

Primordial magnetic fields: Origins and Constraints

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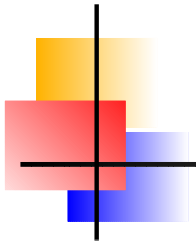


Summary

- **The universe is magnetized.**
- **Early Universe Generation**
- **Magnetic signals in the CMB**
- **Primordial fields and early structure formation**
- Astrophysical batteries and dynamos

K. Subramanian, Magneic fields in the early universe, AN, 2010, 331, 110
K. Subramanian, "Magnetizing the Universe", PoS proceedings, arXiv:0802.2804
K. Subramanian, Primordial magnetic fields and CMB anisotropies, AN, 2006, 327, 403
A. Brandenburg & K. Subramanian, Physics Reports, 417, 1-205 (2005)

The magnetic Universe

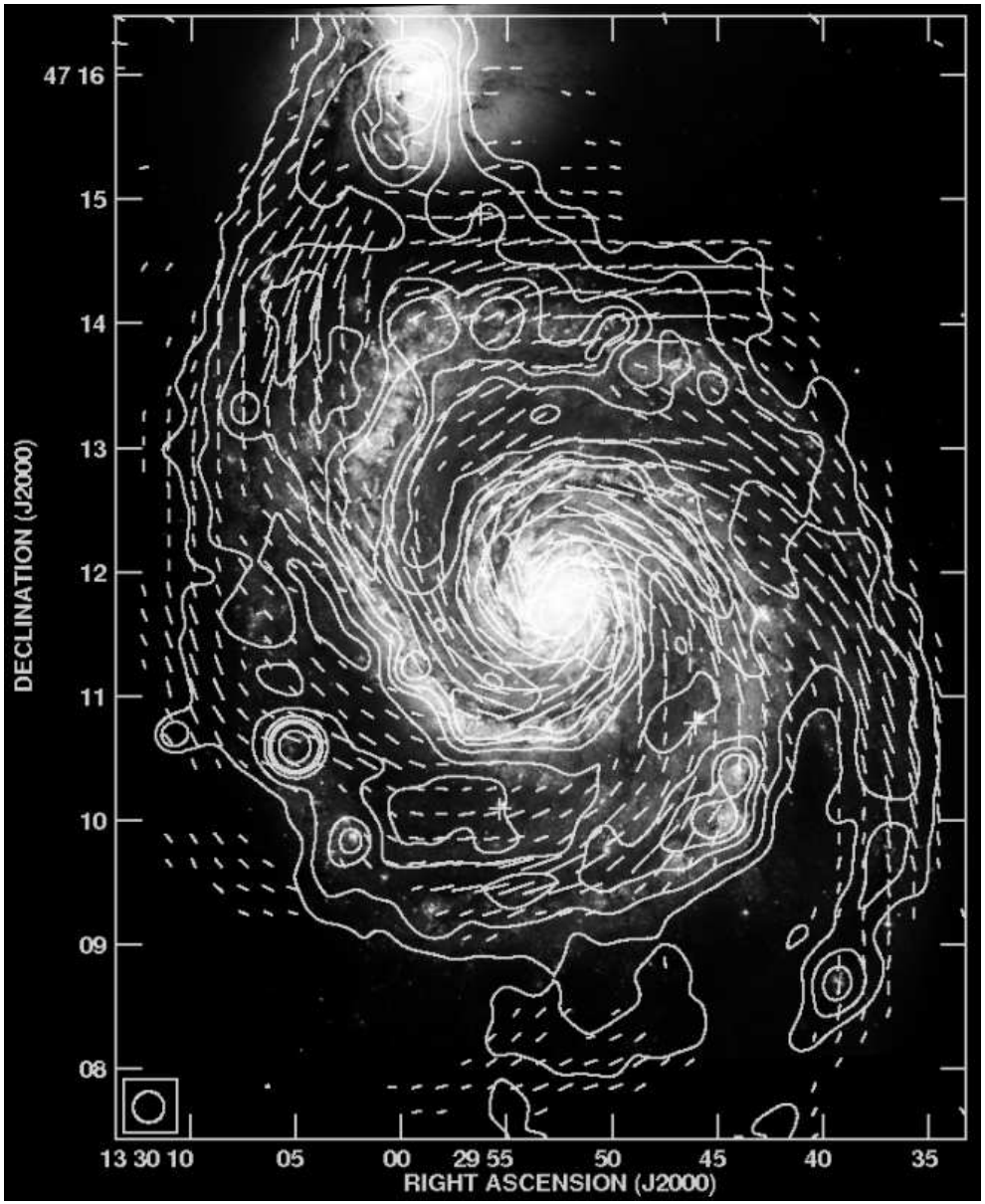
Magnetic fields are ubiquitous in the universe:

- **Galaxies:** $B \sim 10\mu G$**, ordered on 10 kpc scales + random component**
- **Clusters of Galaxies: few** μG **strengths on** ~ 10 **kpc scales**
- **Equally strong** B **in Young** $z \sim 1 - 2$ **galaxies (Bernet et al. 2008)**
- **Even in the IGM and 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?

