

# Cosmic Birefringence as a probe of dark matter nature: Sterile neutrino and dipolar dark matter

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آبان ۱۴۰۱

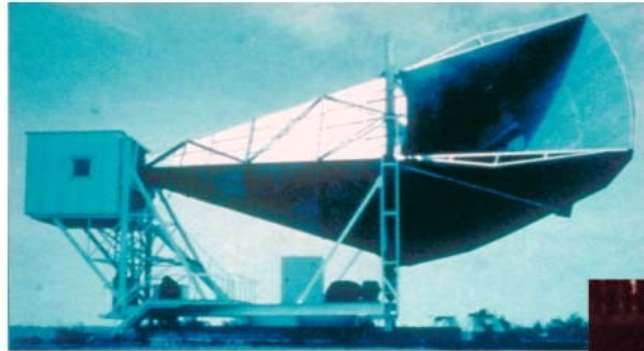
School of Particles and Accelerators

# Outline

- Introduction
  - Cosmic Microwave Background (CMB)
  - Dark Matter Searches
  - Sterile Neutrino
  - Dipolar Dark Matter (DDM)
  - Birefringence
- DDM-photon Interaction
- Quantum Boltzmann Equation
  - Stokes Parameters
- Photon-Sterile Neutrino Interaction
- Birefringence estimation

# Introduction:

## DISCOVERY OF COSMIC BACKGROUND

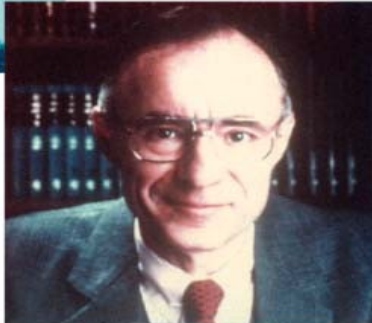


Microwave Receiver

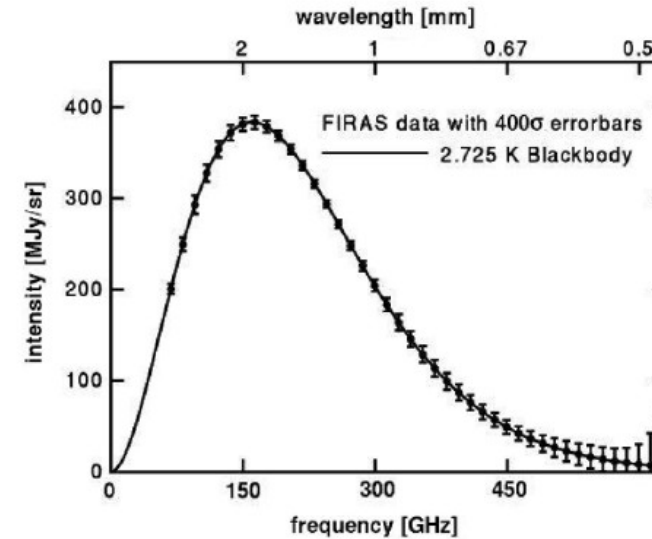


MAP990045

Robert Wilson



Arno Penzias



$$Power = 3.3 \mu W/m^2$$

(Our bodies radiate about  
500 W/m<sup>2</sup>)

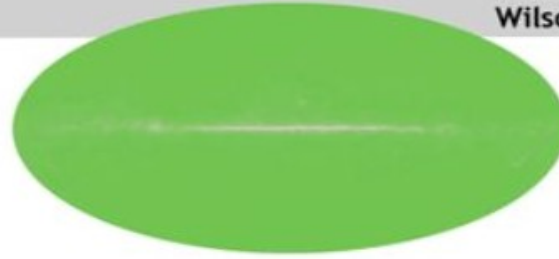
The existence of the CMB radiation was first predicted by Ralph Alpher in 1948 in connection with his research on Big Bang Nucleosynthesis undertaken together with Robert Herman and George Gamow. It was first observed inadvertently in 1965 by Arno Penzias and Robert Wilson at the Bell Telephone Laboratories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

# Cosmic Microwave Background Radiation Overview

1965



Penzias and Wilson



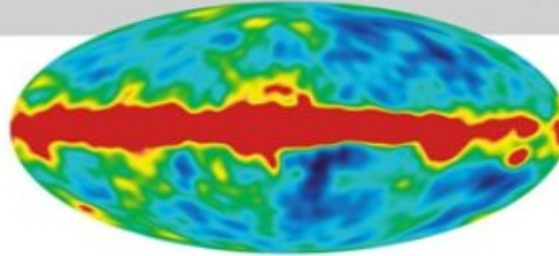
**The oldest light in universe**

Discovered the remnant afterglow from the **Big Bang**.  
→ **2.7 K**

1992

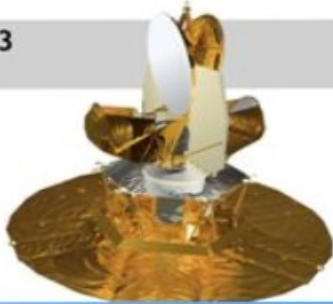


COBE

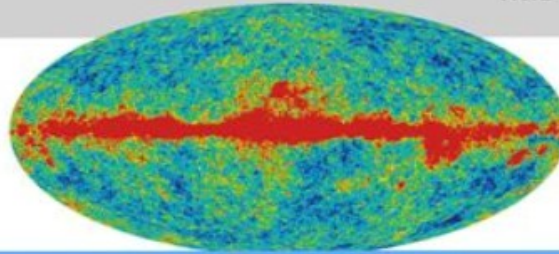


**Blackbody radiation**,  
Discovered the patterns (**anisotropy**) in the afterglow  
→ **angular scale ~ 7°** at a level  $\Delta T/T$  of  $10^{-5}$

