# Primordial magnetic fields: Origin, evolution and signatures

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# Summary

- **The universe is magnetized.**
- **Early Universe Generation**
- **Evolution: Helical fields**
- **Magnetic signals in the CMB**
- **Primordial fields and early structure formation**

A. Brandenburg & K. Subramanian, Physics Reports, 417, 1-205 (2005)
K. Subramanian, “Magnetizing the Universe”, PoS proceedings, arXiv:0802.2804
K. Subramanian, Magneic fields in the early universe, AN, 2010, 331, 110

# *The magnetic Universe*

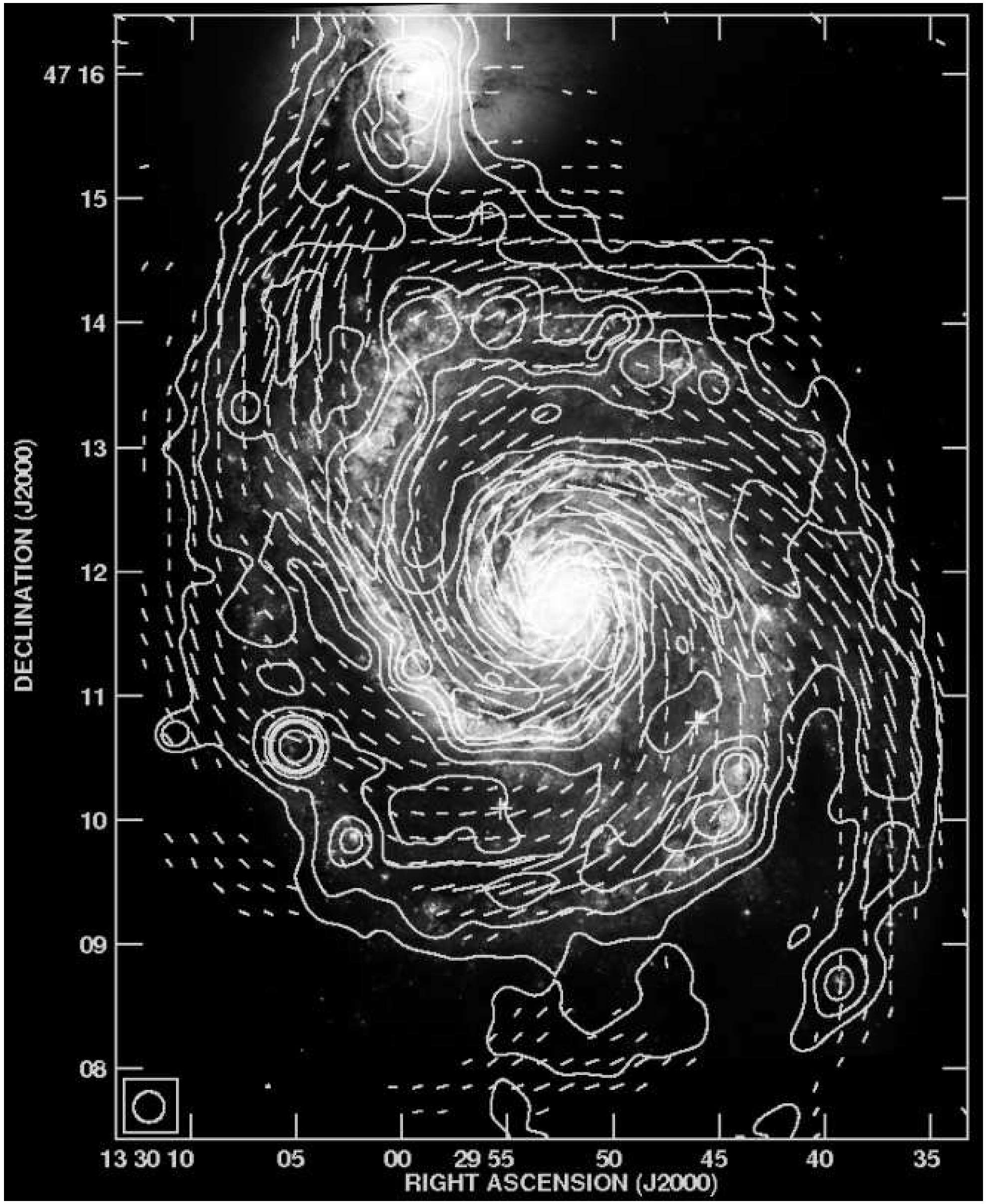
**The universe is Magnetized:**

- **Sun (1 - $10^3$ gauss; 11 yr Solar cycle)**
- **Cosmic fields from synchrotron polarization and Faraday Rotation**
- **Galaxies: $B \sim 10\mu G$, ordered on 10 kpc scales + random component**
- **Clusters of Galaxies: few $\mu G$ strengths on $\sim 10$ kpc scales**
- **Equally strong $B$ in Young $z \sim 1 - 2$ galaxies (Bernet et al. 2008)**
- **Even in the IGM voids? ($B \geq 3 \times 10^{-16}$ Gauss; Mpc scales)**
  (Neronov and Vovk, 2010; ... BUT SEE Broderick et al., 2011)

**How do such large scale fields arise?**

**How can One Constrain/Detect Primordial B fields?**

# Galactic Magnetic Fields: Observations




- Synchrotron polarization and Faraday rotation probe B fields.
- M51 at 6 cm (Fletcher and Beck)
- Few $\mu$G mean Fields coherent on 10 kpc scales
- Correlated with optical spiral
- How do such large scale galactic fields arise?

