# Modelling primordial magnetic fields in galaxy clusters

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MAGCOW

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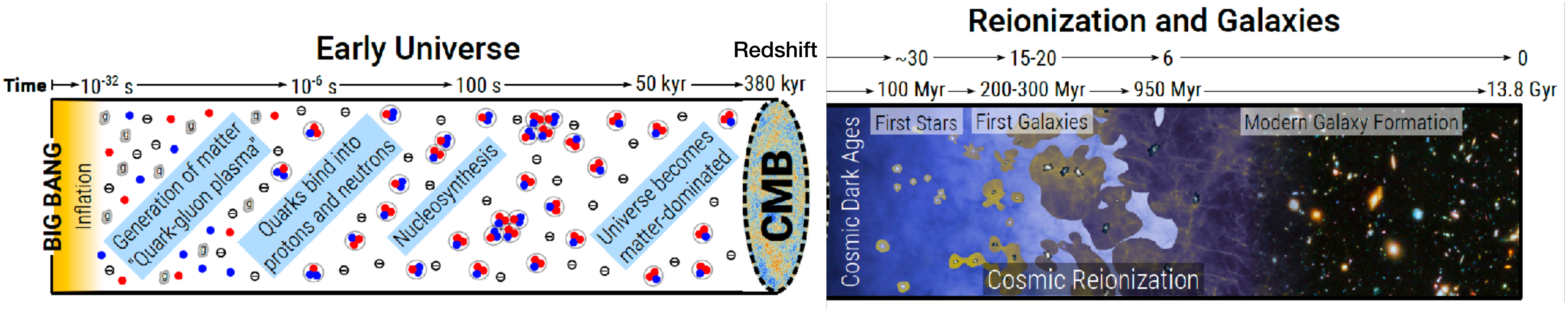
# Origin of magnetic fields




Credit: Wise et al. 2019

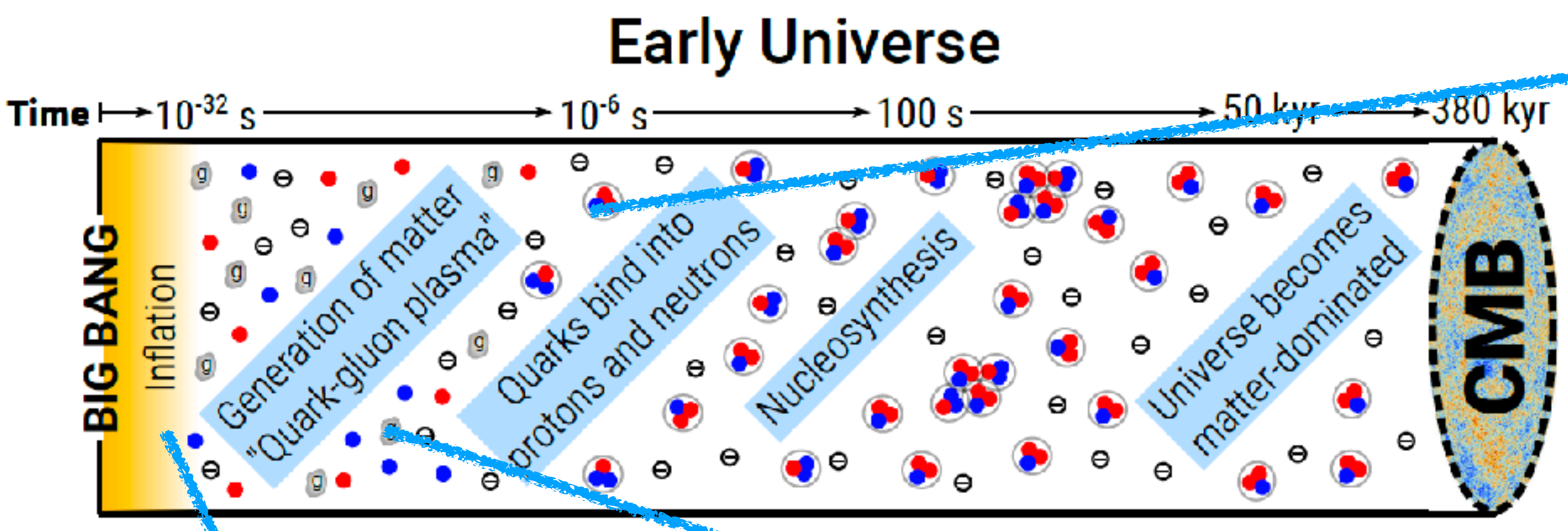
**Primordial**

**Top-down scenario**

**Astrophysical**

**Bottom-up scenario**

# Origin of magnetic fields




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

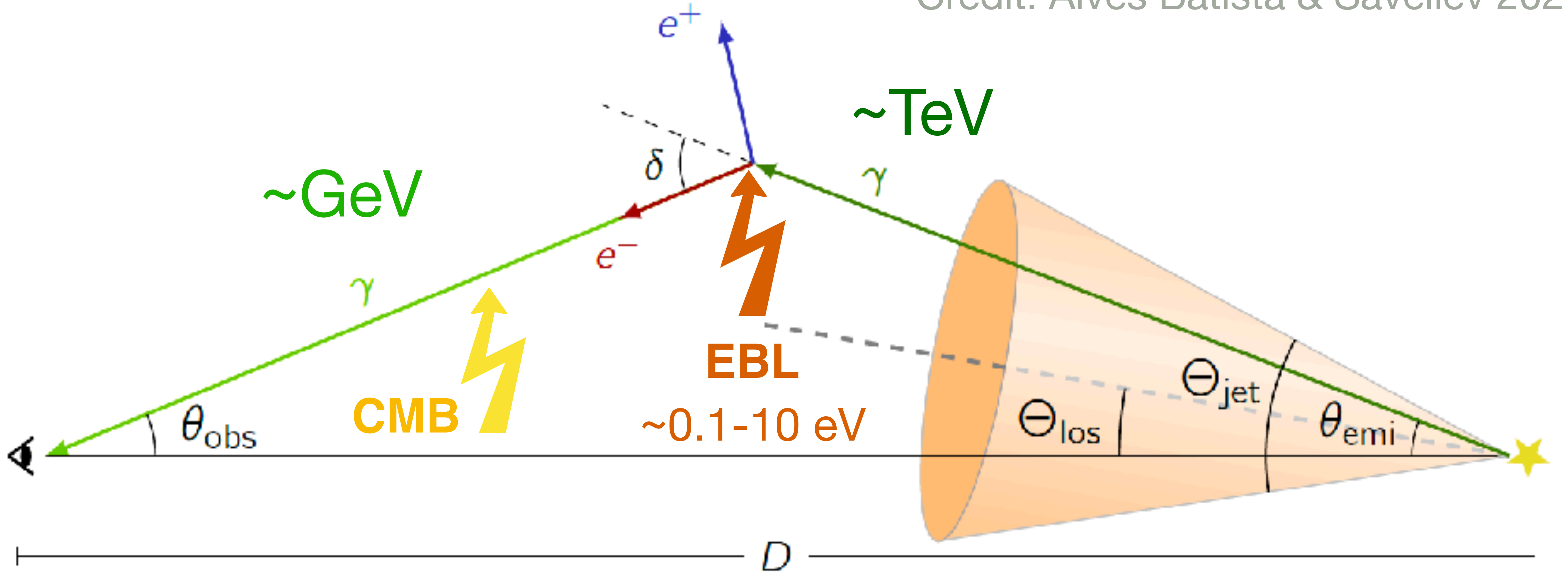
[Turner & Widrow 1988]

- Vacuum fluctuations
- Not limited by causality
  - Coherence length unbound $\lambda_B \gg H^{-1}$

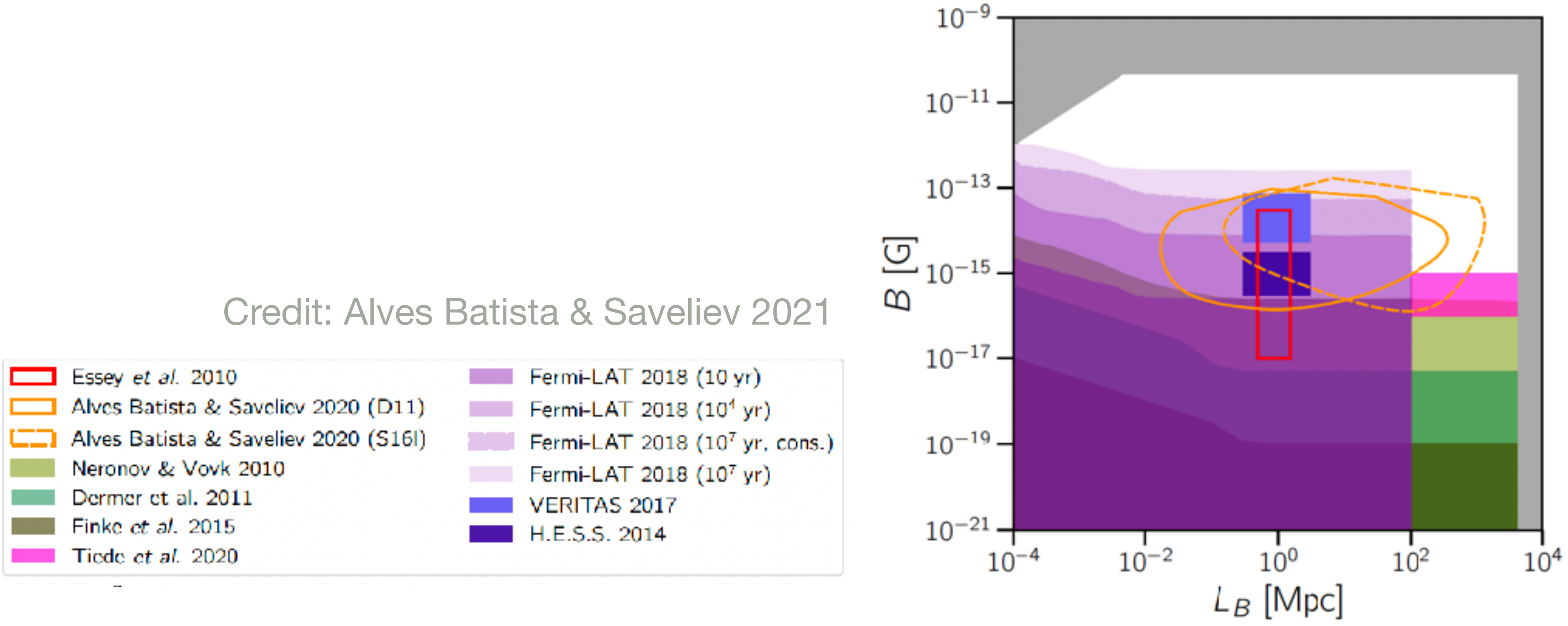
# Origin of magnetic fields

- EM cascades from blazars:
  - TeV Blazars should be observed as GeV halos
  - If a MF is present, $e^+e^-$ get deflected (Lorentz force) and no GeV halo is seen
    [Neronov & Vovk 2010]

Credit: Alves Batista & Saveliev 2021




Credit: Alves Batista & Saveliev 2021




Cosmic voids virtually unaffected by LSS!

- Lower bounds on the strength of IGMFs:
  - $\sim 10^{-18} - 10^{-16}$ G on ~Mpc scales

# Primordial magnetic fields

Effects on:

- CMB temperature and polarization anisotropies

  [Durrer et al.1998]

- Matter power-spectrum affecting the evolution of stars & galaxies

  [Wasserman et al.1998]

- Recombination (possible solution to Hubble tension)

  [Jedamzik & Pogosian 2020]

- Primordial Big Bang Nucleosynthesis

  [Jedamzik et al.1998]

- Reionization of the Universe

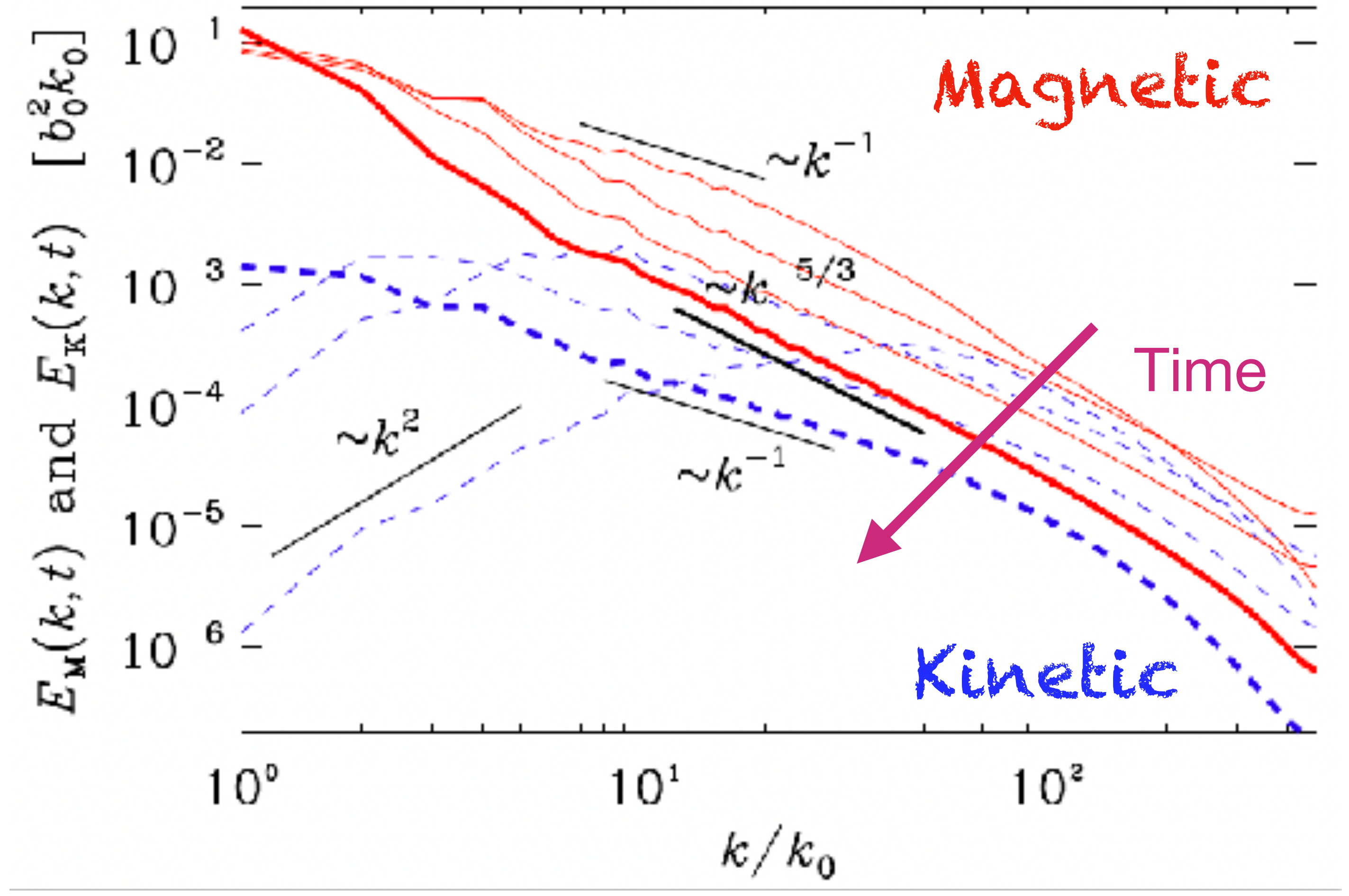
  [Grasso & Rubinstein 1996]