2003



WMAP



(Wilkinson Microwave Anisotropy Probe):  
→ **angular scale ~ 15'**

2009



Planck

→ **angular scale ~ 5'**,  
 $\Delta T/T \sim 2 \times 10^{-6}$ , 30~867 Hz

# DARK MATTER



Sterile Neutrino

GRAVITINO



Dipolar dark matter



**Direct Searches**

**Indirect Searches**

Fermionic and vector dark matter with polarized target, JCAP 11 (2018) 018

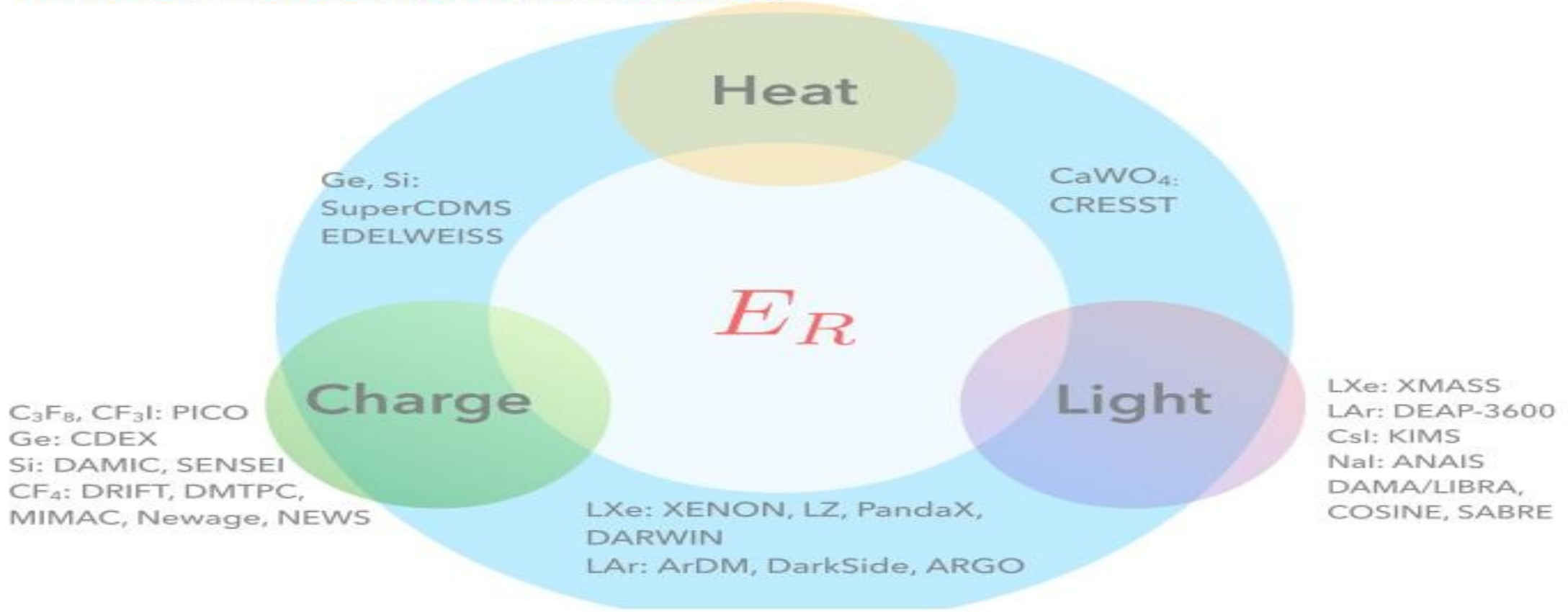
Axion coupled to observable effects including nuclear EDM and Axial nucleon and electron moment, PRD. 88, 035023 (2013)

Scalar Dark Matter, JHEP 06 (2016) 152

**CMB Cross Correlation Power Spectrum**

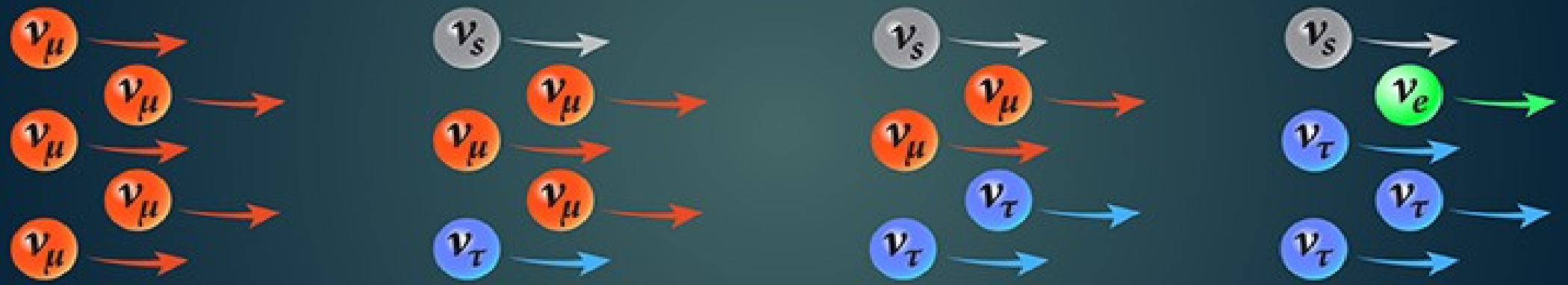
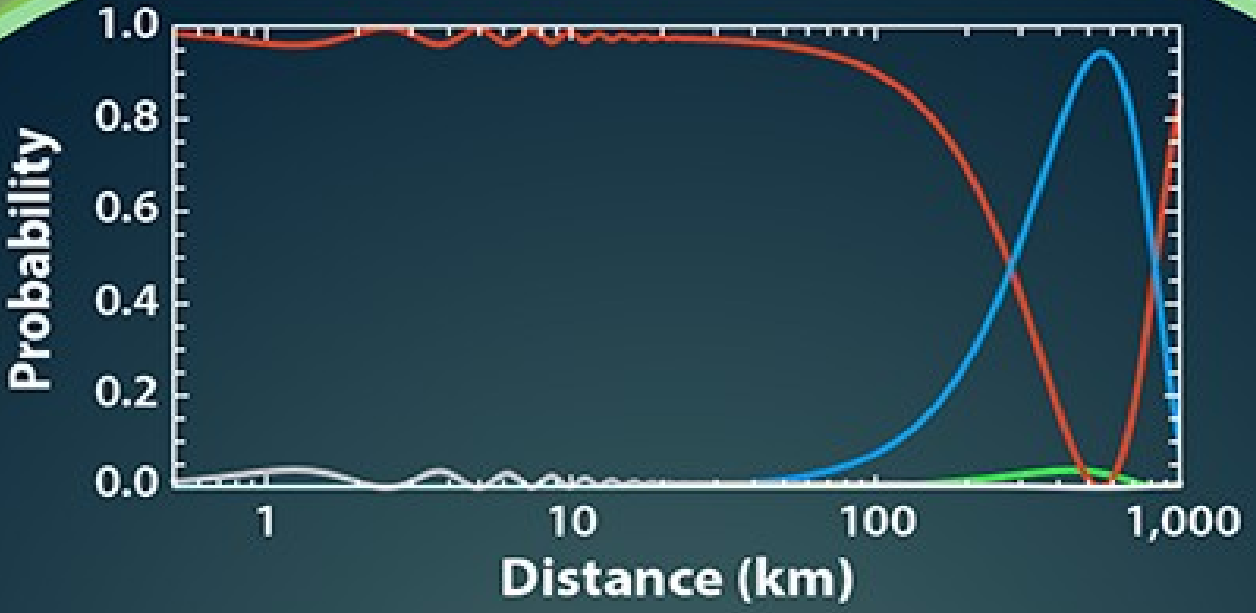
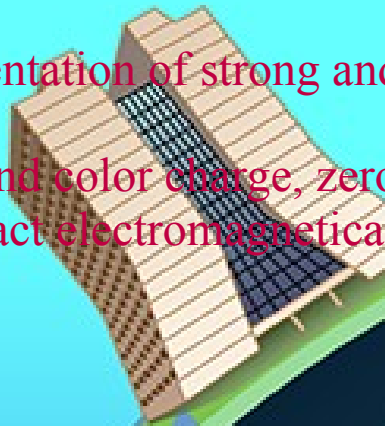
Dark-Matter electric and magnetic dipole moment, PRD. 70, 083501 (2004)

# DIRECT DETECTION SIGNATURES



Singlet representation of strong and weak interaction.

Zero electric and color charge, zero weak hypercharge and isospin.  
Does not interact electromagnetically and weakly and strongly.

