Cosmic Birefringence as a probe of the nature of Dark Matter

Presented by

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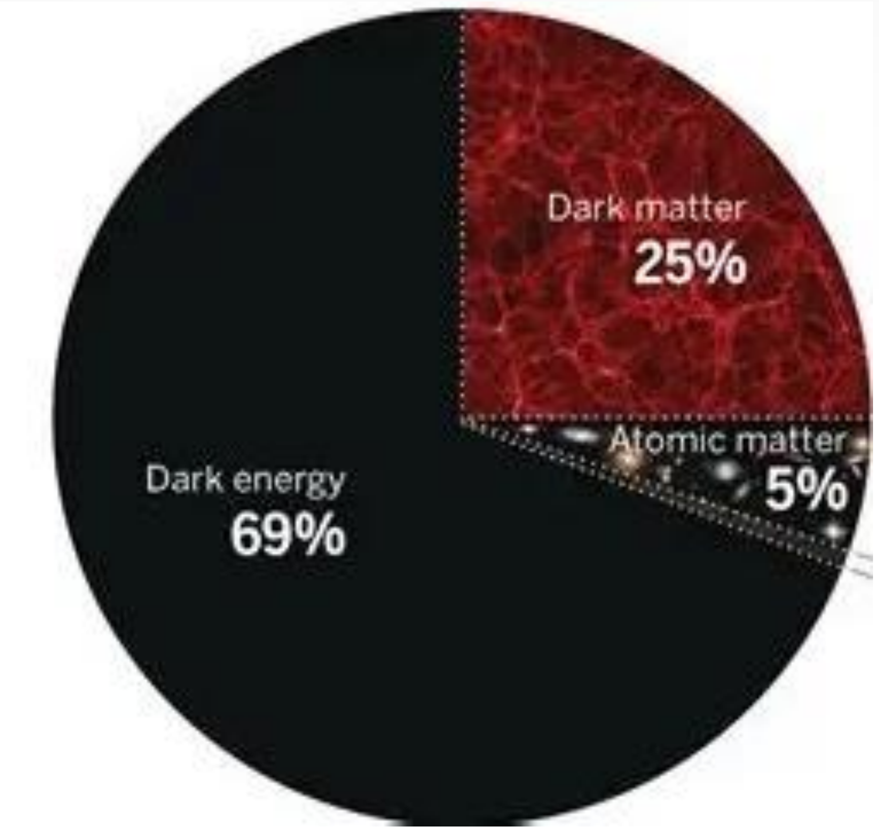
Dark Matter:



DM is a mysterious form of matter that makes up approximately 25% of all matter in the universe.

Unlike ordinary matter, it does not emit, absorb, or reflect light, making it completely invisible to telescopes.

Its presence is inferred solely through its gravitational effects

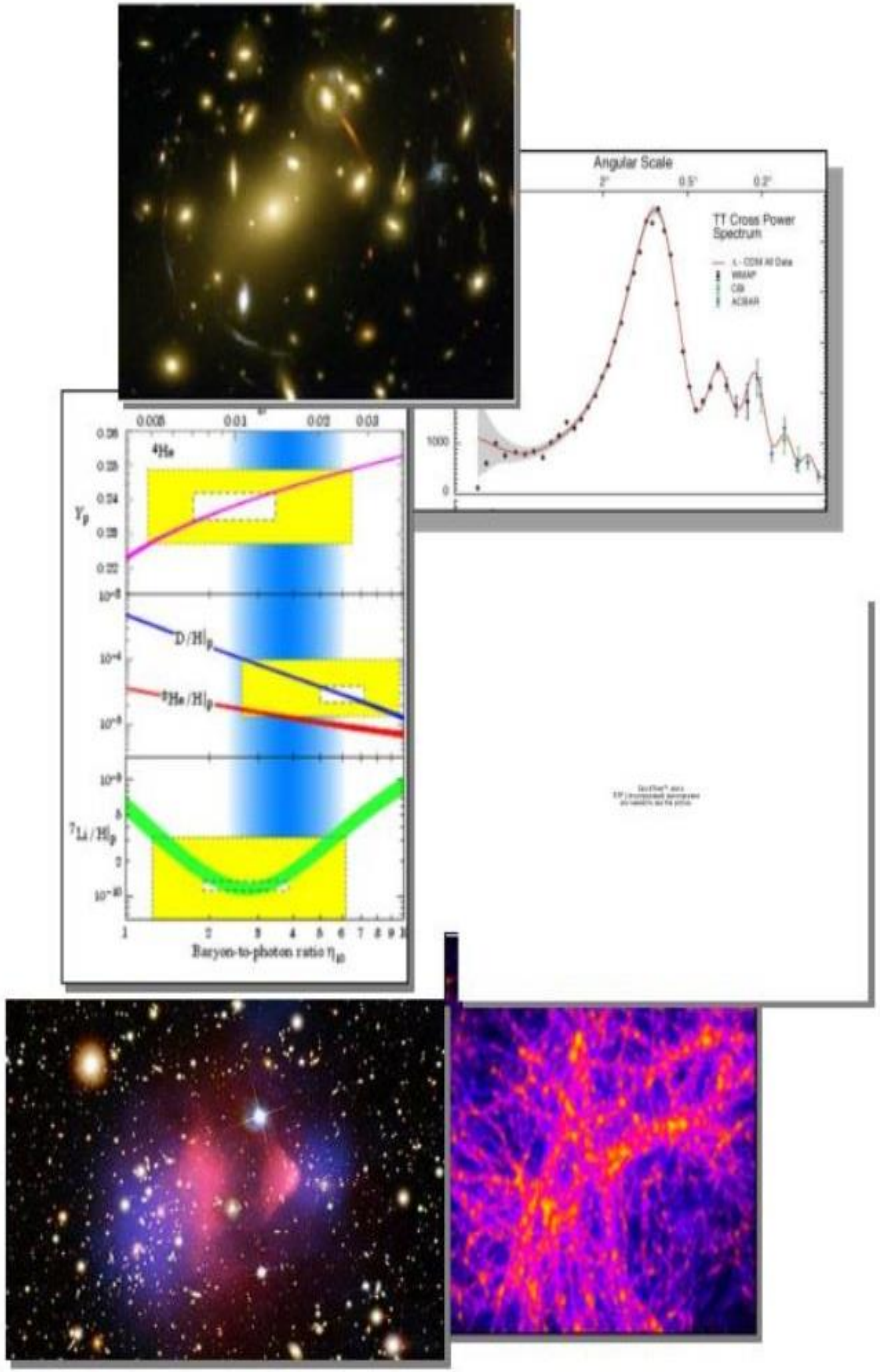
Types of Evidence for Dark Matter

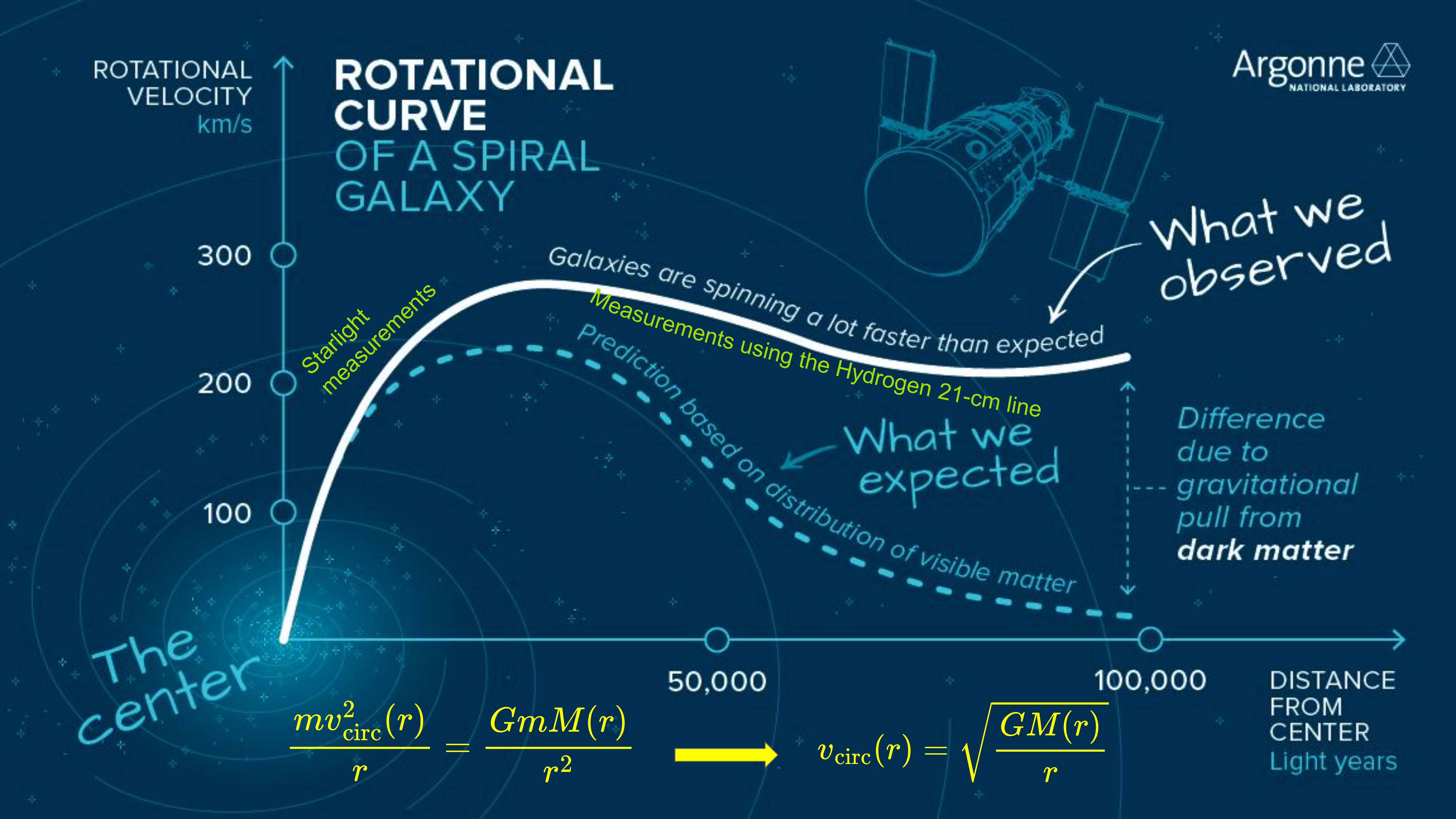
Small-Scale Evidence

- ***Galaxy Rotation Curves****:* *Stars orbit faster than visible mass predicts*
- ***Gravitational Lensing:*** *Deflection of light by unseen mass in galaxies*

Large-Scale Evidence

- ***Cosmic Microwave Background:*** *Temperature fluctuations reveal DM's role*
- ***Large-Scale Structure:*** *Galaxy distribution shaped by dark matter gravity*
- ***Galaxy Cluster Dynamics:*** *Mass inferred from cluster movements exceeds visible mass*

