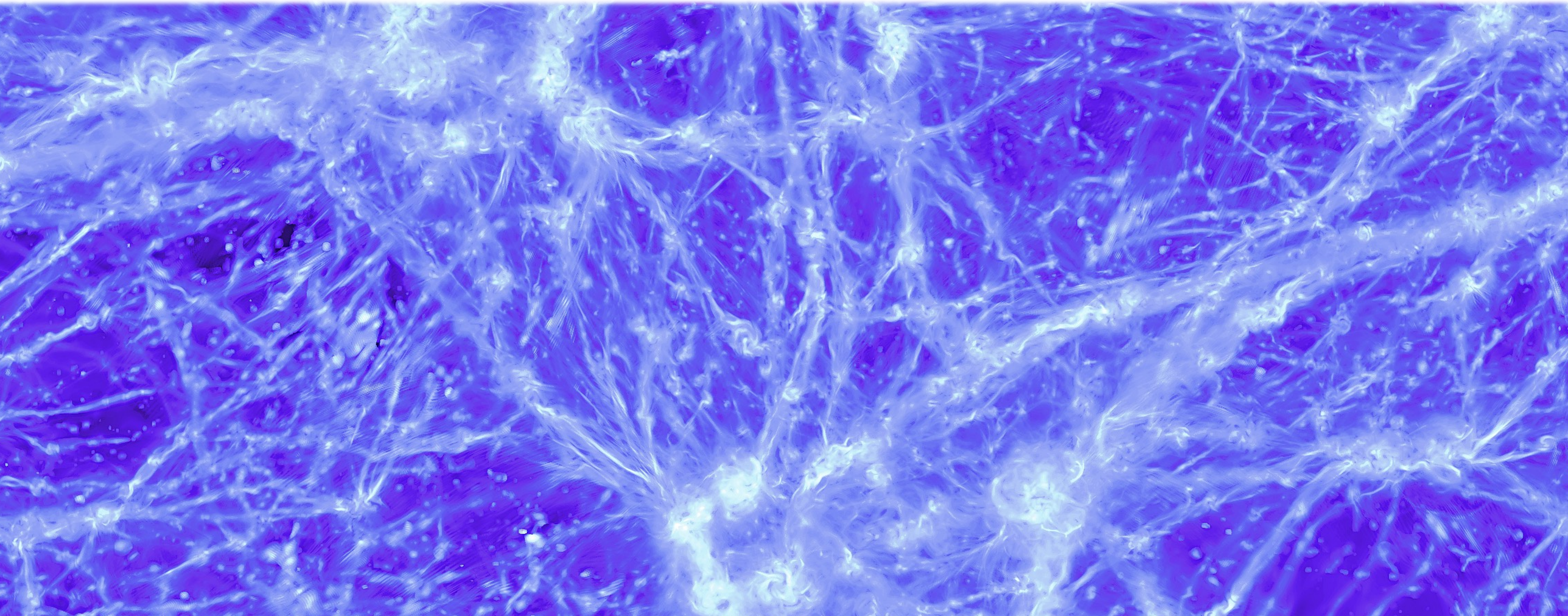
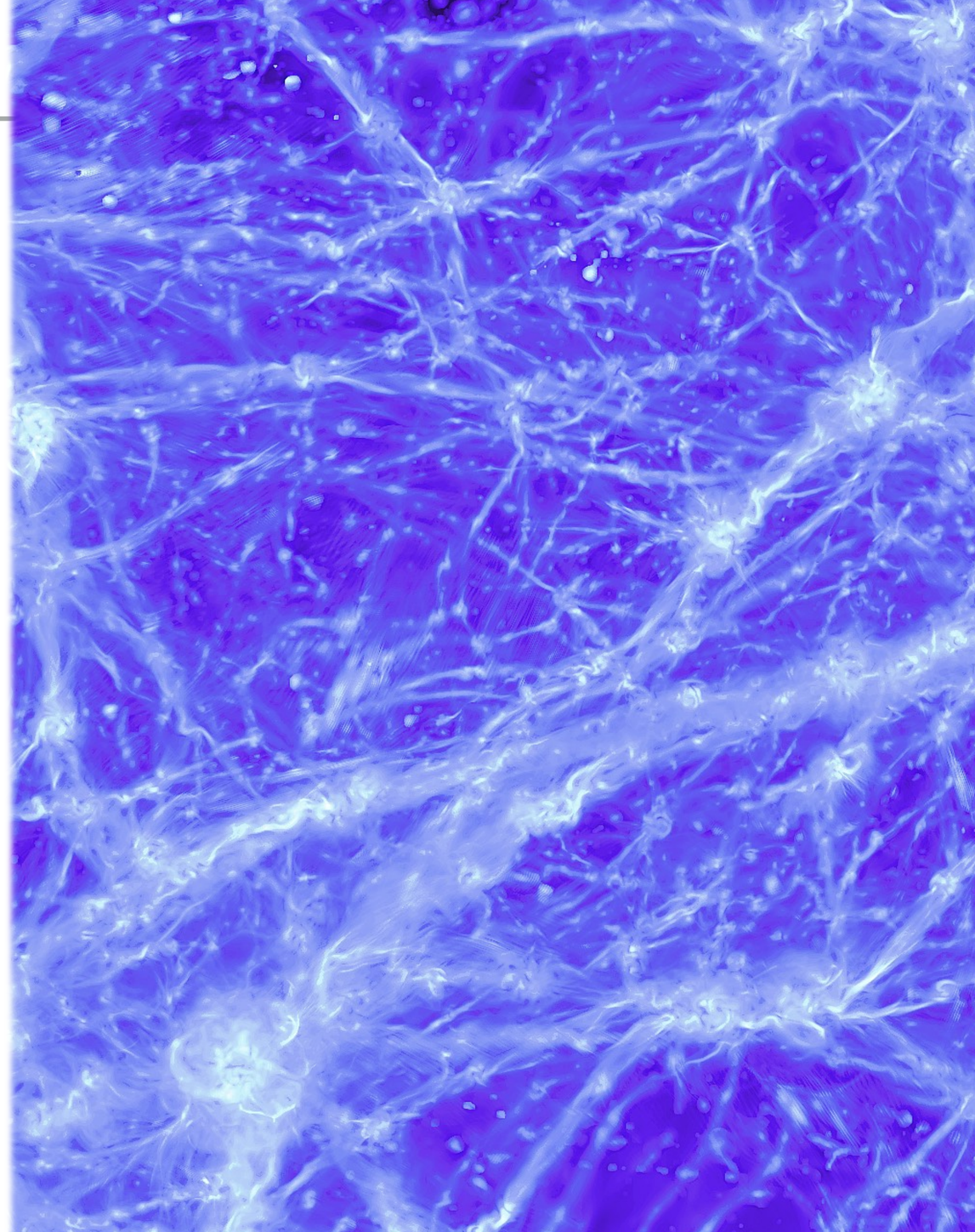
New clues on the (primordial) origin of cosmic magnetism

Franco Vazza
(Bologna Uni.)

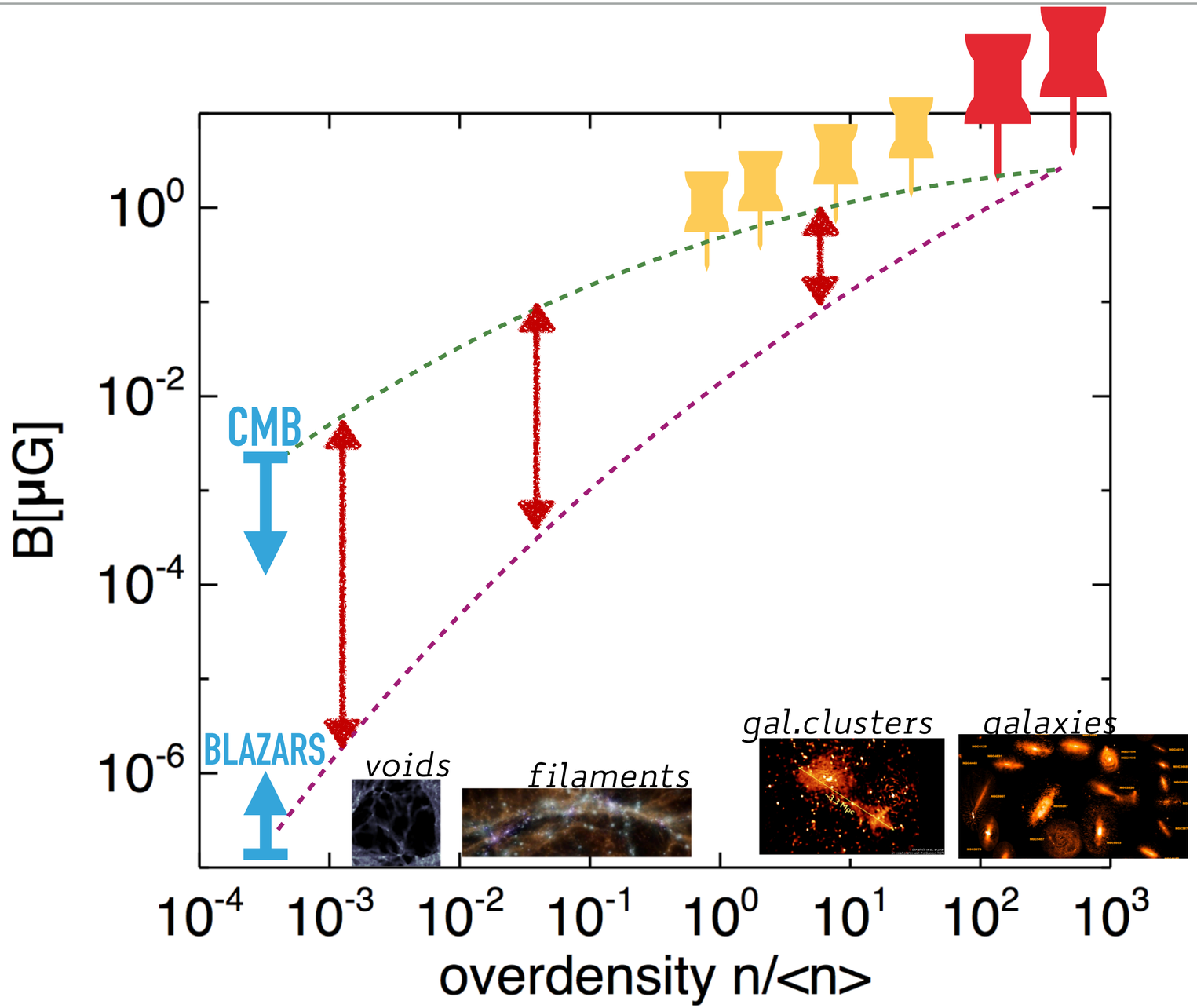


TAKE HOME MESSAGES:

- Today radio & γ-ray observations give the best constraints on extragalactic $\overrightarrow{B}$
- The joint modelling of data with simulations suggests such $\overrightarrow{B}$-field are primordial
- Tantalising connection with SGWB?



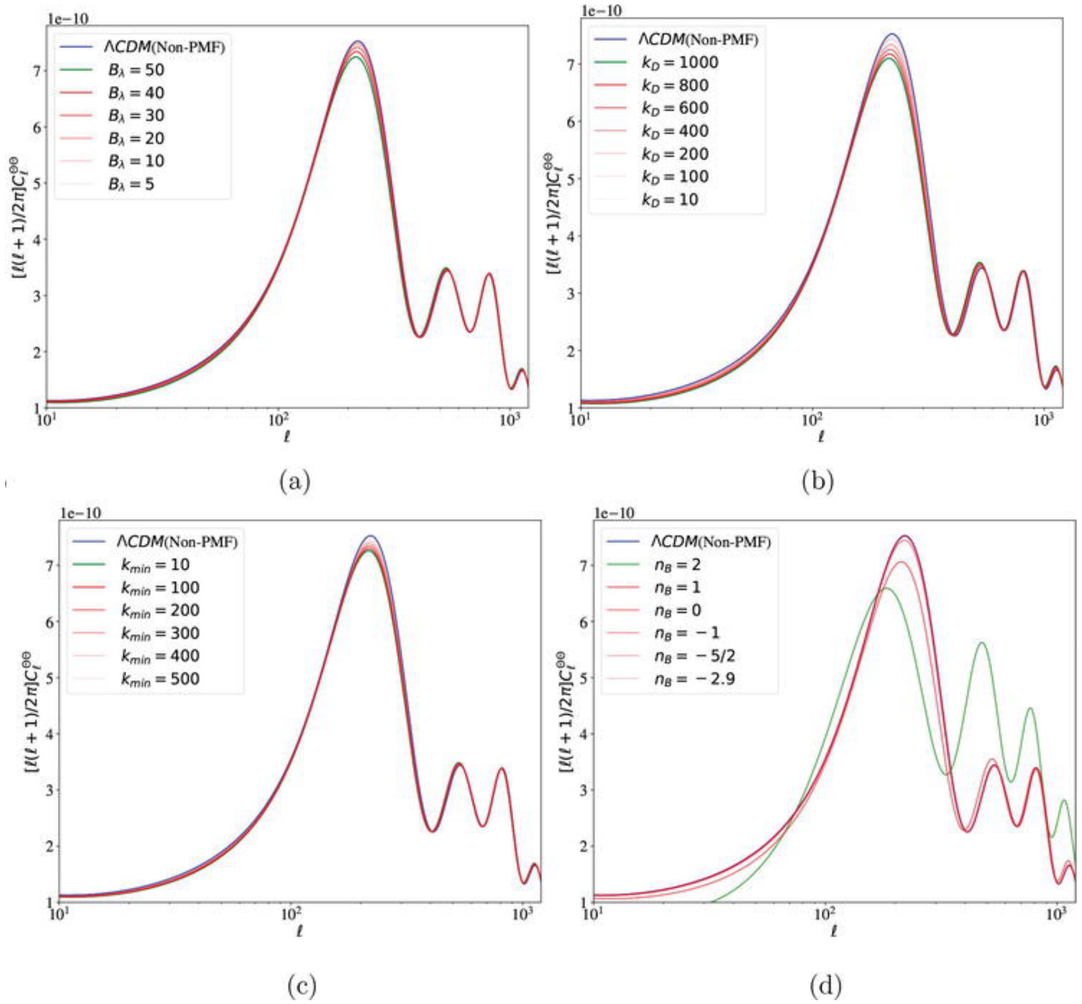
WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

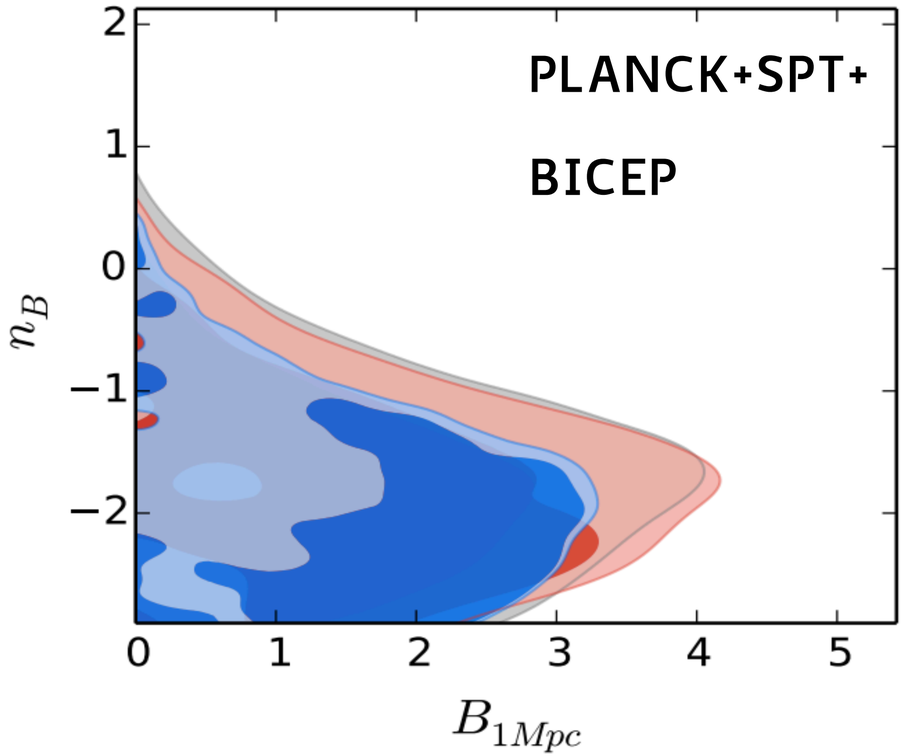


WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

CMB upper limits for power-law magnetic field models:

$$B_\lambda^2 = \int_0^\infty \frac{\mathrm{d}k\, k^2}{2\pi^2}\, \mathrm{e}^{-k^2\lambda^2} P_B(k) = \frac{A_B}{4\pi^2 \lambda^{n_B+3}}\, \Gamma\left(\frac{n_B+3}{2}\right).$$



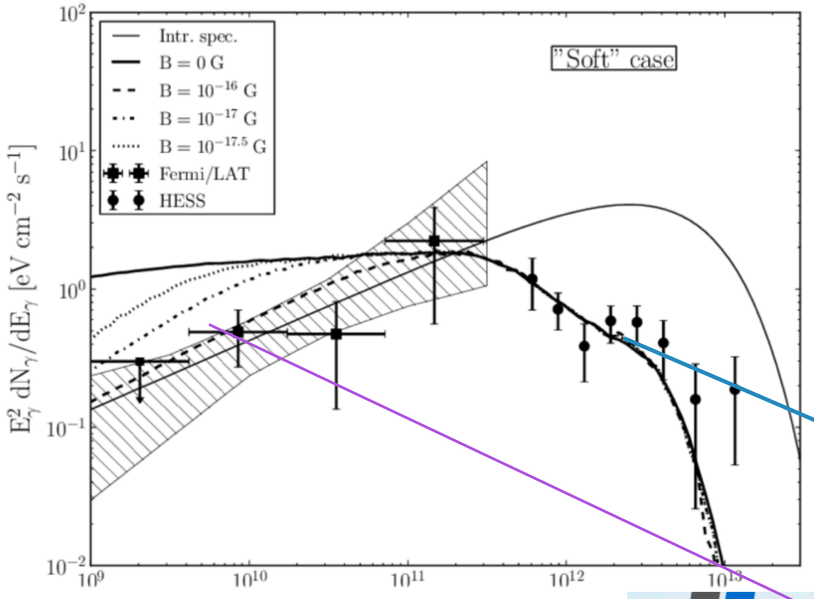


$$B \leq 4 \cdot 10^{-9}\mathrm{G}$$

HORTUA & CASTANEDA (2018)

PAOLETTI & FINELLI (2019)

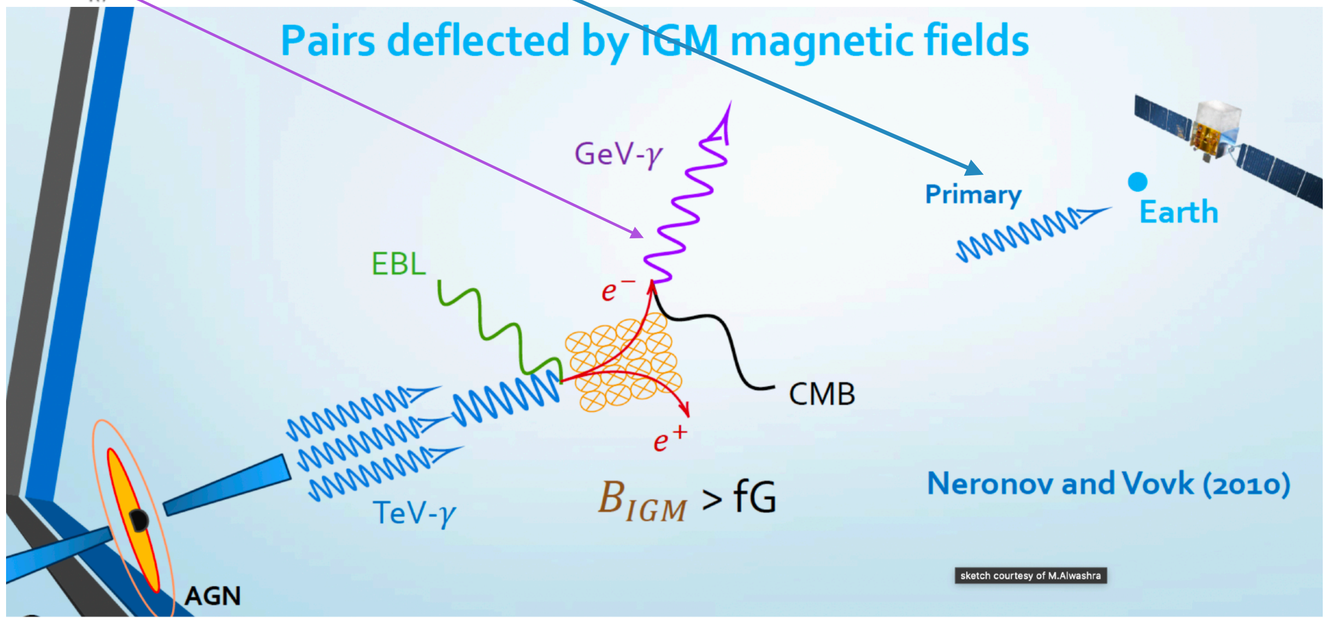
LOWER LIMITS FROM BLAZARS



NERONOV & VOVK 2010

<u>Lower limits</u> from the non-detection of secondary inverse-Compton cascade in blazars

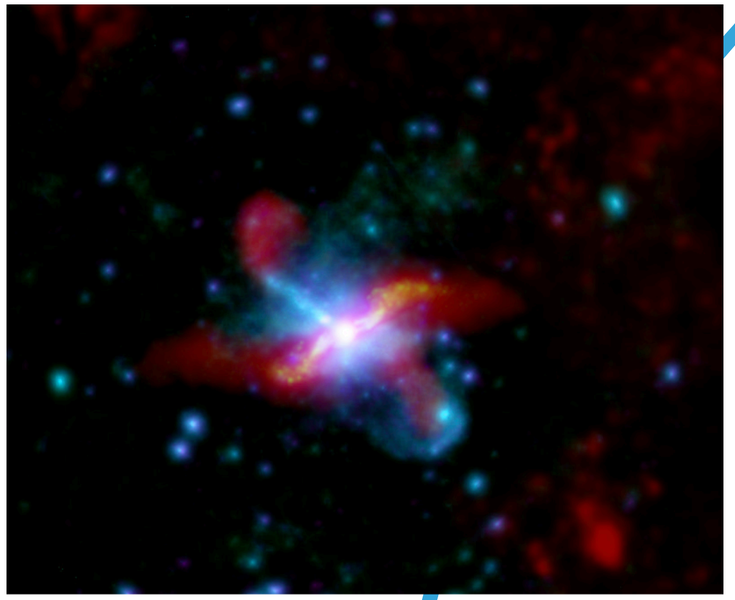
$$B \geq 10^{-16} - 10^{-15}\mathrm{G}$$



WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

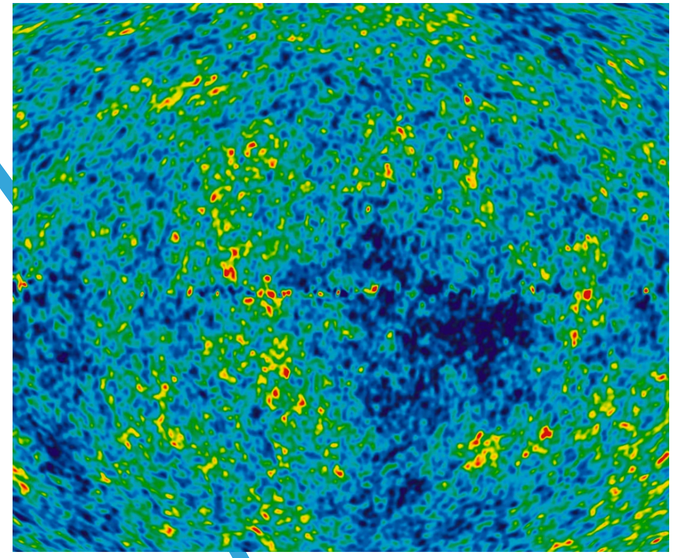
TWO BROAD POSSIBLE SCENARIOS:

"ASTROPHYSICAL"



connected to star formation, active galactic nuclei, jet physics, batteries…

"PRIMORDIAL"

