Cosmological magnetic field measurements

Andrii Neronov

Astroparticle and Cosmology laboratory, University of Paris
Astronomy Department, University of Geneva

Introduction / motivation

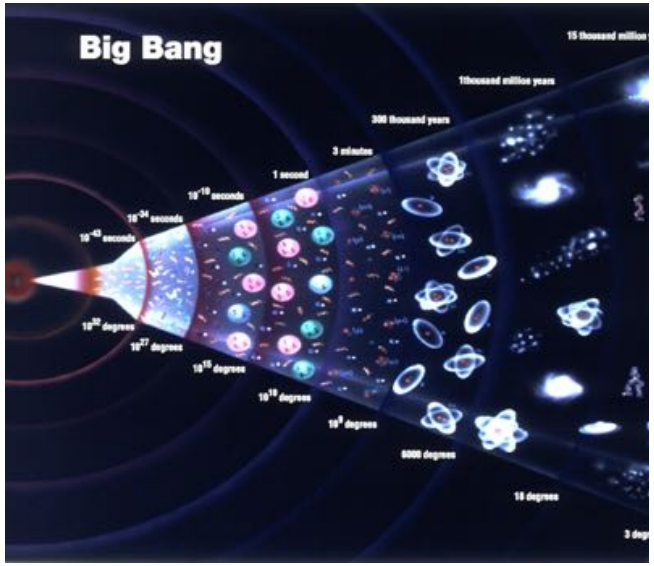
Intergalactic magnetic fields
- – Upper bounds (CMB, Faraday rotation)
- – Lower bound (gamma-rays), prospects with CTA

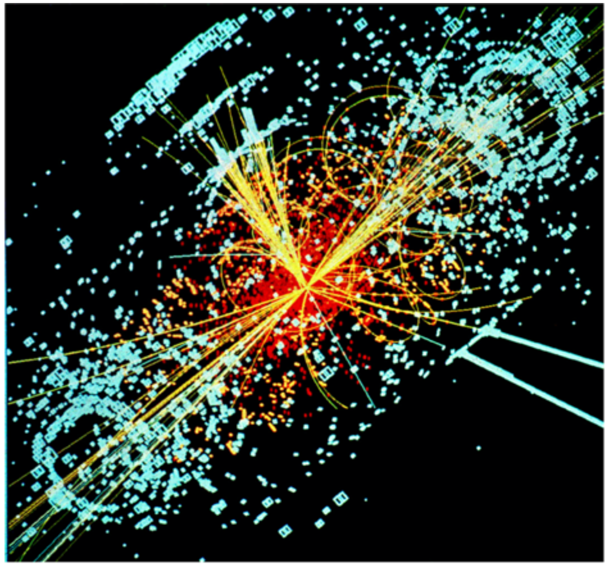
Cosmological magnetic fields
- – evolution
- – gravitational wave signature
- – interpretation of NANOGrav signal

Theoretical implications
- – first order QCD phase transition?
- – cosmological dynamos

Summary / conslusions

Introduction / motivation





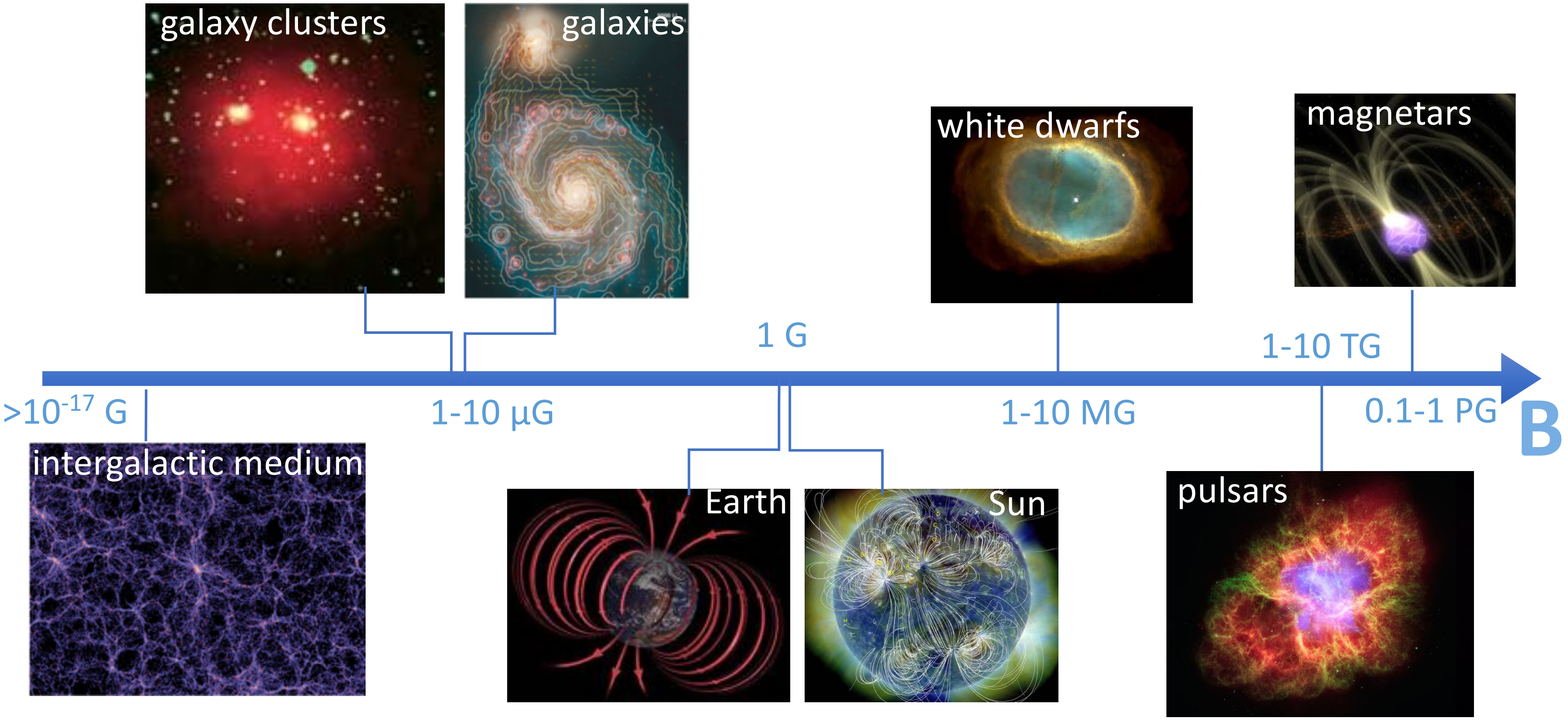
Three "**beyond Standard Model" phenomena** are known in fundamental / particle physics:

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 $T > 100\ \mathrm{MeV}$. They should have left imprint on cosmological observables.

Earliest observables currently available are from Big Bang Nucleosynthesis ($T \sim 1 - 0.01\ \mathrm{MeV}$) and CMB epoch ($T < 1\ \mathrm{eV}$), too low temperature range.
It would be interesting to have new cosmological probe(s) for $T > 100\ \mathrm{MeV}$ epoch ($t_H < 10\ \mu s$).

Introduction / motivation

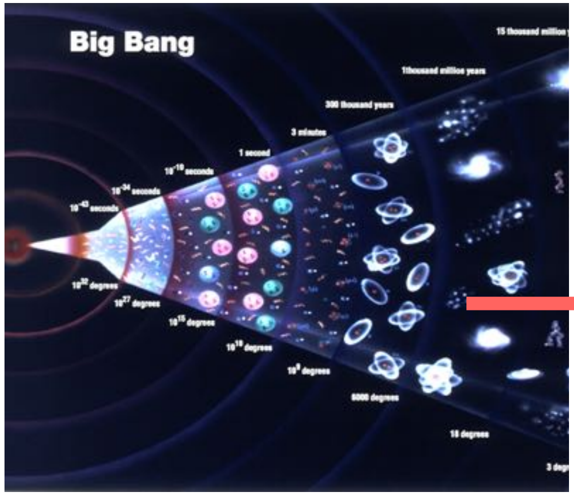


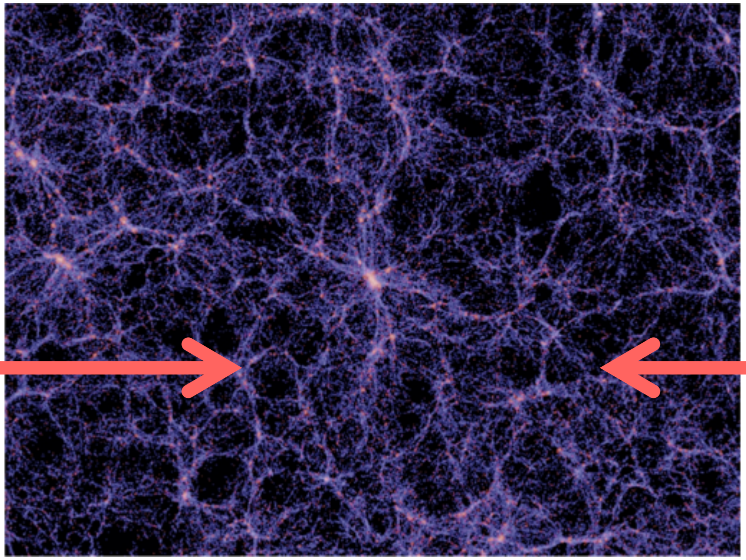
Magnetic fields in astronomical objects are produced through dynamo action on weaker pre-existing fields. The weakest field is found in the intergalactic medium, in voids of the Large Scale Structure.

This field should have been generated "from scratch" before the epoch of formation of galaxies, possibly in the Early Universe, in the temperature range $T > 100\ \mathrm{MeV}$.
It would be interesting to know the nature of the initial seed magnetic field.

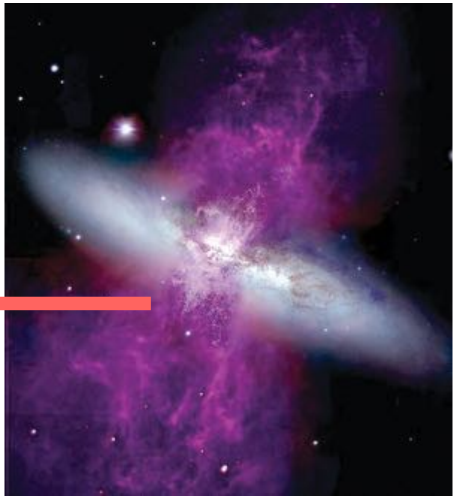
Intergalactic magnetic fields

Cosmological seed fields





Magnetic fields from the baryonic feedback on the Large Scale Structure

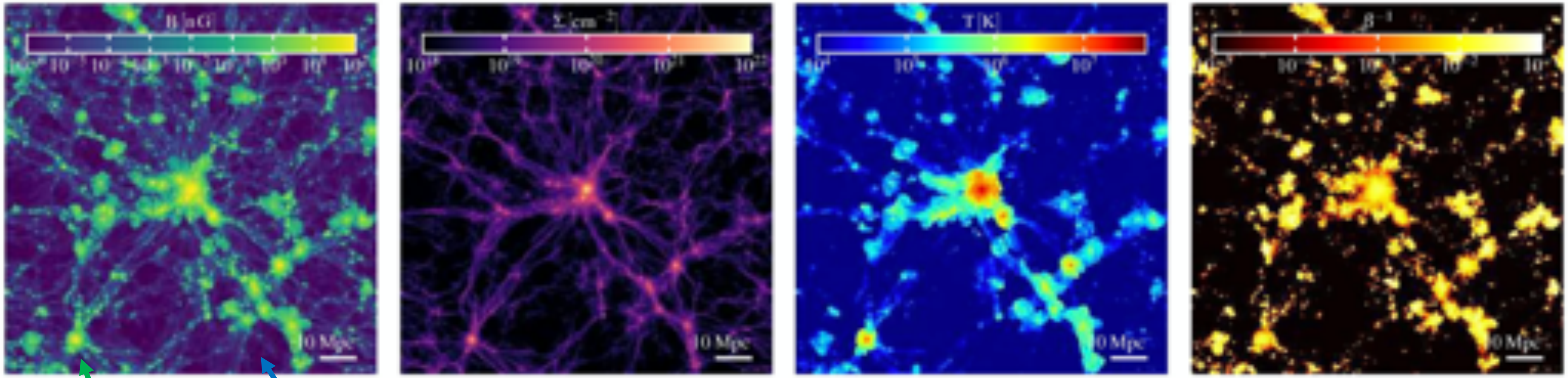


Relic magnetic fields from the Early Universe is not the only possible explanation of the intergalactic magnetic fields (IGMF). The other possible source is the field spread by the “baryonic feedback” on the Large Scale Structure (galactic winds driven by star formation and AGN activity).

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

Intergalactic magnetic fields

Illustris TNG100 simulation



Baryonic feedback field (filaments, nodes)

Cosmological field (voids)

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.

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

Intergalactic magnetic fields

Feedback and primordial IGMF also differ by their properties: strength and correlation length.

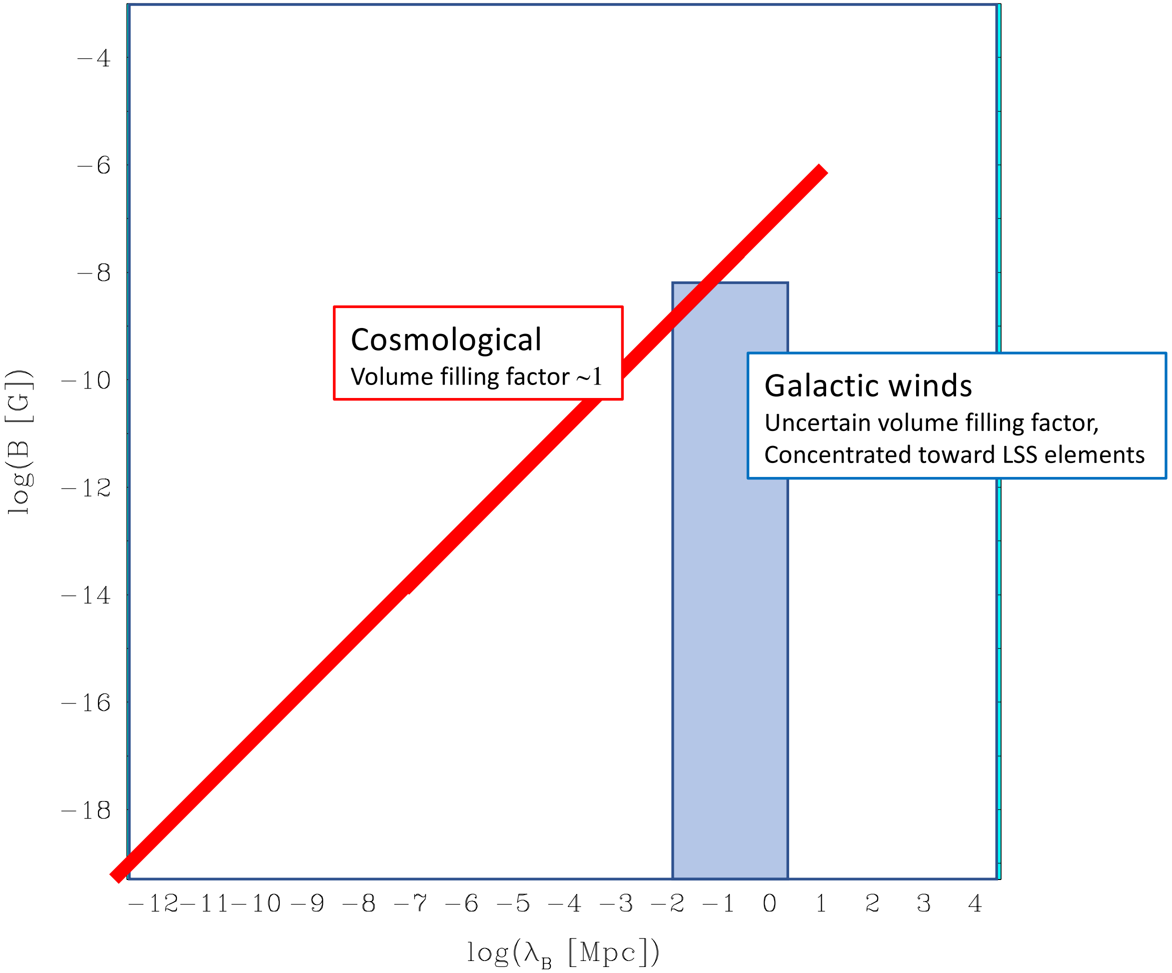
Baryonic feedback magnetic fields have correlation length comparable to the scale of galactic winds.

Cosmological fields have well-defined relation between strength and correlation length corresponding to the "larges 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:

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



Cosmological
Volume filling factor ~1

Galactic winds
Uncertain volume filling factor,
Concentrated toward LSS elements

Intergalactic magnetic fields

Feedback and primordial IGMF also differ by their properties: strength and correlation length.

Baryonic feedback magnetic fields have correlation length comparable to the scale of galactic winds.