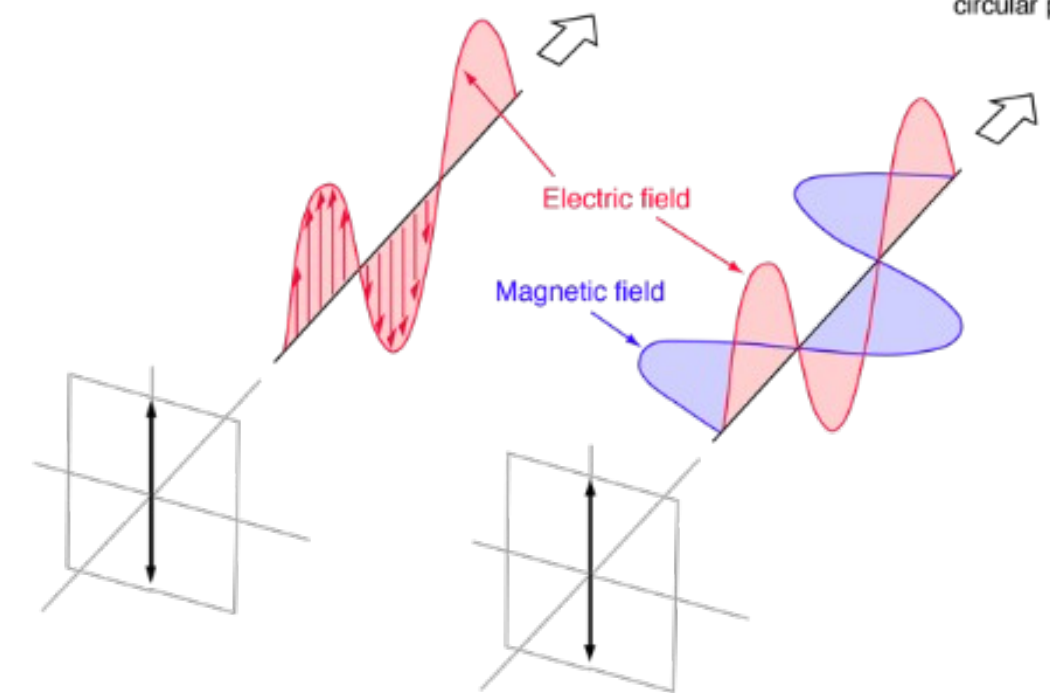
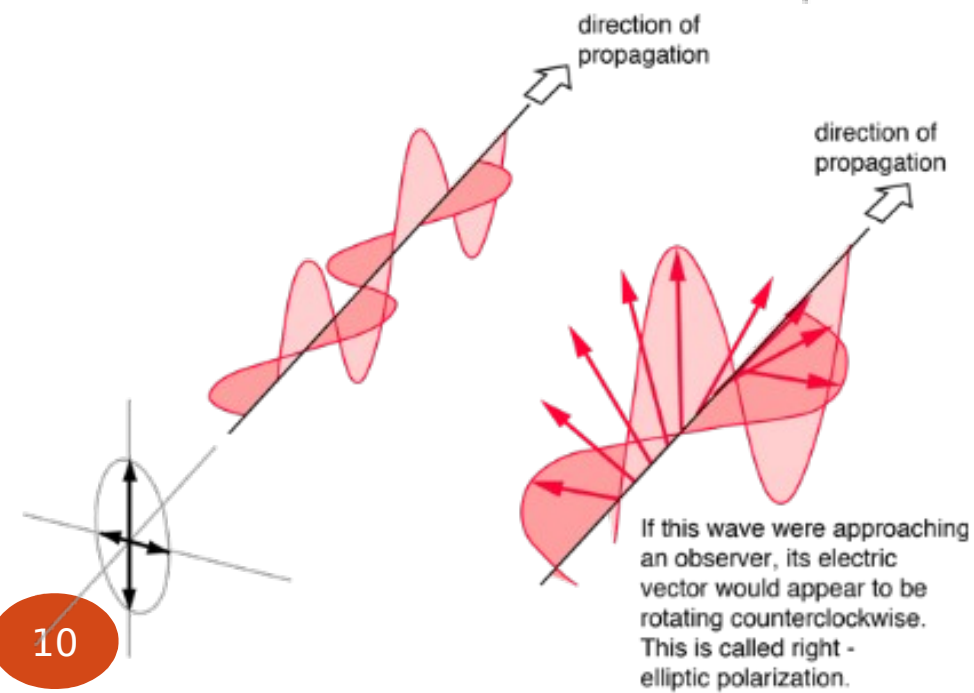
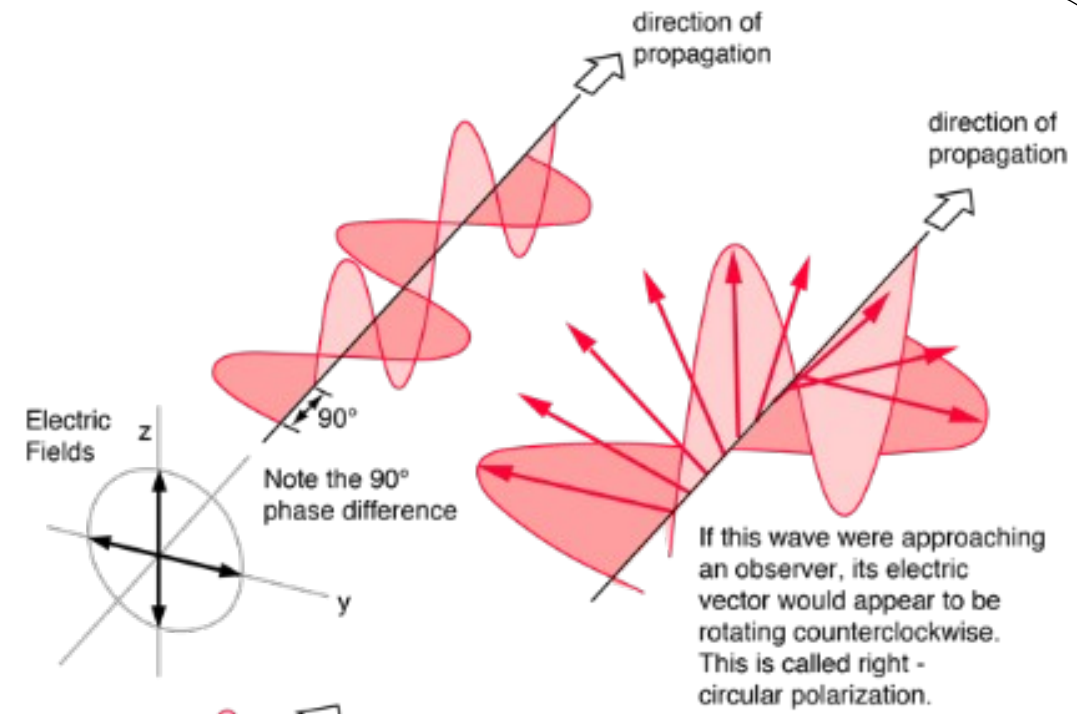
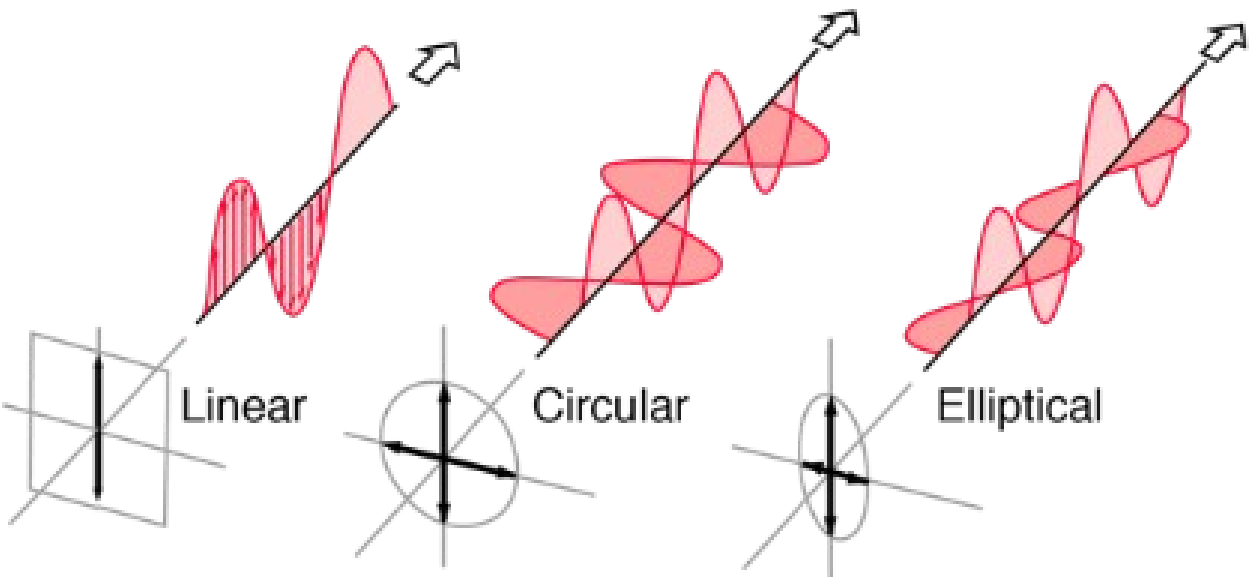


# BEST (Baksan Experiment on Sterile neutrino Transition)



In June 2022, BEST released two papers observing a 20-24% deficit in production the isotope Ge expected From  ${}^{71}\text{Ga} + \nu_e \rightarrow e + {}^{71}\text{Ge}$  (Gallium Anomaly). Pointing that a sterile neutrino explanation can be Consistent with data.

