From Radio Astronomy Interferometry to Table-top Networks for Ultralight Bosons

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Searches for Wave-Like Dark Matter with Quantum Networks

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Outlines

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

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

- **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.
- **Coherent waves** dark matter candidates when $m_{\Psi} < 1$ eV:

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

Supermassive Black Holes
as Detectors for Ultralight Bosons

Superradiance and Gravitational Atom

- **Gravitational Atom** between BH and axion cloud:

$$\text{BL coordinate}: \Psi^{\text{GA}}(x^\mu) = e^{-i\omega t} e^{im\phi} S_{lm}(\theta) R_{lm}(r), \qquad \omega \simeq m_\Phi + i\Gamma.$$

- **Rotational and dissipational medium** can amplify the wave around. [Zeldovich 72']

- **Superradiance** [Penrose, Zeldovichi, Starobinsky, Damour et al]: bosons' wave-functions are exponentially amplified from extracting BH rotation energy when

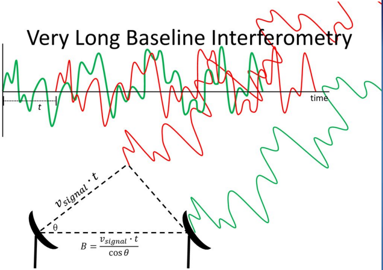
$$\text{Compton wavelength } \lambda_c \simeq \text{ gravitational radius } r_g.$$

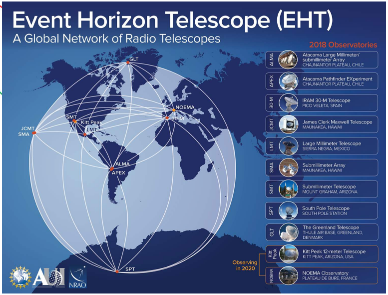
- **Supermassive black holess as detectors for ultralight bosons**:

$$M_{BH} \sim 10^9 M_\odot \leftrightarrow m_\Phi \sim 10^{-21} eV.$$

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.

Event Horizon Telescope: an Earth-sized Telescope

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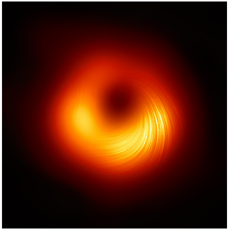
- VLBI: for multiple radio telescopes, the effective D becomes the maximum separation between the telescopes.
- Stokes polarization basis:

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

Total intensity I



Linear polarization Q, U

Axion Cloud and Birefringence

- **Axion cloud** saturates f_a due to self-interactions:

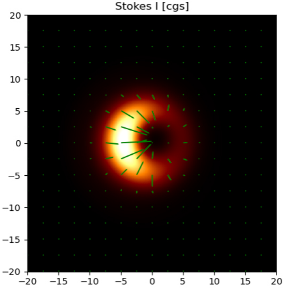
$r_g m_a \approx \mathcal{O}(1)$

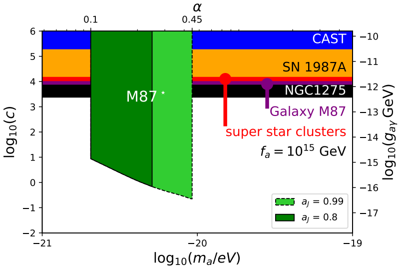
$$a^{\rm GA}(x^\mu) \simeq R_{11}(\mathbf{x}) \cos\left[m_a t - \phi\right] \sin\theta; \qquad a^{\rm GA}_{\rm max} \simeq \mathcal{O}(1)\, f_a; \qquad \omega \simeq m_a.$$

- **Birefringence** induced from axion-photon couplings:
$g_{a\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} \to$ rotate linear polarization orientation $\chi \equiv \arg(Q + i\ U)/2$.

