Unveiling the mysteries of the early universe

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TeVPA 2023

Fermilab

Kavli Institute for Cosmological Physics at the University of Chicago

cherenkov telescope array

Credit: IllustrisTNG

Beyond the SM problems

Particle physics is facing a great challenge:
We are certain that the SM does not explain all phenomena in Nature

Indeed, a number of experimentally established evidence **cannot be explained by the Standard Model**, including:

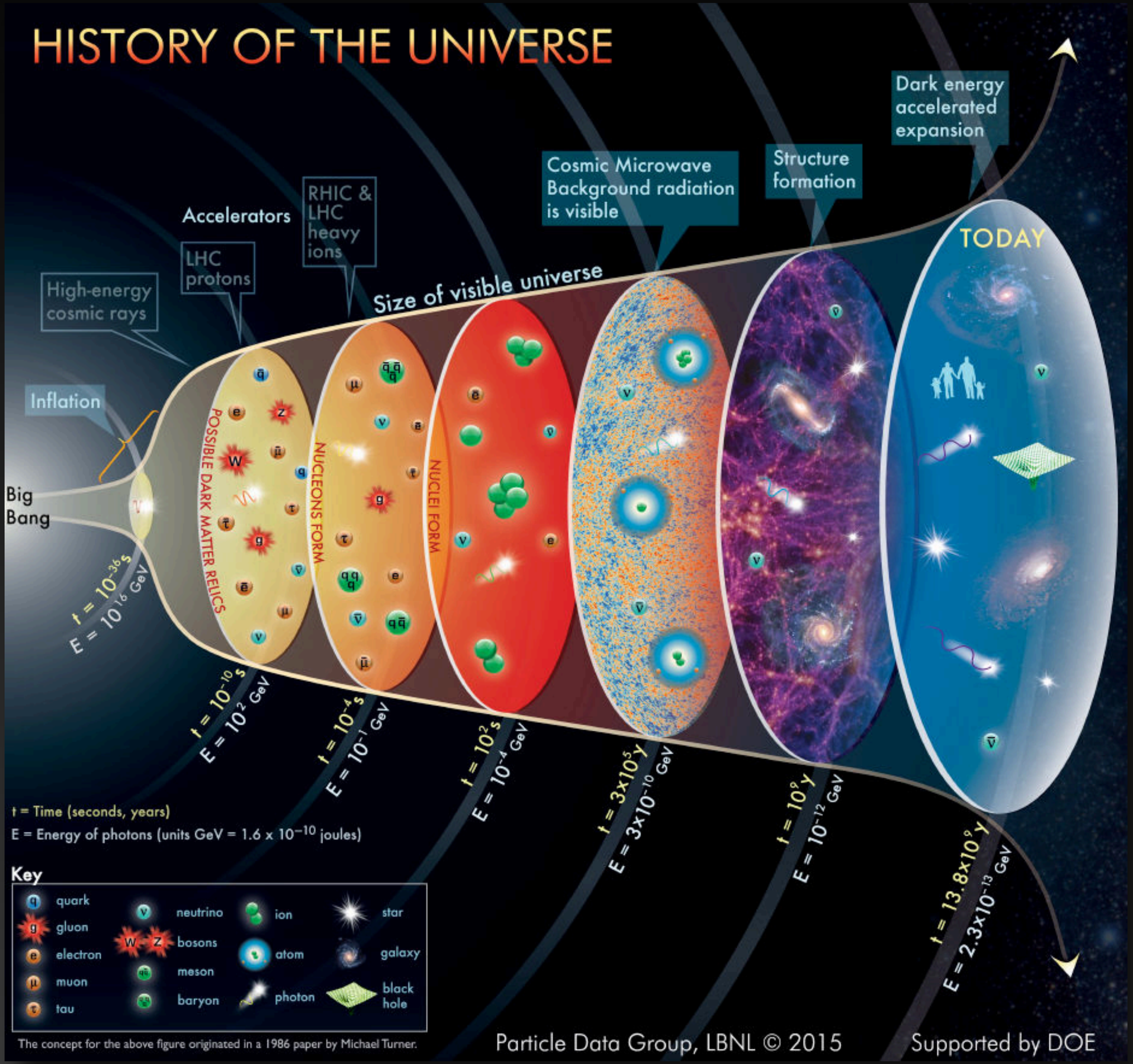
- **Neutrino masses**: Why do neutrinos have a mass?
- **Baryon asymmetry of the Universe**: What mechanism created a tiny matter-antimatter imbalance in the early Universe?
- **Dark Matter**: What is the prevalent kind of matter in the Universe?

New relics?

We would like to probe the Universe from **much earlier epochs** (1<s)

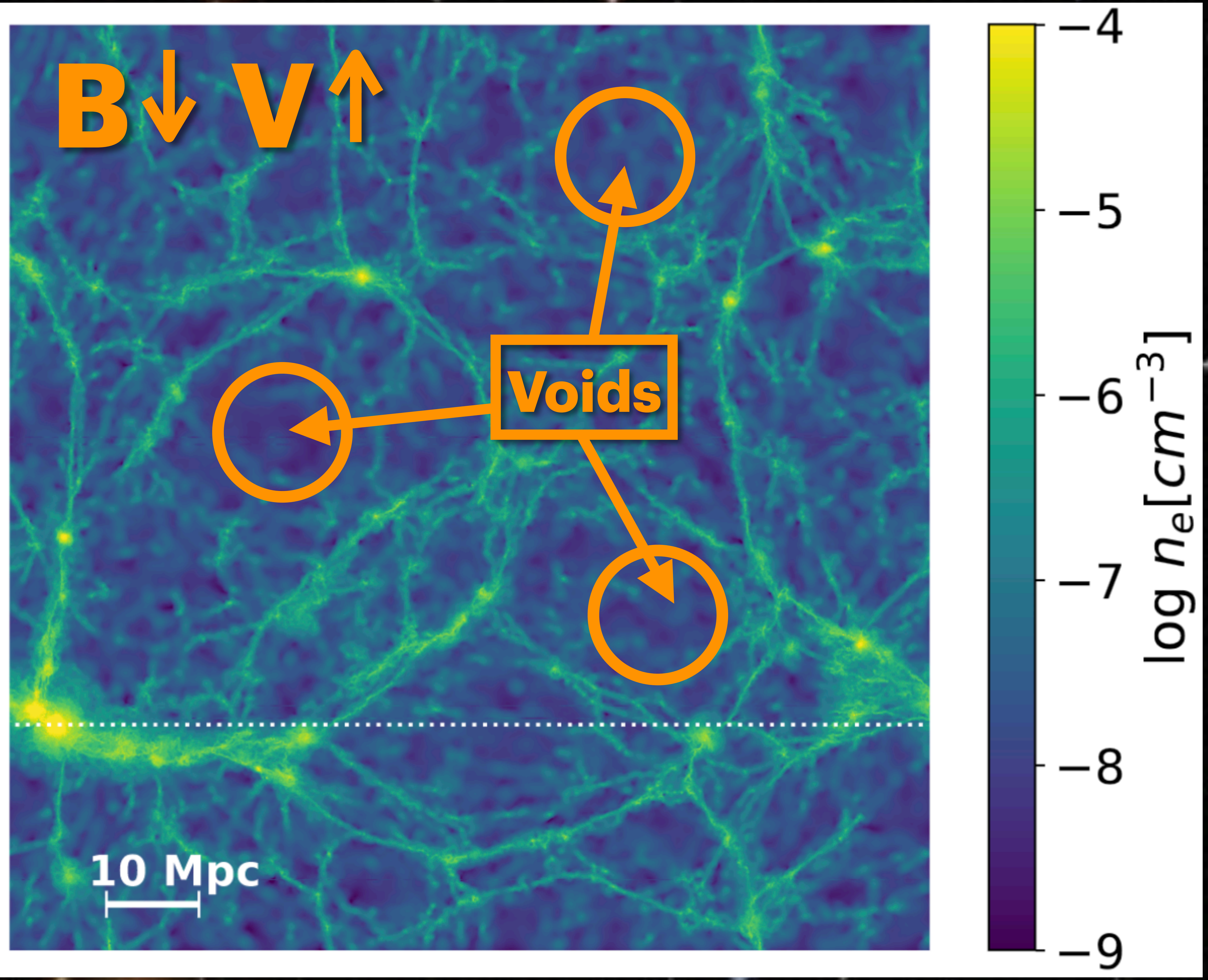
There are other potential messengers from the early Universe:

- Cosmic Neutrino Background
- Primordial gravitational waves?
- **Primordial magnetic fields?**



Searching for primordial MF

- **Intergalactic magnetic fields in voids** (IGMF) should be **very close** to the **initial conditions** (if they exist) and could come from the early Universe



[A. Aramburo-Garcia, AS et al., JCAP, 2020]

Searching for primordial MF

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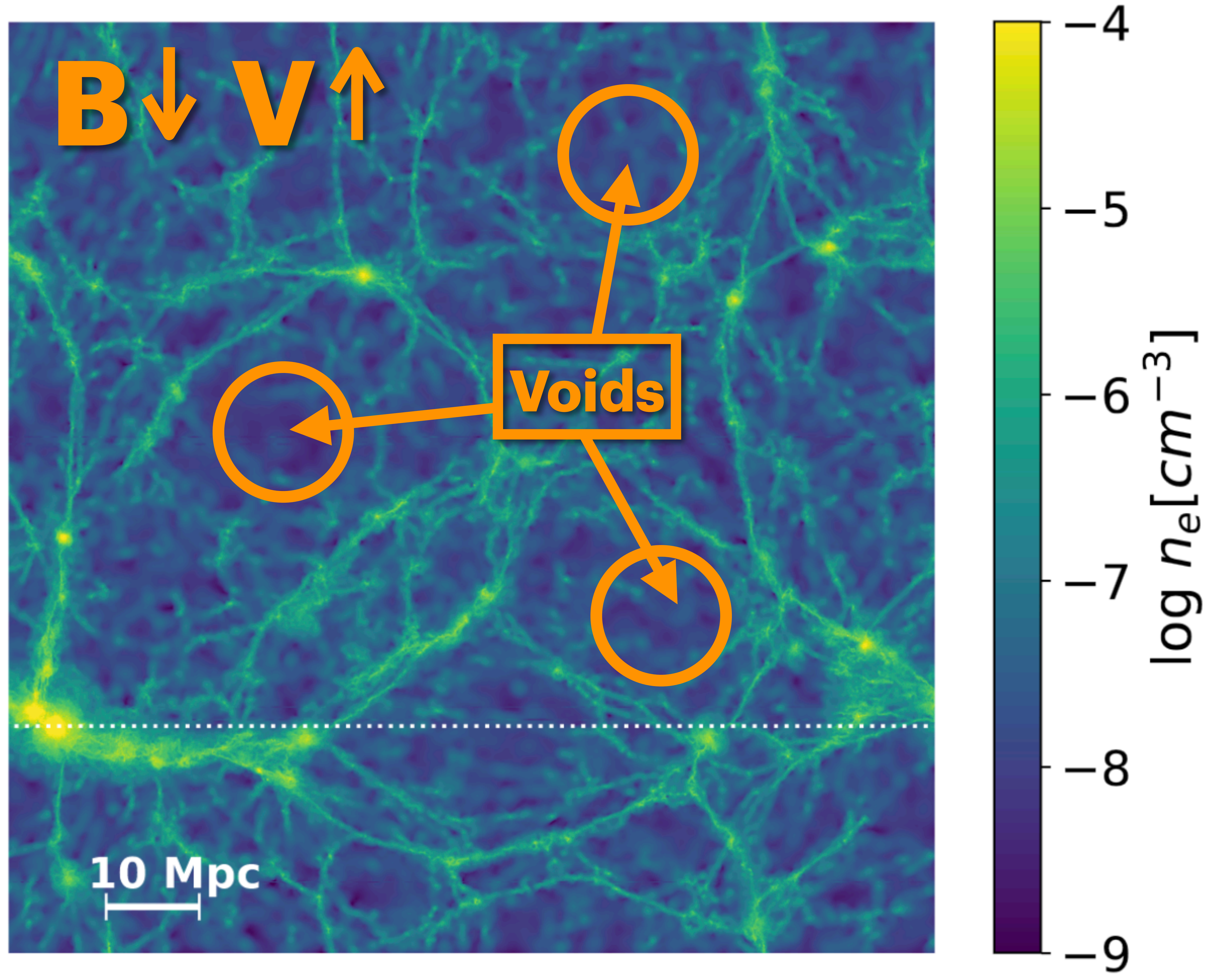
How to measure the IGMF?



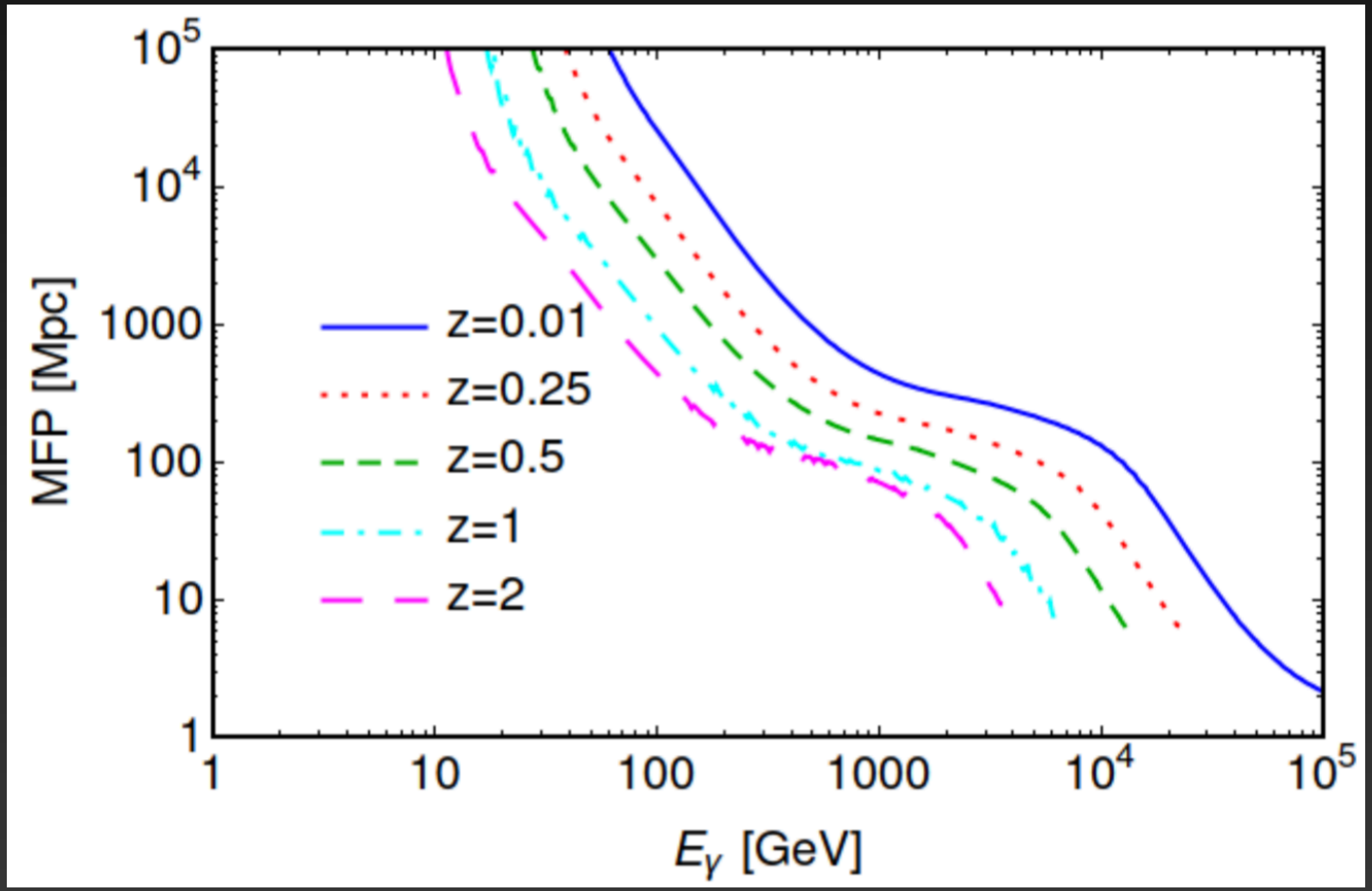
[A. Aramburo-Garcia, AS et al., JCAP, 2020]

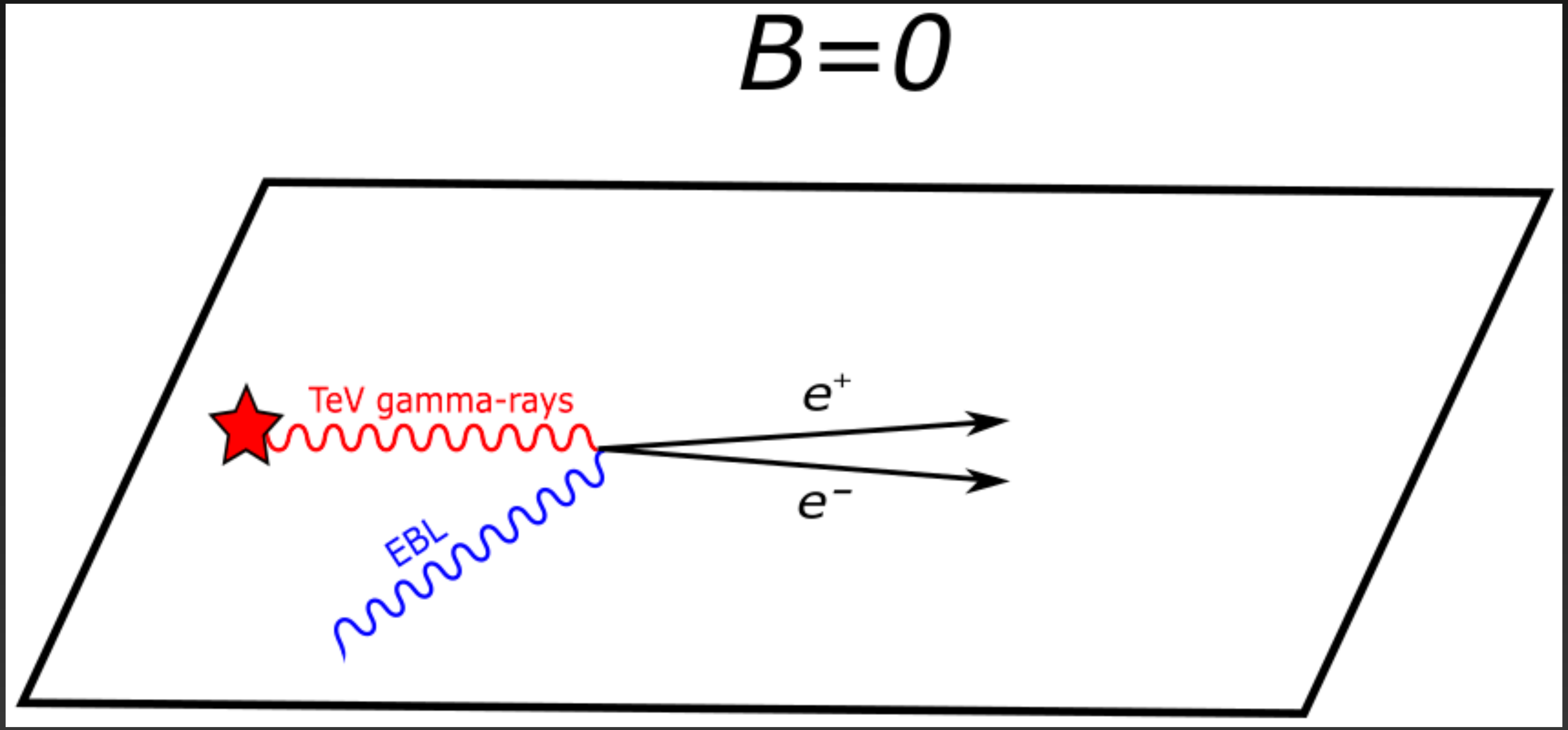
γ-ray telescopes

How to measure the IGMF?

