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

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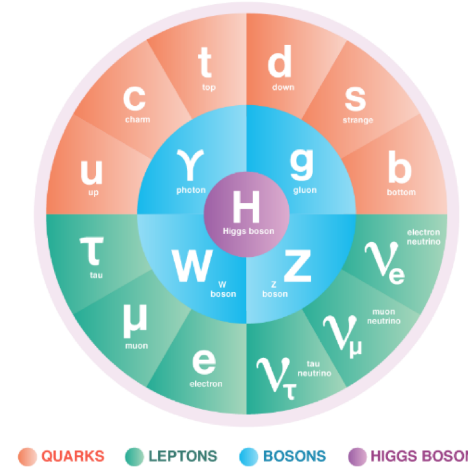
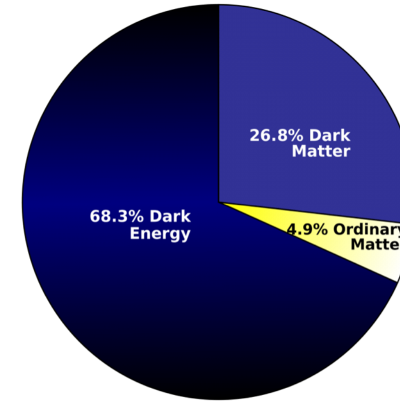
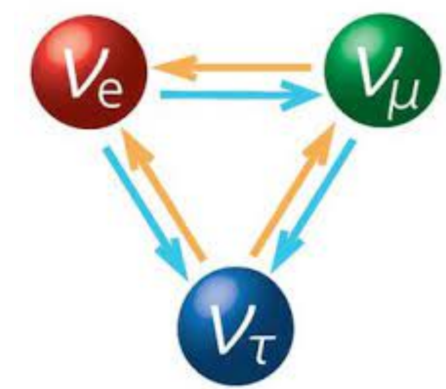
Contents

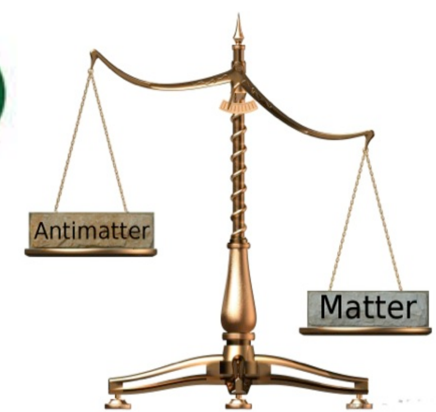
Motivation

- 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
  - ……



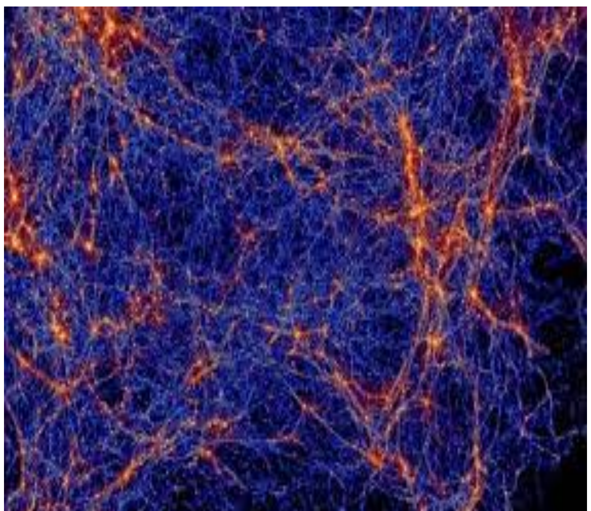
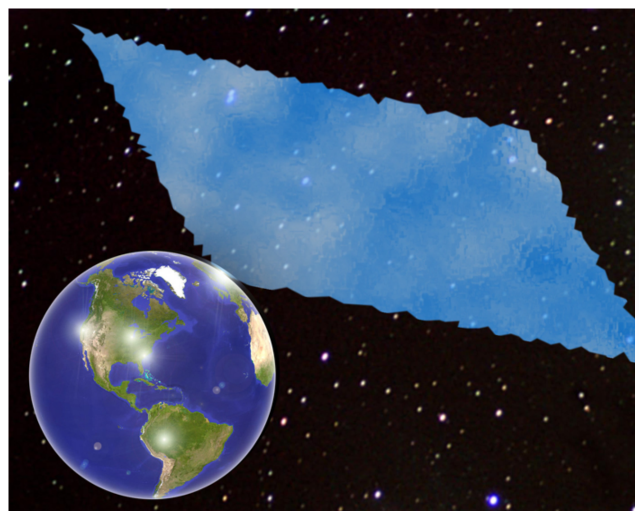
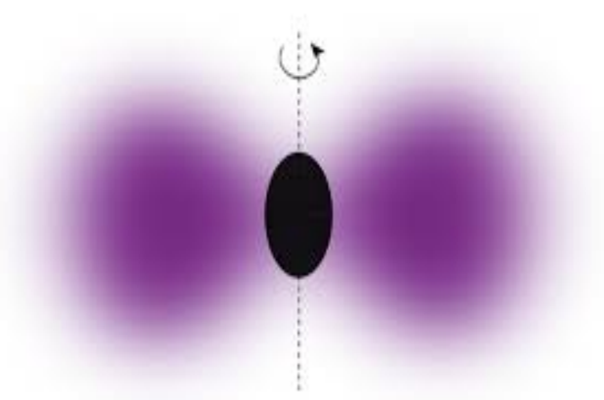






