Magnetic fields in galaxy clusters

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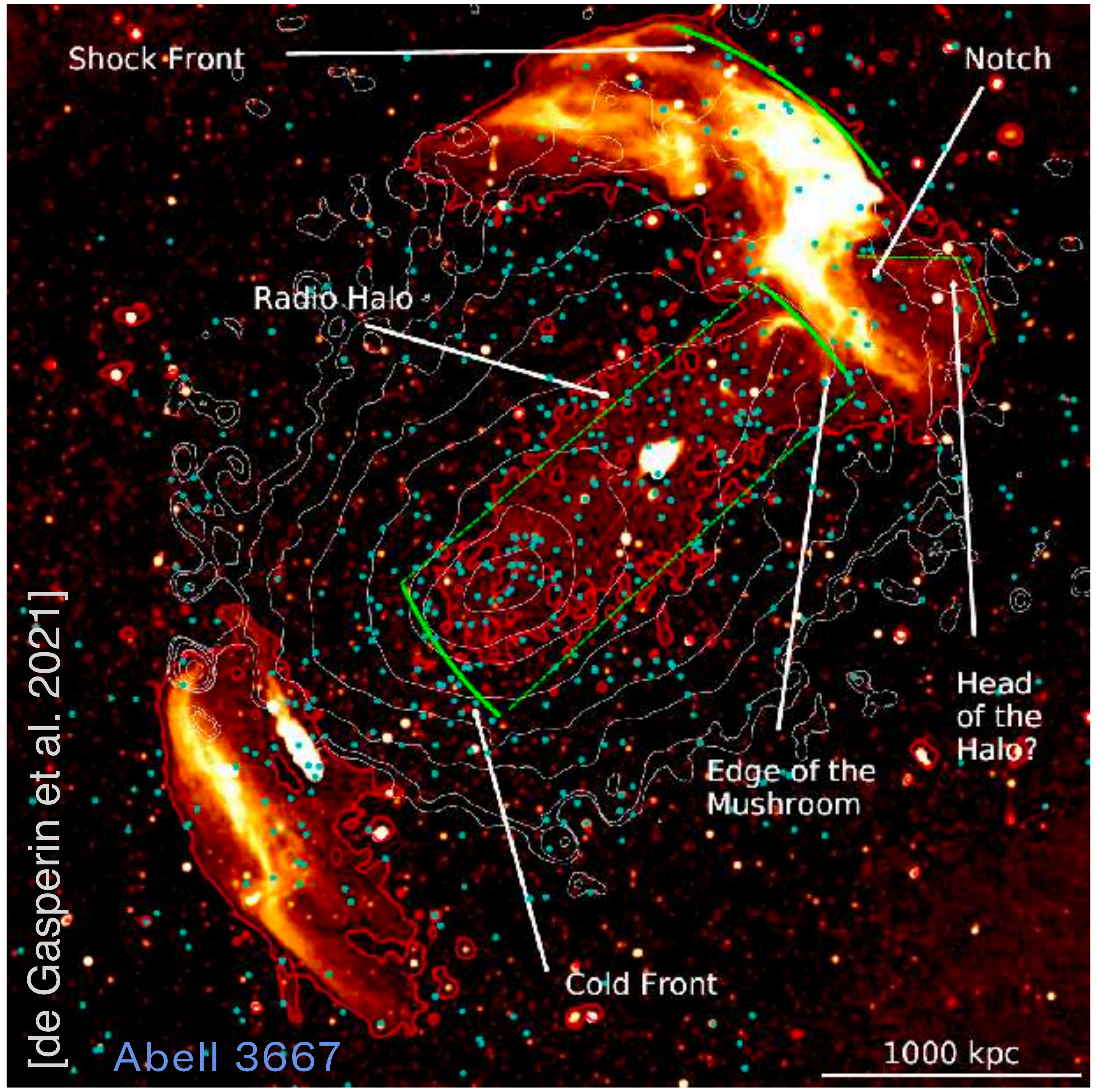
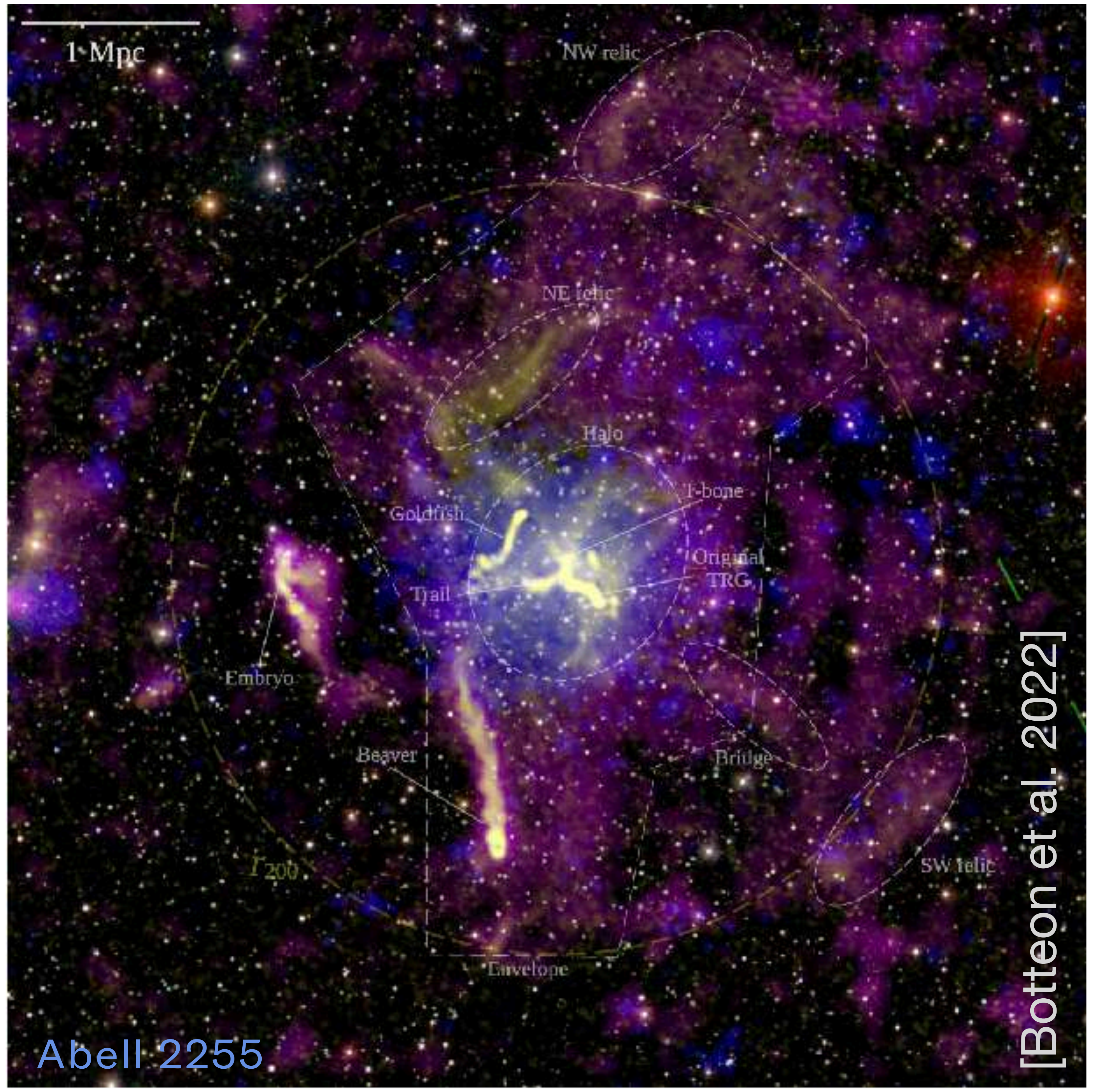
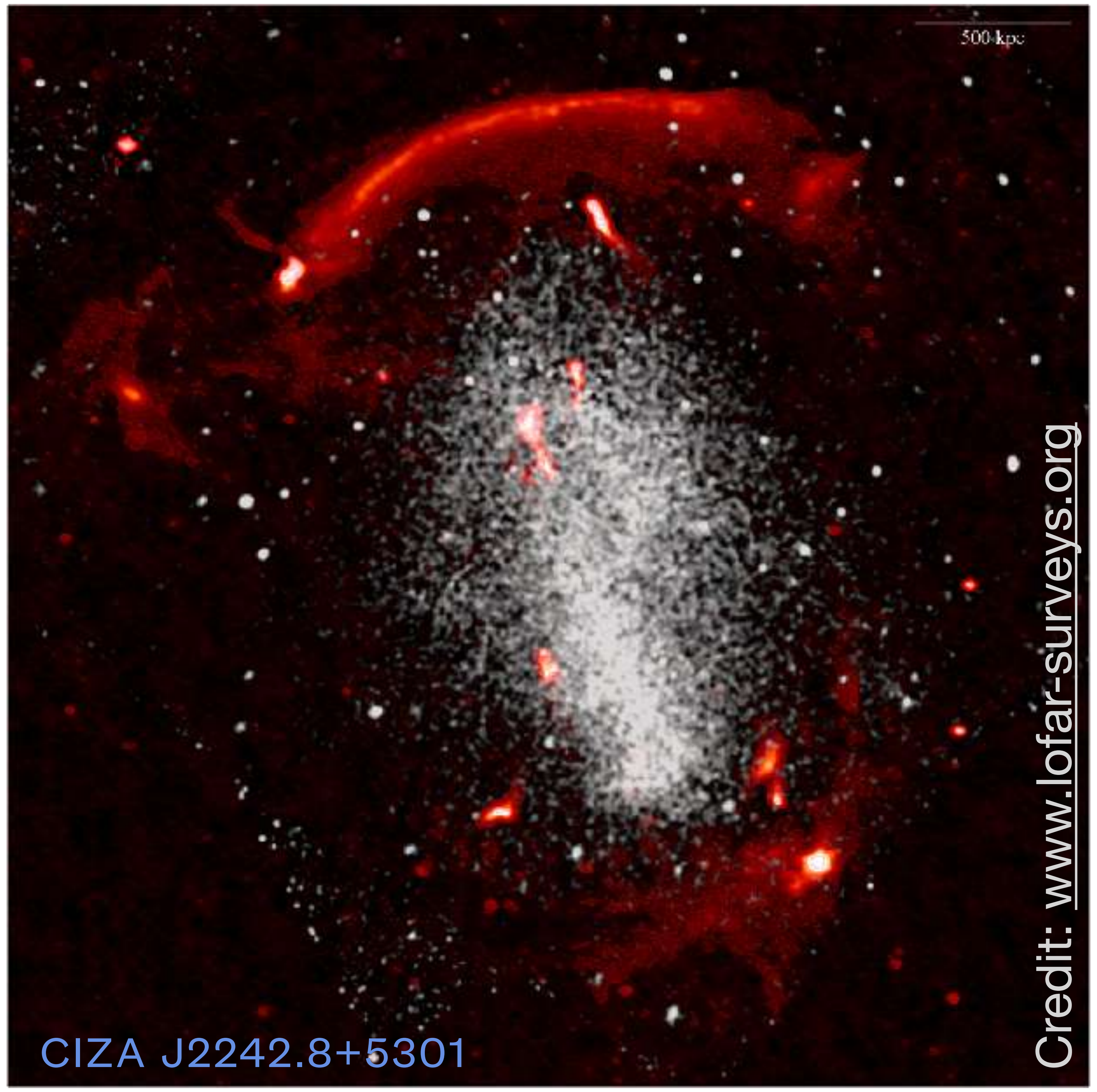
Institute for Theory and Computation

CENTER FOR ASTROPHYSICS HARVARD & SMITHSONIAN

Radio diffuse emission in GCs







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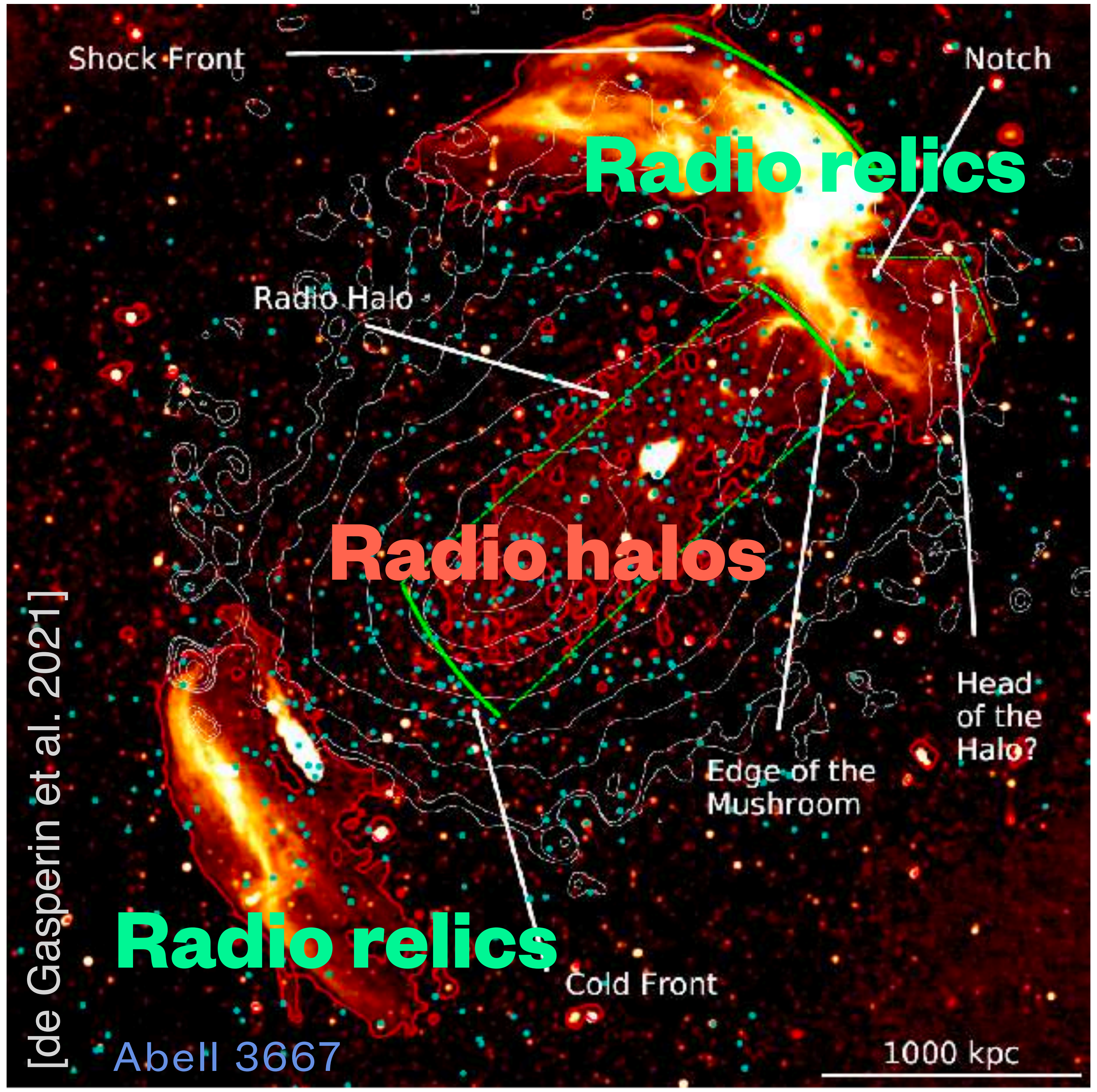
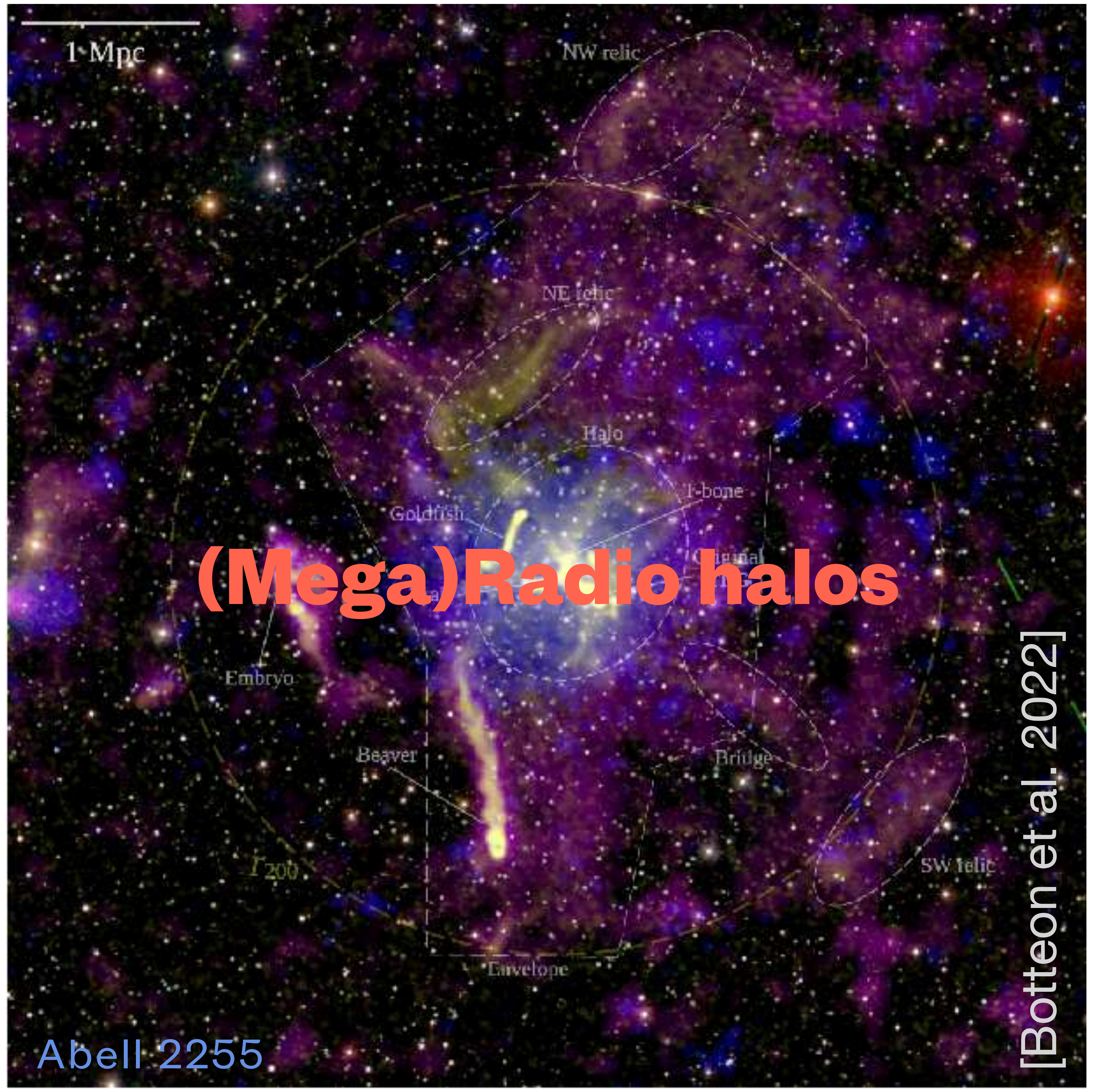
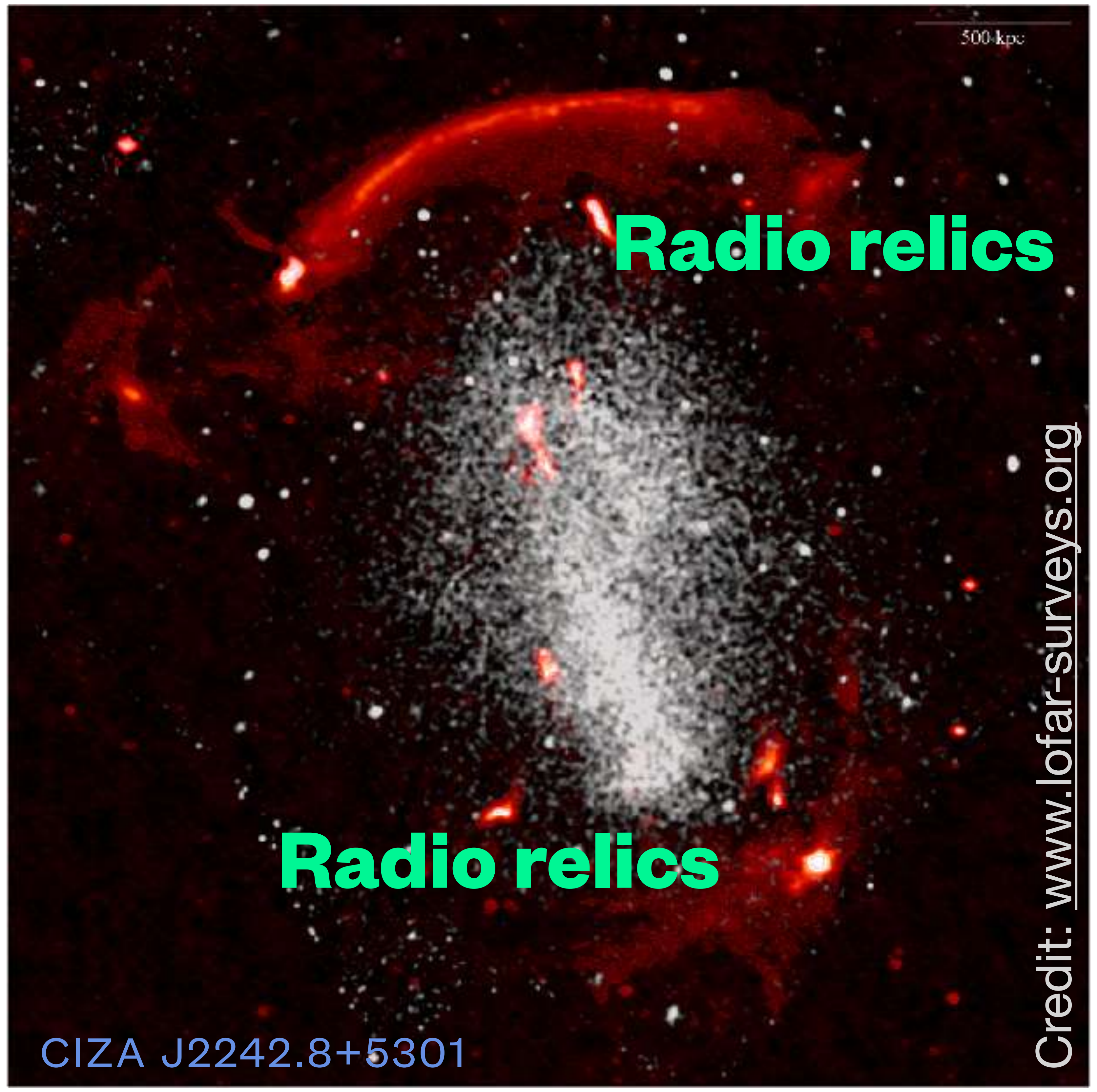
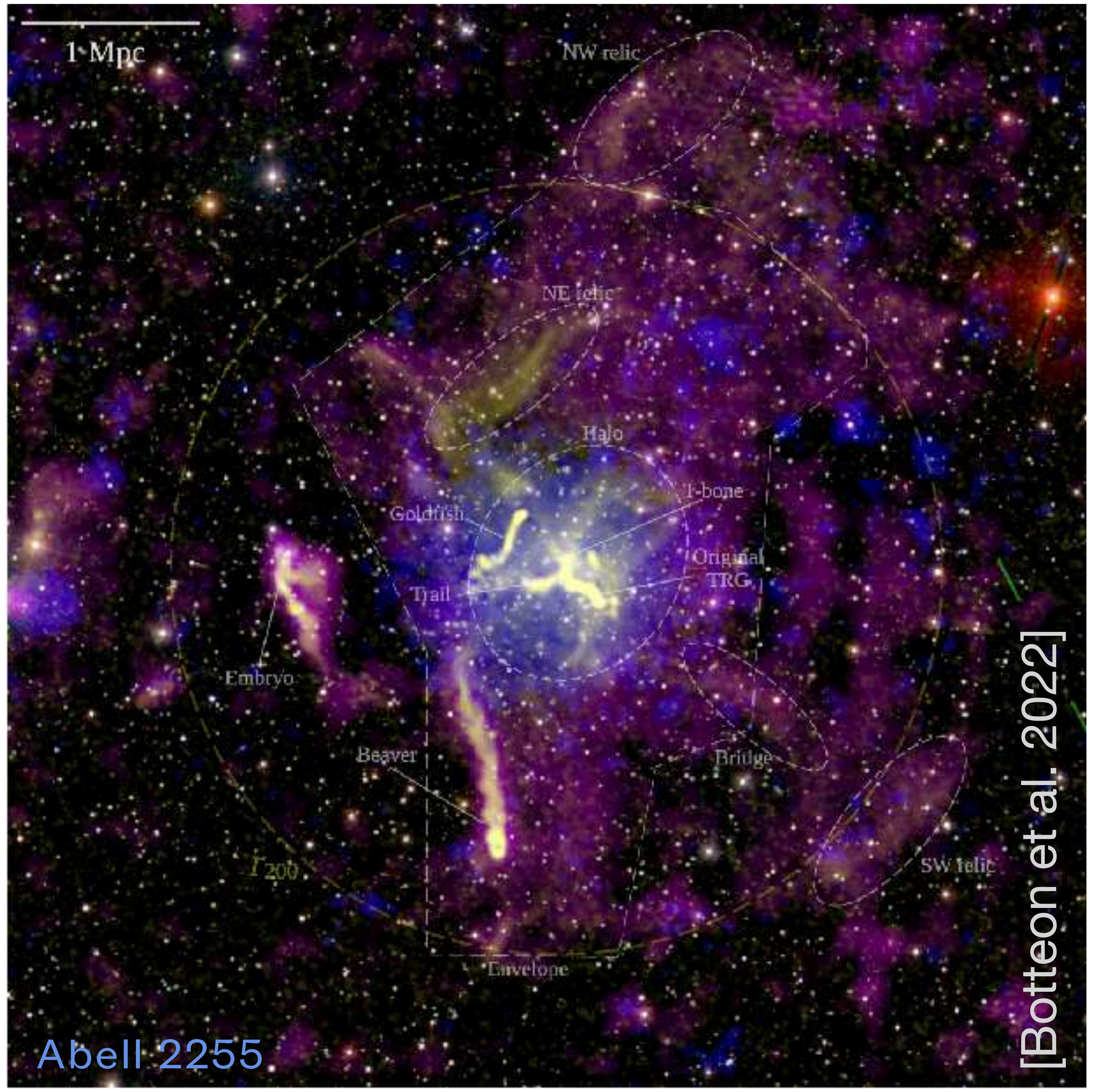
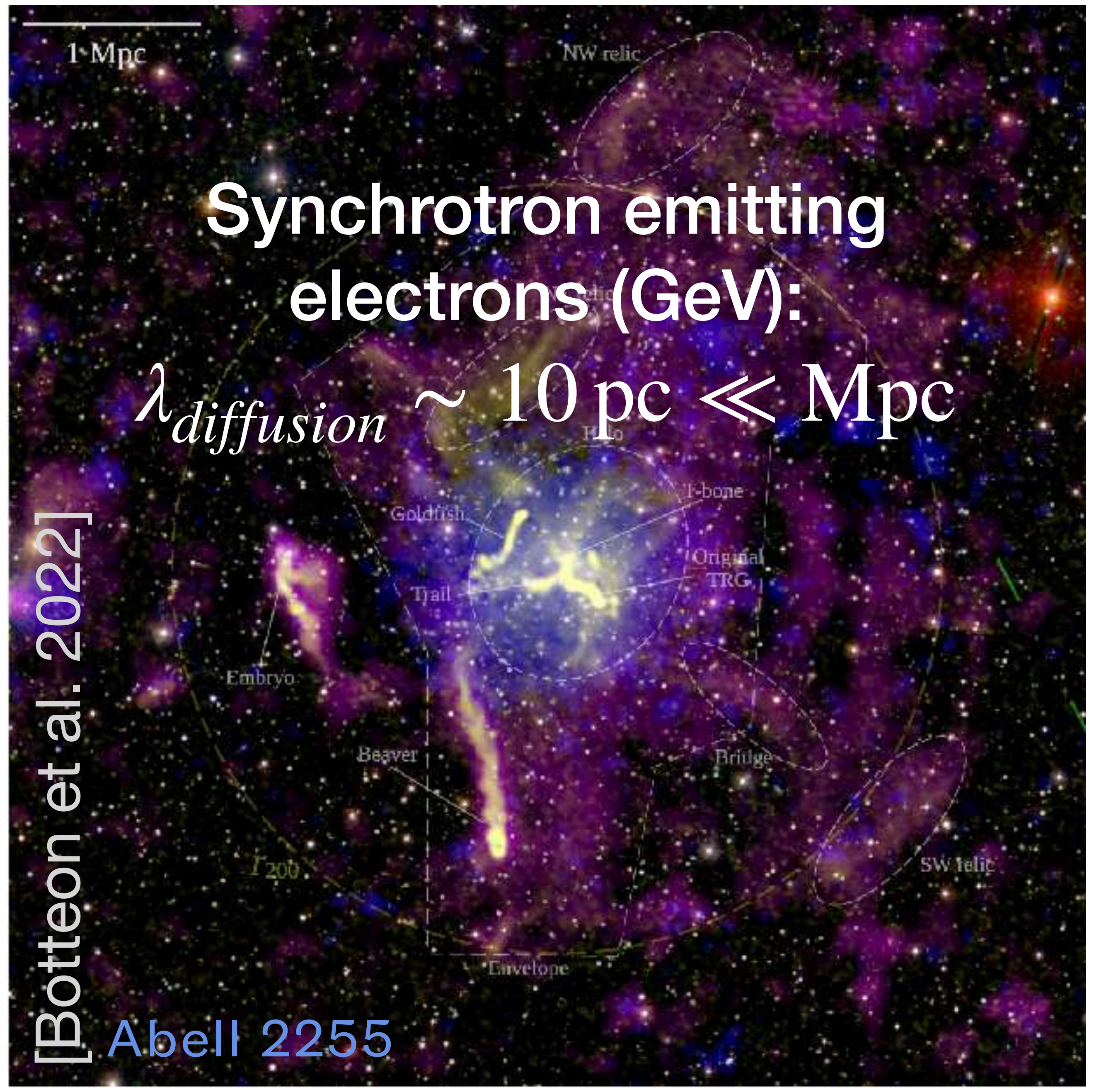







1 Mpc
NW relic
NE relic
Halo
T-bone
Goldfish
Original
TRG
Trail
Embryo
Beaver
Bridge
SW relic
r_{200}
Envelope
Abell 2255
[Botteon et al. 2022]

Radio diffuse emission in GCs



Magnetic Fields

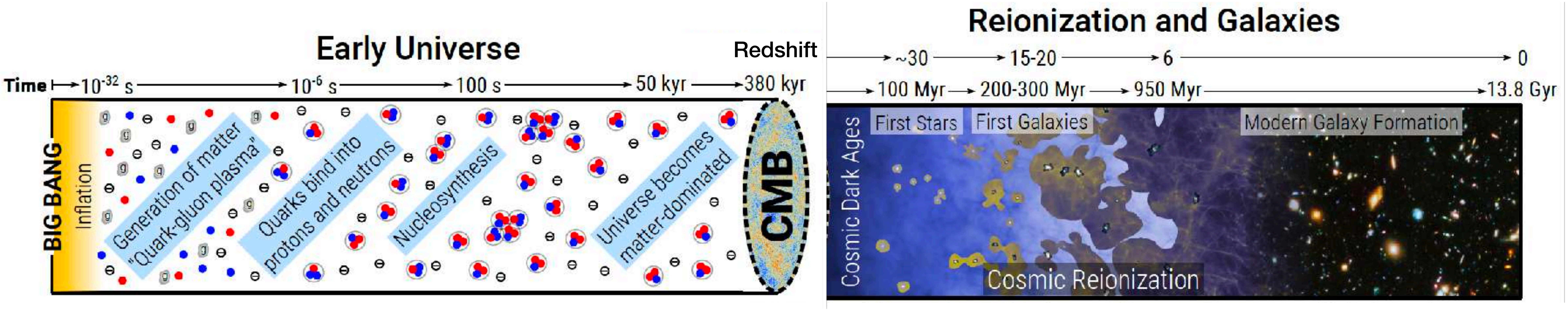
- What is their origin?
- How is it possible to get large-scale coherent magnetic fields (tens of kpc) with strengths of μG values?

