Quantum Sensors for Fundamental Physics II
Dissecting Ultralight Bosons
with A Network of Sensors

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strong.
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Outlines

Dissecting Axion and

Dark Photon Background

Ultralight Bosons: $\Psi = a, B^{\mu}$ and $H^{\mu\nu}$

$$-\frac{1}{2}\nabla^{\mu}a\nabla_{\mu}a - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} + \mathcal{L}_{\rm EH}(H) - V(\Psi)$$

- **Extra dimensions** predict a wide range of ultralight boson mass.
  Dimensional reduction from higher form fields:
  e.g. $g^{MN}(5D) \to g^{\mu\nu}(4D) + B^{\mu}(4D), \quad B^{M}(5D) \to B^{\mu}(4D) + a(4D)$.
- String axiverse/photiverse: logarithmic mass window.
  In $4D$, $m_\Psi \propto e^{-\mathcal{V}_{6D}}$.
- Ultralight m_Ψ as low as $\sim 10^{-22}$ eV can be naturally predicted.
  Solution to small-scale problems in the galaxy?
- **Coherent waves** dark matter candidates when $m_\Psi < 1$ eV:

$$\Psi(x^{\mu}) \simeq \Psi_0(\mathbf{x})\cos\omega t; \qquad \Psi_0 \simeq \frac{\sqrt{\rho}}{m_\Psi}; \qquad \omega \simeq m_\Psi.$$

Property of Ultralight Dark Matter

Galaxy formation: virialization $\rightarrow \sim 10^{-3}c$ velocity fluctuation, thus kinetic energy $\sim 10^{-6} m_\Psi c^2$.
Effectively coherent waves:

$$\Psi(\vec{x}, t) = \frac{\sqrt{2\rho_\Psi}}{m_\Psi} \cos\left(\omega_\Psi t - \vec{k}_\Psi \cdot \vec{x} + \delta_0\right).$$

- Bandwidth: $\delta\omega_\Psi \simeq m_\Psi \left\langle v_{\rm DM}^2 \right\rangle \simeq 10^{-6} m_\Psi,\ Q_\Psi \simeq 10^6$.
- Correlation time: $\tau_\Psi \simeq \mathrm{ms}\,\frac{10^{-6}\mathrm{eV}}{m_\Psi}$.
  Power law detection is used to make integration time longer than τ_Ψ.
- Correlation length: $\lambda_d \simeq 200\ \mathrm{m}\frac{10^{-6}\mathrm{eV}}{m_\Psi} \gg \lambda_c = 1/m_\Psi$.
  Sensor array can be used within λ_d.

Dark Photon Dark Matter

- A new $U(1)$ vector couples in different portals with SM particles:

$$\epsilon F_{\mu\nu}B^{\mu\nu} + B_\mu\bar{\psi}\gamma^\mu(g_V + g_A\gamma_5)\psi + B_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}(g_M + g_E\gamma_5)\psi.$$

- Cavity/circuits for kinetic mixing, optomechanics for hidden U(1), spin sensors for dipole couplings...

- Similar to axion: extra dimensions, misalignment production (or during inflation), coherent waves.

- Novel aspects: **three polarization degrees of freedom**:

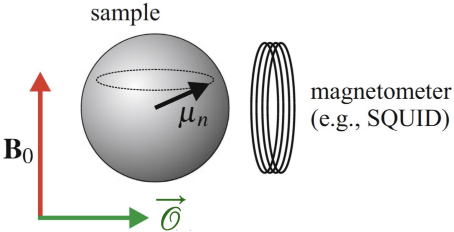
  Longitudinal mode: $\vec{\epsilon}_0(\vec{k}) \propto \vec{k}$.

  Transverse modes: $\vec{\epsilon}_{R/L}$.

Spin Precession from Axion Gradient

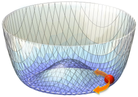
Dipole coupling: $H \propto \vec{\mathcal{O}} \cdot \vec{\sigma}_\psi$.

