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Probing Spin-2 Ultralight Dark Matter with Space-based Gravitational Wave Detectors in the mHz Regime

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In collaboration with

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Outline

- Background: GW detector and spin-2 ultralight dark matter (ULDM)
  - GW detection
    - Space-based GW detectors
  - Using GW detectors to probe ULDM
  - **Spin-2 ULDM**: possible candidate of dark matter
- Our work: Using **space-based** GW detectors to probe **spin-2 ULDM**
  - Change of arm length due to its coupling with matter
  - Applying time delay interferometry (TDI) algorithm to calculate sensitivities
  - Strong constraint on spin-2 ULDM

Background: GW Astronomy

- Ground-based GW detectors (~100Hz)
  - LIGO、Virgo、KAGRA
- Space-based GW detectors (mHz)
  - LISA、Taiji、TianQin
- Pulsar Timing Arrays (nHz)
  - NanoGrav、PPTA、EPTA、CPTA InPTA
- CMB B-mode polarization (10^{-15} Hz)
  - BICEP、Simons、AliCPT

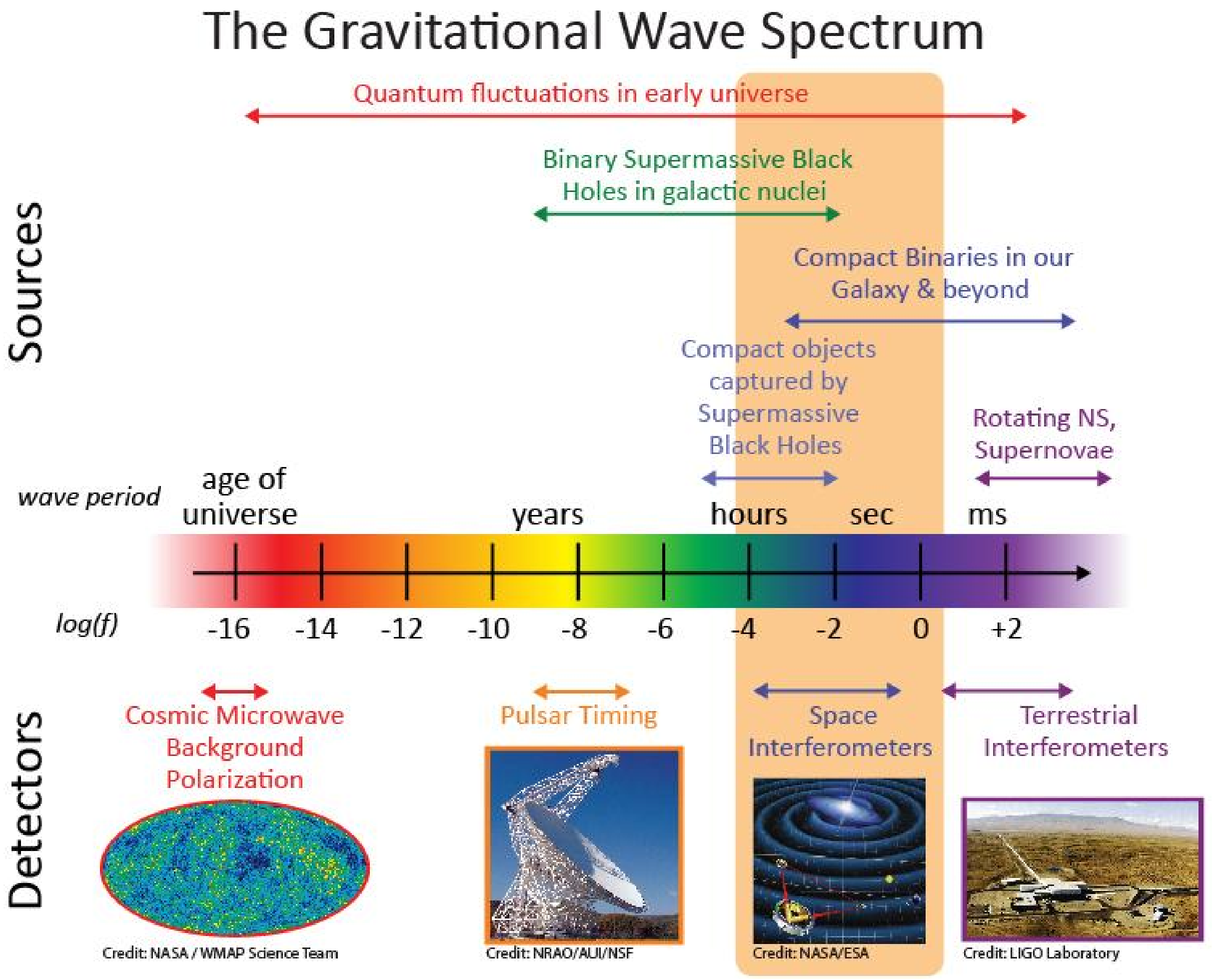
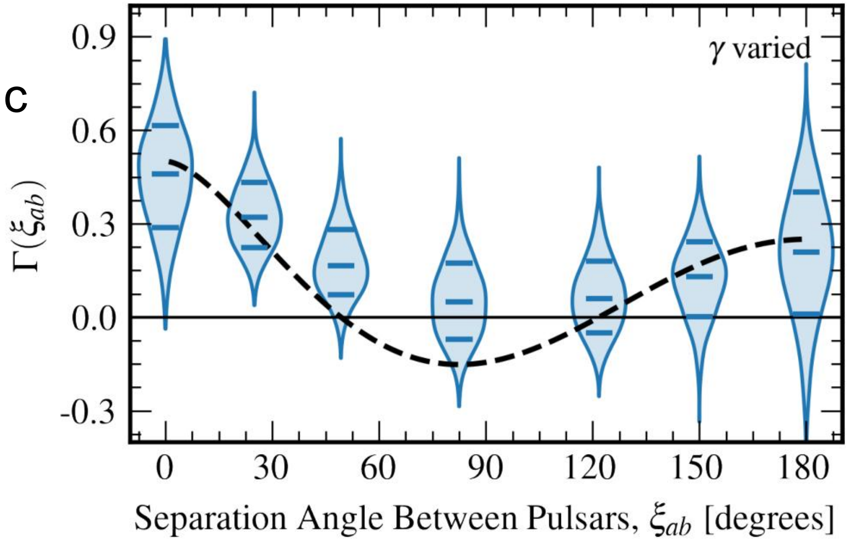