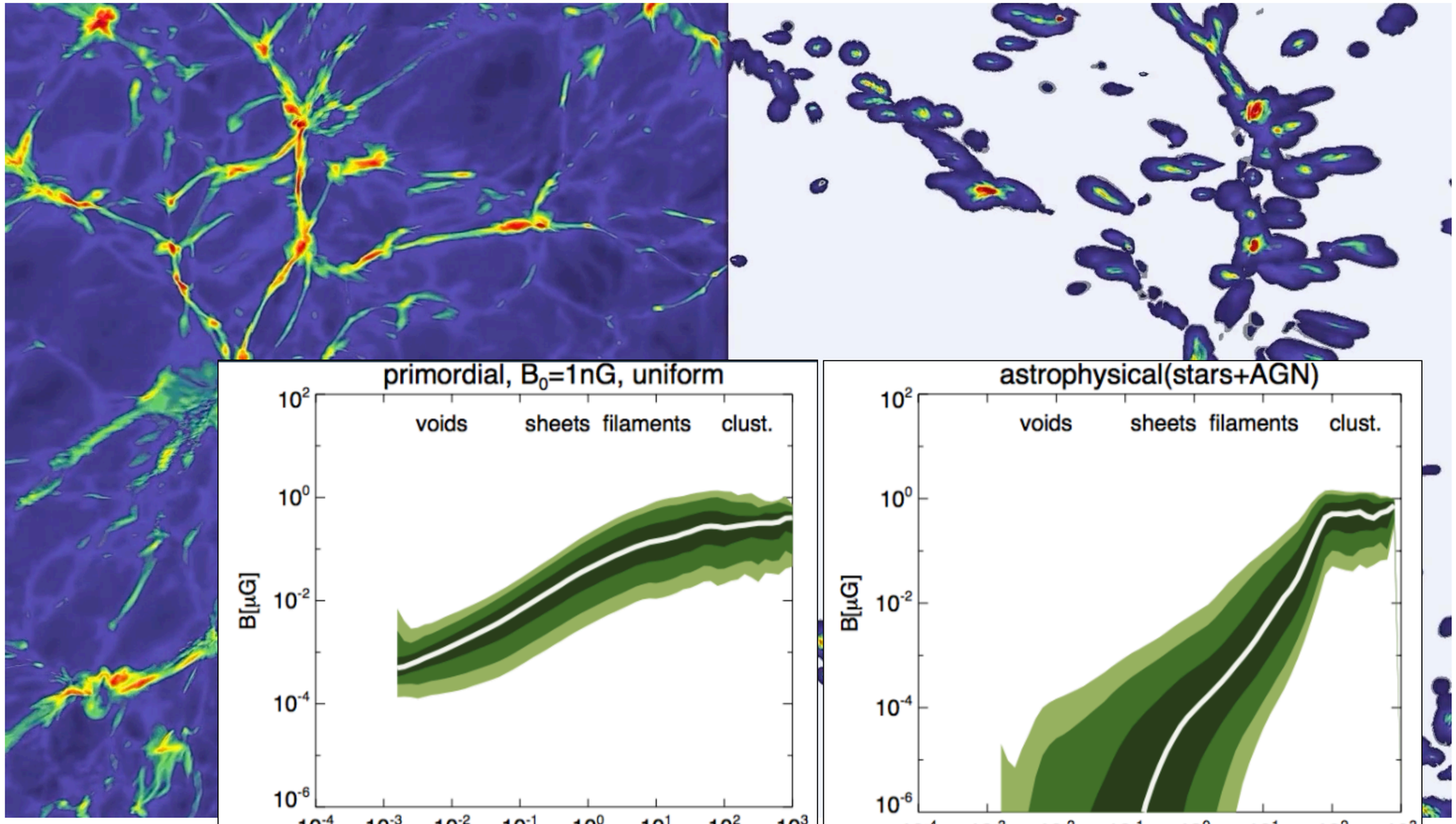


connected to inflation, phase transitions, high-energy particle physics, cosmology…

WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

"Primordial" seeding

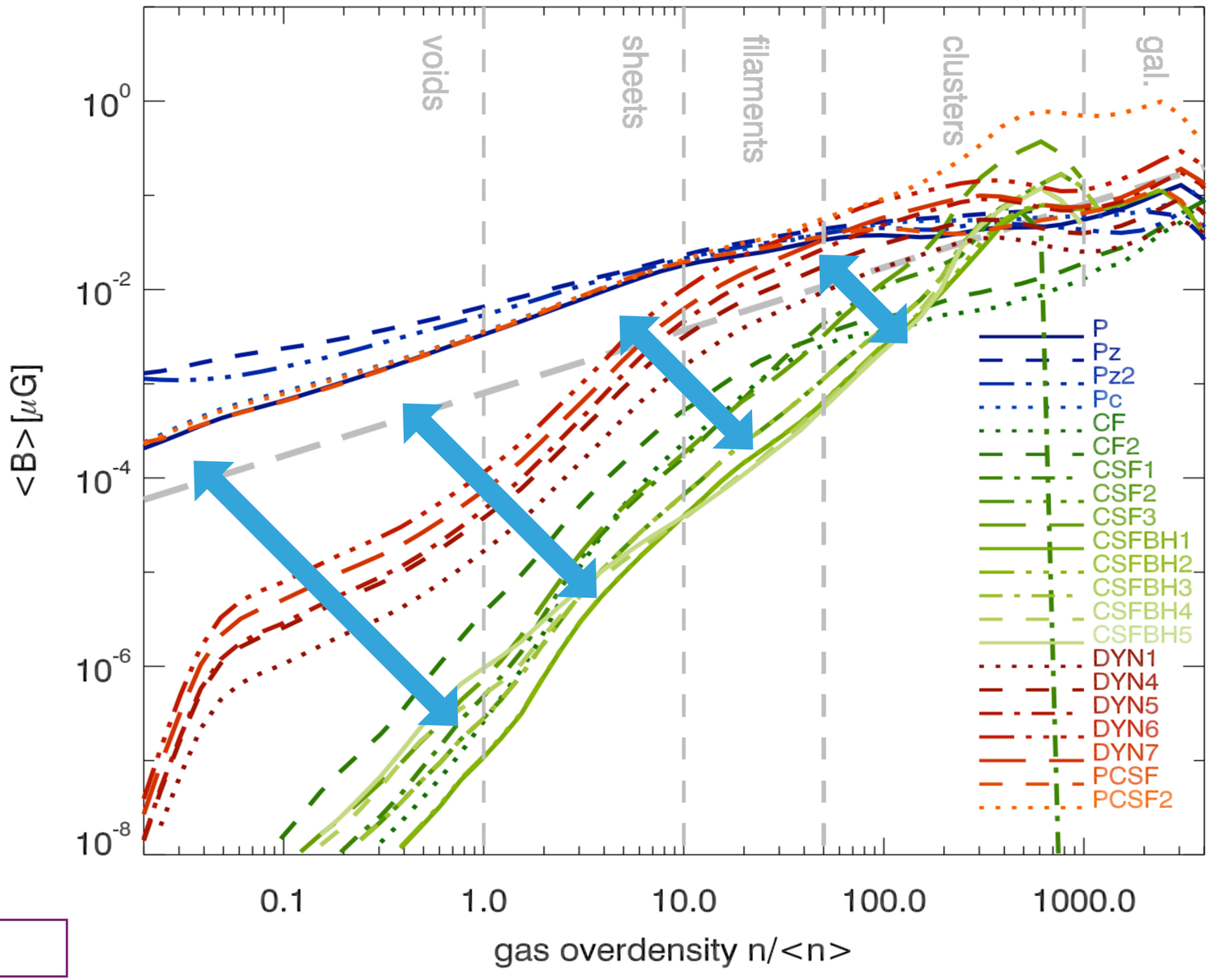
"Astrophysical" seeding



FV+17,20,21...

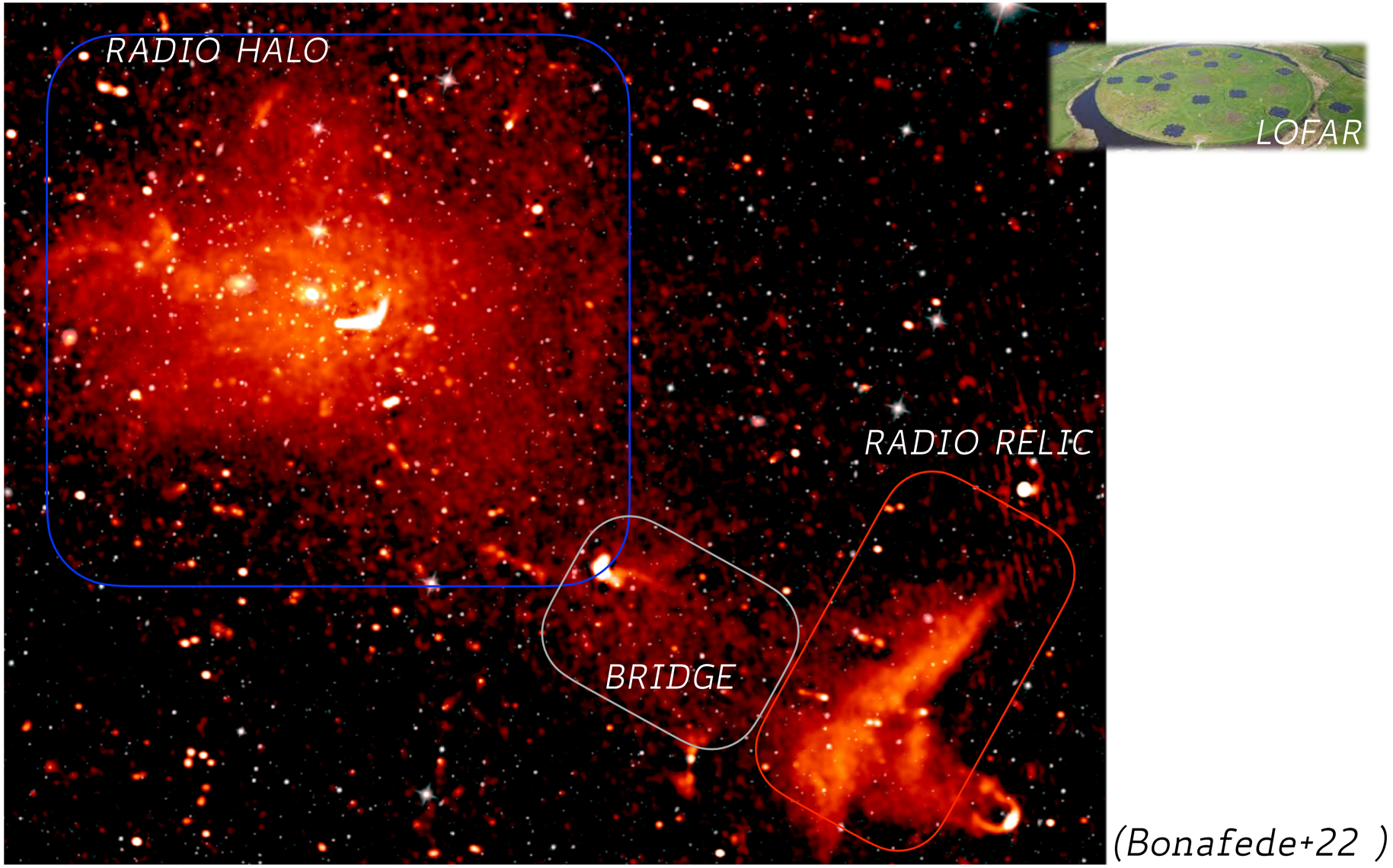
COSMOLOGICAL SIMULATIONS

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



FV + 2017, 21

WHY NOT USING CLUSTERS OF GALAXIES?

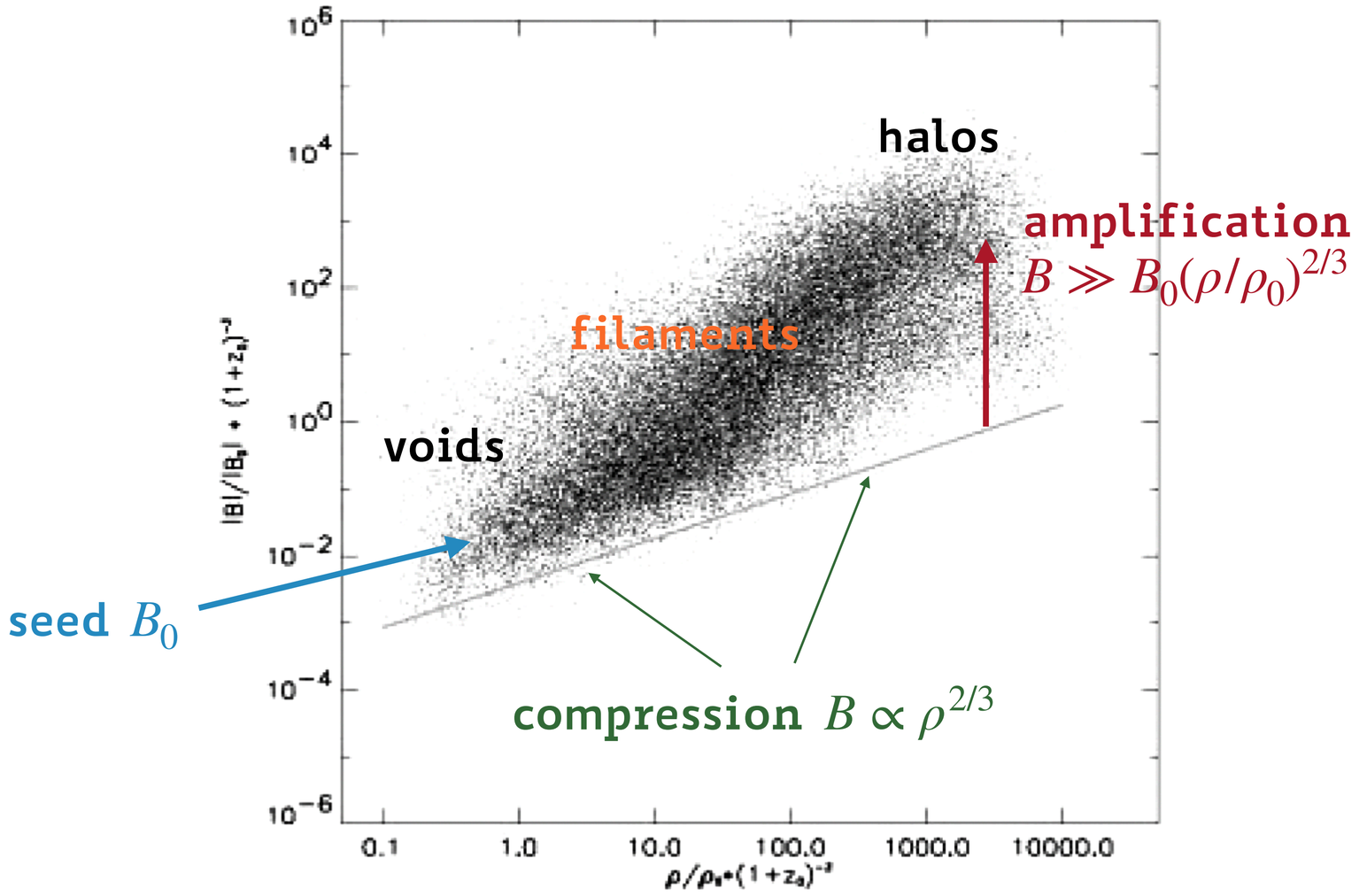


(Bonafede+22)

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

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

WHY NOT USING CLUSTERS OF GALAXIES?

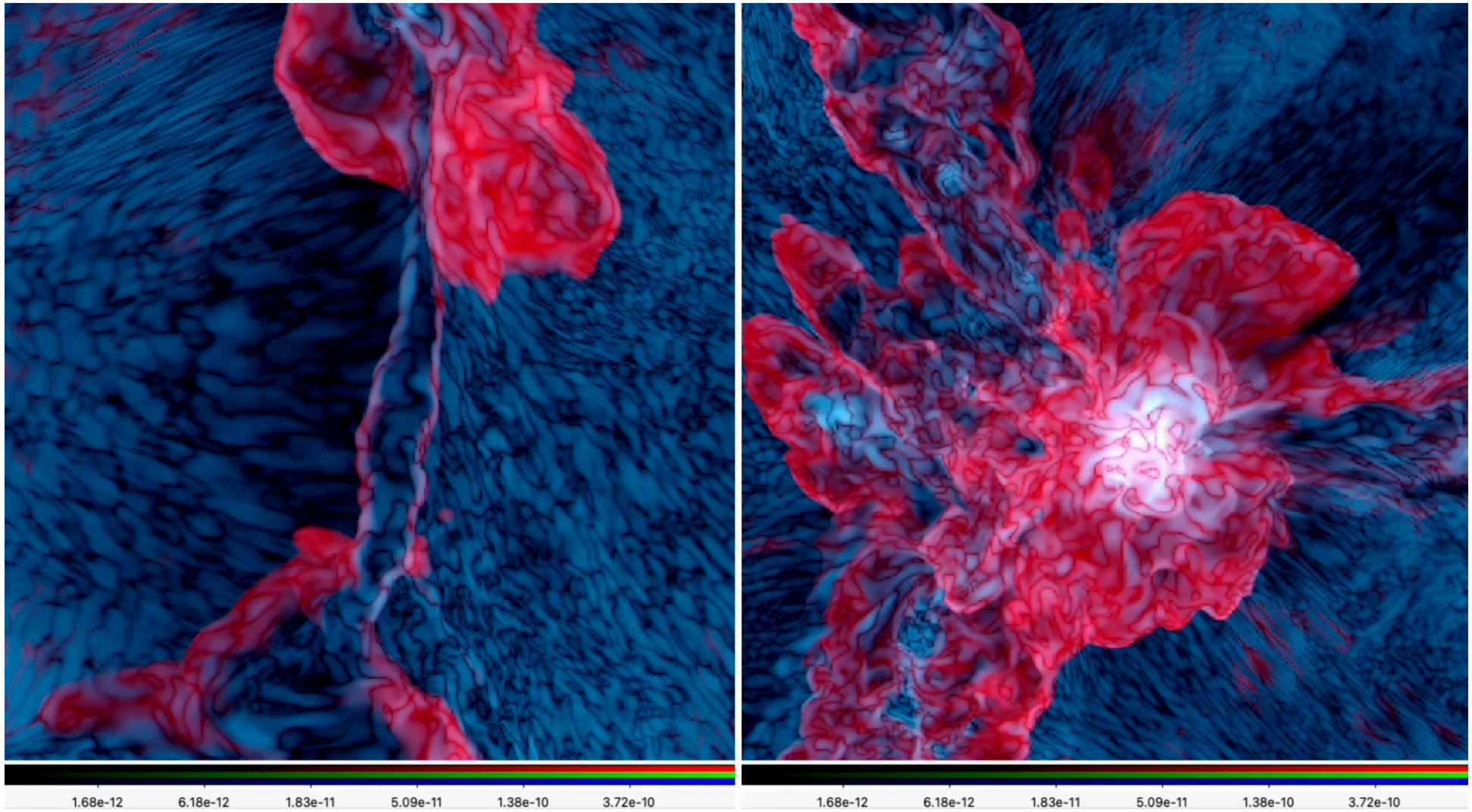


K. DOLAG (PHD THESIS 2000)

WHY NOT USING CLUSTERS OF GALAXIES?

Filaments: no or little dynamo, memory of seed B_0 is **preserved**

Clusters: dynamo amplification, memory of seed B_0 is **lost**



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

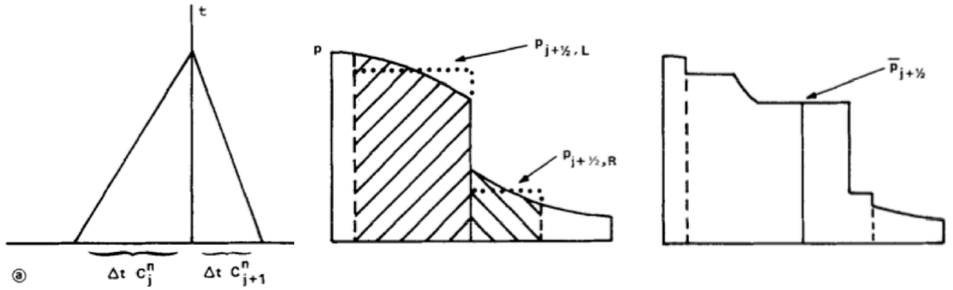
COSMOLOGICAL MHD SIMULATIONS

(Ideal) MHD equations on a comoving grid.

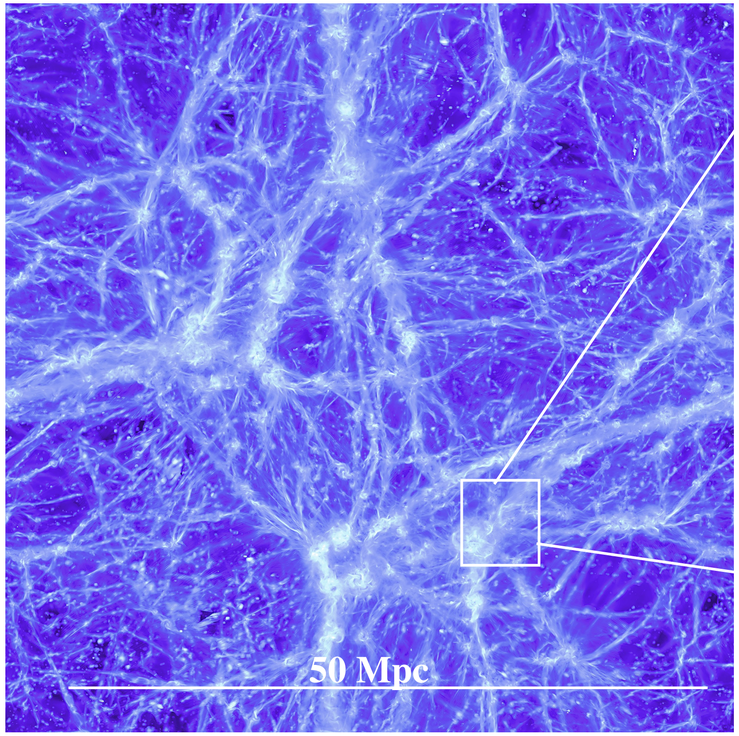
$$\frac{\partial \rho}{\partial t} + \frac{1}{a}\nabla \cdot (\rho \mathbf{v}) = 0$$
$$\frac{\partial \rho \mathbf{v}}{\partial t} + \frac{1}{a}\nabla \cdot (\rho \mathbf{v}\mathbf{v} + \bar{p} - \mathbf{B}\mathbf{B}) = -\frac{\dot{a}}{a}\rho \mathbf{v} - \frac{1}{a}\rho \nabla \Phi$$
$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla \cdot [\mathbf{v}(\bar{p} + E) - \mathbf{B}(\mathbf{B} \cdot \mathbf{v})] = -\frac{\dot{a}}{a}(\rho v^2 + \frac{2}{\gamma - 1}p + \frac{B^2}{2}) - \frac{\rho}{a}\mathbf{v} \cdot \nabla \Phi$$
$$\frac{\partial \mathbf{B}}{\partial t} - \frac{1}{a}\nabla \times (\mathbf{v} \times \mathbf{B}) = -\frac{\dot{a}}{2a}\mathbf{B}$$

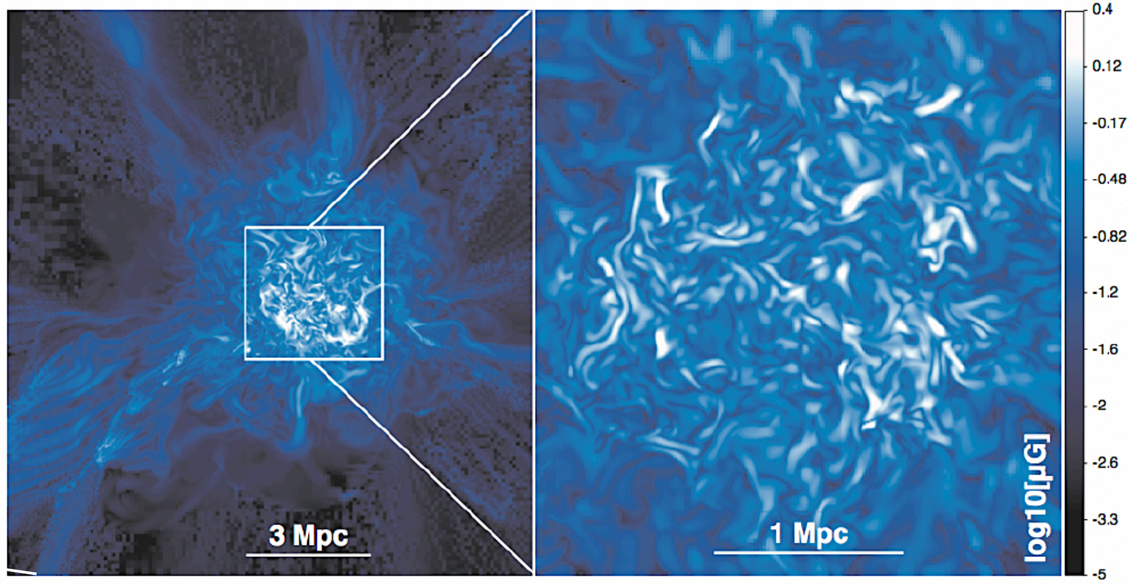
(+ source terms from star/AGN feedback)

