Magnetic dynamos in galaxy clusters

Christoph Pfrommer[1]

in collaboration with

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Perrone,[1] Shalaby,[5] Thomas,[1] Werhahn,[6] Whittingham[1]
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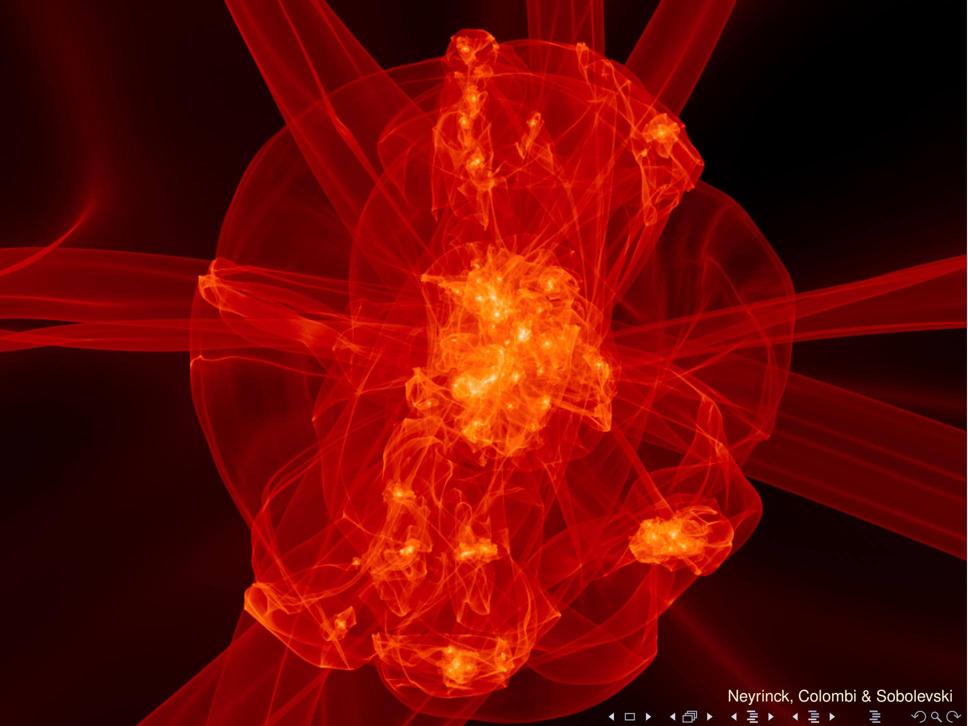
[1]AIP, [2]U of Michigan, [3]NBI, [4]U of Heidelberg, [5]Perimeter Institute, [6]MPA

Magnetic Fields and Cosmic Rays across Scales, CfA Harvard, Sep 2025



Neyrinck, Colombi & Sobolevski

Outline

Observing magnetic fields in clusters

Faraday rotation measures (FRMs) in nearby clusters: $B \sim 10\ \mu\mathrm{G}$ (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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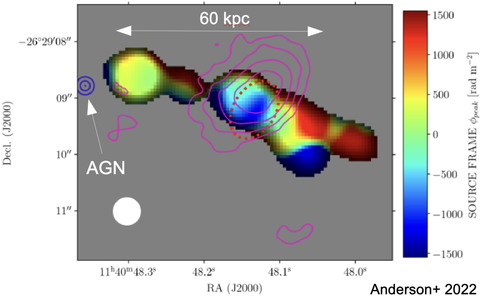
Evidence for early magnetism through FRM observations:

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

(Cordun+ 2023, Chapman+ 2024)



Anderson+ 2022

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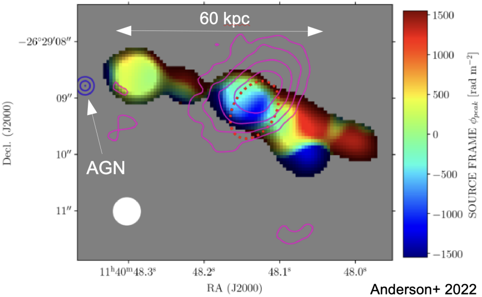

Anderson+ 2022

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)

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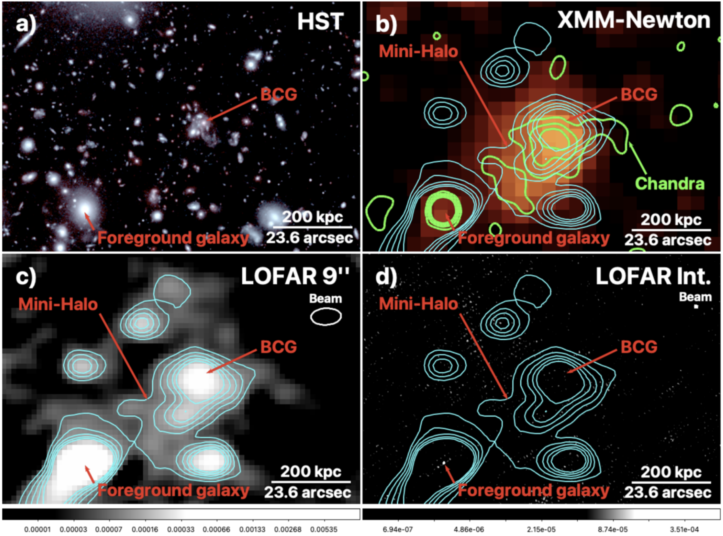
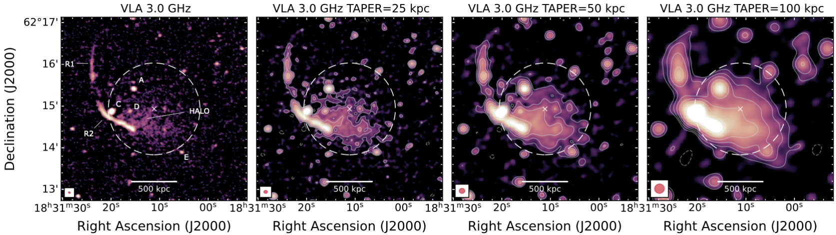
A candidate radio mini-halo in a cool core at $z = 1.7$



Hlavacek-Larrondo, Timmerman, CP+ (2025)

Problems of diffuse radio emission at high redshift

- typically low surface brightness: requires tapering to mitigate the effect of noise



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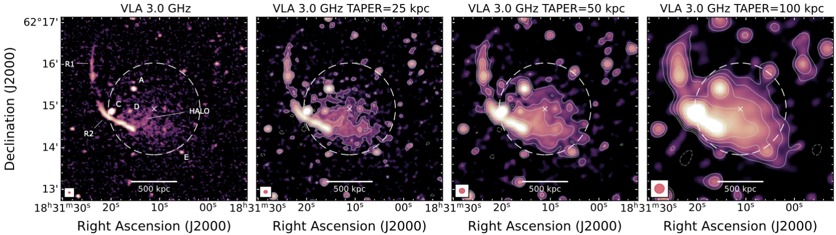
$$I_\nu \equiv \frac{dE}{dt\,d\nu\,dA\,d\Omega}\,\frac{dA}{4\pi D_\mathrm{com}^2} = I_{\nu_\mathrm{rest}}\,\frac{1}{(1+z)^3} = I_0\nu^{-\alpha_\nu}\,\frac{1}{(1+z)^{\alpha_\nu+3}} \propto (1+z)^{-4}$$

for $\alpha_\nu = 1$, where $I_{\nu_\mathrm{rest}} = I_0\nu_\mathrm{rest}^{-\alpha_\nu}$, $d\nu = d\nu_\mathrm{rest}/(1+z)$ and $d\Omega = dA_\mathrm{source}/D_\mathrm{ang}^2$



