

The Generation and Detection of Chiral Gravitational Wave Backgrounds

Speaker: Yun-Long Zhang (NAOC)

National Astronomical Observatories,
Chinese Academy of Sciences

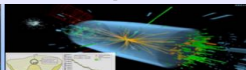
JCAP 05 (2025) 050: J. Chen, C. Liu & Y.L. Zhang

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

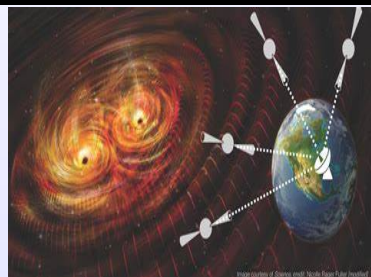
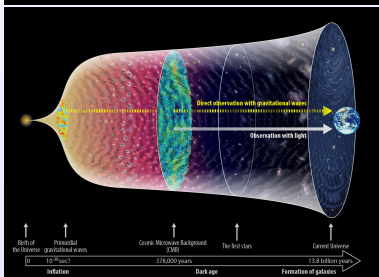
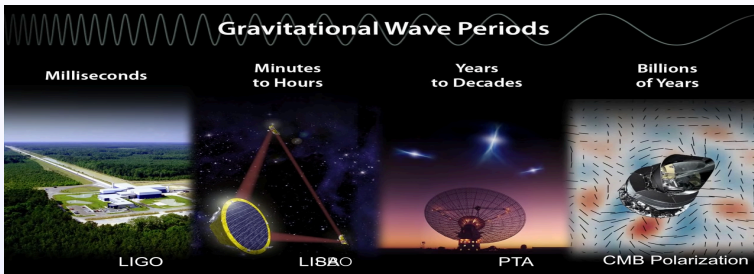
PDU 49 (2025) 101980: B. Xu, K. Ding, H. Su, J. Chen & Y. L. Zhang

2604.08141&2610.29182: B.Xu, H.Jiang, R.G.Cai, M.Sasaki & Y.L.Zhang

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Multi-band gravitational wave detection



Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

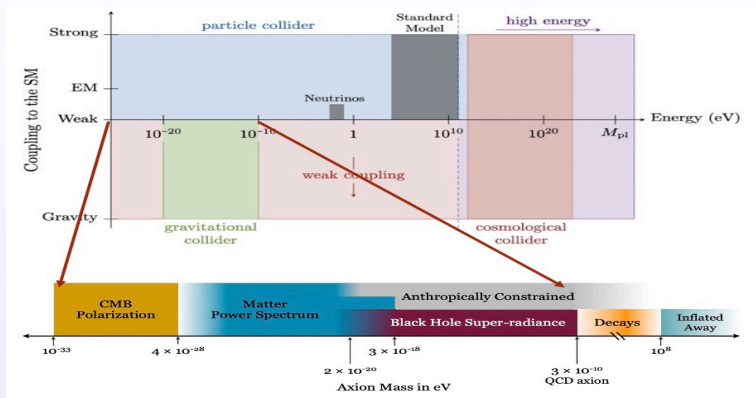
Early universe

Chern-Simons

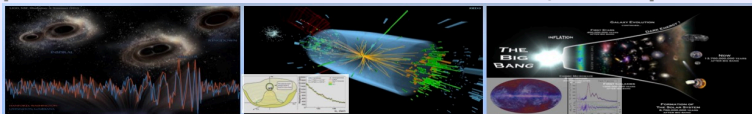
Nieh-Yan

Detection

New physics in ultra-low energy



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



Axion-like Dark Matter

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

Early universe

Chern-Simons

Nieh-Yan

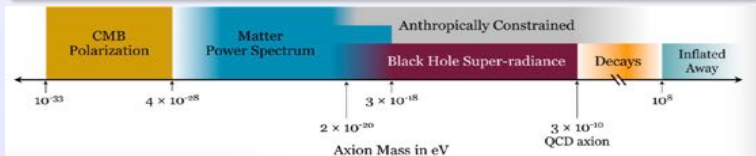
Detection

QCD axion

- $\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^a F_a^{\mu\nu} - \alpha_\theta \theta F_{\mu\nu}^a \tilde{F}_a^{\mu\nu} + \bar{\psi} \left(i\gamma^\mu D_\mu - me^{i\theta'\gamma_5} \right) \psi$
- 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

