CMB constraints on Cosmic Magnetic fields

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Outline

Introduction: Cosmology is a search for relics

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- or the electroweak transition at $t \simeq 10^{-10}$ sec which may have led to the observed baryon asymmetry in the Universe.
- It has been proposed that confinement and, especially the electroweak phase transition but also inflation might generate primordial magnetic fields which represent seeds for the magnetic fields observed in galaxies and clusters.

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- Estimates by equi-partition (e.g. of magnetic field and thermal or turbulent energy).

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- Intergalactic space, voids: The fact that certain blazars do emit TeV γ-radiation but not GeV, means that electrons which are produced by scattering of the TeV γ rays with extragalactic background light and which then generate a cascade of GeV photons by inverse Compton scattering with the CMB must be deflected out of the beam. This requires intergalactic fields of $B \gtrsim 3 \times 10^{-16}$Gauss with coherence scales of 1Mpc (Neronov & Vovk, 2010, Tavecchio et al. 2010, Dolag et al. 2010).

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To generate the galactic fields of μGauss amplitude simply by flux conservation during the formation of the galaxy, primordial fields of about 10^{-9}Gauss would be needed.

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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). Also this leads to limits of the order of $B < 10^{-8}$Gauss. (see Tina's talk)

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It is not surprising that all these limits are comparable, since

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

Magnetic fields of the order 3×10^{-9}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^{-15} or even 10^{-20}Gauss (on galactic scales) in the CMB.

A constant magnetic field in the presence of a relativistic free streaming component

- If a free streaming component of relativistic particles is present, its evolution in a Bianchi I Universe will also develop an anisotropic stress which (to 1st order) exactly cancels the one from the magnetic field and isotropizes the Universe (Adamek, RD, Fenu, Vonlanthen, in prep.).

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- However, if there would be a sufficiently energetic GW background, $\Omega_{gw} \gtrsim 0.1\Omega_\gamma$, this would isotropize the Universe entirely and remove the quadrupole anisotropy.
- This does not modify Faraday rotation.

Effects on the CMB from a stochastic magnetic field

A stochastic magnetic field is described by a spectrum of the form

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

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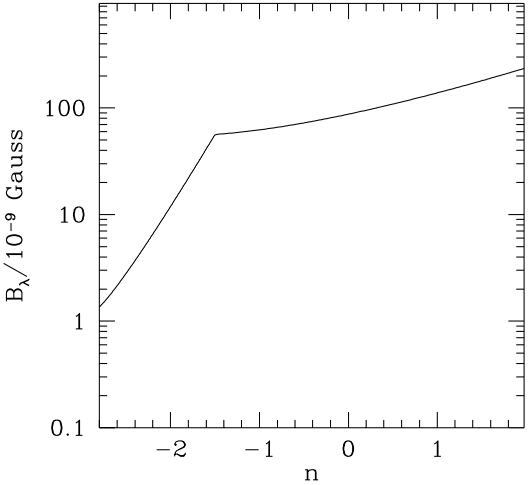
All these lead to magnetic field limits on the order of 10^{-9}Gauss on CMB scales. Depending on the spectral index this leads to different limits on galactic scales $\lambda \sim 0.1$Mpc.



(from: RD, Ferreira & Kahniashvili '98)

Tensor type CMB anisotropies from a magnetic field with spectral index n.

Effects from a stochastic magnetic field

- In the presence of a stochastic magnetic field the 'Bardeen equation' for scalar perturbations is modified:

$$\ddot{\Phi} + 3\mathcal{H}(1+c_s^2)\dot{\Phi} + [3(c_s^2 - w)\mathcal{H}^2 + c_s^2 k^2]\Phi = 3w\frac{\mathcal{H}^2}{k^2}\left[\frac{k^2}{2}\Gamma + \mathcal{H}\dot{\Pi} - \frac{k^2}{3}\Pi \right.$$
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- Assume Δ_B compensated. After ν-decoupling the magnetic anisotropic stress is compensated by the one from the neutrinos (passive mode),

$$\zeta \approx \zeta(\tau_B) - \frac{1}{3}R_\gamma \Pi_B \left[\log\left(\tau_\nu/\tau_B\right) + \left(\frac{5}{8R_\nu} - 1\right)\right],$$

