Probes of Cosmology after Planck: Circular Polarization of CMB and Cosmology at Low Frequencies

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Low frequency CMB experiments

- Primordial magnetic field
- Astrophysical objects such as the first stars
- Useful Astrophysical phenomena: Faraday rotation and conversion, explosion of stars.
- Frequencies of interest <30-40 GHz

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 -> **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

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

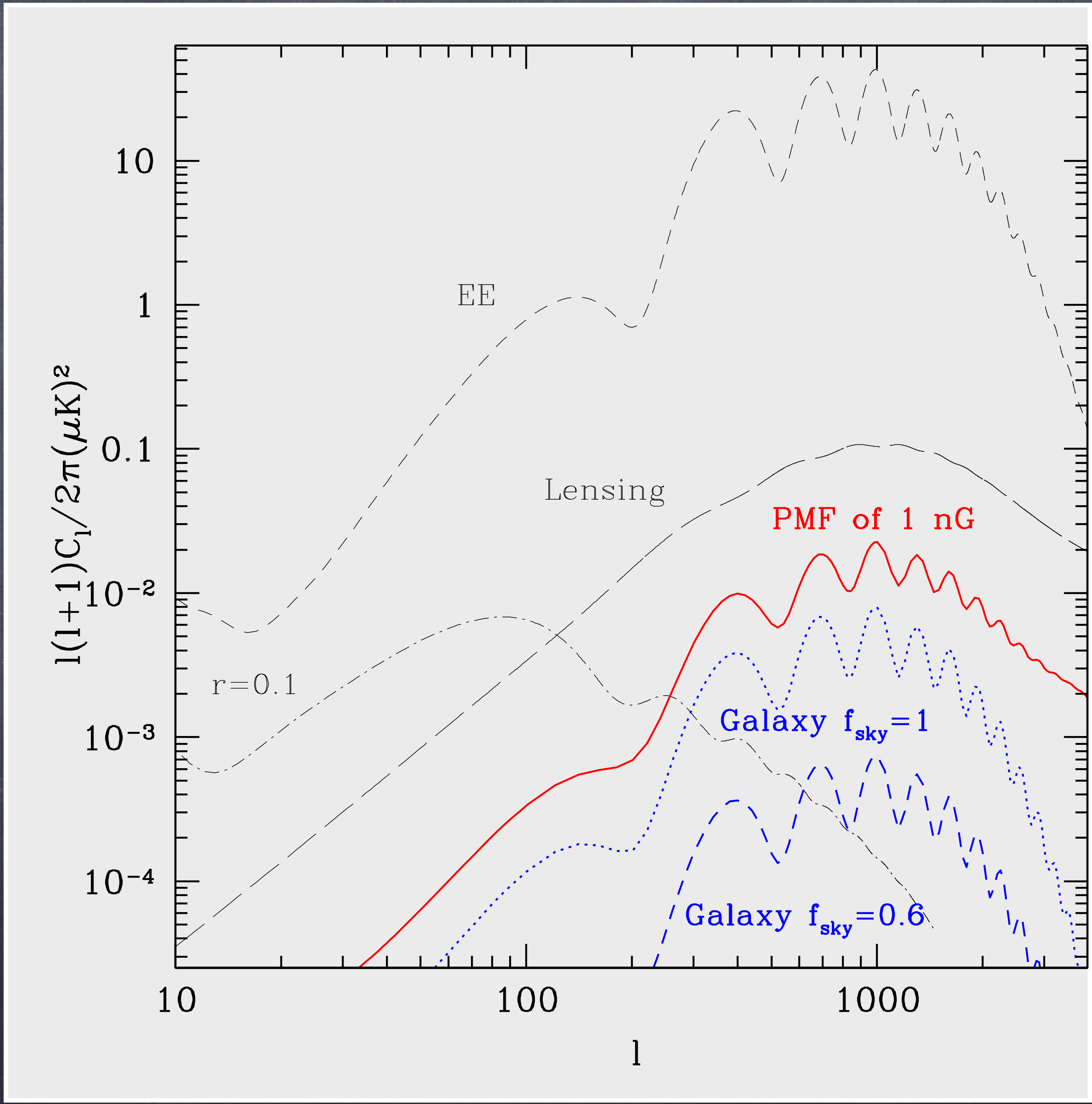
- τ is the optical depth, depends on the free electron density of the medium.

