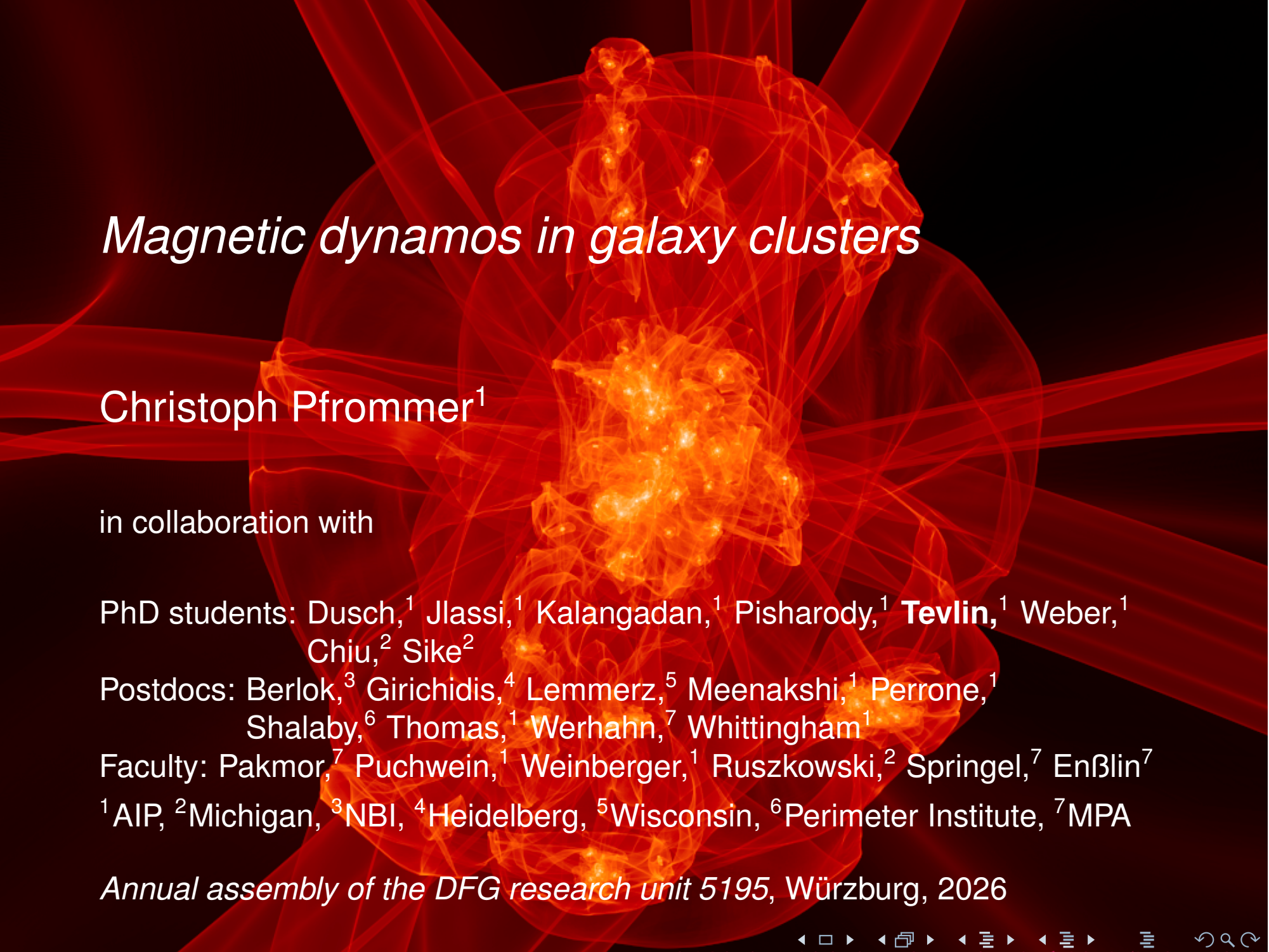


Magnetic dynamos in galaxy clusters

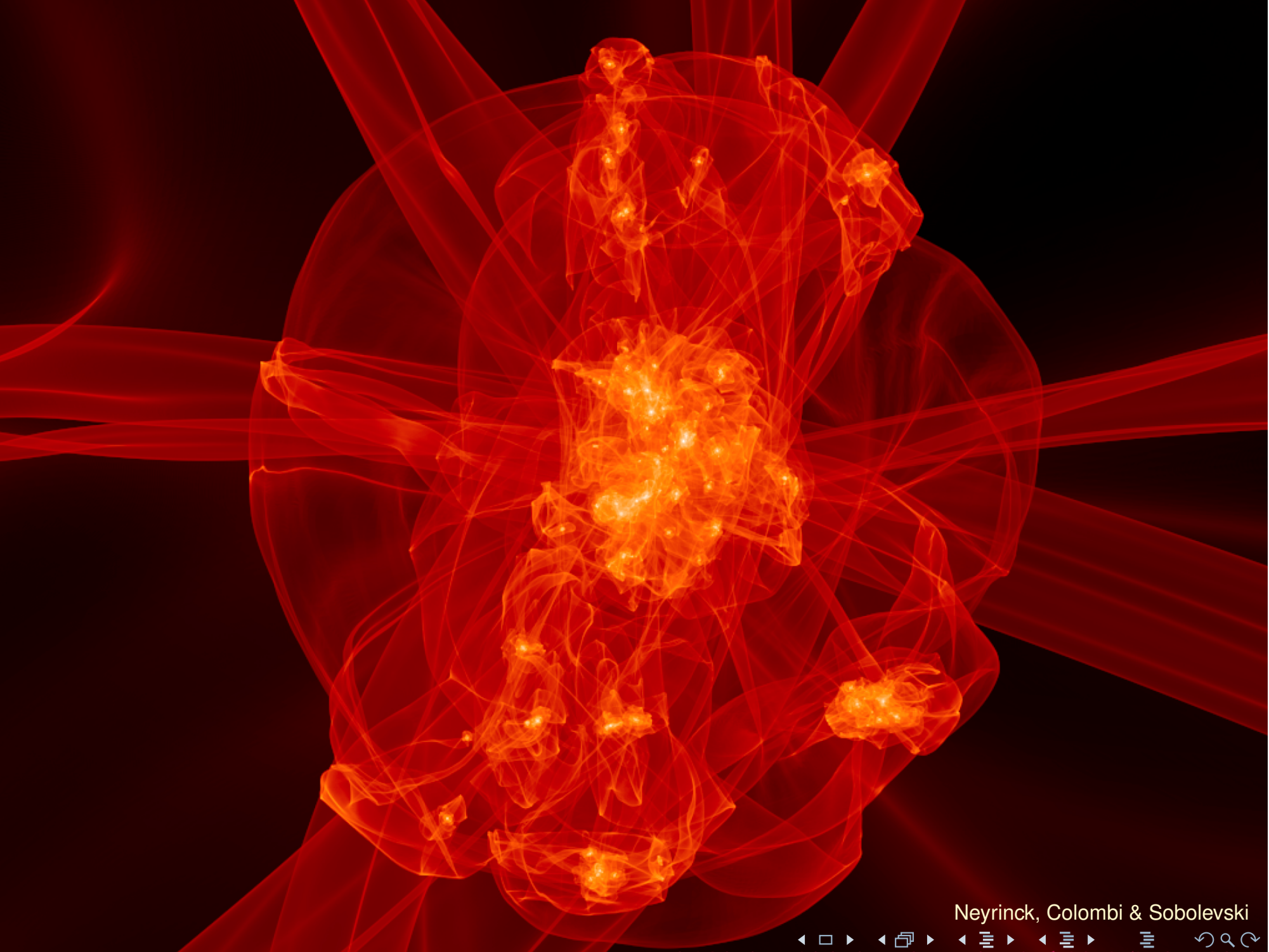
Christoph Pfrommer[1]

in collaboration with

PhD students: Dusch,[1] Jlassi,[1] Kalangadan,[1] Pisharody,[1] **Tevlin,**[1] Weber,[1] Chiu,[2] Sike[2]
Postdocs: Berlok,[3] Girichidis,[4] Lemmerz,[5] Meenakshi,[1] Perrone,[1] Shalaby,[6] Thomas,[1] Werhahn,[7] Whittingham[1]
Faculty: Pakmor,[7] Puchwein,[1] Weinberger,[1] Ruszkowski,[2] Springel,[7] Enßlin[7]

[1]AIP, [2]Michigan, [3]NBI, [4]Heidelberg, [5]Wisconsin, [6]Perimeter Institute, [7]MPA

Annual assembly of the DFG research unit 5195, Würzburg, 2026


Neyrinck, Colombi & Sobolevski

Outline

AIP

Observing magnetic fields in clusters

Faraday rotation measures (FRMs) in nearby clusters: $B \sim 10\ \mu$G (Bonafede+ 2010)

$$\mathrm{RM}(\boldsymbol{x}_\perp) = \frac{e^3}{2\pi\, m_\mathrm{e}^2 c^4} \int_0^L n_\mathrm{e}(\boldsymbol{x}_\perp, l)\, \boldsymbol{B} \cdot \mathrm{d}\boldsymbol{l}$$

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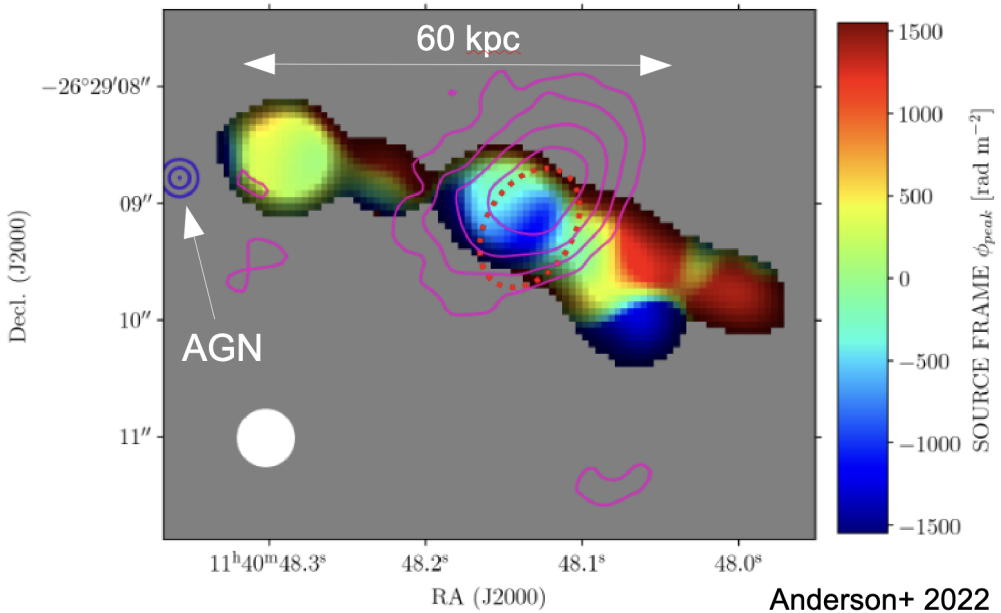
Evidence for early magnetism through FRM observations:

- spiderweb proto-cluster ($z \approx 2.2$) suggest early amplification: $B \sim 9\ \mu$G
- strongly magnetized proto-clusters at $z \approx 2.4$–4.24

  (Cordun+ 2023, Chapman+ 2024)



Anderson+ 2022

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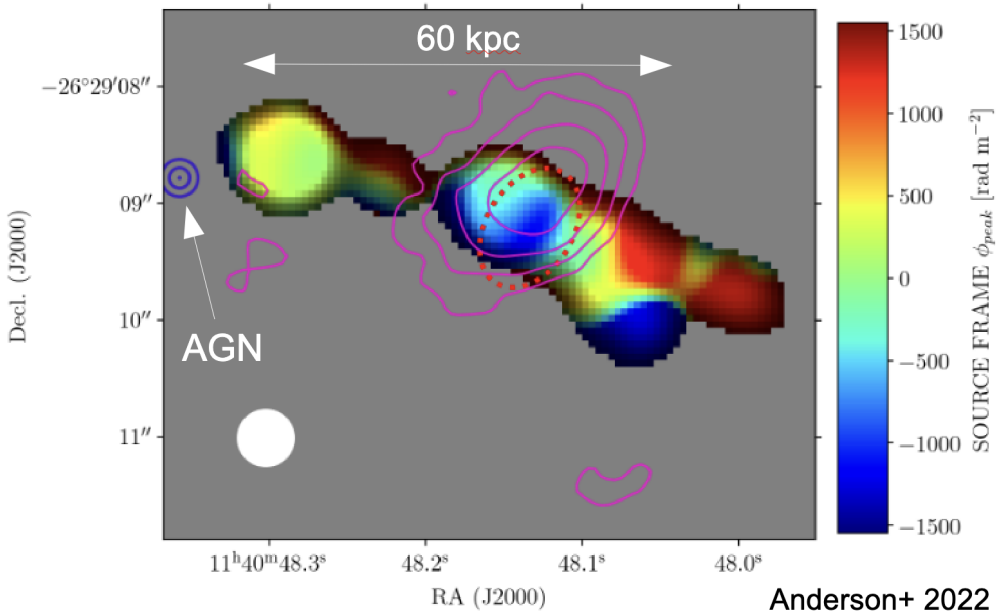

Anderson+ 2022

High-z diffuse radio emission requires large B to beat strong inverse Compton losses of electrons at cosmic microwave background photons:

- clusters at $z \sim 1$–2 have magnetic field strengths similar to low-z clusters

  (Di Gennaro+ 2021, 2023, Hlavacek-Larrondo+ 2025)

Origin and growth of magnetic fields

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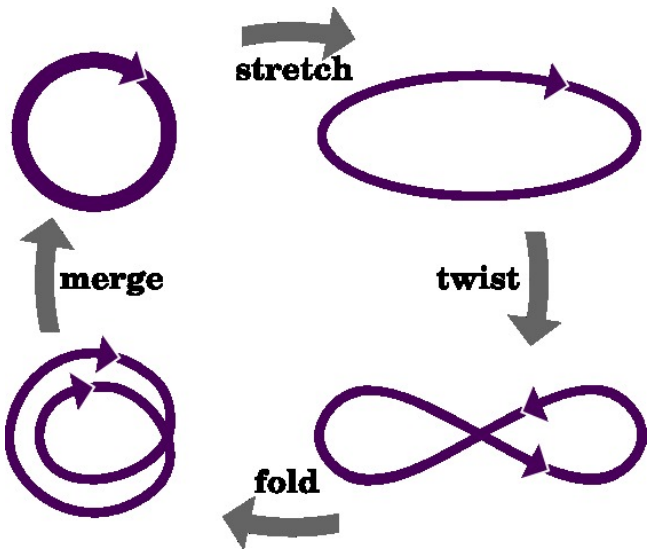

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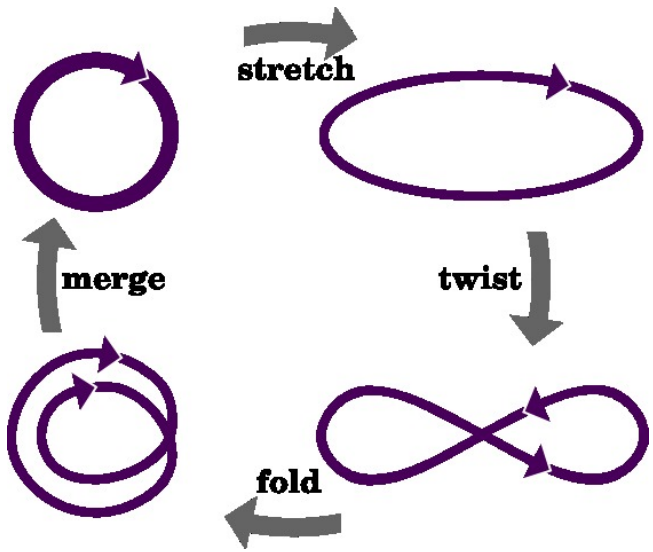
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



The need for a plasma dynamo?

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- ***The intracluster medium (ICM) is weakly collisional;*** large particle mean free path:

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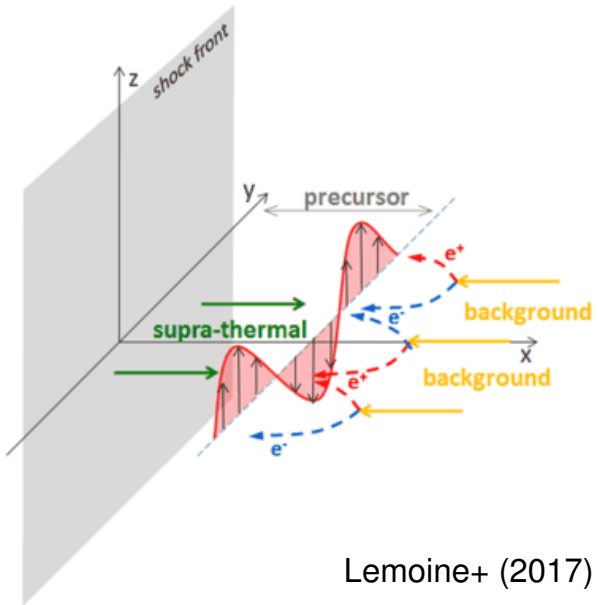

Lemoine+ (2017)

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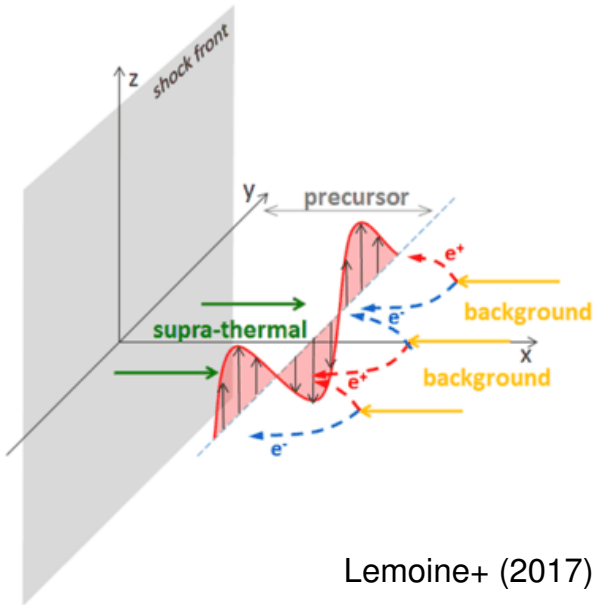

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- ***However, there is a loophole in this argument*** as it assumes clusters to be weakly collisional throughout their entire cosmic growth history!

