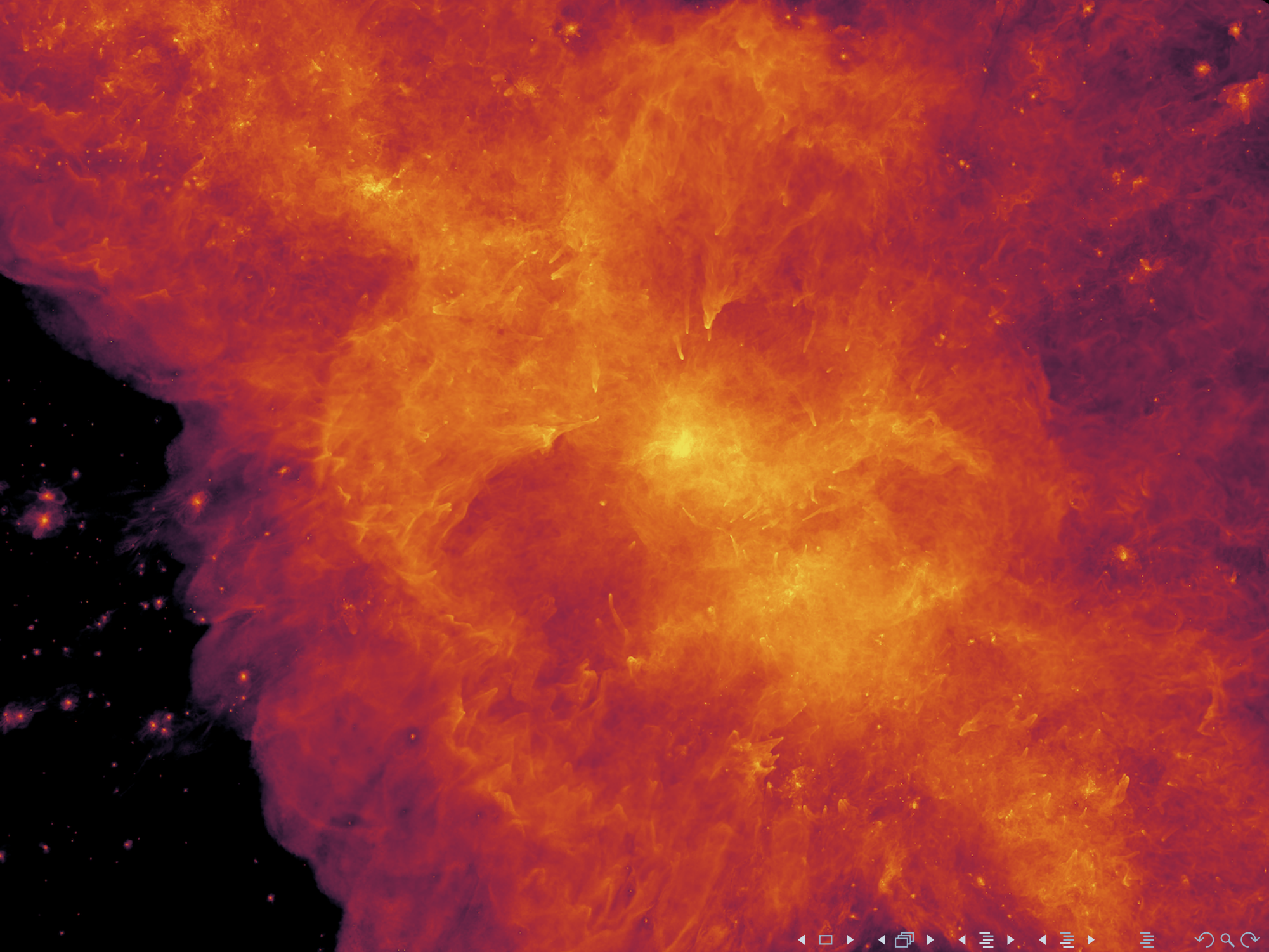
Christoph Pfrommer[1]

in collaboration with

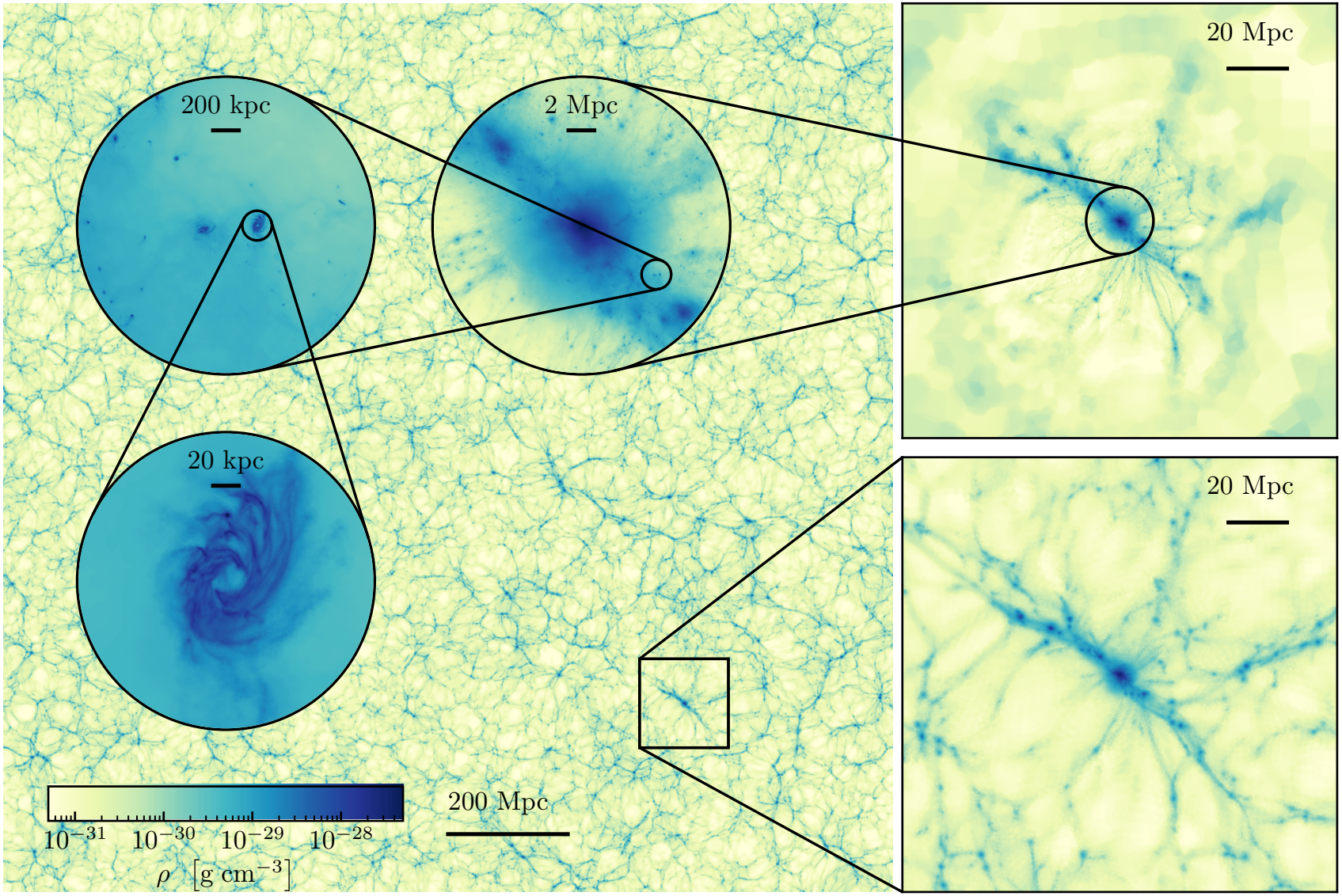
Berlok,[2] Puchwein,[1] Talbot,[3] Pakmor,[3] Perrone,[1] Weinberger,[1] Springel,[3] Whittingham,[1] Tevlin,[1] Dusch,[1] Sparre[1]

[1]AIP, [2]NBI, [3]MPA

8th ICM Theory and Computation Workshop, Brno, 2026

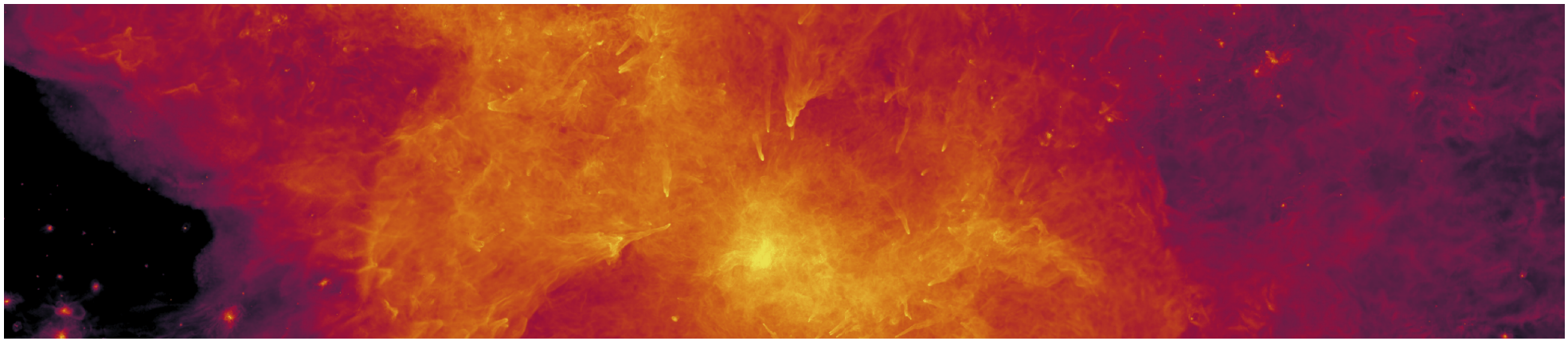


Zooming in on a galaxy cluster



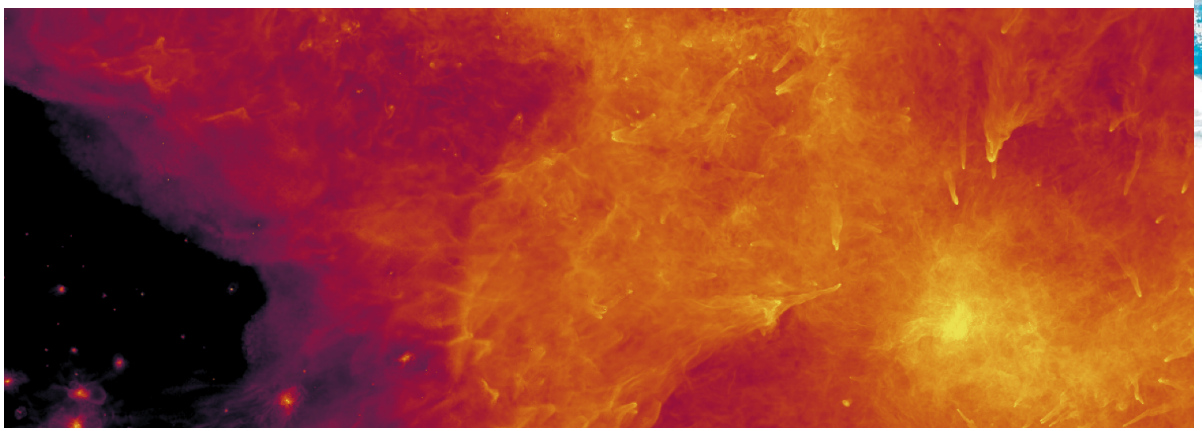
PICO-Clusters (Plasmas In COsmological Clusters)

- ***parent simulation:*** $(1.5\ \mathrm{Gpc})^3$ cosmological volume with 543 clusters $> 10^{14.9}\ \mathrm{M}_\odot$
- 24 cosmological zoom-in runs of massive clusters evolved from $z = 127$ to 0; one extreme resolution run with ∼770 million particles/cells inside R_{200c} ($M_{gas} = 10^6\ \mathrm{M}_\odot$)
- moving mesh code AREPO-2 (with Subfind HBT) (Springel 2010, Springel+ 2022), comoving ideal MHD with Powell cleaning (Pakmor+ 2011, 2013, 2026)
- IllustrisTNG as base galaxy formation model (Weinberger+ 2017, Pillepich+ 2018)



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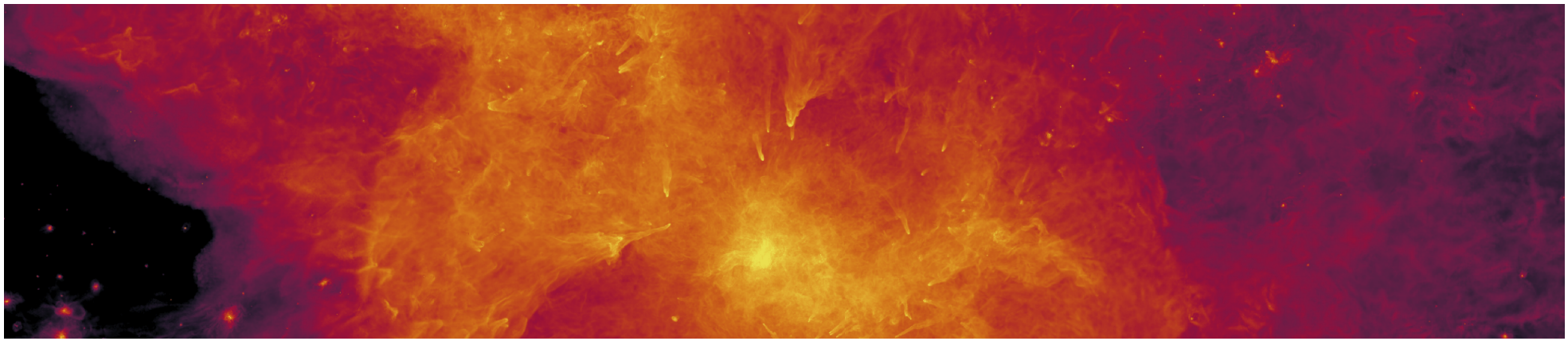