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

Early universe

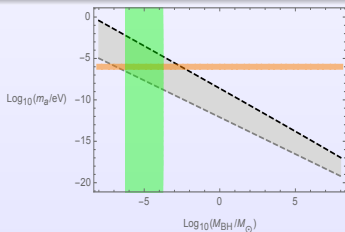
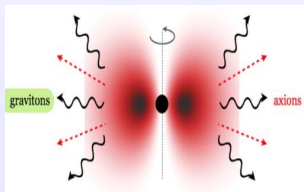
Chern-Simons

Nieh-Yan

Detection

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

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



Energy level transition and Monochromatic GW

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

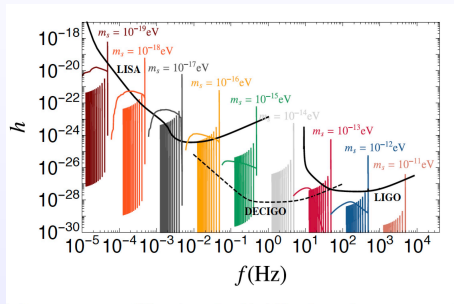
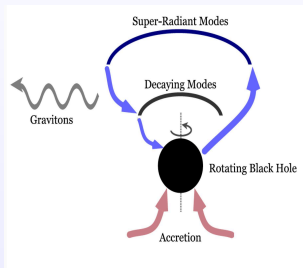
Chiral GWBs

Early universe

Chern-Simons

Nieh-Yan

Detection



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

Axion annihilation and Stochastic GWs

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

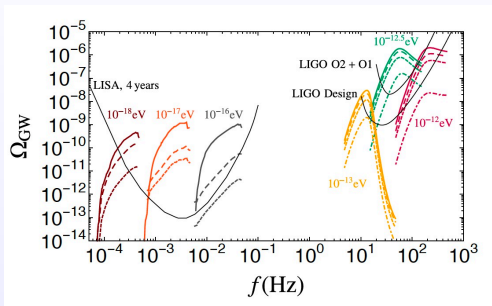
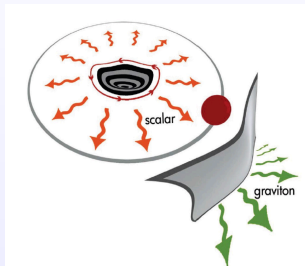
Chiral GWBs

Early universe

Chern-Simons

Nieh-Yan

Detection



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

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

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

Early universe

Chern-Simons

Nieh-Yan

Detection

Stimulated axion clouds around primordial black holes

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

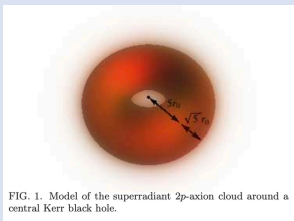
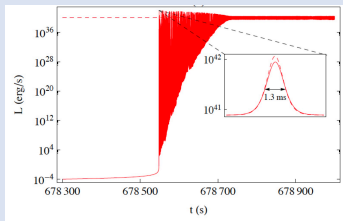


FIG. 1. Model of the superradiant $2p$ -axion cloud around a central Kerr black hole.



- [J. G. Rosa and T. W. Kephart, PRL **120**, 231102 (2018)]

Pseudoscalar or Axial current to Two-graviton

Chiral GWs

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.