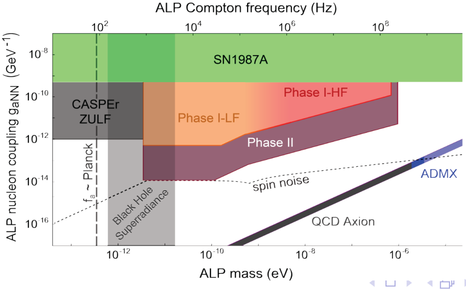
Effective 'magnetic field' $\vec{\mathcal{O}}$ causes precession of the fermions' spin $\vec{\sigma}_\psi$.
[Graham, Rajendran, Budker et al]



E.g., NMR (Casper) , spin-based amplifiers, comagnetometer, magnon ...

- **Axion gradient**: $\partial_\mu a \bar{\psi}\gamma^\mu\gamma^5\psi \to \vec{\mathcal{O}}_a = \vec{\nabla} a \propto \vec{\epsilon}_0$.





CASPEr: NMR-based axion search

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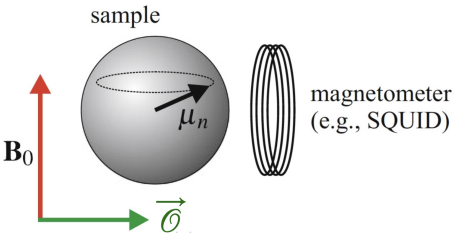

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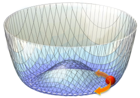
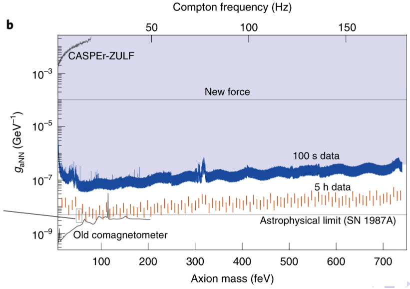




Spin amplifier [Jiang et al 21' Nature Physics]

Dipole Couplings and Spin Precession

Dipole coupling: $H \propto \vec{\mathcal{O}} \cdot \vec{\sigma}_\psi$.

Vector-like signals:

- **Axion gradient**: $\partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi \rightarrow \vec{\mathcal{O}}_a = \vec{\nabla} a \propto \vec{\epsilon}_0$.
- **Dark photon with dipole couplings**:

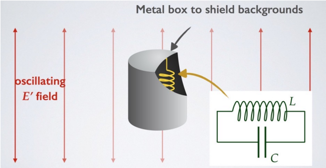
$$B_{\mu\nu} \bar{\psi} \sigma^{\mu\nu} \psi \rightarrow \vec{\mathcal{O}}_{\rm MDM} = \vec{\nabla} \times \vec{B} \propto \vec{\epsilon}_{R/L};$$

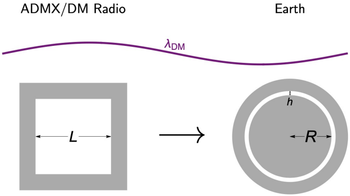
$$B_{\mu\nu} \bar{\psi} \sigma^{\mu\nu} i\gamma^5 \psi \rightarrow \vec{\mathcal{O}}_{\rm EDM} = \partial_0 \vec{B} - \vec{\nabla} B^0 \propto \begin{cases} \vec{\epsilon}, & m \gg |p|, \\ \vec{\epsilon}_{R/L}, & m \ll |p|. \end{cases}$$

Identification of the couplings?

Kinetic Mixing Dark Photon

- **Kinetic mixing U(1)** $\sim F_{\mu\nu}B^{\mu\nu}$ shows up in circuit/cavity. [Chaudhuri et al 15'] or geomagnetic fields [Fedderke et al 21'];



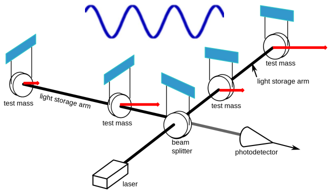


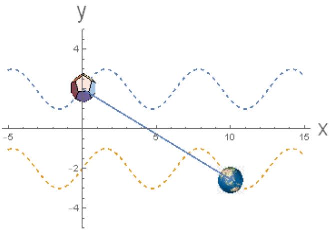
- Effective currents:

$$\vec{J}_{\text{eff}} \propto \hat{\epsilon}.$$

Hidden U(1) Dark Photon

- **U(1) B-L & B** shows up in optomechanical detectors [Graham et al 15', Pierce Zhao et al 18' 20' 21'] or astrometry [Graham et al 15', Xue et al 19' 21'].