# Origin: Primordial?

- Primordial magnetic fields: Origin in an early universe phase transition: Inflation (Turner and Widrow, 1988), Electroweak, QCD.
  - Provide Seed for dynamo? Help induce coherence?
  - Inflation: Strength? EW/QCD transitions: Scale?
- Detecting relic B fields can probe early universe physics?
- Flux freezing: On large scales $B(t)a^2(t) =$ constant, So $B(z) = B_0(1+z)^2$
- $\rho_B = \rho_\gamma$ (due to CMB) implies $B_0 \sim 3\mu$G.
- $B_0 \sim 10^{-9}G$ on galactic scales, interesting for Galaxy formation $+$ galaxy/cluster $B$?
- Current upper limits of sub nanoGauss strength from limits of CMB nongaussianity (TRS,KS, PRL, 2009, Trivedi, TRS, KS, PRL, 2012; 2014)

# *Primordial fields versus Dynamos?*

**Dynamos required to maintain even primordial seed fields?**

# Primordial fields origin during Inflation?

- **Rapid expansion $\rightarrow$ vacuum fluctuations amplified and stretched to long wavelength "classical" fluctuations**
- **Negligible charge density breaks flux freezing.**
- **BUT Need to break conformal invariance of ED (Couple to inflaton $\phi$, higer dimensional scale factor $b(t)$, curvature $R$, axion $\theta$ ...)**

$$S = \int \sqrt{-g}\, d^4x\, [-f^2(\phi, R, b)\frac{1}{16\pi} F_{\mu\nu}F^{\mu\nu} - RA^2 + g\theta F_{\mu\nu}\tilde{F}^{\mu\nu}\,]$$

- **EM wave amplified from vacuum fluctuations**
- **After reheating $\mathbf{E}$ shorted out and $\mathbf{B}$ frozen in.**

$$(d\rho_B/d\ln k) = \left(C(\gamma)/2\pi^2\right) H^4(-k\eta)^{4+2\gamma} \approx (9/4\pi^2)H^4 \quad (\text{for } \gamma = -2)$$

$$B_0 \sim 5 \times 10^{-10}\mathrm{G}\left(\frac{H}{10^{-4}M_{pl}}\right)$$

- **Exponentially sensitive to parameters, as need $B \sim 1/a^{\epsilon}$ Need huge growth of 'charge': a Problem?** (Demozzi et al, 2009)

# Extra dimensional magnetogenesis

- **EM theory with Gauss-Bonnet gravity (Kumar Atmjeet, Isha Pahwa, TRS, KS, PRD, 2014):**

$$S = -\frac{1}{16\pi}\int \sqrt{-\tilde{g}}\, d^{4+D}x\, \tilde{F}_{\mu\nu}\tilde{F}^{\mu\nu} = -\frac{1}{16\pi}\int \sqrt{-g}\, d^4x \left(\frac{b(t)}{b_0}\right)^D F^{\mu\nu}F_{\mu\nu}$$

- $A_i = (\Omega_D b_0^D)^{1/2}\tilde{A}_i$, **Fix gauge:** $A_0(t,\mathbf{x}) = 0$ **and** $\partial_j A^j(t,\mathbf{x}) = 0$
- **To quantize, expand in terms of creation/anhilation operators**

$$A_i(\eta,\mathbf{x}) =$$

$$\int \frac{\mathrm{d}^3k}{(2\pi)^{3/2}}\sum_{\lambda=1}^{2}\epsilon_{i\lambda}(\mathbf{k})\left[b_\lambda(\mathbf{k})A(\eta,k)\mathrm{e}^{i\mathbf{k}\cdot\mathbf{x}} + b_\lambda^\dagger(\mathbf{k})A^*(\eta,k)\mathrm{e}^{-i\mathbf{k}\cdot\mathbf{x}}\right],$$

- **Large class of solutions with** $a(t)\propto e^{\alpha t}$, $b(t)\propto e^{\beta t}$
- **Define** $\mathcal{A}(\eta,k)\equiv a(\eta)(b(\eta)/b_0)^{D/2}A(\eta,k)$ **(**$d\eta = dt/a(t)$**)**

$$\mathcal{A}''(k,\eta) + \left[k^2 - \frac{\xi(\xi-1)}{\eta^2}\right]\mathcal{A}(k,\eta) = 0; \qquad \xi = \frac{D}{2}\left(\frac{-\beta}{\alpha}\right)$$

- **For** $D=4$, $\alpha=\beta$, $\gamma=\xi=-2\rightarrow$ **Scale invaraint spectrum.**
- **Need mechanism for freezing** $b(t)$ **evolution**

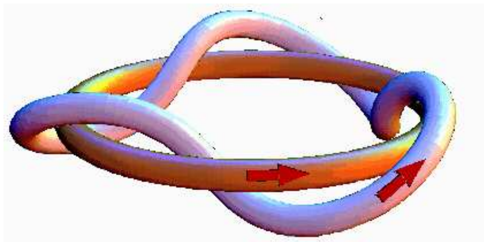
# From Electroweak/QCD Phase transition?

- **Correlation scale usually tiny: $H^{-1} \sim 1$ cm (EW) or $\sim 10^4$ cm QCD phase transition or comoving $R_H \sim 100\mathrm{AU}/0.1$ pc**
  Generates decaying MHD turbulence increasing coherence scale.

