Gravitational Wave Probes to Dark Sectors

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Dark Interactions 2024
Vancouver, Oct. 16-18

Why gravitational waves for dark sectors?

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Era of gravitational wave astrophysics

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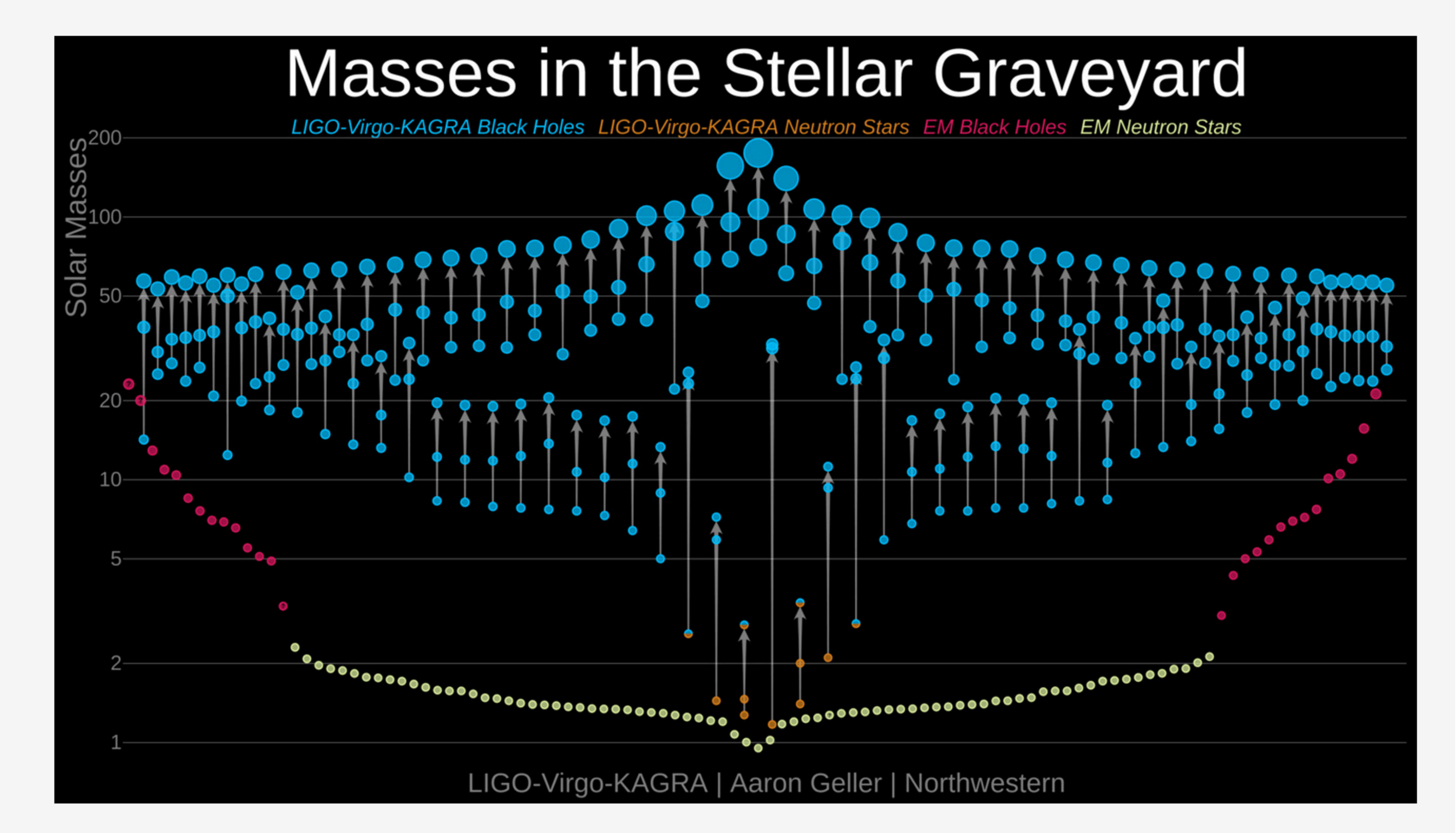
