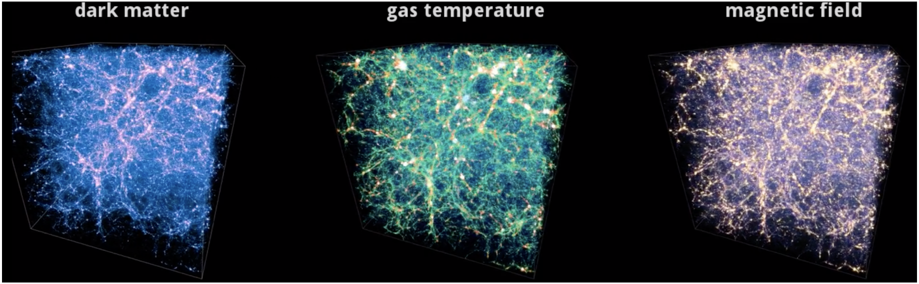
Intergalactic medium as a probe of fundamental physics

Anastasia Sokolenko

University of Chicago, KICP
Fermilab

TeVPA 2022, Kingston, Canada, 2022

Intergalactic Medium and New Physics

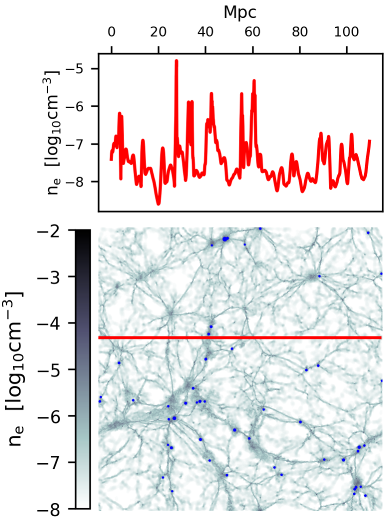


Collaborators: Kyrylo Bondarenko, Alexey Boyarsky, Josef Pradler, ++

[2002.08942], [2003.10465], [2011.11581], [2101.07207], [2106.02690] [2204.05918] [2204.06475]

Intergalactic Medium

- **Intergalactic Medium (IGM)** is a major part of the Universe outside of galaxies and galaxy clusters. It consists of voids, filament, and sheets
- Any extragalactic signal – photons of different energies, from CMB to gamma-rays, high-energy cosmic rays – **propagates through the IGM**
- This propagation can affect both the signal and the IGM itself
- I will show a **few examples** where the IGM is used as a laboratory to probe **new physics**

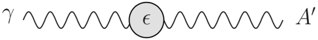


Dark photon resonant conversion

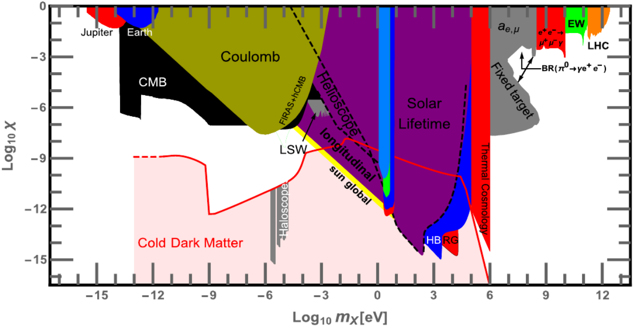
Dark photon

- Dark photon interacts with SM particles through the **kinetic mixing**

$$\Delta\mathcal{L} = -\frac{\epsilon}{2}F_{\mu\nu}F'^{\mu\nu} + \frac{m_{A'}^2}{2}A'^2$$



- Effectively **dark photons interact as ordinary photons** with an additional suppression factor ϵ

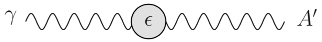


[1711.02961]

Oscillations of photon

- **In vacuum**, photons **oscillate** into dark photons with a very small probability

$$P_{\gamma\to A'} \sim \epsilon^2$$



- **In medium** (plasma), photons become effectively massive

$$\boxed{m_\gamma(z) = \sqrt{\frac{4\pi\alpha n_e(z)}{m_e}}} \qquad (1)$$

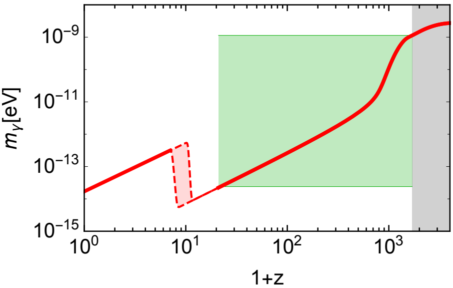
- If the effective mass of a photon is **equal** to the mass of a dark photon, the **resonant oscillation** occur

$$m_\gamma = m_{A'} \quad \Rightarrow \quad P_{\gamma\to A'} = \epsilon^2 \frac{\pi m_{A'}^2}{\omega} \left| \frac{d \log m_\gamma^2}{d\ell} \right|^{-1}_{z=z_{\rm res}} \gg \epsilon^2 \qquad (2)$$

- **The question is: where in the Universe does the resonance condition hold?**

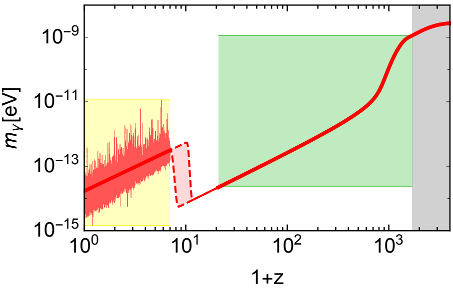
Evolution of free charges in the Universe

- **At high redshifts** the Universe is quite *homogeneous* and free-electron number density decreases with the expansion of the Universe



Evolution of free charges in the Universe

- **At high redshifts** the Universe is quite *homogeneous* and free-electron number density decreases with the expansion of the Universe
- **At lower redshifts** reionization happens increasing n_e. Also, there are a lot of structures where n_e can significantly differ from the average value



