Cosmological-scale magnetic fields from galactic outflows and search for primordial magnetic field

Kyrylo Bondarenko

NORDITA

First Nordic Cosmology Meeting,
Stockholm 2023

Pillars of cosmology (from latest to earliest)

Current pillars:

- Hubble expansion
- Large Scale Structure
- CMB
- BBN

Future pillars:

Pillars of cosmology (from latest to earliest)

Current pillars:

- Hubble expansion
- Large Scale Structure
- CMB
- BBN

Future pillars:

- Early Structure Formation (with 21 cm)
- Cosmic Neutrino Background ($C\nu B$)
- Primordial Gravitational Waves
- Primordial Magnetic Field

Pillars of cosmology (from latest to earliest)

Current pillars:

- Hubble expansion
- Large Scale Structure
- CMB
- BBN

Future pillars:

- Early Structure Formation (with 21 cm)
- Cosmic Neutrino Background (CνB)
- Primordial Gravitational Waves
- **Primordial Magnetic Field**

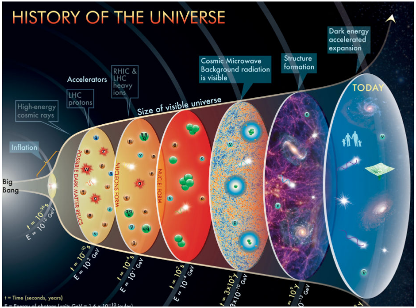
Why Primordial Magnetic Field is interesting?

Why Primordial Magnetic Field is interesting?

- Usually we consider Early Universe as a very homogeneous place with only small perturbations
- However, this simple picture could be wrong

BAU and BSM physics

- We observe more particles than antiparticles around us – **baryon asymmetry of the Universe (BAU)**
- To generate asymmetry in the Early Universe there should be Deviation from thermal equilibrium (one of Sakharov's conditions)

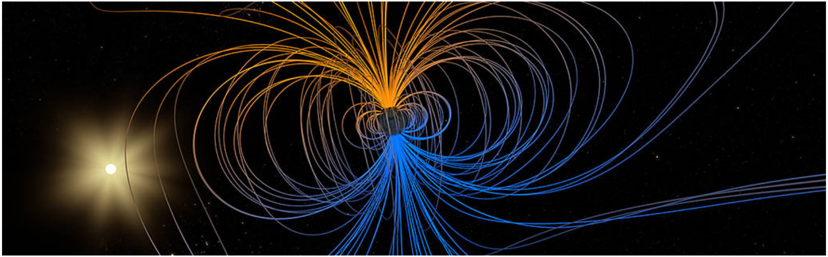


- Are there any additional to BAU signatures of the non-equilibrium physics in the Early Universe that could survive until today?
- The possible signature is the creation of the large-scale magnetic fields during the non-equilibrium stage, **primordial magnetic field**

The measurement of the primordial magnetic field allows us to probe the properties of the Universe even **before BBN** and it is an important step in the direction of understanding the BAU

Magnetic field and structure formation

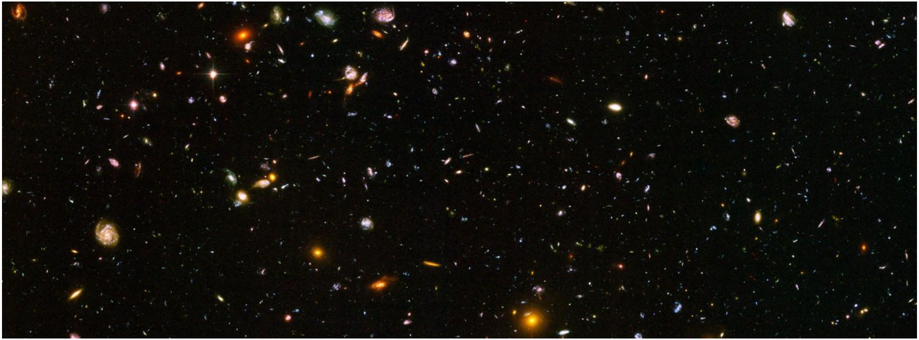
Magnetic field in collapsed structures



- In collapsed structures like galaxies or galaxy clusters magnetic field could be strongly amplified by the **dynamo** mechanism that works in the presence of the turbulent plasma
- Dynamo could amplify magnetic field by many orders of magnitude and reach saturation at magnetic field value of order of tens of μG (that we observe experimentally)

Magnetic field in collapsed structures **"looses memory"** of its initial configuration and cannot help us to derive properties of the primordial magnetic field

Where to look for the primordial magnetic field?



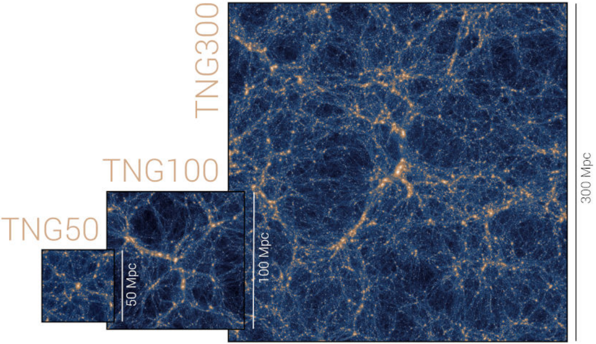
- Collapsed structure occupy only the small fraction of the volume of the Universe, while the primordial magnetic field is volume-filling
- Therefore, if we measure magnetic field outside the collapsed structure, in the **intergalactic medium (IGM)**, we could be able to probe the properties of the primordial magnetic field

Galactic feedback strikes back

- The "genuine" properties of Intergalactic Magnetic Fields (IGMF) can be **affected by processes inside galaxies**
- Indeed, feedback from supernova and active galactic nuclei (AGNs) could **spread out** galactic matter and magnetic field at some distance around galaxies