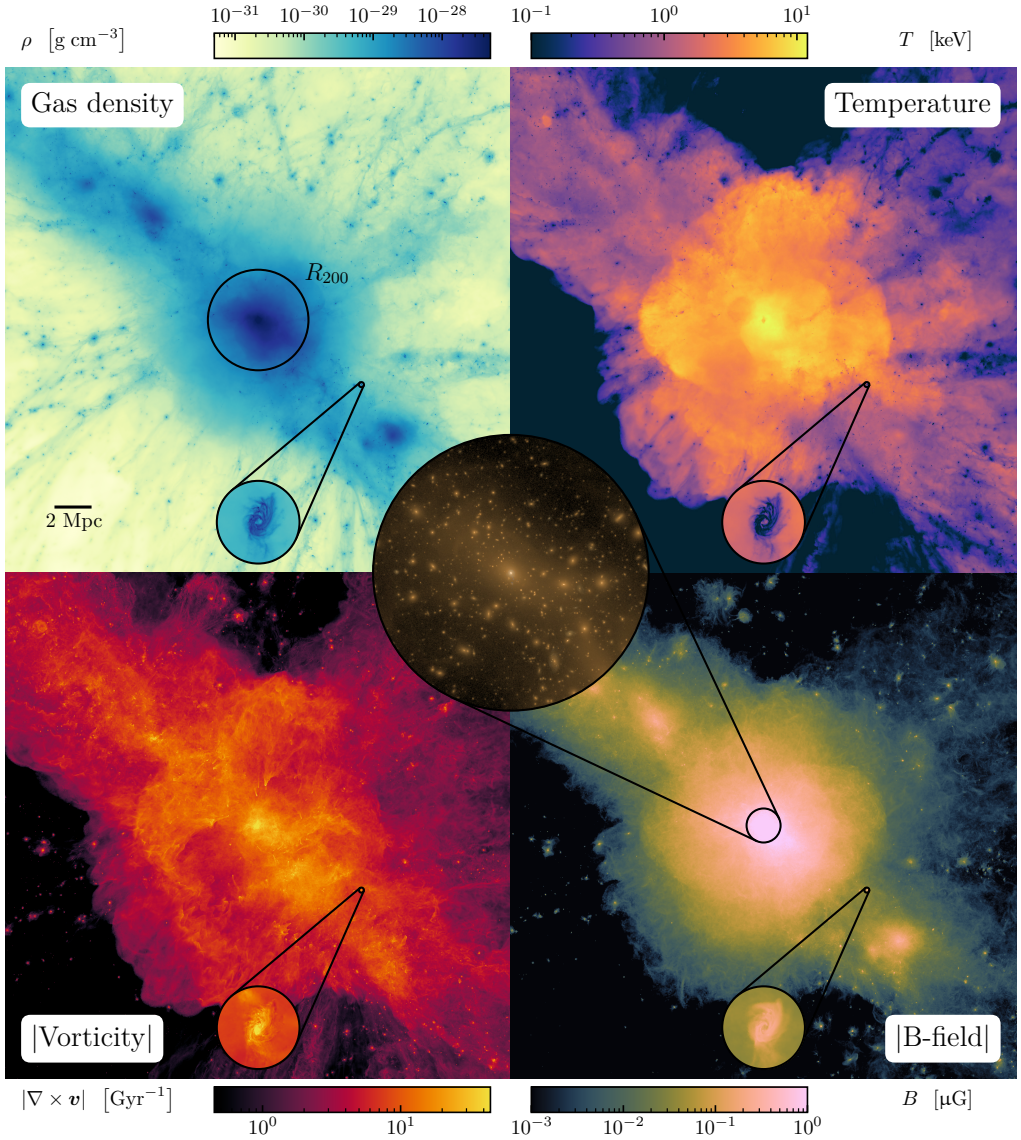
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- IllustrisTNG as base galaxy formation model (Weinberger+ 2017, Pillepich+ 2018)
- solving key questions requires different physics variants (AGN jet feedback, cosmic rays, non-radiative, . . .) and high-resolution meso-scale simulations!

Berlok, CP, Puchwein, Talbot, Pakmor, Perrone, Weinberger, Springel, Whittingham, Tevlin, Dusch, Sparre (2026)



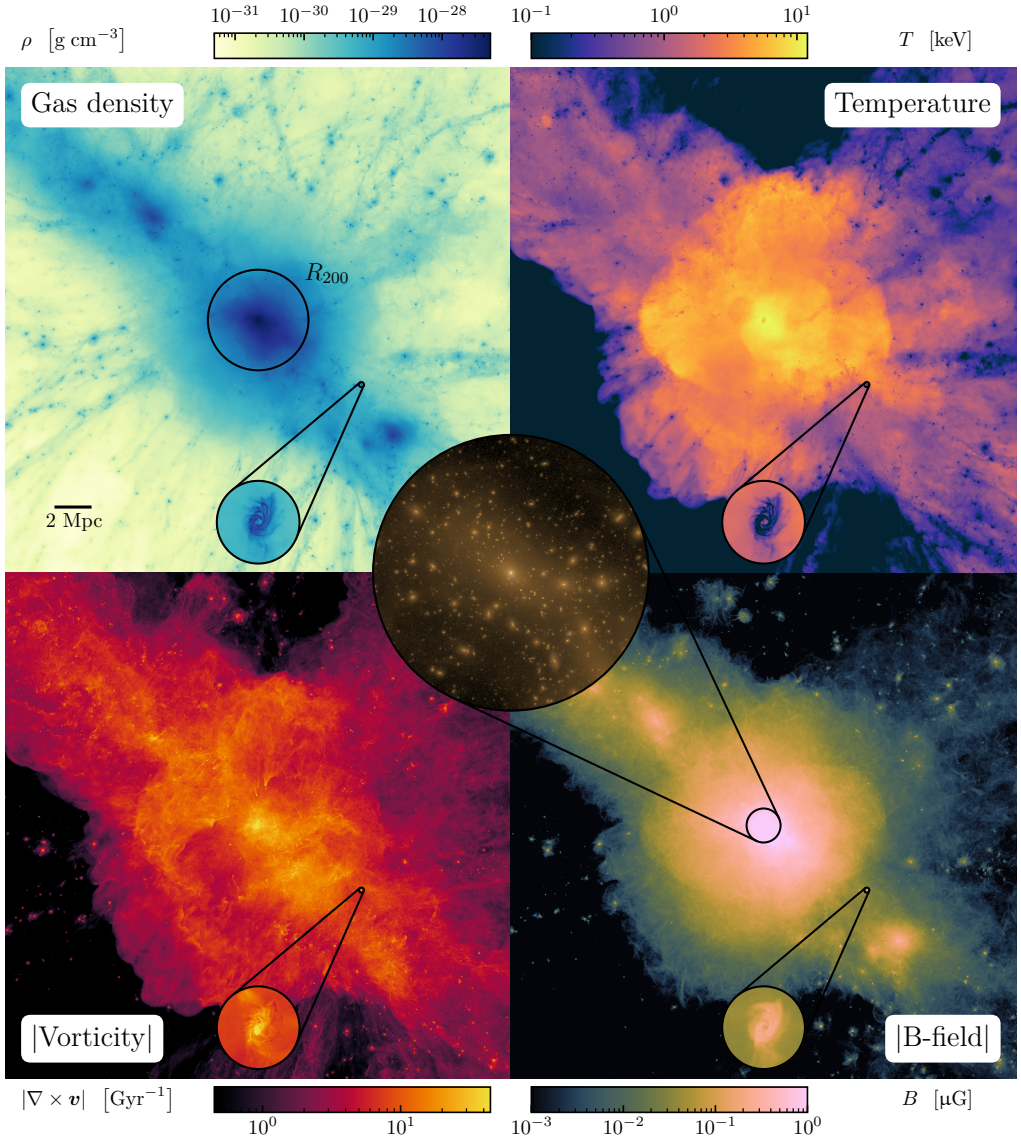
11 key questions of galaxy clusters



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11 key questions of galaxy clusters

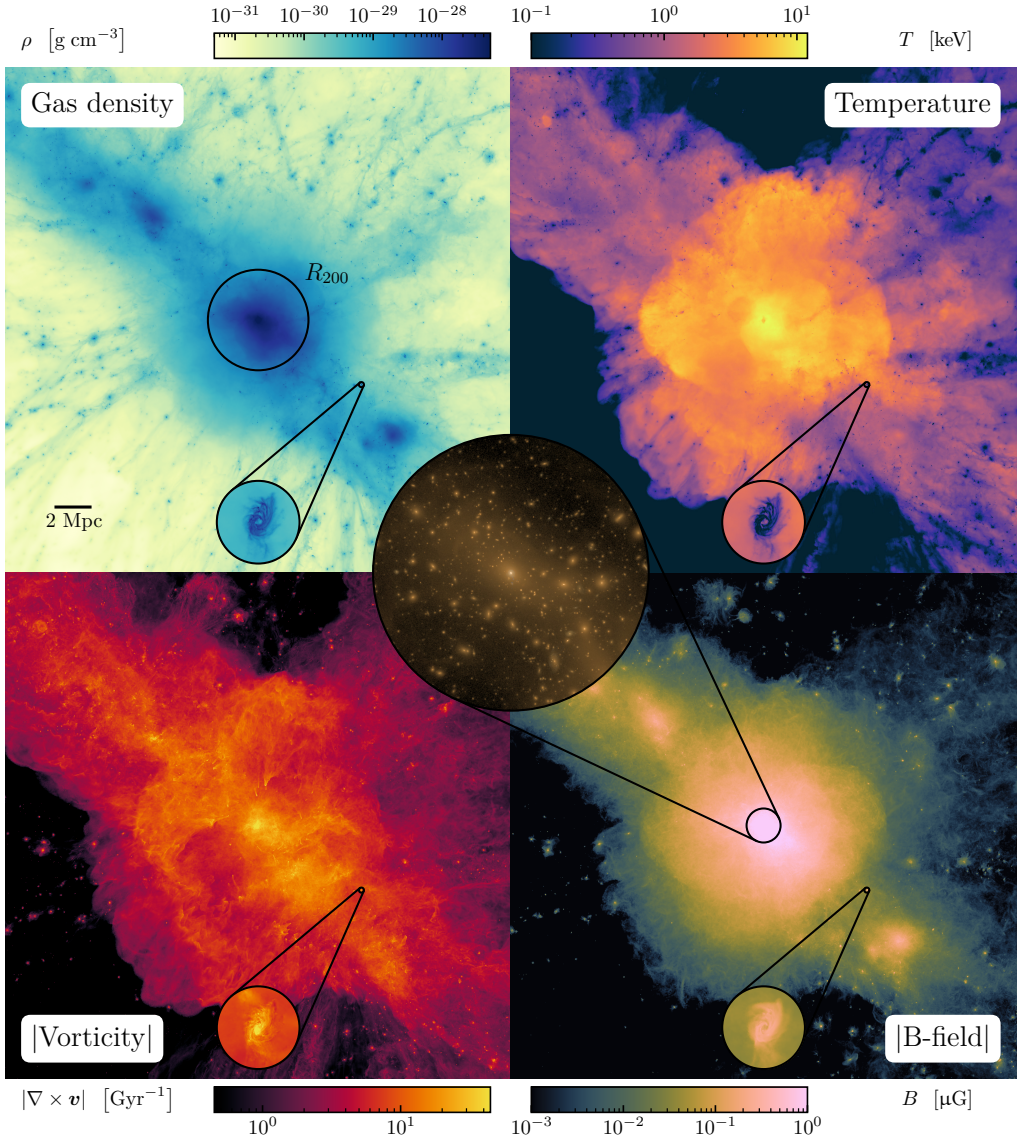
- Why is the central ICM cooling time bimodally distributed?
- Does heating by ***AGN jets*** solve the cooling flow problem? Which heating process is responsible?
- Why is the turbulent ICM energy only a few per cent of the thermal energy in quiescent clusters?
- What are the (observable) consequences of weakly collisional ICM processes?
- What is the origin of cluster magnetic fields? How do they scale with redshift and cluster mass?



Berlok, CP, Puchwein, Talbot+ (2026)

11 key questions of galaxy clusters (cont.'d)

- What is the origin of radio halos?
- Do radio relics trace merger-driven shock waves?
  How can we use them to probe cluster peripheries?
- Why have clusters not yet been detected at gamma rays?
- How are jellyfish galaxies formed?
- What fraction of stars resides in the intracluster light?
- Are galaxy groups and clusters effectively baryonically closed and where does the baryon fraction match the cosmic mean?

