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国际理论物理中心-亚太地区

Probing ultralight dark matter with space-based GW detectors

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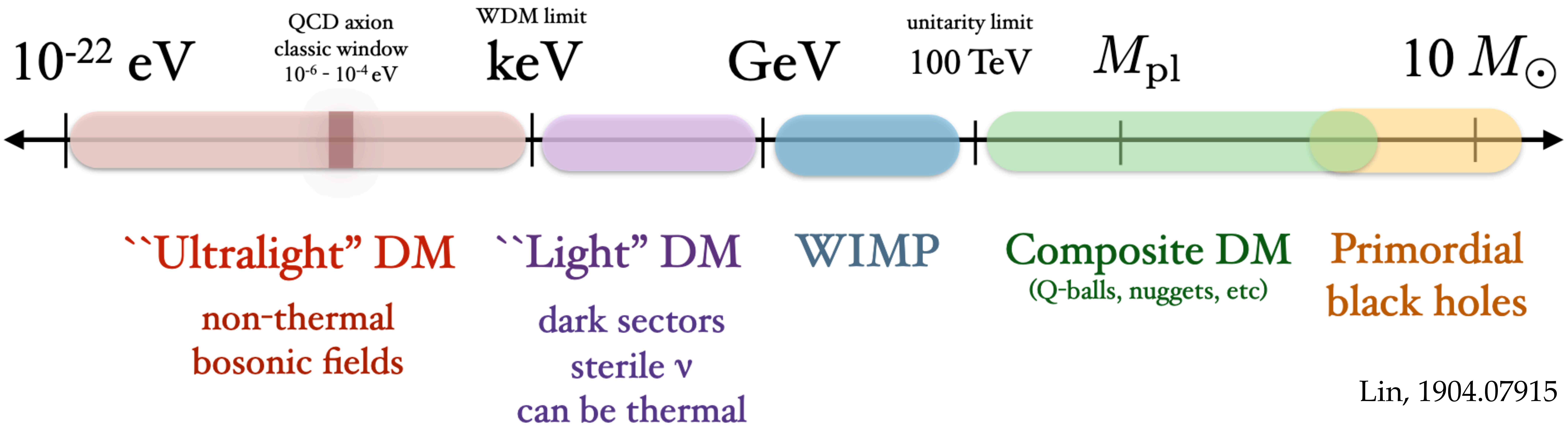
25/08/23@TDLI

Based on 2307.09197, 2404.01494, 2410.22072, 2506.09744, 2508.14655 with Yong Tang, Jiang-Chuan Yu, Yue-Liang Wu, Tingyuan Jiang, Heng-Tao Xu, Wenyan Ren, Di Chen, Yu-Feng Zhou

Dark matter zoo



Lin, 1904.07915

We focus on ultralight DM (ULDM) with mass in 10^{-18} eV ~ 10^{-14} eV, which has a Compton frequency in 0.1 mHz ~ 1 Hz (sensitive band of detectors).

Wave description of ULDM

L.Hui, 2101.11735; A.Derevianko, PRA.97.042506;

Cheong, N.Rodd, Wang, 2408.04696;

H.Kim, 2306.13348

For ULDM particle with mass m and velocity $\vec{v}$

$$f_c = \frac{m}{2\pi} \approx 2.42 \times \left(\frac{m}{10^{-17}\ \text{eV}}\right)\ \text{mHz}, \quad \lambda_{dB} = \frac{2\pi}{m|\vec{v}|} \approx 1.24 \times 10^{11} \left(\frac{10^{-3}}{|\vec{v}|}\right)\left(\frac{10^{-17}\ \text{eV}}{m}\right)\ \text{km}\,.$$

Large occupation number in a de Broglie volume λ_{dB}^3

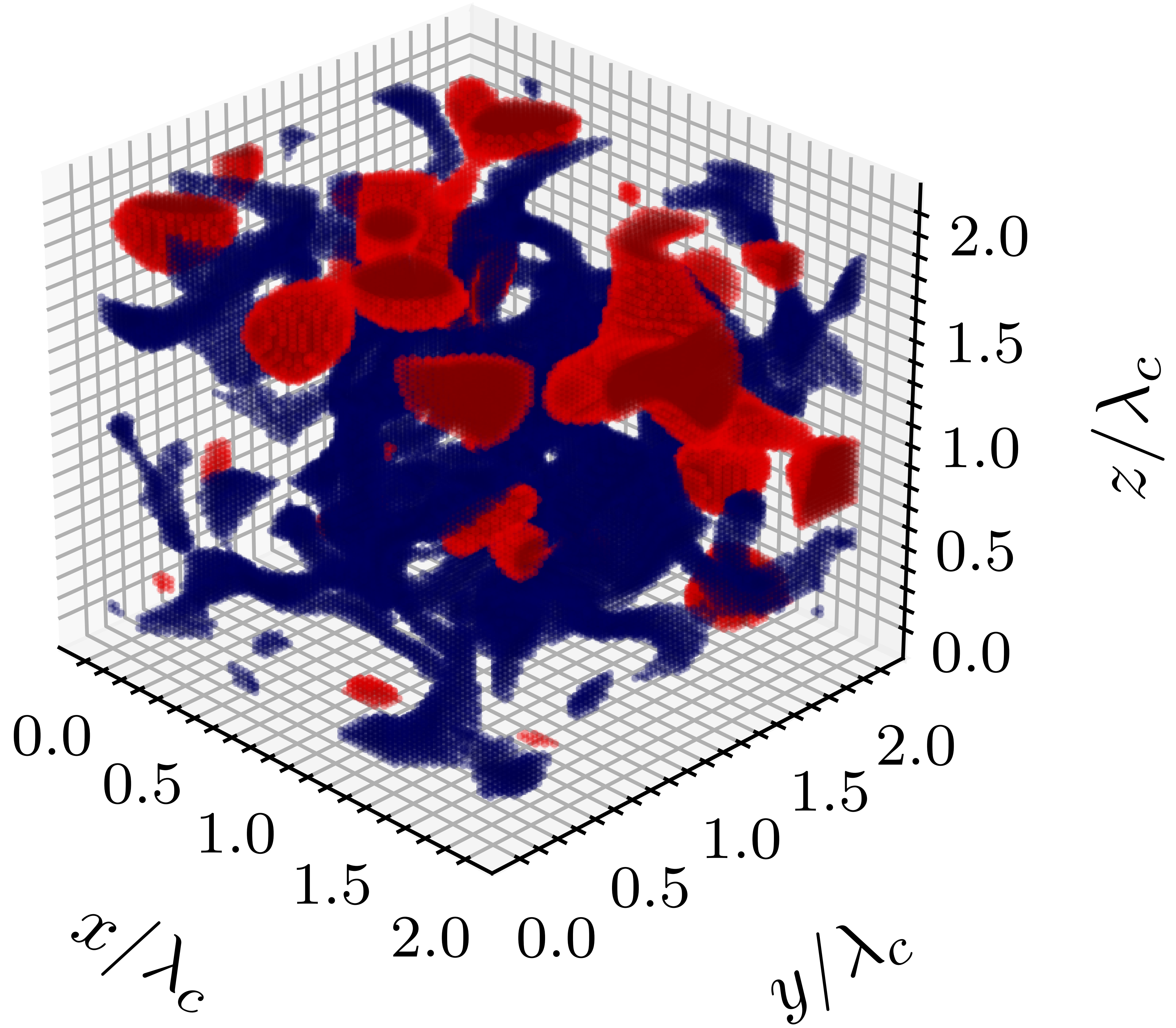
$$N \sim 7.6 \times 10^{64} \left(\frac{\rho_{DM}}{0.4\text{GeV} \cdot \text{cm}^{-3}}\right)\left(\frac{10^{-17}\text{eV}}{m}\right)^4.$$

