Cosmological magnetic fields

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Durrer & AN, A&ARev, 21, 62 (2013)

Progress on Old and New Themes in cosmology (PONT) 2014

14-18 April 2014
Palais des Papes, Avignon

Overview

Magnetic fields in astronomy and cosmology

Characterization of cosmological magnetic fields

Generation of cosmological magnetic fields

Evolution of cosmological magnetic fields

Observations of cosmological magnetic fields

Summary

Magnetic fields in astronomy

All known types astronomical sources possess magnetic fields:

- * Stars : $B \sim 1 - 10^3$ G (e.g. Sun)
  $B \sim 10^{12} - 10^{15}$ G (neutron stars)
- * Planets : $B \sim 1$ G (e.g. Earth)
- * Galaxies : $B \sim 10\ \mu$G (e.g. Milky Way)
- * Galaxy clusters : $B \sim 1\ \mu$G

Ubiquity of cosmic magnetic fields is due to the common presence of charged particles forming high-conductivity plasma in astrophysical environments.

Magnetic field – charged plasma dynamics is typically governed by non-linear MHD equations:

Viscosity dumps motions on small scales

Plasma motions develop turbulence

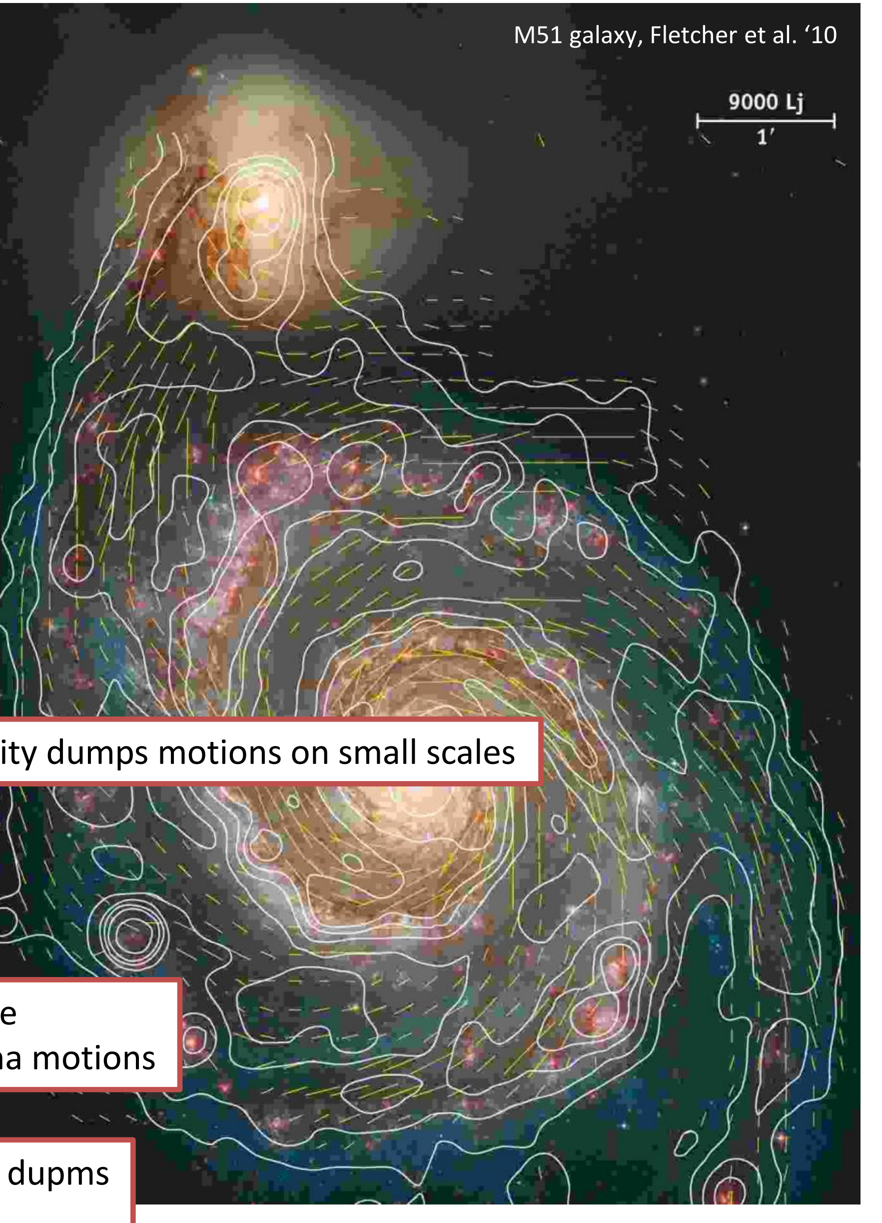
$$\rho\left(\frac{\partial\vec{v}}{\partial t}+(\vec{v}\nabla)\vec{v}\right)+\vec{B}\times(\nabla\times\vec{B})=-\nabla\vec{P}+\rho\vec{g}+\kappa\vec{\nabla}^2 v$$

Magnetic fields produce back-reaction on plasma motions

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

Plasma motions amplify pre-existing weak magnetic fields

Ohmic dissipaiton dupms B on small scales



Magnetic fields in the Early Universe?

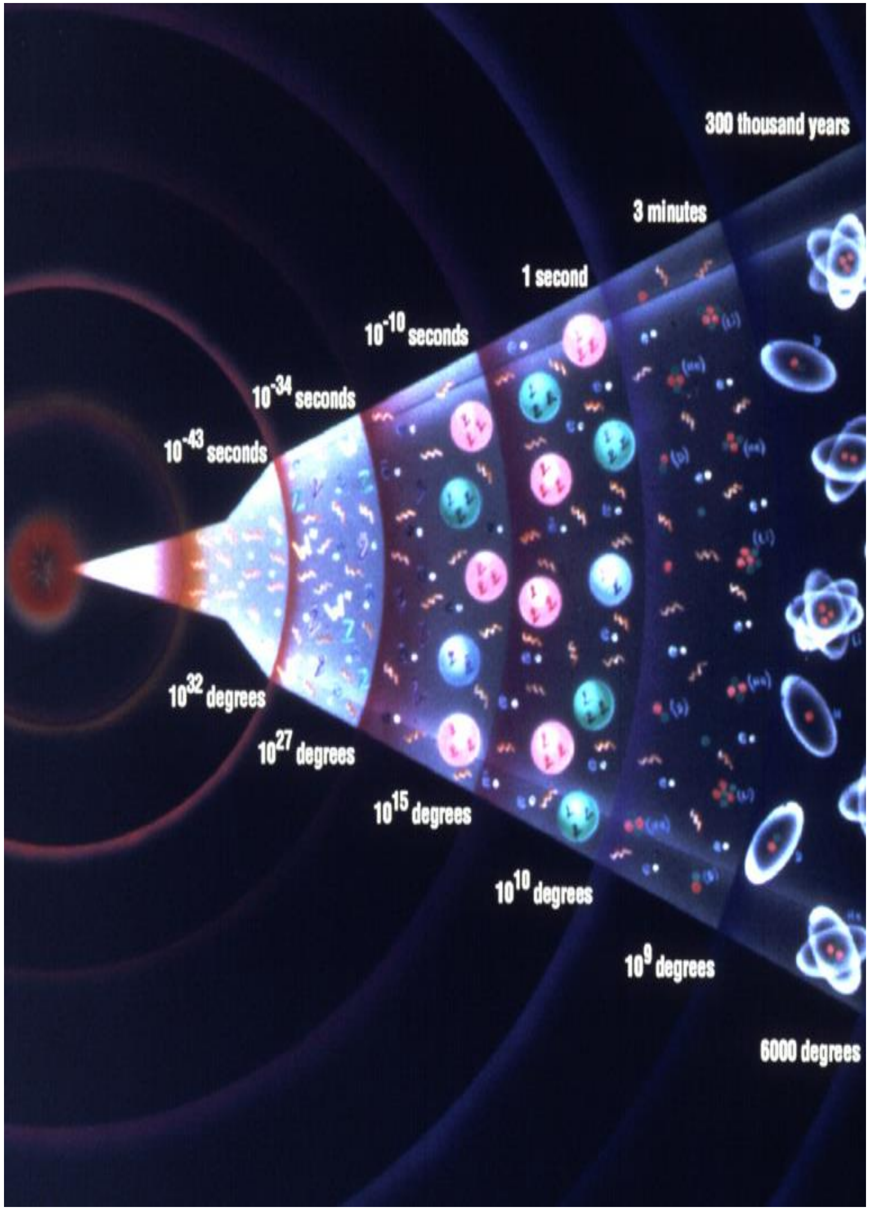
Early Universe was also filled with high conductivity charged plasma. It might have also possessed magnetic field which was in a dynamical co-evolution with expanding matter.

Was magnetic field generated in the Early Universe? How?

If yes, did it play a significant role in physical processes (e.g. expanding plasma dynamics)?

Are there any observable consequences of the presence of magnetic field in the Early Universe?

Are they related to the observed magnetic fields in astronomical objects?

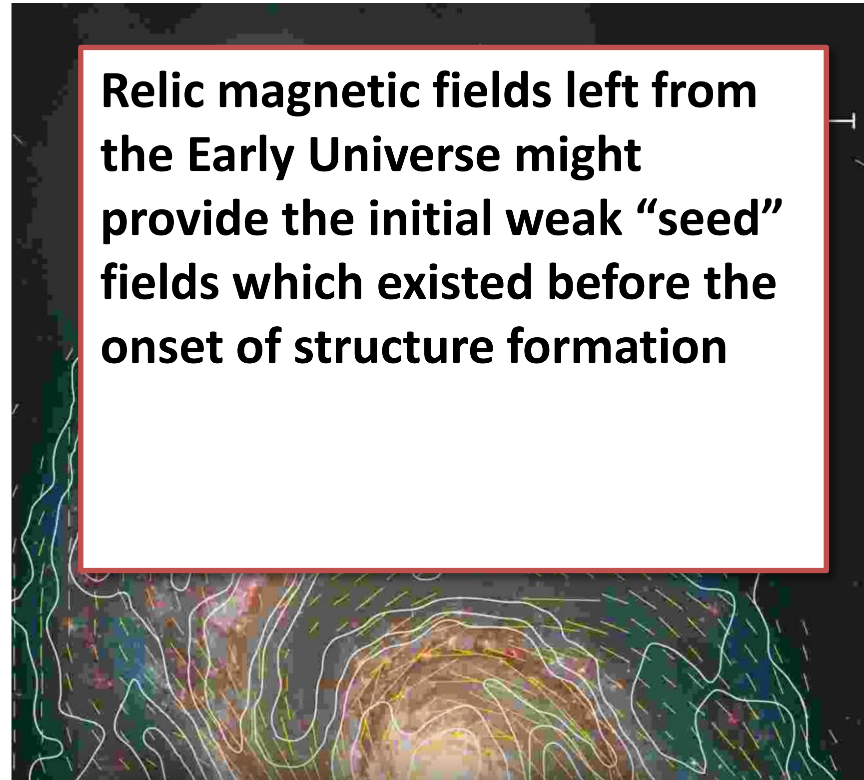


Problem of the origin of cosmic magnetic fields

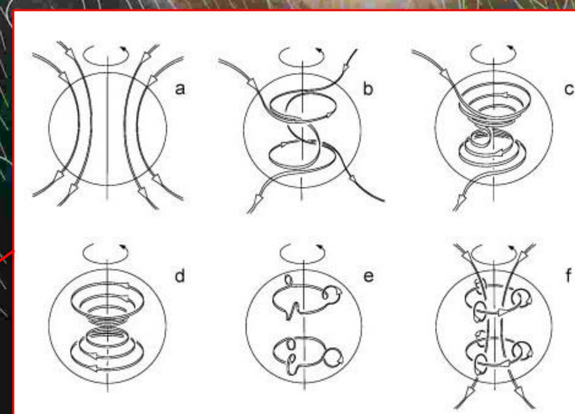
Example: galactic magnetic fields.

