New clues on the (primordial) origin of cosmic magnetism from the low redshift Universe

Franco Vazza
(Bologna Uni.)

ME & MY NETWORK

F.Vazza (UniBO)

Cosmological Simulations:

S. Mtchedlidze (UniBO), C. Gheller (IRA)

Particle acceleration:

G. Brunetti (IRA), L. Beduzzi (IRA), M. Brüggen (UniHH)

Radio observations:

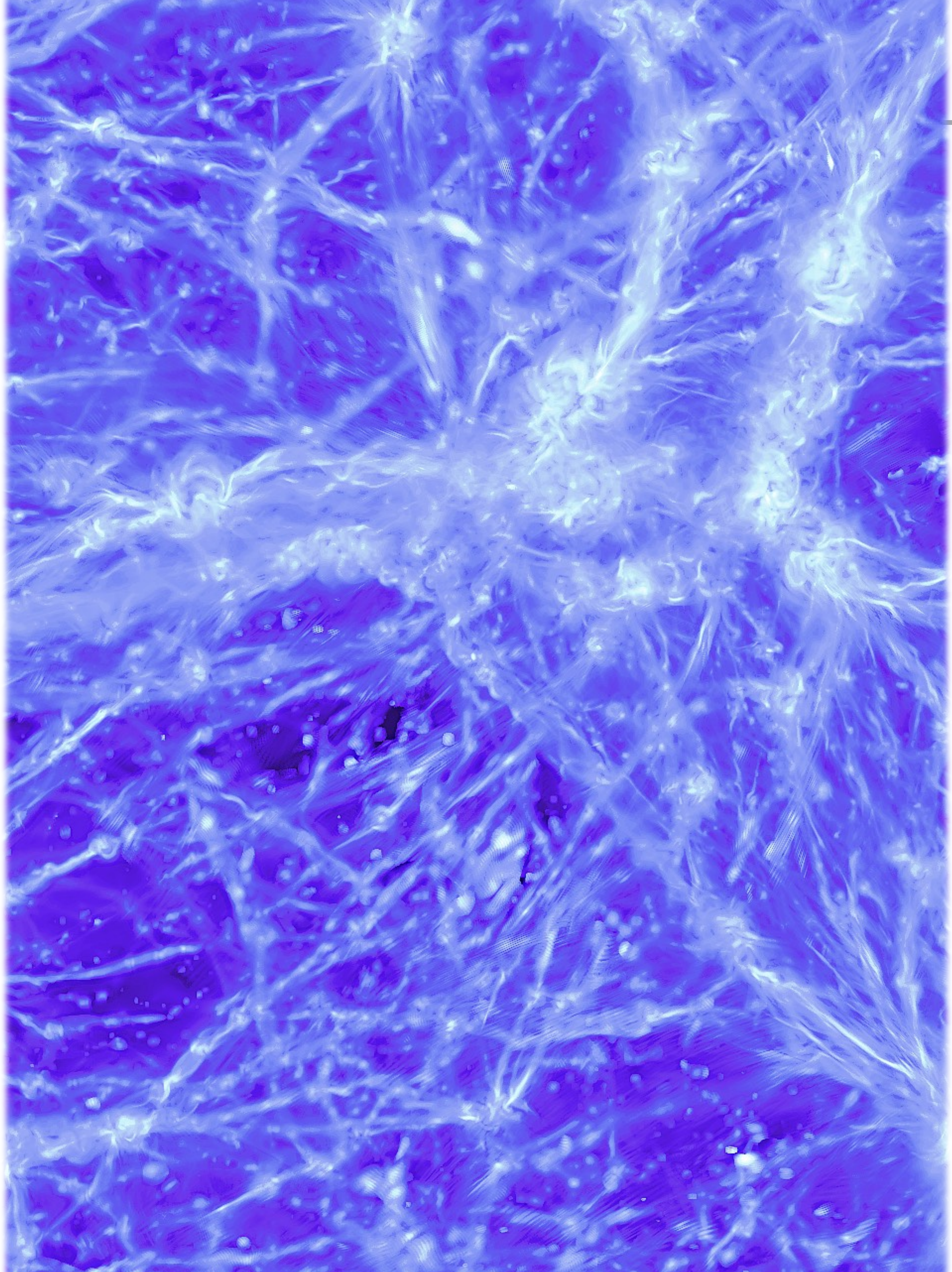
E. Carretti (IRA), S. O'Sullivan (UniMA), T. Vernstrom (CSIRO), V. Cuciti (UniBO), K. Rajpurohit (CFA)

Network Cosmology:

M.Tsizh (UniBO/UniLVIV), A. Rudakovskyi (UniBO/UniKYEV)

"Big Picture":

A. Brandenburg (Nordita), C. Caprini (CERN), A. Neronov (APC)



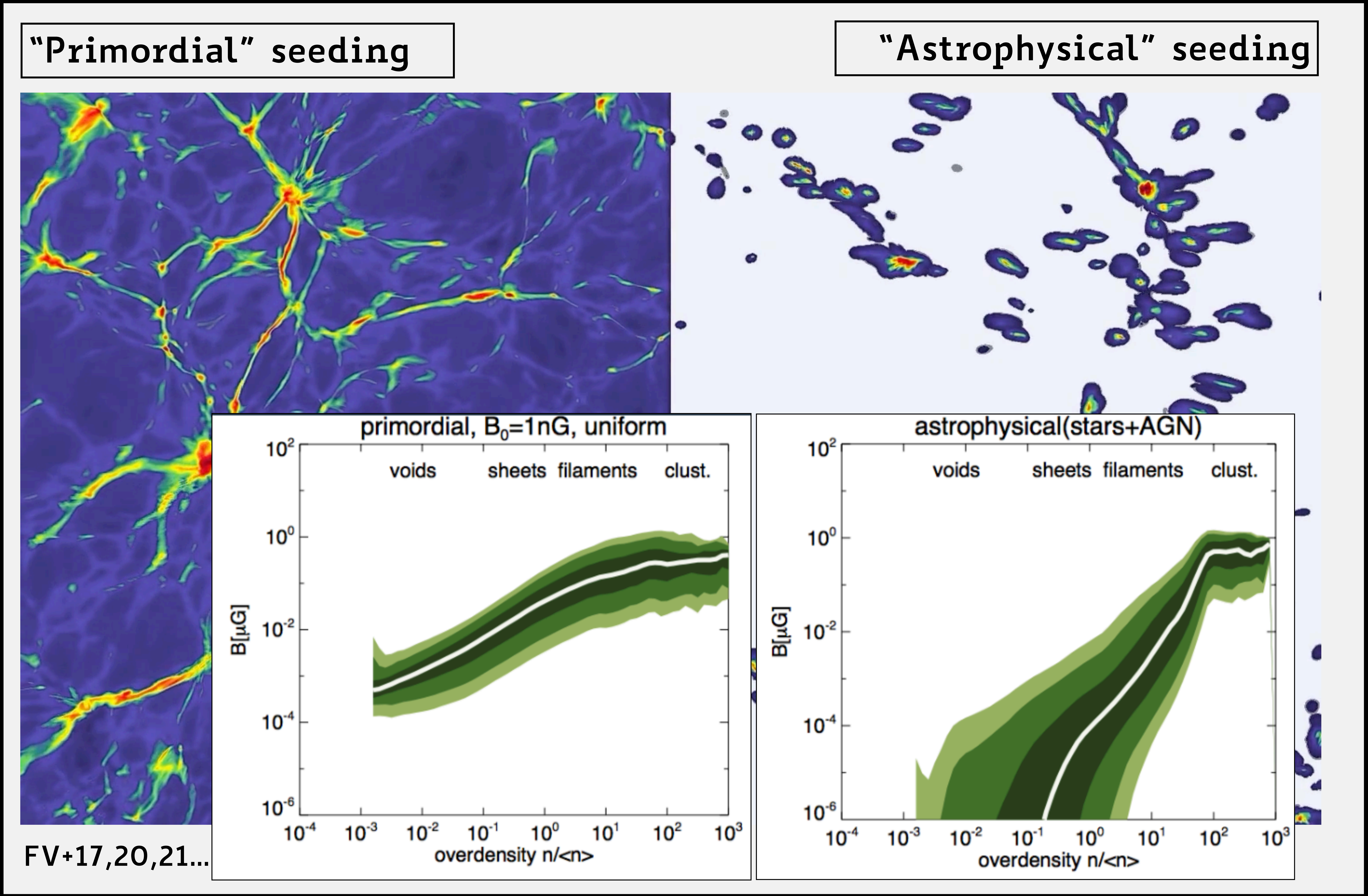
SOME TAKE HOME MESSAGES:

- Detection of extended IGMFs well beyond clusters

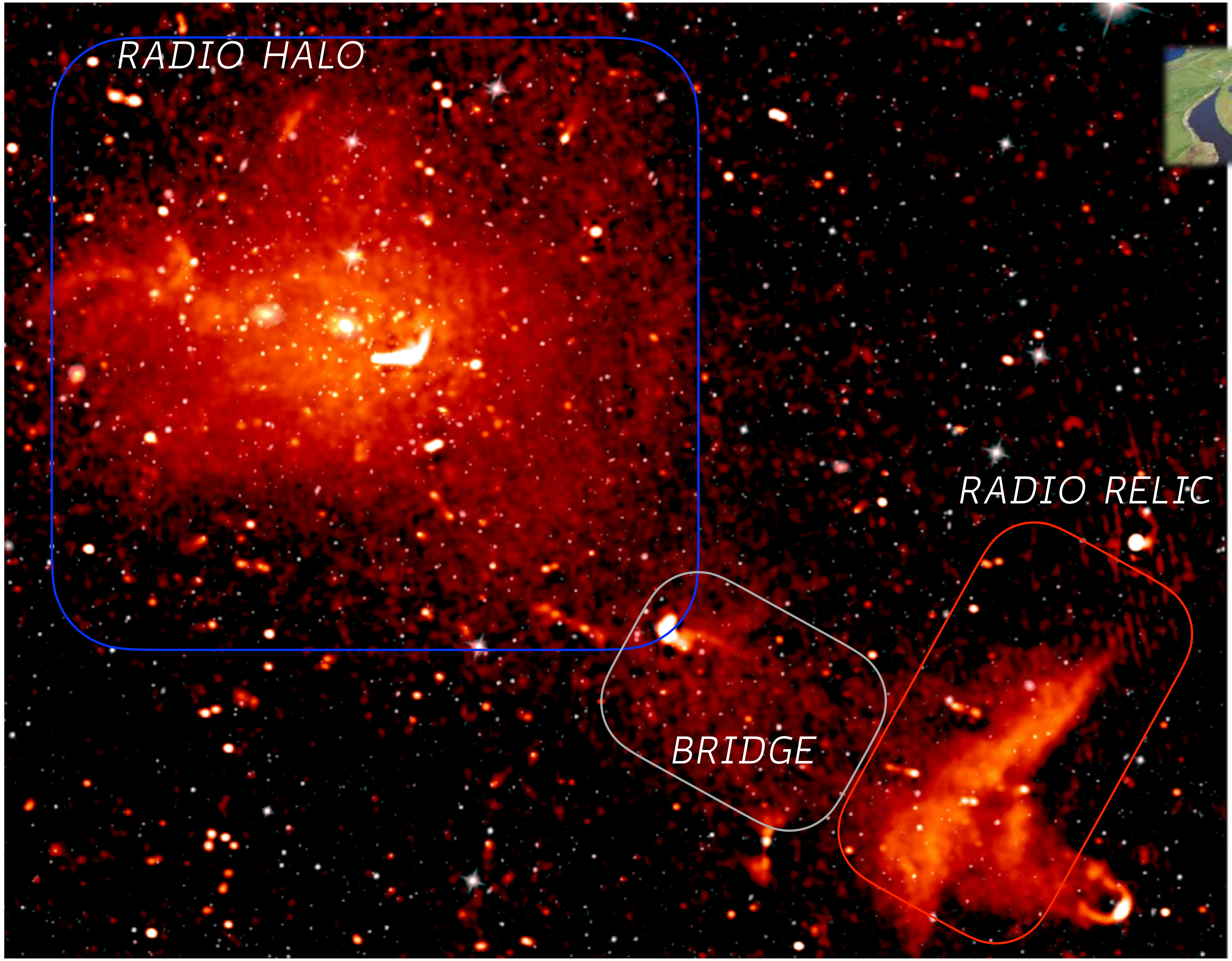
- Modelling these observations with simulations discards purely astrophysical origin scenarios for IGMFs models and prefers primordial large-scale models

- Constraints for IGMFs are below what is presently obtained with CMB. Powerful connections with SGWB and the very early Universe ($\leq \mu s$) ?

WHAT'S THE ORIGIN OF COSMIC MAGNETISM?



WHY NOT USING CLUSTERS OF GALAXIES?

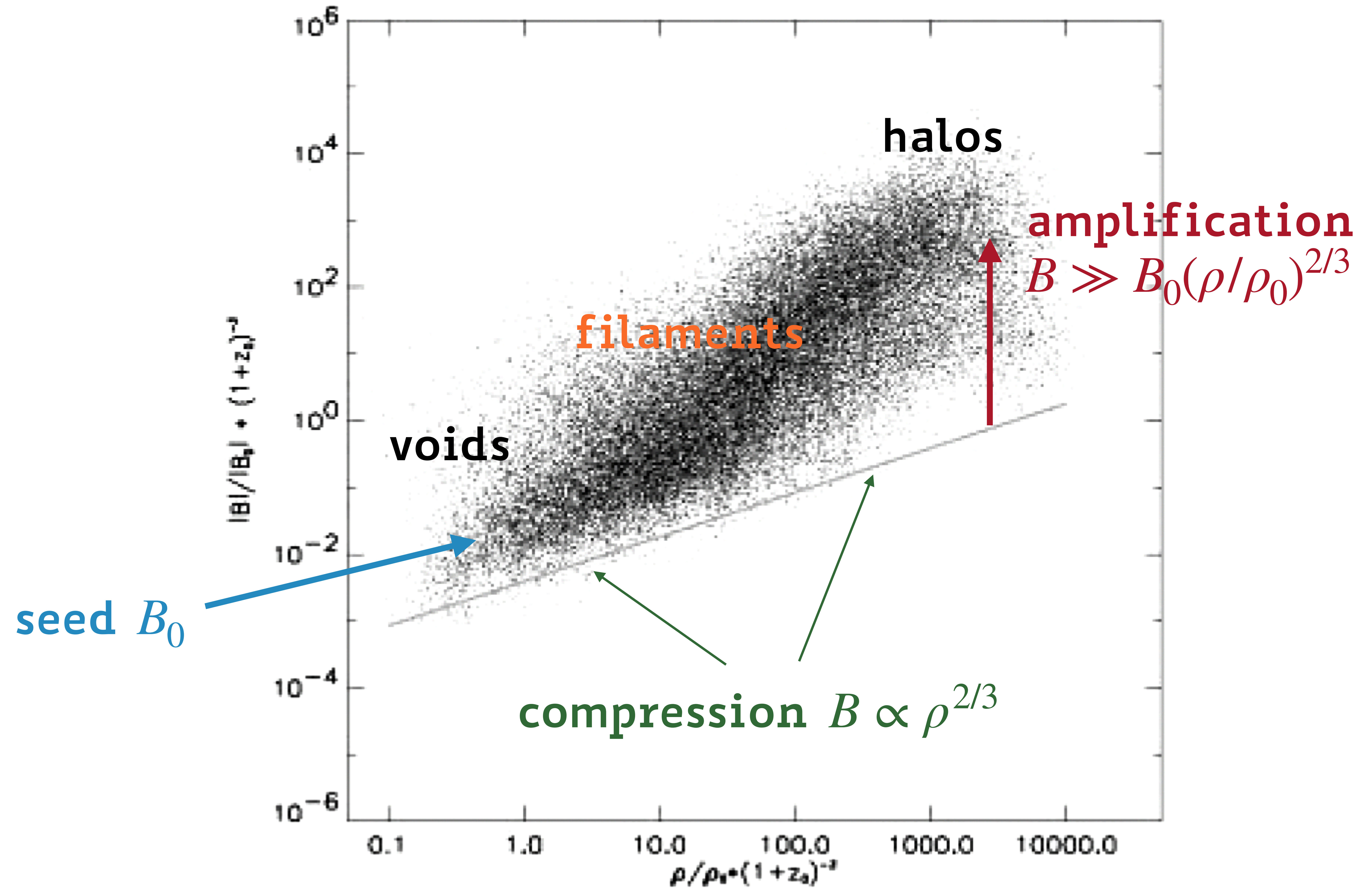


(Bonafede+22)

$B \sim 1 - 5 \mu G$ at least up to a radius of ~ 2 Mpc

Magnetic energy $\sim 1 - 2\,\%$ Gas energy

WHY NOT USING CLUSTERS OF GALAXIES?

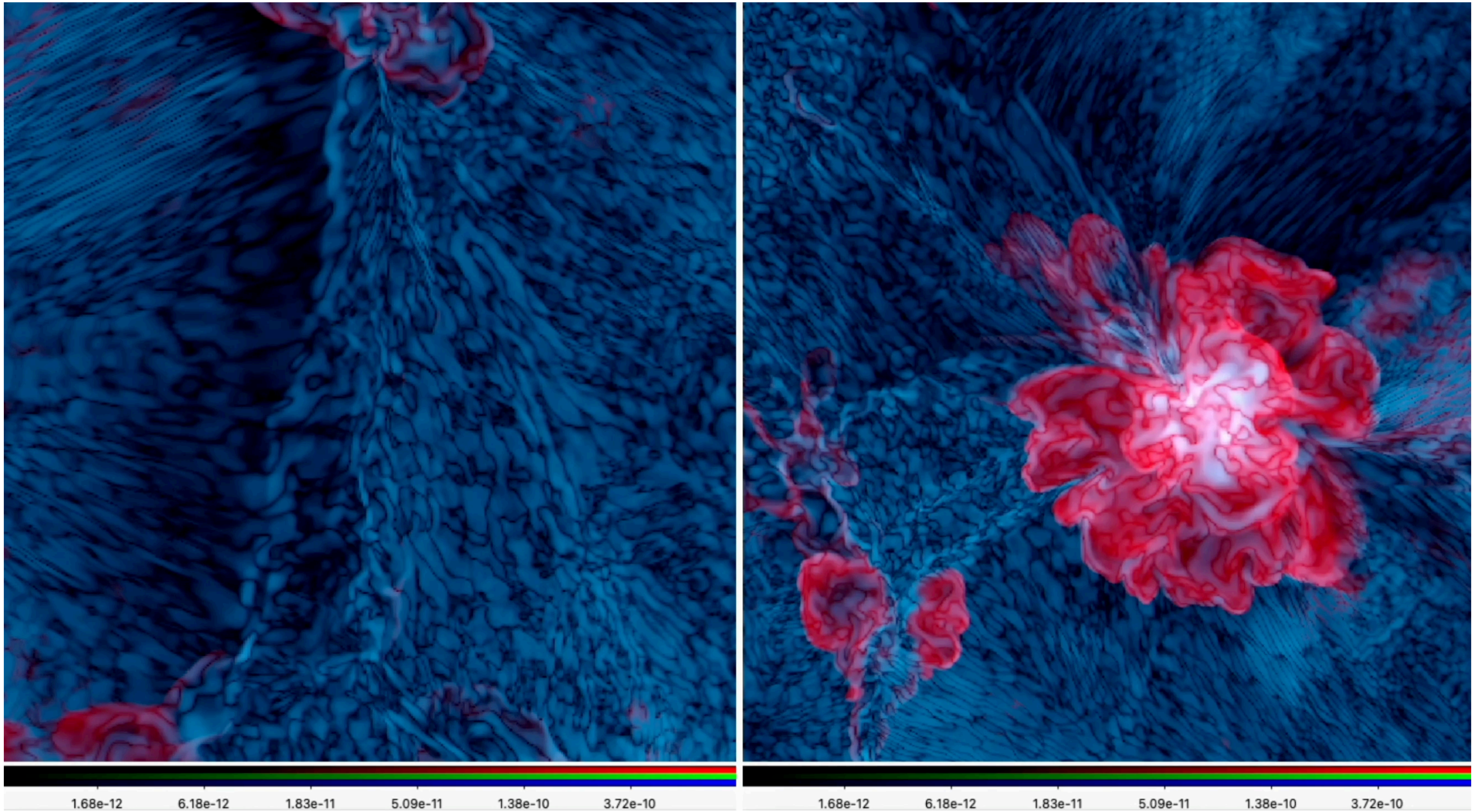


K. DOLAG (PHD THESIS 2000)

WHY NOT USING CLUSTERS OF GALAXIES?

Filaments: <u>no or little dynamo</u>, memory of seed B_0 is **preserved**

Clusters: <u>dynamo amplification</u>, memory of seed B_0 is **lost**



red=gas temperature, blue/yellow= B-field amplitude

HOW TO DETECT EXTRAGALACTIC B-FIELDS

SYNCHROTRON EMISSION $\propto \xi_e B^2$

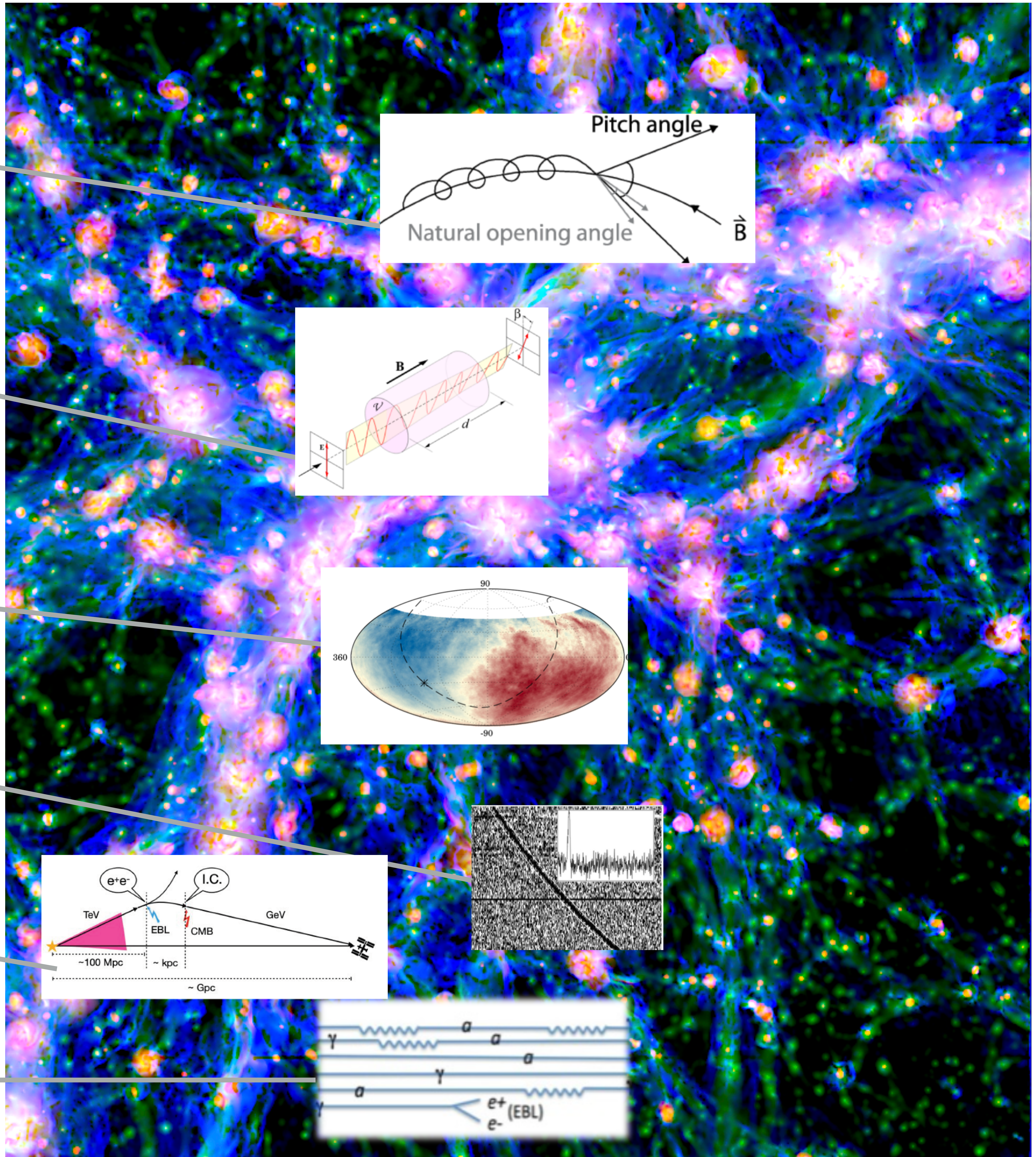
FARADAY ROTATION $\propto nB(k)_{||}$

ULTRA HIGH-ENERGY COSMIC RAYS $\propto Z B_\perp \lambda^{1/2}$

FAST RADIO BURSTS $\propto B(k)_{||}$

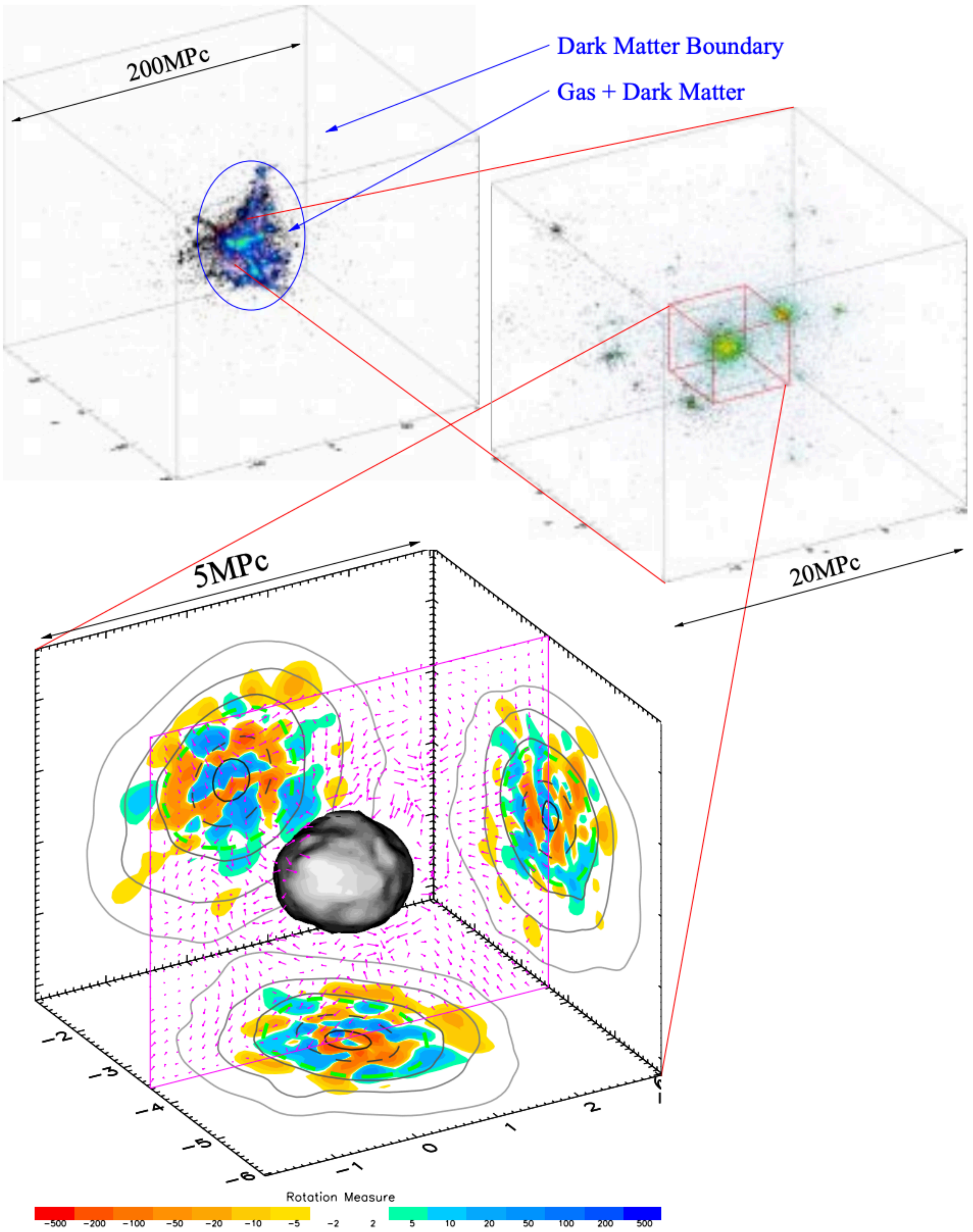
INVERSE COMPTON CASCADE FROM BLAZARS $\propto |B|$

ALPs CONVERSION? $\propto g_{\alpha\beta} B_\perp$



COSMOLOGICAL MHD SIMULATIONS

K. DOLAG (CA. 1999)



F.MINIATI (2001)

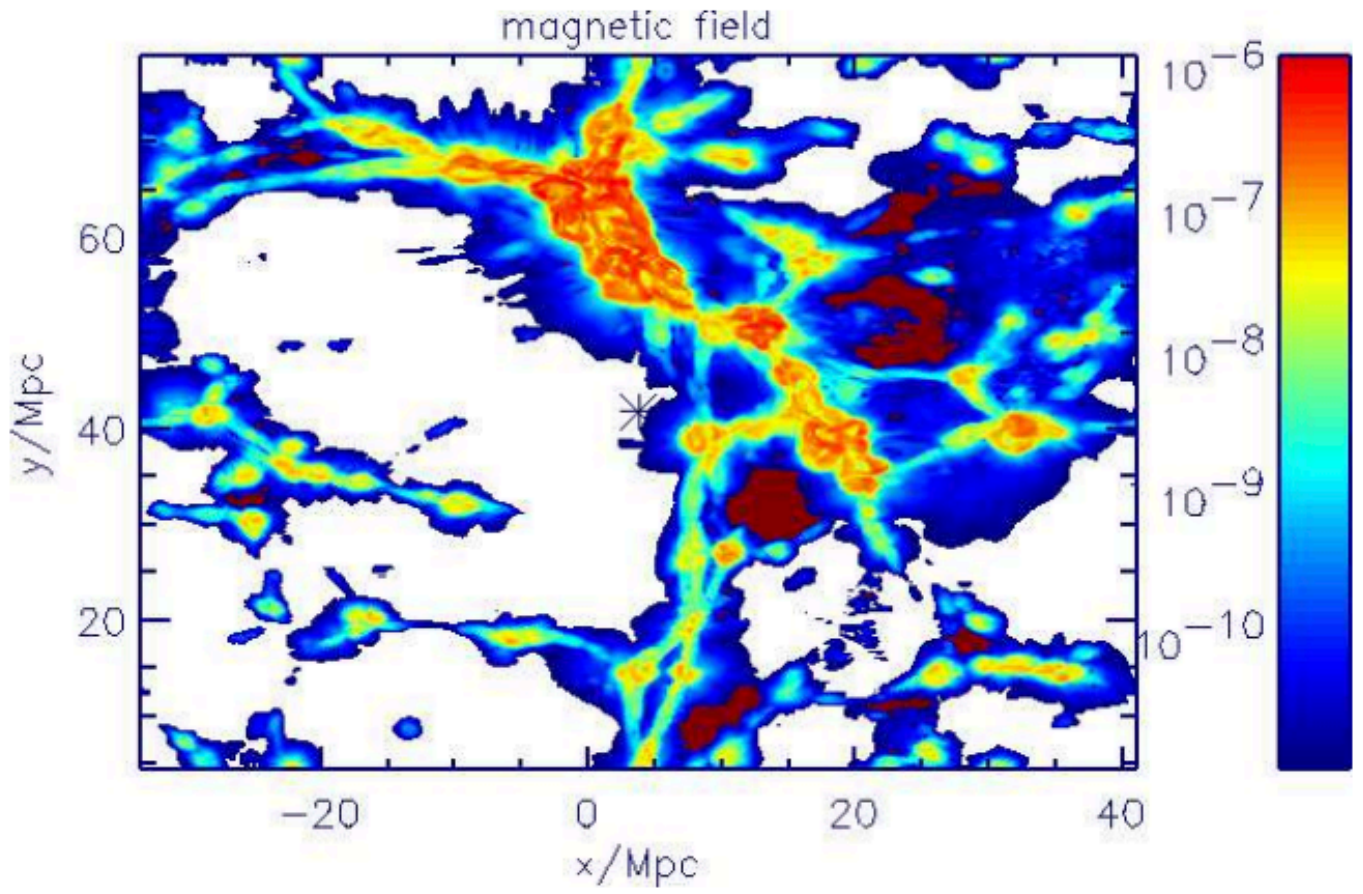
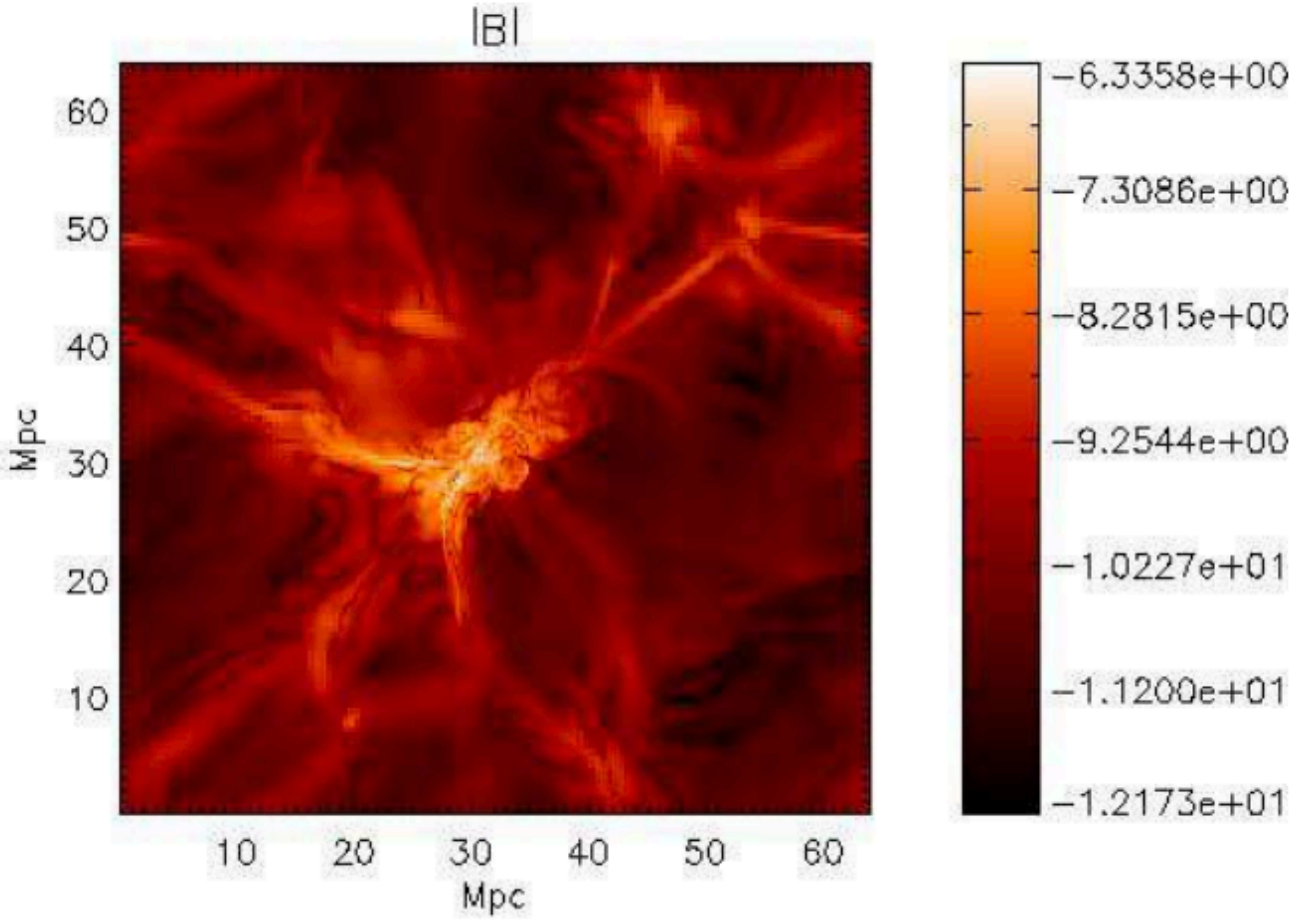


Fig. 7. A two-dimensional cut through a cosmological box simu-



M. BRUGGEN (2005)

COSMOLOGICAL MHD SIMULATIONS enzo

(Ideal) MHD equations on a comoving grid.

$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\nabla\cdot(\rho\mathbf{v}) = 0$$

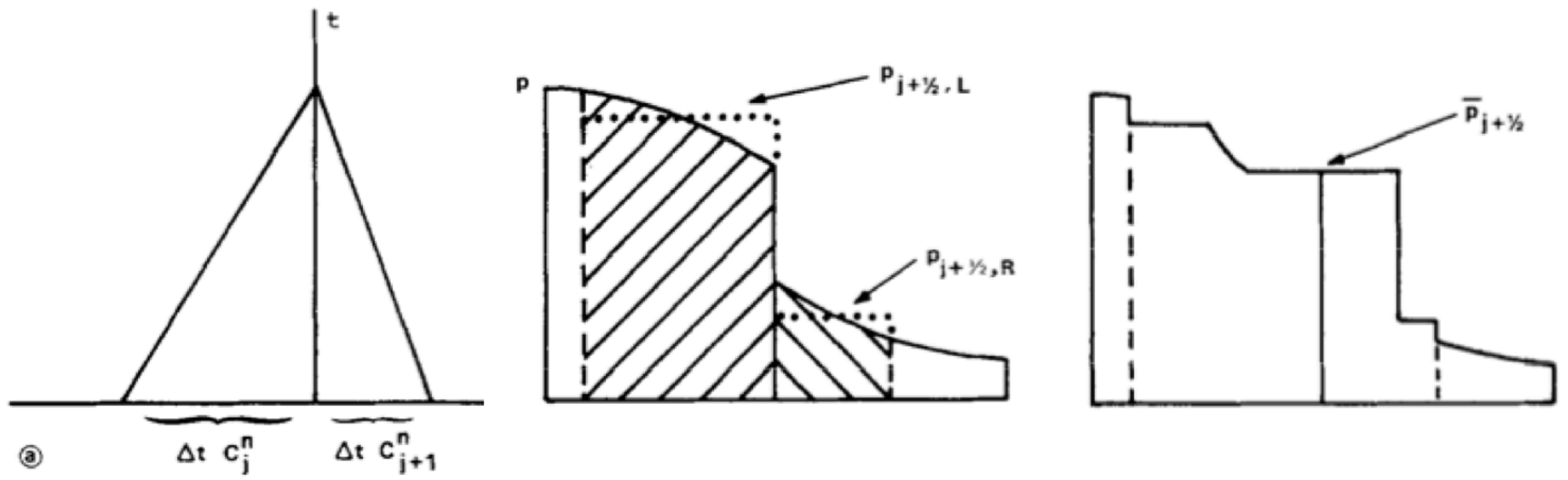
$$\frac{\partial \rho\mathbf{v}}{\partial t} + \frac{1}{a}\nabla\cdot(\rho\mathbf{v}\mathbf{v} + \bar{p} - \mathbf{B}\mathbf{B}) = -\frac{\dot{a}}{a}\rho\mathbf{v} - \frac{1}{a}\rho\nabla\Phi$$

$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla\cdot[\mathbf{v}(\bar{p}+E) - \mathbf{B}(\mathbf{B}\cdot\mathbf{v})] = -\frac{\dot{a}}{a}(\rho v^2 + \frac{2}{\gamma-1}p + \frac{B^2}{2}) - \frac{\rho}{a}\mathbf{v}\cdot\nabla\Phi$$

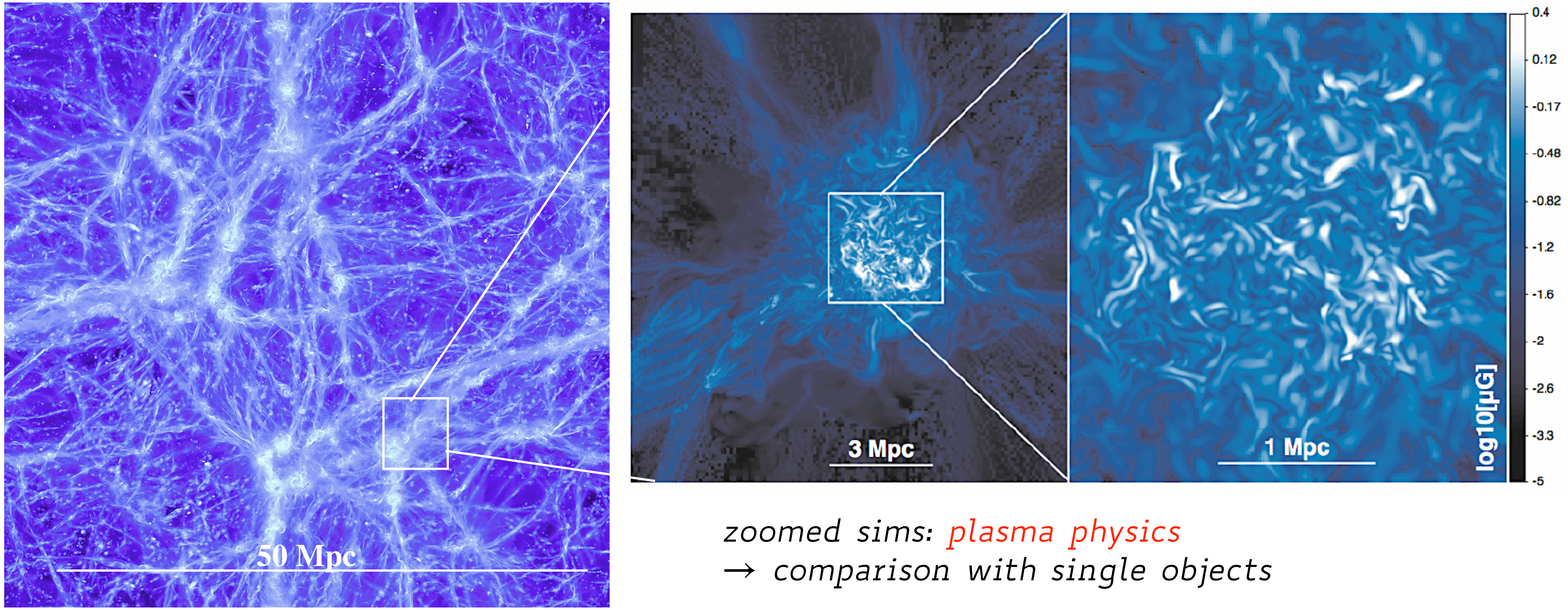
$$\frac{\partial \mathbf{B}}{\partial t} - \frac{1}{a}\nabla\times(\mathbf{v}\times\mathbf{B}) = -\frac{\dot{a}}{2a}\mathbf{B}$$

(+ source terms from star/AGN feedback)

Ideal for discontinuities (shocks), turbulence and hydro-MHD phenomena.



