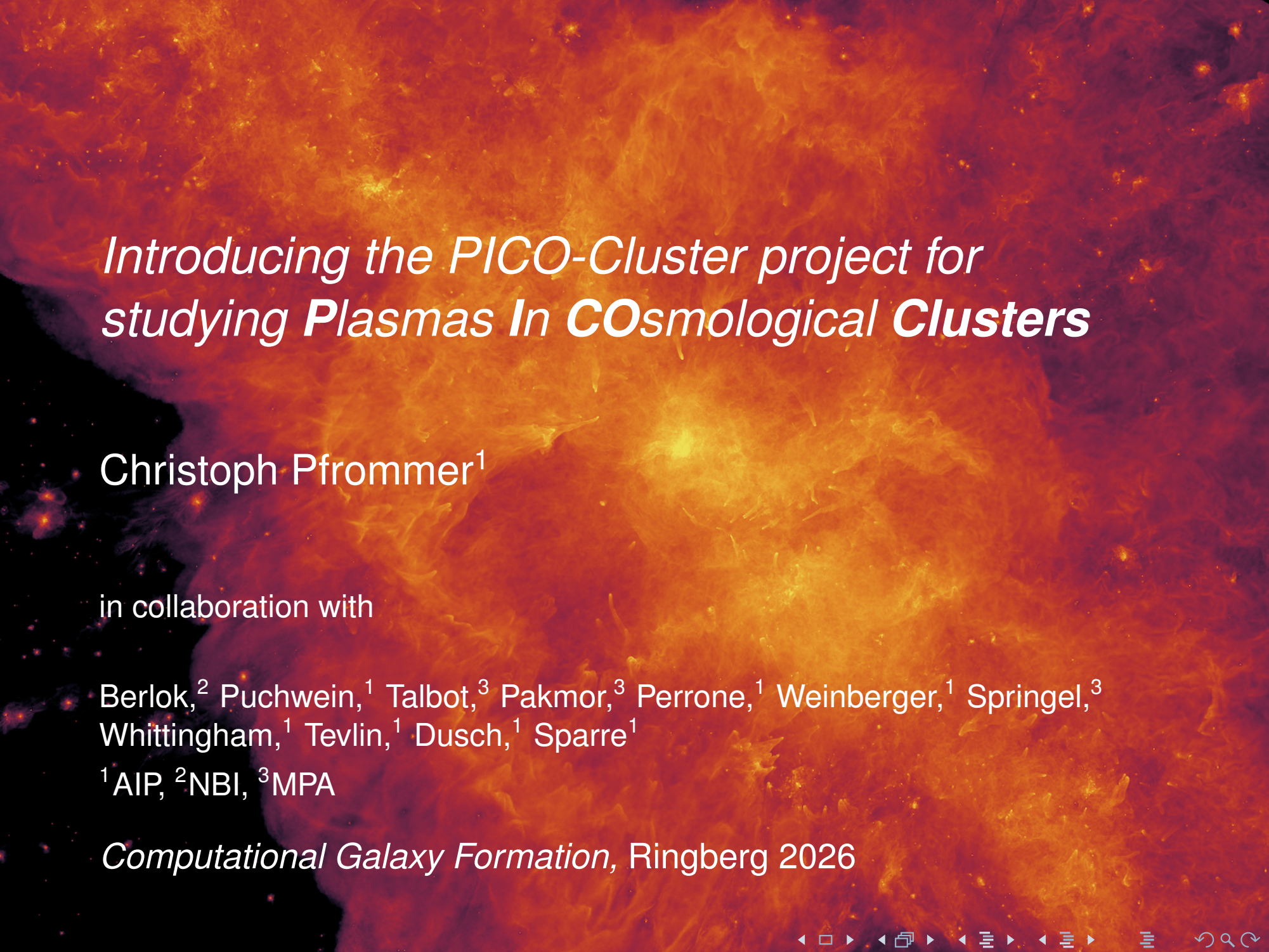


*Introducing the PICO-Cluster project for studying **P**lasmas **I**n **CO**smological **Clusters***

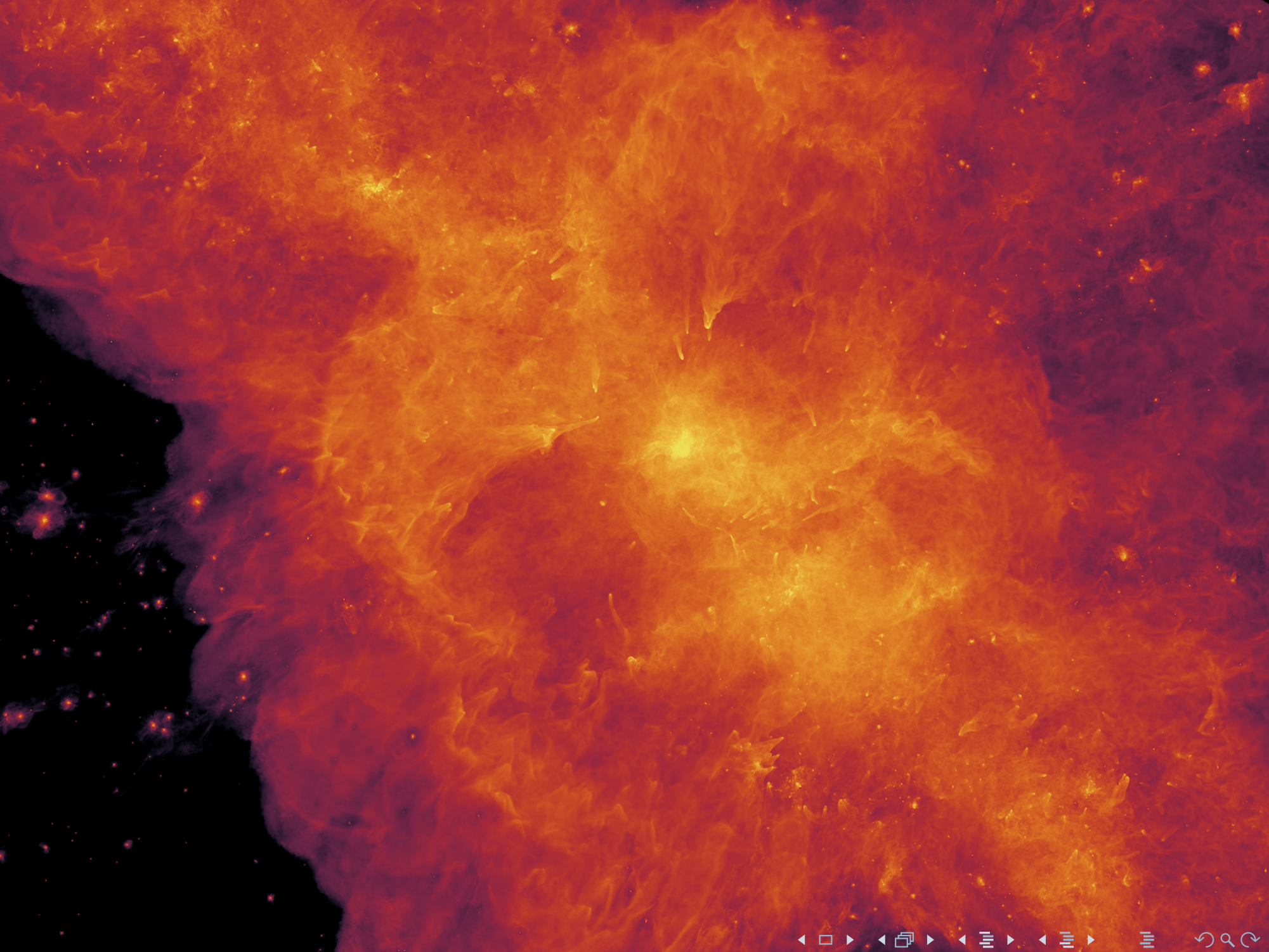
Christoph Pfrommer[1]

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]

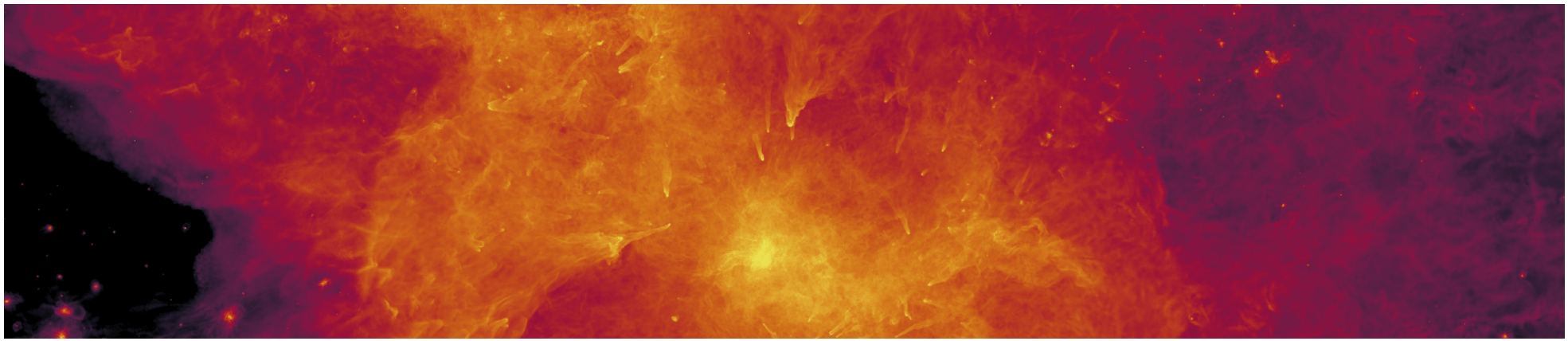
[1]AIP, [2]NBI, [3]MPA

Computational Galaxy Formation, Ringberg 2026



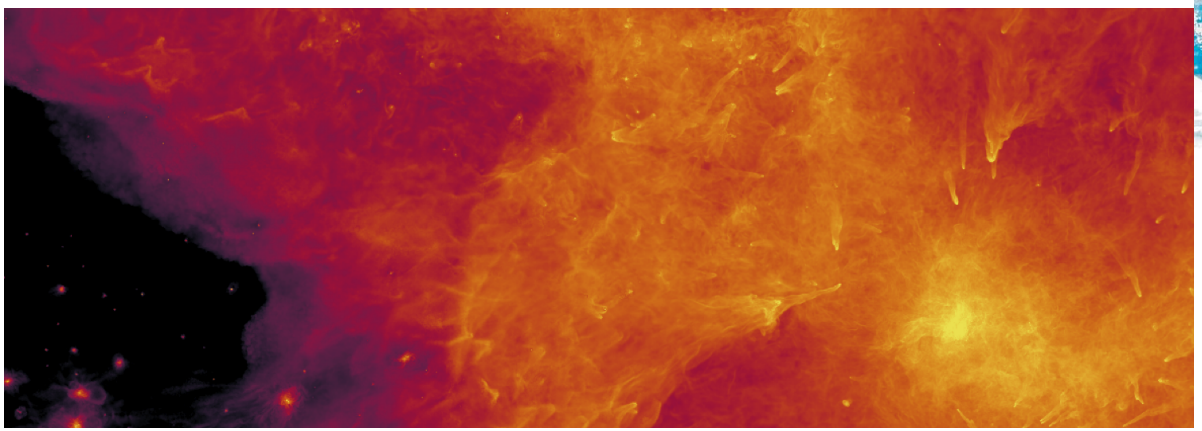
PICO-Clusters (Plasmas In COsmological Clusters)

- ***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} ($M_{\mathrm{gas}} = 10^6\ \mathrm{M}_\odot$)
- moving mesh code AREPO-2 (with Subfind HBT) (Springel 2010, Springel+ 2022), comoving ideal MHD with Powell cleaning (Pakmor+ 2011, 2013, 2026)
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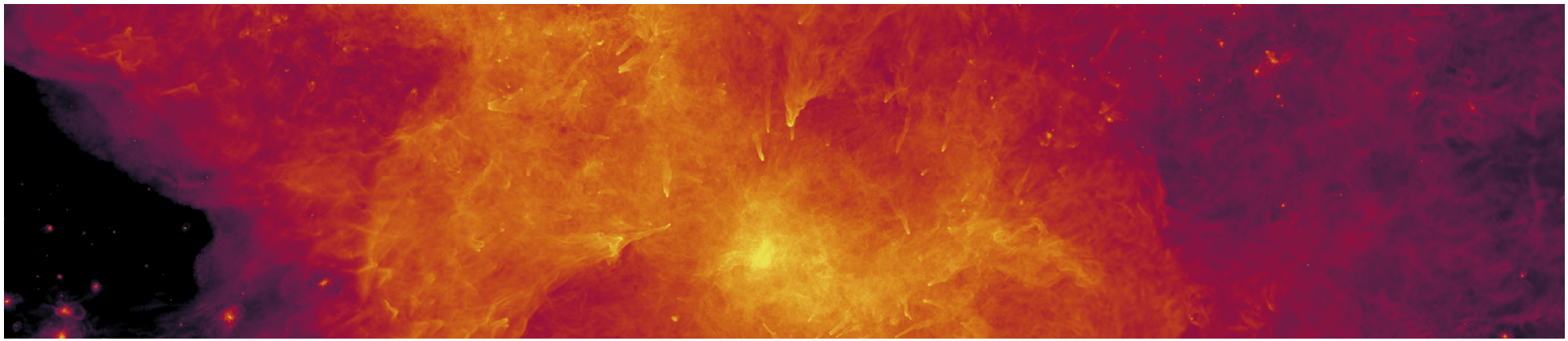




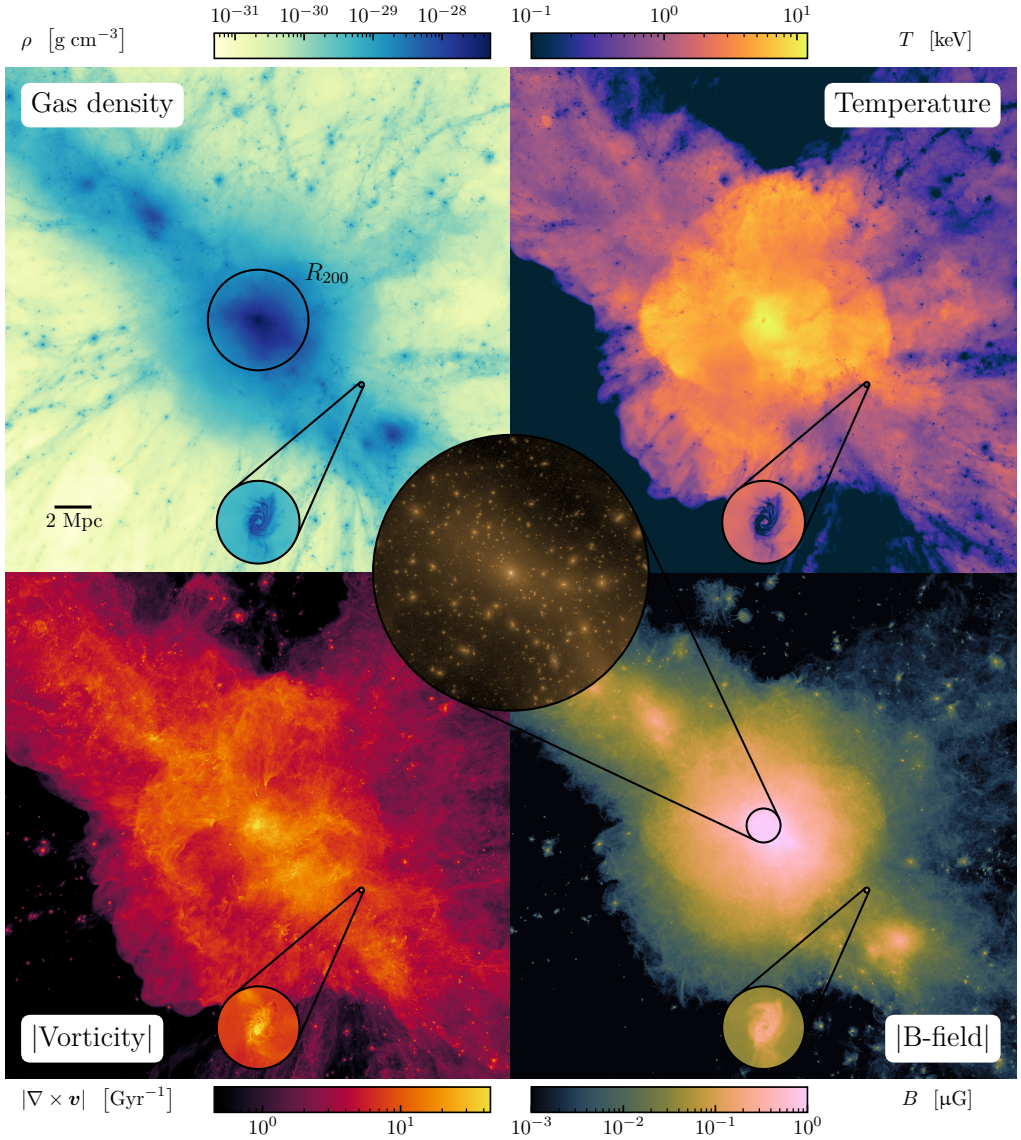
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- solving key questions requires different physics variants (AGN jet feedback, cosmic rays, non-radiative, . . .) and high-resolution meso-scale simulations!

