

Probing Dark Matter with Gravitational-Wave Interferometers in Space

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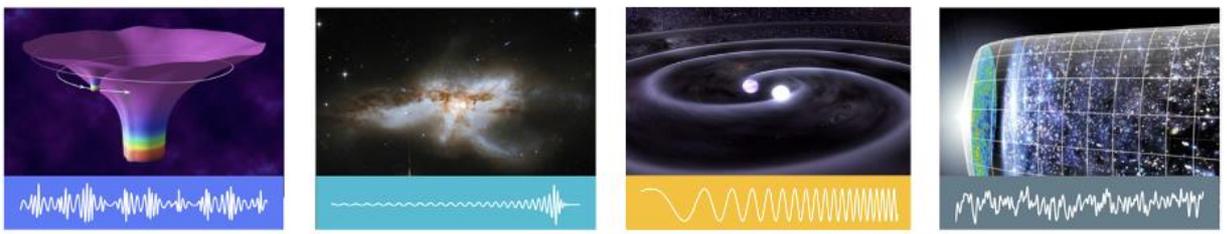
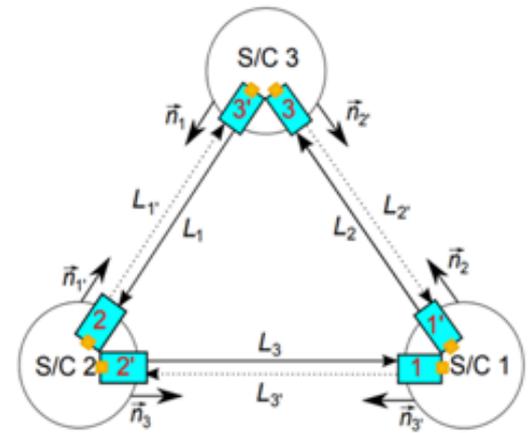
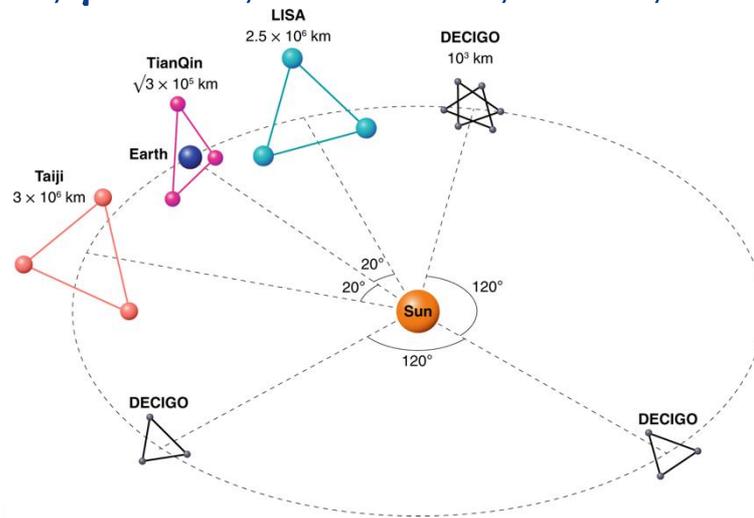
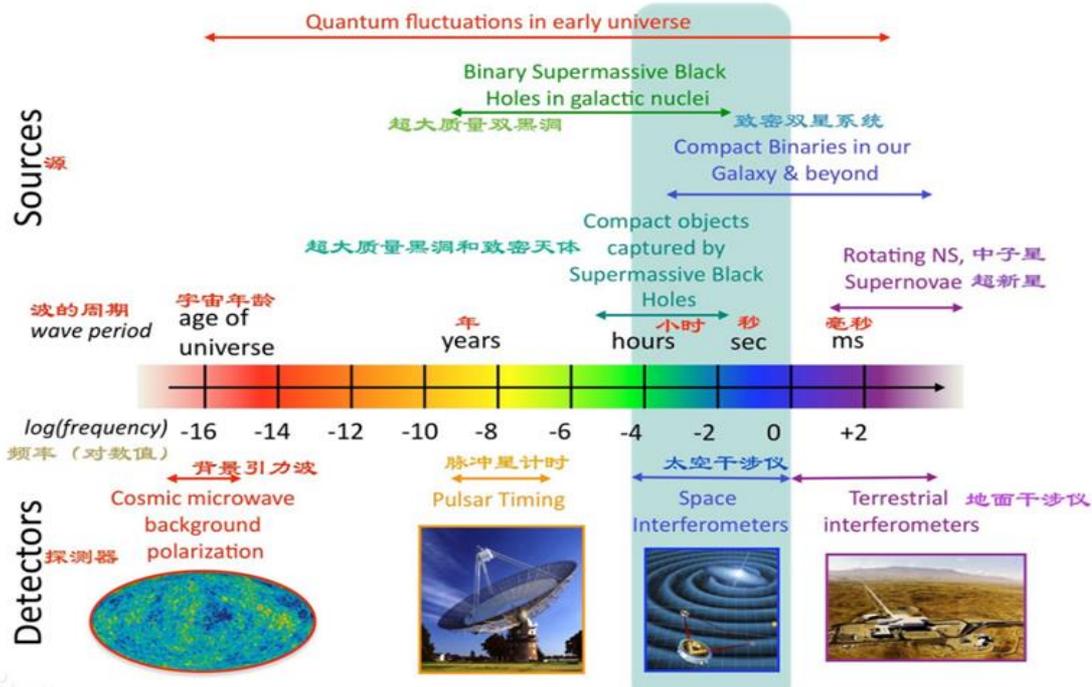
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Summary

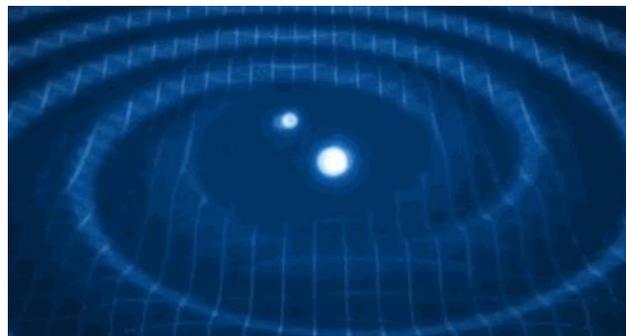
GW Laser Interferometers in Space

- LISA, Taiji, TianQin, LISAmix, Astrod-GW, μ Ares, DECIGO, BBO, ...



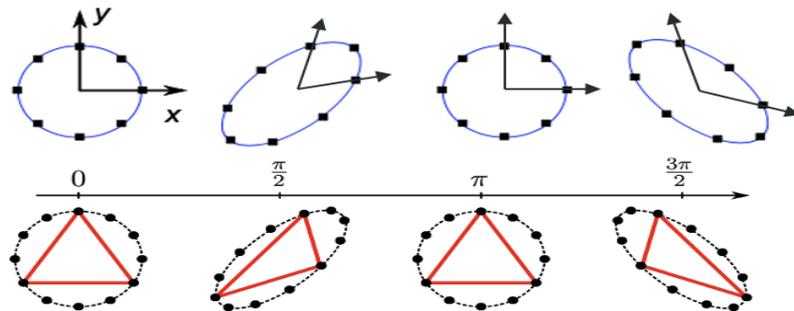
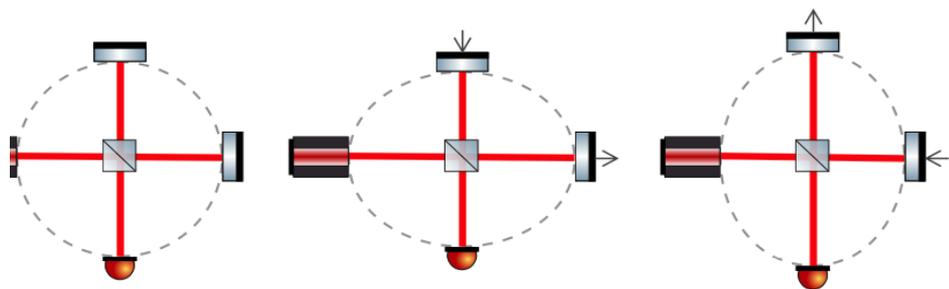
Signal Response

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



- $h \sim \Delta L/L \sim 10^{-12} \text{m}/10^9 \text{m} \sim 10^{-21}$

- One can measure the length/phase by laser



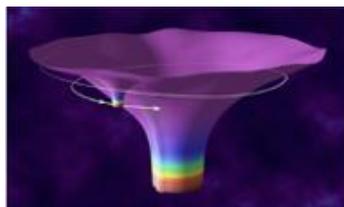
- Doppler shift $\frac{\delta v(t)}{v_0} \equiv y_{BA} = -\frac{1}{2} \frac{n_i n_j}{1 + \vec{k} \cdot \vec{n}} \left[h_{ij} \left(t - \frac{\vec{k} \cdot \vec{x}_B}{c} \right) - h_{ij} \left(t - \frac{\vec{k} \cdot \vec{x}_{A+L}}{c} \right) \right]$

