# Cosmic Birefringence from Neutrino and Dark Matter Asymmetries


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Ren-Peng Zhou, Da Huang, Chao-Qiang Geng, arXiv: 2302.11140

# Content

- Introduction to CB status
- CB from a Fermion Current
- Neutrino Asymmetry
- Dark Matter Asymmetry
- Conclusions

## Introduction to Cosmic Birefringence

- **Cosmic birefringence** is a parity-violating phenomenon, which might indicate the new physics beyond the standard cosmology ($\Lambda$CDM).
- Traditional explanation of CB involves an axion or ALP coupled to the EM tensor via a CS coupling

Ni (1977); Turner & Widrow (1988)

the effective Lagrangian for axion electrodynamics is

Chern-Simons term

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}}, \qquad (3.7)$$

$$\tilde{F}^{\mu\nu} = \sum_{\alpha\beta}\frac{\epsilon^{\mu\nu\alpha\beta}}{2\sqrt{-g}}F_{\alpha\beta}$$

where $g_a$ is a coupling constant of the order $\alpha$, and the vacuum angle $\theta = \phi_a/f_a$ ($\phi_a$ = axion field). The equations

- The axion can be **dark matter** or **dark energy**, which act as a "birefringence material" filling in our Universe.

# Introduction to Cosmic Birefringence

Ni (1977); Turner & Widrow (1988)

$$\mathcal{L} = -\tfrac{1}{2}\partial_\mu\theta\partial^\mu\theta - \tfrac{1}{4}F_{\mu\nu}F^{\mu\nu} + \boxed{g_a\theta F_{\mu\nu}\tilde{F}^{\mu\nu}}$$

$$\boxed{\sum_{\mu\nu} F_{\mu\nu}\tilde{F}^{\mu\nu} = -4\mathbf{B}\cdot\mathbf{E}}$$

**<u>Parity Odd</u>**

- The EOM is modified to

$$\left(-\omega_\pm^2 + k^2\right) A_\pm(\eta) = 0 \Rightarrow \left(-\omega_\pm^2 + k^2 \boxed{\pm 4 g_a k \theta'}\right) A_\pm(\eta) = 0$$

