Cosmological magnetic fields

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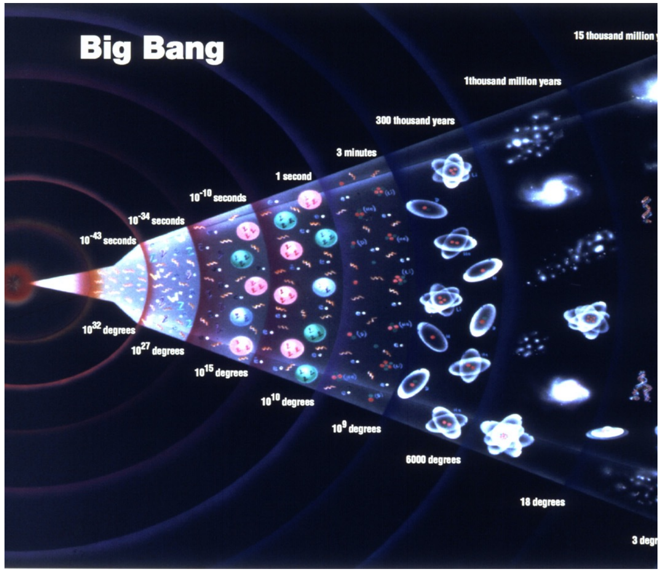
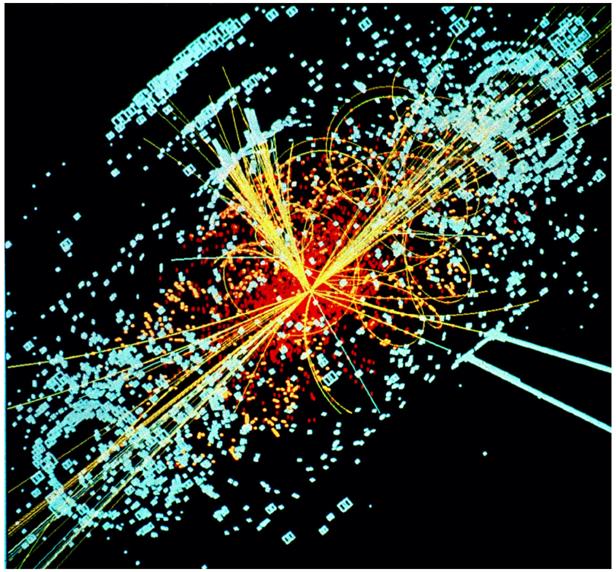
Cosmological magnetic fields ?





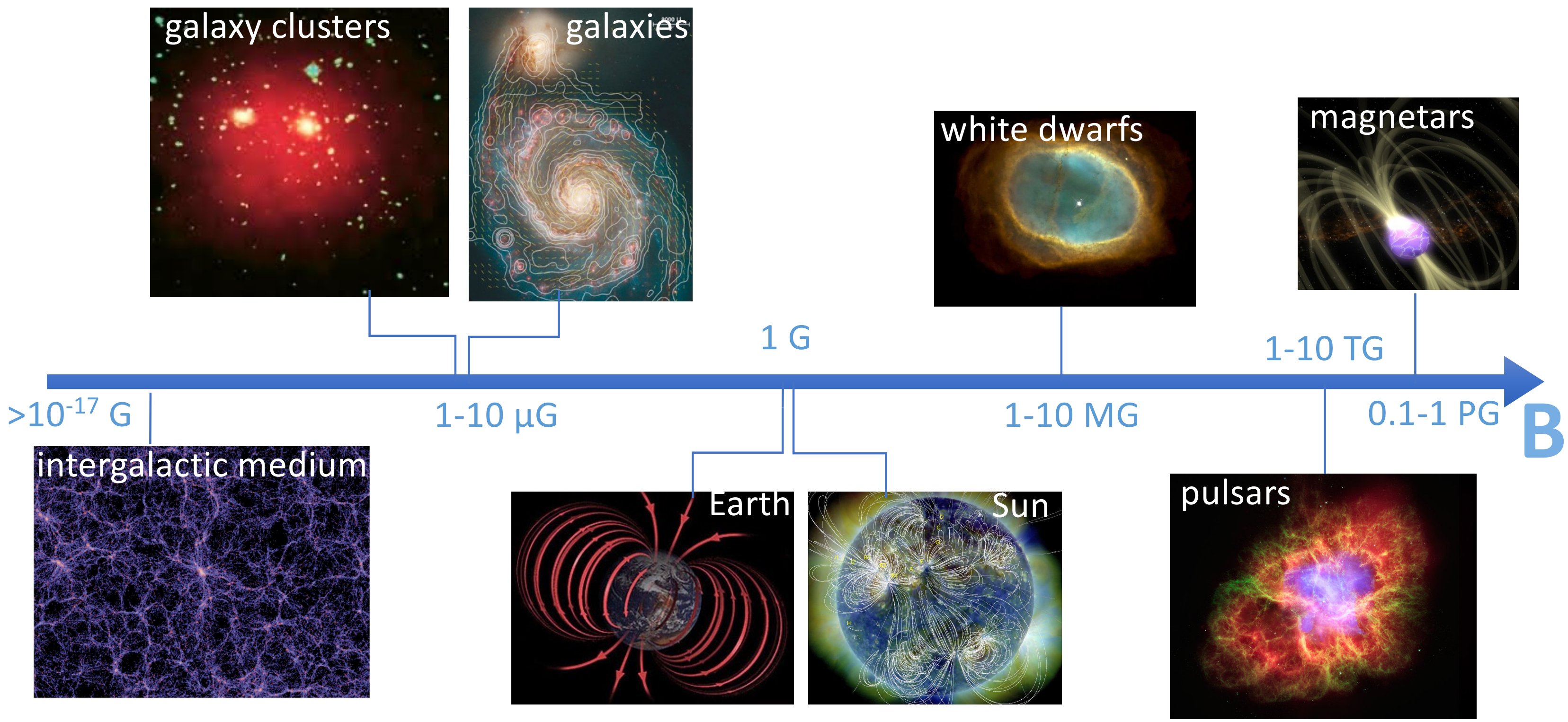
Three "**beyond Standard Model" phenomena** are known in fundamental / particle physics:

(1) Dark Matter / Dark Energy
(2) Baryon Asymmetry of the Universe,
(3) neutrino masses.

Collider and other laboratory based experiments can probe only limited range of DM models (e.g. WIMPs). They can provide limited information relevant for solution of the BAU problem (e.g. measurement of CP violating phases) and have limited sensitivity for absolute measurement of neutrino masses). Alternative probe can be provided by cosmology. Production of DM, generation of BAU should have been dramatic events in the Early Universe when its temperature was $T > 100$ MeV. They should have left imprint on cosmological observables.

Earliest observables currently available are from Big Bang Nucleosynthesis ($t_H \geq 1$ s) and CMB epoch ($t_H \sim 3\times10^5$ yr), temperature ranges much below 100 MeV. **It would be interesting to have new cosmological probe(s) for $T > 100$ MeV epoch ($t_H < 100\ \mu s$).**

Cosmological magnetic fields ?



