Chiral Gravitational Wave Background from Axion-like Fields

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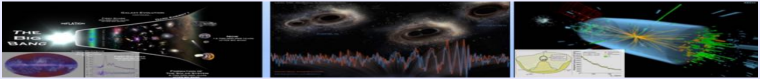
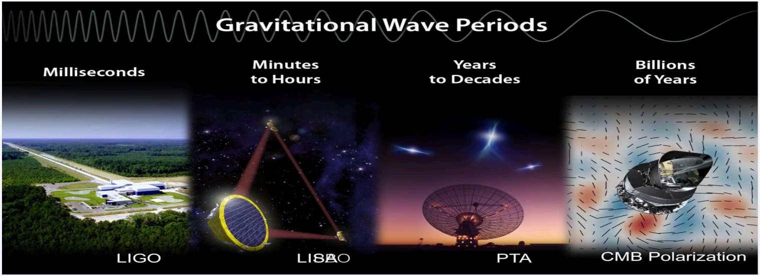
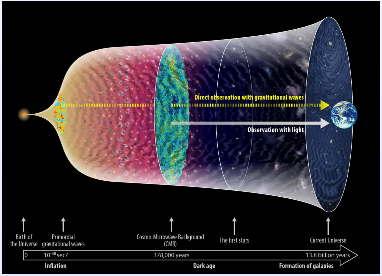
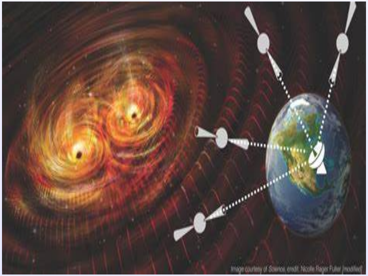
PRD 111 (2025) 084026: J. Chen, C. Liu, G. Wang & Y.L. Zhang
JCAP 05 (2025) 050: J. Chen, C. Liu & Y.L. Zhang
PDU 49 (2025) 101980: B. Xu, K. Ding, H. Su, J. Chen & Y. L. Zhang
2026 Jul 21@Urumqi [email: zhangyunlong@nao.cas.cn]



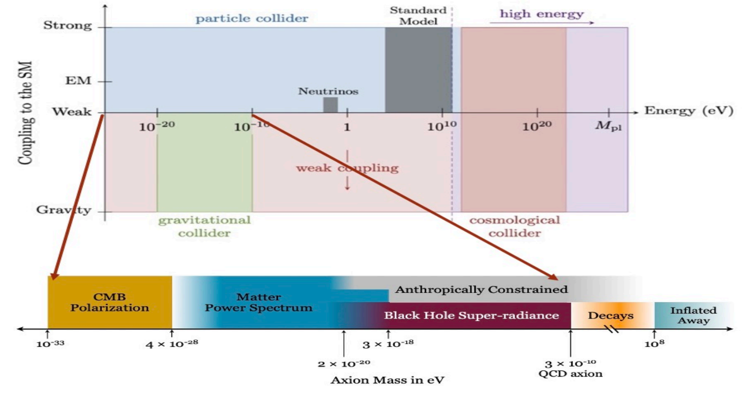
Multi-band gravitational wave detection



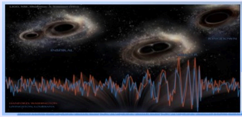
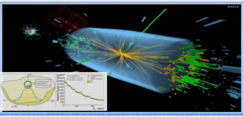
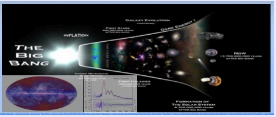




New physics in ultra-low energy



[cf. Baumann-Chia-Porto-Stout, Gravitational Collider Physics, 2019]

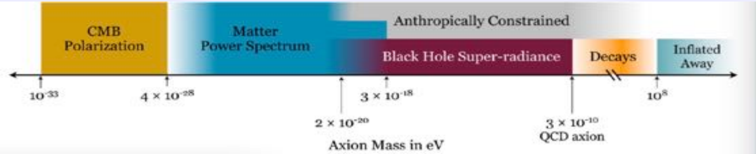
Axion-like Dark Matter

QCD axion

- $\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a - \alpha_\theta \theta F^a_{\mu\nu} \tilde{F}^{\mu\nu}_a + \bar{\psi} \left(i\gamma^\mu D_\mu - m e^{i\theta' \gamma_5} \right) \psi$
- Strong CP problem: no CP violation in measurement
- Peccei–Quinn (1977): introduce new pseudoscalar
- Wilczek- Weinberg: relax the CP-violation parameter

