Abstract: Cosmic Microwave Background (CMB) is a powerful probe to the Universe which carries signatures of cosmic secrets over a vast range of redshifts. Along with spatial fluctuations, spectral distortions of CMB blackbody are also a rich source of cosmological information. In my talk, I will introduce a new kind of spectral distortion of CMB which can arise due to the conversion of CMB photons into Axion-Like Particles (ALPs) in the presence of an external magnetic field. This effect leads to both polarized and unpolarized spatially varying spectral distortion signal with a unique spectral shape when CMB photons undergo resonant and non-resonant conversion into ALPs in the presence of the magnetic field of Milky Way, galaxy clusters and voids. I will discuss the spatial structure of this distortion which can arise from Milky Way and galaxy clusters and will show its uniqueness from other known cosmological and astrophysical signals. I will present the first all-sky map of this distortion which is obtained using the data of Planck satellite and will discuss the capability of this new cosmological window to probe ALPs from the upcoming ground-based and space-based CMB experiments such as CMB-S4, LiteBIRD, Simons Observatory, etc."
A new probe to axion-like particles from upcoming CMB experiments

Suvodip Mukherjee
Lagrange Postdoctoral Fellow
IAP, Paris

Perimeter Institute
Observational Probes

Fundamental forces

The Standard Model of Cosmology

Figure courtesy: ESO
My research interest

Develop connections between cosmological probes and fundamental physics

Fundamental particles

Dark Matter

Dark Energy

Theory of gravity
CMB Sky discovered in 1965
Blackbody with spatial fluctuations

Temperature

- Coie 1992
- WMAP 2003
- Planck 2013

Polarization

Non-Blackbody with (or without) spatial fluctuations

Chluba 1405.6938, Khatri & Sunyaev JCAP 09 (2012) 016

ALPs
Aspects of Spectral Distortions from ALPs

\[ \begin{array}{c}
\gamma \quad \text{Spin}=1 \\
\ldots \\
B_1 \\
\alpha \quad \text{Spin}=0
\end{array} \]
ALPs are also searched by particle physicists

Nature Physics (2017)
Signature from the Milky Way

Mukherjee, Khatri, Wandelt

JCAP 04 (2018) 045
Milky Way scenario

Photons

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Photon to ALPs in Milky Way

\[ I_{\gamma a} = \frac{\Delta I_{\nu}^{\gamma a}}{I_{\nu}} = \frac{I_{\nu}^{\text{obs}} - I_{\nu}}{I_{\nu}} = -P(\gamma \to a) \]
Photon to ALPs in Milky Way

\[ I^{\gamma a} = \frac{\Delta I^{\gamma a}_\nu}{I_\nu} \equiv \frac{I^{\text{obs}}_\nu - I_\nu}{I_\nu} = -P(\gamma \to a) \]
Photon to ALPs in Milky Way

\[ \mathcal{I}_{\gamma a} = \frac{\Delta I_{\nu}^{\gamma a}}{I_{\nu}} \equiv \frac{I_{\nu}^{\text{obs}} - I_{\nu}}{I_{\nu}} = -P(\gamma \rightarrow a) \]

\[
\begin{pmatrix}
\omega + \left( \begin{array}{ccc}
\Delta_e & \Delta_f & \Delta_{x}^{\gamma a} \\
\Delta_f & \Delta_e & \Delta_{y}^{\gamma a} \\
\Delta_{x}^{\gamma a} & \Delta_{y}^{\gamma a} & \Delta_{a}^{\gamma a}
\end{array} \right) + i \partial_z 
\end{pmatrix}
\begin{pmatrix}
A_x \\
A_y \\
a
\end{pmatrix} = 0,
\]

\[ \Delta_{\gamma a} \equiv \frac{g_{\gamma a} |B_T|}{2} \]

\[ \Delta_a \equiv -\frac{m_a^2}{2\omega} \]

\[ \Delta_e \equiv -\frac{m_e^2}{2\omega} \]
Two kinds of conversion

**Resonance conversion**
Happen at places where ALPs mass equals photon mass in the plasma

**Non-Resonance conversion**
Happens throughout the line of sight
Non-Resonant Conversion
Photon to ALPs in Milky Way

\[ I_{\gamma a} = \frac{\Delta I_{\gamma a}^{\text{obs}}}{I_{\gamma}} \equiv \frac{I_{\nu}^{\text{obs}} - I_{\nu}}{I_{\nu}} = -P(\gamma \rightarrow a) \]
\[ I_{\gamma} = \frac{\Delta I_{\gamma}^{\gamma a}}{I_{\gamma}} = \frac{I_{\nu}^{\mathrm{obs}} - I_{\nu}}{I_{\nu}} = -P(\gamma \rightarrow a) \]

\[
\begin{pmatrix}
\omega + \begin{pmatrix}
\Delta e \\
\Delta f \\
\Delta x_{\gamma a} \\
\Delta y_{\gamma a} \\
\Delta a
\end{pmatrix} + i\partial_z
\end{pmatrix}
\begin{pmatrix}
A_x \\
A_y
\end{pmatrix} = 0,
\]