GW sources and waveforms

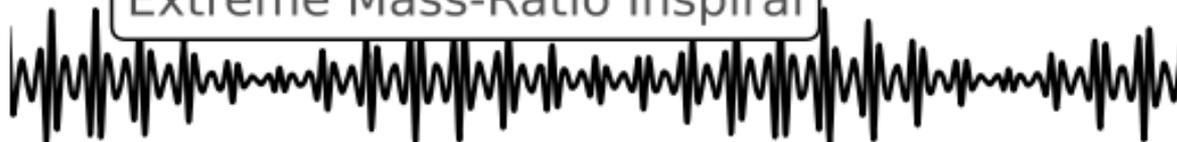
LISA, 2402.07571



Massive BH Binary Merger



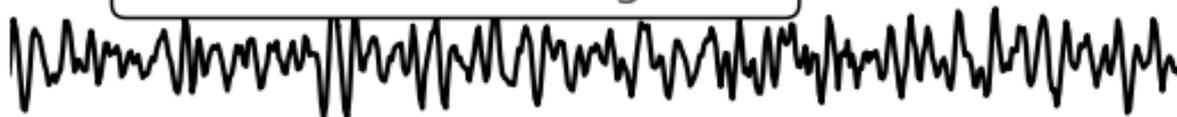
Extreme Mass-Ratio Inspiral



Galactic Binary

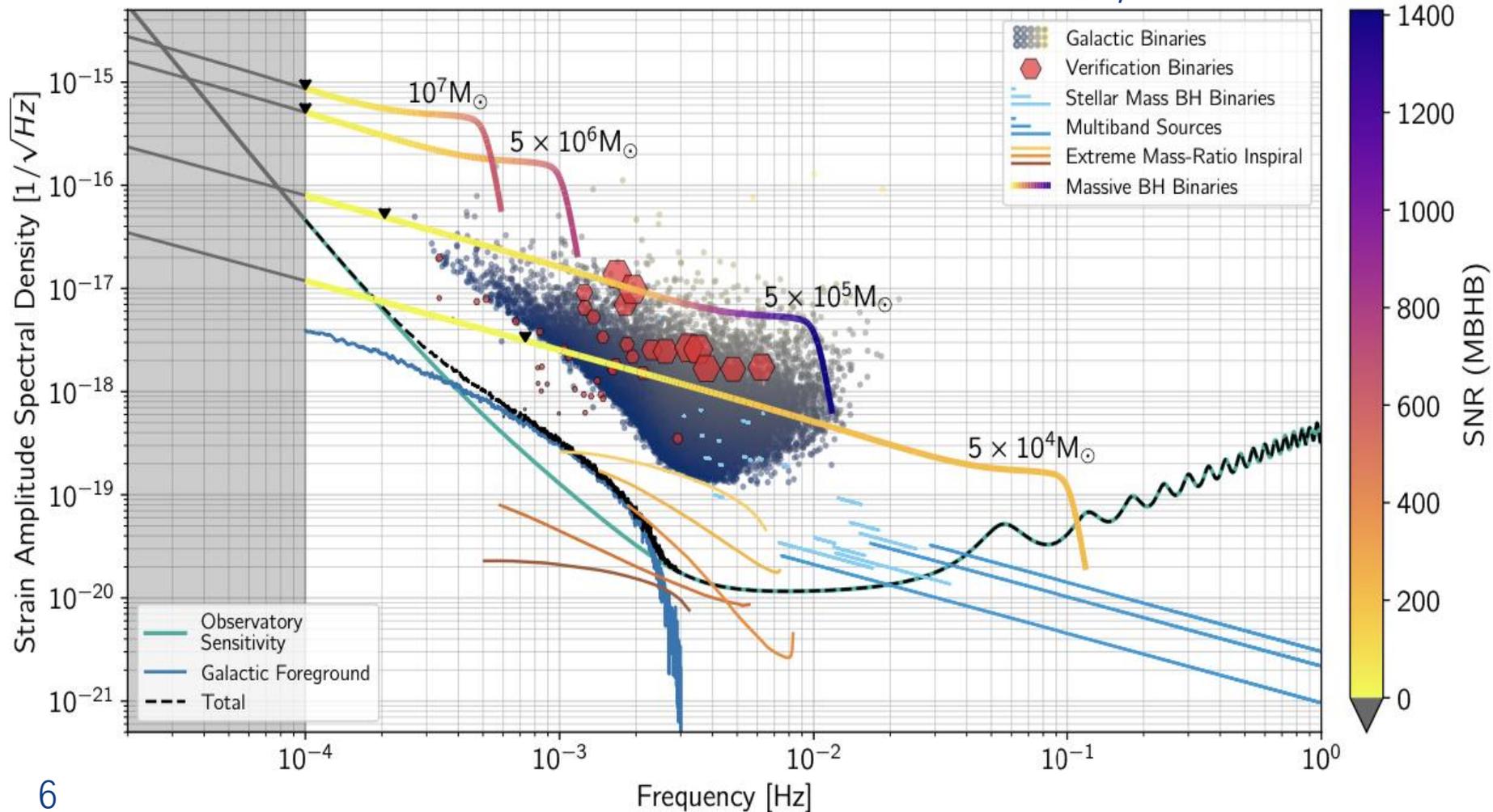


Stochastic GW Background



GW sources and waveforms

LISA, 2402.07571



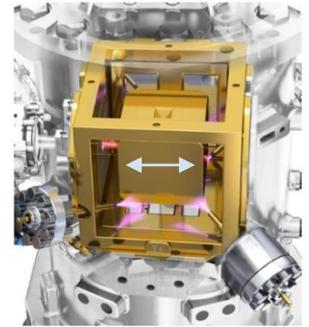
Main Noises

➤ Laser frequency noise

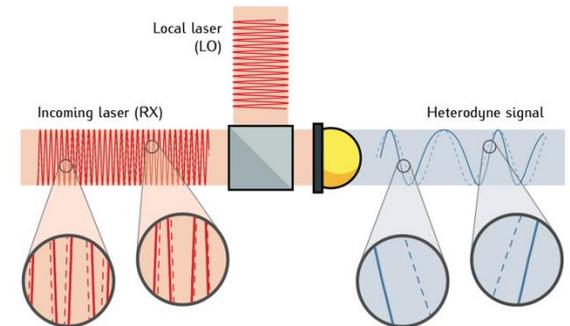
- The laser is not perfectly monochromatic, its frequency fluctuates.
- Need dedicated data analysis - Time-Delay Interferometry

➤ Secondary noises

- Acceleration noise of test mass, $s_{acc} \sim 10^{-15} \text{ m/s}^2$
 - Residual charges, self-gravity, ...
- Optical metrology noise, $s_{oms} \sim 10^{-12} \text{ m}$
 - Shot noise, relative intensity noise, ...



LISA, 2402.07571

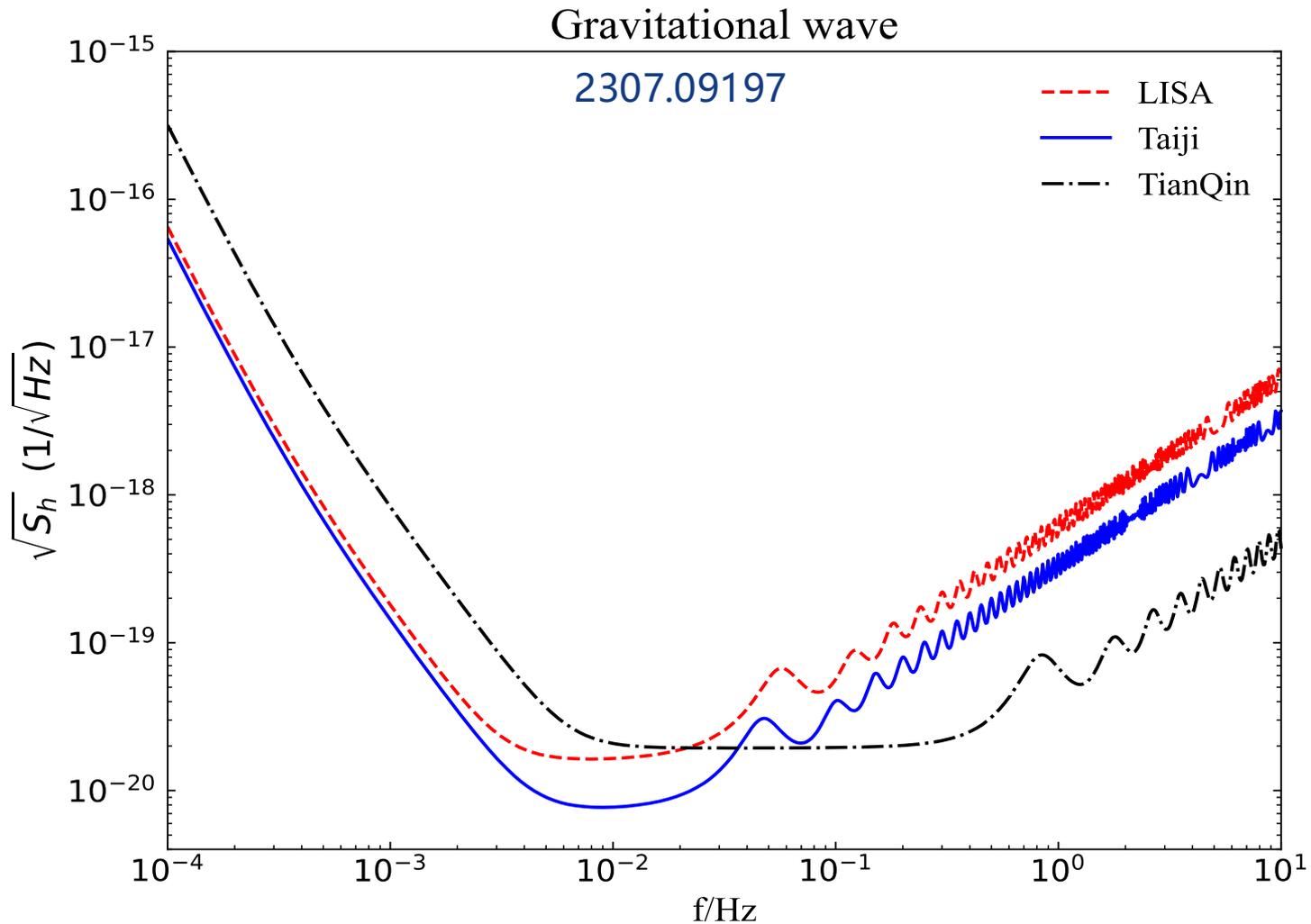


Barke 2015

	LISA	Taiji	Tianqin	BBO	DECIGO
L (10^9 m)	2.5	3	0.17	0.05	1×10^{-3}
s_{acc} ($10^{-15} \frac{\text{m/s}^2}{\sqrt{\text{Hz}}}$)	3	3	1	3×10^{-2}	4×10^{-4}
s_{oms} ($10^{-12} \frac{\text{m}}{\sqrt{\text{Hz}}}$)	15	8	1	1.4×10^{-5}	2×10^{-6}

Sensitivity on GW

- General
 - Arm length
 - Noise level
 - Duration
 - TDI
- Particular
 - Direction
 - Frequency
 - Waveform



Time-Delay Interferometry

- In space arm lengths are not equal
- Laser frequency noise does not cancel

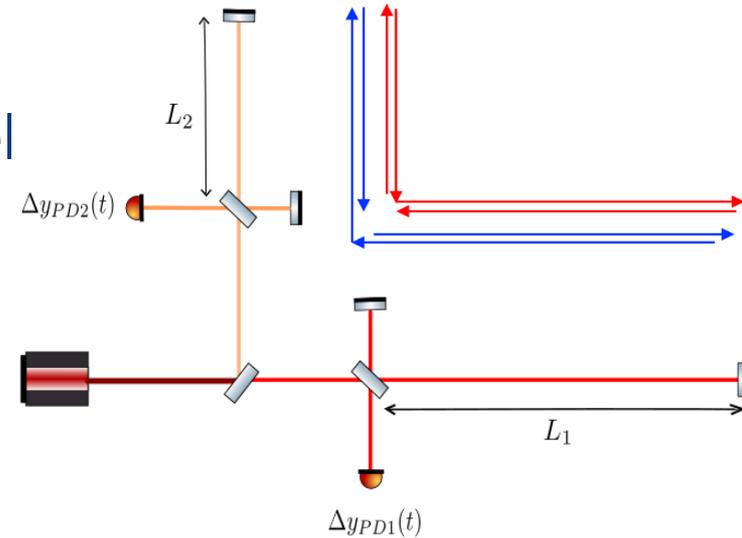
$$\begin{aligned}
 X(t) &\equiv [\Delta y_{PD1}(t) - \Delta y_{PD2}(t)] - [\Delta y_{PD1}(t - T_2) - \Delta y_{PD2}(t - T_1)] \\
 &= [H_1(t) - H_2(t) + p(t - T_1) - p(t - T_2)] \\
 &\quad - [H_1(t - T_2) - H_2(t - T_1) + p(t - T_1) - p(t - T_2)] \\
 &= H_1(t) - H_2(t) - H_1(t - T_2) + H_2(t - T_1),
 \end{aligned}$$

- Michelson interferometry

$$\begin{aligned}
 X(t) &\equiv [\Delta y_{PD2}(t - T_1) + \Delta y_{PD1}(t)] \\
 &\quad - [\Delta y_{PD1}(t - T_2) + \Delta y_{PD2}(t)]
 \end{aligned}$$