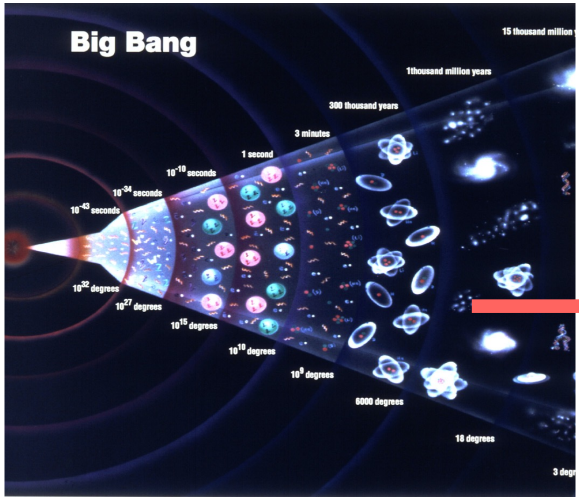
Magnetic fields in astronomical objects are produced through dynamo action on weaker pre-existing fields. The weakest field is found in the intergalactic medium, in voids of the Large Scale Structure.

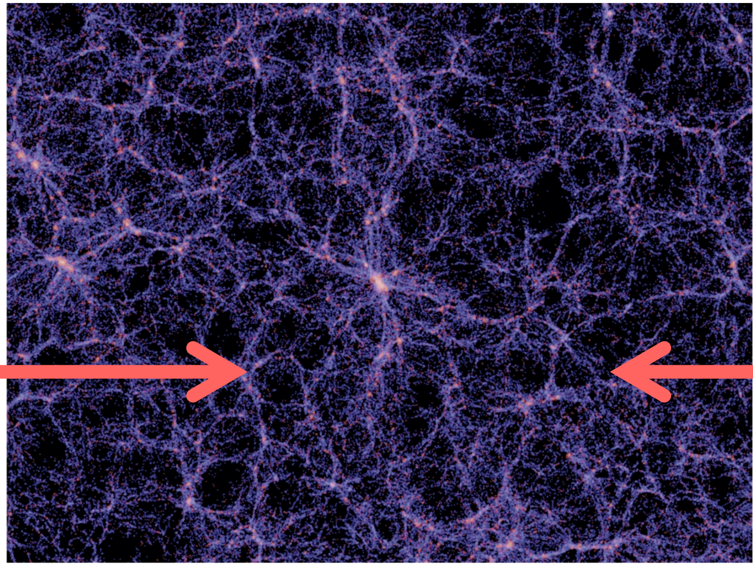
This field should have been generated "from scratch" before galaxies, possibly in the Early Universe, in the temperature range $T > 100$ MeV.

It would be interesting to know the nature of the initial seed magnetic field.

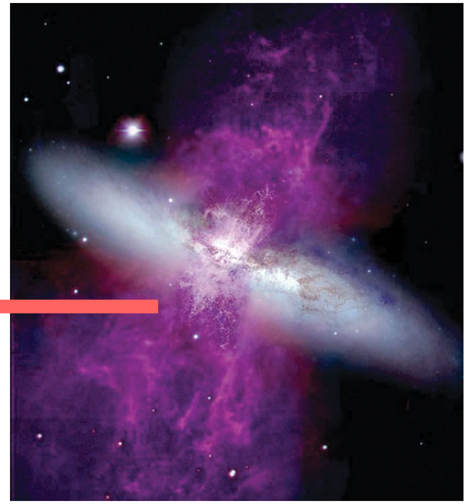
Cosmological → intergalactic magnetic fields

Cosmological seed fields





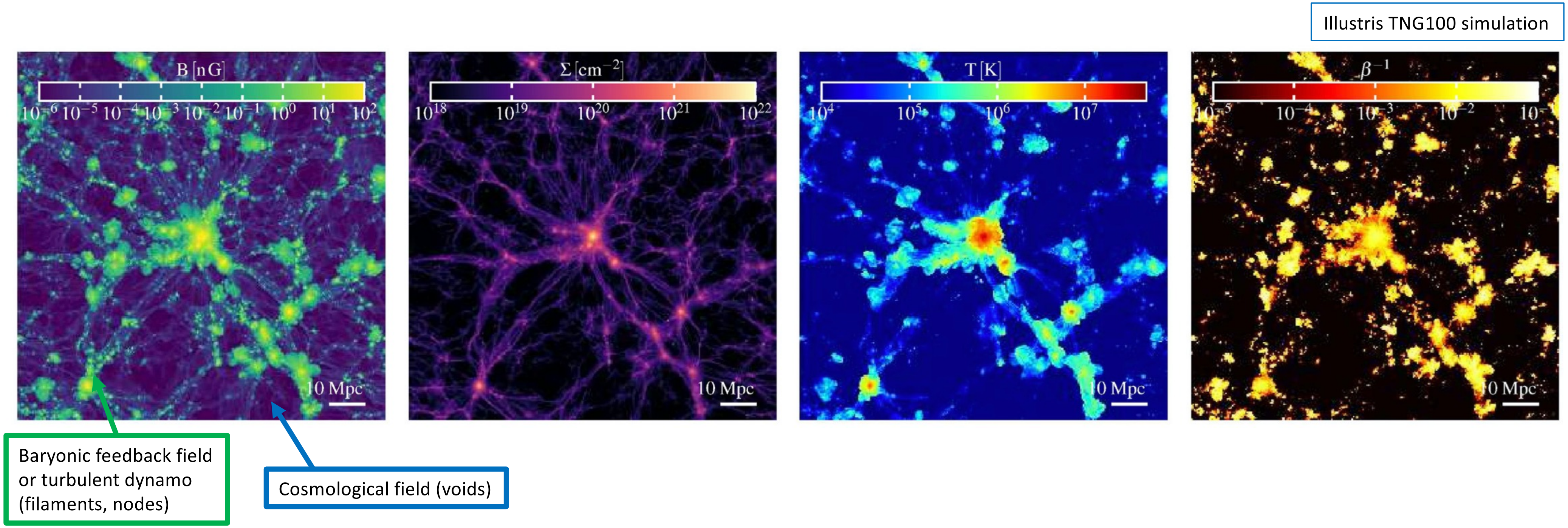
Magnetic fields from the baryonic feedback on the Large Scale Structure



Relic magnetic fields from the Early Universe is not the only possible explanation of the intergalactic magnetic fields (IGMF). The other possible source is the field spread by the “baryonic feedback” on the Large Scale Structure (galactic winds driven by star formation and AGN activity).

The two types of fields may be distinguished through the measurement of their volume filling factor, strength and correlation length.

Cosmological → intergalactic magnetic fields



Relic magnetic fields from the Early Universe are not the only possible explanation of the intergalactic magnetic fields (IGMF). The other possible source is the field spread by the "baryonic feedback" on the Large Scale Structure (galactic winds driven by star formation and AGN activity).