- Force:

$$\vec{F} \propto \hat{\epsilon}.$$

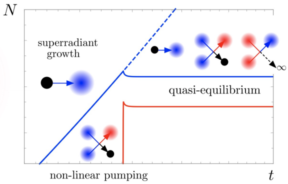
General Axion & Dark Photon Background

- **Cosmological isotropic background** [CaB, Dror et al 21']:

  Thermal freeze out,
  Topological defect decay,
  Parametric resonance/tachyonic instability of inflaton,
  . . .

- **Sources from a specific direction**:

  Cold stream of dark matter,
  Emissions from superradiant clouds.
  Dipole radiations from U(1)' charged binaries
  . . .



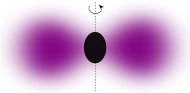
[Baryakhtar et al 20']

Broad spectrum with potential **anisotropy or macroscopic polarization**.

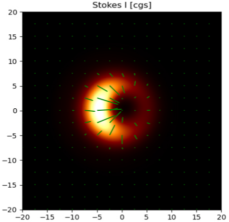
Superradiance and Gravitational Atom

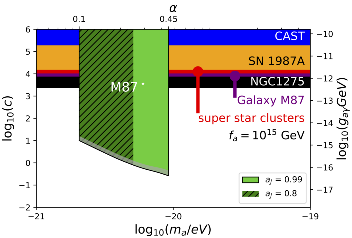
- **Rotational and dissipational medium** can amplify the wave around. [Zeldovichi 72']
- **Superradiance**: the wave-function is exponentially amplified from extracting BH rotation energy when $\lambda_c \simeq r_g$. [Penrose, Starobinsky, Damour et al]
- **Gravitational bound state** around BH:

$$a(x^\mu) = e^{-i\omega t} e^{im\phi} S_{lm}(\theta) R_{lm}(r),$$



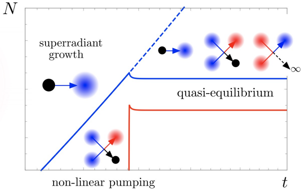
- **Stringent Constraint using EHT data** [EHT 21']:





[YC, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao 21']

Axion Wave from Saturating Axion Cloud



- **Self interaction saturating phase where $a_{\mathbf{max}} \simeq f_a$.**
  [Yoshino, Kodama 12', Baryakhtar et al 20'].

- Two level state with 2, 1, 1 and 3, 2, 2. Annihilations between 3, 2, 2 lead to **'ionized' axion wave** with velocity $v \sim \alpha/6$:

$$B_a \simeq 3 \times 10^{-24}\ \mathrm{T} \times \mathcal{C}_N \left(\frac{\alpha}{0.1}\right)^4 \left(\frac{1\mathrm{kpc}}{r}\right),$$

[Baryakhtar et al 20']

- For BH $\sim 10 M_\odot$, superradiance happens for $m_a \sim 100$ Hz axion.
  Axion gradient/DP signals are expected!

  Multi-messenger astronomy with GNOME, ngEHT and PTA!

- **Localization of the source** ?

Chiral Dark Photon Background [Audible Axions, Machado et al18']

- Axion-DP coupling:

$$\frac{1}{2}\partial_\mu a \partial^\mu a - m_a^2 f_a^2 [1 - \cos(\frac{a}{f_a})] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{\alpha}{4 f_a} a B_{\mu\nu} \tilde{B}^{\mu\nu}.$$

- Rolling a leads to different dispersions between R/L-handed dark photon:

$$\omega_{L/R}^2 = p^2 \mp p \frac{\alpha}{f_a} a'.$$

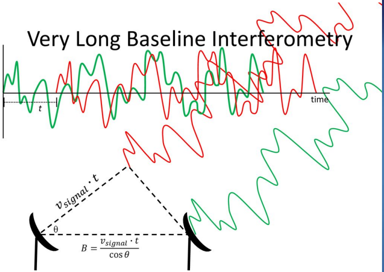
- Tachyonic instability: exponential increase of mode with negative ω^2.