Axion-like: ultra light dark matter

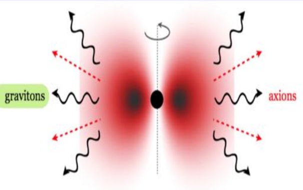
- e.g. Fuzzy Dark Matter, Dark photon dark matter

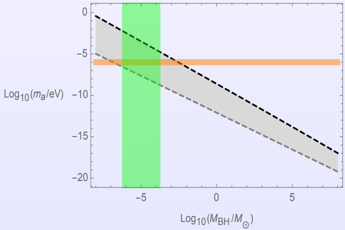


Axion-like Cloud and Black Hole Superradiance

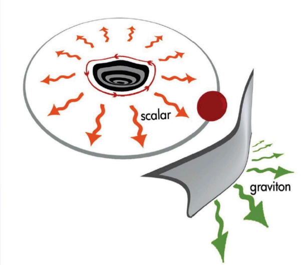
Schwarzschild $R_{BH} = G_N M_{BH}/c^2$, de Broglie wave length $\lambda_\vartheta = \hbar/(m_\vartheta v_\vartheta)$

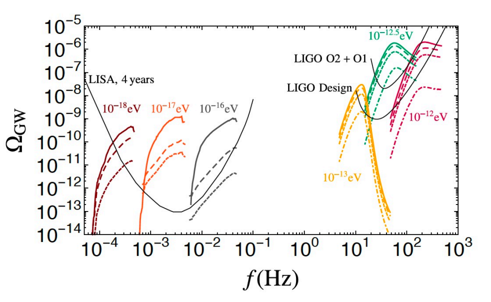
- Characteristic $\alpha \equiv \frac{R_{BH}}{\lambda_\vartheta} \simeq \left(\frac{M_{BH}}{M_\odot}\right)\left(\frac{m_\vartheta}{10^{-10}\mathrm{eV}}\right)\left(\frac{v_\theta}{c}\right)$.
- Formation time $\tau_\vartheta <$ Universe's age $\tau_U \simeq 10^{23}\left(\frac{M_\odot}{M_{BH}}\right) R_{BH}$
- $\tau_{\vartheta\uparrow} \simeq 10^7 e^{1.84\alpha} R_{BH},\ \alpha \gg 1, \quad \tau_{\vartheta\downarrow} \simeq 24\,\alpha^{-9} R_{BH},\ \alpha \ll 1.$





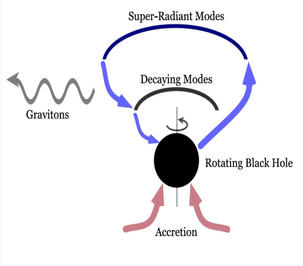
Axion annihilation and Stochastic GWs

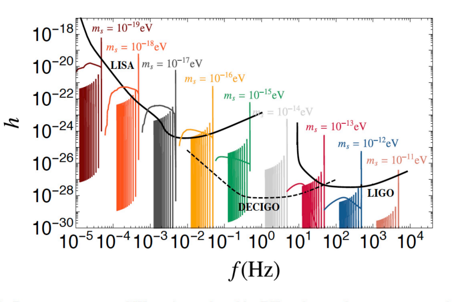




- Axion annihilation $\vartheta + \vartheta \to hh$, Strain $h \sim 10^{-21} - 10^{-32}$.
- Stochastic GW [cf. Brito-Cardoso-Pani, Superradiance 2020]

Energy level transition and Monochromic GW





- Energy transition $\vartheta^+ \to \vartheta^- + h$, Strain $h \sim 10^{-19} - 10^{-27}$
- Monochromic GW [cf. Brito-Cardoso-Pani, Superradiance 2020]