\[
\begin{pmatrix}
\frac{\Delta_{xy}^{\gamma a}}{(\text{Mpc}^{-1})} \\
\Delta_{z}^{\gamma a}
\end{pmatrix}
\approx \frac{g_{\alpha}|B_{xy}|}{2} = 15.2 \left( \frac{B_{xy}}{10^{-11}\text{G}} \right) \left( \frac{E_{\gamma}}{1\text{GeV}} \right),
\]

\[
\begin{pmatrix}
\frac{\Delta_{z}^{\gamma a}}{(\text{Mpc}^{-1})}
\end{pmatrix}
\approx -\frac{m_e^2}{2\nu} = -1.9 \times 10^4 \left( \frac{m_e}{10^{-11}\text{eV}} \right) \left( \frac{100\text{ GHz}}{\nu} \right),
\]

\[
\begin{pmatrix}
\Delta_{z}^{\gamma a}
\end{pmatrix}
\approx \frac{\omega_{\nu}^2}{2\nu}
\end{pmatrix}
\left[-1 + 7.3 \times 10^{-3} n_{\text{Hi}} \left( \frac{\omega}{\text{eV}} \right)^2 \right]
\]

\[
\approx -2.6 \times 10^6 \left( \frac{n_e}{10^{-5}\text{cm}^{-3}} \right) \left( \frac{100\text{ GHz}}{\nu} \right) \times \left[1 - 7.3 \times 10^{-3} \left( \frac{n_e}{n_{\text{Hi}} \text{eV}} \right)^2 \right]
\]

**Electron density model:**
J.M.Cordes & T.J.W.Lazio
Gaensler et al.
arXiv0808.2550[astro-ph]

**Magnetic field model:**
Jansson & Farrar
Non-Resonant conversion from the random magnetic field

\[ P(\gamma \rightarrow a)(r) = \frac{1}{3} \left( 1 - e^{(-3P(\gamma \rightarrow a)r/2d_0)} \right) \quad r >> d_0 \]

A. Mirizzi, G. G. Raffelt, and P. D. Serpico
Phys. Rev. D, 72(2):023501

\[ P(\gamma \rightarrow a) \approx \frac{P(\gamma \rightarrow a)R}{2s} \approx \frac{\Delta_{sa}^2 R_s}{2} = 10^{-9} \left( \frac{g_{\gamma a}}{10^{-10} \text{ GeV}^{-1}} \right)^2 \left( \frac{B_T}{1 \text{ } \mu \text{G}} \right)^2 \left( \frac{R}{1000 \text{ pc}} \right) \left( \frac{s}{10^{-4} \text{ pc}} \right) \]
Resonant Conversion
Photon to ALPs in Milky Way

\[ I_{\gamma}^{a} = \frac{\Delta I_{\nu}^{a}}{I_{\nu}} \equiv \frac{I_{\nu}^{\text{obs}} - I_{\nu}}{I_{\nu}} = -P(\gamma \rightarrow a) \]
Resonant Conversion

ALPs mass: $5 \times 10^{-13}$ eV

Mukherjee, Khatri, Wandelt
JCAP 04 (2018) 045

Solved for 3 Million sky pixels at 150 GHz

Probability of conversion in log-scale
Resonant Conversion

ALPs mass: $5 \times 10^{-12}$ eV

Mukherjee, Khatri, Wandelt
JCAP 04 (2018) 045

Solved for 3 Million sky pixels at 150 GHz

-10 Probability of conversion in log-scale

22
Resonant Conversion

ALPs mass: $5 \times 10^{-13}$ eV

100 % Polarized signal
Spatially fluctuating a unique structure
What about other signals (contaminations)
Two new signals of spectral distortions
Resonant case
Resonant case

For $m_a = 5 \times 10^{-13}$ eV

$g_0^2$

Observational Probes

- PIXIE
- LiteBIRD
- CORE
- CAST
- SN1987A
- X-RAY
Extragalactic sources: Voids

Mukherjee, Khatri, Wandelt
JCAP 04 (2018) 045
Forecast for future CMB mission after marginalizing other contaminations

\[ A_{\nu^2} \]

From void for $m_a \leq 10^{-14} \text{eV}$

Observational Probes:
- PIXIE
- LiteBIRD
- CORE
- CAST
- SN1987A
- X-Ray
ALPs constraints from Simons Observatory and CMB-S4 using Galaxy Clusters

Mukherjee, Spergel, Khatri, Wandelt.
To be submitted
Electron density in galaxy clusters

$\text{Vikhlinin et al. 2006, Bartalucci et al. 2017}$
which ALP mass at which radius?

\[ m_a \times 10^{-14} \text{ eV} \]

radius (in kpc)
Signal profile with radius in galaxy cluster

Different colors indicate different redshifts: 0.1 (blue) to 2.0 (magenta)
Spatial shape of the distortion around a galaxy-cluster

Low mass

Signal from bigger radius

Medium mass

Signal from intermediate radius

High mass

Signal from smaller radius
A simplistic simulated sky map of ALPs signal around galaxy cluster
Model of the signal in the Sky

\[ S_{\nu_i}(\hat{p}) = A_{\nu_i j} x_j(\hat{p}) + n_{\nu_i}(\hat{p}), \]
\[ S(\hat{p}) = A x(\hat{p}) + n(\hat{p}), \]

We added simulated maps of synchrotron, dust, CMB over the ALPs signal at randomly selected cluster locations.