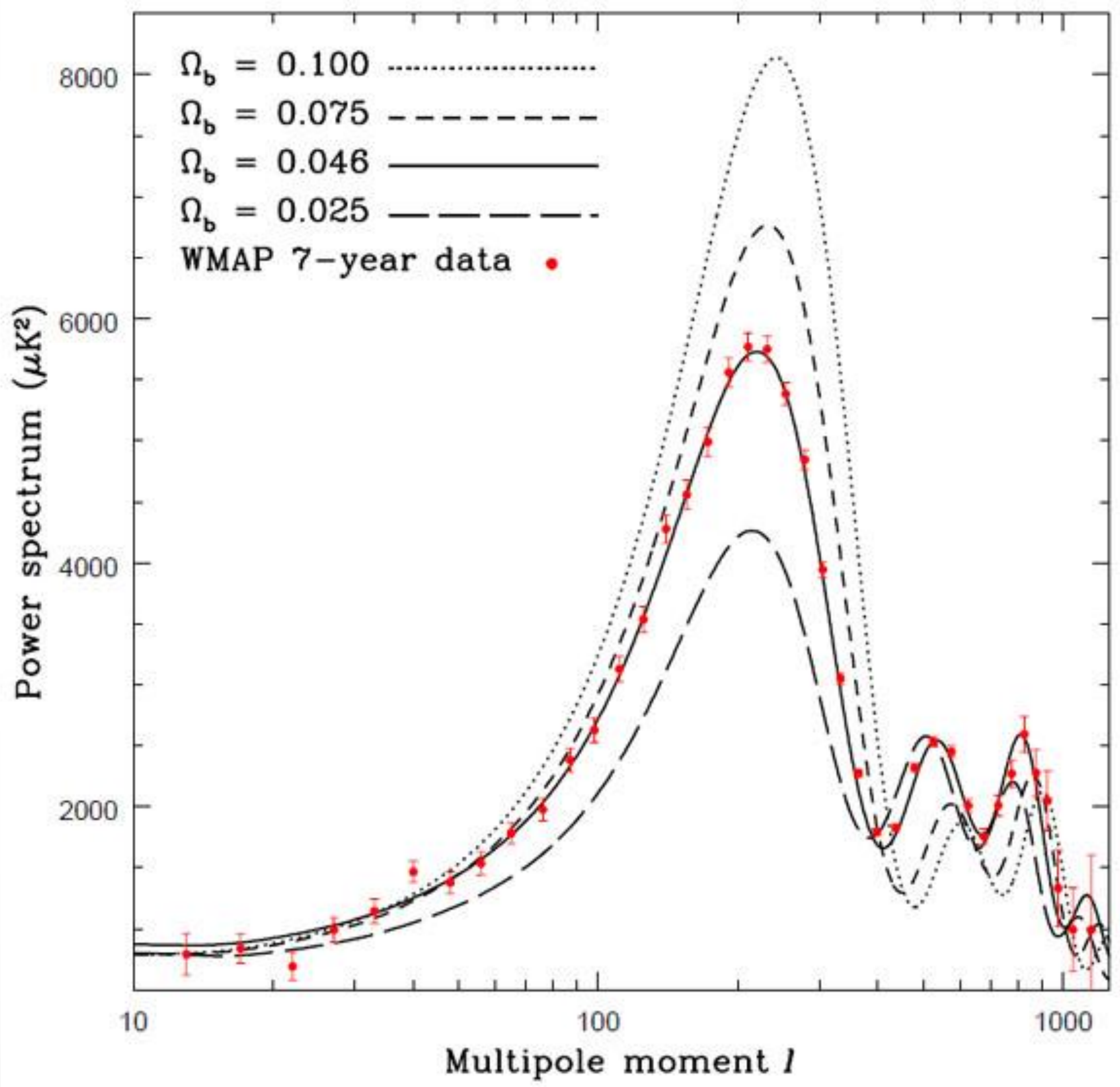




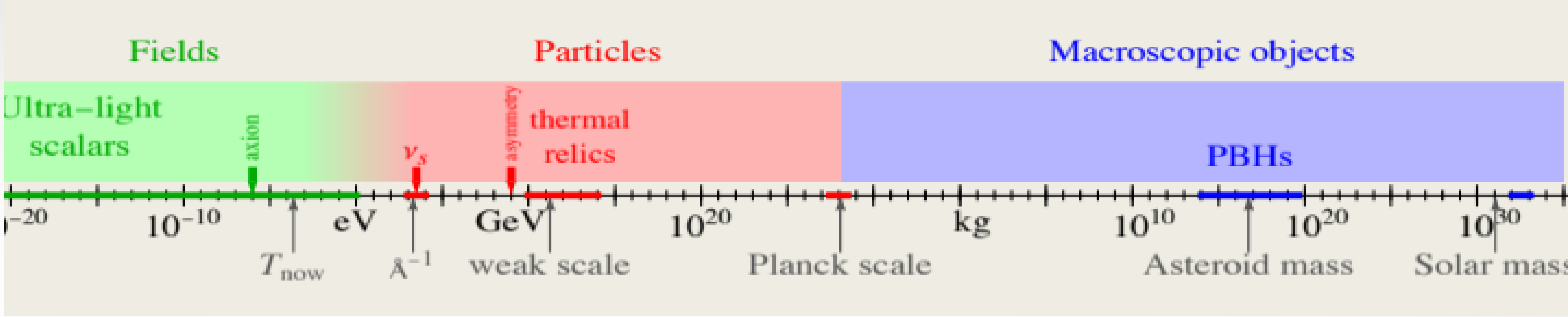
$$\frac{m v_{\mathrm{circ}}^2(r)}{r} = \frac{G m M(r)}{r^2} \longrightarrow v_{\mathrm{circ}}(r) = \sqrt{\frac{G M(r)}{r}}$$

Peak Structure in the Angular Power Spectrum of the CMB:

- ***DM's gravitational effects shape the acoustic peaks in the CMB.***



Mass scale of DM:



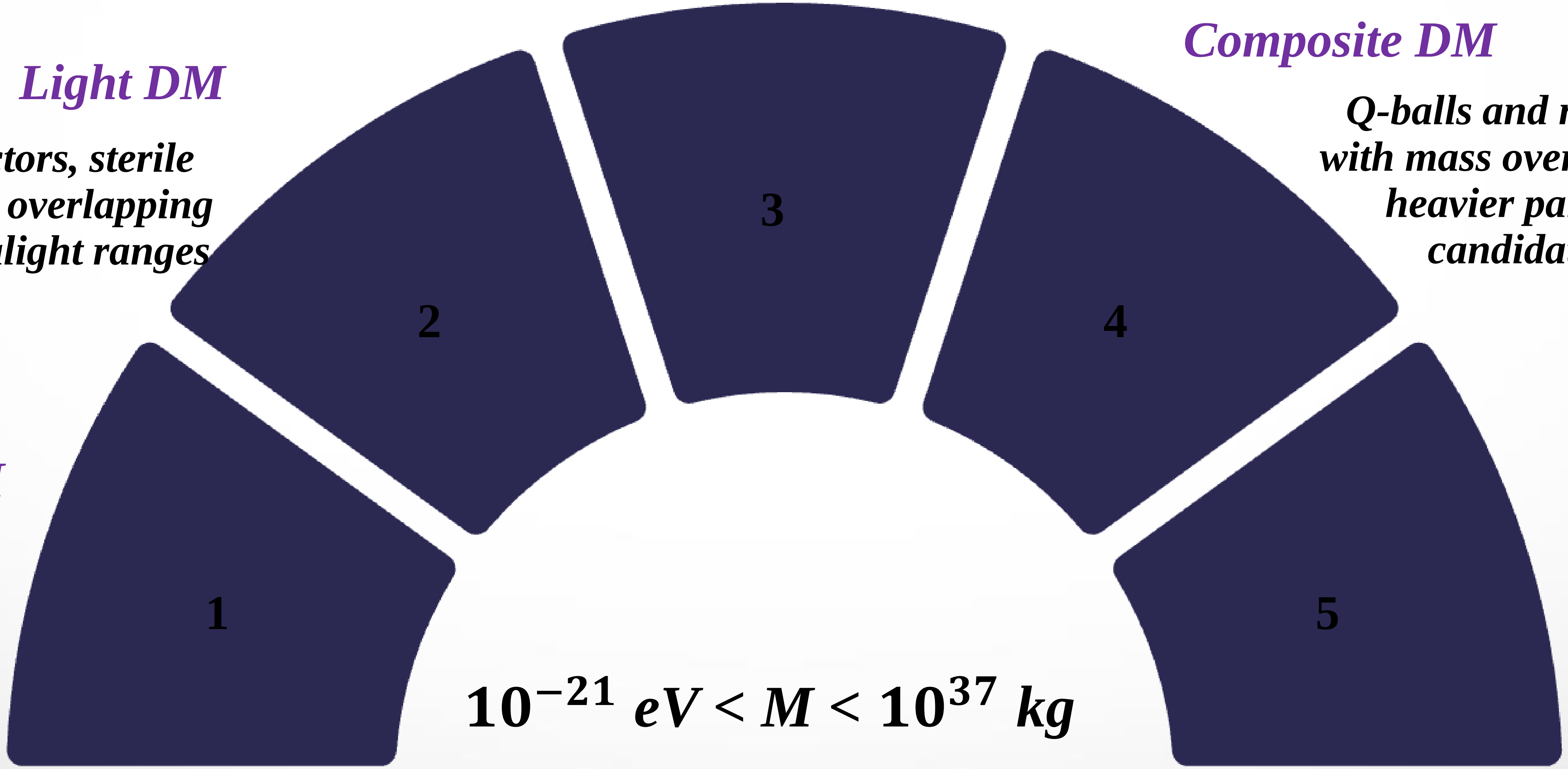
WIMP

Light DM

Dark sectors, sterile neutrinos overlapping with ultralight ranges

Composite DM

Q-balls and nuggets with mass overlap near heavier particle candidates



$$10^{-21}\ eV < M < 10^{37}\ kg$$

Ultralight DM

Non-thermal bosonic fields from ~10^{-22} eV

Primordial BHs

Masses from fraction to 10 solar masses or more

Possible Spin Values of Dark Matter Candidates

Dark matter's spin remains unknown but influences interactions and detection.

1. ***Spin-0 (Scalar Particles)***

   Examples: Axions

2. ***Spin-½ (Fermions)***

   Examples: Sterile Neutrinos

3. ***Spin-1 or Higher (Vector/Tensor Particles)***

   Examples: Hypothetical Bosons

What We Know About Dark Matter

- *Dark matter must be cold or only mildly warm to enable cosmic structure formation.*
- *Its particles have negligible or zero electric charge.*
- *Direct detection experiments impose stringent limits on its interaction strength.*
- *Dark matter particles interact weakly with both themselves and ordinary matter.*
- *These particles must remain stable over cosmic timescales.*

Theoretical Models of Dark Matter

1 **WIMPs**
Weakly Interacting Massive Particles

Axions
Light scalar particles from symmetry breaking

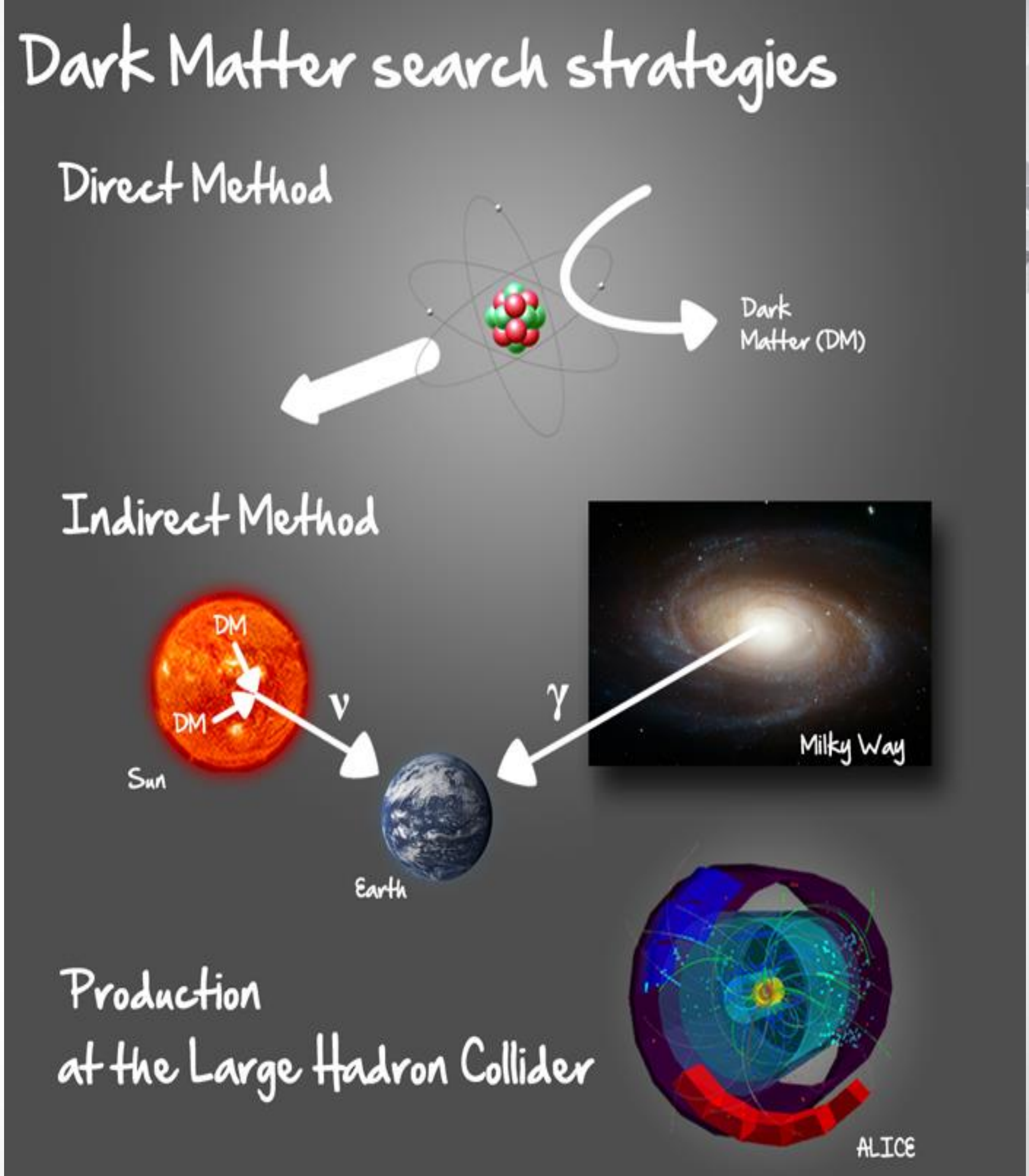
3 **Sterile Neutrinos**
Hypothetical fermions mixing with neutrinos

