Magnetic fields in the early universe

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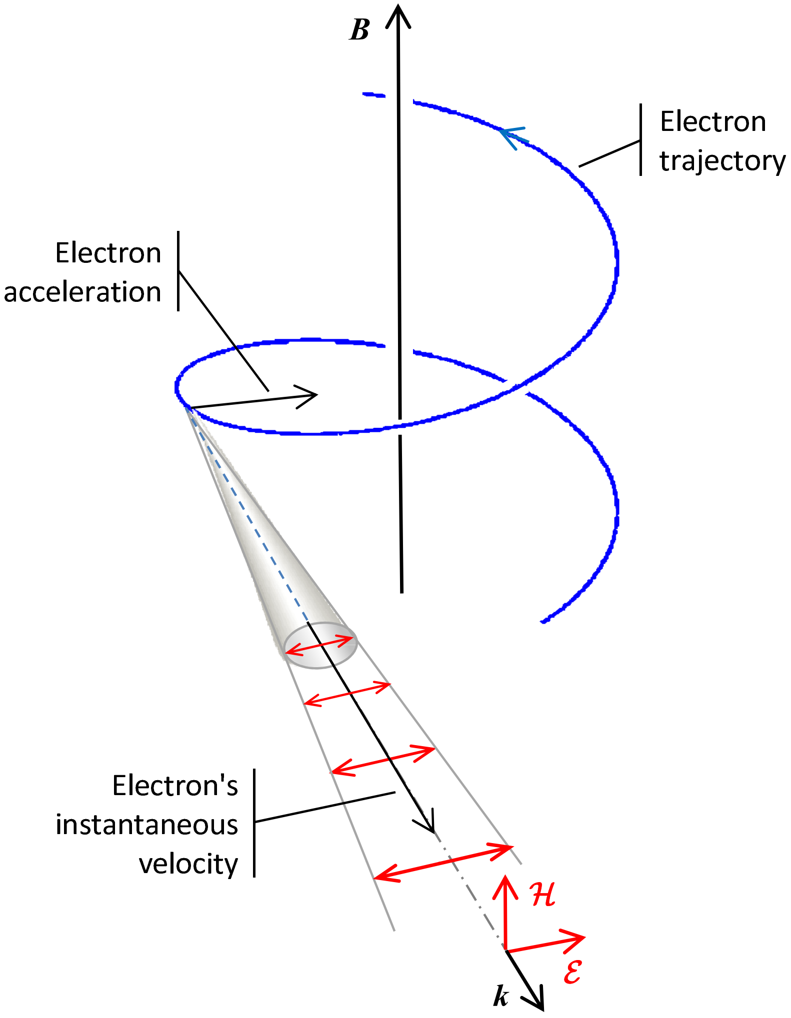
Plan

- Universe is filled with magnetic fields
- Magnetic fields in galaxies and clusters
- Why early universe?
- Early Universe Generation
- Magnetic signals in the CMB
- Primordial fields and early structure formation

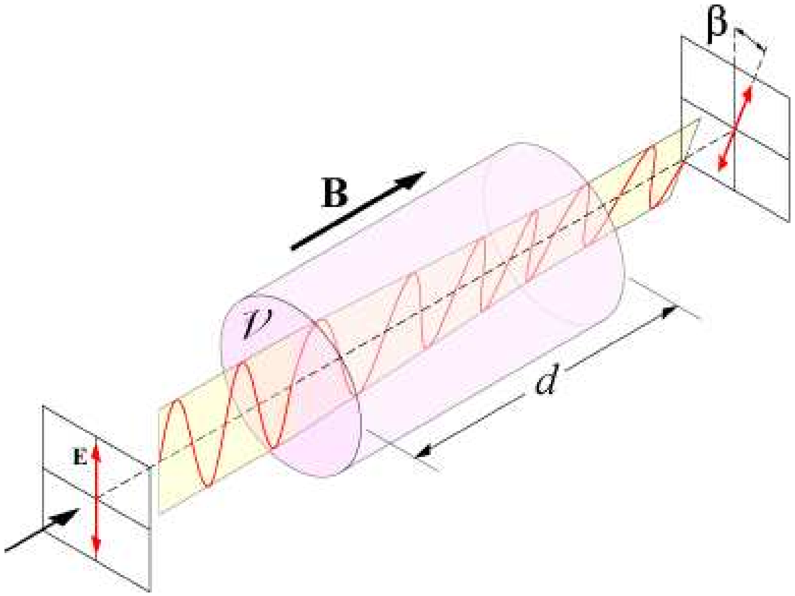
K. Subramanian, “Magnetizing the Universe”, PoS proceedings, arXiv:0802.2804

K. Subramanian, Magneic fields in the early universe, AN (in Press), arXiv:0911.4771

Measuring B fields:Synchrotron Radiation



(http://www.statemaster.com/ encyclopedia/Faraday-effect)

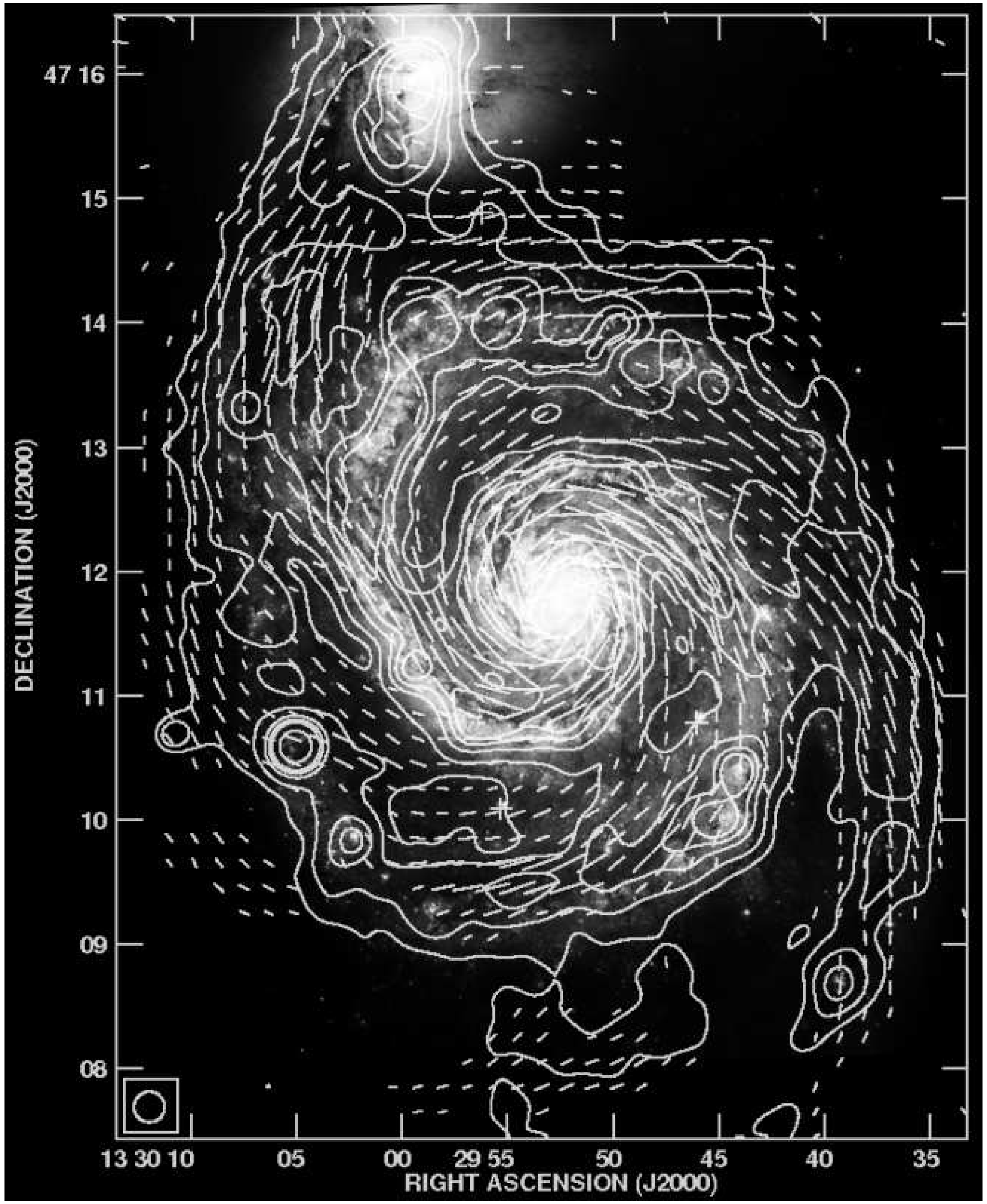


Faraday Rotation gives $B_{||}$

$$RM = 0.81\int n_e \mathbf{B}\cdot d\mathbf{l}\ (\text{rad}\ m^{-2})$$

Synchrotron polarization gives $B_{\perp}$

Galactic Magnetic Fields: Observations

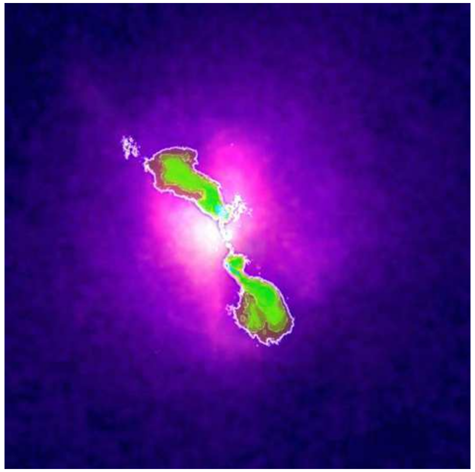


- **Synchrotron polarization and Faraday rotation probe B fields.**
- **M51 at 6 cm (Fletcher and Beck)**
- **Few - ten μG mean Fields coherent on 10 kpc scales**
- **How do such large scale galactic fields arise? Early universe? Dynamos?**