Secondary emission: prediction

Our Universe is **not transparent** for TeV photons: they can interact with EBL photons and create an **electron-positron** pair



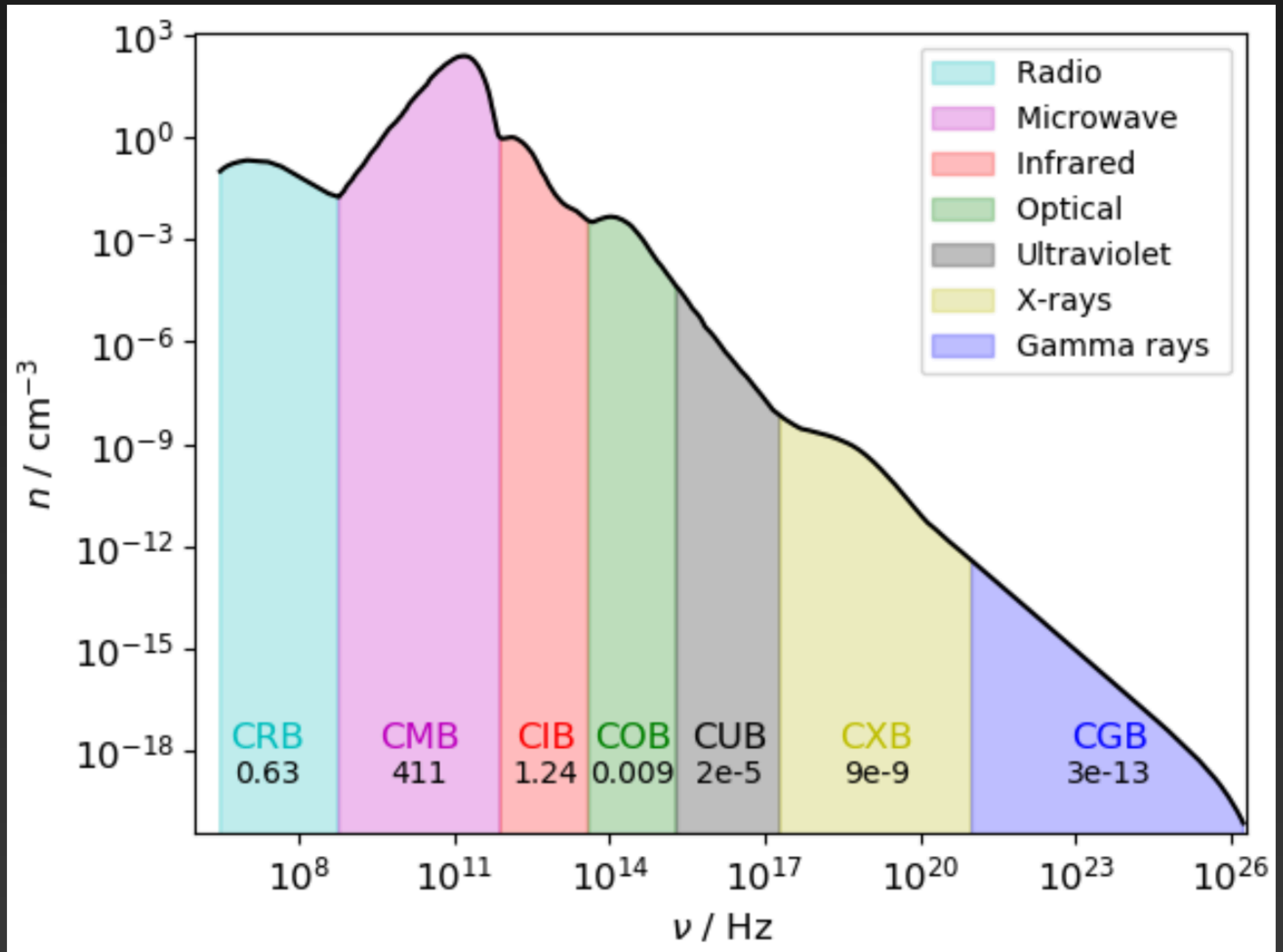


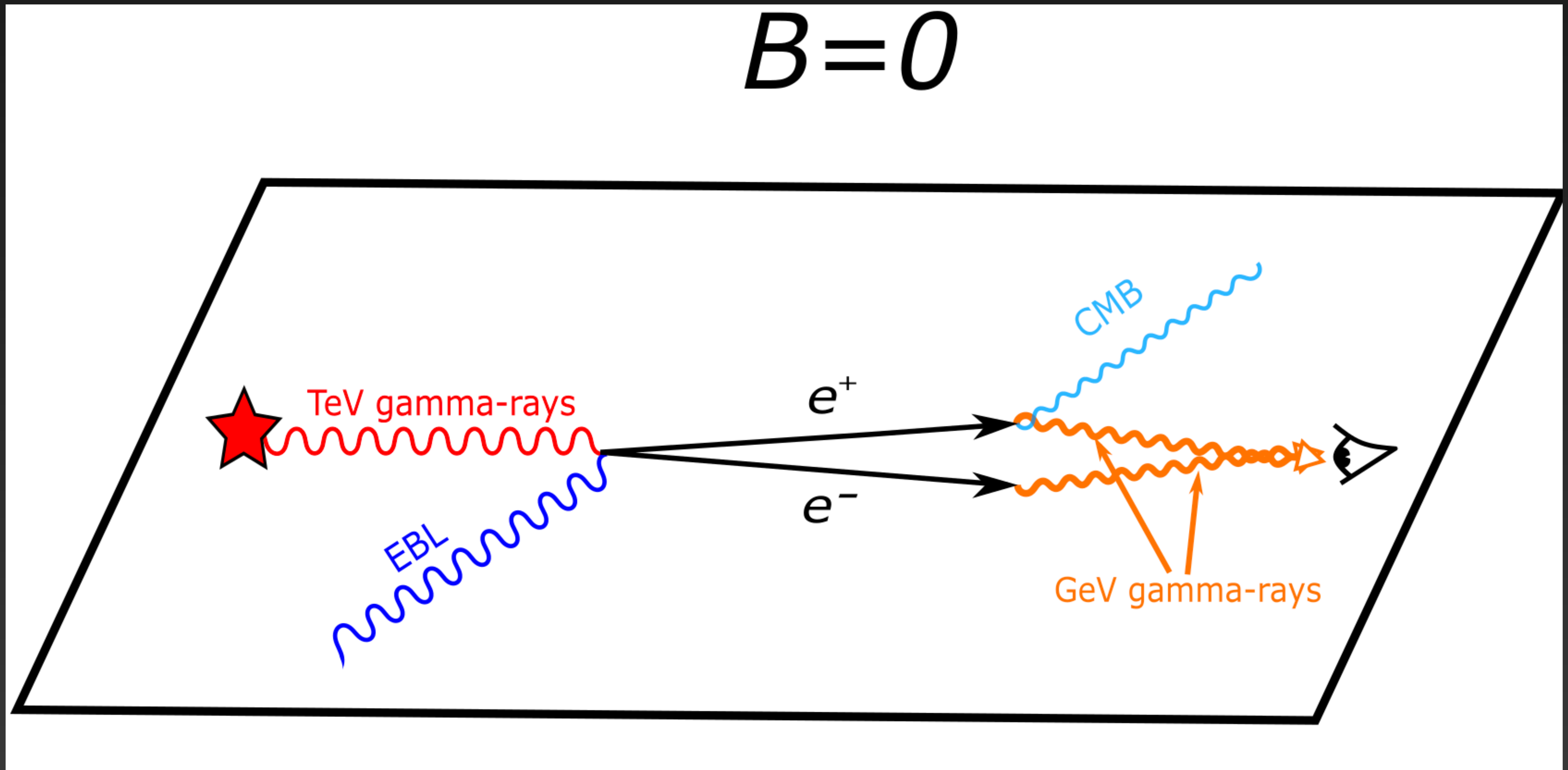
How to measure the IGMF?
Secondary emission: prediction

Charged particles interact with CMB photons via the inverse Compton effect.

This results in the production of GeV photons propagating in the

same direction as the original TeV photons

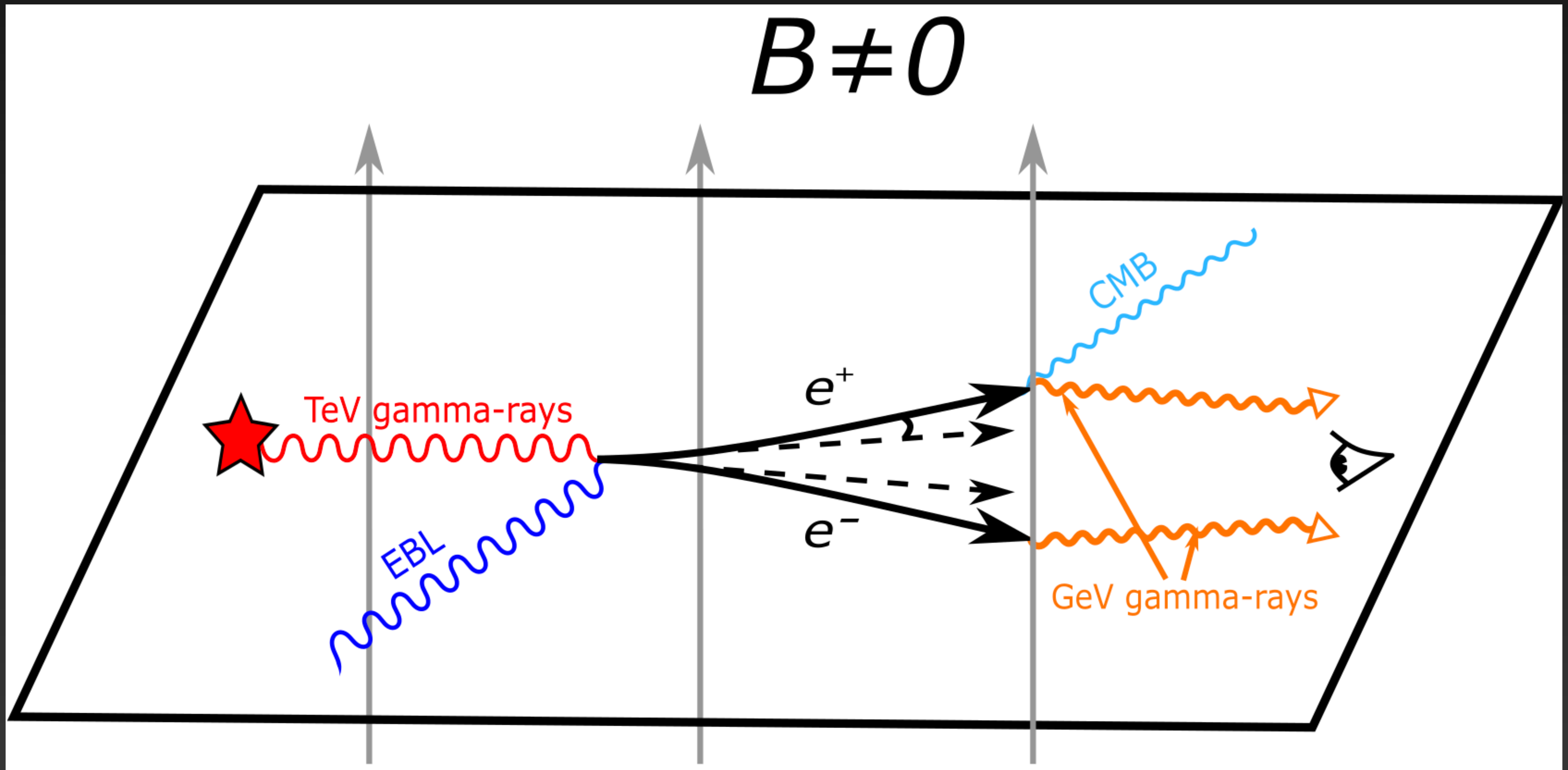




How to measure the IGMF?

Secondary emission: prediction

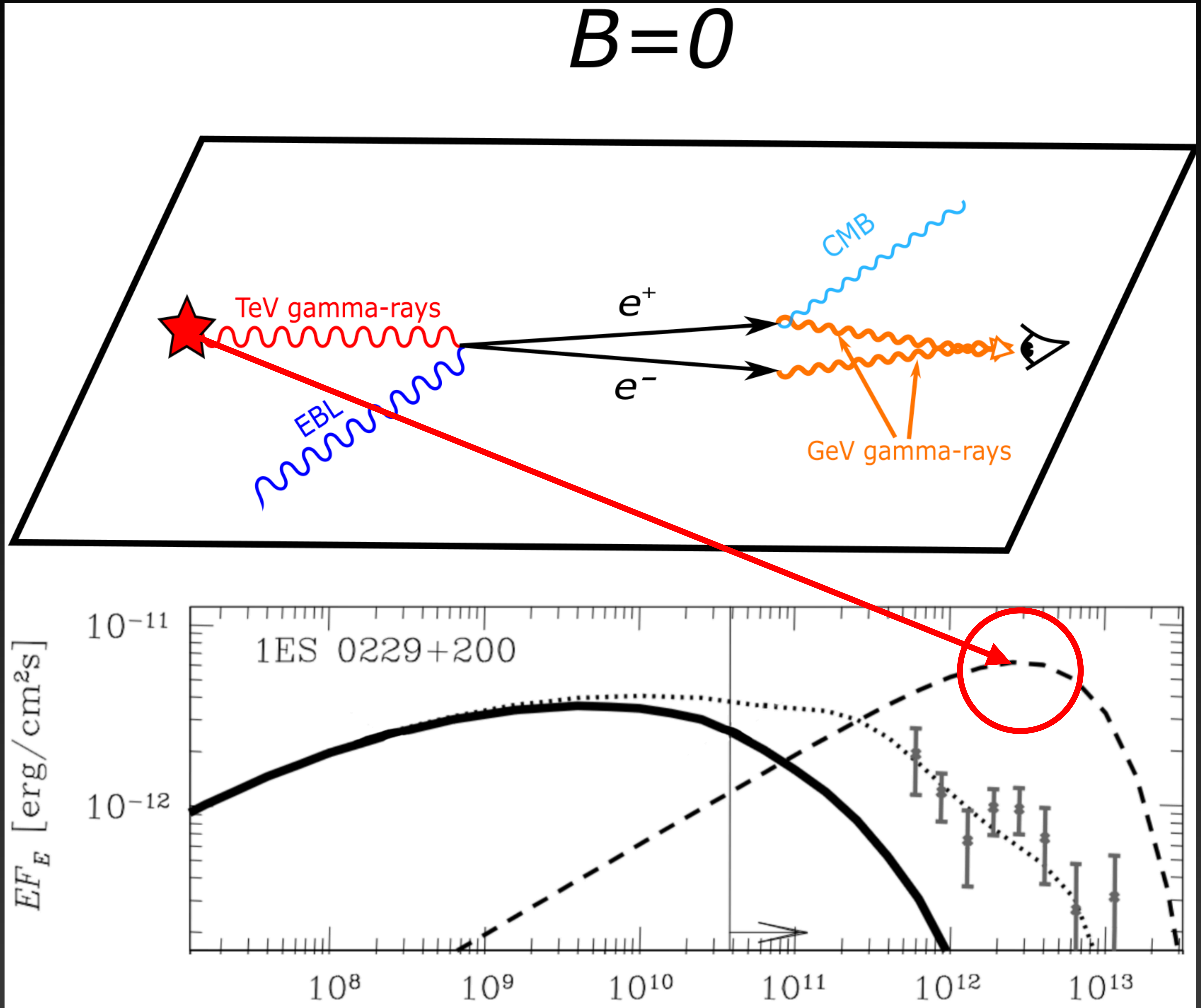
However, if there is a **magnetic field** in between, e^+/e^- will be deflected and **GeV photons** might create an extended emission around TeV point sources



How to measure the IGMF?

Secondary emission: prediction

- **Blazars** have an intrinsic spectrum that grows with energy and emit TeV photons



Neronov & Vovk, 2010

How to measure the IGMF?

Secondary emission: prediction

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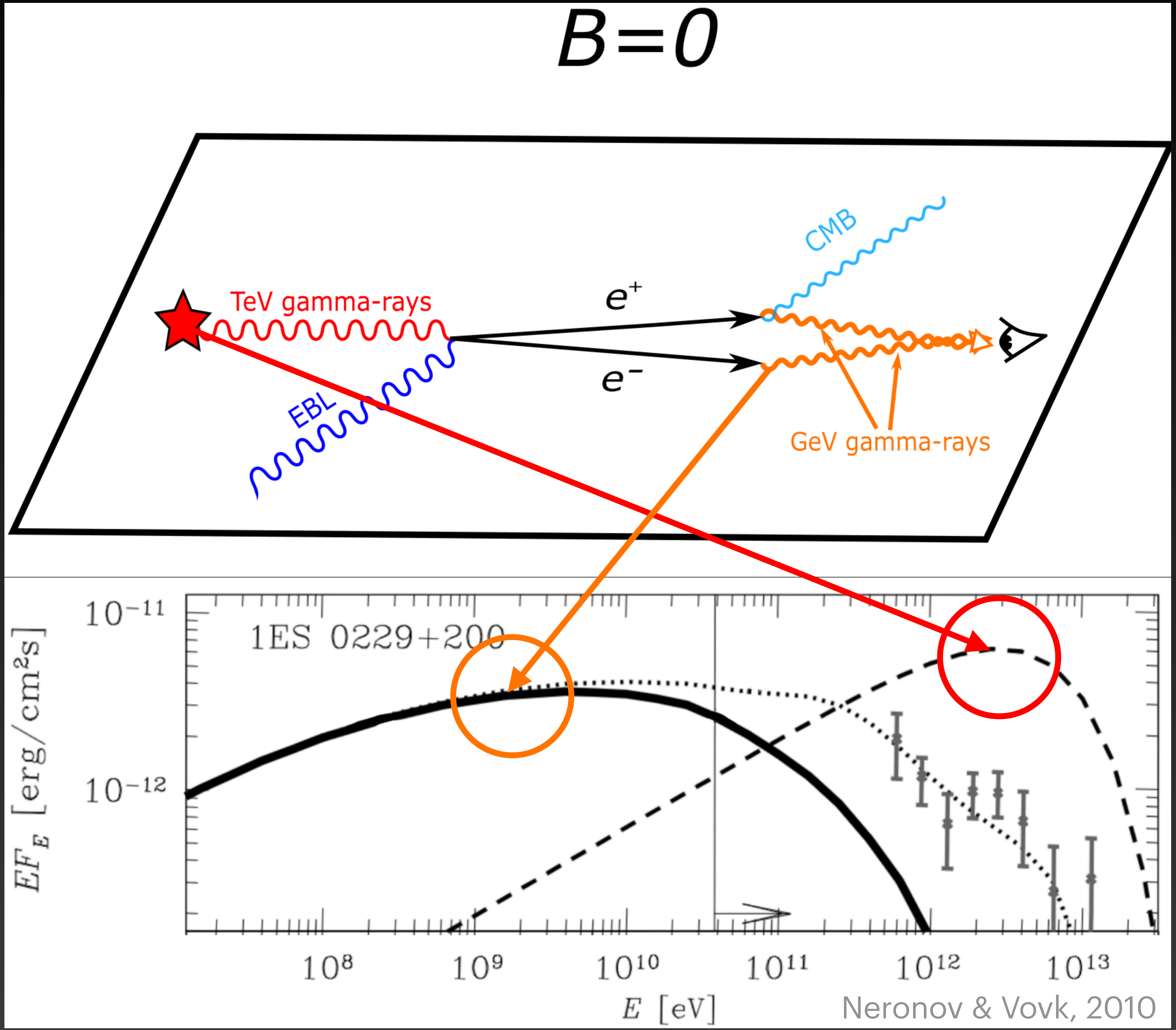
- If there is **no IGMF**, we expect to detect secondary GeV photons