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.

De, Vachaspati and Pogosian, 2013



Galactic RM detection

Name - freq (GHz)	f_{sky}	FWHM (arcmin)	$\Delta_P(\mu\text{K-arcmin})$	$(S/N)_{EB}$ (+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 $f_{\text{DL}} = 0.01$. ([a] based on 0.1 of RM sky.)

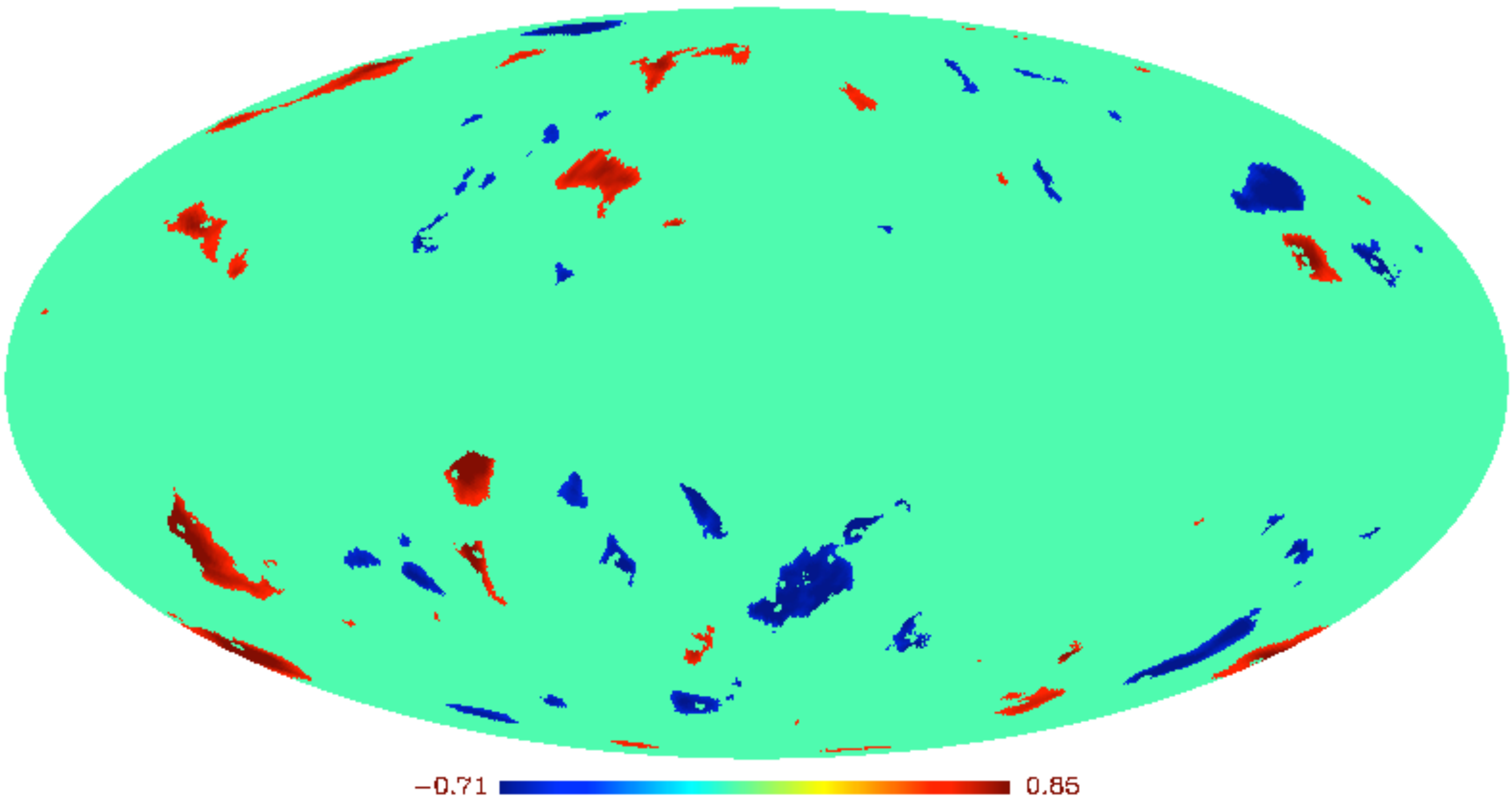
(+DL) ->f_{DL}=0.01

2σ bounds on effective PMF

Name - freq (GHz)	$f_{\rm sky}$ ($f_{\rm sky}^{\rm opt}$)	FWHM (arcmin)	Δ_P(μK-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

