Connecting observations and theories of cosmic magnetism through simulations

Franco Vazza

franco.vazza2@unibo.it

WHAT IS THE ORIGIN OF COSMIC MAGNETISM ?

- magnetic induction $$\frac{\partial \mathbf{B}}{\partial t} - \frac{1}{a}\nabla \times (\mathbf{v} \times \mathbf{B}) = 0.$$

even the most explosive dynamo must start from a non-zero initial seed field B_0

As long as the ideal MHD picture applies to the dynamics of large scale structures we need "seeds" of magnetic field for dynamo to start.

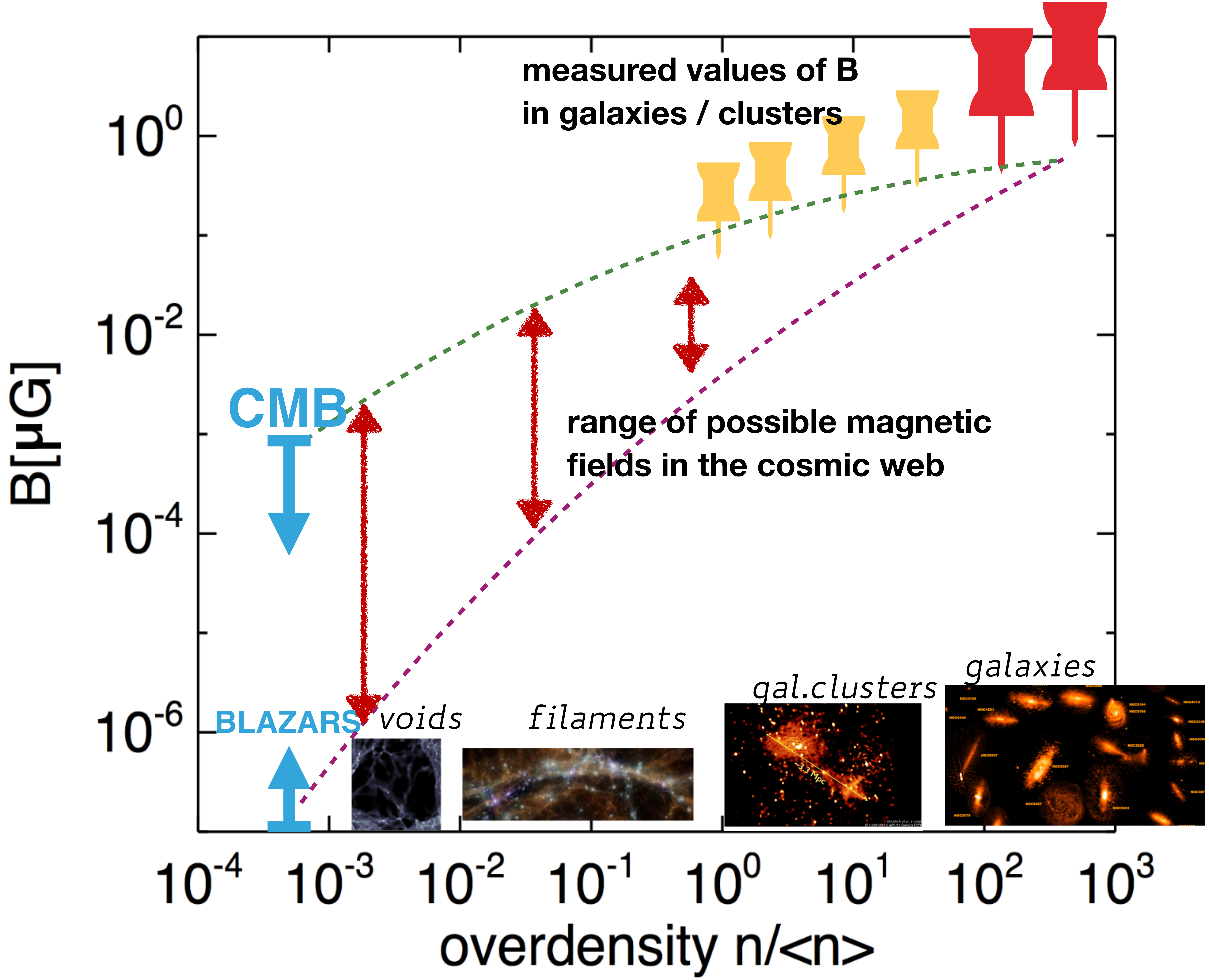
What are the B-field seeds?

Must they be primordial, or can also astrophysical seeding scenarios do the job?

OUTLINE OF THIS LECTURE

- quick overview of primordial and astrophysical scenarios
- connecting real observations with numerical models
- implications and the future

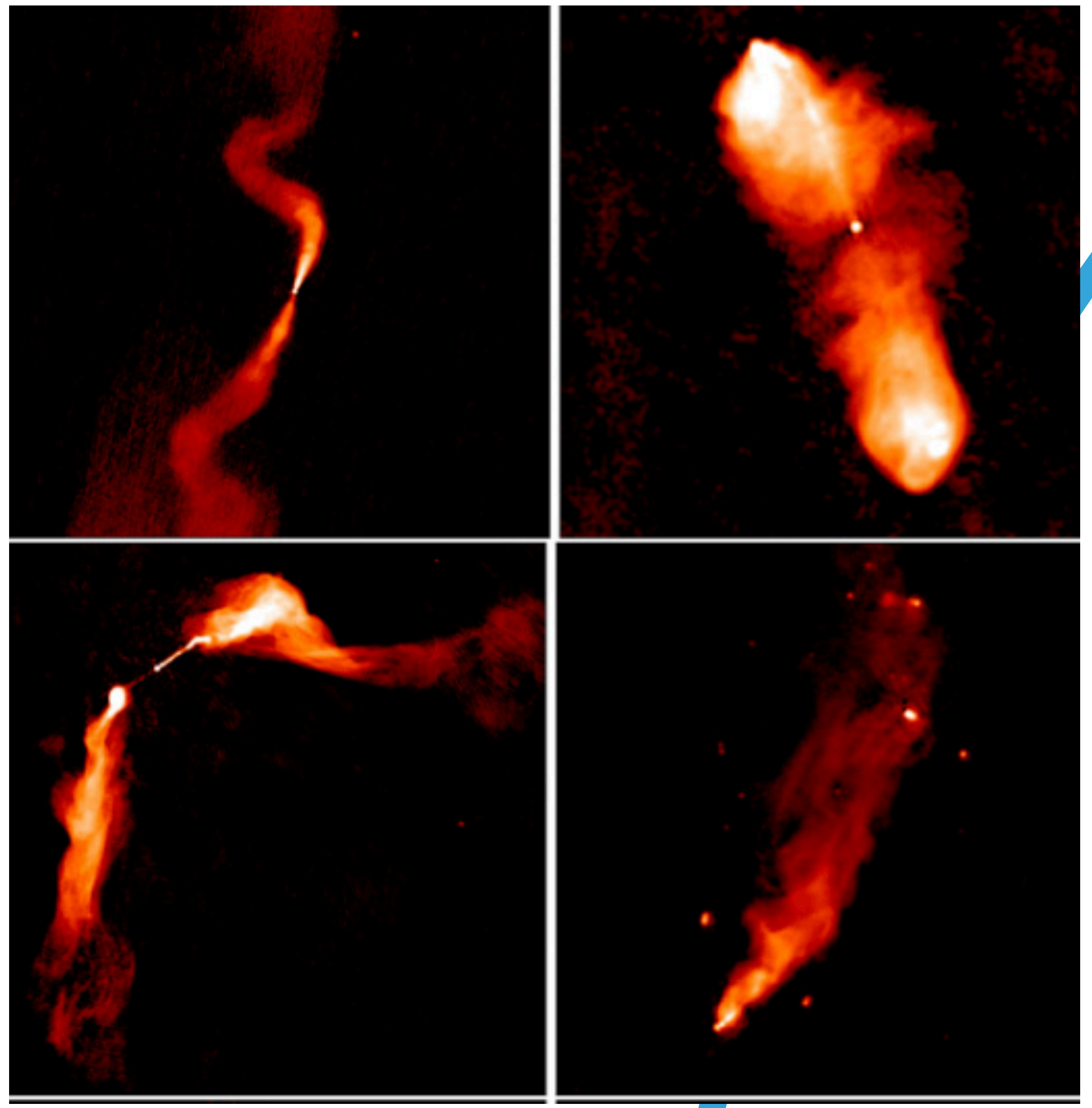
WHAT'S THE ORIGIN OF COSMIC MAGNETISM?



WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

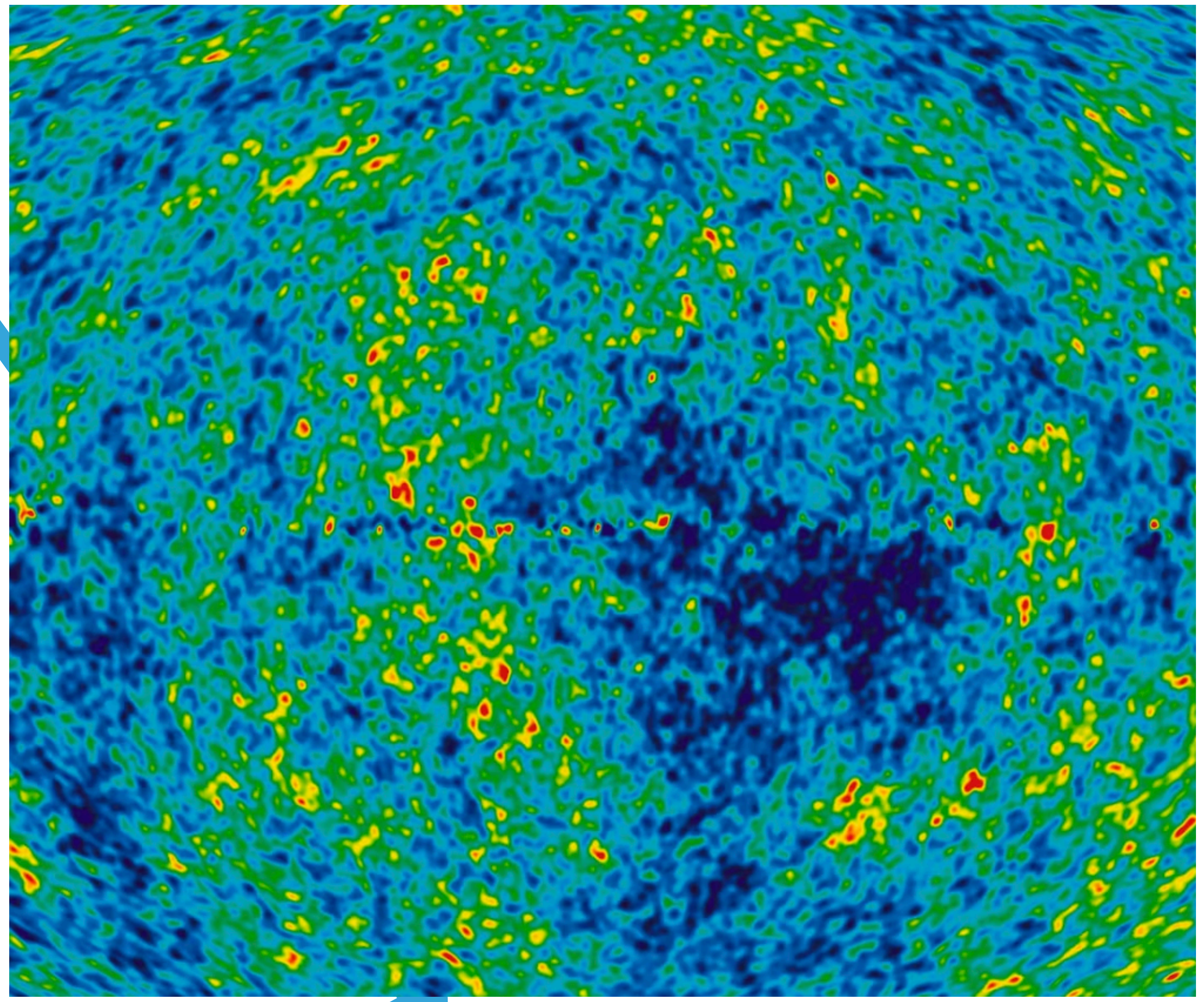
TWO BROAD POSSIBLE SCENARIOS:

"ASTROPHYSICAL"



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

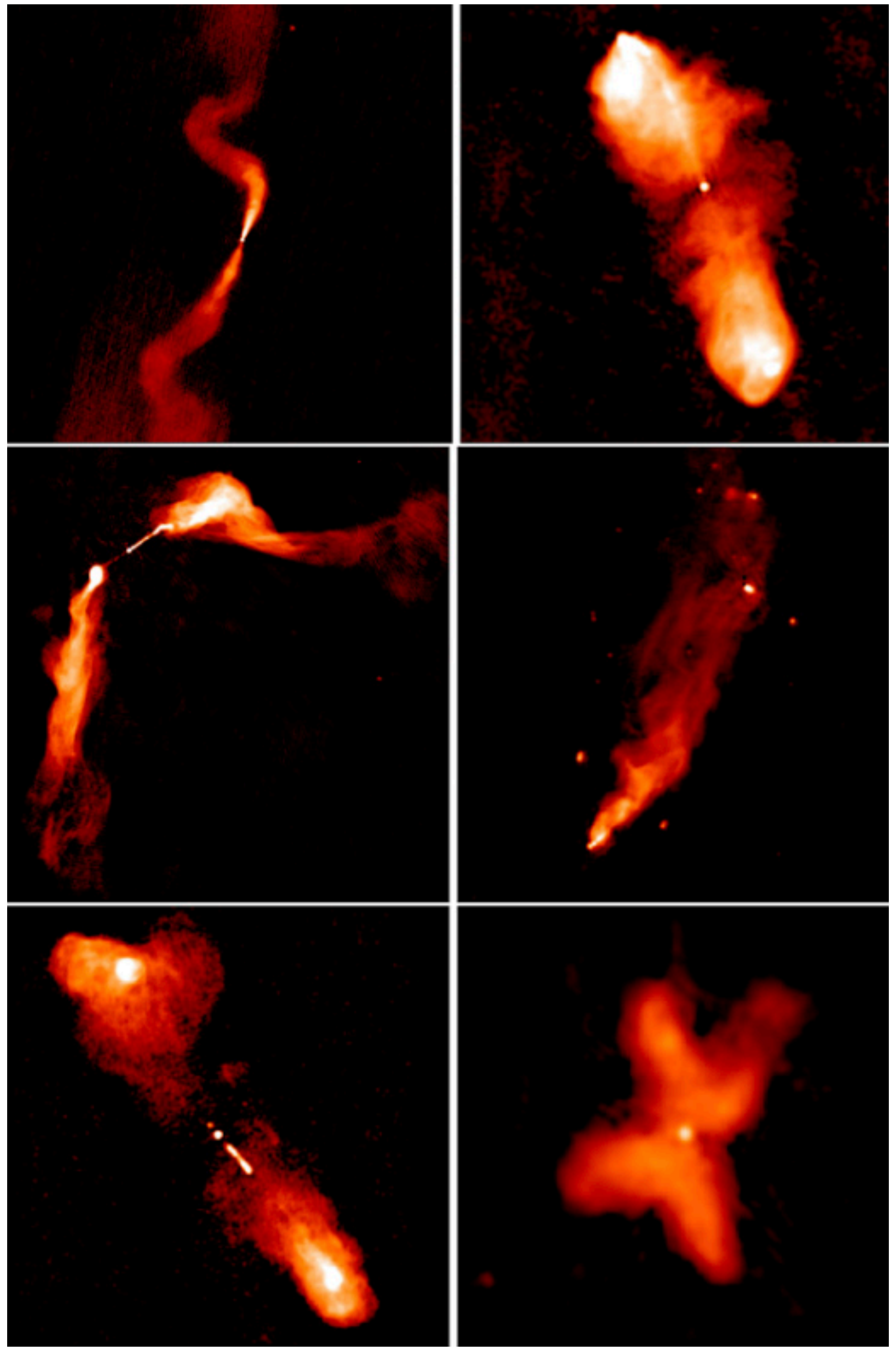
"PRIMORDIAL"



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

WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

"ASTROPHYSICAL"



- **AGN jets:** strongly magnetised ($\sim 1\mathrm{mG}$) jets emerge from supermassive black holes, expand and spread magnetic fields in and outside halos

- **Star formation winds:** magnetised ($\sim 10\mu\mathrm{G}$) winds collectively produced by supernovae in galaxies

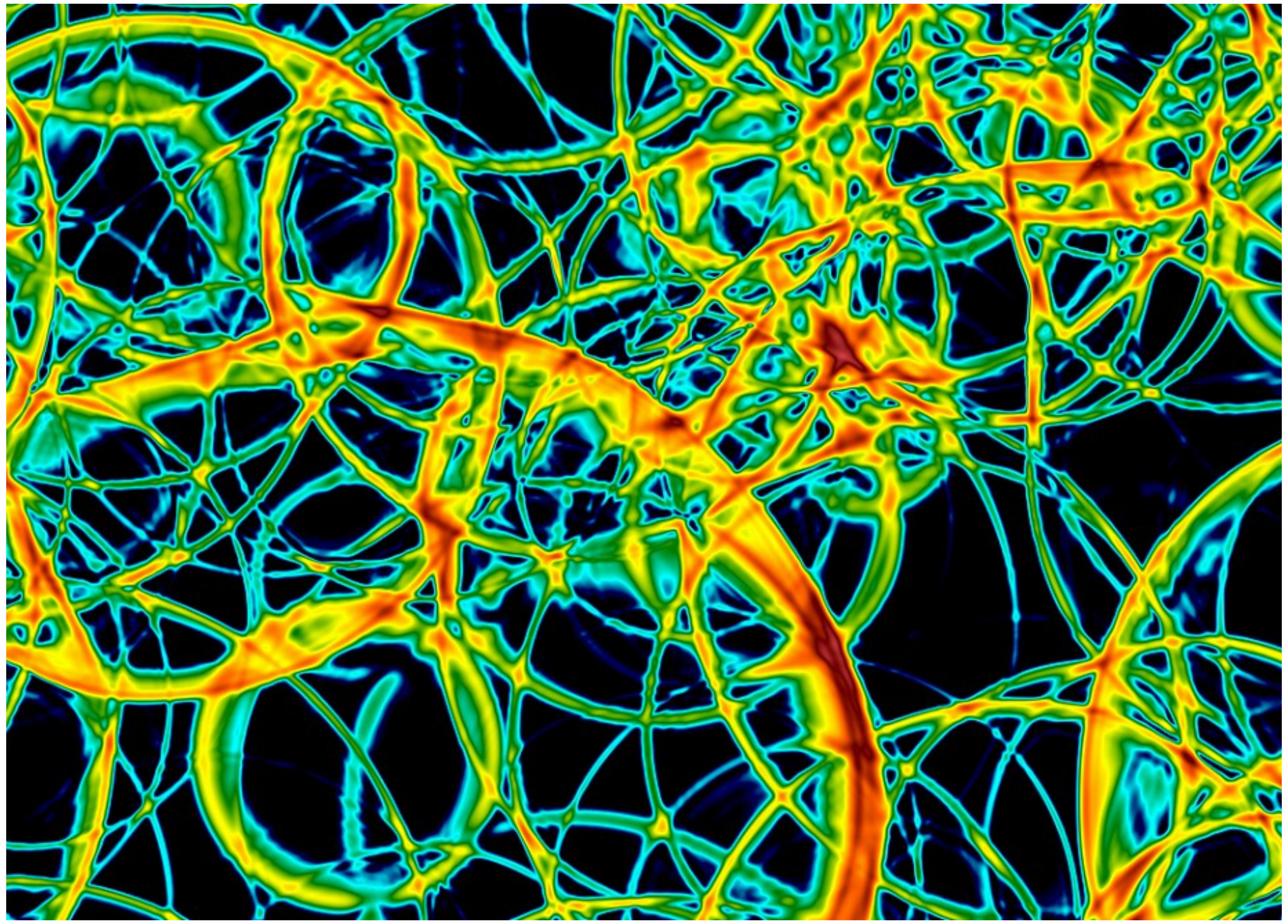
- **Batteries:** protons and electrons detach on small scales at oblique shocks, or at complex ionisation fronts, injecting currents and $\mathbf{B}$-fields from there ($\leq \mathrm{nG}$)

WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

- **Inflationary models:** coupling of Electro-Magnetic field with scalar fields ϕ. Generated $\mathbf{B}$-fields have correlation scales above the cosmological horizon

- **Phase-Transitional:** generation by 1st-order, 2nd-order or cross-over phase transitions, like during the Electro-Weak phase transition ($\sim 160\mathrm{GeV}$) or the QCD epoch ($\sim 150\mathrm{MeV}$). Phase domains collide and inject currents, the resulting $\mathbf{B}$ -fields can have both long or small correlation scales

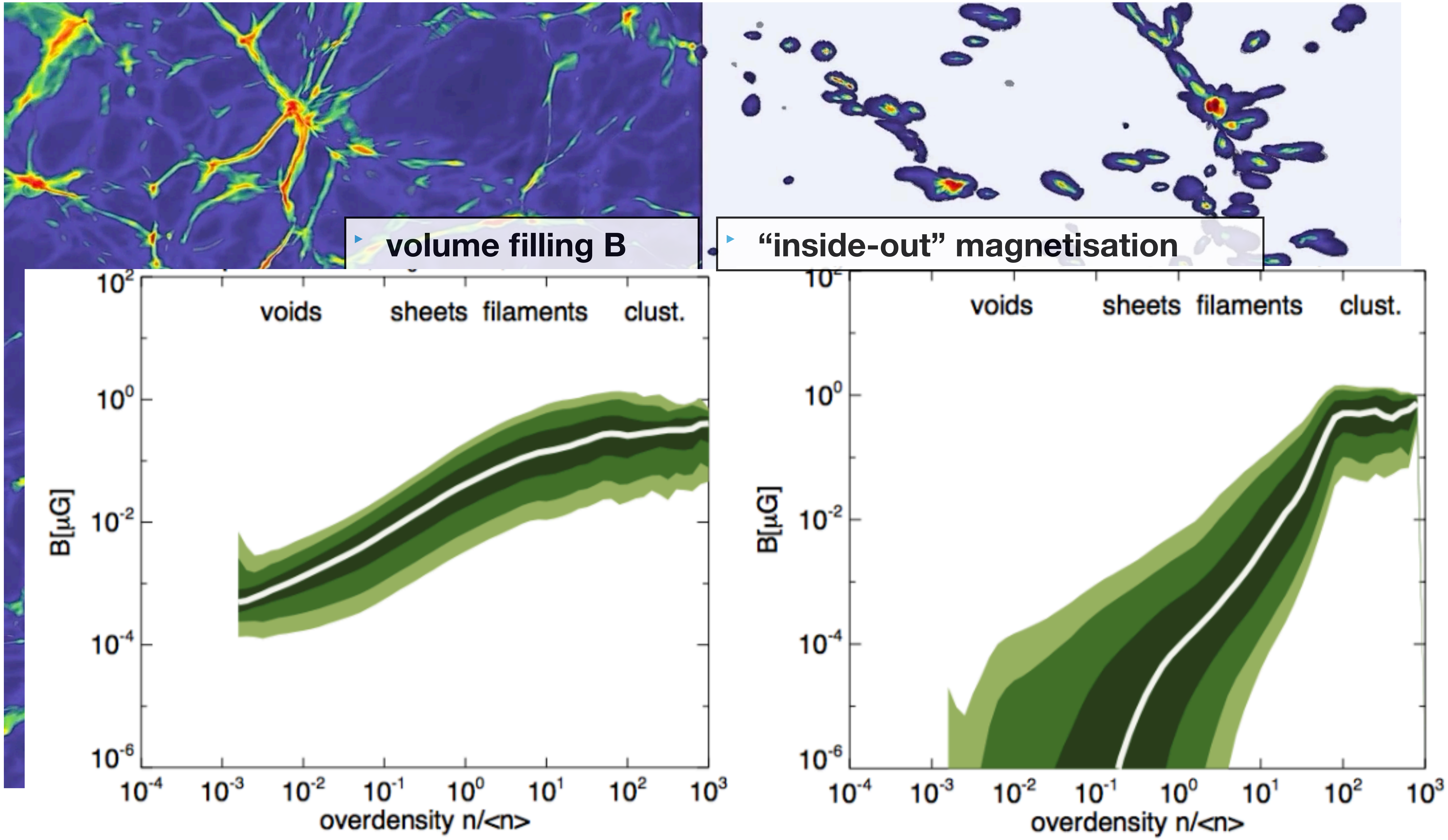
"PRIMORDIAL"



see Caprinis's lectures (21-22/01)

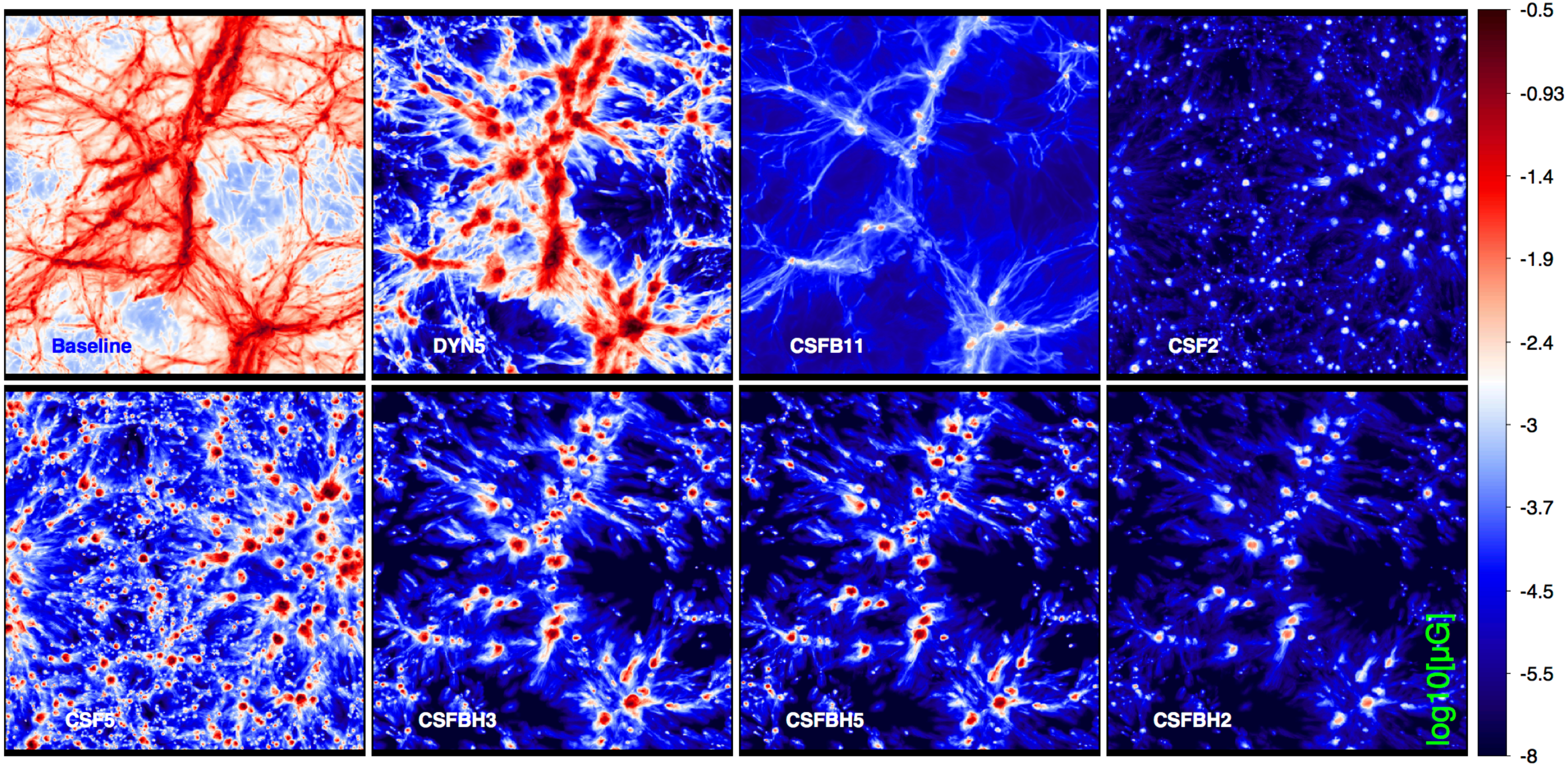
WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

"Primordial" seeding | **"Astrophysical" seeding**



WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

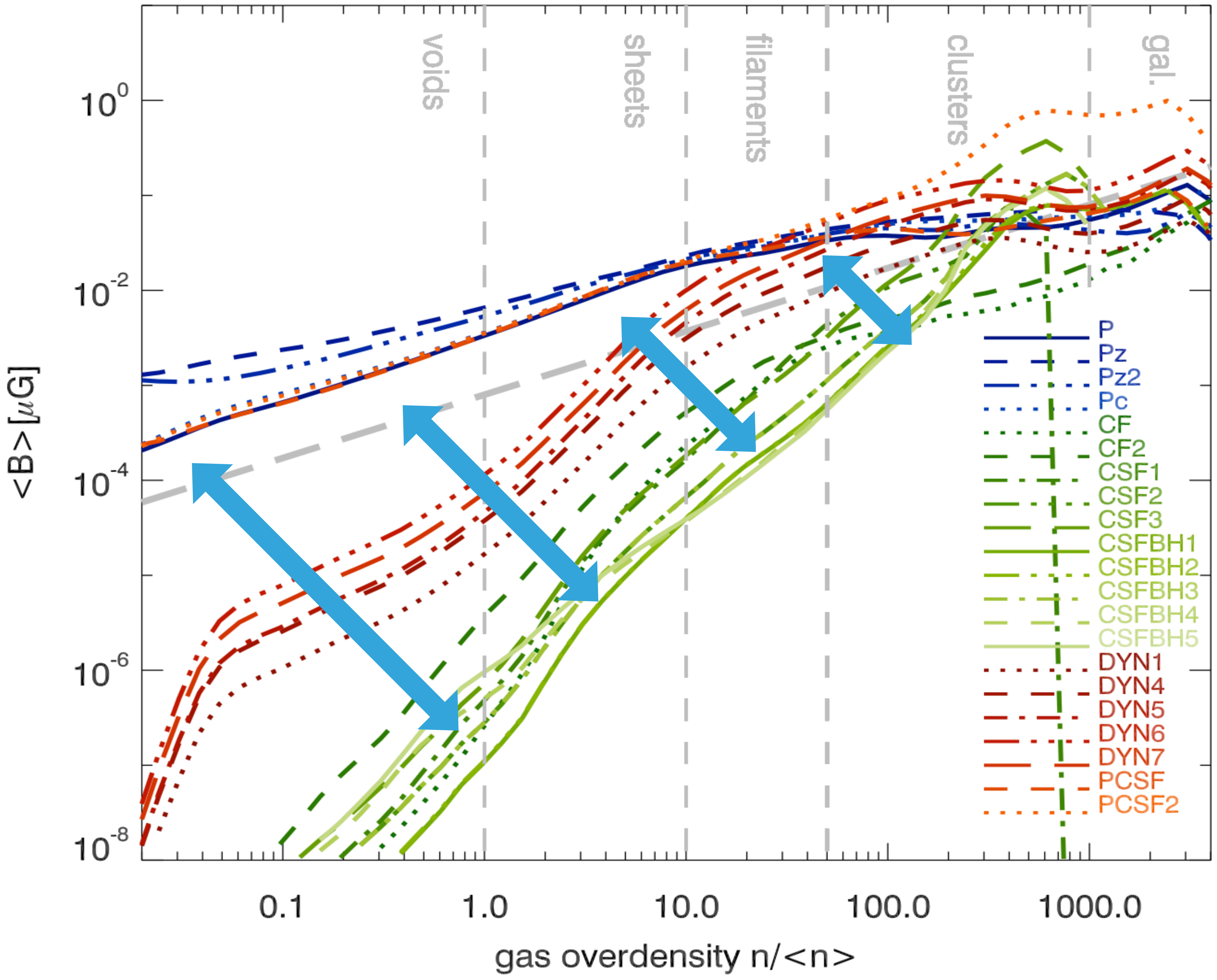
- Many magnetisation models exist and are (a priori) equally reasonable: **only observations can kill models!**
- We can perform different cosmological MHD simulations of the same volume with different magnetism models test them against existing and future observations and see which models survive.
- If we find good ones, we refine the theory to better understand the uncertainties in the assumed model



(a first survey of magnetisation models simulated with ENZO FV+17)

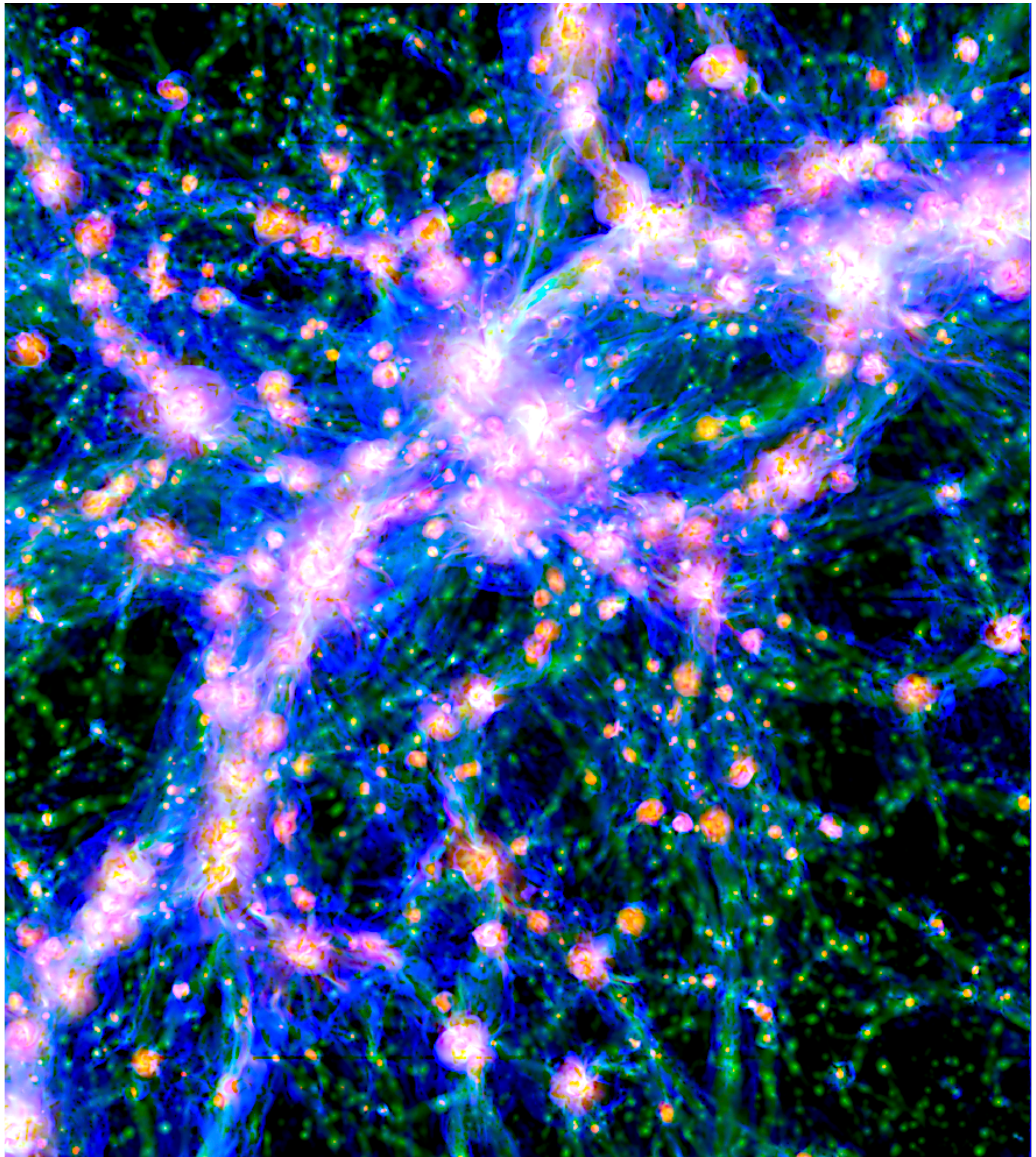
WHAT'S THE ORIGIN OF COSMIC MAGNETISM?

- We need observations to constrain the best models in the area spanned by the cyan arrows



(a first survey of magnetisation models simulated with ENZO FV+17)

DIFFERENT WAYS OF MEASURING MAGNETISM



DISCLAIMER!

In what follows, unlike the previous lectures I will mostly refer to work and simulations by me/my group.

Why?

Because I want to test observational implications of different magnetogenesis models onboard of the same code and for the same simulated volumes in a self-consistent way.

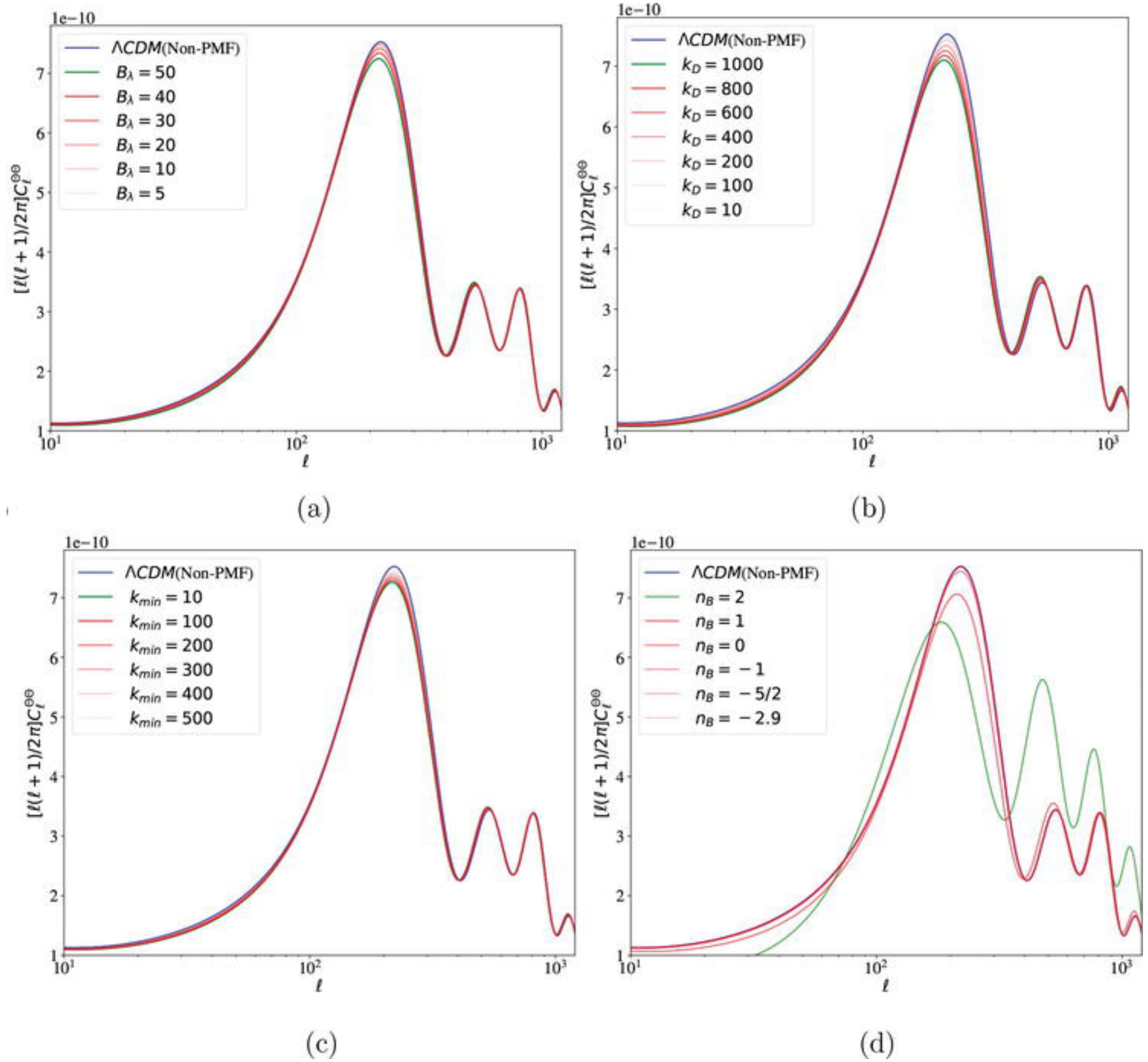
Of course, these simulations are still subject to continuous improvement and a other groups are doing excellent works towards a similar direction (e.g. in Munich, Leiden, Paris, Stanford..)