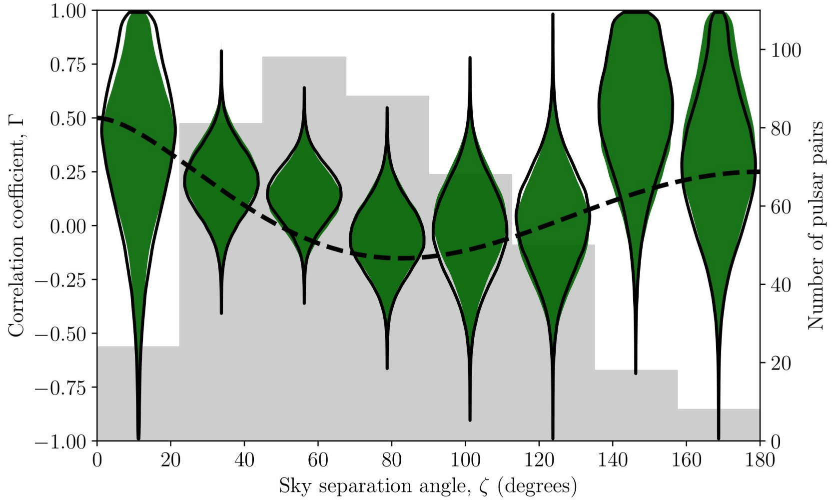
Image from https://lisa.nasa.gov/

Background: Pulsar Timing Array (PTA)

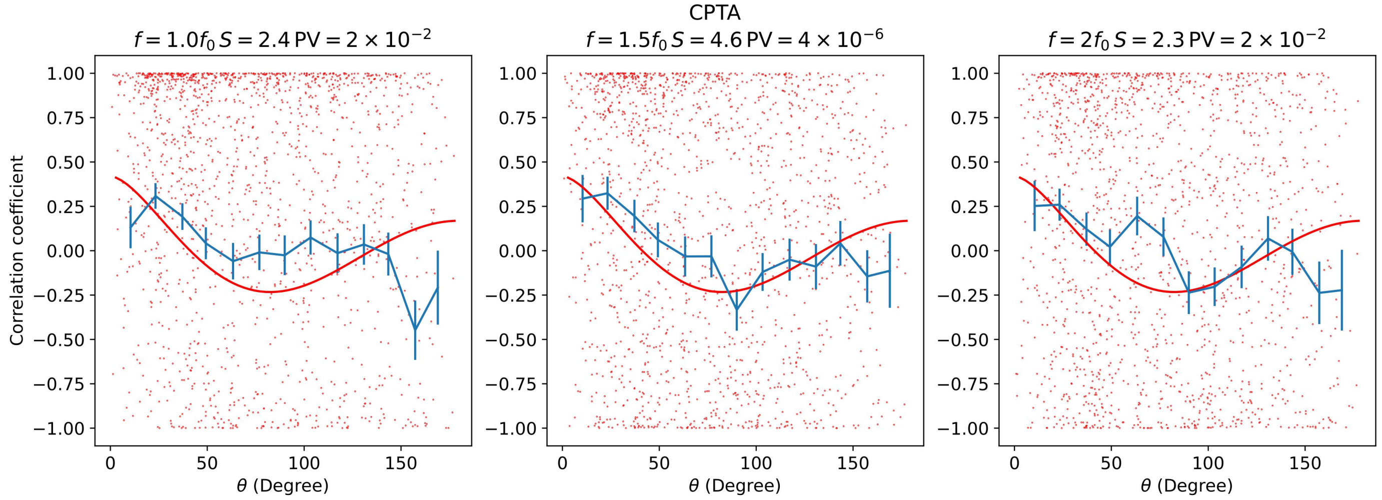
- Evidence for stochastic GW background
- Observation of the Hellings-Downs curve



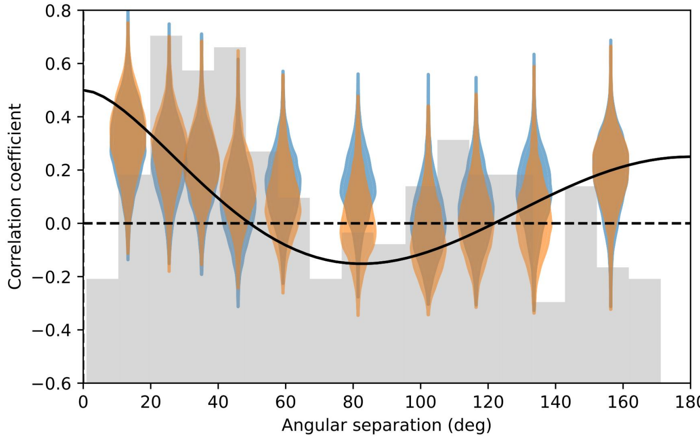
G. Agazie et al, [NANOGrav], Astrophys. J. Lett.,2023