PICO-Cluster simulations

- ***PICO-Clusters (Plasmas In COsmological Clusters):*** suite of cosmological zoom-in cluster simulations (Berlok, Puchwein, CP+ in prep.)
- parent simulation: $(1.5\ \mathrm{Gpc})^3$ cosmological volume containing 272 clusters $> 10^{15}\ \mathrm{M}_\odot$ with high-resolution zoom-ins (up to $M_{\mathrm{gas}} = 10^6\ \mathrm{M}_\odot$) of selected systems and varying plasma physics evolved from $z = 127$ to 0
- moving mesh code AREPO-2 (with Subfind HBT) (Springel 2010, Springel+ 2022)
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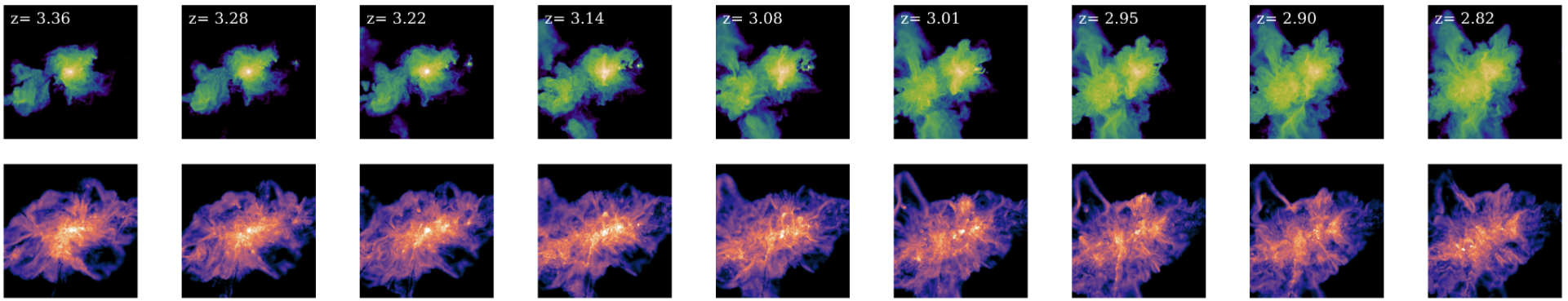

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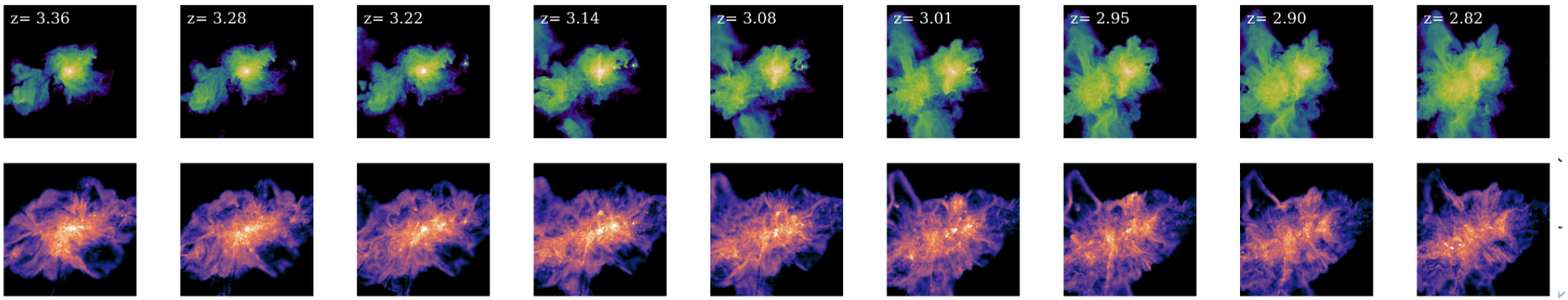
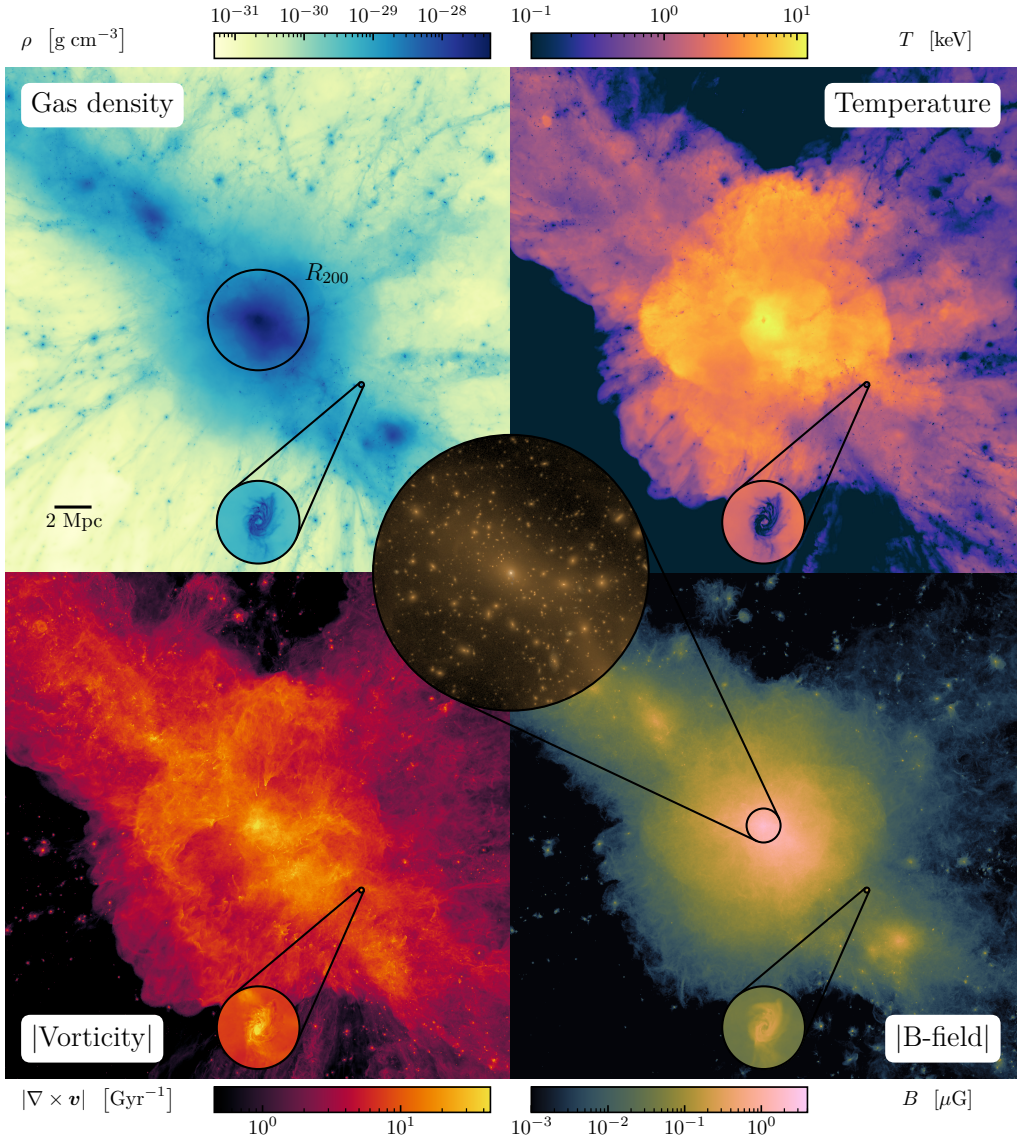


PICO-Cluster simulations

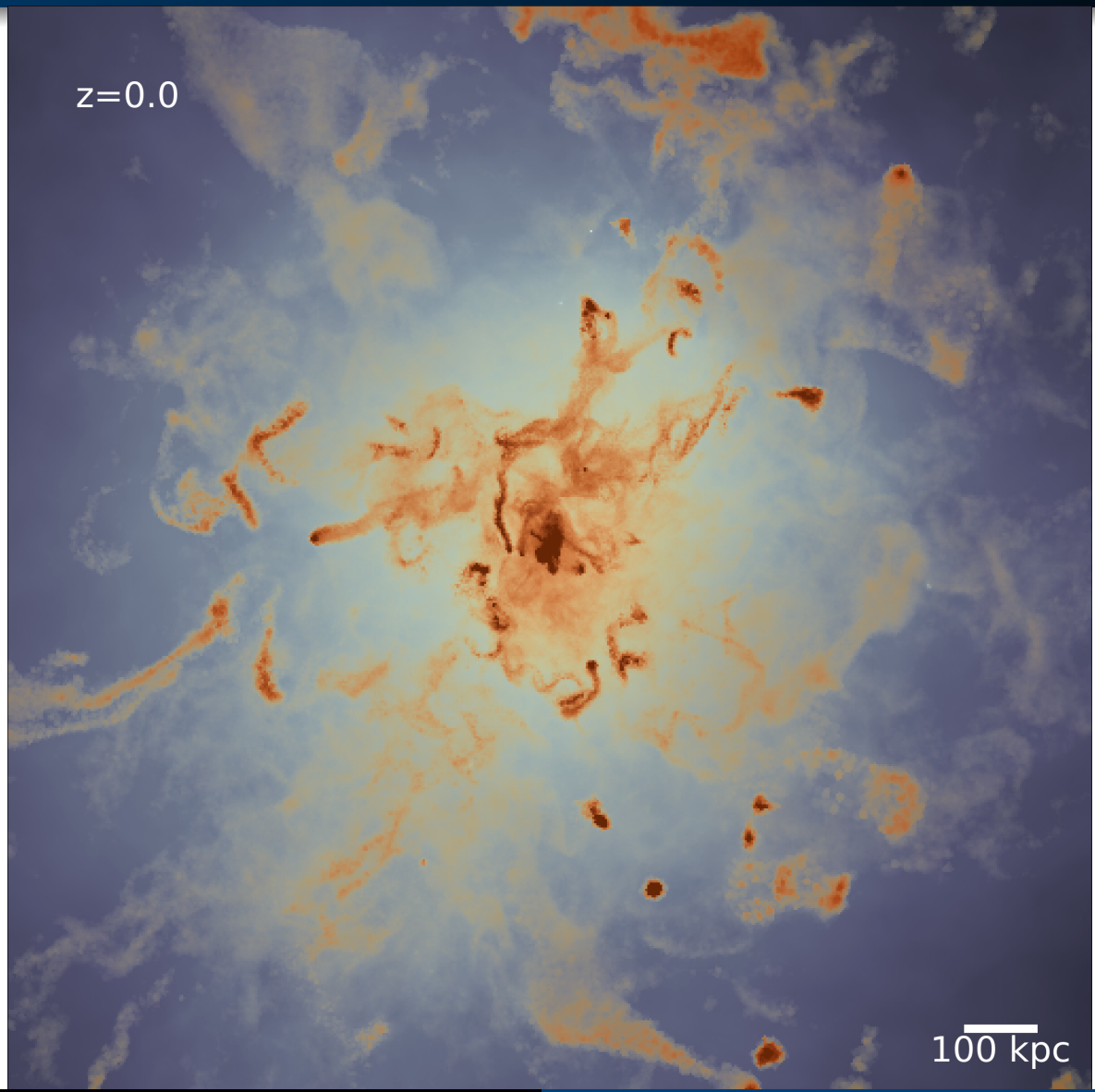
Differences to comparable simulation projects, e.g., TNG-Cluster (Nelson+ 2024):

- our new initial conditions code, ensuring a contamination-free high-resolution region $< 2.8R_{200}$
- improved simulation code: AREPO-2 while TNG-Cluster uses AREPO
- increased resolution (up to $M_{\rm gas} = 10^6\ {\rm M}_\odot$): 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, Puchwein, CP+ (in prep.)

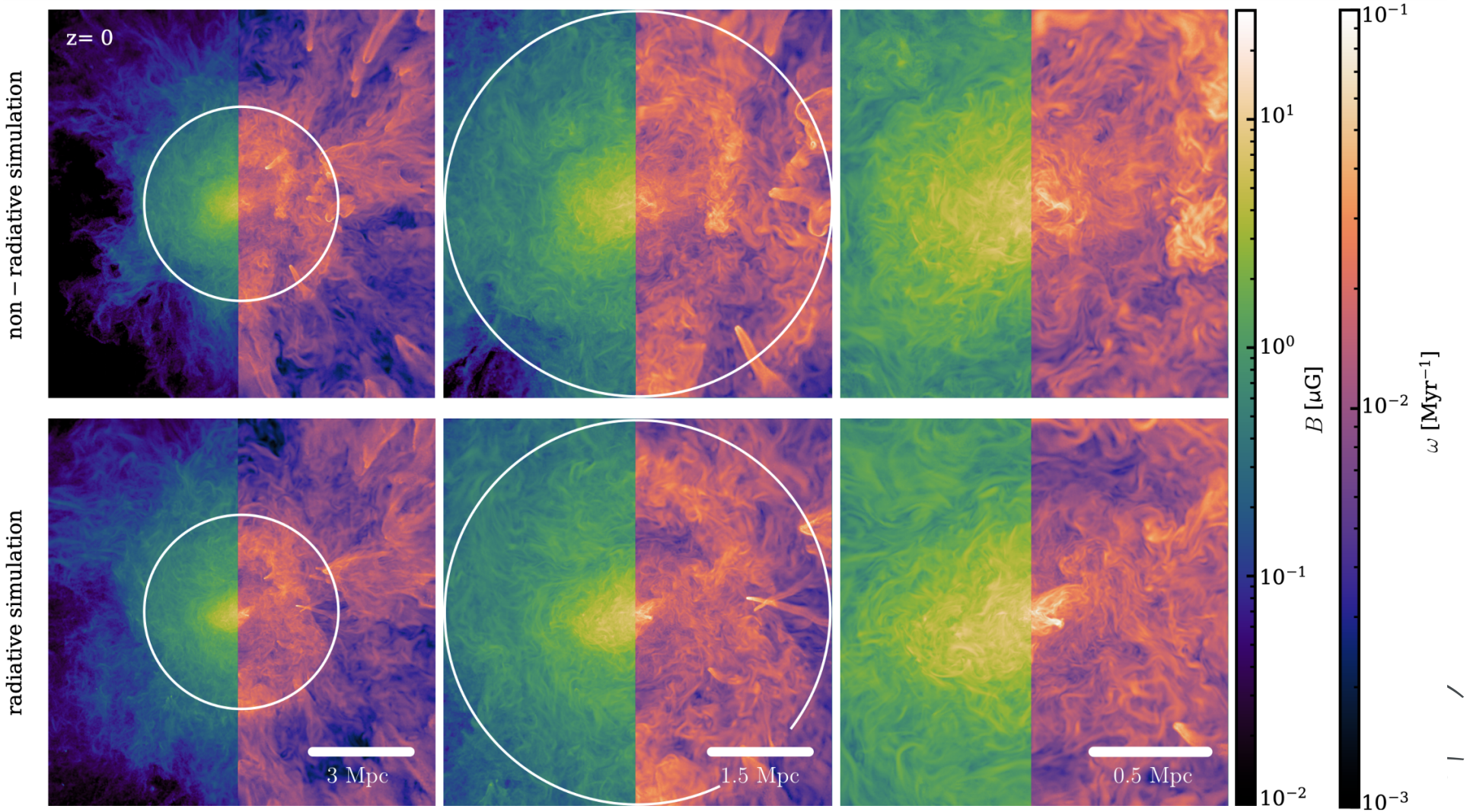
AGN jets in cosmological cluster simulations



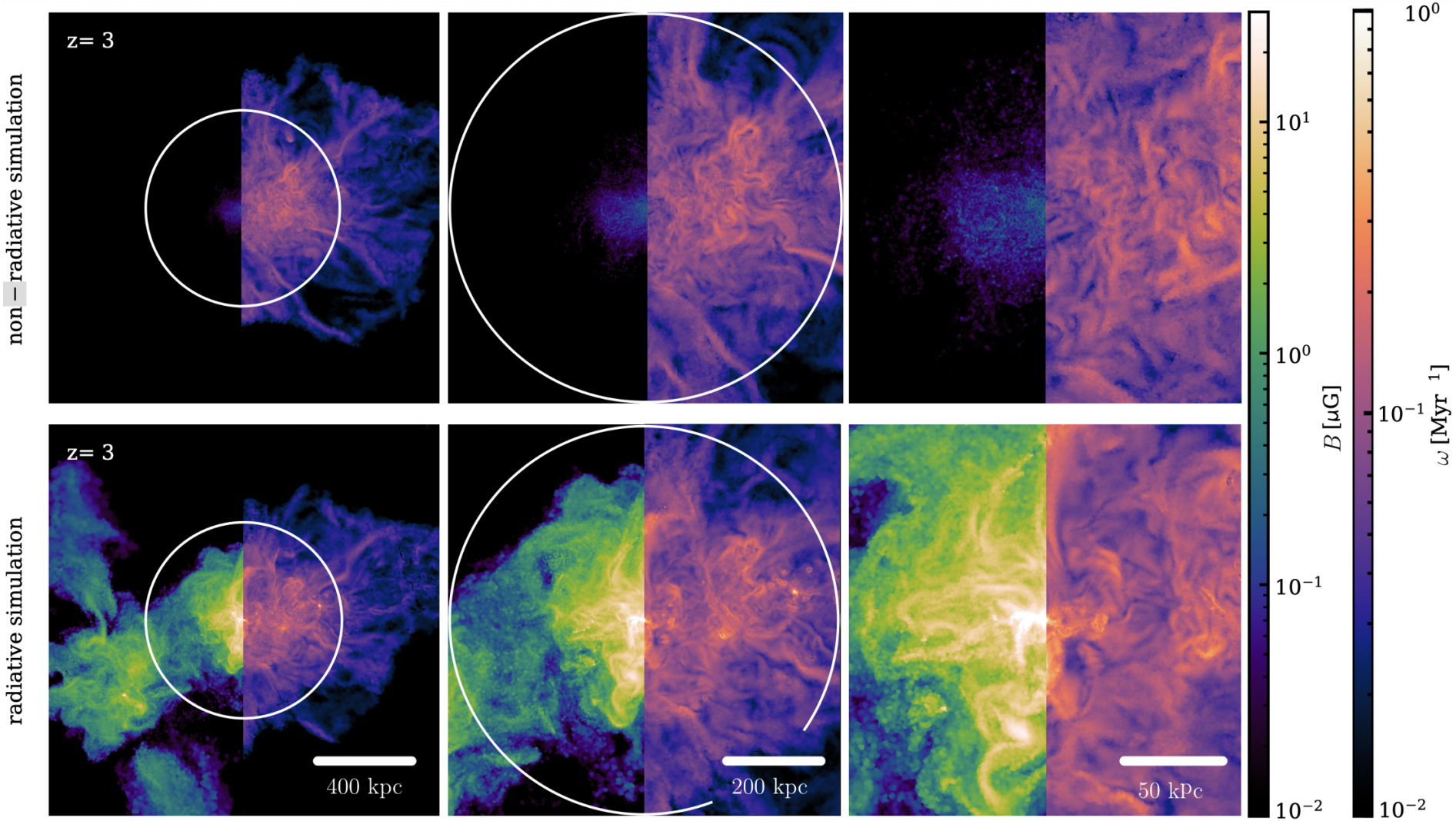
Weinberger, CP+ (in prep.)