Cosmic ray electrons

- What particle acceleration mechanisms can explain observations?
- CRe need to be (re-)accelerated or produced in-situ. What are the sources of seed electrons?

I. MAGNETIC FIELDS

Origin of magnetic fields



Credit: Wise et al. 2019

Primordial

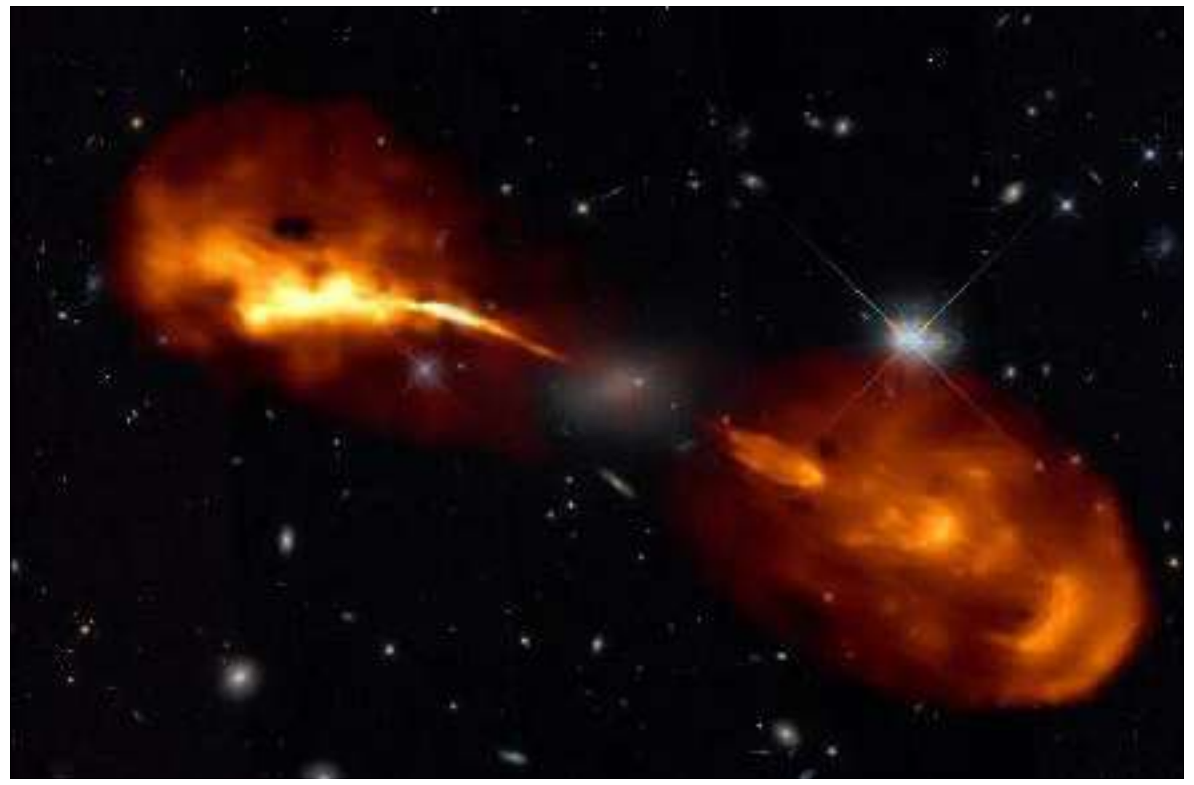
Top-down scenario

Astrophysical

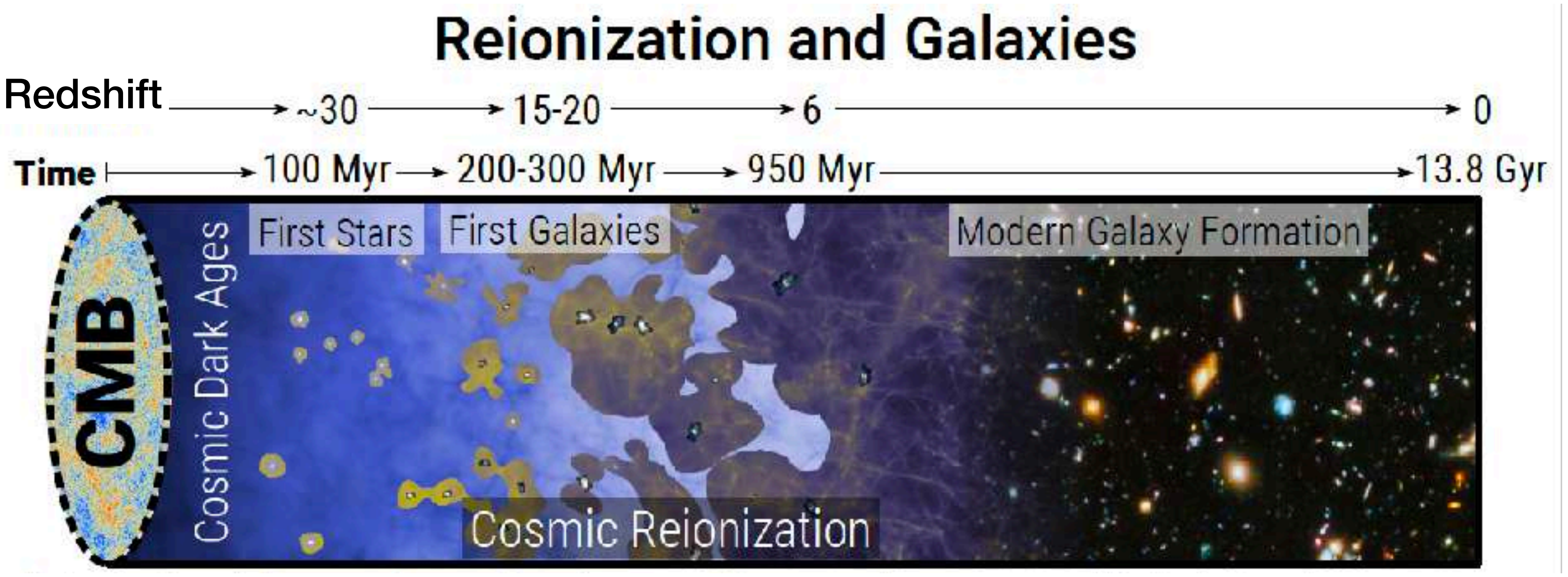
Bottom-up scenario

Astrophysical scenario

I) Magnetic flux transport from sources
(e.g. AGN, SNe)



Credit: Timmerman; LOFAR & HST



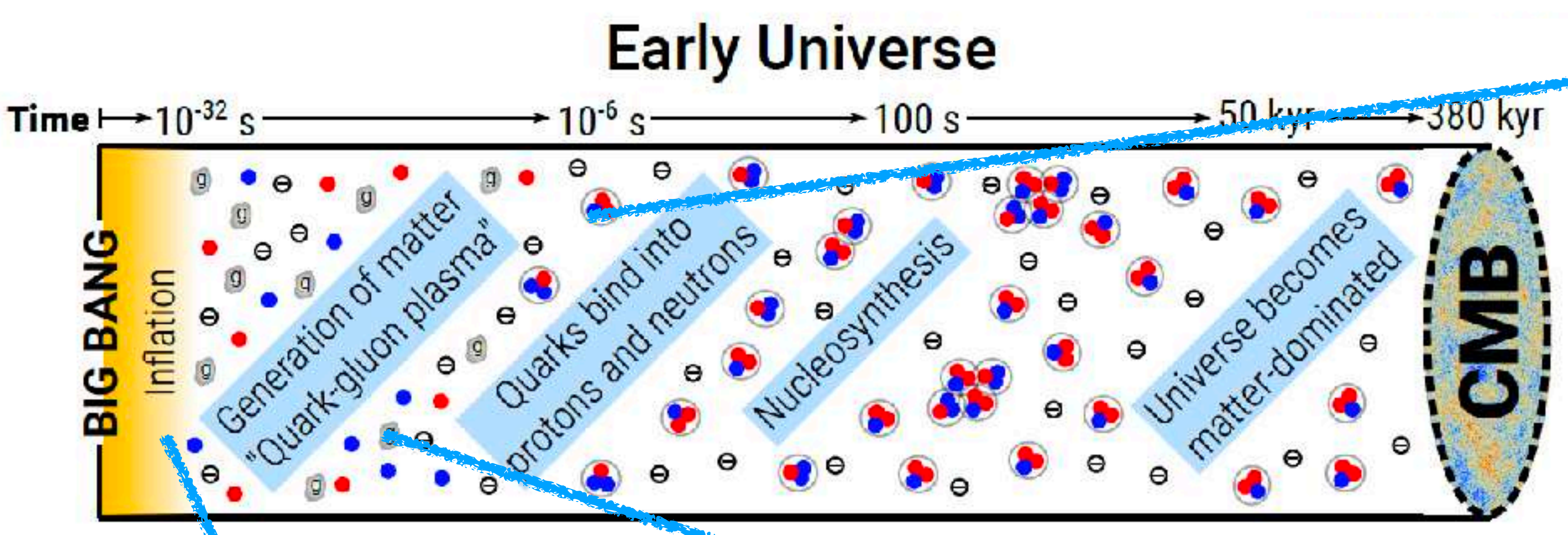
Credit: Wise et al. 2019

Astrophysical

- Battery mechanisms (e.g. Biermann battery, Harrison mechanism)

- Plasma instabilities (e.g. Weibel instability)

Primordial scenario



Credit: Wise et al. 2019

Primordial

QCD ($\sim 10^{-6}$ s)

Electroweak ($\sim 10^{-12}$ s)

Phase-transitional

[Vachaspati 1991]

- Collisions of bubbles
- Limited by causality
  - Bound coherence length

$$\lambda_B < H^{-1}$$

Inflationary

[Turner & Widrow 1988]

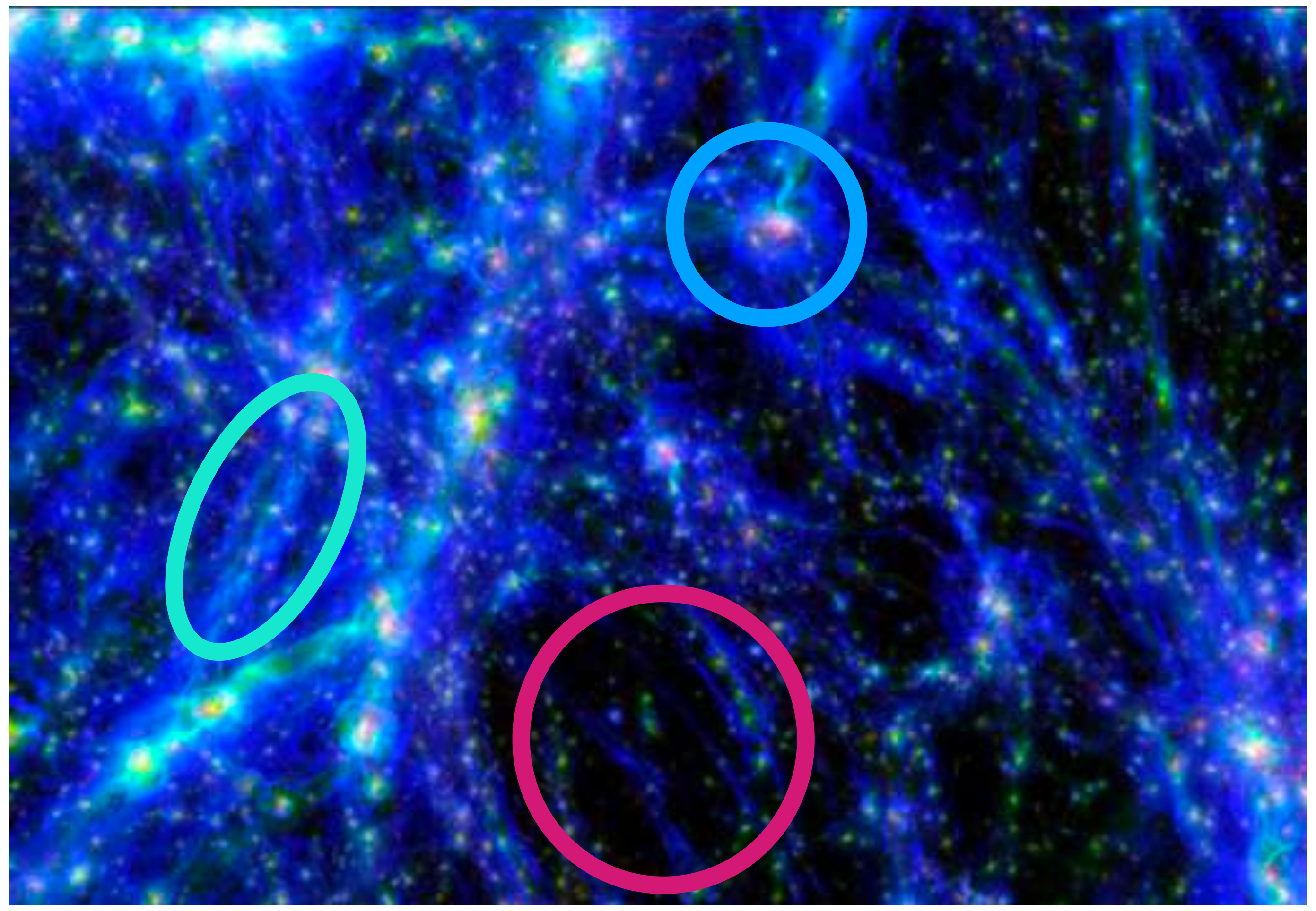
- Vacuum fluctuations
- Not limited by causality
  - Coherence length unbound

$$\lambda_B \gg H^{-1}$$

Simulating magnetic fields

Generation	Evolution
Primordial	Voids
Batteries & instabilities	Filaments
Feedback	Galaxy clusters

Cosmic web



[Vazza et al. 2017]

Galaxy clusters:

$B \sim$ a few μG

Filaments:

$B \sim 10$ nG

Void regions:

$B \gtrsim 10^{-16}$ G

Simulating magnetic fields

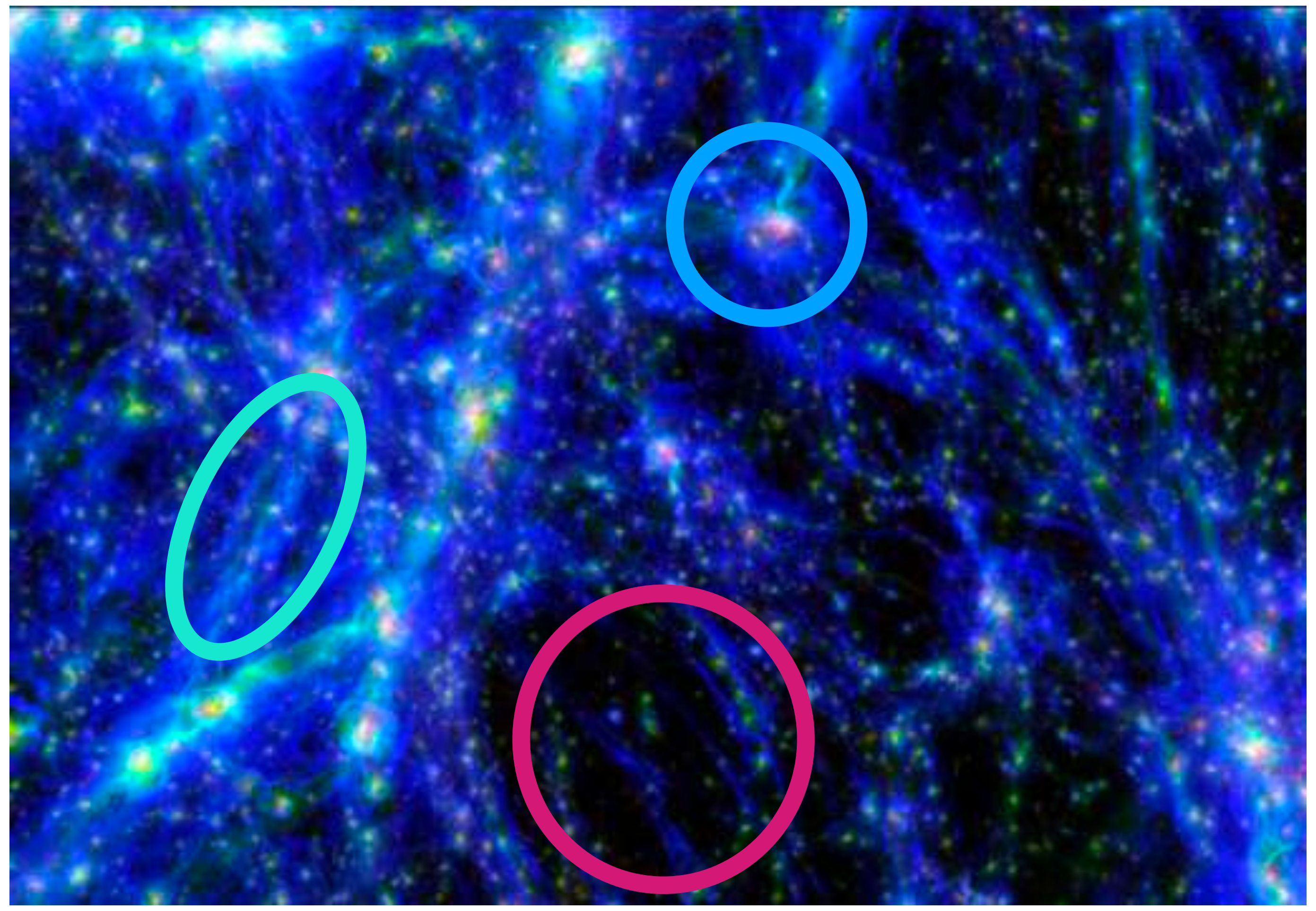
Generation

- Primordial
- Batteries & instabilities
- Feedback

Evolution

- Voids
- Filaments
- Galaxy clusters

Cosmic web



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Cosmological simulations

I) Initial magnetic conditions

II) Modifications to the initial matter PS

Simulating magnetic fields

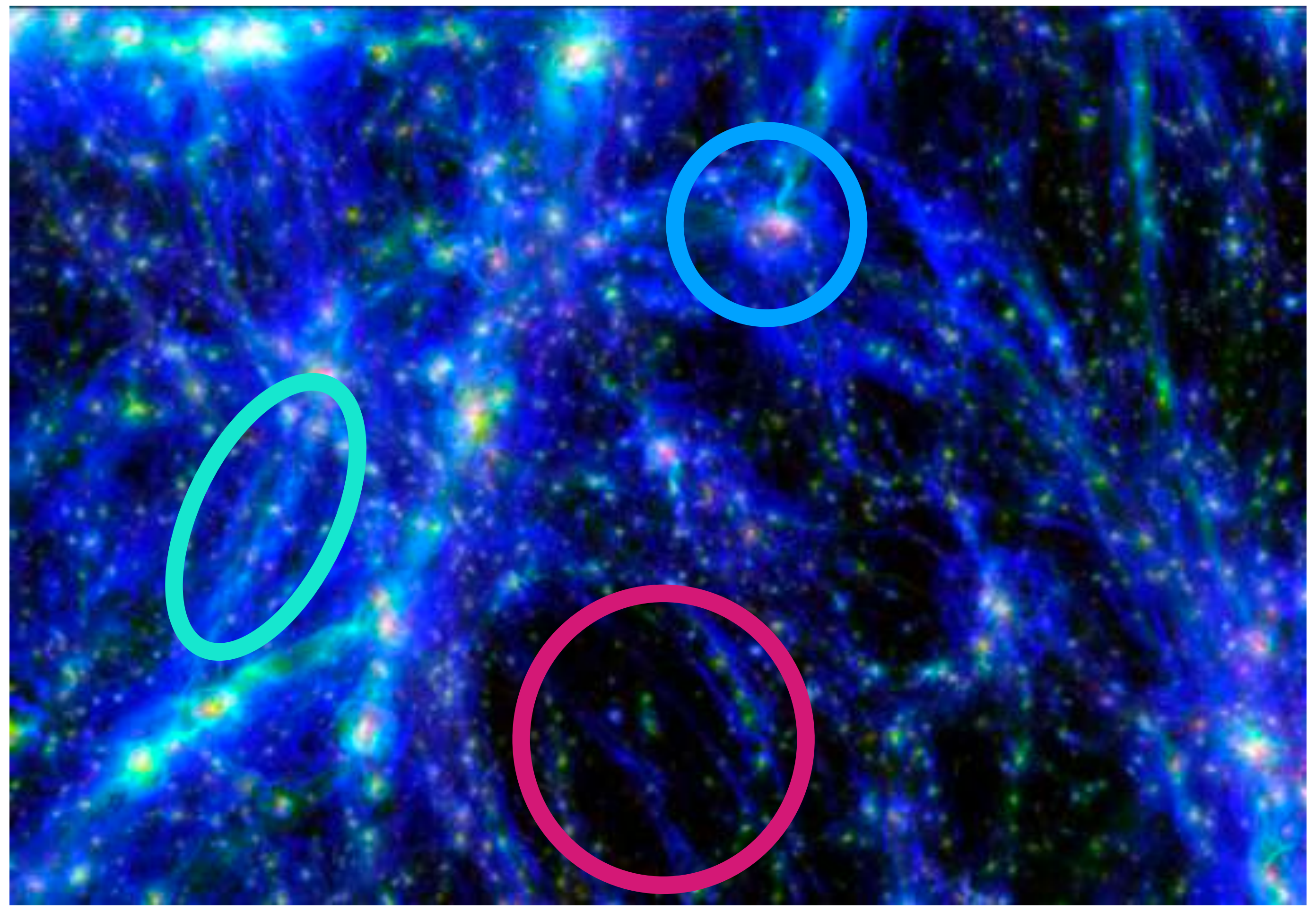
Generation

- Primordial
- Batteries & instabilities
- Feedback

Evolution

- Voids
- Filaments
- Galaxy clusters

Cosmic web



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Cosmological simulations

I) Initial magnetic conditions

II) Modifications to the initial matter PS

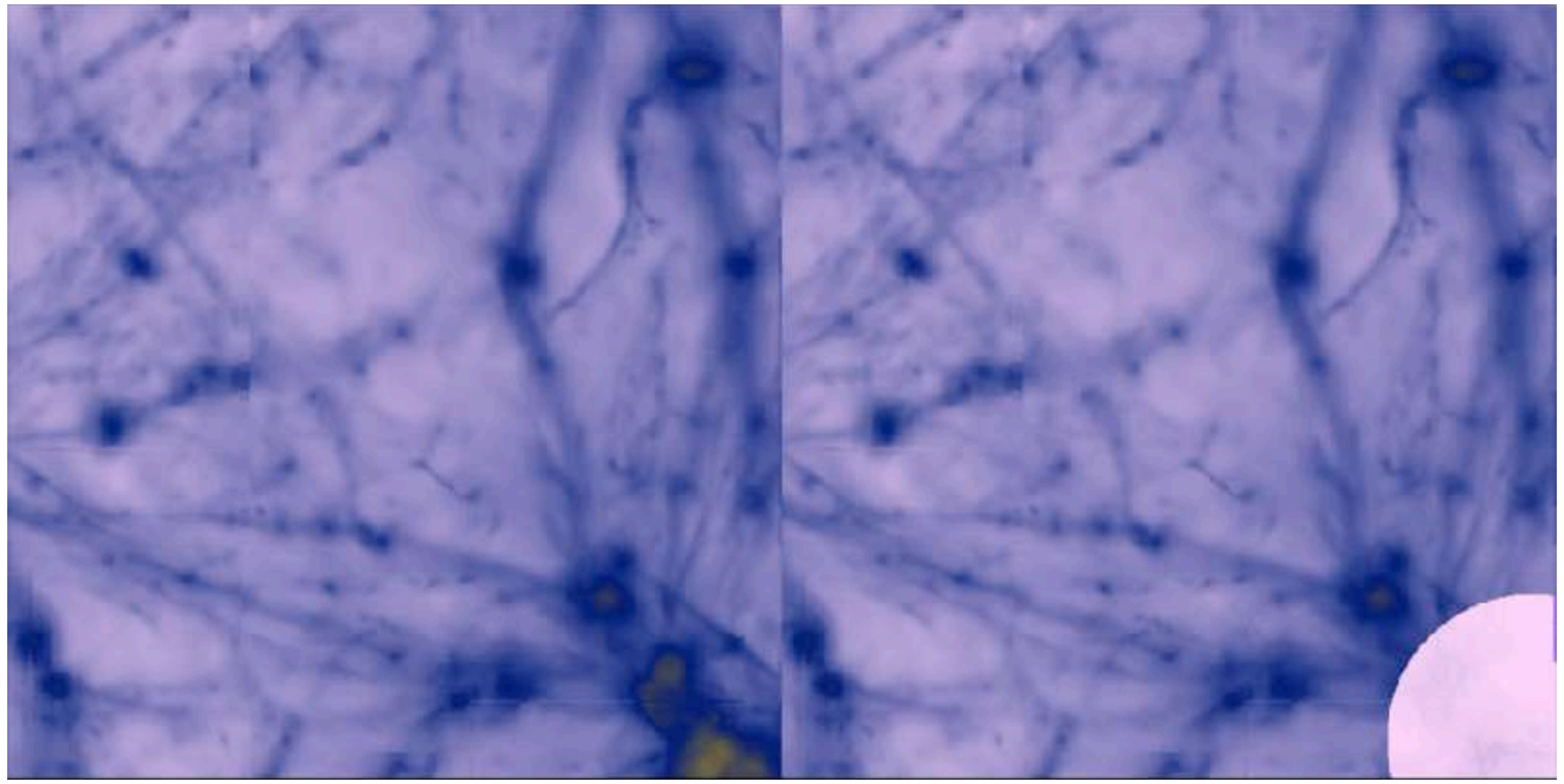
MFs in galaxy clusters:

I) Adiabatic compression

II) Turbulent amplification

Cosmological MHD zoom-in simulations

- Formation of a massive GC: $\sim 10^{15}\,\mathrm{M}_{\odot}$
- Primordial seed: 0.1 nG (comoving)
- Turbulence amplification of $\gtrsim 10^4$
- Evidence of small-scale dynamo amplification

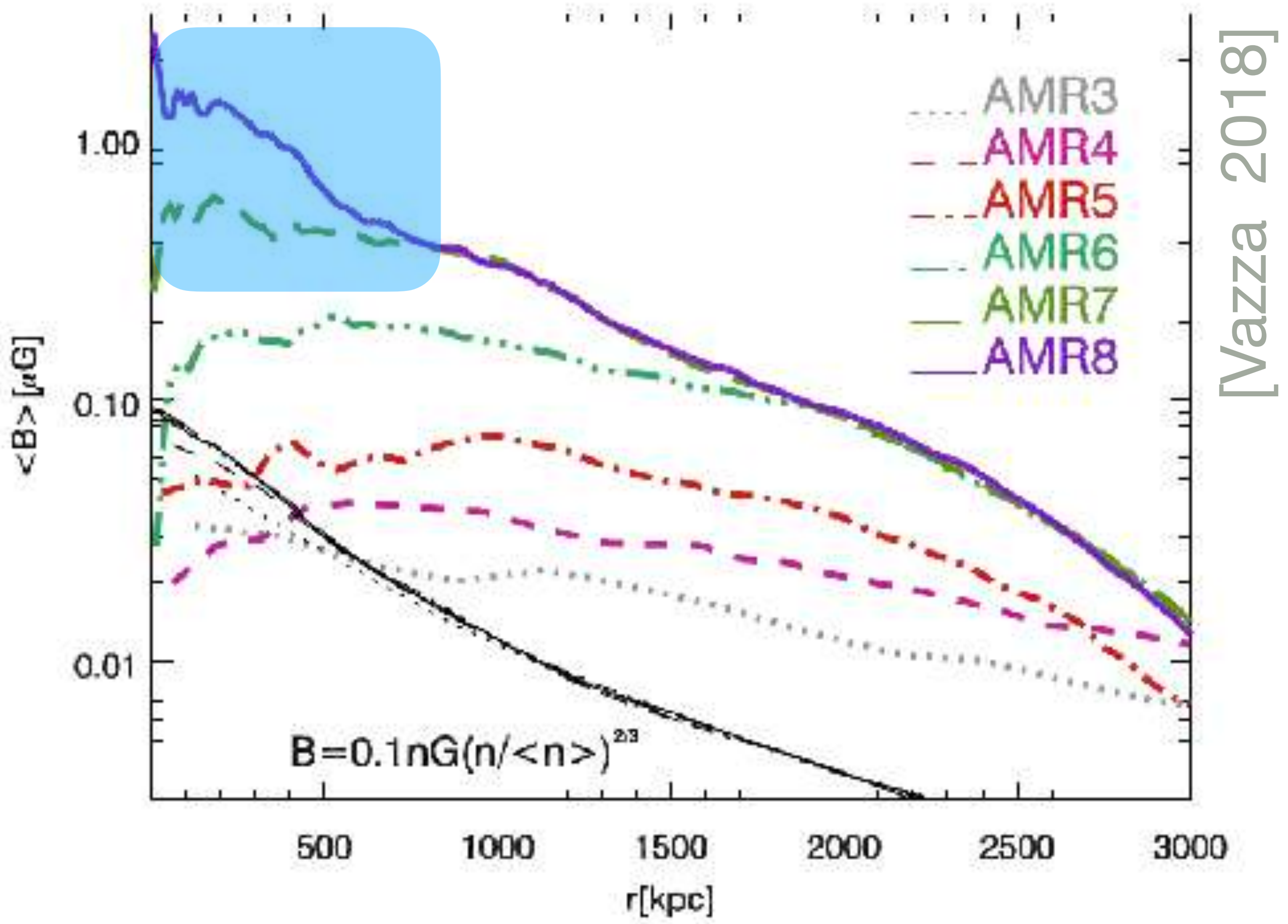


[Domínguez-Fernández et al. 2019]

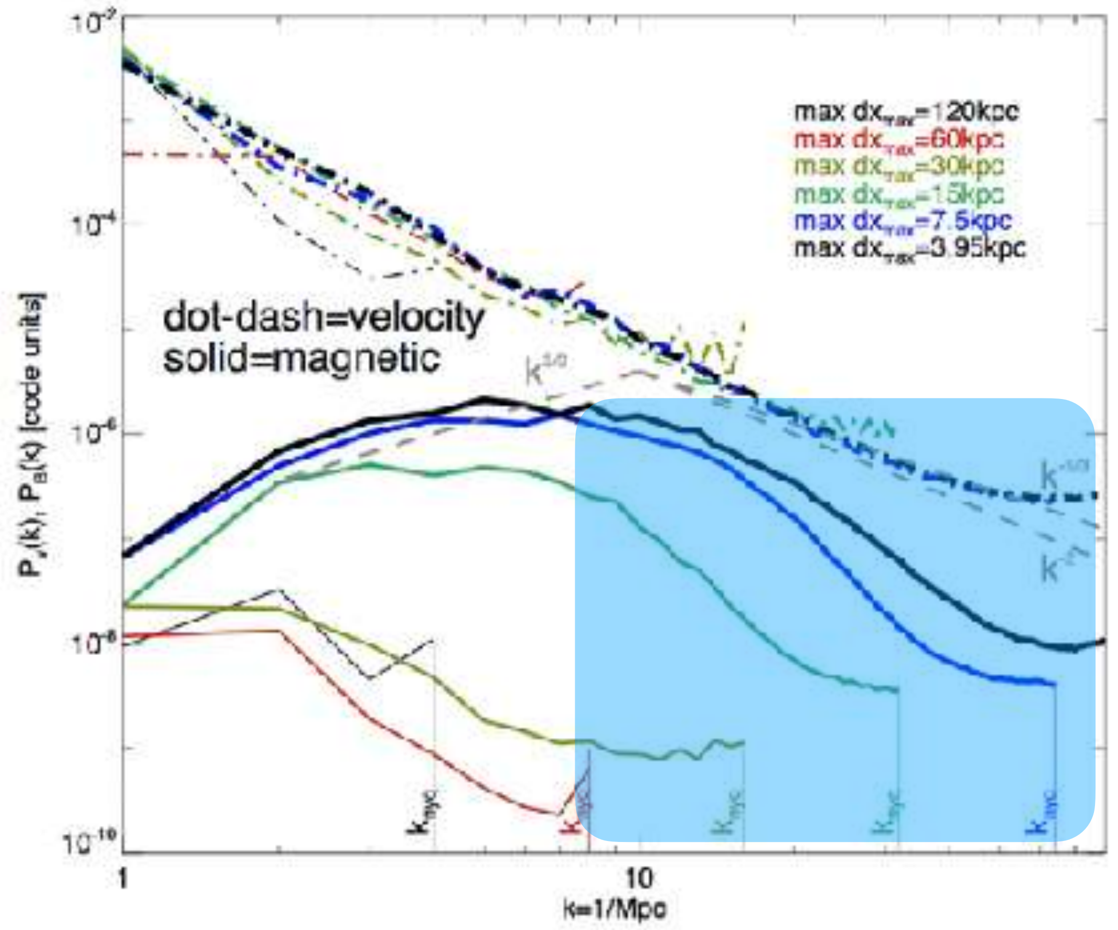
- 7 AMR levels
- Resolution:
  - $\sim 4\,\mathrm{kpc}$
- No cooling or feedback

- $z = 50$, 0.1 nG
- Total volume:
  - $(260\,\mathrm{Mpc})^3$
- Ref. Region:
  - $(25\,\mathrm{Mpc})^3$

μG **values!**



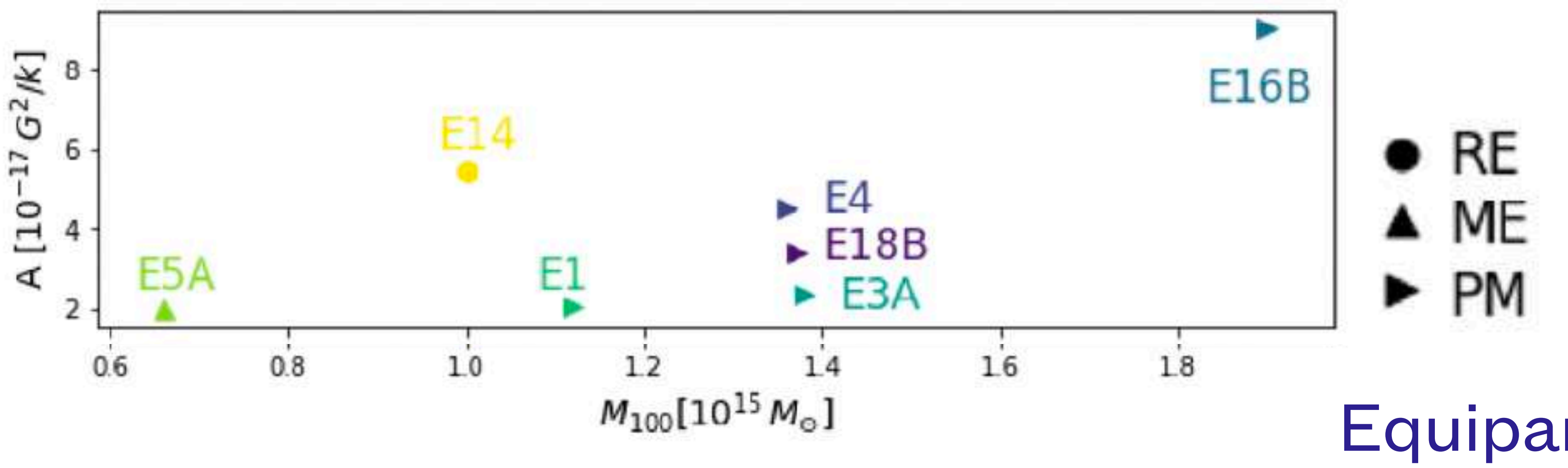
[Vazza 2018]

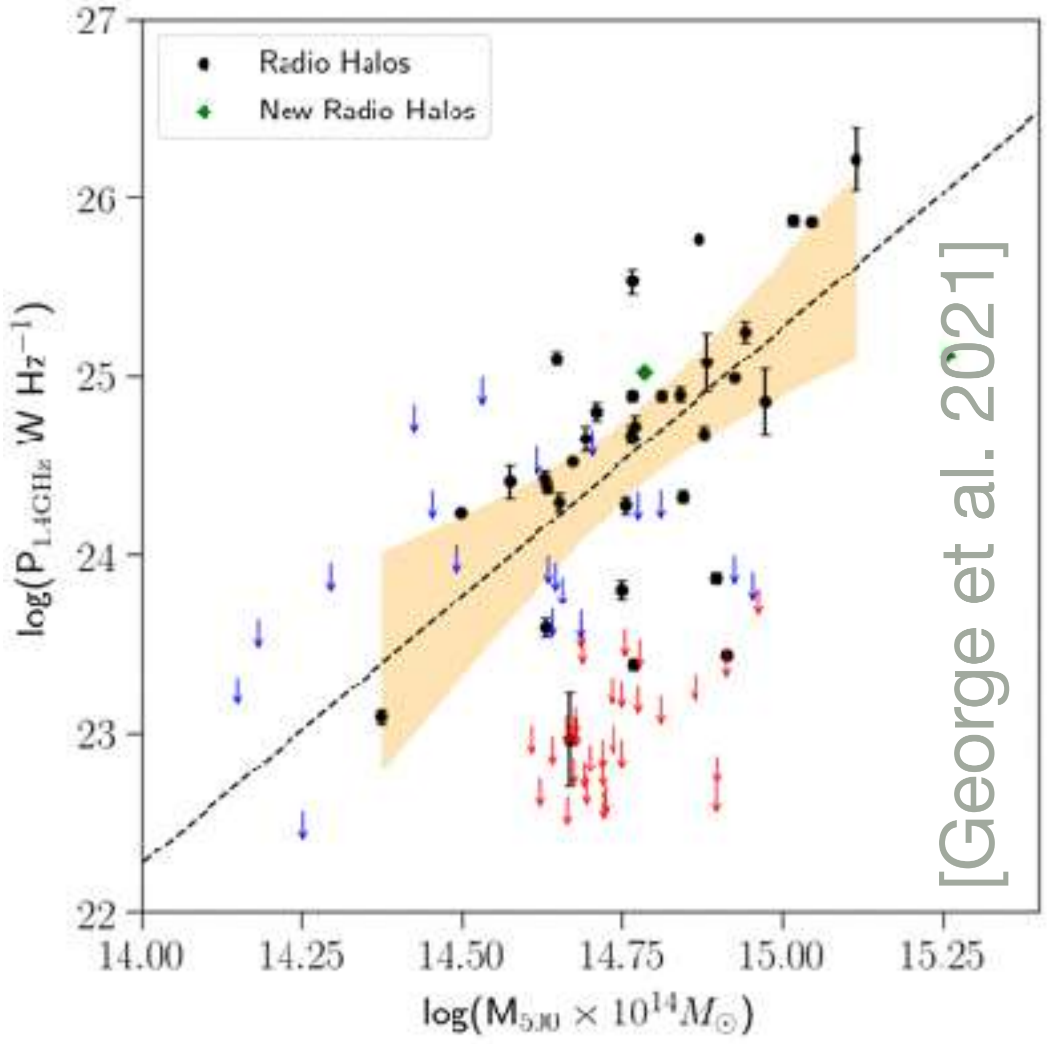


Small-scale dynamo!

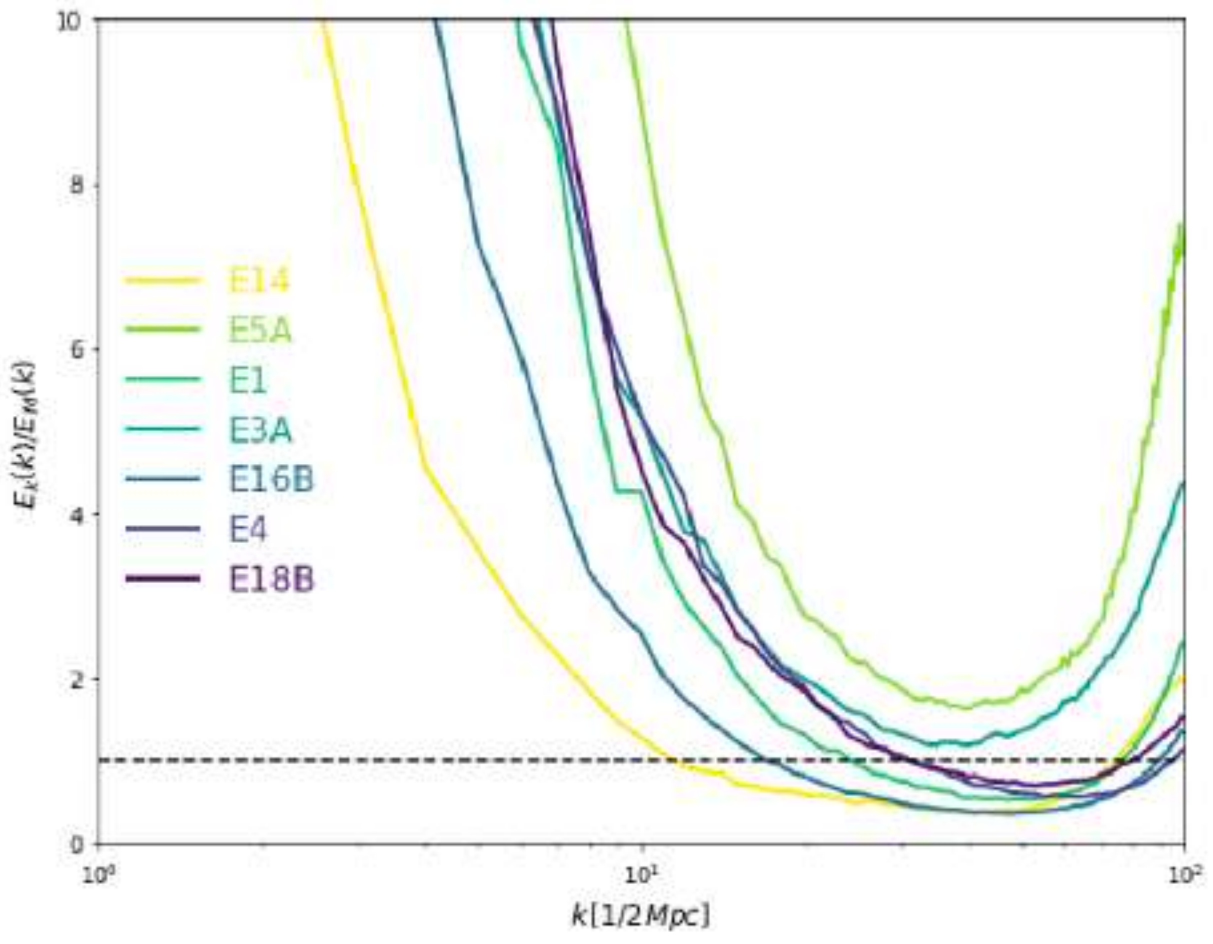
Primordial uniform seed fields

- Correlation with the cluster's mass



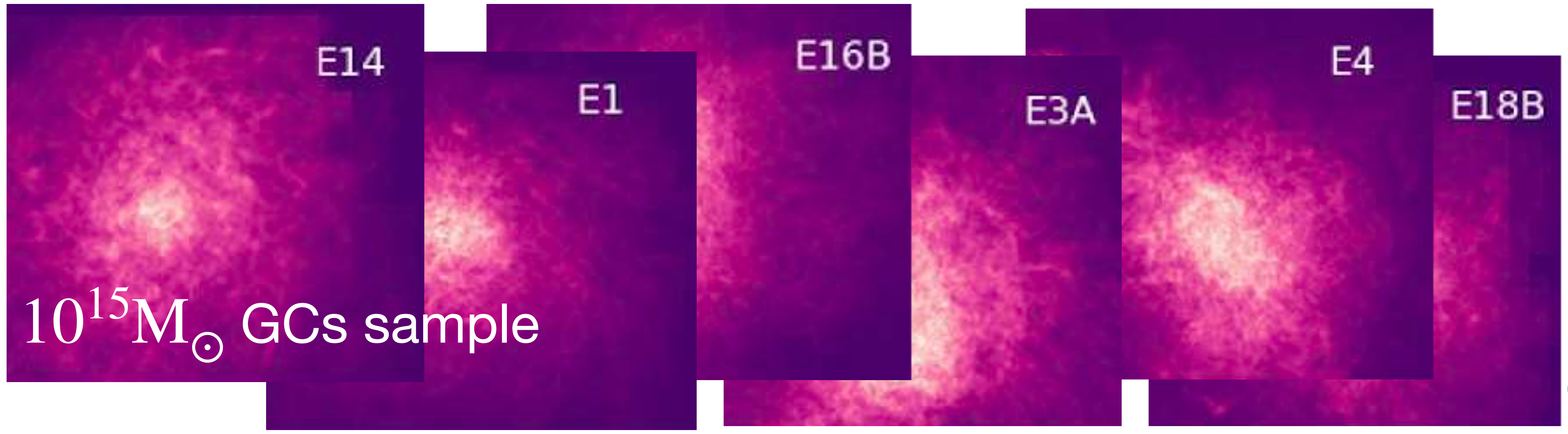


Equipartition at ~50-200 kpc



INITIAL CONDITION:

$E_B = \delta(k=0)$



[Domínguez-Fernández et al. 2019]

Primordial uniform seed fields

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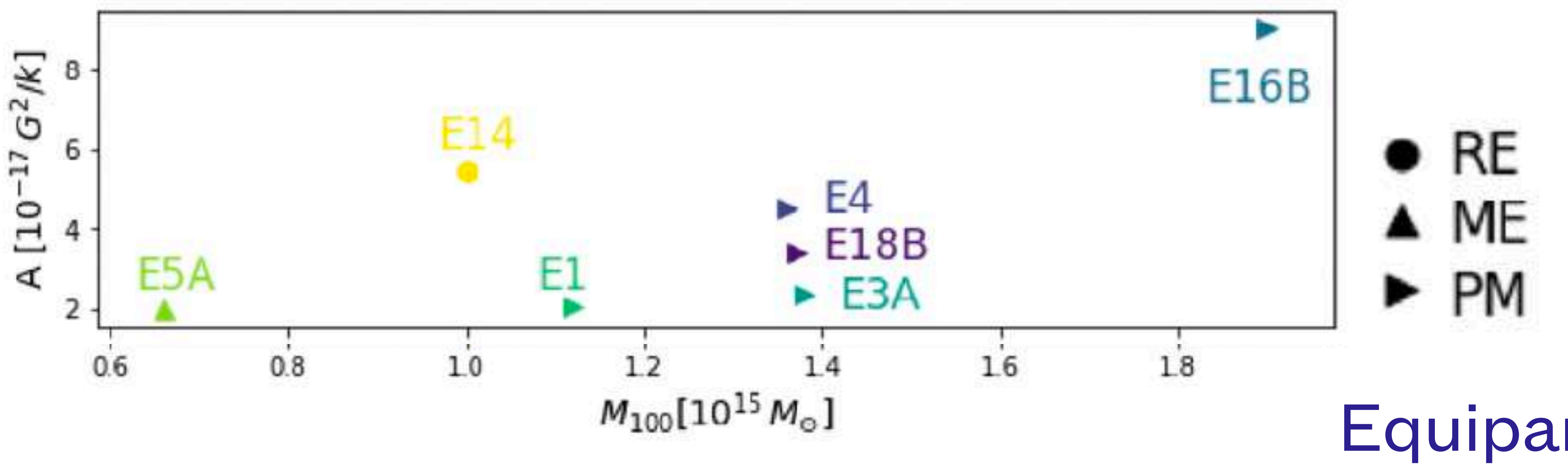
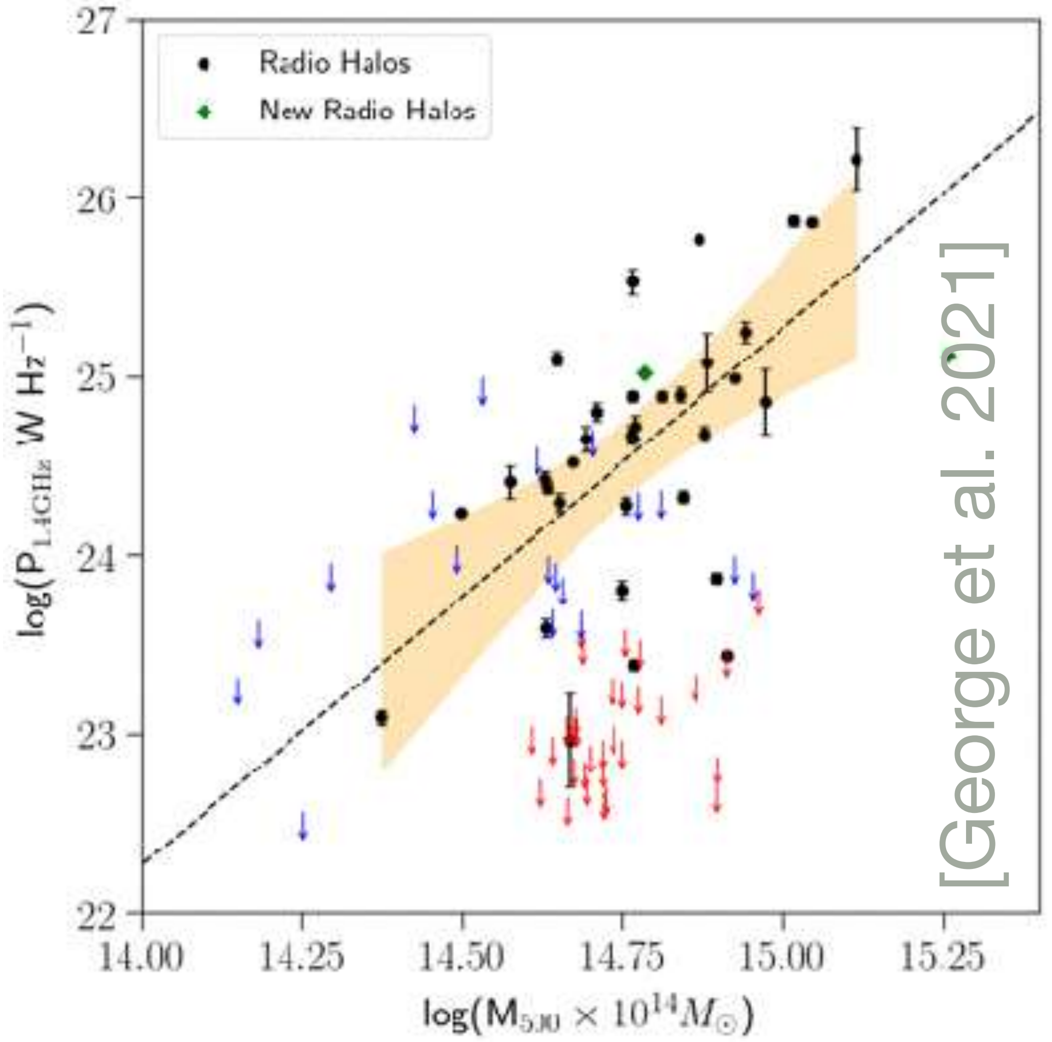
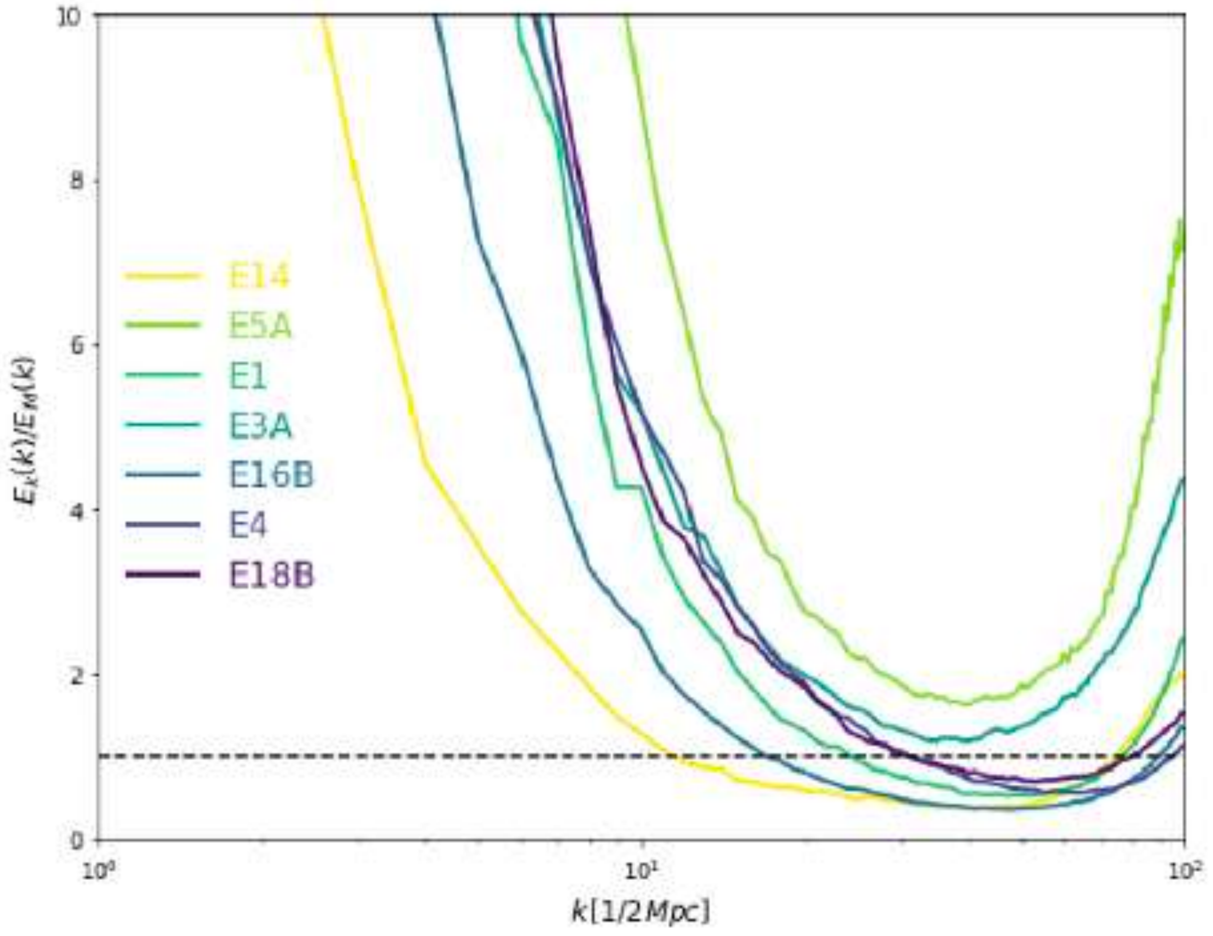




