Study of the nature of neutrinos and dark matter via CMB polarizations

Rohoollah Mohammadi (INMOST)

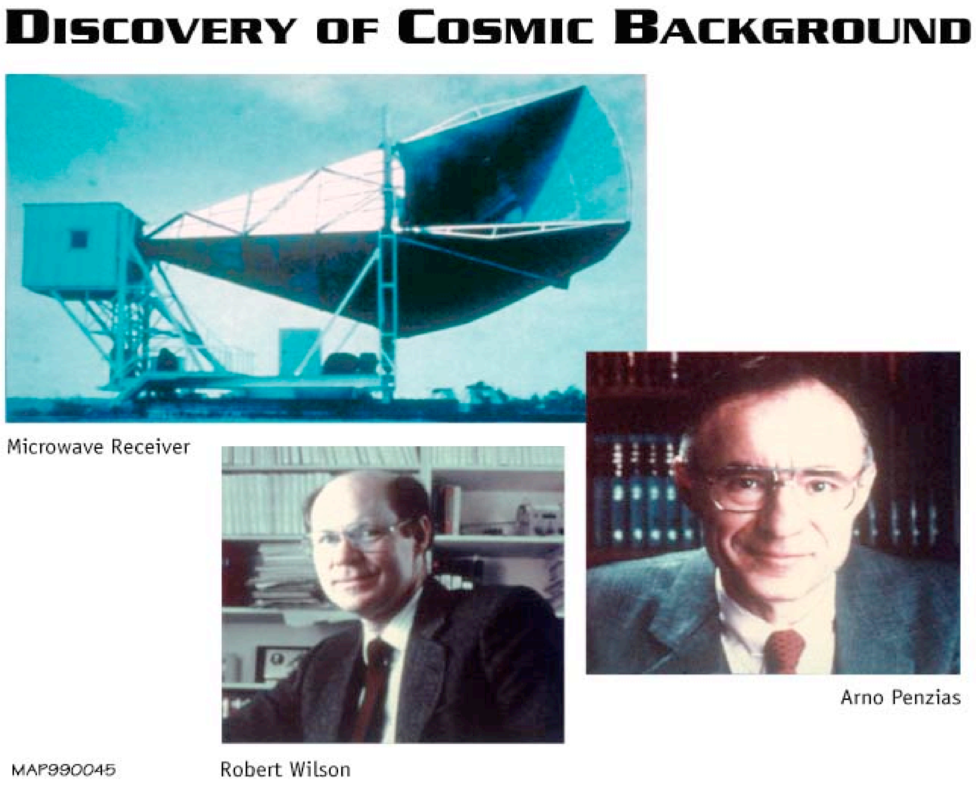
Azar 1399

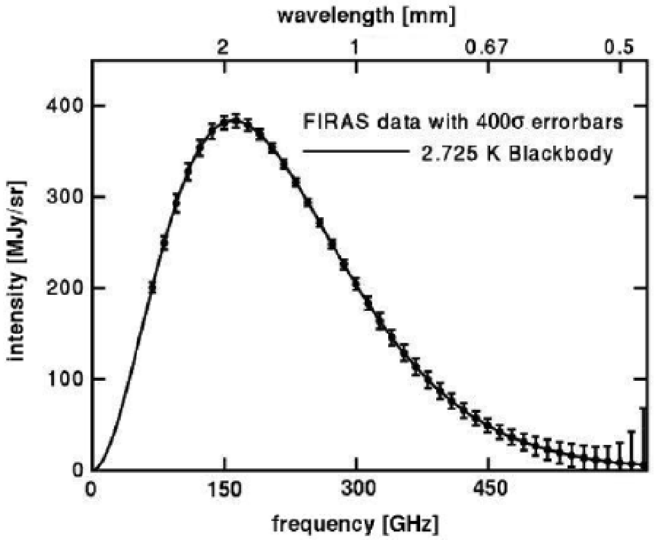
The School of Particles and Accelerators of IPM

outline

- Introduction
  Cosmic Microwave Background (CMB)
  Cosmic Neutrino Background (CNB)
  Dark Matter (DM)
- The Nature of CNB and DM
- Photon-Neutrino Interaction
- Photon-Dark Matter Interaction
- Quantum Boltzmann Equation
  Stokes Parameters
- Generation of Circular and Linear Polarization
- Summery

Introduction:



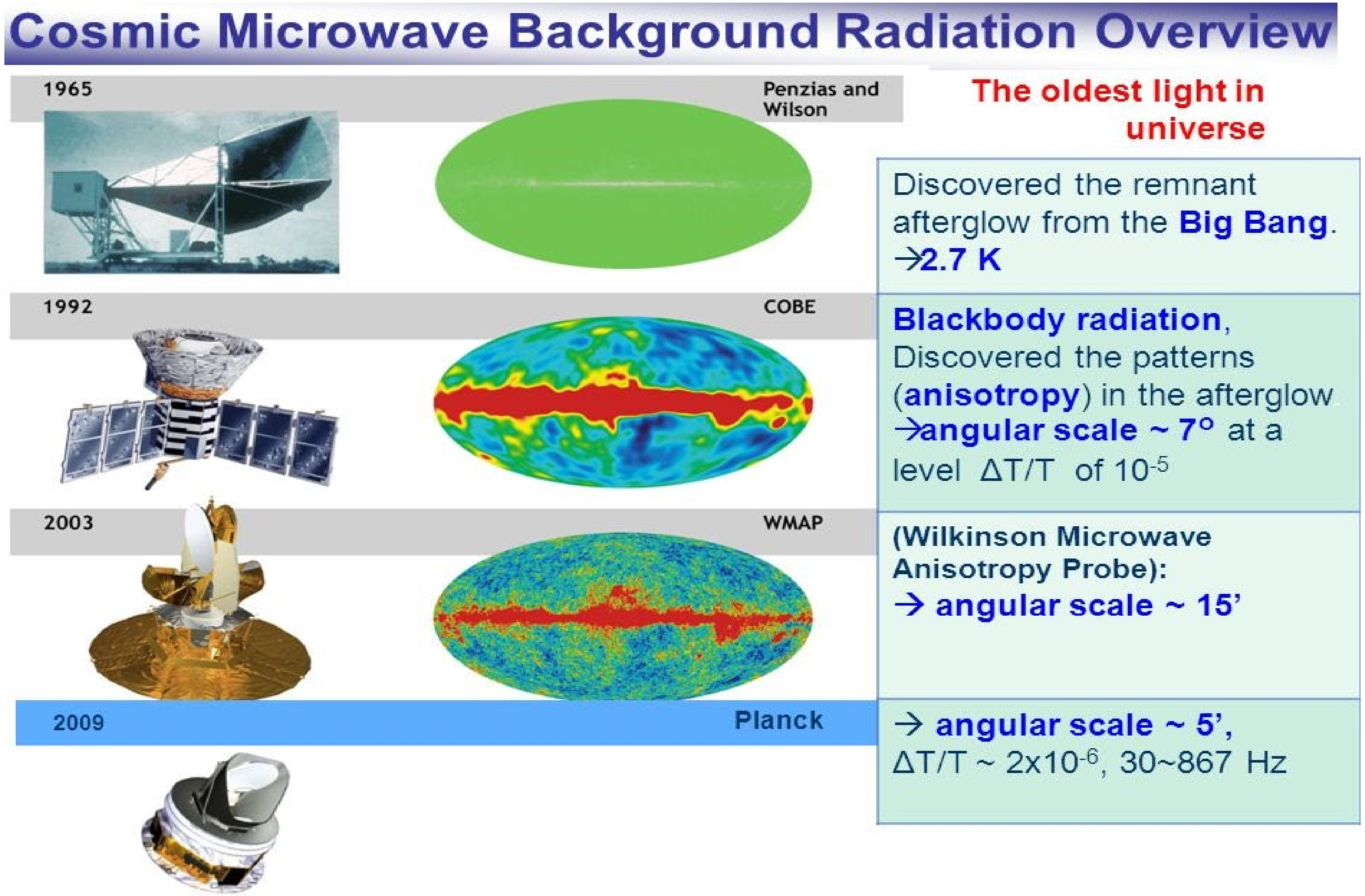


$Power = 3.3\ \mu W/m2$

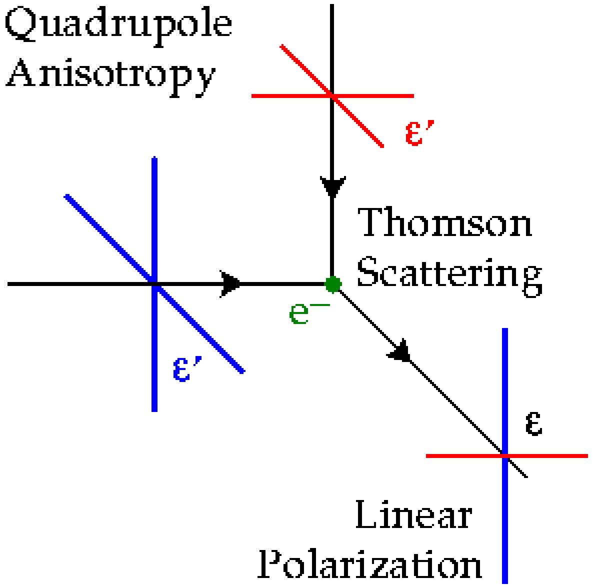
$(Our\ bodies\ radiate\ about\ 500\ W/m2)$

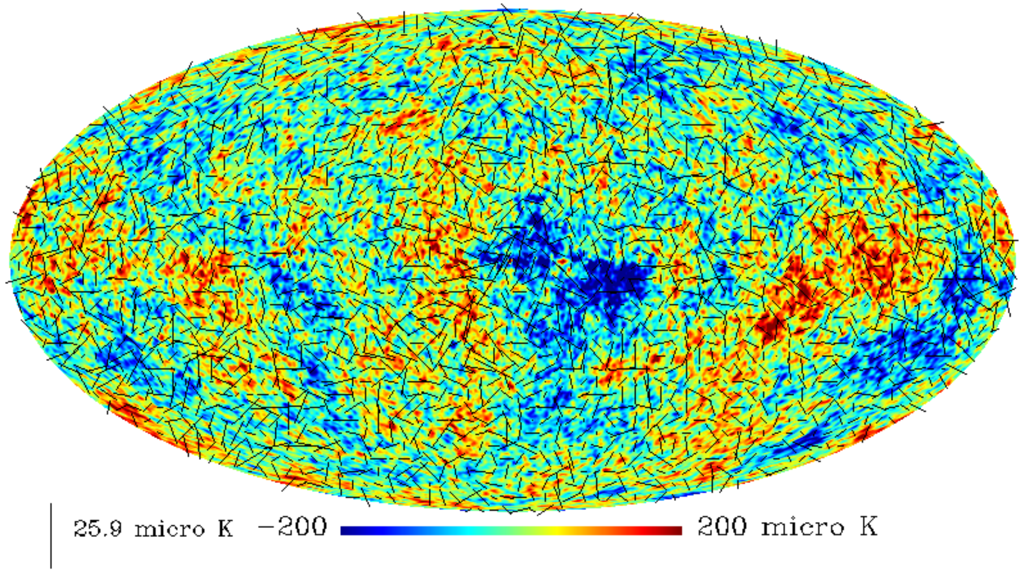
The existence of the CMB radiation was first predicted by Ralph Alpherin 1948 in connection with his research on Big Bang Nucleosynthesis undertaken together with Robert Herman and George Gamow. It was first observed inadvertently in 1965 by Arno Penzias and Robert Wilson at the Bell Telephone Laboratories in Murray Hill, New Jersey.