Large volumes: statistics and lightcones → comparison with radio surveys



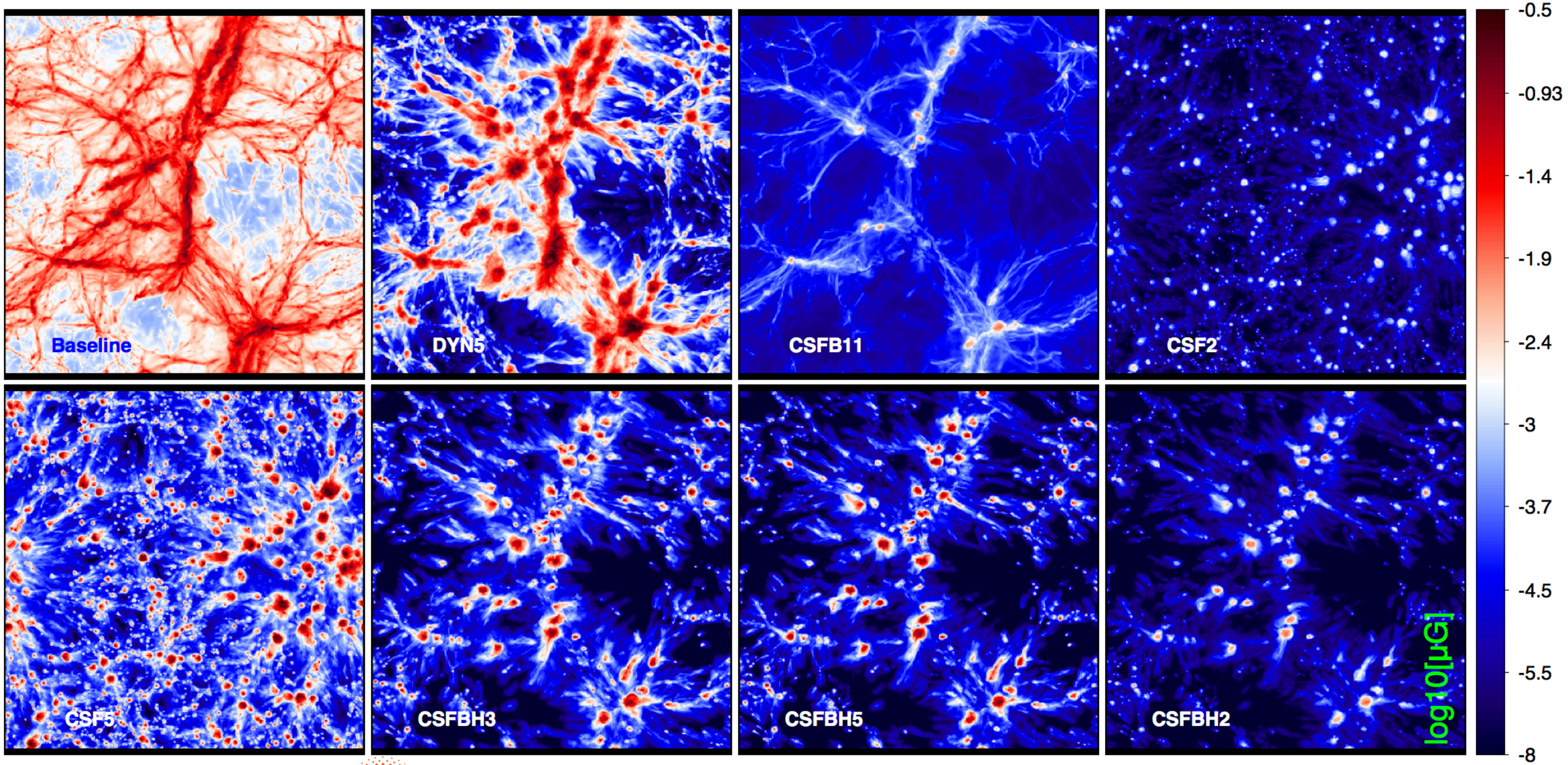
zoomed sims: plasma physics
→ comparison with single objects

COSMOLOGICAL MHD SIMULATIONS

enzo

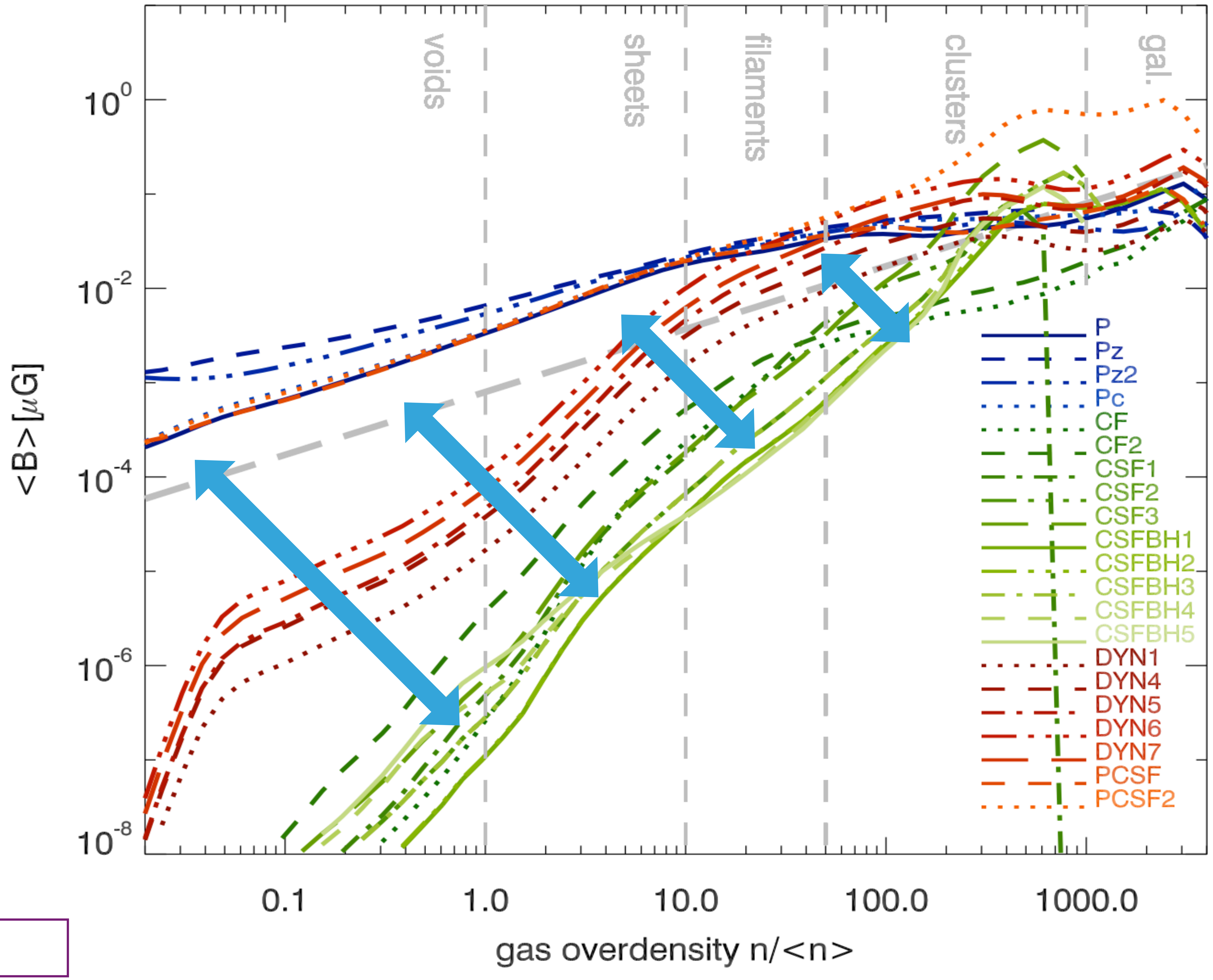
ERC STG MAGCOW (2017-23):

looking for detectable signatures of extragalactic $\vec{B}$-fields in the cosmic web



erc https://cosmosimfrazza.eu/MAGCOW

COSMOLOGICAL SIMULATIONS

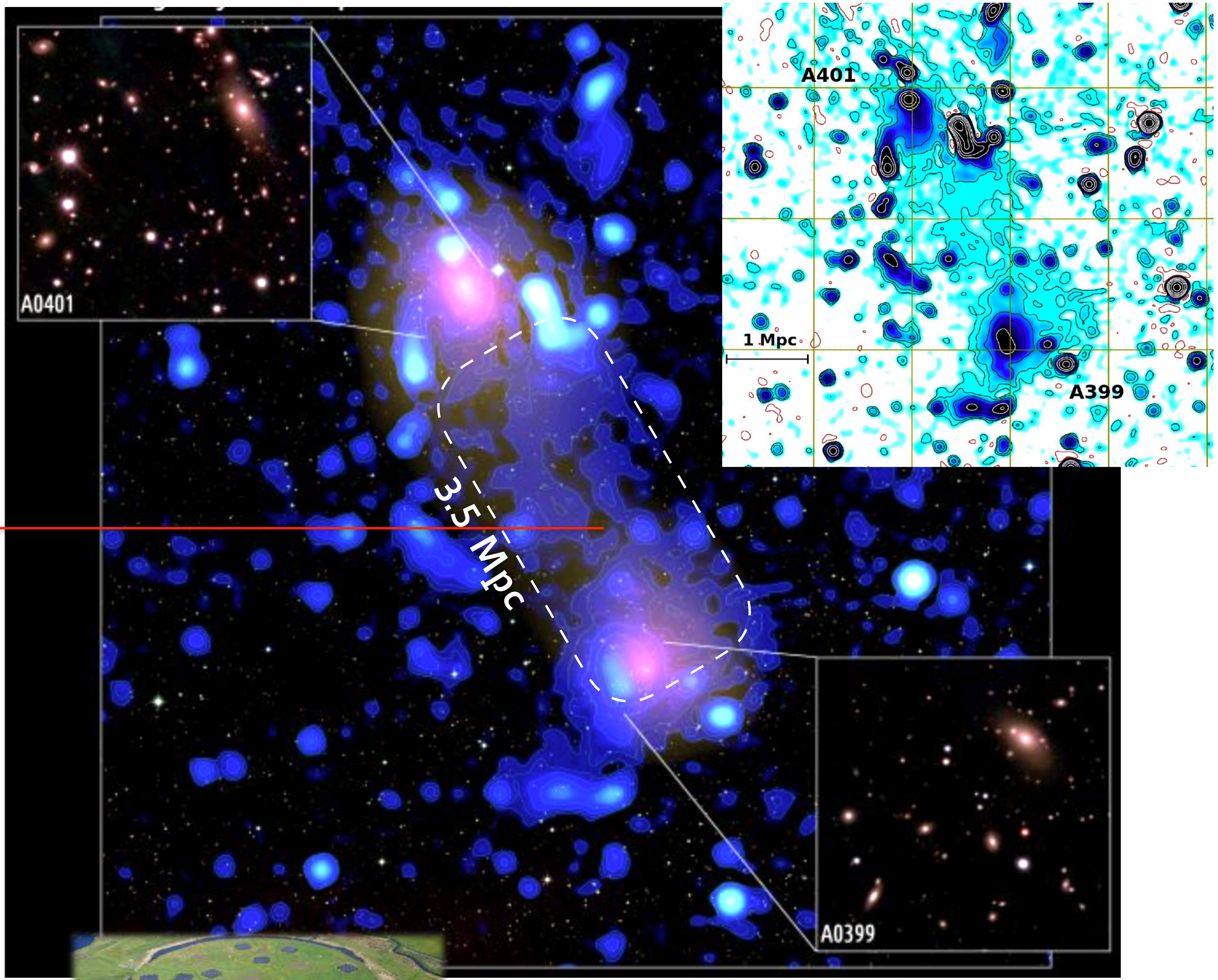


- >30 MHD simulations of various scenarios of magnetism in the cosmic web

FV + 2017, 21

INTRACLUSTER BRIDGES

- LOFAR discovery of a 3.5Mpc long bridges in between galaxies A399 and A401



- *relativistic electrons and magnetic fields ($B \sim 0.5\mu G$) on scales never probed so far.*
- *both components are present <u>before the cluster merger!</u>*

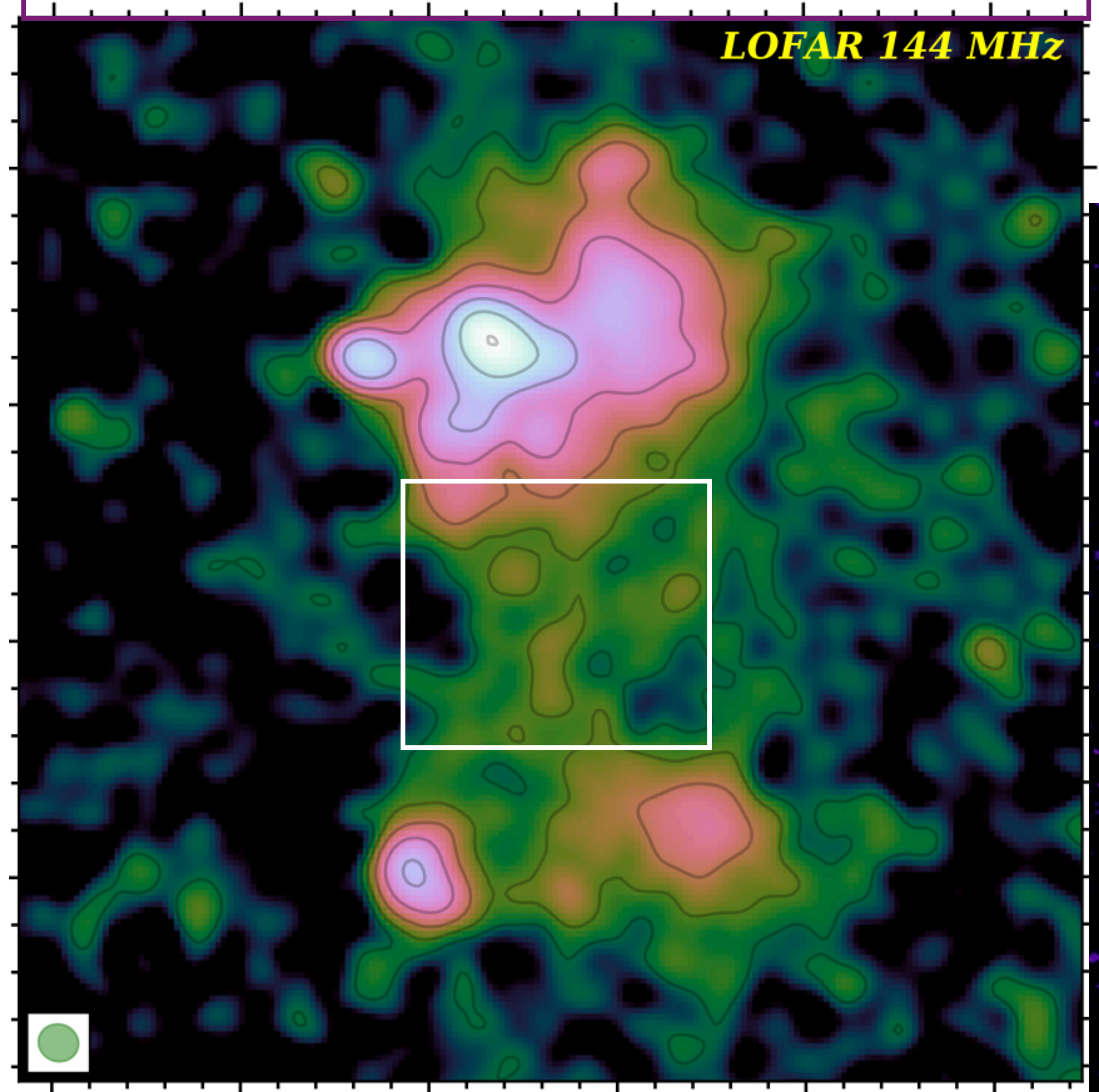
LOFAR

GOVONI ET AL. 2019 SCIENCE
BALBONI+23, PIGNATARO+24

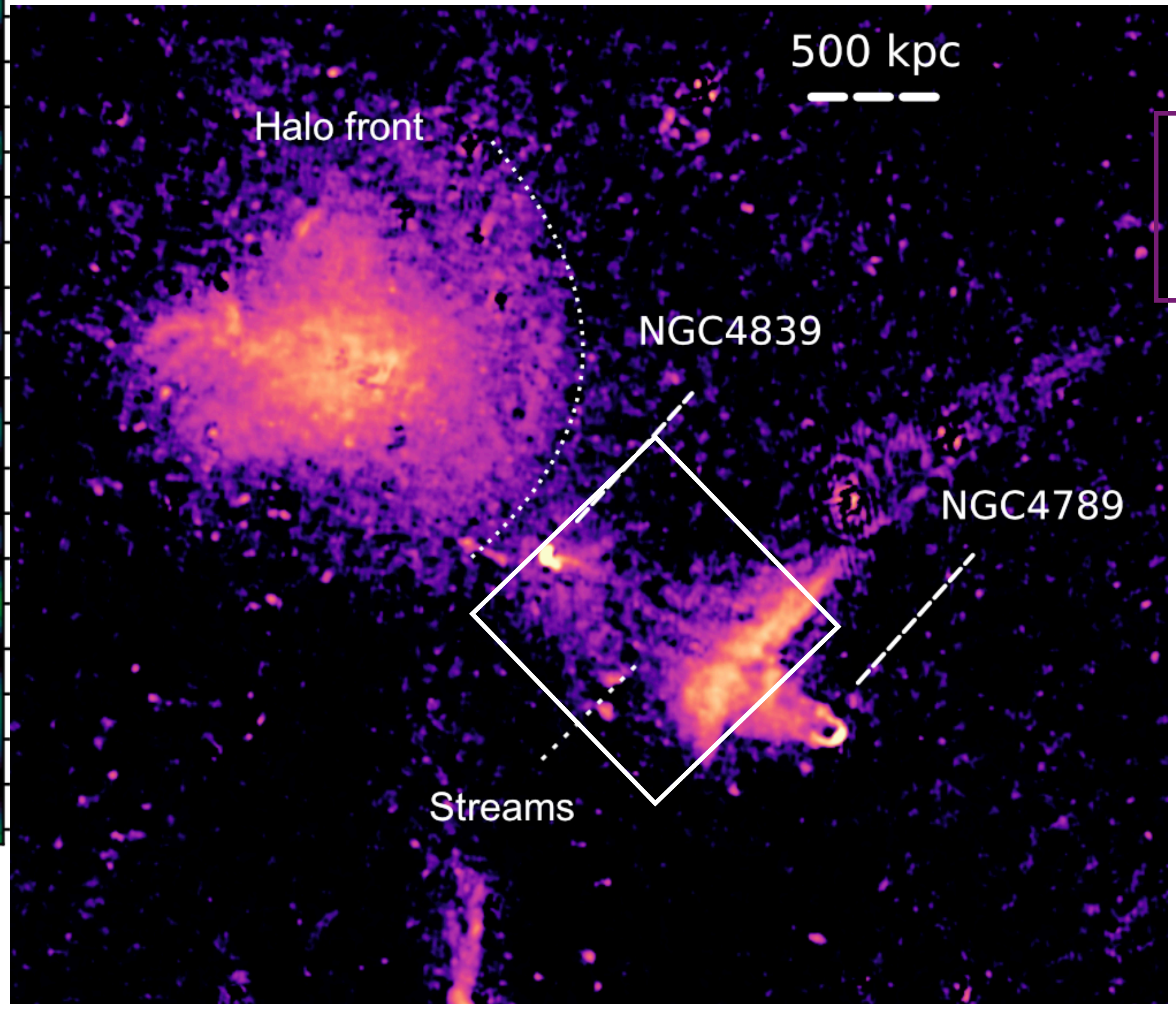
INTRACLUSTER BRIDGES

A few more known cases (sometime with uncertain identification)

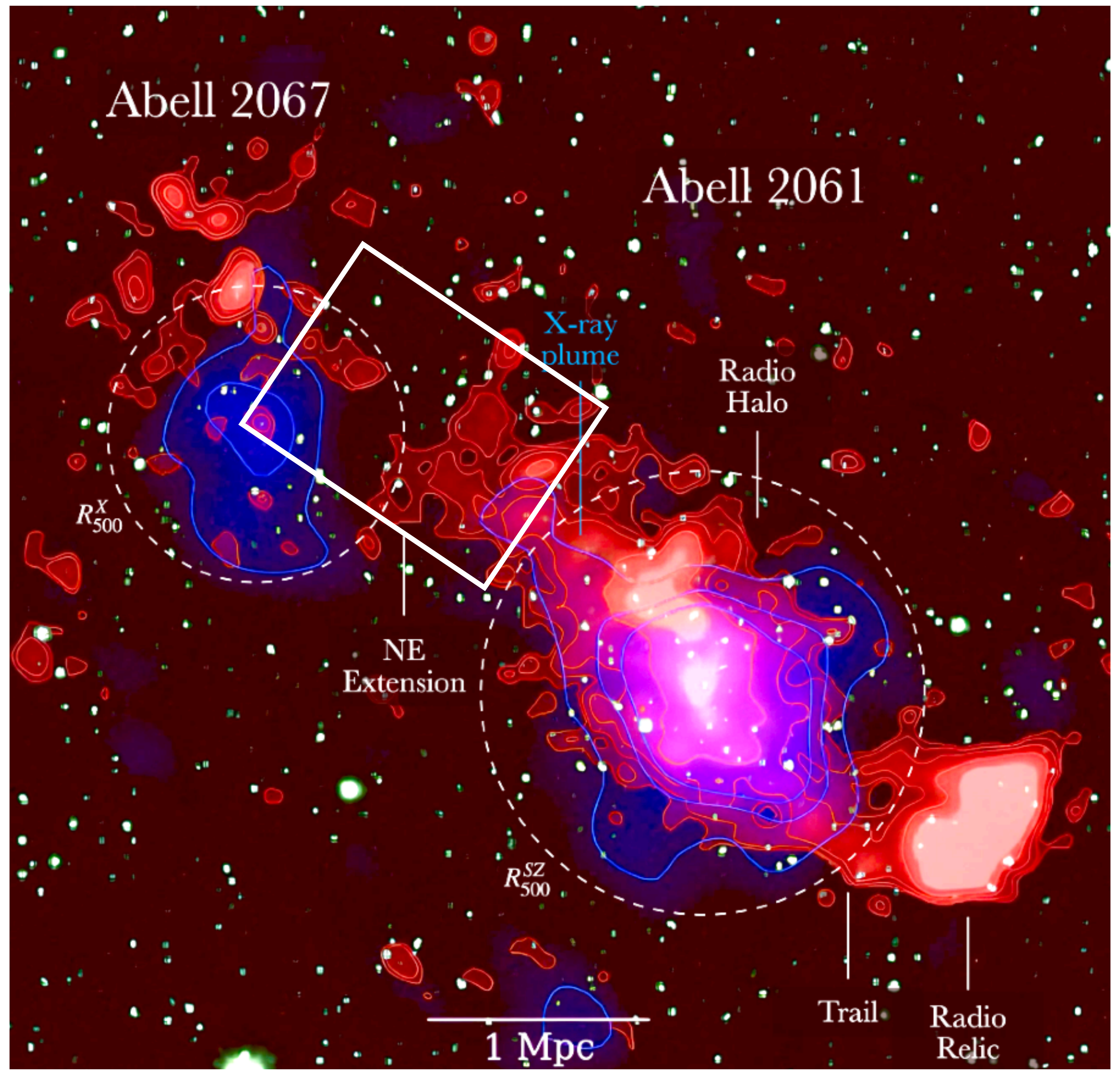
A1758 BOTTEON+20



COMA BONAFEDE+20



CORONA BOREALIS PIGNATARO+24

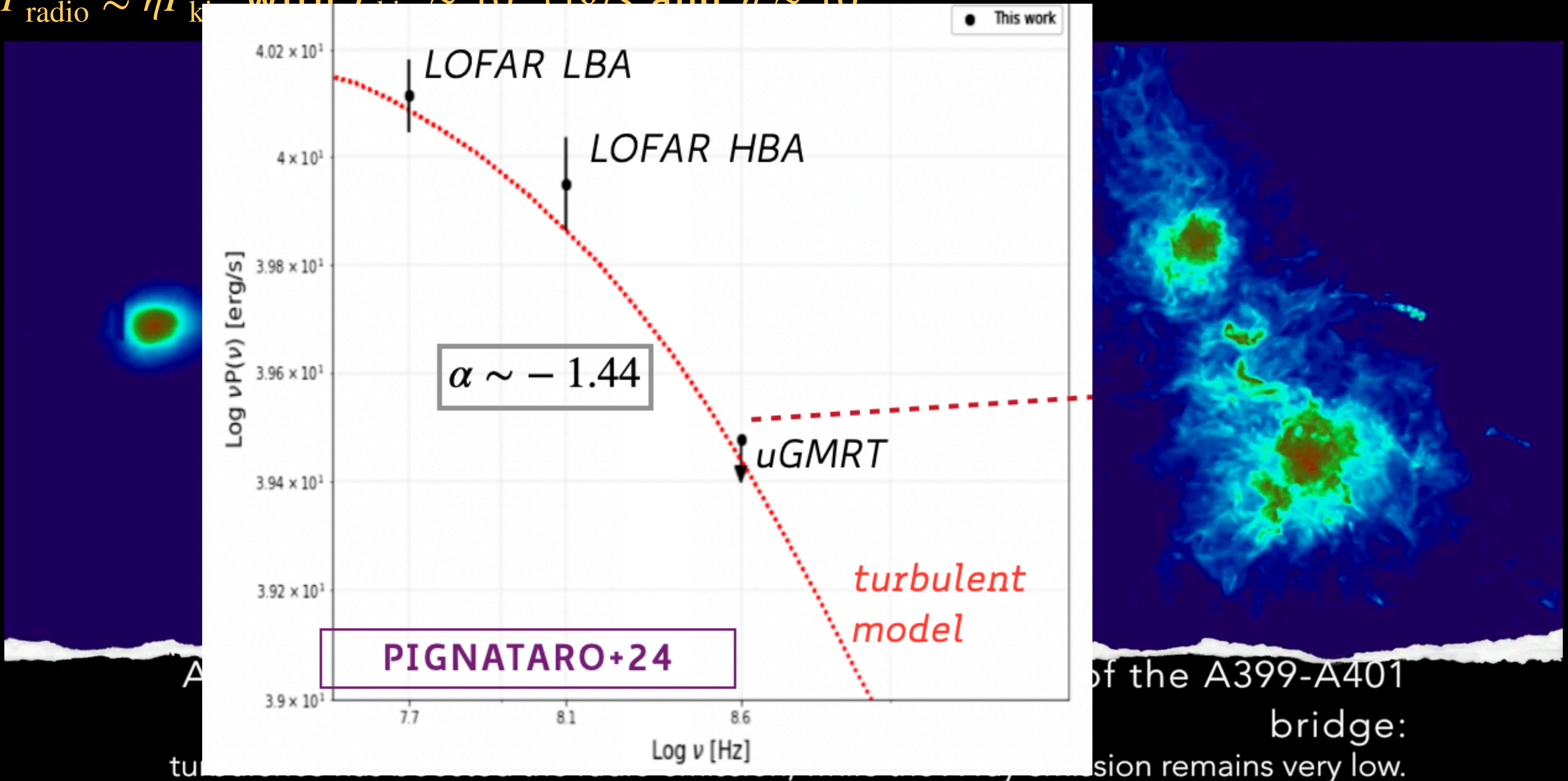


- **Origin?** *(Fermi mechanisms?)*
- **How common?** *(rare!)*
- **Are these cosmic filaments?** *(now: no. in the past: yes)*

LOFAR

INTRACLUSTER BRIDGES - SIMULATIONS

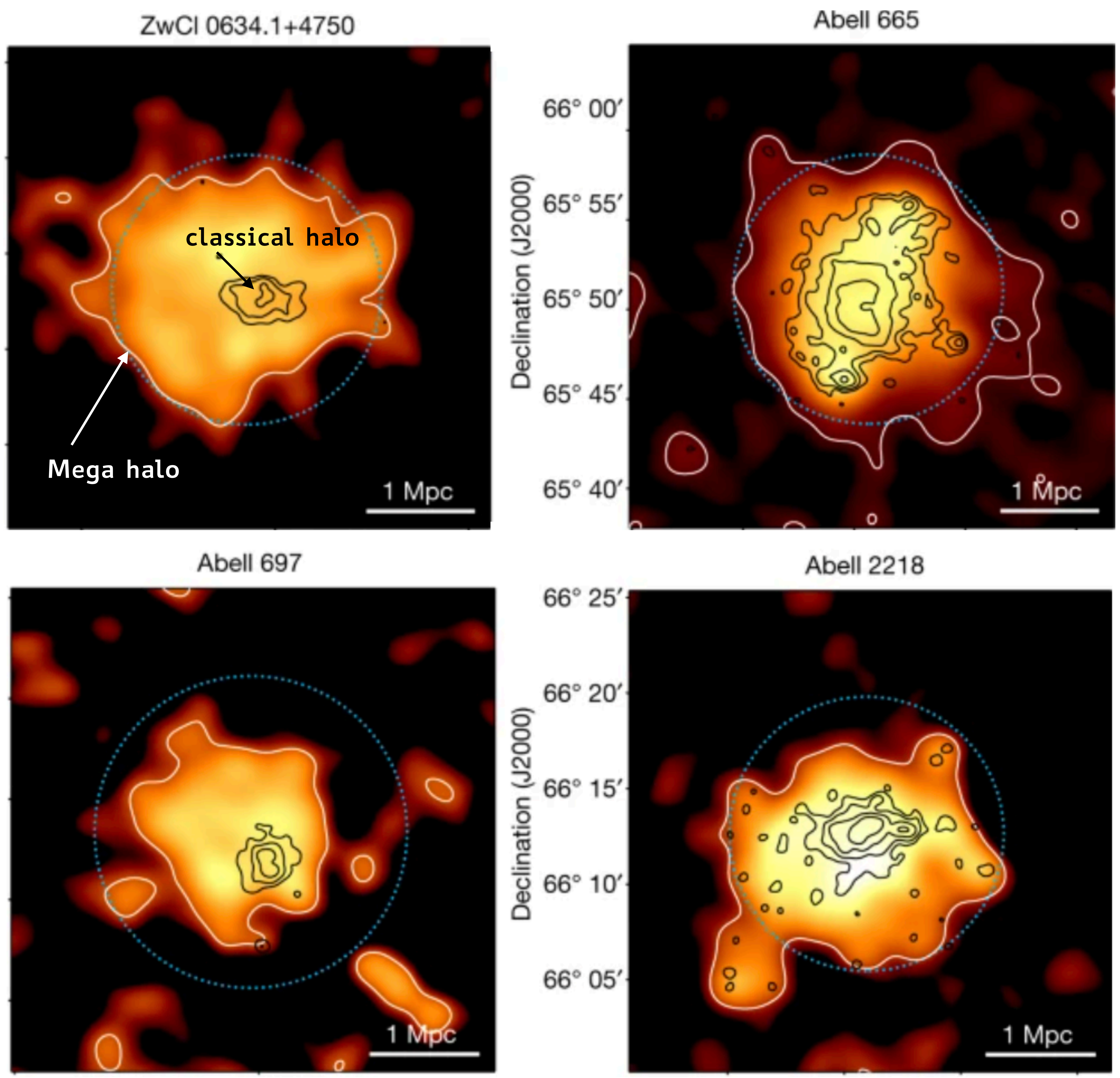
- *Best model:* **Adiabatic Stochastic Acceleration** *(Brunetti & Lazarian 2016)*
- $\sim 1\mathrm{Gyr}$ *"transient" with large solenoidal turbulence (→ FERMI II)*
- $P_{\rm radio} \approx \eta P_{\rm ki}$ **with** $P_{\rm ki} \sim 10^{45}\mathrm{erg/s}$ **and** $\eta \sim 10^{-5}$



A ... of the A399-A401
bridge:
tu ... sion remains very low.

BRUNETTI & VAZZA 2020 PRL

MEGA RADIO HALOS



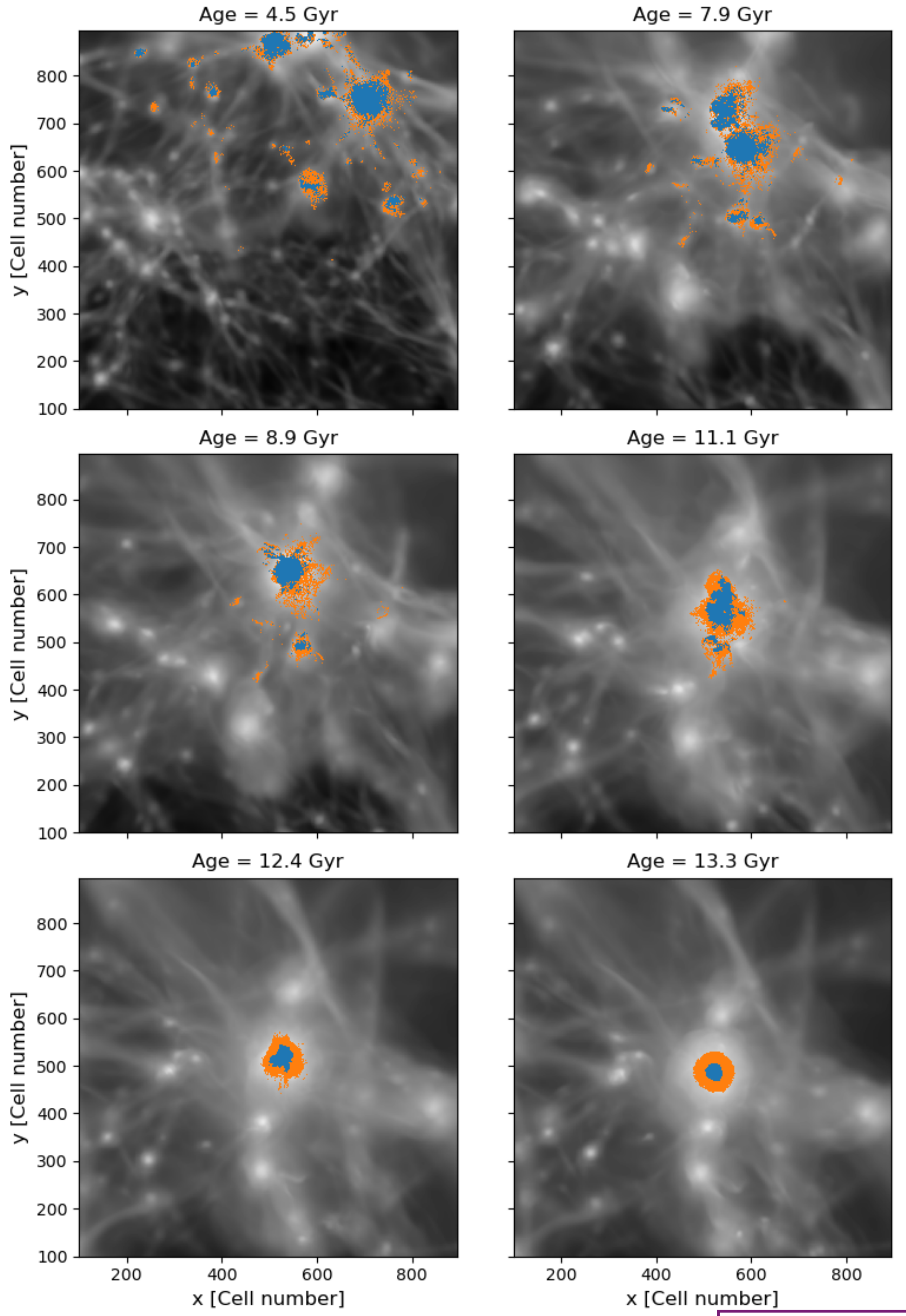
New LOFAR detection of unprecedently low surface brightness radio emission in 4 clusters.

The emission probes a ~ 30 larger cluster volume than classical halos!

What is their origin?

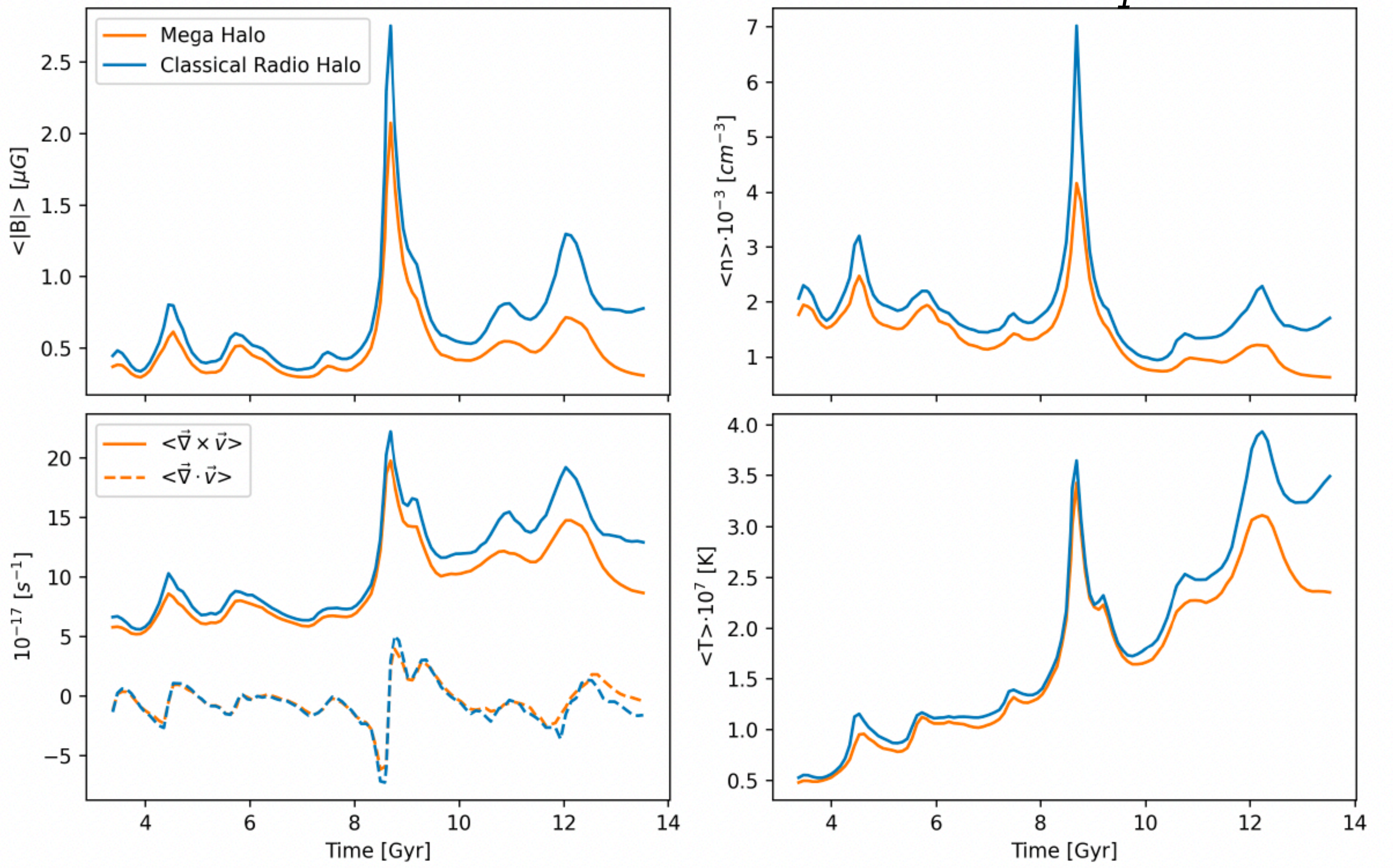
CUCITI ET AL. 2022 NATURE

MEGA RADIO HALOS - SIMULATIONS



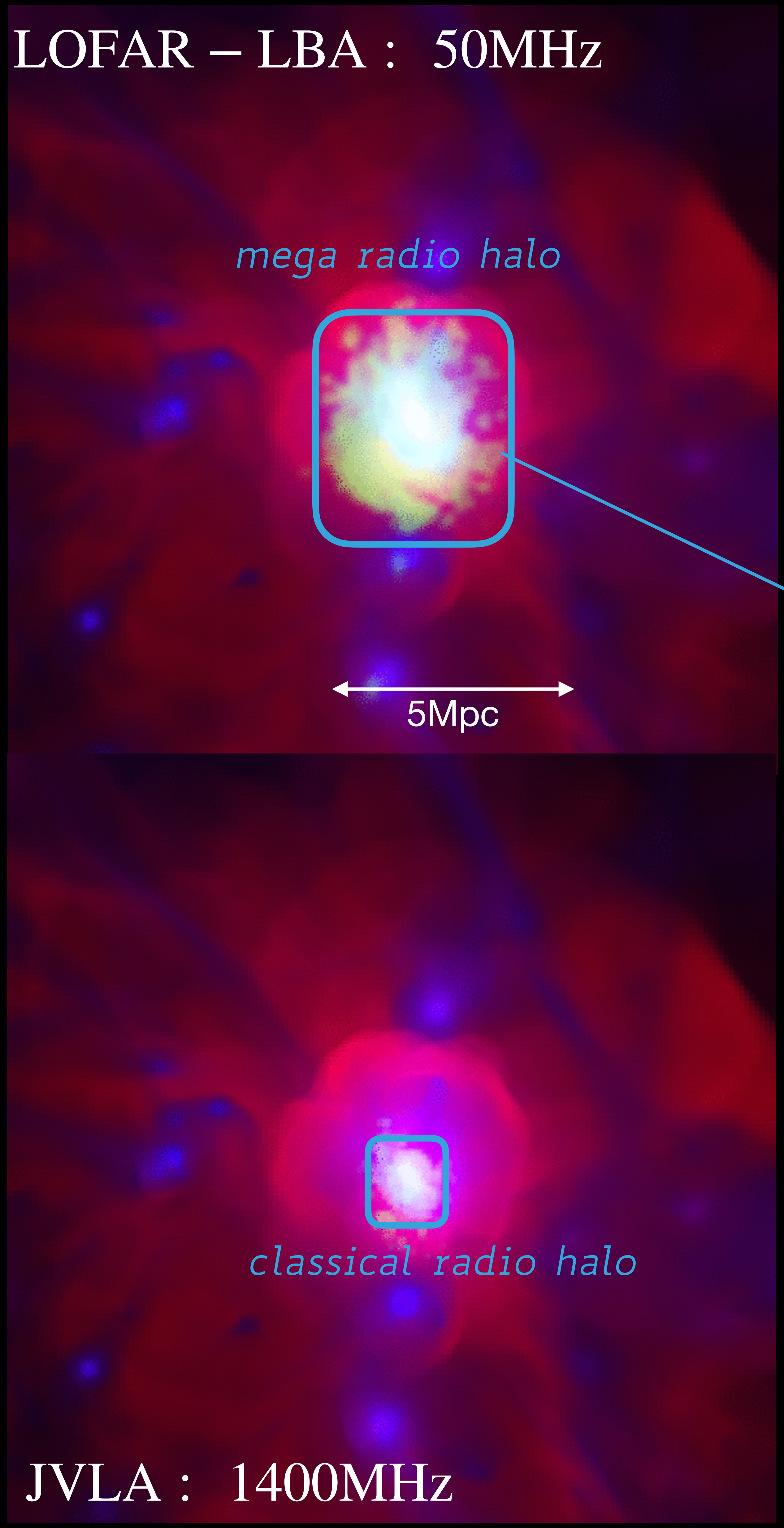
- new ENZO-MHD simulation a massive cluster
- lagrangian tracer particles to track history of gas ending up in the Mega Halo region
- from the history of thermodynamical quantities, we simulate the energy evolution of CR electrons carried by the fluid

time evolution of quantities



BEDUZZI, FV, BRUNETTI CUCITI ET AL. 2023, 2024 A&A

MEGA RADIO HALOS

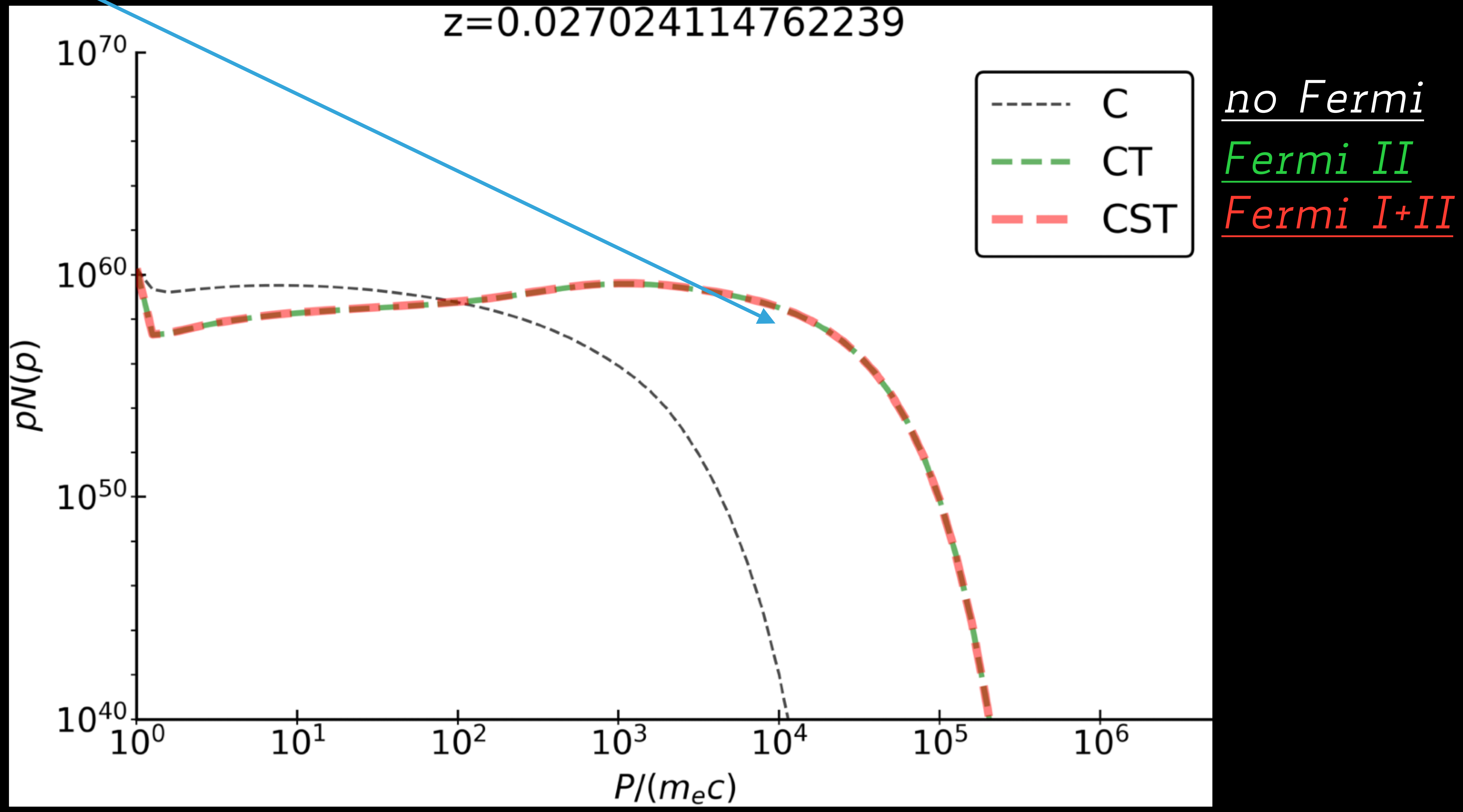


- *Numerical integration of electrons acceleration/losses for $\sim 10^5 - 10^6$ Lagrangian passive tracers (e.g. Donnert+2014)*

$$\frac{\partial N(p)}{\partial t} = \frac{\partial}{\partial p}\left[H(p)N(p) + D_{\rm pp}\frac{\partial N(p)}{\partial p}\right] + Q_{\rm inj}(p,t),$$