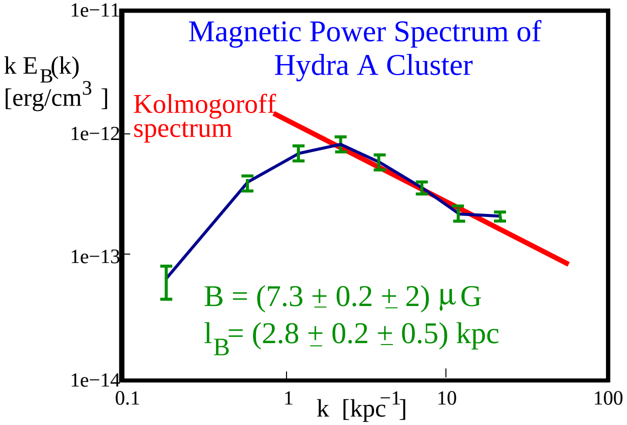
Cluster magnetic fields

- **Cluster fields from Radio halos (B_{total}) and Faraday Rotation ($B_{coherent}$)**
- **Galaxy clusters host few μG fields correlated on 10 Kpc scales**

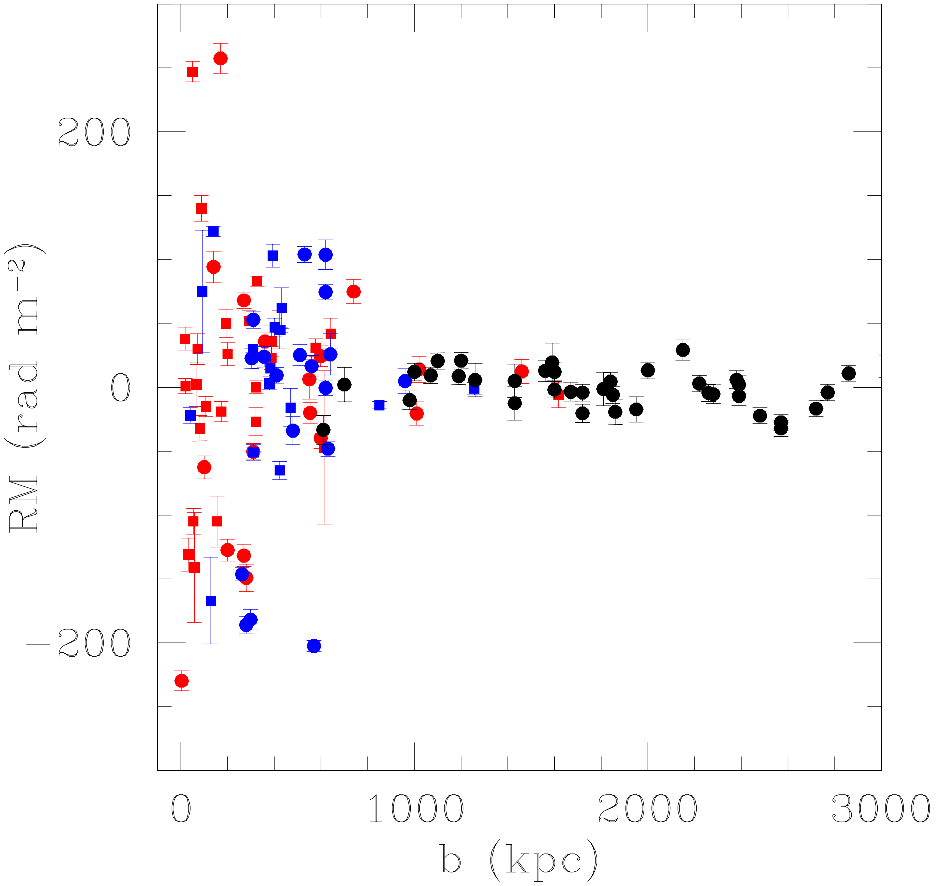
Hydra Cluster



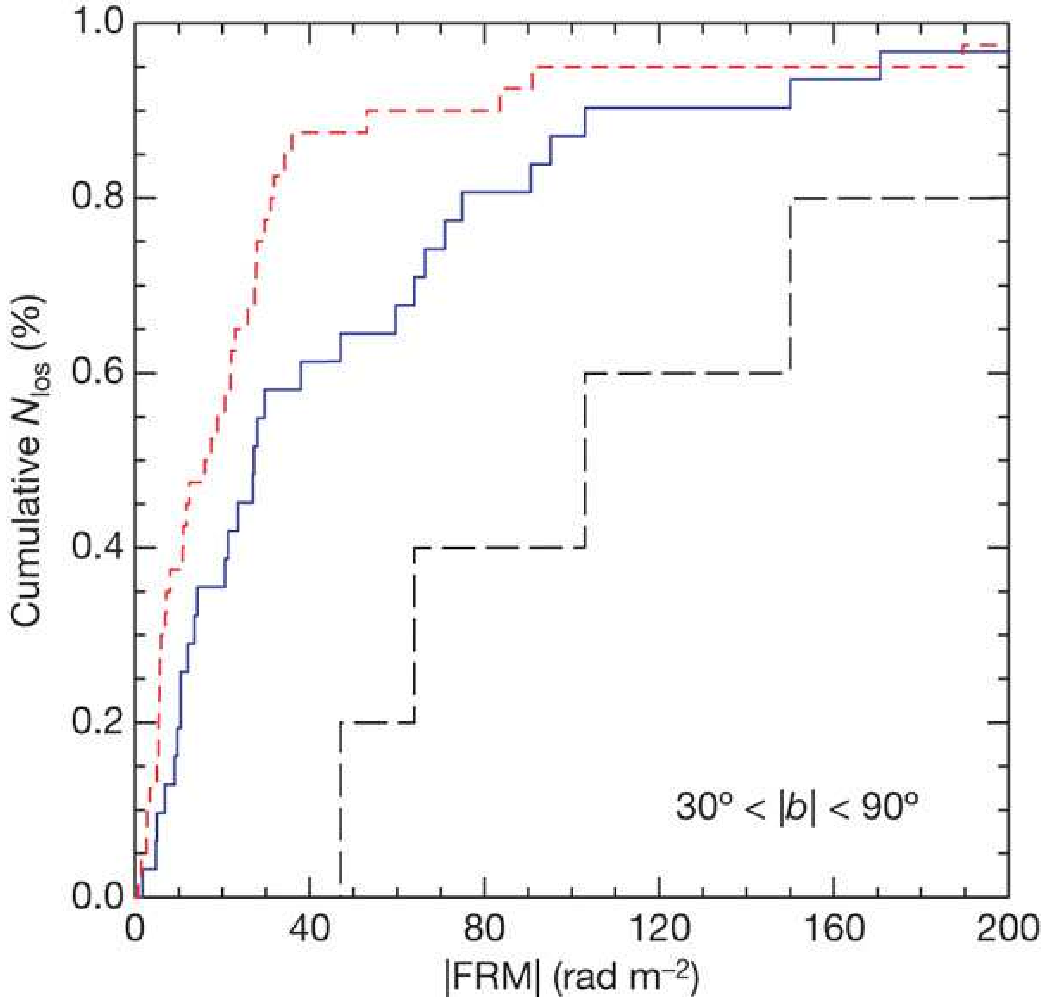
(Vogt and Ensslin, 05)



Statistical RM study, Clarke et al, 2001



Strong B in high z galaxies?



Universe increasingly Faraday opaque at high z?