The two types of fields may be distinguished through the measurement of their volume filling factor, strength and correlation length. Most recent modelling of the baryonic feedback within Illustris TNG simulations suggests that the feedback fields do not fill the volume.

Void magnetic fields (if they exist) have to be of cosmological nature.

Marinacci et al. https://arxiv.org/abs/1707.03396

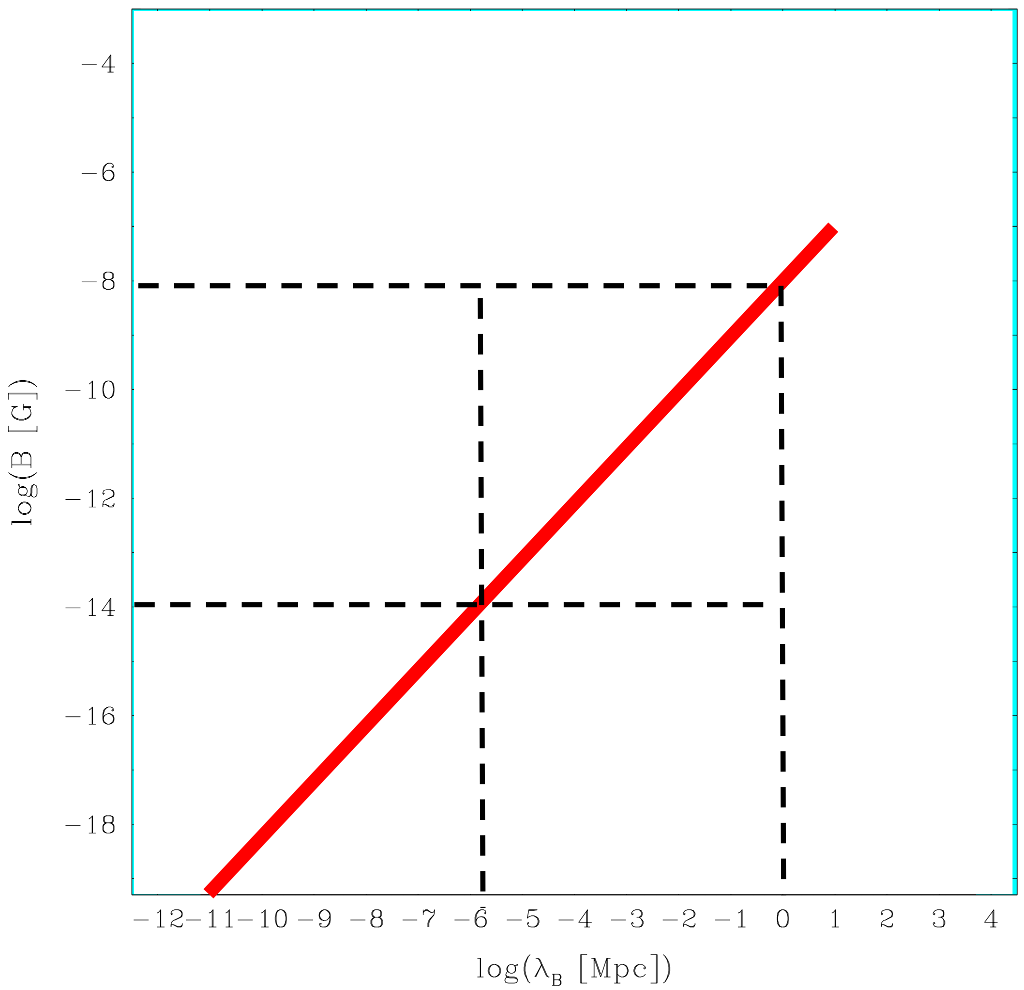
Cosmological → intergalactic magnetic fields

Cosmological fields have well-defined relation between strength and correlation length corresponding to the largest cosmologically processed eddies:

$$L \sim v_A t_H \sim \frac{v_A}{H}$$

(t_H is the Hubble time, v_A is Alfven velocity). Possible strength range: up to "equipartition" with matter / radiation energy density:

$$B \leq \sqrt{2\rho_{CMB}} \sim 3\times10^{-6}\ \mathrm{G}$$



Bounds on void / cosmological magnetic fields

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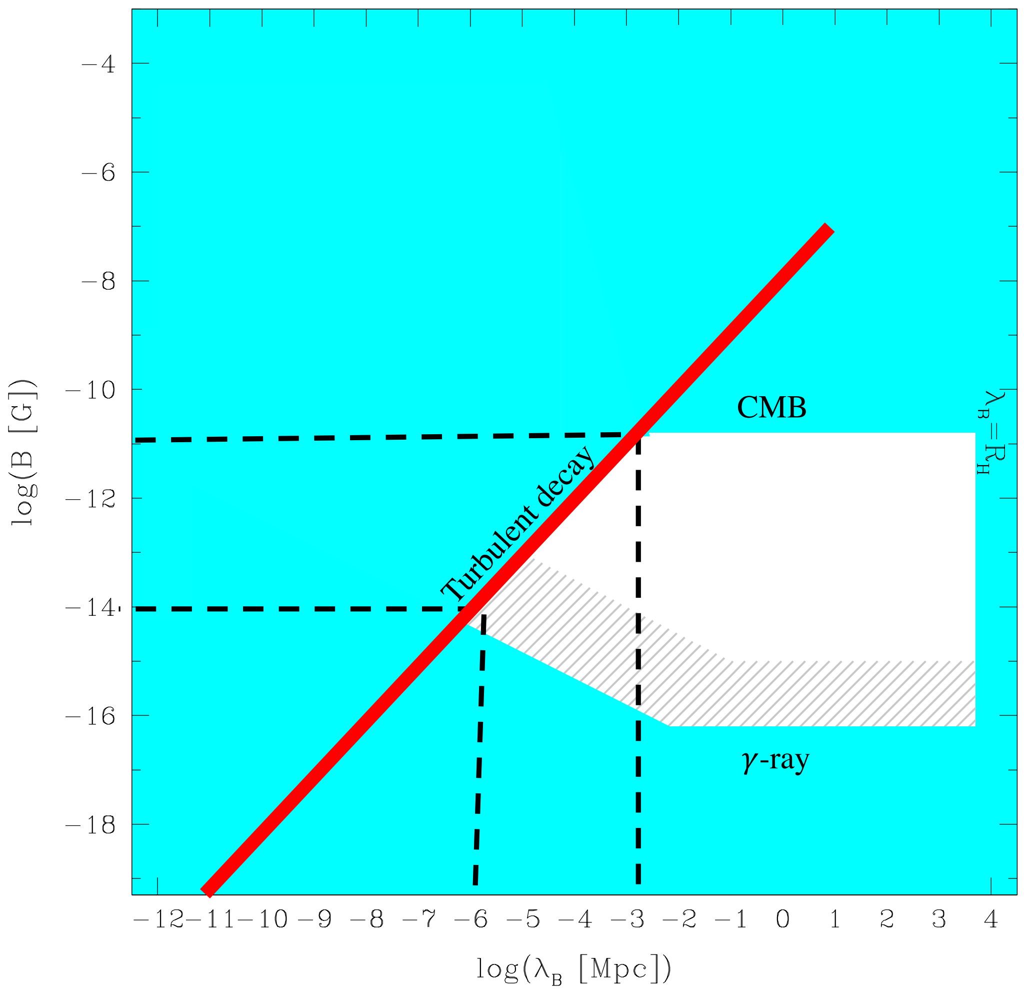