- *parallel and efficient Fokker-Planck solver in* julia

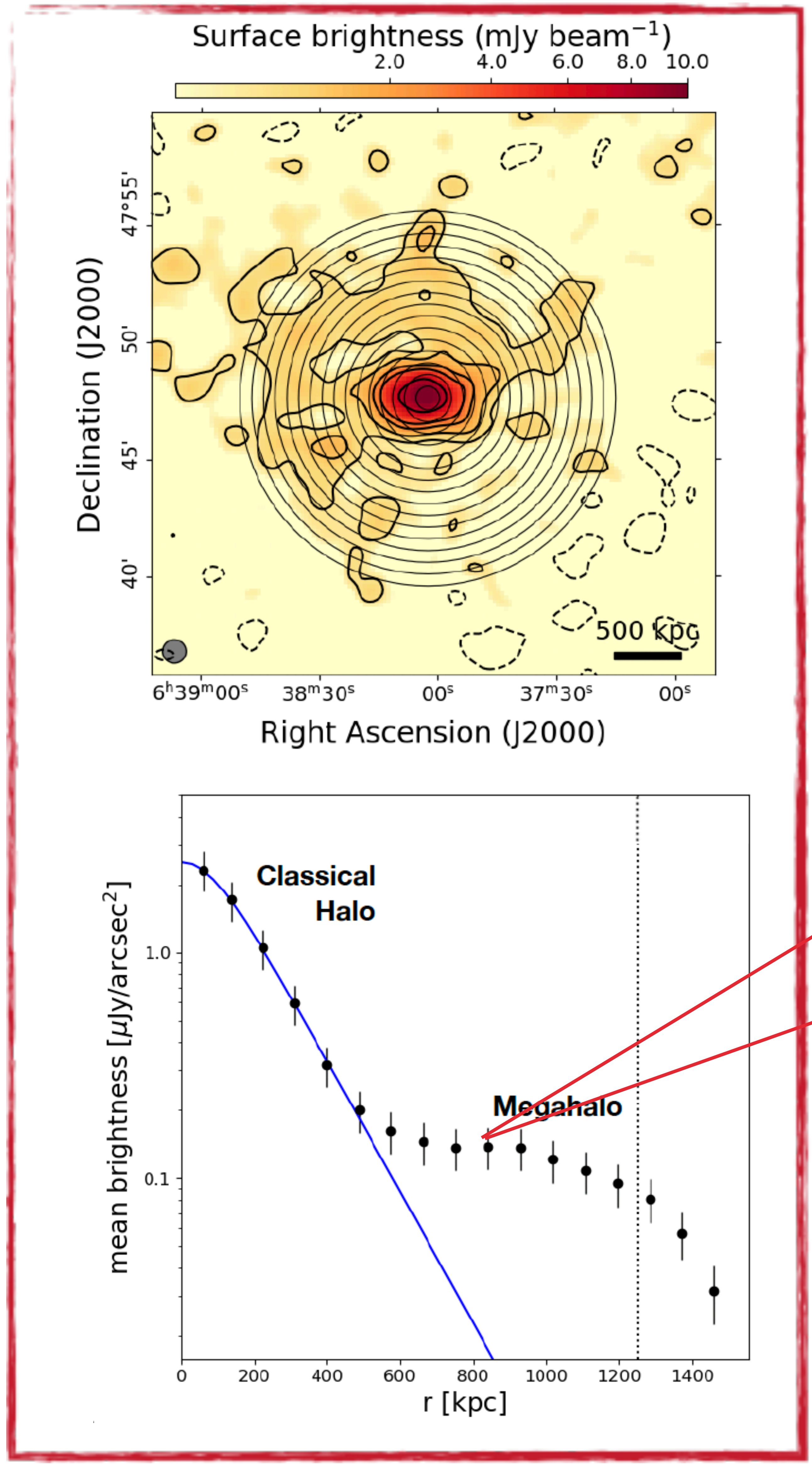
diffuse radio emission "naturally" emerges from the merger induced turbulence



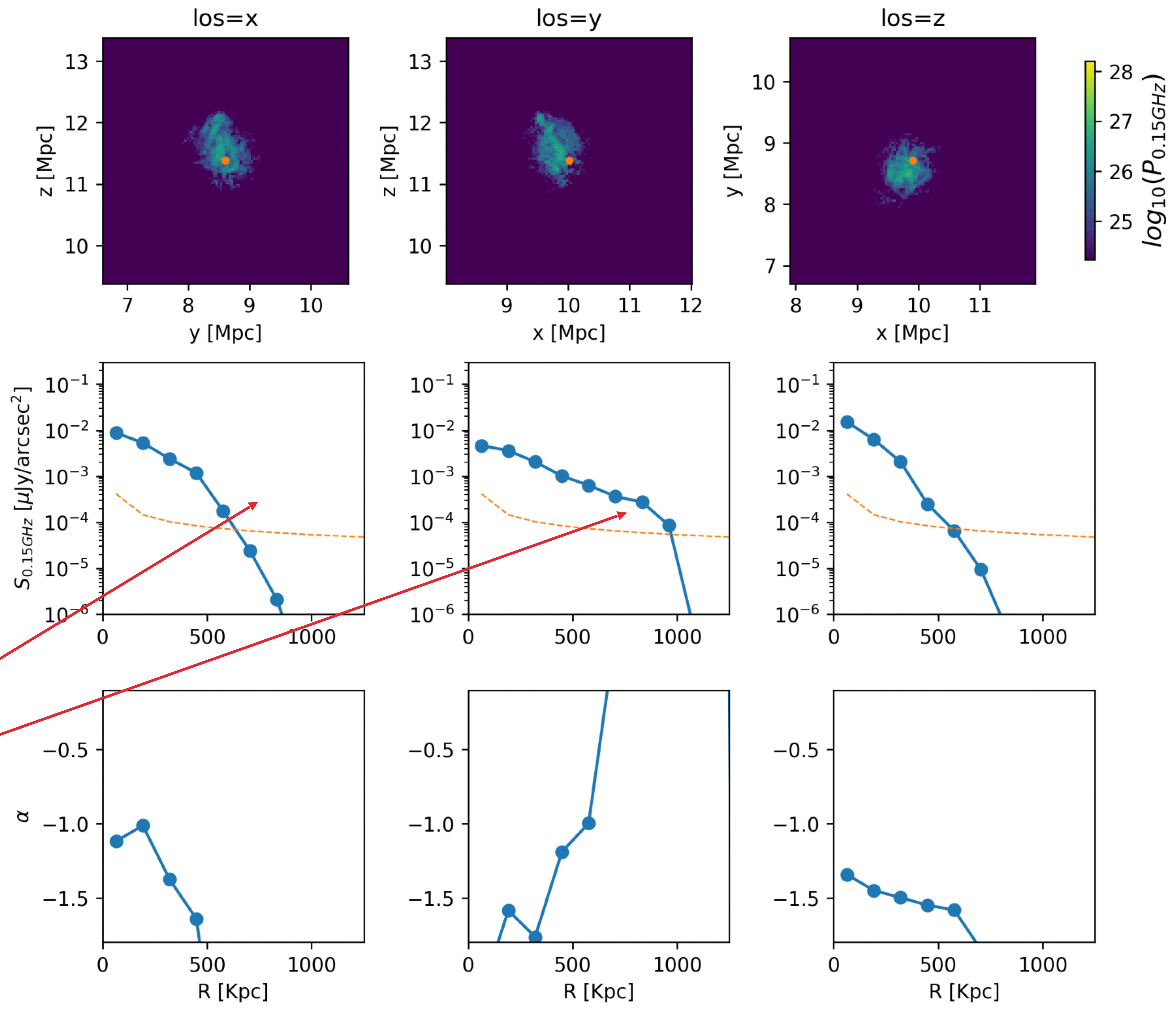
BEDUZZI, FV, BRUNETTI CUCITI ET AL. 2023, 2024 A&A

MEGA RADIO HALOS

Cuciti et al. 2022 Nature



- **formation of asymmetric Mega Radio Halos**
- *how common? Need to check in larger samples*



BEDUZZI, FV, BRUNETTI CUCITI ET AL. 2023, 2024 A&A

THE RADIO COSMIC WEB: SYNCHROTRON EMISSION

Most of baryons predicted to be in **filaments**.

They must have been **shocked** at least once ($\mathscr{M} \geq 10$)

-

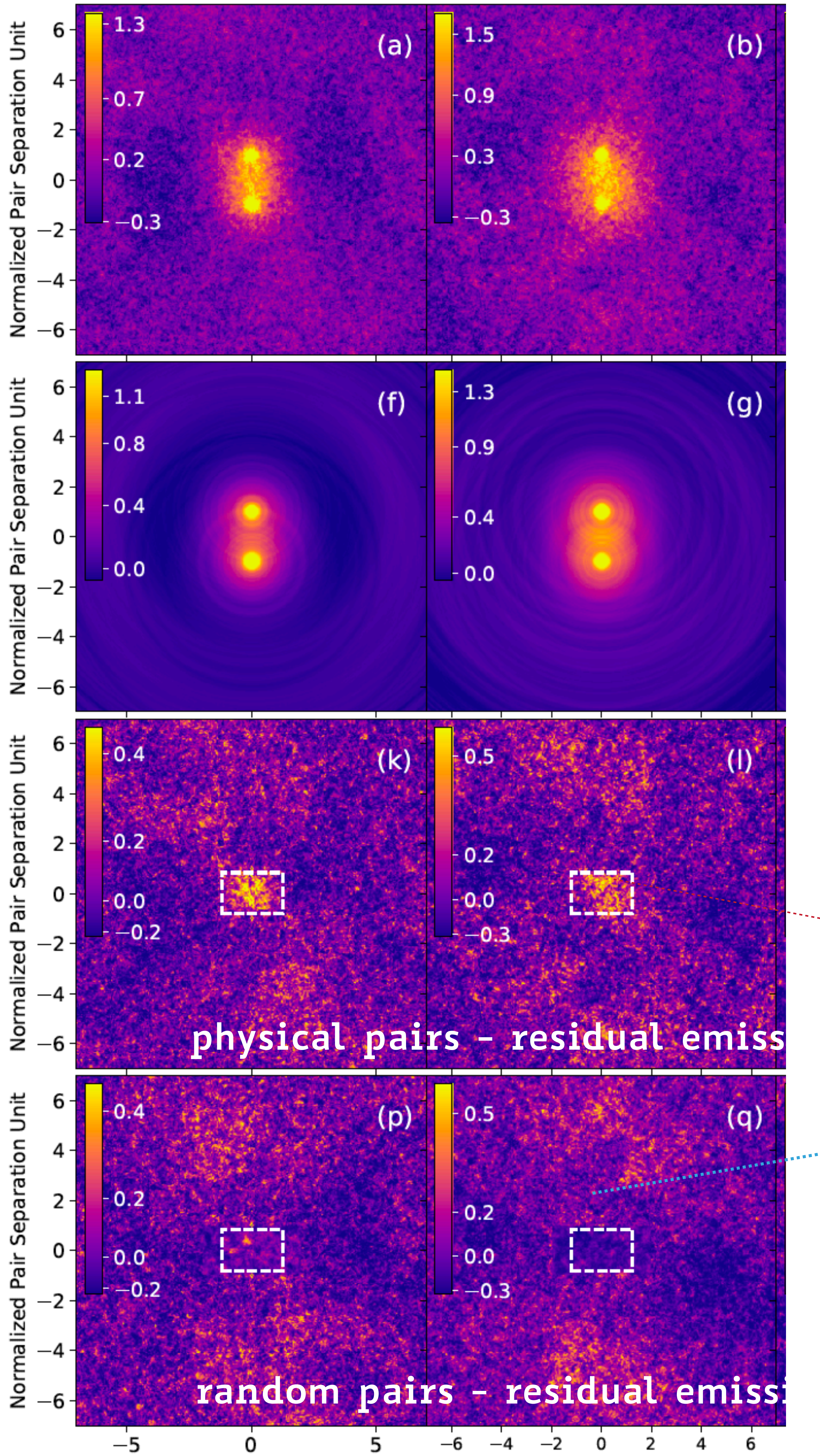
If **diffusive shock acceleration** works:

- $I(\nu) \propto \nu^{-\alpha}$ *spectrum,*

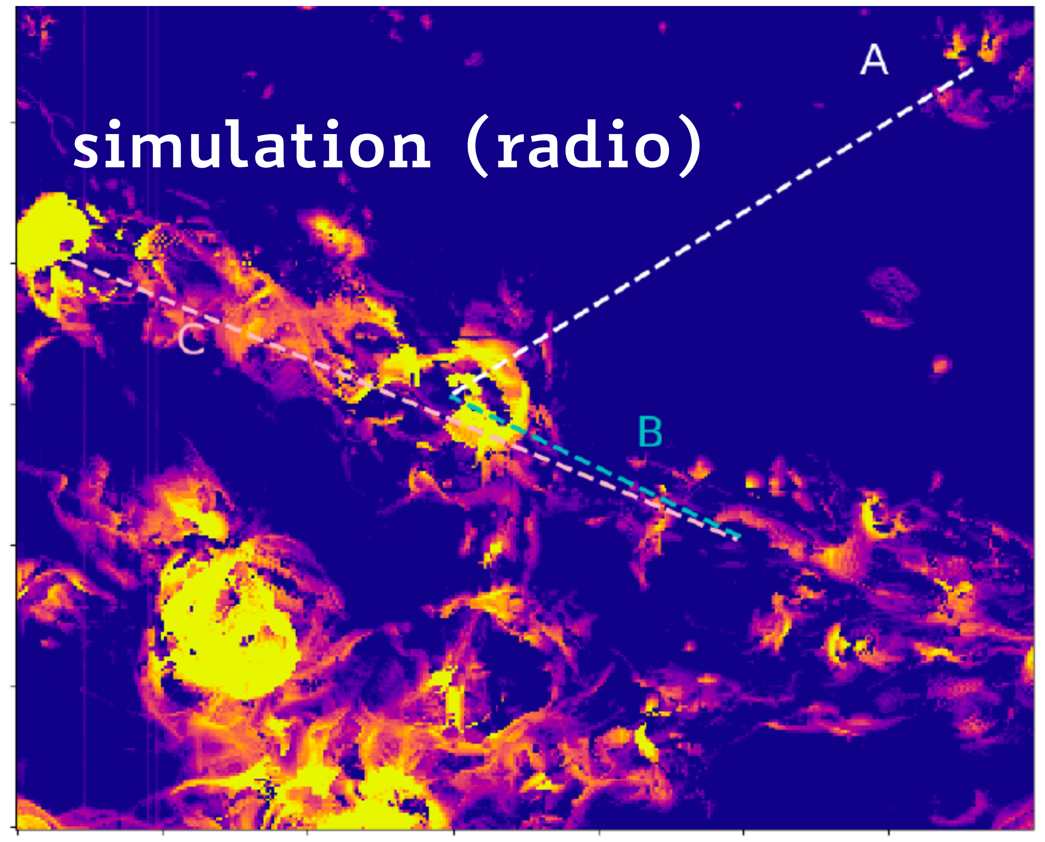
$$\mathscr{M} = \sqrt{\frac{1-\alpha}{-1-\alpha}}$$

- $P_{sync} \propto \xi_e(\mathscr{M}) B^2$
- $\xi_e(\mathscr{M})$ *electron. accel. efficiency* ($\sim 10^{-5} - 10^{-2}$?)

THE RADIO COSMIC WEB: SYNCHROTRON EMISSION



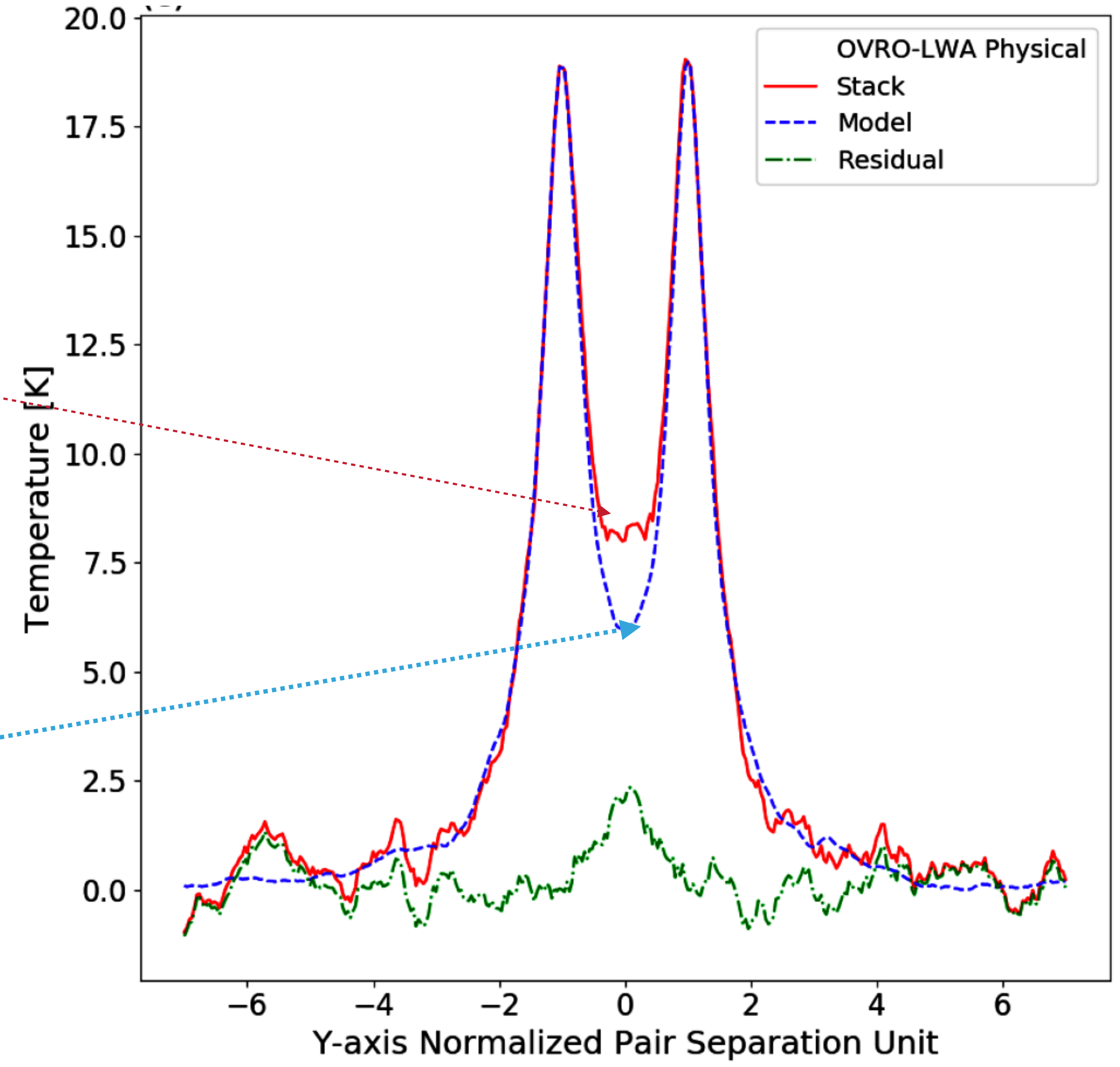
Vernstrom et al.2021: stacking of >200,000 pairs of halos in MWA survey



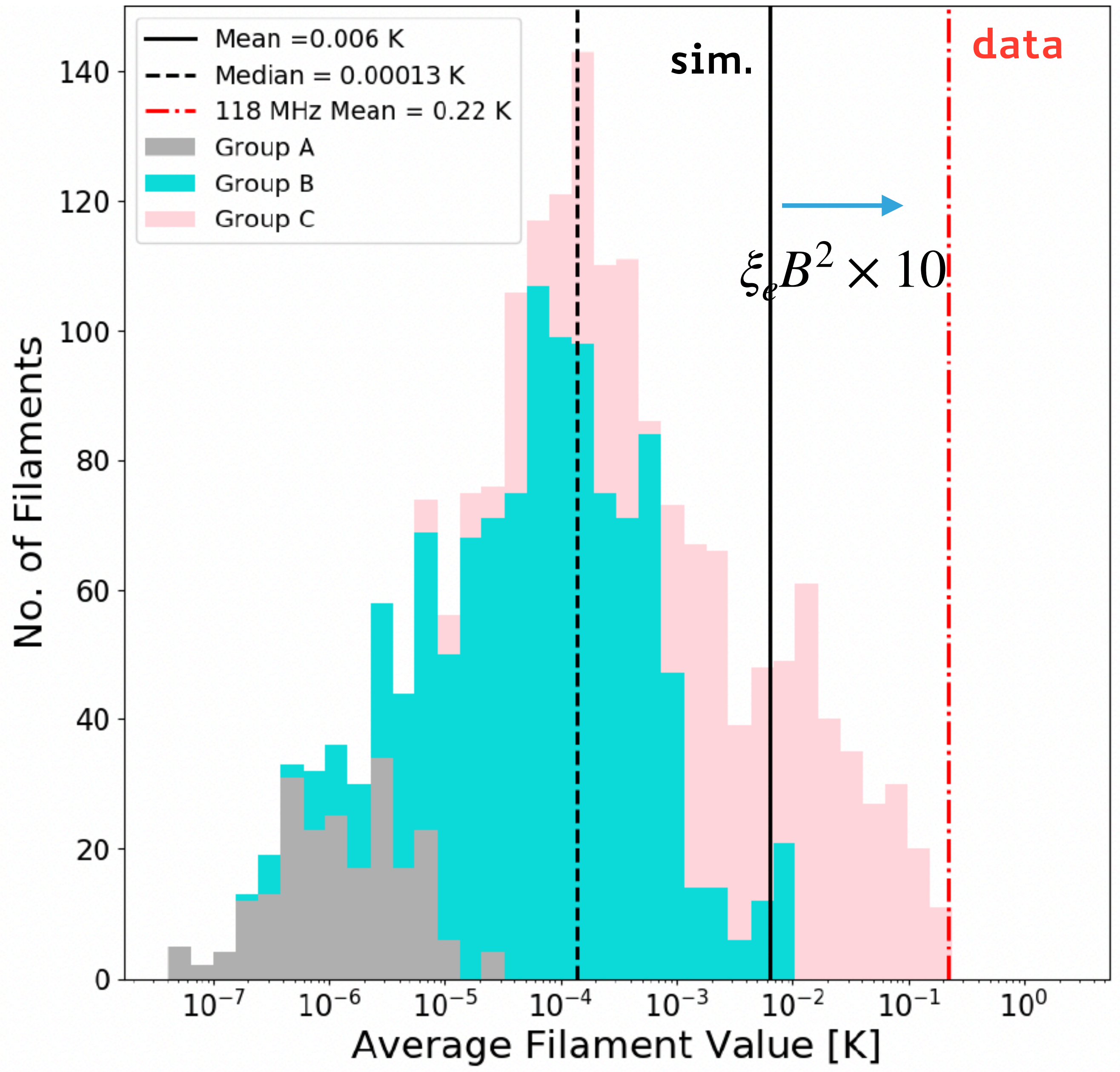
>5σ detection of the statistical excess of radio emission

compatible with synchrotron from shocks around/in filaments.

line profiles



PDF of radio flux



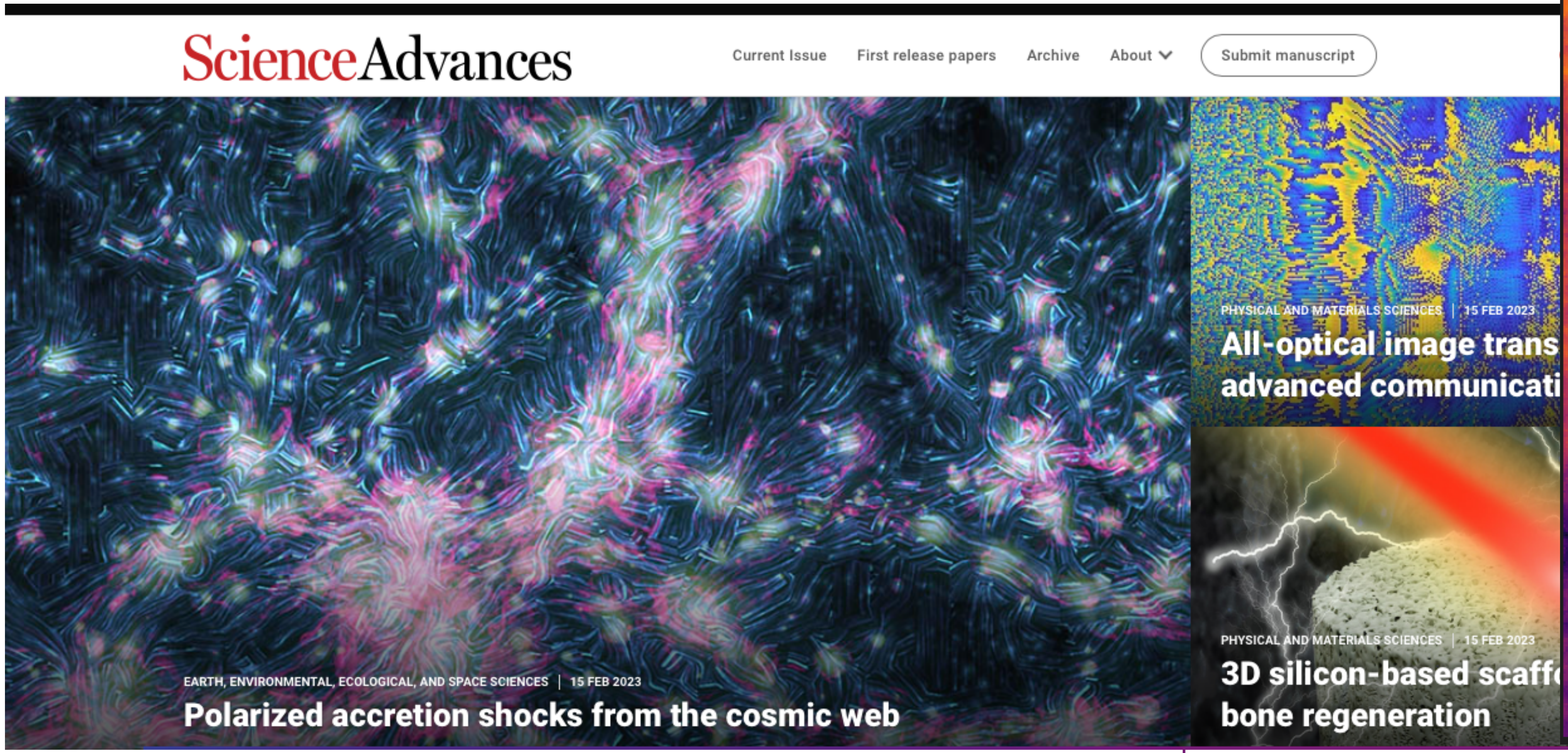
VERNSTROM ET AL. 2021 MNRAS

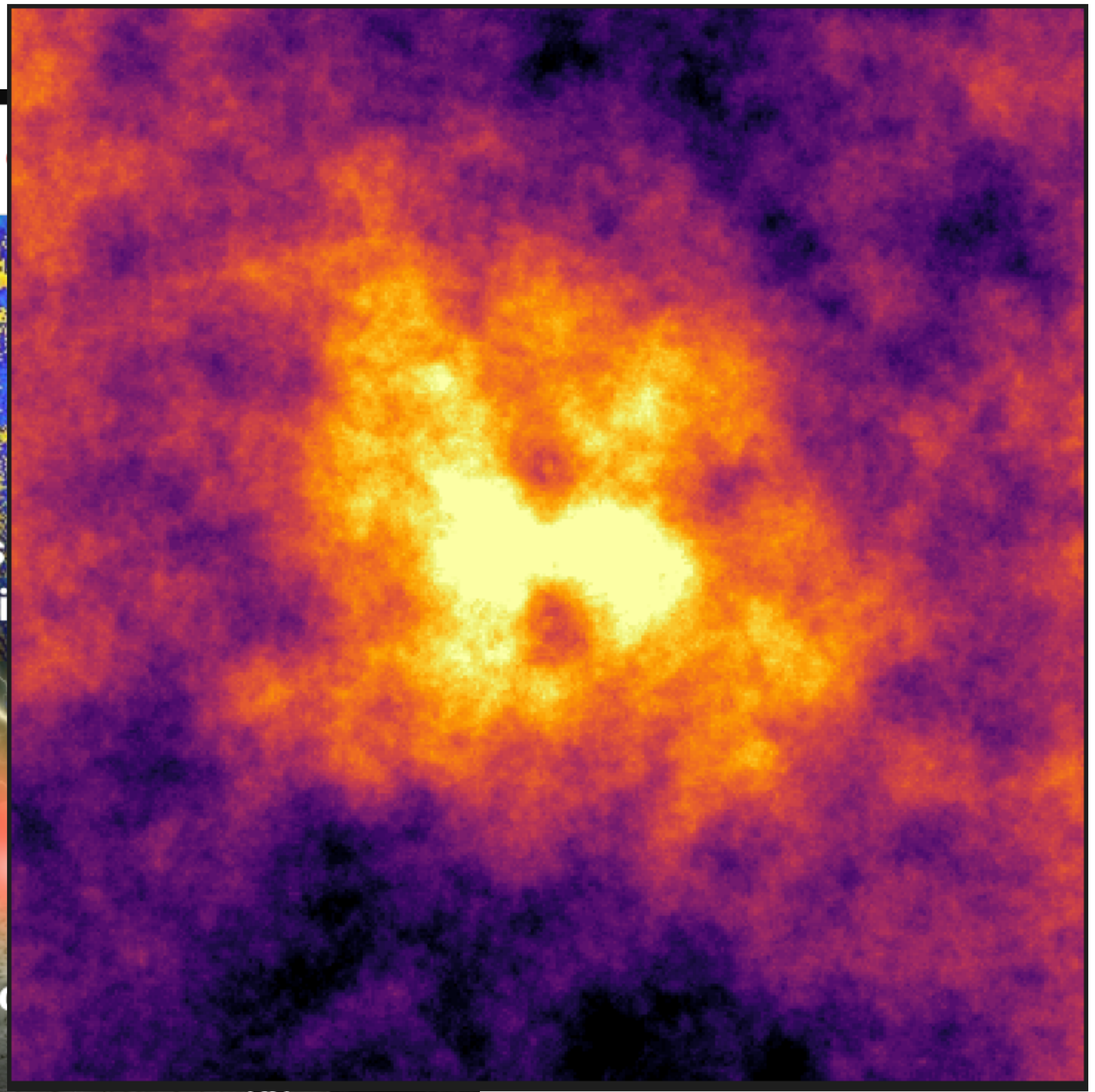
THE RADIO COSMIC WEB: POLARISED SYNCHROTRON EMISSION

Stacking of 600,000 pairs of halos and detected >3-4σ polarised emission ($p \sim 40 - 70\,\%$).

All other (conceivable) alternative explanations for the emission ruled out.

Compatible with radio emission from the shocked cosmic web
Simulations reproduce the stacking if $B \sim 30 - 50\mathrm{nG}$ in filaments.

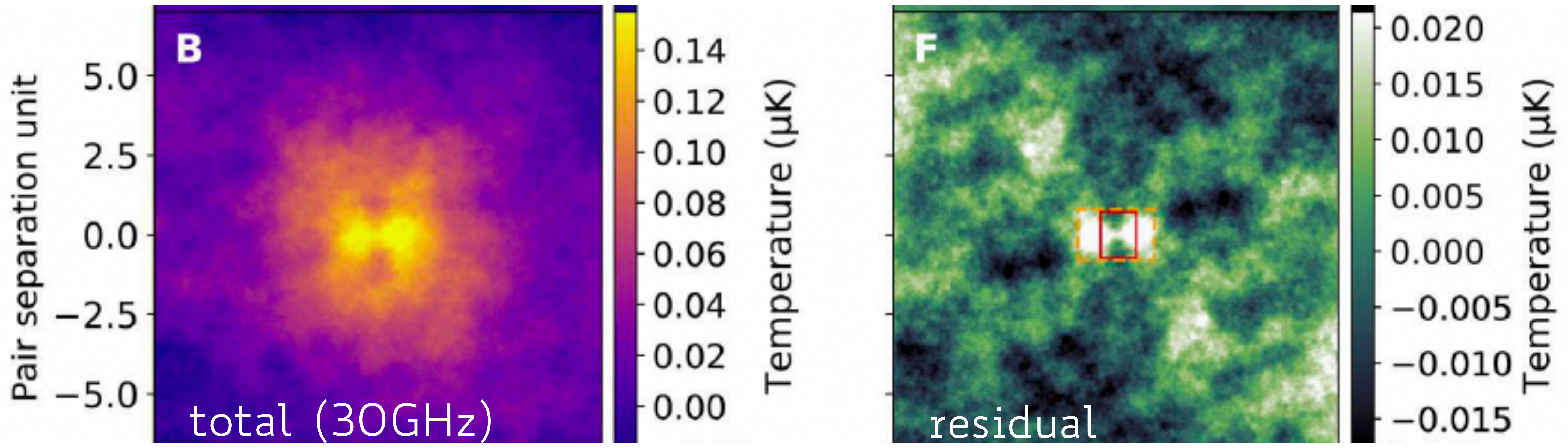


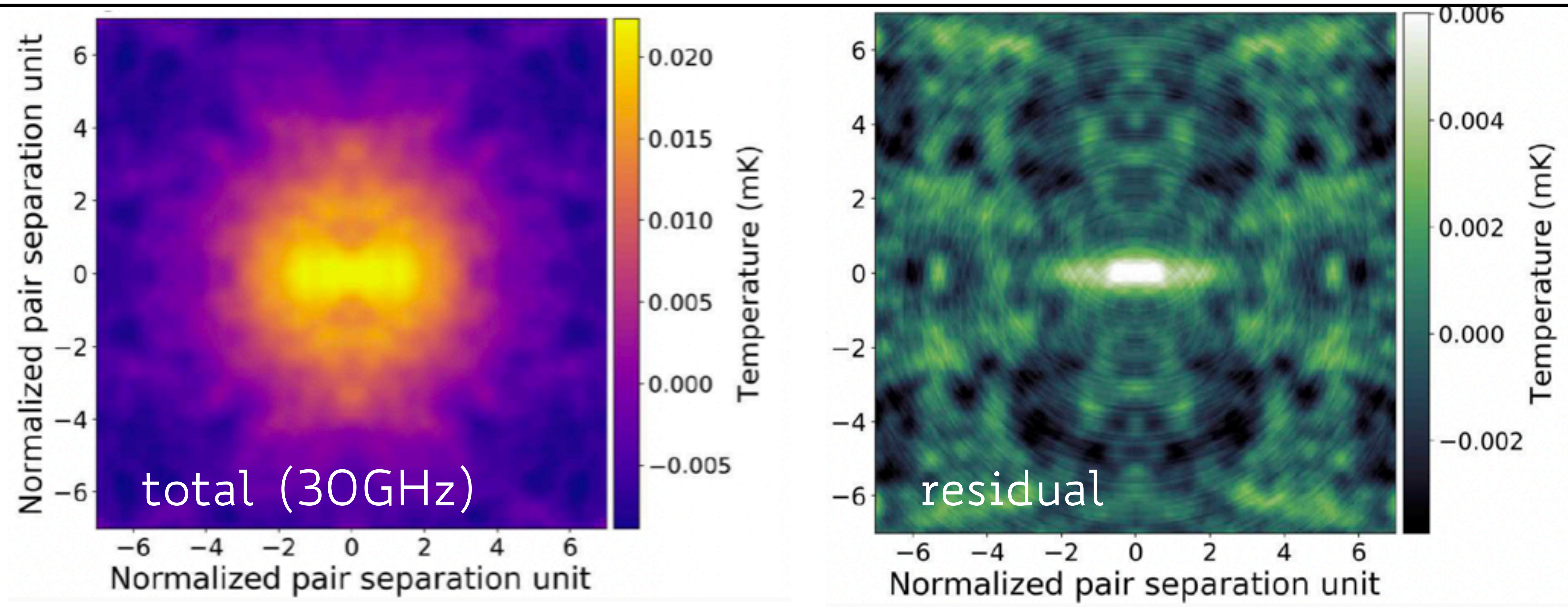


VERNSTROM ET AL. 2023 SC. ADV.

THE RADIO COSMIC WEB : VIA STACKING

- OBSERVED stacking of ~600,000 pairs of halos with 1-15Mpc separations

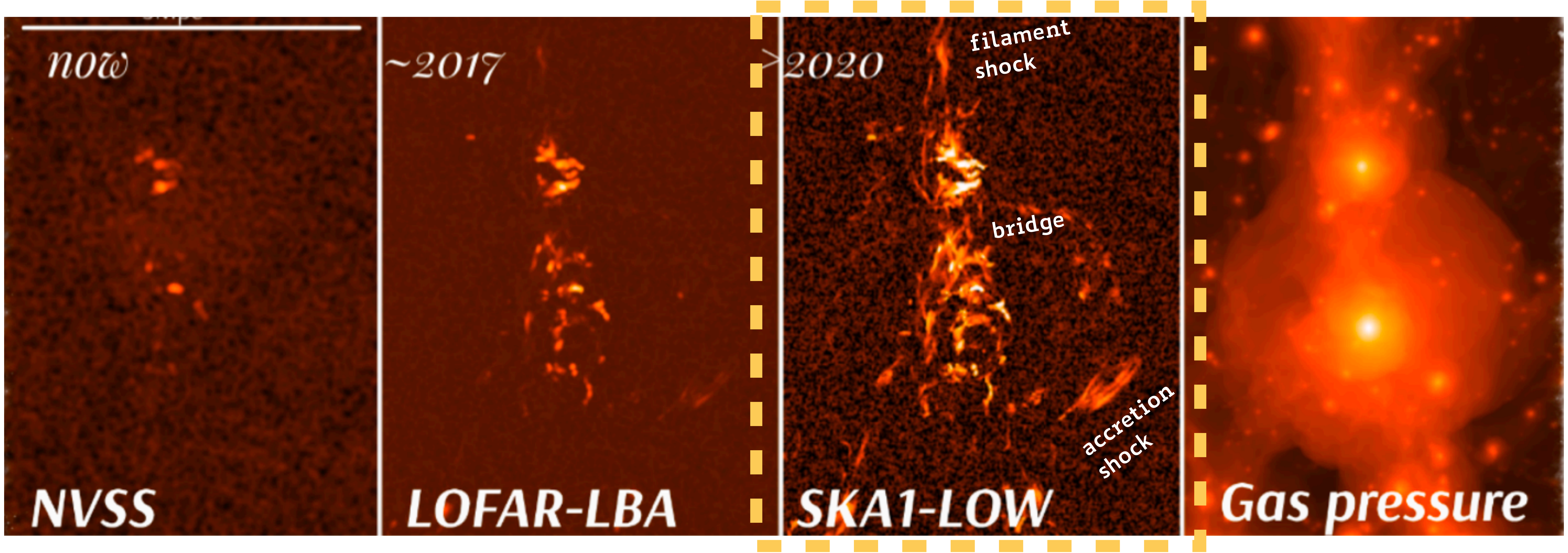




- Stacking of $\sim 10^2$ SIMULATED pairs of halos in the cosmological MHD run.
- it constrains accel. efficiency & <u>seed</u> B-field: $\xi_e B^2 \approx 0.01 \cdot (0.3\mathrm{nG})^2$

WILL THE SKAO DO BETTER?