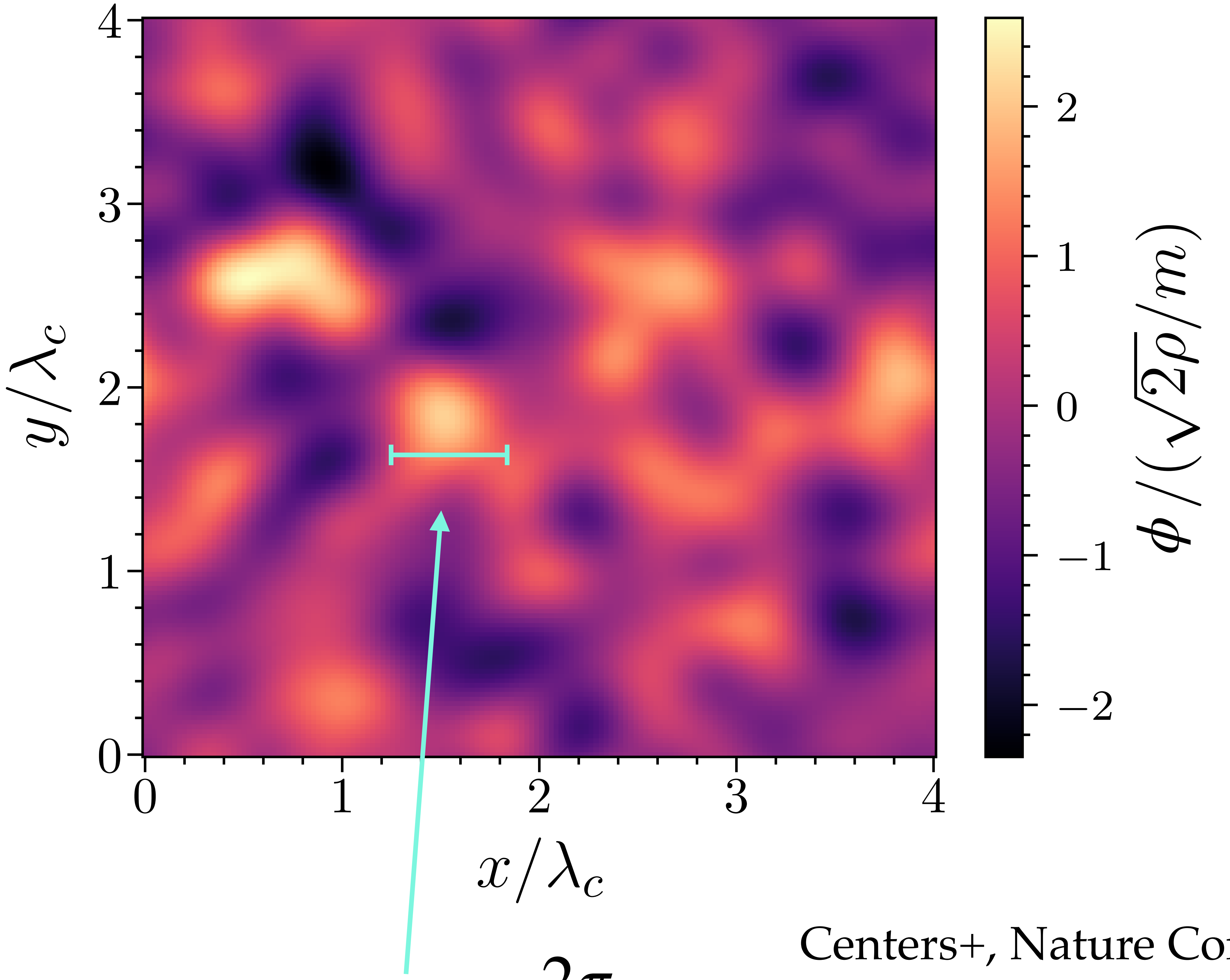
A wave (or classical field) description is a good approximation.

The field is modeled as a superposition of plane waves

$$\phi(t, \vec{x}) \propto \sum_{\vec{v}} e^{i\left(\omega t - \vec{k} \cdot \vec{x} + \theta_{\vec{v}}\right)}.$$

Field configuration at a fixed time $\phi(t_i, \vec{x}) = \phi_0(t_i, \vec{x}) \cos\left(mt_i + \theta(t_i, \vec{x})\right)$





Centers+, Nature Comm;

Yao, Yong Tang, 2404.01494

The size of interference pattern is set by the coherence length $\lambda_c = \dfrac{2\pi}{m\sigma}$.

Simulated with velocity distribution $f(\vec{v}) = \dfrac{1}{(2\pi\sigma^2)^{3/2}} e^{-\vec{v}^2/2\sigma^2}$ with $\sigma \sim 10^{-3}$.

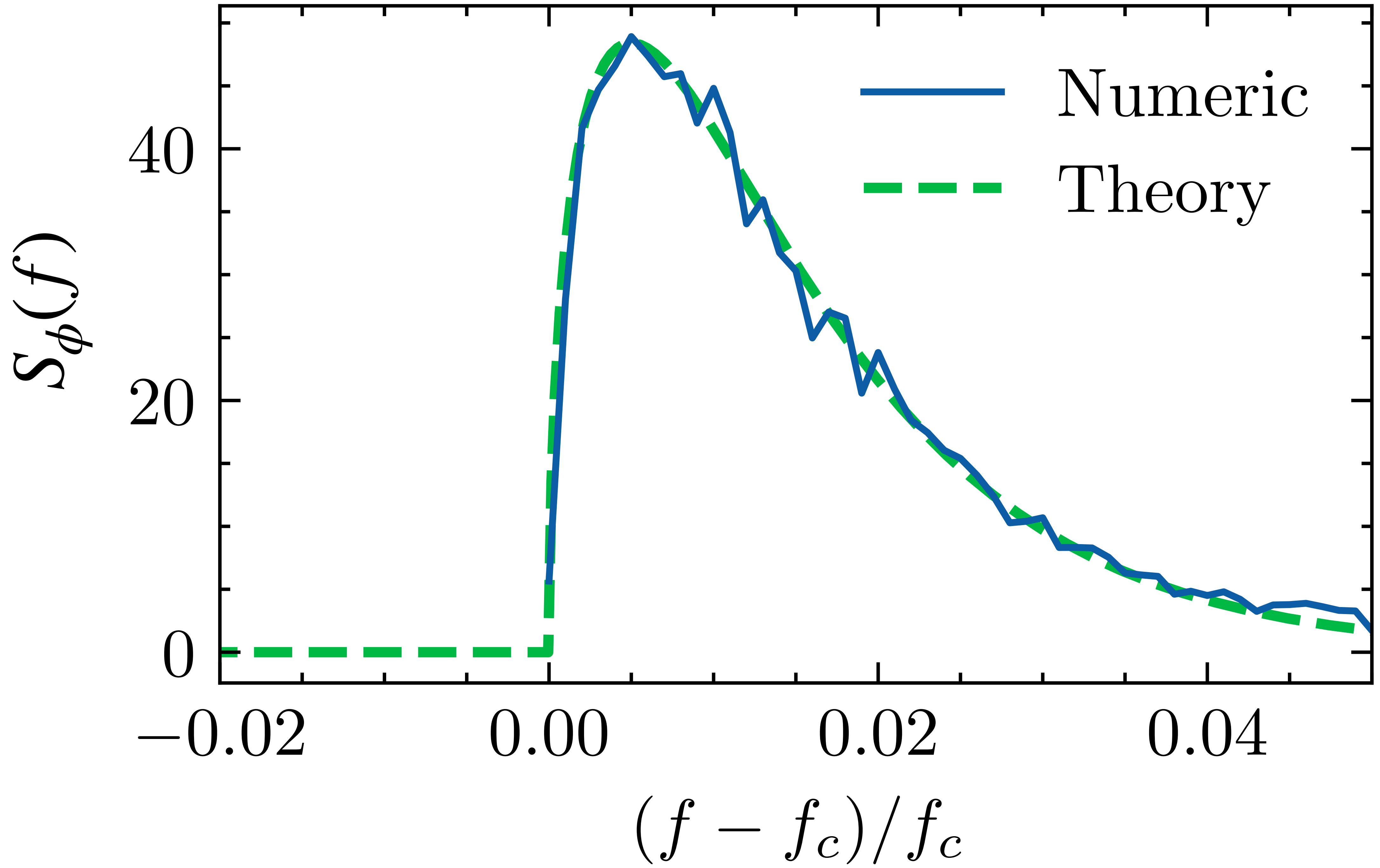
Statistical properties of ULDM field

Two-point correlation function of the field (Gaussian random field):

$$R_\phi(\tau, \vec{d}) := \langle \phi(x)\phi(x') \rangle = \frac{\rho}{m^2} \int d^3v\, f(\vec{v})\ \cos\left[m\left(1 + \frac{v^2}{2}\right)\tau - m\vec{v}\cdot\vec{d} \right],$$

where $\tau = t' - t$, $\vec{d} = \vec{x}' - \vec{x}$, $\langle \cdots \rangle$ denotes ensemble average.

The power spectral density of the field is defined as $S_\phi(f) = \int_{-\infty}^{\infty} d\tau\, e^{-i2\pi f\tau}\, R_\phi(\tau, \vec{0})$.