- **Unless Helicity generation/Conservation leads to Inverse Cascade** (Brandenburg et al, PRD 96, Banerjee & Jedamzik, 2004)

- **Magnetic Helicity** $H = \int_V \mathbf{A} \cdot \mathbf{B}\, dV$, $\nabla \times \mathbf{A} = \mathbf{B}$
  $\mathbf{A}$ **is vector potential**, $V$ **is closed volume**

- **Measures links and twists in** $\mathbf{B}$



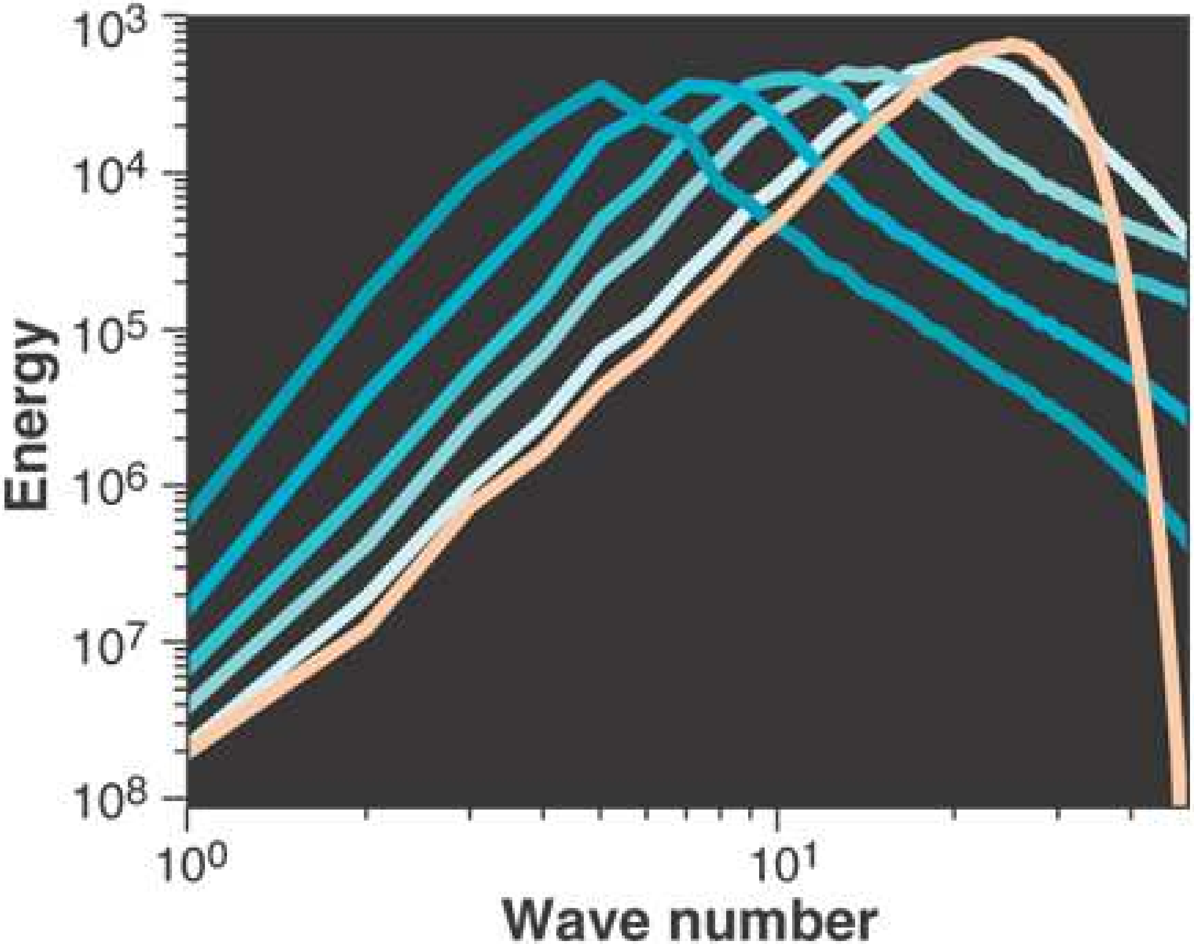
- **Helicity is nearly conserved even when energy dissipated**

- **Helicity generation during EW baryogenesis:** $H/V \sim n_b/\alpha$!
  (Vachaspati, 2001; Copi et al 2008; Diaz-Gil et al, 2008)

- $B \sim 5 \times 10^{-12}(L/1\mathrm{kpc})$! (BJ,05): L quite uncertain.

# *Inverse cascade of helical B*

(Christensson, Hindmarsch, Brandenburg, 2001; Brandenburg 2001)