- Different phase velocities for RH(+) and LH(-) photon polarizations

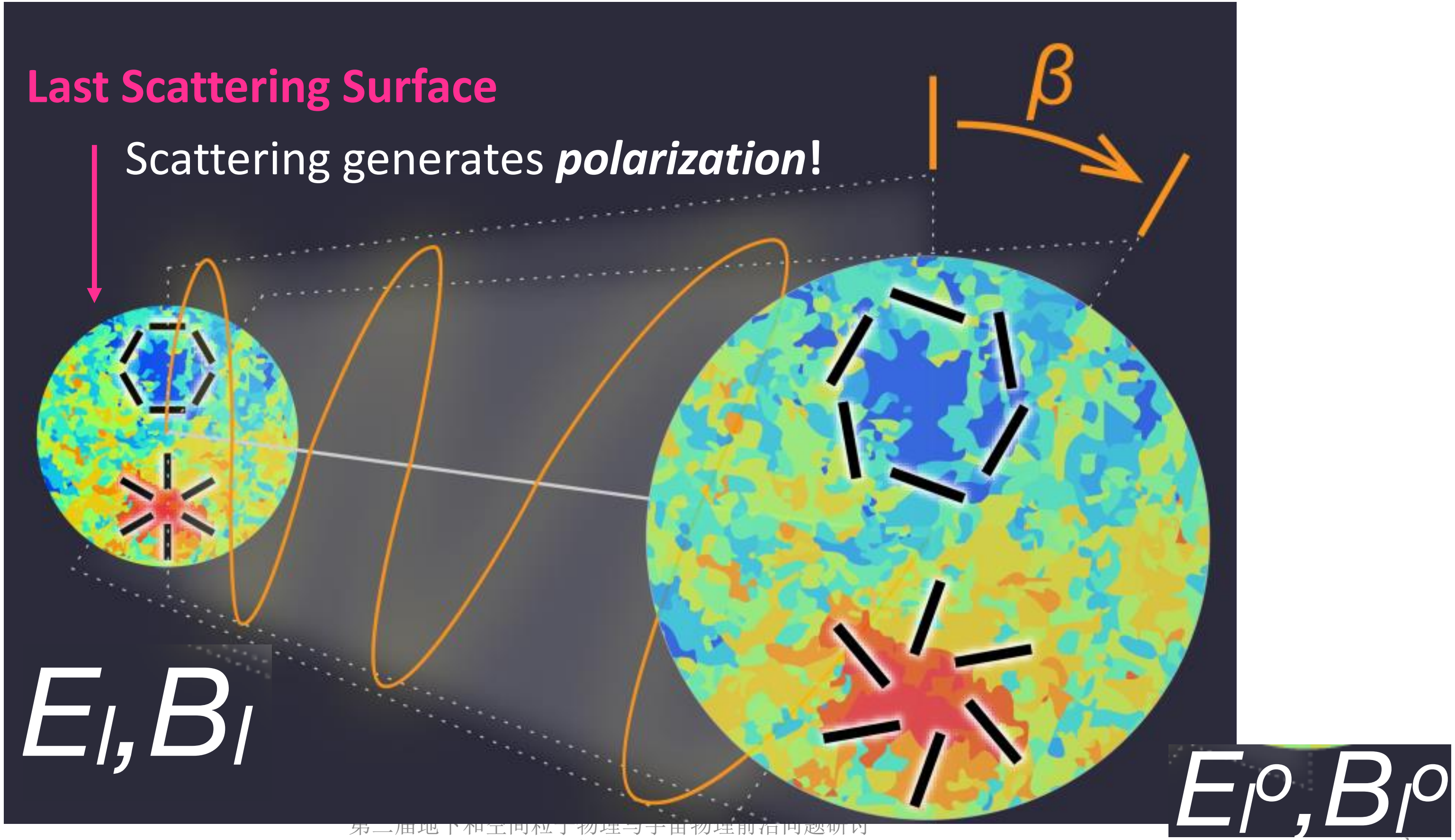
$$\frac{\omega_\pm}{k} \simeq 1 \pm \frac{2g_a\theta'}{k}$$

- CB rotation angle $\beta = -2g_a \int_{t_{emitted}}^{t_{obs}} dt\dot{\theta} = 2g_a\left[\theta(t_e) - \theta(t_o)\right]$

Carroll, Field & Jackiw (1990); Carroll & Field (1991); Harari & Sikivie (1992)

# Cosmic Birefringence in the CMB

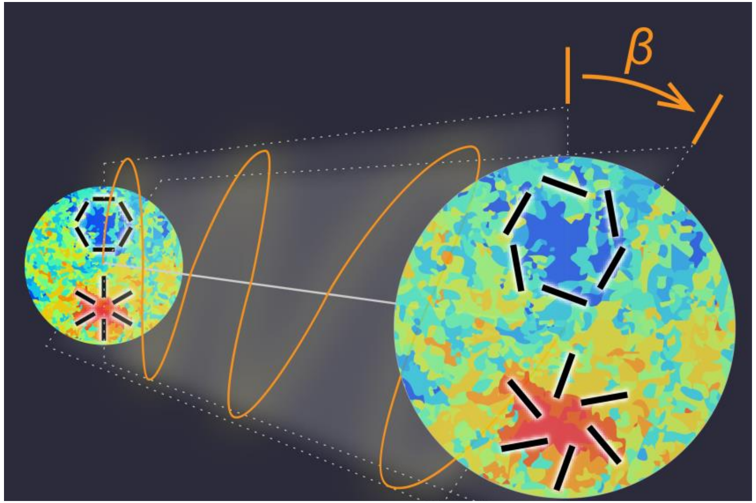
Lue, Wang & Kamionkowski (1999); Feng et al. (2005); Liu et al (2006); Zhao et al. (2015)



# Cosmic Birefringence in the CMB

Lue, Wang & Kamionkowski (1999); Feng et al. (2005); Liu et al (2006); Zhao et al. (2015)

