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

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

Nov.09@BRICA-AGAC2026 [email: zhangyunlong@nao.cas.cn]



Multi-band gravitational wave detection

Chiral GWs

Background

Axion-like DM

Resonance

GW Burst

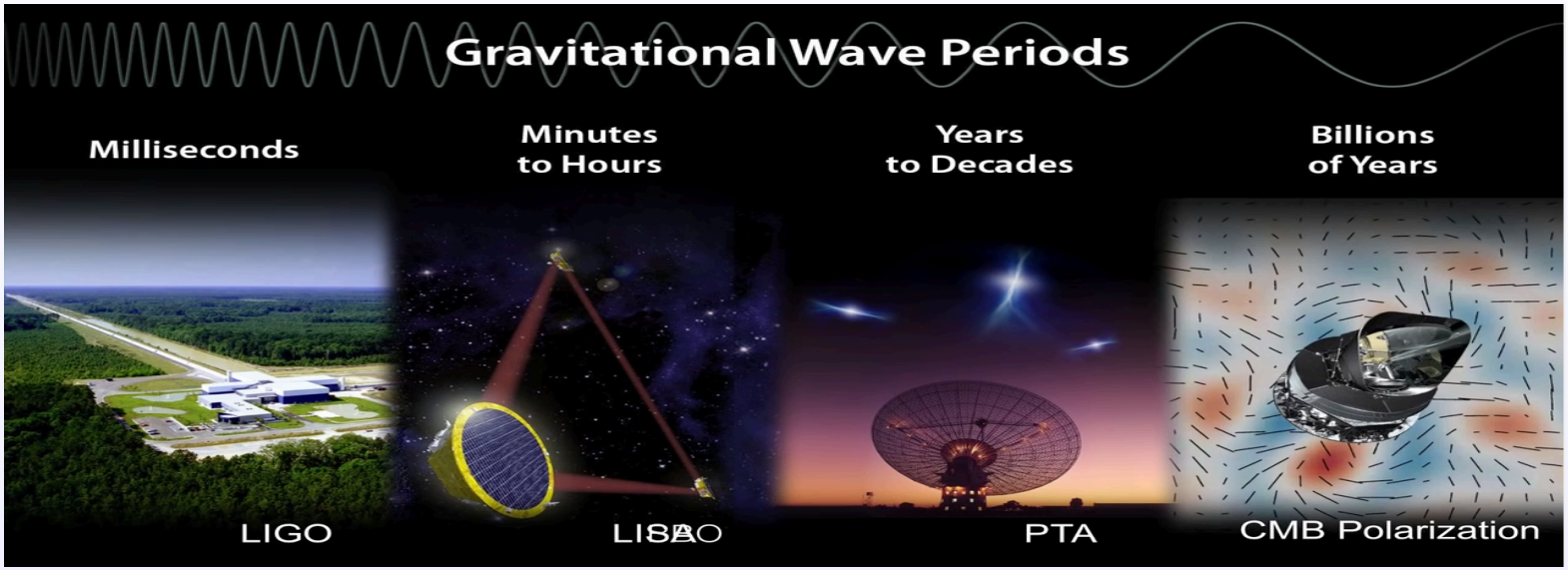
Chiral GWBs

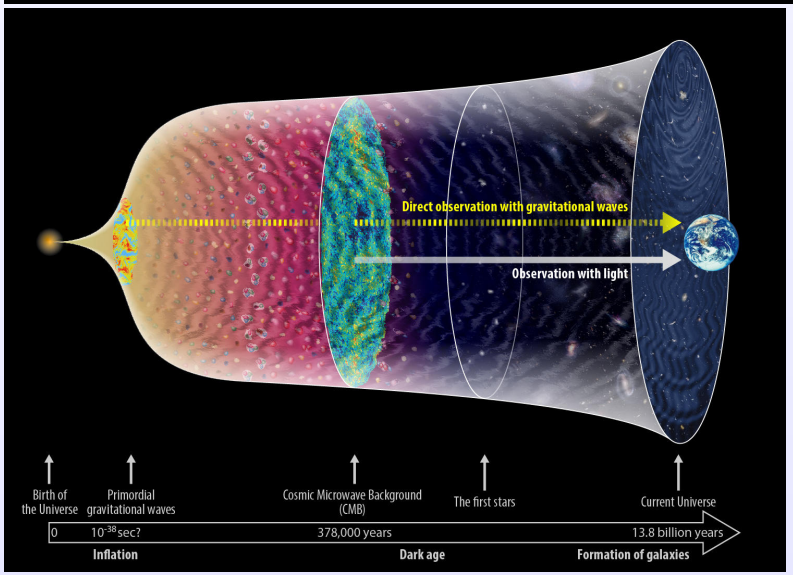
Early universe

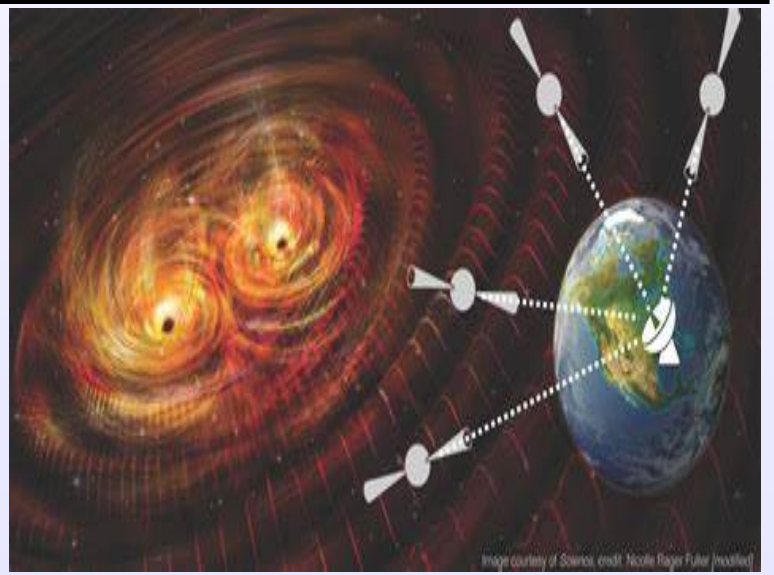
Chern-Simons

Nieh-Yan

Detection

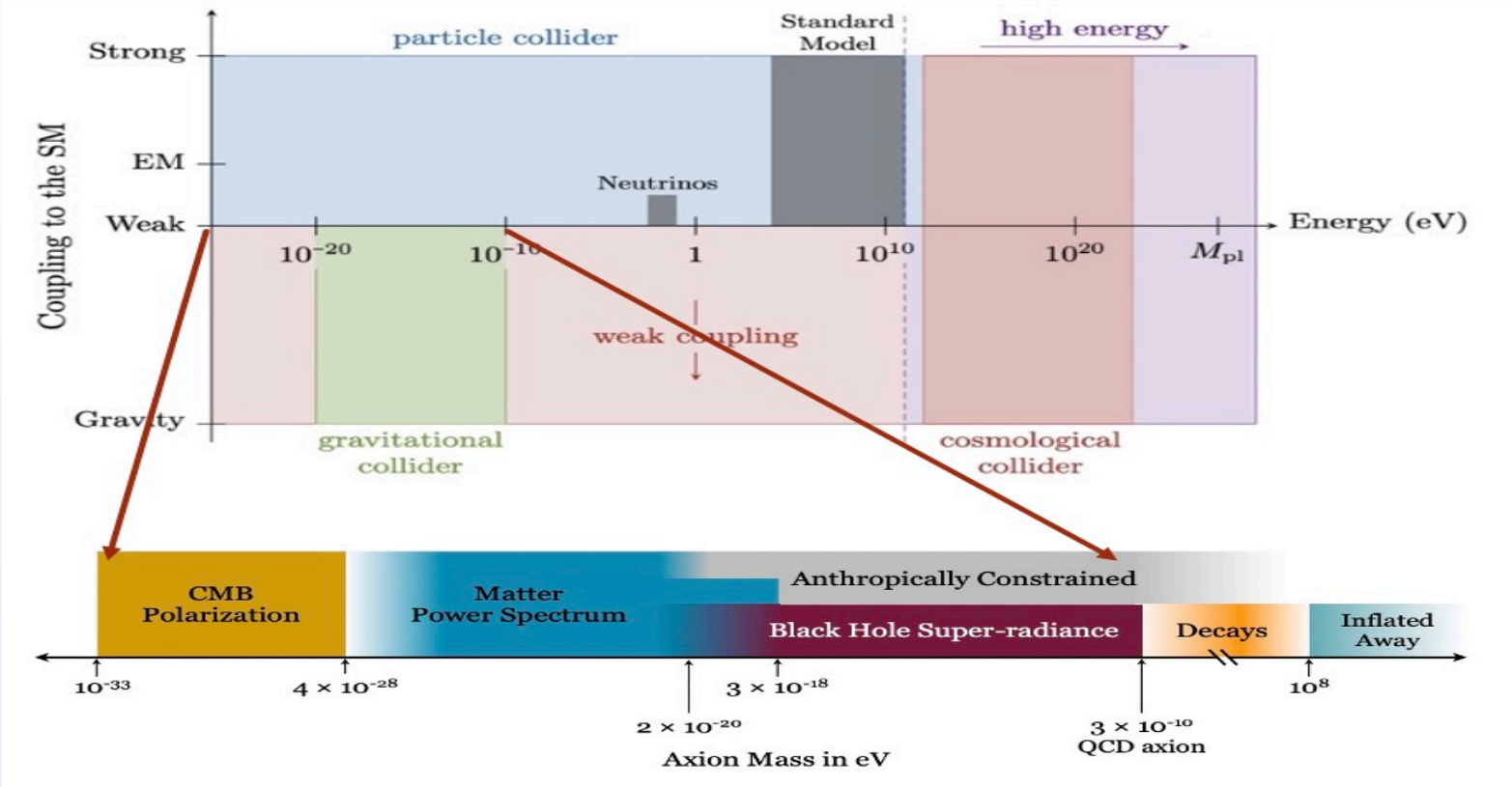




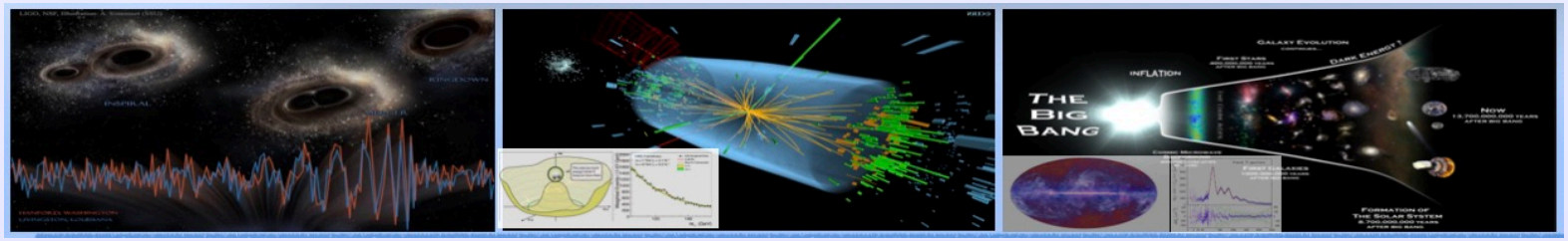


New physics in ultra-low energy

Chiral GWs
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Nieh-Yan
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[cf. Baumann-Chia-Porto-Stout, Gravitational Collider Physics, 2019]