SIMULATING "PRIMORDIAL" MAGNETIC FIELDS

CMB upper limits for power-law magnetic field models:

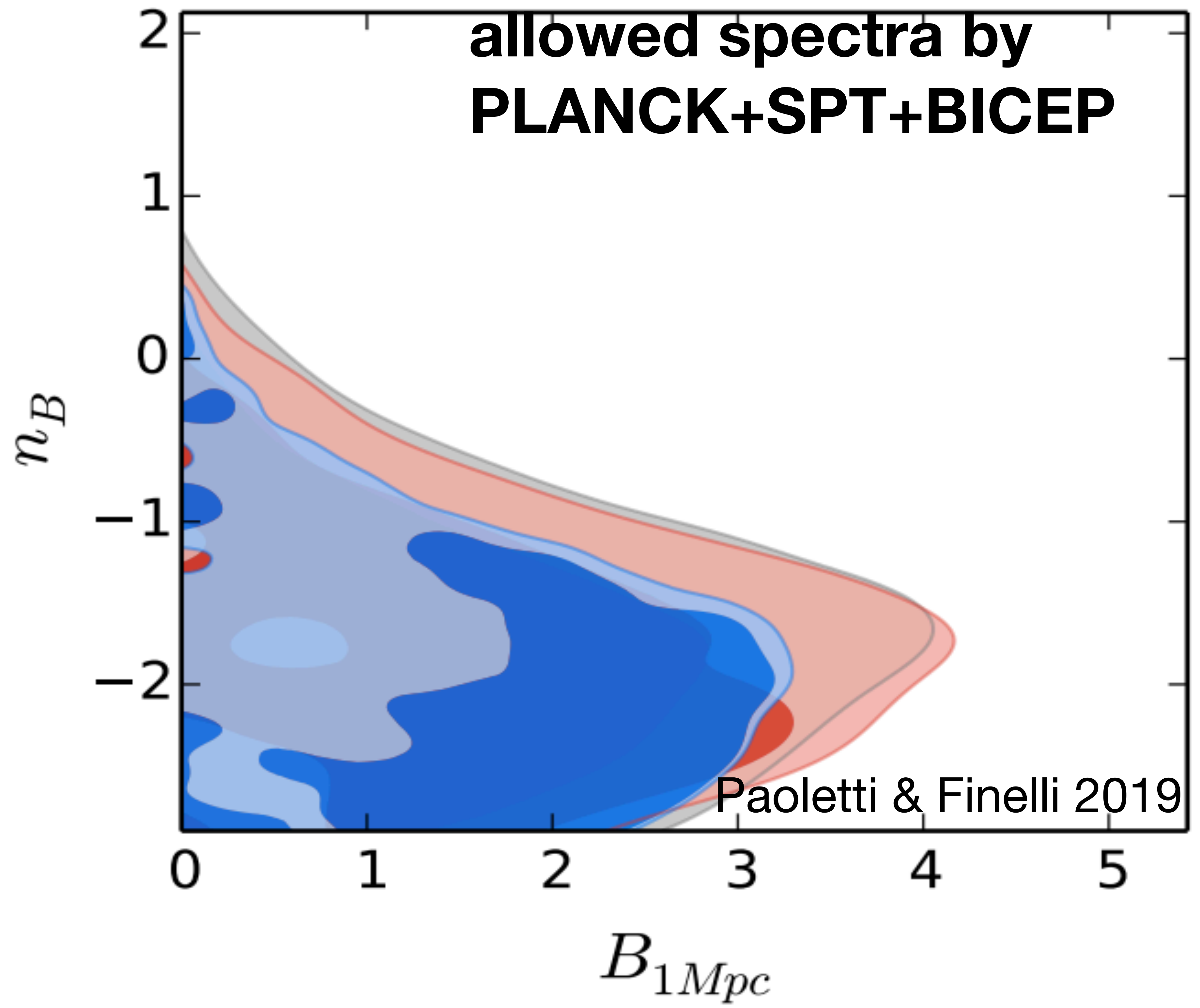
$$\langle B_i^{\star}(\mathbf{k}) B_j(\mathbf{k}')\rangle = \delta^{(3)}(\mathbf{k}-\mathbf{k}') P_{ij}(\hat{\mathbf{k}}) P_B(k) (2\pi)^3,$$

$$P_B(k) = P_B k^{\alpha} = \frac{2\pi^2 \lambda^3 B_\lambda^2}{\Gamma(n_B/2+3/2)} (\lambda k)^{\alpha},$$



Hortua & Castaneda (2018)

- The analysis of the CMB limits the allowed combination of (B, n_B) within ΛCDM

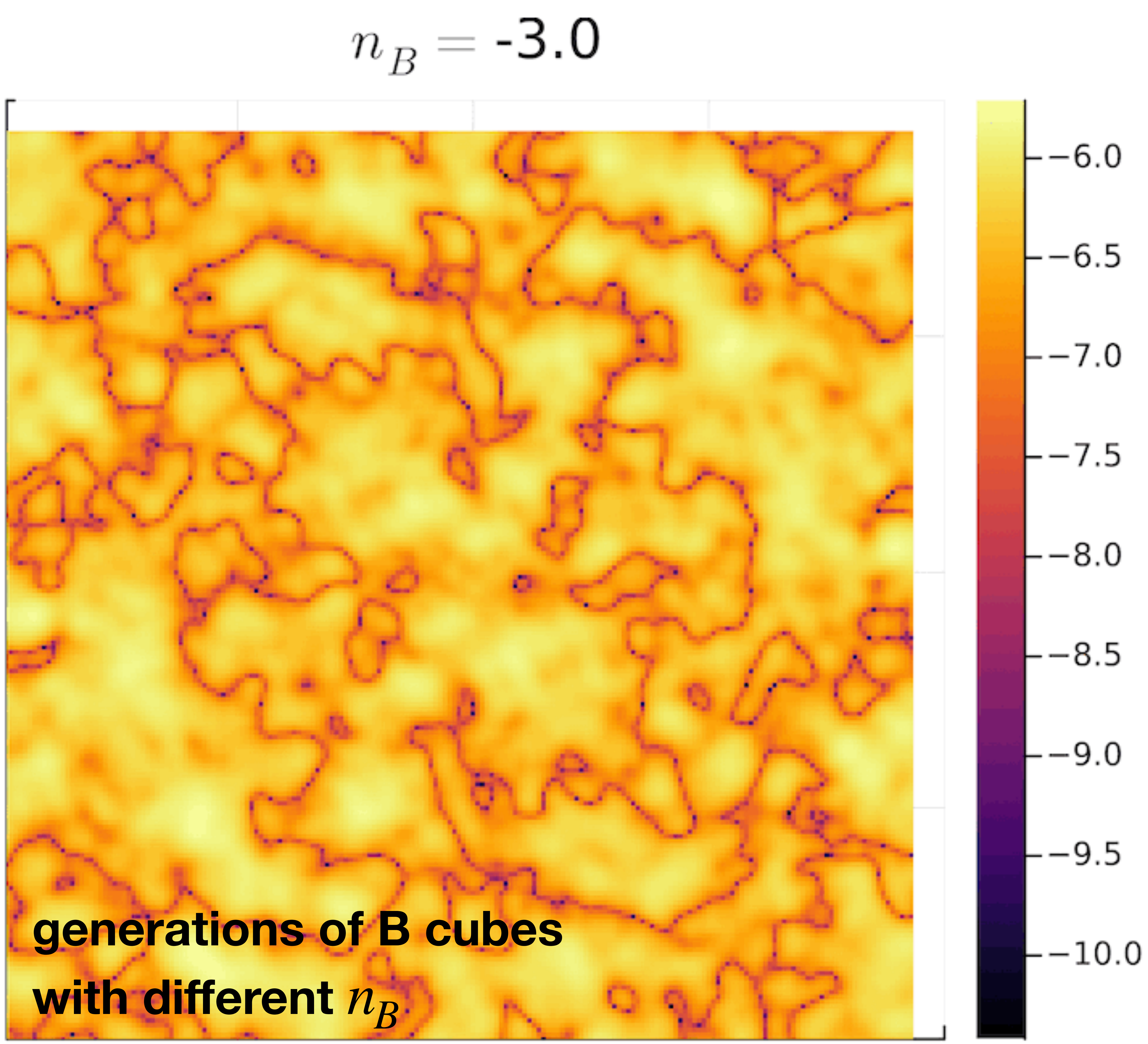


SIMULATING "PRIMORDIAL" MAGNETIC FIELDS

- Use FFT-based techniques to generate a $\nabla \cdot \mathbf{B} = \mathbf{0}$ 3D field drawn from a range of power-law spectra $P_B(k) \propto k^{n_B}$ with $-2.9 \leq n_B \leq 2.0$
- adjust normalisation based on CMB upper limits.
- supply this as initial condition for cosmological MHD simulations at $z \sim 10^2 - 10^3$

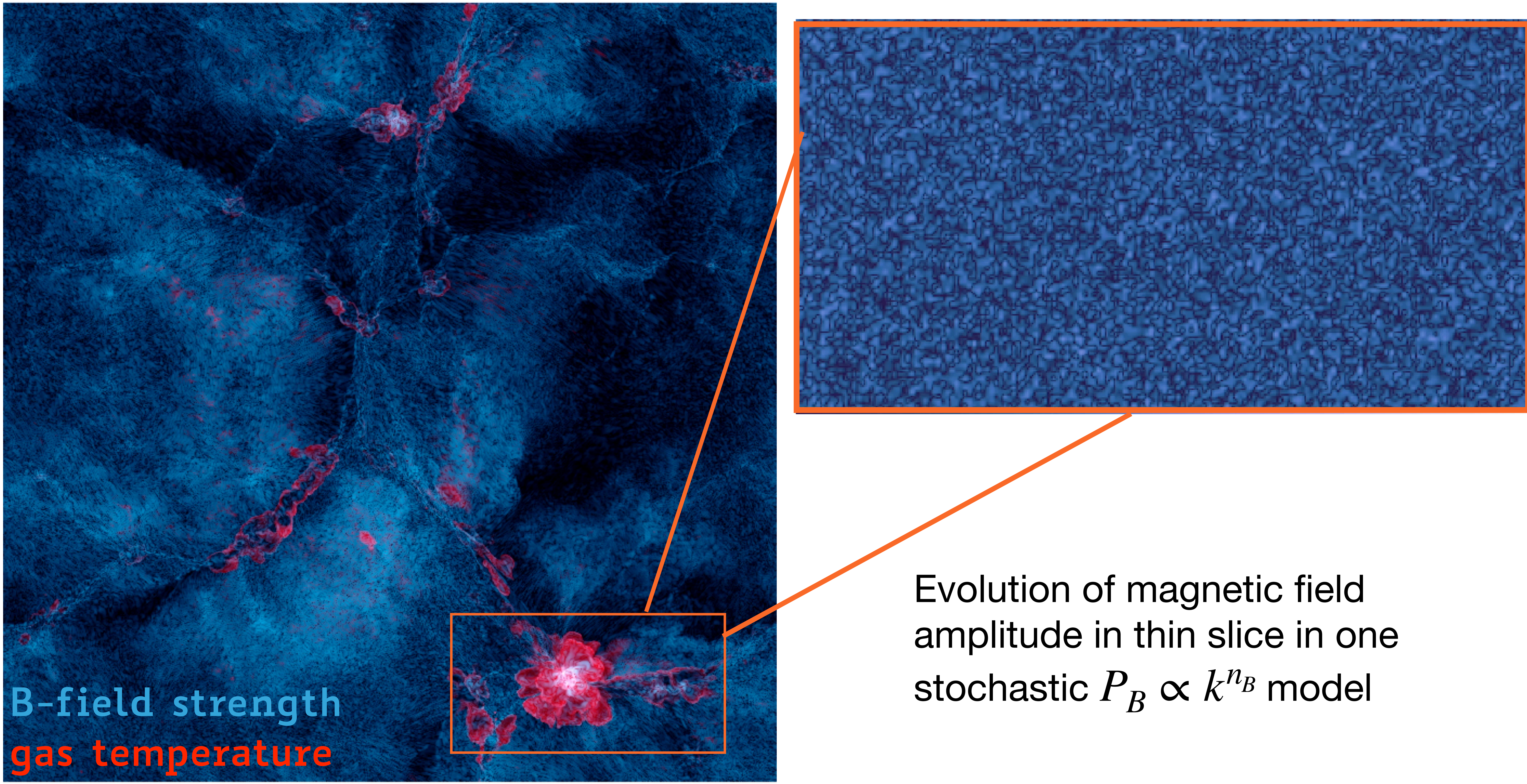
NOTICE 1: so this is not really "primordial": its a post-recombination $\mathbf{B_0}$ field, which we will have to map backwards in time until its generation

NOTICE 2: the modification of $\mathbf{B_0}$ to the initial matter perturbation has so far been (almost always) neglected



FV+21

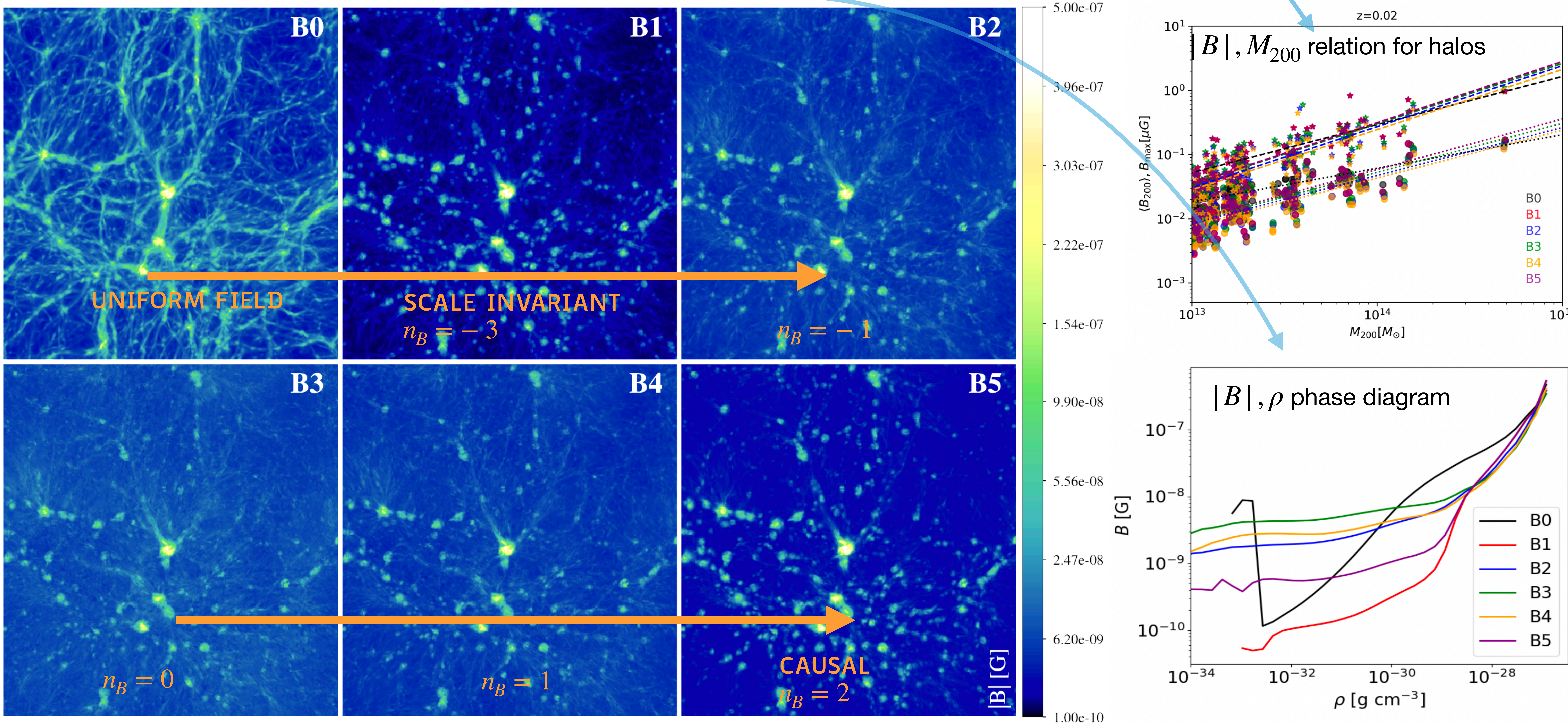
SIMULATING "PRIMORDIAL" MAGNETIC FIELDS



Evolution of magnetic field amplitude in thin slice in one stochastic $P_B \propto k^{n_B}$ model

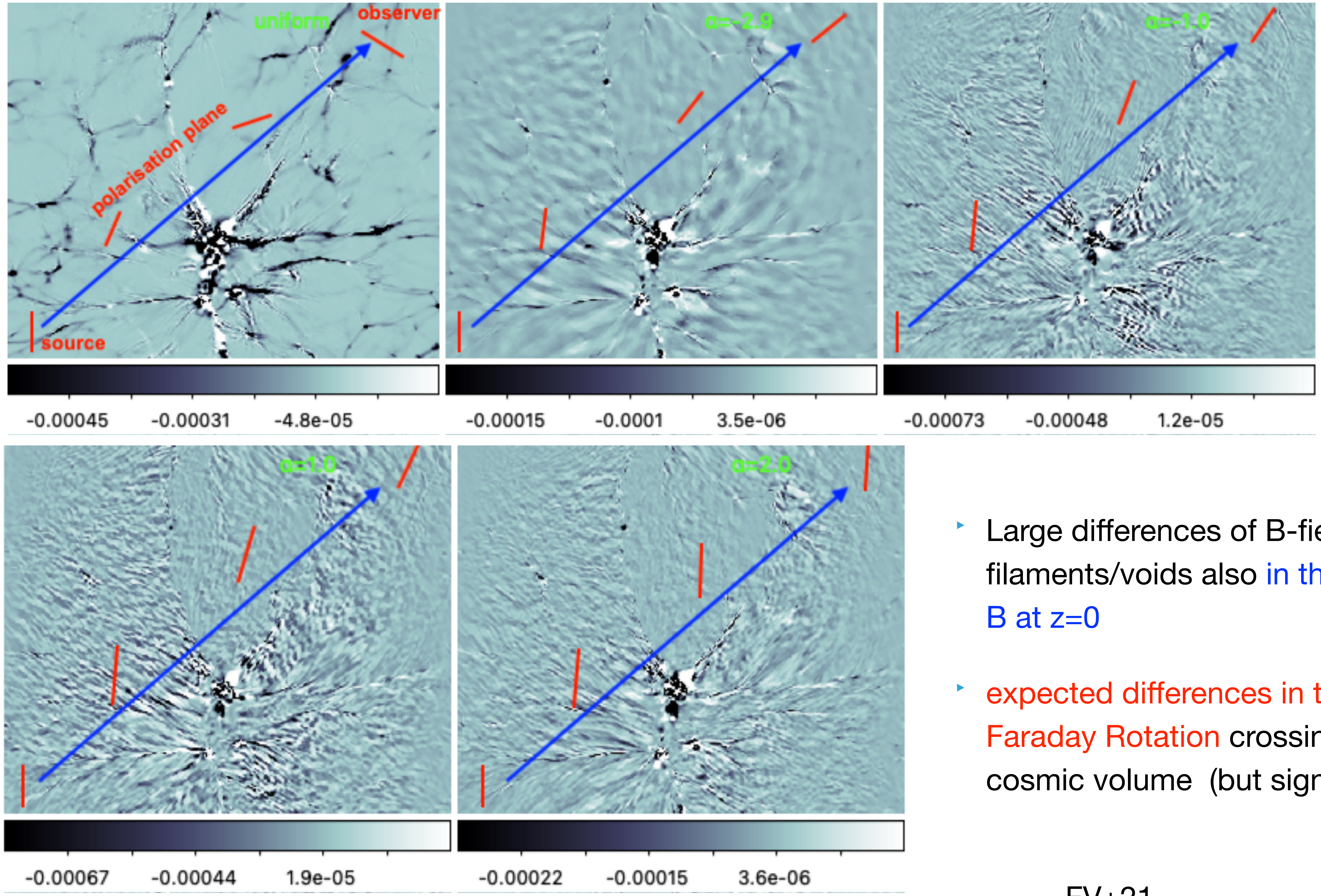
SIMULATING "PRIMORDIAL" MAGNETIC FIELDS

- Result of a $150^3 \mathrm{Mpc}^3$ grid simulation at z=0: similar (amplified) mean magnetic fields in halos, differences increasing outside in filaments and voids



FV+21

SIMULATING "PRIMORDIAL" MAGNETIC FIELDS



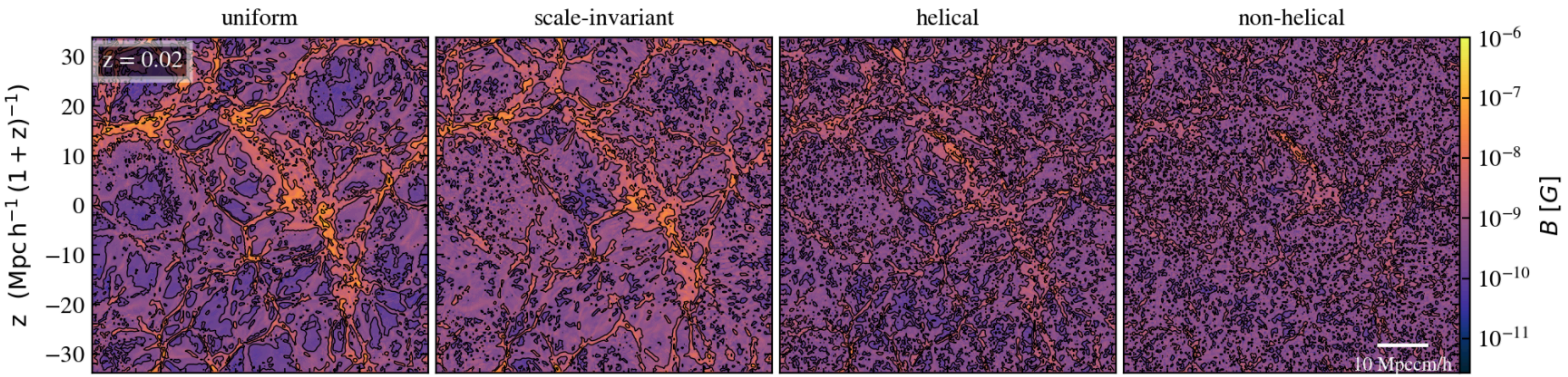
- Large differences of B-fields in filaments/voids also in the topology of B at z=0
- expected differences in the integrated Faraday Rotation crossing the same cosmic volume (but signal is very low!)

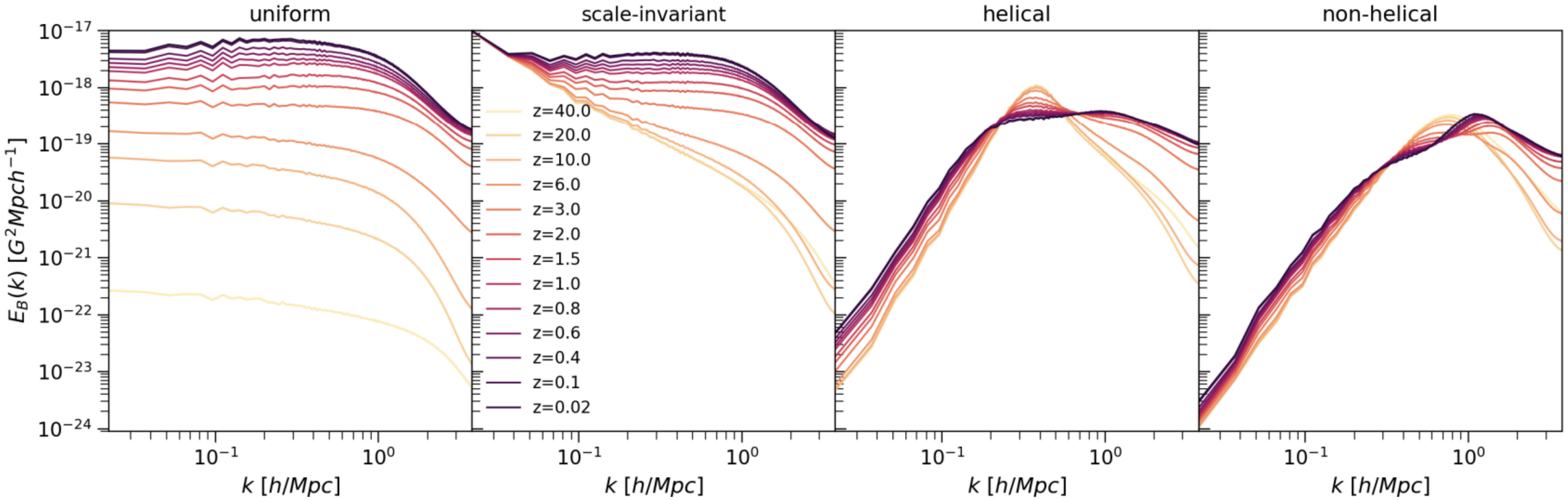
FV+21

SIMULATING "PRIMORDIAL" MAGNETIC FIELDS

ENZO MHD simulations of <u>inflationary vs causal</u> primordial B-fields, using initial conditions produced wit Pencil, also considering:

- a finite maximum scale λ_B (initial conditions from Pencil)
- helical vs non-helical fields





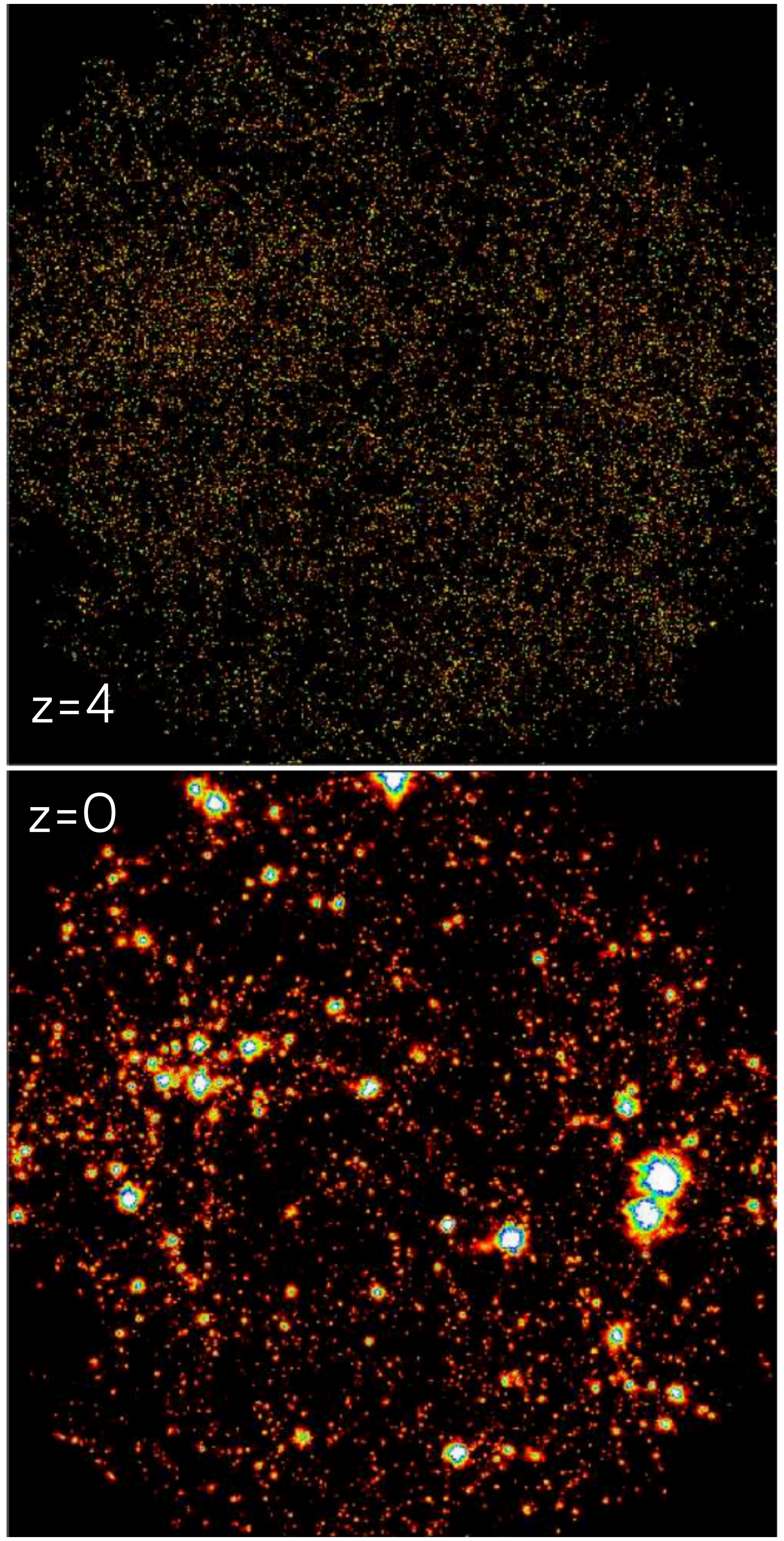
Mtchedlidze et al. 2021, 2024

SIMULATING "ASTROPHYSICAL" MAGNETIC FIELDS

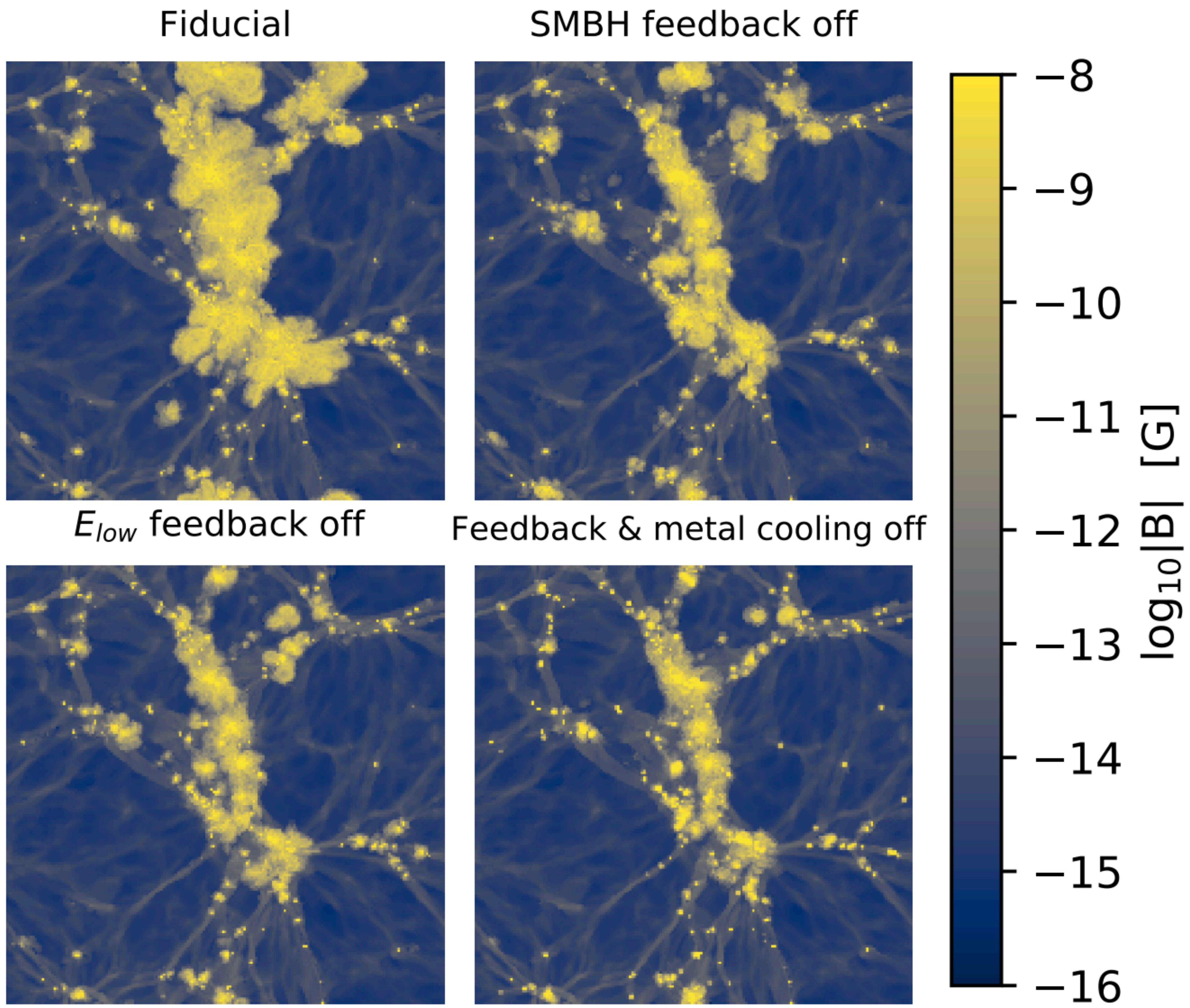
A fraction of the thermal/kinetic feedback by stellar winds and jets from active galactic nuclei can be used to power the injection of additional magnetic field in the simulated volume

MANY UNCERTAINTIES related to **galaxy formation & feedback**

Seeding of B-fields by supernova feedback



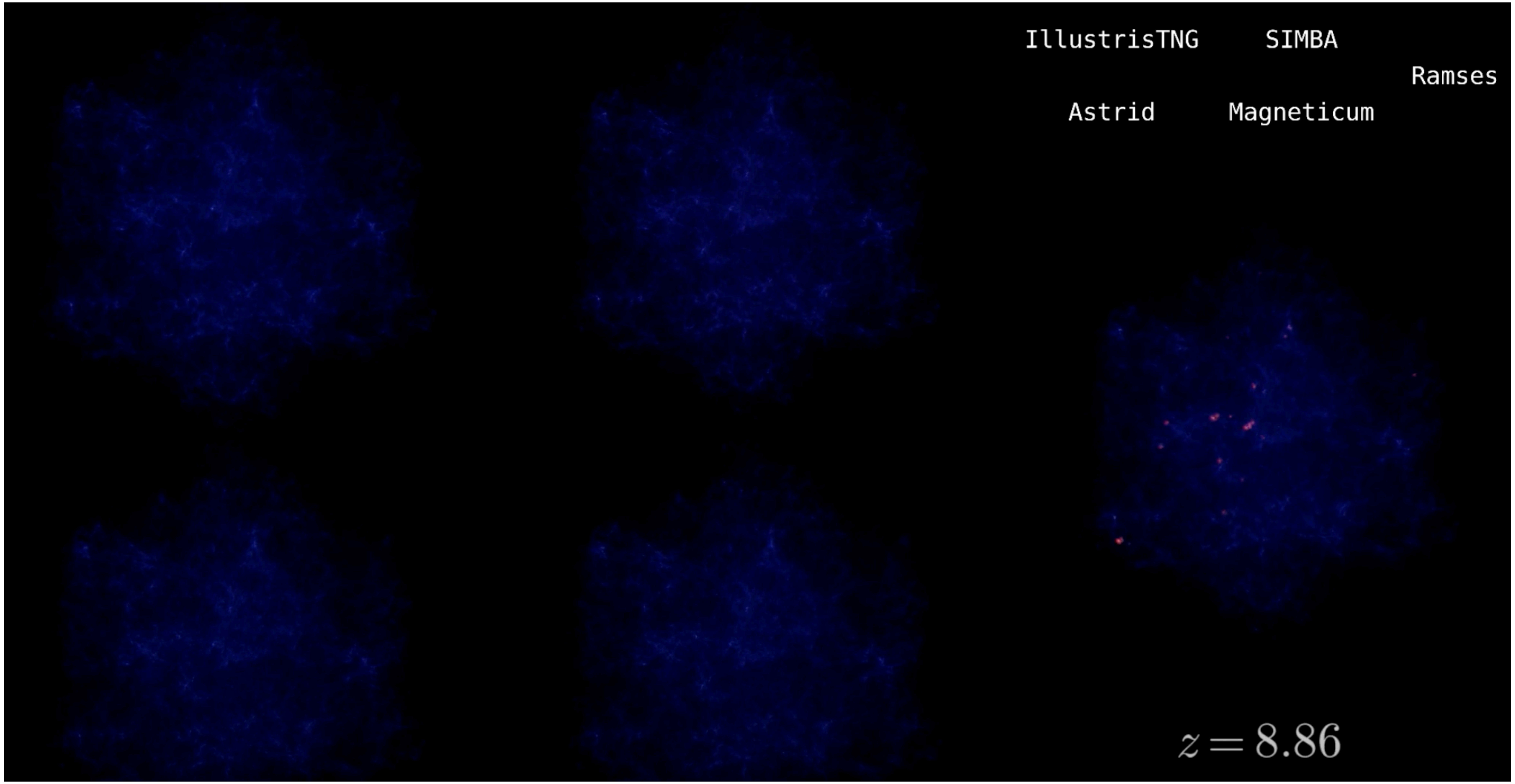
Donnert, Dolag et al. 2009



Aramburo-Garcia, Bondarenko et al. 2021,22

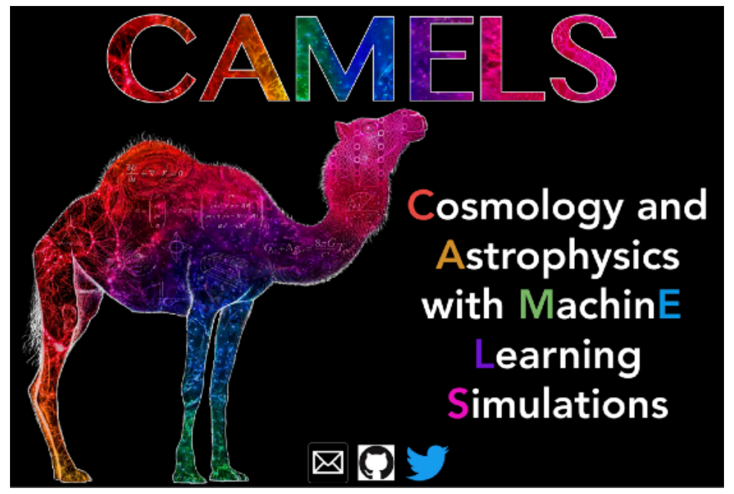
Seeding of B-fields by AGN feedback

SIMULATING "ASTROPHYSICAL" MAGNETIC FIELDS



- 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
- "calibration" of models against observations is essential

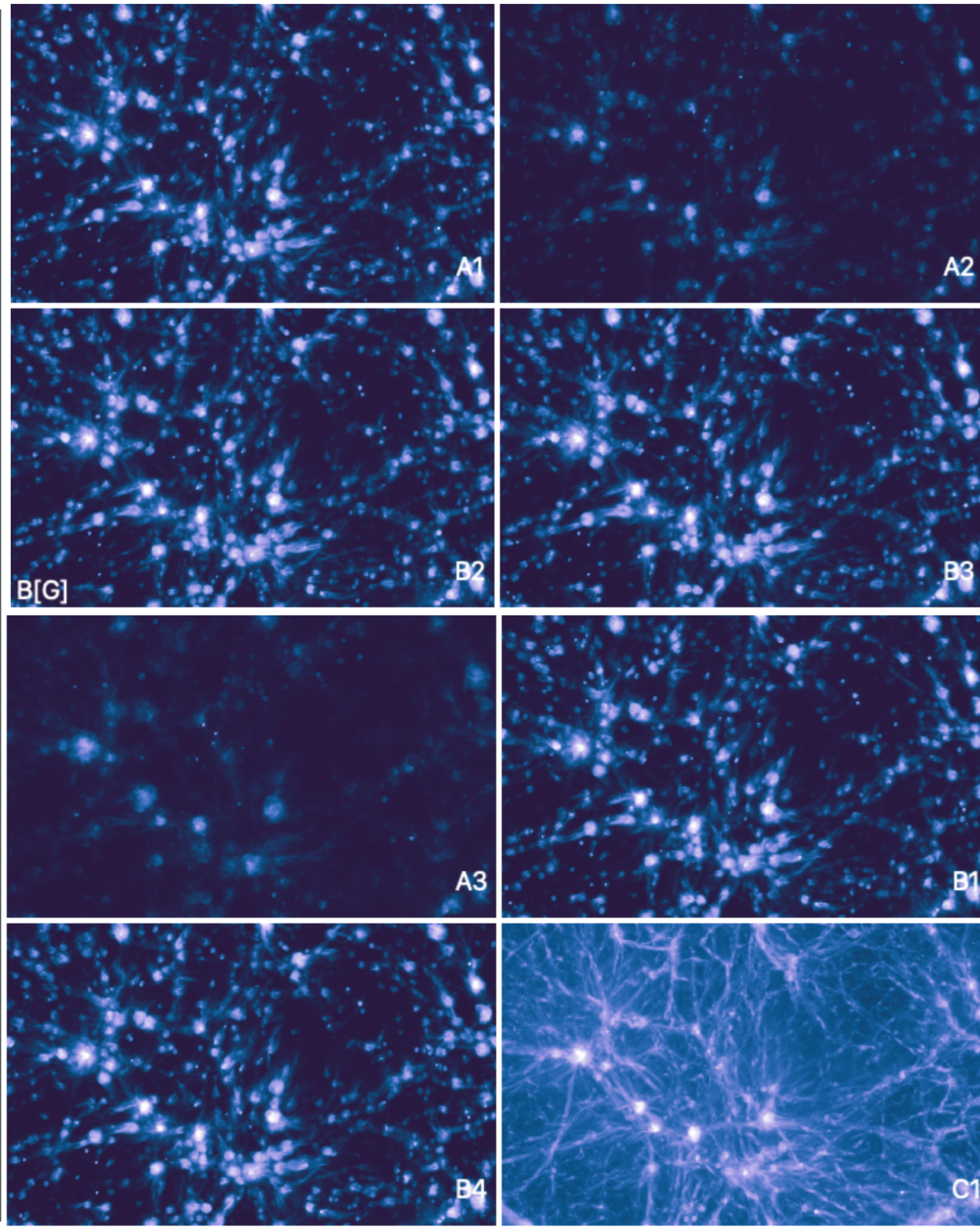
Viallescusa et al CAMELS project



SIMULATING "ASTROPHYSICAL" MAGNETIC FIELDS

A new suite of ENZO-MHD simulations to predict the injection of cosmic ray electrons and B-fields by galaxies/AGN