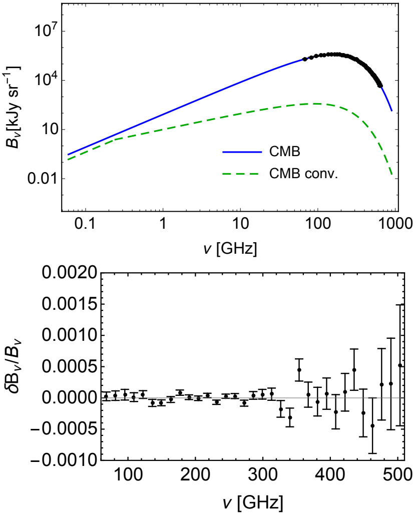
Hence, at low redshifts there are many places where photon may oscillate into dark photon

- **CMB** is a well-studied source that has a **black-body spectrum to a very high precision**
- Conversion of CMB photons to dark photons creates:
  1. **spectral distortions** (COBE/FIRAS)

$$B_\nu^{\text{Obs.}} = B_\nu^{\text{CMB}}(1 - P_{\gamma\to A'})$$

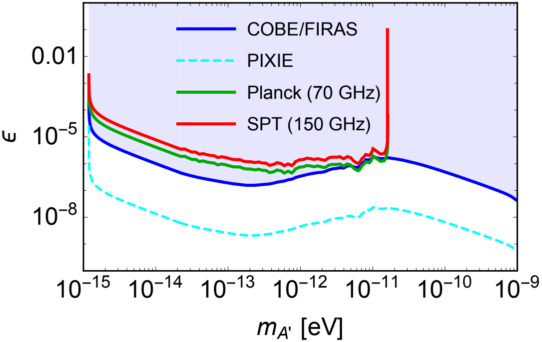
  2. **additional anisotropy** (Planck)

$$\delta T_{\text{CMB}}/T_{\text{CMB}} \sim 10^{-5}$$



Results [2002.08942,2003.10465]

- We used EAGLE simulation from [1604.00020] with a box size 100 cMpc and $N = 1504^3$ particles
- Using simulation data we generated 1000 continuous lines of sight and calculated the mean conversion probability and its variance



We obtained similar constraints both from spectral distortions and anisotropies using all-sky average conversion probability and dispersion

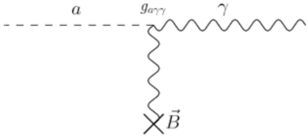
$\gamma \to A'$ conversion introduces additional CMB anisotropies at **small scales**. This potentially allows to further **improve** our constraints

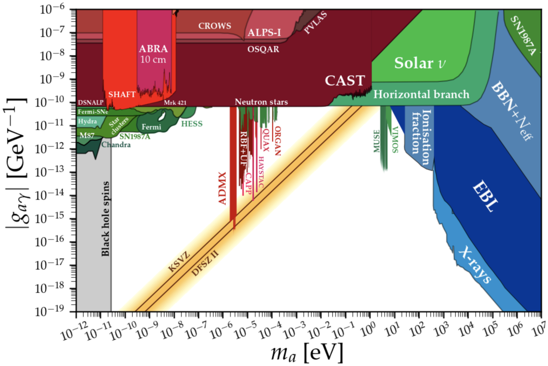
Axion resonant conversion

Axion

- Photon-ALP mixing occurs in the presence of an external magnetic field $\boldsymbol{B}$ due to the interaction term

$$\mathcal{L}_{a\gamma} = \frac{g_a}{4} a F_{\mu\nu} \tilde{F}_{\mu\nu} = g_a a \boldsymbol{E} \cdot \boldsymbol{B} \qquad (3)$$



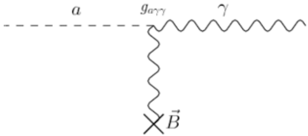


[Ciaran O'HARE]

Oscillations of photon

- **In vacuum**, photons **oscillate** into axions with a very small probability

$$P_{\gamma\to a} \sim g_a^2 \frac{\omega^2 B_T^2}{m_a^4}$$



- **In medium** (plasma), photons become effectively massive

$$\boxed{m_\gamma(z) = \sqrt{\frac{4\pi\alpha n_e(z)}{m_e}}} \quad (4)$$

- If the effective mass of a photon is **equal** to the mass of axion $m_\gamma = m_a$, the **resonant oscillation** occur

$$\boxed{P_{\gamma\to a} = g_a^2 \frac{\pi\omega B_T^2}{m_a^2} \left|\frac{d\log m_\gamma^2}{d\ell}\right|^{-1}_{\ell=\ell_{res}}} \quad (5)$$

- **Where in the Universe do we have proper conditions?**

Magnetic field in the IGM

Magnetic field

- By now, **magnetic fields** have been observed in galaxies and clusters
- **Is there a magnetic field in the IGM**?
- If yes, it is **difficult to observe** e.g. with FRM. There are hints from gamma-ray astronomy **[Neronov,Vovk 2010]**
- While galactic MF can be orders of magnitude amplified by **turbulent dynamos**, IGMF in voids (if they exist) should be very close to the initial conditions (coming from the early Universe?)

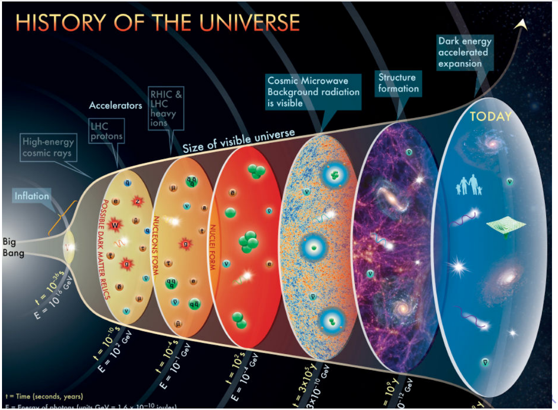
New primordial messengers?

Pillars of cosmology

1. Expansion of the Universe and structure formation ($T \sim$ meV)
2. Cosmic microwave background ($T \sim$ eV)
3. Primordial Nucleosynthesis ($T \sim$ MeV)

We would like...

to have messengers from much earlier Universe $T \sim 100$ GeV.
Primordial magnetic field?



Where to look for the primordial magnetic field?