AIP

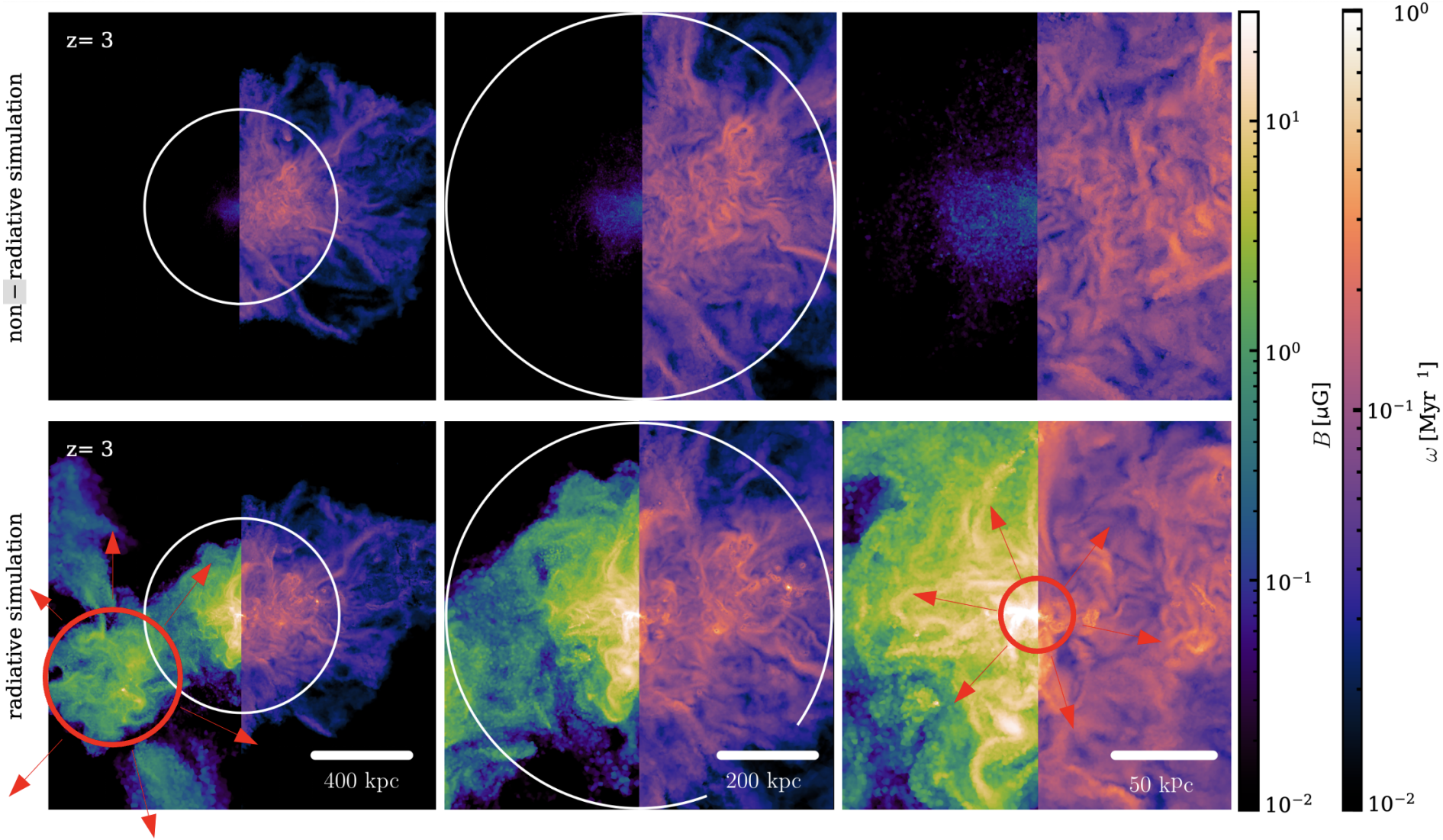
Magnetic fields and vorticity comparable at $z = 0$



Faster magnetic growth in radiative simulation



Feedback pollutes the ICM with magnetic fields



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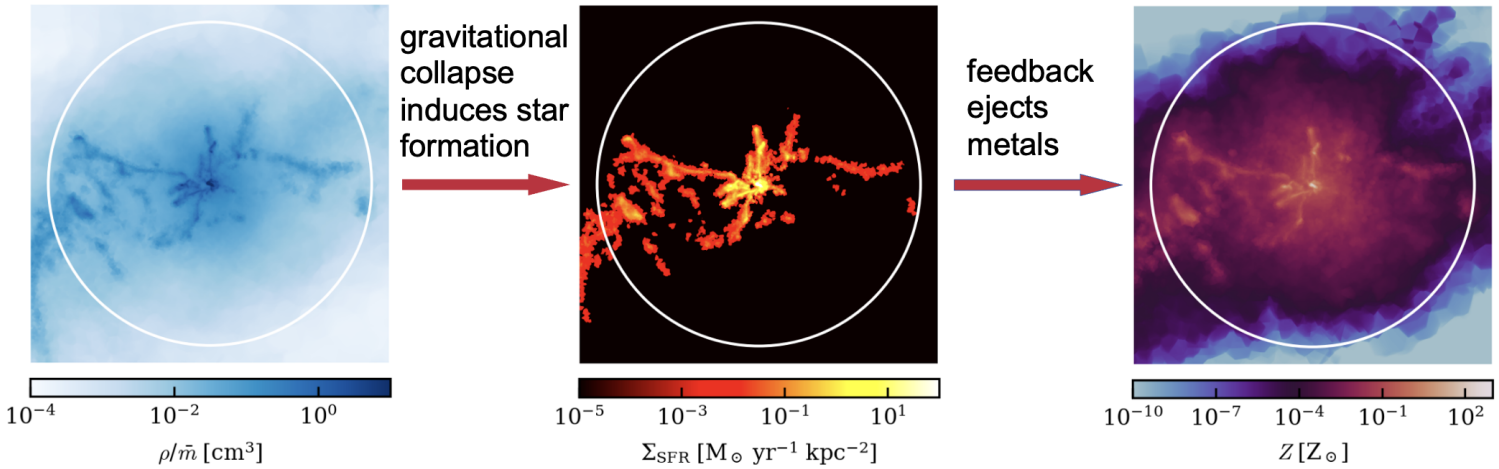

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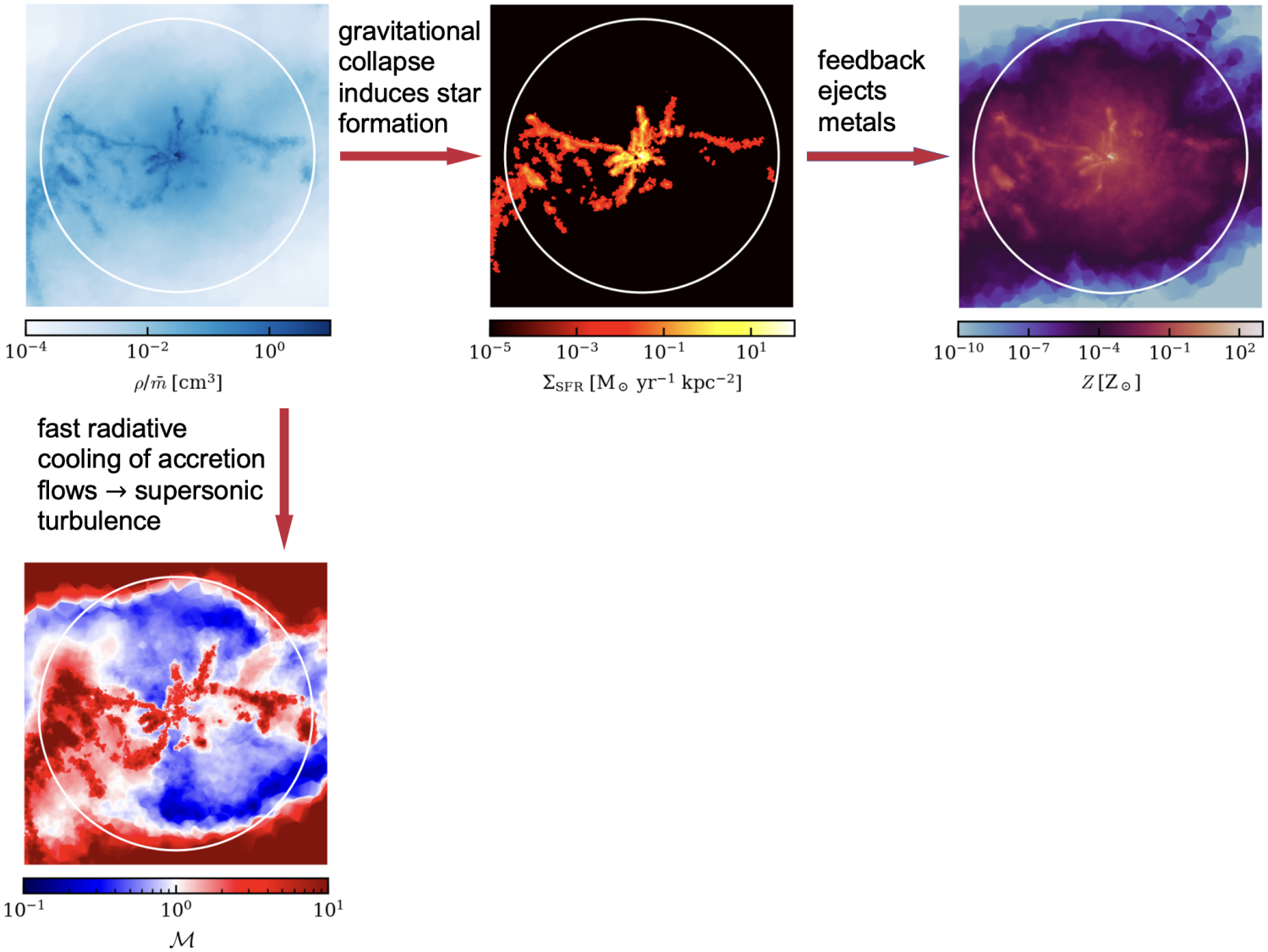

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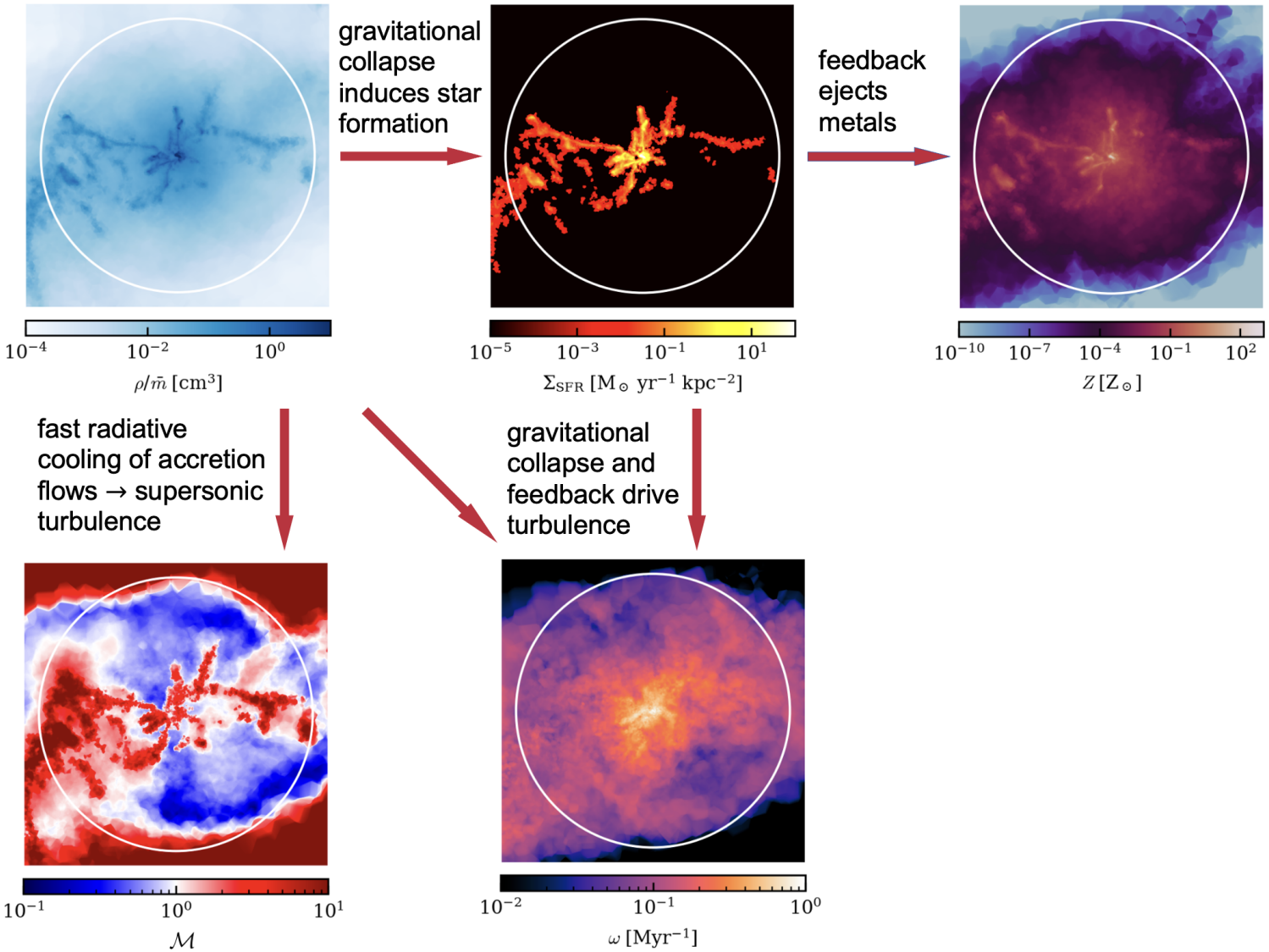

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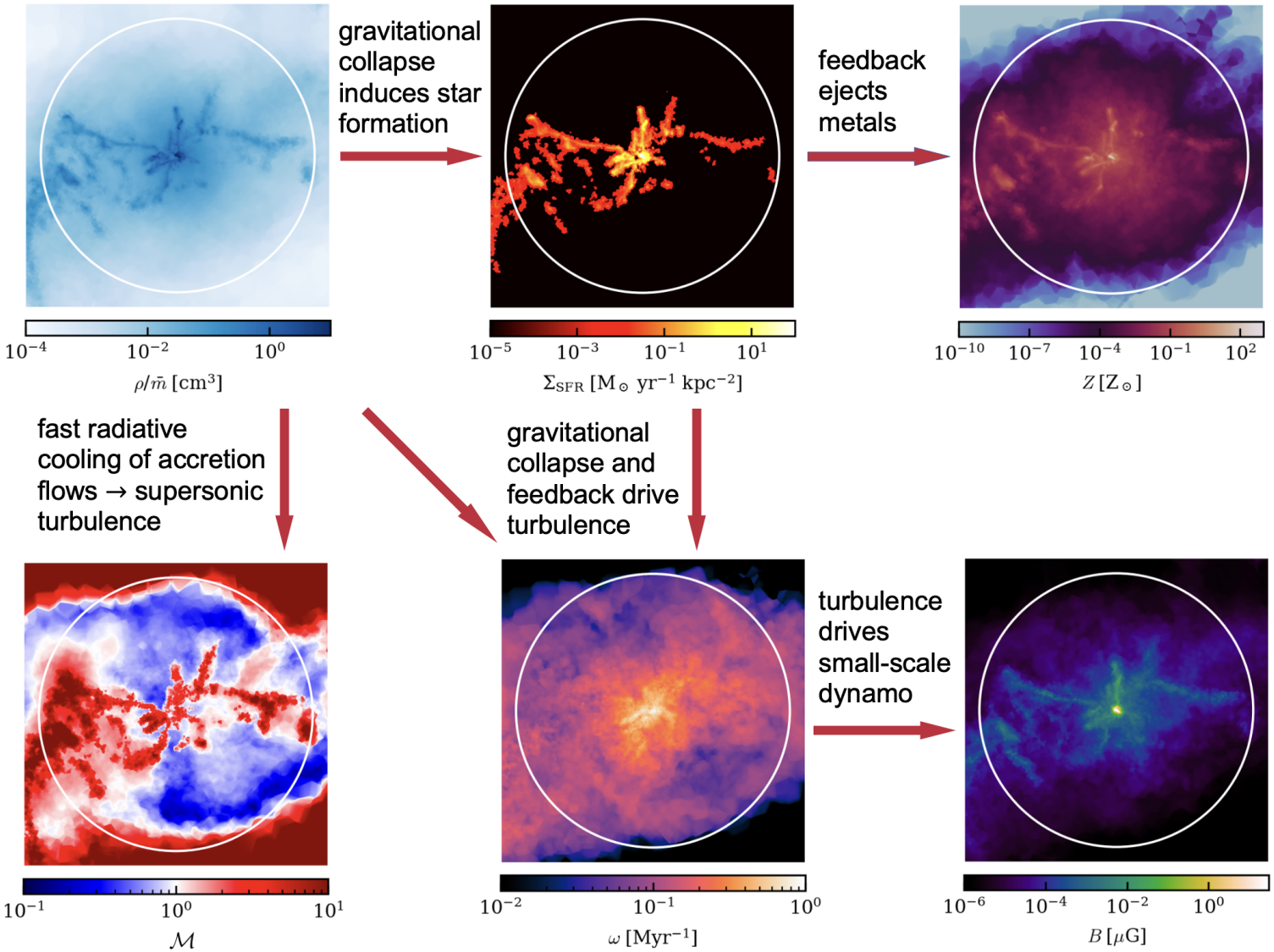