- Gravitational collapse during structure formation leads to compression and amplification of weak field:
  $\Phi = BL^2 \sim const$
- Exponential amplification of magnetic field in the presence of plasma motions
- $$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B})$$
  works on the eddy turnover time scale
  $$t \sim \frac{L}{v} \simeq 10^8 \left[\frac{L}{10\text{ kpc}}\right]\left[\frac{v}{10^2\text{ km/s}}\right]^{-1}\text{ yr}$$
  and is able to amplify galactic magnetic field from, e.g. 10^{-20} G up to 10 μG in some 35 e-folding time, i.e. on several Gyr time scales.
- Most commonly considered amplification mechanism able to produced ordered magnetic field structure in spiral galaxies is "αω" dynamo.

MHD processes are efficient at amplification of ***pre-existing*** magnetic fields.

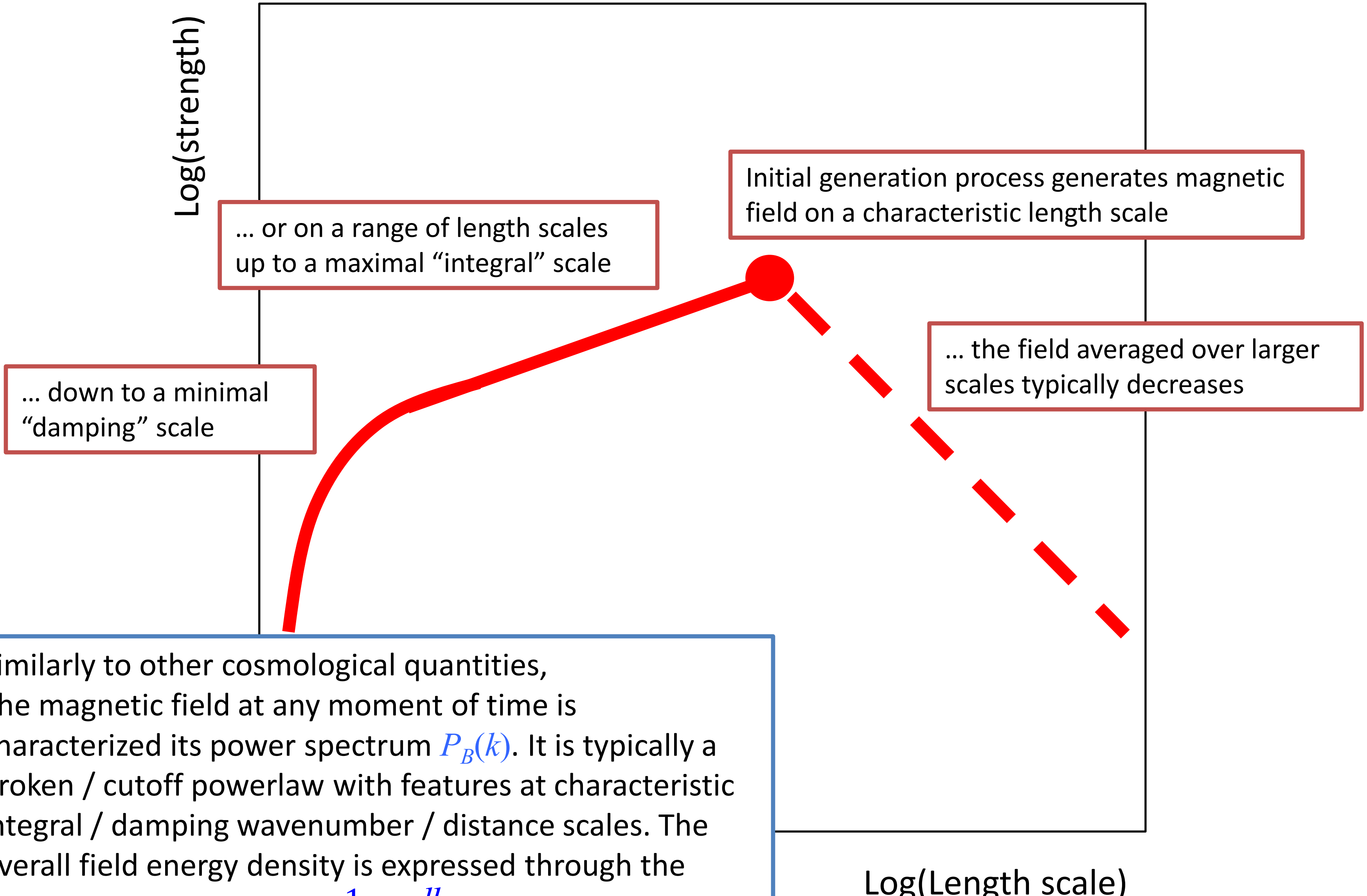


Relic magnetic fields left from the Early Universe might provide the initial weak "seed" fields which existed before the onset of structure formation



Love, J. J., 1999. Astronomy & Geophysics, 40, 6.14-6.19.

Cosmological magnetic field parameters



Similarly to other cosmological quantities,
The magnetic field at any moment of time is characterized its power spectrum $P_B(k)$. It is typically a broken / cutoff powerlaw with features at characteristic integral / damping wavenumber / distance scales. The overall field energy density is expressed through the power spectrum:

$$\rho_B = \frac{1}{2\pi^2}\int \frac{dk}{k} k^3 P_B(k)$$

Generation of cosmological magnetic fields

Generation (rather than *amplification*) of magnetic fields in cosmological conditions is possible only during phase transitions or during Inflation, when out-of-equilibrium processes lead to charge separation.

Magnetic fields from Inflation

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Inflation could, in principle, generate a scale-invariant field with

$$P_B(k) \sim k^{n_s}, \quad n_s = -3$$

However, there is no self-consistent model up to now, which results in such a field.

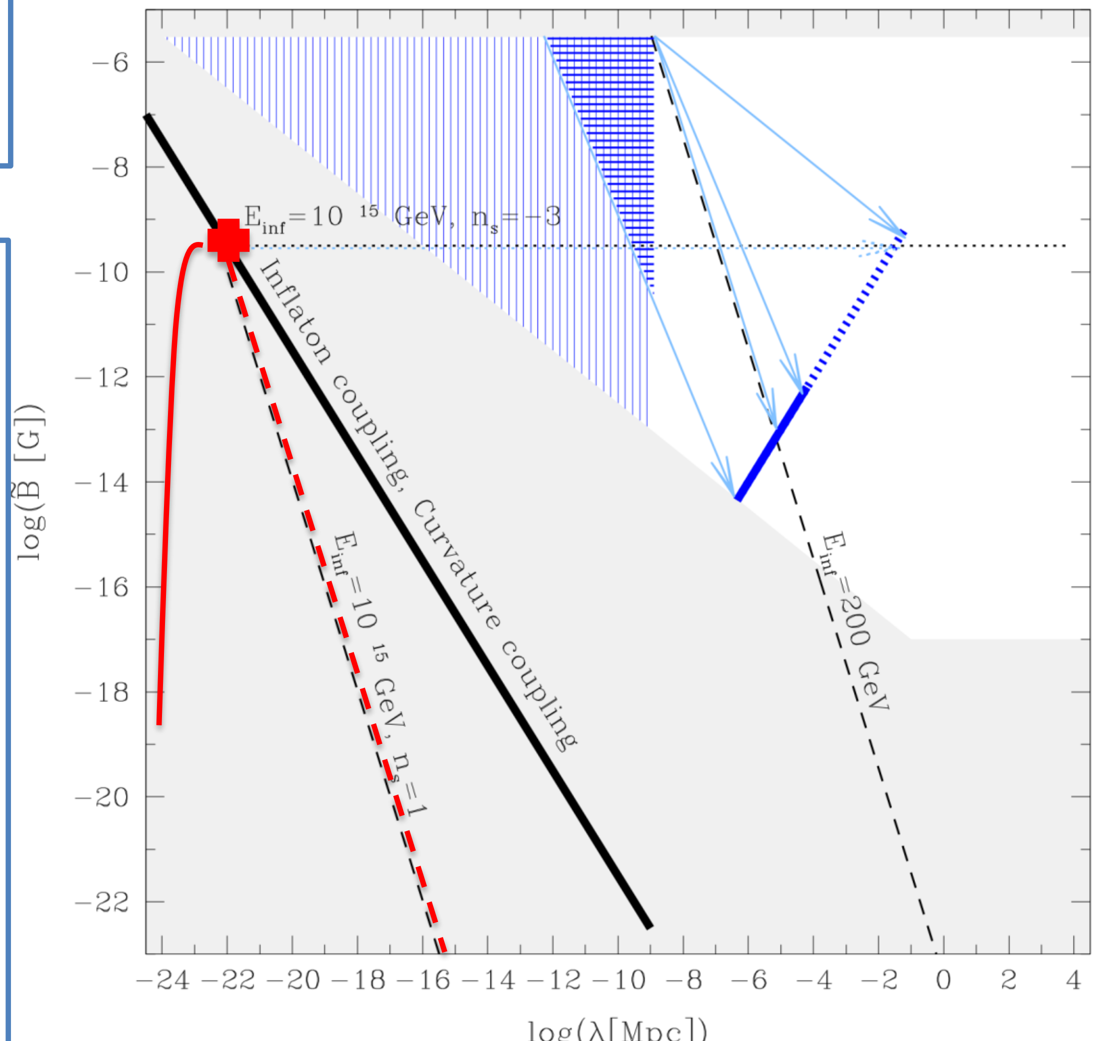
Most of the self-consistent models predict soft power spectrum with $n_s \geq 1$, peaking at a the comoving length scale

$$\lambda_B \sim t_{Inflation} \simeq 10^4 \left[\frac{H_{Inflation}}{10^{14}\ \mathrm{GeV}} \right]^{-1} \mathrm{cm}$$

and reaching the (comoving) field strength at this scale up to

$$B \sim 3 \left[\frac{r_B}{r_{rad}} \right]^{1/2} \mathrm{nG} \sim 10^{-9} \left[\frac{H_{Inflation}}{10^{-3} M_{Pl}} \right] \mathrm{G}$$

At this scale.