# Polarizations



# 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.

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

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

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

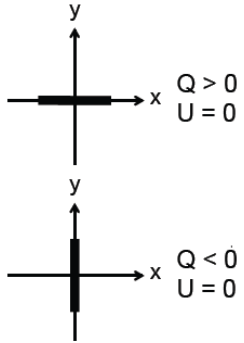
$$V \equiv \langle \hat{V} \rangle = \text{tr} \rho \hat{V} = i\rho_{21} - i\rho_{12},$$

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

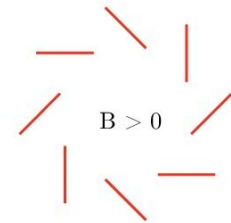
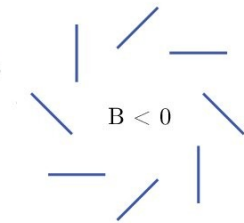
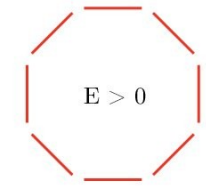
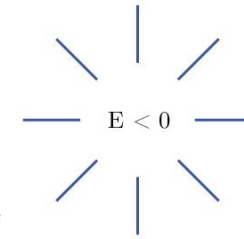
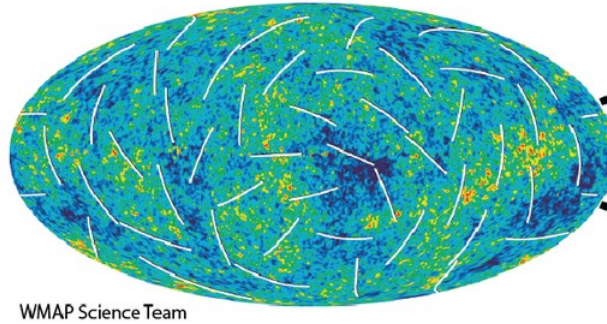
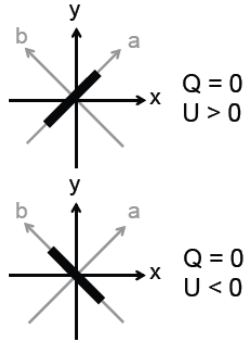


# Linear Polarization

$$Q \equiv |E_x|^2 - |E_y|^2$$



$$U \equiv |E_a|^2 - |E_b|^2 = \text{Im}(E_a E_b^*)$$



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).

# Quantum Boltzmann Equation (QBE)

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

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

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

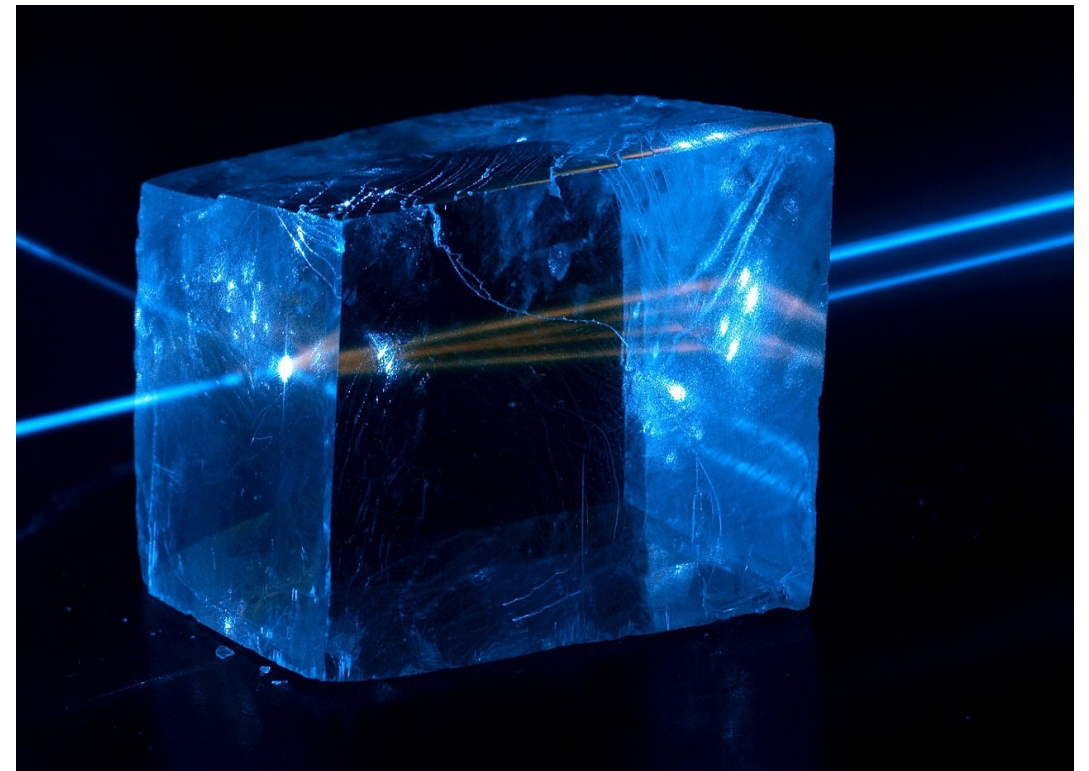
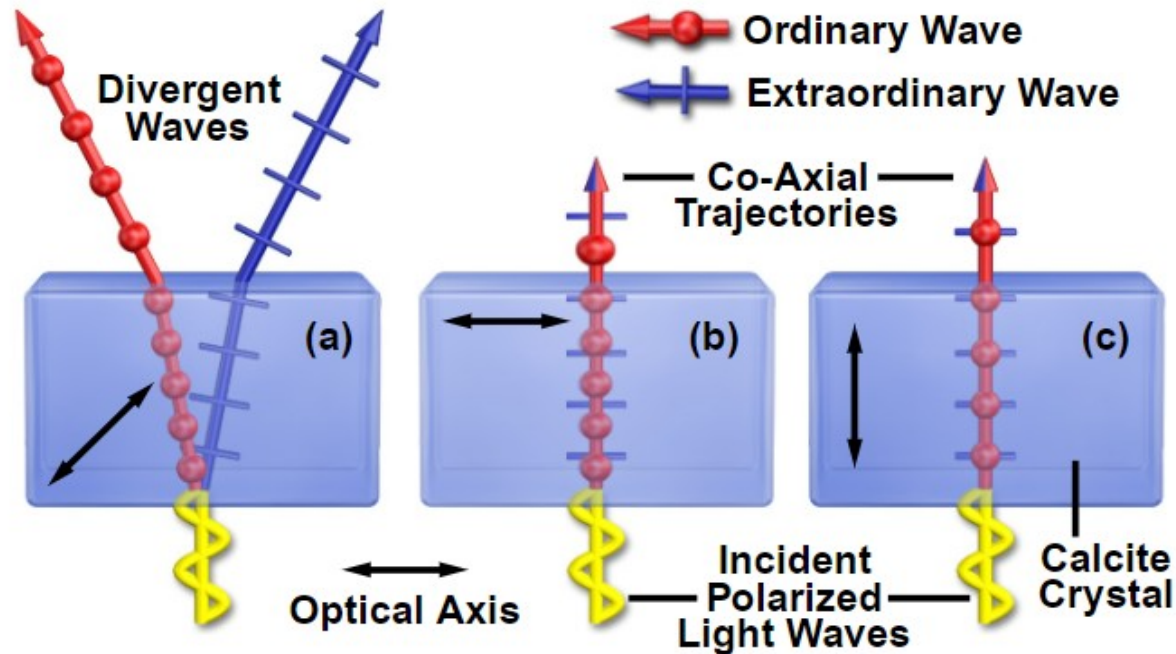
- And on the other hand, the time evolution of the operator  $D_{ij}^0(k)$ , considered in the Heisenberg picture, is