Ultralight Bosonic Fields

- 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

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

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

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

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

- Vector field A_μ

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

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

- DM property

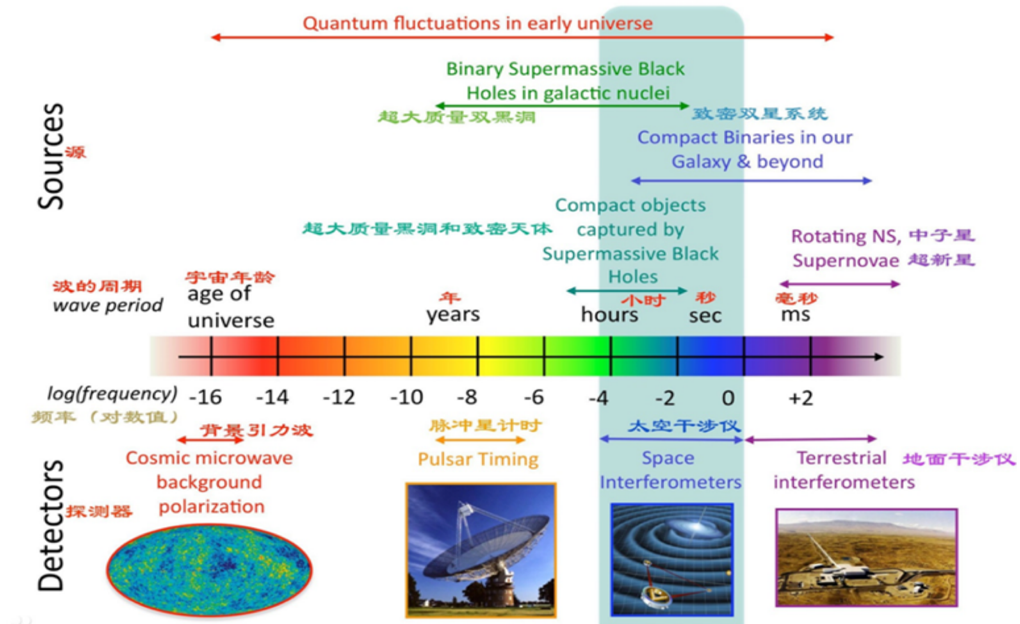
$$\phi_{\vec{k}} = \frac{\sqrt{2\rho_{\rm DM}}}{m_\phi}, \qquad |\vec{A}| = \frac{\sqrt{2\rho_{\rm DM}}}{m_A}, \quad v \sim 10^{-3}, \quad \vec{k} \approx m_\phi \vec{v} \text{ and } \omega \approx m_\phi$$

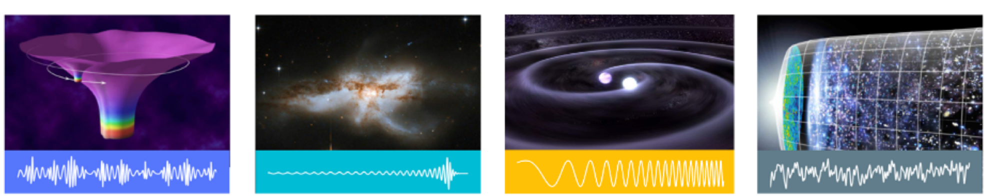
Physical Effects

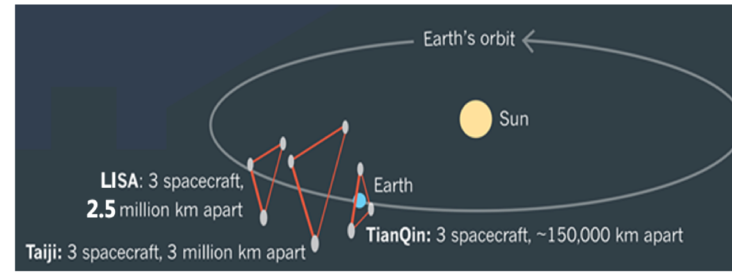
- Atomic physics
  - Arvanitaki, Huang & Tilburg (2014), Graham, Kaplan, Mardon, Rajendran & Terrano (2015), Safronova, Budker, DeMille, Kimball, Derevianko & Clark (2018),
  - Stadnik (2022), ……
- Astrophysical physics
  - Pierce, Riles & Zhao (2018), Morisaki & Suyama (2019), Guo, Riles, Yang & Zhao 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, …