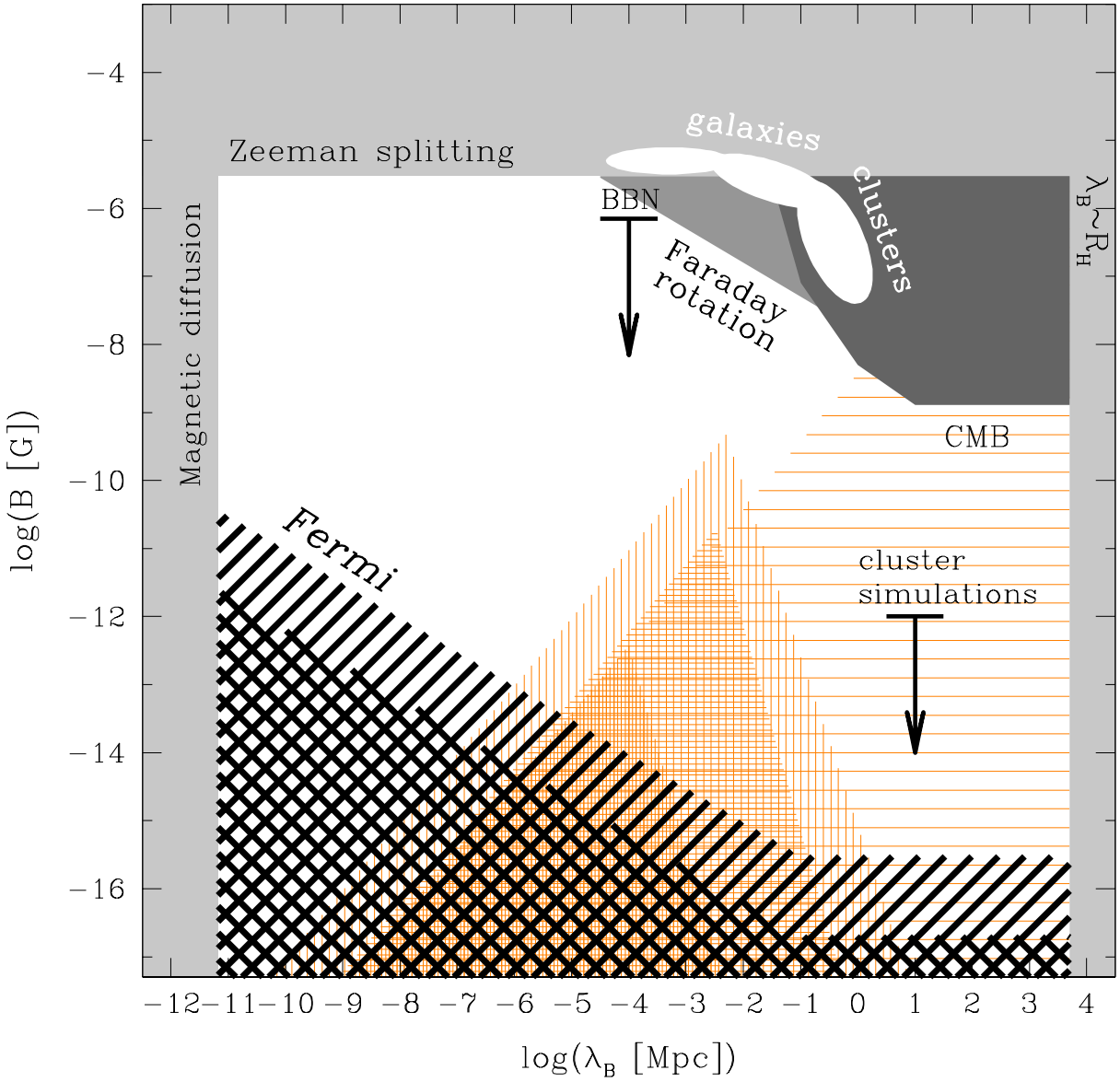
Galactic Magnetic Fields: Observations



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

Constraints on B in the universe

Neronov and Vovk, Science, 328, 73 (2010)



Origin: Dynamos? Primordial?

- **Turbulent Dynamos: Seed field + amplification by motions (turbulence/shear).**
  - Turbulence amplifies fluctuations faster than mean field.
  - Can turbulent dynamos generate sufficiently coherent fields? Voids?
- Primordial magnetic fields: Origin in an early universe phase transition: Inflation, Electroweak, QCD.
  - Provide Seed for dynamo? Help induce coherence?
  - Inflation: Strength? EW/QCD transitions: Scale? Turbulent decay?
- Detecting relic B fields can probe early universe physics?
- Flux freezing: On large scales $B(t)a^2(t) =$ constant, So $B(z) = B_0(1+z)^2$
- $B_0 \sim 10^{-9}G$ on galactic scales, interesting for Galaxy formation + galaxy/cluster B? ($\rho_B = \rho_\gamma$ implies $B \sim 3\mu$G).

Primordial fields versus Dynamos?



Primordial fields origin during Inflation?

(Turner and Widrow, 1988; Ratra 1992; Gasperini et al. 1995)

- **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, dilaton, curvature invariants, axion, charged scalars ..)**
- **EM wave amplified from vacuum fluctuations**
- **After reheating E shorted out and B frozen in.**

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

$$B_0 \sim 5\times 10^{-10}\mathrm{G}\left(\frac{H}{10^{-5}M_{pl}}\right) \qquad (\mathrm{KS}, 2010)$$

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

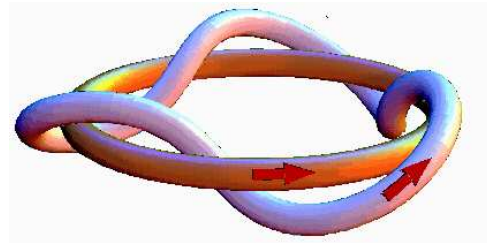
From Electroweak/QCD Phase transition?

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

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



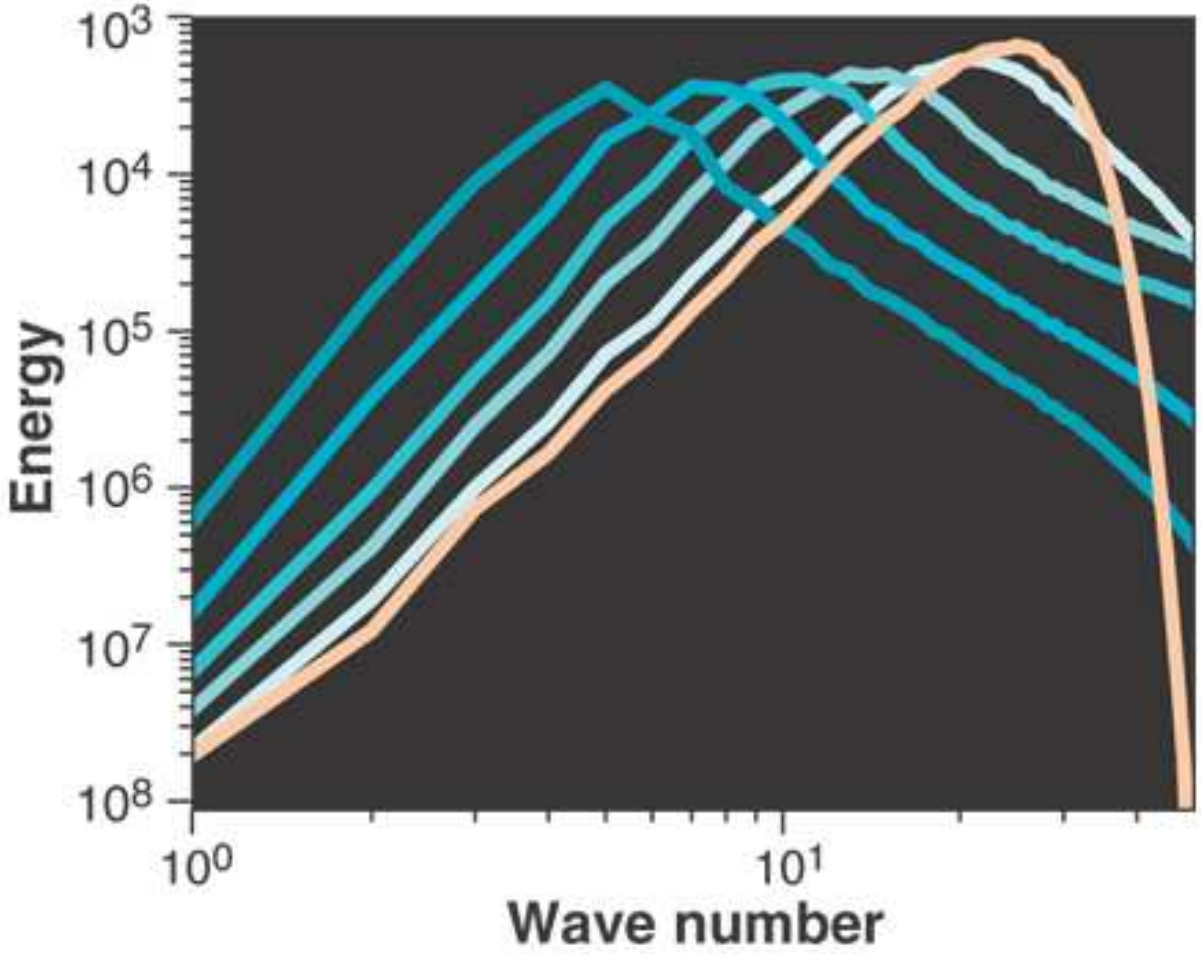
- **Helicity is nearly conserved even when energy dissipated**