- **Stringent constraints** for $c \equiv 2\pi g_{a\gamma} f_a$ using 21' EHT data: [YC, Liu, Lu, Mizuno, Shu, Xue, Yuan, Zhao, Nature Astronomy 22']

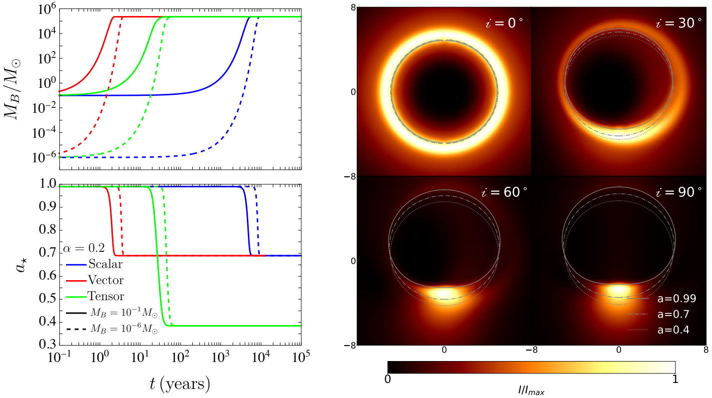
Shift for each photon: $\Delta\chi \approx g_{a\gamma} \times a^{\rm GA}(x^\mu_{\rm emit})$





Superradiant Evolution for Bosons [YC, Roy, Vagnozzi, Visinelli, PRD 22']

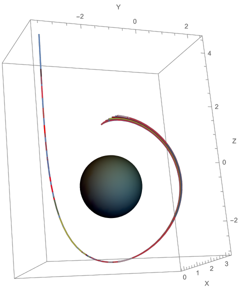
- **Superradiant evolution** for scalar, vector or tensor:

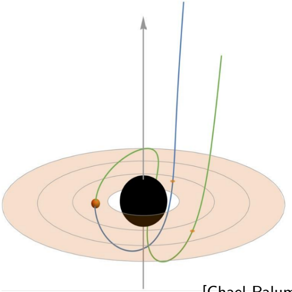


- Superradiant timescale $\propto M_{BH}$, and is shorter for vector or tensor due to $l = 0$ and $j = m = 1$ or 2 from **intrinsic spin**, $\sim \mathcal{O}(10)$ yrs for SgrA*.
- Center of the shadow contour **drifts** $\sim \mathcal{O}(1) r_g$ once the spin decreases.

Massive Tensor Field (Preliminary)

- Massive bimetric tensor with minimal coupling $\sim H_{\mu\nu} T^{\mu\nu}_{\mathrm{EM}}$.
- Quadrature mode $H_{\mu\nu} = \mathrm{Re}[R(r)e^{-i\omega t+2i\phi}\, \epsilon^{R}_{\mu\nu}]$ deflects photon geodesics.





[Chael Palumbo 19']

- Astrometry with **photon ring autocorrelation**:
  A strain $H \sim 10^{-2}$ leads to **azimuthal lapse oscillation** with $\mathcal{A}_\phi \simeq 5^\circ$.

Dissecting Ultralight Bosons

with Sensor Networks

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).

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

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

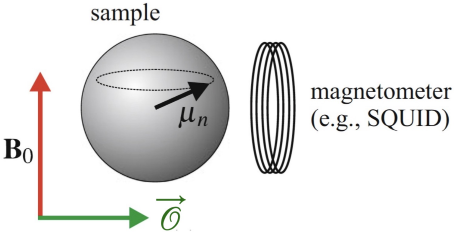
  Transverse modes: $\vec{\epsilon}_{R/L} \perp \vec{k}$.

- Signals projected to the **sensitive direction of a vector sensor**: $\sim \vec{\epsilon} \cdot \hat{l}$.

Spin Precession from Axion Gradient

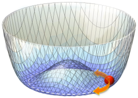
Dipole coupling: $H \propto \vec{\mathcal{O}} \cdot \vec{\sigma}_\psi$.

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



- **Dark photon with dipole couplings**:

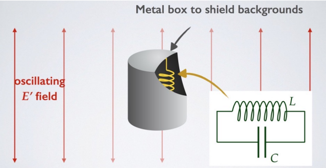
$$B_{\mu\nu}\bar{\psi}\sigma^{\mu\nu}\psi \to \vec{\mathcal{O}}_{\mathrm{MDM}} = \vec{\nabla} \times \vec{B} \propto \vec{\epsilon}_{R/L};$$

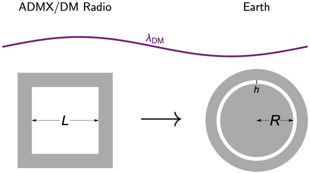
$$B_{\mu\nu}\bar{\psi}\sigma^{\mu\nu} i\gamma^5\psi \to \vec{\mathcal{O}}_{\mathrm{EDM}} = \partial_0 \vec{B} - \vec{\nabla} B^0 \propto \begin{cases} \vec{\epsilon}, & m \gg |p|, \\ \vec{\epsilon}_{R/L}, & m \ll |p|. \end{cases}$$

Identification of the couplings?