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

THE RADIO COSMIC WEB: SYNCHROTRON EMISSION

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

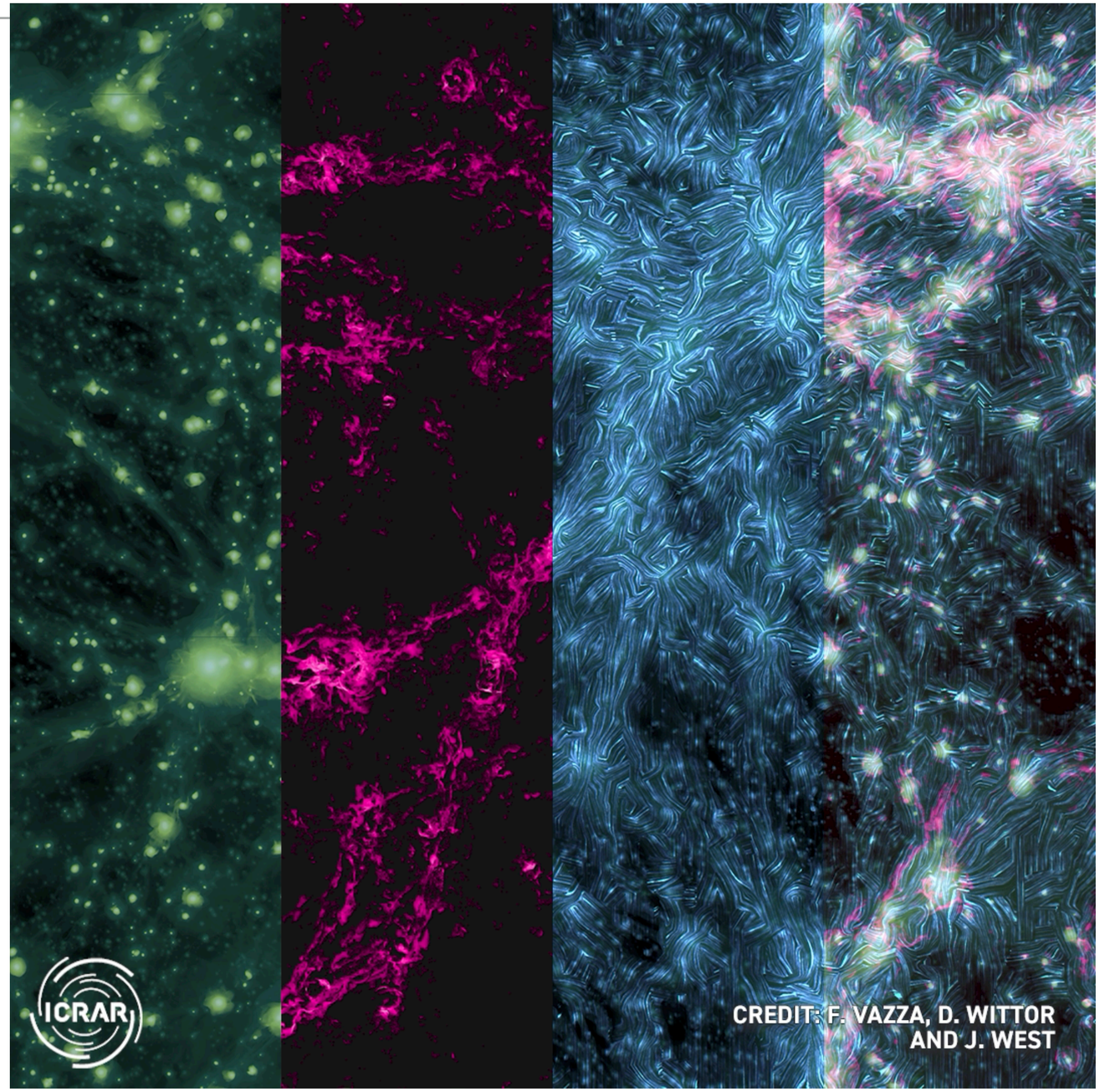
They must have been **shocked** at least once ($\mathscr{M} \geq 10$)

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*



THE RADIO COSMIC WEB: SYNCHROTRON EMISSION

Discussion

GAENSLER: What can your models predict about diffuse radio emission *between* clusters of galaxies?

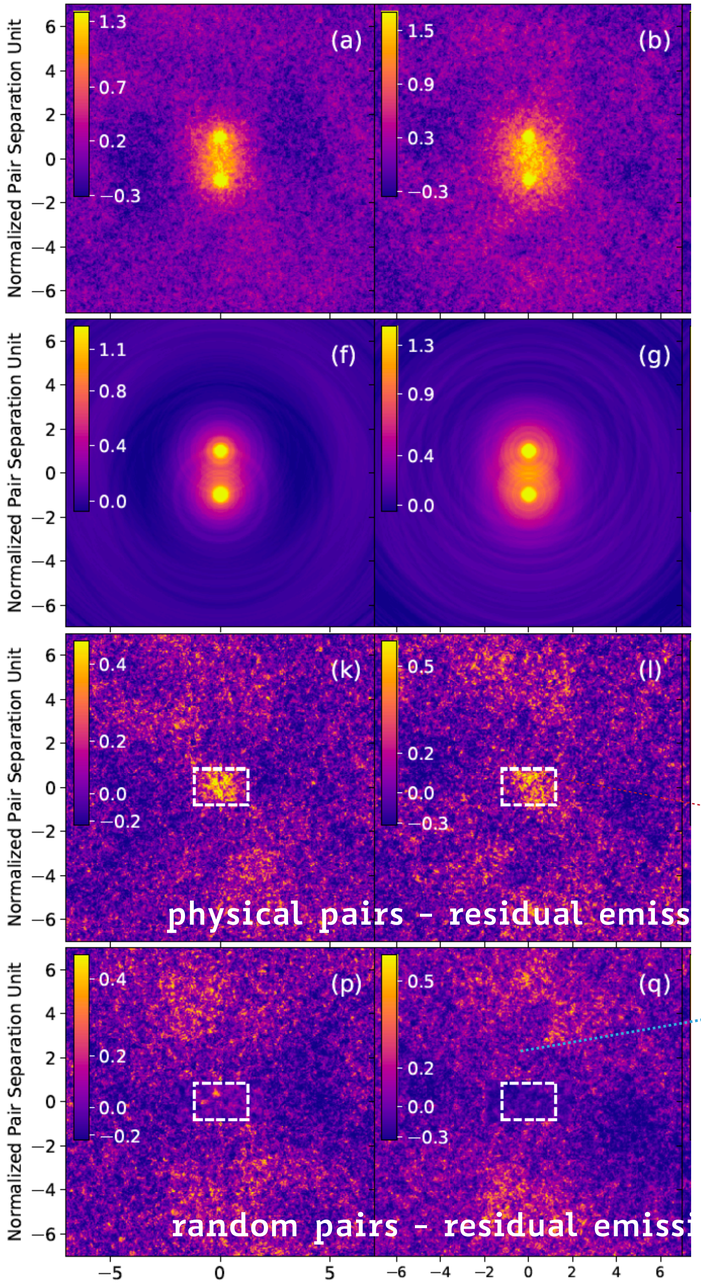
DOLAG: In these models such diffuse emission is extremely small. Such emission is thought to be produced by shocks and directly involve phenomena which are (yet) not included in the presented simulations.

DOLAG: No.

Klaus Dolag

DOLAG+05, IAU PROCEEDING

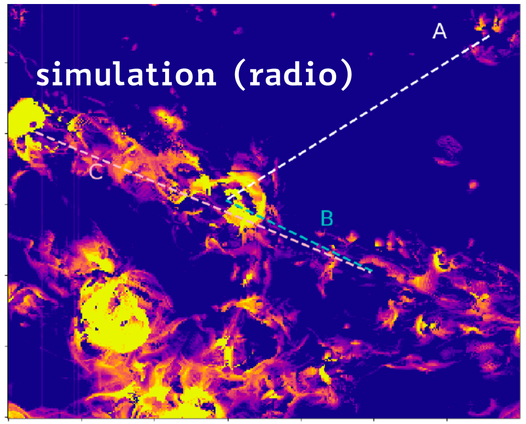
THE RADIO COSMIC WEB: SYNCHROTRON EMISSION



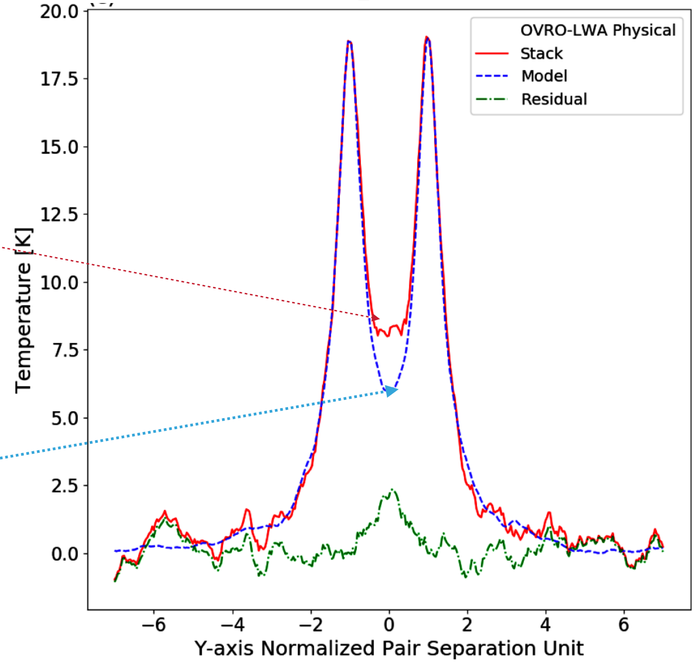
Vernstrom et al.2021: stacking of >200,000 pairs of halos in MWA survey

>5σ detection of the statistical excess of radio emission

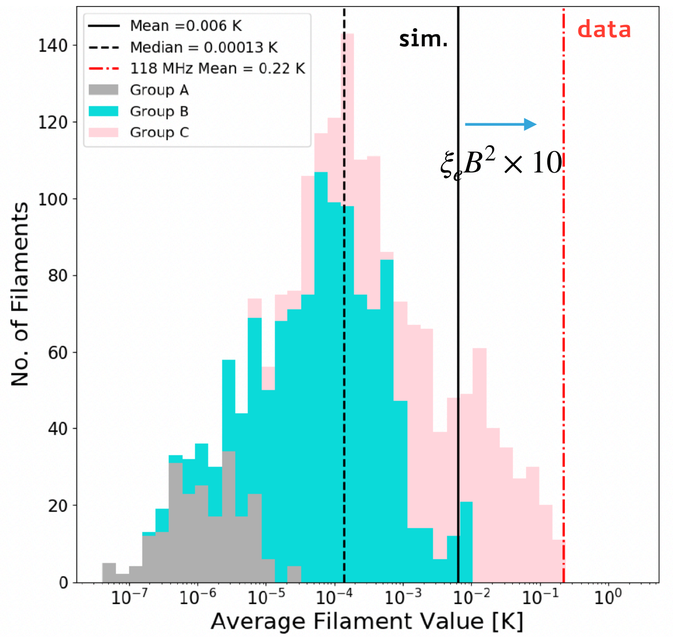
compatible with synchrotron from shocks around/in filaments.



line profiles



PDF of radio flux



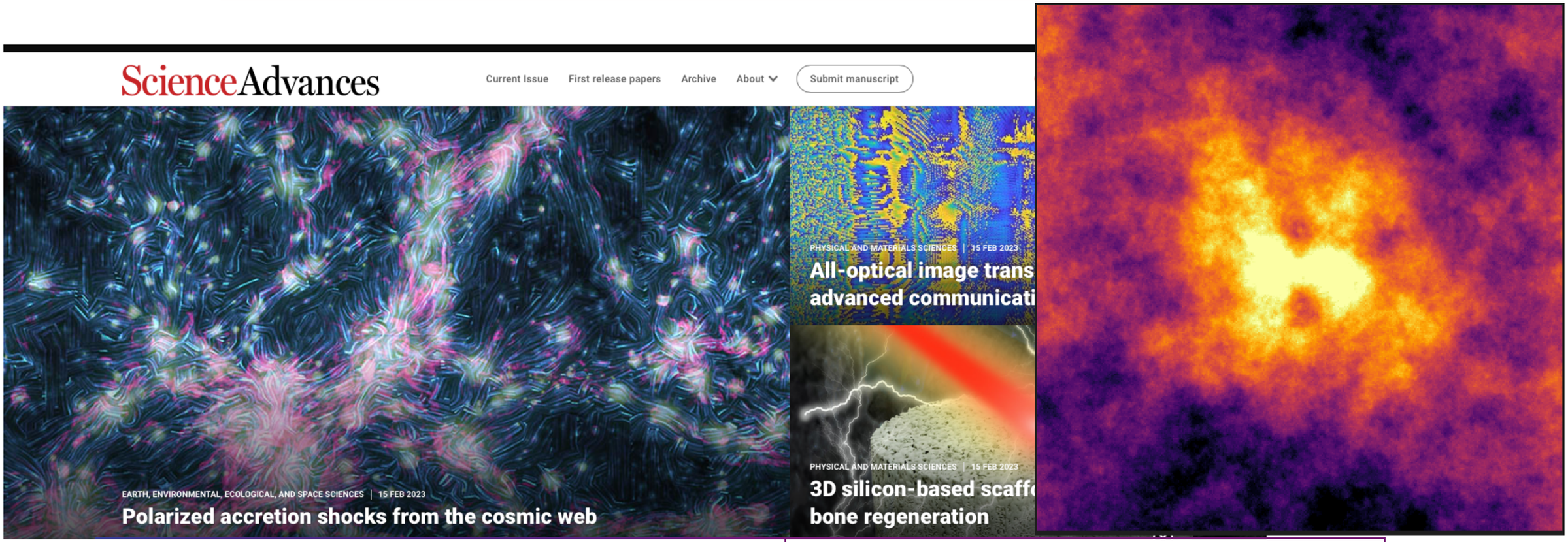
VERNSTROM ET AL. 2021 MNRAS

THE RADIO COSMIC WEB: POLARISED SYNCHROTRON EMISSION

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

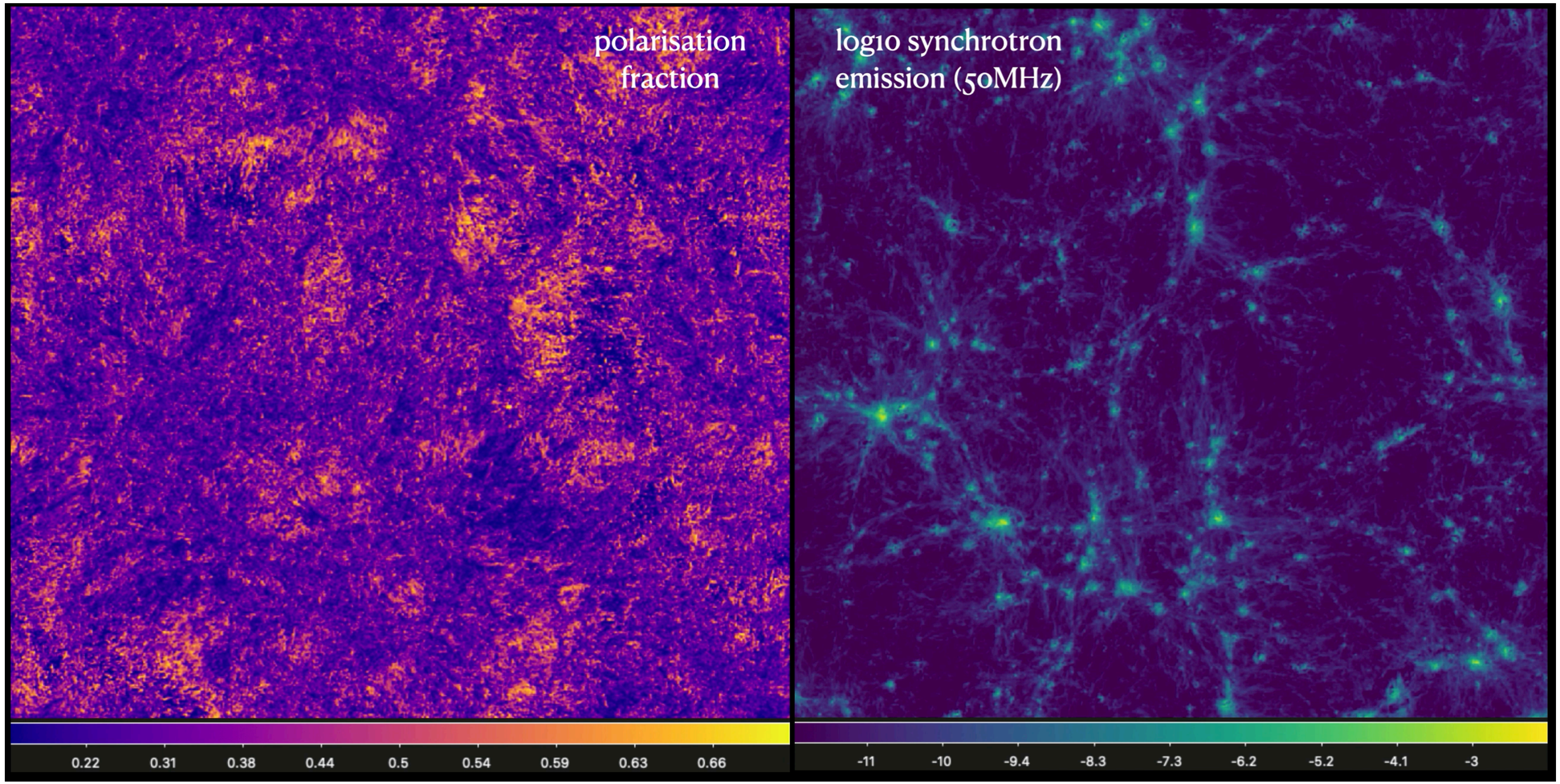
All other (conceivable) alternative explanations for the emission ruled out.

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: POLARISED SYNCHROTRON EMISSION



$$P = Q + iU = pIe^{2i\psi}$$

$$\psi = \psi_0 + \mathrm{RM} \cdot \lambda^2$$

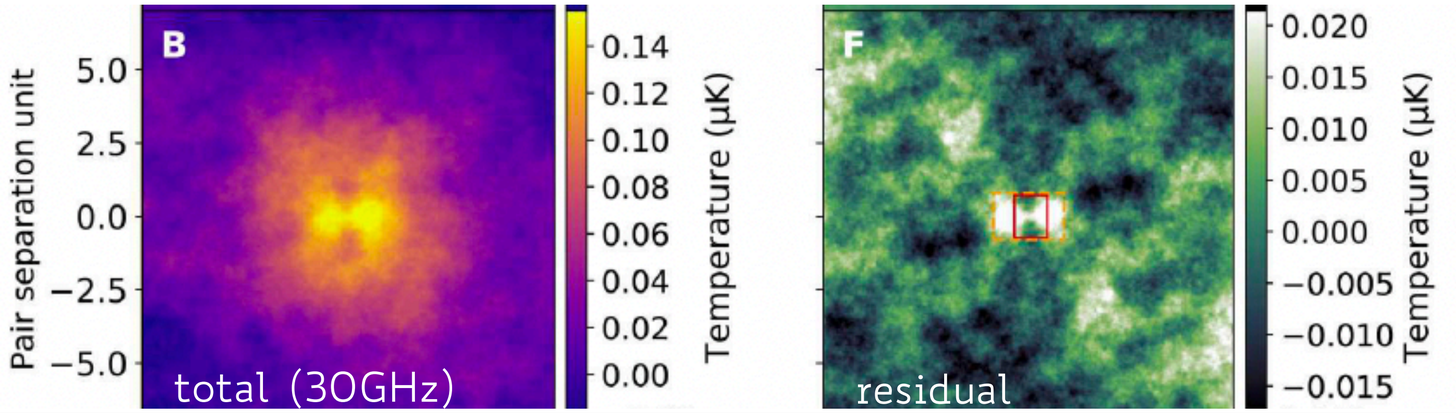
FV, Braun, Bonaldi, Gheller…in prep.

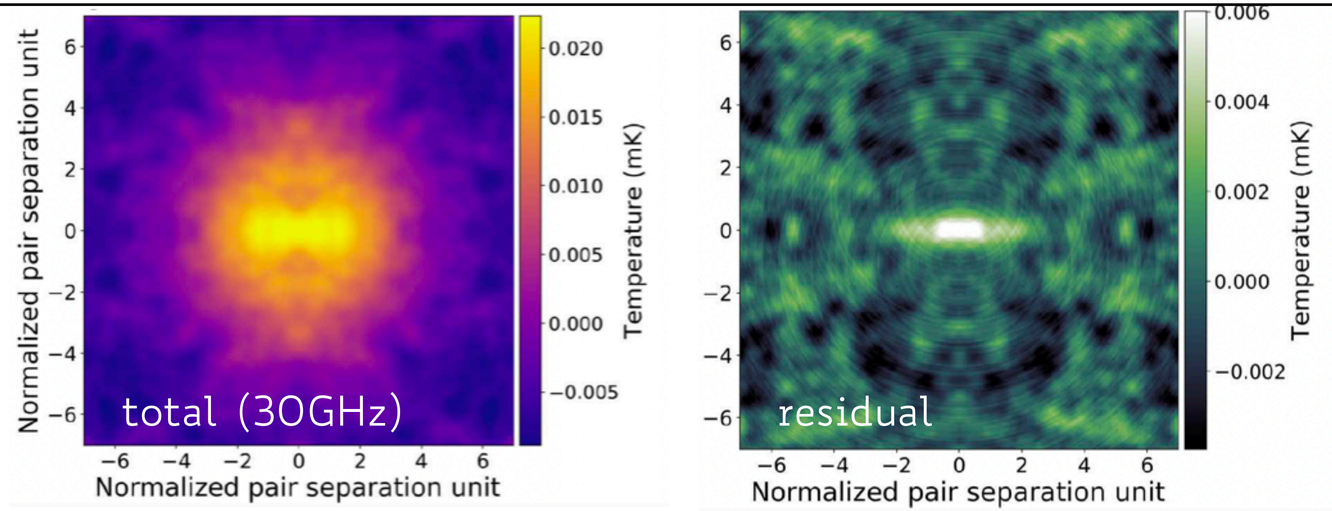
synchrotron emission & integration of Stokes parameters along the LOS:

32 parallel julia *tasks on Leonardo @CINECA, ~20 Tb of data*

THE RADIO COSMIC WEB : VIA STACKING

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



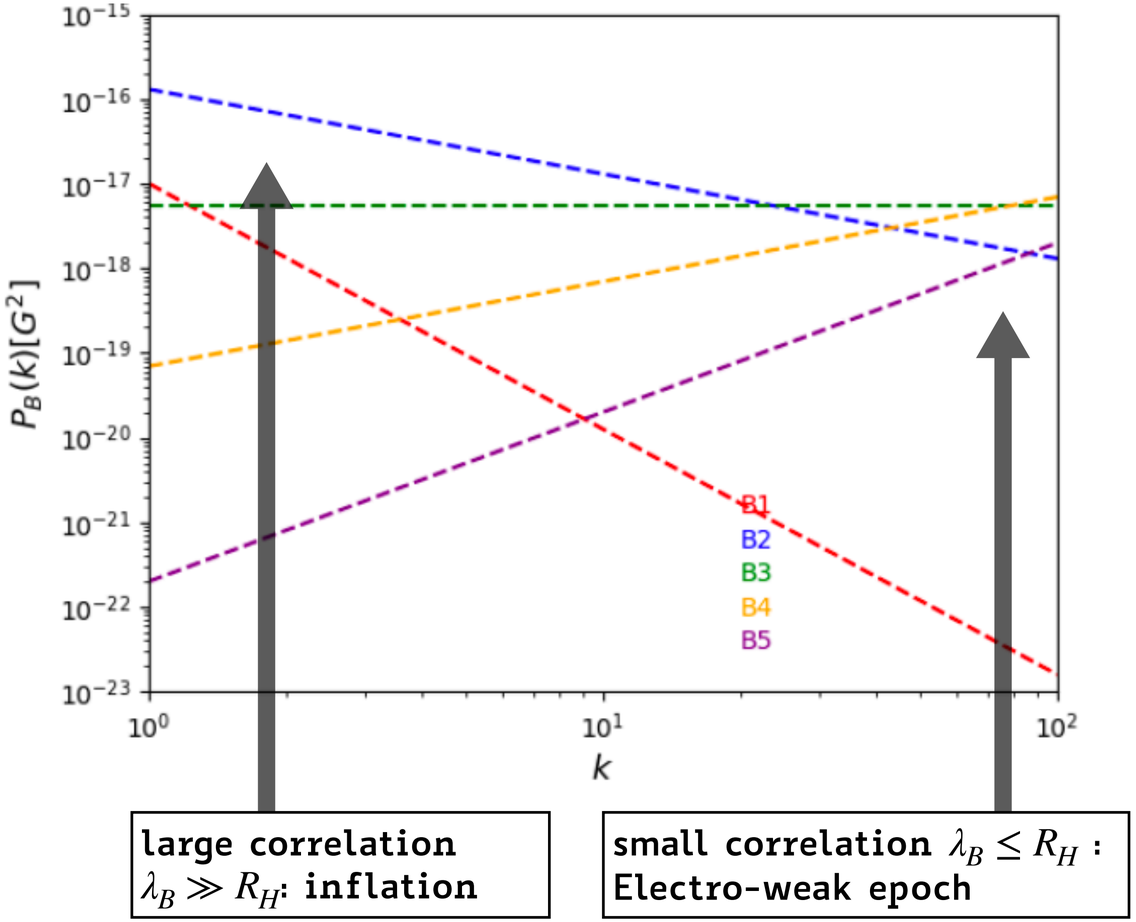


- **Stacking of** $\sim 10^2$ **SIMULATED pairs of halos in the cosmological MHD run.**
- **it constrains accel. efficiency & seed B-field:** $\xi_e B^2 \approx 0.01 \cdot (0.3\mathrm{nG})^2$