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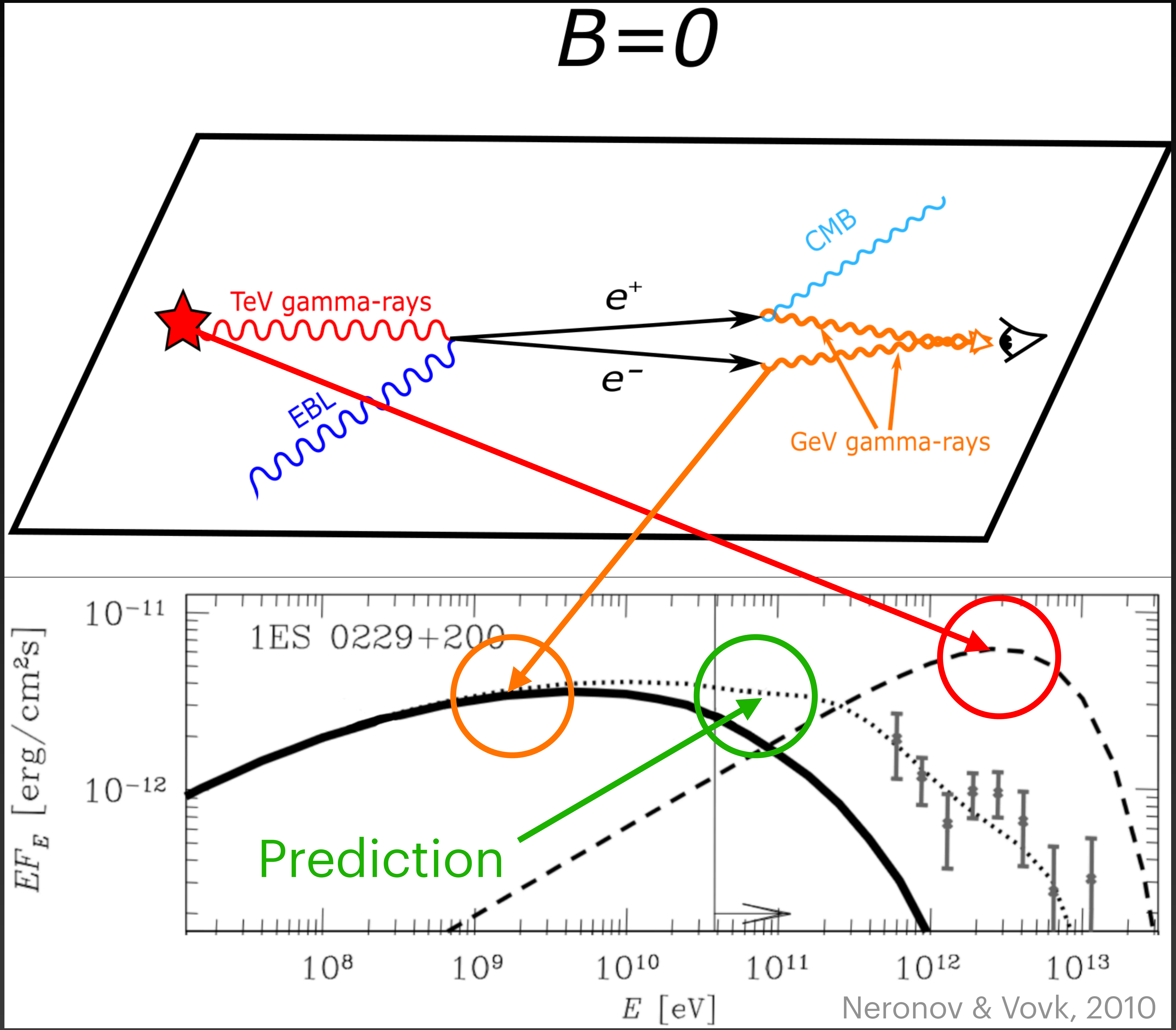
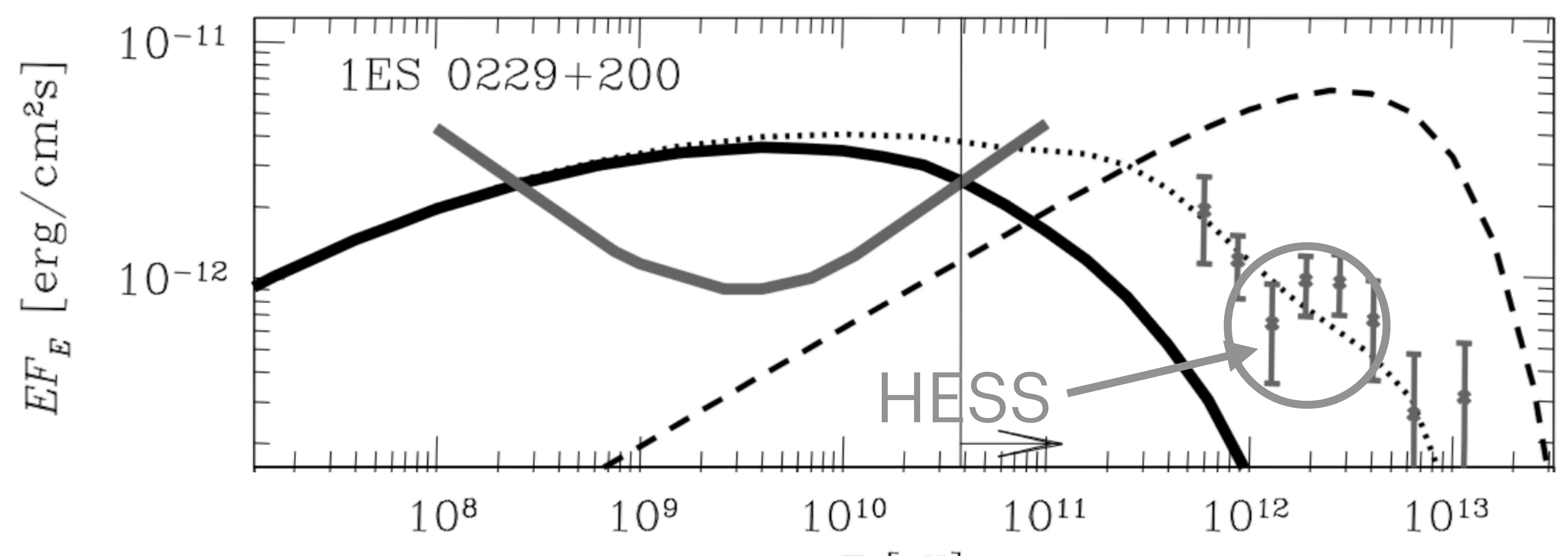


How to measure the IGMF?
Secondary emission: observation

- **HESS** observed the source in the TeV range



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How to measure the IGMF?

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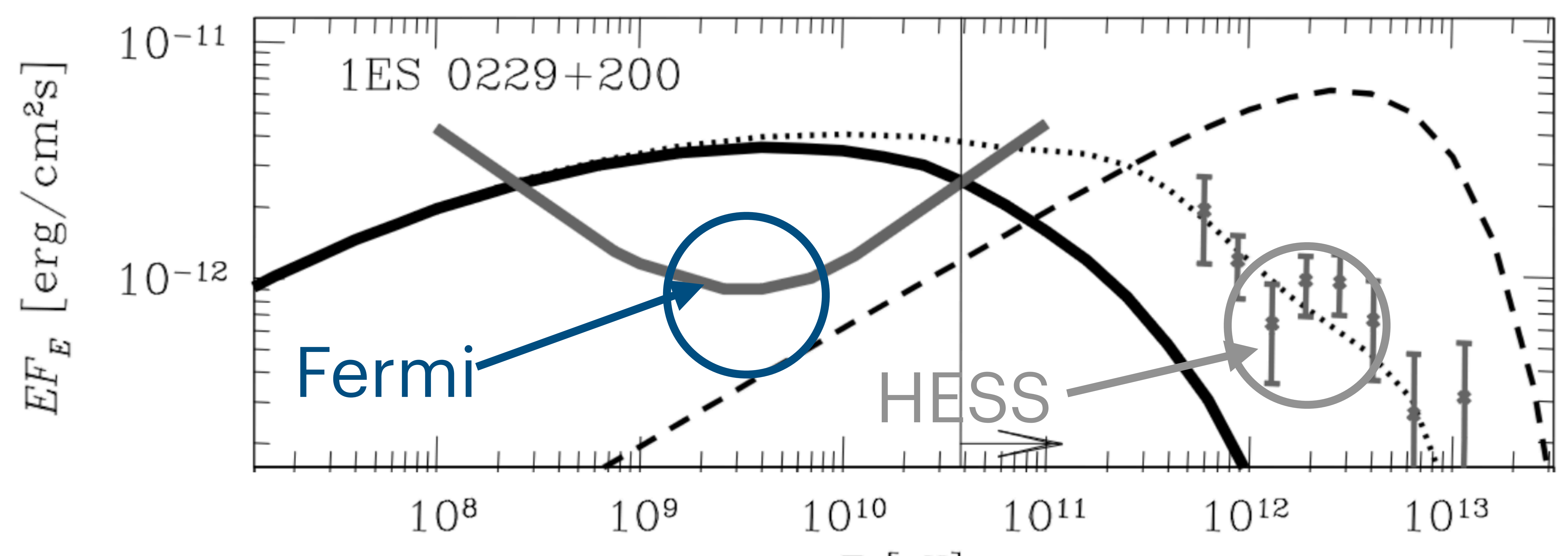
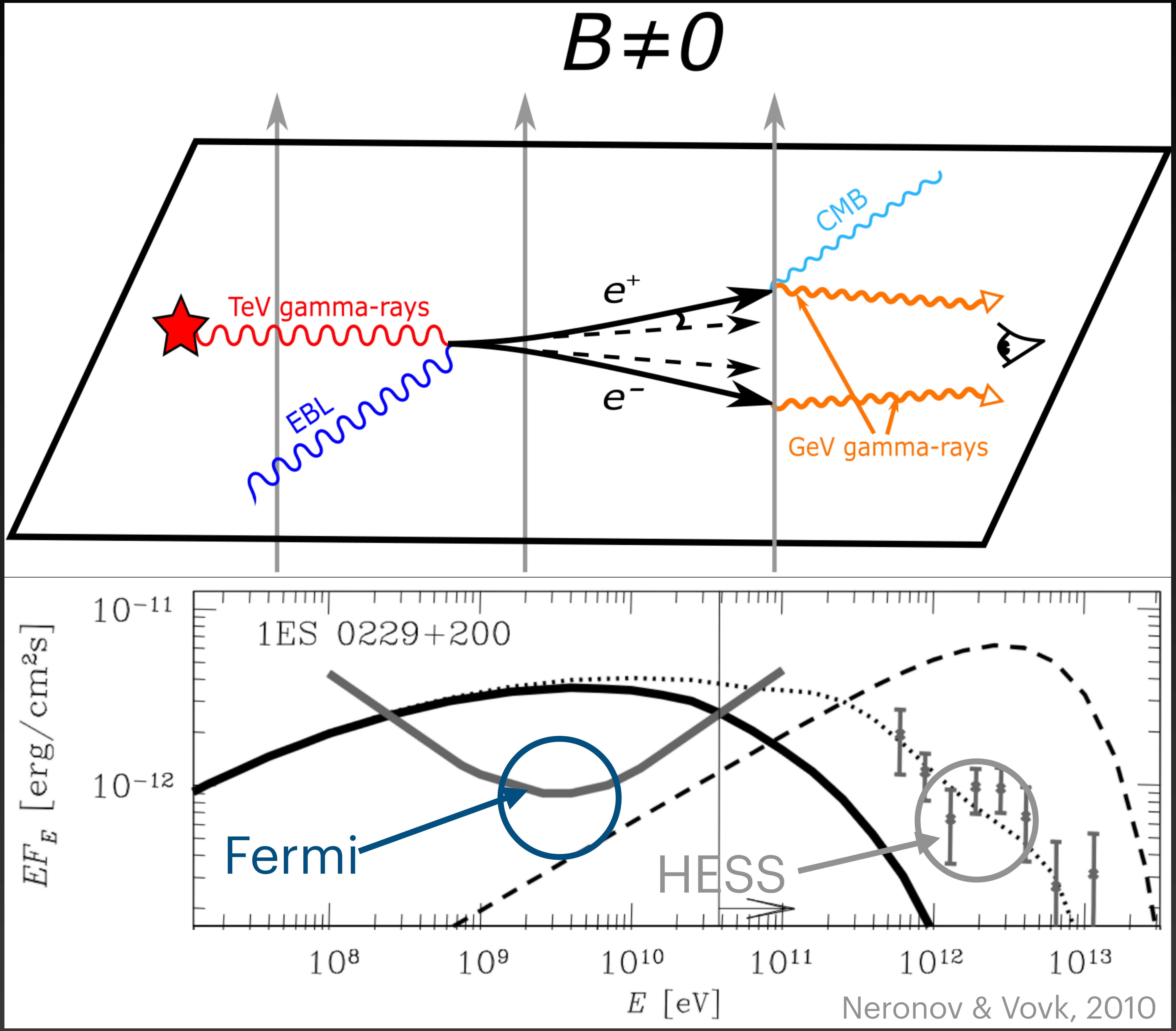


Neronov & Vovk, 2010

How to measure the IGMF?

Secondary emission: explanation

- **HESS** observed the source in the TeV range
- However, **Fermi** did not observed the predicted GeV emission
- This might indicate that we have the **IGMF** where charged particles deflect from their initial trajectories



Galactic feedback

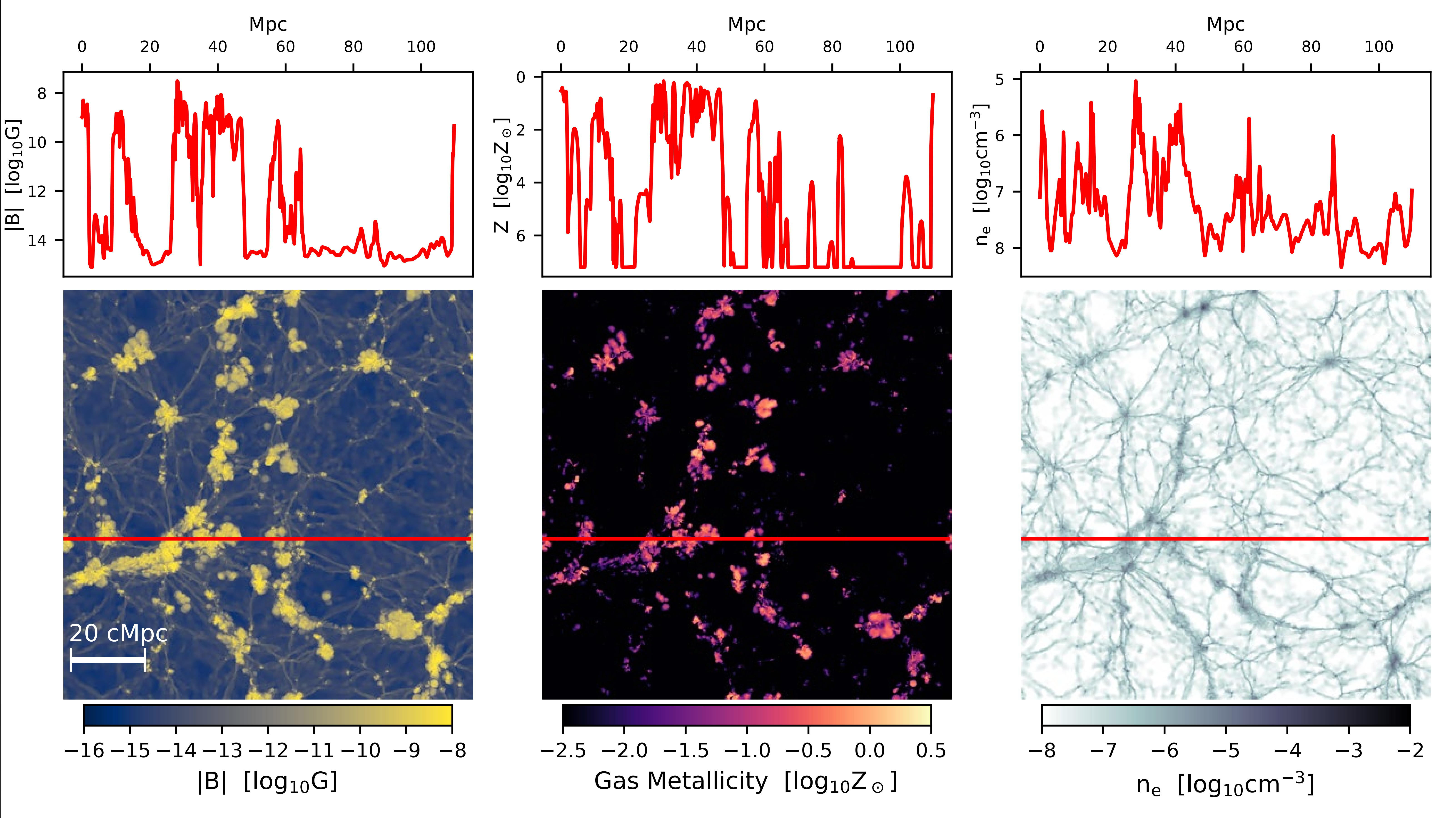
The "genuine" properties of the IGMF can be affected by processes within galaxies

Indeed, **feedback** from **supernovae and active galactic nuclei** (AGNs) could spread out galactic matter and magnetic field at some distance around galaxies

To what extend are the IGMF affected by galactic feedback?
We use cosmological numerical simulations to analyze this question

Over-magnetized bubbles in IllustrisTNG simulations

In IllustrisTNG we have observed **macroscopic (tens Mpc) regions** around clusters of galaxies with **electron densities** as **low** as in the intergalactic medium (IGM) and **magnetic fields** as **strong** as in clusters - over-magnetized bubbles



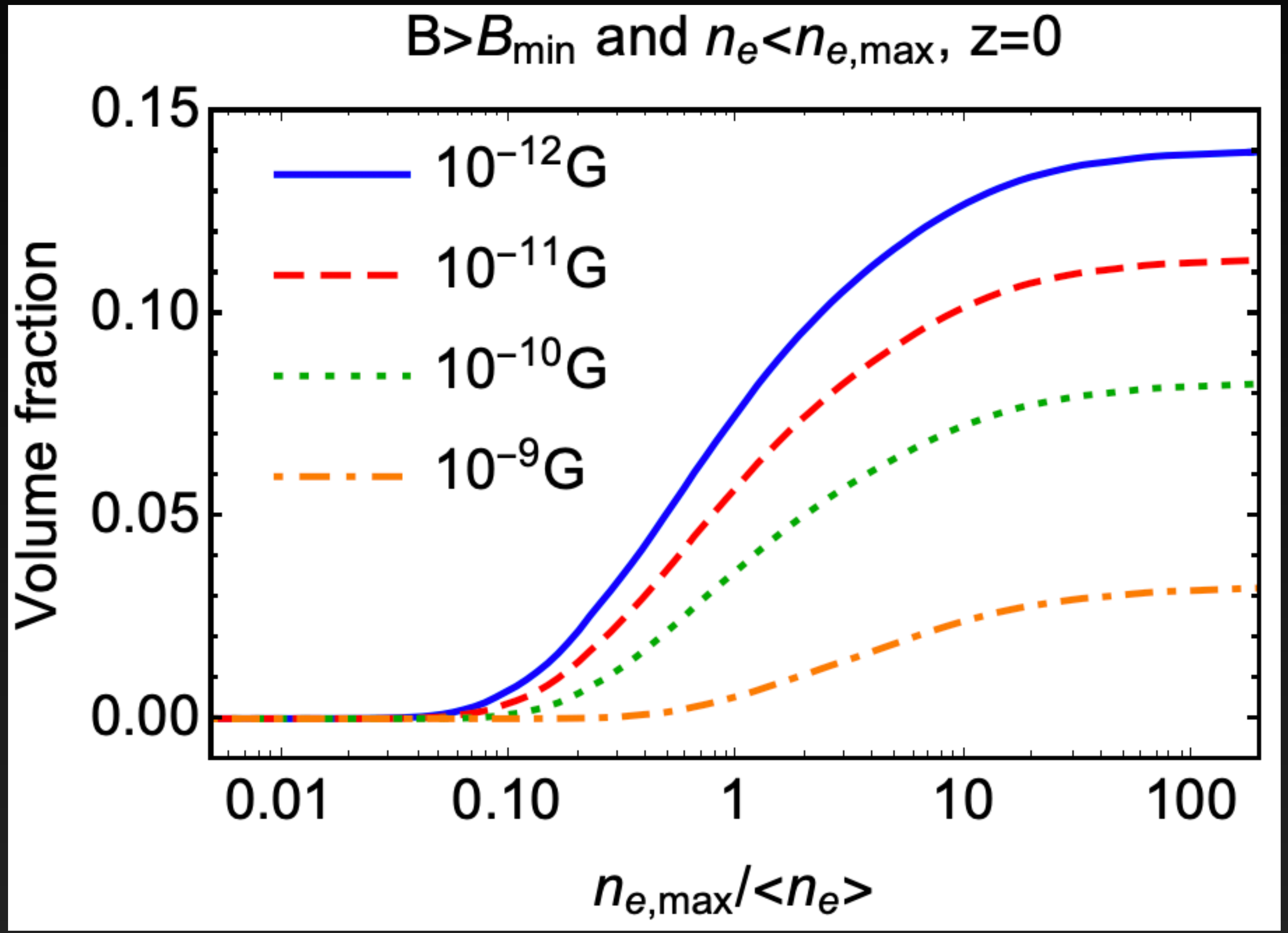
Typical sizes of the bubbles are of an **order of magnitude** larger than the virial radii of their parent clusters.