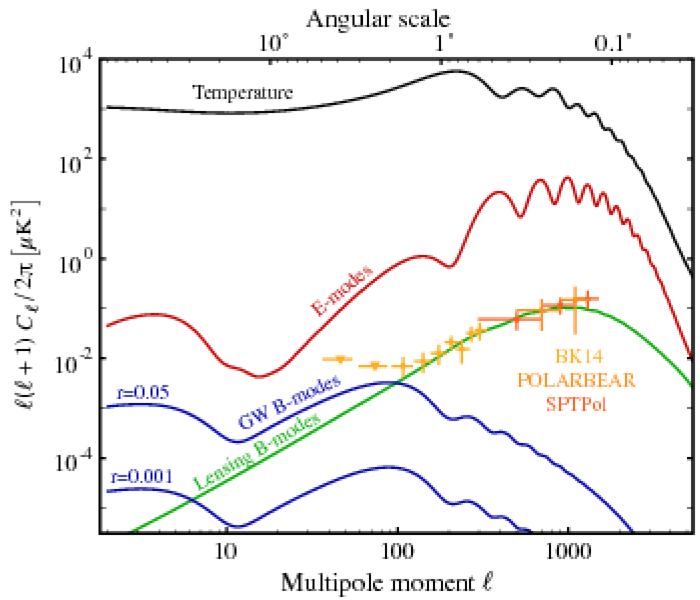
Introduction



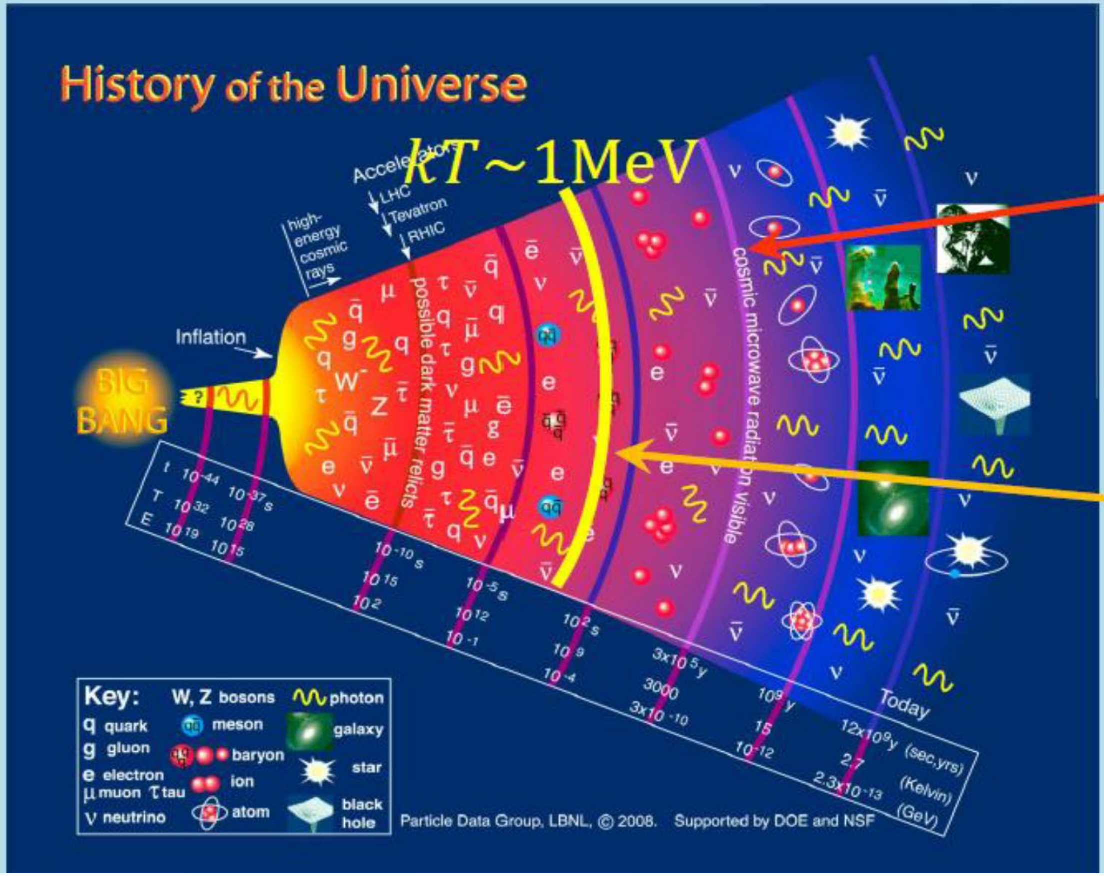
Introduction

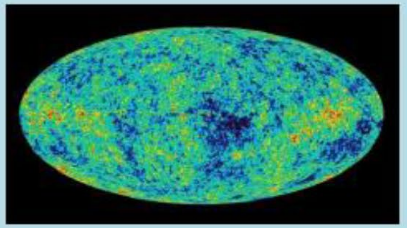






Cosmic Neutrino Background





CMB

$$n_\gamma = 411/\mathrm{cm}^3$$

$$T_\gamma = 2.73\ \mathrm{K}$$

CνB

$$n_\nu = n_{\bar{\nu}} = \frac{3}{4}\left(\frac{T_\nu}{T_\gamma}\right)^3 \frac{n_\gamma}{2}$$

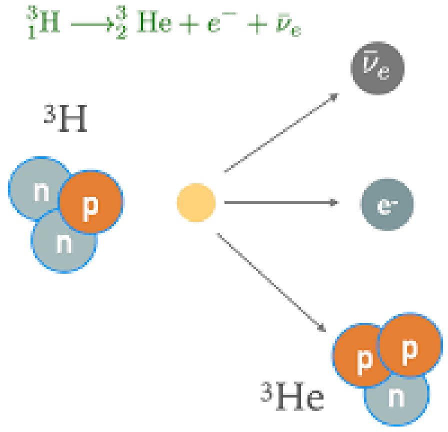
$$= 56/\mathrm{cm}^3$$

$$T_\nu = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_\gamma = 1.95\mathrm{K}$$

Cosmic Neutrino Background

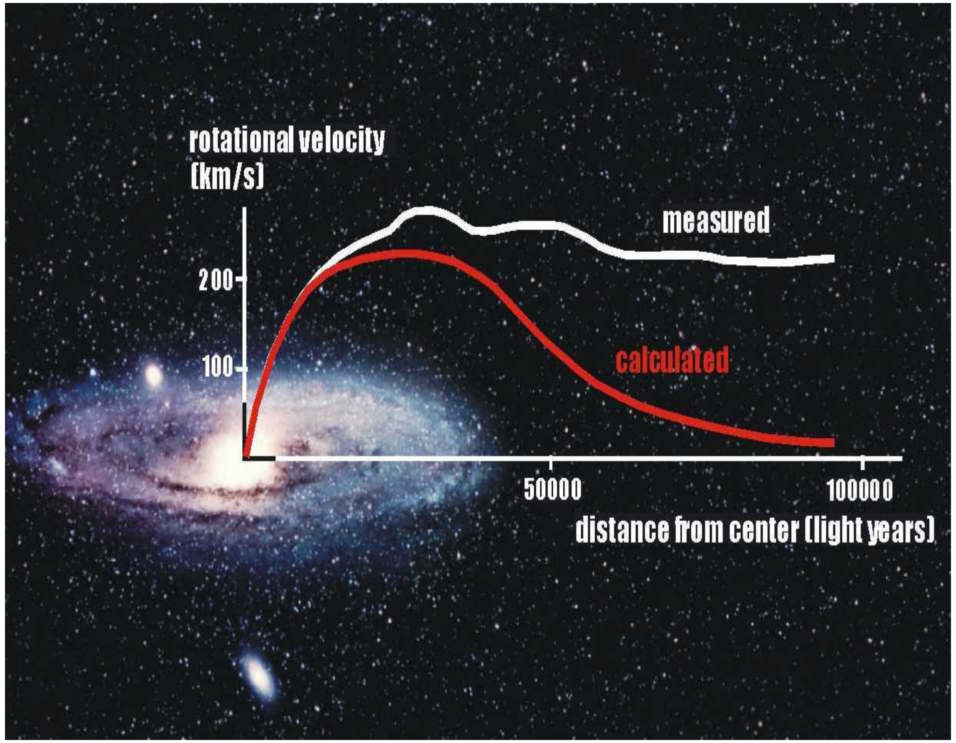
Considering a tritium-target mass of 100 g, as is proposed for PTOLEMY (2022) JCAP 07 (2019) 047

$$\Gamma^{\mathrm{M}}_{\mathrm{C}\nu\mathrm{B}} \approx 8.12\ \mathrm{yr}^{-1} \qquad \text{and} \qquad \Gamma^{\mathrm{D}}_{\mathrm{C}\nu\mathrm{B}} \approx 4.06\ \mathrm{yr}^{-1}$$

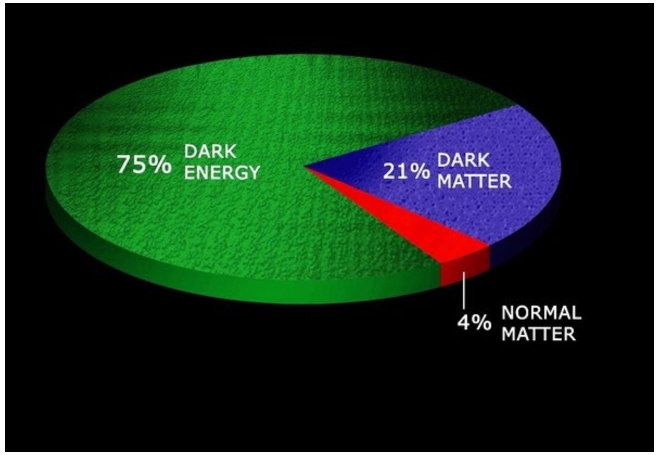


JCAP 1408 (2014) 038 **arxiv:1405.7654**

Introduction: Dark Matter



Today we believe that Ordinary matter, dark matter, dark energy are the constituents of the Universe.



In 1933, the Swiss astrophysicist **Fritz Zwicky**, studied a small group of galaxies in the Coma cluster and found that the dynamic mass of the cluster is much higher than its visible light mass.

The nature of dark matter

✓ Dark matter ←→ Gravitational effects

❑ Particle or (and) Black hole/ …?

If Dark Matter is particle

❑ Mass?

❑ Charge, dipoles , …?

❑ Sector (scalar, vector, spinor…)?

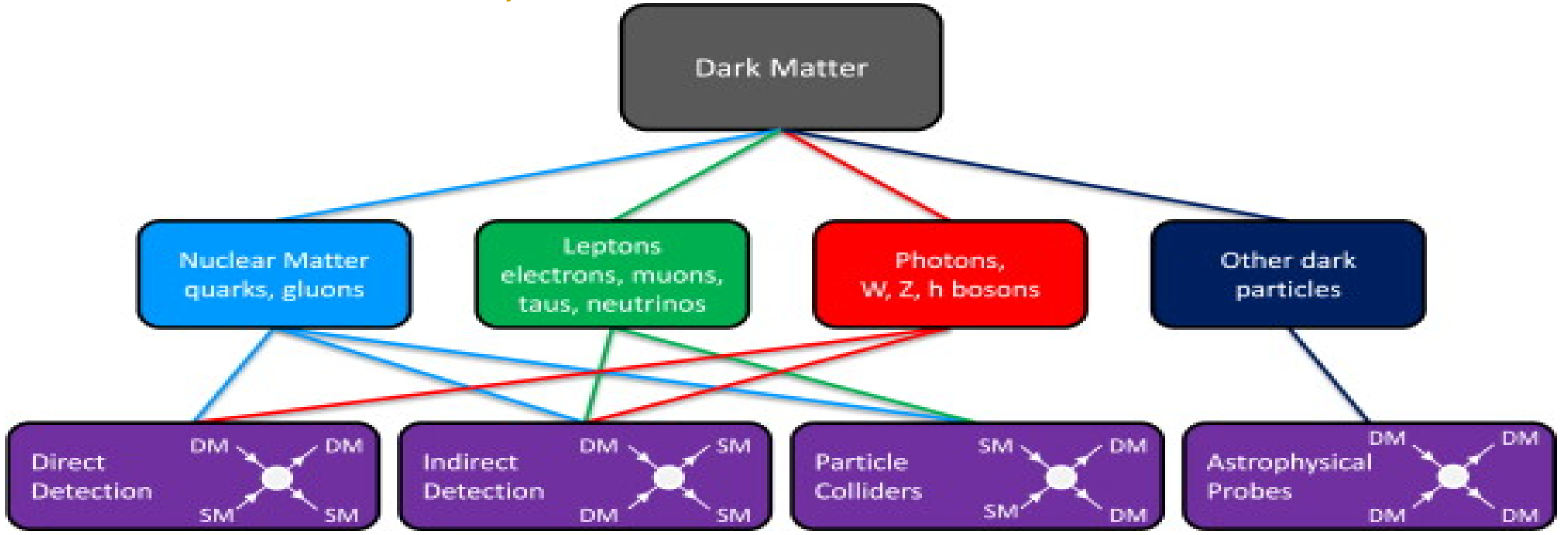
❑ Interaction with matter?