SIMULATING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS

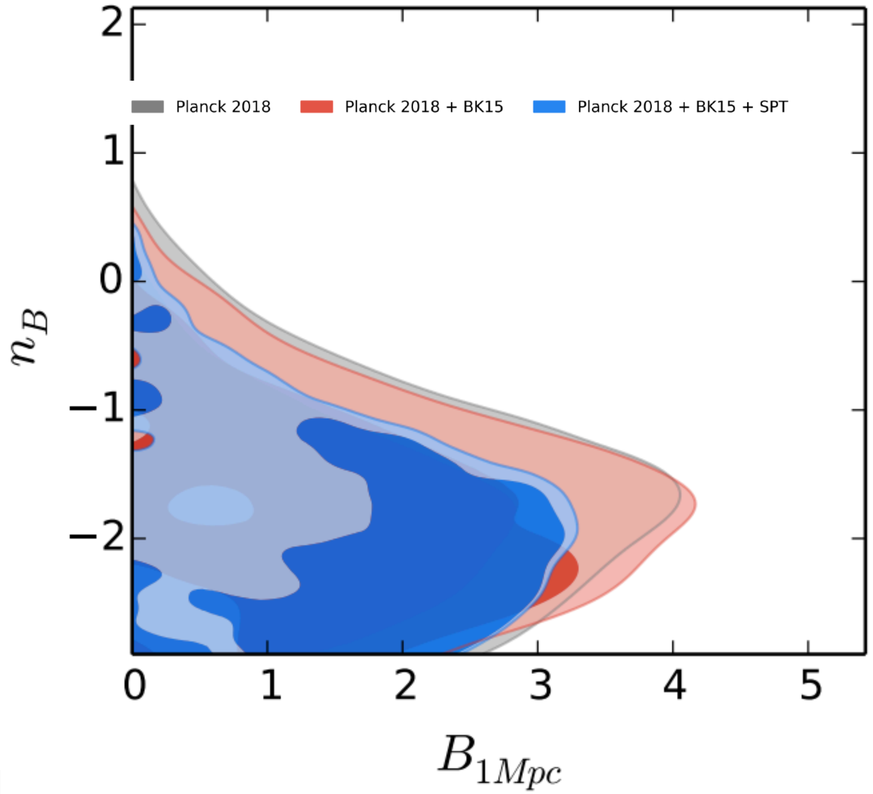
- **Modelling of the Cosmic Microwave Background constrains amplitude of power spectra of B-fields at $z \sim 10^3$**

$$P_B(k) \propto k^{\alpha_B} \ (-2.9 \leq \alpha_B \leq 2.0) \quad \textbf{and} \quad \langle B^2_{1Mpc} \rangle^{0.5} \leq 4\text{nG}$$



large correlation $\lambda_B \gg R_H$: inflation

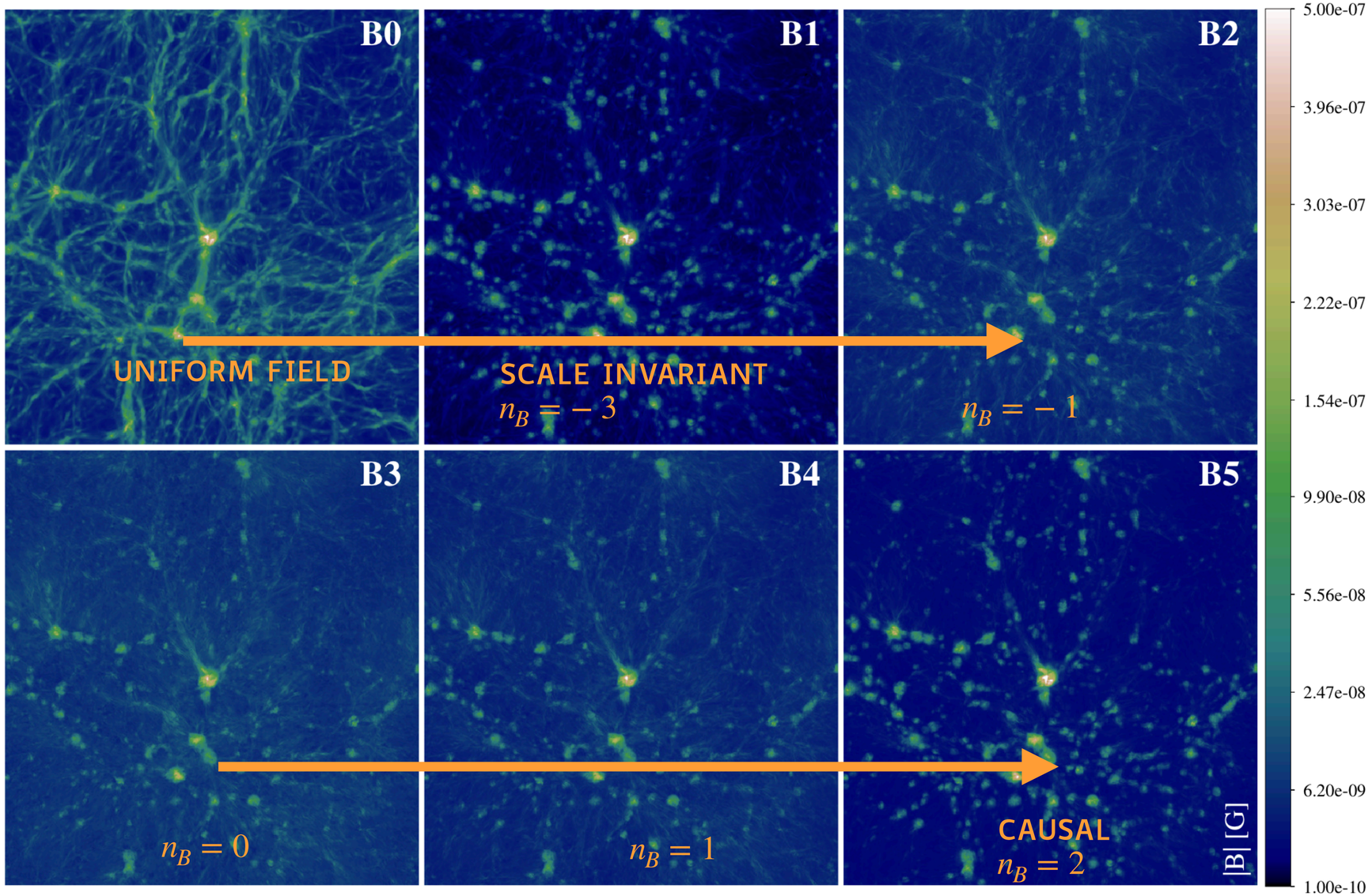
small correlation $\lambda_B \leq R_H$: Electro-weak epoch



PAOLETTI & FINELLI+2019 JCAP

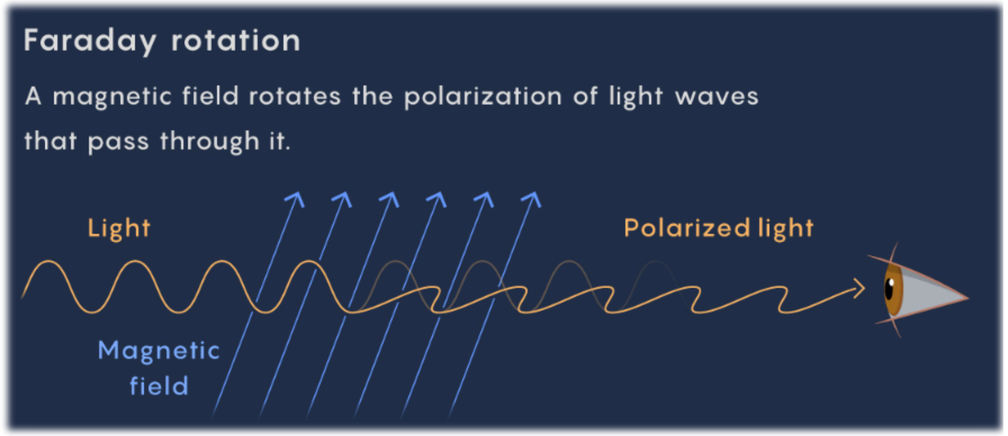
SIMULATING STOCHASTIC PRIMORDIAL MAGNETIC FIELDS

- Large differences of B-fields in filaments/voids



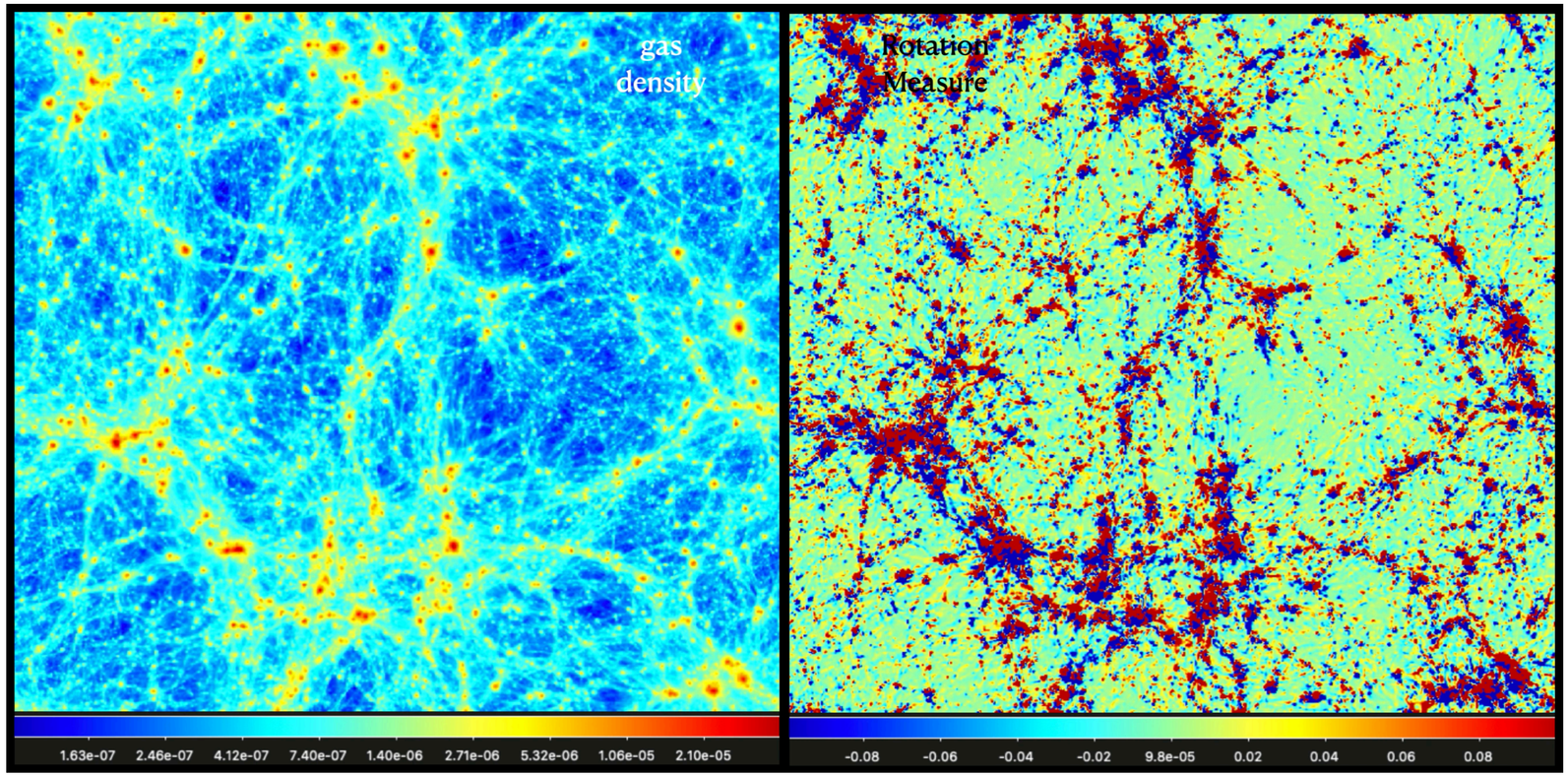
FV, PAOLETTI, BANFI, FINELLI ET AL. 2021 MNRAS

THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION



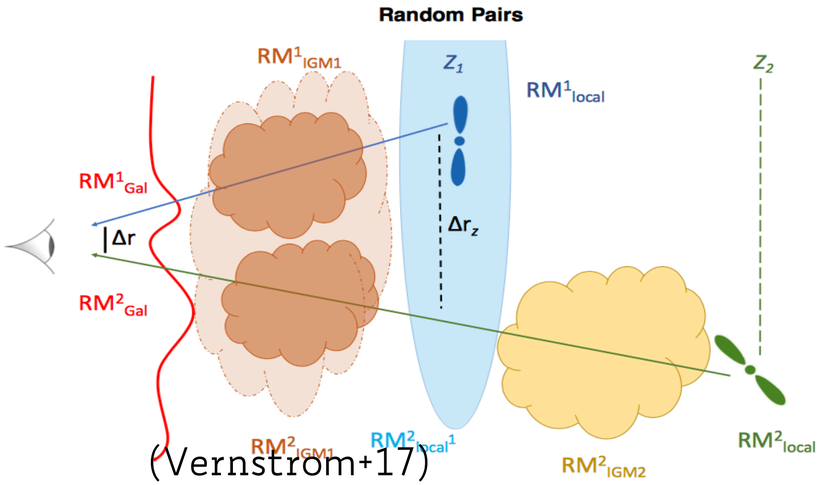
the **Faraday Rotation** effect:

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

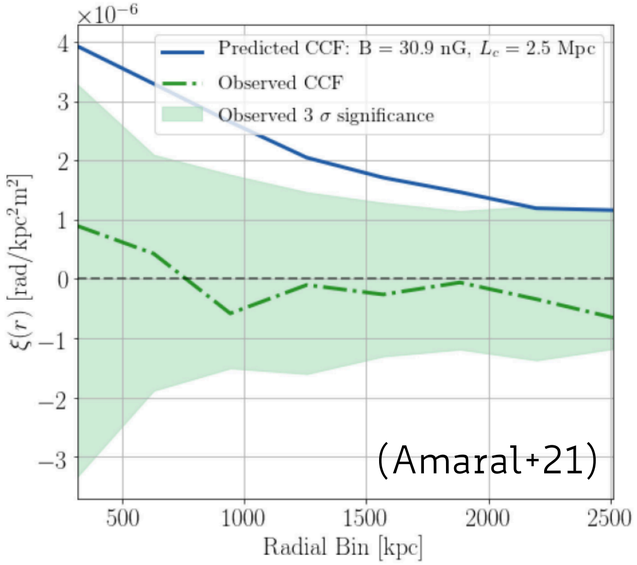


THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION

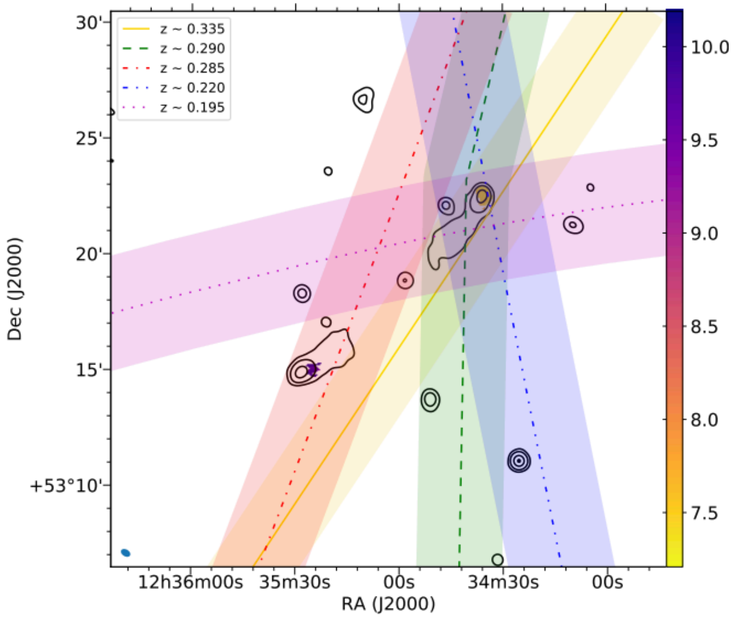
Several important attempts of statistical detection:



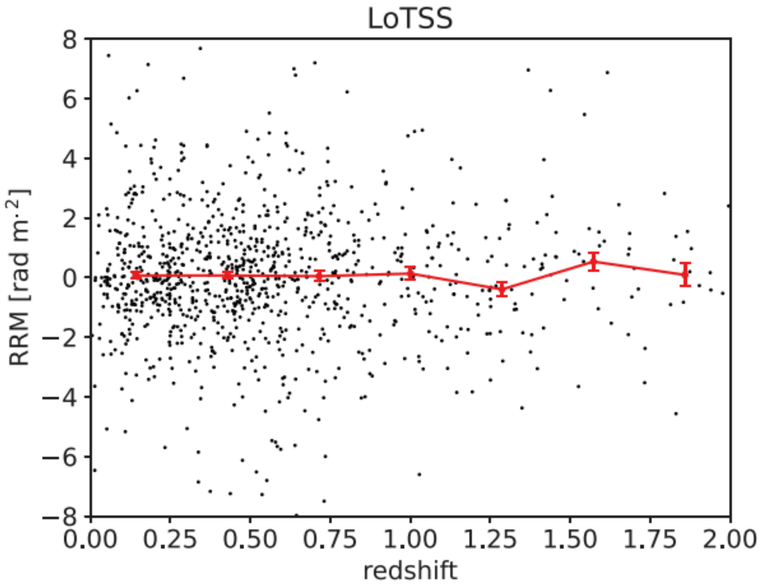
(Vernstrom+17)



(Amaral+21)



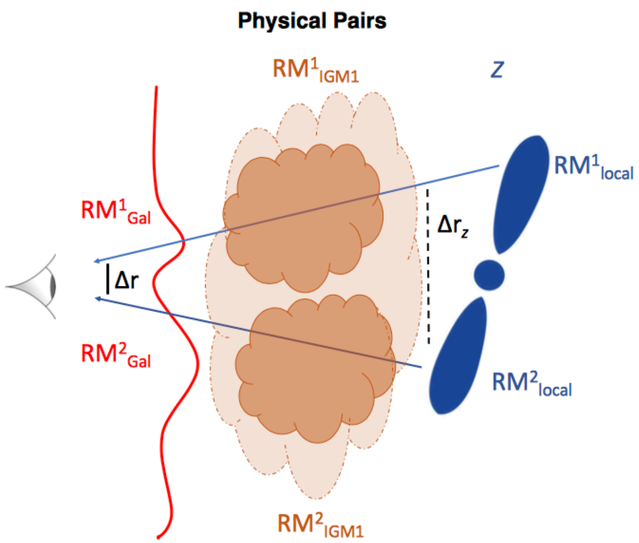
(O'Sullivan+19, 20)

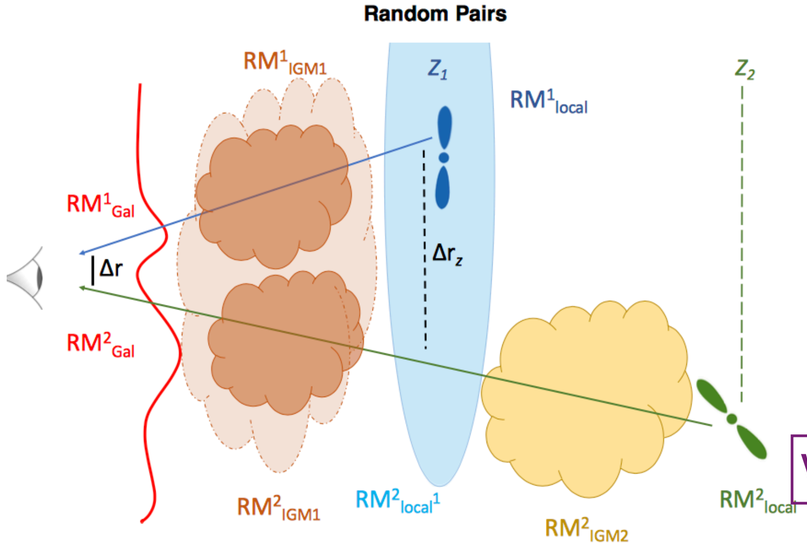


(Carretti+22,23)

THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION

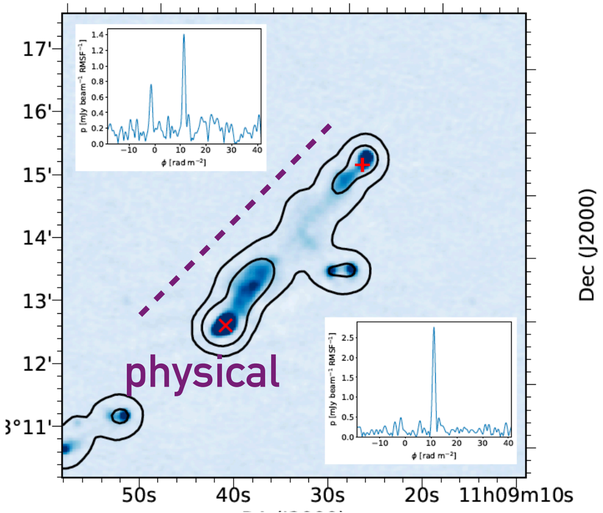
- Excess ΔRM in random pairs: cosmic web contribution?