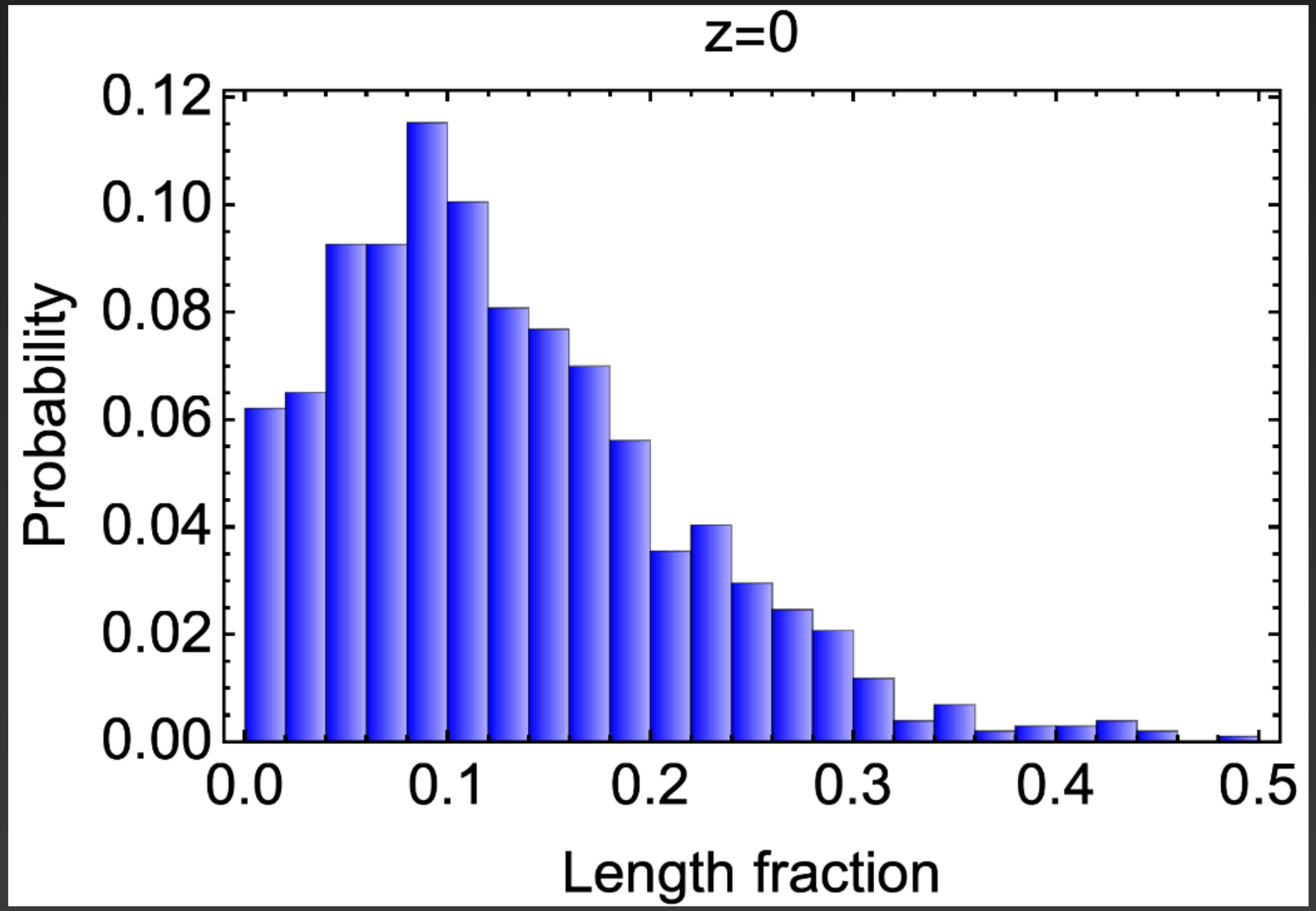
Over-magnetized bubbles in IllustrisTNG simulations

At z = 0, the magnetic field is **stronger** than 10^{-12} G in **15% of the volume**, while it is stronger than 10^{-9} G in 3% of the volume

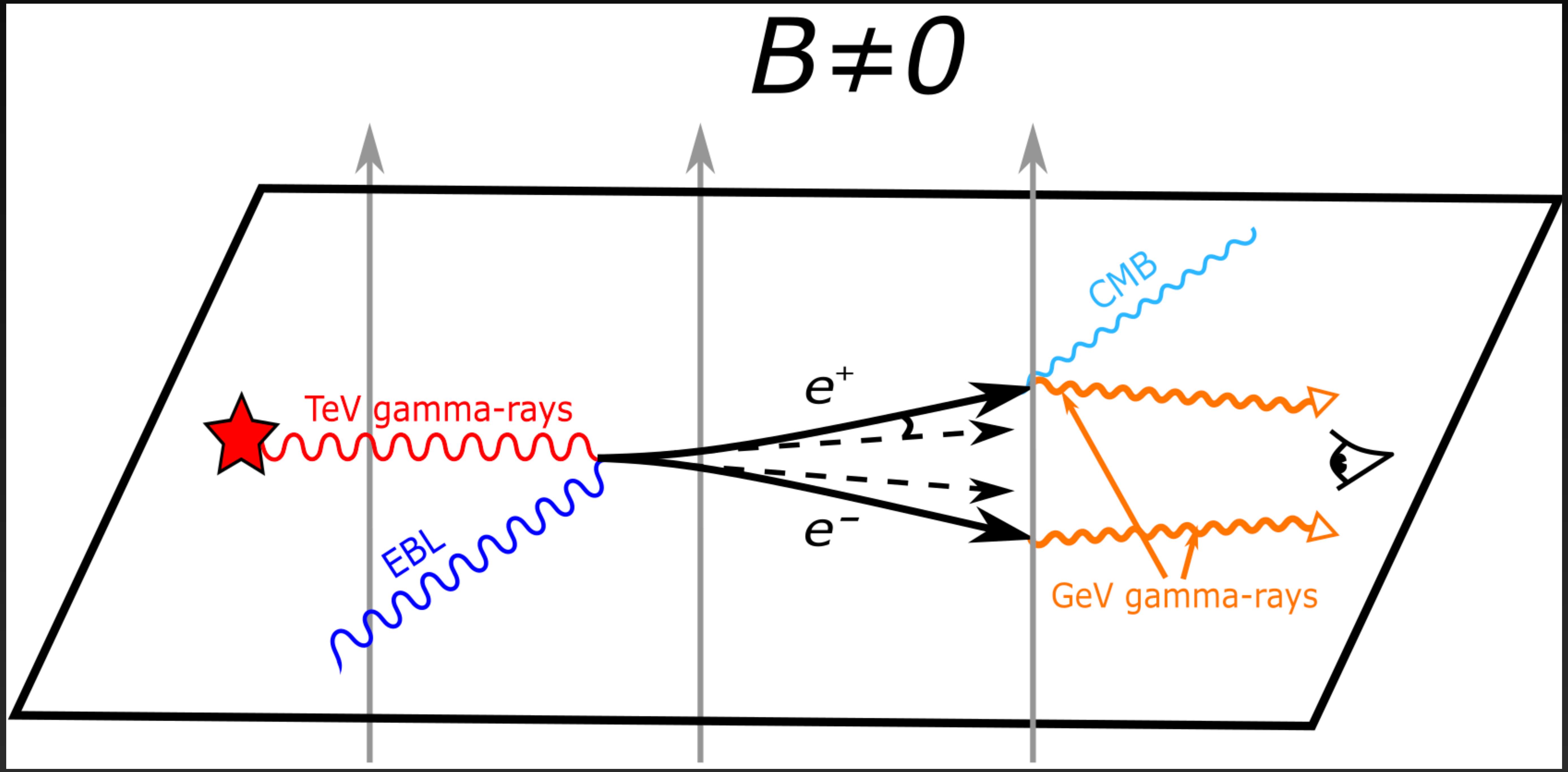
More than **50% of random lines of sight** pass through magnetic bubbles and spend **more that 10%** of their length there

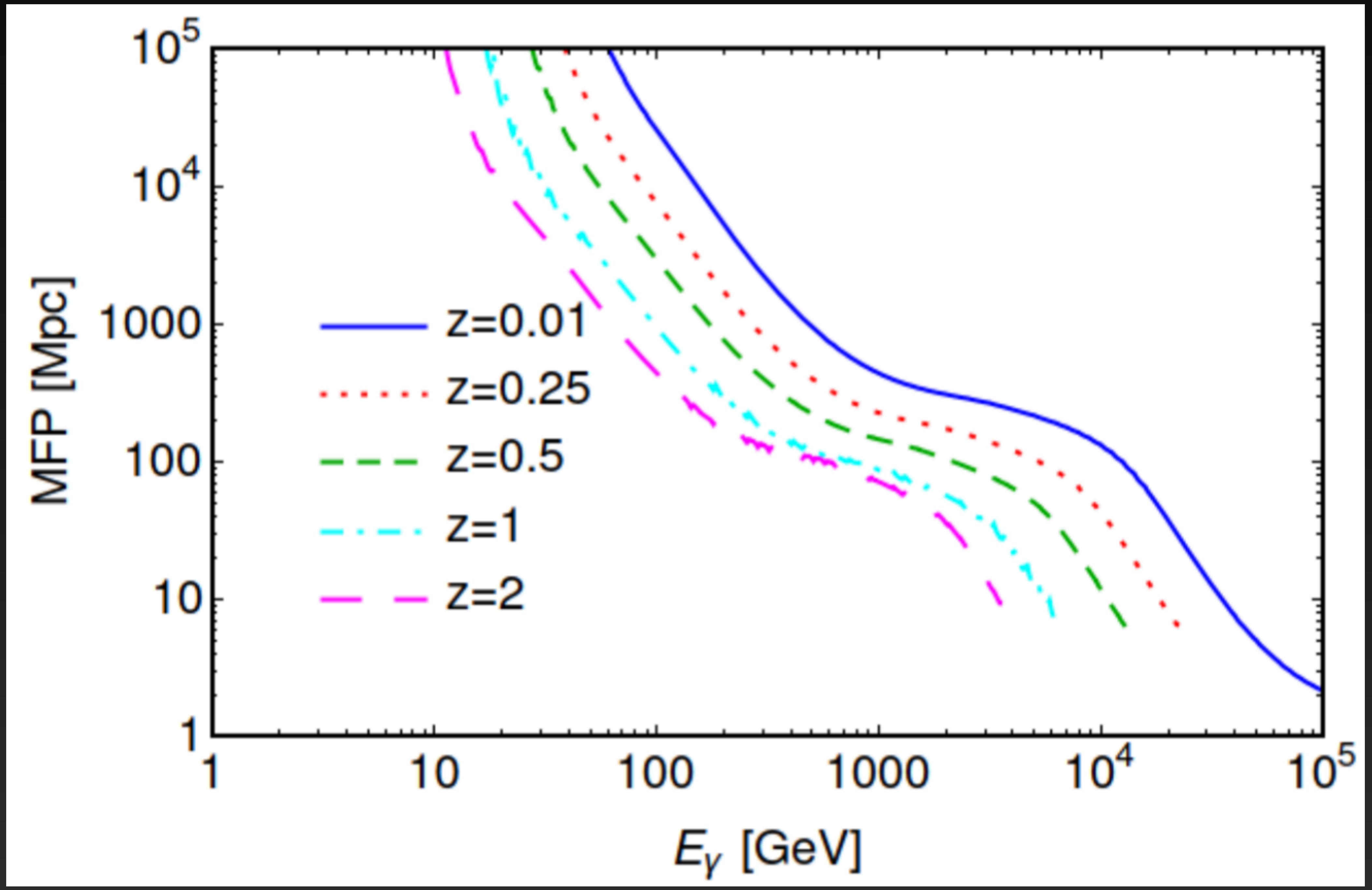
This makes these bubbles **important** for e.g. radio and **γ-ray astronomy**





Can the lower bound on the IGMF be affected by bubbles?





[K. Bondarenko, AS et al., A&A, 2022]

Blazars are very likely **surrounded** by magnetic bubbles. Very **high-energy photons** might convert into an electron-positron pair **inside a magnetic bubble**

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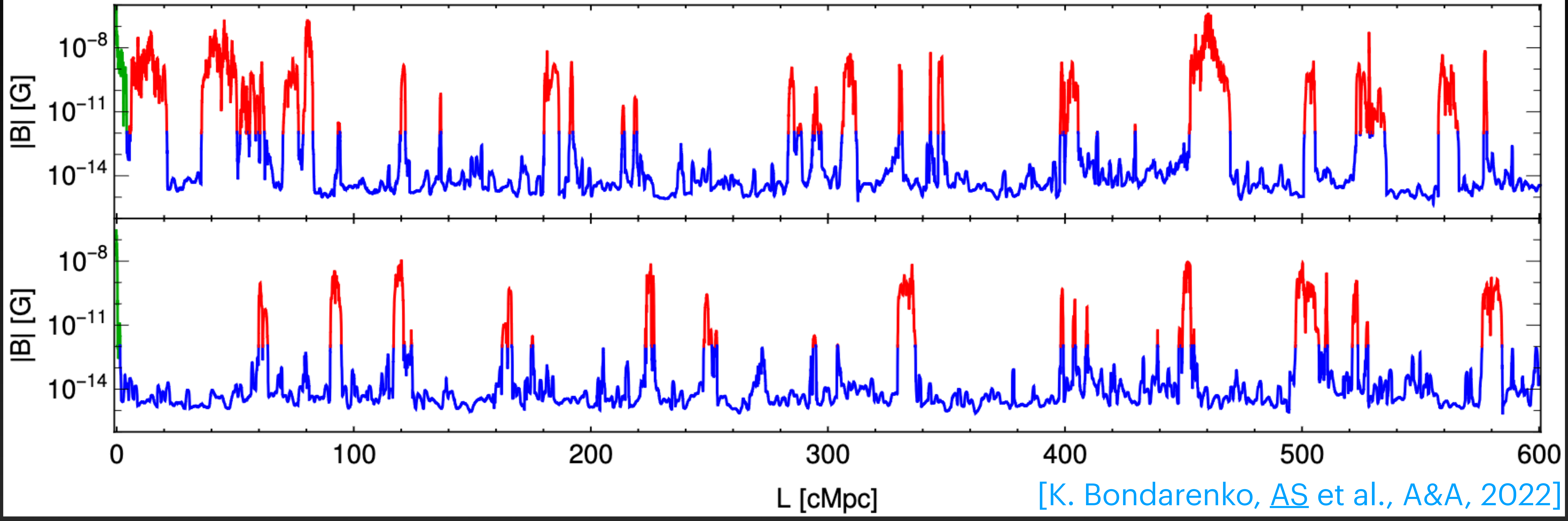
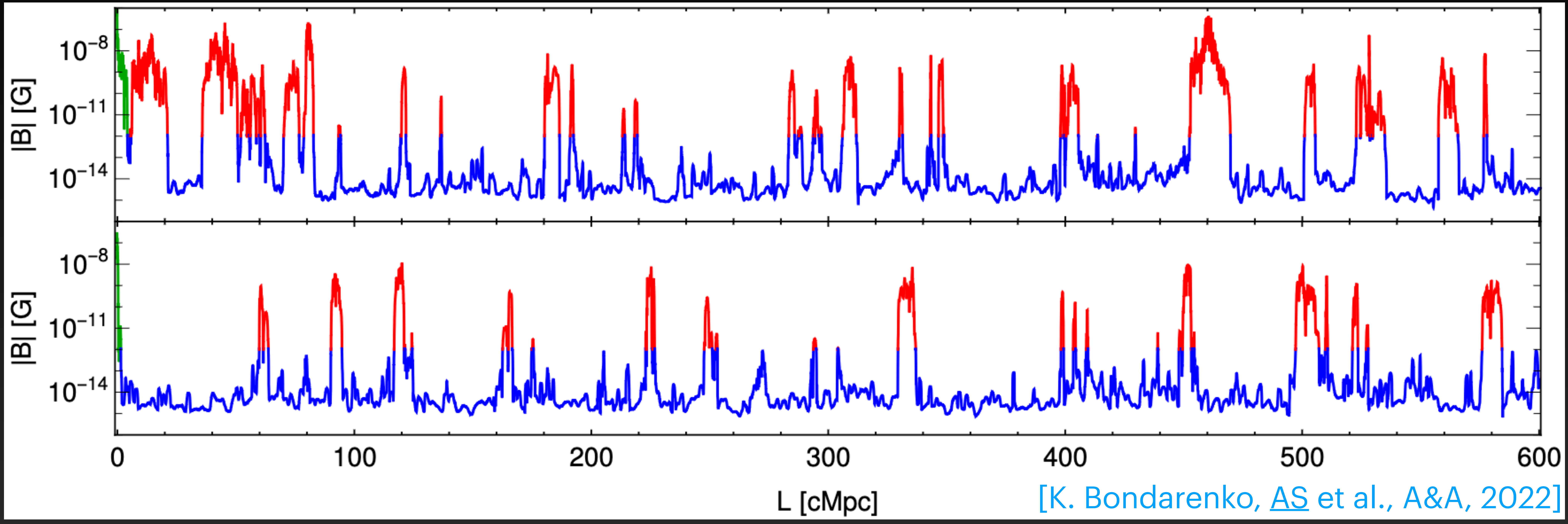


[K. Bondarenko, AS et al., A&A, 2022]

- **Individual sources** can be “unlucky” and have an **extended over-magnetized bubble** along the line of sight to the Earth
- For individual objects, **up to 70% of the energy of secondary emission was lost**, but for most of the systems, the missing energy fraction is below 50%

Can the lower bound on the IGMF be affected by bubbles?



[K. Bondarenko, AS et al., A&A, 2022]

- One way to deal with this problem is to **increase statistics**
- With the **CTA**, we will **significantly increase** both the quantity and quality of observed sources

Differences in hydrodynamic and subgrid physics models: CAMELS

Credit: Francisco Villaescusa-Navarro

Summary

γ-ray astronomy has the potential to probe intergalactic magnetic fields, and a significant advancement is anticipated through future CTA observations

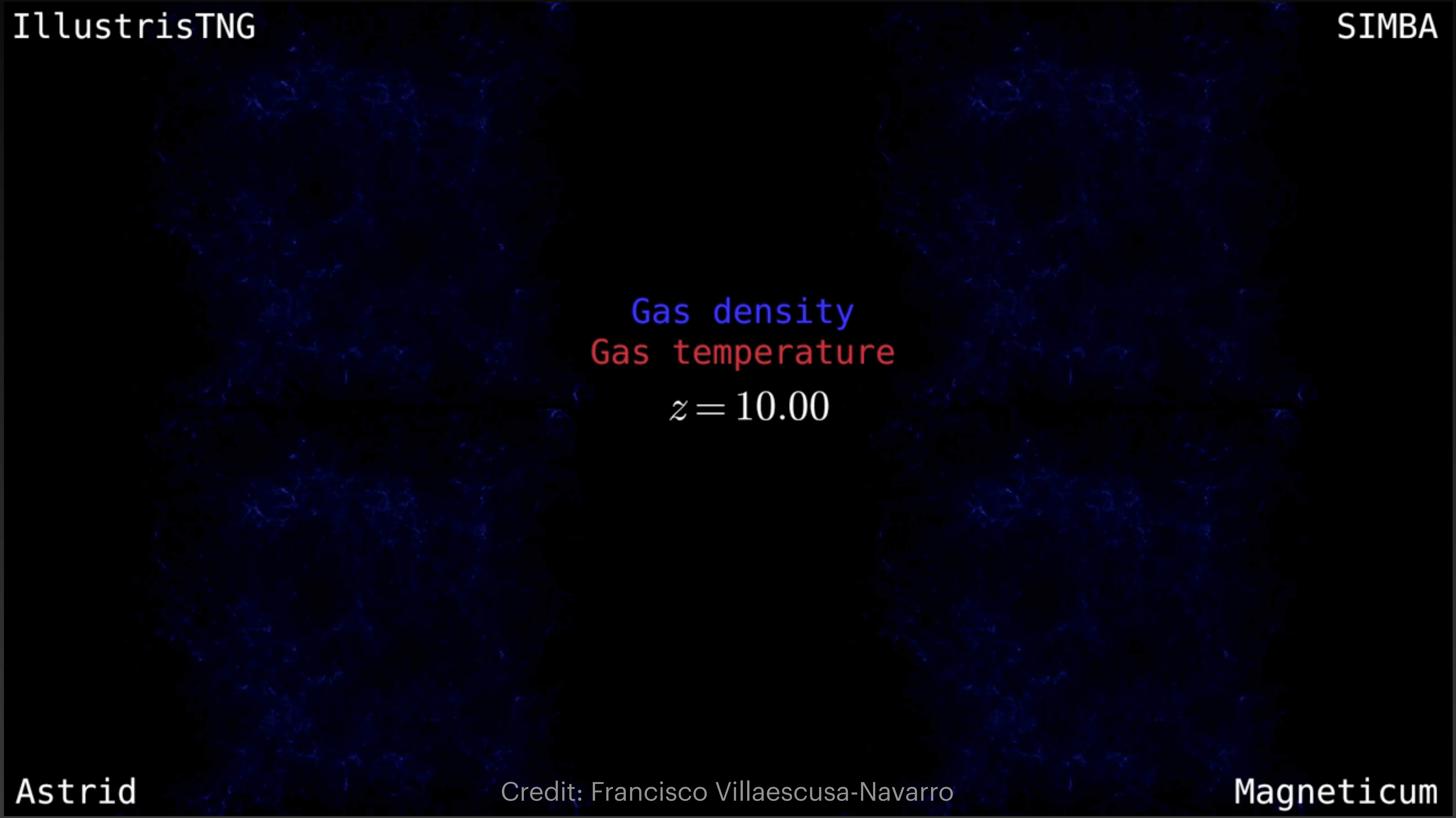
The feedback from galaxies could “pollute" the intergalactic medium. With γ-ray astronomy, we could probe not the large-scale magnetic fields in the intergalactic medium, which could be primordial, but these magnetic bubbles

To detect primordial magnetic fields, it is essential to comprehend galactic feedback and its associated uncertainties, as well as develop methods for distinguishing them from primordial magnetic fields.