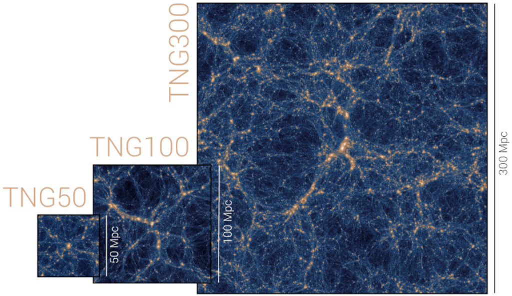
- **To what extend IGMF are affected by galactic feedback?**
- **We will use cosmological numerical simulations to analyze this question**

IllustrisTNG simulations



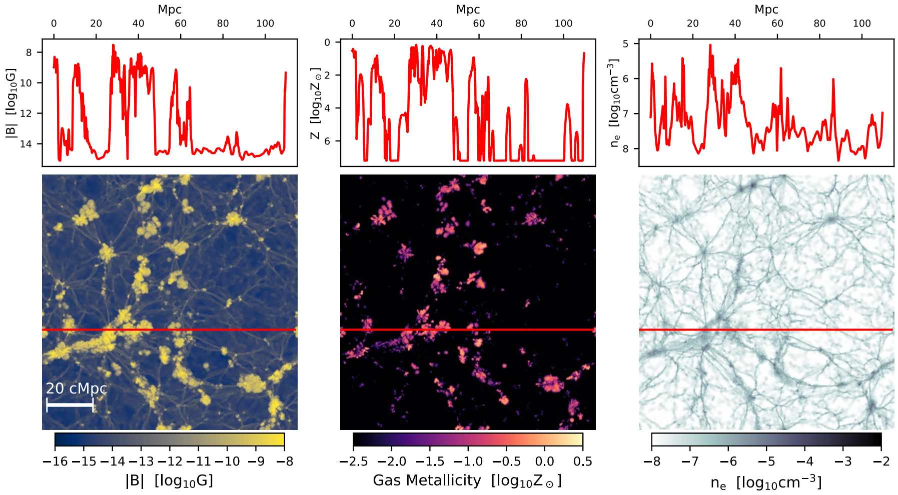
- **IllustrisTNG (TNG)** is a suite of large-volume cosmological gravo-magnetohydrodynamic simulations **[1707.03396]**
- It uses the moving-mesh AREPO code describe self-gravity and ideal MHD **[1108.1792]**
- TNG100 has a $L \sim 100$ cMpc box, 1820^3 of both DM and gas particles

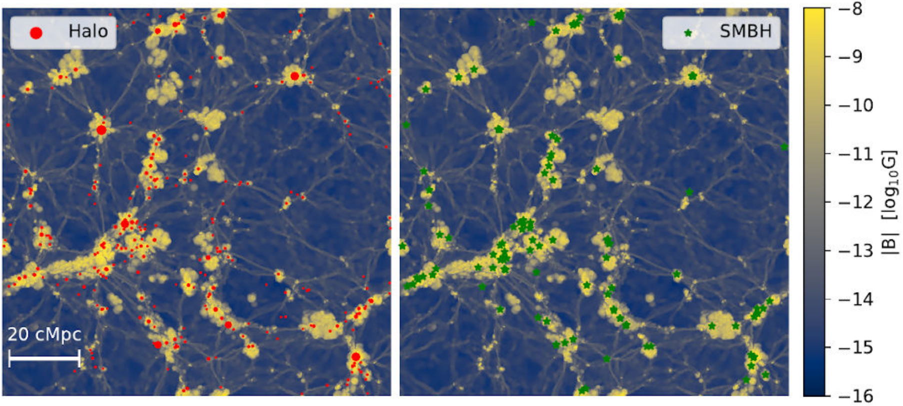
IllustrisTNG simulations



- TNG includes a **comprehensive galaxy formation model** incorporating e.g. gas metal-line cooling and heating, star formation, stellar evolution, heavy element enrichment, supermassive black hole growth
- It also contains models for **AGN feedback** and **supernovae-driven galactic winds**, resulting in matter outflows from galaxies
- Feedback processes are crucial for the properties of galaxies, such as star formation rates. **Feedback models have been calibrated** reproducing properties of many observed galaxies

Over-magnetized bubbles [2011.11581]



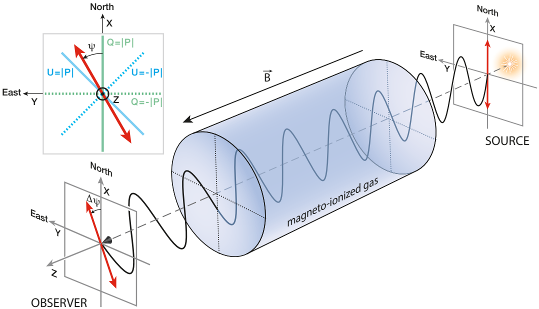


- Magnetic bubbles are produced by the **outflows caused by AGNs and supernovae**

The presence of **magnetic bubbles** should be taken into account when one analyzes different experimental data