230 GHz: Dust map

28 GHz: Synchrotron map

Python Sky Model (PYSM) code
Thorne et al. (2018)
Model of the signal in the Sky

\[ S_{\nu_i}(\hat{p}) = A_{\nu_i j} x_j(\hat{p}) + n_{\nu_i}(\hat{p}), \]
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We added simulated maps of synchrotron, dust, CMB over the ALPs signal at randomly selected cluster locations.

230 GHz: Dust map

28 GHz: Synchrotron map

Then we clean the foregrounds using component separation method:
Internal Linear Combination (ILC)

\[ \hat{x}_{\gamma a}(\hat{p}) = \hat{W}_{\gamma a}^T S(\hat{p}), \]

\[ \hat{W}_{\gamma a}(\nu) = C_{\gamma a}^{-1} a_{\gamma a} (a_{\gamma a}^T C_{\gamma a}^{-1} a_{\gamma a})^{-1} \]

Python Sky Model (PYSM) code
Thorne et al. (2018)
Adding 1000 clusters

Q- polarization map
At different redshifts

This circle is only to guide the signal

Q-polarization maps
Detectability of the signal
ALP mass spatially resolved

![Graph showing the relationship between ALP mass and redshift for different arcmin resolutions](image)
Bound achievable from CMB Ground based experiments (after including foregrounds, CMB, instrument noise)
4.4 \times 10^3 \text{ Current Bound from CERN Axion Solar Telescope (CAST)}

Bound achievable from CMB Ground based experiments (after including foregrounds, CMB, instrument noise)
ALPs distortion map

Mukherjee, Khatri, Wandelt

arXiv:1811.11177

Using the Planck temperature data
(For the non-resonance case)

From Polarization data: In preparation
(For the resonance case)
\[ S_{\nu_i}(\hat{p}) = A_{\nu_i,j} x_j(\hat{p}) + n_{\nu_i}(\hat{p}), \]

\[ S(\hat{p}) = A x(\hat{p}) + n(\hat{p}), \]
Spectrum of the distortion in the Planck frequency bands

![Graph showing the spectrum of the distortion in Planck frequency bands.](image-url)
First all-sky constraints on Non-Resonant ALPs signal from Planck-data

\[ \hat{x}_{\gamma a}(\hat{p}) = \hat{W}_{\gamma a}^T S(\hat{p}), \]
First all-sky constraints on Non-Resonant ALPs signal from Planck-data
My research interest

Develop connections between cosmological probes and fundamental physics

Fundamental particles
Dark Matter
Dark Energy
Theory of gravity
Cosmology with redshift unknown supernovae

Mukherjee and Wandelt
arXiv:1808.06615

Upcoming surveys are going to measure

$10^4$-$10^5$ SN every year

These will primarily rely on photometric redshift measurements
Let us forget the underlying structure and concentrate only on one pair of galaxy-SN.
Identifying the host galaxy of the supernovae
Cross-correlation of galaxies and supernovae

Identifying the host galaxy of the supernovae

More galaxies!! What can we get from them
Cosmology with Gravitational Waves:
Going beyond standard sirens

Mukherjee, Wandelt, Silk
under review in
Nature-Astronomy

Image: LIGO collaboration
1607.08697

Image: LISA Science Proposal
Cosmology with GW

Standard Sirens: Distance Ladder

Schutz,
Nature, 323, 1986

Cosmic Density field

Luminosity Distance
Probing GW lensing using CMB-GW correlation

Mukherjee, Wandelt, Silk (2018)

BBH merger

Lensed CMB photons

Galaxy cluster

Geodesic in the absence of lensing

Lensed GW signal

Geodesic in the presence of lensing
Discovery space

Mukherjee, Wandelt, Silk (2018)

LISA

Cosmic Explorer
Diverse scientific scopes

• Concordant trajectory between electromagnetic waves and gravitational waves

• A probe to the theories of extra-dimensions of spacetime  
  (Deffayet & Menou 2007, LIGO-VIRGO Coll. (2018))

• A probe to the alternative theories of gravity
  (Saltas et al. 2014, Nishizawa 2018)
A Few New Frontiers in Cosmology

Simons Observatory
CMB-S4

LSST
EUCLID
DESI

adv-LIGO
LISA
Cosmic Explorer