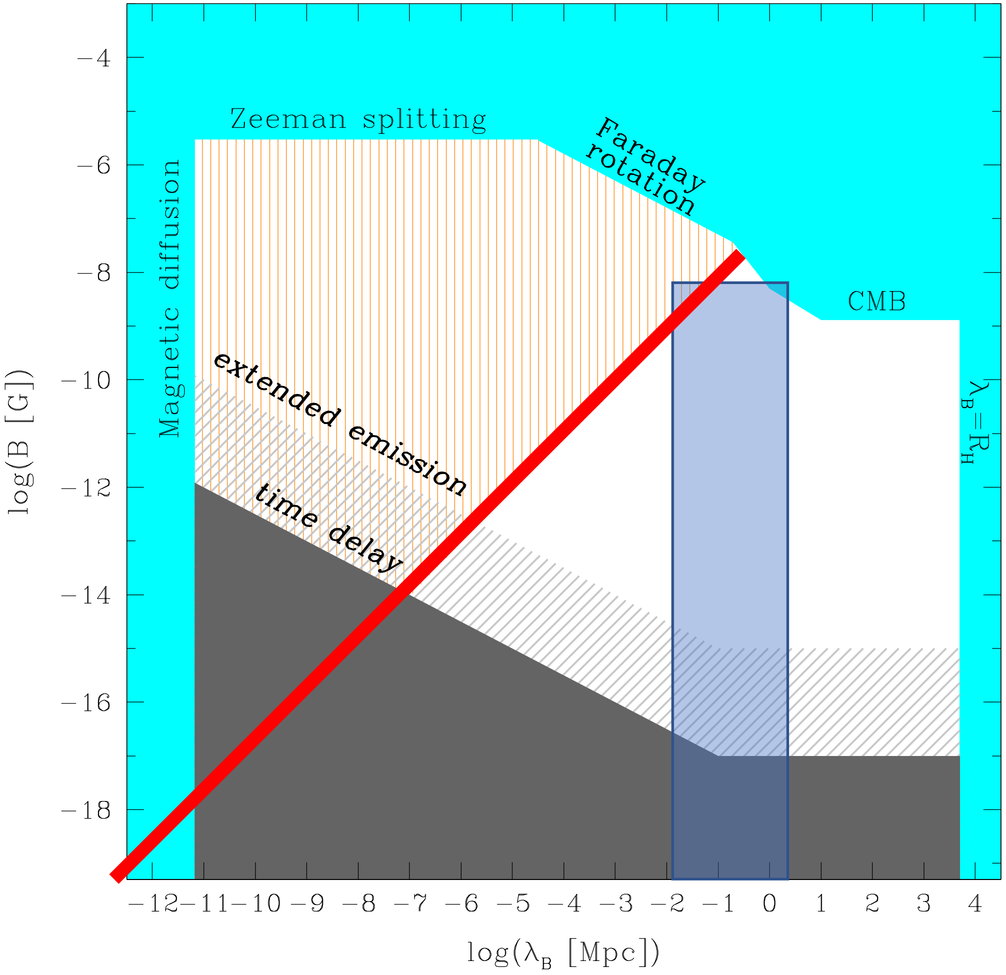
Cosmological fields have well-defined relation between strength and correlation length corresponding to the “larges cosmologically processed eddies:

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

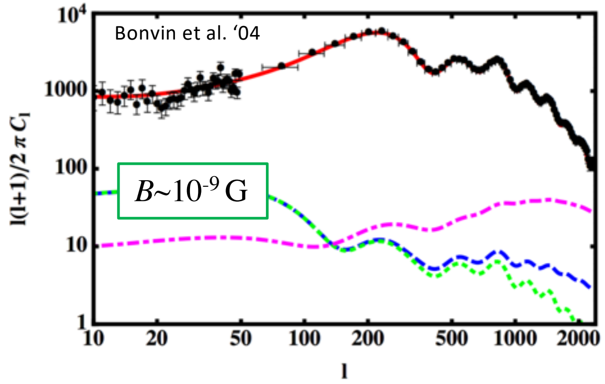
(t_H is the Hubble time, v_A is Alfven velocity). Possible strength range: up to “equipartition” with matter / radiation energy density:

$$B \leq \sqrt{2\rho_{CMB}} \sim 3\times 10^{-6}\ \mathrm{G}$$

The strength and correlation length of IGMF is constrained from above and below by a range of measurements and theoretical arguments.



Intergalactic magnetic fields

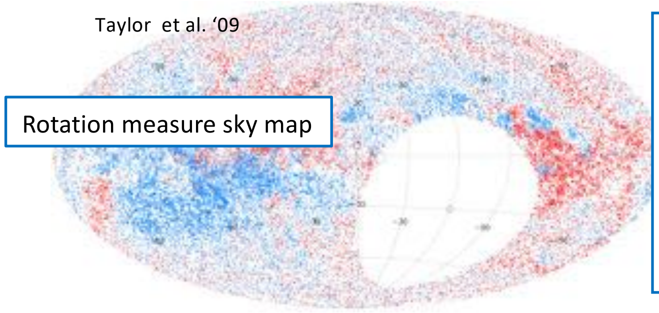


Bonvin et al. '04

$B{\sim}10^{-9}$ G

Presence of magnetic field affects CMB anisotropies and polarization in multiple ways: generation of vector and tensor perturbations, generation of magnetosonic waves, Faraday rotation of polarization, …

Magnetic field does not dominate the structure of CMB anisotropies: $\Omega_B < 10^{-6}, B < 3\times10^{-9}$ G

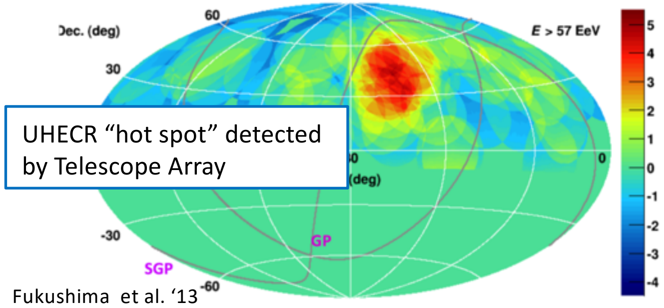


Taylor et al. '09

Rotation measure sky map

Polarized radio signal from extragalactic sources experiences Faraday rotation whose amplitude depends on the integral of magnetic field along the line-of-sight: $RM \sim \int B n_e \, dl.$ Detectable in radio band if B $\geq 10^{-9}$ G.

Contribution of IGMF to the overall Faraday rotation measure of extragalactic sources is small compared to that of the Galactic magnetic field: $RM = RM_{Gal} + RM_{IGMF} + RM_{source}$



UHECR "hot spot" detected by Telescope Array

Fukushima et al. '13

Trajectories of Ultra-High-Energy Cosmic Rays (UHECR) are deflected by magnetic fields:

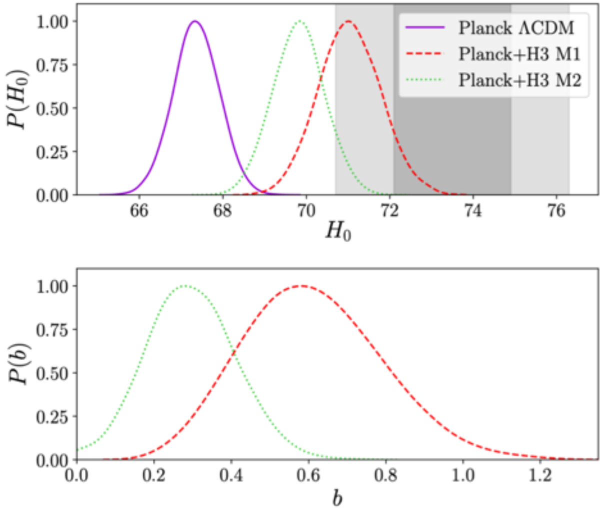
$$\theta \sim 4^o \left(\frac{E}{10^{20}\text{eV}}\right)^{-1} \left(\frac{B}{10^{-10}\text{G}}\right)\left(\frac{D}{50\text{ Mpc}}\right)$$

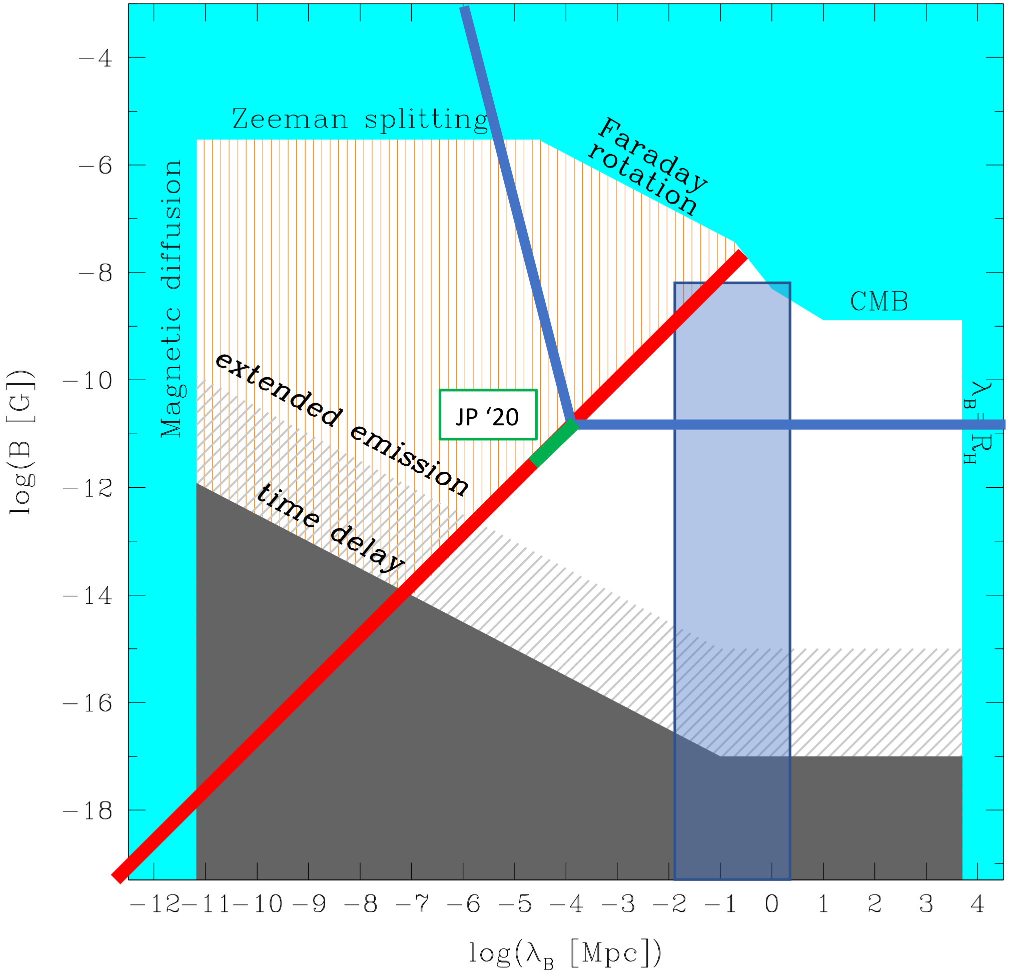
Deflections by IGMF are sub-dominant compared to those by the Galactic magnetic field. Isolated UHECR sources are not yet identified.

Intergalactic magnetic fields: CMB bound /measurement (?)

New effect of magnetic field on CMB has been reported by Jedamzik & Saveliev ‘19. Turbulence introduces clumping in the baryonic matter (with the clumping factor $b = \left(\frac{\delta\rho_b^2}{\rho_b^2}\right) \sim v_A^4$). Clumping modifies the recombination process (ionization rate proportional to ρ_b, recombination proportional to ρ_b^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 & Saveliev, https://arxiv.org/abs/1804.06115, Jedamzik & Pogosyan https://arxiv.org/abs/2004.09487

Intergalactic magnetic fields: gamma-ray bounds

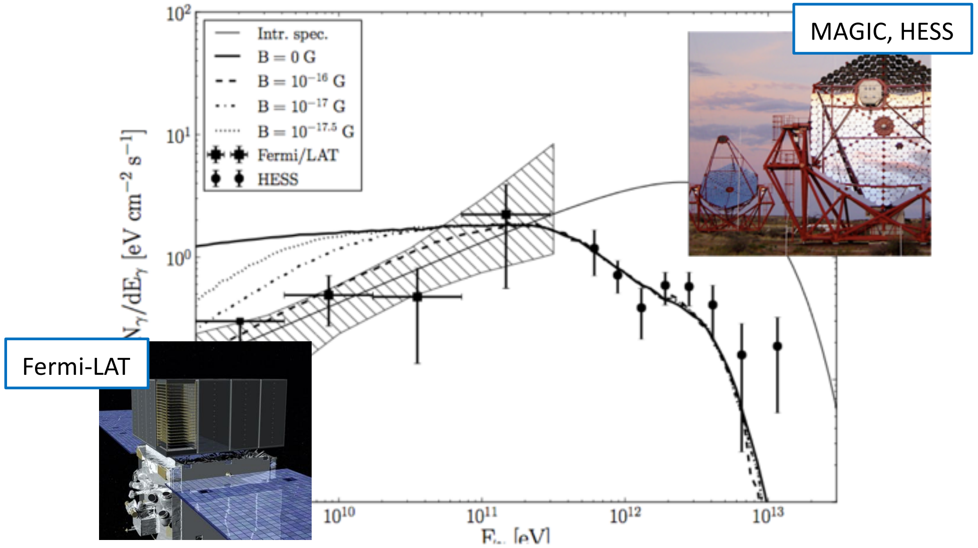
γ-rays with energies above $\sim 0.1\ \mathrm{TeV}$ are absorbed by the pair production on the way from the source to the Earth.

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

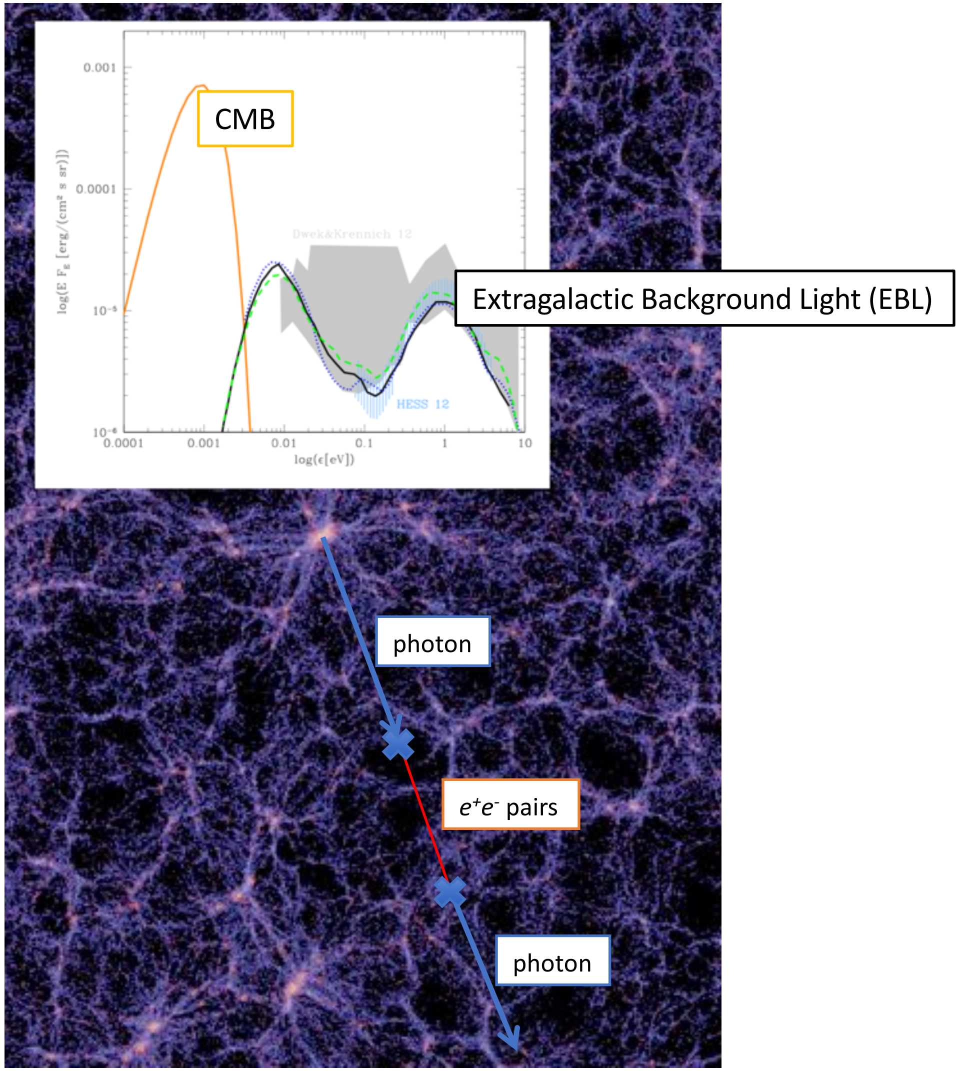
Inverse Compton γ-rays could be detected at lower energies.

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

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



Plaga '95, AN & Semikoz '07, AN & Vovk '10, Tavecchio et al. '10, Dermer et al. '11 , ….

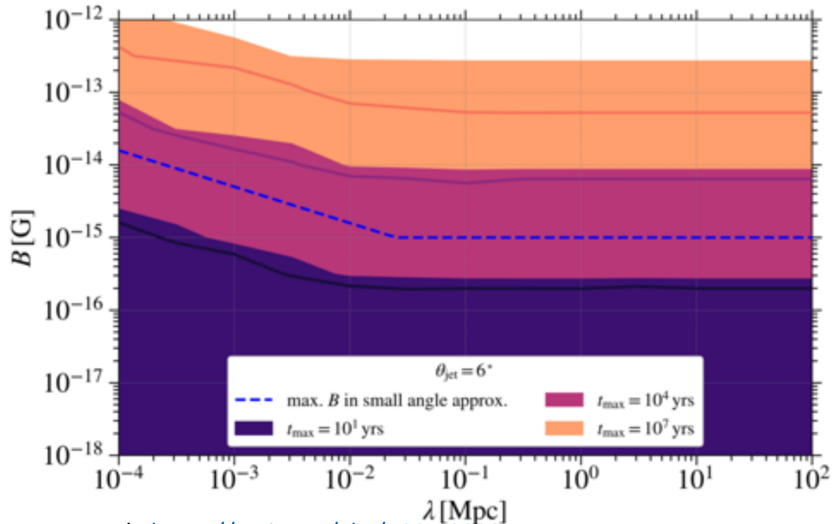


Intergalactic magnetic fields: gamma-ray bounds

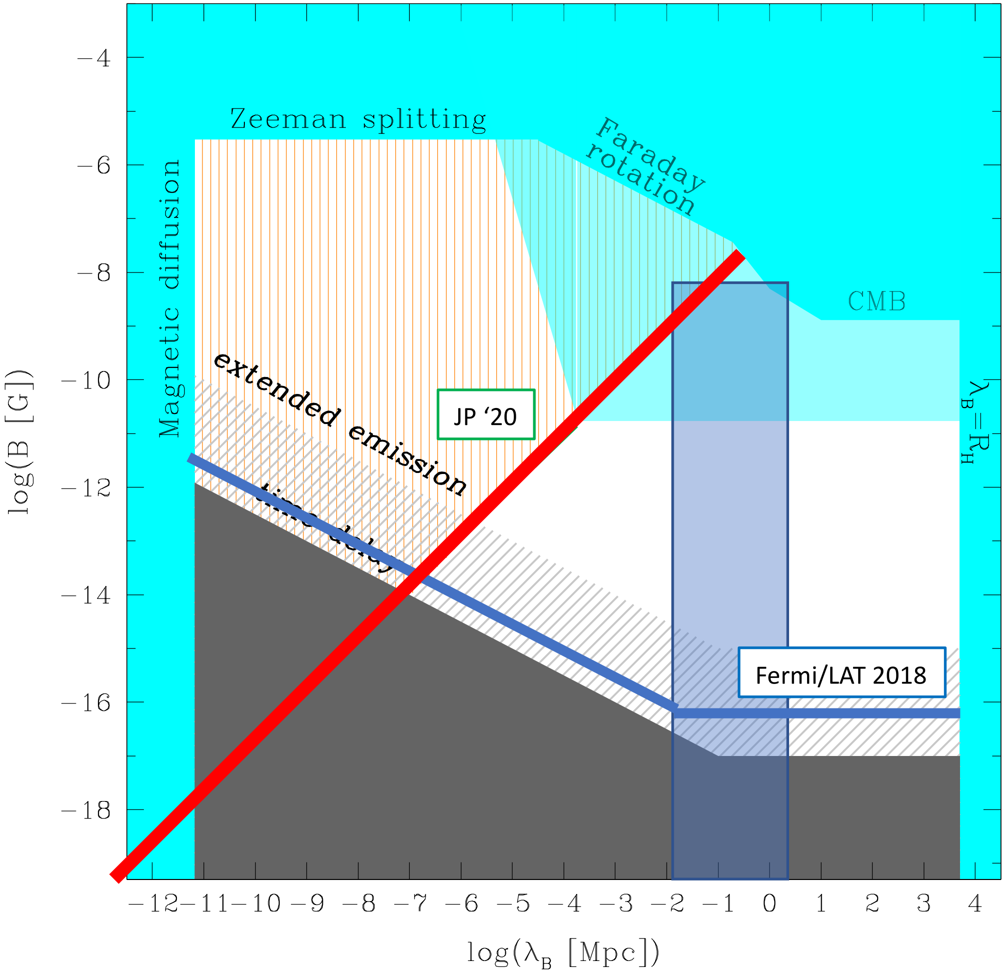
Most recent analysis of γ-ray bounds is from Fermi/LAT collaboration analysis. The ”conservative” lower bound is from the search of time-delayed secondary emission, based on stacking of signal from many blazars.

