

The Trouble with Cosmological Magnetic Fields

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- 2 Effects of magnetic fields on the CMB
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- **Estimates by equi-partition** (e.g. of magnetic field and thermal or turbulent energy).

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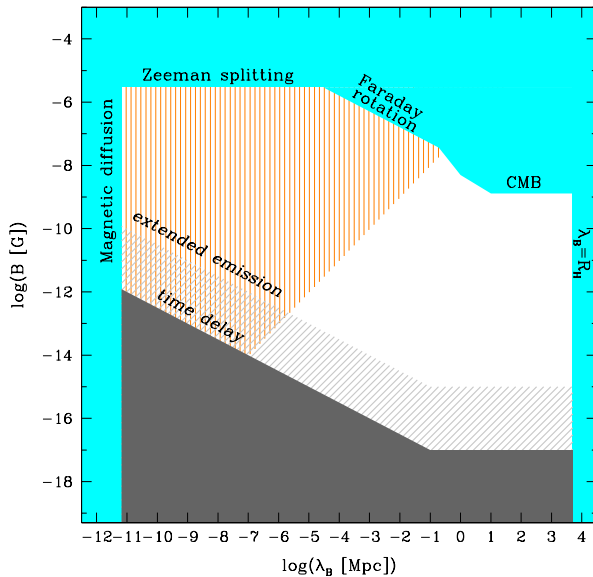
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- **Intergalactic space, voids:** The fact that certain blazars do emit TeV γ -radiation but not GeV, means that lower energy electrons which are produced by scattering with intergalactic background light and which then generate a cascade of GeV photons by inverse Compton scattering must be deflected out of the beam. This requires intergalactic fields of $B \gtrsim 10^{-15} \text{Gauss}$ (direct) to $B \gtrsim 10^{-17} \text{Gauss}$ (delayed) with coherence scales of 1Mpc (Neronov & Vovk, 2010, Taylor, Vovk & Neronov, 2011).



from Taylor, Vovk
& Neronov 2011

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In this talk I concentrate on the possibilities to generate **primordial magnetic fields** and on their limitations.

- **Second order perturbations:** To generate magnetic fields in the cosmic fluid one needs vorticity and a charge and current density. The first can be obtained only in **second order perturbation theory** (first order vector perturbations decay) and the second only in **second order in the tight coupling** limit. Estimates have shown that typical fields on cluster scales are of the order of 10^{-28} Gauss ([Matarrese et al. '04](#), [Ichiki et al. '07](#), [Fenu et al. '10](#)). This is far too small to be consistent with the Neronov-Vovk bound or with the minimal amplitude needed for dynamo amplification.

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- **Phase transitions:** First order phase transitions are violent events which proceed via bubble nucleation. Charge separation and turbulent fluid motion can lead to the generation of magnetic fields ([Vachaspati '91](#), [Joyce & Shaposhnikov '97](#), [Ahonen & Enqvist '98](#)).

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- **Inflation:** The electromagnetic field is conformally coupled to gravity and is therefore usually not generated during inflation. However, if conformal symmetry is explicitly broken, or if the electromagnetic field is coupled to the inflaton, it can also be generated during inflation ([Turner & Widrow '88](#), [Ratra '92](#), [Anber & Sorbo '06](#), [RD, Hollenstein & Jain '10](#)).

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In the remainder of this talk I restrict to the 2nd and 3rd possibility.

Effects of magnetic fields on the CMB: A constant magnetic field

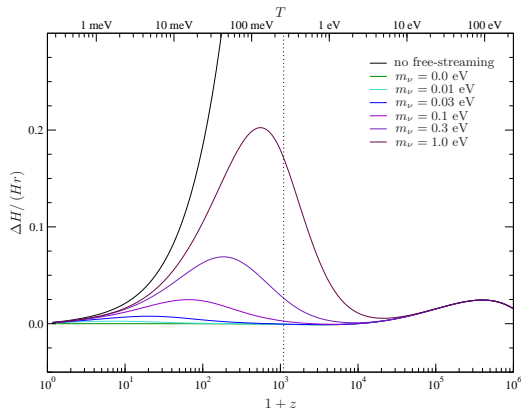
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From [Adamek, RD, Fenu & Vonlanthen, '11](#)

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Since a constant magnetic field breaks parity, its Faraday rotation leads to parity odd correlations between B-polarization and temperature anisotropies (and E- and B-polarization) in the CMB (Scannapieco & Ferreira, '97). This leads to limits of the order of $B < 10^{-8} \text{ Gauss}$.

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CMB limits on magnetic fields are (almost) all of this order. This is not surprising since

$$\Omega_B = 10^{-5} \Omega_\gamma \left(\frac{B}{10^{-8} \text{Gauss}} \right)^2$$

Magnetic fields of the order $3 \times 10^{-9} \text{Gauss}$ (on CMB scales) will leave 10% effects on the CMB anisotropies while 10^{-9}Gauss will leave 1% effects. It is thus clear that we can never detect magnetic fields of the order of 10^{-16}Gauss in the CMB.