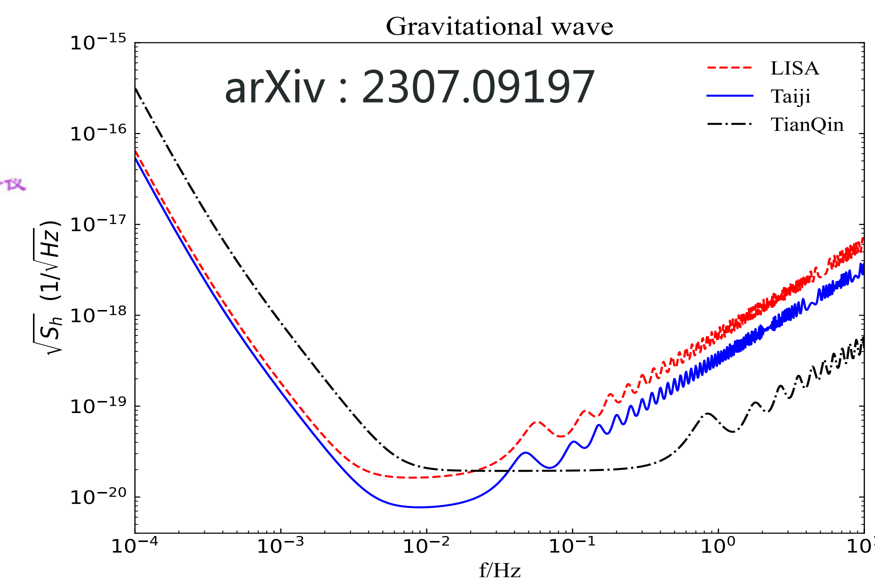
Space-based GW Interferometers

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



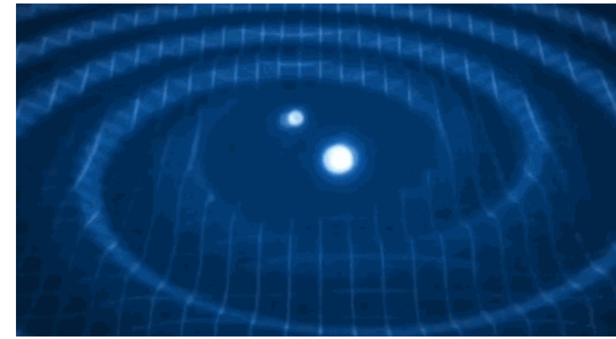




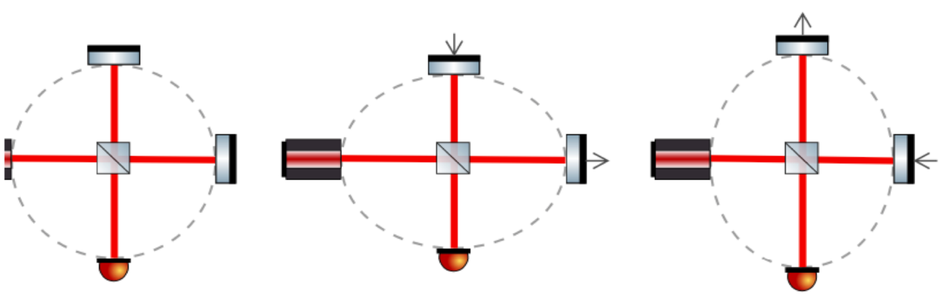


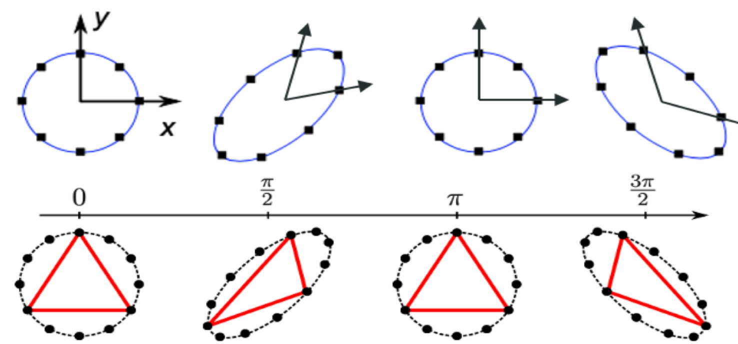
Signal Response

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



- One can measure the phase by laser





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

Signal Response

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

- One-way Doppler shift

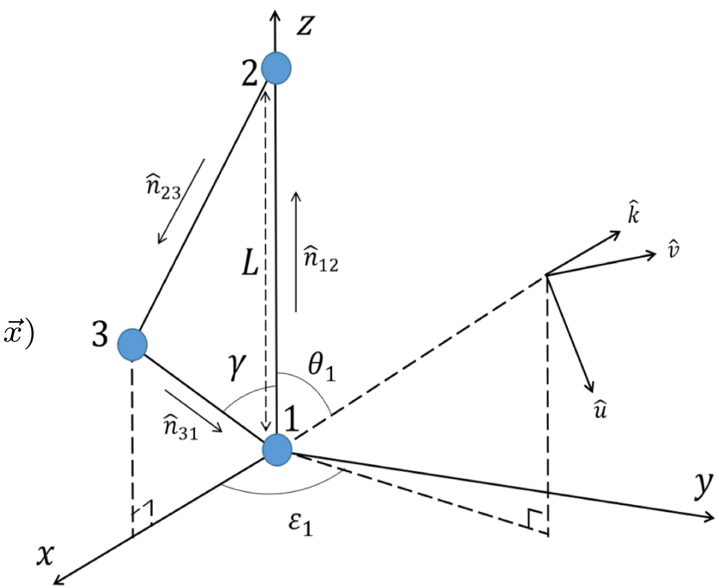
$$\delta t_{rs} = -\hat{n}_{rs} \cdot \left[\delta\vec{x}(t, \vec{x}_r) - \delta\vec{x}(t - L, \vec{x}_s)\right],$$

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

- Fractional frequency change

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

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



Time-Delay Interferometry

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

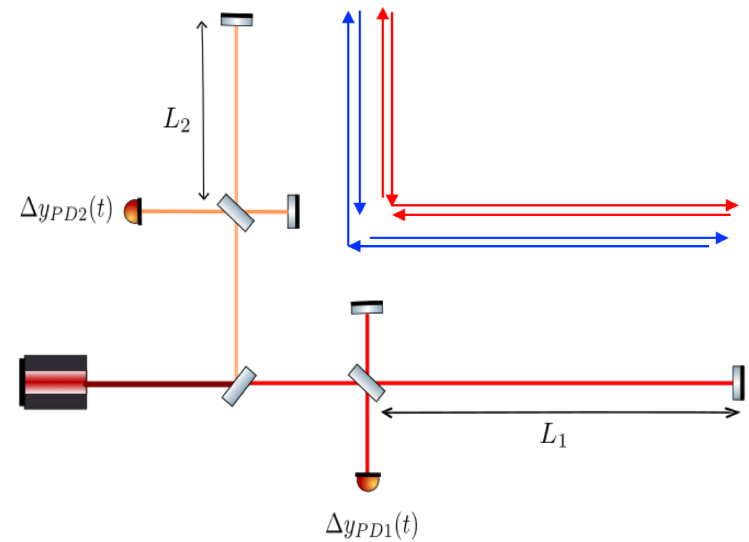
$$\begin{aligned} X(t) &\equiv [\Delta y_{PD1}(t) - \Delta y_{PD2}(t)] - [\Delta y_{PD1}(t-T_2) - \Delta y_{PD2}(t-T_1)] \\ &= [H_1(t) - H_2(t) + p(t-T_1) - p(t-T_2)] \\ &- [H_1(t-T_2) - H_2(t-T_1) + p(t-T_1) - p(t-T_2)] \\ &= H_1(t) - H_2(t) - H_1(t-T_2) + H_2(t-T_1)\,, \end{aligned}$$