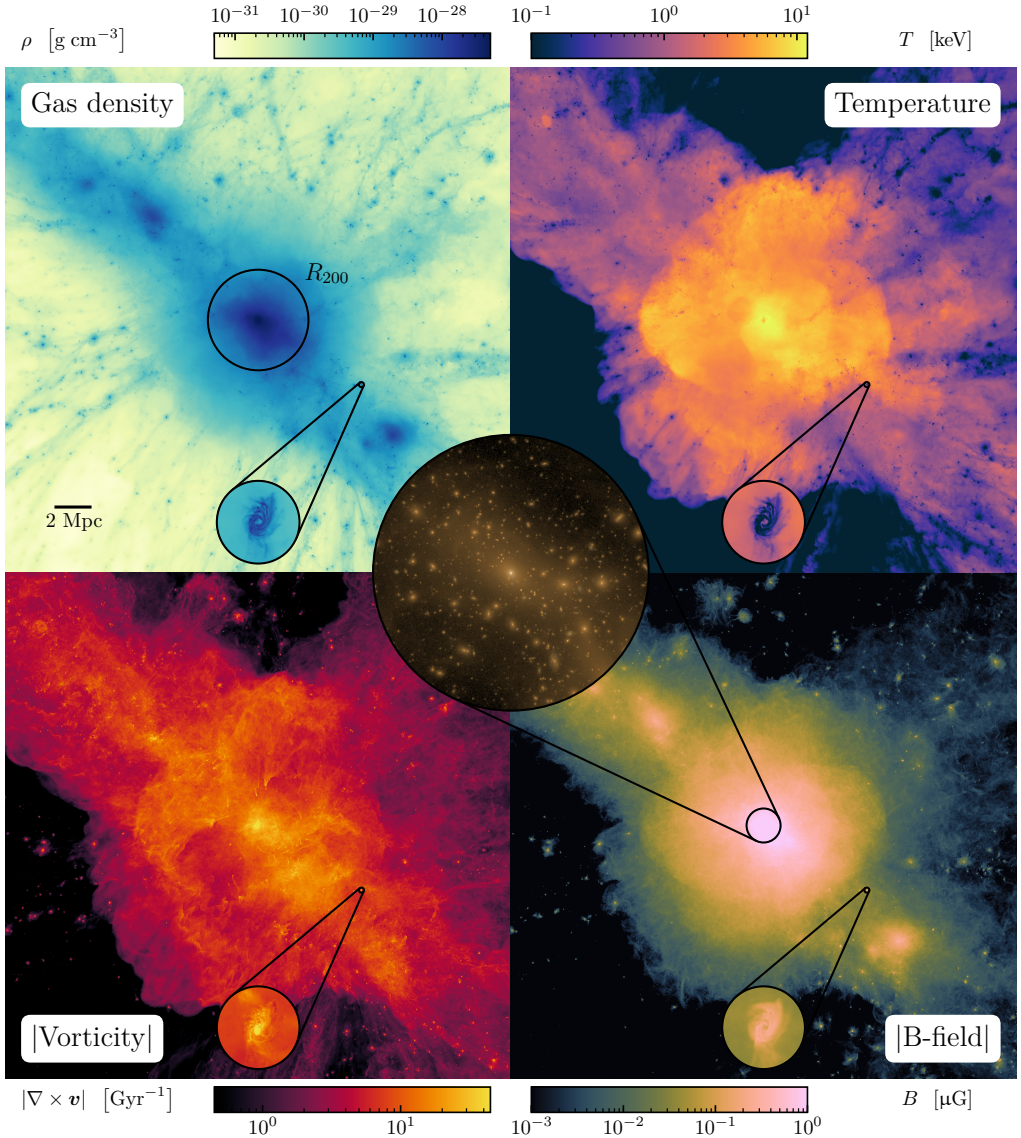


Berlok, CP, Puchwein, Talbot+ (2026)

PICO-Cluster vs. TNG-Cluster

Differences to comparable simulation projects, e.g., TNG-Cluster (Nelson+ 2024):

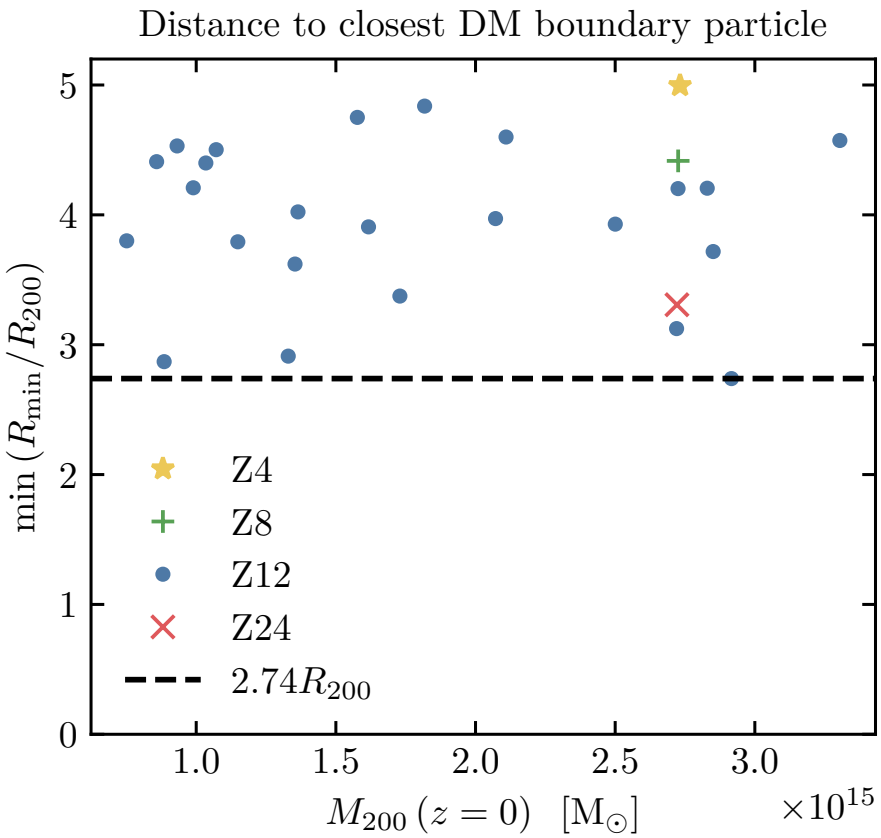
- our new initial conditions code, ensuring a contamination-free high-resolution region $< 2.74 R_{200}$ across all times
- improved simulation code: AREPO-2 while TNG-Cluster uses AREPO
- increased resolution (up to $M_{\rm gas} = 10^6\ \mathrm{M}_\odot$): study numerical convergence of ICM turbulence and magnetic field strength
- the scientific focus as we will be investigating plasma effects in the ICM in PICO-Clusters

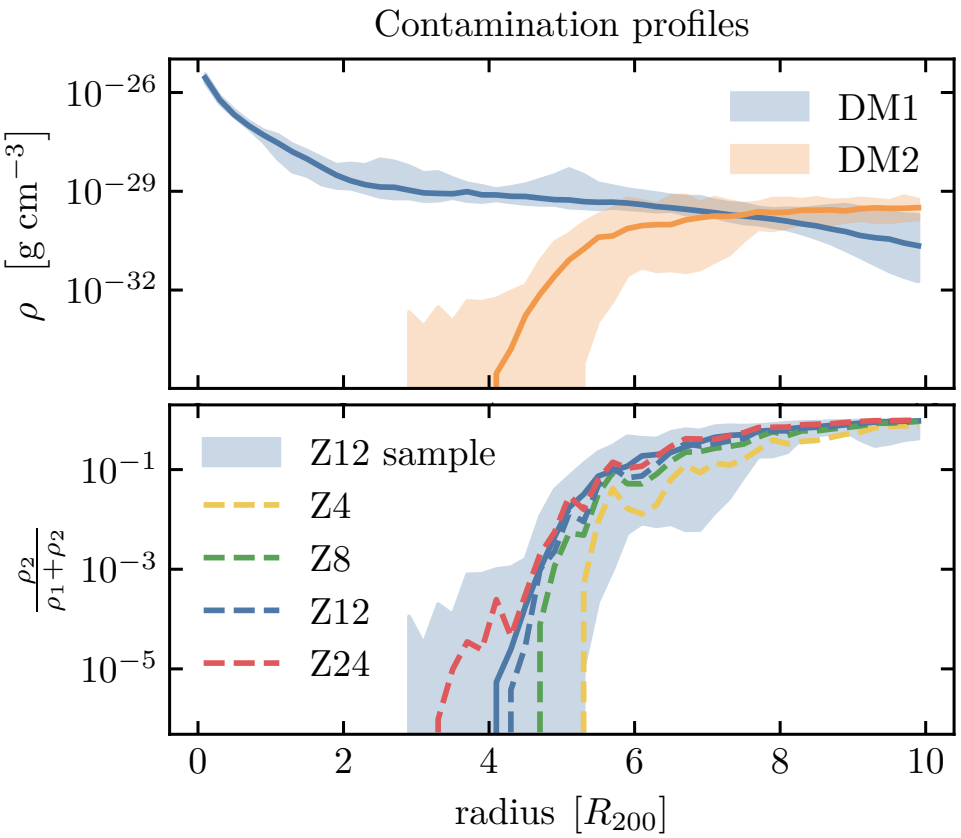


Berlok, CP, Puchwein, Talbot+ (2026)

Quality of initial conditions

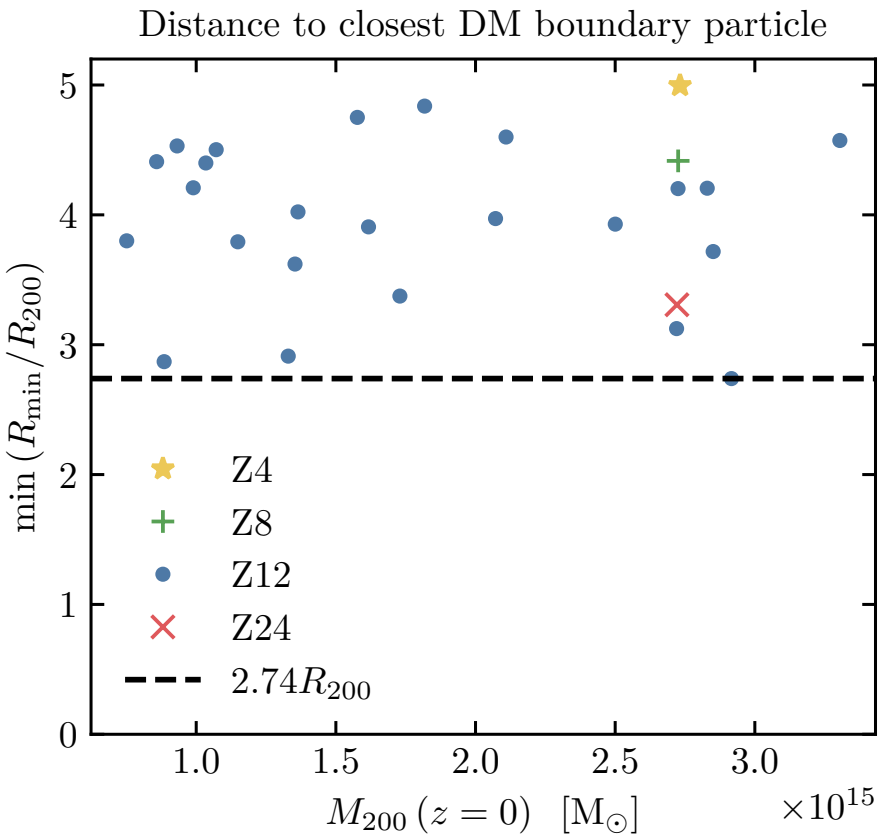
Our accurate initial conditions avoid contamination by heavy boundary particles

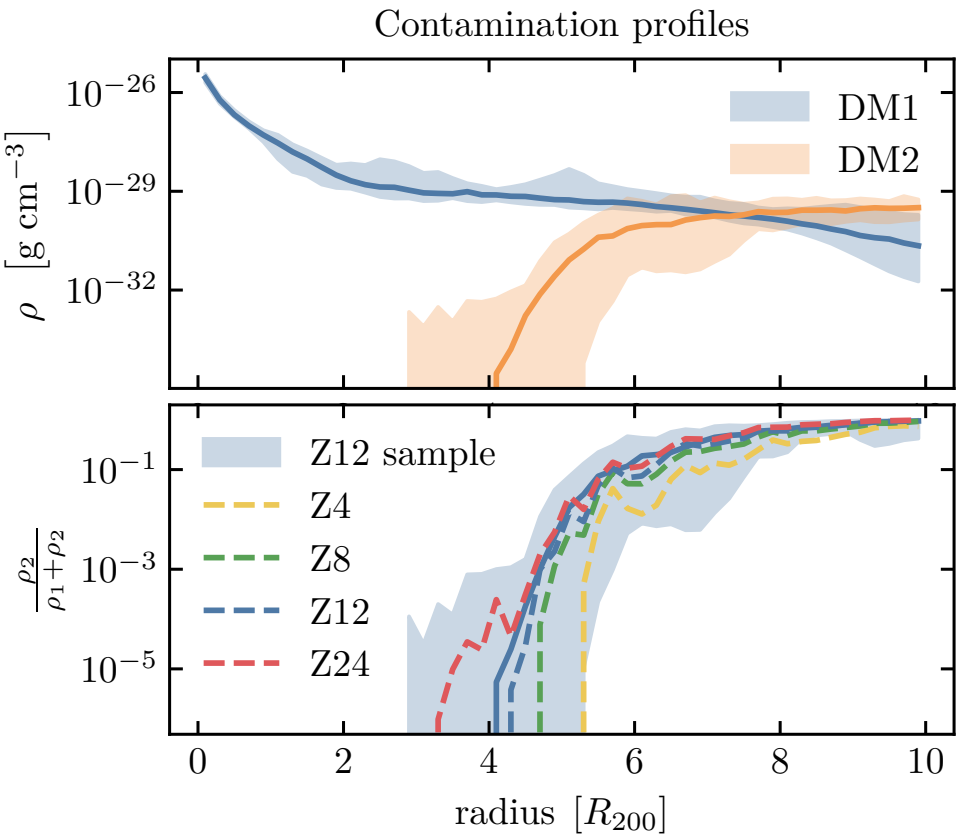




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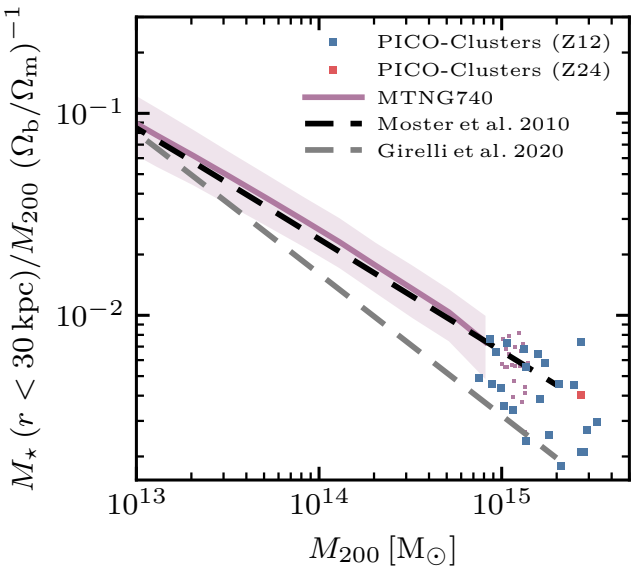