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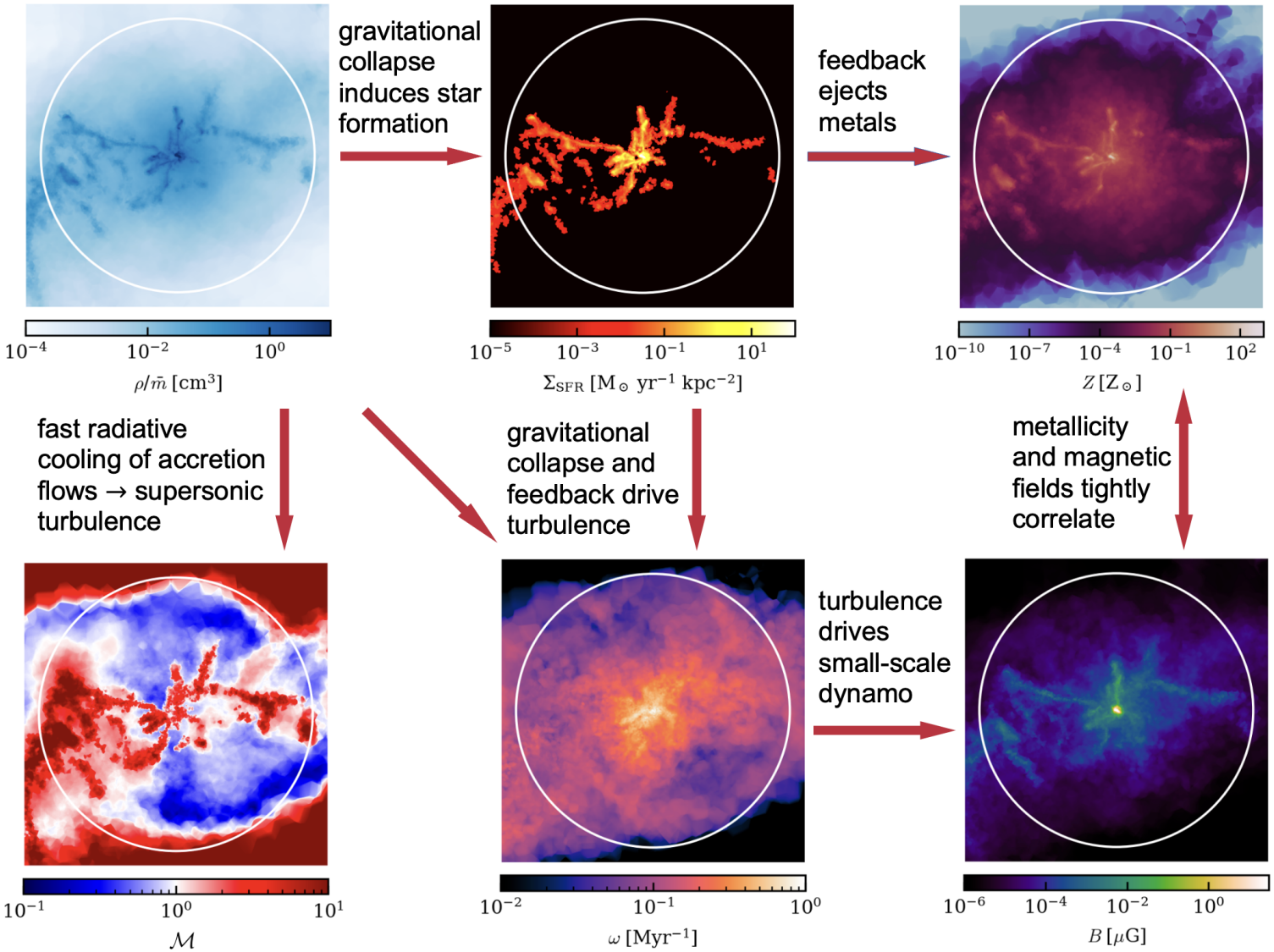

Kinetic and magnetic power spectra in proto-clusters

The emerging picture:

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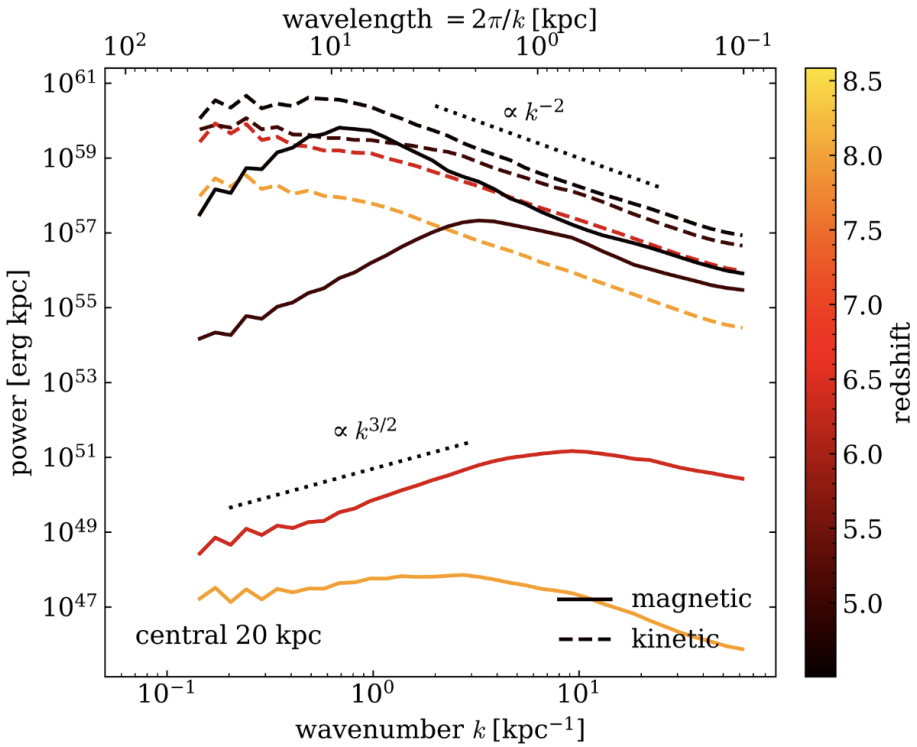

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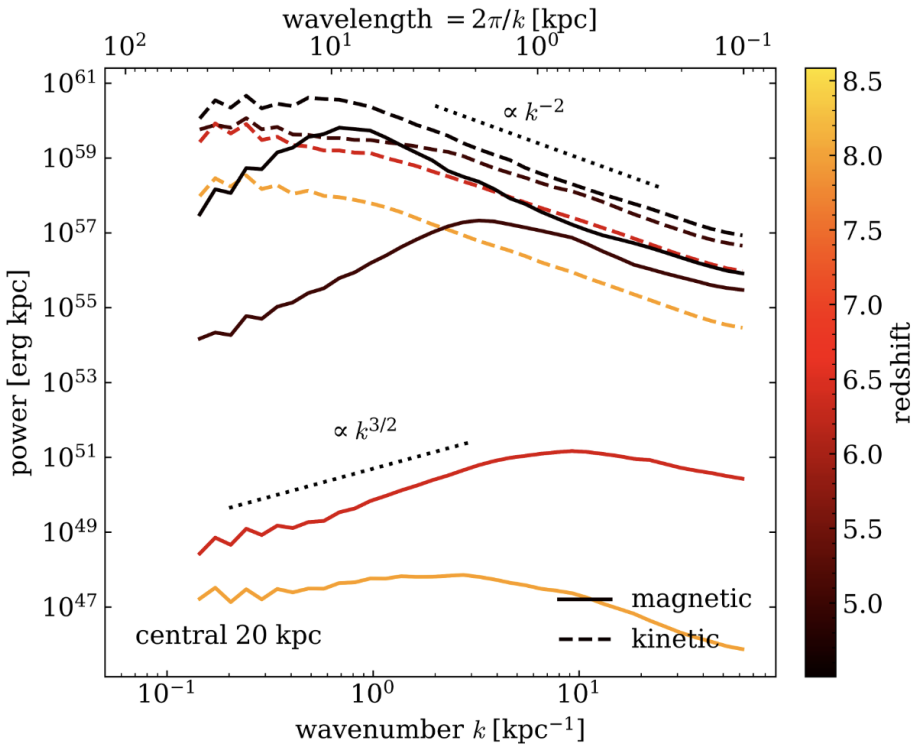

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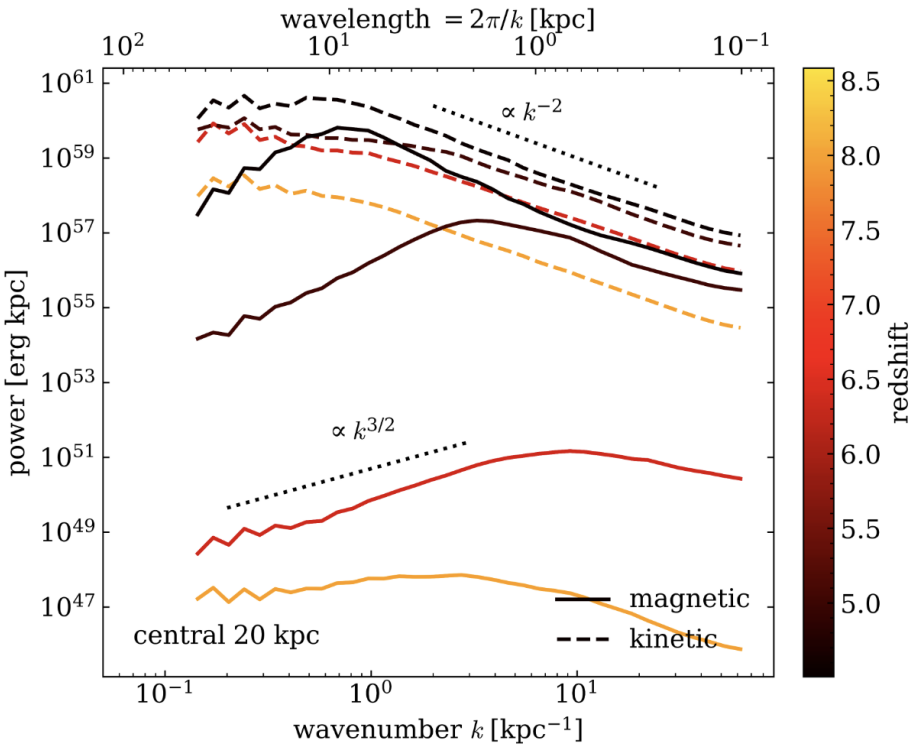

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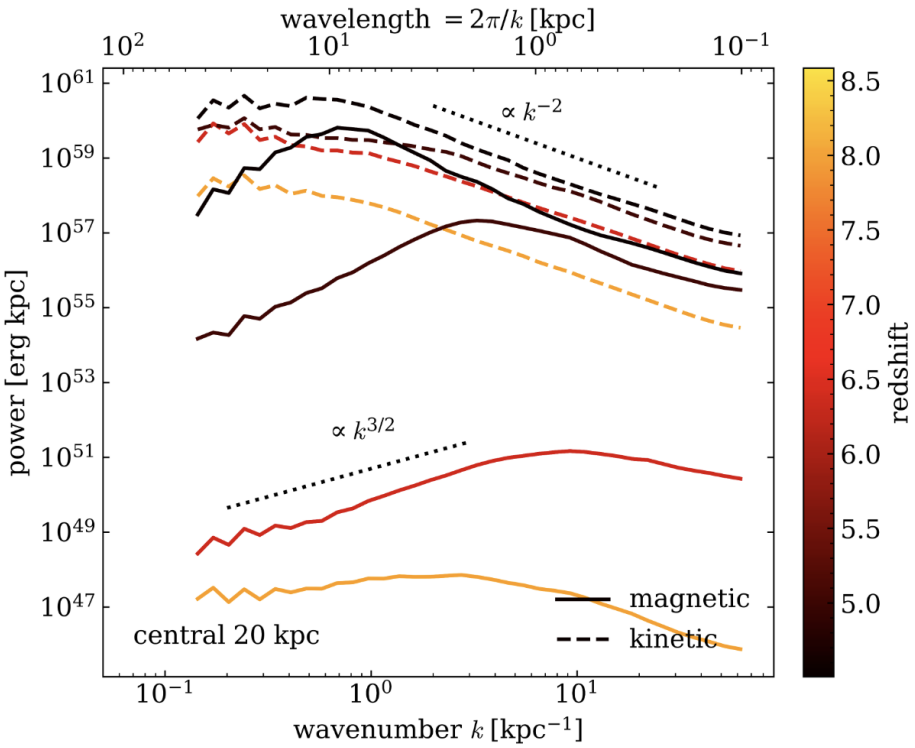
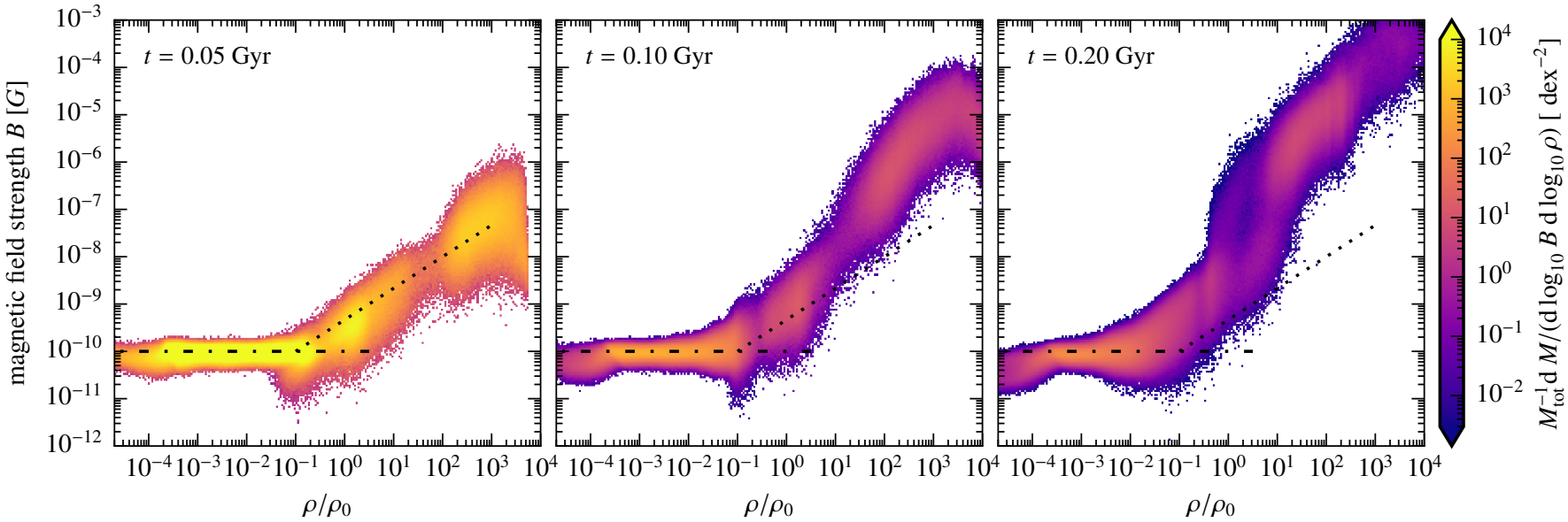
- ***At late times,*** after the field has saturated on small scales, the magnetic coherence scale grows



Identifying magnetic growth phases in a **galaxy**



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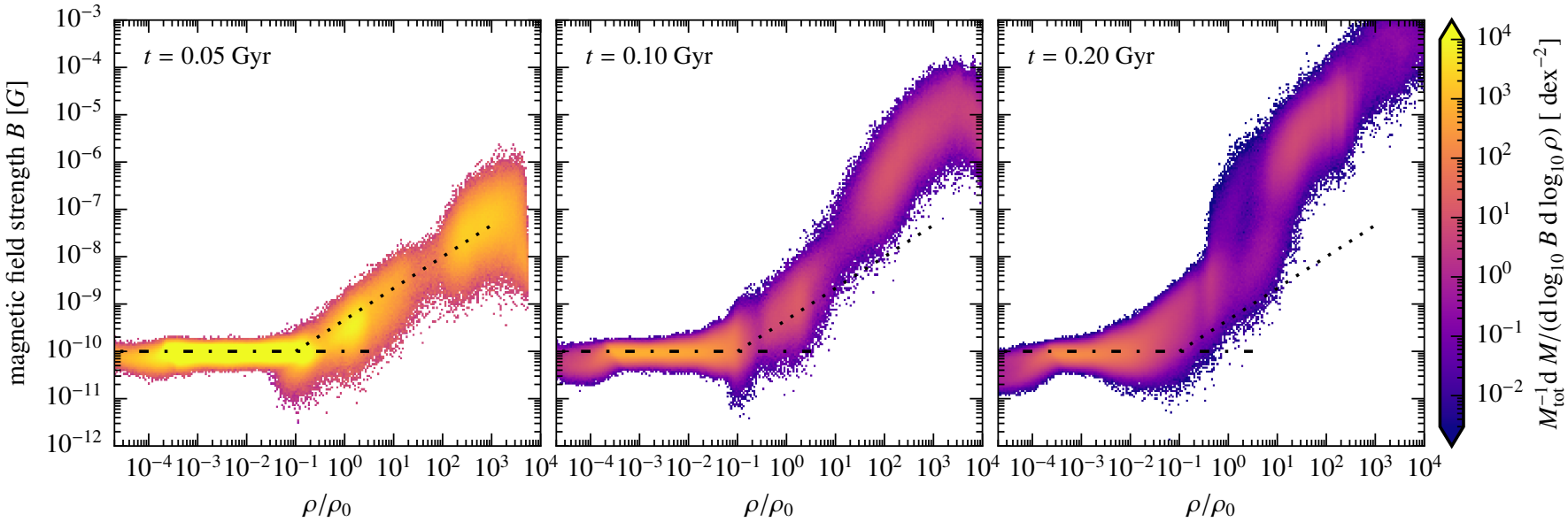

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AIP

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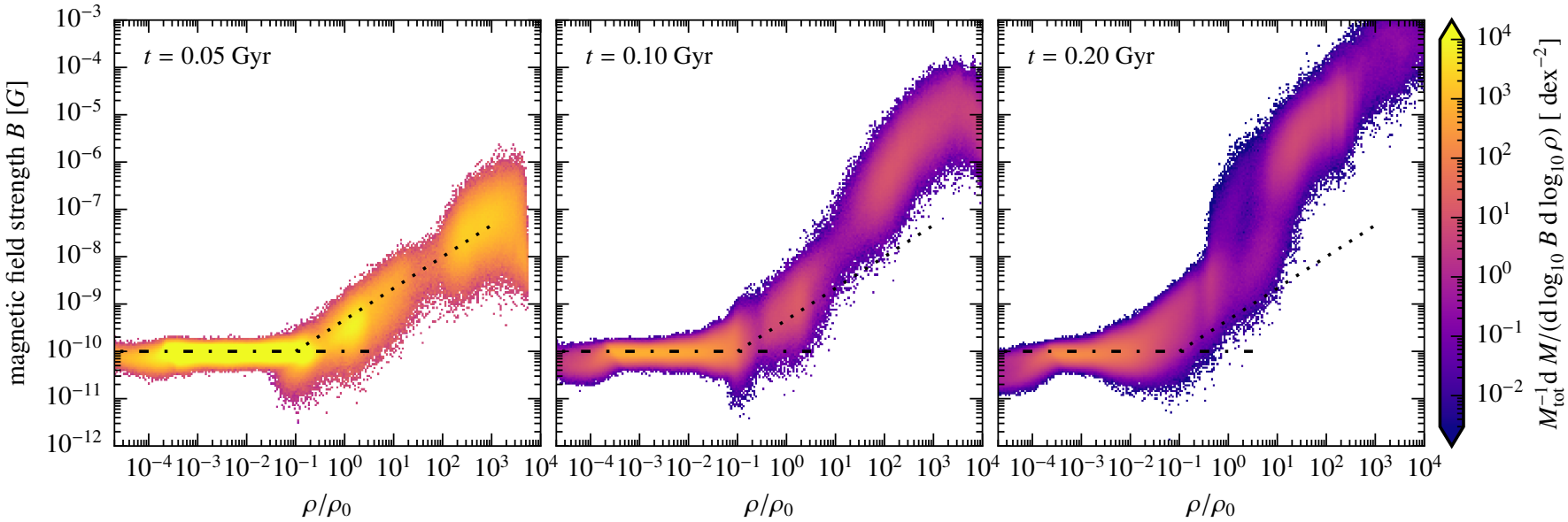