- 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-virtual equal-arm interference

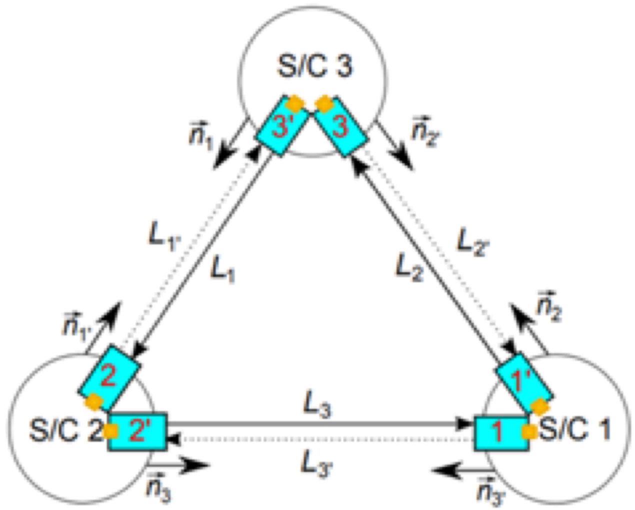
Tinto & Dhurandhar



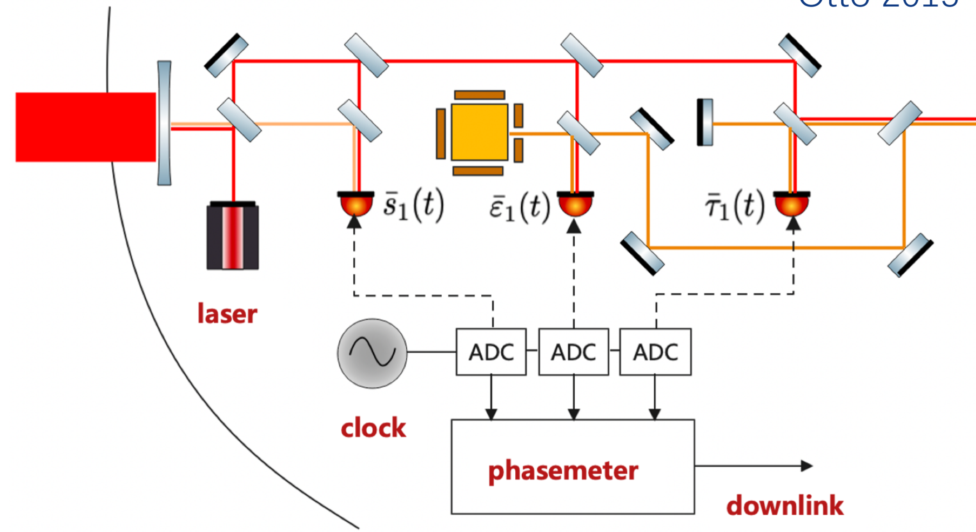
$$\Delta y_{PD1}(t) = H_1(t) + p(t-T_1) - p(t),$$
$$\Delta y_{PD2}(t) = H_2(t) + p(t-T_2) - p(t),$$

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

Time-Delay Interferometry



Otto 2015



- Input for TDI

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

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

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

- TDI cancels laser frequency noise

Time-Delay Interferometry

- There are multiple combinations
- Michelson channels

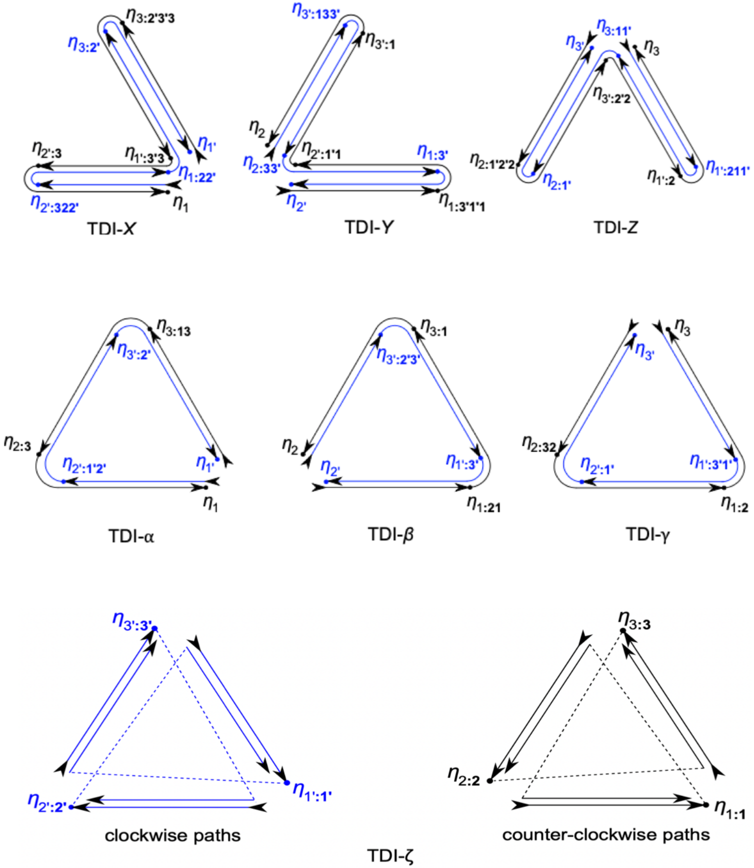
$$
\begin{aligned}
X(t) &= (\eta_{2':\mathbf{322'}} + \eta_{1:\mathbf{22'}} + \eta_{3:\mathbf{2'}} + \eta_{1'}) - (\eta_{3:\mathbf{2'3'3}} + \eta_{1':\mathbf{3'3}} + \eta_{2':\mathbf{3}} + \eta_1), \\
Y(t) &= (\eta_{3':\mathbf{133'}} + \eta_{2:\mathbf{33'}} + \eta_{1:\mathbf{3'}} + \eta_{2'}) - (\eta_{1:\mathbf{3'1'1}}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