# Types of primordial MFs

**Inflationary**

- Large coherence length scale [Sharma et al. 2017]
  - $\sim 10^{-4} - 0.1$ Mpc, $\sim 10^{-13} - 10^{-10}$ G
- Power spectrum (PS): power-law
- No inverse cascade (non-helical and helical) *

*depends if there is an homogeneous (imposed) MF (See Brandenburg et al. 2020)



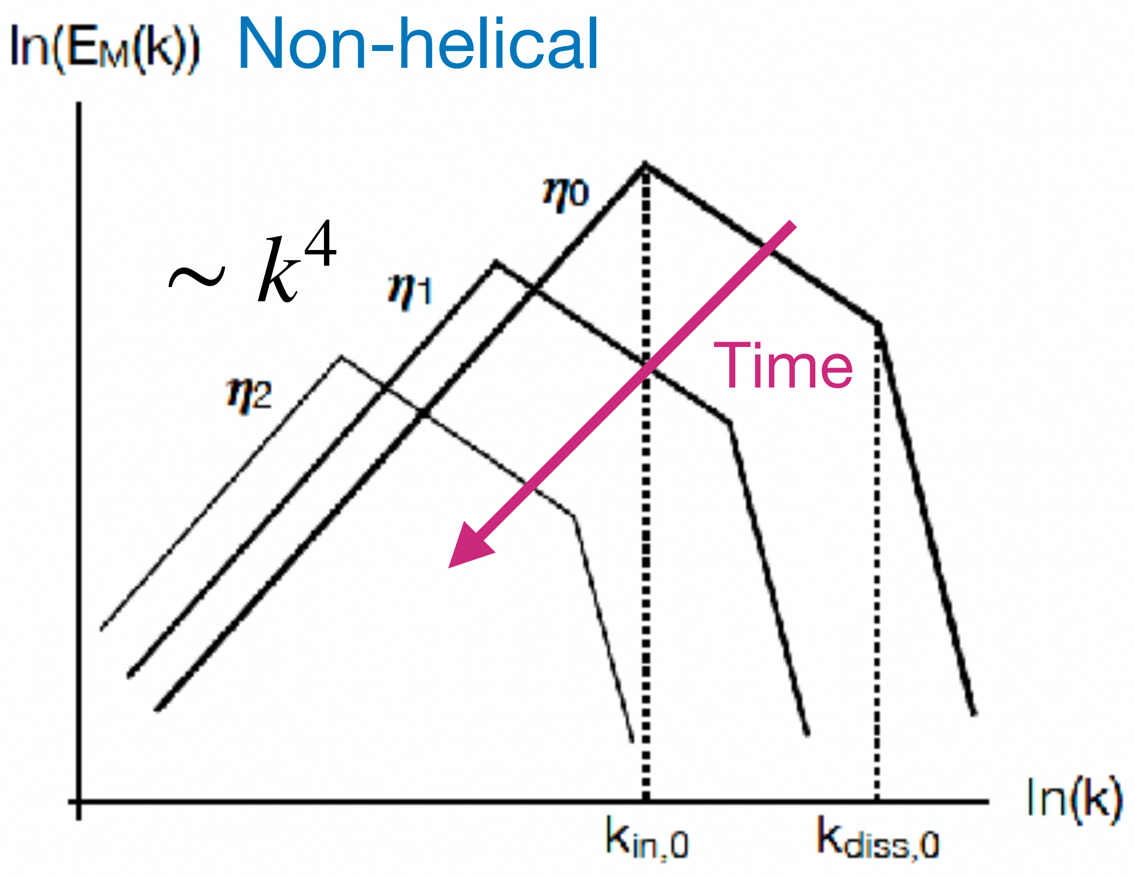

Credit: Kahniashvili et al. 2016

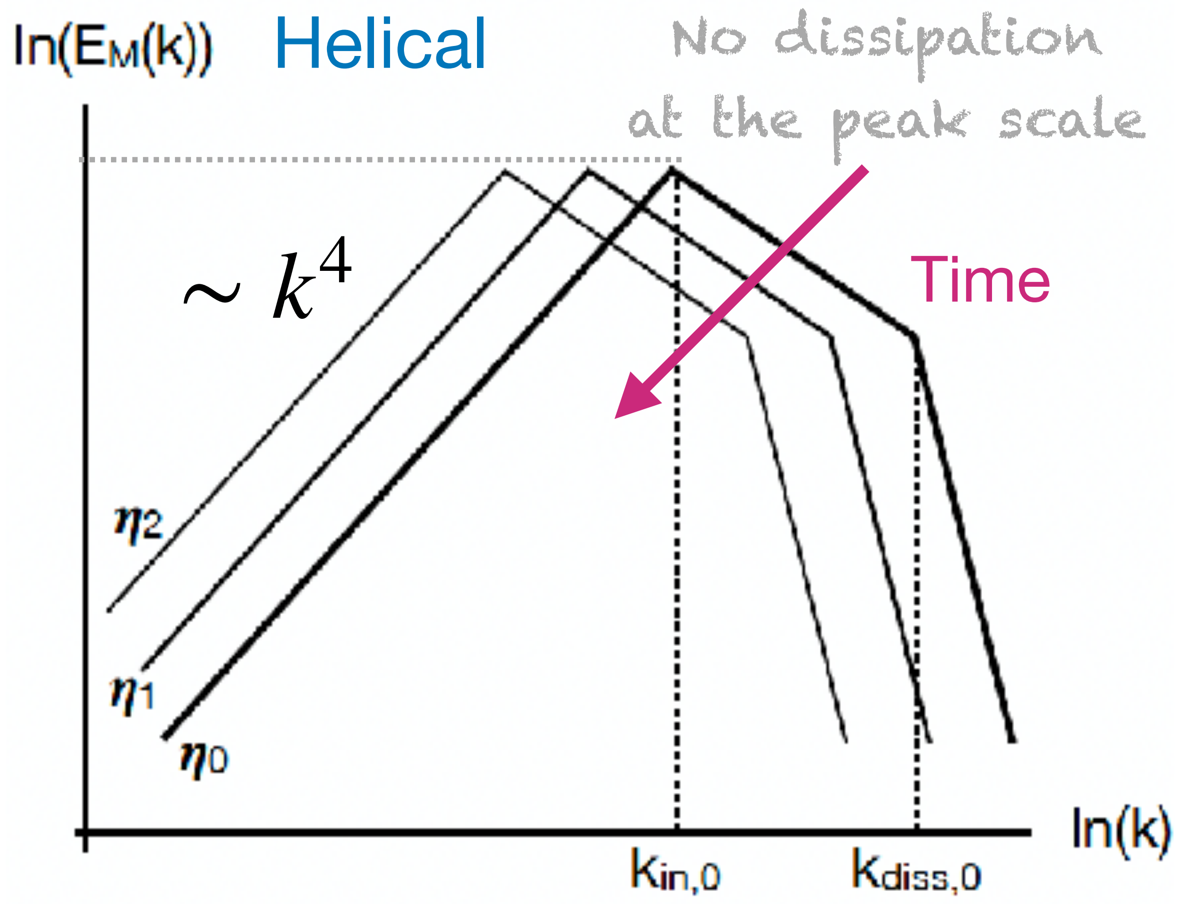
**Phase-transitional**

- Coherence length predicted to be small
  - EW: 0.1 pc - 10 kpc, $\sim 10^{-18} - 10^{-11}$ G
  - QCD (optimistic scenario): ~10 kpc, $\sim 10^{-13}$ G

[Vachaspati 2021; Tevzadze et al. 2020]

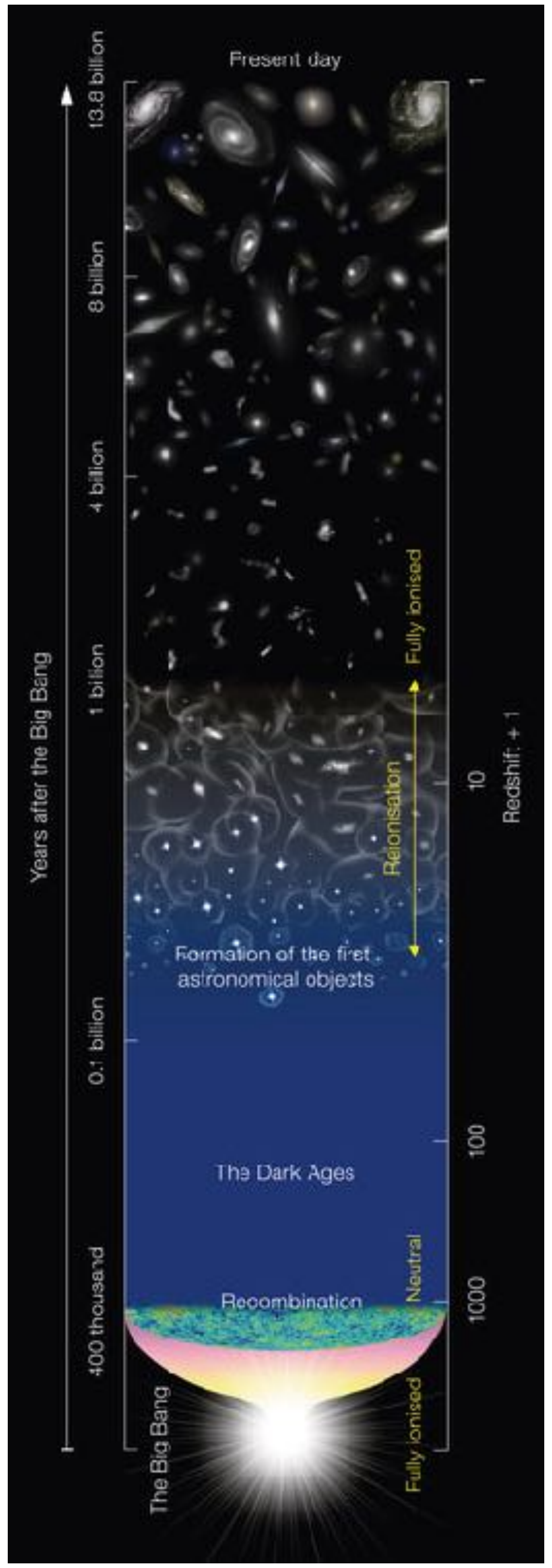
- Power spectrum (PS): power-law or a sharply peaked
- Expected inverse cascade (non-helical and helical)

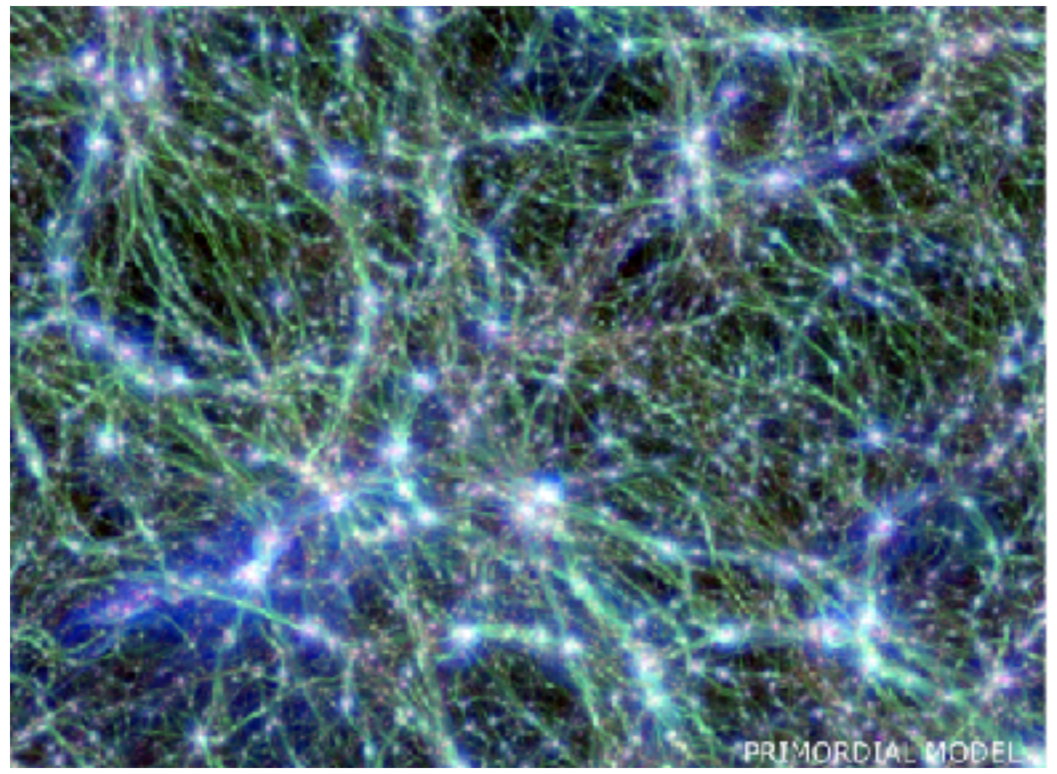



Credit: Vachaspati 2021

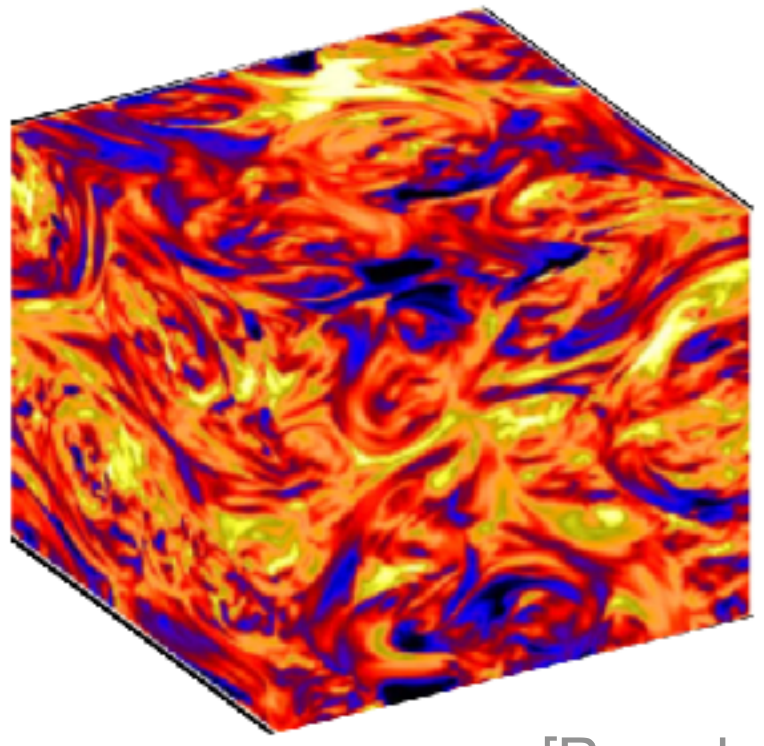
# Primordial MFs through structure formation




[Vazza et al. 2018]

- Matter dominated epoch:
  - Cosmological MHD numerical simulations



[Brandenburg et al. 2017]