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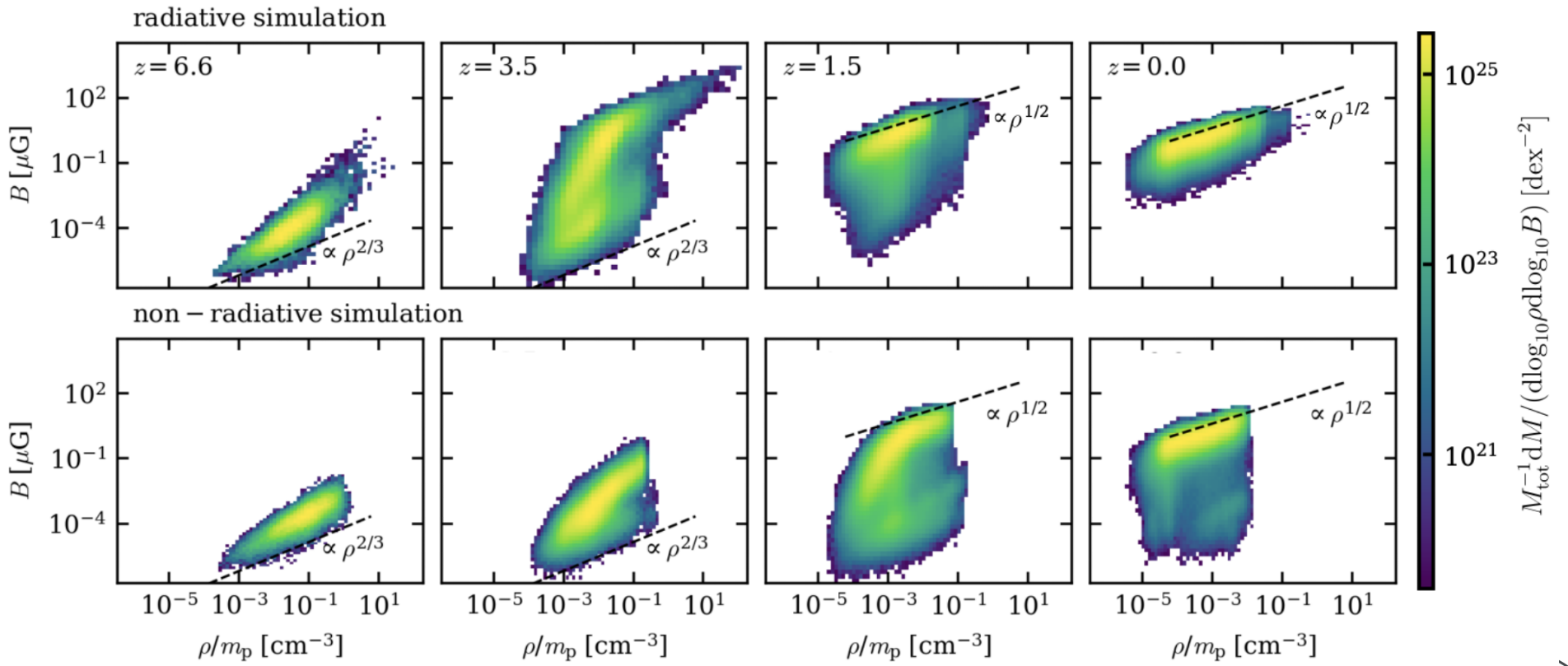

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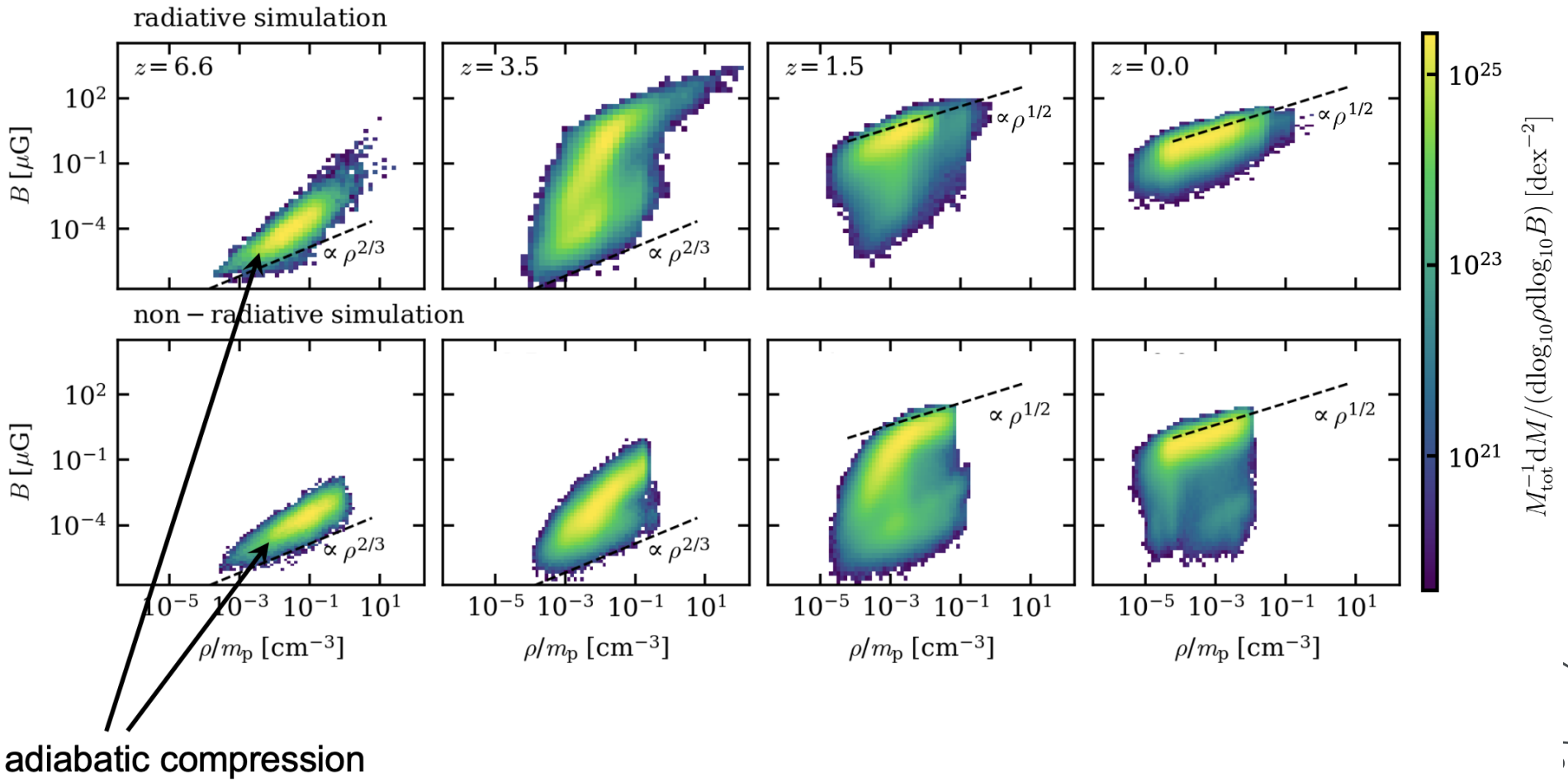

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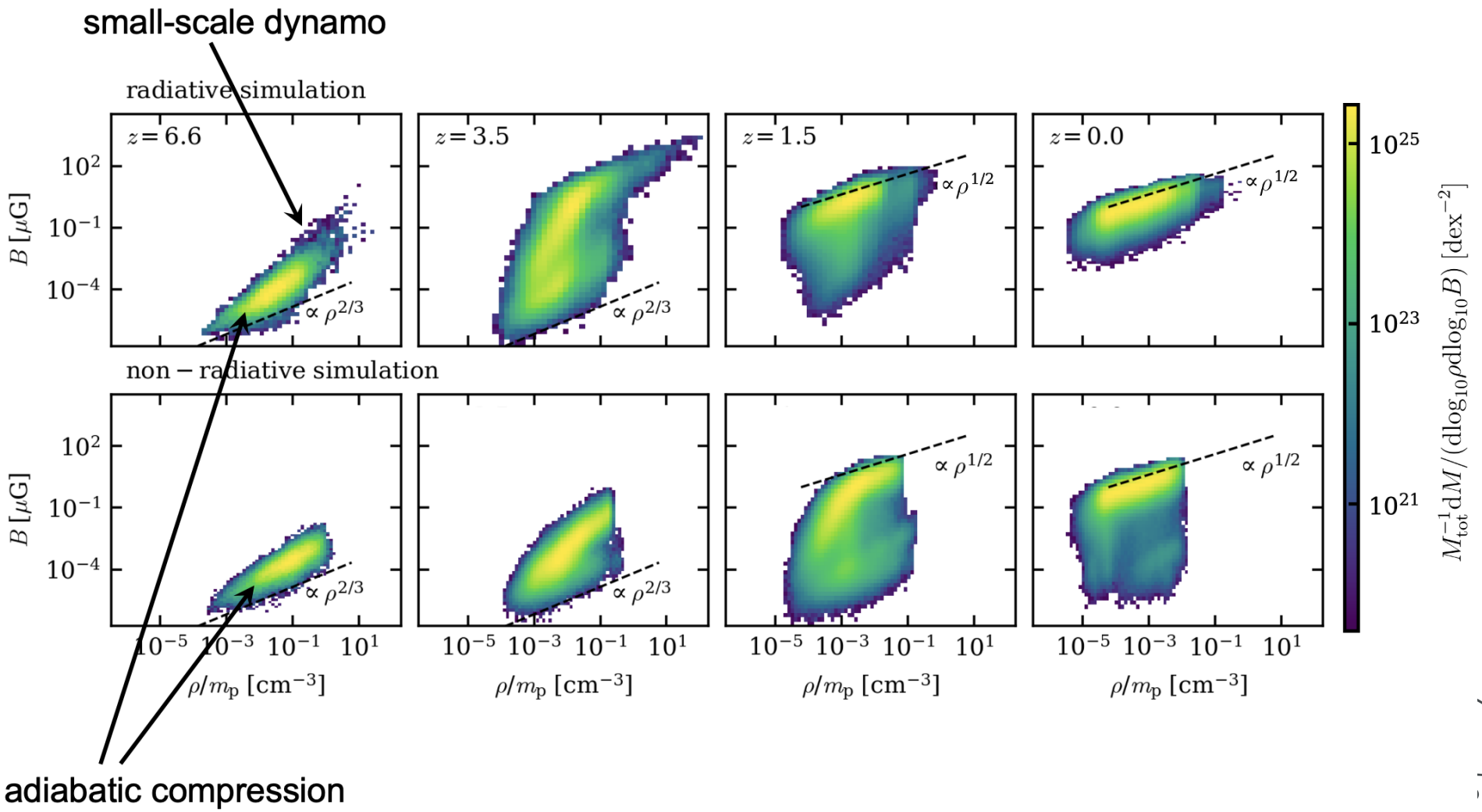

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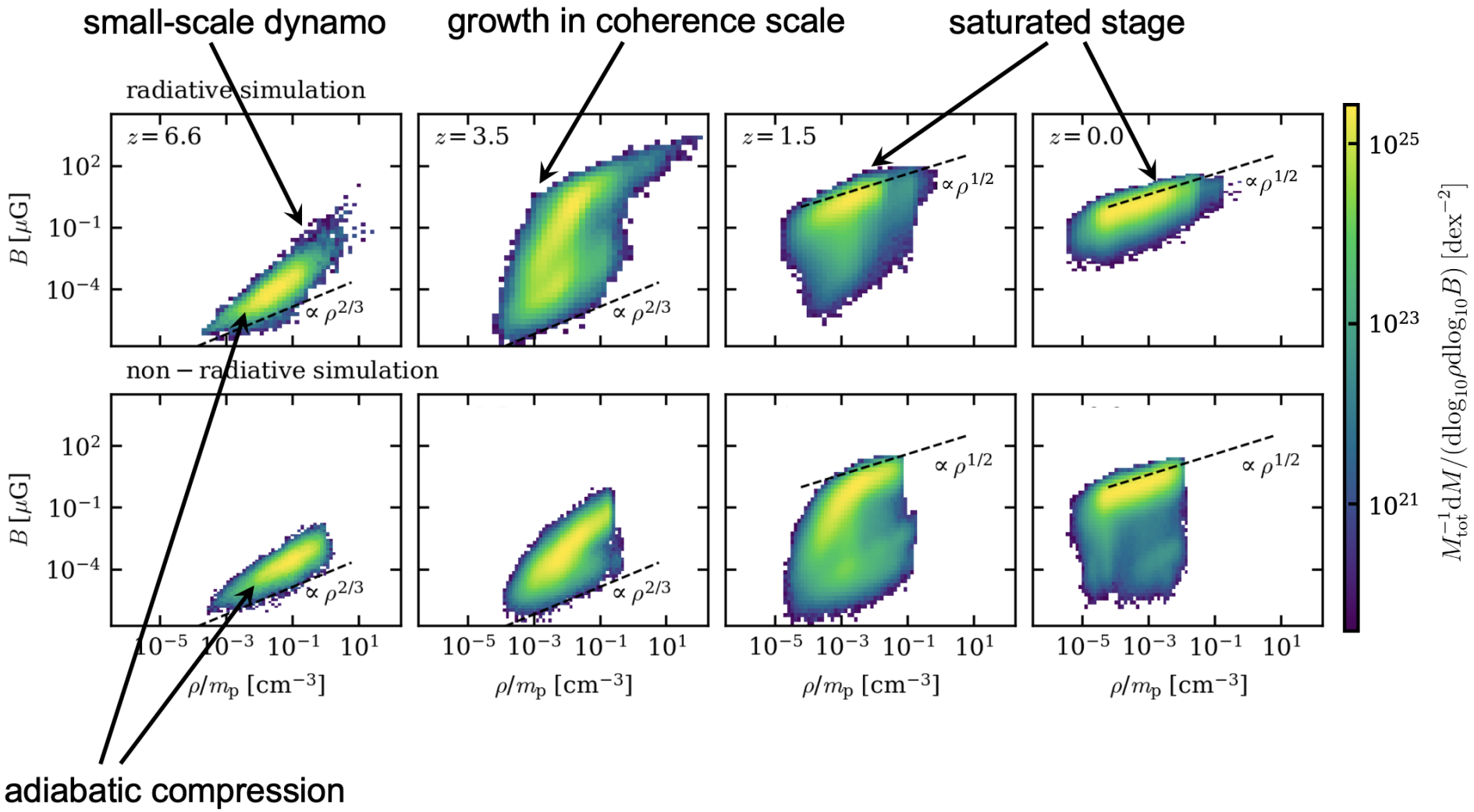