- Sagnac channels

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

- ζ channel

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



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

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

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

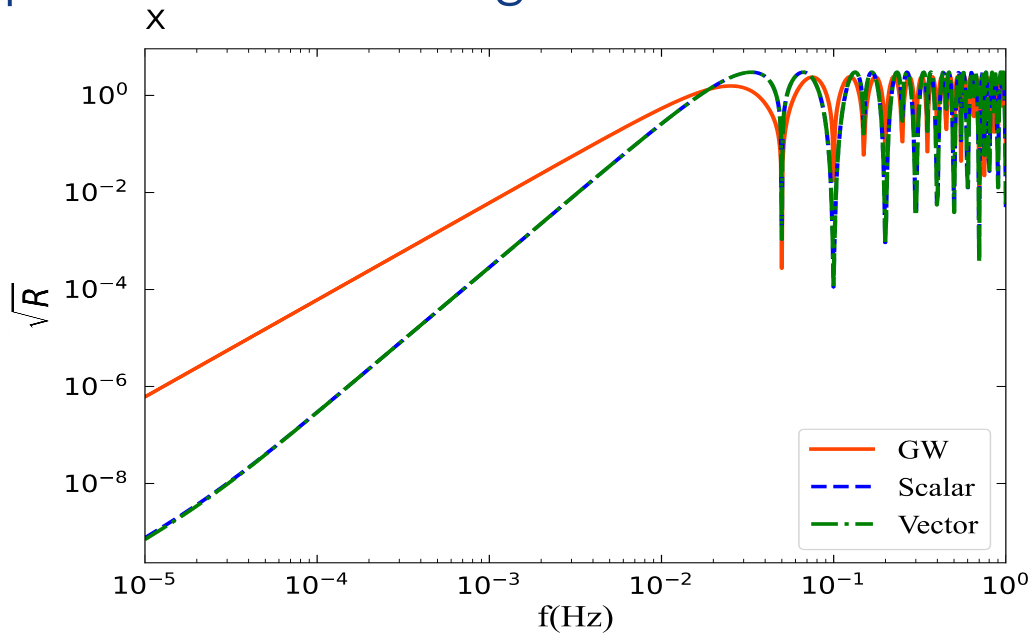
- Transfer function, sky and polarization averaged

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

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

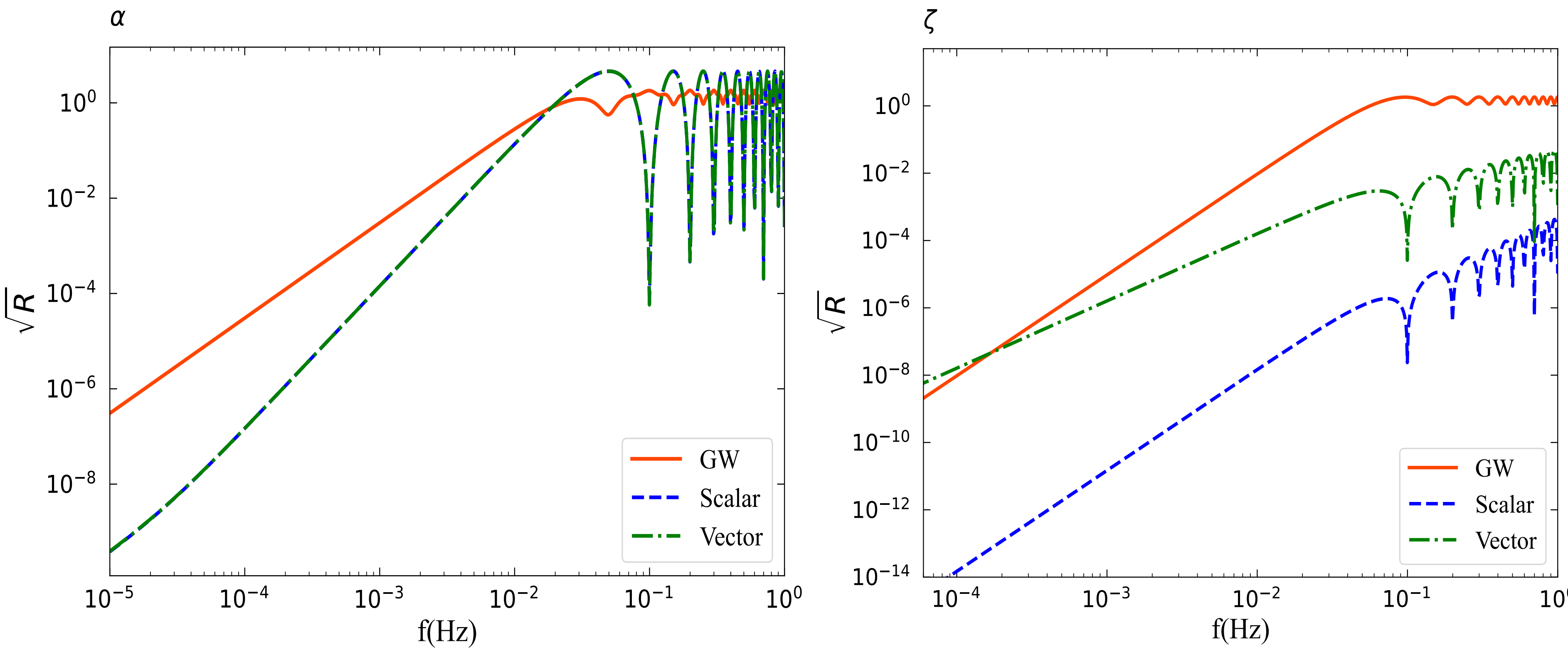
$$I_v \equiv \frac{1}{16\pi^2} \int_{-1}^{1} d\cos\theta_1 \int_0^{2\pi} d\epsilon_1 \int_{-1}^{1} d\cos\theta_2 \int_0^{2\pi} d\epsilon_2 \cdots$$