[George et al. 2021]

Equipartition at ~50-200 kpc



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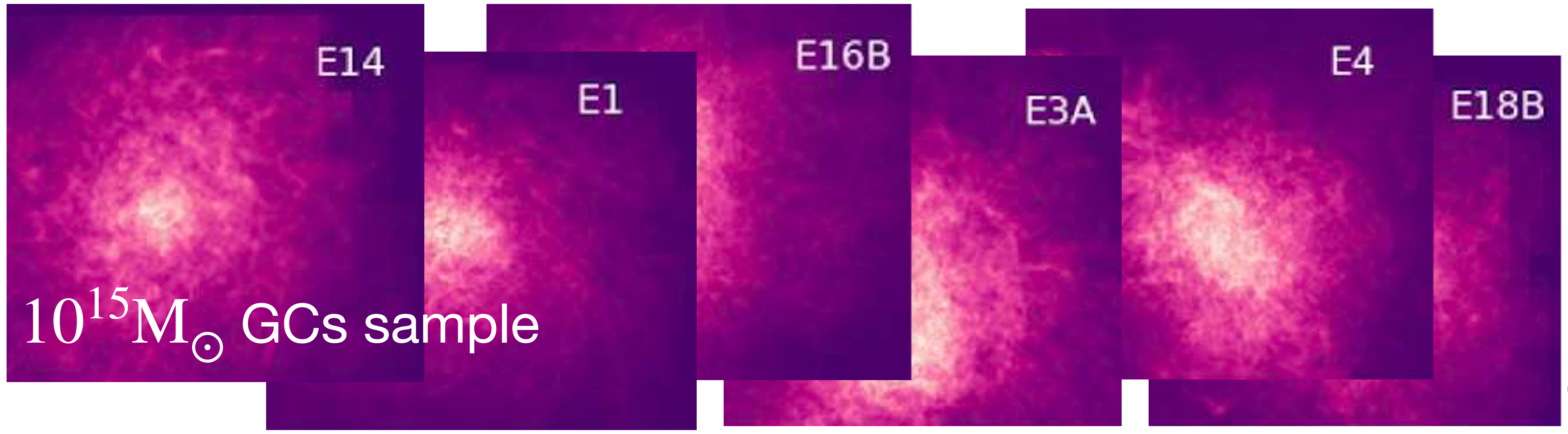
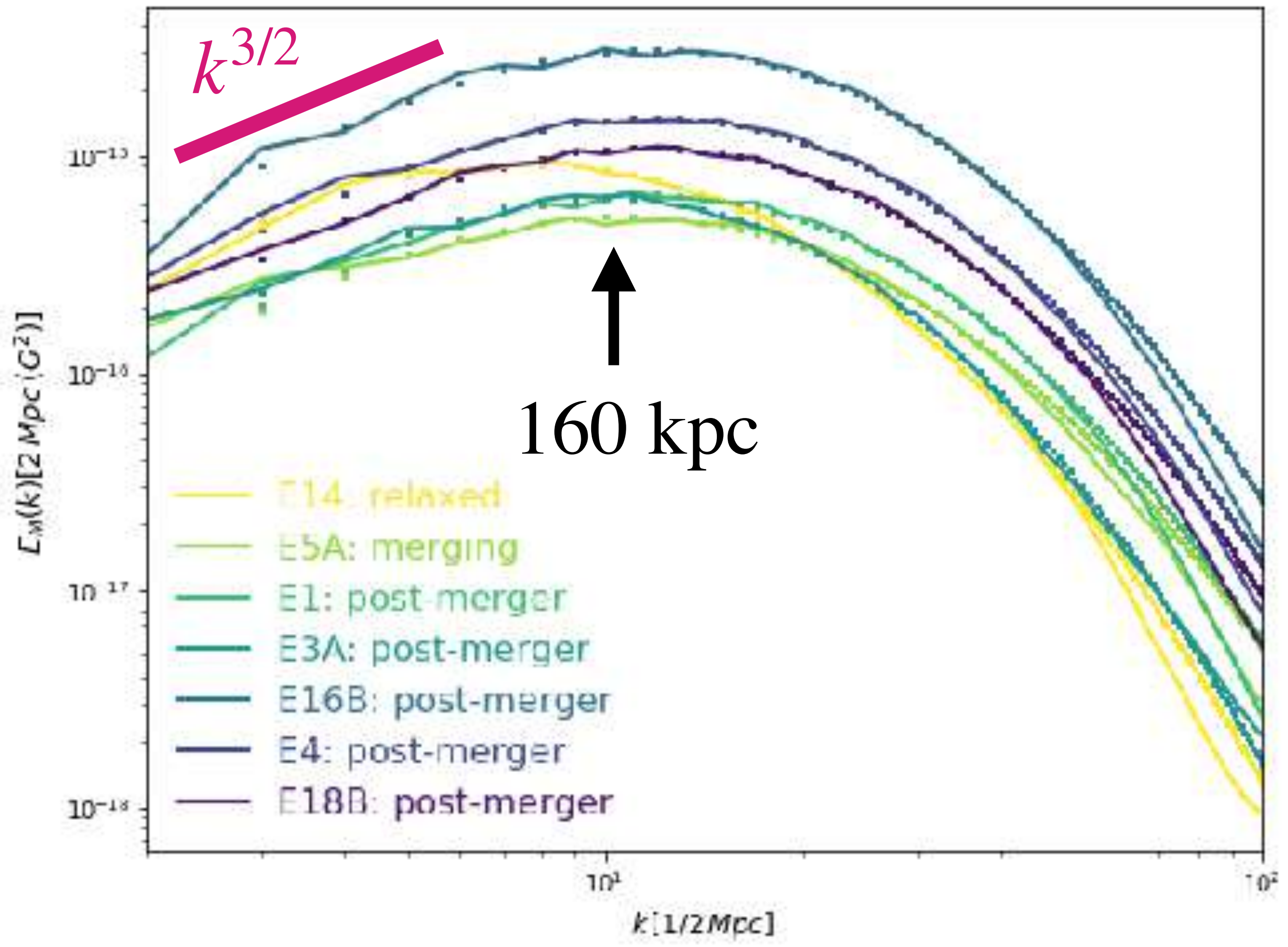


Magnetic energy (Kanzantzev-like)

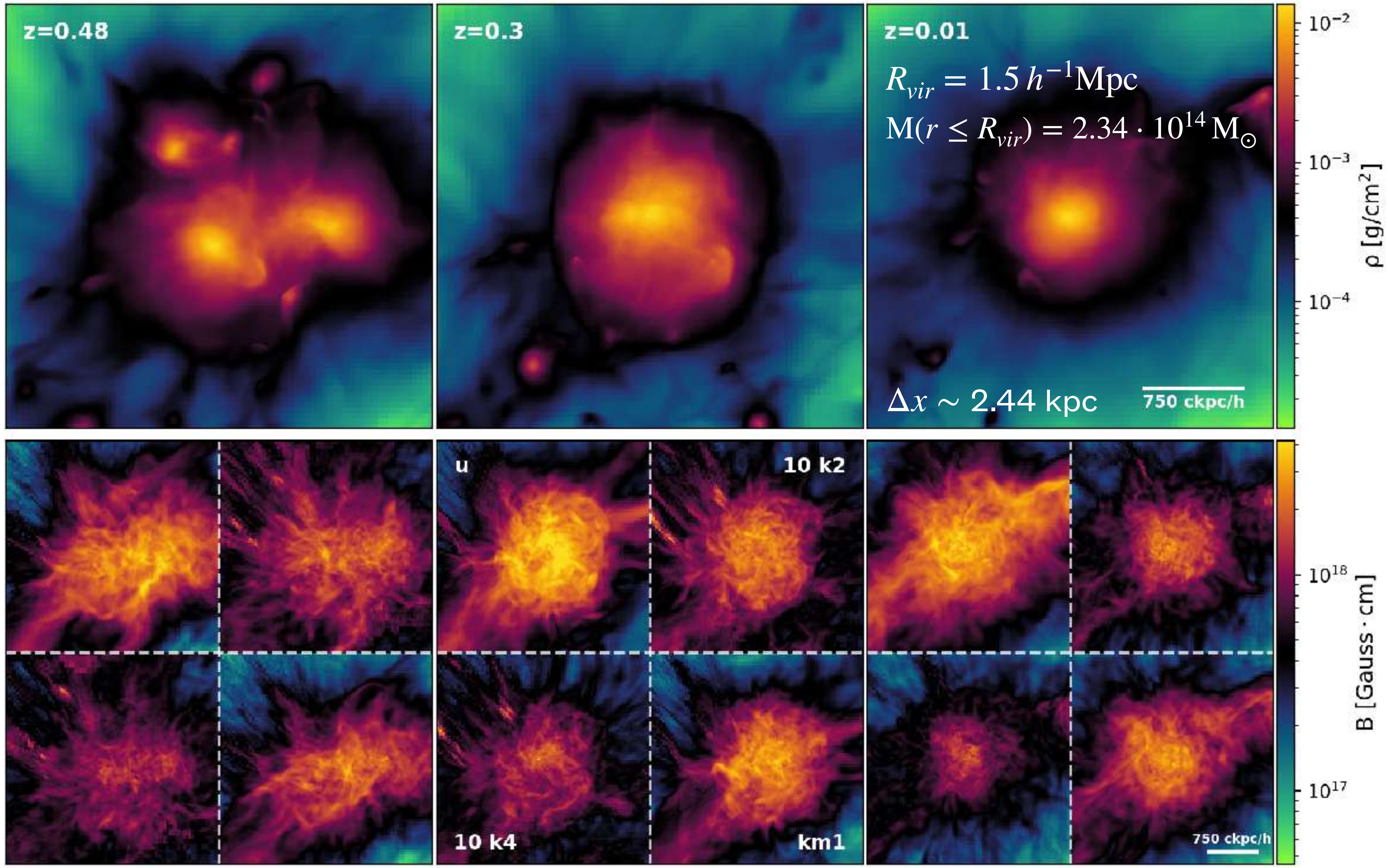


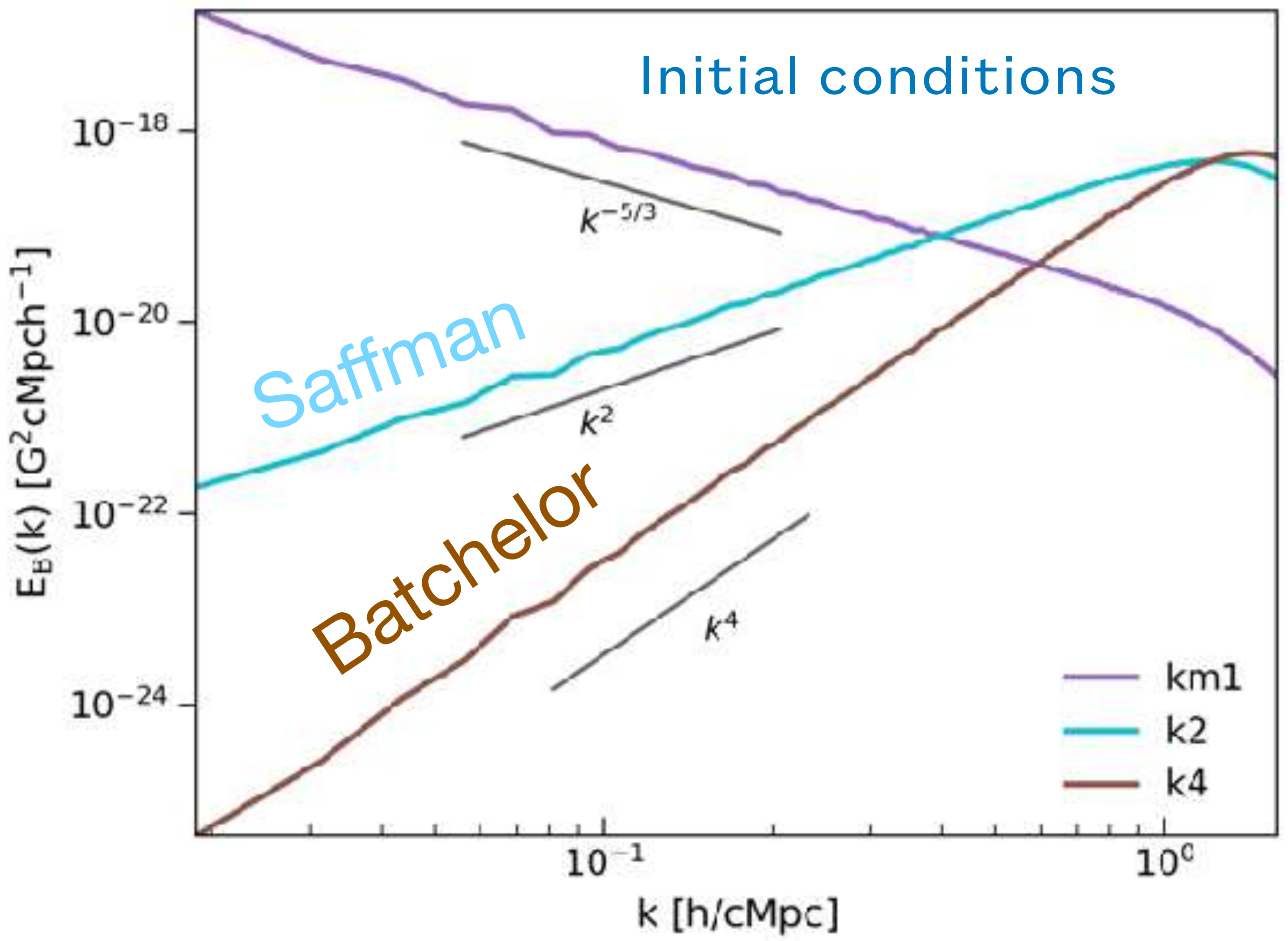
[Domínguez-Fernández et al. 2019]

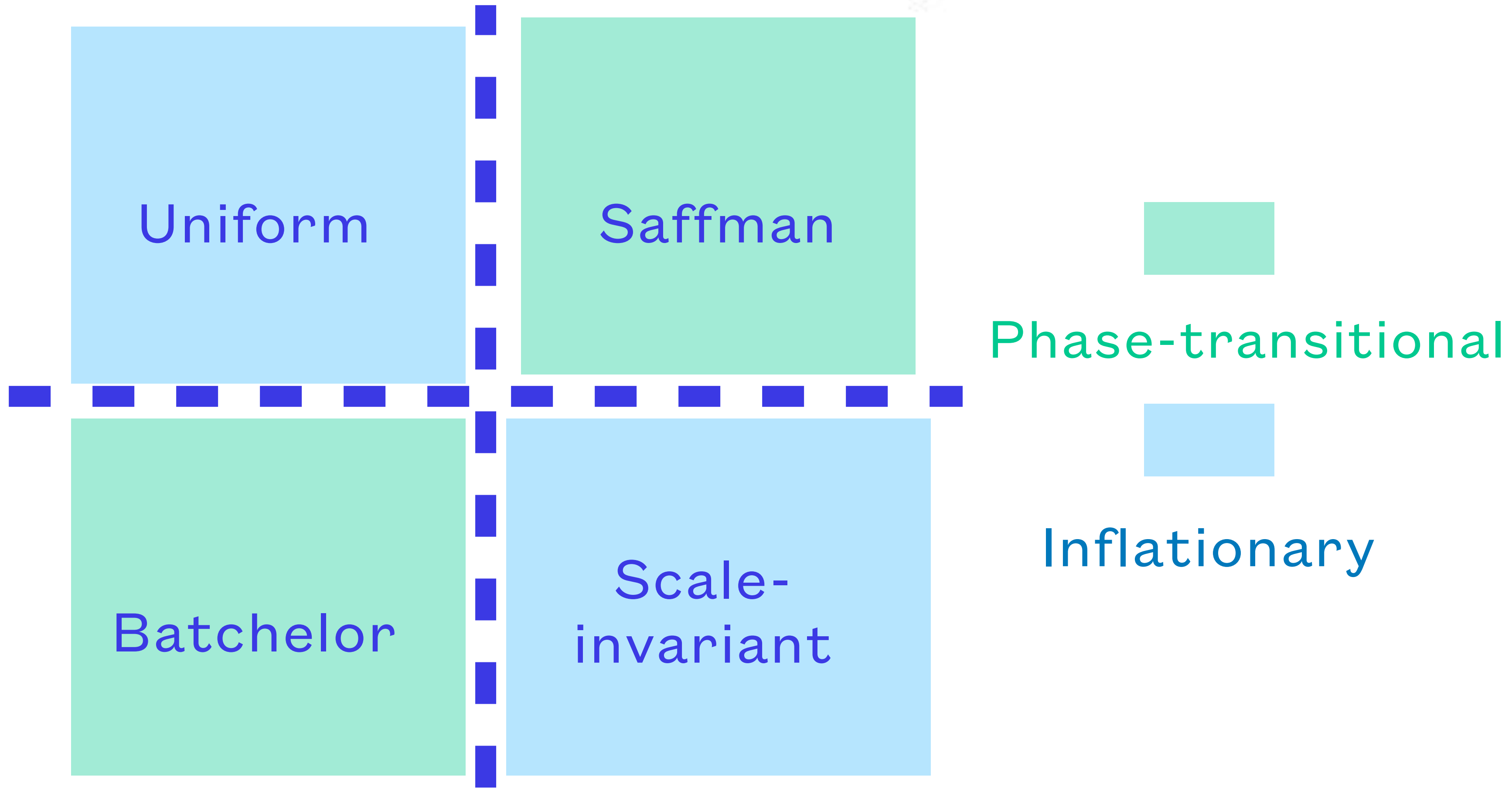
- Final magnetic power-spectrum's shape is fairly independent of the dynamical state

Primordial non-uniform seeds

[Mtchedlidze, Domínguez-Fernández et al. 2023]







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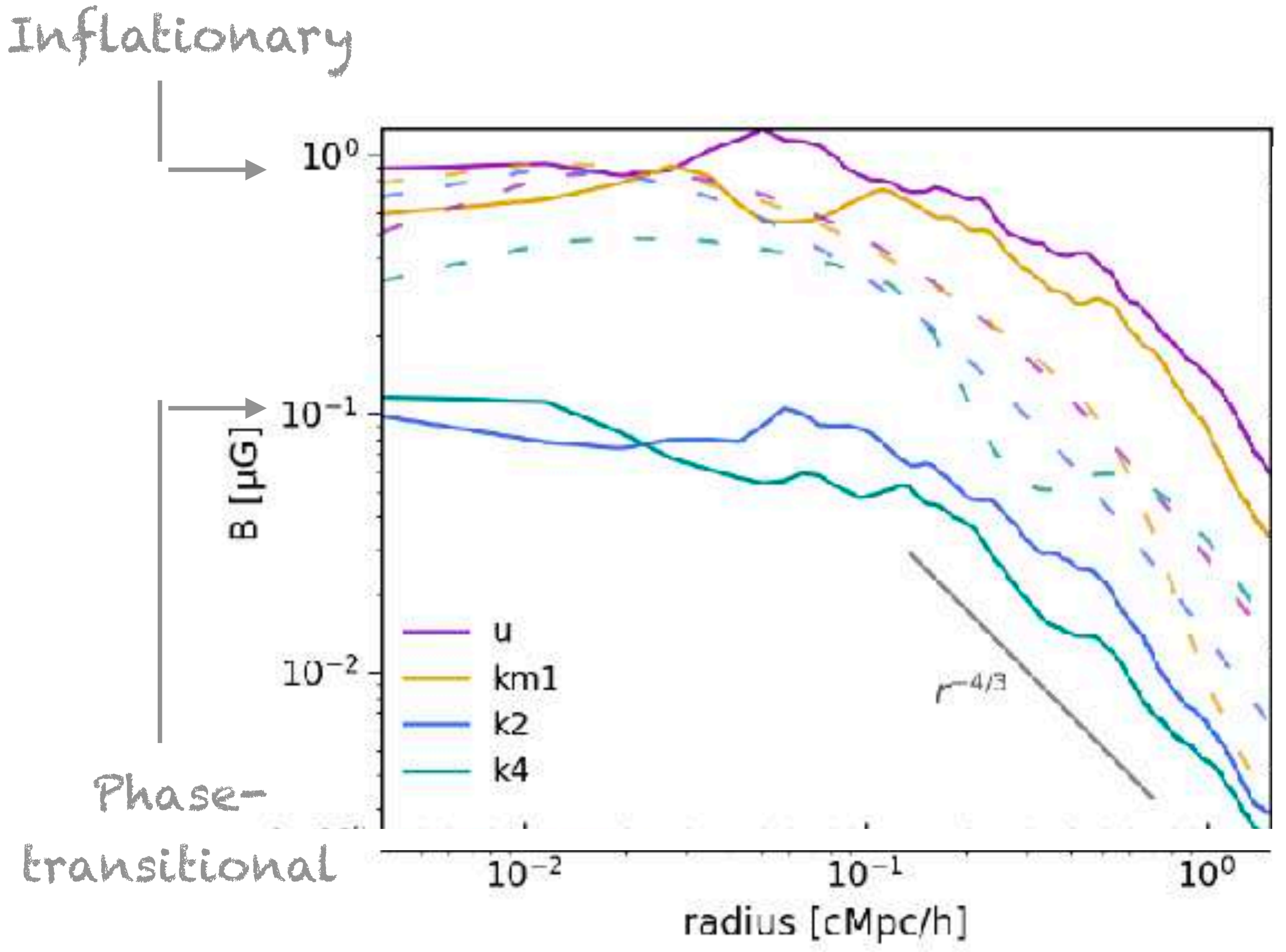
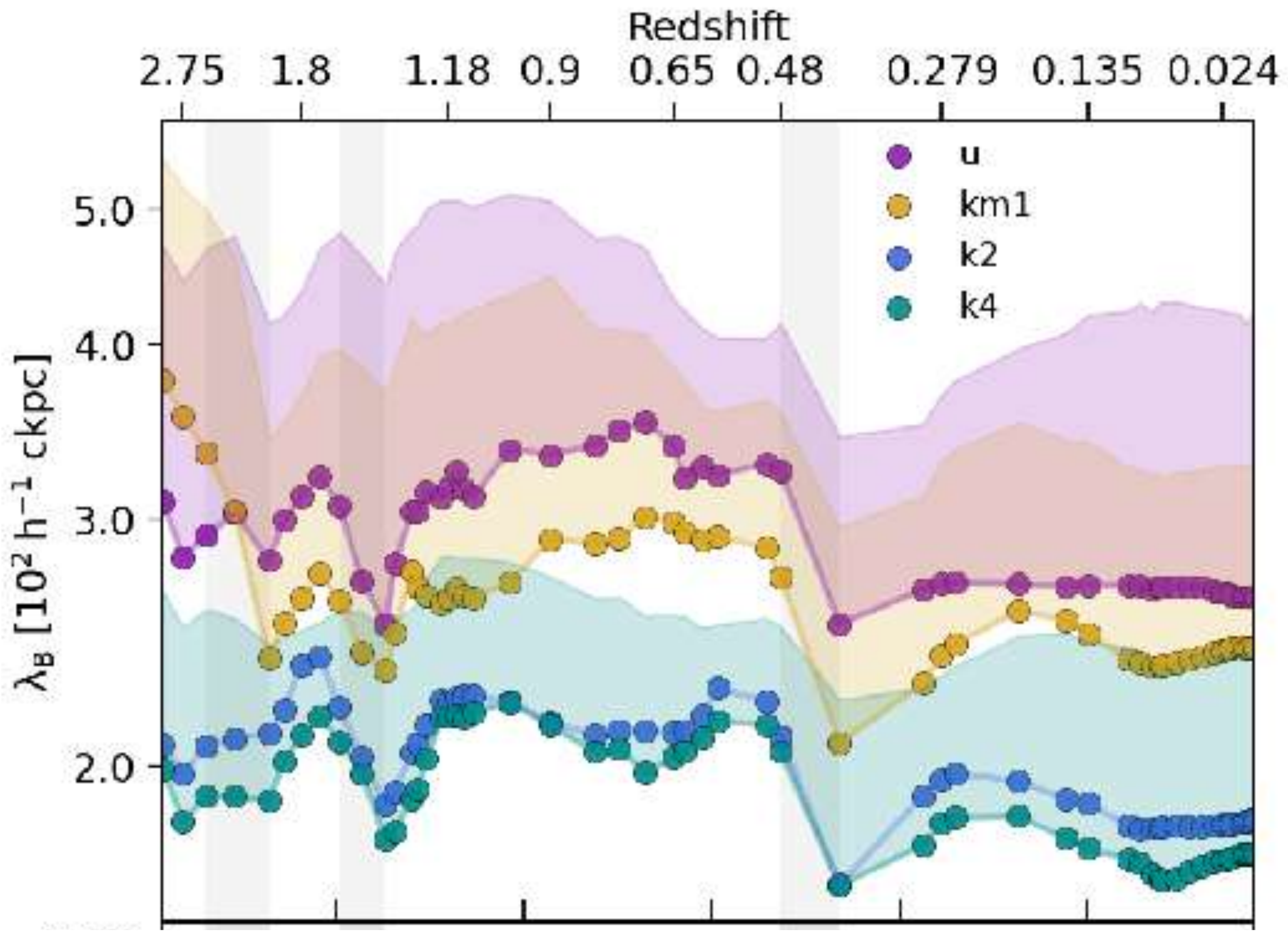
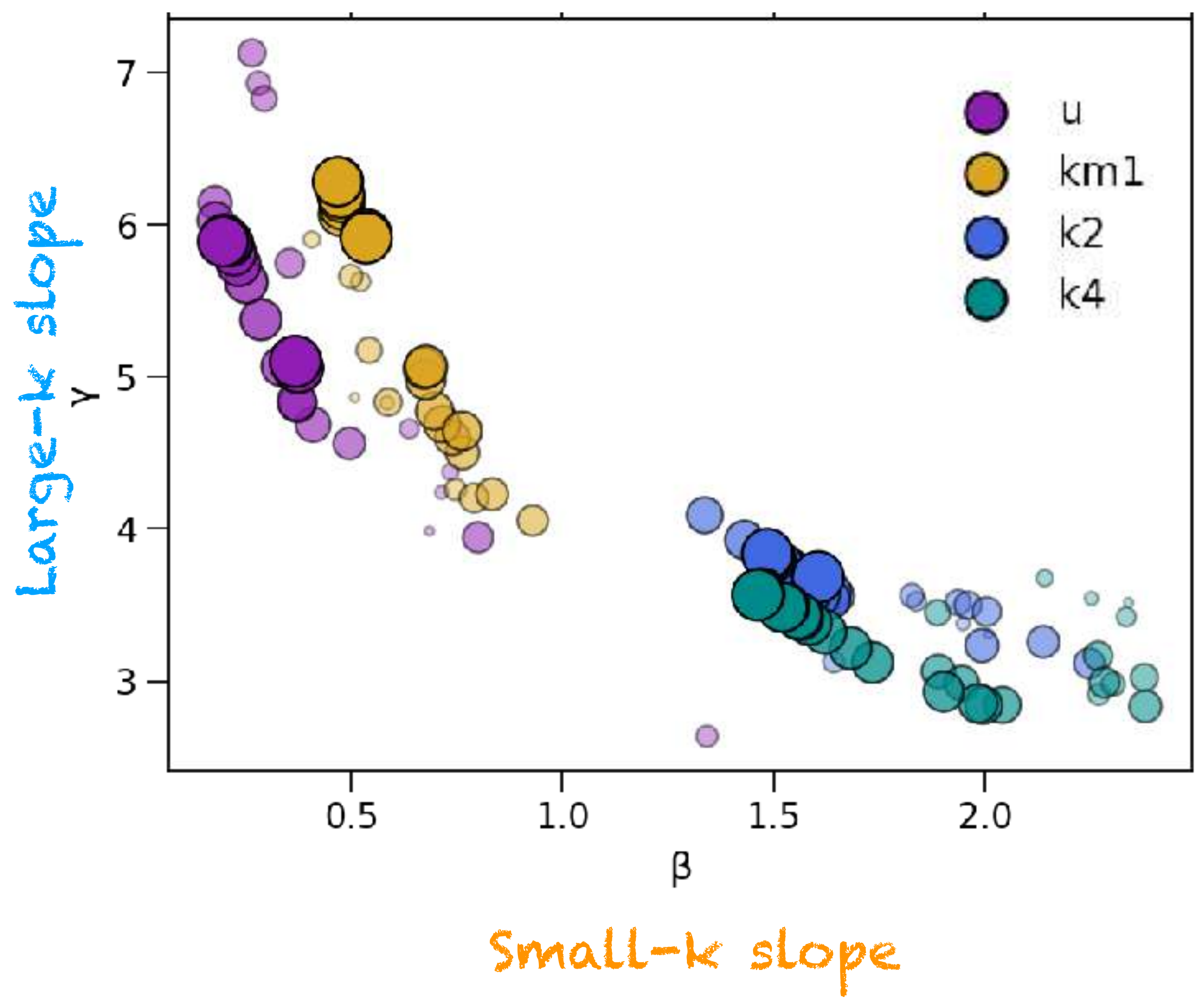
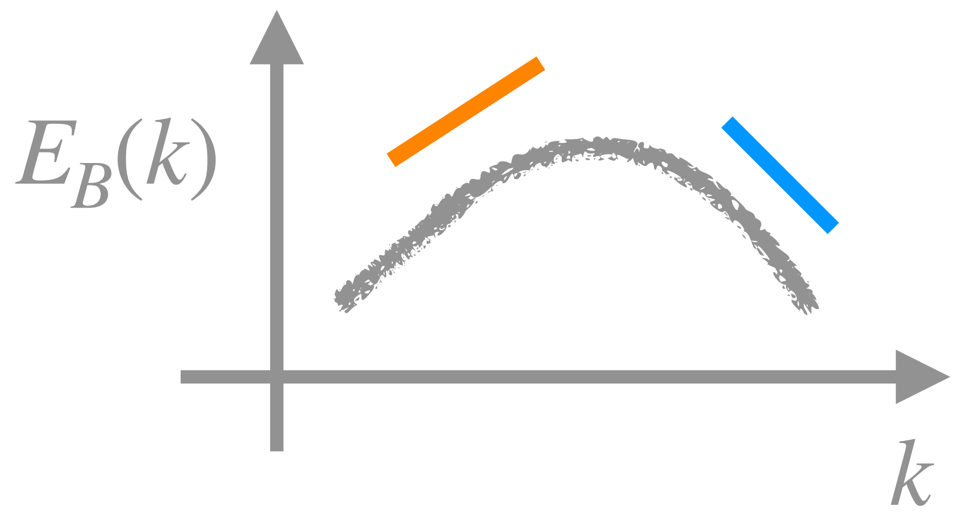