Credit: IllustrisTNG

Backup

Differences in hydrodynamic and subgrid physics models: CAMELS

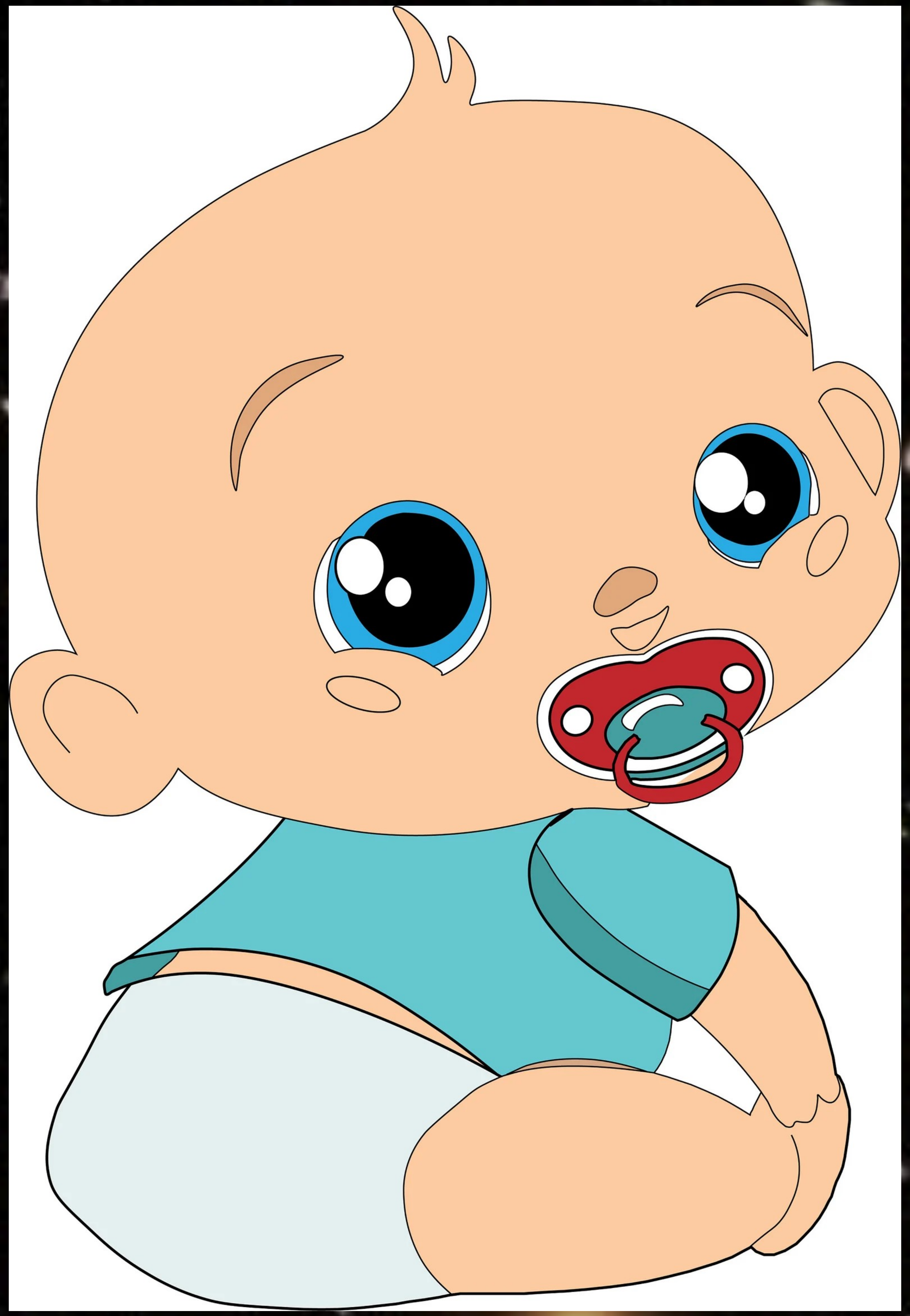


Credit: Francisco Villaescusa-Navarro

Magnetic fields in structures

In order to create e.g. galactic magnetic fields, we need some **seed magnetic field**

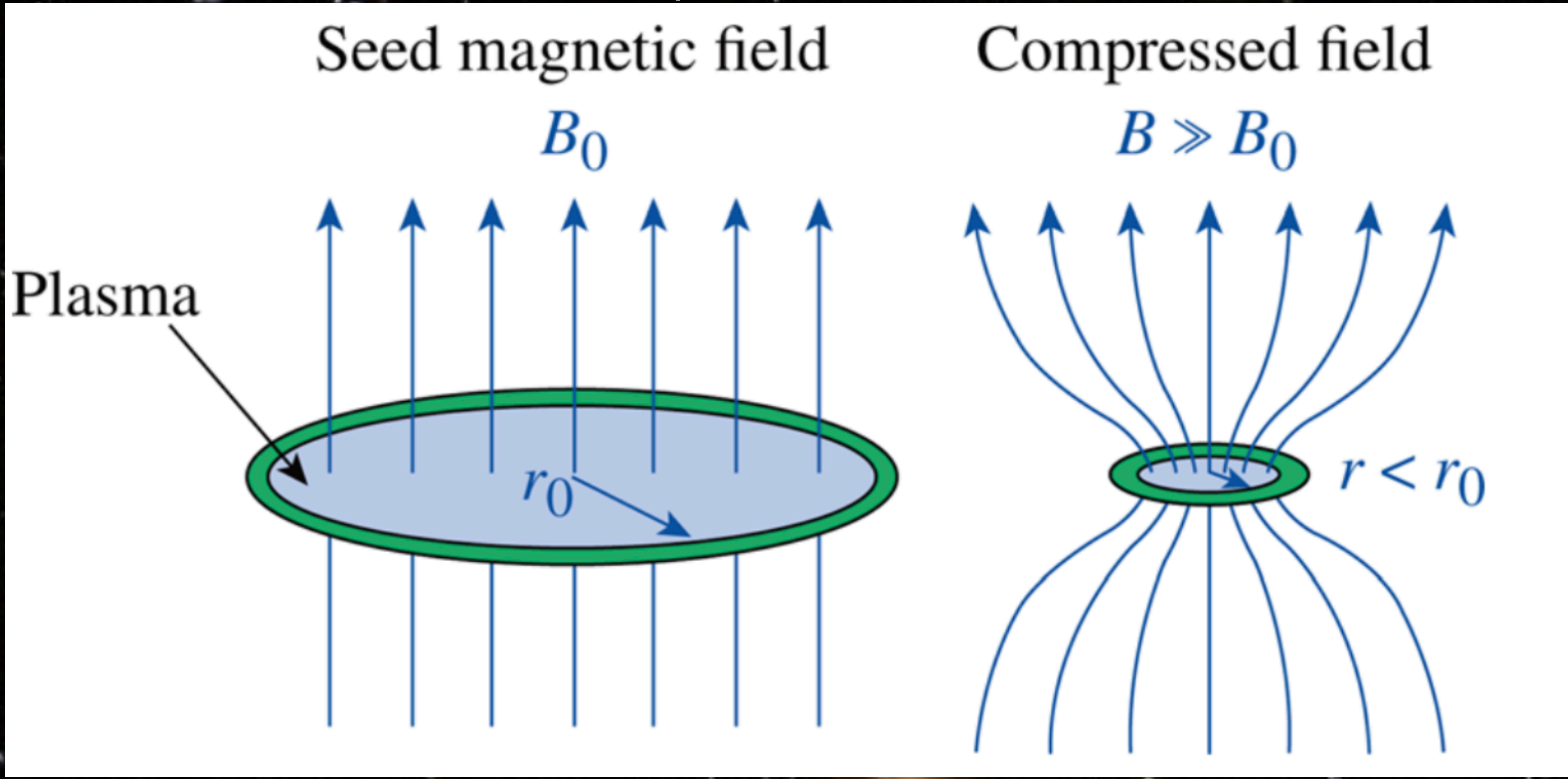
Credit: etsy.com



Magnetic fields in structures

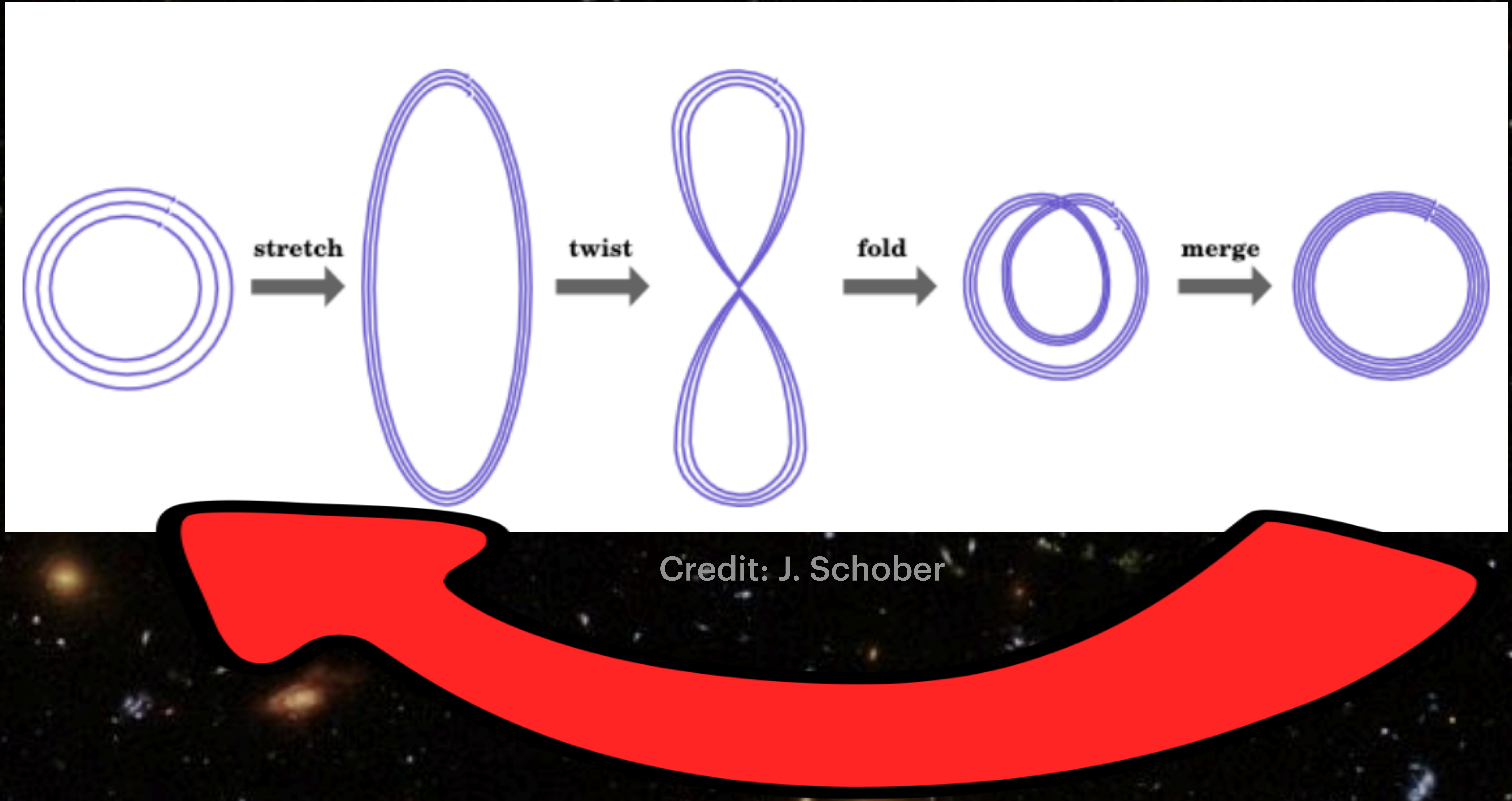
Magnetic fields in collapsed structures were contracted during structure formation

Credit: Phys. Plasmas 19, 056306 (2012)