- E-B mixing by rotation of the linear polarization plane in CMB




$$E_\ell^{\rm o} \pm iB_\ell^{\rm o} = (E_\ell \pm iB_\ell)e^{\pm 2i\beta}$$

which gives

$$E_\ell^{\rm o} = E_\ell \cos(2\beta) - B_\ell \sin(2\beta)$$

$$B_\ell^{\rm o} = E_\ell \sin(2\beta) + B_\ell \cos(2\beta)$$

- <E*B> correlation measures **β**

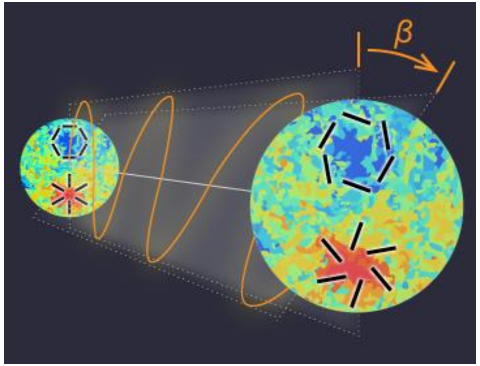
$$C_\ell^{EB,\rm obs} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\beta) + C_\ell^{EB}\cos(4\beta)$$

$$= \frac{1}{2}(C_\ell^{EE,\rm obs} - C_\ell^{BB,\rm obs})\tan(4\beta) + \frac{C_\ell^{EB}}{\cos(4\beta)}$$

# Cosmic Birefringence in the CMB

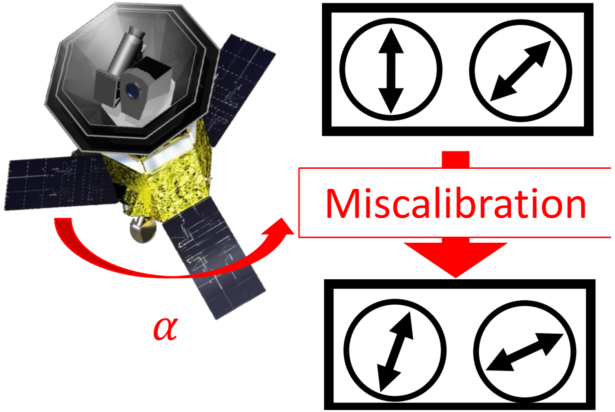
Minami et al. (2019); Minami & Komatsu (2020); Diego-Palazuelos et al. (2022); Eskilt & Komatsu(2022)

- Problem: miscalibration of polarization angles **α** ➔ Only **α+β** measured




Cosmic birefringence

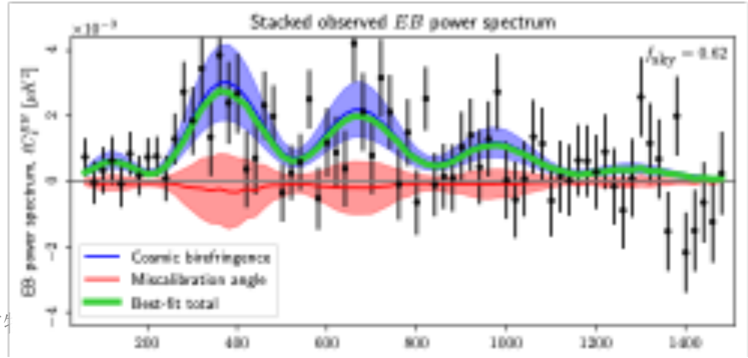
OR




- Develop new method to determine **α** with Galactic foreground and break the degeneracy

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

Diego-Palazuelos et al. (2022)



# Important Question:

Is there any alternative explanation to the nonzero CB angle beyond the axion or ALP?

