Probing Ultralight Dark Matter with Laser Interferometers in Space

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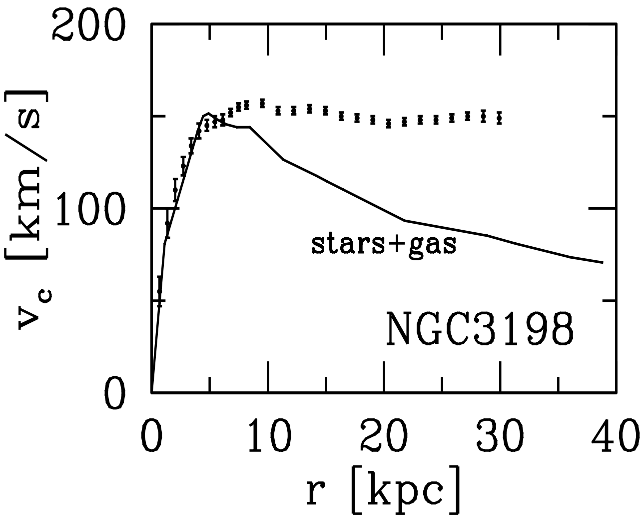
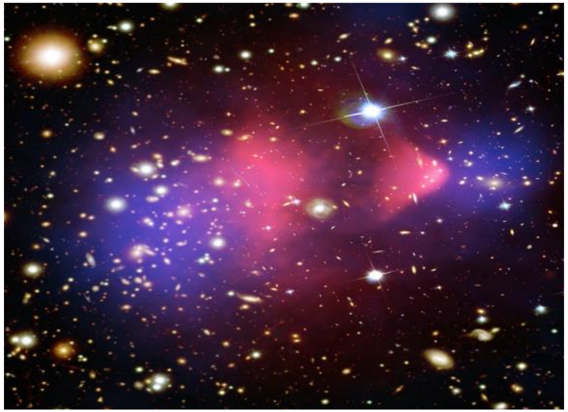
乌鲁木齐

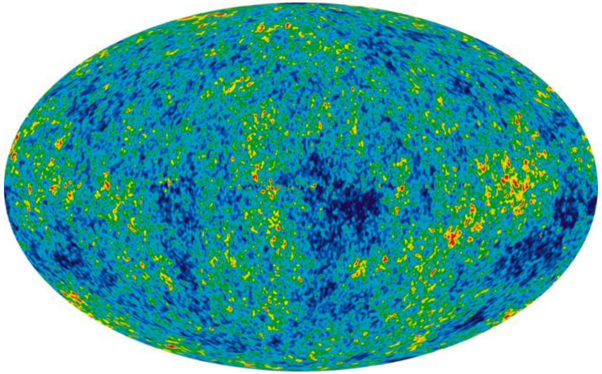
Ref. 2607.13483, 2606.03478, 2508.14655, 2506.09744, ……

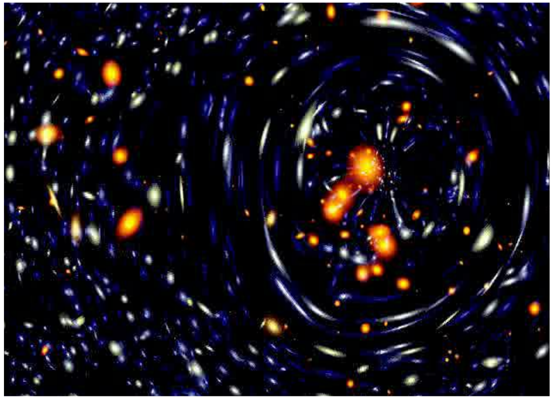
Contents

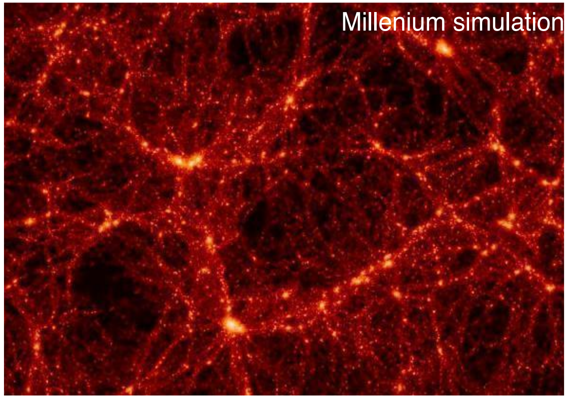
Evidence for Dark Matter

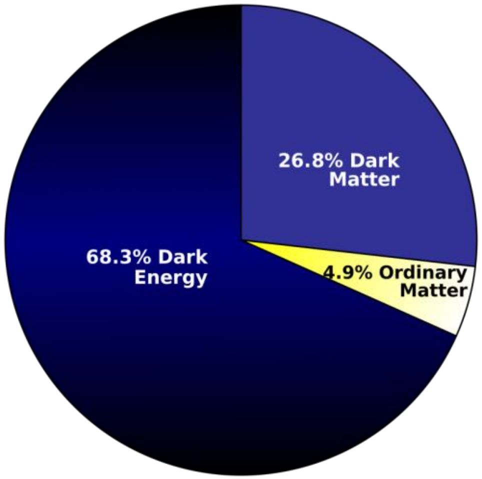






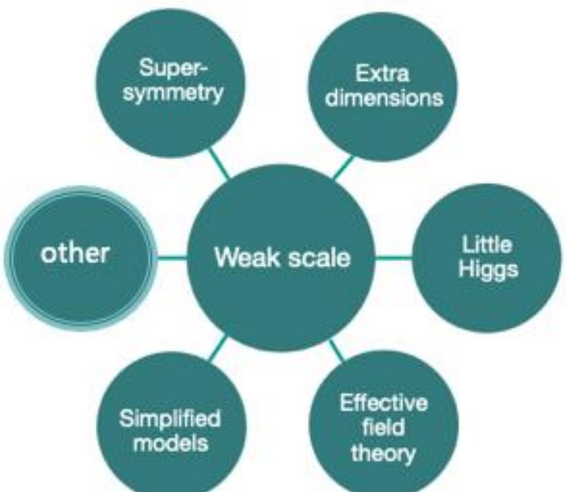


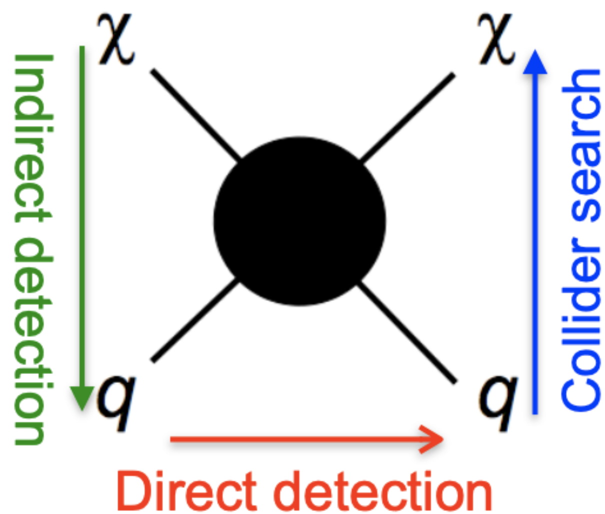


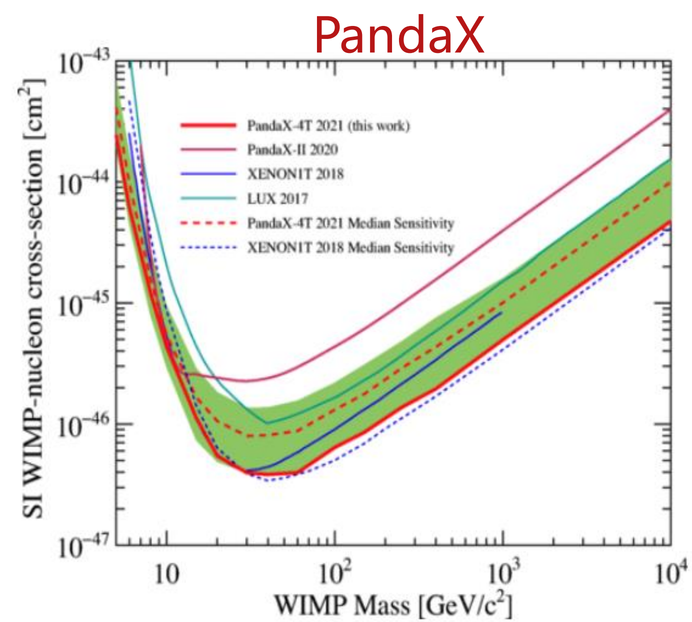


Weakly Interacting Massive Particle (WIMP)

- Theories: supersymmetry, extra dimensions, ……
- Direct, indirect and collider searches
- Impressive progress

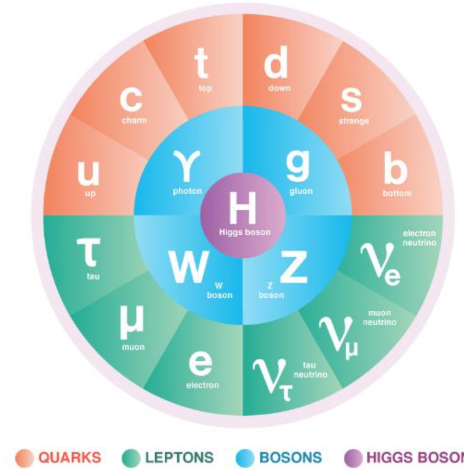


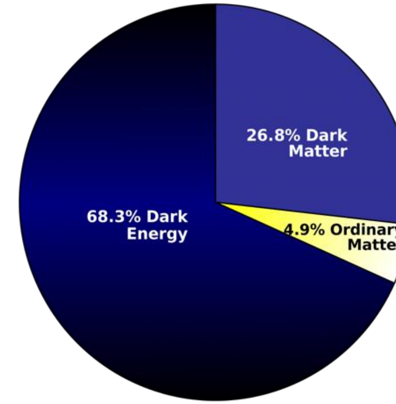


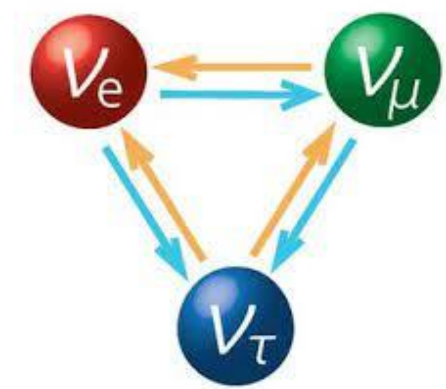


More Motivations

- Standard model is not complete
- Dark Matter and Dark Energy
- Neutrino mass
- Matter-Antimatter asymmetry
- Theoretical Problems
  - Strong CP problem
  - Hierarchy problem
  - Fermion mass hierarchy
  - Unification of forces
  - ……

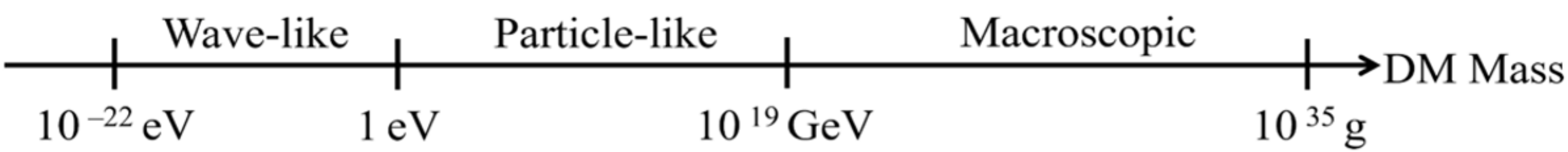






Dark Matter Candidates

- Primordial black holes
- Super heavy particles
- Asymmetric DM
- Hidden sector DM
- Self-Interacting DM ……
- Weakly-Interacting DM
- Strongly-interacting DM
- Sterile neutrino
- **Ultralight DM, Axion (ALP), Dark photon, dilaton etc**

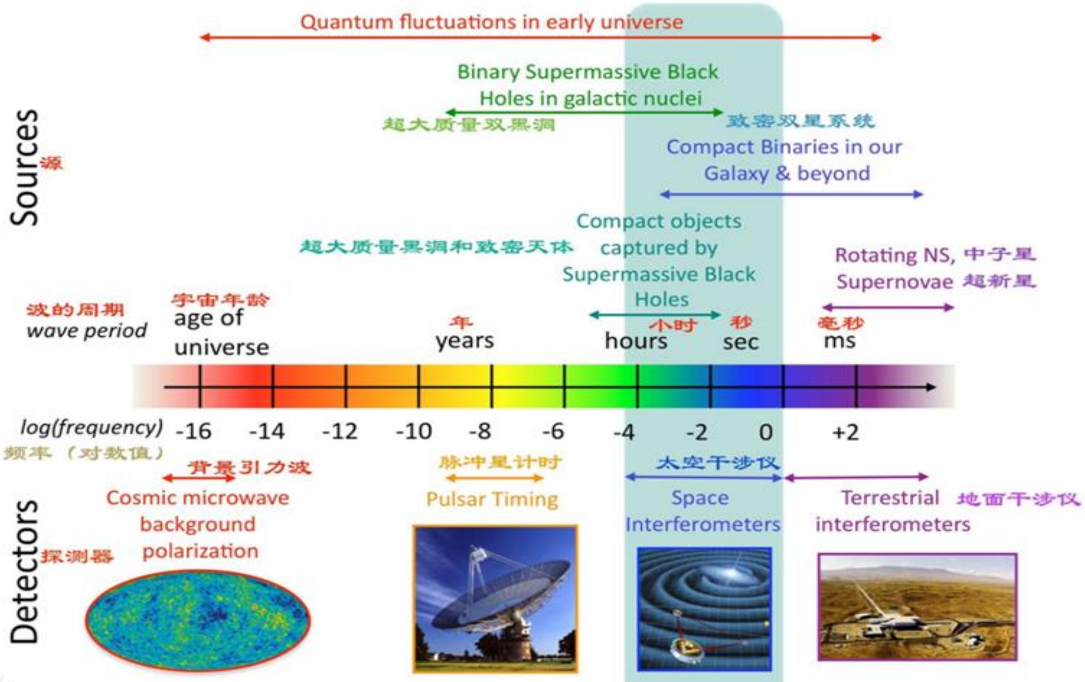


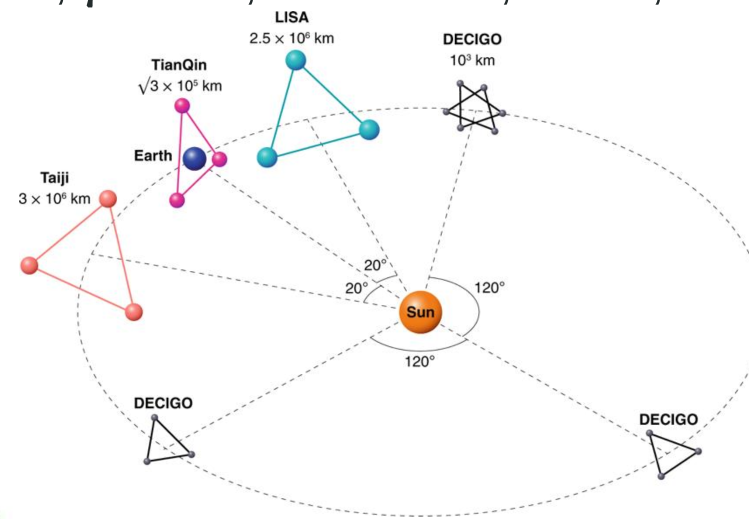
ULDM < 1eV

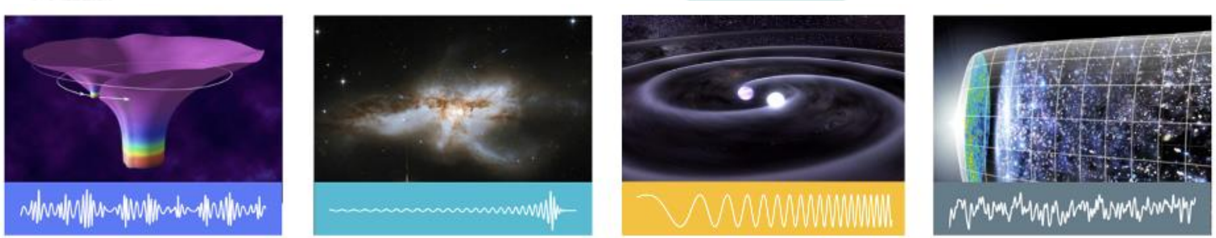
Since we do not know what DM is, we may explore as much as we can!