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



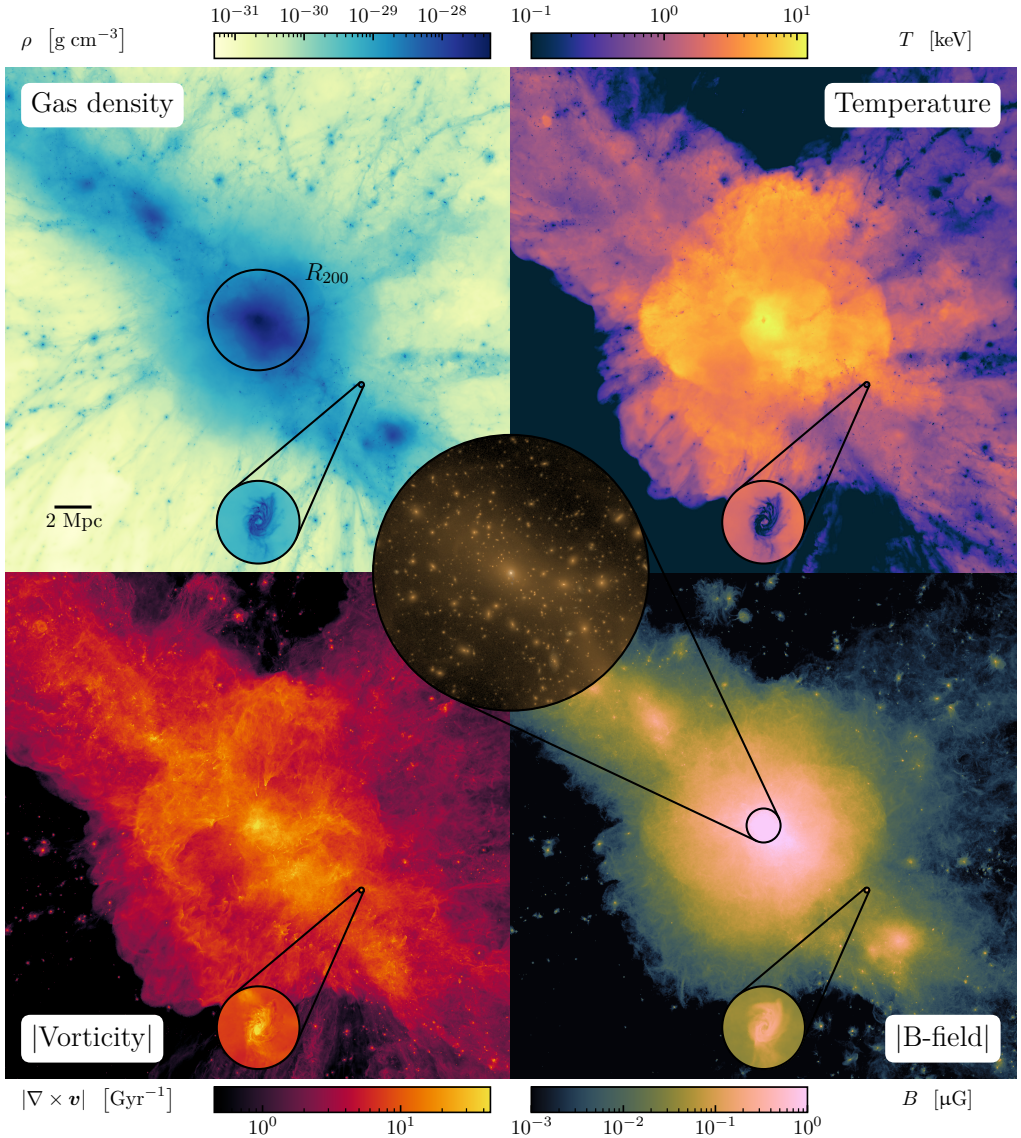
11 key questions of galaxy clusters



Berlok, CP, Puchwein, Talbot+ (2026)

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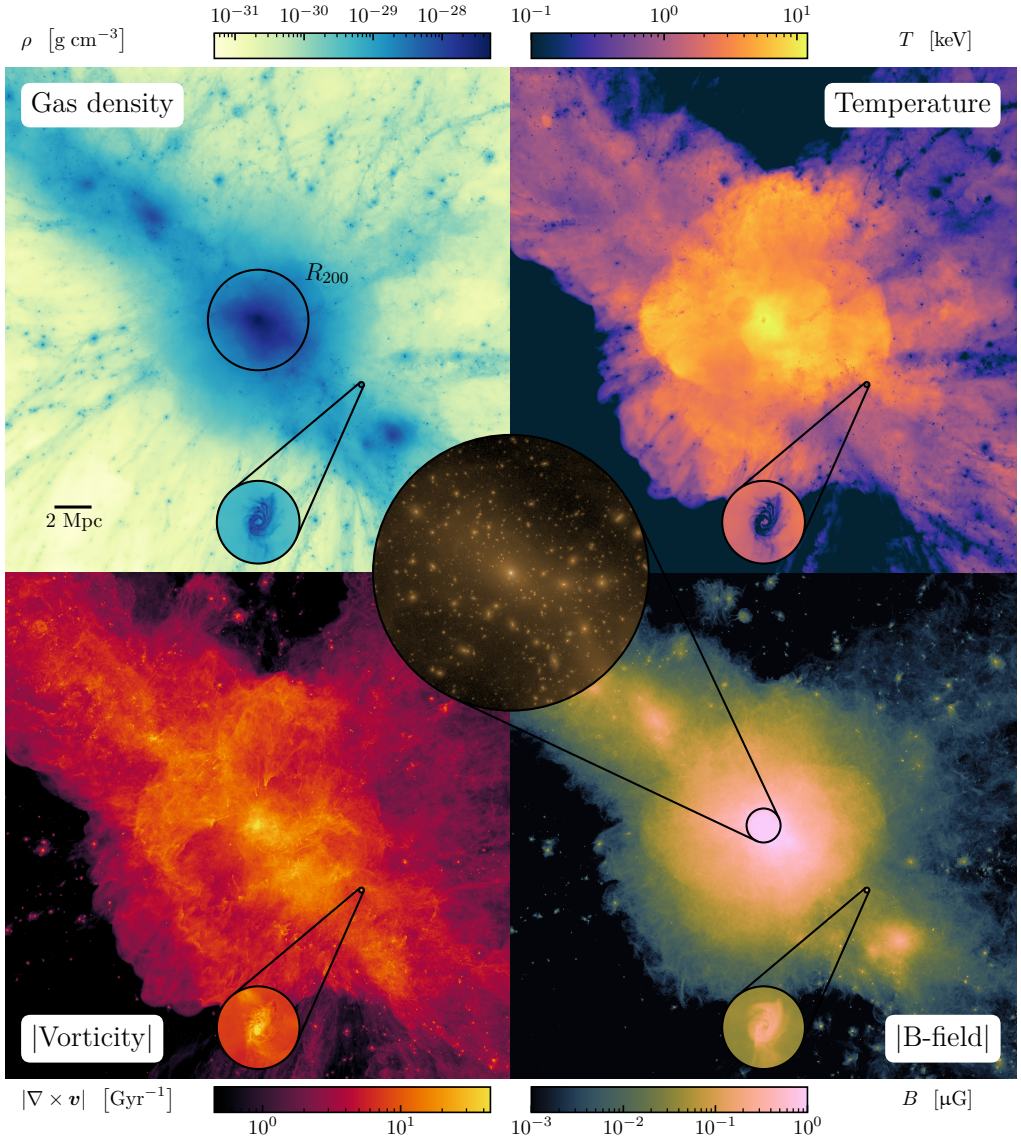
- Why is the central ICM cooling time bimodally distributed?
- Does heating by ***AGN jets*** solve the cooling flow problem? Which heating process is responsible?
- Why is the turbulent ICM energy only a few per cent of the thermal energy in quiescent clusters?
- What are the (observable) consequences 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)

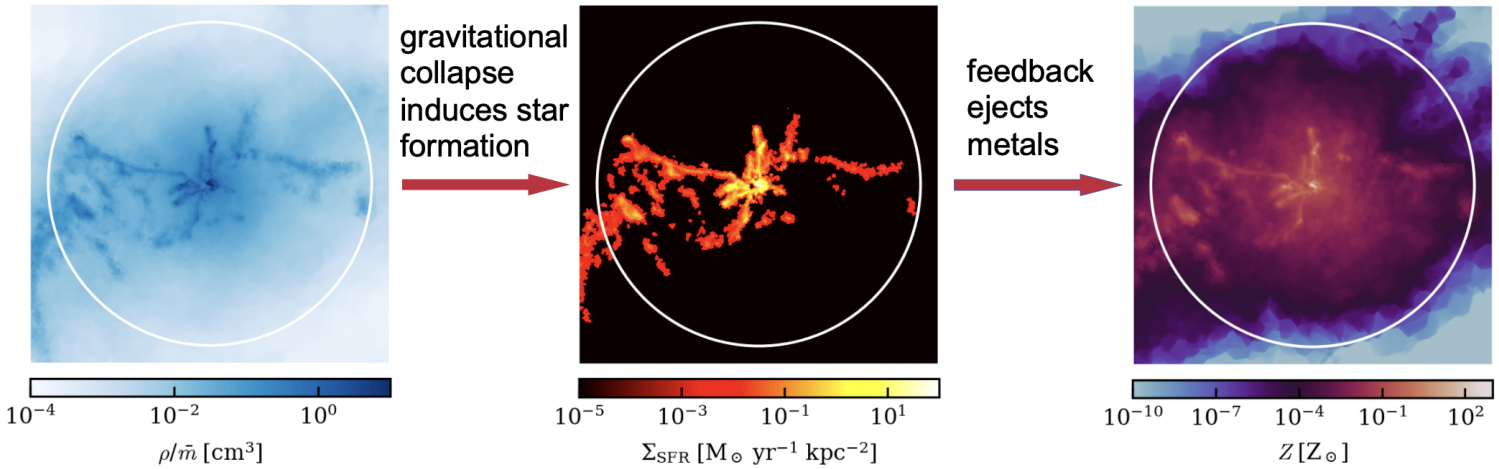
11 key questions of galaxy clusters (cont.'d)

- 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?



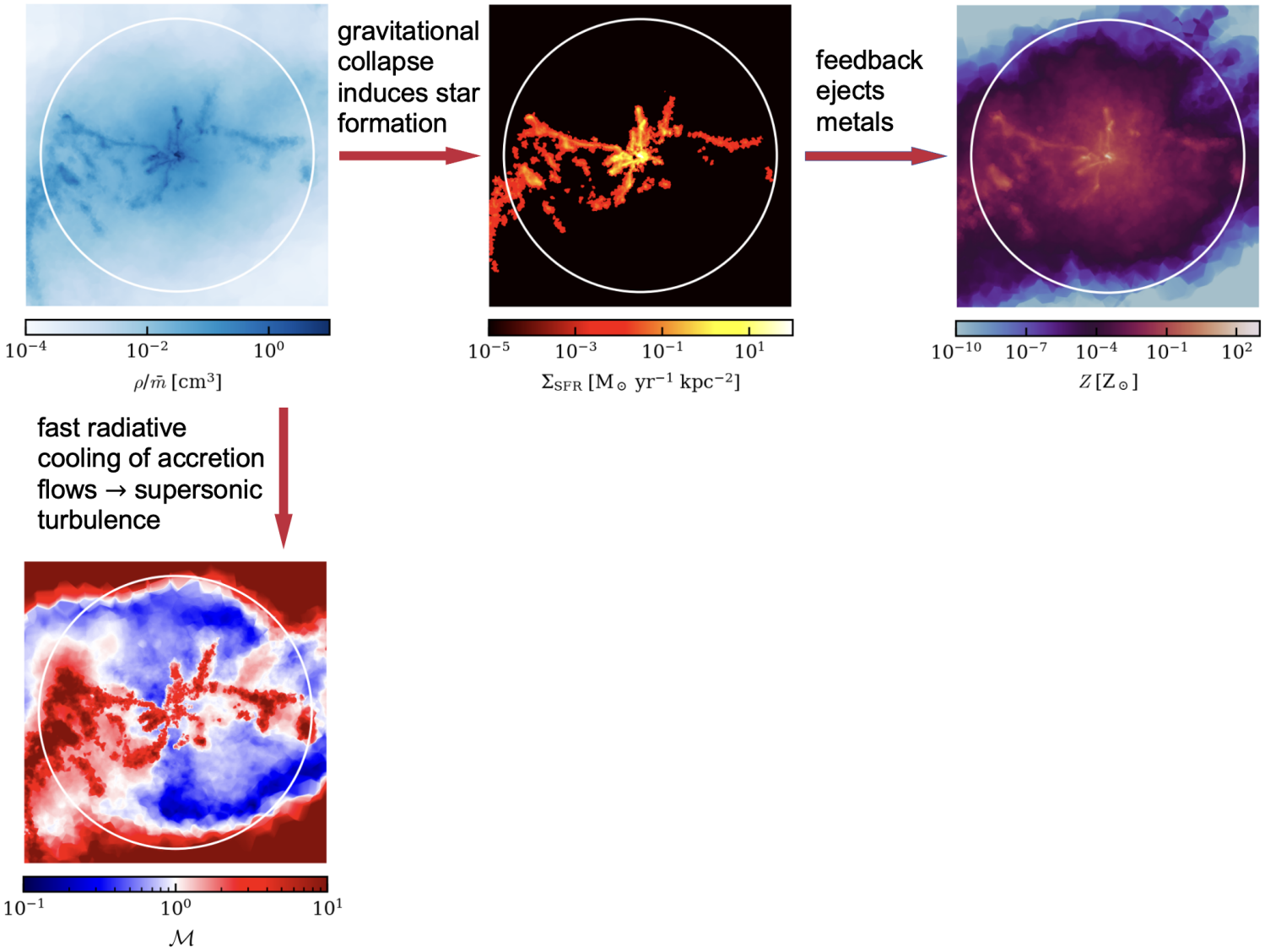
Berlok, CP, Puchwein, Talbot+ (2026)

What grows the magnetic field in proto-clusters?



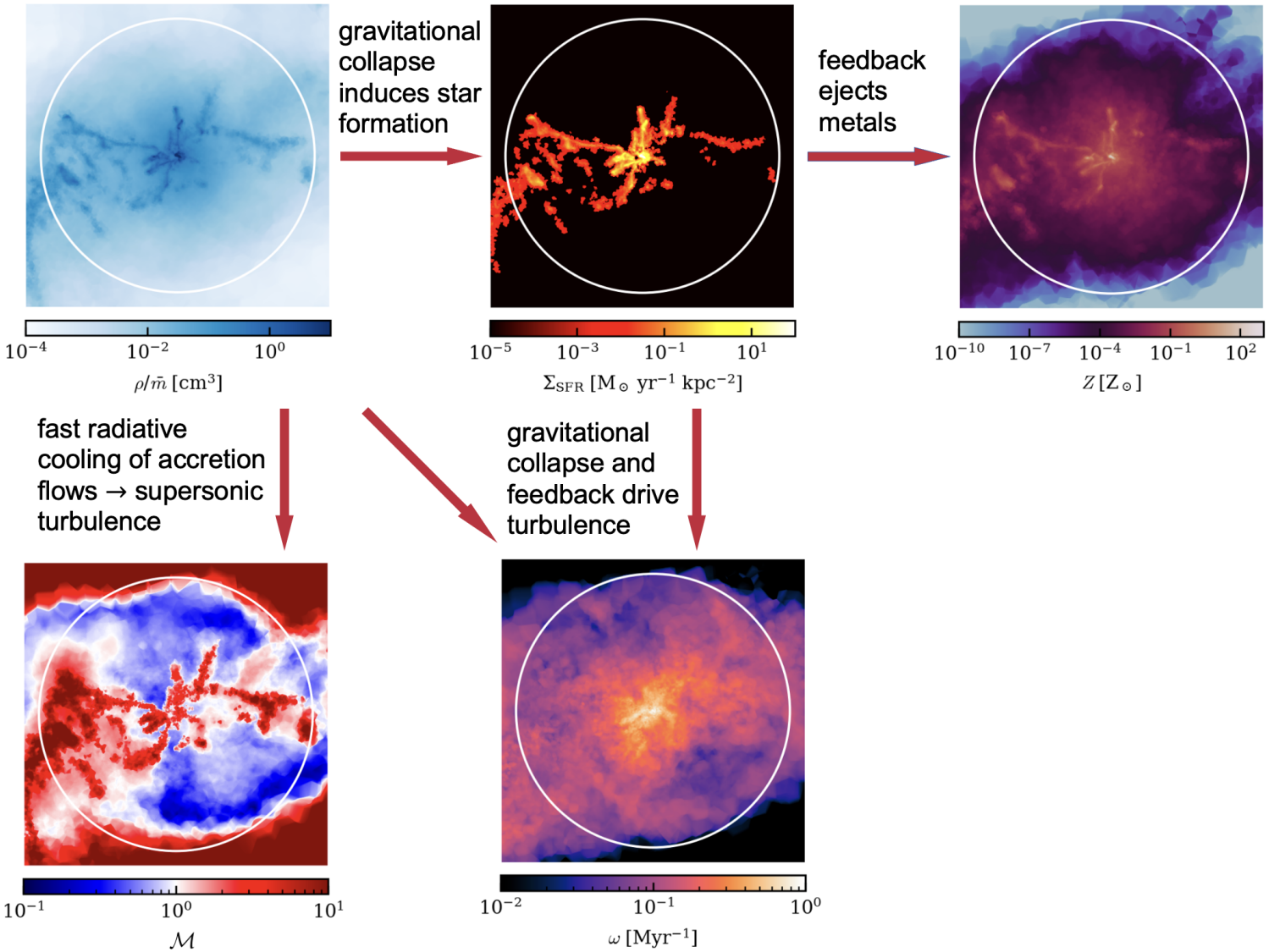
Tevlin, Berlok, CP+ (2025)