Fast radio burst from axion decay $\vartheta \to \gamma\gamma$

Stimulated axion clouds around primordial black holes

- Coupling term $\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4}\vartheta F_{\mu\nu}\tilde{F}^{\mu\nu}$
- $\left[-\partial_t^2 + \partial_z^2 \mp i\alpha_\gamma \dot{\vartheta}(t)\partial_z\right]A_\pm(t,z) = 0, \quad A_\pm = b_\pm(t)e^{ikz}.$
- In momentum space $\ddot{b}_\pm(t) + \left[k^2 \mp \alpha_\gamma k\dot{\vartheta}\right]b_\pm(t) = 0.$
- Amplification factor $e^{\Gamma_\gamma t_\gamma}$, $\Gamma_\gamma = \alpha_\gamma \vartheta_0 \frac{m_\vartheta}{2}, \quad t_\gamma \simeq \frac{1}{m_\vartheta v_\vartheta c}.$

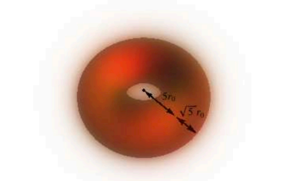
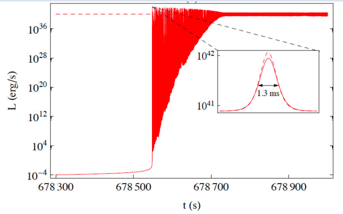


FIG. 1. Model of the superradiant 2p-axion cloud around a central Kerr black hole.



- [cf. Rosa-Kephart , PRL(2018)]

Pseudoscalar or Axial current to Two-graviton

Chiral GWs
Background
Axion-like DM
Resonance
GW Burst
Chiral GWBs
Early universe
Chern-Simons
Nieh-Yan
Detection

Volume 40B, number 3 PHYSICS LETTERS 10 July 1972

THE GRAVITATIONAL CORRECTION TO PCAC

R. DELBOURGO and A. SALAM
Physics Department, Imperial College, London S.W. 7 2B7, U.K.

$$\partial_\alpha A_\alpha = 2m\,P + e^2 \epsilon_{\kappa\lambda\mu\nu} F_{\kappa\lambda} F_{\mu\nu}/16\pi^2 + \epsilon_{\kappa\lambda\mu\nu} R_{\kappa\lambda\rho\sigma} R_{\mu\nu\rho\sigma}/768\pi^2 .$$

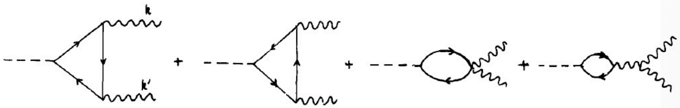
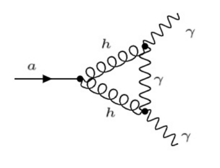
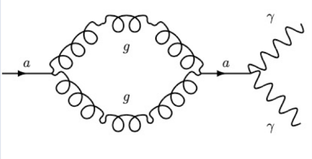


Fig. 1. One-fermion loop contributions to the two-graviton mode.

cf. Partially Conserved Axial vector Current theory (PCAC)

Branch Ratio of EM & GW ($\vartheta \to \gamma\gamma$ & $\vartheta \to hh$)

- The triangle Feynman diagram: where the axion-photon coupling is generated from Chern-Simon gravity coupling.
- $\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4}\vartheta F_{\mu\nu}\tilde{F}^{\mu\nu}, \quad \mathcal{L}_{\vartheta R\tilde{R}} = \frac{\alpha_{\rm g}}{4}\vartheta R^{\beta}{}_{\alpha\gamma\delta}\tilde{R}^{\alpha}{}_{\beta}{}^{\gamma\delta}.$
- 



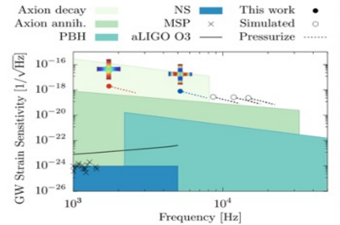
- The triangle diagram is divergent as $\alpha_\gamma \sim \alpha_{\rm g}(\Lambda_{cs}/M_{pl})^4$, where Λ_{cs} is the cut-off for Chern-Simons theory.
- Two powers of M_{pl} from $h_{\mu\nu}T^{\mu\nu}$ coupling.