- TDI-**virtual** equal-arm interference

Tinto & Dhurandhar

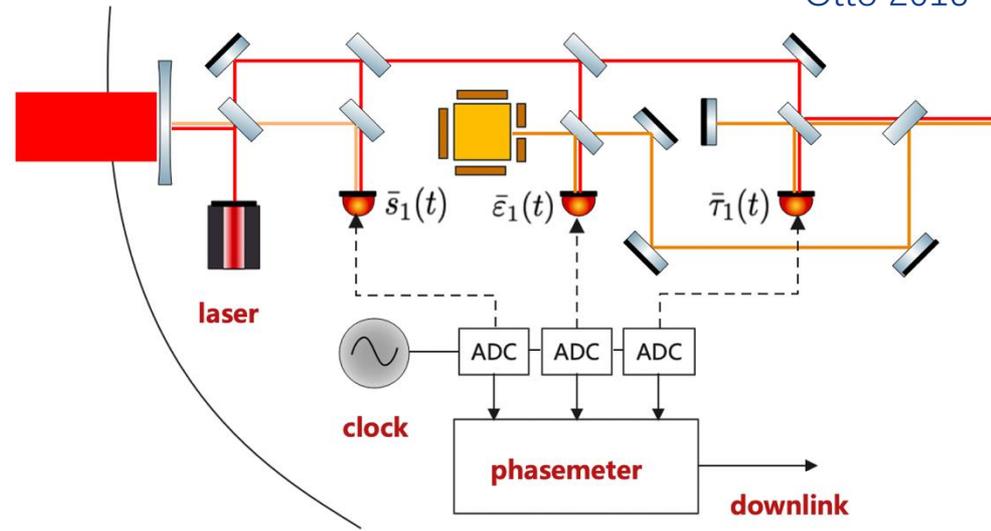
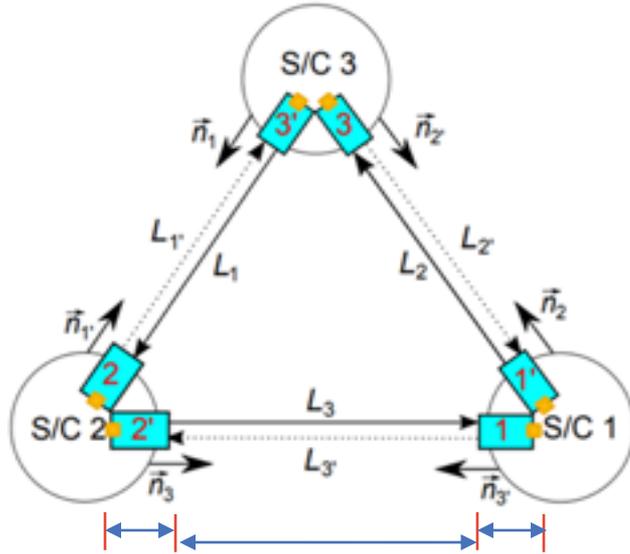


$$\begin{aligned}
 \Delta y_{PD1}(t) &= H_1(t) + p(t - T_1) - p(t), \\
 \Delta y_{PD2}(t) &= H_2(t) + p(t - T_2) - p(t),
 \end{aligned}$$

$$T_1 = 2L_1 \quad T_2 = 2L_2$$

Time-Delay Interferometry

Otto 2015



➤ Input for TDI

$$\eta_{i'} \equiv s_{i'} + \frac{\varepsilon_{i'} - \tau_{i'}}{2} + D_{i+1'} \frac{\varepsilon_{i-1} - \tau_{i-1}}{2} + \frac{\tau_i - \tau_{i'}}{2}$$

$$\eta_i \equiv s_i + \frac{\varepsilon_i - \tau_i}{2} + D_{i-1} \frac{\varepsilon_{i+1'} - \tau_{i+1'}}{2} - D_{i-1} \frac{\tau_{i+1} - \tau_{i+1'}}{2}$$

$$\eta_{1'} \sim D_{2'} p_3 - p_1, \quad \eta_1 \sim D_3 p_2 - p_1,$$

$$\eta_{2'} \sim D_{3'} p_1 - p_2, \quad \eta_2 \sim D_1 p_3 - p_2,$$

$$\eta_{3'} \sim D_{1'} p_2 - p_3, \quad \eta_3 \sim D_2 p_1 - p_3.$$

➤ TDI cancels laser frequency noise

Time-Delay Interferometry

- 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

$$\alpha(t) = (\eta_{2':1'2'} + \eta_{3':2'} + \eta_{1'}) - (\eta_{3:13} + \eta_{2:3} + \eta_1),$$

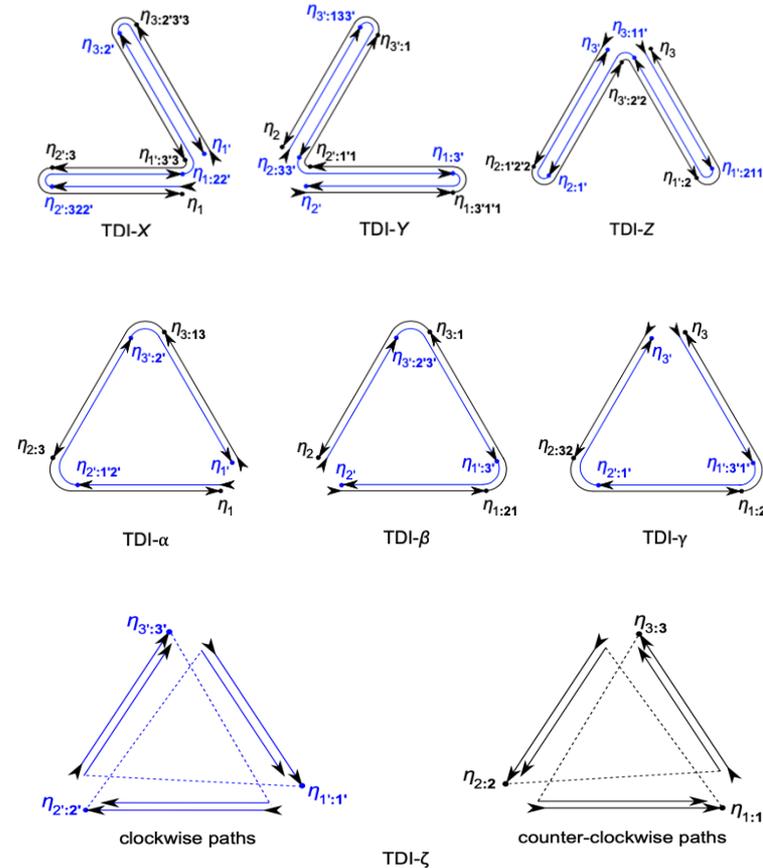
$$\beta(t) = (\eta_{3':2'3'} + \eta_{1':3'} + \eta_{2'}) - (\eta_{1:21} + \eta_{3:1} + \eta_2),$$

$$\gamma(t) = (\eta_{1':3'1'} + \eta_{2':1'} + \eta_{3'}) - (\eta_{2:32} + \eta_{1:2} + \eta_3).$$

- ζ channel

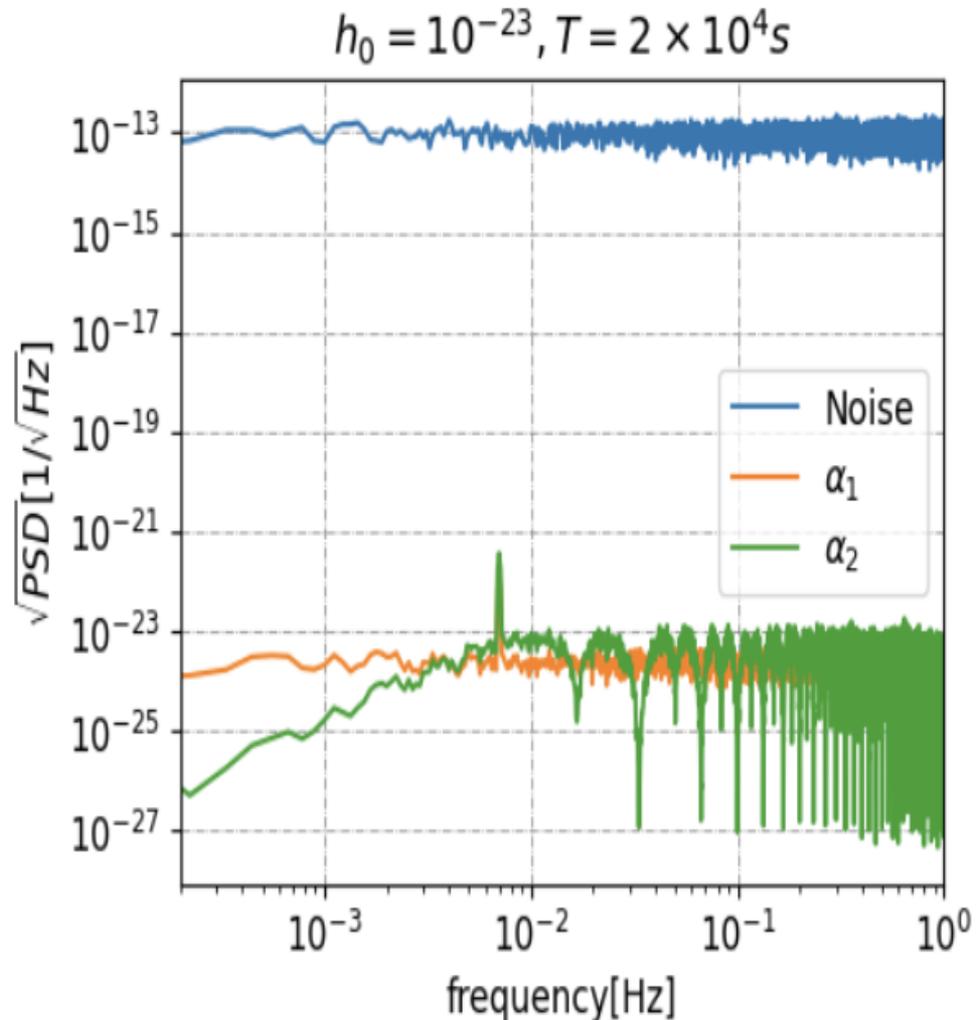
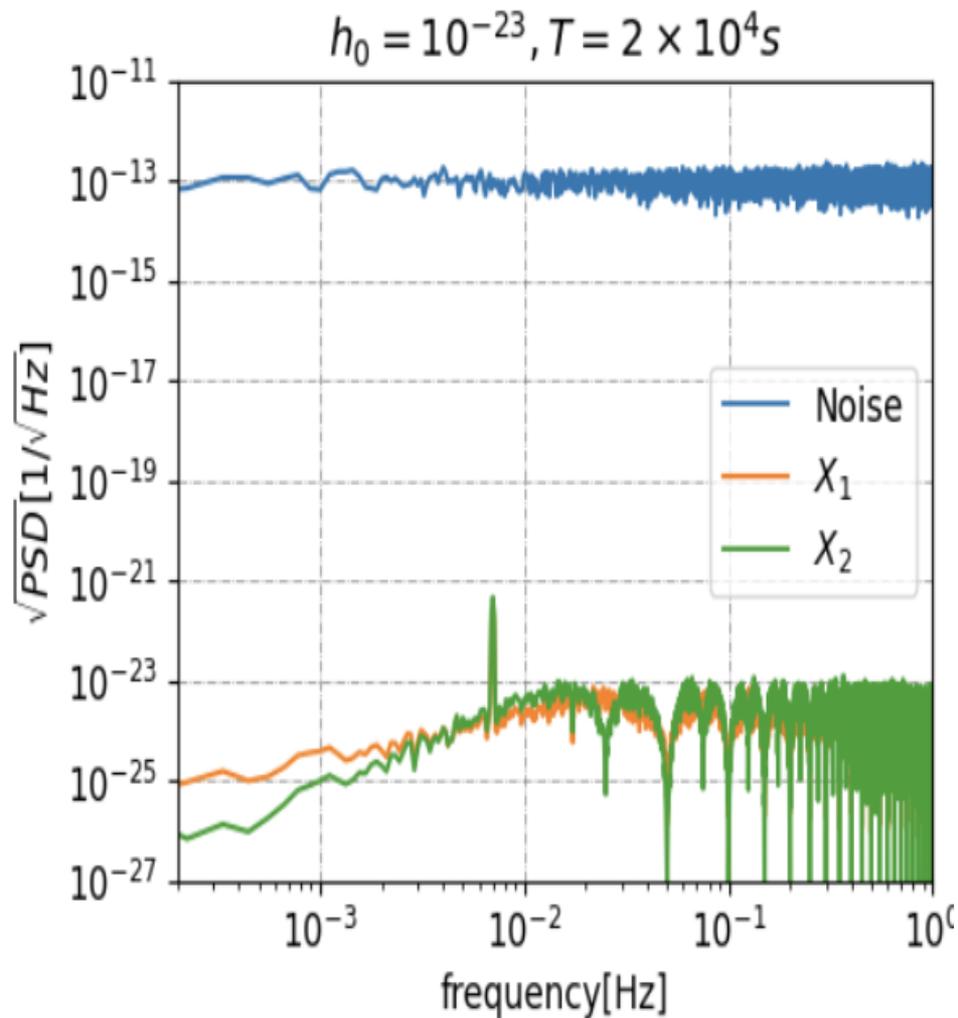
$$\zeta(t) = (\eta_{1':1'} + \eta_{2':2'} + \eta_{3':3'}) - (\eta_{1:1} + \eta_{2:2} + \eta_{3:3}).$$