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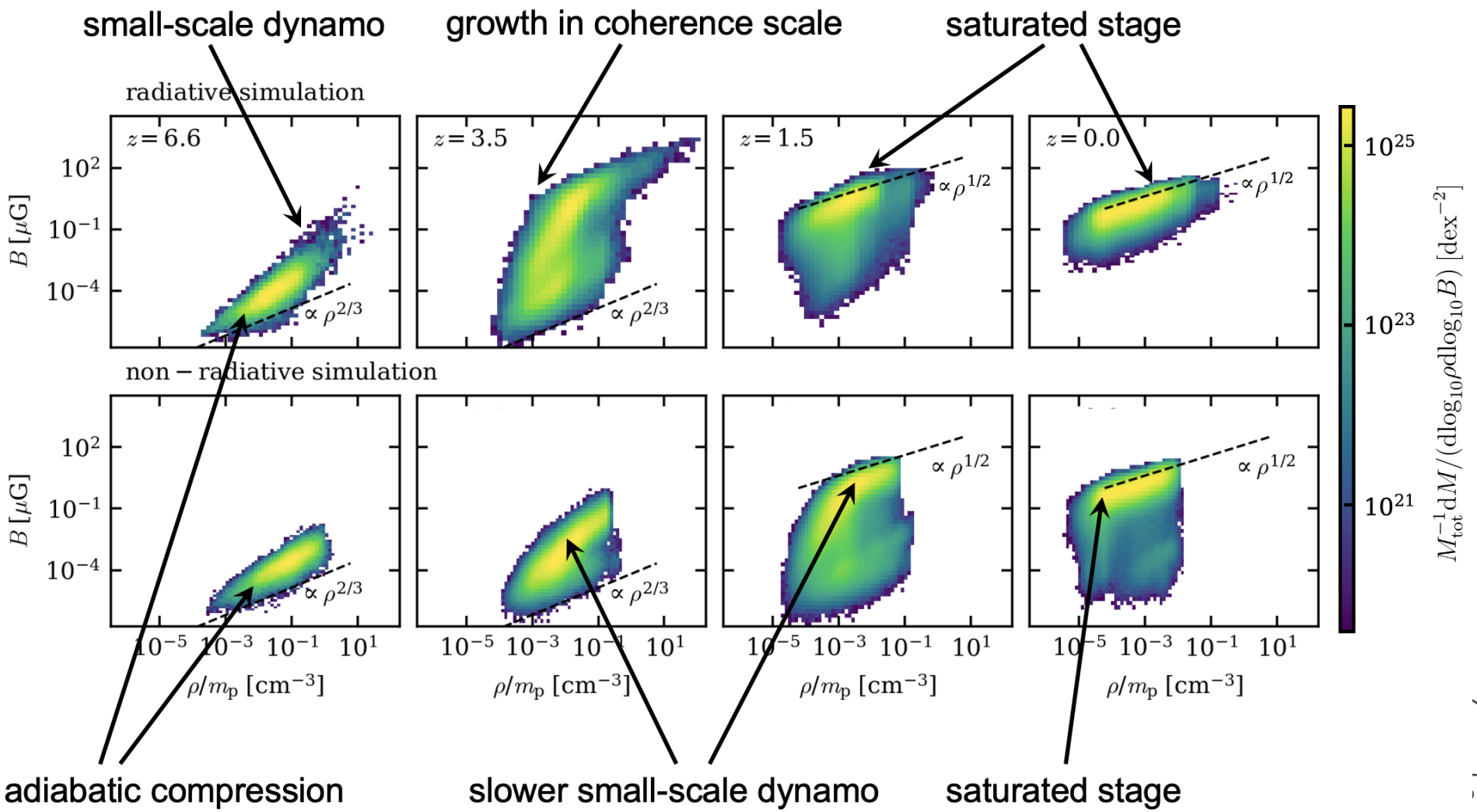
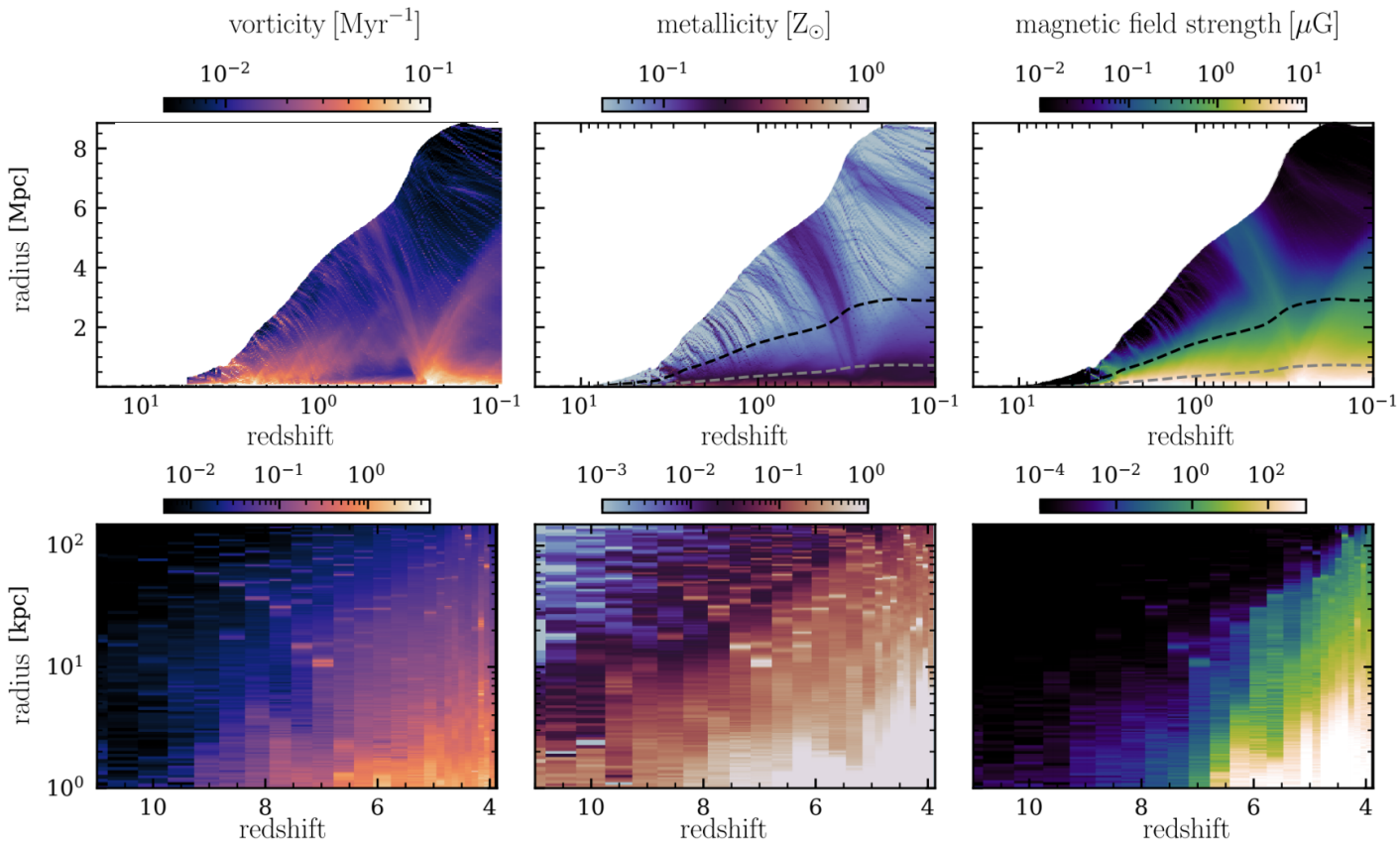


From galaxies & AGNs to the intracluster medium



Enrichment in the entire cluster

Enrichment in BCG

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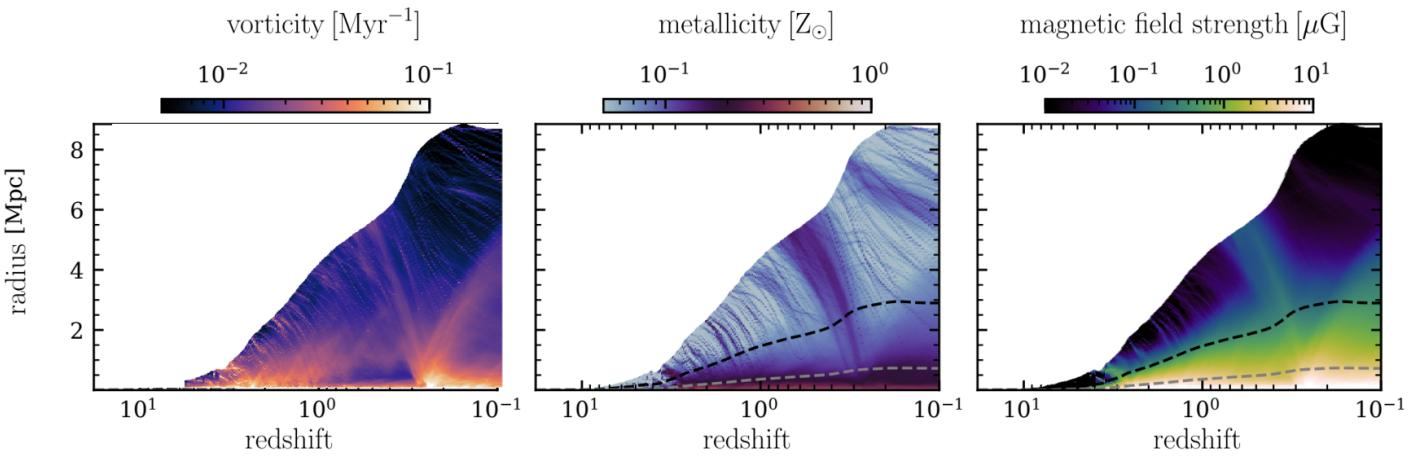

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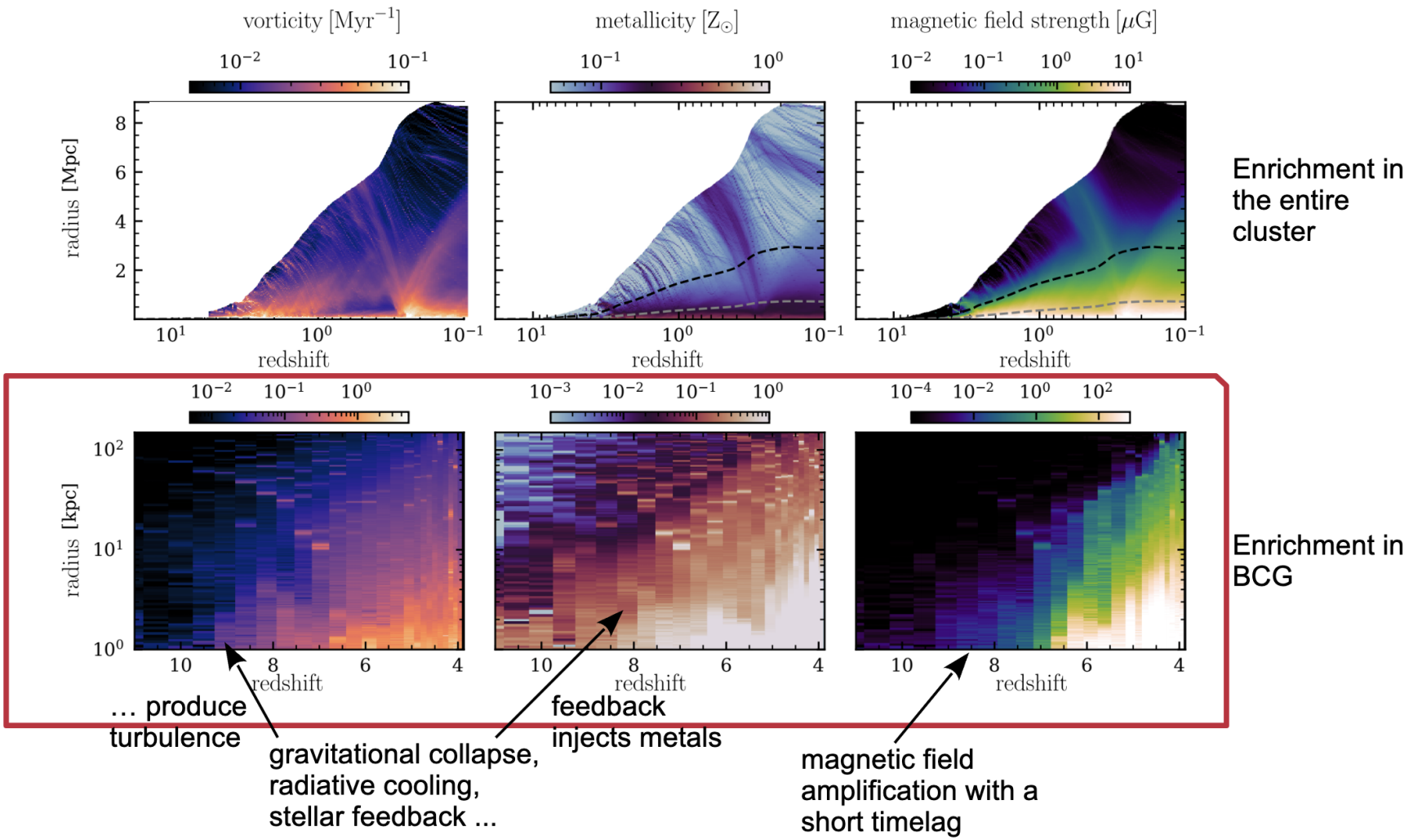

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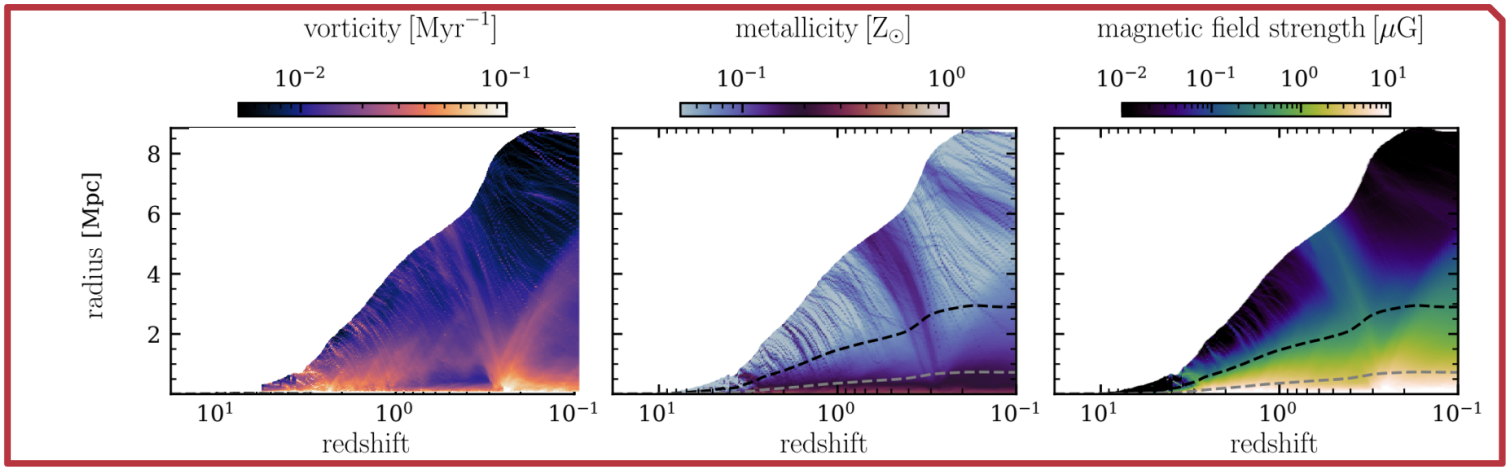
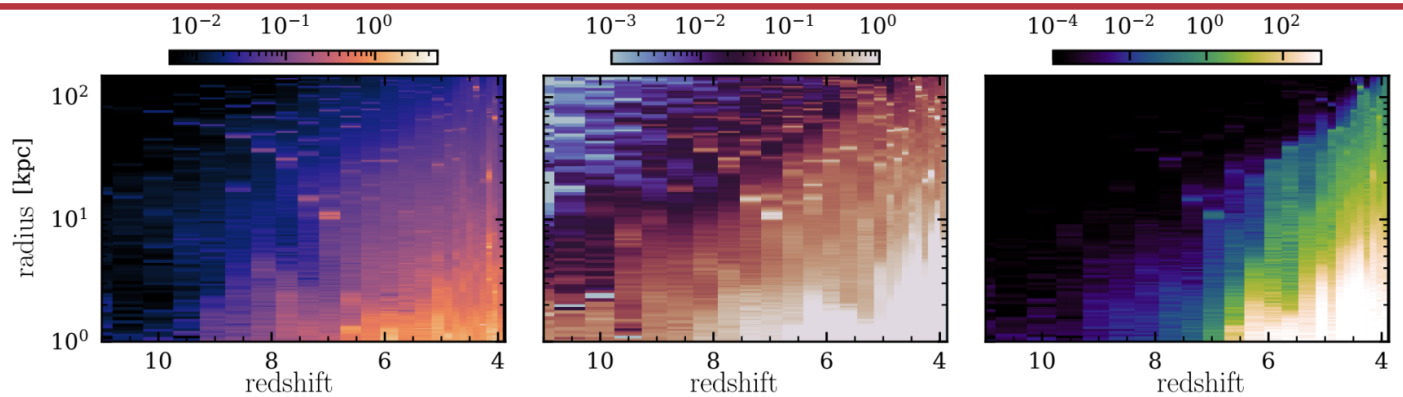
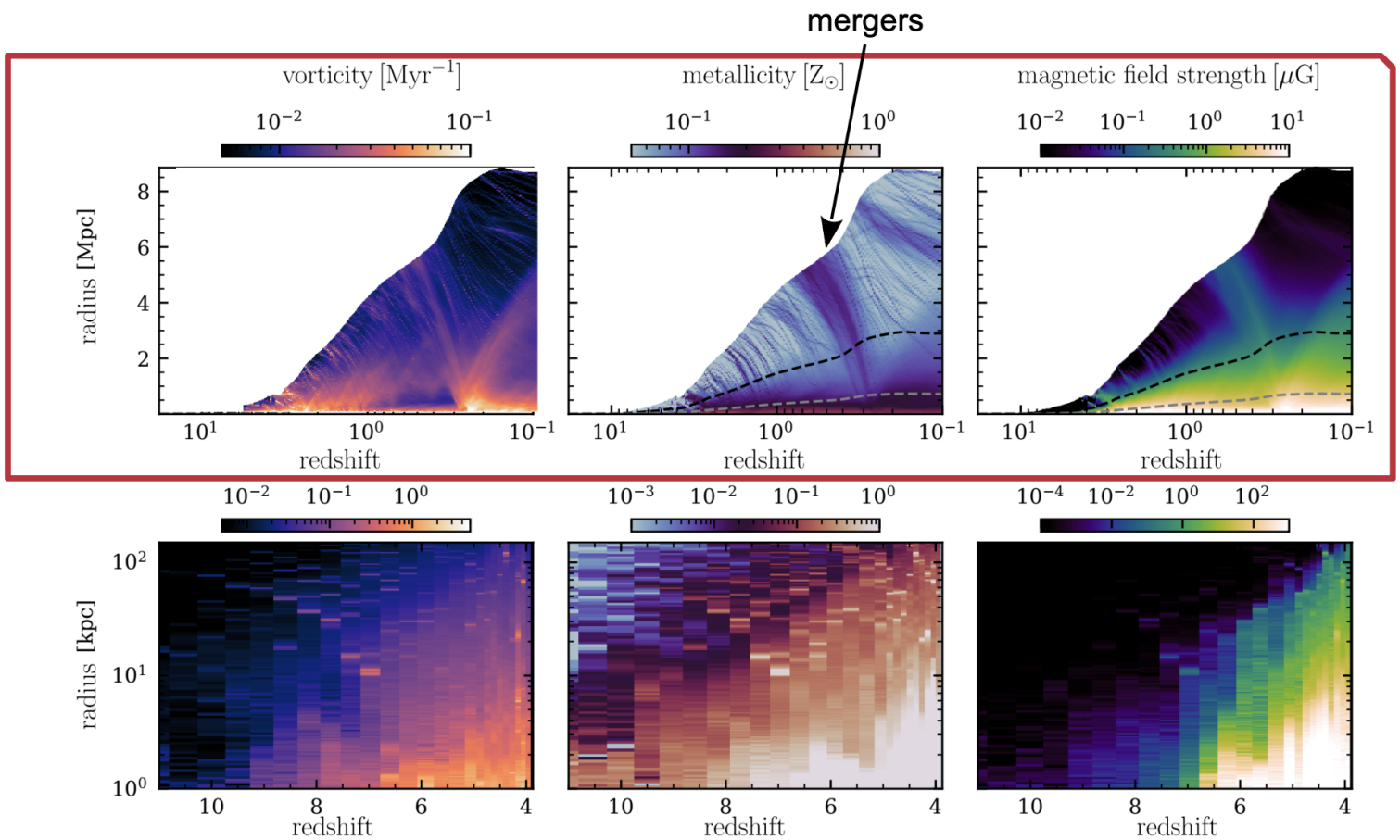