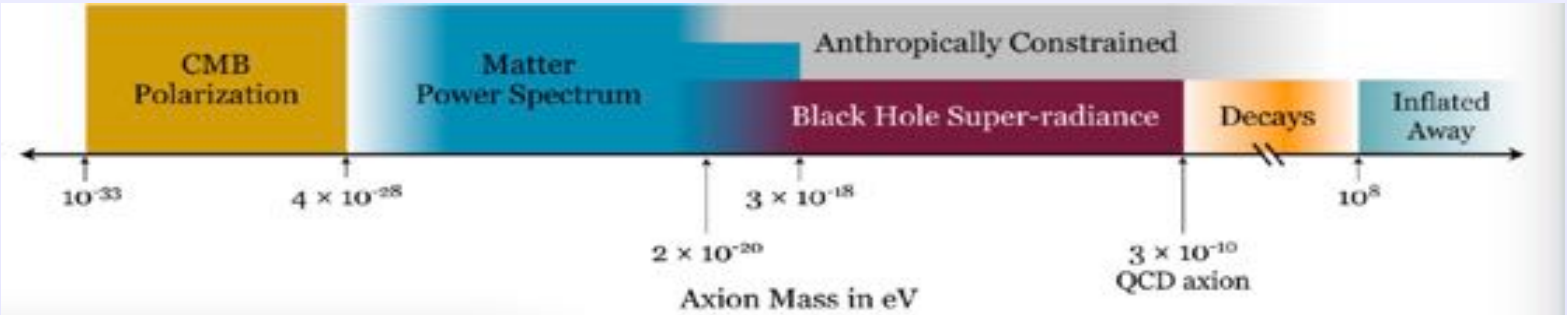
Axion-like Dark Matter

QCD axion

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

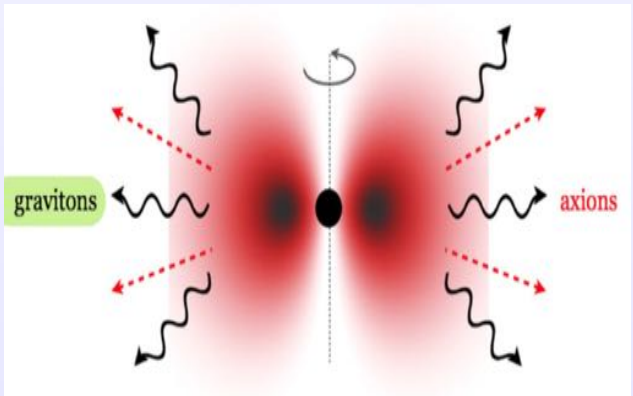


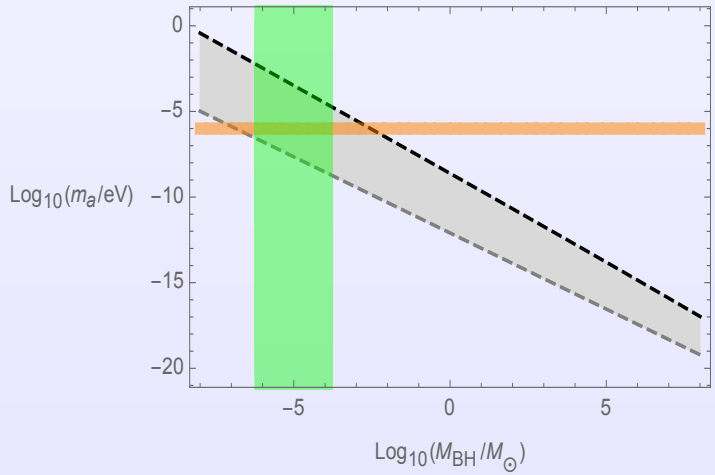
Axion-like Cloud and Black Hole Superradiance

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

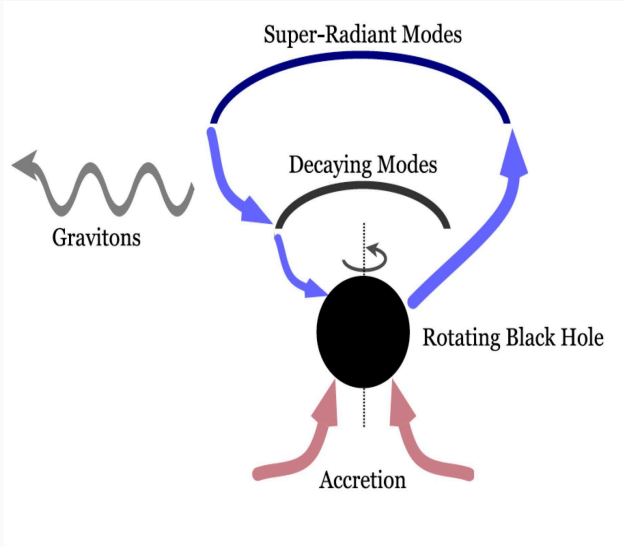
- Characteristic $\alpha \equiv \frac{R_{BH}}{\lambda_\vartheta} \simeq \left(\frac{M_{BH}}{M_\odot}\right)\left(\frac{m_\vartheta}{10^{-10}\text{eV}}\right)\left(\frac{v_\theta}{c}\right)$.
- Formation time $\tau_\vartheta <$ Universe's age $\tau_U \simeq 10^{23}\left(\frac{M_\odot}{M_{BH}}\right) R_{BH}$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