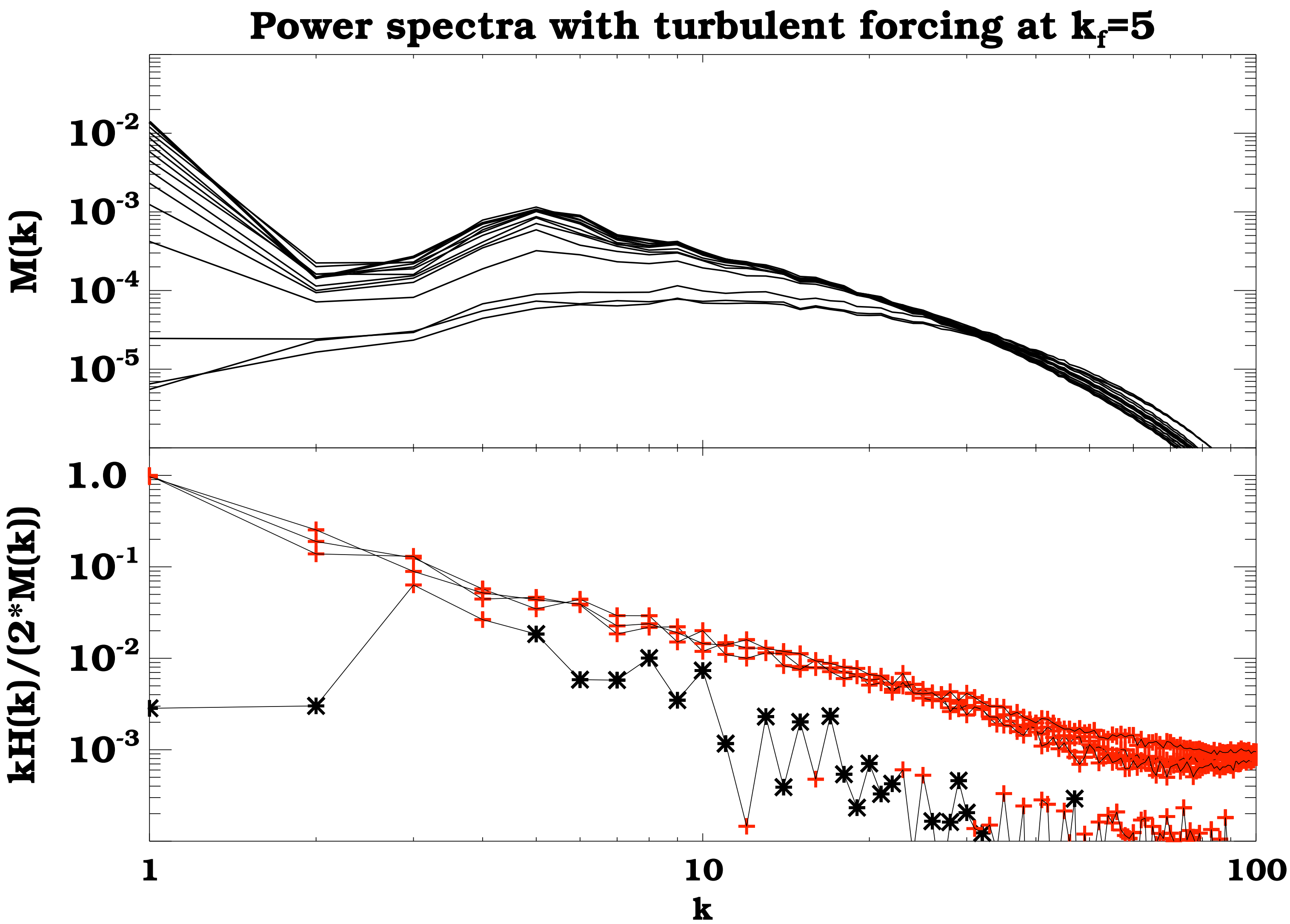



- **Assuming helicity conservation,** $H \sim LB^2 \sim LE \sim$ **constant.**
- **so** $dE/dt \sim E/(L/v) \sim E^{5/2}/H \rightarrow L \propto B^{-2} \propto t^{2/3}$ (Sim. $L \propto t^{1/2}$).

# Helical B resilient to turbulent diffusion

**Even sub equipartition Helical fields decay on slow resistive rate**

**(EB,KS, 2013; Pallavi Bhat, EB, KS, MNRAS, 2014)**



# Probing Early Universe B

- $B^2/(8\pi\rho_{rad}) \sim 10^{-7} B^2_{-9}$. Here $B_{-9} = B_0/(10^{-9}G)$
- Magnetic stress $\Rightarrow$ metric perturbations, including Grav. Waves
- Lorentz force $\mathbf{J} \times \mathbf{B}/c \Rightarrow$ almost incompressible motions
- Overdamped by radiative viscosity, unlike compressible modes. (Jedamzik et al, 1998; KS, JDB 1998)
- Survives damping for $L_A > (V_A/c)L_{Silk} \ll L_{Silk}$
- **CMB signals from metric and velocity perturbations**
- **Post recombination:** $n_{rad}/n_b \gg 1 \Rightarrow$ **compressible motions** $\Rightarrow$ **seeds** $\delta\rho/\rho \Rightarrow$ **First Structures**
- **B field Dissipation** $\rightarrow$ **Ionization, Heating, Molecules**