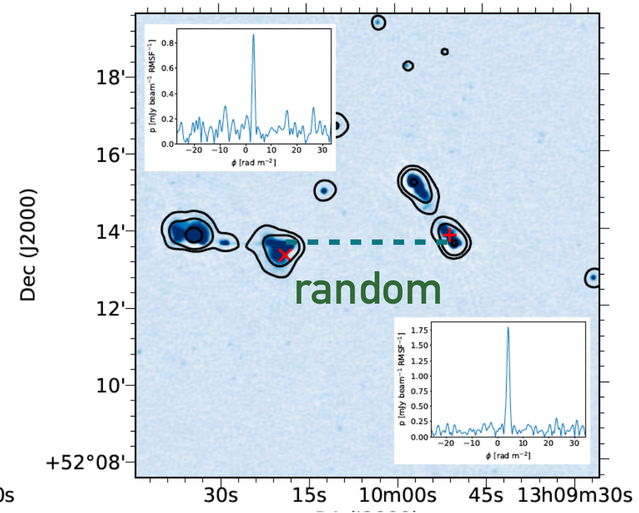


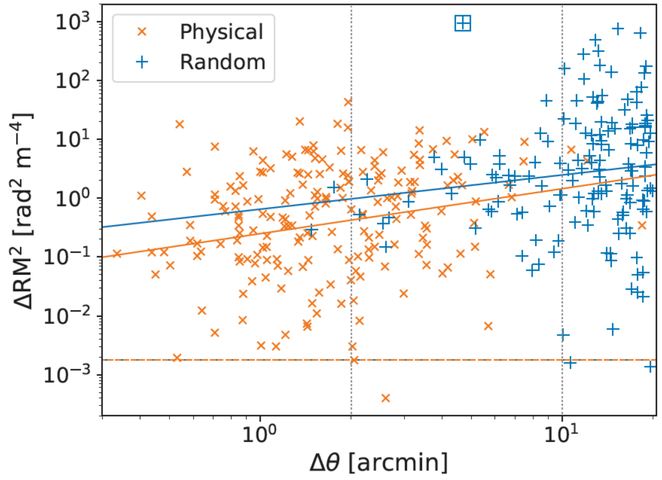


VERNSTROM+19

- ΔRM(θ) measured with LOFAR for 310 pairs



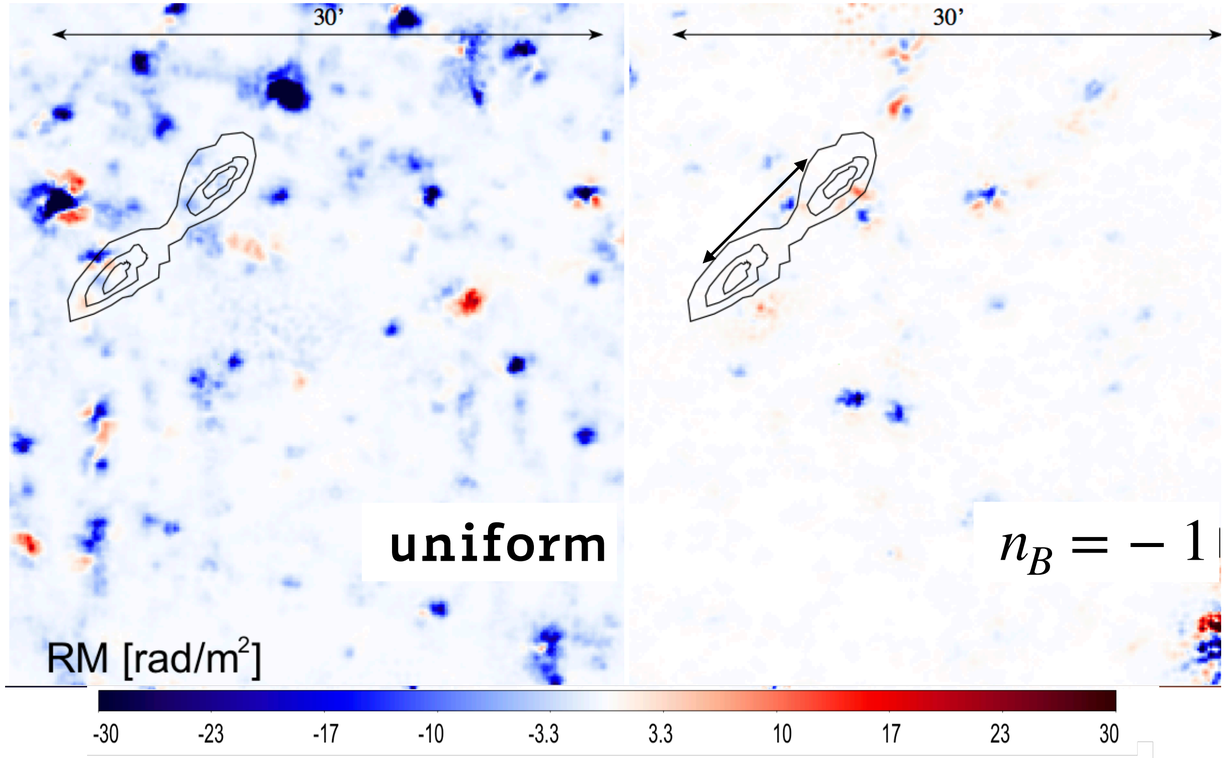


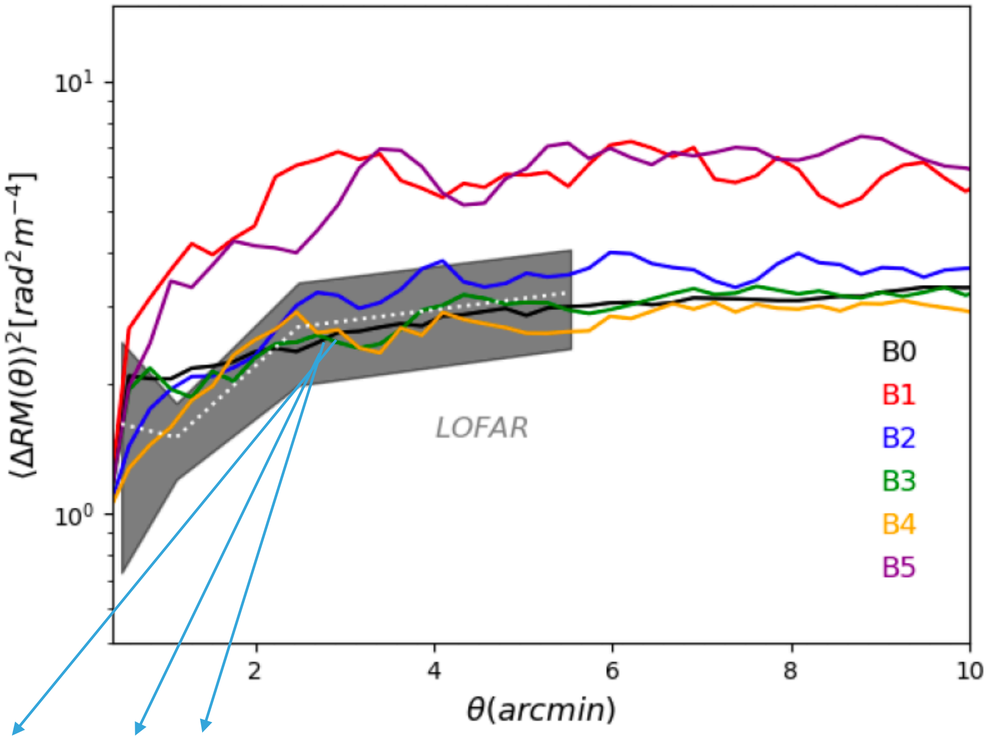


O'SULLIVAN, BRUGGEN, FV +2020

THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION

Simulated trend of **Rotation Measure difference** *with angular scale vs real one observed with LOFAR:*

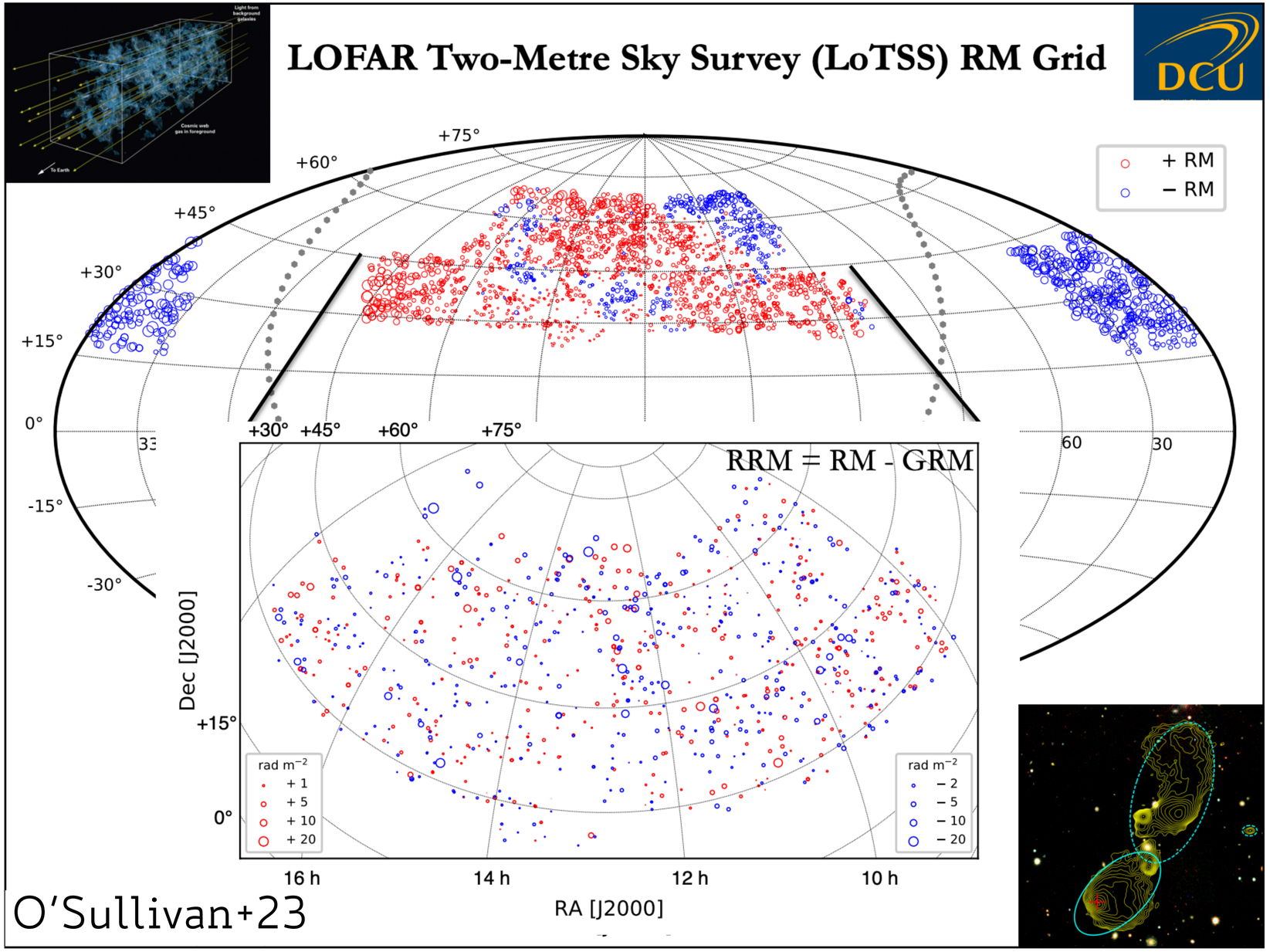




primordial models with $-1.0 \leq n_B \leq 1.0$ **are favoured by ΔRM data. Too "blue" or too "red" models are discared**

FV ET AL. 2021 MNRAS

THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION



LOTSS DR2 survey:

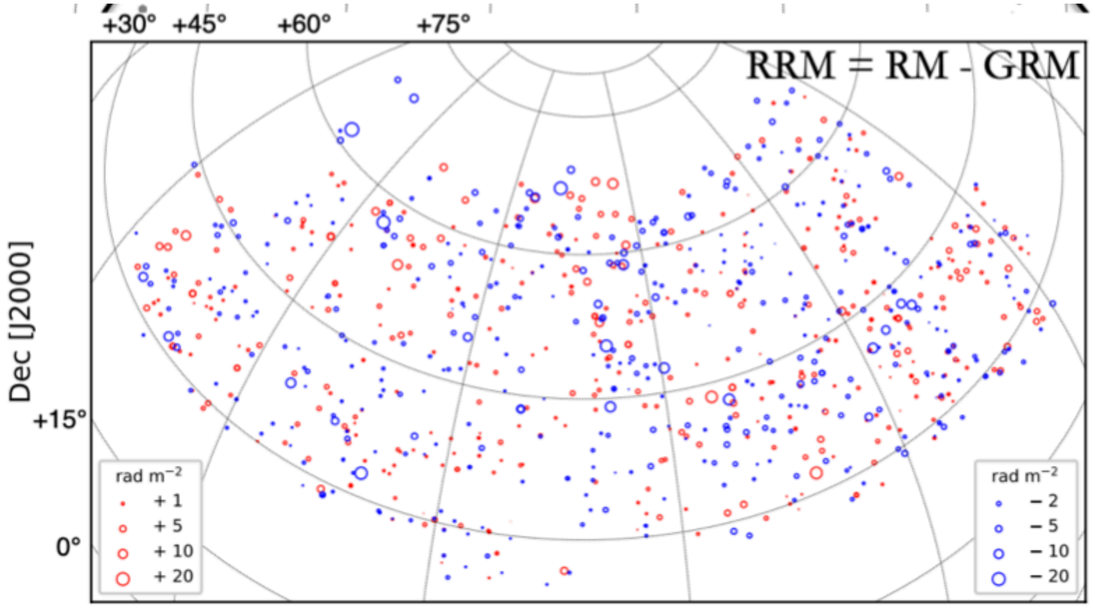
- ~4.4 million radio sources (Shimwell et al. 2022)

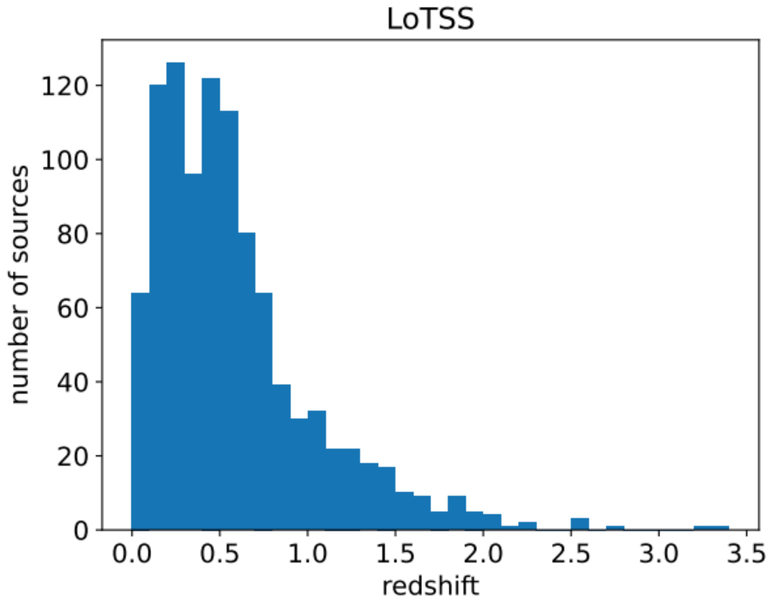
LOTSS RM Grid:

- ~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**: $$\left\langle RRM^2 \right\rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \left\langle RRM_f^2 \right\rangle^{1/2}$$





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°
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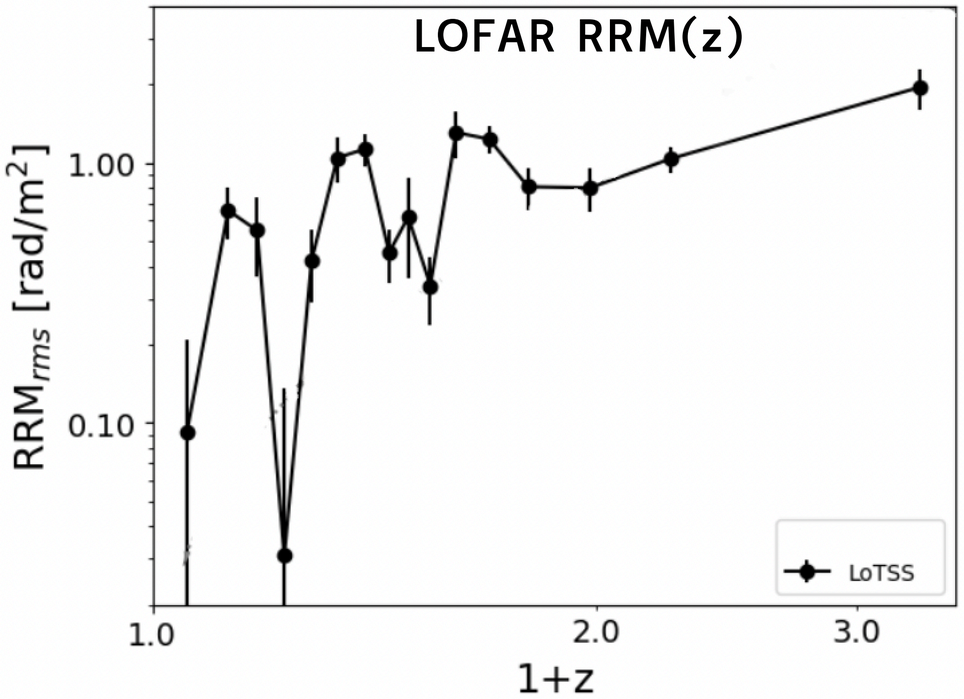

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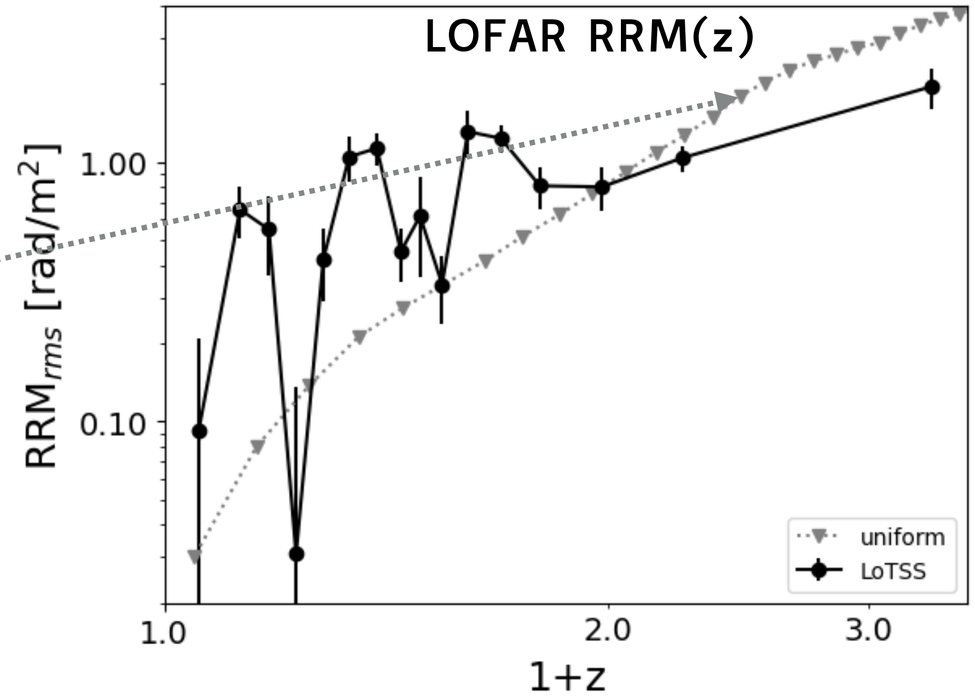
Uniform B model (0.1nG)



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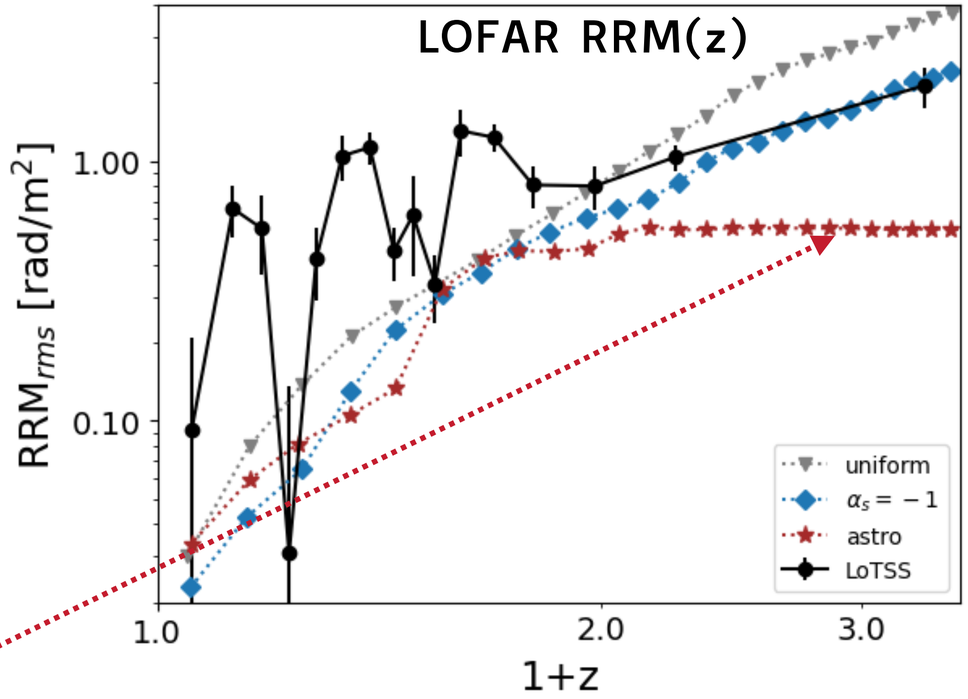

purely astrophysical seeding

(AGN+stellar winds)

CARRETTI + 23, 24

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Primordial model with n_B=-1

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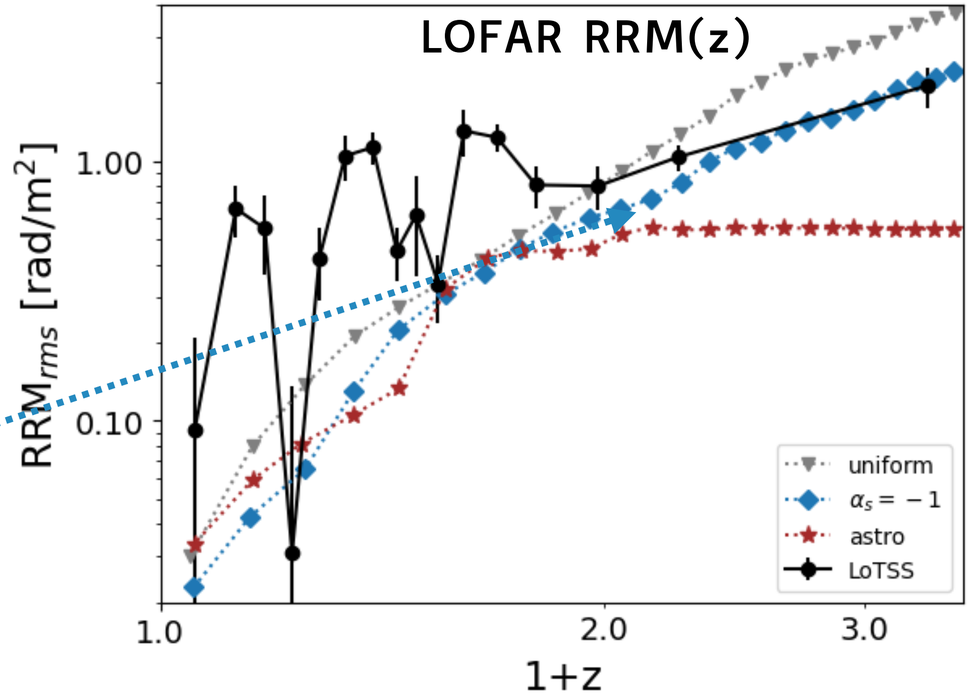

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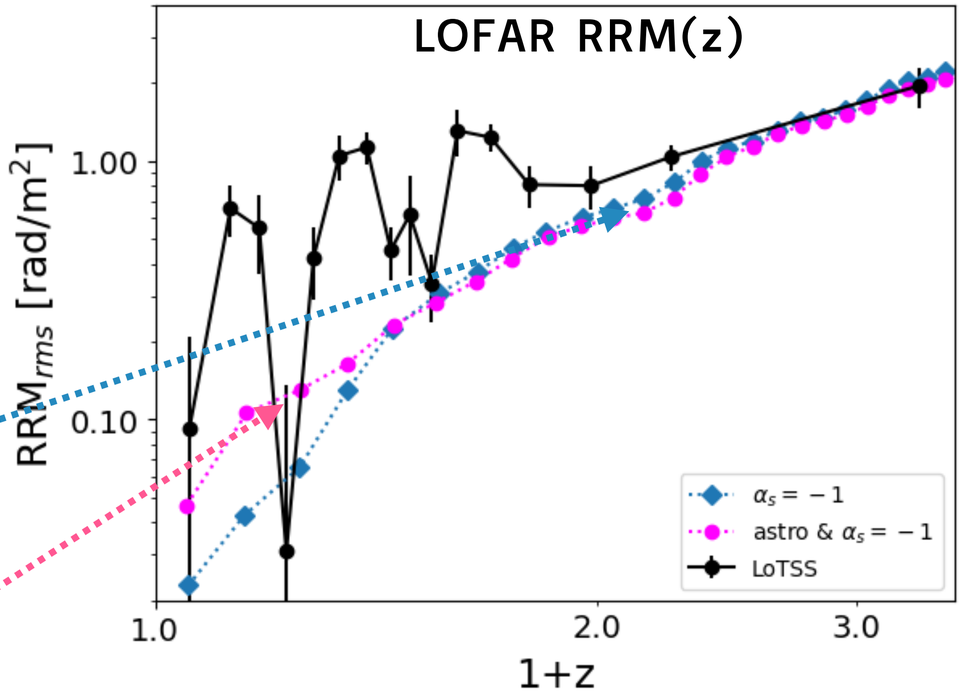
Primordial model with n_B=-1

