Probing Ultralight Dark Matter with Space-based Gravitational-Wave Interferometers

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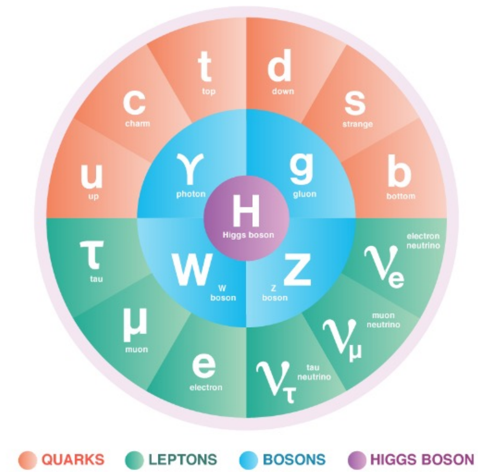
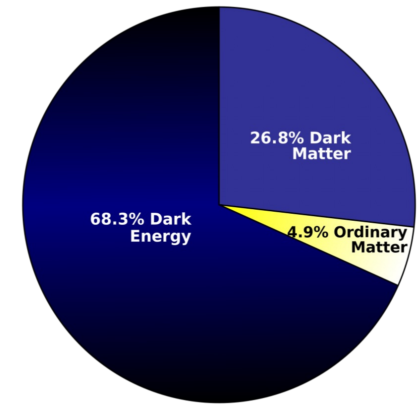
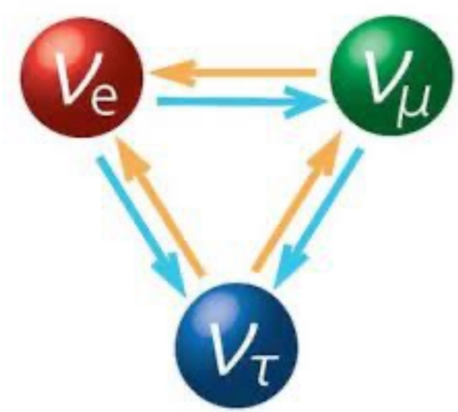
Contents

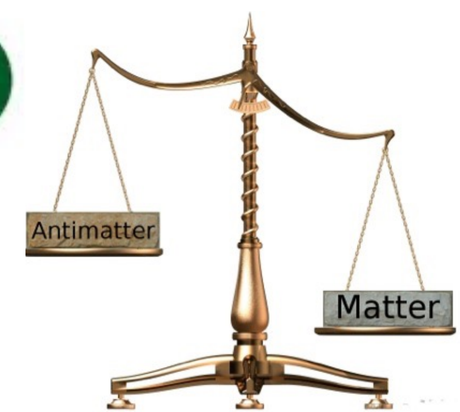
Motivation

- 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
  - ……



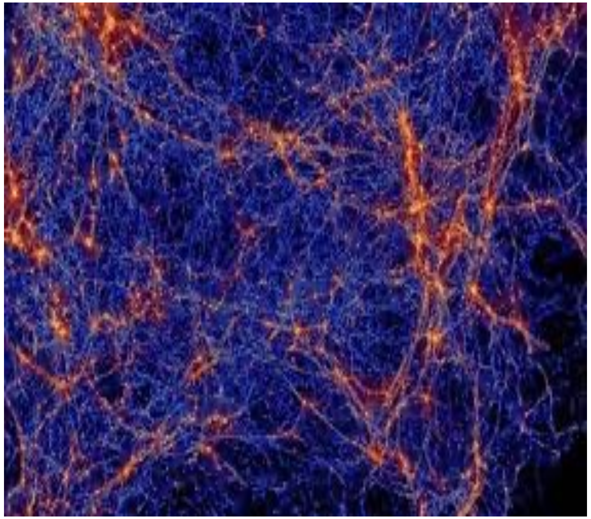


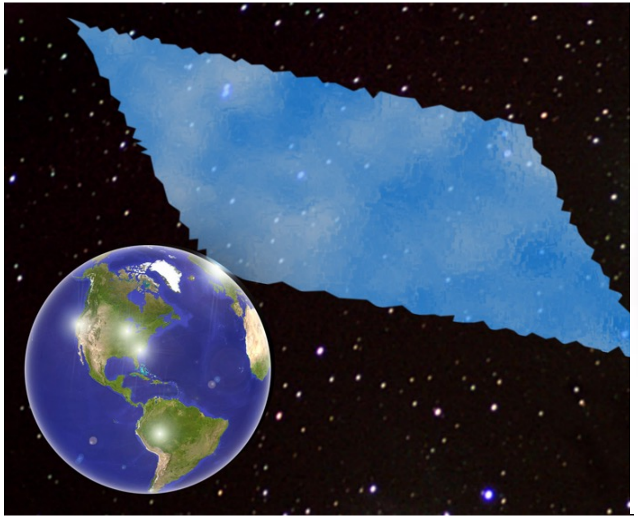


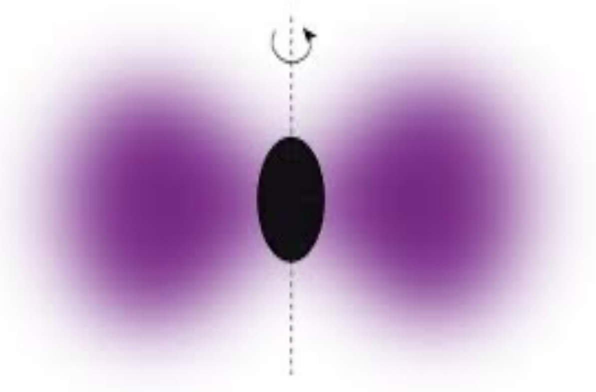


Ultralight Bosonic Fields

- Well-motivated in many physical and cosmological models
- Popular dark matter candidate, dark energy candidate
- Topological objects, domain walls, compact objects, ⋯