# Cosmic Birefringence from a Fermion Current

- Lagrangian

$$\mathcal{L} = \mathcal{L}_{\rm EM} + \mathcal{L}_{\rm CS} = -\frac{1}{4}\sqrt{g}F_{\mu\nu}F^{\mu\nu} - \underline{\frac{1}{2}\sqrt{g}\frac{\beta}{M^2}J_\mu A_\nu \tilde{F}^{\mu\nu}},$$

Break parity, preserve CP

- Photon Field Equation + Bianchi Identity

$$\tilde{F}^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F_{\rho\sigma},$$

$$\nabla_\mu F^{\mu\nu} = \frac{\beta}{M^2}J_\mu \tilde{F}^{\mu\nu}, \qquad \nabla_\mu \tilde{F}^{\mu\nu} = 0.$$

- We are working in the flat FRW universe with metric $ds^2 = -dt^2 + R^2(t)\, d\mathbf{x}^2$, and in the background with nonzero homogeneous fermion current density $J_\mu=(J_t, \mathbf{J})$, where

$$\underline{J_t = \Delta n = n - \bar{n}}, \qquad \mathbf{J} = 0.$$

Fermion Asymmetry

- Transform into the conformal time $d\eta = dt/R$, so $ds^2 = R^2(\eta)\,(-d\eta^2 + d\mathbf{x}^2)$

$$J_\eta = R(\eta)J_t = R(\eta)\Delta n, \qquad \mathbf{J} = 0.$$

C.Q. Geng, S.H. Ho, J.N. Ng, *JCAP* 09(2007)010; R.P. Zhou, **DH**, C.Q. Geng, arXiv: 2302.11140

# Cosmic Birefringence from a Fermion Current

R.P. Zhou, **DH**, C.Q. Geng, arXiv: 2302.11140

- Define **E** and **B** fields

$$F^{\mu\nu} = R^{-2}\begin{pmatrix} 0 & E_x & E_y & E_z \\ -E_x & 0 & B_z & -B_y \\ -E_y & -B_z & 0 & B_x \\ -E_z & B_y & -B_x & 0 \end{pmatrix}, \quad \tilde{F}^{\mu\nu} = R^{-2}\begin{pmatrix} 0 & B_x & B_y & B_z \\ -B_x & 0 & -E_x & E_y \\ -B_y & E_z & 0 & -E_x \\ -B_z & -E_y & E_x & 0 \end{pmatrix}.$$

- Modified Maxwell Equations

$$\frac{\partial}{\partial\eta}\left(R^2\mathbf{E}\right) - \nabla \times \left(R^2\mathbf{B}\right) = \boxed{\frac{\beta}{M^2} J_\eta \left(R^2\mathbf{B}\right)}, \quad \nabla \cdot \mathbf{E} = 0\,,$$

$$\frac{\partial}{\partial\eta}\left(R^2\mathbf{B}\right) + \nabla \times \left(R^2\mathbf{E}\right) = 0\,, \quad \nabla \cdot \mathbf{B} = 0\,,$$

- Modified Wave Equation

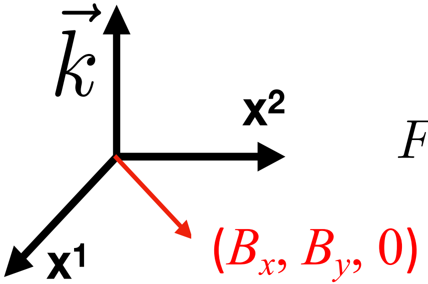
$$\boxed{\frac{\partial^2}{\partial\eta^2}\left(R^2\mathbf{B}\right) - \nabla^2\left(R^2\mathbf{B}\right) = -\frac{\beta}{M^2} J_\eta \nabla \times \left(R^2\mathbf{B}\right)}$$

# Cosmic Birefringence from a Fermion Current

- Go to Fourier space and assume EM wave propagates alone z direction

$$R^2\mathbf{B}(\mathbf{x},\eta) = e^{-ikz}R^2\mathbf{B}(\eta)$$

- Define two circular polarizations




$$F_\pm \equiv R^2 B_\pm(\eta) = R^2(B_x \pm iB_y)$$

$F_+$: Right-handed;

$F_-$: Left-handed;

- WKB Solution: $F_\pm(\eta) = \exp\left[ik\int \left(\boxed{1 \pm \frac{\beta}{M^2}\frac{J_\eta}{k}}\right)^{1/2} d\eta\right]$

Different phase velocities of RH and LH states

- The plane of a linearly polarization rotates by an angle

$$\Delta\alpha \approx \frac{1}{2}\frac{\beta}{M^2}\int J_\eta d\eta = \frac{1}{2}\frac{\beta}{M^2}\int \Delta n\, dt$$