Primordial model with n_B=-1 + astrophysical seeding



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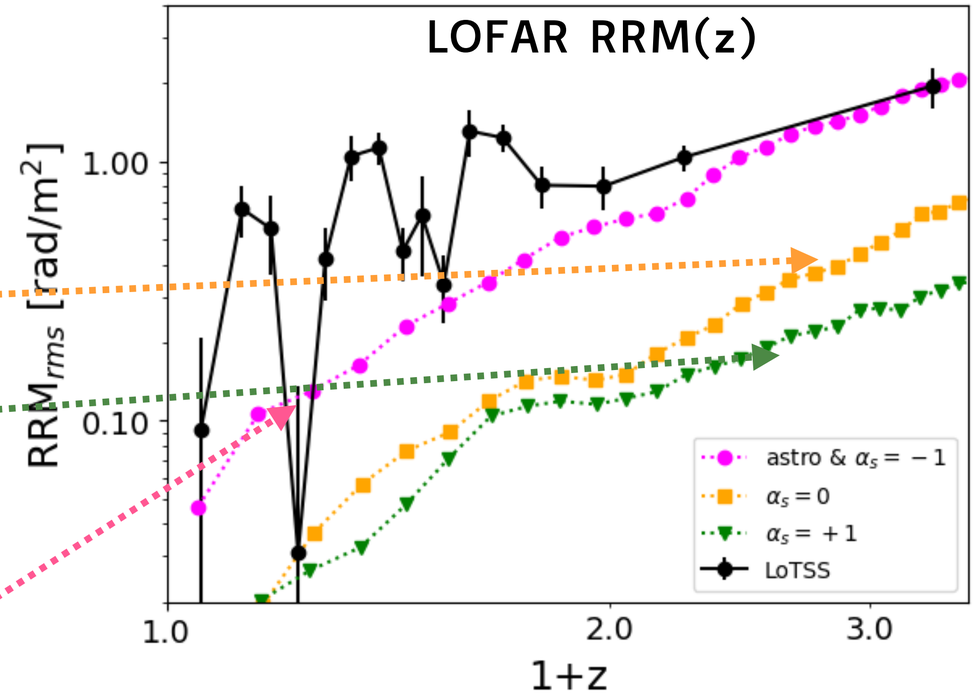
Primordial model with n_B=0

Primordial model with n_B=1

Primordial model with n_B=-1
+ astrophysical seeding



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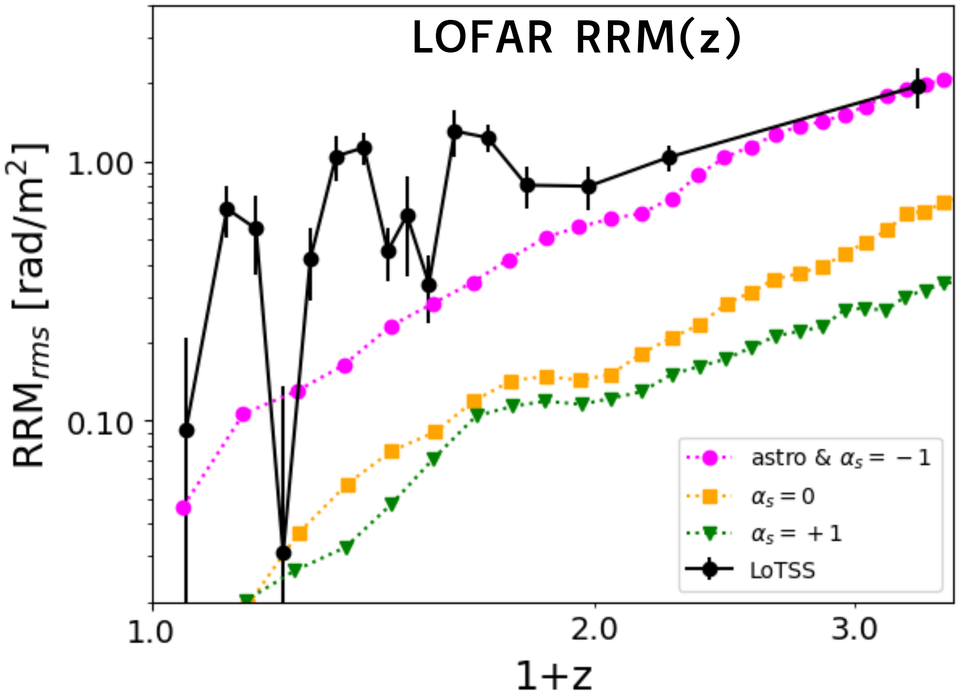

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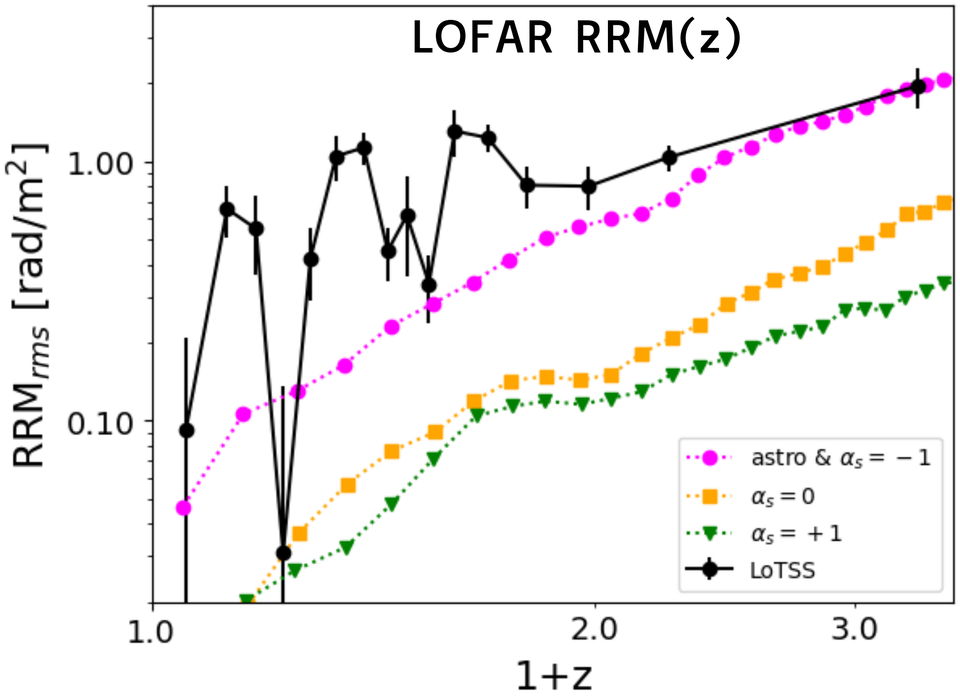
Large improvement over CMB limits:

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

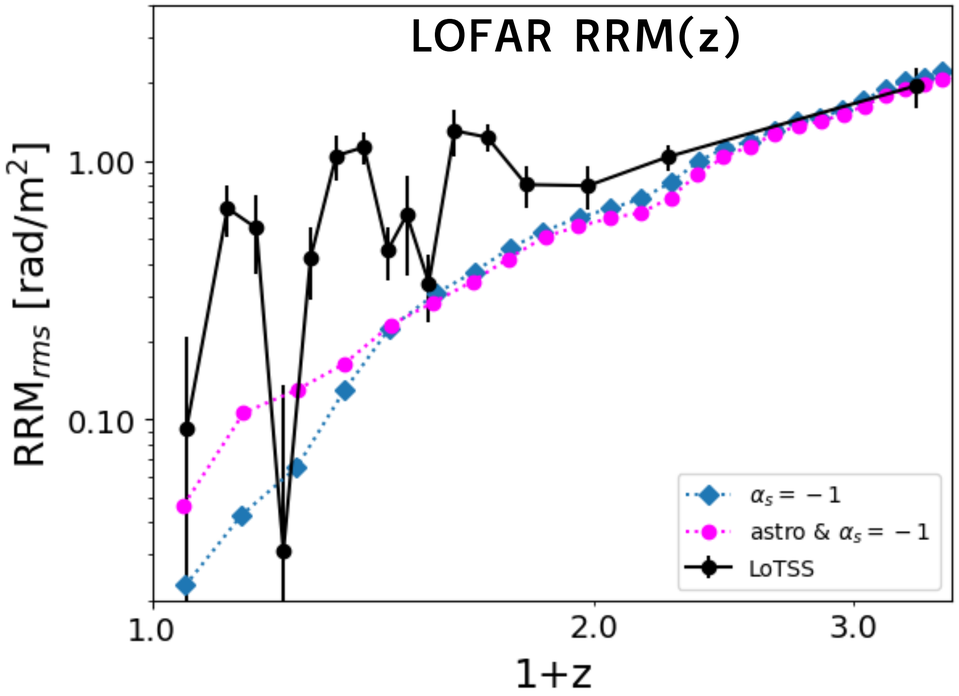


CARRETTI + 23, 24

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 $\langle B^2_{1Mpc} \rangle^{0.5} \leq 0.4\mathrm{nG}$**



CARRETTI + 23, 24

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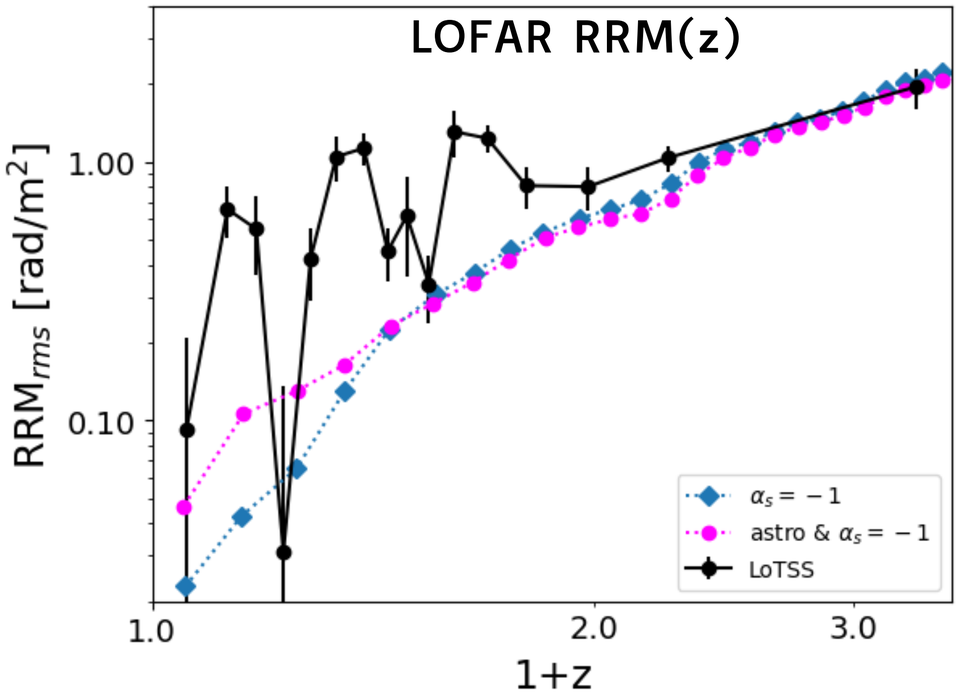
Notice:

- 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

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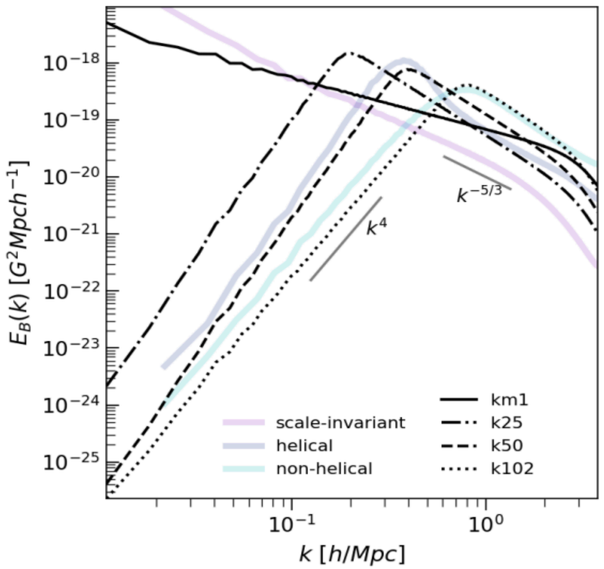
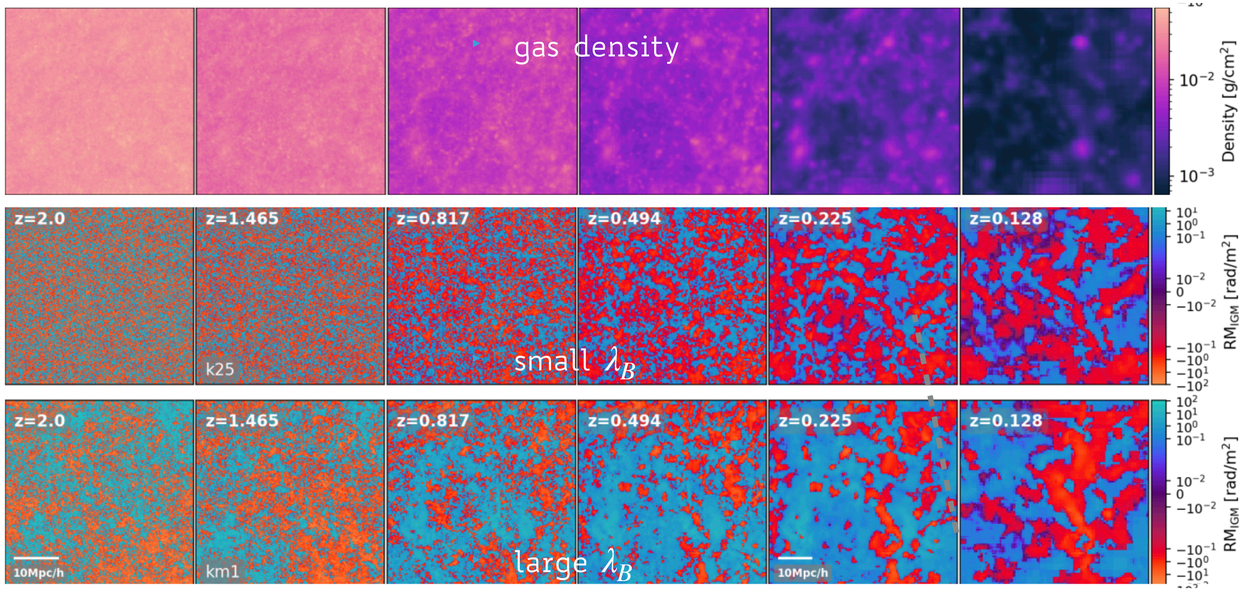
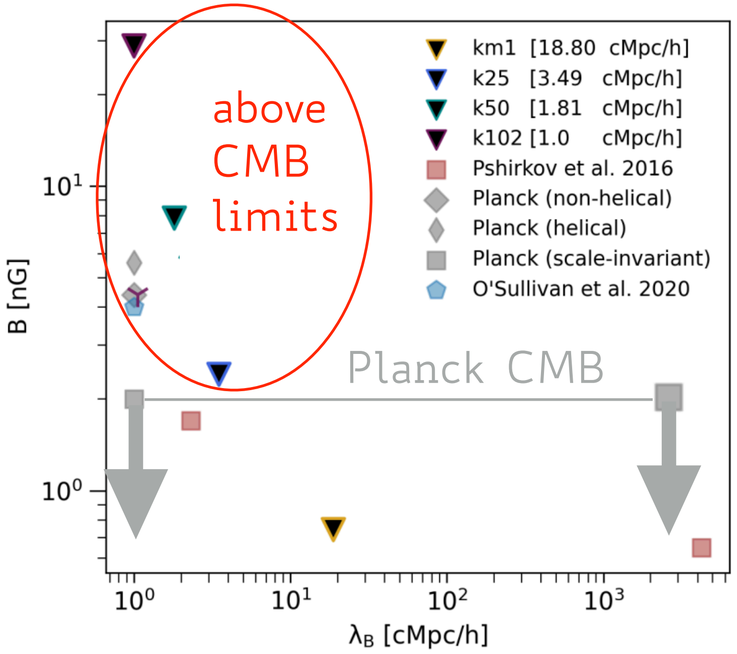




- Simulations of causal primordial B-fields with a finite maximum scale λ_B
- to fit RRM data, small scale causal models require normalisation > CMB allowed limits

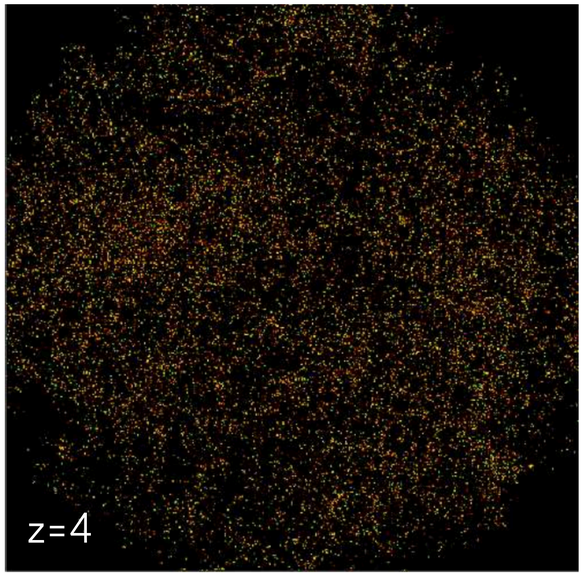


MTCHEDLIDZE ET AL. 2024

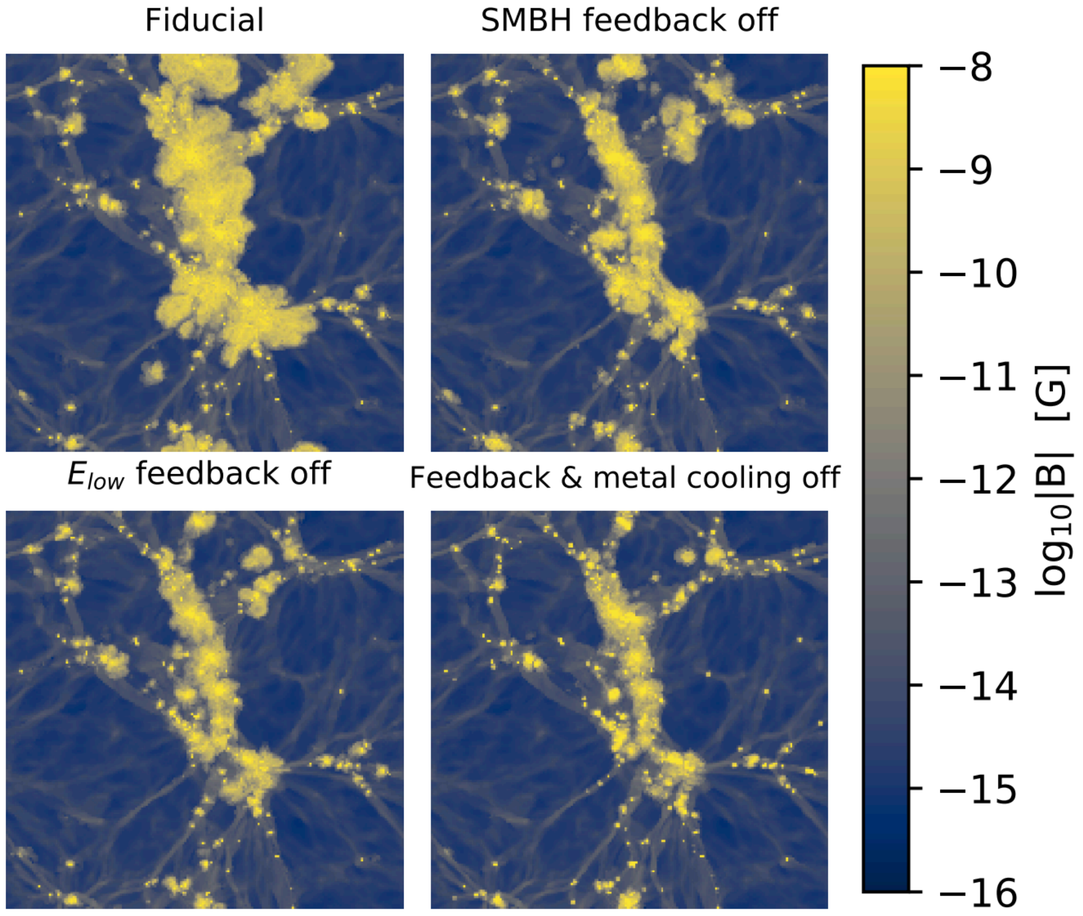
CAN MAGNETISED OUTFLOWS OUTSHINE PRIMORDIAL B-FIELDS?

Filling factors & strength of magnetic fields ejected by galaxies not well constrained.

Uncertainties related to **galaxy formation & feedback**



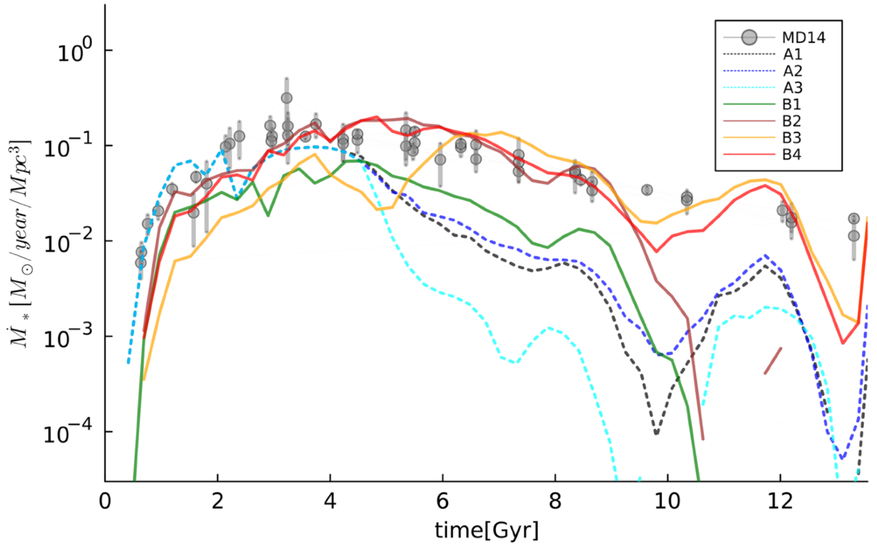
Donnert, Dolag et al. 2009



Aramburo-Garcia, Bondarenko et al. 2021,22

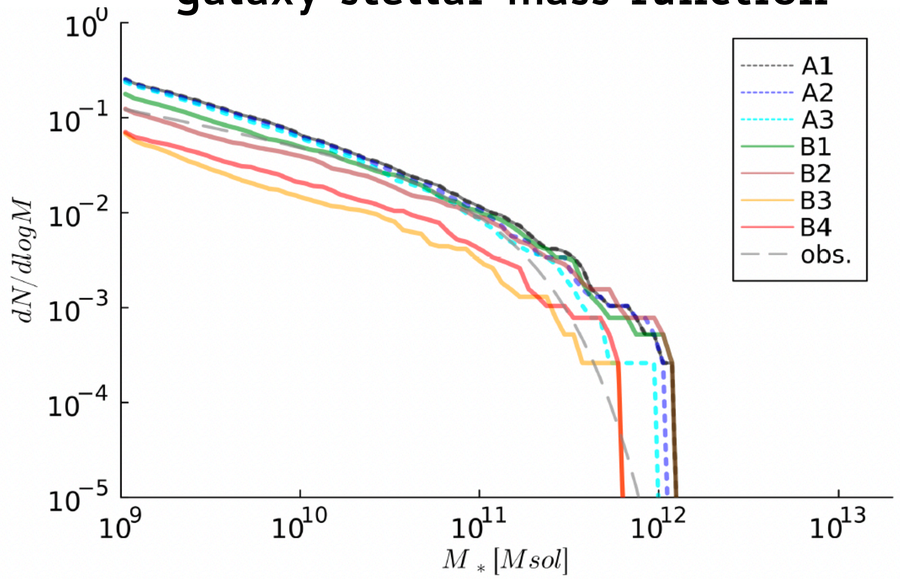
ASTROPHYSICAL SEEDING OF B-FIELDS

cosmic star formation rate

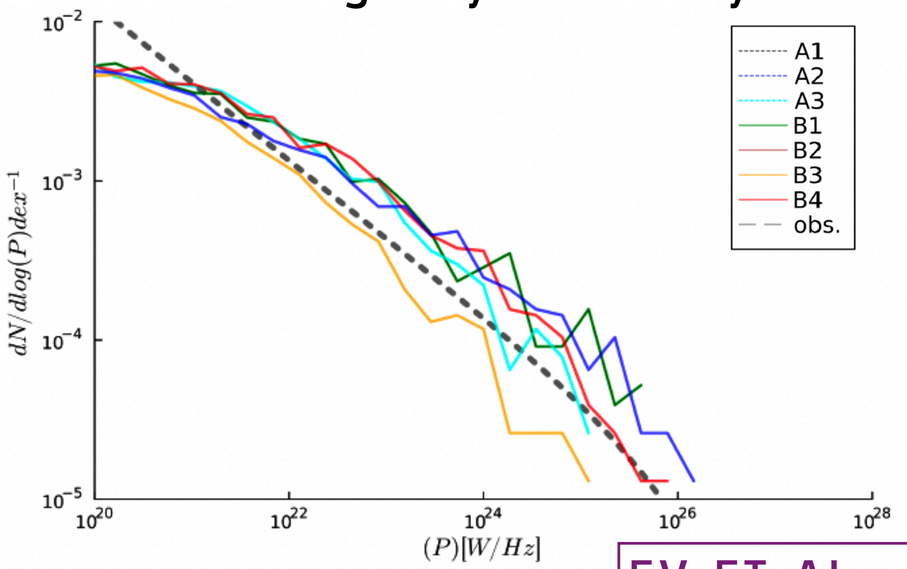


- New ENZO MHD simulations tuned to reproduce **cosmic star formation, stellar mass function, stellar fraction, radio galaxy luminosity functions**
- Star formation (Kravtsov+02) + SMBH feedback (kinetic/thermal) coupled with **B-field**
- CRe fluid sourced by shocks (DSA), star formation and AGNs

