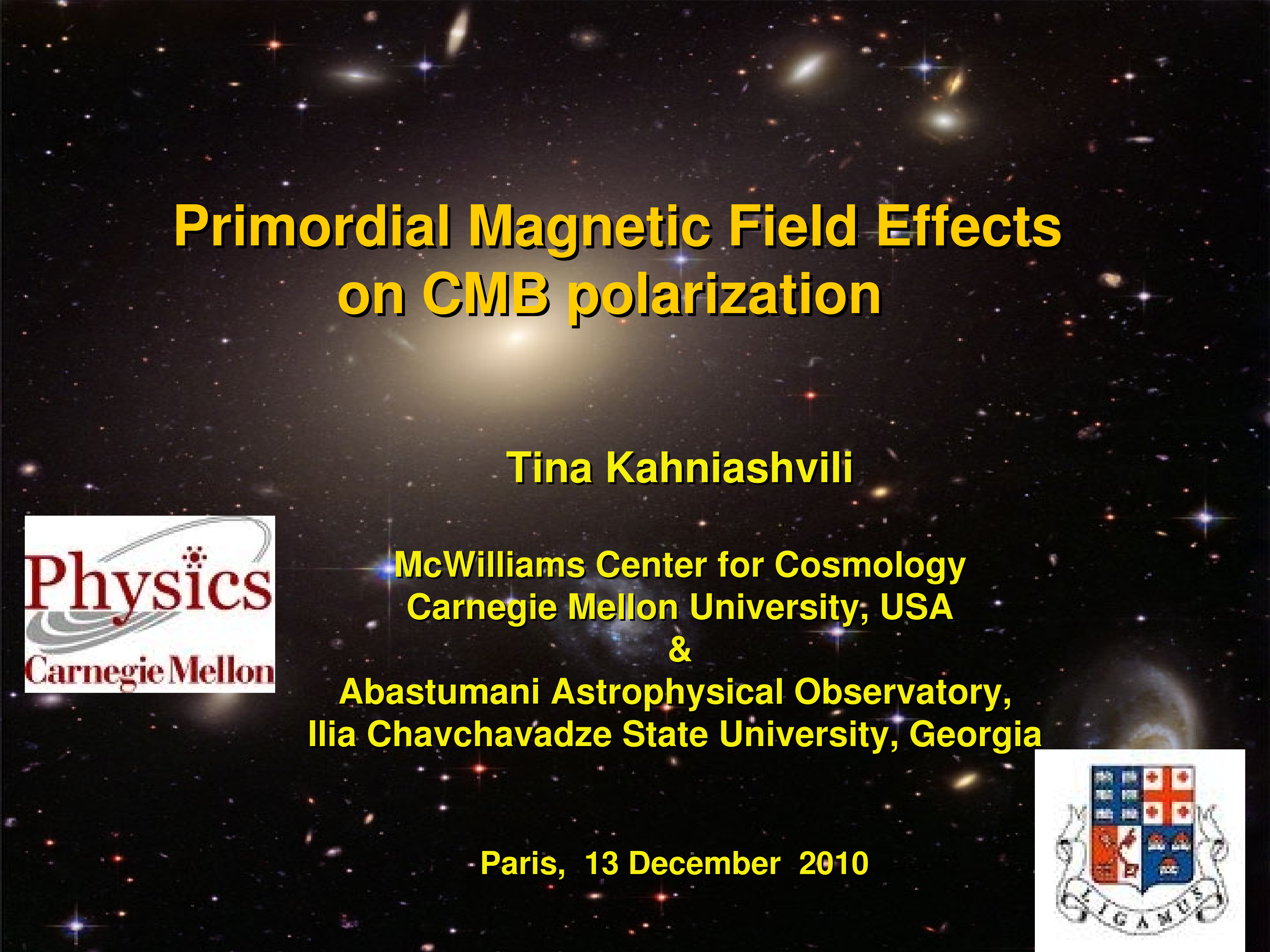

Primordial Magnetic Field Effects on CMB polarization

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Paris, 13 December 2010

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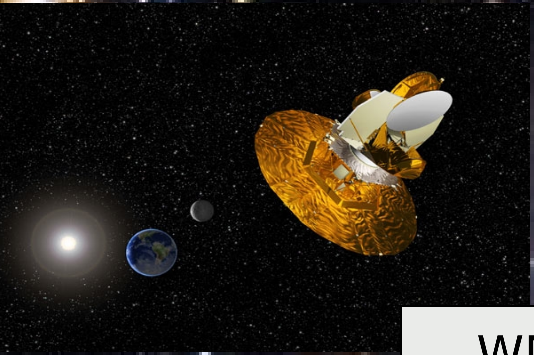
Outline

- General Overview
  - Why Polarization Measurements are Crucial?
- Primordial Magnetic Field Signatures
  - CMB polarization anisotropies
  - Faraday Rotation Effect
- Magnetic Field Limits
  - B-polarization
  - CMB Oddities

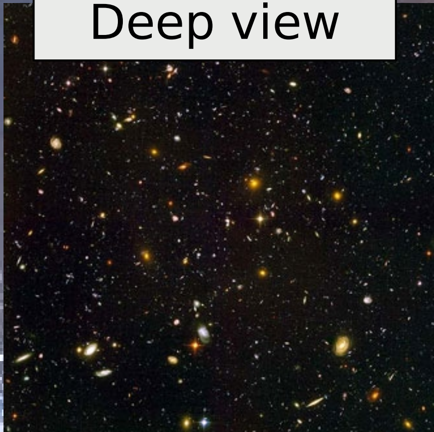
By Now We Observe the Universe Mostly Through


WMAP


PLANCK

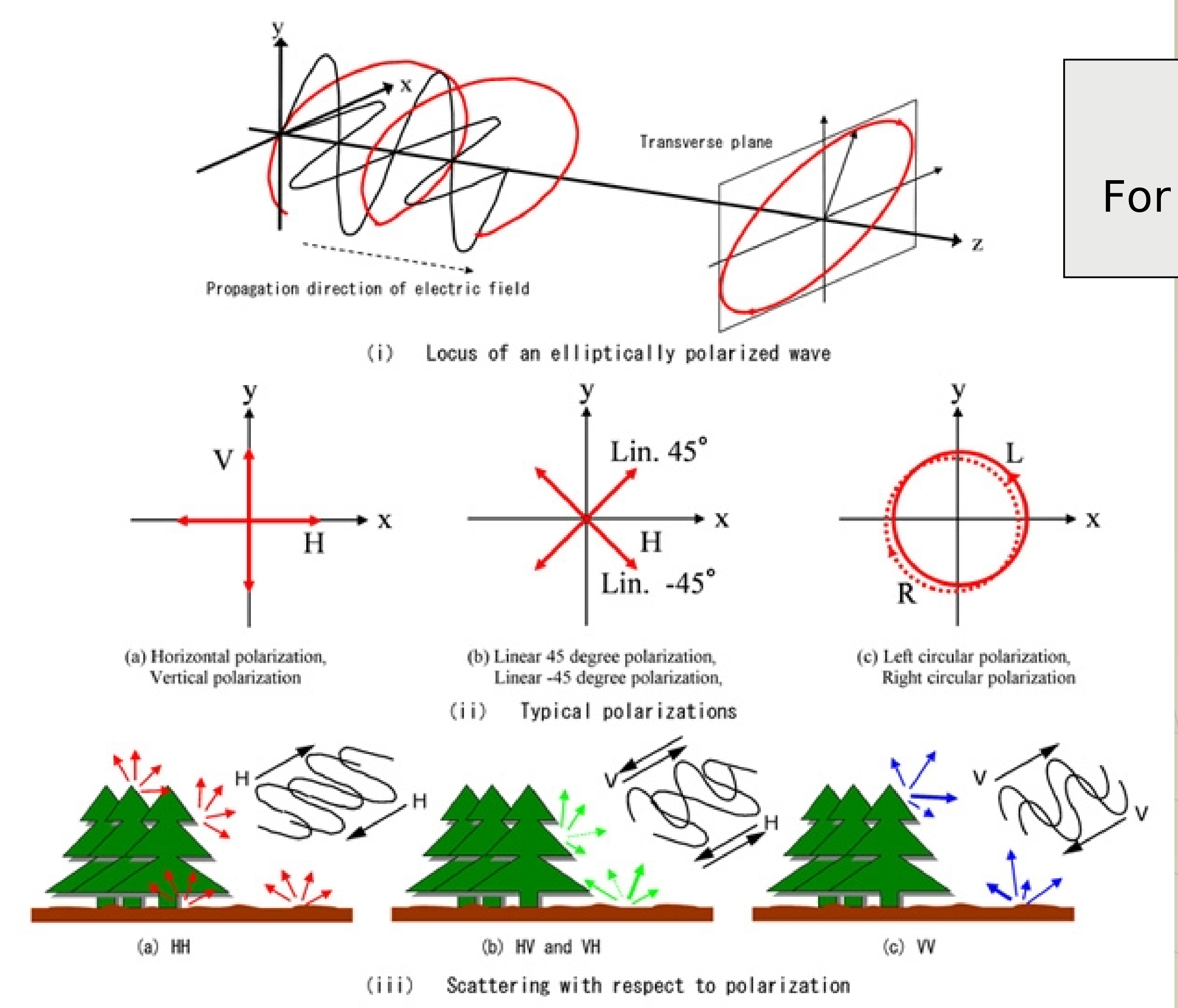
Electromagnetic Waves


Atacama
Space
Telescope


Hubble
Telescope
Deep view

In future:
Neutrinos, Gravitational Waves

In astrophysics EM waves polarization measurements are widely used



(i) Locus of an elliptically polarized wave

(a) Horizontal polarization, Vertical polarization

(b) Linear 45 degree polarization, Linear -45 degree polarization,

(c) Left circular polarization, Right circular polarization

(ii) Typical polarizations

(a) HH

(b) HV and VH

(c) VV

(iii) Scattering with respect to polarization

In particular,
For the magnetic tests

Polarization of Electromagnetic Waves

$$E_x(t) = a_x(t)\cos(\omega_0 t + \phi_x), \quad E_y(t) = a_y(t)\sin(\omega_0 t + \phi_y)$$

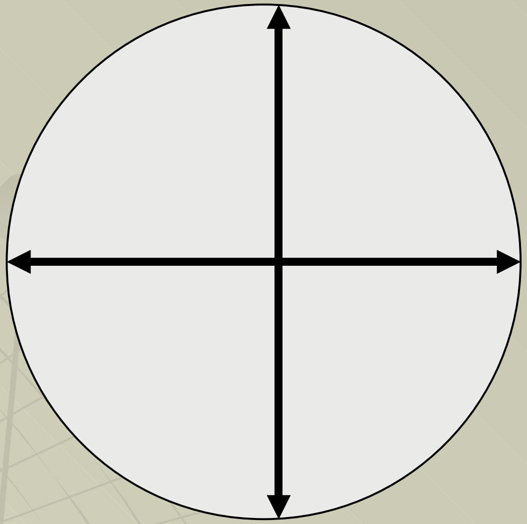
- I – intensity: $a_x^2+a_y^2$
- Q – polarization (linear) $a_x^2-a_y^2$
- U – polarization (linear) $2a_x a_y \cos(\phi_x-\phi_y)$
- V – polarization (circular) $2a_x a_y \sin(\phi_x-\phi_y)$

- I and V – invariants under rotation
- Q exchange U, U exchange Q:
  - Q^2+U^2 invariant