Ultralight Dark Matter

- Scalar field ϕ

$$\mathcal{L}=\frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi-\frac{1}{2}m_{\phi}^{2}\phi^{2}-C\frac{\phi}{M_P}\mathcal{O}_{\mathrm{SM}},\quad \phi\left(t,\vec{x}\right)=\phi_{\vec{k}}e^{i(\omega t-\vec{k}\cdot\vec{x}+\theta_0)},$$

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

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

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

- Vector field A_{μ}

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

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

- DM property

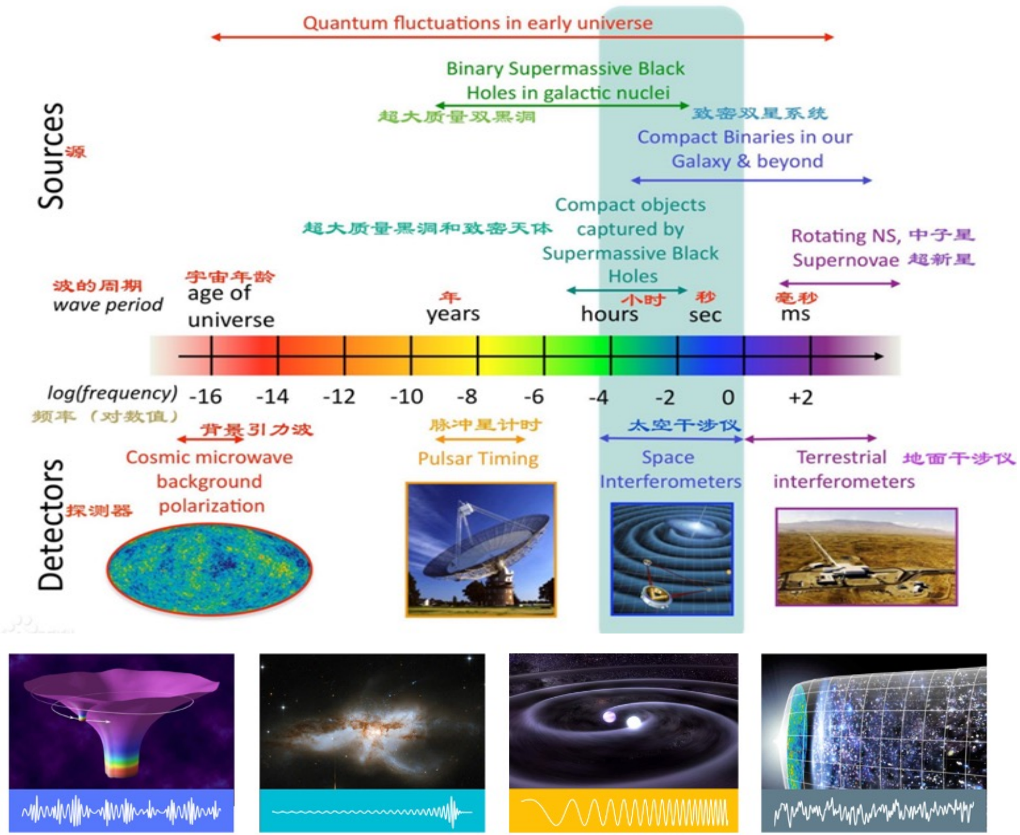
$$\phi_{\vec{k}}=\frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_{\phi}},\qquad |\vec{A}|=\frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_A},\quad v\sim10^{-3},\quad \vec{k}\approx m_{\phi}\vec{v}\text{ and }\omega\approx m_{\phi}$$

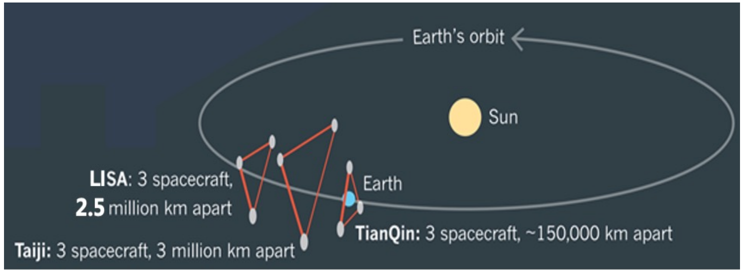
Physical Effects

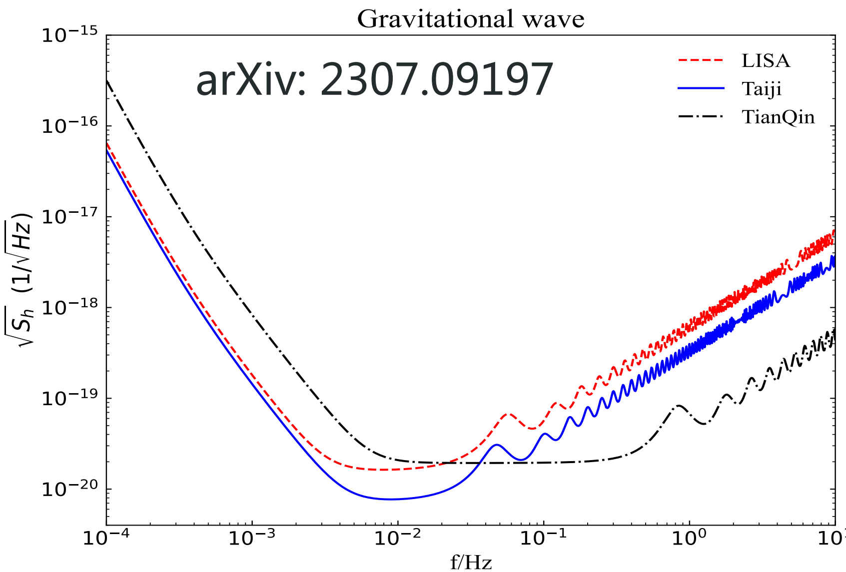
- Atomic physics
  - Arvanitaki, Huang & Tilburg (2014), Graham, Kaplan, Mardon, Rajendran & Terrano (2015), Safronova, Budker, DeMille, Kimball, Derevianko & Clark (2018),
  - Stadnik (2022), ……
- Astrophysical physics
  - Pierce, Riles & Zhao (2018), Morisaki & Suyama (2019), Guo, Riles, Yang & Zhao 2019 , Grote & Stadnik (2019),
  - An, Huang, Liu & Xue (2021), Chen, Shu, Xue, Yuan & Zhao (2019), Xia, Xu & Zhou (2020), Sun, Yang & Zhang (2021), Wu, Chen, & Huang (2023),
  - Liu, Lou & Ren (2021), Luu, Liu, Ren, Broadhurst, Yang, Wang & Xie (2023), ……
- Underground searches
  - Dark Matter Experiments, PandaX, XENONnT, …