Light Dark Matter
Low-mass dark sector particles

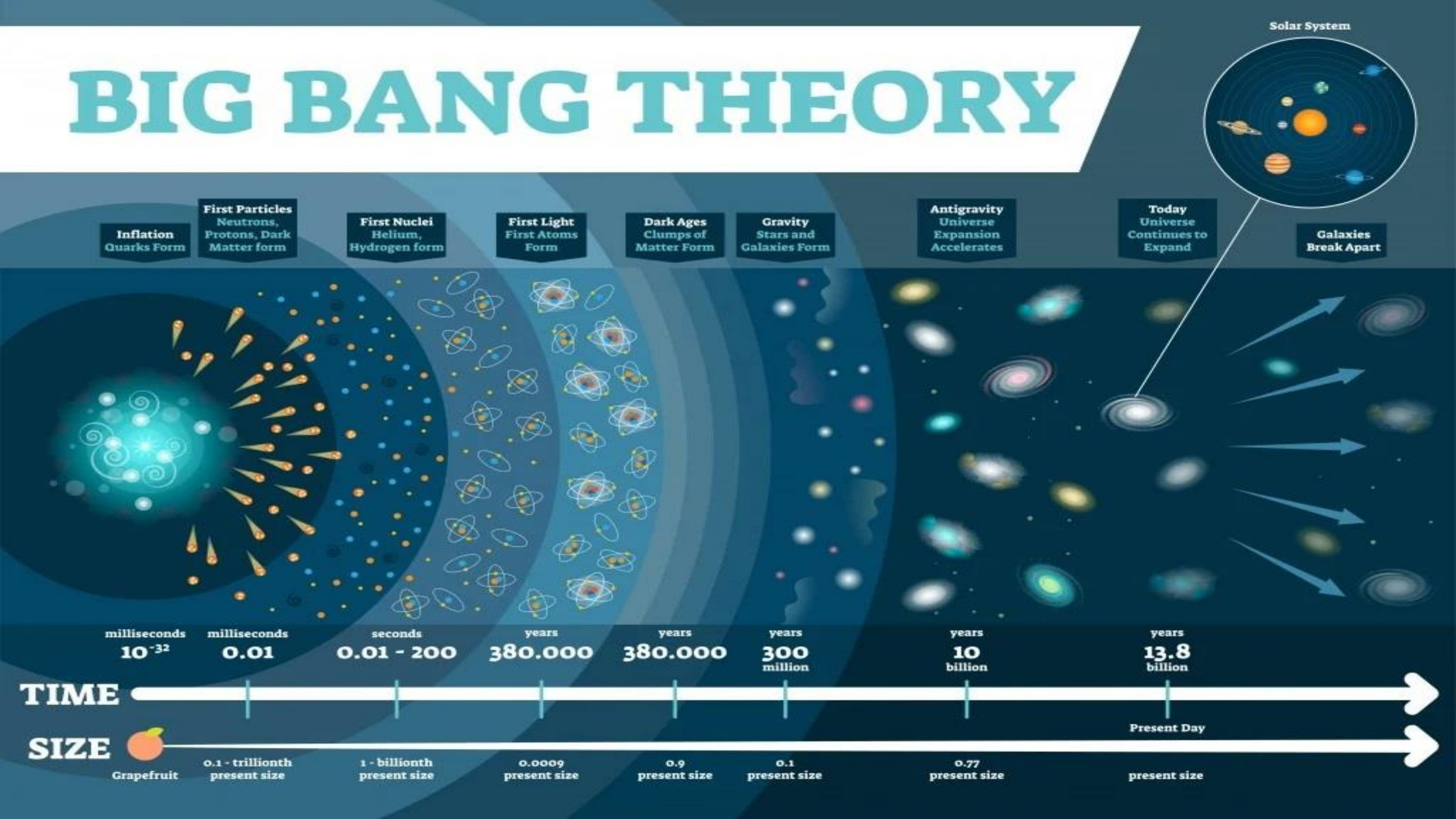
Ultralight Fields
Non-thermal bosonic fields with tiny mass

Composite Models
Bound states like Q-balls or dark nuggets

7 **Primordial Black Holes**
Black holes formed in the early universe



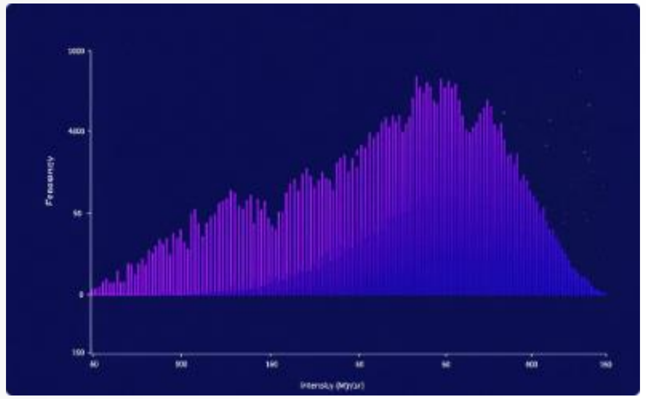
Cosmic Microwave Background Radiation

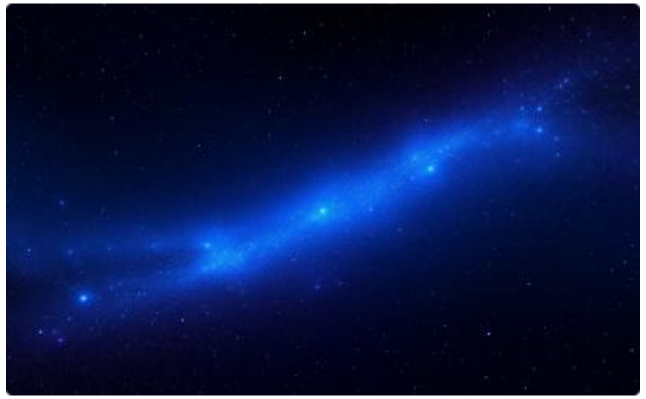

BIG BANG THEORY
Solar System
Inflation
Quarks Form
First Particles
Neutrons, Protons, Dark Matter form
First Nuclei
Helium, Hydrogen form
First Light
First Atoms Form
Dark Ages
Clumps of Matter Form
Gravity
Stars and Galaxies Form
Antigravity
Universe Expansion Accelerates
Today
Universe Continues to Expand
Galaxies
Break Apart
milliseconds
10^-32
milliseconds
0.01
seconds
0.01 - 200
years
380.000
years
380.000
years
300
million
years
10
billion
years
13.8
billion
TIME
Present Day
SIZE
Grapefruit
0.1 - trillionth
present size
1 - billionth
present size
0.0009
present size
0.9
present size
0.1
present size
0.77
present size
present size

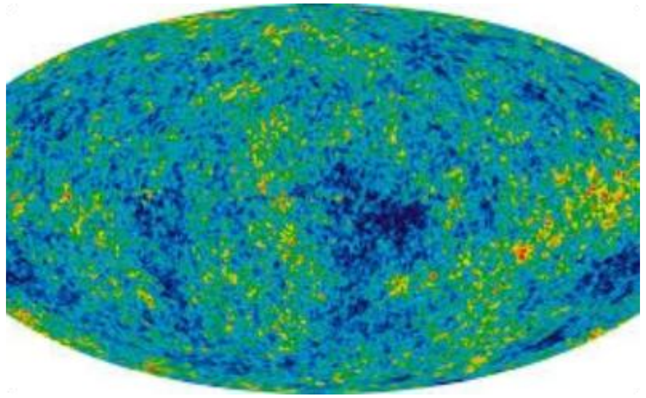
Cosmic Microwave Background Radiation

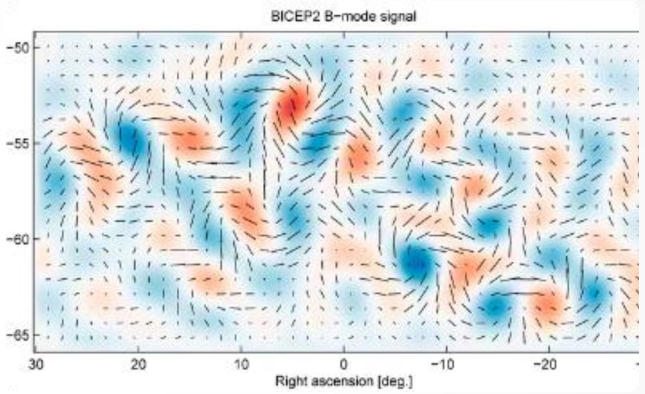
The CMB is a snapshot of the universe about 380,000 years after the Big Bang, when photons decoupled from matter.

Key Properties of the Cosmic Microwave Background









Blackbody Spectrum:

Perfect Planck spectrum matching predictions

Uniformity:

Nearly uniform temperature at 2.7 K across the sky

Slight Anisotropies:

Minute temperature variations revealing early structure

Polarization Pattern:

Light polarization patterns giving insights on inflation

The CMB isn't just a snapshot of the early universe — it's a cosmic laboratory.

CMB Polarization: A Window into New Physics

The polarization of the Cosmic Microwave Background (CMB) is a powerful observational tool, capable of providing indirect evidence of physics beyond the Standard Model (SM).

In the framework of the SM of particle physics and standard cosmology:

Linear polarization is generated during recombination via Thomson scattering of photons with free electrons.

- Only linear polarization in the form of E-mode patterns is predicted to arise from scalar (density) perturbations.
- B-mode polarization is not generated by scalar perturbations. It requires tensor modes (primordial gravitational waves) or lensing of E-modes — or new physics.
- Circular polarization (Stokes V) is not produced at any significant level — the SM contains no known mechanism for generating circular polarization in the CMB.
- Cosmic birefringence is another powerful observational signature, creating new cross-correlations E_B that are not allowed in the SM.