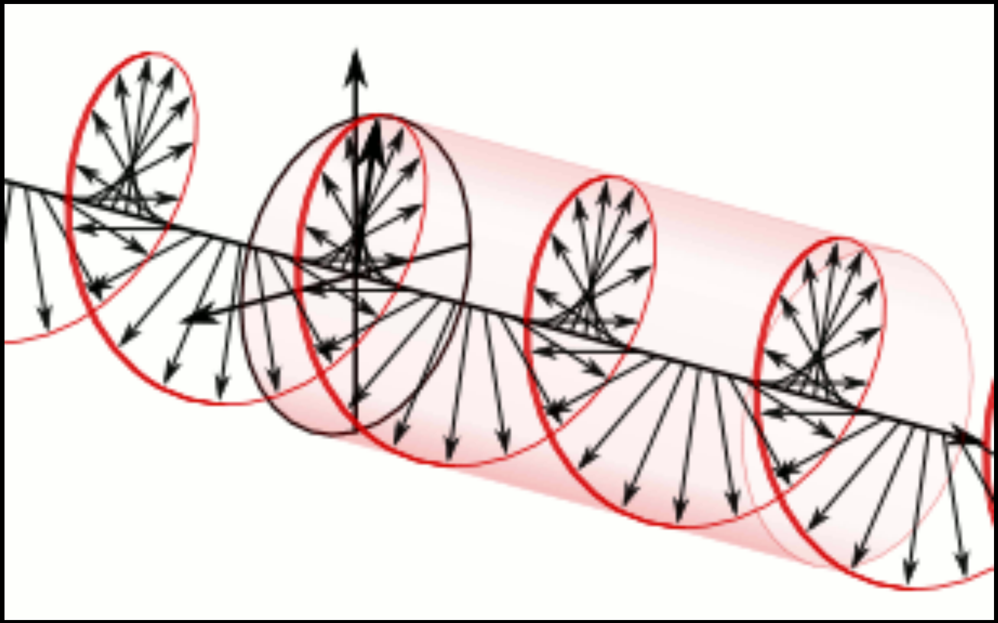
Work in progress



Map space correlation between RM and T_ILC

Circular Polarization

Wikipedia has an animation
Beckert et al(2002)



A linearly polarized wave can be composed of two orthogonal circularly polarized modes shifted in phase. A phase shift would be produced by a plasma in a magnetic field along the propagation direction of the waves (here along the y-direction). The effect of additional phase-shifts on the linear polarization, leading to **Faraday rotation.**

Faraday Conversion A circularly polarized wave can be composed of two orthogonal linearly polarized modes shifted in phase. A phase shift would be produced by a plasma in a magnetic field perpendicular to the propagation direction of the waves (here along the z-direction). Without phase-shift the sum of the two modes would be a purely linearly polarized wave.

Faraday Conversion vs Faraday Rotation

- FC is mainly created by component of magnetic field perpendicular with respect to the line of sight or the direction of photon propagation.

- FR is produced by magnetic field parallel to the line of sight.

- FC is insensitive to e+/e- ratio while FR is not.

Other astrophysical sources of CP

- Quasars
- Blazers
- radio-galaxies
- low FR emission plasma regions filled with Magnetic field and e+/e- or e/p
- CP<0.01LP

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?

Circular polarization generation through Faraday Conversion

$$V(\hat{n}) = -2\int_{r_*}^{0} dr\, U(r,\vec{x},\hat{n})\alpha(r,\vec{x},\hat{n},\hat{b}),$$

alpha is the Faraday conversion rate.
Theta_B is the angle between line of sight and magnetic field
Epsilon is the Lorentz factor

$$\alpha(z,\vec{x},\hat{n},\hat{b}) = \alpha_0 \sin(\theta_B)^{\frac{\gamma+2}{2}},$$
$$\alpha_0 = C_\gamma \frac{e^2}{m_e c} n_{\rm rel}\epsilon_{\rm min}(B_{\rm mag})^{\frac{\gamma+2}{2}} \nu^{-\frac{\gamma+4}{2}},$$

De and Tashiro, 2014, Arxiv:1401.1371 or email me at des@phys.ethz.ch

SN of big stars!