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

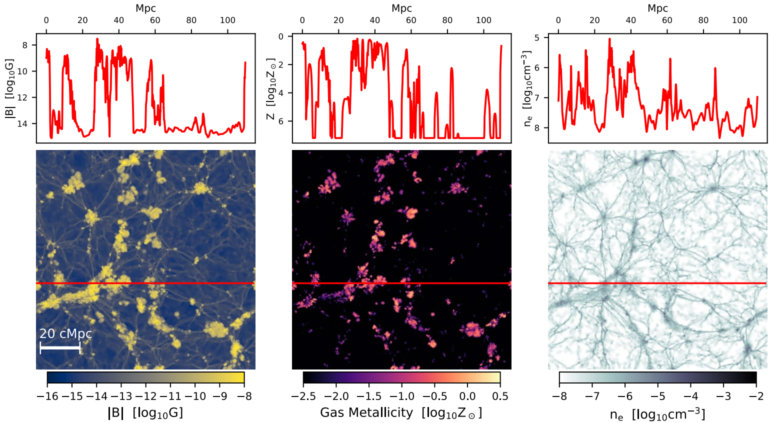
To measure the properties of the primordial magnetic field, we need to study magnetic field in the IGM

IGM and galactic feedback

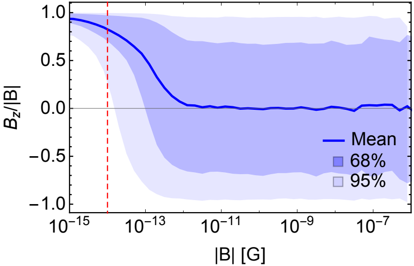
- However, the “genuine” properties of Intergalactic Magnetic Fields (IGMF) can be **affected by processes inside galaxies**
- Indeed, feedback from supernova and active galactic nuclei (AGNs) could **spread out** galactic matter and magnetic field at some distance around galaxies

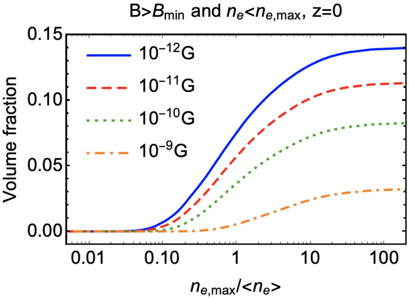
To what extend IGMF are affected by galactic feedback?
We use cosmological numerical simulations to analyze this question

Over-magnetized bubbles in IllustrisTNG simulations

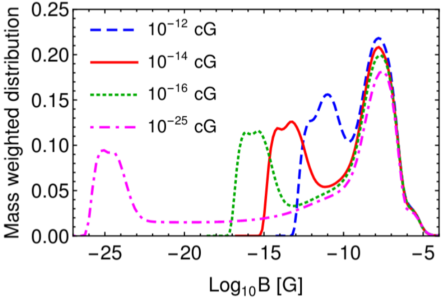


- In TNG we have observed macroscopic (**tens Mpc**) regions around clusters of galaxies with **electron density** is as **low** as in the IGM and **magnetic field** is as strong as in clusters – **over-magnetized bubbles**
- Typical **sizes** of the bubbles are **order of magnitude larger** than virial radii of parent clusters



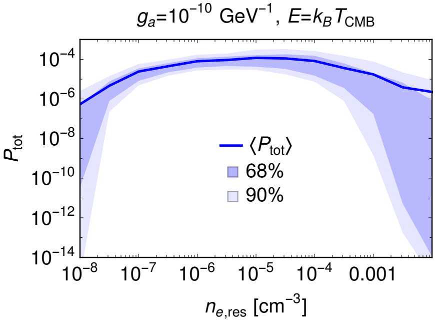


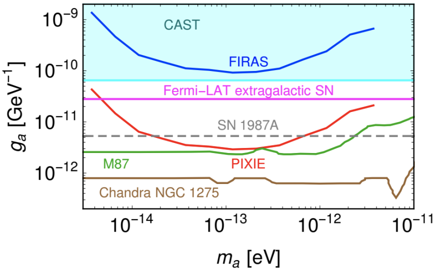
- At $z = 0$, the magnetic field is stronger than 10^{-12} G in 15% of the volume, while it is stronger than 10^{-9} G in 3% of the volume



Applications of over-magnetized bubbles

Example 1: axion conversion in magnetic bubbles

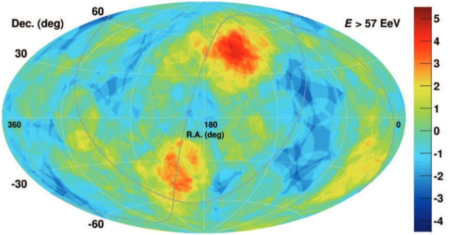




- Axion-photon conversion:
  1. $\propto B^2$ – contribution of bubbles is dominant in the IGM
  2. **Grows with energy** – that is why constraints from CMB spectral distortions are not very strong
  3. Can be improved by e.g. using CMB polarization
  4. Strong bounds on the resonant $a-\gamma$ conversion can be obtained from e.g. magnetars or gamma-ray sources
  5. However, in those cases **negative** contribution to the effective mass m_γ from **light-by-light scattering** has to be taken into account **[2203.08663]**

Example 2: Ultra-High Energy Cosmic Rays (UHECRs)

- Finding UHECRs sources: a central problem of astroparticle physics
- No signatures of sources in the data: the observed UHECRs show a surprisingly **high level of isotropy**, no significant small scale clustering

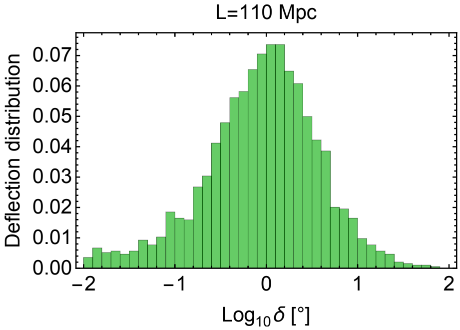


[J. Matthews, 2017]

- This absence of small scale clustering is believed to arise from the **deflection of UHECRs in magnetic fields**
- **Common picture:**
  - Galactic MF is strong in the disk, all other MFs are negligible
  - CR that arrive in the disk plane 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 $\sim 1^\circ$ **[1904.08160]**

Can we really neglect deflection of UHECRs in the IGM?