Turner & Widrow '88, Ratra '92, Subramanian '10, Kunze '10, ……

Magnetic fields from phase transitions

Generation (rather than *amplification*) of magnetic fields in cosmological conditions is possible only during phase transitions or during Inflation, when out-of-equilibrium processes lead to charge separation.

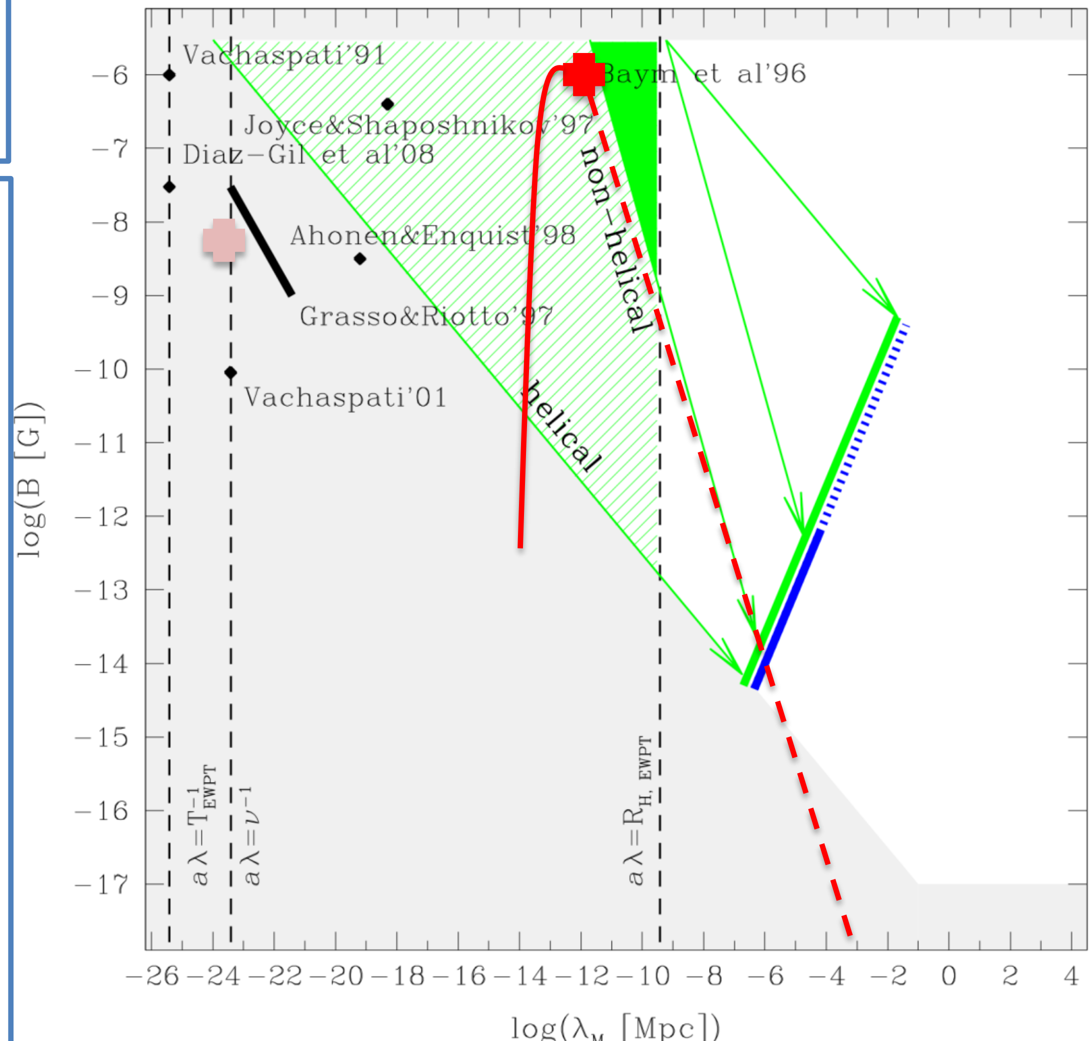
First order phase transitions are expected to proceed via bubble nucleation. Magnetic fields generated at the typical distance scale of the bubbles, which are a fraction of horizon size:

$$\lambda_B \sim \varepsilon t_{EW} \simeq 10^{14} \left[\frac{\varepsilon}{10^{-2}}\right]\left[\frac{E_{EW}}{10^{2}\ \mathrm{GeV}}\right]^{-1} \mathrm{cm}$$

Alternatively, a second-order phase transition or a cross-over would generate magnetic field on much shorter distance scale, $\lambda_B \sim T^{-1}$. Such field is quickly damped by Ohmic dissipation. Models resulting in the field strength up to the equipartition with radiation at this scale

$$B \sim 3\left[\frac{r_B}{r_{rad}}\right]^{1/2} nG$$

Were proposed. Causality requirements limit the slope of the power spectrum to be $n_s \geq 2$.



Vachaspati '91, Enquist & Olesen '93, Kamionkowski et al. '94, Joyce & Shaposhnikov '97, Durrer & Caprini '03, ……

Magnetic fields from phase transitions

Generation (rather than *amplification*) of magnetic fields in cosmological conditions is possible only during phase transitions or during Inflation, when out-of-equilibrium processes lead to charge separation.

First order phase transitions are expected to proceed via bubble nucleation. Magnetic fields generated at the typical distance scale of the bubbles, which are a fraction of horizon size:

$$\lambda_B \sim \varepsilon t_{QCD} \simeq 10^{17} \left[\frac{\varepsilon}{10^{-2}}\right] \left[\frac{E_{QCD}}{10^2 \text{ MeV}}\right]^{-1} \text{cm}$$

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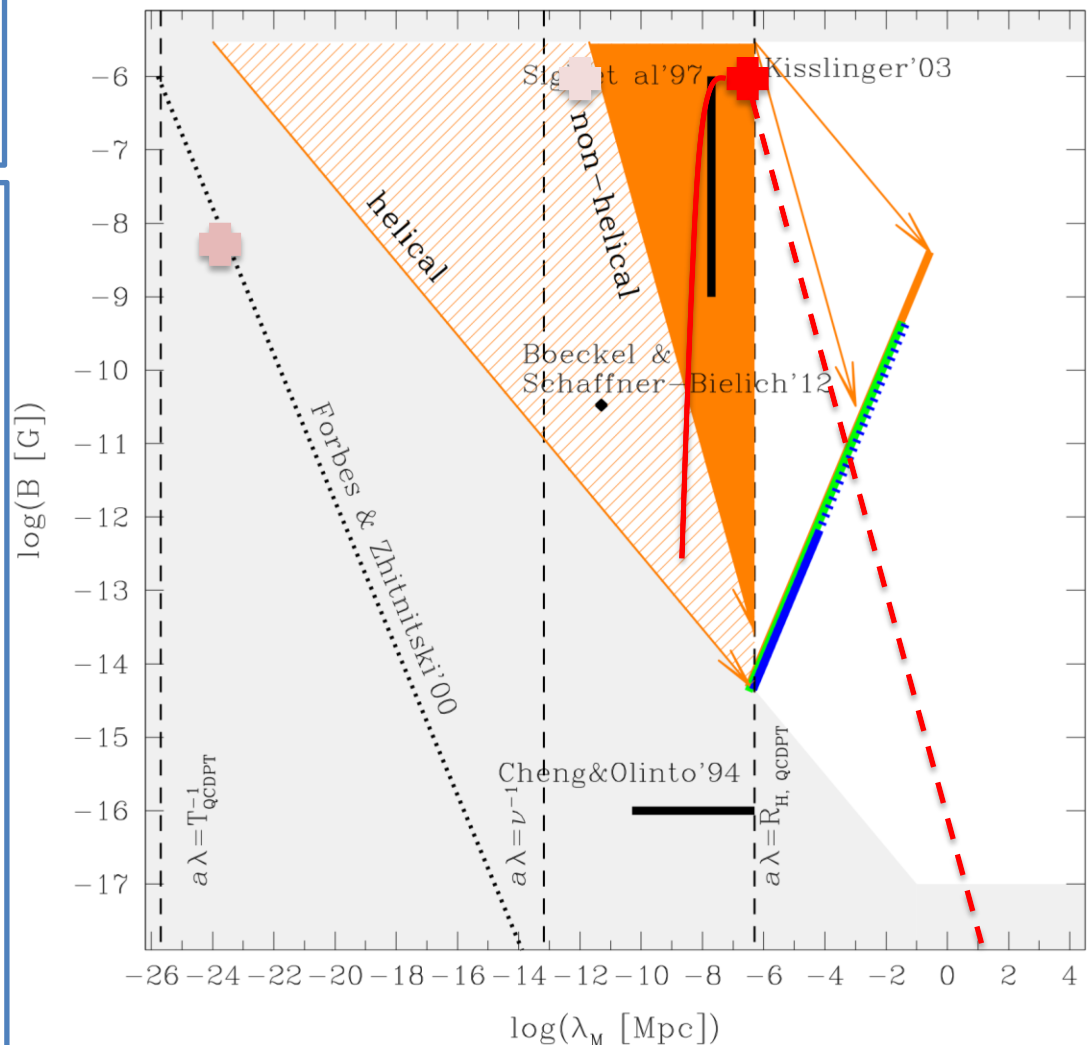
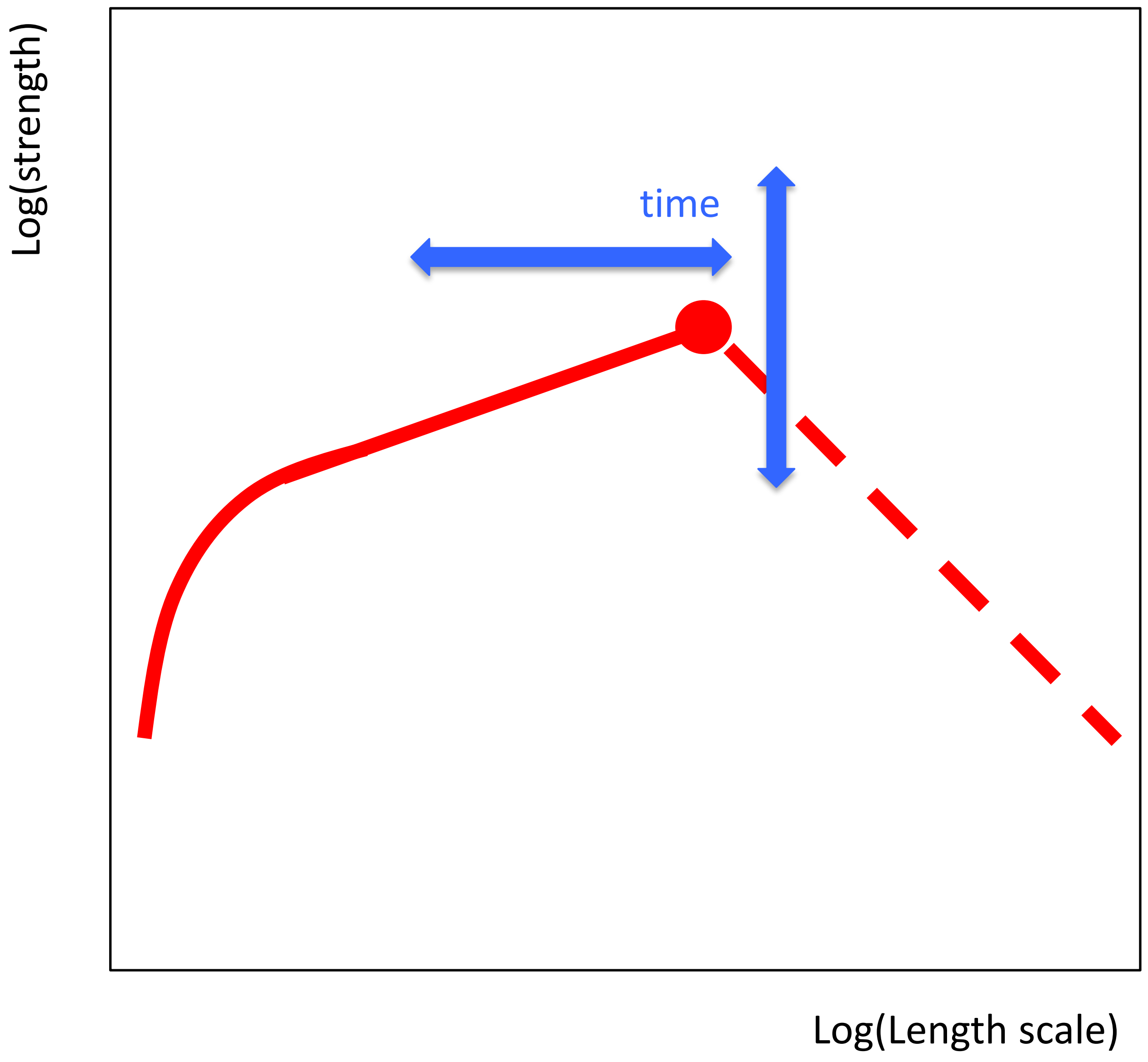
$$B \sim 3 \left[\frac{r_B}{r_{rad}}\right]^{1/2} \text{mG}$$