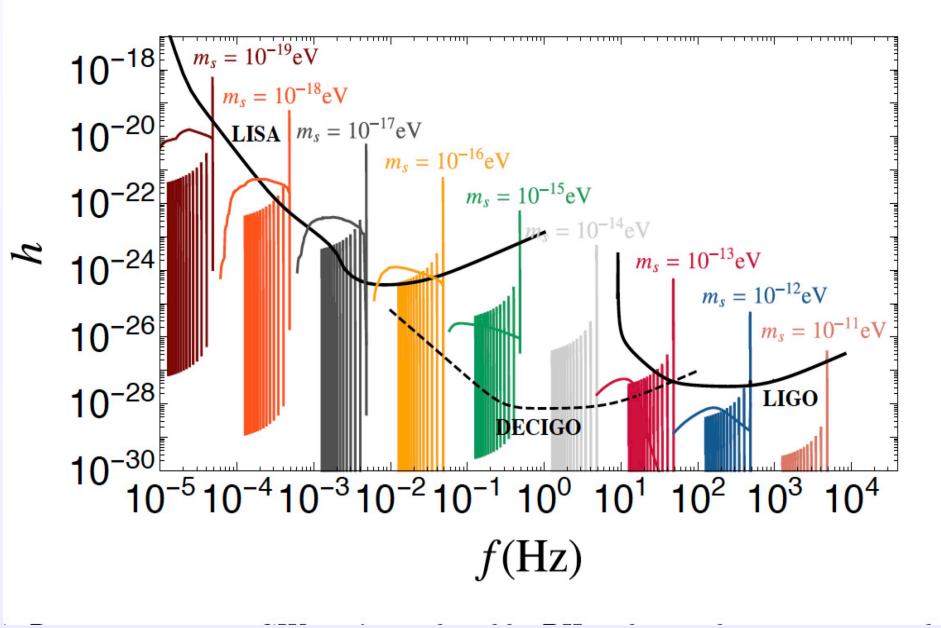




Energy level transition and Monochromic GW

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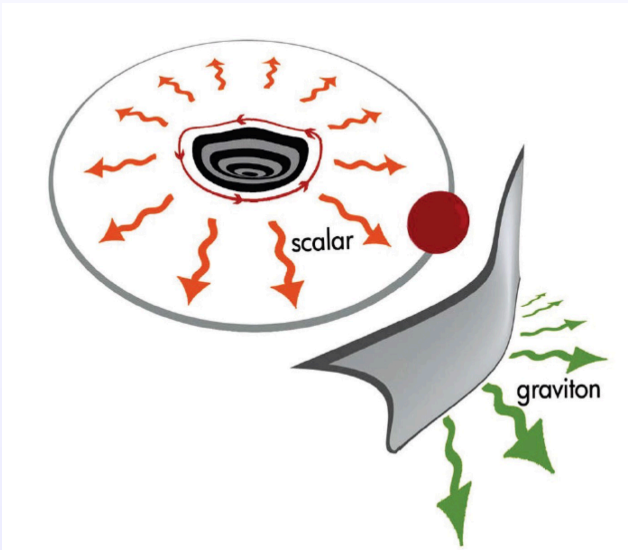


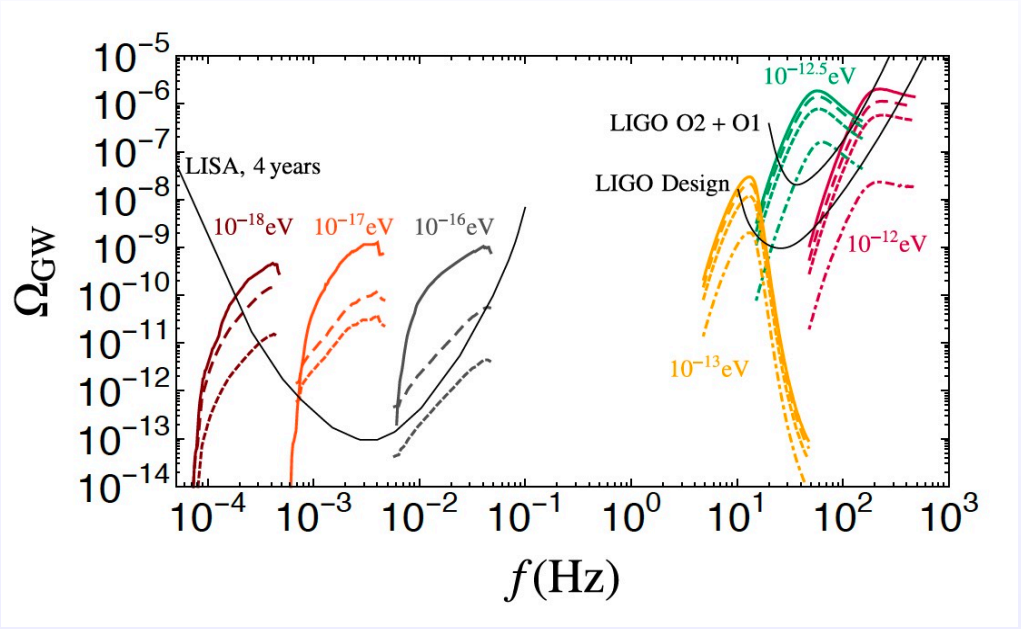


- Energy transition $\vartheta^+ \to \vartheta^- + h$, Strain $h \sim 10^{-19} - 10^{-27}$
- Monochromic GW [cf. Brito-Cardoso-Pani, Superradiance 2020]

Axion annihilation and Stochastic GWs

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

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

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Background
Axion-like DM
Resonance
GW Burst
Chiral GWBs
Early universe
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Detection

Stimulated axion clouds around primordial black holes

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

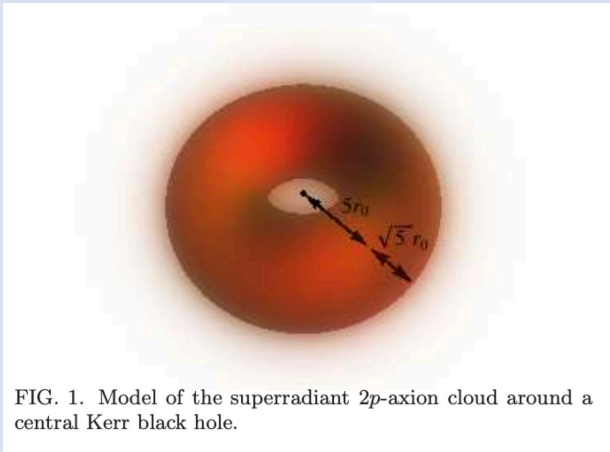
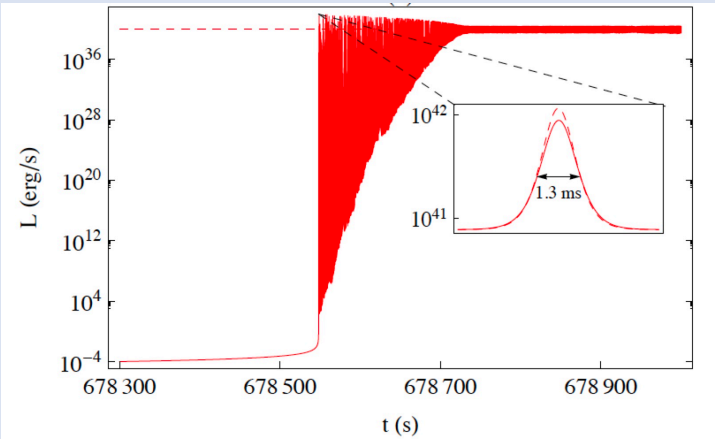


FIG. 1. Model of the superradiant 2*p*-axion cloud around a central Kerr black hole.



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

Pseudoscalar or Axial current to Two-graviton

Chiral GWs
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.

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

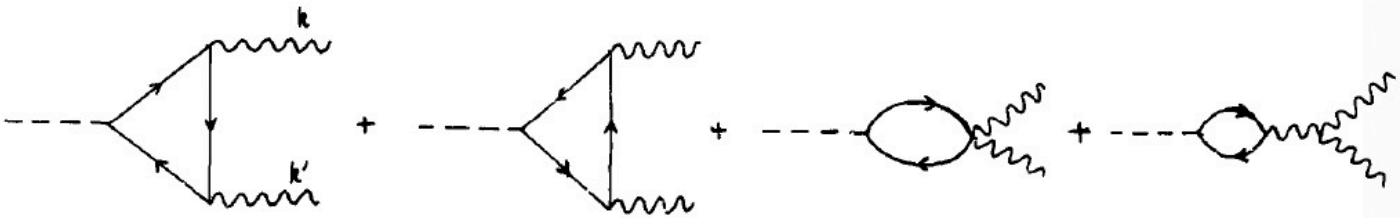
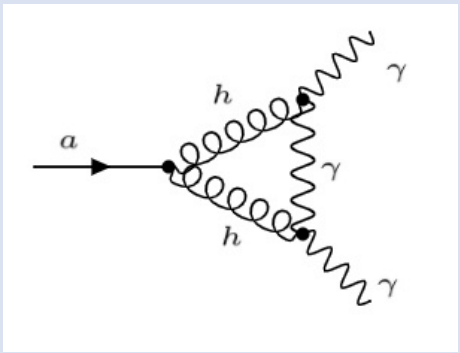


