Linear Polarization of CMB and 21cm
&
Circular Polarization of CMB

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ArXiv: (SD,LP,TV) http://arxiv.org/abs/1305.7225

ArXiv: (SD, HT) http://arxiv.org/abs/1307.3584

Basics of Faraday Rotation

- The direction of linear polarization vector is rotated as CMB passes through ionized medium permeated by magnetic field. Faraday rotation vs temperature anisotropy due to magnetic field :

  CMB temperature anisotropy -> $\mathbf{B_{PMF} <}$ **few nG** sourced by magnetic energy **quadratic** in field strength.

  Faraday rotation is **linear** in field strength

- **Angle of rotation** along a line of sight is proportional to the line integral of **comoving magnetic field** **($B(z)=B_{obs}(1+z)^2$)** times **square** of the **observed wavelength**
- Symbolically

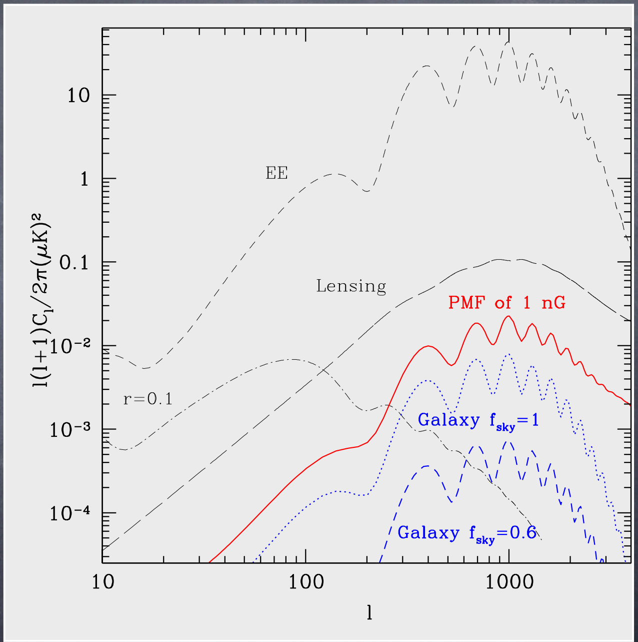
$$\alpha(\hat{\mathbf{n}}) = \lambda_0^2 \; RM(\hat{\mathbf{n}}) = \frac{3}{16\pi^2 e} \lambda_0^2 \int \dot{\tau} \; \mathbf{B} \cdot d\mathbf{l}$$

- τ is the optical depth, depends on the free electron density of the medium.

CMB B-mode spectra at 30GHz due to Faraday Rotation caused by primordial and Milky way magnetic field

Galactic RM data is from Oppermann et al (2012)

PMF (1 nG) B-mode peak power ≈0.03(μK)^2.
Galactic (RM ≈30 rad/m^2) and at 30GHz givens a rotation angle 3 X10^{-3} rad.
B-mode peak power ≈0.01 (μK)^2
PMF is assumed to be scale-invariant.
Similar shape of B-mode spectra from PMF and Galactic magnetic field.



Galactic RM detection

Name - freq (GHz)	$f_{\rm sky}$	FWHM (arcmin)	$\Delta_P(\mu$K-arcmin)	$(S/N)_{EB}$ (+DL)	$(S/N)_{TB}$ (+DL)	$(S/N)_{BB}$ (+DL)
Planck LFI - 30	0.6	33	240	5.3E-4 (same)	2.2E-3 (same)	2.3E-4 (same)
Planck HFI - 100	0.7	9.7	106	1.4E-3 (same)	7.5E-4 (same)	6E-5 (same)
Polarbear - 90	0.024[a]	6.7	7.6	1.3E-2 (1.5E-2)	1.6E-3 (2.0E-3)	4.6E-4 (6.0E-4)
QUIET II - 40	0.04[a]	23	1.7	0.3 (0.8)	0.05 (0.2)	0.02 (0.08)
CMBPOL - 30	0.6	26	19	1.0 (same)	0.4 (same)	0.05 (same)
CMBPOL - 45	0.7	17	8.25	2.1 (2.3)	0.8 (0.9)	0.12 (0.15)
CMBPOL - 70	0.7	11	4.23	2.0 (2.6)	0.6 (0.9)	0.08 (0.14)
CMBPOL - 100	0.7	8	3.22	1.4 (2.0)	0.3 (0.6)	0.03 (0.07)
Suborbital - 30	0.1	1.3	3	2.0 (3.1)	0.3 (0.7)	0.08 (0.2)
Space - 30	0.6	4	1.4	18 (28)	7 (14)	5 (30)
Space - 90	0.7	4	1.4	3.3 (6.8)	1.0 (2.4)	0.09 (0.64)