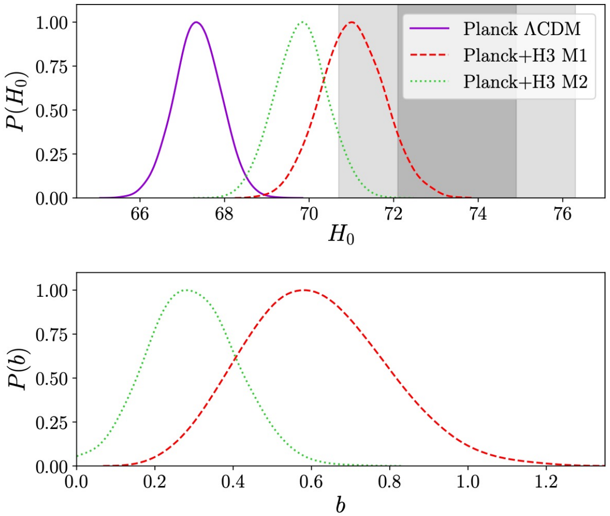
Bounds on void / cosmological magnetic fields

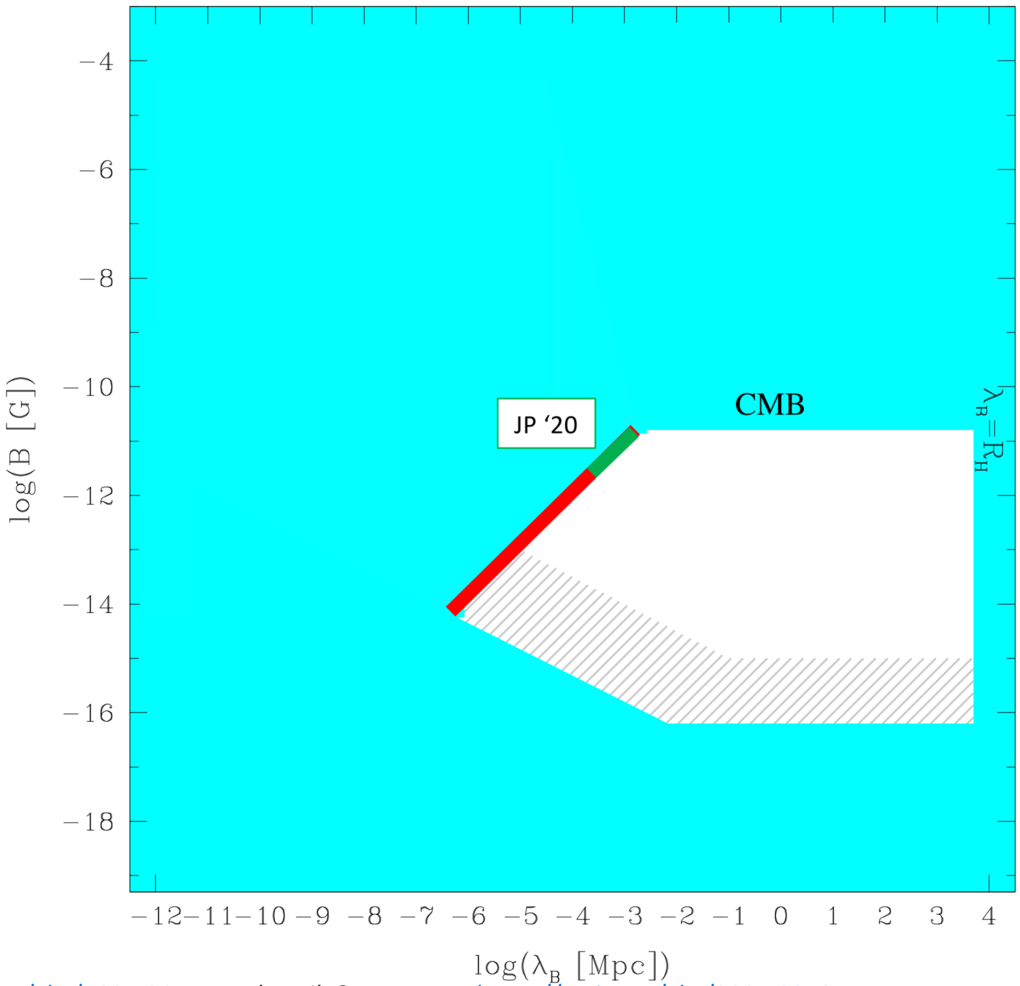
Magnetic field also induces clumping of recombining plasma $\left(\frac{\delta\rho}{\rho}\right) \sim \left(\frac{v_A}{c_s}\right)^2$ on distance scales about the largest processed eddy size $L = v_A t_H$. Clumping modifies the recombination process:

$$\frac{dn_e}{dt} + 3Hn_e = -C\left(\alpha_e n_e^2 - \beta_e n_{HI} e^{-\frac{h\nu}{T}}\right)$$

(ionization rate proportional to n_{HI}, recombination proportional to n_e^2). The limit on IGMF is $B \leq 10^{-11}$ G, much tighter than the CMB anisotropy limits.

Most recently, Jedamzik & Pogosyan argued that including clumping effect in the CMB analysis leads to a revised estimate of the Hubble parameter, more consistent with the low redshift measurements of H_0, thus relieving the ”Hubble tension”.





Jedamzik&Abel https://arxiv.org/abs/1108.2517, Jedamzik & Saveliev, https://arxiv.org/abs/1804.06115, Jedamzik & Pogosyan https://arxiv.org/abs/2004.09487

Bounds on void / cosmological magnetic fields

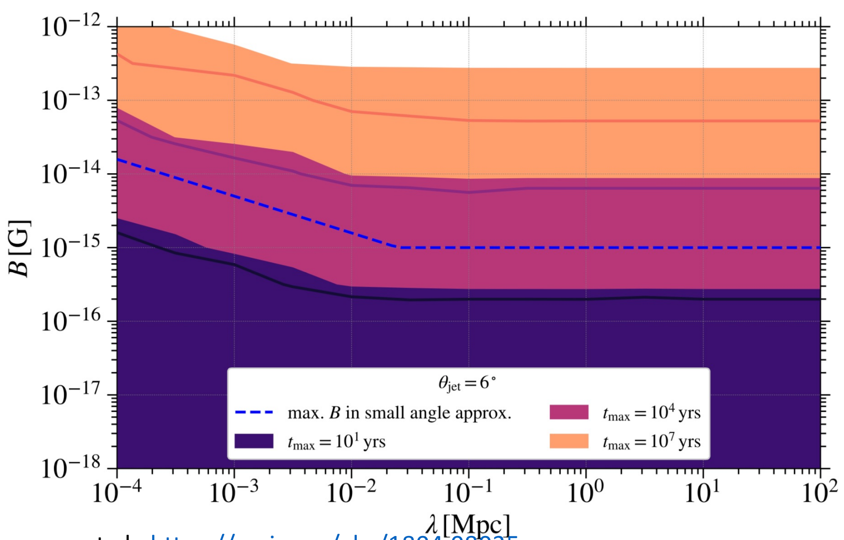
γ-rays with energies above ~0.1 TeV are absorbed by the pair production on the way from the source to the Earth.

e^+e^- pairs re-emit γ-rays via inverse Compton scattering of CMB photons.