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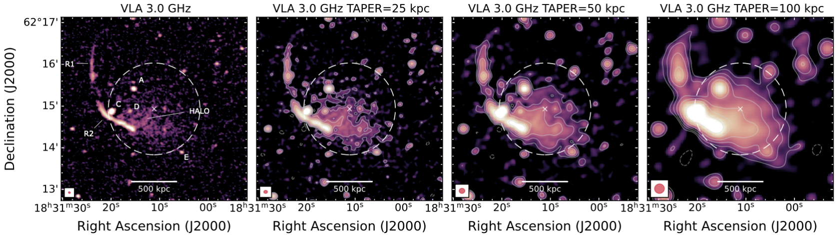
- highly clumped emission (e.g. filaments) can beat redshift dimming! Hadronic radio emission $j_\nu \propto \rho\varepsilon_{\mathrm{CRp}}B^{1+\alpha_\nu}$ with a clumped density distribution is one way out



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Origin and growth of magnetic fields

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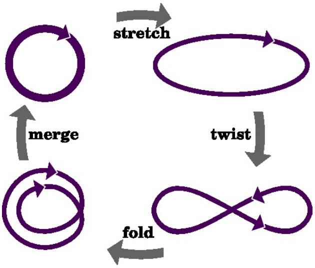

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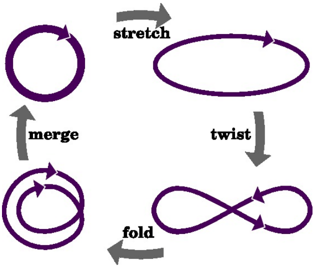
- ***Saturation.*** Field growth stops at a sizeable fraction of the turbulent energy when magnetic forces become strong enough to resist the stretching and folding motions



The need for a plasma dynamo?

The may be a problem with the classic picture:

- ***The ICM is weakly collisional*** with a large particle mean free path of

$$\lambda_{\mathrm{mfp}} \sim \frac{1}{\pi n \ln \Lambda} \left(\frac{k_{\mathrm{B}} T_{\mathrm{e}}}{Z e^2} \right)^2 \sim 50 \left(\frac{n}{10^{-4}\ \mathrm{cm}^{-3}} \right)^{-1} \left(\frac{k_{\mathrm{B}} T_{\mathrm{e}}}{6\ \mathrm{keV}} \right)^2 \ \mathrm{kpc}$$

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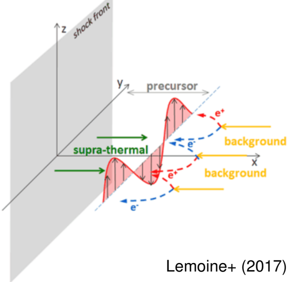

Lemoine+ (2017)

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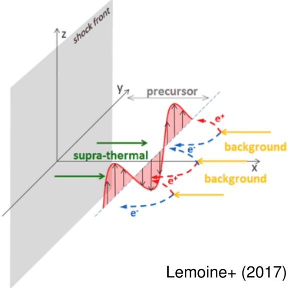

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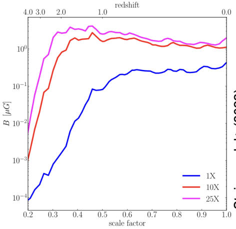
- ***However, there is a loophole in this argument*** as it assumes clusters to be weakly collisional throughout their entire cosmic growth history!

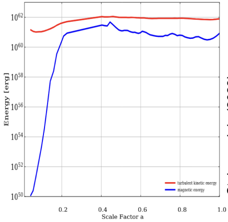
Previous simulation work

Cosmological non-radiative cluster simulation (SPH):



Steinwandel+ (2022)

higher resolution



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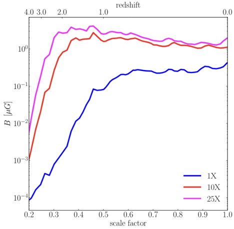

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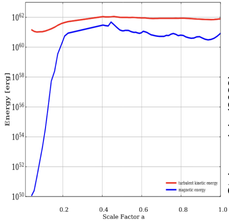

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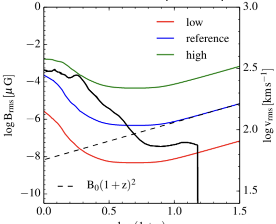

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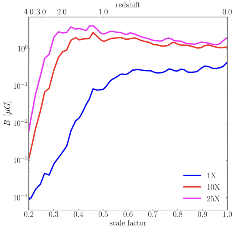

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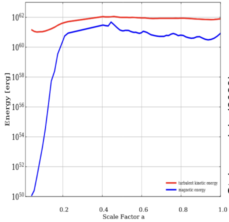

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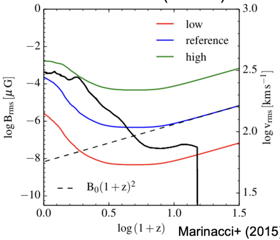

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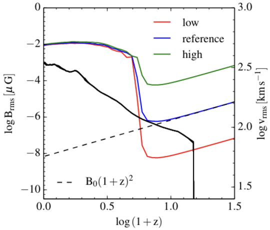

Previous simulation work

- What amplifies magnetic fields at high redshifts to match observations?
- And what about collisionless plasma physics?

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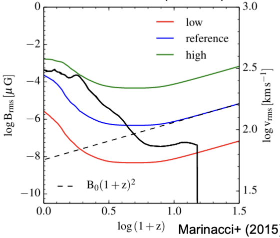

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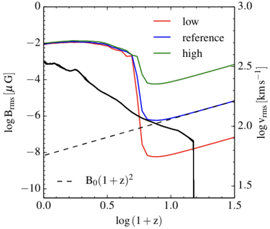
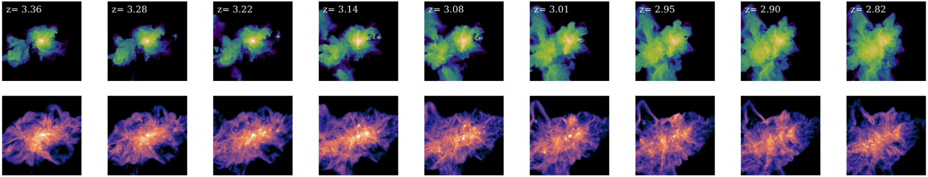


PICO-Cluster simulations

- ***PICO-Clusters (Plasmas In COsmological Clusters):*** suite of cosmological zoom-in cluster simulations (Berlok+ 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)
- comoving ideal MHD (Pakmor+ 2011, 2013)
- galaxy formation model IllustrisTNG (Weinberger+ 2017, Pillepich+ 2018)
- ***Tevlin, Berlok,*** CP, Talbot, Whittingham, Puchwein, Pakmor, Weinberger, Springel (2025): dynamo anaysis of 4 clusters; compare radiative vs. non-radiative runs