A.Derevianko, PRA.97.042506;

J.Foster, N.Rodd, B.Safdi, 1711.10489;

Gramolin+, 2107.11948;

Yao+, 2508.14655

$f_c = m/2\pi$

Probing DM with GWs (indirect) and GW detectors (direct)

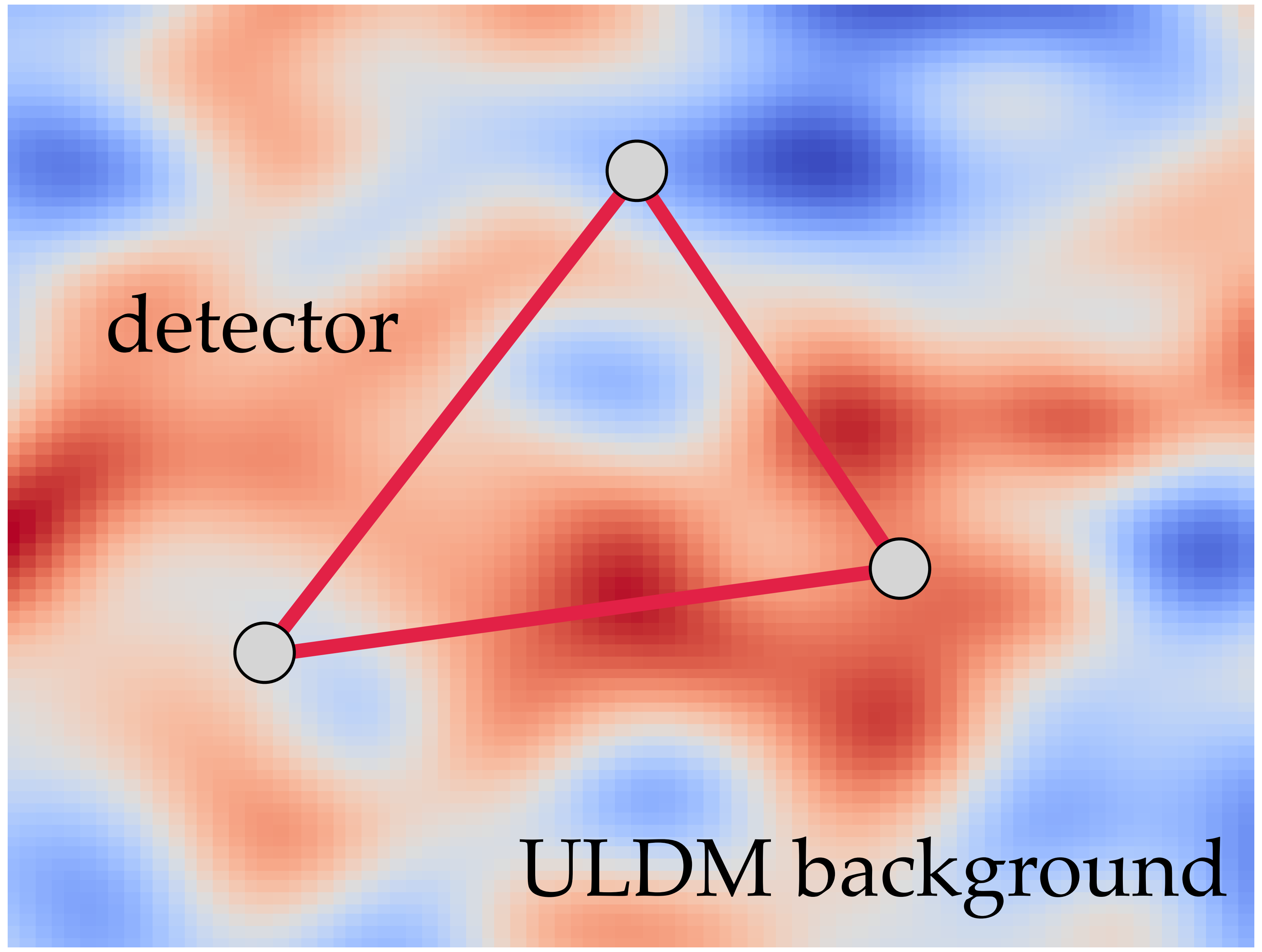
Indirect: GWs as a messenger carrying information about DM, G.Bertone+, 1907.10610

e.g. 1. The presence of DM modifies the evolution of binary systems and emitted GWs.

2. Some DM involved processes produce GWs directly.

3.….

Direct: DM directly interacts with GW detectors. No GWs! A.Miller, 2503.02607



Why GW interferometers can be used to search for ULDM?

Interferometers measure light distance between test masses with a high precision (10^{-21}).

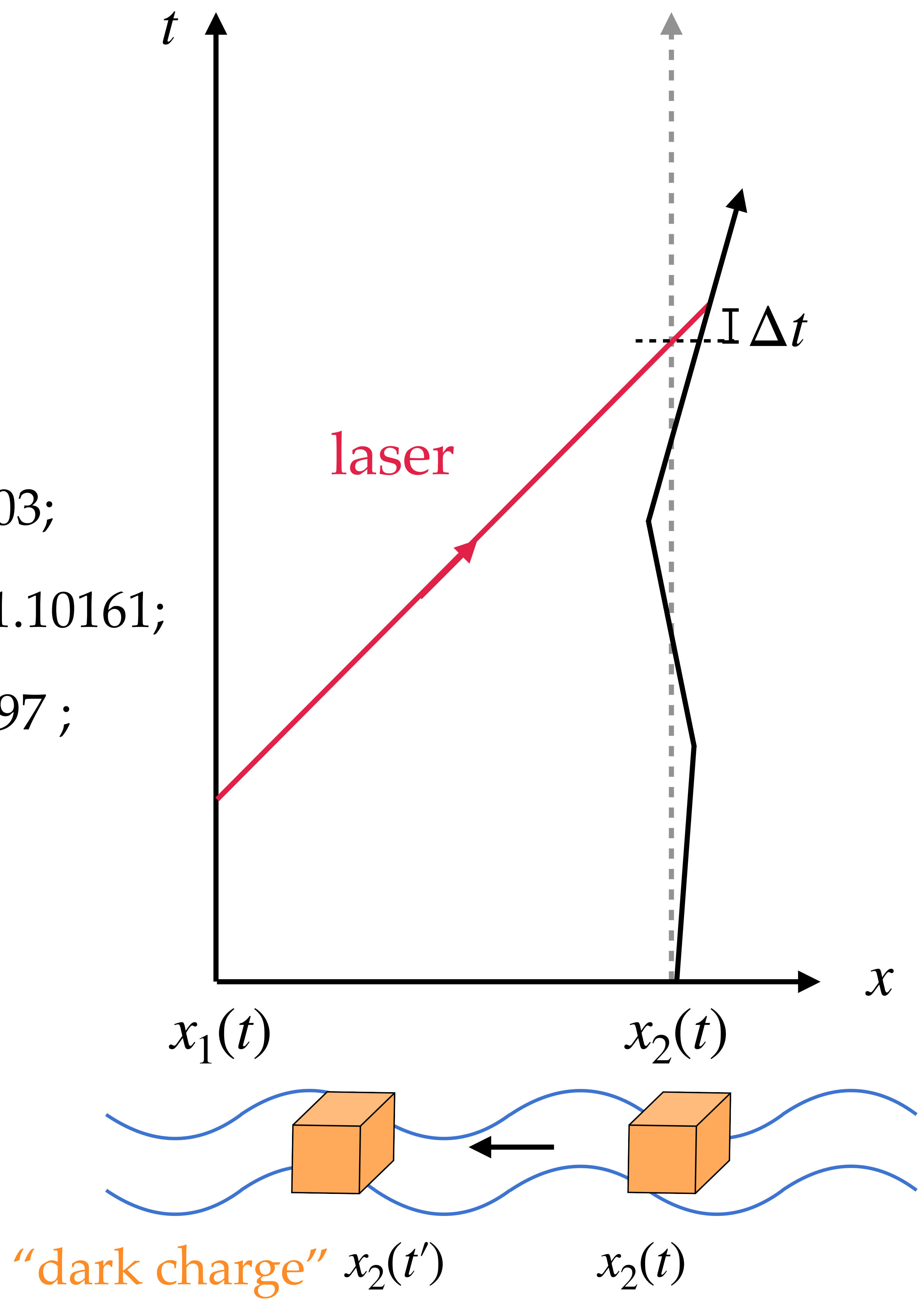
Morisaki, Suyama, 1811.05003;

A.Pierce, K.Riles, Zhao, 1801.10161;