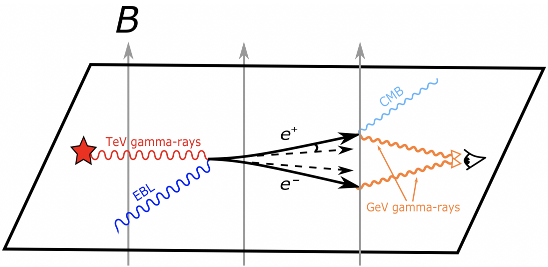
Example 2: propagation of UHECR

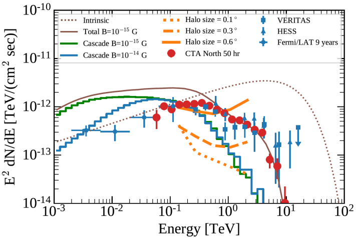


- The distribution of deflection angles is quite wide with an average value around 1° **[2101.07207]**
- The influence of intergalactic magnetic fields on the propagation of the UHECRs could be important and must to be taken into account when searching for the sources of these particles

Over-magnetized bubbles and measurement of primordial magnetic field

Magnetic fields in voids





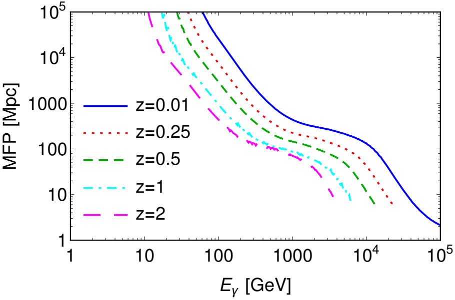
[2010.01349]

- γ-ray astronomy has a potential to measure **long-range magnetic fields** in the **Intergalactic Medium** (IGM)
- **Can the lower bound be affected by bubbles?**

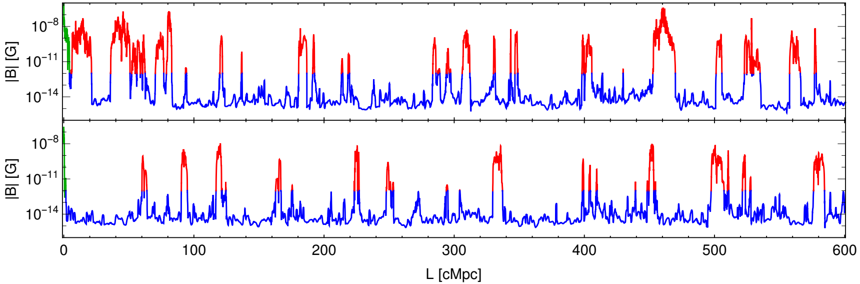
Influence of over-magnetized bubbles

- The electron-positron pair could be created anywhere along the line of sight. Over-magnetized bubbles have a volume filling fraction of $10 - 15\%$, 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

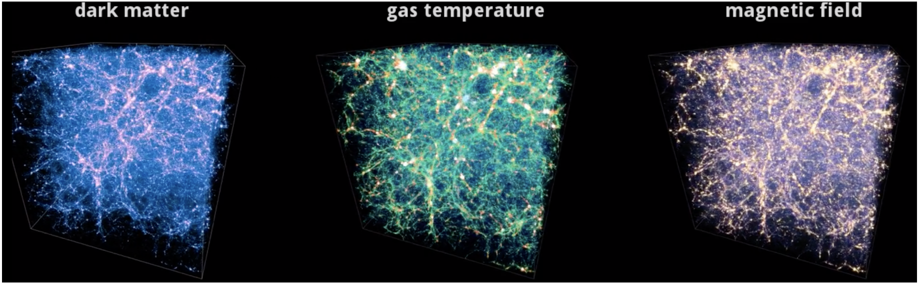


Influence of over-magnetized bubbles



- Individual sources can be unlucky enough they have an **extended over-magnetized bubble** along the line of sight to the Earth
- In our recent paper **[2106.02690]** we make a preliminary study of this effect. We found that for individual objects, 70% of energy of secondary emission was lost, but for most of the systems, the missing energy fraction is below 50%
- One way to deal with this problem is to increase statistics. With CTA, we will significantly increase the amount and quality of observed sources

Summary

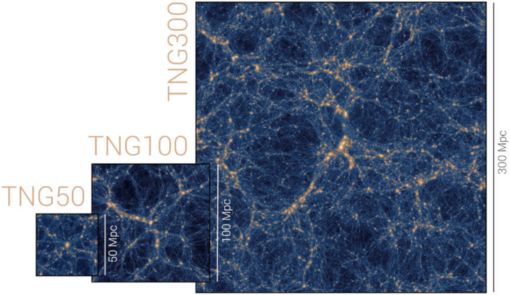


- Intergalactic medium is a **powerful tool** to study different types of new physics
- With **new instruments** (DESI, SKA, CTA, etc) a lot of progress can be expected in the near future
- IGMF, if robustly measured, can become a **new pillar of cosmology**
- To make proper use of it, a **better understanding** of the physics of the IGM itself is required