**The effect accumulates over long distances!**

R.P. Zhou, **DH**, C.Q. Geng, arXiv: 2302.11140

# CB from Neutrino Asymmetry

- Identify fermions in the current as electron neutrinos $\boldsymbol{\nu}_e$

$$J_\mu^{\nu_e} = \overline{(\nu_e)}_L \gamma_\mu (\nu_e)_L$$

- Polarization angle rotation of CMB photons

$$\Delta\alpha = \frac{1}{2}\frac{\beta}{M^2}\int J_\eta^{\nu_e} d\eta = \frac{1}{2}\frac{\beta}{M^2}\int \Delta n_{\nu_e} dt$$

$$\boxed{\Delta n_{\nu_e} \equiv n_{\nu_e} - n_{\bar{\nu}_e}}$$

- In the literature, $\boldsymbol{\nu}_e$ asymmetry is parametrized by

$$\eta_{\nu_e} = \frac{\Delta n_{\nu_e}}{n_\gamma} = \frac{1}{12\zeta(3)}\left(\frac{T_\nu}{T_\gamma}\right)^3 \left(\pi^2 \xi_{\nu_e} + \xi_{\nu_e}{}^3\right) \xrightarrow{\boxed{(T_\nu/T_\gamma)^3 = 4/11}} \eta_{\nu_e} \simeq 0.249 \xi_{\nu_e}$$

- $\boldsymbol{\nu}_e$ asymmetry: $\quad \Delta n_{\nu_e} = \eta_{\nu_e} n_\gamma \simeq 0.061 \xi_{\nu_e} T_\gamma^3$

$$\boxed{n_\gamma = \left(\frac{2\zeta(3)}{\pi^2}\right) T_\gamma^3}$$

$\boldsymbol{\xi_{\nu e}}$: $\boldsymbol{\nu}_e$ degeneracy parameter

P.D. Serpico & G. Raffelt, PRD**71**(2015)127301
J. Lesgourgues & S. Pastor, Phys.Rept.**429**(2006)307

# CB from Neutrino Asymmetry

- CB rotation angle

$$\Delta\alpha = 0.03\beta\left(\frac{\xi_{\nu_e}T_{\gamma 0}^3}{M^2}\right)\int_0^{z_D}\frac{(1+z)^2}{H(z)}dz \approx 0.03\beta\left(\frac{\xi_{\nu_e}T_{\gamma 0}^3}{M^2 H_0}\right)\frac{2}{3}(1+z_D)^{3/2}$$

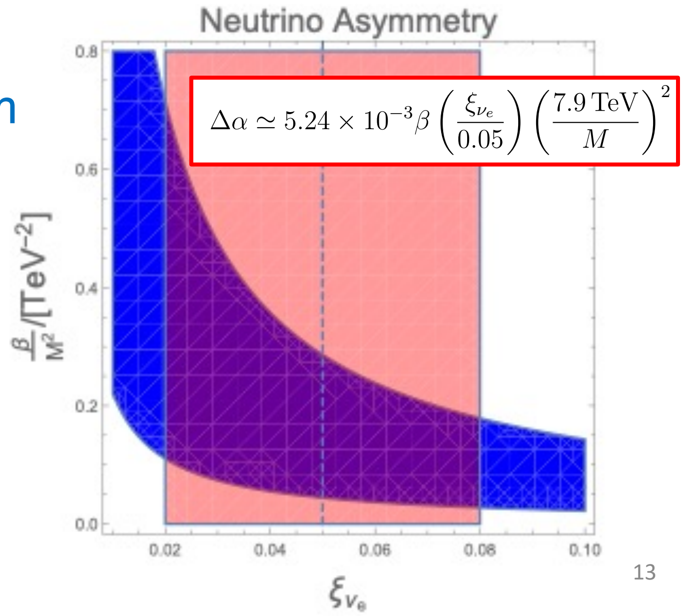
where we have used $T_\gamma = T_{\gamma 0}(1+z).$ $dt = \frac{dR}{HR} = -\frac{dz}{(1+z)H},$

$$H(z) = H_0(1+z)^{3/2},$$

- Recently, by measuring the primordial helium abundance in the metal poor galaxies, the EMPRESS survey has found a tension with SM prediction, indicating a remarkably nonzero $\nu_e$ degeneracy parameter