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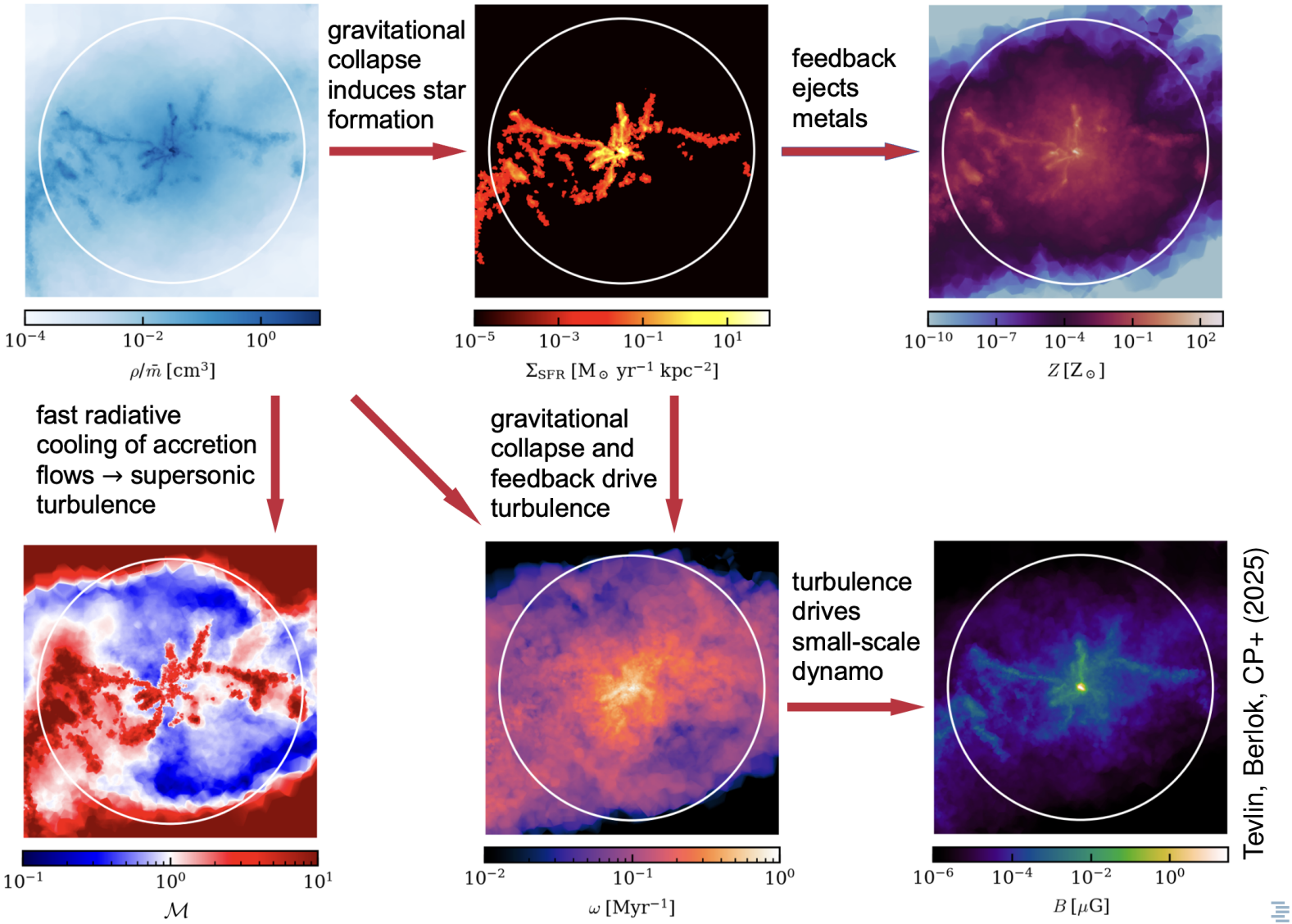
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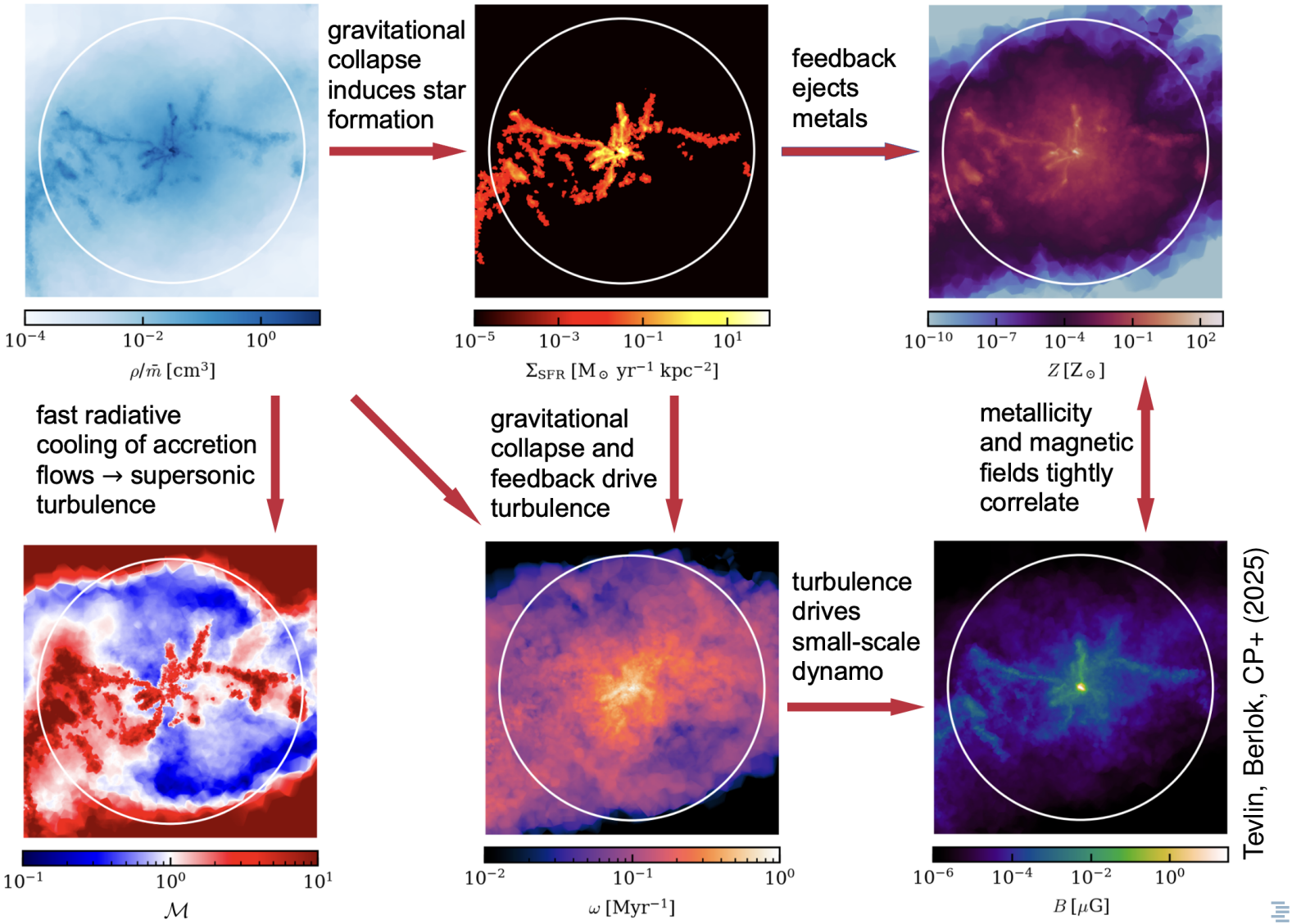


Tevlin, Berlok, CP+ (2025)

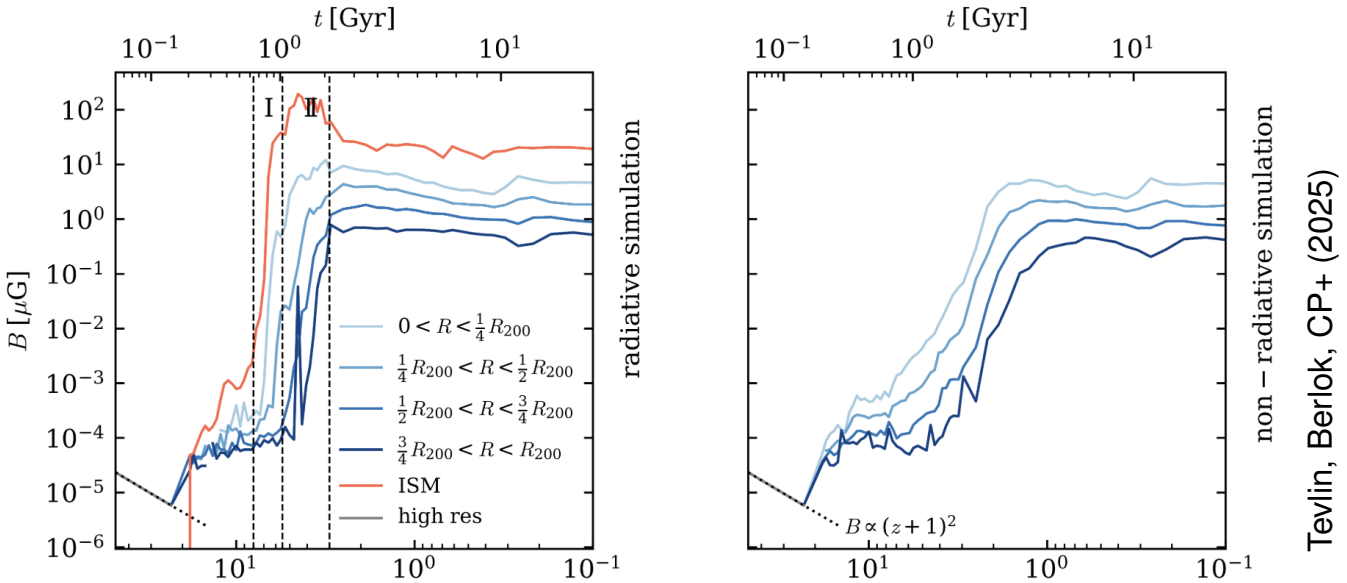
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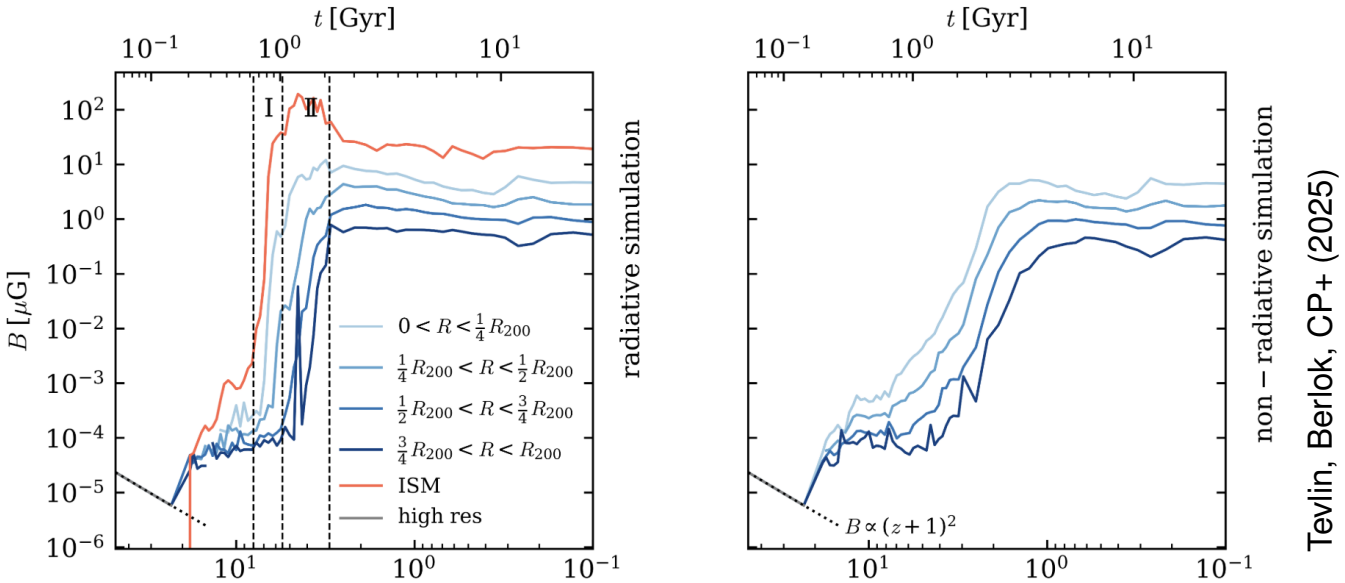
Magnetic field evolution in galaxy clusters



Cluster magnetic field growth intrinsically linked to galaxy formation:

- *1st phase:* early galaxies grow magnetic fields via supersonic small-scale dynamo driven by cold accretion, stellar and AGN feedback

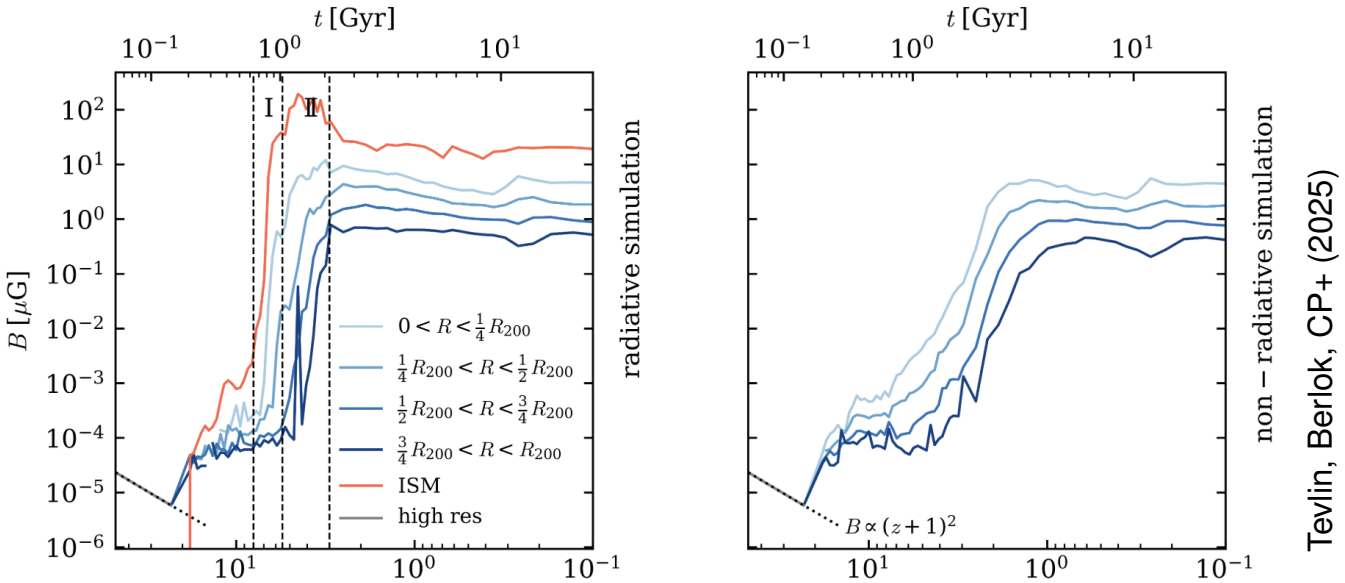
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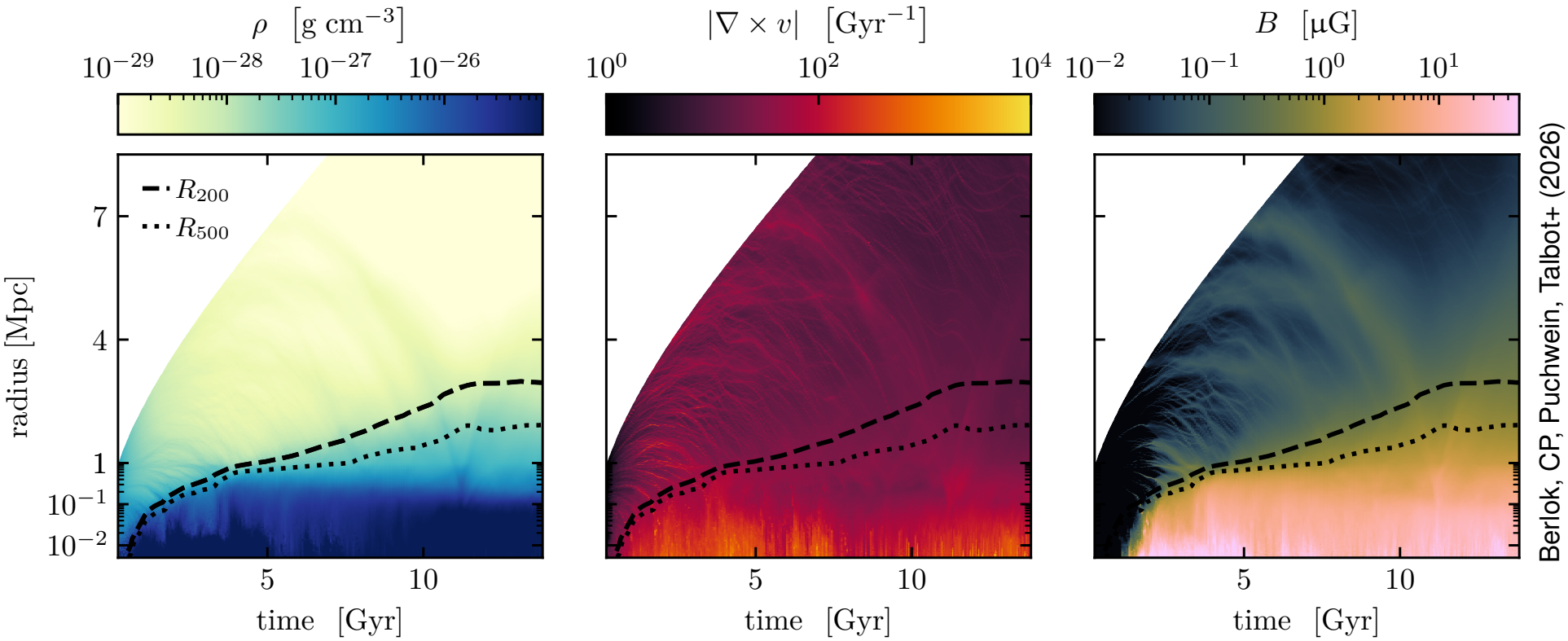
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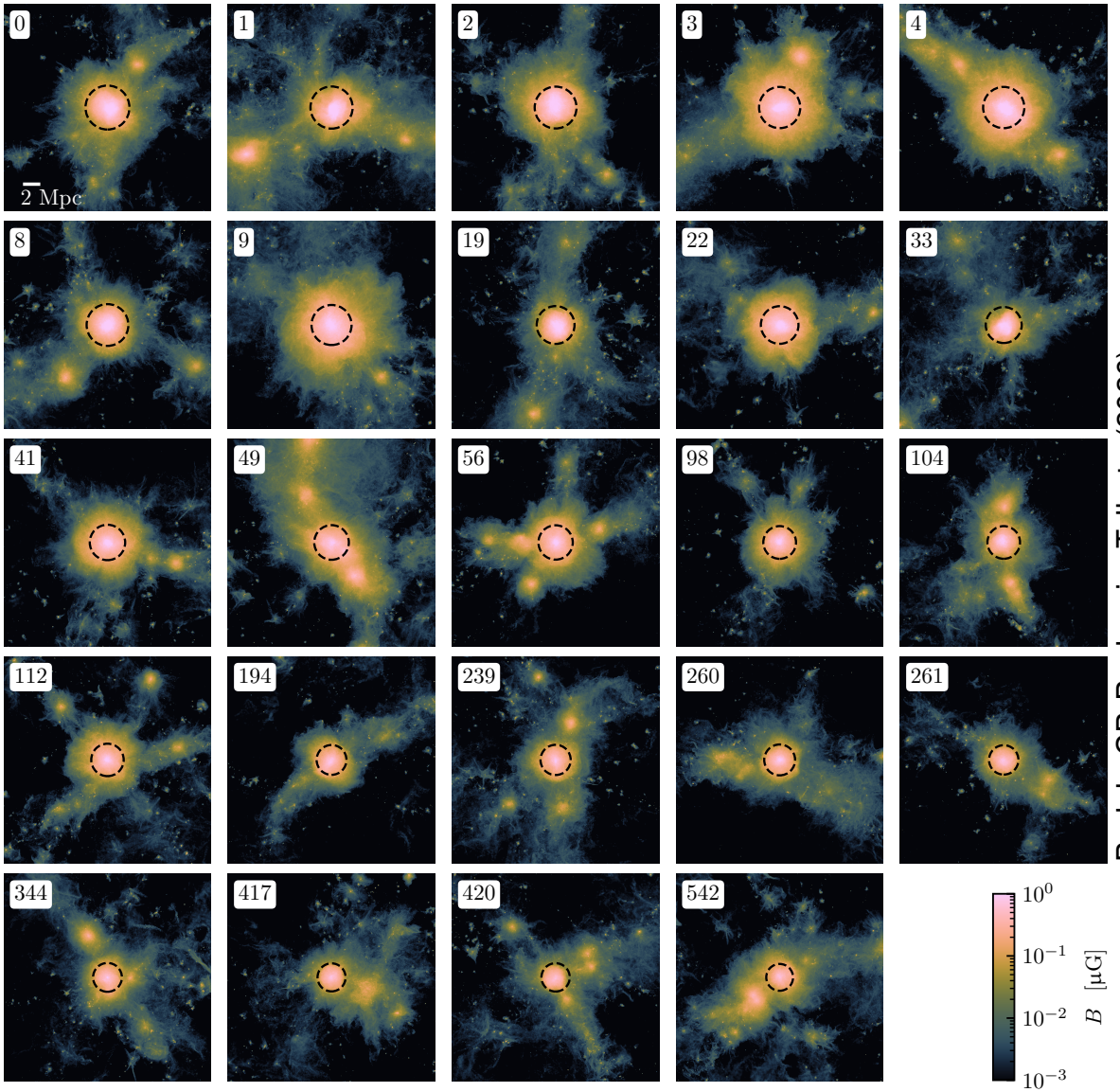
- *1st phase:* early galaxies grow magnetic fields via supersonic small-scale dynamo driven by cold accretion, stellar and AGN feedback
- *2nd phase:* galactic winds & ram-pressue stripping from accreted galaxies enrich ICM with magnetic fields
- *3rd phase:* subsonic small-scale dynamo in ICM maintains field strength and grows coherence length