❑ And so on…

For the rest, we consider Dark Matter as a particle with different sector.
We also consider relevant effective interactions for photon-dark matter in different cases.
Finally, effects of photon-Dark Matter interaction on the CMB polarization will be investigated.

Photon-Dark Matter interaction

Physics of the Dark Universe, 7–8, (2015) 16-23

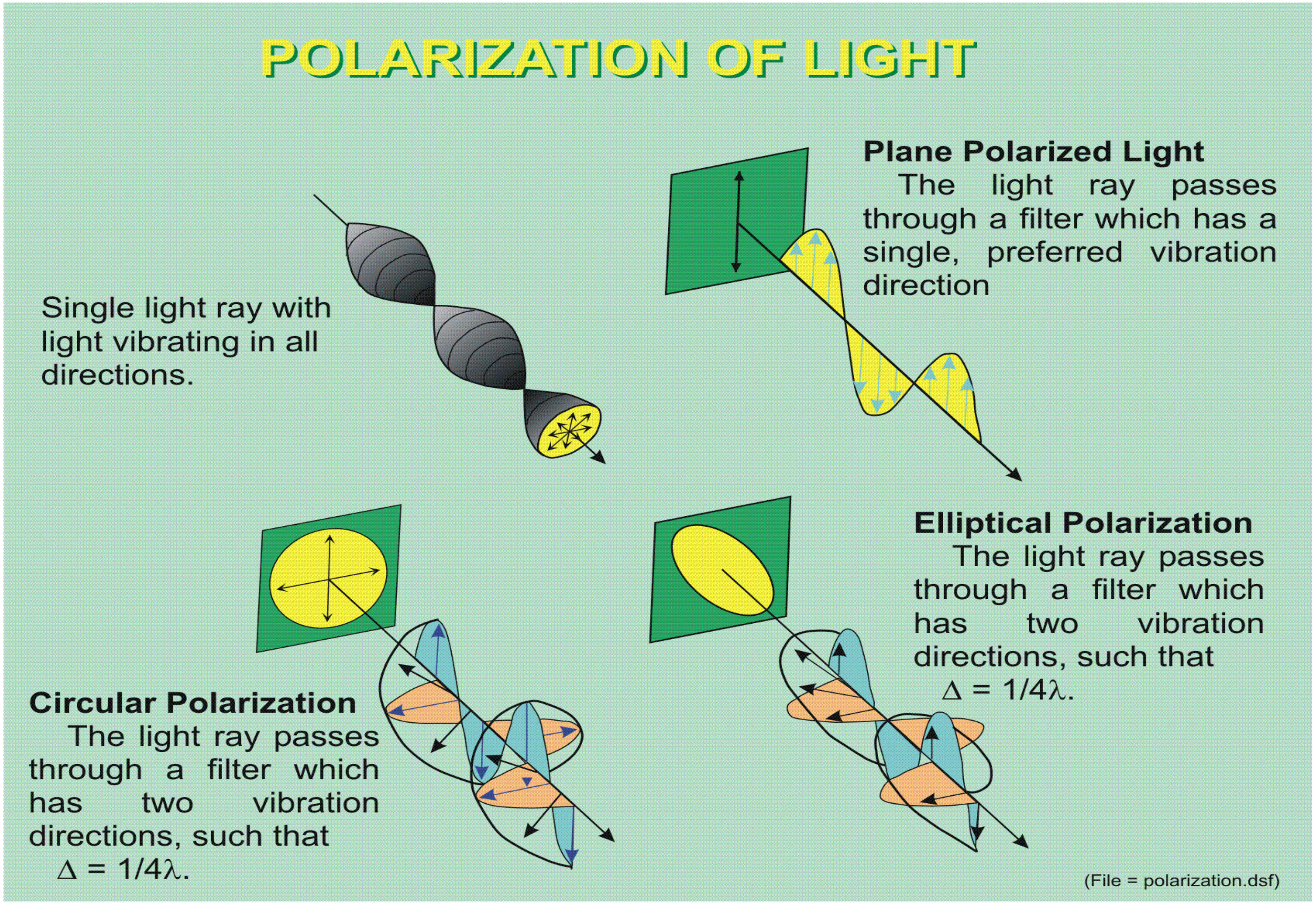


Scalar Dark Matter→ $\mathcal{L}_{int} = -\frac{g_\phi}{4}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu}$

Dipolar Dark Matter→ $\mathcal{L}_{\rm DDM} = -\frac{i}{2}\bar{\psi}\sigma_{\mu\nu}(M+\gamma^5 D)\psi F^{\mu\nu},$ Phys. Rev. D **70** , 083501 (2004) [Phys. Rev. D **73**, 089903 (2006)].

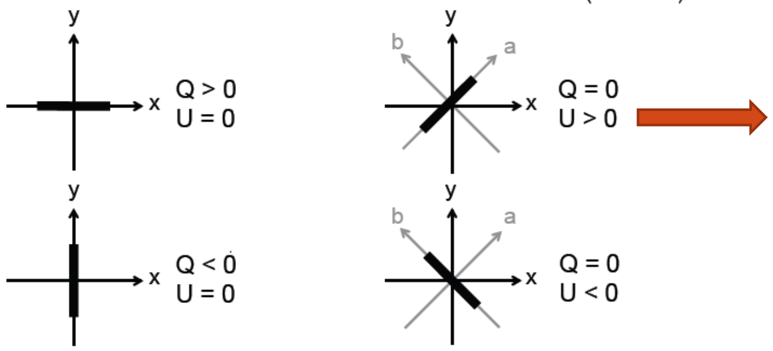
Vector Dark Matter→ $L_I = g_v \cos\theta_w F^{\mu v} V_\mu V_v' + g_v' \cos\theta_w \varepsilon^{\mu v \alpha\beta} F_{\mu v} V_\alpha V_\beta'$ Phys. Lett. B **724**, 84 (2013).

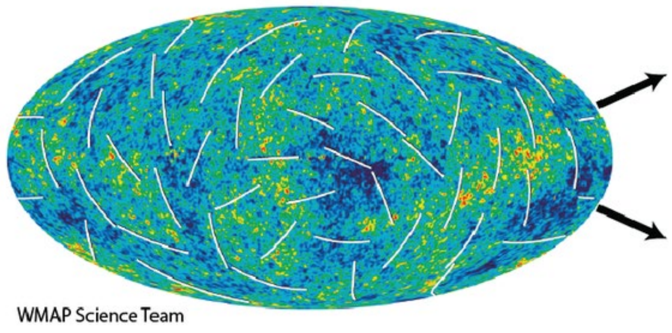
Polarizations

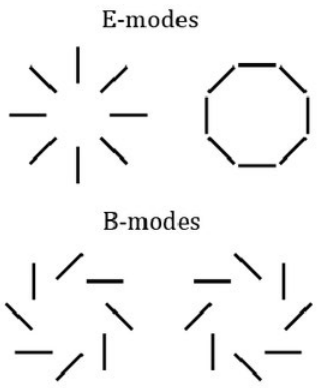


Linear Polarization

$$Q \equiv |E_x|^2 - |E_y|^2 \qquad U \equiv |E_a|^2 - |E_b|^2 = \mathrm{Im}(E_a E_b^*)$$







The CMB anisotropy polarization map may be decomposed into curl-free even-parity E-modes and divergence- free odd-parity B-modes. Primordial B-modes are only created by tensor perturbations (inflationary gravitational waves).

CMB Experiments

https://lambda.gsfc.nasa.gov/product/expt/

Cosmic Microwave Background Anisotropy Experiments

Links to Project Website	Data At LAMBDA	Full Name	Year	Status	l-min	l-max	Frequ-ency (GHz)	Detectors	Polariz-ation Values	Type
SPT-3G	-	South Pole Telescope - third generation	2018-date	Active	50	11000	95, 150, 220	Bolometer	Yes	Ground
CLASS	DATA	Cosmology Large-Angular Scale Surveyor	2016-date	Active	2	200	40, 90, 150, 220	Bolometer	Yes	Ground
SPIDER	DATA	Spider	2015-date	Active	10	300	90, 150, 280	Bolometer	Yes	Balloon
BICEP3	-	Background Imaging of Cosmic Extragalactic Polarization 3	2015-date	Active	21	335	95	Bolometer	Yes	Ground
ACTPol	DATA	Atacama Cosmology Telescope - Polarization	2013-date	Active	225	8725	90, 146	Bolometer	Yes	Ground
EBEX	-	The E and B Experiment	2012-2013	Completed	25	1000	150-450	Bolometer	Yes	Balloon
POLARBEAR	DATA	POLARization of Background microwave Radiation	2012-date	Active	50	2000	150	Bolometer	Yes	Ground
SPTpol	DATA	South Pole Telescope - Polarization	2012-date	Active	50	8000	95, 150	Bolometer	Yes	Ground
QUIJOTE	-	Q U I JOint TEnerife	2012-date	Active	10	300	11, 13, 17, 19, 30, 40	Polarizer/OMT	Yes	Ground
ABS	DATA	Atacama B-mode Search	2011-2014	Completed	25	200	145	Bolometer	Yes	Ground
KECKArray	DATA	Keck Array	2010-date	Active	21	335	95, 150, 220, 270	Bolometer	Yes	Ground
Planck	DATA	Planck	2009-2013	Completed	2	2500	30 - 857	Radio, Bolometer	Yes	Satellite

CMB Experiments

https://lambda.gsfc.nasa.gov/product/expt/

SPT	DATA	South Pole Telescope	2007-date	Active	650	9500	95, 150, 220	Bolometer	No	Ground
BICEP1	Power Spectra	Background Imaging of Cosmic Extragalactic Polarization	2006-2008	Completed	21	335	100, 150, 220	Bolometer	Yes	Ground
AMI	-	Arcminute MicroKelvin Imager	2005-date	Active	n/a	22000	12-18	Interferometer	No	Ground
QUaD	DATA	QUEST (Q and U Extra-Galactic Sub-mm Telescope) and DASI (Degree Angular Scale Interferometer)	2005-2010	Completed	~200	2000	100, 150	Bolometer	Yes	Ground
KUPID	-	KU-band Polarization IDentifier	2003-date	Active	100	600	12-18	HEMT	Yes	Ground
CBI	Power Spectra	Cosmic Background Imager	2002-2008	Completed	300	3000	26-36,in 10 channels	Interferometer/ HEMT	No	Ground
PIQUE	-	Princeton I, Q, and U Experiment	2002	Completed	69	362	90	Bolometer	Yes	Ground
TopHat	-	TopHat	2002-2004	Completed	10	700	150-720	Bolometer	No	Balloon
VSA	Power Spectra	Very Small Array	2002-2004	Completed	130	1800	26-36	Interferometer/ HEMT	No	Ground
CAPMAP	Power Spectra	Cosmic Anisotropy Polarization MAPper	2002-2008	Completed	500	1500	90 and 40	MMIC/ HEMT	Yes	Ground
WMAP	DATA	Wilkinson Microwave Anisotropy Probe	2001-2010	Completed	2	1200	23, 33, 41, 61, 94	HEMT	Yes	Satellite
ACBAR	Power Spectra	Arcminute Cosmology Bolometer Array Receiver	2001-2008	Completed	60	2700	150, 219, 274	Bolometer	No	Ground
DASI	Power Spectra	Degree Angular Scale Interfer-ometer	2001-2003	Completed	200	900	26-36,in 10 bands	HEMT	Yes	Ground