Space-based GW Interferometers

- LISA, Taiji and TianQin, sensitivity band 0.1 mHz ~ 0.1 Hz

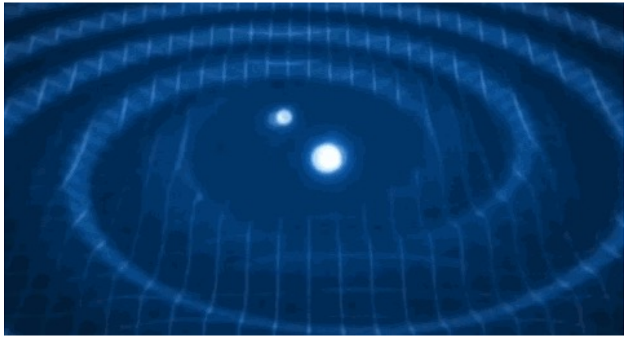




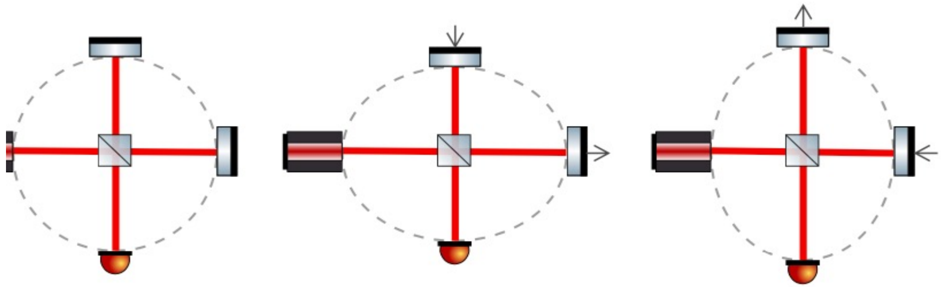


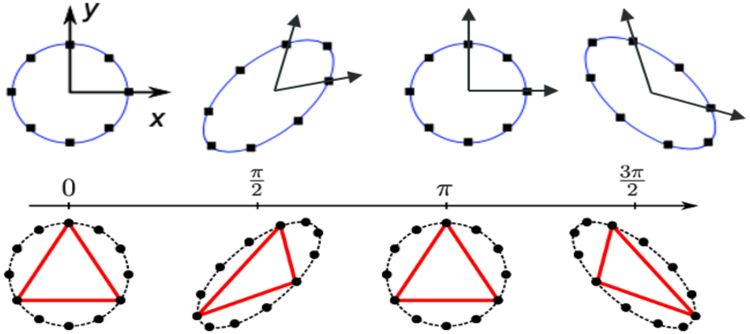
Response

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



- One can measure the phase by laser





- Response $\frac{\delta\nu(t)}{\nu_0} \equiv y_{BA} = -\frac{1}{2}\frac{n_i n_j}{1+\vec{k}\cdot\vec{n}}\left[h_{ij}\left(t - \frac{\vec{k}\cdot\vec{x}_B}{c}\right) - h_{ij}\left(t - \frac{\vec{k}\cdot\vec{x}_A + L}{c}\right)\right]$

Response

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

- One-way Doppler shift

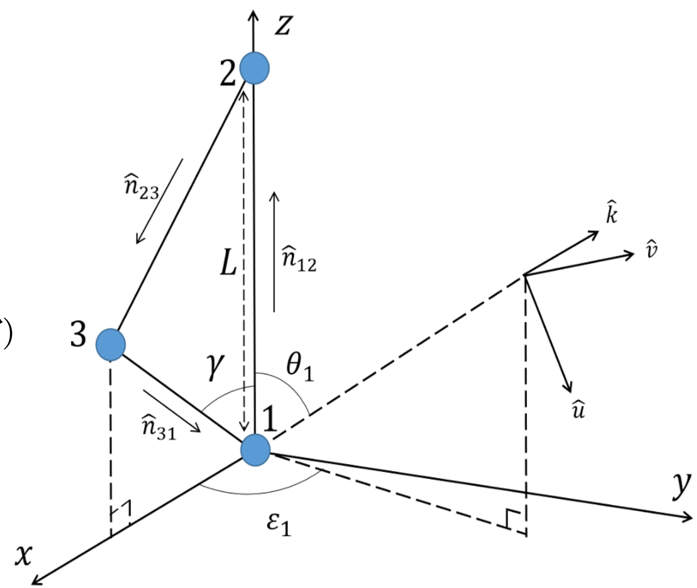
$$\delta t_{rs} = -\hat{n}_{rs} \cdot \left[\delta \vec{x}(t, \vec{x}_r) - \delta \vec{x}(t - L, \vec{x}_s)\right],$$