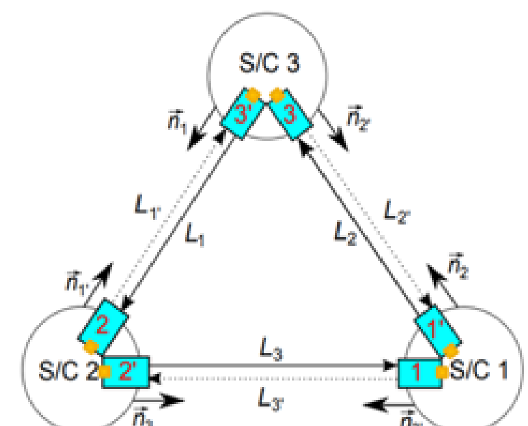
Future Laser Interferometers in Space -- GW

- LISA, Taiji, TianQin, LISAmax, Astrod-GW, μAres, DECIGO, BBO,⋯









Time-Delay Interferometry

Review by Tinto & Dhurandhar 2021

- There are multiple combinations
- Michelson channels

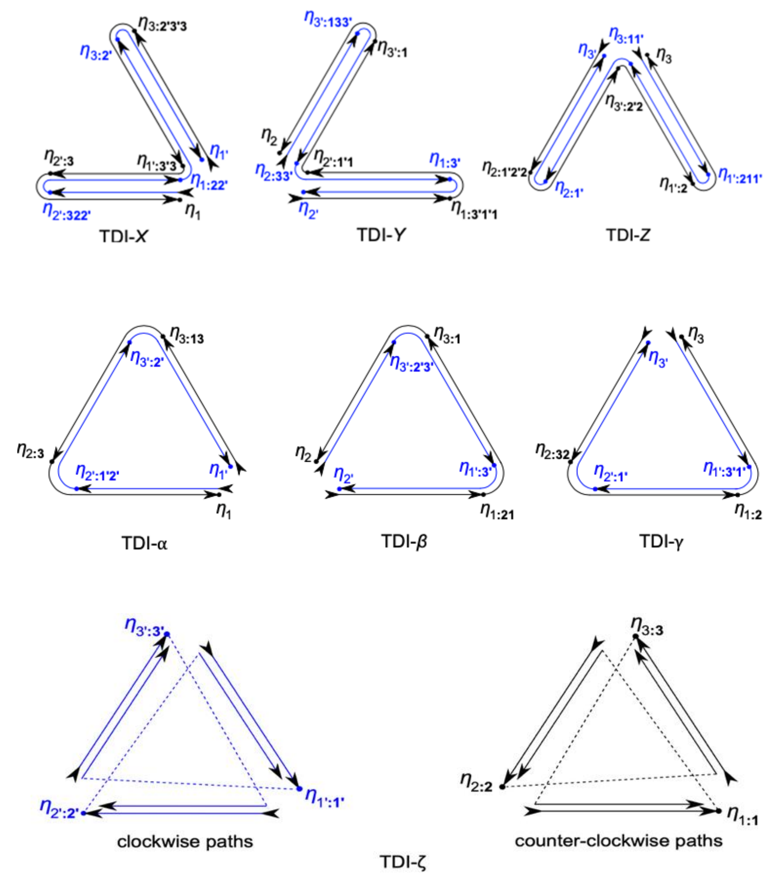
$$X(t) = (\eta_{2':322'} + \eta_{1:22'} + \eta_{3:2'} + \eta_{1'}) - (\eta_{3:2'3'3} + \eta_{1':3'3} + \eta_{2':3} + \eta_1),$$
$$Y(t) = (\eta_{3':133'} + \eta_{2:33'} + \eta_{1:3'} + \eta_{2'}) - (\eta_{1:3'1'1} + \eta_{2':1'1} + \eta_{3':1} + \eta_2),$$
$$Z(t) = (\eta_{1':211'} + \eta_{3:11'} + \eta_{2:1'} + \eta_{3'}) - (\eta_{2:1'2'2} + \eta_{3':2'2} + \eta_{1':2} + \eta_3).$$

- Sagnac channels

$$\alpha(t) = (\eta_{2':1'2'} + \eta_{3':2'} + \eta_{1'}) - (\eta_{3:13} + \eta_{2:3} + \eta_1),$$
$$\beta(t) = (\eta_{3':2'3'} + \eta_{1':3'} + \eta_{2'}) - (\eta_{1:21} + \eta_{3:1} + \eta_2),$$
$$\gamma(t) = (\eta_{1':3'1'} + \eta_{2':1'} + \eta_{3'}) - (\eta_{2:32} + \eta_{1:2} + \eta_3).$$

- ζ channel

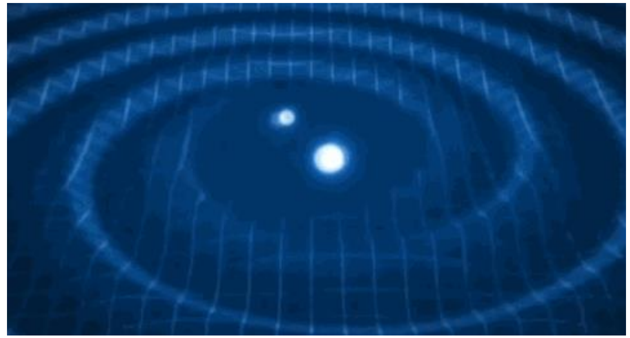
$$\zeta(t) = (\eta_{1':1'} + \eta_{2':2'} + \eta_{3':3'}) - (\eta_{1:1} + \eta_{2:2} + \eta_{3:3}).$$



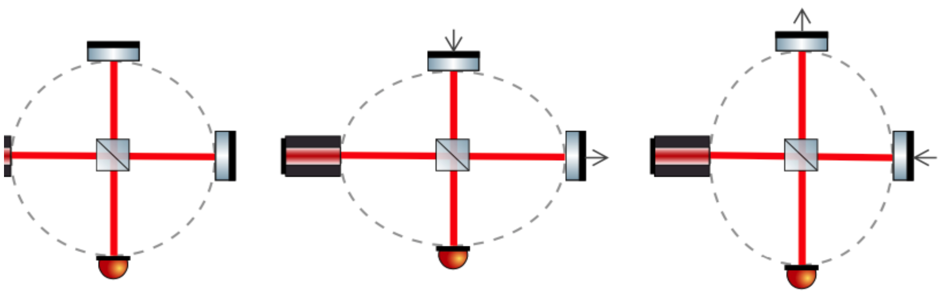
Credit: Otto 2015

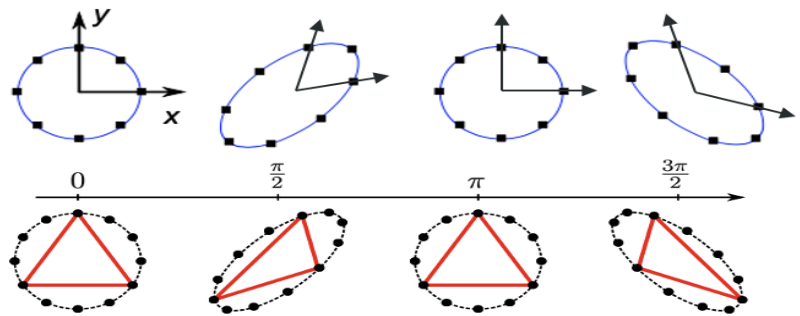
Signal Response

- Gravitational wave can change the structure of spacetime, and the physical distance between objects



- $h \sim \Delta L / L \sim 10^{-12}\mathrm{m} / 10^{9}\mathrm{m} \sim 10^{-21}$
- One can measure the length/phase by laser

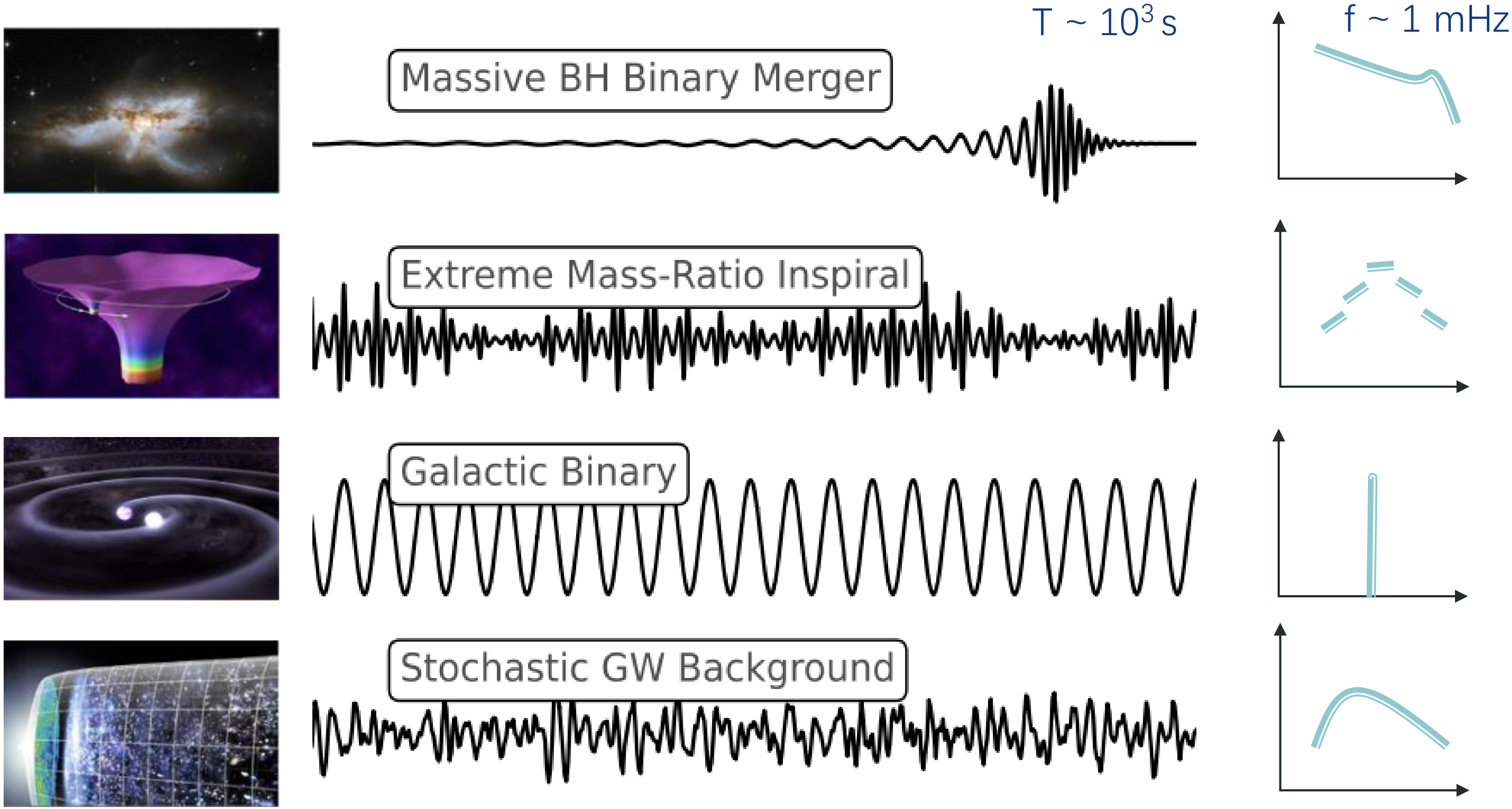




- Doppler shift $\frac{\delta v(t)}{v_0} \equiv y_{BA} = -\frac{1}{2}\frac{n_i n_j}{1+\vec{k}\cdot\vec{n}}\left[h_{ij}\left(t-\frac{\vec{k}\cdot\vec{x}_B}{c}\right)-h_{ij}\left(t-\frac{\vec{k}\cdot\vec{x}_A+L}{c}\right)\right]$

Waveform in time domain $X(t) \leftrightarrow \widetilde{X}(f)$ Power spectrum in frequency domain