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



Transfer Functions

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



Sensitivity

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

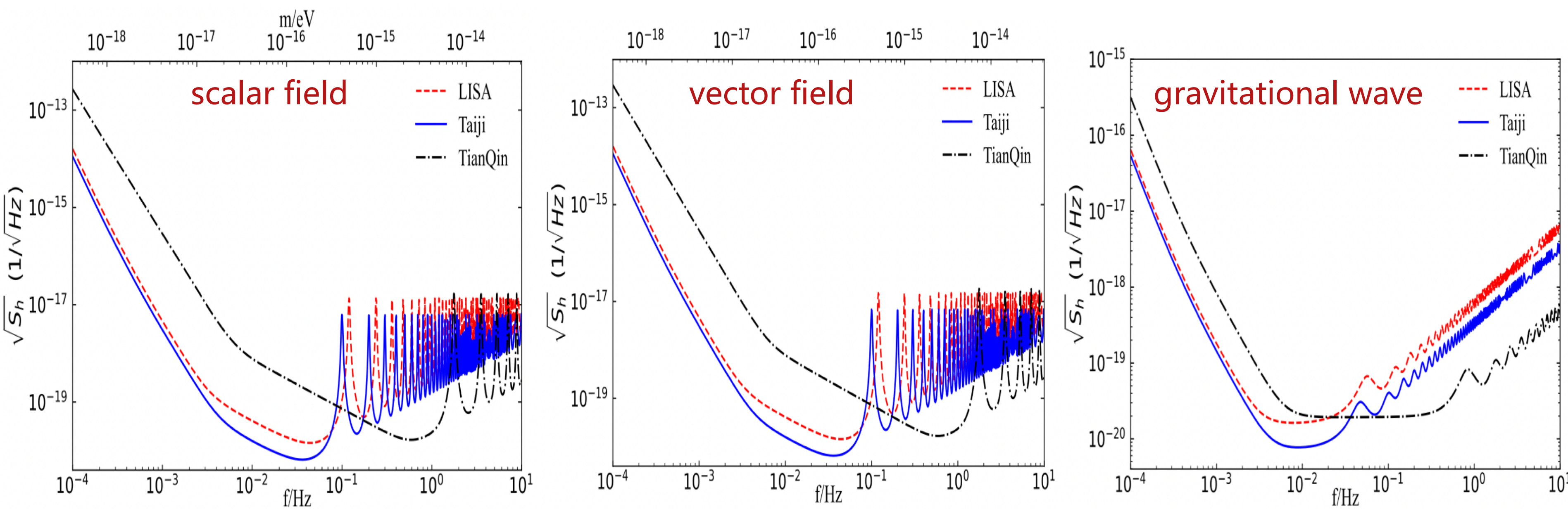
$$S_{oms}(f) = \left(s_{oms}\,\frac{2\pi f}{c}\right)^2 \left[1 + \left(\frac{2\times 10^{-3}\ \mathrm{Hz}}{f}\right)^4\right] \frac{1}{\mathrm{Hz}},$$