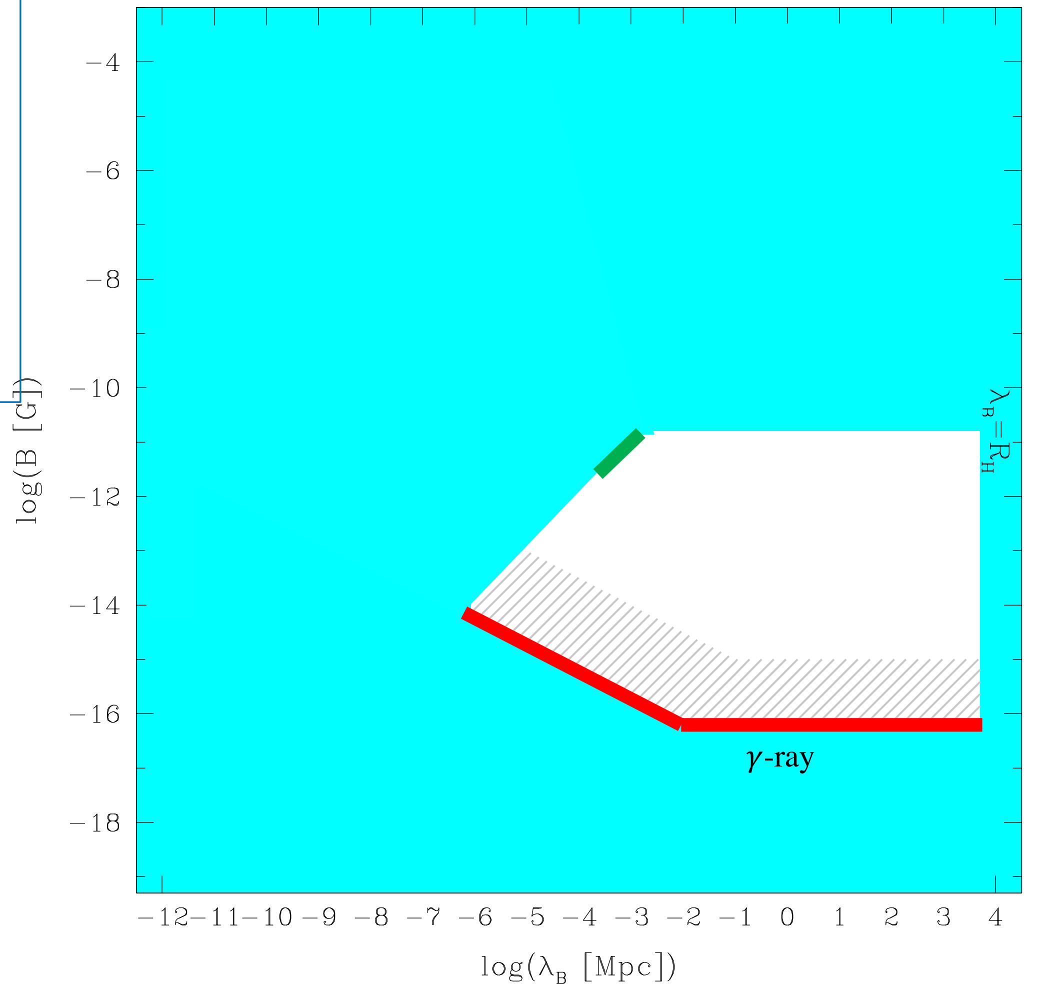
Inverse Compton γ-rays could be detected at lower energies.

Timing and spatial morphology of the secondary emission from e^+e^- pairs is sensitive to the intergalactic magnetic fields.

The most constraining source is currently 1ES 0229+200 (z=0.13).



Ackermann et al. https://arxiv.org/abs/1804.08035



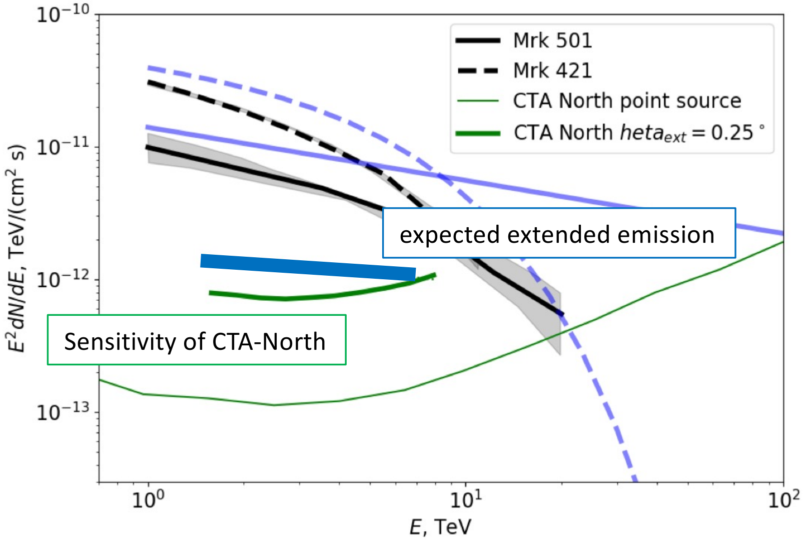
Sensitivity reach of CTA to void magnetic fields