Quantum Boltzmann Equation (QBE)

- Boltzmann equation is a systematic mechanism in order to describe the evolution of the distribution function under gravity and collisions. Ones can consider each polarization state of each laser beam as the phase space distribution function

$$\frac{d}{dt}\xi = \mathcal{C}(\xi)$$

$$\langle\, D^0_{ij}(k)\,\rangle \equiv \mathrm{tr}[\hat{\rho} D^0_{ij}(k)] = (2\pi)^3\delta^3(0)(2k^0)\rho_{ij}(k).$$

- And on the other hand, the time evolution of the operator $D^0_{ij}(k)$, considered in the Heisenberg picture, is

$$\frac{d}{dt}D^0_{ij}(k) = i[H, D^0_{ij}(k)],$$

$$(2\pi)^3\delta^3(0)(2k^0)\frac{d}{dt}\rho_{ij}(k) = i\langle[H^0_I(t); D^0_{ij}(k)]\rangle - \frac{1}{2}\int dt\langle[H^0_I(t); [H^0_I(0); D^0_{ij}(k)]]\rangle,$$

Stokes parameters

- An arbitrary polarized state of a photon propagating in the *z*-direction, is given by

$$|\epsilon\rangle = a_1 \exp(i\theta_1)|\epsilon_1\rangle + a_2 \exp(i\theta_2)|\epsilon_2\rangle,$$

- The parameter ***I*** is total intensity, ***Q*, *U*** and ***V*** parameters indicate linear and circular polarized intensities of electromagnetic waves, notice that ***V***–parameter shows the difference between left- and right- circular polarizations intensities.

$$\rho_{ij} \equiv (\,|\epsilon_i\rangle\langle\epsilon_j|/\mathrm{tr}\rho) \Rightarrow$$

$$I \equiv \langle \hat{I} \rangle = \mathrm{tr}\rho\hat{I} = 1,$$

$$Q \equiv \langle \hat{Q} \rangle = \mathrm{tr}\rho\hat{Q} = \rho_{11} - \rho_{22},$$

$$U \equiv \langle \hat{U} \rangle = \mathrm{tr}\rho\hat{U} = \rho_{12} + \rho_{21},$$

$$V \equiv \langle \hat{V} \rangle = \mathrm{tr}\rho\hat{V} = i\rho_{21} - i\rho_{21},$$

CMB Power Spectrum

$$C^{(S)}_{X,l} = \frac{1}{2l+1} \sum_m < a^{\star}_{X,lm} a_{X,lm} >$$

Which $X \epsilon \{T, E, B\}$ and

$$a_{T,V} = \int d\Omega Y^{\star}_{lm} \Delta^{(S)}_{T,V}(\hat{\mathbf{n}}) \quad , \quad a_{B,E} = \int d\Omega Y^{\star}_{lm} \Delta^{(S)}_{B,E}(\hat{\mathbf{n}})$$

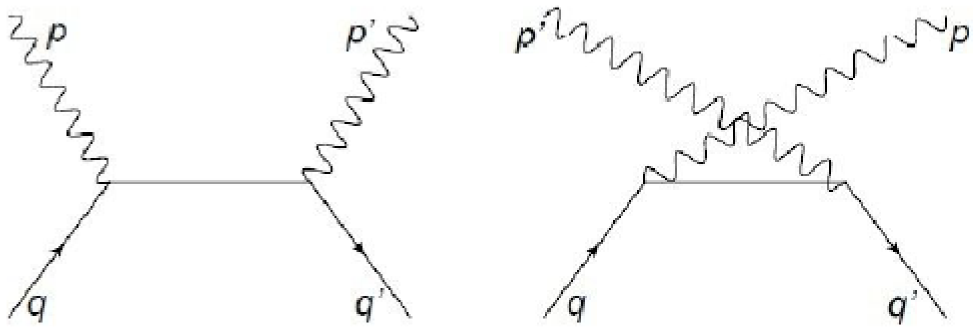
$$C_{Tl} = \frac{1}{2l+1} \sum_m \langle a^*_{T,lm} a_{T,lm} \rangle$$

$$C_{El} = \frac{1}{2l+1} \sum_m \langle a^*_{E,lm} a_{E,lm} \rangle$$

$$C_{Bl} = \frac{1}{2l+1} \sum_m \langle a^*_{B,lm} a_{B,lm} \rangle$$

$$C_{Cl} = \frac{1}{2l+1} \sum_m \langle a^*_{T,lm} a_{E,lm} \rangle$$

Generation of Polarization via CMB- Dipolar DM Interaction



$$\mathcal{L}_{\rm DDM} = -\frac{i}{2}\bar{\psi}\sigma_{\mu\nu}(M + \gamma^5 D)\psi F^{\mu\nu},$$

FIG. 1: The typical diagrams for photon-dark matter scattering

$$H_I(t) = \int d\mathbf{q} d\mathbf{q}' d\mathbf{p} d\mathbf{p}' (2\pi)^3 \delta^{(3)}(\mathbf{q} + \mathbf{p} - \mathbf{q}' - \mathbf{p}') e^{i(q^0 + p^0 - q'^0 - p'^0)}$$
$$[b^\dagger_{r'}(q') a^\dagger_{s'}(p') \mathcal{M} a_s(p) b_r(q)],$$

CMB- Dipolar DM Forward Scattering

$$i\langle [H_I^0(0), D_{ij}(\mathbf{k})]\rangle = i\int d\mathbf{q}\, n_d(\mathbf{x}, \mathbf{q})(\delta_{is}\rho_{s'j}(k) - \delta_{js'}\rho_{is}(k))(2\pi)^3\delta^{(3)}(0)\mathcal{M},$$

Generation of Polarization via CMB- Dipolar DM Interaction

$$\frac{d\rho_{ij}}{dt} = -iM^2 v_b \int d\mathbf{q} n_d(\mathbf{x},\mathbf{q})(\delta_{is}\rho_{s'j}(k) - \delta_{js'}\rho_{is}(k))(\vec{\epsilon}_{s'} \times \vec{\epsilon}_s)\cdot\hat{k},$$

where $\hat{k} = \vec{k}/k^0$. Consequently, the stokes parameters evolve as

dark matter number density n_d

$$\frac{dI}{dt} = C^I_{e\gamma},$$

$$\frac{d}{dt}(Q \pm iU) = C^{\pm}_{e\gamma} \mp i\dot{\tau}_d(Q \pm iU),$$

$$\frac{dV}{dt} = C^V_{e\gamma},$$

where $v_b = |\vec{q}|/m_f$ is the bulk velocity of dark matter

$C^I_{e\gamma}$,$C^V_{e\gamma}$ and $C^{\pm}_{e\gamma}$ show the effects of Thomson scattering

$$\dot{\tau}_d = v_b \frac{3}{4\pi}\left(\frac{m_e}{m_d}\right)^2 \frac{\sigma_T}{\alpha^2}\sqrt{2\pi\langle\sigma v\rangle}\ \rho_d,$$

$$\frac{\dot{\tau}_d}{\dot{\tau}_e} = 5.2\times10^{-11}\ \left(\frac{m_d}{1GeV}\right)^{-2}\ \left(\frac{\langle\sigma v\rangle}{10^{-28}\frac{cm^3}{s}}\right)\left(\frac{\Omega_d}{0.26}\right)\left(\frac{\Omega_{B.M}}{0.04}\right)\left(\frac{m_p}{1GeV}\right)\left(\frac{v_b}{300\,Km\,s^{-1}}\right),$$

Generation of Polarization via CMB- Dipolar DM Interaction

$$\Delta_E^{(S)}(\eta_0, K, \mu) \equiv -\frac{1}{2}\left[\bar{\eth}^2\,\Delta_P^{+(S)}(\eta_0, K, \mu) + \eth^2\Delta_P^{-(S)}(\eta_0, K, \mu)\right],$$

$$\Delta_B^S(\eta_0, K, \mu) \equiv \frac{i}{2}\left[\bar{\eth}^2\,\Delta_P^{+S}(\eta_0, K, \mu) - \eth^2\Delta_P^{-S}(\eta_\circ, K, \mu)\right],$$

$$\Delta_P^{\pm S} = Q^S \pm iU^S,$$

$$C_l^{EE,S} = (4\pi)^2\frac{(l+2)!}{(l-2)!}\int d^3K\,P_S(K)\left|\frac{3}{4}\int_0^{\eta_0} d\eta\,g_e(\eta)\,\Pi(\eta,K)\frac{j_l}{x^2}\,\cos\tau_d\right|^2,$$

$$C_l^{BB,S} = (4\pi)^2\frac{(l+2)!}{(l-2)!}\int d^3K\,P_S(K)\left|\frac{3}{4}\int_0^{\eta_0} d\eta\,g_e(\eta)\,\Pi(\eta,K)\,\frac{j_l}{x^2}\,\sin\tau_d\right|^2,$$

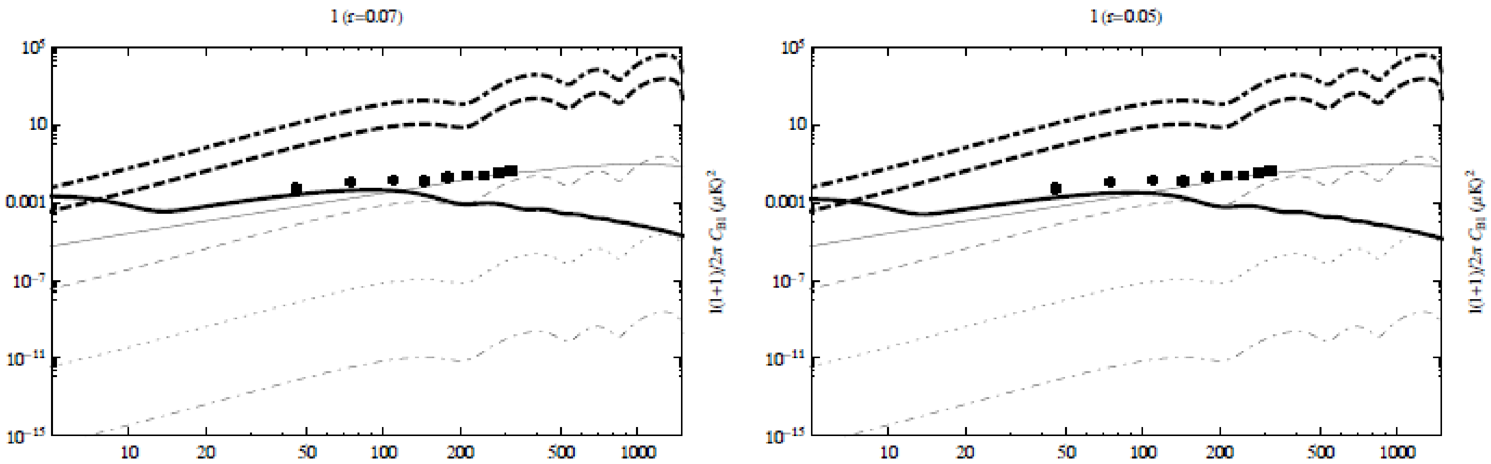
If we neglect CMB-DM interaction, the standard results will be obtained

$$\tau_d = 0 \rightarrow C_l^{BB,S} = 0, C_l^{EE,S} = C_l^{EE,S}|_{SD}$$

$$r = C_l^{BB,T}/C_l^{EE,S} = (C_l^{BB,ob} - C_l^{BB,S})/C_l^{EE,S} = r^* - C_l^{BB,S}/C_l^{EE,S}$$