D. J. Reardon et al, [PPTA], Astrophys. J. Lett., 2023



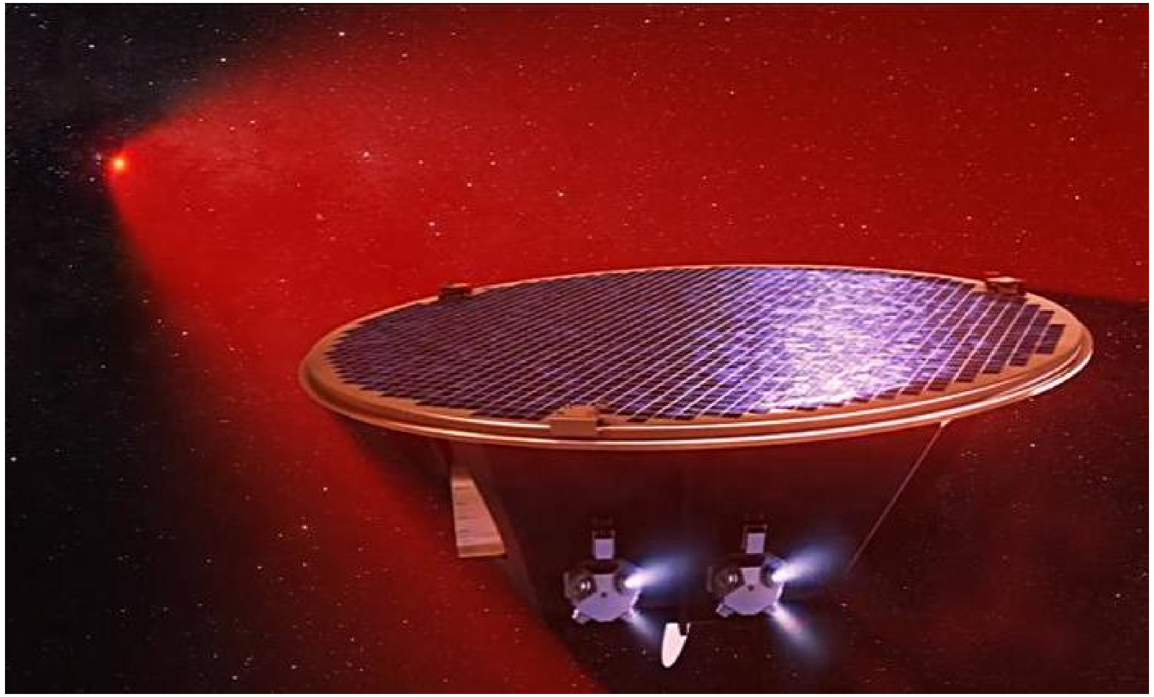
Heng Xu et al, [CPTA], Res.Astron.Astrophys., 2023



J. Antoniadis et al, [EPTA], Astron. Astrophys., 2023

Background: Space-based GW Detectors

- Various projects in preparation: LISA, Taiji, TianQin
- Expanding our detection range to low-frequency GWs



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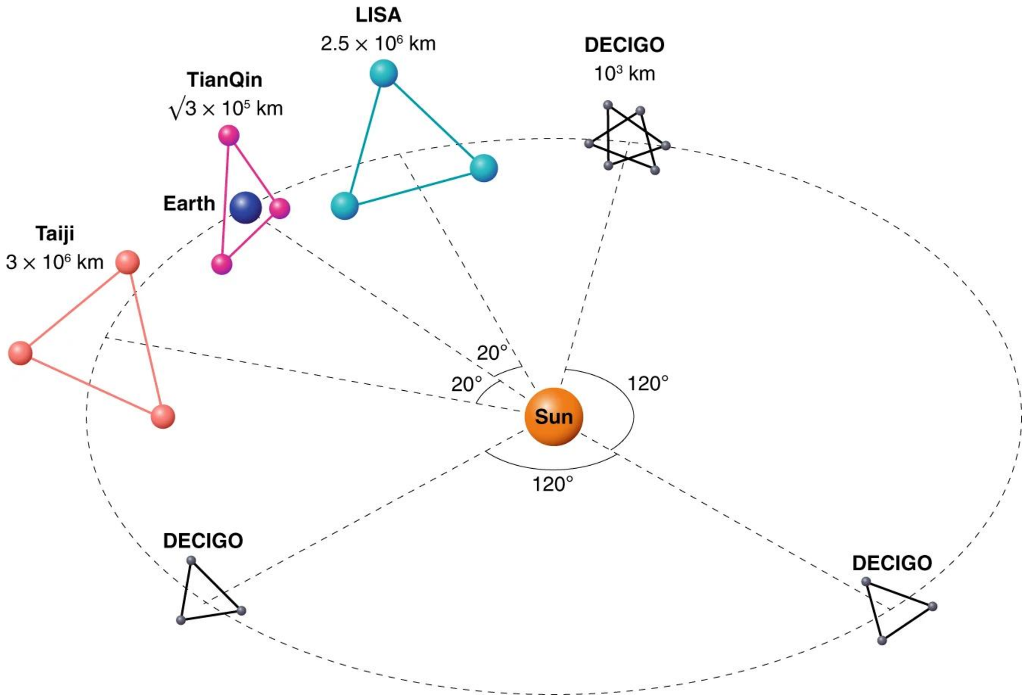
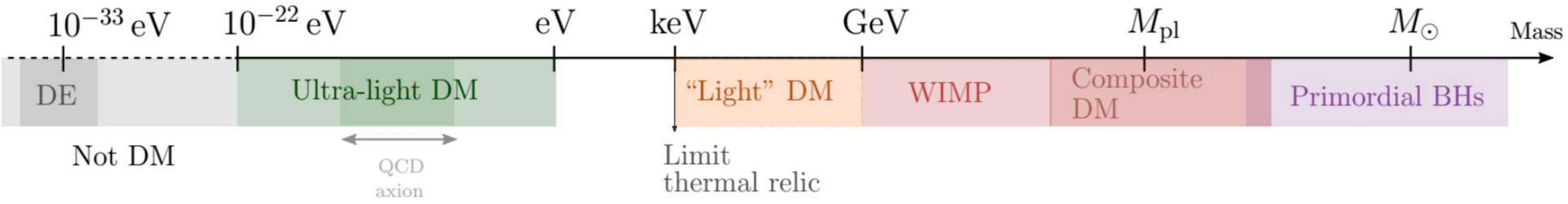


Y. Gong, et al, Nature Astron. **5**, no.9, 881 (2021)

Background: Ultralight Dark Matter (ULDM)