Review by Tinto & Dhurandhar 2021



Credit: Otto 2015

Time-Delay Interferometry



Possible Effects from Dark Matter

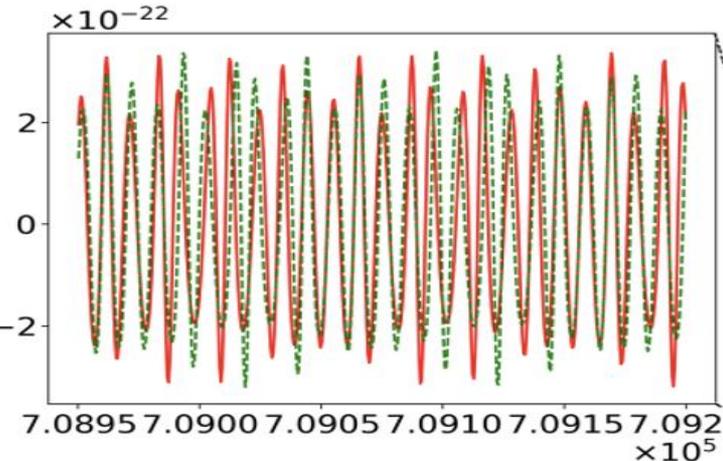
- Direct - Interact with the detector directly
 - Induce additional motion of test mass
 - Change the size of test mass, etc
 - Modify the propagation of laser light



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

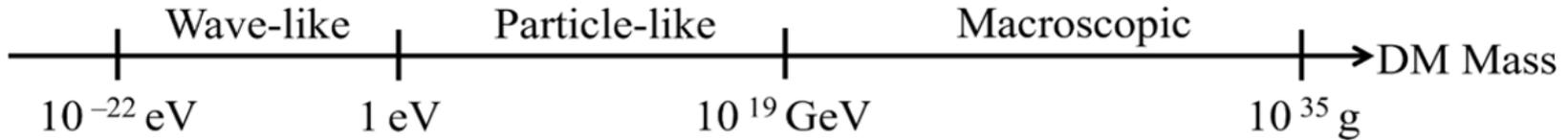
- Indirect - Affect the messengers that interact with the detector
 - Modify the GW from astrophysical sources
 - Cosmological phase transition
 - As new GW sources, PBHs, ...

Refs. Eda, Itoh, Kuroyanagi & Silk 2013, Yue, Han, Chen 2017, Bertone et al 2020, Cardoso et al 2022,



Dark Matter Candidates

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



**Axion, ALP, DP,
Ultralight DM, etc**

e.g. Sungwoo Youn, Deog Ki Hong's talks

Ultralight/Wave Dark Matter

➤ Mass < 1 eV, QCD axion, ALP, Dark Photon, ...

➤ A phenomenological approach

➤ Scalar $\mathcal{L} = \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - C \frac{\phi}{M_P} \mathcal{O}_{\text{SM}},$

➤ Light dilaton, $\delta\mathcal{L} = \frac{\phi}{M_P} \left[-\frac{d_g \beta_3}{2g_3} F_{\mu\nu}^A F^{A\mu\nu} - \sum_{i=u,d} (d_{m_i} + \gamma_{m_i} d_g) m_i \bar{\psi}_i \psi_i \right]$ Damour & Donoghue 2010

➤ ALP, $-\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu},$

➤ Vector $\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} + \frac{1}{2} m_A^2 A^\nu A_\nu - \epsilon_D e J_D^\nu A_\nu,$

➤ Baryon number, B-L, Dark $U(1)$,

➤ Production Mechanism – viable DM candidate

scalar: misalignment, ...

vector: Graham, Mardon & Rajendran 2015, Ema, Nakayama & Tang 2020, Kolb & Long 2024

.....

Wave Dark Matter Background

Foster, Rodd, Safdi 2018

- Number density is very large, behaves as classical wave

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

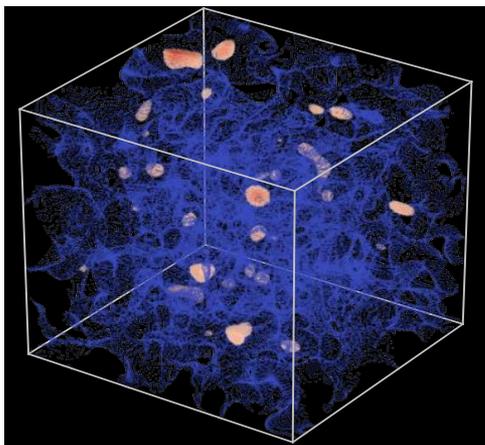
$$\vec{k} = m\vec{v}, \omega = 2\pi f \simeq m, v \sim 10^{-3},$$

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

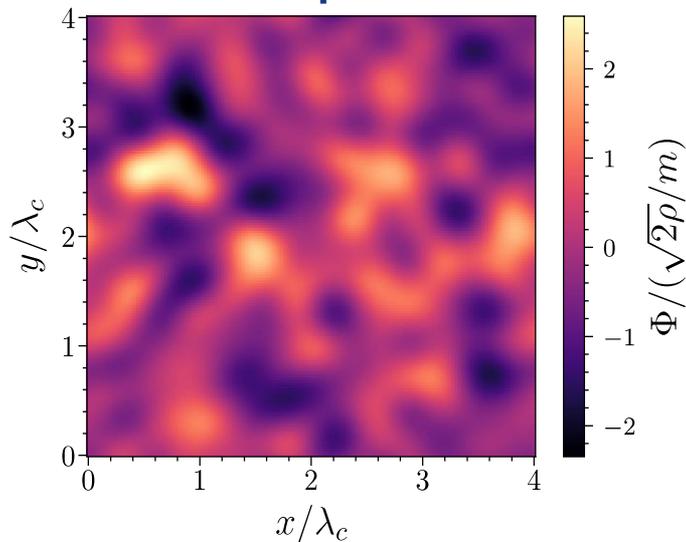
at a specific point \sim monochromatic within τ_c .

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

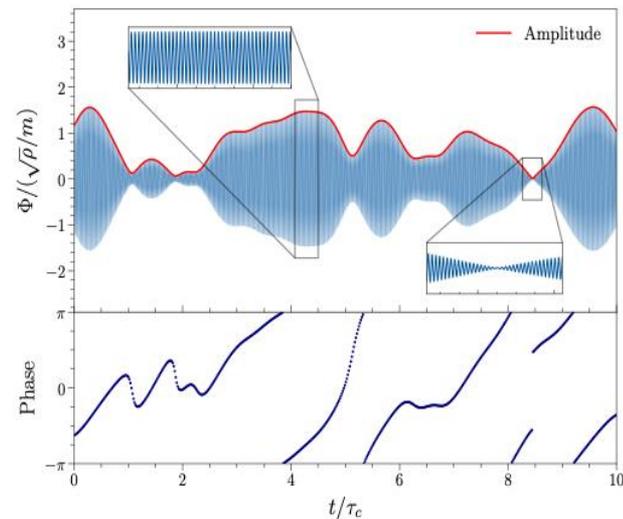
3D snapshot



2D snapshot



at some point



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 , $\mathcal{L} = \frac{1}{2} \partial^\mu \phi \partial_\mu \phi - \frac{1}{2} m_\phi^2 \phi^2 - C \frac{\phi}{M_P} \mathcal{O}_{\text{SM}}$,

➤ Interaction depending on the underlying theory, e.g.

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

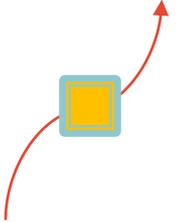
➤ Additional gradient or force

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

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

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

➤ 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



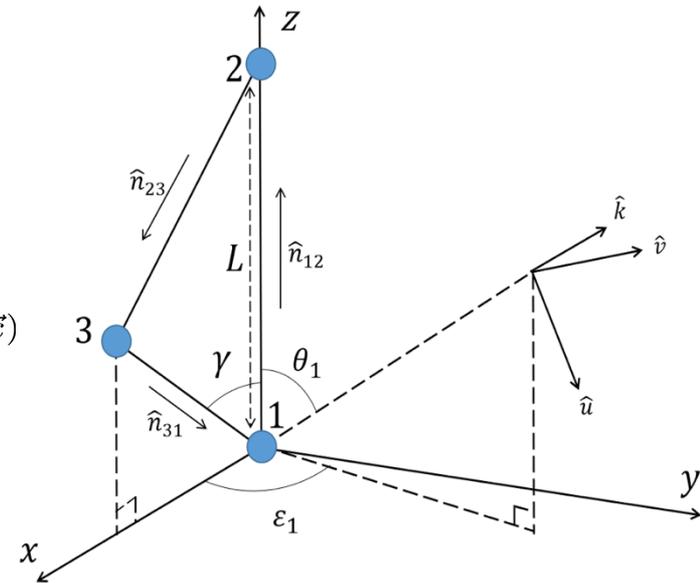
$$\delta t_{rs} = -\hat{n}_{rs} \cdot [\delta \vec{x}(t, \vec{x}_r) - \delta \vec{x}(t - L, \vec{x}_s)],$$

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

- Fractional frequency change

$$y_{rs}(t) \equiv \frac{\delta \nu_{rs}}{\nu_0} = \mu_{rs} [h(t, \vec{x}_r) - h(t - L, \vec{x}_s)], \quad h(t, \vec{x}) \propto e^{im(t - v \hat{k} \cdot \vec{x})}$$

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



Yu, Yao, Tang, Wu, 2307.09197

Transfer Functions

➤ Fourier transform

$$h(t) = \frac{\sqrt{T}}{2\pi} \int_0^\infty \tilde{h}(\omega) e^{i\omega t} d\omega$$

➤ One-way single link

$$y_{rs}(t) = \mu_{rs} \frac{\sqrt{T}}{2\pi} \int_0^\infty d\omega \tilde{h}(\omega) e^{i\omega t} \left[e^{-i\vec{k}\cdot\vec{x}_r} - e^{-i(\tau+\vec{k}\cdot\vec{x}_s)} \right],$$

$$\tilde{y}_{rs}(\omega) = \mu_{rs} \tilde{h}(\omega) \left[e^{-i(\vec{k}\cdot\vec{x}_r)} - e^{-i(\tau+\vec{k}\cdot\vec{x}_s)} \right]. \quad \tau = 2\pi f L$$

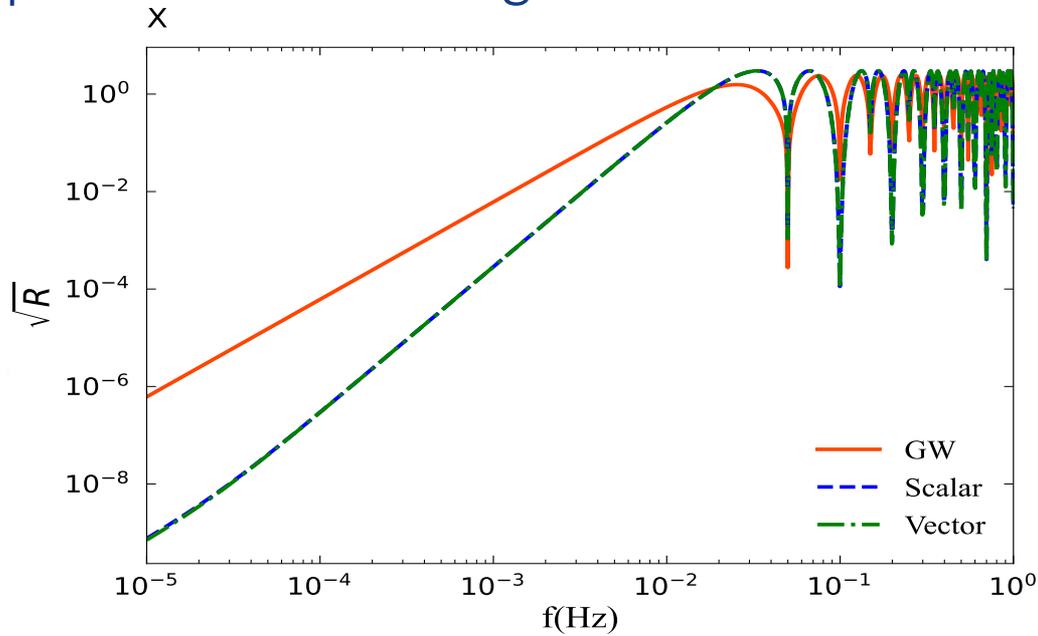
➤ Transfer function, sky and polarization averaged

$$R(\omega) = \left| \frac{\tilde{y}_{rs}(\omega)}{\tilde{h}(\omega)} \right|^2,$$

$$I_s \equiv \frac{1}{4\pi} \int_{-1}^1 d\cos\theta_1 \int_0^{2\pi} d\epsilon_1 \dots,$$

$$I_v \equiv \frac{1}{16\pi^2} \int_{-1}^1 d\cos\theta_1 \int_0^{2\pi} d\epsilon_1 \int_{-1}^1 d\cos\theta_2 \int_0^{2\pi} d\epsilon_2 \dots$$