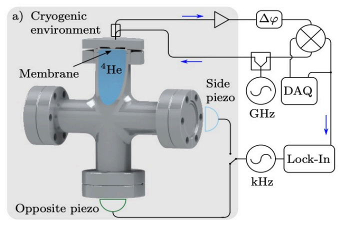
[cf. S. Sun, Y. L. Zhang, Gravitational Wave Burst from Axion Clumps, PRD'21]

GW burst & high frequency detection

Branch Ratio and GWs

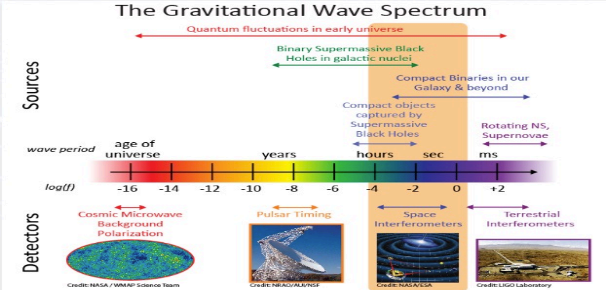
- $\frac{\mathrm{Br}(\vartheta\to gg)}{\mathrm{Br}(\vartheta\to\gamma\gamma)} \simeq \frac{\alpha_g^2}{\alpha_\gamma^2} \simeq \left(\frac{M_{pl}}{\Lambda_{cs}}\right)^8$, (Power of FRB $P_{(\gamma)} \sim 10^{42}$ergs/s).
- High frequency $h_{(g)} \sim 10^{-26}\left(\frac{1\mathrm{GHz}}{\nu}\right)\left(\frac{P_{(g)}}{P_{(\gamma)}}\right)^{1/2}\left(\frac{1\mathrm{kpc}}{L}\right)$
- Low freq. $h_{(g)} \sim 10^{-21}\left(\frac{10^{-2}\mathrm{Hz}}{\nu}\right)^{1/2}\left(\frac{M_{\mathrm{BH}}}{10^7 M_\odot}\right)^{1/2}\left(\frac{1\mathrm{kpc}}{L}\right)$

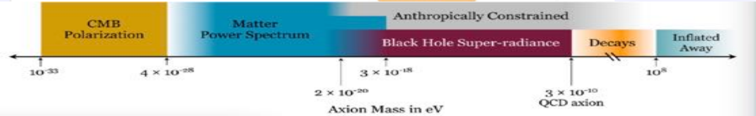


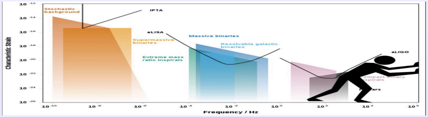


cf. PRD'21, S. Sun, Y. L. Zhang, Gravitational Wave Burst from Axion Clumps.
PRD'21, V. Vadakkumbatt et al, Prototype superfluid gravitational wave detector.
L.H. Du's group, Evidence for chiral graviton modes in fractional quantum Hall liquids

Spectrum of gravitational wave and axion mass





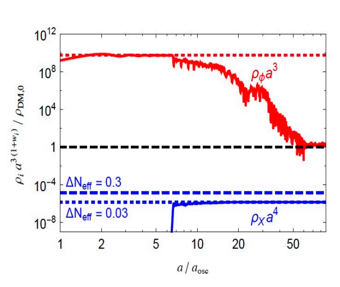


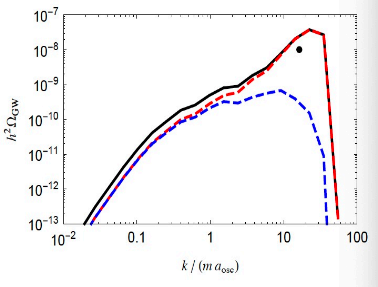
[cf. LISA/Ultra-High-Frequency Gravitational Waves Initiative]