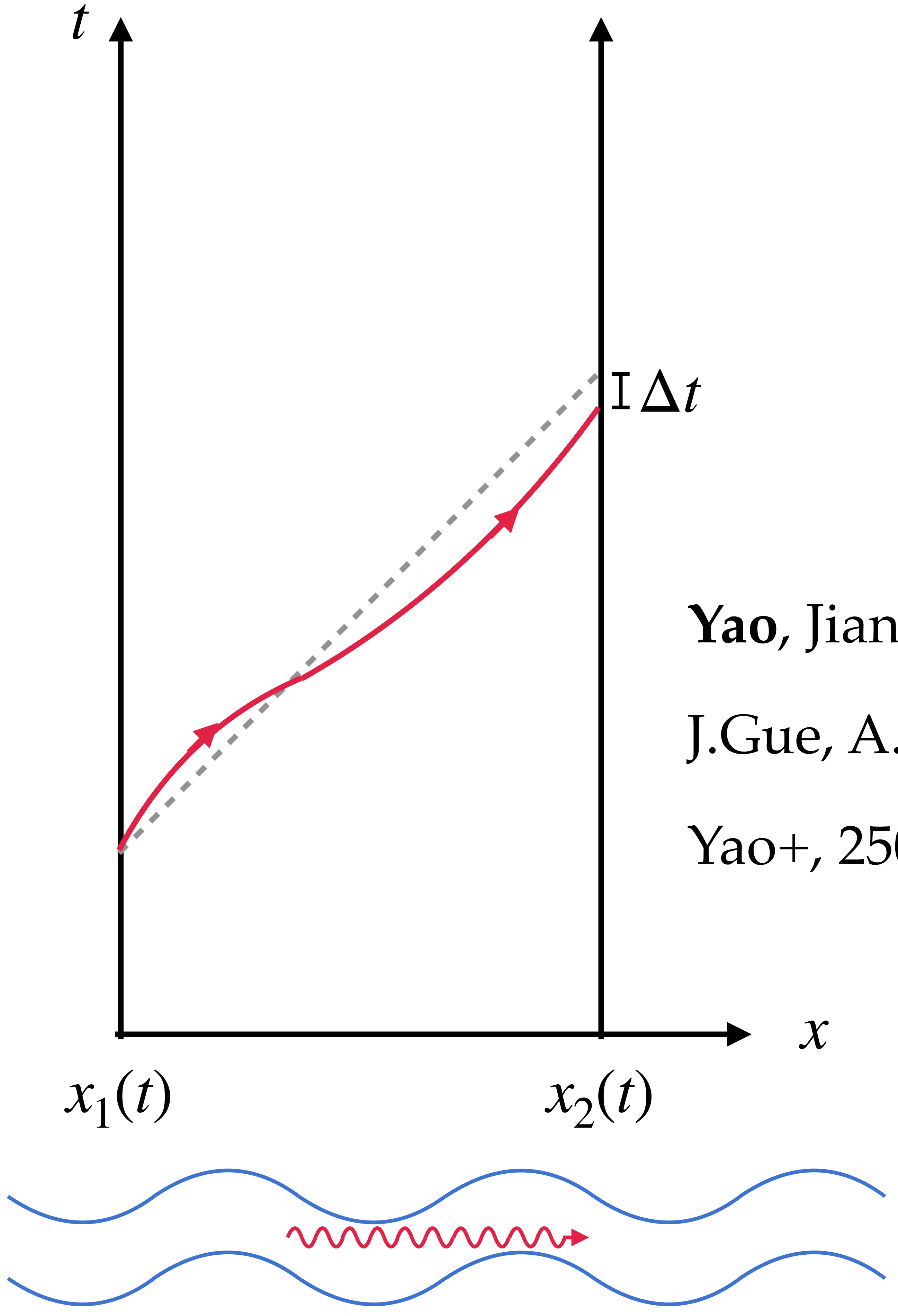
Yu, **Yao**, Tang, Wu, 2307.09197 ;

Yao, Yong Tang, 2404.01494

1. Test mass's motion



2. Light's propagation



Yao, Jiang, Tang, 2410.22072;

J.Gue, A.Hees, P.Wolf, 2410,17763;

Yao+, 2504.10083.

Example: a vector ULDM coupled with the baryon number (B) or baryon minus lepton number (B-L)

The Lagrangian is given by

$$\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\nu A_\nu - \epsilon e J^\nu A_\nu \quad ,$$

where A_μ is the ULDM, J^ν the B or $B-L$ current, ϵ the dimensionless coupling strength.

The equation of motion of test mass is

$$\vec{a}(t,\vec{x}) = \epsilon e \frac{q}{M} \partial_t \overrightarrow{A}(t,\vec{x}) \quad ,$$

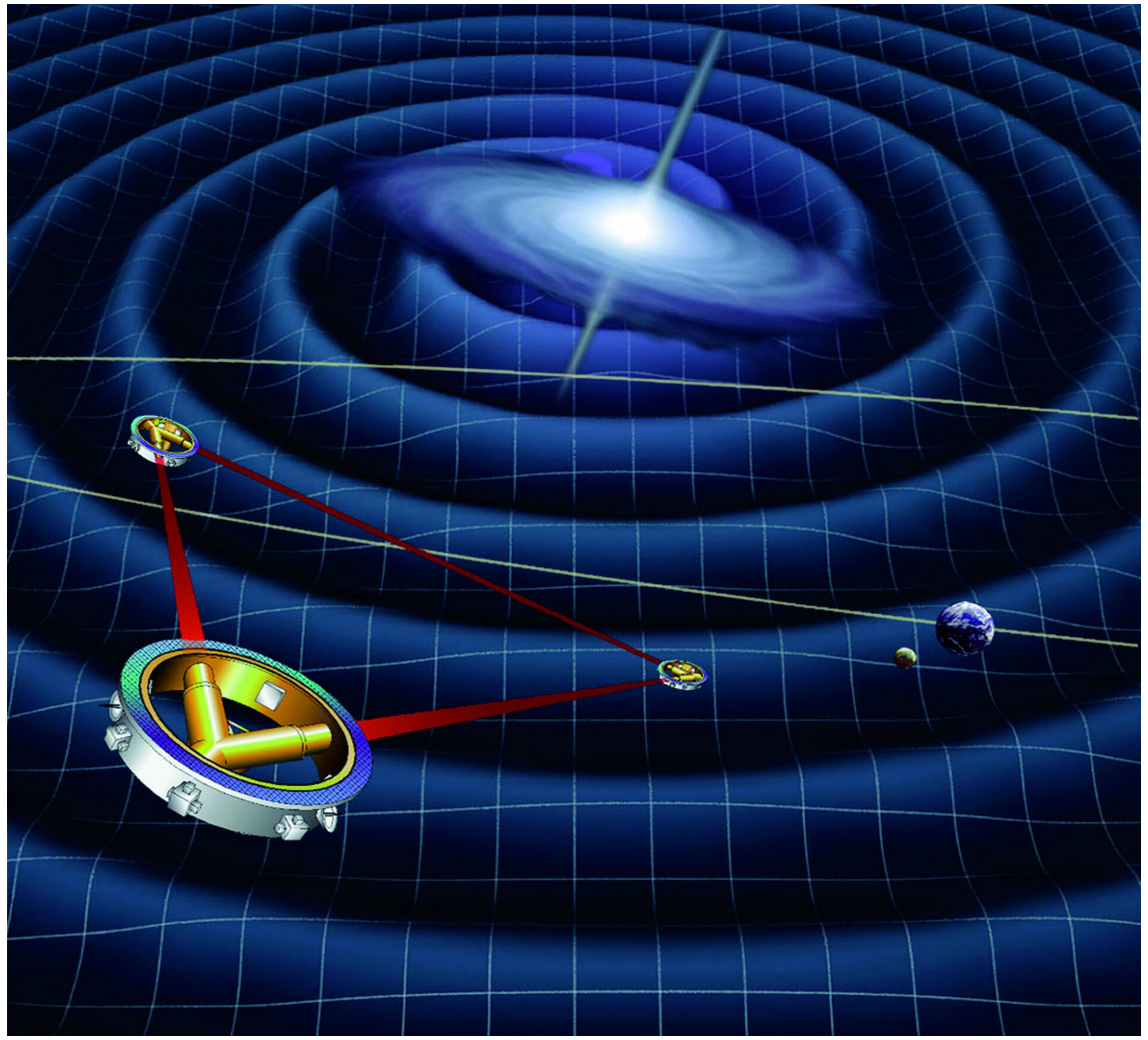
where q and M the B or $B-L$ charge and mass of test mass.