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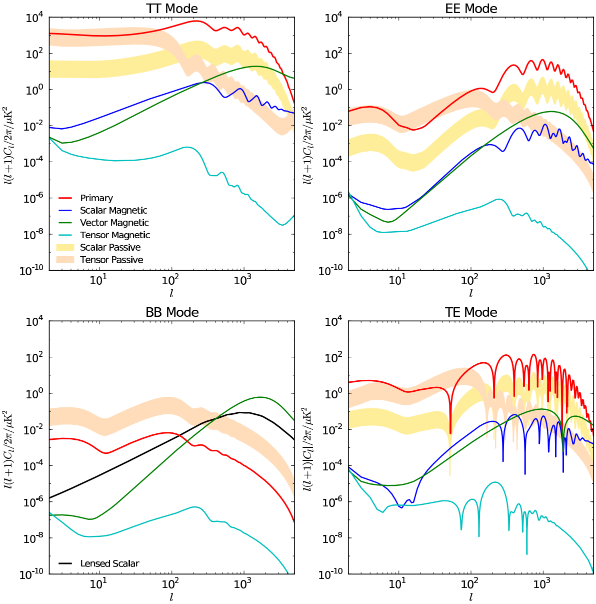
- Vector perturbations: $k\left(\dot{\sigma}^{(1)} + 2\mathcal{H}\sigma^{(1)}\right) = 3\mathcal{H}^2 w\Pi^{(1)}$.
- Tensor perturbations: $\ddot{H}^{(2)} + 2\mathcal{H}\dot{H}^{(2)} + k^2 H^{(2)} = 3\mathcal{H}^2 w\Pi^{(2)}$.
  Passive mode, after neutrino decoupling.

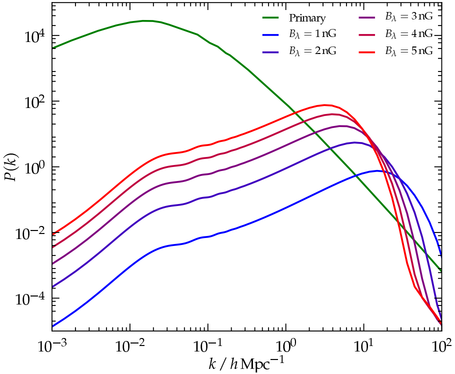
$$H^{(2)} \approx R_\gamma \Pi_B^{(2)}\left[\log(\tau_\nu/\tau_B) + \left(\frac{5}{8R_\nu} - 1\right)\right]$$

Effects from a stochastic magnetic field

Full (tensor + vector + scalar) CMB anisotropies from a magnetic field with spectral index $n = -2.9$, $B_\lambda = 4.7 \times 10^{-9}$Gauss, $\lambda = 1$Mpc, $\sum m_\nu = 0.47$eV.
(from: Shaw & Lewis '09)



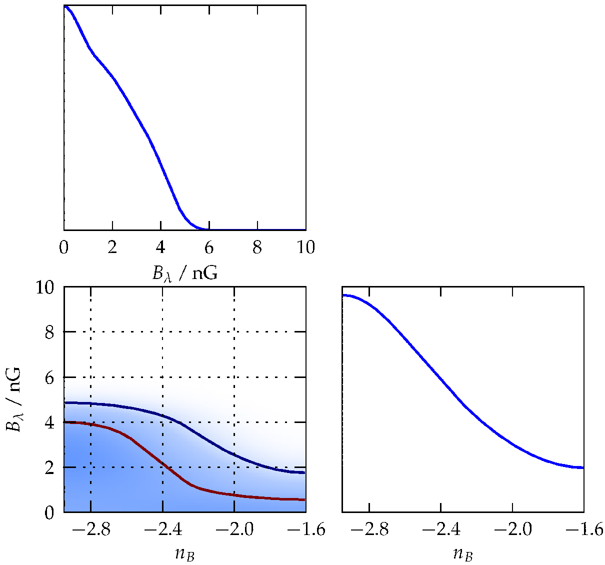
On small scales, $\lambda \lesssim v_A \lambda_{\rm Silk}$, magnetic fields are damped via Alfvèn wave damping. This energy is transferred into the baryon-electron plasma.