Bernet et al, Nature, 454, 302, 2008; Kronberg et al. 2008

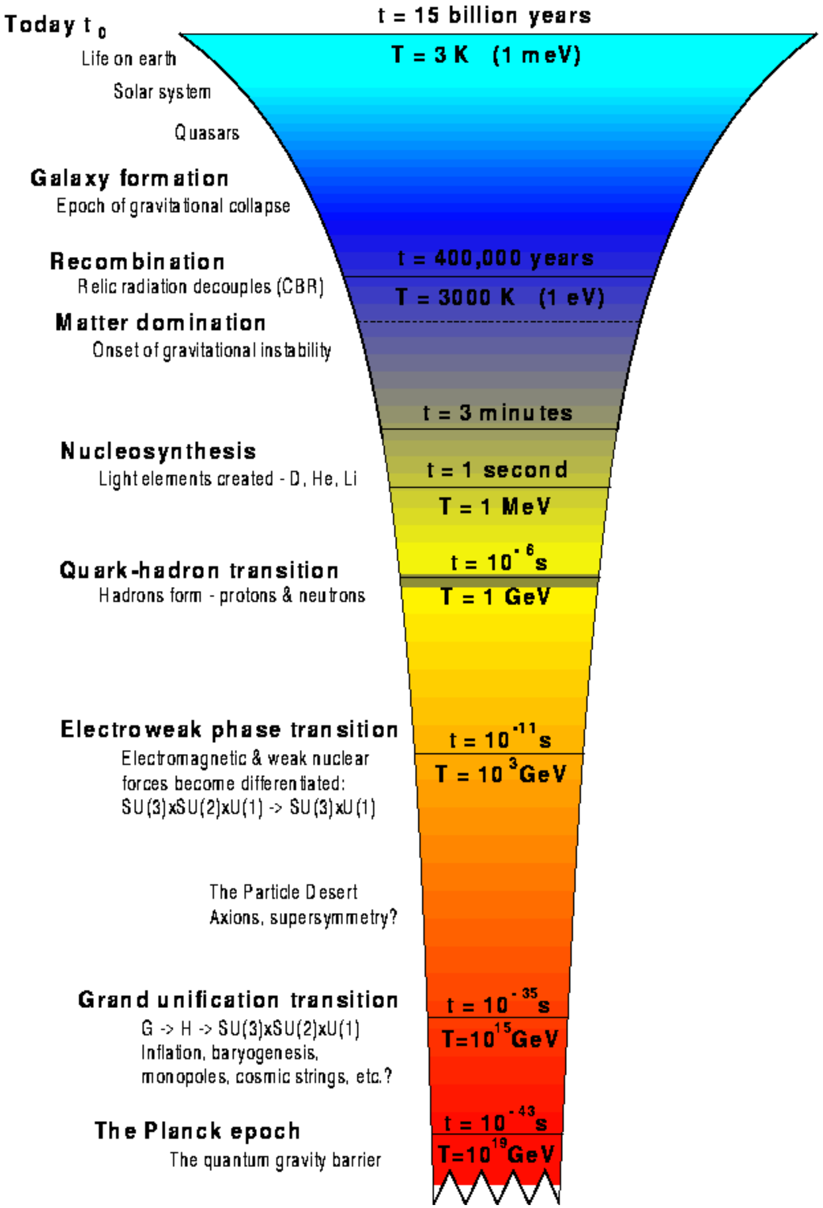
Why Early universe?

- **WHY NOT?** – **Scalar/Tensor perturbations generated. Why not B fields? In an Early universe Phase transition?**
- **Coherent Galaxy and Cluster fields? – Dynamos??**
  Brandenburg & Subramanian, Phys. Rep. 417 (2005) 1-209
  - Seed field + amplification by motions (turbulence/shear)
  - Can turbulent dynamos generate required coherence?
- **Could probe early universe physics**
- **CMB Puzzles? CBI Excess Power? Alignments? Non Gaussianities?**
- **Flux freezing:** $B(t)a^2(t) =$ **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).**

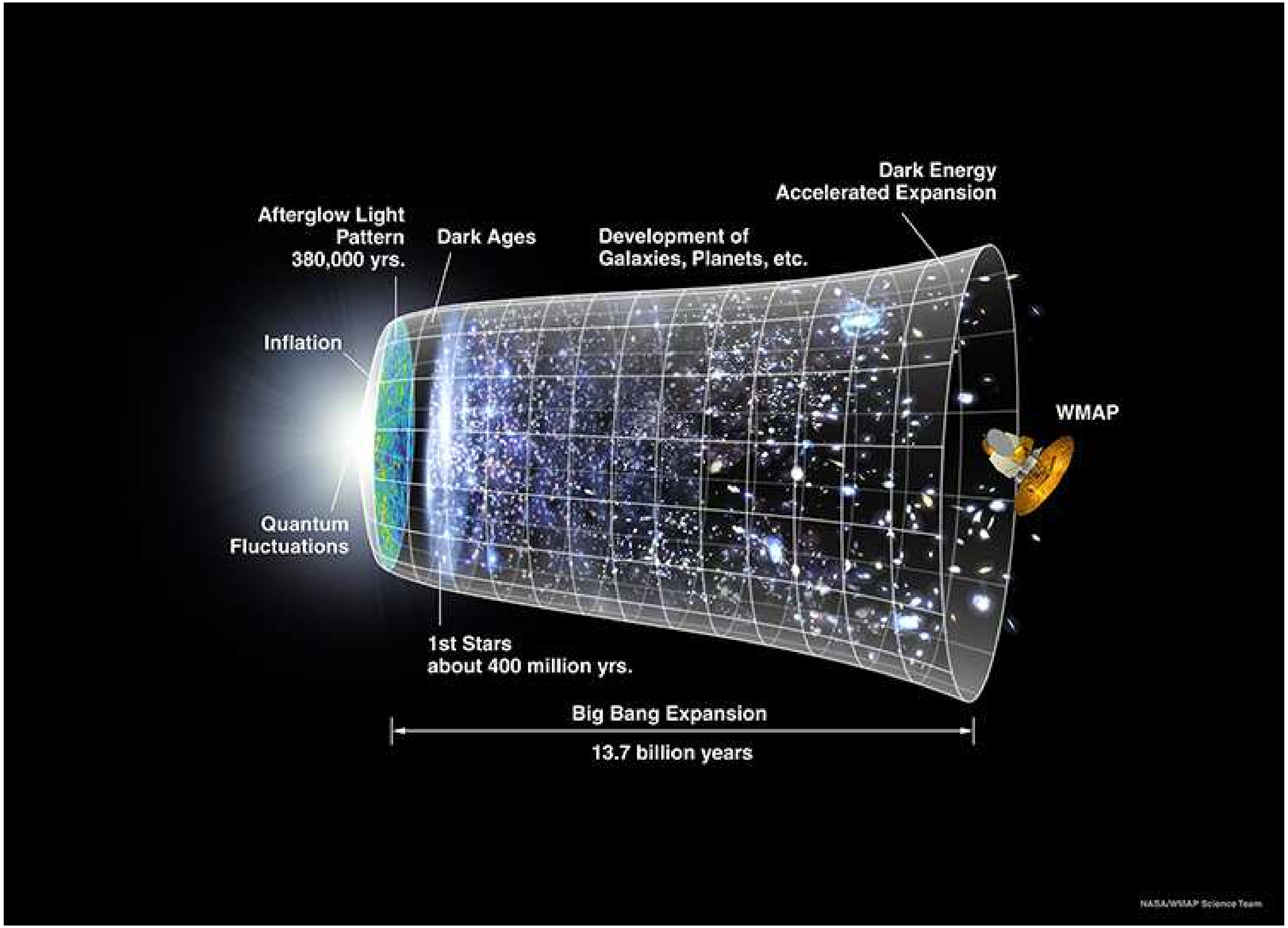
How can One Constrain/Detect Primordial B fields?

Early Universe timeline

(http://www.damtp.cam.ac.uk/research/gr/public/images)



Quantum fluctuations to Galaxies



(http://wmap.gsfc.nasa.gov/)

Primordial fields from Inflation?

Origin during Inflation: (Turner and Widrow, PRD, 1988)

- **Rapid expansion → vacuum fluctuations stretched to long wavelength "classical" fluctuations**
- **Negligible charge density breaks flux freezing.**
- **BUT Need to break conformal invariance of 'ED'**
- **Consider EM action** $(F_{\mu\nu} = A_{\nu;\mu} - A_{\mu;\nu} = A_{\nu,\mu} - A_{\mu,\nu})$:

$$S = \int \sqrt{-g}\, d^4x\, \frac{1}{4} F_{\mu\nu} F^{\mu\nu} = \int \sqrt{-g}\, d^4x\, \frac{1}{4} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta}$$

- **Consider conformal transformation**: $g^*_{\mu\nu} = \Omega^2 g_{\mu\nu}$: implies $\sqrt{-g^*} = \Omega^4 \sqrt{-g}$, $g^{*\mu\alpha} = \Omega^{-2} g^{\mu\alpha}$, $A^*_\mu = A_\mu$. $\Rightarrow S^* = S$.
- **FRW is conformal to flat space ⇒ can transform EM conformally to flat space. So no "amplification" of EM waves.**

Primordial fields from Early Universe?