E and B polarization

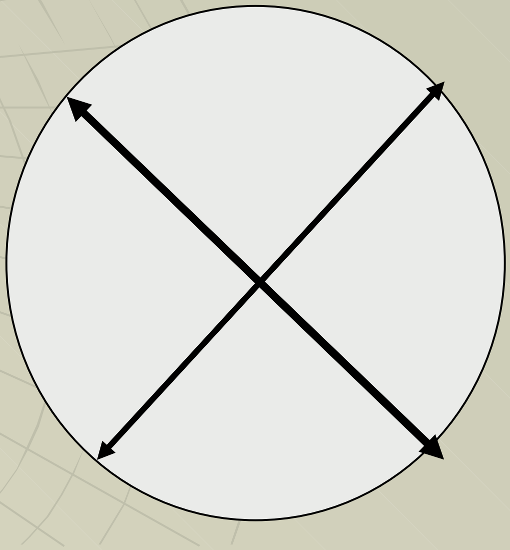
- E_l – electric $(-1)^l$

  Pure Q
  - North/South
  - East/West



- B_l – magnetic $(-1)^{l+1}$

  Pure U
  - Northeast/Southwest
  - Northwest/Southeast



Magnetic Field on the Universe

Faraday Rotation effect

- Observations:
  - Magnetic field in galaxies and clusters,

    10^{-6}-10^{-5} Gauss
  - Cosmic rays propagation

    10^{-11} Gauss on 1 Mpc
- Numerical simulations
- Theoretical models
  - Nonlinear process, magnetic field amplification, MHD
  - Cosmological magnetic field

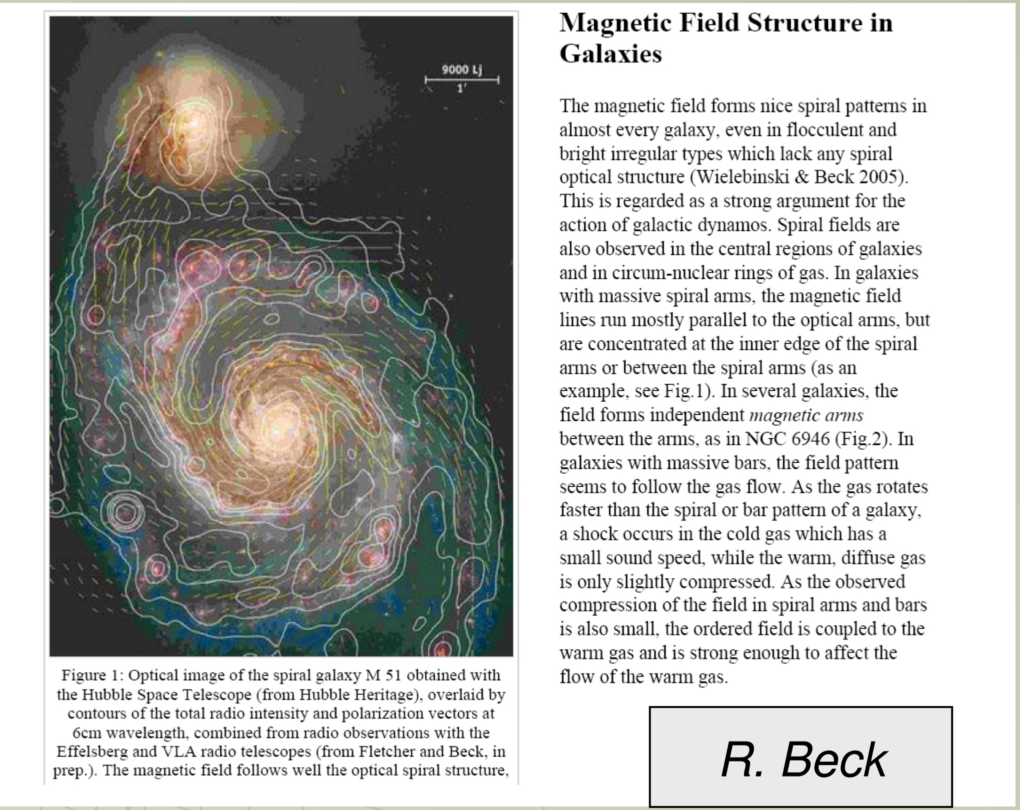


Figure 1: Optical image of the spiral galaxy M 51 obtained with the Hubble Space Telescope (from Hubble Heritage), overlaid by contours of the total radio intensity and polarization vectors at 6cm wavelength, combined from radio observations with the Effelsberg and VLA radio telescopes (from Fletcher and Beck, in prep.). The magnetic field follows well the optical spiral structure,

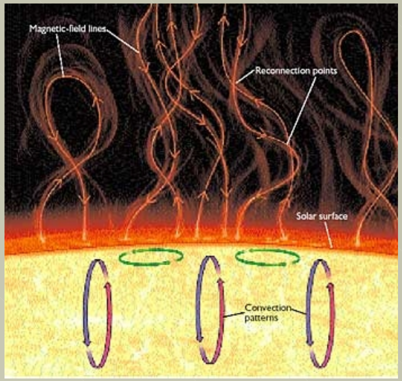
Magnetic Field Structure in Galaxies

The magnetic field forms nice spiral patterns in almost every galaxy, even in flocculent and bright irregular types which lack any spiral optical structure (Wielebinski & Beck 2005). This is regarded as a strong argument for the action of galactic dynamos. Spiral fields are also observed in the central regions of galaxies and in circum-nuclear rings of gas. In galaxies with massive spiral arms, the magnetic field lines run mostly parallel to the optical arms, but are concentrated at the inner edge of the spiral arms or between the spiral arms (as an example, see Fig.1). In several galaxies, the field forms independent *magnetic arms* between the arms, as in NGC 6946 (Fig.2). In galaxies with massive bars, the field pattern seems to follow the gas flow. As the gas rotates faster than the spiral or bar pattern of a galaxy, a shock occurs in the cold gas which has a small sound speed, while the warm, diffuse gas is only slightly compressed. As the observed compression of the field in spiral arms and bars is also small, the ordered field is coupled to the warm gas and is strong enough to affect the flow of the warm gas.

R. Beck

- E. Fermi *"On the origin of the cosmic radiation"*, PRD, 75, 1169 (1949)
- F. Hoyle in Proc. *"La structure et l'evolution de l'Universe"* (1958) "

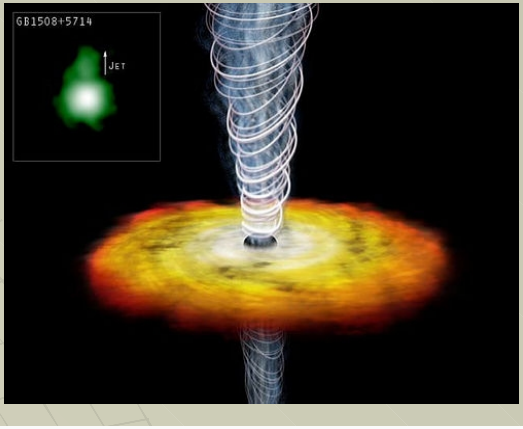
Magnetic Helicity



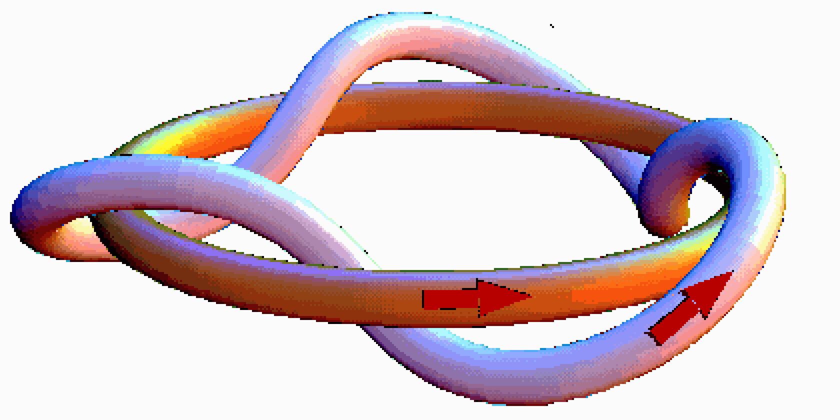
- **Astrophysical Observations**

(Mirror symmetry breaking)