Adding CMB-DM interactions do suppress r-parameter

Generation of Polarization via CMB- Dipolar DM Interaction



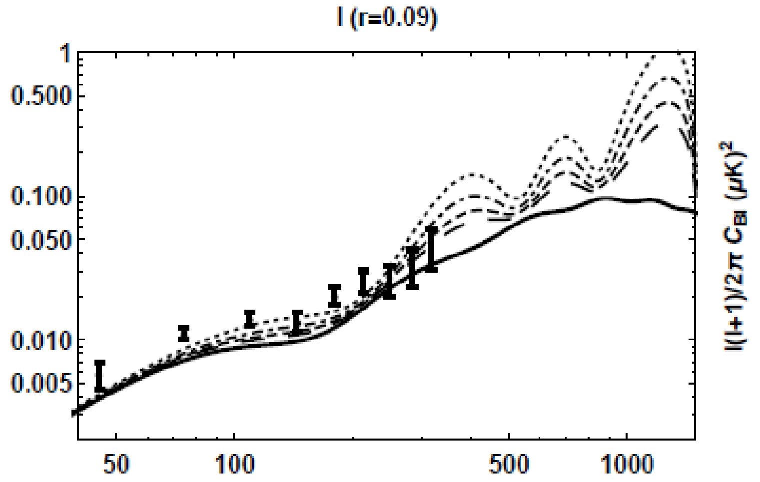
(a) To plot above curves, $<\sigma v> \simeq 10^{-28} cm^3 s^{-1}$ and $r = 0.07$ are considered.

(b) To plot above curves, $<\sigma v> \simeq 10^{-28} cm^3 s^{-1}$ and $r = 0.05$ are considered.

- S. Mahmoudi, M. Haghighat, S.Al. Modares Vamegh, R. Mohammadi *Eur.Phys.J.C* 80 (2020) 5, 402

FIG. 2: The magnetic like linear polarization angular power spectrum $l(l+1)/(2\pi)\, C_l^{BB}$ for different values of the tensor to scalar ratio r is plotted in terms of $(\mu K)^2$; narrow, thick, thick-dashed-dotted, thick-dashed, dashed, dotted and dashed-dotted lines indicate C_l^{BB} due to: the gravitation lensing effects, the standard contribution due to Compton scattering in the presence of tensor perturbations with r mentioned in sub-caption, the Dark matter magnetic moment contribution in the presence of scalar metric perturbations with different masses $m_D \equiv \{10KeV, 50KeV, 0.5MeV, 1MeV, 10MeV\}$, respectively. The points with error bars show the BICEP2/Keck Array data. We have chosen the Planck best fit values for the cosmological parameters.

Generation of Polarization via CMB- Dipolar DM Interaction



(a) To plot above curves, $<\sigma v> \simeq 10^{-28} cm^3 s^{-1}$ and $r = 0.09$ are considered.

FIG. 5: The magnetic like linear polarization angular power spectrum $l(l+1)/(2\pi)\, C_l^{BB}$ is plotted in terms of $(\mu K)^2$; The plot shows: Compton scattering in presence of the tensor perturbations with $r = 0.09$ and gravitation lensing effect without considering DDM interactions (thick line), Compton scattering in the presence of the tensor perturbations and gravitation lensing plus DDM interactions in the presence of scalar perturbations by considering different masses for dark matter $m_D = 7MeV$ (dotted line), $m_D = 8MeV$ (dashed-dotted line), $m_D = 9MeV$ (dashed line), $m_D = 10MeV$ (big-dashed line), respectively. The points with error bars show the BICEP2/Keck Array data. We have chosen the Planck best fit values for the cosmological parameters.

Generation of Polarization via CMB- Dipolar DM Interaction

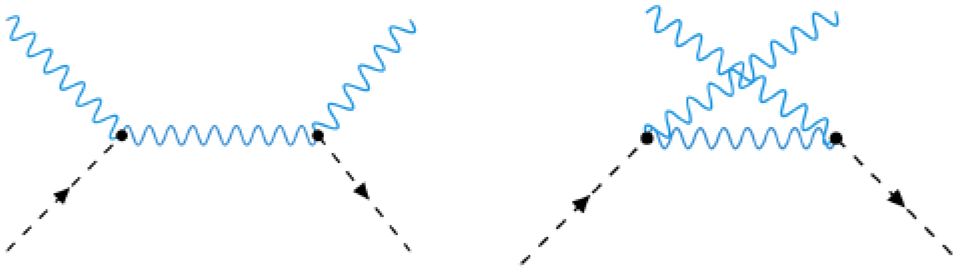
We consider a fermionic dark matter particle as a singlet Majorana fermion which carrying magnetic dipole moment to explore its contribution on the polarization of cosmic microwave background (CMB) photons. We show that this type of interaction leads to the B-mode polarization in presence of primordial scalar perturbations which is in contrast with standard scenario for the CMB polarization. We numerically calculate the B-mode power spectra and plot C_l^{BB} for different dark matter masses and the r-parameter. We show that the dark matter with masses about few MeV have valuable contribution on C_l^{BB}. Meanwhile, the dark matters with mass $m_d \leq 0.5MeV$ for $r = 0.07$ ($m_d \leq 8MeV$ for $r = 0.09$) can be excluded experimentally. Furthermore, our results put a bound on the magnetic dipole moment about $M \leq 10^{-15} e\ cm$ in agreement with the other reported constraints.

- S. Mahmoudi, M. Haghighat, S.Al. Modares Vamegh, R. Mohammadi *Eur.Phys.J.C* 80 (2020) 5, 402

Generation of Polarization via CMB- Scalar DM Interaction

Axions and, in general, other pseudoscalar particles are among the most favoured particle physics candidates for the cold dark matter (CDM). They interact with photons according to the lagrangian:

$$\mathcal{L}_{int} = -\frac{g_\phi}{4}\phi F_{\mu\nu}\widetilde{F}^{\mu\nu} \tag{9}$$



CP Strong Problem

FIG. 1: Axion-Photon scattering ($\phi_a + \gamma \Rightarrow \phi_a + \gamma$)

$$\frac{d}{dt}\rho_{ij}(\mathbf{k}) \approx \frac{ig_s^2}{2k_0}\int \frac{d^3q}{(2\pi)^3}(\frac{m_\phi}{q_0})(\frac{n_\phi(q)}{2})[\delta_{is}\rho_{s'j}(\mathbf{k}) - \delta_{js'}\rho_{is}(\mathbf{k})]\epsilon^{\mu\nu\alpha\beta}\epsilon^{\mu'\nu'\alpha'}{}_{\beta}k_\mu k_{\mu'}\epsilon_{s\nu}(k)\epsilon_{s'\nu'}(k)$$
$$\times\bar{u}(q)\left[\frac{(k+q)_{\alpha'}(k+q)_\alpha}{m_\phi^2 + 2k\cdot q} + \frac{(k-q)_{\alpha'}(k-q)_\alpha}{m_\phi^2 - 2k\cdot q}\right]u(q)$$

The contribution of Forward Scattering is vanished and the damping term has very small contribution On the CMB polarization. This means the CMB polarizations can not help us in the case of scalar DM.

Photon-Photon scattering via Axion exchange

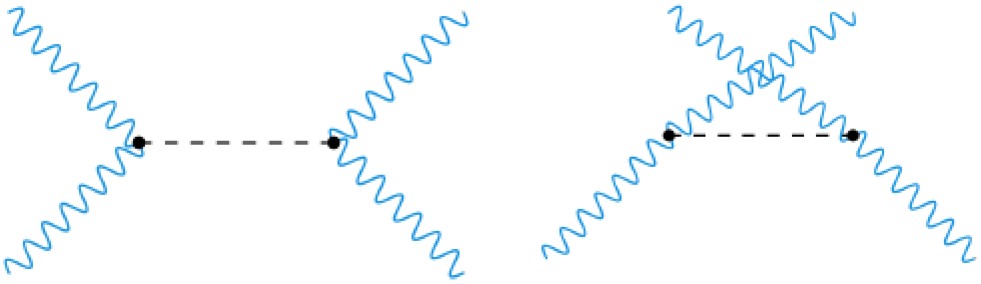


FIG. 1: Photon-Photon scattering via axion exchange ($\gamma + \gamma \Rightarrow \gamma + \gamma$)

$$\frac{d}{dt}Q(\mathbf{k}) = \dot{\rho}_{11} - \dot{\rho}_{22} = \frac{-8g_s^2}{k_0}\int \frac{d^3p}{(2\pi)^3 2p^0}\left[\frac{m_\phi^2 A_Q}{4(p\cdot k)^2 - m_\phi^4}\right] V(\mathbf{k})$$

$$\frac{d}{dt}U(\mathbf{k}) = \dot{\rho}_{12} + \dot{\rho}_{21} = \frac{4g_s^2}{k_0}\int \frac{d^3p}{(2\pi)^3 2p^0}\left[\frac{m_\phi^2 A_U}{4(p\cdot k)^2 - m_\phi^4}\right] V(\mathbf{k})$$

$$\frac{d}{dt}V(\mathbf{k}) = i(\dot{\rho}_{12} - \dot{\rho}_{21}) = \frac{-4g_s^2}{k_0}\int \frac{d^3p}{(2\pi)^3 2p^0}\left[\frac{m_\phi^2}{4(p\cdot k)^2 - m_\phi^4}\right] \times \left(A_U Q(\mathbf{k}) - 2A_Q U(\mathbf{k})\right)$$

$$\frac{\dot{V}(\bar{\mathbf{k}})^{\mathrm{Axion}}}{\dot{V}(\bar{\mathbf{k}})^{\mathrm{QED}}} = \left[\frac{1.6\times 10^{-10}}{4(\frac{\bar{k}_0}{m_\phi})^2(\frac{\bar{p}_0}{m_\phi})^2(1-\cos\bar{\theta})^2 - 1}\right]$$

- There is a resonance in the case of Axion exchange
- QED effects play very important role.
- May we can see in two laser beam collision

Generation of Polarization via CMB- Vector DM Interaction

a DM-photon direct couple through a large unsuppressed gauge invariant coupling as fallows

$$L_I = g_v \cos\theta_W F^{\mu\upsilon} V_\mu V'_\nu + g'_v \cos\theta_W \varepsilon^{\mu\nu\alpha\beta} F_{\mu\upsilon} V_\alpha V'_\beta$$