A somewhat optimistic prediction from ~2015:



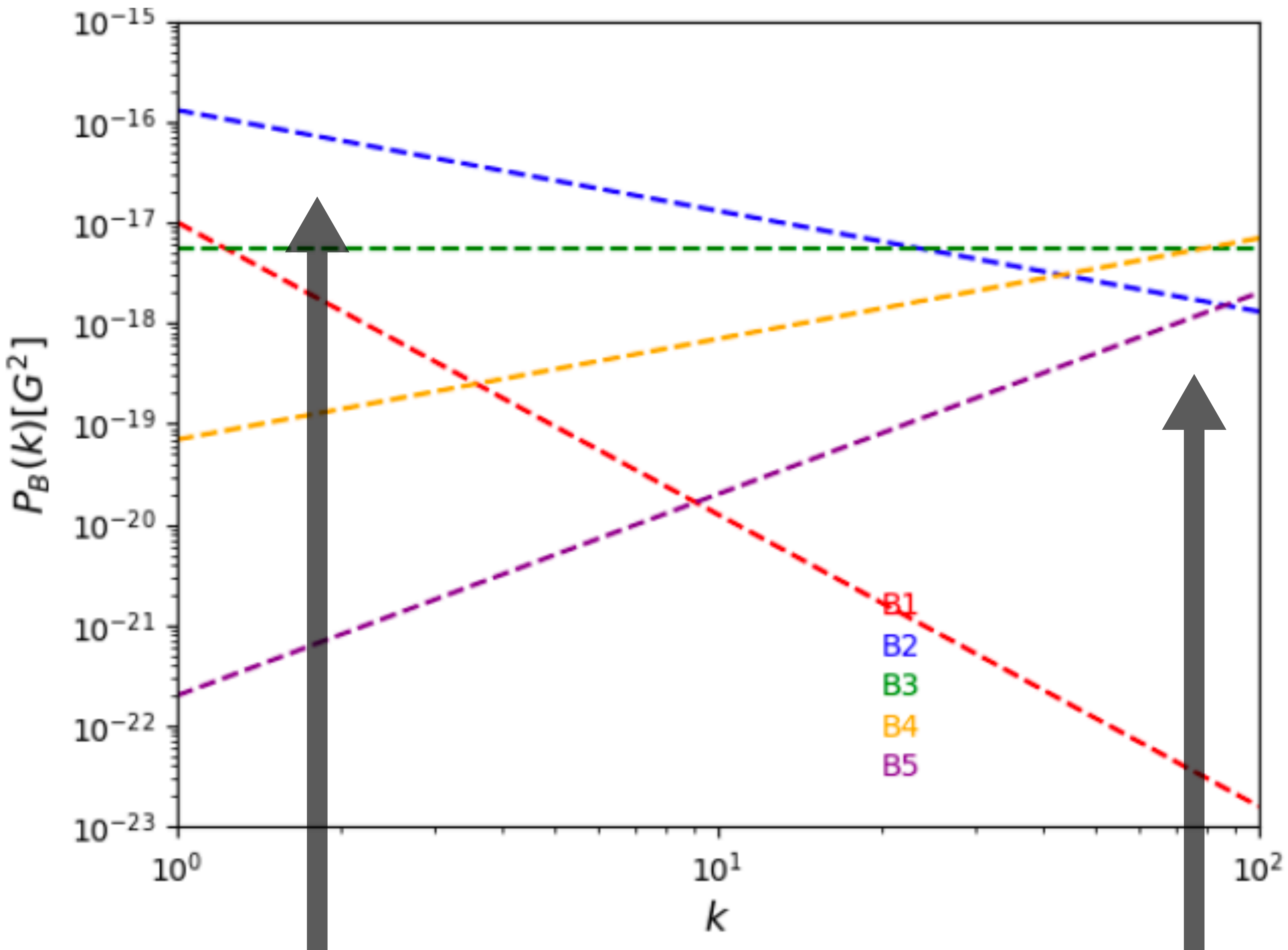
INTRACLUSTER BRIDGES: *The SKA-LOW survey should triple the number of intracluster objects compared to LOFAR-HBA at the moment.*

COSMIC FILAMENTS: *SKA-LOW will allow more resolved and deeper stacking studies, and image the "tip of the iceberg" of the full distribution.*
The combination with SKA-MID should allow polarisation cross-matching and better understand the emission mechanism

SIMULATING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS

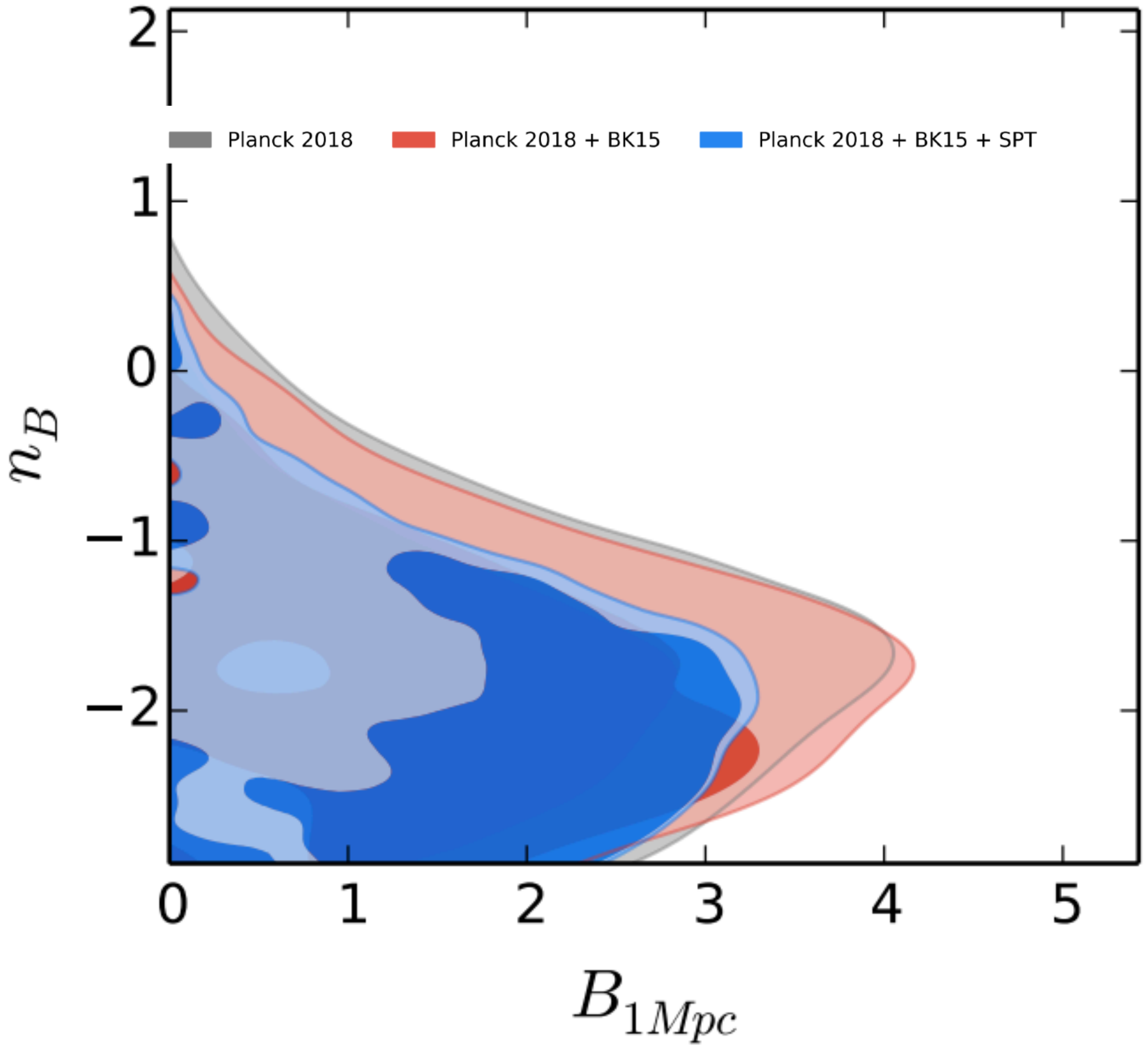
- **Modelling of the Cosmic Microwave Background constrains amplitude of power spectra of B-fields at $z \sim 10^3$**

$$P_B(k) \propto k^{\alpha_B} \; (-2.9 \leq \alpha_B \leq 2.0)$$



large correlation $\lambda_B \gg R_H$: inflation

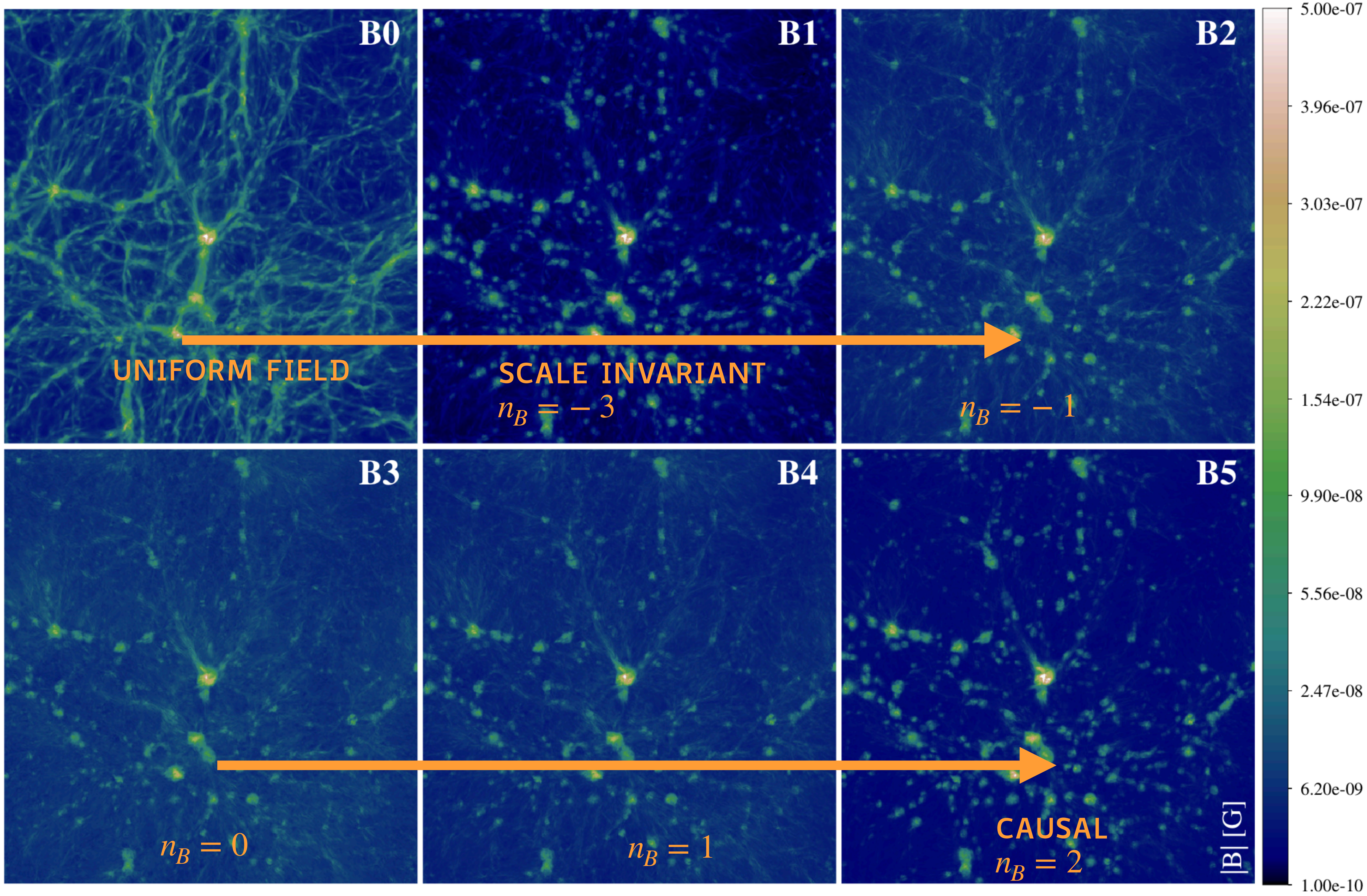
small correlation $\lambda_B \leq R_H$: Electro-weak epoch



PAOLETTI & FINELLI+2019 JCAP

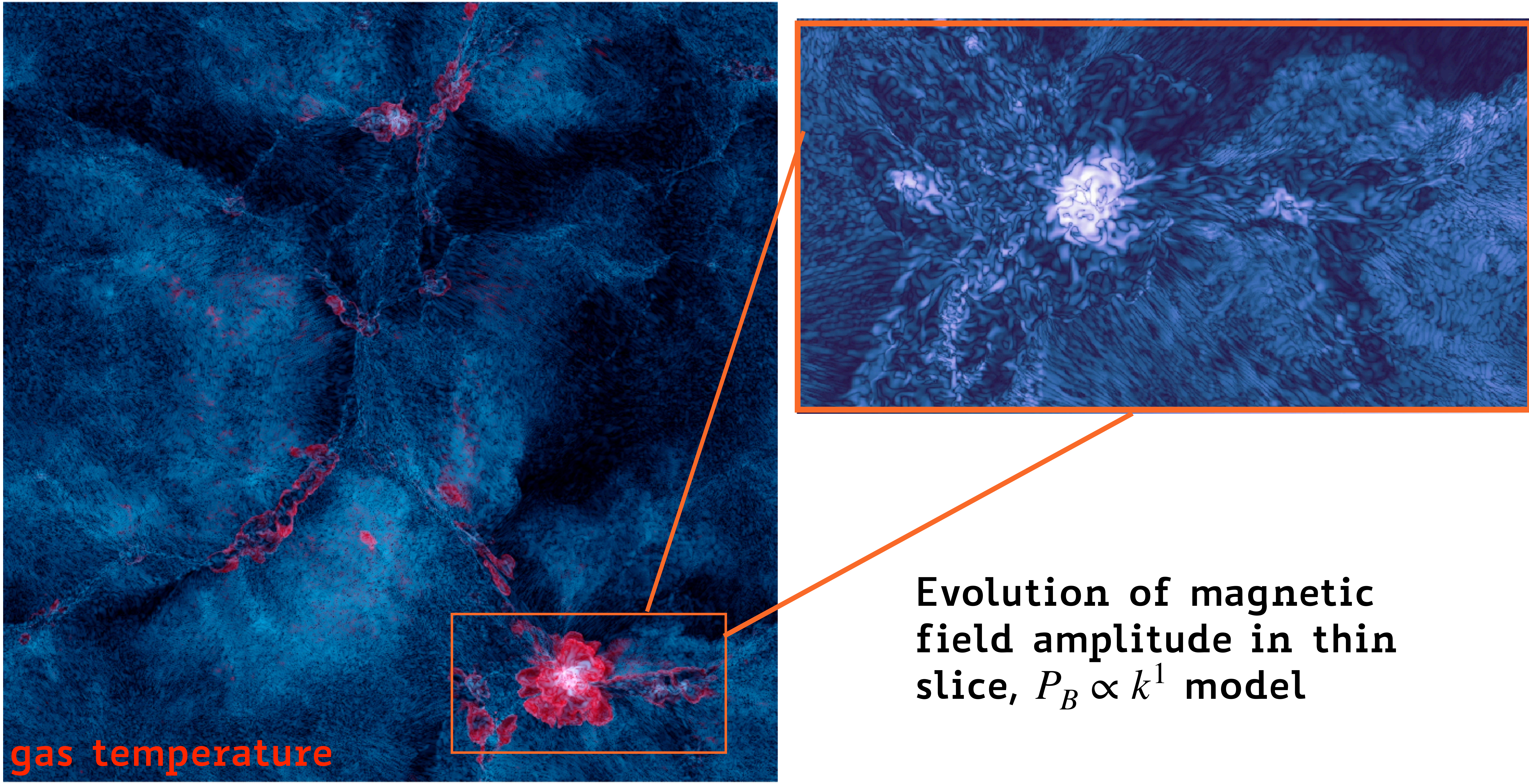
SIMULATING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS

- Large differences of B-fields in filaments/voids



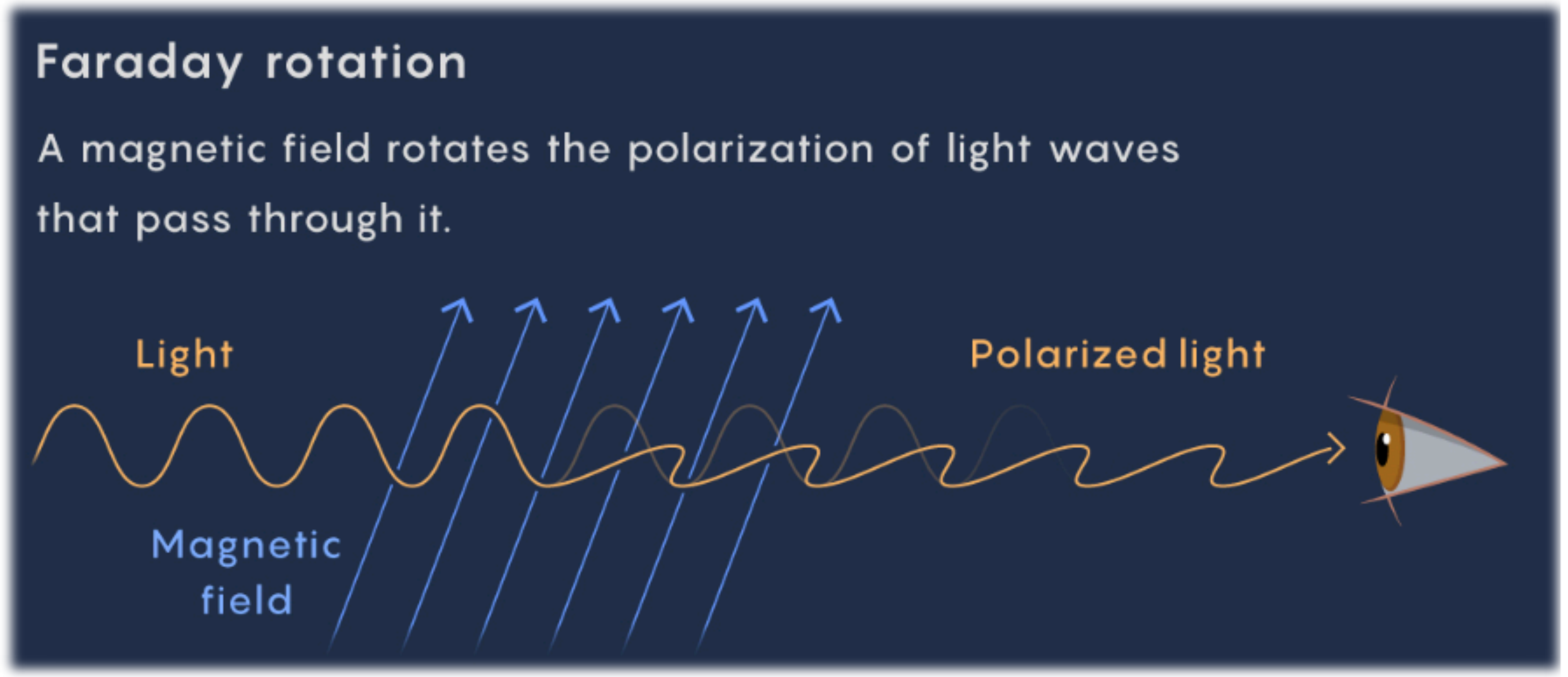
FV, PAOLETTI, BANFI, FINELLI ET AL. 2021 MNRAS

SIMULATING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS



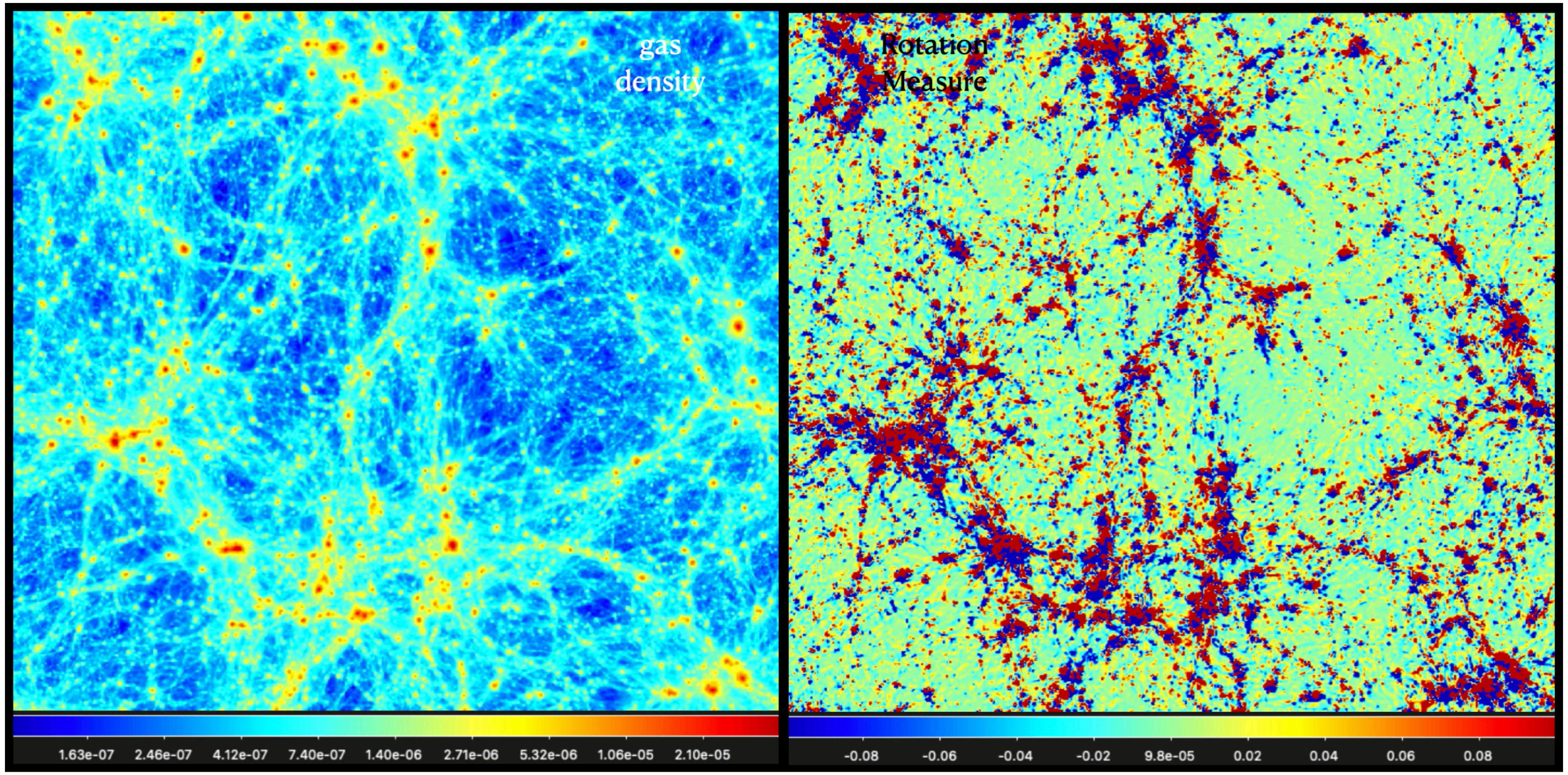
Evolution of magnetic field amplitude in thin slice, $P_B \propto k^1$ model

THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION



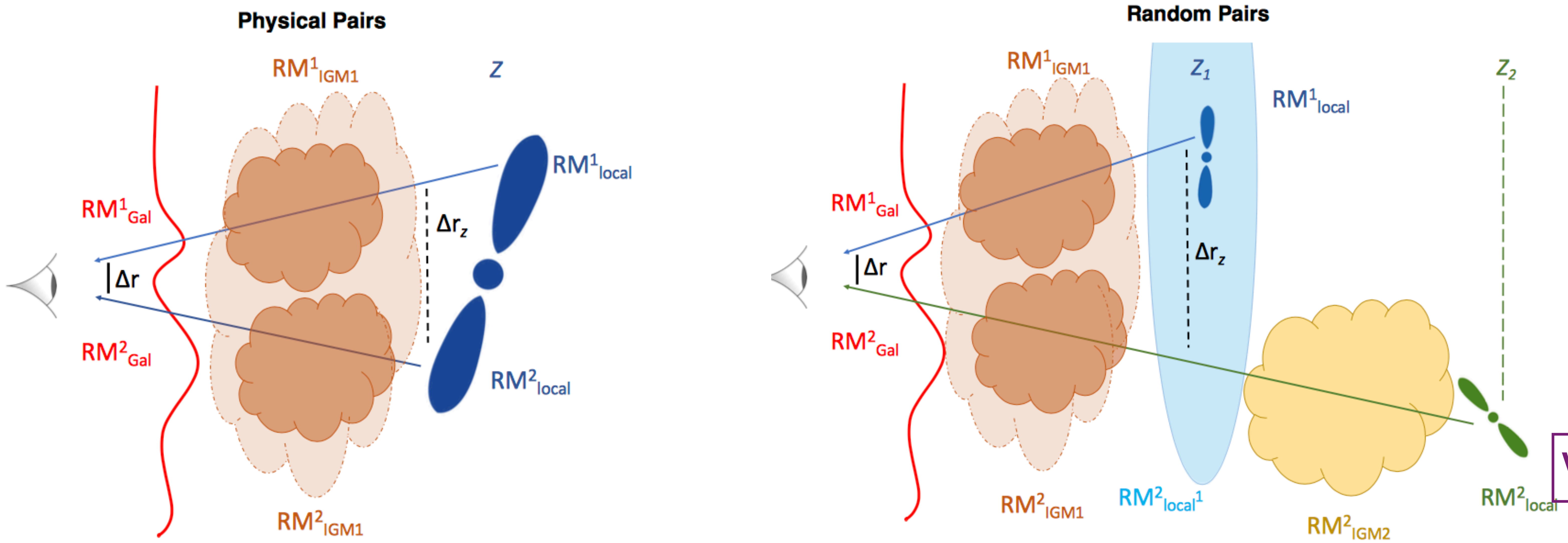
the Faraday Rotation effect:

$$\mathrm{RM} = 0.812 \int_z^0 \frac{n_e(z')B_{\parallel}(z')}{(1+z')^2} \frac{dl}{dz'} dz'$$



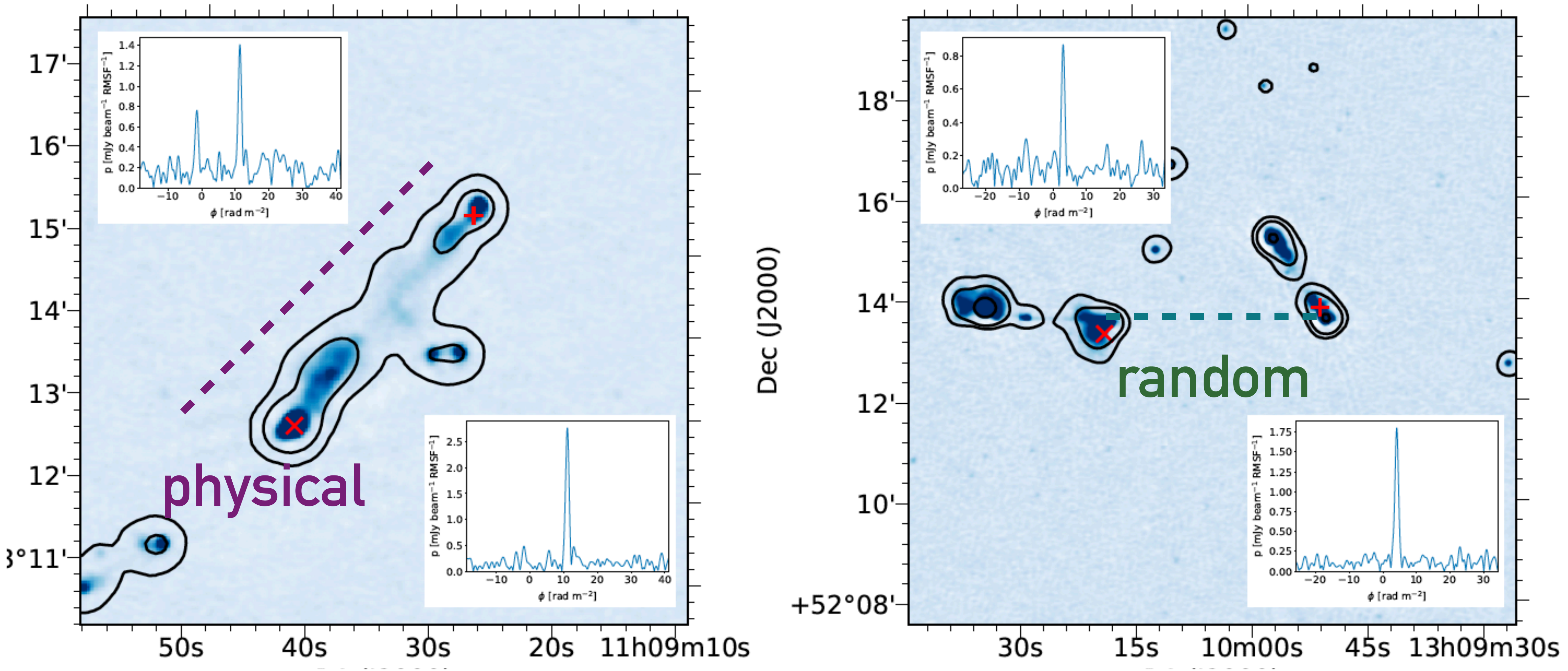
THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION

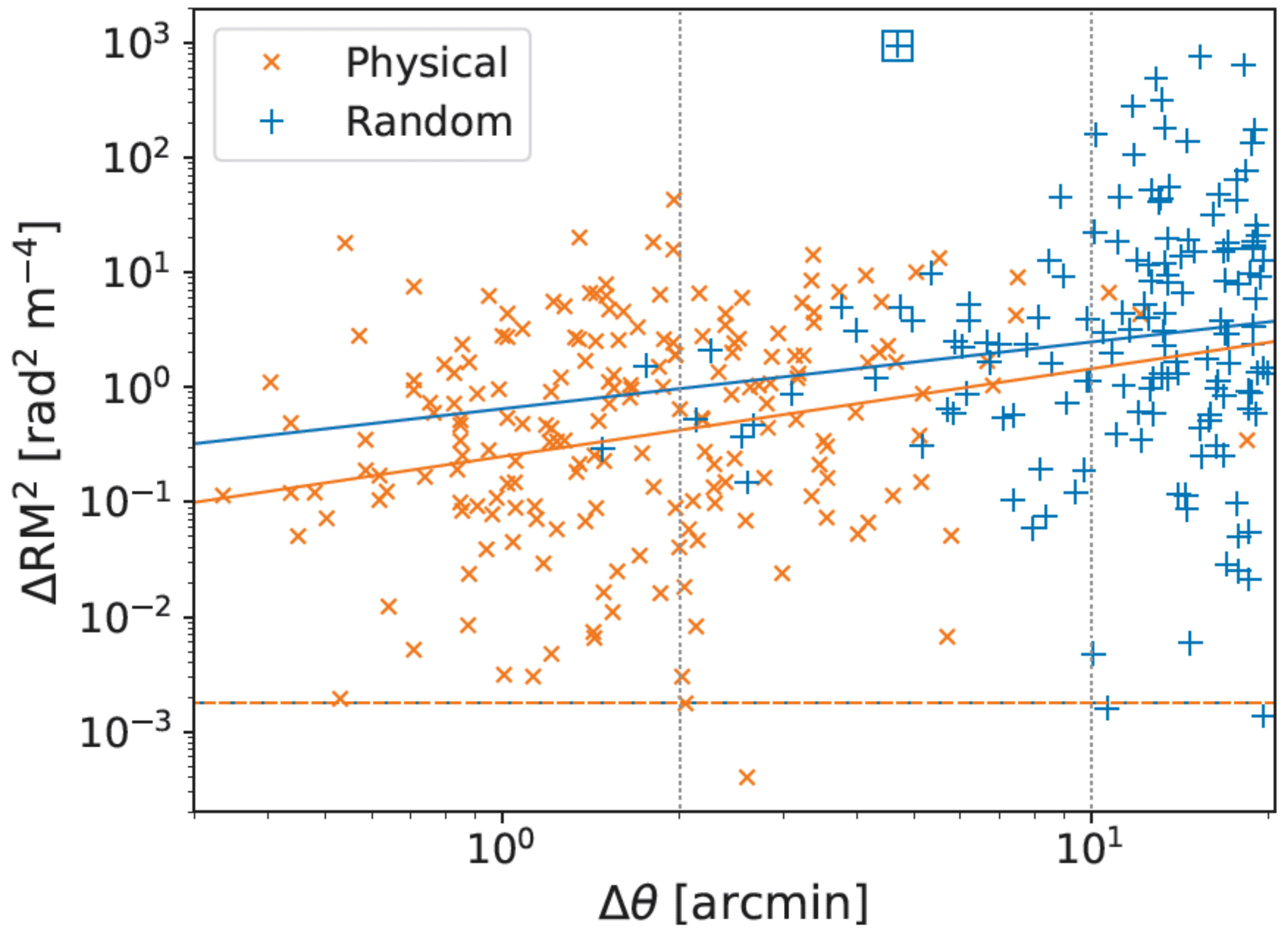
- Excess ΔRM in random pairs: cosmic web contribution?



VERNSTROM+19

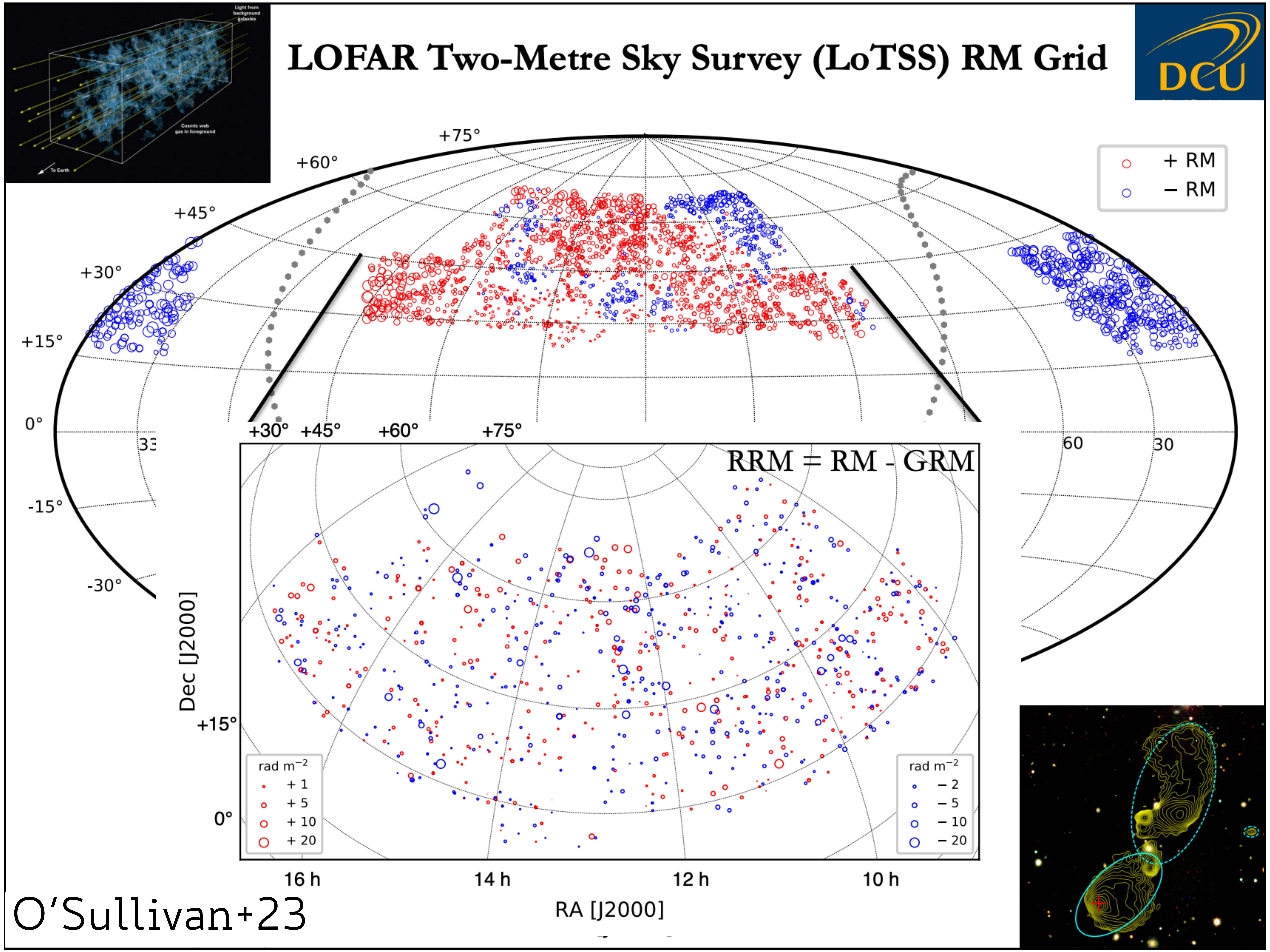
- ΔRM(θ) measured with LOFAR for 310 pairs





O'SULLIVAN, BRUGGEN, FV +2020

THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION



LOTSS DR2 survey:

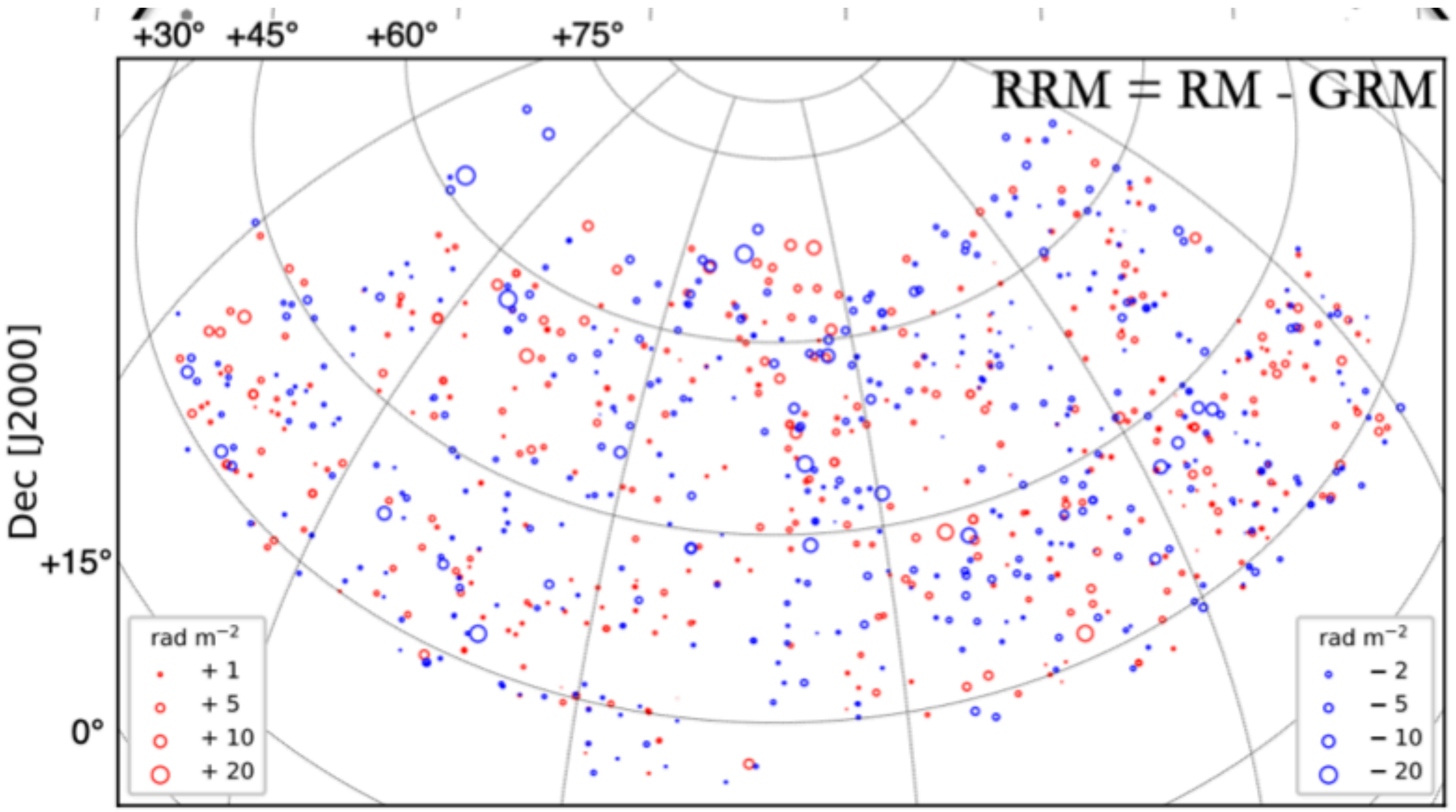
- ~4.4 million radio sources (Shimwell et al. 2022)

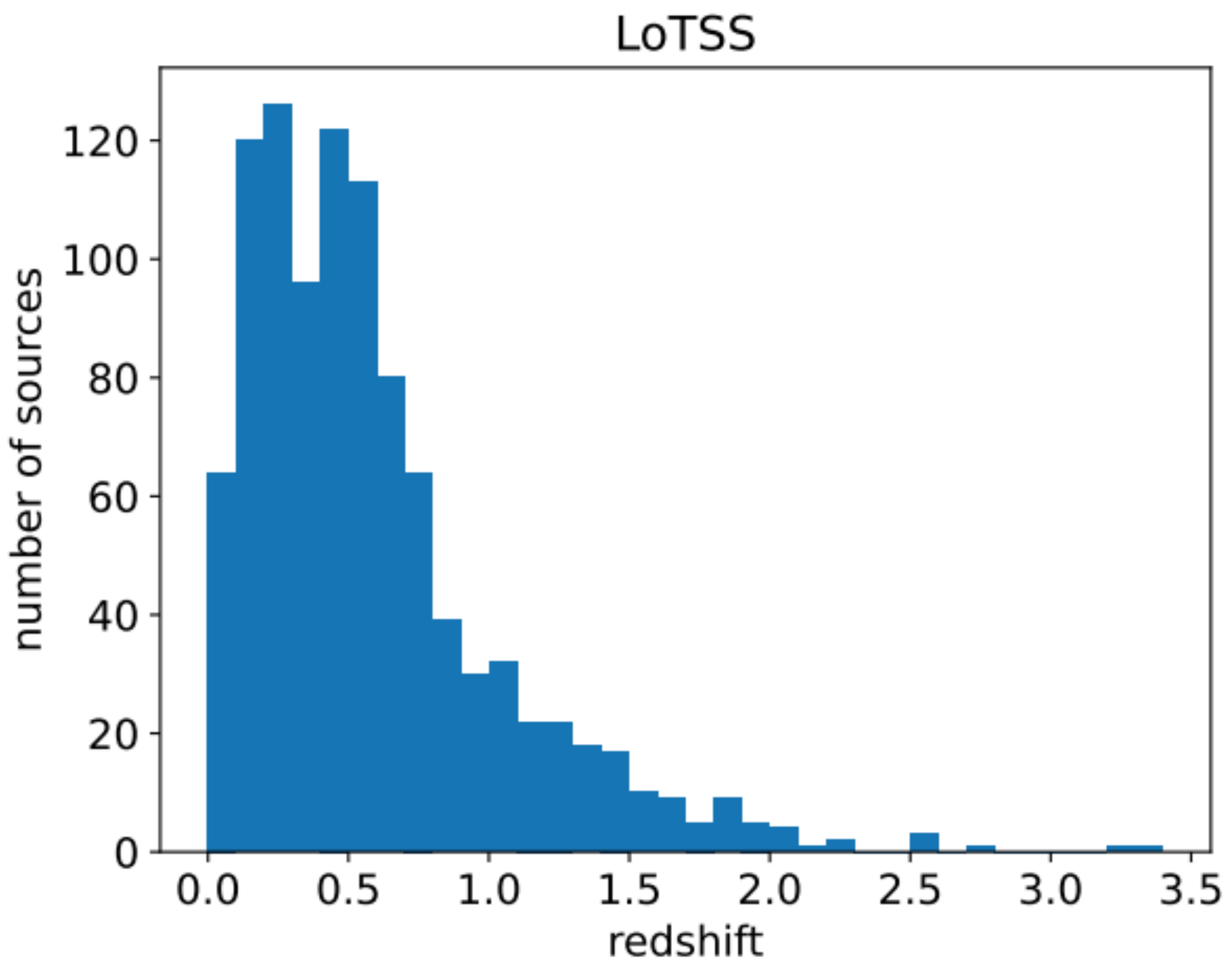
LOTSS RM Grid:

- ~2500 polarized (>8σ)
- Excellent RM precision: O(0.05 rad/m2)
- redshift for 79% of sources

DETECTING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS (?)

- Analysis of **1016 lines of sight** with $0 \leq z \leq 3$ in LOTSS DR2 , |b|>25°
- **Galactic foreground** (MAD filtering <0.5° radius, of Hutschenreuter+22 map): $RRM_f = RM - GRM$
- Removal of LOS with **known halos contaminating within r<R100 exclusion**
- **"Residual" Rotation Measure**: $$\langle RRM^2 \rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \langle RRM_f^2 \rangle^{1/2}$$





CARRETTI + 23, 24

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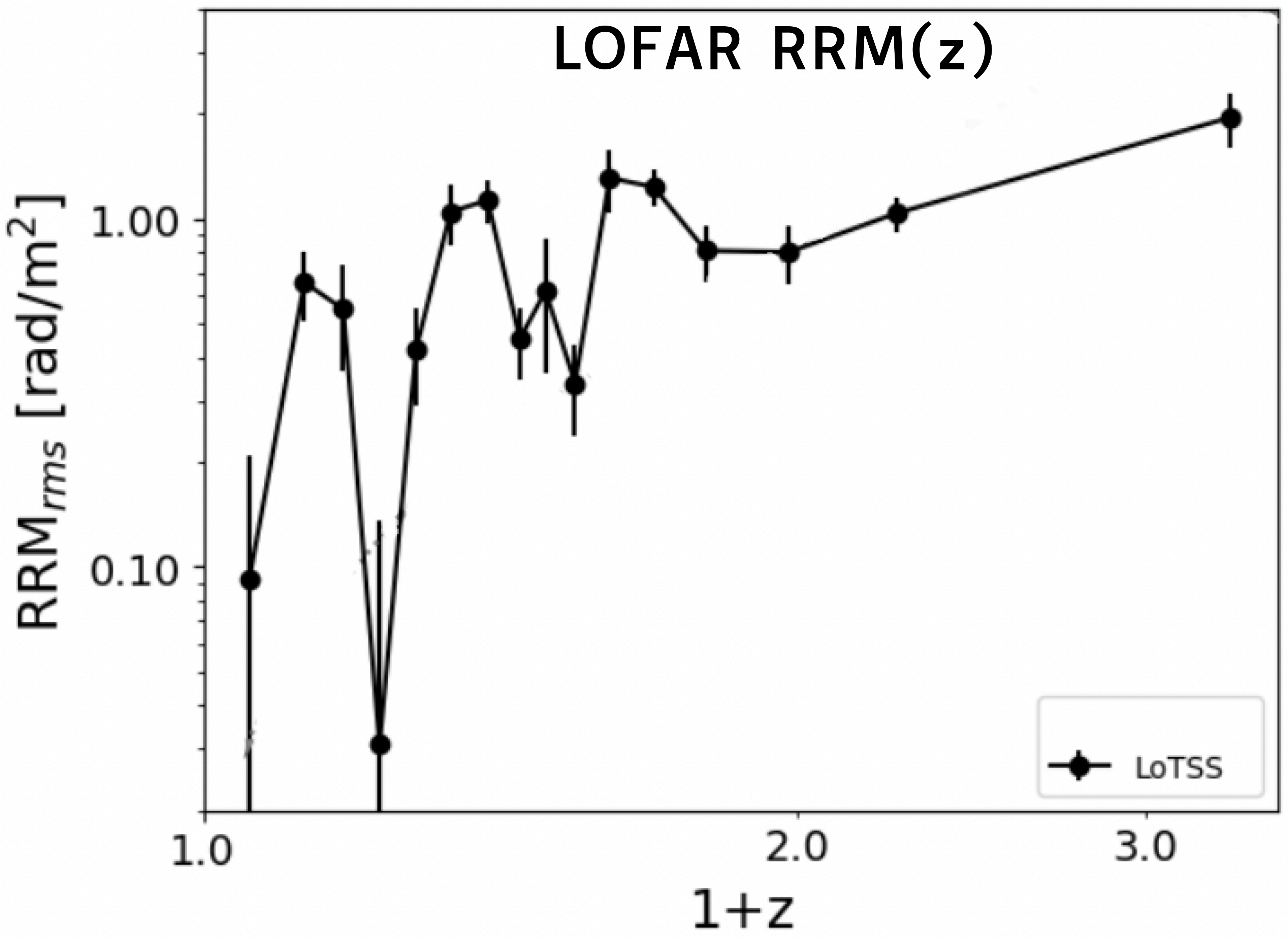
- **"Residual" Rotation Measure**: $$\langle RRM^2 \rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \langle RRM_f^2 \rangle^{1/2}$$

- trend with redshift until $z \sim 1$:

  cannot be of galactic origin

- flattening for $1 \leq z \leq 3$



CARRETTI + 23, 24

DETECTING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS (?)