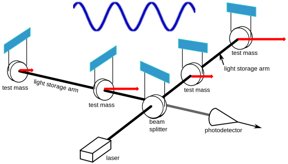
Kinetic Mixing and Hidden U(1) Dark Photon

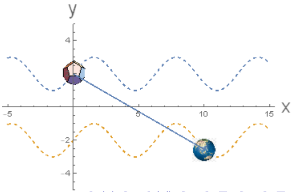
- Effective currents: $\hat{\epsilon} \to \vec{J}_{\text{eff}}$.
  Kinetic mixing U(1) $\sim F_{\mu\nu}B^{\mu\nu}$ shows up in circuit/cavity. [Chaudhuri et al 15'] or geomagnetic fields [Fedderke et al 21'];





- Force: $\hat{\epsilon} \to \vec{F}$.
  U(1) B-L & B shows up in optomechanics [Graham et al 15', Pierce et al 18'] or astrometry [Graham et al 15', Xue et al 19' 21'].





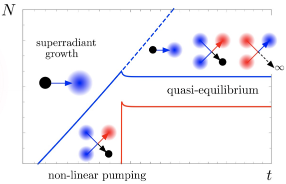
General Axion & Dark Photon Stochastic Background

- **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']

Microscopic nature: **spin, interaction**.

Macroscopic property: spectrum, anisotropy and macroscopic polarization.

Scalar Field Interferometry

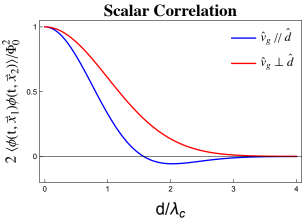
Two point correlation function of the scalar field [Derevianko 18']:

$$\langle a(\vec{0})a(\vec{d})\rangle = \frac{\rho_a}{\bar{\omega}} \int d^3\vec{v} \frac{f_{\rm DM}(\vec{v})}{\omega} \cos\left[m_a \vec{v}\cdot\vec{d}\right]$$

$$\propto \exp\left[-\frac{d^2}{2\lambda_c^2}\right] \cos\left[m_a \vec{v}_g\cdot\vec{d}\right].$$

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']



Vector Sensor Interferometry For Isotropic Backgrounds

A pair of vector sensors separated by a baseline $\vec{d}$: [YC, Jiang, Shu, Xue, Zeng, PRR 22']

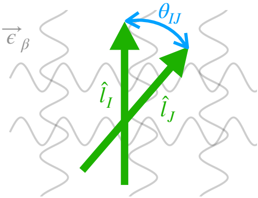
$$\mathcal{F}(\vec{d}, \vec{l}_I, \vec{l}_J) \propto \langle (\vec{\mathcal{O}}(t, \vec{x}_I) \cdot \hat{l}_I)(\vec{\mathcal{O}}(t, \vec{x}_J) \cdot \hat{l}_J) \rangle, \qquad \vec{d} \equiv \vec{x}_I - \vec{x}_J.$$

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

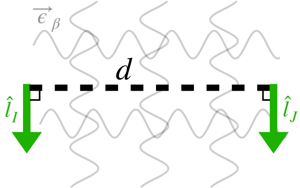
- **Dipole correlation** for each mode of $\vec{\epsilon}$ at $d = 0$.

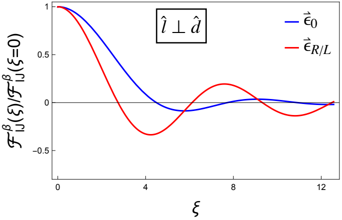
  $$\mathcal{F} \propto \hat{l}_I \cdot \hat{l}_J = \cos\theta_{IJ}$$