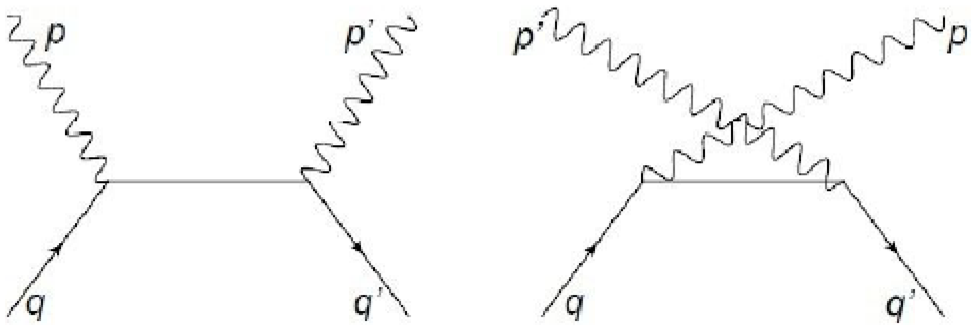


FIG. 1: Feynman diagrams for VDM-photon scattering

At first, in order to calculate the time evaluation of Stockes parameters due to forward scattering, we consider a completely uniform distribution function $\rho^0(\mathbf{x}, \mathbf{q})$ for unpolarized VDM which leads to

$$\dot{I}(k) = 0$$

$$\dot{Q}(k) = 0$$

$$\dot{U}(k) = 0$$

$$\dot{V}(k) = 0$$

Uniform and un-polarized Vector-DM distribution can not generate any polarization in the case of forward scattering

Generation of Polarization via CMB- Vector DM Interaction

Polarized Vector DM

This is while, if we suppose a slight deviation in VDM distribution such that its density matrix elements are

$$\rho_{rr}(\mathbf{x},\mathbf{q}) = \begin{cases} (\frac{1}{3}+\frac{\Delta}{2})\rho^0(\mathbf{x},\mathbf{q}) & r=1,2 \\ [illegible] \end{cases}$$

$$\dot{Q}(k) = \frac{3\pi\, m_{_V} k^0 \sin^2\alpha}{4m^2_{_{V'}}(m^2_{_V}-m^2_{_{V'}})}\Delta\, n_{2DM}(x)\,(-CV(k)) \tag{18}$$

$$\dot{U}(k) = \frac{3\pi\, m_{_V} k^0 \sin^2\alpha}{4\, m^2_{_{V'}}(m^2_{_V}-m^2_{_{V'}})}\Delta\, n_{2DM}(x)\,(-DV(k)) \tag{19}$$

$$\dot{V}(k) = \frac{3\pi\, m_{_V} k^0 \sin^2\alpha}{4m^2_{_{V'}}(m^2_{_V}-m^2_{_{V'}})}\Delta\, n_{2DM}(x)\Big(CQ(k)+DU(k)\Big) \tag{20}$$

where $C = 4g'_{_V} g_{_V} \cos^2\theta_W$ and $D = (4g'^2_{_V} - g^2_{_V})\cos^2\theta_W$. Also, $n_{2DM}(x)$ is the non-zero term (the second order) of fourier-Legendre expansion of DM density (see appendix A)

$$n_{2DM}(\mathbf{x}) \equiv \int \frac{d^3q}{(2\pi)^3}\rho^0(\mathbf{x},\mathbf{q})P_2(\cos\theta) \tag{21}$$

which $P_2(\cos\theta)$ is the Legendre polynomial of rank 2. This means that the distribution of VDM is quadrupole.

Generation of Polarization via CMB- Vector DM Interaction

Damping term

S. Modares Vamegh, M. Haghighat, S. Mahmoudi , R. Mohammadi ; 1911.02264 [hep-ph] PhysRevD.100.103024

$$\dot{Q}(k) = -\frac{4}{15}\frac{n_{DM}(x)}{m_V^2}\frac{k^{\circ 4}\sin^2\theta\cos^4\theta_W}{(m_{V'}^2 - m_V^2)^2}(g_V^4 - 16 g_V'^4)\left(I(k)\int\frac{d\Omega'}{4\pi}P_2(\cos\theta')\right)$$

$$\dot{U}(k) = -\frac{16}{15}\frac{n_{DM}(x)}{m_V^2}\frac{k^{\circ 4}\sin^2\theta\cos^4\theta_W}{(m_{V'}^2 - m_V^2)^2}g_V g_V'(g_V^2 + 4 g_V'^2)\left(I(k)\int\frac{d\Omega'}{4\pi}P_2(\cos\theta')\right)$$

$$\dot{V}(k) = 0$$

$$\frac{\dot{\tau}_{DM}}{\dot{\tau}_e} = 10^{-3} \Longrightarrow m_V = 10^{-2}ev$$

$$\frac{\dot{\tau}_{DM}}{\dot{\tau}_e} = 10^{-8} \Longrightarrow m_V = 1000ev$$

$$\rho_{ij}(\mathbf{x},\mathbf{q}) = \begin{cases} \frac{1}{2}\rho^{\circ}(\mathbf{x},\mathbf{q}) & i = j \\ 0 & i \neq j \end{cases}$$

The contribution of Vector DM on the CMB polarization is very small, but
For high energy photon (like x-ray and Gamma ray) can be enough large.

Generation of Polarization via CMB- Sterile Neutrino Interaction

Thus the Sterile neutrinos interacts with the SM particles as follows

$$\mathcal{L} \supset \sum_l -\frac{g}{\sqrt{2}} \bar{N}\,\Theta^\dagger \gamma^\mu\, l_{\rm L}\, W_\mu^+ - \sum_l \frac{g}{\sqrt{2}} \bar{l}_{\rm L}\, \gamma^\mu\, \Theta\, N\, W_\mu^- - \frac{g}{2\cos\theta_{\rm W}} \bar{N}\,\Theta^\dagger \gamma^\mu\, \nu_{l_{\rm L}}\, Z_\mu$$
$$-\frac{g}{2\cos\theta_{\rm W}}\, \bar{\nu}_{l_{\rm L}}\, \gamma^\mu\, \Theta\, N\, Z_\mu - \frac{g}{\sqrt{2}} \frac{M_{\rm N}}{m_{\rm W}}\, \Theta\, h\, \bar{\nu}_{l_{\rm L}}\, N - \frac{g}{\sqrt{2}} \frac{M_{\rm N}}{m_{\rm W}}\, \Theta^\dagger\, h\, \bar{N}\, \nu_{l_{\rm L}}.$$

$$C_{V\,l} = \frac{1}{2l+1} \sum_m \langle a^*_{V,lm}\, a_{V,lm} \rangle$$
$$\simeq \frac{1}{2l+1} \int d^3K\, P_\phi^{(S)}(K) \left| \sum_m \int d\Omega\, Y^*_{lm}(\mathbf{n}) \int_0^{\eta_0} d\eta\, \dot{\eta}_{e\gamma}\, e^{ix\mu - \eta_{e\gamma}}\, \eta_{\rm B}\, \tilde{\eta}\, \Delta_P^{(S)} \right|^2,$$

$$\tilde{\eta} = \frac{\dot{\eta}^{\rm C}_{\rm DM}}{\dot{\eta}_{e\gamma}} = \frac{\sqrt{2}}{8\pi^2} \frac{m_e^2}{\alpha\,\chi_e} \frac{m_p}{p_0} \frac{\Omega_{\rm DM}}{\Omega_{\rm BM}}\, G_{\rm F}\, \theta^2\, \bar{\beta}_{\rm DM},$$

$$\tilde{\eta}_{\rm ave} = \frac{1}{\eta_0 - \eta_{lss}} \left(\int_{\eta_0}^{\eta_{\rm rei}} d\eta\, \tilde{\eta} + \int_{\eta_{\rm rei}}^{\eta_{lss}} d\eta\, \tilde{\eta} \right) \simeq 3\times 10^{-4} \left(\frac{\theta^2}{10^{-2}}\right)\left(\frac{\bar{\beta}_{\rm DM}}{10^{-5}}\right).$$

•M. Haghighat, S. Mahmoudi, R. Mohammadi, S. Tizchang, S.S. Xue; *Phys.Rev.D* 101 (2020)

Generation of Polarization via CMB- Sterile Neutrino Interaction

In this paper, we explore the possibility of the polarization conversion of a wide energy range of cosmic photons to the circular polarization through their interactions with right handed Sterile neutrinos as a candidate for dark matter. By considering the Sterile neutrino in the seesaw mechanism framework and right-handed current model, we examine the Faraday conversion $\Delta\phi_{\rm FC}$ of gamma ray burst (GRB) photons at both the prompt and afterglow emission levels as well as the radio photons emitted from our galaxy and extra-galactic sources interacting with the Sterile neutrinos. Consequently, for the Sterile neutrino with mixing angle $\theta^2 \lesssim 10^{-2}$ motivated by models with a hidden sector coupled to the sterile neutrino, the Faraday conversion can be estimated as $\Delta\phi_{\rm FC} \lesssim 10^{-3} - 10^{-18}$ rad for GRB, $\Delta\phi_{\rm FC} \lesssim 10^{-6} - 10^{-11}$ rad for radio emission source from our galaxy and $\Delta\phi_{\rm FC} \lesssim 10^{-6} - 10^{-15}$ rad for extra-galactic sources. We also examine the V-mode power spectrum C_{Vl} of the cosmic microwave background (CMB) at the last scattering surface. We show that the circular polarization power spectrum at the leading order is proportional to the linear polarization power spectrum C_{pl} and the mixing angle where for $\theta^2 \lesssim 10^{-2}$ leads to $C_{Vl} \lesssim 0.01$ Nano-Kelvin squared.

•M. Haghighat, S. Mahmoudi, R. Mohammadi, S. Tizchang, S.S. Xue; *Phys.Rev.D* 101 (2020)

Generation of Polarization via CMB- CNB Interaction

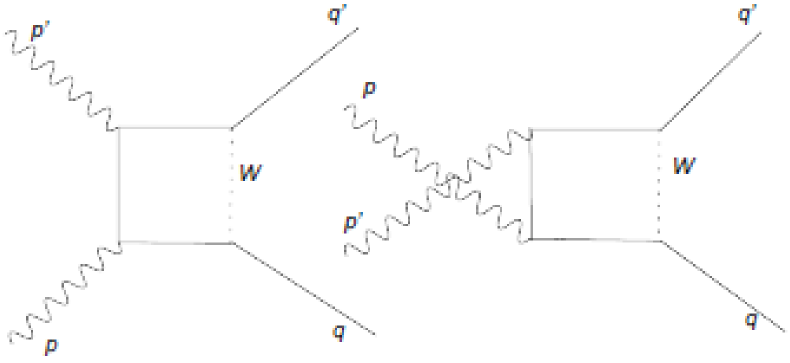


Fig. 1 The typical diagrams of photon–neutrino scattering

$$\frac{d}{dt}(Q \pm iU) = C_{e\gamma}^{\pm} \mp i\dot{\kappa}_{\pm}(Q \pm iU) + \mathcal{O}(V)$$

$$\frac{dV}{dt} = C_{e\gamma}^{V} + \dot{\kappa}_Q Q + \dot{\kappa}_U U,$$

$$\dot{\kappa}_{\pm} = -\frac{\sqrt{2}}{6\pi k^0}\alpha\, G^F \int d\mathbf{q}\, f_\nu(x,q) \times (\varepsilon_{\mu\nu\rho\sigma}\, \epsilon_2^{\mu}\epsilon_1^{\nu}k^{\rho}q^{\sigma})$$

$$\dot{\kappa}_Q = -\frac{\sqrt{2}}{3\pi k^0}\alpha\, G^F\, n_\nu\, \langle v_\alpha q_\beta\rangle \epsilon_2^{\alpha}\, \epsilon_1^{\beta}$$

$$\dot{\kappa}_U = -\frac{\sqrt{2}}{6\pi k^0}\alpha\, G^F\, n_\nu\, \left(\langle v_\alpha q_\beta\rangle \epsilon_1^{\alpha}\, \epsilon_1^{\beta} - \langle v_\alpha q_\beta\rangle \epsilon_2^{\alpha}\, \epsilon_2^{\beta}\right),$$