- Analysis of **1016 lines of sight** with $0 \leq z \leq 3$ in LOTSS DR2 , |b|>25°
- **Galactic foreground** (MAD filtering <0.5° radius, of Hutschenreuter+22 map): $RRM_f = RM - GRM$
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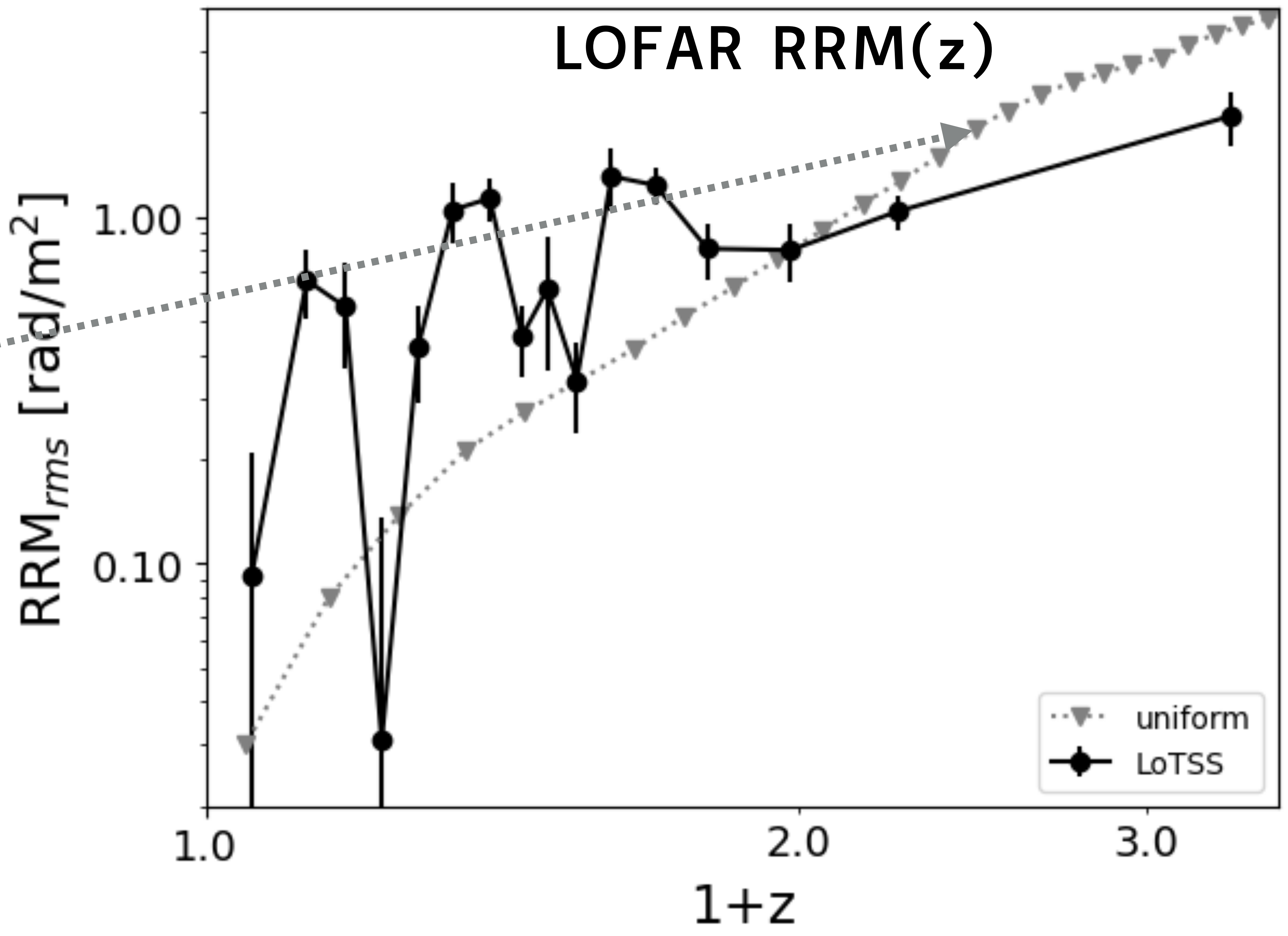
Uniform B model (0.1nG)



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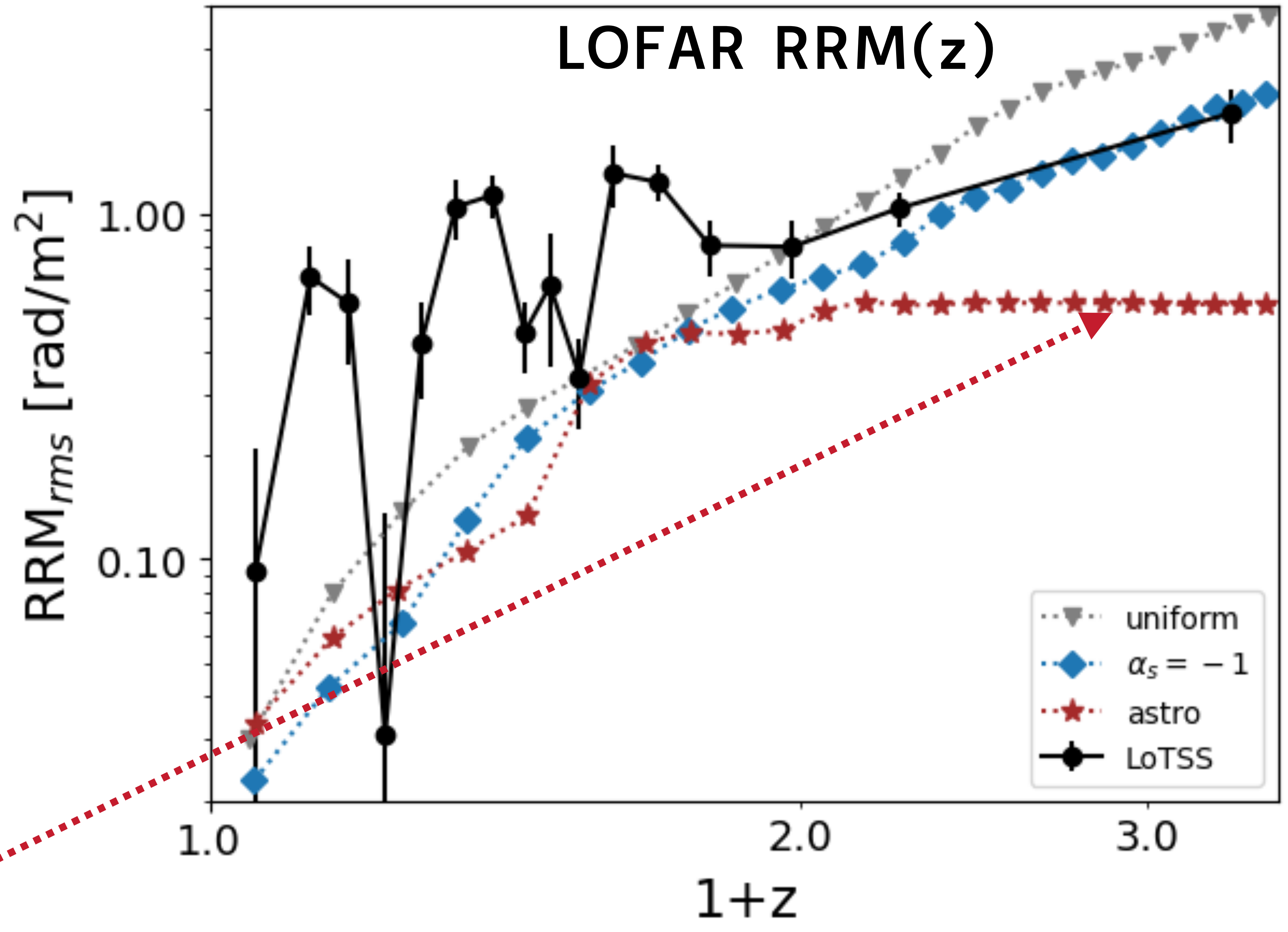
~~Uniform B model (0.1nG)~~

purely astrophysical seeding

(AGN+stellar winds)



CARRETTI + 23, 24

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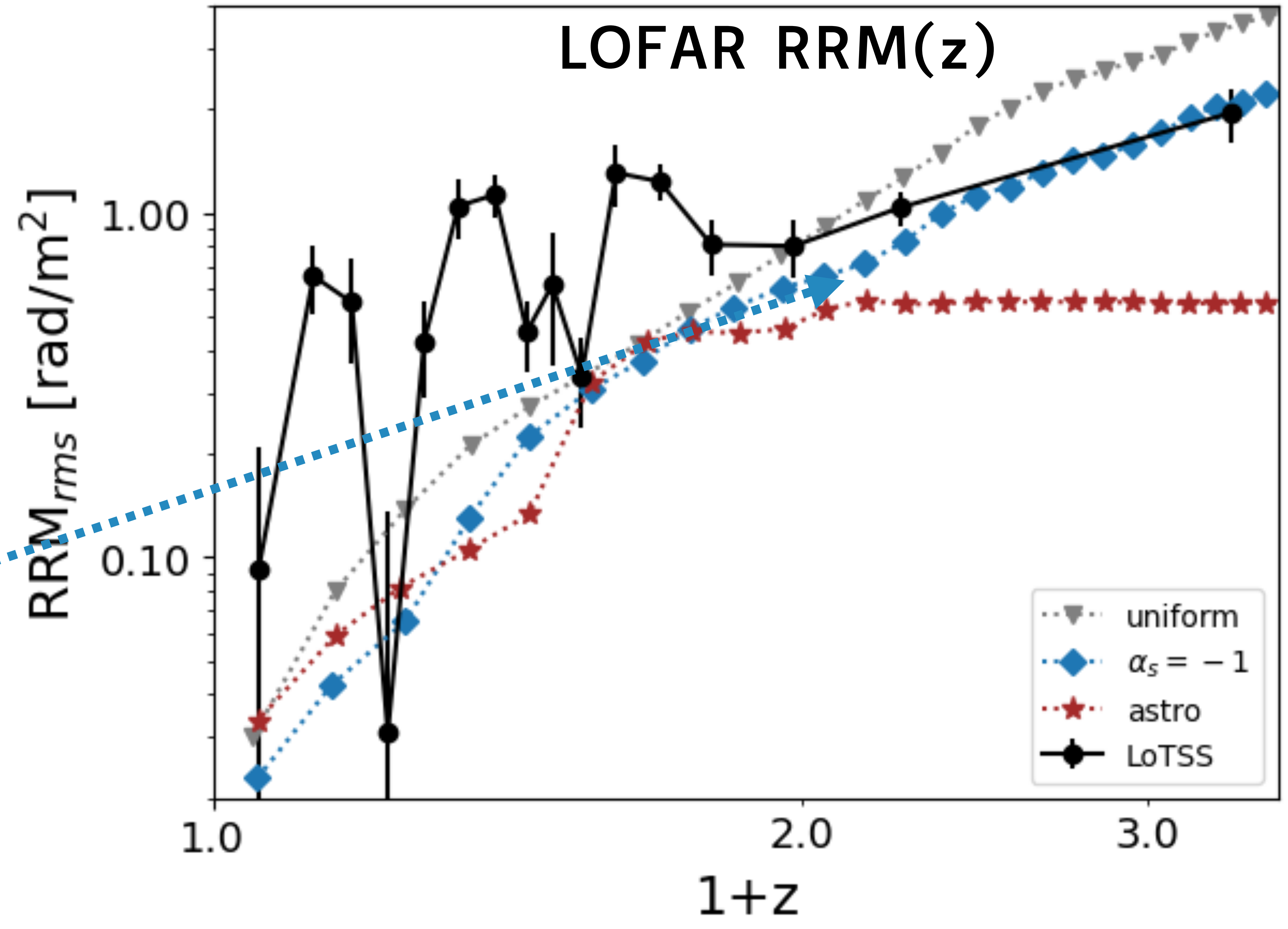
~~Uniform B model (0.1nG)~~

Primordial model with $P_B \propto k^{-1}$

~~purely astrophysical seeding~~

~~(AGN+stellar winds)~~



CARRETTI + 23, 24

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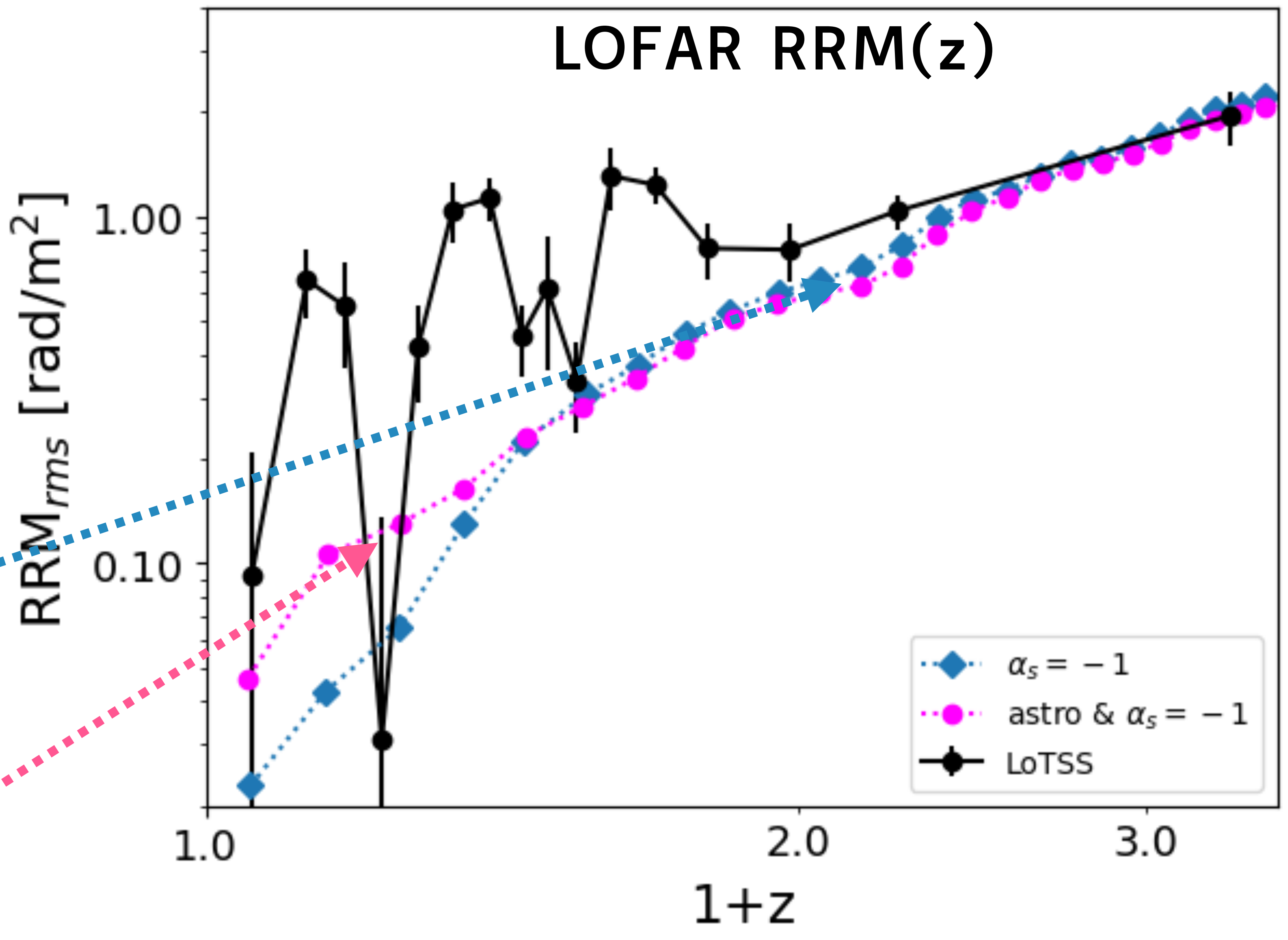

Primordial model with $P_B \propto k^{-1}$

Primordial model with $P_B \propto k^{-1}$ +astrophysical seeding

CARRETTI + 23, 24

DETECTING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS (?)

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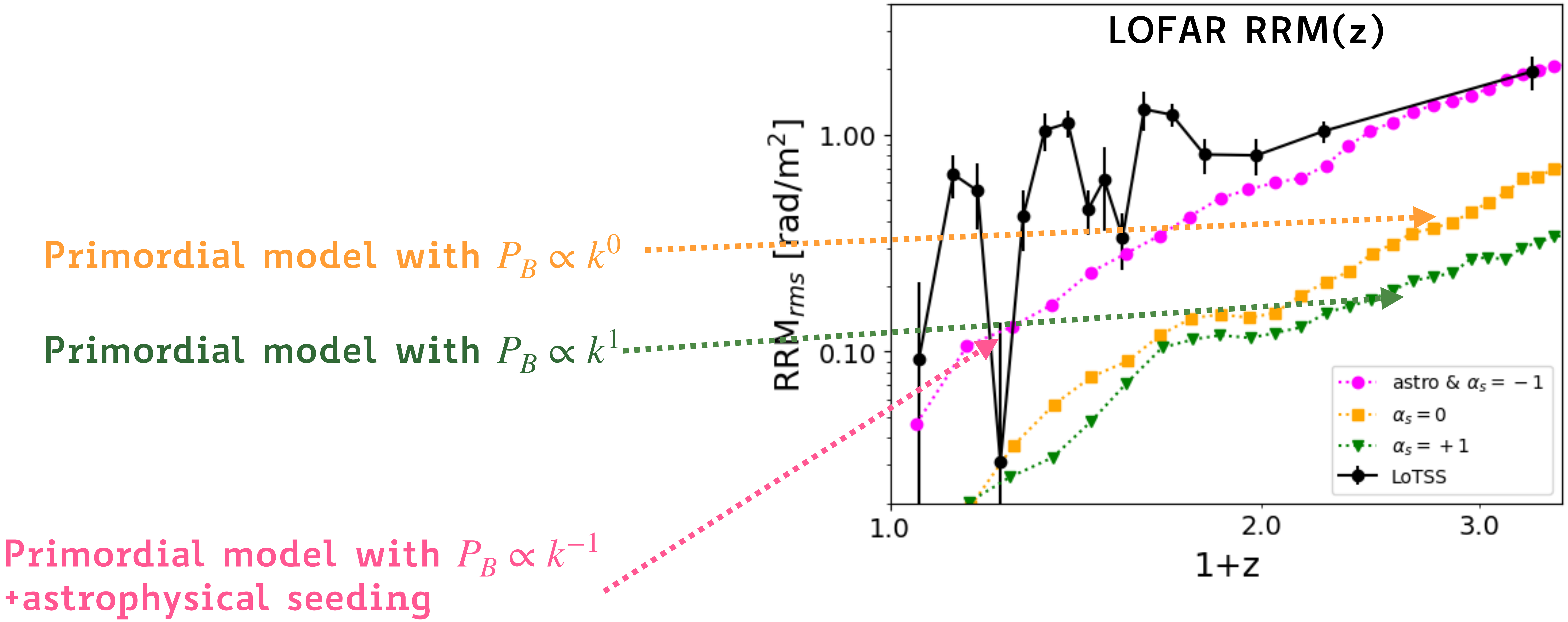

CARRETTI + 23, 24

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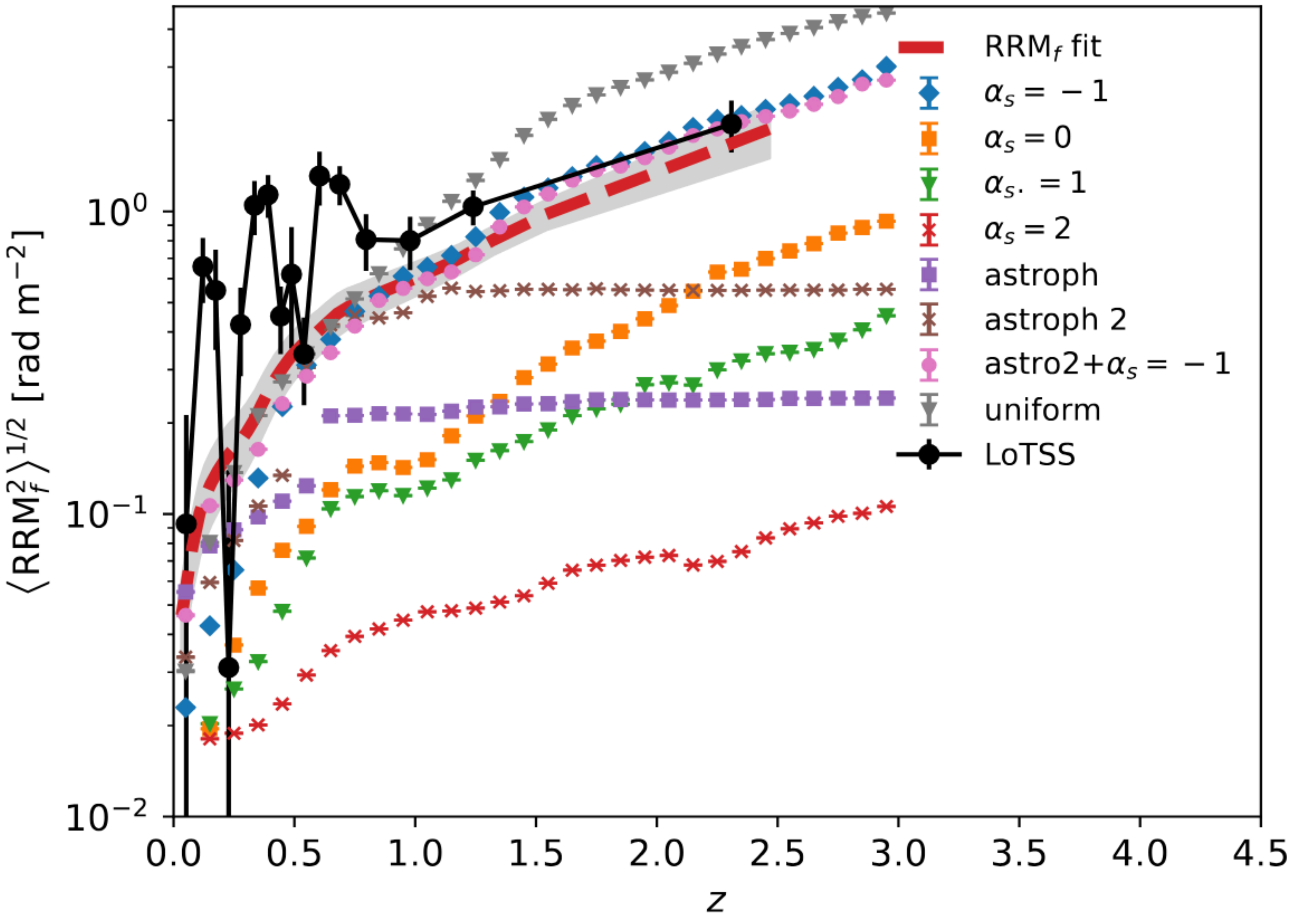


improvement over CMB limits

(Paoletti & Finelli 19) :

- $n_B = -1$ $1.87\text{nG} \rightarrow \sim 0.4\text{nG}$
- $n_B = 0$ $0.34\text{nG} \rightarrow \sim 0.07\text{nG}$
- $n_B = 1$ $0.04\text{nG} \rightarrow 0.004\text{nG}$

CARRETTI + 23, 24

DETECTING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS (?)

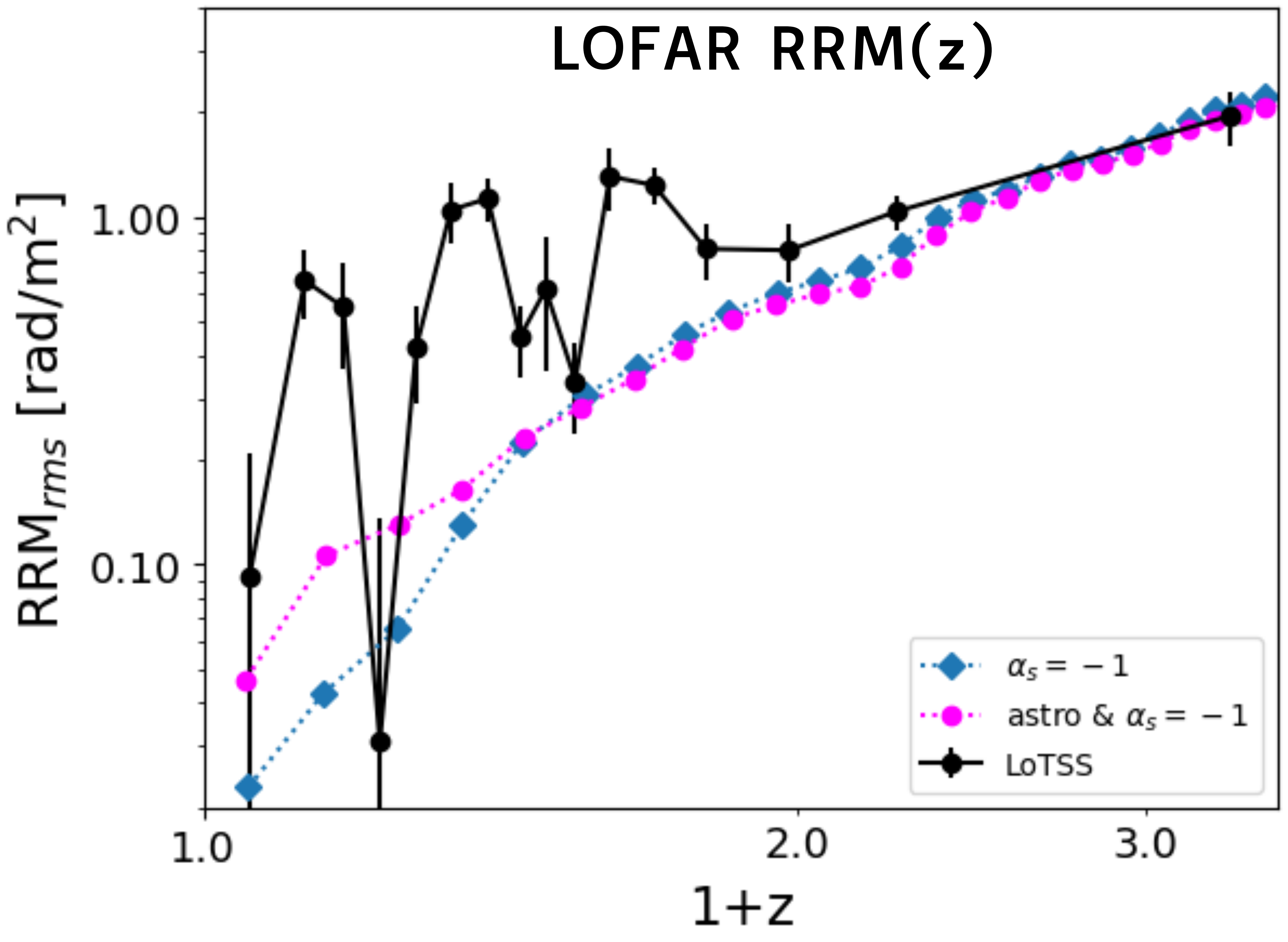
Bottom line:

- observed Residual Faraday Rotation implies volume filling B-fields up to $z \sim 3$, best explained by "primordial" models with $P_B \propto k^{-1}$ and $\langle B^2_{1Mpc} \rangle^{0.5} \leq 0.4\mathrm{nG}$

Notice:

- still wiggles and scatter in data
- procedure to remove the galactic FG is not settled
- interpretation depends on simulations (e.g. Bondarenko+24, Blunier & Neronov 24)

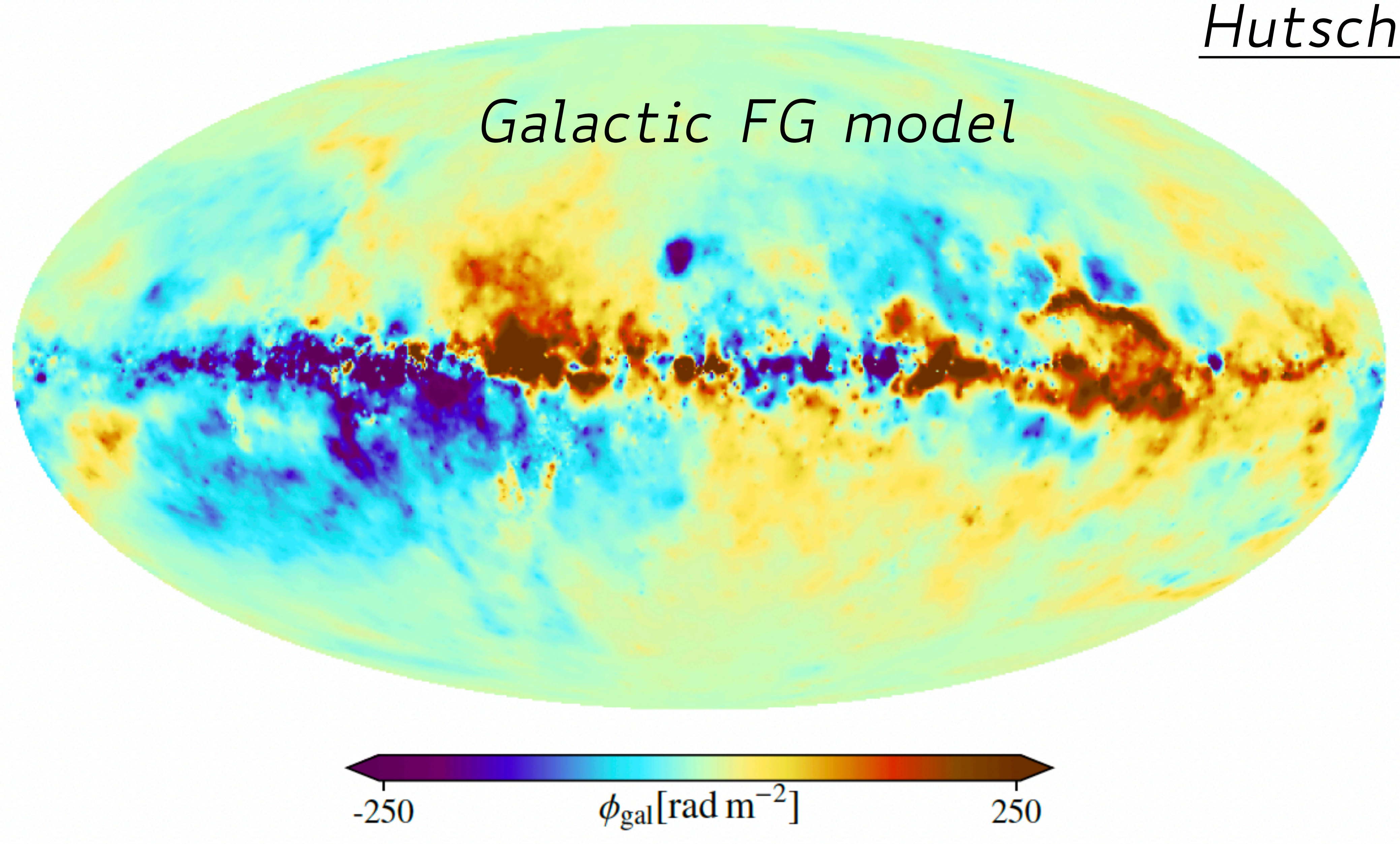
stil…enormous potential, which the SKA will fully exploit

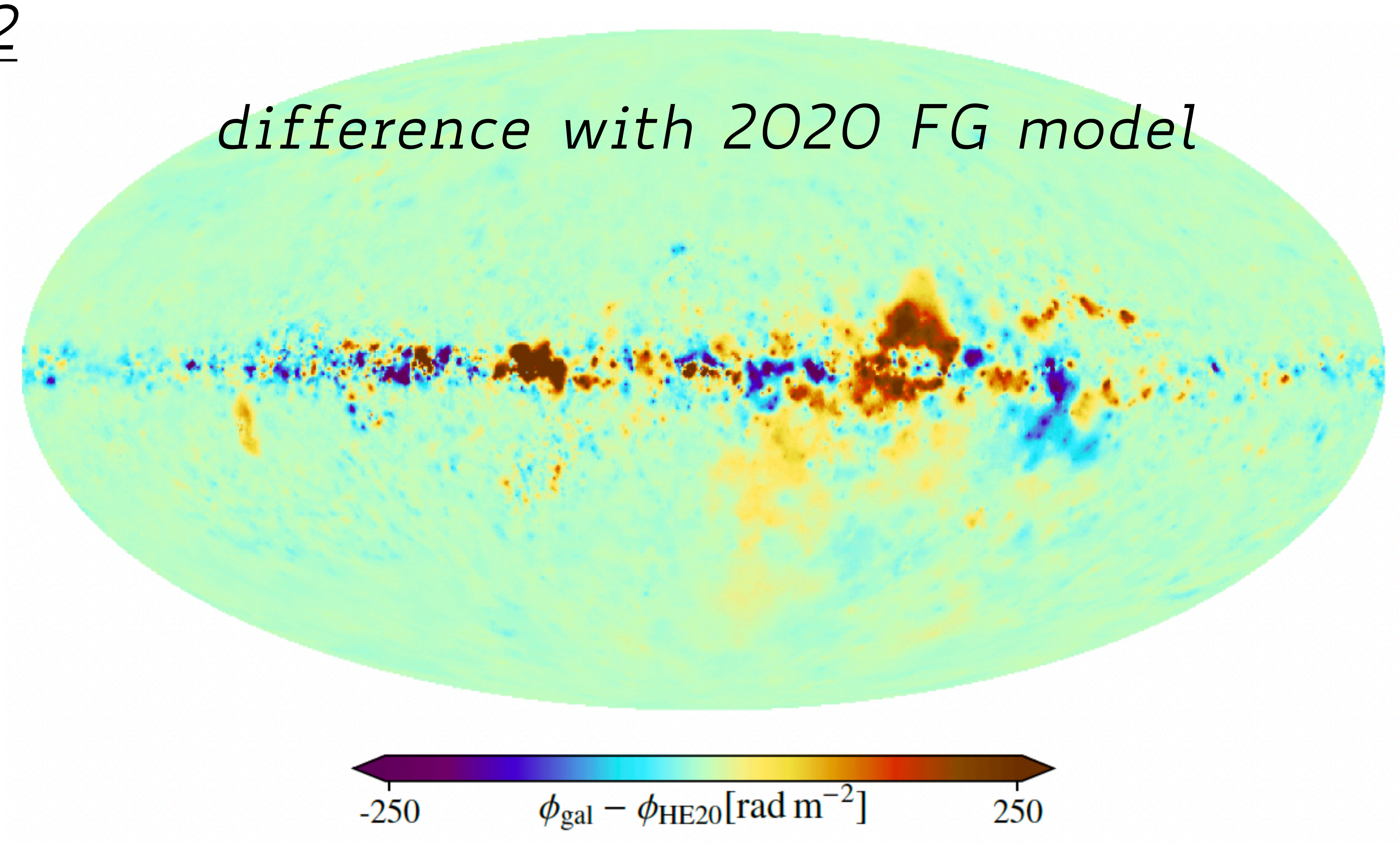


CARRETTI + 23, 24

CAVEATS..

<u>*Hutschenreuter+22*</u>



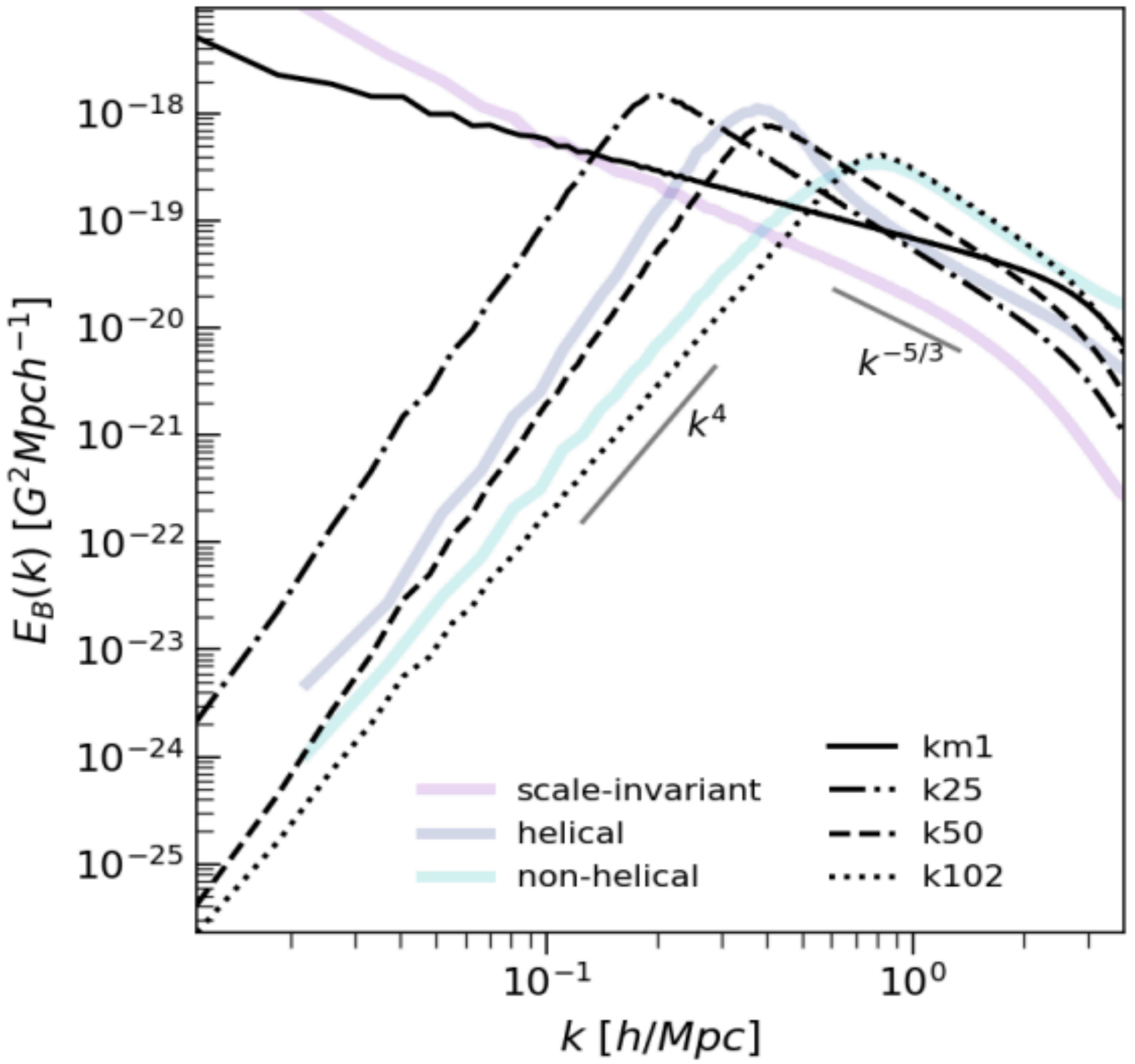


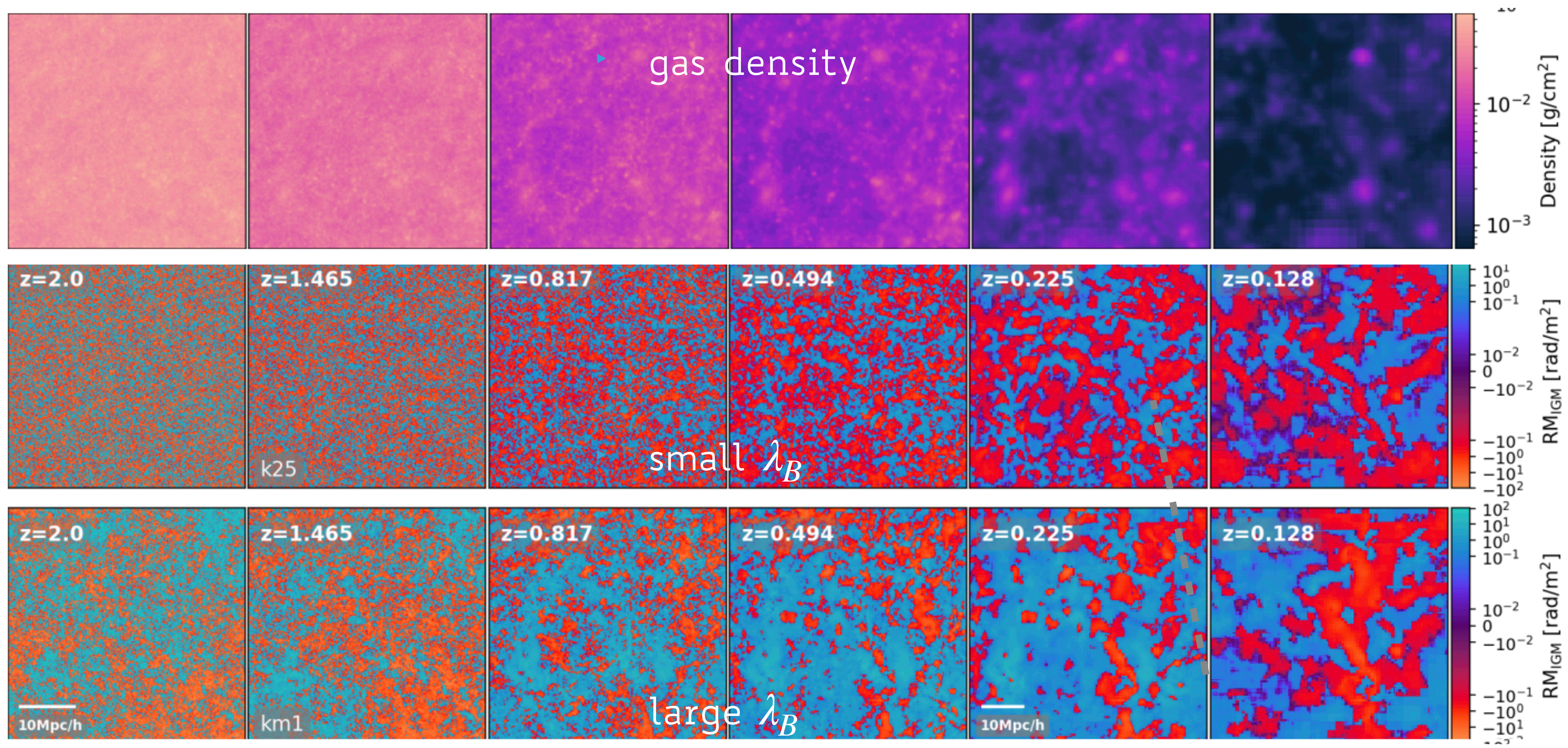
GALACTIC FOREGROUND MODEL: *different possible approaches can lead to slightly different estimates. Small-scale galactic contributions important?*

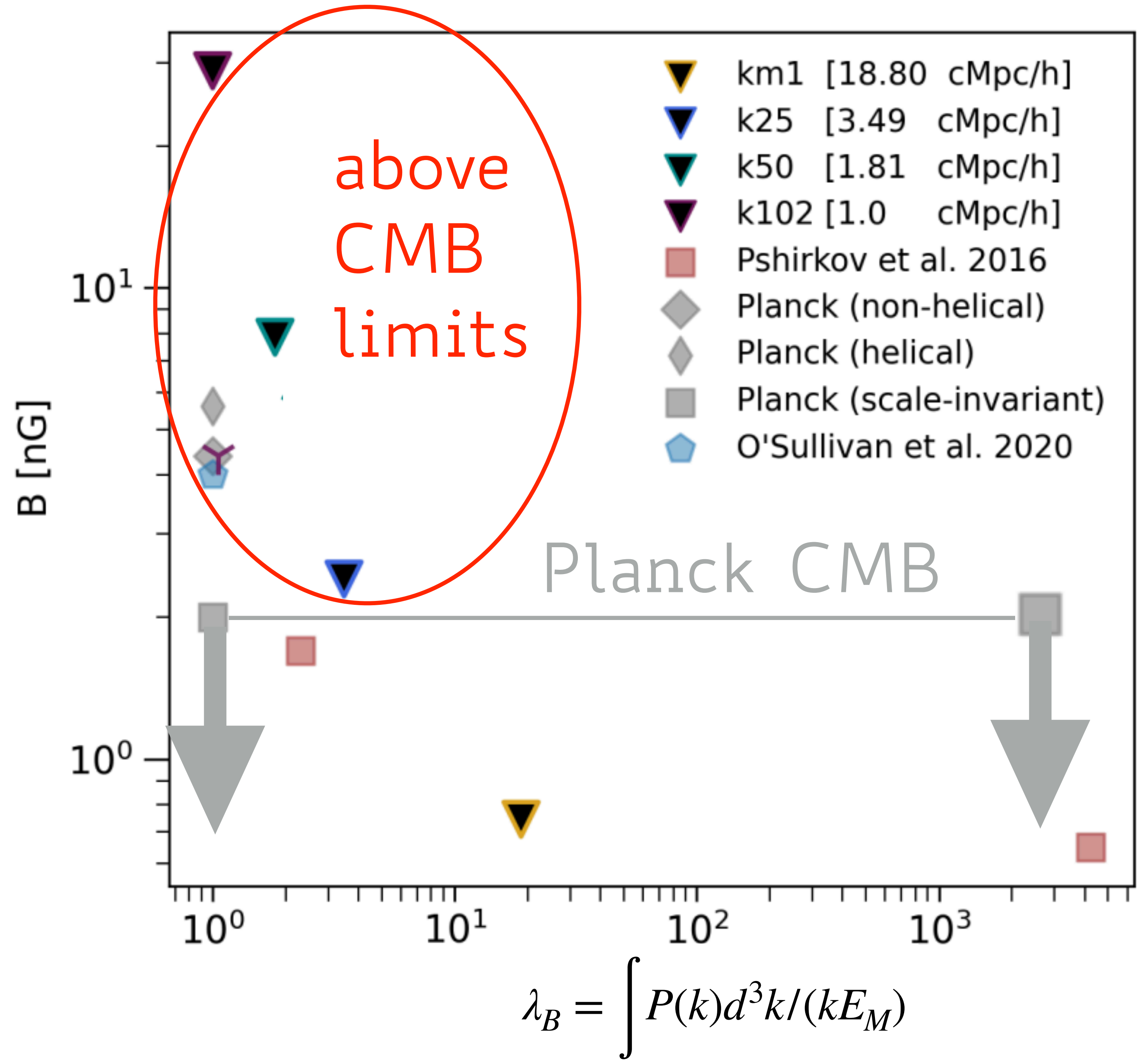
DIFFERENCE BETWEEN SIMULATIONS (or groups looking at the same simulations): e.g. Bondarenko+24 vs Blunier & Neronov 24 using IllustrisTNG

The future: the Square Kilometre Array *will allow a finer and more reliable reconstruction of the Galactic FG model (also using FRBs).*

DETECTING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS (?)