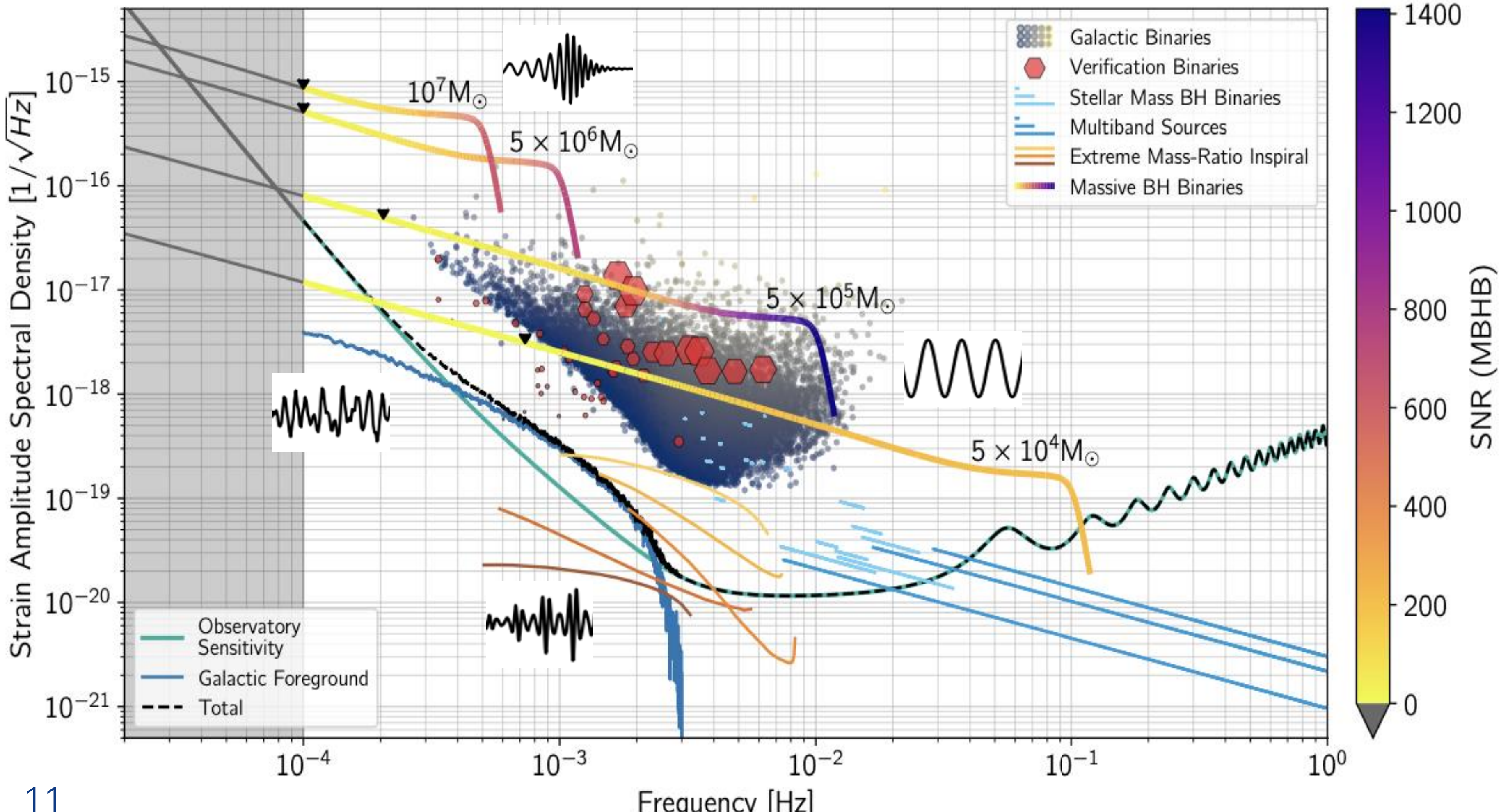
GW waveforms (time and frequency)



LISA, 2402.07571

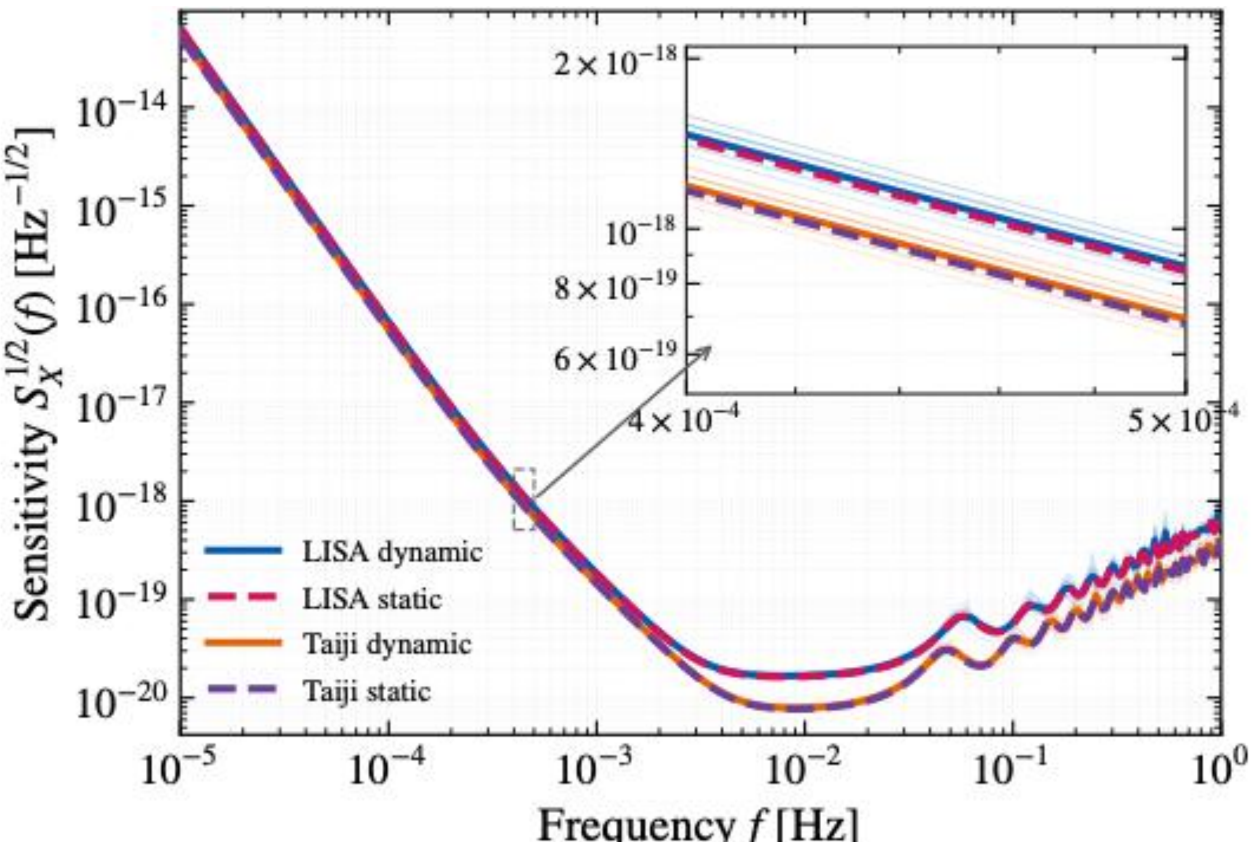
GW sources and waveforms

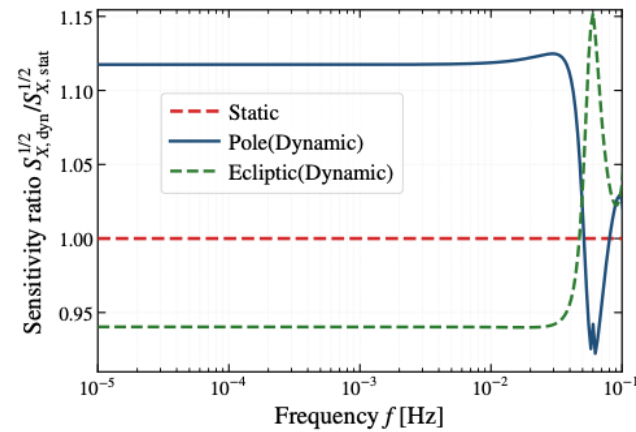
LISA, 2402.07571

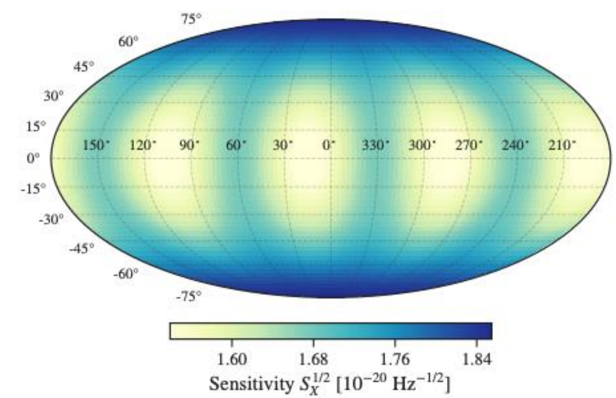


Sensitivity Curve for Dynamic LISA and Taiji

- Dynamic orbit, 20% (70%) diff in distance (volume) over directions



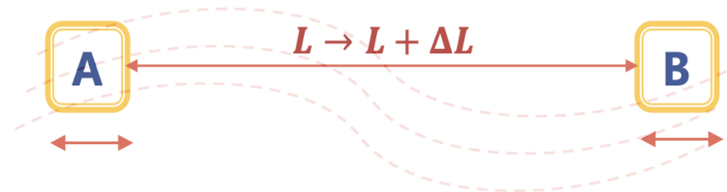




石鸿宇, Tang, 2606.28071

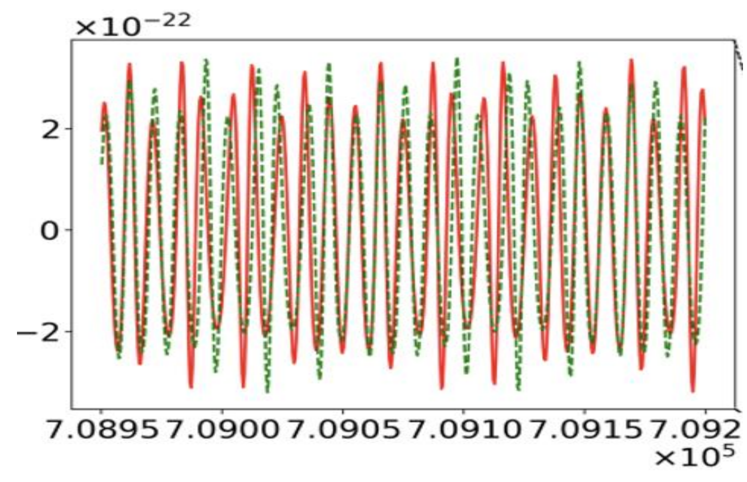
Possible Effects from Dark Matter

- Direct - Interact with the detector directly
  - Induce additional motion of test mass
  - Change the size of test mass, etc
  - Modify the propagation of laser light



Refs. Pierce, Riles & Zhao 2018, Grote & Stadnik 2019, Morisaki & Suyama 2019, Miller 2025,……

- Indirect - Affect the messengers that interact with the detector
  - Modify the GW from astrophysical sources
  - Cosmological phase transition
  - As new GW sources, PBHs, ···



Refs. Eda, Itoh, Kuroyanagi & Silk 2013, Yue, Han, Chen 2017, Bertone et al 2020, Cardoso et al 2022, Gong et al, Kadota, Kim, Ko, Yang, ……

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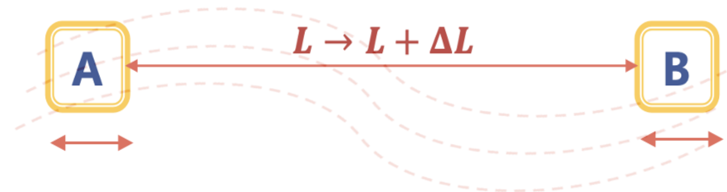

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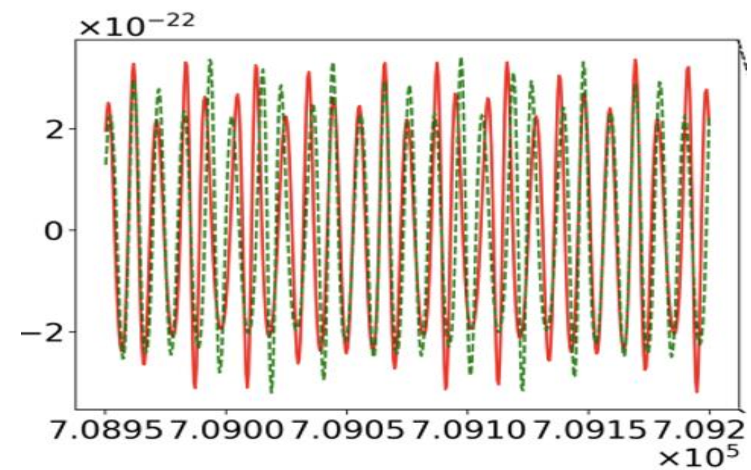

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Ultralight/Wave Dark Matter

- Mass < 1 eV, QCD axion, ALP, Dark Photon, ⋯
- A phenomenological approach
- Scalar $\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - C\frac{\phi}{M_P}\mathcal{O}_{\rm SM},$
  - Light dilaton, $\delta\mathcal{L} = \frac{\phi}{M_P}\left[\frac{d_e}{4e^2}(F_{\mu\nu})^2 - \frac{d_g\beta_3}{2g_3}(G_{\mu\nu})^2 - \sum_{i=e,u,d}(d_{m_i} + \gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right],$

    Damour & Donoghue 2010
  - ALP, $-\frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu},$
- Vector $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2A^\nu A_\nu - \epsilon_D eJ_D^\nu A_\nu,$
  - Baryon number, B-L, Dark $U(1)$, ⋯⋯
- Production Mechanism – viable DM candidate

scalar: misalignment, ⋯

vector: Graham, Mardon & Rajendran 2015, Ema, Nakayama &Tang 2019, Kolb & Long 2024

Wang, Tang & Wu 2023, ⋯⋯

Wave Dark Matter Background

Foster, Rodd, Safdi 2018

- Number density is very large, behaves as classical wave

$$\Phi(x) = \sum_{\mathbf{v}} \frac{\sqrt{2\rho/N}}{m} e^{i(\omega t - \mathbf{k}\cdot\mathbf{x} + \theta_{\mathbf{v}})},$$

at a specific point ~ monochromatic within τ_c.

$$\vec{k} = m\vec{v}, \omega = 2\pi f \simeq m,\ v \sim 10^{-3},$$

$$f \approx 2.4 \times \left(\frac{m}{10^{-17}\mathrm{eV}}\right) \mathrm{mHz}$$

- Illustration for two components

$$\cos(\omega_1 t + \mathbf{k}_1\cdot\mathbf{x} + \theta_1) + \cos(\omega_2 t + \mathbf{k}_2\cdot\mathbf{x} + \theta_2)$$

$$= 2\cos\frac{1}{2}[(\omega_1 - \omega_2)t + (\mathbf{k}_1 - \mathbf{k}_2)\cdot\mathbf{x} + \theta_1 - \theta_2]$$

$$\cos\frac{1}{2}[(\omega_1 + \omega_2)t + (\mathbf{k}_1 + \mathbf{k}_2)\cdot\mathbf{x} + \theta_1 + \theta_2]$$

$$\simeq 2\cos[\frac{mv^2}{4}t + \mathbf{k}_3\cdot\mathbf{x} + \theta_3]\cos[\omega t + \mathbf{k}\cdot\mathbf{x} + \theta]$$

Coherent time

$$\tau_c \sim \frac{1}{mv^2}$$

Coherent length

$$\lambda_c \sim \frac{1}{mv}$$

Yao, YT, 2404.01494

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Foster, Rodd, Safdi 2018

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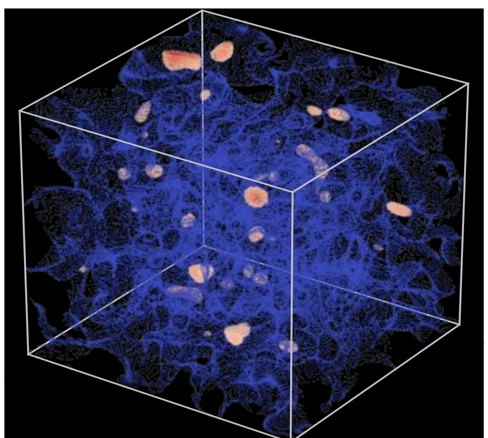
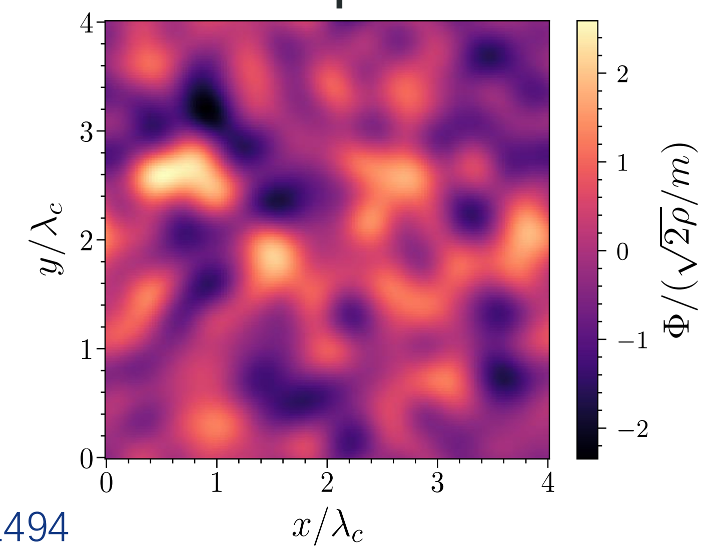
at a specific point ~ monochromatic within τ_c.