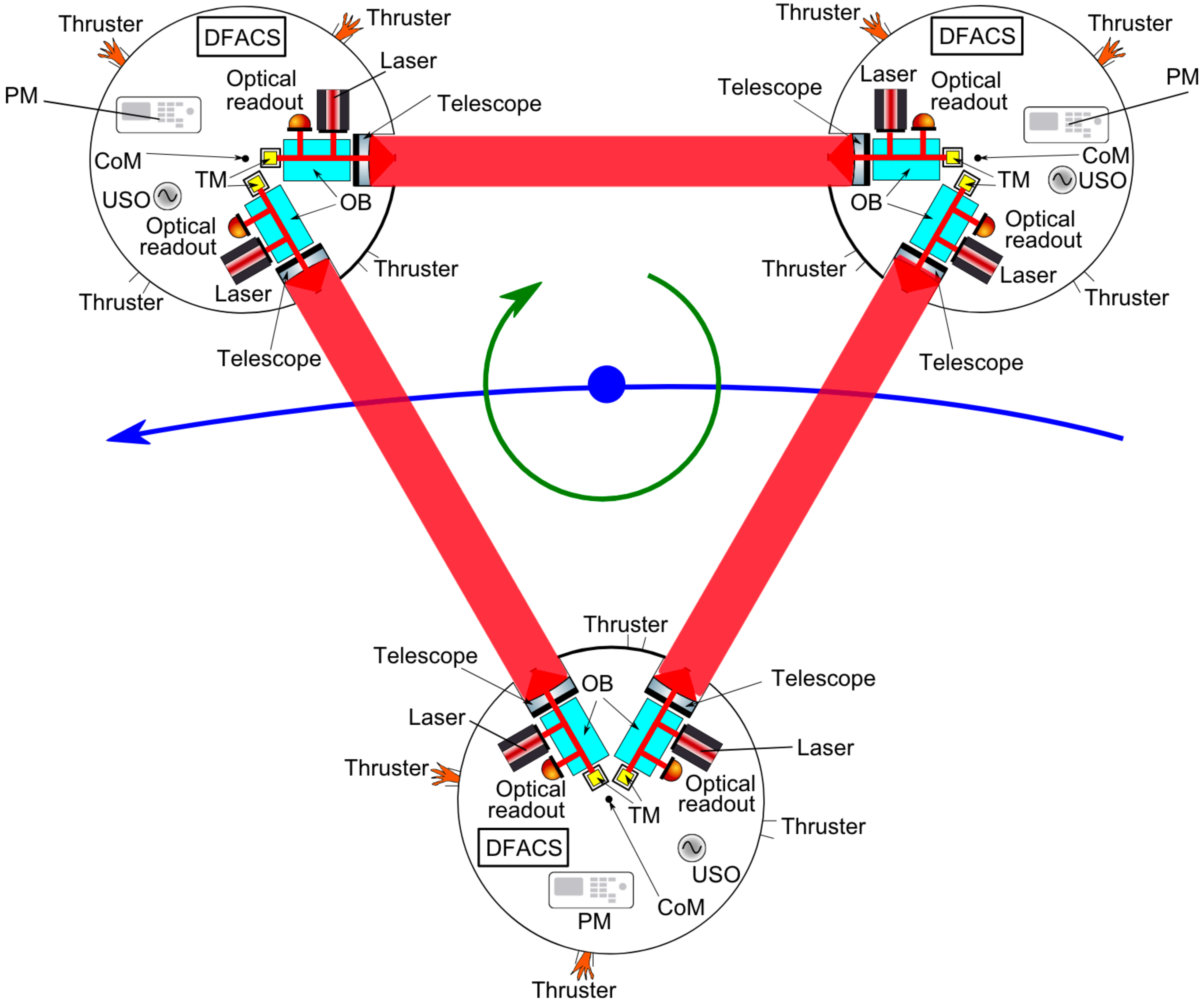
Then, the laser frequency fluctuation arising from the relative motion between test masses is

$$y_{rs}(t) \propto \hat{n}_{rs} \cdot \left(\overrightarrow{A}(t,\vec{x}_r) - \overrightarrow{A}(t_s,\vec{x}_s) \right) \quad ,$$

where $\vec{x}_r$ and $\vec{x}_s$ are position vectors of the test masses and $\hat{n}_{rs} = (\vec{x}_r - \vec{x}_s)/|\vec{x}_r - \vec{x}_s|$.

Space-based GW interferometer





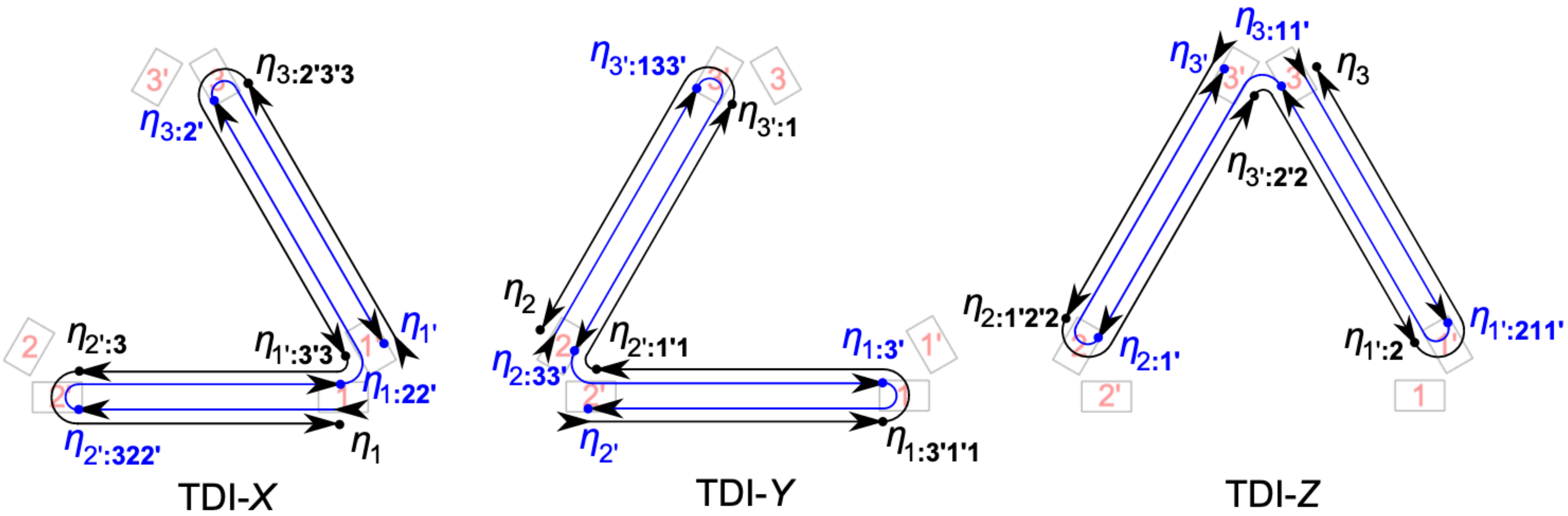
Credit: M.Otto

Time-delay interferometry (TDI)

Tinto, Dhurandhar, Living review

The Michelson channel: $X(t) = \left[y_{13} + y_{31,2'} + y_{12,22'} + y_{21,322'}\right] - \left[y_{12} + y_{21,3} + y_{13,3'3} + y_{31,2'3'3}\right]$,

where $y(t)_{rs,ij'} = y(t - L_i - L_{j'})$ is the time-delay operation.