Space-time plots visualize magnetic field growth



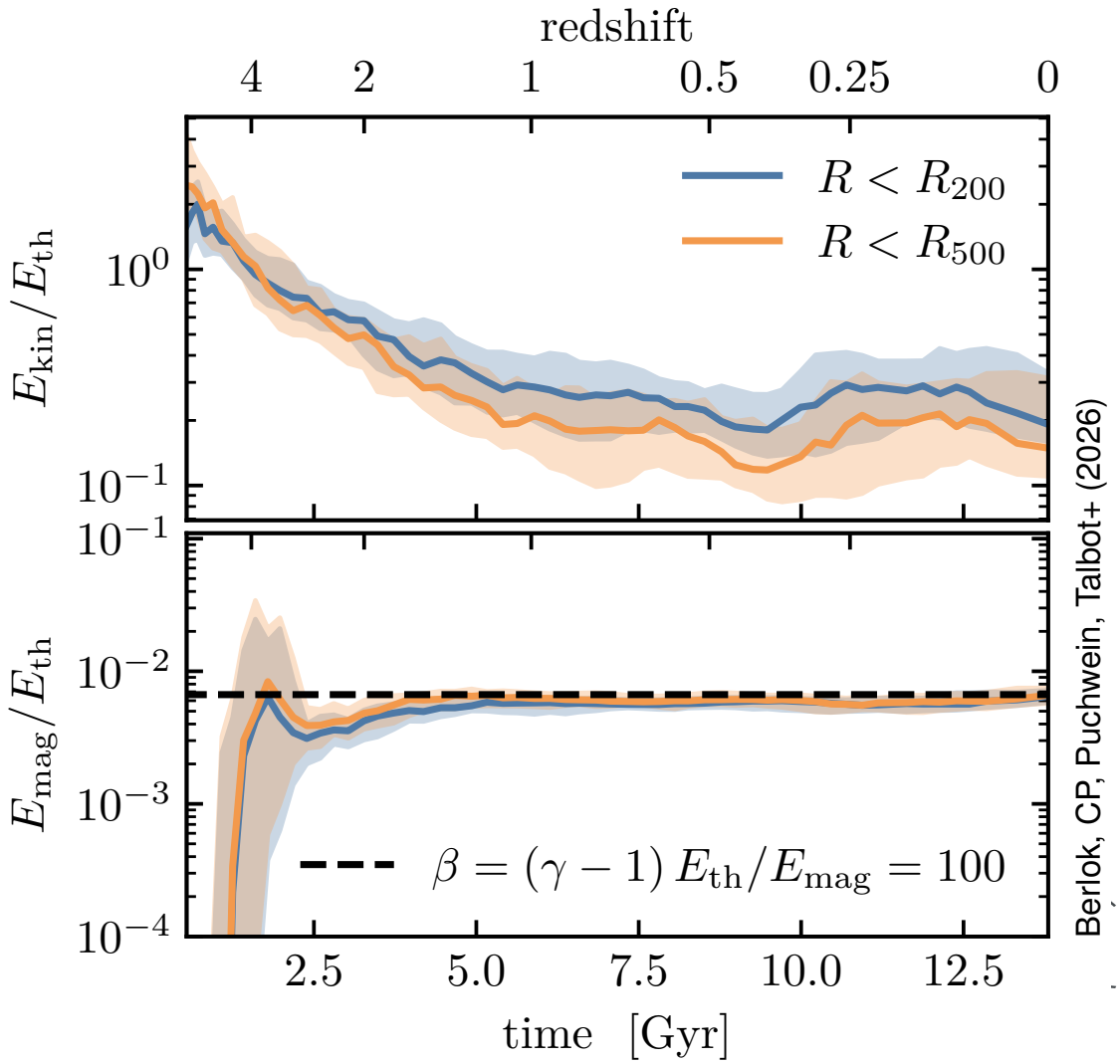
- variation at small radii signals AGN feedback
- early magetic field growth via small-scale dynamo driven by cold accretion, stellar and AGN feedback
- later magnetic enrichment of ICM due to infalling galaxies

Magnetic field strength across PICO-Clusters



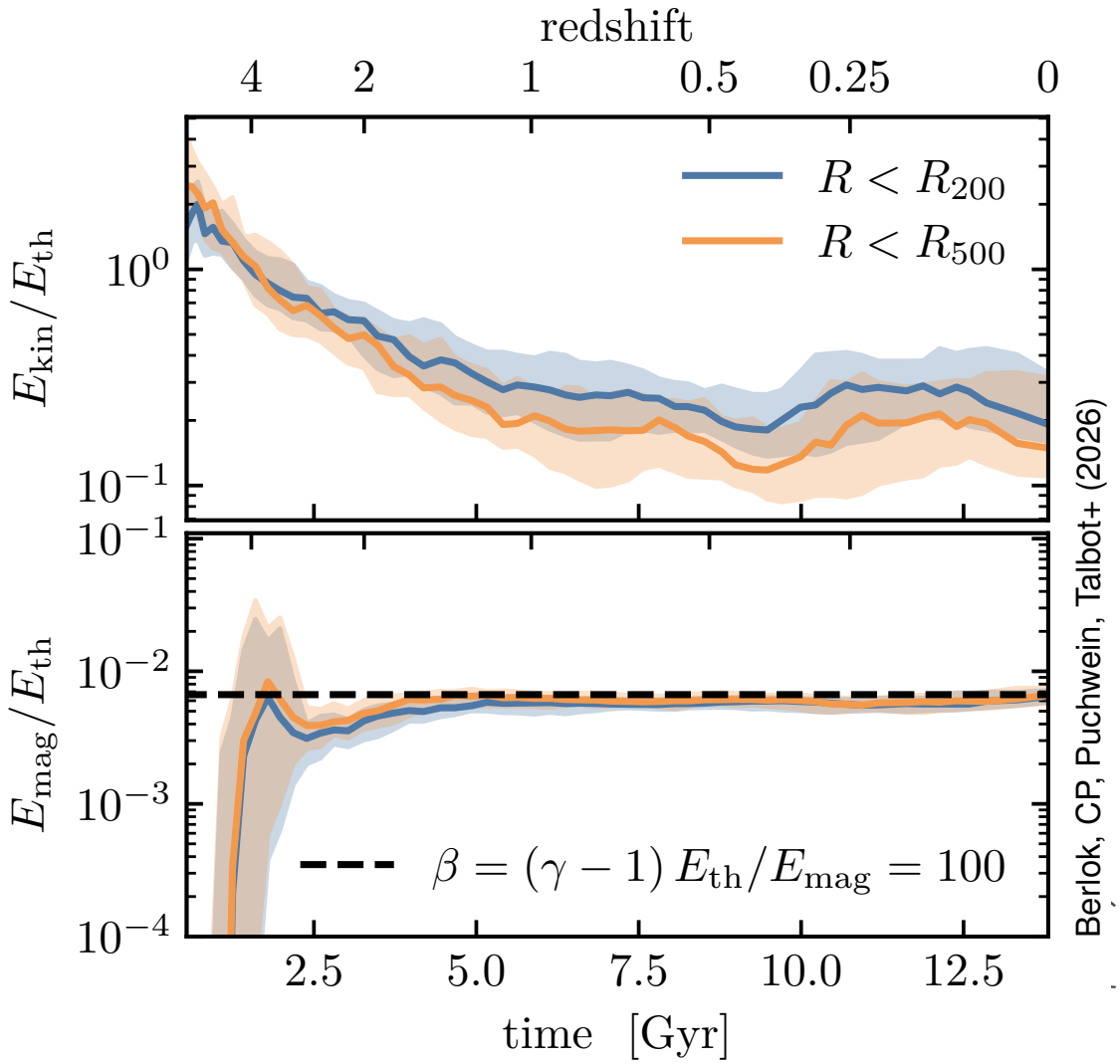
Time evolution of energy ratios

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

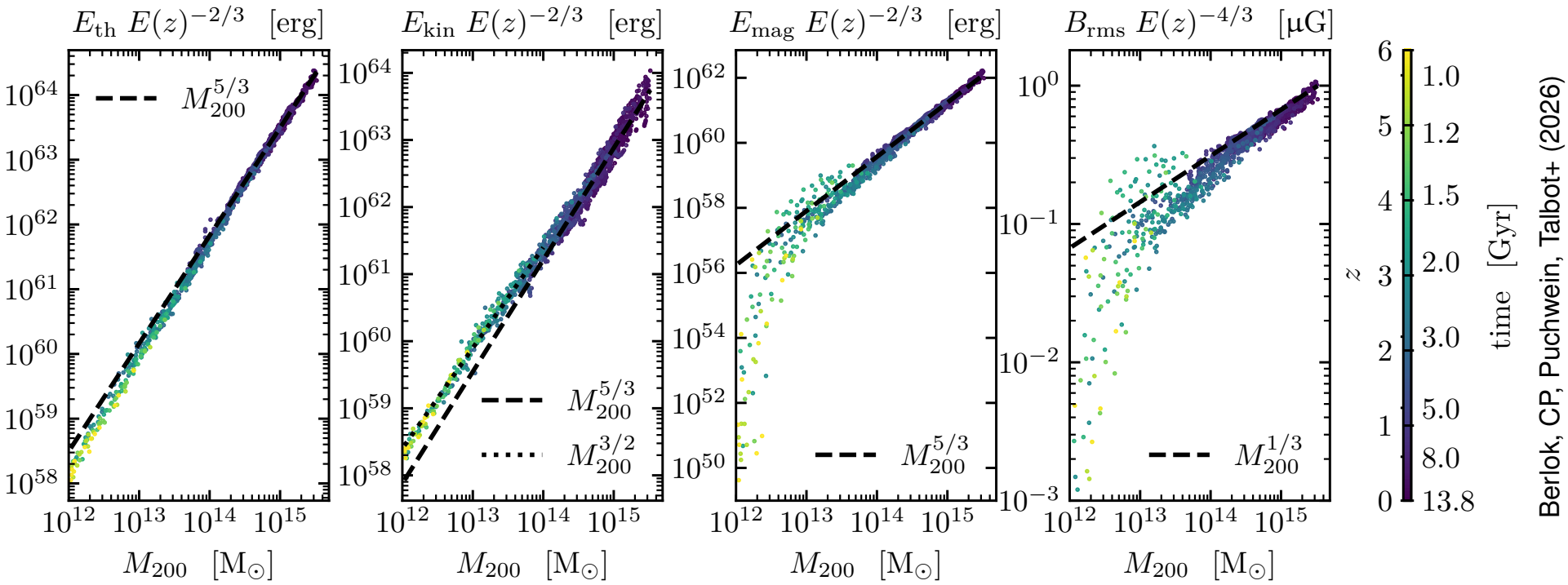


Time evolution of energy ratios

- elevated $E_{\rm kin}/E_{\rm th}$ at early times (cold accretion, strong stellar/AGN feedback)
- $E_{\rm kin}/E_{\rm th}$ constant at late times with large dispersion caused by mergers
- magnetic uniformity across clusters with small scatter
- constant magnetic energy fraction ($\beta \approx 100$): what does this imply for ICM turbulence?

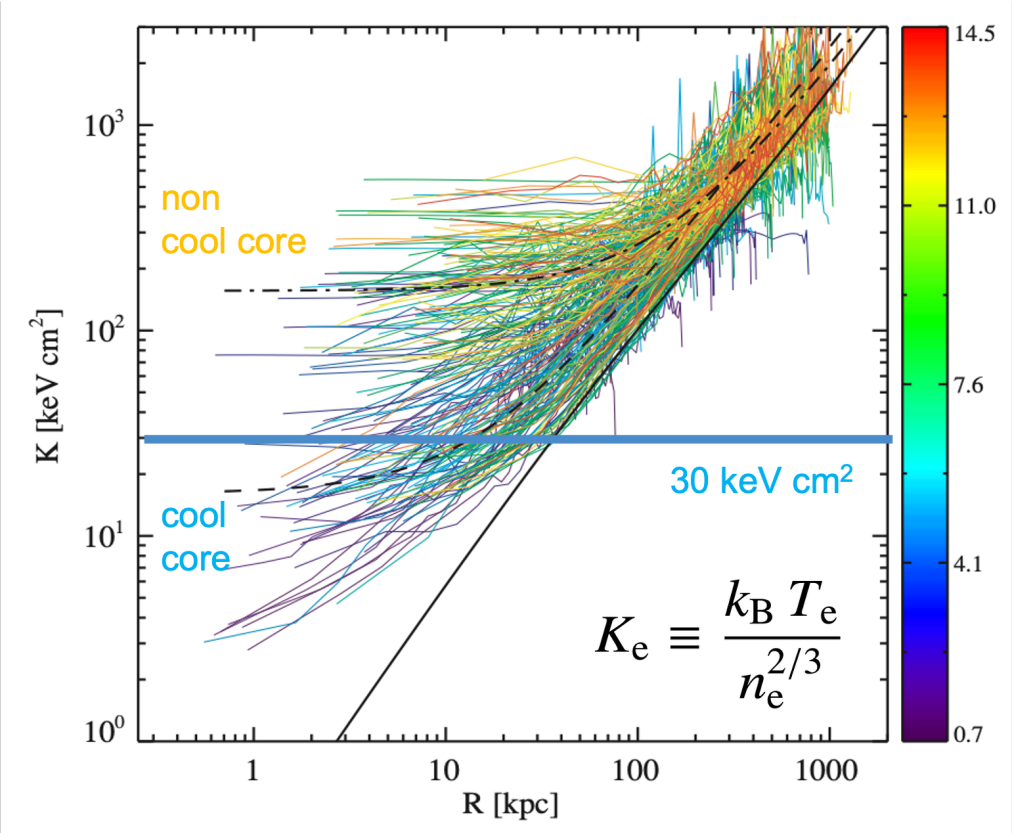


Cluster (non-)thermal scaling relations



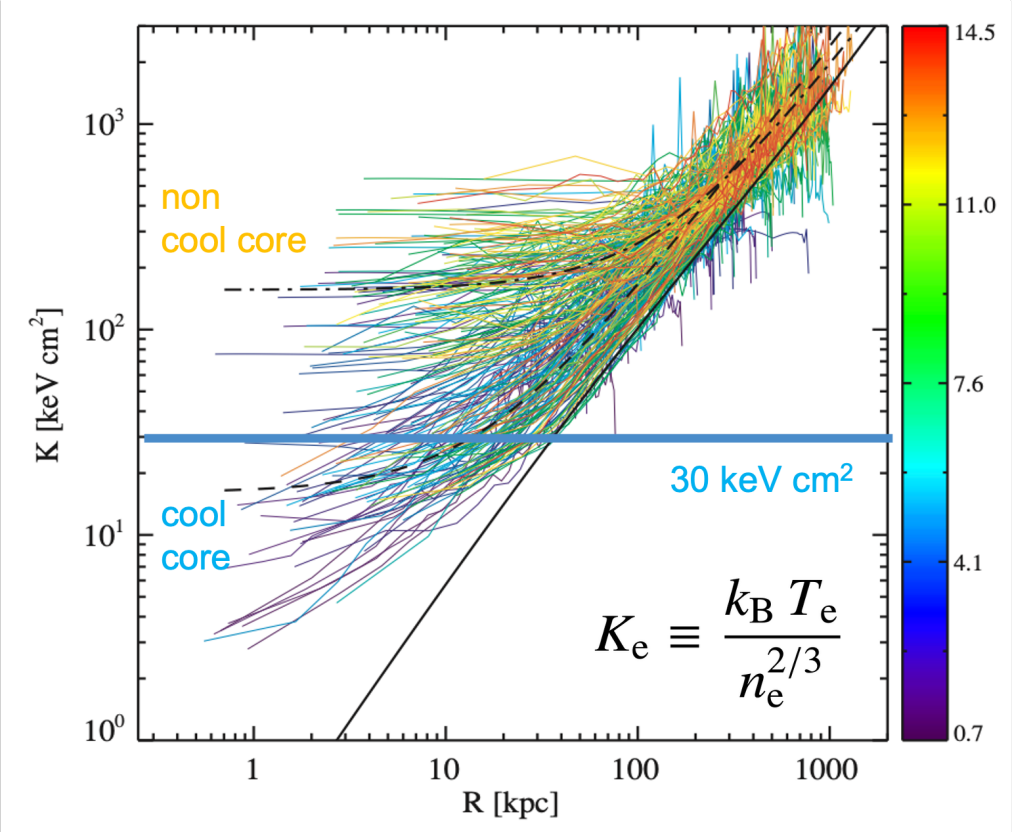
- deviations from self-similar relations at early times caused by strong kinetic pressure support ($E_{\rm th}$) and growing magnetic dynamo ($E_{\rm mag}$)
- (non-)thermal ICM obeys self-similar scaling relations at late times
- new magnetic scaling relations: $E_{\rm mag} \propto M_{200}^{5/3}$ and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

Cluster entropies are related to gas cooling times



Cavagnolo et al. (2009)

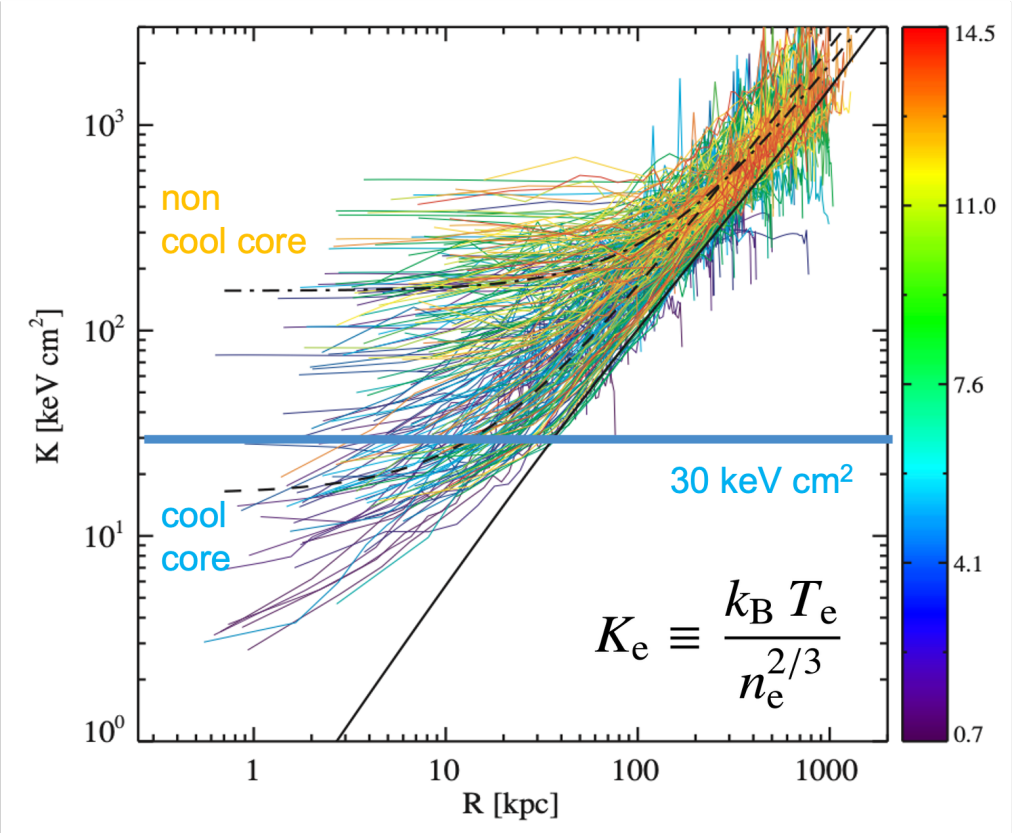
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Cavagnolo et al. (2009)

$$K_e \approx 30\,\mathrm{keV\,cm^2} \left(\frac{t_{\mathrm{cool}}}{1\,\mathrm{Gyr}}\right)^{2/3} \left(\frac{k_B T}{3\,\mathrm{keV}}\right)^{2/3}$$