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

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

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

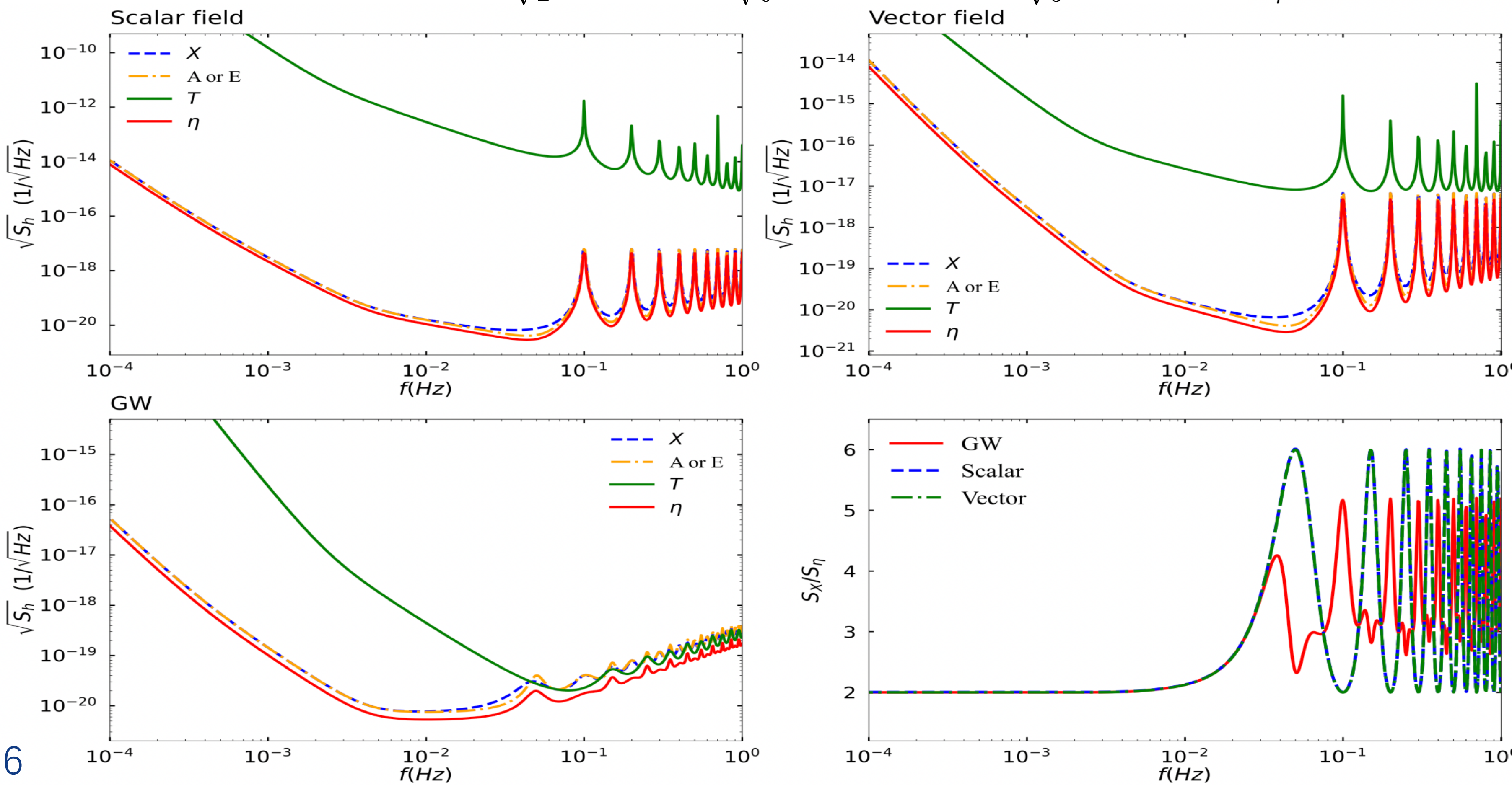
$$\mathrm{TianQin}: \quad s_{oms} = 1\times 10^{-12}\ \mathrm{m},\ s_{acc} = 1\times 10^{-15}\ \mathrm{m/s^2}.$$



Sensitivity

Prince, Tinto, Larson & Armstrong

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



Sensitivity on scalar DM

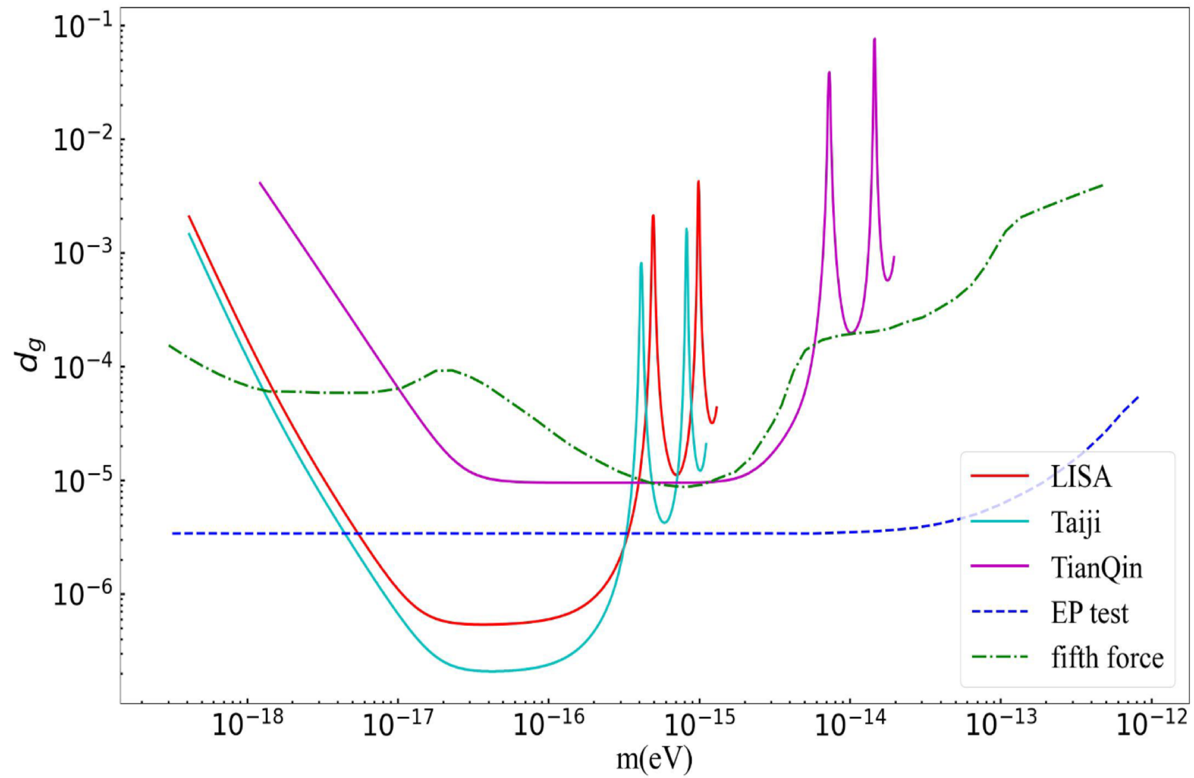
- Strong sector $\delta\mathcal{L} = \frac{\phi}{M_P}\left[-\frac{d_g\beta_3}{2g_3}F^A_{\mu\nu}F^{A\mu\nu} - \sum_{i=u,d}\left(d_{m_i} + \gamma_{m_i}d_g\right)m_i\bar{\psi}_i\psi_i\right]$ Damour & Donoghue