**Coherent primordial nG fields potentially detectable**

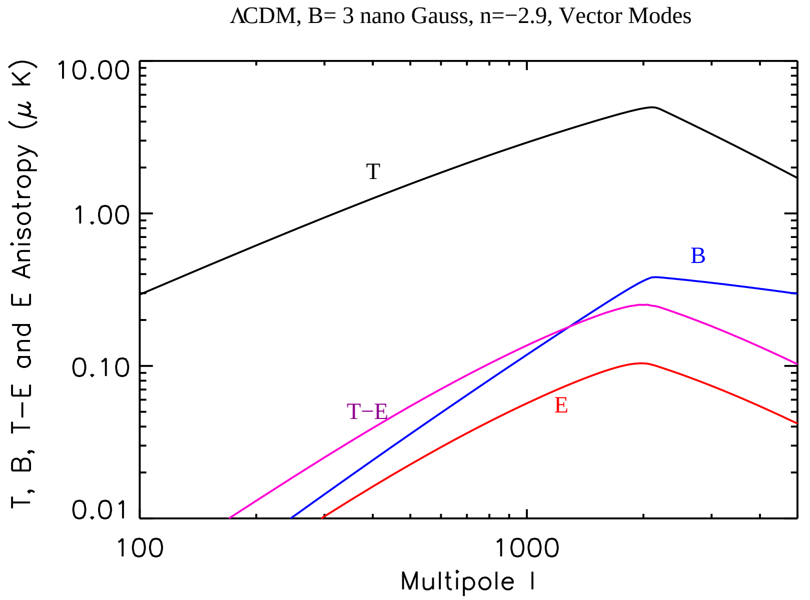
# CMB signals from tangled B fields

- **Scalar Modes – Subdominant to Inflation generated signal,** (Shaw/Lewis, Giovannini/Kunze, Yamazaki et al., Finelli et al. Bonvin et al.)
- **Vortical motion of fluid at LSS (Vector modes)** (KS & Barrow 1998, KS, Seshadri, Barrow 2003)
- **Tensors – Significant at** $l < 100$, (Durrer, Ferreira, Kahniashvilli, 2000 ..)
- **Polarization – B (Curl) modes due to Vectors/Tensors – Scalars only induce E (Gradient) modes** (Seshadri & KS, 2001; Mack et al 2002; Lewis 2004; Gopal & Sethi, 2005 )
- **Faraday Rotaion – Converts E to B mode signals**
- **Helical fields can also cause** $T - B$, $E - B$ **cross correlations!**
- **Non Gaussian Statistics** (Seshadri, KS 2009, Caprini et al 2009, Trivedi, KS, TRS, 2010, 2012,2014 ..)

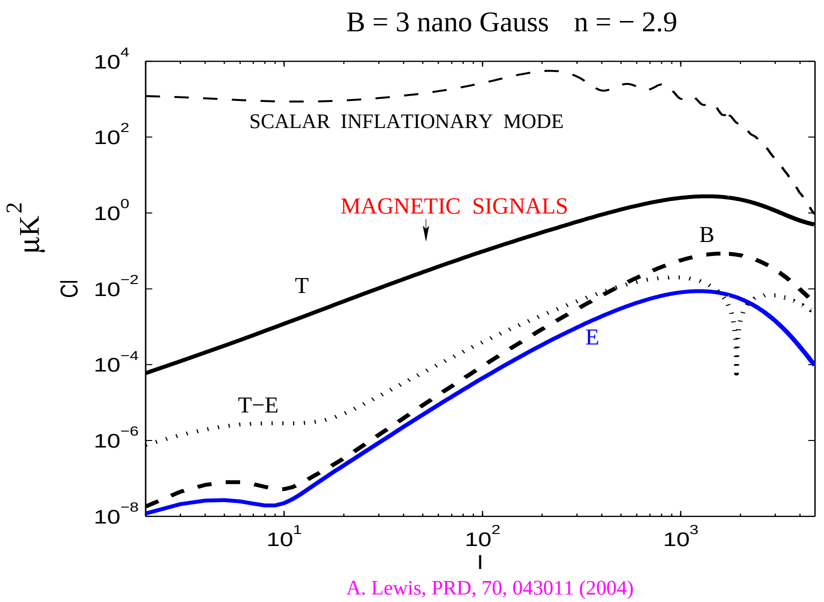
**Primordial few nG magnetic fields potentially detectable using the CMB**