Example 1: Faraday rotation

- In **dense structures** we can to measure MFs using the **Faraday effect**



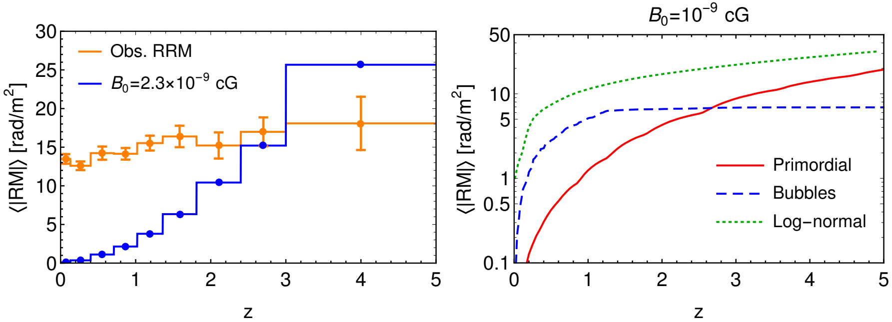
- Reminder: the Faraday effect causes a polarization rotation $\Delta\theta$,

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

where λ is a light wavelength and RM is the Faraday rotation measure

- Typical values of the observed MFs: $\sim 10^{-6}$ G in galaxies and central parts of clusters, $\sim 10^{-8}$ G in filaments between two close clusters **[2101.09331]**

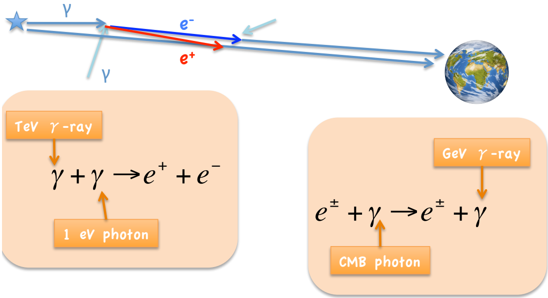
Constraint on primordial MF and magnetic bubbles

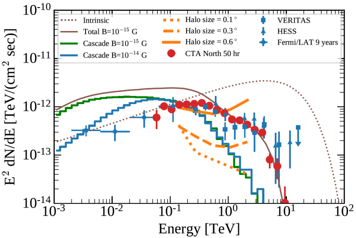


- Using the same catalog NRAO VLA Sky Survey of radio sources **[Hammond 2012]** as in **[Pshirkov 2016]**, we revised the actual constraint on the primordial magnetic field **[2204.06475]**
- We have found that the constraint relaxes by a factor of 3
- Also, in **[2204.06475]** we made a prediction for the contribution from magnetic bubbles. It has a very different redshift dependence and we speculate that it should be seen by future radio surveys

Example 2: Gamma-rays

- **How do we measure magnetic fields in the Universe?**



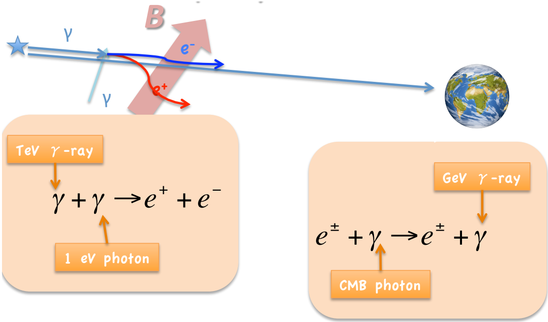


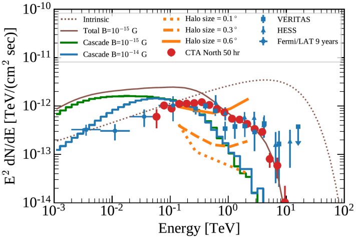
[2010.01349]

- γ-ray astronomy has a potential to measure **long-range magnetic fields** in the **Intergalactic Medium** (IGM)

Example 2: Gamma-rays

- **How do we measure magnetic fields in the Universe?**





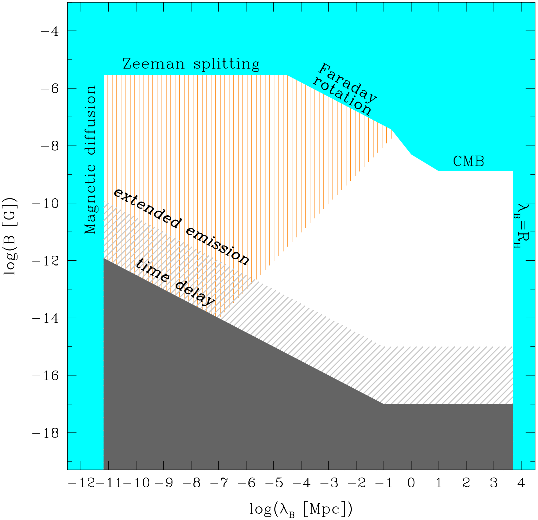
[2010.01349]

- γ-ray astronomy has a potential to measure **long-range magnetic fields** in the **Intergalactic Medium** (IGM)

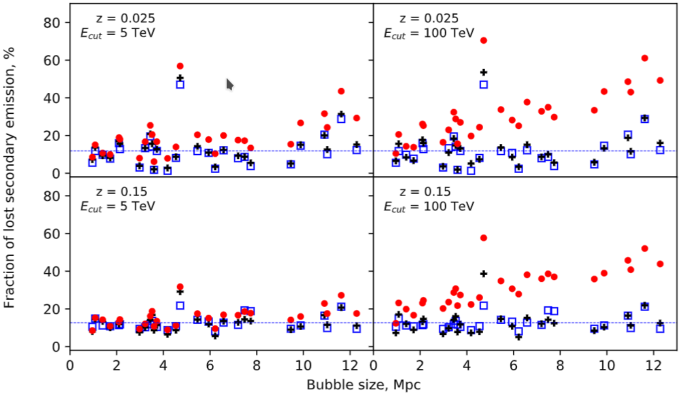
Cosmological magnetic fields observed?

Neronov & Vovk, Science (2010); Dolag et al. (2010); Tavecchio et al. (2011)

- Summary of different bounds on cosmological magnetic fields **[Taylor 2011]**
- Can the lower bound be affected by bubbles?