The limit is valid under *assumption* that the TeV flux from sources is stable on decade time scale.

This assumption will be overcome in forthcoming MAGIC collab. paper on 1ES 0229+200: details of the TeV-band variability can be properly taken into account in data analysis.



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



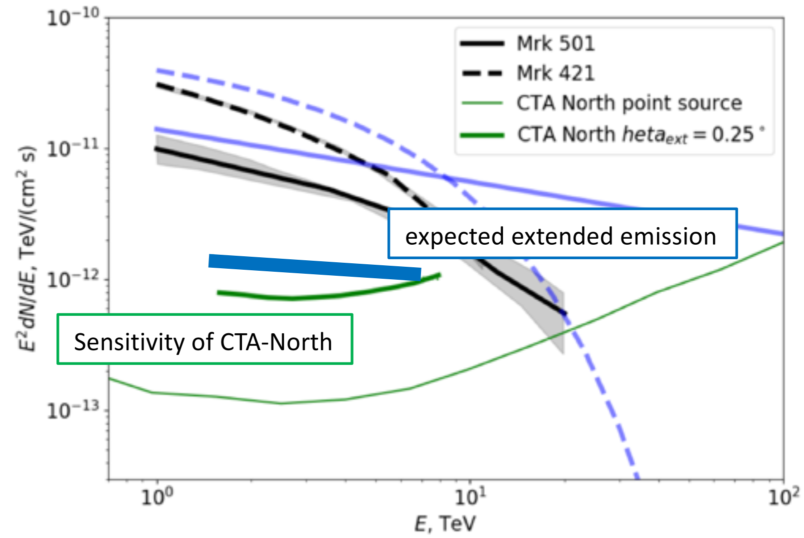
Intergalactic magnetic fields: sensitivity reach of CTA

The claim of evidence for cosmological magnetic field by Jedamzik and Pogosyan raises a question if the field with characteristics shown by the green integral on figure is detectable with gamma-ray technique.

Electrons are deflected by an angle

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

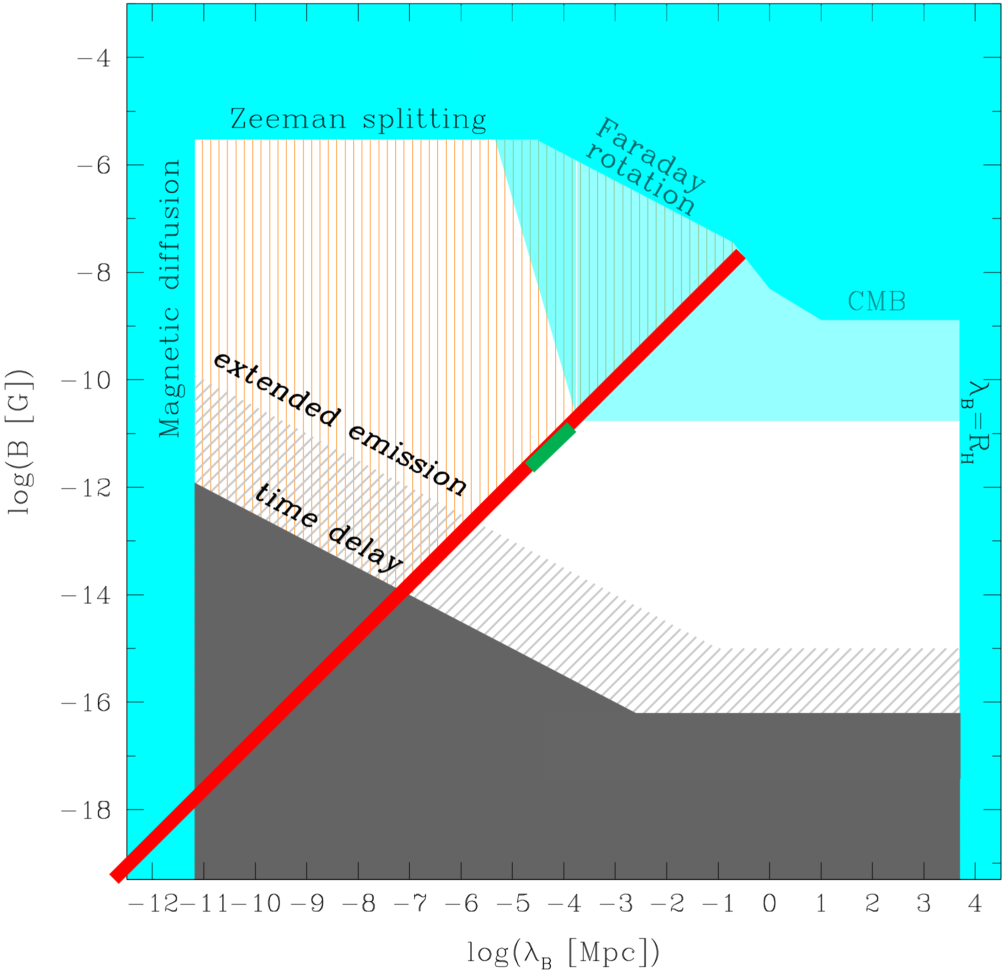
Strong magnetic field isotropises directions of relatively low energy electrons. Only the highest energy electrons emitting inverse Compton at ~ 10 TeV. Sensitivity of CTA is needed for reasonably high statistics of the signal in multi-TeV band.



expected extended emission

Sensitivity of CTA-North

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



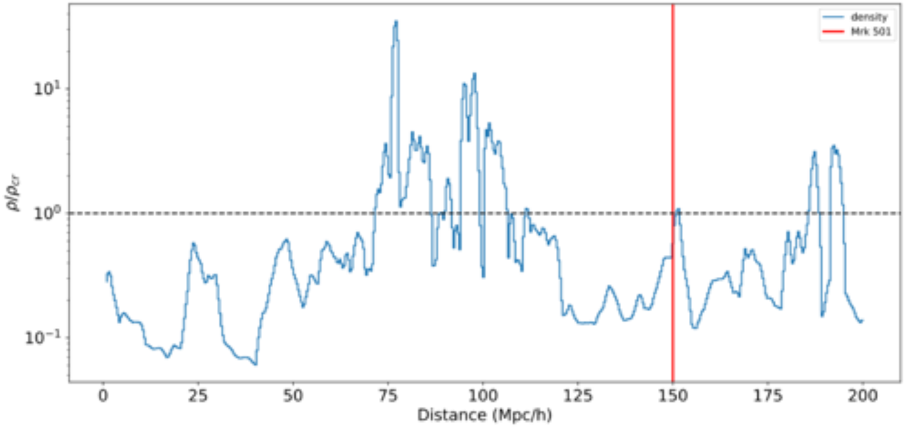
Intergalactic magnetic fields: sensitivity reach of CTA

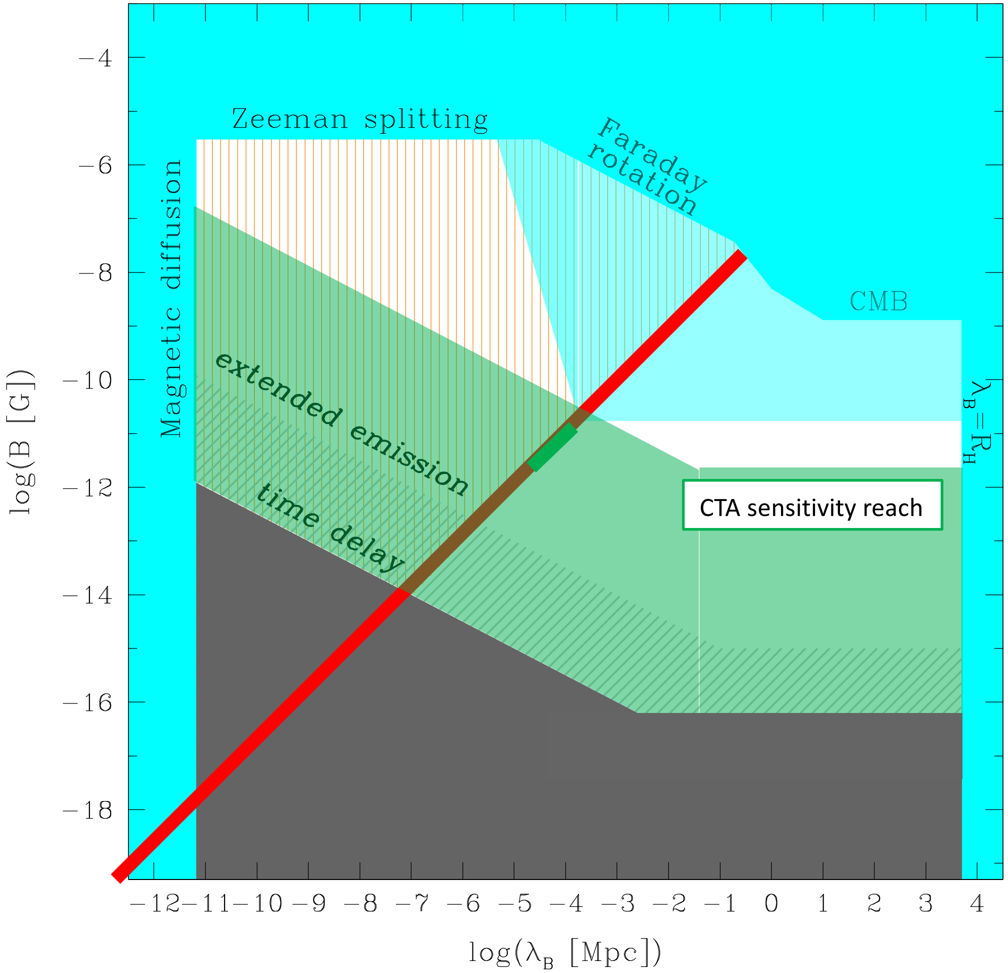
The mean free path of the primary γ-rays that produce electrons responsible for the multi-TeV secondary inverse Compton emission is in 50-100 TeV range. The mean free path of those primary γ-rays is only

$$\lambda_\gamma \simeq 2.5 \left[\frac{E_\gamma}{100\ \mathrm{TeV}}\right]^{-1.6} \mathrm{Mpc}$$

The γ-ray method probes IGMF in the direct vicinity of the source. The necessary condition is that the source is not part of extended magnetized region, like high-mass galaxy cluster.

Overdensity profile from BORG constrained simulation of LSS along the line of sight to Mrk 501.

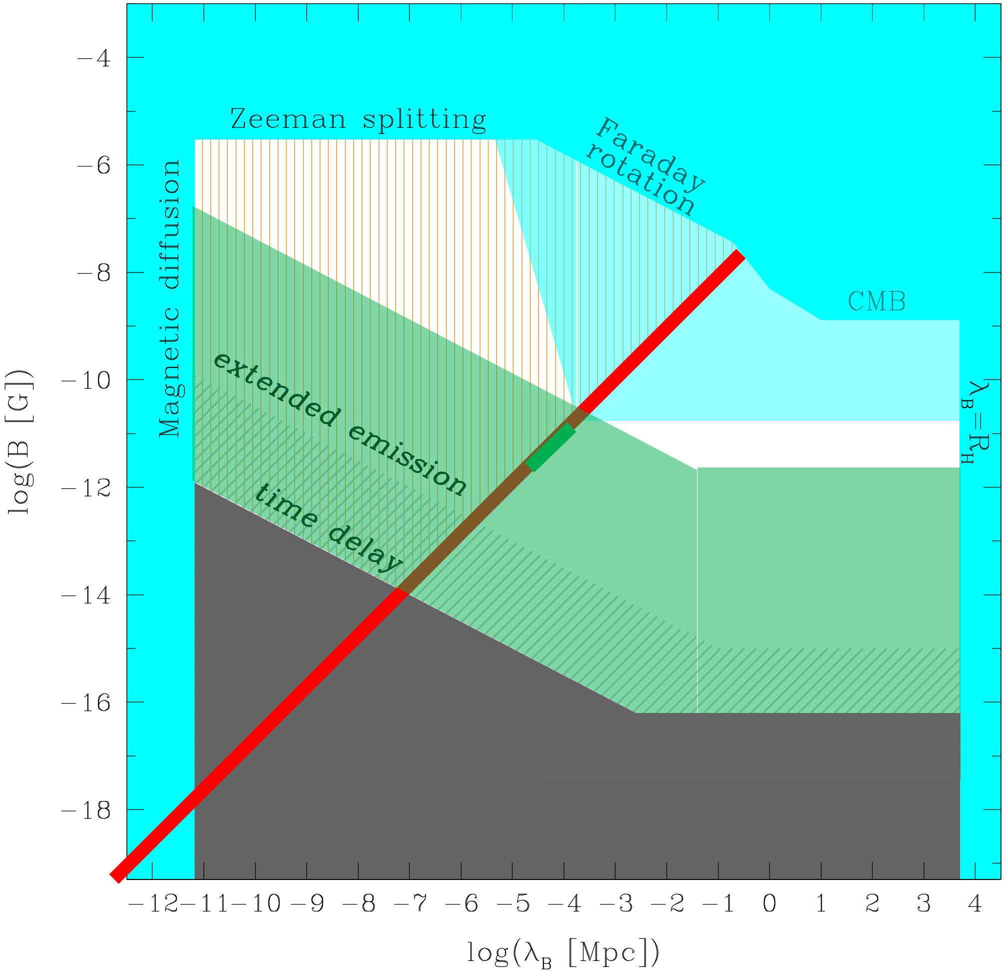




Korochkin, Kalashev, AN, Semikoz https://arxiv.org/abs/2007.14331

Intergalactic magnetic fields

A combination of γ-ray and CMB probes exhausts the parameter space of IGMF of cosmological origin. If magnetic field in the voids of the LSS is relic cosmological magnetic fields, can be measured over the next decade.



---

* Limitation: a "robust" lower bound on IGMF will not significantly improve compared to existing bound (grey range). Measurements of IGMF are possible for the field parameters within the green range if AGN γ-ray sources with sufficiently high intrinsic cut-off energy situated outside rich galaxy clusters are available.

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.

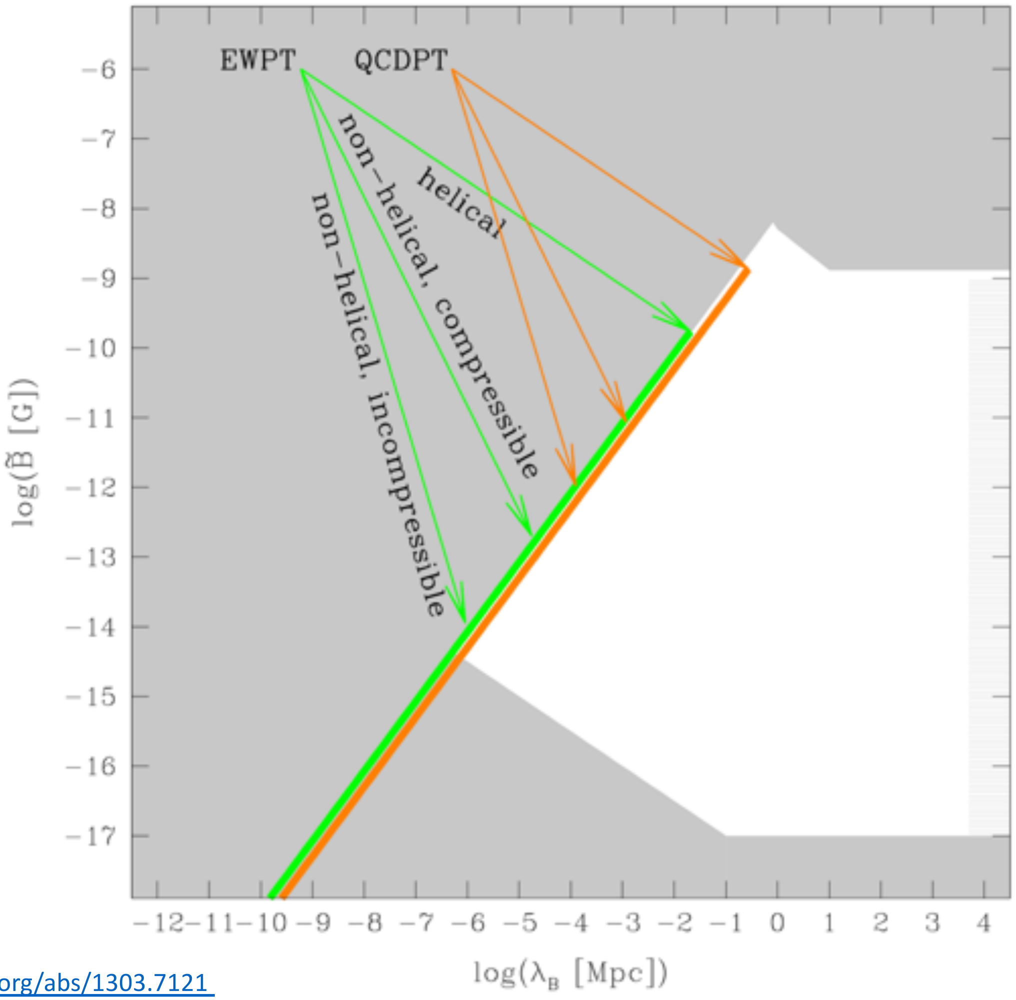
Most of the cosmological magnetic field models consider field generation at cosmological phase transitions:

- 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

Cosmological magnetic fields: evolution

Comoving magnetic field strength and correlation length:

$$\tilde{B} = \frac{B}{a^2}; \qquad \tilde{\lambda}_B = a\lambda_B$$

$$a = \frac{g^{1/3}T}{g_0^{1/3}T_0}$$

where a is the scale factor, T, T_0 are the temperatures at the moment of magnetogenesis and today ($T_0 = 2.7\ \mathrm{K}$) and g_*, g_0 are the number of effective degrees of freedom of relativistic particles at the epoch of magnetogenesis and today.