- Other physical effects may affect GW detectors
- **Ultralight dark matter**
  - The mass range of ULDM is compatible with GW detectors: $m = 2\pi f$
    - 10^{-22} eV： nHz： PTA (A. Khmelnitsky, V. Rubakov, JCAP **02**, 019 (2014))
    - 10^{-18}~10^{-16} eV： 0.1mHz~1Hz： LISA、Taiji
      (Jiang-Chuan Yu, Yue-Hui Yao, Yong Tang, Yue-Liang Wu, Phys. Rev. D **108**, no.8, 8 (2023))
    - 10^{-13}~10^{-11} eV： ~100Hz： LIGO、Virgo、KAGRA
      (A. Pierce, K. Riles, Yue Zhao, Phys. Rev. Lett. **121**, no.6, 061102 (2018))
  - Small scale problems of ΛCDM may be resolved by ULDM
  - Early research on axion, ALP. Later: dark photon, **spin-2 ULDM**
  - Indirect detection： effects on binary inspiral (eg. dynamic friction)



E. G. M. Ferreira, Astron. Astrophys. Rev. **29**, no.1, 7 (2021)

Background: Spin-2 ULDM

- Theoretical origin: bimetric gravity (a generalization of dRGT massive gravity)

  (S. F. Hassan, R. A. Rosen, JHEP **02**, 126 (2012))

  - Mass spectrum: 1 massless graviton + 1 massive graviton
  - The massive graviton: possible candidate for dark matter
- Probing spin-2 ULDM with GW detectors based on:
  - Coupling with ordinary matter (J. M. Armaleo, D. L. Nacir, F. R. Urban, JCAP **09**, 031 (2020))
  - Gravitational effects (Yu-Mei Wu, Zu-Cheng Chen, Qing-Guo Huang, JCAP **09**, 021 (2023))
- GW detectors can be used to probe spin-2 ULDM

Background: Spin-2 ULDM

- Derived directly from modified gravity
- Spin-2 ULDM comes from the extra spin-2 degrees of freedom in bimetric gravity
- The action of bimetric gravity

$$S=\frac{M_{\rm Pl}^2}{1+\alpha^2}\int d^4x\left[\sqrt{|\tilde{g}|}R(\tilde{g})+\alpha^2\sqrt{|f|}R(f)-2\frac{\alpha^2 M_{\rm Pl}^2}{1+\alpha^2}\sqrt{|\tilde{g}|}V(\tilde{g},f;\beta_n)\right]+\int d^4x\sqrt{|\tilde{g}|}\mathcal{L}_{\rm m}(\tilde{g},\Psi)$$

- Perturbative expansion: $g_{\mu\nu}=\bar{g}_{\mu\nu}+\epsilon h_{\mu\nu}\quad f_{\mu\nu}=\bar{f}_{\mu\nu}+\epsilon\ell_{\mu\nu}\quad \bar{f}_{\mu\nu}=\bar{g}_{\mu\nu}$
- Mass eigenstates by linear combinations of the two metrics:

$$h_{\mu\nu}=\frac{1}{M_{\rm Pl}}(\hat{g}_{\mu\nu}-\alpha M_{\mu\nu})$$

$$\ell_{\mu\nu}=\frac{1}{M_{\rm Pl}}(\hat{g}_{\mu\nu}+\frac{1}{\alpha}M_{\mu\nu})$$

Background: Spin-2 ULDM

$$S = \frac{M_{\rm Pl}^2}{1+\alpha^2}\int d^4x\left[\sqrt{|\tilde{g}|}R(\tilde{g}) + \alpha^2\sqrt{|f|}R(f) - 2\frac{\alpha^2 M_{\rm Pl}^2}{1+\alpha^2}\sqrt{|\tilde{g}|}V(\tilde{g}, f; \beta_n)\right] + \int d^4x\sqrt{|\tilde{g}|}\mathcal{L}_{\rm m}(\tilde{g}, \Psi)$$

- Resummation gives back to GR and additional spin-2 ULDM

$$S^{(2)} = \int d^4x\sqrt{|\bar{g}|}\left[\mathcal{L}^{(2)}_{\rm GR}(\mathcal{G}) + \mathcal{L}^{(2)}_{\rm FP}(M) - \frac{1}{M_{\rm Pl}}(\mathcal{G}_{\mu\nu} - \alpha M_{\mu\nu})T^{\mu\nu}(\Psi)\right]$$

where $\mathcal{L}^{(2)}_{\rm FP}(M)$ is the Fierz-Pauli lagrangian for spin-2 ULDM

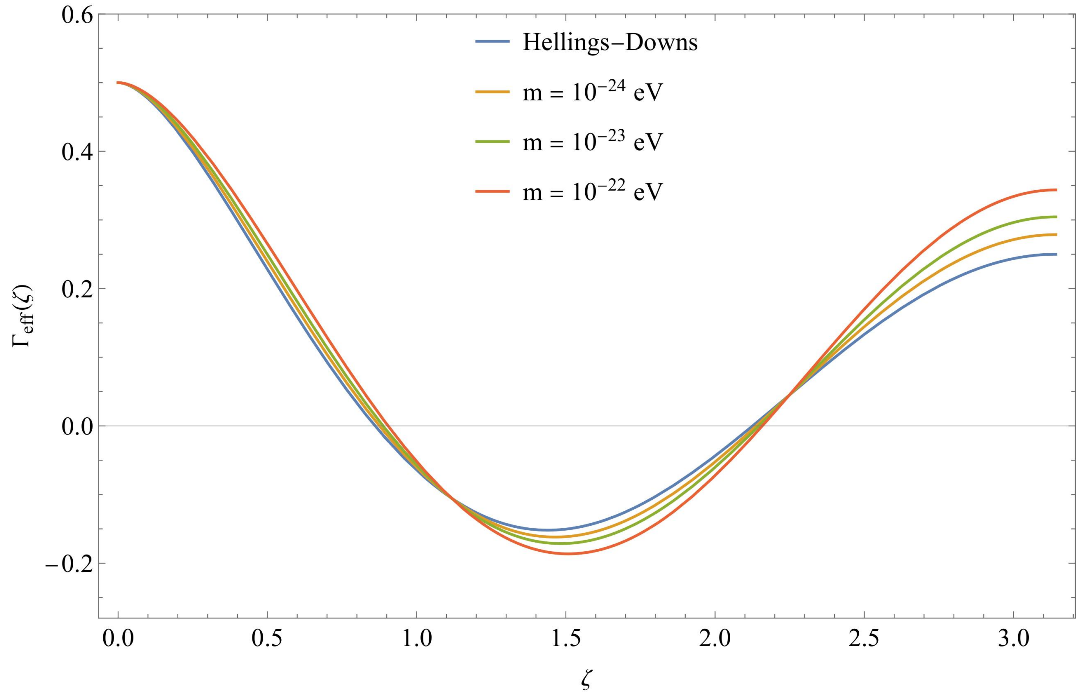
$$\mathcal{L}^{(2)}_{\rm FP}(M) = \mathcal{L}^{(2)}_{\rm GR}(M) - \frac{m^2}{4}(M_{\mu\nu}M^{\mu\nu} - M^2)$$