$$\lambda_c = \frac{2\pi}{mv} \approx 1.24 \times 10^{11} \times \left(\frac{10^{-17}\mathrm{eV}}{m}\right) \mathrm{km},\ \ \tau_c = \frac{\lambda_c}{v} \approx 4 \times 10^{8} \times \left(\frac{10^{-17}\mathrm{eV}}{m}\right) \mathrm{s},$$

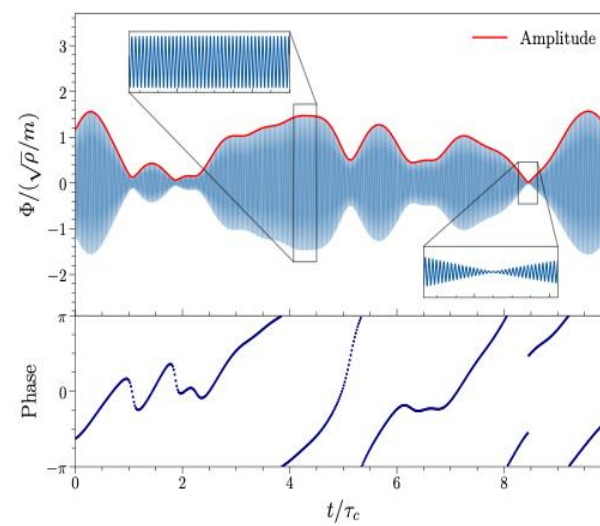
3D snapshot



2D snapshot



at some point

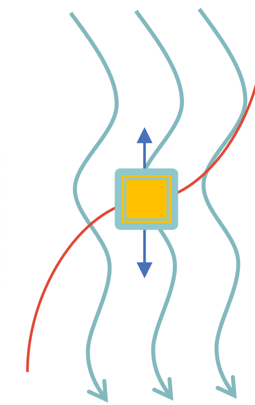


Yao, YT, 2404.01494

Physical Effects

- Plane wave within τ_c, $\phi(t,\vec{x}) = \phi_{\vec{k}} e^{i(\omega t - \vec{k}\cdot\vec{x} + \theta_0)}$,
- Scalar ϕ, $\mathcal{L} = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - \frac{1}{2}m_\phi^2\phi^2 - C\frac{\phi}{M_P}\mathcal{O}_{\rm SM}$,
- Interaction depending on the underlying theory, e.g.

$$C\frac{\phi}{M_P}m_\psi\bar{\psi}\psi \Rightarrow m_\psi \to \left(1 + C\frac{\phi}{M_P}\right)m_\psi,\ S = -\int m(\phi)\sqrt{-\eta_{\mu\nu}dx^\mu dx^\nu}.$$



- Additional oscillation around geodesic

$$\delta x^i(t,\vec{x}) = \mathcal{M}_s \hat{k}^i e^{im_\phi(t - v\hat{k}\cdot\vec{x})}, \mathcal{M}_s \propto \phi_{\vec{k}}|\vec{k}|/m_\phi^2$$

- Vector $\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\nu A_\nu - \epsilon_D e J_D^\nu A_\nu$, $\vec{A}(t,\vec{x}) = |\vec{A}|\hat{e}_A e^{i(\omega t - \vec{k}\cdot\vec{x})}$,

$$\delta x^i(t,\vec{x}) = \mathcal{M}_v \hat{e}_A^i e^{im_A(t - v\hat{k}\cdot\vec{x})}, \mathcal{M}_v \propto \epsilon_D e q_{D,j}|\vec{A}|/m_A M_j$$

- Axion – laser propagation

Ultralight/Wave DM - Signal Response

- DM couples to SM particles, inducing oscillations of test mass, effectively changing the length

- One-way Doppler shift

$$\delta t_{rs} = -\hat{n}_{rs} \cdot [\delta \vec{x}(t, \vec{x}_r) - \delta \vec{x}(t - L, \vec{x}_s)] \,,$$

$$\frac{\delta \nu_{rs}}{\nu_0} = \frac{\nu_{rs} - \nu_0}{\nu_0} = -\frac{d\,\delta t_{rs}}{dt}.$$

- Fractional frequency change

Yu, Yue-Hui Yao, Tang, Wu, 2307.09197

$$y_{rs}(t) \equiv \frac{\delta \nu_{rs}}{\nu_0} = \mu_{rs}\,[h(t, \vec{x}_r) - h(t - L, \vec{x}_s)],$$

$$h(t, \vec{x}) \propto e^{im(t - v\hat{k}\cdot\vec{x})}$$

$$\mu_{rs} = \begin{cases} \hat{k} \cdot \hat{n}_{rs} & \text{for scalar field,} \\ \hat{e}_A \cdot \hat{n}_{rs} & \text{for vector field,} \\ \dfrac{\hat{n}^i_{rs}\hat{n}^j_{rs} e_{ij}(\hat{k}, \psi)}{2(1 + \hat{n}_{rs} \cdot \hat{k})} & \text{for gravitational wave,} \end{cases}$$

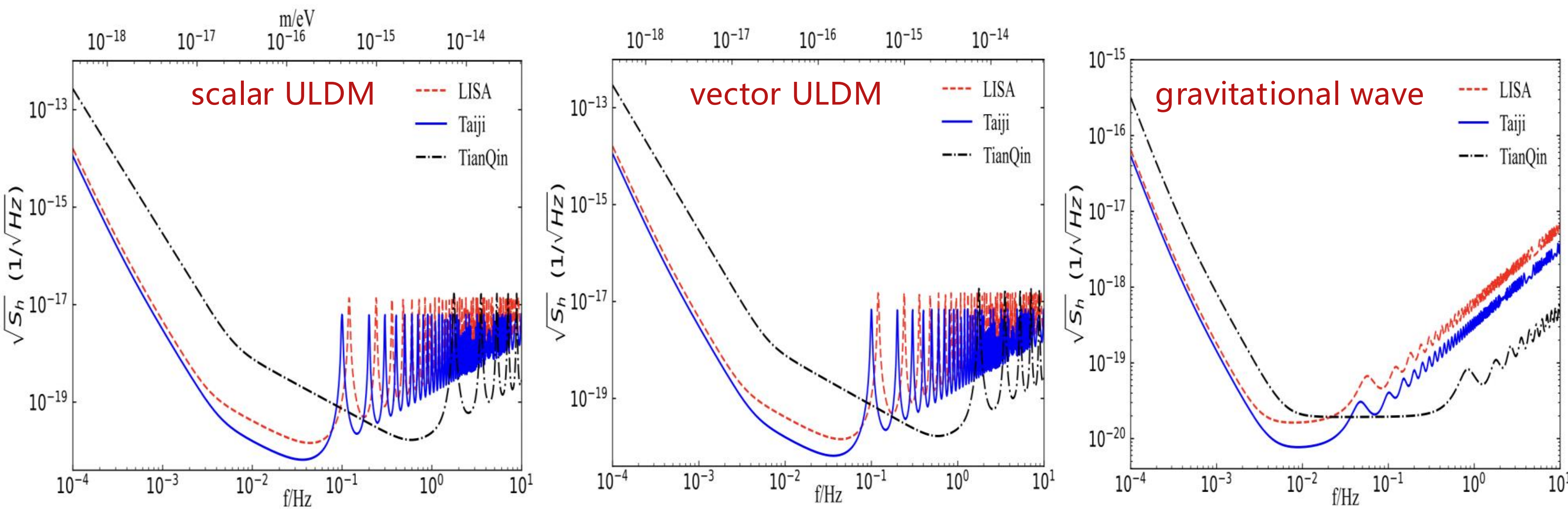
Sensitivity – Michelson Interferometer

- Defined by $S_O(f) = \dfrac{N_O(f)}{R_O(f)}$, $N_X = 16\sin^2(\tau)\,\{[3+\cos(2\tau)]\,S_{acc} + S_{oms}\}$, $\tau = 2\pi f L$

$$S_{oms}(f) = \left(s_{oms}\,\frac{2\pi f}{c}\right)^2 \left[1 + \left(\frac{2\times10^{-3}\ \mathrm{Hz}}{f}\right)^4\right] \frac{1}{\mathrm{Hz}},$$

$$S_{acc}(f) = \left(\frac{s_{acc}}{2\pi f c}\right)^2 \left[1 + \left(\frac{0.4\times10^{-3}\ \mathrm{Hz}}{f}\right)^2\right] \left[1 + \left(\frac{f}{8\times10^{-3}\ \mathrm{Hz}}\right)^4\right] \frac{1}{\mathrm{Hz}},$$

$$\begin{aligned} \text{LISA}: &\quad s_{oms} = 15\times10^{-12}\ \mathrm{m},\ s_{acc} = 3\times10^{-15}\ \mathrm{m/s^2}, \\ \text{Taiji}: &\quad s_{oms} = 8\times10^{-12}\ \mathrm{m},\ s_{acc} = 3\times10^{-15}\ \mathrm{m/s^2}, \\ \text{TianQin}: &\quad s_{oms} = 1\times10^{-12}\ \mathrm{m},\ s_{acc} = 1\times10^{-15}\ \mathrm{m/s^2}. \end{aligned}$$

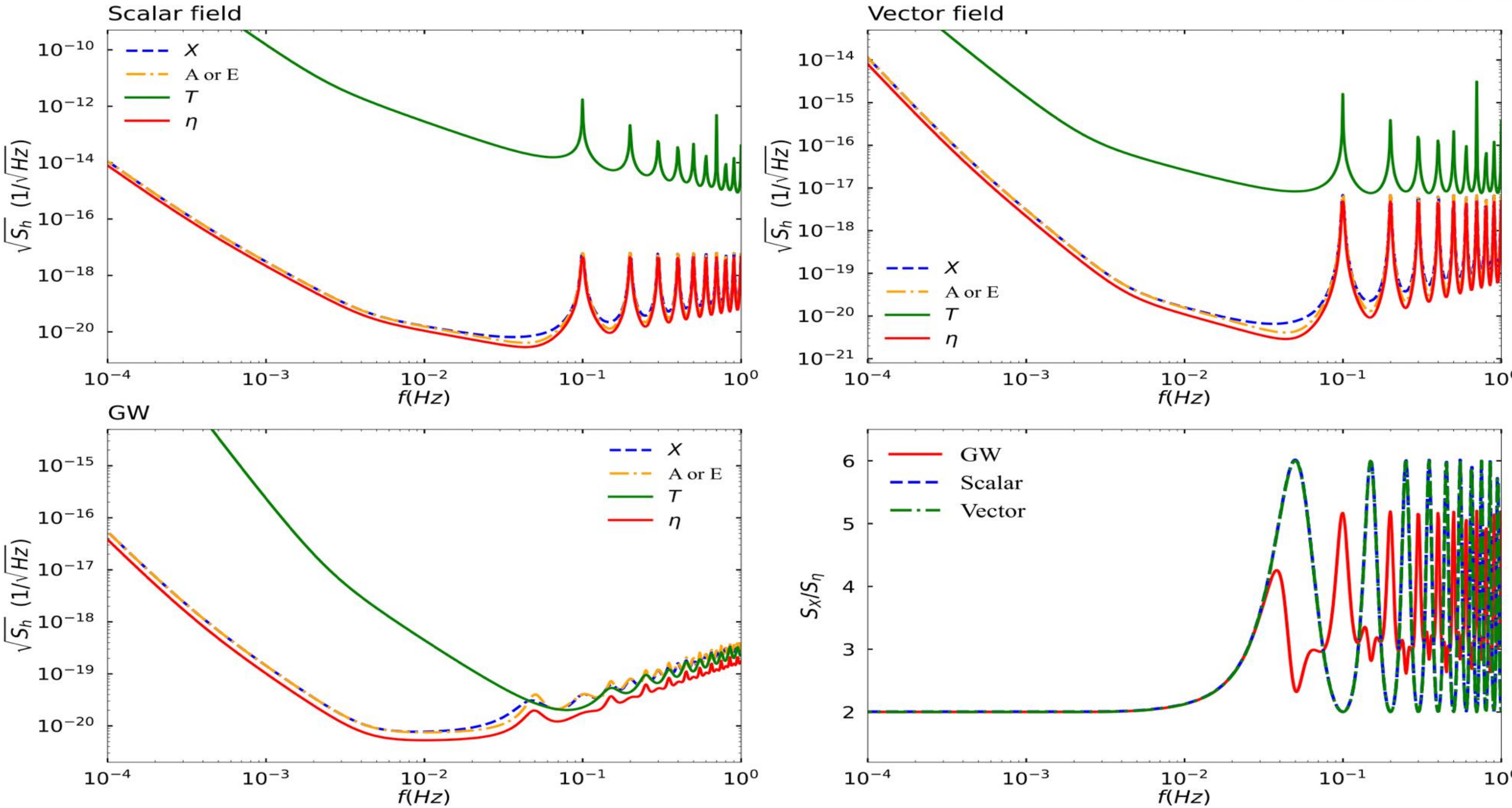


Yu, Yao, Tang, Wu, 2307.09197

Sensitivity – Other Interferometers

Prince, Tinto, Larson & Armstrong

- Optimal channels $A = \frac{1}{\sqrt{2}}[Z - X], E = \frac{1}{\sqrt{6}}[X - 2Y + Z], T = \frac{1}{\sqrt{3}}[X + Y + Z].$ $\frac{1}{S_\eta} = \frac{1}{S_A} + \frac{1}{S_E} + \frac{1}{S_T}$