Were proposed. Causality requirements limit the slope of the power spectrum to be $n_s \geq 2$.



Vachaspati '91, Enquist & Olesen '93, Kamionkowski et al. '94, Joyce & Shaposhnikov '97, Durrer & Caprini '03, ……

Co-evolution of magnetic fields and plasma



Co-evolution of magnetic fields and plasma

Nonlinear "mode coupling" term(s)

Viscous dissipation

$$\rho\left(\frac{\partial \vec{v}}{\partial t}+(\vec{v}\nabla)\vec{v}\right)+\vec{B}\times(\nabla\times\vec{B})=-\nabla\vec{P}+\rho\vec{g}+\kappa\left(\nabla^2\vec{v}+\frac{1}{3}\nabla(\nabla\vec{v})\right)$$

Euler equation

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

Induction equation

Ohmic dissipation

* Valid for "comoving" fields

Comoving magnetic field $B\sim a^2B_{phys}$ is conserved in the linear regime on the scales much larger than the Ohmic dissipation scale. Linear approximation is not valid at the distance scales shorter or comparable to the "largest processed eddy" scale, $L\sim vt$.

Nonlinear terms are responsible for the transfer of power from larger to smaller scales and for development of turbulence:

$$v\sim\sin(kx)$$

$$v\nabla v\sim k\sin(kx)\cos(kx)\sim k/2\sin(2kx)$$

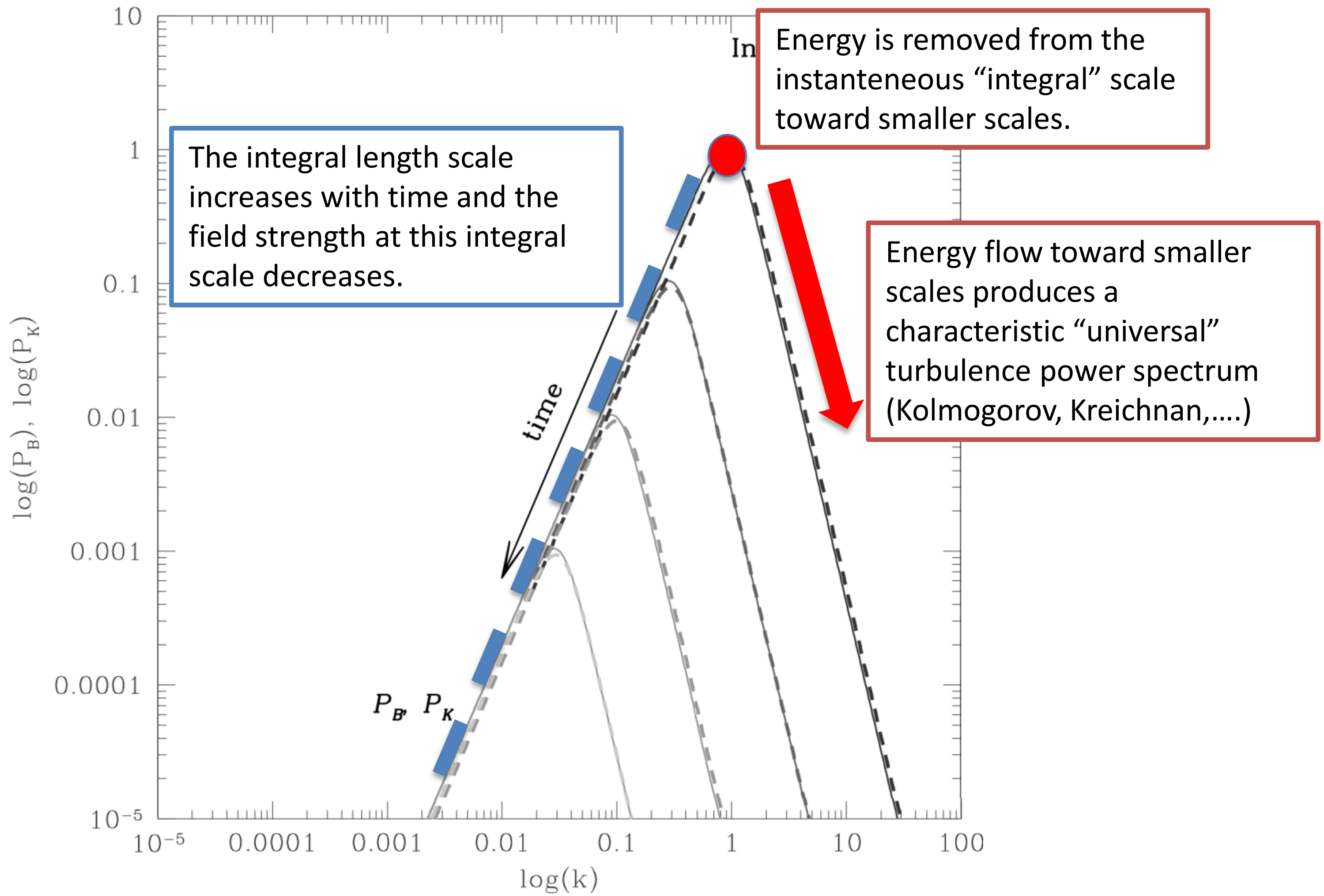
Nonlinear terms dominate on the distance scales $l>\frac{k}{v},\ l>\frac{1}{s\,v}$, i.e. as long as the kinetic and magnetic Reynolds numbers are

$$R_k=\frac{lv}{k}\sim\frac{lv}{l_{mfp}}\gg 1,\qquad R_m=lvs\gg 1$$

As soon as $R_k\sim 1$ at the integral scale, turbulence development stops. Viscous term dominates and plasma motions are suppressed, $v\rightarrow 0$. If R_m is still large, magnetic field stops evolving, $B\sim const$.

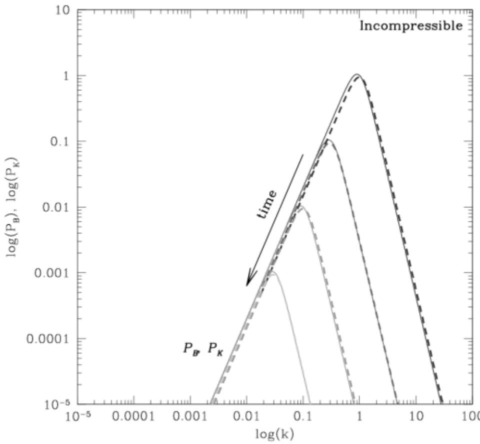
Example: neutrino decoupling: $\kappa\sim\lambda_{mfp,\nu}$. or photon decoupling, $\kappa\sim\lambda_{mfp,\gamma}$.