Our Previous Work: Effects of Spin-2 ULDM on PTAs

- The presence of spin-2 ULDM deforms the Hellings-Downs curve

Models	B	$\ln(B)$	χ^2
Hellings-Downs	-	-	10.25
Genetic Algorithms	-	-	2.83
Ultralight vector DM	0.29	-1.24	6.39
Spin-2 ultralight DM	0.80	-0.22	8.43
Massive gravity	1.51	0.41	6.91
Non-Gaussianity of SGWB	0.06	-2.85	3.17

R. Arjona, S. Nesseris and S. Kuroyanagi, arXiv:2412.12975

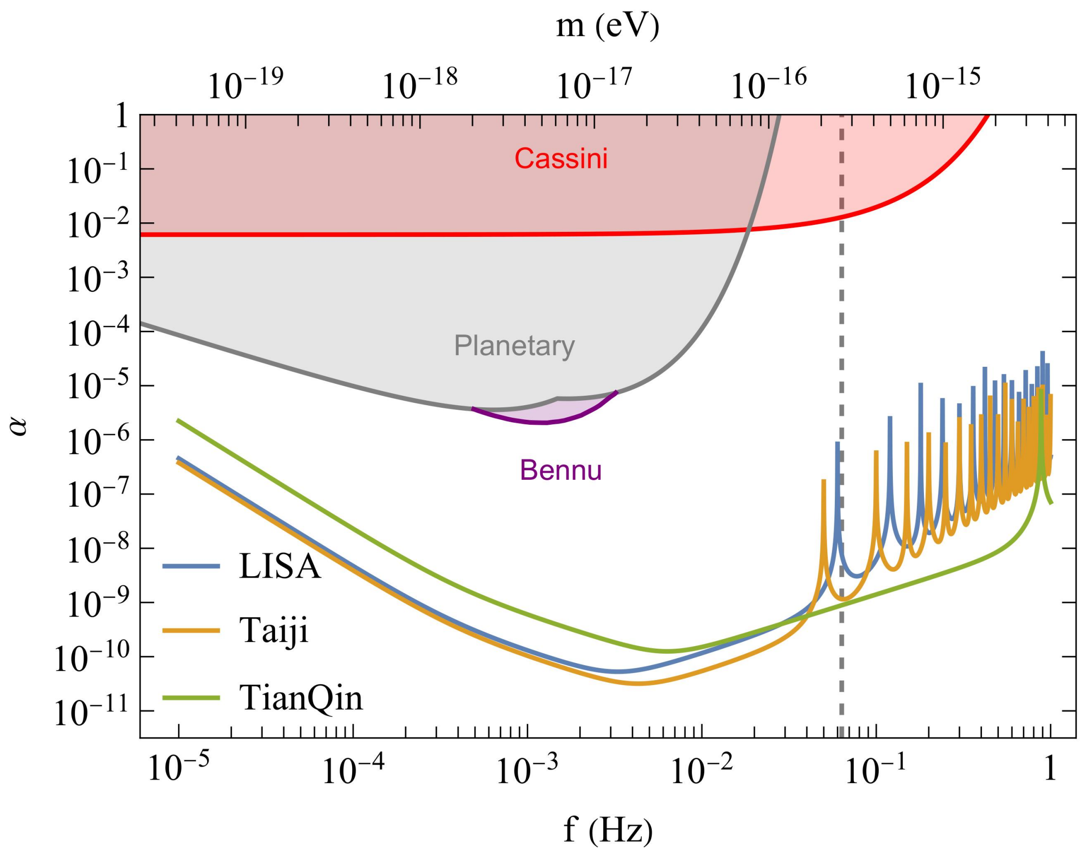


$\alpha = 10^{-6}$

RG Cai, JR Zhang and YL Zhang, Phys. Rev. D 110, no.4, 044052 (2024)

Our Work: Probing Spin-2 ULDM Using Space-based GW Detectors

- Space-based GW detectors are powerful tools for probing spin-2 ULDM.
- Asymmetric time delay interferometry (TDI) channels have better response.
- Strong constraints for α: around 10^{-10}



JR Zhang, J Chen, HS Jiao, RG Cai and YL Zhang, Phys. Rev. D **112**, no.6, 064030 (2025).

Spin-2 ULDM

- Treating spin-2 ULDM as a coherent classical field:

$$\frac{\rho_{\rm DM}}{m\cdot(mv)^3}\approx 10^{67}\left(\frac{\rho_{\rm DM}}{0.4\ \mathrm{GeV/cm^3}}\right)\left(\frac{10^{-16}\ \mathrm{eV}}{m}\right)^4\left(\frac{10^{-3}}{v}\right)^3$$

$$T_{\rm coh}=\frac{2\pi}{\frac{1}{2}mv^2}\approx 8\times 10^7\ \mathrm{s}\left(\frac{10^{-16}\mathrm{eV}}{m}\right)$$

$$L_{\rm coh}=\frac{2\pi}{mv}\approx 1\times 10^{13}\ \mathrm{m}\left(\frac{10^{-16}\mathrm{eV}}{m}\right)$$