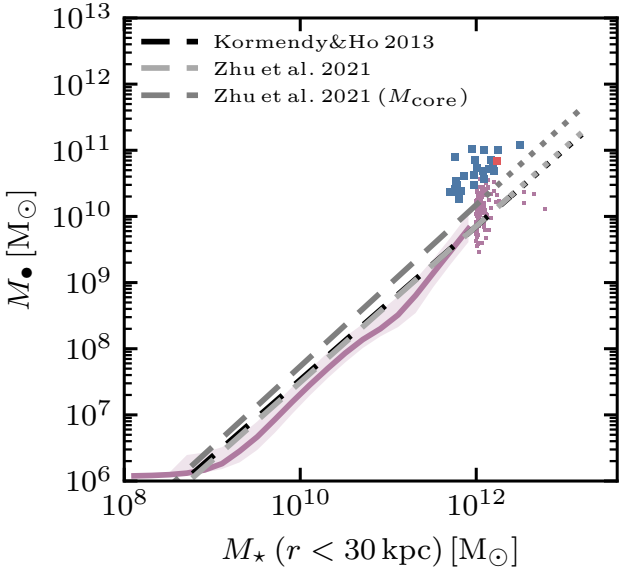


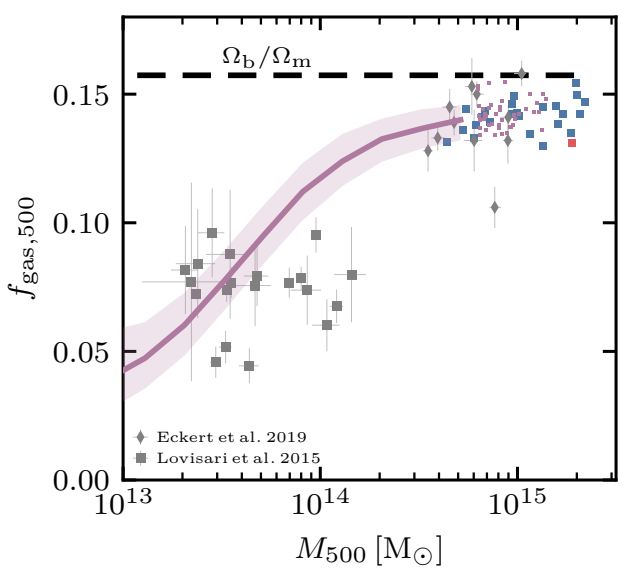
→ New CosmoZoomIC code by Puchwein+ (in prep.): public release 2027!

Verification and Validation of PICO-Clusters

Comparing component masses to MilleniumTNG simulations and observations





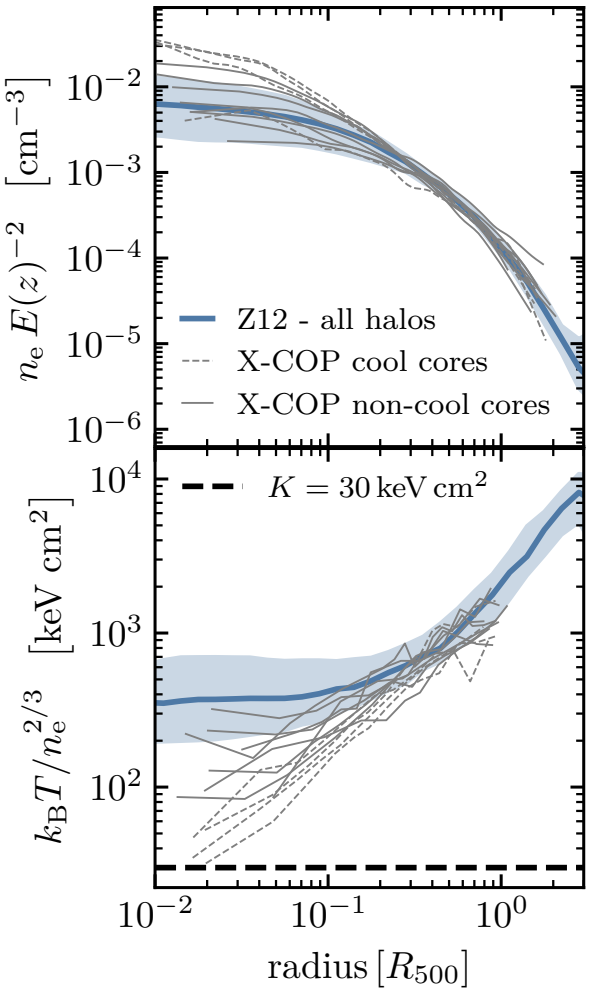


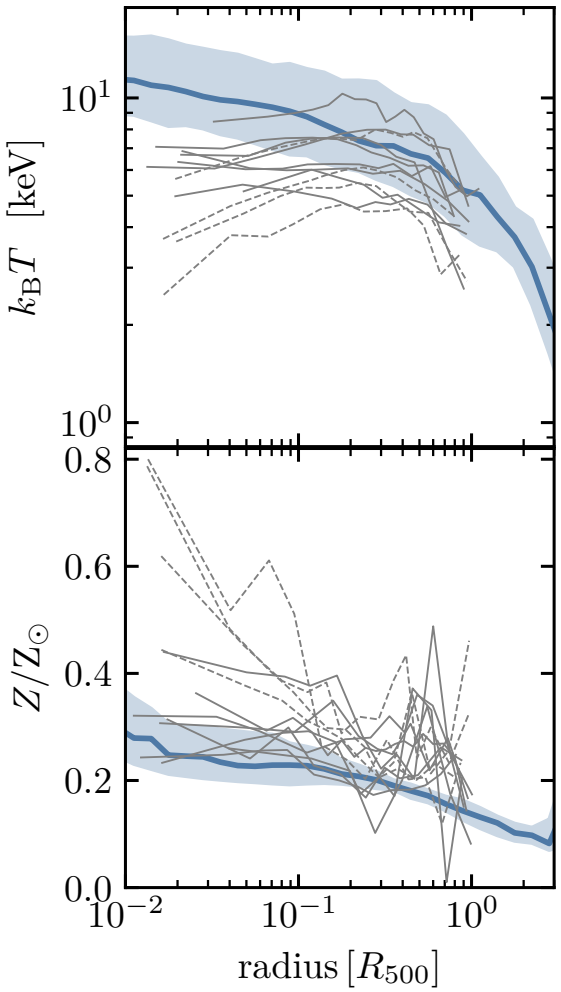
- ***Gas masses*** in agreement with MilleniumTNG and observations
- ***Supermassive black hole masses*** too high by factor 2–3 due to "black-hole overmerging" → too much AGN feedback
- ***Central stellar masses*** slightly too low

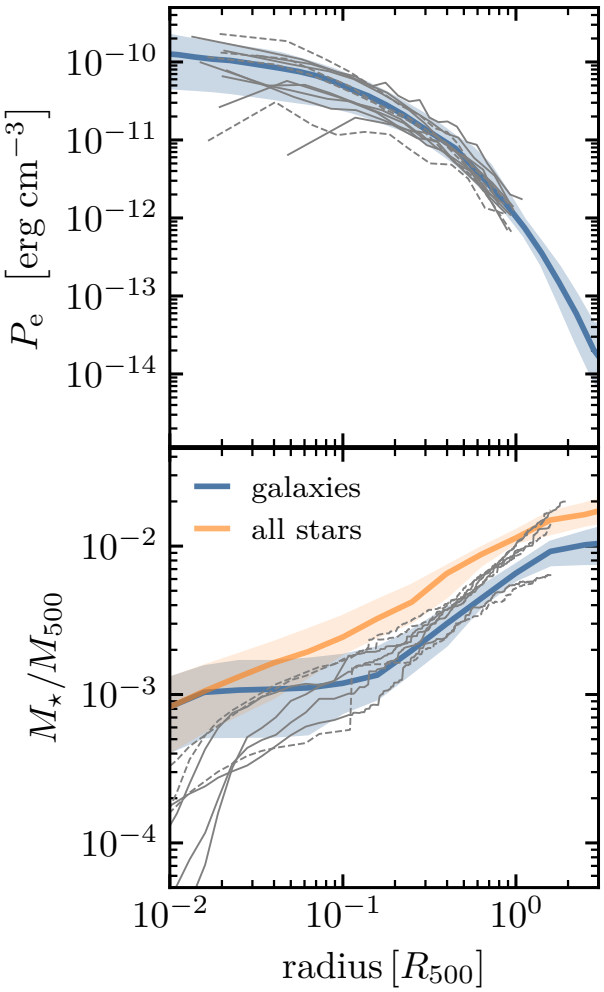
AIP

Verification and Validation of PICO-Clusters

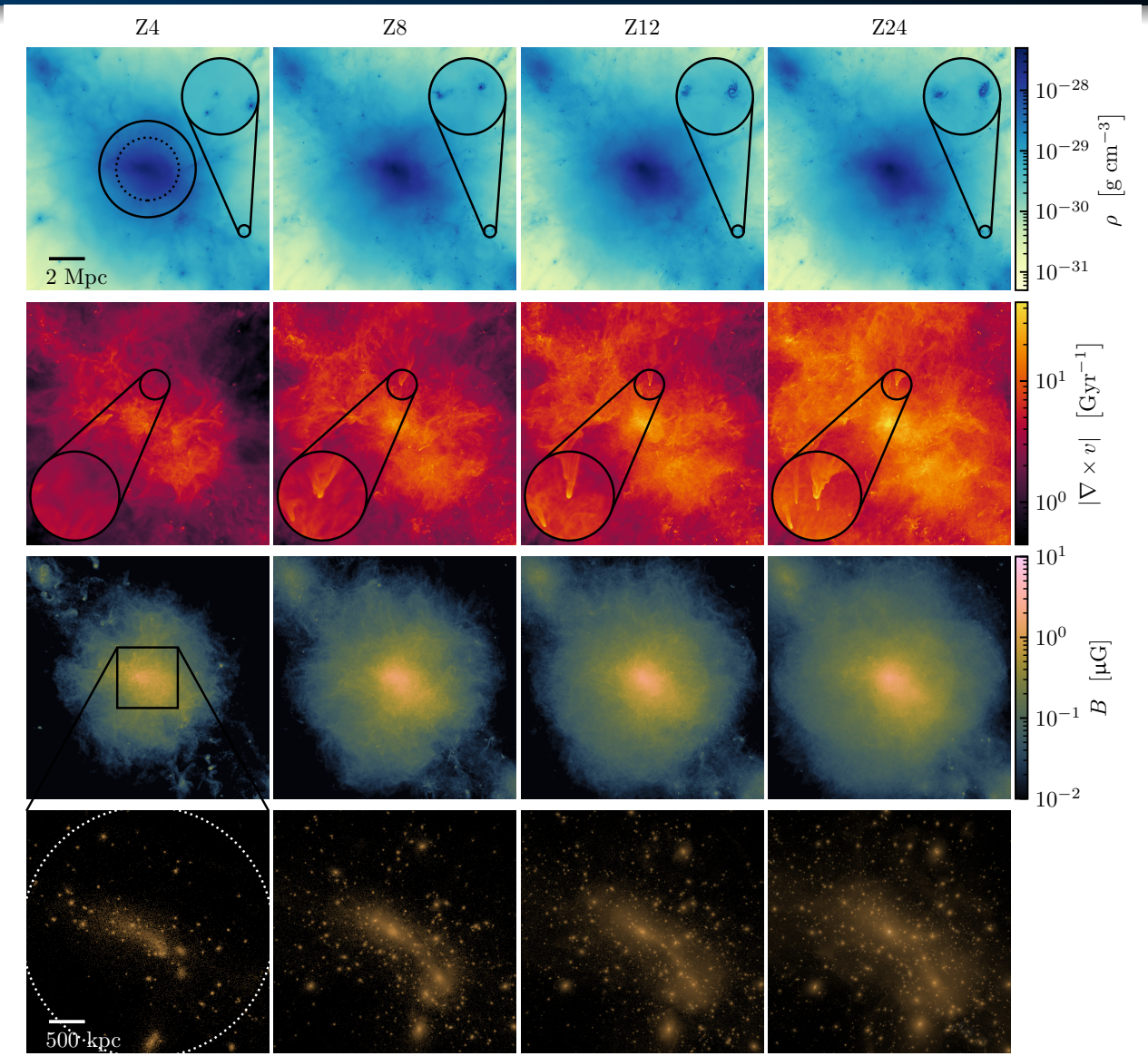
Observational comparison demonstrates scarcity of cool-core clusters in IllustrisTNG