ABLE I: S/N of the overall detection of the galactic RM spectrum with Planck, Polarbear, QUIET, CMBPOL and ptimistic future sub-orbital and space experiments. Results are presented without and with (+DL) de-lensing by a factor $f_{\rm DL} = 0.01$. ([a] based on 0.1 of RM sky.)

(+DL) ->$f_{\rm DL}$=0.01

2σ bounds on effective PMF

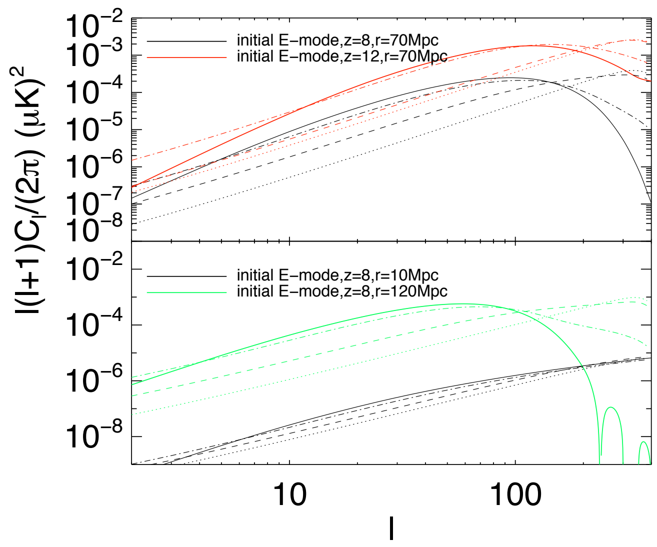
Name - freq (GHz)	$f_{\rm sky}$ ($f_{\rm sky}^{\rm opt}$)	FWHM (arcmin)	$\Delta_P(\mu$K-arcmin)	$B_{\rm eff}$ (2σ, nG)	+DL (nG)	+DL+DG (nG)
Planck LFI - 30	0.6	33	240	16^b	same	same
Planck HFI - 100	0.7	9.7	106	23	same	same
Polarbear - 90	0.024^a	6.7	7.6	3.3	3.0	same
QUIET II - 40	0.04^a	23	1.7	0.46	0.26	0.25
CMBPOL - 30	0.6	26	19	0.56	0.55	0.51
CMBPOL - 45	0.7	17	8.25	0.38	0.35	0.29
CMBPOL - 70	0.7	11	4.23	0.39	0.32	0.26
CMBPOL - 100	0.7	8	3.22	0.52	0.4	0.34
Suborbital - 30	0.1	1.3	3	0.09	0.07	0.05
Suborbital - 90	0.1	1.3	3	0.63	0.45	same
Space - 30	0.6 (0.2)	4	1.4	0.06	0.04	0.02
Space - 90	0.7 (0.4)	4	1.4	0.26	0.15	0.12