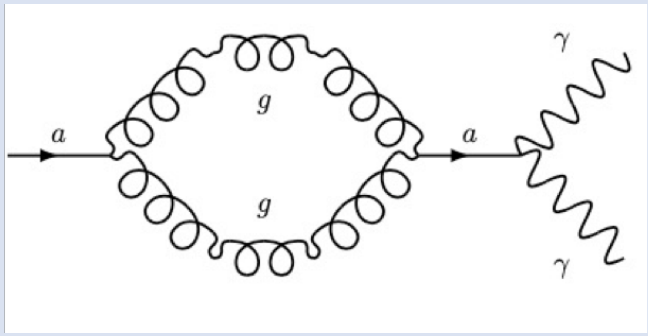
Fig. 1. One-fermion loop contributions to the two-graviton mode.

cf. Partially Conserved Axial vector Current theory (PCAC)

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

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



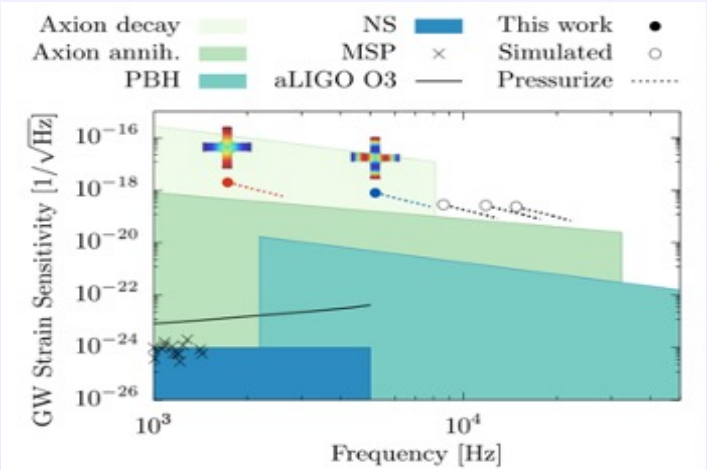
- The triangle diagram is divergent as $\alpha_\gamma \sim \alpha_g(\Lambda_{cs}/M_{pl})^4$, where Λ_{cs} is the cut-off for Chern-Simons theory.
- Two powers of M_{pl} from $h_{\mu\nu}T^{\mu\nu}$ coupling.

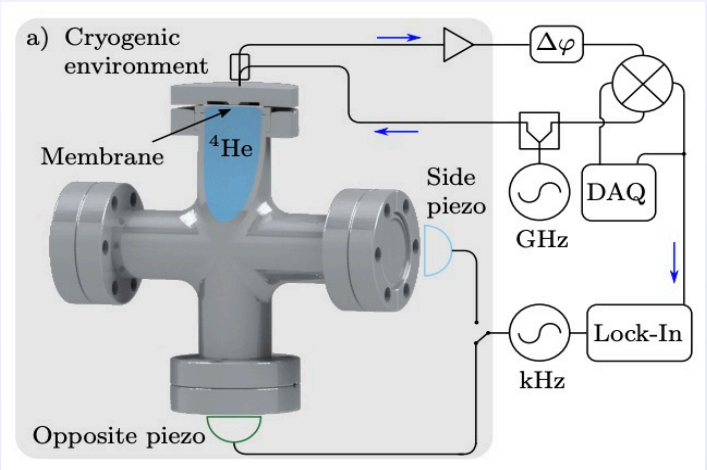
[cf. S. Sun, Y. L. Zhang, Gravitational Wave Burst from Axion Clumps, PRD'21]

GW burst & high frequency detection

Branch Ratio and GWs

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

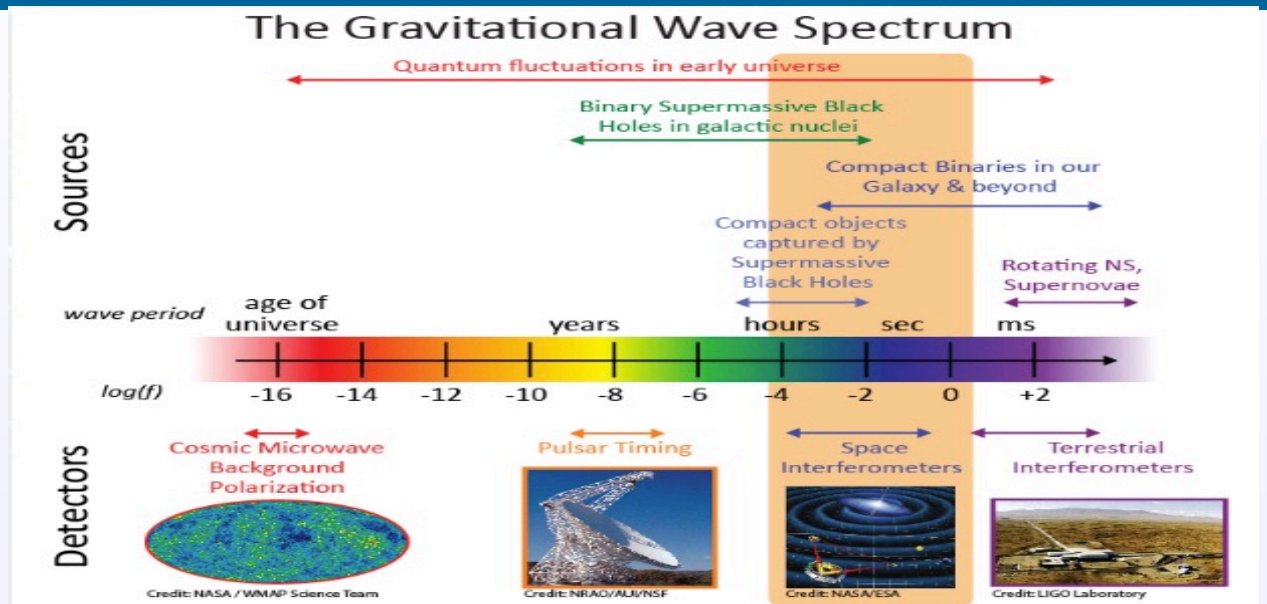


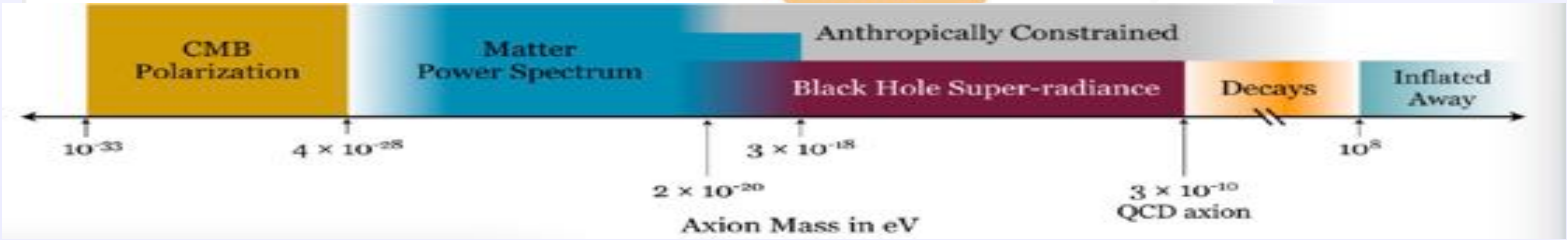


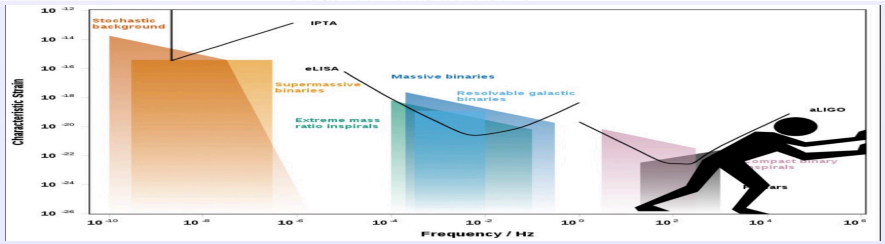
cf. PRD'21, S. Sun, Y. L. Zhang, Gravitational Wave Burst from Axion Clumps.
PRD'21, V. Vadakkumbatt et al, Prototype superfluid gravitational wave detector.
L.H. Du's group, Evidence for chiral graviton modes in fractional quantum Hall liquids