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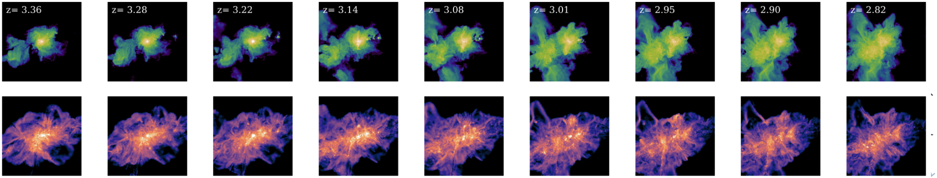
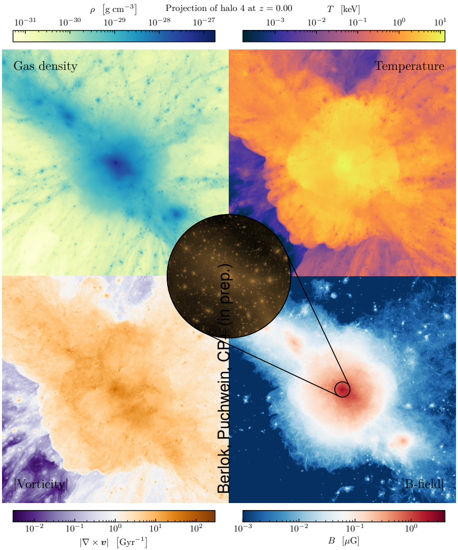


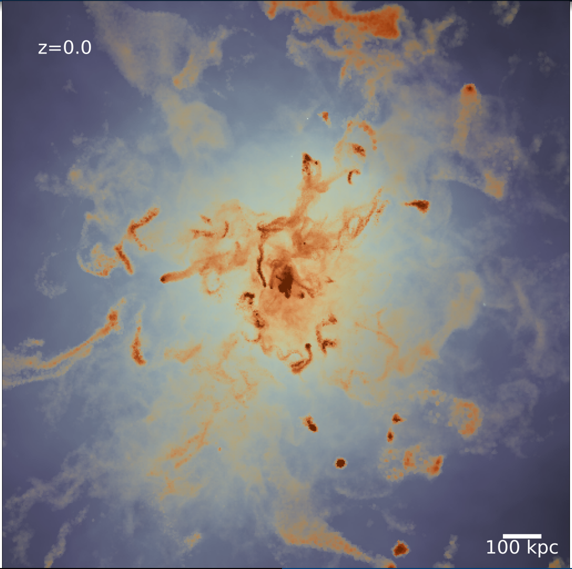
PICO-Cluster simulations

The differences between other simulations such as TNG-Cluster (Nelson+ 2024) and our PICO-Cluster project are:

- our new initial conditions code, ensuring a contamination-free high-resolution region $< 2.8 R_{200}$
- improved simulation code: we use AREPO-2 while TNG300 and TNG-Cluster use AREPO
- increased resolution (up to $M_{\rm gas} = 10^6\ M_\odot$) to address 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

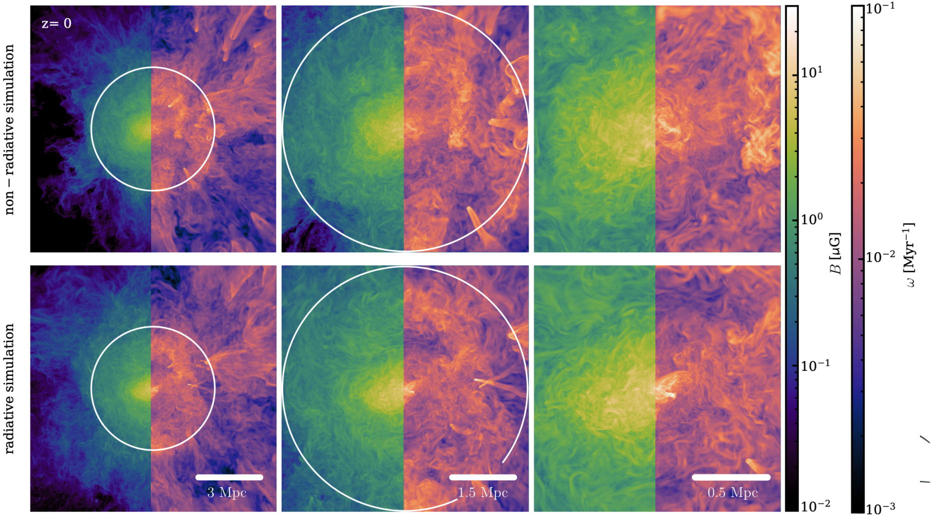


AGN jets in cosmological cluster simulations

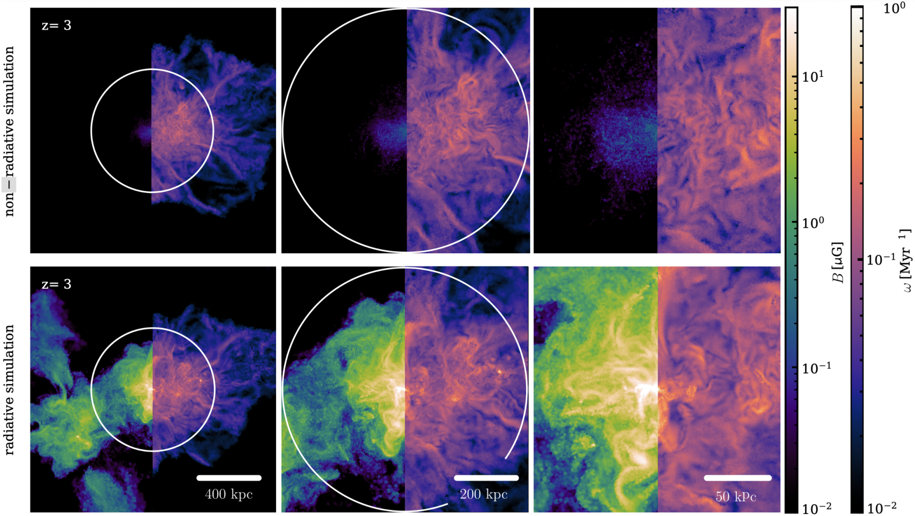


Weinberger, CP+ (in prep.)

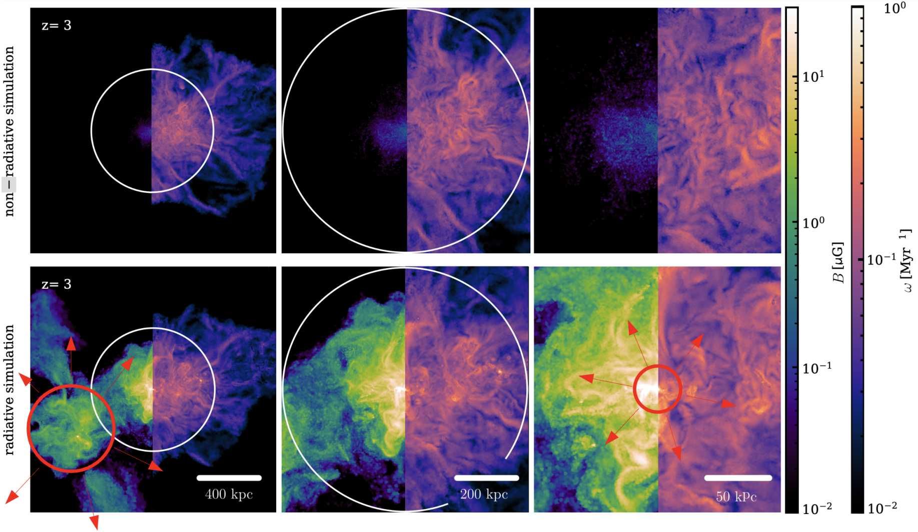
Magnetic fields and vorticity comparable at $z = 0$