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

- Fractional frequency change

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

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



Time-Delay Interferometry

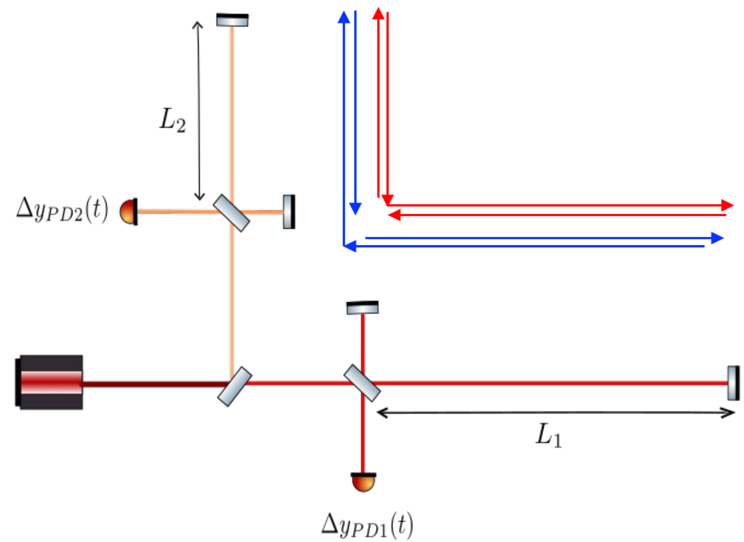
- The arm lengths are not equal
- Laser frequency noises dominate

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

- Michelson interferometry

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

- TDI

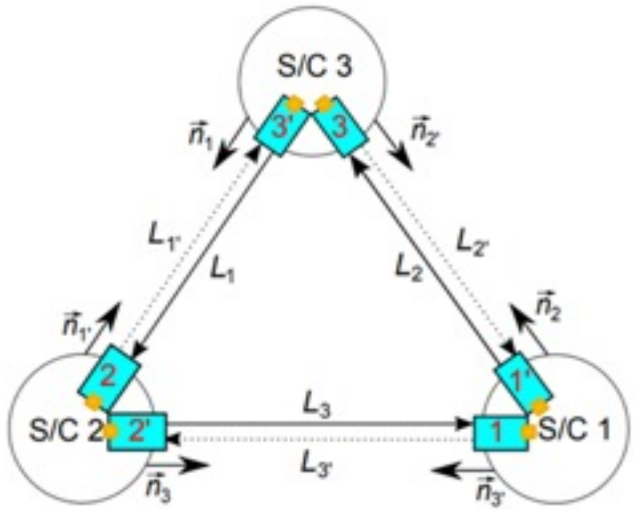


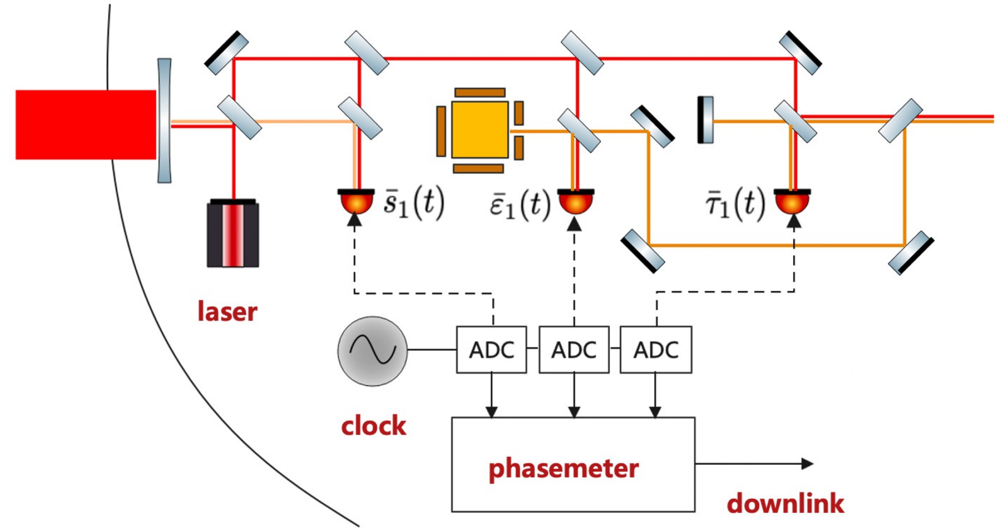
$$\Delta y_{PD1}(t) = H_1(t) + p(t-T_1) - p(t),$$

$$\Delta y_{PD2}(t) = H_2(t) + p(t-T_2) - p(t),$$

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

Time-Delay Interferometry





- Input for TDI

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

$$\eta_{1'} \sim D_{2'}p_3 - p_1,\ \eta_1 \sim D_3 p_2 - p_1,$$
$$\eta_{2'} \sim D_{3'}p_1 - p_2,\ \eta_2 \sim D_1 p_3 - p_2,$$
$$\eta_{3'} \sim D_{1'}p_2 - p_3,\ \eta_3 \sim D_2 p_1 - p_3.$$