Spectrum of gravitational wave and axion mass

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







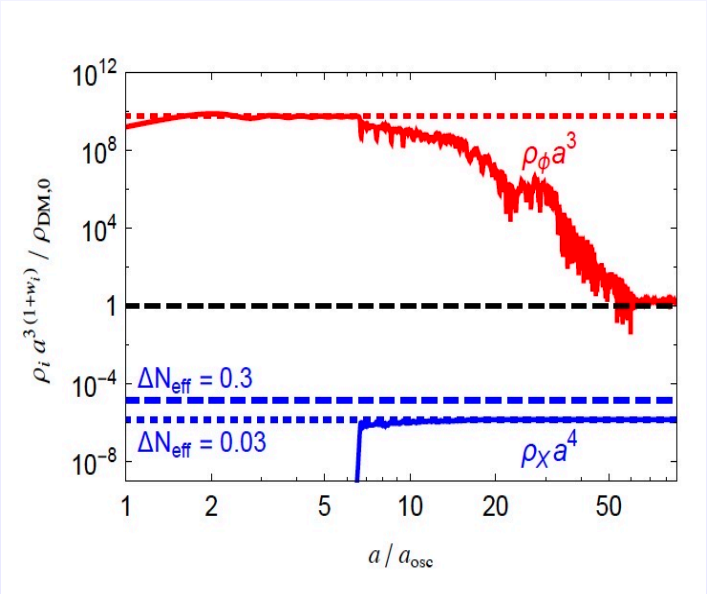
[cf. LISA/Ultra-High-Frequency Gravitational Waves Initiative]

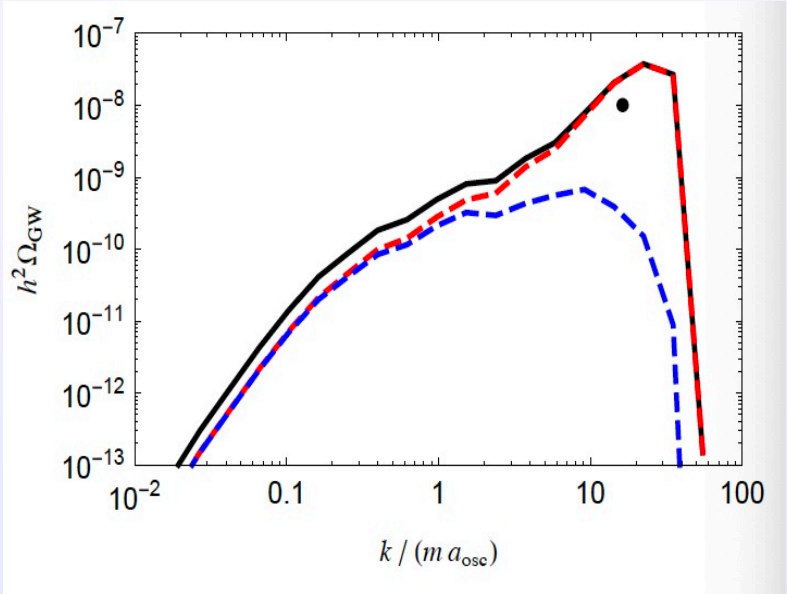
Chiral GWs from Axion-like fields

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

Axions→ 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





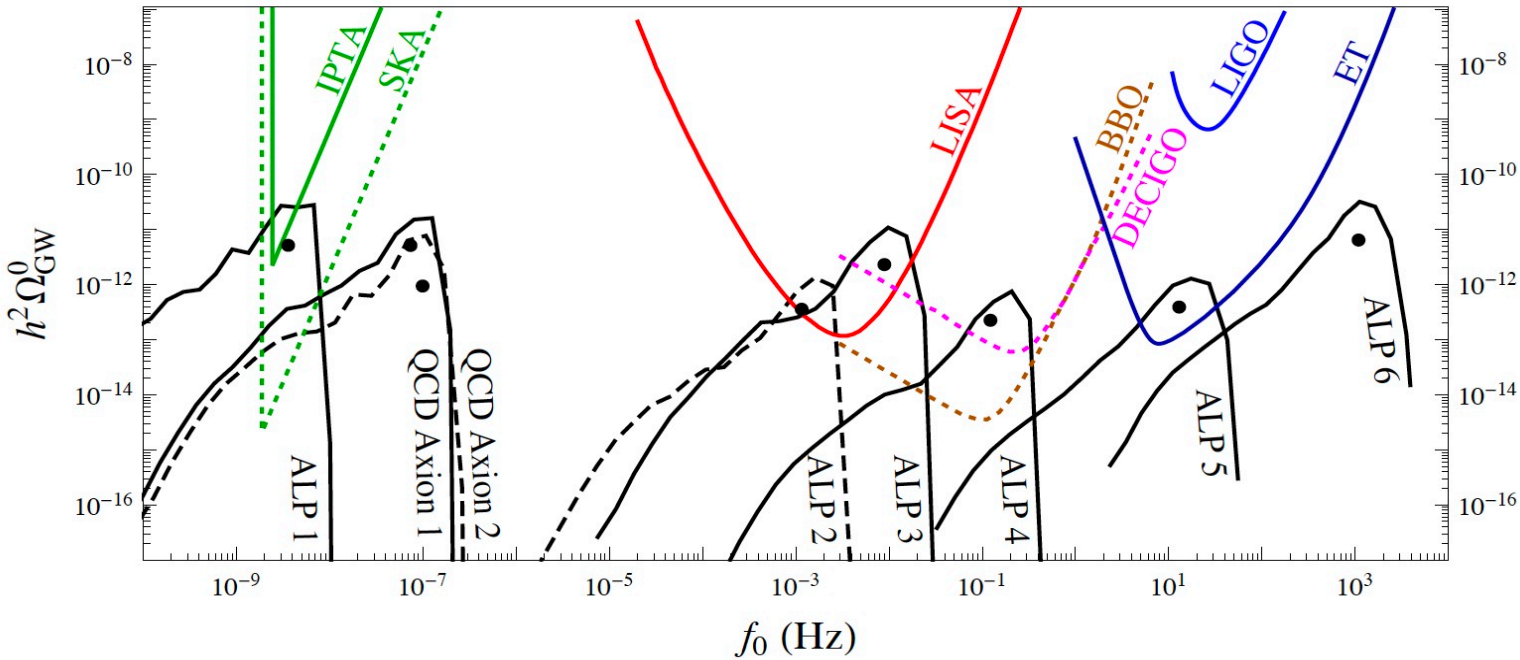
[cf. Machado, Ratzinger, Schwaller, Stefanek, "Audible Axions," JHEP (2019)]

Axion-like fields in early universe

Chiral GWs
Background
Axion-like DM
Resonance
GW Burst
Chiral GWBs
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Chern-Simons
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Axions→ Photons→Induced GWs

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



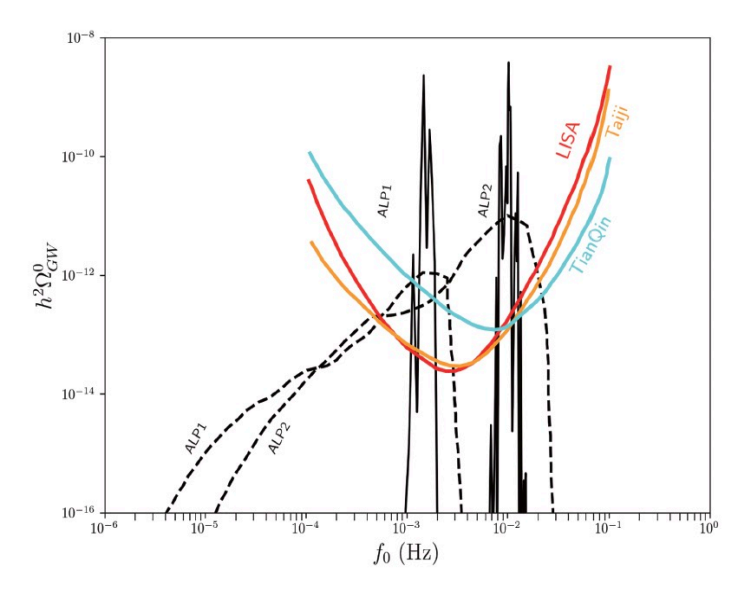
[cf. Machado, Ratzinger, Schwaller, Stefanek, "Audible Axions," JHEP (2019)]