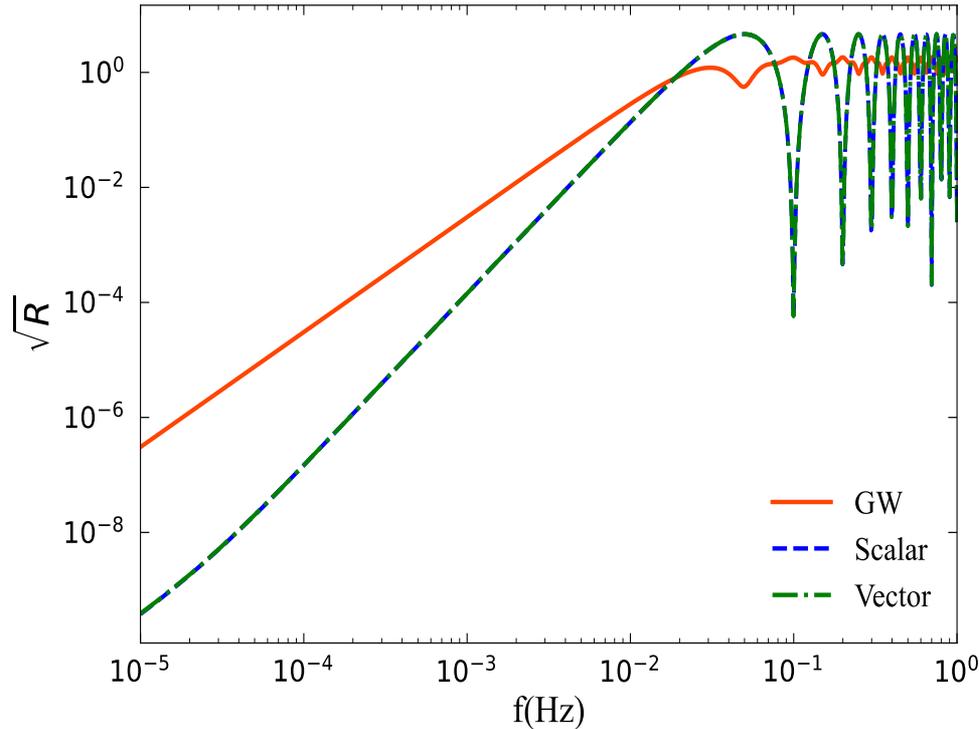
$$I_{GW} \equiv \frac{1}{8\pi^2} \int_{-1}^1 d\cos\theta_1 \int_0^{2\pi} d\epsilon_1 \int_0^{2\pi} d\psi \dots$$



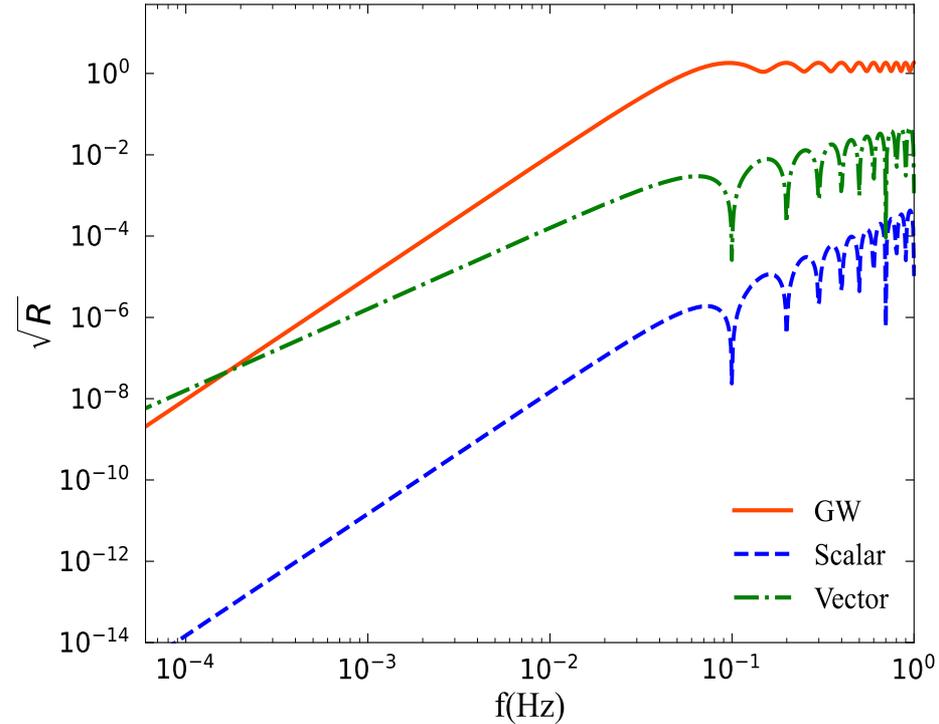
Transfer Functions

- Different channels have different transfer functions
- DM is also different from gravitational wave, velocity effect, ...

α



ζ



Sensitivity

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

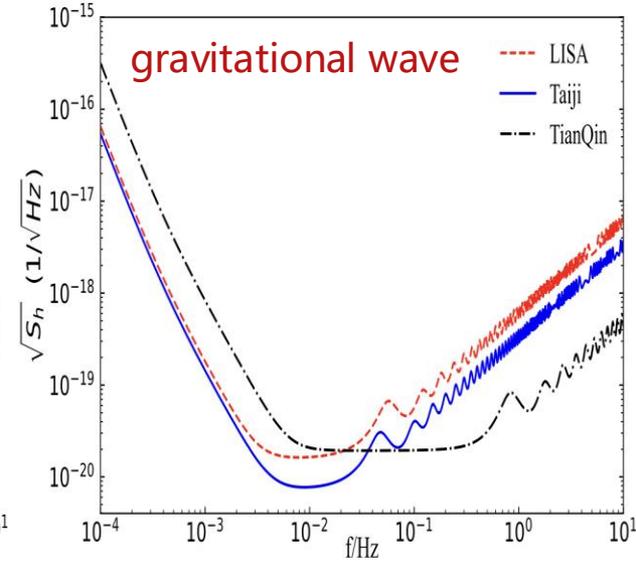
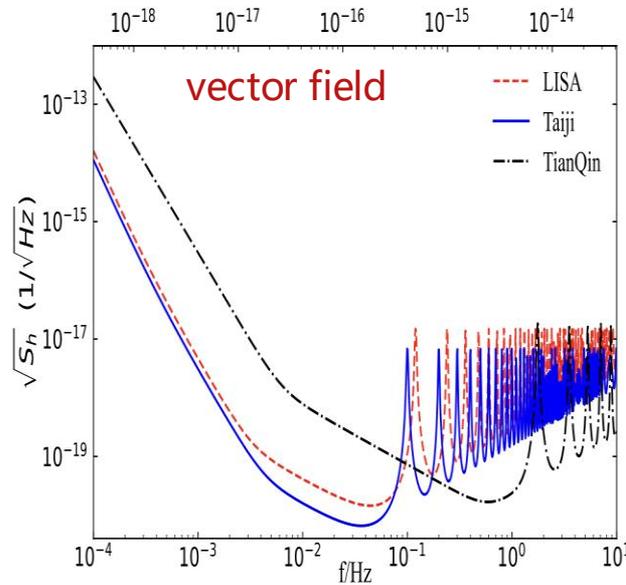
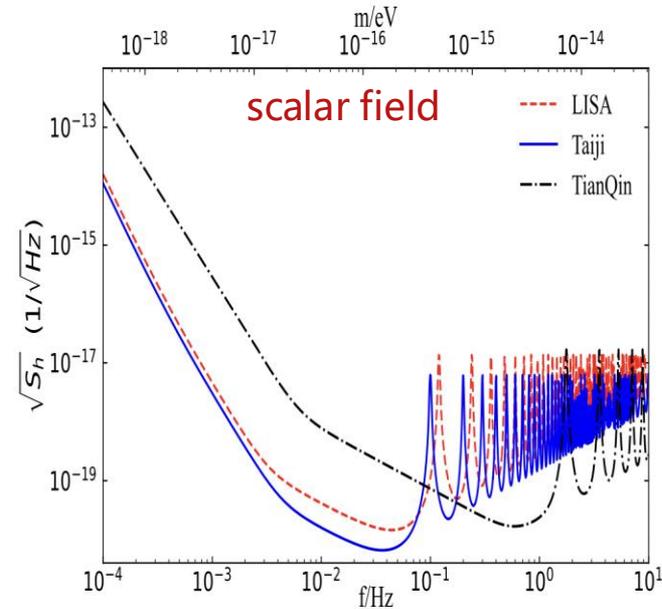
$$S_{oms}(f) = \left(s_{oms} \frac{2\pi f}{c} \right)^2 \left[1 + \left(\frac{2 \times 10^{-3} \text{ Hz}}{f} \right)^4 \right] \frac{1}{\text{Hz}},$$

$$S_{acc}(f) = \left(\frac{s_{acc}}{2\pi f c} \right)^2 \left[1 + \left(\frac{0.4 \times 10^{-3} \text{ Hz}}{f} \right)^2 \right] \left[1 + \left(\frac{f}{8 \times 10^{-3} \text{ Hz}} \right)^4 \right] \frac{1}{\text{Hz}},$$

LISA : $s_{oms} = 15 \times 10^{-12} \text{ m}$, $s_{acc} = 3 \times 10^{-15} \text{ m/s}^2$,

Taiji : $s_{oms} = 8 \times 10^{-12} \text{ m}$, $s_{acc} = 3 \times 10^{-15} \text{ m/s}^2$,