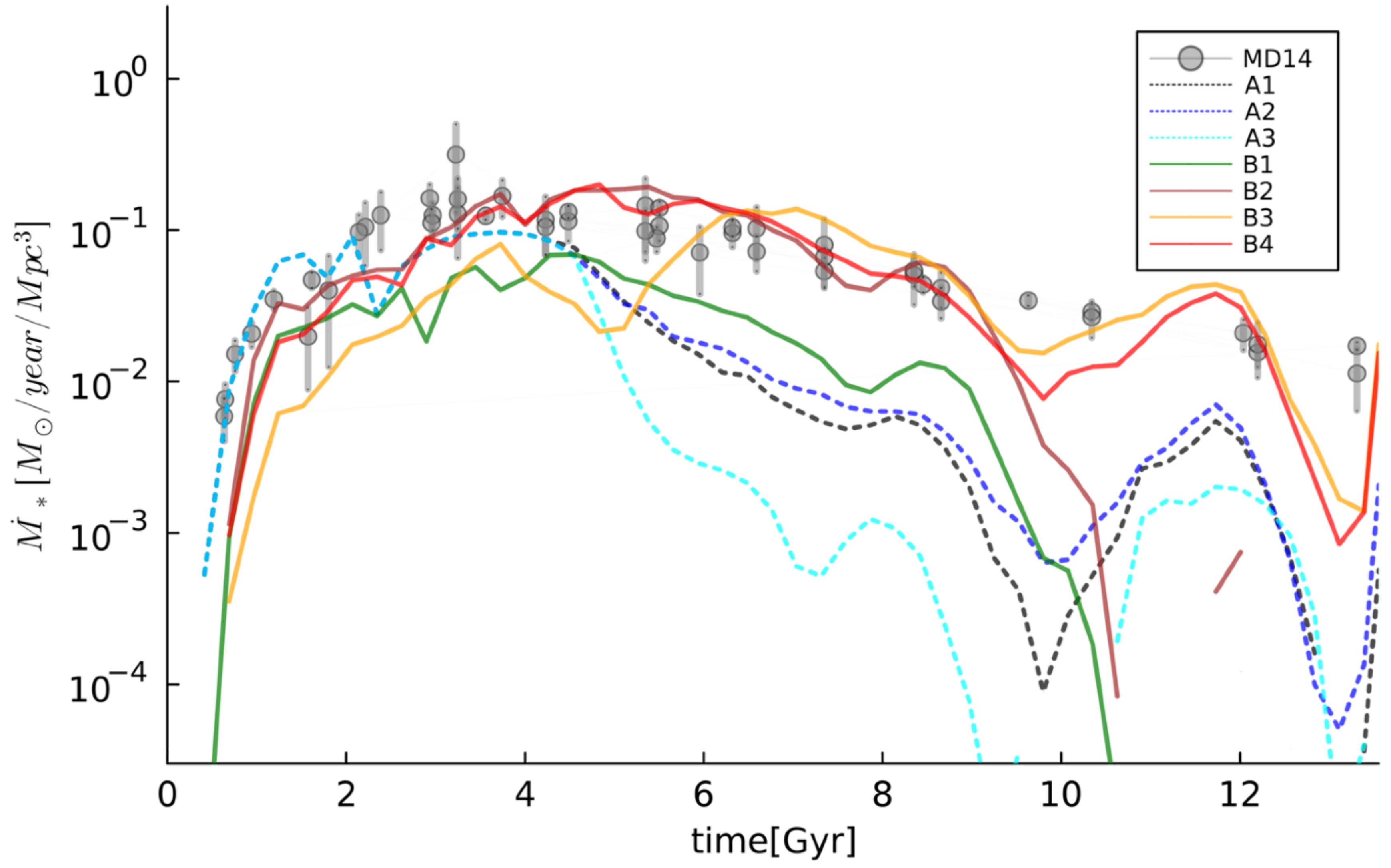
SMBH	• *not grown self-consistently: assumed to be in place in every galaxy at any timestep, following* $M_{BH} \propto M_g^{\alpha}$ • *hot and cold gas accretion*
AGN FEEDBACK	• *cold accretion* → *mostly thermal feedback ("quasar")* • *hot accretion* → *mostly bipolar kinetic feedback ("radio")* • *both cases : 10% energy in* **magnetic fields**
STAR FORMATION	• *based on local gas density (Kravtsov+03) model* • *isotropic thermal+magnetic feedback*
COSMIC RAYS	• *passively advected with the fluid (no CR diffusion)* • *injected by shocks, AGN and star feedback, separately tracked* • *efficiency tuned against radio observables*
MAGNETIC FIELDS	• *injected by AGN and star feedback* • *primordial fields* • *affect shock acceleration through obliquity*



FV et al. 2017, 2025

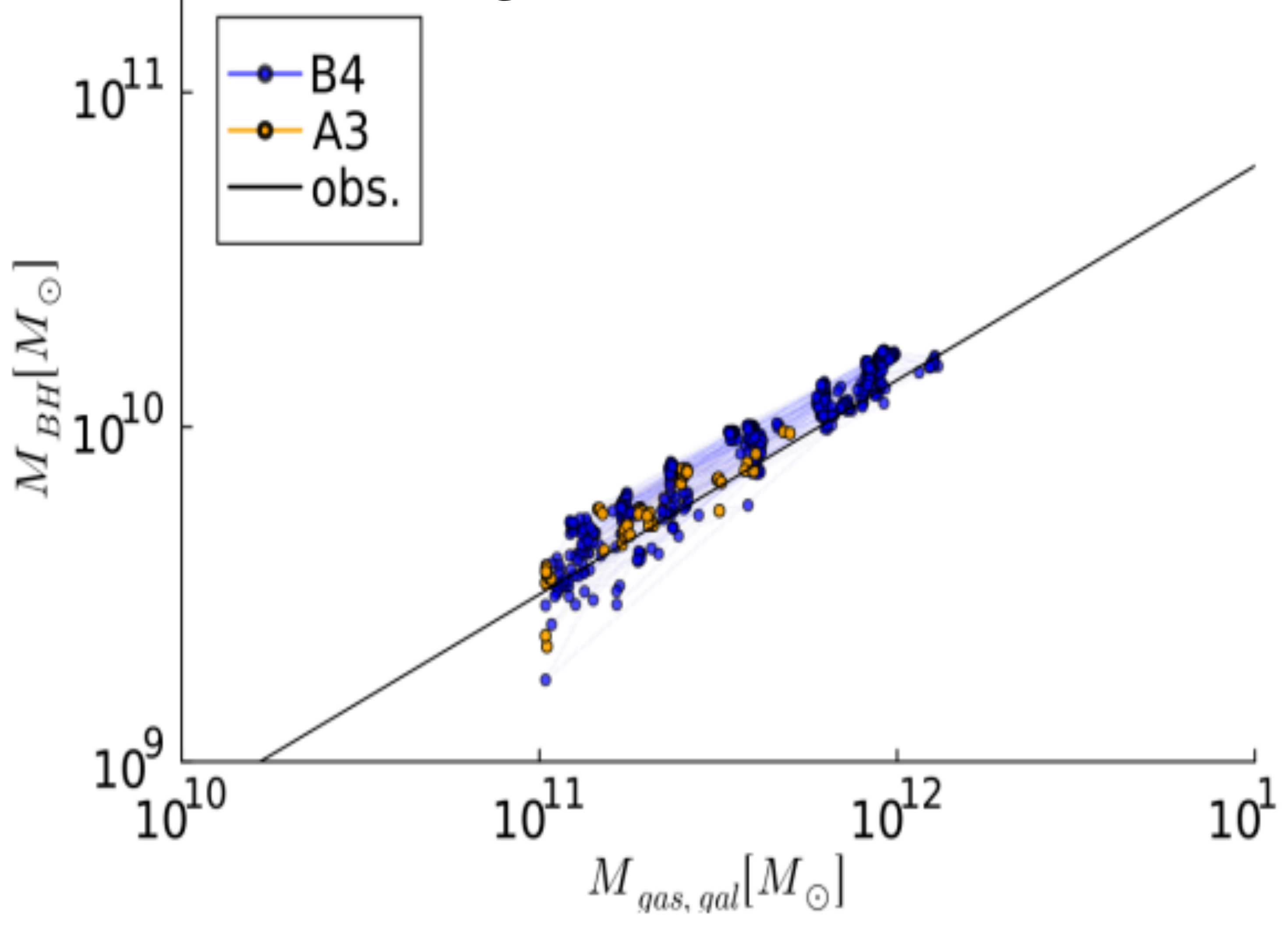
SIMULATING "ASTROPHYSICAL" MAGNETIC FIELDS

cosmic star formation rate

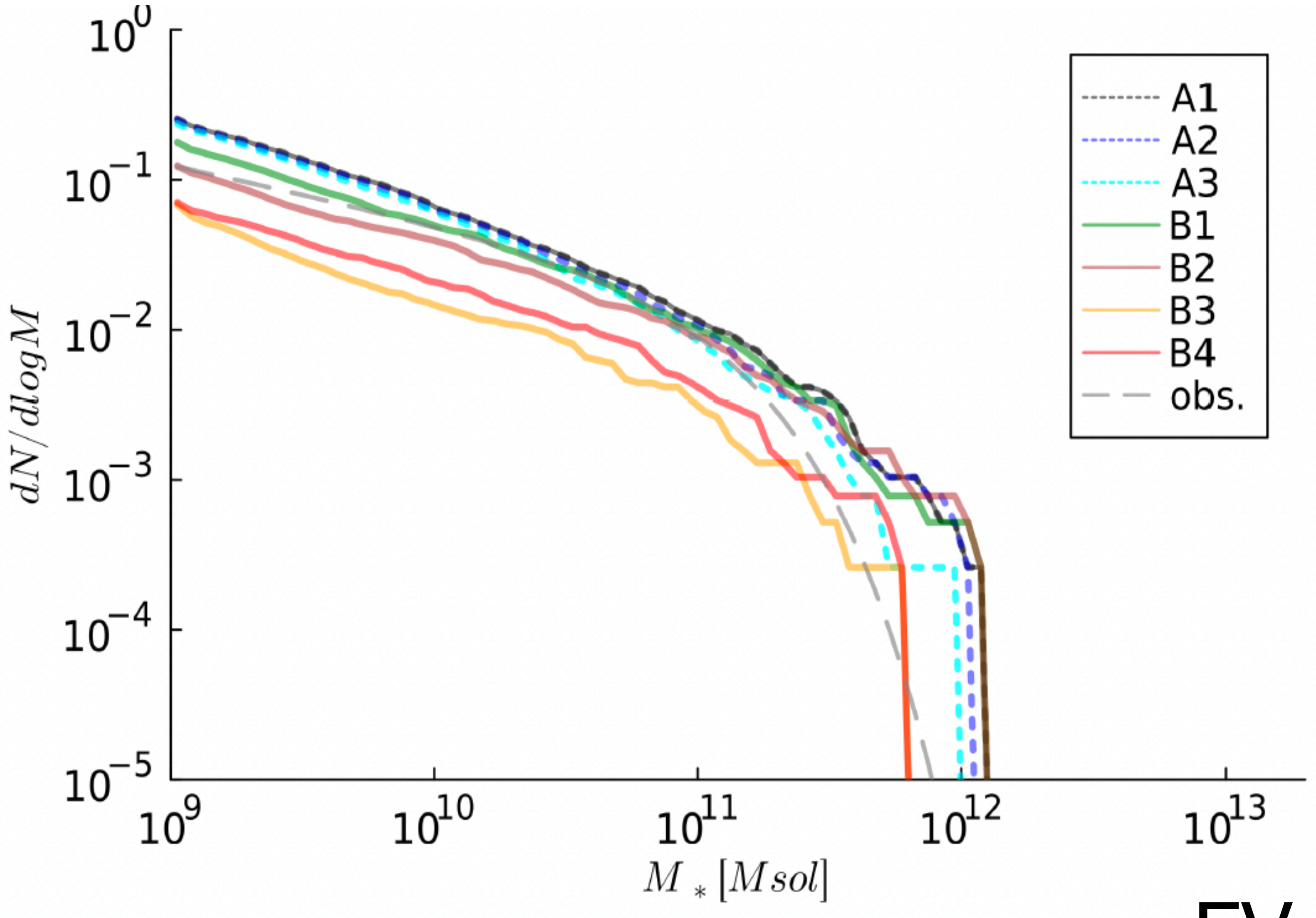


- sub-grid physics calibrated to reproduce many galaxy properties
- can be used to predict pollution of cosmic ray electrons and magnetic fields by **star formation** and **AGNs** (and **shocks**)
- LIMITATIONS: small volume $(42^3\mathrm{Mpc}^3)$ and resolution (40kpc)

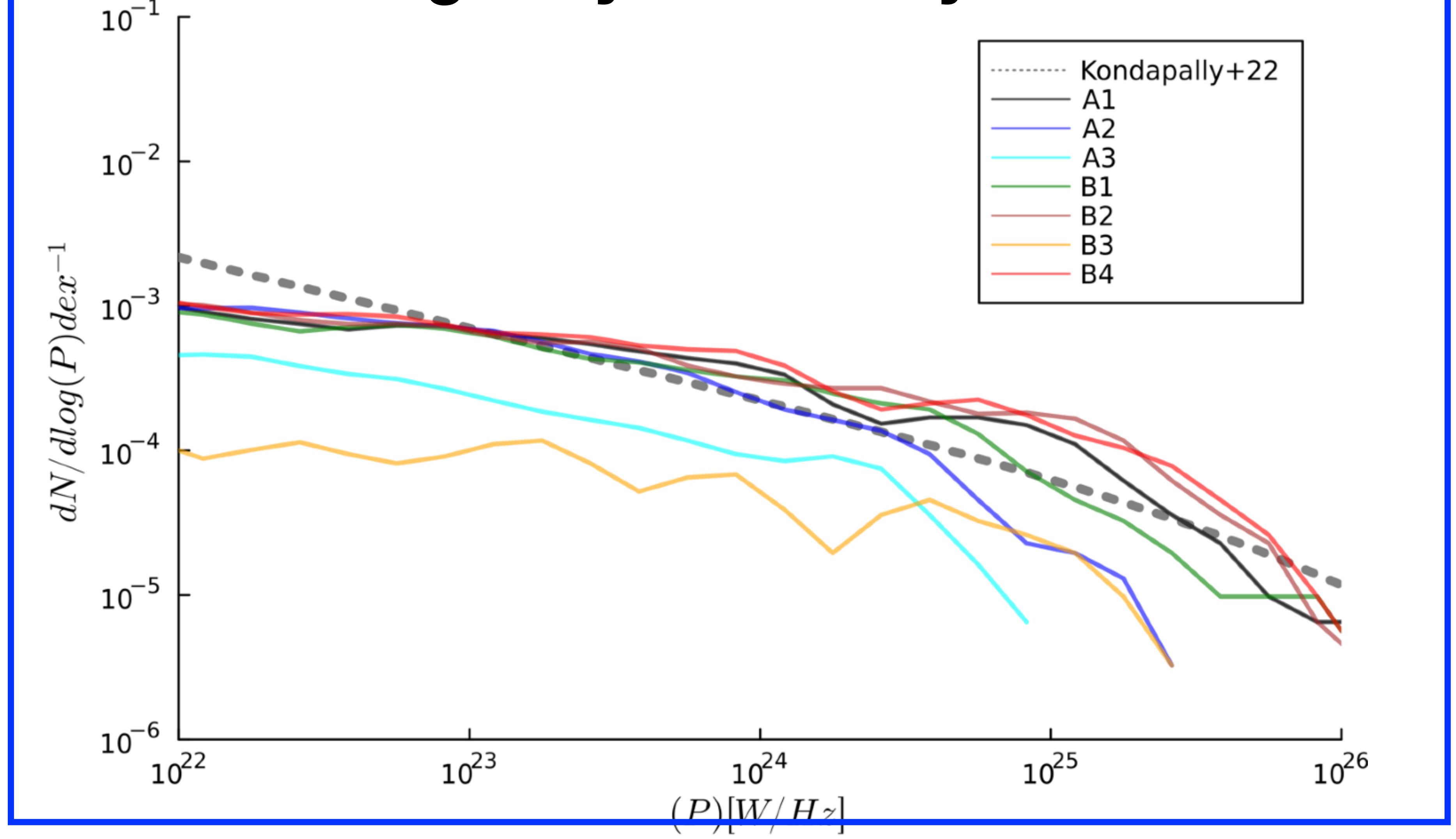
BH - halo gas mass relation



galaxy stellar mass function

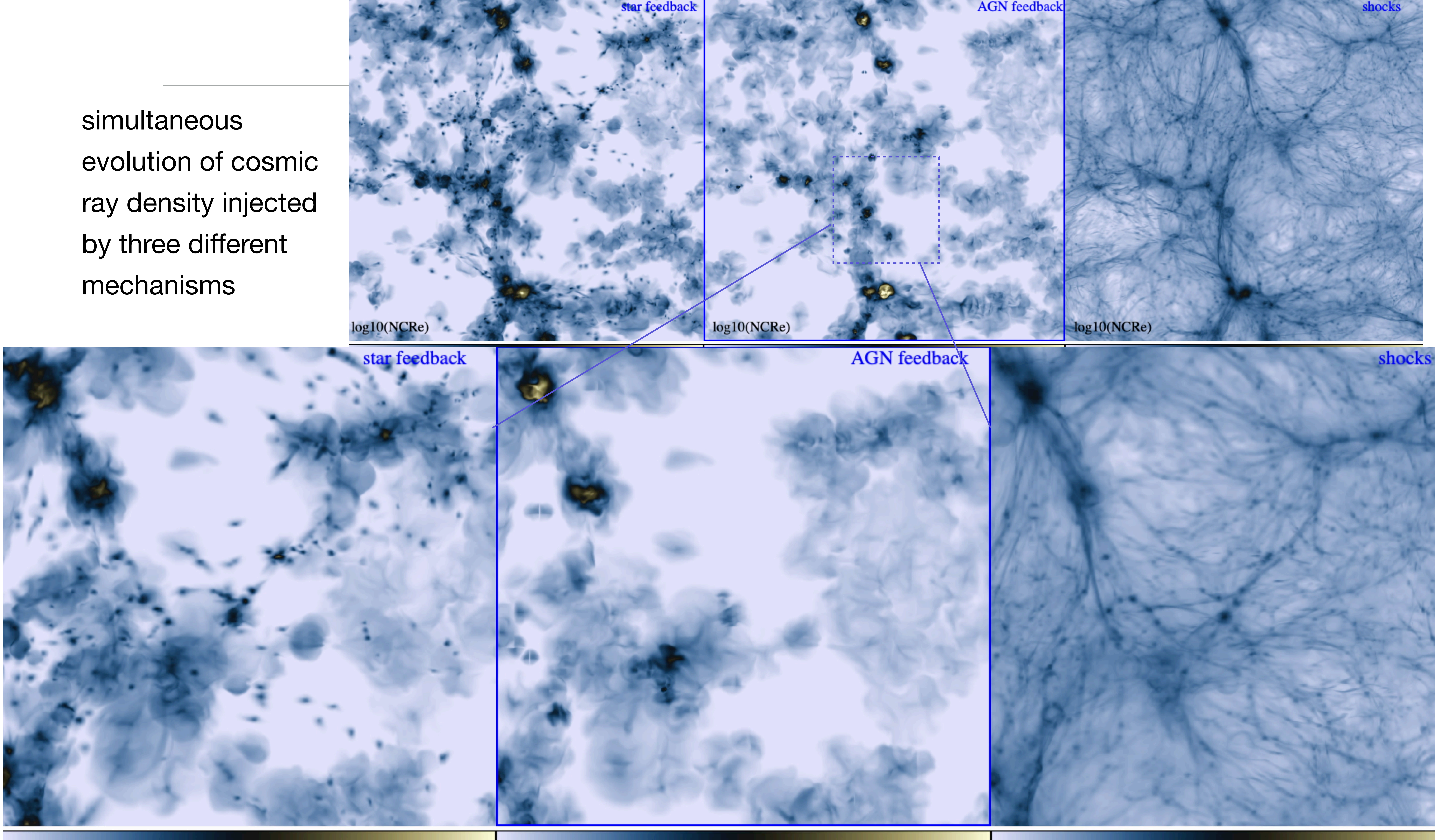


radio galaxy luminosity function



FV et al. 2017, 2025

simultaneous evolution of cosmic ray density injected by three different mechanisms



SIMULATING "ASTROPHYSICAL" MAGNETIC FIELDS

Physically motivated release of magnetisation bubbles following cosmic SFR and AGNs

FV et al. 2017, 2025

DIFFERENT WAYS OF MEASURING MAGNETISM

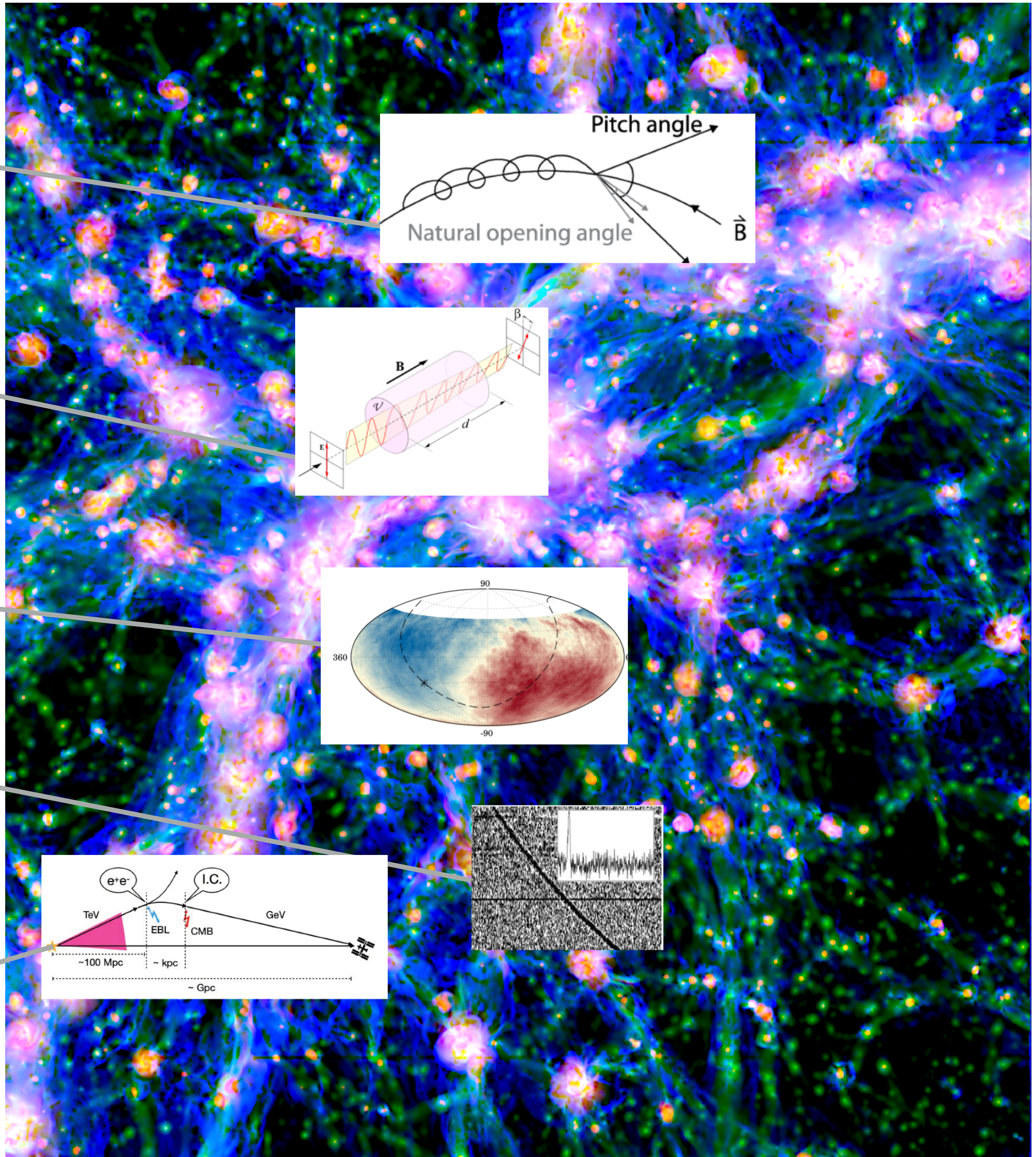
SYNCHROTRON EMISSION $\propto \xi_e B^2$

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 $\propto |B|$

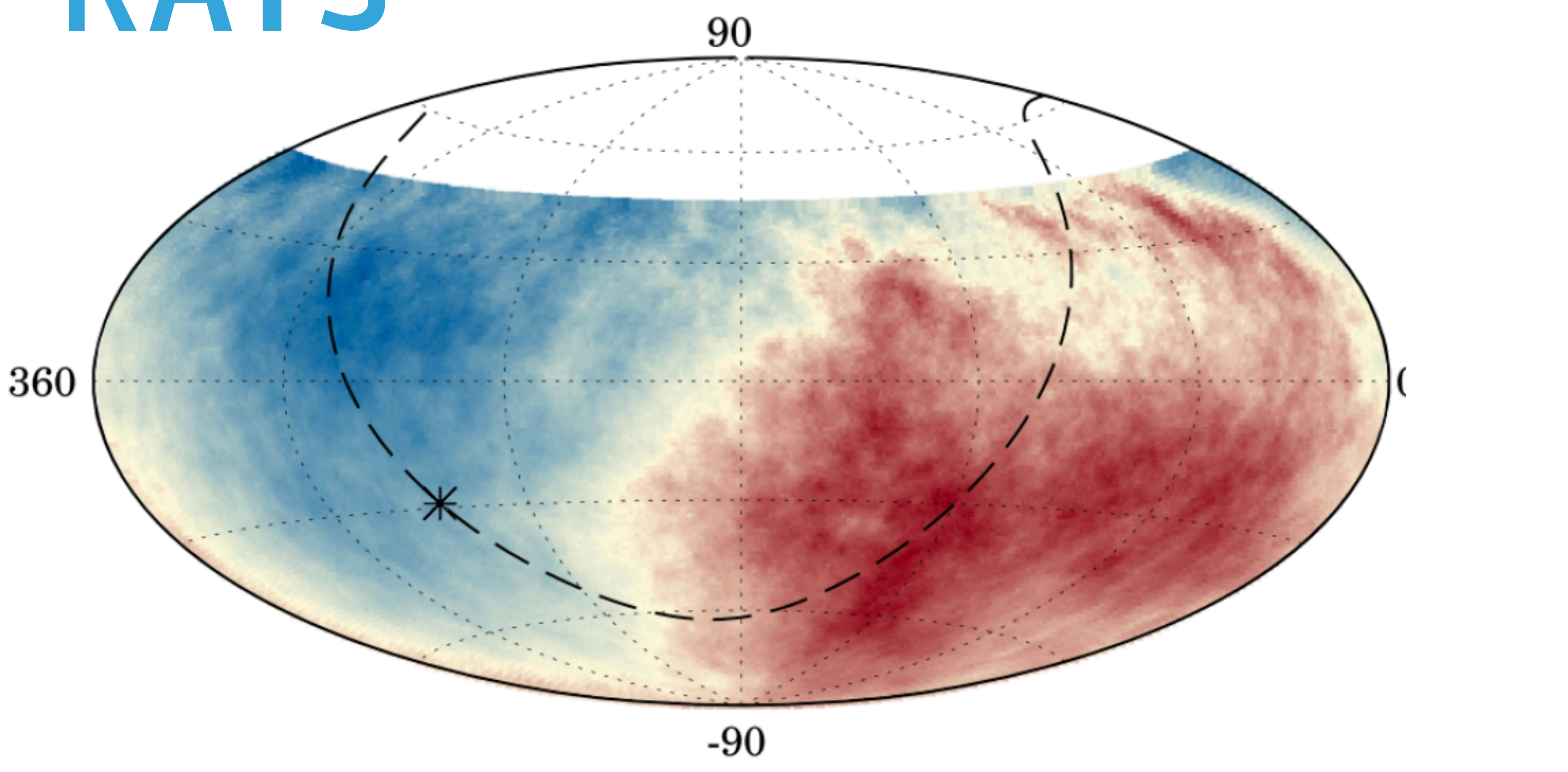


ULTRA HIGH ENERGY COSMIC RAYS

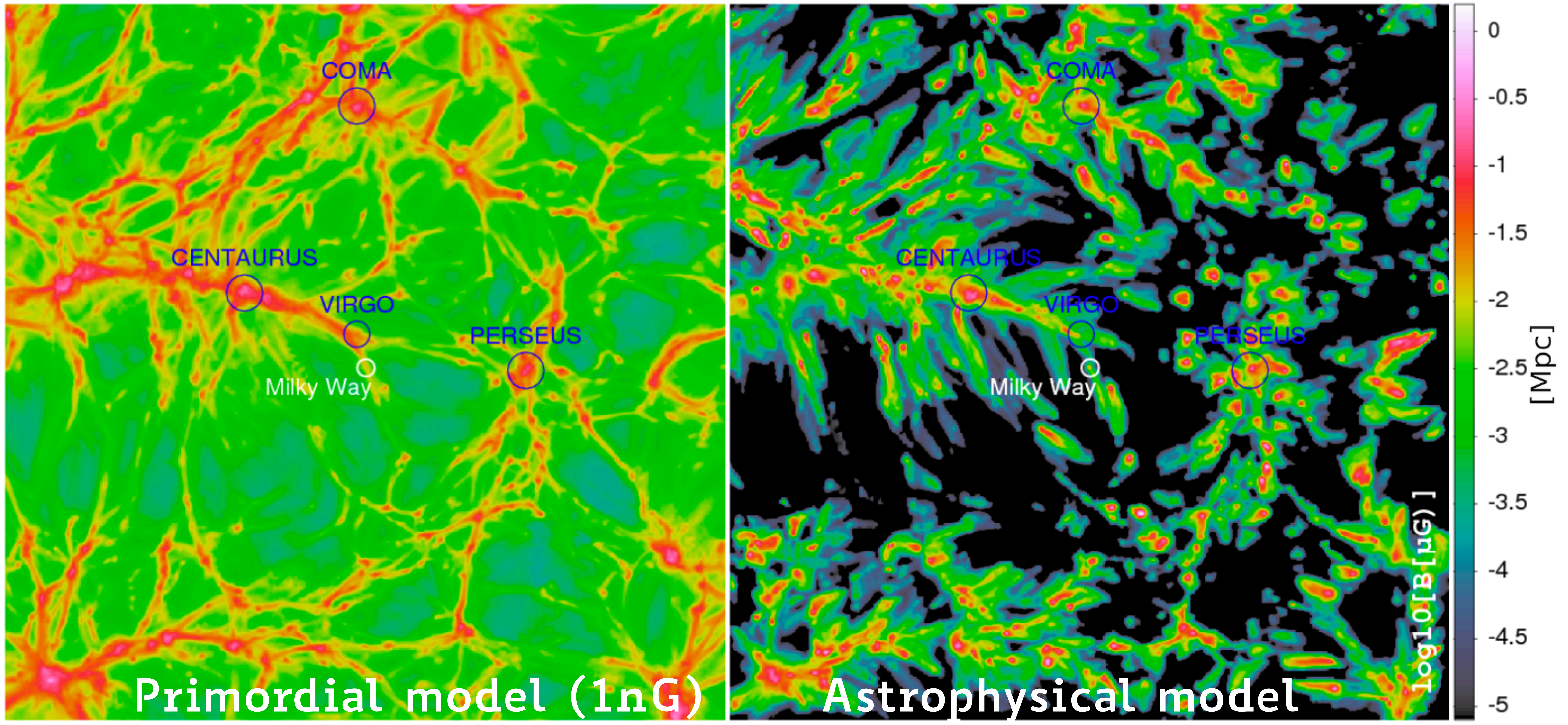
- Deflection angle of UHECRs

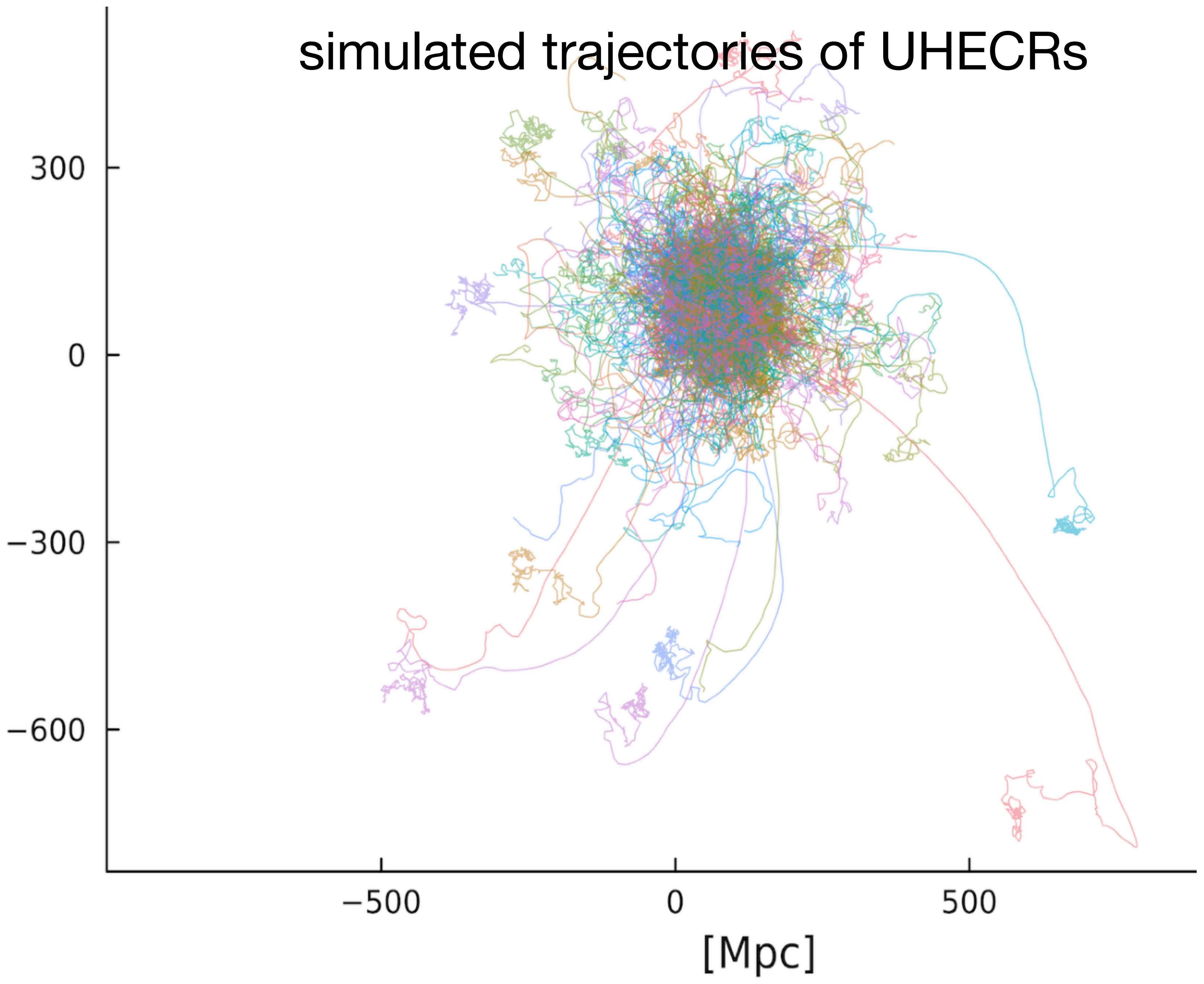
$$\theta \propto \frac{Z\, D^{1/2}\, B\, \lambda_B^{1/2}}{E}$$