galaxy stellar mass function

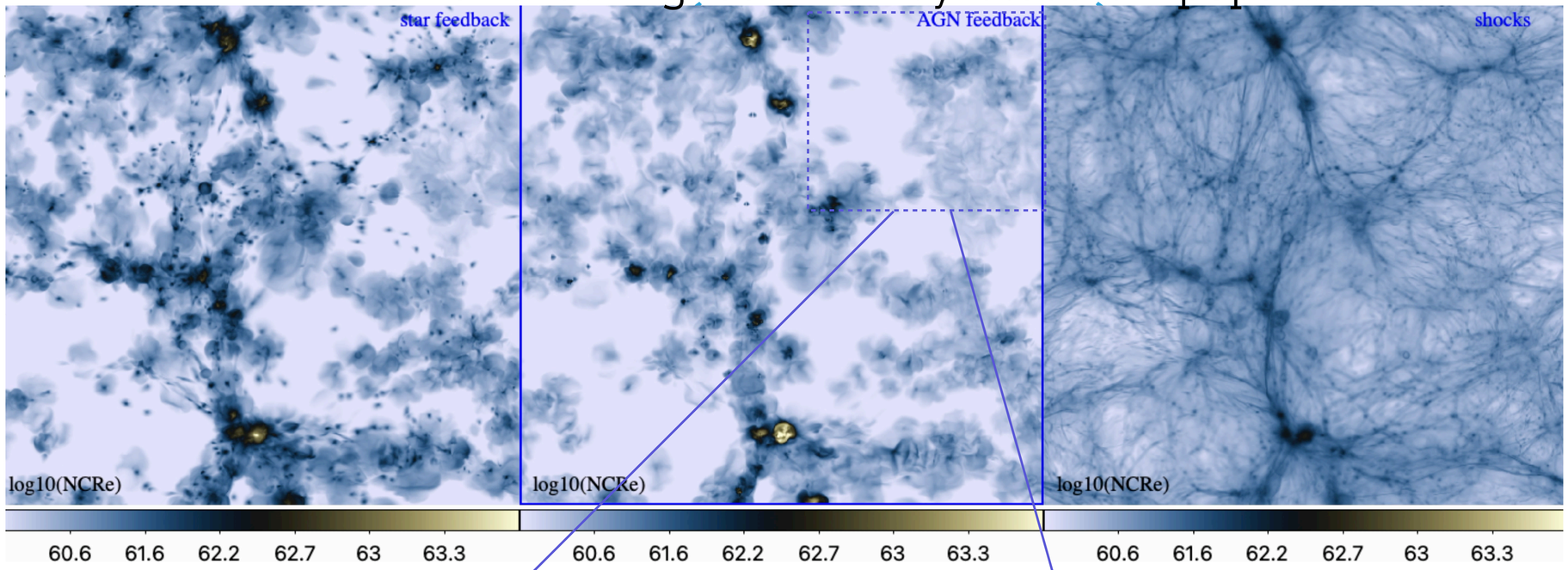


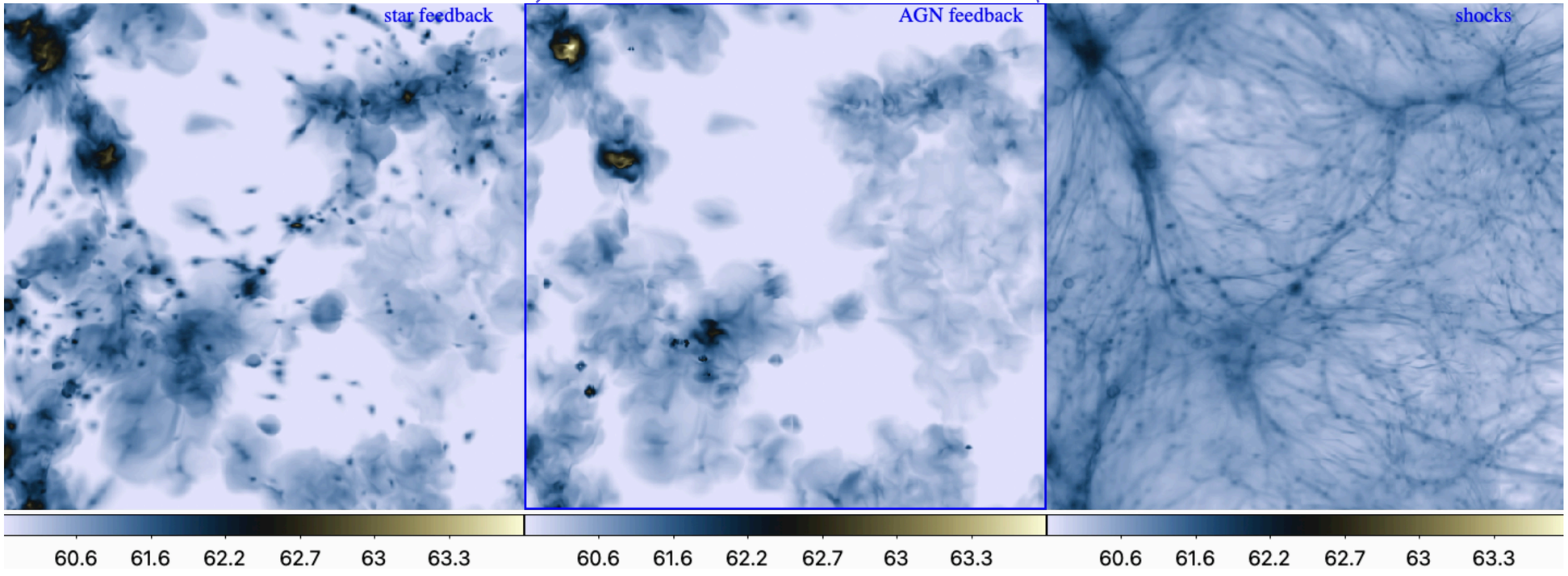
radio galaxy luminosity function



FV ET AL., A&A SUB.

NEW ENZO RUNS: evolving Cosmic Ray electron populations

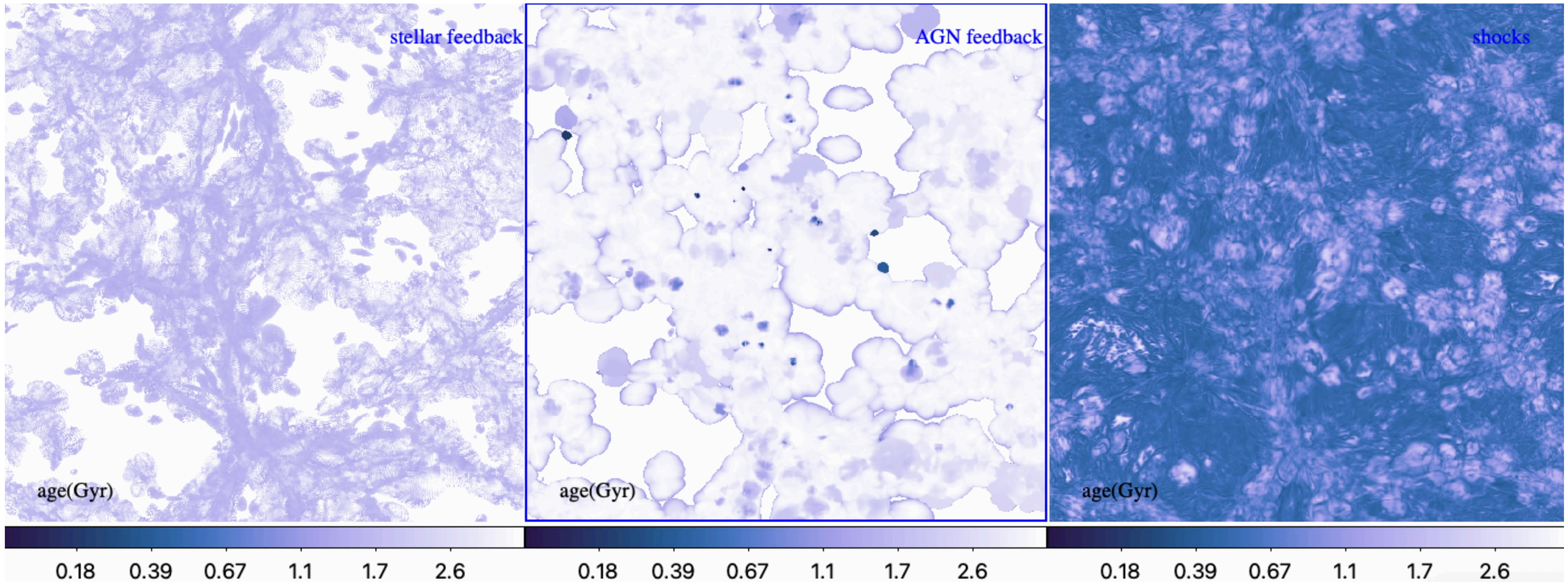




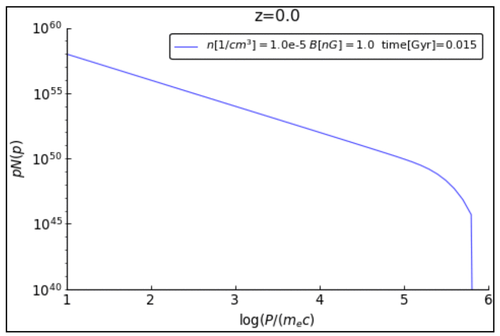
SEEDING OF ELECTRONS (AND B-FIELDS) BY RADIO JETS

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

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



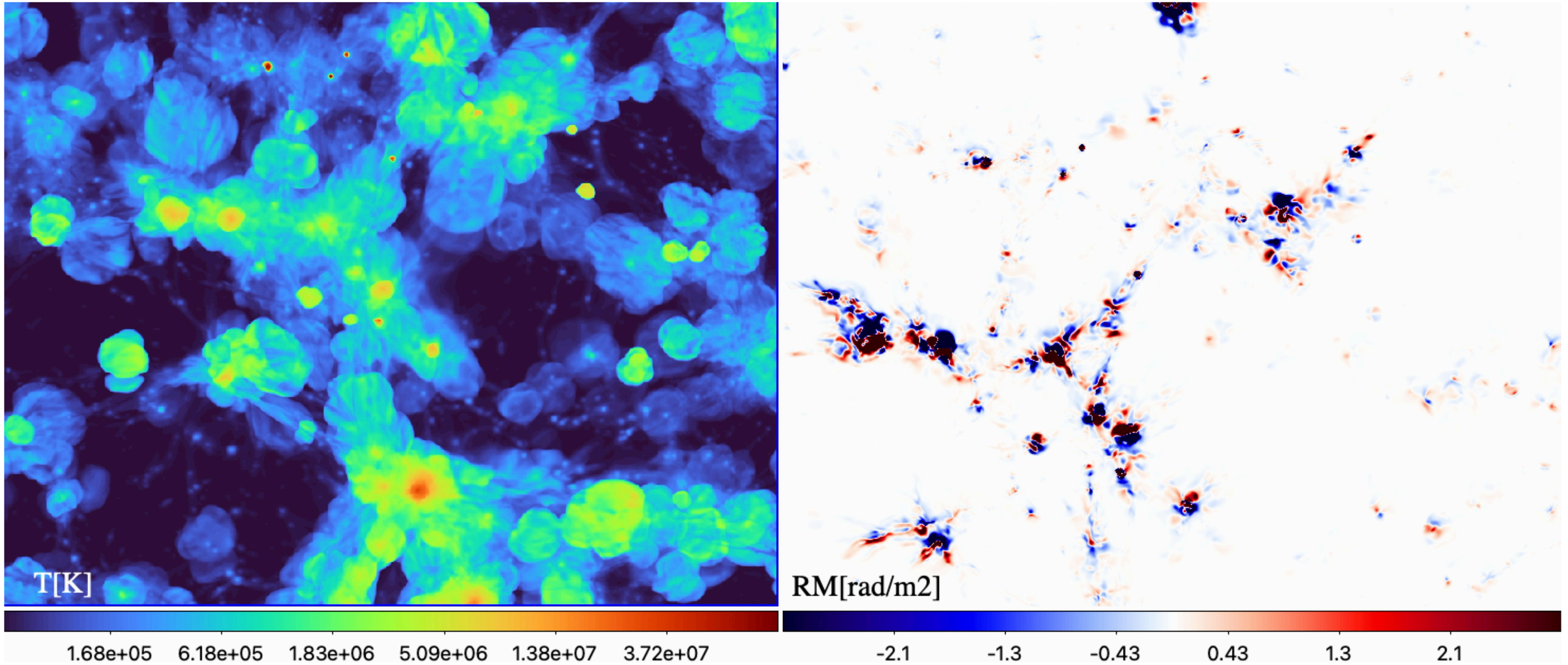
From the age & local conditions (ρ, B, T) we can compute with good approximation the radio emission



FV ET AL., A&A SUB.

ASTROPHYSICAL SEEDING OF B-FIELDS

updated view on RM for purely astrophysical scenarios:



(thin slice)

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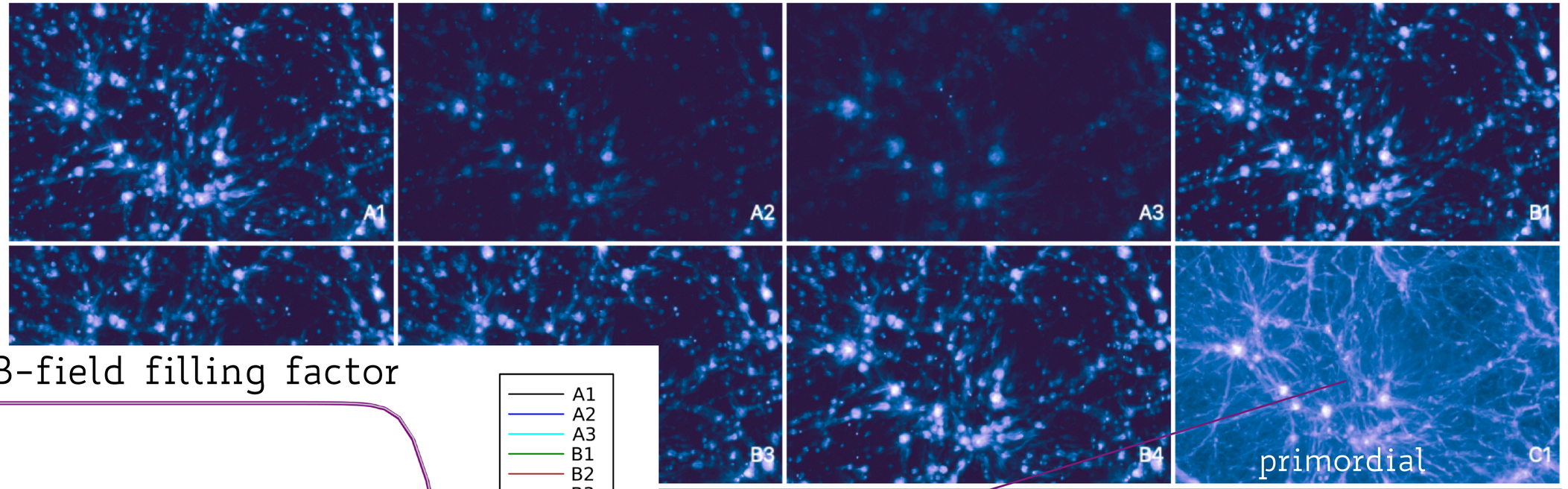
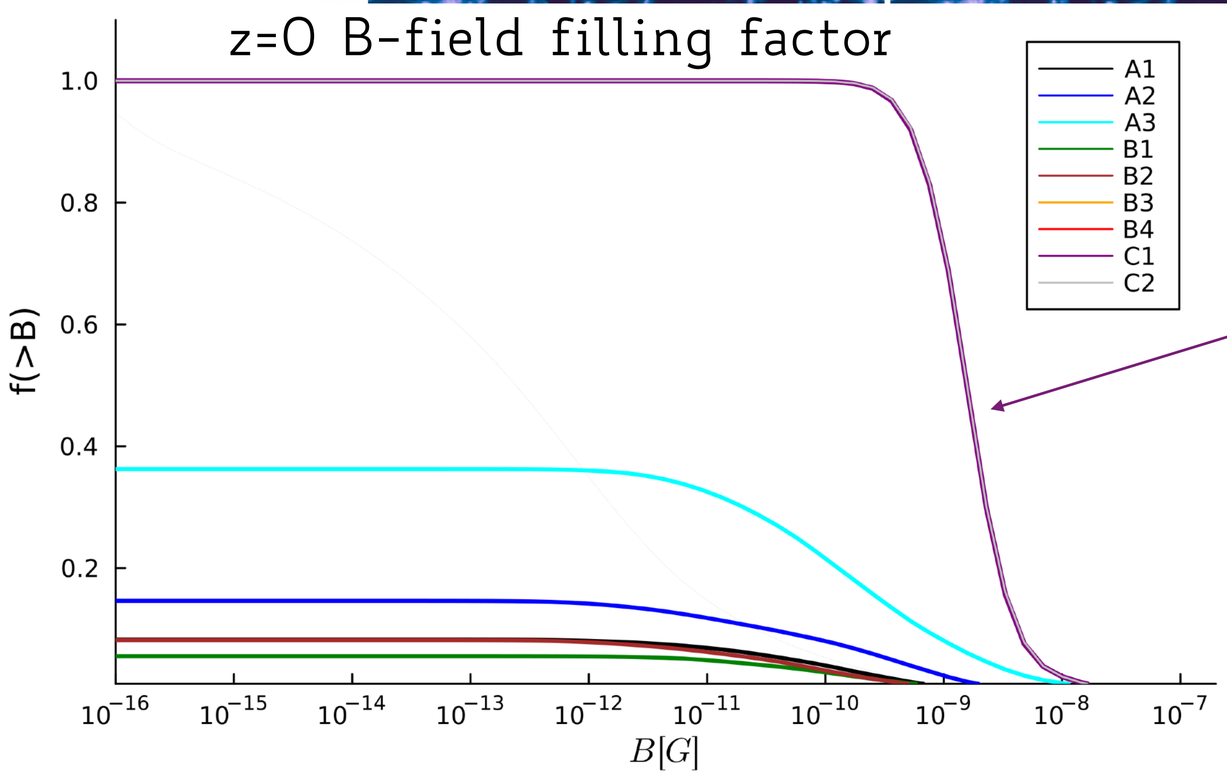
ASTROPHYSICAL SEEDING OF B-FIELDS





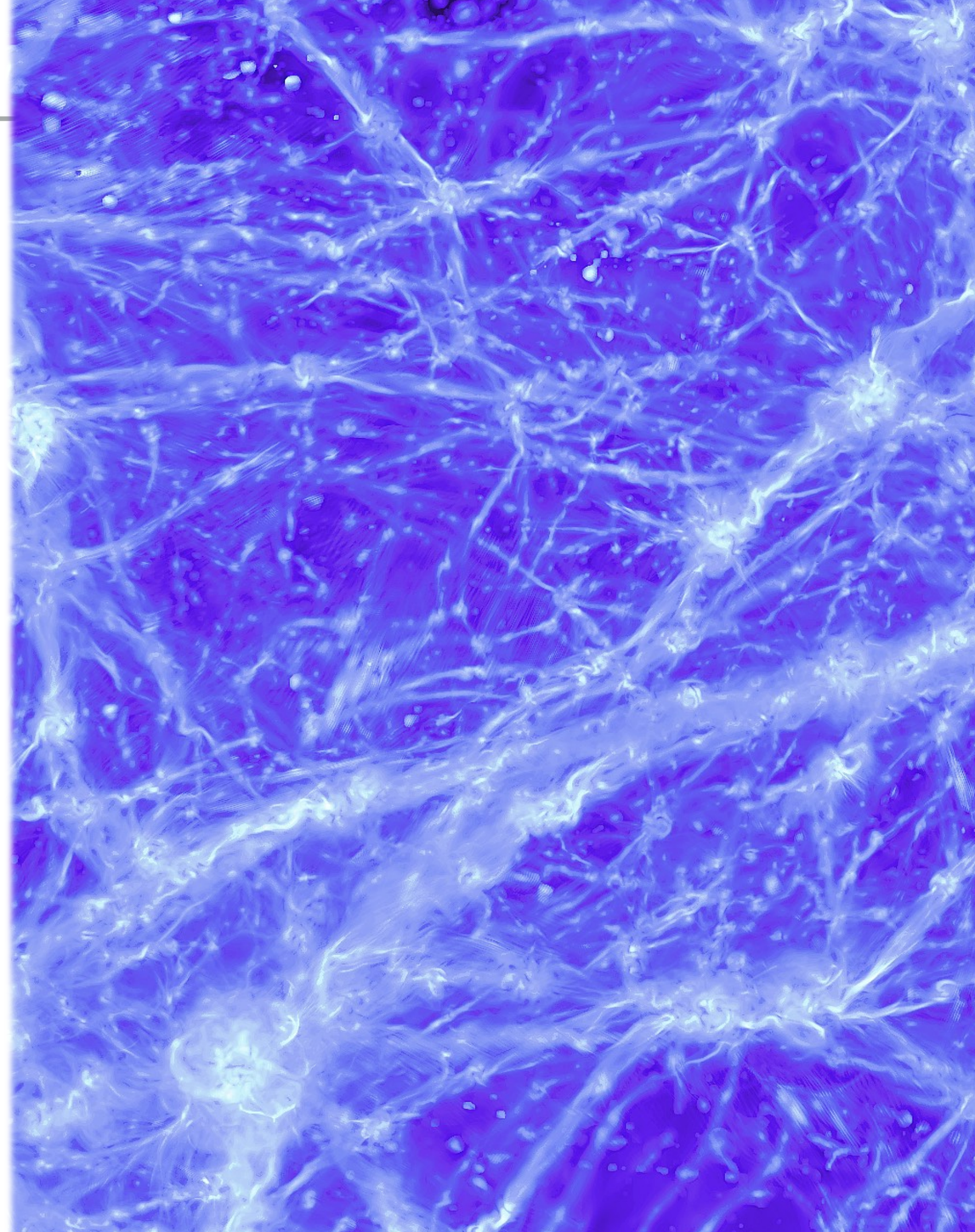
Purely astrophysical scenarios magnetise <37% of the cosmic volume (at most!)

(<15% in most realistic model)

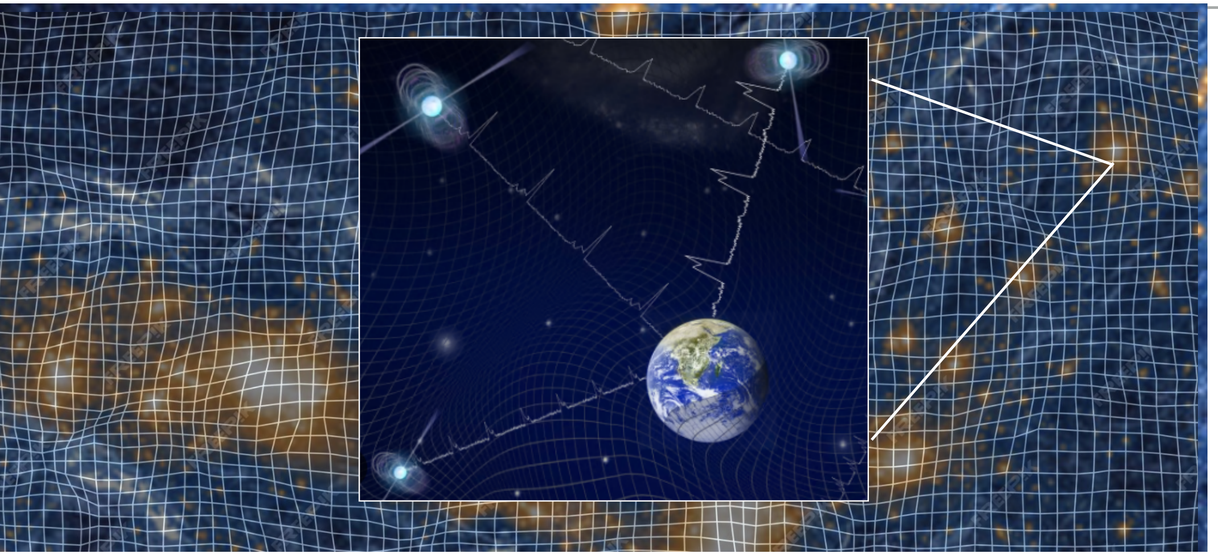
FV ET AL., A&A SUB.