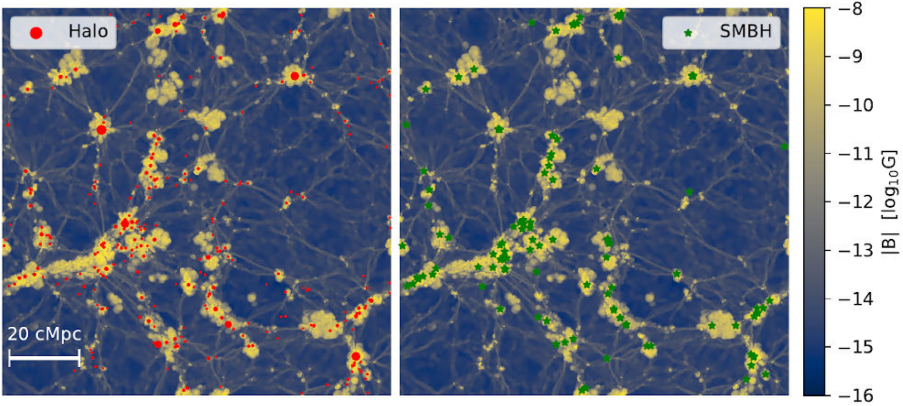
Backup slides

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]**

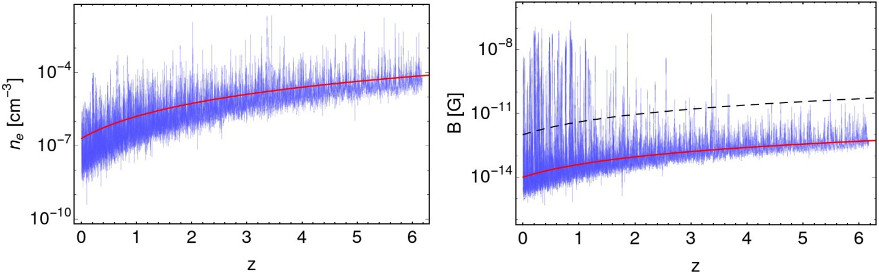


- TNG100 has a $L \sim 100$ cMpc box, 1820^3 of both DM and gas particles
- TNG includes a comprehensive galaxy formation model incorporating e.g. gas metal-line cooling and heating, star formation, stellar evolution, and heavy element enrichment, supermassive black hole growth



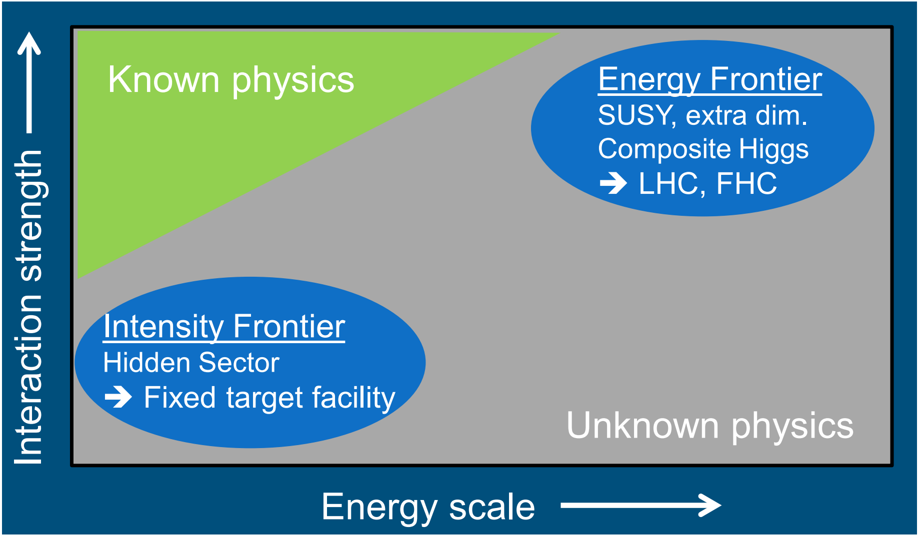
- Magnetic bubbles are produced by the **outflows caused by AGNs and supernovae**

Example 1: axion conversion in magnetic bubbles



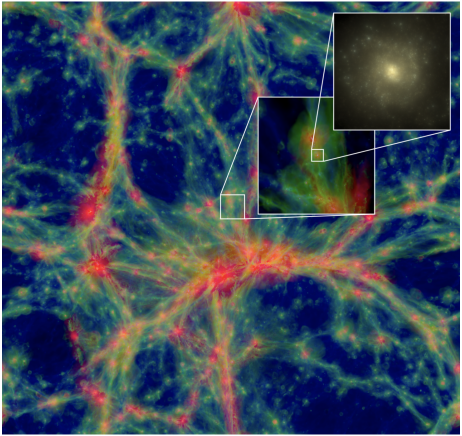
- Using the TNG simulation volume we constructed continuous lines of sight from $z = 0$ to $z = 6$ following **[2002.08942]**
- To be conservative, be calculate only contribution from large magnetic fields $B > 10^{-12}$ cG

Why don't we see new particles at accelerators?



EAGLE simulation

- In this work we used EAGLE simulation from **[1604.00020]** with a box size 100 cMpc
- Dark matter and baryons are modeled with $N = 1504^3$ particles each with a particle mass of $1.81 \times 10^6\ \mathrm{M}_\odot$ for baryons and $9.7 \times 10^6\ \mathrm{M}_\odot$ for dark matter
- The spatial resolution for gas reaches a minimum of 1 kpc within galaxies



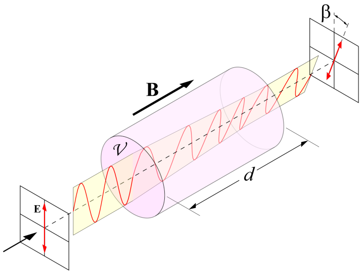
- We have 29 discrete "snapshots", unequally spaced in redshifts between $z = 120$ and $z = 0$

Faraday rotation

- The difference in time of the two opposite handed waves to travel a path length dl results

$$\Delta t \simeq \frac{\omega_p \Omega_e dl}{\omega^3} = \frac{4\pi e^3}{\omega^3 m_e^2} n_e B dl, \qquad (6)$$

where $\Omega_e = eB/m_e$ is the cyclotron frequency and ω_p is the plasma frequency



- The phase difference between the two signals is $\Delta_\phi = \omega \Delta t$
- Therefore, traveling along the path length L, the intrinsic polarization angle $\Psi_{\rm Int}$ will be rotated by an angle $\Delta\Psi = 1/2\Delta_\phi$

$$\Psi_{\rm Obs}(\lambda) = \Psi_{\rm Int} + \Delta\Psi = \Psi_{\rm Int} + \frac{e^3\lambda^2}{2\pi m_e^2} \int_0^L n_e(l) B_{||}(l) dl, \qquad (7)$$

where $B_{||}$ is the component of the magnetic field along the line of sigh

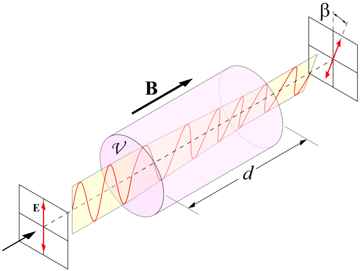
Faraday rotation

- Ψ_{Obs} is usually written in terms of the rotation measure, RM

$$\Psi_{\text{Obs}}(\lambda) = \Psi_{\text{Int}} + \lambda^2 \text{RM}, \qquad (8)$$