f_{DG} =0.1, f_{DL} =0.01

ArXiv: (SD,LP,TV) http://arxiv.org/abs/1305.7225

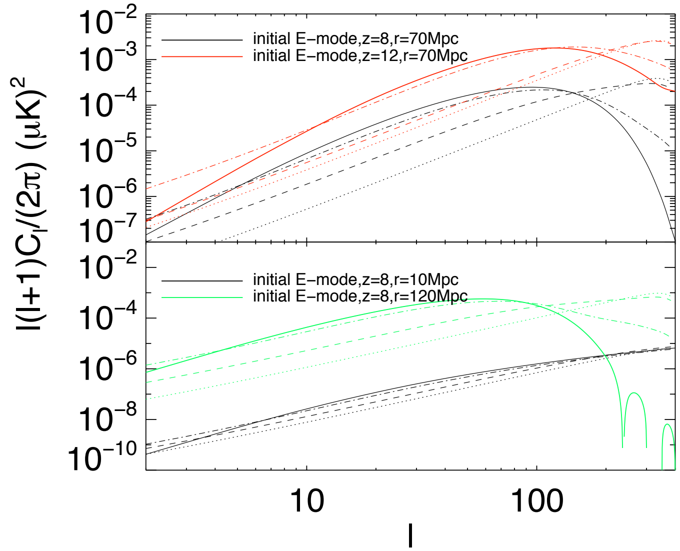
Recovery of MW RM from CMB polarization data: De and Mauskopf, Dec 2013 , in prep

E-mode polarization spectra of 21 cm photons after they pass through the Milky Way



Solid lines indicate the initial E-modes. Dotted, dashed and dash-dotted lines indicate generated E-mode when when RM is 100,10,1 percent of the actual value. The peak scale corresponds to the typical size of the ionized bubbles.

B-mode polarization spectra of 21cm photons after they pass through the Milky Way



Solid lines indicate the initial E-modes. Dotted, dashed and dash-dotted lines indicate generated B-mode when when RM is 100,10,1 percent of the actual value.

ArXiv: (SD, HT) http://arxiv.org/abs/1307.3584

Circular polarization of CMB ?

- Magnetic field, relativistic electrons due to the process of Faraday conversion creates circular polarization in CMB.
- We don't expect CMB to have circular polarization at the surface of last scattering. Current upper limit on V/T_{CMB} ~10^{-4} (Ref: Mainini, 2013) using MIPOL at Testa Grigia observatory at the Italian Alps.
- The Milky way magnetic field is too small to generate any significant effect.
- Explosion of first stars have good prospects of generating conditions for CMB circular polarization. Therefore could CMB circular polarization be a good probe for the unobserved first stars? Could galaxy clusters be a significant source as well?

Steps to get to the V-parameter, the degree of circular polarization

Linear polarization of CMB

$$\frac{dV}{ds}(z,\vec{x},\vec{n}) = U(z,\vec{x},\vec{n})\delta K_r(z,\vec{x},\vec{n},\vec{n}_B)$$

Path length to the observers

Properties of the first stars or the galaxies

spectral index of the relativistic electrons

$$\delta K_r \Rightarrow (N_r^{tot}, \gamma_L, B, \theta_B, \nu_L, \nu, \beta)$$

(Sazonov,1969)

number density of the relativistic electrons

lower limit of the Lorentz factor

Angle between line of sight and B

Larmor's frequency

frequency of the CMB photons

linear polarization

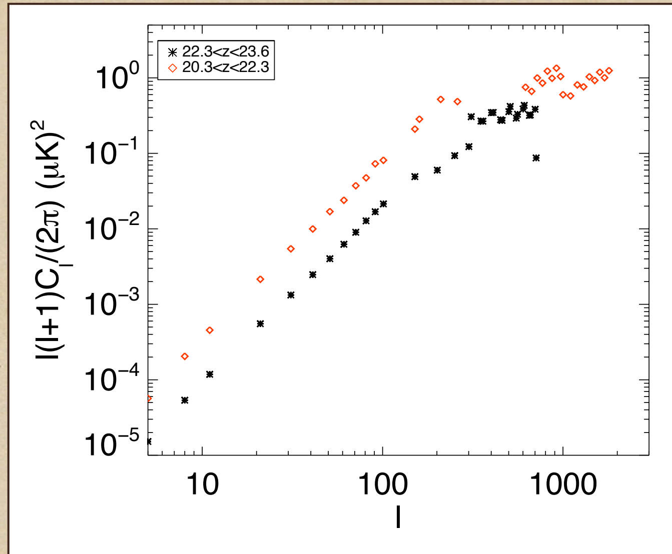
$$C_l^{VV} = < V_{lm}V_{lm}^{*} > \Rightarrow (P(k), P_\alpha, P_{E_{lm}})$$