- unknown sources, composition, energy spectra
- Pierre Auger Obs. : small anisotropy at E~4-8 10^{18} eV
- ENZO+CRPROPA simulation of Local Universe



maps of UHECRs detected by Auger





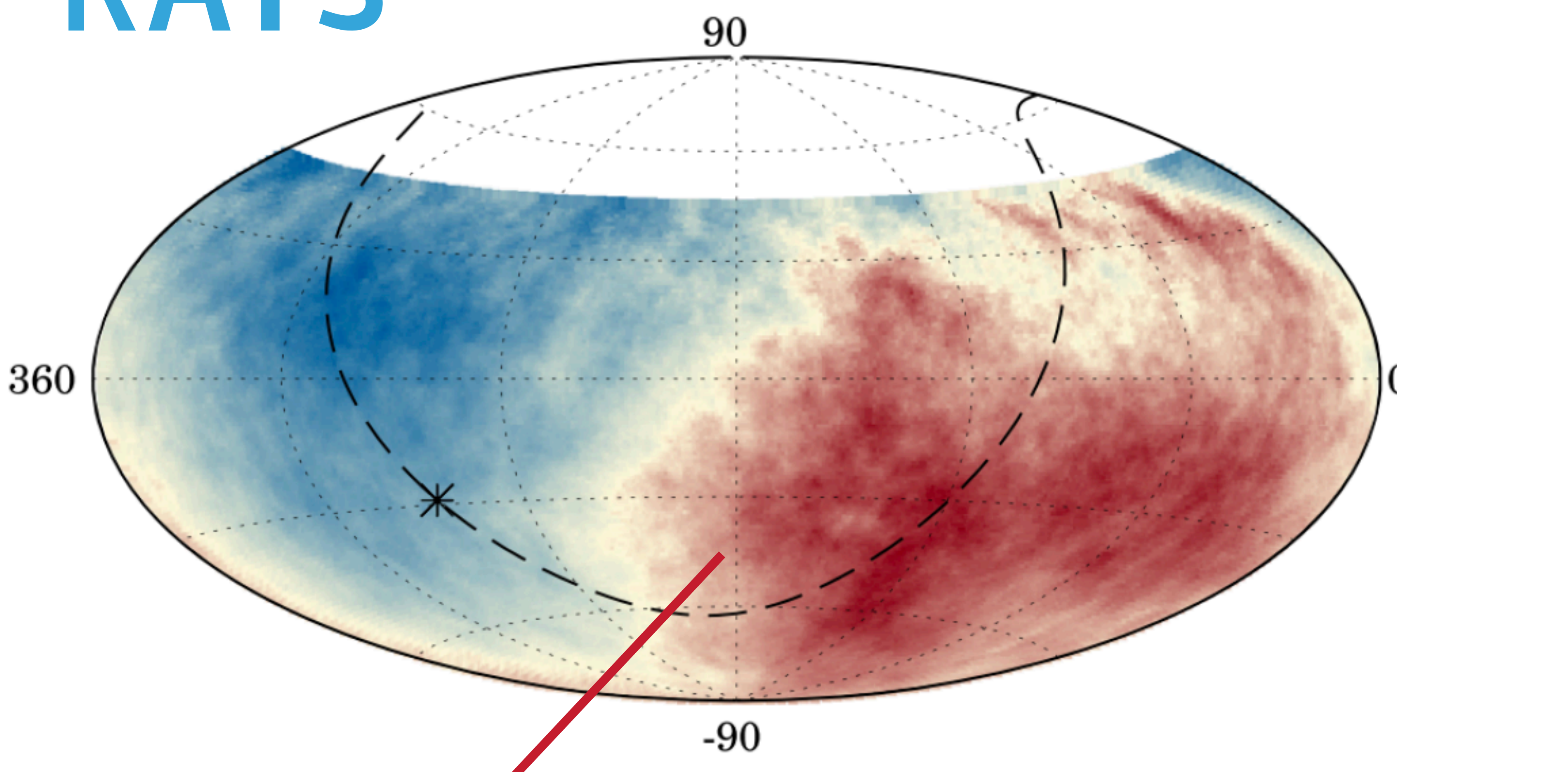
Hackstein+17,18

ULTRA HIGH ENERGY COSMIC RAYS

- Deflection angle of UHECRs

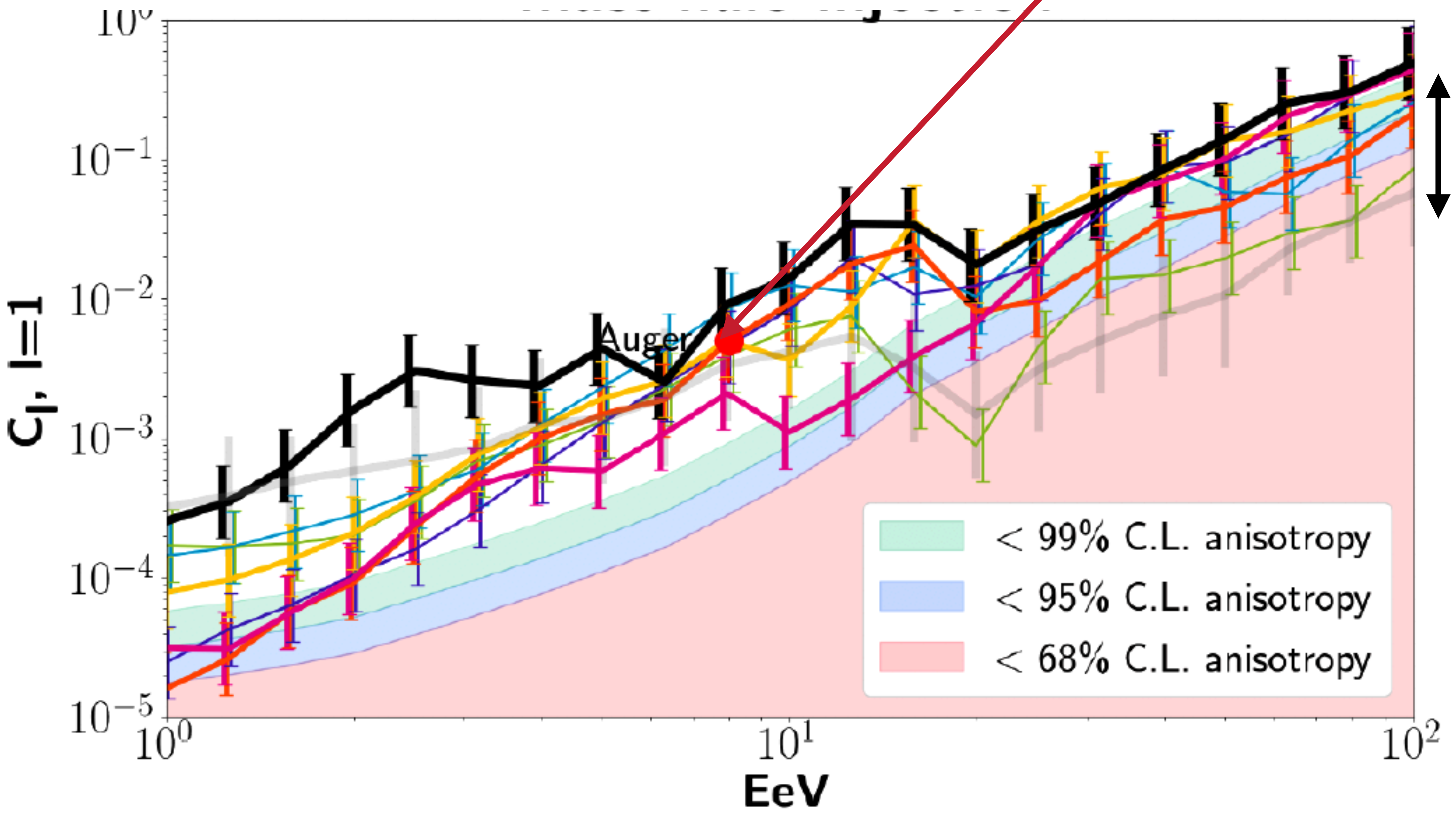
$$\theta \propto \frac{Z\, D^{1/2}\, B\, \lambda_B^{1/2}}{E}$$

- unknown sources, composition, energy spectra
- Pierre Auger Obs. : small anisotropy at E~4-8 10^{18} eV
- ENZO+CRPROPA simulation of Local Universe



maps of UHECRs detected by Auger

- almost no constrain on magnetic field models: observed PAO dipole compatible even with B=0 models (local structures are not isotropic)
- only by constraining the sources of UHECRs we can study magnetism
- important to study the composition of UHECR at $\sim 10^{18}$eV ("Magnetic Horizon")

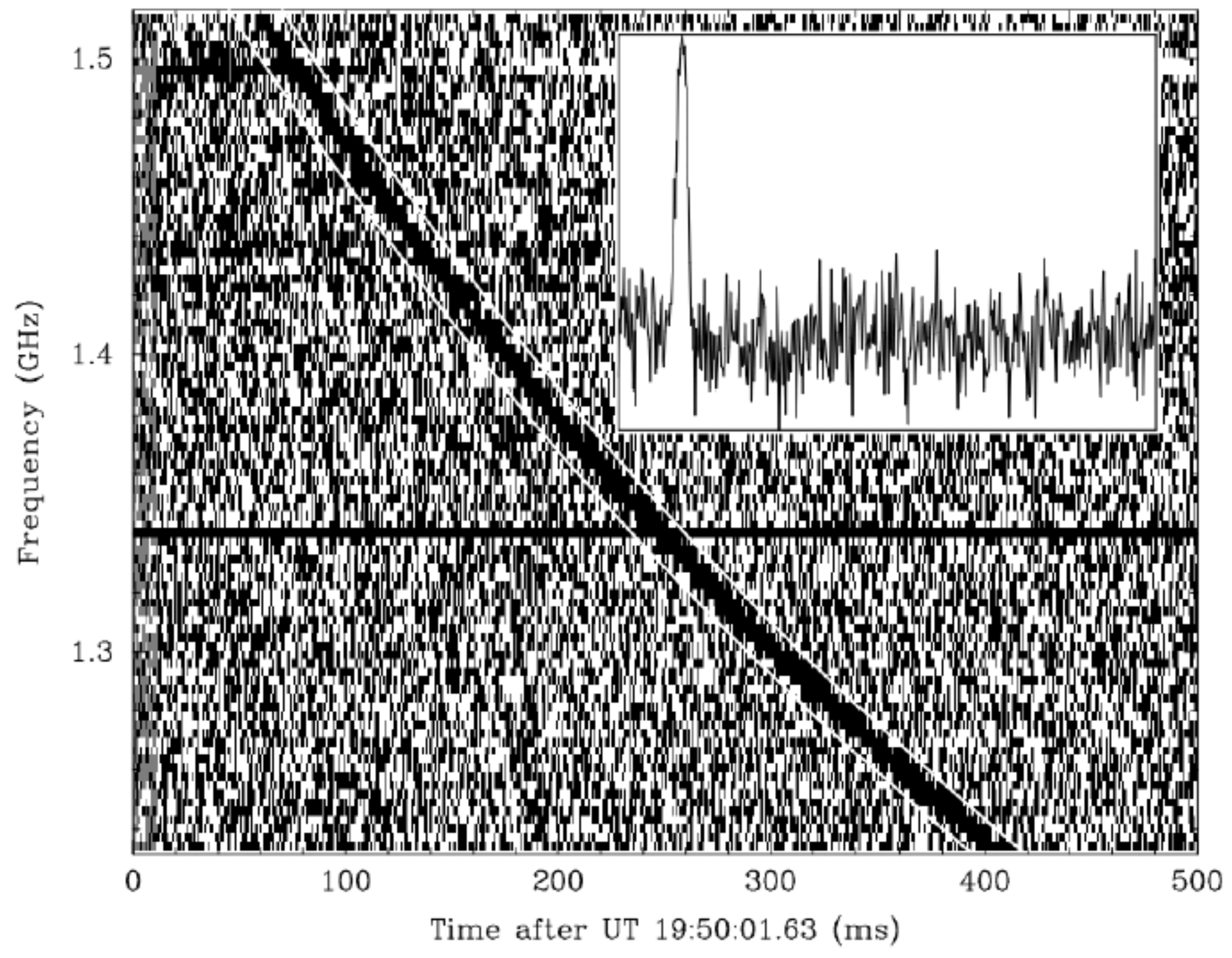


all astrophysical and primordial models

Hackstein+17,18

FAST RADIO BURSTS

- Fast Radio Bursts are powerful radio pulses which at the same time can probe intergalactic density and magnetic fields on extragalactic scales:



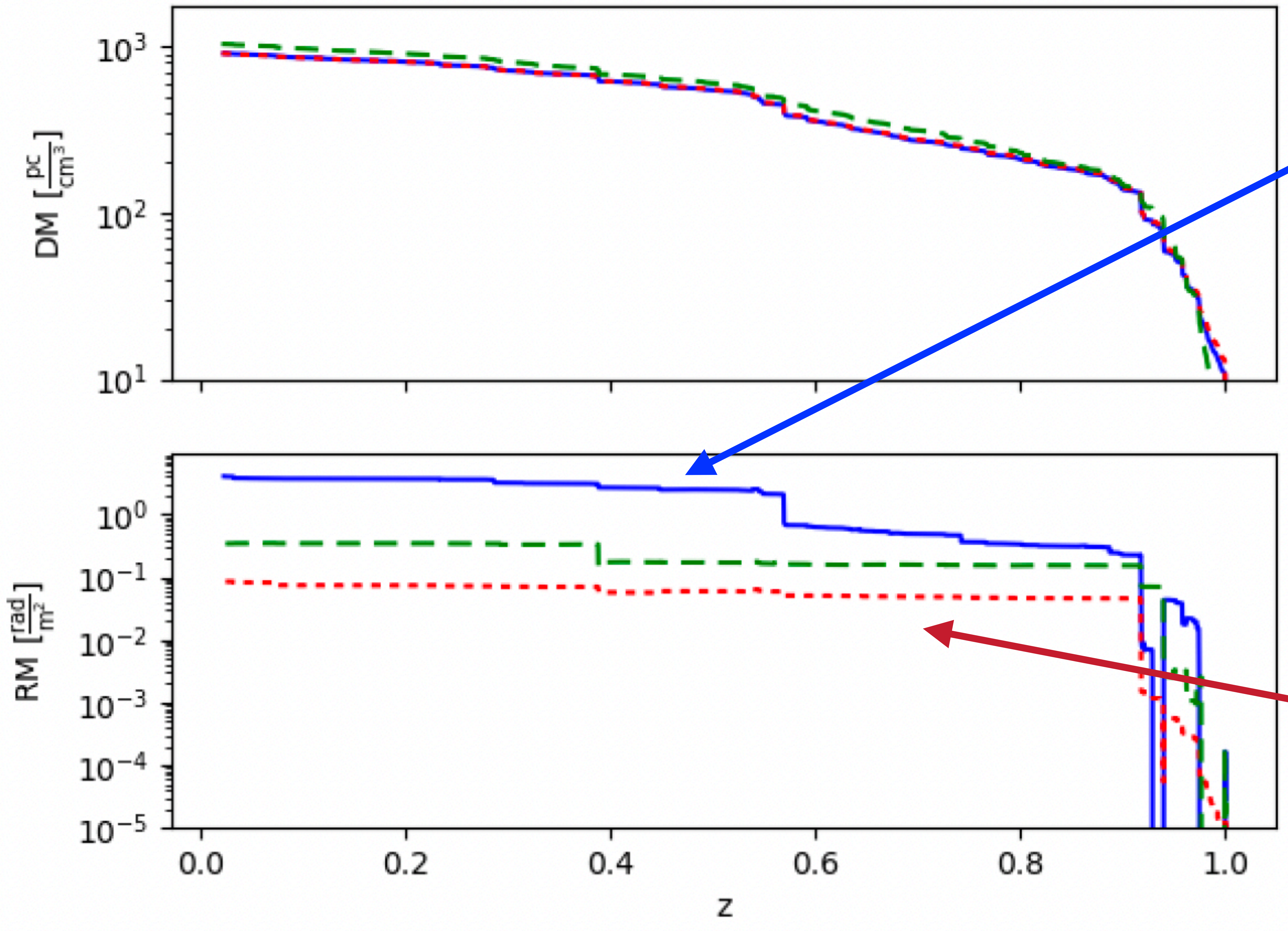
Lorimer+2007

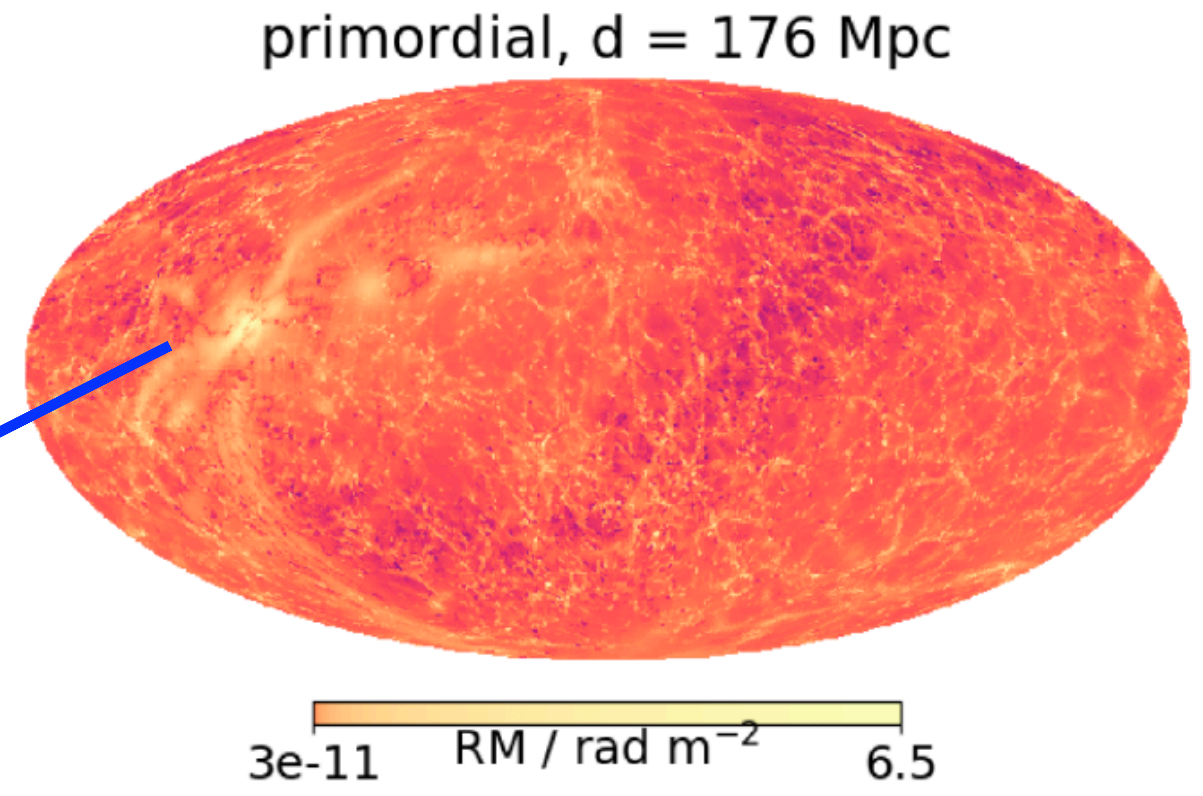
ROTATION MEASURE: $\propto \int_L n_e B_{||} dl$ & DISPERSION MEASURE $\propto \int_L n_e dl$

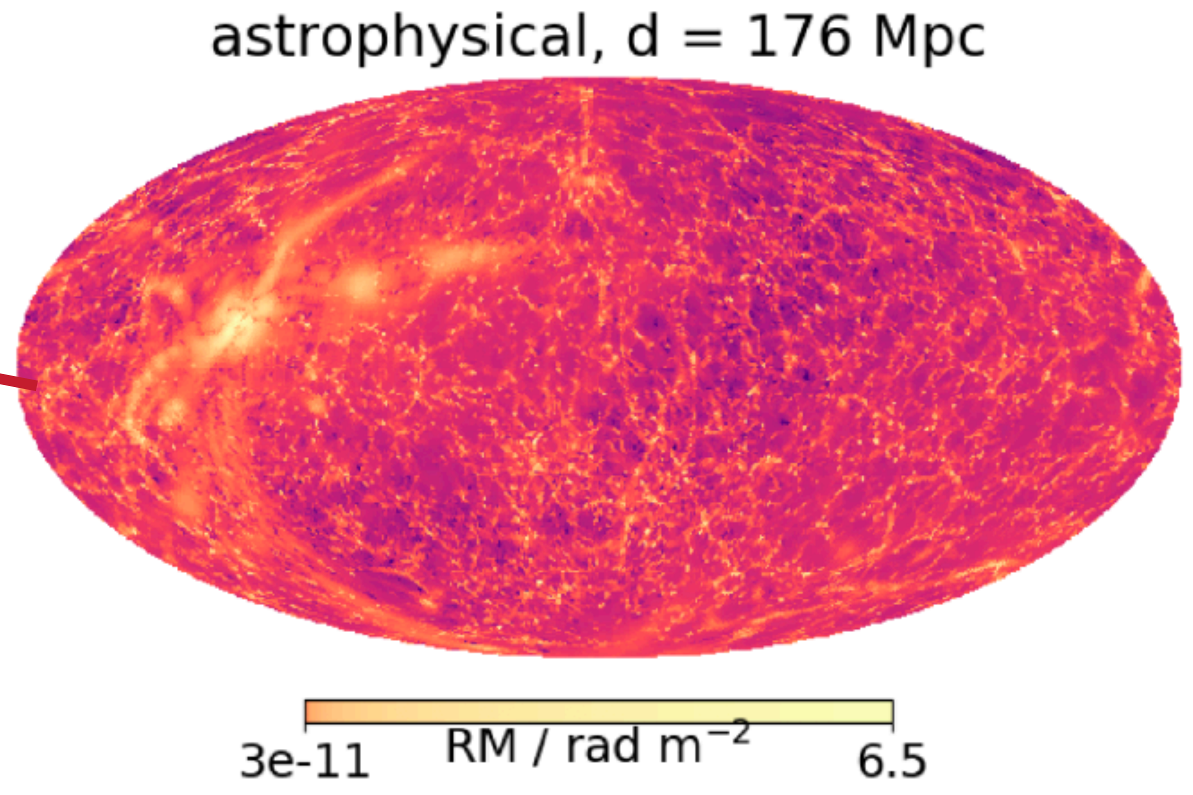
$$\rightarrow B_{||} \approx \mathrm{RM/DM}$$

- at present: too large uncertainties in the redshift of sources, host environement, Galactic Foreground

- In the future: with > 10,000 RMs (need the SKA!) primordial & astrophysical models will be testable

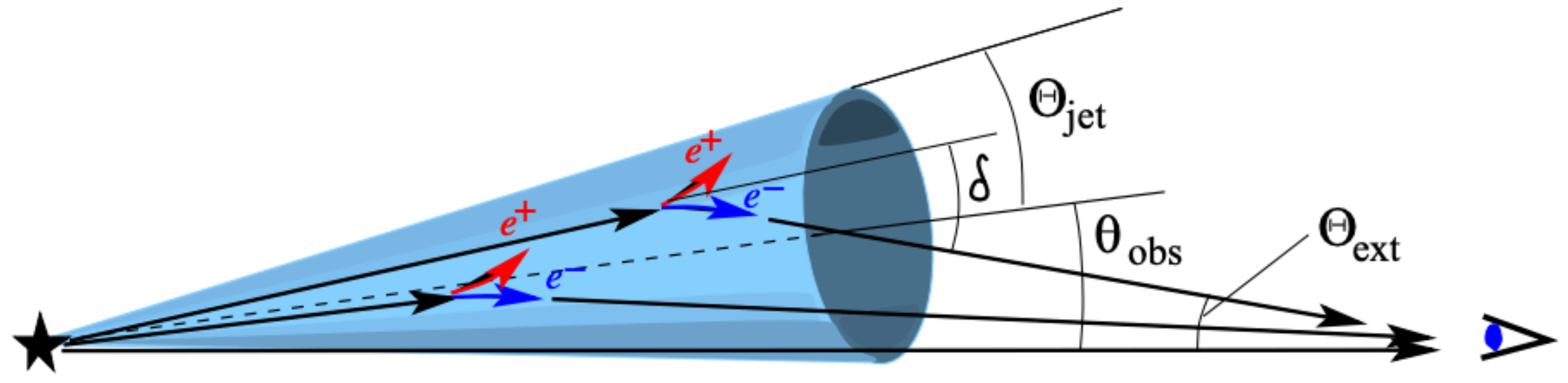






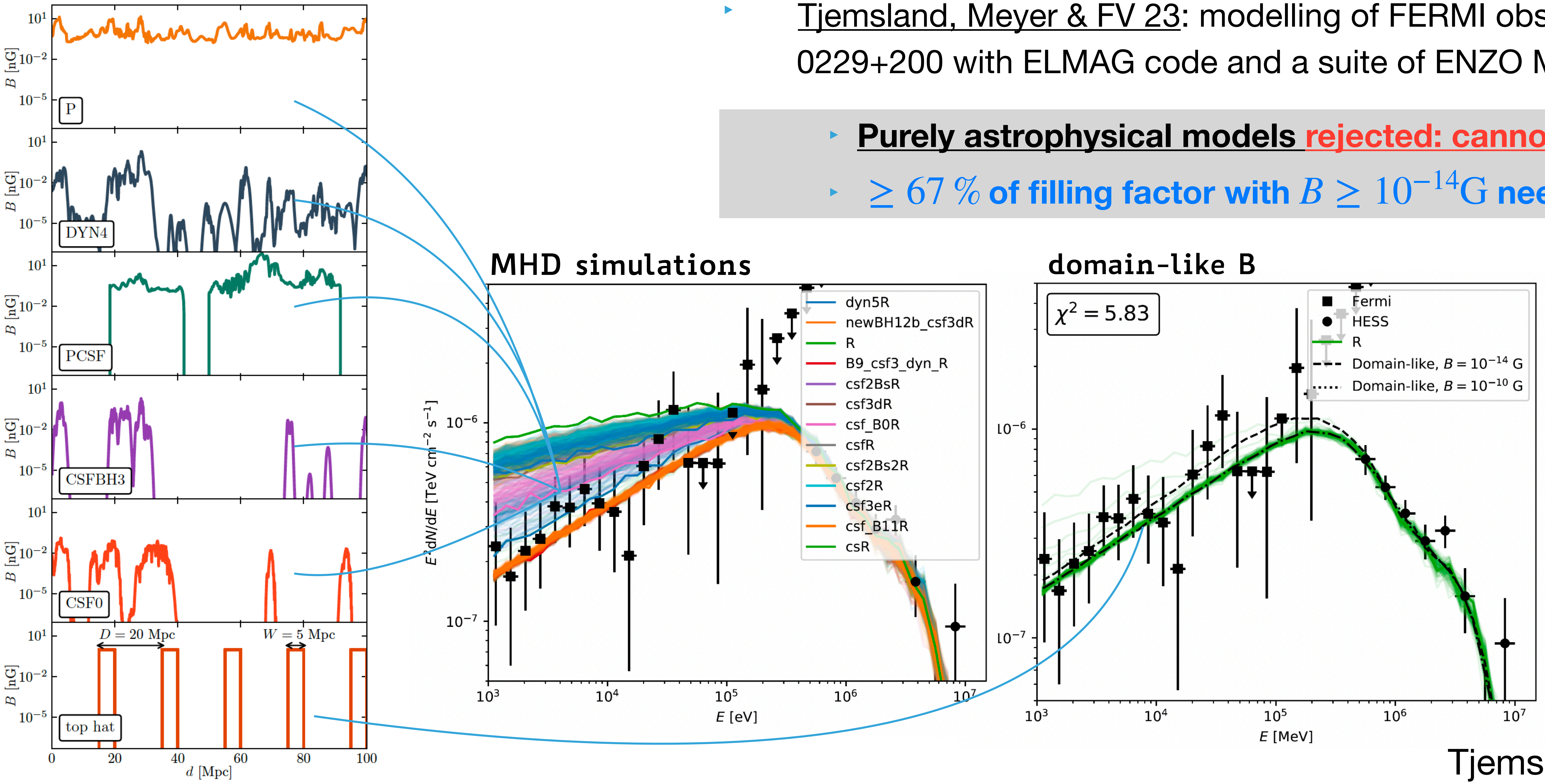
FV+18, Hackstein+19,21

LOWER LIMITS FROM BLAZARS



The deflection by $B \geq 10^{-16}$G in voids can explain the suppression of (secondary) inverse-compton-cascade (ICC) from blazars at 1-100 GeV (**Neronov & Vovk 2010**, Arlen+2014, Mayer+2016…)

- Tjemsland, Meyer & FV 23: modelling of FERMI observations of 1ES 0229+200 with ELMAG code and a suite of ENZO MHD simulations.
  - **Purely astrophysical models rejected: cannot suppress ICC**
  - **$\geq 67\,\%$ of filling factor with $B \geq 10^{-14}$G needed!**



Tjemsland, Meyer & FV 23

SYNCHROTRON EMISSION

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

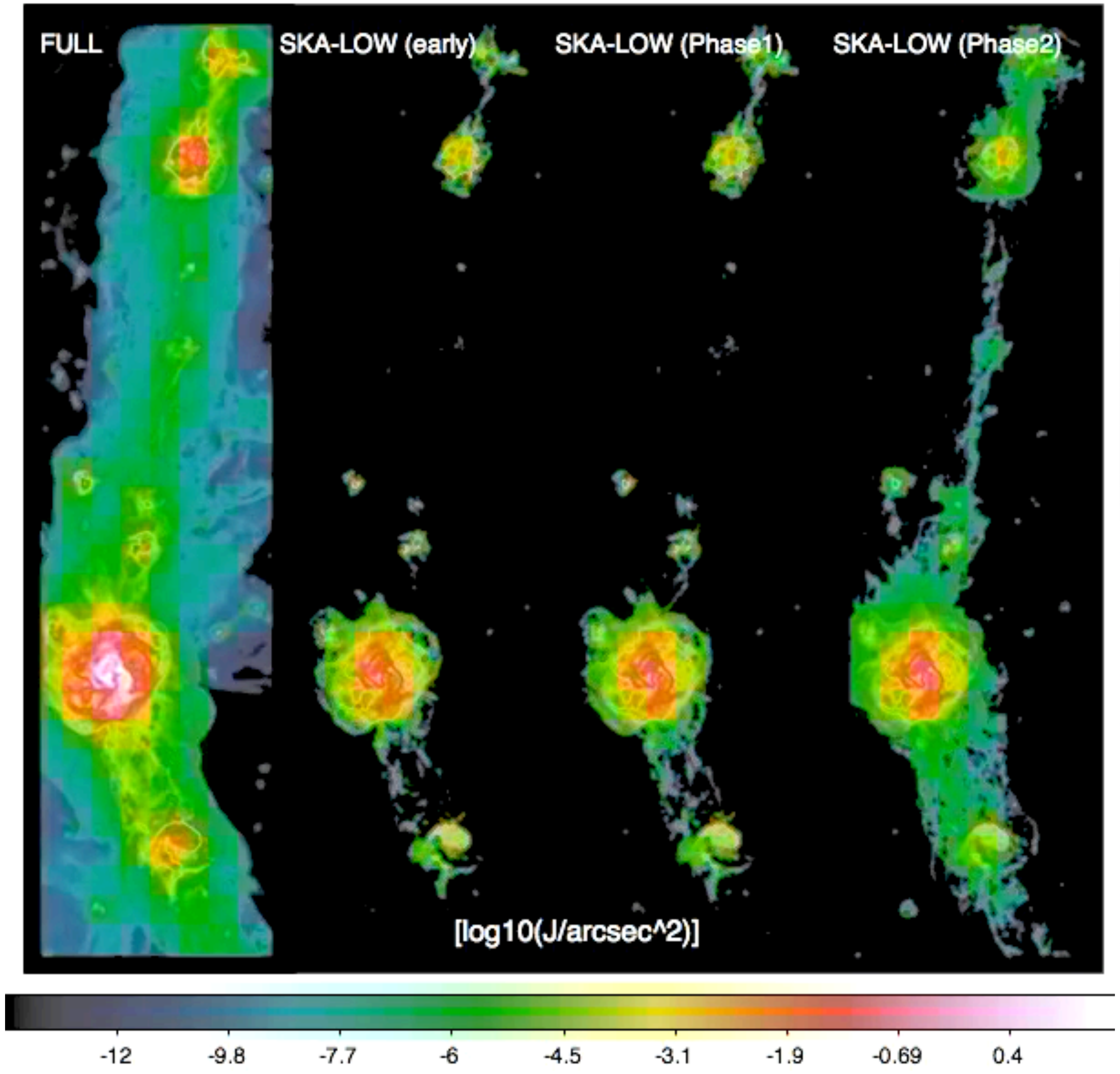
They must have been **shocked** at least once ($\mathcal{M} \geq 10$)

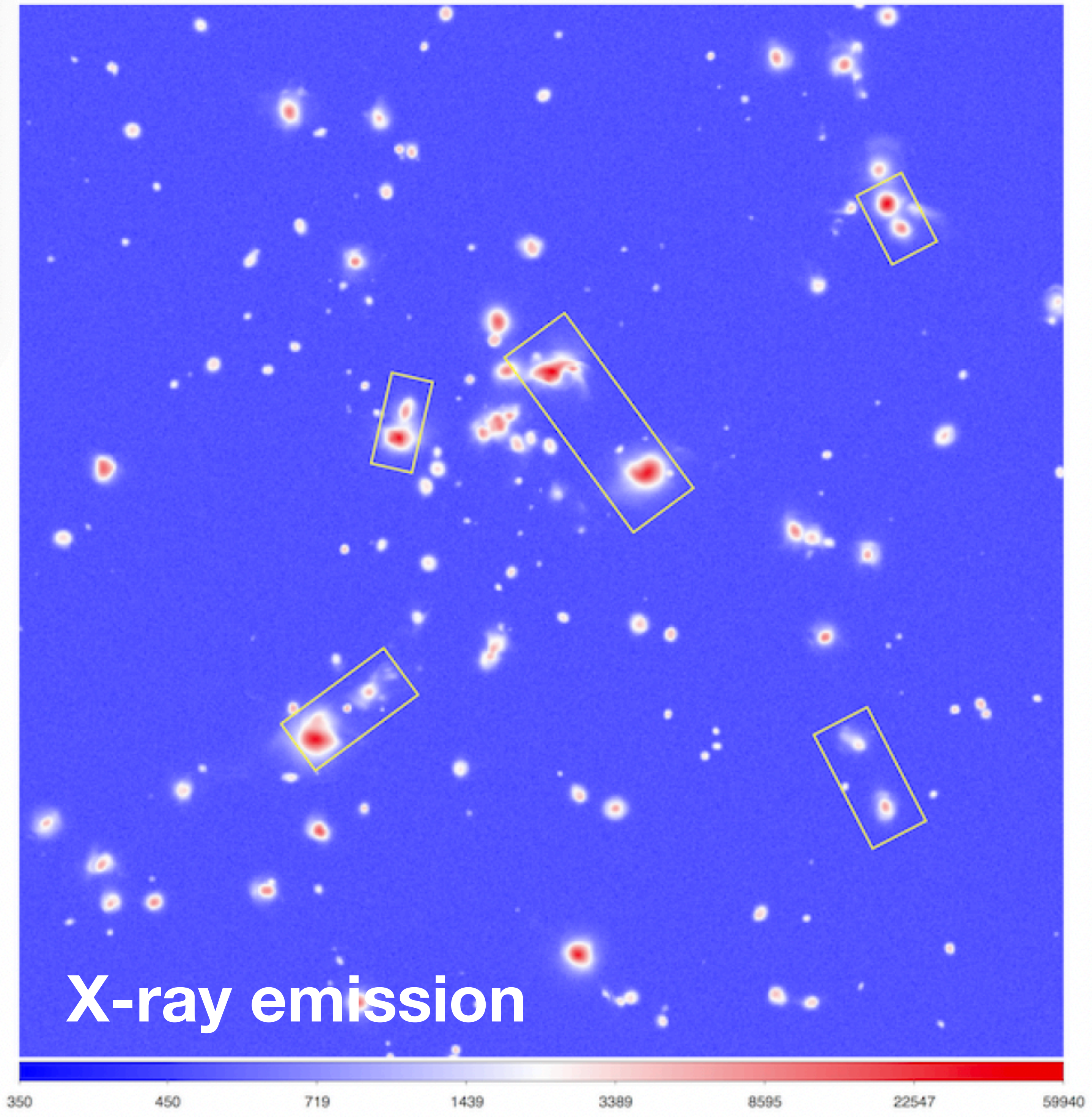
If **diffusive shock acceleration** works:

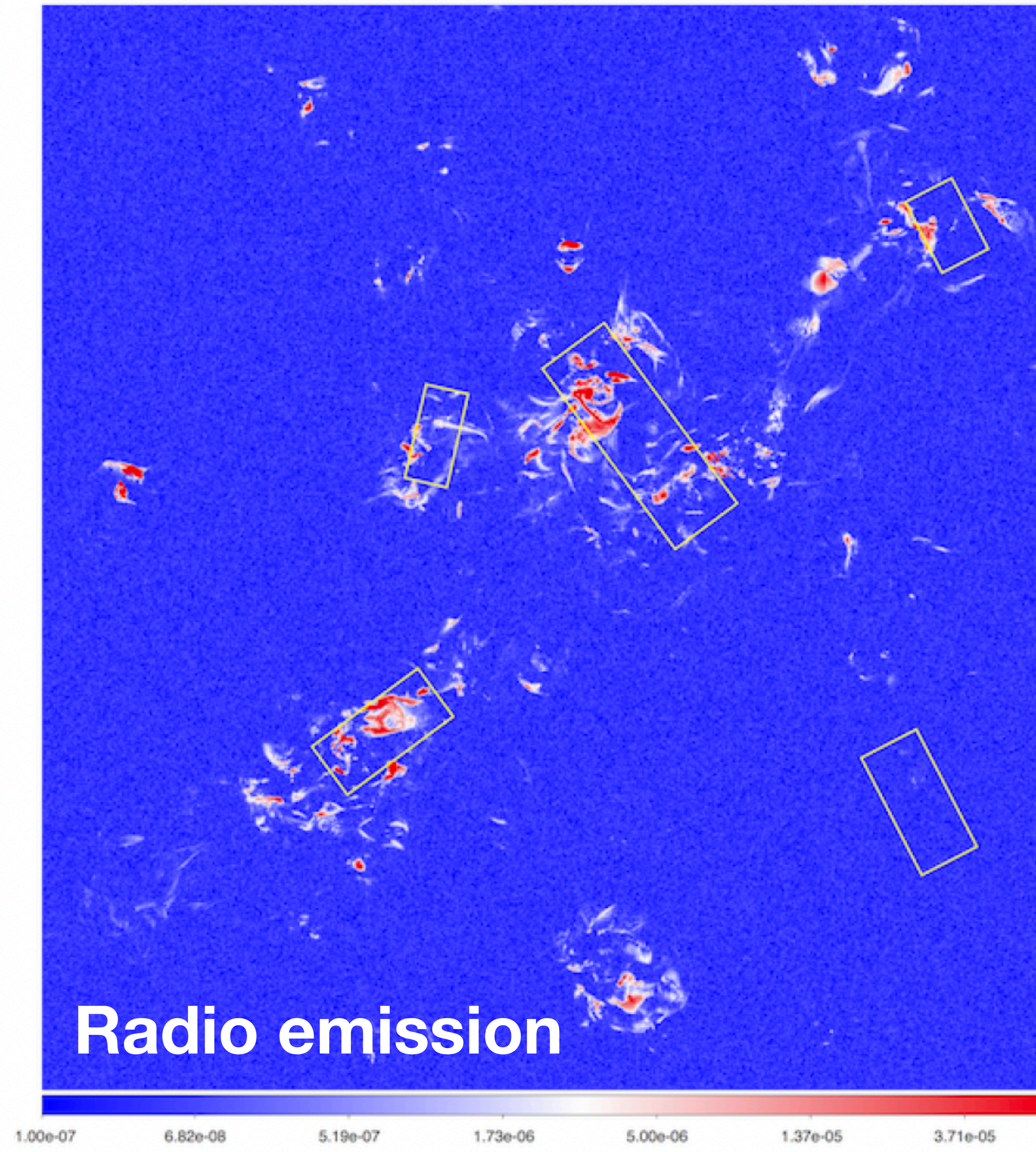
- $I(\nu) \propto \nu^{-\alpha}$ *spectrum*
- *highly polarised emission*
- $\mathcal{M} = \sqrt{\frac{1-\alpha}{-1-\alpha}}$
- $P_{sync} \propto \xi_e(\mathcal{M})B^2$
- $\xi_e(\mathcal{M})$ *electron. accel. efficiency* ($\sim 10^{-5} - 10^{-2}$ *?)*

SYNCHROTRON EMISSION

- DSA model calibrated to reproduce the known distributions of radio relics
- predictions for the average synchrotron emission by shocks in filaments: $P_{WHIM} \simeq \frac{5\,mJy}{deg^2} \nu_{100}^{-1} \frac{B_{\mu G}^2}{0.05^2} \frac{\xi_e}{10^{-3}}$
  - ξ_e = acceleration efficiency of electrons by DSA
  - $B_{\mu G}$ = average magnetic field in filaments
- only "the tip of the iceberg" of the radio cosmic web may be visible