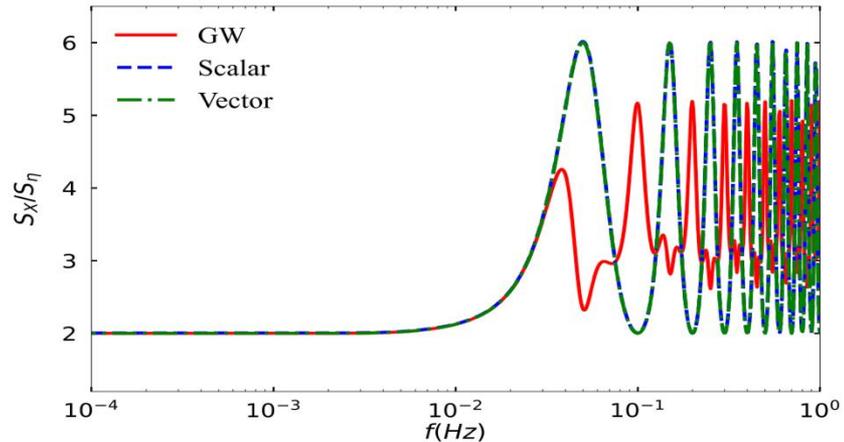
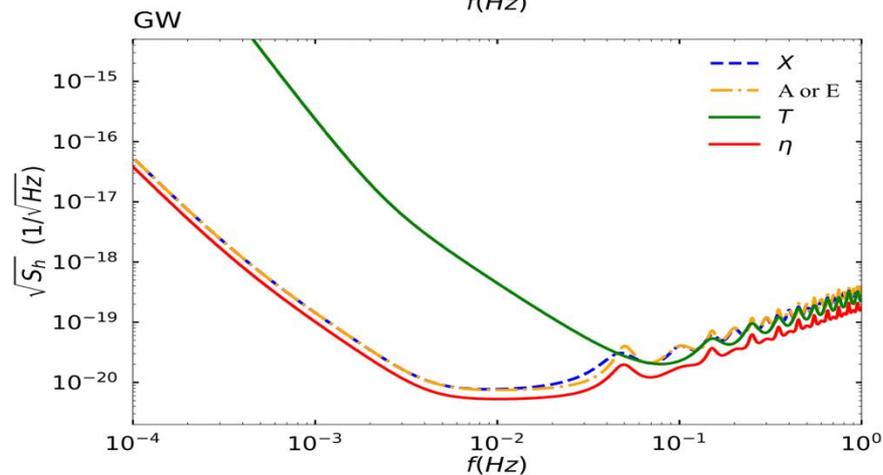
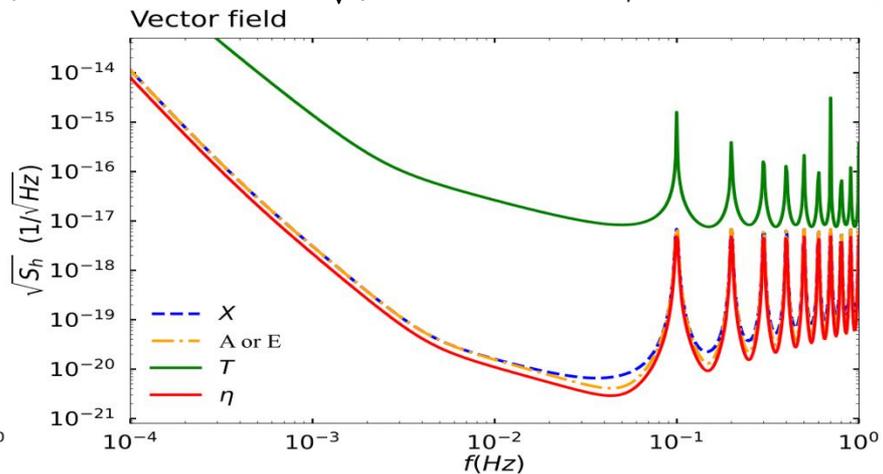
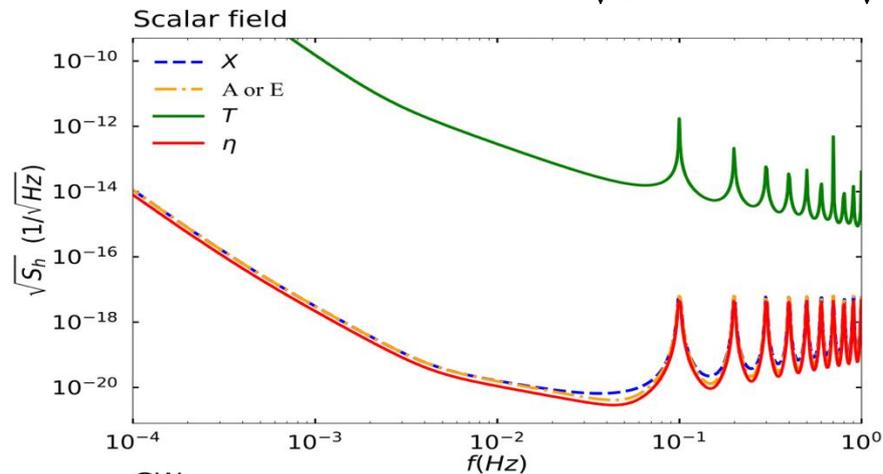
TianQin : $s_{oms} = 1 \times 10^{-12} \text{ m}$, $s_{acc} = 1 \times 10^{-15} \text{ m/s}^2$.



Sensitivity

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

Damour & Donoghue

$$d_{\hat{m}} \equiv \frac{d_{m_d} m_d + d_{m_u} m_u}{m_d + m_u},$$

$$d_g^* \approx d_g + 0.093(d_{\hat{m}} - d_g).$$

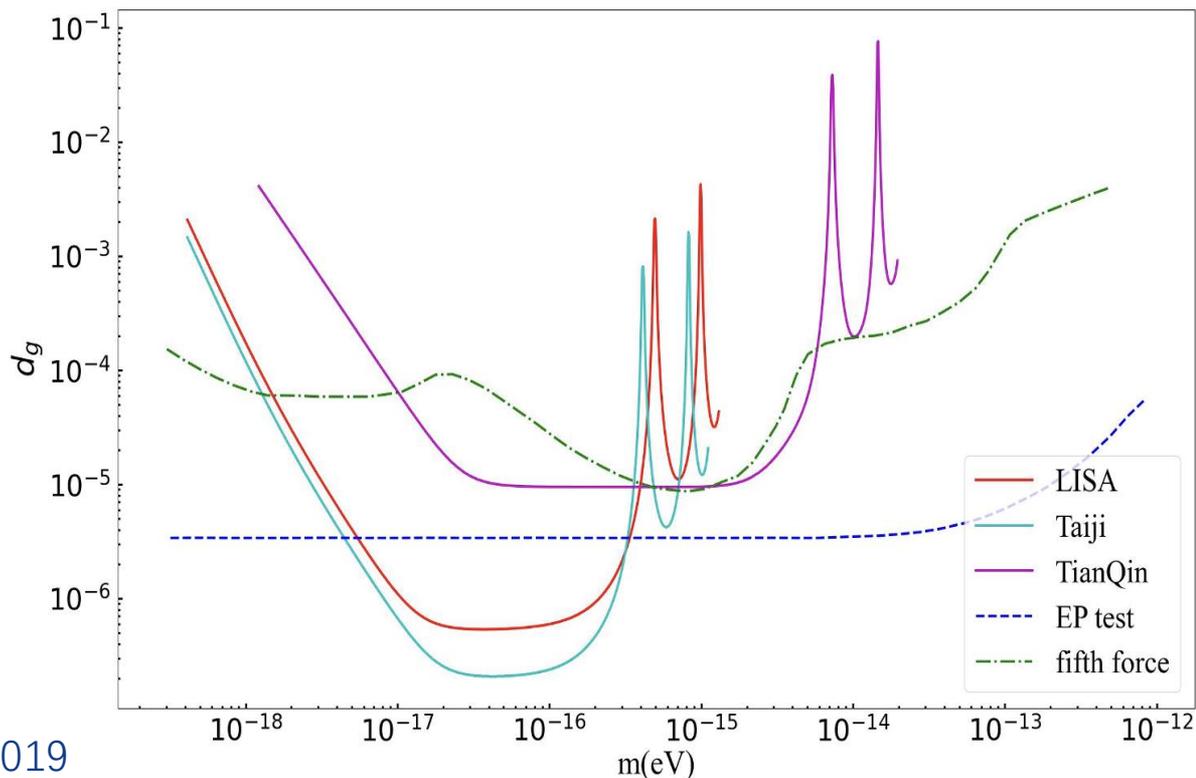
assuming $d_m = 0$ and $d_g^* \approx 0.9d_g$.

➤ Equivalence principle is violated.

➤ MICROSCOPE

➤ Pulsars

Shao, Wex, Kramer 2019



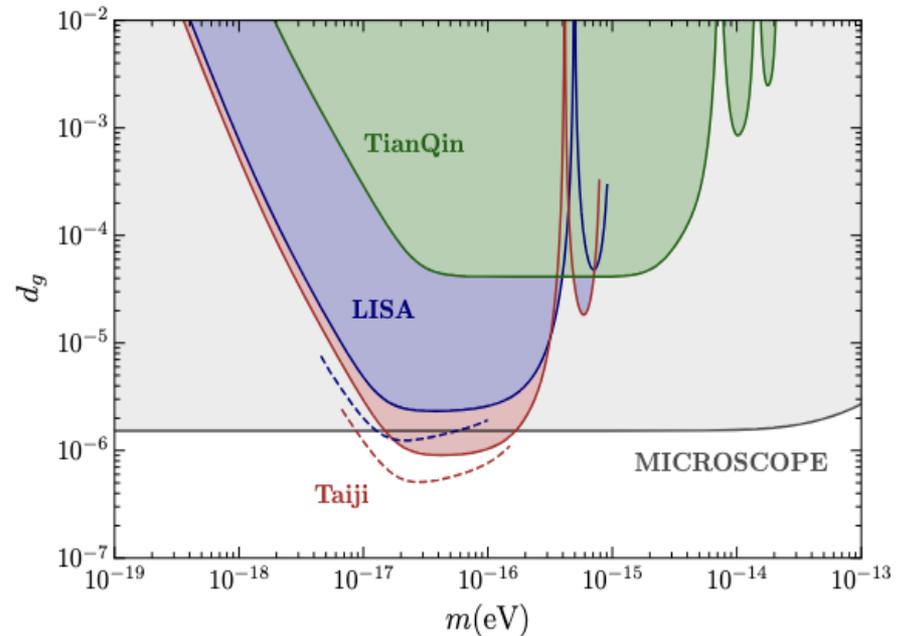
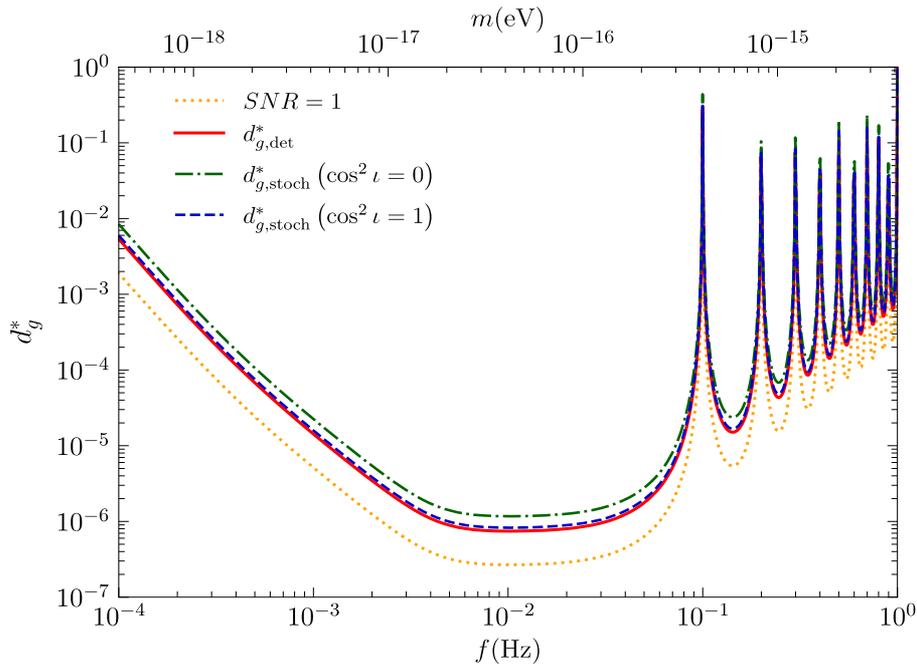
Statistical Effects

➤ Velocity distributions, likelihood analysis

$$S_O(\lambda_{\min}) = \left(\frac{\ln \alpha}{\ln \gamma} - 1 \right) N_O, \quad \lambda_{\min}^2 = \frac{N_O}{\Gamma_O S_\Phi} \left(\frac{\ln \alpha}{\ln \gamma} - 1 \right).$$