Influence of over-magnetized bubbles



- In our paper **[2106.02690]** we make a preliminary study of this effect. Red dots here show the fraction of secondary emission in the range $1 - 10$ GeV removed by the presence of over-magnetized bubbles
- We see that for individual objects this effect could reach 70%, but for most of the systems, it is below 50%

Summary

- Primordial magnetic field is an important messenger from the Early Universe. It could become a new pillar of cosmology, giving us information about the pre-BBN Universe

- However, large, outflow-driven, over-magnetized bubbles form around collapsed halos and should be taken into account in our attempts to search for a primordial magnetic field
- We need to further study over-magnetized bubbles in simulations with different models of galactic feedback and also try to search them with radio measurements of FRM, synchrotron (SKA), and gamma-ray data (CTA)

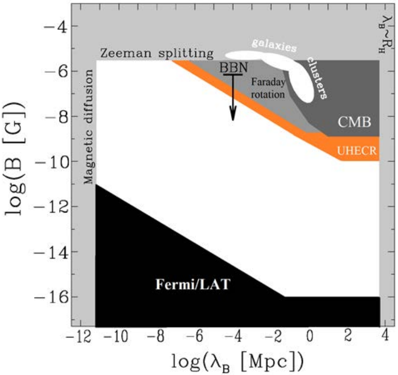
- Over-magnetized bubble is an interesting system by itself. They could influence different observables such as UHECR, FRM, gamma-rays
- Constrained simulation of our local volume can help to make our theoretical prediction more detailed and realistic

Backup slides

Magnetic fields in Universe

Magnetic fields exist in all astrophysical objects on all observable scales of the visible Universe:

- **Neutron stars**: $10^{12} - 10^{15}$ G
- **Stars**: $1 - 10^{3}$ G
- **Planets**: ~ 1 G
- **Galaxies**: $\sim 10^{-5} - 10^{-6}$ G
- **Galaxy clusters**: $\sim 10^{-6} - 10^{-7}$ G

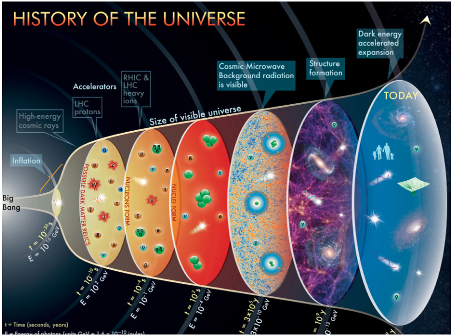


[Neronov&Vovk, Science **328**, 73 (2010); Neronov et al., arXiv:2112.08202]

Since 2010, there is evidence of MF detection also in the intergalactic medium — **in cosmic voids**: $10^{-16}\,\text{G} \lesssim B_0 \lesssim 10^{-10}$ G [Tavecchio *et al.*, MNRAS **406**; Ando & Kusenko, Astrophys. J. Lett. **722**; Neronov & Vovk, Science **328**]

Seed magnetic field

- Seed fields can be generated either during **structure formation** (Biermann battery) or they can have **primordial origin**
- After adiabatic contraction and dynamo amplification, magnetic fields in galaxies saturate and **forget about seed field** configuration
- Magnetic fields **outside collapsed structures** are expected to be close to the **seed fields** by their strength and remember their geometry.



We can use measurements of magnetic fields outside structures to infer the properties of seed magnetic fields. These fields could have a **primordial origin** and be the first messenger from the **Universe before BBN**

Magnetic field evolution in the Early Universe

- Small-scale magnetic field decays because of the magnetic diffusion,

$$\frac{\partial \boldsymbol{B}}{\partial t} = \boldsymbol{\nabla} \times [\boldsymbol{v} \times \boldsymbol{B}] + \underbrace{\frac{1}{\sigma}\Delta \boldsymbol{B}}_{=-k^2 B/\sigma} \tag{1}$$

- At large temperatures the horizon size is smaller than length of magnetic field that can be erased by diffusion
- Does it mean that magnetic field could not survive until today?

Magnetic field evolution in the Early Universe

- Small-scale magnetic field decays because of the magnetic diffusion,

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times [\boldsymbol{v} \times \boldsymbol{B}] + \underbrace{\frac{1}{\sigma}\Delta \boldsymbol{B}}_{=-k^2 B/\sigma} \tag{1}$$

- At large temperatures the horizon size is smaller than length of magnetic field that can be erased by diffusion
- Does it mean that magnetic field could not survive until today?
- **No!** There are different mechanisms to conserve magnetic field:
  1. If primordial magnetic field where created helical, the inverse cascade pushes MF from smaller to larger scales and work against magnetic diffusion;
  2. If primordial magnetic field where generated during inflation, they could have superhorizon correlation length and are not affected by the magnetic diffusion

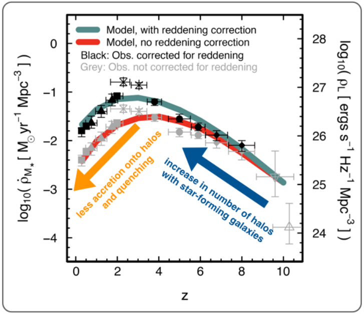
Evolution of the magnetic field in the Early Universe is a complicated and rich area of research (see e.g. [1303.7121]). The main message for us: **the primordial magnetic field could survive up until today**