- **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. $L \propto t^{1/2}$).

Probing Early Universe B

- $B^2/(8\pi\rho_{rad}) \sim 10^{-7} B_{-9}^2$. 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**

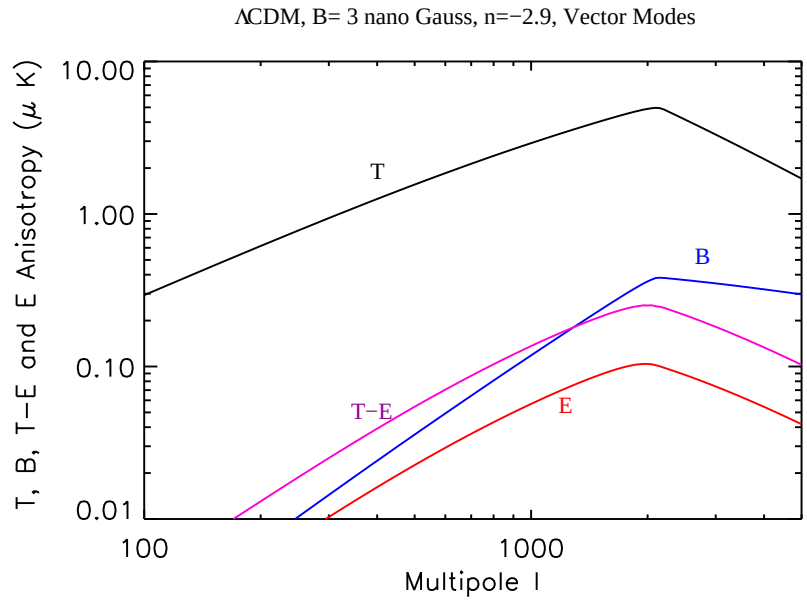
Coherent primordial nG fields potentially detectable

CMB signals from tangled B fields

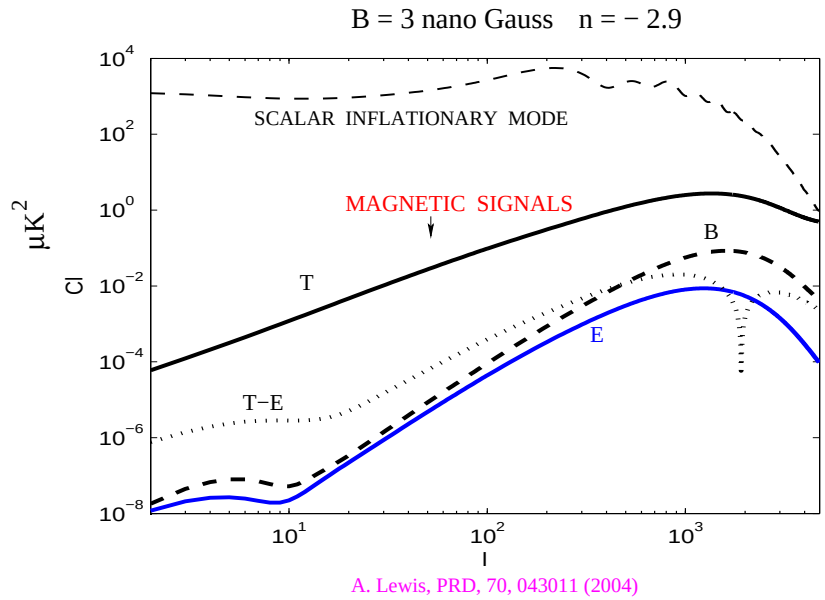
- **Scalar Modes – Subdominant to Inflation generated signal**, (Shaw and Lewis, 2010, M. Giovannini, 2008, Yamazaki et al. 2008)
- **Vortical motion of fluid at LSS (Vector modes)** (KS & Barrow 1998, KS, Seshadri, Barrow 2003)
- **Tensors – Significant at** $l < 100$, (Durrer, Ferreira, Kahniashvili, 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** (Kosowsky & Loeb, 1996; Scoccola et al. 2004; Kahniashvili et al. 2009)
- **Helical fields can also cause** $T - B$, $E - B$ **cross correlations!** (Caprini et al, 2004; Kahniashvili 2006, ...)
- **Non Gaussian Statistics** (Seshadri, KS 2009, Caprini et al 2009, Trivedi, KS, TRS, 2010, Shiraishi et al, 2010a,b; 2011a,b,c ...)