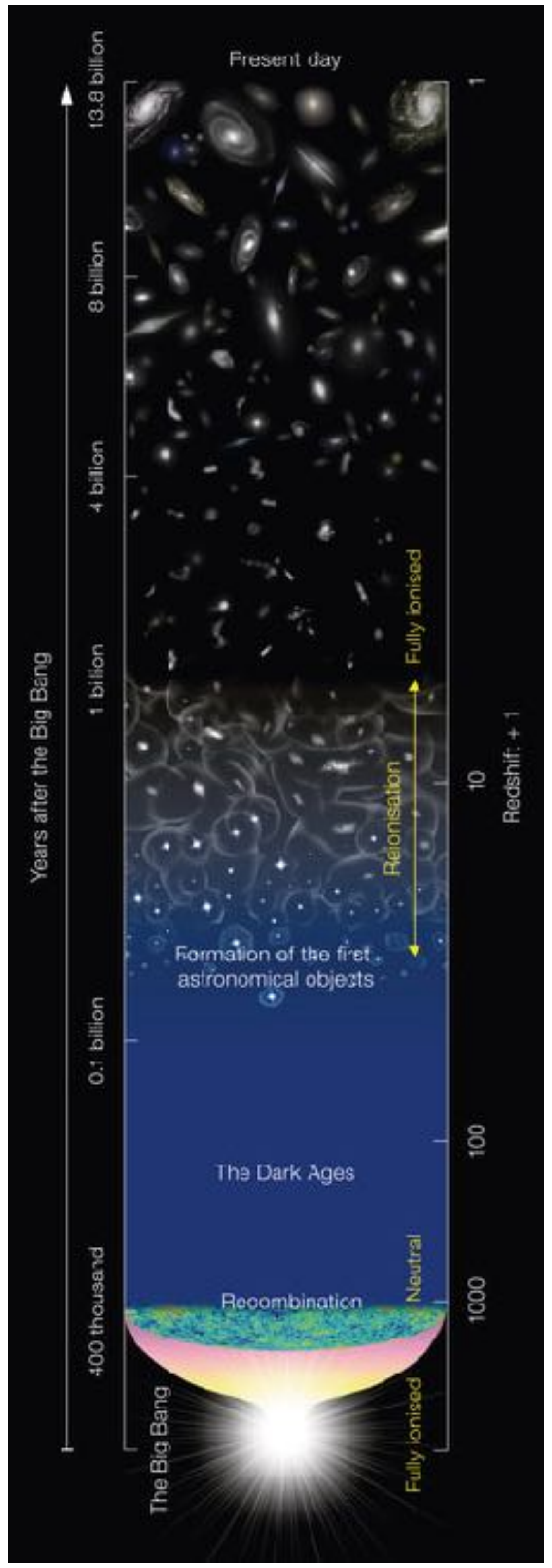
- Radiation dominated epoch:
  - MHD numerical simulations

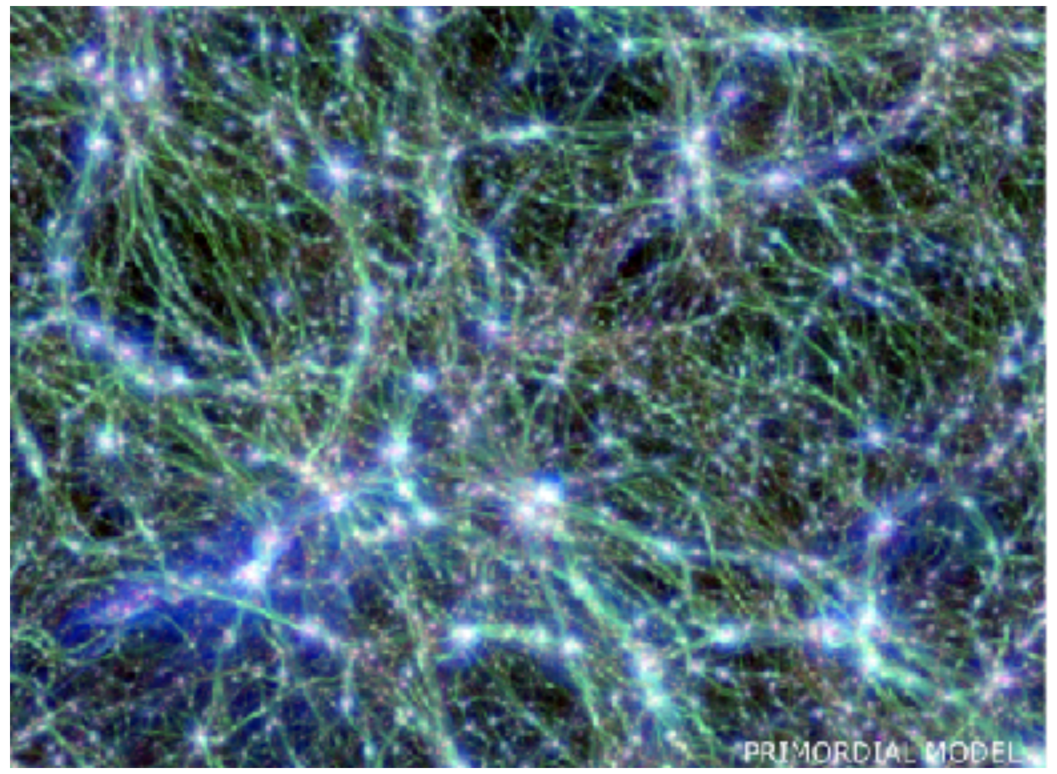
Evolution

↑

Generation

# Primordial MFs through structure formation

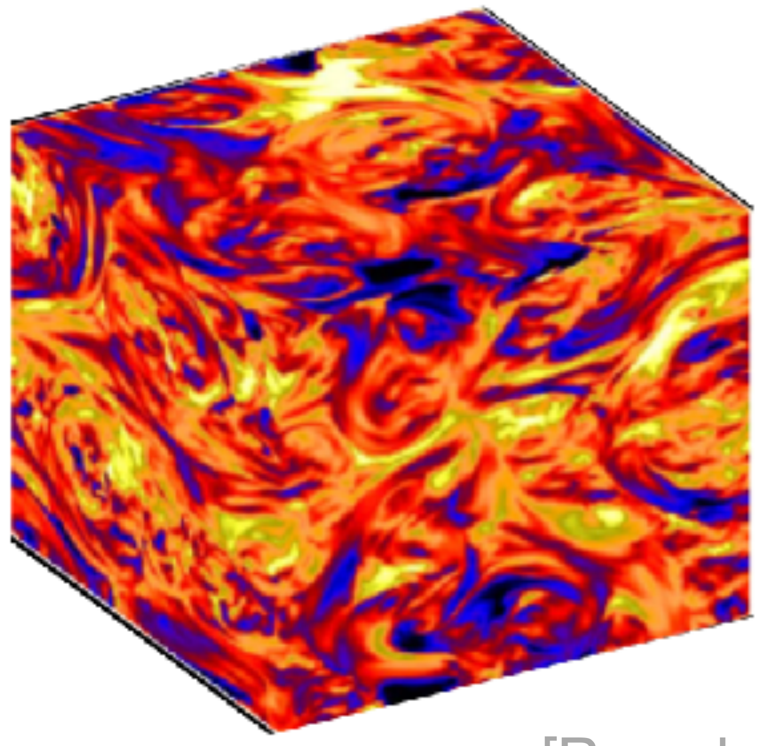



[Vazza et al. 2018]

- Evolution through structure formation
  - ENZO code (cosmological MHD)

[Bryan et al. 2014]



[Brandenburg et al. 2017]

- Initial magnetic field conditions:
  - Uniform seed
  - Non-uniform seed:
    - PENCIL code (MHD)

[PENCIL collab. 2021]

Inflationary

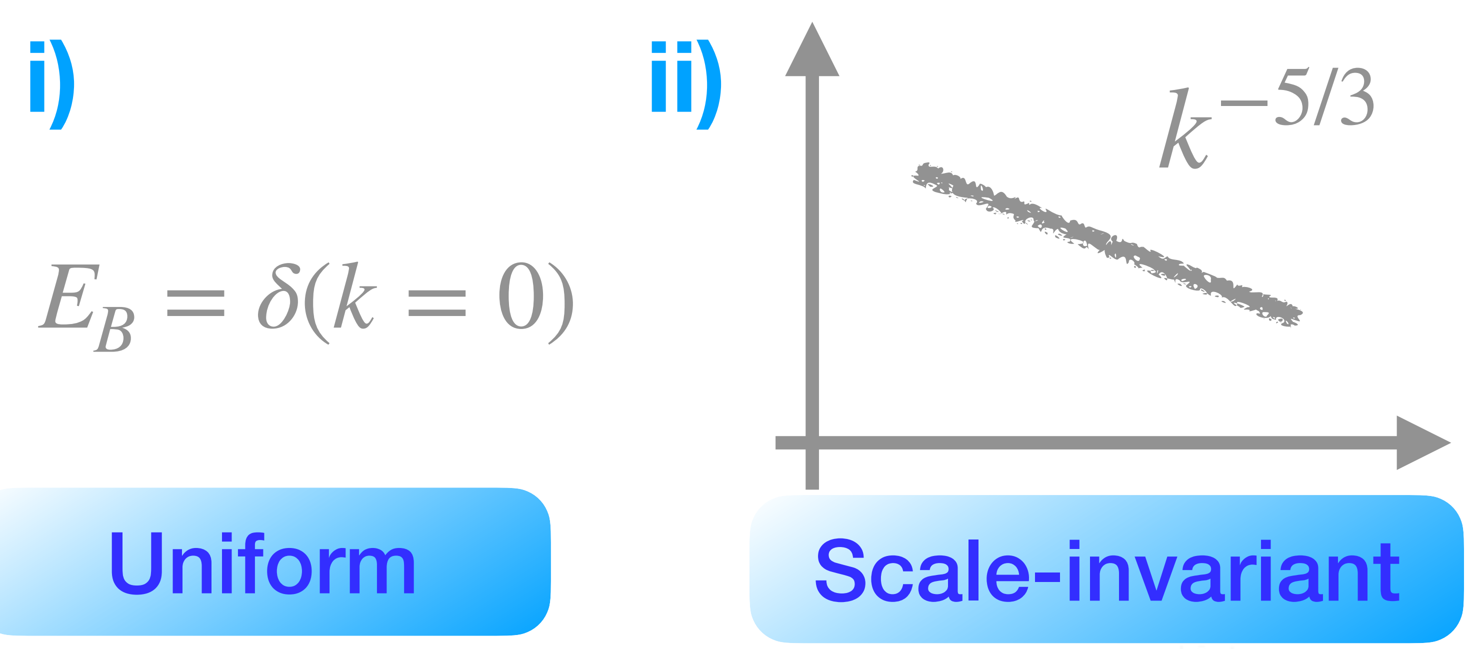
Phase-transitional

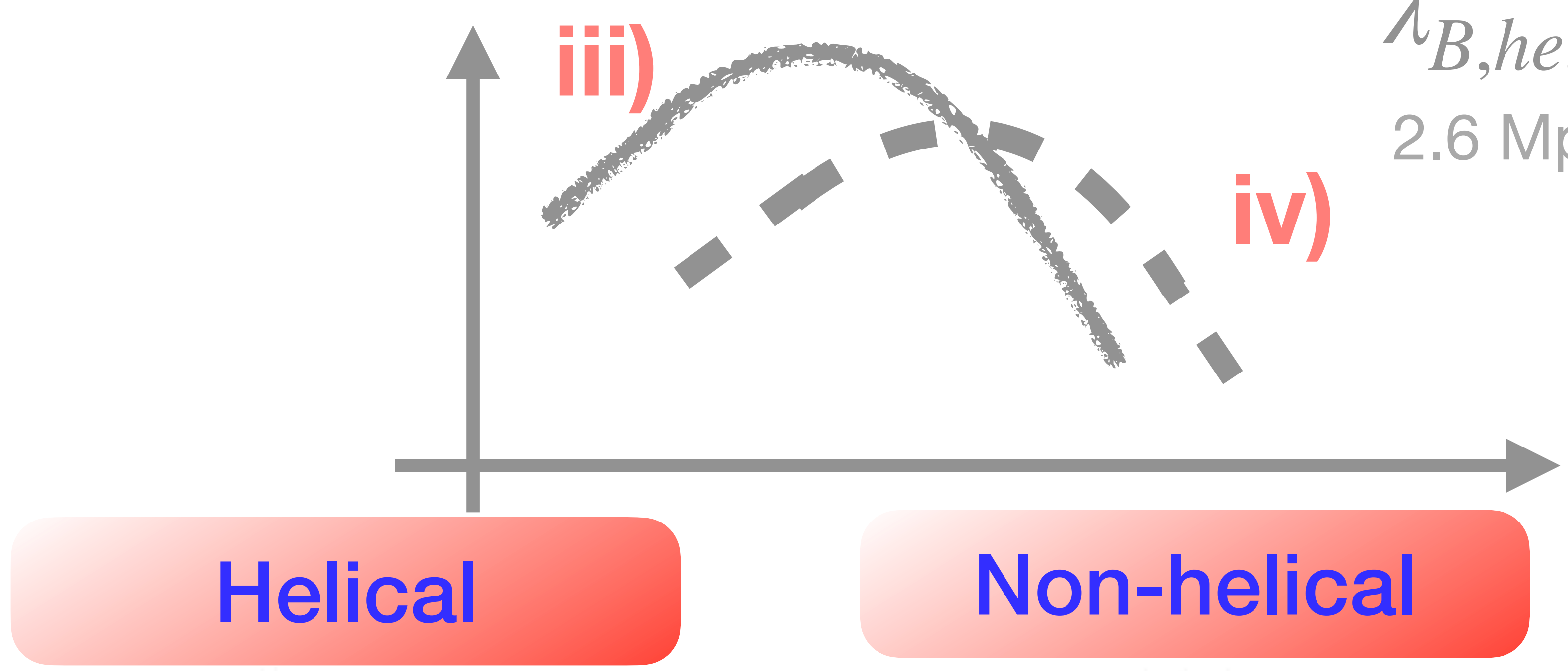
# Primordial MFs in the cosmic web

- Initial conditions:

Inflationary *    * alike!    Phase-transitional *    S. Mtchedlidze's talk!

same mean magnetic energy density



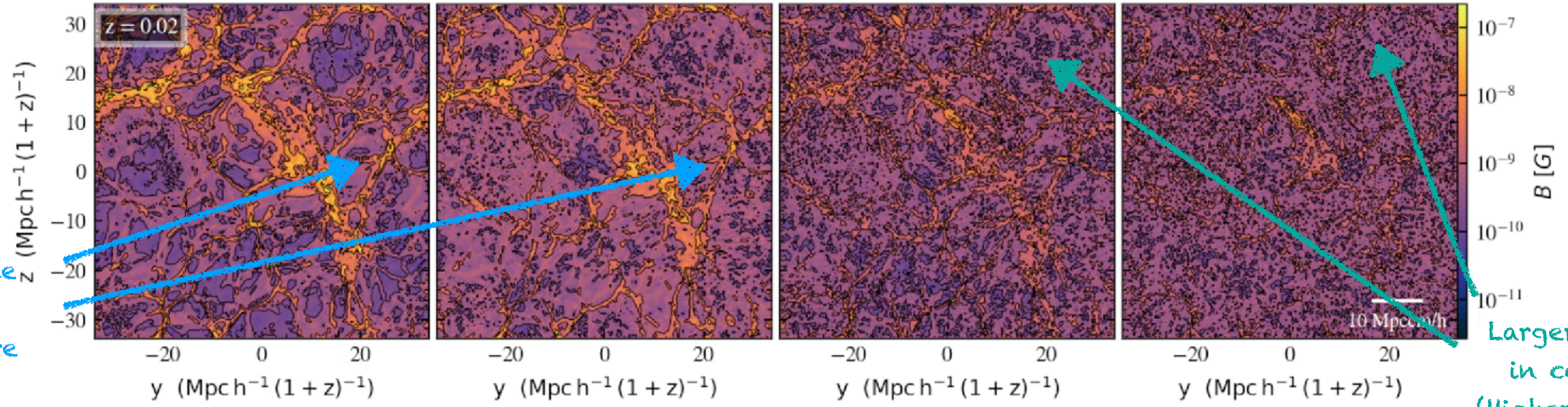




$\lambda_{B,helical} > \lambda_{B,non-helical}$

2.6 Mpc/h    1.3 Mpc/h

Expected from inverse cascade

- $z = 0$:




Amplification due to adiabatic compression more efficient!