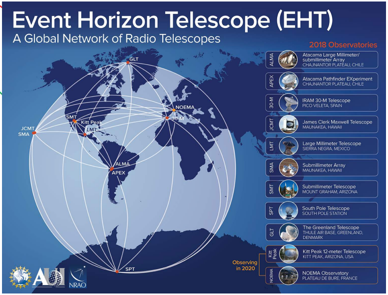
- Potential chiral spectrum. **How to identify the macroscopic circular polarization**?

Network of Detectors

Event Horizon Telescope: an Earth-sized Telescope

- For single telescope with diameter D, the angular resolution for photon of wavelength λ is around $\frac{\lambda}{D}$;
- VLBI: for multiple radio telescopes, the effective D becomes the maximum separation between the telescopes.





- As good as being able to see  on the moon from the Earth.

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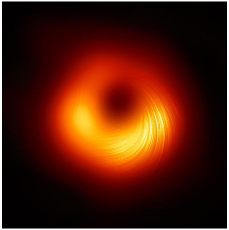
- Stokes polarization basis:

$$\begin{pmatrix} I_{IJ} + V_{IJ} & Q_{IJ} + iU_{IJ} \\ Q_{IJ} - iU_{IJ} & I_{IJ} - V_{IJ} \end{pmatrix} \propto \begin{pmatrix} \langle \epsilon_R \epsilon_R^\star \rangle_{IJ} & \langle \epsilon_R \epsilon_L^\star \rangle_{IJ} \\ \langle \epsilon_L \epsilon_R^\star \rangle_{IJ} & \langle \epsilon_L \epsilon_L^\star \rangle_{IJ} \end{pmatrix}$$

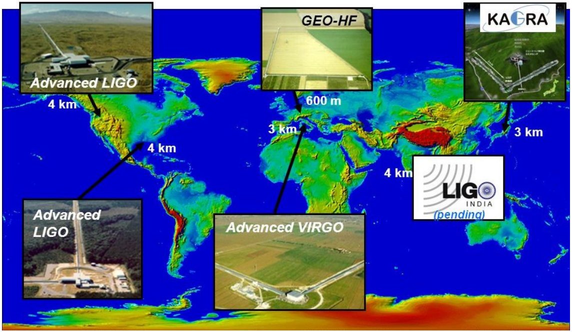
Total intensity I



Linear polarization Q, U

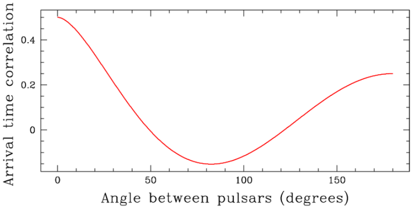
Globa Gravitational Wave Detector Network

- Localization due to long baseline $\sigma_\theta \propto \lambda_h / R_E$.
- Macroscopic polarization from correlation of detectors.



Pulsar timing array

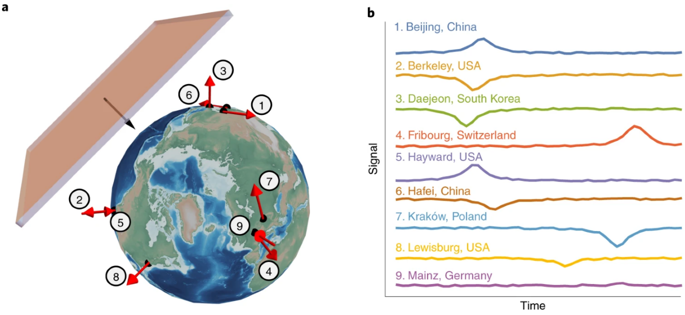
- Angular correlation for stochastic isotropic unpolarized GW: HD curves.



- Microscopic tensor nature shows up in macroscopic correlations.

Sensor Network For Domain Wall [GNOME 21' Nature Physics]

GNOME: worldwide coordinated search for domain wall passing through sensors:



- Transient signals for axion or dilaton domain wall in spin sensors or atomic clocks.