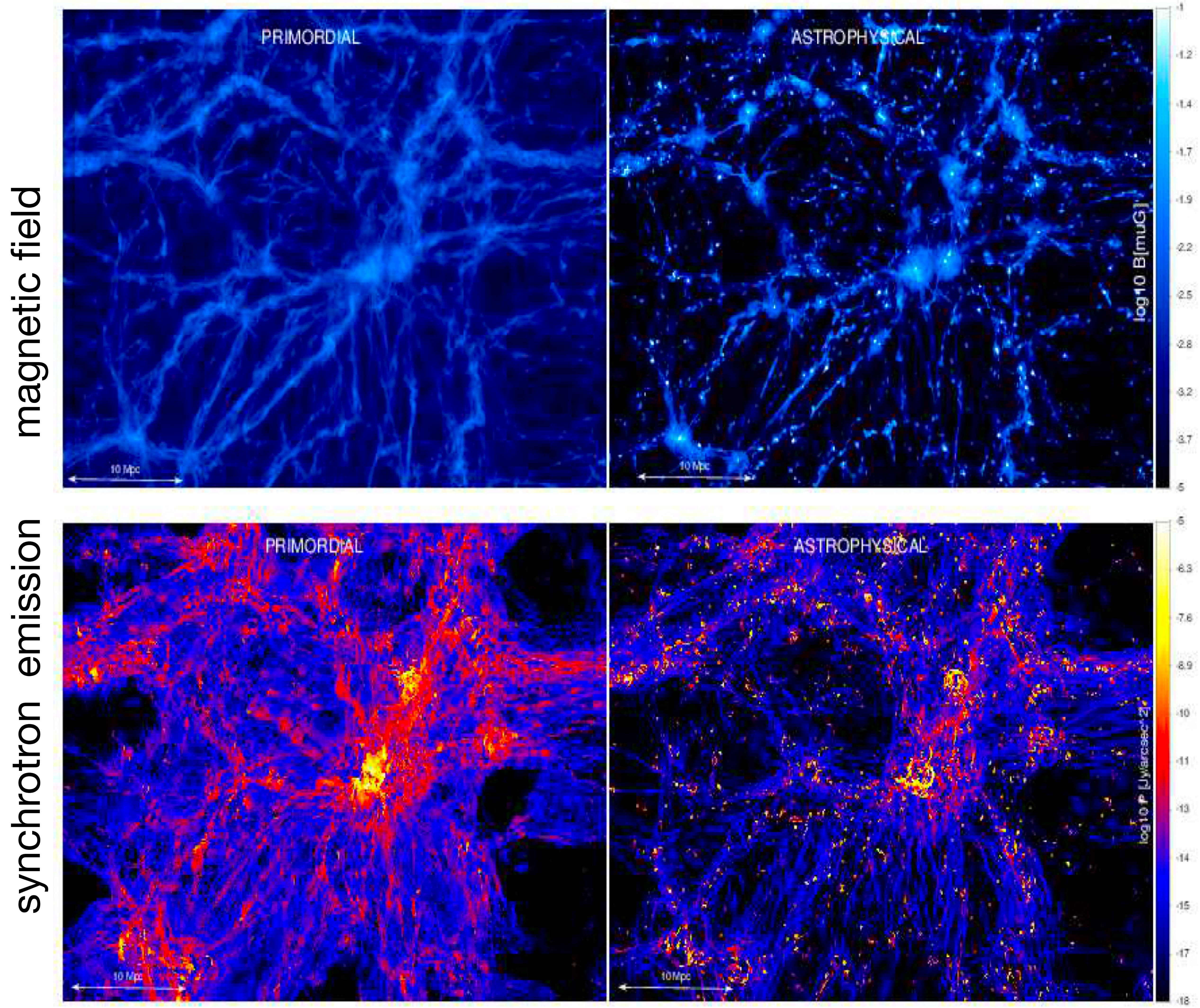




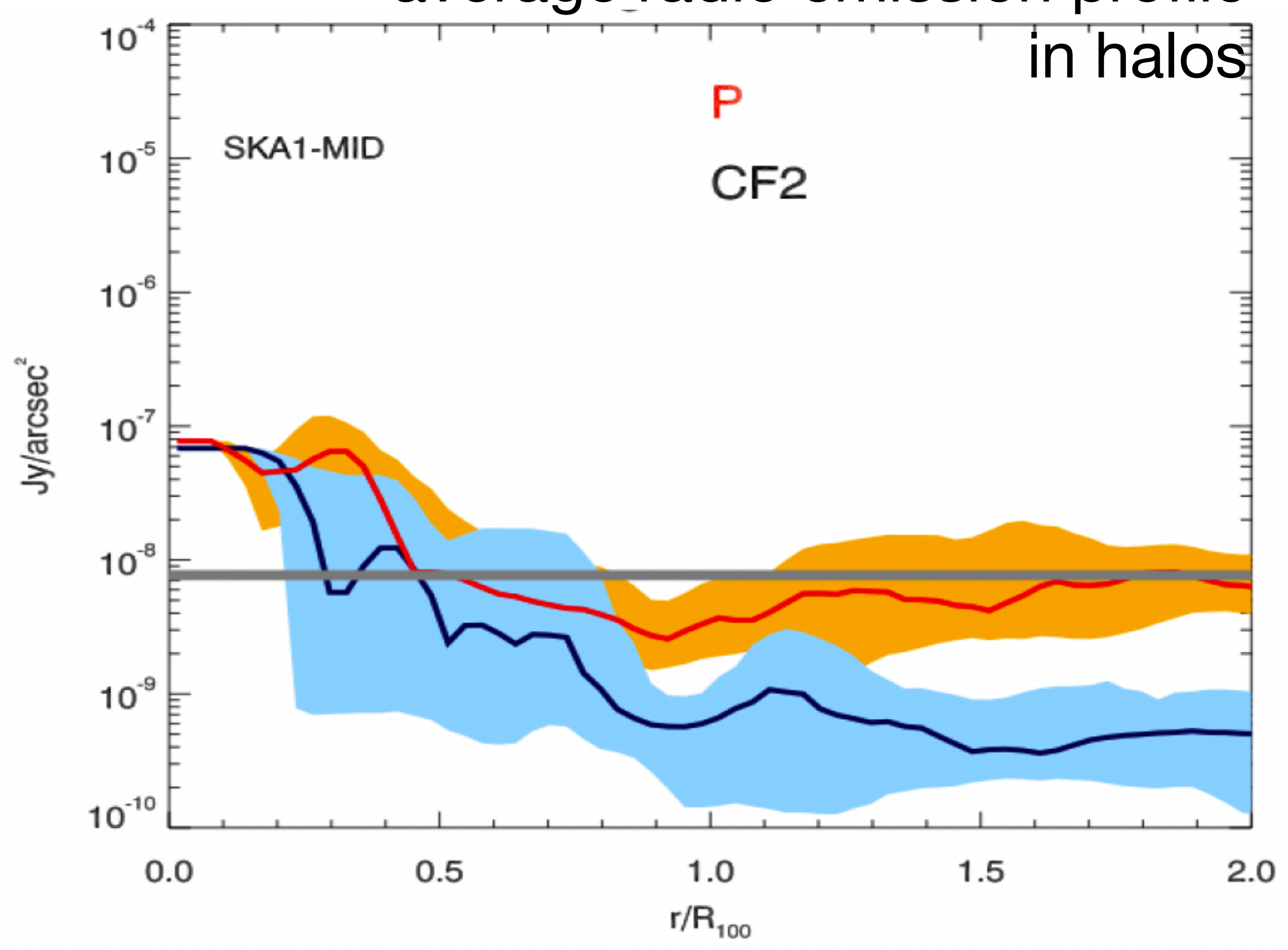
FV+14, 19

SYNCHROTRON EMISSION

- DSA model calibrated to reproduce the known distributions of radio relics
- predictions for the average synchrotron emission by shocks in filaments: $P_{WHIM} \simeq \frac{5\,mJy}{deg^2} \nu_{100}^{-1} \frac{B_{\mu G}^2}{0.05^2} \frac{\xi_e}{10^{-3}}$



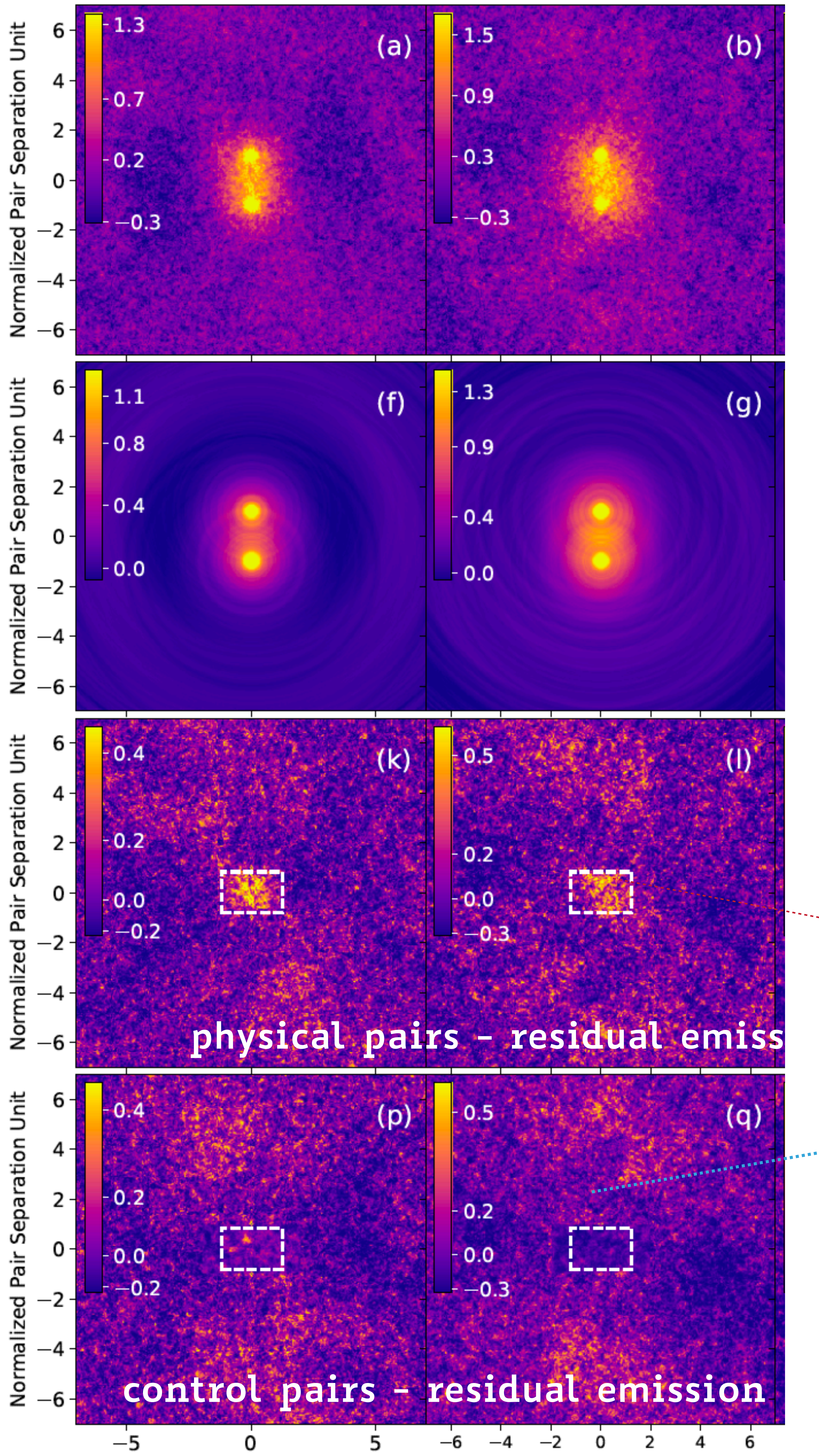
average radio emission profile in halos



- the expected radio emission outside of halos is ~ 10 times higher in primordial than in astrophysical models

FV+16, 17

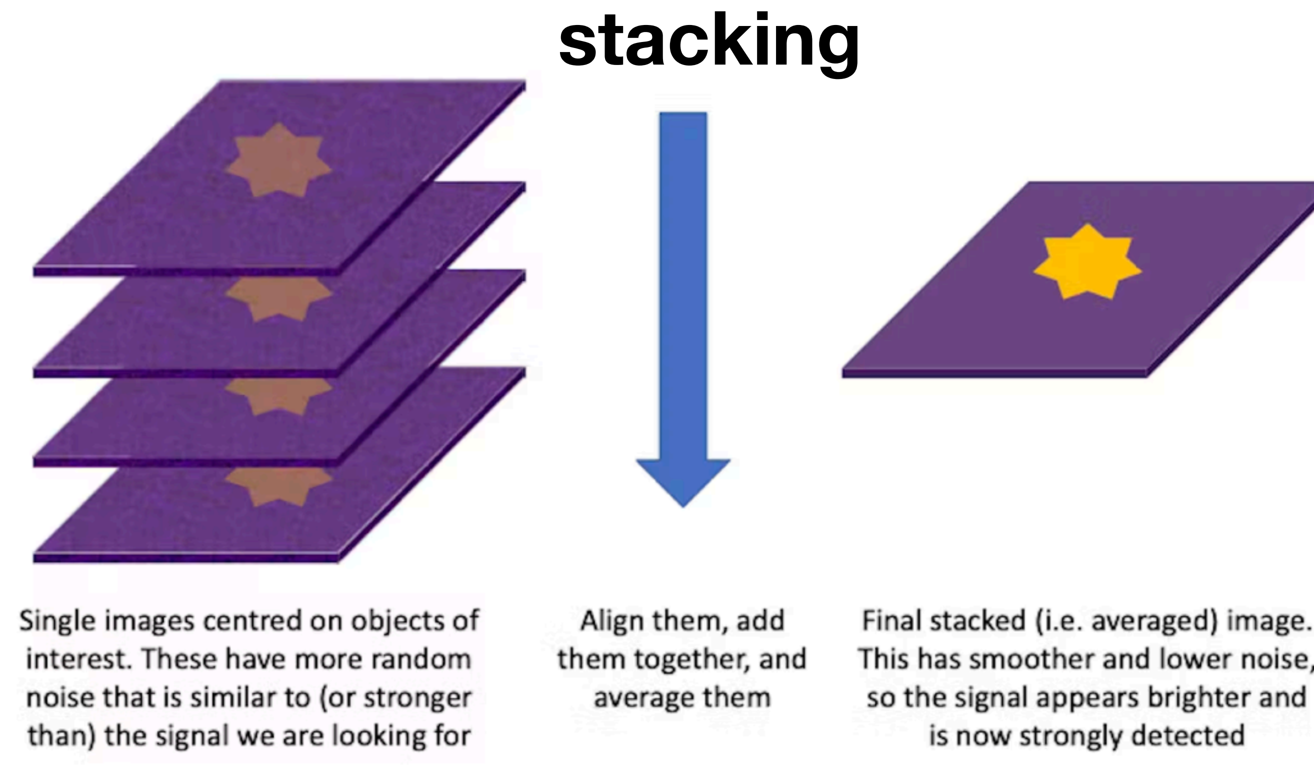
SYNCHROTRON EMISSION

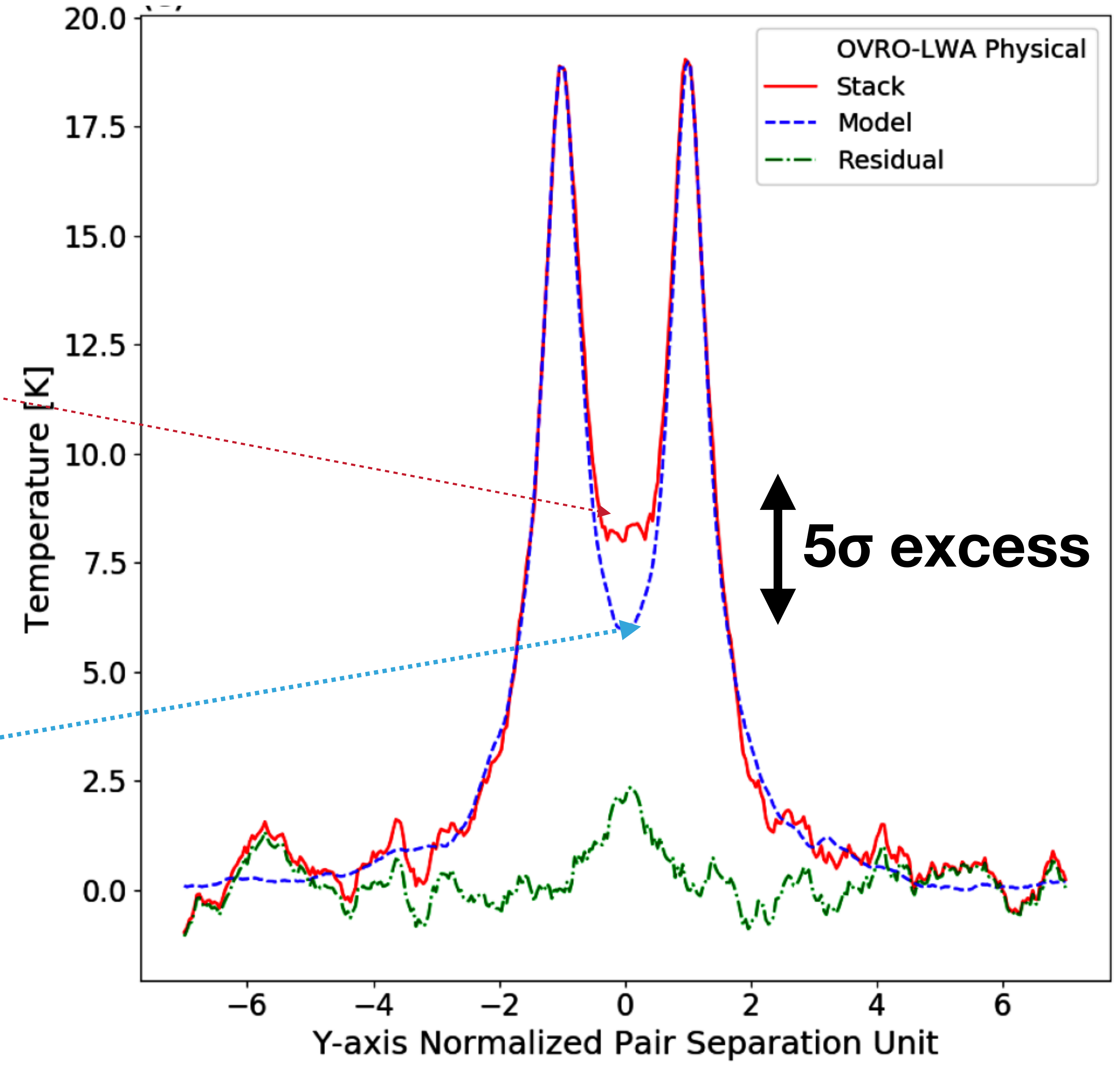


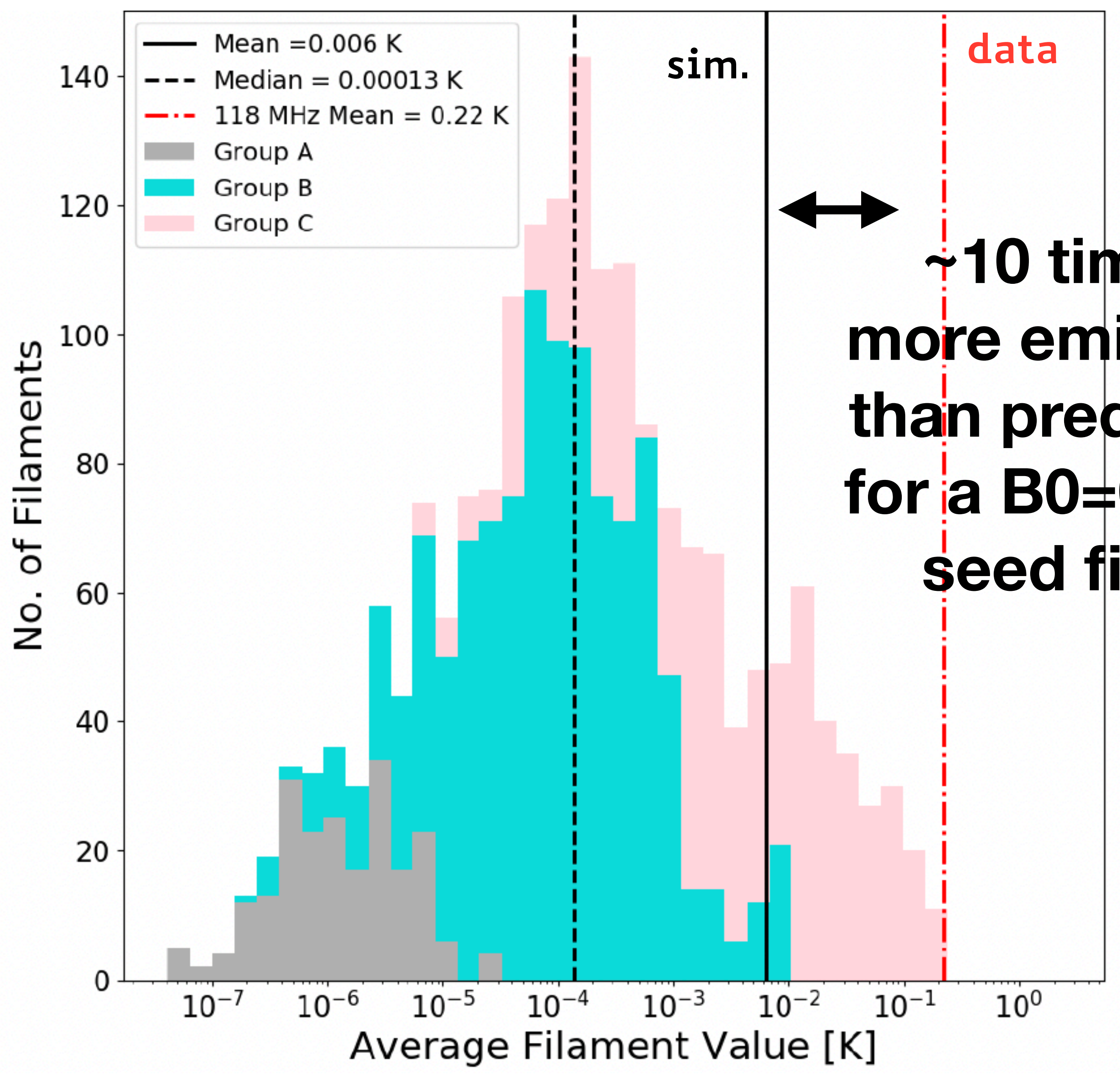
Vernstrom et al.2021: stacking of >200,000 pairs of halos in MWA survey

>5σ detection of the statistical excess of radio emission in physical pairs of halos, compared to the control sample of random pairs.

→flat spectrum, compatible with synchrotron from shocks around/in filaments, not explained by other sources (radio galaxies etc).







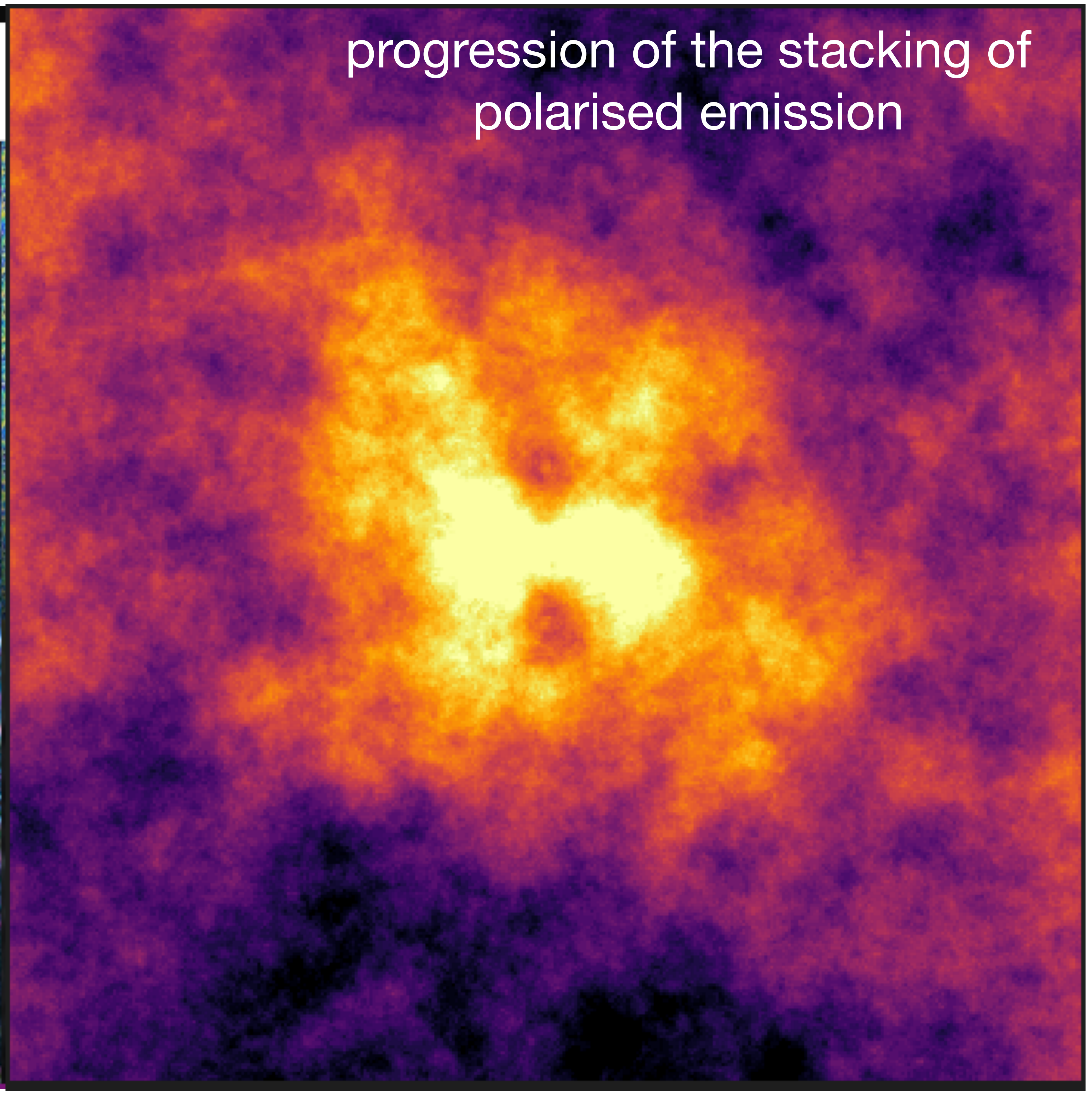
Vernstrom et al. 2021

SYNCHROTRON EMISSION

Vernstrom+23: stacking of 600,000 pairs of halos at higher frequency.

>3σ detection of the statistical excess of POLARISED (p~40-70%) radio emission in physical pairs of halos, compared to the control sample of random pairs.

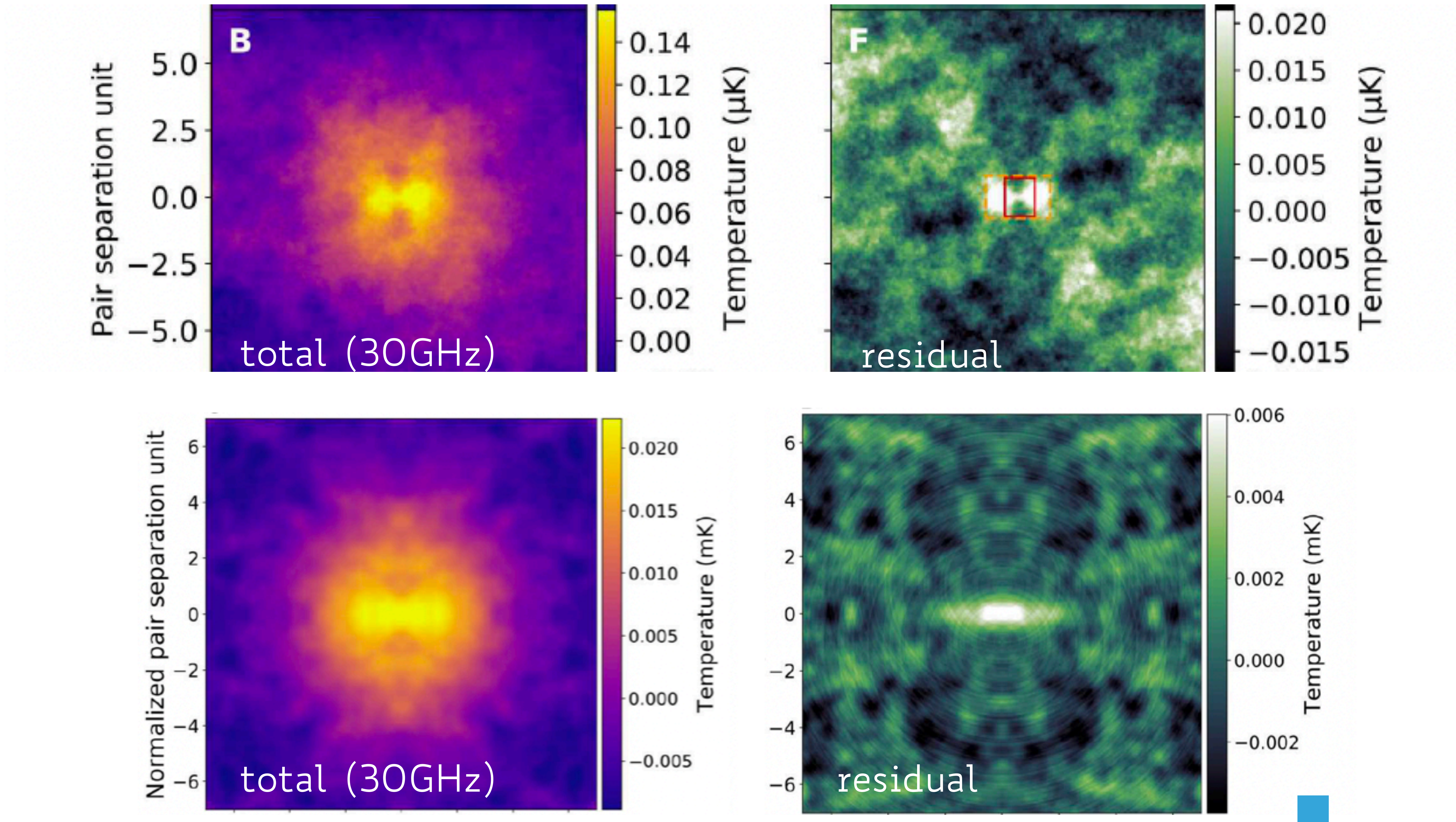
→this rules out any conceivable other source (radio galaxies, radio bridges, star forming galaxies…all would produce un-polarised signal)



Vernstrom et al. 2023

SYNCHROTRON EMISSION

- **REAL STACKING** of ~600,000 pairs of halos with 1-15Mpc separations



- **SIMULATED STACKING** of ~100 pairs of halos in the cosmological MHD run

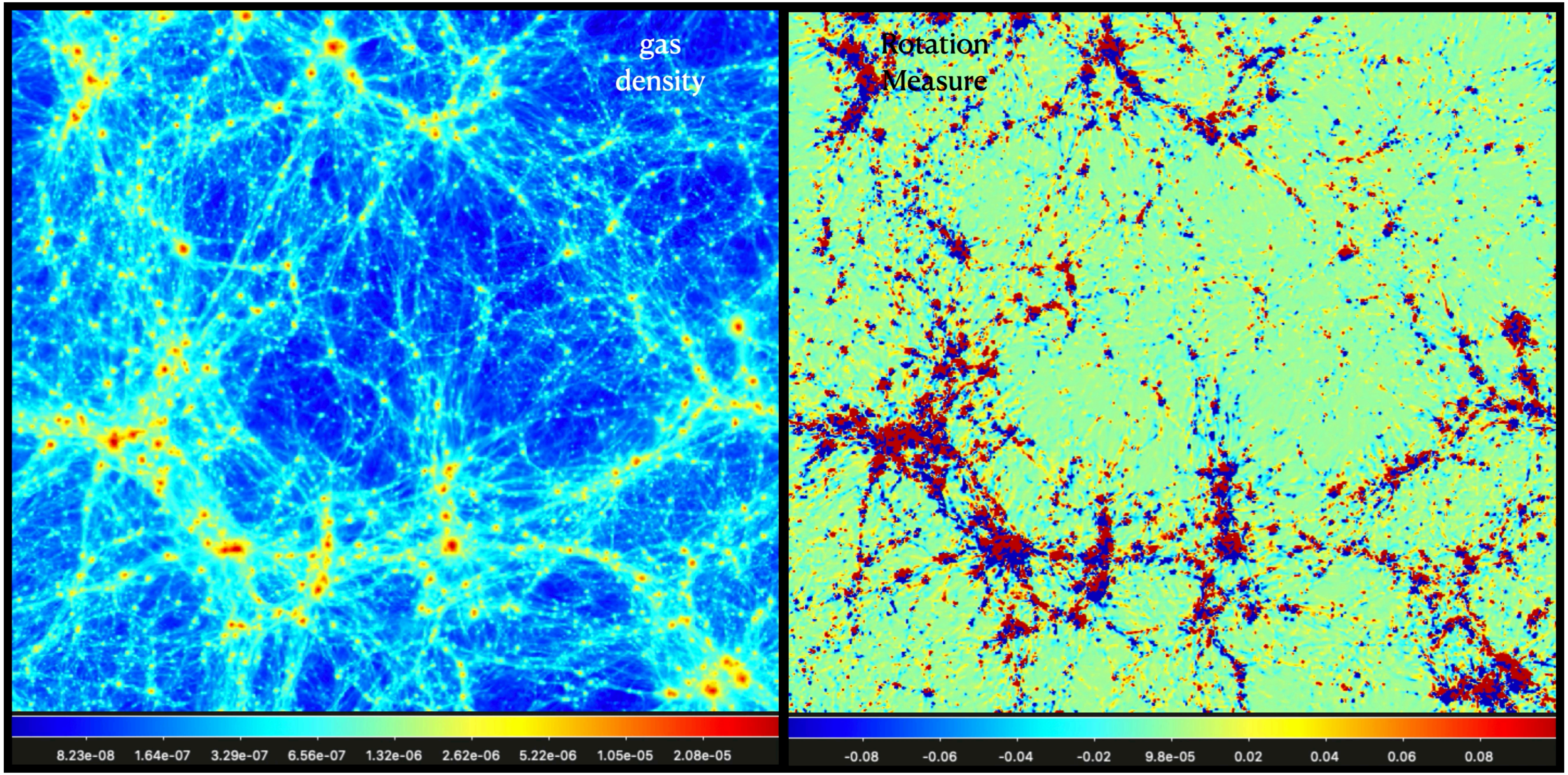
This strongly constrains the combination of accel. efficiency & seed B-fields: $\xi_e \times B_0^2$

For plausible accel.efficiency, only primordial models with $B_0 \sim 0.1 - 0.3$nG can do this

FARADAY ROTATION

Measuring RM in single simulated box is simple: it is just the integral of

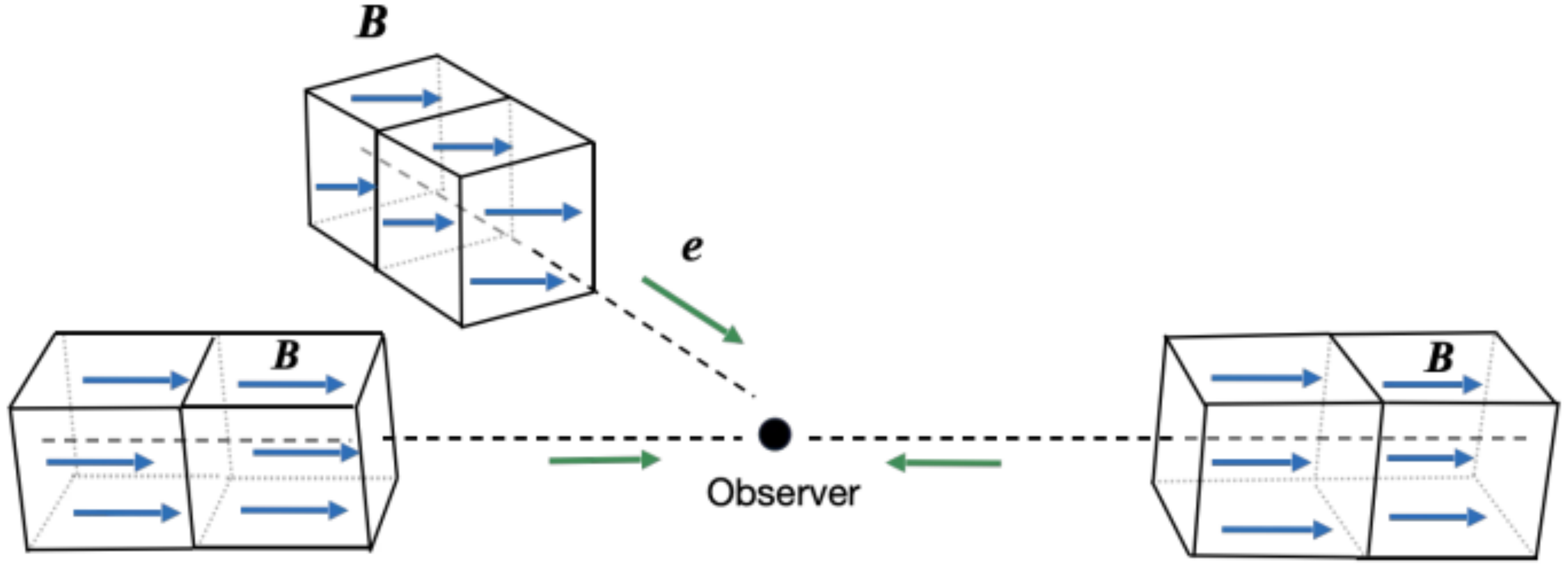
$$\mathrm{RM} \propto \int_{z2}^{z1} B_{||} n_e \frac{dl}{dz} dz$$



FARADAY ROTATION

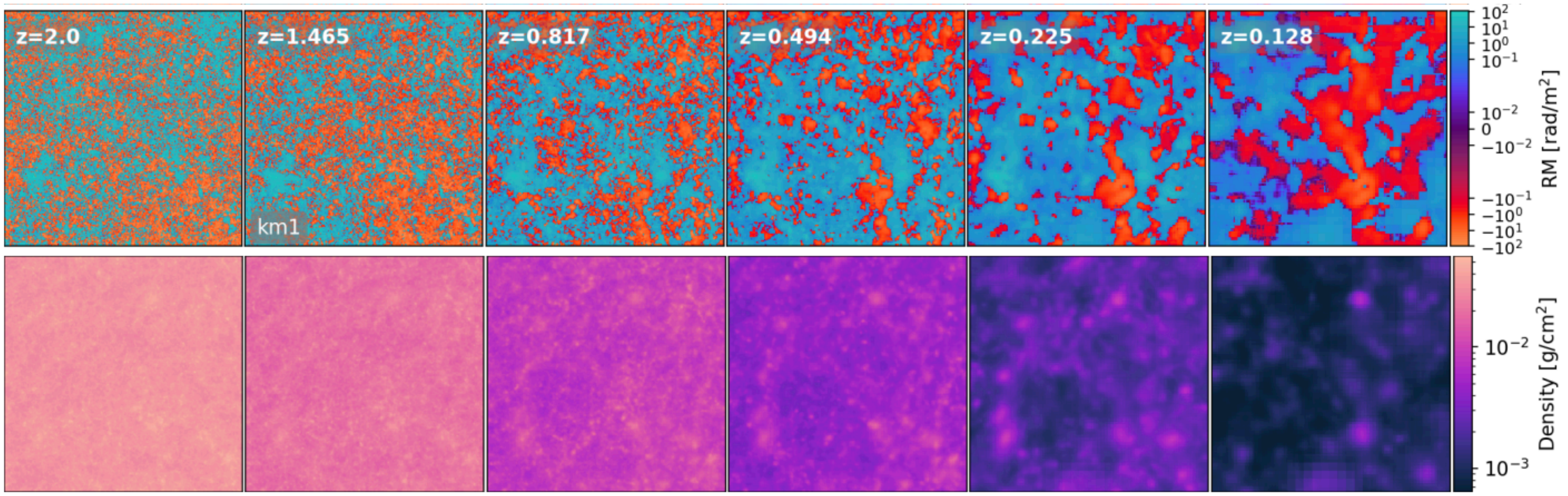
Measuring RM in single simulated volume is simple: just the integral of

$$\mathrm{RM} \propto \int_{z2}^{z1} B_{||} n_e \frac{dl}{dz} dz$$



Instead, dealing with very long ($\sim$ Gpc) lines of sight instead requires to generate "lightcones" and take into account a number of geometrical effects

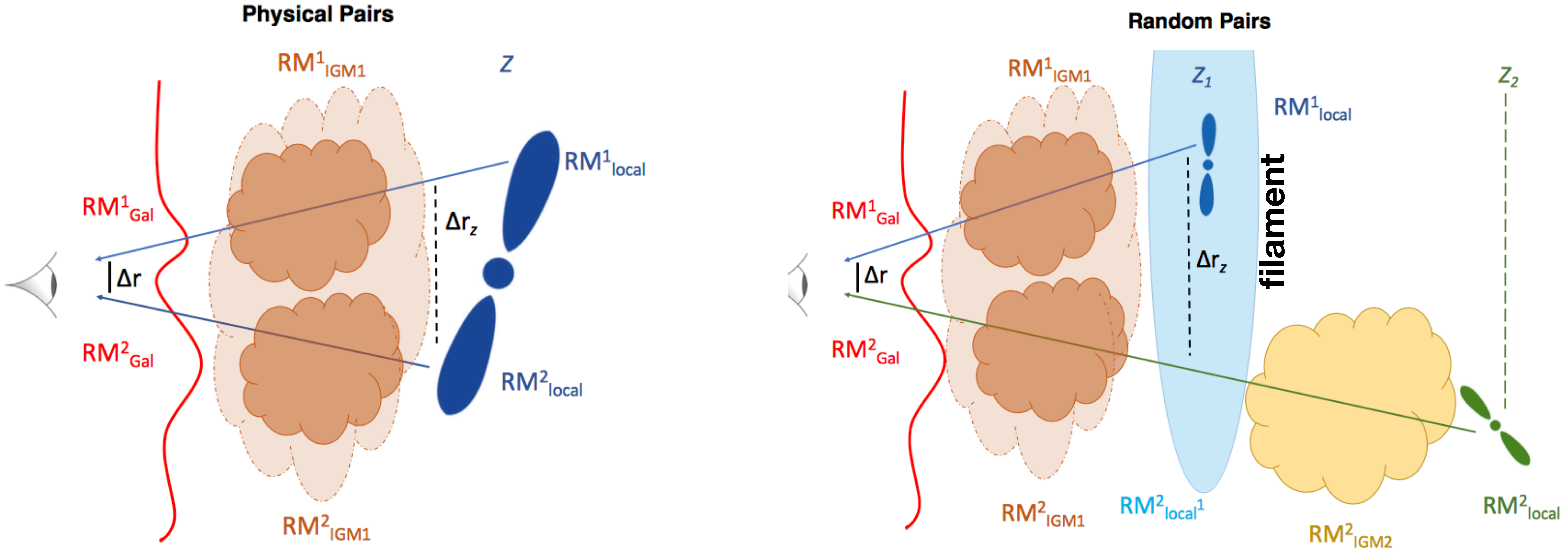
Mtchedlidze+24,25



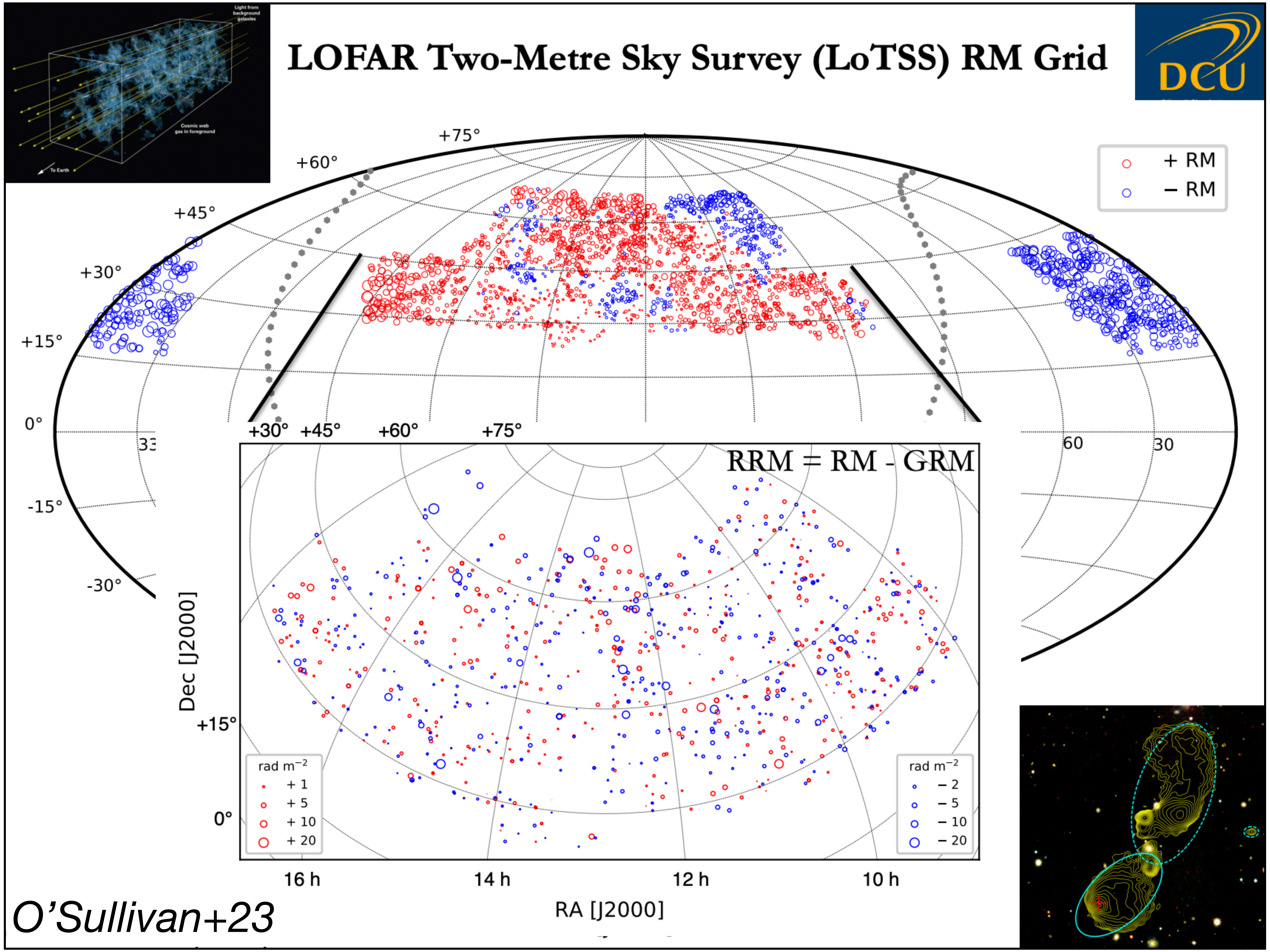
FARADAY ROTATION

- Vernstrom+19, idea: if we measure $\Delta RM = |RM_2 - RM_1|$ between a physical pair of radio lobes, and in a random pair (=not physically associated) pairs of lobes, will we see any difference?