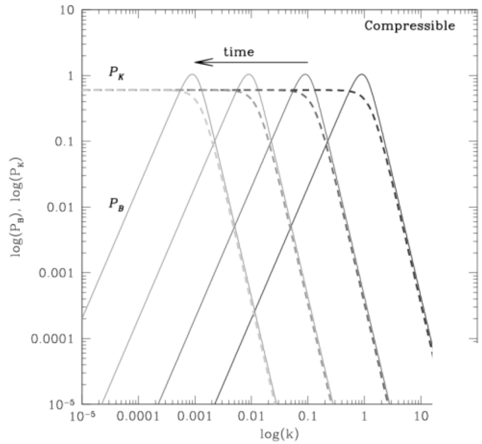
Co-evolution of magnetic fields and plasma



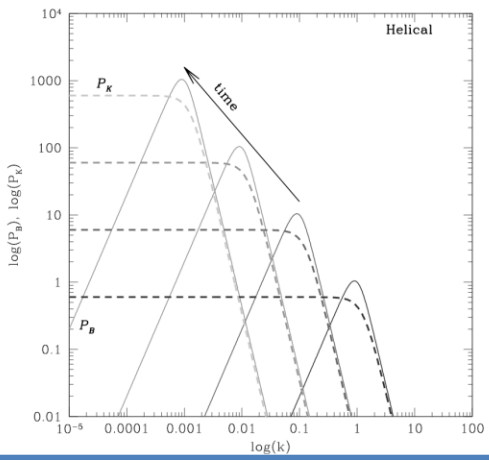
Subramanian & Barrow '98, Jedamzik, Katalinic & Olinto '98, Banerjee & Jedamzik '04

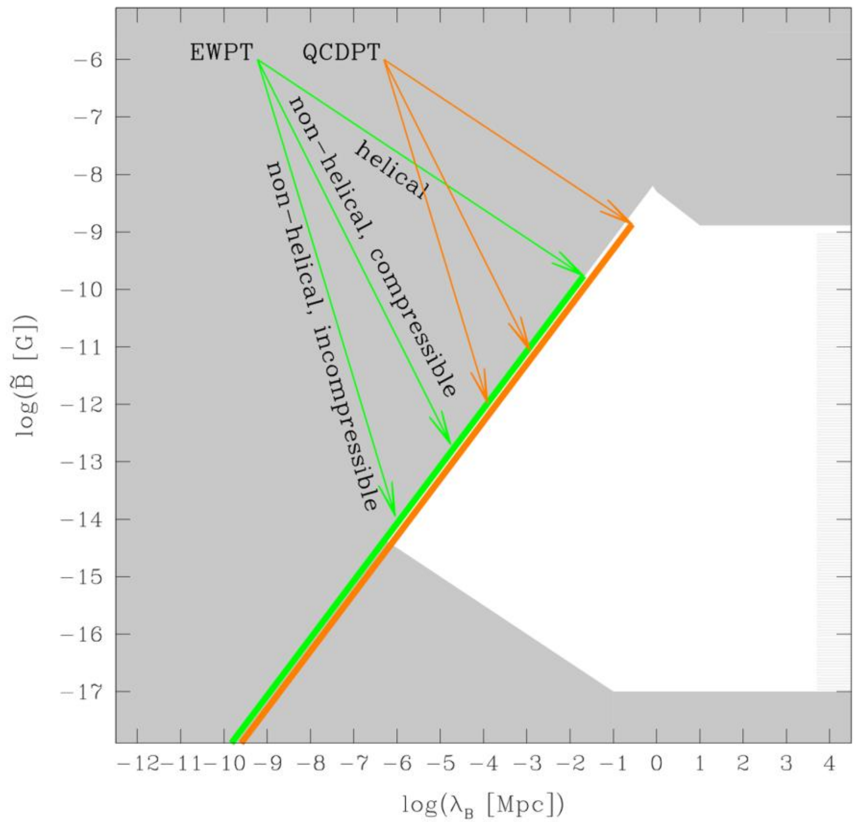
Co-evolution of magnetic fields and plasma





Transfer of power between magnetic field and plasma motion modes might result in different time evolution patterns of integral scale and field strength at the integral scale.





The turbulent co-evolution of magnetic field and plasma naturally stops at the epoch of recombination / matter-radiation equality.
At this moment of time, the integral scale is

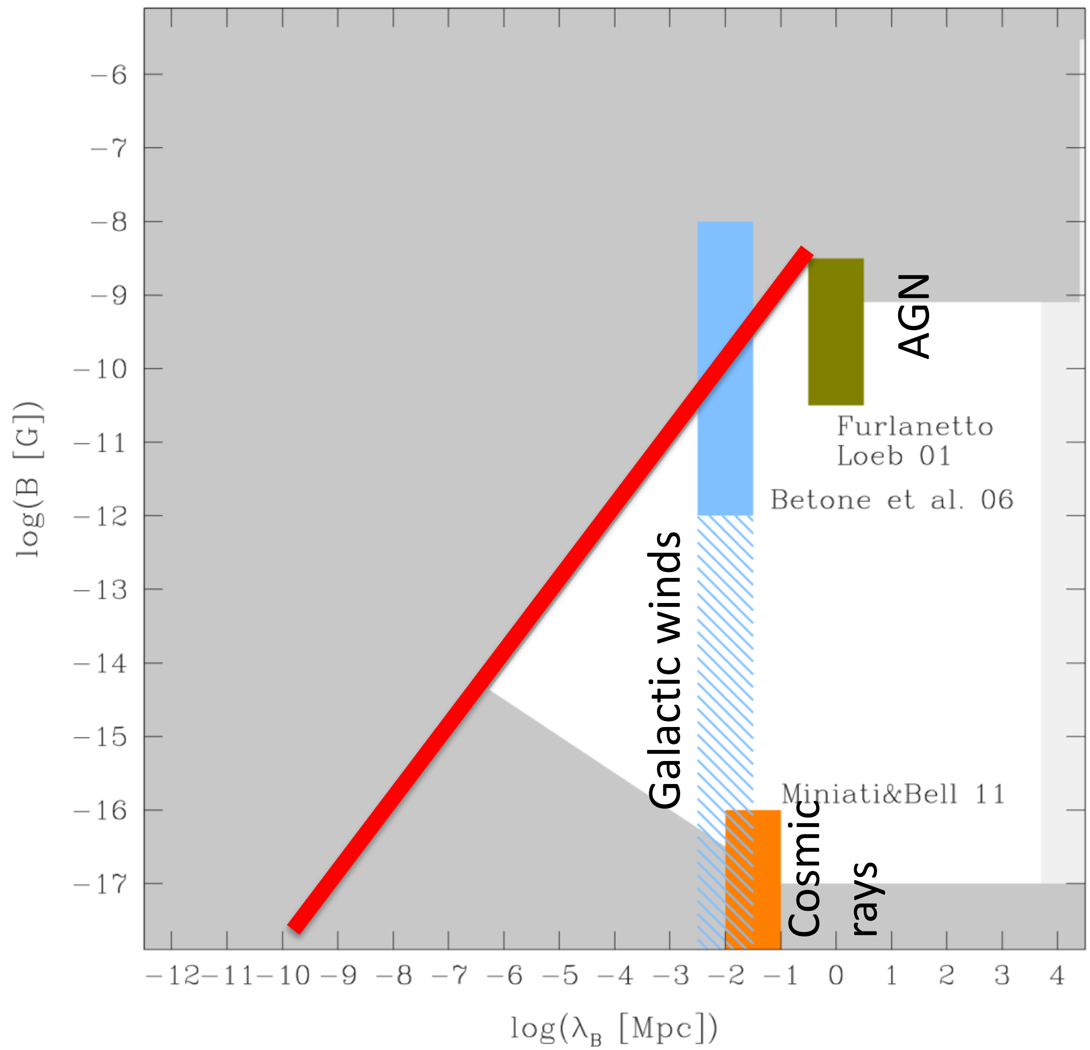
$$l \sim v t_{rec} \sim \sqrt{\frac{r_B}{r} t_{rec}} \sim 1\left[\frac{B}{10^{-8}\ \mathrm{G}}\right] \mathrm{Mpc}$$

Jedamzik & Sigl '12, Kahniashvili et al '13, Durrer & AN '13, …

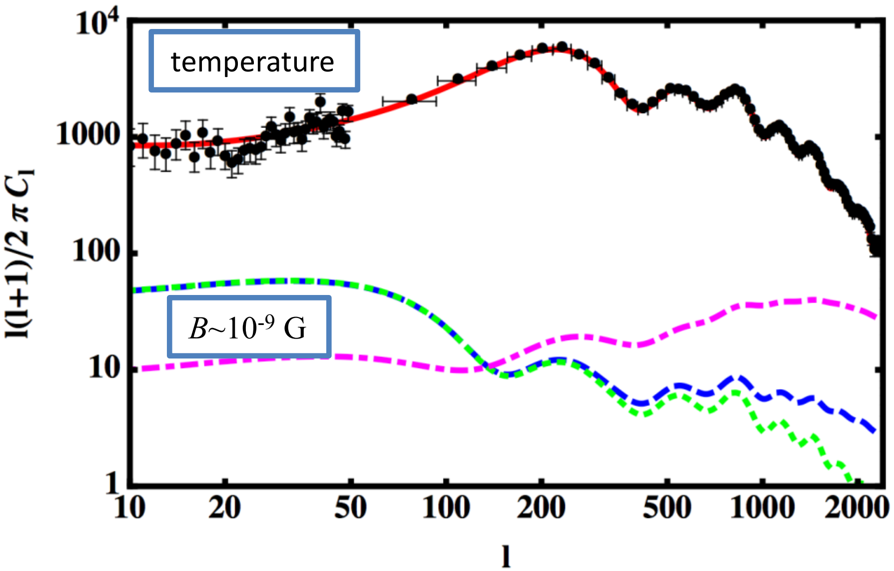
Observability of cosmological MF

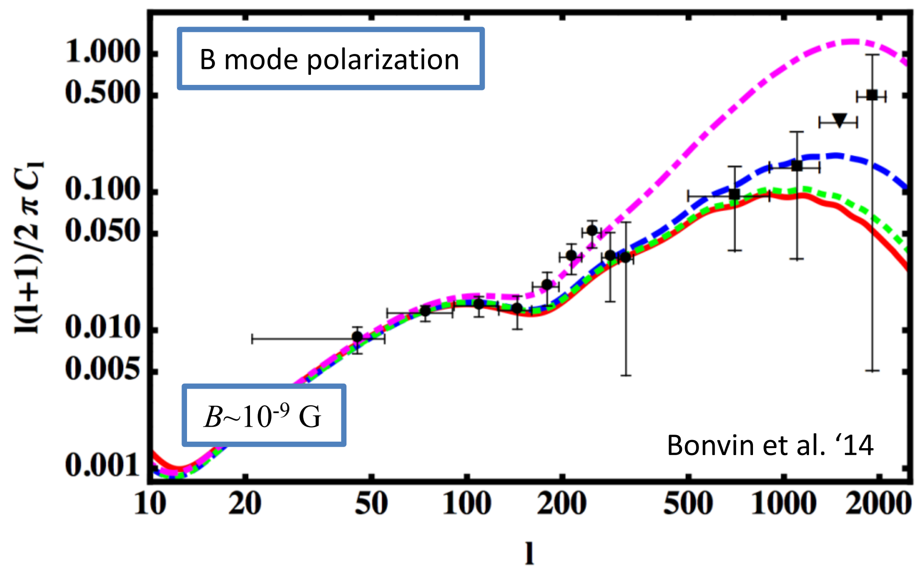
Cosmological magnetic fields are characterized by a well-defined observational signature: a relation between the strength and correlation length.

If relic field survive till today, the only place where they could be found in their original form is intergalactic medium (IGM).