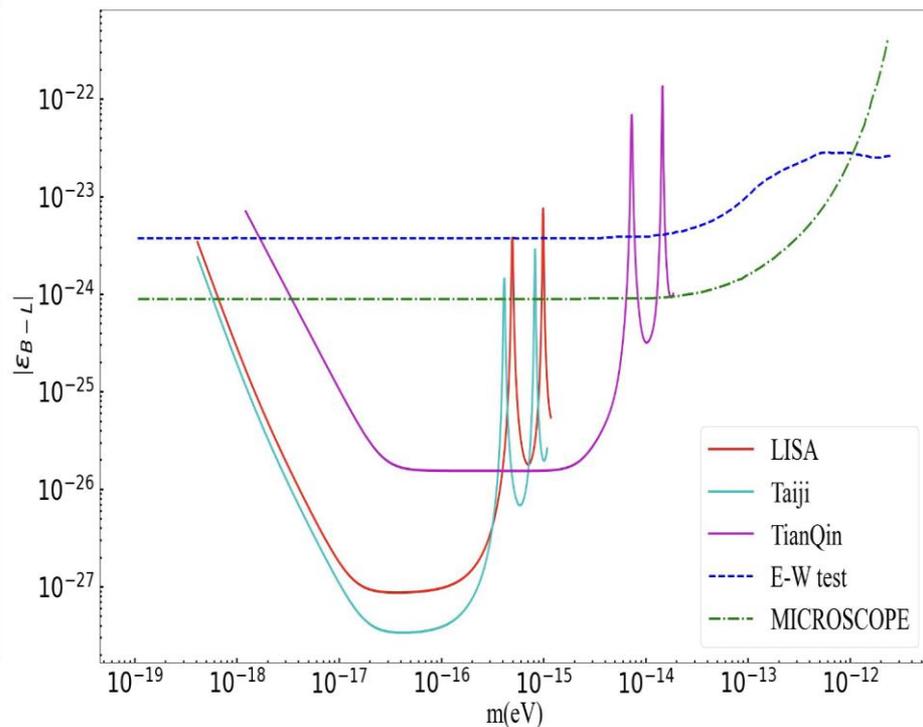
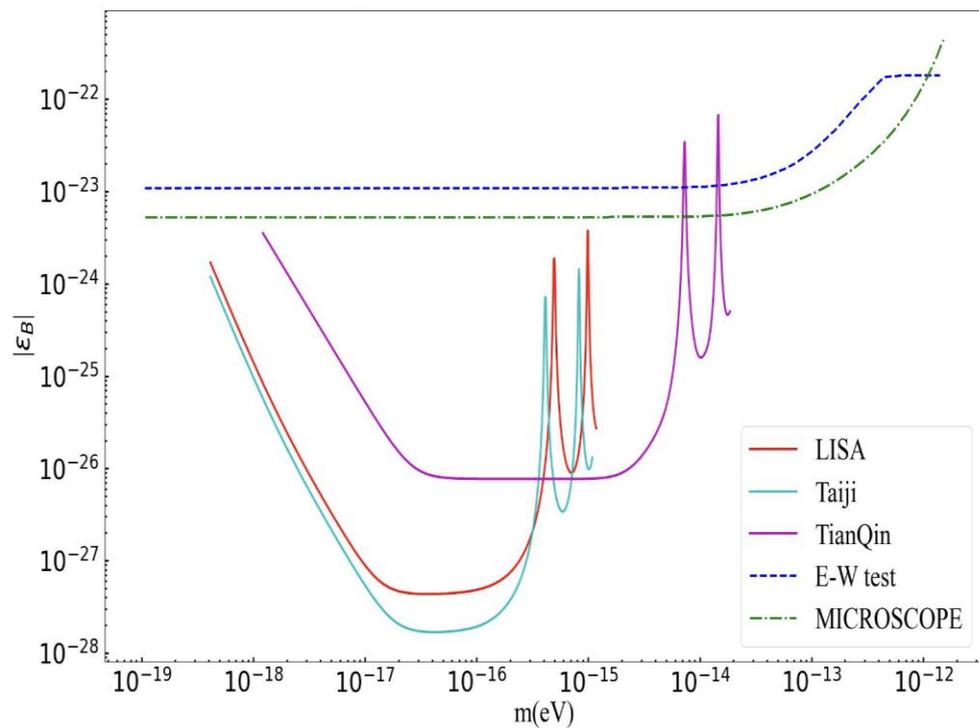
$$\gamma = \int_{P_*(\alpha)}^{\infty} dP \mathcal{L}_{\text{stoch}} \left(\tilde{d} \mid S_O(\lambda_{\min}), N_O \right), \quad \text{detection probability}$$

$$\alpha = \int_{P_*}^{\infty} dP \mathcal{L}_{\text{stoch}} \left(P \mid \lambda = 0, N_O \right). \quad \text{false alarm rate}$$



Sensitivity on vector DM

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



Sensitivity on Axion-Photon Coupling

- Axion-photon coupling

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

- Modifies Maxwell's eqs

$$\nabla \cdot \mathbf{E} = -g_{a\gamma}\nabla a \cdot \mathbf{B},$$

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

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

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

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

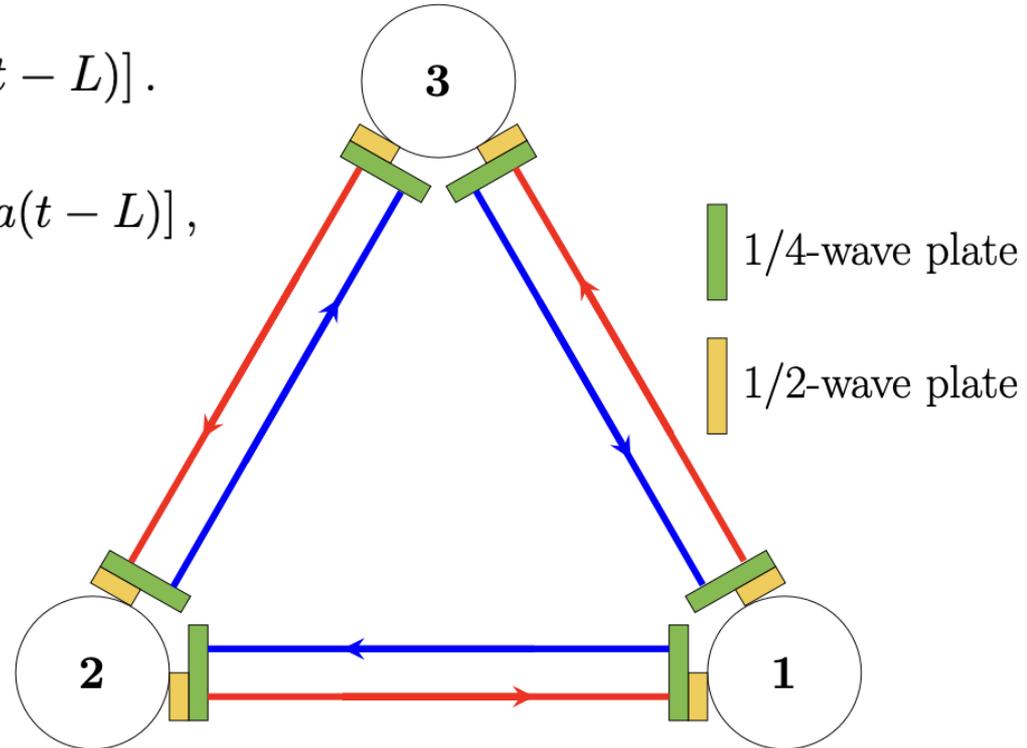
- Linearly polarized – pol angle

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

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

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

- Need modifications



Sensitivity on Axion-Photon Coupling

- Signal response
- Equivalent phase changes

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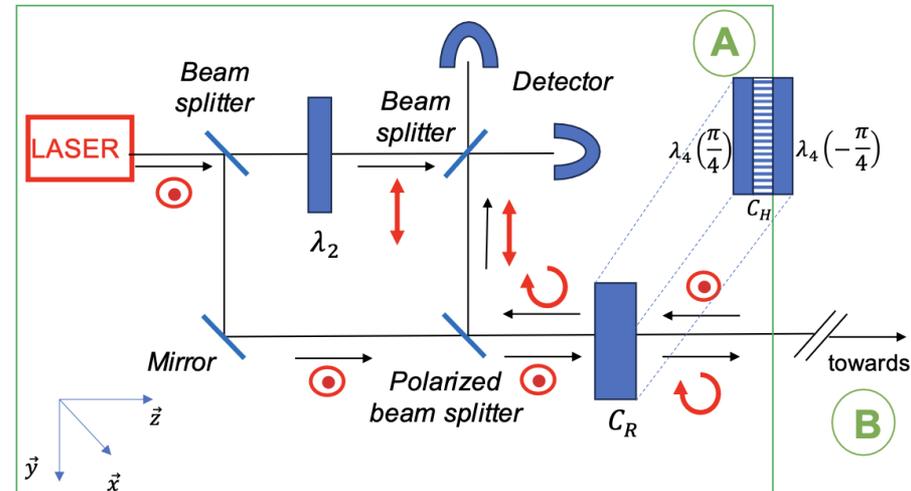
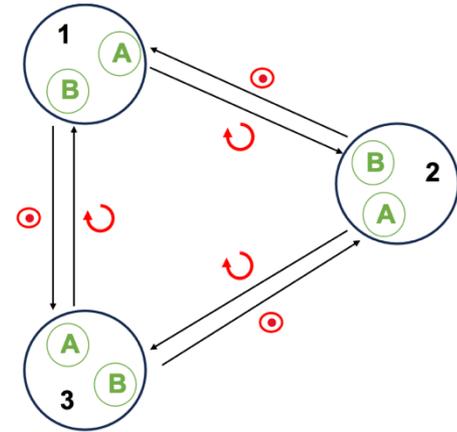
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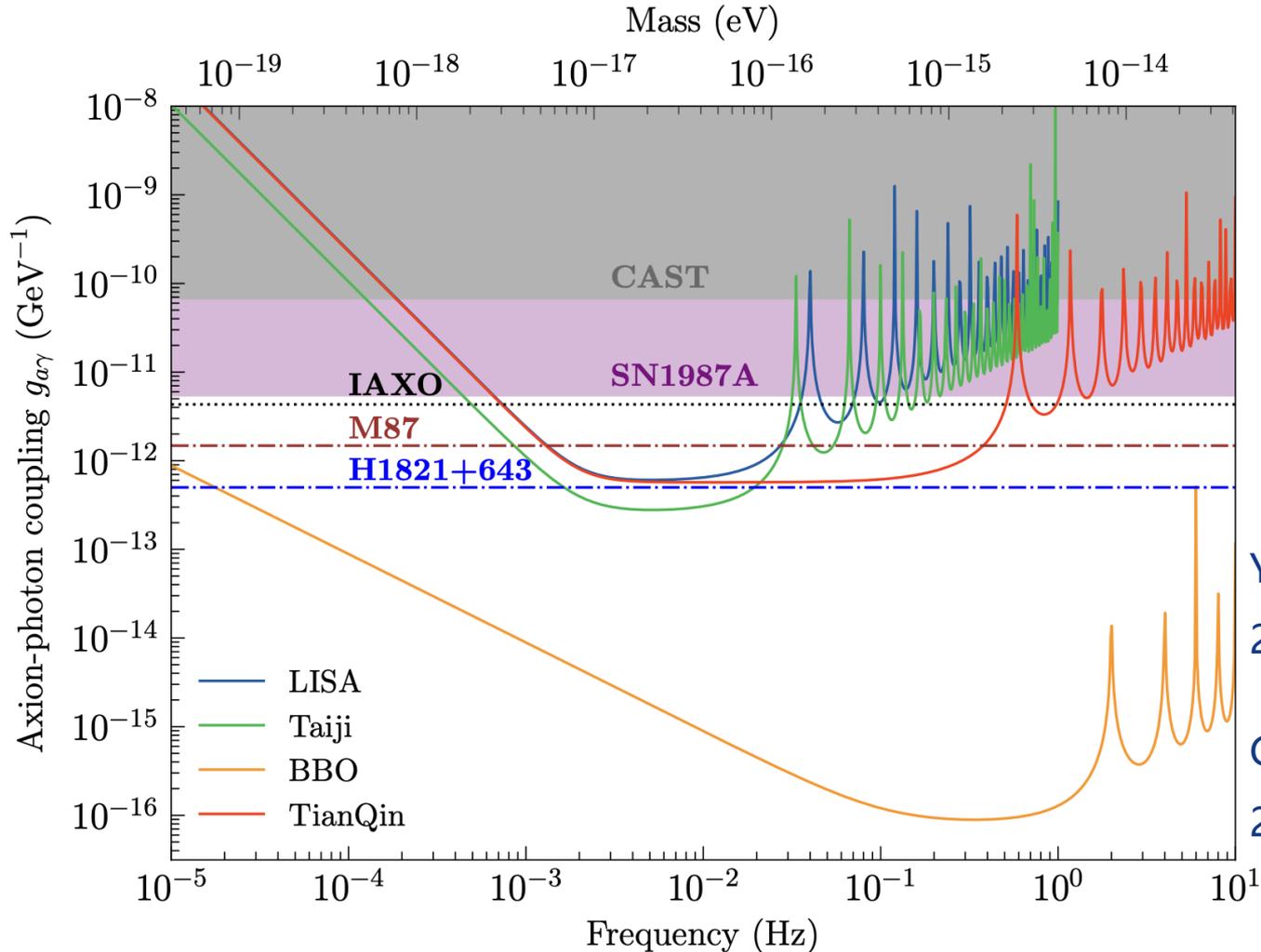
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- Need modifications