with

$$\text{RM} = \frac{e^3}{2\pi m_e^2} \int_0^L n_e(l) B_{||}(l) dl \qquad (9)$$



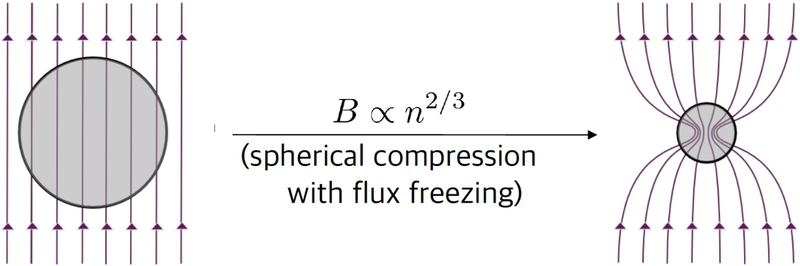
- In practical units

$$\text{RM}[\text{rad/m}^2] = 812 \int_0^L n_e[\text{cm}^{-3}] B_{||}[\mu\text{G}] dl[\text{kpc}] \qquad (10)$$

- By convention, RM is positive (negative) for a magnetic field directed toward (away from) the observer

Magnetic field evolution

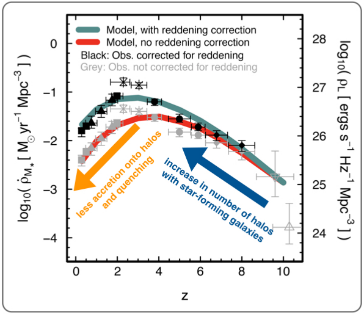
- Consider a primordial magnetic field that survived up to CMB decoupling (evolution of the magnetic field in the Early Universe is a complicated and rich area of research, see e.g. **[1303.7121]**). What happens with magnetic field later?



- Lines of magnetic field are frozen in plasma and the strength of magnetic field evolves adiabatically $B \propto n^{2/3}$
- This results in weakening of magnetic field during the expansion of the Universe and their later increase during the structure formation

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]**)

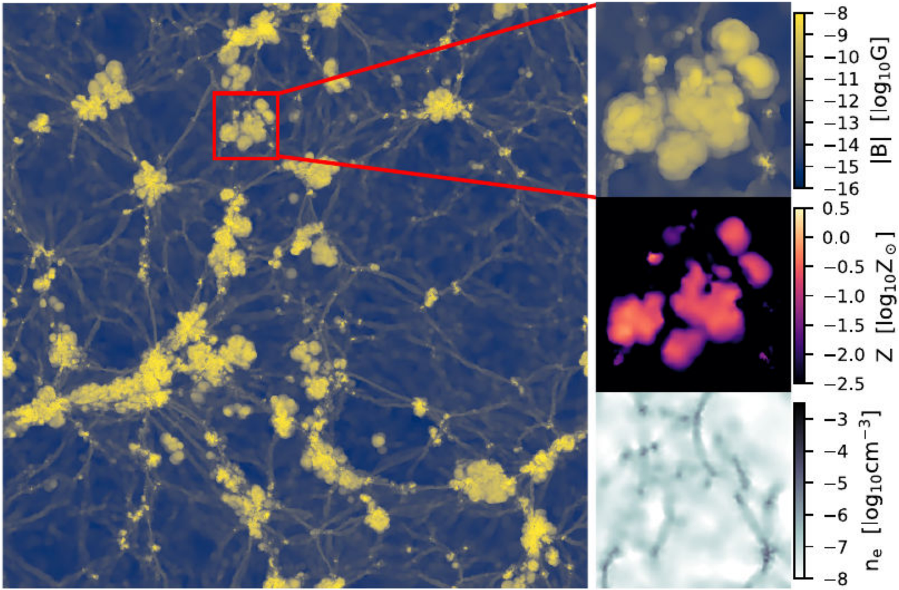


AGN model

- 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

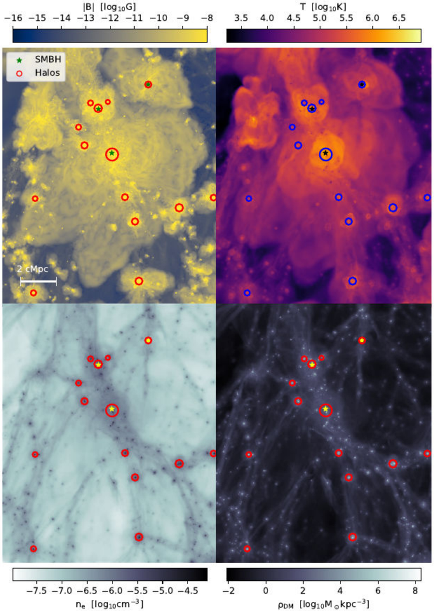
ANG model

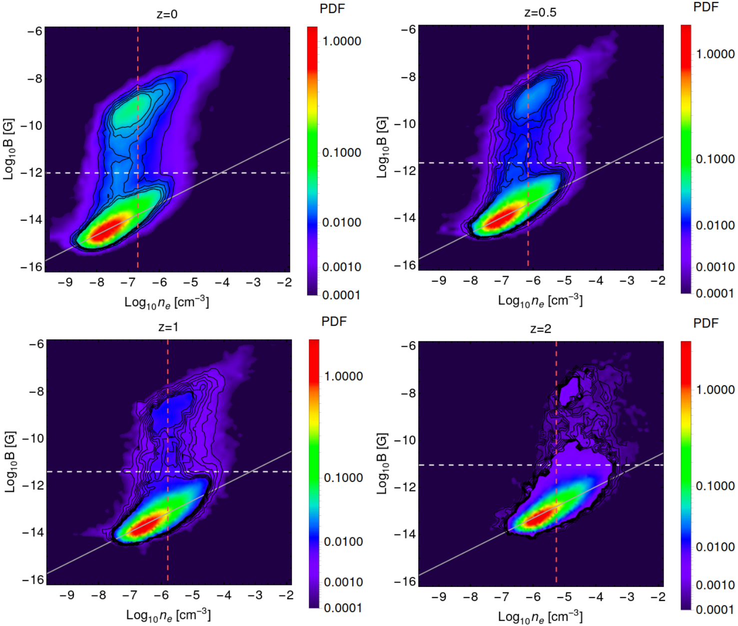
- These two modes of feedback are motivated both by theoretical conjectures for the existence of different types of accretion flows as well as recent observational evidence for the importance of kinetic AGN winds in quenching galaxies **[1607.03486]**
- A large fraction of the injected kinetic energy 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]**