Chiral GWs from Axion-like fields

Axions→ Photons→Induced GWs

- $\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$
- Time evolution of energy density v.s. polarizations



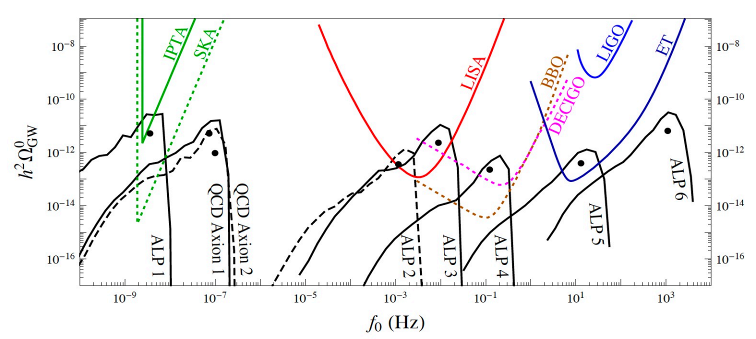


[cf. Machado, Ratzinger, Schwaller, Stefanek, "Audible Axions," JHEP (2019)]

Axion-like fields in early universe

Axions→ Photons→Induced GWs

- $\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{f}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}$

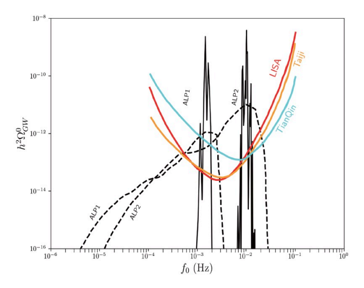


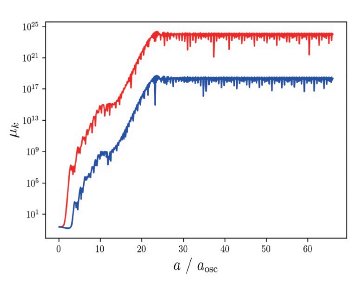
[cf. Machado, Ratzinger, Schwaller, Stefanek, "Audible Axions," JHEP (2019)]

Chiral GWs: Chern-Simons term

Axion like fields → Chiral GWs

- $\mathcal{L} = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{\alpha_g}{f}\phi R\tilde{R}$
- Chiral GWs in the millihertz frequency band





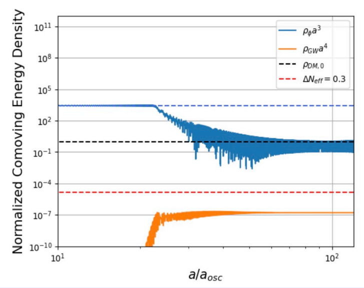
[cf. K.Ding, C. Fu, B.Y. Xu & Y.L. Zhang, SSPMA (2024)]

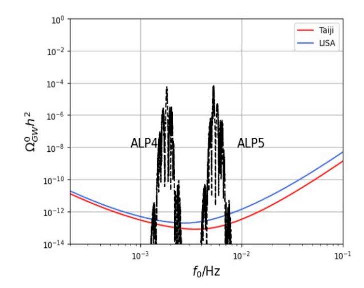
M. Li, S. Sun, Q.S.Yan, Z. Zhao, EPJC(2024)

Chiral GWs: Nieh-Yan term

Axion like fields → Chiral GWs

- $\mathcal{L}_\phi = -\frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{\alpha}{f}\phi T\tilde{T}$
- $\mathcal{L}_h = h'^2_{ij} - \left(\partial_i h_{jk}\right)^2 - \frac{\alpha\phi'}{f_\alpha}\epsilon^{ijk}h_{il}\partial_j h_{kl}$



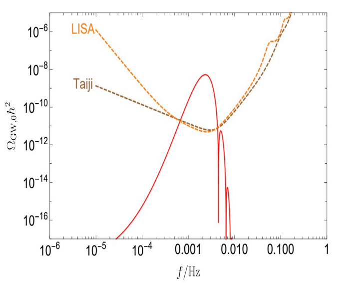


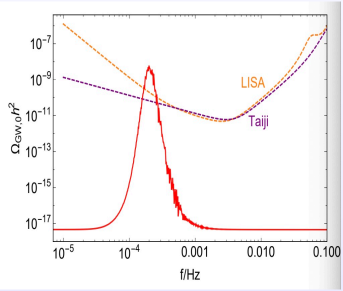
[cf. B. Xu, K. Ding, H. Su, J. Chen and Y. L. Zhang: PDU 49 (2025) 101980]