- The field of spin-2 ULDM can be written as

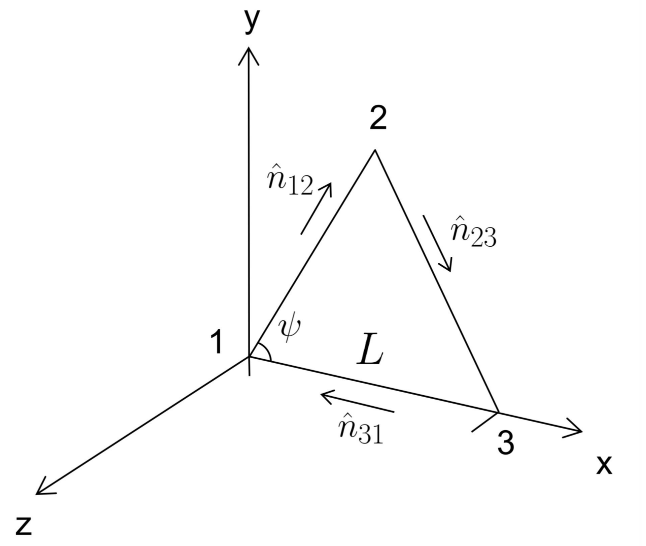
$$M_{ij}(t,\vec{x})=\frac{\sqrt{2\rho_{\rm DM}}}{\sqrt{5}m}\sum_A \varepsilon_{ij}^A e^{i(\omega t-m\vec{v}\cdot\vec{x}+\delta_A)}$$

Change of Arm Length

- Trick: work with $\tilde{g}_{\mu\nu} = \mathcal{G}_{\mu\nu} + \frac{\alpha}{M_{\rm Pl}} M_{\mu\nu}$

- Geodesic equations for photons $p^{\mu} = \nu(1, -\hat{n}^i_{rs})$

$$\frac{\mathrm{d}p^t}{\mathrm{d}u} = \frac{\alpha\nu^2}{2M_{\rm Pl}} \partial_t M_{ij} \hat{n}^i_{rs} \hat{n}^j_{rs}$$



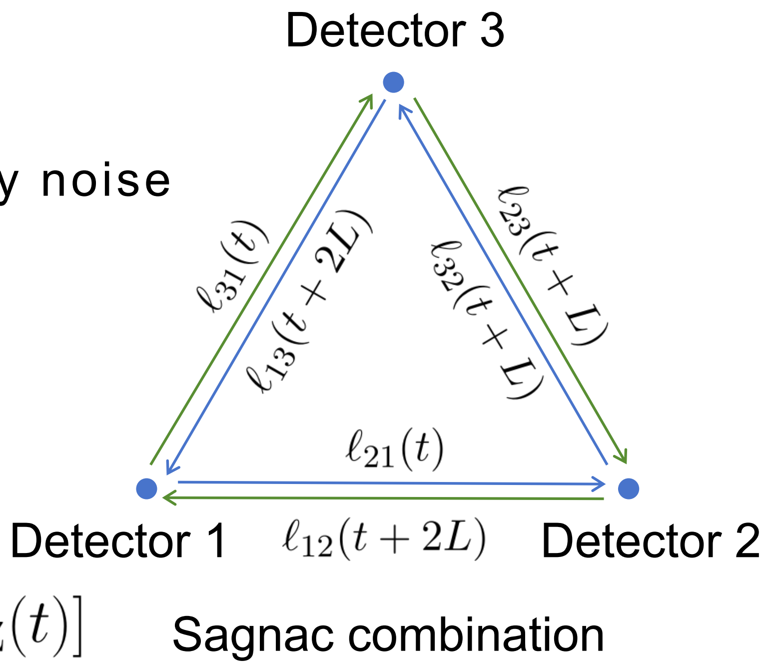
- Frequency shift of the photon

$$z_{rs}(t) = \frac{\Delta\nu}{\nu_o} = -\frac{\alpha}{2M_{\rm Pl}(1 + \vec{v}\cdot\hat{n}_{rs})} \hat{n}^i_{rs}\hat{n}^j_{rs}[M_{ij}(t_r, \vec{x}_r) - M_{ij}(t_s, \vec{x}_s)],$$

- Change of arm length

$$s(t) = \frac{\Delta L}{L} = \frac{\ell_{rs} - L}{L} = -\frac{\alpha \hat{n}^i_{rs}\hat{n}^j_{rs}\left[M_{ij}(t+L, \vec{x}_r) - M_{ij}(t, \vec{x}_s)\right]}{2iM_{\rm Pl} m L(1 + \vec{v}\cdot\hat{n}_{rs})}$$

Time Delay Interferometry (TDI)



- In realistic situation, TDI is needed to reduce laser frequency noise
- Using TDI to construct the virtual equal arm interferometer
- Michelson: (1→2→1) - (1→3→1)
- Michelson X(YZ): (1→2→1→3→1) - (1→3→1→2→1)
- AET:

$$s_{\mathrm{A}}(t)=\frac{1}{\sqrt{2}}[s_{\mathrm{Z}}(t)-s_{\mathrm{X}}(t)] \quad s_{\mathrm{E}}(t)=\frac{1}{\sqrt{6}}[s_{\mathrm{X}}(t)-2s_{\mathrm{Y}}(t)+s_{\mathrm{Z}}(t)]$$

$$s_{\mathrm{T}}(t)=\frac{1}{\sqrt{3}}[s_{\mathrm{X}}(t)+s_{\mathrm{Y}}(t)+s_{\mathrm{Z}}(t)]$$

- Sagnac $\alpha(\beta\gamma)$: (1→3→2→1) - (1→2→3→1)

$$s_\alpha(t)=\frac{1}{3L}\left[\ell_{31}(t)+\ell_{23}(t+L)+\ell_{12}(t+2L)-\ell_{21}(t)-\ell_{32}(t+L)-\ell_{13}(t+2L)\right]$$

- Different TDI channels give different responses for spin-2 ULDM

Response Function and Sensitivity (Single Link)

- Decomposition of the signal $s(t) = \mathrm{D}^{ij}(\vec{v})h_{ij}(t,\vec{x}_s)$

$$h_{ij}(t,\vec{x}_s) = -\frac{h_M}{\sqrt{5}}\sum_A \varepsilon^A_{ij} e^{i(mt - m\vec{v}\cdot\vec{x}_s + \delta_A)} \qquad h_M = \frac{\alpha\sqrt{2\rho_{\mathrm{DM}}}}{mM_{\mathrm{Pl}}}$$