- Inflationary models:
  - Tangling of the large-scale field (larger magnetic amplification)
  - Reaching ~μG values and ~300 kpc correlation length
- Phase transitional models:
  - Reaching ~0.1 μG values at the center and ~200 kpc correlation length



[Mtchedlidze, Domínguez-Fernández at al. 2023]

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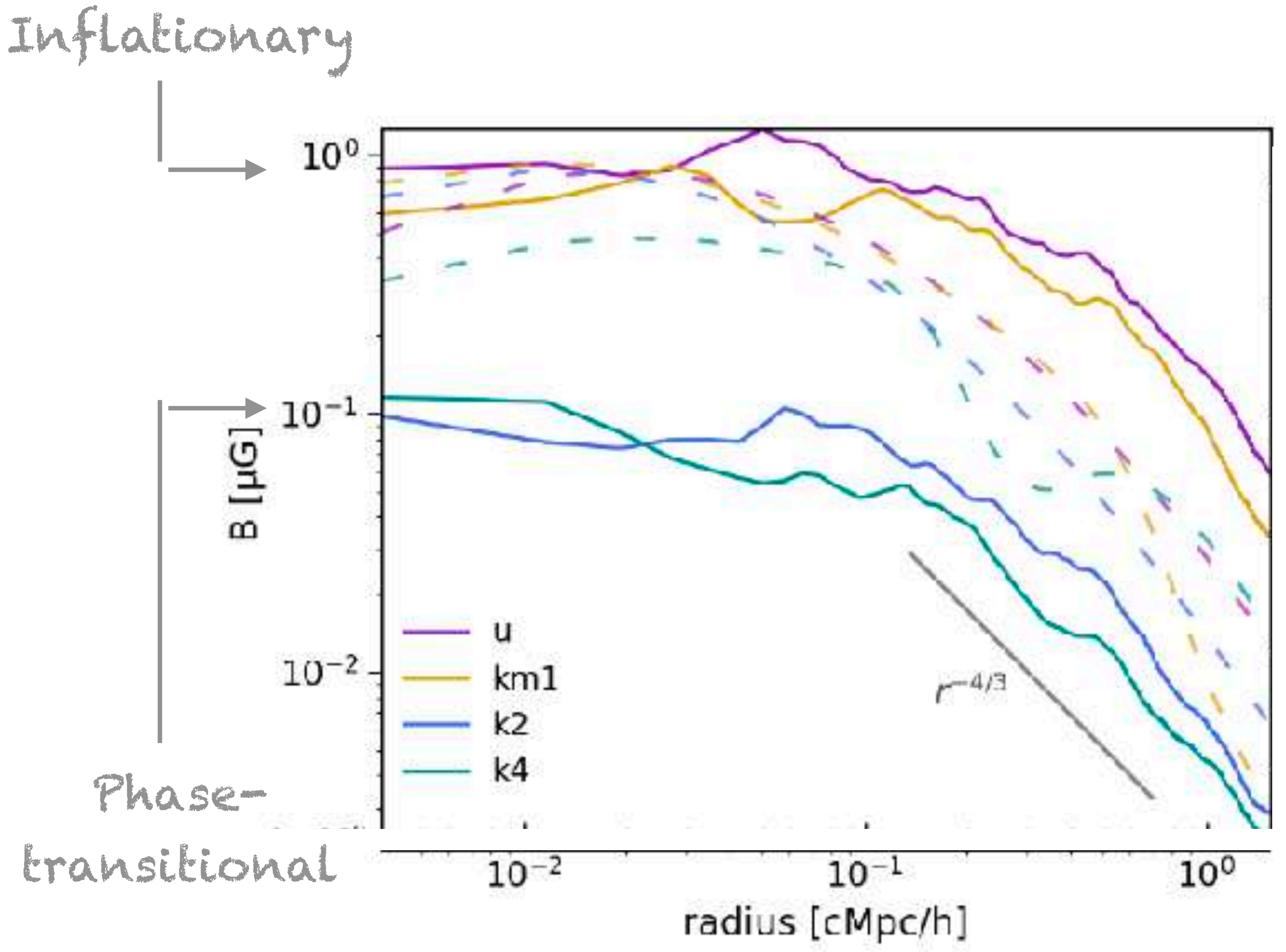
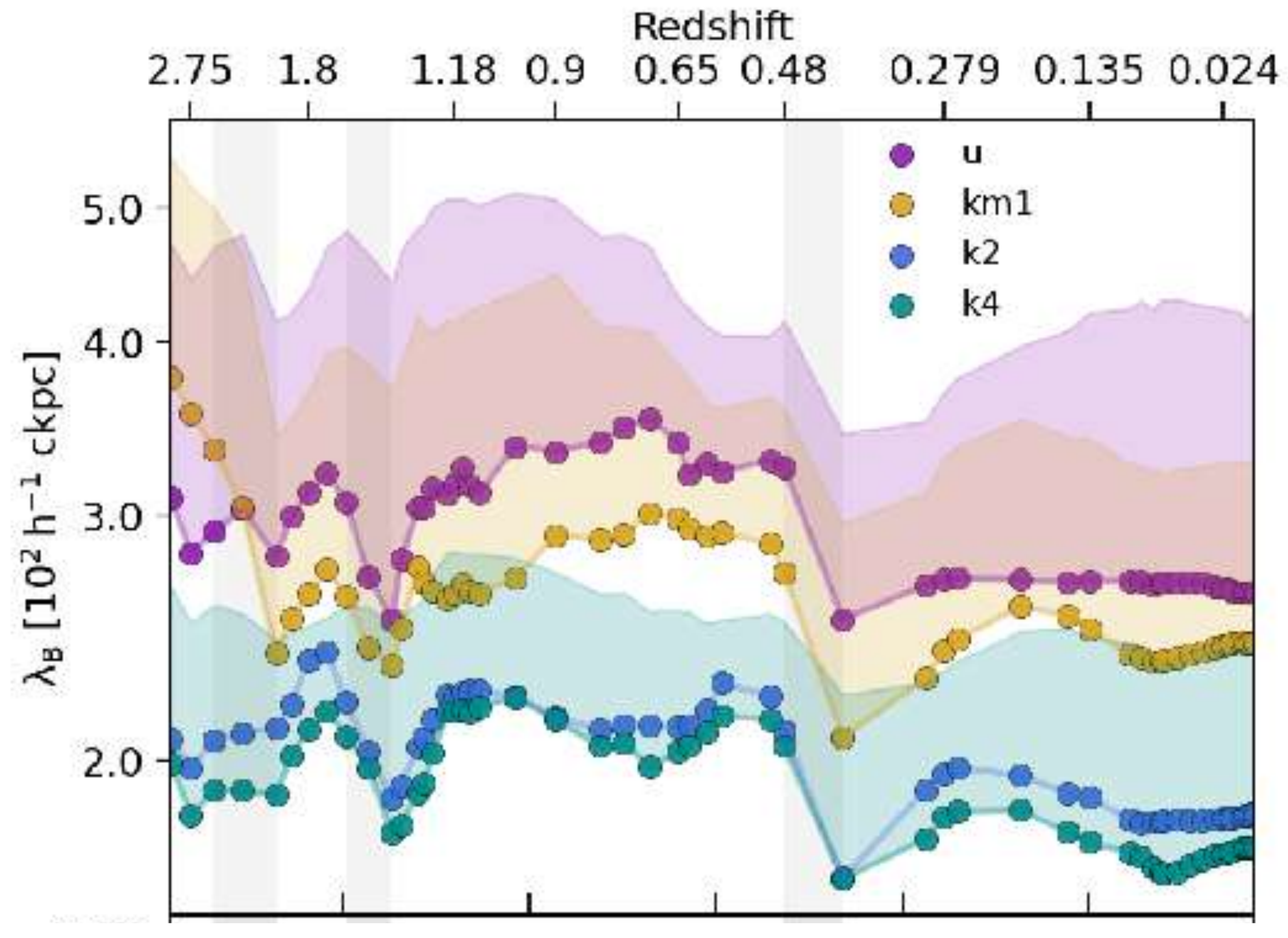
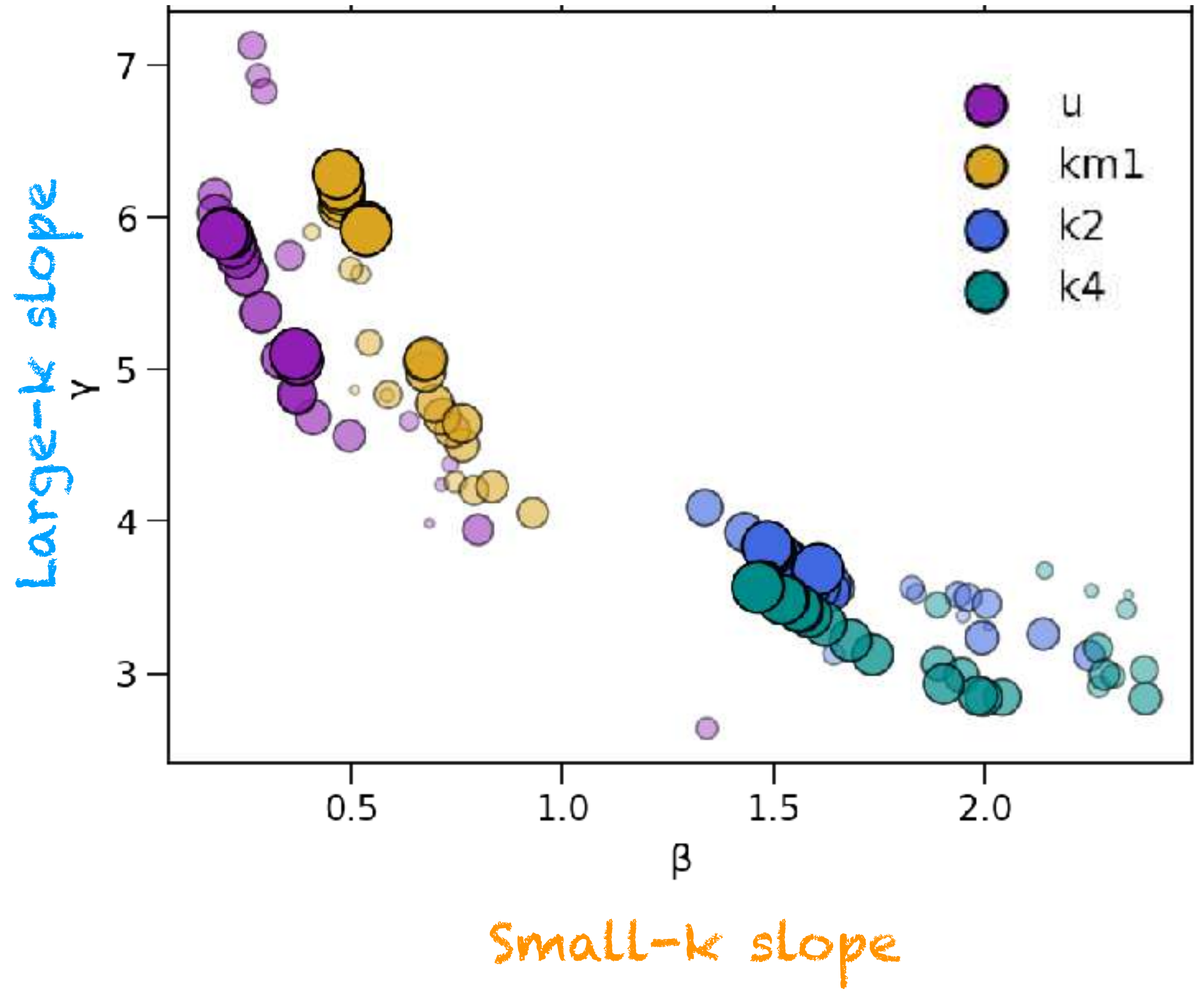


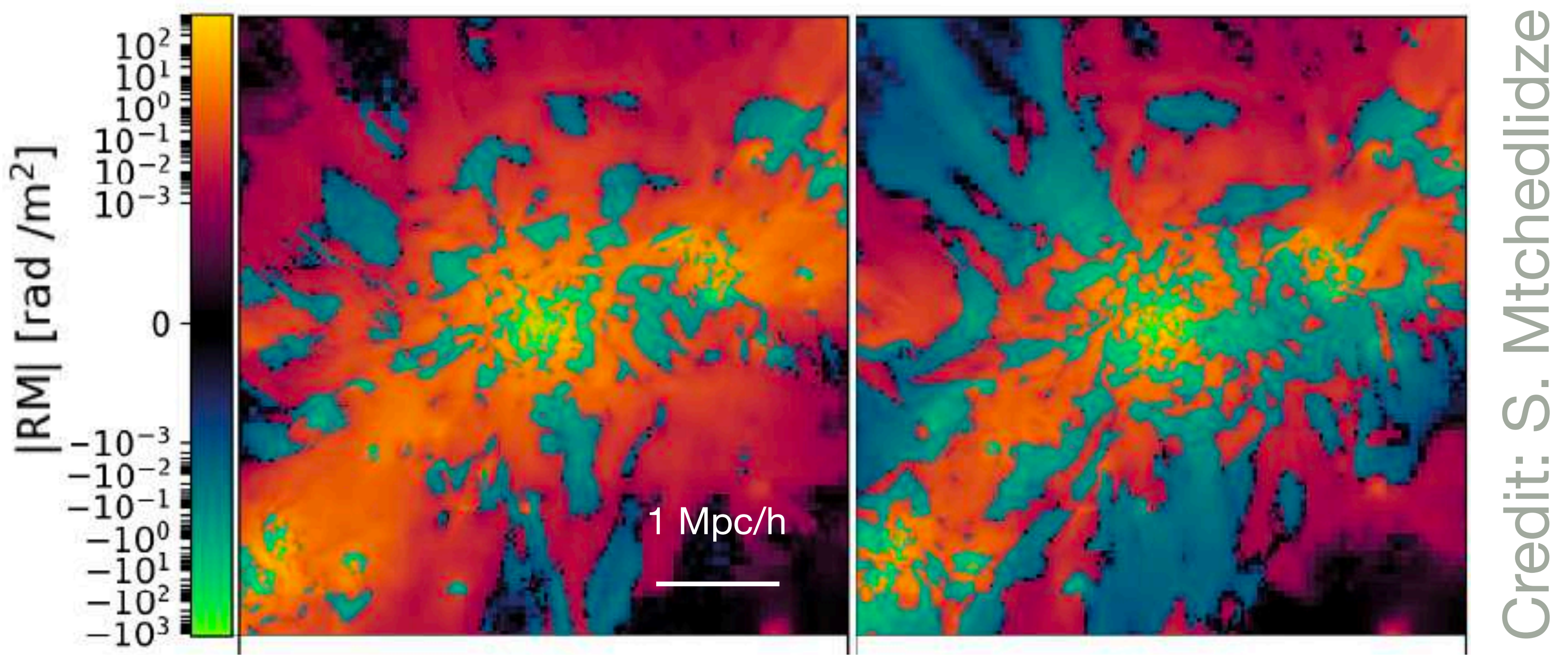


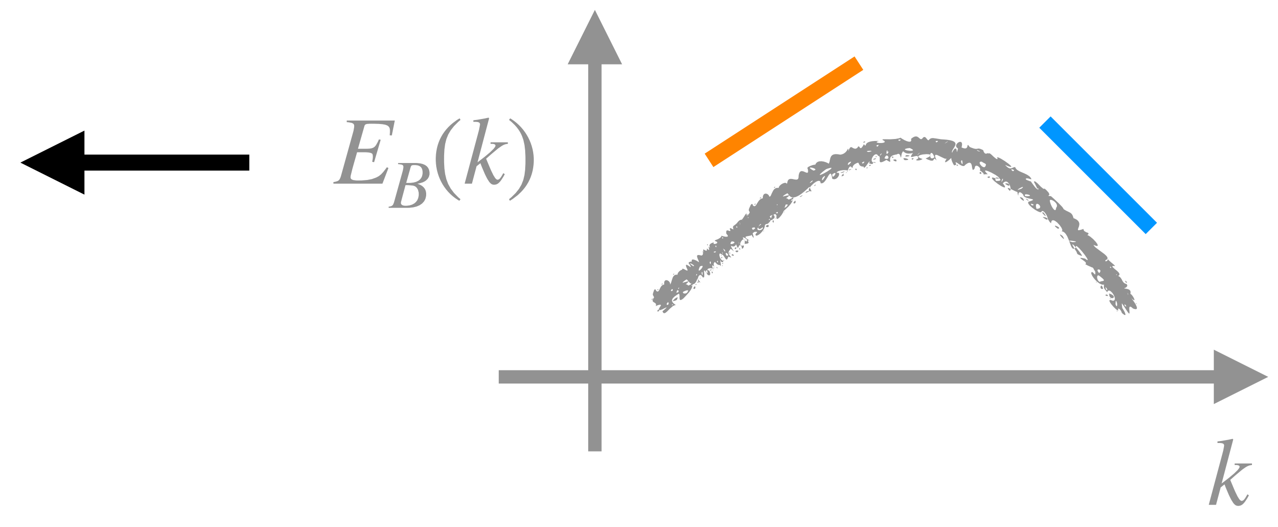


Inflationary Uniform

Inflationary Stochastic

Potential RM differences only for $r > r_{200}$

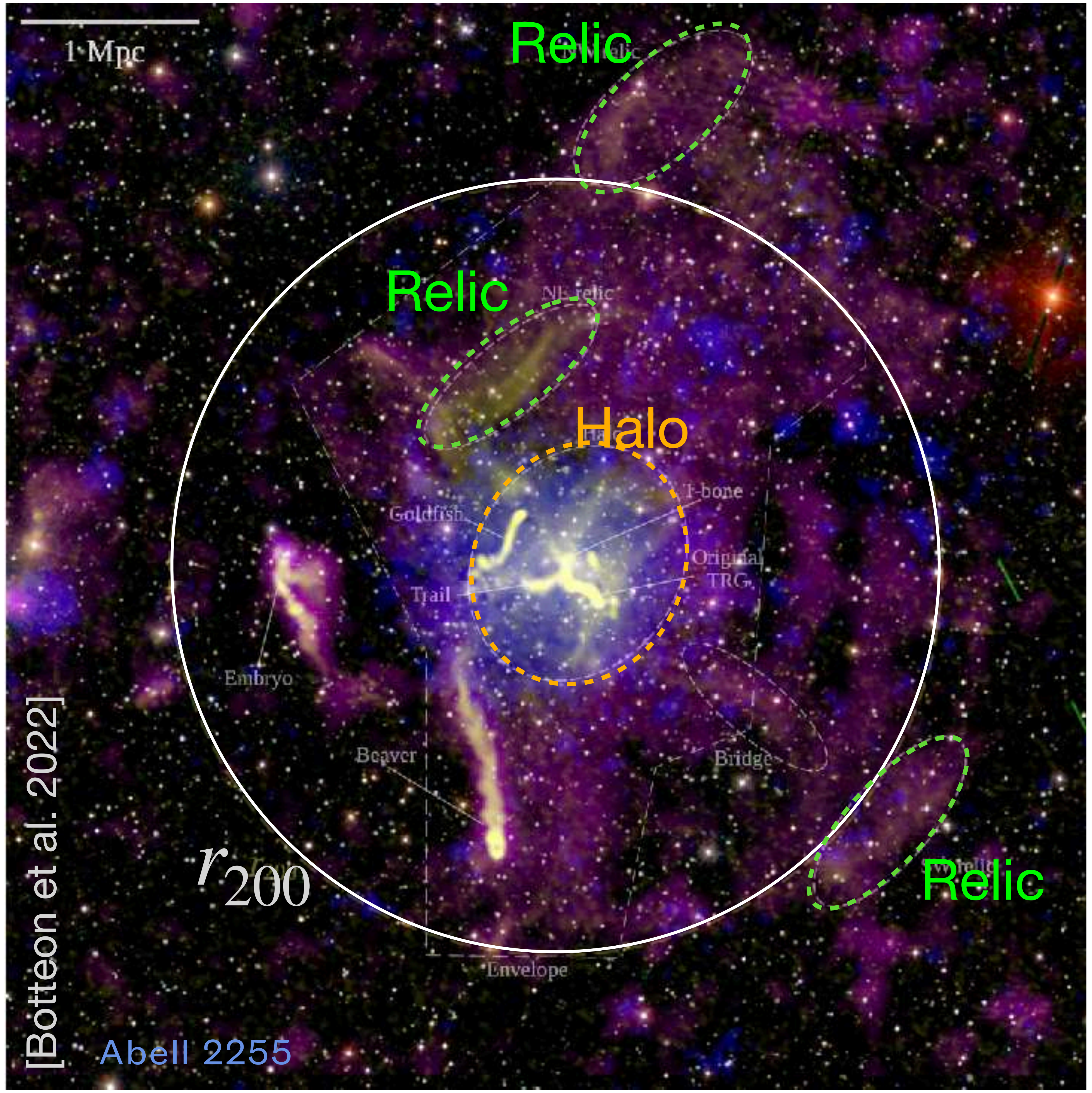




[Mtchedlidze, Domínguez-Fernández at al. 2023]

II. COSMIC RAY ELECTRONS

Towards the outskirts of GCs



Understanding the outskirts with

- Radio relics:
  - Diffusive shock acceleration
- Mega-radio halos (emission beyond that of common halos):
  - Turbulent (re)-acceleration

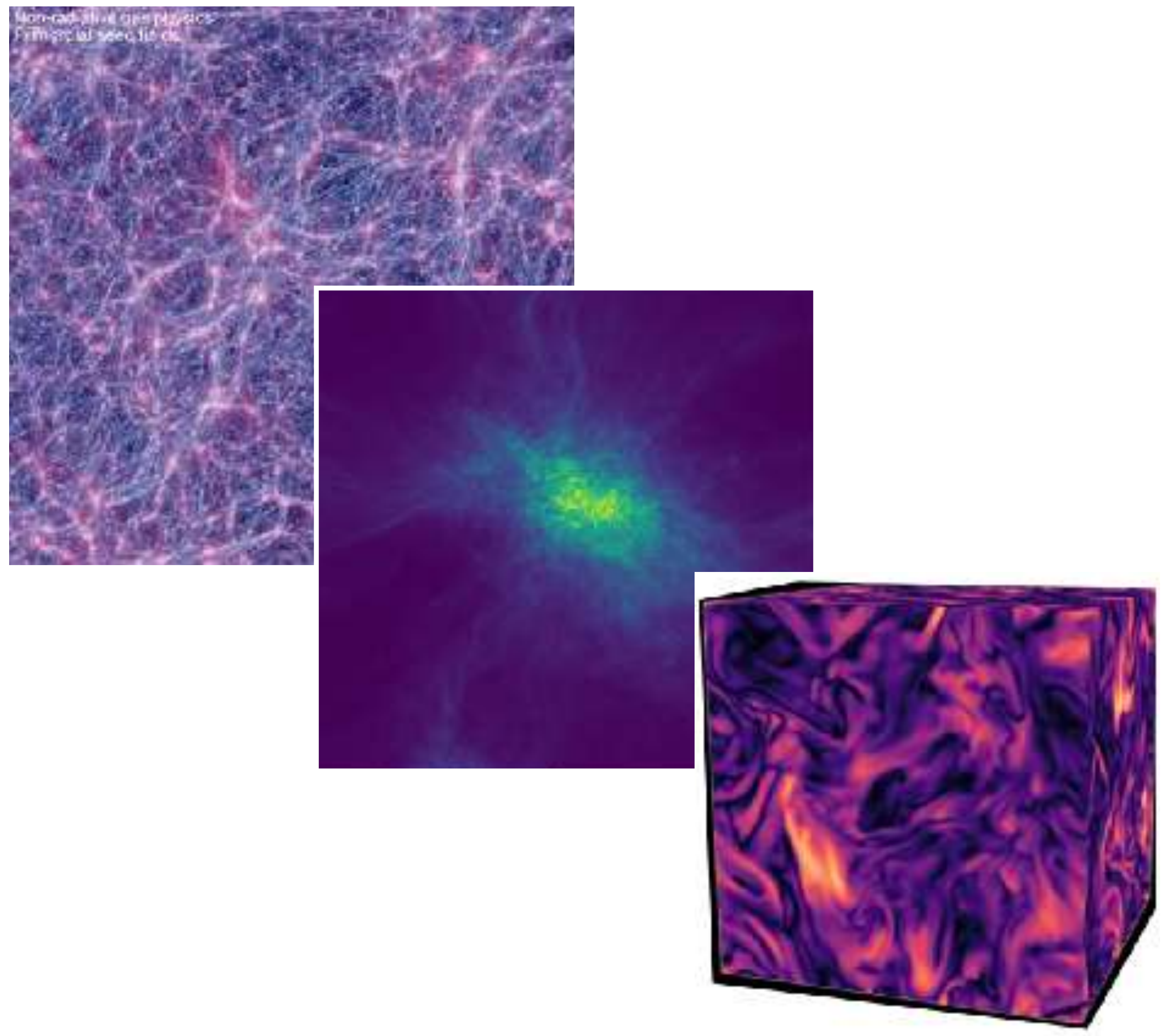
Acceleration in-situ: fossil electrons (from AGN?)