Credit: M.Otto

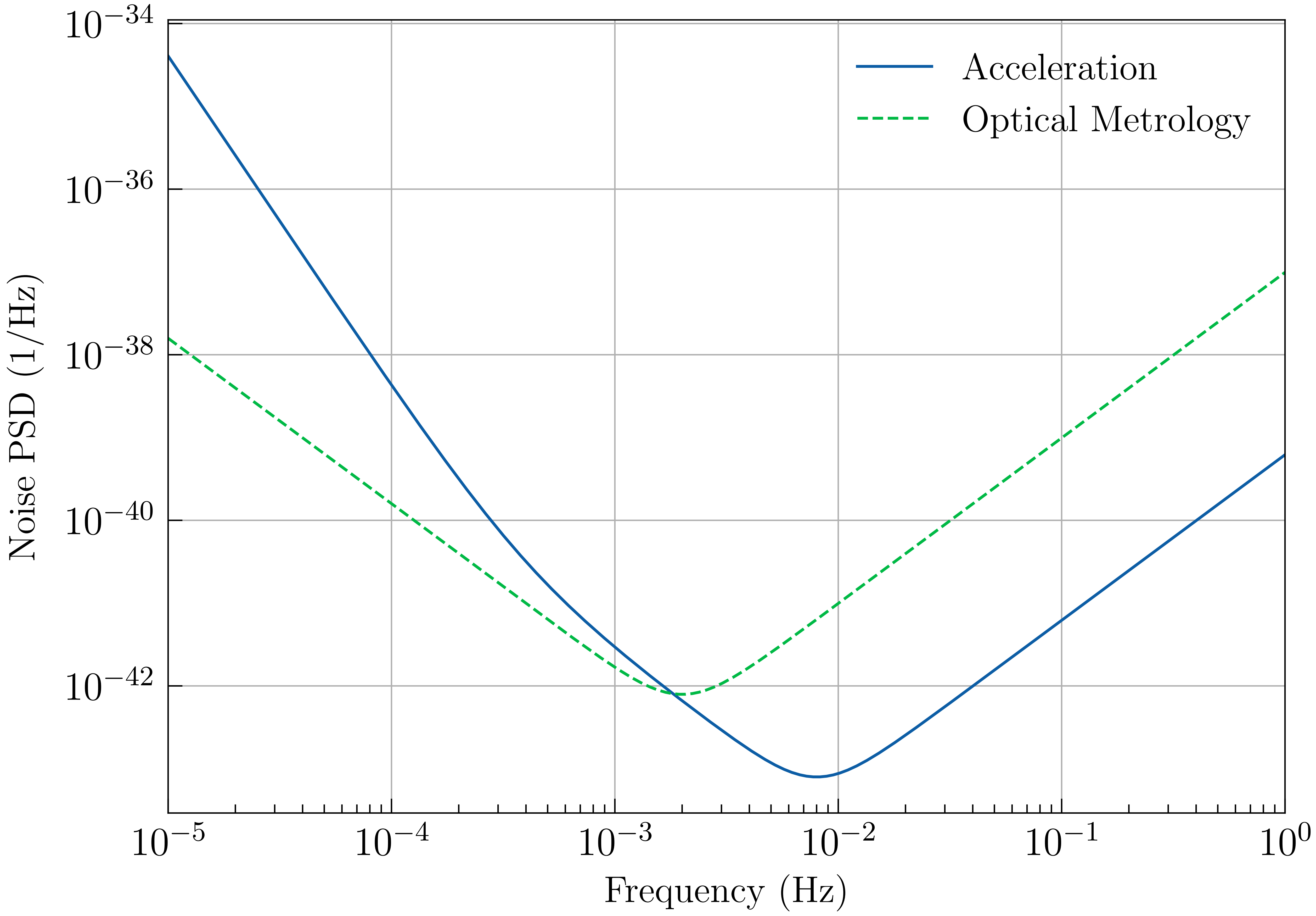
Response function of TDI channel

R quantifies how much the power of the field is transferred into the signal.