AGN model

- A supermassive black hole (SMBH) is created in all dark matter halos which exceed a total mass of $\sim 7 \times 10^{10}\,\mathrm{M}_\odot$, by placing a SMBH at the potential minimum with an initial mass of $\sim 10^{6}\,\mathrm{M}_\odot$
- These black holes grow via binary mergers with each other or via smooth gas accretion (using the Bondi-Hoyle-Lyttleton model **[1607.03486]**), which depends on the black hole mass, local gas density, and relative velocity between the black hole and its surroundings
- SMBH creates feedback differently in two regimes: high-accretion state (above $\sim 10\%$ of the Eddington rate), and low-accretion state
- At high accretion rates, energy is deposited in a continuous manner, by thermally heating gas
- At low accretion rates, kinetic energy is injected in a discrete rather than continuous fashion, such that feedback events occur once enough energy accumulates

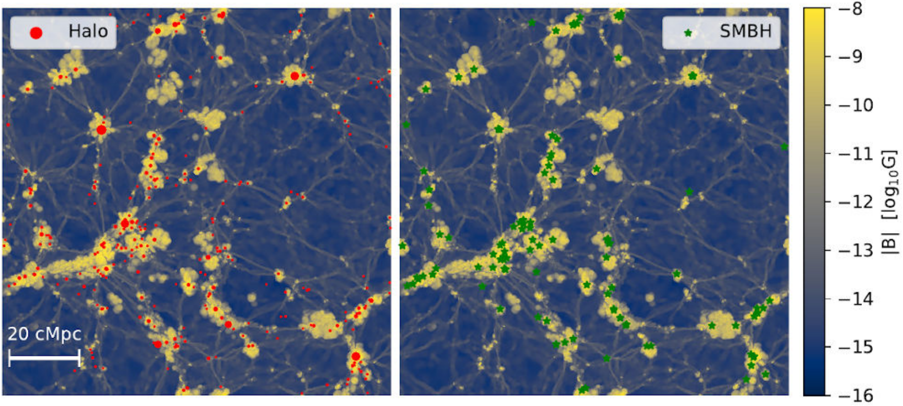
AGN feedback and observed properties of galaxies

- The strongest feedback comes from AGNs – supermassive black holes (SMBH) in the central parts of galaxies
- The source of energy for the SMBH is the accreted matter. This process is so effective, that $\mathcal{O}(10\%)$ of the mass of accreted matter transforms in radiation. This makes AGNs the **most bright permanent sources** of light in the Universe
- Feedback of AGNs heats up matter around and injects a lot of matter in the IGM. This affects **star formation rate** and creates **Fermi bubbles** seen in X-rays (see e.g. [1204.4114])

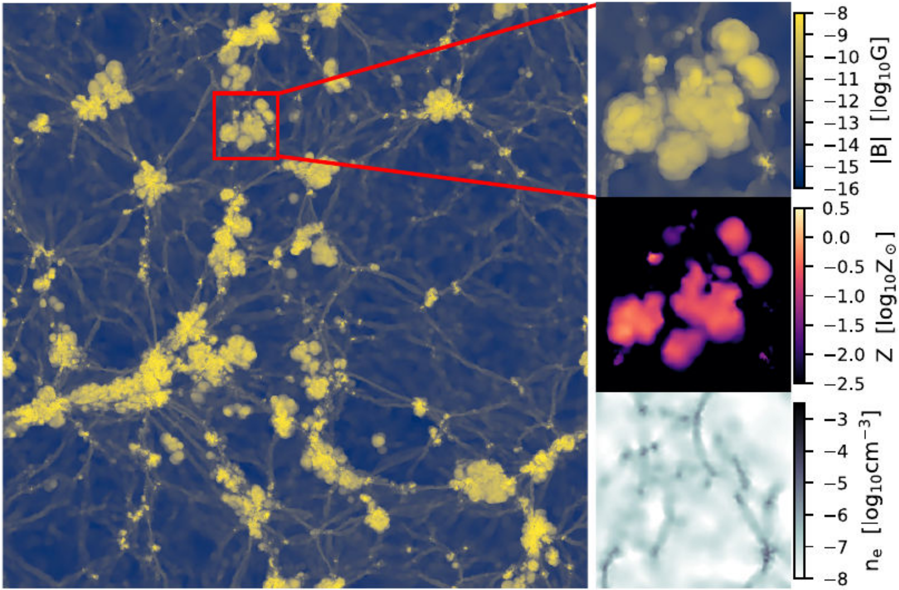


AGN model

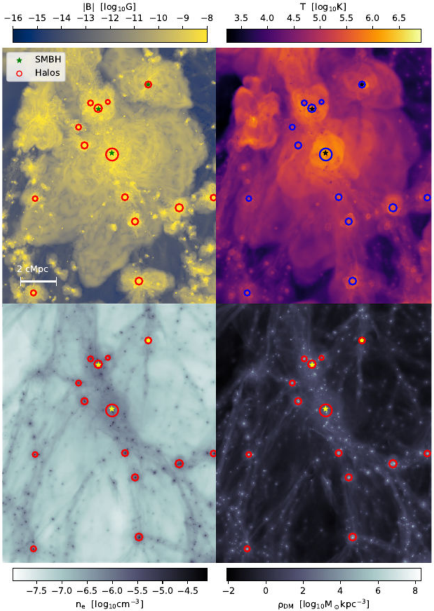
- These two modes of feedback are motivated both by theoretical conjectures for the existence of different types of accretion flows as well as recent observational evidence for the importance of kinetic AGN winds in quenching galaxies **[1607.03486]**
- A large fraction of the injected kinetic energy in this mode thermalizes via shocks in the surrounding gas, thereby providing a distributed heating channel
- The model is calibrated by star formation in massive elliptical galaxies
- In the TNG model, slowly accreting SMBHs drive the most powerful outflows **[1902.05554]**