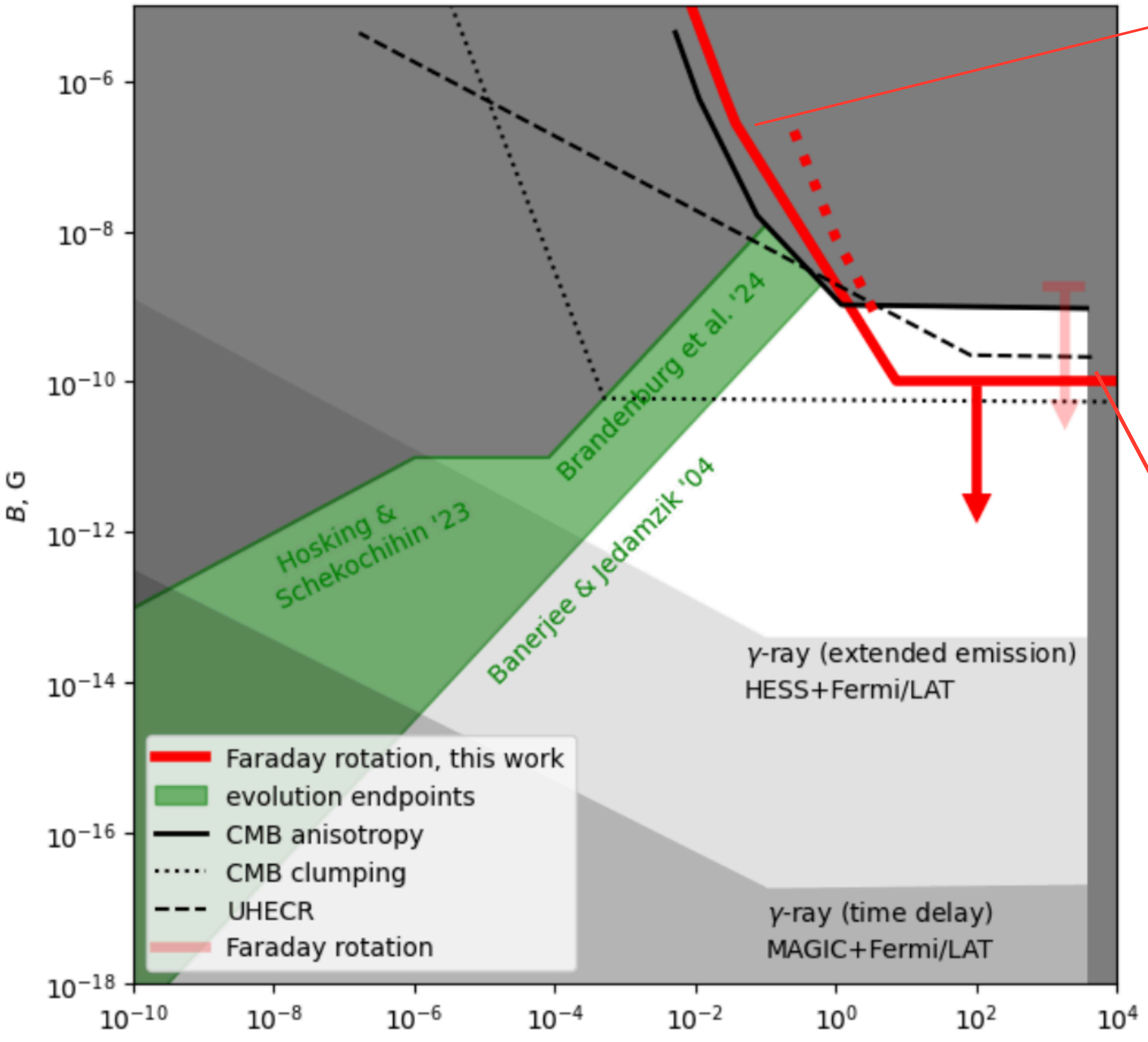




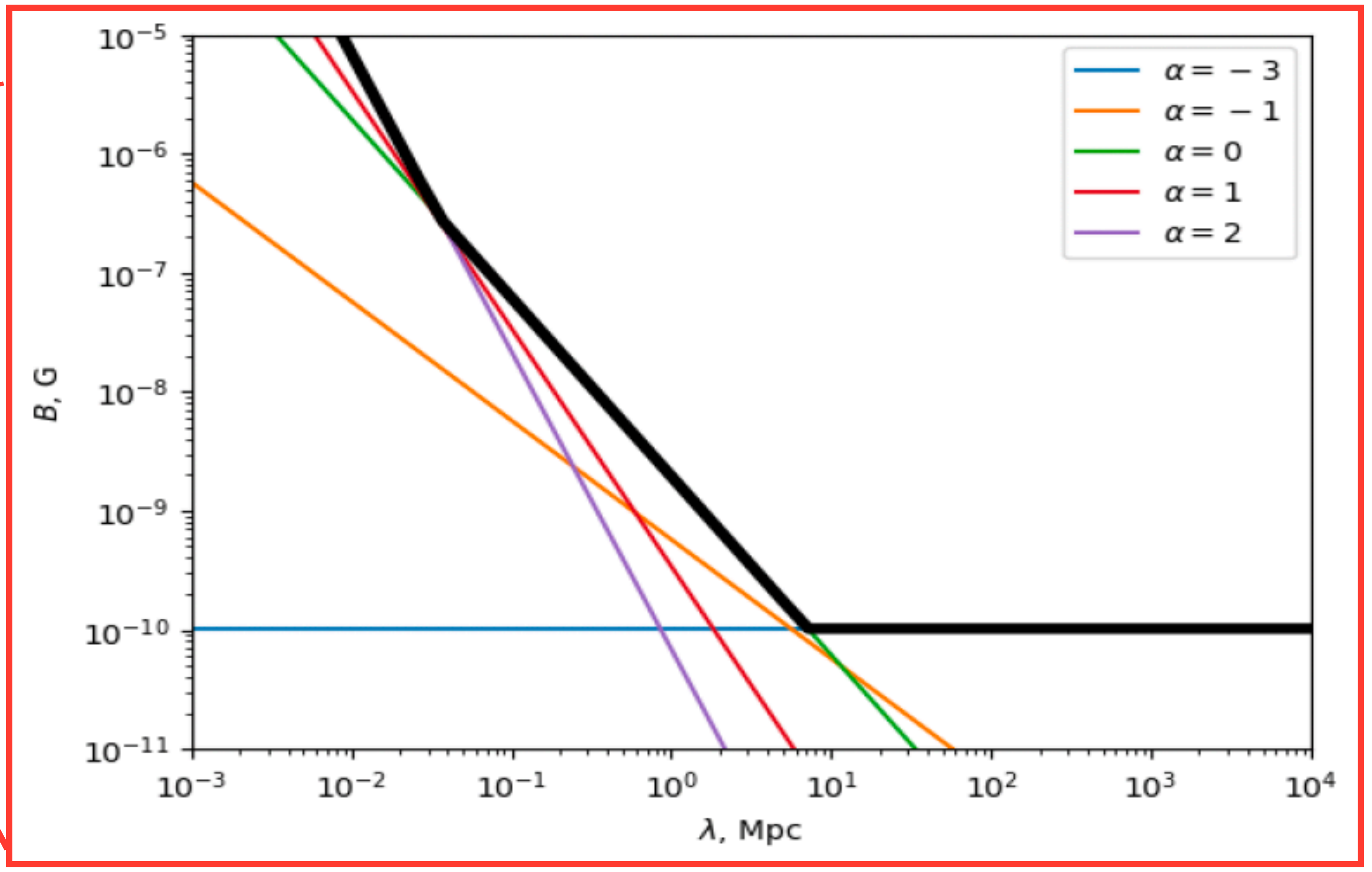
- Simulations of causal primordial B-fields with a finite maximum scale λ_B (initial conditions from Pencil)
- to fit RRM data, small scale causal models require normalisation > CMB allowed limits

MTCHEDLIDZE ET AL. 2024

DETECTING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS (?)



$$\lambda_B = \int P(k) d^3k / (k E_M)$$



combinations of (λ_B, B, n_B) allowed by LOFAR RRM

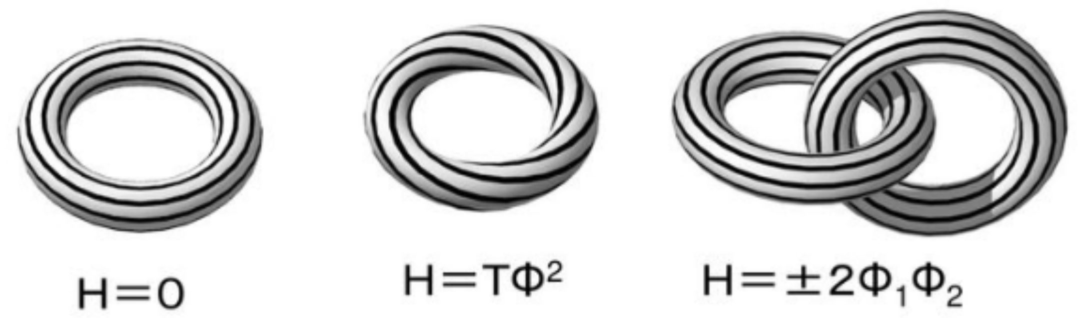
- Low-z radio data now more constraining than CMB for scale-invariant (like) spectra.
- CMB anistotropies & clumping better constrain $\lambda_B \ll 1\text{Mpc}$ fields.
- Detection of $\lambda_B \ll 1\text{Mpc}$ fields would be inexplicable also for astrophysical models!

NERONOV, FV, MTCHEDLIDZE & CARRETTI, SUBMITTED

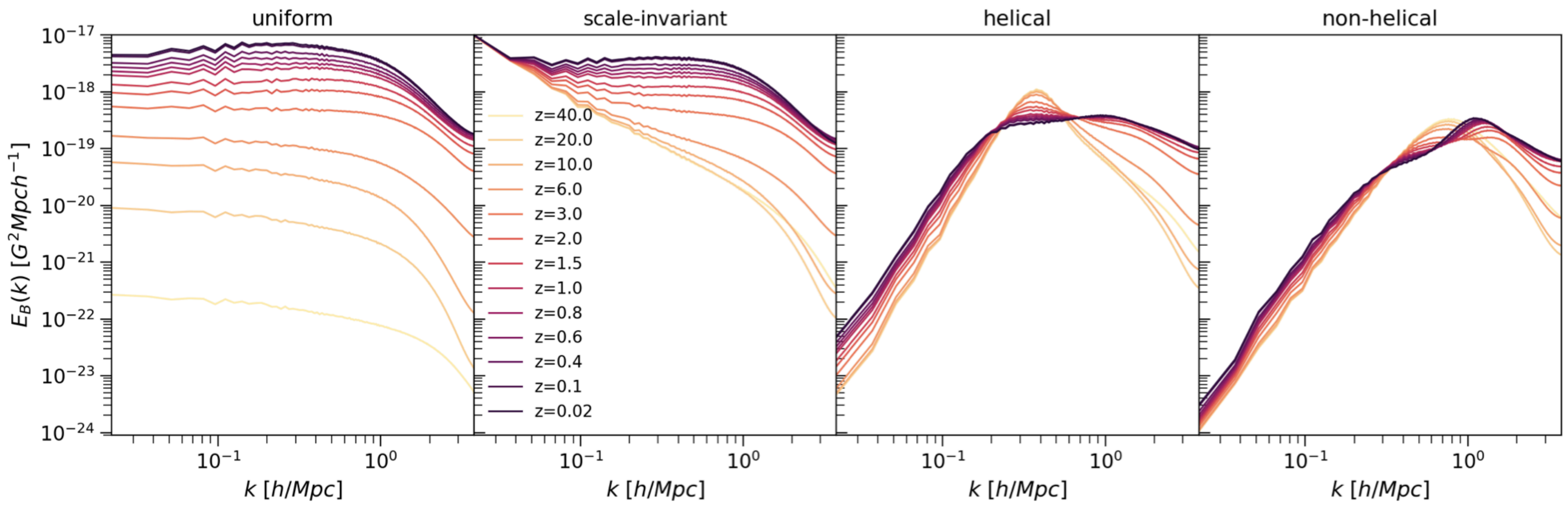
HELICAL PRIMORDIAL FIELDS

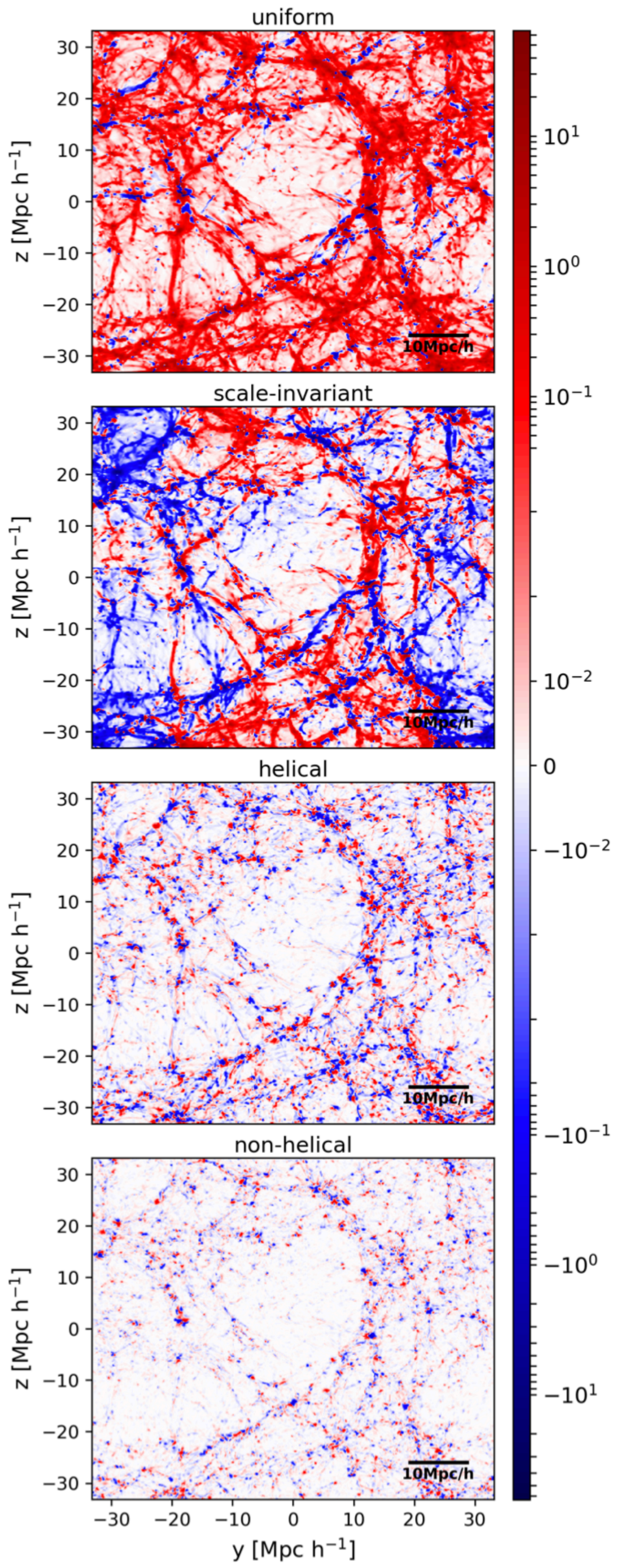
$$H = \int \vec{A} \cdot \vec{B} \, d^3x$$

(conserved in high conductive plasma)



- First simulations of helical magnetic fields in cosmology. Does helicity lead to different (and detectable) large-scale IGMFs?
- Detecting primordial helicity would directly imply parity violation and explain matter-antimatter asymmetry!



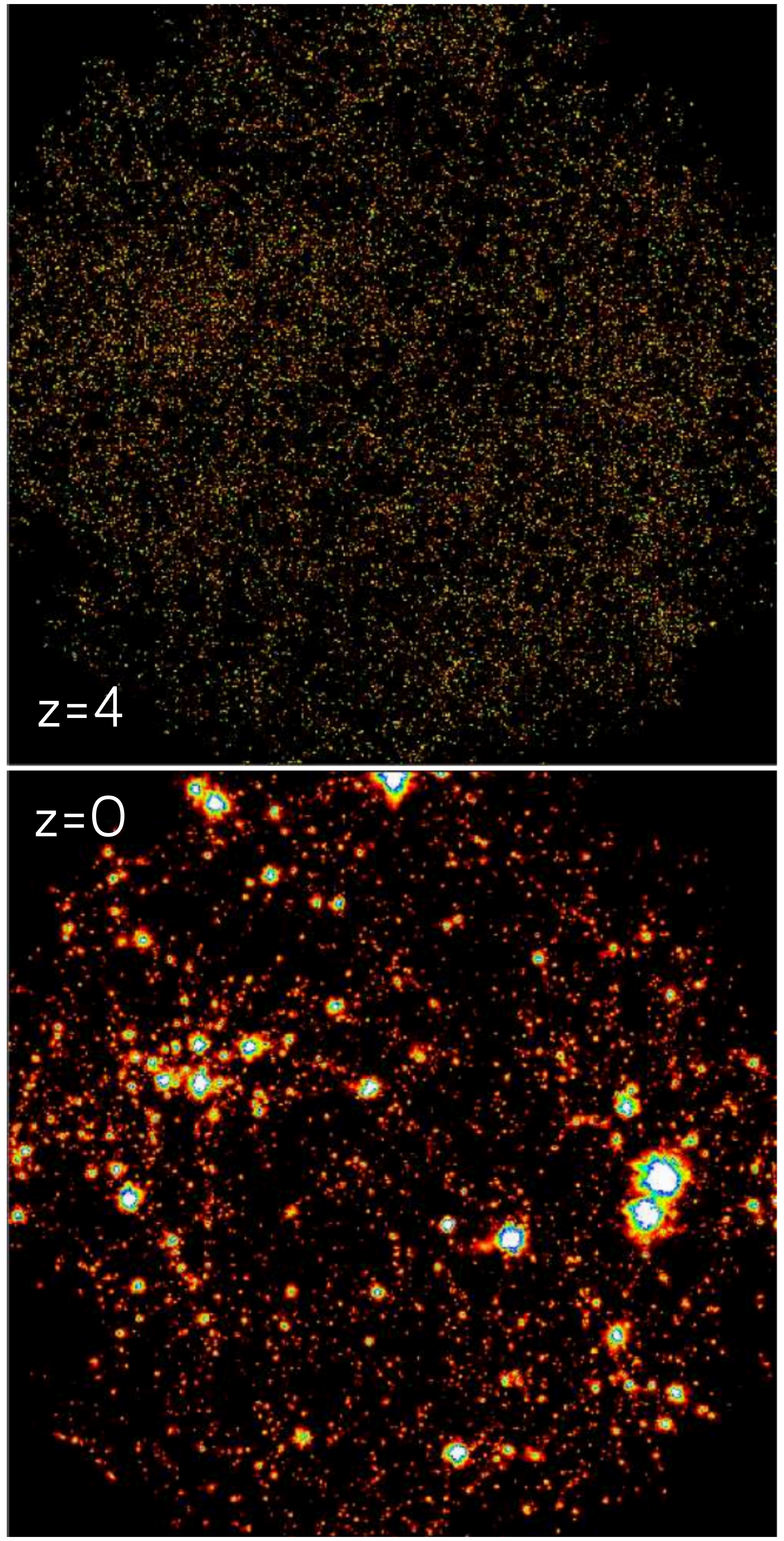


MTCHEDLIDZE+22, 23

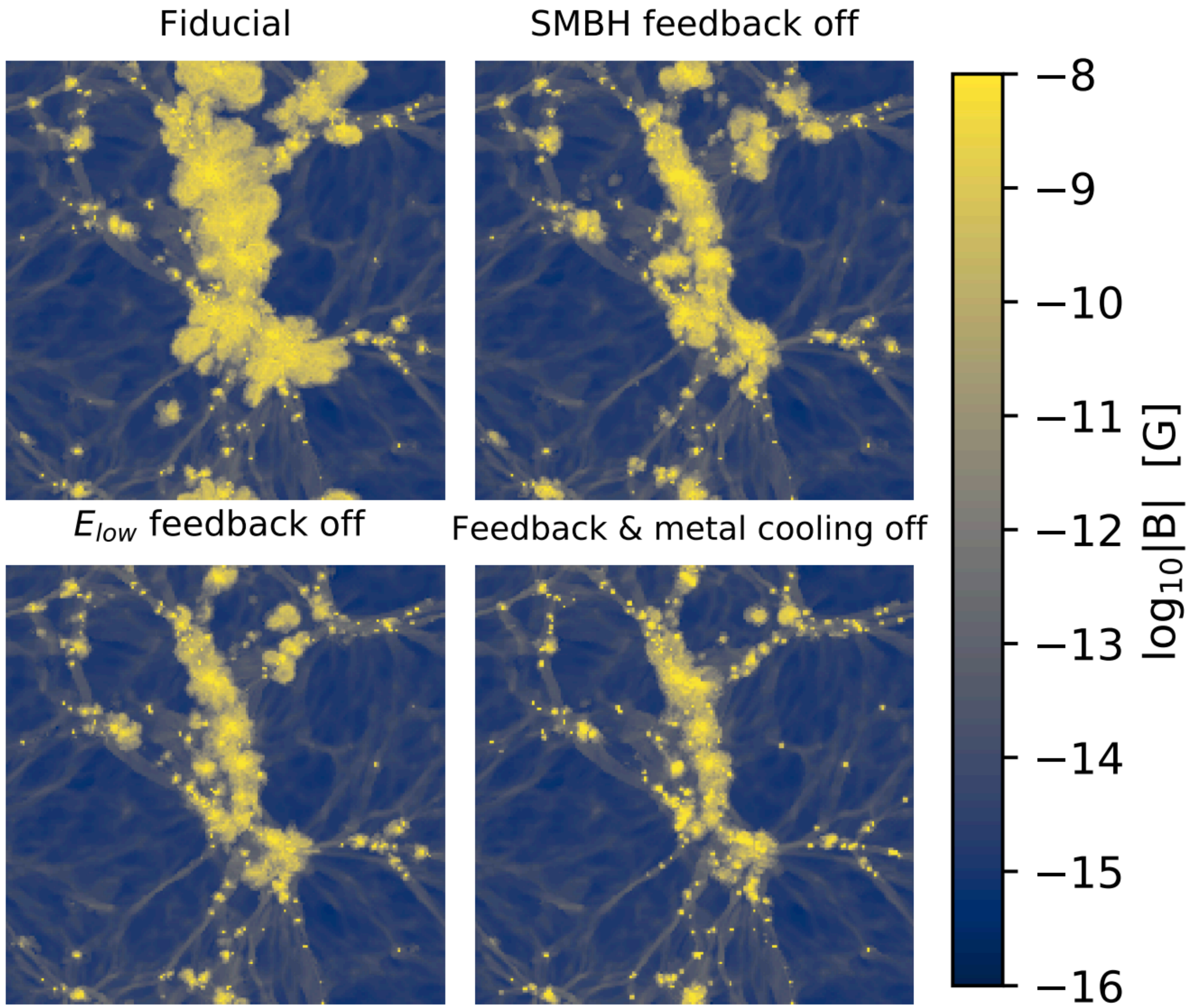
CAN FEEDBACK OUTSHINE PRIMORDIAL B-FIELDS?

Filling factors & strength of magnetic fields ejected by galaxies <u>not well constrained.</u>

Uncertainties related to **galaxy formation & feedback**



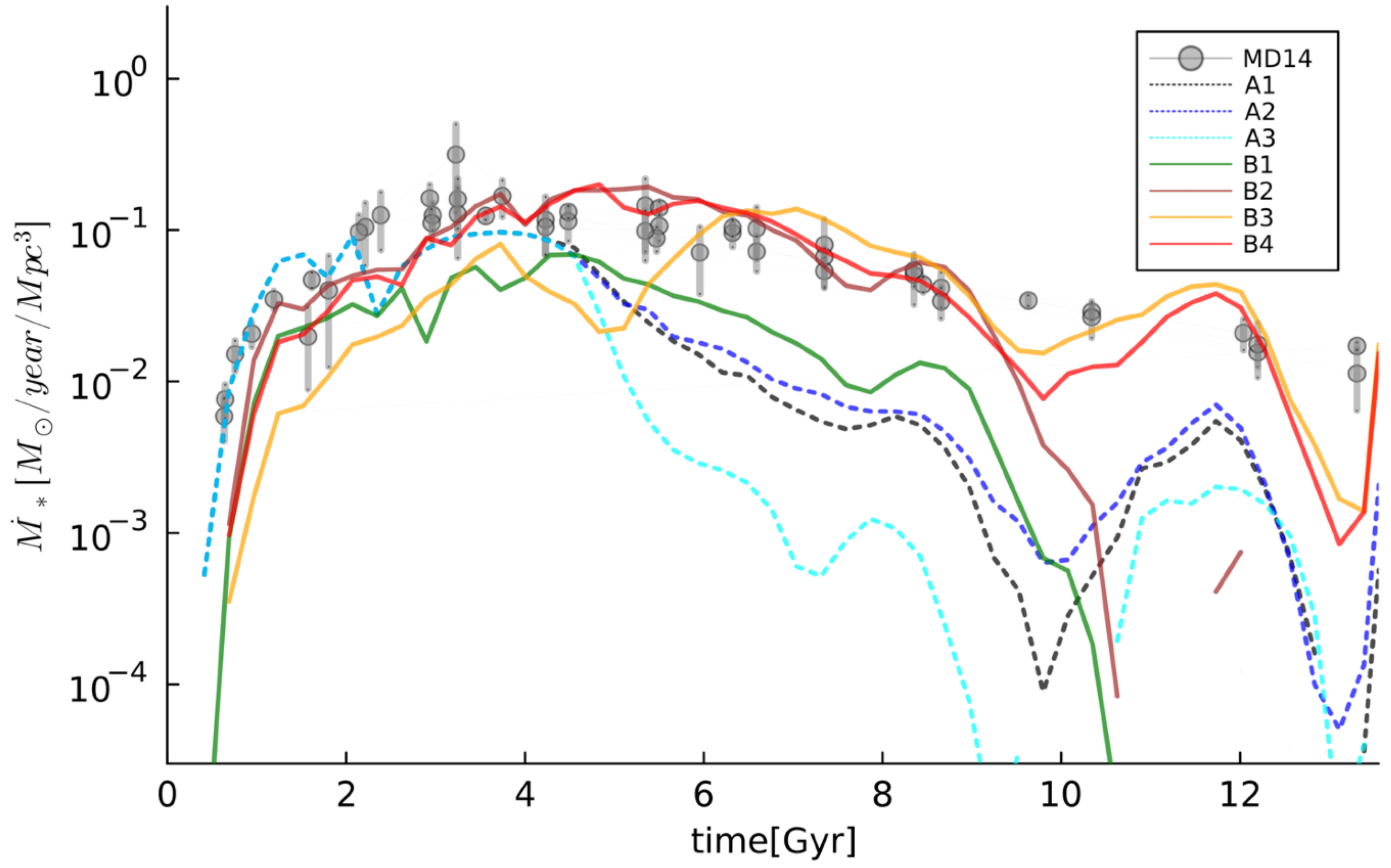
Donnert, Dolag et al. 2009



Aramburo-Garcia, Bondarenko et al. 2021,22

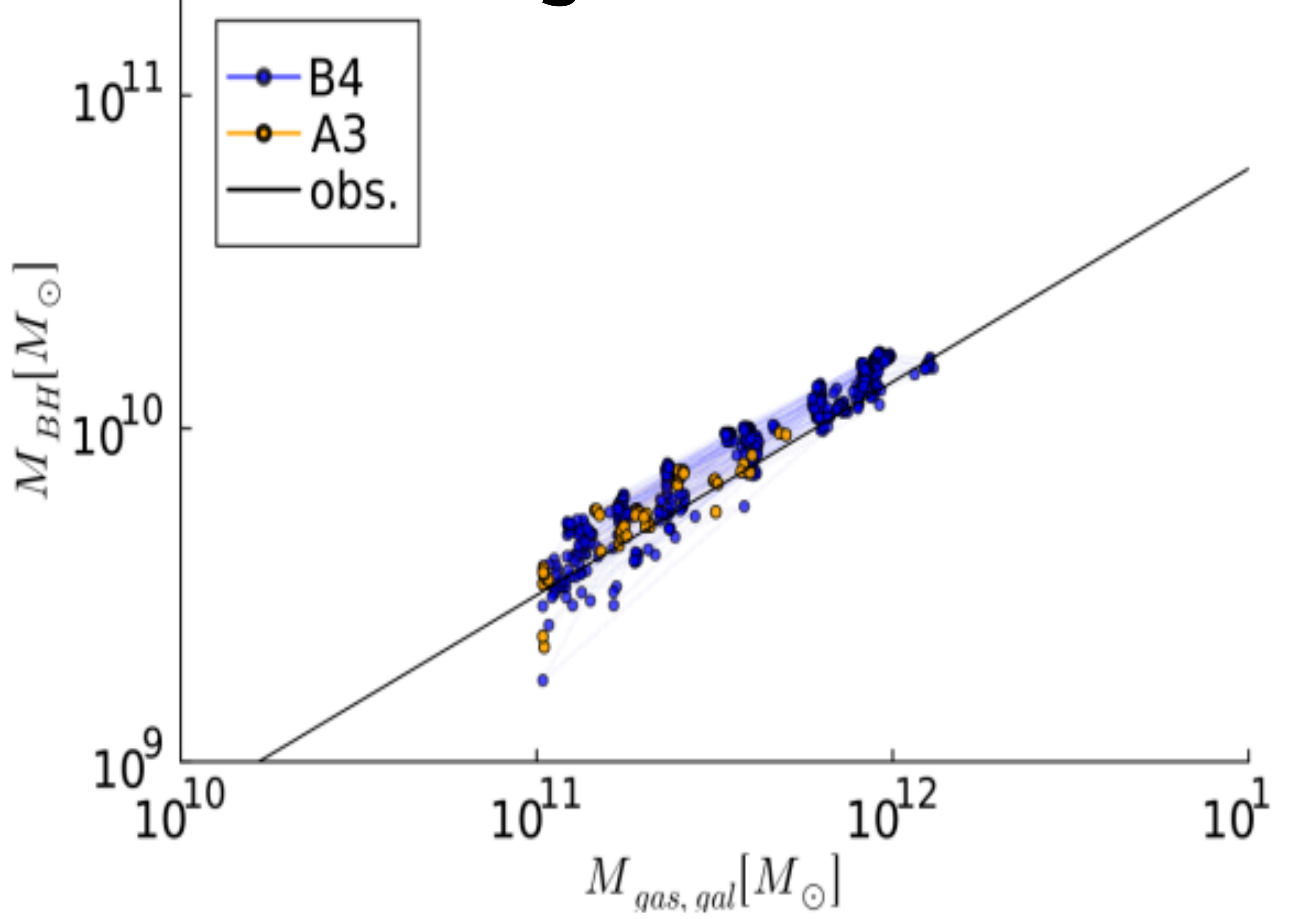
CAN FEEDBACK OUTSHINE PRIMORDIAL B-FIELDS?

cosmic star formation rate

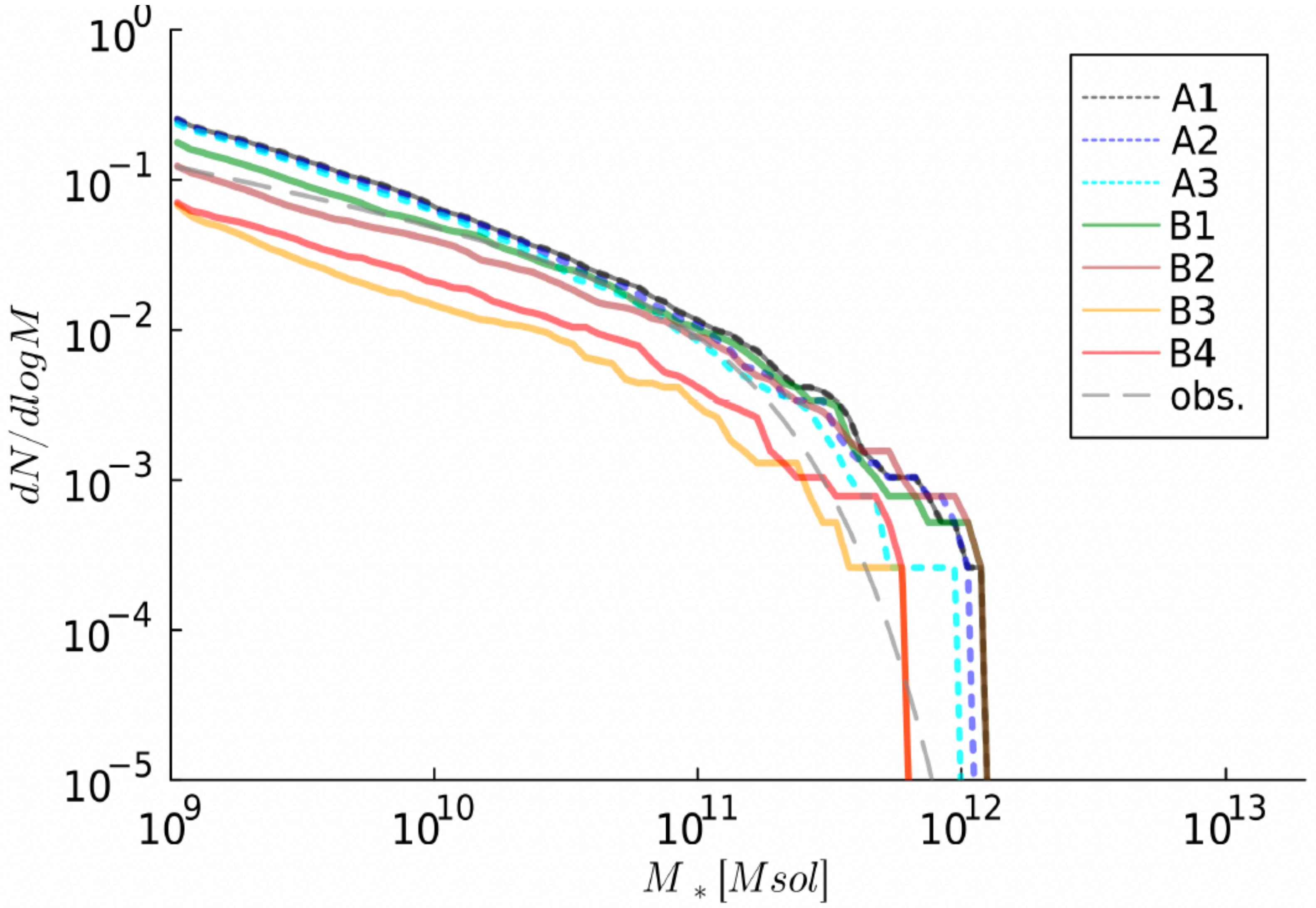


- New ENZO MHD simulations tuned to reproduce **cosmic star formation, stellar mass function, stellar fraction, radio galaxy luminosity functions**
- Star formation (Kravtsov+02) + SMBH feedback (kinetic/thermal) coupled with **B-field**
- CRe fluid sourced by shocks (DSA), star formation and AGNs

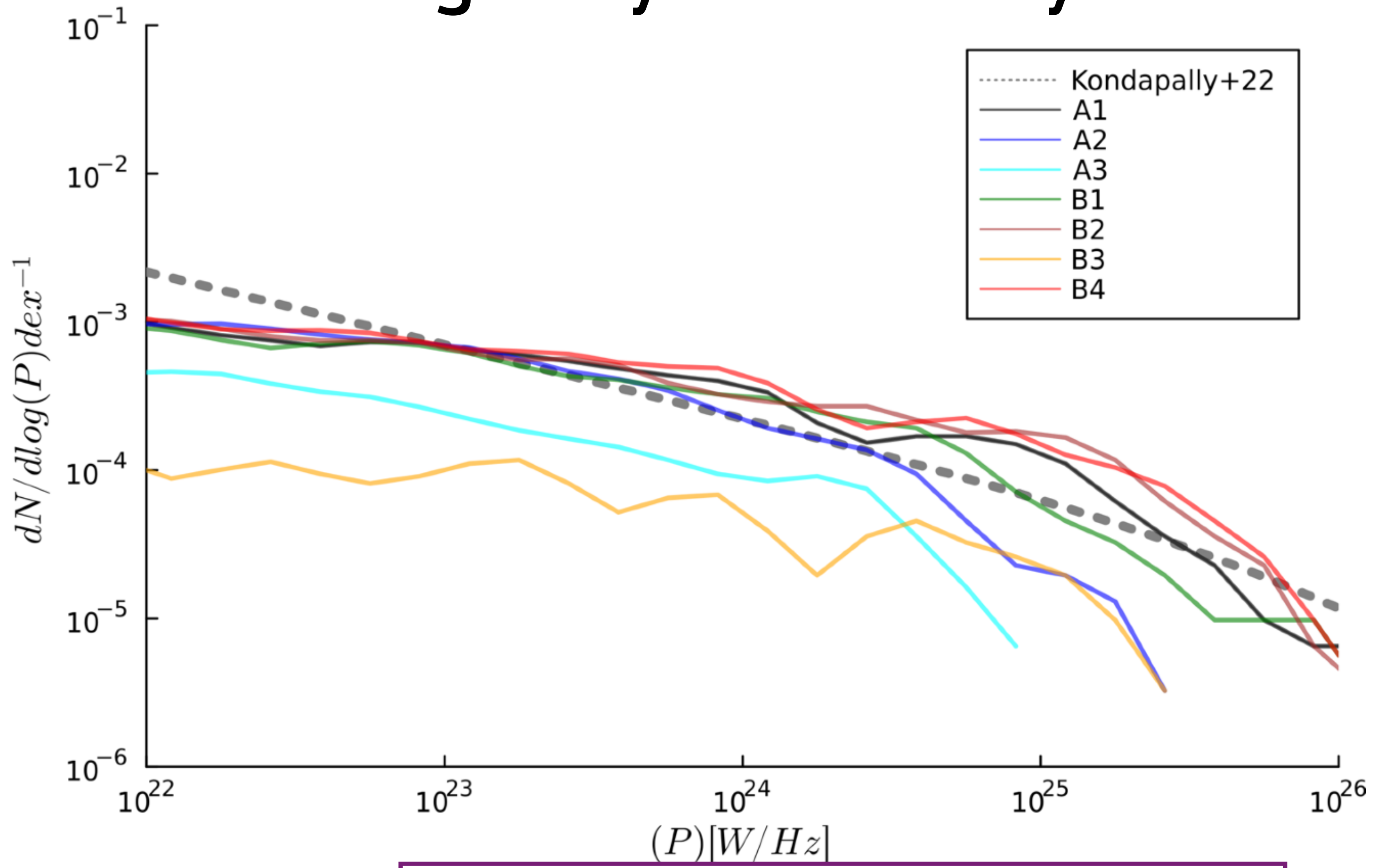
BH - halo gas mass relation



galaxy stellar mass function

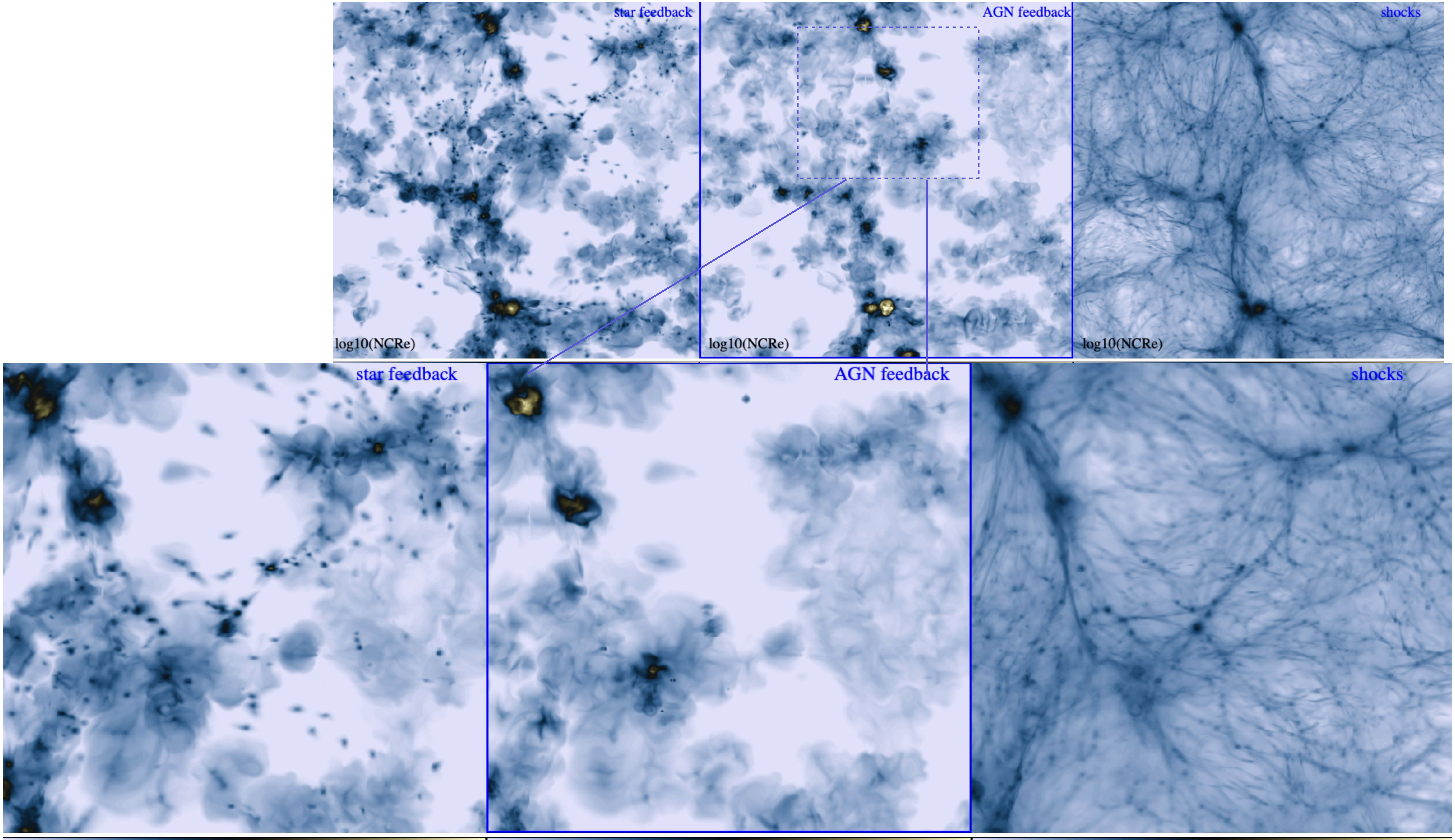


radio galaxy luminosity function



FV ET AL., 2025 A&A

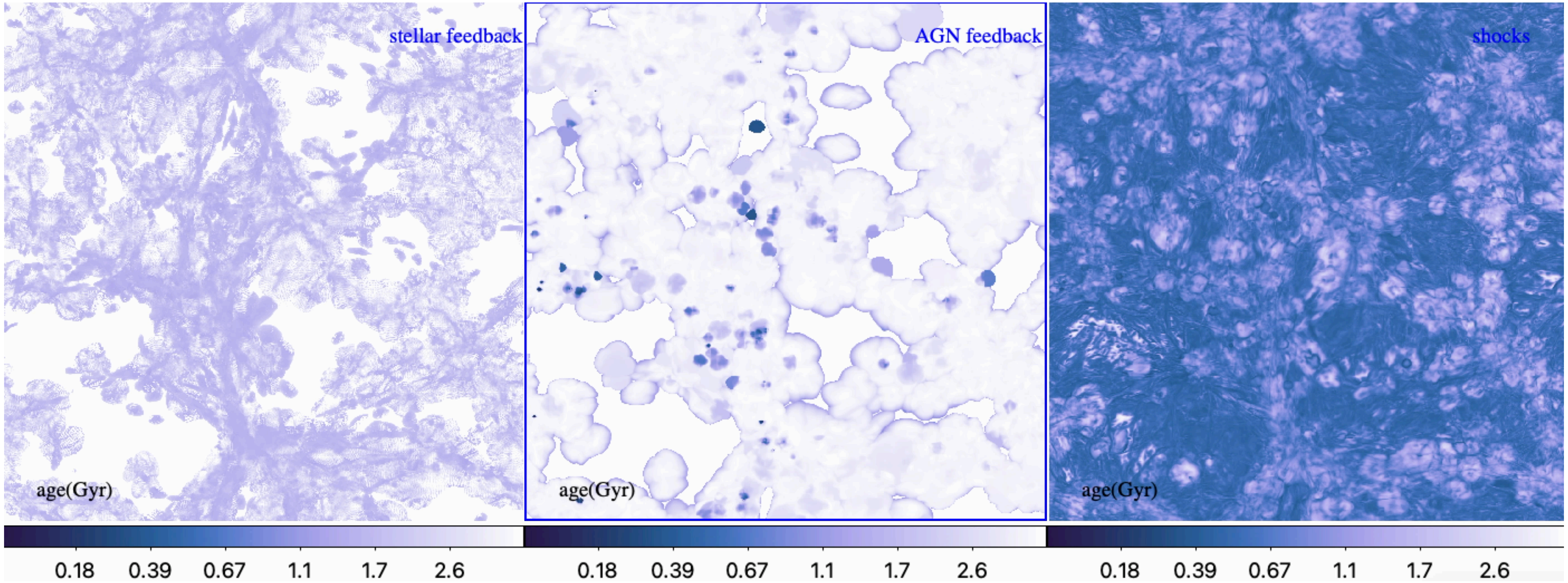
CAN MAGNETISED OUTFLOWS OUTSHINE PRIMORDIAL B-FIELDS?