$$\xi_{\nu_e} = 0.05^{+0.03}_{-0.02}$$

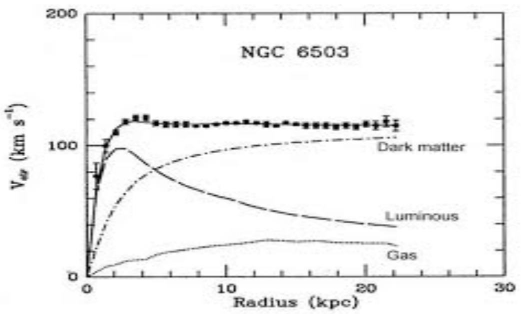
A. Matsumoto et al., APJ**941**(2022)167;
A.-K. Burns et al. 2206.00693;
M. Escudero et al. 2208.03201



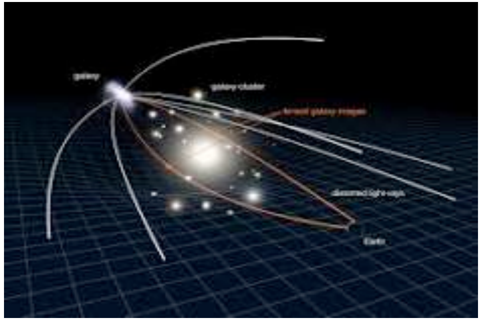
# CB from Asymmetric Dark Matter

- Evidence for dark matter

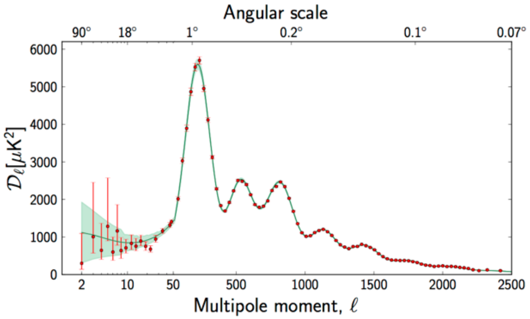
- Rotation Curves of Spiral Galaxies



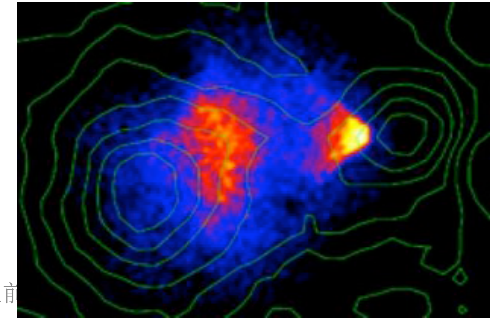

- Gravitational Lensing



- CMB




- Bullet Cluster



# CB from Asymmetric Dark Matter

- It is interesting to consider CB from a fermionic DM current

$$J_\mu^\chi = \bar{\chi}\gamma_\mu\chi$$

- Source of CB is $J_0^\chi = \Delta n_\chi = n_\chi - n_{\bar{\chi}}$ → **Asymmetric DM**


- Many models for producing ADM has been proposed in the literature. Especially when $M_\chi \simeq 5$ GeV, ADM can help explain the density ratio between visible and dark matters.

S. Nussinov (1985); D.B. Kaplan (1992); D.E. Kaplan+(2009); K.M. Zurek(2014);

- Here we do not specify the ADM production mechanism and assume it can induce CB via its coupling with photon CS term.

# CB from Asymmetric Dark Matter

- Recall the CB rotation angle

$$\Delta\alpha \approx \frac{1}{2}\frac{\beta}{M^2}\int J_\eta d\eta = \frac{1}{2}\frac{\beta}{M^2}\int \Delta n\, dt$$

- For ADM, $\Delta n_\chi = n_\chi$, and cosmological DM abundance is parametrized by

$$\Omega_{\chi 0} = \frac{\rho_{\chi 0}}{\rho_{c0}} = \frac{8\pi G M_\chi n_{\chi 0}}{3H_0^2} \quad \text{with} \quad \boxed{\rho_{\chi 0} = M_\chi n_{\chi 0}} \quad \boxed{\rho_{c0} = 3H_0^2/(8\pi G)}$$