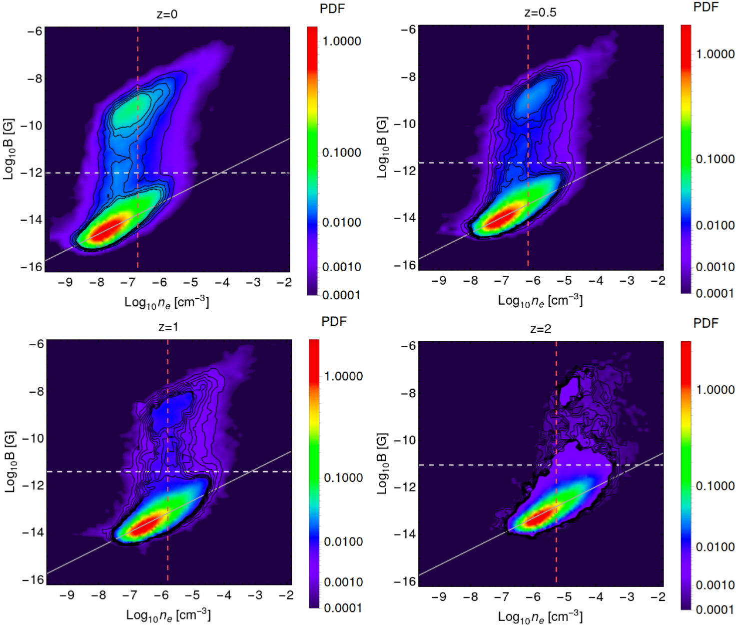


- Hypothesis: magnetic bubbles are caused by the **outflows caused by AGNs and supernovae**
- To check this we show massive halos and AGNs within 2 Mpc from the slice
- We see that some bubble does not correspond to any halo or AGN. How could it be?


−8
−9
−10
−11
−12
−13
−14
−15
−16
$|B|$ $[\log_{10}G]$
0.5
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
Z $[\log_{10}Z_\odot]$
−3
−4
−5
−6
−7
−8
n_e $[\log_{10}cm^{-3}]$

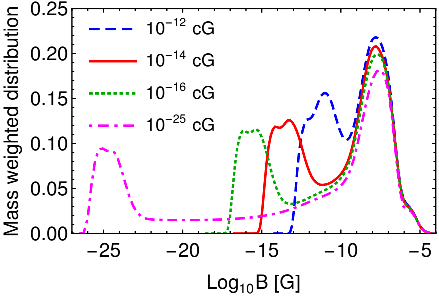
- Zooming to the volume occupied by this bubble $\sim$ (10 Mpc)^3 we see presence of massive halos with AGNs
- Magnetic field forms the butterfly-like configuration around the massive halo, suggesting that it was produced by outflows

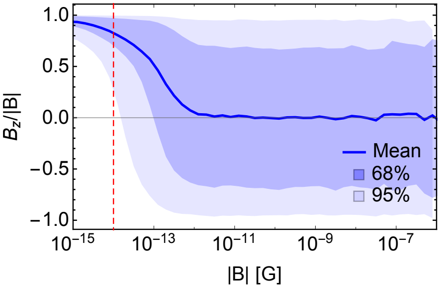




The effect of bubbles is also in the relation between B and n_e

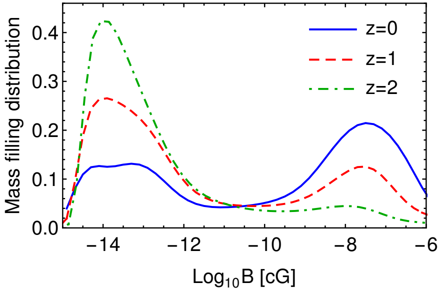
Magnetic field in bubbles forgets initial conditions

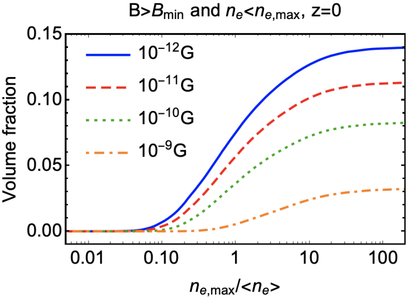




- The formation of over-magnetized bubbles weakly depends on the magnitude of the initial magnetic field in the simulation
- At $z = 0$ for MFs with $B > 10^{-12}$ cG there is **no** longer a **preferred direction** of the field (seed field was along z axis with $B = 10^{-14}$ cG)

Simulated magnetic fields in bubbles **"forget"** the initial properties of the seed magnetic field!





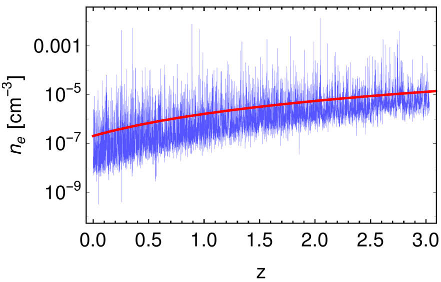
- Over-magnetized bubbles **formed quite recently**, at redshifts $z \lesssim 2$
- At $z = 0$, the magnetic field is stronger than 10^{-12} G in 15% of the volume, while it is stronger than 10^{-9} G in 3% of the volume

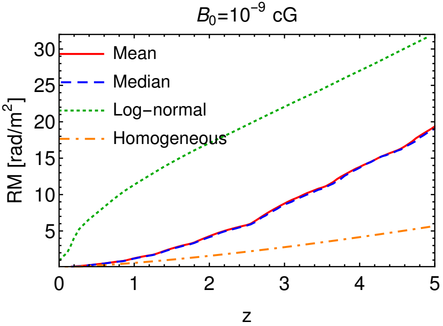
RM for the primordial magnetic field

$$\text{RM} = \frac{e^3}{2\pi m_e^2} \int \frac{n_e B_\parallel}{(1+z)^2} \frac{d\ell}{dz} dz$$