Effects of magnetic field on CMB





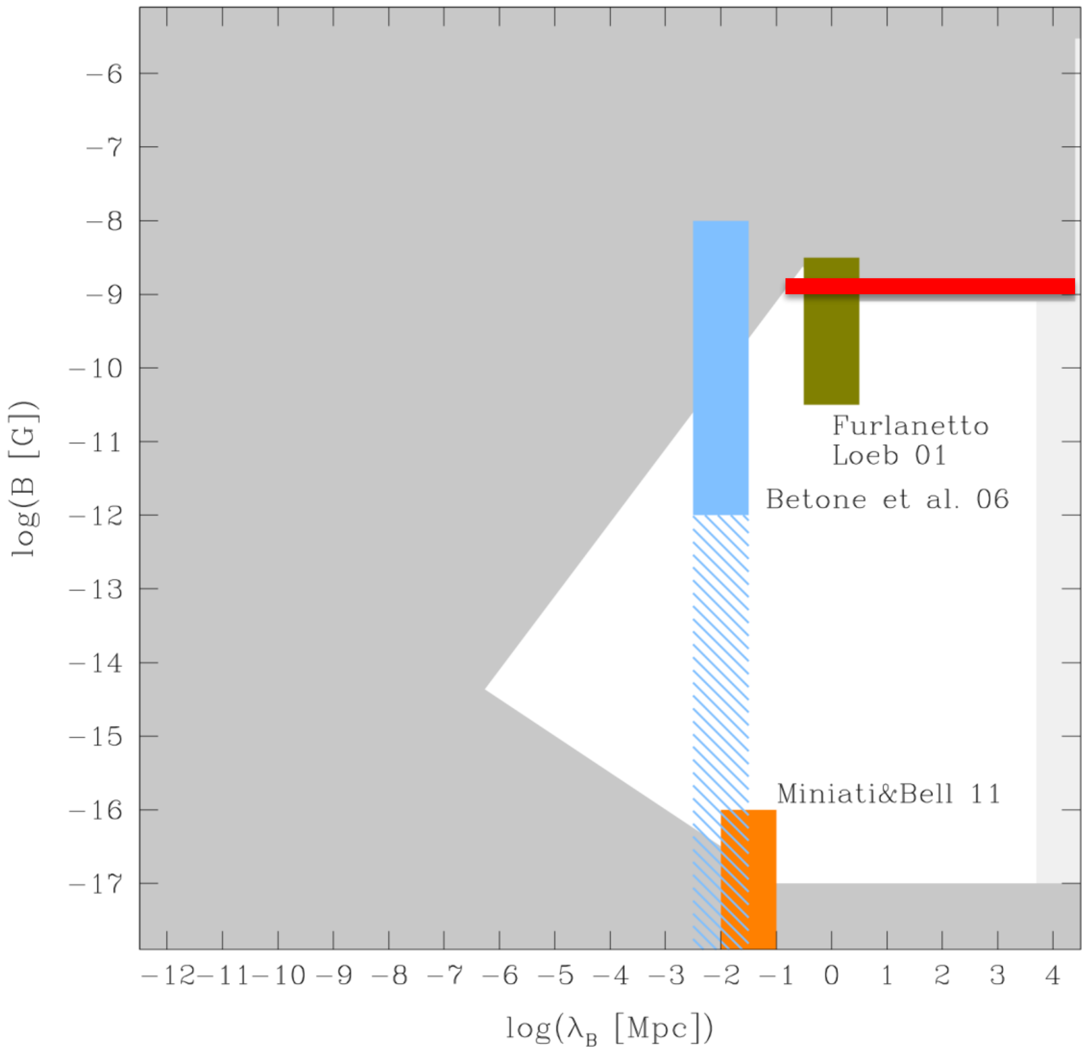
Presence of magnetic field affects CMB anisotropies and polarization in multiple ways: generation of vector and tensor perturbations, generation of magnetosonic waves, Faraday rotation of polarization, …

Magnetic field does not dominate the structure of CMB anisotropies: $\rho_B < 10^{-6} \rho_{cr} \sim (3\times10^{-9}\text{ G})^2/8\pi$

Spectrum B polarization due to vector (dashed) and tensor (solid) modes generated by magnetic field with nearly scale-invariant spectrum n_s=-2.9 and strength $B=3\times10^{-9}$ G (Lewis '04), compared to the B-mode polarization spectrum measured by BICEP2.

* Somewhat stronger bound on B might arise from the non-gaussianity constraints.

Barrow et al '97, Seshadri & Subramanian '01, Lewis '04, Kahniashvili & Ratra '07, Durrer '07, Shaw & Lewis '10, '12, …



Furlanetto
Loeb 01
Betone et al. 06
Miniati&Bell 11
log(B [G])
log(λ_B [Mpc])

Faraday rotation of signal from distant quasars

Polarization angle of electromagnetic wave Propagating though magnetized plasma rotates by an angle

$$\Psi = RM\,\lambda^2, \quad RM = \frac{e^3}{2\pi m_e^2}\int_{los}\frac{n_e B_\parallel}{(1+z)^2}dx$$

Knowing the distribution of electrons in the intergalactic medium (?) and measuring the RM one could measure $B_\parallel$. The total RM is

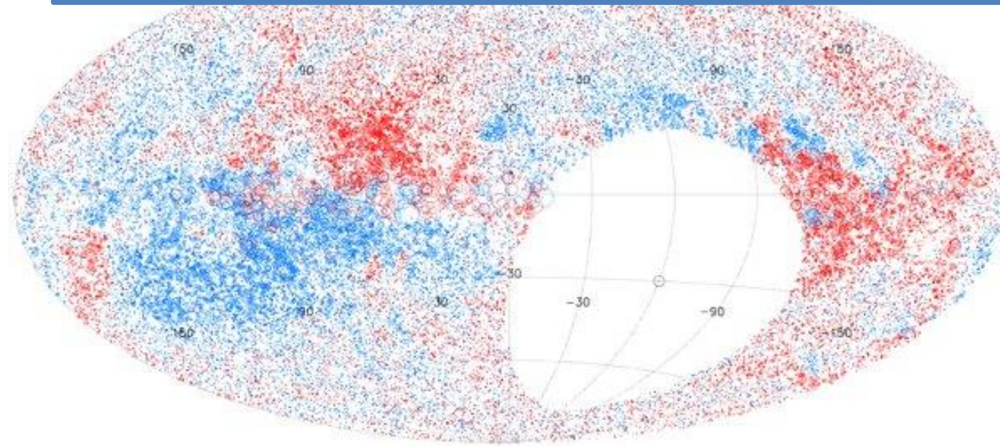
$$RM = RM_{Galactic} + RM_{IGM} + RM_{source}$$

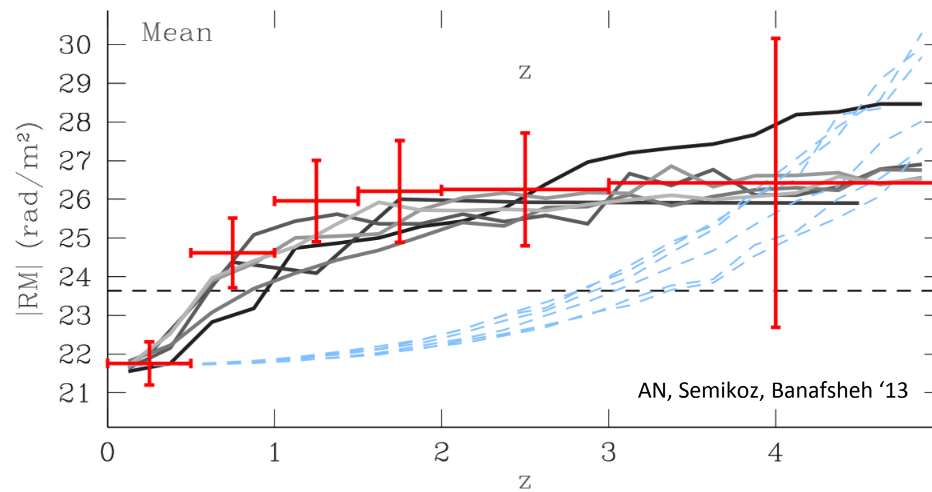
RM from the intergalactic medium is expected to depend on the distance to the source, i.e. to scale with the redshift z.

Such z dependence is detected at 3σ level in the largest RM data set from the NVSS sky survey and in other data sets.

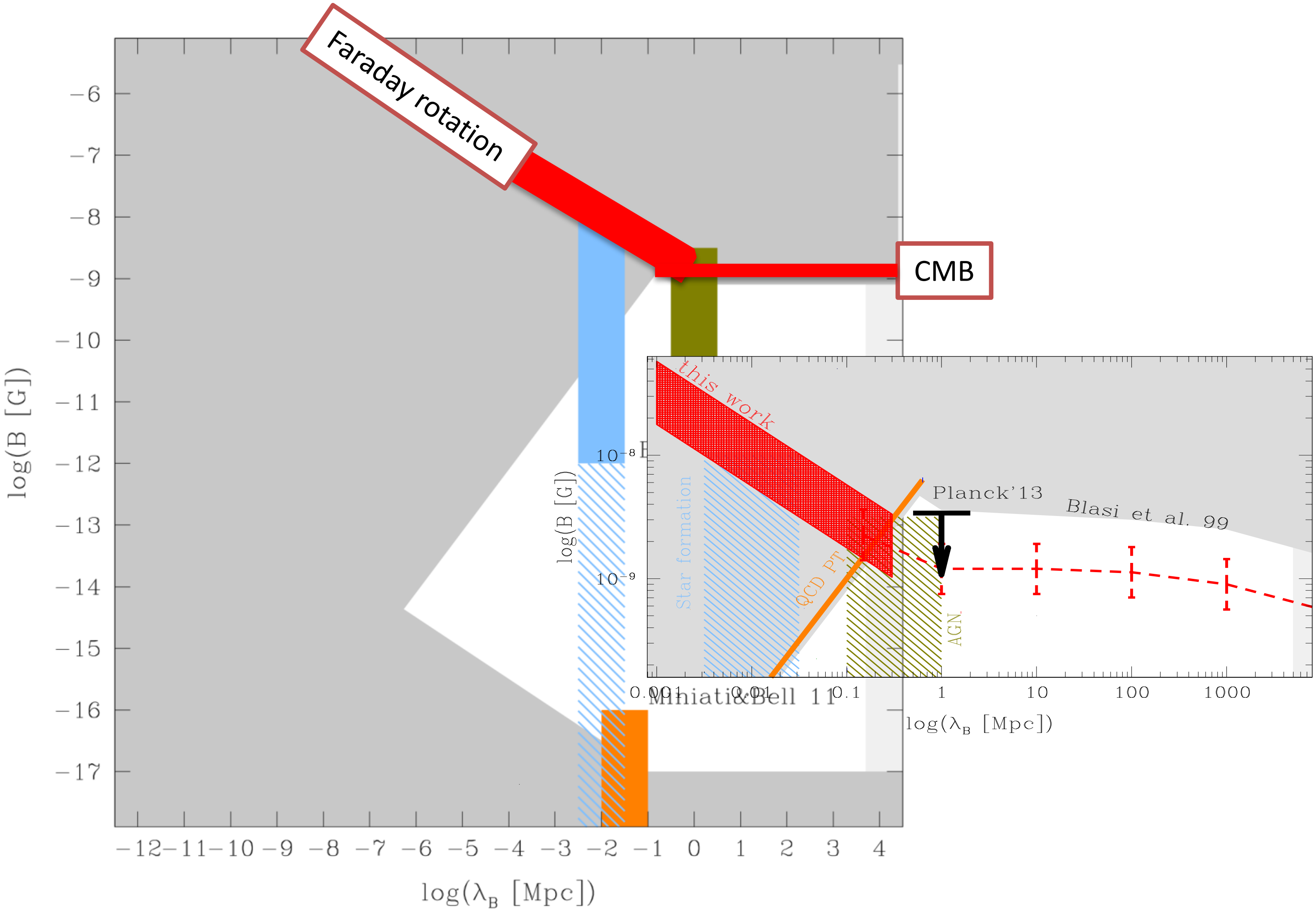
It is not clear if the effect is due to cosmological fields. Alternative interpretations are e.g. fields at the far outskirts of galaxies.