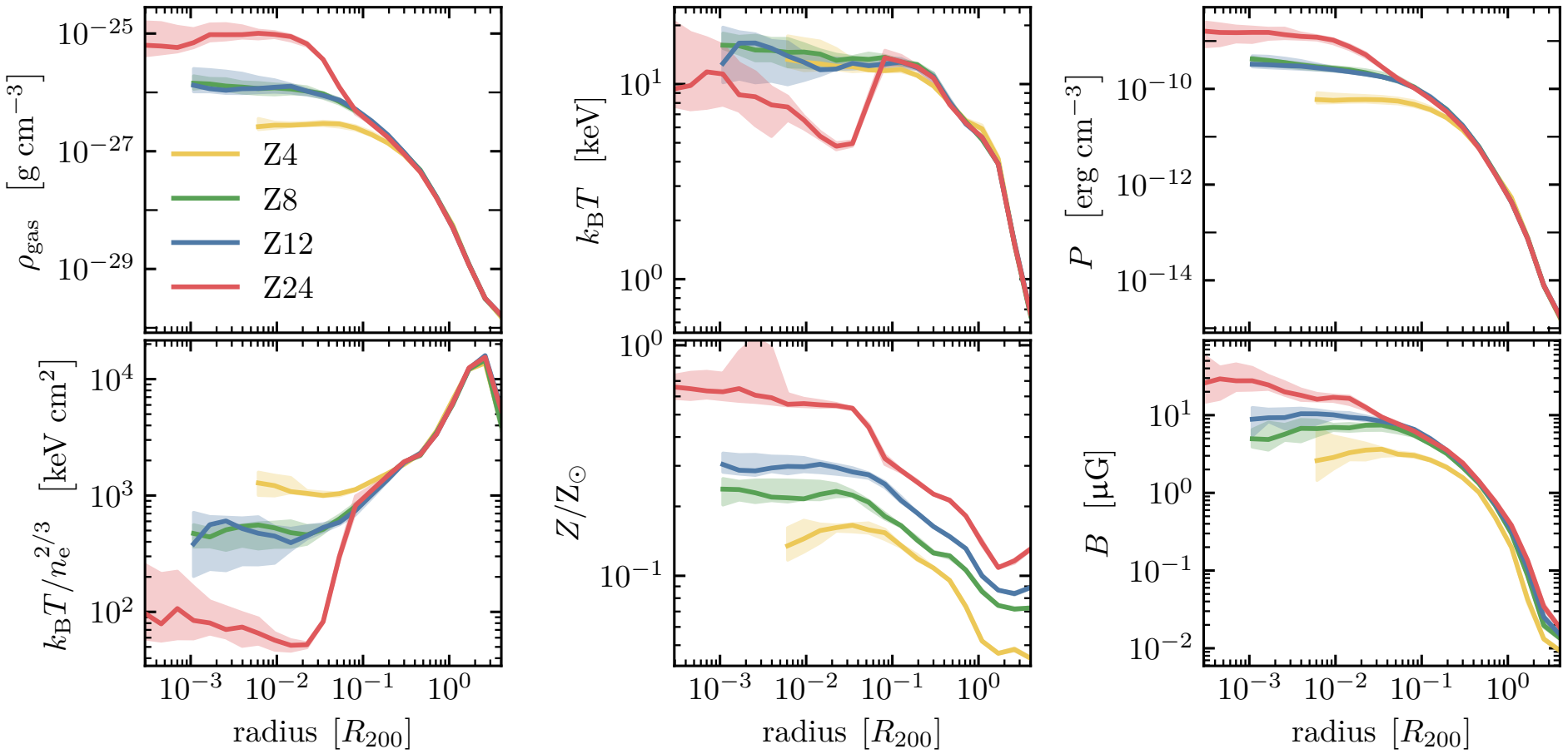




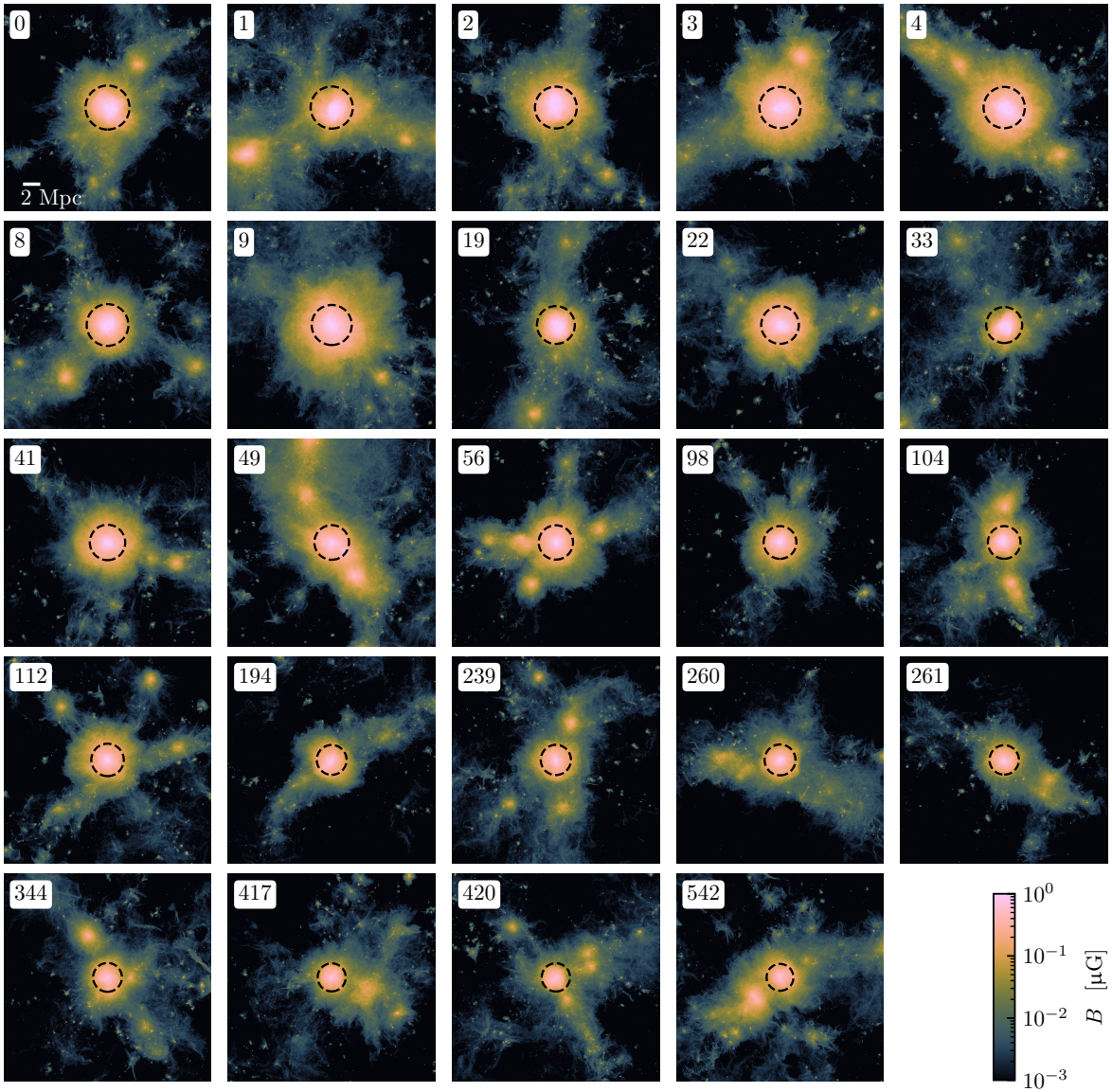
Resolution study: maps



Resolution study: thermodynamic profiles

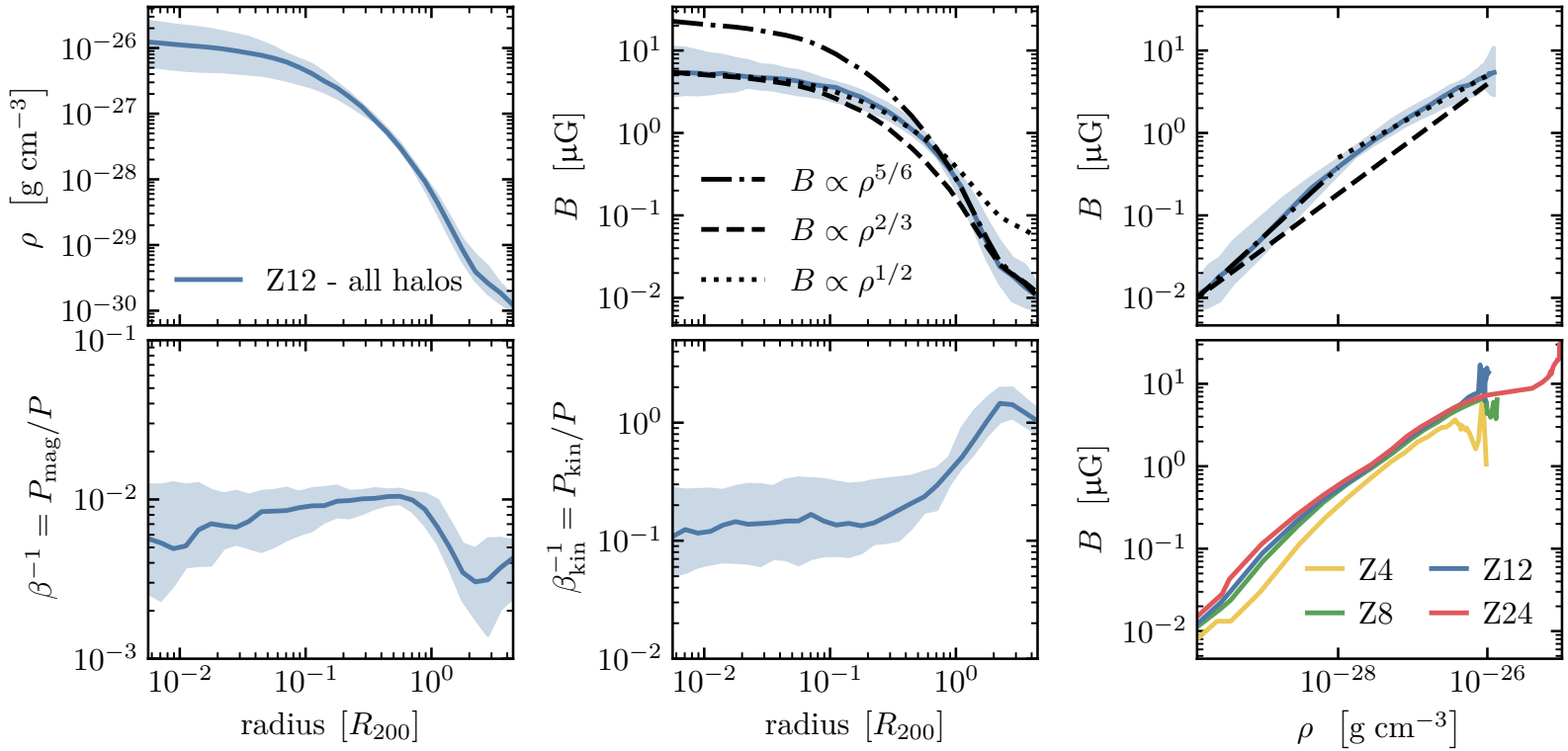


Magnetic field strength across PICO-Clusters



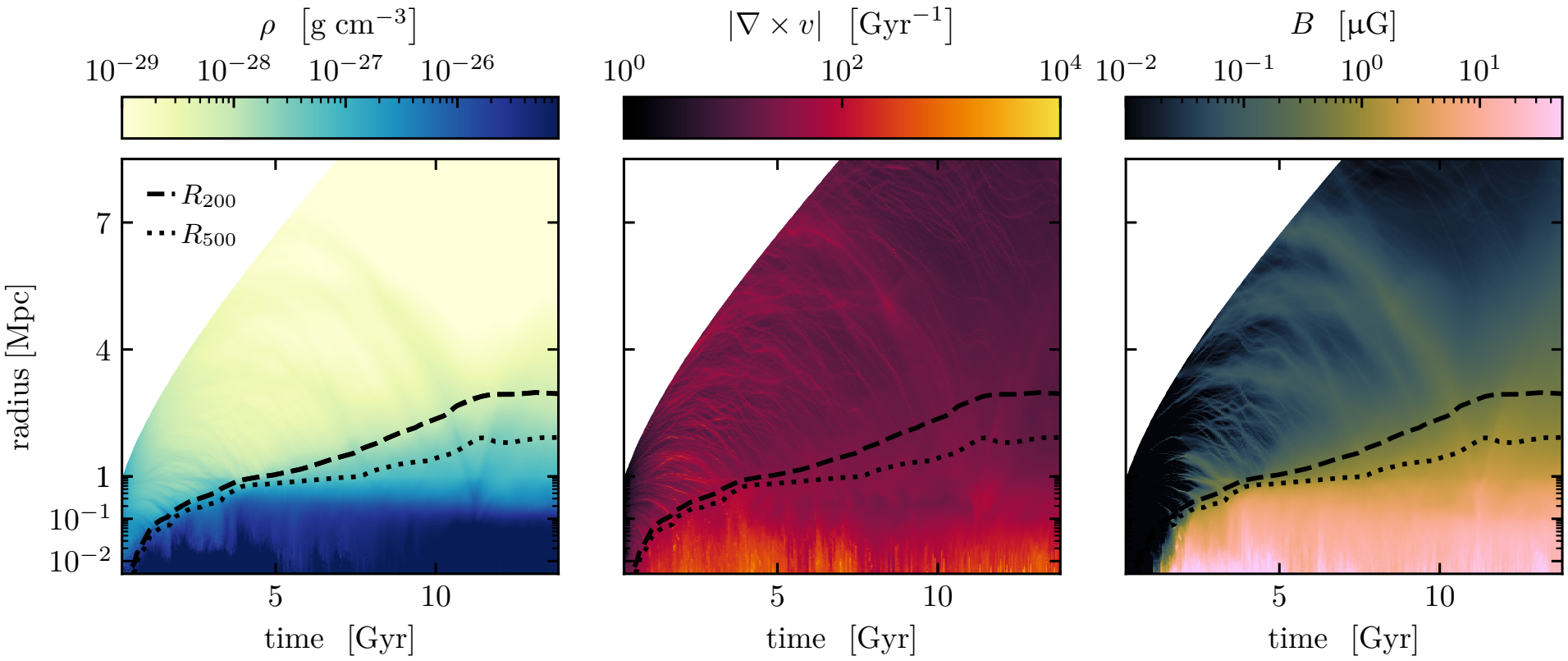
Magnetic field profiles and correlations