Generation of Polarization via CMB- CNB Interaction

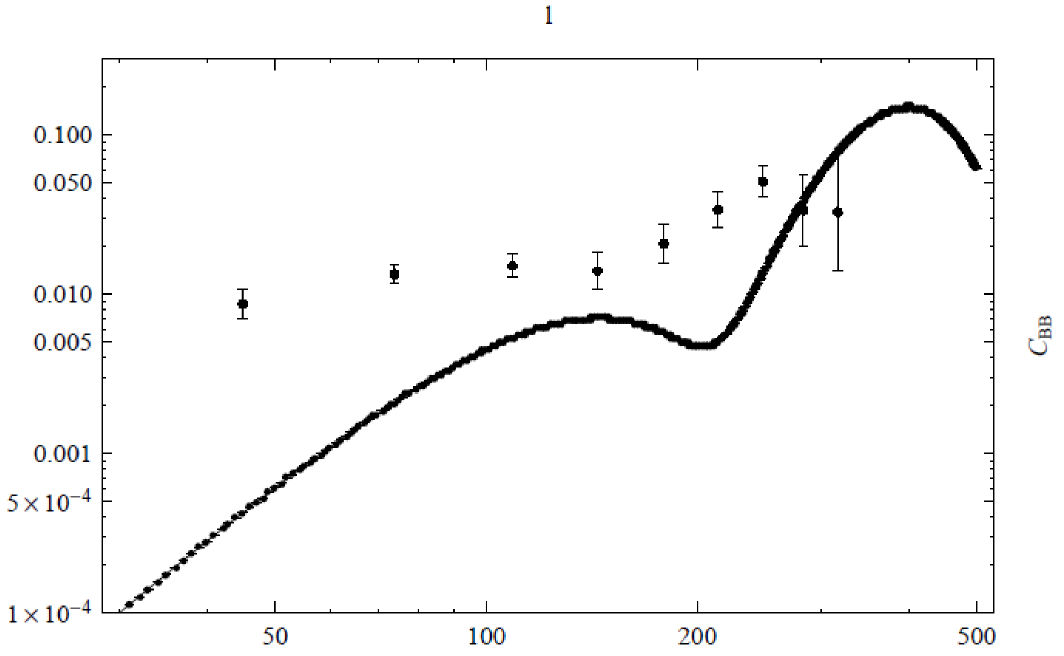


FIG. 1. The solid line represents $\ell(\ell+1)C_B^{\ell(S)}/2\pi[\mu K^2]$ due to the primordial scalar perturbations and photon-neutrino (CNB) scattering. The experiment BICEP2 results (dots with their error bars) are plotted.

•M. Haghighat, S. Mahmoudi, R. Mohammadi, S. Tizchang, S.S. Xue; *Phys.Rev.D* 101 (2020)

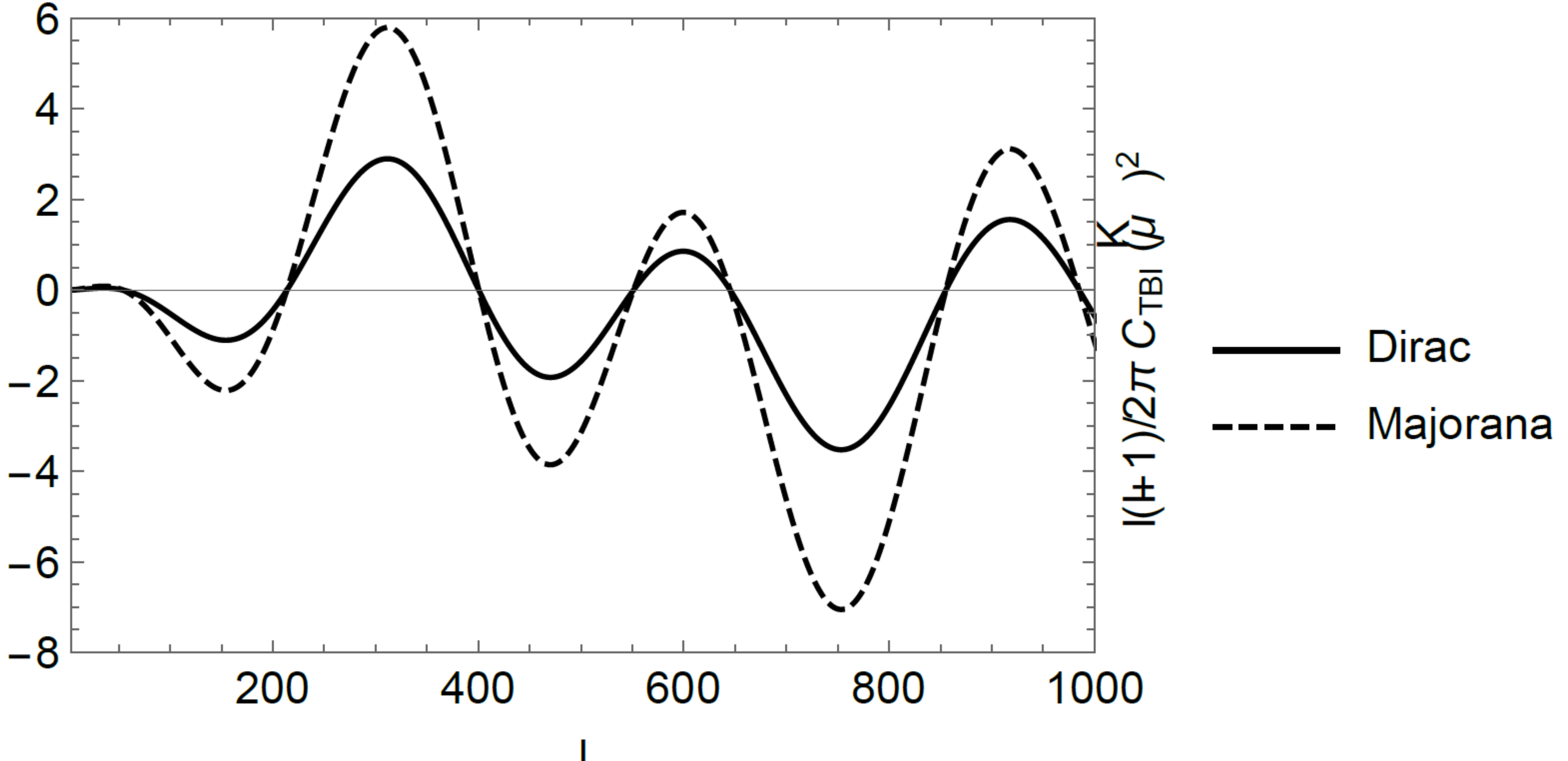
CMB Cross Power Spectra via CNB-CMB interaction

$$C_{EB}^{l(S)} \cong \frac{1}{2}\sin(2\bar{\kappa})\bar{C}_{EE}^{l(S)}$$
$$C_{ET}^{l(S)} \cong \cos(\bar{\kappa})\bar{C}_{ET}^{l(S)}$$
$$C_{BT}^{l(S)} \cong \sin(\bar{\kappa})\bar{C}_{ET}^{l(S)}$$

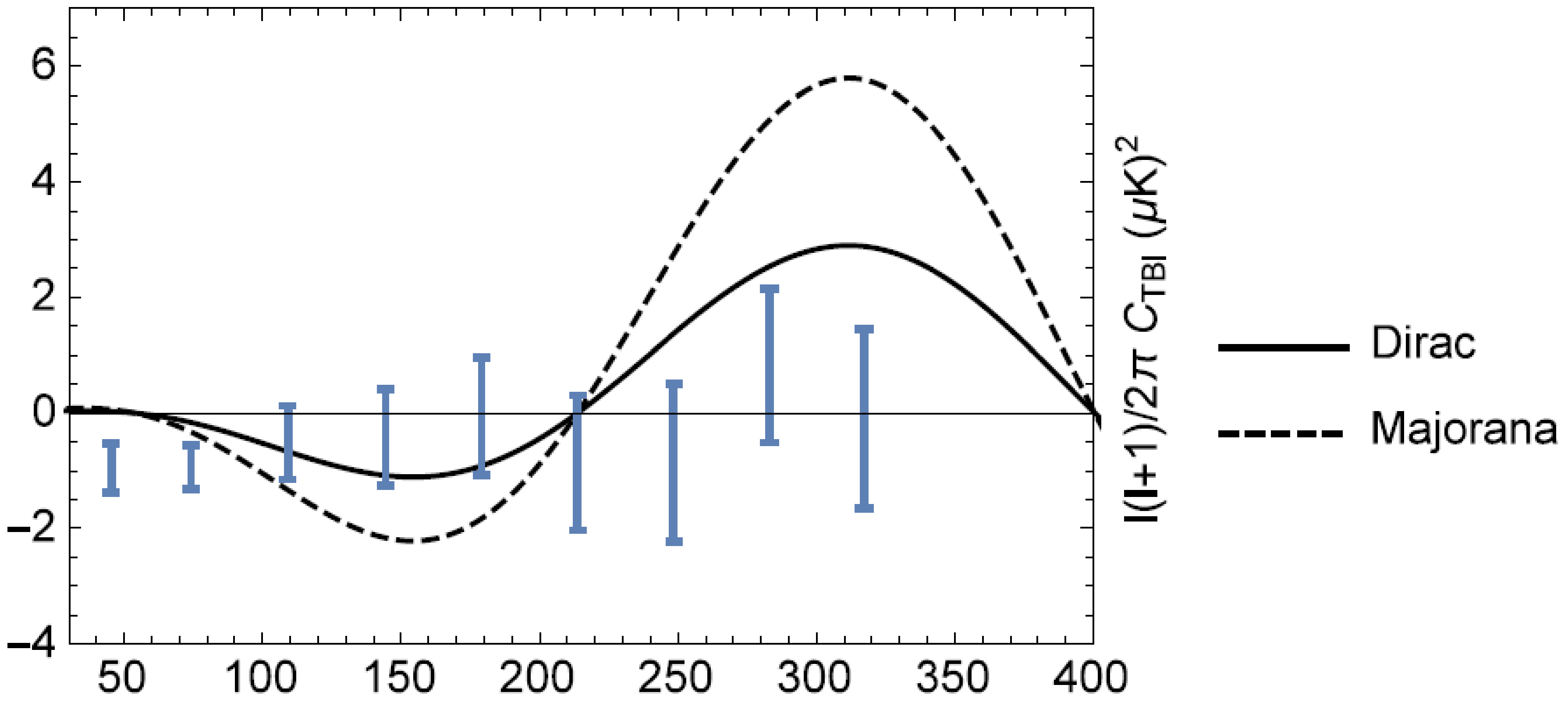
$\Rightarrow$

$$\kappa(z) = \int_{\eta}^{\eta_0} a\, d\eta \dot{\kappa}_{\pm} = \frac{\sqrt{2}}{12\pi}\alpha\, G^F n_\nu^0 \int_z^{z_1} dz' \frac{(1+z')^2}{H(z')}$$
$$= \frac{\sqrt{2}}{12\pi}\alpha\, G^F n_\nu^0 \frac{2H(z')}{3\Omega_M^0 H_0^2}\Big|_z^{z_l}$$
$$\bar{\kappa} \equiv \frac{1}{z_1 - z_0}\int_{z_1}^{z_0} dz\, \kappa(z) \approx 0.16,$$