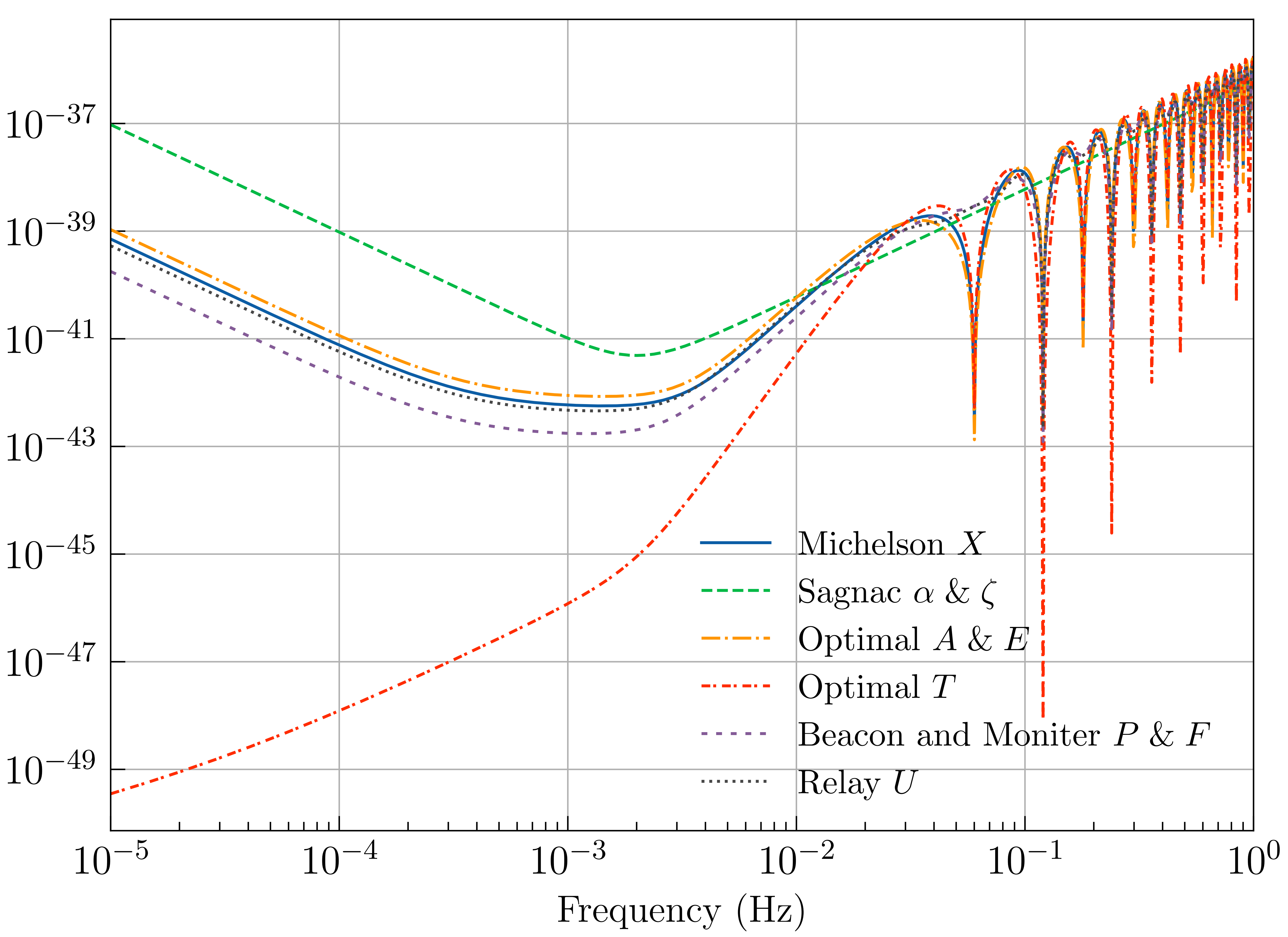
Yu, **Yao**, Tang, Wu, 2307.09197

Noise performance

Test mass and optical noise

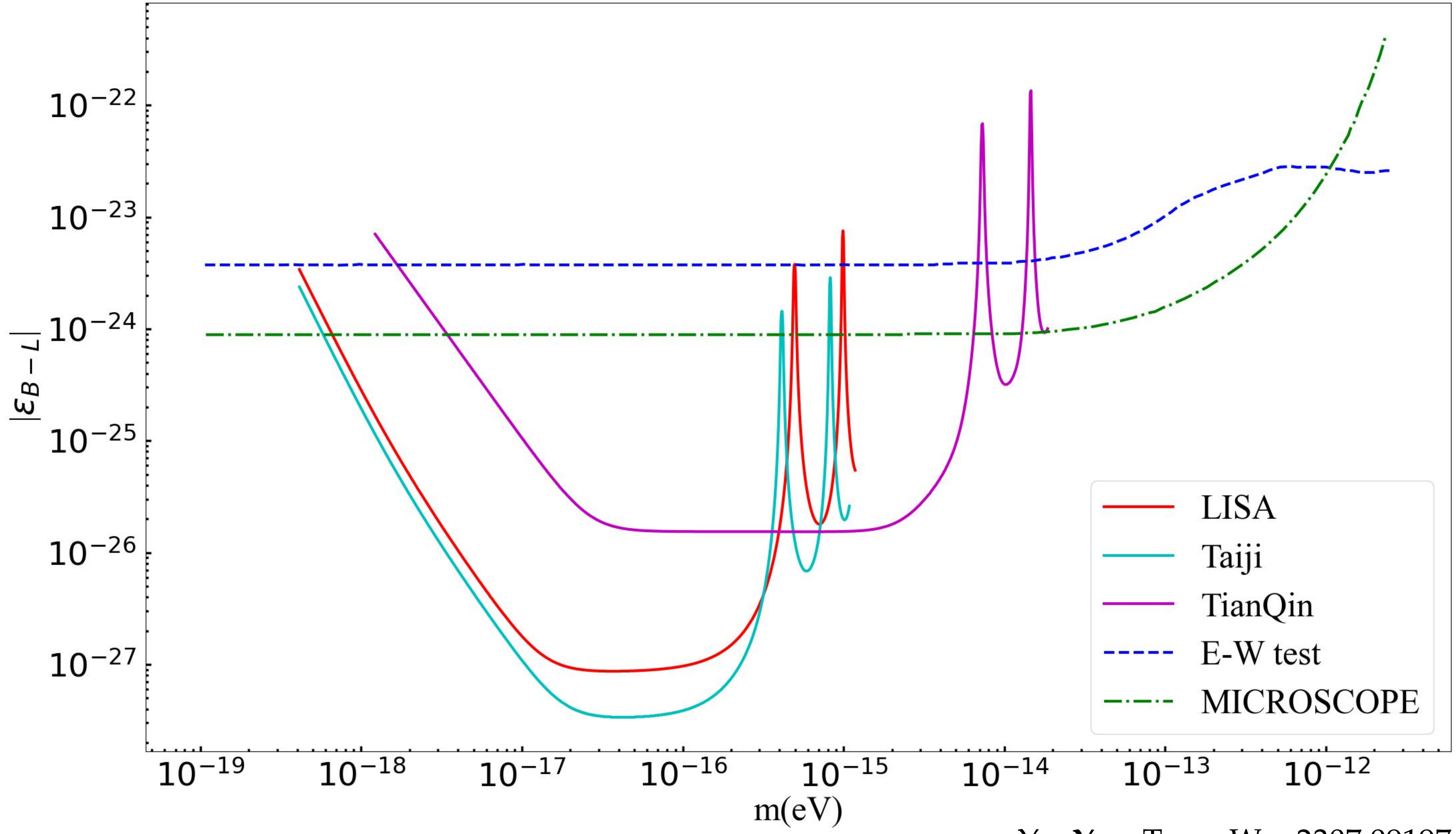


Noise power spectral density in channels



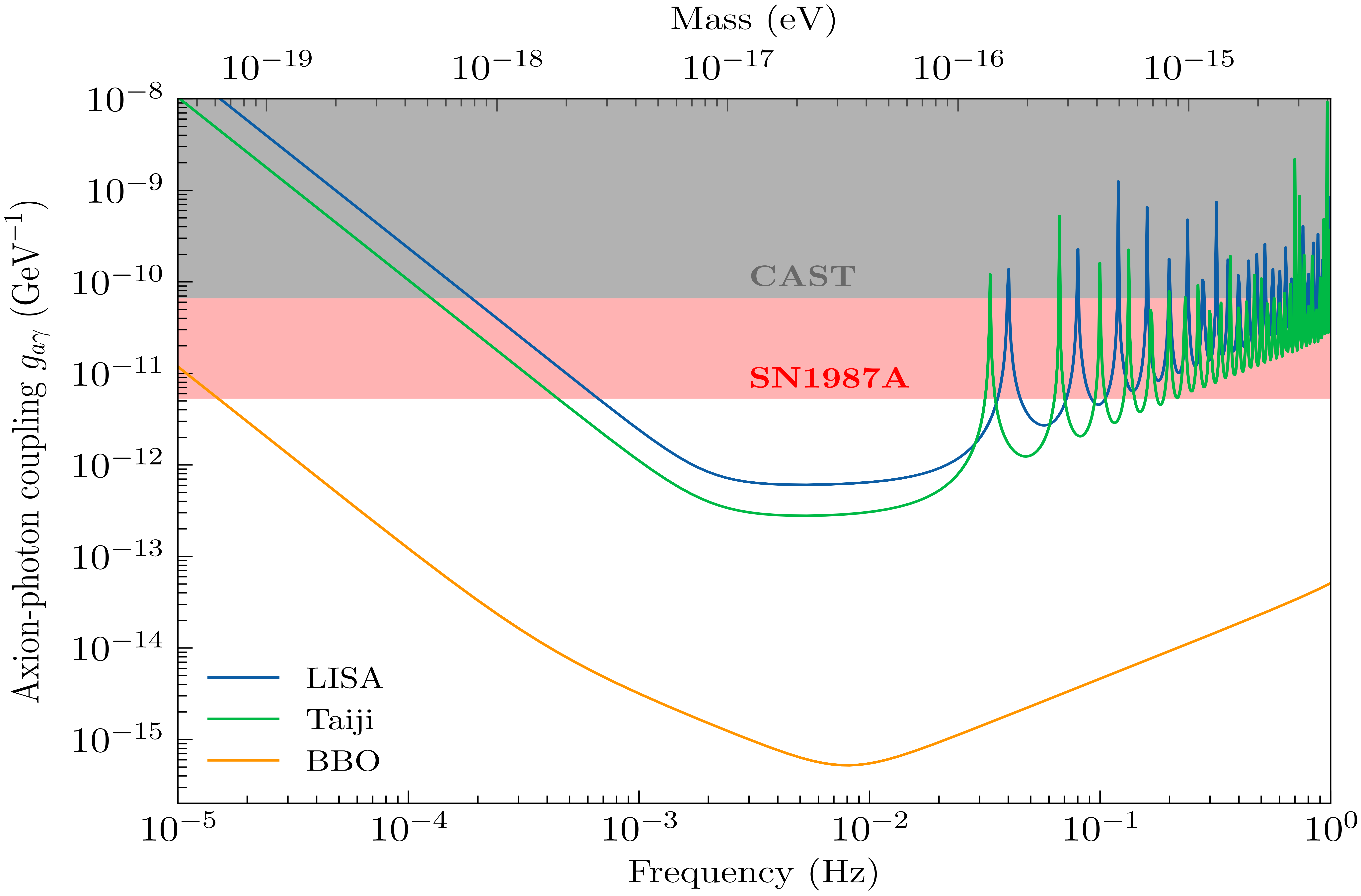
Sensitivity := The coupling strength yielding a signal power equal to that of noise.

Projected sensitivity on the coupling ϵ_{B-L}, $\mathscr{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m_A^2 A^\nu A_\nu - \epsilon e J^\nu A_\nu$



Yu, **Yao**, Tang, Wu, 2307.09197

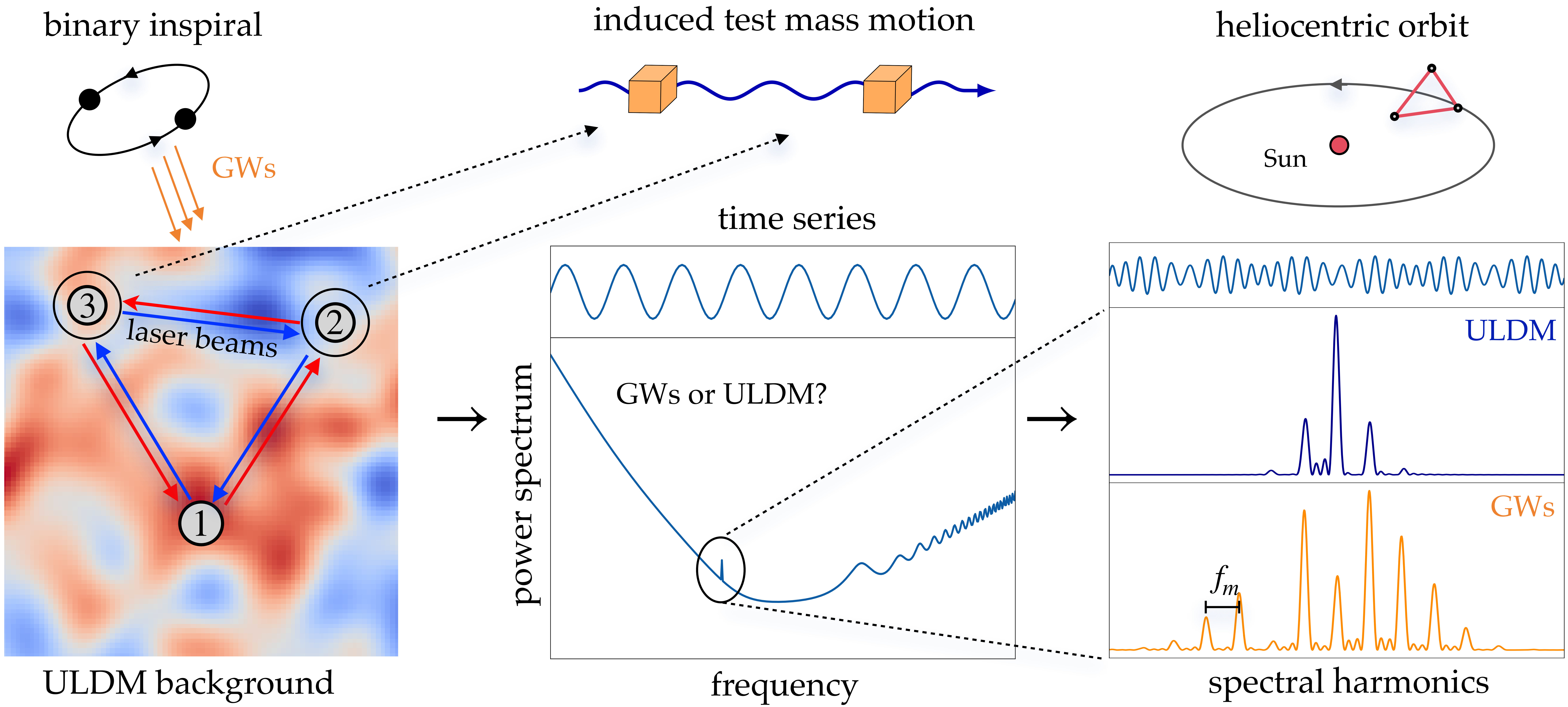
Projected sensitivity on the coupling $g_{a\gamma}$, $\mathscr{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m^2a^2 - \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu}$