Larger mean values in cosmic voids! (Higher temperatures)

[Mtchedlidze, Domínguez-Fernández et al. 2021]

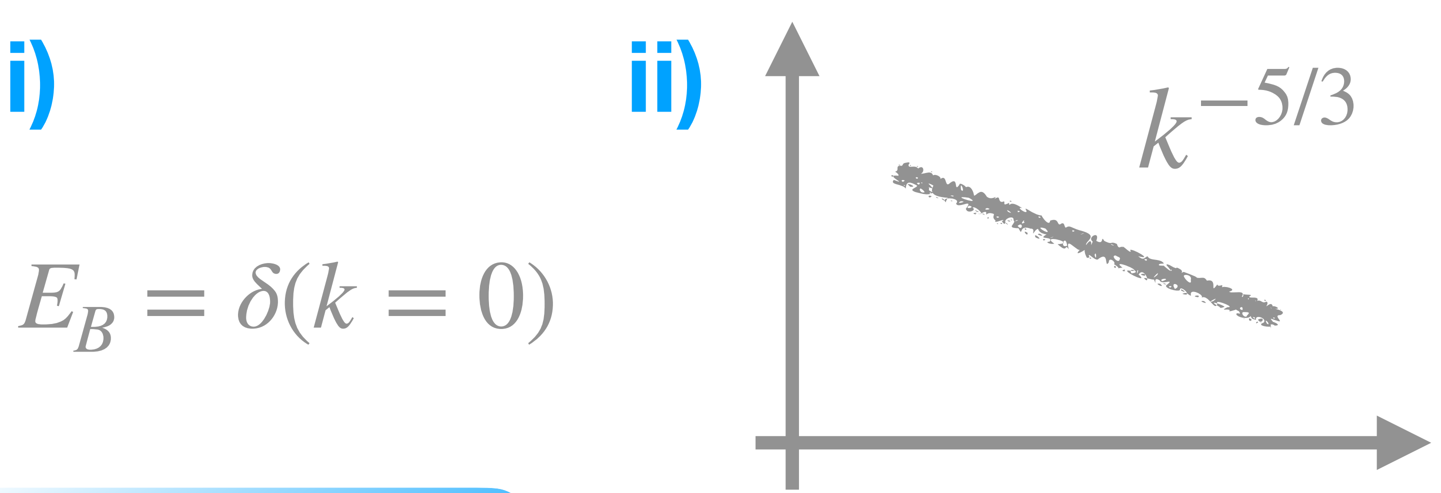
# Primordial MFs in the cosmic web

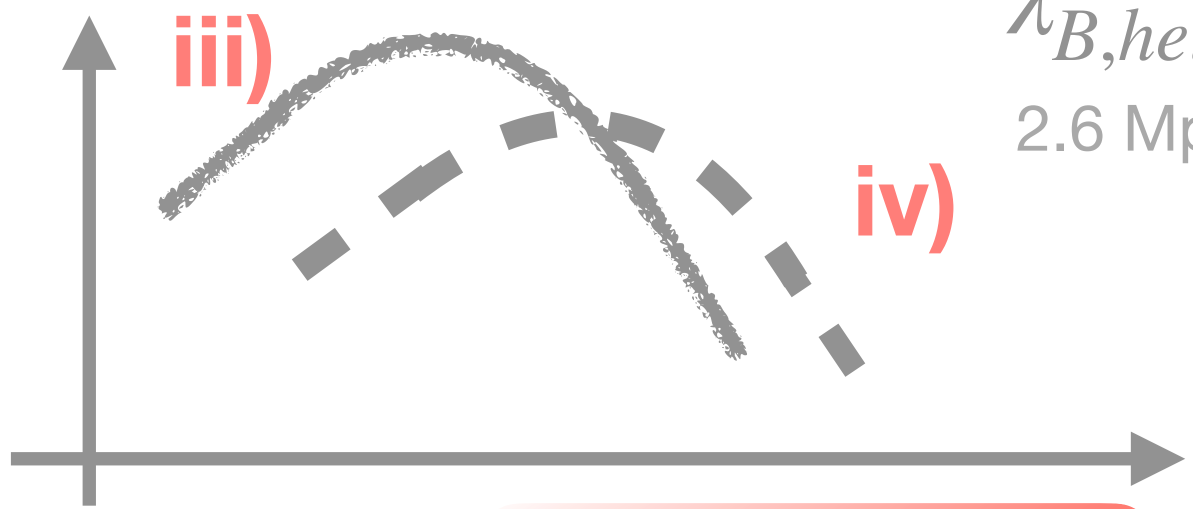
- Initial conditions:

Inflationary

Phase-transitional

S. Mtchedlidze's talk!




$\lambda_{B,helical} > \lambda_{B,non-helical}$

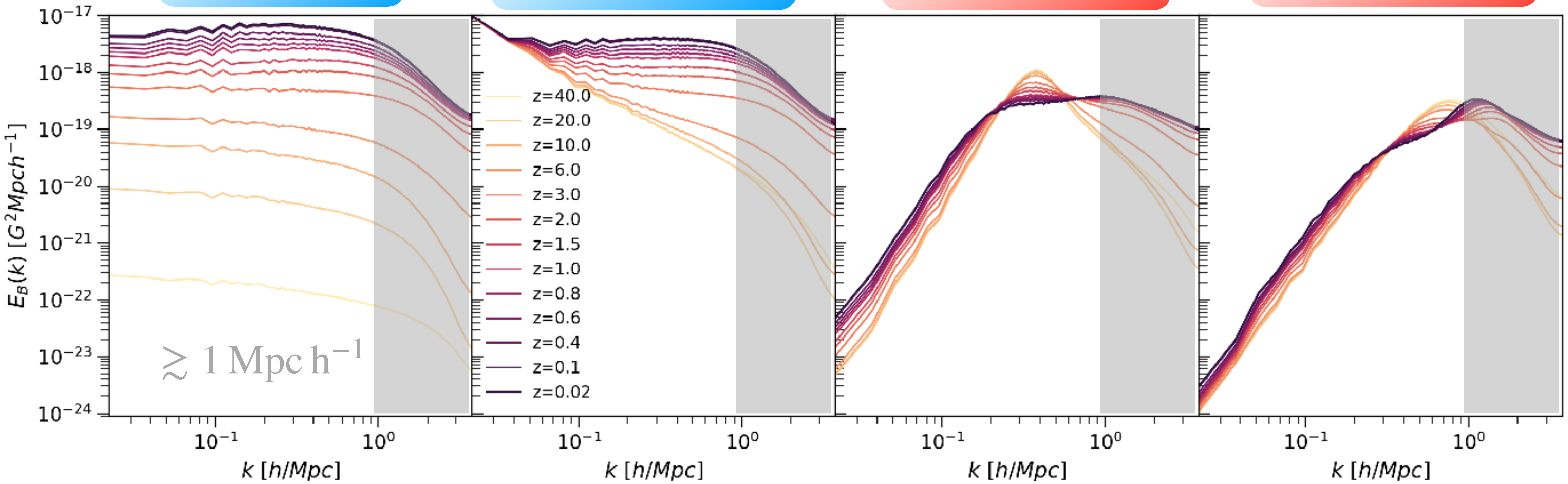
2.6 Mpc/h    1.3 Mpc/h

Expected from inverse cascade

Uniform | Scale-invariant | Helical | Non-helical

- $z = 0$:

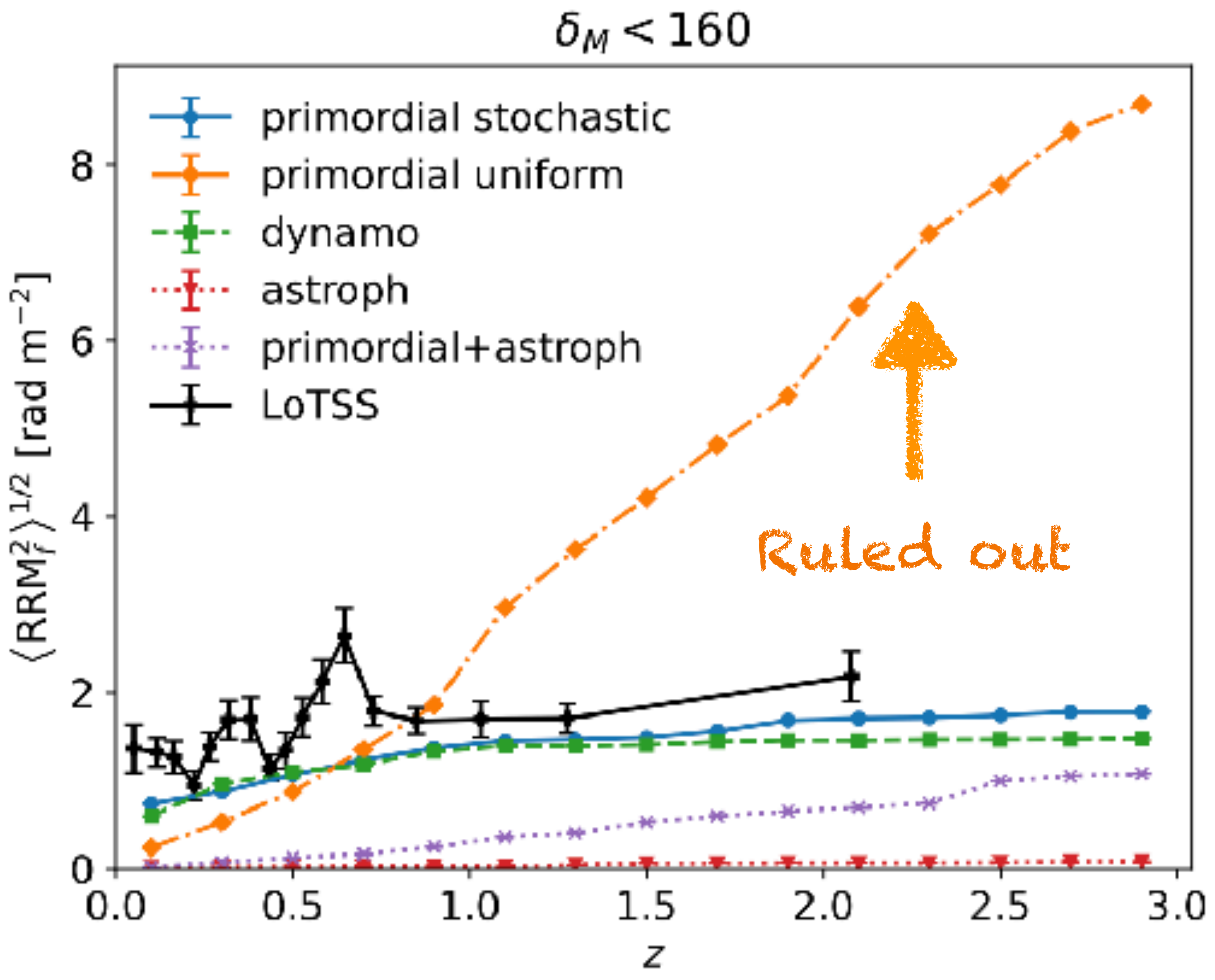
Larger $\lambda_B$



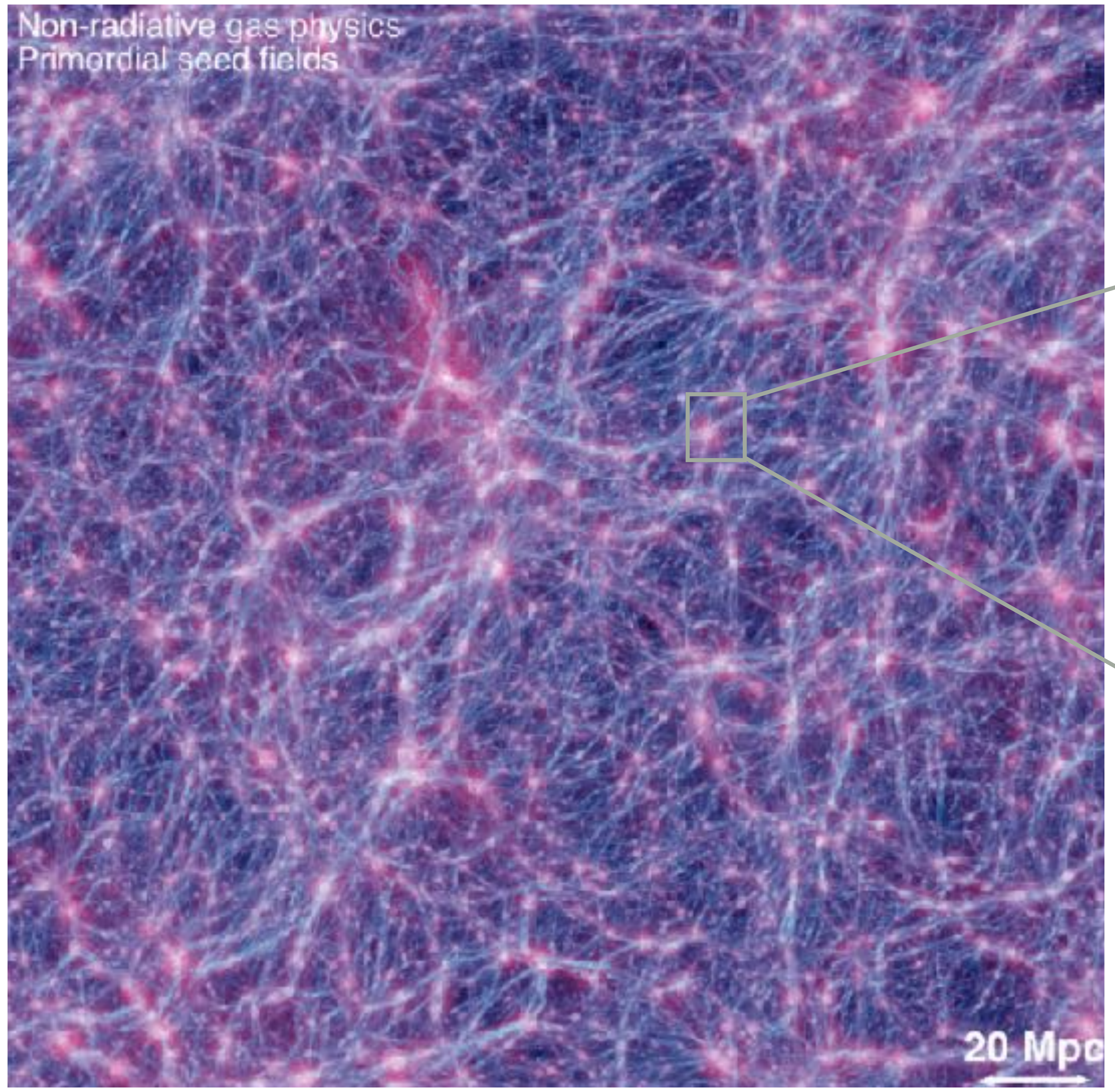

Smaller $\lambda_B$

# Primordial MFs in the cosmic web

Cosmic filaments

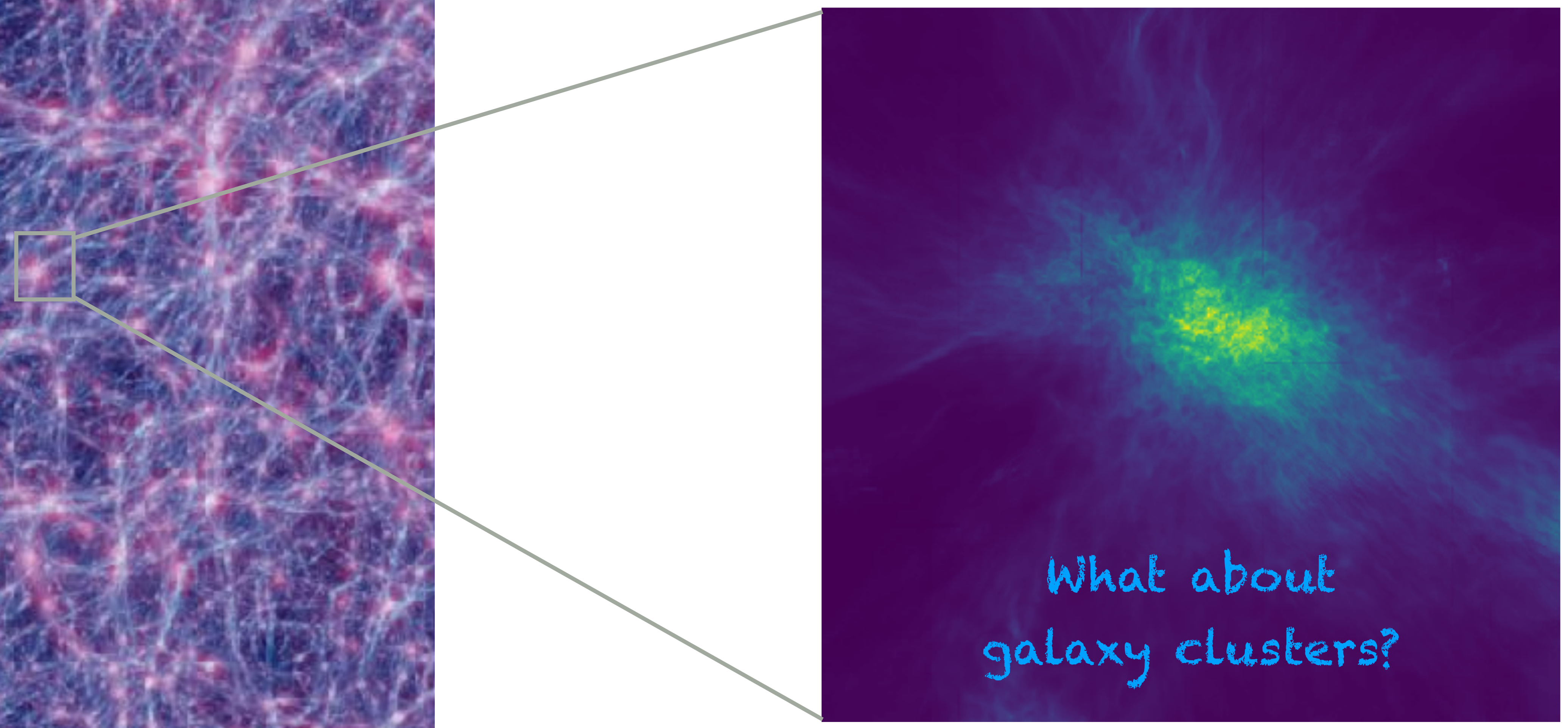



[Carretti et al. 2023]




[Vazza et al. 2017]

Galaxy clusters




[Domínguez-Fernández et al. 2019]

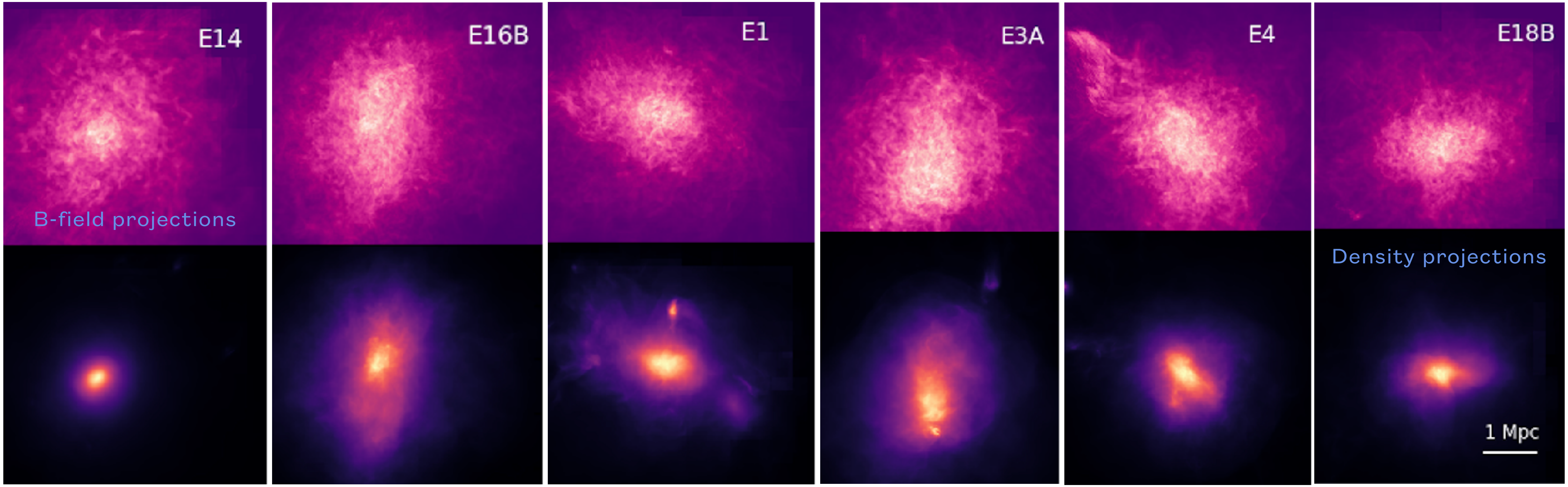
- RM studies rule out primordial uniform MF models

- If there is a primordial magnetogenesis, it should also explain MFs in clusters

- Is the seed field information really lost?

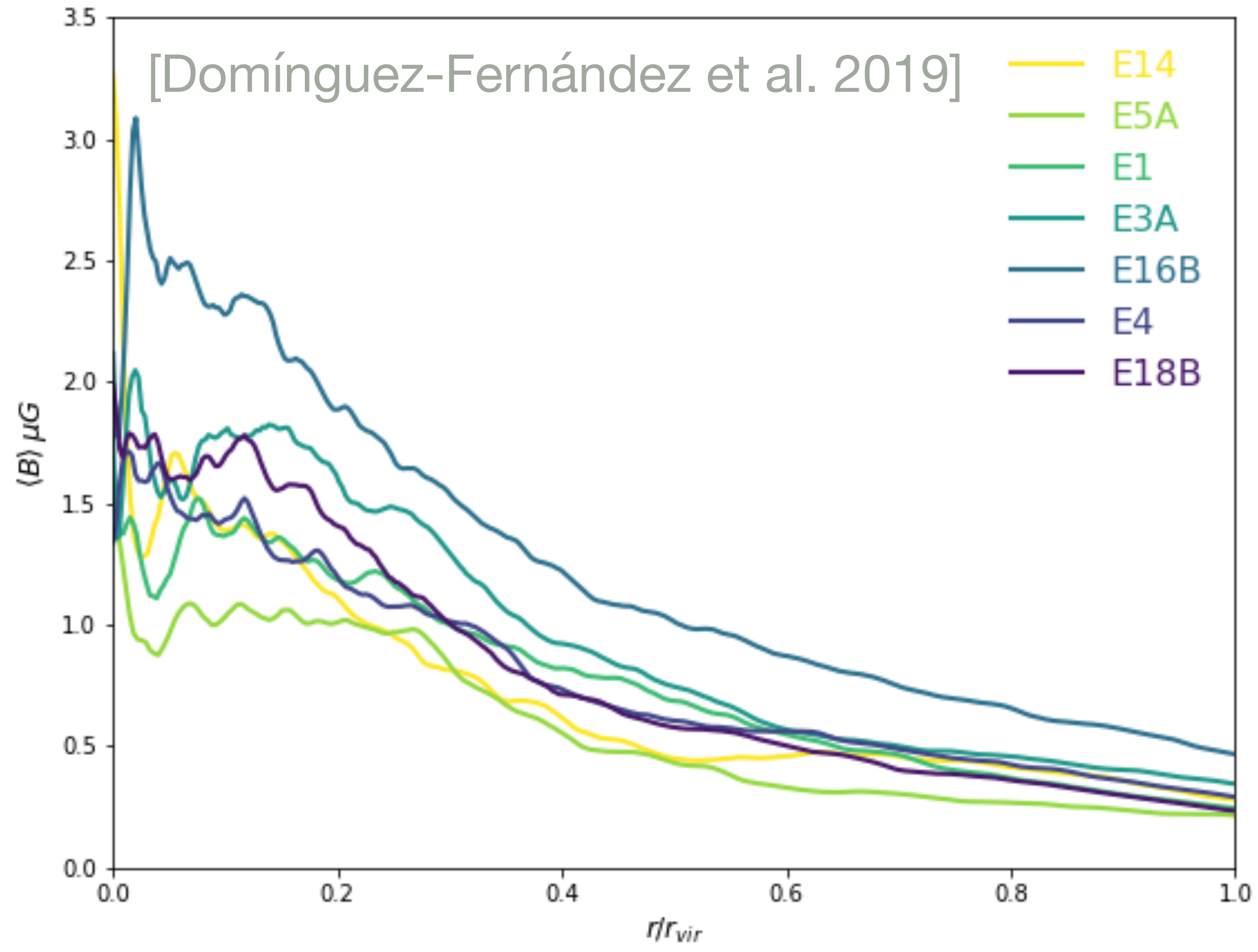
# Primordial uniform seed

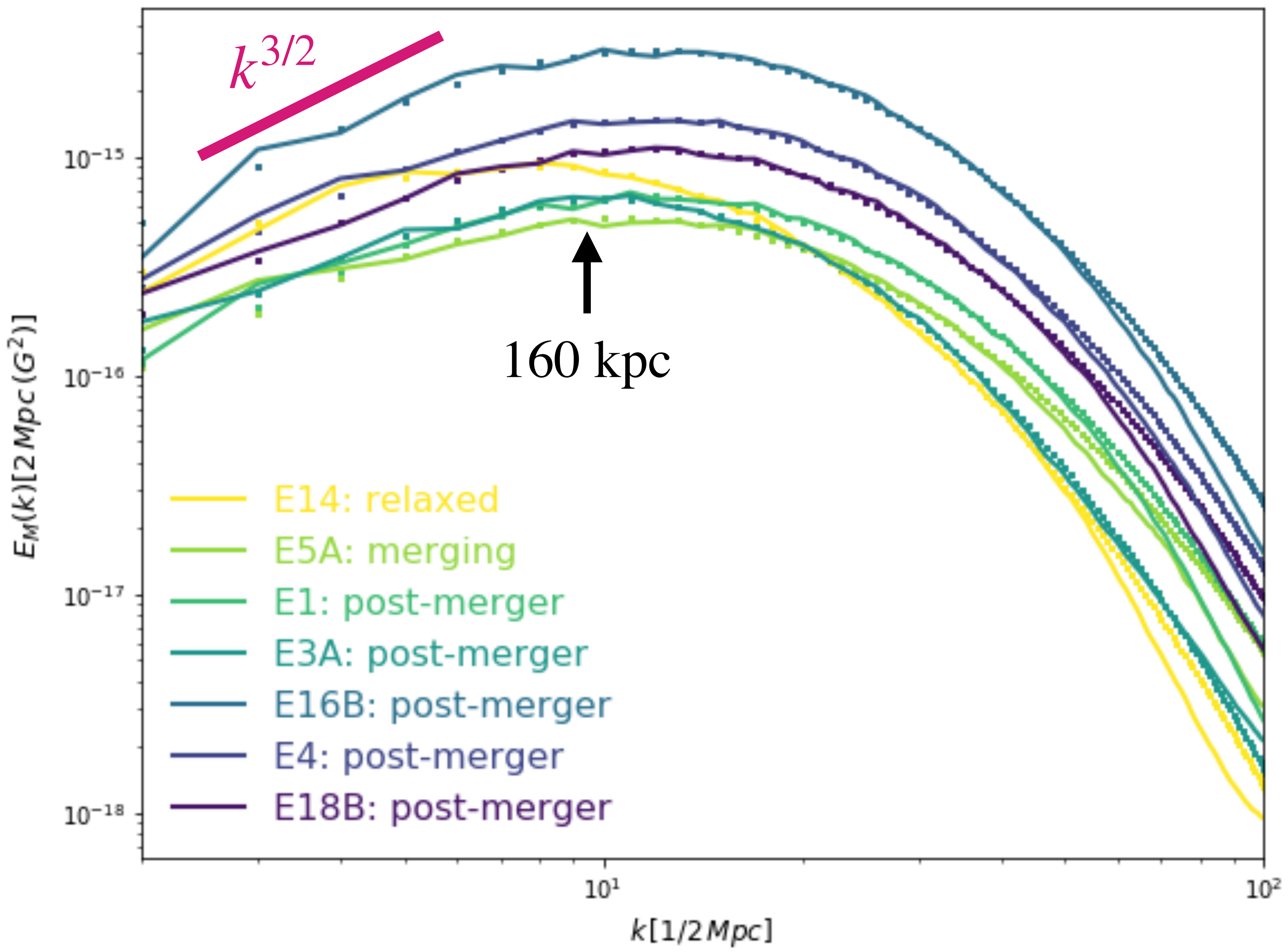
[Domínguez-Fernández et al. 2019]




- Initial conditions: [Vazza et al. 2017]
  - $z = 50$, 0.1 nG (comoving)
  - Total volume: $(260\,\mathrm{Mpc})^3$ (comoving) volume.
- Refinement region: $(25\,\mathrm{Mpc})^3$
- 7 AMR levels, 4 kpc resolution
- No cooling or feedback

# Primordial uniform seed




| ID | $M_{100}$ ($M_\odot$) | $R_{100}$ (Mpc) |
|---|---|---|
| E14 | $1.00 \cdot 10^{15}$ | 2.60 |
| E5A | $0.66 \cdot 10^{15}$ | 2.18 |
| E1 | $1.12 \cdot 10^{15}$ | 2.67 |
| E3A | $1.38 \cdot 10^{15}$ | 2.82 |
| E16B | $1.90 \cdot 10^{15}$ | 3.14 |
| E4 | $1.36 \cdot 10^{15}$ | 2.80 |
| E18B | $1.37 \cdot 10^{15}$ | 2.80 |

- Primordial seed AND small-scale dynamo amplification can reach $\sim \mu$G values.
- Amplification of the order of $10^4$ in the innermost regions.
- Similar power-spectrum independent of the dynamical state (and evolution).