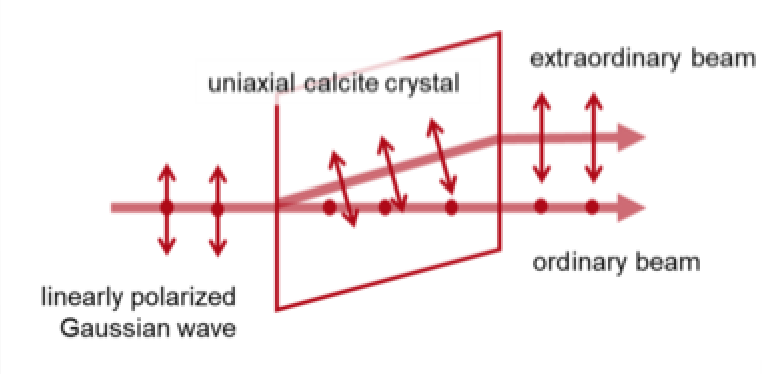
CMB Birefringence: A New Probe of Fundamental Physics

- ***Birefringence** is the phenomenon where the polarization of light rotates as it passes through a medium with different refractive indices for different polarizations.*

❖ ***Anisotropic materials:*** *Materials whose optical properties depend on the direction of light propagation and polarization.*

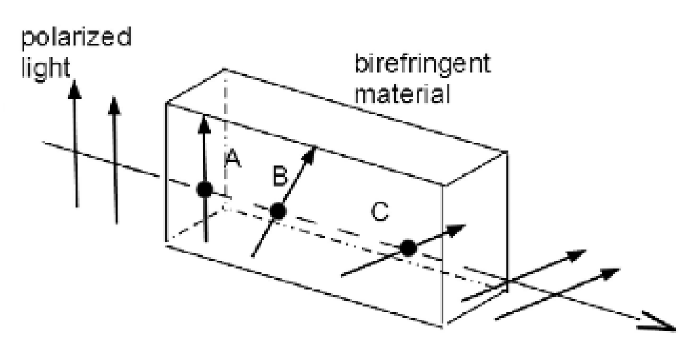
❑ *When linearly polarized light enters a birefringent material, the electric field vector $\vec{E}$ of the incoming wave must be expressed in terms of the eigenmodes (or natural polarization states) that the medium supports:*

$$\vec{E}_{\rm in} = E_{\|}\,\hat{e}_{\|} + E_{\perp}\,\hat{e}_{\perp}$$



The o-ray and e-ray travel at different speeds (since ($n_o \neq n_e$)),

$$\Delta\phi = \frac{2\pi d}{\lambda}(n_e - n_o)$$



Hence, the polarization is modified.

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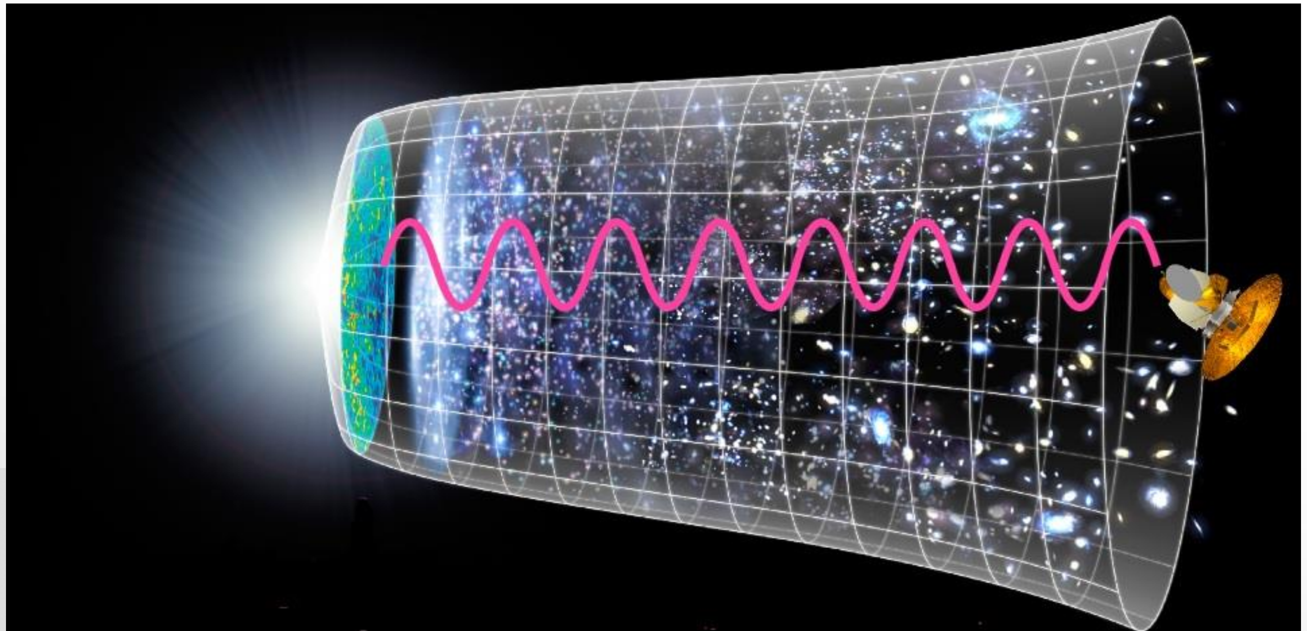
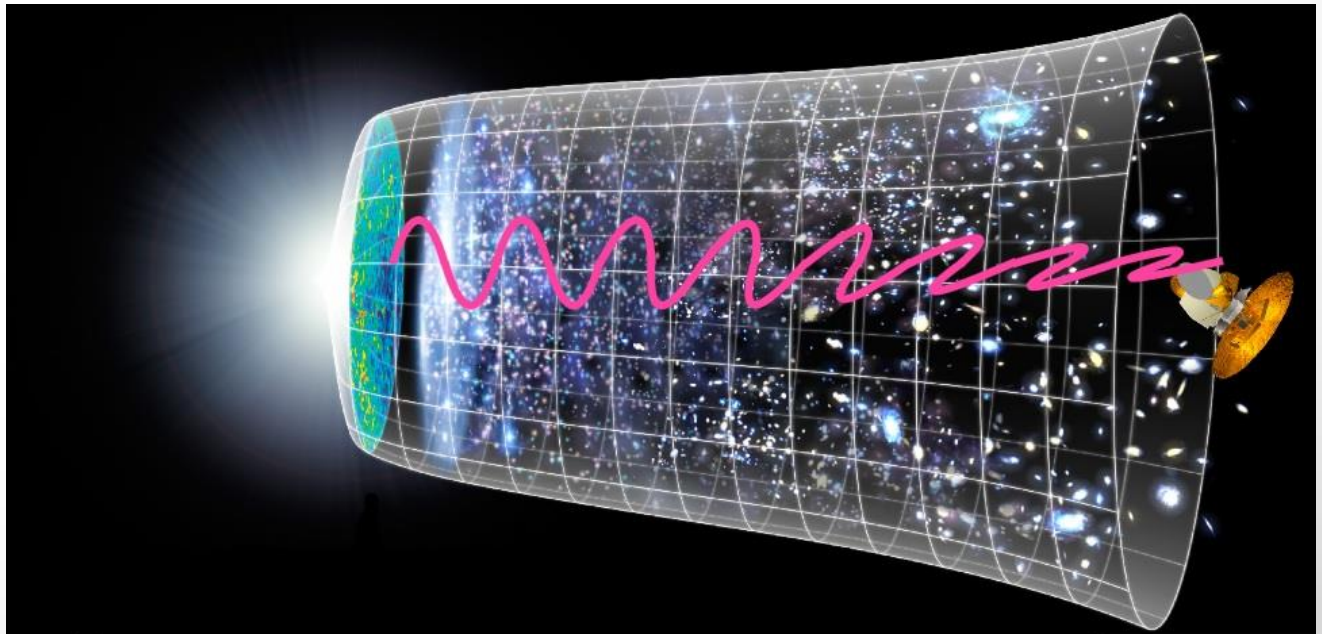
Extending this idea to cosmology:

Instead of a birefringent material, space itself—or rather, the vacuum—can act like a birefringent medium under certain exotic physical conditions.

- ***In cosmology, we consider a cosmic birefringence, where the plane of polarization of CMB photons rotates due to interactions with new physics — such as axion-like particles or violations of fundamental symmetries — during their journey across the universe, similar to how it would in a birefringent crystal.***





Stokes parameters:

- ***Consider a nearly monochromatic plane electromagnetic wave propogating in the z-direction***

$$E_x(t) = \varepsilon_x(t)\cos(\omega t - \delta_x) \qquad E_y(t) = \varepsilon_y(t)\cos(\omega t - \delta_y),$$

- ***Stokes parameters are defined as the following time averages:***

$$I \equiv I_0 + I_{90} = \langle \varepsilon_x^2 \rangle + \langle \varepsilon_y^2 \rangle,$$

$$Q \equiv I_0 - I_{90} = \langle \varepsilon_x^2 \rangle - \langle \varepsilon_y^2 \rangle,$$

$$U \equiv I_{-45} - I_{+45} = \langle 2\varepsilon_x \varepsilon_y \cos(\delta_x - \delta_y) \rangle,$$

$$V \equiv I_{LCP} - I_{RCP} = \langle 2\varepsilon_x \varepsilon_y \sin(\delta_x - \delta_y) \rangle.$$

Polarization fraction:

$$P = \frac{\sqrt{Q^2 + U^2 + V^2}}{I}$$

❖ ***The parameters I and V are physical observables independent of the coordinate system.***

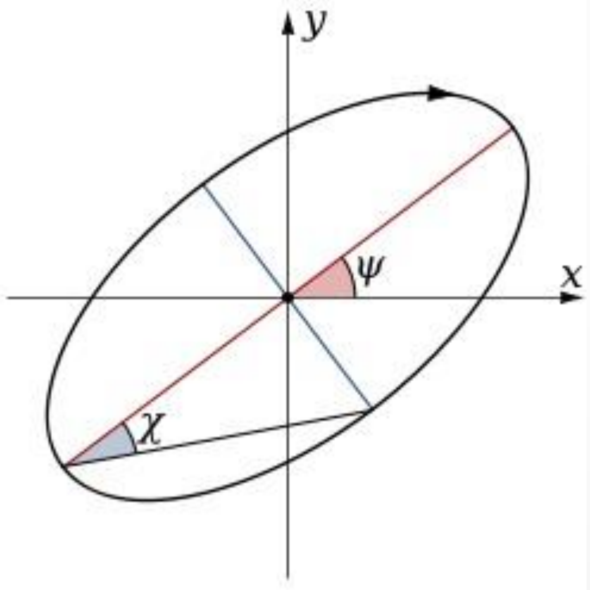
❖ ***The parameters Q and U depend on the coordinate system.***

$$I \equiv \langle \varepsilon_x^2 \rangle + \langle \varepsilon_y^2 \rangle = \varepsilon_0^2,$$

$$Q \equiv \langle \varepsilon_x^2 \rangle - \langle \varepsilon_y^2 \rangle = \varepsilon_0^2 \cos 2\chi \cos 2\psi,$$

$$U \equiv \langle 2\varepsilon_x \varepsilon_y \cos(\delta_x - \delta_y) \rangle = \varepsilon_0^2 \cos 2\chi \sin 2\psi,$$

$$V \equiv \langle 2\varepsilon_x \varepsilon_y \sin(\delta_x - \delta_y) \rangle = \varepsilon_0^2 \sin 2\chi,$$