Surprising magnetic uniformity across clusters



- ***inner profile saturated:*** $B \propto \rho^{2/3}$
- ***outer profile dominated by infall*** and not fully converged: $B \propto \rho^{5/6}$

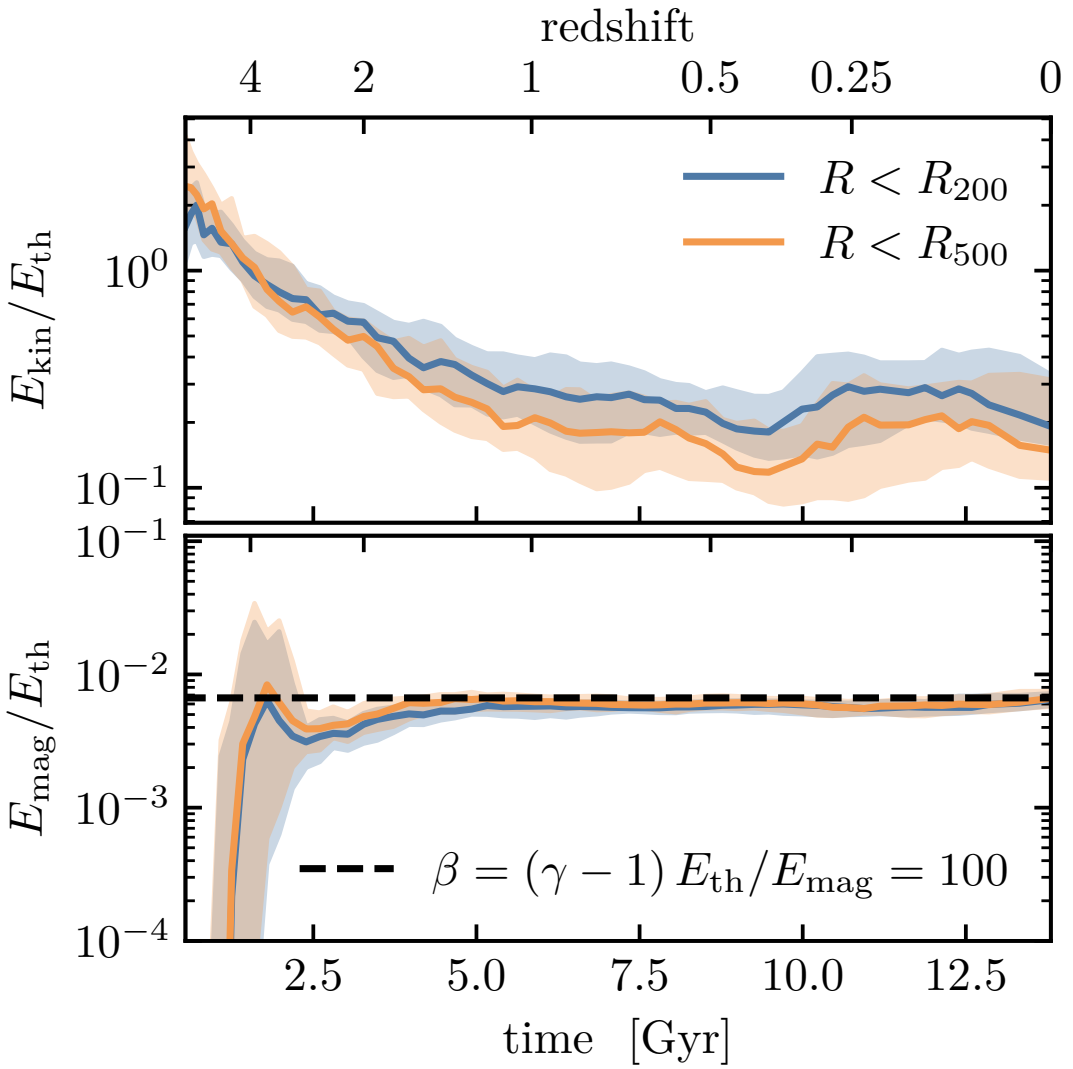
Space-time plots show magnetic field growth



- variation at small radii signals AGN feedback
- early magetic field growth due to small-scale dynamo driven by stellar and AGN feedback
- later magnetic enrichment of ICM due to infalling galaxies

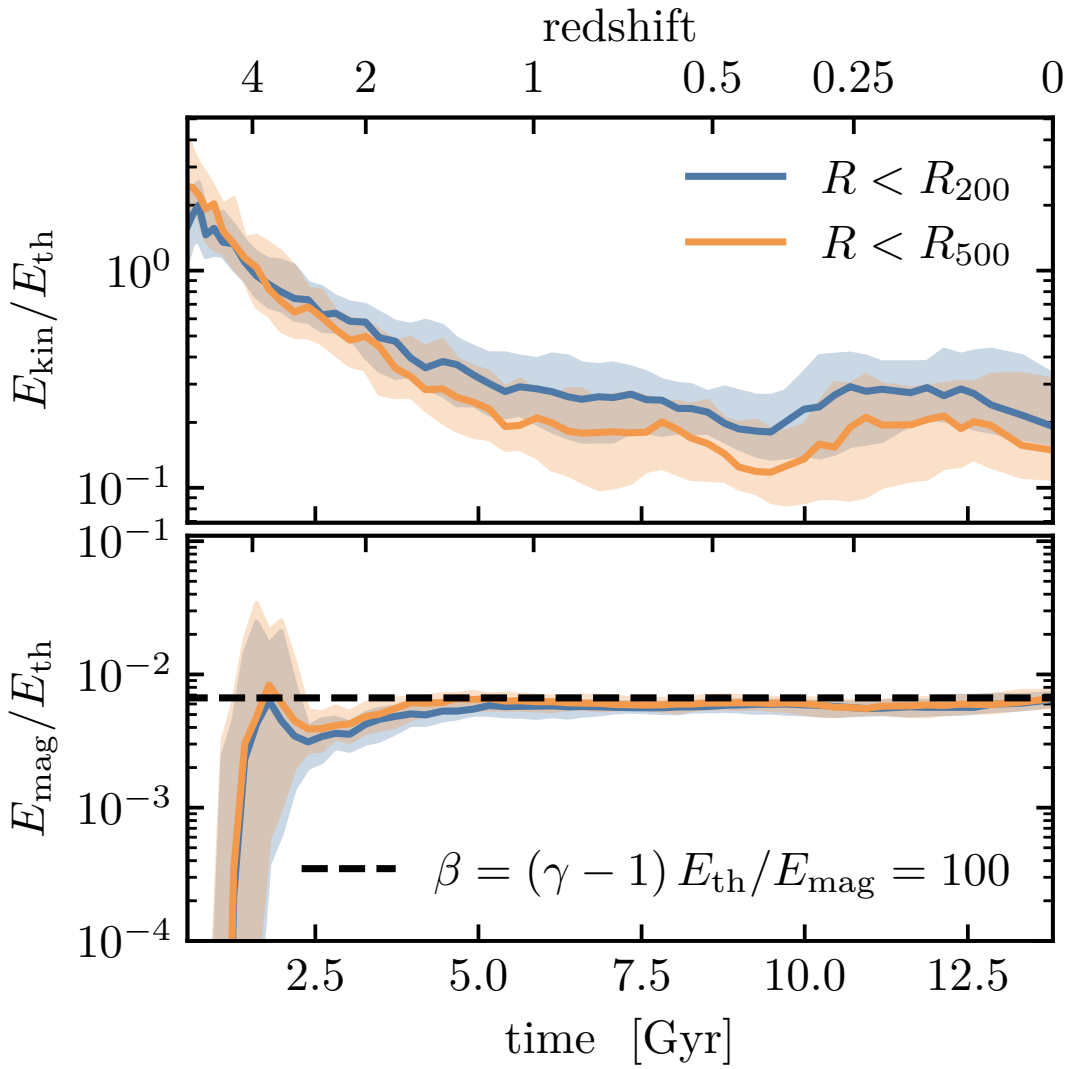
Time evolution of energy ratios

- elevated $E_{\mathrm{kin}}/E_{\mathrm{th}}$ at early times (cold accretion, strong stellar/AGN feedback)
- $E_{\mathrm{kin}}/E_{\mathrm{th}}$ constant at late times with large dispersion caused by mergers

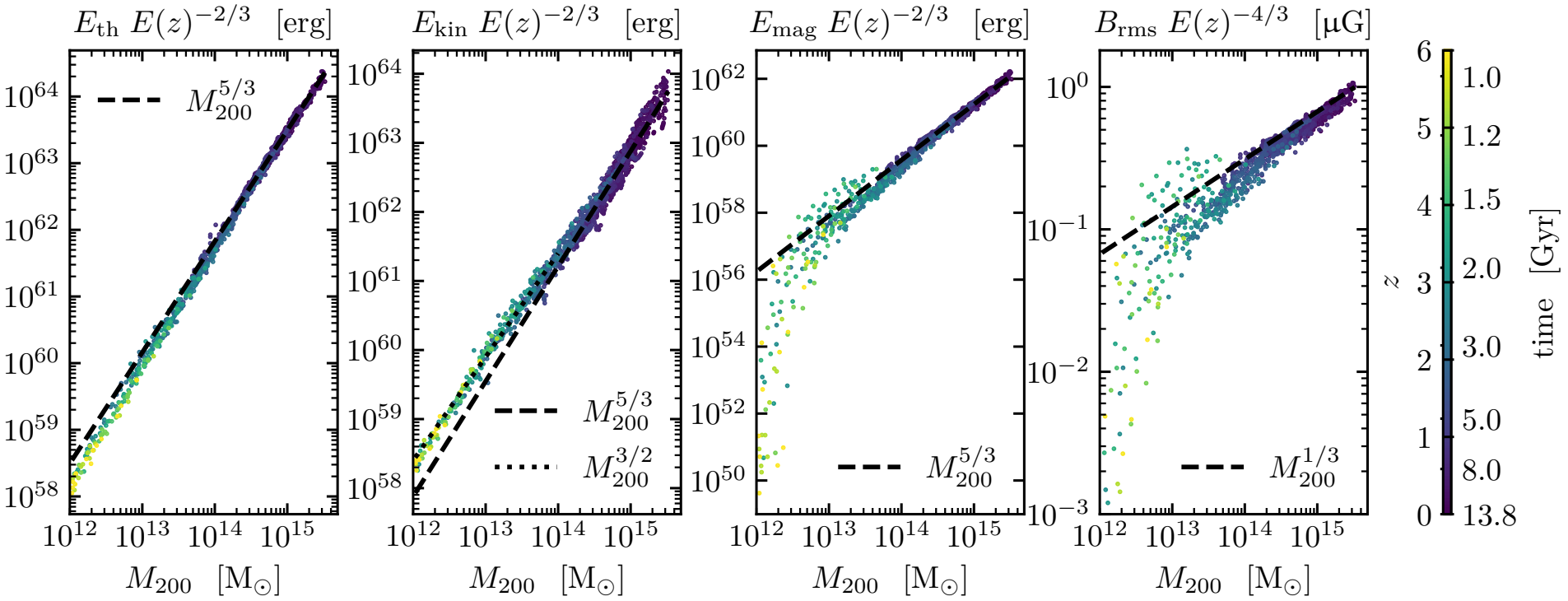


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- magnetic uniformity across clusters with small scatter
- constant magnetic energy fraction ($\beta \approx 100$): what does this imply for ICM turbulence?