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

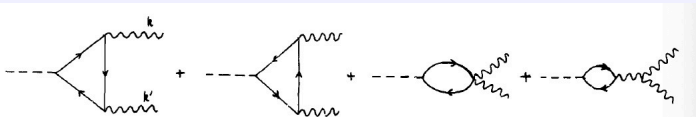


Fig. 1. One-fermion loop contributions to the two-graviton mode.

cf. Partially Conserved Axial vector Current theory (PCAC)

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

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

Early universe

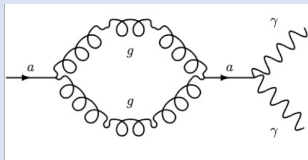
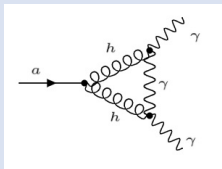
Chern-Simons

Nieh-Yan

Detection

- The triangle Feynman diagram: where the axion-photon coupling is generated from Chern-Simons gravity coupling.

$$\mathcal{L}_{\vartheta F\tilde{F}} = -\frac{\alpha_\gamma}{4} \vartheta F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad \mathcal{L}_{\vartheta R\tilde{R}} = \frac{\alpha_g}{4} \vartheta R^\beta_{\alpha\gamma\delta} \tilde{R}^\alpha_{\beta}{}^{\gamma\delta}.$$



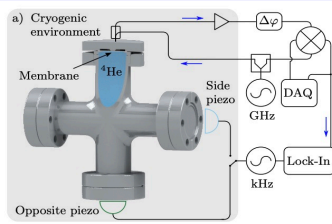
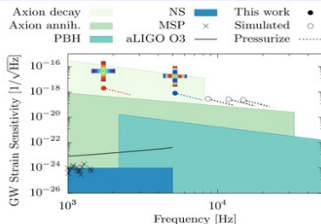
- The triangle diagram is divergent as $\alpha_\gamma \sim \alpha_g (\Lambda_{cs}/M_{pl})^4$, where Λ_{cs} is the cut-off for Chern-Simons theory.
- Two powers of M_{pl} from $h_{\mu\nu} T^{\mu\nu}$ coupling.

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

GW burst & high frequency detection

Branch Ratio and GWs

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



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

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

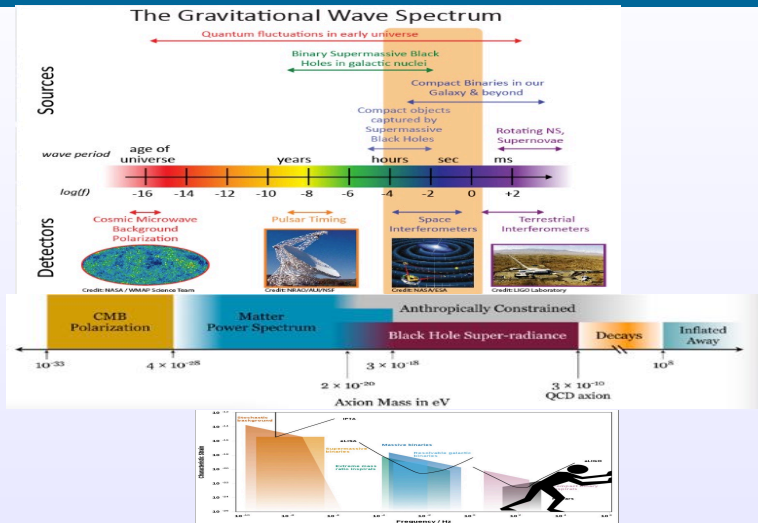
Chiral GWBs

Early universe

Chern-Simons

Nieh-Yan

Detection



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

Chiral GWs from Axion-like fields

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

Early universe

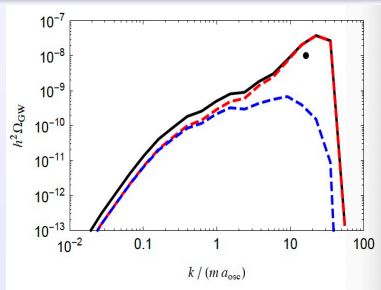
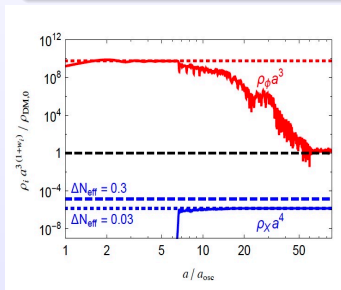
Chern-Simons