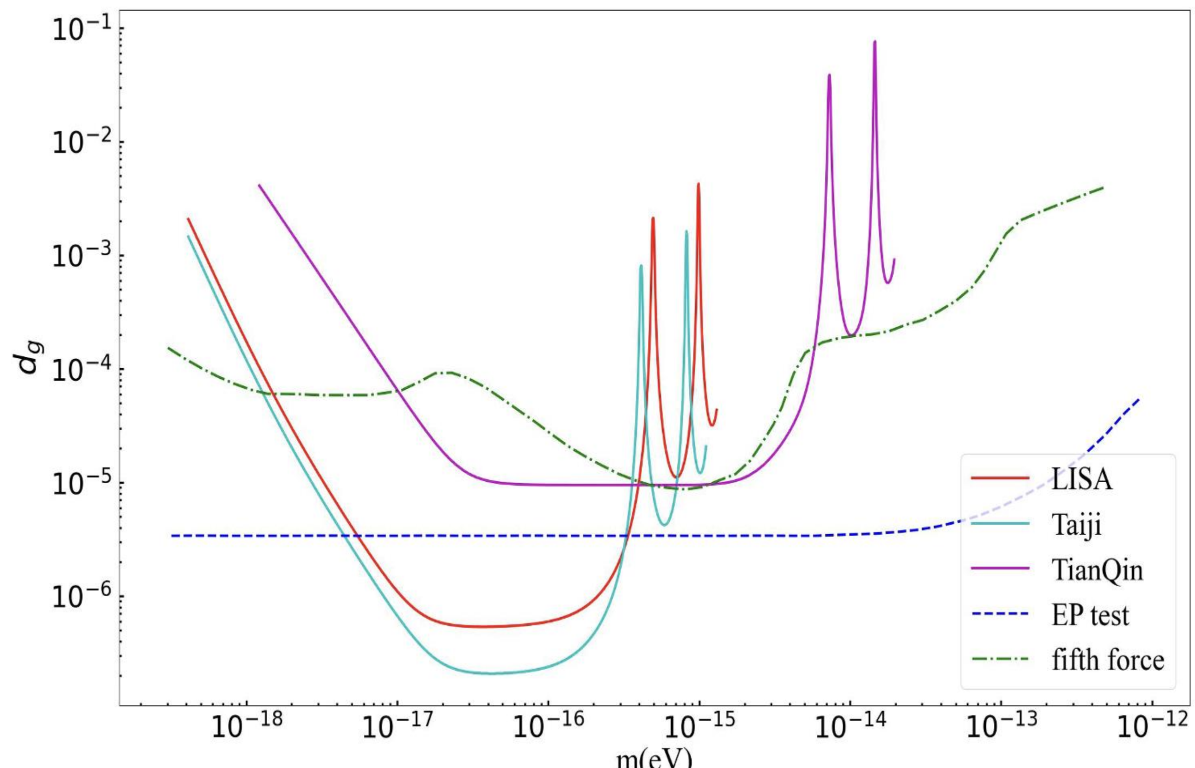
Sensitivity on scalar DM

- Strong sector $$\delta\mathcal{L} = \frac{\phi}{M_P}\left[\frac{d_e}{4e^2}(F_{\mu\nu})^2 - \frac{d_g\beta_3}{2g_3}(G_{\mu\nu})^2 - \sum_{i=e,u,d}(d_{m_i}+\gamma_{m_i}d_g)m_i\bar{\psi}_i\psi_i\right],$$

Damour & Donoghue

- At nucleus level, coupling is not ∝ mass
- Equivalence principle is violated.
- MICROSCOPE
- Pulsars

Shao, Wex, Kramer 2019

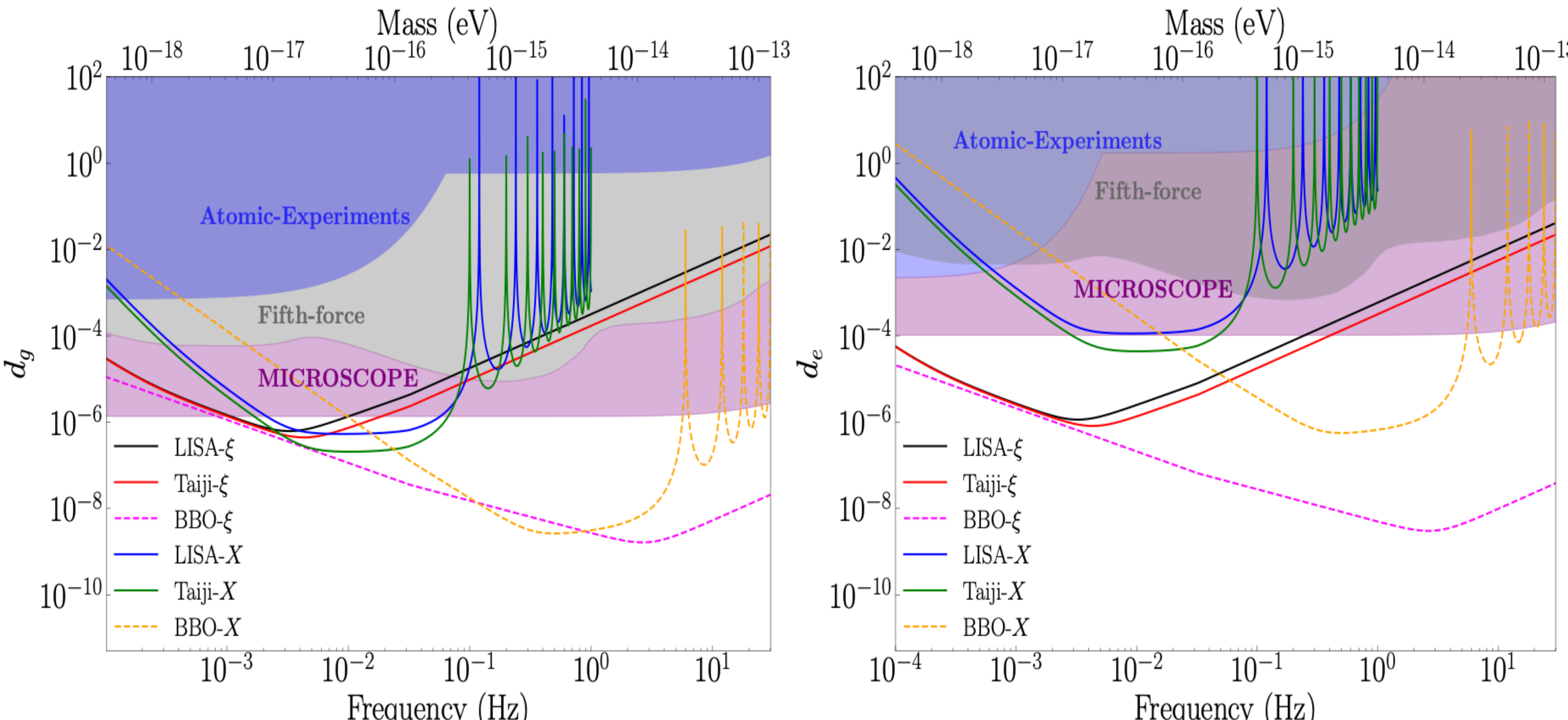


Yu, Yao, Tang, Wu, 2307.09197(PRD) Yao, Tang, 2404.01494(PRD)

Sensitivity on scalar DM

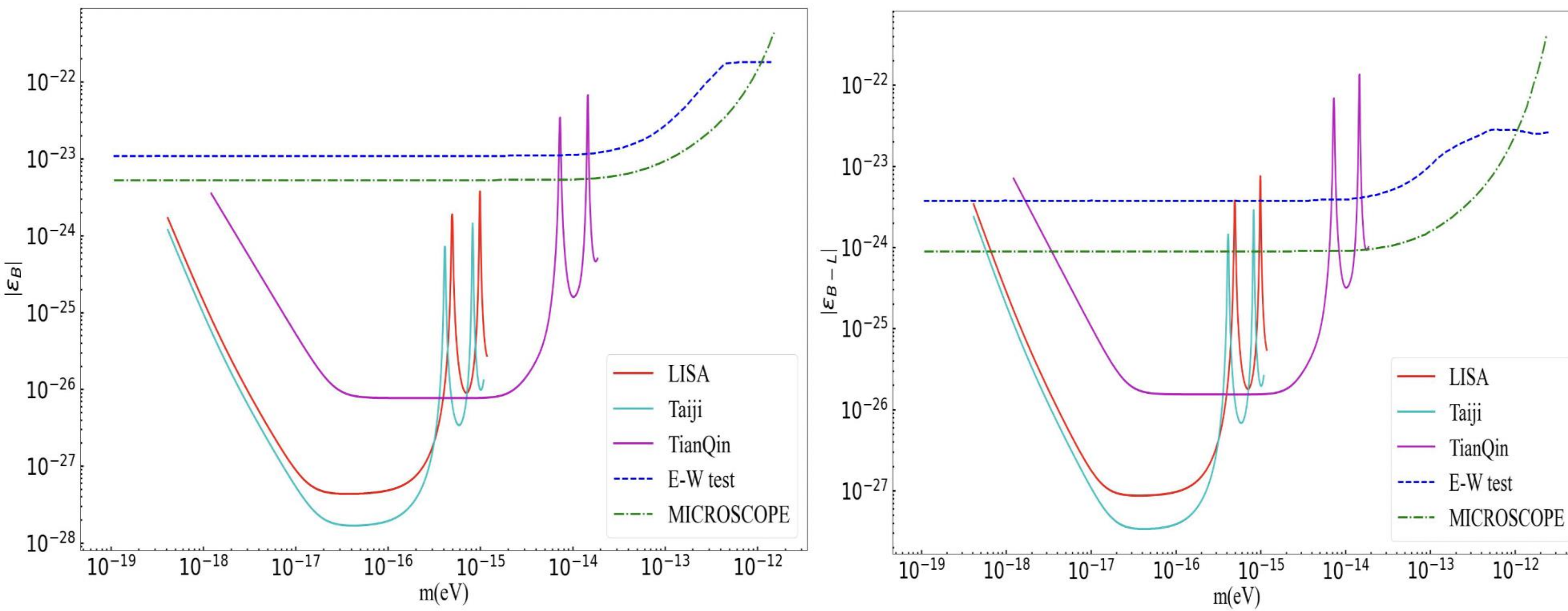
➢ Different sensitivity for different couplings

Jiang, Tang, 2606.03478



Sensitivity on vector DM

➢ For example, vector fields couple to baryon number *B*, or *B*-*L*, effectively neutron number. Sensitivity on ratio $\epsilon_D = e_D/e$



Yu, Yao, Tang, Wu, 2307.09197(PRD)

Sensitivity on Axion-Photon Coupling

- Axion-photon coupling

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m^2 a^2 - \frac{g_{a\gamma}}{4} a F_{\mu\nu}\tilde{F}^{\mu\nu},$$

- Modifies Maxwell's eqs $\nabla \cdot \boldsymbol{E} = -g_{a\gamma}\nabla a \cdot \boldsymbol{B},$

$$\frac{\partial \boldsymbol{E}}{\partial t} - \nabla \times \boldsymbol{B} = -g_{a\gamma}\left(\frac{\partial a}{\partial t} \cdot \boldsymbol{B} + \nabla a \times \boldsymbol{E}\right), \left(\frac{\partial^2}{\partial t^2} - \nabla^2\right)\boldsymbol{B} = g_{a\gamma}\dot{a}\nabla \times \boldsymbol{B}.$$

- Dispersion relation for two polarizations, $\omega^2 - k^2 = \pm g_{a\gamma}\dot{a}k$ Birefringence
- Axion dark matter background affects the phase speed of laser with different polarization, $v_\pm = \frac{\omega}{k} \simeq 1 \pm \frac{g_{a\gamma}\dot{a}}{2\omega}.$
- Equivalent phase changes
- Might be detected by LISA and Taiji detectors, etc
- Need modifications

Melissinos 2009,
DeRocco & Hook 2018
Nagano+2019
DarkGEO 2024
LIDA 2024, ⋯

Sensitivity on Axion-Photon Coupling

- Signal response $L = \int_{t-\Delta T_\pm}^{t} dt\, v_\pm = \Delta T_\pm \pm \frac{g_{a\gamma}}{2\omega}\left[a(t) - a(t-\Delta T_\pm)\right],$
- Equivalent phase changes

$$\Delta T_\pm \simeq L \mp \frac{g_{a\gamma}}{2\omega}\left[a(t) - a(t-L)\right].$$

$$\eta_{rs}(t) = -\frac{d\left(\Delta T_\pm\right)}{dt} = \pm \frac{i m g_{a\gamma}}{2\omega}\left[a(t) - a(t-L)\right],$$

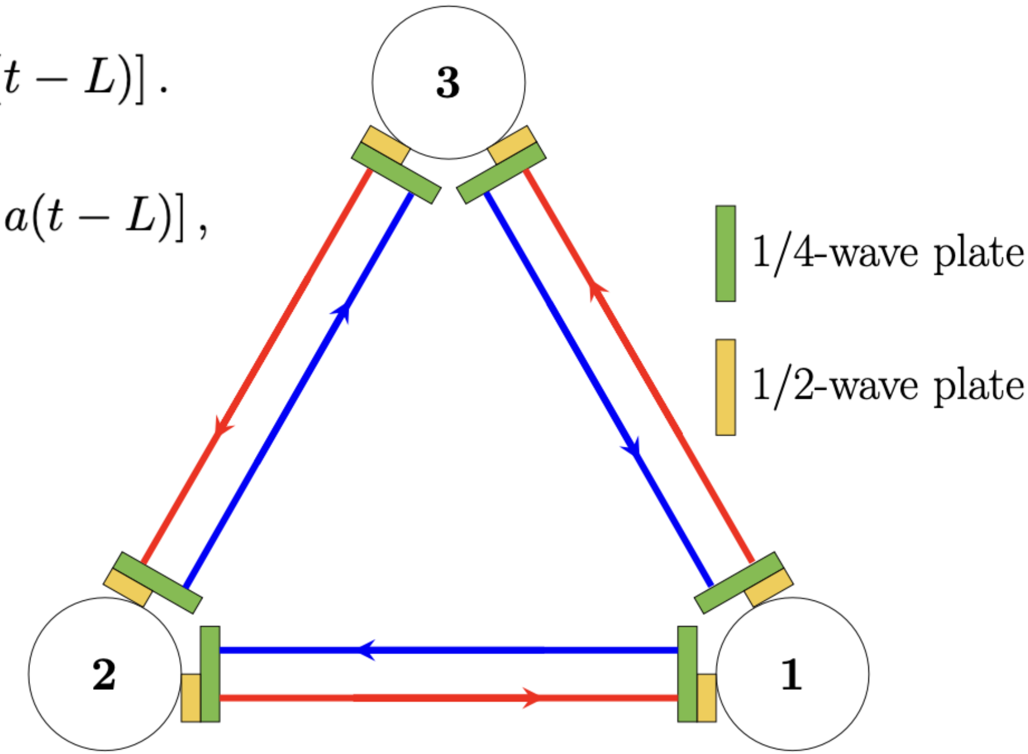
- Linearly polarized – pol angle

$$\boldsymbol{E}_r(t) = \begin{bmatrix} 1 \\ i \end{bmatrix} \frac{e^{i\omega(t-\Delta T_+)}}{2} + \begin{bmatrix} 1 \\ -i \end{bmatrix} \frac{e^{i\omega(t-\Delta T_-)}}{2}.$$

$$E_x = +\cos\left[g_{a\gamma}\frac{a(t) - a(t-L)}{2}\right]\cos[\omega(t-L)]$$

$$E_y = -\sin\left[g_{a\gamma}\frac{a(t) - a(t-L)}{2}\right]\cos[\omega(t-L)]$$

- Need modifications



Yao, Jiang, YT, 2410.22072

Sensitivity on Axion-Photon Coupling

➢ Signal response

➢ Equivalent phase changes

$$\Delta T_{\pm} \simeq L \mp \frac{g_{a\gamma}}{2\omega}\left[a(t) - a(t-L)\right].$$

$$\eta_{rs}(t) = -\frac{d\left(\Delta T_{\pm}\right)}{dt} = \pm\frac{img_{a\gamma}}{2\omega}\left[a(t) - a(t-L)\right],$$