(from: Shaw & Lewis ’10)

Effects from a stochastic magnetic field

Likelihoods for B and n from CMB anisotropies and SZ observations.
(from: Shaw & Lewis '10)



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- A full calculation of the induced non-Gaussanity is very involved, but several partial attempts to compute the bi-spectrum on large scales (compensated mode, Seshadri et al., 2009; Caprini et al. 2009; passive scalar mode, Trivedi et al. 2010; vector mode, Kahniashvili et al. 2010) have been made.

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- A full calculation of the induced non-Gaussanity is very involved, but several partial attempts to compute the bi-spectrum on large scales (compensated mode, Seshadri et al., 2009; Caprini et al. 2009; passive scalar mode, Trivedi et al. 2010; vector mode, Kahniashvili et al. 2010) have been made.
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- If Planck reaches $f_{NL} \sim 1$ this will produce a limit of $100^{1/6} \simeq 2$ times better on B ($B^{m_1 m_2 m_3}_{\ell_1 \ell_2 \ell_2} \propto B^6$).

What can we learn about magnetic fields from CMB observations?

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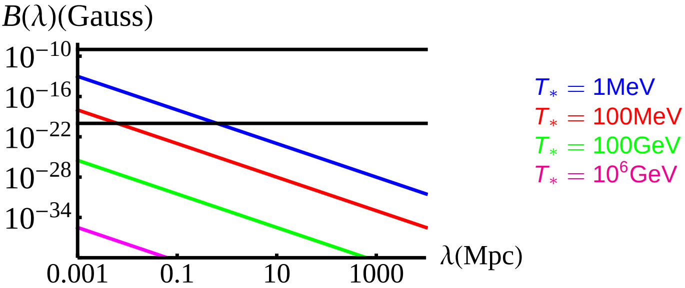
- If the magnetic field is produced after inflation (causally) it has a spectral index $n = 2$, so that $\rho_B(\lambda) \propto \lambda^{-(n+3)} \propto \lambda^{-5}$.
- In this case the simple requirement that the magnetic energy density may not overclose the Universe already gives stringent constraints on large scales:

$$B(\lambda) < 10^{-33}\mathrm{Gauss}\left(\frac{\mathrm{Mpc}}{\lambda}\right)^{5/2}\left(\frac{100\mathrm{GeV}}{T_*}\right)^{5/2} .$$



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- Causal spectra from the early Universe, $T_* > 1$MeV, are too blue to leave an imprint on the CMB and also too blue to provide the needed intergalactic magnetic fields, $B(\lambda) > 10^{-15}$Gauss, $\lambda \gtrsim 0.1$Mpc.

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- CMB anisotropies constrain only close to scale invariant spectra to $B \lesssim$ a few $\times 10^{-9}$Gauss
- SZ constraints, coming from smaller scales fare somewhat better.

Conclusions

- Magnetic fields are observed on all cosmological scales (galaxies, clusters, filaments and probably even voids) with significant amplitudes. Intergalactic fields with coherence length of about 1Mpc and amplitudes of 10^{-20}Gauss (for dynamo amplification) or even 3×10^{-16}Gauss (Neronov-Vovk-bound) are required.

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- Fields from phase transition are too blue, they do not have enough power on large scales.

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- But all these effects are probably undetectable if $B \ll 10^{-9}$Gauss.
- So the CMB might not be the best tool to constrain primordial magnetic fields?