- ***It is useful to introduce two scalar quantities E(n) and B(n) defined as***

$$\tilde{E}(\hat{n}) \equiv \frac{1}{2}\left[\bar{\eth}^2(Q+iU)+\eth^2(Q-iU)\right] = \sum_{lm}\left[\frac{(l+2)!}{(l-2)!}\right]^{\frac{1}{2}} a_{E,lm}\, Y_{lm}(\hat{n}),$$

$$\tilde{B}(\hat{n}) \equiv \frac{i}{2}\left[\bar{\eth}^2(Q+iU)-\eth^2(Q-iU)\right] = \sum_{lm}\left[\frac{(l+2)!}{(l-2)!}\right]^{\frac{1}{2}} a_{B,lm}\, Y_{lm}(\hat{n}).$$

where

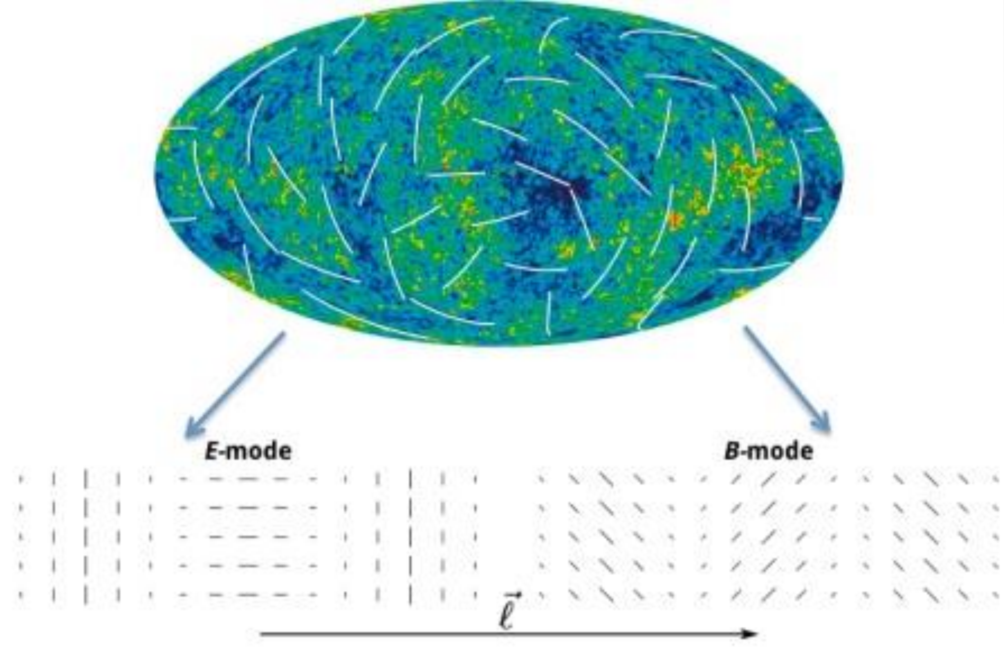
$$\eth\ {}_sf(\theta,\phi) = -\sin^s(\theta)\left[\frac{\partial}{\partial\theta}+i\csc(\theta)\frac{\partial}{\partial\phi}\right]\sin^{-s}(\theta)\ {}_sf(\theta,\phi)$$

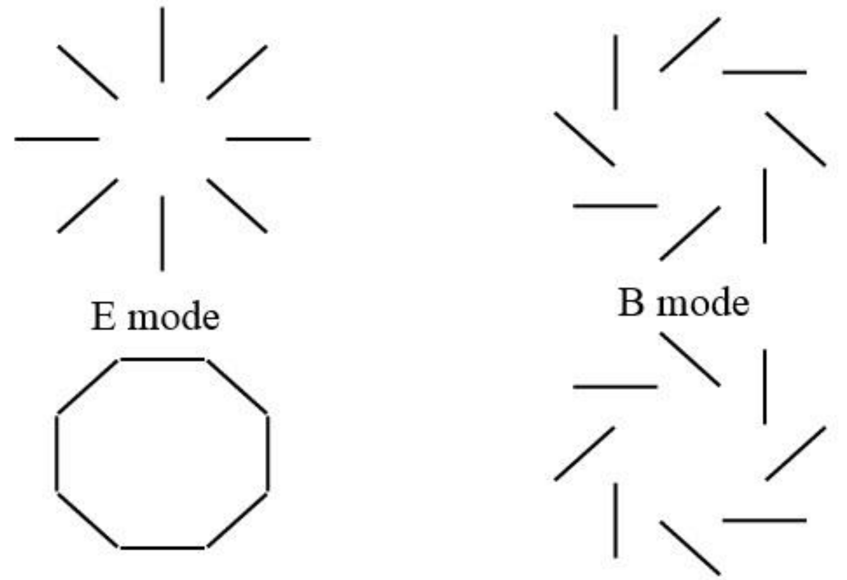
$$\bar{\eth}\ {}_sf(\theta,\phi) = -\sin^{-s}(\theta)\left[\frac{\partial}{\partial\theta}-i\csc(\theta)\frac{\partial}{\partial\phi}\right]\sin^{s}(\theta)\ {}_sf(\theta,\phi)$$

- ***The Stokes parameters Q and U are transformed into E-mode (even-parity, gradient-like) and B-mode (odd-parity, curl-like) components using spin-weighted spherical harmonics:***

$$(Q \pm iU)(\hat{n}) = \sum_{\ell m} a_{\ell m}^{\pm 2}\ {}_{\pm 2}Y_{\ell m}(\hat{n})$$

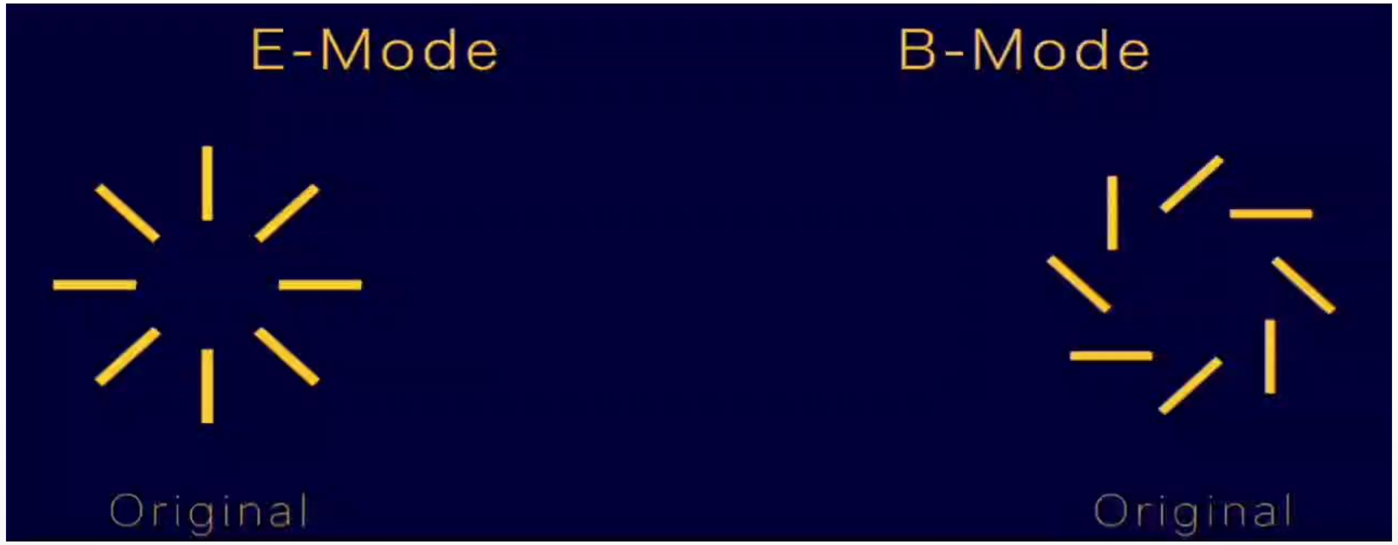
$$E_{\ell m} = -\frac{1}{2}\left(a_{\ell m}^{2} + a_{\ell m}^{-2}\right), \quad B_{\ell m} = \frac{i}{2}\left(a_{\ell m}^{2} - a_{\ell m}^{-2}\right)$$





✓*E mode*: ***Polarization directions*** ***parallel*** ***or*** ***perpendicular*** ***to the wave vector.***

✓*B mode*: ***Polarization directions*** ***45 degree*** ***with the respect to the wave vector.***



❖ *If there are physical effects that cause a rotation in the polarization plane of CMB photons as they propagate through space, then this rotation alters the Stokes parameters Q and U as follows:*

$$(Q \pm iU)' = (Q \pm iU)e^{\mp 2i\alpha}$$

❖ *This transformation mixes the two fundamental modes of CMB polarization, the E- and B-modes:*

$$E' = E\cos(2\alpha) - B\sin(2\alpha)$$
$$B' = B\cos(2\alpha) + E\sin(2\alpha)$$

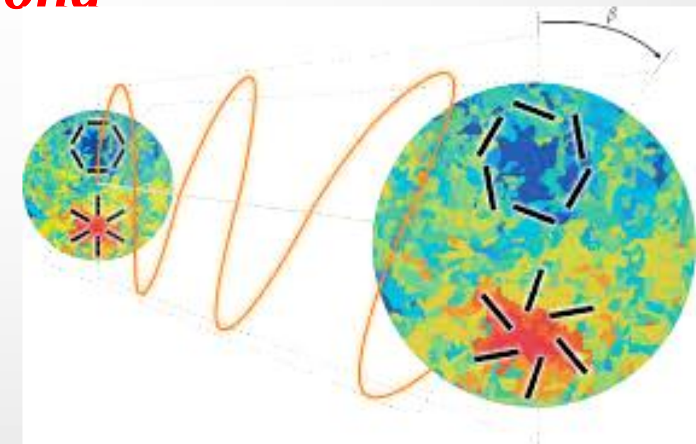
❖ *If the primordial B-modes are very small or zero, a nonzero α will induce B-modes from existing E-modes.*

SM does not contain any known mechanism that can produce this kind of vacuum-induced polarization rotation.

If we detect a nonzero α, it would be a compelling indication of new physics beyond the Standard Model."

❖ *The latest reported value for the rotation angle of the CMB polarization is*

$$\alpha = 0.342^{+0.094}_{-0.091}\ \text{deg} \quad (3.6\sigma)$$



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Observational Signatures via TB and EB Spectra:

- *The CMB sky can be thought of as a random field of fluctuations in temperature and polarization across different directions.*

  - *Observations show that the temperature fluctuations follow a Gaussian (normal) distribution.*
  - *This means the entire statistical behavior can be described by just the mean and the variance.*
  - *Variance measures the spread of temperature values around the mean:*

$$\sigma^2 = \langle (T - \bar{T})^2 \rangle$$

  - *For a Gaussian field like the CMB, variance contains most of the statistical information.*
  - *However, we need more than one variance value to understand different scales.*

CMB fluctuations occur on various angular scales:
→ *Large scales (low multipole ℓ): broad patterns*
→ *Small scales (high ℓ): fine structures*

We need a tool that describes how fluctuations vary with angular size.

The angular power spectrum, C_l, quantifies variance per angular scale ℓ.

- ***The CMB power spectrum quantifies temperature and polarization anisotropies in the CMB as a function of angular scale.***
  - ***It describes how temperature (or polarization) fluctuations vary with scale across the sky.***
  - ***The power spectrum C_l tells us how much variance (or "power") exists at each angular scale l.***

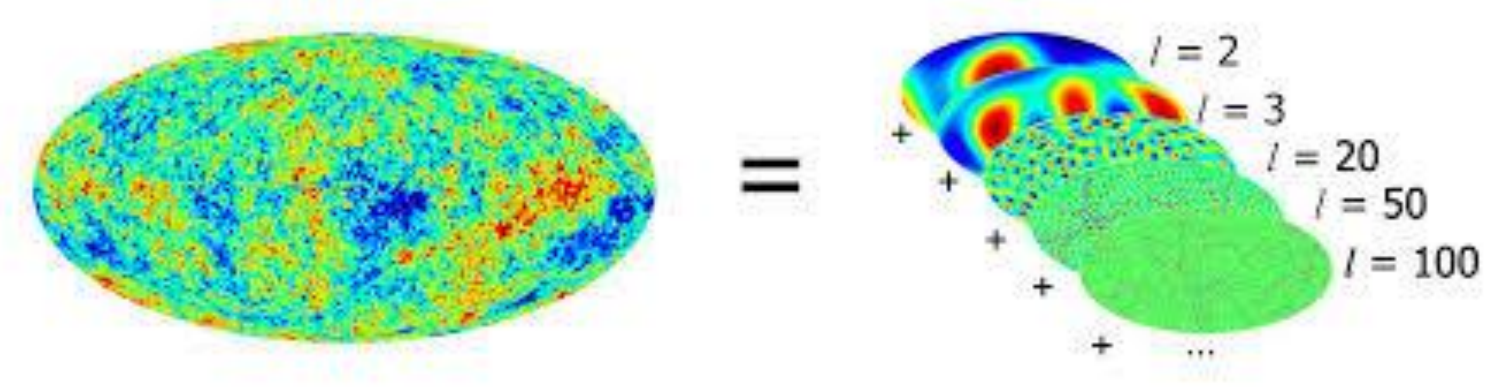
- ***In order to understand how to get to the CMB power spectrum from our computed quantities, let us first recall the definition of the spherical harmonics transform of the CMB temperature field,***

$$\Delta T(\hat{n}) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\hat{n})$$

direction on the sky — $\hat{n}$

spherical harmonics coefficients — $a_{\ell m}$

spherical harmonics — $Y_{\ell m}(\hat{n})$



- ***Because of the physical coherence, the temperature at point A on the sky tells us something about the temperature at point B-This correlation is captured mathematically by the two-point correlation function:***

$$\langle \Delta T(\hat{n}) \Delta T(\hat{n}') \rangle$$

$$C_\ell \equiv \langle |a_{\ell m}|^2 \rangle = \langle a_{\ell m} a^*_{\ell m} \rangle$$