Vector Mode anisotropies

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



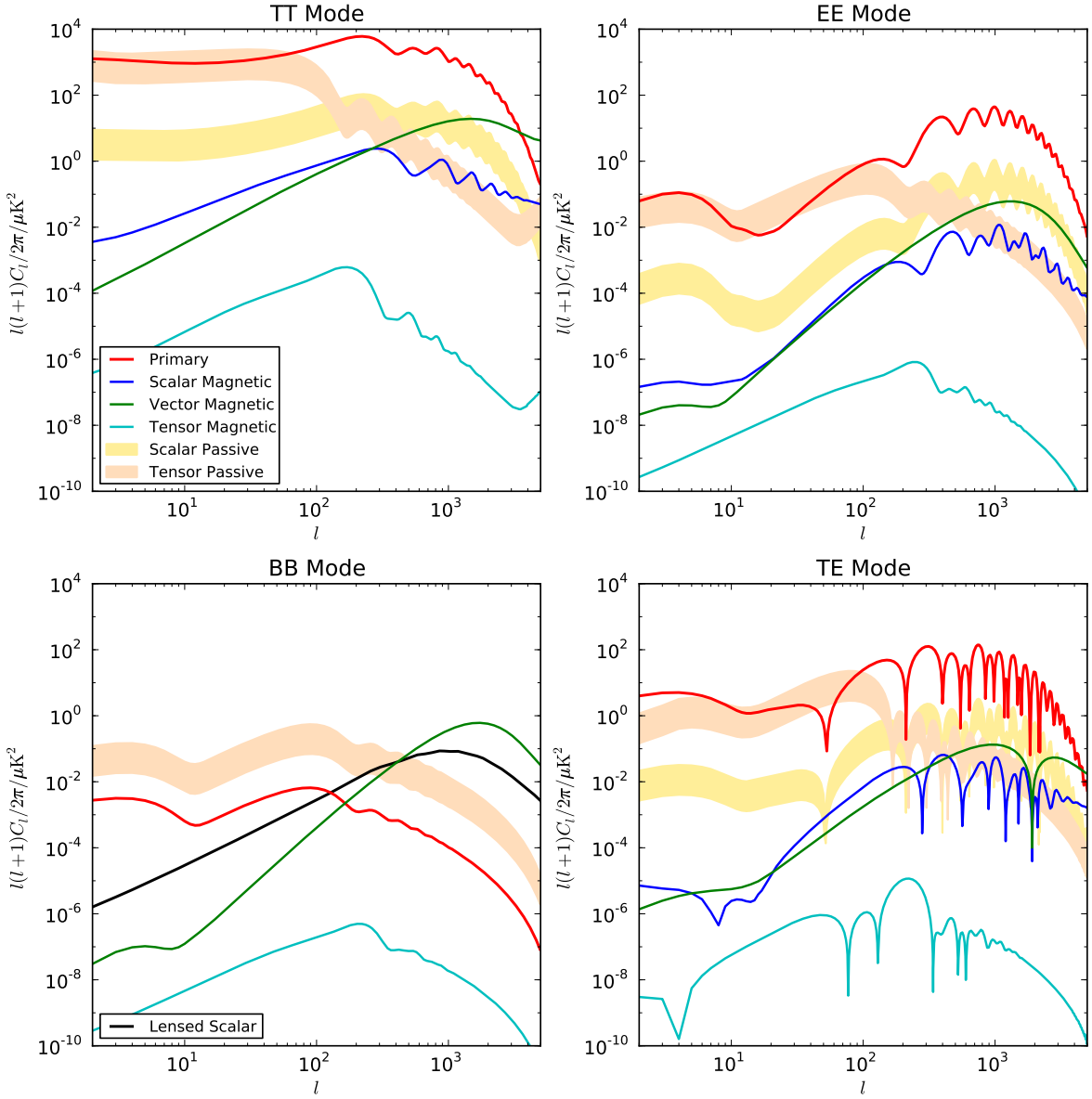
- CAMB code, Lewis,
  PRD 2004



A. Lewis, PRD, 70, 043011 (2004)

CMB signals: scalar+Tensor + Vector

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



Structure formation signals

- **B field dissipation $\rightarrow$ heating, ionization (altered visibility), molecules**
  (Sethi, KS 2005; Schleicher, Banerjee, Klessen, 08, 09; Sethi, Nath, KS 2008).

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

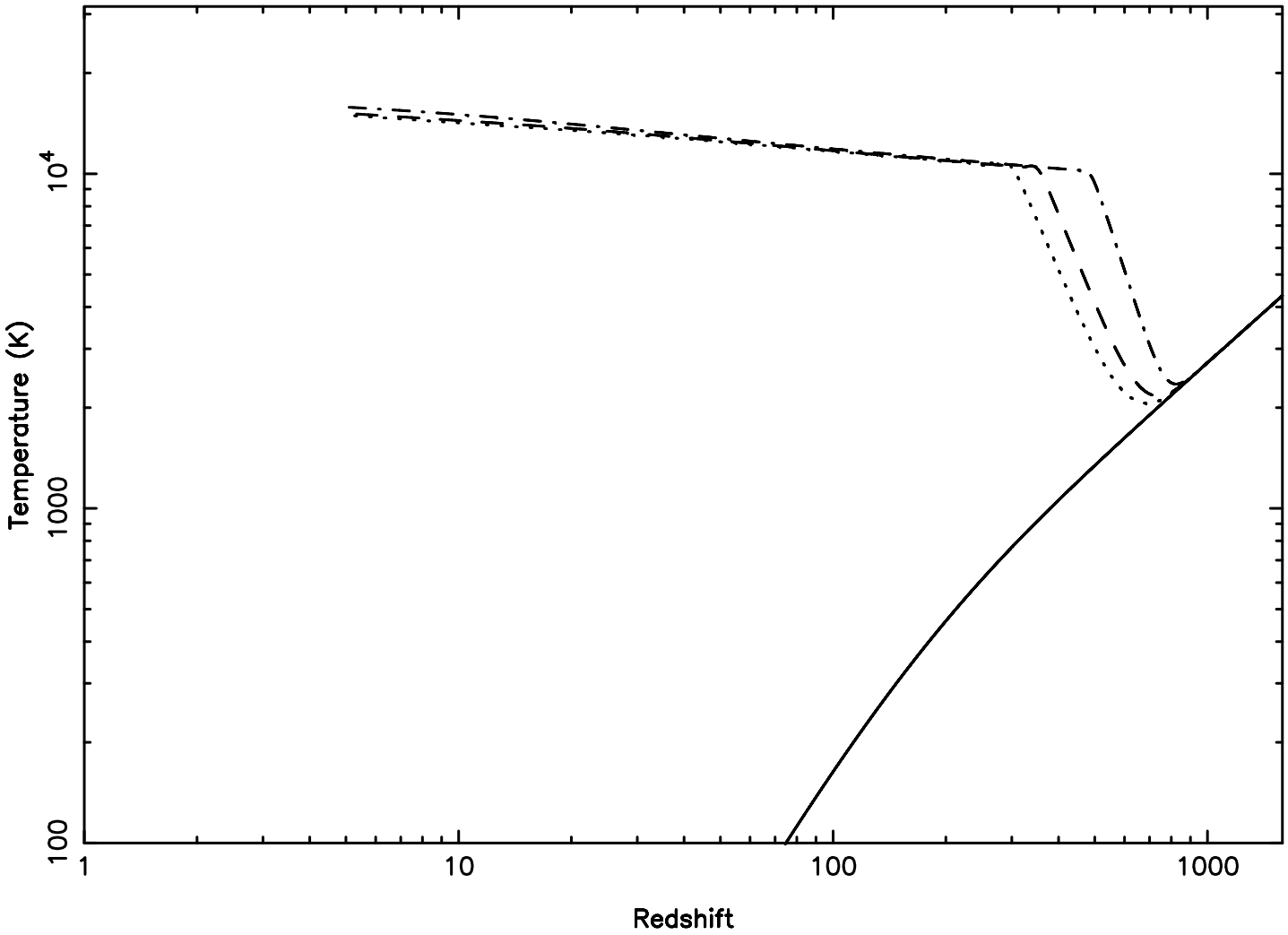
- **First dwarf galaxies form at high $z > 10$ even for $B \sim 0.1nG$, but for masses larger than magnetic and thermal Jeans mass.**