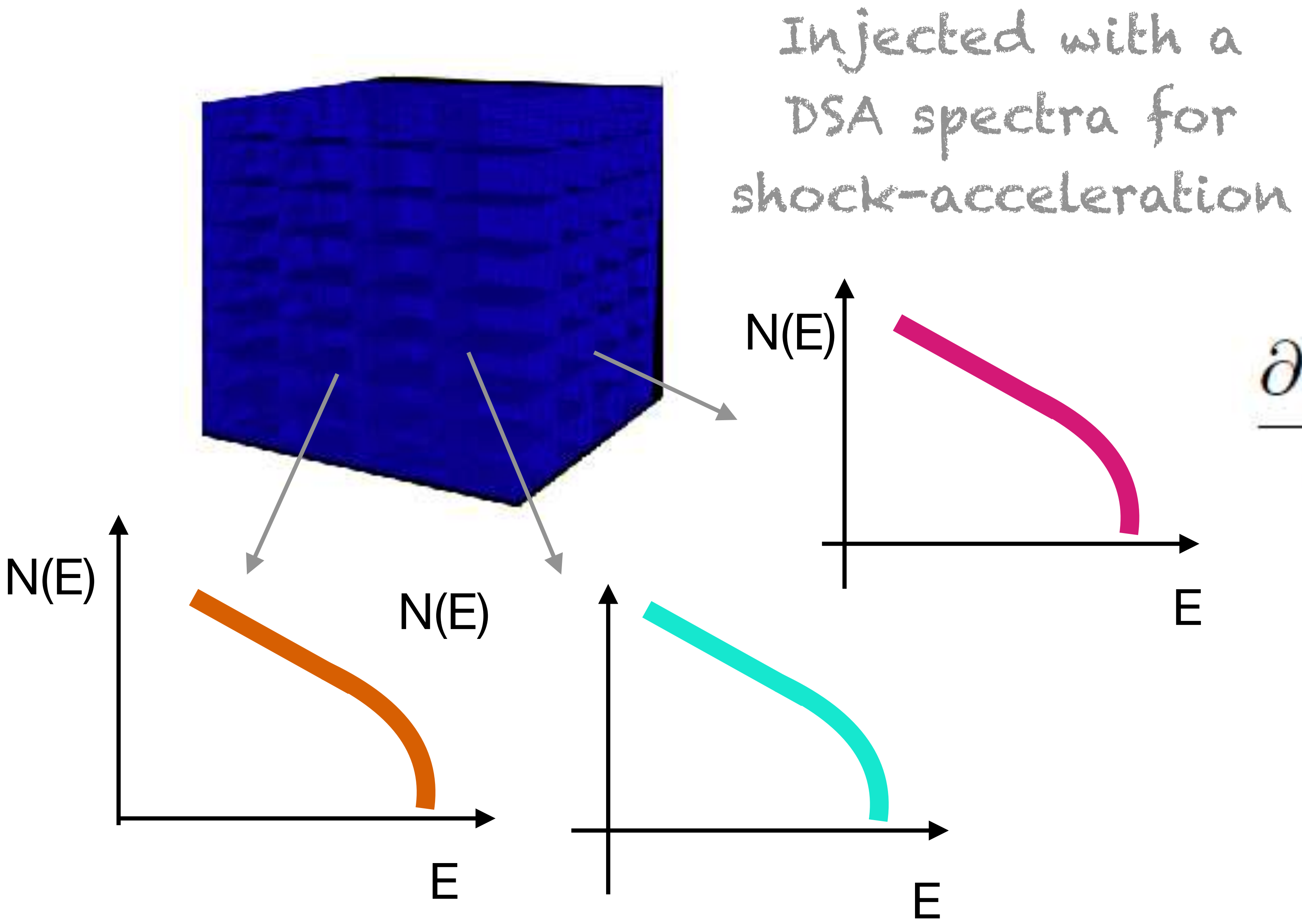
Hybrid numerical frameworks

1. MHD simulation

2. Tracer particles

3. Fokker-Planck solver



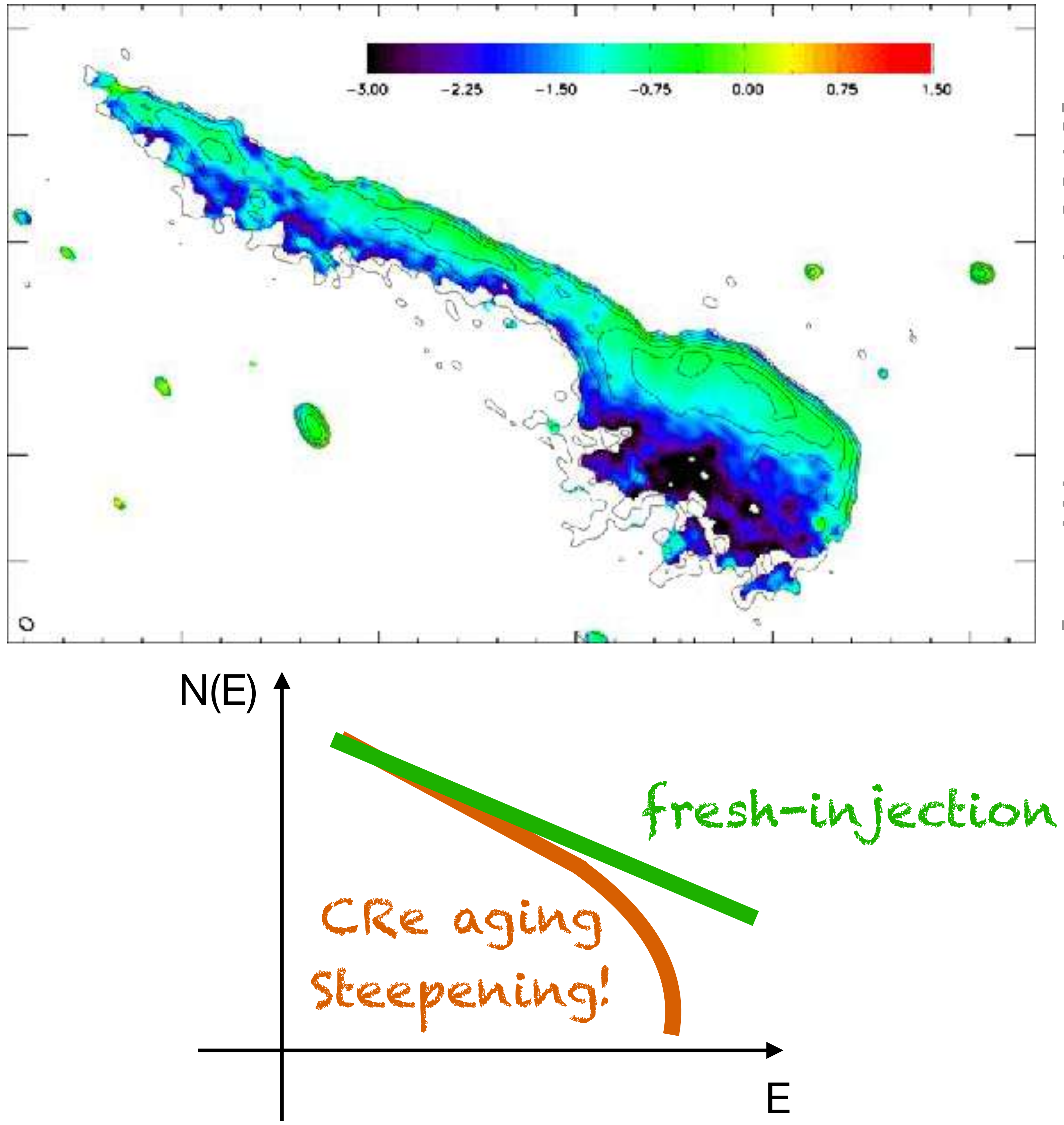


Energy Losses   Energy Gain (Turbulence)

$$\frac{\partial n(p)}{\partial t} = \frac{\partial}{\partial p}\left[H(p)n(p) + D_{\mathrm{pp}}\frac{\partial n(p)}{\partial p}\right] - \frac{n(p)}{T_{\mathrm{e}}(p,t)} + Q_{\mathrm{e}}(p,t)$$

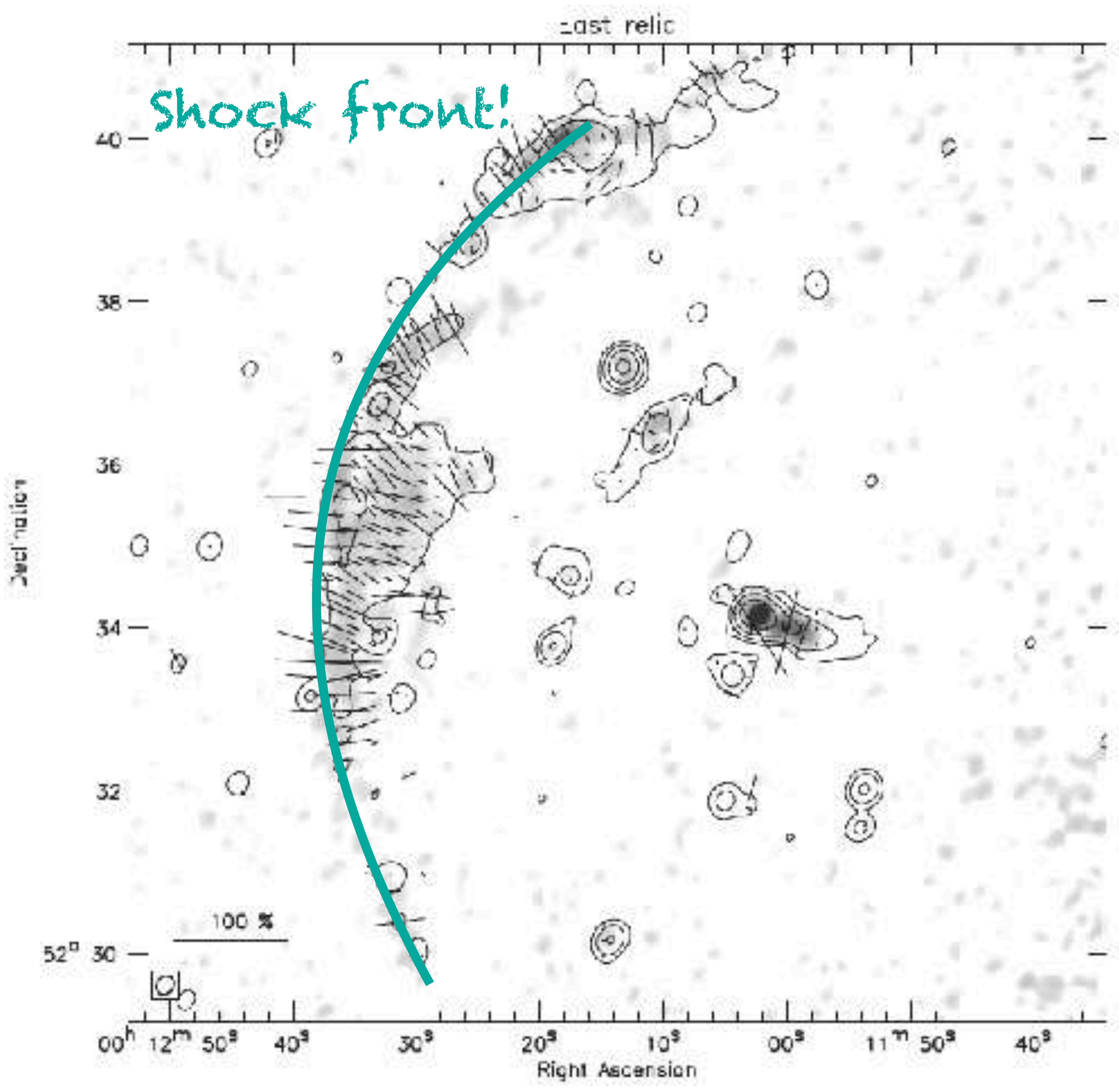
Escape of the system   Particle injection

Characteristics of radio relics



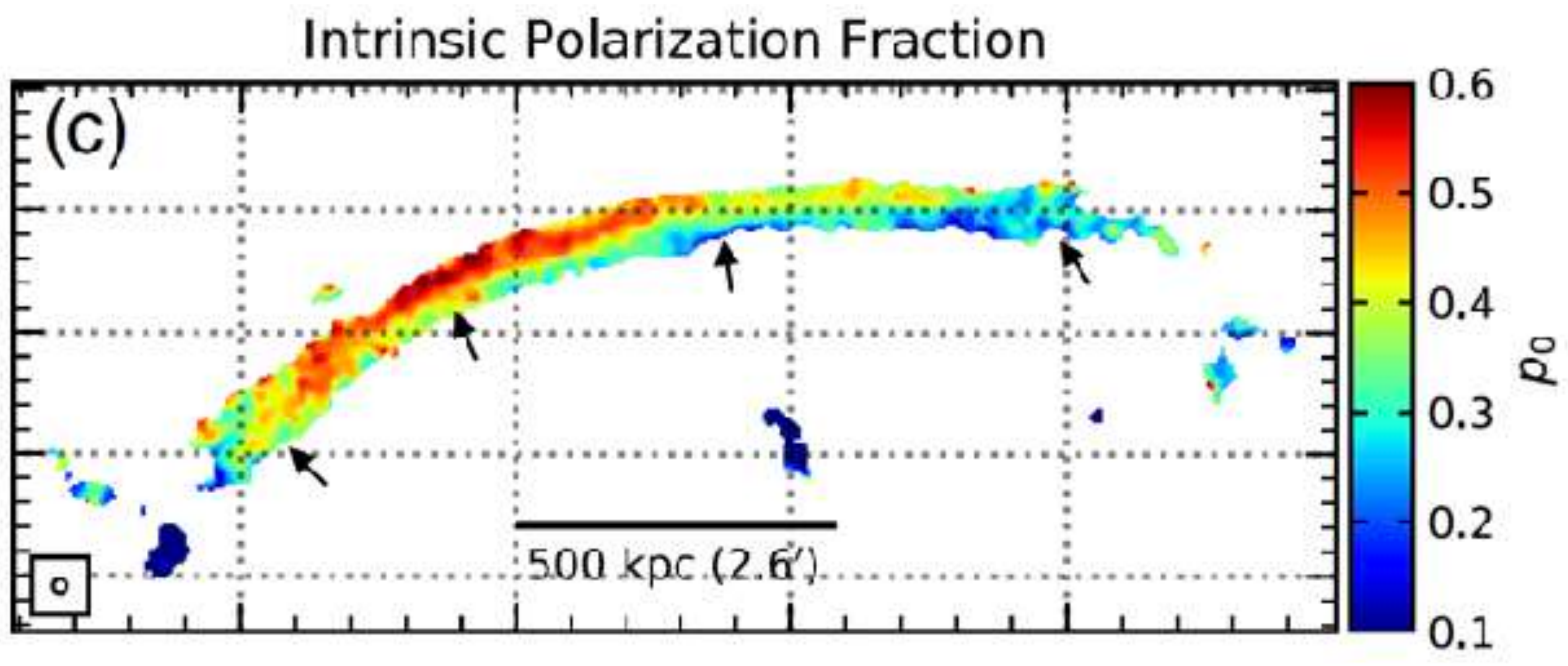
[van Weeren et al. 2012]

1. Spectral aging towards the downstream

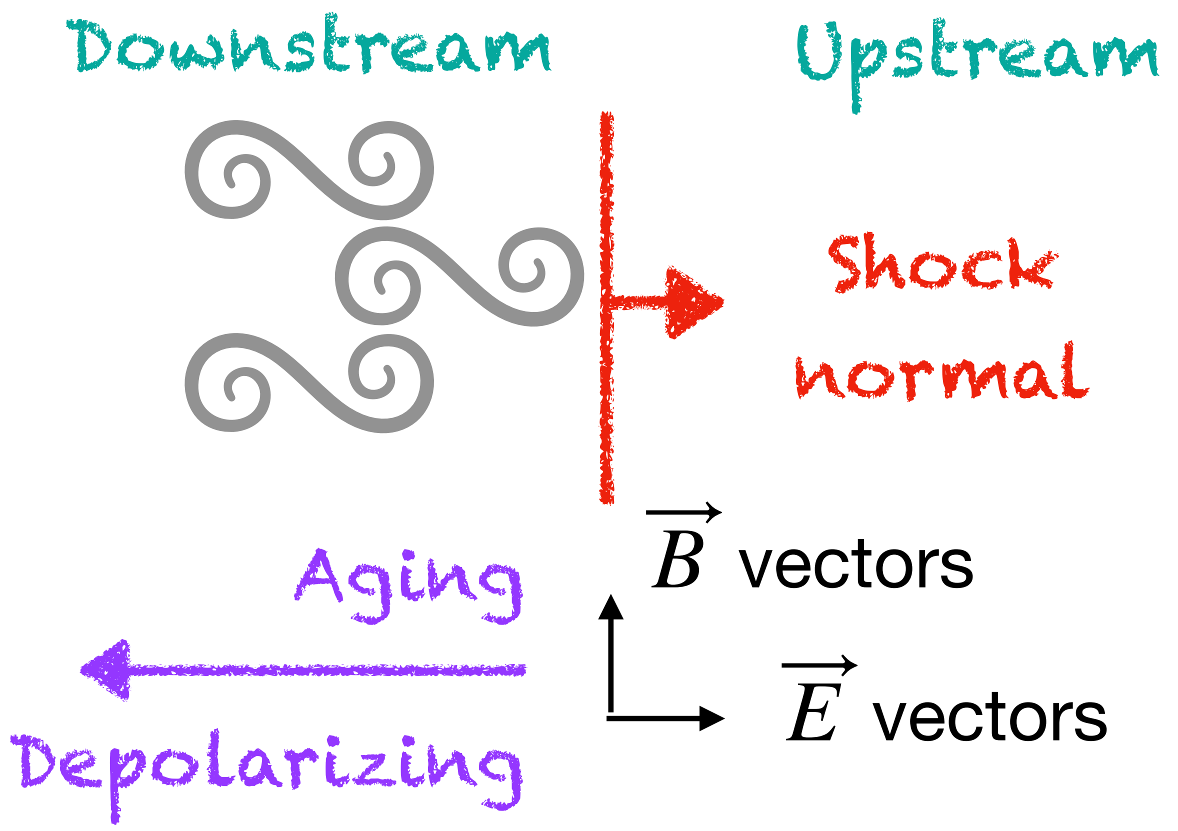


[Golovich et al. 2017]

2. Polarization E-vectors aligned with the shock normal

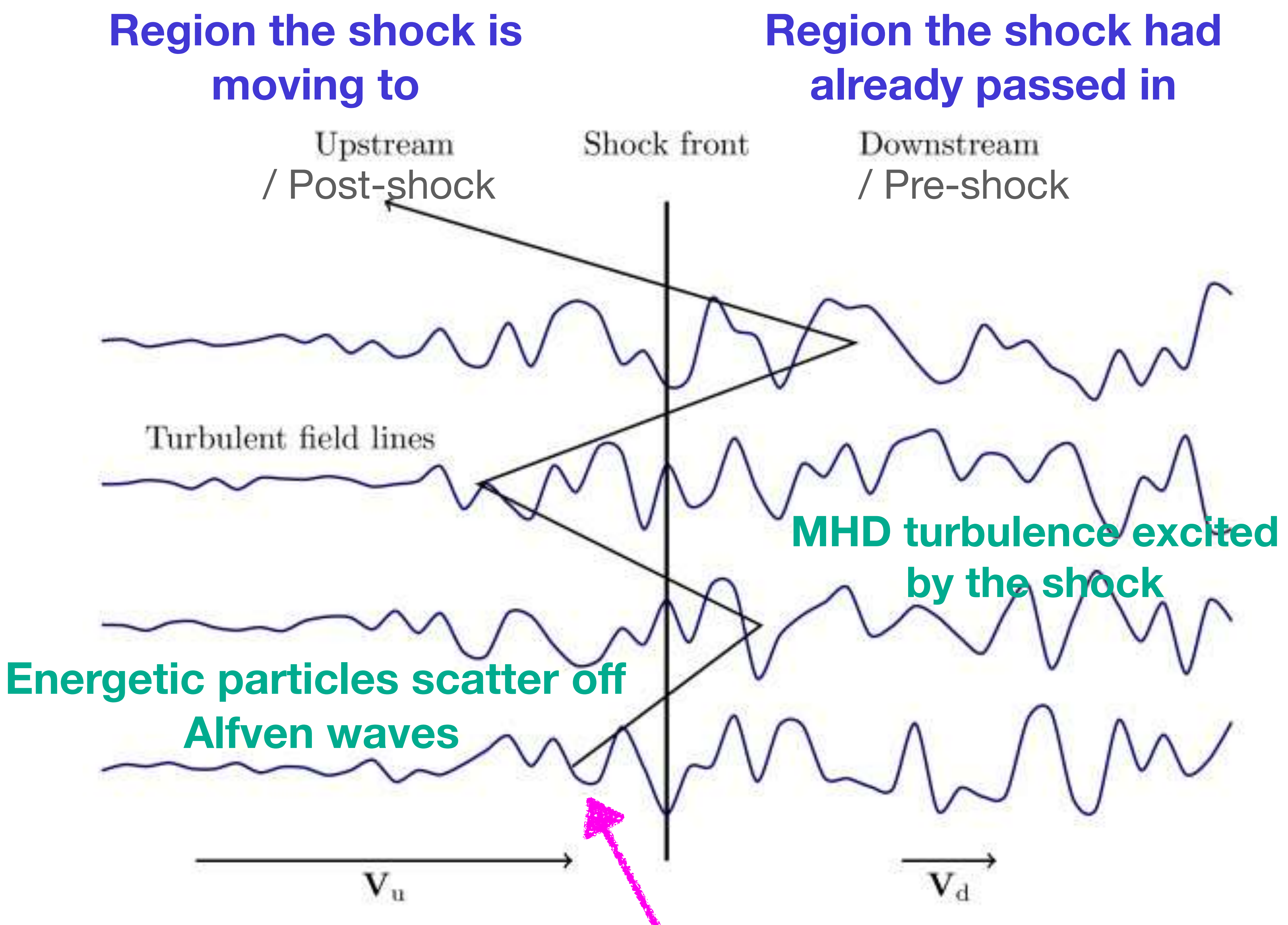


[Di Gennaro et al. 2021]



3. Polarization fraction decreasing towards the downstream

Diffusive shock acceleration (Fermi I)



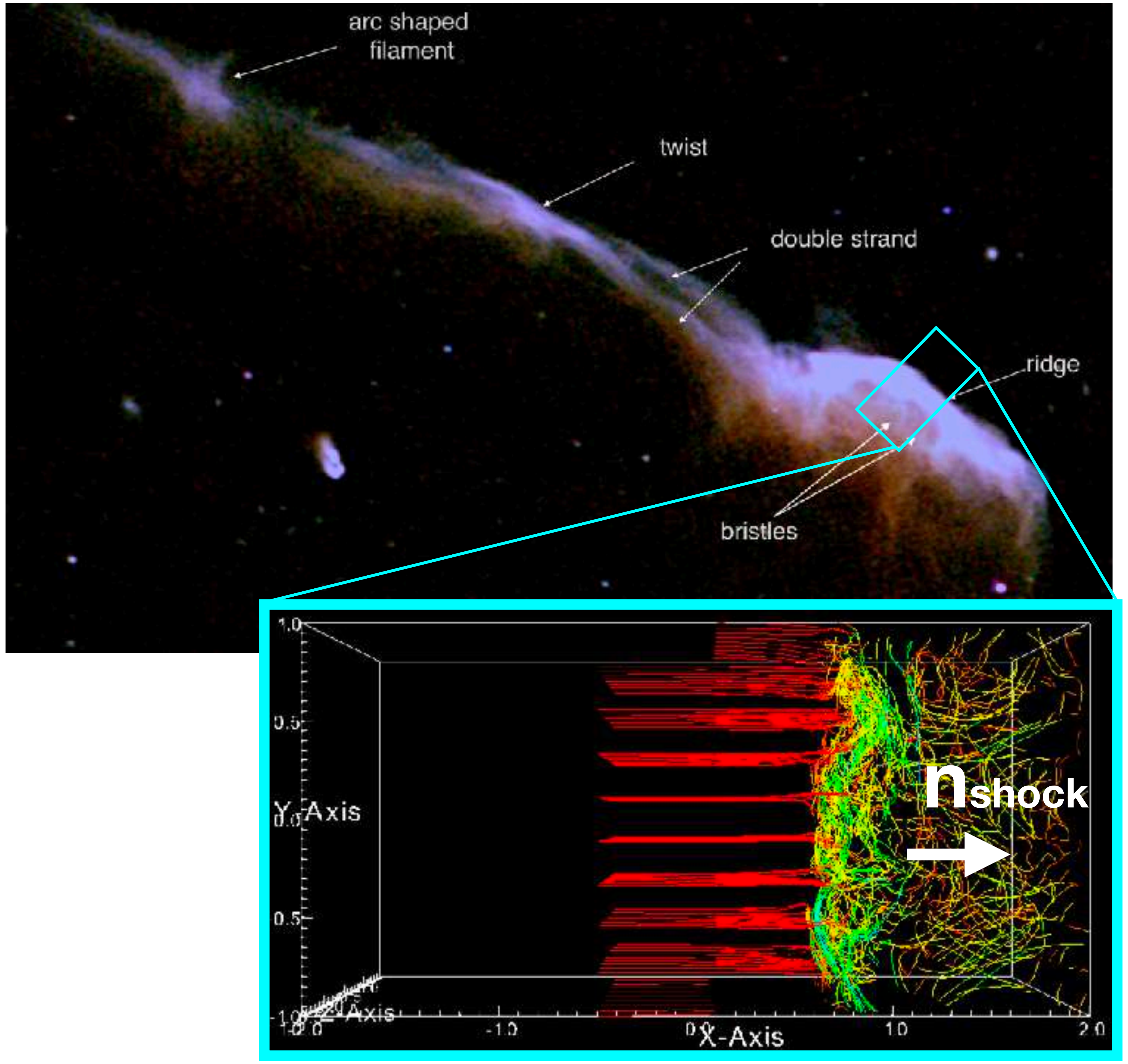
Credit: SSL UC Berkeley

Particle with $r_B \gg l_{shock}$

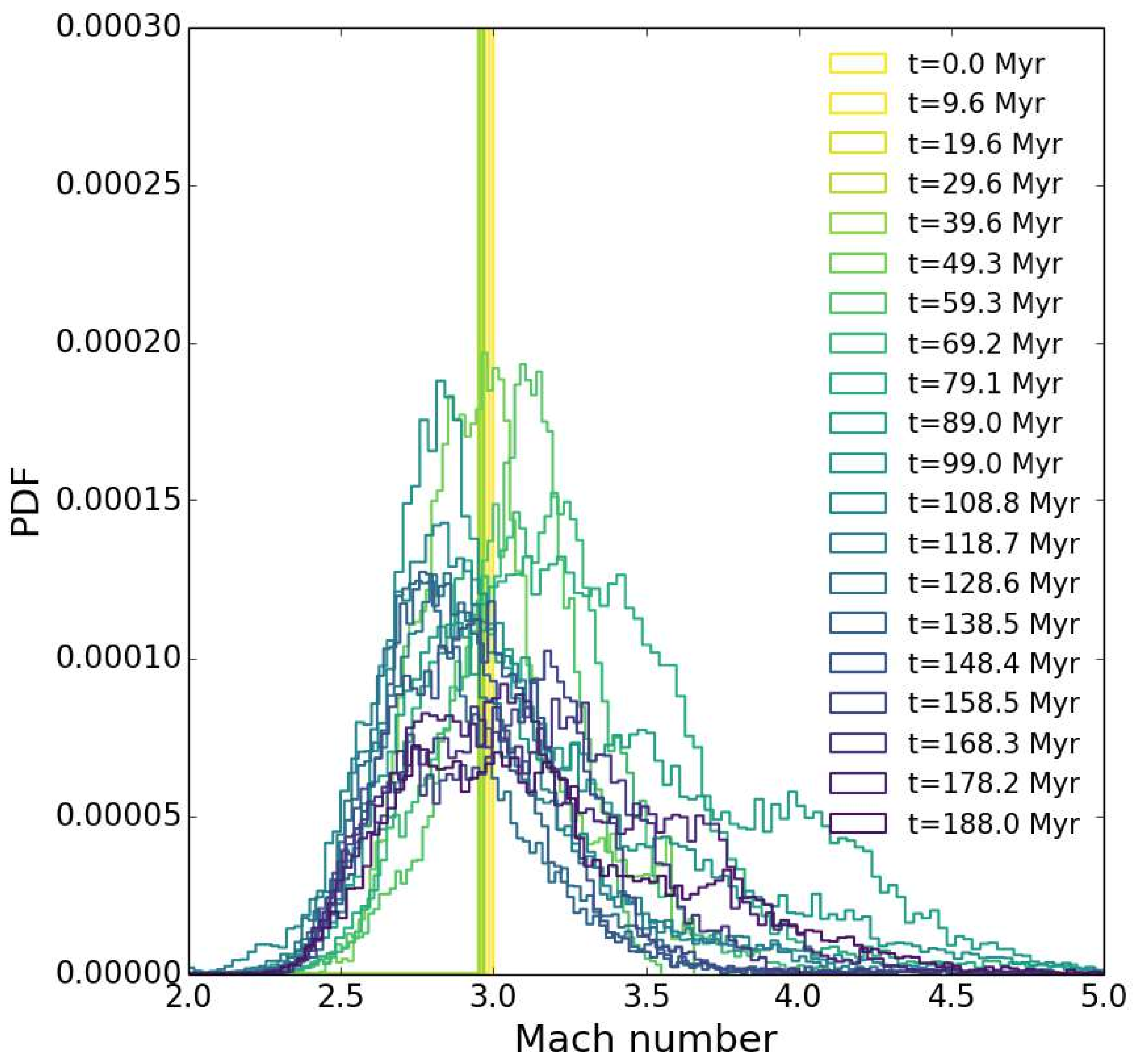
- Magnetic turbulence can scatter and deflect charged particles
- Each encounter with the shock yields an average gain of energy
  - $\Delta p \sim p\frac{u}{v}$
- After many crossings, the particle is accelerated up to CR energies
  - $N(E)\,dE = N_0\,E^{-q}dE$