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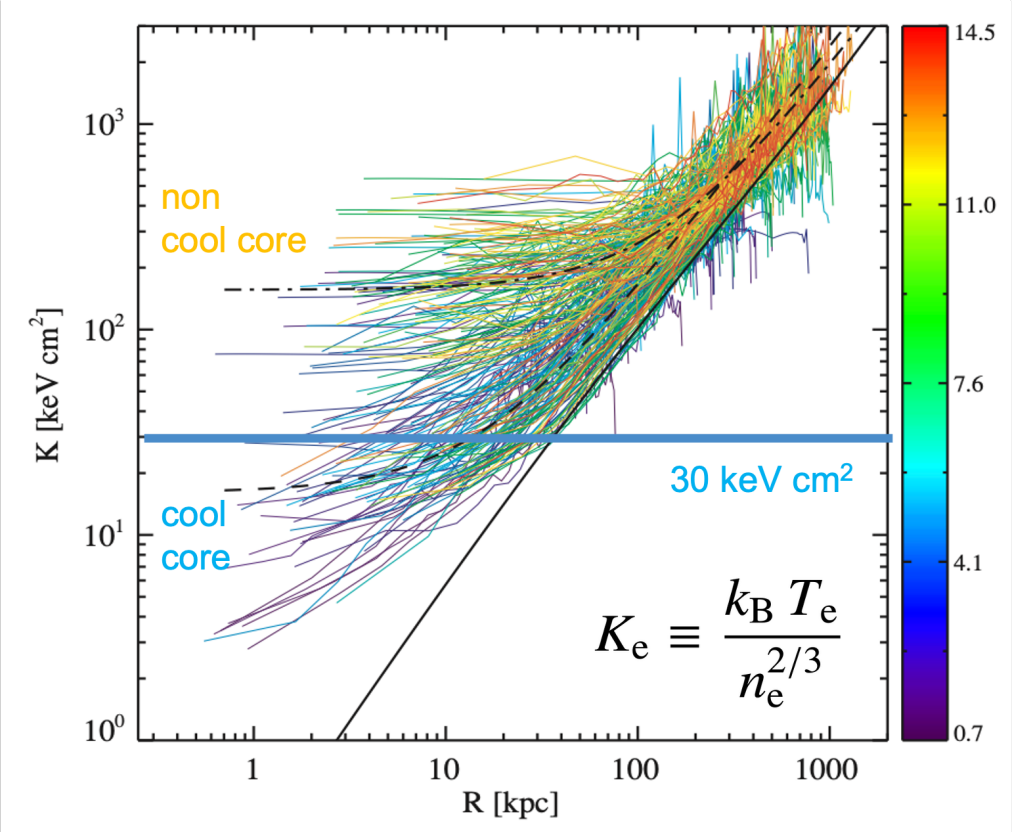
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- Bondi accretion rate:

$$\dot{M} \propto M_\bullet^2 K_e^{-3/2}$$

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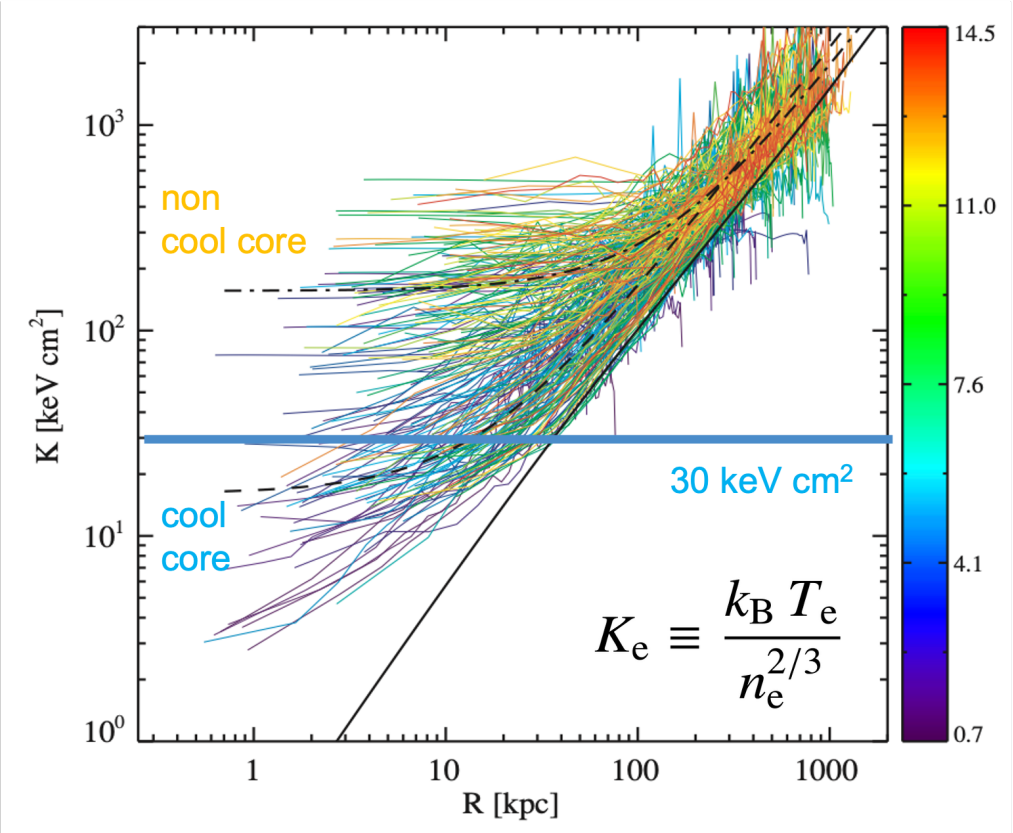
$$\dot{M} \propto M_\bullet^2 K_e^{-3/2}$$

- self-regulated jet power:

$$\dot{E} = \varepsilon \dot{M} c^2 = \langle L_{\rm cool} \rangle \propto M_{500}^{3/2}$$

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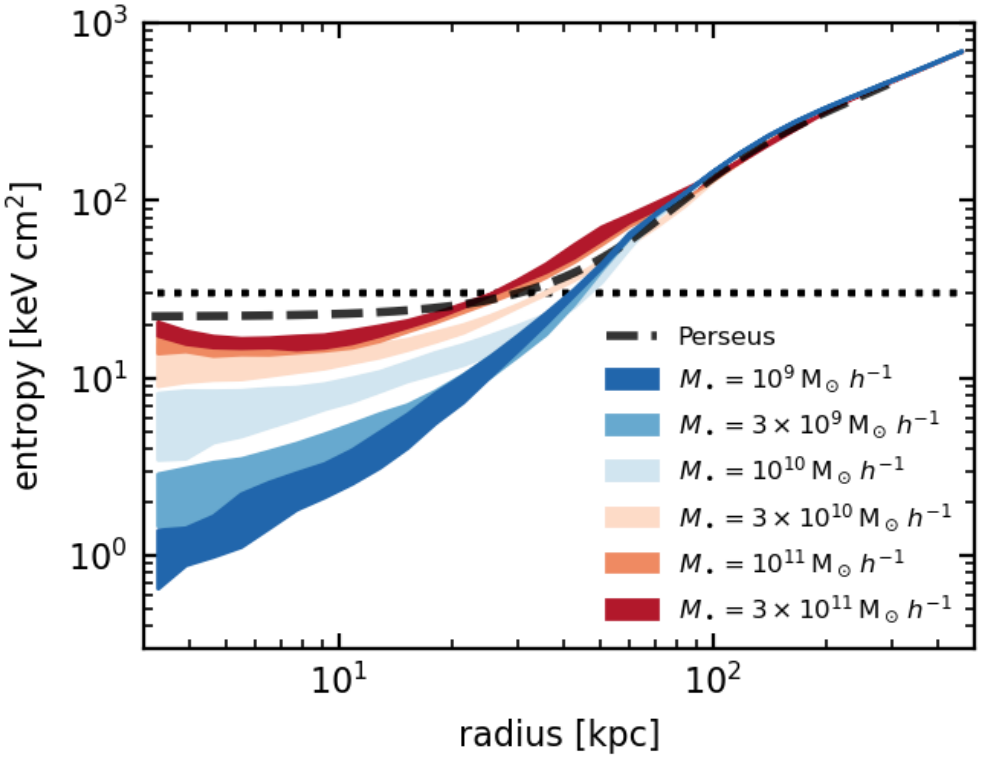
$$\dot{E} = \varepsilon \dot{M} c^2 = \langle L_{\rm cool} \rangle \propto M_{500}^{3/2}$$

- equilibrium entropy:

$$K_e = 18.3\,\mathrm{keV\,cm^2} \times \left(\frac{M_\bullet}{10^{10}\,\mathrm{M_\odot}}\right)^{4/3} \left(\frac{M_{500}}{10^{15}\,\mathrm{M_\odot}}\right)^{-1}$$

Churazov+ (2002), Weinberger & CP (2026)

Entropy profiles – isolated cluster simulations

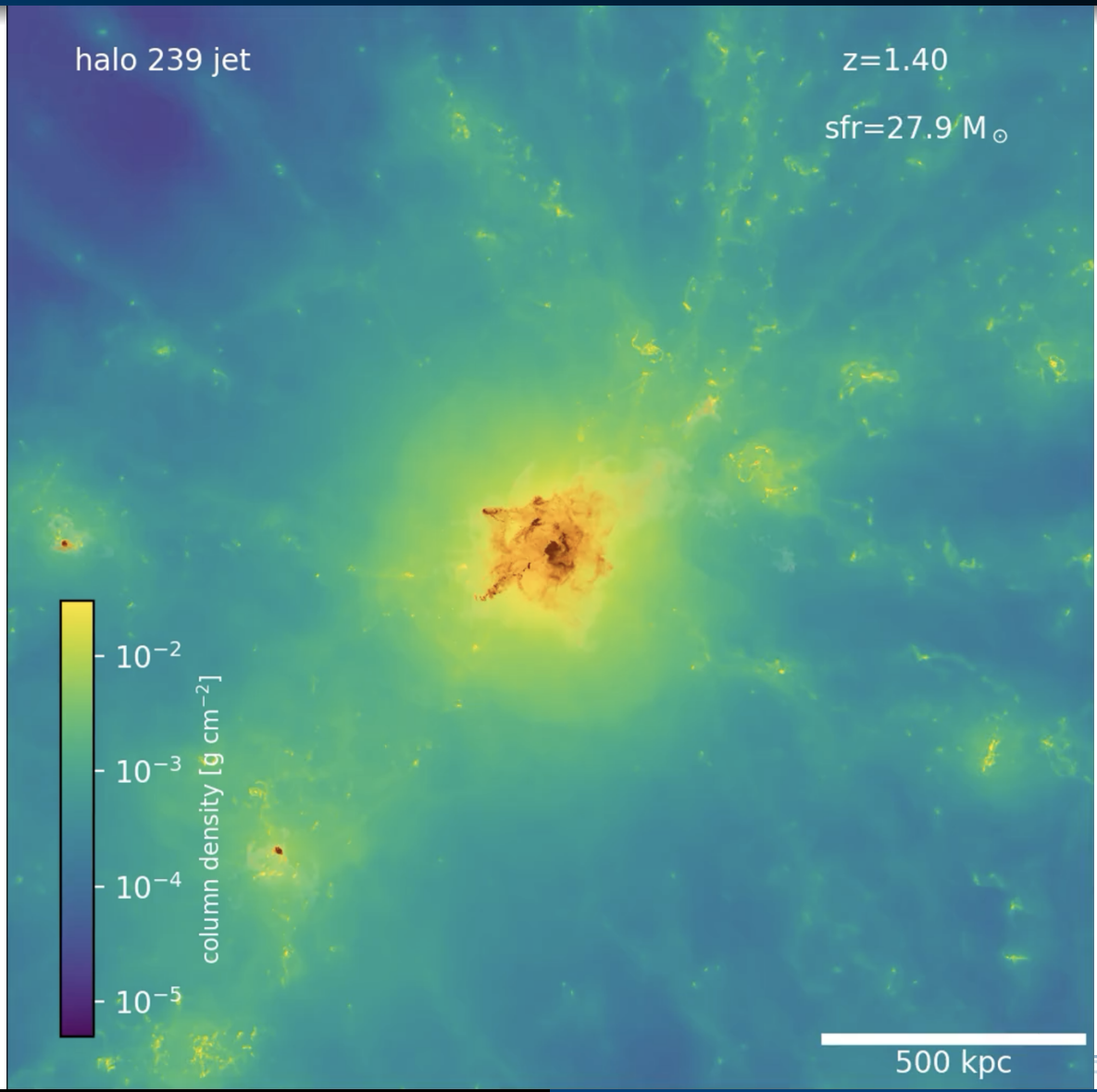


- analytic gravitational potential
- ideal MHD & radiative cooling
- gas inflow via Bondi formula
- jet power proportional to inflow rate
- ***equilibrium central entropy depends on black hole mass***

Weinberger & CP (2026)

AIP

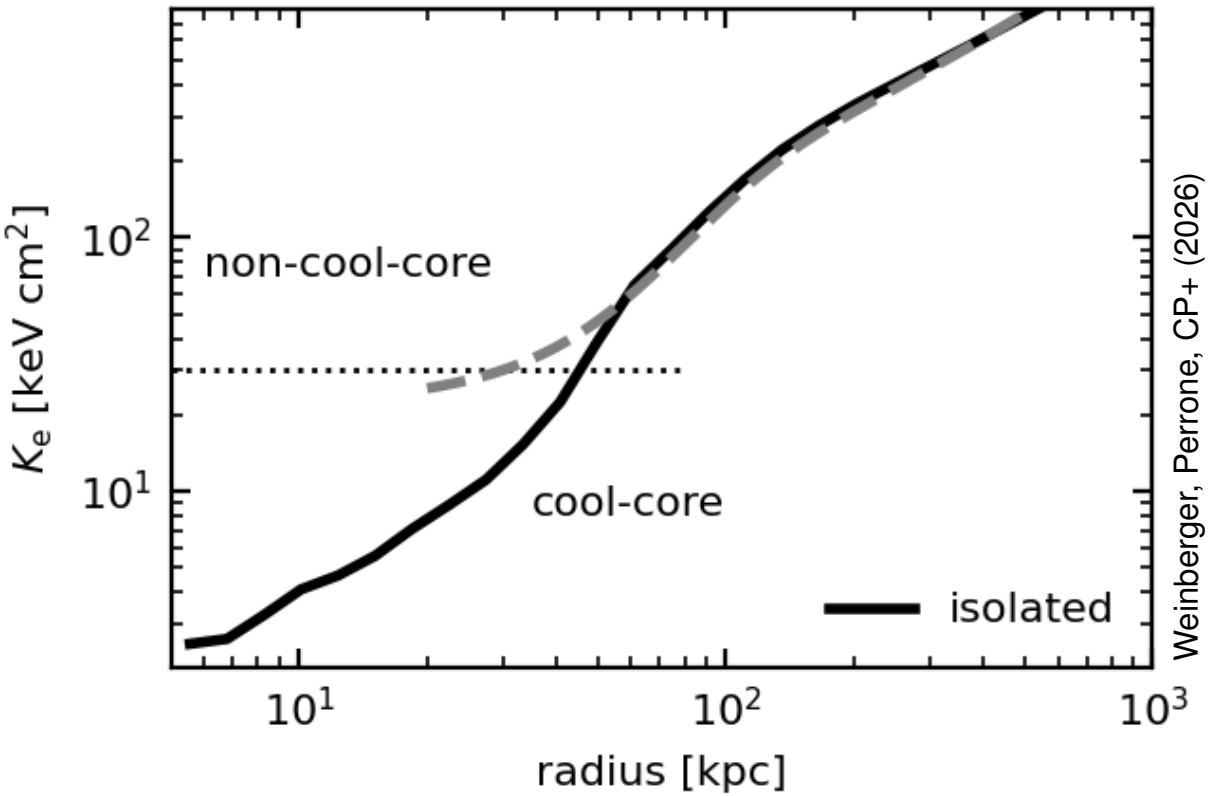
Cosmological galaxy cluster formation with jets



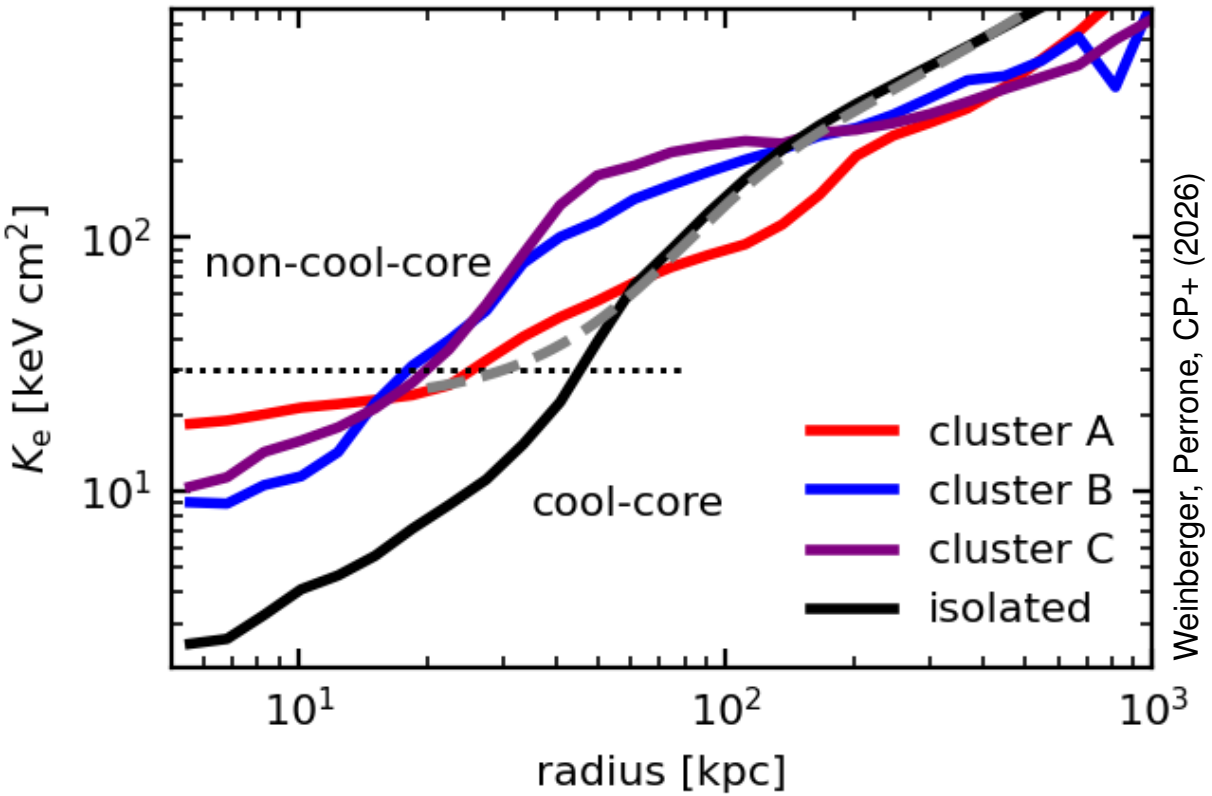
Weinberger, CP+ (in prep.)