Sensitivity on Axion-Photon Coupling



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

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

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

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

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

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

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

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

$$h_{ij}^s \simeq h_0 v^2 / 2$$

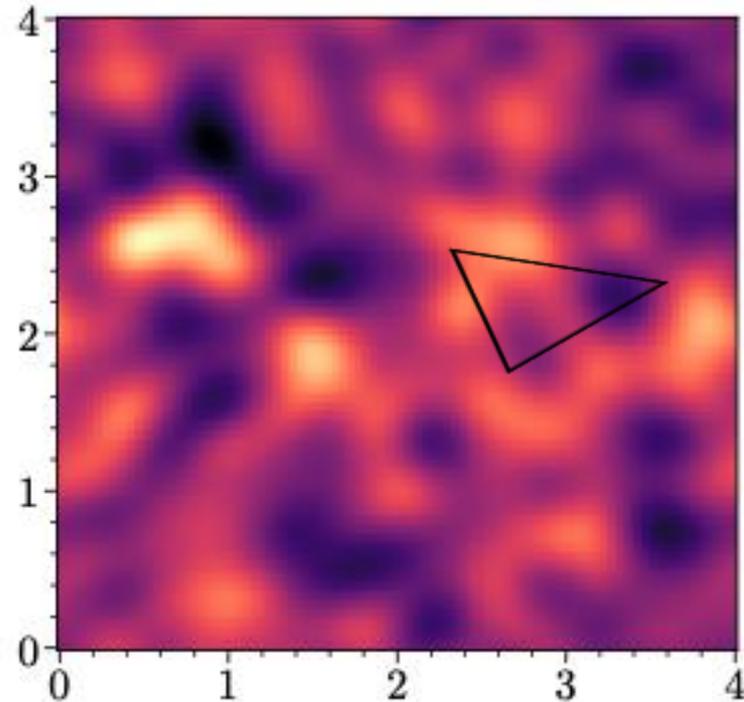
- Perturbation for scalar is suppressed.

H. Kim 2023

- Not for h_{ij} from vector

Nomura, Ito & Soda 2020

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

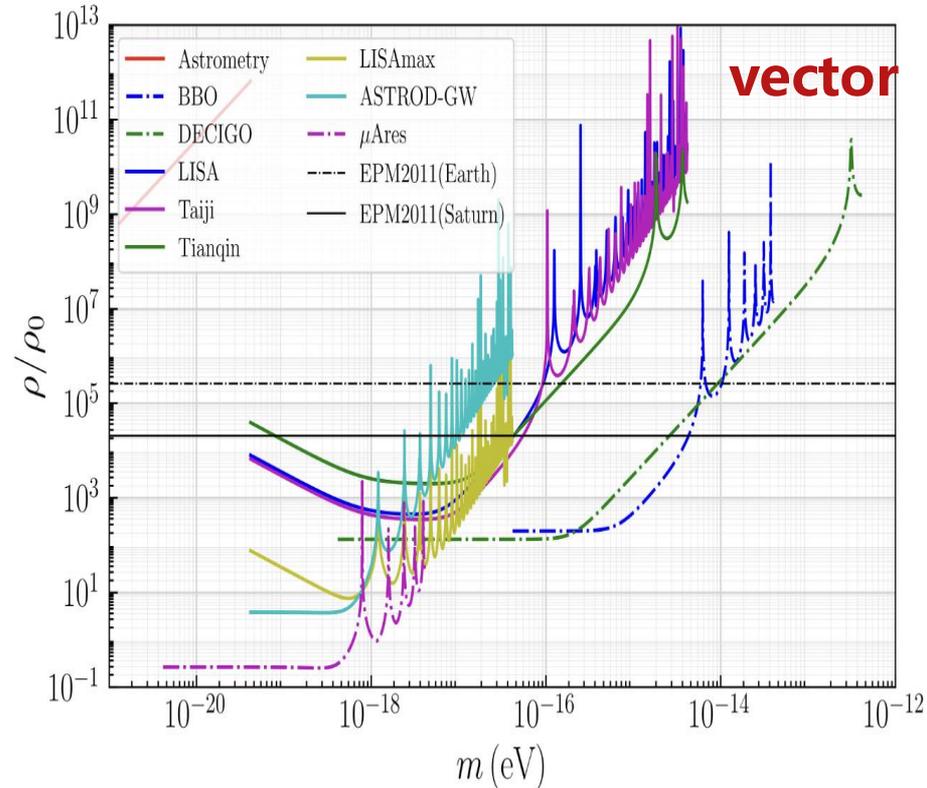
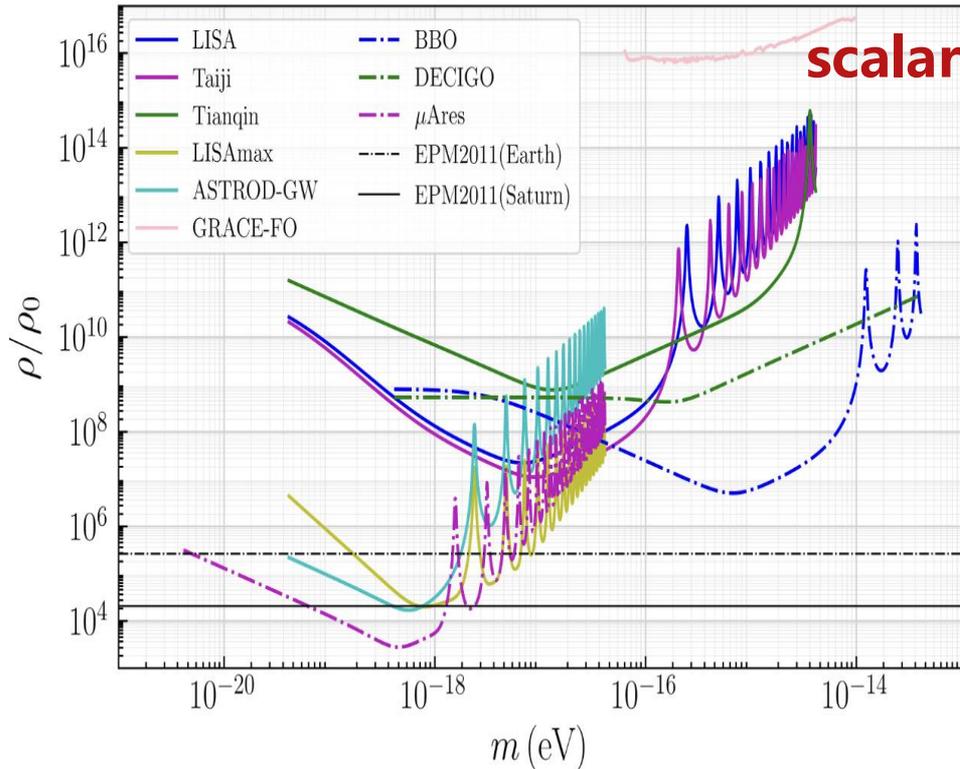


Detecting Ultralight Dark Matter Gravitationally

➤ Tensor perturbation

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

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



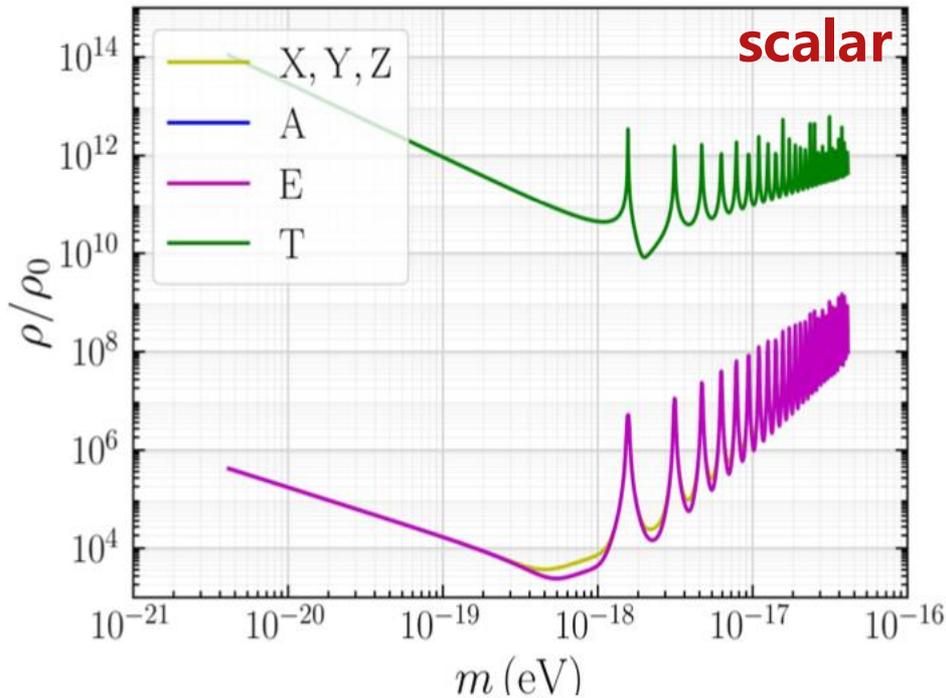
Detecting Ultralight Dark Matter Gravitationally

➤ Tensor perturbation

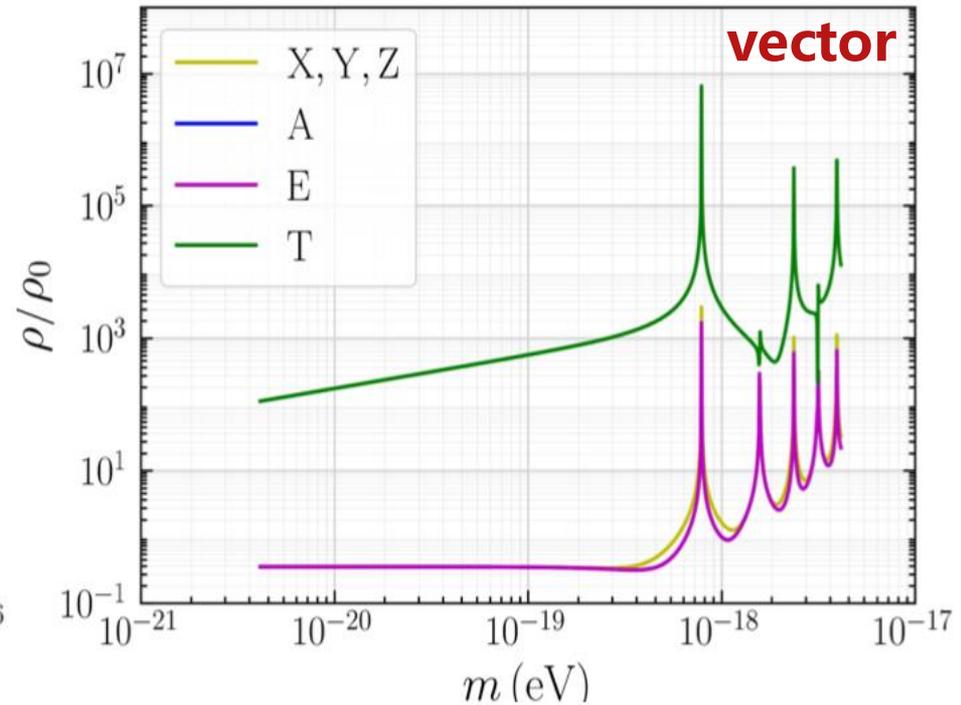
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scalar field



vector field



Summary

- We discuss how gravitational-wave laser interferometers in space may help to understand the nature of dark matter.
- Wave/Ultralight Dark Matter
 - can couple to normal matter and induce the oscillation of test masses, leading to signals in detectors and very good sensitivities.
 - Sensitive to axion-photon coupling
 - Metric perturbation by vector ULDM may be detectable in next-generation interferometers.