- Detector tensor $\mathrm{D}^{ij}(\vec{v}) = \frac{1}{2}\mathcal{T}(\vec{v}\cdot\hat{n}_{rs})\hat{n}^i_{rs}\hat{n}^j_{rs}$

- Transfer funtion $\mathcal{T}(\vec{v}\cdot\hat{n}_{rs}) = \mathrm{sinc}[\phi_m(1+\vec{v}\cdot\hat{n}_{rs})]e^{i\phi_m(1+\vec{v}\cdot\hat{n}_{rs})}$ $\quad \mathrm{sinc}x \equiv \frac{\sin x}{x} \quad \phi_m \equiv \frac{mL}{2}$

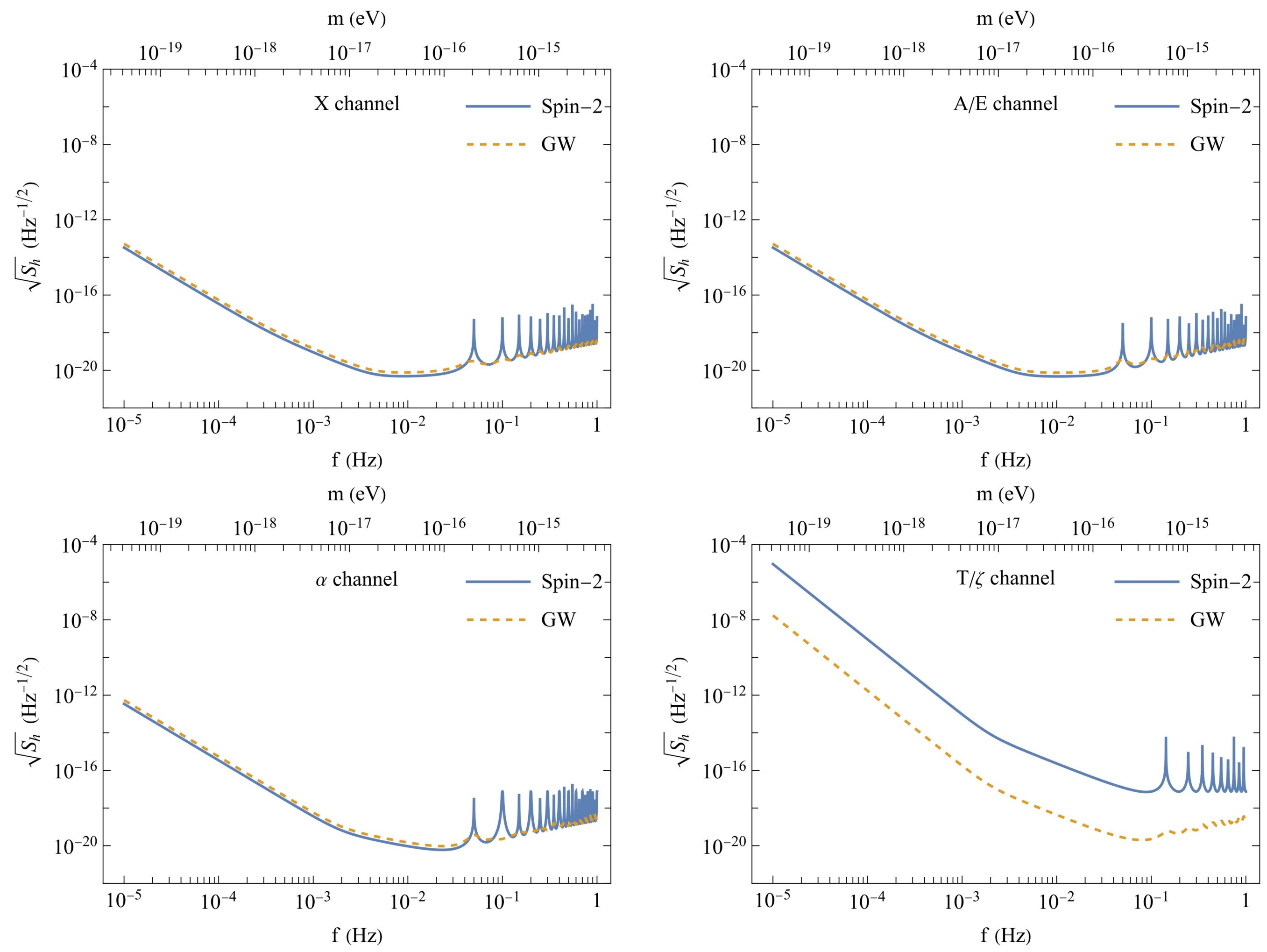
- Antenna pattern function $F^A(\vec{v}) = \mathrm{D}^{ij}(\vec{v})\varepsilon^A_{ij}$

- Response function $\mathcal{R} = \frac{1}{5}\int\frac{\mathrm{d}^2\hat{v}}{4\pi}\int\frac{\mathrm{d}^2\hat{r}}{4\pi}\sum_A F^{A*}(\vec{v})F^A(\vec{v})$

- Sensitivity $S_h = \frac{N_h}{\mathcal{R}_h}$, $\quad N_h$: one-sided noise spectral density