Electrons emitting secondary γ with E_γ are deflected by an angle

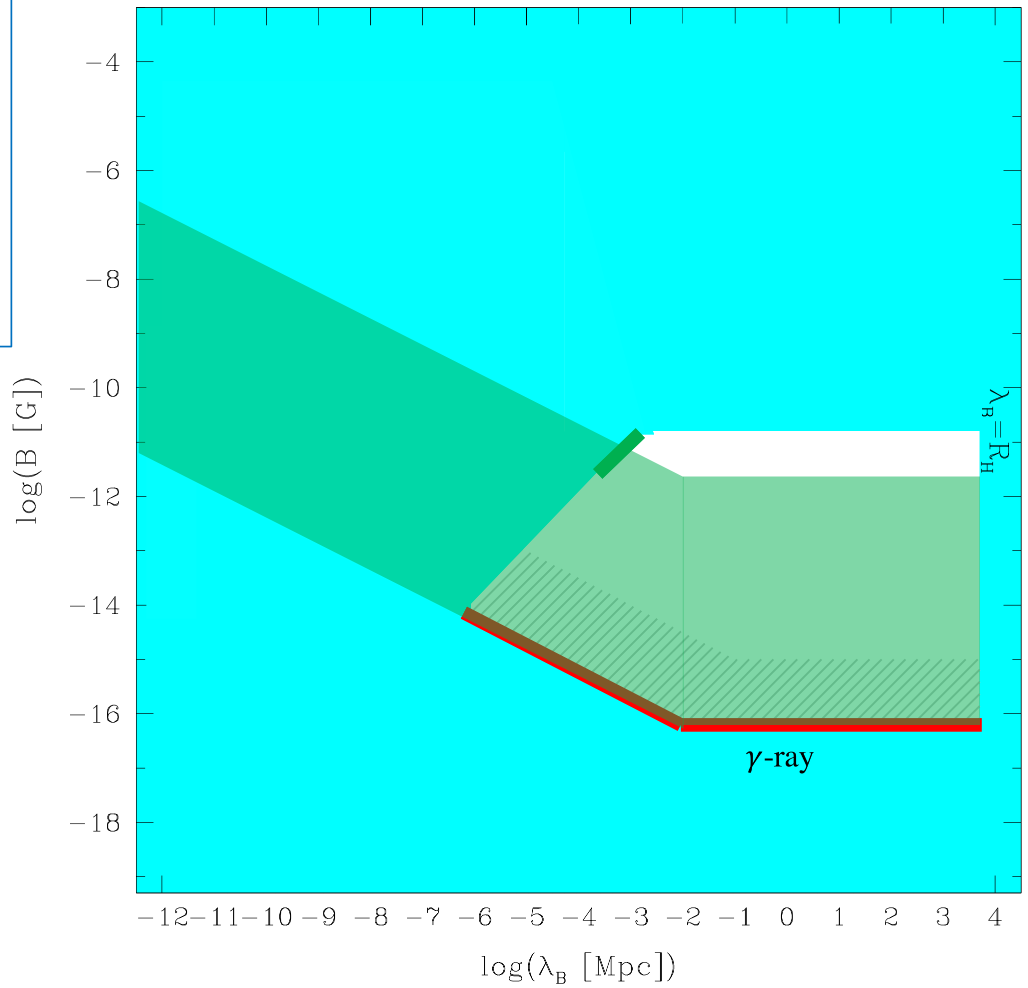
$$\Delta \simeq 0.2 \left[\frac{E_\gamma}{8\ \mathrm{TeV}}\right]^{-\frac{3}{4}} \left[\frac{B}{10^{-11}\mathrm{G}}\right]^{3/2}$$

Strong magnetic field isotropises directions of relatively low energy electrons. Only the highest energy electrons emitting inverse Compton at ~ 10 TeV are not strongly deflected.

Sensitivity of CTA is needed for searches of extended emission in the TeV band. CTA will be able to probe void magnetic fields in the range up to the CMB upper limit.



Korochkin, Kalashev, AN, Semikoz https://arxiv.org/abs/2007.14331



Cosmological magnetic fields

Gamma-ray and CMB measurements sample cosmological magnetic field parameters at redshifts $z = 0$ and $z \sim 10^3$, far from the epoch of the field generation.

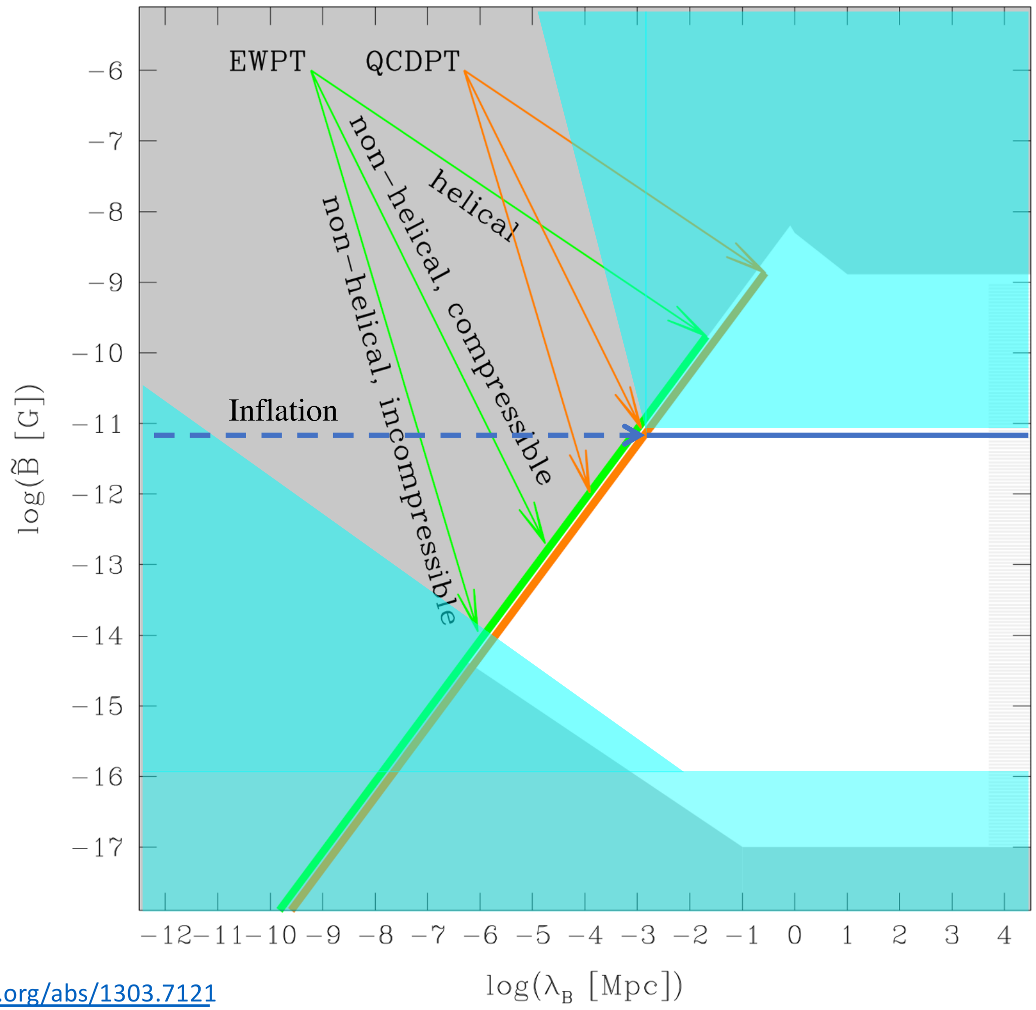
Most of the cosmological magnetic field models consider field generation at cosmological phase transitions:

- Electroweak phase transition (EWPT)
- QCD phase transition (QCDPT)

or from the epoch of

- Inflation.

The same relic magnetic field might originate from from one or the other epoch, there is (almost) no way to distinguish different cosmological magnetogenesis scenaria observationally.