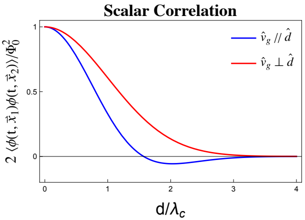
Scalar Field Interferometry

Two point correlation function of the scalar field [Derevianko 18']:

$$\langle a(\vec{0})a(\vec{d})\rangle = \frac{\rho_a}{\bar{\omega}}\int d^3\vec{v}\,\frac{f_{\rm DM}(\vec{v})}{\omega}\cos\left[m_a\vec{v}\cdot\vec{d}\right]$$
$$\propto \exp\left[-\frac{d^2}{2\lambda_c^2}\right]\cos\left[m_a\vec{v}_g\cdot\vec{d}\right].$$

where $f_{\rm DM}(\vec{v}) \propto \exp[-\frac{(\vec{v}-\vec{v}_g)^2}{2v_{\rm vir}^2}]$ and $\vec{v}_g$ is the Earth velocity in the halo.

- **Velocity fluctuation** $\sim v_{\rm vir}$ leads to **decoherence at dB length scale**.
- **Negative correlation** appears when $\vec{d}//\vec{v}_g$.
- **Localization** with $\sigma_\theta \propto \lambda/d$ and **Daily modulation** due to the self-rotation of the Earth. [Foster, Kahn et al 20']



- **Identification of the macroscopic and microscopic nature?**

Vector Sensor Network

based on
arxiv: 2111.06732, Phys. Rev. Res.

YC, Min Jiang, Jing Shu, Xiao Xue and Yanjie Zeng.

Vector Sensor Interferometry For Isotropic Backgrounds

A pair of vector sensors separated by a baseline $\vec{d}$:

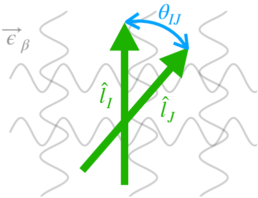
$$\mathcal{F}(\vec{d}, \vec{l}_I, \vec{l}_J) \propto \langle (\vec{\mathcal{O}}(t, \vec{x}_I) \cdot \hat{l}_I)(\vec{\mathcal{O}}(t, \vec{x}_J) \cdot \hat{l}_J) \rangle, \qquad \vec{d} \equiv \vec{x}_I - \vec{x}_J.$$

For isotropic sources $f_{\rm iso}(p, \hat{\Omega}) = \frac{f_{\rm iso}(p)}{4\pi p^2}$:

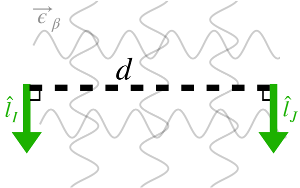
- Dipole correlation for each mode of $\vec{\epsilon}$ at $d = 0$.

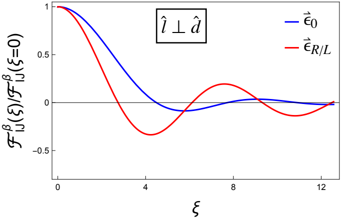
  $$\mathcal{F} \propto \hat{l}_I \cdot \hat{l}_J = \cos\theta_{IJ}$$

  Any deviation is a sign of anisotropy.



- Finite baseline distinguishes $\vec{\epsilon}_0$ from $\vec{\epsilon}_{R/L}$ at $\xi \equiv p_0\, d \approx 4$.





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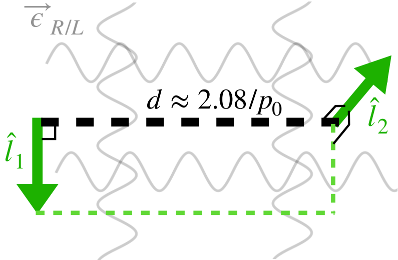
For isotropic sources $f_{\rm iso}(p, \hat{\Omega}) = \frac{f_{\rm iso}(p)}{4\pi p^2}$:

- A twisted setup can identify the macroscopic circular polarization.

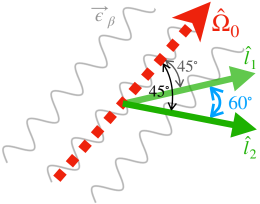


Right and left handed DP respond differently to such setup.

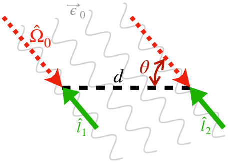
Localization

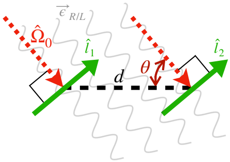
Sources from a specific direction $f_{\rm str}(p,\hat\Omega) = \frac{f_{\rm str}(p)}{p^2}\,\delta^2(\hat\Omega - \hat\Omega_0)$:

- Short baseline limit with $d = 0$:
  The optimal arrangements of the sensors are the same for $\vec\epsilon_0$ and $\vec\epsilon_{R/L}$, reaching $\sigma_\Omega \approx 1/\mathrm{SNR}$.