Yao, Jiang, Tang, 2410.22072

Orbital modulation

Yao+, 2508.14655



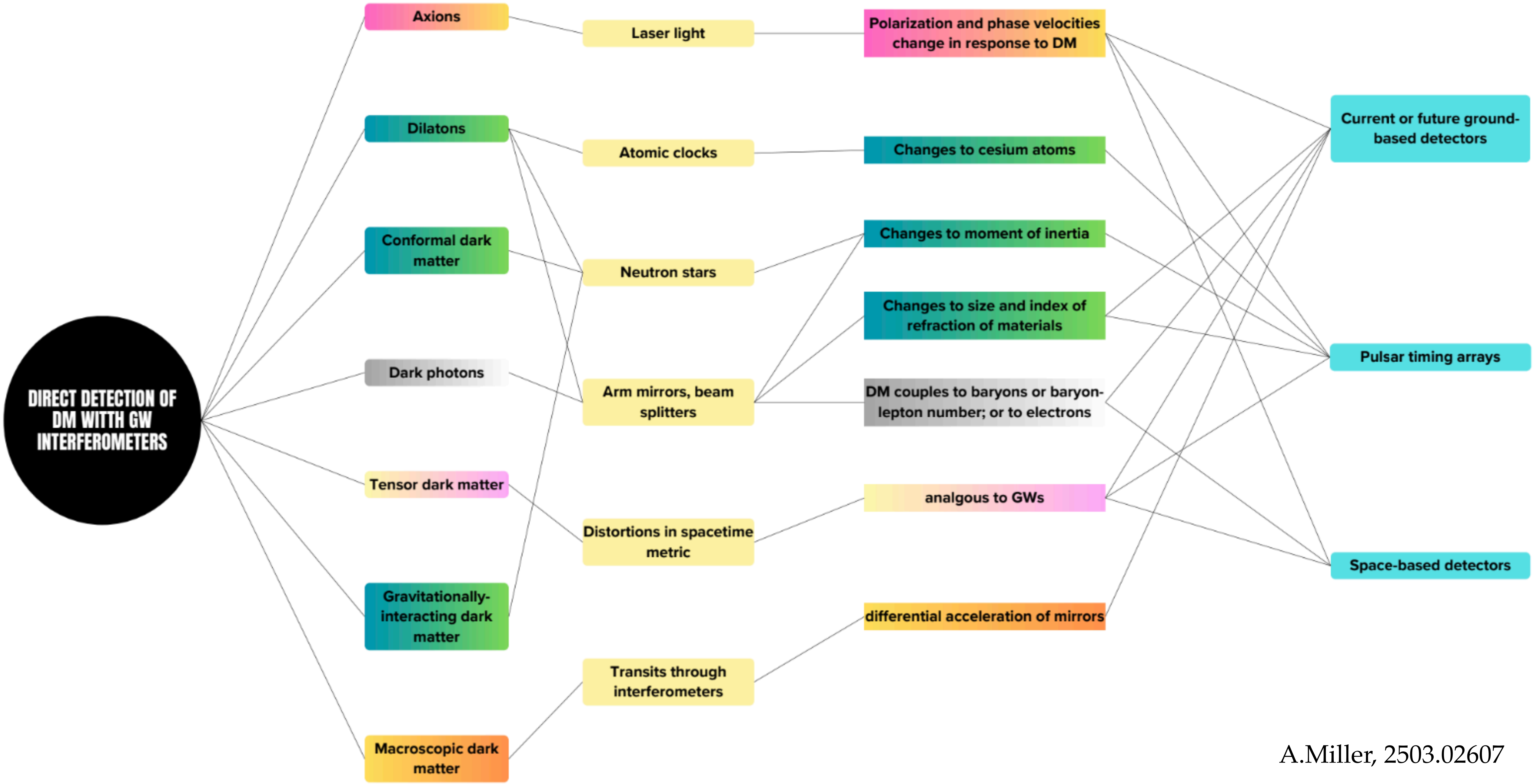
GWs and ULDM exhibit distinct modulation patterns, which can be used to distinguish two types of signals.

Conclusion

1. Although designed for GW detection, GW interferometers are also sensitive to other physical processes, such as ultralight dark matter. Powerful constraints and projected sensitivity have been obtained in this way.

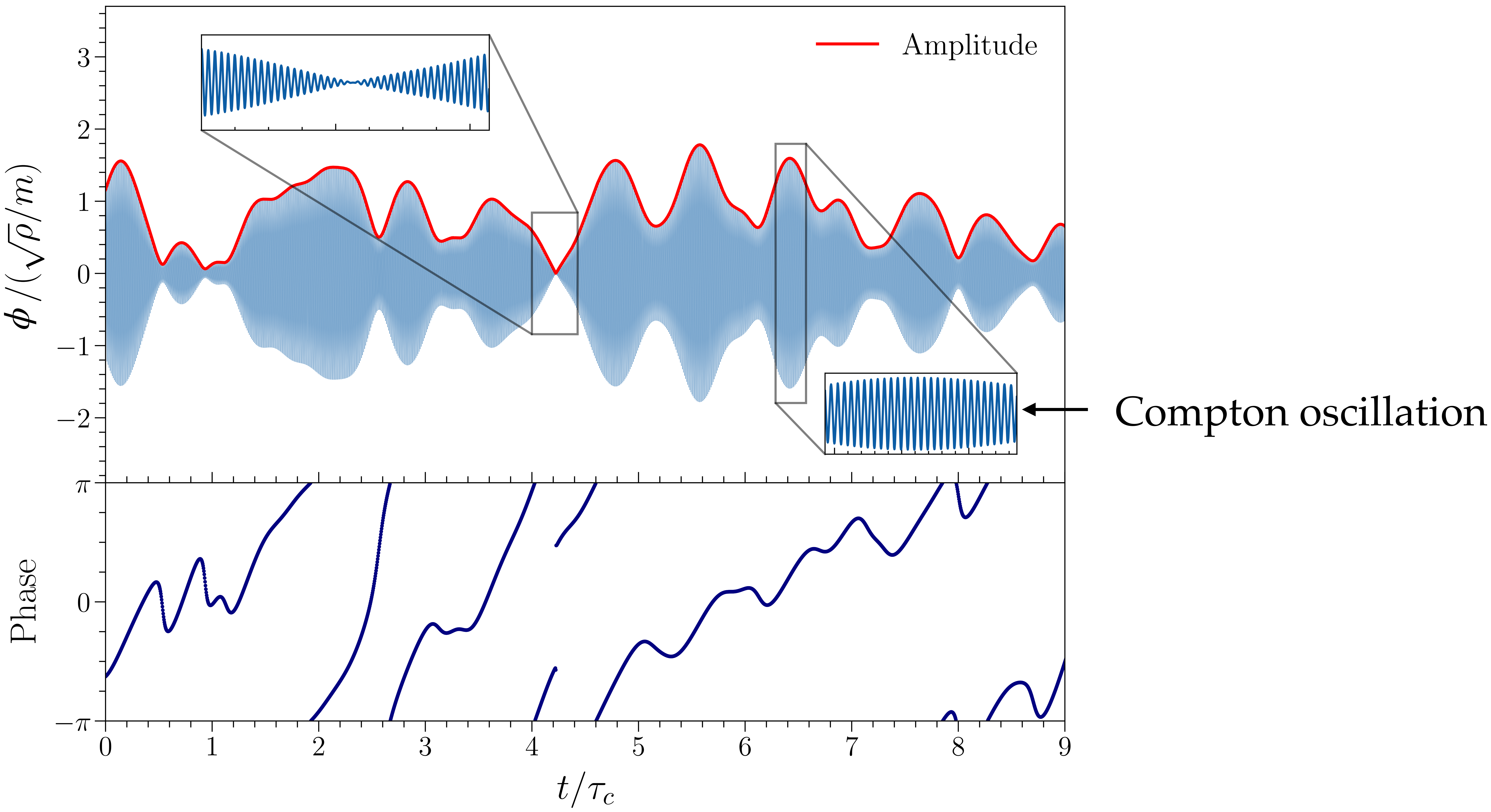
2. While existing studies have shown that ULDM can induce signals in detectors, a thorough investigation of how different ULDM models leave their imprints and of the full signal characterization is still lacking.

Thanks for your attention!



A.Miller, 2503.02607

Field evolution at a fixed point $\phi(t, \vec{x}_i) = \phi_0(t, \vec{x}_i)\cos\left(mt + \theta(t, \vec{x}_i)\right)$



The amplitude and phase fluctuate stochastically over the coherence time $\tau_c = 2\pi/m\sigma^2 \simeq 10^6 f_c^{-1}$.