Banerjee, Jedamzik https://arxiv.org/abs/astro-ph/0410032, Durrer, AN https://arxiv.org/abs/1303.7121

Evolution of cosmological magnetic fields

Starting from the moment of magnetogenesis, the magnetic field evolves via free turbulence decay, as long as its strength and correlation length are outside the viscous damping range. The energy density power spectrum

$$\rho_B = \int \frac{dk}{k} k^3 P_B(k) \propto k^5$$

$$B_k \propto k^{\frac{5}{2}} \propto \lambda_B^{-\frac{5}{2}}$$

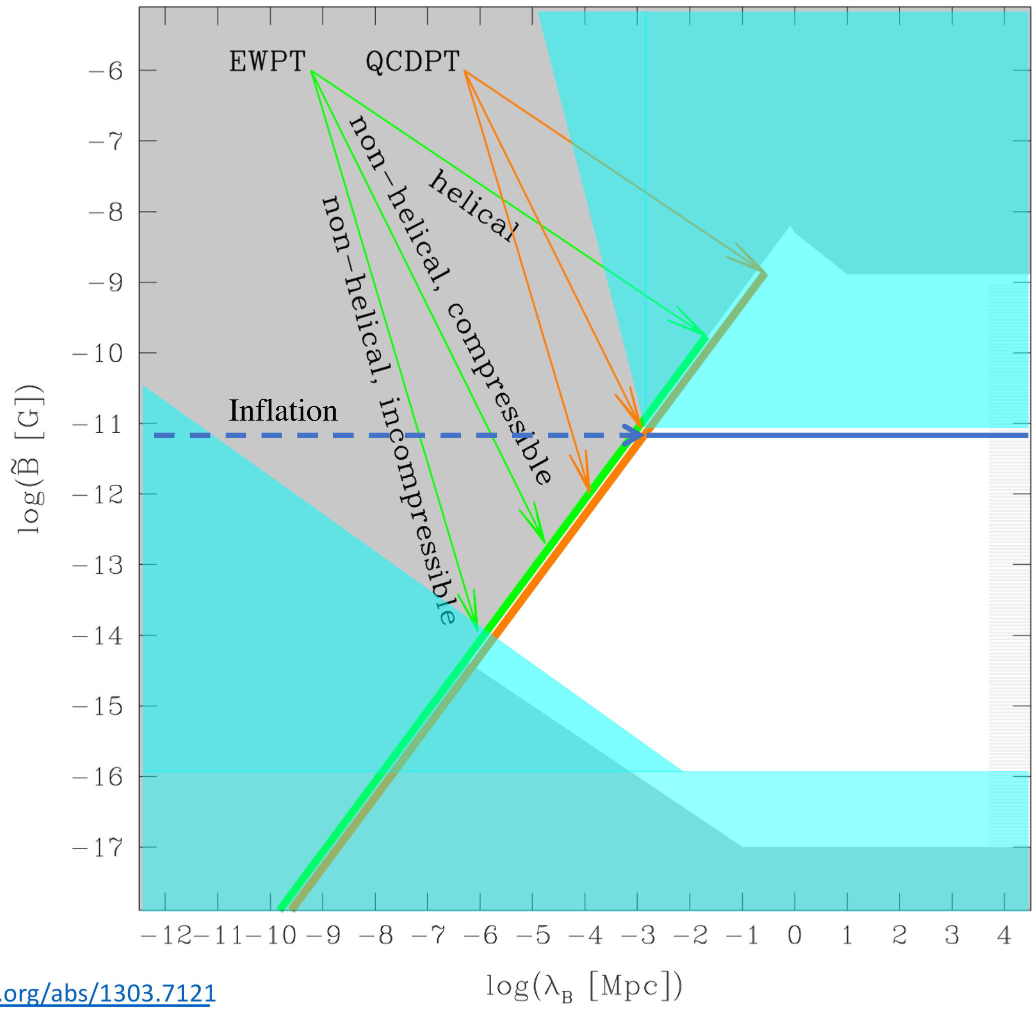
for small k ($P_B(k)$behavior imposed by divergence-free nature of B). In the simplest case, eddies with smaller and smaller k are gradually processed by turbulence and their power is dissipated.

If magnetic field is helical, $H = \int A \cdot B \, d^3x \neq 0$, conservation of helicity imposes $B \propto \lambda_B^{-1/2}$ evolution.

Magnetic field excites fluid motions and produces kinetic energy density with power spectrum

$$\rho_K = \int \frac{dk}{k} k^3 P_K(k) \propto k^3$$

($P_K$behavior at small k can be $P_K \propto k^0$). If magnetic field is subsequently driven toward equipartition with kinetic energy, $\rho_B \sim \rho_K$, B can decay as $B \propto \lambda_B^{-3/2}$.



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Cosmological magnetic fields and gravitational waves

Turbulent magnetic field and plasma motions generate stress-energy tensor that sources gravitational wave. Gravitational wave equation for modes with wavenumber k

$$\frac{\partial^2 h}{\partial t^2} + k^2 h = \frac{16\pi}{aM_{Pl}^2} T^{TT}$$

(prime is time derivative, $T^{TT}$is transverse traceless part of stress-energy tensor) Is that of a forced oscillator subject to external force $F = \frac{16\pi}{aM_{Pl}^2} T^{TT} \propto B^2$. If the force is constant and the oscillator is initially at $h = h' = 0$, the amplitude of oscillations is $h = \frac{F}{k^2} \sim \frac{B^2}{k^2}$.

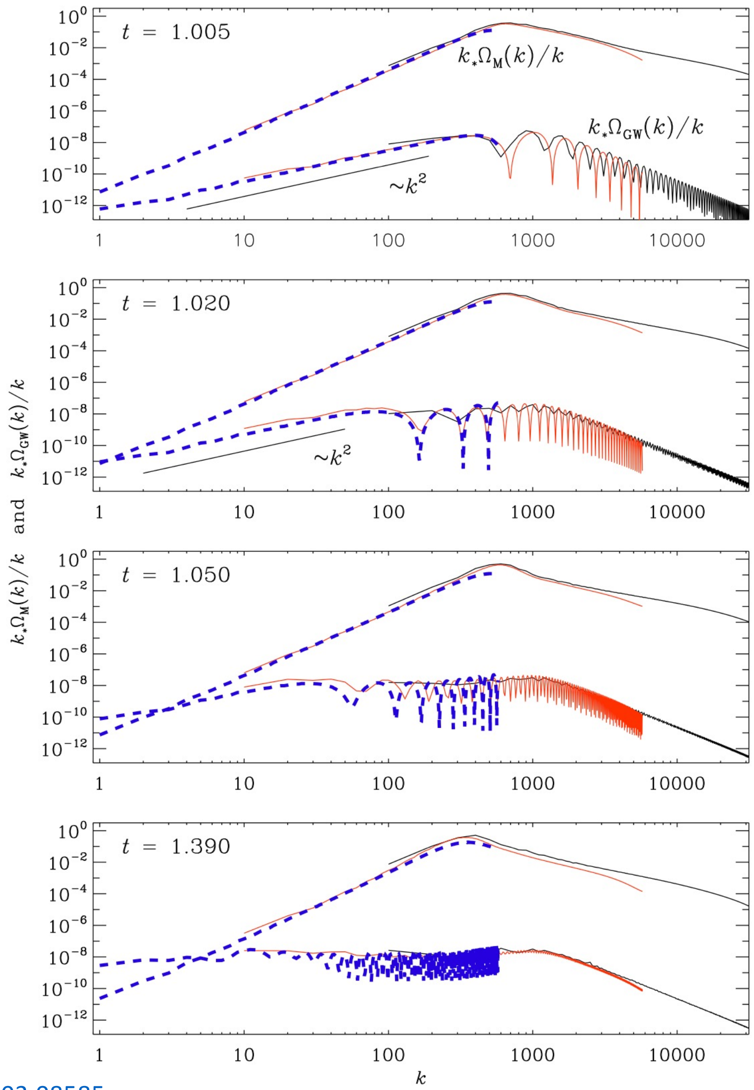
The energy density of gravitational waves is