$$r_s = 2.3\ \mathrm{pc} \left(\frac{E_{\rm SN}}{10^{51}\mathrm{erg}}\right)^{\frac{1}{5}} \left(\frac{\rho_b}{10^{-24}\mathrm{g/cm^3}}\right)^{-\frac{1}{5}} \left(\frac{t_{\rm age}}{100\ \mathrm{yr}}\right)^{\frac{2}{5}},$$

rs is the radius of the shock
t_age is time since explosion
rho_b is the baryonic mass density of the ambient medium
E_SN energy released by the SN explosion

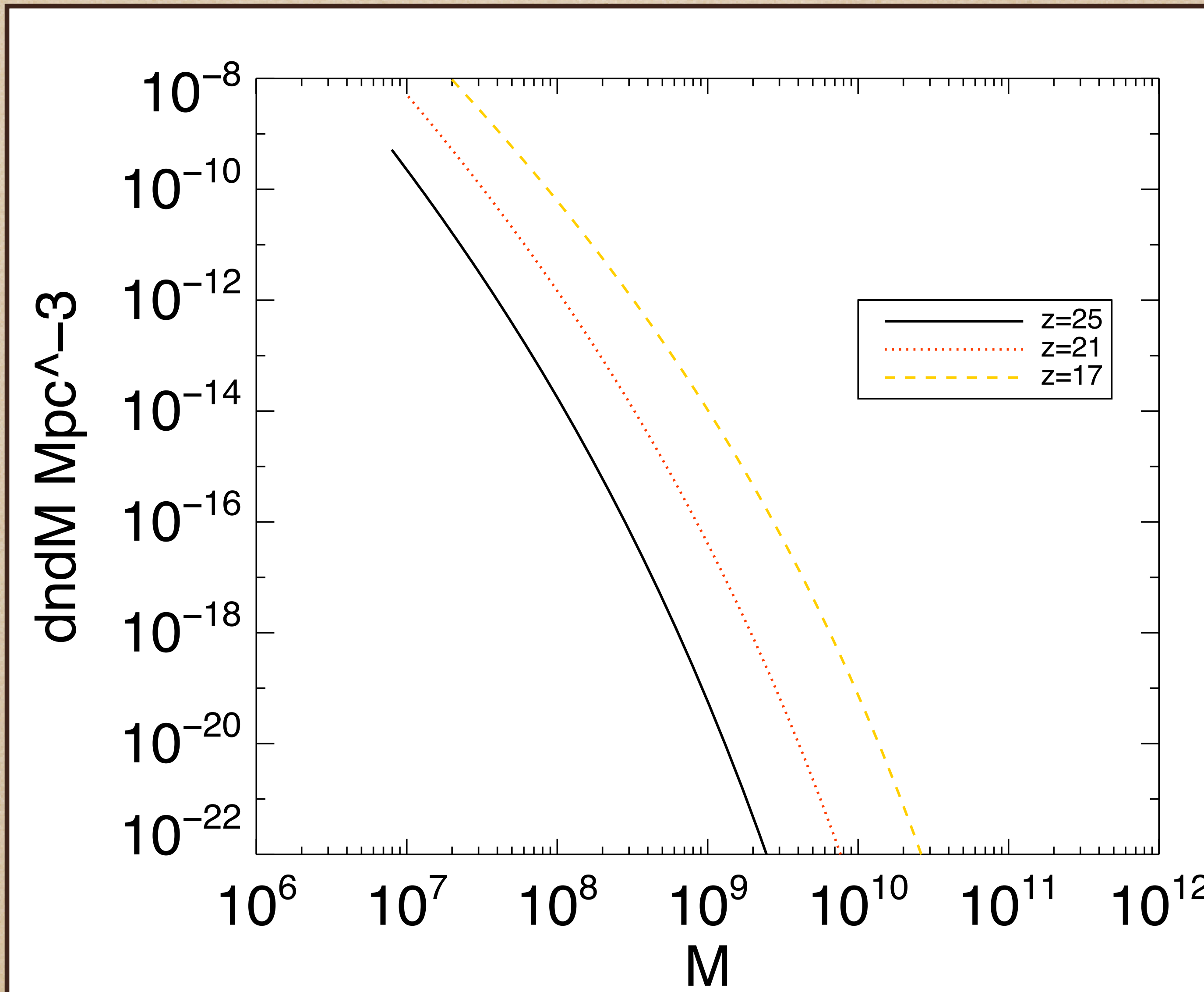
$$\frac{B_{\rm mag}^2}{8\pi} V_{\rm rem} = f_{\rm mag} E_{\rm SN}.$$