Characteristic distance scales:

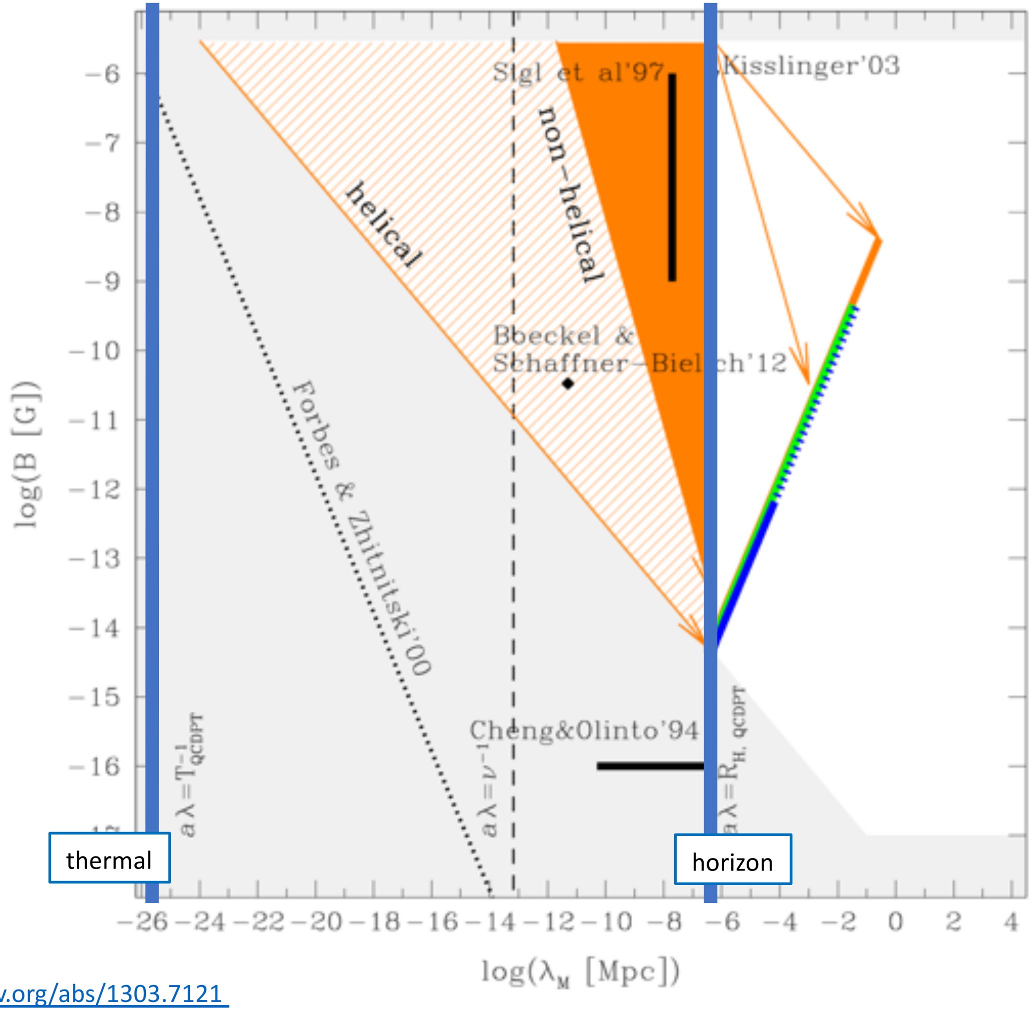
– "thermal" : inverse of of the temperature,

$$\tilde{\lambda}_B = \frac{a}{T} \simeq \frac{g^{\frac{1}{3}}}{T_0} \simeq 0.1\ \mathrm{cm}$$

– horizon scale

$$\lambda_H = H^{-1} = \sqrt{\frac{90\, M_{Pl}^2}{8\pi^3 g\, T^4}} \simeq 1 \left[\frac{T}{100\ \mathrm{MeV}}\right]^{-2} \mathrm{pc}$$

Example: QCDPT



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

Cosmological magnetic fields: evolution

Free turbulence decay.

$$\frac{\partial B}{\partial t} = \nabla\times(v\times B) + \frac{1}{\sigma}\nabla^2 B$$

If the first term on the r.h.s. of induction equation is much larger than the second, time evolution of B modes with wavenumber k (distance scale $\lambda \sim k^{-1}$) occurs on the time scale

$$t_k = \frac{1}{vk} = \frac{\lambda}{v}$$

The largest processed eddies are the modes for which the evolution time scale is equal to the Hubble time

$$\lambda_B = \frac{v_A}{H}$$

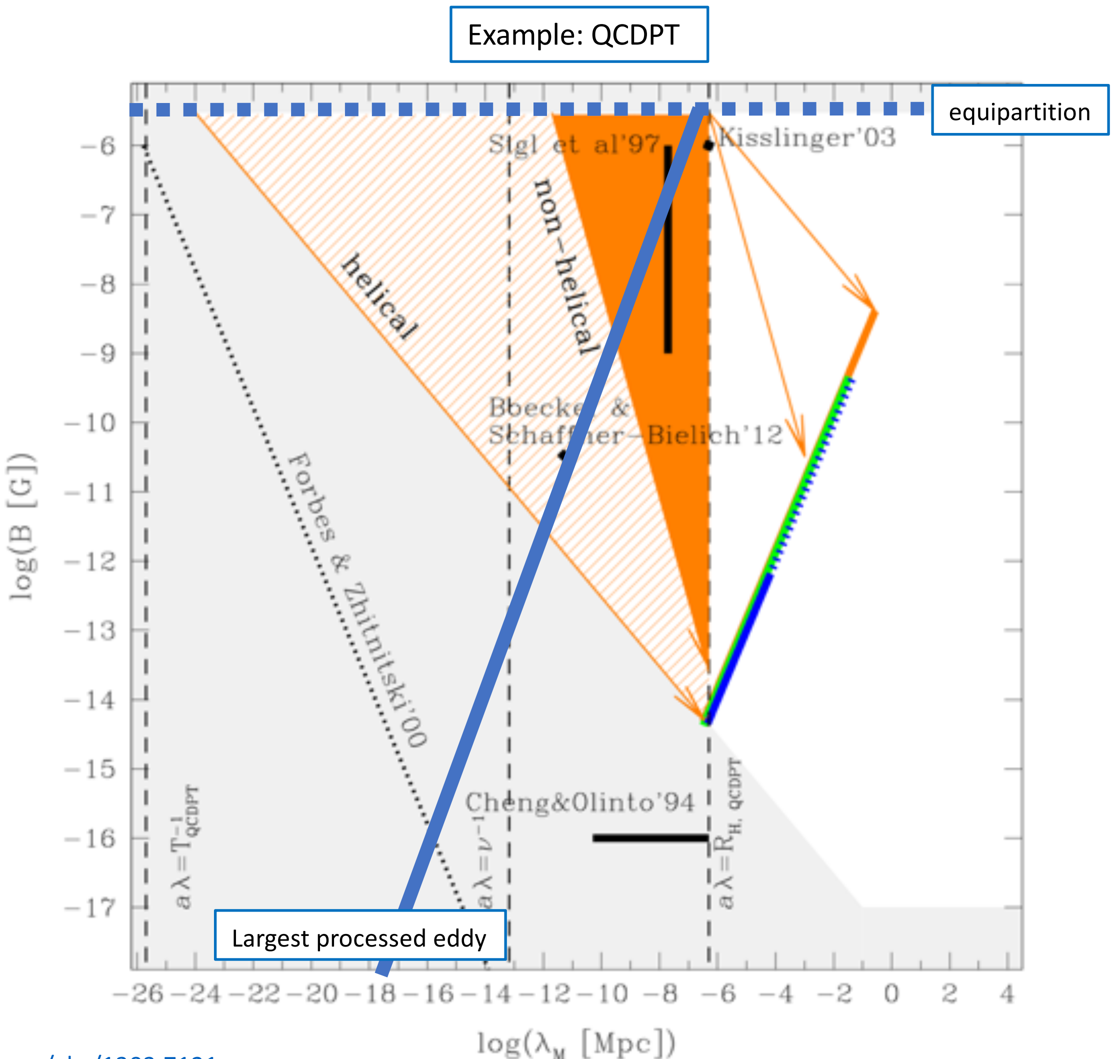
For these modes B scales proportionally to λ_B:

$$\tilde{B} = \frac{4\pi^2\ g_0 T_0^3 T}{30\ M_{Pl}}\tilde{\lambda} \simeq 3\left[\frac{\lambda}{\lambda_H}\right]\mu\text{G}$$

Alfven velocity $v_A = \sqrt{B^2/2\rho}$ is close to 1 for equipartition magnetic field:

$$\rho_B = \rho_{rad}: \qquad \tilde{B} \simeq 3\ \mu\text{G}$$

In this case the largest processed eddy size is close to the horizon scale.



Example: QCDPT

equipartition

Largest processed eddy

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

Cosmological magnetic fields: evolution

Magnetic field excites plasma motion::

$$\frac{\partial v}{\partial t} + v\nabla v + \frac{B\times\nabla\times B}{\rho + p} + \ \ldots = \nu\left(\nabla^2 v + \frac{1}{3}\nabla(\nabla v)\right)$$

Where ν is kinematic viscosity

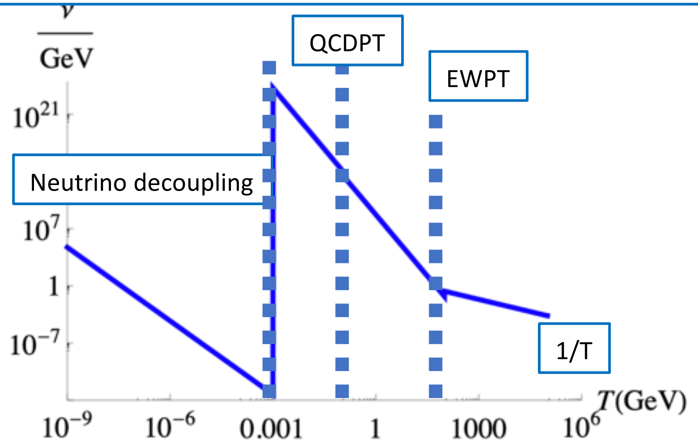
$$\nu = \frac{\lambda_{mfp}}{5}$$

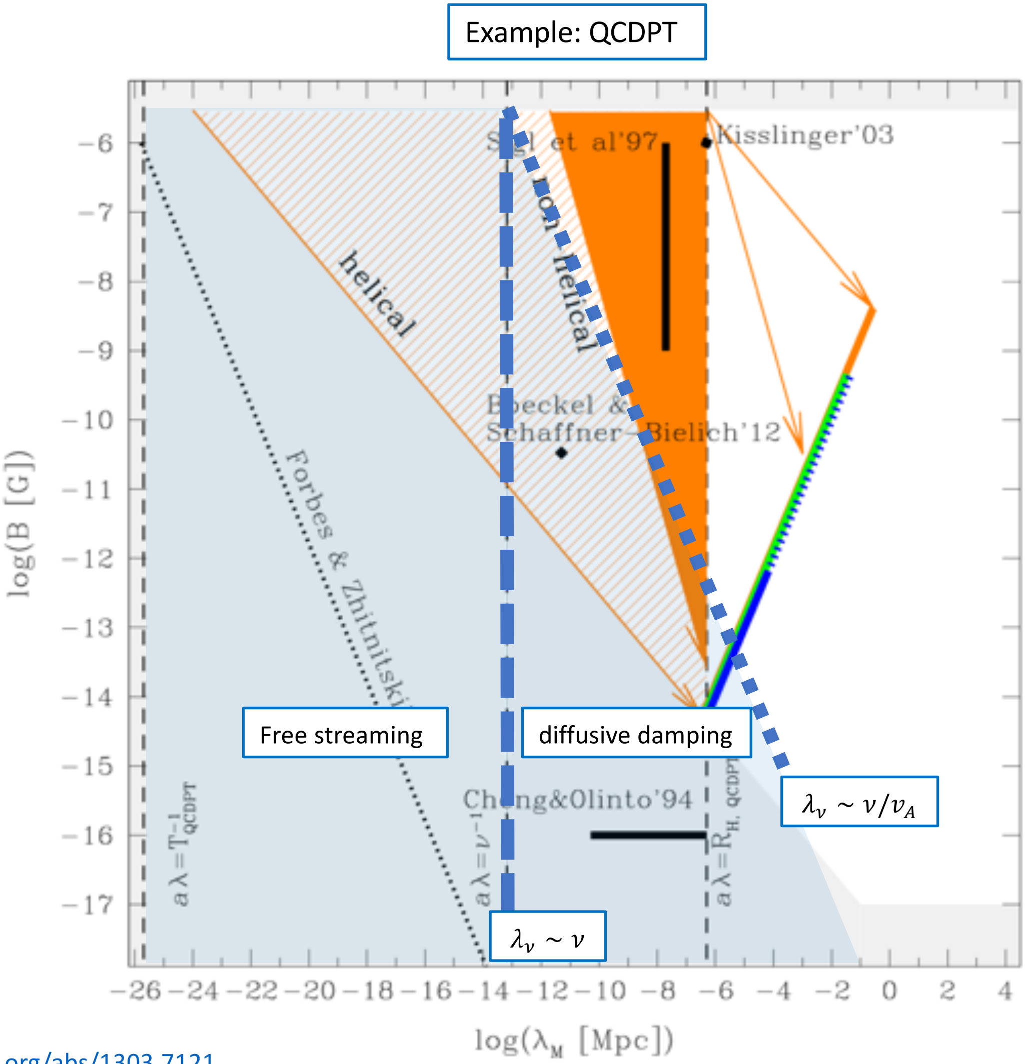
with λ_{mfp} being the mean free path of the least coupled particle in the plasma. Modes with $k < \nu^{-1}$ are damped by free streaming of least coupled particles.

At the shortest scales, terms on the r.h.s. of Euler equation become important. The kinetic energy of plasma is dissipated into heat. Modes with wavenumbers

$$\nu^{-1} < k < \frac{v}{\nu}$$

are affected by viscosity.





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

Cosmological magnetic fields: evolution

Magnetic field excites plasma motion::

$$\frac{\partial v}{\partial t} + v\nabla v + \frac{B\times\nabla\times B}{\rho + p} + \ \dots = \nu\left(\nabla^2 v + \frac{1}{3}\nabla(\nabla v)\right)$$

Where ν is kinematic viscosity

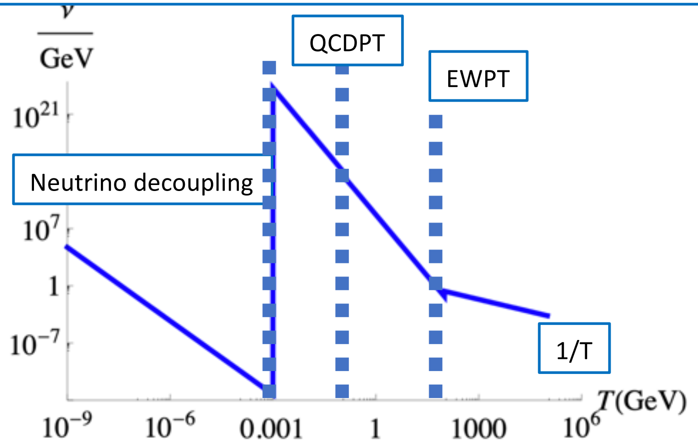
$$\nu = \frac{\lambda_{mfp}}{5}$$

with λ_{mfp} being the mean free path of the least coupled particle in the plasma. Modes with $k < \nu^{-1}$ are damped by free streaming of least coupled particles.

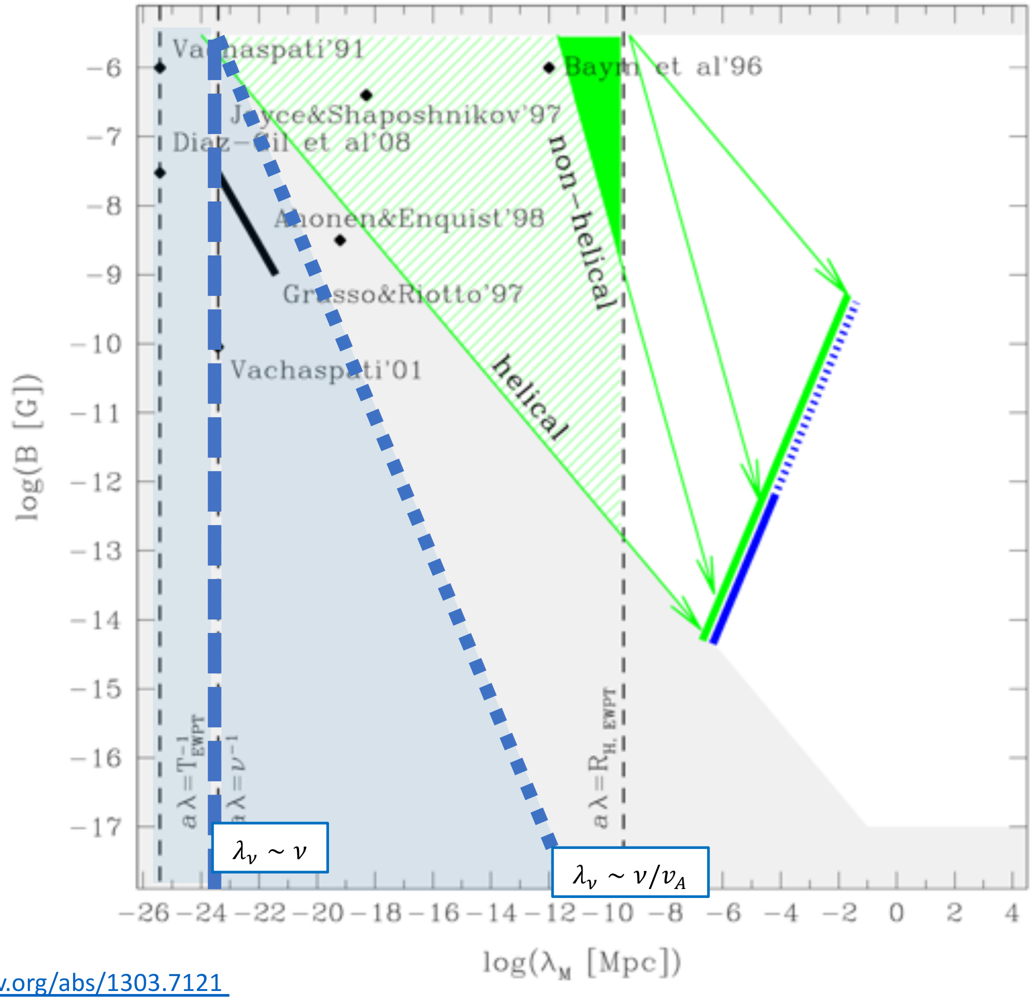
At the shortest scales, terms on the r.h.s. of Euler equation become important. The kinetic energy of plasma is dissipated into heat. Modes with wavenumbers

$$\nu^{-1} < k < \frac{v}{\nu}$$

are affected by viscosity.