  - Sun magnetic field
  - Active galactic nuclei
  - Jets



- **How we observe magnetic helicity**



  - The polarization of emitted synchrotron radiation

T.A. Ensslin, 2003; J. P. Valee, 2004

$$\mathcal{H} = \frac{1}{V}\int_V d^3x\, \mathbf{A}\cdot\mathbf{B}$$

Neronov and Vovk, Science 2010

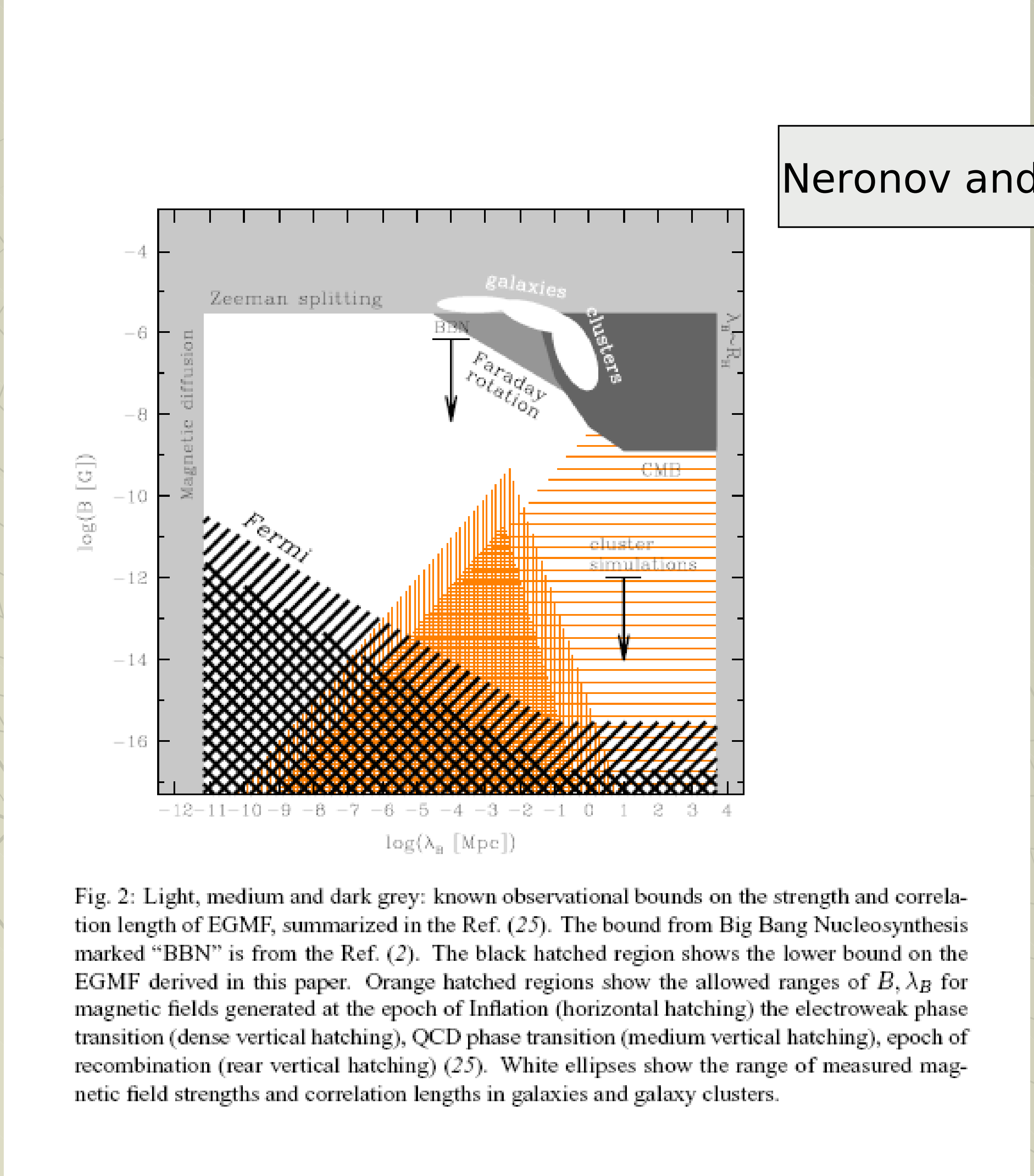


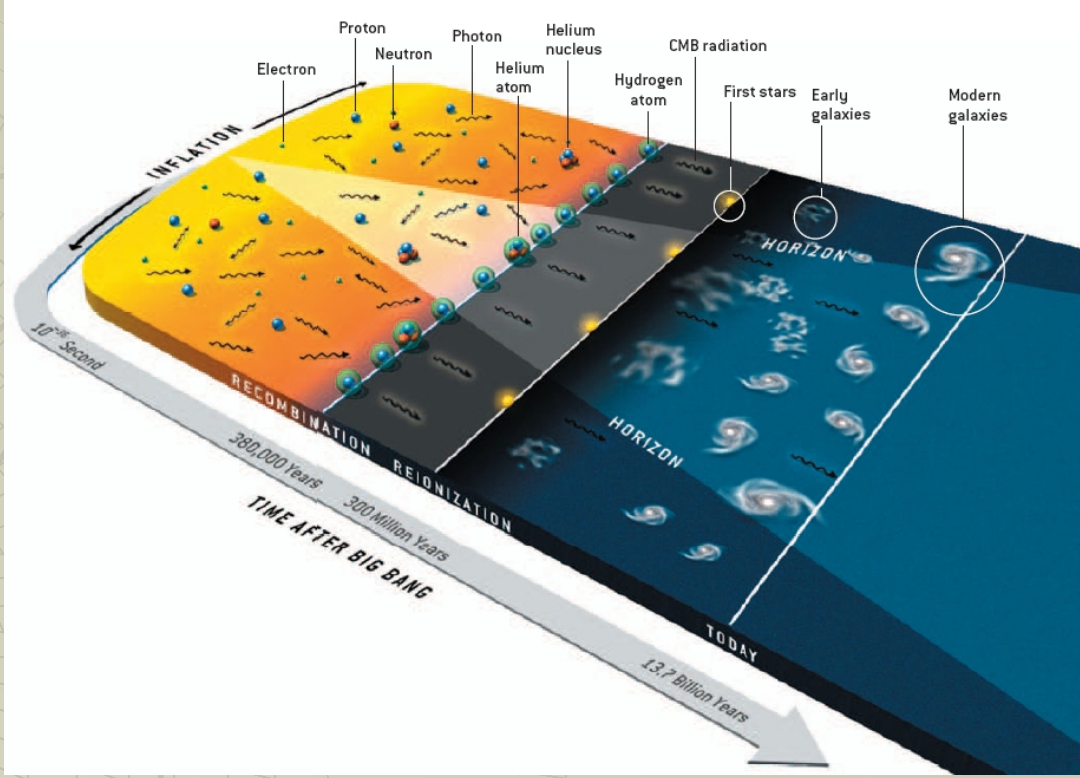
Fig. 2: Light, medium and dark grey: known observational bounds on the strength and correlation length of EGMF, summarized in the Ref. (*25*). The bound from Big Bang Nucleosynthesis marked "BBN" is from the Ref. (*2*). The black hatched region shows the lower bound on the EGMF derived in this paper. Orange hatched regions show the allowed ranges of B, λ_B for magnetic fields generated at the epoch of Inflation (horizontal hatching) the electroweak phase transition (dense vertical hatching), QCD phase transition (medium vertical hatching), epoch of recombination (rear vertical hatching) (*25*). White ellipses show the range of measured magnetic field strengths and correlation lengths in galaxies and galaxy clusters.

Why Cosmological Magnetic Fields are attractive?

- Might serve as seeds for the observed fields in galaxies and clusters
- Might be responsible for large scale correlated magnetic fields in the voids
- Might explain some cosmological observations

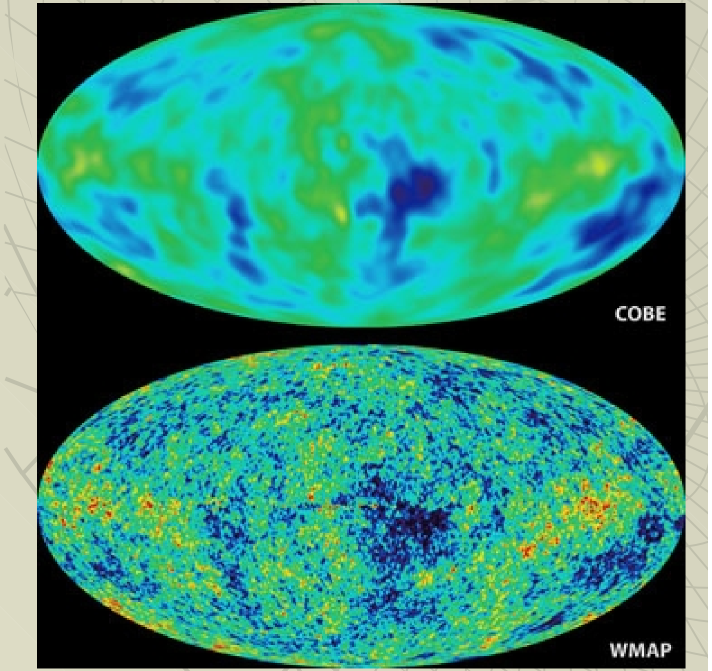
Generation Mechanisms

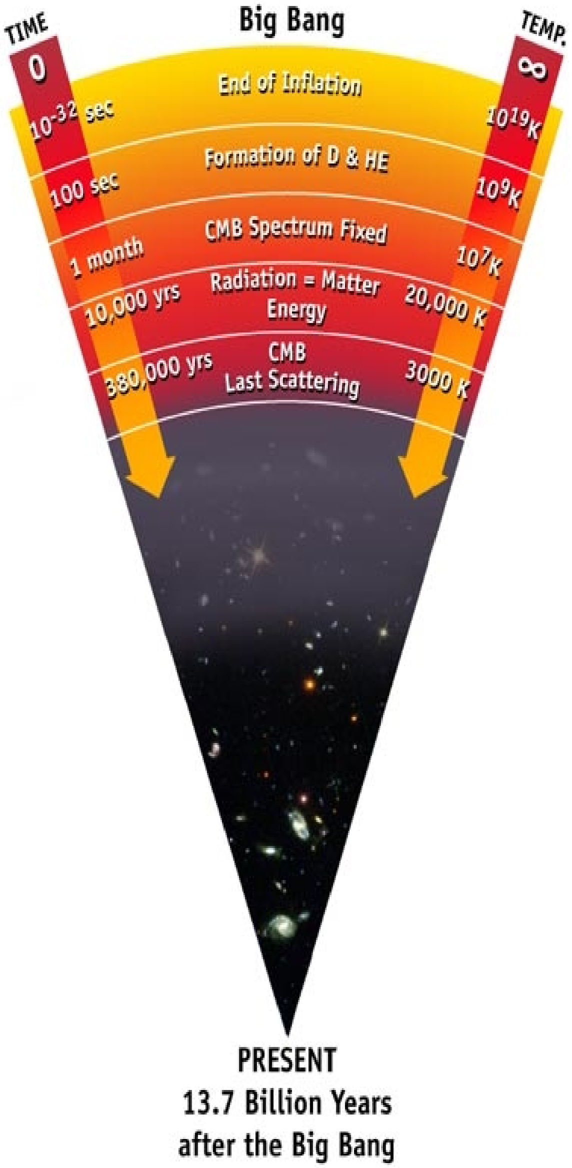
- Inflation
- Phase transitions
- Supersymmetry
- String Cosmology
- Topological deffects



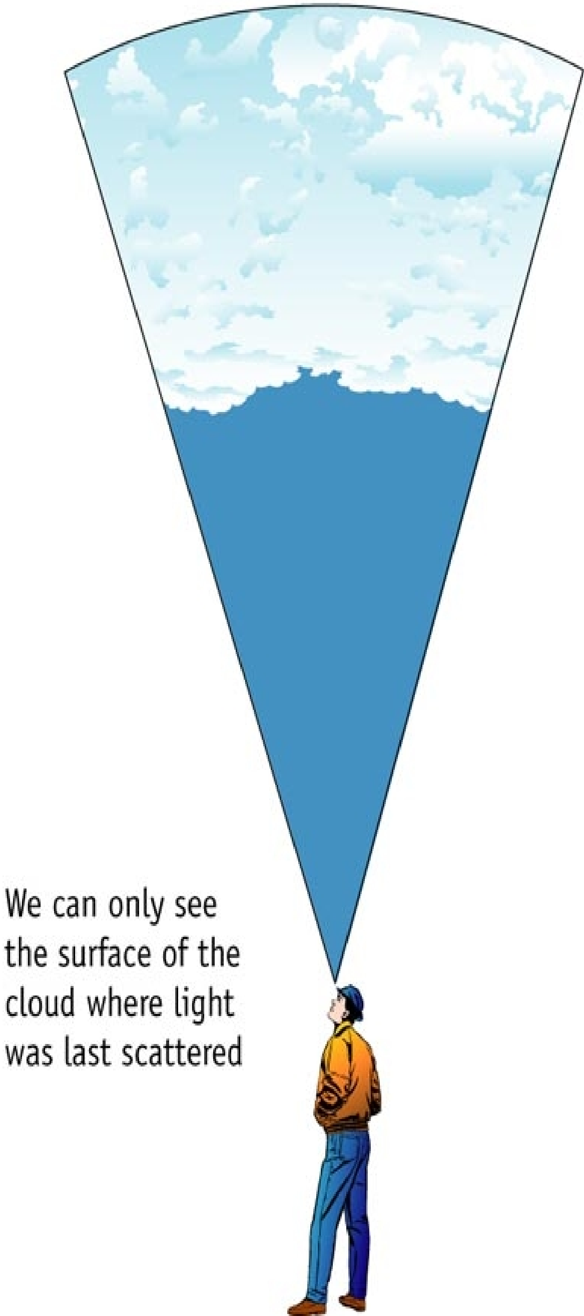
- The EM Waves for the past - CMB

CMB allows us “see” until last scatering surface





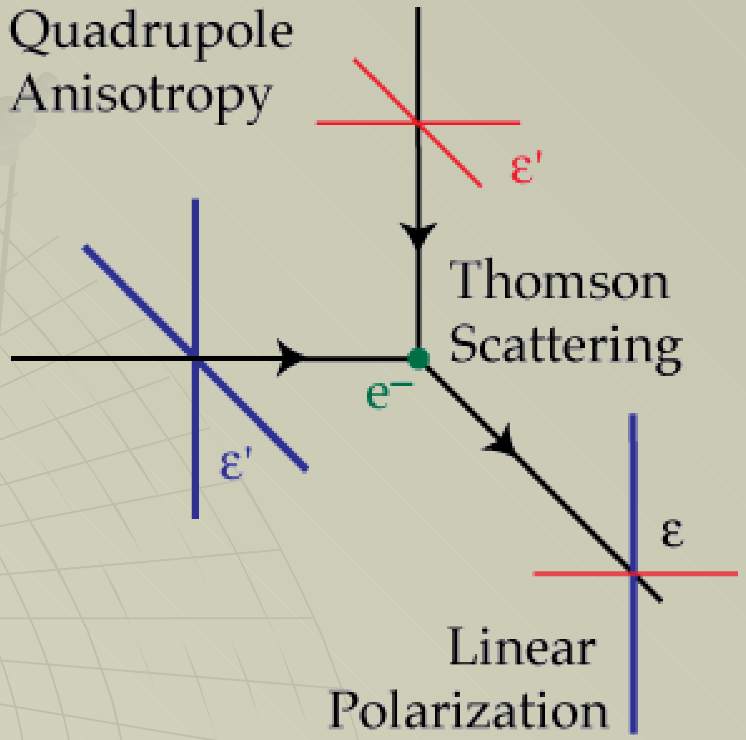
The cosmic microwave background Radiation’s “surface of last scatter” is analogous to the light coming through the clouds to our eye on a cloudy day.