Magnetic field

$$f_{\rm rel} E_{\rm SN} = V_{\rm rem} \int_{\epsilon_{\rm min}}^{\epsilon_{\rm max}} n_0 m_e c^2 \epsilon^{1-\gamma}.$$

Relativistic electrons

Number density per mass bin



Power spectrum of Faraday conversion

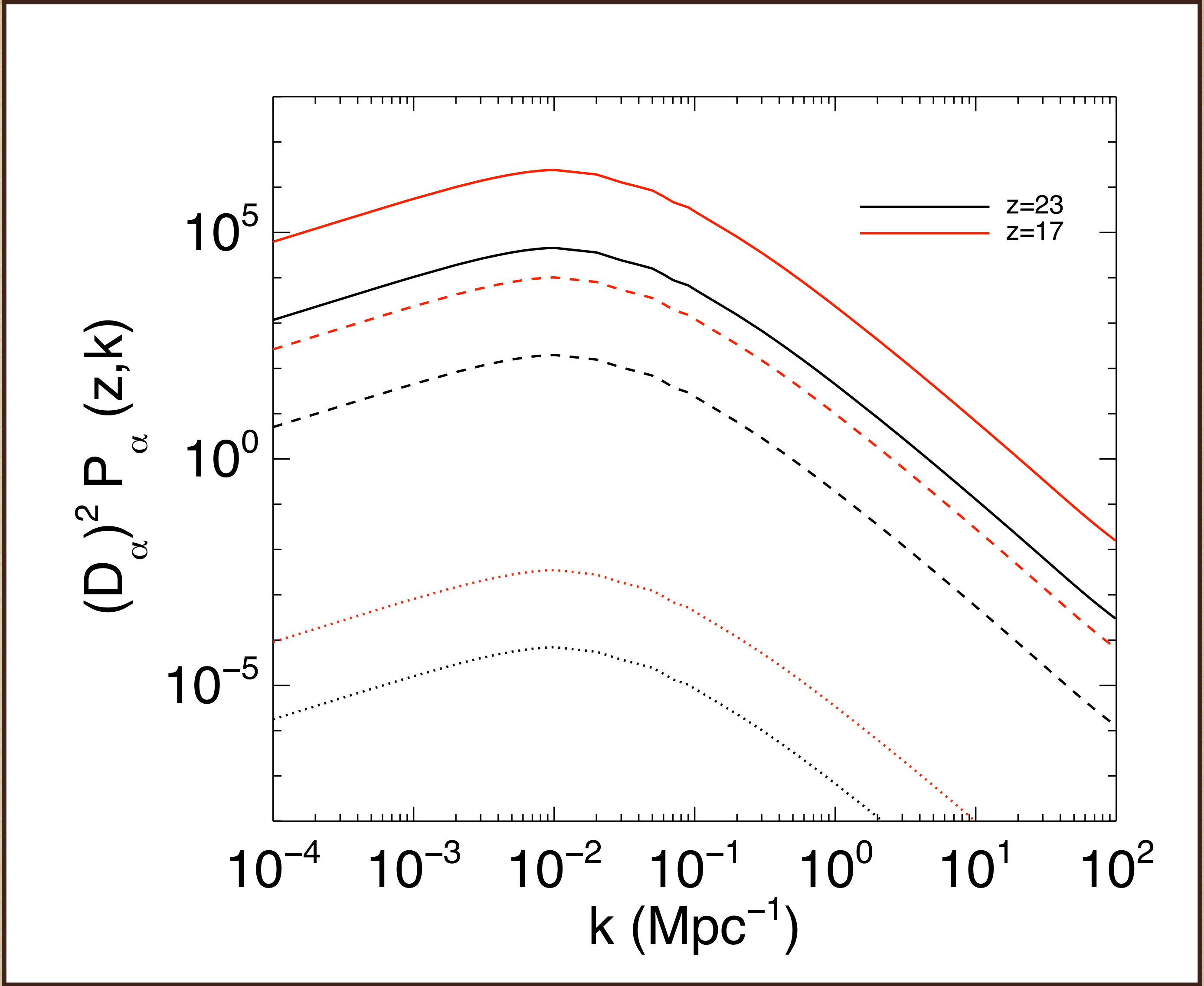
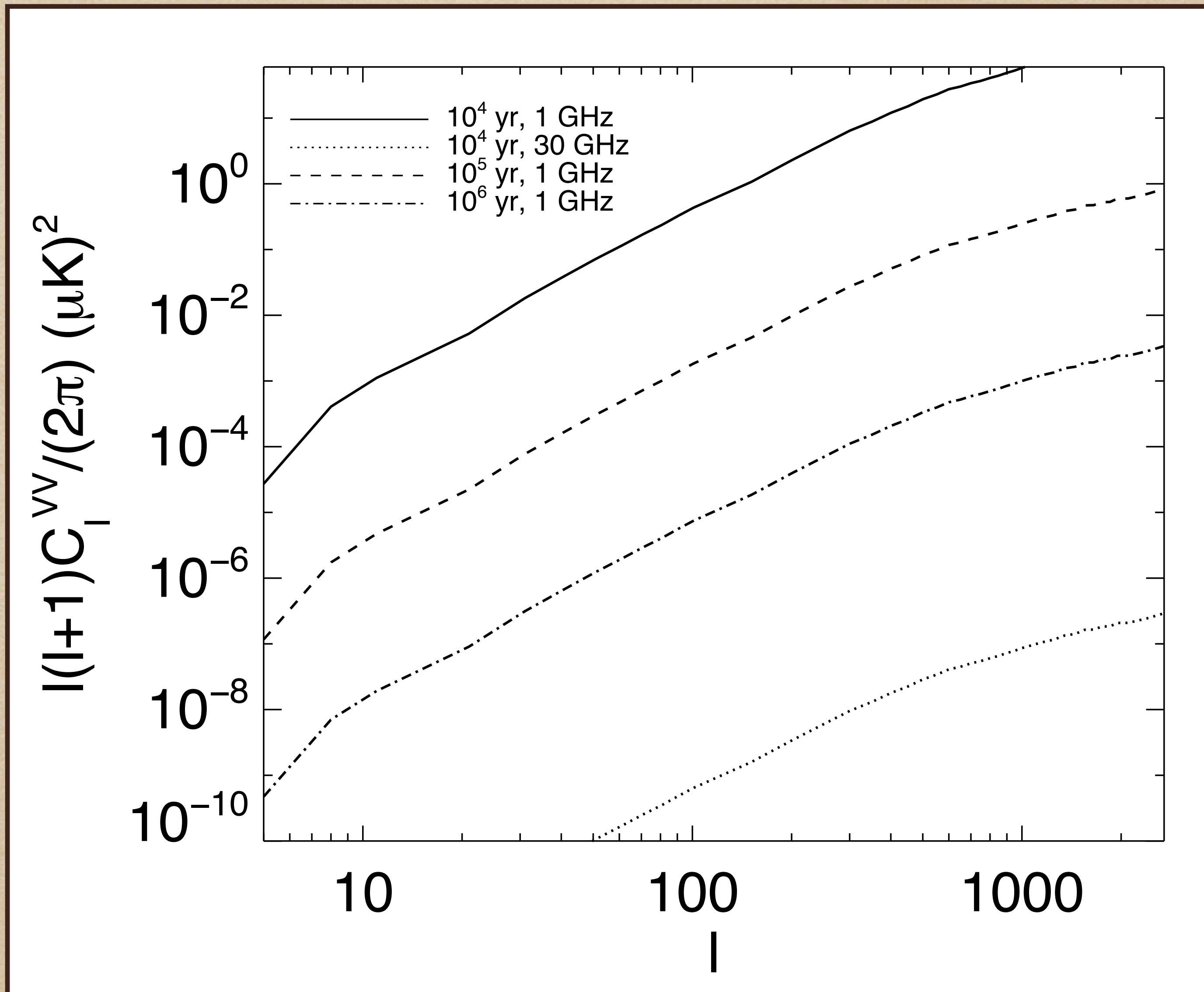