Example: EWPT



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

Cosmological magnetic fields: evolution

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

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

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

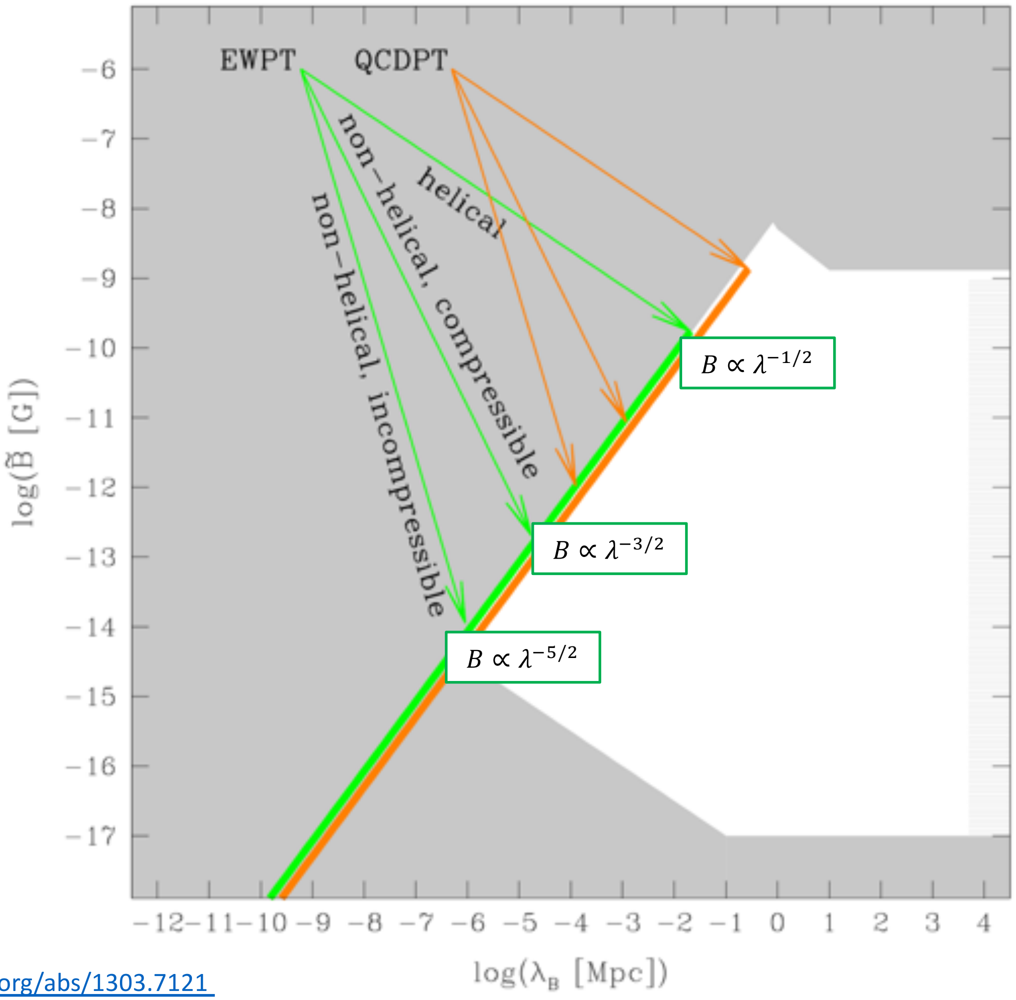
for small k ($P_B(k)$behavior imposed by divergence-free nature of B). In the simplest case, eddies with smaller and smaller k are gradually processed by turbulence and their power is dissipated.

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 $B \propto \lambda_B^{-3/2}$.



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

Cosmological magnetic fields: evolution

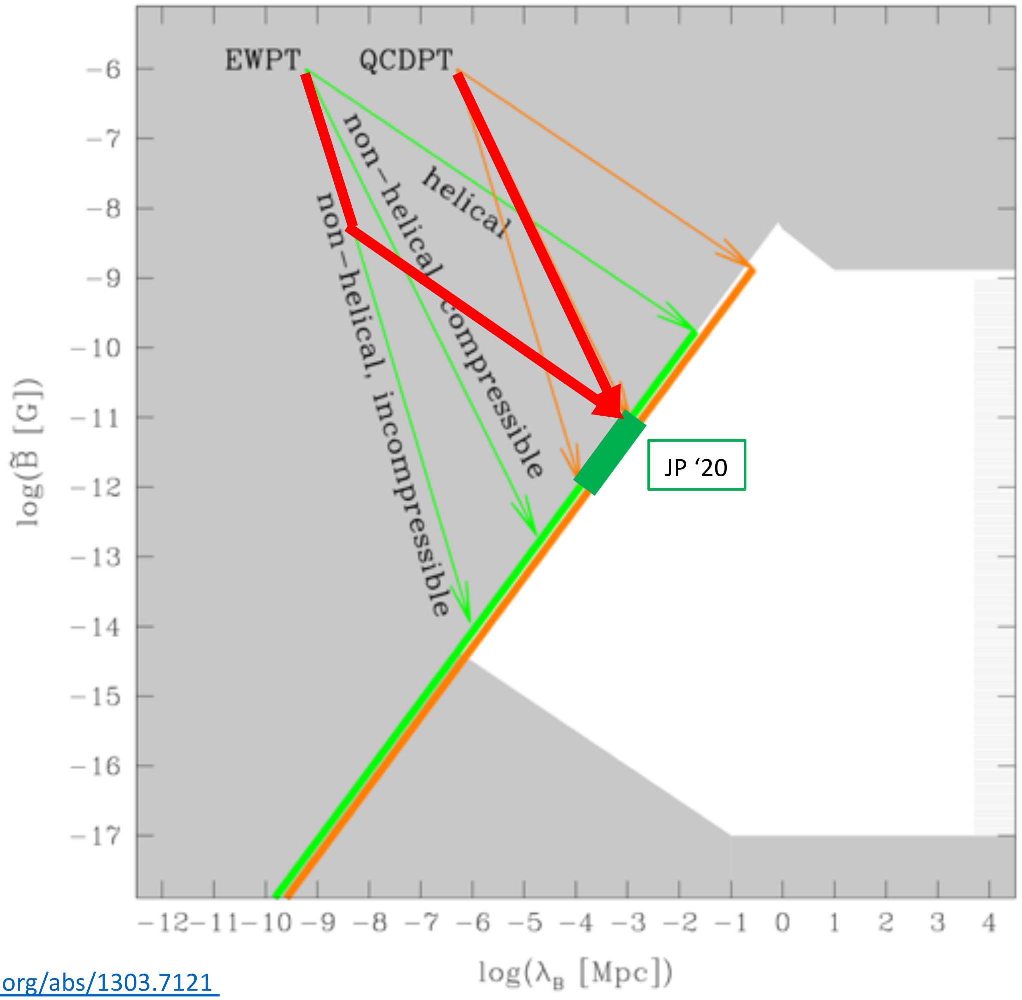
The evolution drives the magnetic field parameters to the largest processed eddy line at $z = 0$:

$$\tilde{B} \simeq 10^{-8}\left[\frac{\tilde{\lambda}_B}{1\ \mathrm{Mpc}}\right]\ \mathrm{G}.$$

Evolution erases the memory of initial parameters of magnetic field.

Measurement of IGMF at $z = 0$ cannot provide information on the magneto-genesis scenario (only if magnetic field would be found to be helical, one would be able to trace back its evolution, in a limited sense).

For example, the field with parameters derived by Jedamzik & Pogosyan ’20 can be non-helical field originating from QCD phase transition, but can also be partially helical field from the EWPT.



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

Cosmological magnetic fields: 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 $h=\frac{F}{k^2}\sim\frac{B^2}{k^2}$.

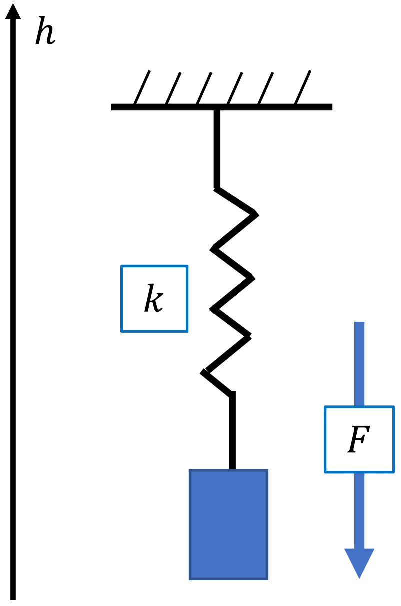
The energy density of gravitational waves is

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

It can be comparable to the radiation energy density if $\tilde{B}$ is close equipartition, $\tilde{B}\sim 3\ \mu\text{G}$ 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.



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

Cosmological magnetic fields: gravitational waves

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

Magnetic field has power spectrum

$$\frac{d\Omega_{GW}}{d(\log k)} \propto k$$

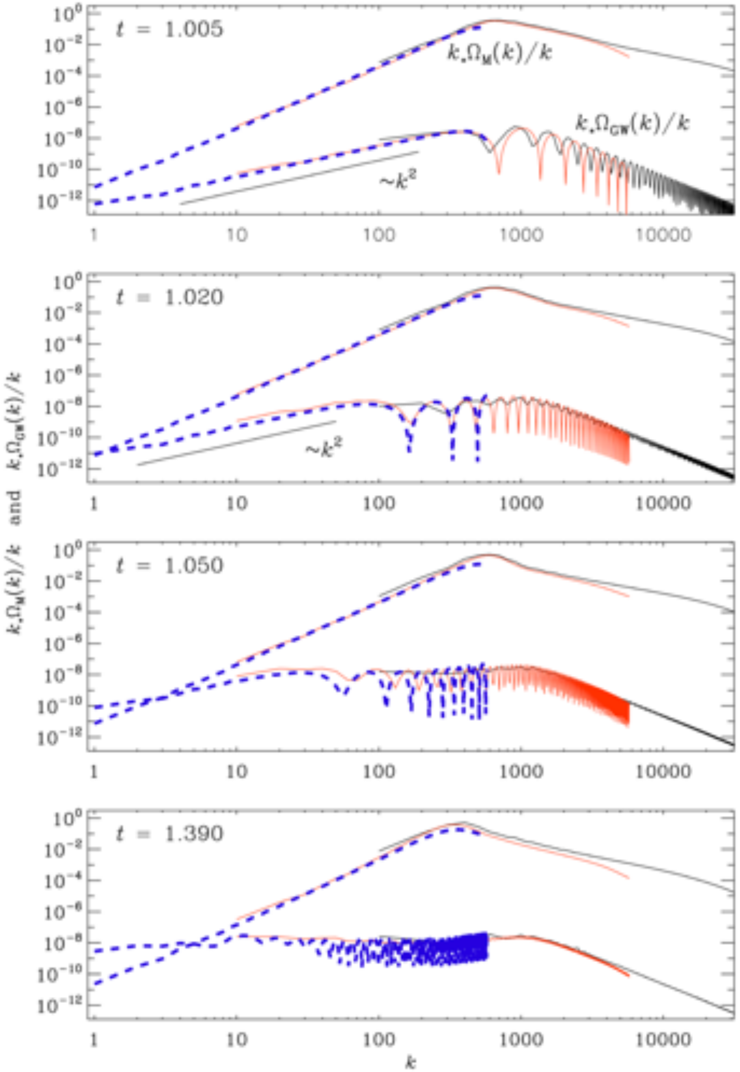
In the wavenumber interval

$$\frac{1}{t} < k < k_B$$

where t is the time scale on which MHD modes with $k \sim k_B$ decay. The low-k tail of the gravitational wave spectrum is

$$\frac{d\Omega_{GW}}{d(\log k)} \propto k^3$$

Based on generic causality conditions $k \to 0$ limit.



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: gravitational waves

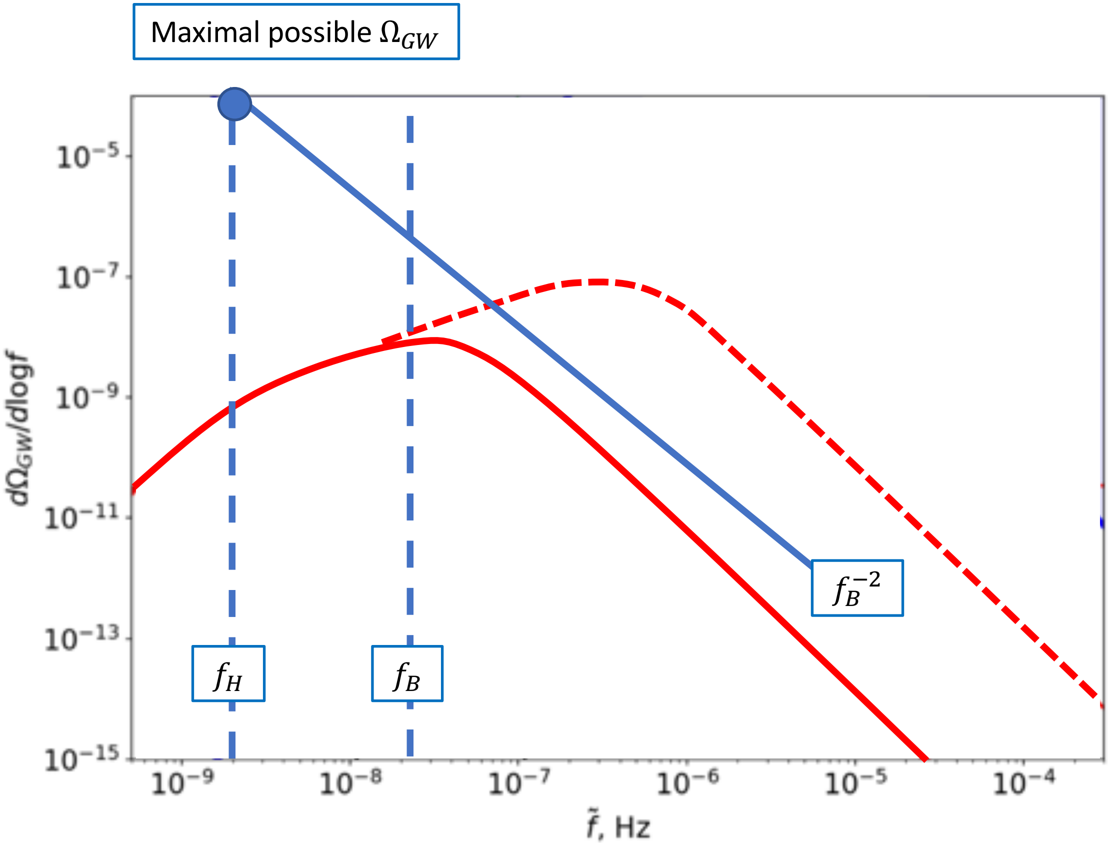
In the specific case of QCD phase transition, the comoving horizon size is $\tilde{\lambda}_H = aH^{-1} \simeq 1$ pc, so that the minimal frequency is

$$f_{H,QCDPT} \sim \frac{H}{2\pi a} \simeq 2\times 10^{-9}\ \mathrm{Hz}.$$

As an example, we can assume that nearly equipartition magnetic field is produced on the scales $k_B = \lambda_B^{-1}$ ($f_B = k_B/(2\pi)$):

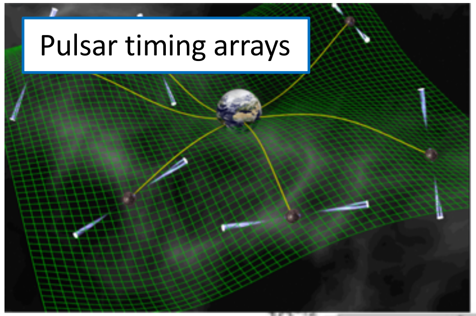
$$\Omega_{GW} \sim \Omega_{CMB}\left[\frac{B}{3\ \mu\mathrm{G}}\right]^4\left[\frac{k}{H}\right]^{-2} \sim 4\times 10^{-5}\left[\frac{\tilde{B}}{3\ \mu\mathrm{G}}\right]^4\left[\frac{f_B}{2\times 10^{-9}\ \mathrm{Hz}}\right]^{-2}$$

If magnetic field with the strength close to equipartition level has been produced at the QCD phase transition, it should have generated stochastic gravitational wave background (SGWB).