Faster magnetic growth in radiative simulation



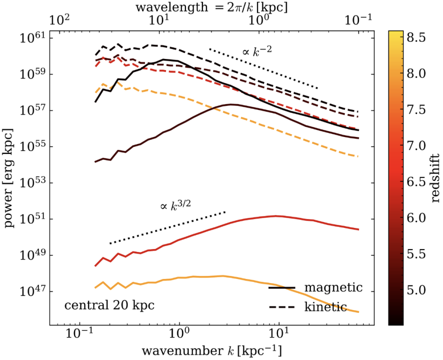
Feedback pollutes the ICM with magnetic fields



Kinetic and magnetic power spectra in proto-clusters

The emerging picture:

- ***Supersonic, compressible Burgers (1969) turbulence in proto-cluster,*** which increases in power as a result of hierarchical merging



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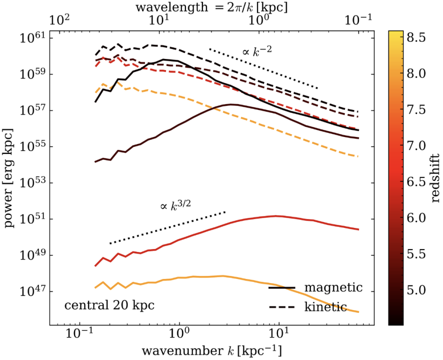

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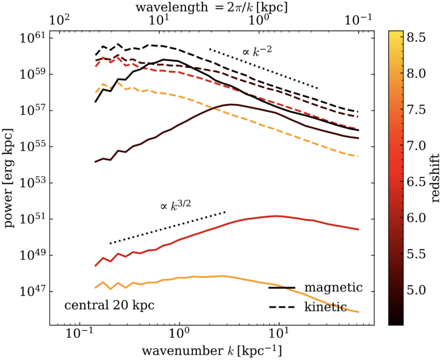

AIP

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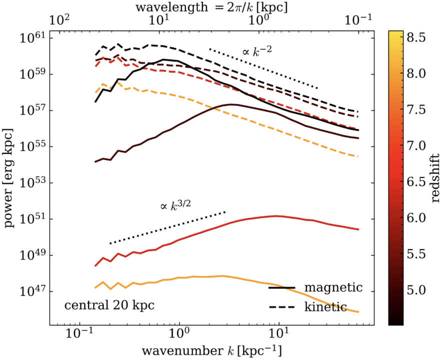
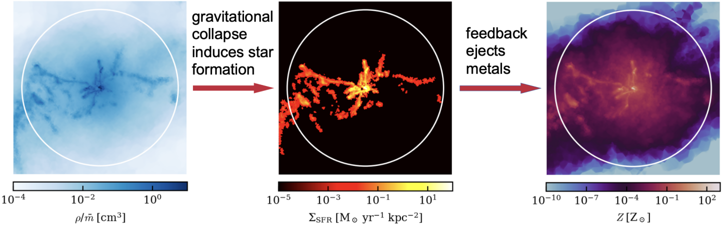
- ***At late times,*** after the field has saturatd on small scales, the magnetic coherence scale grows



What grows the magnetic field in proto-clusters?



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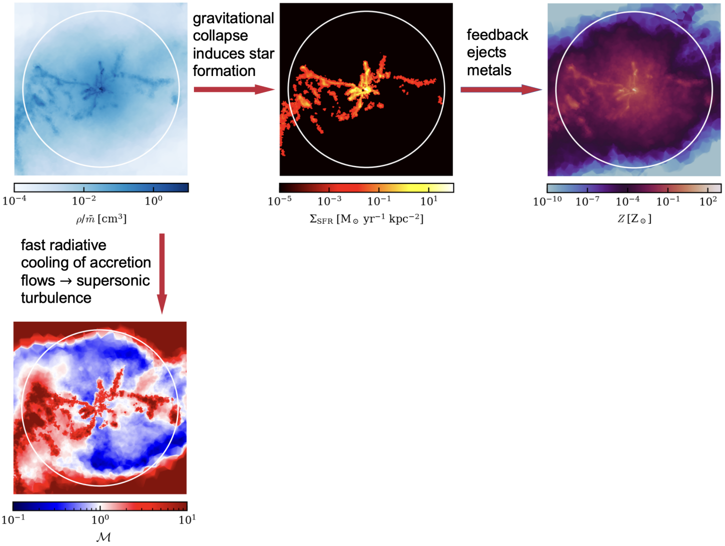

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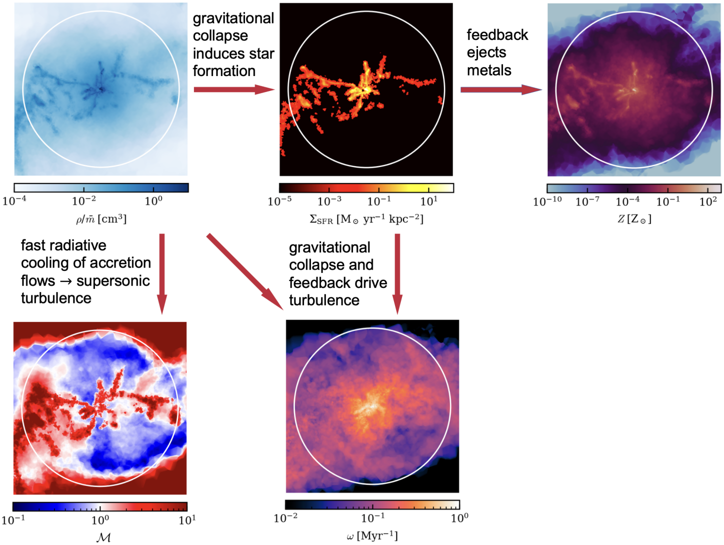

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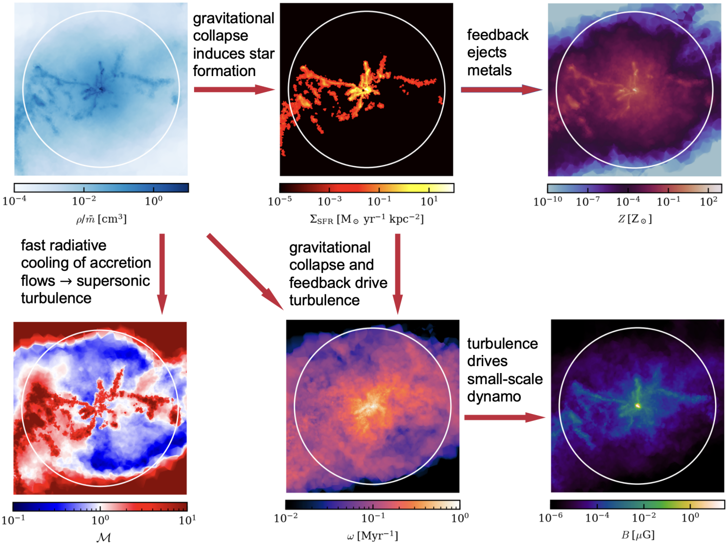