- Let the Universe is filled with homogeneous primordial magnetic with strength B_0 today
- At redshift z the strength of magnetic field is $B(z) = B_0(1+z)^2$ because of adiabatic contraction. Also, $n_e \propto (1+z)^3$, so we expect quite strong growth of RM with the redshift ($\text{RM} \propto (1+z)^{3/2}$ for matter dominated epoch)
- **[Blasi 1999]** pointed out that it is important to take into account strong Universe inhomogeneity. As $B \propto n_e^{2/3}$, the quantity under the integral $n_e B_\parallel \propto n_e^{5/3}$ and strongly depends on electron density distribution

RM for the primordial magnetic field



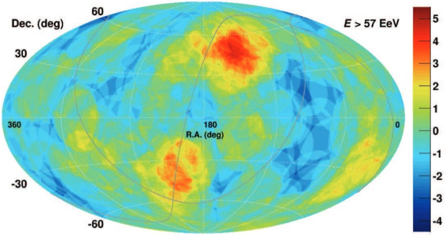


- **[Blasi 1999]** made their prediction based on the phenomenological model of electron density distribution (log-normal model). It was later used by **[Pshirkov 2016]** to put constraints on the primordial magnetic field
- In **[2204.06475]** we revised results of this models using IllustrisTNG simulation. We have found that modeling in the previous works was too simplistic compared to full MDH treatment and excluding regions affected by magnetic bubbles

Ultra-high energy cosmic rays (UHECR)

Problem of UHECR

- The identification of the sources of ultra-high energy cosmic rays (UHECRs) is one of the central problems of astroparticle physics
- No strong signatures of sources have been seen in the data so far – the observed UHECRs show a surprisingly high level of isotropy, with no significant small scale clustering

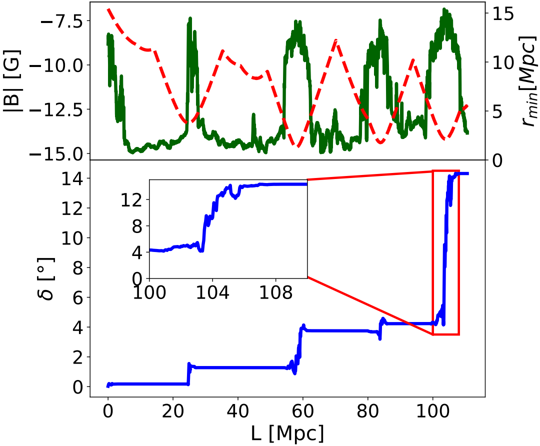


- This absence of small scale clustering is believed to arise from the deflection of UHECRs in magnetic fields during their propagation between the sources and Earth
- For protons outside of the galactic plane with energy 5×10^{19} eV the deflection angles is $\sim 1^\circ$ **[1904.08160]**
- What is a contribution of outflow-driven bubbles to the total deflection angle?

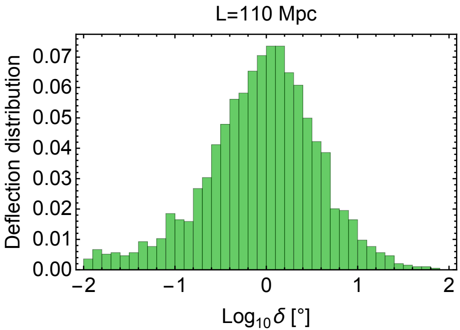
Propagation of UHECR

- In [2101.07207] to study the effect of the over-magnetized bubbles on the propagation of UHECRs we trace trajectories of high-energy protons with energy $E_p = 10^{20}$ eV
- The trajectory is calculated iteratively using equation of motion,

$$\Delta \boldsymbol{v} = \frac{e}{E_p} \int [\boldsymbol{v} \times \boldsymbol{B}] dl$$



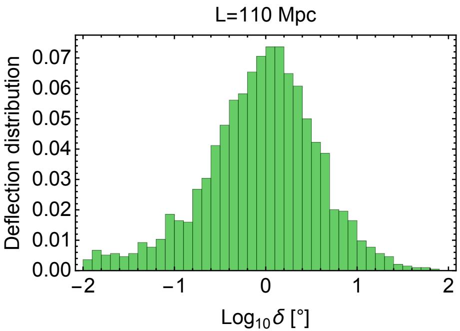
Propagation of UHECR



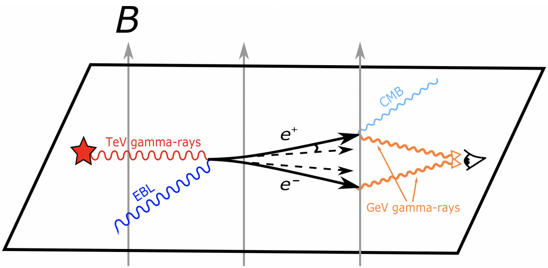
- The distribution of deflection angles is quite wide with an average value around 1° **[2101.07207]**
- The influence of intergalactic magnetic fields on the propagation of the UHECRs is important and **must be taken into account** when searching for the sources of these particles
- However, UHECR is definitely **not a good observable to study IGMF**

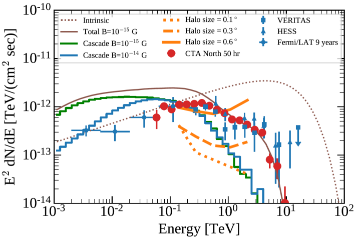
Example of application: UHECR

- The identification of the sources of ultra-high energy cosmic rays (UHECRs) is an important **unsolved problem** of astroparticle physics
- The sources are unknown because UHECRs are deflected by magnetic fields
- It is widely believed that for protons with energy 5×10^{19} eV the **deflection in the IGM** is **relatively small** ($\lesssim 1^\circ$ degree **[astro-ph/0410419]**)
- However, IGMF could give an important contribution **[2101.07207]**