AIP

Entropy profiles – cosmological cluster simulations

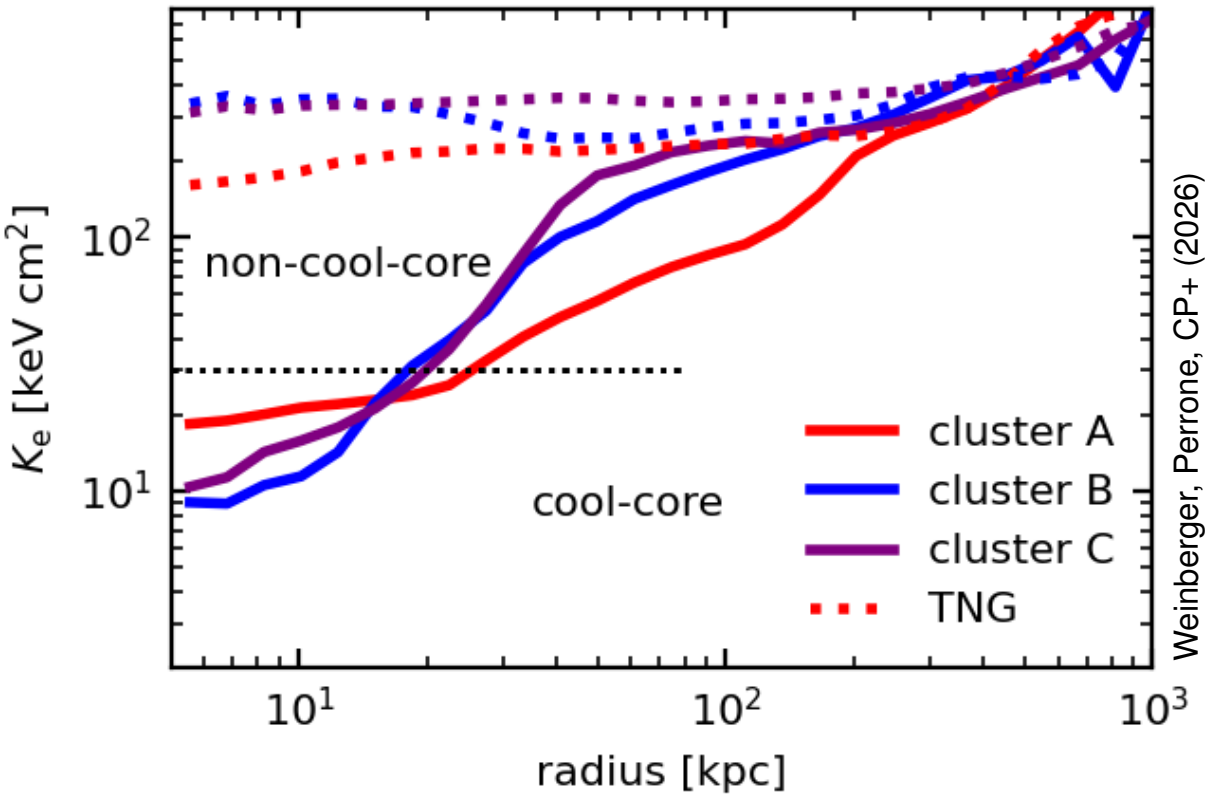


Entropy profiles – cosmological cluster simulations



- ***cosmological jet simulations form cool cores*** with increased entropy because of heavier black holes and turbulent heating/mixing

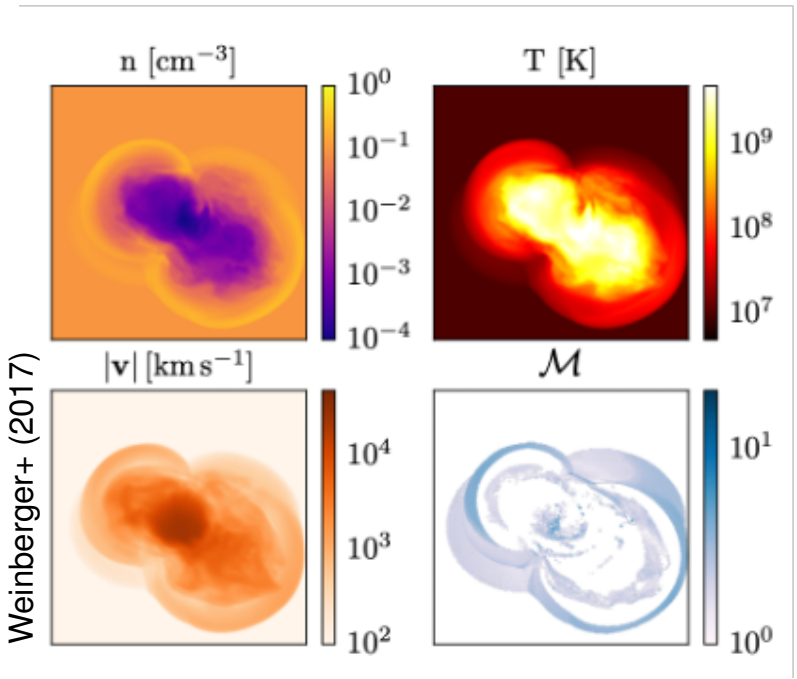
Entropy profiles – cosmological cluster simulations



- ***cosmological jet simulations form cool cores*** with increased entropy because of heavier black holes and turbulent heating/mixing
- ***cosmological TNG simulations with identical initial conditions form non-cool cores*** because of strong shock heating

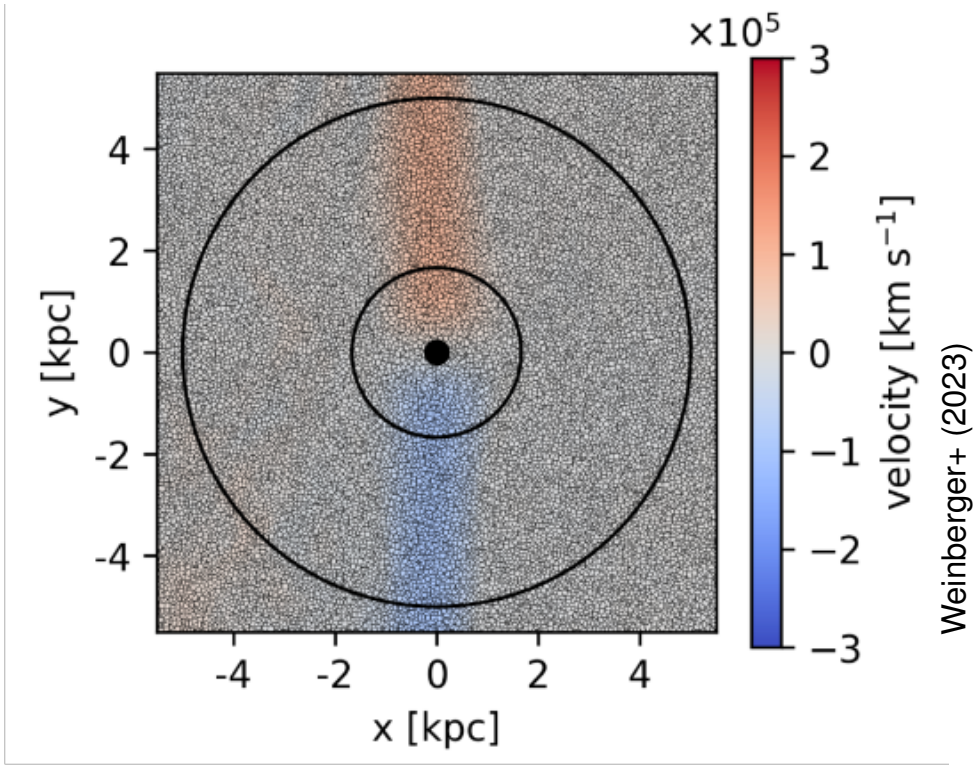
Feedback model differences

TNG kinetic AGN feedback



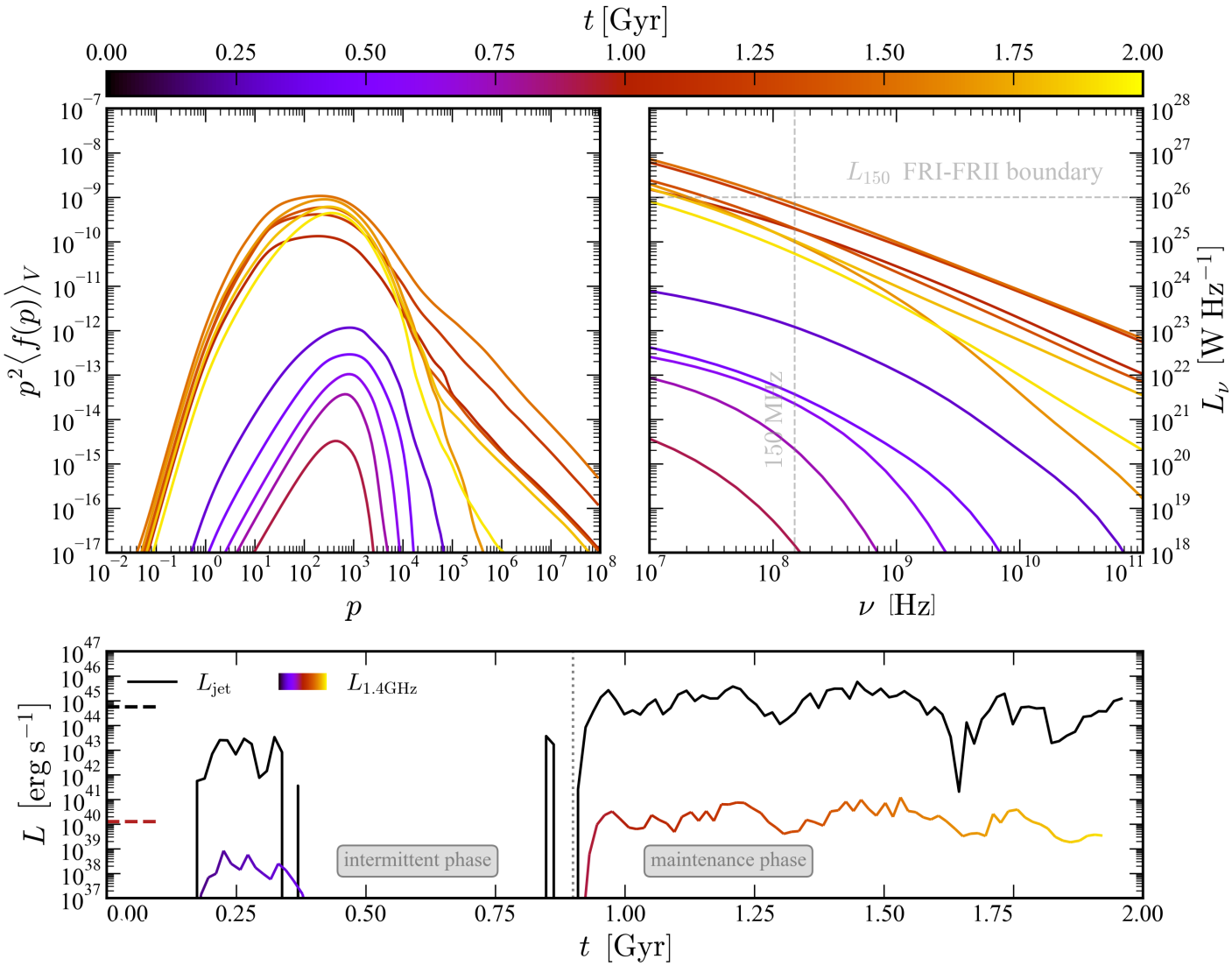
- feedback energy quickly dissipated via shocks, which rises entropy