Amplification of the primordial gravitational wave

Axion like fields $\to$ Chiral GWs

- Nieh-Yan $\phi T\tilde{T}$ v.s.Chern-Simons $\phi R\tilde{R}$

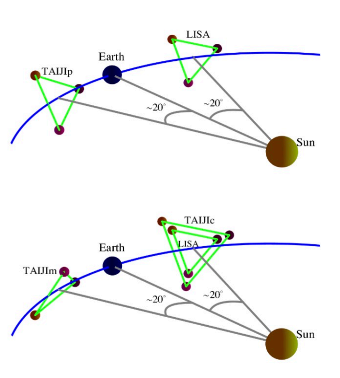


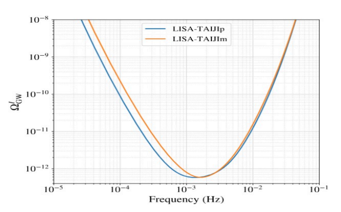


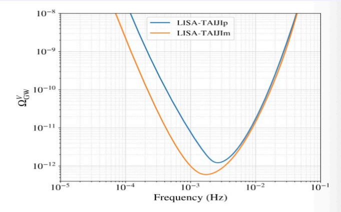
[cf. R. G. Cai, C. Fu and W. W. Yu, PRD (2022)]

[Z. Z. Peng, Z. M. Zeng, C. Fu and Z. K. Guo, PRD(2022)]

LISA-TAIJIp v.s. LISA-TAIJIm

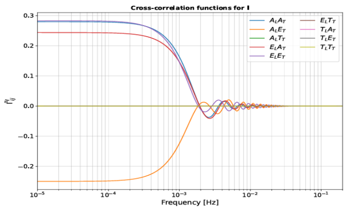




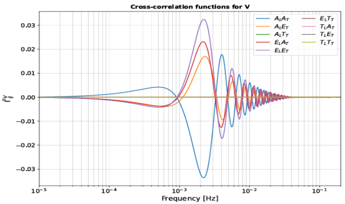


J. Chen, C. Liu, Y. L. Zhang, G. Wang, PRD 111 (2025) 084026

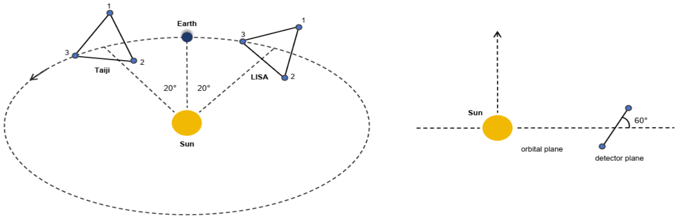
Detection of chiral GWs and detector networks



(a) Cross-correlation functions $\tilde{\Gamma}^I_{ij}(f)$ for LISA-Taiji.

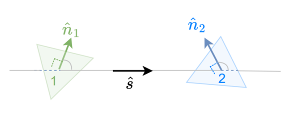


(b) Cross-correlation functions $\tilde{\Gamma}^V_{ij}(f)$ for LISA-Taiji.



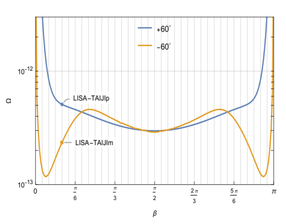
H. Su, B. Xu, J. Chen, C. Liu and Y. L. Zhang, CTP 77 (2025) 115403