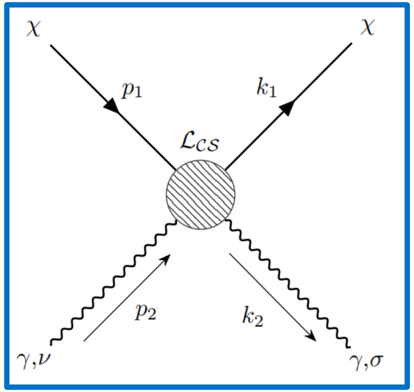
- According to cosmological evolution, $n_\chi = (1+z)^3 n_{\chi 0}$ and $H = (1+z)^{3/2} H_0$

$$\Delta\alpha = \frac{1}{2}\frac{\beta}{M^2}\frac{\rho_{c0}\Omega_{\chi 0}}{M_\chi}\int_0^{z_D}(1+z)^3\frac{dz}{H(1+z)} \approx \frac{1}{2}\frac{\beta}{M^2}\frac{3H_0\Omega_{\chi 0}}{8\pi G M_\chi}\frac{2}{3}(1+z_D)^{3/2}$$

$$= 5.24\times 10^{-3}\beta\left(\frac{1.77\,\mathrm{GeV}}{M}\right)^2\left(\frac{5\,\mathrm{GeV}}{M_\chi}\right)$$

# 5 GeV ADM: Constraints

- For the conventional ADM with $M_\chi \simeq 5$ GeV, the model can suffer exp. constraints from CMB power spectrum and DM direct searches.
- CMB constraint: the interaction between ADM $\chi$ and CMB photons would cause power suppression at high multipoles and dark BAO:




- Computation of Feynman diagram gives the temperature-dependent $\chi$-$\gamma$ cross section

$$\langle \sigma v_{\text{Møl}} \rangle_{\chi\gamma} \simeq \frac{3\zeta(5)}{2\pi\zeta(3)} \frac{\beta^2 T_\gamma^2}{M^4} = 0.412 \left( \frac{\beta^2 T_\gamma^2}{M^4} \right)$$

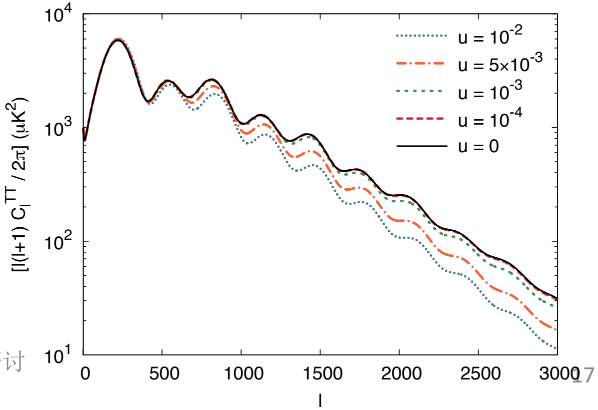
- Data from CMB TT and EE modes constrain

$$\langle \sigma v_{\text{Møl}} \rangle_{\chi\gamma}(T_\gamma^0) \lesssim 6 \times 10^{-40} \left( \frac{M_\chi}{\text{GeV}} \right) \text{cm}^2 , \quad \text{at } 68\% \text{ C.L.}$$

$$\Rightarrow \quad \frac{\beta}{M^2} \lesssim 8.24 \times 10^6\, \text{GeV}^{-2} \left( \frac{M_\chi}{\text{GeV}} \right)^{1/2}$$

R.J. Wilkinson et al (2013)

**Too Weak !**

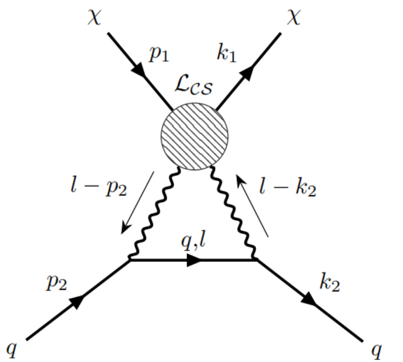


# 5 GeV ADM: Constraints

- DM direct searches
- Effective ADM-quark interaction

$$\mathcal{L}_{\chi q} = -\sum_q \frac{1}{m_{V_q}^2} \bar{\chi}\gamma_\mu \chi \bar{q}\gamma^\mu \gamma^5 q$$