Magnetic fields effect the CMB via

- their energy-momentum tensor which leads to metric perturbations \Rightarrow perturbed photon geodesics
- magnetosonic waves affect the acoustic peaks in the CMB spectrum
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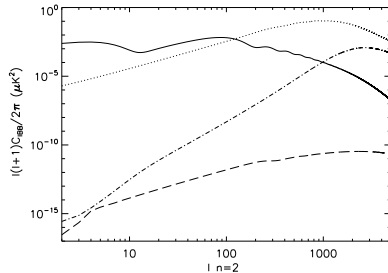
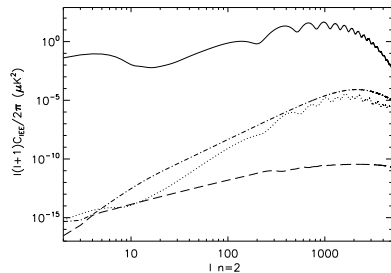
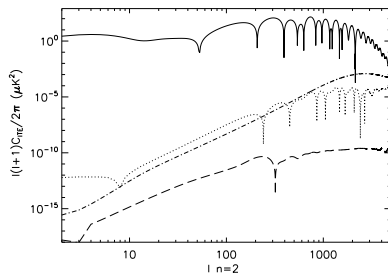
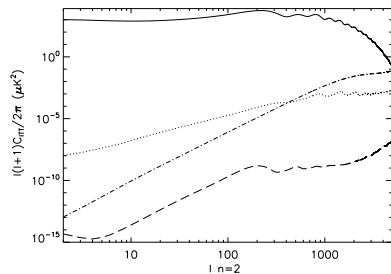
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Caveat: During recombination small scale (kpc) magnetic fields may induce large fluctuations in the baryon density and modify the recombination history \Rightarrow modify the CMB peaks. Planck may detect magnetic fields as small as **$B \sim 10^{-11}$ Gauss** by this imprint! ([Abel & Jedamzek '11](#))

Other effects on the CMB



(from: Paoletti, Finelli & Paci '08)

The spectrum of causally generated magnetic fields

We assume that the process leading to a magnetic field is statistically homogeneous and isotropic. A magnetic field spectrum generated by such a process is of the form

$$\langle B_i(\mathbf{k}) B_j^*(\eta, \mathbf{q}) \rangle = \frac{(2\pi)^3}{2} \delta(\mathbf{k} - \mathbf{q}) \left\{ (\delta_{ij} - \hat{k}_i \hat{k}_j) P_S(k) - i \epsilon_{ijn} \hat{k}_n P_A(k) \right\}$$

The Dirac- δ is due to statistical homogeneity and the requirement $\nabla \cdot \mathbf{B} = 0$ dictates the tensor structure. Note that the pre-factor of P_S is even under parity while the one of P_A is odd under parity.

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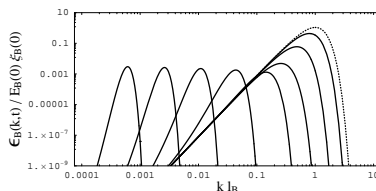
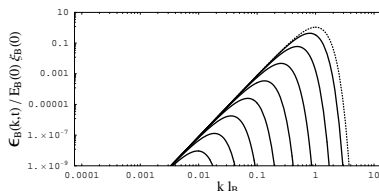
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On small scales the magnetic field is damped by the viscosity of the cosmic plasma, $P_S = P_A = 0$ for $k > k_d(t)$. Here $k_d(t)$ is a time-dependent damping scale.

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However, if the field is helical, **helicity conservation leads to an inverse cascade** which moves the correlation scale to larger and larger scales (numerical simulations by [Banerjee & Jedamzik '04](#), [Campanelli, '07](#))



Campanelli, 2007

If the magnetic field is generated during a phase transition, its **correlation length is finite**. It is typically of the size of the largest bubbles when they coalesce and the phase transition terminates. This is a fraction of the Hubble scale at the transition. On scales larger than the Hubble scale, correlations vanish by causality.

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For the energy density per log-k-interval this implies

$$\frac{d\rho_B}{d\log(k)} \propto k^5$$

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But a closer look at their paper yields that they assume an input k^3 spectrum for the turbulent velocity field and that the magnetic field evolves towards equi-partition with the kinetic energy.

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Hence the question is still open...

Limits on magnetic fields from phase transitions

As we now show this already implies very stringent limits on magnetic fields from phase transitions. Be $\epsilon = \Omega_B^*/\Omega_r^*$ the ratio of the magnetic field to the radiation energy density at the moment of formation and k_* the cutoff scale. Since radiation and magnetic fields scale the same way, at later times and scales larger than the cutoff, the magnetic field to radiation density is given by

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$$\left(\frac{B(k_1)}{10^{-6}\text{Gauss}} \right)^2 \simeq \Omega_r^{-1} \frac{d\Omega_B}{d\log(k_1)} < \epsilon \times 10^{-46}$$

Requiring $\epsilon < 1$ this implies $B(k_1) < 10^{-29}\text{Gauss}$. Using slightly more model dependent but also more realistic numbers (e.g. $k_* \simeq 100\mathcal{H}_*$ one arrives at $B(k_1) < 10^{-31}\text{Gauss}$.