- if so, ΔRM can be plausibly due to the **excess magnetic field in the cosmic web**



THE MAGNETIC COSMIC WEB WITH FARADAY ROTATION



O'Sullivan+23

LOTSS DR2 survey:

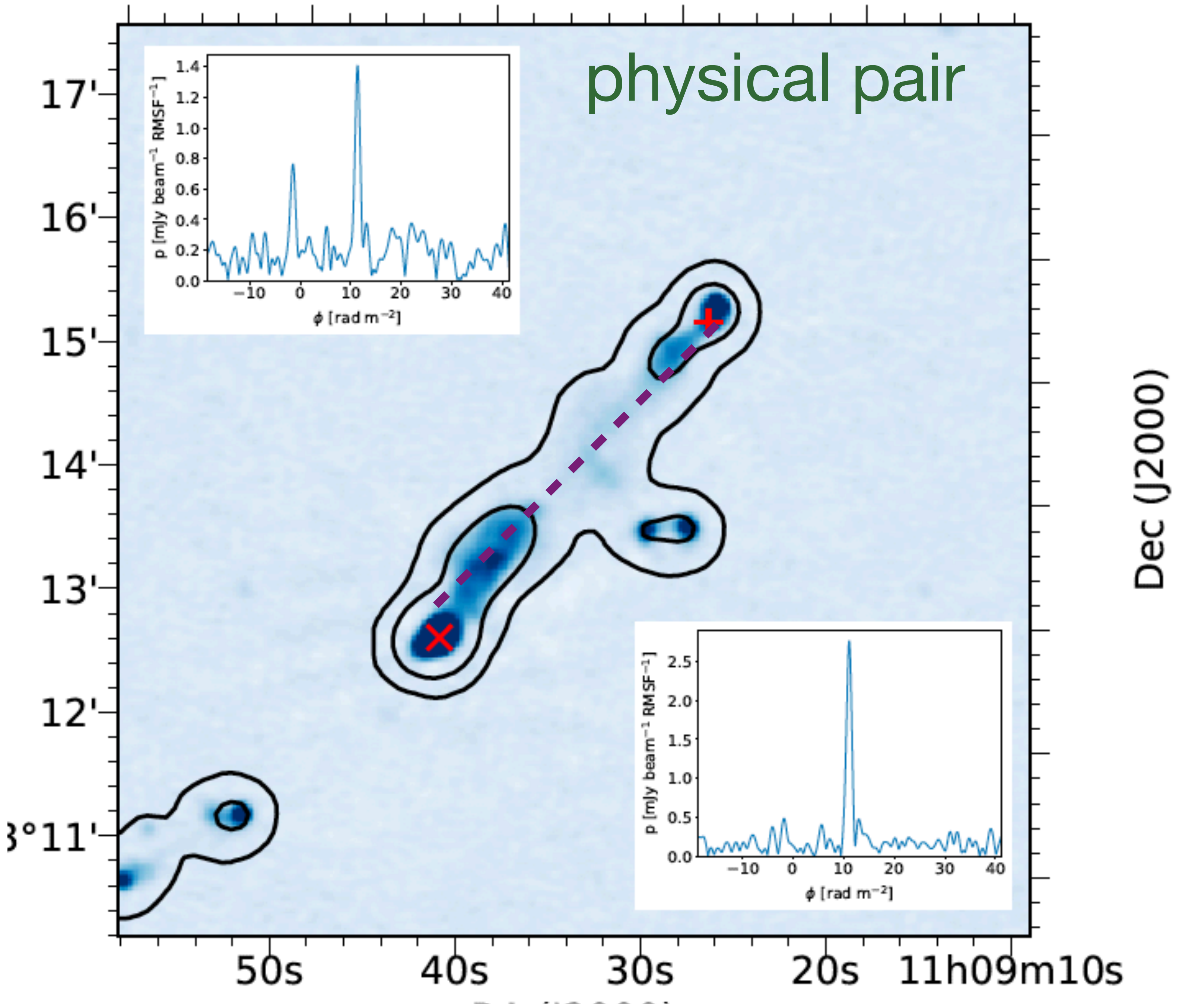
- ~4.4 million radio sources (Shimwell et al. 2022)

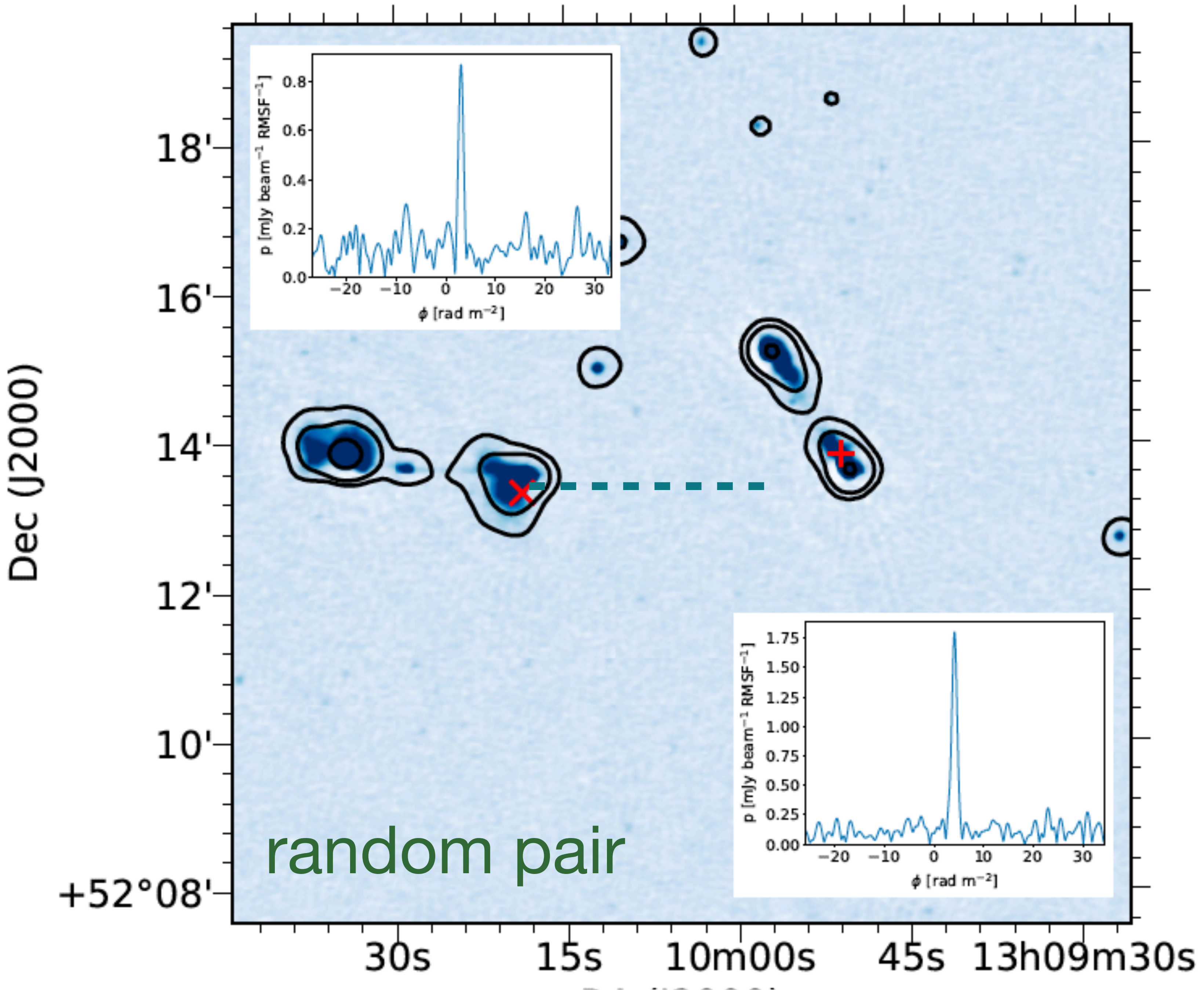
LOTSS RM Grid:

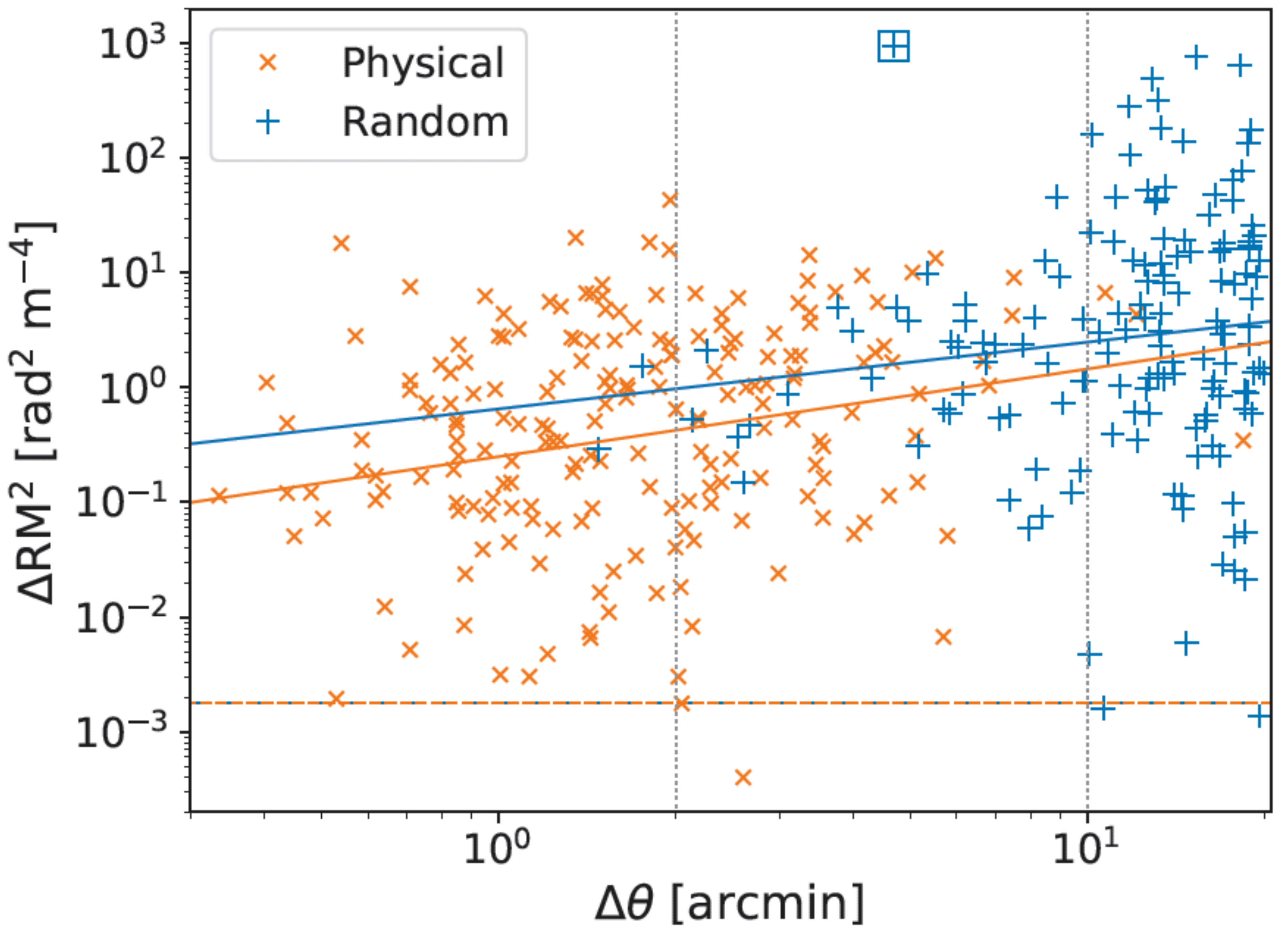
- ~2500 polarized (>8σ)
- Excellent RM precision: O(0.05 rad/m2)
- redshift for 79% of sources

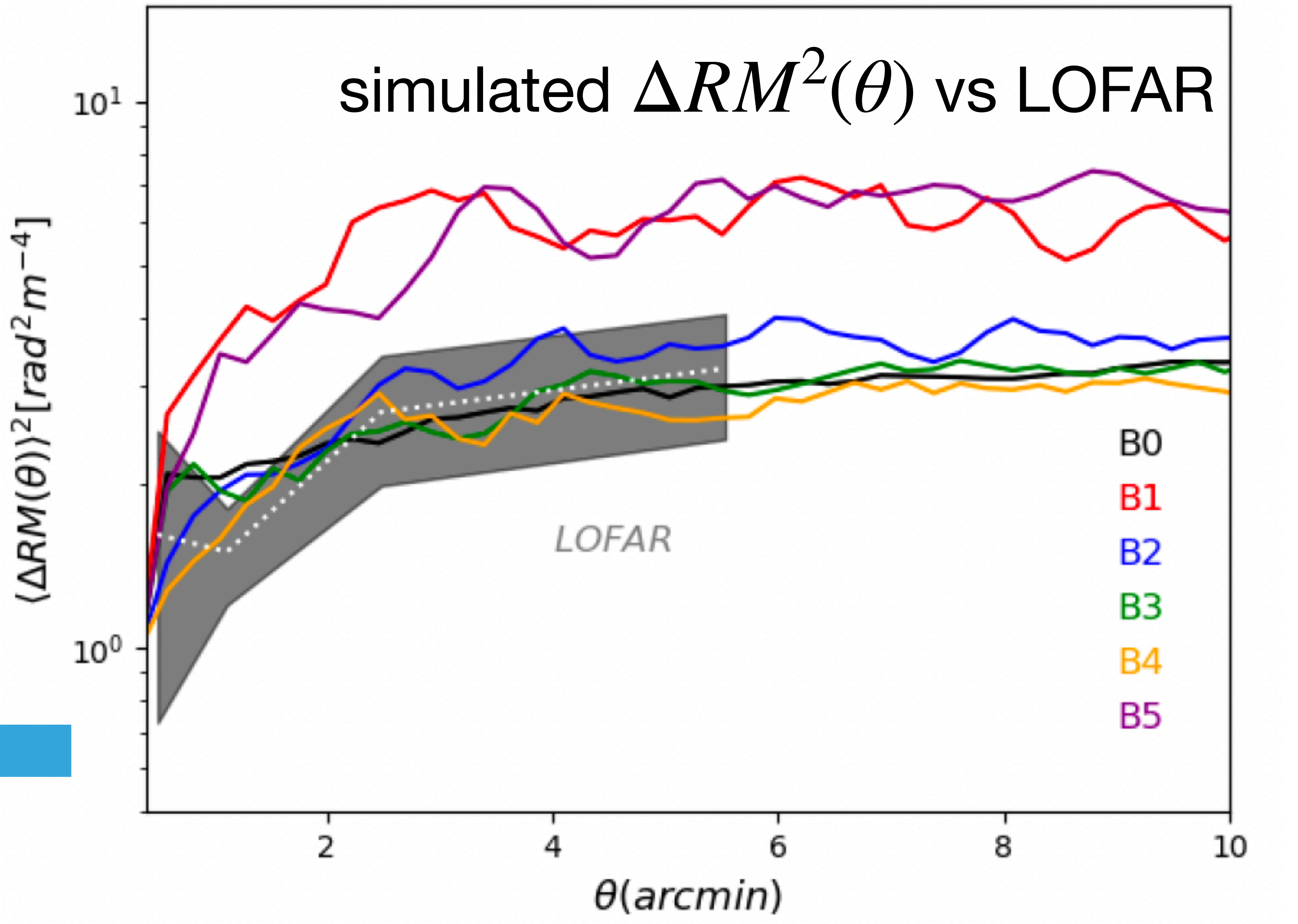
FARADAY ROTATION

- O'Sullivan+19, 21: statistical measure of the excess ΔRM in 310 random pairs using **LOFAR**





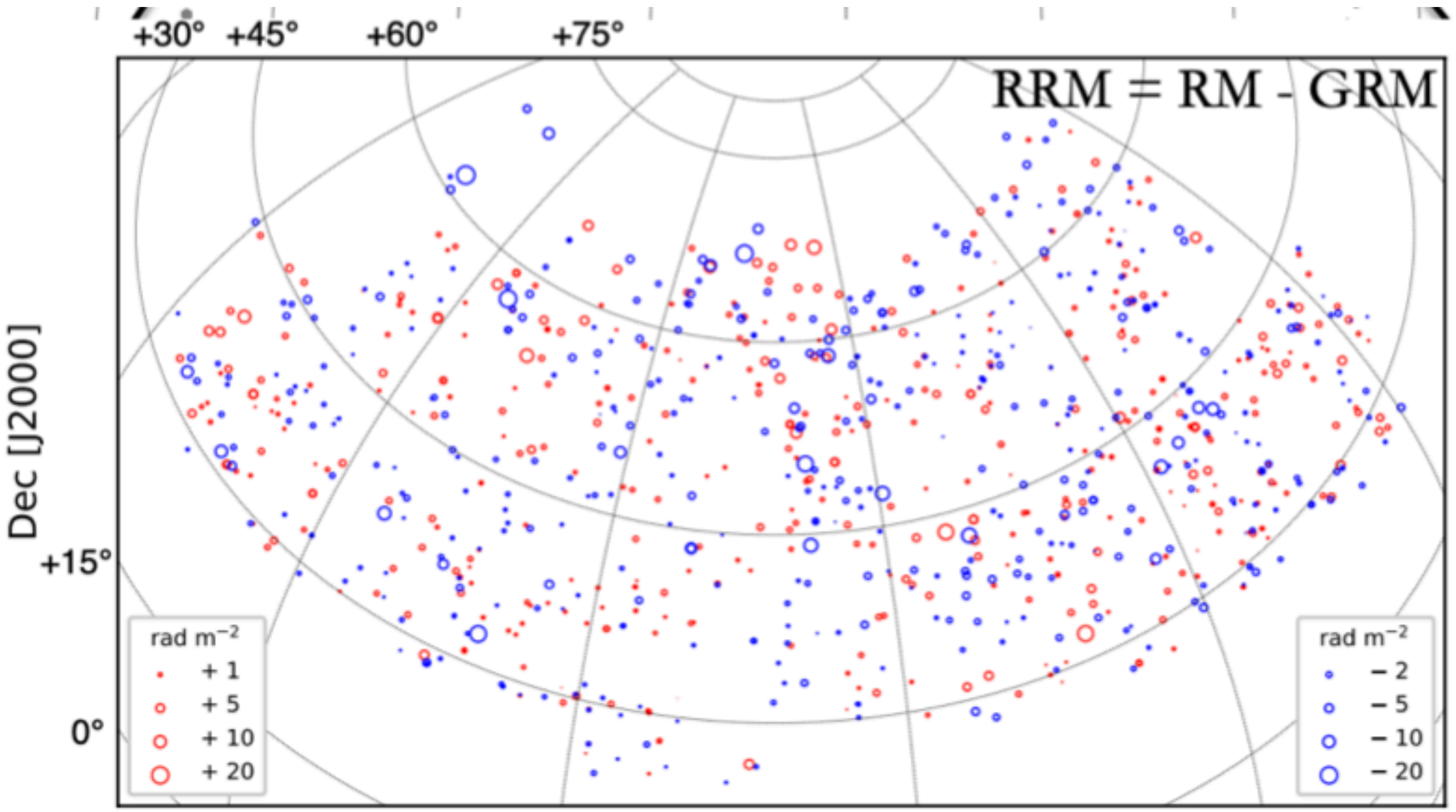


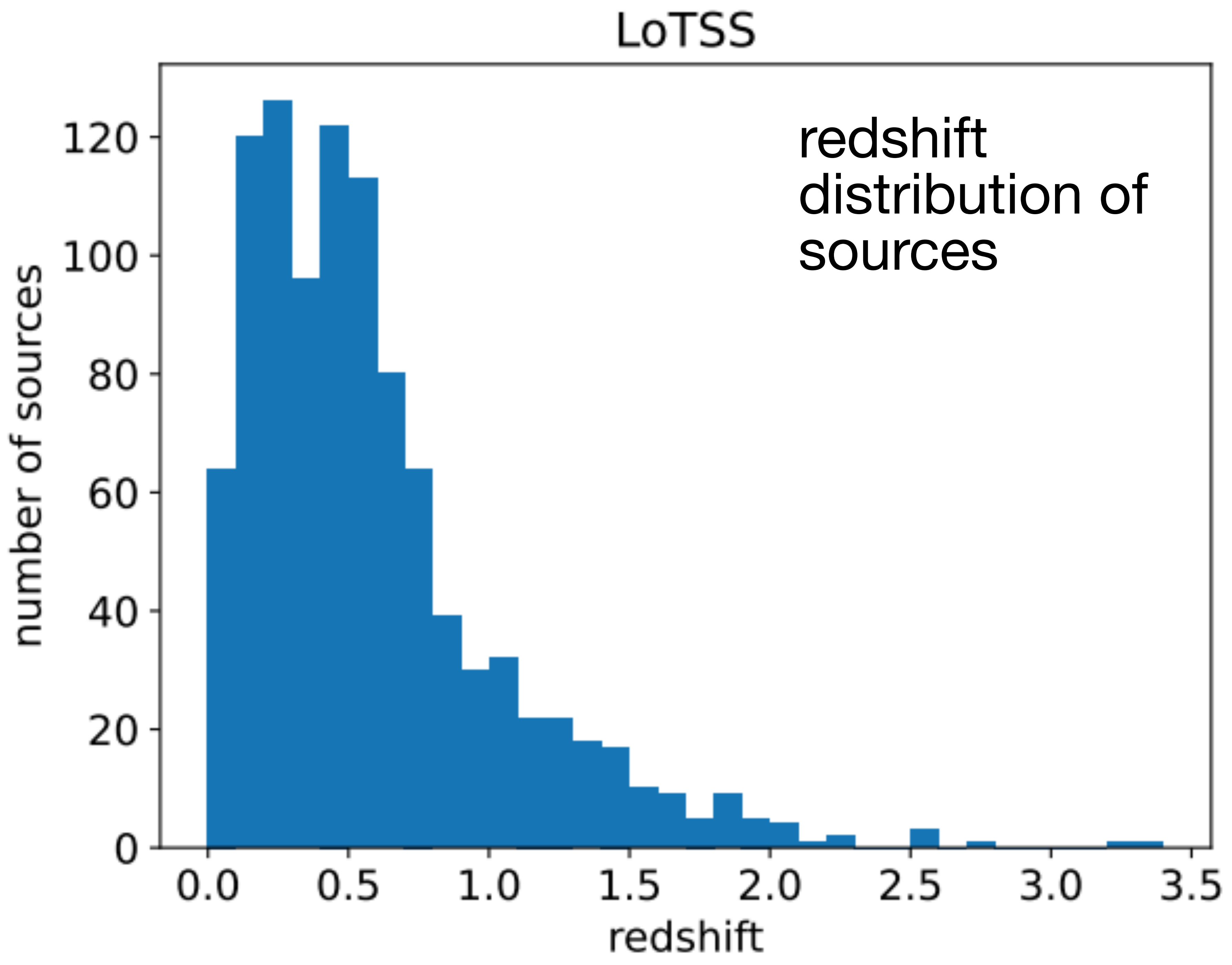


- Comparison with simulated primordial models: only fields with $2 \geq n_B \geq -1$ and $B_{Mpc} \sim 0.04 - 1.8\text{nG}$ appear to be compatible with data

FARADAY ROTATION

- **Carretti et al. 23, 24, 25:** Analysis of 1016 sources with known redshift $0 \leq z \leq 3$ in LOTSS DR2 , |b|>25°
- **Galactic foreground** (MAD filtering <0.5° radius, of Hutschenreuter+22 map): $RRM_f = RM - GRM$

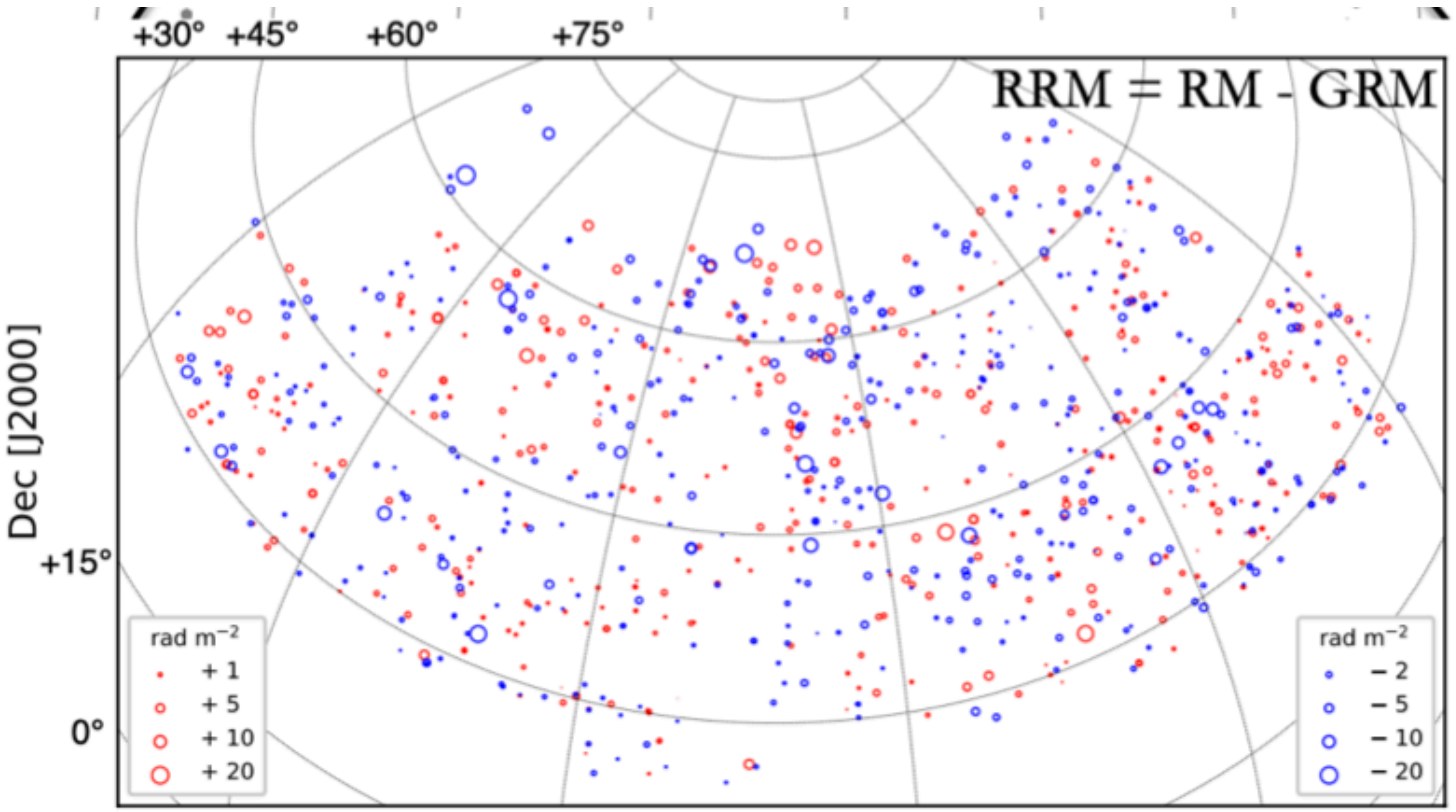




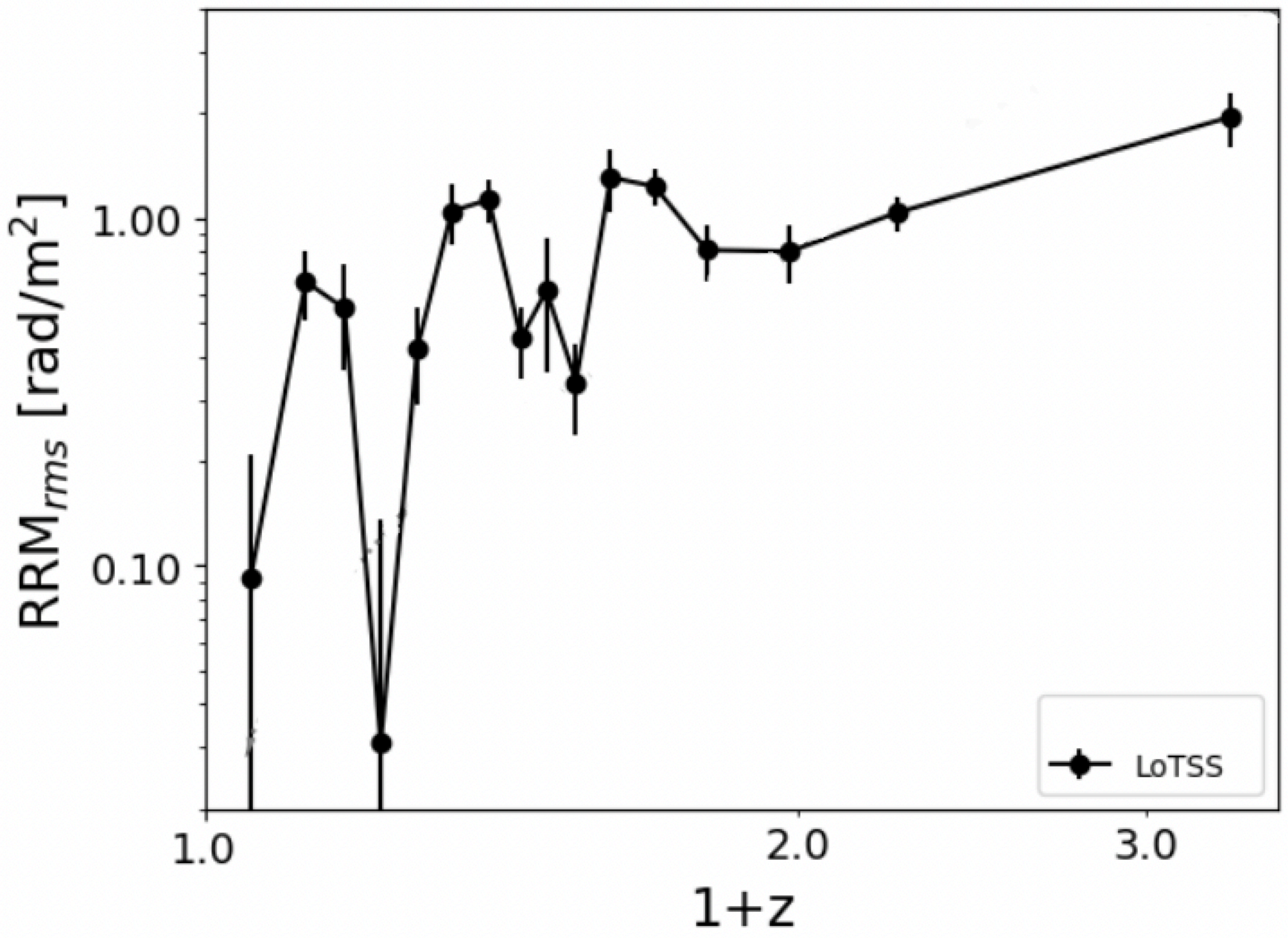
see Neronov's lecture on (15/01)

FARADAY ROTATION

- Carretti et al. 23, 24, 25: Analysis of **1016 sources with known redshift** $0 \leq z \leq 3$ 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 the RM (all $r \leq R_{100}$ region is excluded)**
- **"Residual" Rotation Measure**: $\langle RRM^2 \rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \langle RRM_f^2 \rangle^{1/2}$



Residual RM binned in redshift



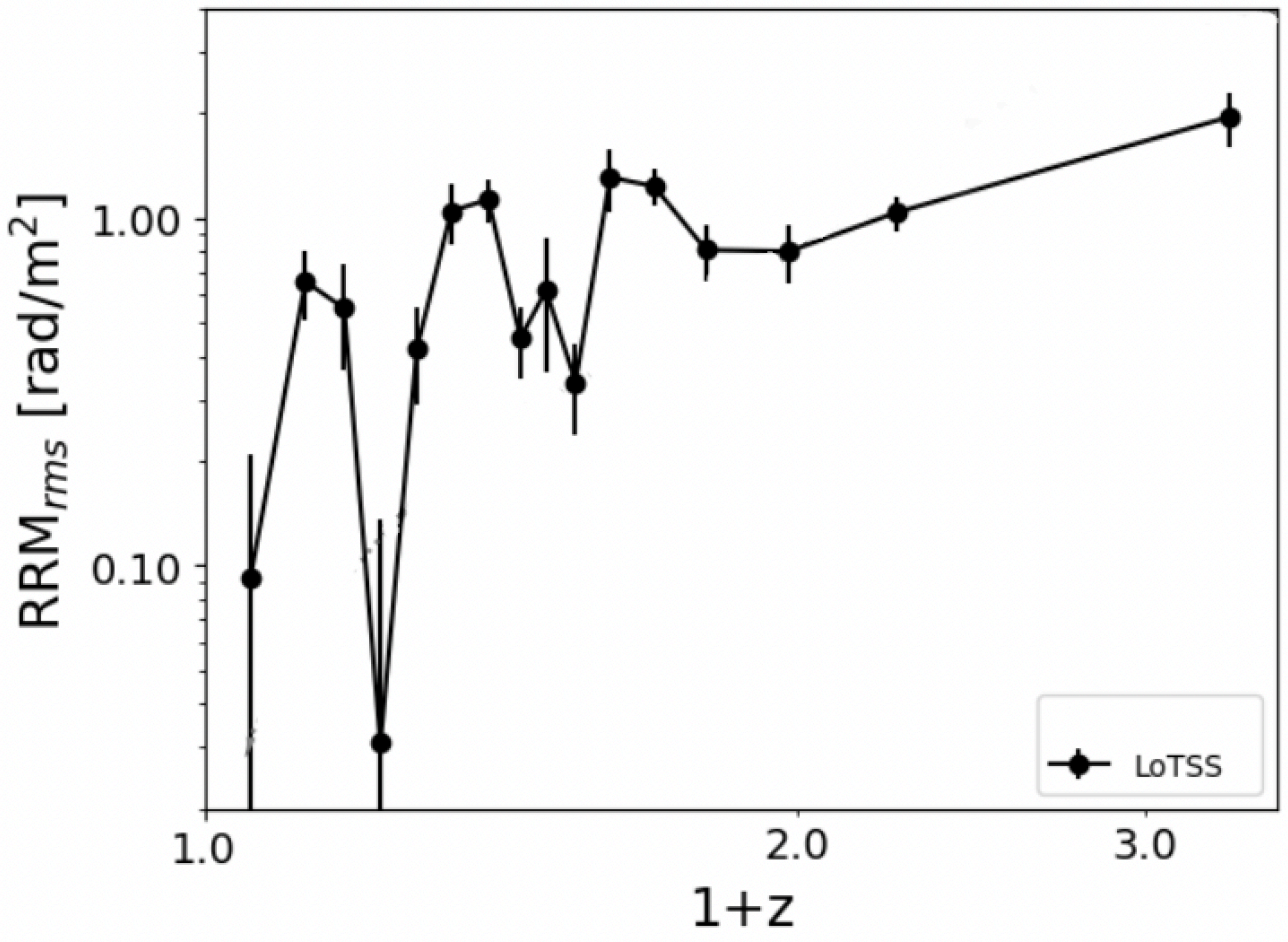
see Neronov's lecture on (15/01)

FARADAY ROTATION

- Carretti et al. 23, 24, 25: Analysis of **1016 sources with known redshift** $0 \leq z \leq 3$ 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 the RM (all $r \leq R_{100}$ region is excluded)**
- **"Residual" Rotation Measure**: $\left\langle RRM^2 \right\rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \left\langle RRM_f^2 \right\rangle^{1/2}$

- present data are still noisy (although wiggles seem to correlate with real density of galaxies)
- increasing trend with redshift until $z \sim 2$ it cannot be contamination by the Galaxy (why should it scale with z?)