37000 RM measurements from NVSS survey, Taylor et al. '09





Kronberg & Perry '84, Kronberg '94, Blasi et al. '99, Bernet et al., '10, …


Faraday rotation
CMB
log(B [G])
log(λB [Mpc])
this work
Star formation
QCD PT
AGN
Planck'13
Blasi et al. 99
Mhiati&Bell 11

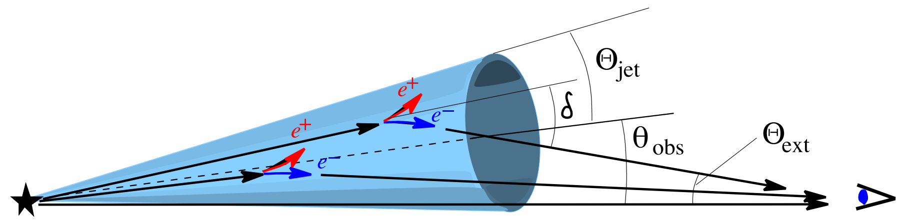
Lower bound from gamma-ray observations

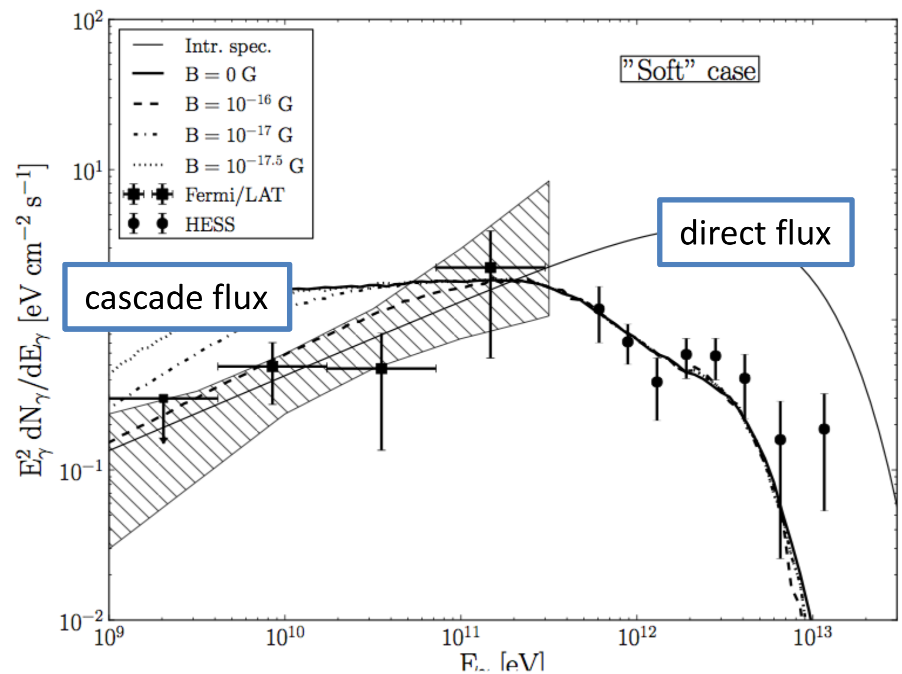
High-energy gamma-rays from distant sources interact in the intergalactic medium producing electron positron pairs. These pairs loose energy on secondary "cascade" gamma-ray emission, after being deviated by the intergalactic magnetic field.

Measurement of the spectral and timing characteristics of the secondary cascade emission provides information on intergalactic magnetic field strength.

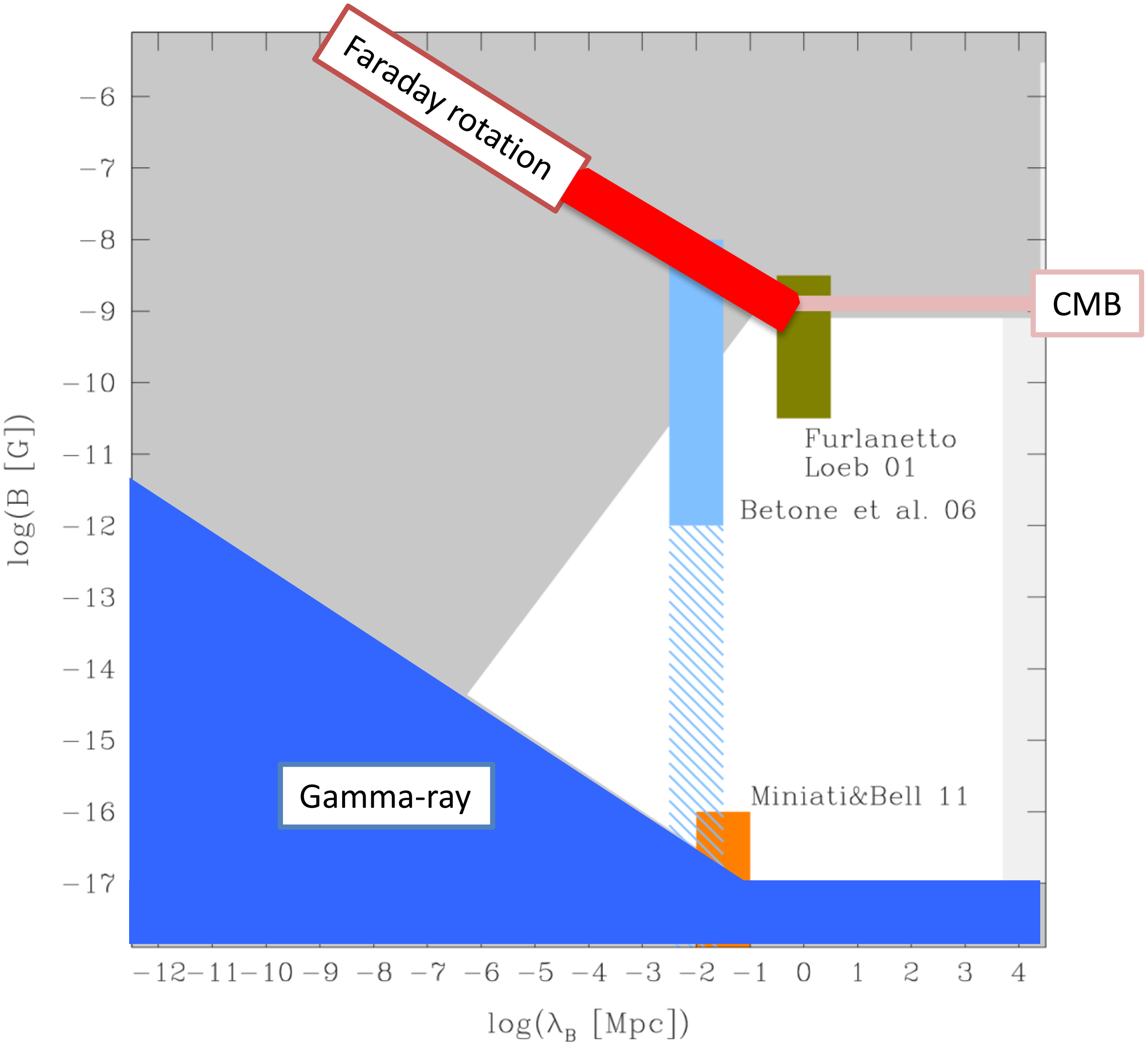
Non-observation of the cascade emission in the GeV band initiated by the pair production by TeV gamma-rays imposes a lower bound on the intergalactic magnetic field at the level of 10^{-17} G.

Stronger magnetic fields (up to 10^{-12} G) could be probed by future observations of cascade emission at higher energies and / or from more distant sources by Cherenkov Telescope Array (CTA).





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



Faraday rotation
CMB
Furlanetto
Loeb 01
Betone et al. 06
Miniati&Bell 11
Gamma-ray
log(B [G])
log(λ_B [Mpc])
−6
−7
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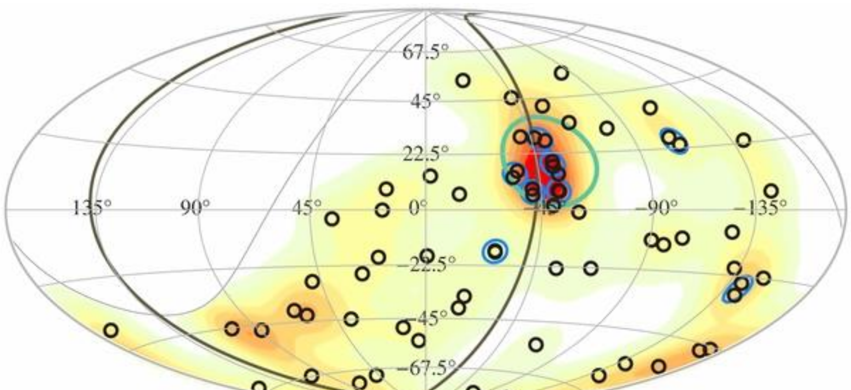
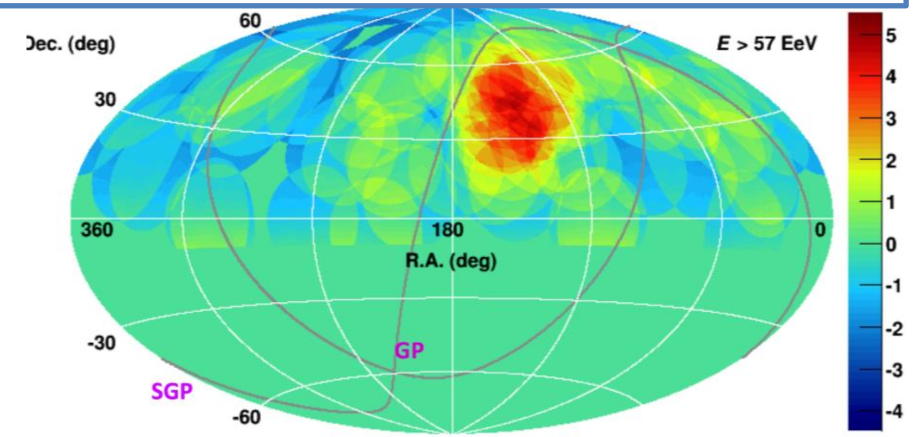
−12 −11 −10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4