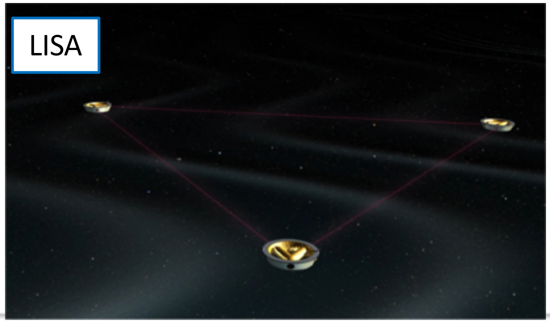


AN, Pol, Semikoz, Caprini https://arxiv.org/abs/2009.14174

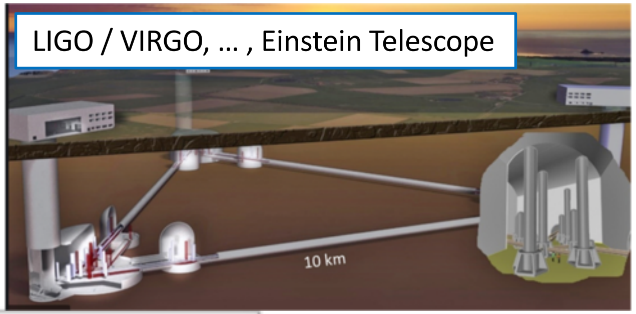
Gravitational wave detectors



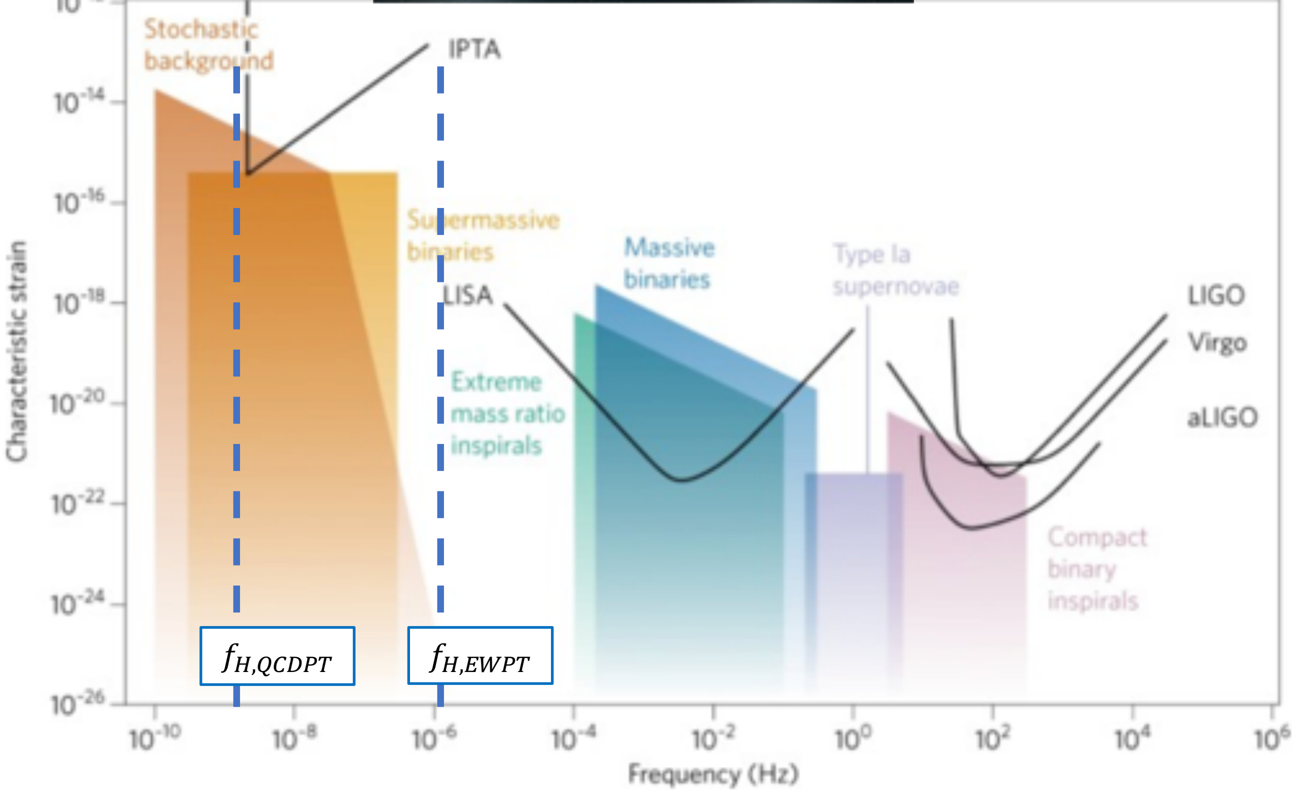
Pulsar timing arrays



LISA



LIGO / VIRGO, … , Einstein Telescope



Cosmological magnetic fields: gravitational waves

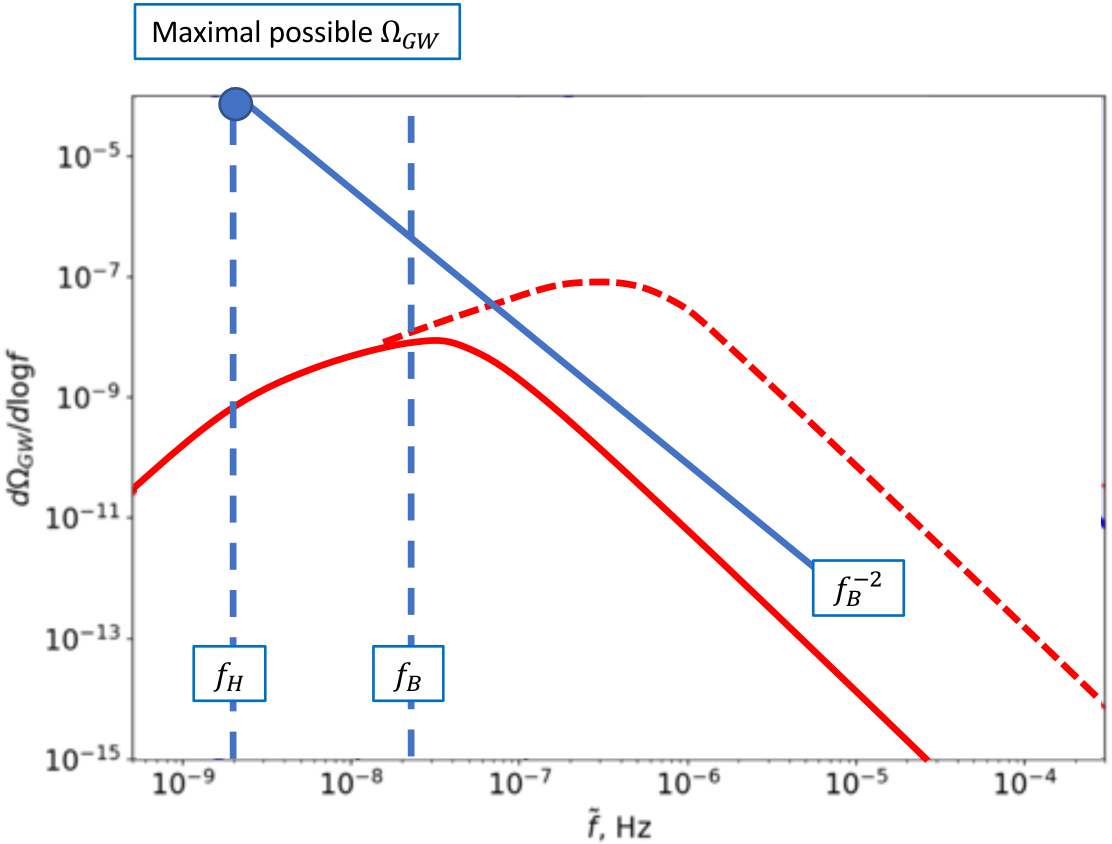
In the specific case of QCD phase transition, the comoving horizon size is $\tilde{\lambda}_H = aH^{-1} \simeq 1$ pc, so that the minimal frequency is

$$f_{H,QCDPT} \sim \frac{H}{2\pi a} \simeq 2\times10^{-9}\ \mathrm{Hz}.$$

As an example, we can assume that nearly equipartition magnetic field is produced on the scales $k_B = \lambda_B^{-1}$ ($f_B = k_B/(2\pi)$):

$$\Omega_{GW} \sim \Omega_{CMB}\left[\frac{B}{3\ \mu\mathrm{G}}\right]^4\left[\frac{k}{H}\right]^{-2} \sim 4\times10^{-5}\left[\frac{\tilde{B}}{3\ \mu\mathrm{G}}\right]^4\left[\frac{f_B}{2\times10^{-9}\ \mathrm{Hz}}\right]^{-2}$$

If magnetic field with the strength close to equipartition level has been produced at the QCD phase transition, it should have generated stochastic gravitational wave background (SGWB).



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

Cosmological magnetic fields: gravitational waves

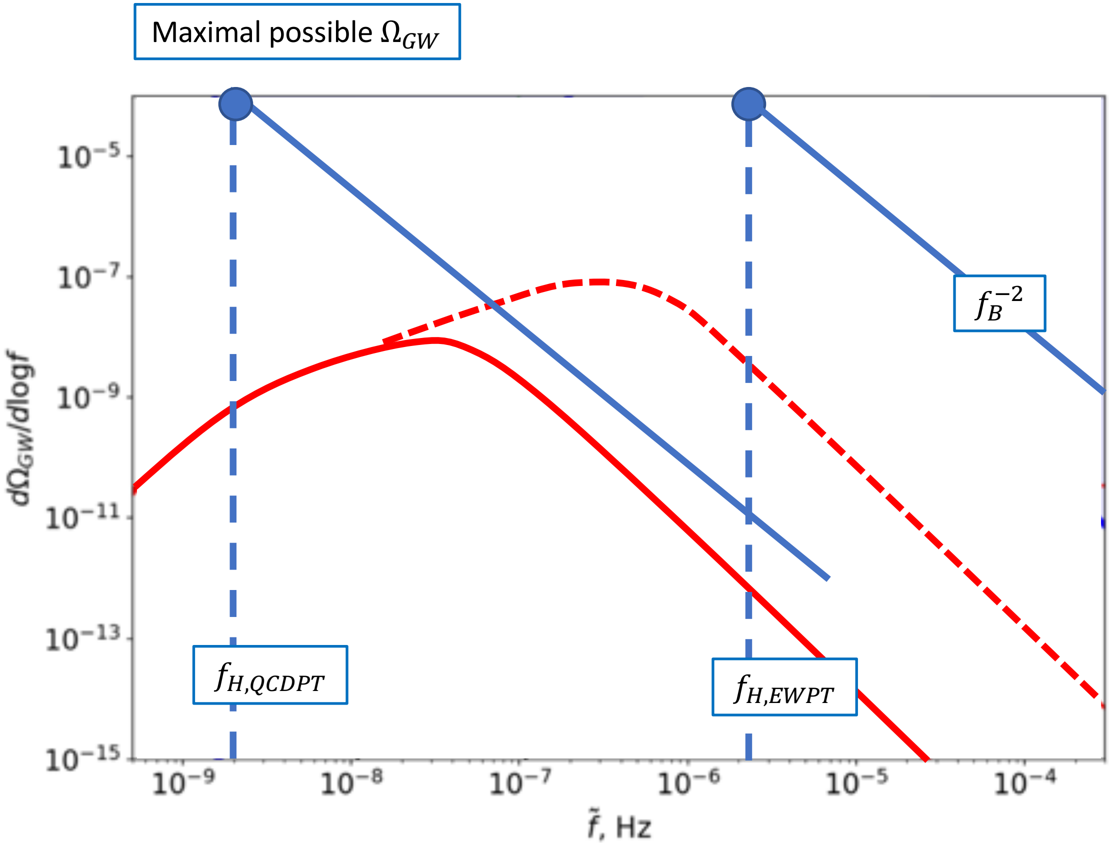
In the specific case of QCD phase transition, the comoving horizon size is $\tilde{\lambda}_H = aH^{-1} \simeq 1$ pc, so that the minimal frequency is

$$f_{H,QCDPT} \sim \frac{H}{2\pi a} \simeq 2\times10^{-9}\ \mathrm{Hz}.$$

As an example, we can assume that nearly equipartition magnetic field is produced on the scales $k_B = \lambda_B^{-1}$ ($f_B = k_B/(2\pi)$):

$$\Omega_{GW} \sim \Omega_{CMB}\left[\frac{B}{3\ \mu\mathrm{G}}\right]^4\left[\frac{k}{H}\right]^{-2} \sim 4\times10^{-5}\left[\frac{\tilde{B}}{3\ \mu\mathrm{G}}\right]^4\left[\frac{f_B}{2\times10^{-9}\ \mathrm{Hz}}\right]^{-2}$$

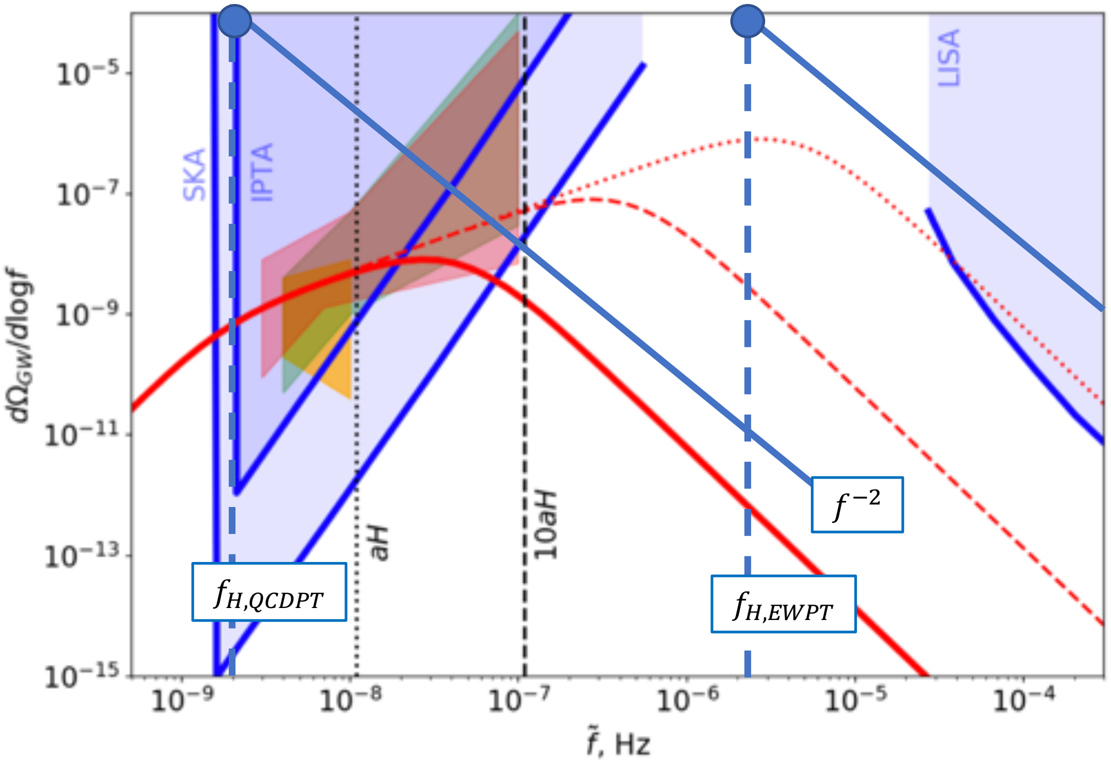
If magnetic field with the strength close to equipartition level has been produced at the QCD phase transition, it should have generated stochastic gravitational wave background (SGWB).



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

Cosmological magnetic fields: gravitational waves

Gravitatonal waves generated by MHD processes at Electroweak and QCD phase transitions are, in principle detectable with pulsar timing arrays and LISA



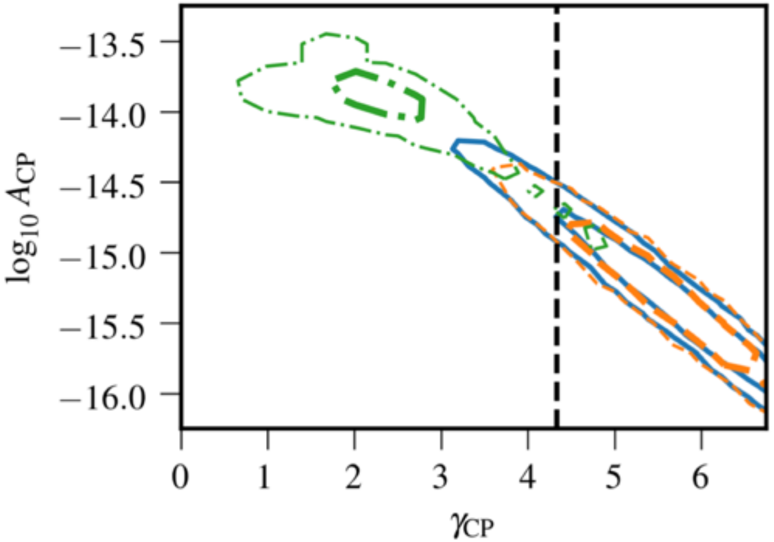
AN, Pol, Semikoz, Caprini https://arxiv.org/abs/2009.14174

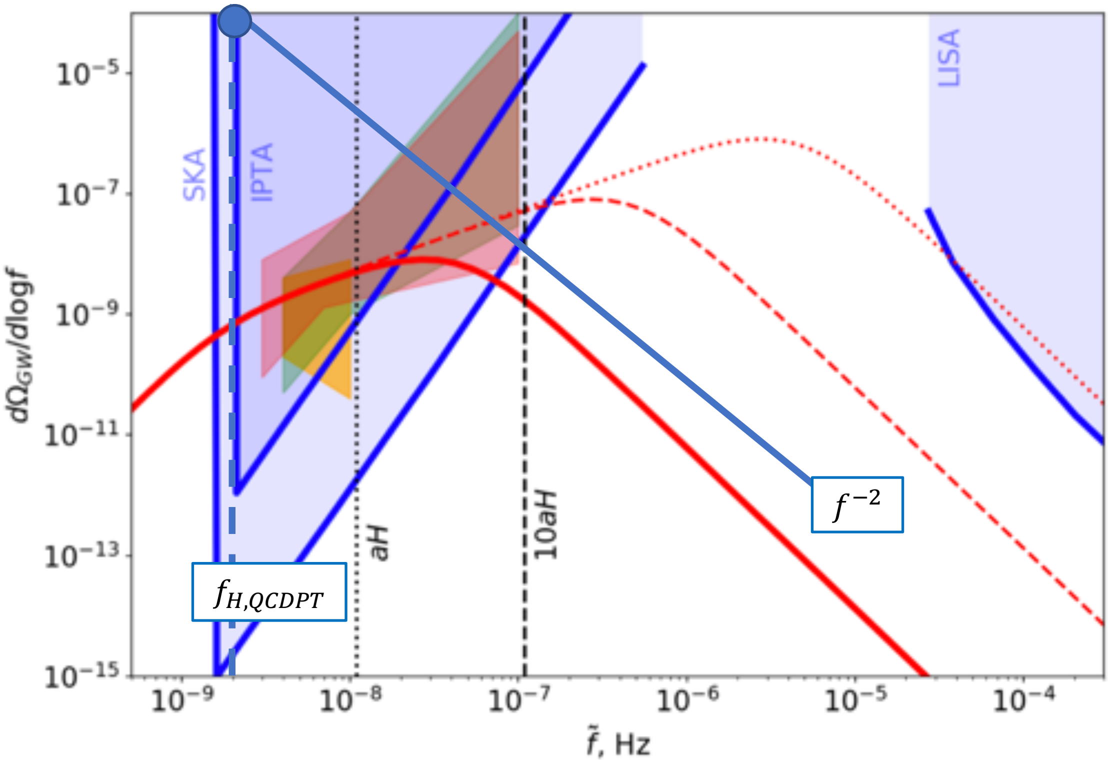
Cosmological magnetic fields: gravitational waves

Evidence for existence of “correlated stochastic process” (a proxy for SGWB) has been reported by NANOGrav pulsar timing array. Similar signal hint is also measured in the European Pulsar Timing Array (EPTA) data.