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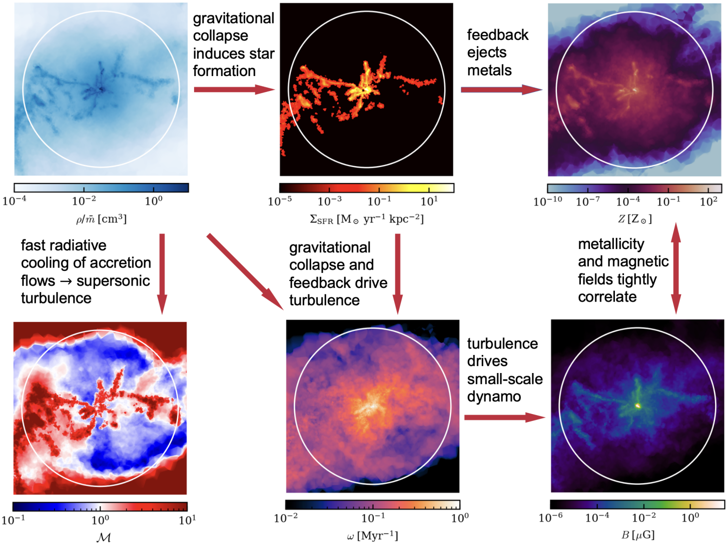
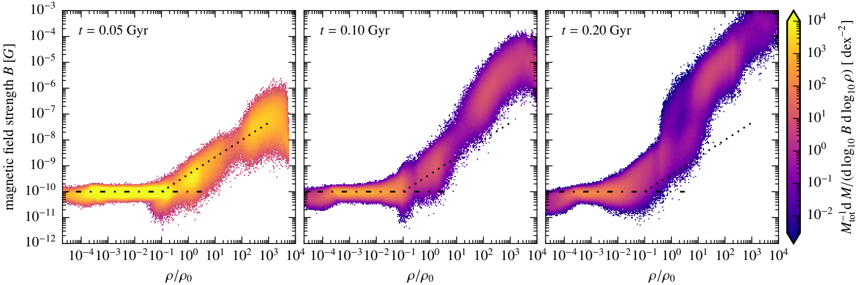


AIP

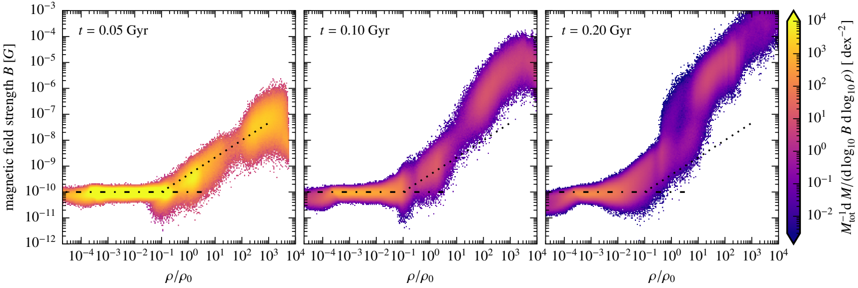
Identifying different growth phases



CP+ (2022): small-scale dynamo in isolated star-forming galaxies

- *1st phase:* adiabatic growth with $B \propto \rho^{2/3}$ (isotropic collapse)

Identifying different growth phases



CP+ (2022): small-scale dynamo in isolated star-forming galaxies

- *1st phase:* adiabatic growth with $B \propto \rho^{2/3}$ (isotropic collapse)
- *2nd phase:* additional growth at high density ρ with small dynamical times $t_{\mathrm{dyn}} \sim (G\rho)^{-1/2}$

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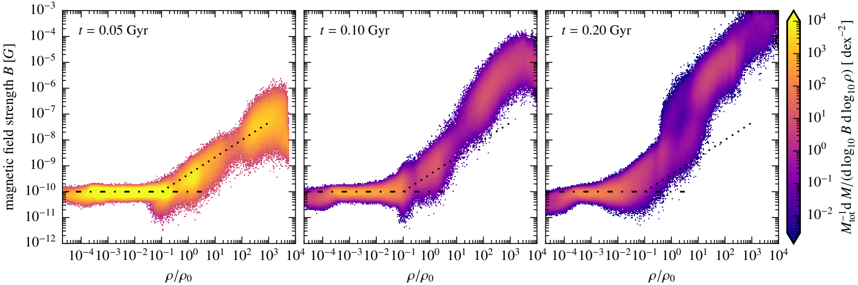

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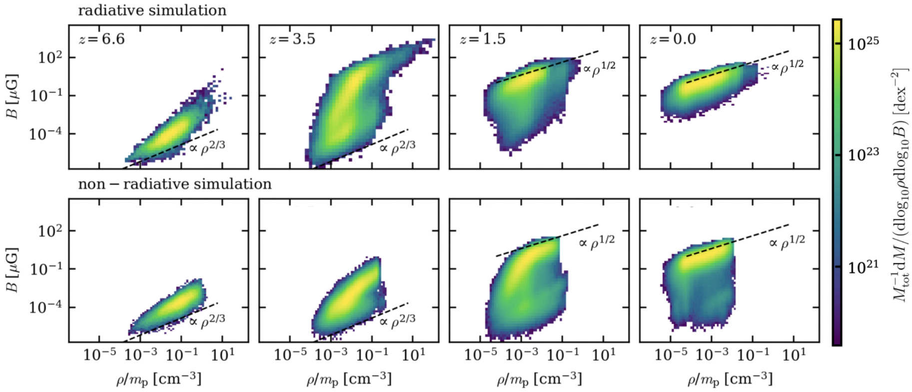
- *3rd phase:* growth migrates to lower ρ on larger scales $\propto \rho^{-1/3}$

Adiabatic compression vs. turbulent dynamo



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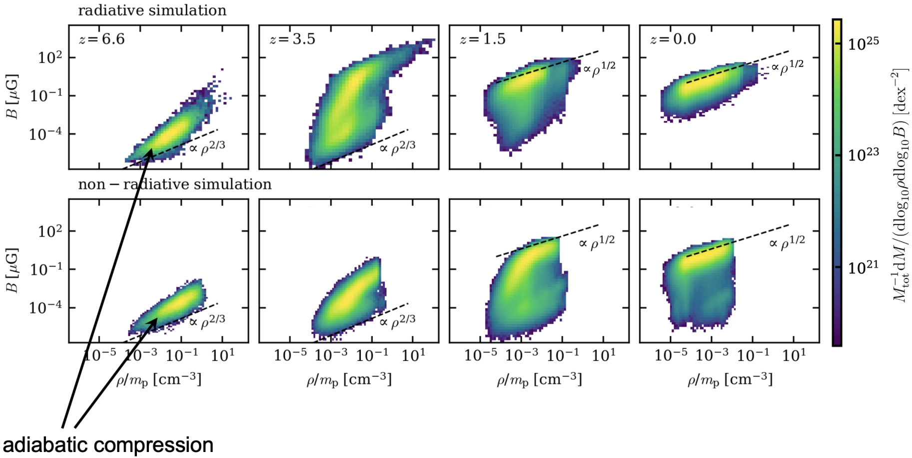

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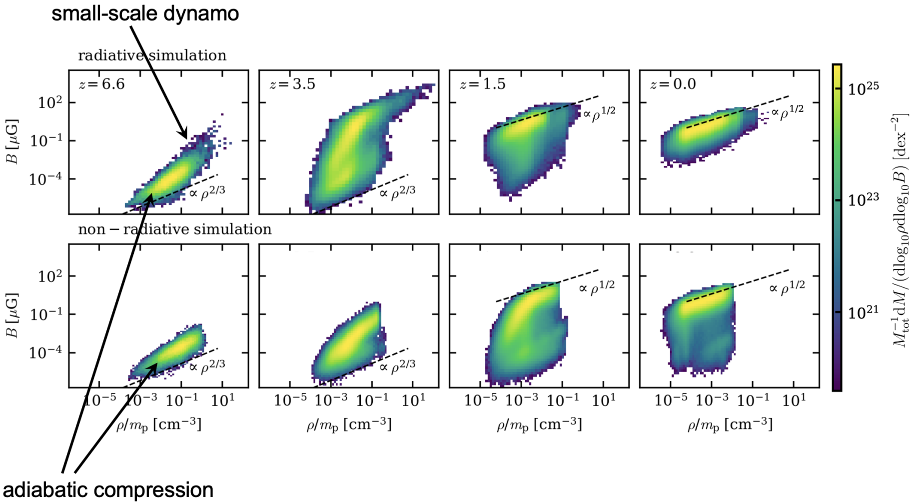