# Initial magnetic conditions

Inflationary *

Uniform — i) $E_B(k) = \delta(k=0)$ [Mukhoyama 2016]

Scale-invariant — ii) Generation $\propto k^{-1}$ → End of recombination $\propto k^{-5/3}$

Turbulent decay

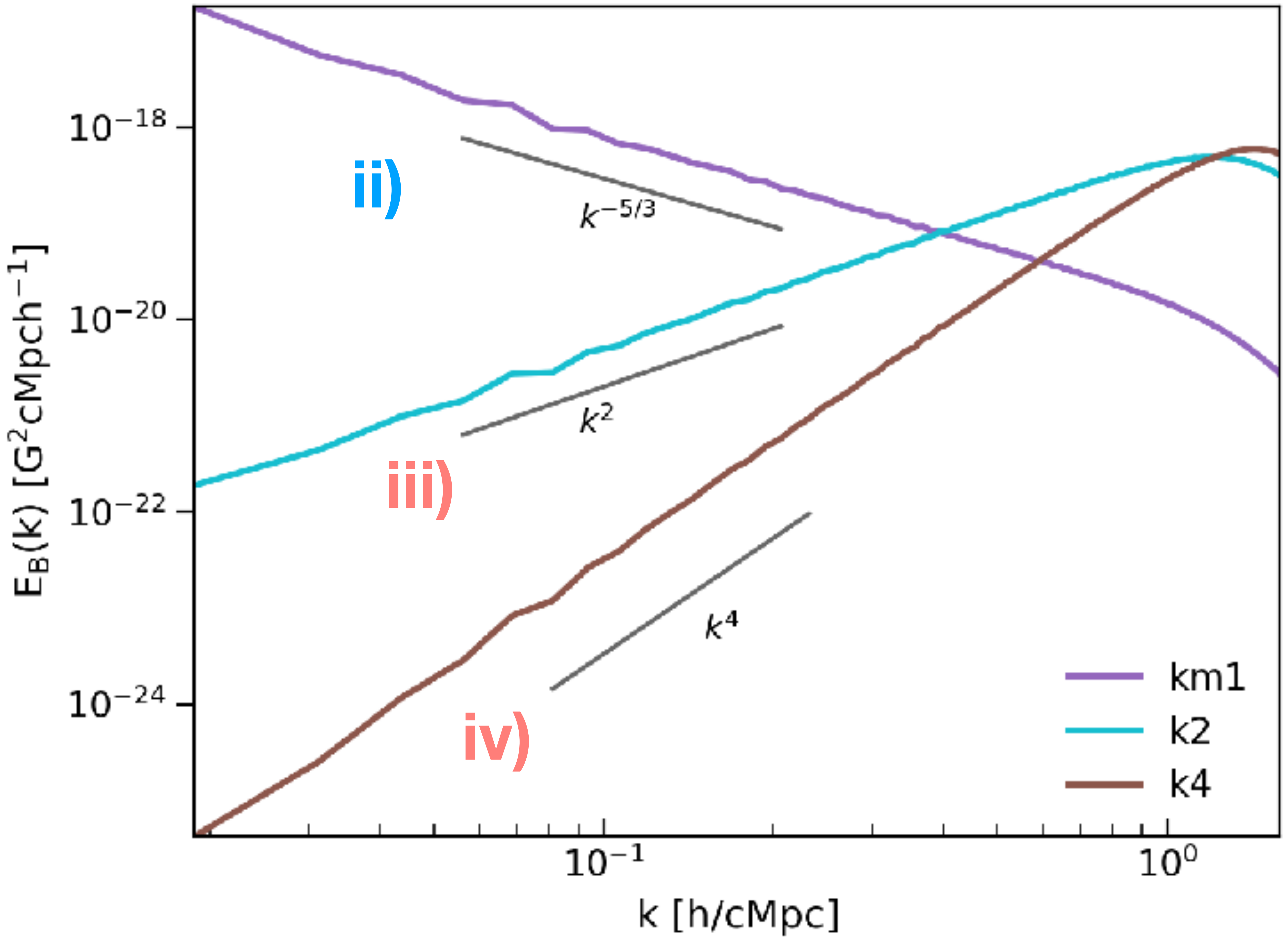
Phase-transitional *

Saffman — iii) $\propto k^2$

Batchelor — iv) $\propto k^4$

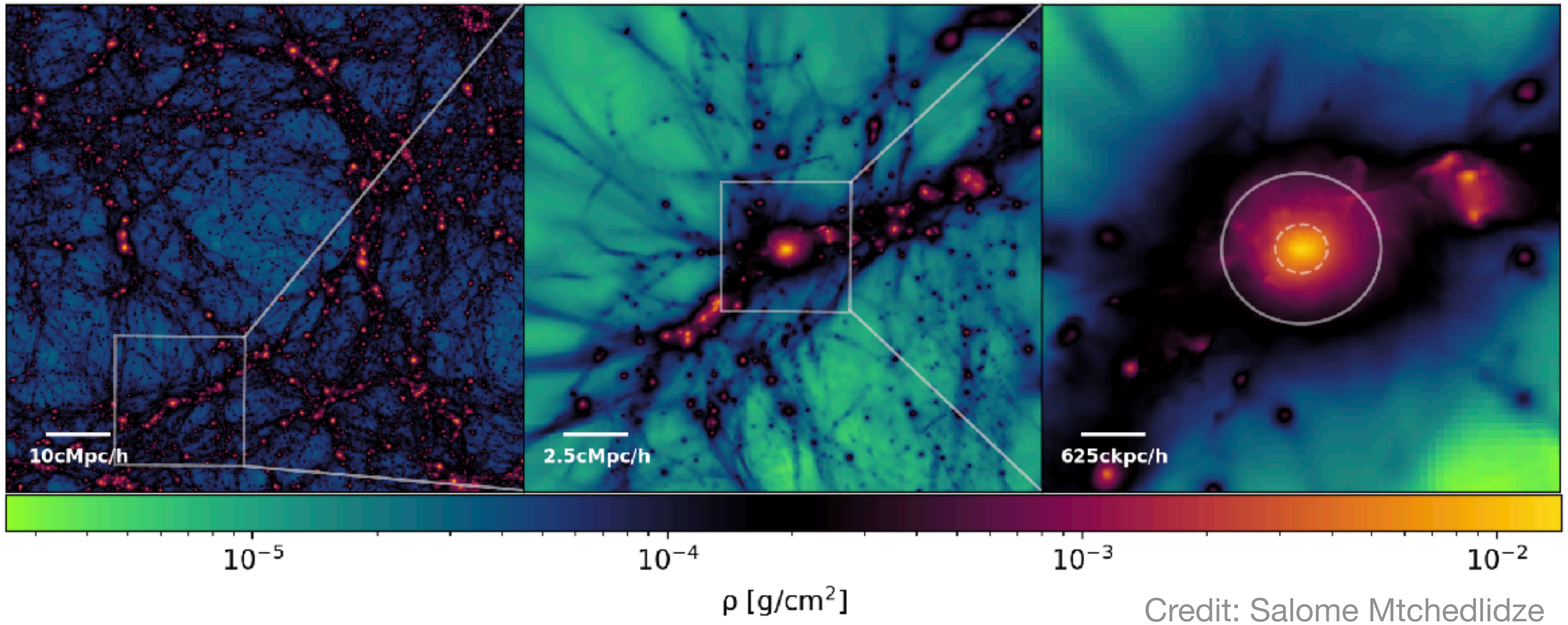
Expected from causal PMF generation + Decaying turbulence

* alike!



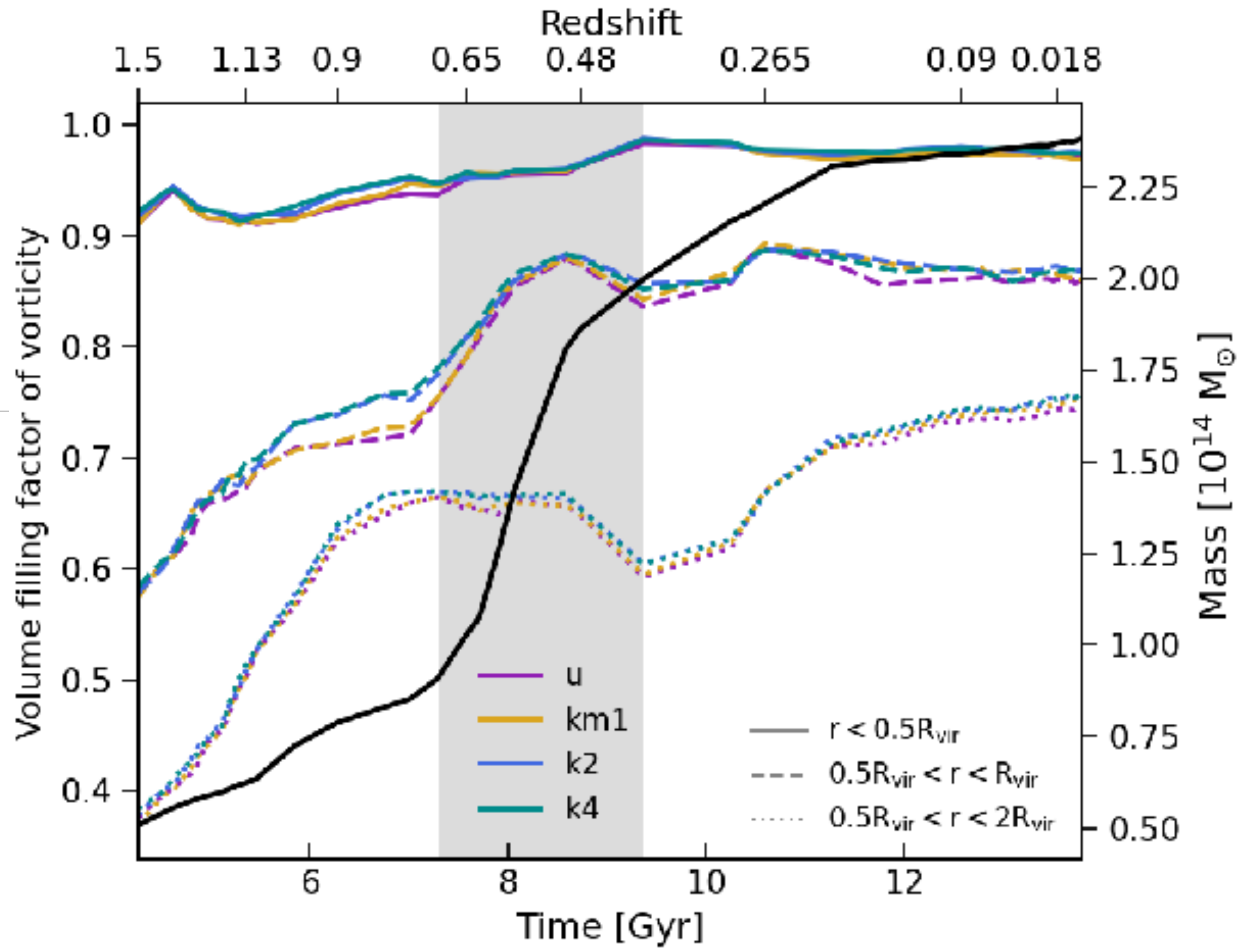

[Mtchedlidze, Domínguez-Fernández et al. accepted]

# Primordial non-uniform seeds



Credit: Salome Mtchedlidze

- Relaxed cluster:
  - $R_{vir} = 1.5\, h^{-1}\mathrm{Mpc}$
  - $\mathrm{M}(r \leq R_{vir}) = 2.34 \cdot 10^{14}\, \mathrm{M}_{\odot}$



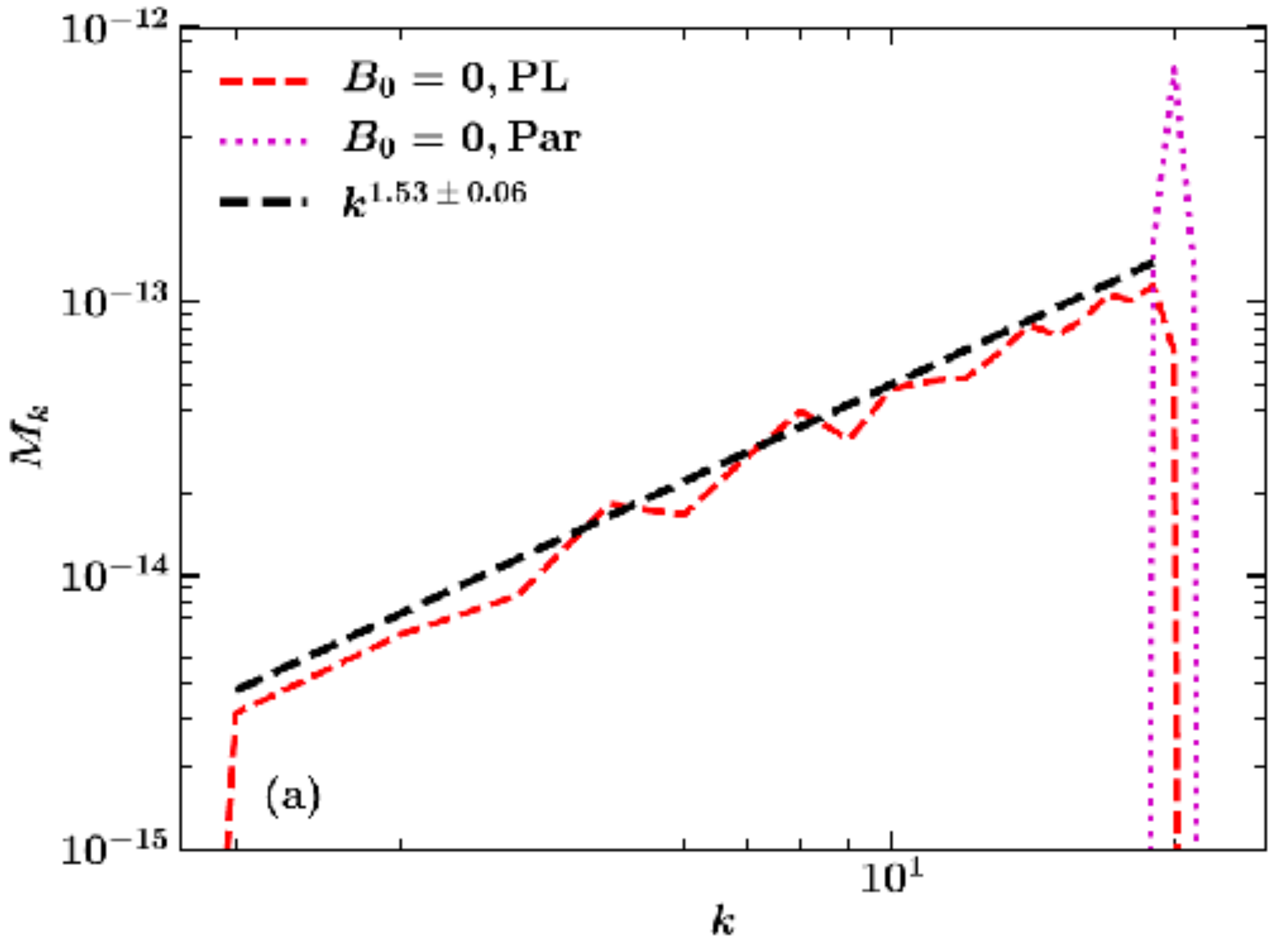

[Mtchedlidze, Domínguez-Fernández at al. accepted]