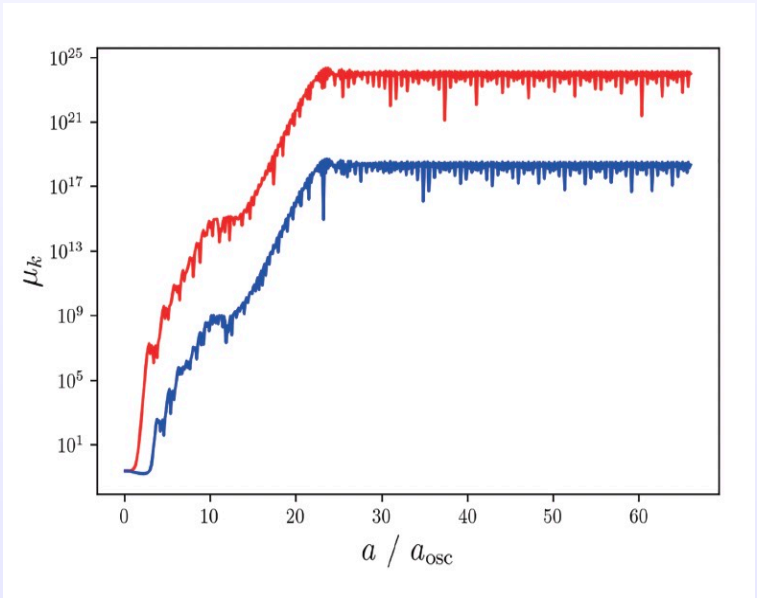
Chiral GWs: Chern-Simons term

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

Axion like fields $\rightarrow$ Chiral GWs

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





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

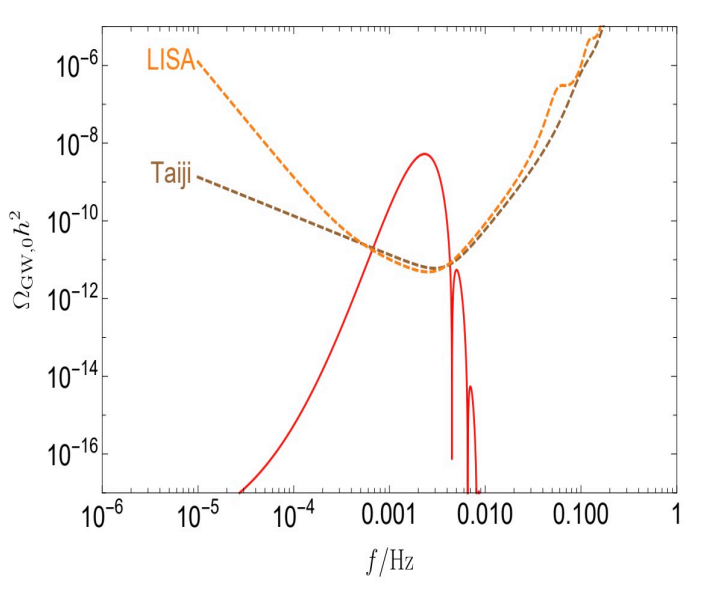
M. Li, S. Sun, Q.S.Yan, Z. Zhao, EPJC(2024)

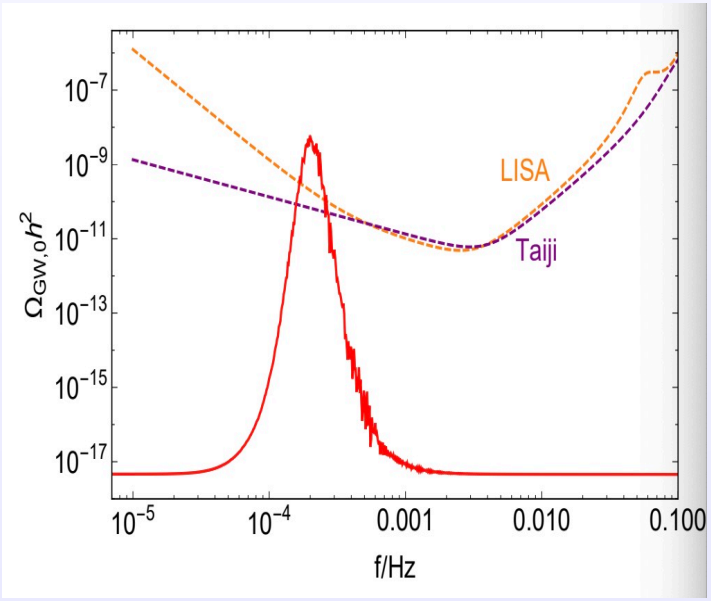
Amplification of the primordial gravitational wave

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

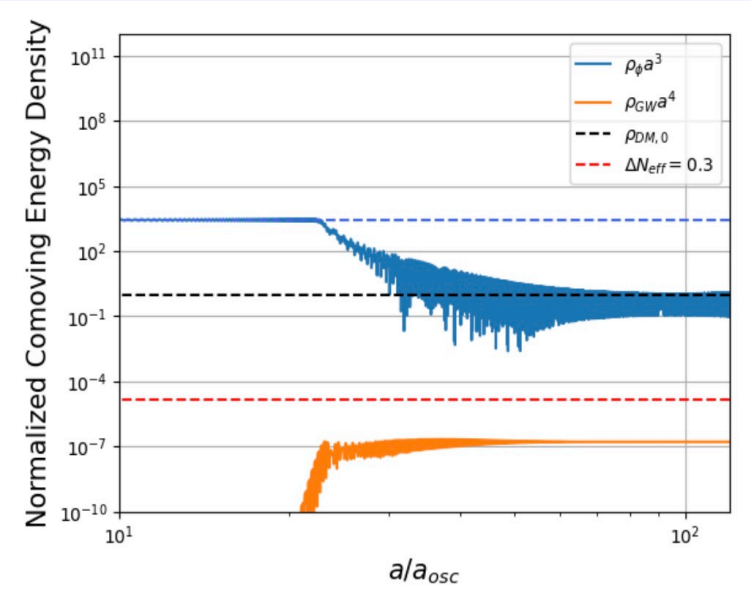
[Z. Z. Peng, Z. M. Zeng, C. Fu and Z. K. Guo, PRD(2022)]

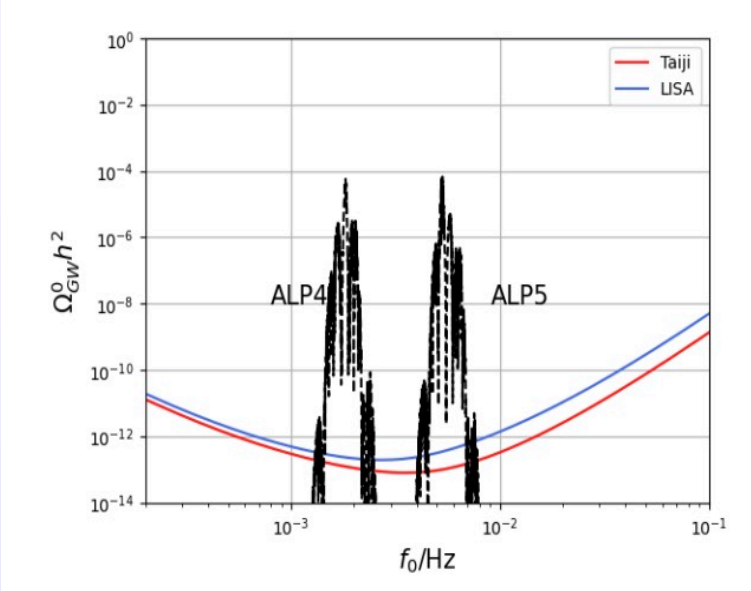
Chiral GWs: Nieh-Yan term

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

Axion like fields $\rightarrow$ Chiral GWs

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

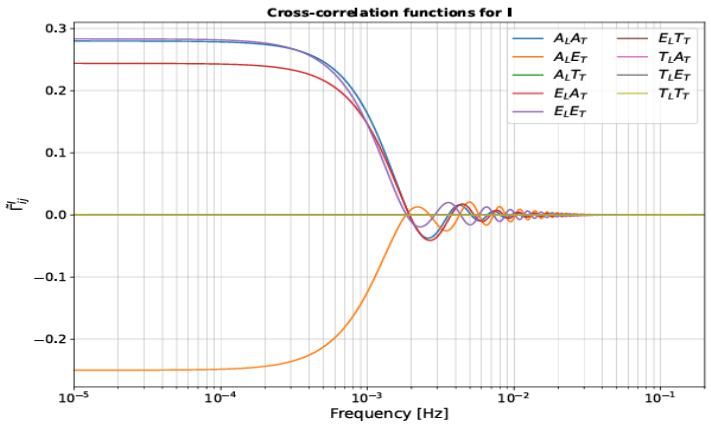




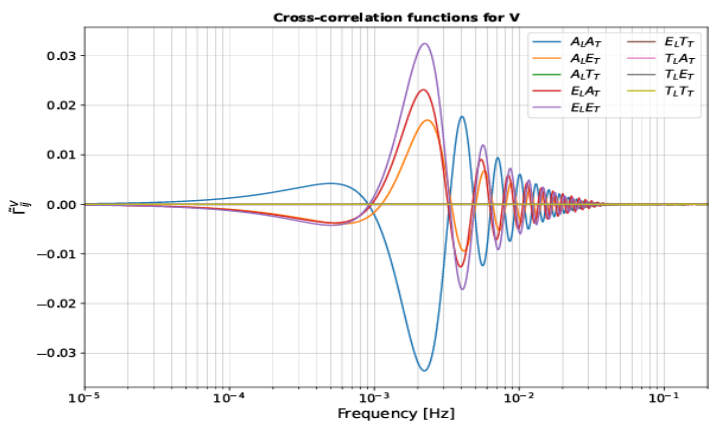
[cf. B. Xu, K. Ding, H. Su, J. Chen and Y. L. Zhang: PDU 49 (2025) 101980]