Residual RM binned in redshift



FARADAY ROTATION

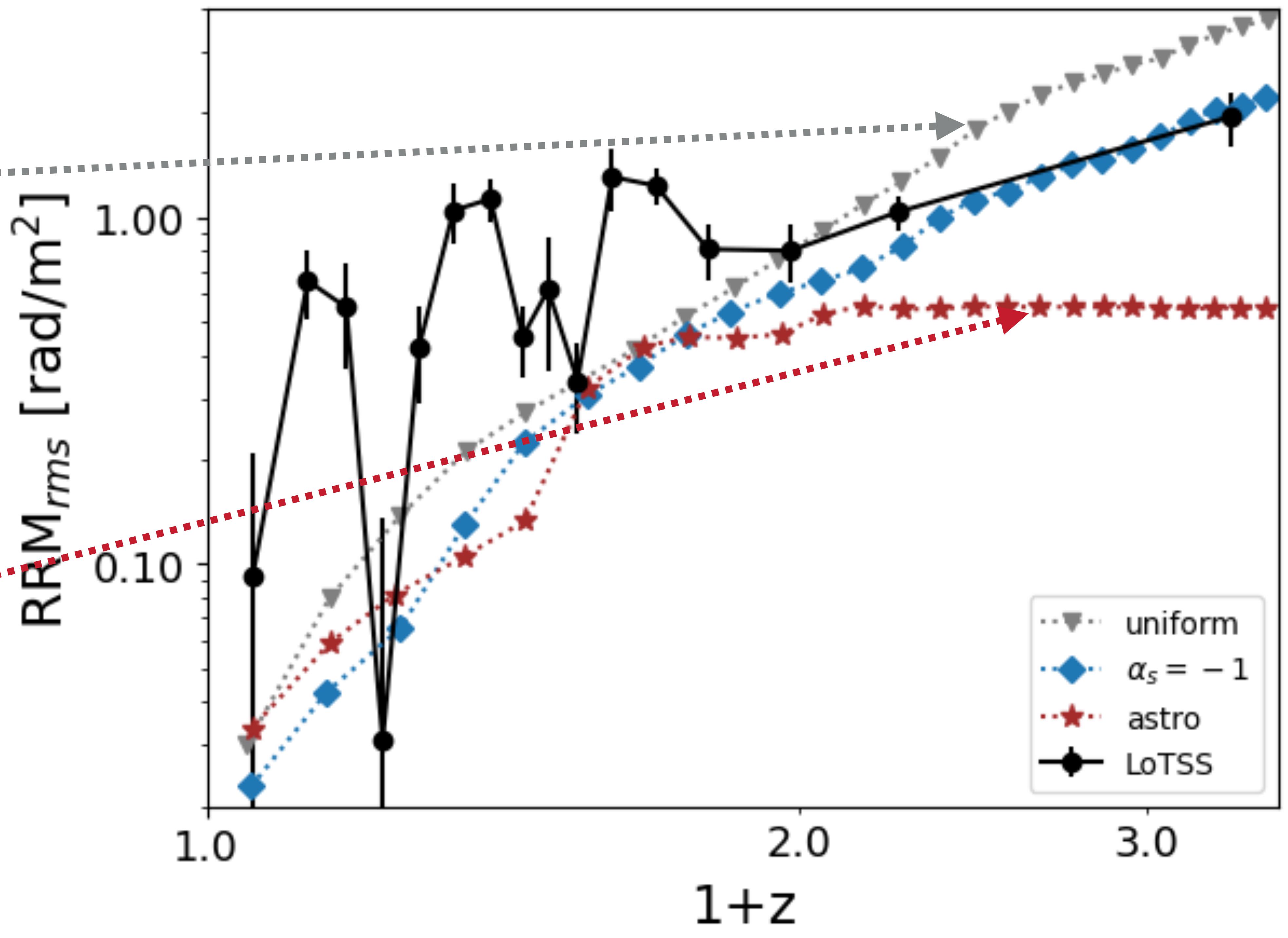
- Carretti et al. 23, 24, 25: Analysis of **1016 sources with known redshift** $0 \leq z \leq 3$ in LOTSS DR2 , |b|>25°
- **Galactic foreground** (MAD filtering <0.5° radius, of Hutschenreuter+22 map): $RRM_f = RM - GRM$
- Removal of LOS with **known halos contaminating the RM (all $r \leq R_{100}$ region is excluded)**
- **"Residual" Rotation Measure**: $$\langle RRM^2 \rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \langle RRM_f^2 \rangle^{1/2}$$

Comparison with simulated RRMs:

Uniform B model (B0=0.1nG) : too steep rise

"best" purely **astrophysical** model: underestimates RRM at most z

Residual RM binned in redshift



FARADAY ROTATION

- Carretti et al. 23, 24, 25: Analysis of **1016 sources with known redshift** $0 \leq z \leq 3$ 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 the RM (all $r \leq R_{100}$ region is excluded)**
- **"Residual" Rotation Measure**: $$\langle RRM^2 \rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \langle RRM_f^2 \rangle^{1/2}$$

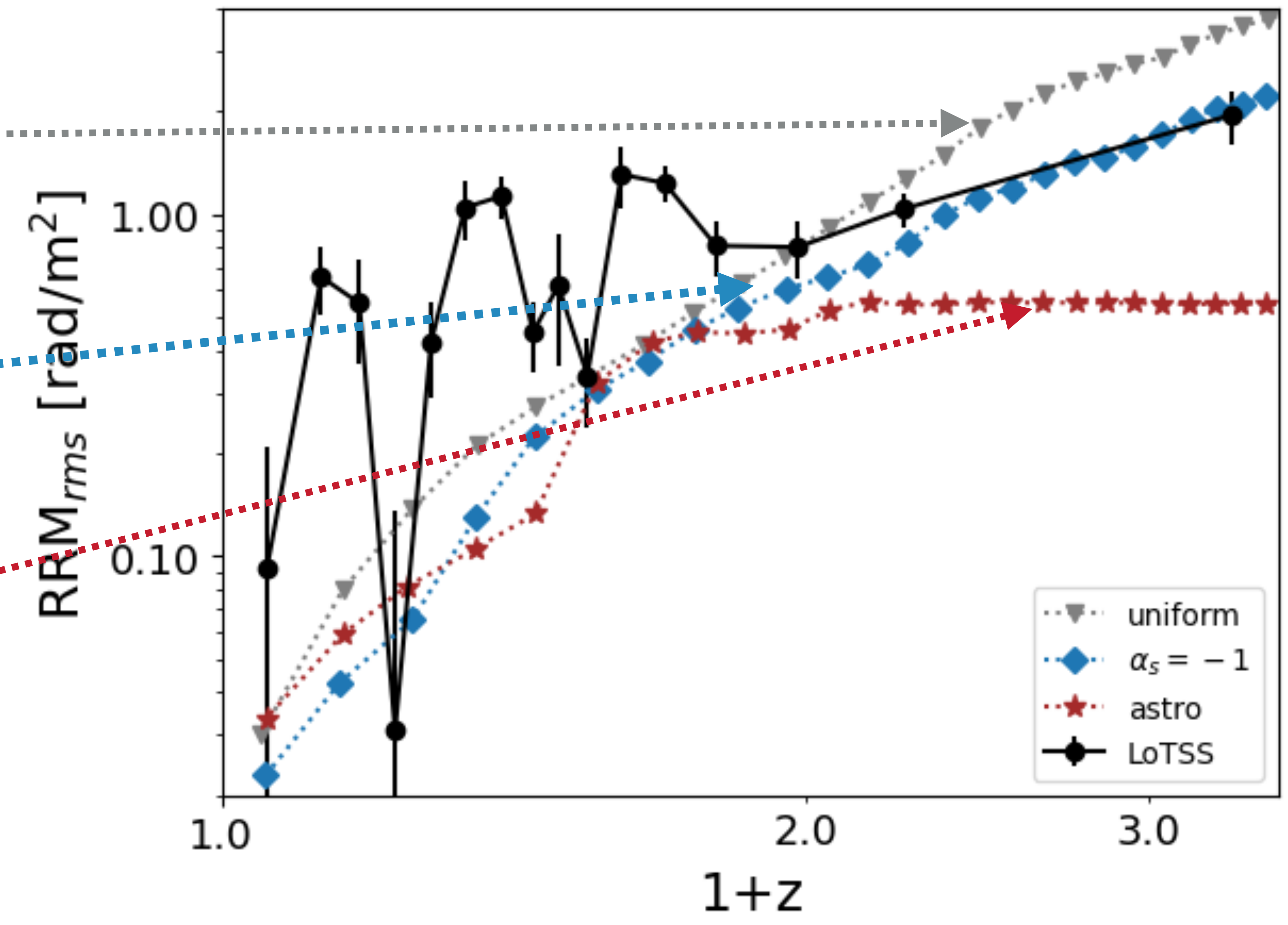
Comparison with simulated RRMs:

Uniform B model (B0=0.1nG) : too steep rise

Primordial model with $n_B = -1$ and $B_{Mpc} = 0.4nG$: better match (but not for z<1)

"best" purely **astrophysical** model: underestimates RRM at most z

Residual RM binned in redshift



FARADAY ROTATION

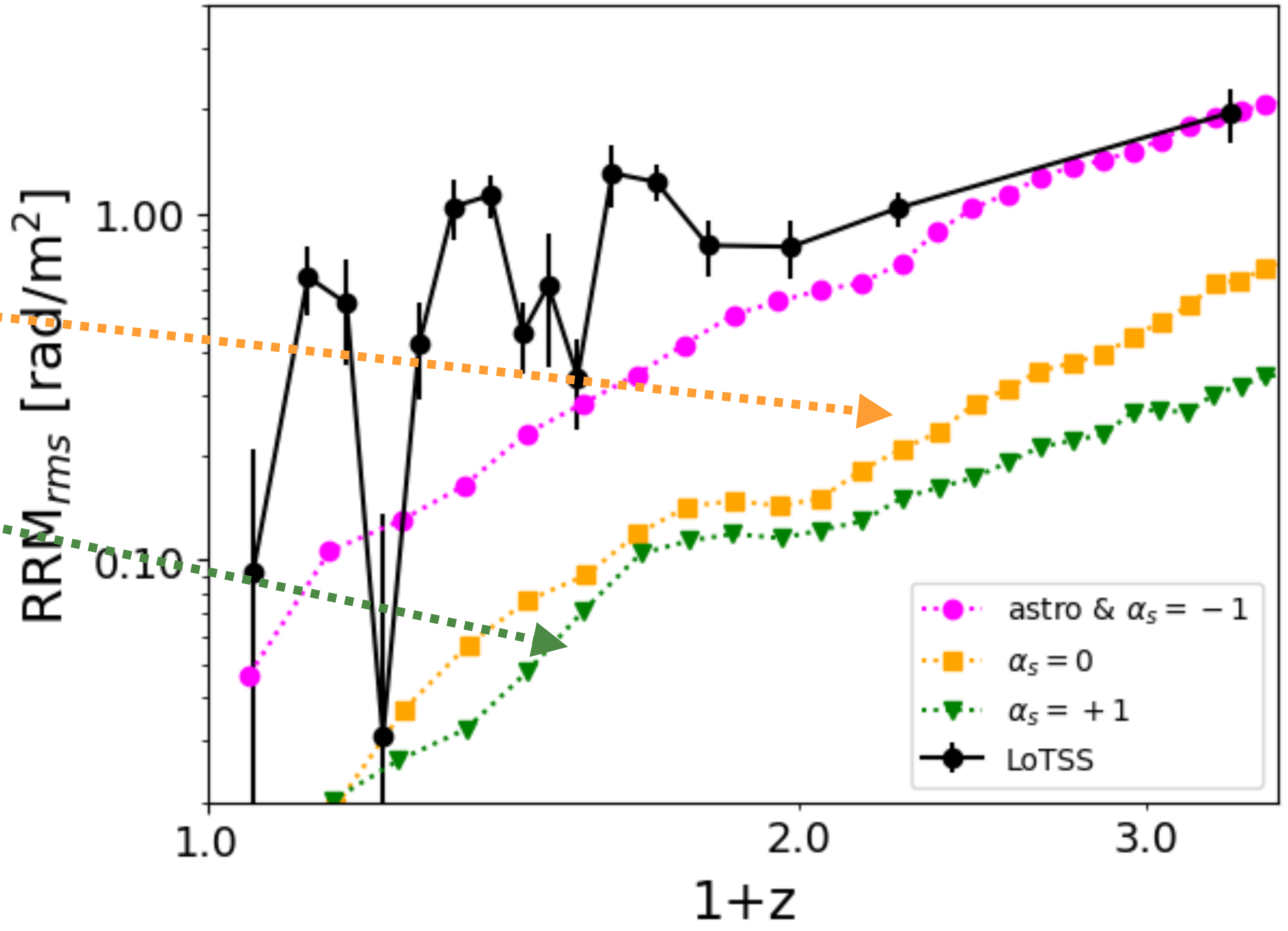
- Carretti et al. 23, 24, 25: Analysis of **1016 sources with known redshift** $0 \leq z \leq 3$ in LOTSS DR2 , |b|>25°
- **Galactic foreground** (MAD filtering <0.5° radius, of Hutschenreuter+22 map): $RRM_f = RM - GRM$
- Removal of LOS with **known halos contaminating the RM (all $r \leq R_{100}$ region is excluded)**
- **"Residual" Rotation Measure**: $\langle RRM^2 \rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \langle RRM_f^2 \rangle^{1/2}$

Comparison with simulated RRMs:

Primordial model with $P_B \propto k^0$

Primordial model with $P_B \propto k^1$

Residual RM binned in redshift



most of tested spectra (except $n_B = -1$)

fall short of observed RRM(z)

FARADAY ROTATION

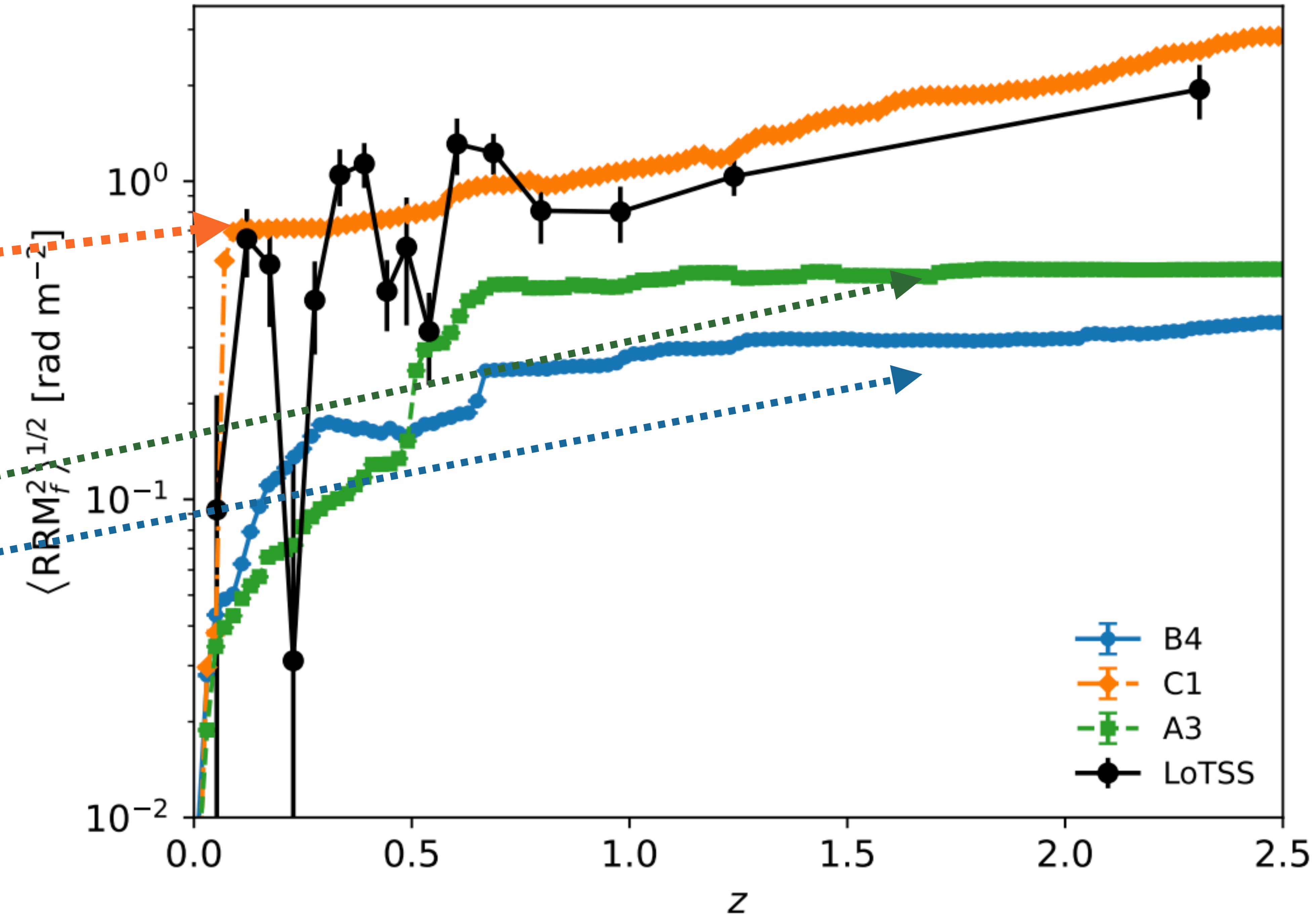
- Carretti et al. 23, 24, 25: Analysis of **1016 sources with known redshift** $0 \leq z \leq 3$ in LOTSS DR2 , |b|>25°
- **Galactic foreground** (MAD filtering <0.5° radius, of Hutschenreuter+22 map): $RRM_f = RM - GRM$
- Removal of LOS with **known halos contaminating the RM (all $r \leq R_{100}$ region is excluded)**
- **"Residual" Rotation Measure**: $$\langle RRM^2 \rangle^{1/2} = \frac{A_{rrm}}{(1+z)^2} + \langle RRM_f^2 \rangle^{1/2}$$

Comparison with simulated RRMs:

Best match:
Primordial model with $n_B = -1$ and $B_{Mpc} = 0.4nG$ also **including astrophysical sources**
(radio galaxies DO exist!)

all tested purely astrophysical scenario (AGN+stars): underestimate RRM at most z

Residual RM binned in redshift

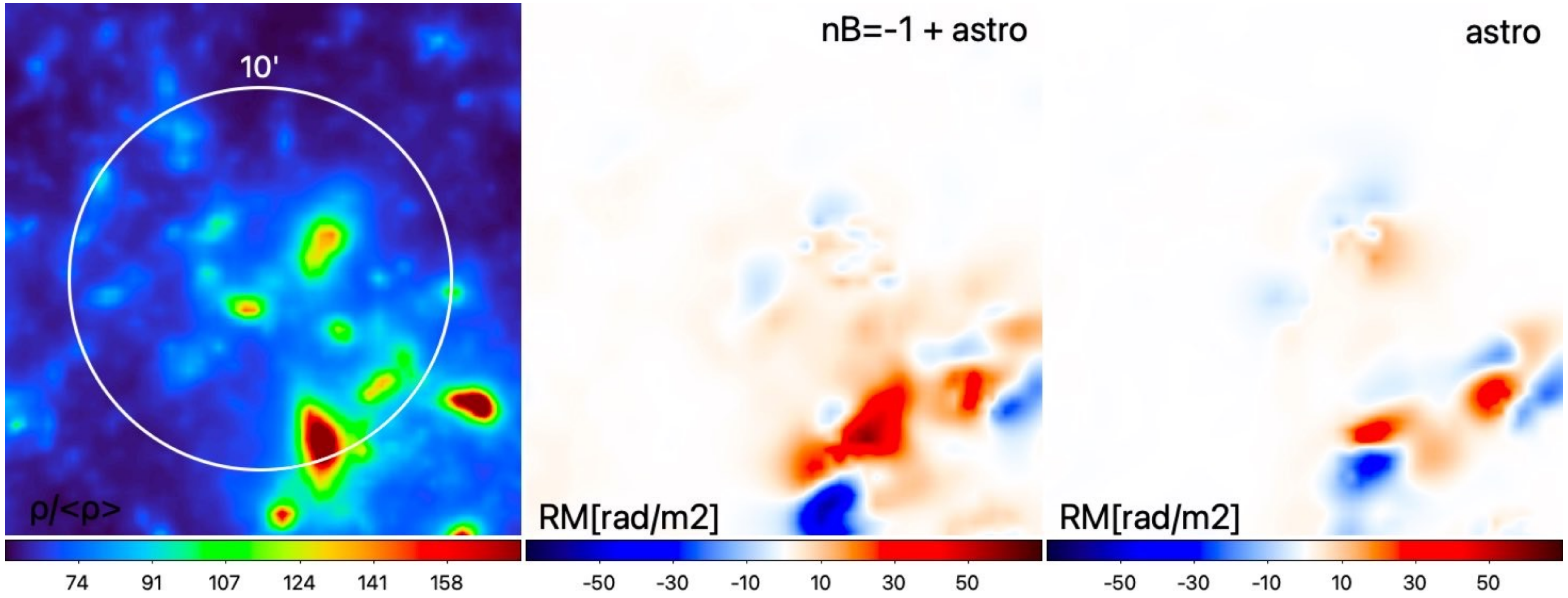


FARADAY ROTATION

Integrated RRM

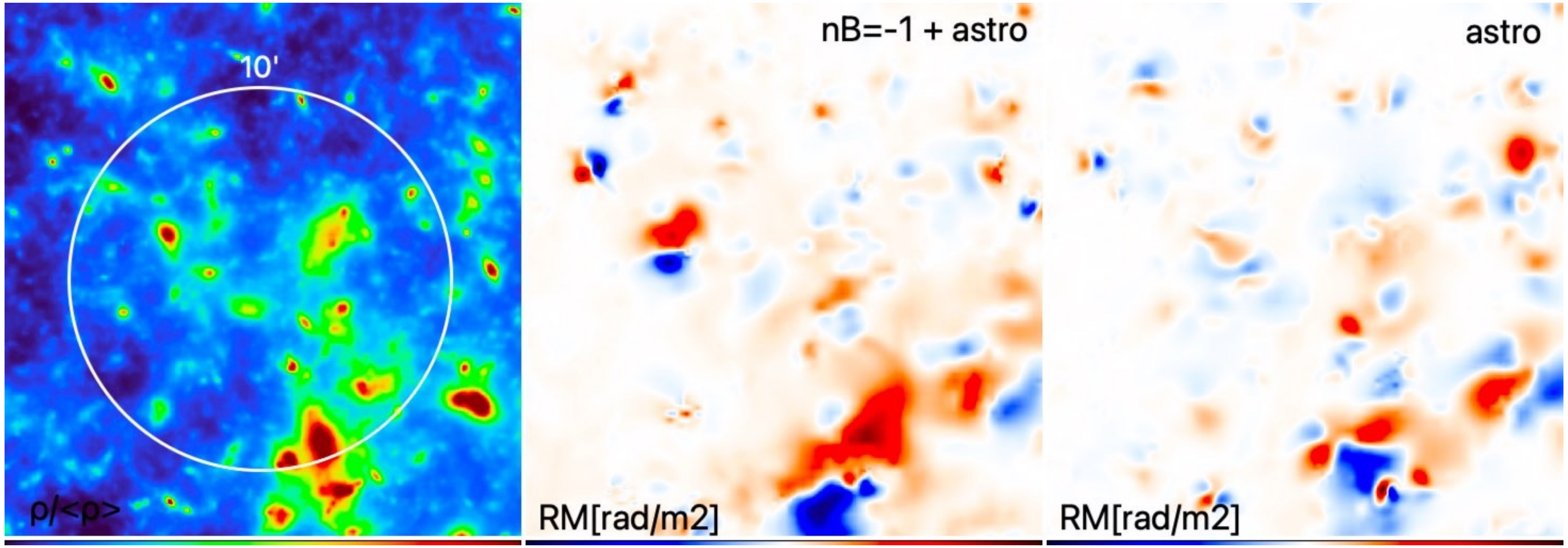
for 0<z<0.1

(dl ~ 420Mpc)



for 0<z<2

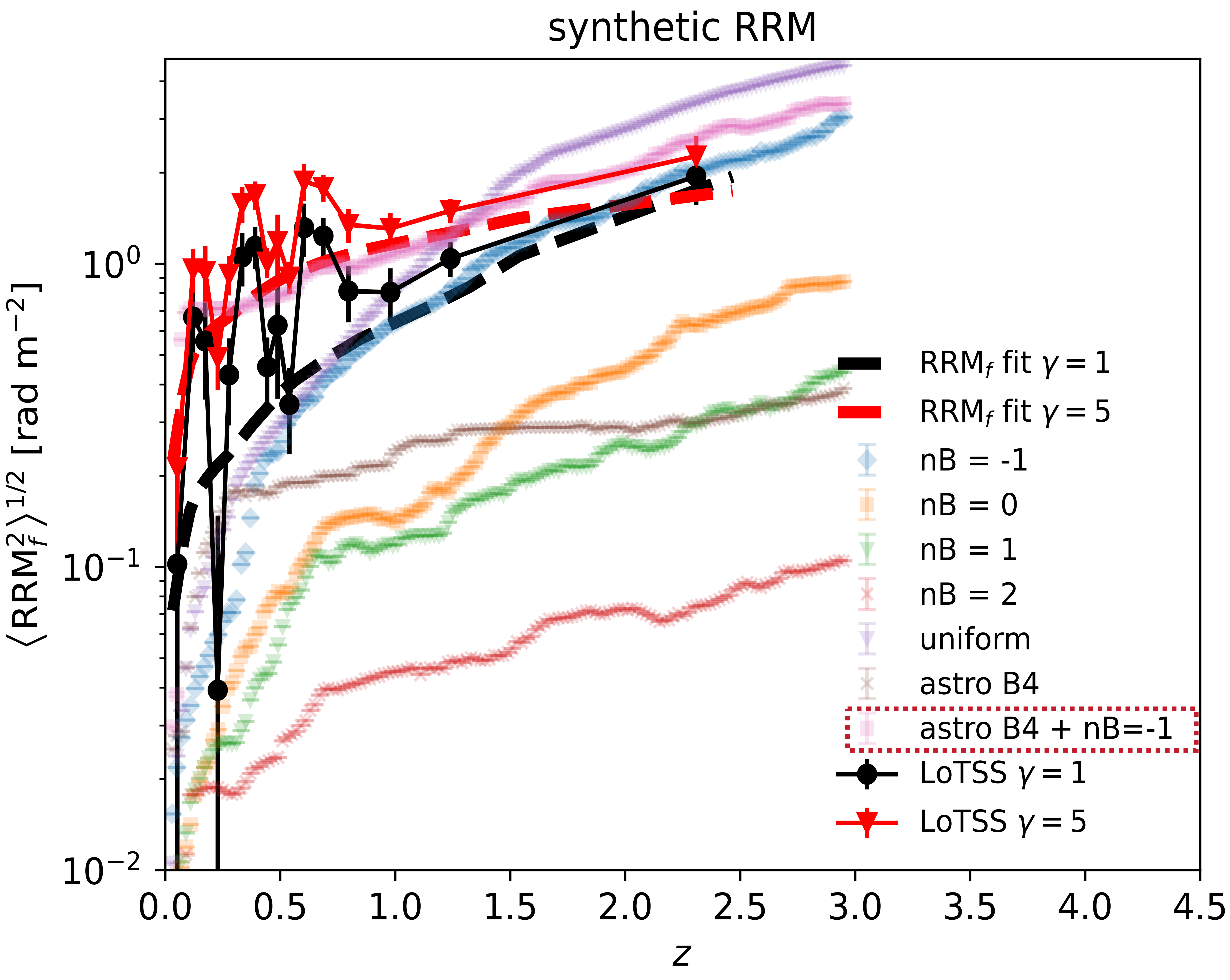
(dl ~ 5.2Gpc)



FARADAY ROTATION

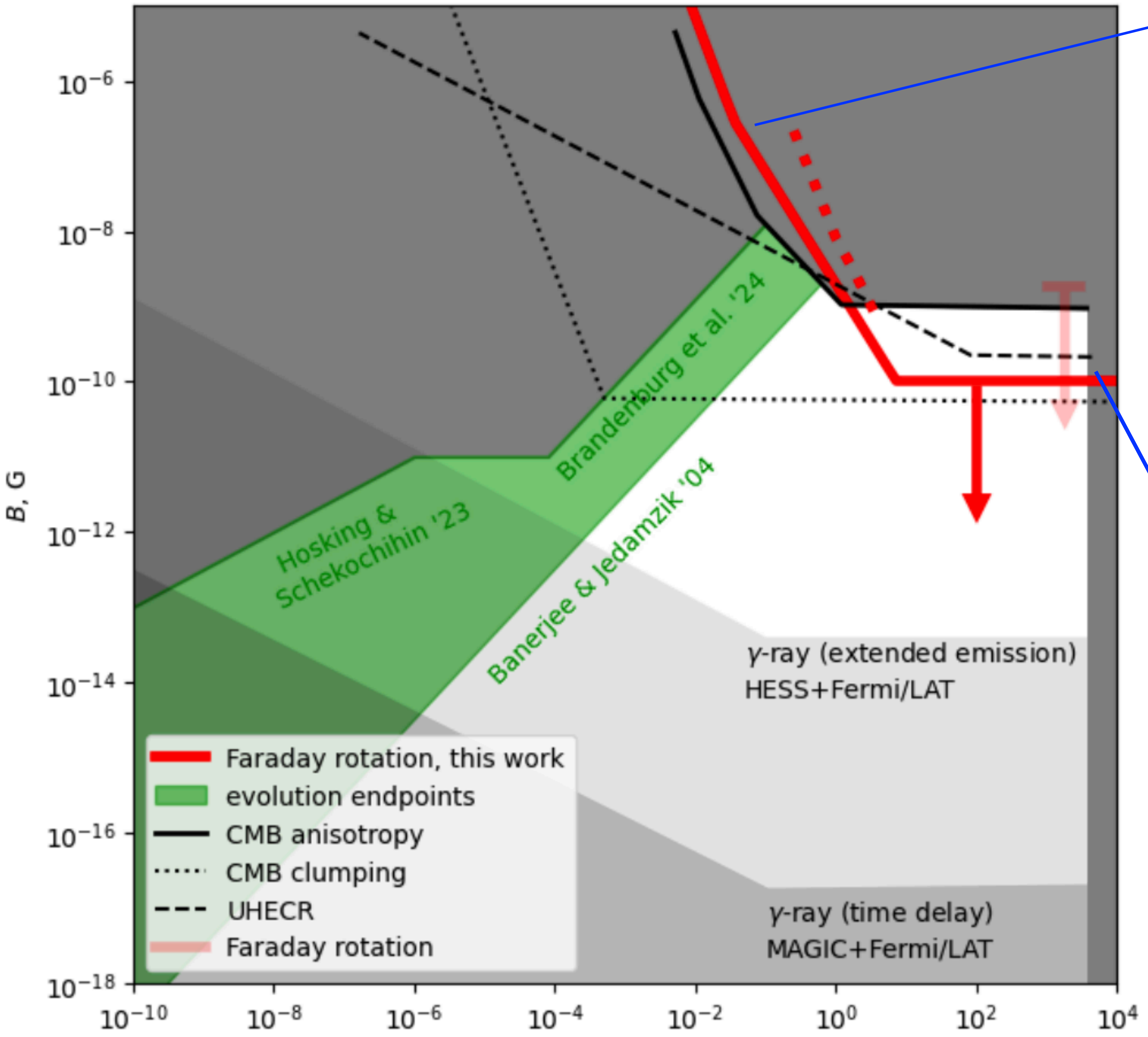
Key results using LOFAR RRM(z):

- observed RRM(z) requires volume filling B-fields up to $z \sim 3$, best explained by "primordial" models with $P_B \propto k^{-1}$ and $B_{1Mpc} \sim 0.4\mathrm{nG}$
- all other tested $P_B(k)$ initial models do not reproduce high-z trends - although they use the largest B allowed by CMBs.
- no pure (even optimistic) astrophysical scenarios can explain RRM(z)
- but adding astrophysical seeding to the $P_B \propto k^{-1}$ greatly improves match to LOFAR RRM(z)

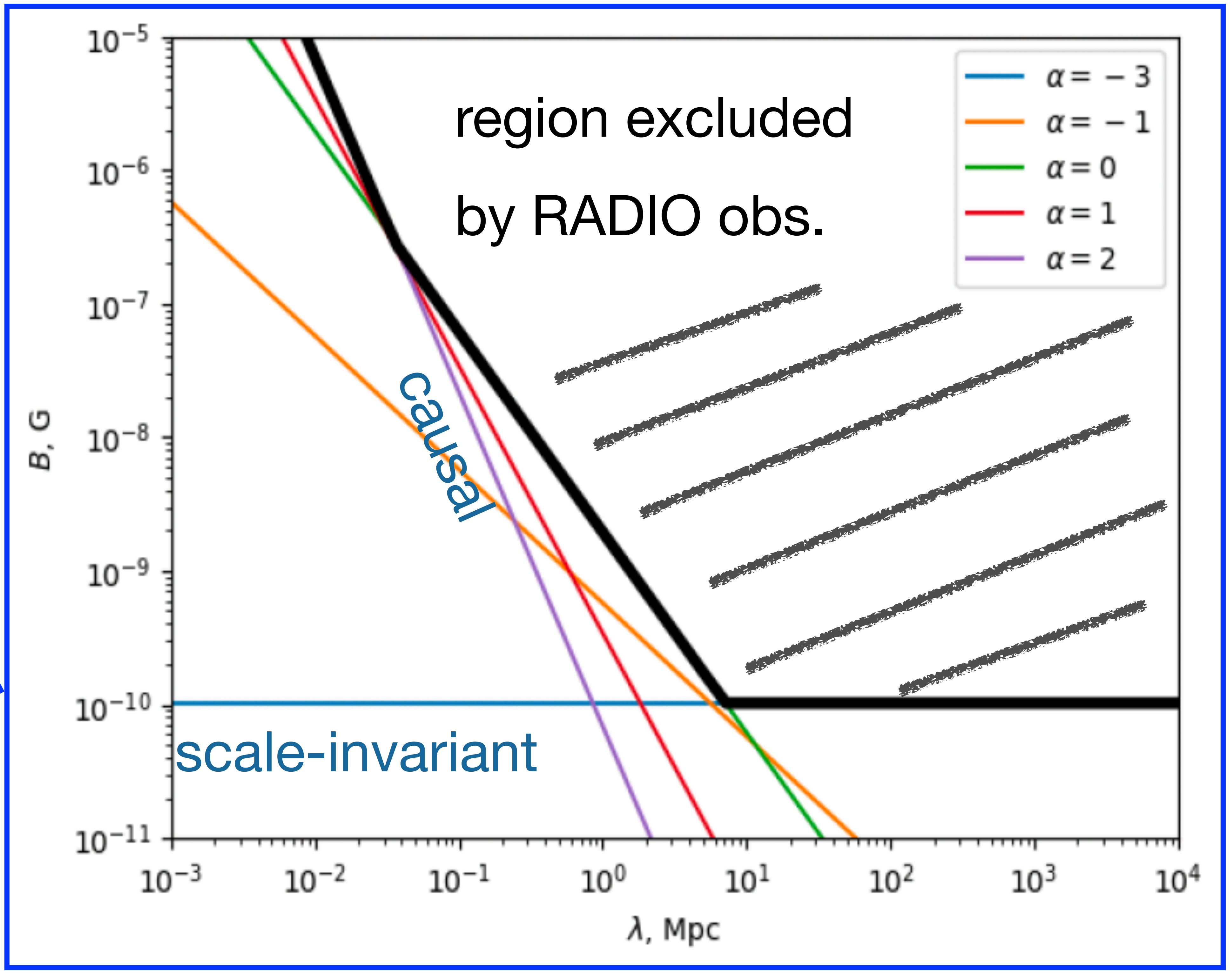


Carretti & FV 25

PUTTING IT ALL TOGETHER (1)



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

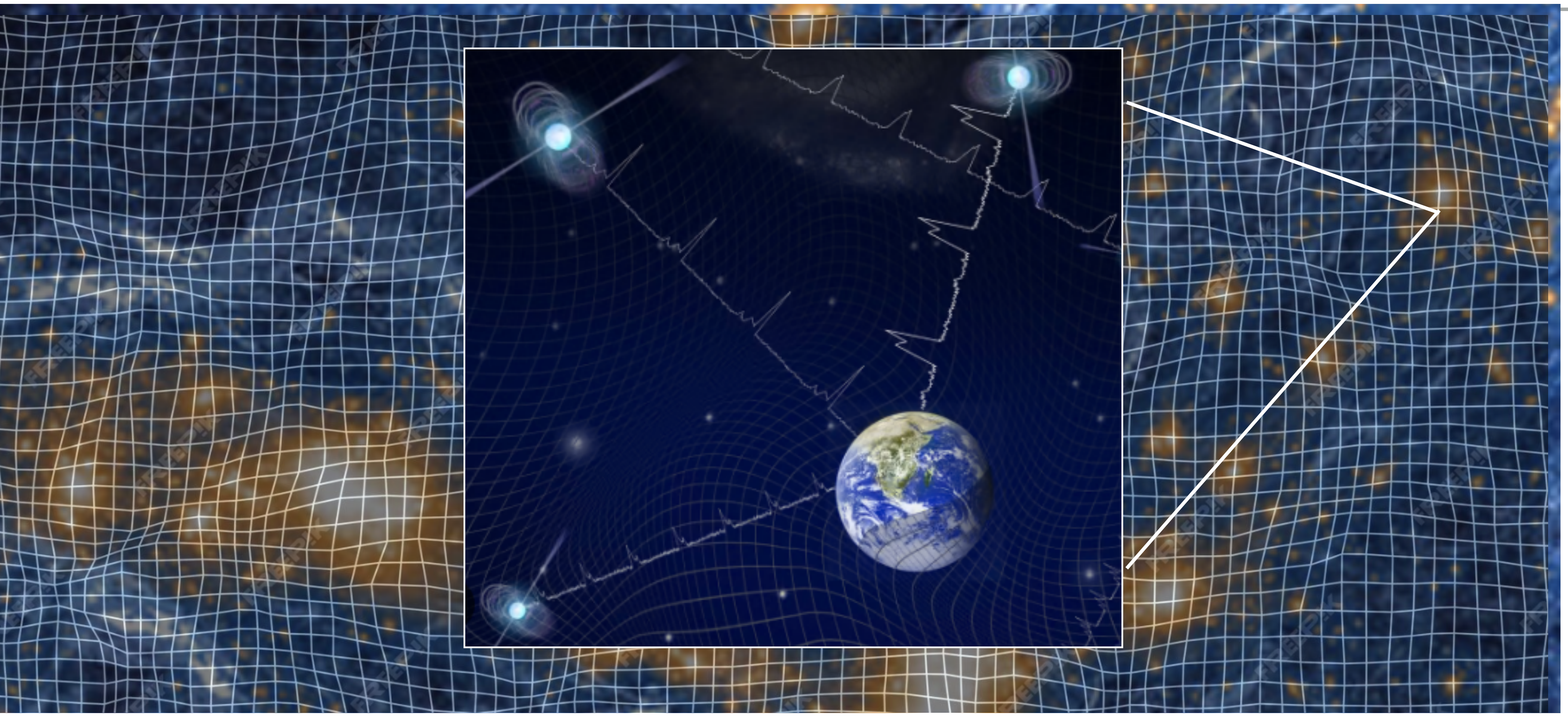


different primordial models

- Radio data (z<3) can now better constrain primordial magnetism than CMB for $n_B \leq 1$ power-law spectra.
- It will even improve with SKA. Radio is powerful!

Neronov, FV, Mtchedlidze, Carretti 25

THE BIG PICTURE (?)