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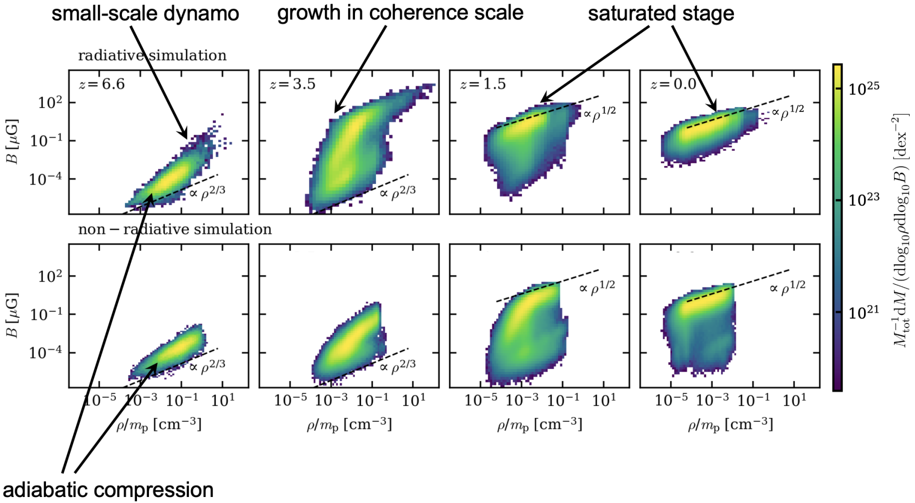

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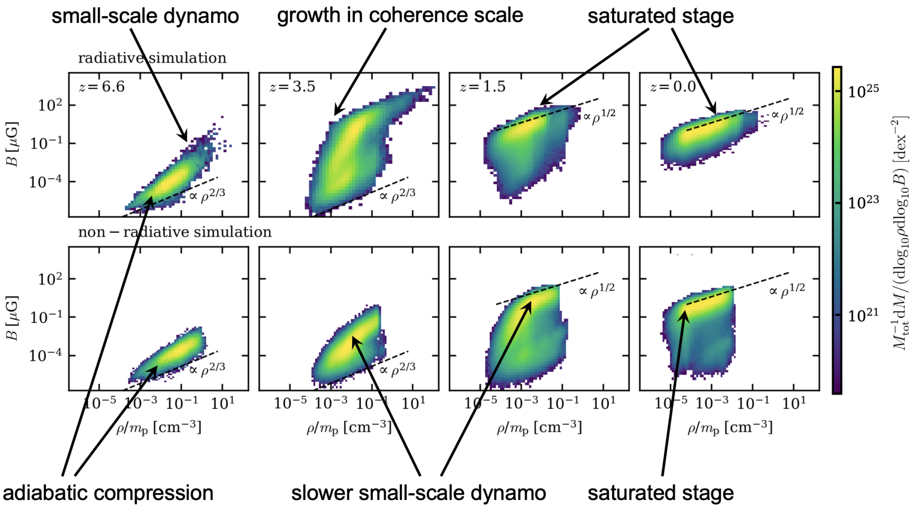
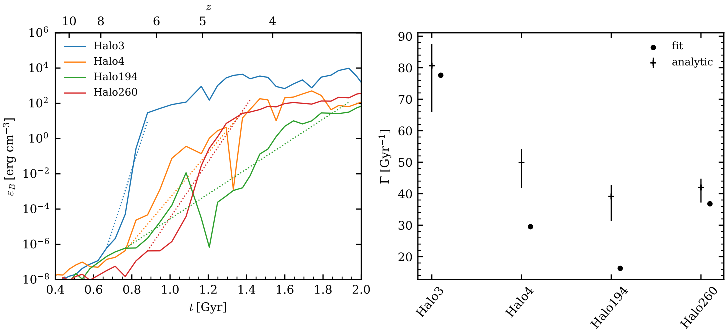


Exponential dynamo growth rates

Simulated dynamo growth rates match analytic expectation for Burgers turbulence



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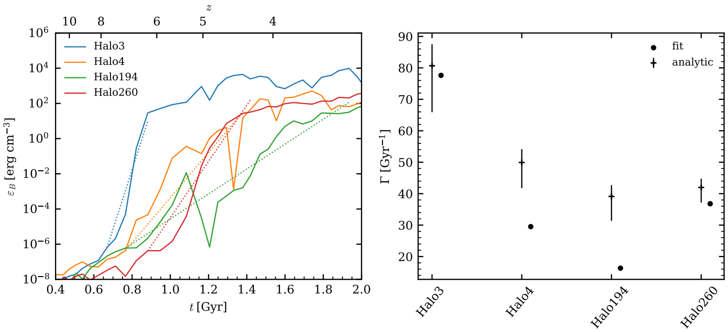


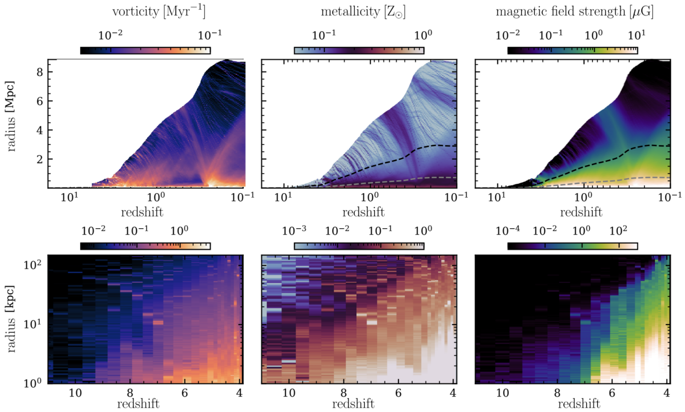
- ***small-scale dynamo growth rate depends on type of turbulence:***

(Schober+ 2012, CP+ 2022)

$$\Gamma \propto \frac{\mathscr{V}}{\mathscr{L}} \mathrm{Re}_{\mathrm{num}}^{(1-\theta)/(1+\theta)}, \quad \mathrm{Re}_{\mathrm{num}} = \frac{\mathscr{L}\mathscr{V}}{\nu_{\mathrm{num}}} = \frac{3\mathscr{L}\mathscr{V}}{d_{\mathrm{cell}}\, v_{\mathrm{th}}}$$

and $\theta = 1/3$ for Kolmogorov and $\theta = 1/2$ for Burgers turbulence

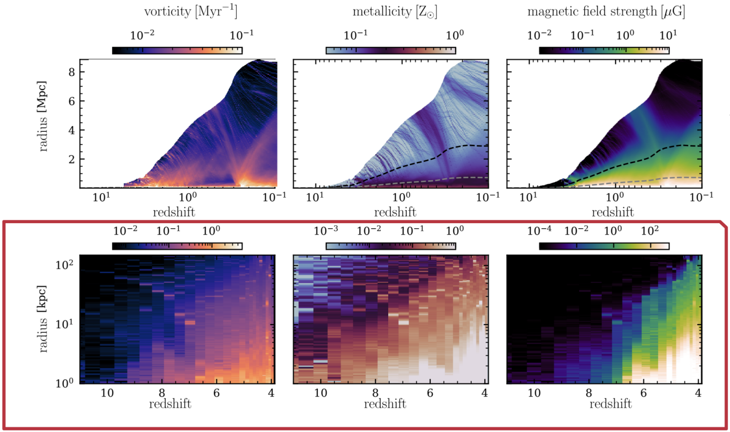
From galaxies to the intracluster medium