# Vector Mode anisotropies

- Semianalytics by
  KS, JDB, PRL 1998
  TRS, KS, PRL 2001
  KS, TRS, JDB, 2003

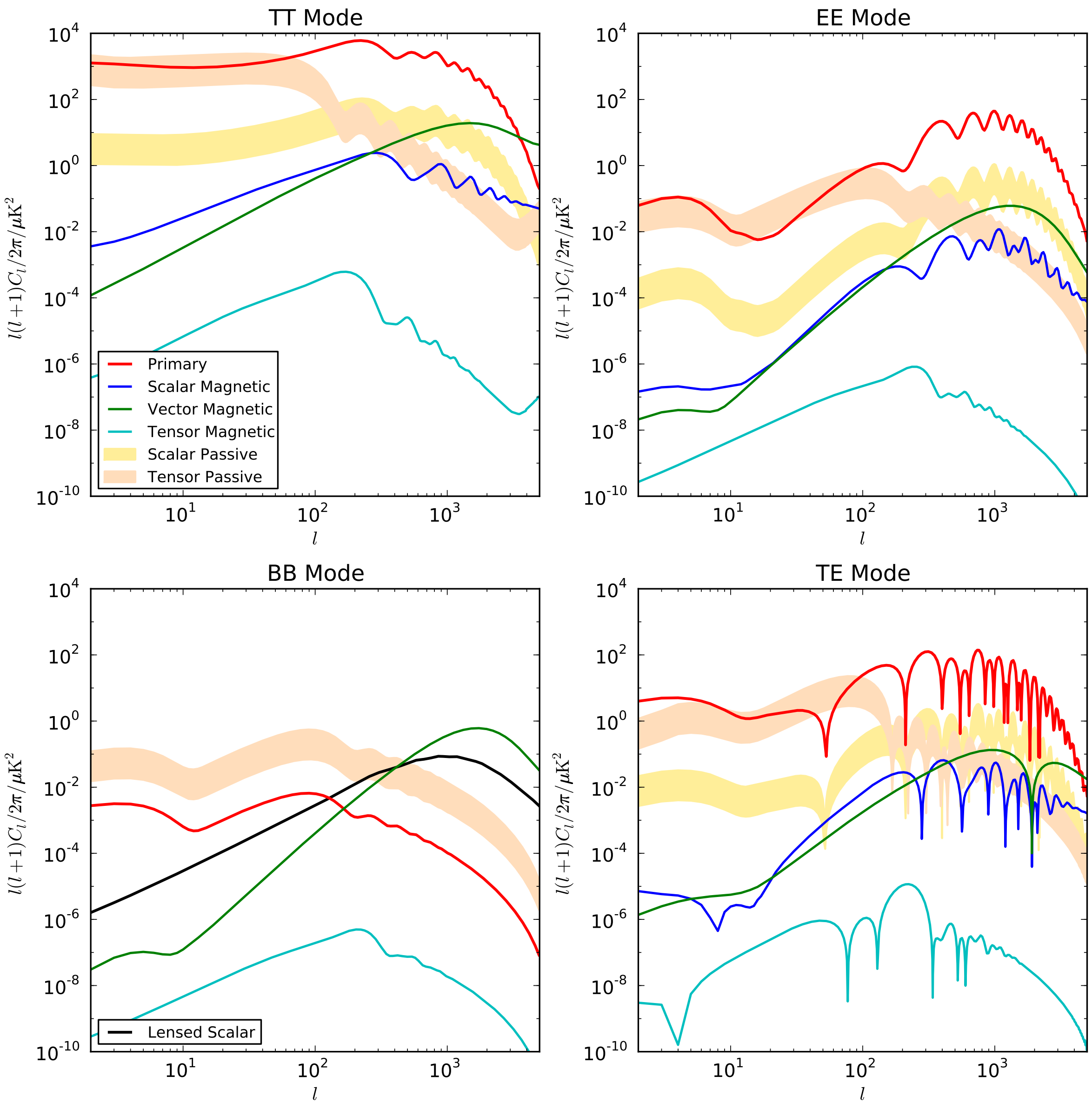



- CAMB code, Lewis, PRD 2004



# CMB signals: scalar+Tensor + Vector

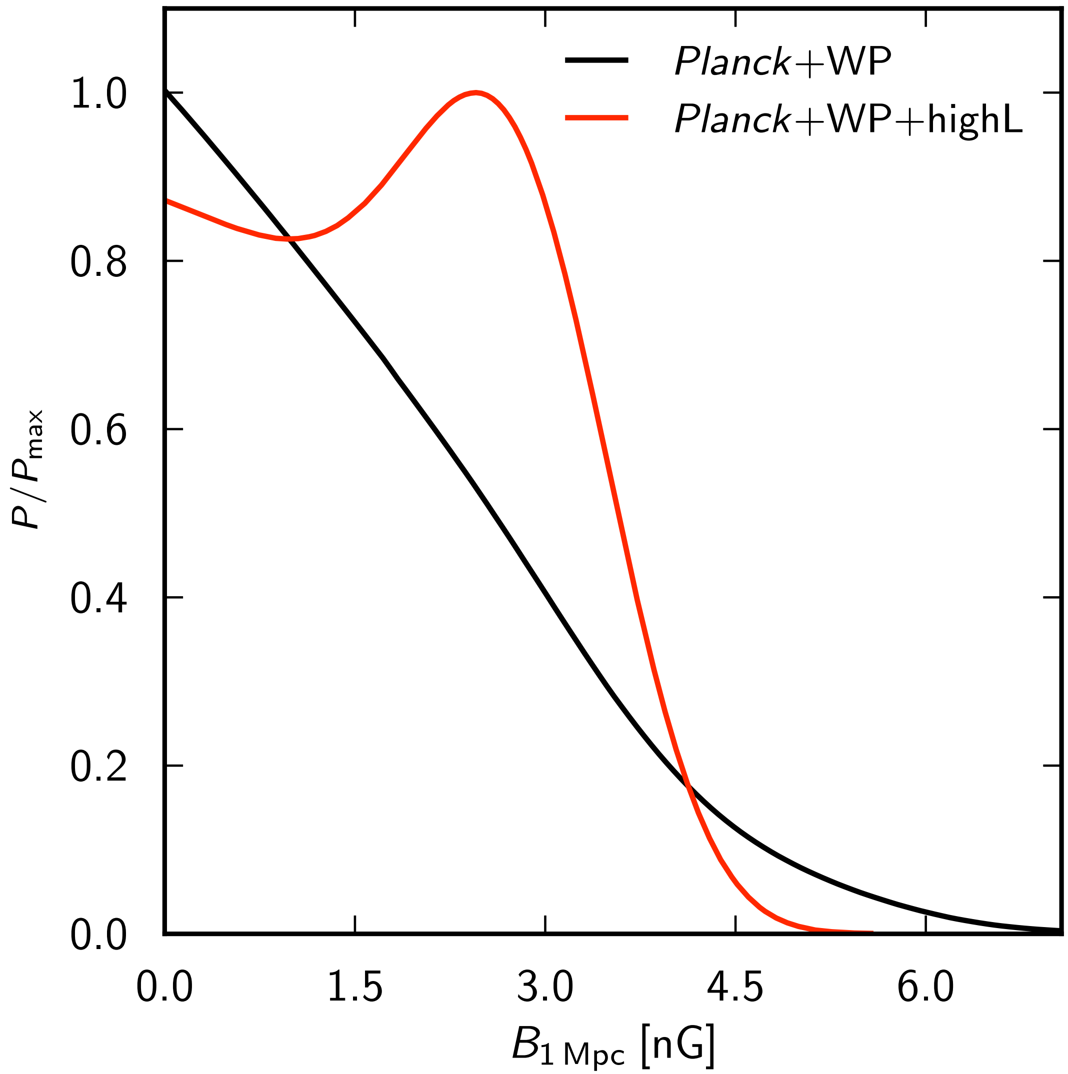
$B_\lambda = 4.7\mu$G, $n \sim -3$, Including passive component, Shaw & Lewis, PRD, 2010



# Planck Constraints on primordial B

Constraints on RMS B field, on $1\,\mathrm{Mpc}$ scale assuming scale invariant spectrum

**Ade et al. Arxiv: 1303.5076v2**



# CMB Non Gaussianity from primordial B

Brown, Crittenden, PRD, 2005; Seshadri, KS, PRL, 2009; Caprini et al., JCAP, 2009 ....