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

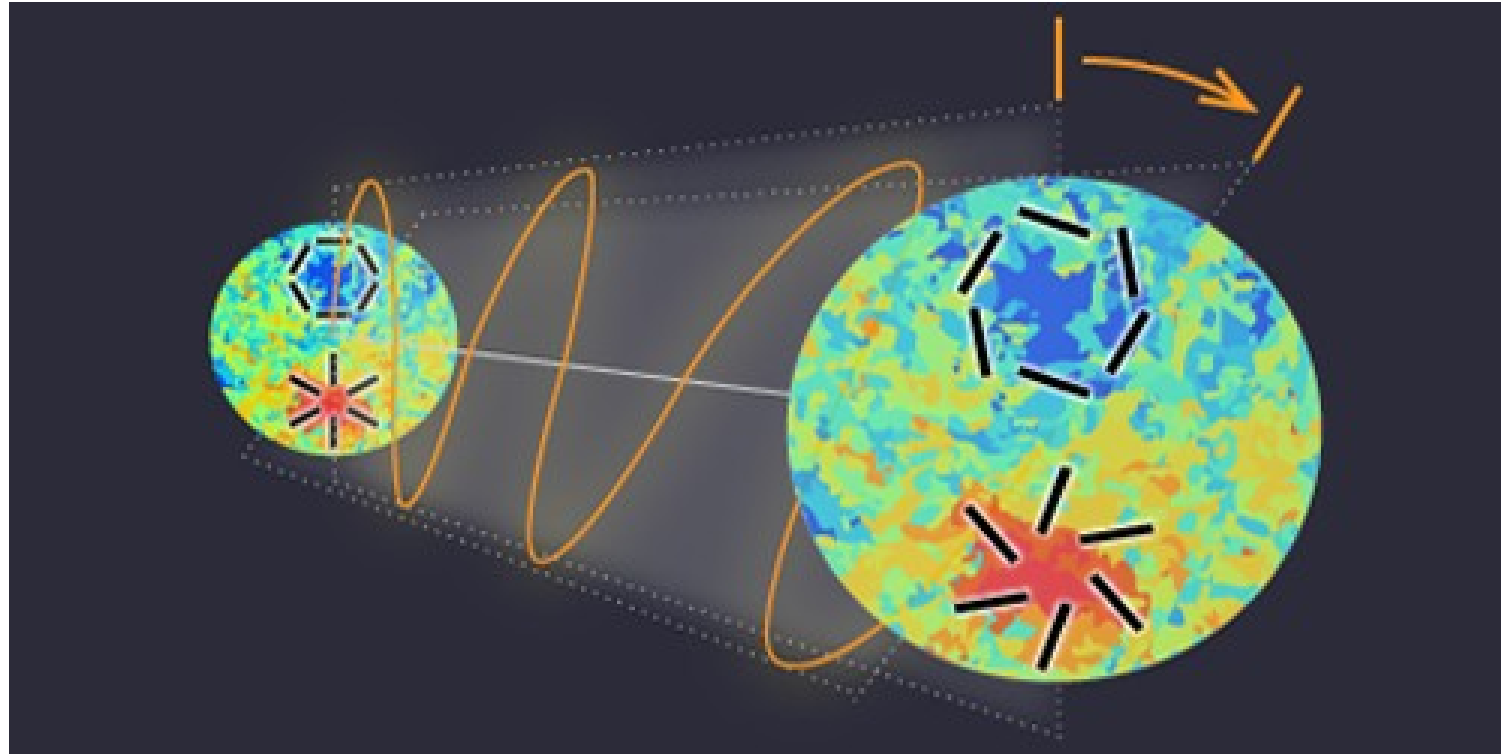
$$(2\pi)^3 \delta^3(0) (2k^0) \frac{d}{dt} \rho_{ij}(k) = i \langle [H_I^0(t); D_{ij}^0(k)] \rangle - \frac{1}{2} \int dt \langle [H_I^0(t); [H_I^0(0); D_{ij}^0(k)]] \rangle,$$

# Birefringence

**Birefringence** is formally **defined** as the double refraction of light in a transparent, molecularly ordered material, which is manifested by the existence of orientation-dependent differences in refractive index.



# Cosmic Birefringence



Rotation angle of the linear polarization plane of Cosmic Microwave Background by amount of angle.

- The amount of Cosmic Birefringence angle is very sensitive to the Parity-Violating Physics.

Stokes parameters of Linear Polarization (Q and U) transform as a spin-2 field under rotation.

So, they can be expanded in terms of spin-weighted spherical Harmonics

$$Q(\hat{n}) \pm iU(\hat{n}) = - \sum_{lm} (E_{lm} \pm B_{lm})_{\pm 2} Y_{lm}(\hat{n})$$