Enrichment in the entire cluster

Enrichment in BCG

From galaxies to the intracluster medium



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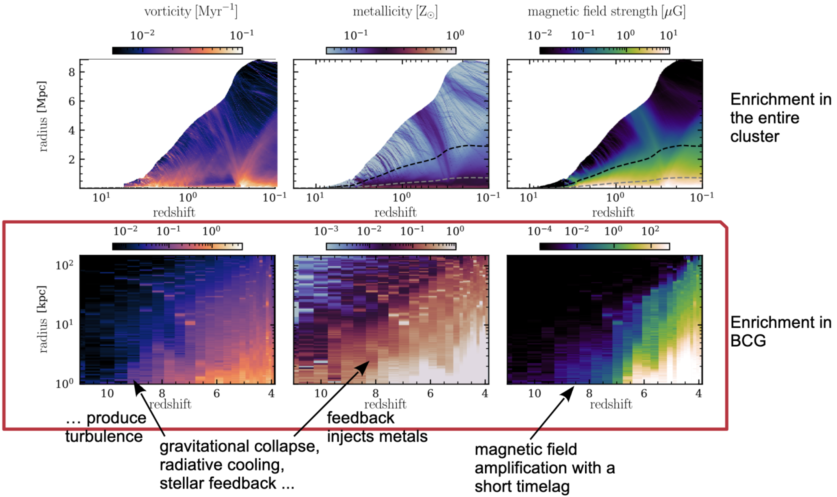

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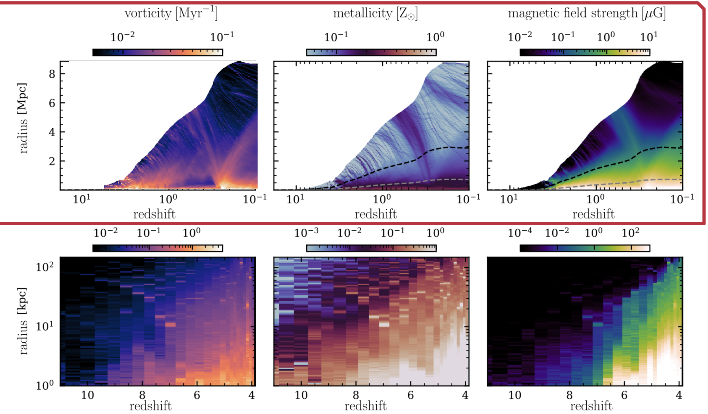

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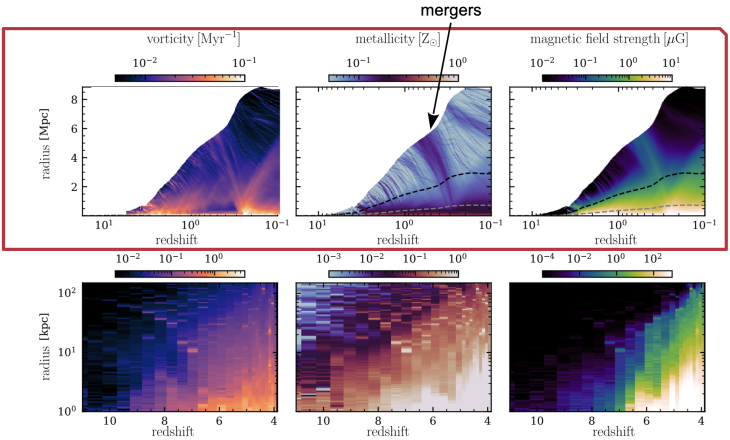

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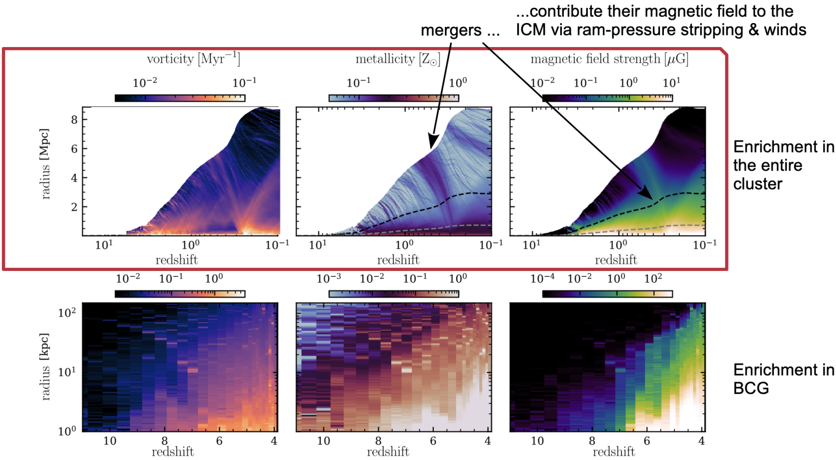

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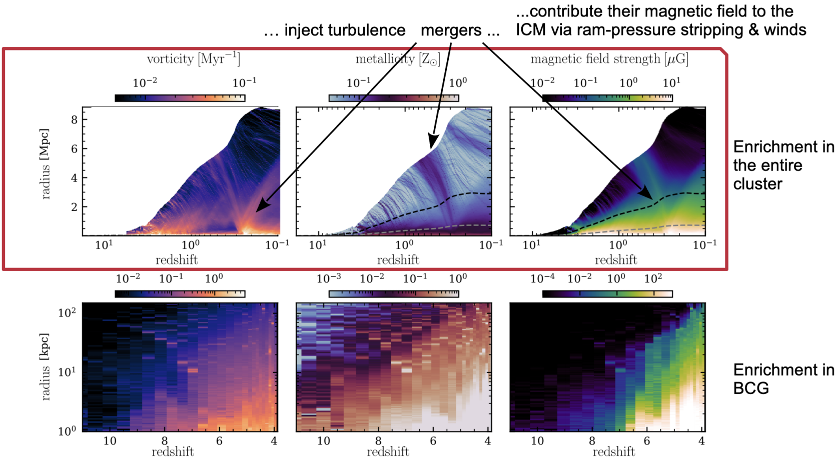
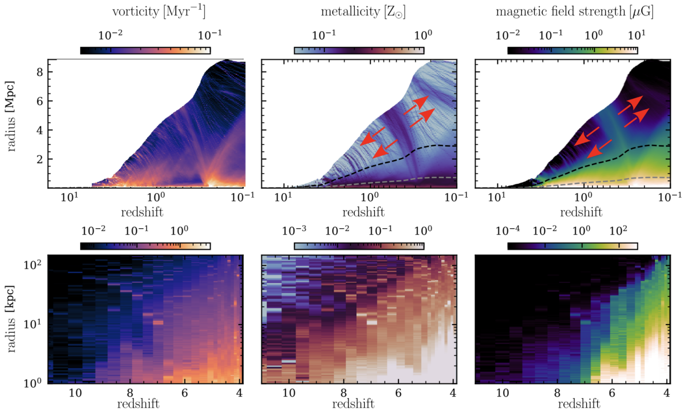