Magnetic fields in structures

and exponentially **amplified** by turbulent dynamos

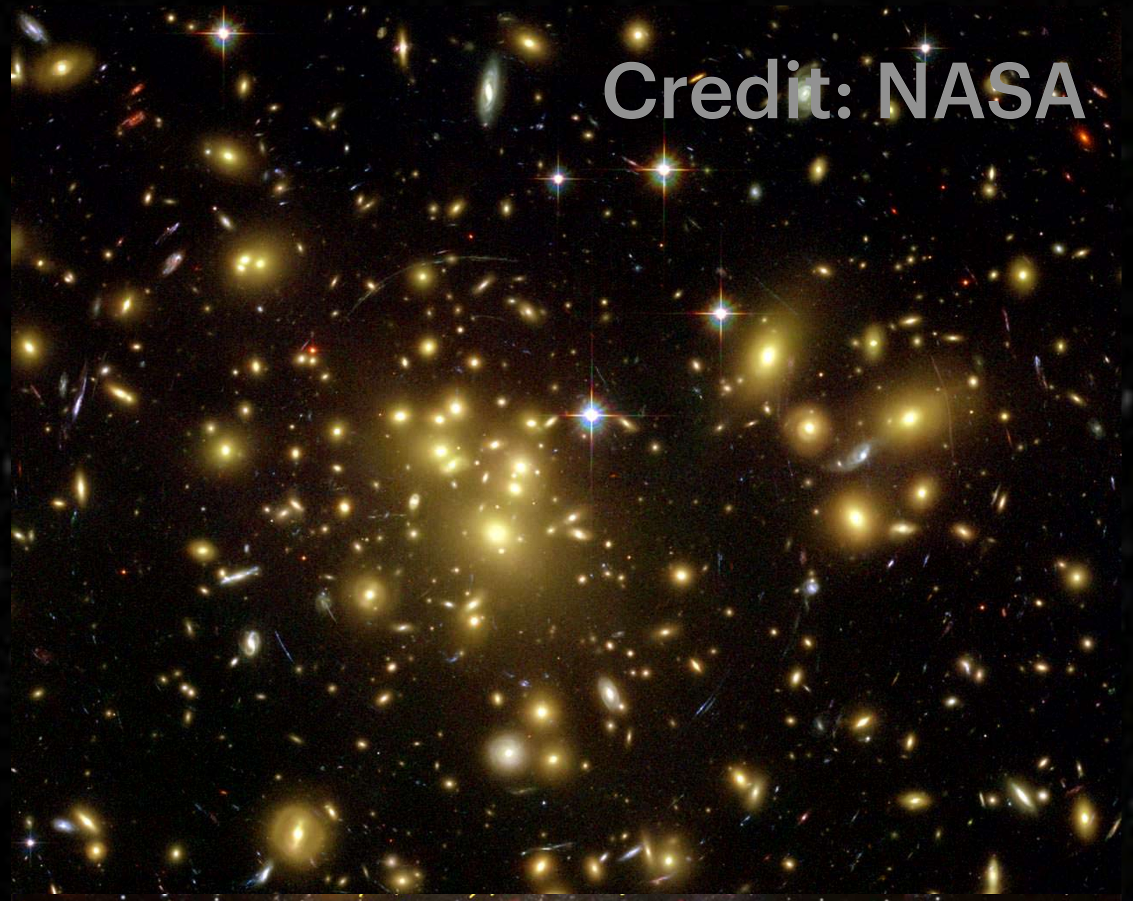


Credit: J. Schober

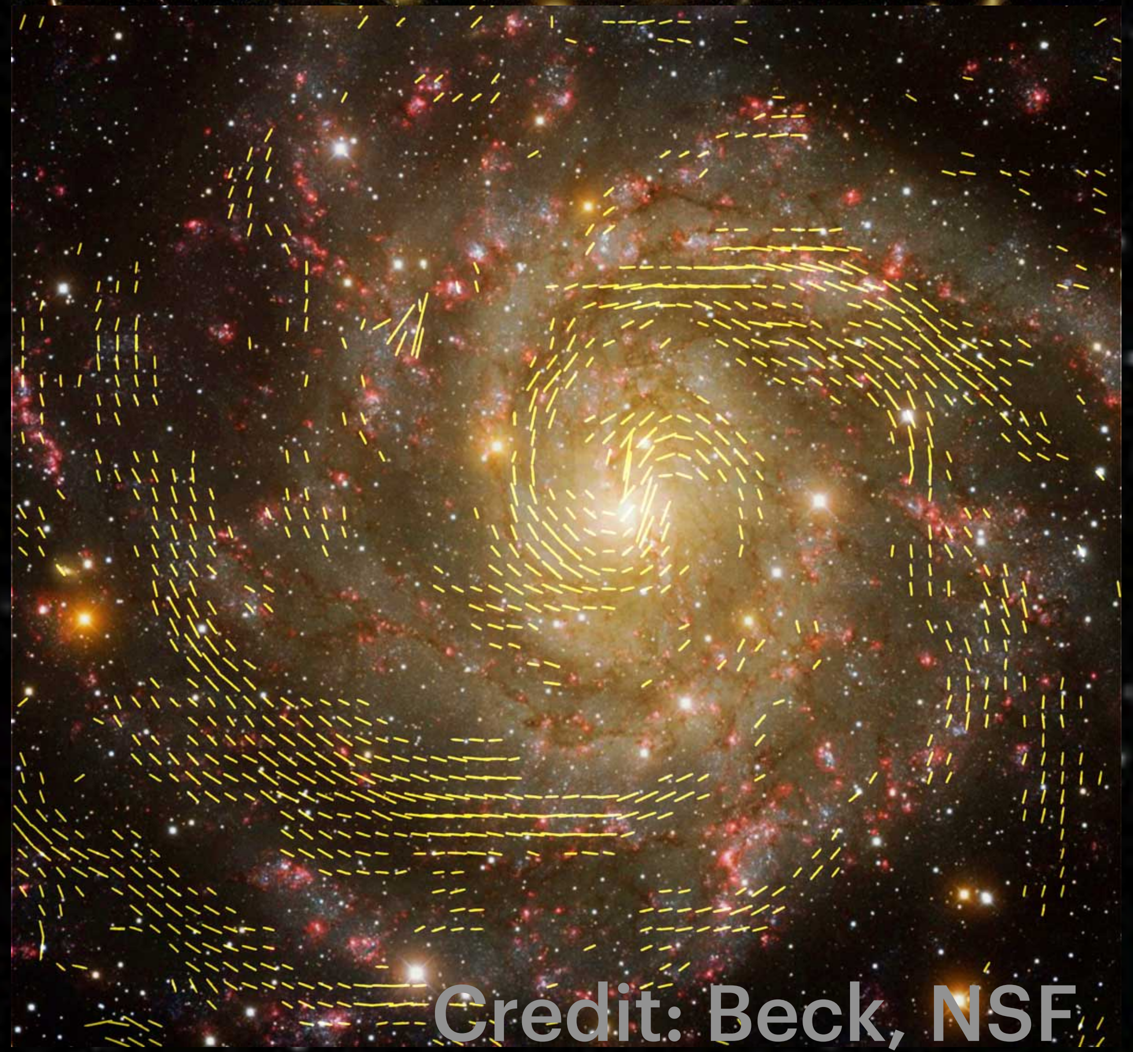
Magnetic fields in structures

Magnetic fields in collapsed structures “**forget**” their initial conditions

Credit: dreamstime.com



Credit: NASA



Credit: Beck, NSF

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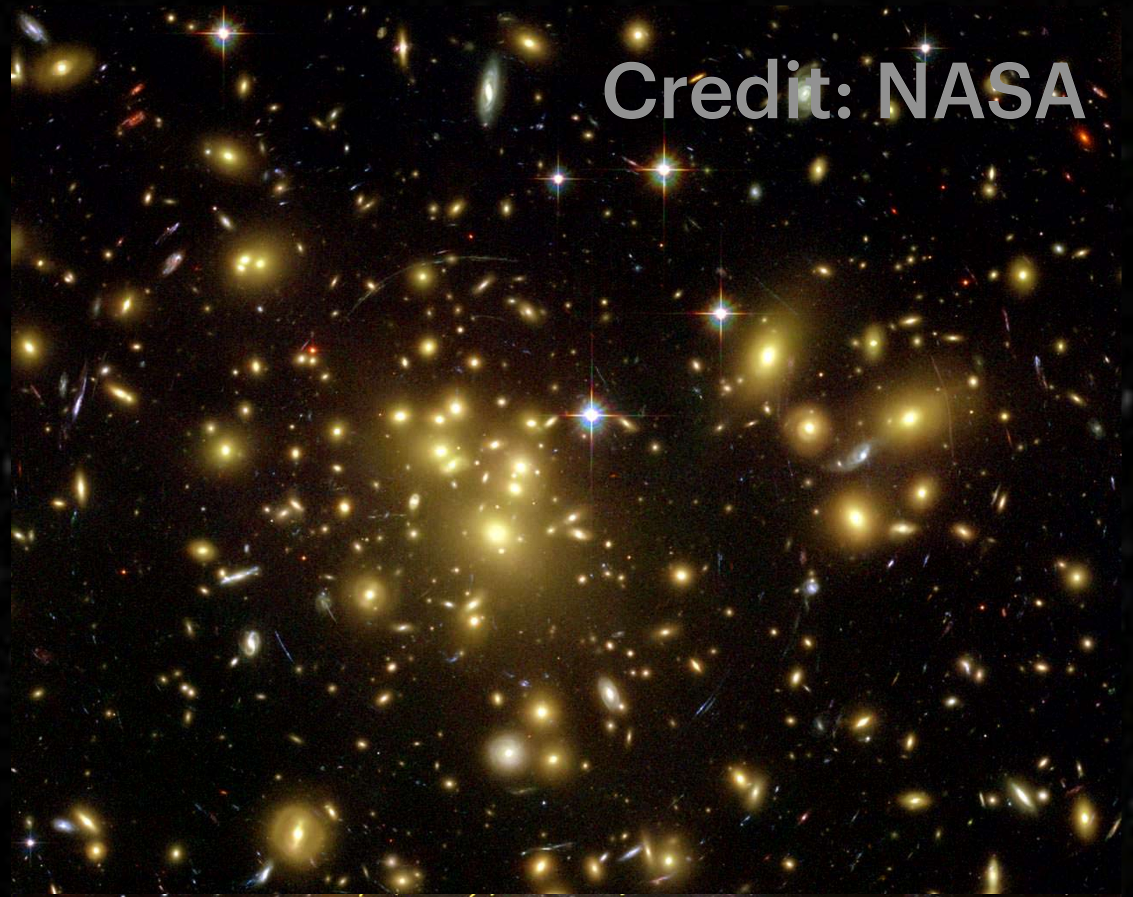
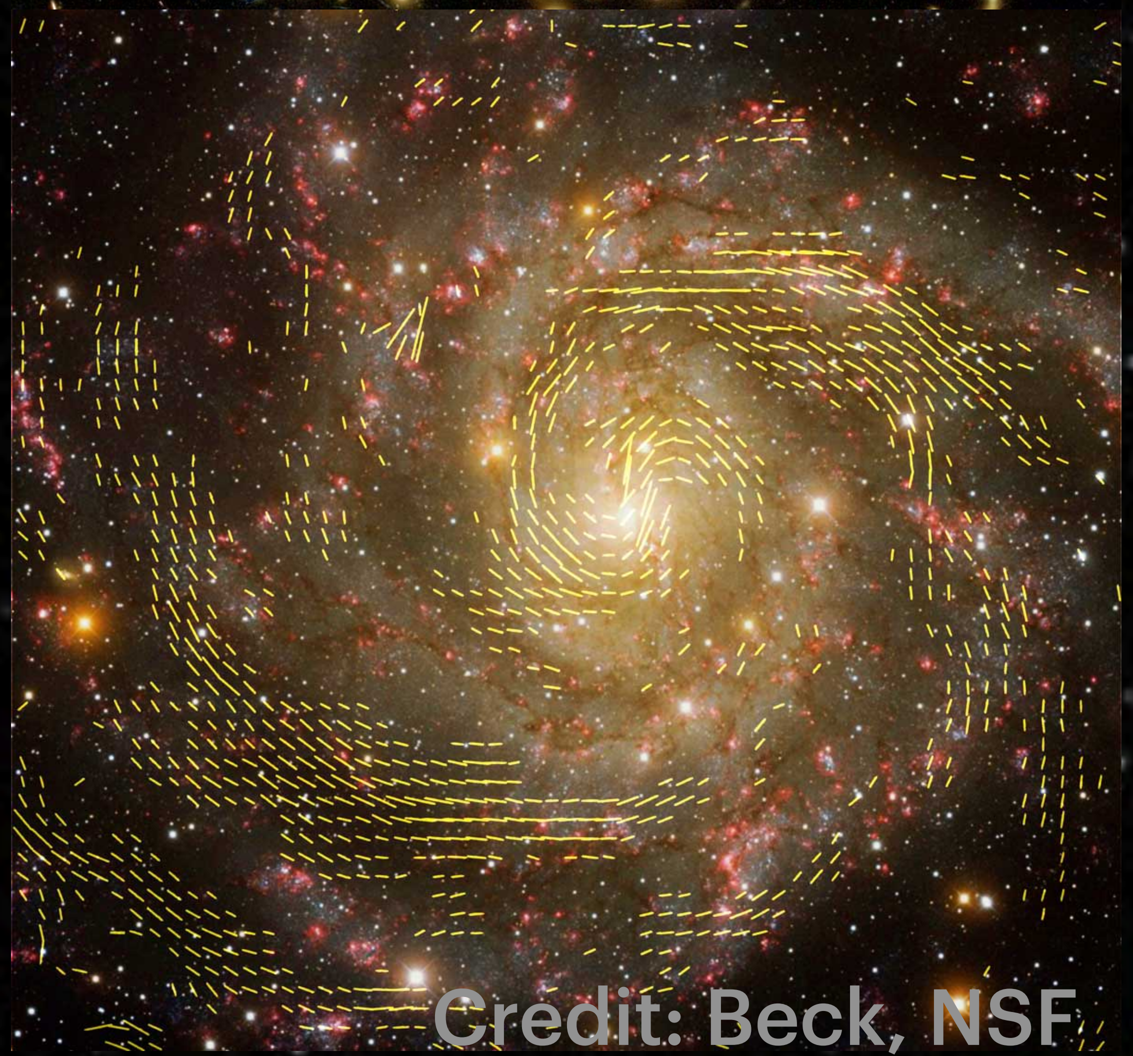


Credit: NASA



Credit: Beck, NSF

How can we study the primordial magnetic fields?

CTA

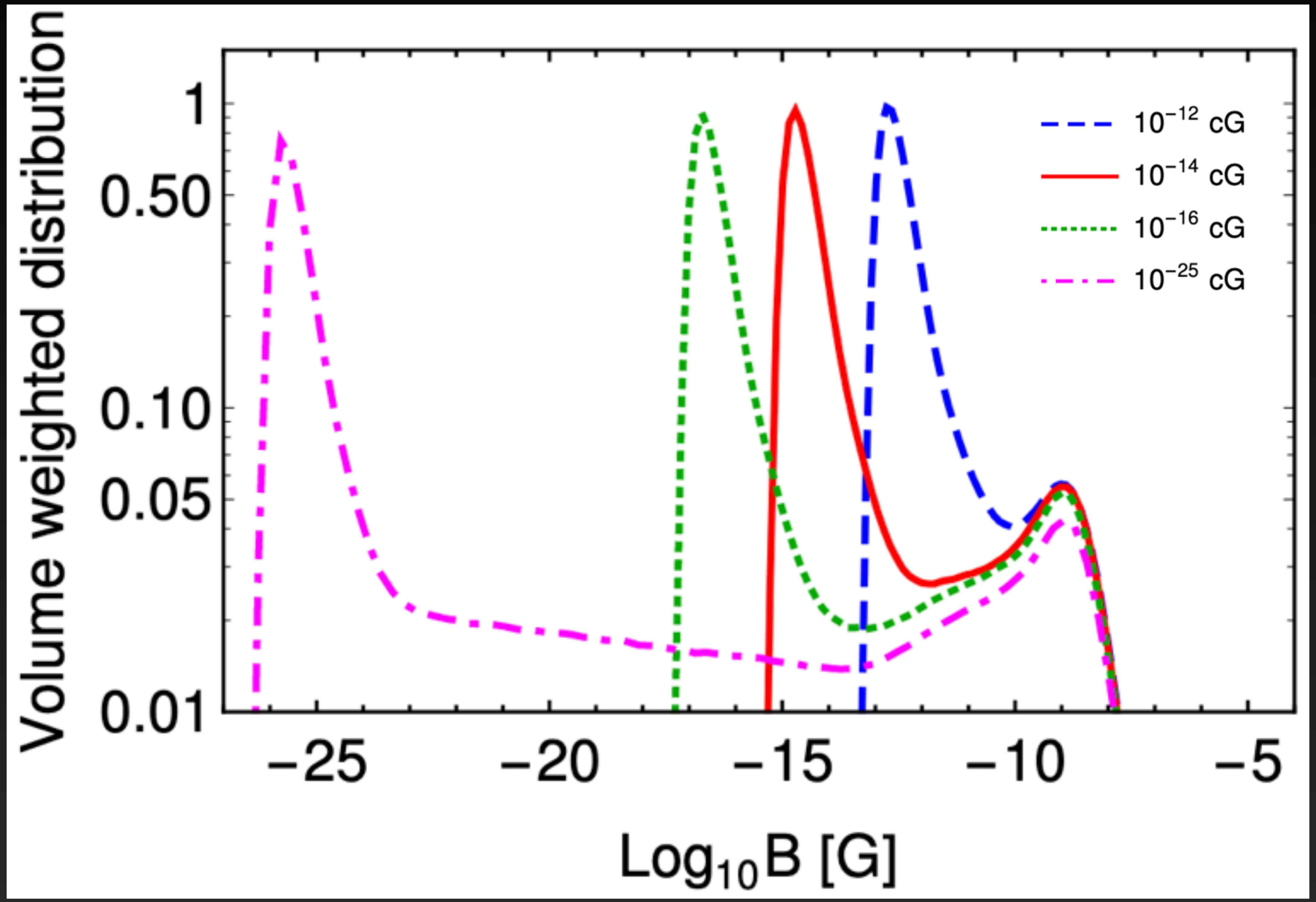
CTA consists of two sites:
North (La Palma) and South (Chile)

There are three types of the telescopes:

- Large (23 m; 4 North, 4 South)
- Medium (12 m; 15 North, 25 South)
- Small (5 m; 0 North, 70 South)

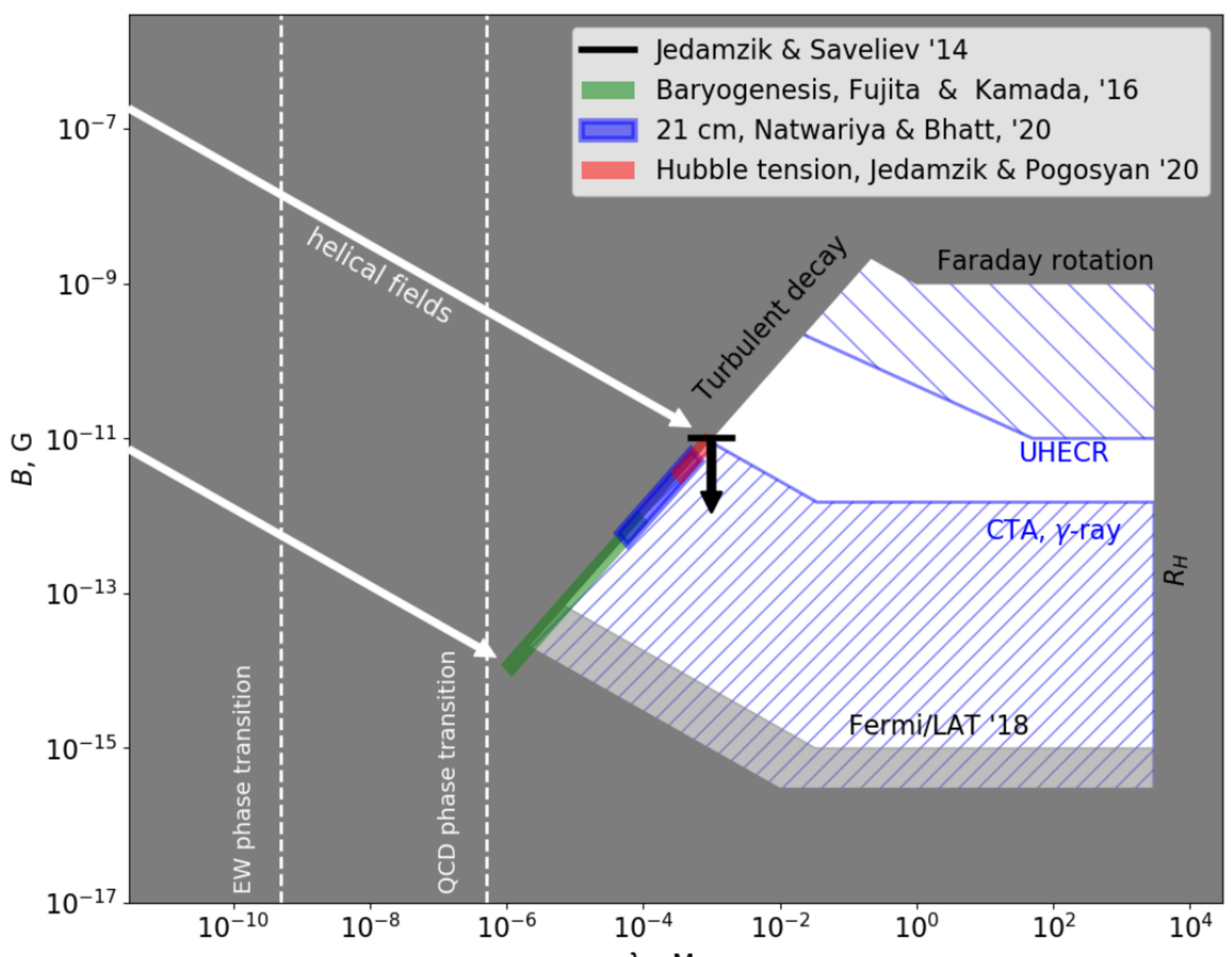
The energy range is from 10 GeV up to 300 TeV

Magnetic fields in bubbles forget initial conditions!



- Distributions of magnetic fields are calculated for TNG25 simulations with **different initial conditions** for the initial fields
- The distribution of **large magnetic fields is the same** regardless of the initial value of the magnetic field

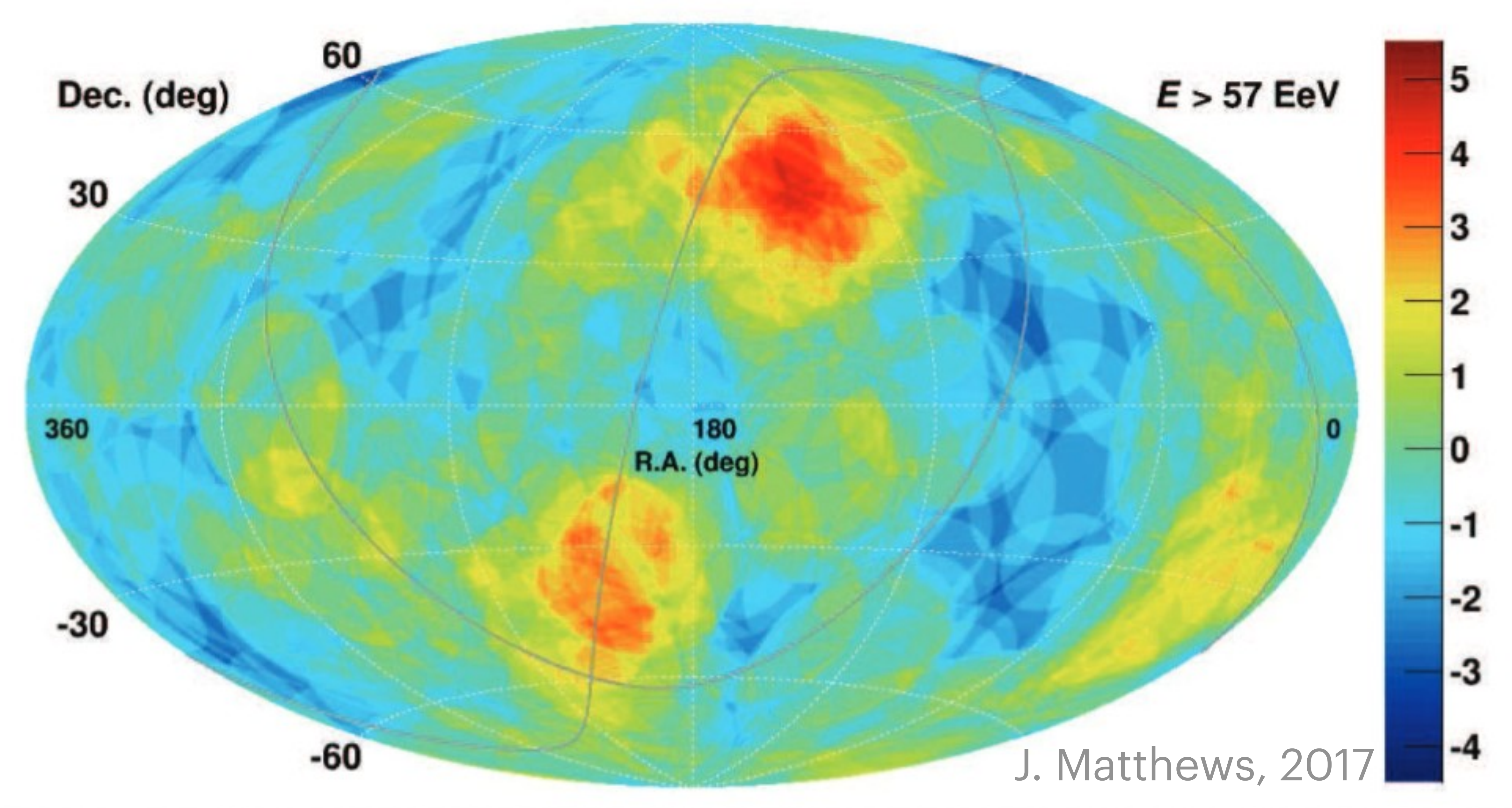
Constraints on the IGMF



Korochkin et al., 2020

Impact of magnetic bubbles
Ultra-High Energy Cosmic Rays (UHECRs)

- **Finding UHECRs sources**: a central problem of astroparticle physics
- **No signatures of sources**: UHECRs show a surprisingly high level of isotropy

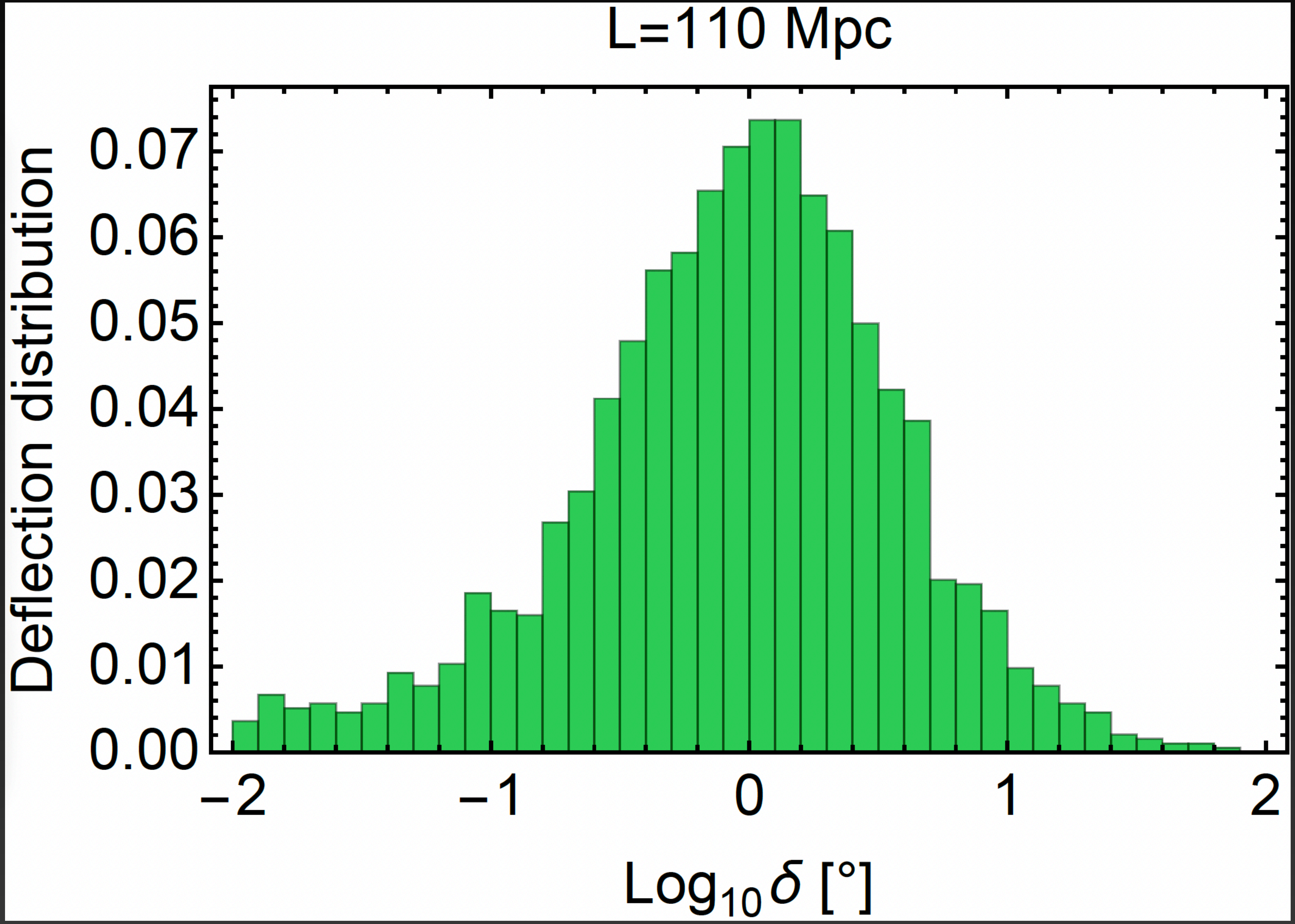


- This absence of small-scale clustering is believed to arise from the **deflection of UHECRs in magnetic fields**
- *Common picture:* CRs in the disk diffuse to high angles. CRs transverse to the disk are deflected only while crossing the plane, for $E \sim 5 \times 10^{19}$ eV the angle is $\sim 1°$