Enrichment in the entire cluster



Enrichment in BCG

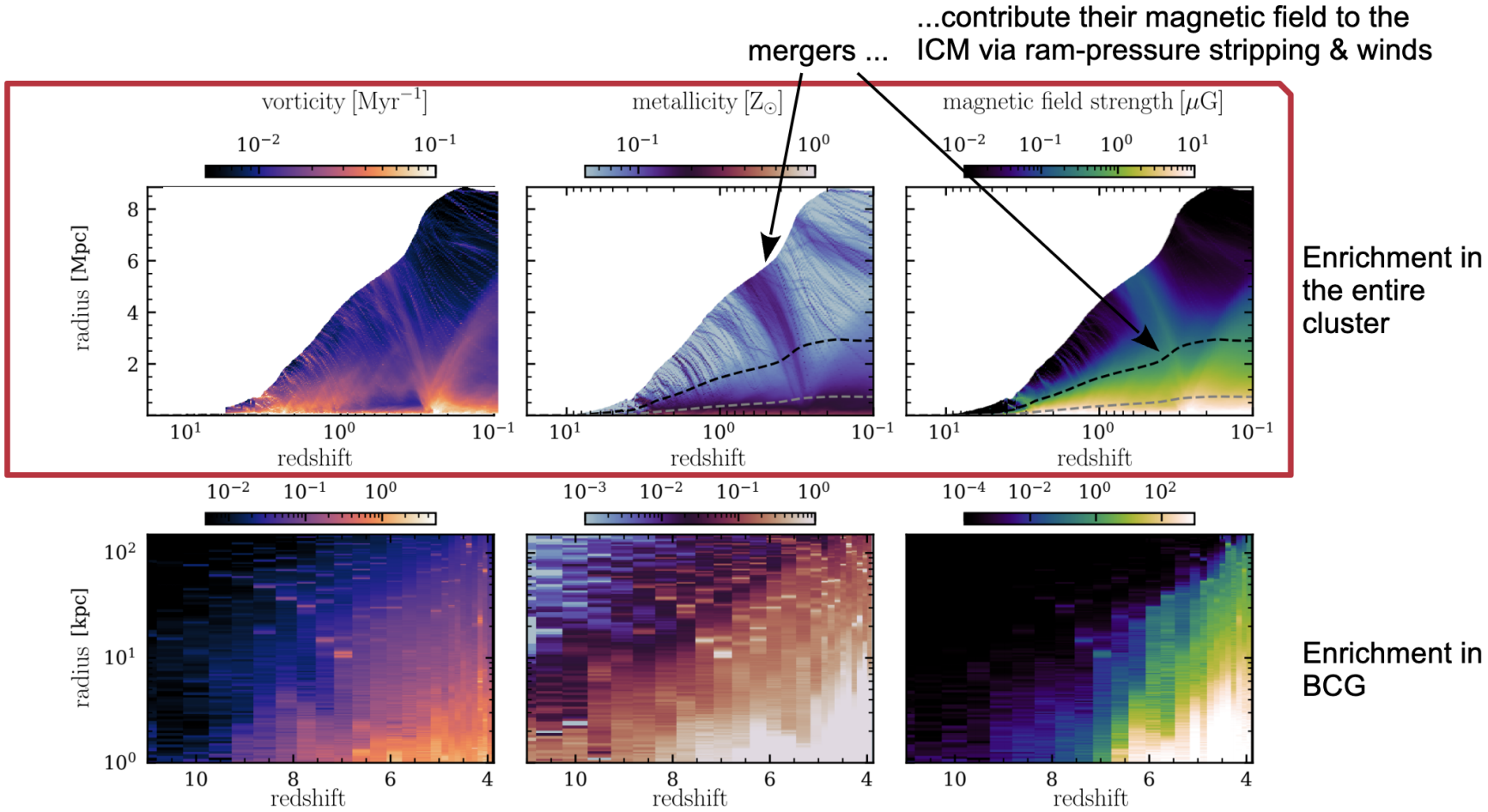
From galaxies & AGNs to the intracluster medium



Enrichment in the entire cluster

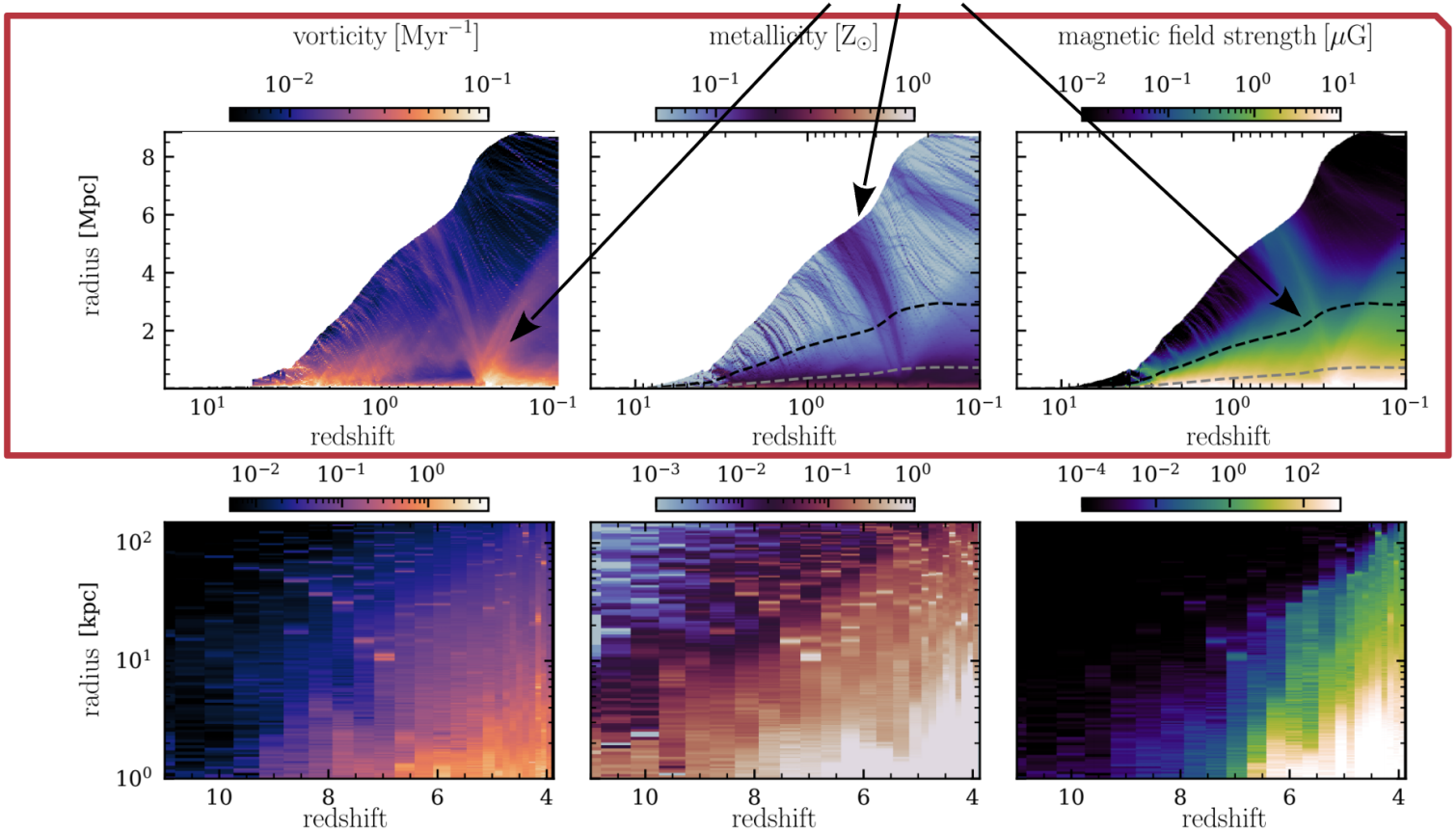
Enrichment in BCG

From galaxies & AGNs to the intracluster medium



From galaxies & AGNs to the intracluster medium

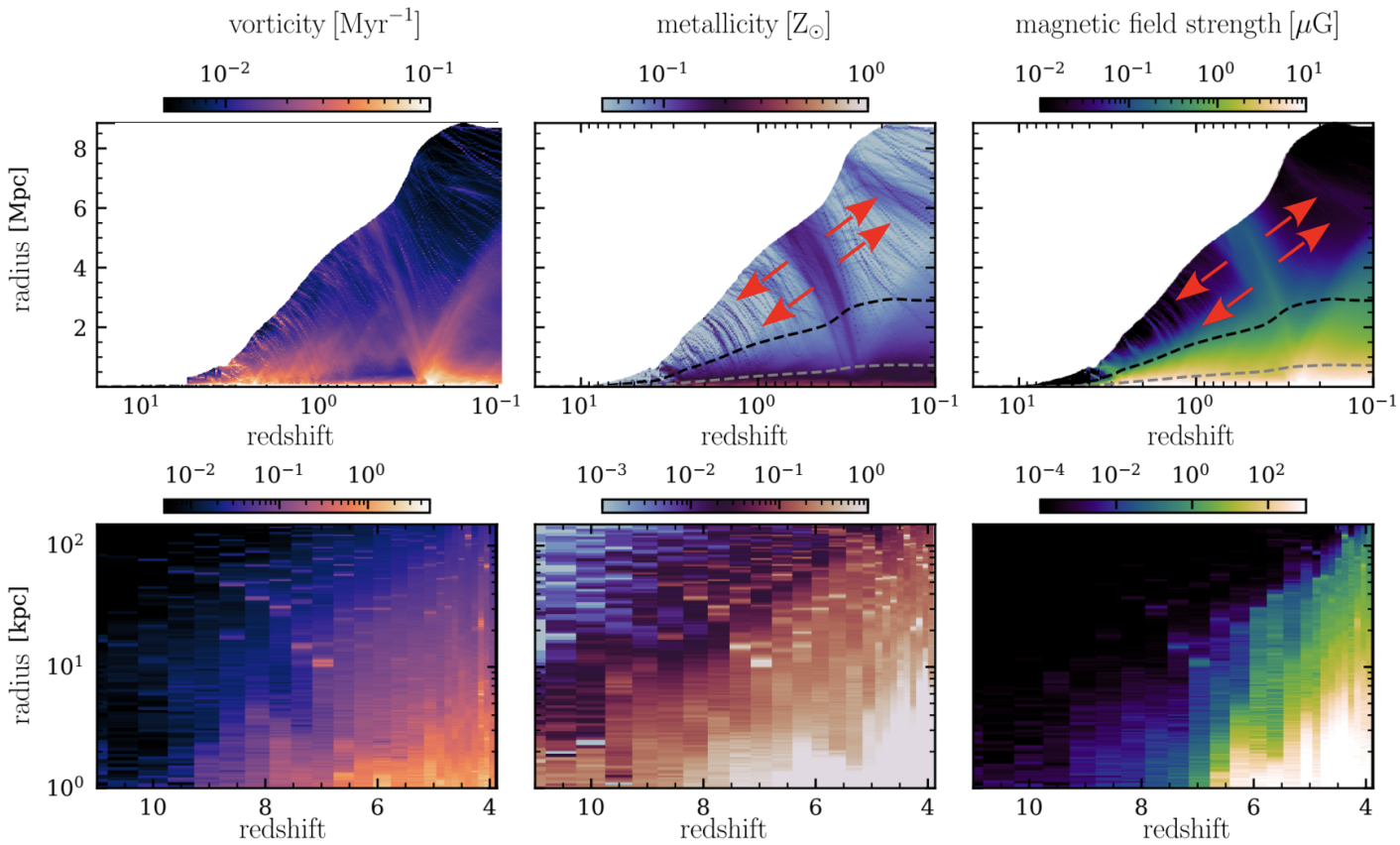
… inject turbulence mergers ... ...contribute their magnetic field to the ICM via ram-pressure stripping & winds



Enrichment in the entire cluster

Enrichment in BCG

Cluster magnetic fields are linked to galaxy formation

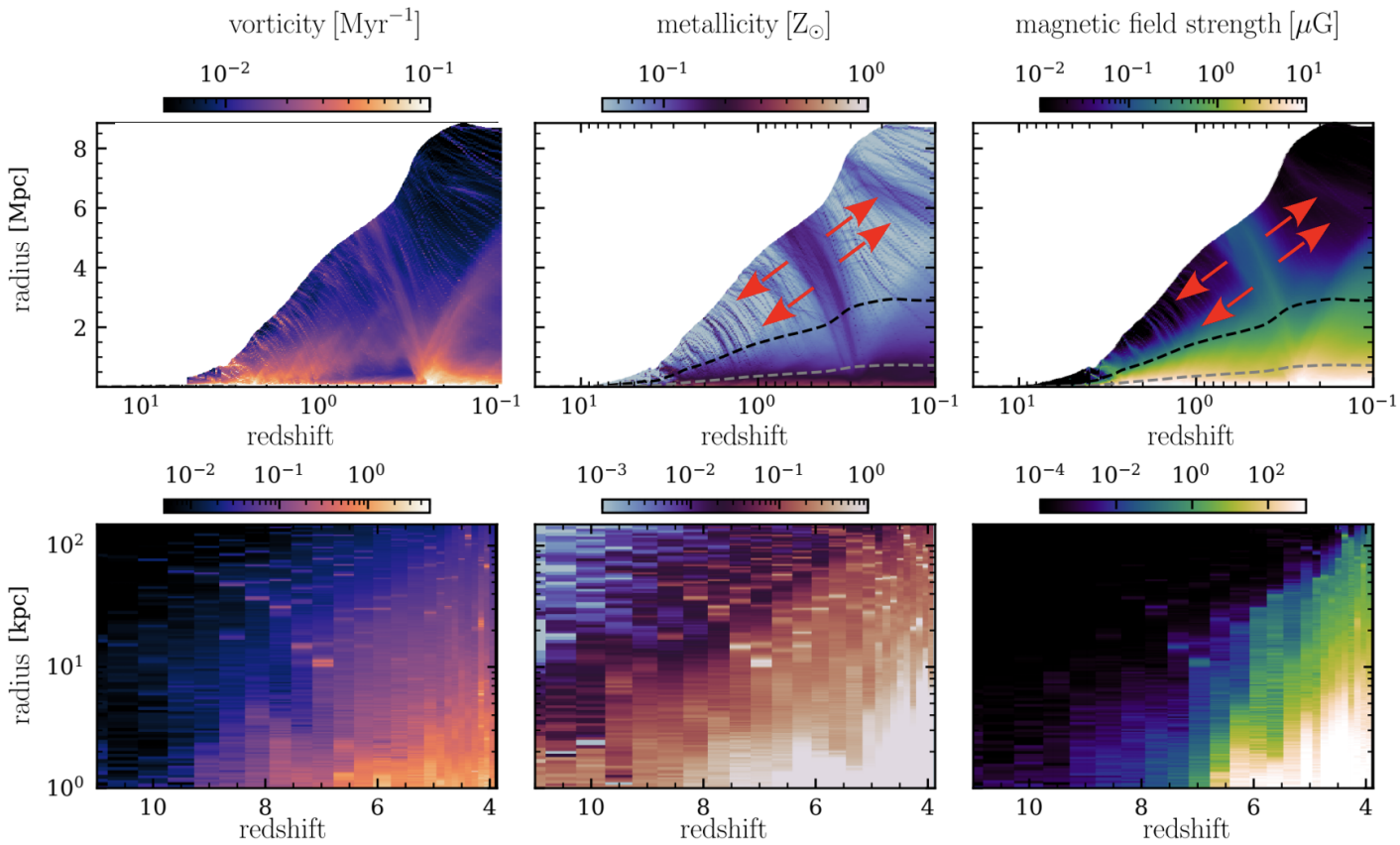


Enrichment in the entire cluster

Enrichment in BCG

→ Ram-pressure stripping and galactic winds gravitationally unbind the pre-enriched gas from galaxies

Cluster magnetic fields are linked to galaxy formation

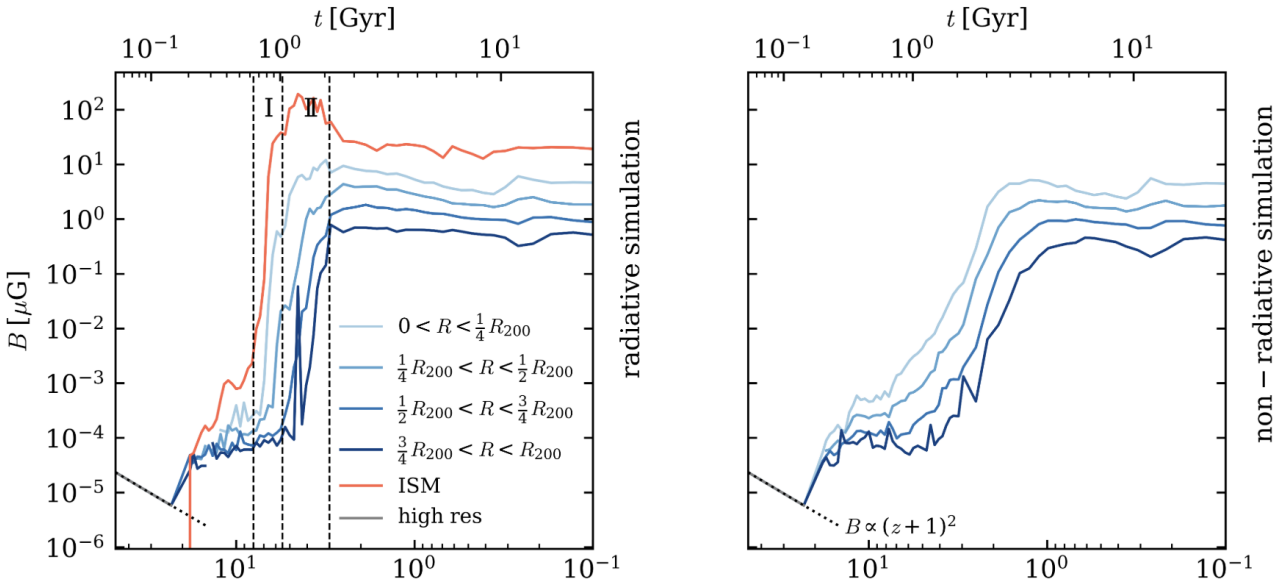


Enrichment in the entire cluster

Enrichment in BCG

→ Magnetic fields are intrinsically linked to galaxy cluster formation:
- first, magnetic fields grow in the earliest galaxies
- subsequently, accreted galaxies enrich the ICM with pre-magnetized plasma