−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}]

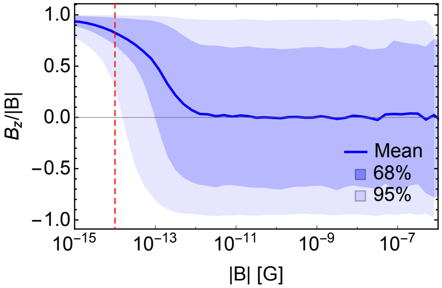
- Zooming to the volume occupied by this bubble $\sim (10\ \mathrm{Mpc})^3$ we see presence of massive halos with AGNs
- Magnetic field forms the butterfly-like configuration around the massive halo, suggesting that it was produced by outflows

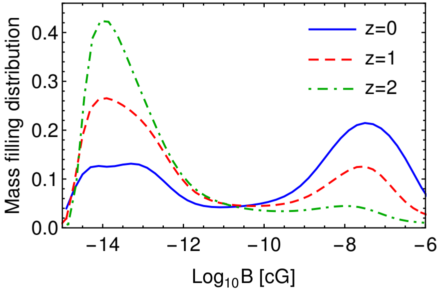




The effect of bubbles is also in the relation between B and n_e

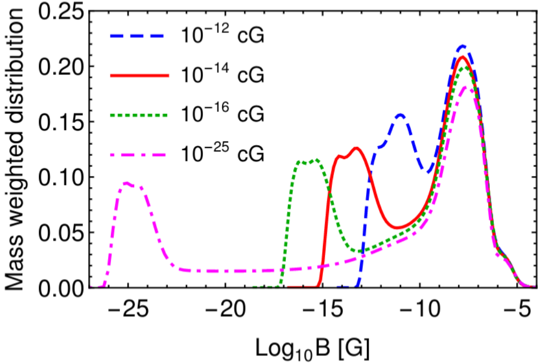
MFs in bubbles forget initial conditions





- At $z = 0$ for MFs with $B > 10^{-12}$ cG there is **no** longer a **preferred direction** of the field (for seed field was along z axis with $B = 10^{-14}$ cG)
- Over-magnetized bubbles **formed quite recently**, at redshifts $z \lesssim 2$
- Simulated magnetic fields in bubbles "**forget**" the initial orientation of the seed magnetic field!

MFs in bubbles forget initial conditions

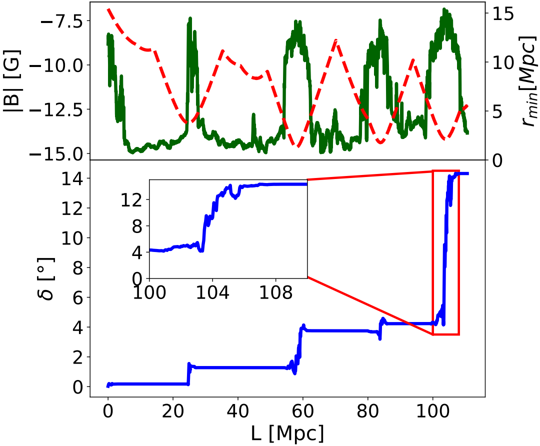


- Moreover, different seed magnetic field values results in similar distribution of magnetic field in bubbles

Example of application: 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,

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

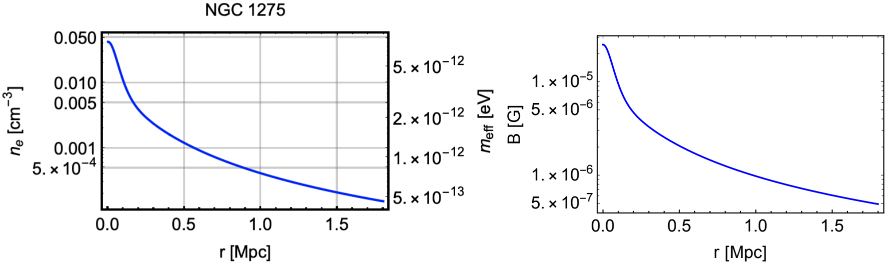


Magnetic field measurements

- **How do we measure magnetic fields in the Universe?**
- In **dense structures** we can to measure MFs using the **Faraday effect**
- Reminder: the Faraday effect causes a polarization rotation $\Delta\theta$,

$$\Delta\theta = \mathrm{RM}\lambda^2, \qquad \mathrm{RM} = \frac{e^3}{2\pi m_e^2}\int n_e B_{\parallel} d\ell, \tag{11}$$

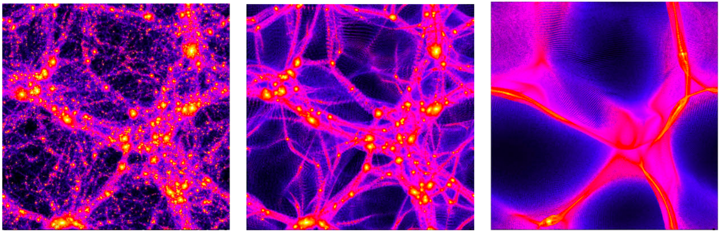
- Typical values of the observed MFs: $\sim 10^{-6}$ G in galaxies and central parts of clusters, $\sim 10^{-8}$ G in filaments between two close clusters **[2101.09331]**



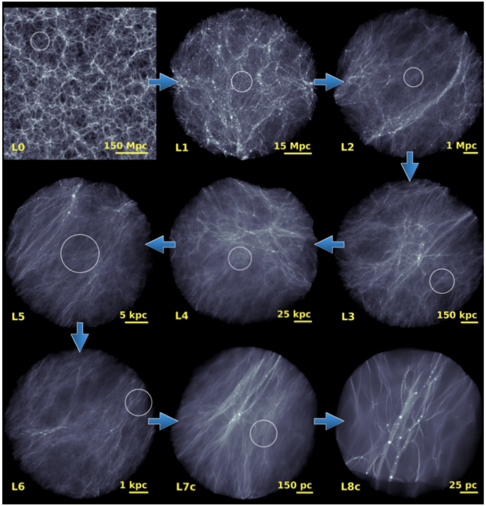
[1907.05475]