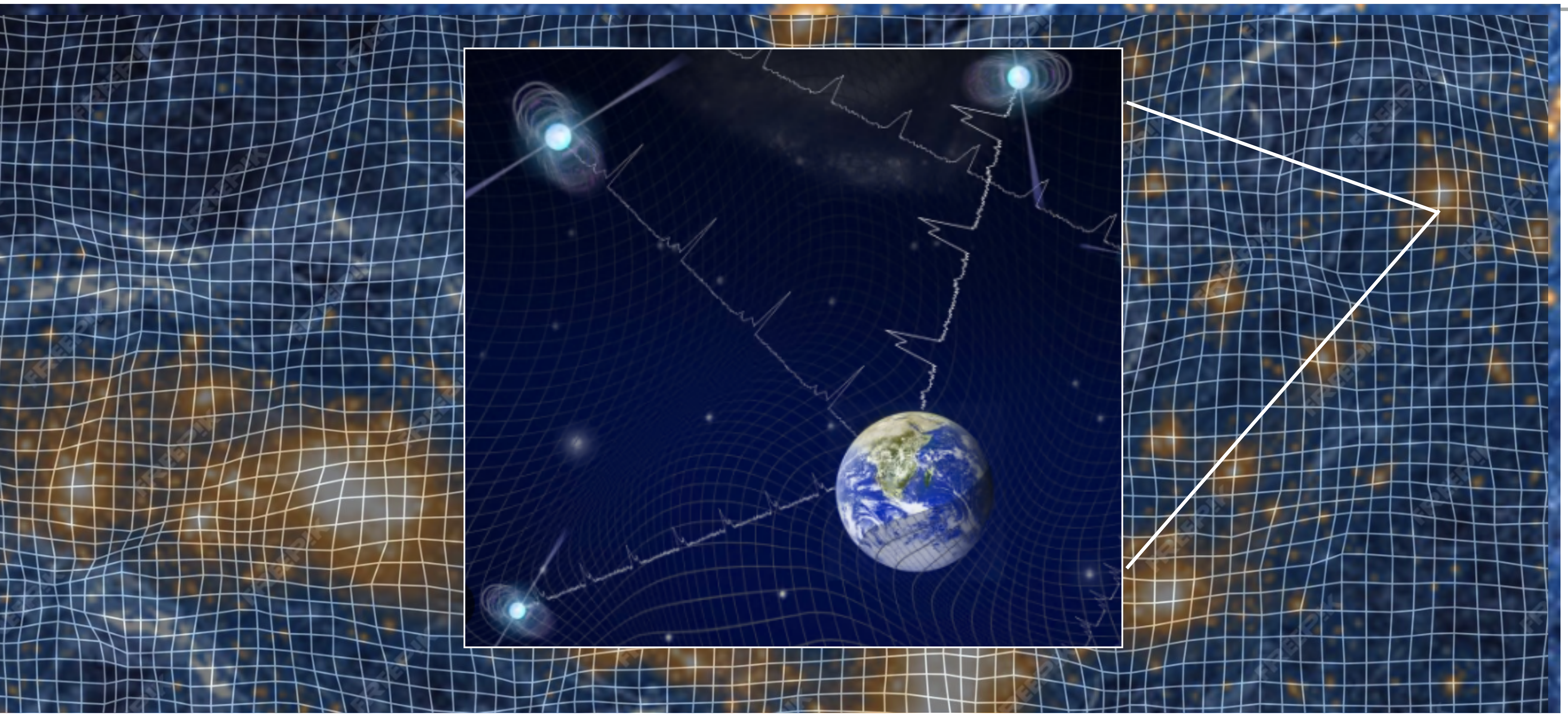


2023: Detection of the Stochastic Gravitational Waves Background with Pulsar Timing Array.

Possible interpretations:

- supermassive BH binaries
- inflation, cosmic strings, topological defects…

THE BIG PICTURE (?)



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 constrains B-field parameters:

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

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

energy density of GW

energy density of B-fields

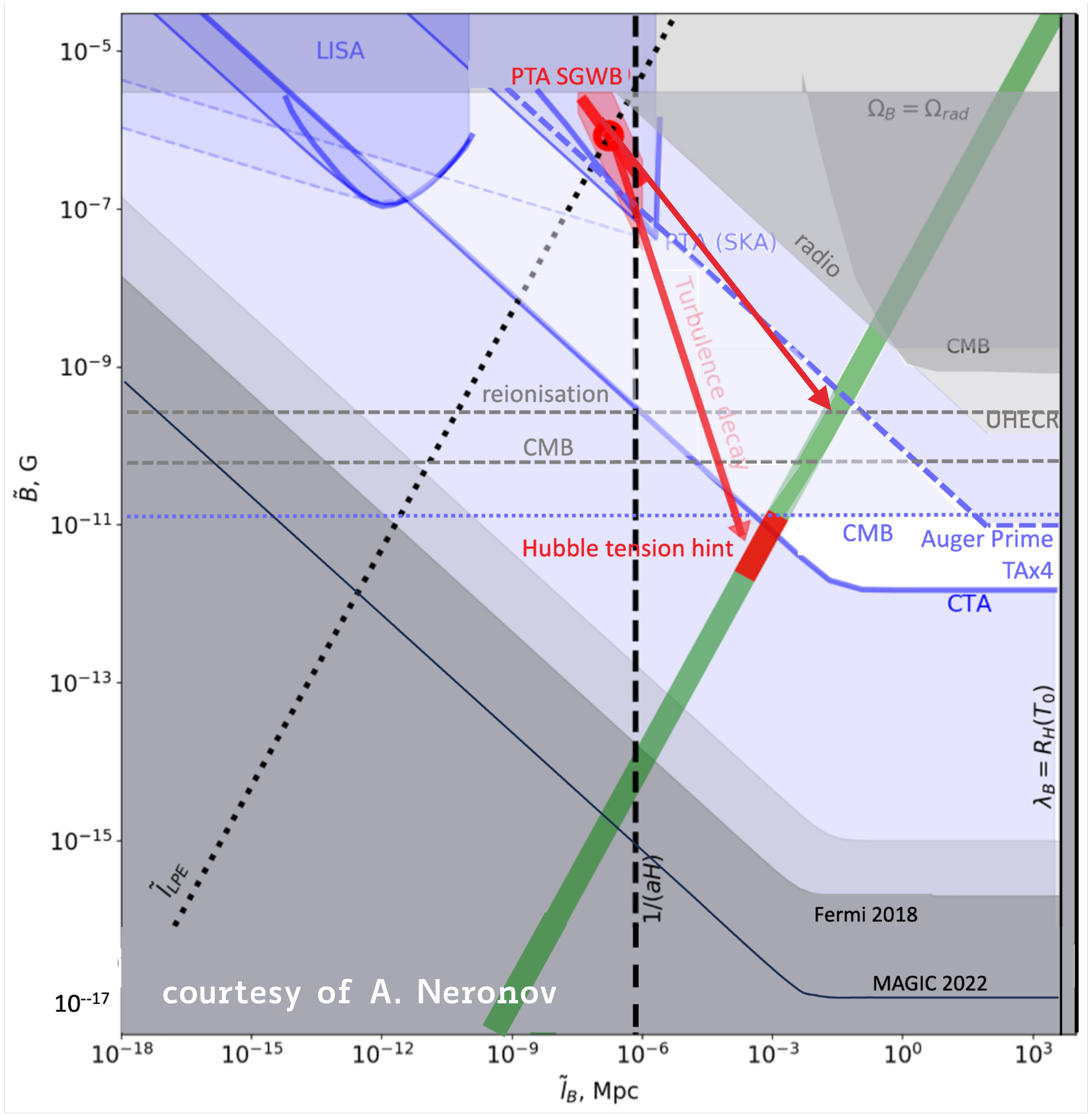
number of relativistic degrees of freedom

Horizon radius

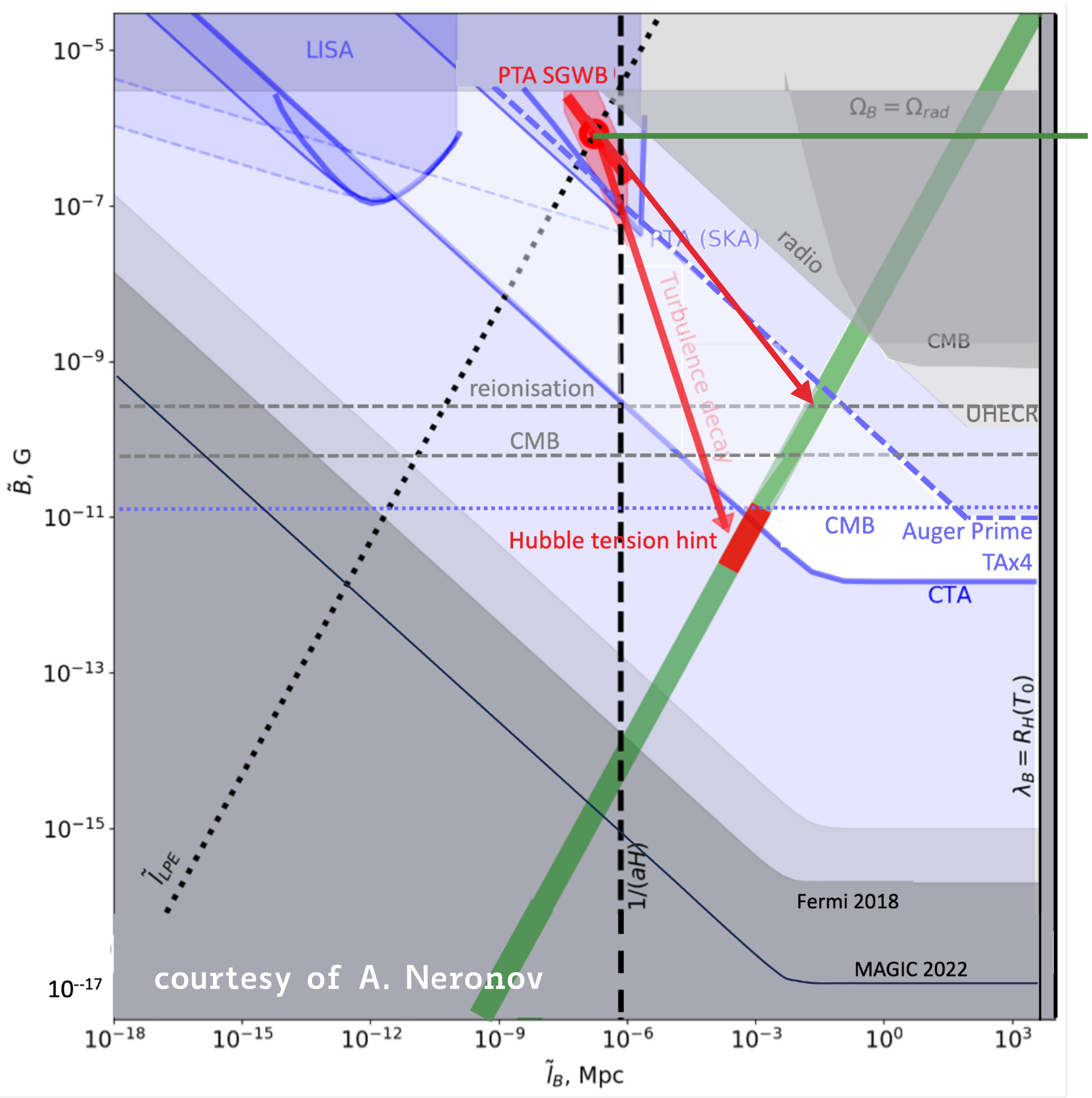
scale length of B-fields

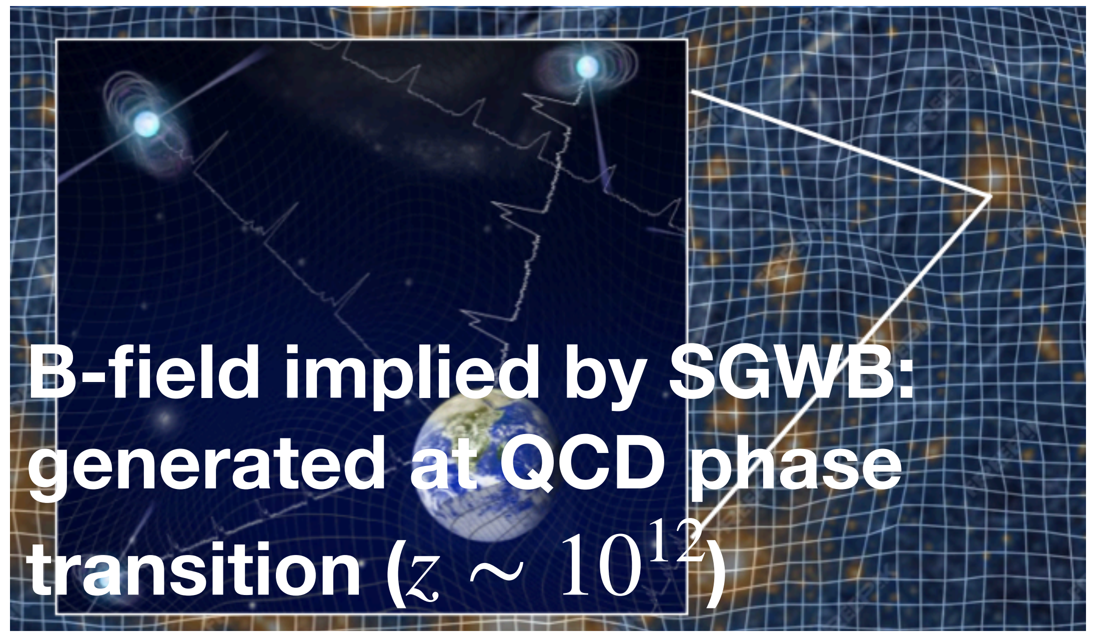
temperature of the Universe

THE BIG PICTURE (?)



THE BIG PICTURE (?)

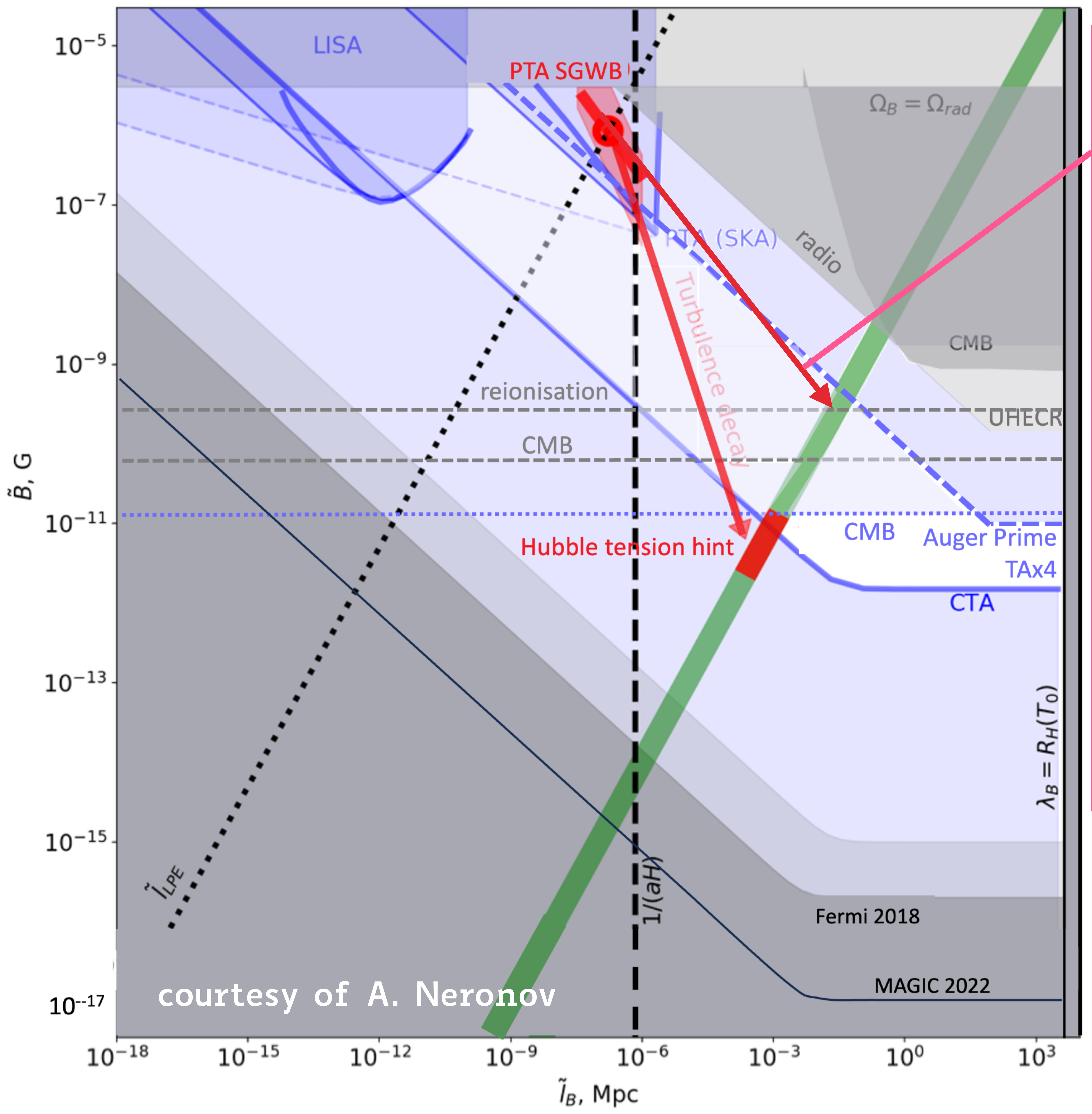


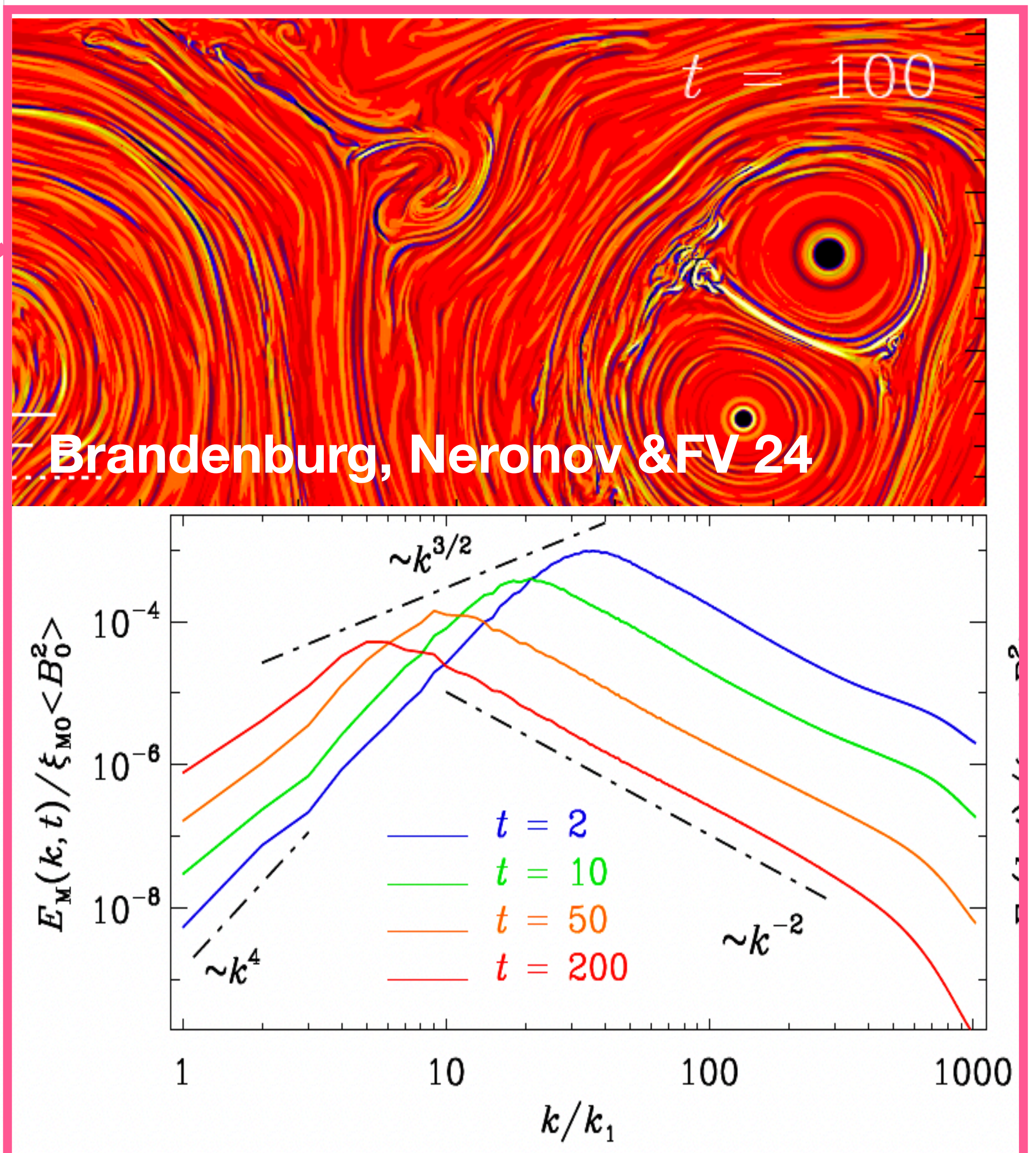


$$h^2\Omega_{\mathrm{GW},0} \sim 7 \times 10^{-5} \left[\frac{N_{\mathrm{eff}}}{10}\right]^{-\frac{1}{3}} \Omega_B^{n+1}$$

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

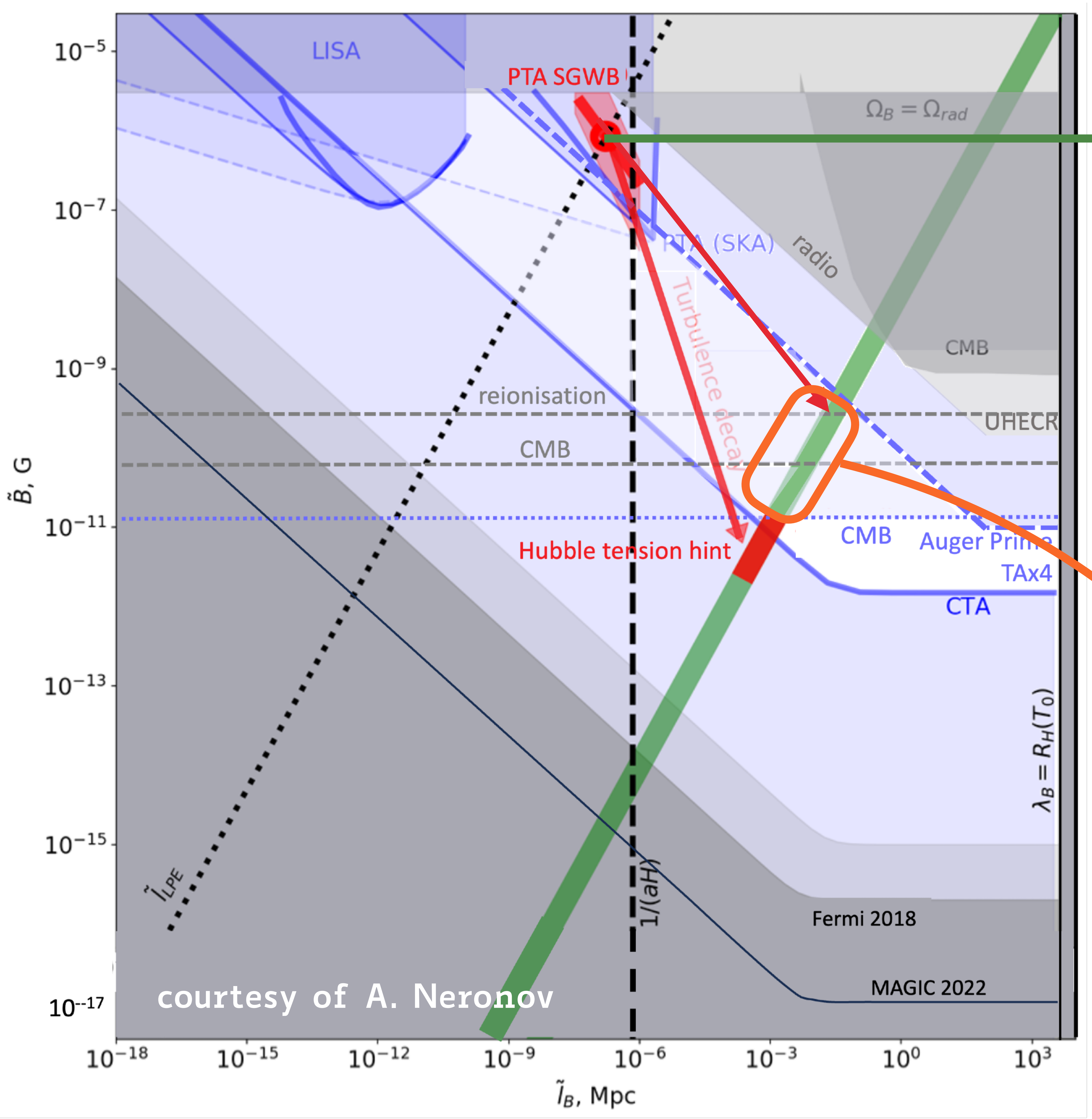
THE BIG PICTURE (?)

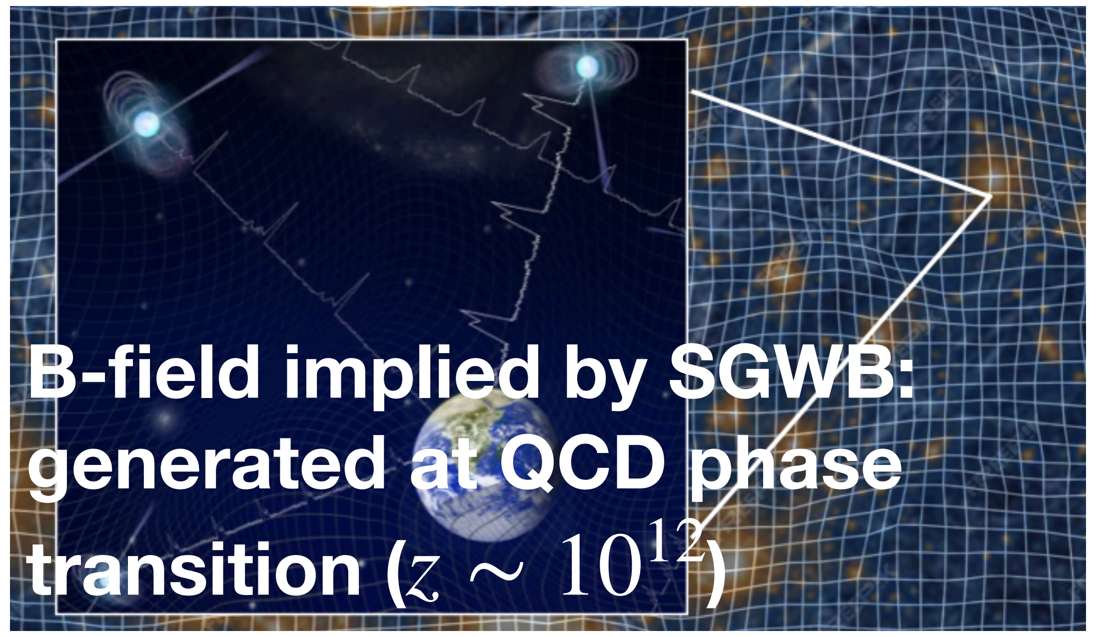




Evolutionary tracks of primordial B-fields undergoing inverse cascade (helicity-dependent)

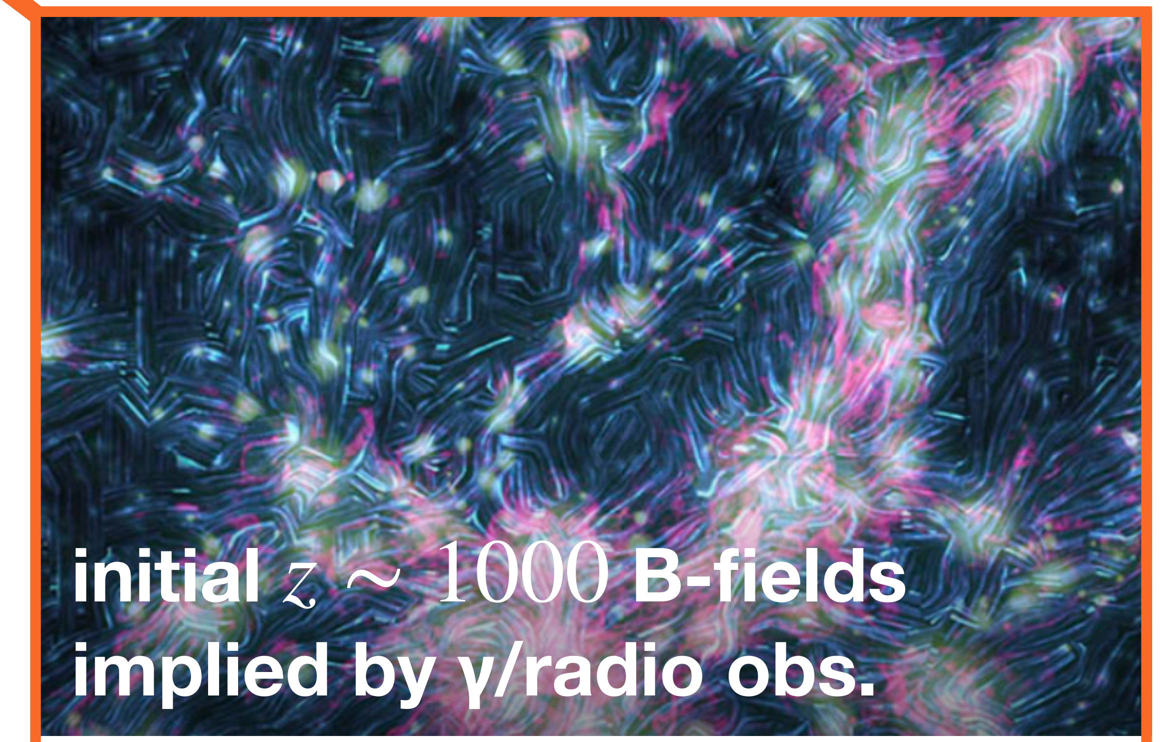
THE BIG PICTURE (?)





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

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

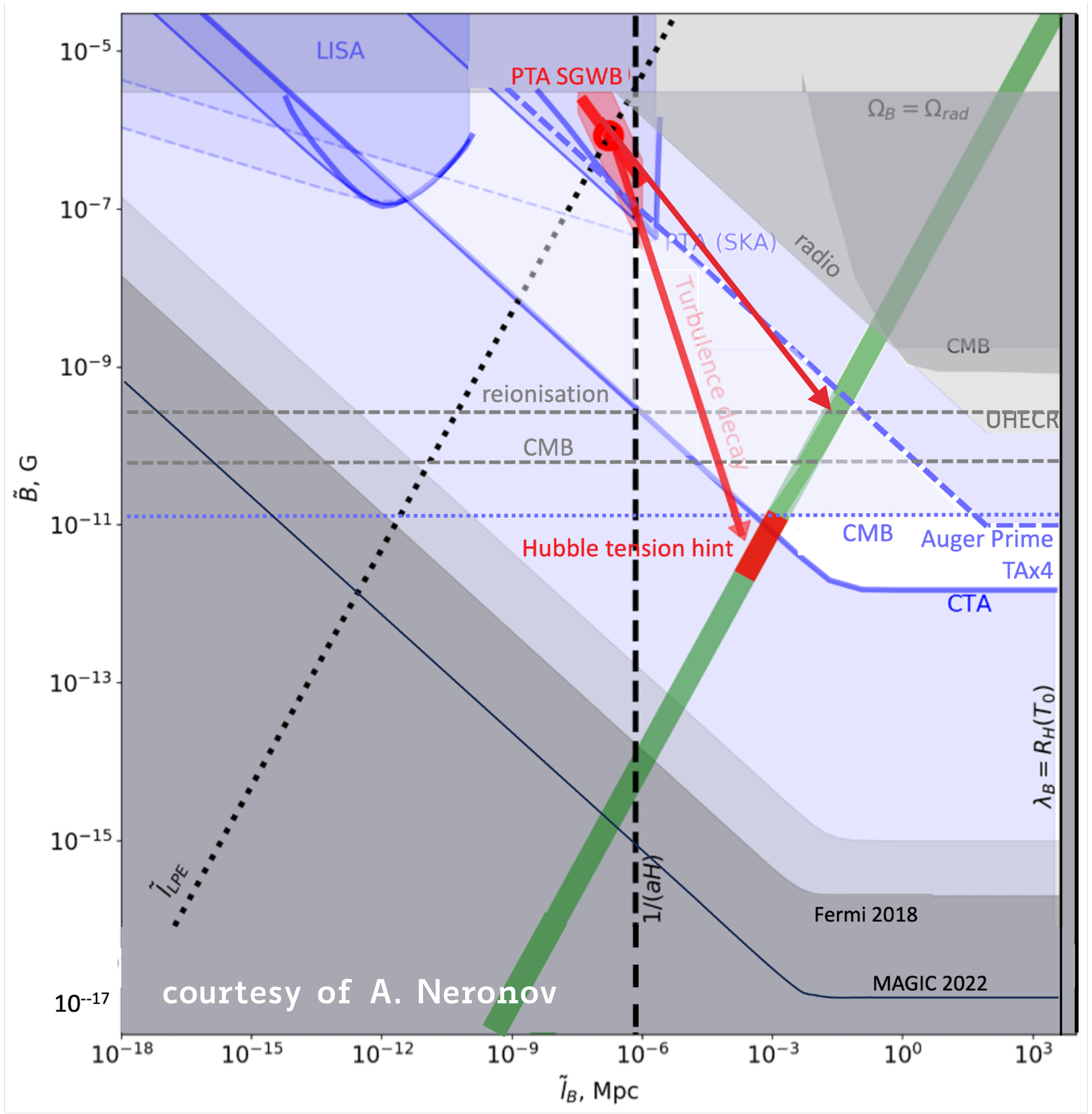


$P_B(k) \propto k^{\alpha_B}$ **with**

$-1.0 \leq \alpha_B \leq 2.0$ **and**

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

THE BIG PICTURE (?)



- So: the magnetic field models selected by the recent modelling of recent radio observations (synchrotron & RM) and blazars, compatible with CMB limits, are also close to the ones that would produce the SGWB detected by PTA
- If so, we may have an incredible window into the **first microsecond of the Universe**

MANY PROBLEMS TO WORK ON:

SIMULATIONS

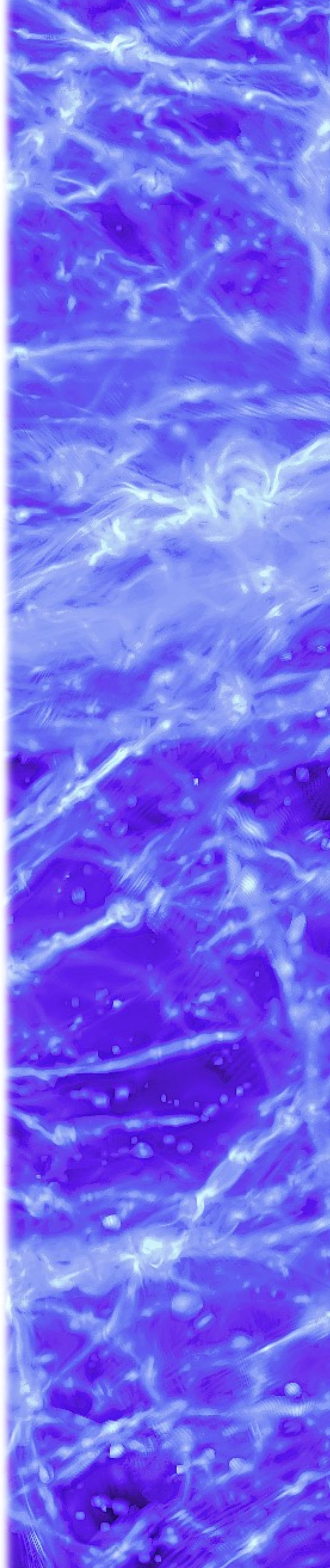
- **MHD assumptions? Kinetic plasma effects?** Ideal MHD seems ok for most scales and epochs we are concerned with. However, kinetic effects can further induce magnetic field generation at very small scales (in voids, too?)
- **Astrophysical sources? First galaxies? Reionisation?** unclear how much our understanding of galaxy formation and feedback must be revolutionised after JWST high-z observations
- **Dynamo? Resolution? Helicity? Reconnection ?** Always hard to make extrapolation towards $R_M \gg 1, Pr_M \gg 1$ with existing simulations

OBSERVATIONS

- **Radio:** contamination from the Galaxy, improve source selection, reduce biases in RM analysis
- **Gamma:** source selection, understand assumptions, plasma effects on gamma-ray beams
- **Gravitational Waves:** contamination by supermassive black holes, cosmic variance

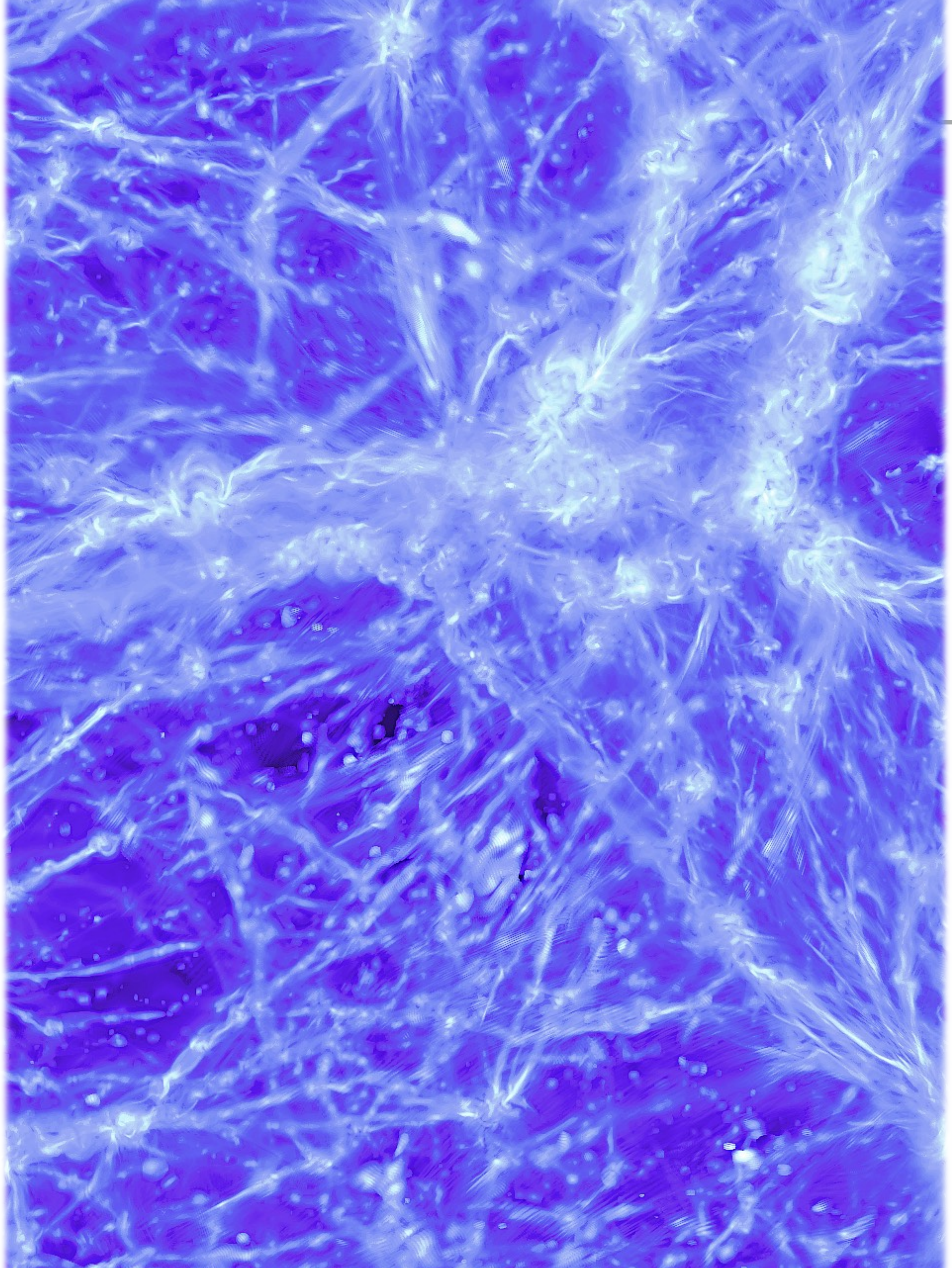
THEORY

- Each possible generation model (inflationary, EW, QCD..more?) has **plenty of open problems** and potential **ground-breaking connections with fundamental physics** !



MANY PROBLEMS TO WORK ON:

Big Bang
COSMOMAG
Probing the first microseconds of the Universe
with magnetic fields
1 μs
quark-gluon
plasma
protons
neutrons
3 minutes
Big Bang Nucleosynthesis
atomic nuclei
Cosmic Microwave Background
radiation
400 000 years
atoms
Time
14 billion years (today)
Cosmic Web
erc
European Research Council
2026-2032 Synergy Grant



FINAL MESSAGES

- **Detection of intergalactic magnetic fields** well beyond clusters - hard to model
- **Purely astrophysical** scenarios rejected. Volume-filling B-fields are required.
- **Primordial mechanisms** seem the most natural explanation
- There is a possibility that many observations in the early, intermediate and late Universe combine into the same picture of primordial generation at QCD, also explaining the Stochastic Gravitational Wave background.
- **If so: unprecedented probe of the $\sim \mu s$ Universe!!**

SUGGESTED FURTHER READINGS

- Carretti & Vazza 2025 " Radio Observations as a Probe of Cosmic Web Magnetism" https://arxiv.org/pdf/2505.18619
- Neronov, Vazza, Mtchedlidze & Carretti "Revision of upper bound on volume-filling intergalactic magnetic fields with LOFAR" https://arxiv.org/pdf/2412.14825
- Neronov, Pol, Caprini, Semikoz, "NANOGrav signal from magnetohydrodynamic turbulence at the QCD phase transition in the early Universe", https://arxiv.org/pdf/2009.14174