CMB Polarization

Bond & Efstathiou 1984 Polnarev 1985, Kosowsky 1996, Kamionkowski et al. 1997; Zaldarriaga & Seljak 1997, Hu & White 1997

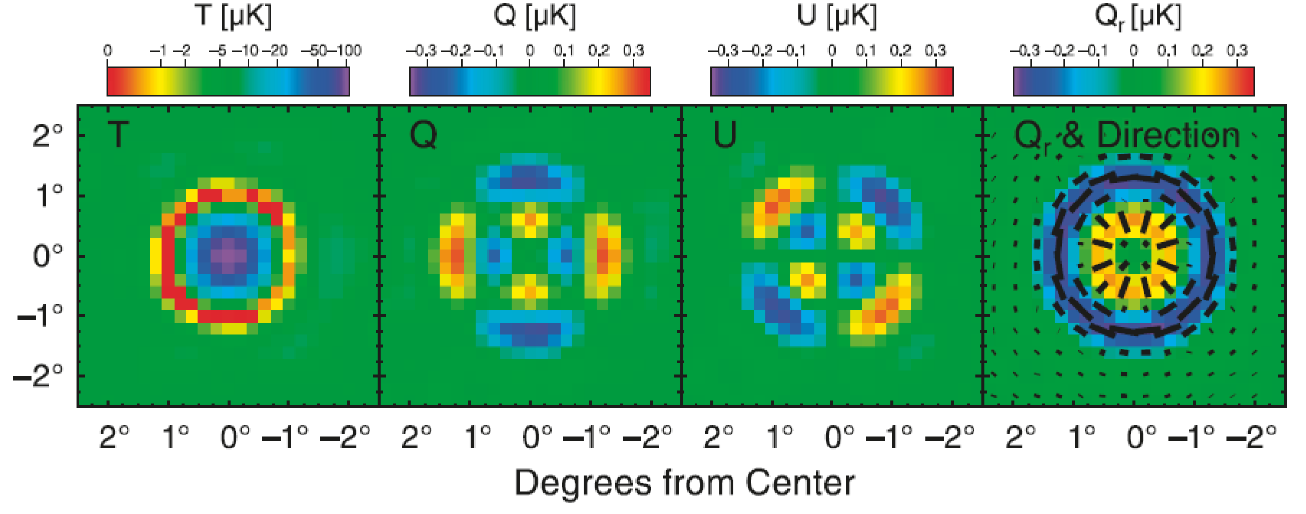
- Generation of Polarization anisotropy
  - Boltzmann equation
  - Scalar mode – only E-polarization
- Propagation effects
  - Birefrigence
  - Lensing
  - Lorentz symmetry
    - Input: E –polarization
    - Output: B-polarization

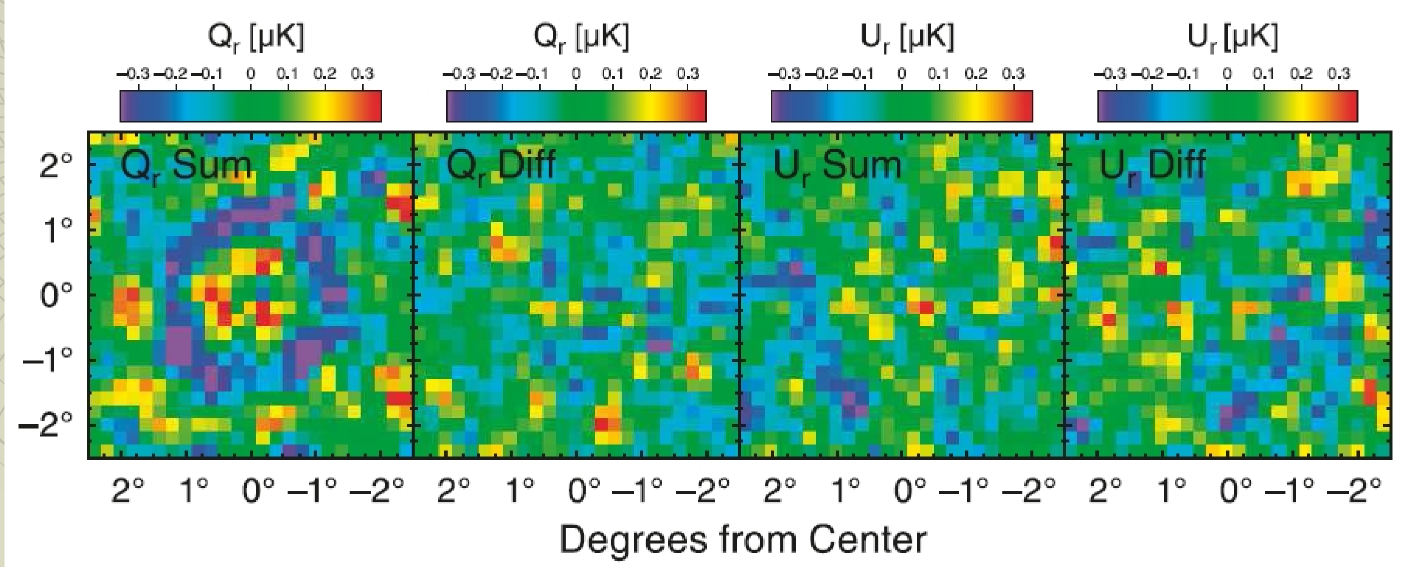


Wayne Hu Web-page

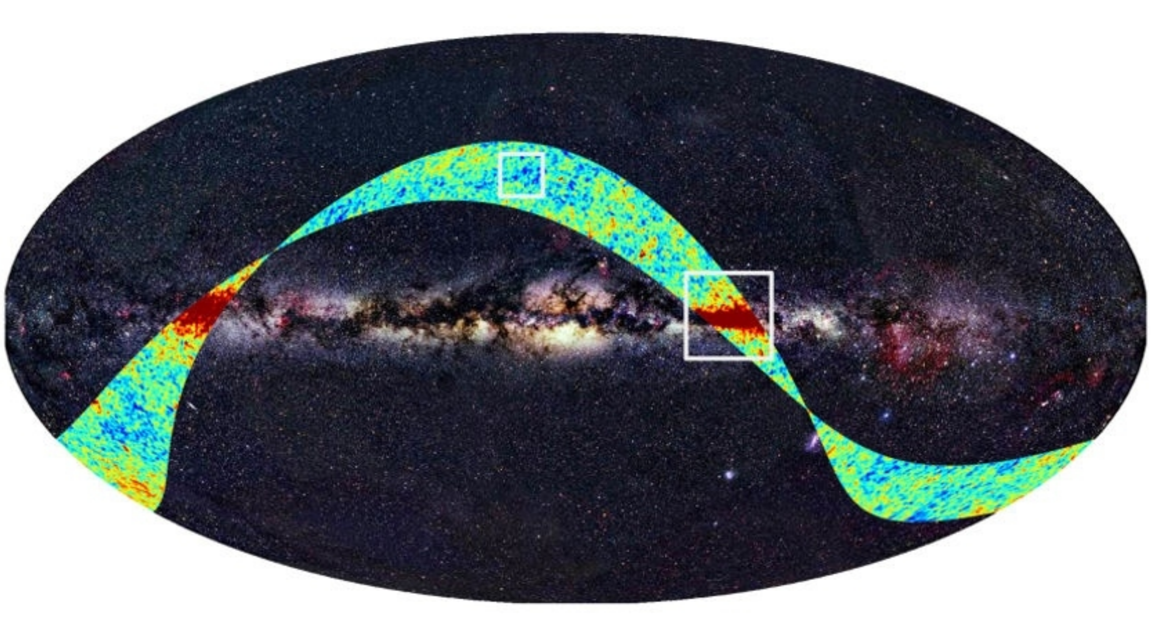
SEVEN-YEAR WILKINSON MICROWAVE ANISOTROPY PROBE (*WMAP*[1]) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

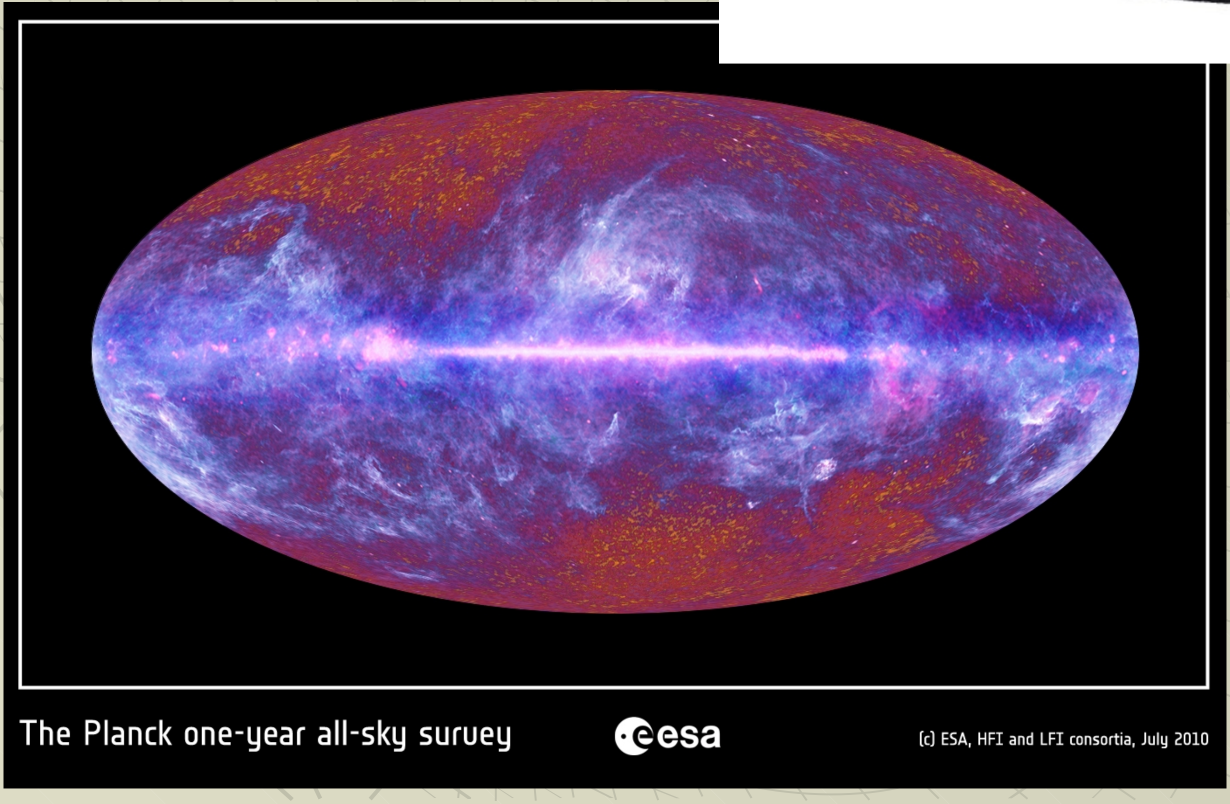
E. Komatsu[2], K. M. Smith[3], J. Dunkley[4], C. L. Bennett[5], B. Gold[5], G. Hinshaw[6], N. Jarosik[7], D. Larson[5], M. R. Nolta[8], L. Page[7], D. N. Spergel[3,9], M. Halpern[10], R. S. Hill[11], A. Kogut[6], M. Limon[12], S. S. Meyer[13], N. Odegard[11], G. S. Tucker[14], J. L. Weiland[11], E. Wollack[6], and E. L. Wright[15]





PLANCK First Images





The Planck one-year all-sky survey

esa

(c) ESA, HFI and LFI consortia, July 2010

Polarization Plane Rotation Angle: WMAP
Lorentz Symmetry or Parity Symmetry Violation?