(De & Tashiro, in prep,Dec 2013)

growth of structure

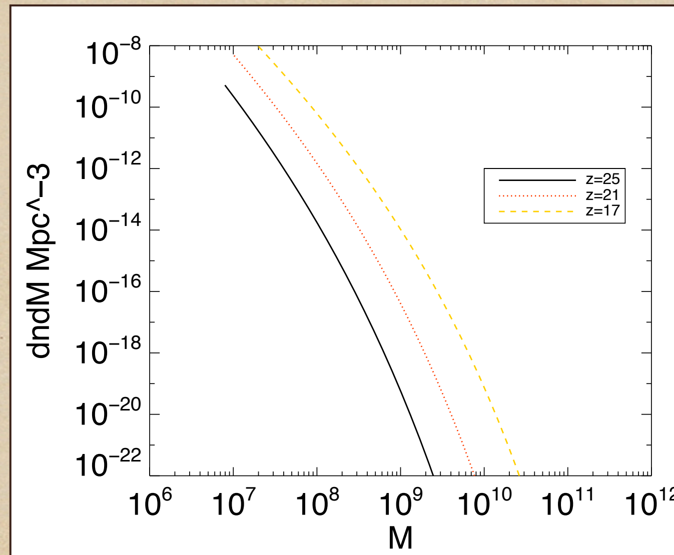
First star astrophysics

Predicted Signal of V

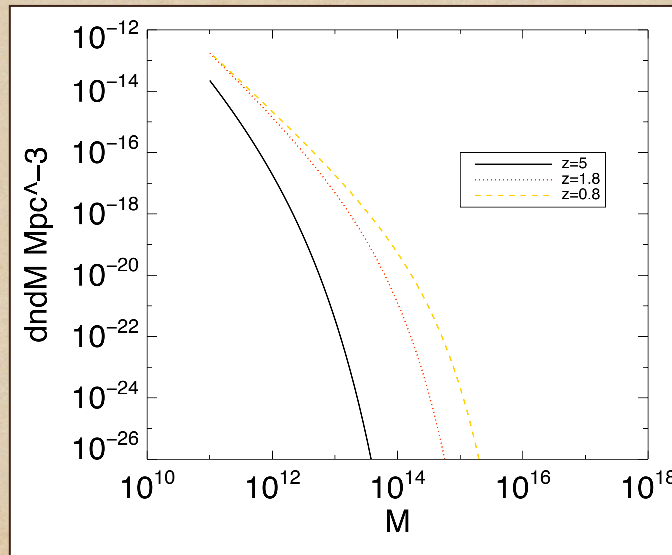


semi-analytic

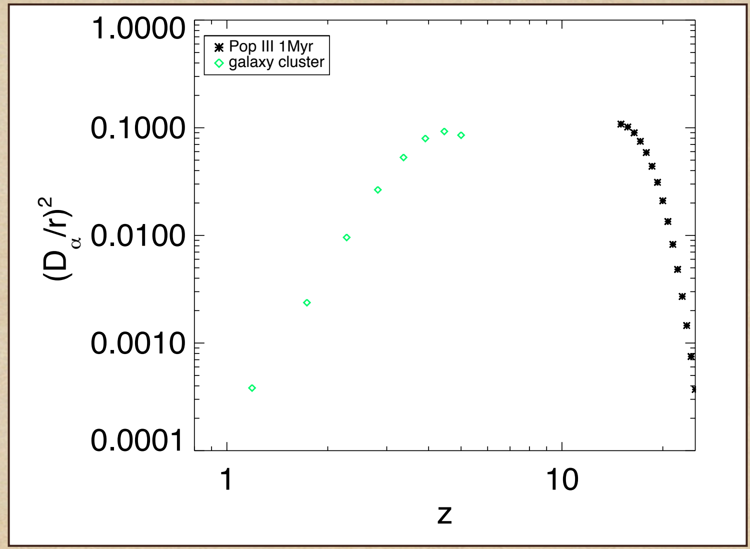
Number density per mass bin



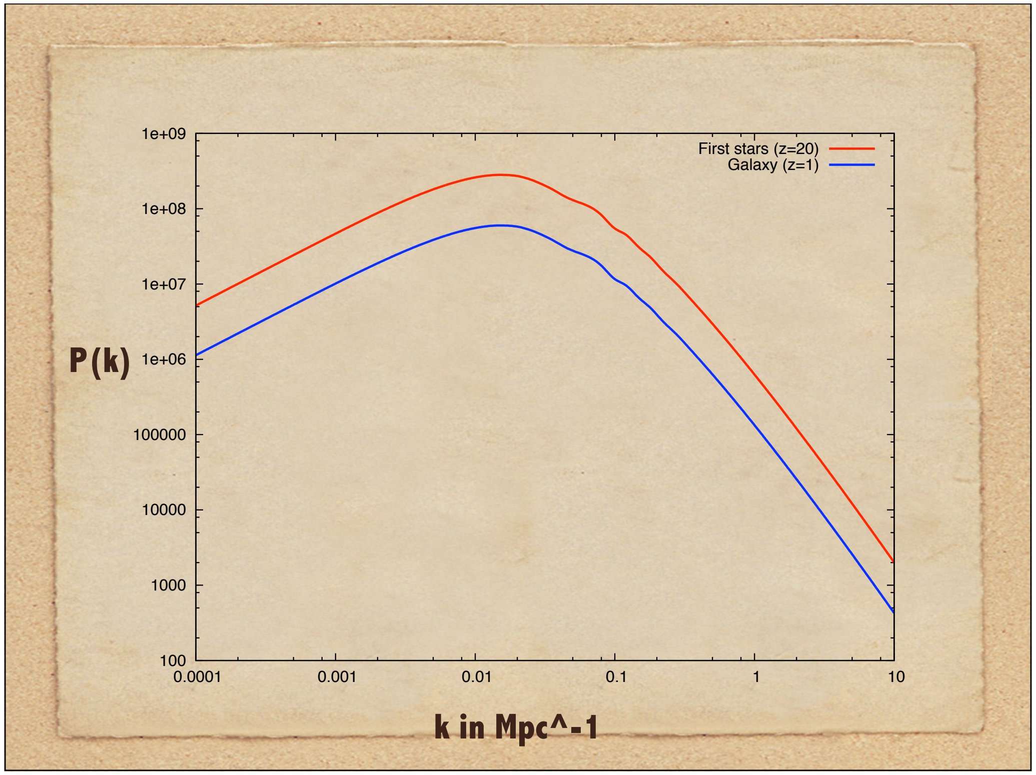
Number density per mass bin of galaxy clusters



Comparison of Astrophysical contributions



semi-analytic



P(k)
k in Mpc^-1
First stars (z=20)
Galaxy (z=1)
1e+09
1e+08
1e+07
1e+06
100000
10000
1000
100
0.0001
0.001
0.01
0.1
1
10

Conclusion and Future prospects

- Low frequency measurement of V signal at high multipoles is a relatively foreground free way to detect the first stars and unique frequency signature (De and Tashiro in prep, 2013).