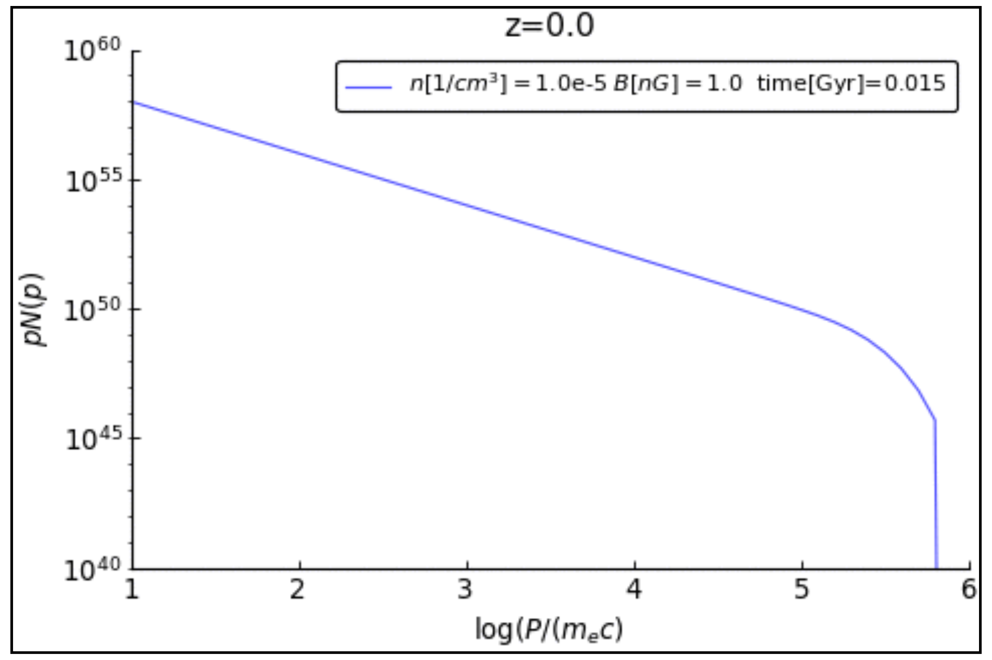
SEEDING OF ELECTRONS (AND B-FIELDS) BY RADIO JETS

"Age" of the CRe fluid (i.e. elapsed time since last injection)

$n'_{CRe} \propto e^{-t/\tau}$ → $t_{age} = -\tau \log\left(\frac{n'_{CRe}(t)}{n_{CRe}(t)}\right),$



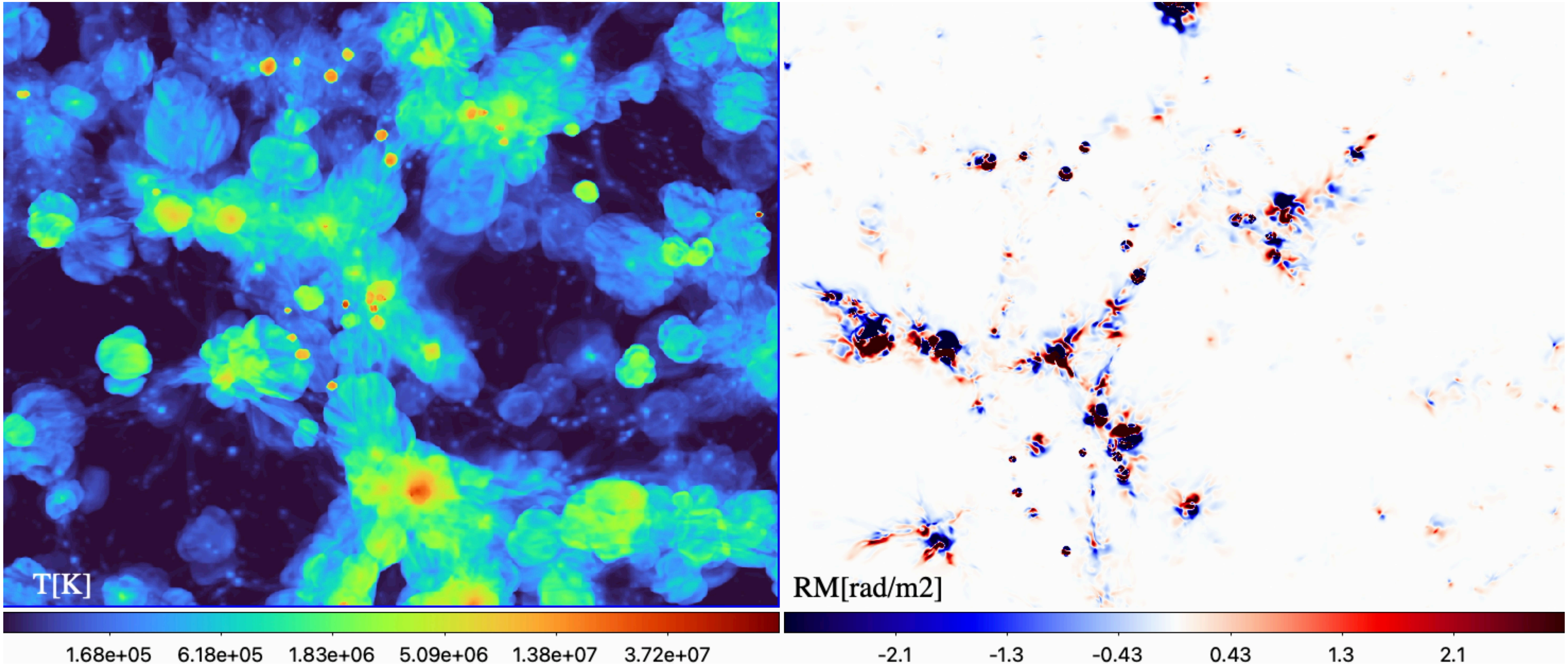
From the age & local conditions (ρ, B, T) we can compute with good approximation the radio emission



FV ET AL., 2025 A&A

ASTROPHYSICAL SEEDING OF B-FIELDS

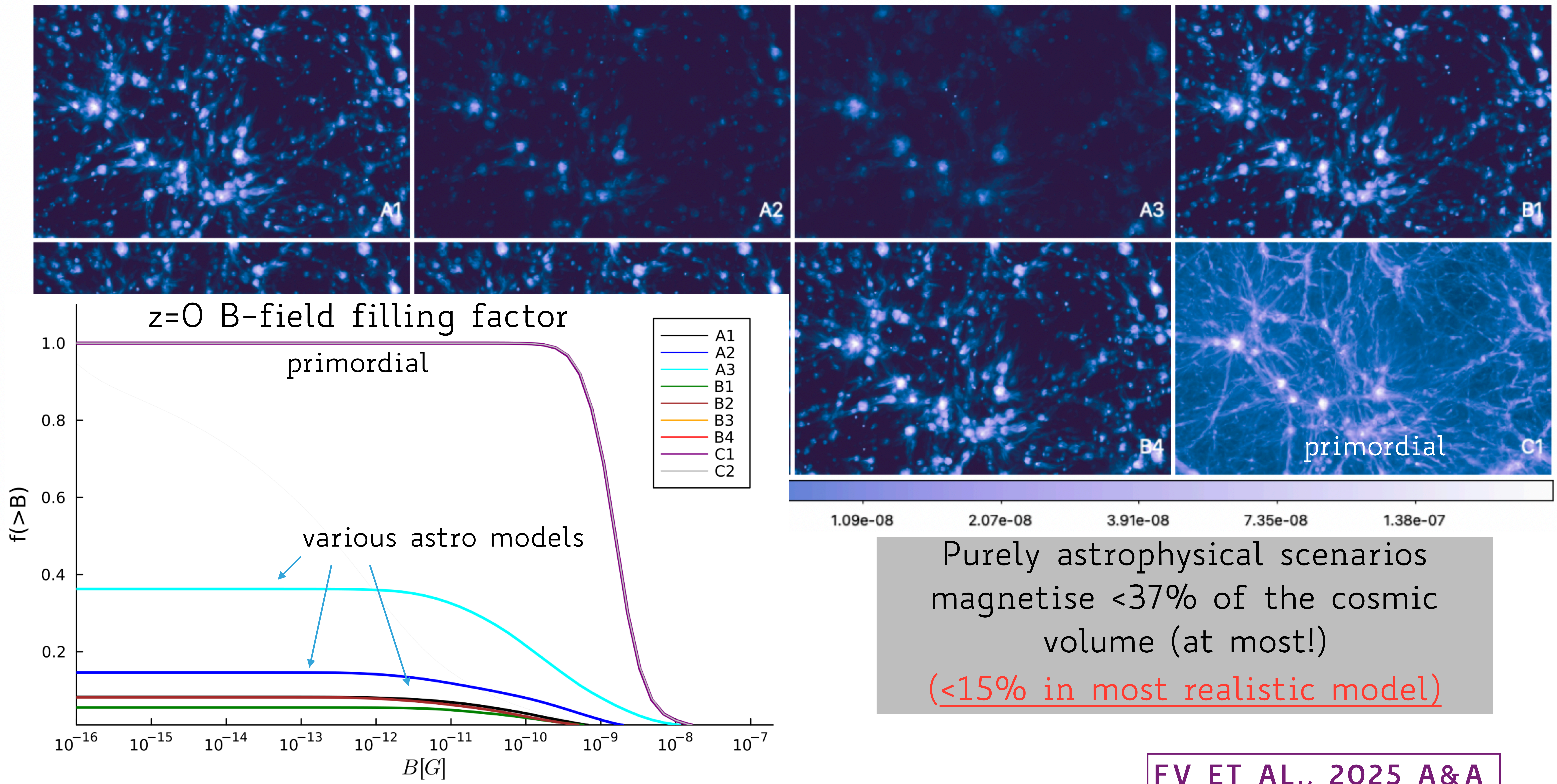
updated view on RM from the best purely astrophysical scenario:



(just a 42 Mpc depth along the LOS)

FV ET AL., 2025 A&A

PRIMORDIAL VS ASTROPHYSICAL SEEDING OF B-FIELDS

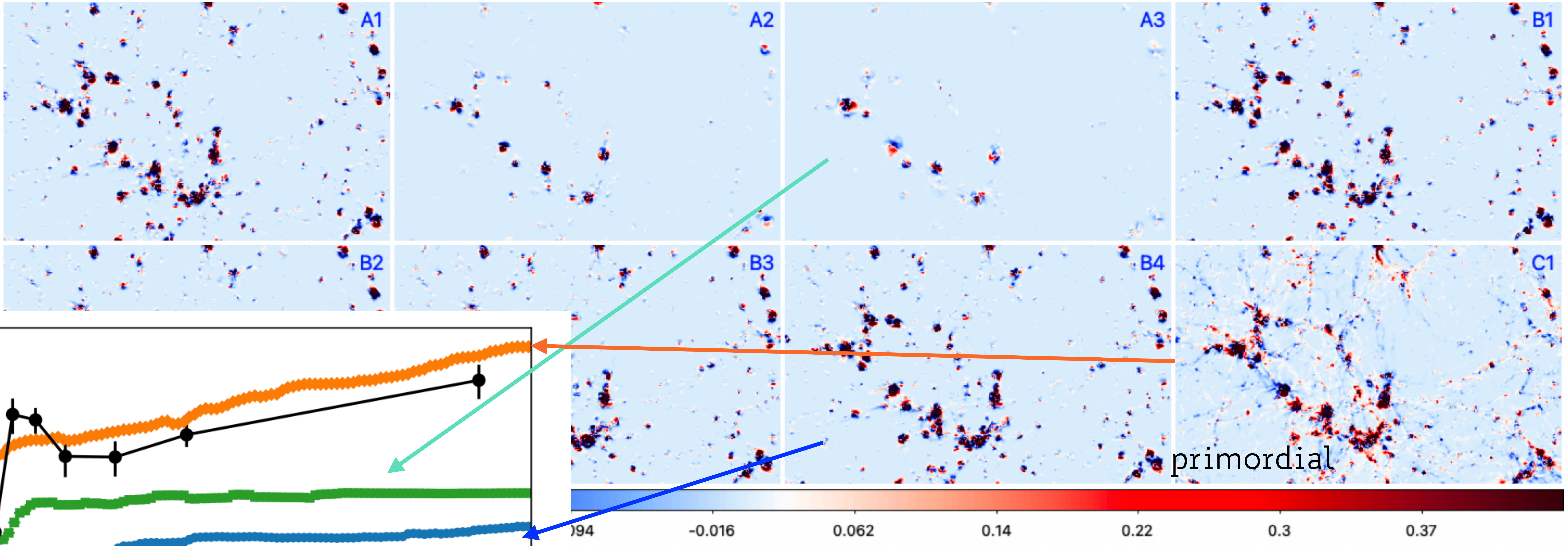


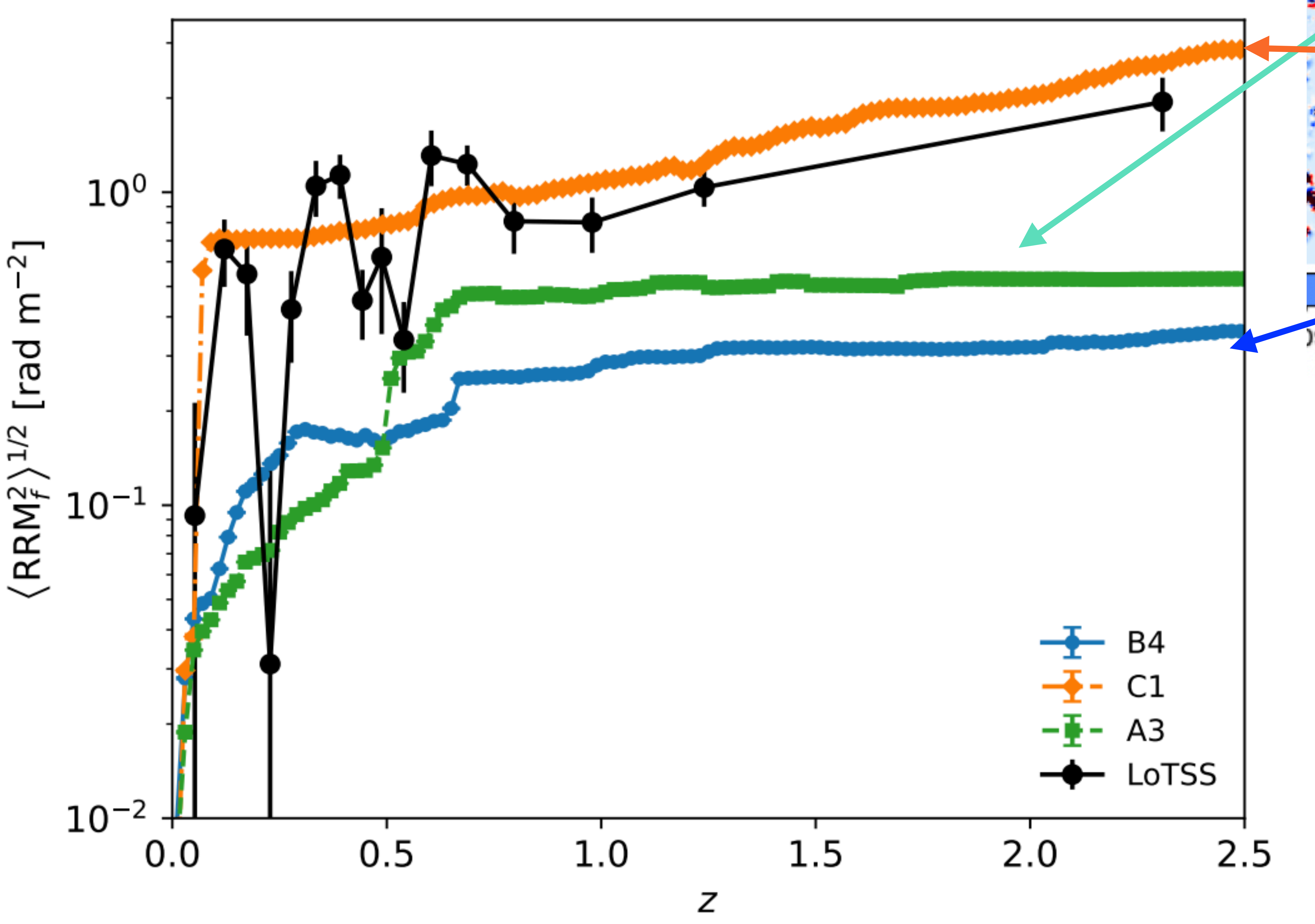
Purely astrophysical scenarios magnetise <37% of the cosmic volume (at most!)

(<15% in most realistic model)

FV ET AL., 2025 A&A

PRIMORDIAL VS ASTROPHYSICAL SEEDING OF B-FIELDS



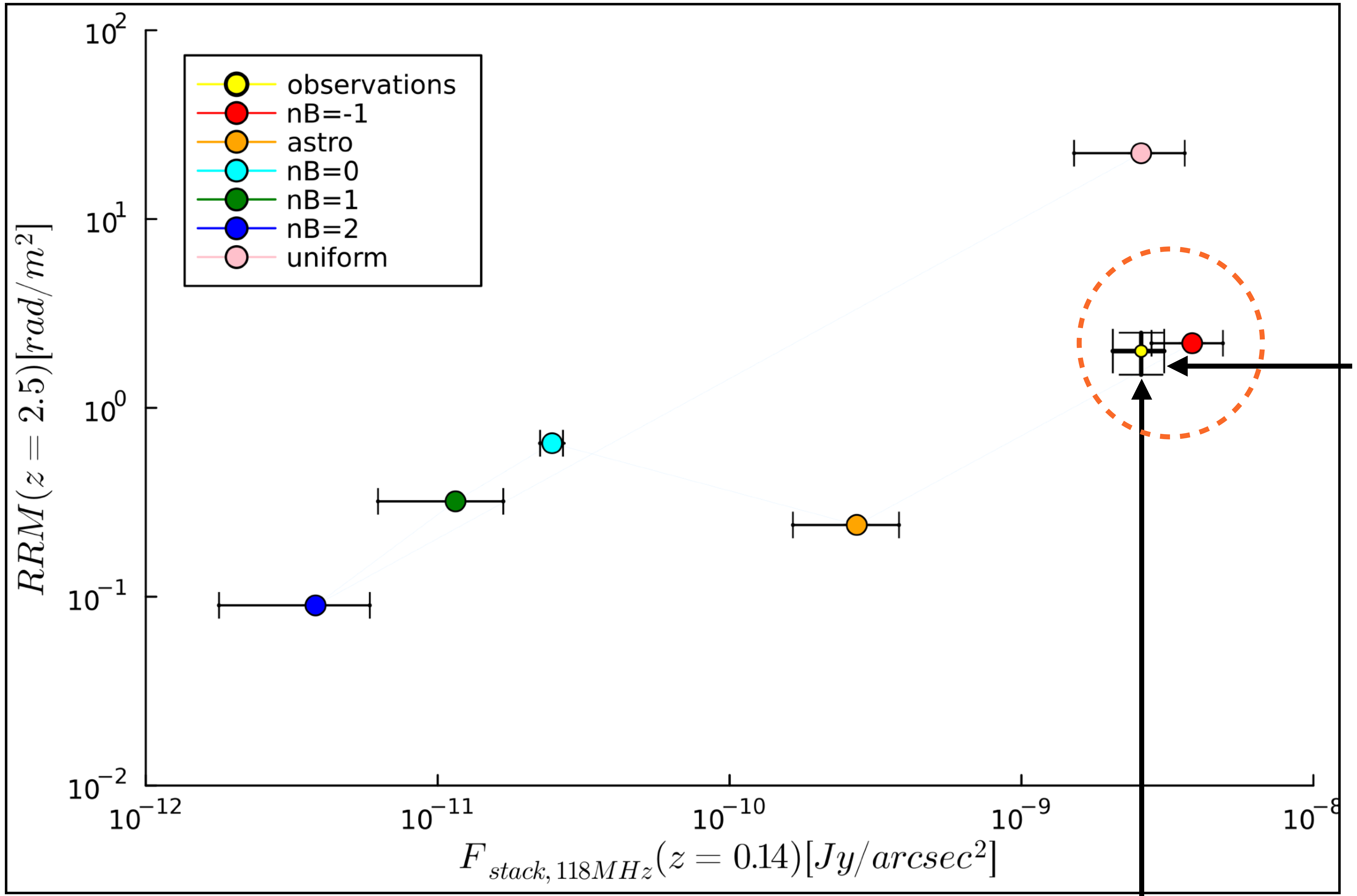


Astrophysical B-fields cannot outshine primordial B-fields if $B_0 \geq 0.05\mathrm{nG}$

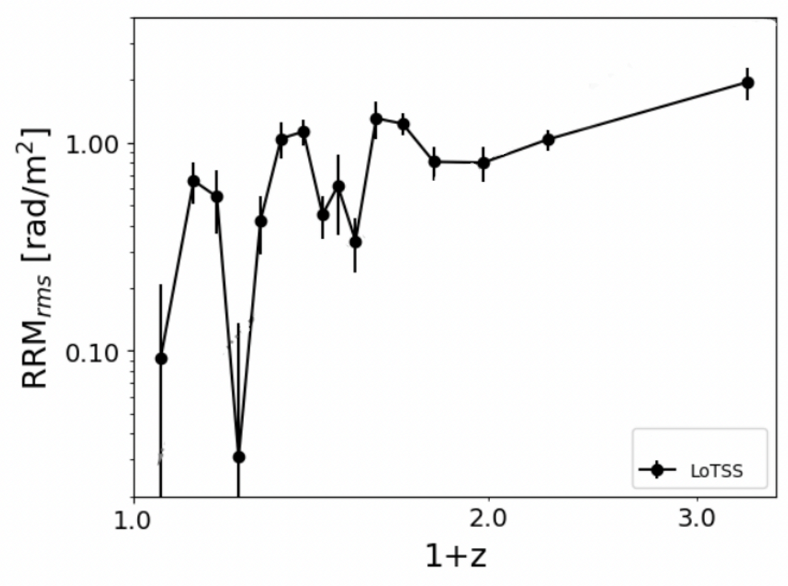
LOFAR RRM(z) suggest a primordial component

FV ET AL., 2025 A&A

PRIMORDIAL VS ASTROPHYSICAL SEEDING OF B-FIELDS



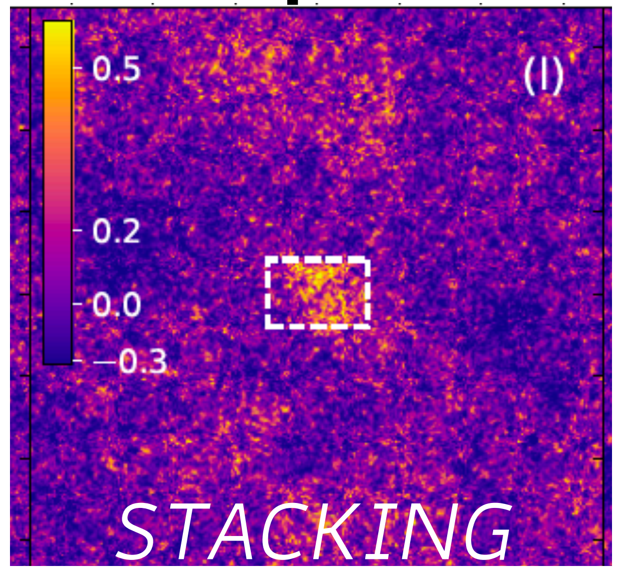
RRM (z=2.5)



New:

consistency check of RRMs vs synchrotron stacking constraints: are they compatible?

YES



Our currently best model $(n_B = -1, \langle B_{1Mpc} \rangle = 0.35\text{nG})$ to explain RRM observations can also well explain the stacking detection in synchrotron. All other model fails!

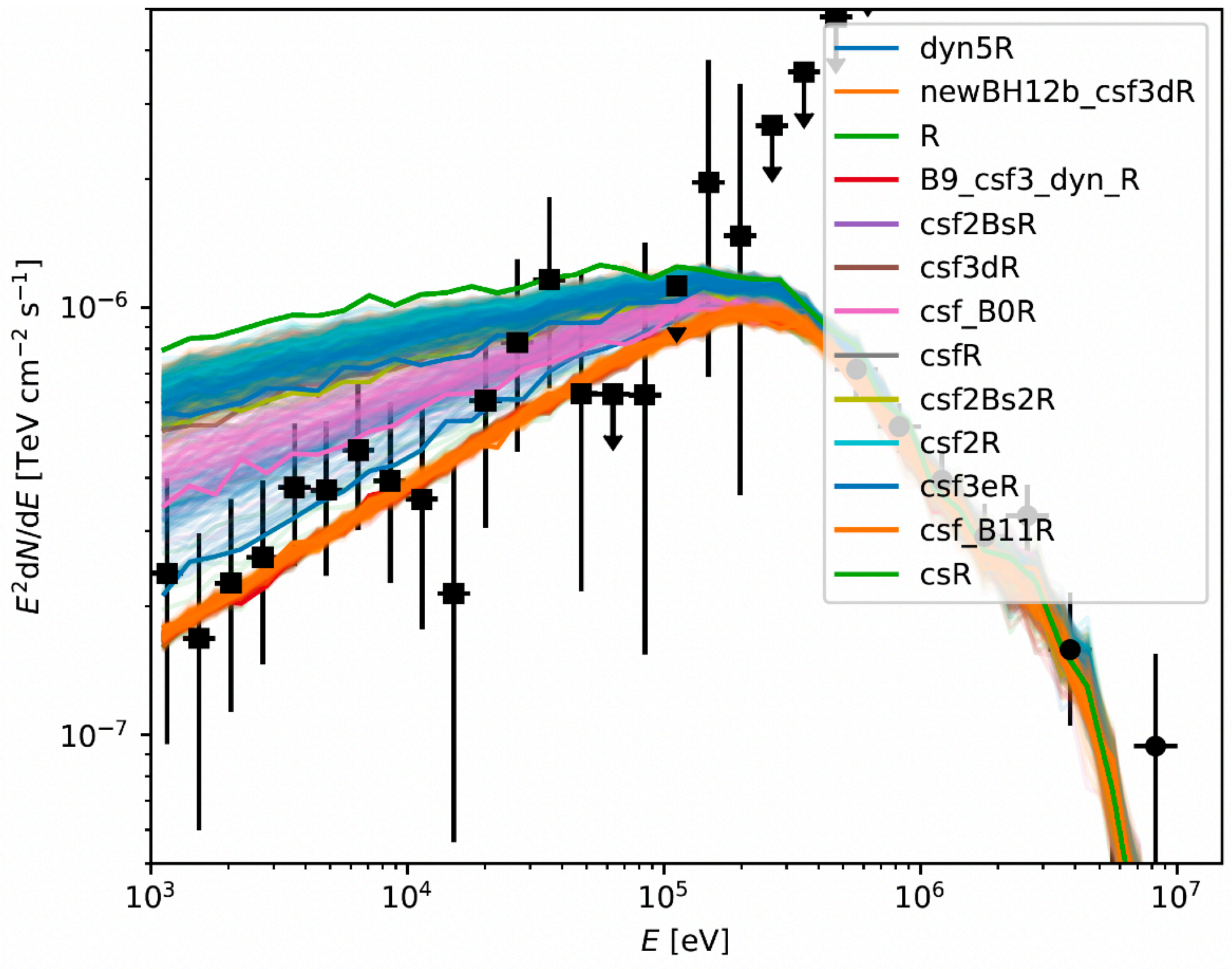
CARRETTI & FV, TO BE SUBMITTED

LOWER LIMITS FROM BLAZARS

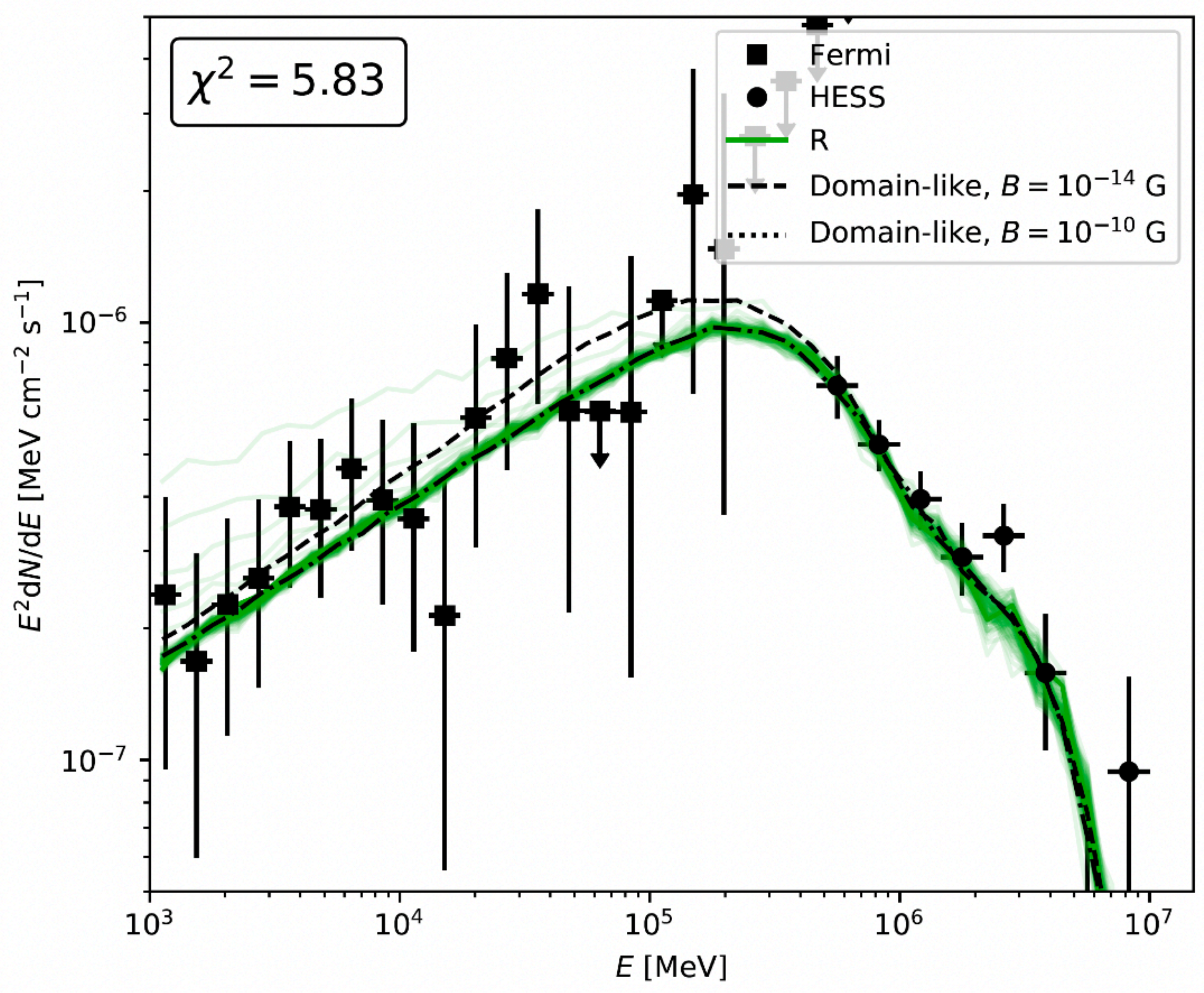
Deflection by IGM magnetic fields can explain the suppression of (secondary) inverse-compton-cascade from blazars at 1-100 GeV

(**<u>Neronov & Vovk 2010</u>**, *Arlen+2014; Mayer+2016…*)

astrophysical models



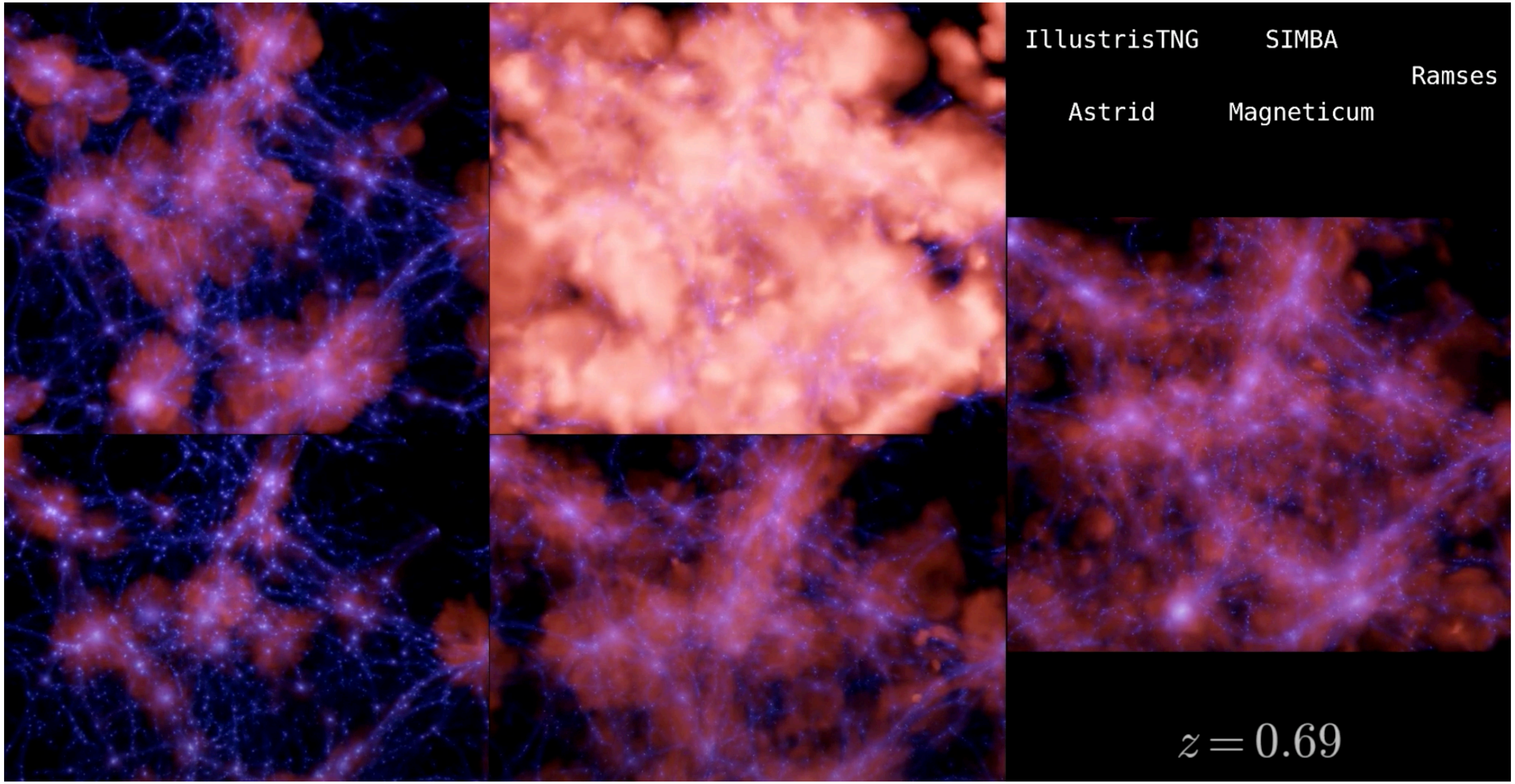
primordial seeding



Observed FERMI spectra <u>rejects purely astrophysical scenarios: >60% of filling factor needed!</u>

TJEMSLAND, MEYER, FV 2024 APJ

CAVEATS…

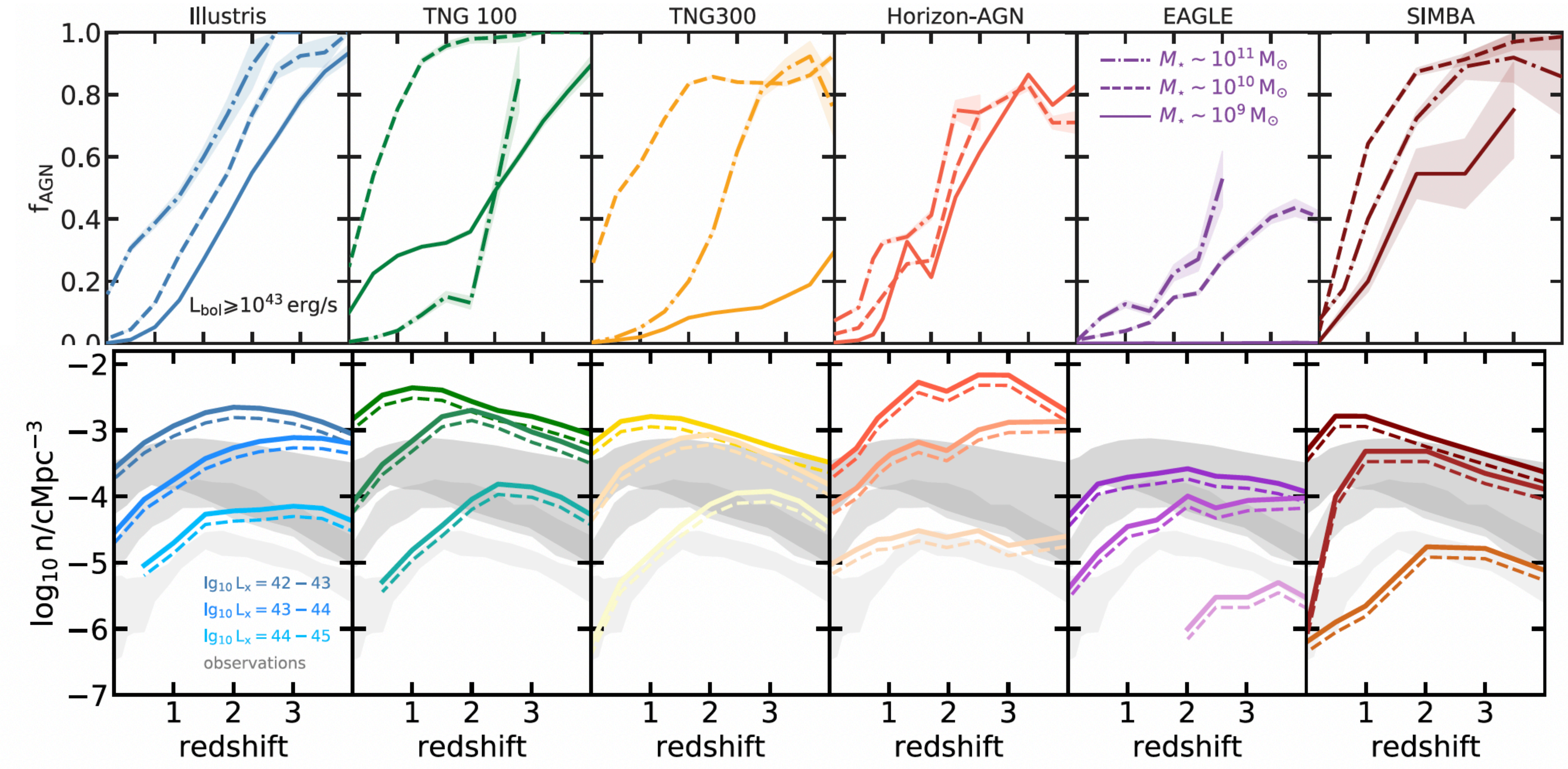


Viallescusa et al

CAMELS project

- The effect of AGN feedback on the IGM (temperature, metallicity, filling factor…) is very different even for all simulations on the market
- This must produce big differences magnetisation too

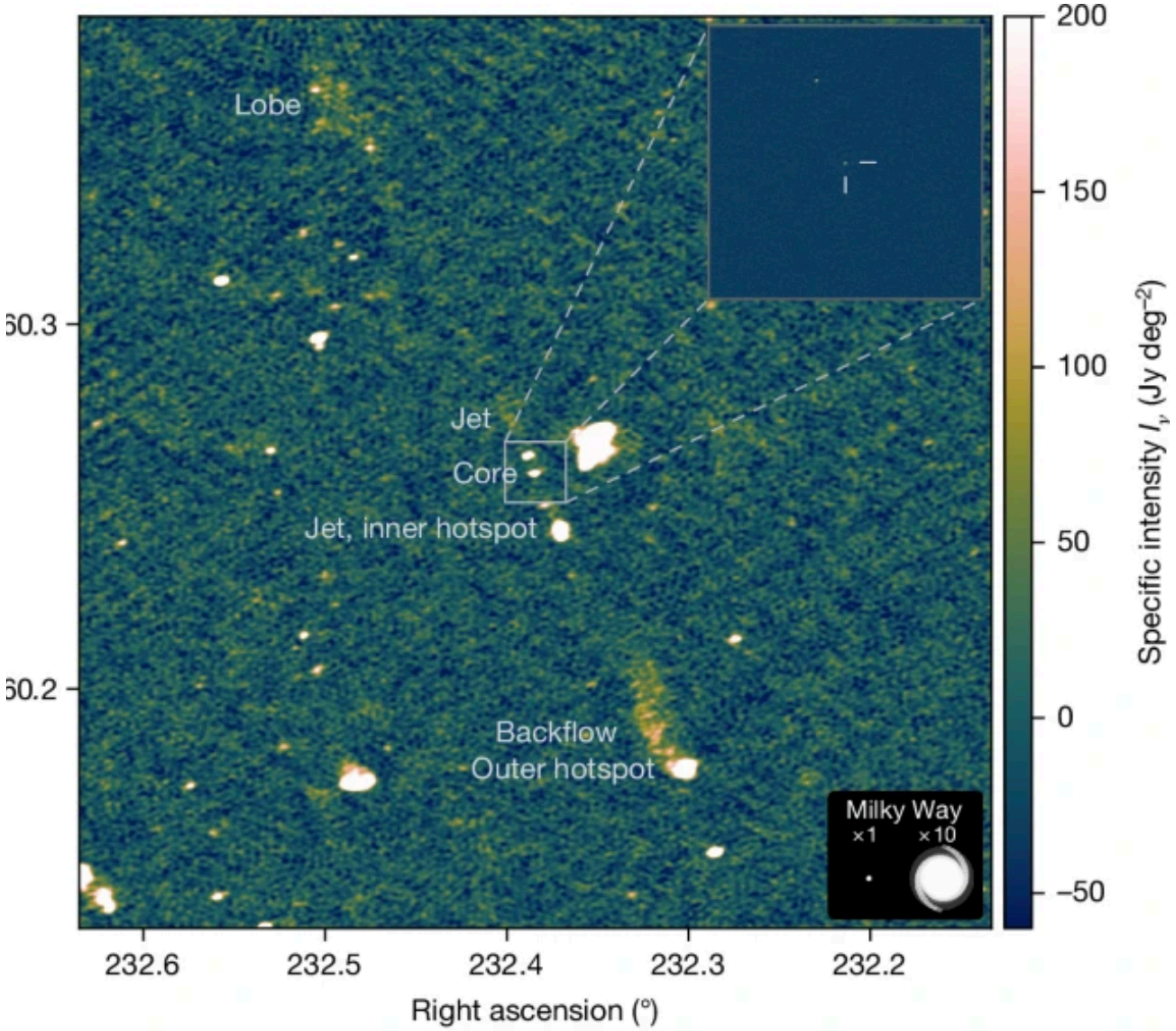
CAVEATS…

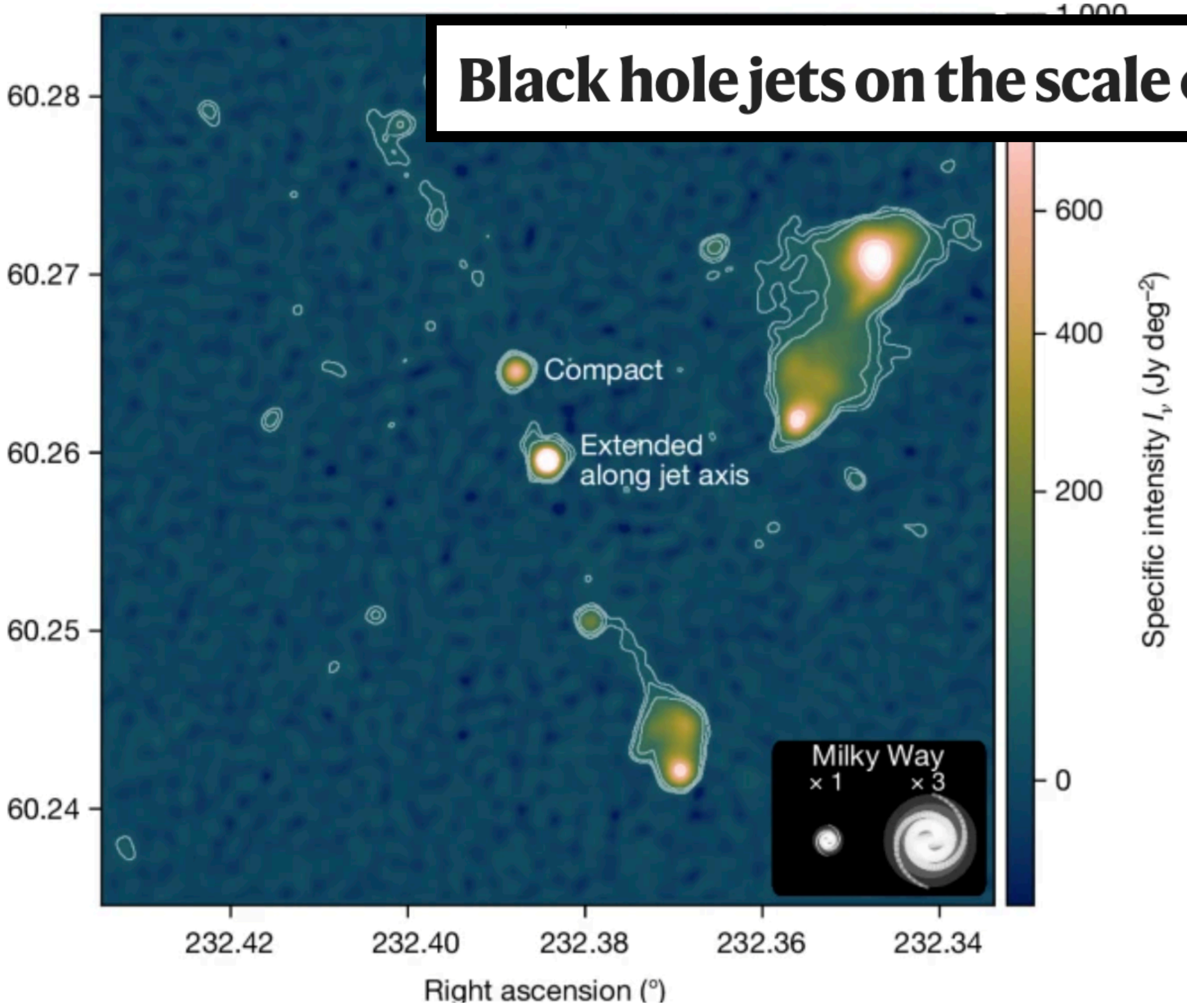


Habouzit et al.2022

- **Even the most sophisticated feedback recipes (calibrated to reproduce $z \sim 0$ galaxy properties) predict hugely different evolutions of AGN and of the Circumgalactic medium (Lau+2025)**

GIANT RADIO GALAXIES: CAN THEY MAGNETISE VOIDS?