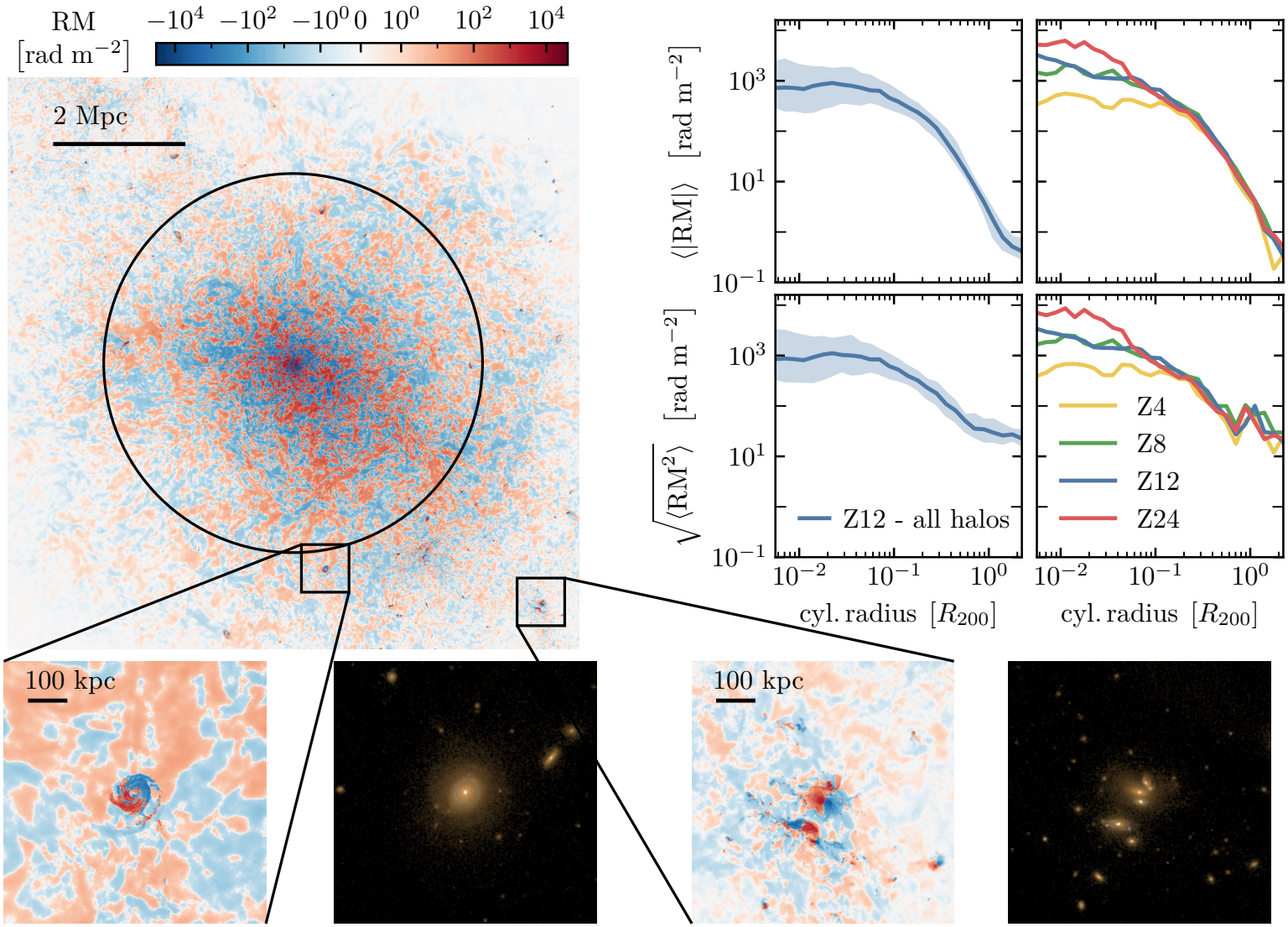


Cluster (non-)thermal scaling relations



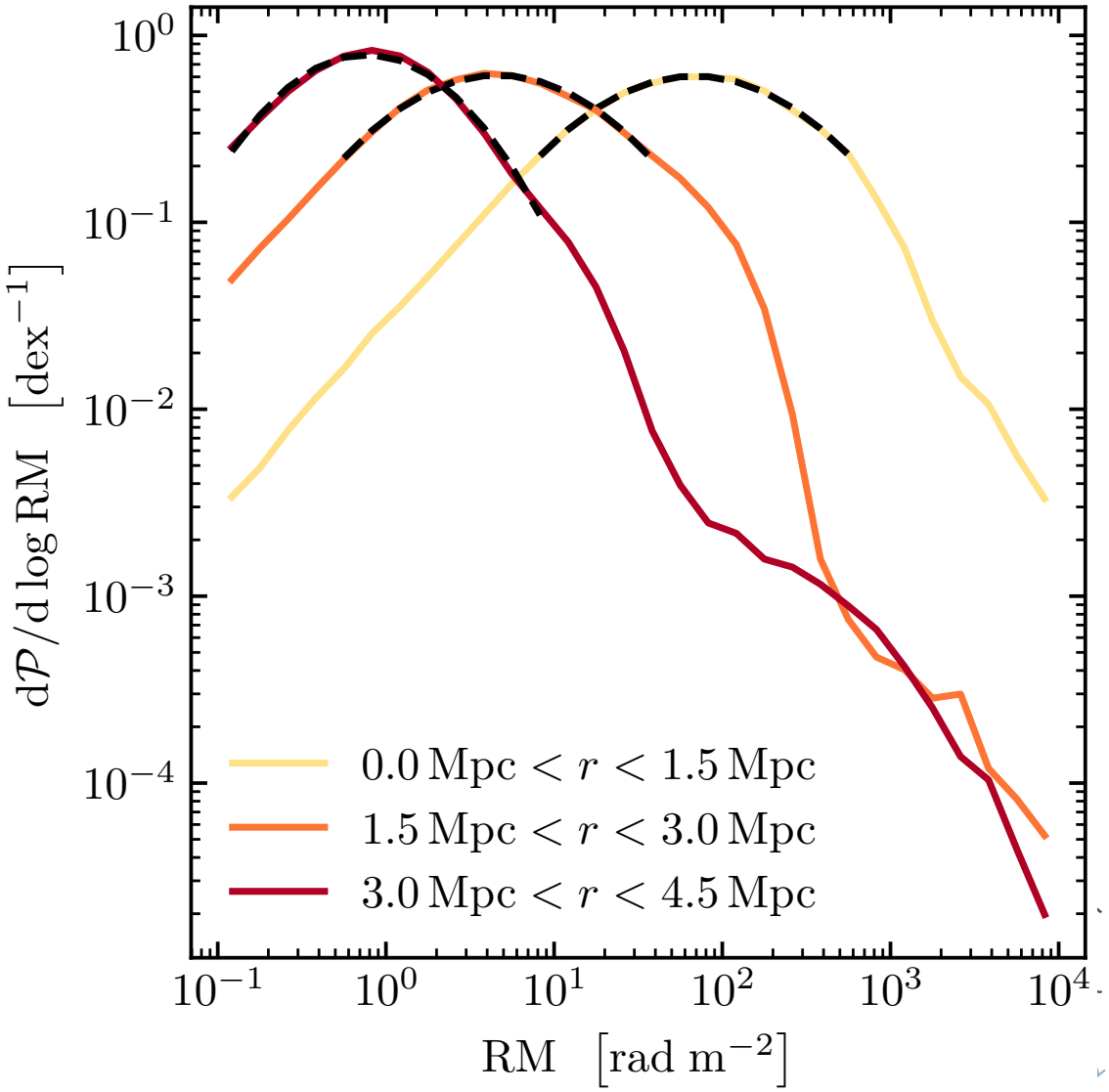
- deviations from self-similar relations at early times caused by strong kinetic pressure support ($E_{\rm th}$) and growing magnetic dynamo ($E_{\rm mag}$)
- (non-)thermal ICM obeys self-similar scaling relations at late times
- new magnetic scaling relations: $E_{\rm mag} \propto M_{200}^{5/3}$ and $B \propto M_{200}^{1/3}$

Cluster Faraday rotation measures (RMs)



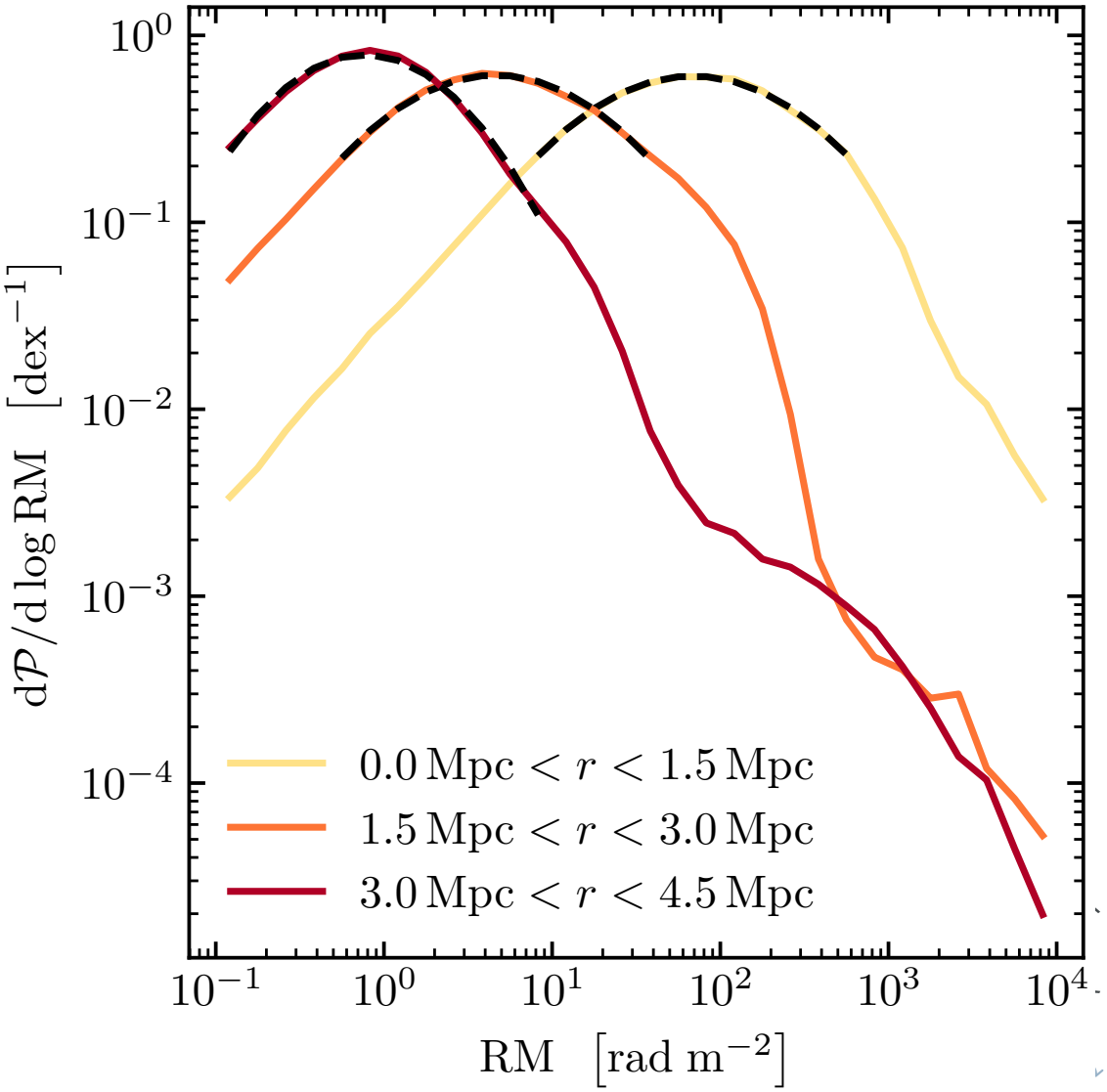
Faraday rotation measure probability distributions

- Faraday RMs in ICM are log-normally distributed at each radius
- mean of the Faraday RM values declines with radius



Faraday rotation measure probability distributions

- Faraday RMs in ICM are log-normally distributed at each radius
- mean of the Faraday RM values declines with radius
- power-law tail toward large RM values at large radii originates from galaxies
- $\sqrt{\langle \mathrm{RM}^2 \rangle}$ becomes larger than $\langle |\mathrm{RM}| \rangle$ at outskirts because of dominating galaxies



Branginskii heating

- ***in weakly-collisional plasmas,*** fluid motions like shear and compression can drive a non-zero pressure anisotropy, $\Delta P \equiv P_{\perp} - P_{\parallel}$, and ***Braginskii viscosity relaxes*** ΔP ***while also heating the plasma***



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- ***Branginskii heating rate*** depends on the amplitude of the driving, the viscosity coefficient and the direction of the local magnetic field:

$$\mathcal{H}_{\text{Brag}} = -\boldsymbol{\Pi} : \boldsymbol{\nabla} \boldsymbol{v} = \frac{\eta_\parallel}{3} \left(3\boldsymbol{bb} : \boldsymbol{\nabla} \boldsymbol{v} - \boldsymbol{\nabla} \cdot \boldsymbol{v}\right)^2 = \frac{(\Delta P)^2}{3\eta_\parallel},$$

$$\text{where} \quad -\frac{2}{\beta} < \frac{\Delta P}{P} < \frac{1}{\beta}$$

is the criterion for stability to firehose and mirror instability



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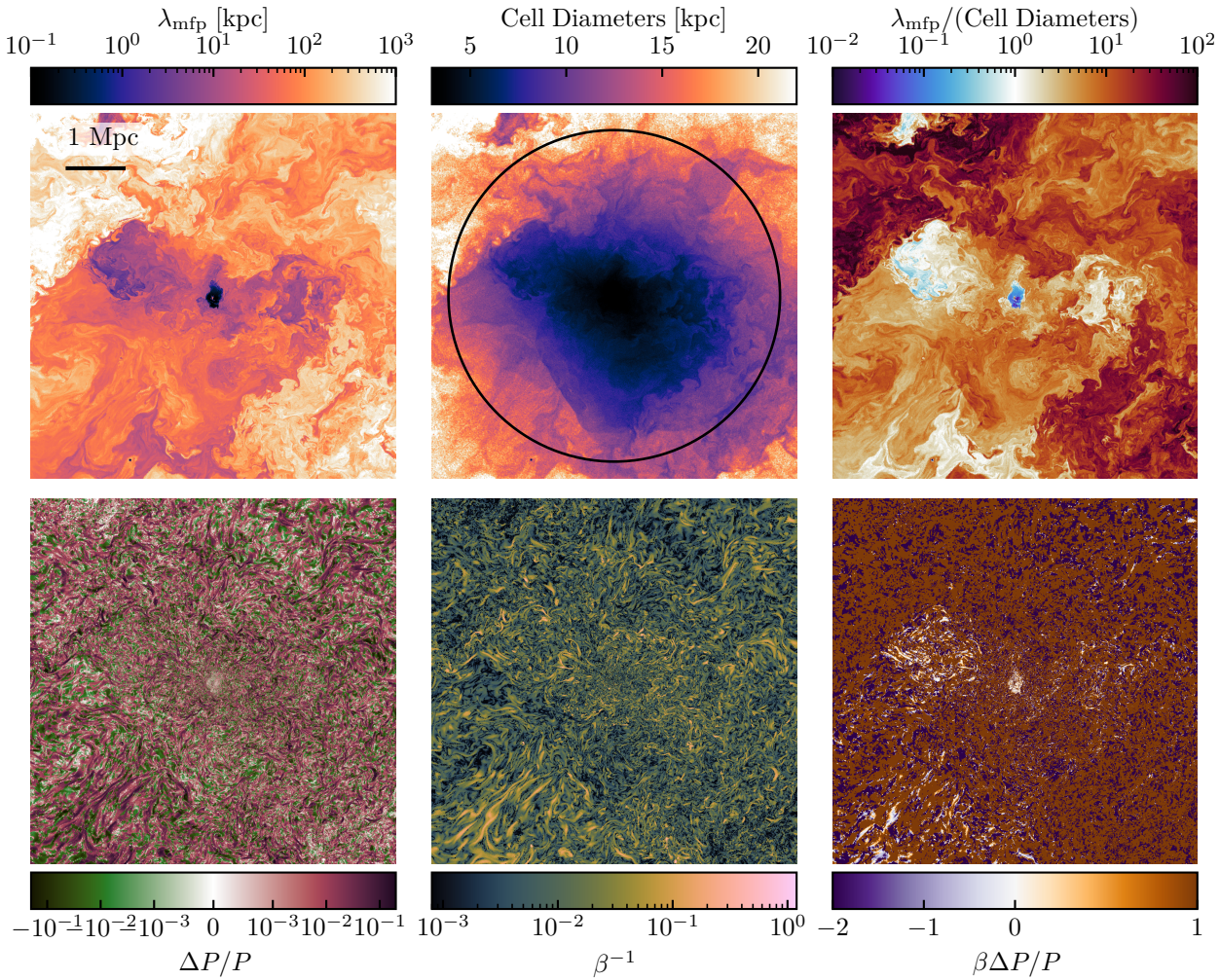
  is the criterion for stability to firehose and mirror instability