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

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

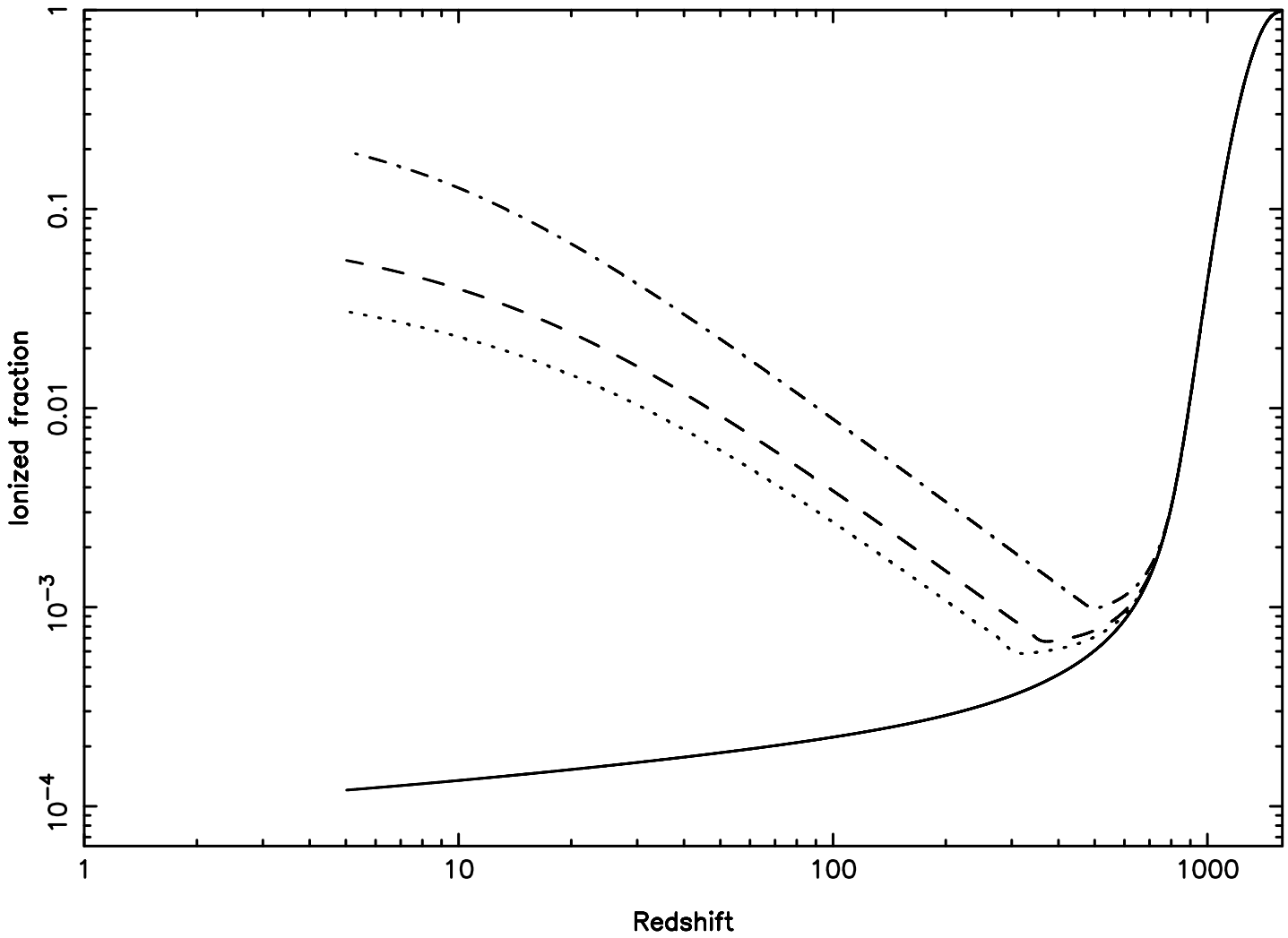
Primordial nG magnetic fields potentially detectable
using Structure formation signals