- **Many ways considered for breaking CI during inflation**:

$$S=\int\sqrt{-g}\,d^4x\,[-f(\phi,R)\frac{1}{4}F_{\mu\nu}F^{\mu\nu}-bRA^2+g\theta F_{\mu\nu}\tilde{F}^{\mu\nu}-D_\mu\psi(D^\mu\psi)^*\,]$$

- **Coupling of "EM" action to inflaton, dilaton, curvature invariants, axion, charged scalars, ...**
- **EM wave amplified from vacuum fluctuations**
- **After reheating $\mathbf{E}$ shorted out and $\mathbf{B}$ frozen in.**
- **Exponentially sensitive to parameters, as need** $B\sim 1/a^{\epsilon}$
- $B\sim 10^{-9}$ **to** 10^{-65} **G**, for $f(\phi)\sim e^{\alpha\phi}$, for $\alpha\sim 20-0$ (Ratra, 1992)
- **Need huge growth of charge: a Problem?** (Demozzi et al, 2009)

A worked example

- **Consider $f = a^\alpha$, $a(\eta) = a_0|(\eta/\eta_0)|^{1+\beta}$, ($\eta$ is conformal time).**
- **For $\gamma = \alpha(1+\beta) \leq 1/2$, and using $(k/aH) = (-k\eta)$,** (KS, 2009)

$$\frac{d\rho_B}{d\ln k} = \frac{C(\gamma)}{2\pi^2} H^4 \left(\frac{k}{aH}\right)^{4+2\gamma} = \frac{C(\gamma)}{2\pi^2} H^4 (-k\eta)^{4+2\gamma} \approx \boldsymbol{\frac{9}{4\pi^2} H^4}$$

(for $\gamma = -2$, c.f nearly exponential expansion $\beta \approx -2$ and $\alpha \approx 2$)

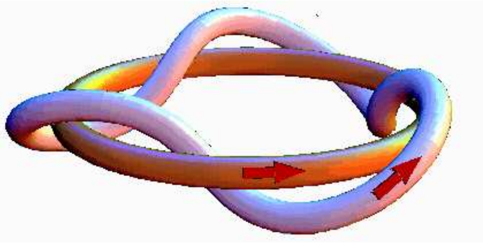
- **Using $\rho_B(0) = \rho_B(a_f/a_0)^4$, instantaneous reheating, gT^3a^3 conservation afterwards, gives**

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

- **When $f = f_0$ is constant: $F^{\mu\nu}{}_{;\,\nu} = (4\pi J^\mu)/f_0^2$, OR $e_N \sim e/f_0^2$**
- **But $f = f_i(a/a_i)^\alpha \propto a^2$ during inflation; So theory either strongly coupled initially or very weakly coupled at end!**

From Electroweak/QCD Phase transition?

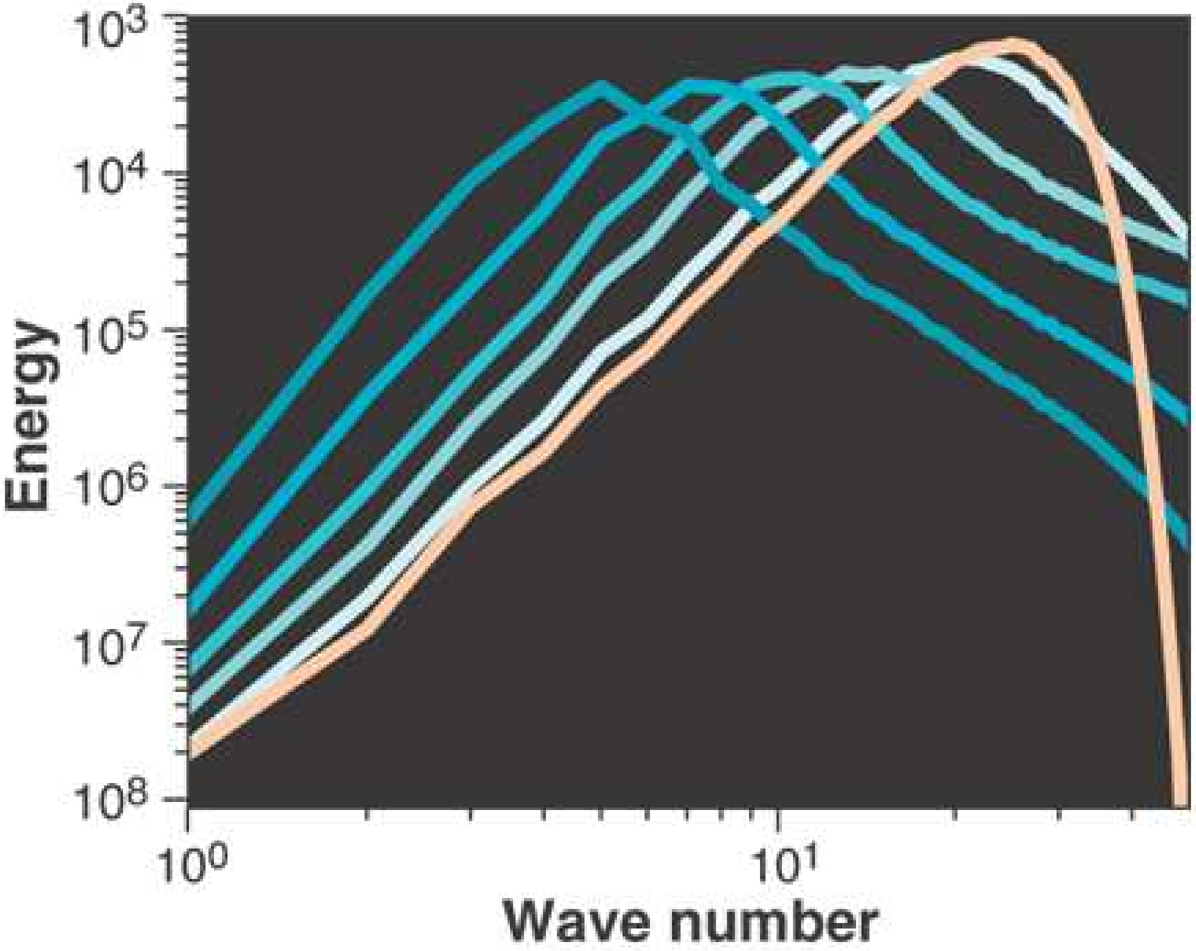
- **Correlation scale usually tiny: $H^{-1} \sim 1$ cm (EW) or $\sim 10^4$ cm QCD phase transition or comoving $R_H \sim 100\mathrm{AU}/0.1$ pc**
- **Unless Helicity generation/Conservation leads to Inverse Cascade** (Brandenburg et al, PRD 96, Banerjee & Jedamzik, 2004)
- **Magnetic Helicity $H = \int_V \mathbf{A}\cdot\mathbf{B}\, dV$, $\quad \nabla\times\mathbf{A} = \mathbf{B}$**
  $\mathbf{A}$ 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)

Inverse cascade of helical B

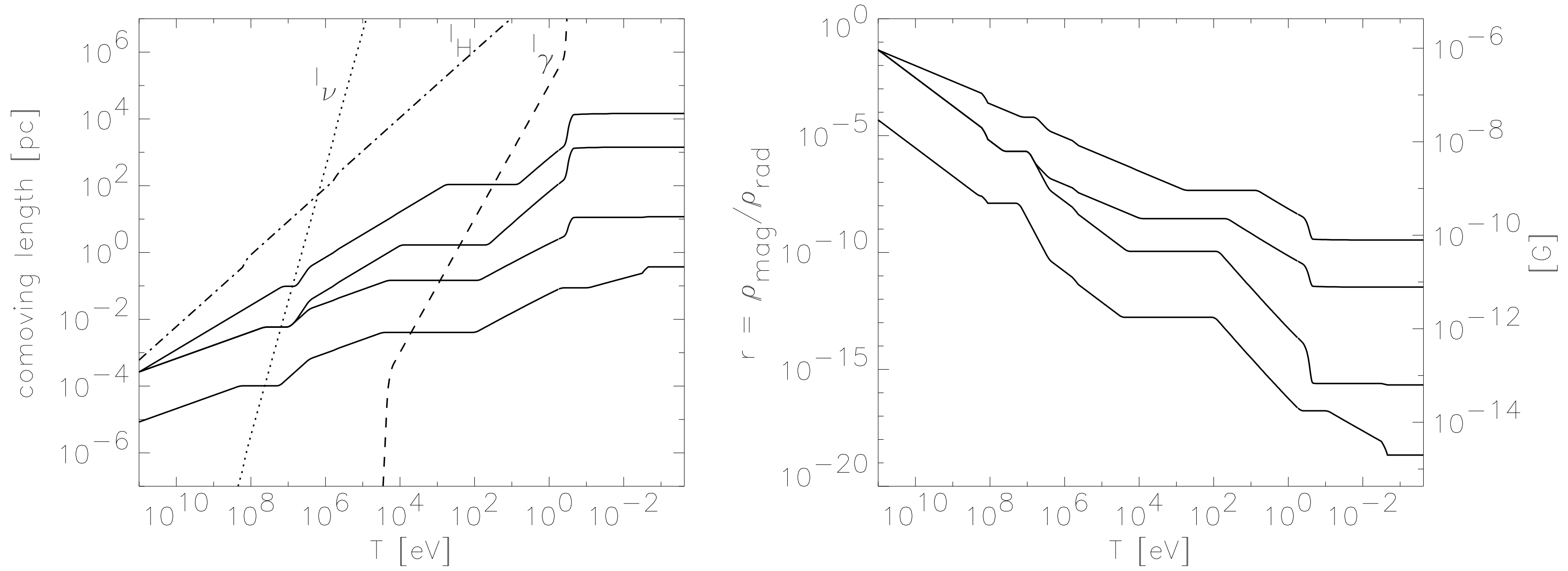
(Christensson, Hindmarsch, Brandenburg, 2001; Brandenburg 2001)