- TDI cancels laser frequency noise

Time-Delay Interferometry

- There are multiple combinations
- Michelson channels

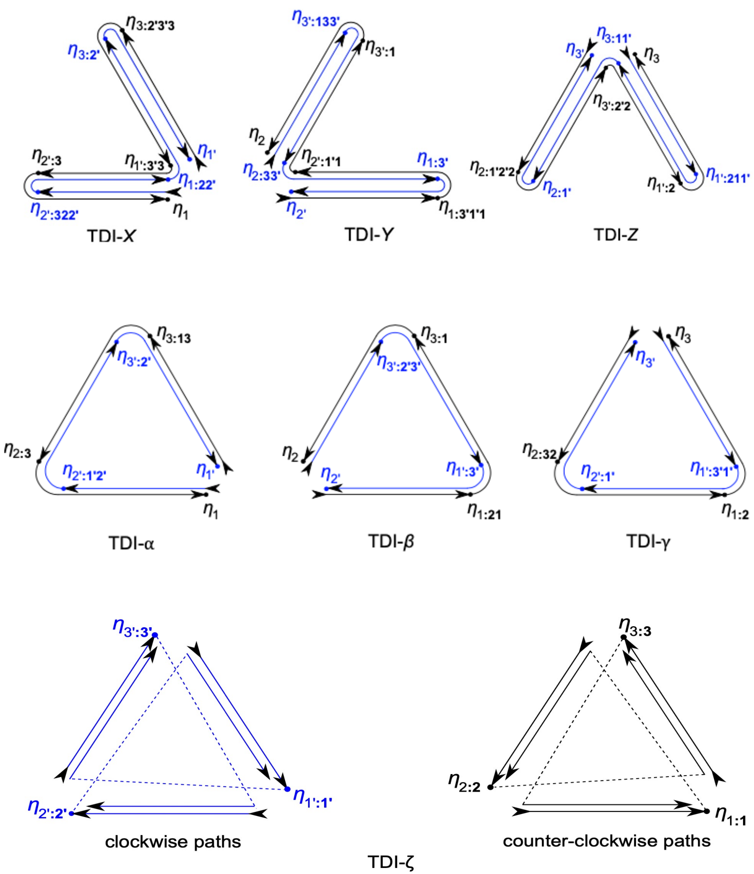
$$
\begin{aligned}
X(t) &= (\eta_{2':322'} + \eta_{1:22'} + \eta_{3:2'} + \eta_{1'}) - (\eta_{3:2'3'3} + \eta_{1':3'3} + \eta_{2':3} + \eta_1),\\
Y(t) &= (\eta_{3':133'} + \eta_{2:33'} + \eta_{1:3'} + \eta_{2'}) - (\eta_{1:3'1'1} + \eta_{2':1'1} + \eta_{3':1} + \eta_2),\\
Z(t) &= (\eta_{1':211'} + \eta_{3:11'}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

- Sagnac channels

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

- 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

Transfer Function

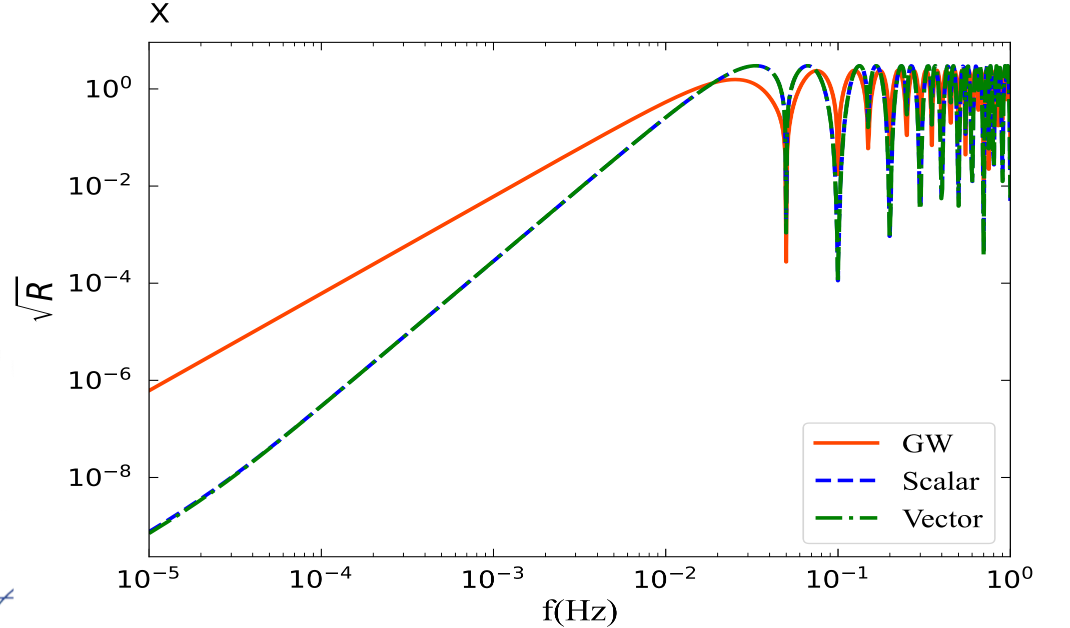
- Fourier transform $$h(t)=\frac{\sqrt{T}}{2\pi}\int_0^\infty \tilde{h}(\omega)e^{i\omega t}d\omega$$
- One-way single link $$y_{rs}(t)=\mu_{rs}\,\frac{\sqrt{T}}{2\pi}\int_0^\infty d\omega\;\tilde{h}(\omega)e^{i\omega t}\left[e^{-i\vec{k}\cdot\vec{x}_r}-e^{-i(\tau+\vec{k}\cdot\vec{x}_s)}\right],$$ $$\tilde{y}_{rs}(\omega)=\mu_{rs}\,\tilde{h}(\omega)\left[e^{-i(\vec{k}\cdot\vec{x}_r)}-e^{-i(\tau+\vec{k}\cdot\vec{x}_s)}\right].$$
- Transfer function, sky and polarization averaged