Nieh-Yan

Detection

Axions $\rightarrow$ Photons $\rightarrow$ 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, Stefaneke, "Audible Axions," JHEP (2019)]

Axion-like fields in early universe

Chiral GWs

Axions $\rightarrow$ Photons $\rightarrow$ Induced GWs

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

Background

Axion-like DM

Resonance

GW Burst

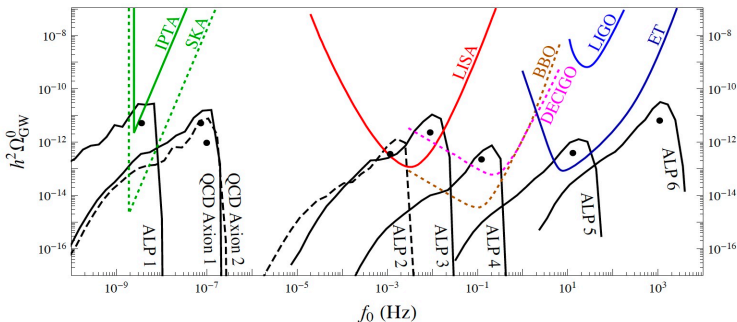
Chiral GWBs

Early universe

Chern-Simons

Nieh-Yan

Detection



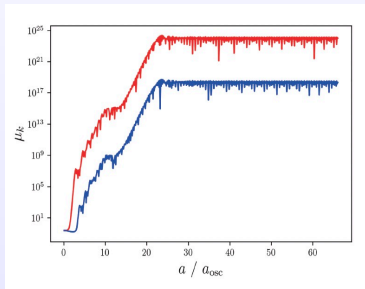
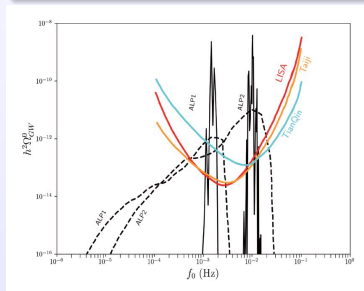
[cf. Machado, Ratzinger, Schwaller, Stefanek, "Audible Axions," JHEP (2019)]

Chiral GWs: Chern-Simons term

Chiral GWs

Axion like fields $\rightarrow$ 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)

Amplification of the primordial gravitational wave

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

Early universe

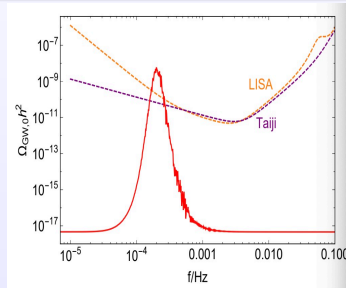
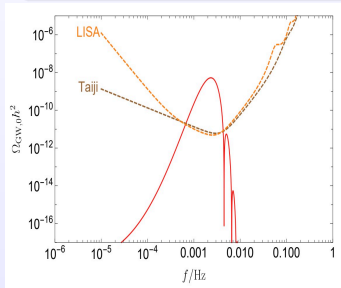
Chern-Simons

Nieh-Yan

Detection

Axion like fields $\rightarrow$ 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)]

Chiral GWs: Nieh-Yan term

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

Early universe

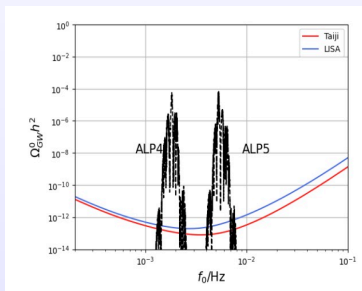
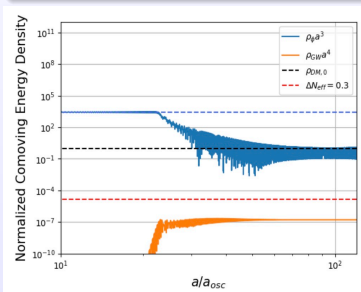
Chern-Simons