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

Magnetic field evolution

Banerjee and Jedamzik, PRD, 70, 123003, 2004



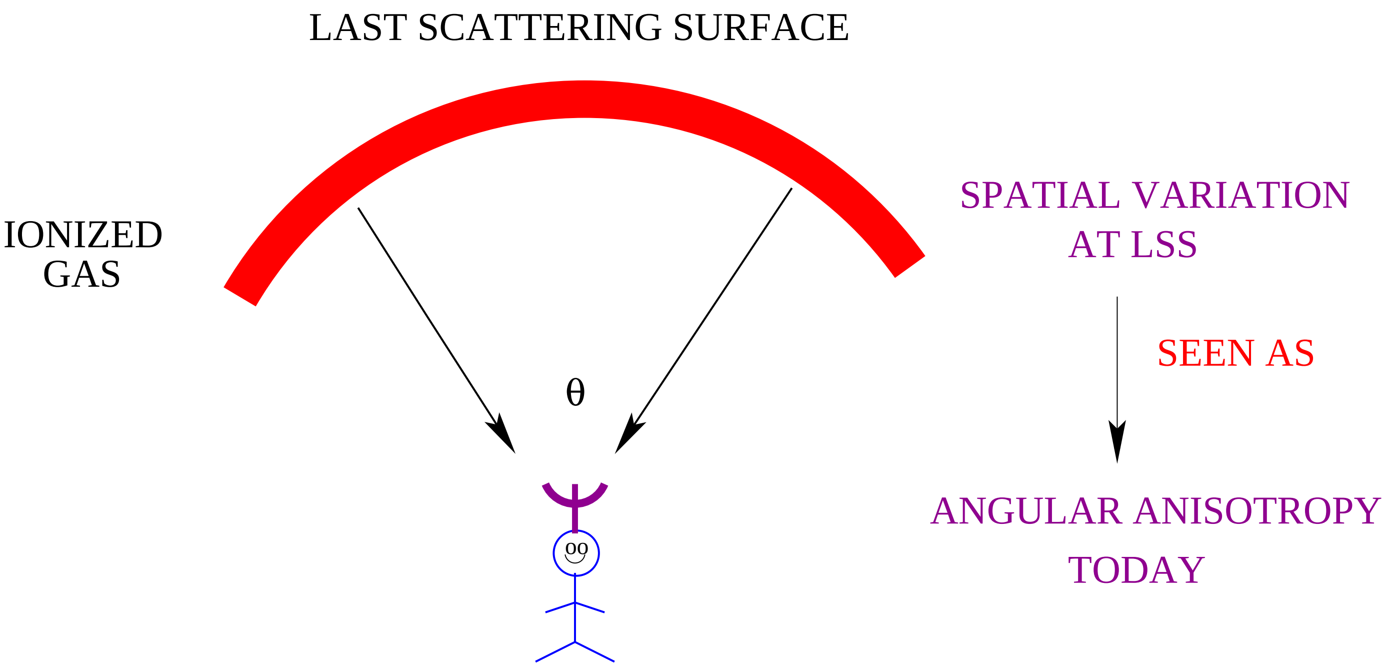
- $B^2/(8\pi\rho_{rad}) \sim 10^{-7}(B_0/10^{-9}G)^2$
- **Conductivity high; Viscosity important around neutrino/photon decoupling.**
- From top to bottom, (a) $h = 1$ $r = 10^{-2}$, (b) $h = 10^{-3}$ $r = 10^{-2}$ $n = 3$, (c) $h = 0$ $r = 10^{-2}$ $n = 3$, (d) $h = 1$ $r = 10^{-5}$ $n = 3$. $T_g = 100$ GeV.

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 ⇒ 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 ⇒ seeds $\delta\rho/\rho \Rightarrow$ First Structures
- B field Dissipation → Ionization, Heating, Molecules

Coherent primordial nG fields potentially detectable

CMB ANISOTRPIES



LAST SCATTERING SURFACE

IONIZED
GAS

θ

SPATIAL VARIATION
AT LSS

SEEN AS

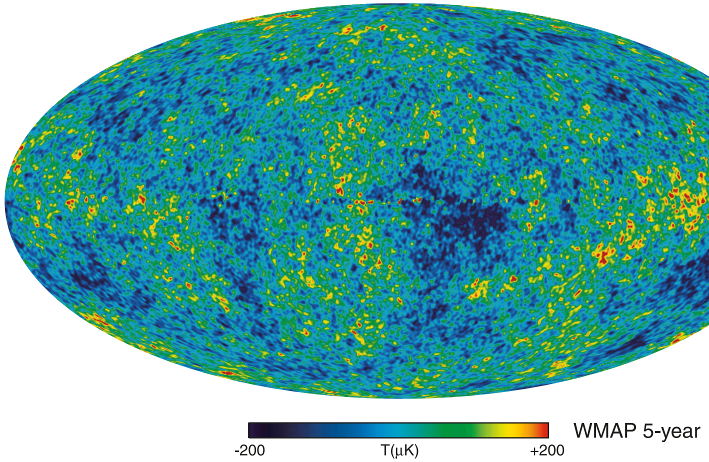
ANGULAR ANISOTROPY
TODAY

$$\frac{\Delta T}{T}(\theta,\phi) = \sum_{lm} a_{lm} Y_{lm}(\theta,\phi); \qquad \langle a_{lm} a_{l'm'} \rangle = C_l \delta_{ll'} \delta_{mm'} .$$

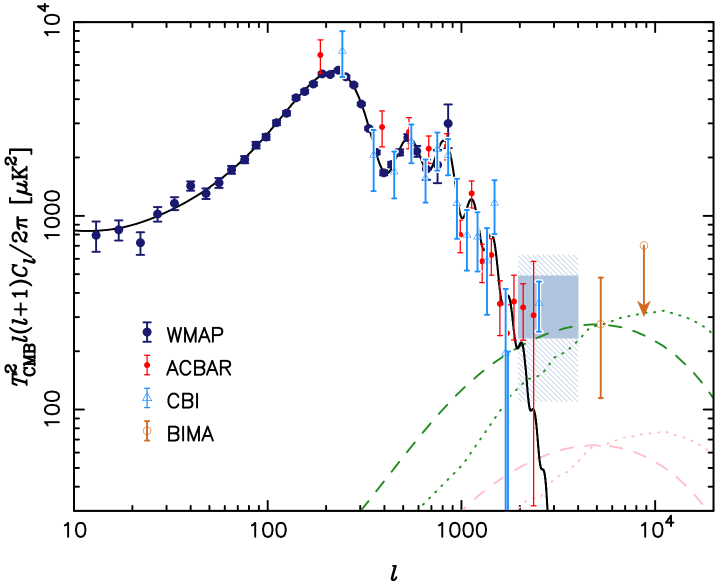
$$\frac{\langle (\Delta T)^2 \rangle}{T^2} = \sum_{l} C_l \frac{2l+1}{4\pi} \approx \int \frac{l(l+1)C_l}{2\pi}\, d\ln l$$