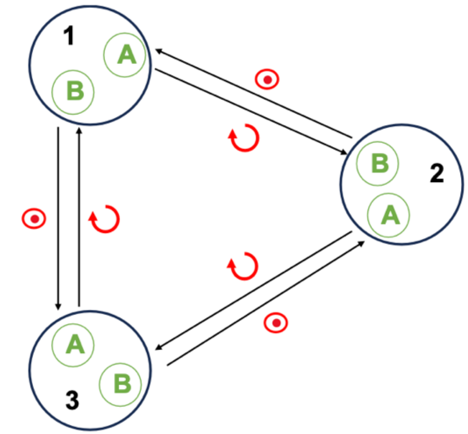
➢ Linearly polarized – pol angle

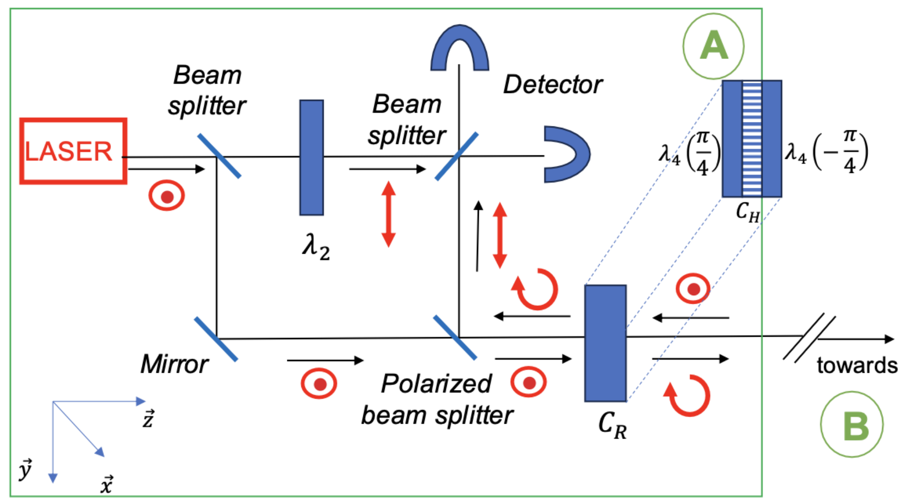
$$\boldsymbol{E}_r(t) = \begin{bmatrix} 1 \\ i \end{bmatrix} \frac{e^{i\omega(t-\Delta T_+)}}{2} + \begin{bmatrix} 1 \\ -i \end{bmatrix} \frac{e^{i\omega(t-\Delta T_-)}}{2}.$$

$$E_x = +\cos\left[g_{a\gamma}\frac{a(t)-a(t-L)}{2}\right]\cos[\omega(t-L)]$$

$$E_y = -\sin\left[g_{a\gamma}\frac{a(t)-a(t-L)}{2}\right]\cos[\omega(t-L)]$$

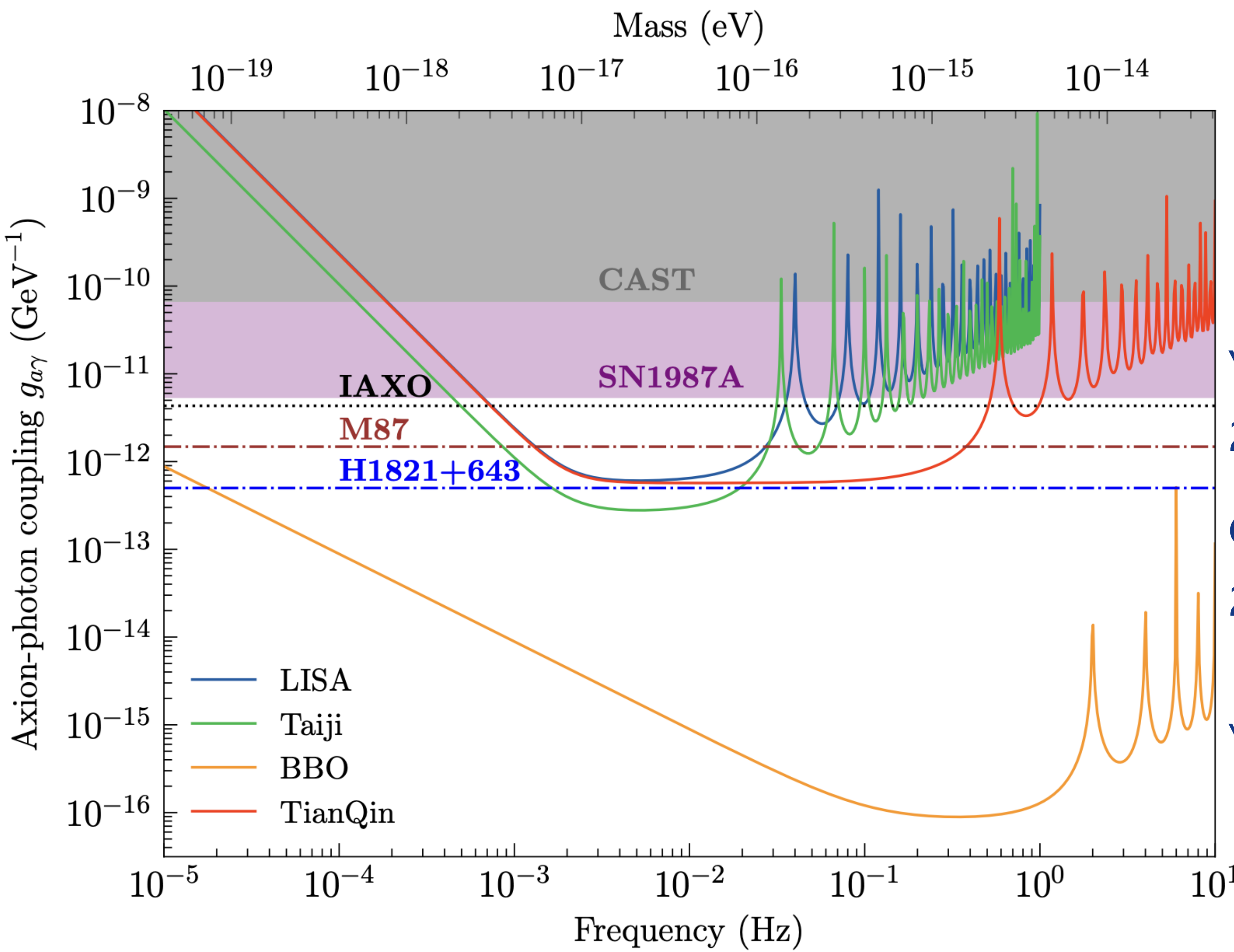
➢ Need modifications





Gue, Hees, Wolf, 2410.17763

Sensitivity on Axion-Photon Coupling



Yao, Jiang, YT, 2410.22072, Oct 29, 2024

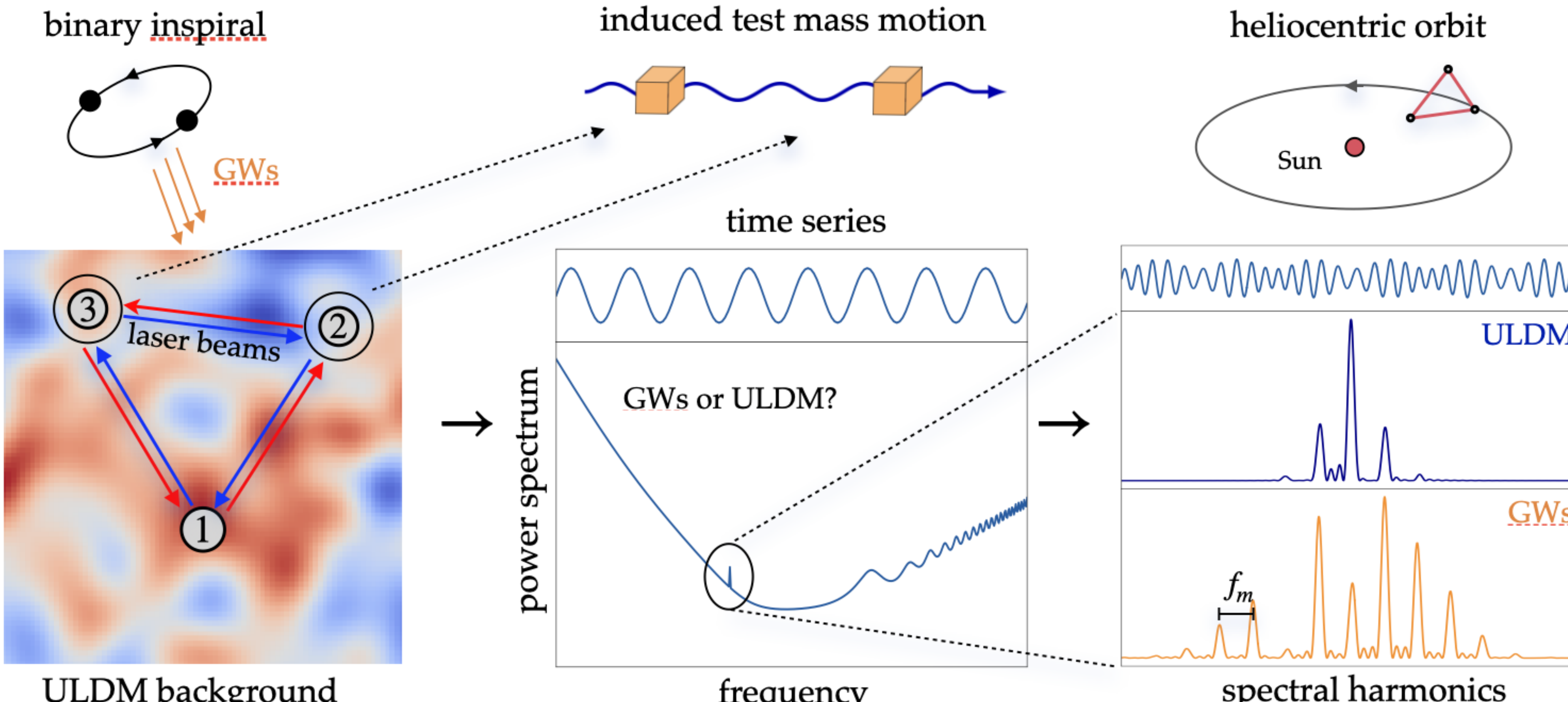
Gue, Hees, Wolf, 2410.17763, Oct 23, 2024

Yao, Bi, Yin, Huang, 2504.10083

Liu, et al, 2511.15438

Degeneracy → Orbital Modulation → Spectral split

- Response $y_{rs}(t) \supset \hat{n}_{rs} : \frac{\boldsymbol{h}(t_s - \hat{k}\cdot\mathbf{x}_s) - \boldsymbol{h}(t - \hat{k}\cdot\mathbf{x}_r)}{2(1-\hat{k}\cdot\hat{n}_{rs})} : \hat{n}_{rs},$ $y_{rs}(t) \supset g\hat{n}_{rs}\cdot[\mathbf{A}(t,\mathbf{x}_r) - \mathbf{A}(t_s,\mathbf{x}_s)]\,,$

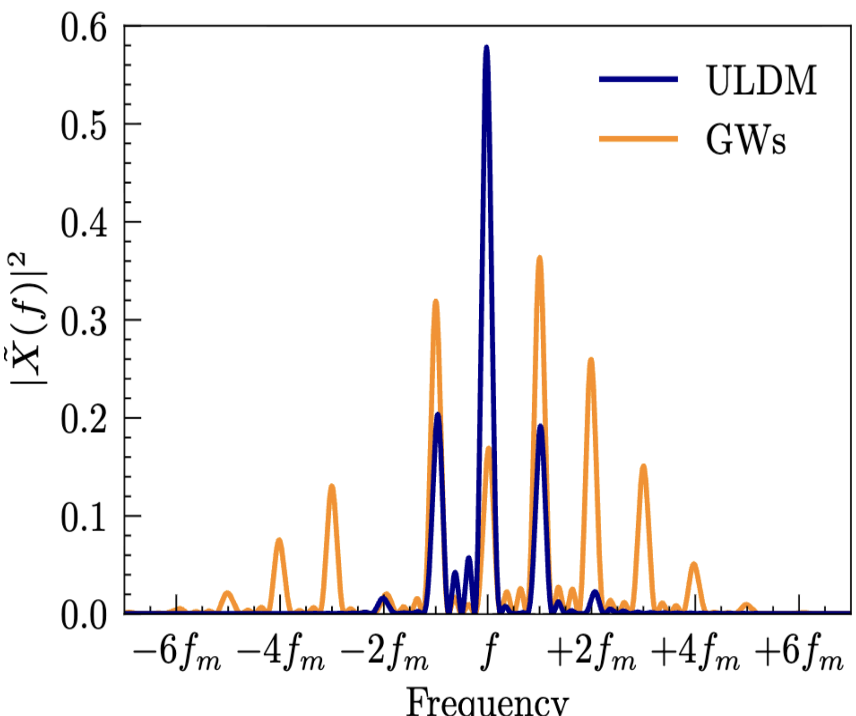


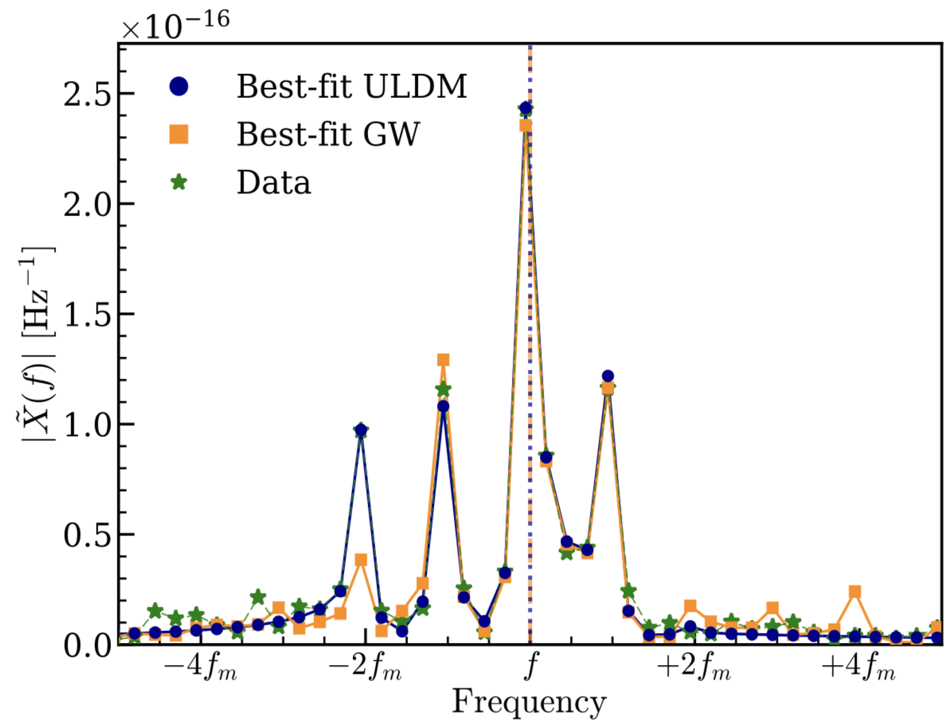
Yue-Hui Yao *et al*, 2508.14655

Orbital Modulation → Spectral split

- Response $y_{rs}(t) \supset \hat{n}_{rs} : \frac{\boldsymbol{h}(t_s - \hat{k}\cdot\mathbf{x}_s) - \boldsymbol{h}(t - \hat{k}\cdot\mathbf{x}_r)}{2(1-\hat{k}\cdot\hat{n}_{rs})} : \hat{n}_{rs},$ $y_{rs}(t) \supset g\hat{n}_{rs}\cdot[\mathbf{A}(t,\mathbf{x}_r) - \mathbf{A}(t_s,\mathbf{x}_s)]\,,$

$$X(t) = (y_{13} + y_{31,2} + y_{12,22} + y_{21,322}) - (y_{12} + y_{21,3} + y_{13,33} + y_{31,233})\,,$$