AGN jet feedback

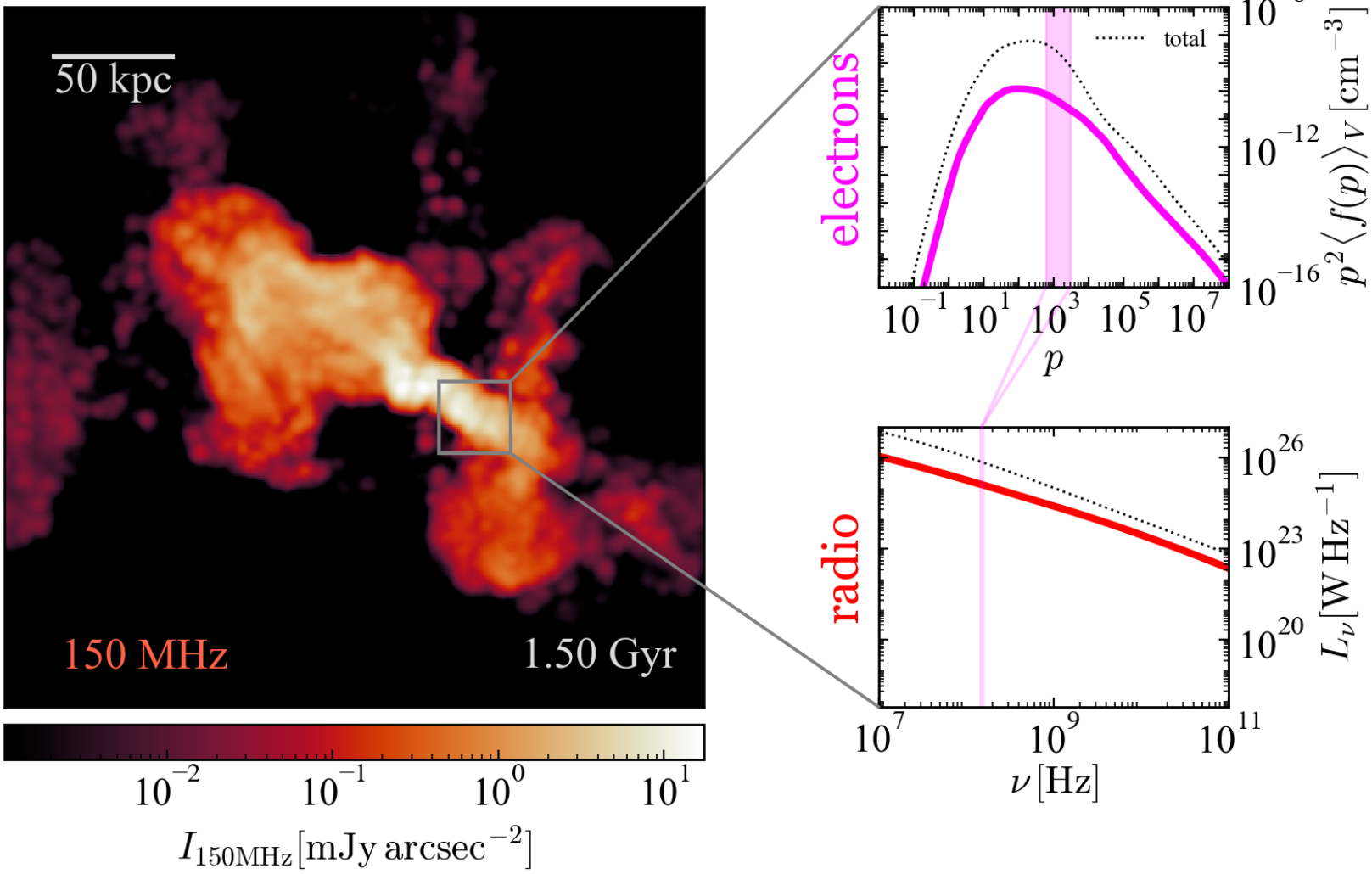


- low-density jets inflate lobes that slowly heat via turbulent heating/mixing

Self-regulated jets: electron & radio spectral evolution

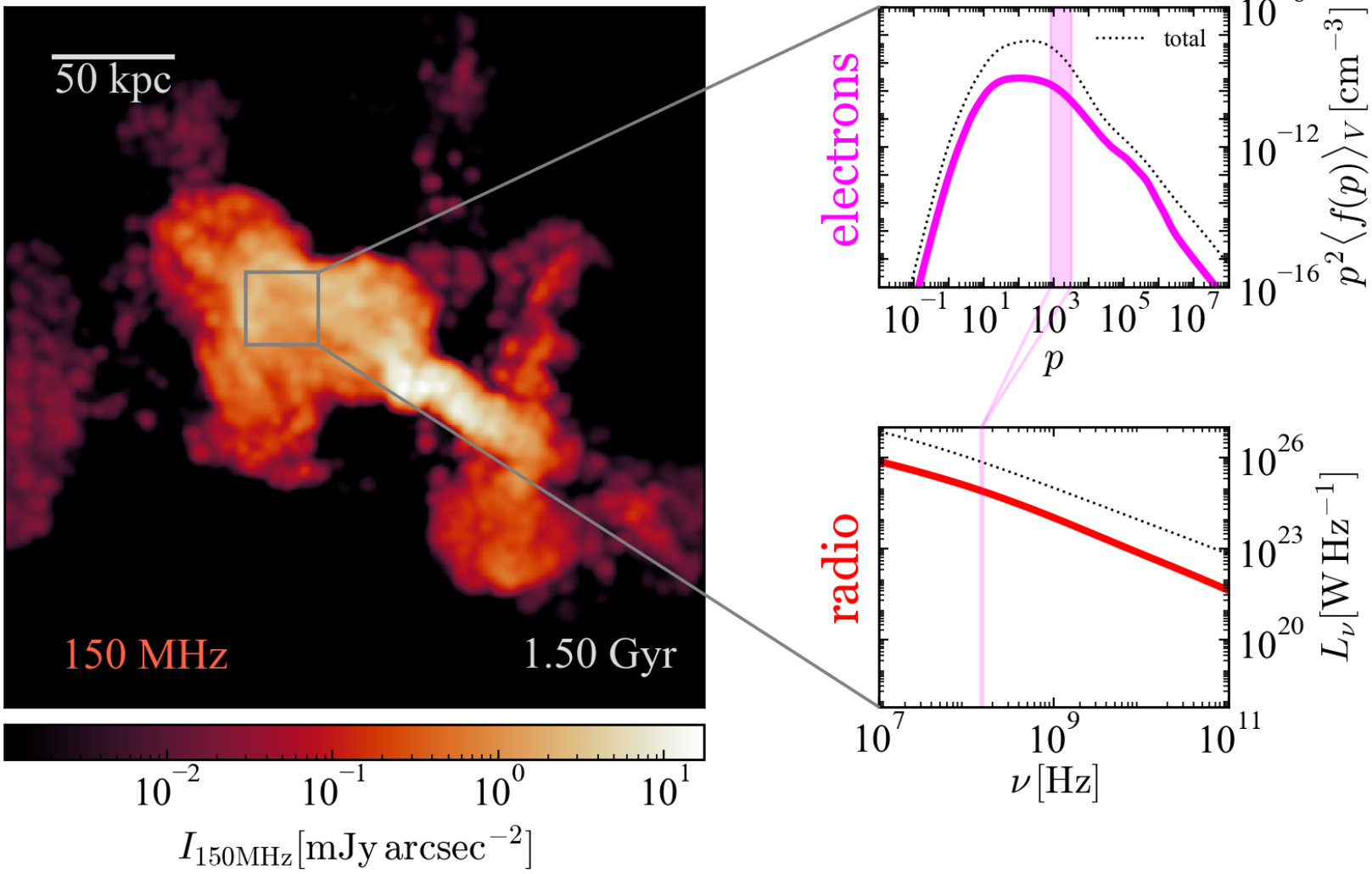


Self-regulated jets: electron & radio spectral evolution



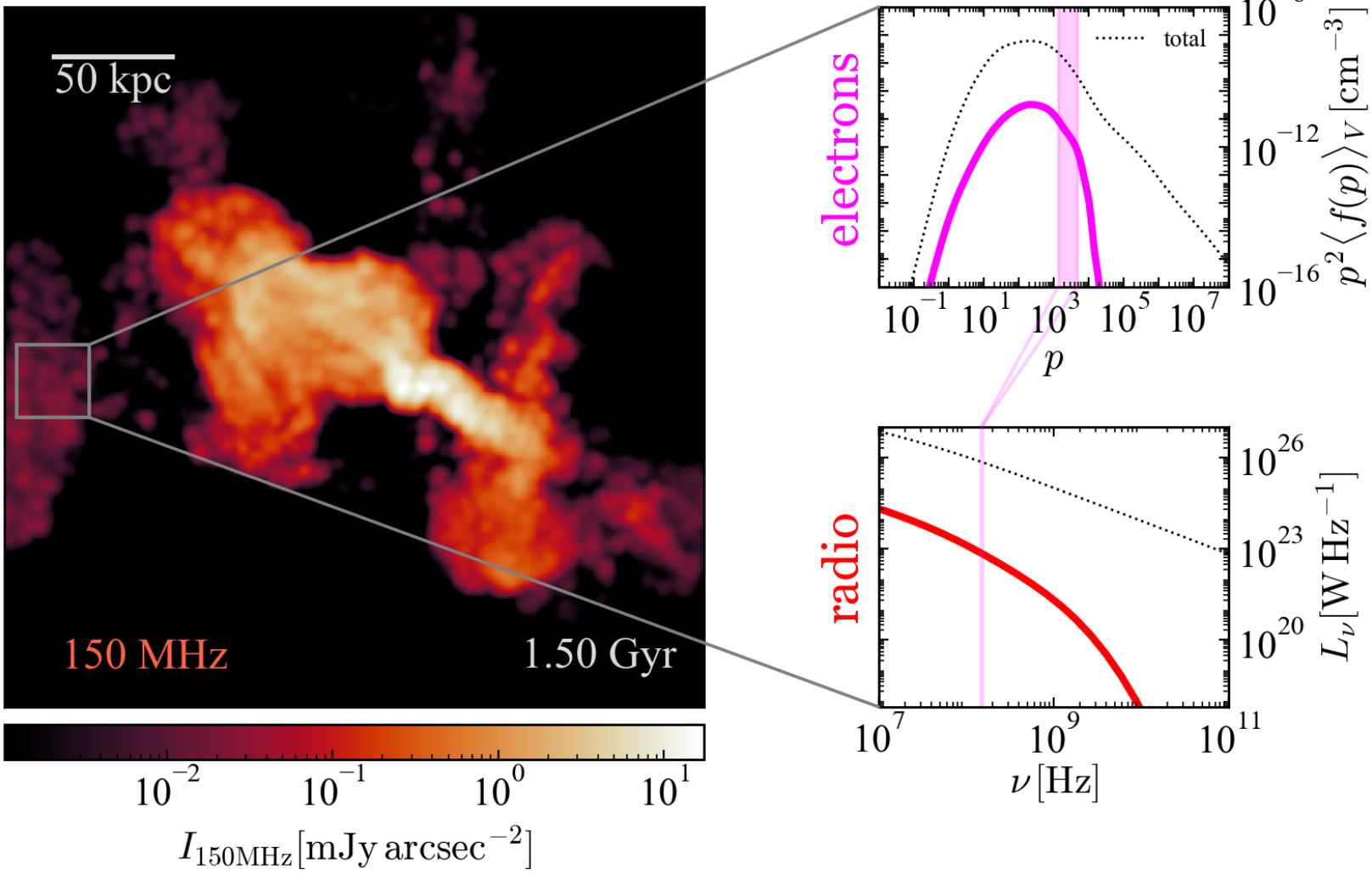
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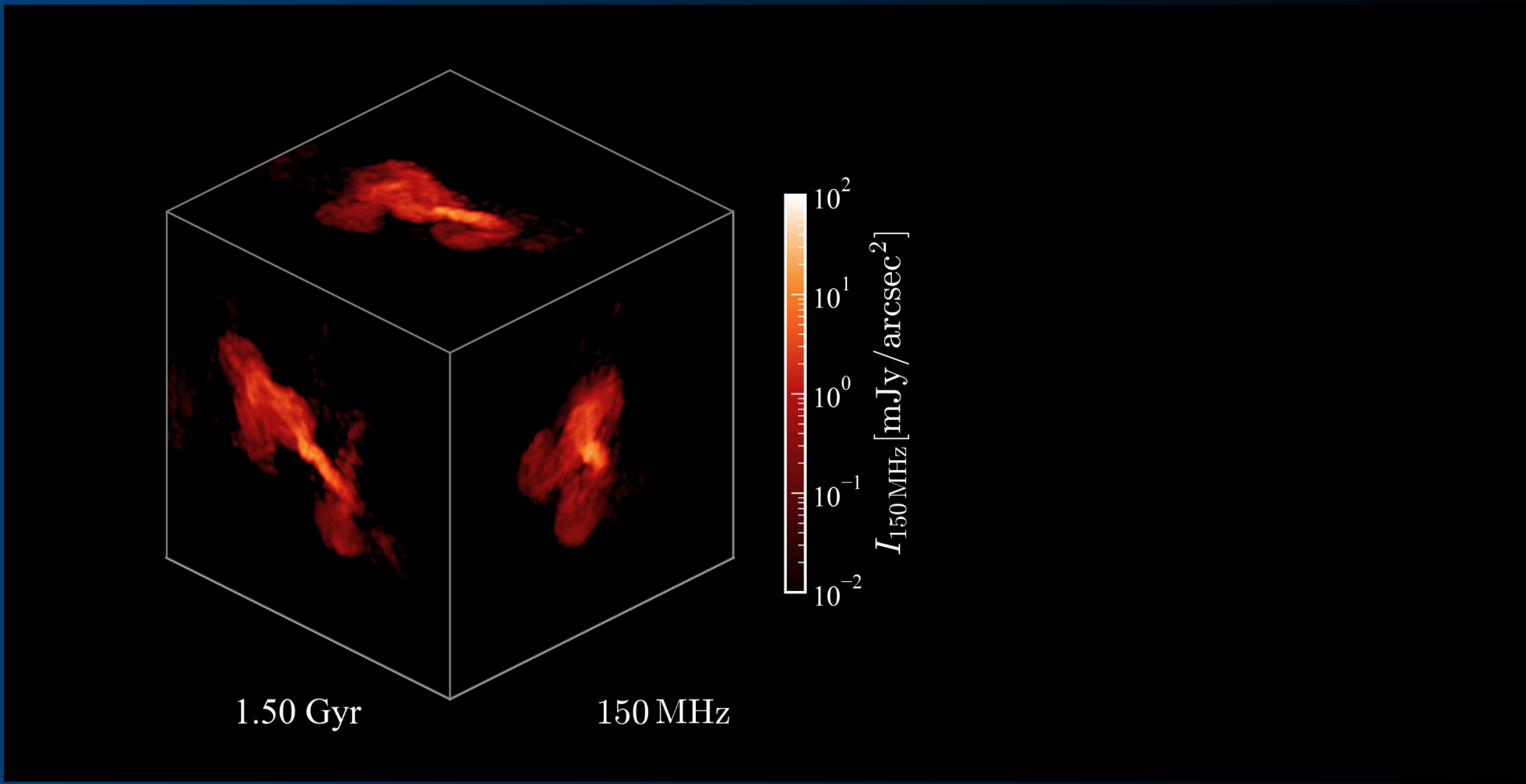
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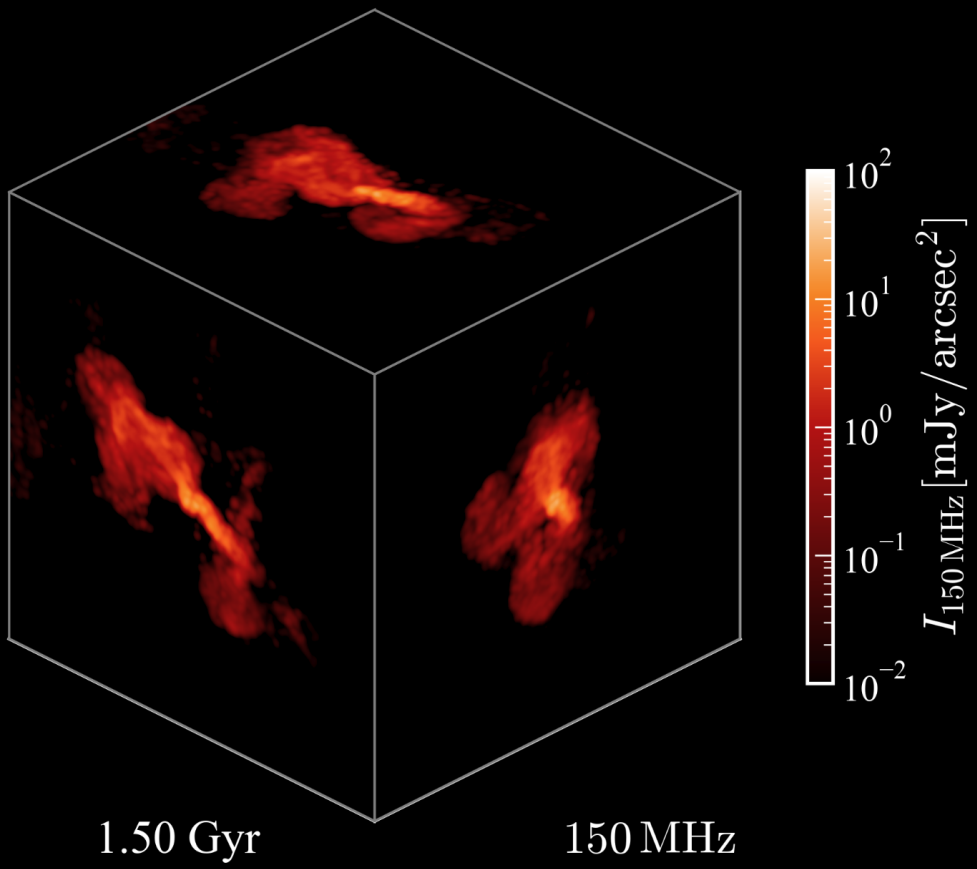
AIP

3D view of self-regulated jets



Jlassi, Weinberger, CP+ (2026b)

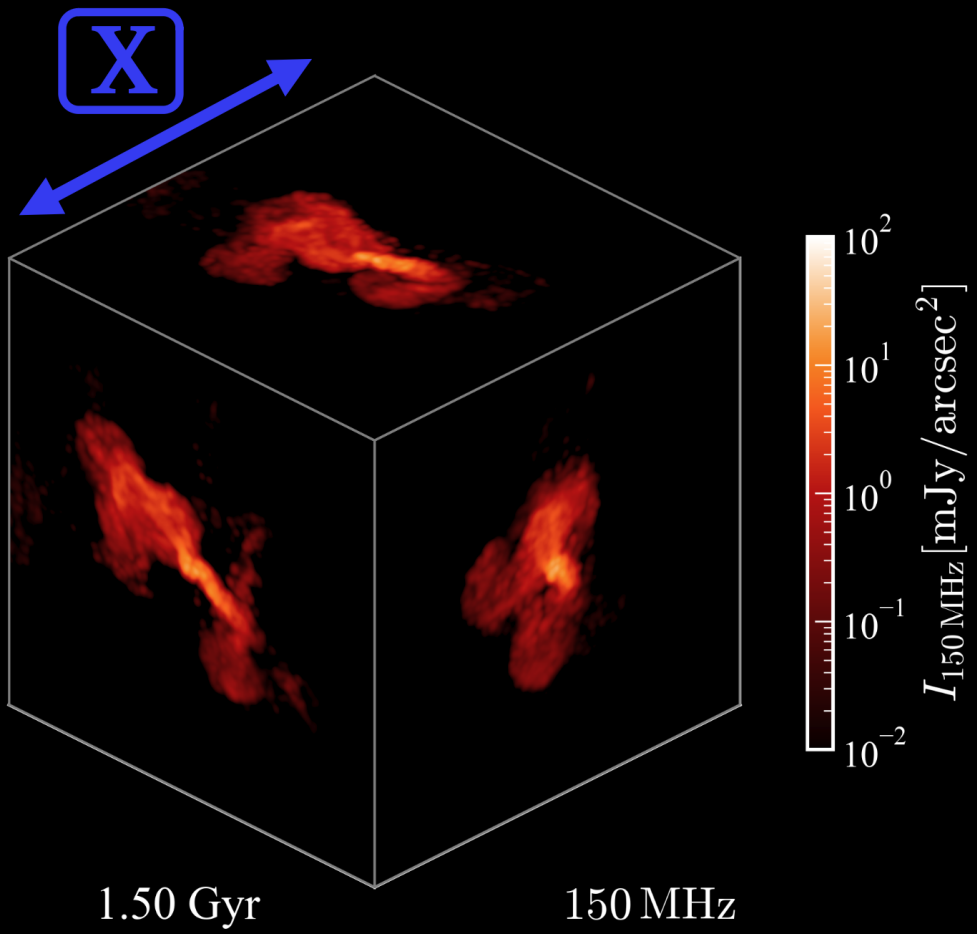
3D view of self-regulated jets



Which direction is the jet launched in?

Jlassi, Weinberger, CP+ (2026b)

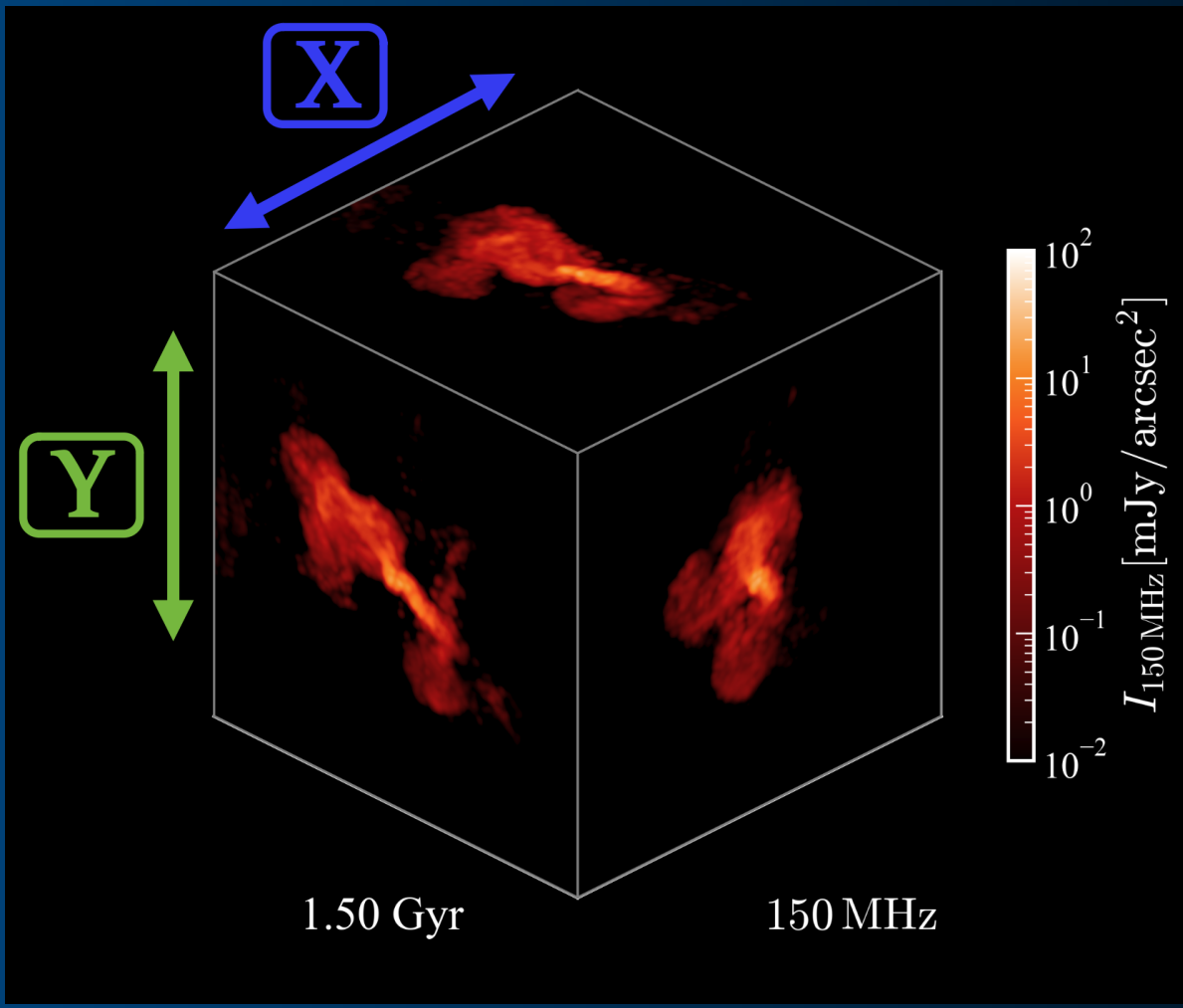
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Which direction is the jet launched in?