Kachelriess, Semikoz, 2019

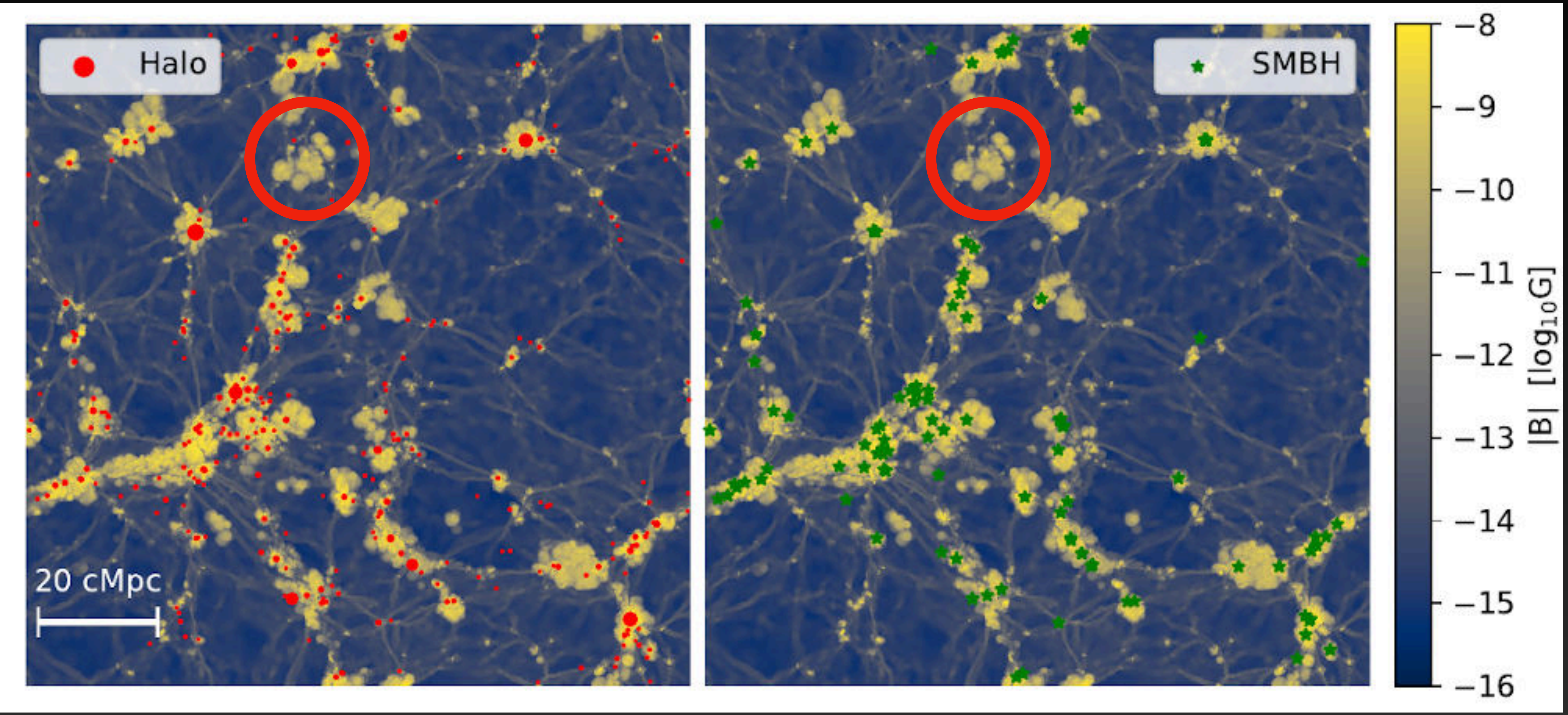
Impact of magnetic bubbles
Ultra-High Energy Cosmic Rays (UHECRs)

- The **distribution of deflection angles is quite wide** with an average value around 1°
- The influence of **intergalactic magnetic fields** on the **propagation of the UHECRs** could be **important**



[A. Aramburo-Garcia, AS et al., PRD, 2021]

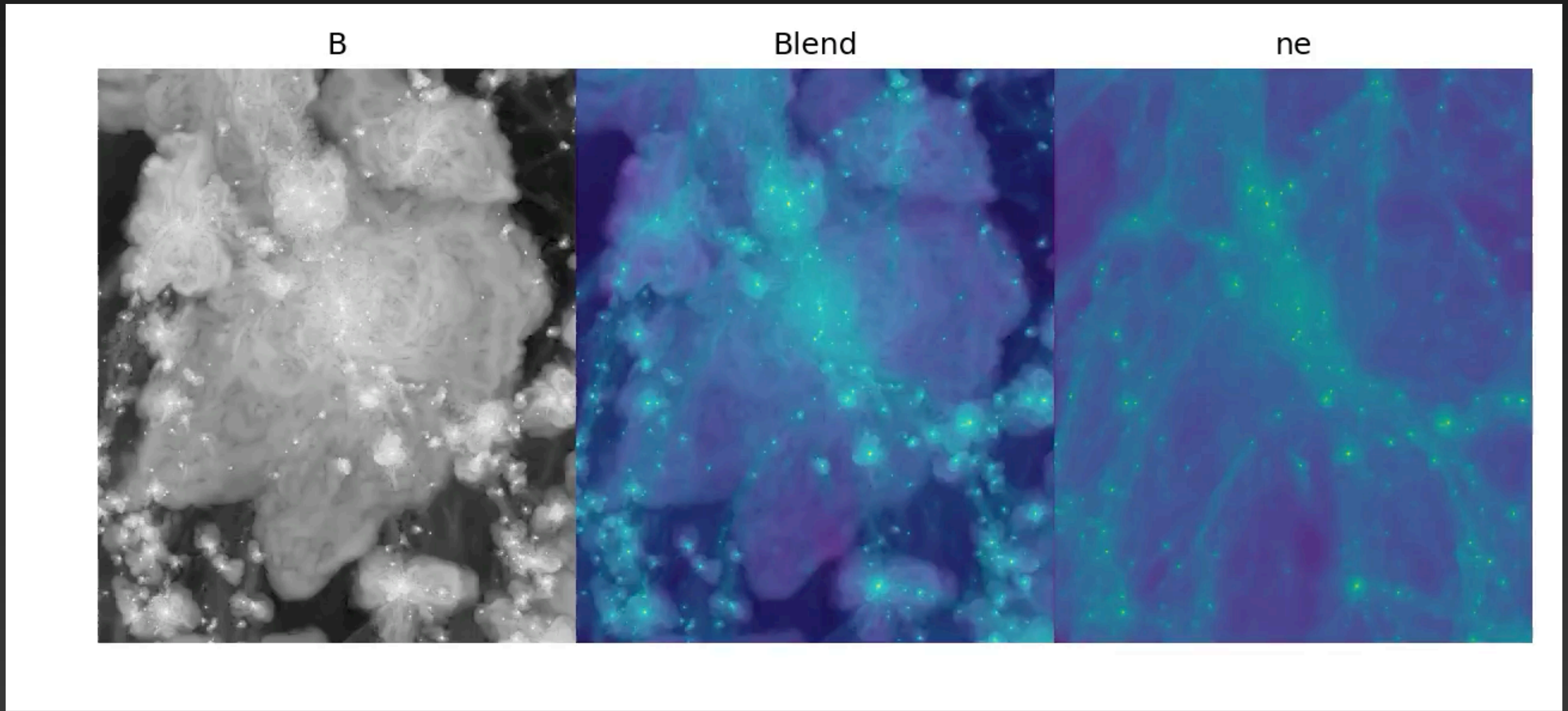
Over-magnetized bubbles in IllustrisTNG simulations

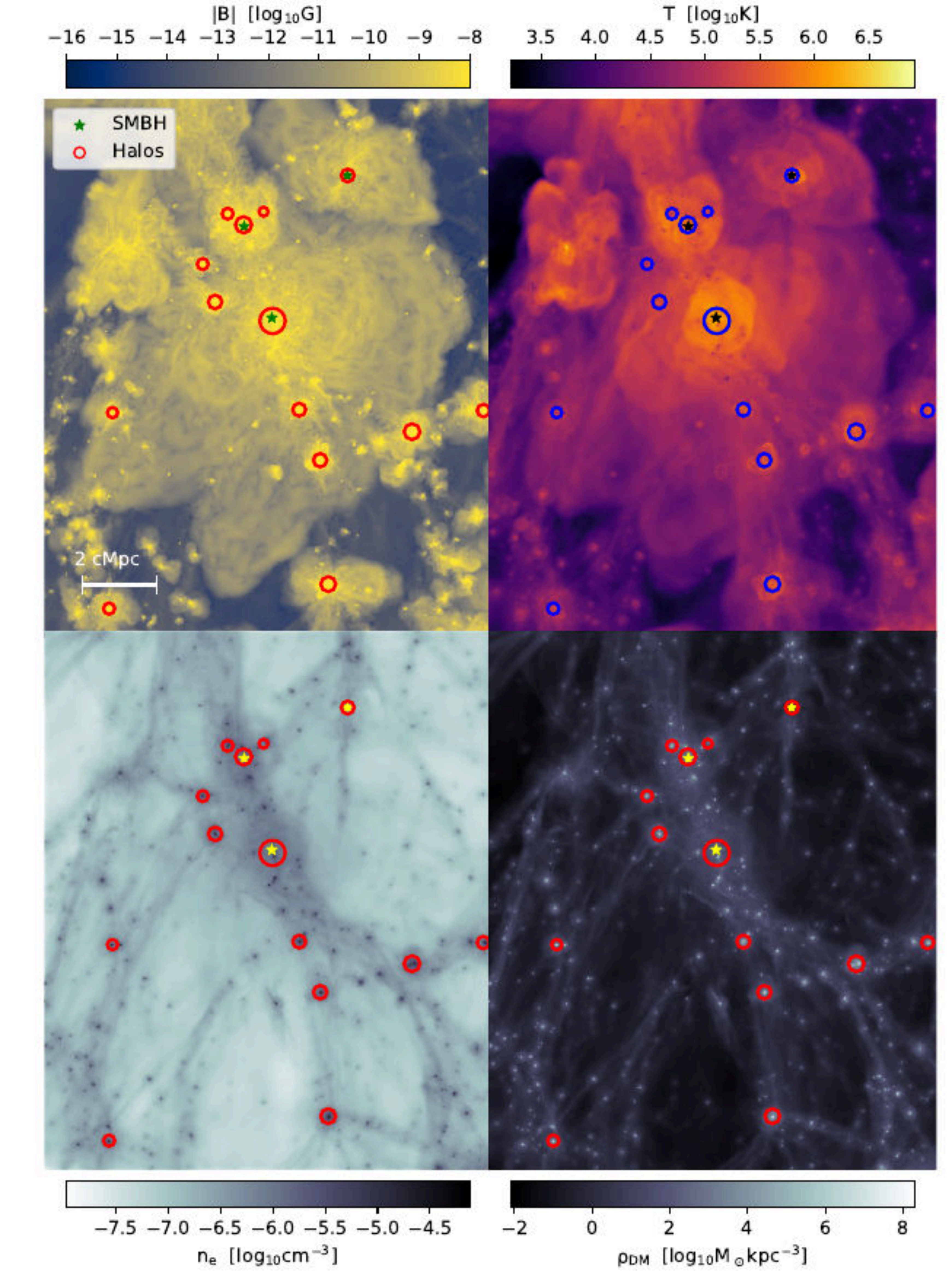


Hypothesis: magnetic bubbles are **caused by the outflows** caused by AGNs and supernovae. We see that **some bubble does not correspond to any halo or AGN**. How could this be?

Over-magnetized bubbles in IllustrisTNG simulations

Zooming in to the volume occupied by this magnetic bubble we found the the source!

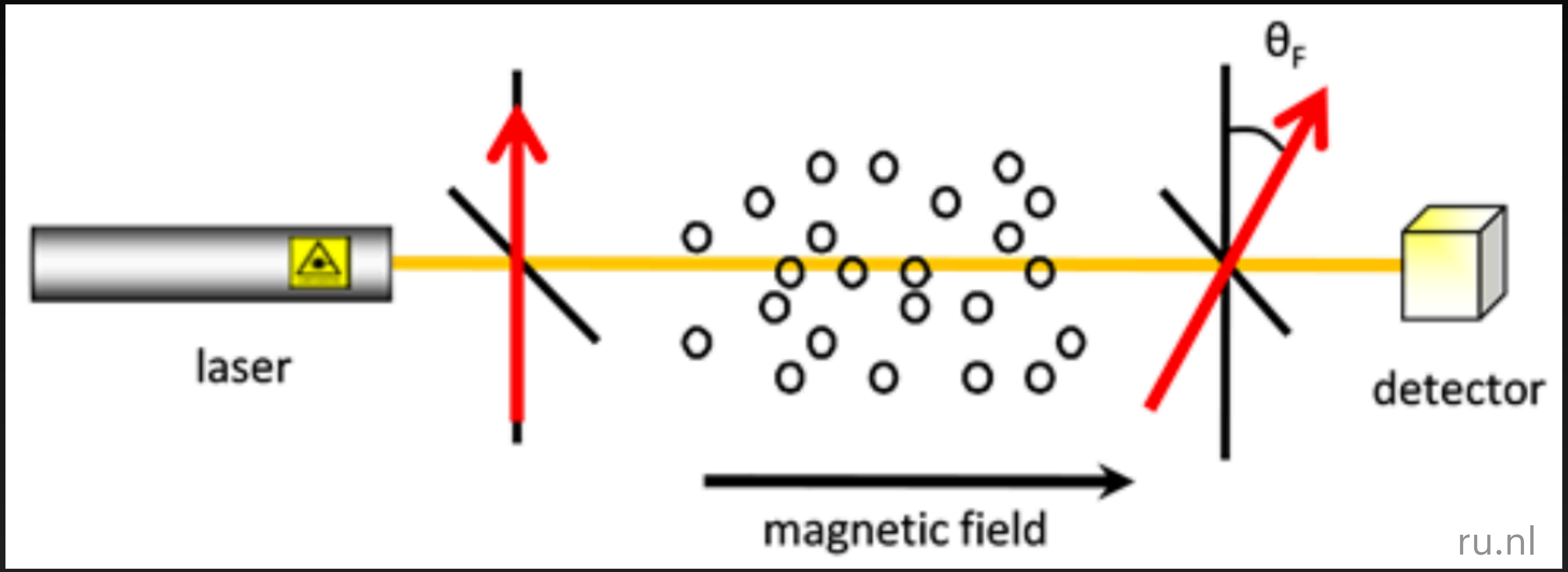




How to detect these bubbles?

Faraday rotation

- In dense structures we can **measure magnetic fields** using the **Faraday effect**
- Polarized **light rotates** by θ_F in the **magnetic field**



$$\Delta\theta_F = \mathrm{RM} \cdot \lambda^2, \qquad \mathrm{RM} = \frac{e^3}{2\pi m_e^2} \int \frac{n_e \cdot B_{||}}{(1+z)^2} \frac{dl}{dz} dz$$

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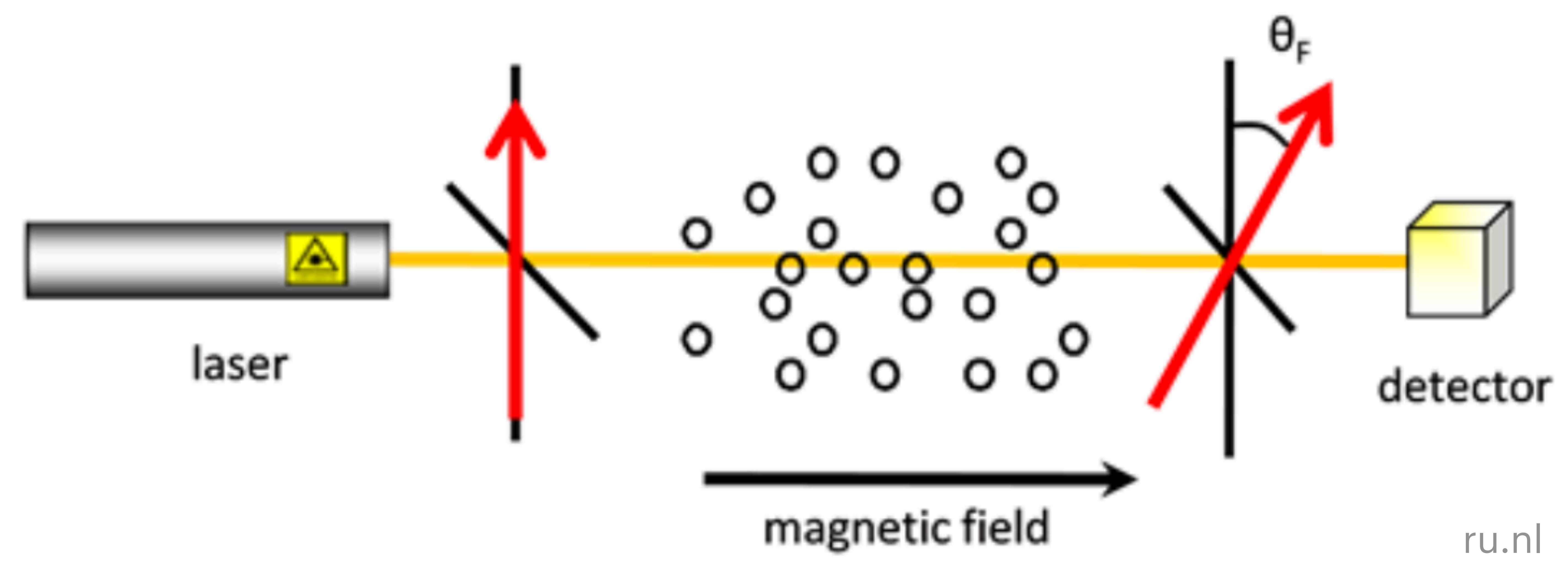

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$\boxed{\text{light wavelength}}$

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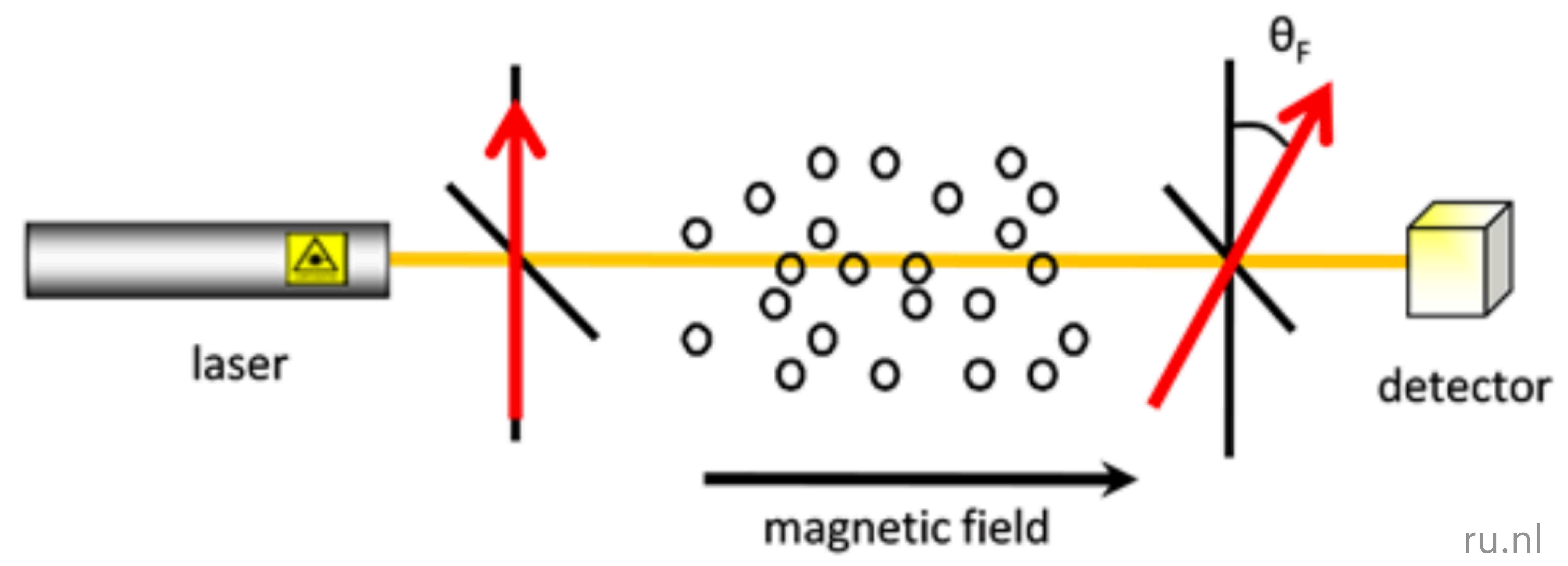