Magnetic fields in voids

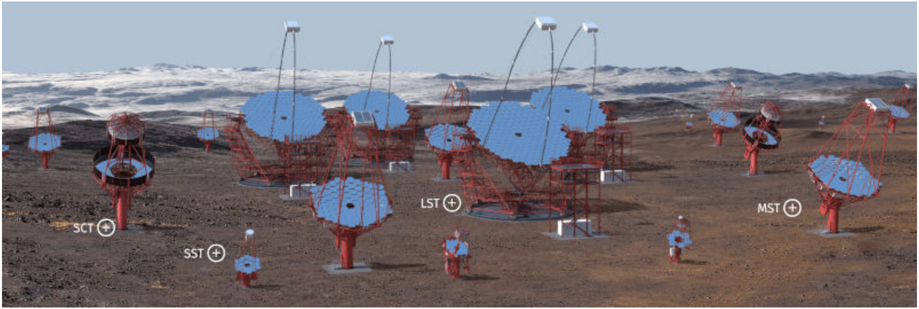




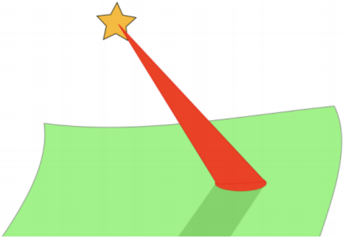
[2010.01349]

- γ-ray astronomy has a potential to measure **long-range magnetic fields** in the **Intergalactic Medium** (IGM)

Cherenkov Telescope Array (CTA)



- Fermi telescope cannot detect the extended halo (as the halo size is smaller than Fermi's PSF)
- Possibility to detect the halo with CTA

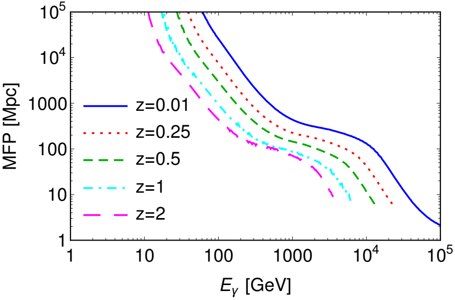


Influence of over-magnetized bubbles

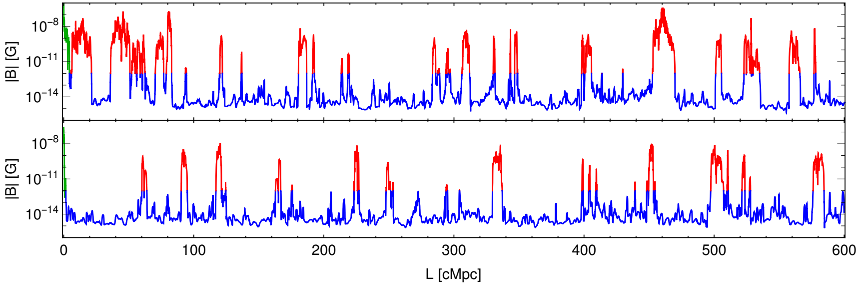
- The electron-positron pair could be created anywhere along the line of sight. Over-magnetized bubbles have volume filling fraction much smaller than one, so it seems that their presence **should not significantly influence the secondary emission**

Influence of over-magnetized bubbles

- The electron-positron pair could be created anywhere along the line of sight. Over-magnetized bubbles have volume filling fraction much smaller than one, so it seems that their presence **should not significantly influence the secondary emission**
- This is correct only for the gamma-rays with long enough mean free path (MFP)
- Highest-energy gamma-rays have short means free path and secondary emission from them is sensitive to the **local environment** around the source

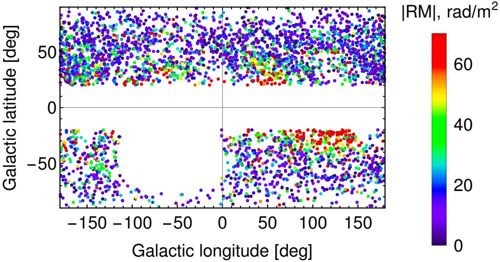


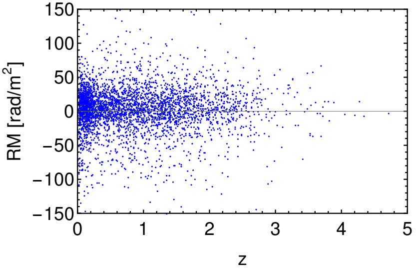
Influence of over-magnetized bubbles



- Each individual source can be unlucky enough the have an extended over-magnetized bubble along the line of sight to the Earth
- One way to deal with this problem is to increase statistic. With CTA we will be significantly increase amount and quality of observed sources
- With higher sensitivity we should be albe to search for the extended halo of secondary emission around the main source. Its size depends on the value of IGMF and can be affected by over-magnetized bubbles

NRAO VLA Sky Survey





- We use **[Hammond 2012]** catalog of Faraday rotation measures and redshifts for 4003 extragalactic radio sources derived from the NRAO VLA Sky Survey **[Condon 1998, Taylor 2009]**
- We remove objects close to the Galactic plane ($\ell < 20^\circ$) and get 3650 sources
- Data for rotation measure in the catalog were measured at two close frequencies and, therefore, may be subject to a wrapping uncertainty **[Taylor 2009]** with $\Delta \mathrm{RM} = 652.9\ \mathrm{rad/m^2}$
- To find the extragalactic contribution to the rotation measure, we subtract the Galactic RM (GRM) from **[Hutschenreuter (2020)]**