Komatsu et al. 2008

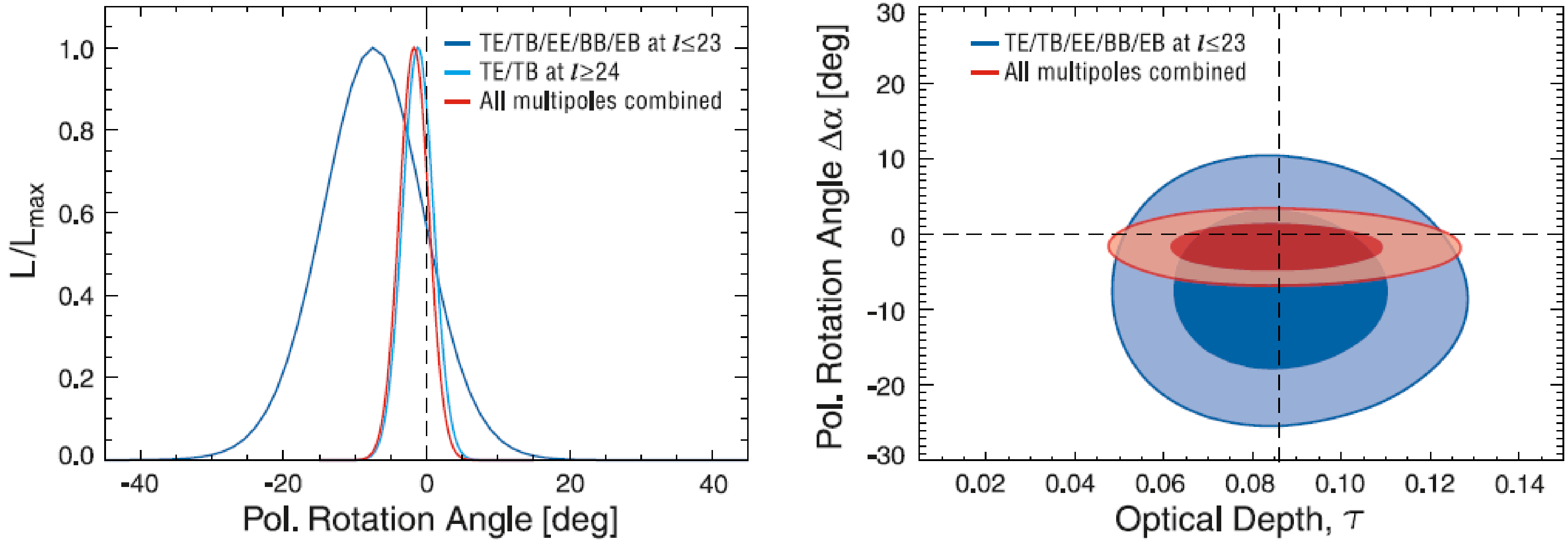


FIG. 10.— Constraint on the polarization rotation angle, $\Delta\alpha$, due to a parity-violating interaction that rotates the polarization angle of CMB (§ 4.3). We have used the polarization spectra (TE/TB/EE/BB/EB at $l \le 23$, and TE/TB at $l \ge 24$), and did not use the TT power spectrum. (*Left*) One-dimensional marginalized constraint on $\Delta\alpha$ in units of degrees. The dark blue, light blue, and red curves show the limits from the low-l ($2 \le l \le 23$), high-l ($24 \le l \le 450$), and combined ($2 \le l \le 450$) analysis of the polarization data, respectively. (*Right*) Joint two-dimensional marginalized constraint on τ and $\Delta\alpha$ (68% and 95% CL). The bigger contours are from the low-l analysis, while the smaller ones are from the combined analysis. The vertical dotted line shows the best-fitting optical depth in the absence of parity violation ($\tau = 0.086$), whereas the horizontal dotted line shows $\Delta\alpha = 0$ to guide eyes.

A Primordial Magnetic Filed?

Magnetic Field Spectrum

- Two point correlation function Fourier space

$$F_{ij}^{M}(\mathbf{k},\tau) = P_{ij}(\mathbf{k})\frac{E^{M}(k,t)}{4\pi k^{2}} + i\varepsilon_{ijl}k_{l}\frac{H^{M}(k,t)}{8\pi k^{2}}.$$

Isotropic & helical divergence free vector field

- The averaged helicity spectrum amplitude $H^M(k,t)$
- The averaged magnetic field energy spectrum amplitude $E^M(k,t)$
- Schwatz’s inequality

$$|H^M(k,t)| \cdot 2\, E^M(k,t)/k$$

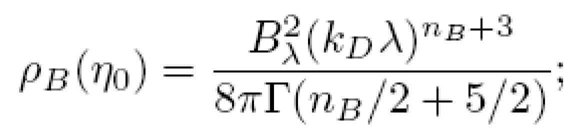
Smoothed Magnetic Field

- The smoothed field value

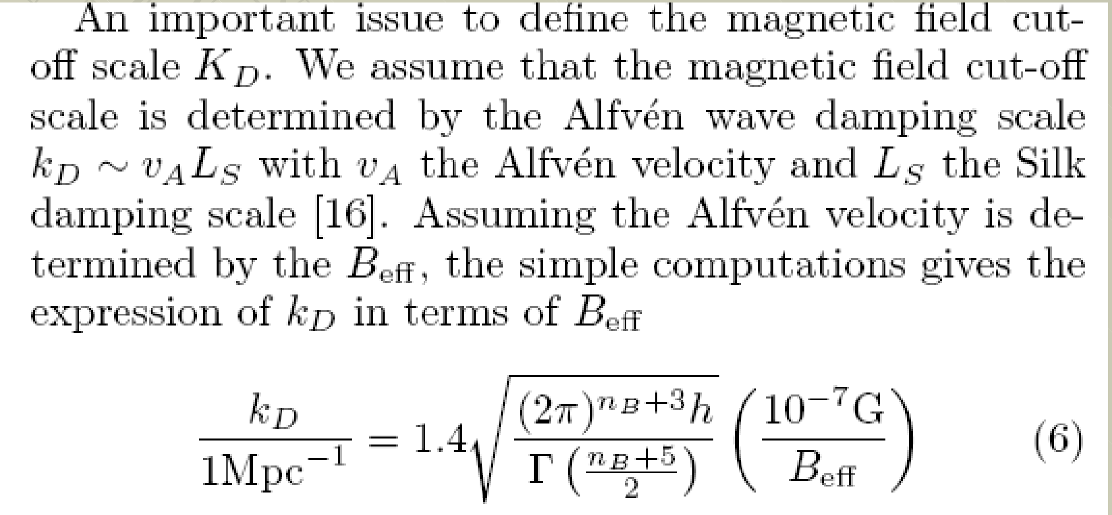
$$B_\lambda{}^2 = \langle \mathbf{B}(\mathbf{x}) \cdot \mathbf{B}(\mathbf{x}) \rangle|_\lambda .$$

- The magnetic energy density

$\rho_B = B_{eff}^2/8\pi$



$$\rho_B(\eta_0) = \frac{B_\lambda^2 (k_D \lambda)^{n_B+3}}{8\pi\Gamma(n_B/2+5/2)};$$



An important issue to define the magnetic field cut-off scale K_D. We assume that the magnetic field cut-off scale is determined by the Alfvén wave damping scale $k_D \sim v_A L_S$ with v_A the Alfvén velocity and L_S the Silk damping scale [16]. Assuming the Alfvén velocity is determined by the $B_{\rm eff}$, the simple computations gives the expression of k_D in terms of $B_{\rm eff}$

$$\frac{k_D}{1\mathrm{Mpc}^{-1}} = 1.4 \sqrt{\frac{(2\pi)^{n_B+3} h}{\Gamma\left(\frac{n_B+5}{2}\right)}} \left(\frac{10^{-7}\mathrm{G}}{B_{\rm eff}} \right) \qquad (6)$$

k_D definition

Subramanian and Barrow 1998

Jedamzik, Katalinic, and Olinto 2000

B_{eff} vs B_{λ}

- If the magnetic field is generated during inflation and has a scale invariant spectrum with n_B -> -3 then

  $B_{\lambda} = B_{eff}$ for any value of λ and this result does not depend on n_B
- For any other fields the difference between B_{eff} and B_{λ} (λ =1Mpc) might be enormous, while the physical effects depend on B_{eff} we proposed to derive all effects in terms of the total magnetic energy density present in the Universe.