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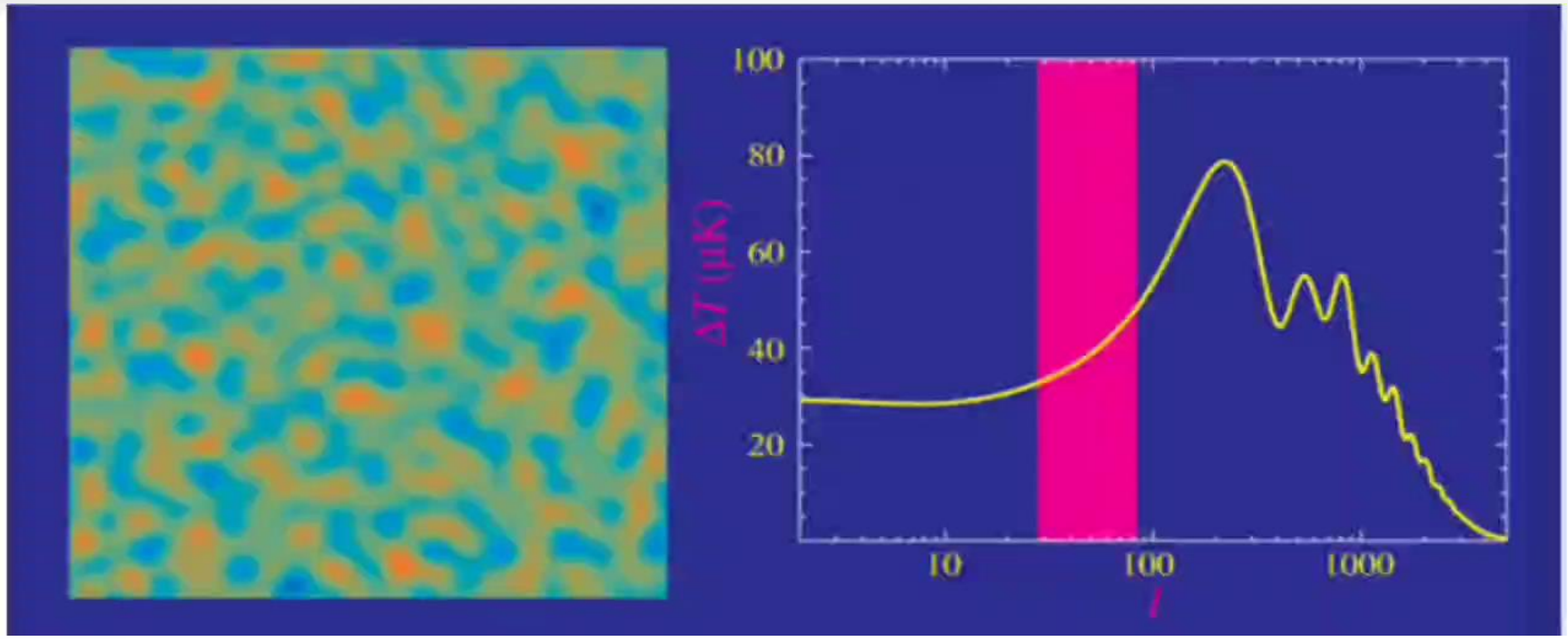


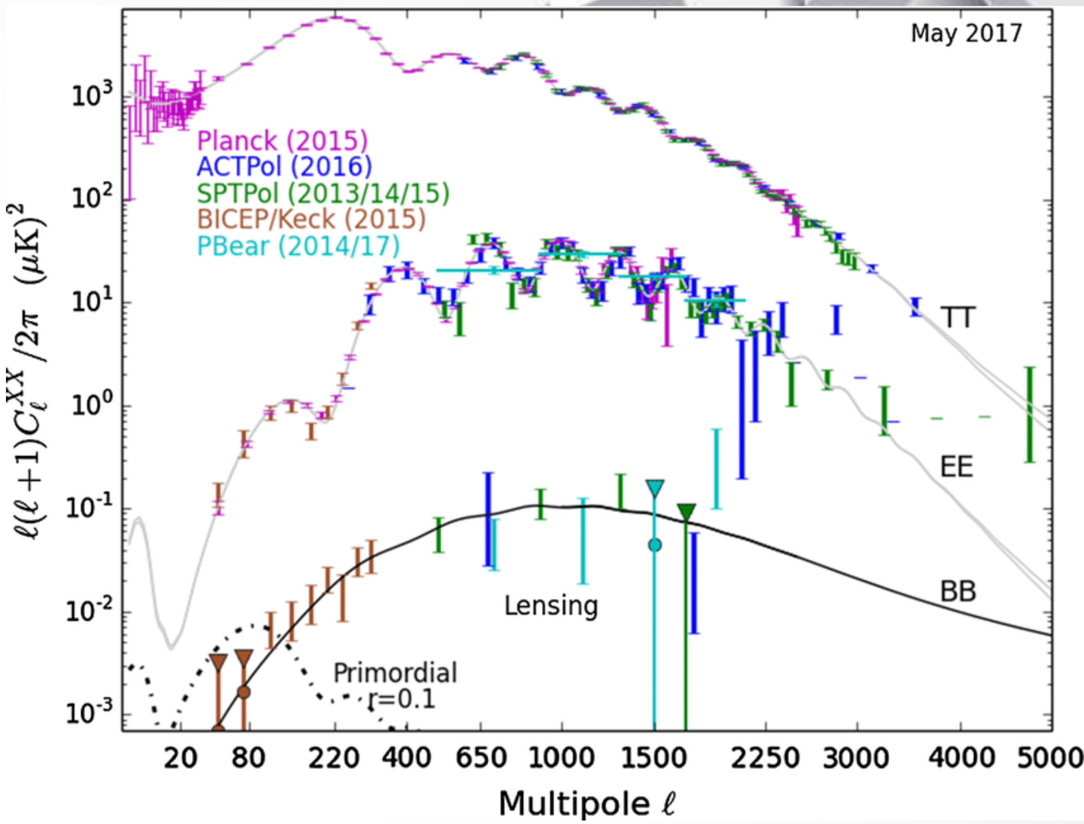
Peaks in the power spectrum reflect acoustic oscillations in the early plasma.
The height and position of these peaks tell us about:

- *→ Total matter and baryon density*
- *→ Dark matter and dark energy content*
- *→ Geometry and curvature of the Universe*

Comparison with theory allows precision cosmology.

In CMB analysis, we compute the power spectrum between different types of CMB fields:

- ✓ C_l^{TT}: *temperature auto-correlation*
- ✓ C_l^{TE}: *temperature-E-mode cross-correlation*
- ✓ C_l^{EE}: *E-mode auto-correlation*
- ✓ C_l^{BB}: *B-mode auto-correlation*
- ✓ C_l^{TB} , C_l^{EB} : *cross-correlations involving B-modes*



Parity Symmetry and Expectations Without Birefringence

- ➤ ***E-modes are parity-even**: they don't change sign under spatial inversion.*
- ➤ ***B-modes are parity-odd**: they do change sign.*

❖ *Under parity conservation, the cross-correlations C_l^{TB} , C_l^{EB} must vanish:*

$$C_\ell^{TB} = 0, \quad C_\ell^{EB} = 0$$

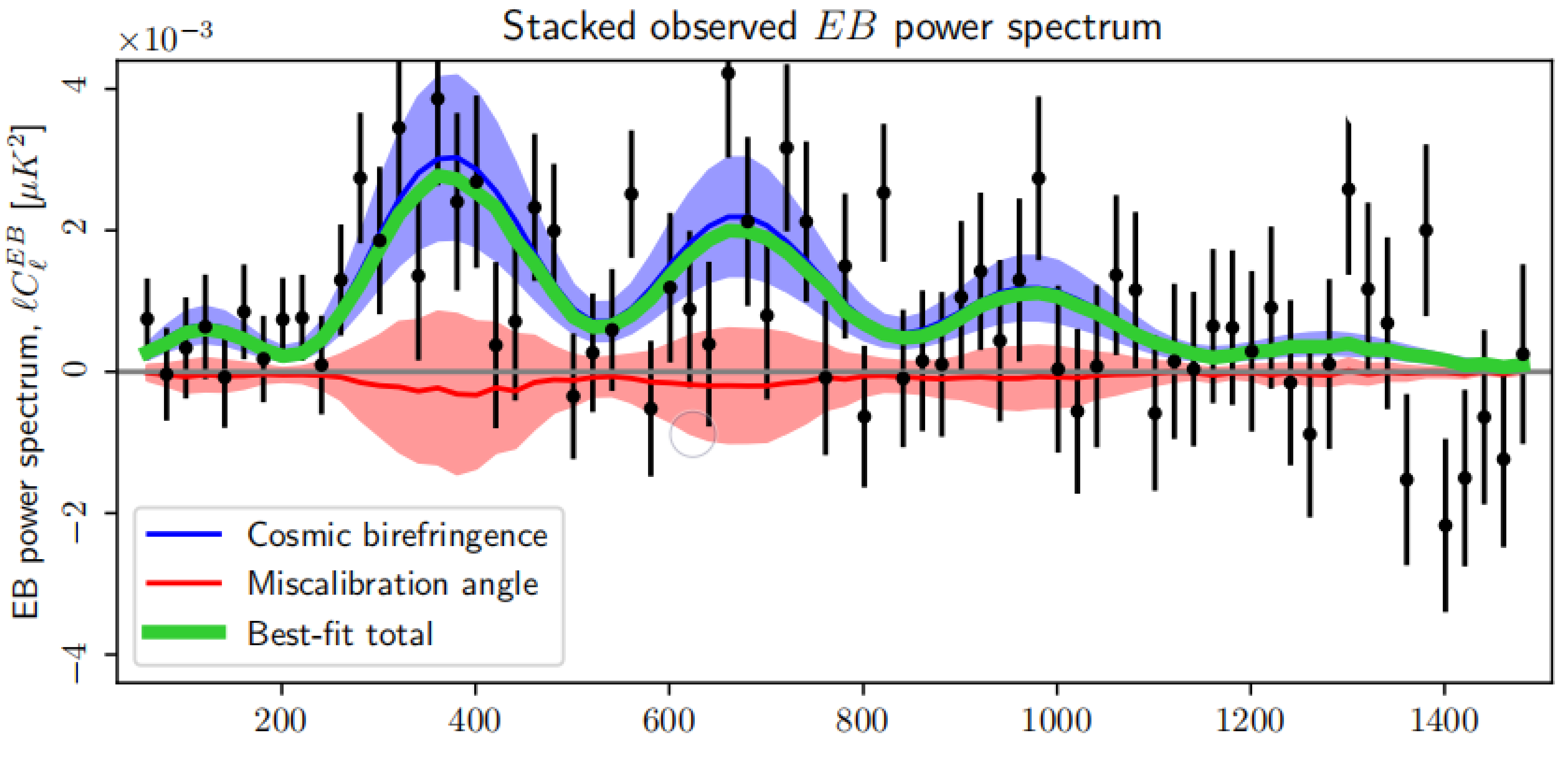
This is because a parity-even field (like E or T) cannot correlate with a parity-odd field (like B) unless parity is broken.