CMB Anisotropies – Observations

WMAP

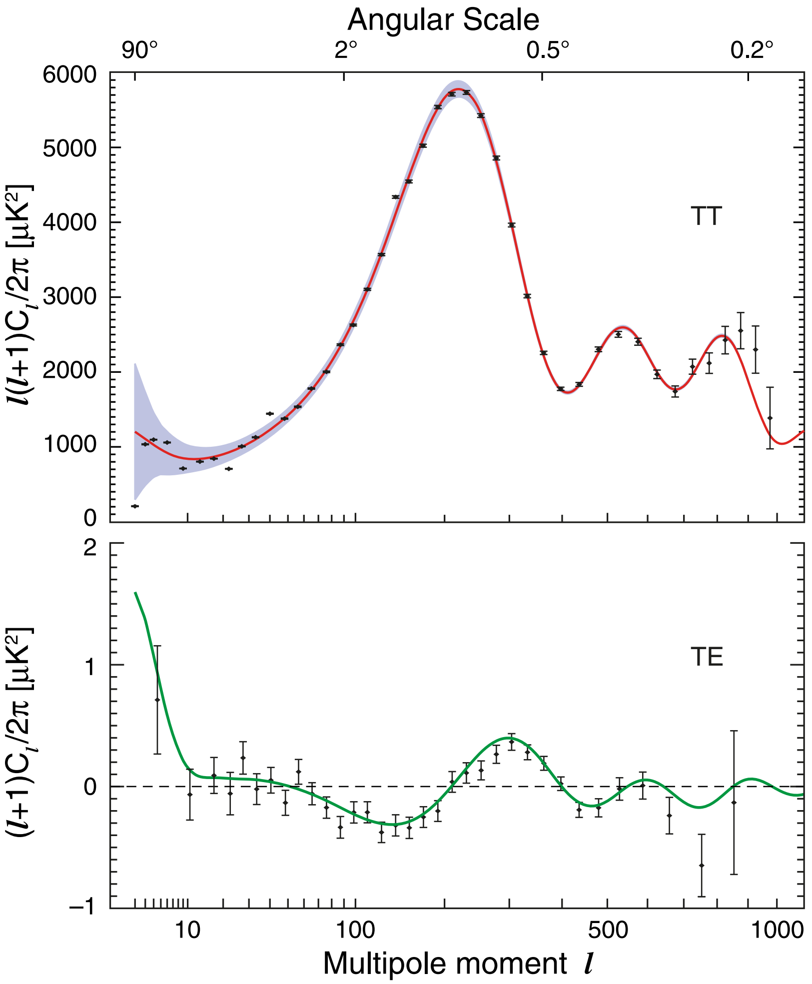


Readhead et al., ApJ, 609, 498, 2004



CBI Excess Power?

http://map.gsfc.nasa.gov



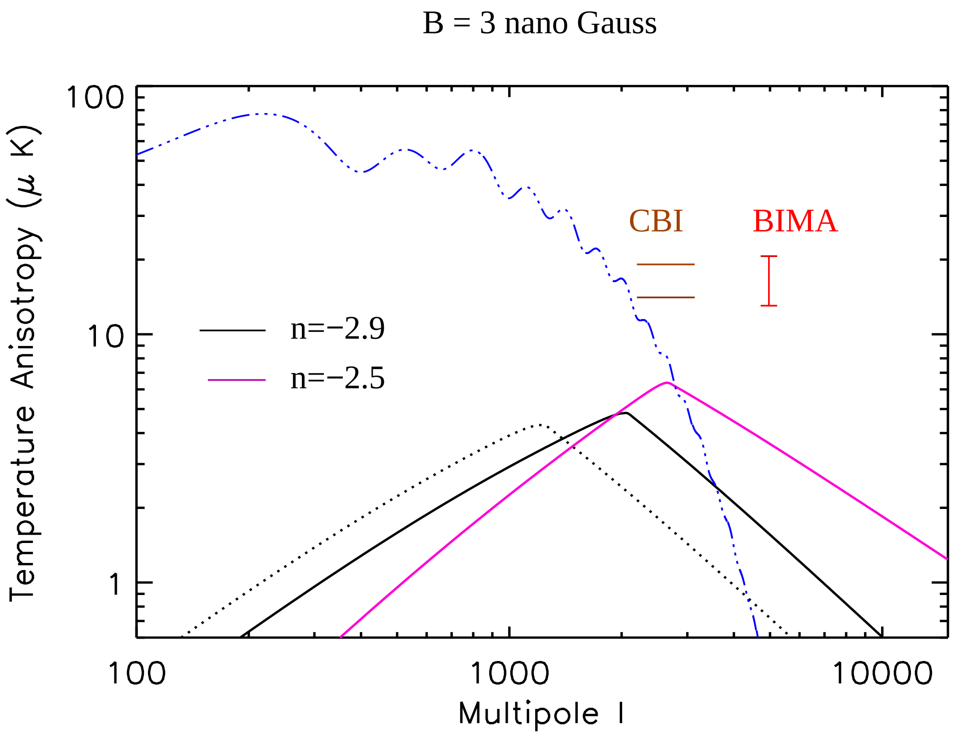
TT and TE Power spectrum

CMB signals from tangled B fields

- **Scalar Modes – Subdominant to Inflation generated signal,** (Shaw and Lewis, 2009, 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, 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)

Primordial few nG magnetic fields potentially detectable using the CMB

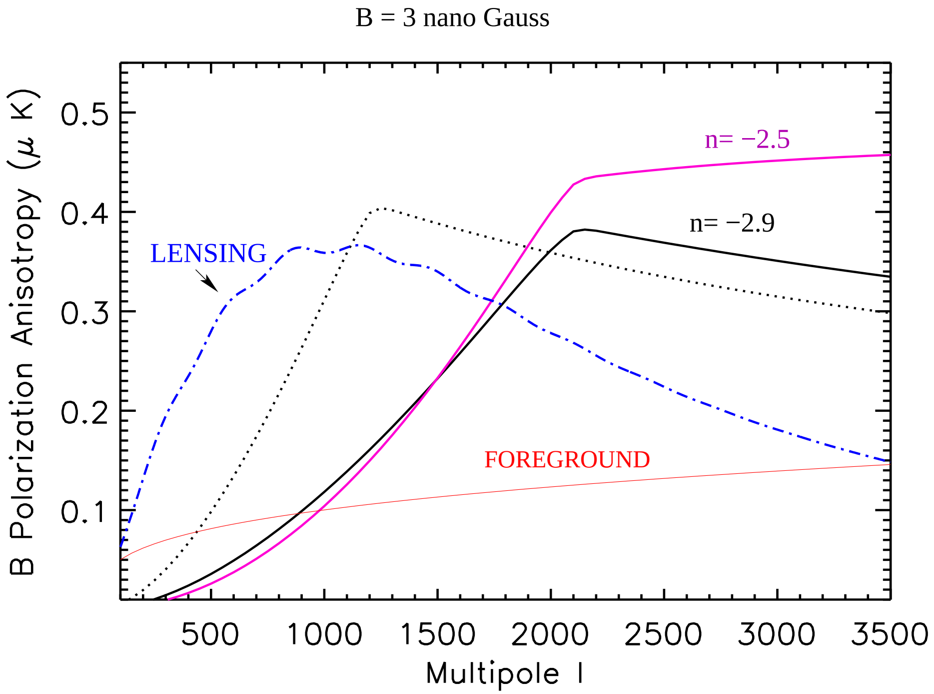
Vector mode CMB Signals



- Vortical motion of fluid at LSS (Vector modes)
- Can partially explain CBI Excess?
- Non Gaussian Statistics because $F_L \propto B^2$

KS,JDB, PRL, 81, 3375 (1998); MN, 335, L57 (2002); KS,TRS,JDB, MN, 344, L31 (2003)