Modified thermal history



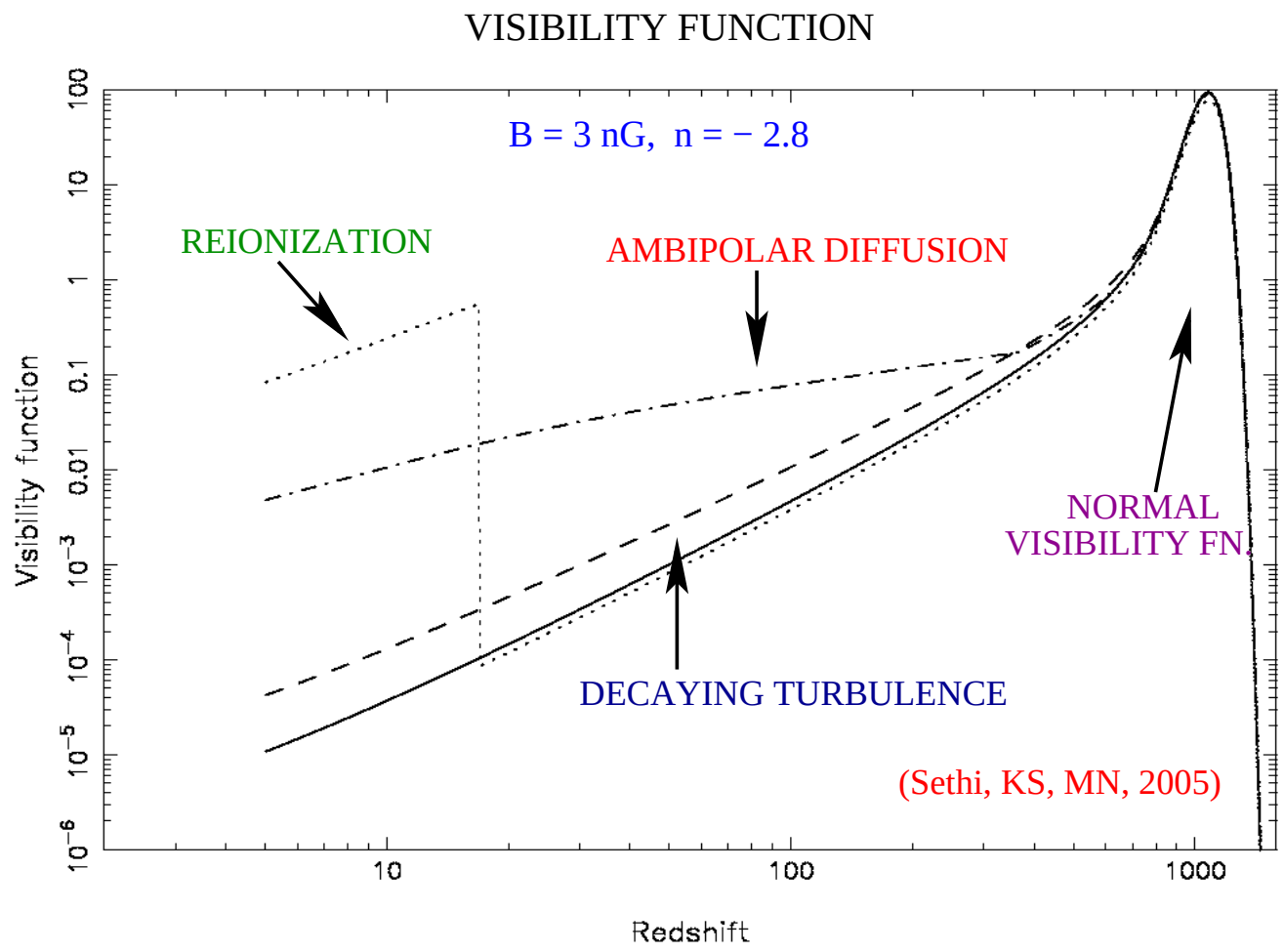
$B_0 = 3$ nG, n=-2.9, -2.8 spectra or all power at k_{max}