CMB Faraday rotation

- Kosowsky & Loeb 1996

CMB polarization rotation angle

$$\langle\varphi^2\rangle^{1/2} \approx \frac{e^3 B_0}{2\sqrt{2}\pi m^2 \sigma_T \nu_0^2} = 1.6^\circ \left(\frac{B_0}{10^{-9}\mathrm{Gauss}}\right)\left(\frac{30\ \mathrm{GHz}}{\nu_0}\right)^2,$$

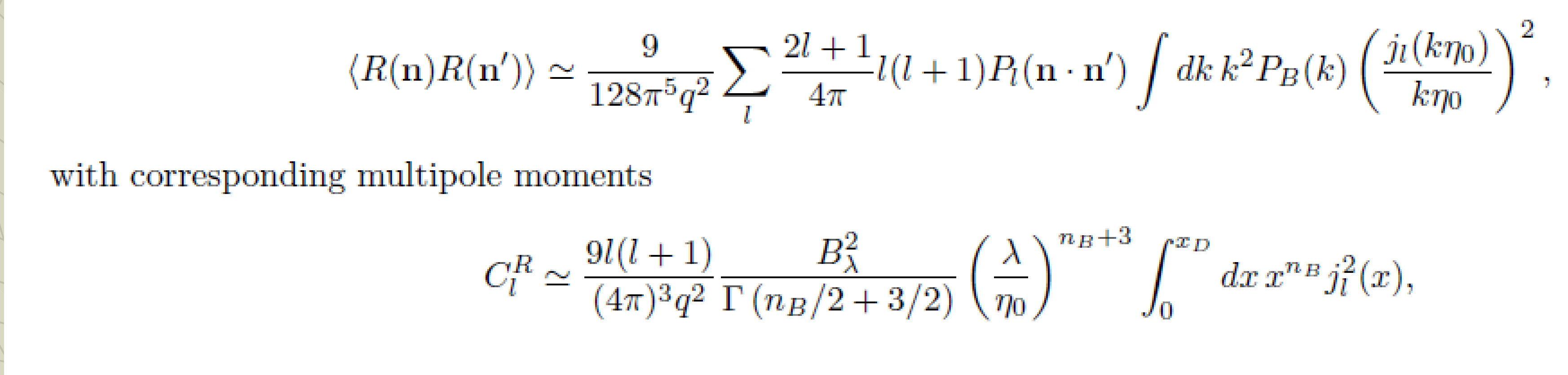
- Scannapieco & Ferreira 1997

CMB temperature and polarization anisotropies cross-correlations

Limits – around 10^{-8}-10^{-9} Gauss

Faraday Rotation by a Stochastic Magnetic Field

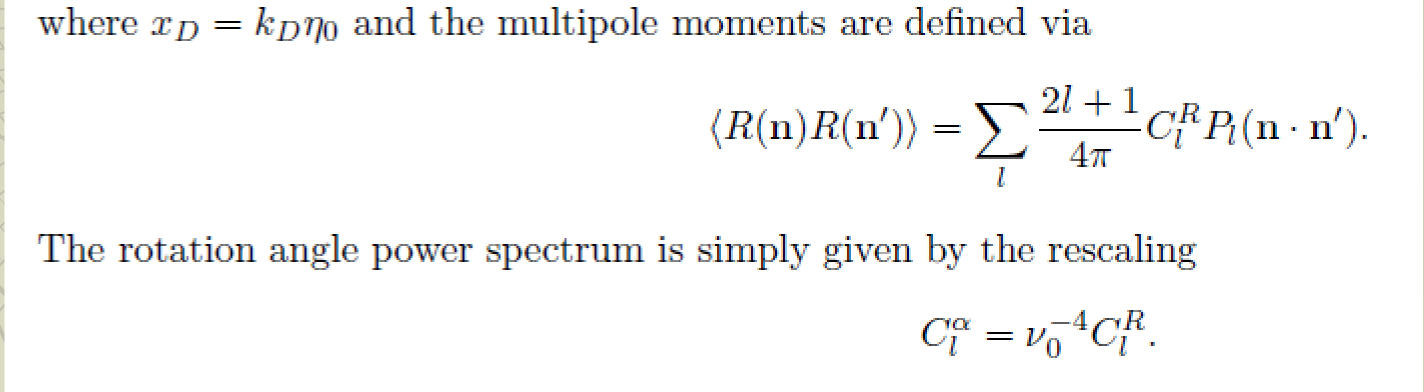
Kosowsky, Kahniashvili, Lavrelashvili, and Ratra 2005



$$\langle R(\mathbf{n})R(\mathbf{n}')\rangle \simeq \frac{9}{128\pi^5 q^2}\sum_l \frac{2l+1}{4\pi} l(l+1) P_l(\mathbf{n}\cdot\mathbf{n}') \int dk\, k^2 P_B(k) \left(\frac{j_l(k\eta_0)}{k\eta_0}\right)^2 ,$$

with corresponding multipole moments

$$C_l^R \simeq \frac{9l(l+1)}{(4\pi)^3 q^2} \frac{B_\lambda^2}{\Gamma\left(n_B/2+3/2\right)} \left(\frac{\lambda}{\eta_0}\right)^{n_B+3} \int_0^{x_D} dx\, x^{n_B} j_l^2(x),$$



where $x_D = k_D\eta_0$ and the multipole moments are defined via

$$\langle R(\mathbf{n})R(\mathbf{n}')\rangle = \sum_l \frac{2l+1}{4\pi} C_l^R P_l(\mathbf{n}\cdot\mathbf{n}').$$

The rotation angle power spectrum is simply given by the rescaling

$$C_l^\alpha = \nu_0^{-4} C_l^R.$$

$$(\langle\alpha^2\rangle)^{1/2} \simeq 0.14^\circ \left(\frac{B_{\rm eff}}{10^{-9}{\rm G}}\right)\left(\frac{100{\rm GHz}}{\nu_0}\right)^2 \frac{\sqrt{n_B+3}}{(k_D\eta_0)^{(n_B+3)/2}}\Big[\sum_{l=0}^{\infty}(2l+1)l(l+1) \int_0^{x_S} dx\, x^{n_B} j_l^2(x)\Big]^{1/2} \qquad (11)$$

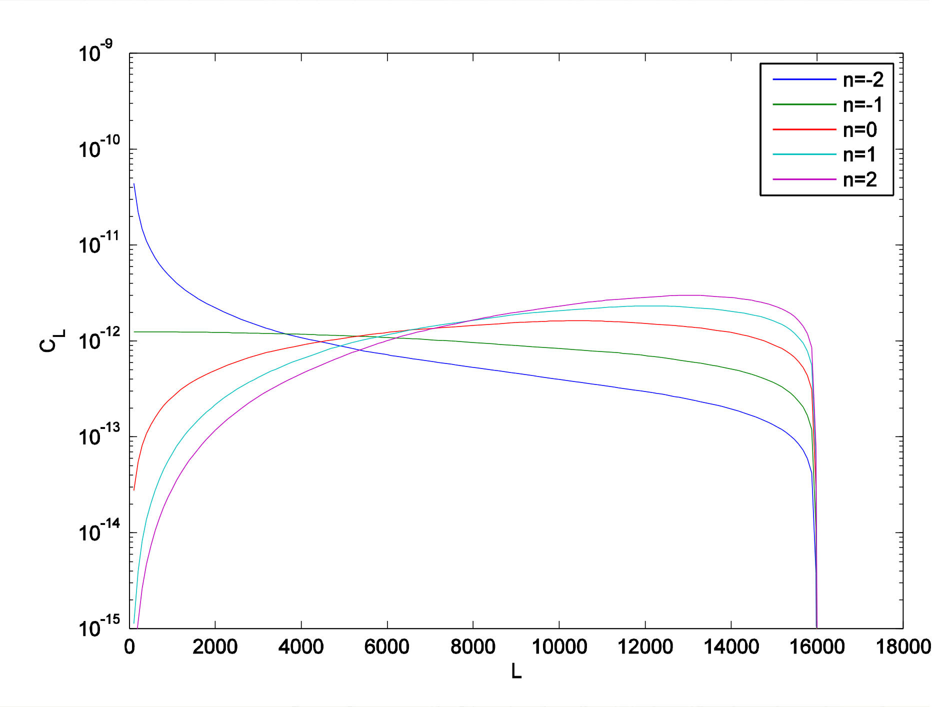
One might be interested to compare Eq. (11) with the corresponding result, Eq. 2 from Ref. [3] derived for an homogeneous magnetic field and the frequency $\nu_0 = 30$ GHz,

$$(\langle\alpha^2\rangle)^{1/2} \simeq 1,6^\circ \left(\frac{B_0}{10^{-9}{\rm G}}\right)\left(\frac{30{\rm GHz}}{\nu_0}\right)^2 \qquad (12)$$

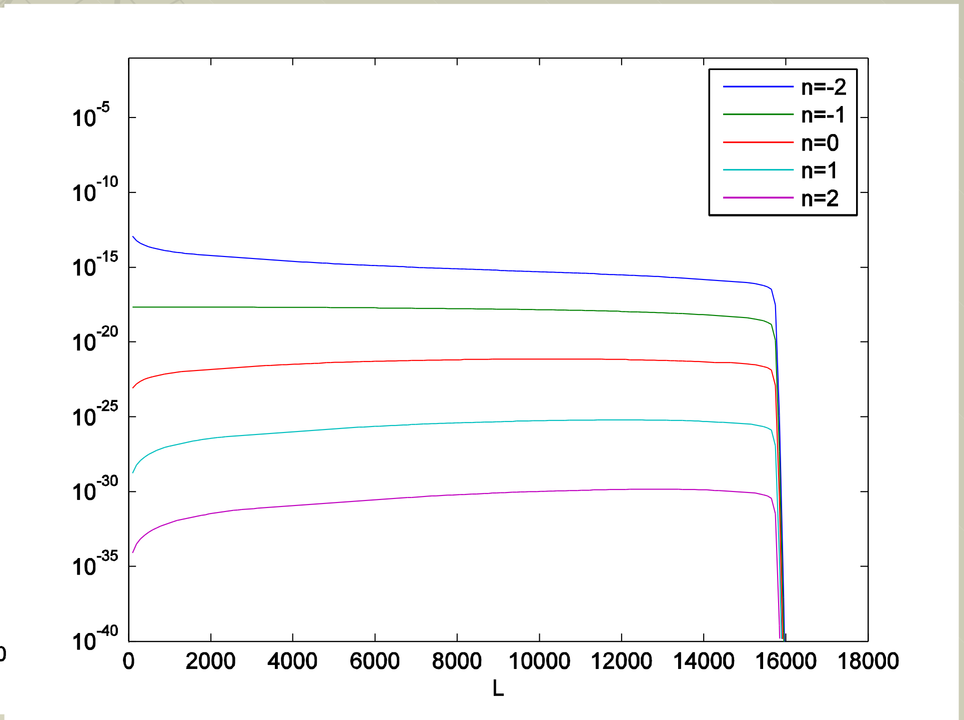
Both equations are in an agreement for $n_B \to -3$ under accounting for $\sum_l (2l+1) j_l^2(x) = 1$ and the property of Bessel functions that they peak at $x \sim l$ for given l (see

B_λ vs. B_{eff}

- Campanelli, et al. 2004, Kosowsky, Kahniashvili, et al. 2005



- Kahniashvili, Tevzadze, et al. 2010



B-polarization from Faraday Rotation

T.K., Maravin, and Kosowsky 2008

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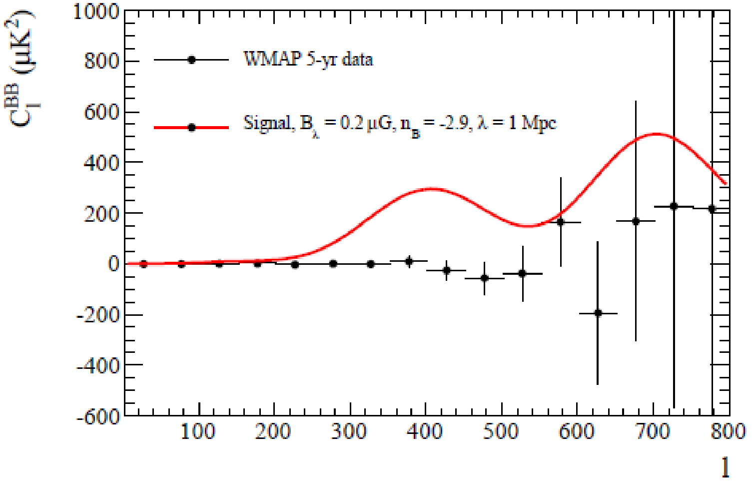


FIG. 1: The solid line shows the B-polarization power spectrum due to Faraday rotation from the WMAP best-fit cosmology, plus a stochastic magnetic field with amplitude $B_\lambda = 0.2\ \mu$G, $\lambda = 1$ Mpc, $\nu = 30$ GHz, and power law index $n_B = -2.9$. The data points show binned WMAP 5-year B-polarization data with $l < 800$. Note that this magnetic field amplitude and power spectrum is ruled out by the data in the region between $l = 300$ and $l = 500$. Points with $l < 150$ do not contribute significantly to the constraint.