Detection of chiral GWs and detector networks

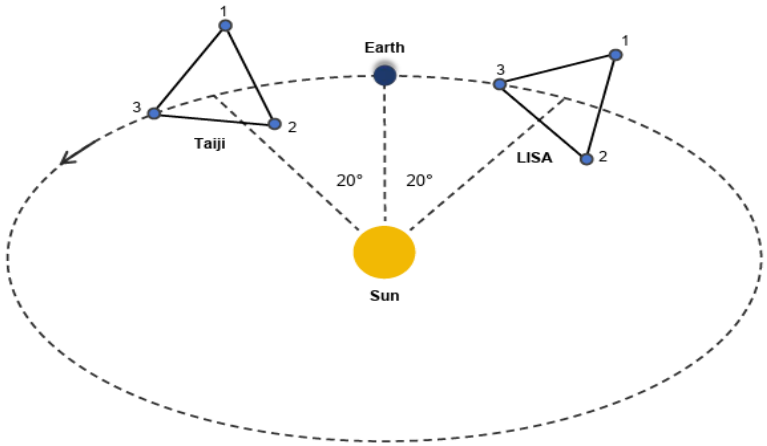
Chiral GWs
Background
Axion-like DM
Resonance
GW Burst
Chiral GWBs
Early universe
Chern-Simons
Nieh-Yan
Detection

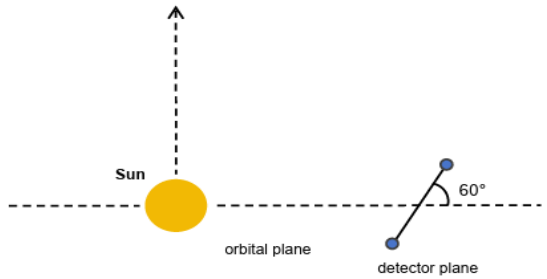


(a) Cross-correlation functions $\tilde{\Gamma}^I_{ij}(f)$ for LISA-Taiji.



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

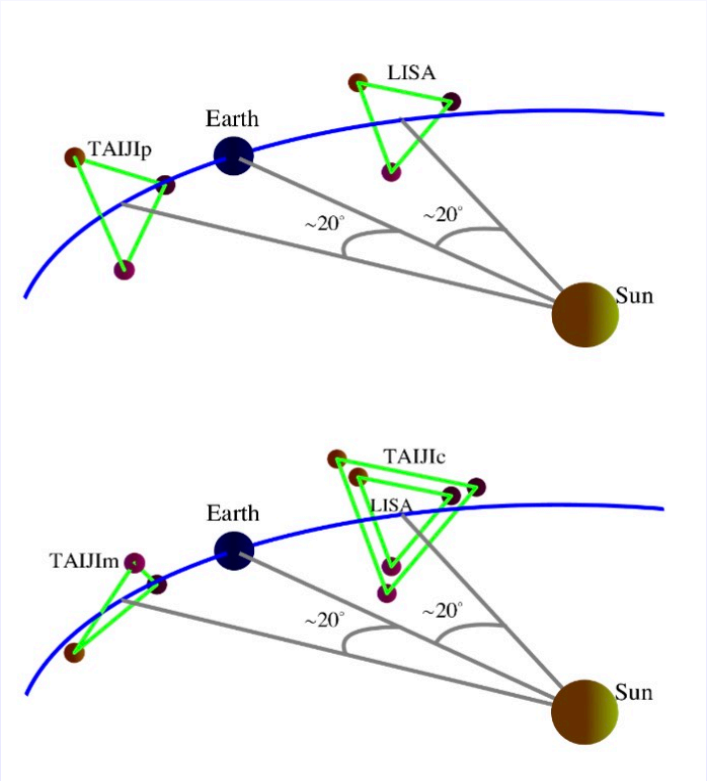


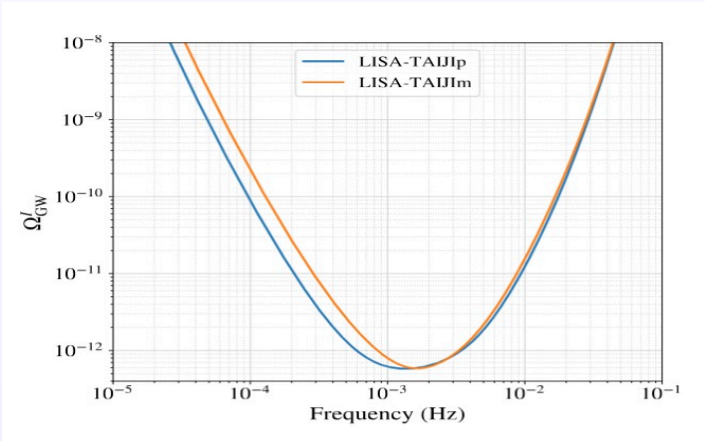


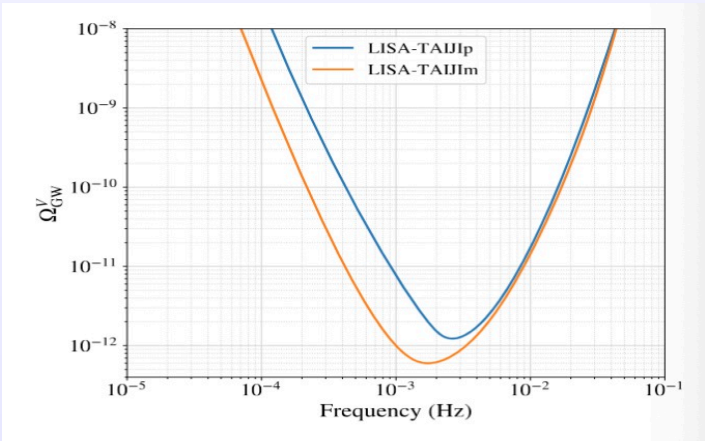
N. Seto, "Measuring Parity Asymmetry of Gravitational Wave Backgrounds with a Heliocentric Detector Network in the mHz Band," PRL **125**, 251101 (2020)
H. Su, B. Xu, J. Chen, C. Liu and Y. L. Zhang, CTP 77 (2025) 115403

Detection of chiral GWs and detector networks

LISA-TAIJIp v.s. LISA-TAIJIm



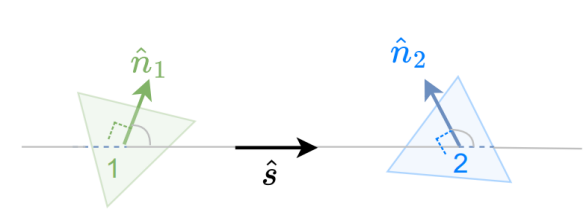


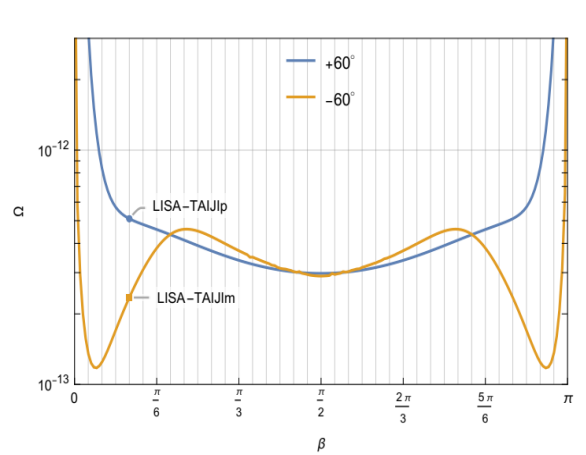


J. Chen, C. Liu, Y. L. Zhang, G. Wang, PRD 111 (2025) 084026

General network of space-borne triangular detectors

Search for circularly polarized gravitational wave background





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

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

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

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

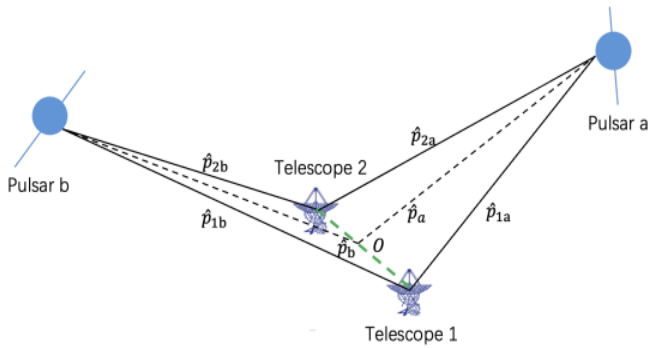
$$\sum_\kappa \gamma_\kappa^I \gamma_\kappa^V = \sum_{m=0}^{2}\sum_{n=0}^{1} b_m^I(\iota)\, b_n^V(\iota)\, X_{mn}^{IV},$$