Cluster magnetic fields are linked to galaxy formation



Enrichment in the entire cluster

Enrichment in BCG

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

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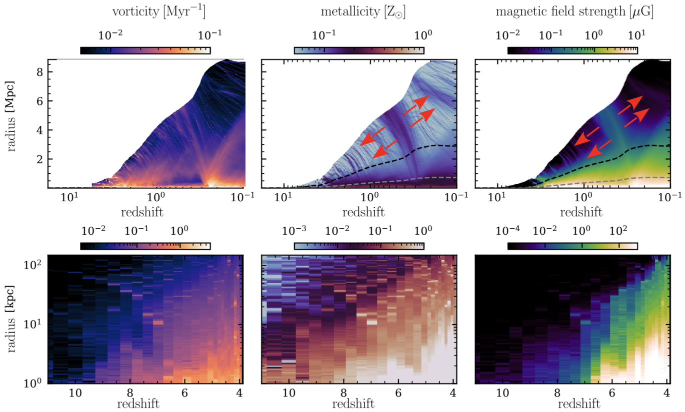
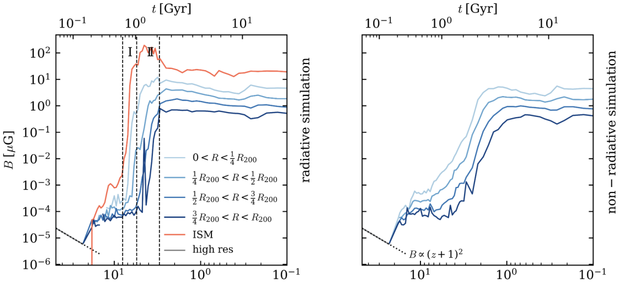


Enrichment in the entire cluster

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)

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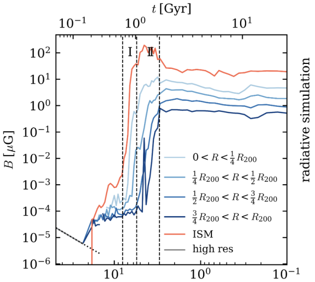

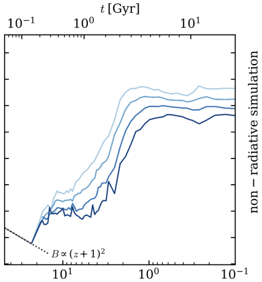

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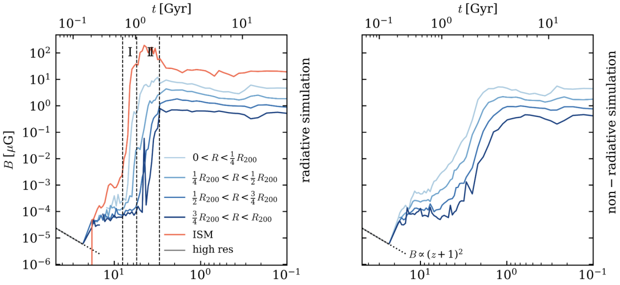

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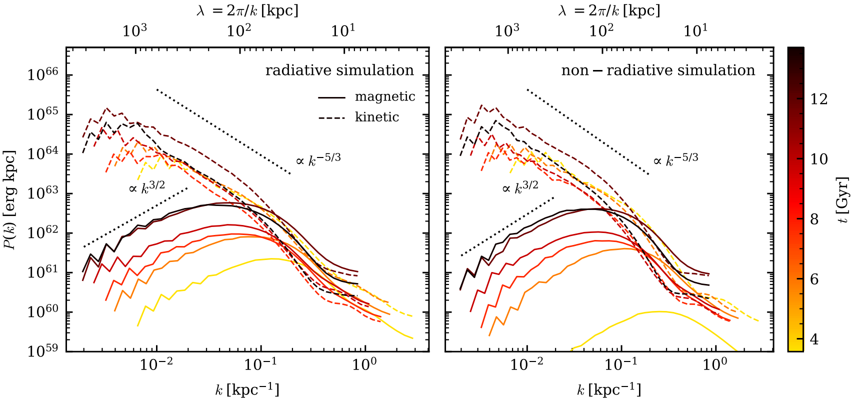
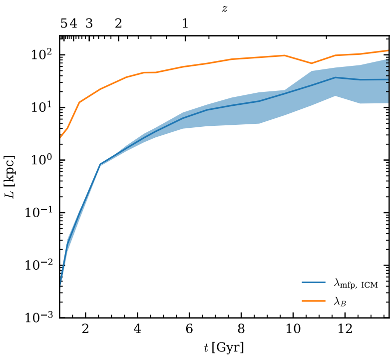
Small-scale dynamo in the intracluster medium



- 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

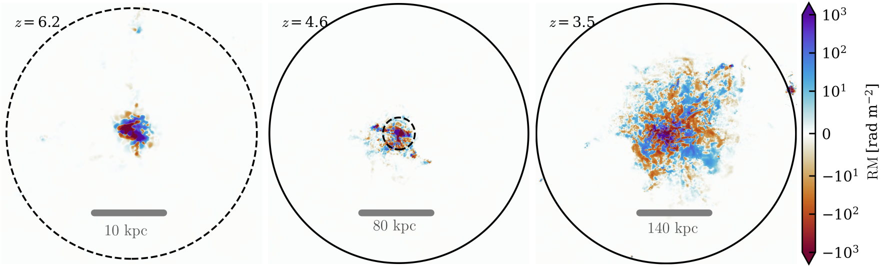
Comparison of the particle mean free path λ_{mfp} and the magnetic coherence length λ_B



- $\lambda_B \gg \lambda_{\mathrm{mfp}}$ 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

AIP

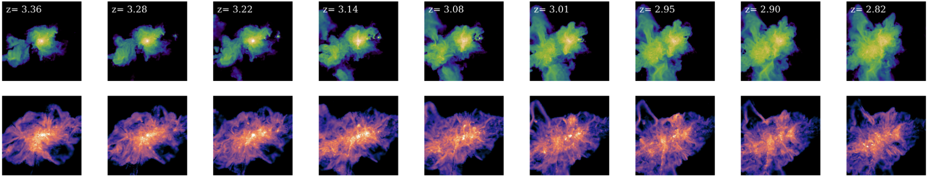
Probing the cluster magnetization observationally



- 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

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



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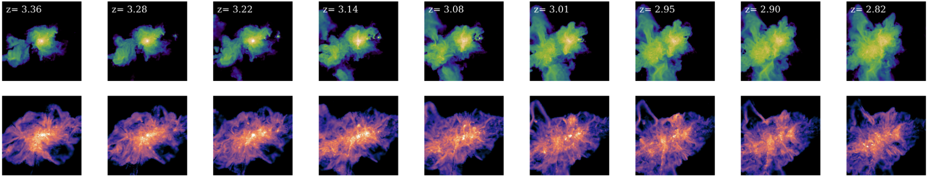

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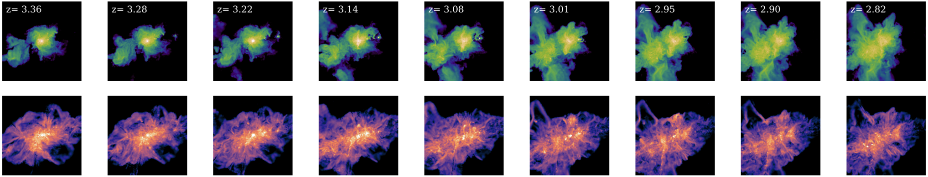
- magnetic field growth always happens on collisional scales – first in the ISM at $z \sim 8$ and later in the ICM on scales $>$100 kpc so that MHD always applies!



PICOGAL: From Plasma KInetics to COsmological GALaxy Formation

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).

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.