➢ ***Cosmic birefringence induces a small rotation α in the polarization direction as CMB photons travel through space. This rotates the Q and U parameters and leads to:***

- ***Mixing of E- and B-modes.***

- ***Creation of new non-zero TB and EB spectra, even if there were no primordial B-modes!***

$$C_\ell^{TB} = C_\ell^{TE}\sin(2\alpha)$$
$$C_\ell^{EB} = \frac{1}{2}(C_\ell^{EE} - C_\ell^{BB})\sin(4\alpha)$$



$$\alpha = 0.342^{+0.094}_{-0.091}\ \text{deg} \quad (3.6\sigma)$$

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Dipolar DM

Dipolar DM model proposes that DM particles carry intrinsic electric and/or magnetic dipole moments, enabling their interaction with photons via higher-dimensional operators.

- ***If Dark matter is Dirac particle***

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

where

$$\sigma^{\mu\nu} = \frac{i}{2}[\gamma^\mu, \gamma^\nu]$$

Magnetic dipole Moment
Electric dipole Moment
Electromagnetic field

- ***If Dark matter is Majorana particle***

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

Transition magnetic moment
Transition electric moment

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Jafar Khodagholizadeh, S. Mahmoudi, Rohoollah Mohammadi, Mahdi Sadegh, Phys. Rev. D 108, no.2, 023023 (2023)

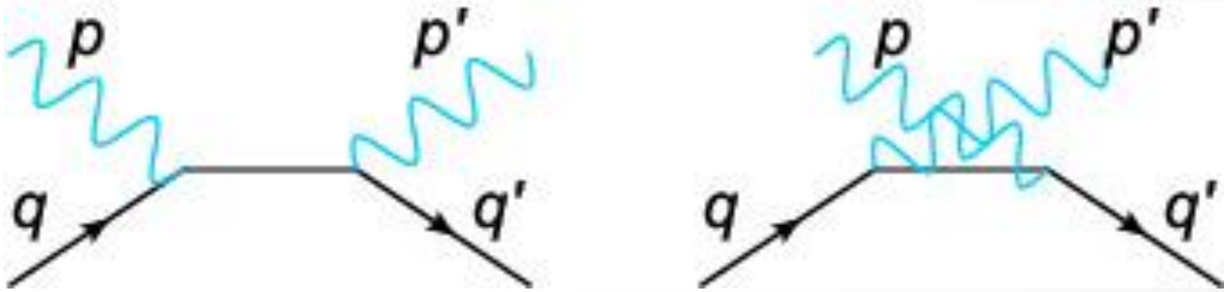
Cosmic Birefringence as a probe of the nature of DM:

$$H_I(t) = -M^2 \int d^4x' \int d^3\mathbf{x}\ \bar{\psi}^-(x)\sigma^{\mu\nu}S_F(x-x')\sigma^{\alpha\beta}(\partial_\mu A_\nu^-(x)\partial_\alpha A_\beta^+(x') + \partial_\alpha A_\beta^-(x')\partial_\mu A_\nu^+(x))\psi^+(x')$$

$$A_\mu(x) = \int \frac{d^3\mathbf{p}}{(2\pi)^3 2p^0} \sum_s [a_s(p)\epsilon_{s\mu}(p)e^{-ip.x} + a_s^\dagger(p)\epsilon_{s\mu}^*(p)e^{ip.x}],$$

$$\psi(x) = \int \frac{d^3\mathbf{q}}{(2\pi)^3}\frac{m}{q^0} \sum_r [b_r(q)\,u_r(q)e^{-iq.x} + d_r^\dagger(q)\,v_r(q)e^{iq.x}],$$

$$S_F(x) = \int \frac{d^4k}{(2\pi)^4}\frac{\not{k}+m}{k^2-m^2+i\theta}e^{-ik.x},$$



Using the Boltzmann Equation:

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

$$\frac{dI}{dt} = C_{e\gamma}^I,$$

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

$$\frac{dV}{dt} = C_{e\gamma}^V,$$

where

$$\dot{\tau}_{\rm DM} = \frac{3}{8\pi}\left(\frac{m_e}{\alpha}\right)^2\sigma_T\,M^2\ n_{\rm DM},$$

Jafar Khodagholizadeh, S. Mahmoudi, Rohoollah Mohammadi, Mahdi Sadegh, Phys. Rev. D 108, no.2, 023023 (2023)

Cosmic Birefringence as a probe of the nature of DM:

Photon-dipolar DM forward scattering affects the time evolution of the linear polarization of the CMB:

$$\frac{d}{d\eta}\Delta_{\mathrm{P}}^{\pm\mathrm{S}} + iK\mu\Delta_{\mathrm{P}}^{\pm\mathrm{S}} = \dot{\tau}_{\mathrm{e}}\left[-\Delta_{\mathrm{P}}^{\pm\mathrm{S}} - \frac{1}{2}[1 - P_2(\mu)]\Pi\right] \mp ia(\eta)\dot{\tau}_{\mathrm{DM}}\Delta_{\mathrm{P}}^{\pm\mathrm{S}},$$

After calculation of $\Delta_P^{\pm}$

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

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

and then

$$\Delta_{\mathrm{E}}^{\mathrm{S}}(\eta_0, K, \mu) = -\frac{3}{4}\int_0^{\eta_0} d\eta\, g_{\mathrm{e}}(\eta)\Pi(\eta, K)\partial_\mu^2[(1 - \mu^2)e^{ix\mu}\cos\tau_{\mathrm{DM}}],$$

$$\Delta_{\mathrm{B}}^{\mathrm{S}}(\eta_0, K, \mu) = \frac{3}{4}\int_0^{\eta_0} d\eta\, g_{\mathrm{e}}(\eta)\Pi(\eta, K)\partial_\mu^2[(1 - \mu^2)e^{ix\mu}\sin\tau_{\mathrm{DM}}],$$

Finally

$$C_{E,B}^{\ell\,(S)} = \frac{1}{2\ell + 1}\frac{(\ell - 2)!}{(\ell + 2)!}\int d^3\mathbf{K}P_S(\mathbf{K})\left|\sum_m \int d\Omega\, Y_{lm}^*(\hat{\mathbf{n}})\Delta_{E,B}^S(\eta_0, K, \mu)\right|^2.$$

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Jafar Khodagholizadeh, S. Mahmoudi, Rohoollah Mohammadi, Mahdi Sadegh, Phys. Rev. D 108, no.2, 023023 (2023)

Cosmic Birefringence as a probe of the nature of DM:

$$C^{(\mathrm{S})}_{EE,\ell}\Big|_{\mathrm{DM}} = (4\pi)^2 \frac{(\ell+2)!}{(\ell-2)!} \int d^3K P_S(K) \left[\frac{3}{4}\int_0^{\eta_0} d\eta\, g_e(\eta)\, \Pi(K,\eta)\, \frac{j_\ell(x)}{x^2} \cos(\tau_{DM})\right]^2,$$

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

$$C^{(\mathrm{S})}_{EB,\ell}\Big|_{\mathrm{DM}} = \frac{(4\pi)^2}{4} \frac{(\ell+2)!}{(\ell-2)!} \int d^3K P_S(K) \left[\frac{3}{4}\int_0^{\eta_0} d\eta\, g_e(\eta)\, \Pi(K,\eta)\, \frac{j_\ell(x)}{x^2} \sin(2\tau_{DM})\right]^2.$$

Tese relations can be approximated as follows

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

Therefore,

$$\alpha \approx \frac{1}{2}\tilde{\tau}_{DM},$$ ***where*** $$\dot{\tau}_{\mathrm{DM}} = \frac{3}{8\pi}\left(\frac{m_e}{\alpha}\right)^2 \sigma_T M^2\, n_{\mathrm{DM}}$$

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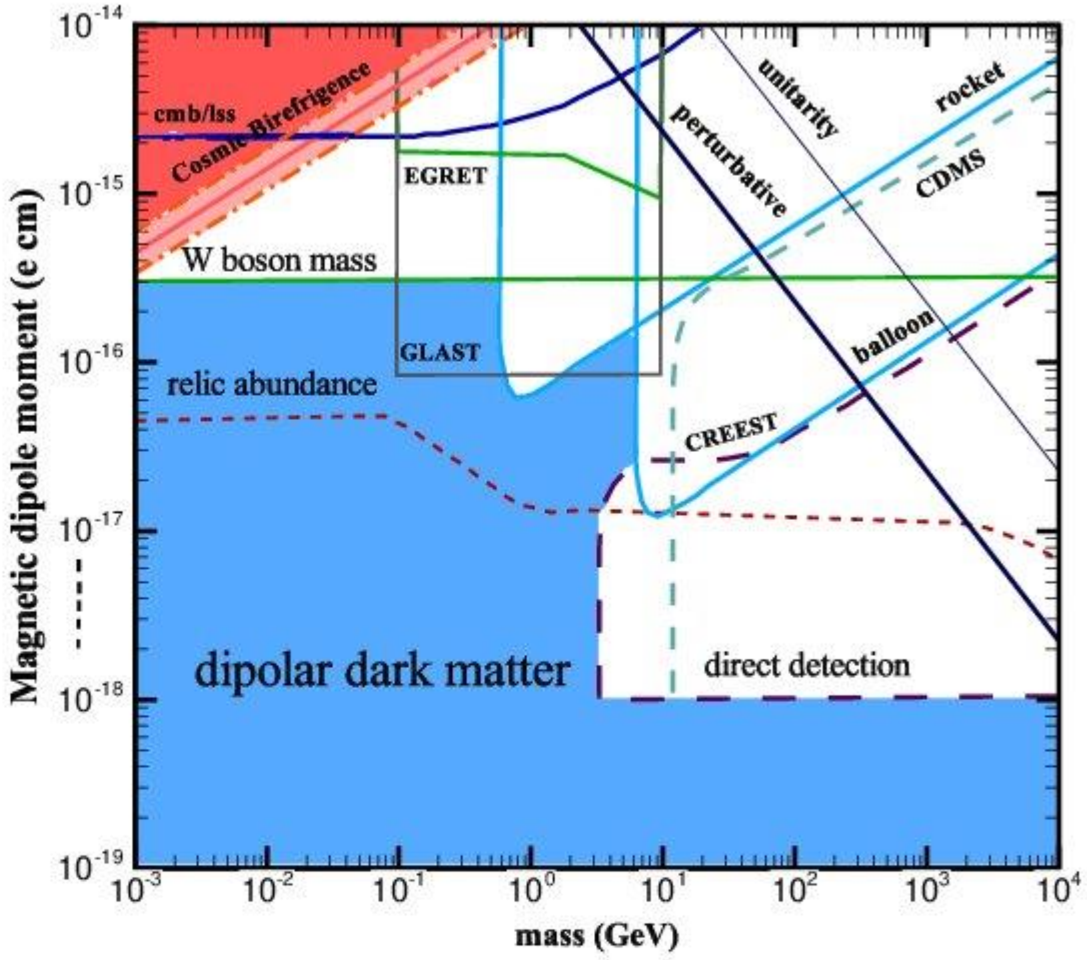

- ***Our calculations put a bound on the Majorana magnetic dipole moment about***

$$\mathcal{M} \leqslant 1.4 \times 10^{-14} \frac{\beta}{0.34^\circ} \sqrt{\frac{m_{\rm DM}}{1\,GeV}}\, e.\,\rm cm$$

- ***Constraints obtained on Majorana dipolar DM, including the constraints that come from the direct detection experiments, study DM particles whose mass is around GeV or higher, while the constraint that we obtain here is regarding the sub-GeV DM particles.***

- ***Although an experiment like W boson mass excludes the sub-GeV Dirac dipolar DM with a magnetic moment larger than $7 \times 10^{-16} ecm$, part of this region will be accessible for Majorana dipolar DM based on the CB effect of the CMB.***