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The limits from the **QCD phase transition** are somewhat less stringent but still discouraging, $B(k_1) < 10^{-28}\text{Gauss}$.

If the magnetic field is helical, the inverse cascade which moves power from small to larger scales can help. But a detailed calculation ([Caprini, RD, Fenu, '09](#)) shows

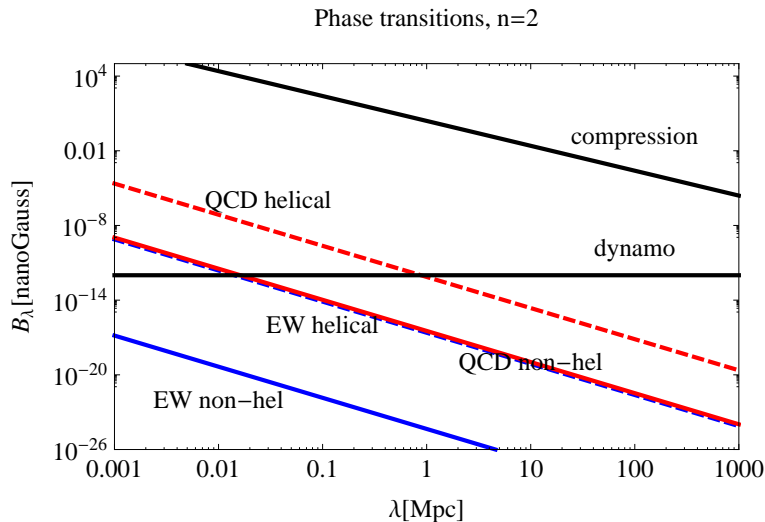
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and

$B(k_1) < 10^{-21}$ Gauss for the QCD transition. This result could be marginally sufficient dynamo amplification, but is still several orders of magnitude below the Neronov-Vovk-bound.



(from: [Caprini 2011](#))

Magnetic fields from inflation

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Let us discuss a simple case where we couple the inflation to the electromagnetic field.

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This is a wave equation with a time-dependent mass term. We know how to calculate the generation of its modes out of the vacuum. This case has been discussed for the first time in ([Ratra '92](#)).

Magnetic fields from inflation: example

For example if $f \propto a^\gamma$ is a simple power law, we can compute the resulting **magnetic fields spectrum** to

$$P_S \propto k^n \quad \text{with} \quad n = \begin{cases} 1 + 2\gamma & \text{if } \gamma \leq 1/2 \\ 3 - 2\gamma & \text{if } \gamma > 1/2 \end{cases}$$

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During inflation we cannot assume that the Universe is highly conducting and the electric field is damped. We therefore also have to compute the **electric field spectrum**. One finds ([Martin & Yokoyama '08](#), [Subramanian '10](#))

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Since there is no infrared cutoff, the spectral index should not be less than -3 otherwise $\frac{d\rho_B}{d\log(k)} \propto k^3 P_S \propto k^{3+n}$ or $\frac{d\rho_E}{d\log(k)} \propto k^3 P_E \propto k^{3+m}$ diverges. This limits $-2 \lesssim \gamma \lesssim 2$.

$\gamma \simeq -2$ gives a scale invariant spectrum for the magnetic field!

If the spectrum of magnetic fields from inflation is blue, the fact that they should not dominate the energy density of the Universe leads to very stringent constraints on small scales. Since the Hubble scale at the end of inflation is so small, the spectrum needs not be very blue for this to happen.

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Hence during inflation the electron charge was much larger than 1. In this regime we cannot trust perturbation theory and our calculation does actually not apply...

([Demozzi et al. '09](#)).

This problem can probably be avoided by modifying not only electrodynamics but also the Dirac equation. But there is worse...

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- However, we have found (Bonvin, Caprini & RD, in prep.) that for all 'reasonable' matching conditions from inflation to the radiation era, a part of this term $\Psi_{\text{inhom}} \propto \Pi_B/k^2$ leaks into the constant mode $\Psi_0 = \alpha \Pi_B(k, t_r)/k^2 + \beta \Psi_1(k) = \text{constant}$.

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- During the radiation phase, H decreases, very rapidly $\frac{\text{Weyl}}{\text{Ricci}}$ becomes of order unity and perturbation theory breaks down.
- Hence the formation of such magnetic fields is in contradiction with the homogeneity and isotropy of the Universe!

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- **Inverse cascade of helical magnetic fields** can mitigate this problem but seems not quite sufficient to solve it.
- ~~Magnetic fields from inflation~~ can have many different spectra. They can actually be scale invariant leading to sufficient fields on large scales, but in this case, they generate perturbation of the metric which become very large in the subsequent radiation era, destroying the homogeneity and isotropy of the Universe.

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