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Faraday Rotation Measure

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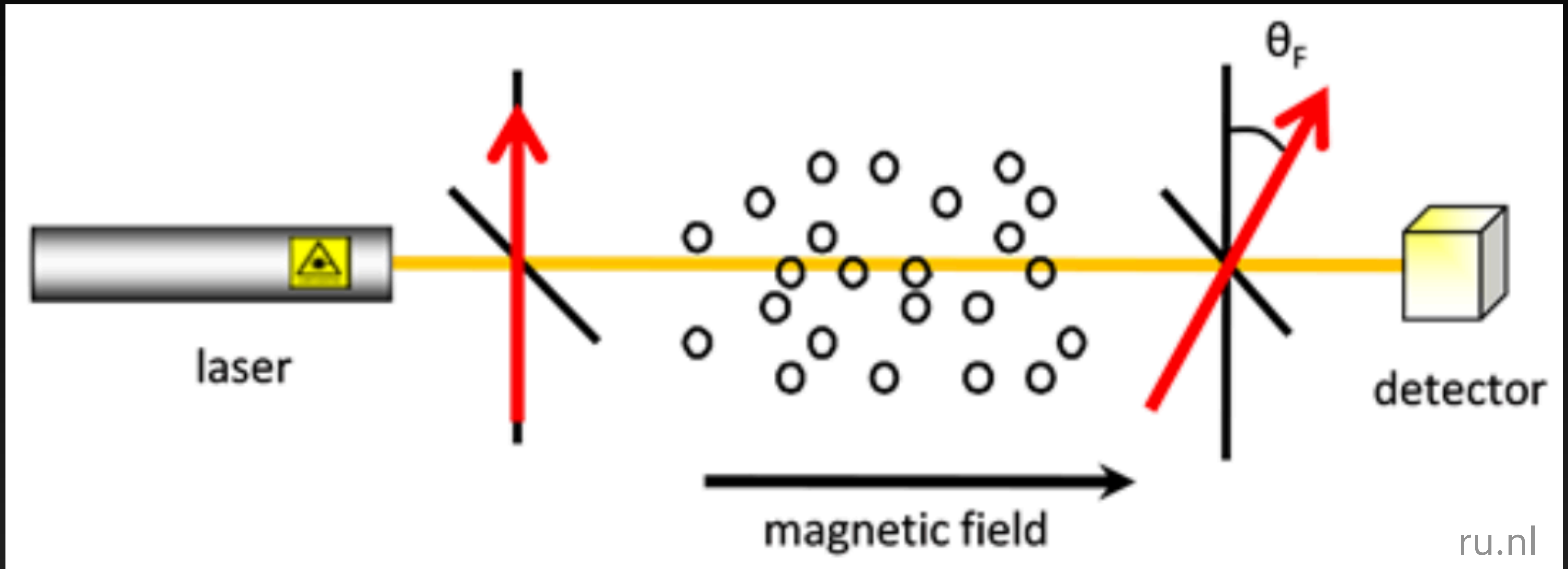

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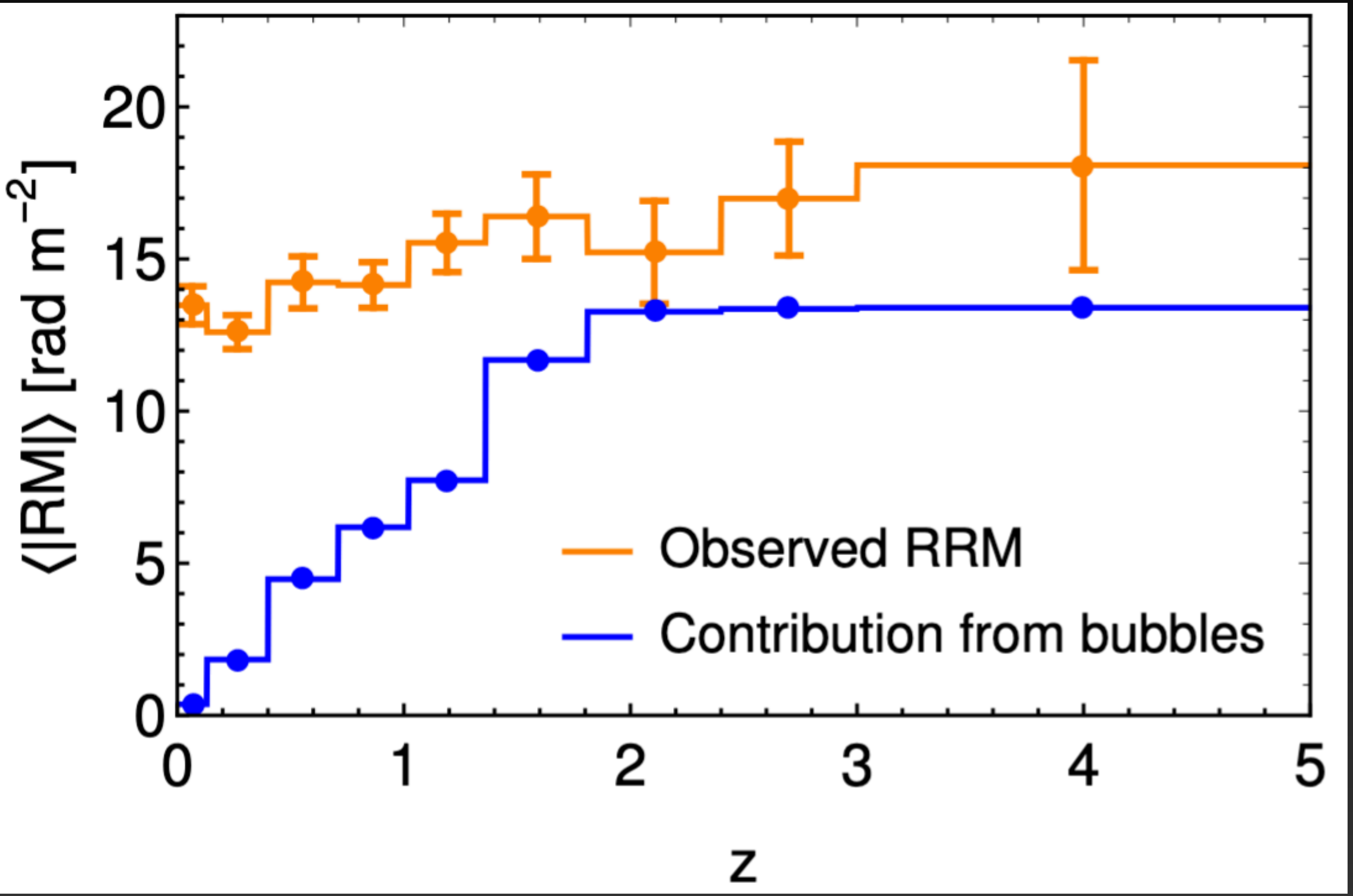
number density of charged particles × magnetic field

Constraints from Faraday rotation

- The **Faraday rotation** technique provides a powerful probe of astrophysical magnetic fields
- We used the catalog of radio sources NRAO VLA Sky Survey (NVSS) Hammond et al., 2012 and **predicted** mean and median values of **RM** from TNG as a function of redshift



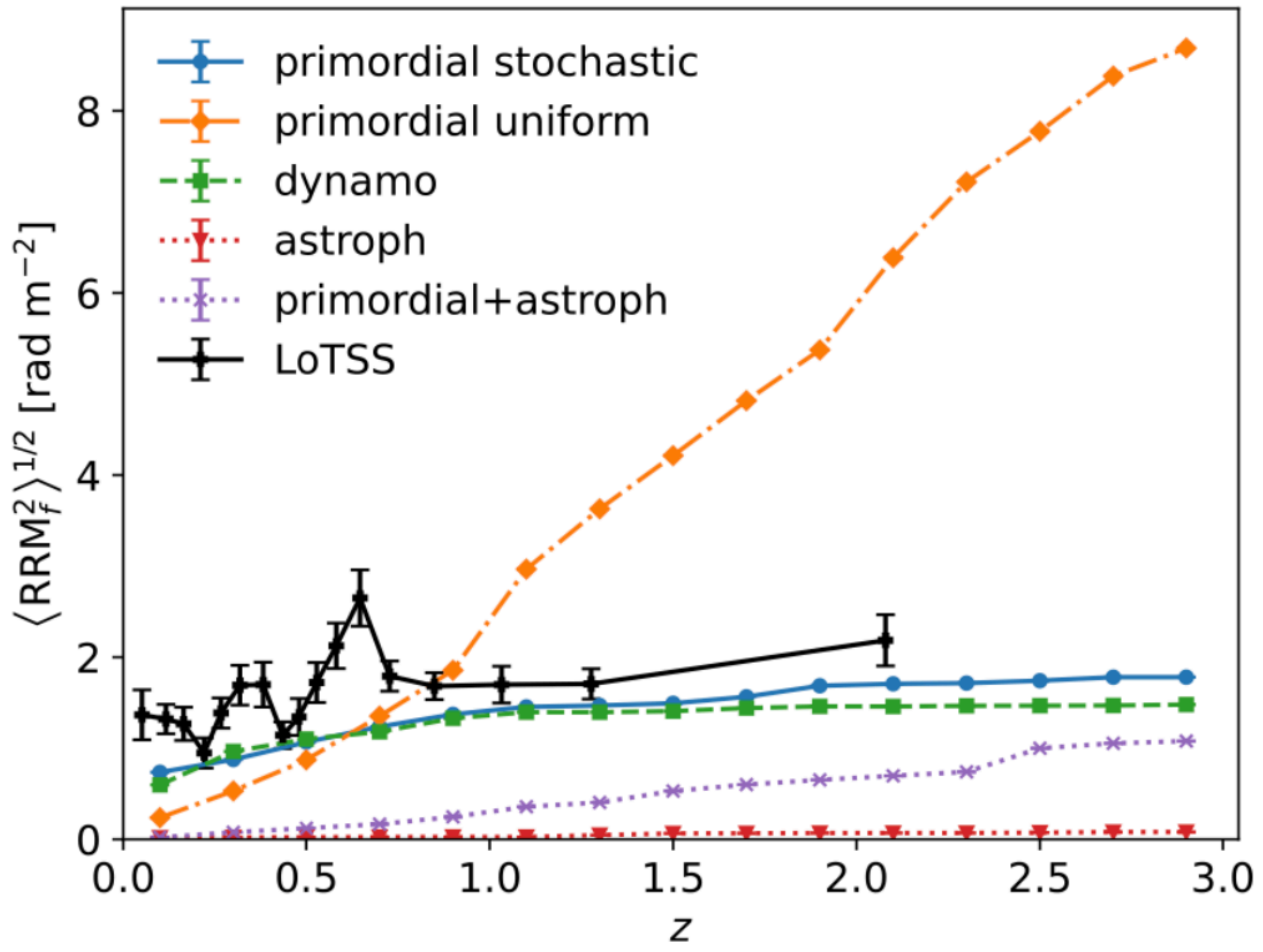
[A. Aramburo-Garcia, AS et al., MNRAS, 2022]

Constraints from Faraday rotation

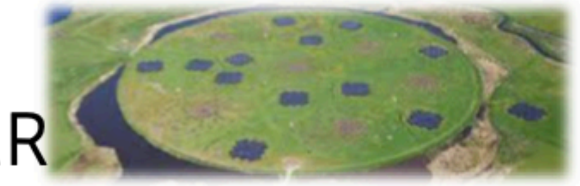
THE MAGNETIC COSMIC WEB: DETECTIONS IN FARADAY ROTATION

- Faraday Rotation Measure of up to z=3 for ~ 1900 polarised sources detected by LOFAR
- "Residual" Rotation Measure: $$\mathrm{RRM} = 0.812 \int_z^0 \frac{n_e(z')B_\parallel(z')}{(1+z')^2} \frac{dl}{dz'} dz'$$
- Little to no evolution of RRM(z)
- each LOS crosses a few tens of filaments

- Flat RRM(z) incompatible with simple uniform seed fields.
- Its amplitude also rejects purely astroph. models
- stochastic primordial magnetic fields are favoured



LOFAR

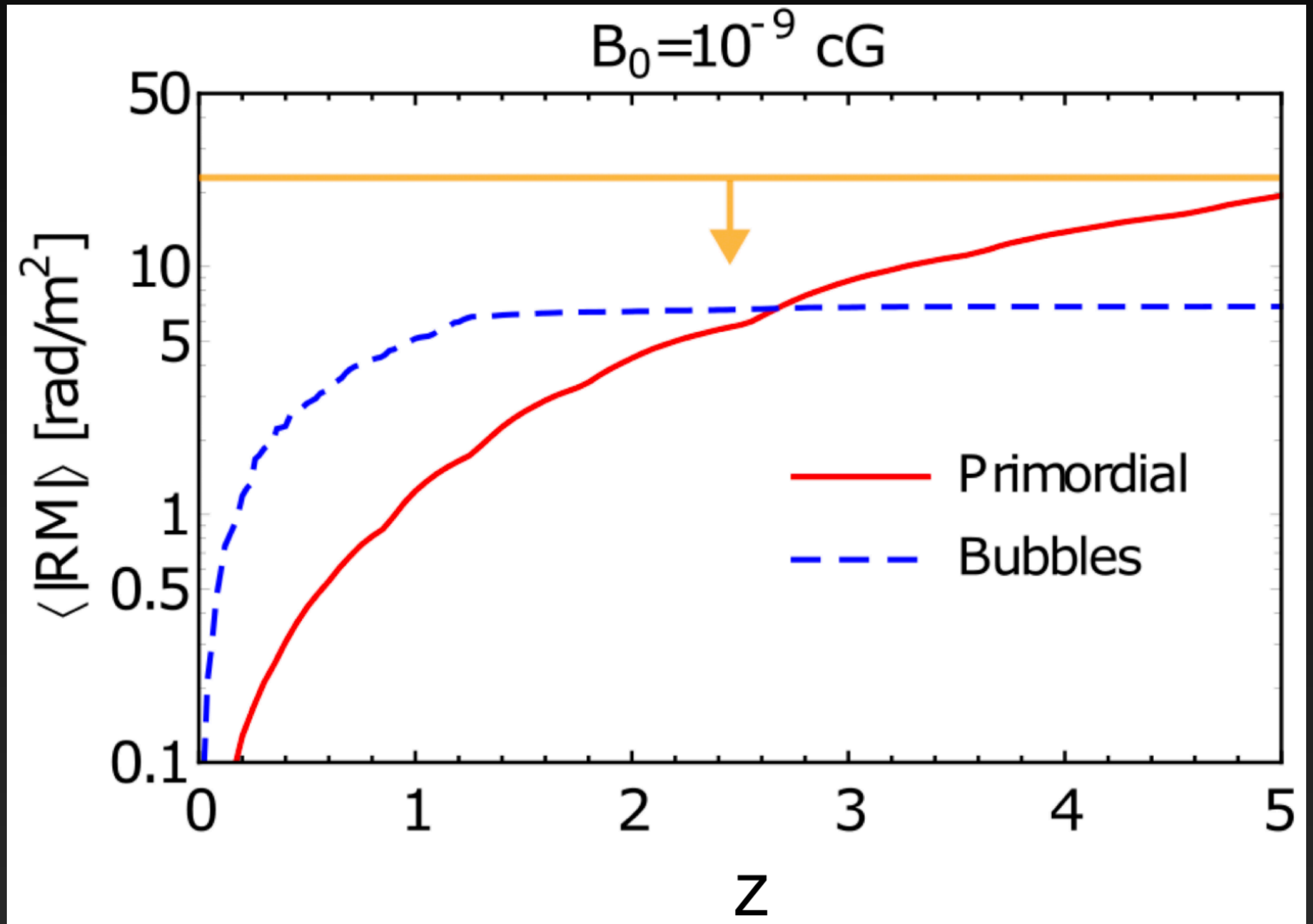


CARRETTI+22,23
POMAKOV+22

Credit: F. Vazza

Future: exploring magnetic bubbles

- **If** IllustrisTNG is **correct**, tens Mpc regions with **large magnetic field surround galaxy clusters**
- Eagle is implementing MHD, will provide an alternative picture of the MF dynamics during galaxy formation. Compare predictions of different simulation suits
- Observationally, it is challenging to detect a bubble, stacking might work



New LOFAR data and SKA will improve the results

Future: searching for the IGMF

If we **discover the IGMF** and prove that they are due to galactic feedback - **primordial magnetic fields**

Credit: IllustrisTNG

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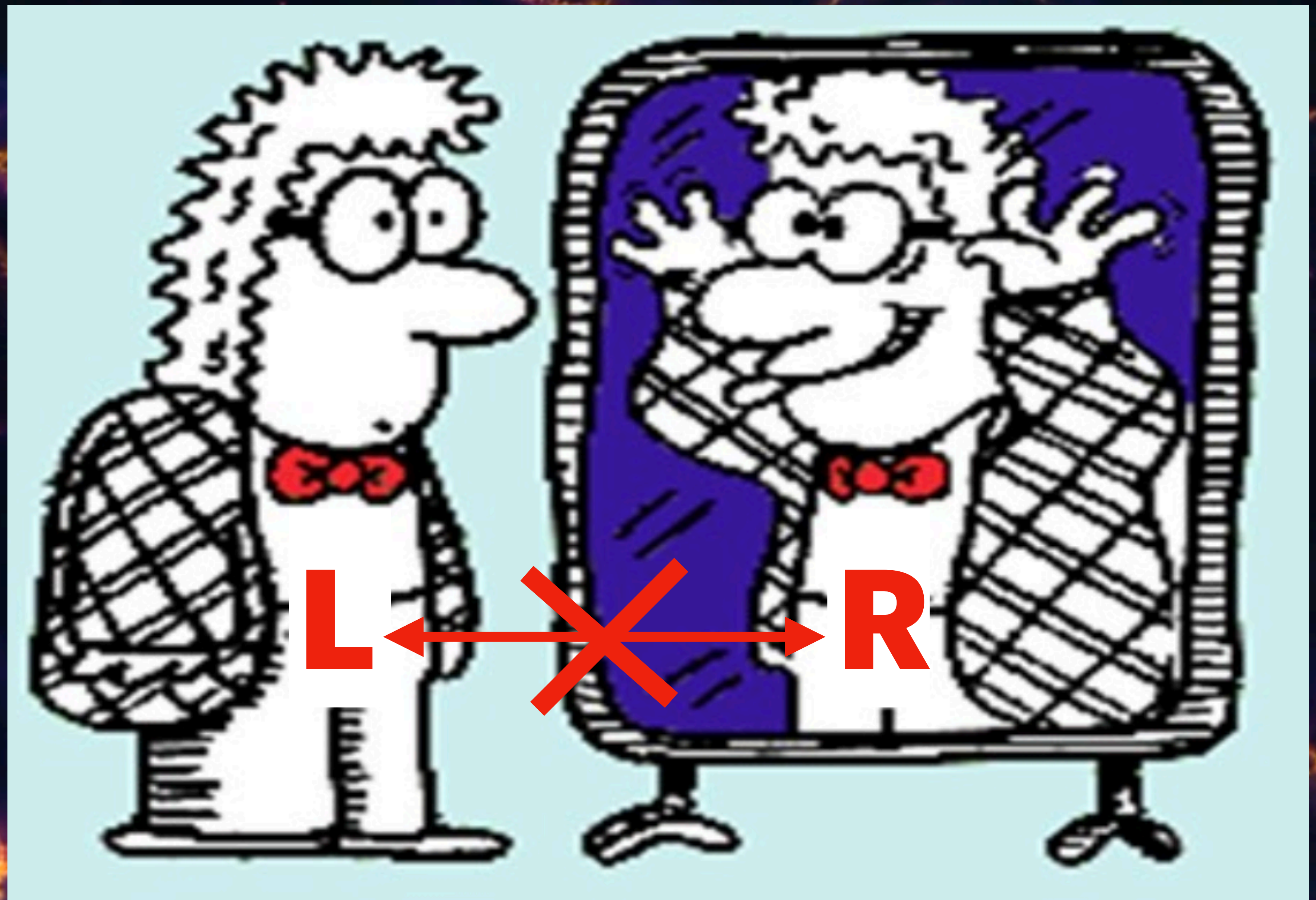
Future: searching for the IGMF

If we **discover the IGMF** and prove that they are due to galactic feedback - **primordial magnetic fields**

- In the **Standard Model primordial magnetic fields do not exist!**
- **Parity must be violated** in the electromagnetic sector to create primordial magnetic fields



Credit: IllustrisTNG

Future: searching for the IGMF

If we **discover the IGMF** and prove that they are not due to galactic feedback - **primordial magnetic fields**

- In the **Standard Model primordial magnetic fields do not exist!**
- **Parity must be violated** in the electromagnetic sector to create primordial magnetic fields
- There are several **classes of extensions of the SM** which violate parity:
  1. **Fermions**: sterile neutrinos, ...
  2. **Bosons**: axions, ...
  3. **Phase transitions**: topological defects, ...

Credit: IllustrisTNG