The NANOGrav evidence for SGWB can be interpreted in terms of relic SGWB from QCD phase transition. It suggests that the magnetic field and gravitational waves are forces on the distance scale 0.1 of horizon. The field strength is close to equipartition at QCDPT.

This is possible if QCD phase transition has been first order.





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

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

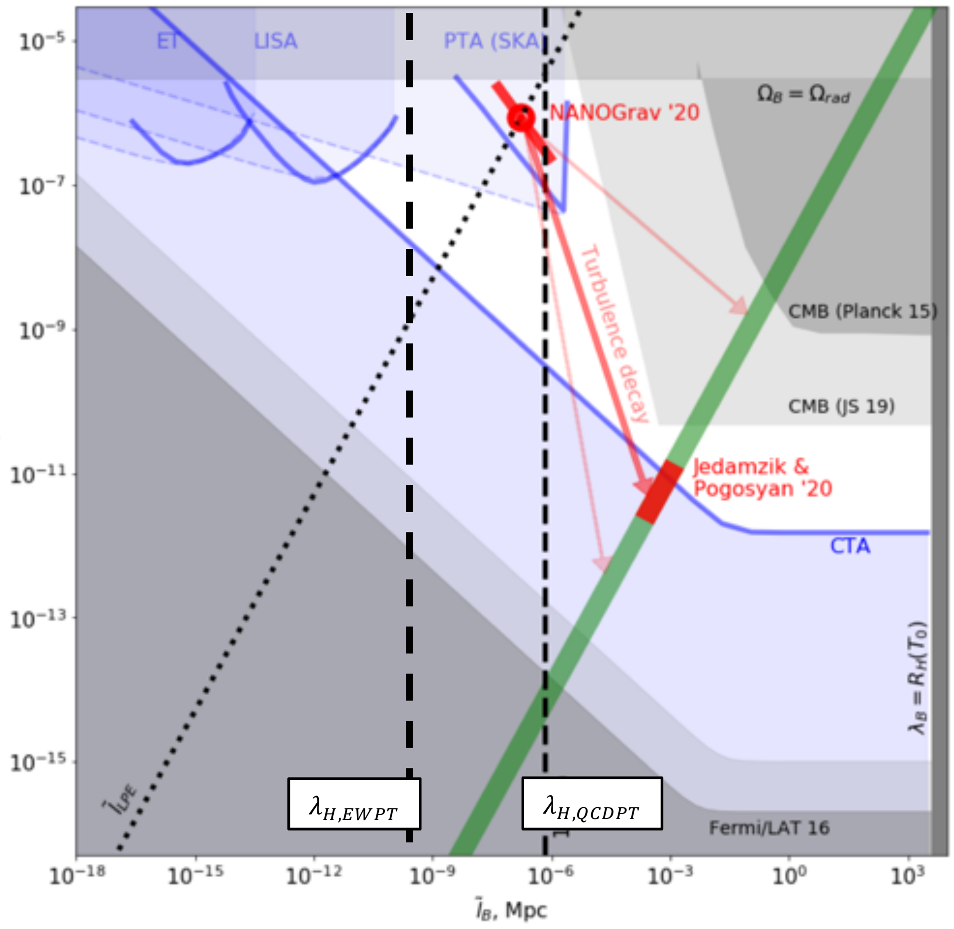
Gravitational wave + IGMF probe of cosmological magnetic field

A combination of gravitational wave and magnetic field measurements can provide data needed for full reconstruction of generation and evolution of cosmological magnetic field from magnetogenesis to $z = 0$ epoch.

This can yield detailed information on the properties of cosmological magnetic field:

- strength,
- correlation length,
- helicity,
- coupling to primordial plasma,

and constitute a new probe of physical conditions in the Universe at the epochs of phase transitions, much before the BBN and CMB epochs.



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

Gravitational wave background from supermassive black hole mergers?

An alternative interpretation of NANOGrav signal is SGWB produced by mergers of supermassive black holes in the course of structure formation process.

Most of the galaxies pass through mergers in the course of assembly. Scaling of the supermassive black hole mass with galaxy mass suggests that the central black holes also pass through mergers.

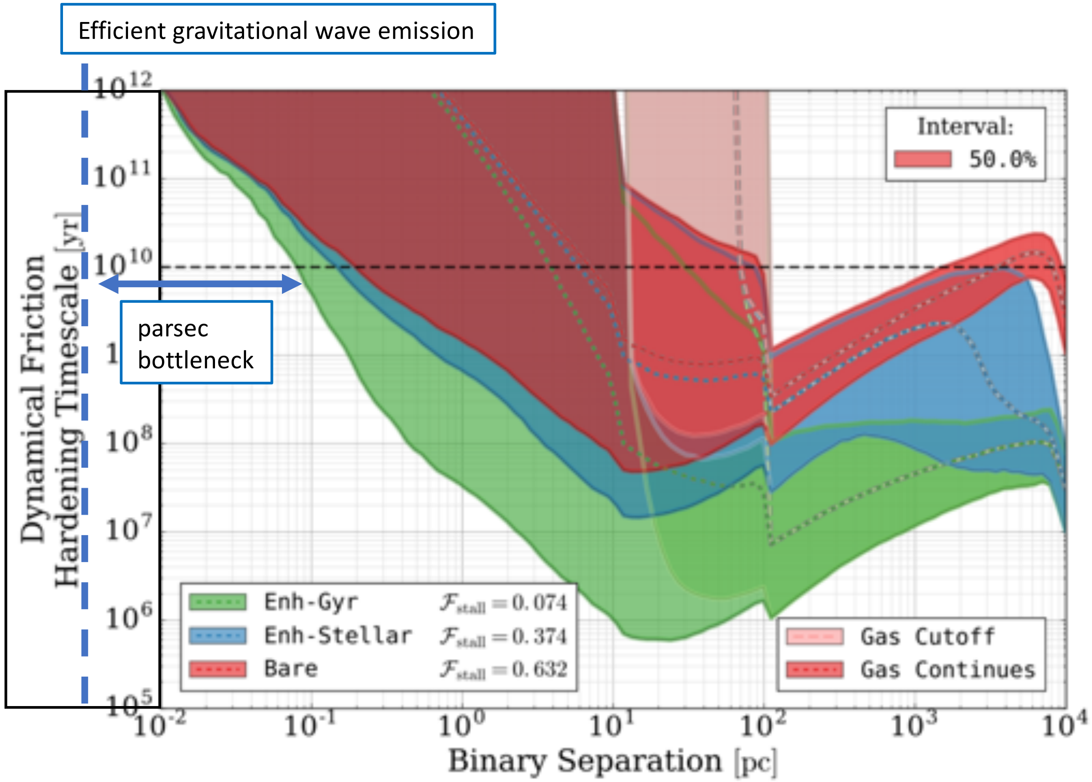
A binary black hole system in circular orbit of radius r and mass M emits gravitational waves with luminosity

$$L \sim \frac{32(GM)^5}{5G\,r^5} \simeq 3\times10^{59}\left[\frac{r}{R_{grav}}\right]^{-5}\frac{\text{erg}}{\text{s}}$$

The gravitational energy dissipated at binary separation r is $E_{grav} = GM^2/r$. The dissipation time scale is

$$t_r = \frac{E_{grav}}{L} = \frac{5r^4}{32(GM)^3} \simeq 10^2\left[\frac{M}{10^7 M_\odot}\right]\left[\frac{r}{R_{grav}}\right]^4 \text{s}$$

As long as $r > 10^4 R_{grav} \sim 10^{16}$ cm for $10^7 M_\odot$ black hole, gravitational wave emission can not assure merger within Hubble time scale. Binary black holes should dissipate energy through scattering of stars or through accretion before they reach the stage at which they loose energy via gravitational wave emission.



Efficient gravitational wave emission

parsec bottleneck

Begelman, Blandford, Rees, '80, Kelley et al. https://arxiv.org/abs/1606.01900

Gravitational wave background from supermassive black hole mergers?

An alternative interpretation of NANOGrav signal is SGWB produced by mergers of supermassive black holes in the course of structure formation process.

Most of the galaxies pass through mergers in the course of assembly. Scaling of the supermassive black hole mass with galaxy mass suggests that the central black holes also pass through mergers.

A binary black hole system in circular orbit of radius r and mass M emits gravitational waves with luminosity

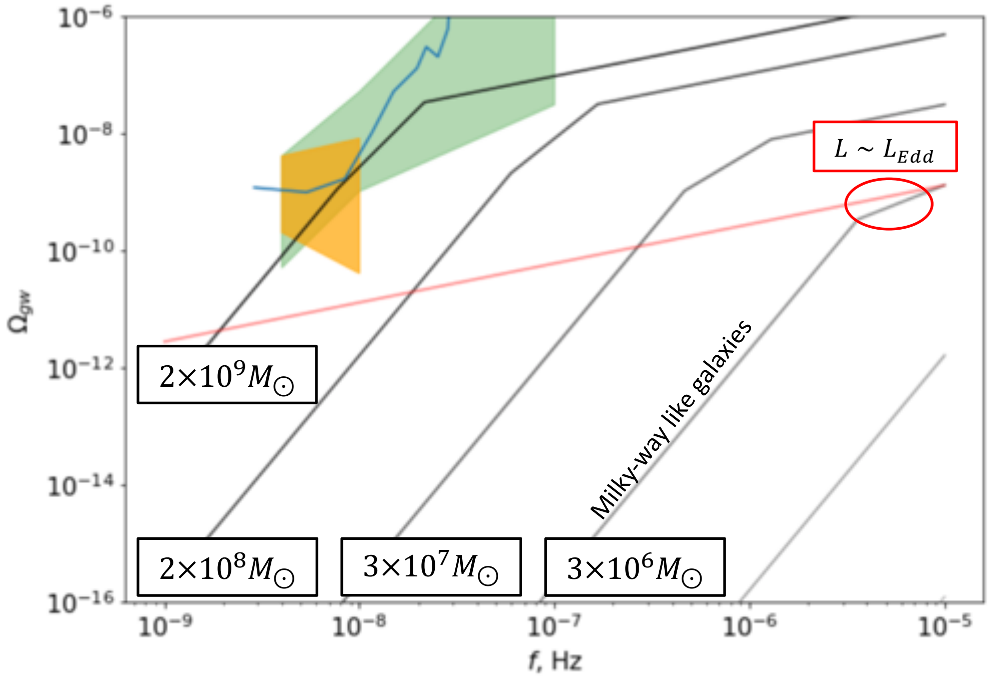
$$L \sim \frac{32(GM)^5}{5G\,r^5} \simeq 3\times10^{59}\left[\frac{r}{R_{grav}}\right]^{-5}\frac{\mathrm{erg}}{\mathrm{s}}$$

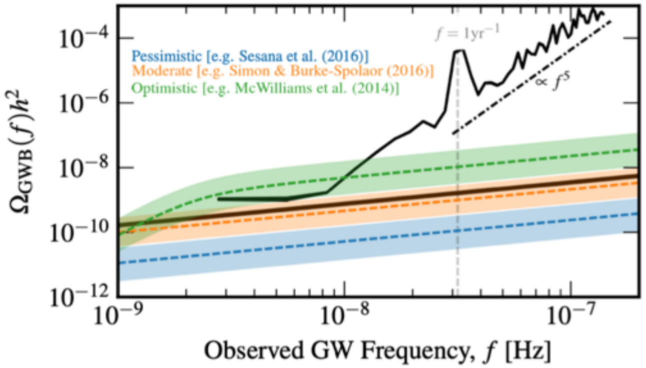
The gravitational energy dissipated at binary separation r is $E_{grav} = GM^2/r$. The dissipation time scale is

$$t_r = \frac{E_{grav}}{L} = \frac{5r^4}{32(GM)^3} \simeq 10^2\left[\frac{M}{10^7 M_\odot}\right]\left[\frac{r}{R_{grav}}\right]^4 \mathrm{s}$$

As long as $r > 10^4 R_{grav} \sim 10^{16}$ cm for $10^7 M_\odot$ black hole, gravitational wave emission can not assure merger within Hubble time scale. Binary black holes should dissipate energy through scattering of stars or through accretion before they reach the stage at which they loose energy via gravitational wave emission.

The orbital frequency of a black hole binary of $10^7 M_\odot$ at separation $10^4 R_{grav}$ is $f_{orb} \sim 5\times10^{-9}\mathrm{Hz}$.



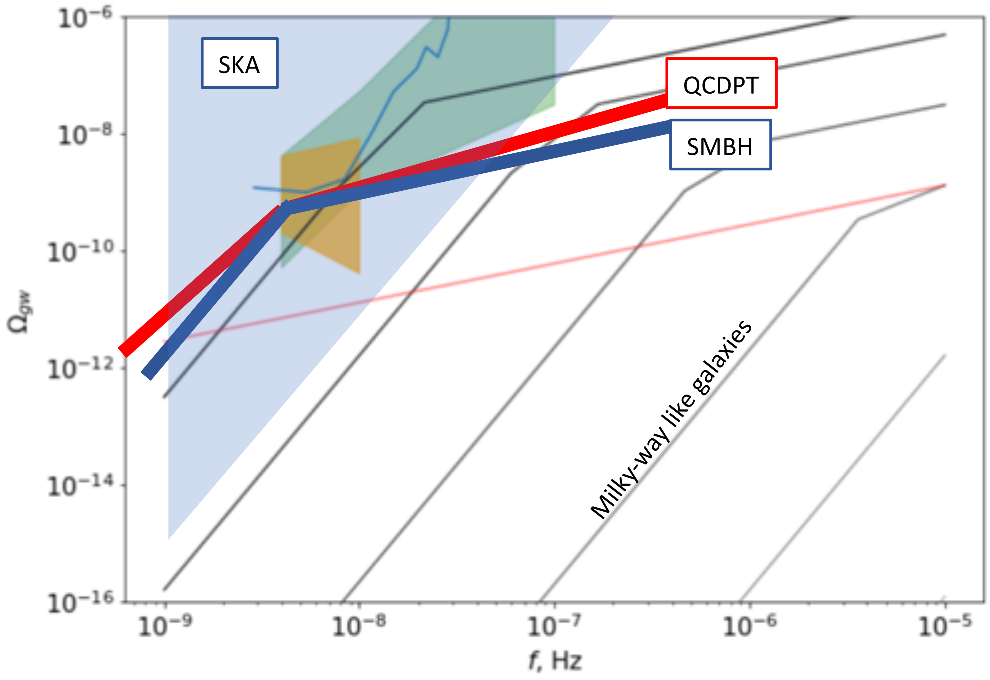


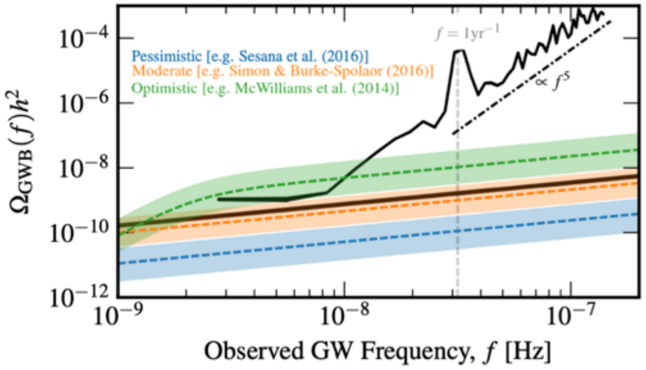
Arzoumanian et al. https://arxiv.org/abs/1801.02617

Gravitational wave background from supermassive black hole mergers?

Both SGWB from first-order QCD phase transition in the Early Universe and SGWB produced by supermassive black hole mergers are expected to generate broken powerlaw type spectra in the sensitivity range of pulsar timing arrays.

The two models can be distinguished via measurement of the spectral shapes: slopes and position of the break. This requires precision measurement of the spectrum over wide frequency range. This should be possible with SKA.



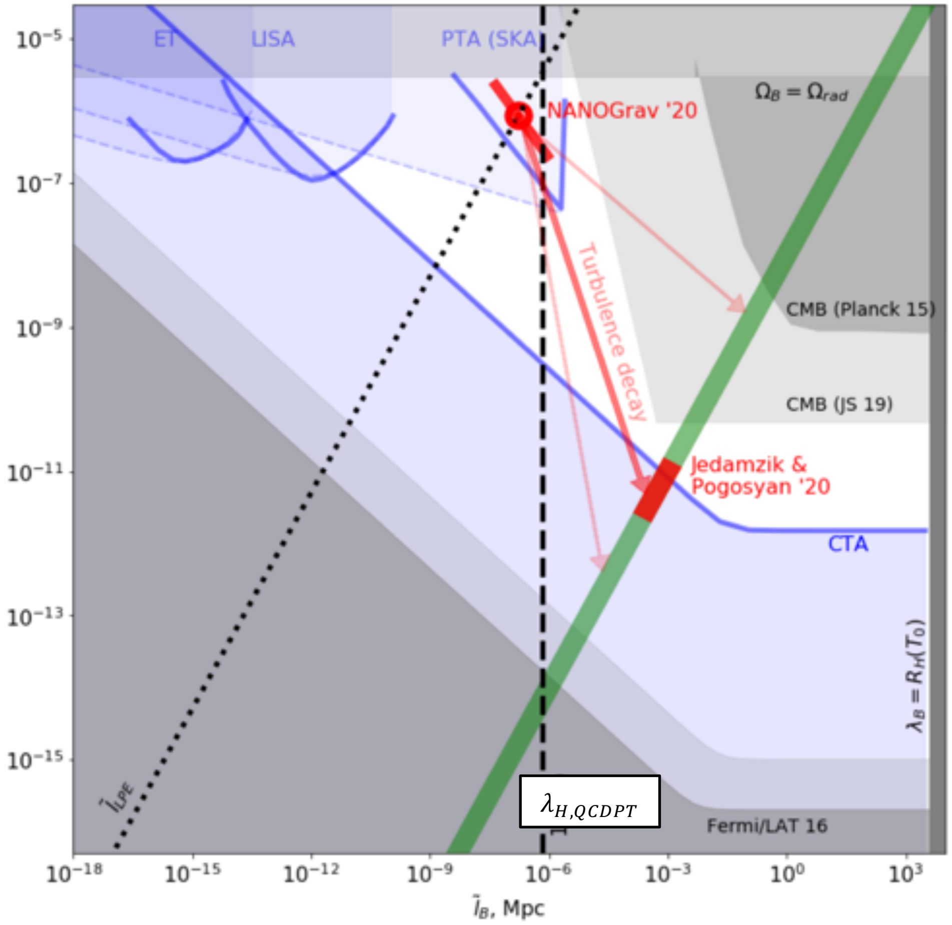


Arzoumanian et al. https://arxiv.org/abs/1801.02617

First order QCD phase transition?