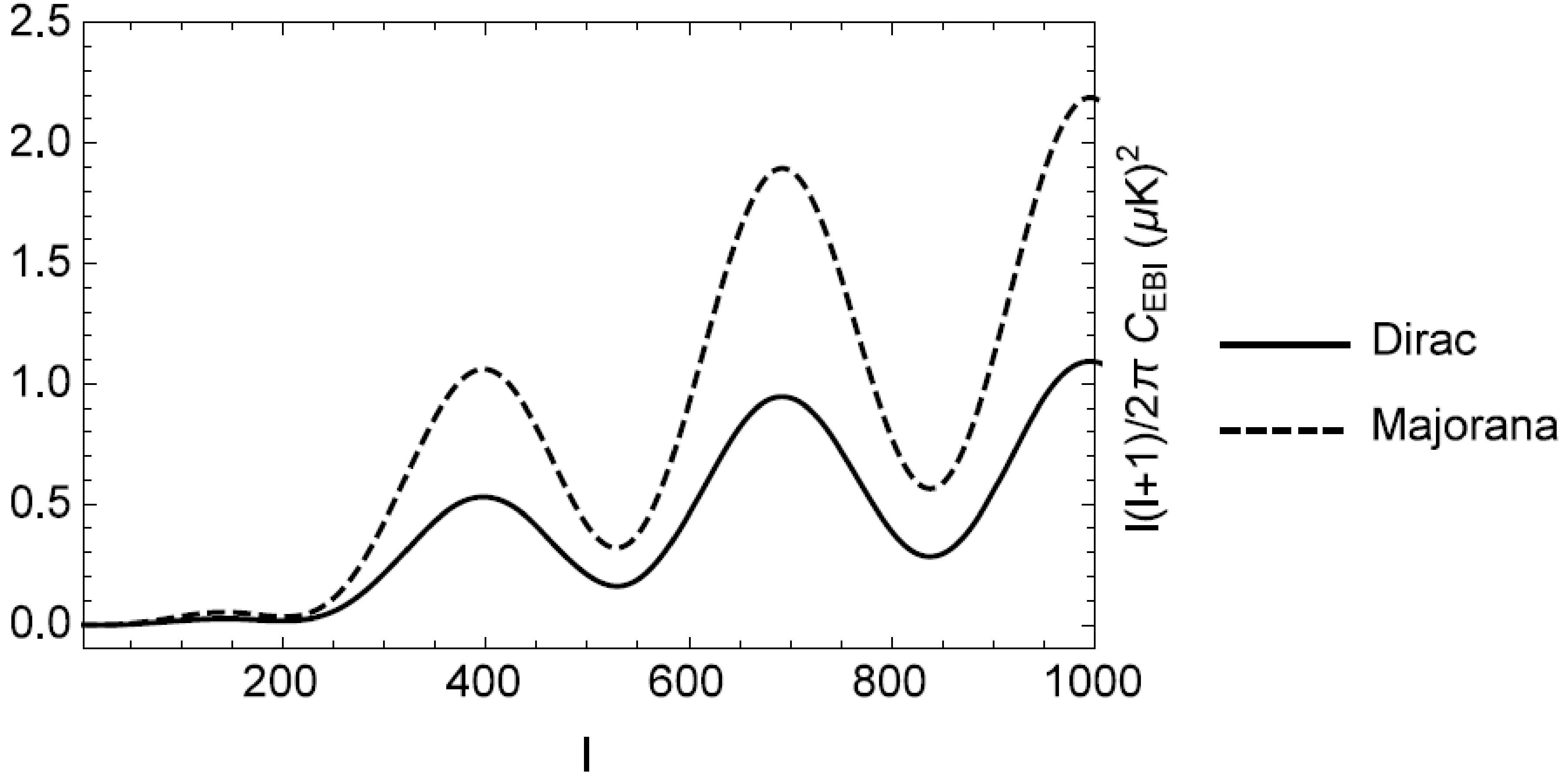
TB Cross Spectrum in presence of scalar perturbation of matter via CMB-CNB interaction



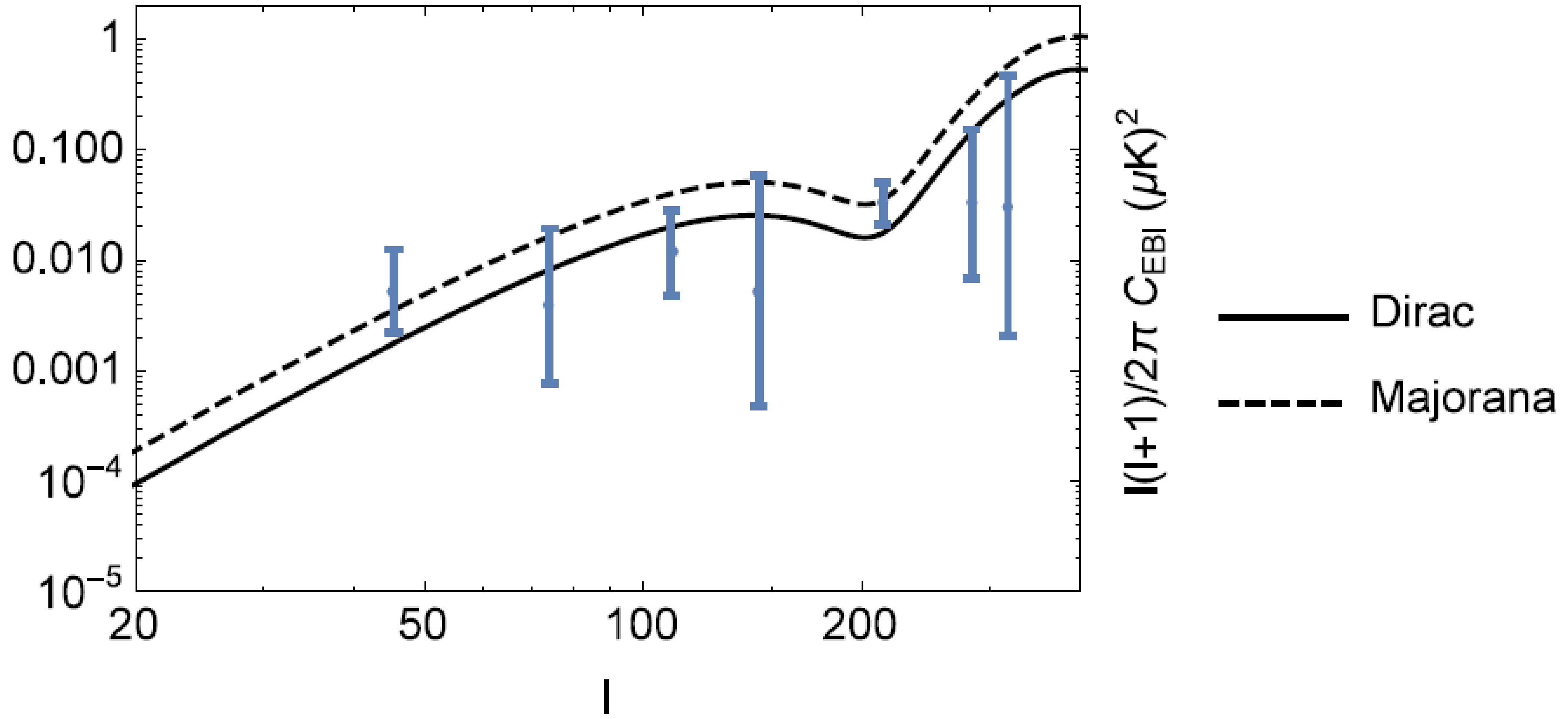
TB Cross Spectrum in presence of scalar perturbation of matter via CMB-CNB interaction



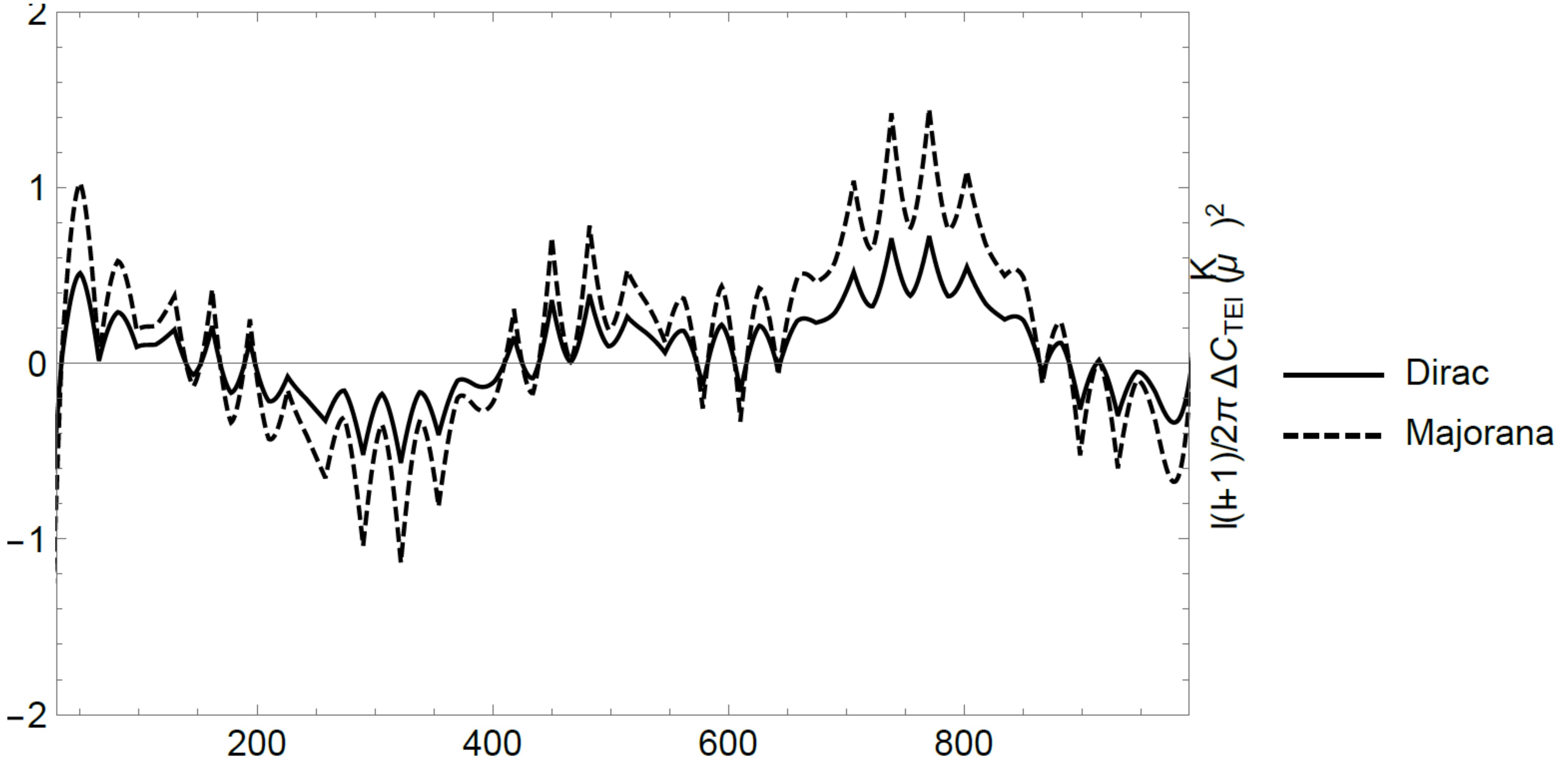
EB Cross Spectrum in presence of scalar perturbation of matter via CMB-CNB interaction



TB Cross Spectrum in presence of scalar perturbation of matter via CMB-CNB interaction



TE power spectrum
Deviation from standard scenario



Summery

- CMB-Dipolar DM & CMB-CNB interaction generates B-mode in the case of scalar perturbation which suppresses r-parameter
- One can find a limit for mass and coupling of Dipolar DM by using B-mode polarization
- Vector DM –CMB interaction can generate B-mode and Circular polarization, if its distribution has quadrupole perturbation and polarized degree freedom.
- Vector DM-photon interaction is important in the case of high energy photons
- Damping term for CMB-DM interaction can be neglect.
- CMB-CMB interaction via Axion exchange can play important roles to generate circular and there is a resonance in this case
- **TB and EB Cross Spectrum in presence of scalar perturbation of matter via CMB-CNB interaction**

با سپاس فراوان