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

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

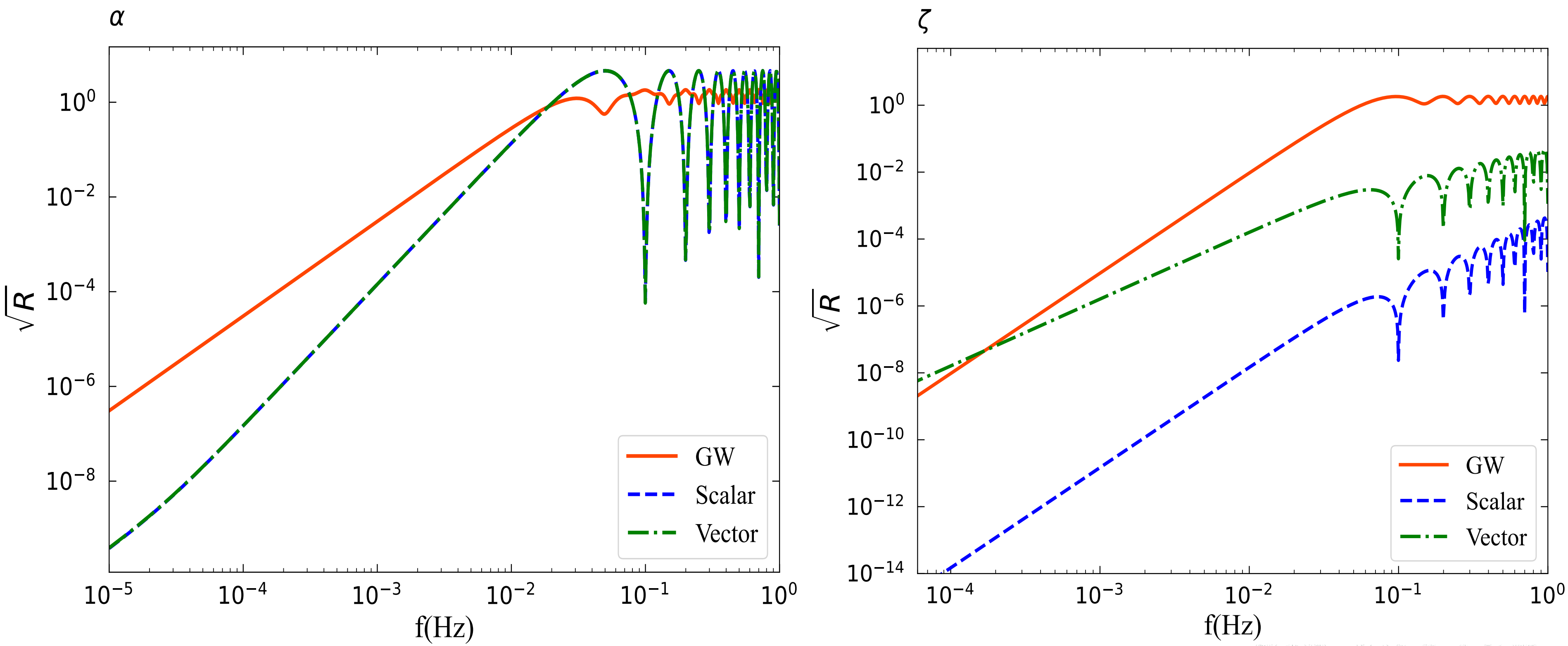
$$I_v\equiv\frac{1}{16\pi^2}\int_{-1}^{1}d\cos\theta_1\int_0^{2\pi}d\epsilon_1\int_{-1}^{1}d\cos\theta_2\int_0^{2\pi}d\epsilon_2\cdots$$