Nieh-Yan

Detection

Axion like fields $\rightarrow$ Chiral GWs

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



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

Detection of chiral GWs and detector networks

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

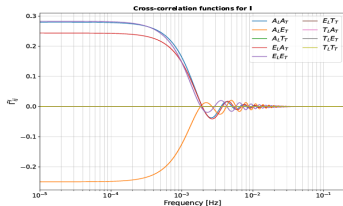
Chiral GWBs

Early universe

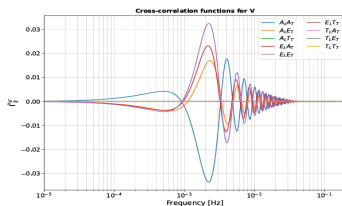
Chern-Simons

Nieh-Yan

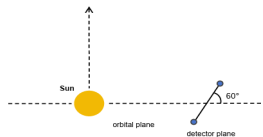
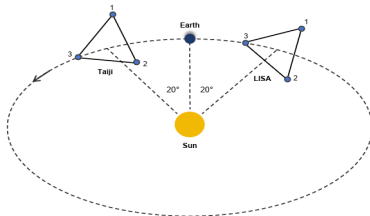
Detection



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



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



N. Seto, "Measuring Parity Asymmetry of Gravitational Wave Backgrounds with a Heliocentric Detector Network in the mHz Band," PRL 125, 251101 (2020)

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

Detection of chiral GWs and detector networks

Chiral GWs

LISA-TAIJp v.s. LISA-TAIJm

Background

Axion-like DM

Resonance

GW Burst

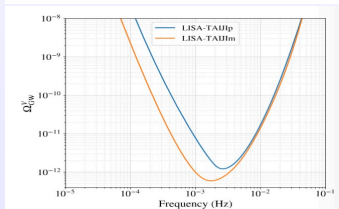
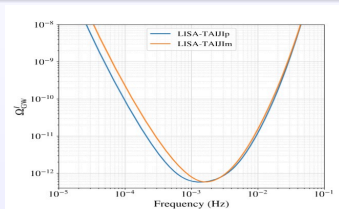
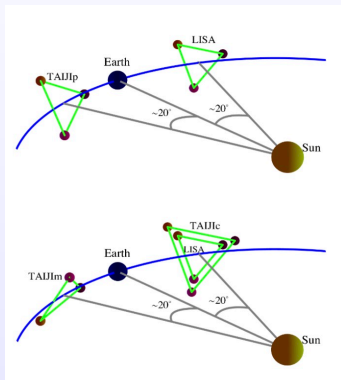
Chiral GWBs

Early universe

Chern-Simons

Nieh-Yan

Detection



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

General network of space-borne triangular detectors

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

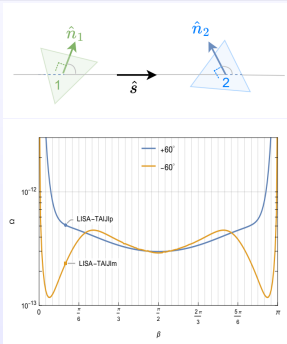
Early universe

Chern-Simons

Nieh-Yan

Detection

Search for circularly polarized gravitational wave background



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

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

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

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

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

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

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

Detecting Chiral Gravitational Wave Background

with a Dipole Pulsar Timing Array(dPTA)