Jlassi, Weinberger, CP+ (2026b)

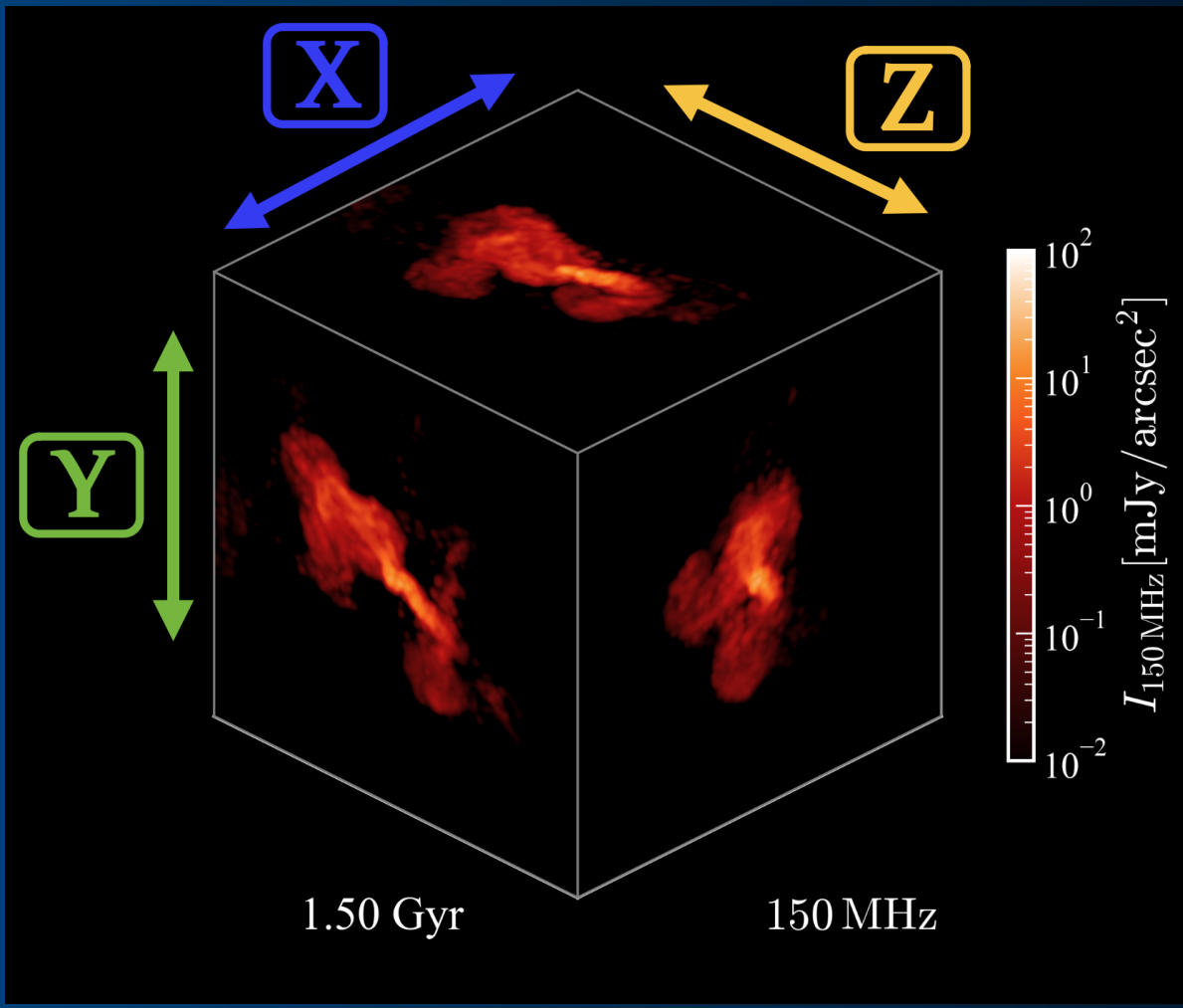
3D view of self-regulated jets



Which direction is the jet launched in?

Jlassi, Weinberger, CP+ (2026b)

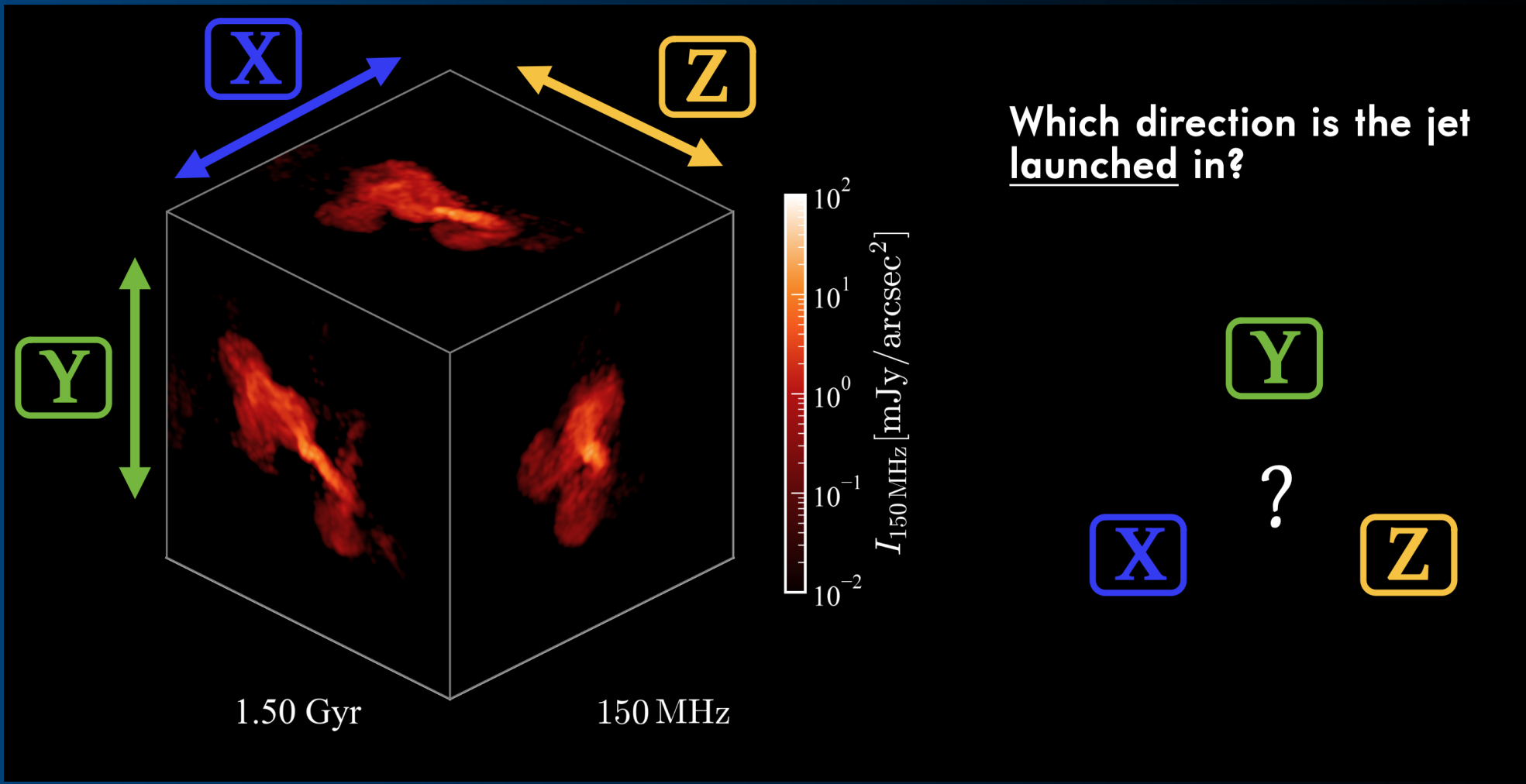
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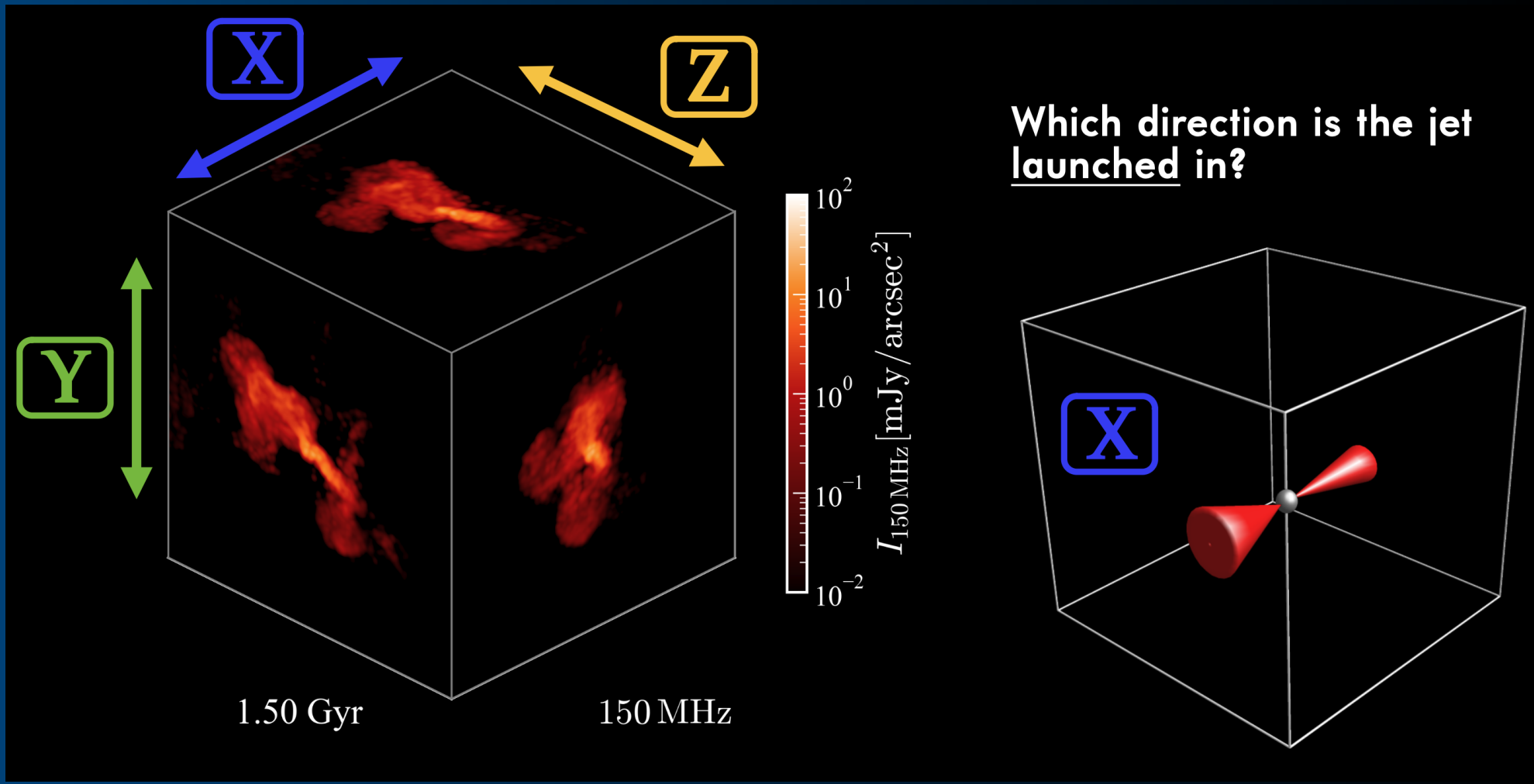
Jlassi, Weinberger, CP+ (2026b)

3D view of self-regulated jets



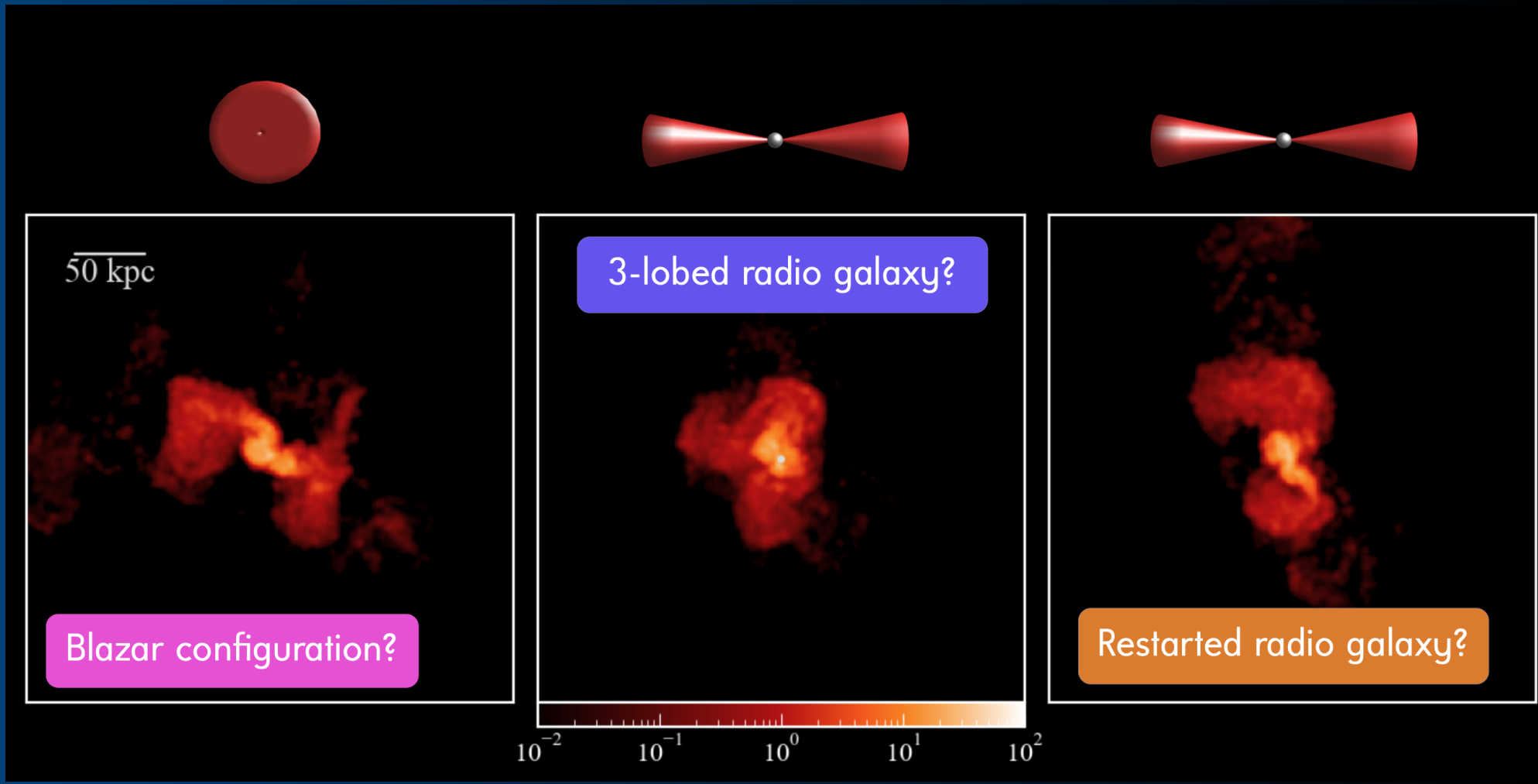
Jlassi, Weinberger, CP+ (2026b)

3D view of self-regulated jets



Jlassi, Weinberger, CP+ (2026b)

3D view of self-regulated jets



Jlassi, Weinberger, CP+ (2026b)

Conclusions

PICO-Cluster project:

- challenging scale separation between kinetic plasma processes and cosmological scales $\rightarrow$ linking cluster physics and cosmology communities
- solving key cluster science questions requires different physics variants and high-resolution meso-scale simulations



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AGN jet feedback:

- central cooling time set by self-regulated ***jet power = cooling luminosity***
- light AGN jets heat smoothly $\neq$ strong shock heating via kinetic feedback
- realistic radio emission from FR I jets requires light AGN jets + Fokker–Planck electron modeling



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 – 1

PICO-Cluster, turbulence and magnetic dynamos:

- 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 MNRAS, submitted, arXiv:2606.23798
- Perrone, Berlok, Puchwein, Pfrommer, *Characterizing turbulence in galaxy clusters: defining turbulent energies and assessing multi-scale versus fixed-scale filters,* 2026, A&A, submitted, arXiv:2601.06250
- Tevlin, Berlok, Pfrommer, Talbot, Whittingham, Puchwein, Pakmor, Weinberger, Springel, *Magnetic dynamos in galaxy clusters: the crucial role of galaxy formation physics at high redshifts,* 2025, A&A, 701, A114.



Literature for the talk – 2

AGN jet feedback:

- Weinberger, Perrone, Pfrommer, Berlok, Puchwein, Jlassi, Talbot, Whittingham, Pakmor, Springel, *Active galactic nucleus driven jet feedback in cosmologically forming cool-core galaxy clusters I: The effect of hierarchical assembly on intra-cluster medium properties,* 2026, A&A, submitted, arXiv:2606.23775
- Weinberger, Pfrommer, *How supermassive black holes shape central entropies in galaxy clusters,* 2026, A&A Letter, 706, L13
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- Jlassi, Weinberger, Pfrommer, Werhahn, Whittingham, Girichidis, *Simulating cosmic ray electron spectra and radio emission from an AGN jet outburst in a cool-core cluster,* 2026a, A&A, 710, A184
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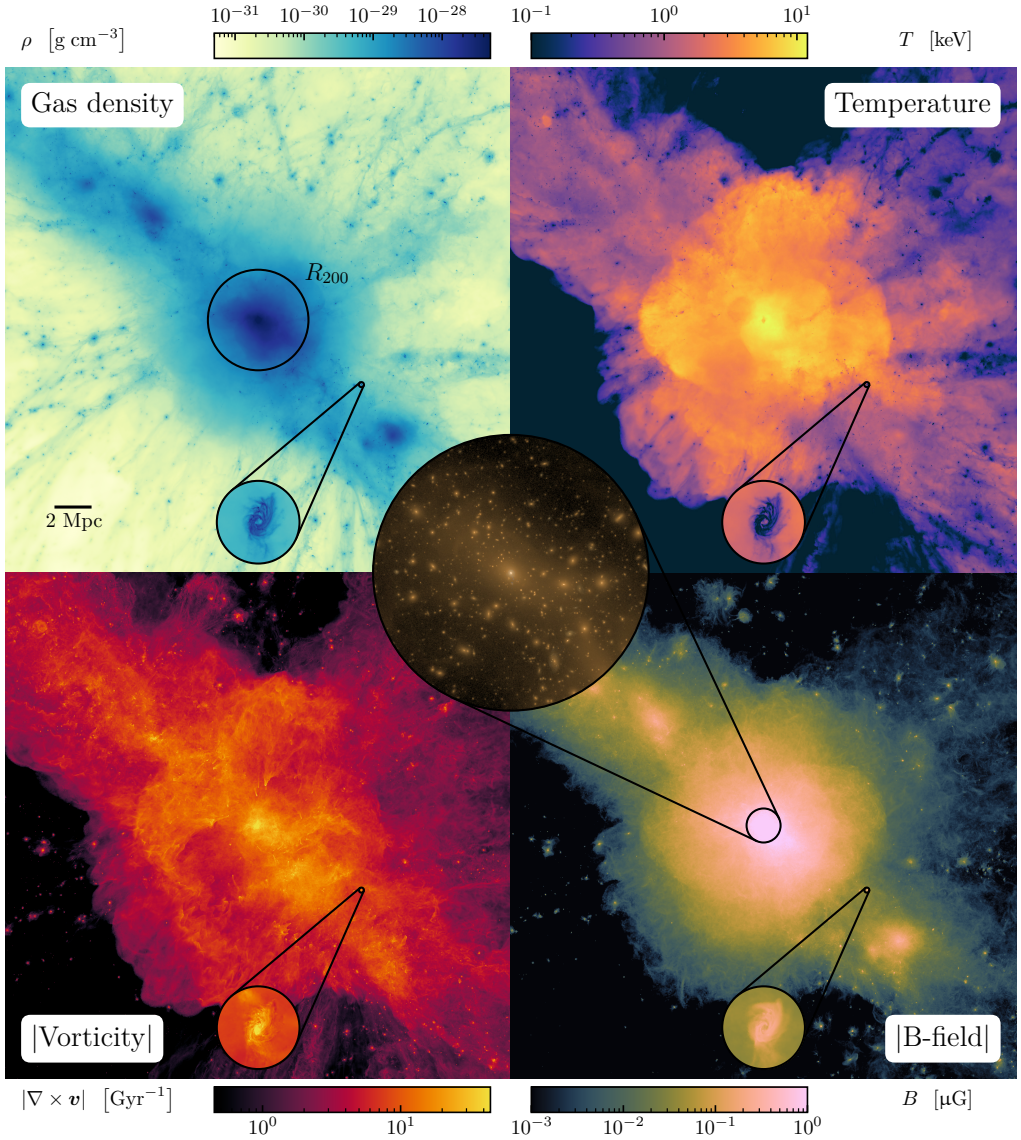
Additional slides



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)