Modified ionization history



$B_0 = 3$ nG, n=-2.9, -2.8 spectra or all power at k_{max}

Modified visibility function

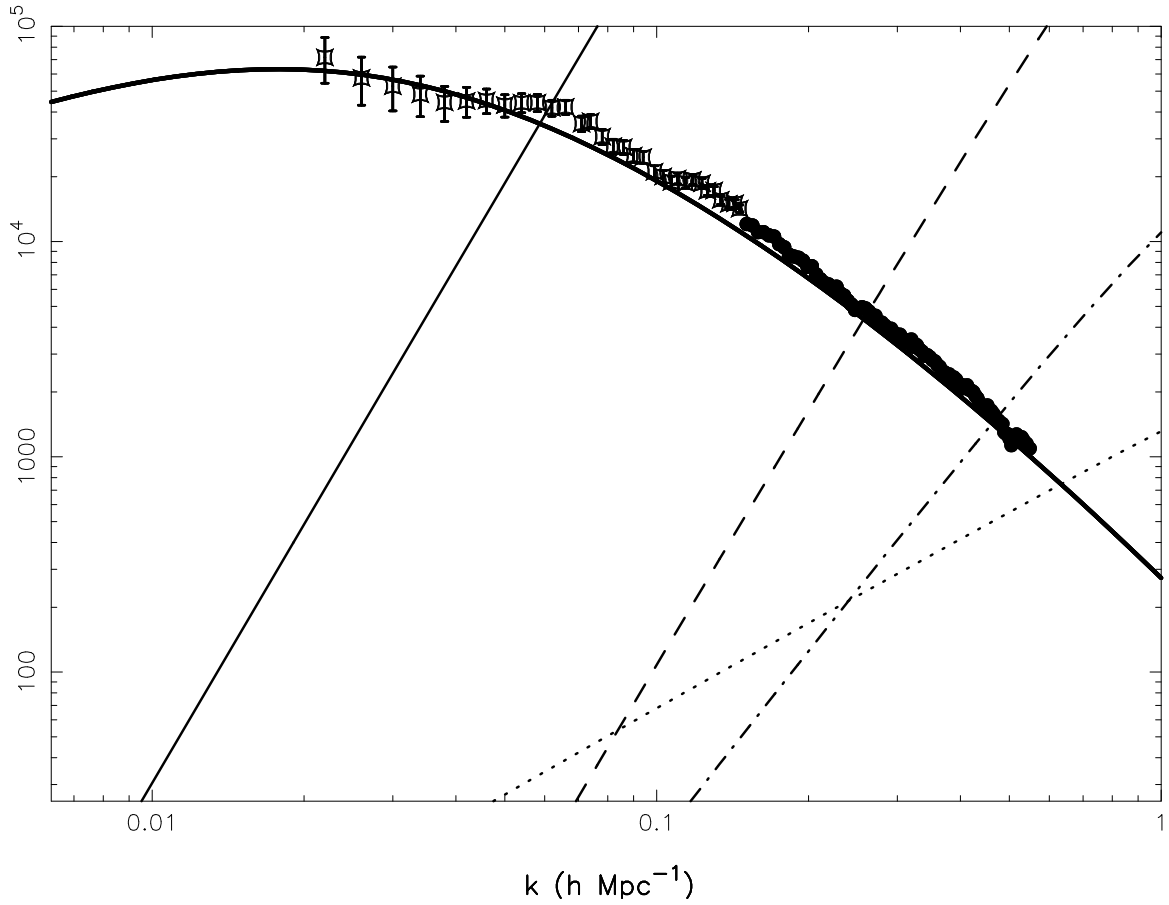


Ambipolar damping and Turbulence decay $\Rightarrow$ gradual re-ionization

$\Rightarrow$ Modified Visibility Function

Structure formation signals

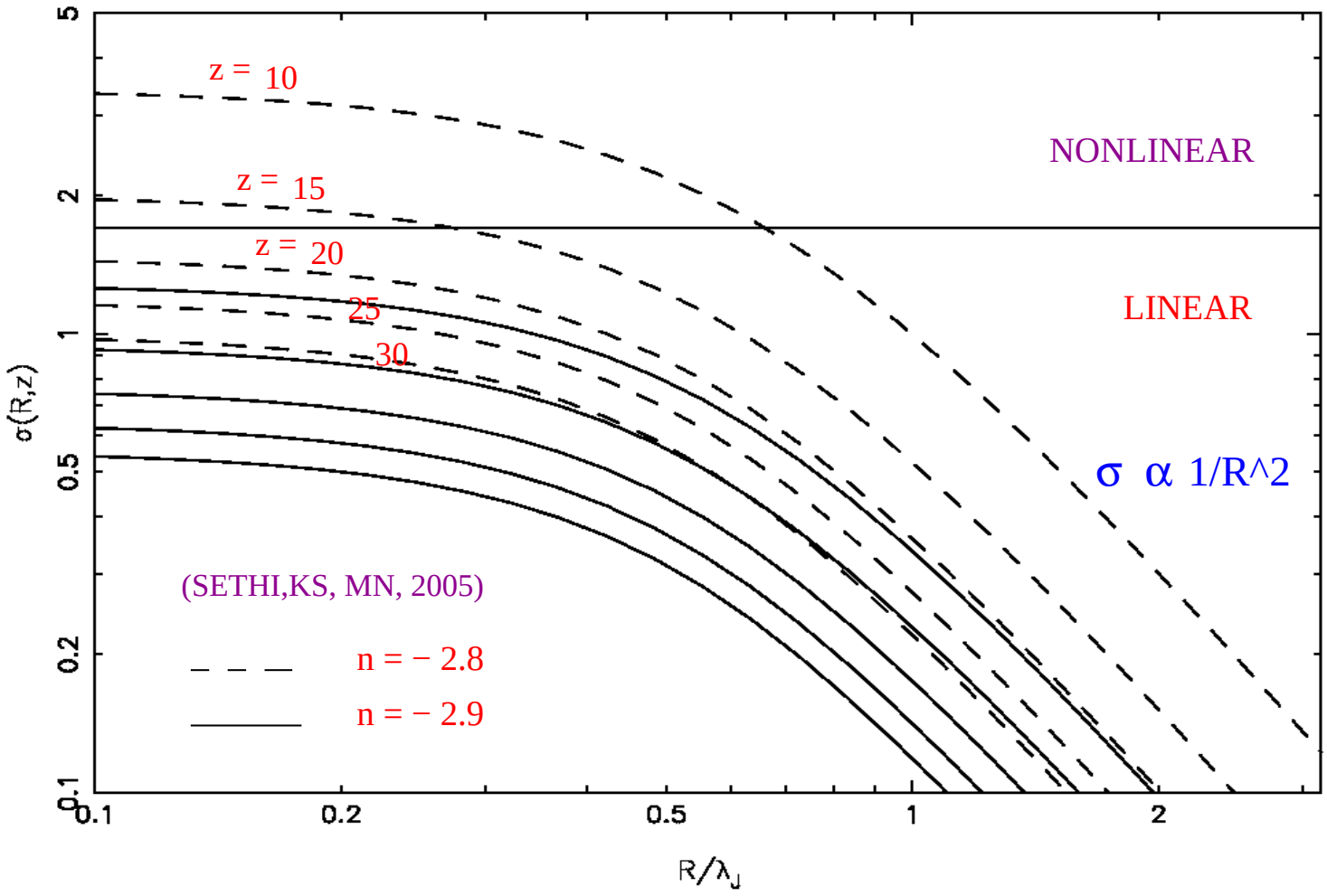
Extra power in the matter power spectrum on small scales
Gopal, Sethi, JAA, 2003; 3 nG, $n = 0, -1, -2, -2.9$; LCDM