TAKE HOME MESSAGES:

- Today radio & γ-ray observations give the best constraints on extragalactic $\overrightarrow{B}$
- The joint modelling of data with simulations suggests such $\overrightarrow{B}$-field are primordial
- Tantalising connection with SGWB?



WERE B-FIELDS GENERATED DURING QCD EPOCH?



2023: Detection of the Stochastic Gravitational Waves Background with Pulsar Timing Array.

Possible interpretations:

- supermassive BH binaries
- inflation, cosmic strings, topological defects...
  - primordial magnetic fields

NERONOV, POL, CAPRINI & SEMIKOZ (2021):

the amplitude and frequency of the SGWB constraint B-field parameters:

$$h^2\Omega_{\mathrm{GW},0} \sim 7\times10^{-5}\ \ \Omega_B^{n+1}\left[\frac{N_{\mathrm{eff}}}{10}\right]^{-\frac{1}{3}}$$

energy density of GW

energy density of B-fields

number of relativistic degrees of freedom

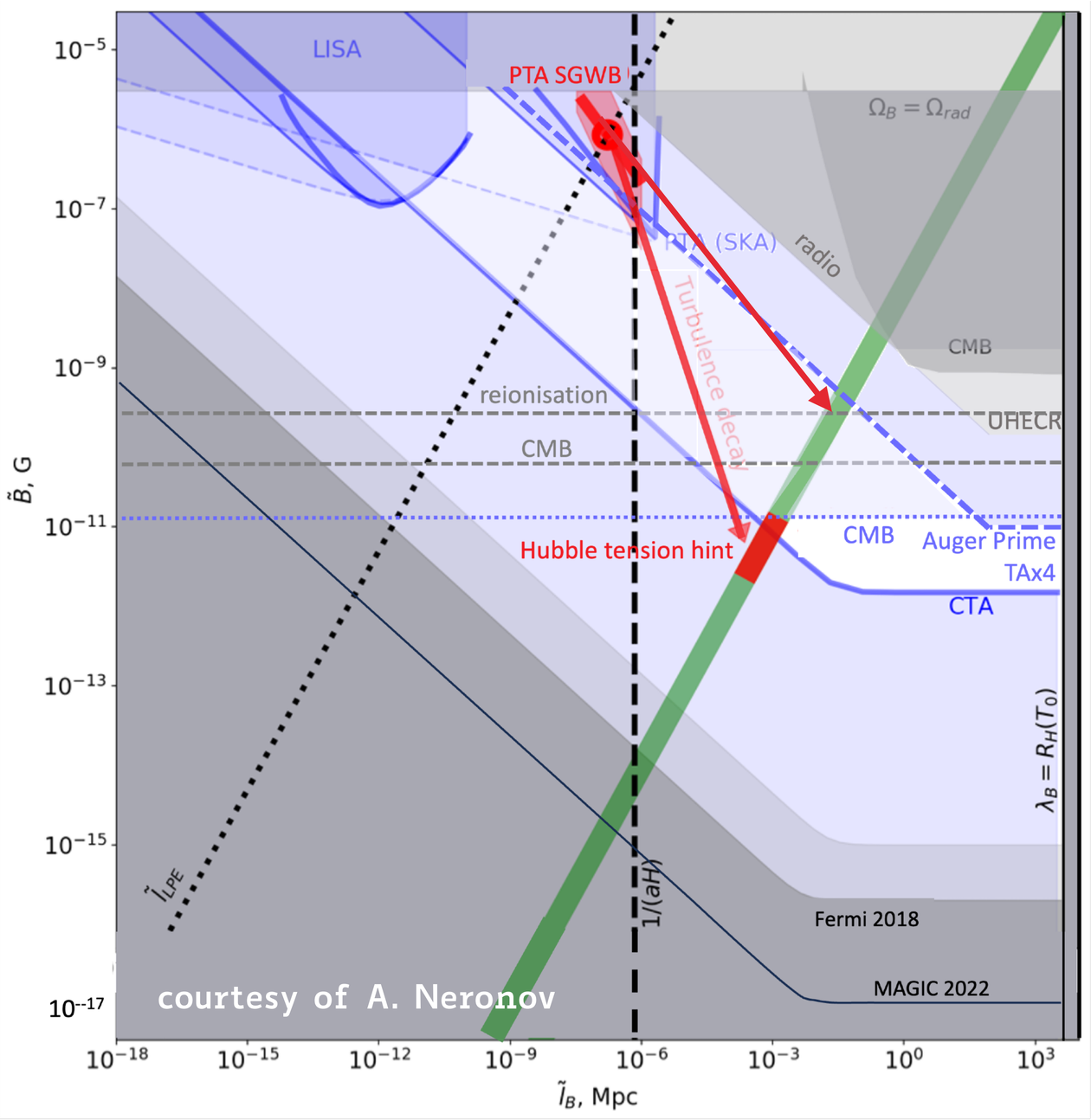
$$f \sim 2\times10^{-4}(\tilde{l}_B/\tilde{R}_H)^{-1}(T/1\,\mathrm{TeV})\,\mathrm{Hz}$$

Horizon radius

scale length of B-fields

temperature of the Universe

WERE B-FIELDS GENERATED DURING QCD EPOCH?



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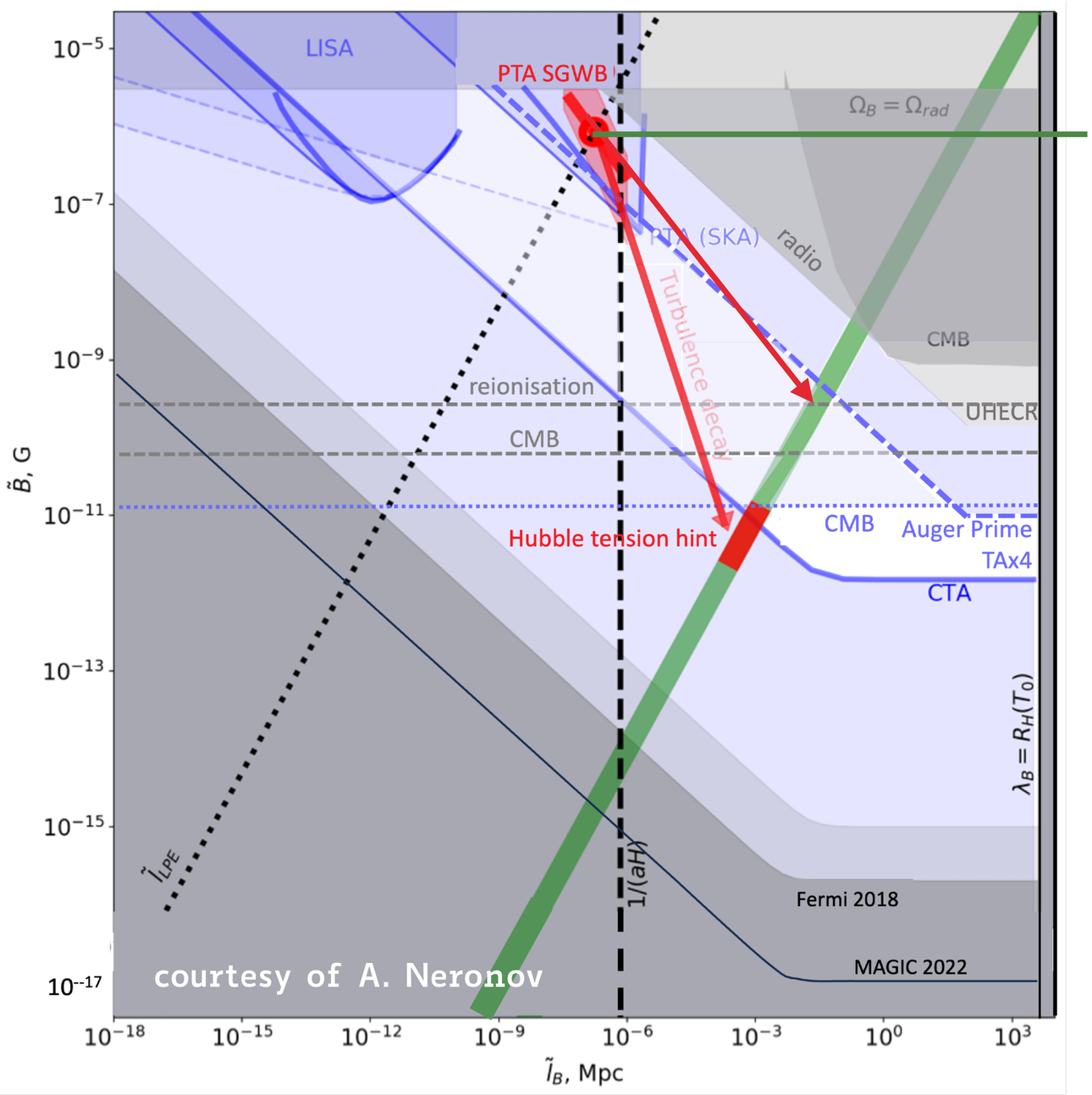

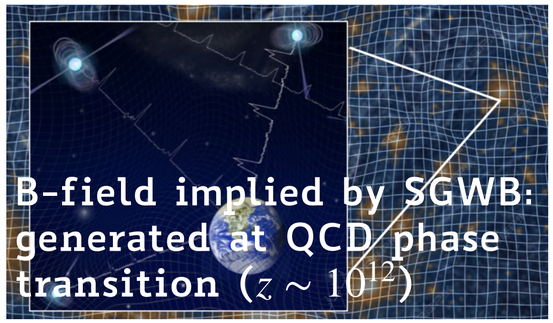

$$h^2\Omega_{\mathrm{GW},0} \sim 7 \times 10^{-5} \left[\frac{N_{\mathrm{eff}}}{10}\right]^{-\frac{1}{3}} \Omega_B^{n+1}$$

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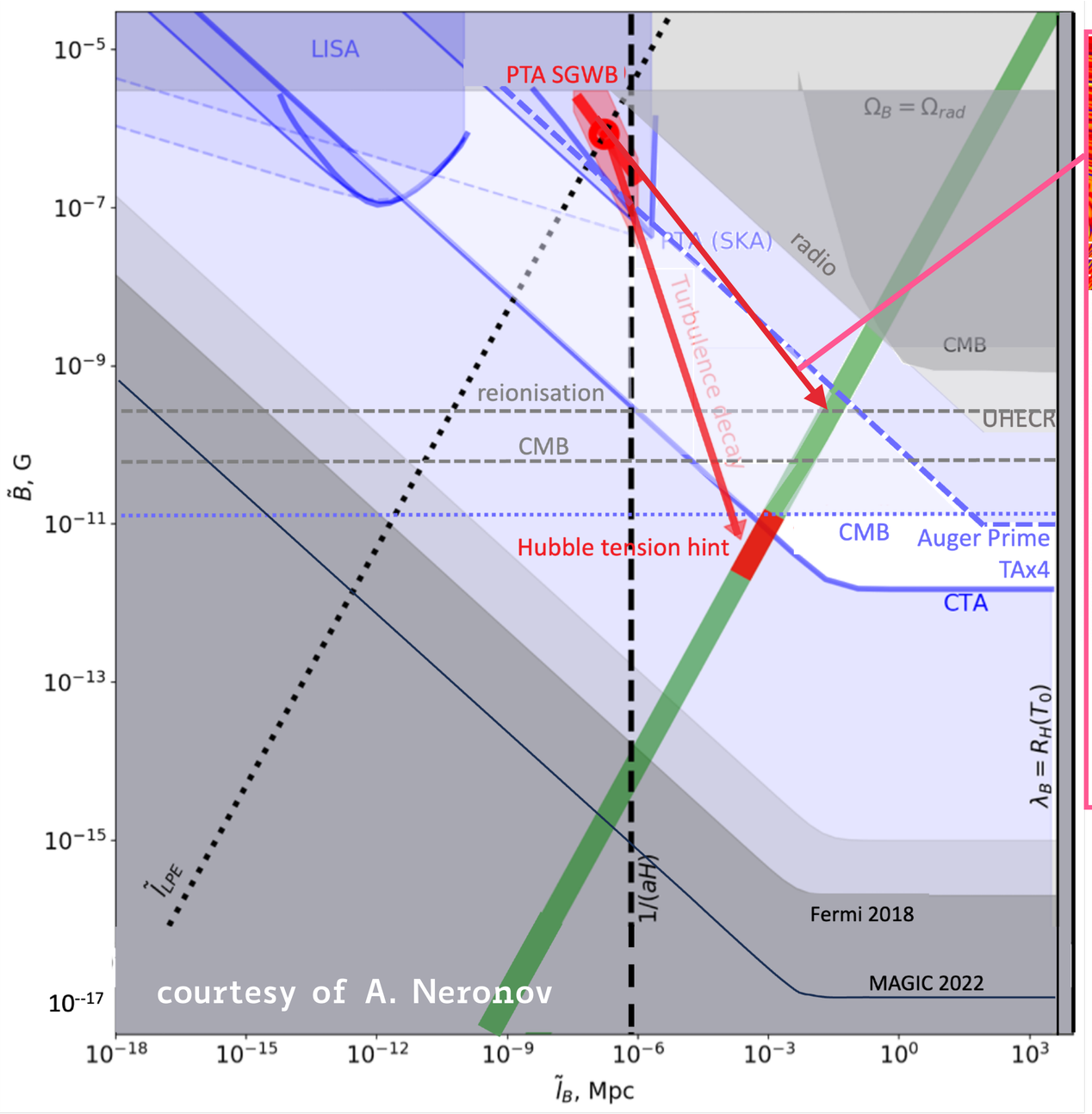
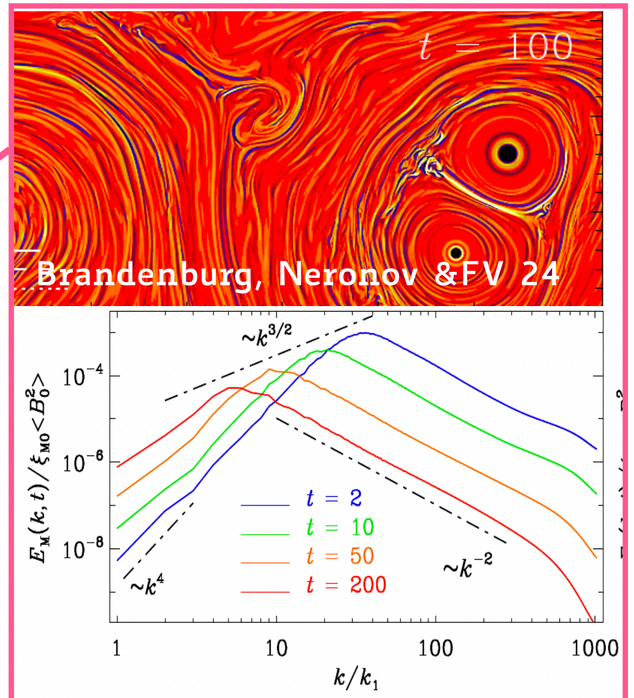
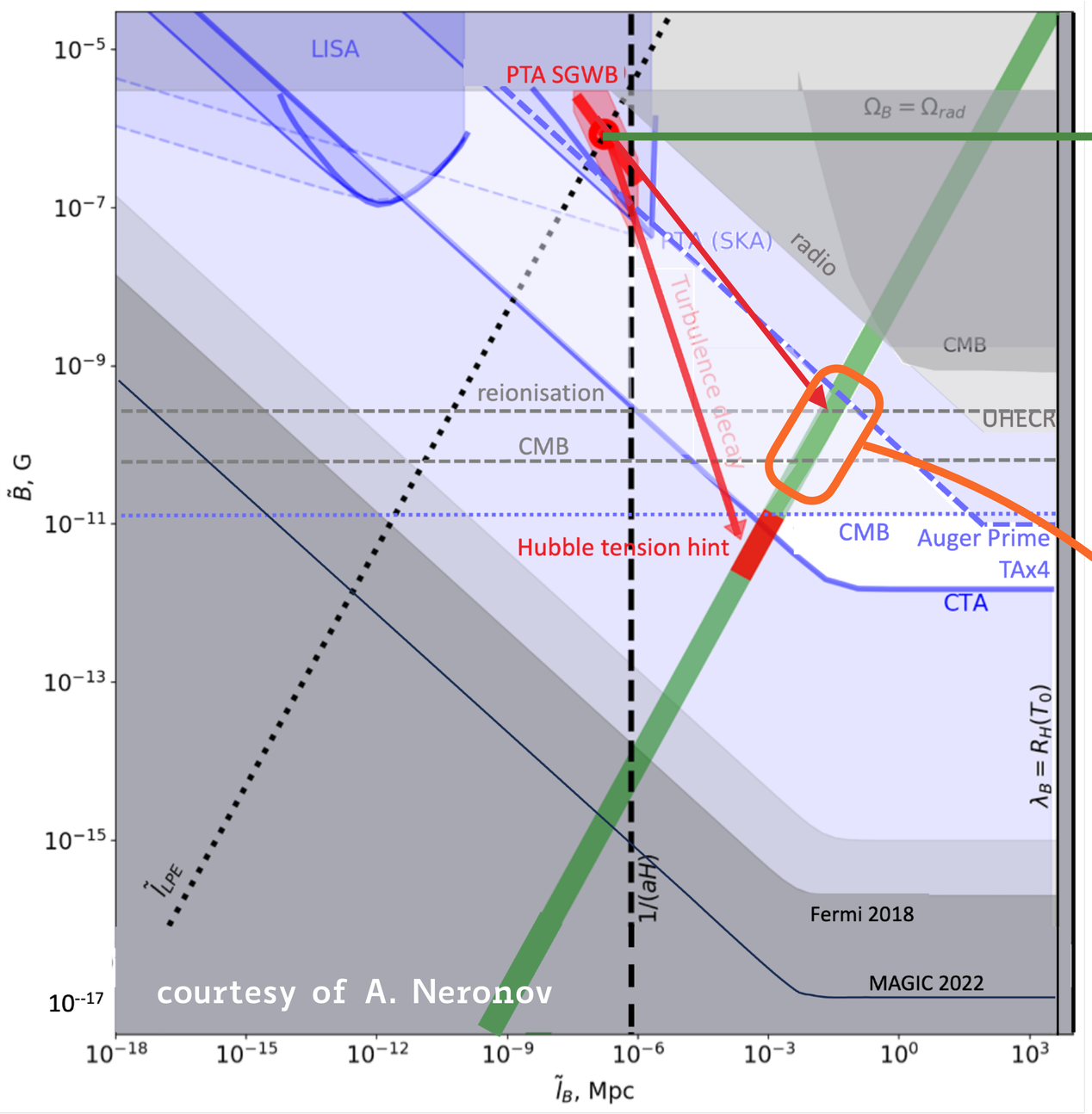
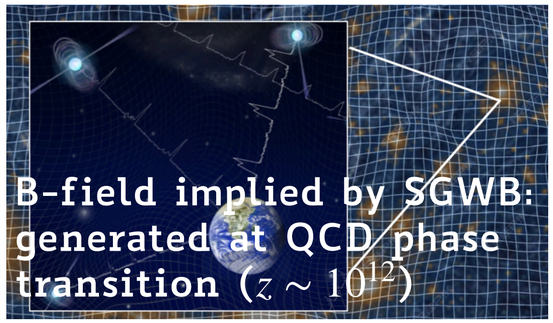




Evolutionary tracks of primordial B-fields undergoing inverse cascade (helicity-dependent)

WERE B-FIELDS GENERATED DURING QCD EPOCH?





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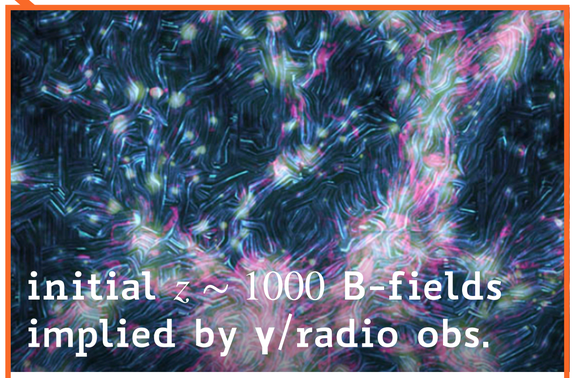
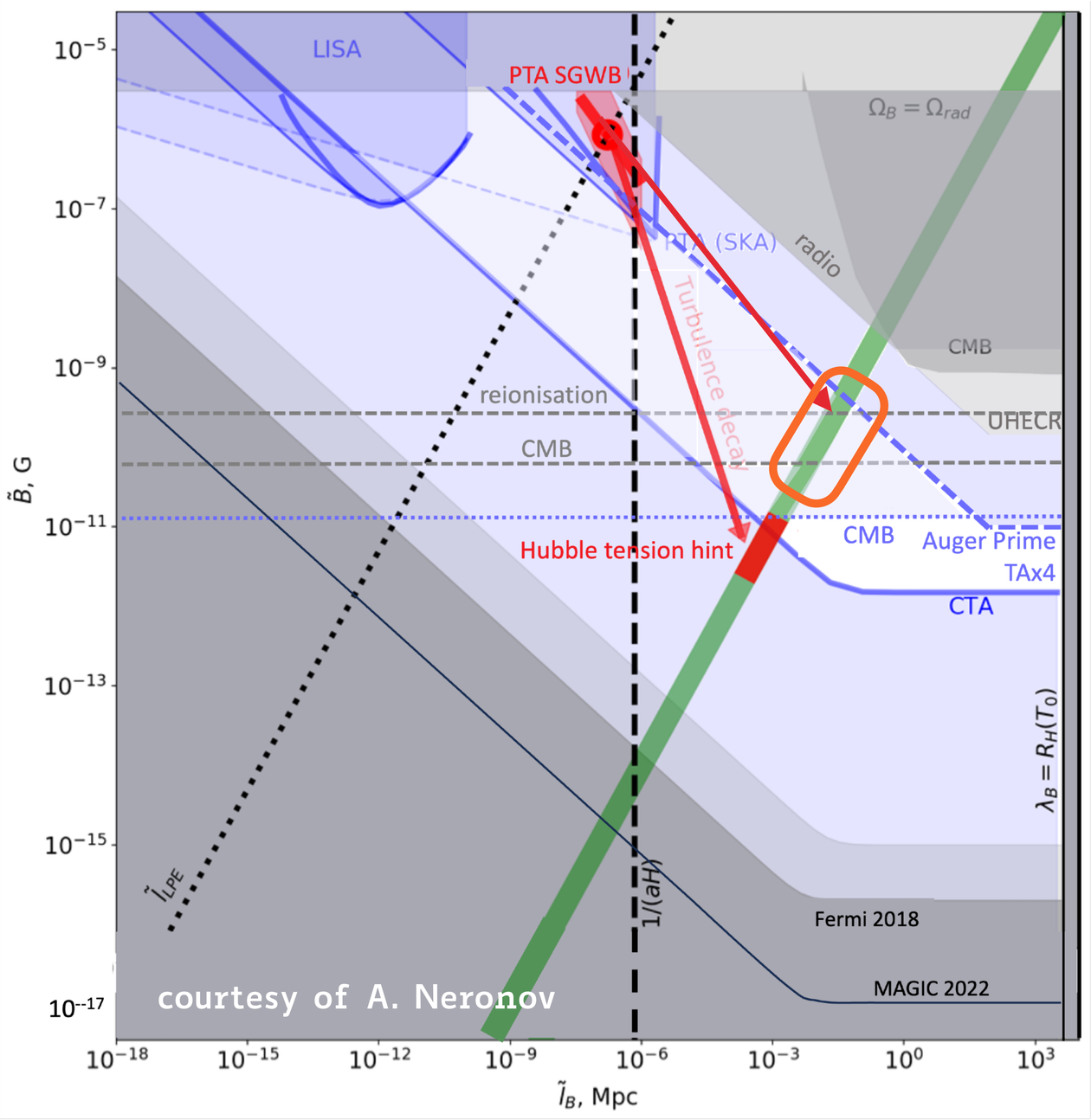


$P_B(k) \propto k^{\alpha_B}$ **with** $-1.0 \leq \alpha_B \leq 1.0$
and $\langle B^2_{1Mpc} \rangle^{0.5} \leq 0.4\mathrm{nG}$

WERE B-FIELDS GENERATED DURING QCD EPOCH?



- The magnetic fields implied by the modelling of recent radio observations (synchrotron & RM) are in the ballpark of the one producing the SGWB detected by PTA
- **If so, we may have a powerful window into the $\sim \mu$s "old" Universe**