CMB Polarization – Vector Modes

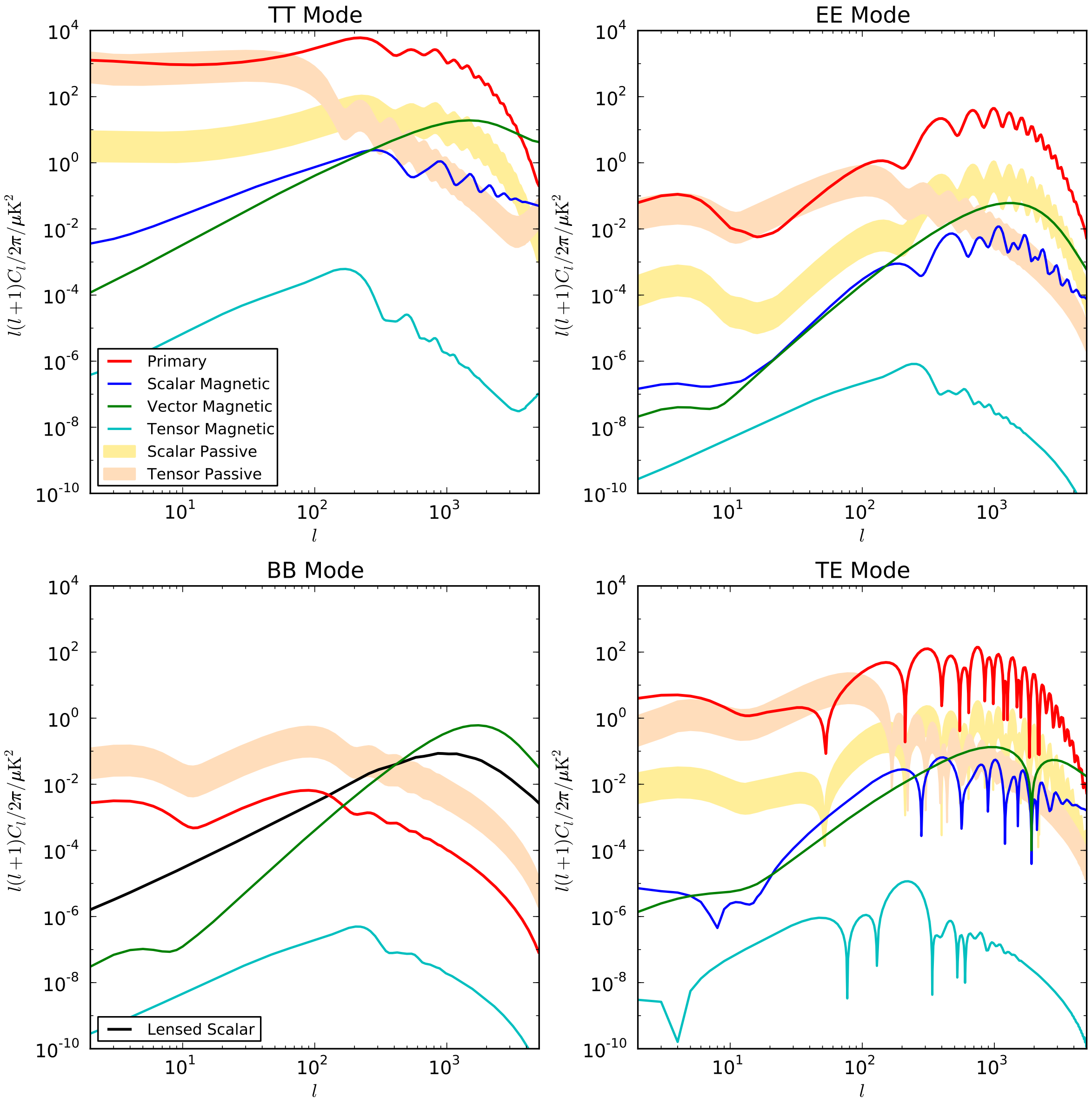


- Thomson Scattering + quadrupole at LSS $\Rightarrow$ Polarization
- B - Type Polarization (unlike inflationary Scalar Modes)
- Signals below Silk Damping scale ($l \geq 10^3$)

TRS, KS, PRL, 87, 101301 (2001); KS,TRS,JDB, MN, 344, L31 (2003)

CMB signals: scalar+Tensor + Vector

$B_\lambda = 4.7\mu\text{G}, n \sim -3$, Including passive component, Shaw & Lewis, arXiv:0911.2714

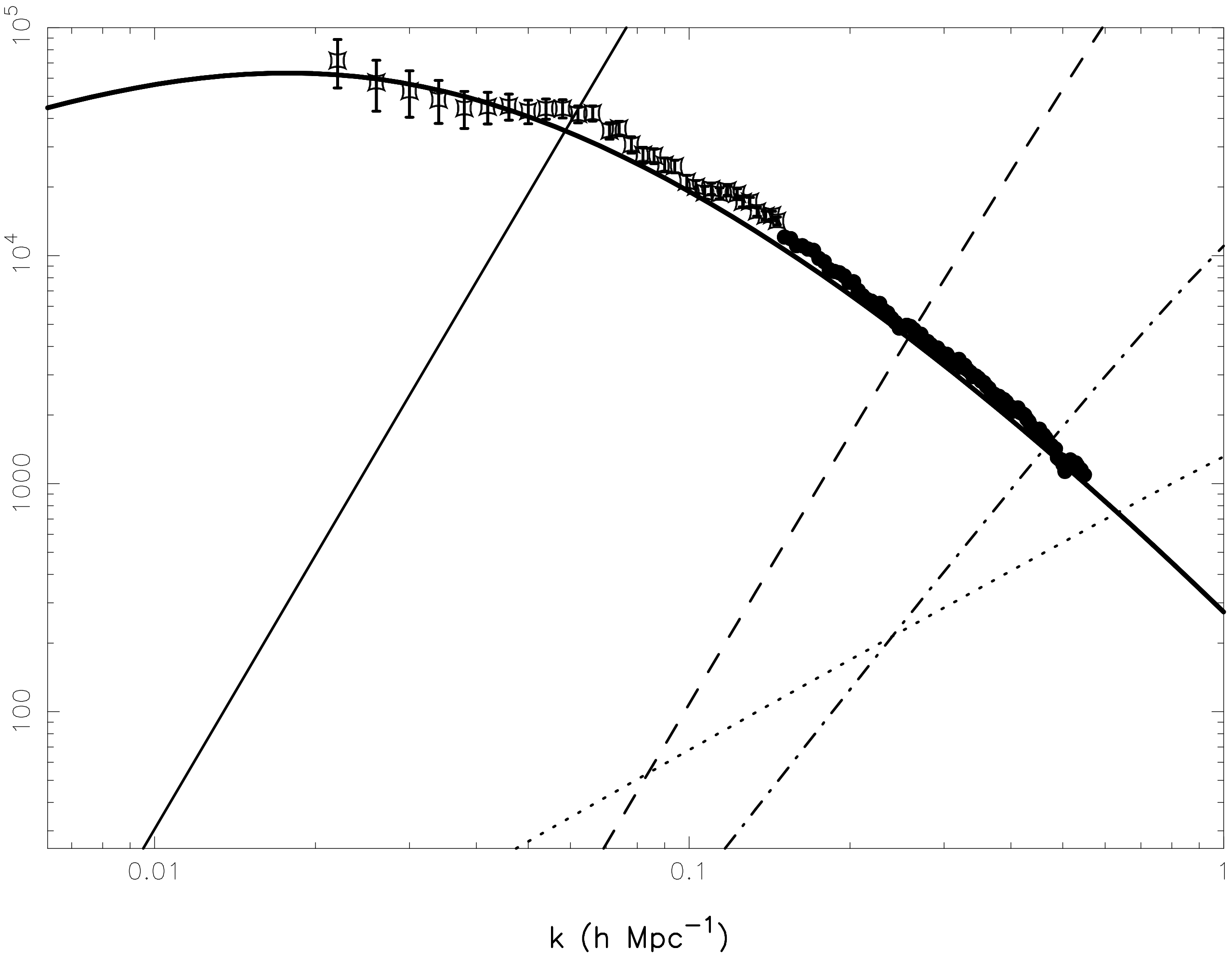


Structure formation signals

- **Extra power in the matter power spectrum on small scales** (Gopal, Sethi, 2003)
- **Damping of B field energy by ambipolar diffusion and decaying turbulence, can heat/ionize universe at $z \sim 100$** (Sethi, KS 2005; Schleicher, Banerjee, Klessen, 08).
- **Altered Visibility function → Additional CMB anisotropies**
- 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)