- **Magnetic stresses quadratic in B $\rightarrow$ Magnetically induced CMB signals non-Gaussian even at lowest order!**
- **Due to scalar passive mode, on large angular scales, $l_1(l_1+1)l_3(l_3+1)b_{l_1 l_2 l_3} \sim 6-9\times 10^{-16}$, for $B_0 \sim 3$ nG, nearly scale invariant magnetic spectrum. (Trivedi, KS, Seshadri, PRD, 2010)**
- **Signal scales as $B_0^6$ and one gets upper limit $B_0 < 1-2$ nG, just from scalar SW contribution**
- **Stronger sub nano Gauss limit from tripspectrum (Trivedi, TRS, KS, PRL, 2012; Trivedi, KS, TRS, PRD, 2014 )**
- **Lots still need to be calculated and compared to data!**

# *Structure formation signals*

- **Extra power in the matter power spectrum on small scales** (Gopal, Sethi, 2003)

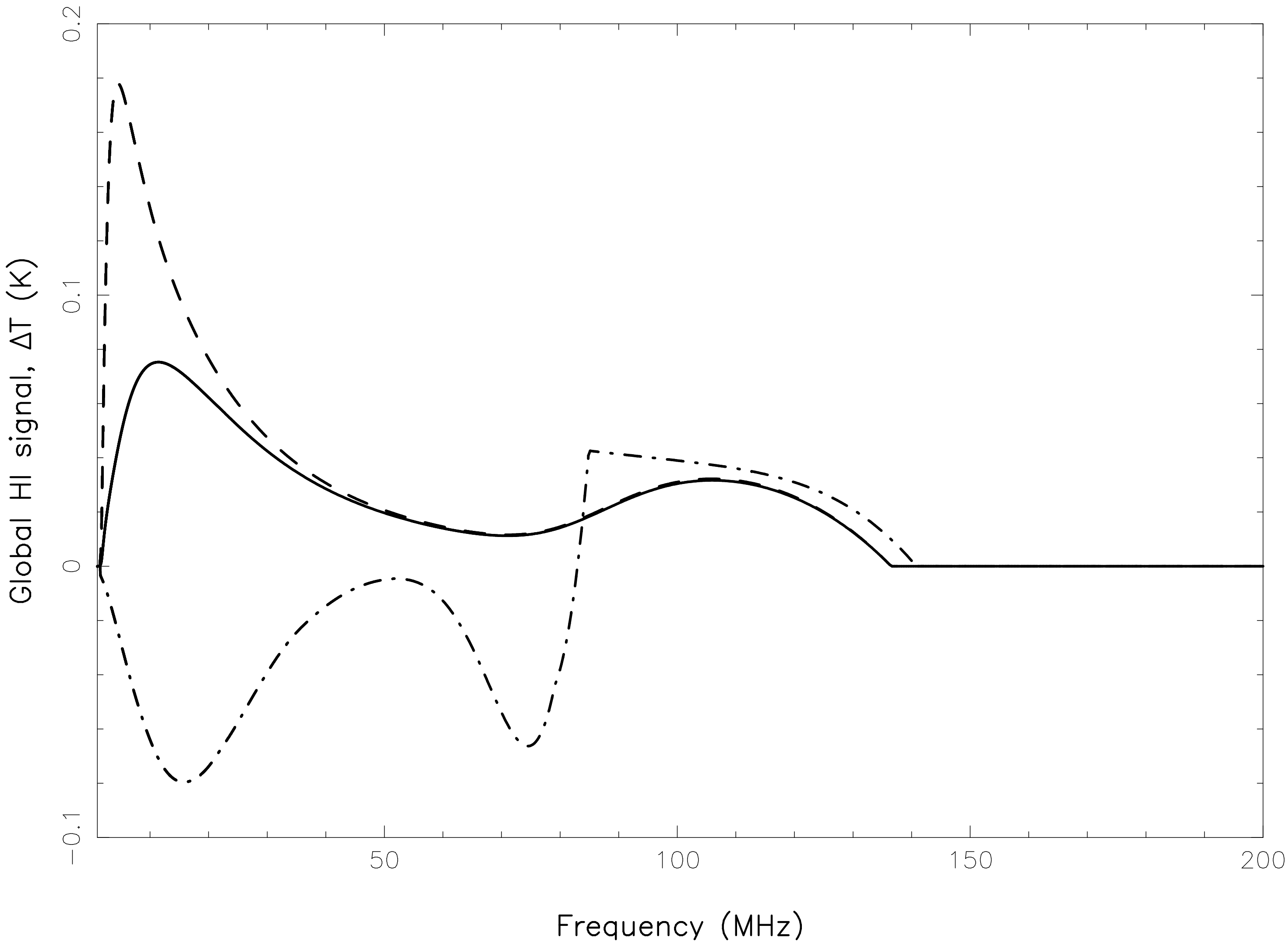
- **First dwarf galaxies form at high $z > 10$ even for $B \sim 0.1nG$, but for masses larger than magnetic and thermal Jeans mass.**

- **B field induced first structures — Reionization?** (Sethi, KS 2005, Tashiro, Sugiyama, 2006; Schleicher, Banerjee, Klessen, 08).