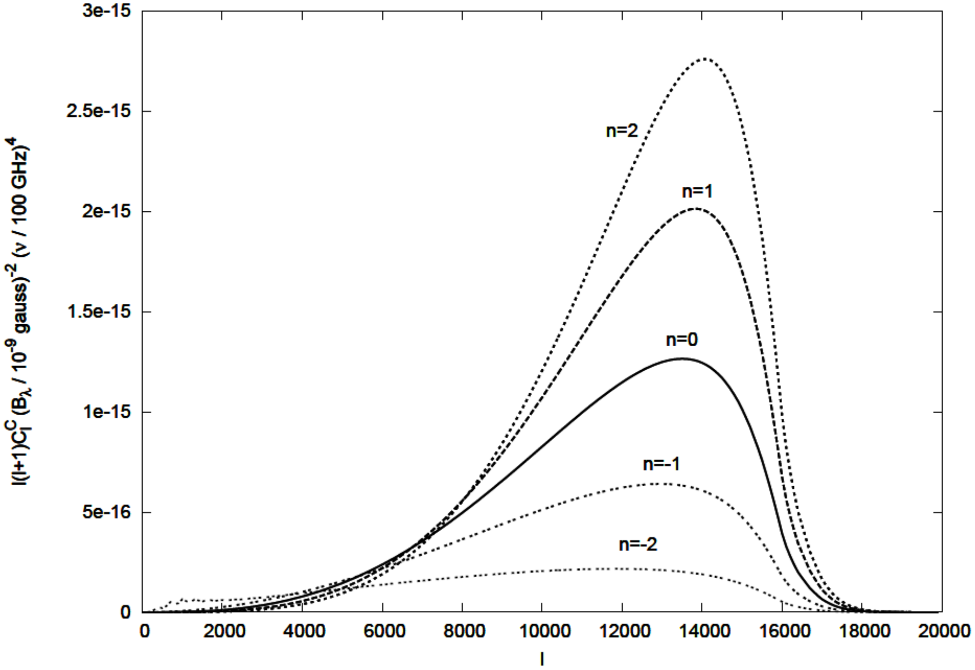


FIG. 2: The C-polarization power spectrum of the microwave background induced by the Faraday rotation field in Fig. 1, again with the magnetic field normalization scale $\lambda = 1$ Mpc.

Kosowsky et al. 2004

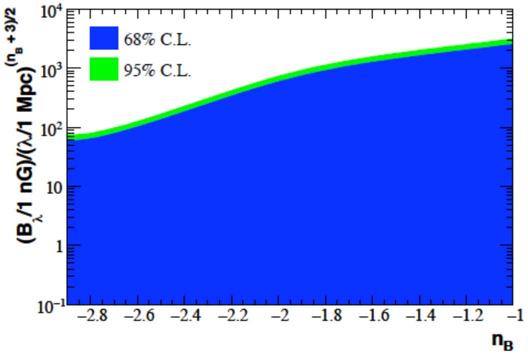


FIG. 2: The 68% and 95% C.L. limit bands on the B_λ as function of n_B for $\lambda = 1$ Mpc.

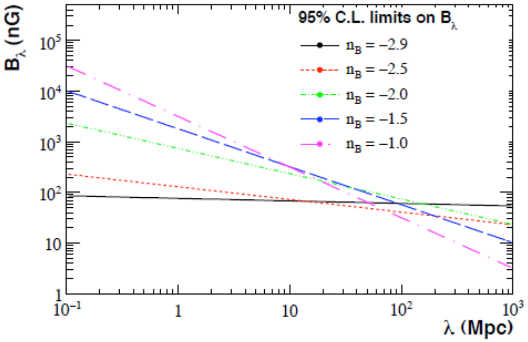


FIG. 3: 95% C.L. upper limits on B_λ for fixed values of $n_B = -2.9$, -2.5, -2.0, -1.5, and -1.0 as functions of λ.

T.K., Maravin, and Kosowsky 2008

Giovannini and Kunze 2008

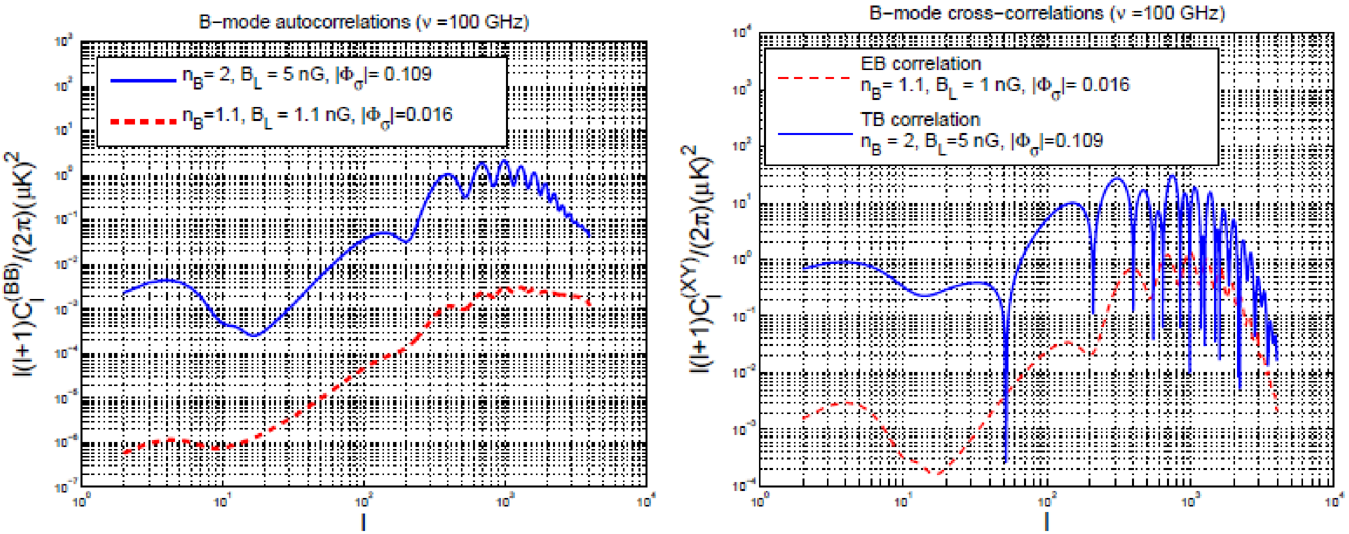


Figure 1: The angular power spectra of the B-mode autocorrelations (plot at the left) and the absolute values of the cross-correlations (plot at the right) are reported in the case when the pseudo-scalar background and the magnetized background are simultaneously present. The ΛCDM parameters have been chosen in accordance with the best fit to the WMAP5-yr data alone [1].

CMB polarization rotation angle limits

Kahniashvili, Tevzadze, Sethi, Pandey, and Ratra 2010

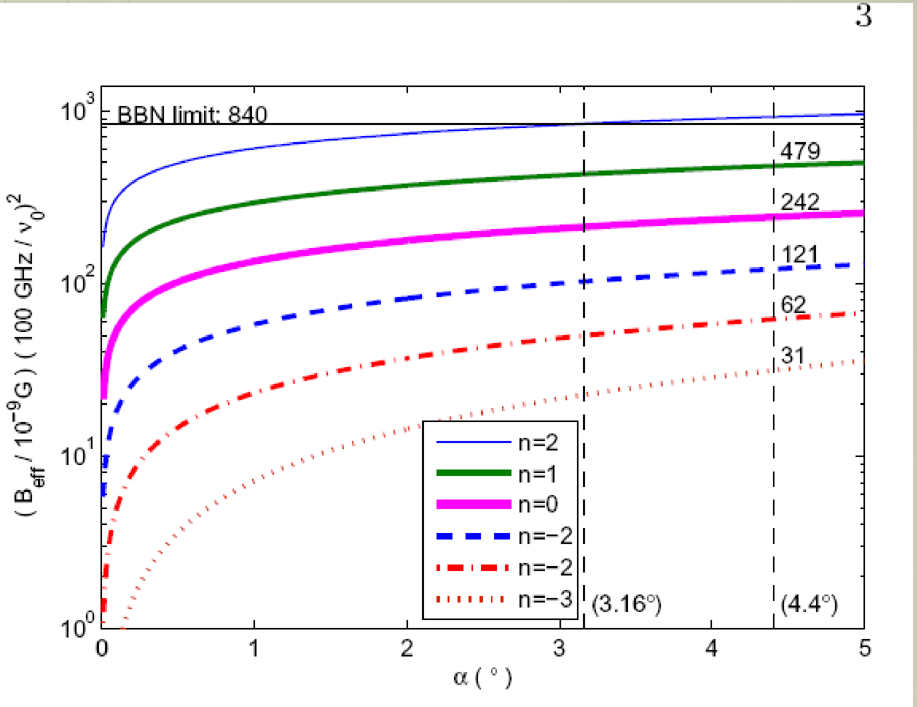


FIG. 2: Effective magnetic field limits set by the rotation angles α for different spectral indices ($n_B = -3, -2, -1, 0, 1, 2$). horizontal solid line shows upper limit set by BBN constraints. Vertical dashed lines correspond to the angles $\alpha = 3.16^\circ$ that is set by the BBN limit on the effective magnetic field with spectral index $n = 2$ and $\alpha = 4.4^\circ$ set by the 7-year ... . The values of the effective magnetic field constraints at $\alpha = 4.4^\circ$ angle are shown on the graph for different spectral indices, respectively.

CMB B-polarization

- Scalar mode does not produce CMB B-polarization signal.
- CMB B-polarization detection is a powerful test to probe inflation (gravitational waves); It will also will significantly improve the existing limits on the primordial magnetic fields (10^{-10}-10^{-11} Gauss)

B-polarization Magnetic Sources

- Up to l ~ 60 – gravitational waves (tensor mode) generated by the magnetic field anisotropic stress
- Vorticity perturbations from the magnetic field (Alfven waves); Contribution to the CMB anisotropies – in particular B-mode (peaks at l~ 2000)
- Secondary B-polarization arising from the birefrigence (Faraday rotation of the initial E-mode – secondary B-mode); peaks at l ~ 16000

B-polarization

$$\frac{B_l^{(V)}(\eta_0,k)}{2l+1} = -\sqrt{6}\int_0^{\eta_0} d\eta\, \dot\tau e^{-\tau} P^{(V)} \beta_l^{(V)}[k(\eta_0-\eta)],$$

$$P^{(V)} = \frac{\sqrt{3}}{9}\frac{k}{\dot\tau} v_b^{(V)} \simeq \frac{\sqrt{3}}{9}\frac{k}{\dot\tau}\Omega$$

$$\beta_l^{(V)}(x) = \frac{1}{2}\sqrt{(l-1)(l+2)}\frac{j_l(x)}{x}$$

Hu and White 1997

$$\frac{B_l^{(T)}(\eta_0,k)}{2l+1} = -\sqrt{6}\int_0^{\eta_0} d\eta\, \dot\tau e^{-\tau} P^{(T)} \beta_l^{(T)}[k(\eta_0-\eta)],$$

$$P^{(T)} = -\frac{1}{3}\frac{\dot h}{\dot\tau}$$

$$\beta_l^{(T)}(x) = \frac{1}{2}\left[j_l'(x) + 2\frac{j_l(x)}{x}\right]$$

Metric Perturbations

$$\dot{\Omega}_{\gamma i} + \dot{\tau}(v_{\gamma i}^{(V)} - v_{bi}^{(V)}) = 0,$$

$$\dot{\Omega}_{bi} + \frac{\dot{a}}{a}\Omega_{bi} - \frac{\dot{\tau}}{R}(v_{\gamma i}^{(V)} - v_{bi}^{(V)}) = \frac{L_i^{(V)}(\mathbf{k})}{a^4(\rho_b + p_b)}.$$

$$\Omega_i(\eta, \mathbf{k}) \simeq \frac{k\Pi_i^{(V)}(\mathbf{k})\eta}{(1+R)(\rho_{\gamma 0} + p_{\gamma 0})}.$$

$$\Omega_i(\eta, \mathbf{k}) \simeq \frac{\Pi_i^{(V)}(\mathbf{k})}{(kL_\gamma/5)(\rho_{\gamma 0} + p_{\gamma 0})}, \qquad k > k_S.$$