- Long baseline limit:
  The sensitive directions should overlap with the signals as much as possible with $\sigma_\theta \approx 1/(\mathrm{SNR}\,p\,d)$.





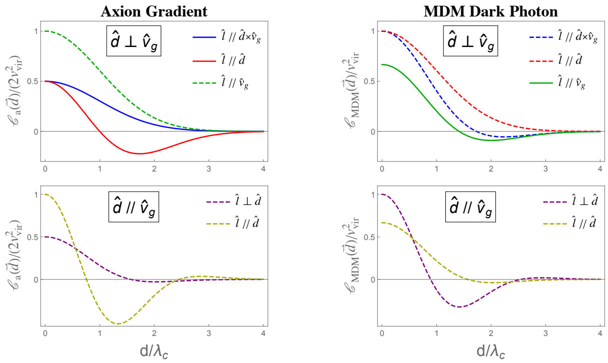
Multi-messenger astronomy with **GNOME** [Dailey et al 21']!

Axion Gradient and MDM DP Dark Matter

3×3 matrix of vector correlation: $\mathscr{C}(\vec{d})_{IJ} \propto \langle (\vec{\mathcal{O}}(t, \vec{x}_I) \cdot \hat{l}_I)(\vec{\mathcal{O}}(t, \vec{x}_J) \cdot \hat{l}_J) \rangle$ with $f_{\rm DM}(\vec{v}) \propto \exp[-(\vec{v} - \vec{v}_g)^2/(2v_{\rm vir}^2)]$.

- 5 possibilities when two $\hat{l}_i$ align:

$\vec{\mathcal{O}}^a \propto \vec{\epsilon}_0$



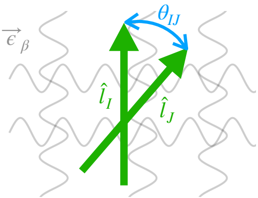
$\vec{\mathcal{O}}^{\rm MDM} \propto \vec{\epsilon}_{R/L}$

- **Straight lines** are not influenced by $\vec{v}_g$.
- Axion and MDM DP **have totally different spatial correlations**.

Dipole Angular Correlation

For $f_{\rm DM}(\vec{v}) \propto \exp[-(\vec{v}-\vec{v}_g)^2/(2v_{\rm vir}^2)]$,

Tune $\vec{l}_1$ and $\vec{l}_2$ with **certain directions at the same location**:



$$\Gamma(\vec{l}_1,\vec{l}_2) = \left(\vec{l}_1\right)^{\rm T}\cdot\mathscr{C}(0)\cdot\vec{l}_2$$

$$= \begin{cases} \frac{v_{\rm vir}^2}{2}\,\vec{l}_1\cdot\vec{l}_2 + \frac{1}{2}\left(\vec{l}_1\cdot\vec{v}_g\right)\left(\vec{l}_2\cdot\vec{v}_g\right) & \text{Axion Gradient;} \\ \frac{v_{\rm vir}^2}{2}\,\vec{l}_1\cdot\vec{l}_2 - \frac{1}{6}\left(\vec{l}_1\cdot\vec{v}_g\right)\left(\vec{l}_2\cdot\vec{v}_g\right) & \text{MDM DP;} \\ \frac{1}{6}\,\vec{l}_1\cdot\vec{l}_2 & \text{EDM DP.} \end{cases}$$

- **Universal dipole angular correlation:** $\vec{l}_1\cdot\vec{l}_2 = \cos\theta$, in constrast with monopole or quadruple (H.D. curve) for stochastic GW searches.
- $\vec{v}_g$ brings in anisotropy, with different signs for axion gradient and MDM DP.

Summary

- **Correlations of vector sensors** can identify the macroscopic property and the microscopic nature of the bosonic background:

  Coupling type, macroscopic polarization and localization/anisotropy ...

  $\rightarrow$ **Multi-messenger astronomy/cosmology**!

- How to improve sensitivity based on those information?

- **Quantum metrology** can play huge rules in fundamental physics!

Thank you!

Appendix