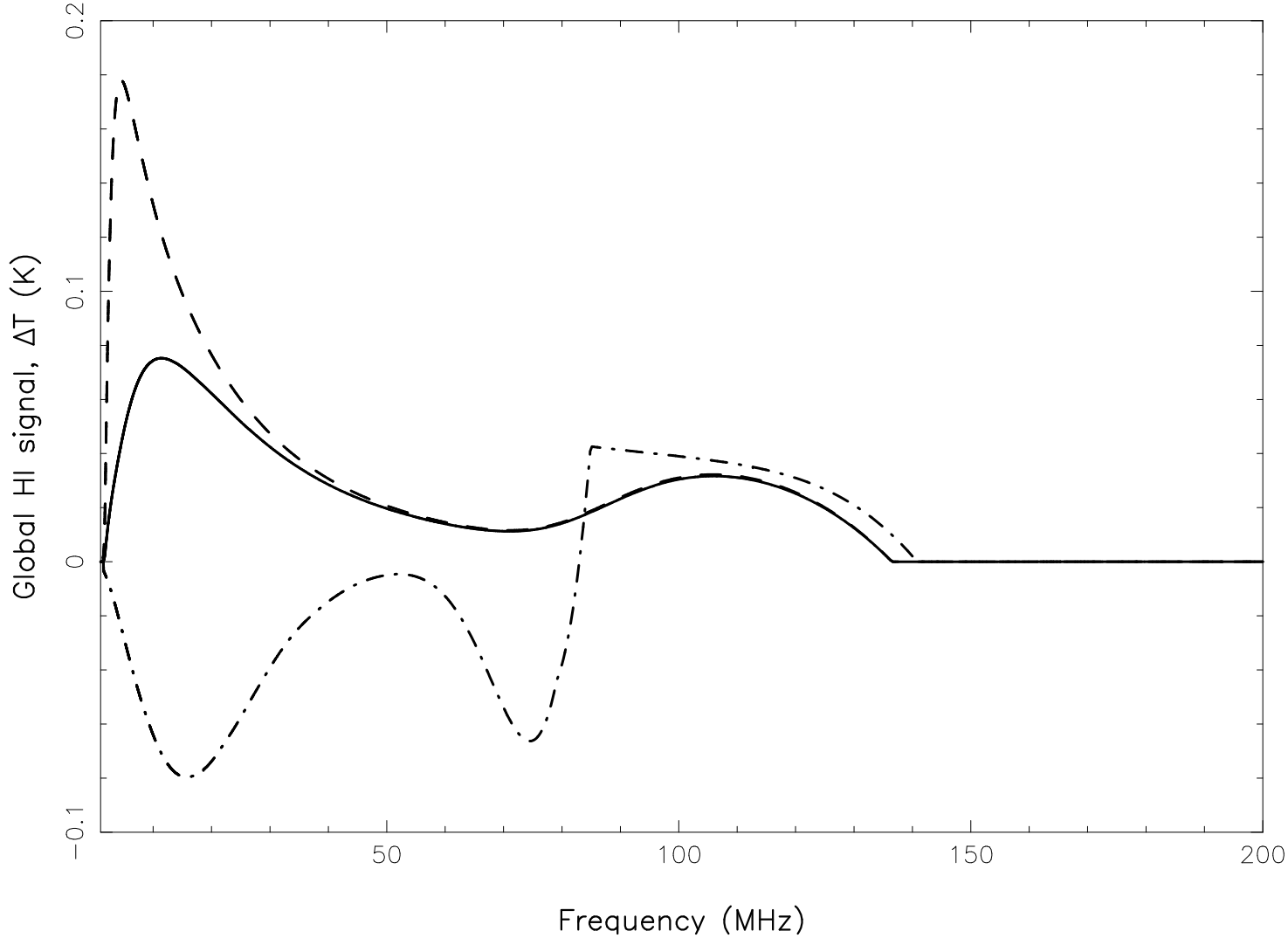
Post Recombination Blues

- **Even $B = 0.1nG$ can induce $10^6 M_\odot$ dwarf galaxy collapse at high $z > 15$ causing early re-ionization** (Sethi, KS MN, 2005)

FIRST STRUCTURES SEEDED BY PRIMORDIAL B FIELDS



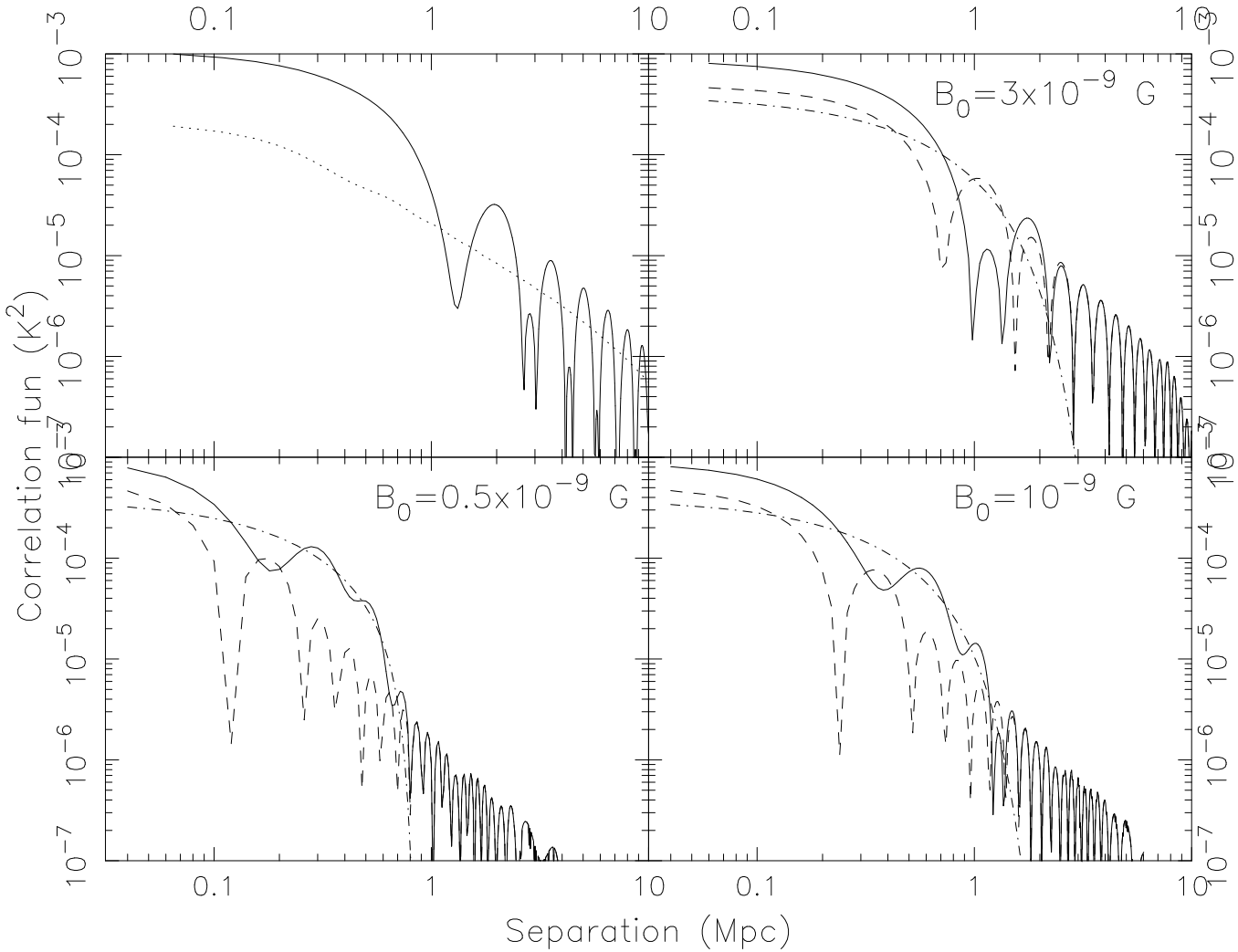
Global 21 cm signals from reionization



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

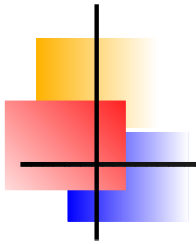
HI global signal only seen in emission in magnetised models

HI correlation signals from reionization



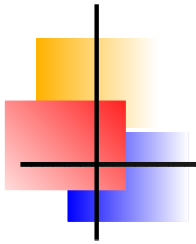
Sethi, KS, 2009; $0.5, 1, 3$ nG

Both ionization and density inhomogeneities contribute



Final Thoughts?

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



THANK YOU!