Search for circularly polarized gravitational wave background



$$SNR_I^2 = \left(\frac{3}{10}\right)^2 T_{\rm obs} \int df \left[\sum_\kappa (\gamma_\kappa^I)^2 - \frac{\left(\sum_\kappa \gamma_\kappa^I \gamma_\kappa^V\right)^2}{\sum_\kappa (\gamma_\kappa^V)^2}\right] I^2/N^2,$$

$$SNR_V^2 = \left(\frac{3}{10}\right)^2 T_{\rm obs} \int df \left[\sum_\kappa (\gamma_\kappa^V)^2 - \frac{\left(\sum_\kappa \gamma_\kappa^I \gamma_\kappa^V\right)^2}{\sum_\kappa (\gamma_\kappa^I)^2}\right] V^2/N^2.$$



$$\sum_\kappa (\gamma_\kappa^I)^2 = \sum_{m=0}^{2}\sum_{n=0}^{2} b_m^I(\iota)\, b_n^I(\iota)\, X_{mn}^I,$$

$$\sum_\kappa (\gamma_\kappa^V)^2 = \sum_{m=0}^{1}\sum_{n=0}^{1} b_m^V(\iota)\, b_m^V(\iota)\, X_{mn}^V,$$

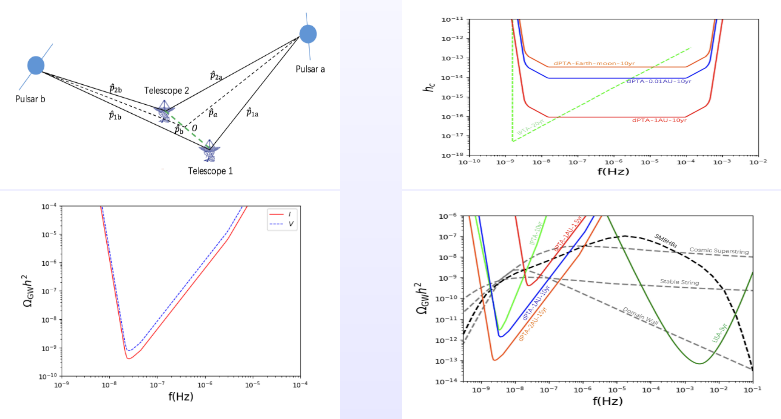
$$\sum_\kappa \gamma_\kappa^I \gamma_\kappa^V = \sum_{m=0}^{2}\sum_{n=0}^{1} b_m^I(\iota)\, b_n^V(\iota)\, X_{mn}^{IV},$$

$$X_{mn}^I = \sum_\kappa \chi_\kappa^{Im}\chi_\kappa^{In}, \quad X_{mn}^V = \sum_\kappa \chi_\kappa^{Vm}\chi_\kappa^{Vn}, \quad X_{mn}^{IV} = \sum_\kappa \chi_\kappa^{Im}\chi_\kappa^{Vn},$$

Ju Chen, Chang Liu, Yun-Long Zhang, JCAP 05 (2025) 050

Detecting Chiral Gravitational Wave Background

with a Dipole Pulsar Timing Array

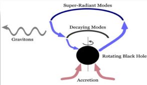


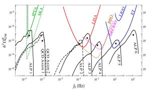
B. Xu, H. Jiang, R.-G. Cai, M. Sasaki, Yun-Long Zhang, arXiv: 2604.08141

Summary and Outlook

GWs from ultralight dark matter (BH superradiance)

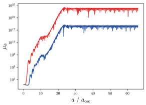
- ULDM annihilation $\vartheta + \vartheta \to h$ (Stochastic GW)
  Energy transition $\vartheta^+ \to \vartheta^- + h$ (Monochromic)
- **EM+ GW Burst** $\sim \vartheta F\tilde{F} + \vartheta R\tilde{R}$ $(\vartheta \to \gamma\gamma + hh)$

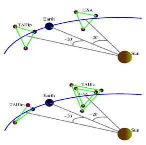




Chiral GWs from axion-like DM (early universe)

- Chiral GWs from Chern-Simons $\sim \vartheta R\tilde{R}$ $(\vartheta \to hh)$
- Chiral GWs from Nieh-Yan $\sim \vartheta T\tilde{T}$ $(\vartheta \to hh)$
- Generation of Chiral GWs from Astrophysics





Detection of chiral GWBs (detector networks)

- LISA-Taiji-TianQin & LVK networks
- Pulsar Timing Arrays & Astrometry