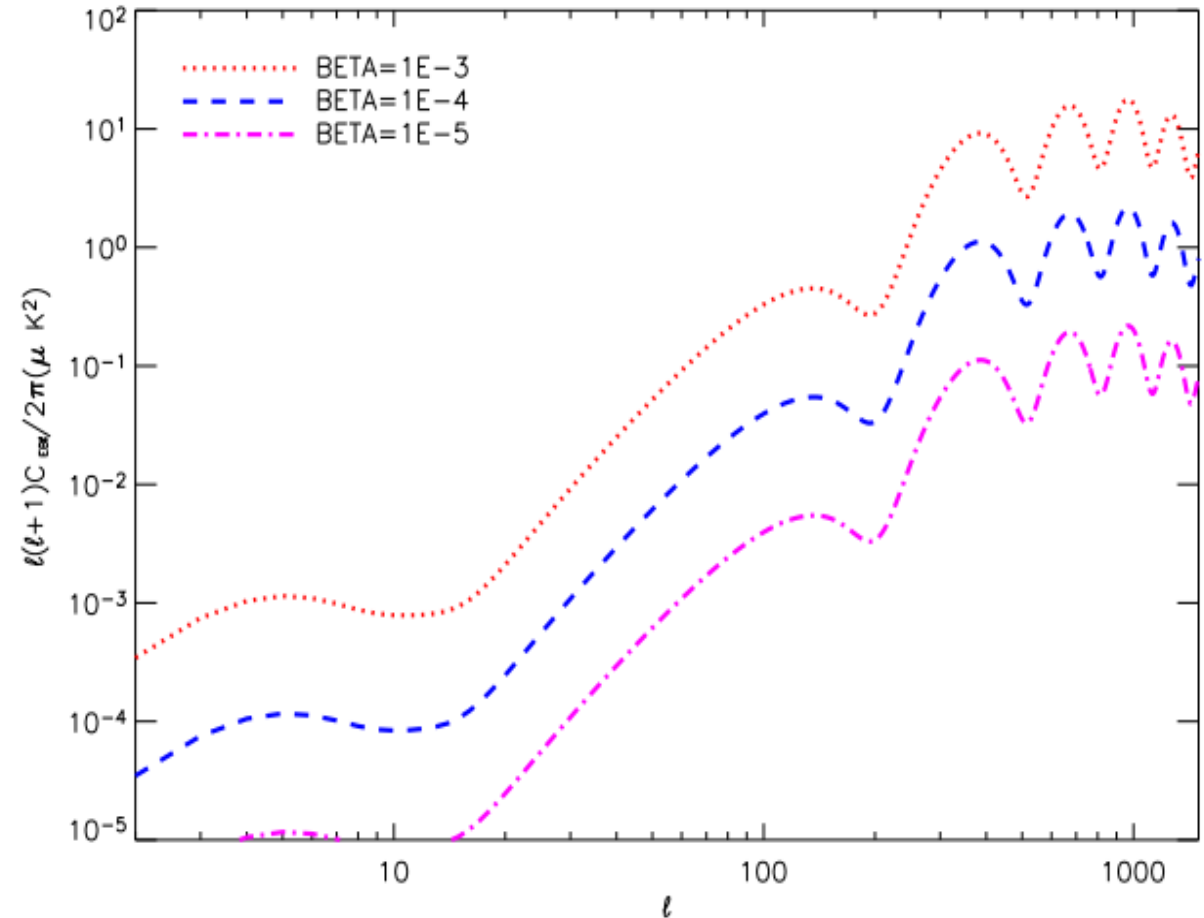
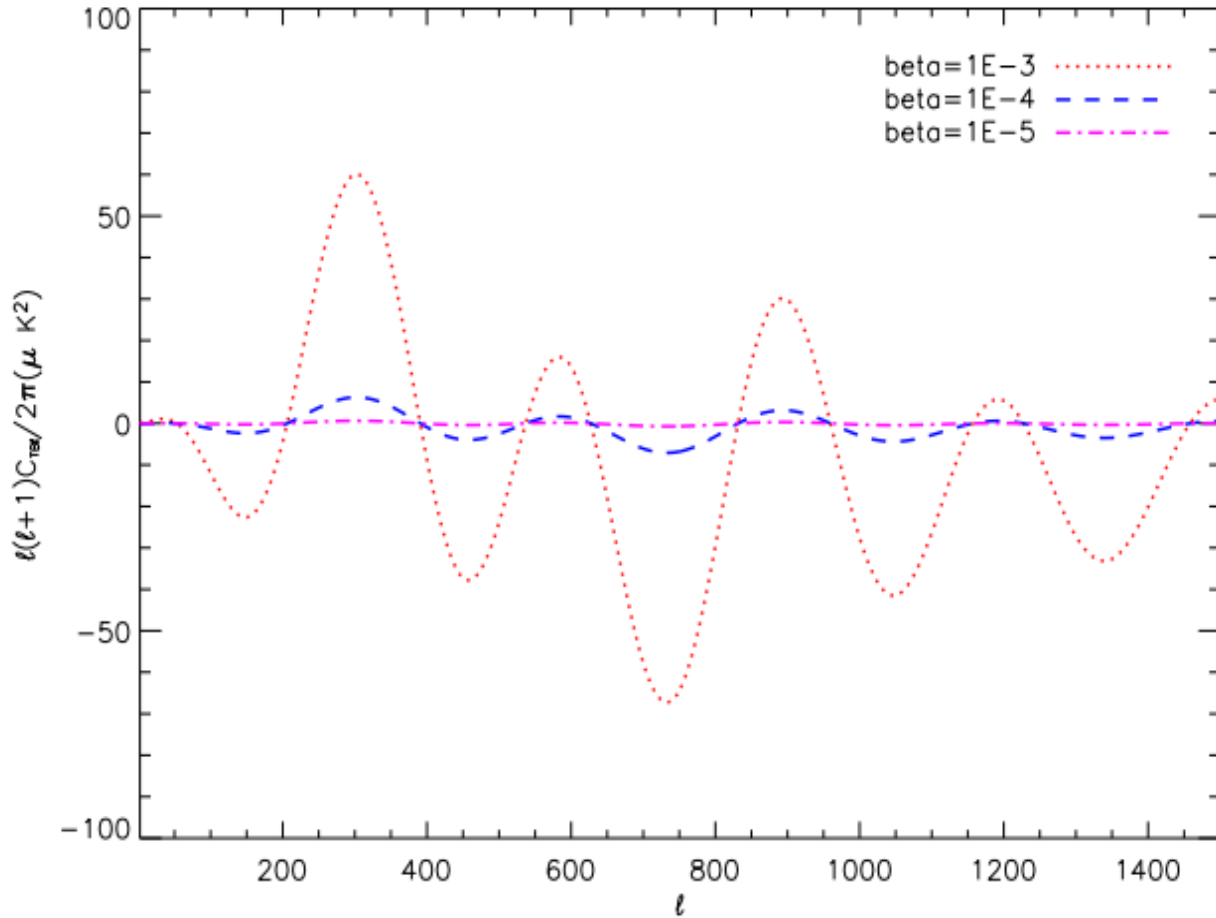
Under parity transformation,

$E_{lm}$           Even-Parity

$B_{lm}$           Odd-Parity

So, we expected in standard model Cosmology, there is no EB and TB CMB powers spectra.

For example effect of parity violating Axion-like particle as dark-matter On CMB power spectra can generate non-zero TB and EB power spectra



# Non-zero Cross correlations

$$C_{EE,\ell} = \cos^2(2\beta)\bar{C}_{EE,\ell} + \sin^2(2\beta)\bar{C}_{BB,\ell},$$

$$C_{BB,\ell} = \cos^2(2\beta)\bar{C}_{BB,\ell} + \sin^2(2\beta)\bar{C}_{EE,\ell},$$

$$C_{EB,\ell} = \frac{1}{2} \sin(4\beta)(\bar{C}_{EE,\ell} - \bar{C}_{BB,\ell}),$$

## Generation of Polarization via CMB- Dipolar Dark Matter Interaction

Effective Lagrangian for dipolar dark matter is

$$L = \frac{-i}{2} \bar{\psi}_2 \sigma_{\mu\nu} (M_{12} + \gamma^5 D_{12}) \psi_1 F^{\mu\nu} + H.C.$$

Where  $M_{12}$  is transition magnetic moment and  $D_{12}$  transition electric moment.