Classification

- If DM particles are created **non-relativistic** we call them **Cold Dark Matter** (CDM). They can fall on **any over-density and form halos of all sizes**
- **Warm Dark Matter** (WDM) and **Hot Dark Matter** (HDM) are particles that were created **relativistic**. They **cannot be confined by an over-density** as long as they are still **relativistic** and their velocities are close to the speed of light
- The distance that a particle travels from the place where it was *created* to the place where it was *gravitationally bound* is called the **free streaming length**



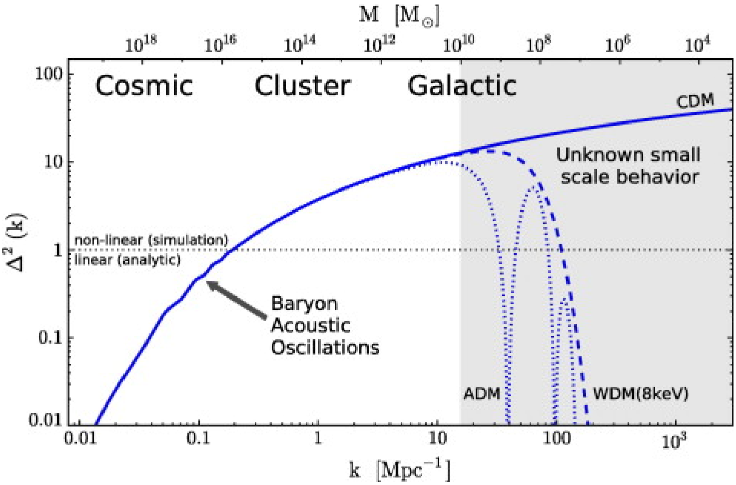
Cold dark matter – self-similar structure formation



[Nature 585, 39-42 (2020)]

Below certain scale, most of these structures can be completely dark!

CDM vs. non-CDM power spectra



[Kuhlen et al. (2012), 1209.5745]

- We need to **reconstruct DM distribution at small scales**, where our method is likely to have limitations
- This means that we have to study in details **two main questions**
  1. How does the hydrogen distribution differ from DM distribution?
  2. How to restore hydrogen distribution from observations (Lyman-α forest)?

3D power spectrum

- How to characterize the difference between CDM and non-CDM case **quantitatively**?
- Consider a density distribution $\rho(\boldsymbol{r})$ in the Universe at some redshift z. The **density contrast** and its Fourier transformation is defined as

$$\delta(\boldsymbol{r}) = \frac{\rho(\boldsymbol{r}) - \bar{\rho}}{\bar{\rho}} = \int \frac{d^3 k}{(2\pi)^3} \delta(\boldsymbol{k}) e^{i\boldsymbol{k}\cdot\boldsymbol{r}}, \qquad [\delta(\boldsymbol{r})] = 1 \tag{12}$$

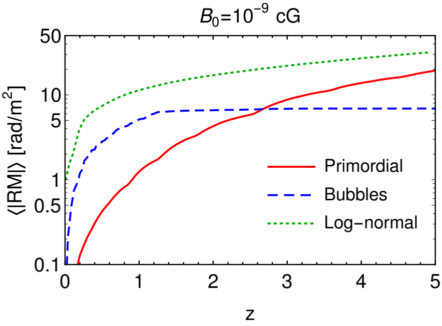
  where $\bar{\rho}$ is the average density in the Universe
- The number of inhomogeneities with scale $L = 2\pi/k$ is given by **3D power spectrum** $P_{3D}(k)$,

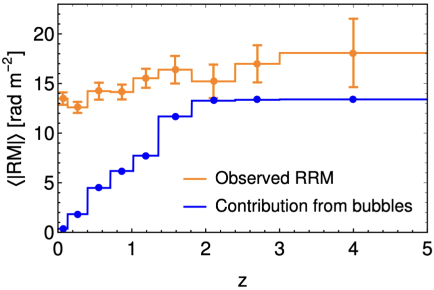
$$P_{3D}(k) = \frac{1}{V}\langle|\delta(k)|^2\rangle, \qquad [P_{3D}(k)] = L^3 \tag{13}$$

- People often work with a **dimensionless 3D power spectrum**

$$\Delta_{3D}(k) \equiv \frac{k^3}{2\pi^2} P_{3D}(k), \qquad [\Delta_{3D}(k)] = 1 \tag{14}$$

Constraints on extragalactic Faraday rotation



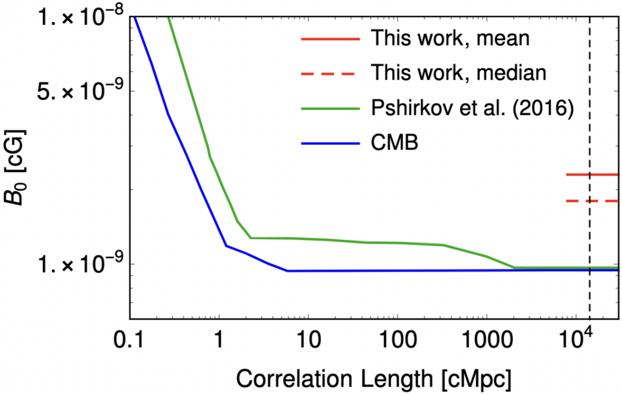


- The **Faraday rotation** technique provides a powerful probe of astrophysical magnetic fields across different elements of Large Scale Structure
- Reminder: the Faraday effect causes a polarization rotation $\Delta\theta$,

$$\Delta\theta = \mathrm{RM}\lambda^2, \qquad \mathrm{RM} = \frac{e^3}{2\pi m_e^2}\int n_e B_{\parallel}\, d\ell, \tag{15}$$

- Prediction for the mean median values of RM from TNG as a function of redshift **[2204.XXXXX]**

Constraints on the primordial magnetic field from TNG



- 2σ limits on the primordial magnetic field strength for different correlation lengths from Faraday Rotation Measure using the IllustrisTNG simulations for mean **[2204.XXXXX]**