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



Transfer Functions

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



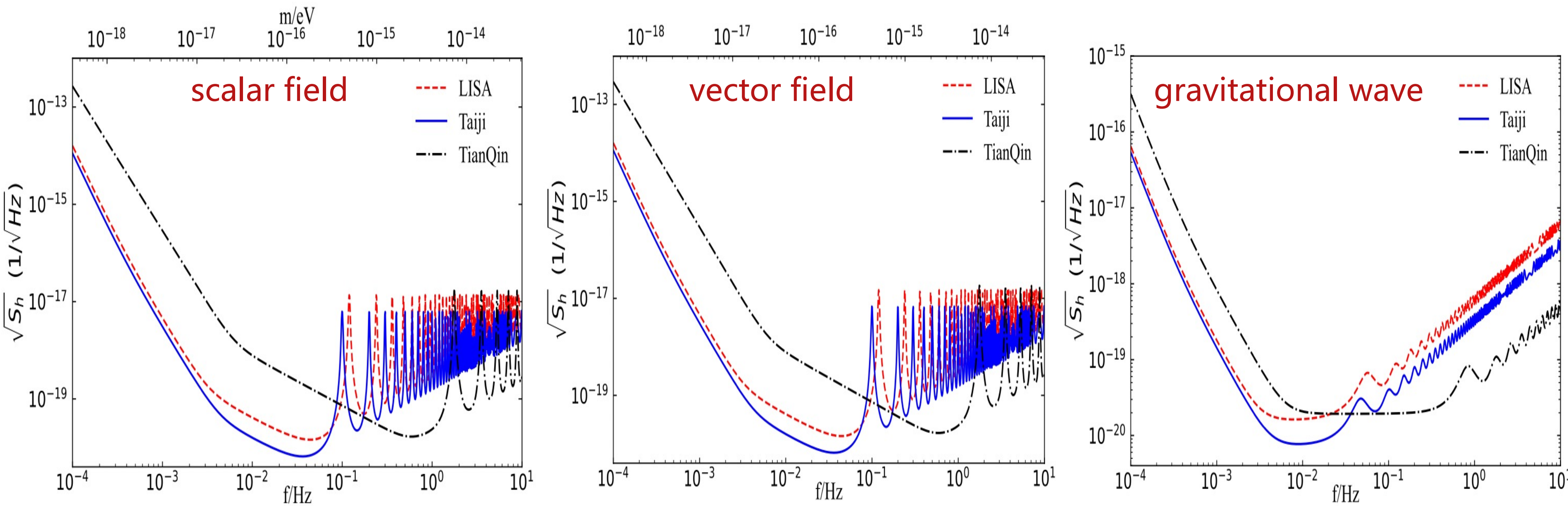
Sensitivity

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

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

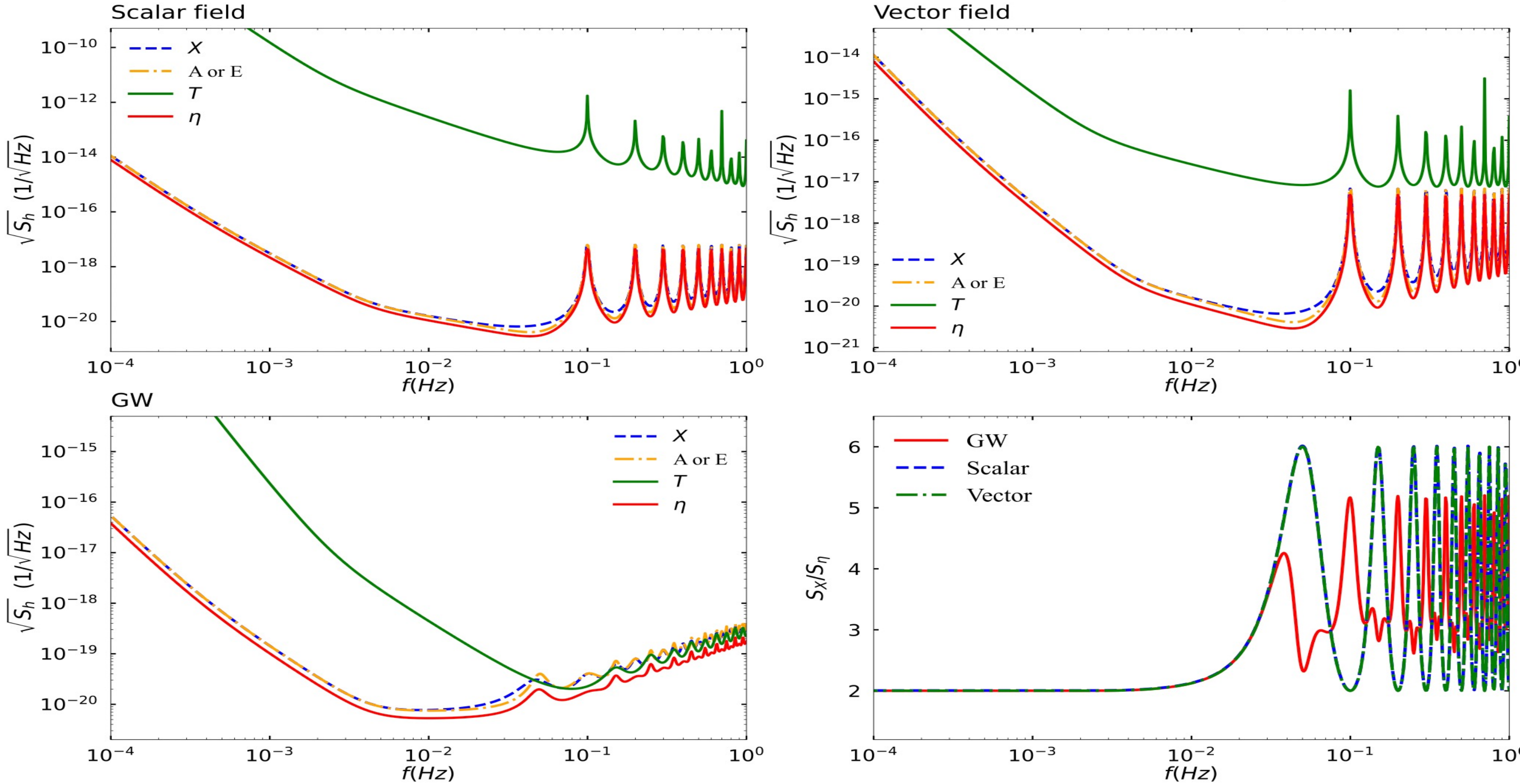
$$S_{acc}(f) = \left(\frac{s_{acc}}{2\pi f c}\right)^2\left[1+\left(\frac{0.4\times10^{-3}\ \mathrm{Hz}}{f}\right)^2\right]\left[1+\left(\frac{f}{8\times10^{-3}\ \mathrm{Hz}}\right)^4\right]\frac{1}{\mathrm{Hz}},$$