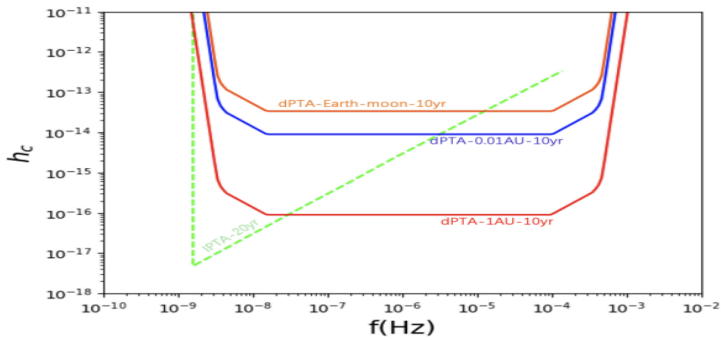
$$X_{mn}^I = \sum_\kappa \chi_\kappa^{Im}\chi_\kappa^{In}, \quad X_{mn}^V = \sum_\kappa \chi_\kappa^{Vm}\chi_\kappa^{Vn}, \quad X_{mn}^{IV} = \sum_\kappa \chi_\kappa^{Im}\chi_\kappa^{Vn},$$

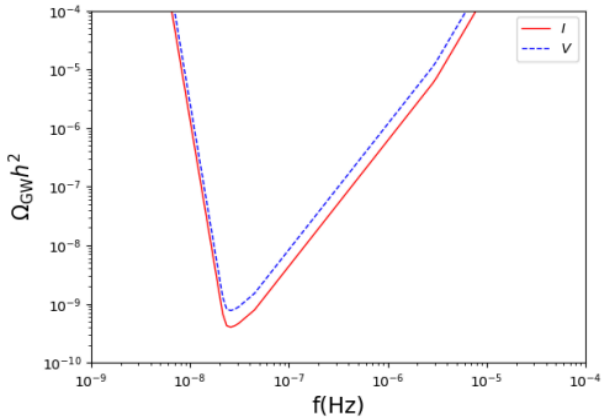
Ju Chen, Chang Liu, Yun-Long Zhang, JCAP 05 (2025) 050

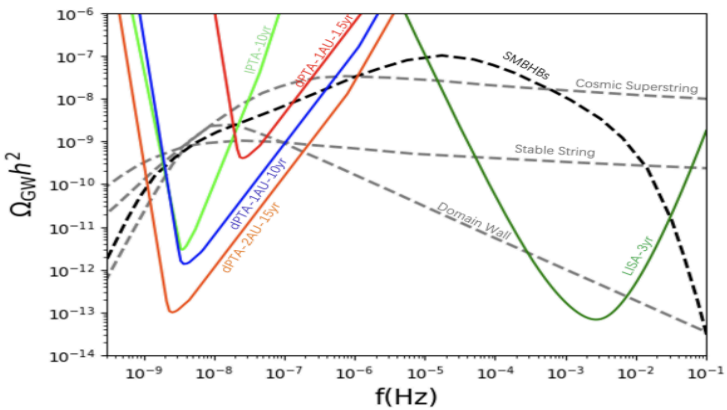
Detecting Chiral Gravitational Wave Background

with a Dipole Pulsar Timing Array(dPTA)









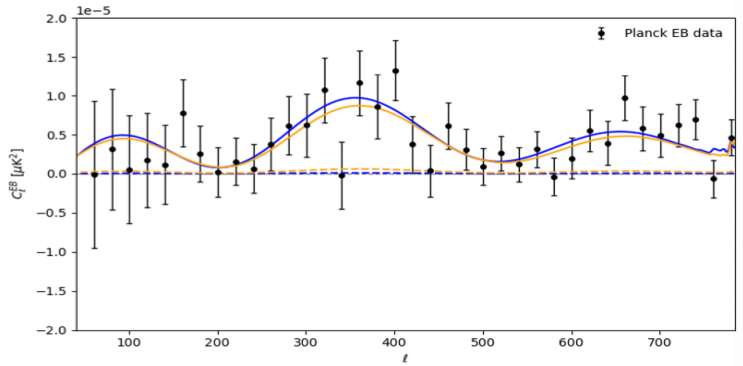
B. Xu, H. Jiang, R.-G. Cai, M. Sasaki, Yun-Long Zhang, arXiv: 2604.08141

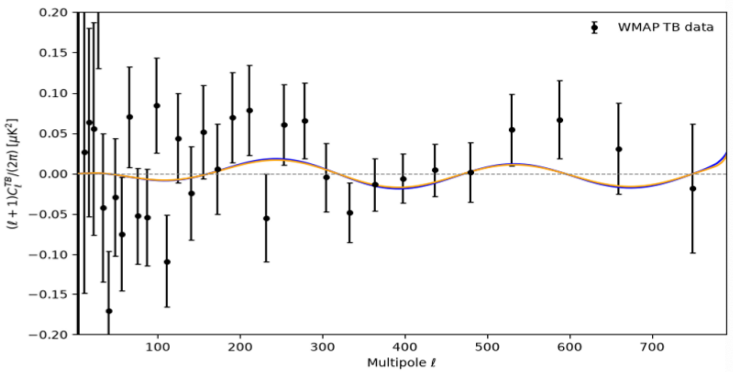
Chiral GWs
Background
Axion-like DM
Resonance
GW Burst
Chiral GWBs
Early universe
Chern-Simons
Nieh-Yan
Detection

Detecting Chiral Gravitational Wave Background

Chiral GWs
Background
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Chiral GWBs
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Chern-Simons
Nieh-Yan
Detection

with EB in TB in cosmic microwave background(CMB)





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

$$C_\ell^{TB} = -\frac{1}{2\ell+1}\sum_{\ell' L}\left\{C_L^{\phi\Omega}G^{\phi}_{\ell\ell' L}K_{\ell\ell' L}C_{\ell'}^{TE}P^{-}_{\ell\ell' L} - \left[C_L^{\phi\Omega}G^{\Omega}_{\ell\ell' L}K_{\ell\ell' L} - 2C_L^{\phi\psi}H^{\psi}_{\ell\ell' L}K_{\ell\ell' L}\right]C_{\ell'}^{TE}P^{+}_{\ell\ell' L}\right\}$$

$$C_L^{\phi\Omega} = \int \frac{k^2\mathrm{d}k}{2\pi^2}\left[P_{\mathrm{L}}(k)-P_{\mathrm{R}}(k)\right]F_L^{\phi}F_L^{\Omega},$$

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

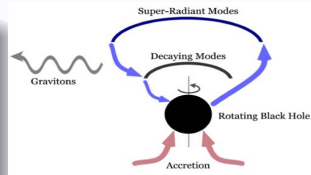
c.f. B. Xu, Yun-Long Zhang, arXiv: 2610.29182
Parity-odd CMB Correlations induced by a Chiral Gravitational Wave Background

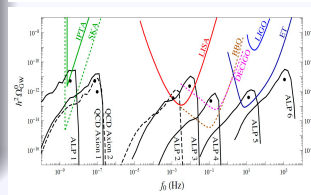
Summary and Outlook

Chiral GWs
Background
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Early universe
Chern-Simons
Nieh-Yan
Detection

GWs from ultralight dark matter (BH superradiance)

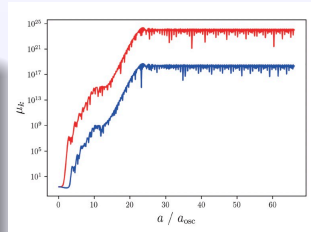
- ULDM annihilation $\vartheta + \vartheta \to h$ (Stochastic GW)
  Energy transition $\vartheta^+ \to \vartheta^- + h$ (Monochromic)
- **EM+ GW Burst** $\sim \vartheta F\tilde{F} + \vartheta R\tilde{R}$ $(\vartheta \to \gamma\gamma + hh)$

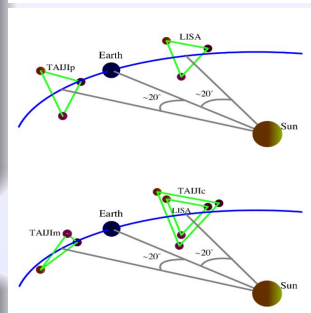




Chiral GWs from axion-like DM (early universe)

- 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 & Ligo-Virgo-KIGRA networks
- Pulsar Timing Arrays & Astrometry & CMB