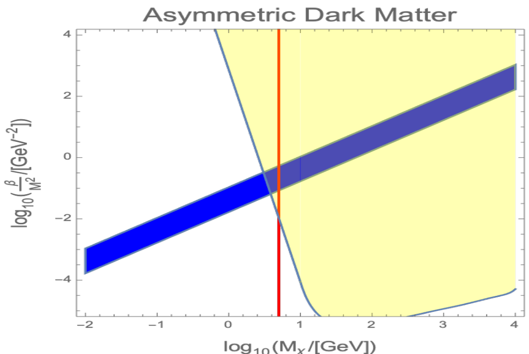
$$\boxed{\frac{1}{m_{V_q}^2} = \frac{3\alpha}{8\pi}\frac{\beta}{M^2} Q_q^2 \ln \frac{\Lambda^2}{m_q^2}}$$



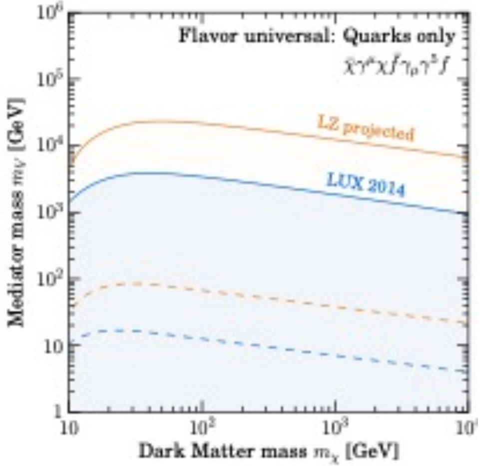

➡ Velocity and momentum suppressed spin-dependent DM-nucleon DD signal

- RG running ➔ Mixing with $\bar{\chi}\gamma_\mu \chi \bar{q}\gamma^\mu q$;

➡ Strong constraints from SI DD signal




**5 GeV ADM Excluded by LZ!**




F. D'Eramo et al (2016)

# 5 keV Warm ADM

- Lower the ADM mass to **warm DM** range with $M_\chi$ = 5 keV
- CB angle from CMB $$\Delta\alpha = 5.24 \times 10^{-3} \beta \left(\frac{1.77\,\mathrm{TeV}}{M}\right)^2 \left(\frac{5\,\mathrm{keV}}{M_\chi}\right)$$
- Weak Constraints:

**Evade all Constraints!**

- Free from DM DD constraints;
- DM phase-space distribution in dSphs ➔ $M_\chi \gtrsim 1$ keV; A. Boyarsky et al (2008)
- Detection of CMB spectral distortions from FIRAS data

$$\frac{\beta}{M^2} \lesssim \left(\frac{M_\chi}{5\,\mathrm{keV}}\right)^{1/2} \left(\frac{1}{1.2 \times 10^{-4}\,\mathrm{TeV}}\right)^2$$

Y. Ali-Haimoud et al (2015)

- Lyman-α forest; A. Boyarsky et al (2009)
- Matter power spectrum; M. Escudero et al (2018)

# Conclusions

- **Cosmic Birefringence** is a remarkable parity-violating effect, which is beyond the standard cosmology prediction;
- Recently, new technique breakthrough in CMB data analysis leads to a hint towards a nonzero CB rotation angle;
- We provide a new explanation towards the CMB CB, which is caused by the CS-like coupling between a fermion current and photons. As a result, the source for CB is the fermion number asymmetry;
- By identifying fermions as cosmological electron neutrinos, CB rotation angle can be explained by the $\nu_e$ asymmetry indicated recently by the EMPRESS survey;
- For the ADM case, the conventional ADM with $M_\chi \simeq 5$ GeV is excluded by DM DD data from LZ, while the warm ADM of $M_\chi \simeq 5$ keV can satisfy all constraints.

THANK YOU！