Deflections of UHECR



Pierre Auger Observatory
"hot spot" at 20° angular scale in the direction around Centaurus A, Abraham et al. '08

Telescope Array "hot spot" at 20° angular scale, Fukushima et al. '13

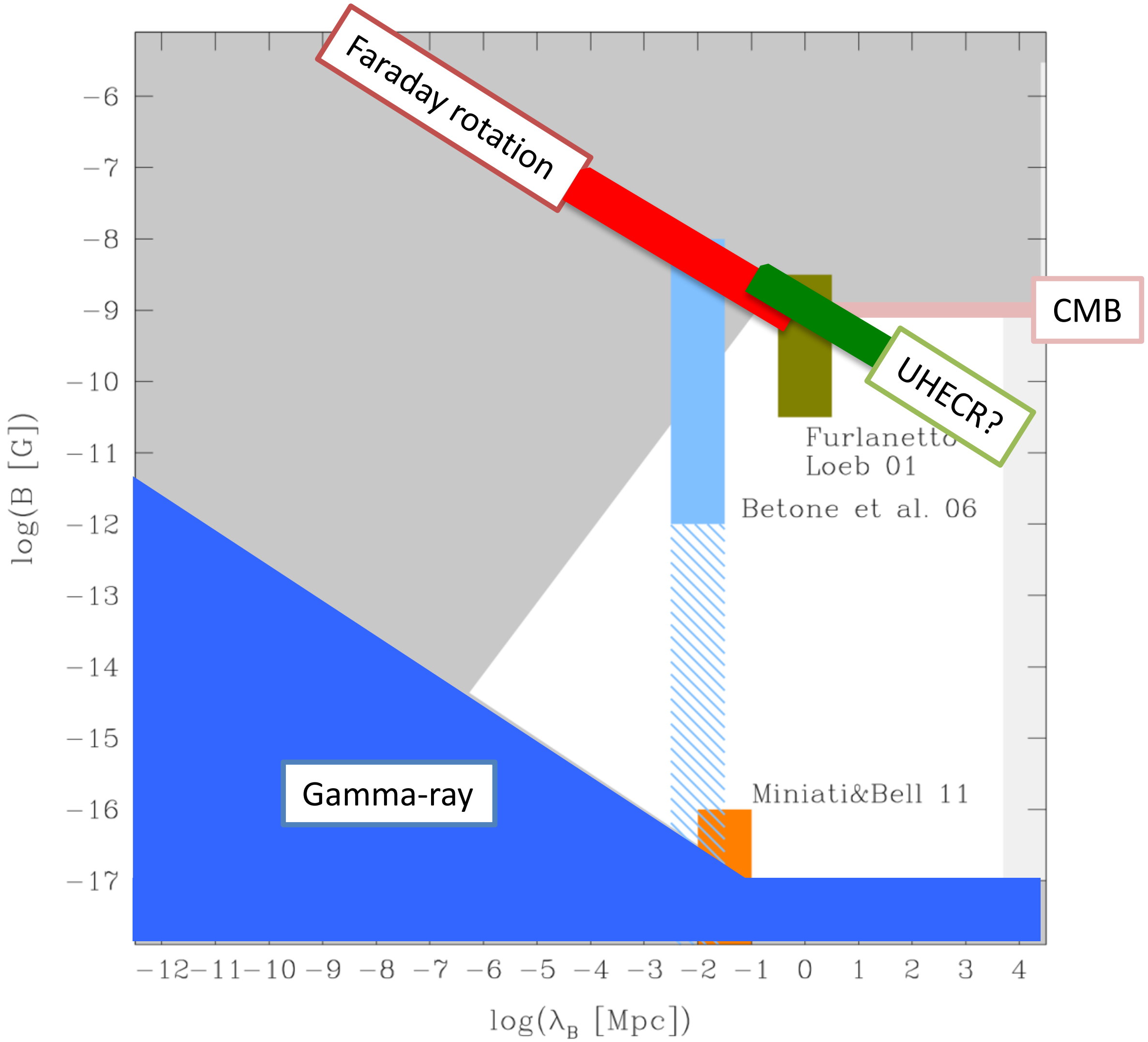


Trajectories of charged Ultra-High-Energy Cosmic Ray particles (UHECR) are deflected by Galactic and intergalactic magnetic fields. The deflection angle by intergalactic magnetic field with strength B and correlation length λ is

$$\theta = \frac{ZeB\sqrt{D\lambda}}{E_{UHECR}} \simeq 4^{o} Z \left[\frac{E_{UHECR}}{10^{20}\ \mathrm{eV}}\right]^{-1} \left[\frac{B}{10^{-9}\ \mathrm{G}}\right] \left[\frac{D}{50\ \mathrm{Mpc}}\right]^{1/2} \left[\frac{\lambda}{1\ \mathrm{Mpc}}\right]^{1/2}$$

Strong intergalactic magnetic field broadens angular distribution of UHECR around the direction of the source.

Measurement of the energy-dependent angular spread of UHECR around the source would provide a measurement of intergalactic magnetic field.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Gamma-ray
log(B [G])
−6
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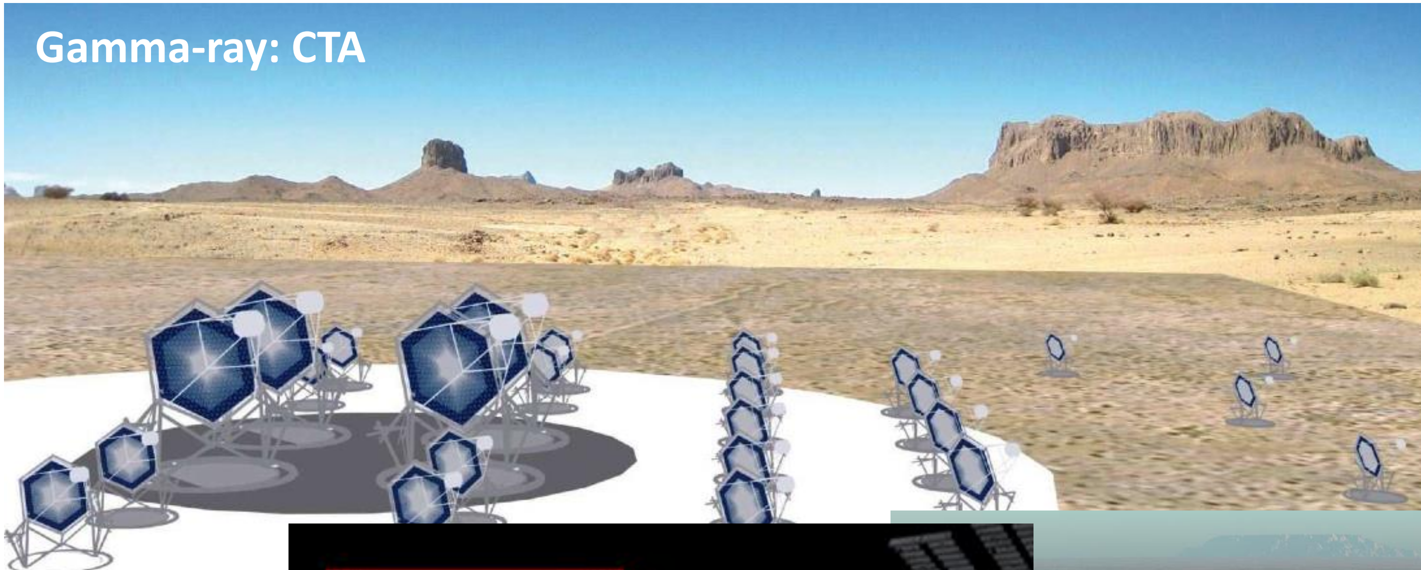
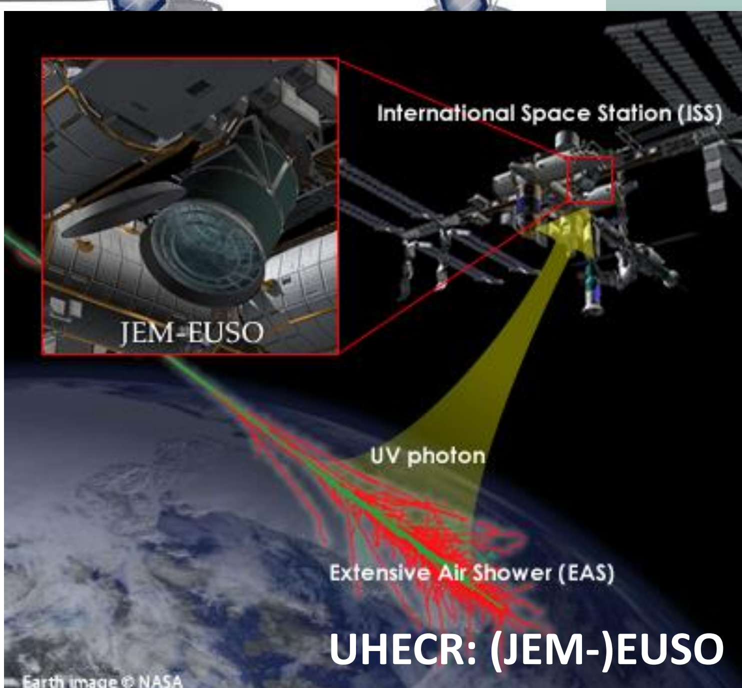
−12 −11 −10 −9 −8 −7 −6 −5 −4 −3 −2 −1 0 1 2 3 4
log(λ_B [Mpc])

Prospects for improvement of bounds / measurements





Summary

Cosmological magnetic fields could be generated at the epoch of Inflation or during Electroweak and QCD phase transitions

Their power is initially concentrated at short distance scales (except possibly for Inflationary field).

Subsequent co-evolution with plasma (development of turbulence, damped evolution) leads to the increase of the correlation length and to the decrease of the field strength. The field parameters follow an "evolutionary track" on the B-λ parameter plane.

The end-point of evolution is a line $B \approx 10^{-8} (\lambda / 1 \text{ Mpc})$ G.

Cosmological magnetic fields are detectable via their imprint on CMB ($z=10^3$) or via their effects in the present day Universe ($z=0$): Faraday rotation, UHECR deflections, effect on gamma-ray cascades.