Singlet Majorana fermion  $\chi_1, \chi_2$  interact with photon via transition magnetic moment as follow

$$L = \frac{-i}{2} M_{12} \bar{\chi}_2 \sigma_{\mu\nu} \chi_1 F^{\mu\nu} + H.C.$$

$$\frac{d}{d\eta} \Delta_I^S + iK\mu\Delta_I^S + 4[\dot{\Psi} - iK\mu\Phi]$$

$$= \dot{\tau}_e \left[ -\Delta_I^S + \Delta_I^{S\circ} + i\mu v_b + \frac{1}{2} P_2(\mu)\Pi \right],$$

$$\frac{d}{d\eta} \Delta_P^{\pm S} + iK\mu\Delta_P^{\pm S} = \dot{\tau}_e \left[ -\Delta_P^{\pm S} - \frac{1}{2} [1 - P_2(\mu)]\Pi \right]$$

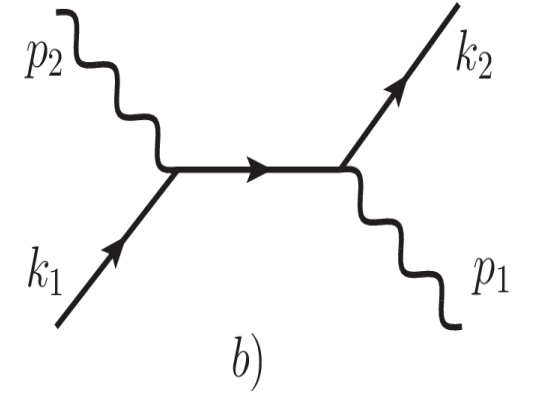
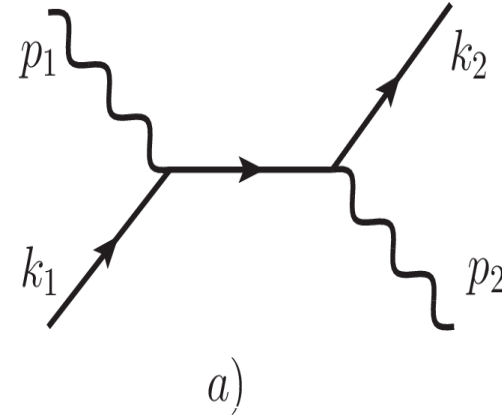
$$\mp ia(\eta) \dot{\tau}_{DM} \Delta_P^{\pm S},$$

$$\Delta_P^{\pm(S)} = Q^{(S)} \pm iU^{(S)}, \Pi \equiv \Delta_I^{2(S)} + \Delta_P^{2(S)} + \Delta_P^{0(S)},$$

$$C_{EE,\ell}^{(S)} \Big|_{DM} = (4\pi)^2 \frac{(\ell+2)!}{(\ell-2)!} \int k^2 dk P_\varphi(k) \left[ \frac{3}{4} \int_0^{\eta_0} d\eta g(\eta) \Pi(K, \eta) \frac{j_\ell(x)}{x^2} \cos(\tau_{DM}) \right]^2,$$

$$C_{BB,\ell}^{(S)} \Big|_{DM} = (4\pi)^2 \frac{(\ell+2)!}{(\ell-2)!} \int k^2 dk P_\varphi(k) \left[ \frac{3}{4} \int_0^{\eta_0} d\eta g(\eta) \Pi(K, \eta) \frac{j_\ell(x)}{x^2} \sin(\tau_{DM}) \right]^2.$$

$$\dot{\tau}_{DM} = \frac{\mathcal{M}^2}{m_{DM}} \rho_{DM},$$



$$C_{EB,\ell}^{(S)} \Big|_{\text{DM}} = \frac{(4\pi)^2 (\ell + 2)!}{4 (\ell - 2)!} \int k^2 dk P_\varphi(k) \left[ \frac{3}{4} \int_0^{\eta_0} d\eta g(\eta) \Pi(K, \eta) \frac{j_\ell(x)}{x^2} \sin(2\tau_{DM}) \right]^2.$$

$$C_{EE,\ell}^{(S)} \Big|_{\text{DM}} \cong \cos^2(\tau_{DM}) \bar{C}_{EE,\ell}^{(S)},$$

$$C_{BB,\ell}^{(S)} \Big|_{\text{DM}} \cong \sin^2(\tau_{DM}) \bar{C}_{EE,\ell}^{(S)},$$

$$C_{EB,\ell}^{(S)} \Big|_{\text{DM}} \cong \frac{1}{4} \sin^2(2\tau_{DM}) \bar{C}_{EB,\ell}^{(S)}.$$



$$\tau_{\text{DM}}(z) = \frac{\mathcal{M}^2}{m_{\text{DM}}} \rho_{\text{DM}}^0 \int_0^z dz' \frac{(1+z')^2}{H(z')} = \frac{\mathcal{M}^2}{m_{\text{DM}}} \rho_{\text{DM}}^0 \frac{2H(z')}{3\Omega_M^0 H_0^2} \Big|_0^z,$$

Here  $\tau_{DM}$  is the effective opacity is generated by CMB-Dipolar dark matter interaction.

$$\tilde{\tau}_{DM} \approx 4.6 \times 10^{25} \left( \frac{\mathcal{M}}{e \text{ cm}} \right)^2 \left( \frac{\text{GeV}}{m_{\text{DM}}} \right), \left( \frac{\rho_{\text{DM}}^0}{2.5 \times 10^{-30} \text{ g/cm}^3} \right)$$