back up slides

Astrophysical Magnetic Fields

magnetic field in Gauss

10^{-9}	10^{-6}	10^{-3}	1	10^{3}	10^{6}	10^{9}
Voids	Clusters, Galaxies		stars	white dwarfs	Neutron stars	
10^{26}	10^{25} 10^{23}		10^{10}	10^{9}	10^{6}	

linear size in cm

10^{13} 10^{11}	1	1	1

mass in solar mass units

- Magnetic fields are prevalent in galaxies and galaxy clusters. Field strengths are typically 1μG and 1-10 μG with coherence lengths of 1 Kpc and 10-100 Kpc respectively

How to recover faraday rotation angle from CMB data ?

Stokes parameters and Observations

Stokes parameters Q, U and V characterizing polarization

Explore the rotation of the linear polarization in different frequency channels (De and Mauskopf, 2013 in prep)

$$\alpha(\hat{n}) = \sum_{L,M} \alpha_{LM} Y_{LM}(\hat{n})$$

$$B_{lm} = 2\sum_{LM}\sum_{l'm'} \alpha_{LM} E_{l'm'} \xi^{LM}_{lml'm'} H^L_{ll'}$$

$$\xi^{LM}_{lml'm'} \equiv (-1)^m \sqrt{\frac{(2l+1)(2L+1)(2l'+1)}{4\pi}} \times \begin{pmatrix} l & L & l' \\ -m & M & m' \end{pmatrix}$$

$$H^L_{ll'} \equiv \begin{pmatrix} l & L & l' \\ 2 & 0 & -2 \end{pmatrix},$$

At a given frequency band explore the coupling between E-modes and Faraday rotation (FR) induced B-modes.

Therefore extract the rotation at a given point in sky by exploring coupling between E and B-modes from a given realization under small angle approximation

In the detection process of PMF Milky way magnetic field is an important foreground whose nature needs to be investigated.

Kamionkowski et al 2009, Pogosian et al 2012

B-mode spectra (PMF)

Stochasticity and isotropy allows us to write

$$\begin{aligned}\langle B^*_{l'm'} B_{lm}\rangle &= 4\sum_{LM}\sum_{L'M'}\sum_{l_2m_2}\sum_{l'_2m'_2}\xi^{LM}_{lml_2m_2}H^L_{ll_2}\xi^{L'M'}_{l'm'l'_2m'_2}H^{L'}_{l'l'_2}\langle\alpha^*_{LM}E^*_{l_2m_2}\alpha_{L'M'}E_{l'_2m'_2}\rangle \\ &= \delta_{ll'}\delta_{mm'}4\sum_L\frac{(2L+1)}{4\pi}C^{\alpha\alpha}_L\sum_{l_2}(2l_2+1)C^{EE}_{l_2}(H^L_{ll_2})^2\end{aligned}$$

$$C^{BB}_l = \frac{1}{\pi}\sum_L(2L+1)C^{\alpha\alpha}_L\sum_{l_2}(2l_2+1)C^{EE}_{l_2}(H^L_{ll_2})^2$$

E,B-mode spectra (21 cm)

Fluctuations of neutral are only due to baryonic density and ionization fluctuations, hence only E-modes. Polarization due to ionization fluctuations dominate at EoR. This depends on EoR models.

$$C_l^{E,i}(\nu) = \frac{2}{\pi}\int k^2 dk[x_H^2 P_\delta(k)(\Delta_\delta^E(k,\nu))^2 + P_x(k)(\Delta_x^E(k,\nu))^2]$$

$$C_l^{BB,obs} = \sum_L \frac{2L+1}{4\pi} C_L^{Sin(2\alpha)} \sum_{l'} (2l'+1) C_{l'}^{EE} (H_{ll'}^L)^2$$

$$C_l^{EE,obs} = \sum_L \frac{2L+1}{4\pi} C_L^{Cos(2\alpha)} \sum_{l'} (2l'+1) C_{l'}^{EE} (H_{ll'}^L)^2$$