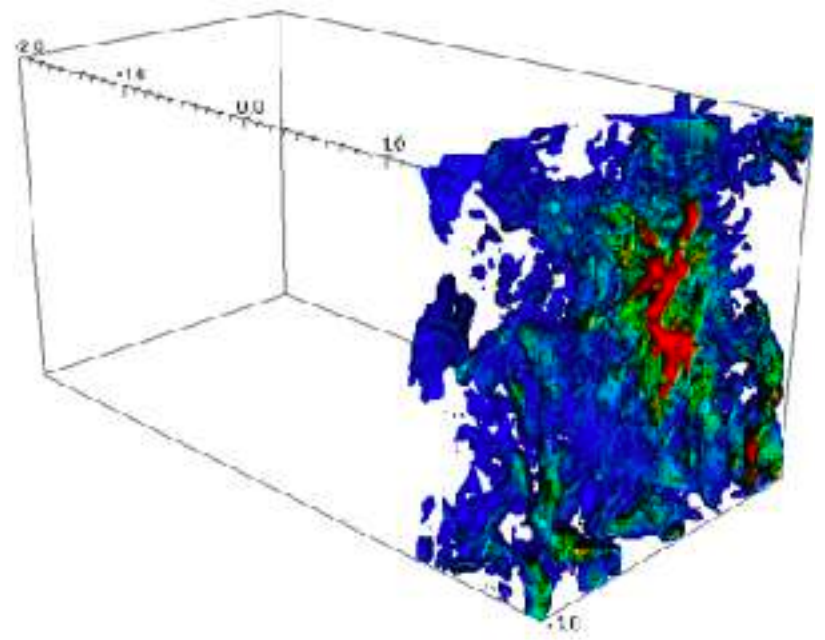
Related to the Mach number $\mathcal{M} = v/c_s$

Towards the outskirts of GCs: Relics



[Rajpurohit et al. 2019]





Shock compression of a turbulent ICM
+
DSA of thermal electrons (fresh-injection)

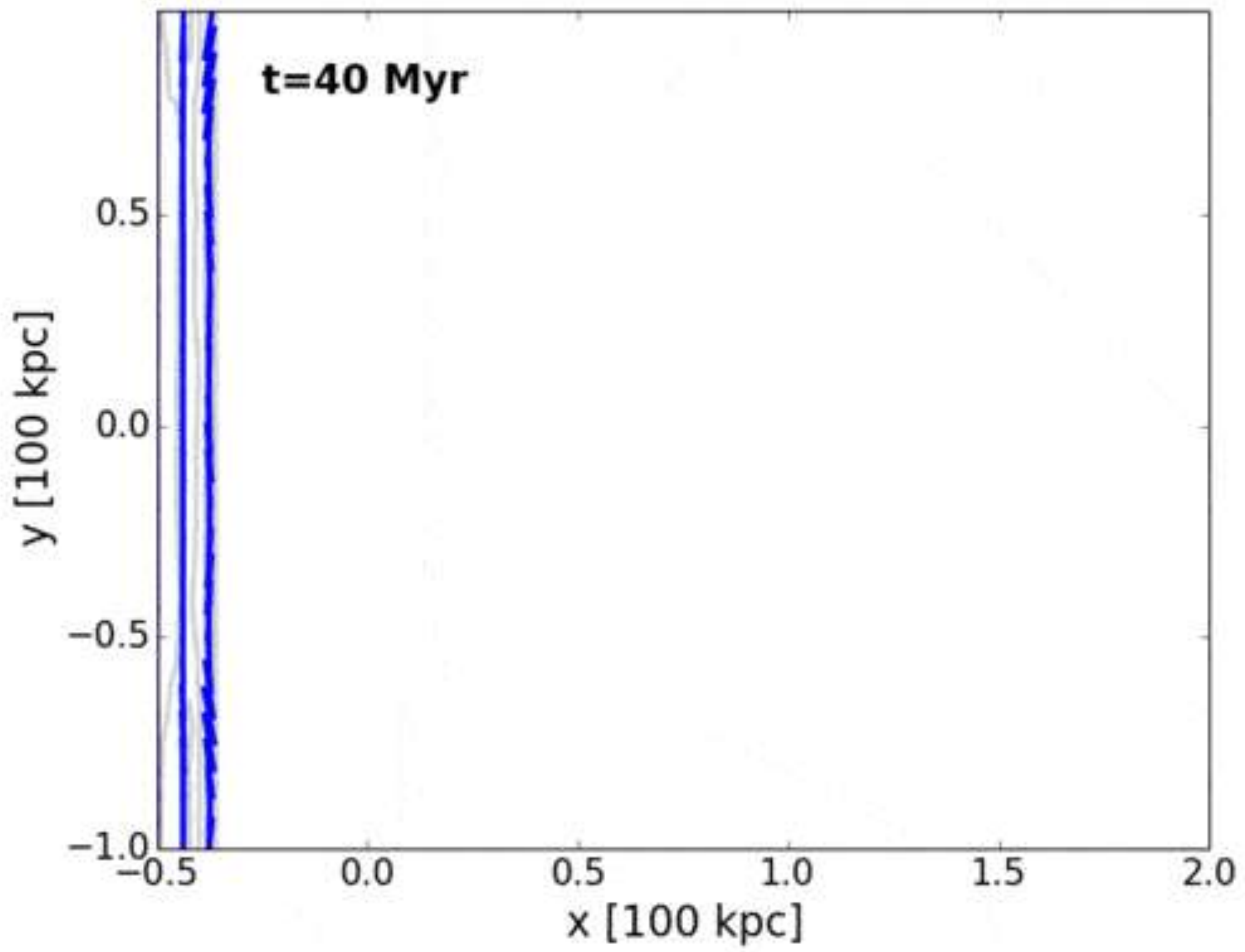
[Domínguez-Fernández et al. 2020, 2021]

- Pre-shock turbulence naturally induces substructure in the synchrotron emission
- Mach number distribution (& obliquity) and type of turbulence define the substructure

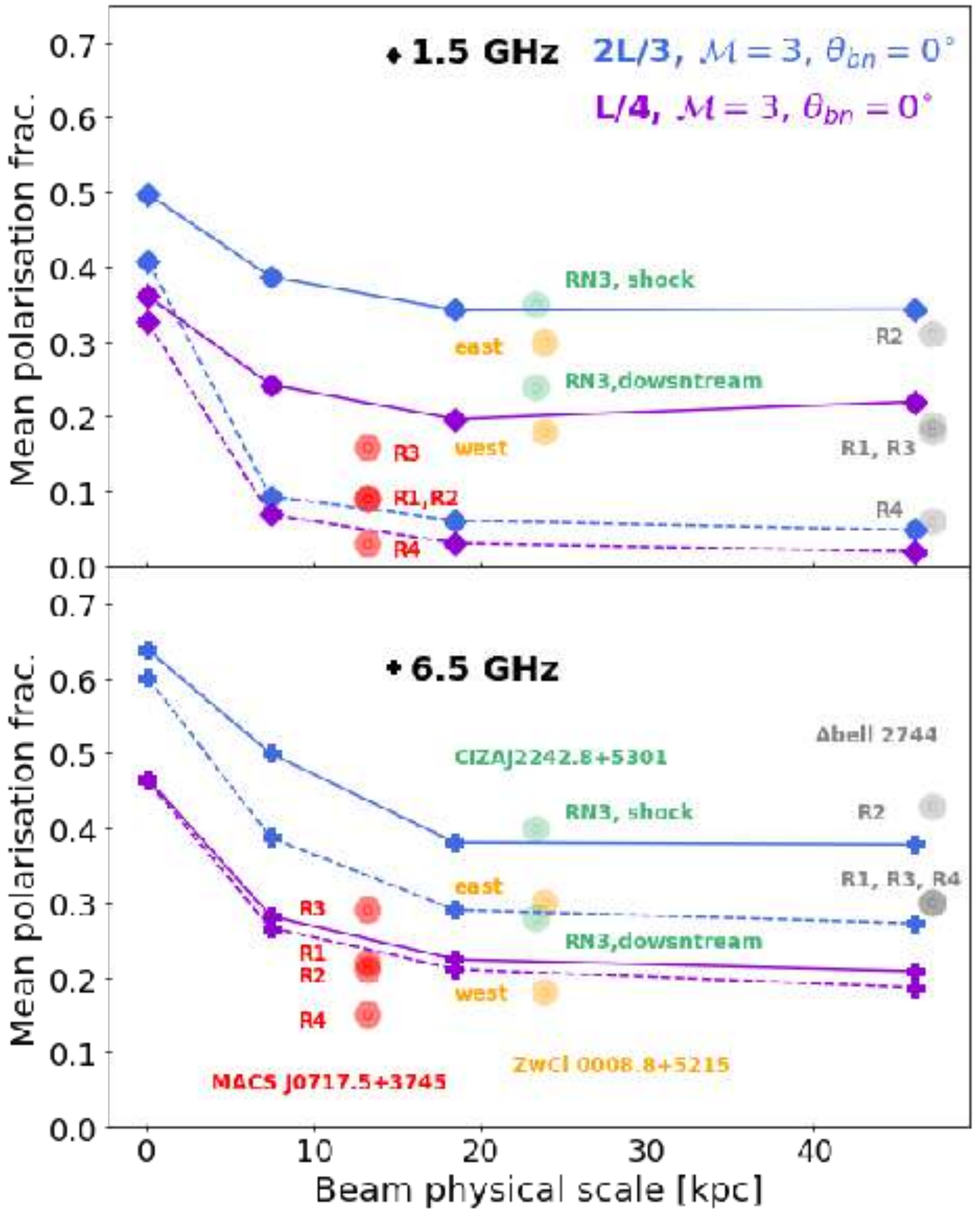
Towards the outskirts of GCs: Relics

- Polarization studies: Injection scales $\gtrsim 130$ kpc needed

Polarization E-vectors



[Domínguez-Fernández et al. 2021]



$$\mathcal{P}_\nu = \mathcal{J}_{\rm pol}(\nu_{\rm obs}, x, y, z)\exp\left[2i(\hat{\chi} + {\rm RM}\lambda^2_{\rm obs})\right]$$

Intrinsic polarization

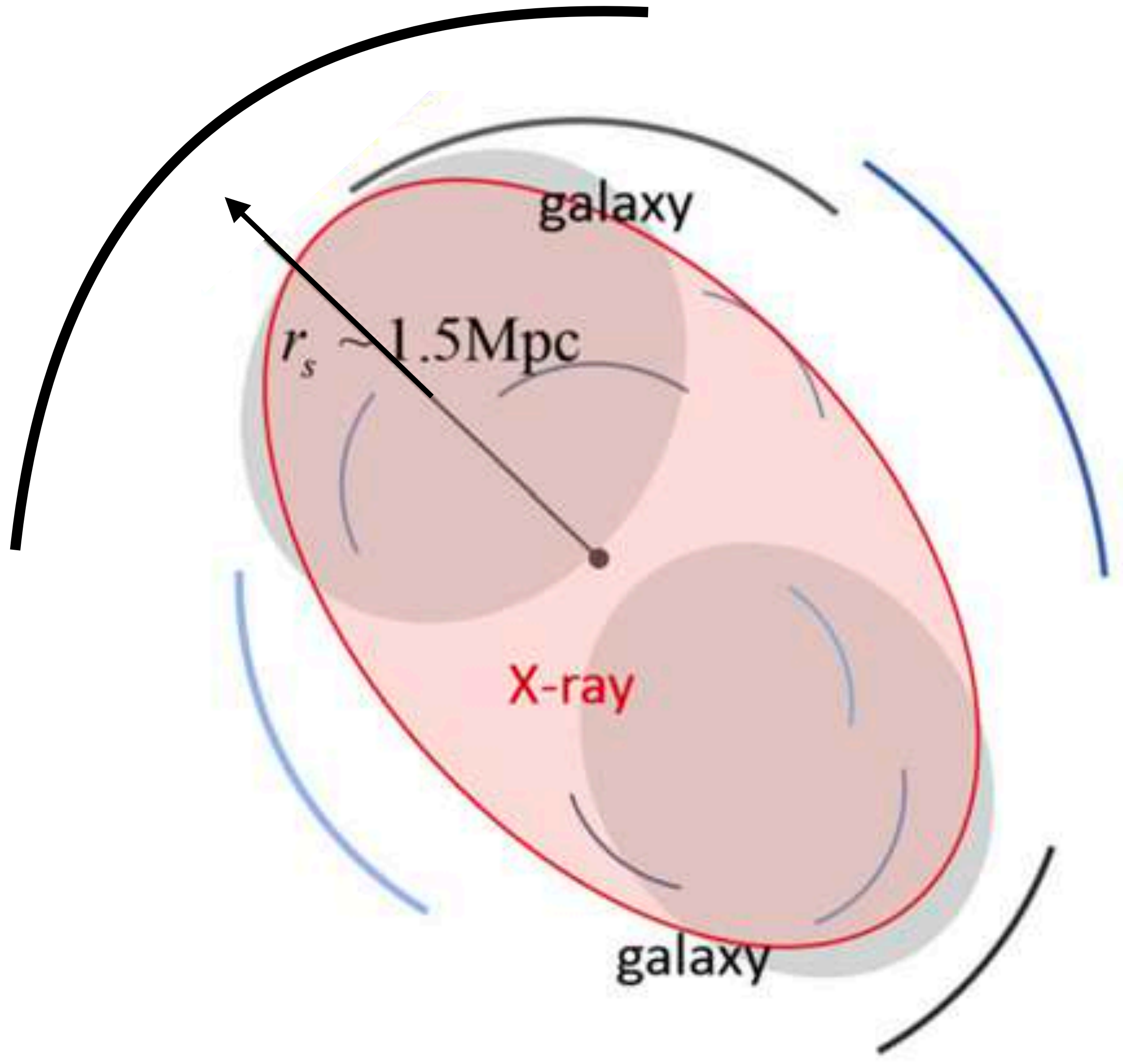
Contribution of Faraday Rotation Measure

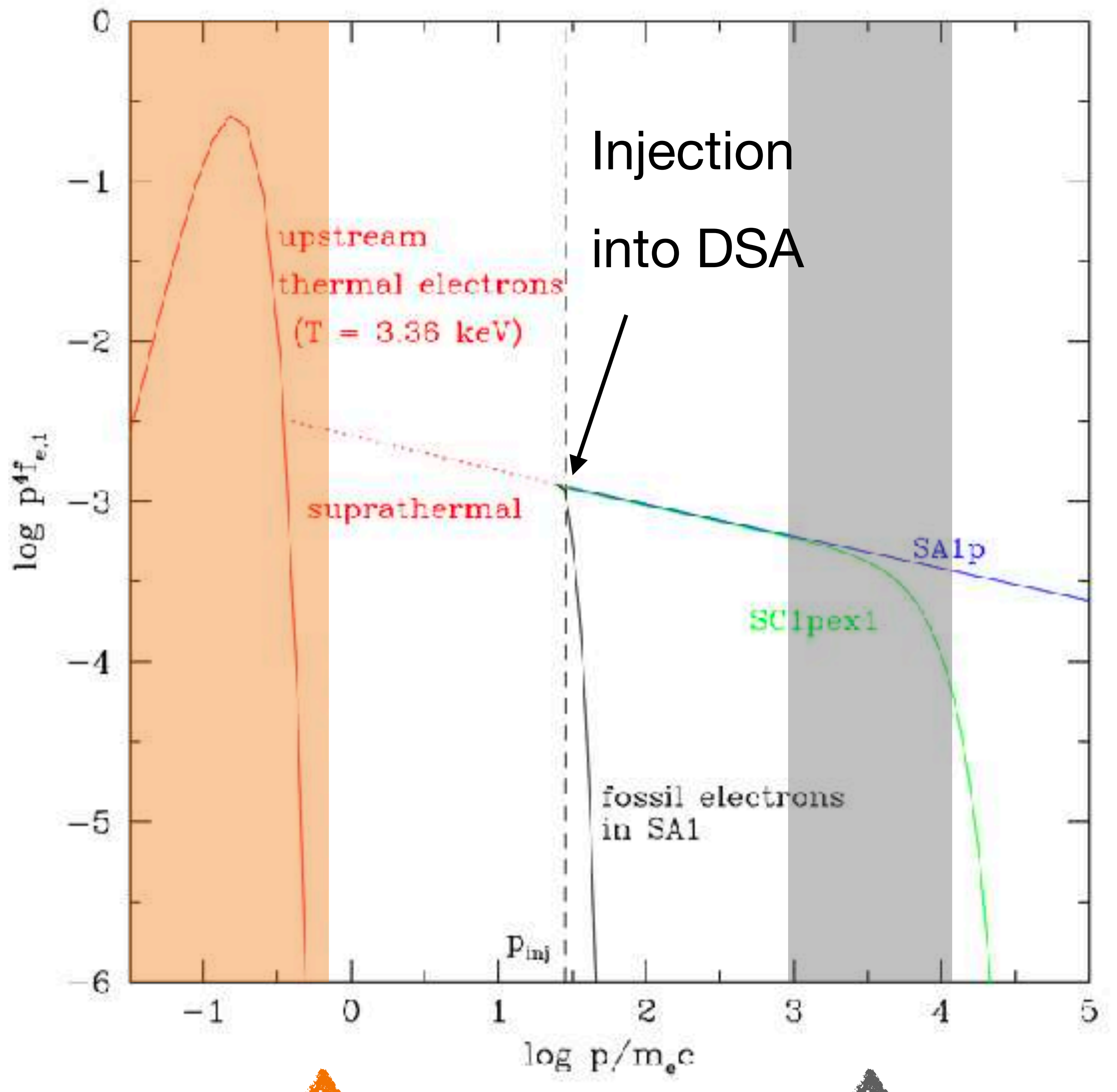
- Few matches with observations:
  - R1, R2 in MACS J0717.5
  - R4 in Abell 2744

Various turbulent models could help us constrain MFs' characteristics in the outskirts of clusters

Towards the outskirts of GCs: Relics

Fresh-injection



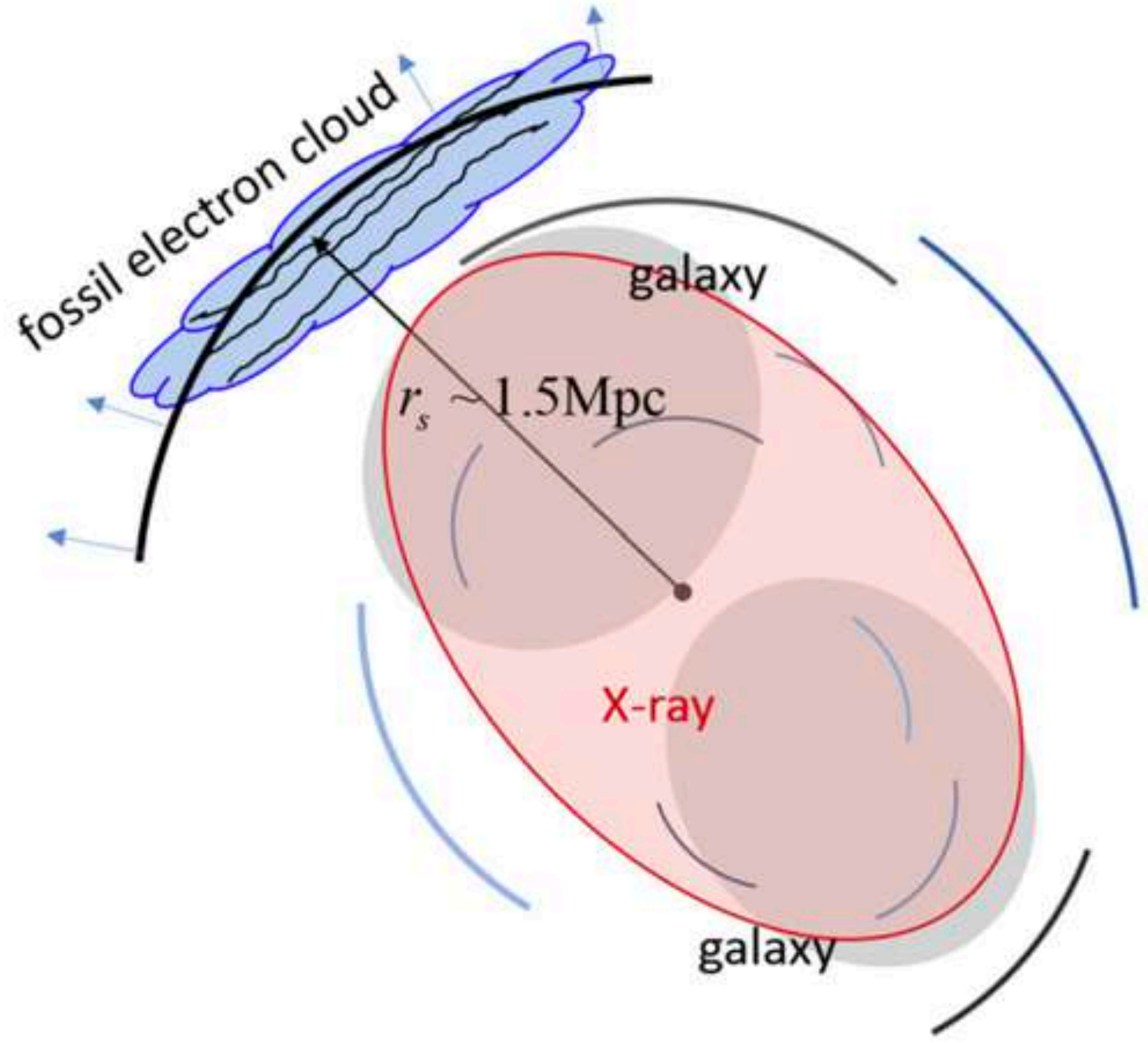


what we see in X-ray

what we see in radio

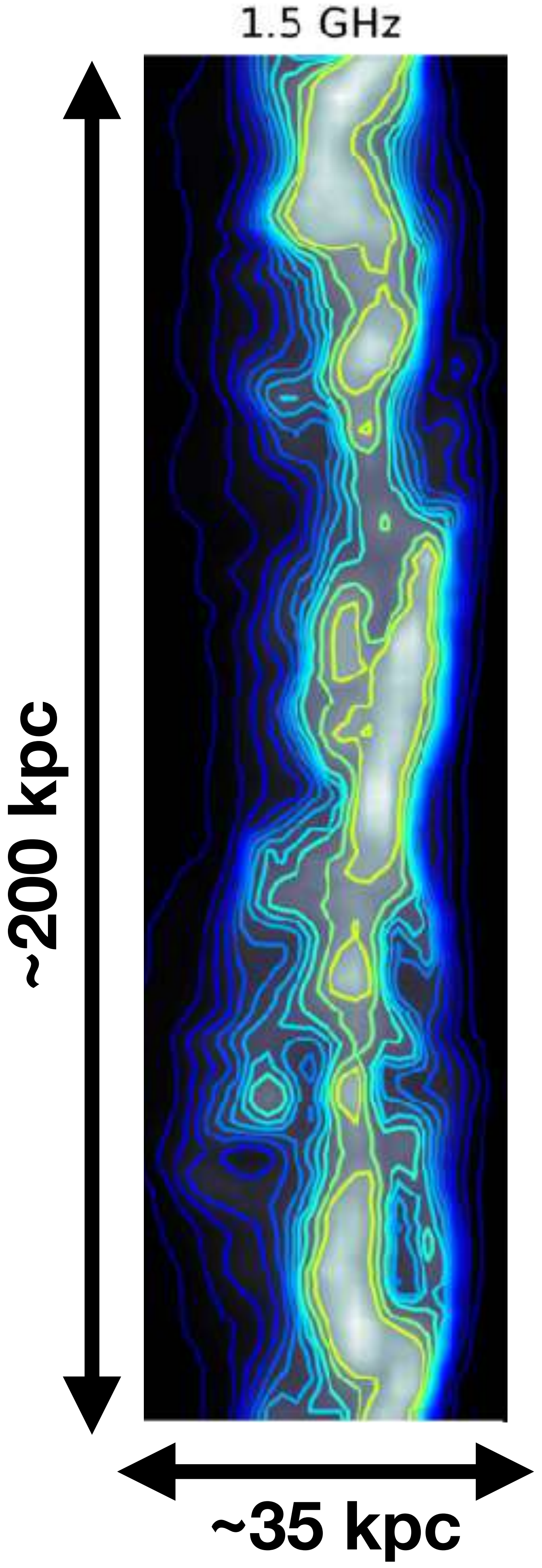
Re-acceleration

$\gamma_{e,inj} \sim 20 - 30$



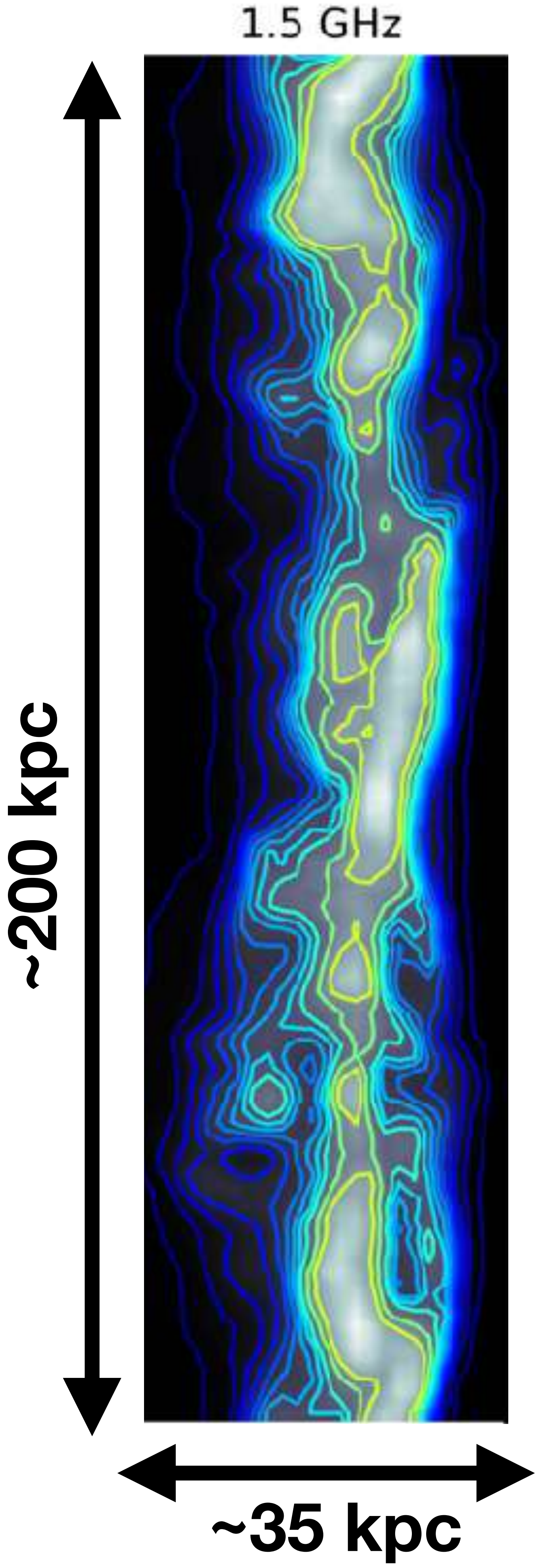
[Kang et al. 2015]

Fresh-injection model vs re-acceleration



- Studies of radio surface variations: $\delta_{S_\nu} = S_\nu / \bar{S}_\nu - 1$