- Initial conditions:
  - $z = 50$, 1 nG (comoving)
  - $(80\,\mathrm{Mpc})^3$ (comoving) volume.
  - Refinement region: $(20\,\mathrm{Mpc})^3$
  - 6 AMR levels, 2.44 kpc resolution

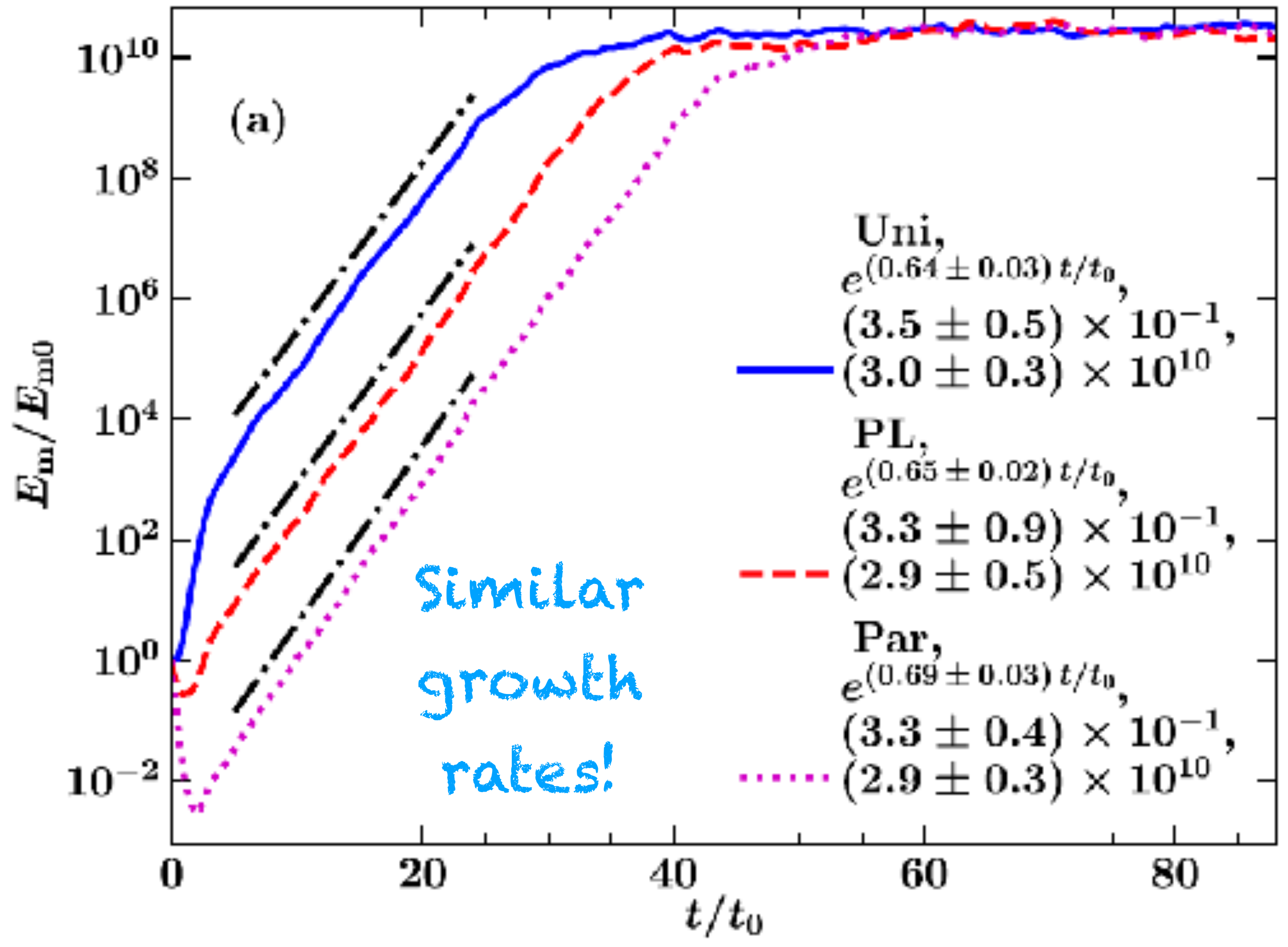
# Expectations from MHD only simulations

- The strength & structure of the seed field does not affect the growth rate & saturation level of the magnetic energy

Same initial magnetic energy

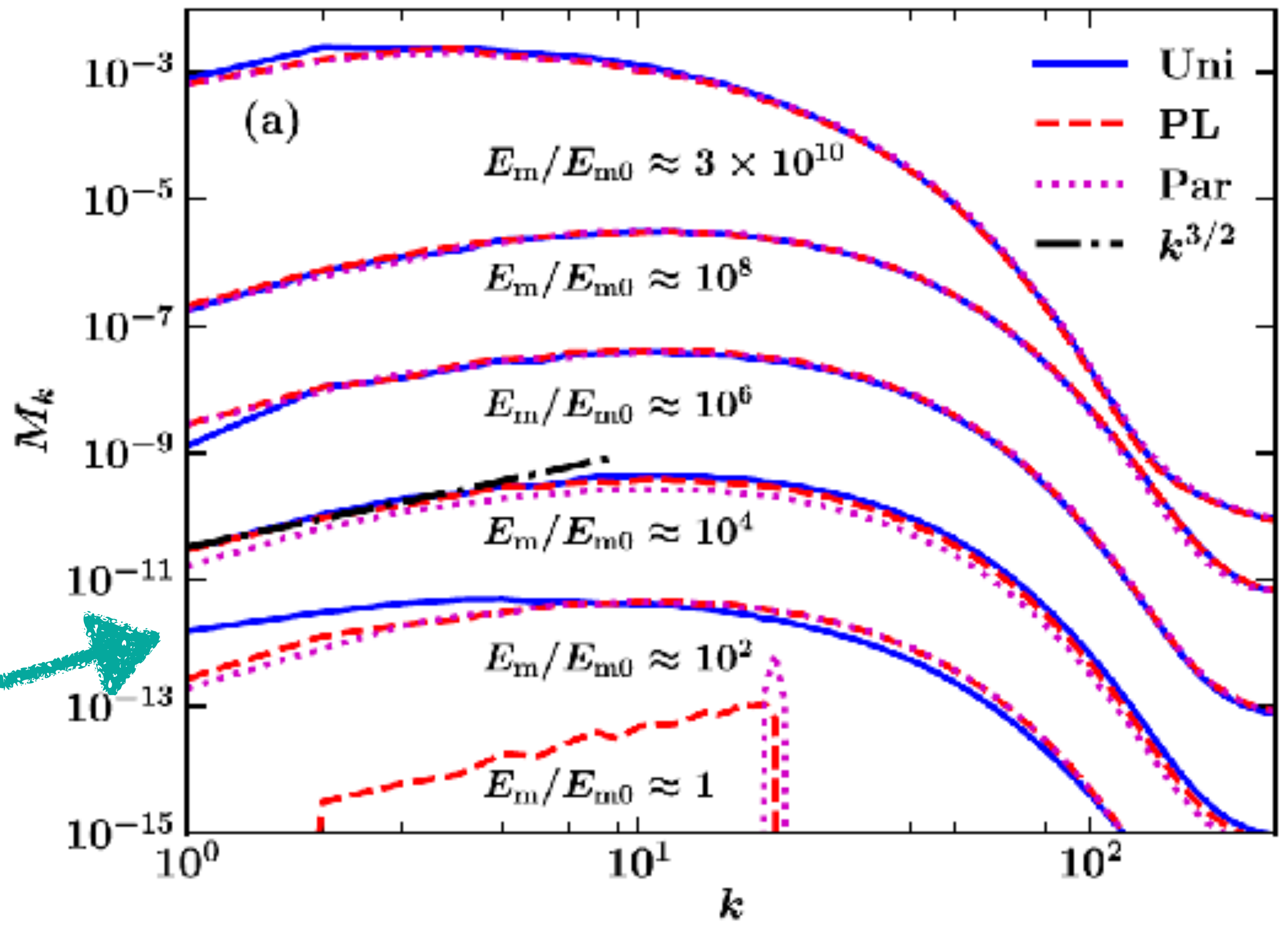



[Seta et al. 2020]




Similar growth rates!

Similar Saturation levels!




The field spreads quickly in k-space!

Additional tangling of the mean field (Transient phase)