- ***if firehose and mirror instabilities are active,*** ΔP ***is regulated to the limiting cases:*** this allows estimating Branginskii heating by post-processing MHD simulations (while neglecting the back-reaction of the anisotropic viscosity on the flow)
- otherwise, Braginskii MHD simulations are required



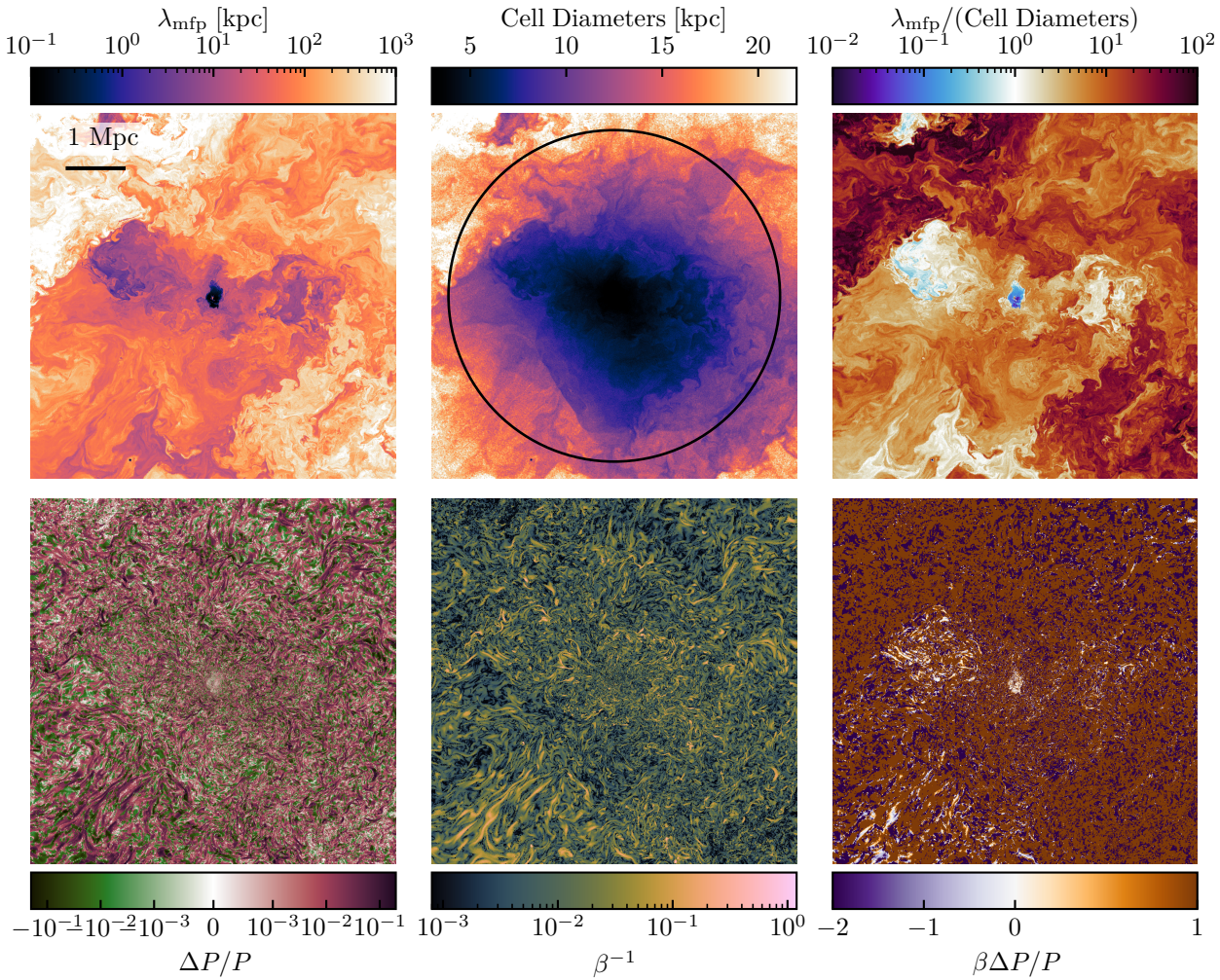
Magnetic filaments and Branginskii heating

(1) PICO-Clusters resolve mean-free path and show active firehose/mirror instability

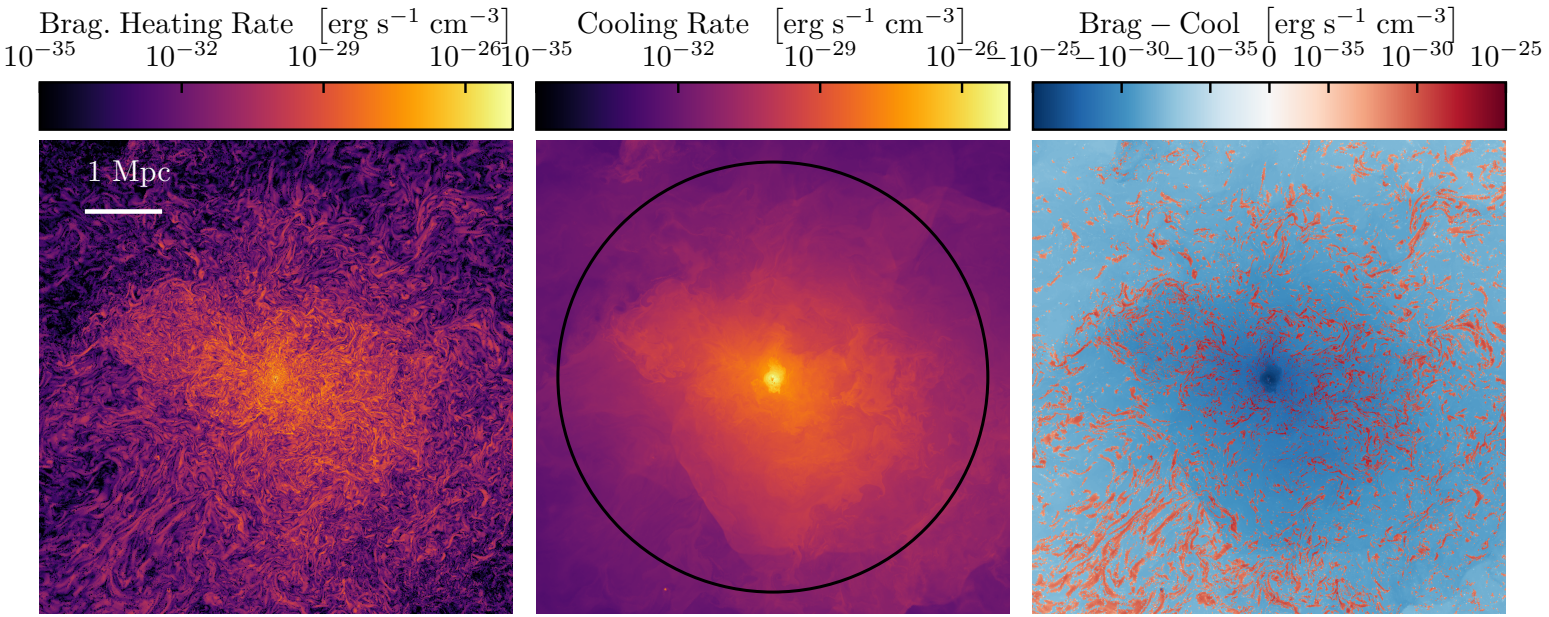


Magnetic filaments and Branginskii heating

(1) PICO-Clusters resolve mean-free path and show active firehose/mirror instability
(2) Strongly magnetized, Mpc-sized magnetic filaments at the cluster outskirts



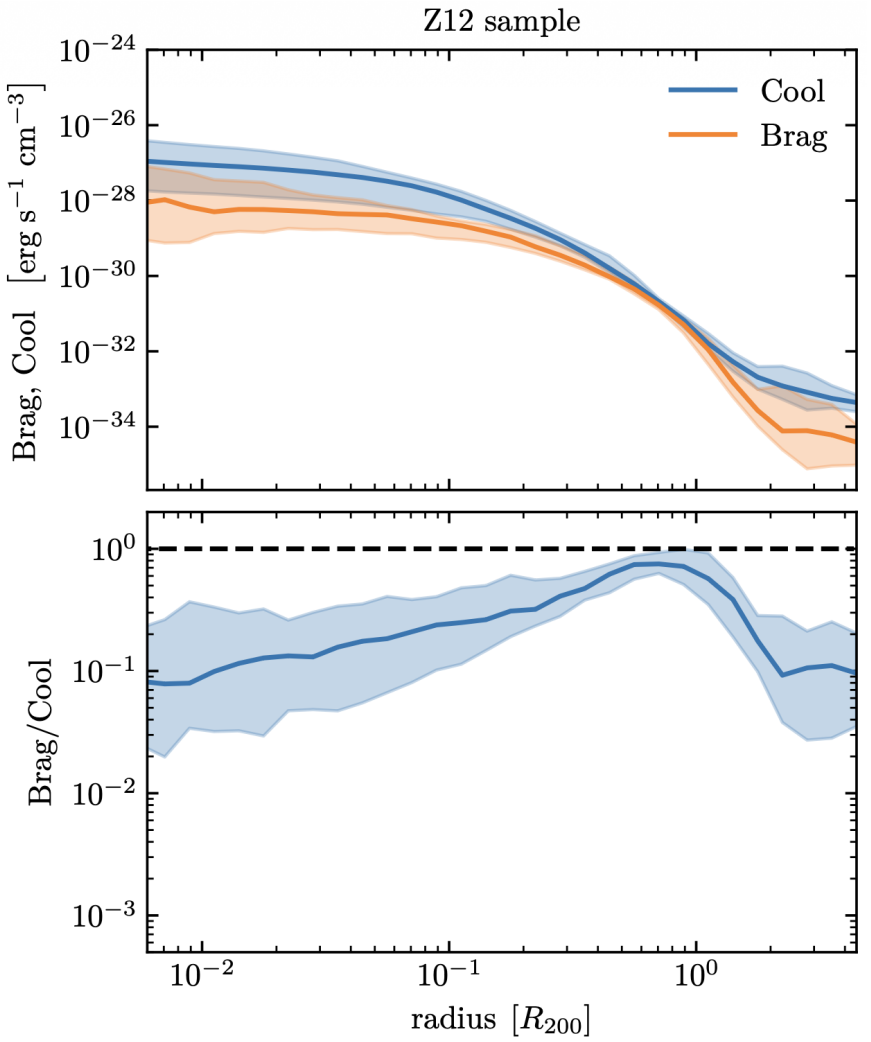
Branginskii heating vs. radiative cooling: maps



- radiative cooling declines smoothly with radius from the center
- viscous Branginskii heating occurs in localised patches due to the spatial intermittency of the plasma-β
- viscous heating arises from dissipation of motions but β controls its rate because the firehose/mirror instability limiters are nearly always active

Branginskii heating vs. radiative cooling: profiles

- Braginskii heating rate is systematically below the cooling rate for the cluster sample
- Braginskii heating is not important in the center
- Braginskii heating can exceed 50 per cent of the cooling towards the virial radius



AIP

Conclusions

PICO-Cluster project:

- despite their successes, state-or-the-art galaxy formation models face major challenges: scarcity of cool cores, black-hole overmerging, ...
- solving key cluster science questions requires different physics variants and high-resolution meso-scale simulations



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- galaxy-formation physics important for early growth of cluster magnetic fields
- magnetic uniformity across clusters and self-similar magnetic scalings
- Faraday rotation measures dominated by galaxies in cluster outskirts



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Weakly collisional ICM:

- viscous heating arises from dissipation of motions but β controls its rate because the firehose/mirror instability limiters are nearly always active
- Braginskii heating can be locally important while it is globally subdominant



PICOGAL: From Plasma KInetics to COsmological GALaxy Formation



This project has received funding from the European Research Counsil (ERC) under the European Union's Horizon 2020 research and innovation program (grant agreement No PICOGAL–101019746).

AIP

Literature for the talk

- Berlok, Pfrommer, Puchwein, Talbot, Pakmor, Perrone, Weinberger, Springel, Whittingham, Tevlin, Dusch, Sparre, *The PICO-Cluster Project: presenting the galaxy cluster sample and studying magnetic field growth, Faraday rotation and Braginskii heating*, 2026 A&A, submitted, arXiv:2606.23798



Additional slides



Verification and Validation of PICO-Clusters

Comparing scaling relations to MilleniumTNG simulations and observations