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

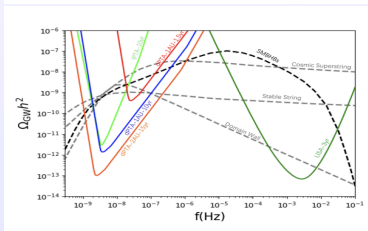
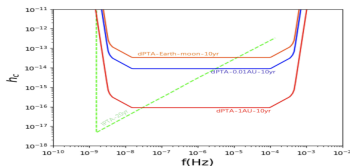
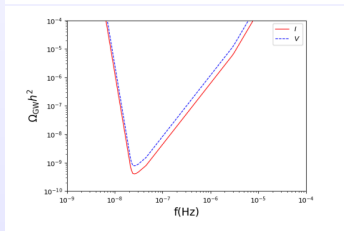
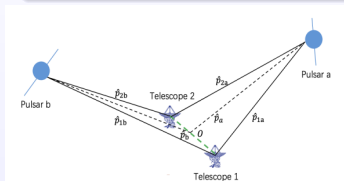
Chiral GWBs

Early universe

Chern-Simons

Nieh-Yan

Detection



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

Detecting Chiral Gravitational Wave Background

Chiral GWs

with EB in TB in cosmic microwave background(CMB)

Background

Axion-like DM

Resonance

GW Burst

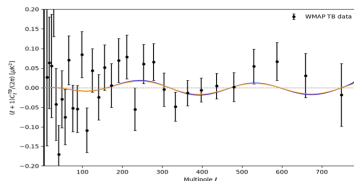
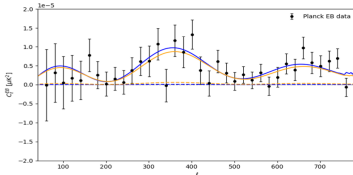
Chiral GWBs

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Chern-Simons

Nieh-Yan

Detection



$$C_{\ell}^{EB} = -\frac{1}{2\ell+1} \sum_{\ell'L} (-1)^{\ell+\ell'+L} \left\{ C_L^{\Omega\phi} G_{\ell\ell'L}^{\Omega} G_{\ell\ell'L}^{\phi} - 2C_L^{\phi\psi} H_{\ell\ell'L}^{\psi} G_{\ell\ell'L}^{\phi} \right\} [C_{\ell'}^{EE} - C_{\ell'}^{BB}].$$

$$C_L^{\phi\Omega} = \int \frac{k^2 dk}{2\pi^2} [P_L(k) - P_R(k)] F_L^{\phi} F_L^{\Omega},$$

$$C_{\ell}^{TB} = -\frac{1}{2\ell+1} \sum_{\ell'L} \left\{ C_L^{\phi\Omega} G_{\ell\ell'L}^{\phi} K_{\ell\ell'L} C_{\ell'}^{TE} P_{\ell\ell'L}^{-} - [C_L^{\phi\Omega} G_{\ell\ell'L}^{\Omega} K_{\ell\ell'L} - 2C_L^{\phi\psi} H_{\ell\ell'L}^{\psi} K_{\ell\ell'L}] C_{\ell'}^{TE} P_{\ell\ell'L}^{+} \right\}$$

$$\mathcal{P}_V^{\text{BPL}} = \sigma_{L,R} \mathcal{P}_c \left(\frac{k}{k_c} \right)^{\alpha_1} \left[1 + 0.75 \left(\frac{k}{k_c} \right)^{\Delta} \right]^{\frac{\alpha_2 - \alpha_1}{\Delta}}.$$

c.f. B. Xu, Yun-Long Zhang, arXiv: 2610.29182

Parity-odd CMB Correlations induced by a Chiral Gravitational Wave Background

Summary and Outlook

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

Chiral GWBs

Early universe

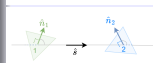
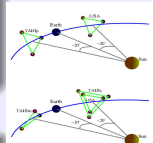
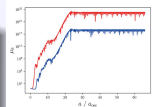
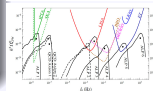
Chern-Simons

Nieh-Yan

Detection

GWs from ultralight dark matter (BH superradiance)

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



Chiral GWs from axion-like DM (early universe)

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

Detection of chiral GWBs (detector networks)

- LISA-Taiji-TianQin & Ligo-Virgo-KAGRA networks
- Pulsar Timing Arrays & Astrometry & CMB