Combining NANOGrav evidence for SGWB and Jedamzik & Pogosyan '20 evidence of influence of magnetic field on recombination from CMB data, we find an evidence for generation of

- non-helical magnetic field
- with correlation length about 10% of horizon scale
- at QCD phase transition.



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

First order QCD phase transition?

Combining NANOGrav evidence for SGWB and Jedamzik & Pogosyan ‘20 evidence of influence of magnetic field on recombination from CMB data, we find an evidence for generation of

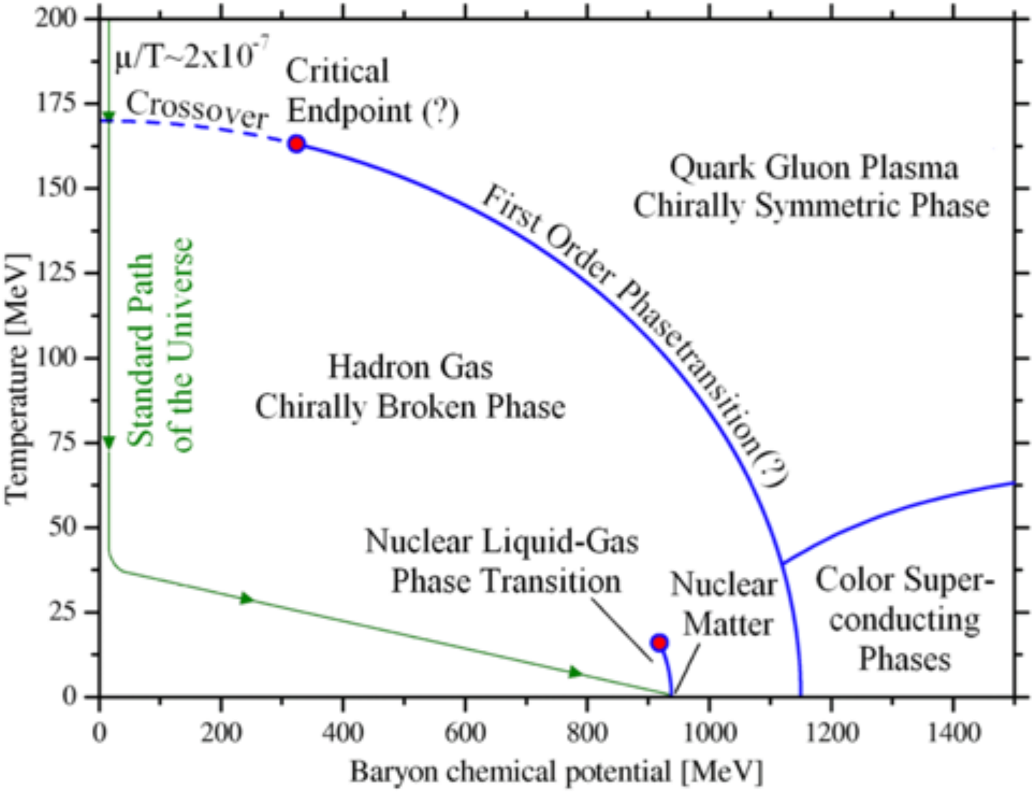
- non-helical magnetic field
- with correlation length about 10% of horizon scale
- at QCD phase transition.

This is surprising, because in the Standard Model the QCD phase transition is believed to be a cross-over, because of the low abundance of baryons:

$$\eta_b = \frac{n_b - n_{ab}}{s} \sim 10^{-10}$$

Lattice simulations show that the order of QCD phase transition is regulated, among other parameters, including the magnetic field, by the baryon chemical potential (energy cost of addition of an extra baryon to the plasma)

$$\eta_b \propto \frac{\mu_b}{T}; \quad \mu_b \ll T$$



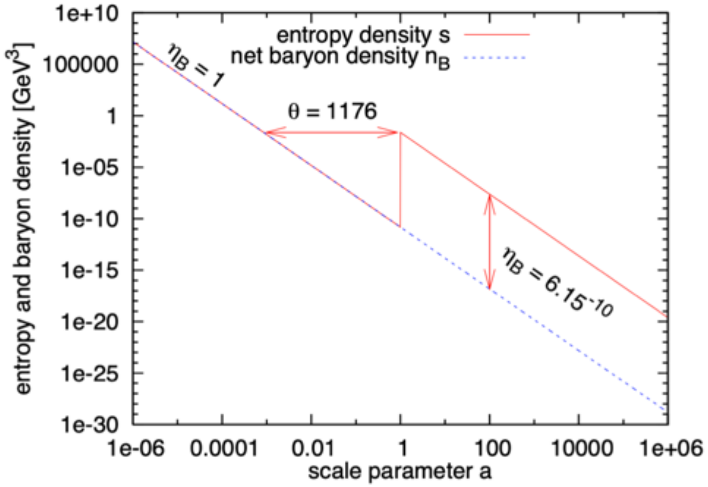
Boekel, Schaffner-Bielich, https://arxiv.org/abs/1105.0832; Schwarz, Stuke https://arxiv.org/abs/0906.3434

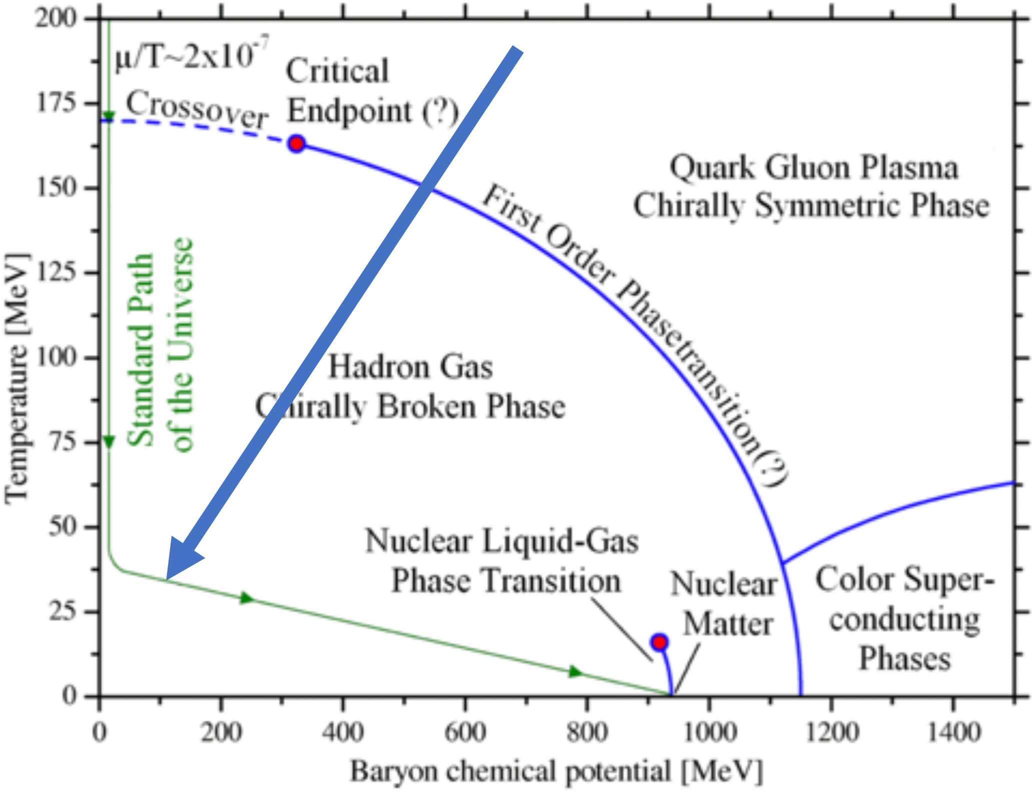
First order QCD phase transition?

Large baryon chemical potential might be present in the plasma just before the QCD phase transition. In this case the transition can be first order.

During the first order phase transition, the Universe remains trapped in the false vacuum phase, its energy density dominated by vacuum energy. In this case the Universe experiences a short "little inflation" period that dilutes the baryon density from $\eta_b \sim 1$ down to $\eta_b \sim 10^{-10}$.

Collisions of bubbles of new phase generate magnetic field and gravitational waves.



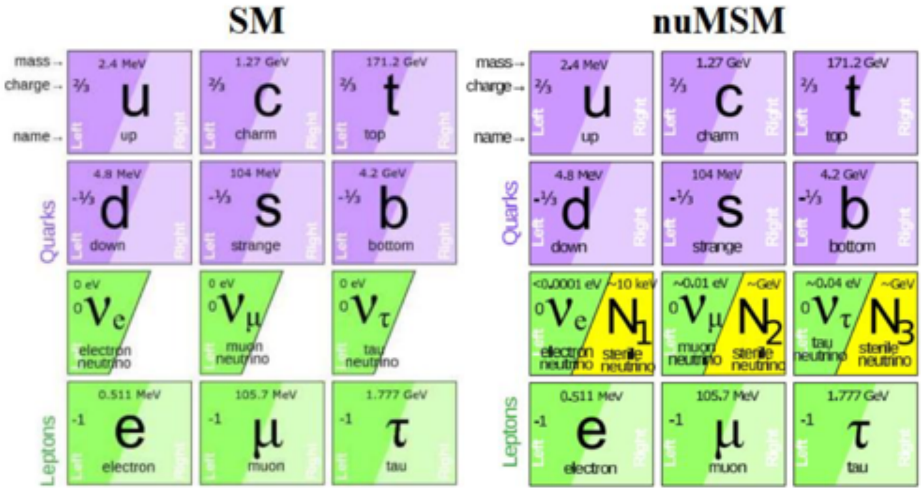


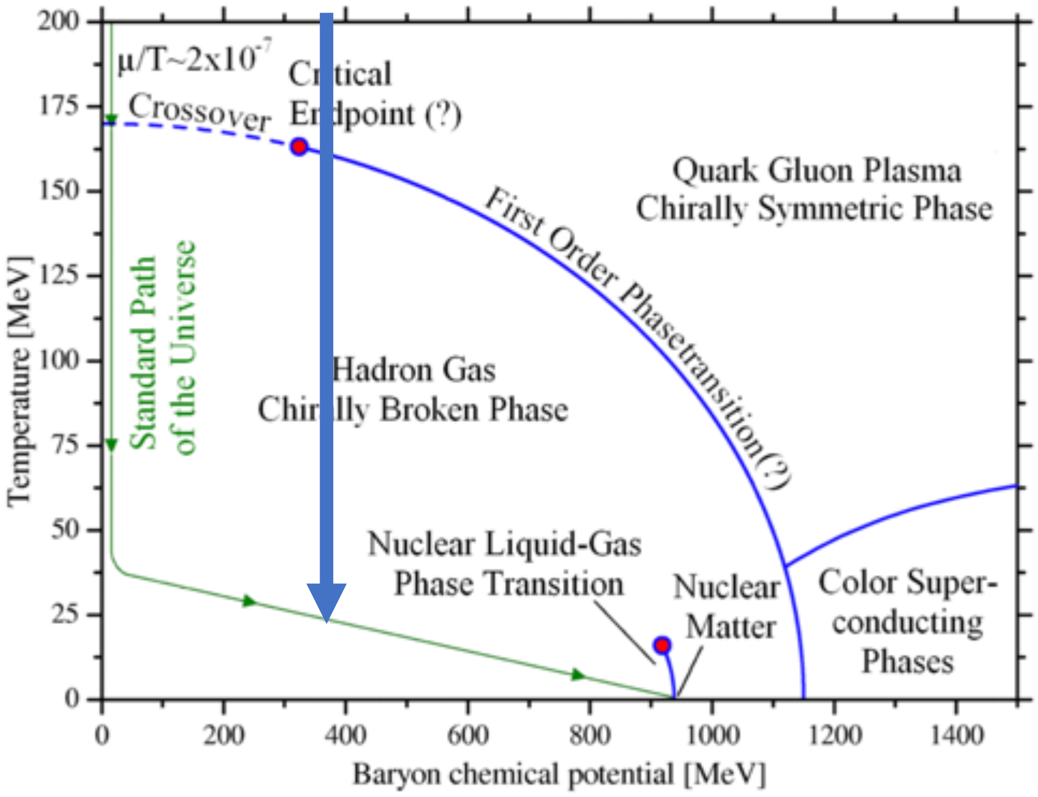
Boekel, Schaffner-Bielich, https://arxiv.org/abs/1105.0832; Schwarz, Stuke https://arxiv.org/abs/0906.3434

First order QCD phase transition?

Large lapton asymmetry can be generated via decays of heavy particles, as e.g. in the νMSM model that completes the neutrino sector of the Standard Model with three heavy “sterile” neutrinos.

The lightest sterile neutrino forms dark matter in present-day Universe. The two heavier sterile neutrinos decay at the temperature close to that of the QCD phase transition $T \sim 100\ \mathrm{MeV}$. The level of lepton asymmetry regulates the abundance of the dark matter and BAU.





Boekel, Schaffner-Bielich, https://arxiv.org/abs/1105.0832; Schwarz, Stuke https://arxiv.org/abs/0906.3434

Cosmological dynamos

Baryon and lepton asymmetries, as well as chiral (left-right particle) asymmetries also directly generate (hyper)magnetic fields due to the anomalous coupling

$$\nabla_\mu j^\mu_f = C^f_{\rm y}\frac{\alpha_{\rm y}}{4\pi}Y_{\mu\nu}\tilde{Y}^{\mu\nu} + C^f_{\rm w}\frac{\alpha_{\rm w}}{8\pi}W^a_{\mu\nu}\tilde{W}^{a\mu\nu} + C^f_{\rm s}\frac{\alpha_{\rm s}}{8\pi}G^b_{\mu\nu}\tilde{G}^{b\mu\nu}$$

Large initial lepton / baryon / chiral asymmetry (e.g. generated via heavy particle decays) generates helical magnetic fields.

Joyce & Shaposhnikov ‘97 have introduced the description of this effect in terms of dynamo-like process:

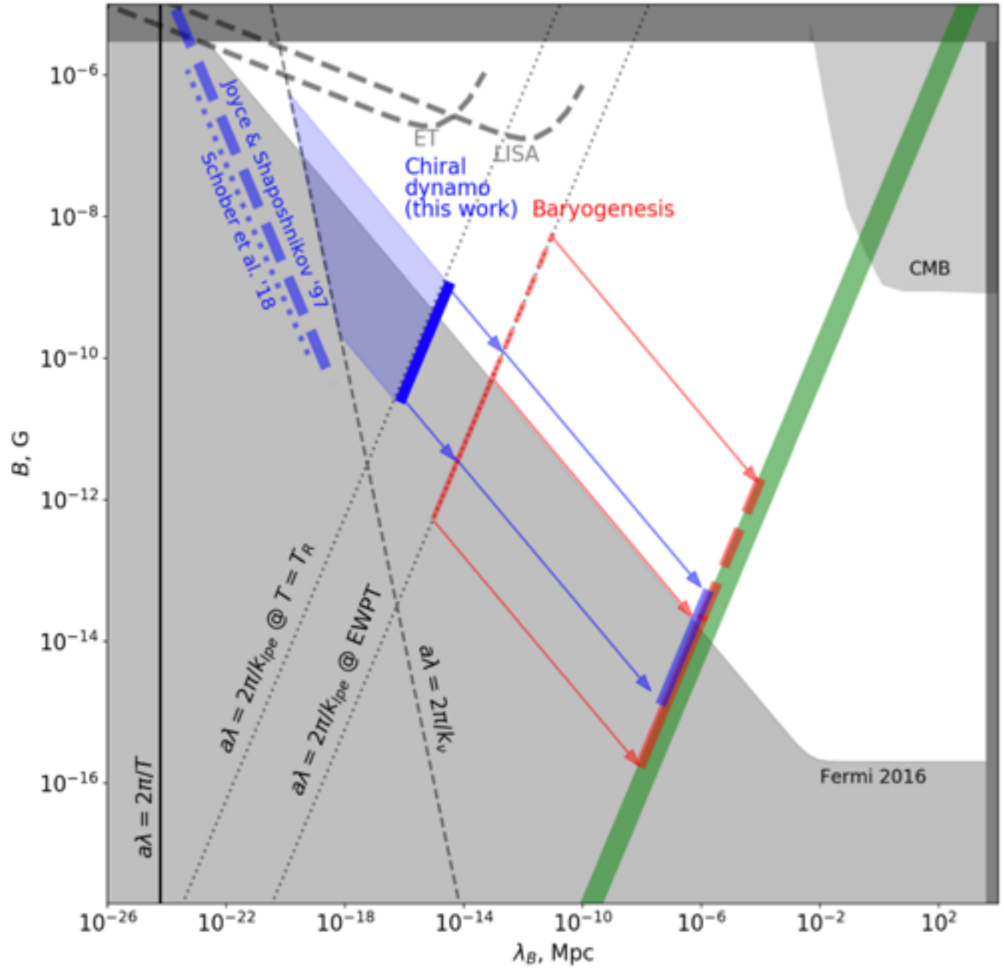
$$\frac{\partial B}{\partial t} = \nabla\times(v\times B) + \frac{1}{\sigma}\nabla\times(\nabla\times B + 4\mu B)$$

where μ is the chiral chemical potential $(\mu \propto (n_R - n_L)$ in JS’97 model). The mechanism can efficiently amplify the field modes with wavenumber k at the rate $t_\mu^{-1} \sim 4k\mu/\sigma$ up to

$$B \sim 300\ \mu T$$

The fastest growing modes are, in general, affected by turbulence and viscous damping, so that the mechanism ultimately produces field with parameters corresponding to the largest processed eddies at the generation energy scale.

Chiral dynamo fields would be (marginally) detectable through the SGWB, if they would not be influenced by the viscous damping. Chiral dynamo fields are still detectable through via gamma-ray detection technique.



Joyce, Shaposhnikov, https://arxiv.org/abs/astro-ph/9703005 Rogachevskii et al., , https://arxiv.org/abs/1705.00378,
AN, Semikoz, https://arxiv.org/abs/2010.13571, Fujita, Kamada https://arxiv.org/abs/1602.02109

Summary

Robust lower bound on IGMF is imposed at the level 10^{-16} G for large correlation length field and $\boldsymbol{> 10^{-14}\ \mathrm{G}}$ 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.

Tight upper bound on cosmological magnetic field $\boldsymbol{< 10^{-11}\ \mathrm{G}}$ 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 $\boldsymbol{10^{-12} - 10^{-11}\ \mathrm{G}}$ 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 $\boldsymbol{\tilde{B} \sim 1\ \mu\mathrm{G}}$ comoving field strength and $\boldsymbol{\tilde{\lambda}_B \sim 0.1\ \mathrm{pc}}$ comoving correlation length.