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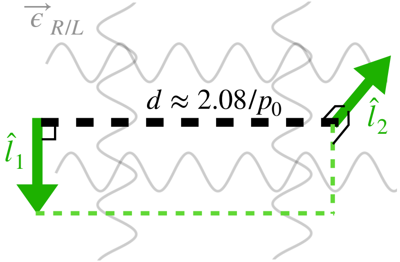
$$\mathcal{F}(\vec{d}, \vec{l}_I, \vec{l}_J) \propto \langle (\vec{\mathcal{O}}(t, \vec{x}_I) \cdot \hat{l}_I)(\vec{\mathcal{O}}(t, \vec{x}_J) \cdot \hat{l}_J) \rangle, \qquad \vec{d} \equiv \vec{x}_I - \vec{x}_J.$$

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

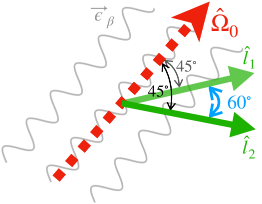
- A **twisted** setup can **identify the macroscopic circular polarization**.



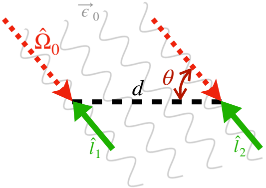
Right and left handed DP respond differently to such setup.

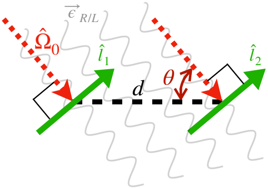
Localization [YC, Jiang, Shu, Xue, Zeng, PRR 22']

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 $\sigma_\theta \approx 1/(\mathrm{SNR}\,p\,d)$.





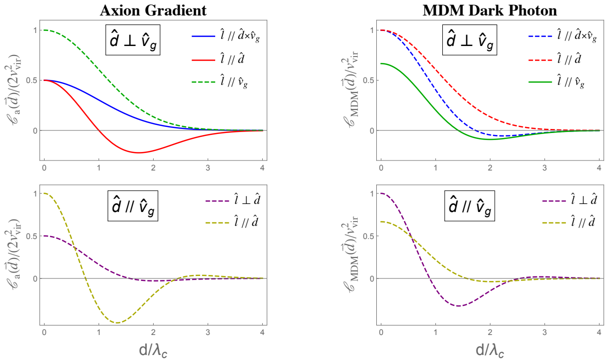
Multi-messenger astronomy with **GNOME** [Dailey et al 21']!

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: [YC, Jiang, Shu, Xue, Zeng, PRR 22']

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



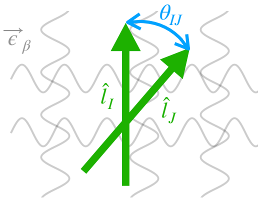
$\vec{\mathcal{O}}^{\rm MDM} \propto \vec{\epsilon}_{R/L}$

- Axion and MDM DP **have totally different spatial correlations**.

Dipole Angular Correlation [YC, Jiang, Shu, Xue, Zeng, PRR 22']

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?

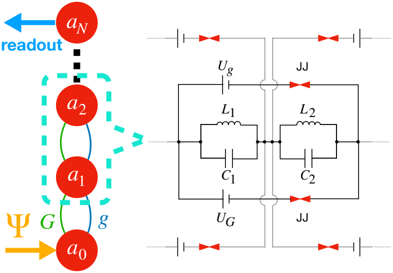
- Prospect: sensitivity of multi-mode systems, tensor-like correlations.

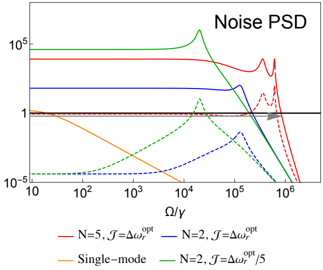
Simultaneous Resonant and Broadband Detection

- **Standard quantum limit for power law detection**:

  SNR^2 $\propto$ **range where** $S_{\rm int} \gg S_{\rm r}$. [Chaudhuri, Irwin, Graham, Mardon, 19']

- Scan bandwidth can be significantly increased in a multi-mode system:

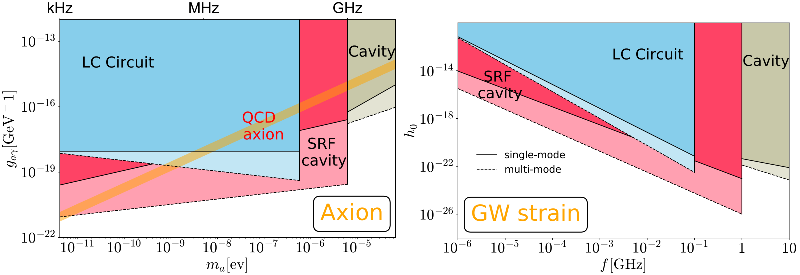




- New quantum limit for multi-mode resonators. [YC, Liu, Shu, Song, Yang, Zeng, 22'] [YC, Jiang, Ma, Shu, Yang, PRR 22']

Quantum Limit for Multi-mode Resonators

- $\text{SNR}^2 \propto \left(\frac{g}{\gamma n_{\rm occ}}\right)^{\frac{2n}{2n+1}} \to \frac{Q_{\rm int}}{n_{\rm occ}}$. [YC, Liu, Shu, Song, Yang, Zeng, 22'] [YC, Jiang, Ma, Shu, Yang, PRR 22']

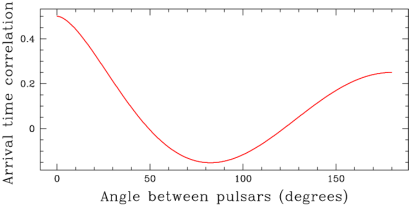


- LC circuit: ineffective at low frequency due to large $n_{\rm occ}$.

- High $Q_{\rm int}$ and constant $n_{\rm occ}$ for **SRF upconversion** with multi-mode upgrade can cover $m_a >$ kHz QCD axion dark matter potentially.

Tensor-like Angular Correlations

- Pulsar timing array for stochastic GW background: Angular correlation shows Hellings-Downs curves.



- Microscopic tensor nature shows up in macroscopic correlations.

- On-going: Hellings-Downs in table-top detectors? e.g., high frequency GW or massive tensor dark matter.

Thank you!

Appendix

Property of Ultralight Dark Matter

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

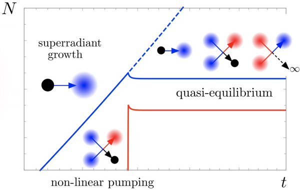
Effectively coherent waves:

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

- Bandwidth: $\delta\omega_\Psi \simeq m_\Psi \left\langle v_{\mathrm{DM}}^2 \right\rangle \simeq 10^{-6} m_\Psi,\ Q_\Psi \simeq 10^6$.
- 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.

Axion Wave from Saturating Axion Cloud

- **Self interaction saturating phase where $a_{\max} \simeq f_a$.** [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 $v \sim \alpha/6$:

$$B_a \simeq 3 \times 10^{-24}\ \mathrm{T} \times \mathcal{C}_N \left(\frac{\alpha}{0.1}\right)^4 \left(\frac{1\mathrm{kpc}}{r}\right), \qquad \text{[Baryakhtar et al 20']}$$

- 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** ?

Azimuthal Lapse

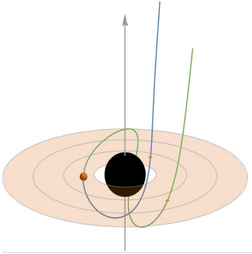
- At low inclination angles,

  photon ring autocorrelation:

  $\mathcal{C}(T,\varphi) \equiv \iint \mathrm{d}r\mathrm{d}r'\, r\, r' \, \langle \Delta I(t,r,\phi)\Delta I\,(t+T,r',\phi+\varphi)\rangle$

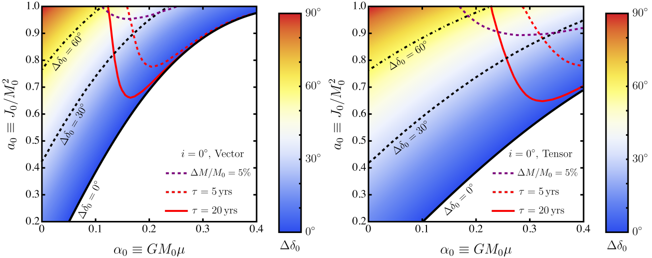
  peaks at $T = \tau_0$ and $\varphi = \delta_0$,

  where δ_0 is the azimuthal lapse.



[Chael Palumbo]

- δ_0 is sensitive to **spin evolution** due to frame dragging.



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**?

Global Gravitational Wave Detector Network

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