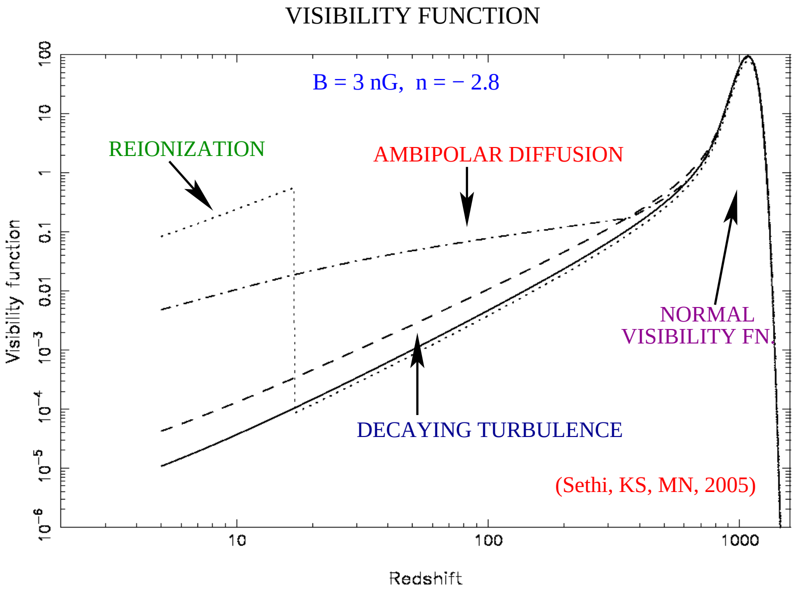
Modified matter power spectrum

Gopal, Sethi, JAA, 2003; 3 **nG,** $n = 0, -1, -2, -2.9$**; LCDM**

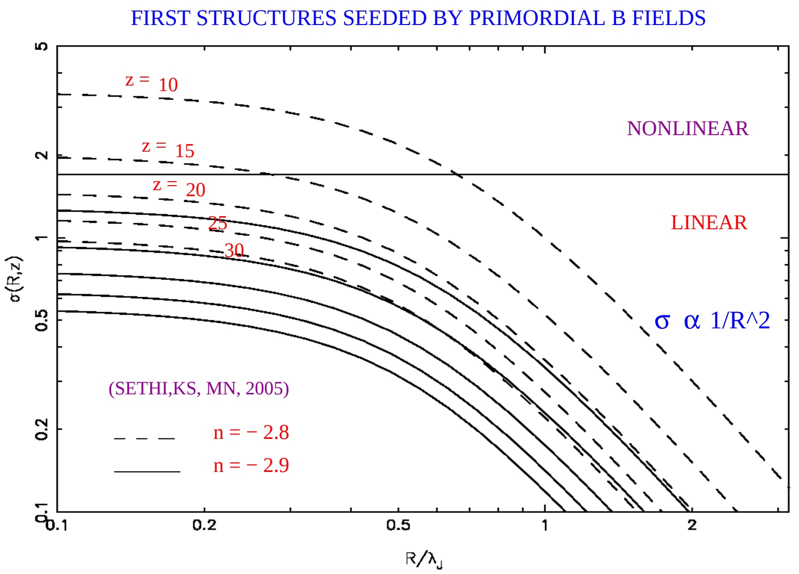


Post Recombination Blues

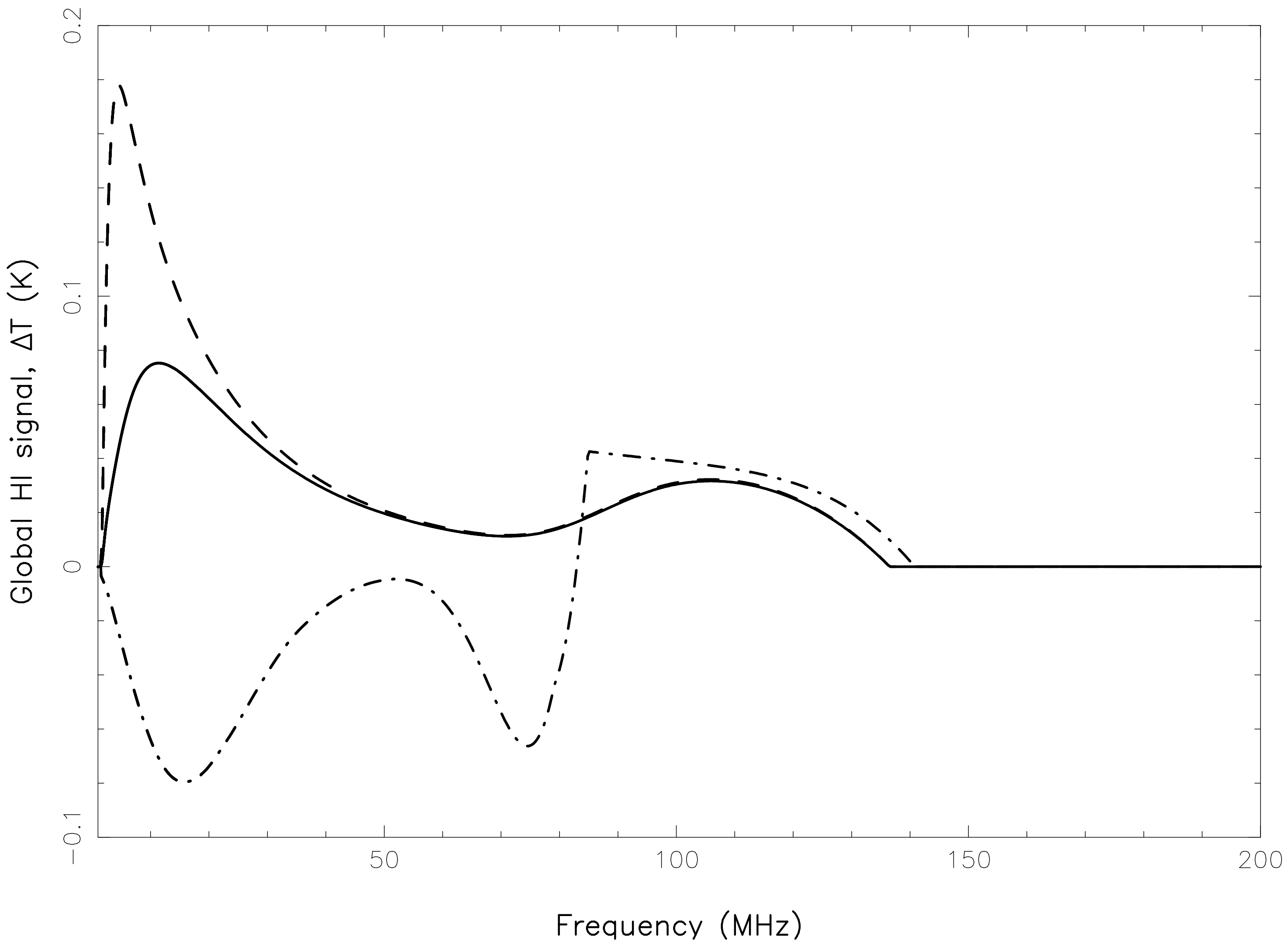
- Ambipolar damping and Turbulence decay $\Rightarrow$ gradual re-ionization $\Rightarrow$ Modified Visibility Function (Sethi, KS MN, 2005)



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



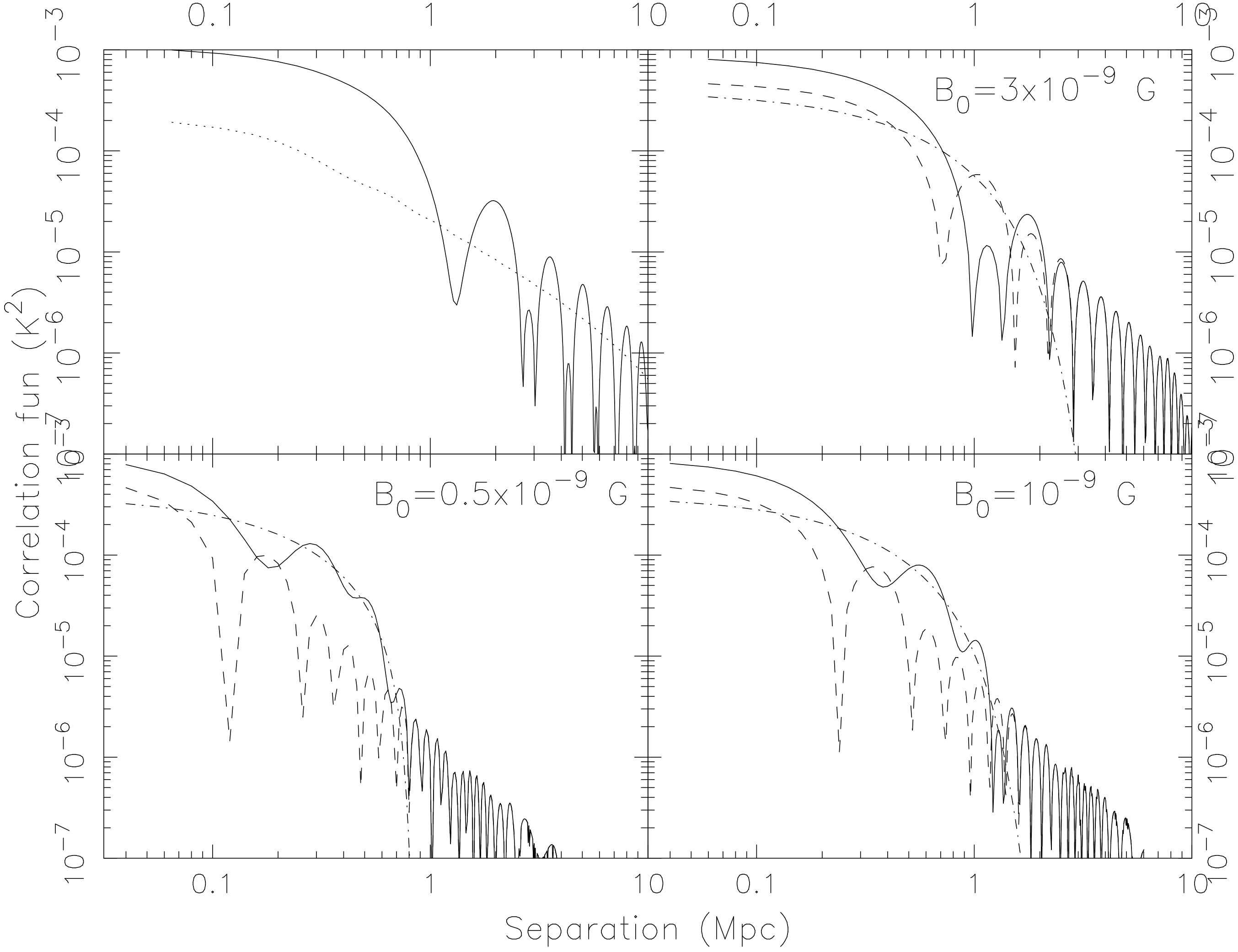
Global 21 cm signals from reionization



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?
- 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: Radio RMs (SKA) and High energy CRs
- Dynamos certainly needed to maintain fields BUT
  Need to understand their saturation better

THANK YOU!