Yue-Hui Yao, T.Y. Jiang, W.Y. Ren, YT, Y.F. Zhou, 2508.14655

Degeneracy → Null-Response Channel

- For a source from some direction, we construct a null-response channel that is insensitive to ULDM or GWs,

$$\tilde{\eta} = a_1\tilde{\alpha} + a_2\tilde{\beta} + a_3\tilde{\gamma}.$$

- The Signal-to-Noise Ratio (SNR)

$$\mathrm{SNR}_\eta^2 = \int df \, \frac{\left|a_1\tilde{\alpha}_s + a_2\tilde{\beta}_s + a_3\tilde{\gamma}_s\right|^2}{\mathbf{a}^\dagger \mathbf{S}_\alpha(f)\mathbf{a}},$$

- SNR = 0 gives

$$a_1\tilde{\alpha}_s + a_2\tilde{\beta}_s + a_3\tilde{\gamma}_s = 0.$$

Xu, Yao, Tang, Wu, 2506.09744 (PRD)

Null-Response Channel

- In GR, two polarizations of GW, the response can be written as

$$\tilde{\alpha}_s = \alpha_+^{\rm gw}(f,\hat{k})\tilde{h}_+(f) + \alpha_\times^{\rm gw}(f,\hat{k})\tilde{h}_\times(f),$$

- The condition $a_1\tilde{\alpha}_s + a_2\tilde{\beta}_s + a_3\tilde{\gamma}_s = 0$ can be satisfied by

$$\left(\mathbf{a}\cdot\mathbf{x}_+^{\rm gw}(\hat{k})\right)\tilde{h}_+ + \left(\mathbf{a}\cdot\mathbf{x}_\times^{\rm gw}(\hat{k})\right)\tilde{h}_\times = 0,$$

- Where

$$\mathbf{x}_p^{\rm gw}(\hat{k}) = [\alpha_p^{\rm gw}(\hat{k}), \beta_p^{\rm gw}(\hat{k}), \gamma_p^{\rm gw}(\hat{k})]^T$$

- This can be solved by

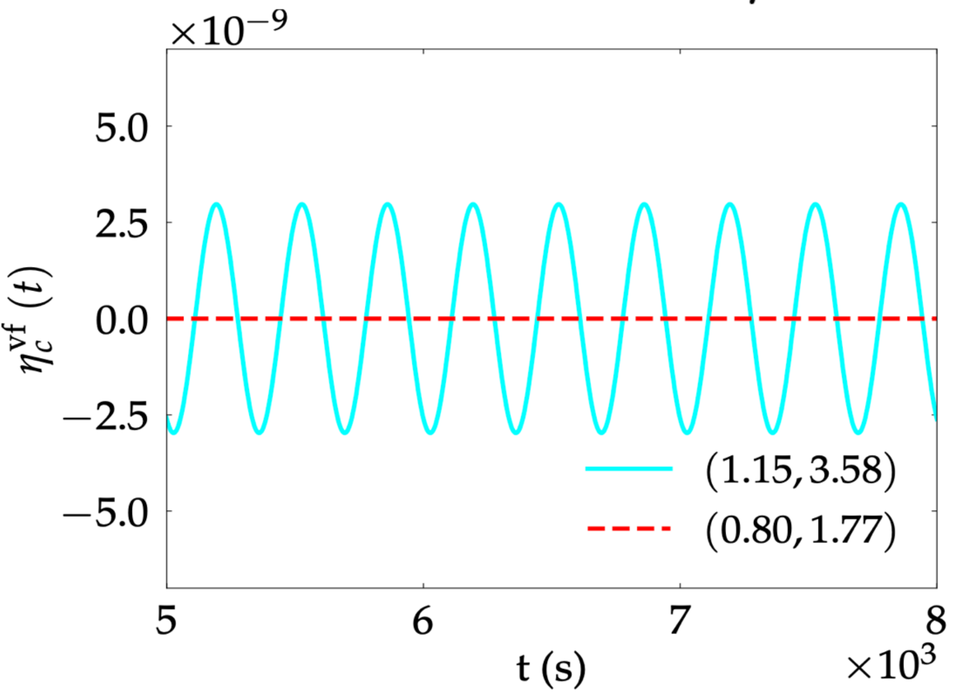
$$\mathbf{a}_c^{\rm gw}(\hat{k}) = \mathbf{x}_+^{\rm gw}(\hat{k}) \times \mathbf{x}_\times^{\rm gw}(\hat{k}).$$

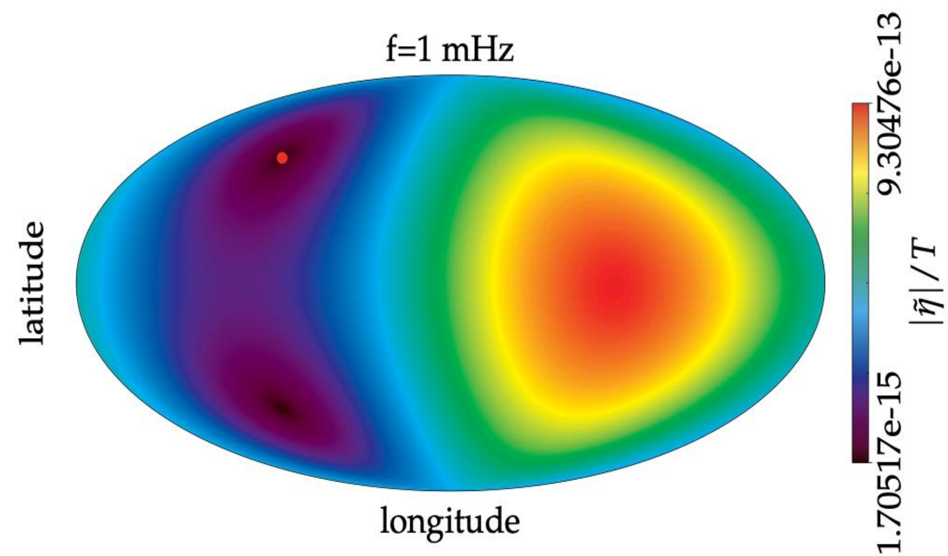
- So NRC is given by $\tilde{\eta}_c^{\rm gw}(f,\hat{k};\hat{k}_c) = \mathbf{a}_c^{\rm gw}(\hat{k}_c)\cdot[\tilde{\alpha},\tilde{\beta},\tilde{\gamma}]$

Null-Response Channel

- For a source from some direction, we construct a null-response channel that is insensitive to ULDM or GWs,

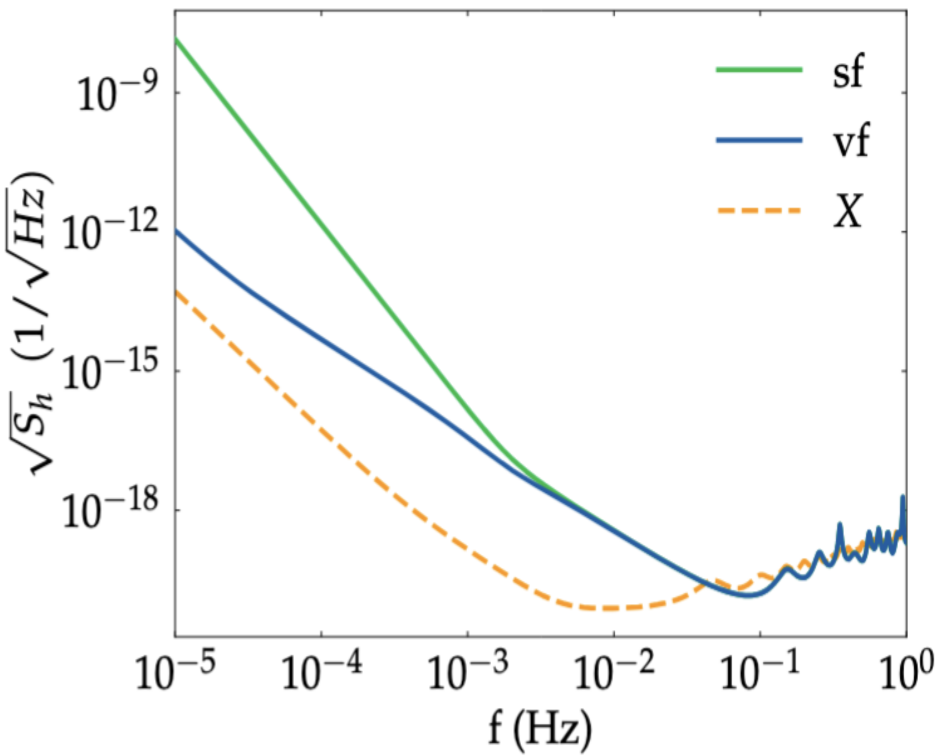
$$\tilde{\eta} = a_1\tilde{\alpha} + a_2\tilde{\beta} + a_3\tilde{\gamma}.$$

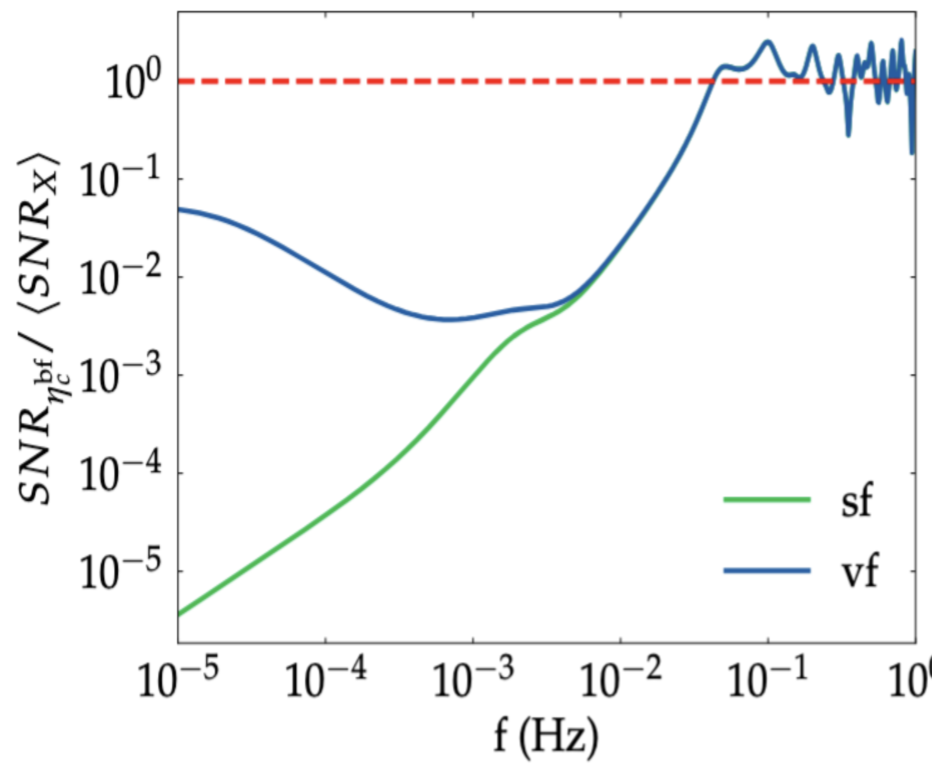




Null-Response Channel

- For a source from some direction, we construct a null-response channel that is insensitive to ULDM or GWs

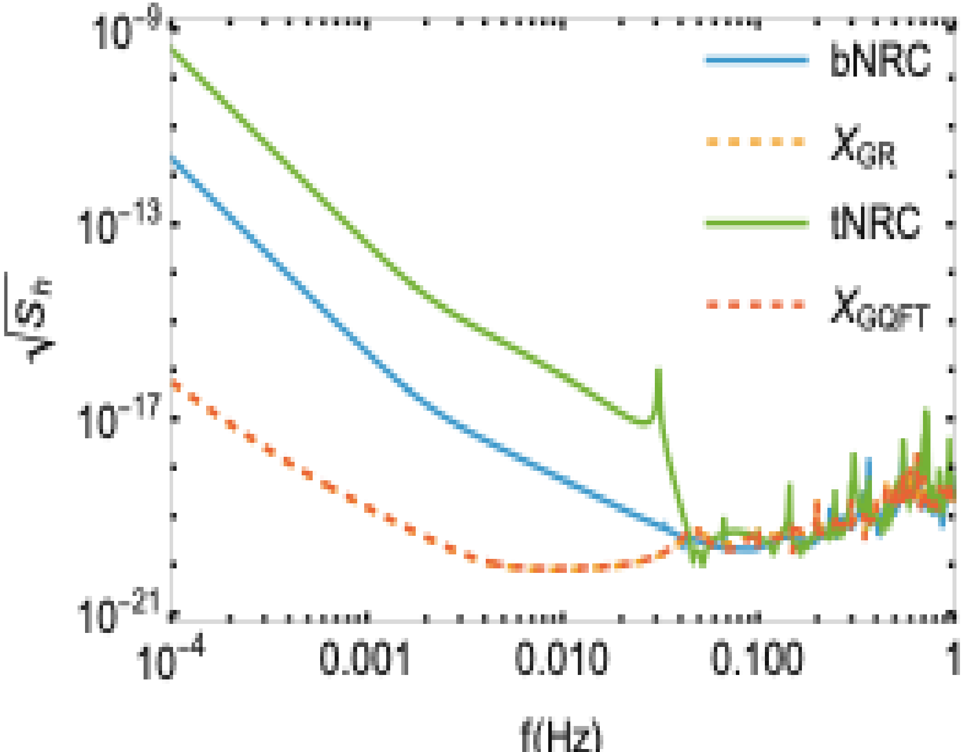


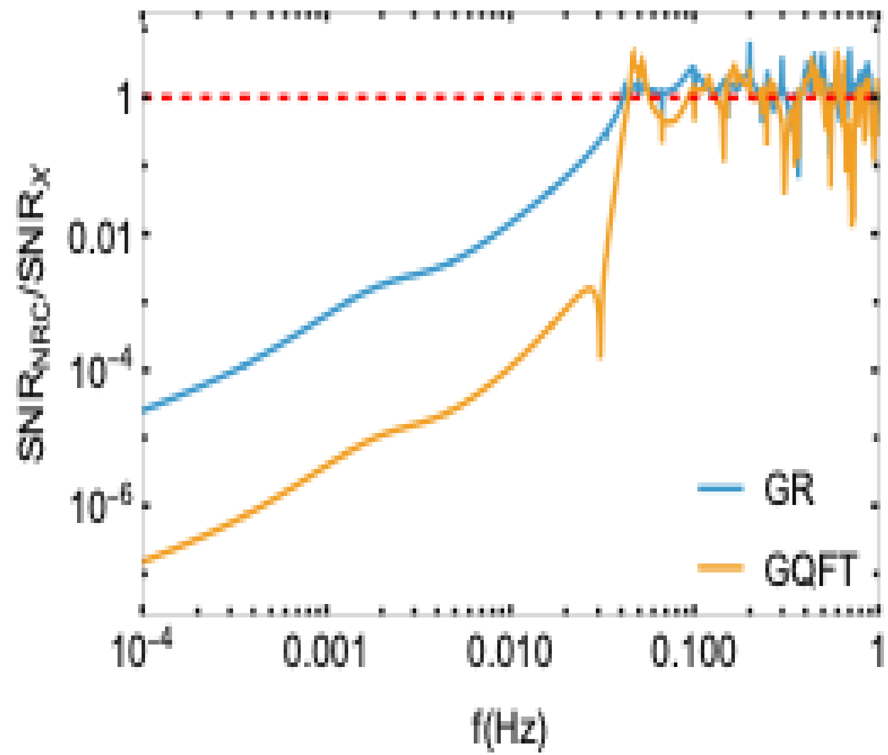


Xu, Yao, Tang, Wu, 2506.09744 (PRD)