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Sterile neutrino DM

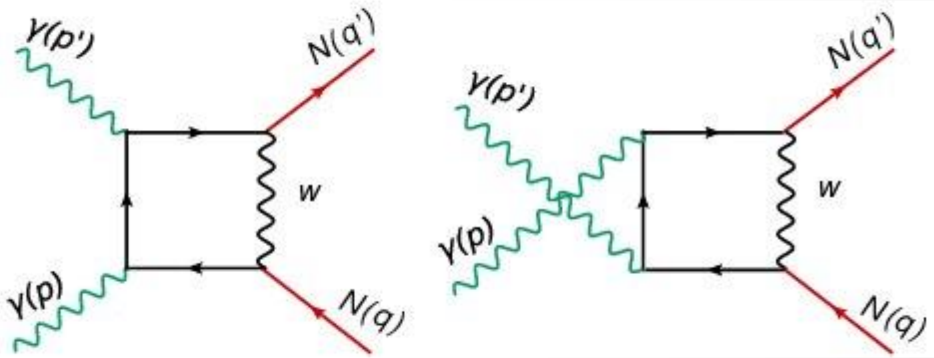
In type-I seesaw model the SM is extended by at least two heavy Sterile neutrino singlets ν_R^i

$$\mathcal{L} = \mathcal{L}_{\rm SM} + y^{\nu}_{ij}\bar{\ell}^i_{\rm L}\tilde{H}\nu^j_{\rm R} + \frac{1}{2}M^i_{\rm R}\bar{\nu}^{ic}_{\rm R}\nu^i_{\rm R} + h.c.$$

$$M_\nu = \begin{bmatrix} 0 & m_D \\ m_D^T & M_R \end{bmatrix}$$

$$N = V_{\rm N}^{\dagger}\nu_{\rm R} + \Theta^{\rm T}\nu^c_{\rm L} + h.c.\ , \quad \text{and} \quad \nu = V_\nu^{\dagger}\nu_{\rm L} - U_\nu^{\dagger}\theta\nu^c_{\rm R} + h.c.\ ,$$

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



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

$$\mathcal{M}_{tot} \equiv \mathcal{M}_1(\mathbf{q}'r', \mathbf{p}'s', \mathbf{q}r, \mathbf{p}s)$$
$$+ \mathcal{M}_2(\mathbf{q}'r', \mathbf{p}'s', \mathbf{q}r, \mathbf{p}s)$$
$$- \mathcal{M}_3(\mathbf{q}'r', \mathbf{p}'s', \mathbf{q}r, \mathbf{p}s)$$
$$- \mathcal{M}_4(\mathbf{q}'r', \mathbf{p}'s', \mathbf{q}r, \mathbf{p}s),$$

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Cosmic Birefringence as a probe of the nature of DM:

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

$$\frac{dI}{dt} = C_{e\gamma}^I,$$

$$\frac{d}{dt}\Delta_P^{\pm} = C_{e\gamma}^{\pm} \mp i\dot{\eta}_{\rm DM}^{\rm P}\Delta_P^{\pm} + \mathcal{O}(V),$$

$$\dot{\eta}_{\rm DM}^{\rm P} = \frac{\sqrt{2}}{3\pi p^0\, M}\,\alpha\, G_{\rm F}\,\theta^2 \int d\mathbf{q}\, f_{\rm DM}(\mathbf{x},\mathbf{q}) \times (\varepsilon_{\mu\,\nu\,\rho\,\sigma}\epsilon_2^{\mu}\,\epsilon_1^{\nu}\,p^{\rho}\,q^{\sigma})$$

$$\frac{dV}{dt} = C_{e\gamma}^V + \frac{1}{2}\left(\dot{\eta}_{\rm DM}^{\rm C-}\Delta_P^{+} + \dot{\eta}_{\rm DM}^{\rm C+}\Delta_P^{-}\right),$$

$$\dot{\eta}_{\rm DM}^{\rm C\pm} = \frac{\sqrt{2}}{3\pi p^0\, M}\,\alpha\, G_{\rm F}\,\theta^2 \int d\mathbf{q}\, f_{\rm DM}(\mathbf{x},\mathbf{q})\Big[(-\,q\cdot\epsilon_1\,q\cdot\epsilon_2 - q\cdot\epsilon_2\,q\cdot\epsilon_1) \pm i(q\cdot\epsilon_1\,q\cdot\epsilon_1\; - q\cdot\epsilon_2\,q\cdot\epsilon_2)\Big],$$

where $\Delta_P^{\pm} = Q \pm i\,U$

❖ ***CB angle of the CMB due to the interaction with the sterile neutrinos can be approximated as***

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

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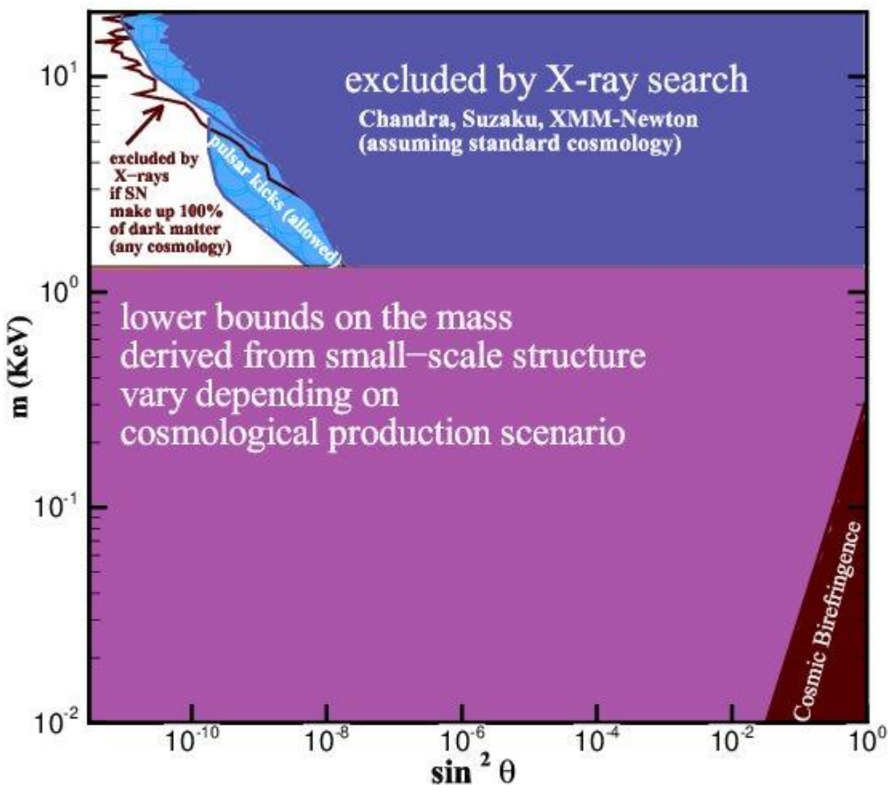

- ***One of the most important issues of sterile neutrinos is to address the question of how they have been produced in the early universe.***
- ***Sterile neutrinos can be produced by neutrino oscillation in the primordial plasma via a tiny active-sterile neutrino mixing angle θ, as first described by Dodelson and Widrow (DW).***
- ***More complex mechanisms for the production of DM, such as the Shi-Fuller mechanism which describes resonant oscillation production or other non-thermal production mechanisms including the decay of an extra-singlet scalar have been proposed.***

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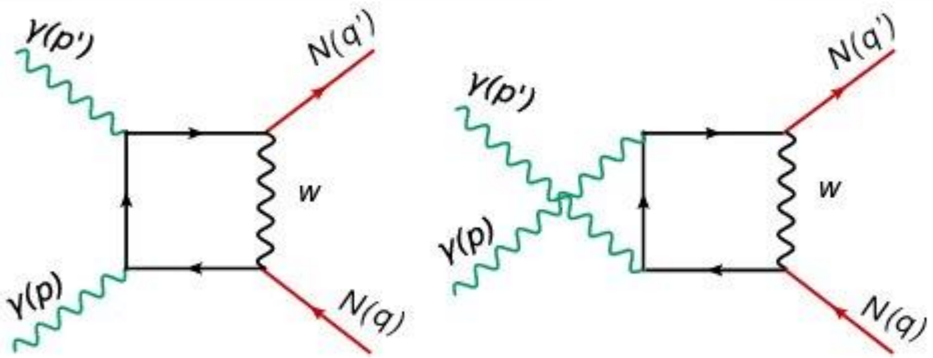
Cosmic Birefringence as a probe of the nature of DM:

Cosmic Neutrino Interactions with SM Gauge Bosons:



- *we consider a primordial asymmetry (δ_ν) between the number densities of cosmic neutrinos and antineutrinos.*
- *Such an asymmetry can be generated by mechanisms like leptogenesis*

➢ *The CB angle of the CMB due to the interaction with the cosmic neutrinos can be obtained as*

$$\beta^\nu = \frac{1}{2}\tilde{\tau}_\nu \simeq 1.717\ \delta_\nu rad \equiv 98.38\delta_\nu\, degree,$$

which results in an upper bound over $\delta_\nu < 3 \times 10^{-3}$ to consistent with $\beta = 0.342^{\circ}{}^{+0.094^\circ}_{-0.091^\circ}$ (68%C.L.).

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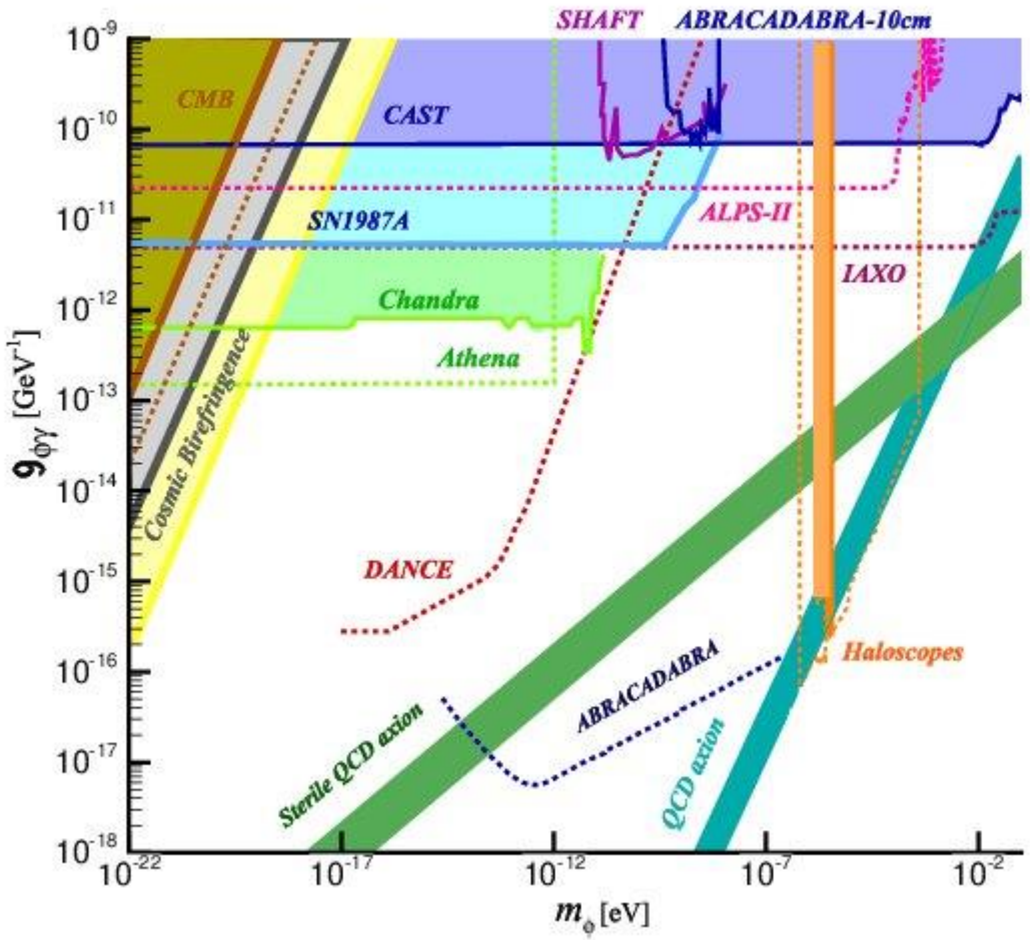
- ***By combining the results of cosmic neutrinos and ALPs:***

$$\beta^{ob} = \beta_\nu + \beta_a,$$

Choosing $\mathbf{0.0001 < \delta_\nu < 0.0029}$, we get

$$\beta_a^{min} = \beta^{ob} - \beta_\nu(\delta_\nu = 0.0029) = 0.000248206\, rad$$
$$\beta_a^{max} = \beta^{ob} - \beta_\nu(\delta_\nu = 0.0001) = 0.005058214\, rad.$$



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Thank You for Your Attention

Questions are welcome.

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