Sensitivity Curves

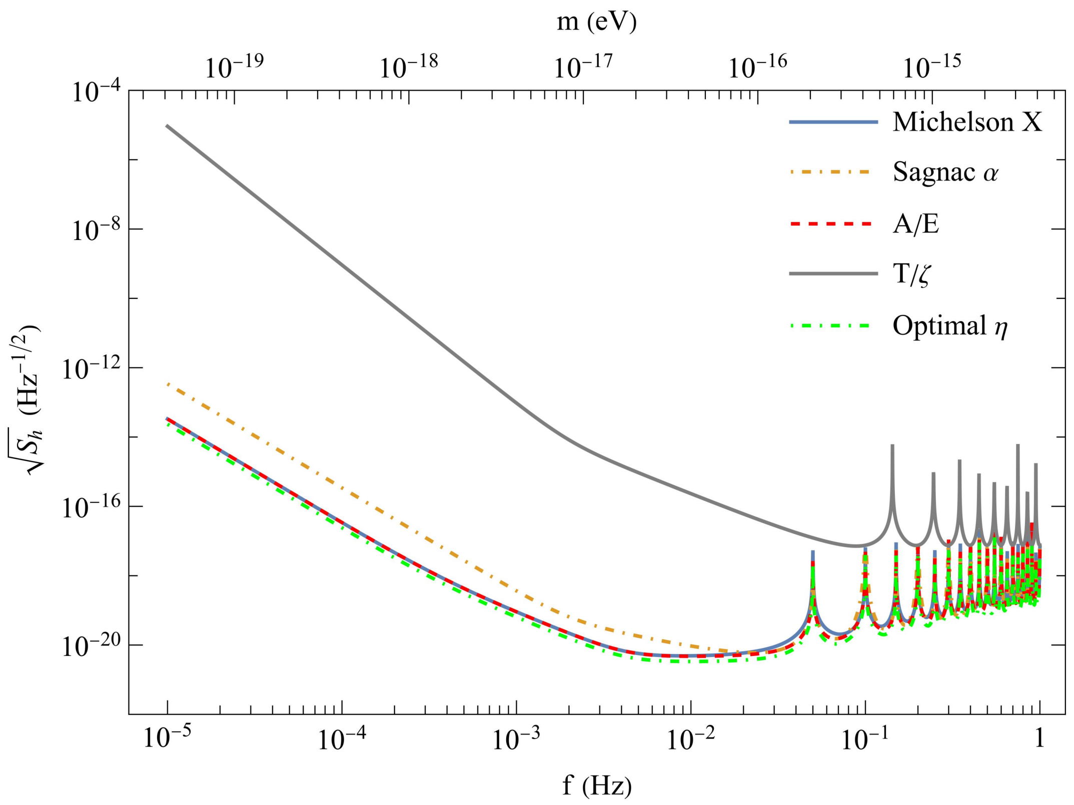
- Asymmetric TDI channels show similar sensitivities
- Asymmetric channels have better sensitivities compared with symmetric channels



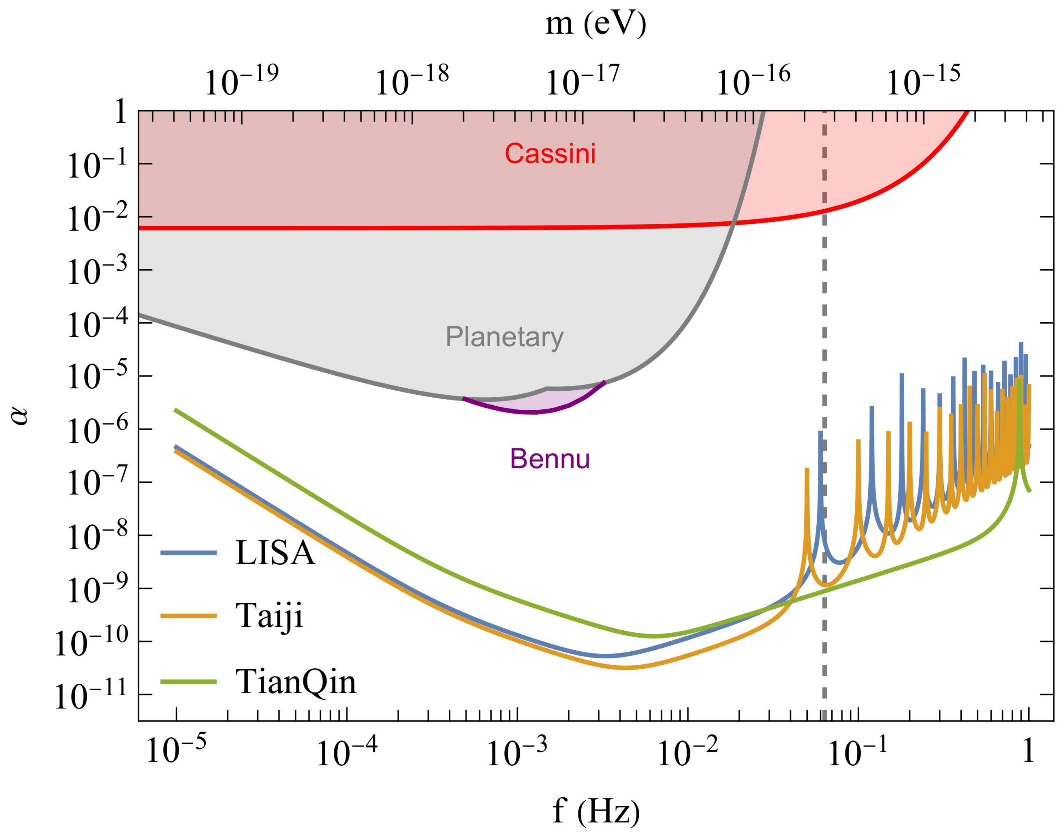
JR Zhang, J Chen, HS Jiao, RG Cai and YL Zhang, Phys. Rev. D **112**, no.6, 064030 (2025).

Constraints for Spin-2 ULDM

- Space-based GW detectors exhibit remarkable sensitivity to spin-2 ULDM



Sensitivity curves



Constraints on α

JR Zhang, J Chen, HS Jiao, RG Cai and YL Zhang, Phys. Rev. D **112**, no.6, 064030 (2025).

Summary

- Probing spin-2 ultralight dark matter with space-based GW detectors
  - GW detectors can be used to probe ultralight dark matter
  - Candidate of dark matter: spin-2 ULDM
  - Space-based GW detectors offer unique detectability for spin-2 ULDM
  - Asymmetric time delay interferometry (TDI) channels have better sensitivity
  - Strong constraints ($\alpha \sim 10^{-10}$) can be put on spin-2 ULDM based on space-based GW detectors

Thank you for listening!