Testing Modified Gravity-GQFT

- For a source from some direction, we construct a null-response channel that is insensitive to scalar or tensor GWs





Xu, Tang, Wu, 2607.13483

Detecting Ultralight Dark Matter Gravitationally

- Can we probe DM with gravitational interaction in solar system
- What if dark matter has only gravitational interaction?
- Motivations from theories of gravity, particle physics, …
- Viable scenarios in cosmology
  - Axion or axion-like particle, misalignment
  - Dark photon, vacuum fluctuation

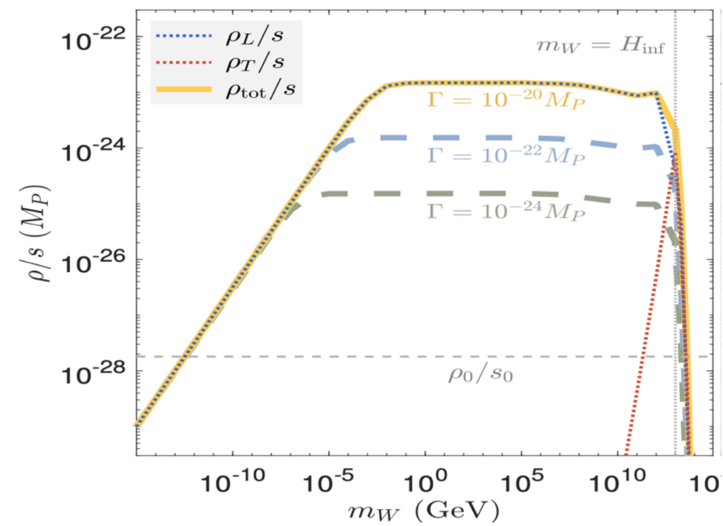
Graham, Mardon, Rajendran,1504.02102(PRD)

Ema, Nakayama, Tang, 1903.10973(JHEP),

Ahmed, Grzadkowski, Socha, 2005.01766(JHEP)

Kolb, Long, 2009.03828(JHEP), …

王清扬, Tang, Wu, 2203.15452(PRD)



Detecting Ultralight Dark Matter Gravitationally

- Metric perturbation in solar system

$$ds^2 = -(1+2\Psi)dt^2 + (1-2\Phi)\delta_{ij}dx^i dx^j + h_{ij}dx^i dx^j$$

- Einstein equations

PTA, e.g. Khmelnitsky & Rubakov 2014,⋯

$$\partial_i\partial^i\Phi = 4\pi G T_{00},$$

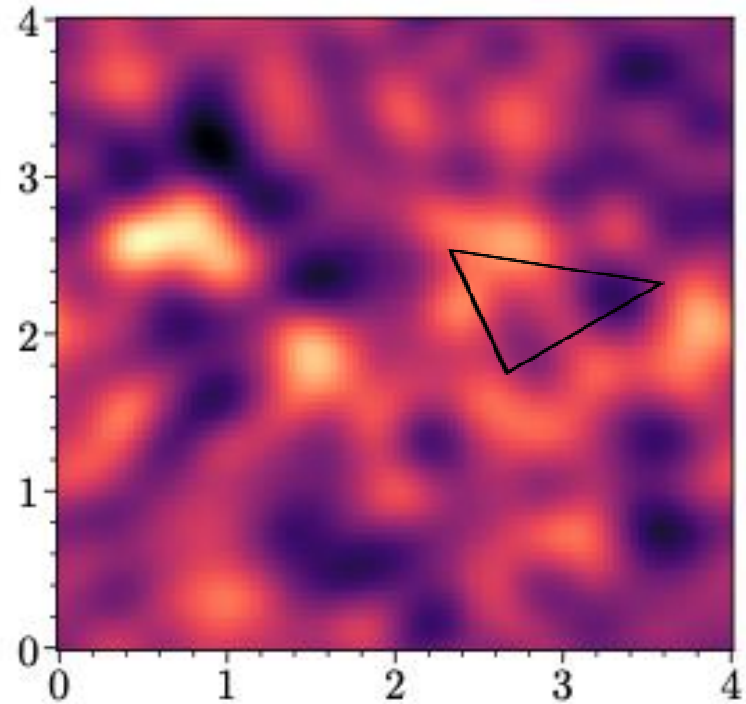
$$3\ddot{\Phi} + \partial_i\partial^i(\Psi - \Phi) = 4\pi G T^k_k,$$

$$\ddot{h}_{ij} = 16\pi G\left(T_{ij} - \frac{1}{3}\delta_{ij}T^k_k\right),$$

$$\Psi^j \simeq \Phi^j \simeq \pi G\frac{\rho}{m^2} = \frac{7\times10^{-26}\rho}{0.4\,\mathrm{GeV/cm^3}}\left(\frac{10^{-18}\mathrm{eV}}{m}\right)^2,$$

$$h^v_{ij} \propto h_0 \simeq \frac{8}{3}\pi G\frac{\rho}{m^2} = \frac{2\times10^{-25}\rho}{0.4\,\mathrm{GeV/cm^3}}\left(\frac{10^{-18}\mathrm{eV}}{m}\right)^2,$$

$$h^s_{ij} \simeq h_0 v^2/2$$



- Perturbation for scalar is suppressed.

H. Kim 2023

- Not for h_{ij} from vector

Nomura, Ito & Soda 2020

Detecting Ultralight Dark Matter Gravitationally

- Tensor perturbation

$$S_\Phi^s \simeq \frac{64}{15}\kappa^4\rho^2 v^2 L^4 T\left[v^2\sin^2\gamma + 5m^2L^2\sin^2\frac{\gamma}{2}\right],$$

scalar

$$S_h^v(\epsilon_{ij}) \simeq \frac{256}{9}\kappa^4\rho^2 L^4 T[(\hat{n}_{12}^i\hat{n}_{12}^j - \hat{n}_{13}^i\hat{n}_{13}^j)\epsilon_{ij}]^2$$

vector

TABLE I. Arm lengths and instrumental noises of several planned laser interferometers in space. In the last row we give the sensitivities on vector ULDM with mass 5.0×10^{-19} eV. Here L is the nominal arm length of triangle constellation, while $s_{\rm acc}$ and $s_{\rm oms}$ are the acceleration noise of test mass and noise from optical metrology system, respectively. Note that LISA/LISAmax/Taiji/Tianqin adopt frequency-dependent noise power spectra [101], $s_{\rm acc}^2 \propto [1+(0.4\times10^{-3}\ {\rm Hz}/f)^2][1+(f/8\times10^{-3}\ {\rm Hz})^4]$ and $s_{\rm oms}^2 \propto 1+(2\times10^{-3}\ {\rm Hz}/f)^4$.

	LISA	Taiji	Tianqin	BBO	DECIGO	μAres	LISAmax	ASTROD-GW
L (10^9 m)	2.5	3	0.17	0.05	1×10^{-3}	395	260	260
$s_{\rm acc}$ ($10^{-15}\ \frac{\rm m/s^2}{\sqrt{\rm Hz}}$)	3	3	1	3×10^{-2}	4×10^{-4}	1	3	3
$s_{\rm oms}$ ($10^{-12}\ \frac{\rm m}{\sqrt{\rm Hz}}$)	15	8	1	1.4×10^{-5}	2×10^{-6}	50	15	100
$\frac{\rho}{\rho_0}$ (5.0×10^{-19} eV)	7.95×10^2	6.53×10^2	3.82×10^3	2.00×10^2	1.34×10^2	0.44	7.67	4.32

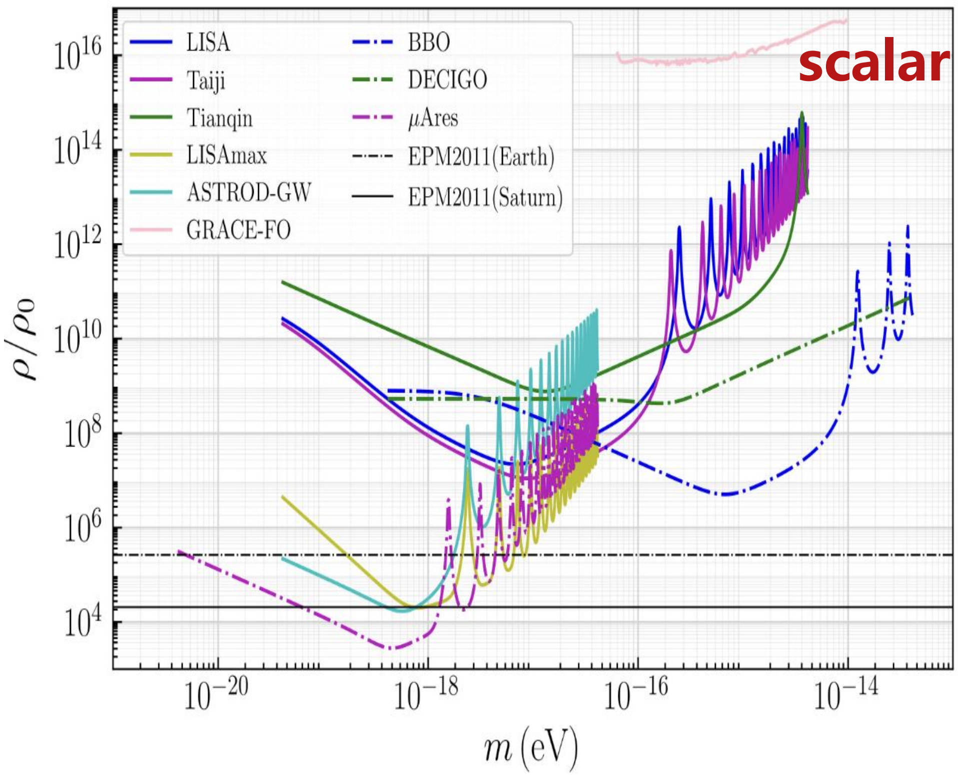
Yu, Cao, Tang, Wu, 2404.04333

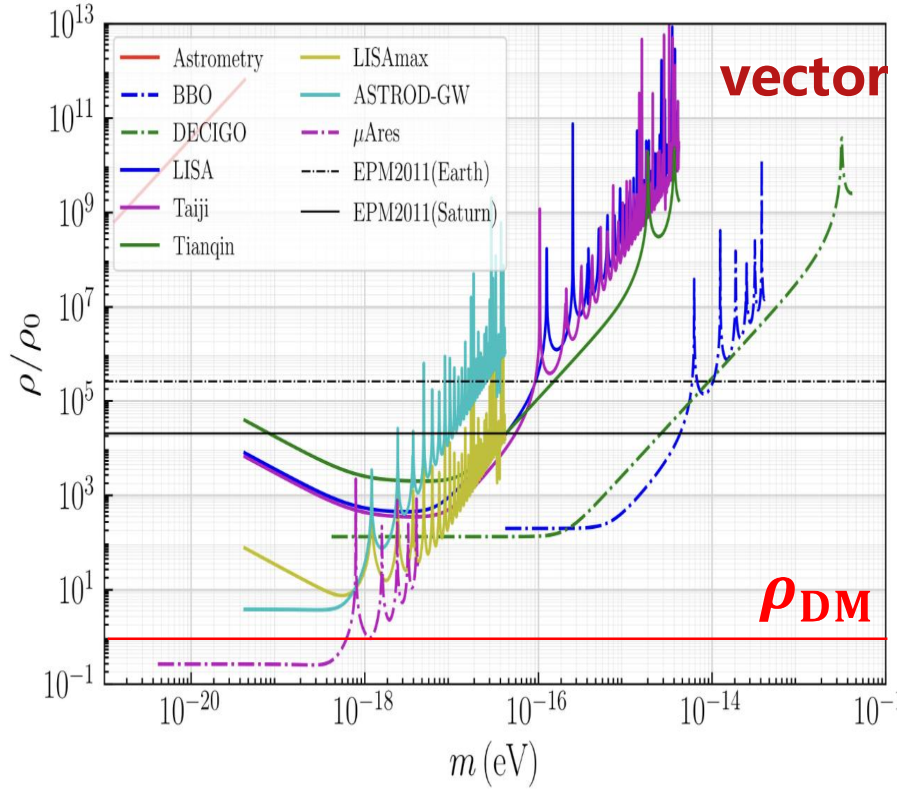
Detecting Ultralight Dark Matter Gravitationally

➢ Tensor perturbation

$$S_{\Phi}^{s} \simeq \frac{64}{15}\kappa^4\rho^2 v^2 L^4 T\left[v^2\sin^2\gamma + 5m^2L^2\sin^2\frac{\gamma}{2}\right],$$

$$S_h^v(\epsilon_{ij}) \simeq \frac{256}{9}\kappa^4\rho^2 L^4 T[(\hat{n}_{12}^i\hat{n}_{12}^j - \hat{n}_{13}^i\hat{n}_{13}^j)\epsilon_{ij}]^2$$





Yu, Cao, Tang, Wu, 2404.04333

Summary

- We discuss how GW laser interferometers in space may be able to probe dark matter.
- Wave/Ultralight Dark Matter
  - induce the oscillation of test masses, leading to signals in detectors. Also sensitive to axion-photon coupling,
  - monochromatic signal can be distinguished from GW from compact binaries,
  - metric perturbation by vector ULDM may be detectable in next-generation interferometers.

Thanks!