- **Influence formation of first structures through catalyzing Molecule formation** (Sethi, Nath, KS 2008; Schleicher et al 2009)

- **Probe through redshifted HI 21 cm signals** (Tashiro, Sugiyama, 06;Schleicher, Banerjee, Klessen, 09; Sethi, KS 09)

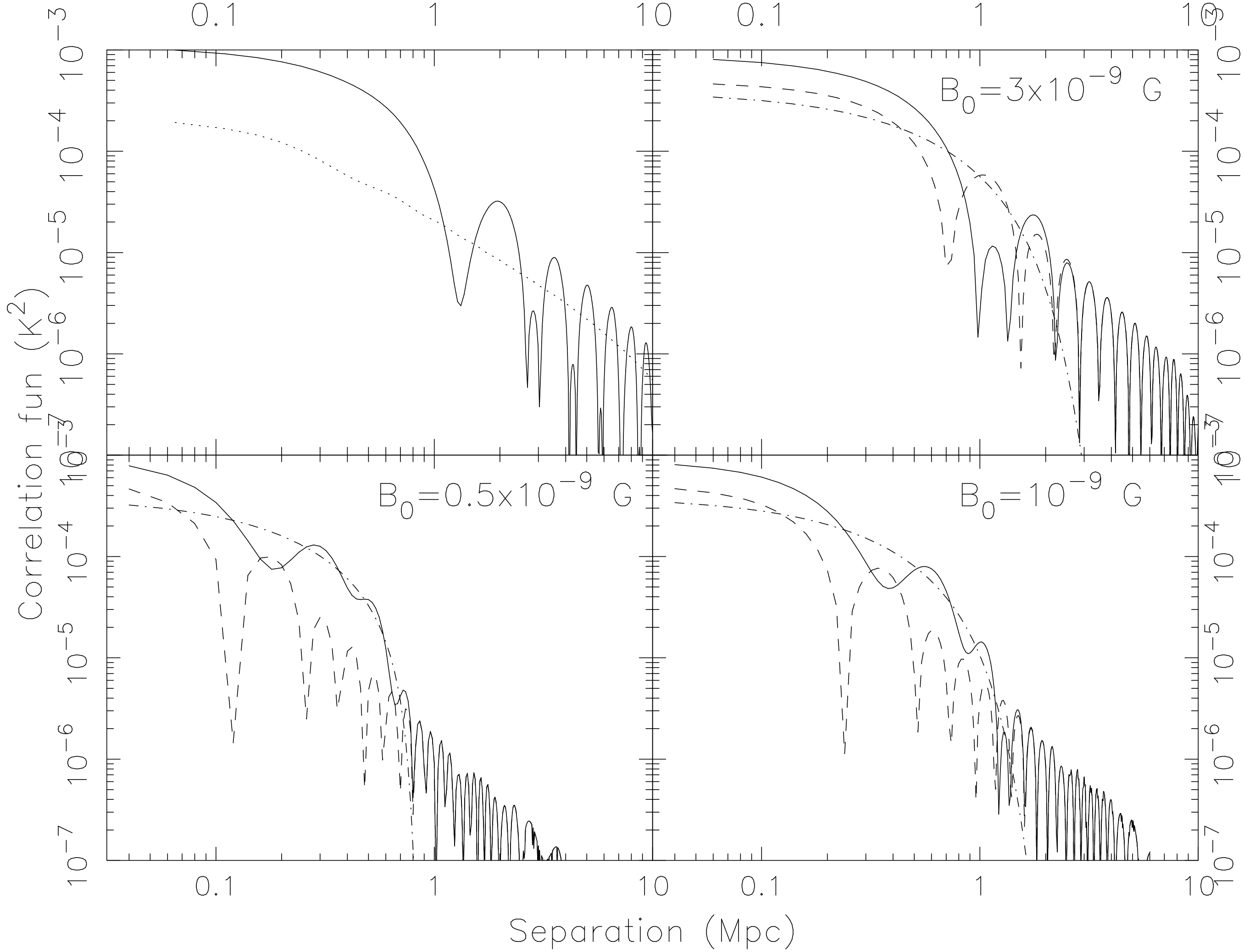
# Global 21 cm signals from reionization




Sethi, KS, 2009; $0, 0.5, 1$ nG

**HI global signal only seen in emission in magnetised models**

# HI correlation signals from reionization




Sethi, KS, 2009; $0.5, 1, 3$ nG

**Both ionization and density inhomogeneities contribute**

# *Final Thoughts?*

- **Universe is Magnetized!**
- **Origin from the early universe phase transitions?**
  **Helical magnetic fields particularly interesting.**
- **Need Compelling generation mechanism or Observations**
- **Primordial fields leave signatures in CMB, Structure formation**
- **Redshifted 21 cm signals detectable with upcoming radio telescopes for $B_0 \sim 0.5$ nG**
- **Also Radio RMs (SKA), High energy CRs and Gamma Rays!**
- **Dynamos certainly needed to maintain fields BUT**
  **Need to understand their saturation better.**

# THANK YOU!