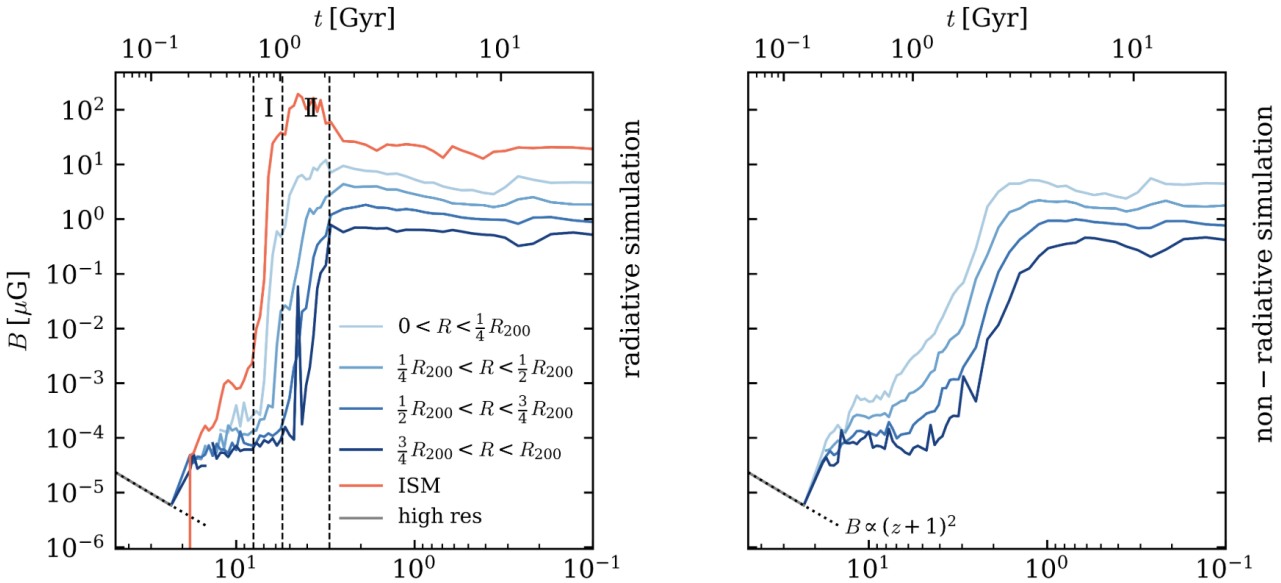
Magnetic field evolution in galaxy clusters



Cluster magnetic field growth intrinsically linked to galaxy formation:

- *1st phase:* growth in the earliest galaxies (adiabatic compression, small-scale dynamo)

Magnetic field evolution in galaxy clusters



Cluster magnetic field growth intrinsically linked to galaxy formation:

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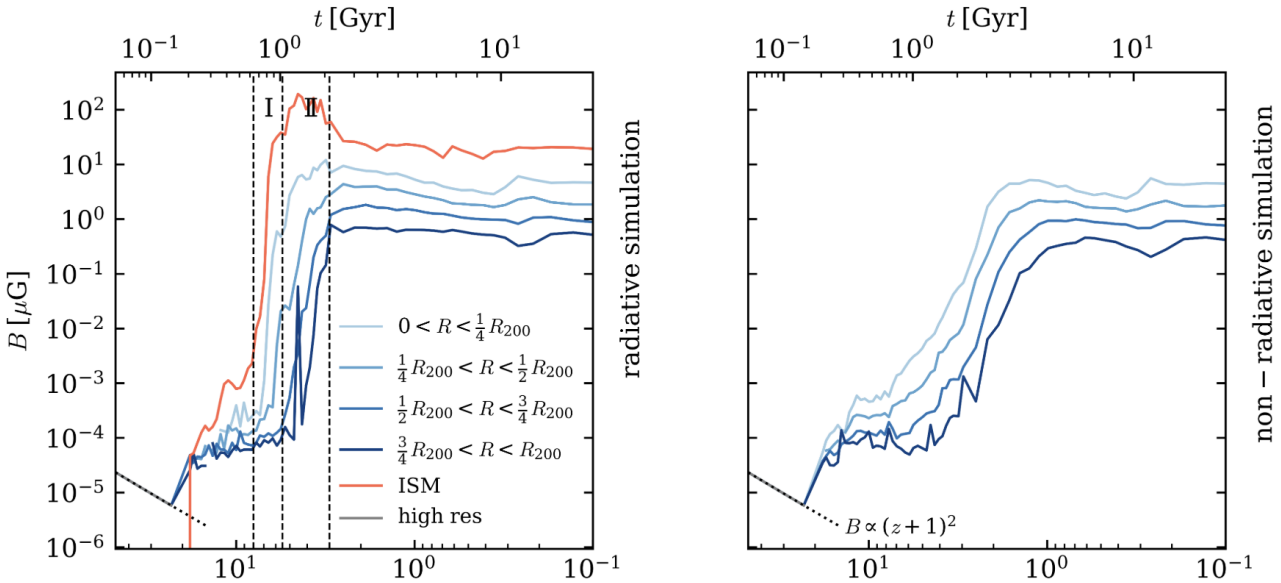
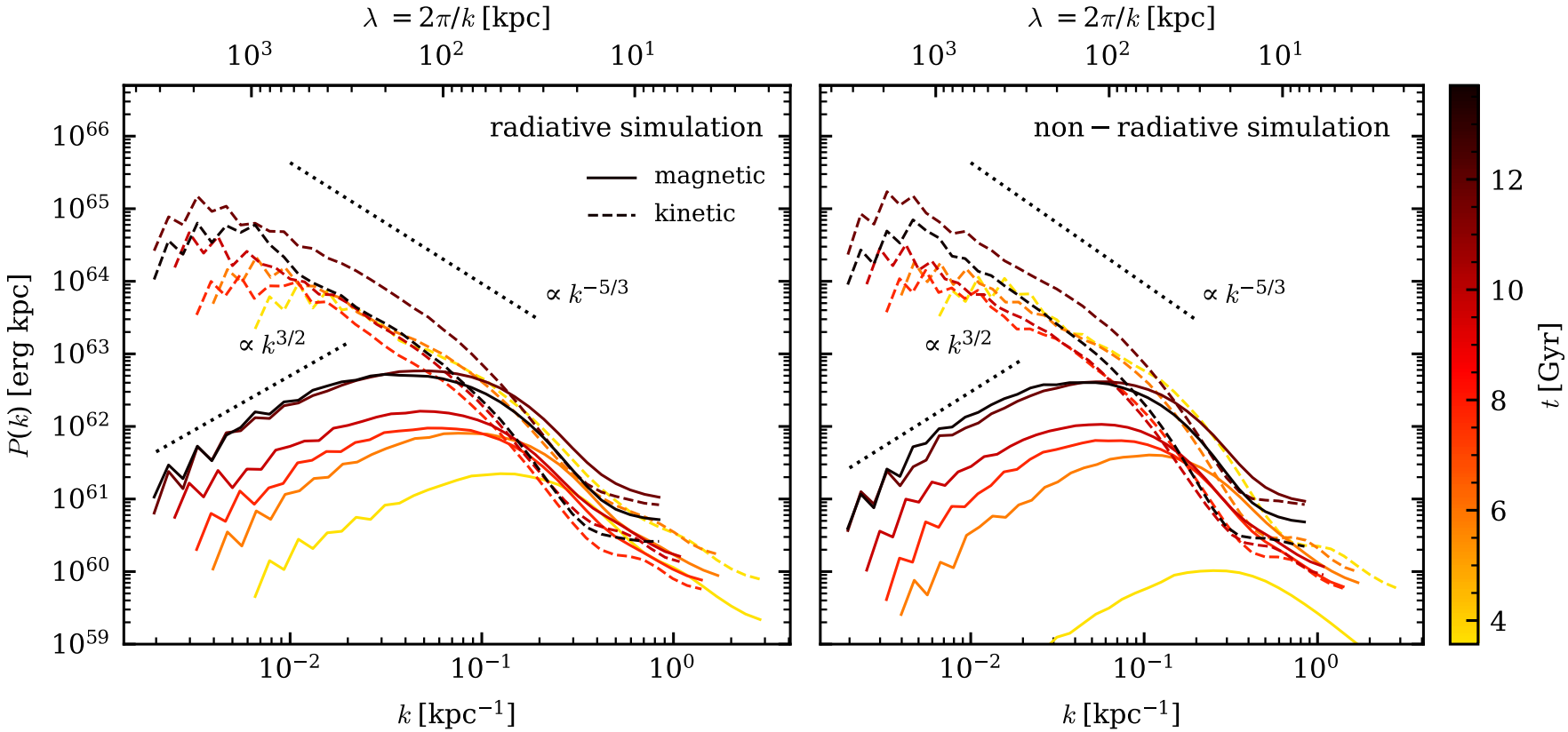


Cluster magnetic field growth intrinsically linked to galaxy formation:

- *1st phase:* growth in the earliest galaxies (adiabatic compression, small-scale dynamo)
- *2nd phase:* galactic winds & ram-pressue stripping from accreted galaxies enrich ICM magnetically
- *3rd phase:* small-scale dynamo in ICM grows coherence length and maintains field strength

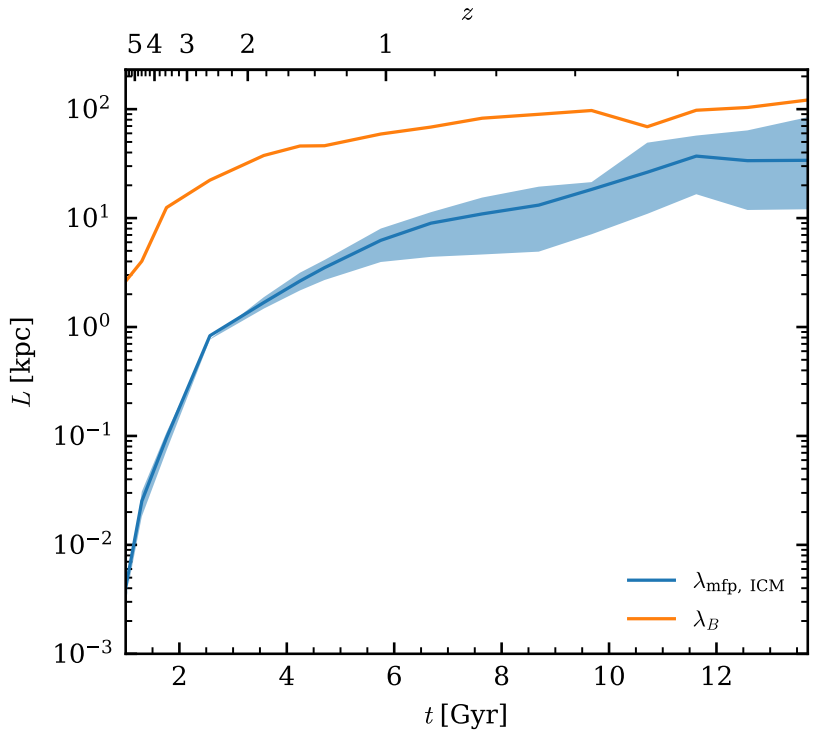
Small-scale dynamo in the intracluster medium



- At late times, subsonic turbulence in the ICM is excited by cluster mergers and cosmic accretion and grows coherence length and maintains field strength via a small-scale dynamo

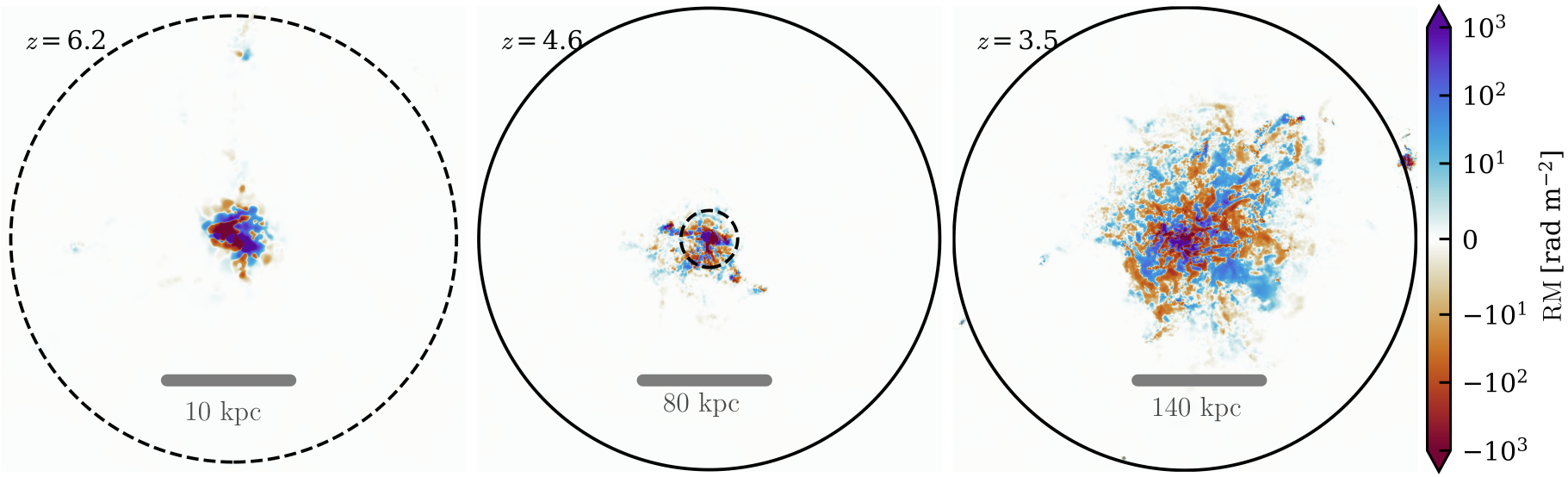
The case against a collisionless plasma dynamo

Comparison of the particle mean free path λ_{mfp} and the magnetic coherence length λ_B



- $\lambda_B \gg \lambda_{\mathrm{mfp}}$ during dynamo action ($z \simeq 5.5$) due to magnetic expansion into the ICM by means of galactic winds and ram pressure stripping
- ICM dynamo operates in the fully collisional regime throughout the entire cosmic history, rendering the MHD approximation valid

Probing the cluster magnetization observationally

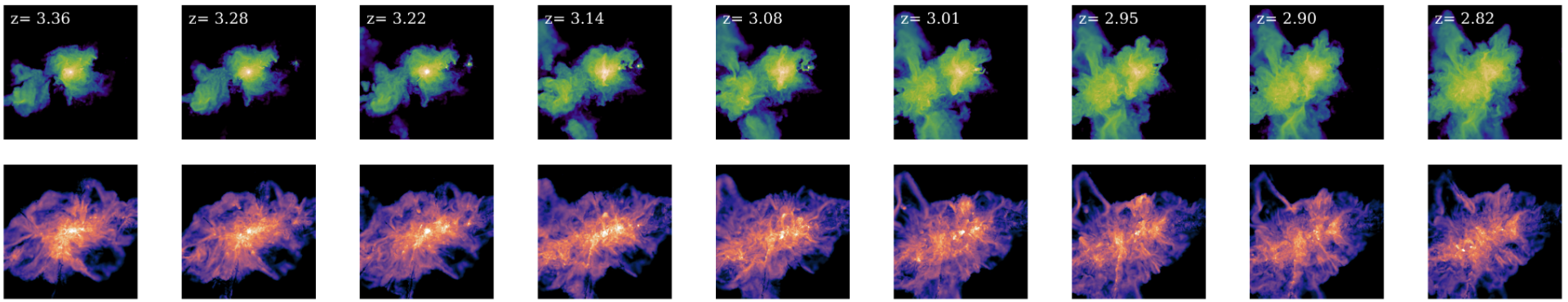


- SKA mock Faraday rotation observations at 3 different redshifts
- SKA is up for probing the onset of cluster magnetization for a sufficiently dense grid of background and embedded polarized sources

AIP

Conclusions

- magnetic fields grow fast in radiative cluster simulations (saturation @ $z \sim 6$)
- first, magnetic fields grow in galaxies via adiabatic compression and a small-scale dynamo driven by compressible turbulence induced by gravitational collapse



Conclusions

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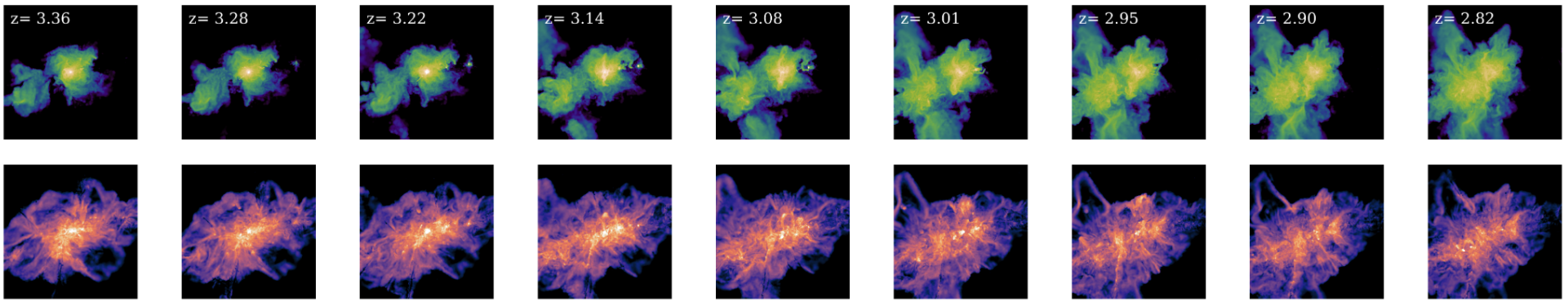
- first, magnetic fields grow in galaxies via adiabatic compression and a small-scale dynamo driven by compressible turbulence induced by gravitational collapse
- AGN feedback, galactic winds, and ram-pressure-stripping transport the magnetized plasma outwards and pollute the ICM
- cluster mergers/cosmic accretion drives a small-scale dynamo in the ICM that grows the magnetic coherence lengths and maintains its field strength



Conclusions

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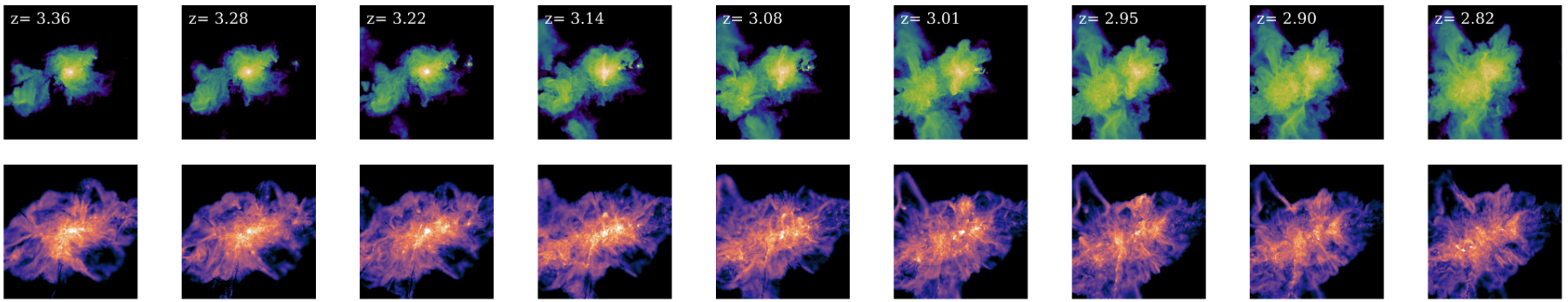
- cluster mergers/cosmic accretion drives a small-scale dynamo in the ICM that grows the magnetic coherence lengths and maintains its field strength
- magnetic field growth always happens on collisional scales – first in the ISM at $z \sim 8$ and later in the ICM on scales $>$100 kpc so that MHD always applies!



PICOGAL: From Plasma KInetics to COsmological GALaxy Formation

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Literature for the talk

Magnetic dynamo in clusters:

- 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.