$$\rho_{GW} = \frac{M_{Pl}^2 \langle h'^2 \rangle}{32} \propto \frac{B^4}{k^2}$$

It can be comparable to the radiation energy density if $\tilde{B}$ is close equipartition, $\tilde{B} \sim 3\ \mu$G and $k \sim H$. This means that

$$\Omega_{GW} \sim \Omega_{CMB} \left[\frac{B}{3\ \mu\text{G}}\right]^4 \left[\frac{k}{H}\right]^{-2}$$

Magnetic field modes with wavenumber k are processed on time scale $t_k = (vk)^{-1}$. This is much longer than the time scale of oscillations of gravitational waves, $t \sim k^{-1}$, as long as $v \ll 1$. MHD turbulence provides a "quasi-constant" force in the r.h.s. of the wave equation.



Caprini, Durrer, https://arxiv.org/abs/astro-ph/0603476

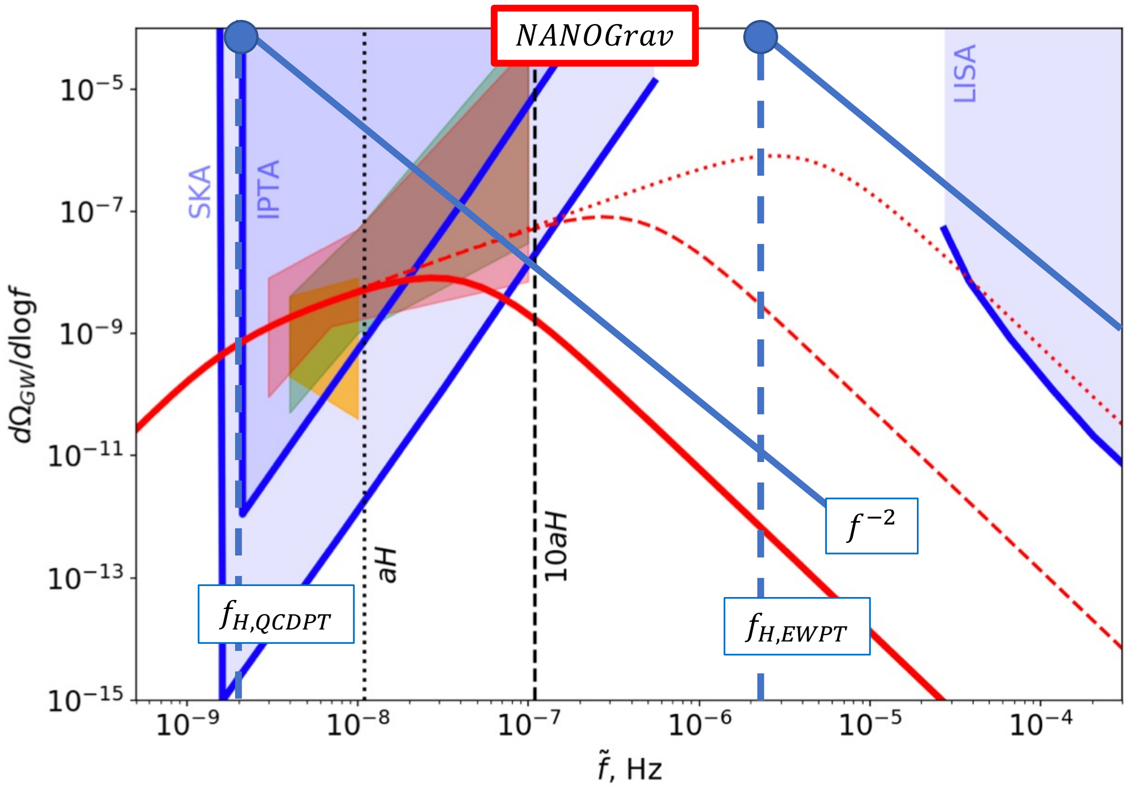
AN, Pol, Semikoz, Caprini https://arxiv.org/abs/2009.14174, Pol et al. https://arxiv.org/abs/1903.08585

Cosmological magnetic fields and gravitational waves

MHD turbulence at QCD phase transition can provide an alternative explanation of NANOGrav evidence for existence of stochastic gravitational wave background.

Nano-Hertz frequency corresponds to the wavelength of gravitational waves about the size of cosmological horizon at QCD epoch.

Upcoming pulsar timing array data (EPTA, IPTA, SKA) will have sensitivity to test this hypothesis.



Arzoumanian et al. https://arxiv.org/abs/2009.04496

AN, Pol, Semikoz, Caprini https://arxiv.org/abs/2009.14174

Summary

Robust lower bound on IGMF is imposed at the level 10^{-16} G for large correlation length field and $> \mathbf{10^{-14}}$ **G** for IGMF of cosmological origin by gamma-ray searches of time-delayed emission from the variable TeV-band emission from AGN (blazars, specifically 1ES 0229+200).

Detection of cosmological IGMF with the strength up to 10^{-11} G is possible with CTA, at least using the signal of Mrk 501, but possibly of further TeV-loud AGN.

Upper bound on cosmological magnetic field $< \mathbf{10^{-11}}$ **G** is imposed by analysis of the influence of turbulence-induced clumping on recombination, from the CMB analysis.

Account of the magnetic field induced clumping relaxes the Hubble tension problem, if IGMF is in $\mathbf{10^{-12} - 10^{-11}}$ **G** range.

New cosmological probe of $T > 100$ MeV epoch can be obtained via combination of cosmological magnetic field and gravitational wave measurements.

Recent evidence for stochastic gravitational wave background from NANOGrav can be interpreted in terms of magnetogenesis at the QCD phase transition, with $\tilde{\boldsymbol{B}} \sim \mathbf{1}\ \boldsymbol{\mu}\mathbf{G}$ comoving field strength and $\tilde{\boldsymbol{\lambda}}_{\boldsymbol{B}} \sim \mathbf{0.1\ pc}$ comoving correlation length.