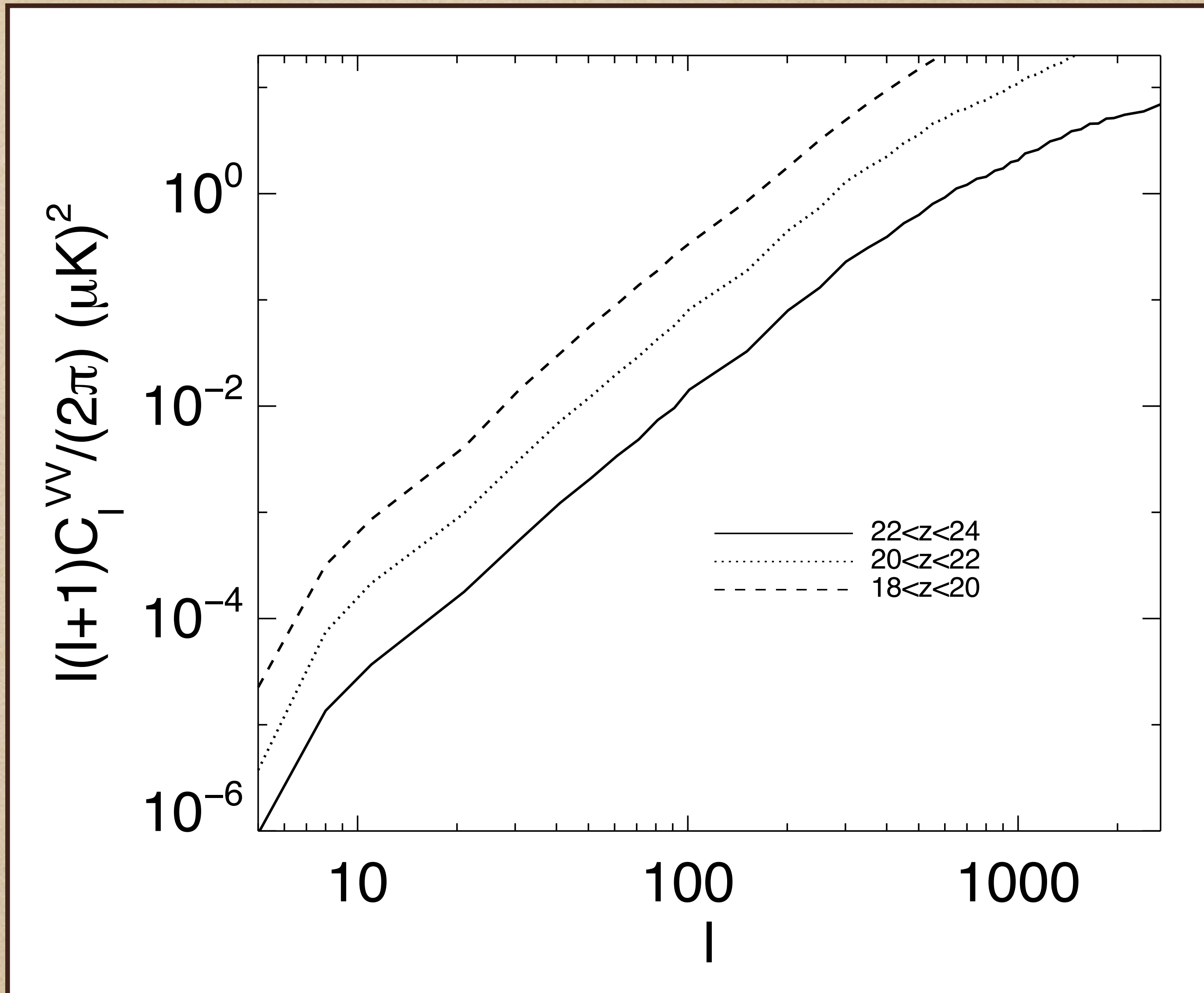
FIG. 1: Power spectra of Faraday conversion generated by the First stars at different redshifts. The solid lines correspond to $t_{age} = 10^4$ years and $\nu = 1$ GHz. The dashed lines correspond to $t_{age} = 10^5$ years and $\nu = 1$ GHz. Lastly, the dotted lines correspond to $t_{age} = 10^4$ years and $\nu = 30$ GHz. Here, ν is the frequency of the CMB photons observed today.

Predicted Signal of V



semi-analytic

Redshift dependence of the signal



Summary on CP due to First stars

- Lots of room for improvement in magnetic field modeling
- Foregrounds/ FR of incoming signal
- Metal pollution reducing the size of PopIII