$$\beta \approx \frac{1}{2} \tilde{\tau}_{DM},$$

So using last CB measurement using  
Planck data release 2018

$$\beta = 0.30^\circ \pm 0.11^\circ \text{ (68\%C.L.)}$$

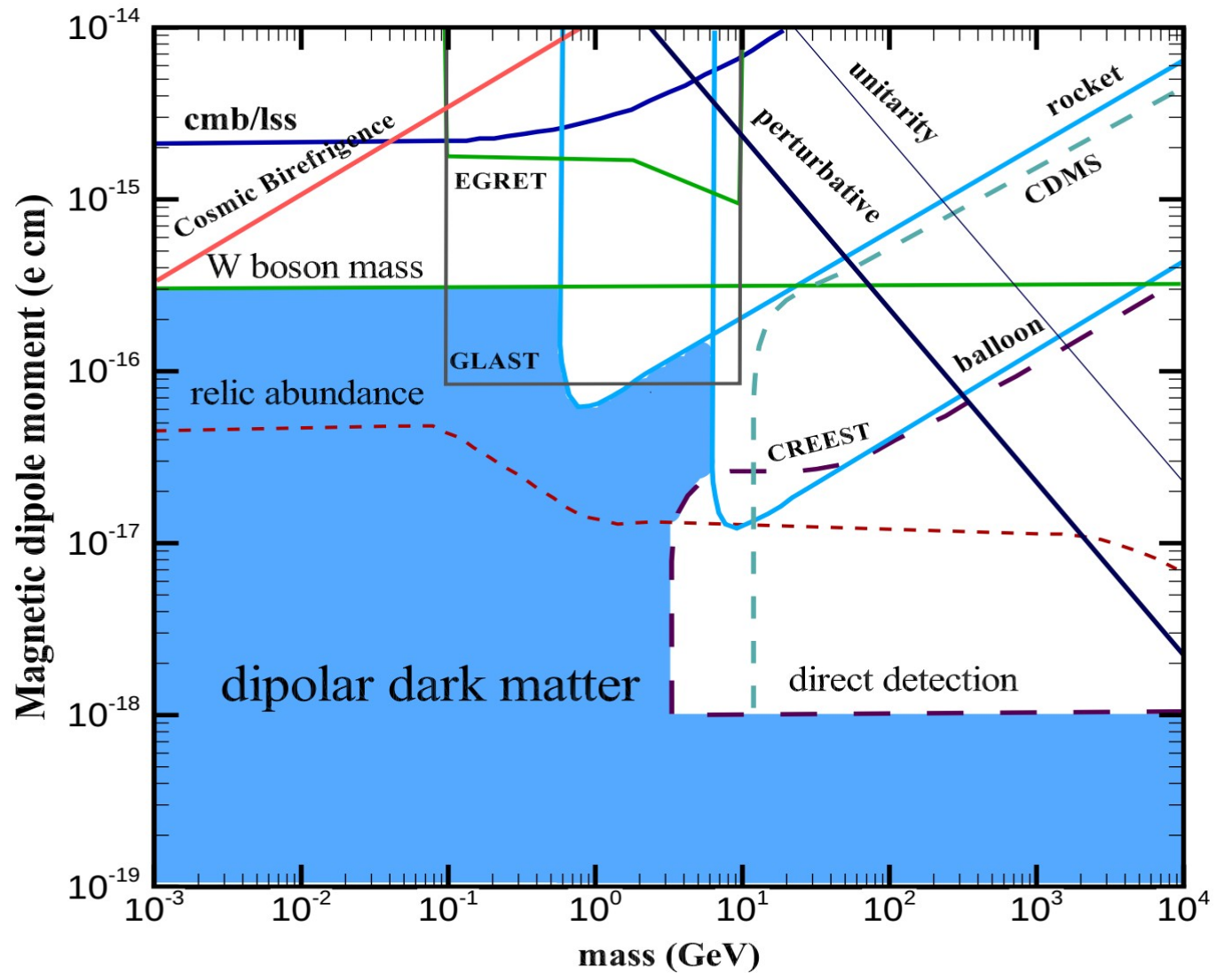
As well as maximum effective opacity

$$\tilde{\tau}_{DM}$$

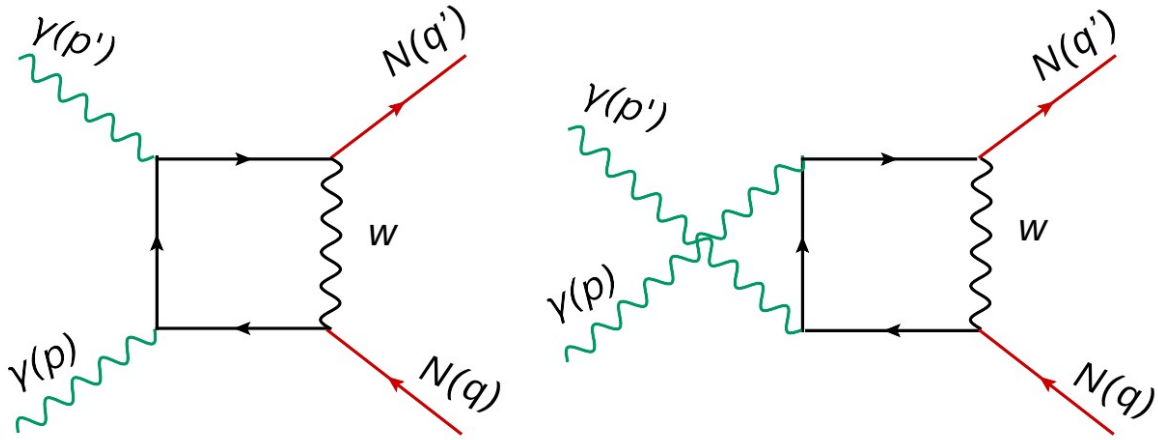
We can put some constraint on  
magnetic dipole moment

$$\mathcal{M} \approx 9 \times 10^{-16} \text{ e cm}$$

For dipolar mass larger than 3 MeV  
Which is in agreement with reported  
constraints



# Sterile neutrino



$$\dot{\tau}_{DM} = \frac{\sqrt{2}}{3\pi} \alpha G_F \theta^2 n_{DM},$$

$$\tau_{DM} = \frac{\sqrt{2}}{3\pi m_{DM}} \alpha G_F \theta^2 \rho_{DM}^0 \frac{2H(z')}{3\Omega_M^0 H_0^2} \Big|_0^z,$$

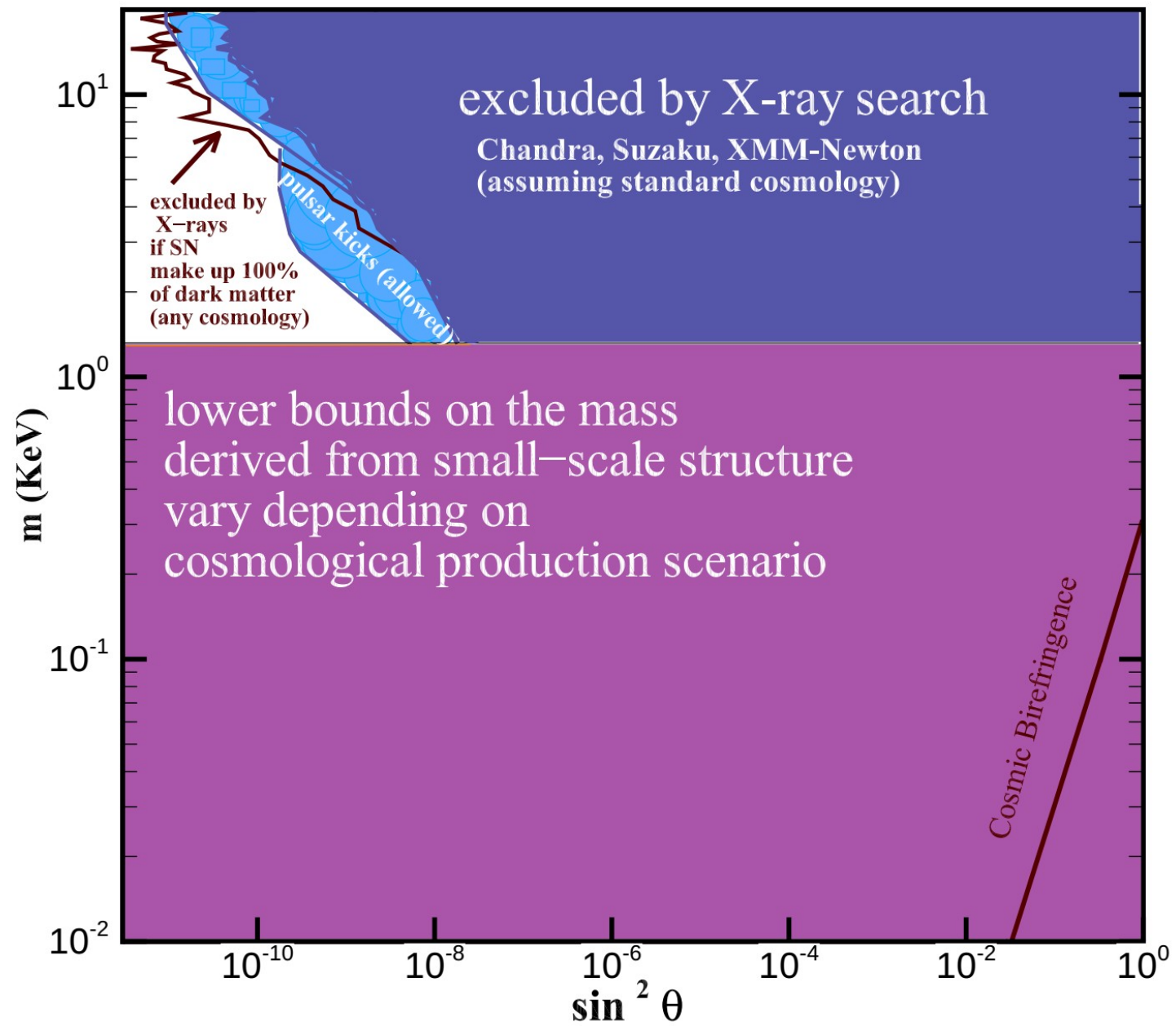
$$\tilde{\tau}_{DM} \approx 3 \times 10^{-9} \theta^2 \left( \frac{GeV}{m_{DM}} \right) \left( \frac{\rho_{DM}^0}{10^{-47} GeV^4} \right).$$

$$\beta \approx 1.5 \times 10^{-9} \theta^2 \left( \frac{GeV}{m_{DM}} \right),$$

where for Sterile neutrino DM with mass around 100 eV and the mixing angle  $\theta \approx 10^{-3}$ .

$\beta$  Can be estimated by value of  $\beta_{DM} \approx 1.6 \times 10^{-5} rad$ .

That means about 0.3% of CB angle measurement can be contributed by sterile neutrinos (if exist).



# با سپاس فراوان