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

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

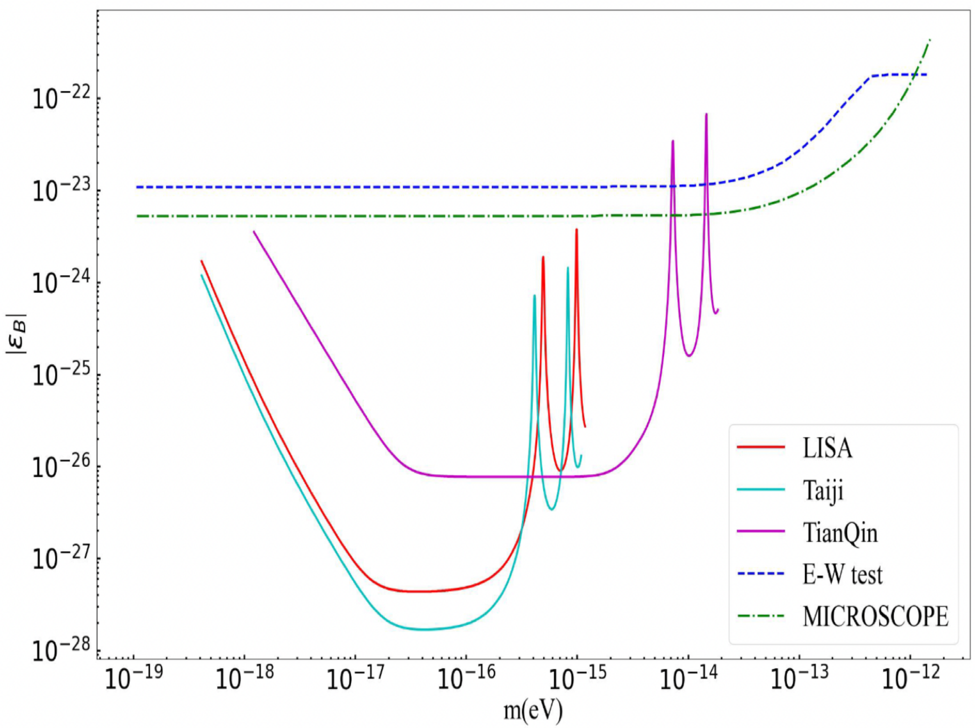
assuming $d_m = 0$ and $d_g^* \approx 0.9d_g$.

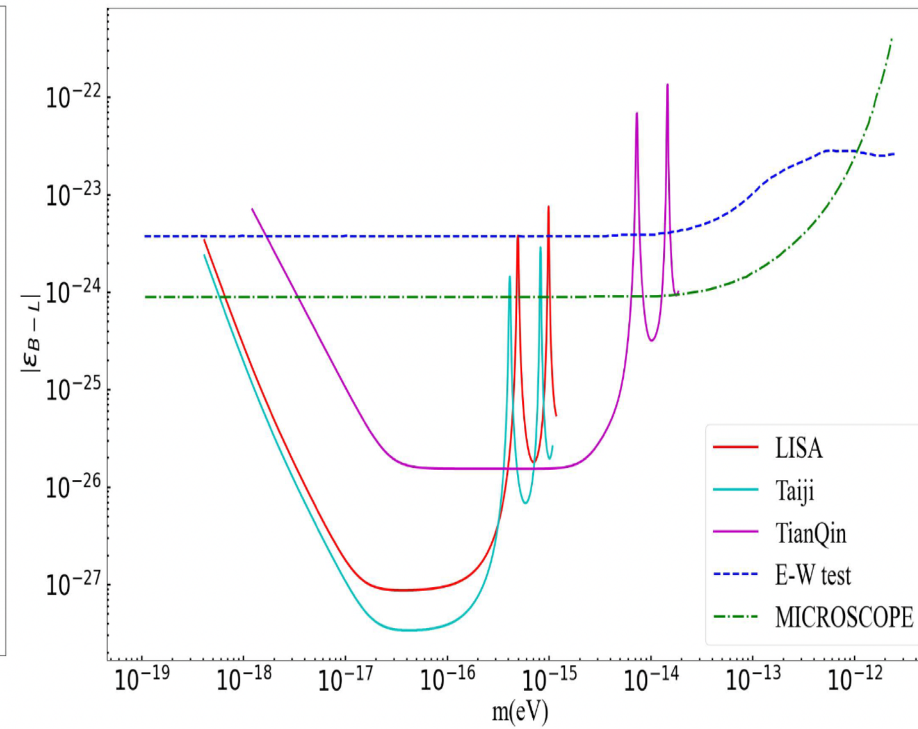
- Equivalence principle is violated.
- MICROSCOPE



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
- Stochastic effect barely changes the conclusion

See arXiv : 2307.09197(PRD) for details.

Thanks!