Black hole jets on the scale of the cosmic web

Oei et al.
2024 Nature.

LLS ~ 7Mpc
record breaker
in radio galaxy

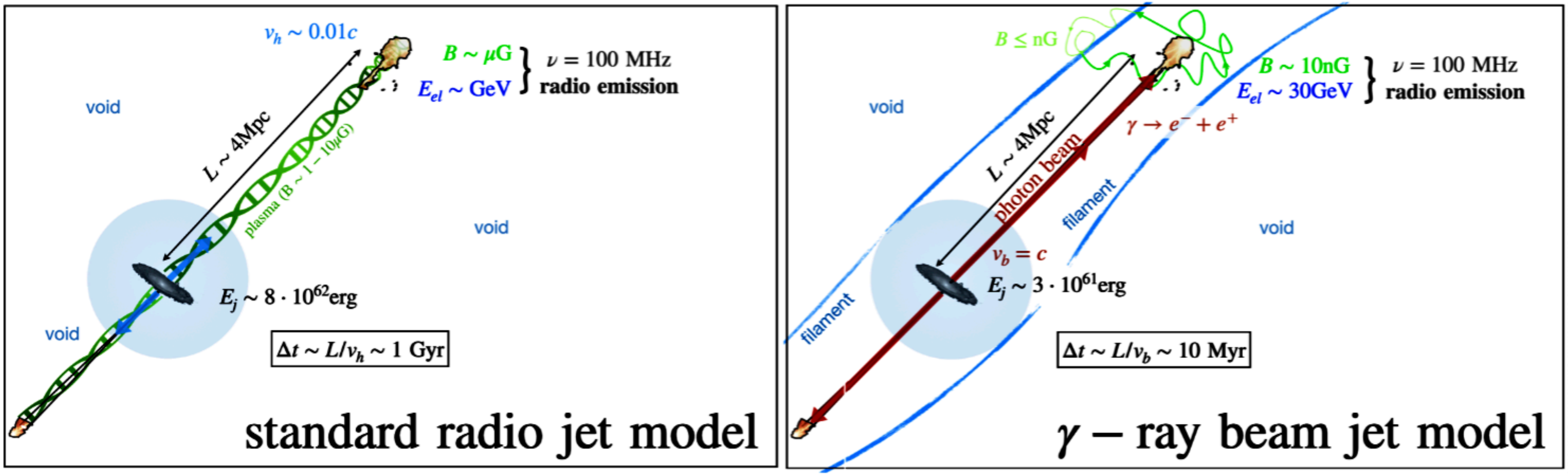
Average jet power of $P_j \sim 10^{46}\mathrm{erg/s}$ active for $\tau \sim 1.9\mathrm{Gyr}$. The total deposited energy is $\sim 8 \cdot 10^{62}\mathrm{erg}$ $\rightarrow \Delta M c^2 \sim 10^9 M_\odot c^2$. Association with the $z \sim 0.8$ quasar in the region ($M_{\mathrm{quasar}} \sim 2 \cdot 10^8 M_\odot$) is thus impossible.

Only other possible host is a RE AGN in a $M_* \sim 6.7 \cdot 10^{11} M_\odot$ galaxy at $z \approx 0.89$ in a filament.

PUZZLES: Lack of precession for 2 Gyr? Perfect collimation? Lack of interaction with environment?

GIANT RADIO GALAXIES: CAN THEY MAGNETISE VOIDS?

Intergalactic magnetism in a γ-ray beam as a model of Porphyrion



Can Porphyrion be a jet-like feature produced by a beam of very-high-energy γ-rays producing electron-positron pairs in IGMs?

NERONOV, FV, BRANDENBURG & CAPRINI, SUBMITTED TO A&A ARXIV:2411.01640

GIANT RADIO GALAXIES: CAN THEY MAGNETISE VOIDS?

- *no detection of γ-ray emission with FERMI-LAT implies* $B \geq 8\mathrm{nG}$ *(comoving)*

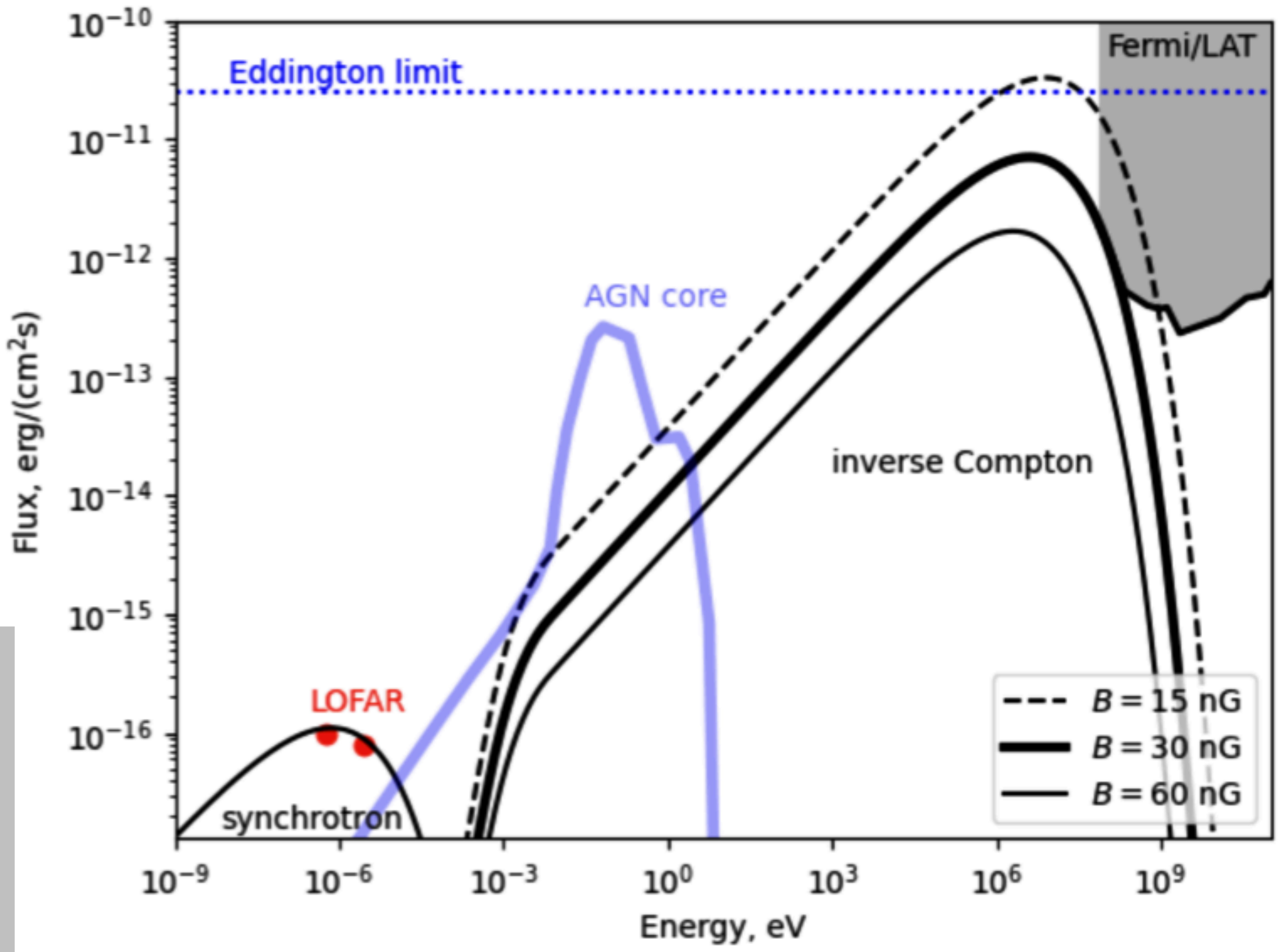
$$\nu_s \simeq 100 \left[\frac{B}{10\,\mathrm{nG}}\right] \left[\frac{E_e}{30\ \mathrm{GeV}}\right]^2 \ \mathrm{MHz},$$

↓

$$E_\gamma \simeq 6 \left[\frac{E_e}{30\ \mathrm{GeV}}\right]^2 \ \mathrm{MeV}.$$

↓

$$\frac{F_{IC}}{F_s} = \frac{U_{CMB}}{U_B} \simeq 10^6 \left[\frac{B}{10\,\mathrm{nG}}\right]^{-2}$$



Idea:

a misaligned TeV blazar which deposited pairs along its propagation $D_\gamma \sim 1 - 10\mathrm{Mpc}$ *for* $10 - 30\mathrm{TeV}$ *interacting with EBL (z=1)*

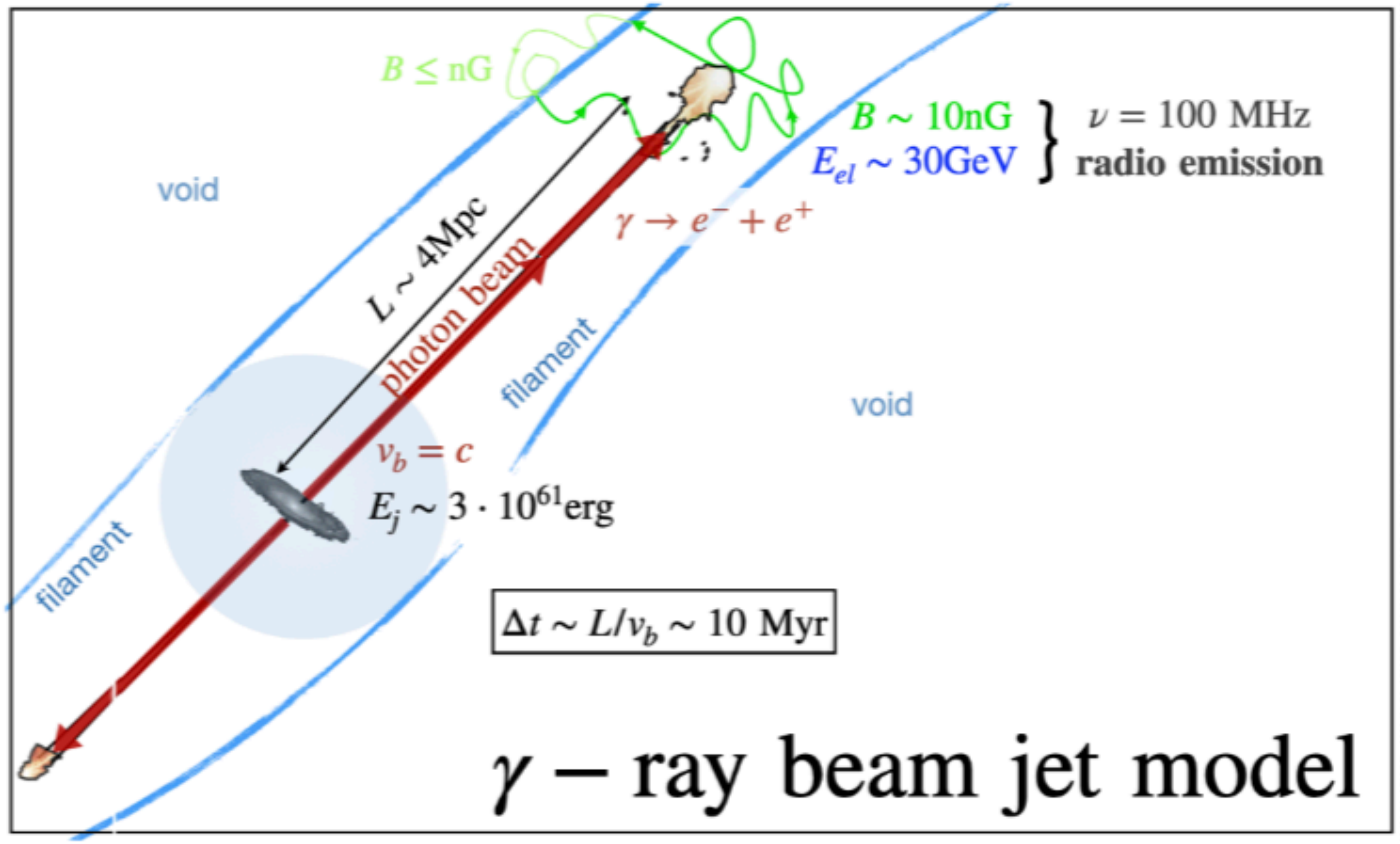
NERONOV, FV, BRANDENBURG & CAPRINI, SUBMITTED TO A&A ARXIV:2411.01640

GIANT RADIO GALAXIES: CAN THEY MAGNETISE VOIDS?

Electrons and positrons injected with $E_e \sim (0.1 - 1)\mathrm{E}_\gamma$

IC cooling with CMB: $t_{\mathrm{cool}} \simeq 1.5 \left[\frac{E_e}{30\ \mathrm{GeV}}\right]^{-1} \mathrm{Myr}$

- *This cooling time is close to the light travel time across the extent of Porphyrion!* $t_{\mathrm{cool}} \sim L_j/c$
- *it implies γ-ray luminosity of the AGN has decreased over the last* $\sim 10\mathrm{Myr}$ *(below FERMI limits)*



what is providing $\geq 8\mathrm{nG}$ *magnetic fields?*

NERONOV, FV, BRANDENBURG & CAPRINI, SUBMITTED TO A&A ARXIV:2411.01640

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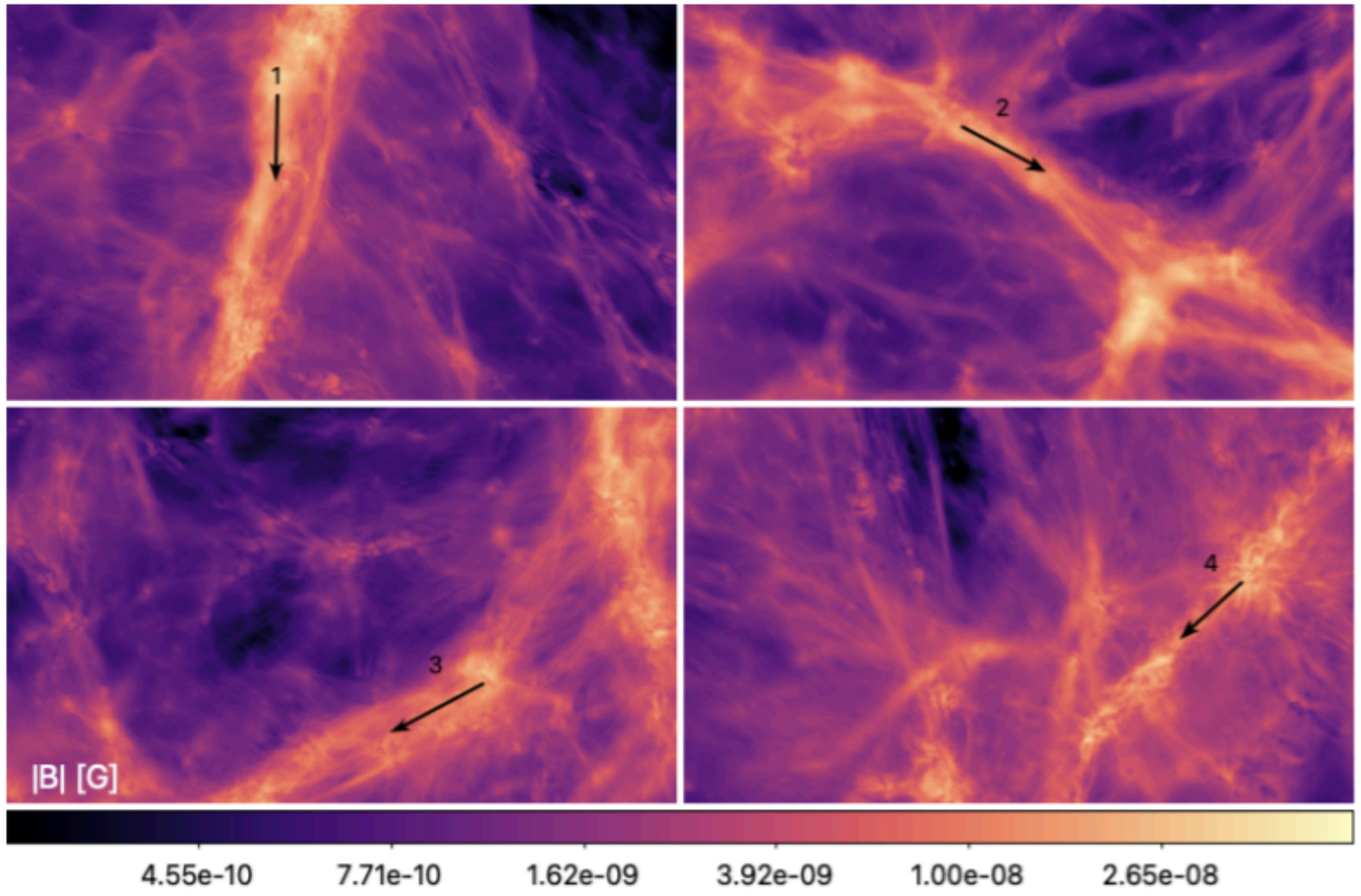
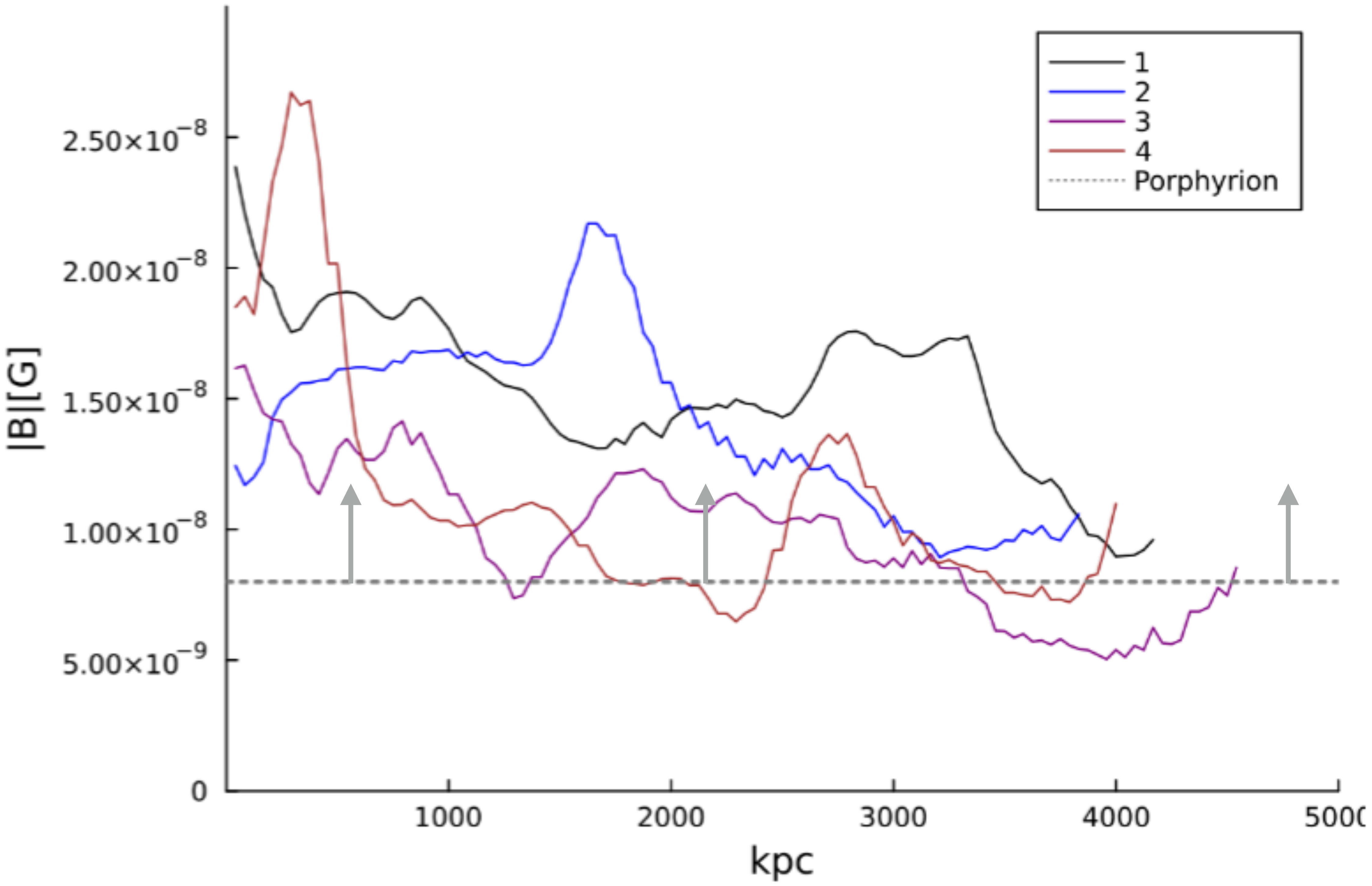
The γ-ray beam must be crossing cosmic filaments





Distribution of magnetic field strength along 4 filaments connected to $\sim 10^{12} M_{\odot}$ halos in cosmological simulations with primordial seed field $\langle B \rangle_{1Mpc} = 0.3\mathrm{nG}$ (compatible with RRM and stacking data)

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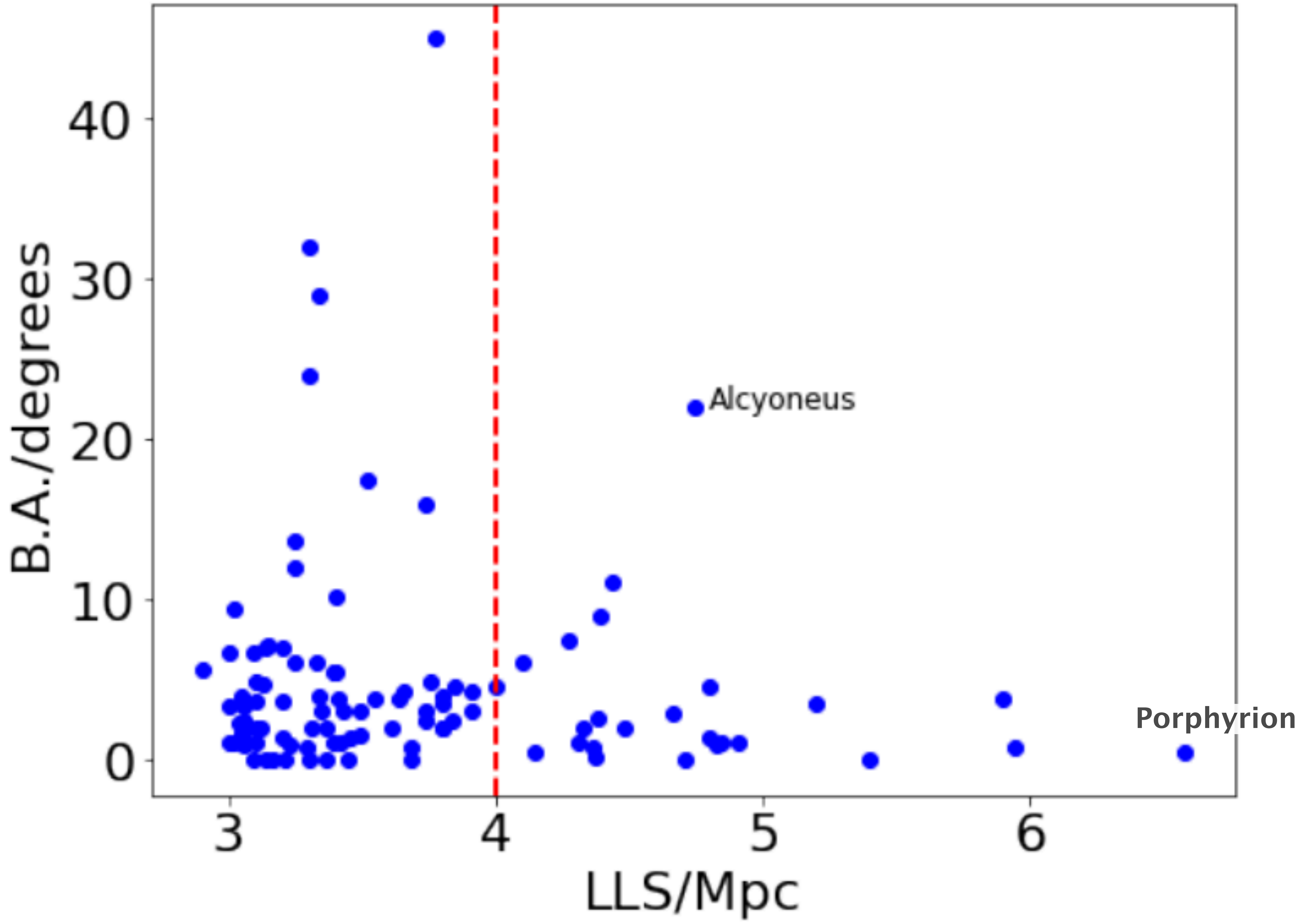
Is Porphyrion just a weird outlier? No, there are 110 straight jets >3Mpc long



More puzzles:

- *no dependence on environment:*

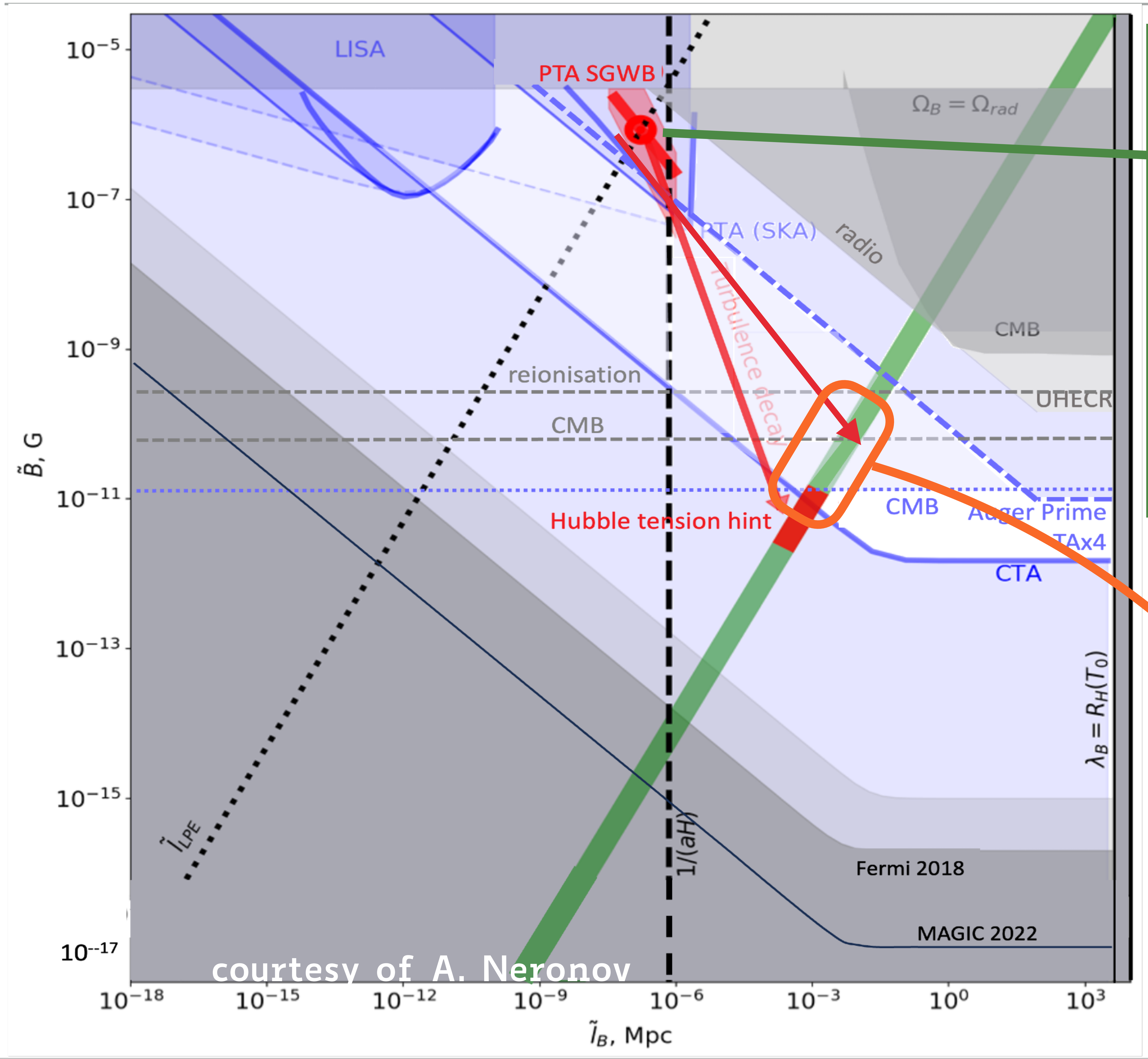
  ~1/3 of them in clusters!

- *no dependence on redshift*

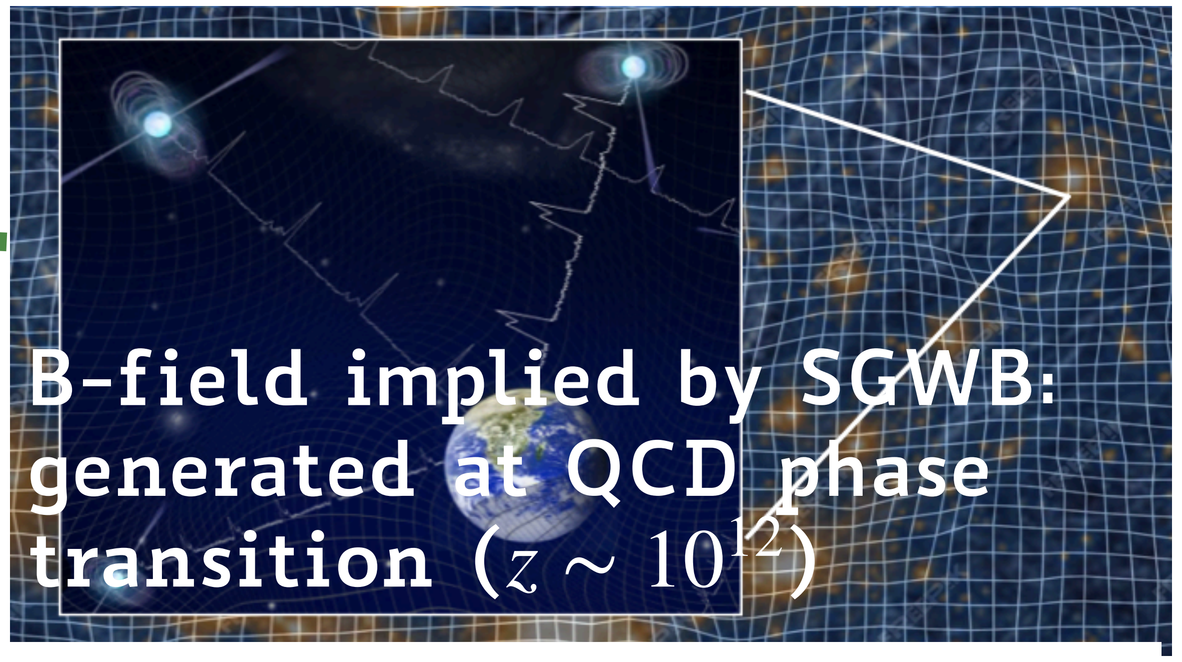
- *longest jets have smaller bending*

courtesy of
Andernach & Brüggen, submitted

CONNECTIONS WITH STOCHASTIC GRAVITATIONAL WAVE BG

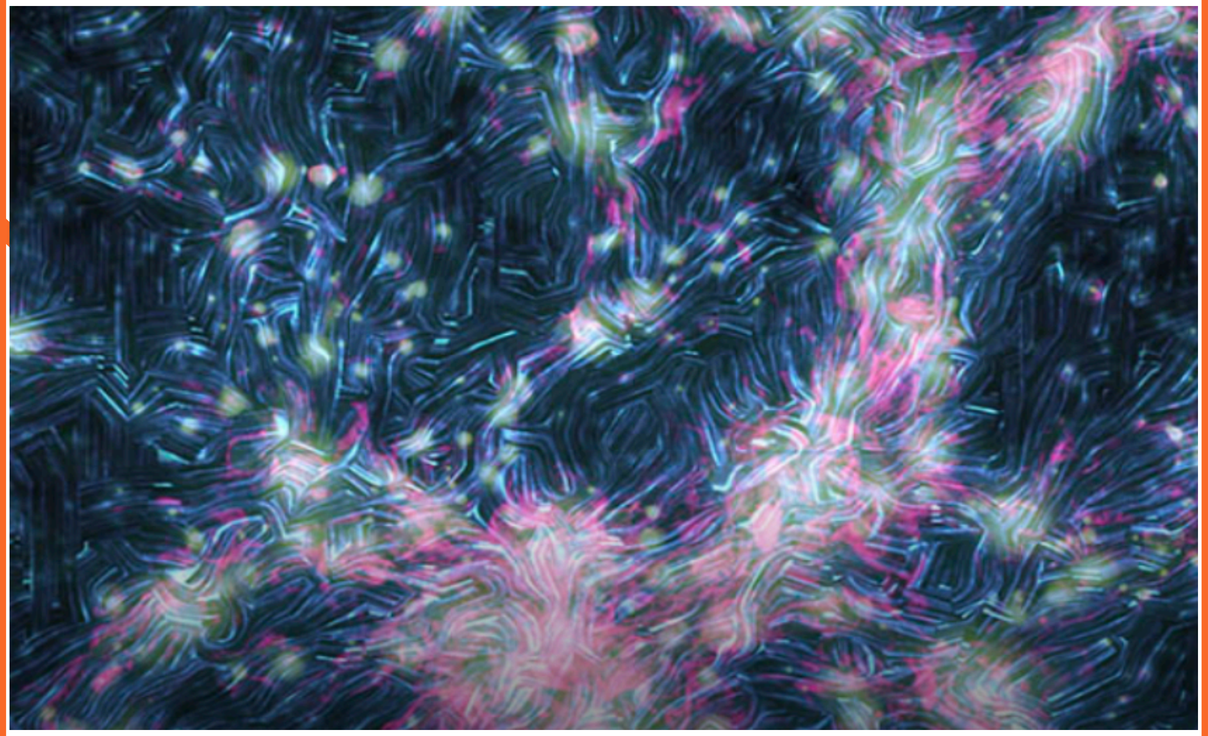


NERONOV, POL, CAPRINI & SEMIKOZ (2021):



$$h^2\Omega_{\mathrm{GW},0} \sim 7 \times 10^{-5} \left[\frac{N_{\mathrm{eff}}}{10}\right]^{-\frac{1}{3}} \Omega_B^{n+1}.$$

$$f \sim 2 \times 10^{-4} (\tilde{l}_B/\tilde{R}_H)^{-1} (T/1\,\mathrm{TeV})\,\mathrm{Hz}$$



$P_B(k) \propto k^{\alpha_B}$ **with** $-1.0 \le \alpha_B \le 1.0$
and $\langle B^2_{1Mpc} \rangle^{0.5} \le 0.4\mathrm{nG}$

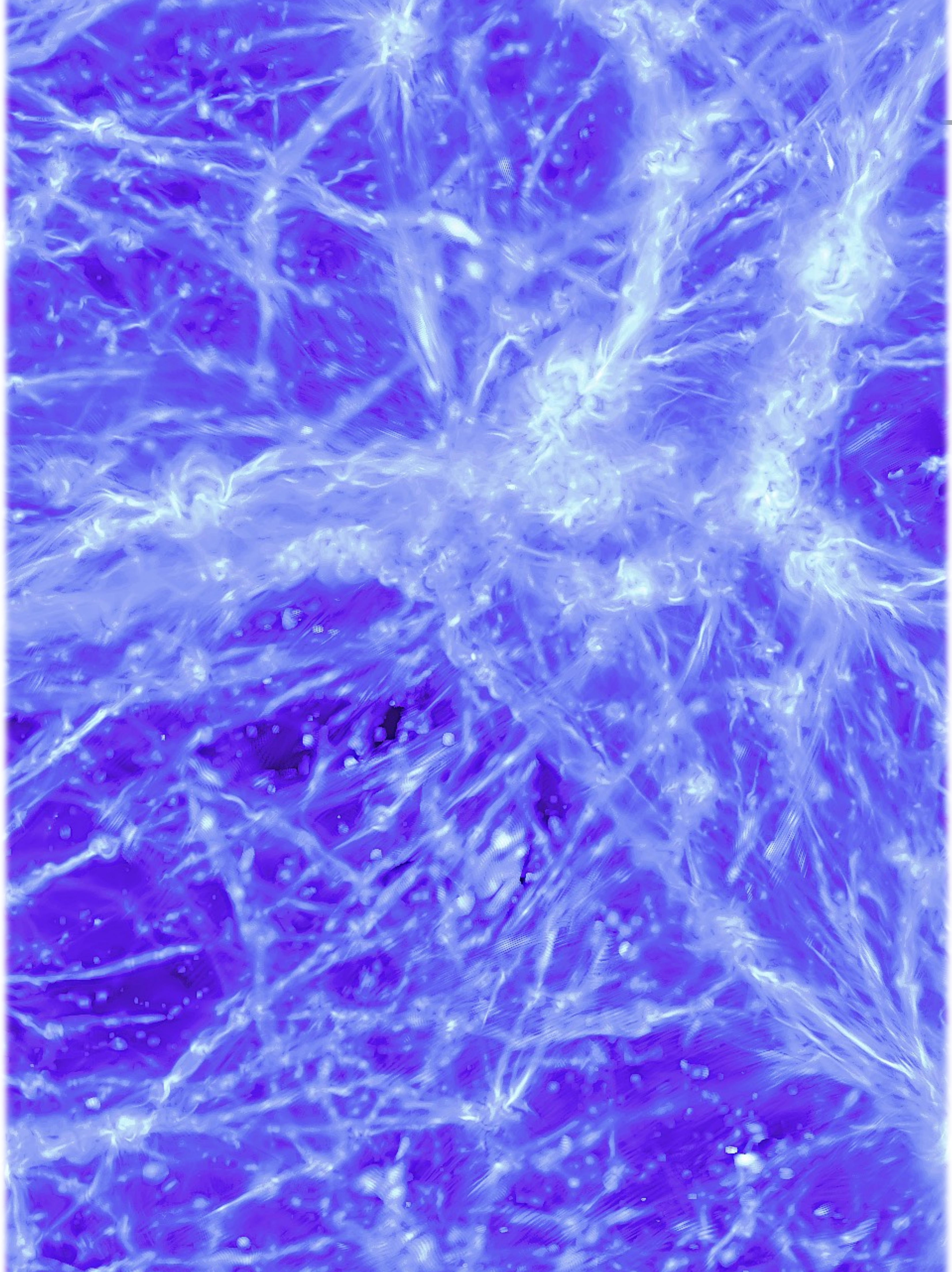
B-fields implied by radio data, compatible with CMB and γ-ray constraints might also explain the SGWB detected by PTA! *(caveat: not easy to simulate evolution from $z \sim 10^{12}$ to $z \sim 10^{3}$)*

MORE CAVEATS...

- **MHD assumption?** *Reasonable at most scales and epochs we are concerned with. However, kinetic effects can further induce magnetic field generation at very small scales (in voids, too?)*

- **Resolution?** *Always hard to make extrapolation for high R_M regimes with finite resolution simulations. Strong dynamo not expected in filaments. But power on small scales for causal primordial spectra might be underestimated*

- **Coupling with cosmological initial conditions?** *See recent works by Ralengakar, Pavicevic... : B-fields impact the initial baryon velocity fields and affect structure growth (and Ly-α). Likely a correction to the interpretation of RRM data.*



SUMMARY

- Detection of extended IGMFs well beyond clusters

- Modelling these observations with simulations discards purely astrophysical origin scenarios for IGMFs models and prefers primordial large-scale models

- Constraints for IGMFs are below what is presently obtained with CMB. Powerful connections with SGWB and the very early Universe ($\leq \mu s$) ?