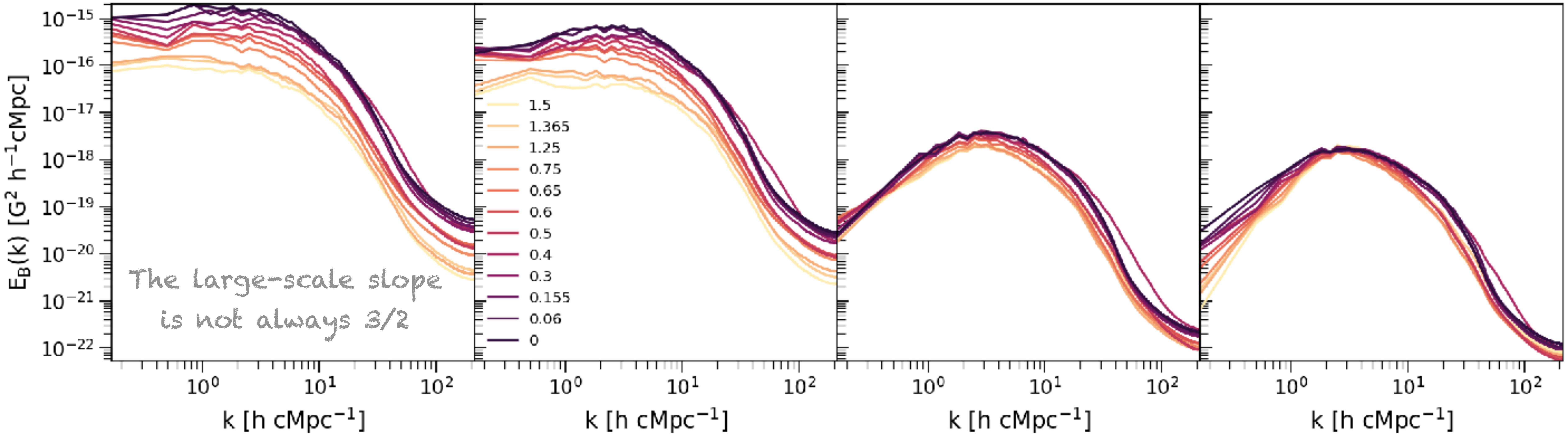
# Primordial non-uniform seeds

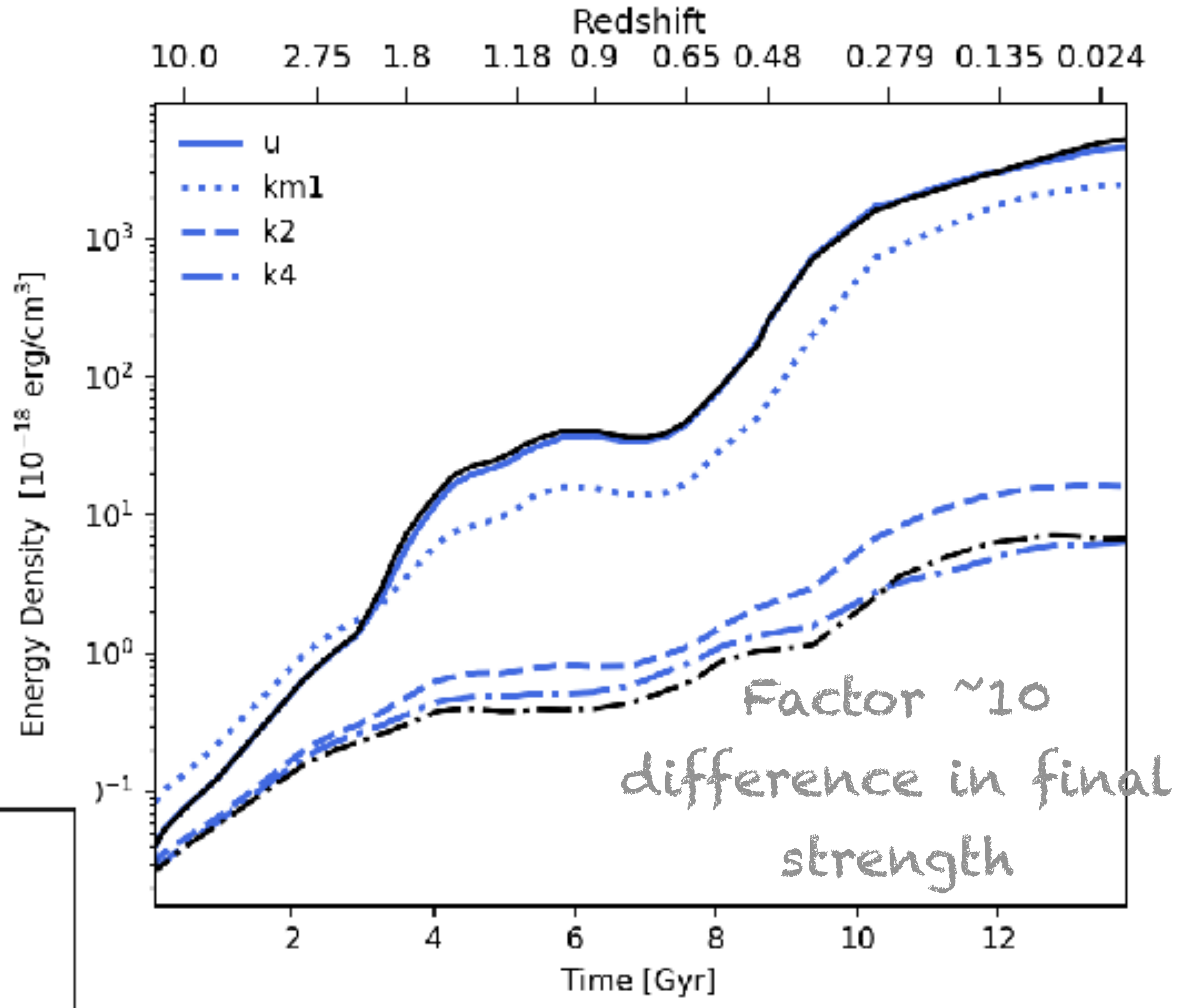
Initially large-scale correlated fields

Initially small-scale correlated fields

$\propto k^{-5/3}$ $\propto k^{2}$ $\propto k^{4}$

Uniform | Scale-invariant | Saffman | Batchelor



# Primordial non-uniform seeds

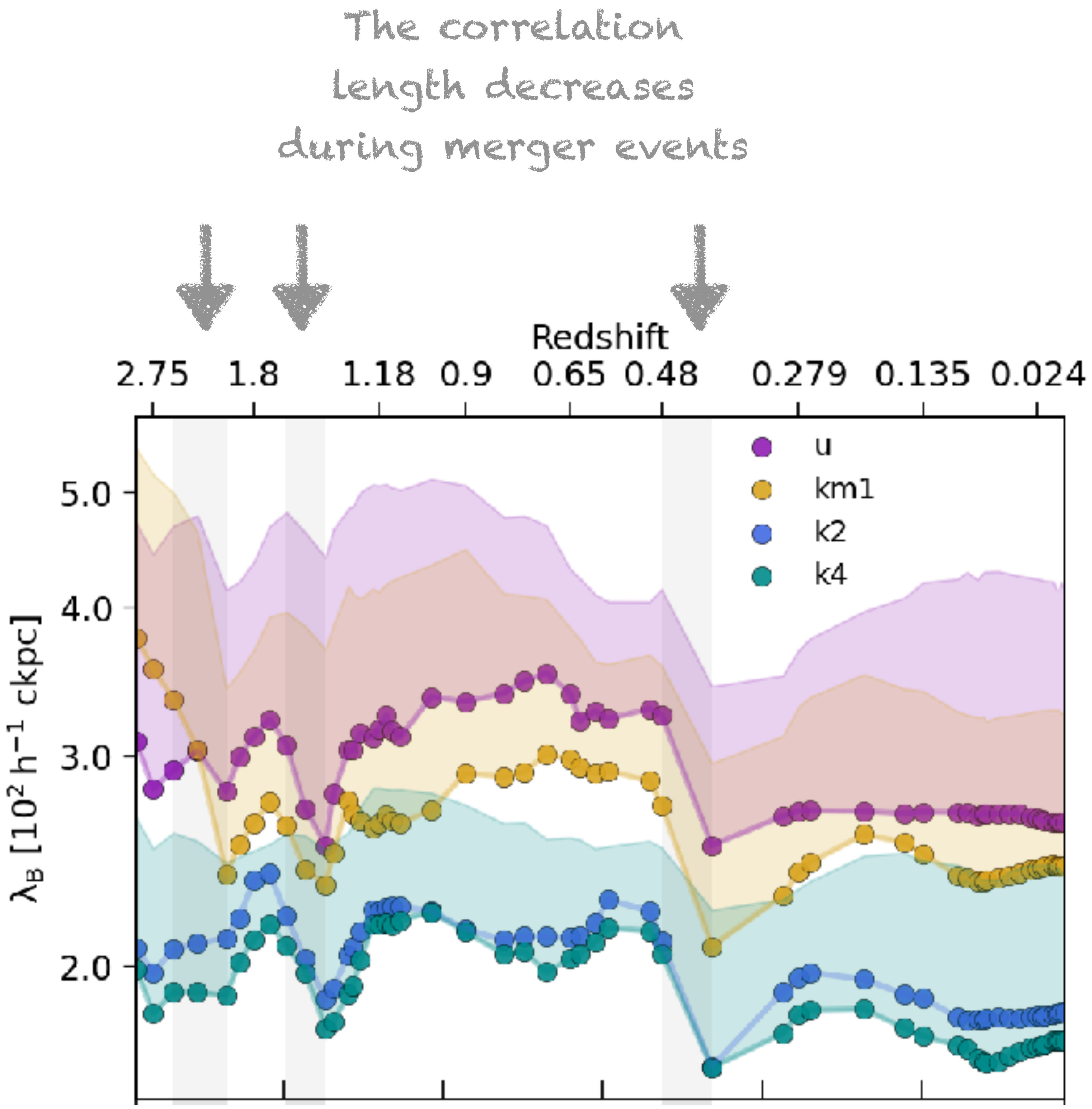
- In a relaxed cluster with:
  - $R_{vir} = 1.5\,h^{-1}\mathrm{Mpc}$
  - $\mathrm{M}(r \leq R_{vir}) = 2.34 \cdot 10^{14}\,\mathrm{M}_{\odot}$

**Inflationary**

- Tangling of the large-scale field (larger magnetic amplification)
- Reaching ~$\mu$G values and ~300 kpc correlation length

**Phase-transitional**

- Reaching ~0.1 $\mu$G values at the center and ~200 kpc correlation length



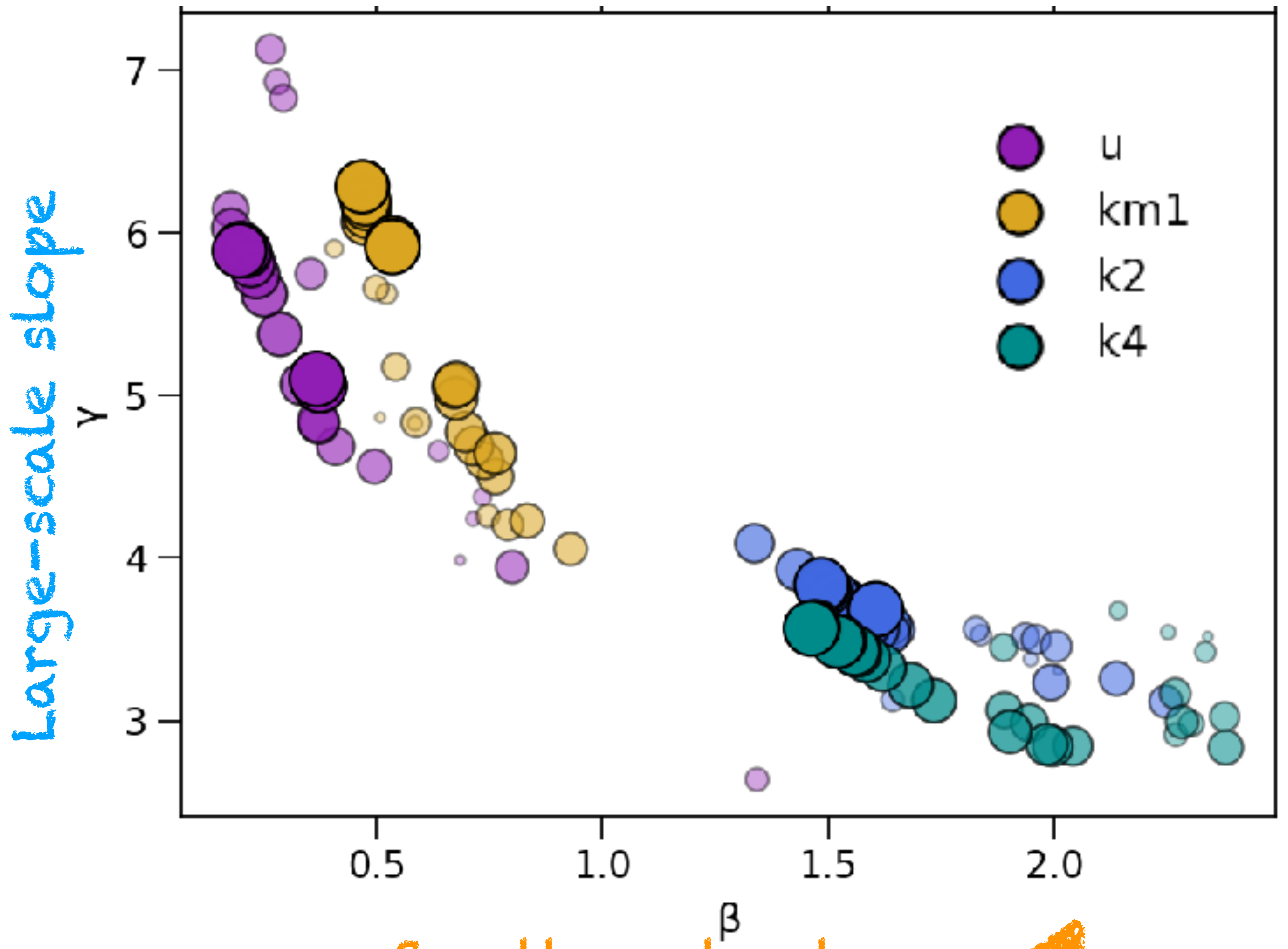

[Mtchedlidze, Domínguez-Fernández accepted]

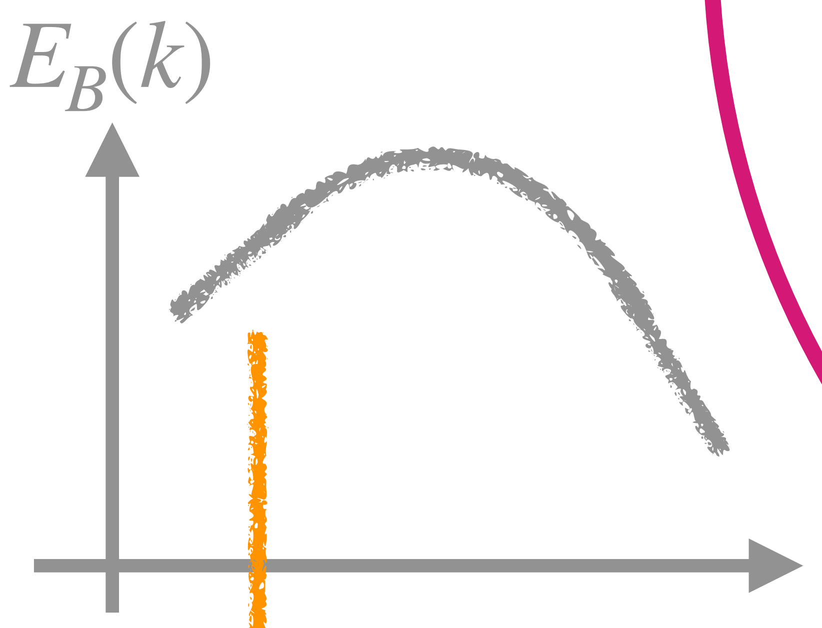
# Fair comparison to small-scale dynamo theory?

MAGNETIC AMPLIFICATION DOES NOT ONLY DEPEND ON TURBULENCE IN GALAXY CLUSTERS

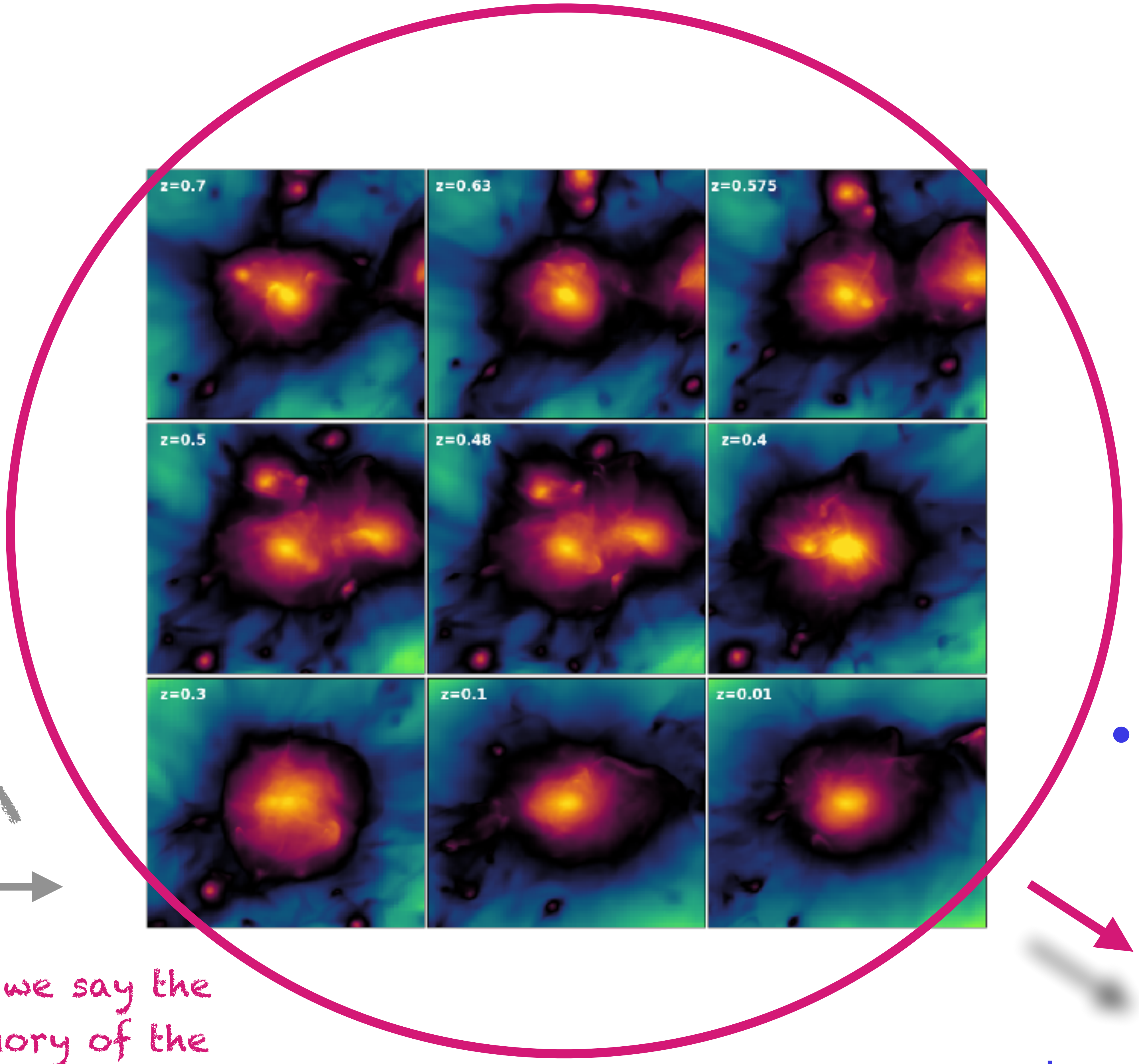
MERGER HISTORY INFLUENCES THE MAGNETIC AMPLIFICATION

HINT ON MAGNETIC SPECTRAL DIFFERENCES




Can we say the memory of the seed is entirely lost?




Not one-to-one relation

VELOCITY FIELD

- Not $\delta$-correlated in time

MERGERS/ACCRETION EVENTS

- Large-scale component present

# Summary

**Primordial MFs can explain the observed magnetization in galaxy clusters (simulations)**

- Mergers affect the small-scale dynamo amplification.
- Cosmological MHD simulations do not exhibit a small-scale dynamo that can be compared one-to-one to the Kazantsev theory.
- Is the seed field memory really lost?

1. Inflationary
   I. $\sim \mu$G VALUES, LARGER $\lambda_B$, MORE MAGNETIC POWER AT $\gtrsim 0.5\, h^{-1}\mathrm{cMpc}$ → Favored to explain some observations and mega haloes?
2. Phase-transitional
   I. $\sim 0.1\mu$G VALUES, SMALLER $\lambda_B$ *

Future studies (also with helicity) needed!