Subramanian and Barrow 1998
Mack, Kahniashvili, and Kosowsky 2002

$$\ddot{h}_{ij}(\eta, \mathbf{k}) + 2\frac{\dot{a}}{a}\dot{h}_{ij}(\eta, \mathbf{k}) + k^2 h_{ij}(\eta, \mathbf{k}) = 8\pi G \Pi_{ij}^{(T)}(\mathbf{k})/a^2,$$

$$h(\eta, k) = \frac{2\pi G \Pi^{(T)}(k) z_{\rm eq}^2 \eta_{\rm eq}^2}{(3 - 2\sqrt{2})k\eta} \int_{\eta_{\rm in}}^{\eta} d\eta' \, \frac{\sin[k(\eta - \eta')]}{\eta'}, \qquad \eta < \eta_{\rm eq},$$

Deriagin, Sazhin and Veryaskin 1982;
Durrer, Ferreira, and Kahniashvili 2000

What we should account for?

- Gravitational lensing – $l \sim 1000$
- Lorentz symmetry violation – similar to the Faraday rotation – different frequency dependence
- Any other vector mode (defects, strings, neutrinos…)

Strategy

- The magnetic field induces all kinds of perturbations and so we must cross check
  - Do we observe the Doppler peaks shifts? (magnetosound waves in the Universe)

    Adams, Danielson, Grasso, and Rubinstein, 1996, Kahniashvili and Ratra 2007
  - Do we observe the CMB non-gaussianity?

    Seshadri and Subramanian 2009, Caprini et al. 2009; M. Shiraishi et al. 2010, Kahniashvili & Lavrelashvili 2010
  - Do we see tensor mode contribution (additional) at low l-s?

    Durrer, Ferreira, and Kahniashvili 2000, Mack, Kahniashvili, and Kosowsky 2002; Lewis 2004

Magnetic Field Limits

- CMB non-gaussianity – few nanoGauss Trivedi, Subramanian, and Seshadri 2010
- CMB polarization fluctuations – few nanoGauss Yamazaki et al. 2010
- CMB Faraday rotation – few nanoGauss T.K., Tevzadze, et al. 2010
- LSS first object formation – few nanoGauss Sethi and Subramaian 2005

CMB Oddities

- Low multipole anomalies
  - Off-diagonal cross correlations
  - North-South asymmetry
- Parity violation
  - Temperature-B-polarization
  - E- and B-polarization

Magnetic Helicity Generation

- **Cosmological Sources**
  Cornwall, 1997; Giovannini, 2000: Field and Carroll, 2000; Vachaspati 2001; Giovannini and Shaposhnikov 2001, Sigl 2002, Campanelli and Gianotti 2005, Semikoz and Sokoloff 2005, Campanelli, Cea and Tedesco 2008, Campanelli 2008

- **MHD Processes in Astrophysical Plasma**
  Vishniac and Cho, 2001; Brandenburg and Blackman, 2002; Subramanian, 2003; Vishniac, Lazarian and Cho, 2003; Subramanian and Brandenburg, 2004; Banerjee and Jedamzik, 2004, Subramanian 2007

- **Turbulence**
  Christensson, Hindmarsh, and Brandenburg, 2002; Verma and Ayyer, 2003, Boldyrev, Cattaneo and Rosner 2005;

Primordial Magnetic Helicity

- If magnetic helicity is present the large-scale properties of the magnetic field are significantly affected.
- Reflects a manifestation of the parity symmetry violation
- Ways to detect
  - Cosmic rays arrival velocities
  - CMB polarization measurements
  - Direct detection of gravitational wave polarizations

CMB anisotropies
parity even & odd power spectra

- **Parity-even power spectra:**

  C_l^{TT}, C_l^{EE}, C_l^{BB}, C_l^{TE}

- **Parity-odd power spectra:**

  C_l^{TB}, C_l^{EB}

  - **Vanishing in the standard model**
  - **Present if**
    - **Lorentz symmetry is broken**
    - **Cosmological helical magnetic field**
    - **Parity symmetry is violated**

Vector – Tensor modes comparison

- **Vector mode**

Surviving up to small angular scales.

Subramanian and Barrow, 1998;
Lewis, 2004

Vanishing E-B polarization
cross correlations (with respect of temperature-B-
polarization).

Kahniashvili and Ratra, 2005

- **Tensor mode**

Gravitational wave source

damping after equality !
contribution in CMB for
large angular scales (l <100)

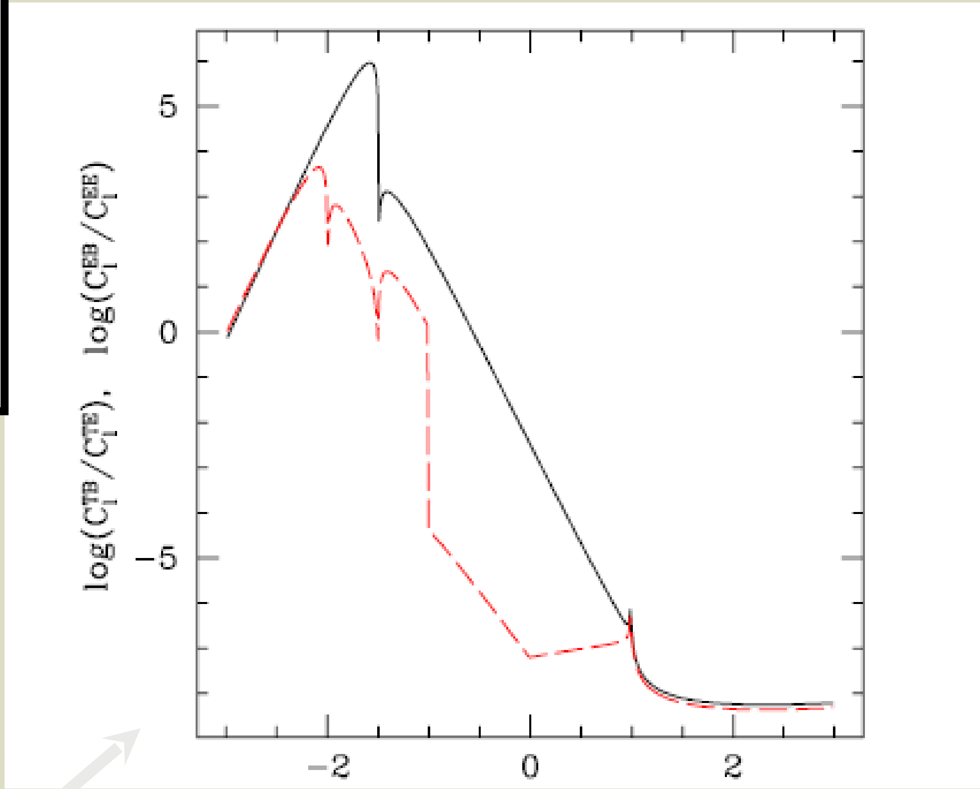
The same order of magnitude for temperature –
B-polarization and
E-B polarization cross correlations.

Caprini, Durrer, and Kahniashvili, 2004

GWs sourced by a helical magnetic field

B-polarization signal: thepeak position insures to distinguish the source of the signal

- *Zaldariagga and Seljak, 1997*
- *Kamionkowsky, Kosowsky, & Stebbins, 1997*



Caprini, Durrer, and Kahniashvili 2004

CMB anisotropy parity odd power spectra (tensor mode) might reflect the presence of primordial magnetic helicity

C_l^{TB}/C_l^{TE} (black); C_l^{EB}/C_l^{EE} (red)

$l=50$, $n_s=-3$

Parity symmetry violation in the early Universe

- **Gravitational Chern-Simons term**

Lue, Wang, Kamionkowsky, 1999

Specific signatures on CMB – non-zero parity odd cross correlations between temperature & B-polarization;
E & B-polarization anisotropies

Lyth,Quimbay,Rodriguez 2005
Satoch, Kanno, Soda 2008
Saito, Ichiki, Taruya 2007
Seto, Taruya 2008

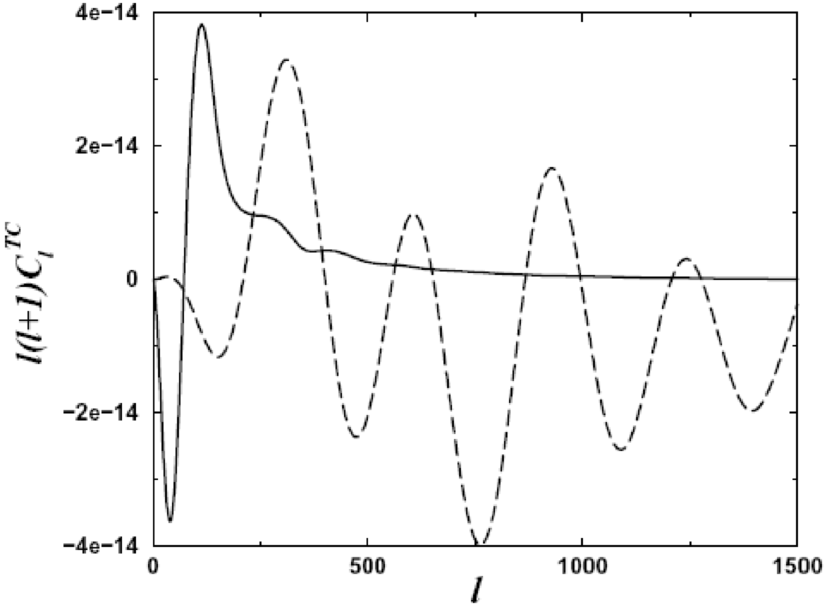


FIG. 1. The dashed curve shows the C_l^{TC} power spectrum induced by rotation of the polarization of an initially P symmetric CMB polarization pattern by 0.05°. The solid curve shows the C_l^{TC} power spectrum produced by a GW background that consists of only right-handed GWs.

Parity Odd CMB fluctuations

- An crucial test for the fundamental symmetry breakings.
- It is more promising way to test primordial inflation or short-after inflation generated helicity.
- This apply also for the Chern-Simons term induced parity symmetry violation (*Lue, Wang, Kamionkowski 1999*), but it has been shown that the signal is not observable through current or nearest future CMB missions

Conclusion

- Cosmological magnetic field order of 0.1 nanoGauss can be detectable by the nearest future CMB polarization measurements
- On the other hand if the field is significantly smaller – it would satisfy the LOWER limit bound but would not been observable through cosmological observations

THANKS