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



Sensitivity

- 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

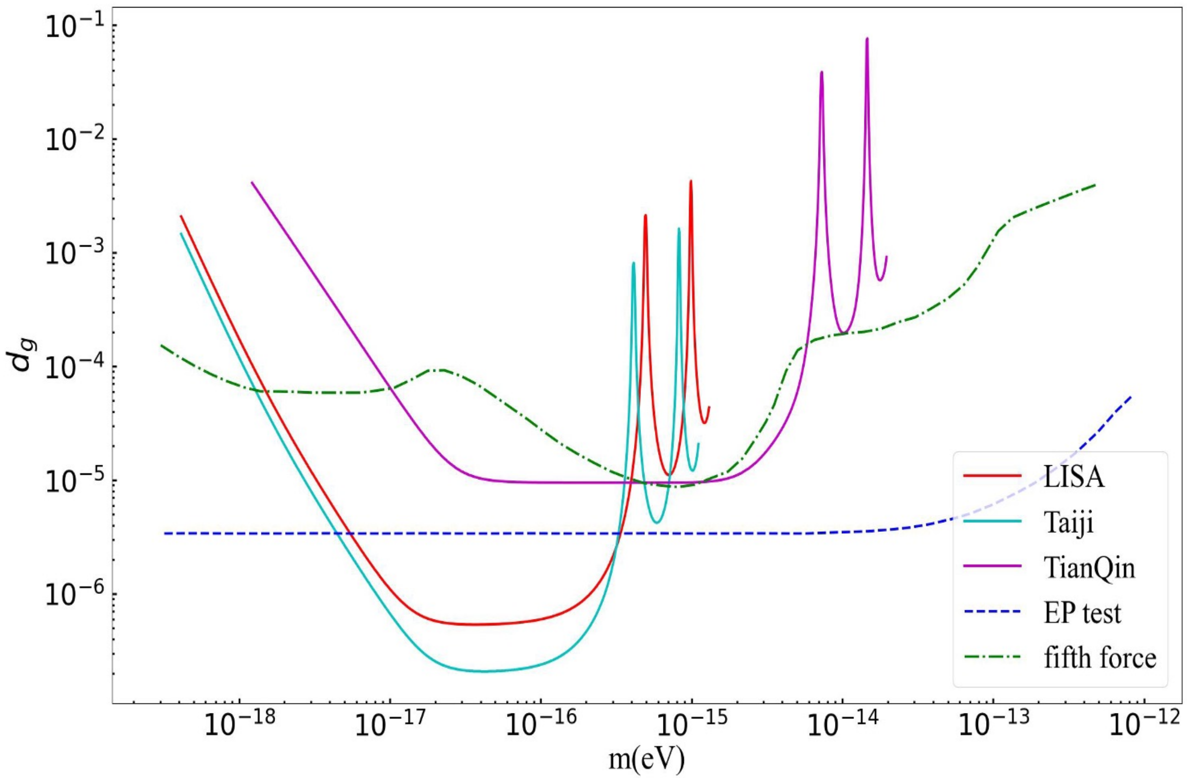
➢ Strong sector

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

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

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

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

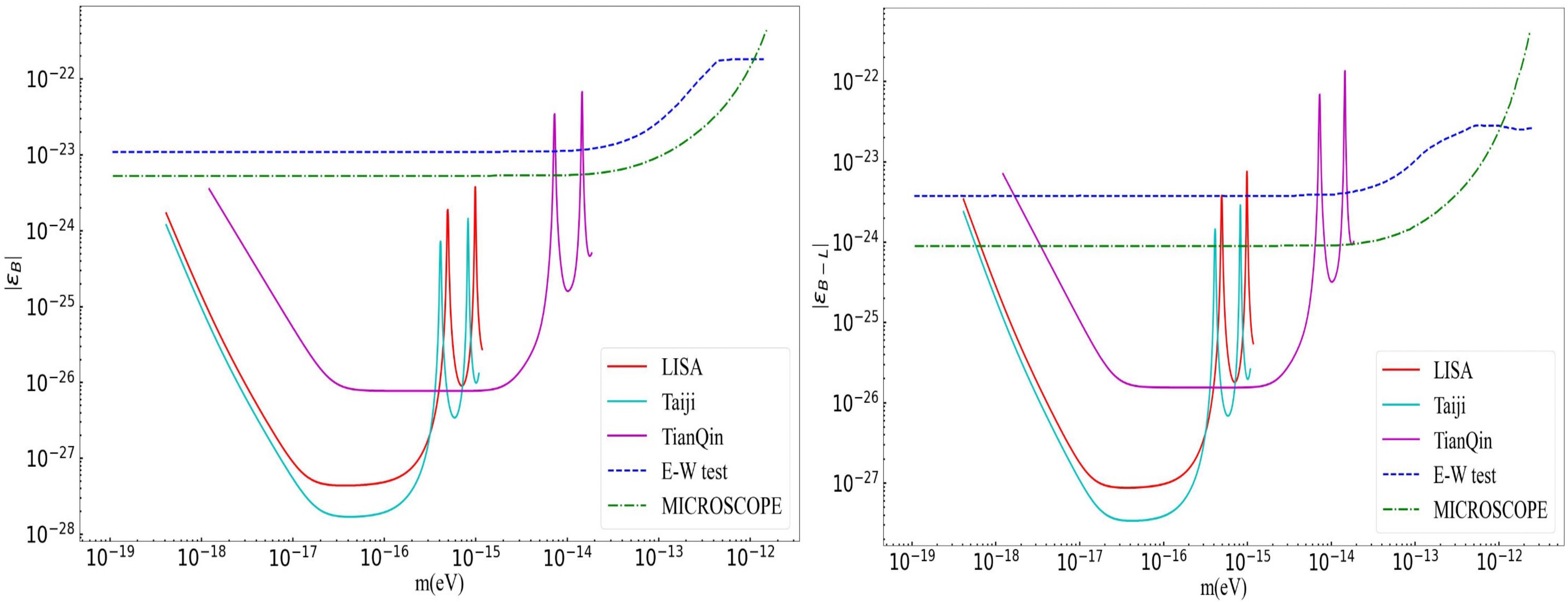


➢ Equivalence principle is violated.

➢ MICROSCOPE

Sensitivity on vector DM

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



Summary

- Ultralight bosonic fields (ULBFs) are motivated and predicted in many physical and cosmological theories
- ULBFs can also be dark matter candidates, ULDM
- The tiny coupling between ULBFs and standard model particles can induce observable physical effects
- We use the space-based gravitational-wave interferometers to probe ULBFs and ULDM, taking the various time-delay interferometry channels into account
- Good sensitivity can be obtained in some parameter region
- Caveat: Stochastic effect to be implemented, stay tuned

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Thanks for your attention!