Fresh-injection model vs re-acceleration



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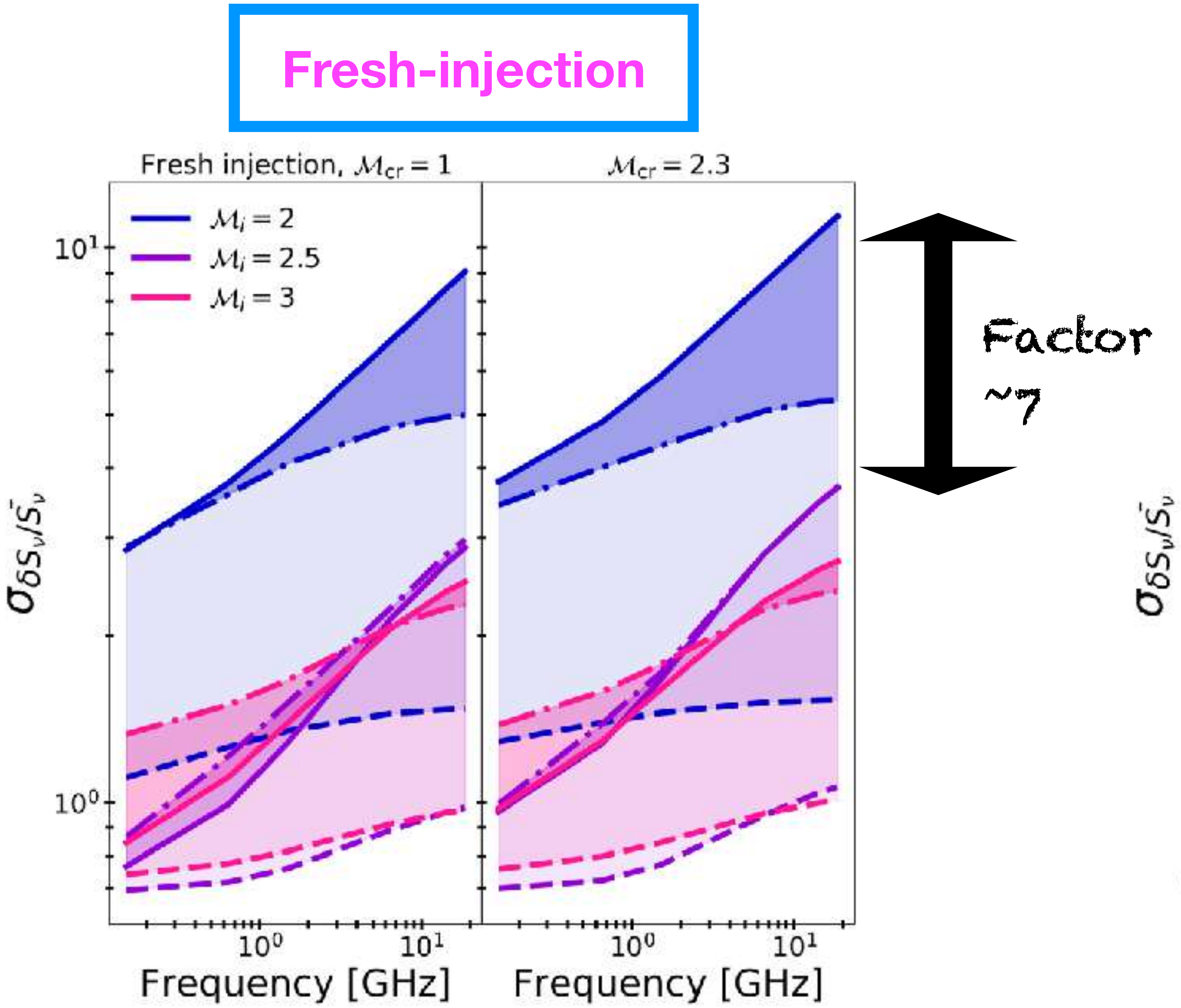
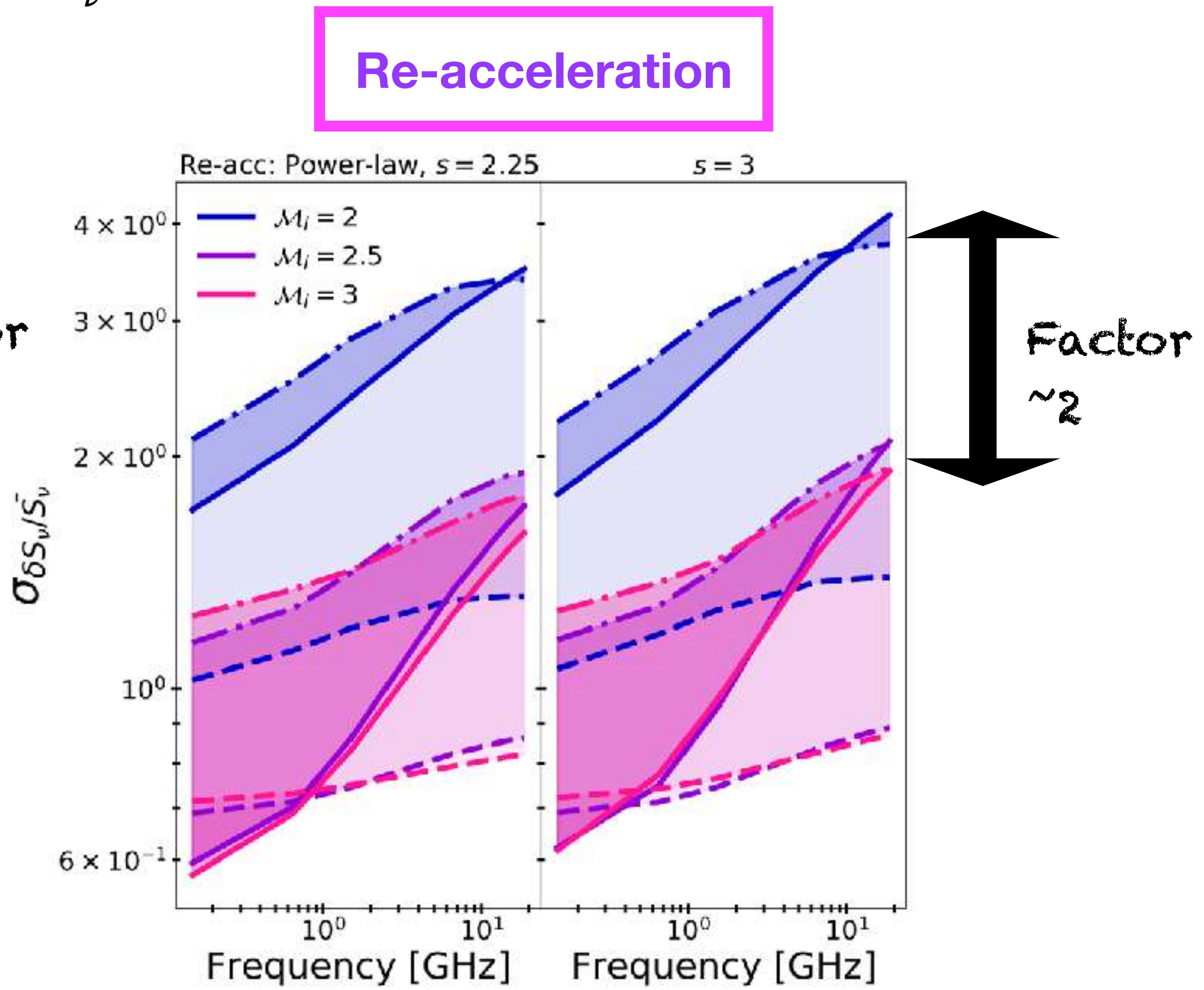




[Domínguez-Fernández et al. 2024]

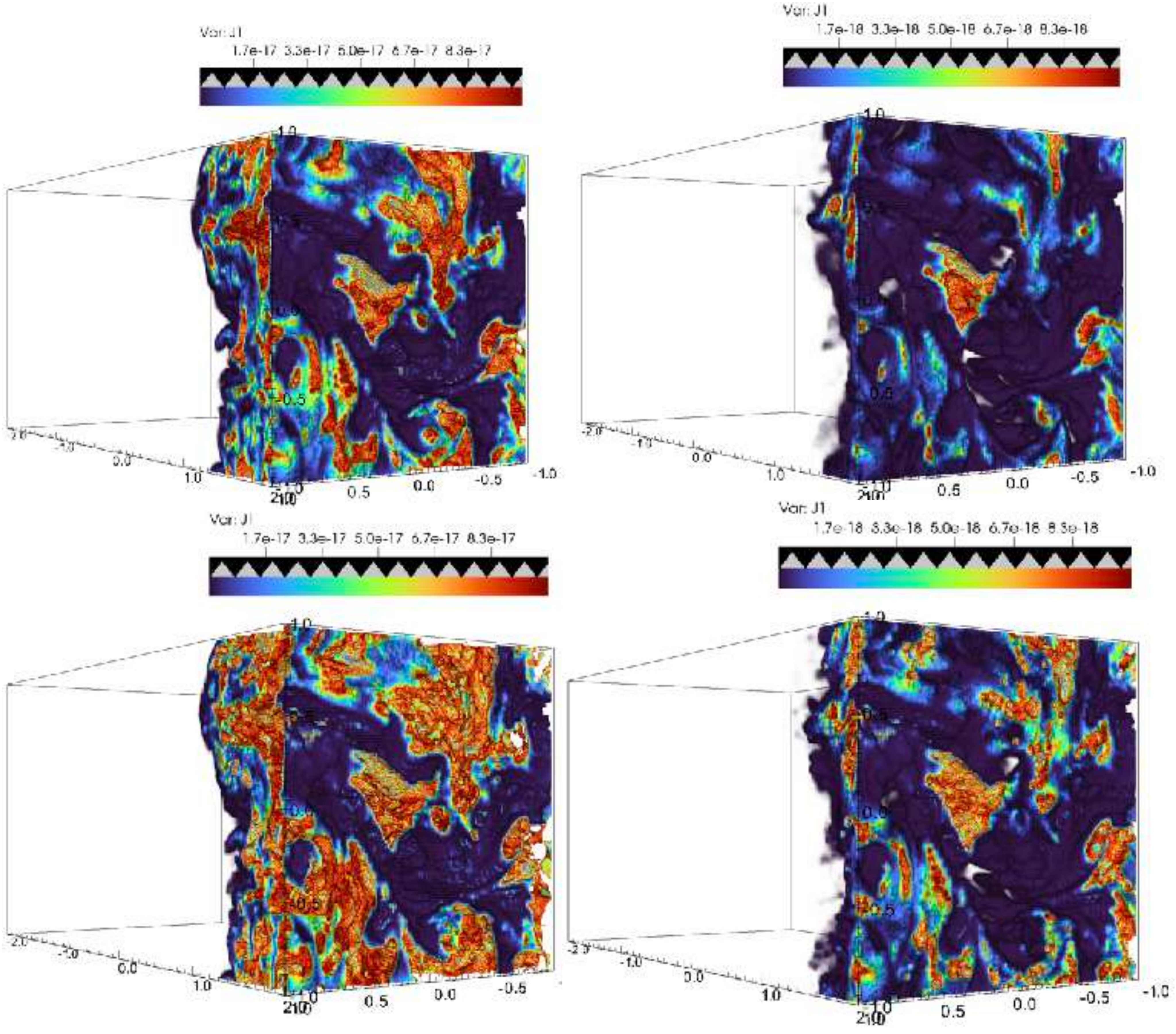
Fresh-injection model vs re-acceleration

Fresh-injection

Patchier at high frequencies

Re-acceleration

Patchier at high frequencies (subtle difference)



650 MHz

18.6 GHz

[Domínguez-Fernández et al. 2024]

- The relative radio surface brightness variations, $\delta_{S_\nu} = S_\nu / \bar{S}_\nu - 1$:
  - Increase with frequency
  - Increase with lowering the mean Mach number of the shock

Fresh injection model

Too patchy substructures, specially at low Mach number shocks

Simple DSA with thermal electrons cannot explain $\mathcal{M} \sim 2$ shocks

Fossil electrons needed?

AGN bubble's contribution

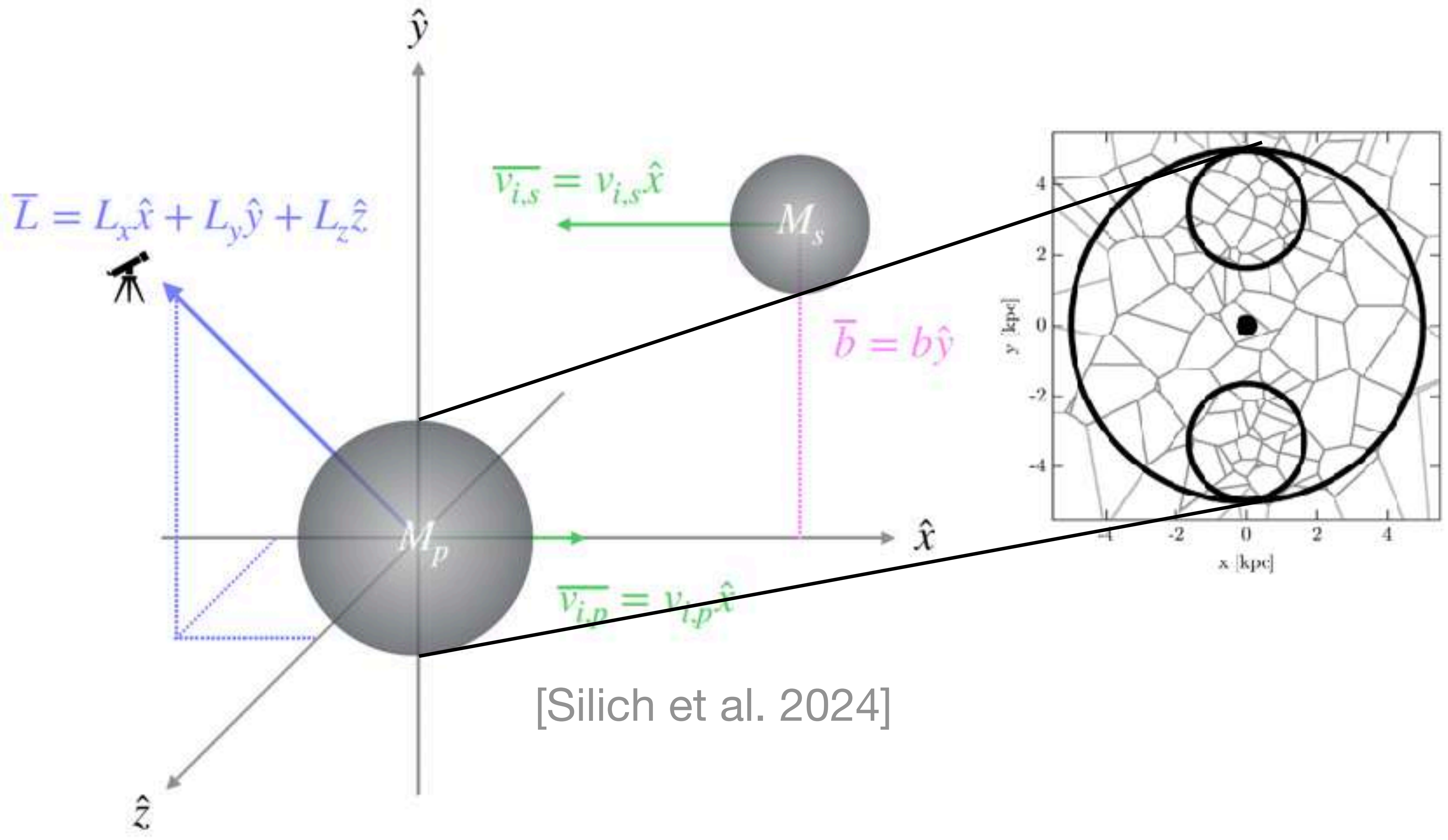
- Main cluster's mass: $6 \times 10^{14}\,\mathrm{M}_\odot$
- Varying:
  - Impact parameter
  - Initial jet direction
  - Mass ratios: R=1:2, 1:5

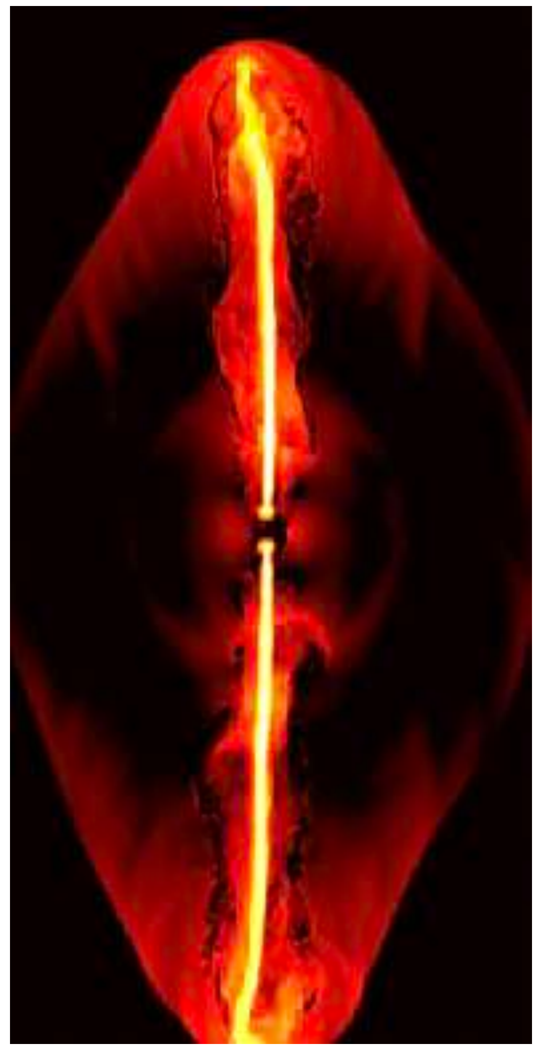
Jet

- $\mathrm{M_{BH}} = 6.7 \times 10^{8}\mathrm{M}_\odot$
- $P_{\rm jet} = 3 \times 10^{45}\,\mathrm{erg\,s^{-1}}$
- $\rho_{\rm jet} = 1.51 \times 10^{-28}\,\mathrm{g\,cm^{-3}}$
- $\beta_{\rm jet} = P_{th}/P_B = 1$

AGN bubbles in a cluster environment

[Weinberger et al. 2017]





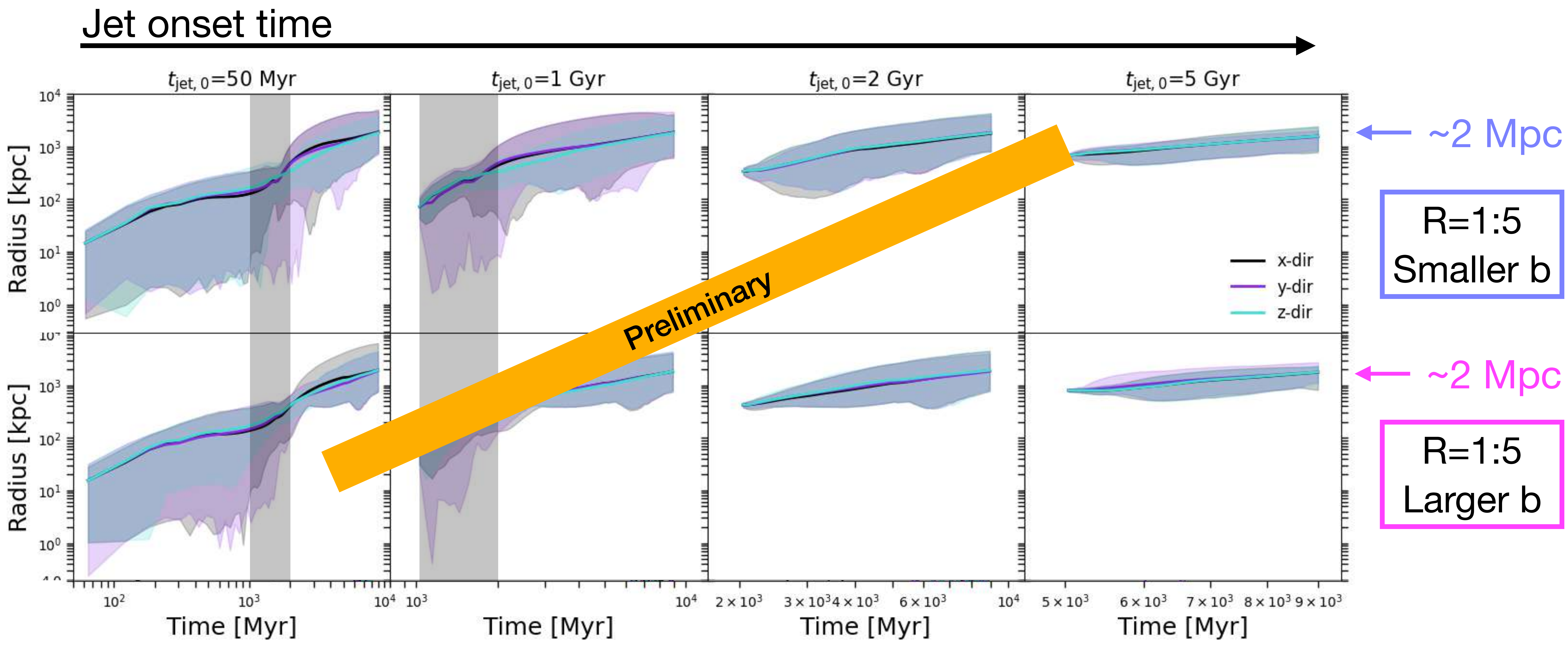
[Silich et al. 2024]

- Energy injection: Kinetic Magnetic Thermal CRs

AGN bubble's contribution

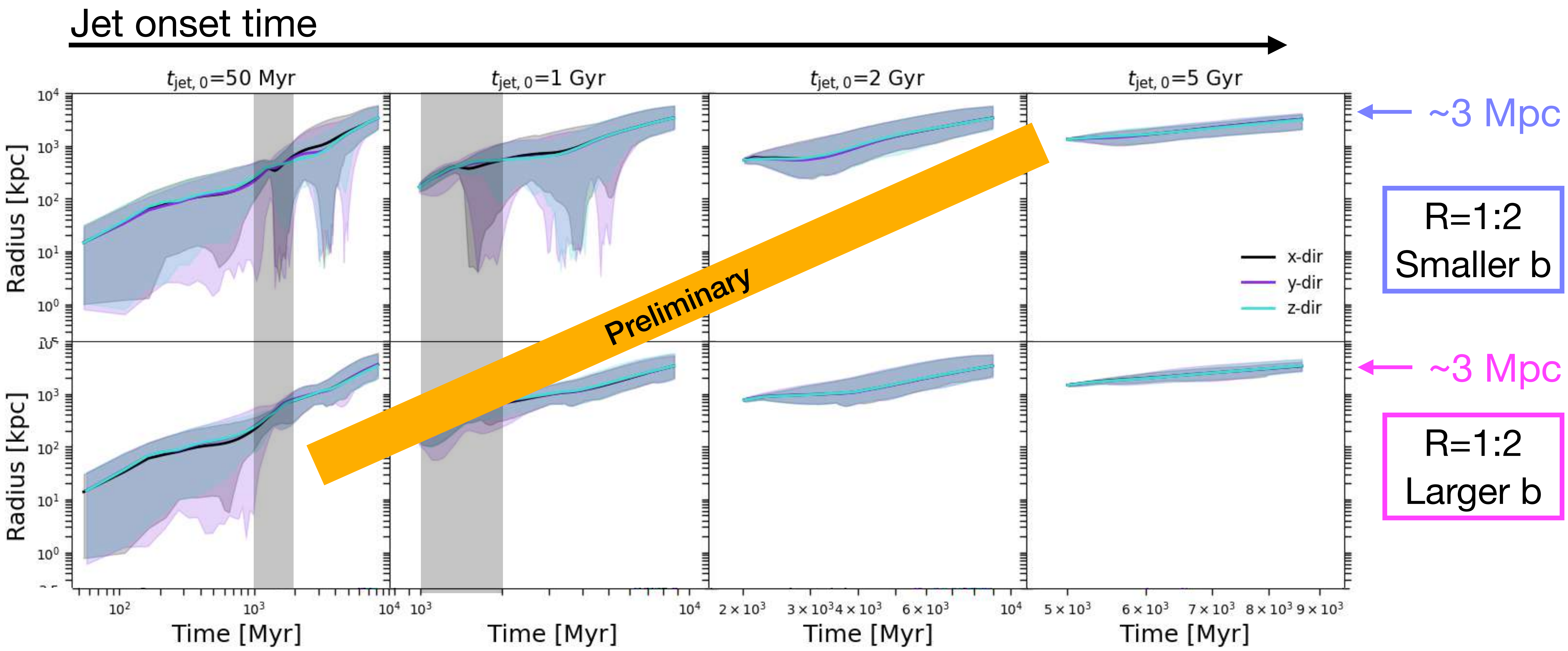
[Domínguez-Fernández , ZuHone et al. in prep.]

AGN bubble's contribution



[Domínguez-Fernández, ZuHone et al. in prep.]

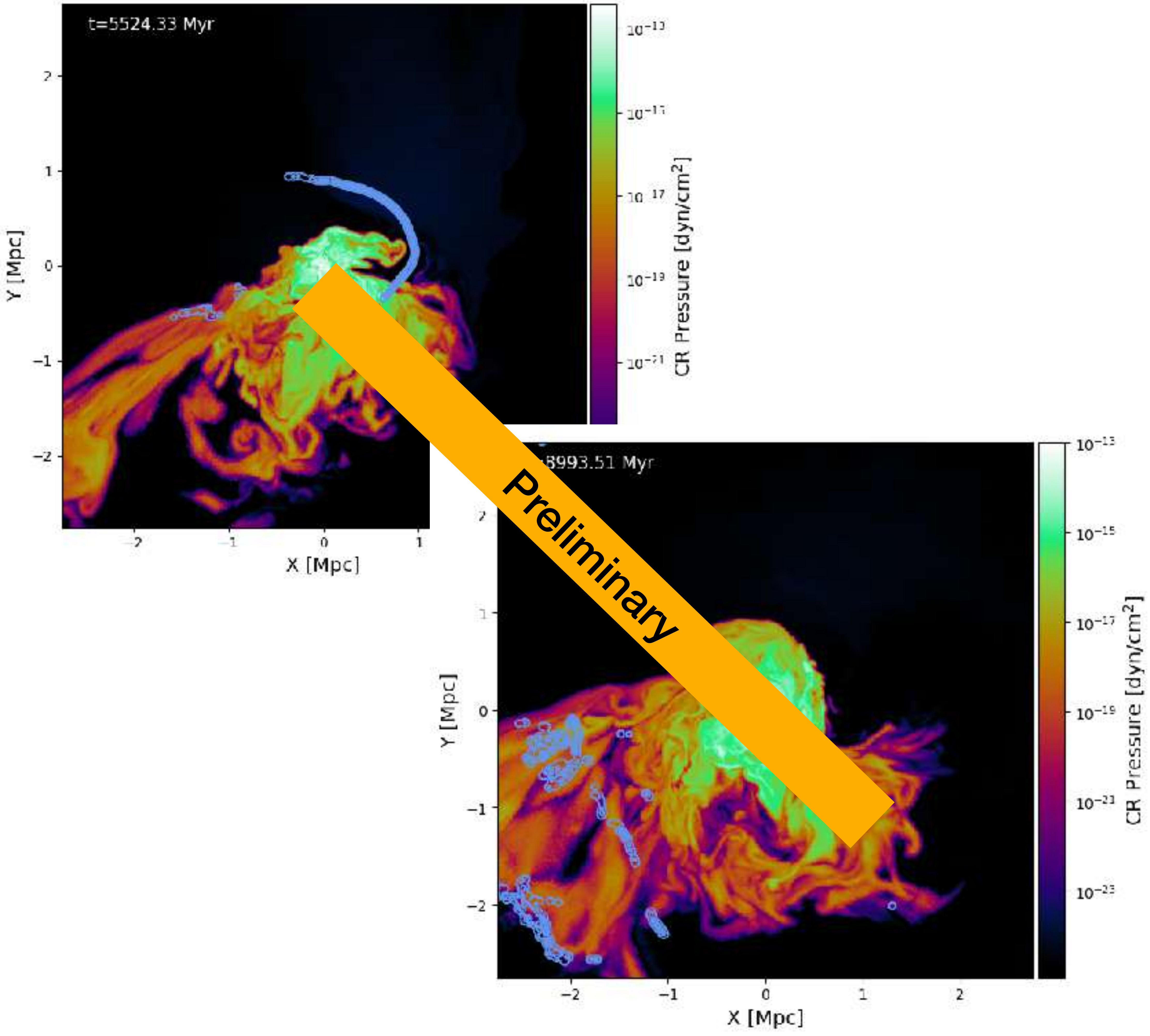
AGN bubble’s contribution



[Domínguez-Fernández, ZuHone et al. in prep.]

AGN bubble's contribution

- AGN bubbles easily permeate a Mpc region of GCs in a few Gyr after ignition
- Possible explanation for:
  - Radio halos? Yes, but turbulence re-acceleration is needed (coming up)
  - Radio relics?
    - No if only central AGN bubbles (contribution of ~1/3 LLS)
    - Yes if there's contribution from other off-center radio galaxies



[Domínguez-Fernández, ZuHone et al. in prep.]

Take away messages

Primordial MFs

- They can explain the magnetization of galaxy clusters
- Inflationary models seem to be favored (larger MF strength and coherent scales) BUT these simulations cannot definitely rule out phase-transitional-like fields

Radio diffuse emission

- Radio relics could be good tracers for outskirts MFs specially in polarization
- Fossil electrons seem to be a viable option for explaining radio halos and smooth radio relics BUT additional contribution from off-center radio sources is probably needed

Future with radio observations

- Outskirts and radio bridges BUT the emission seems to be also linked to some turbulent acceleration mechanism
- More studies with stacking cluster pairs and filaments
- More extragalactic RM studies

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Aurorae in Cambridge!

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