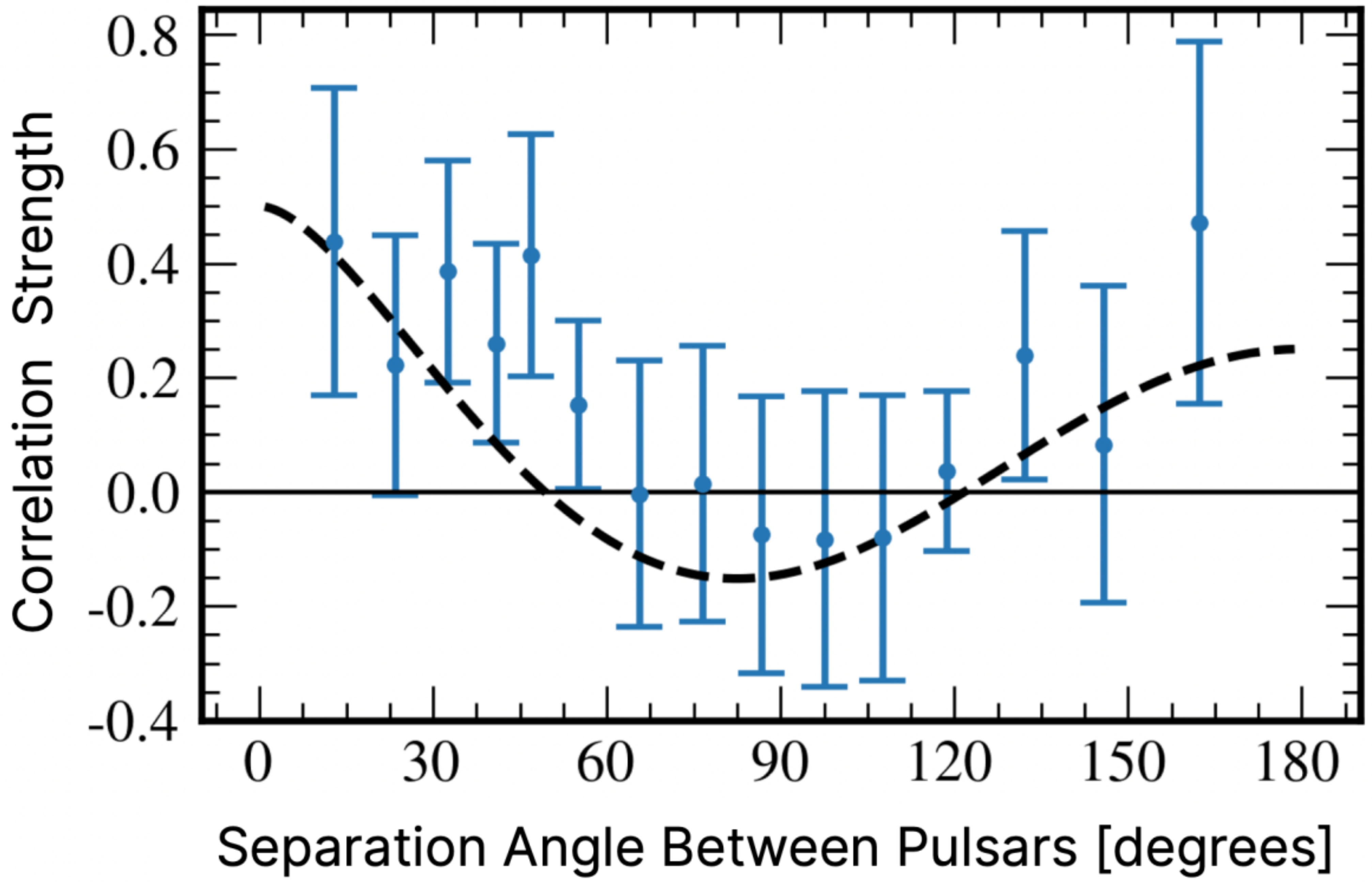


Transient gravitational wave signals

LIGO-Virgo-KARAGA



Evidence for a stochastic gravitational wave background

NANOGrav 2023

Why gravitational wave for dark sectors?

Era of gravitational wave astrophysics

New venue for indirect probes to dark sectors

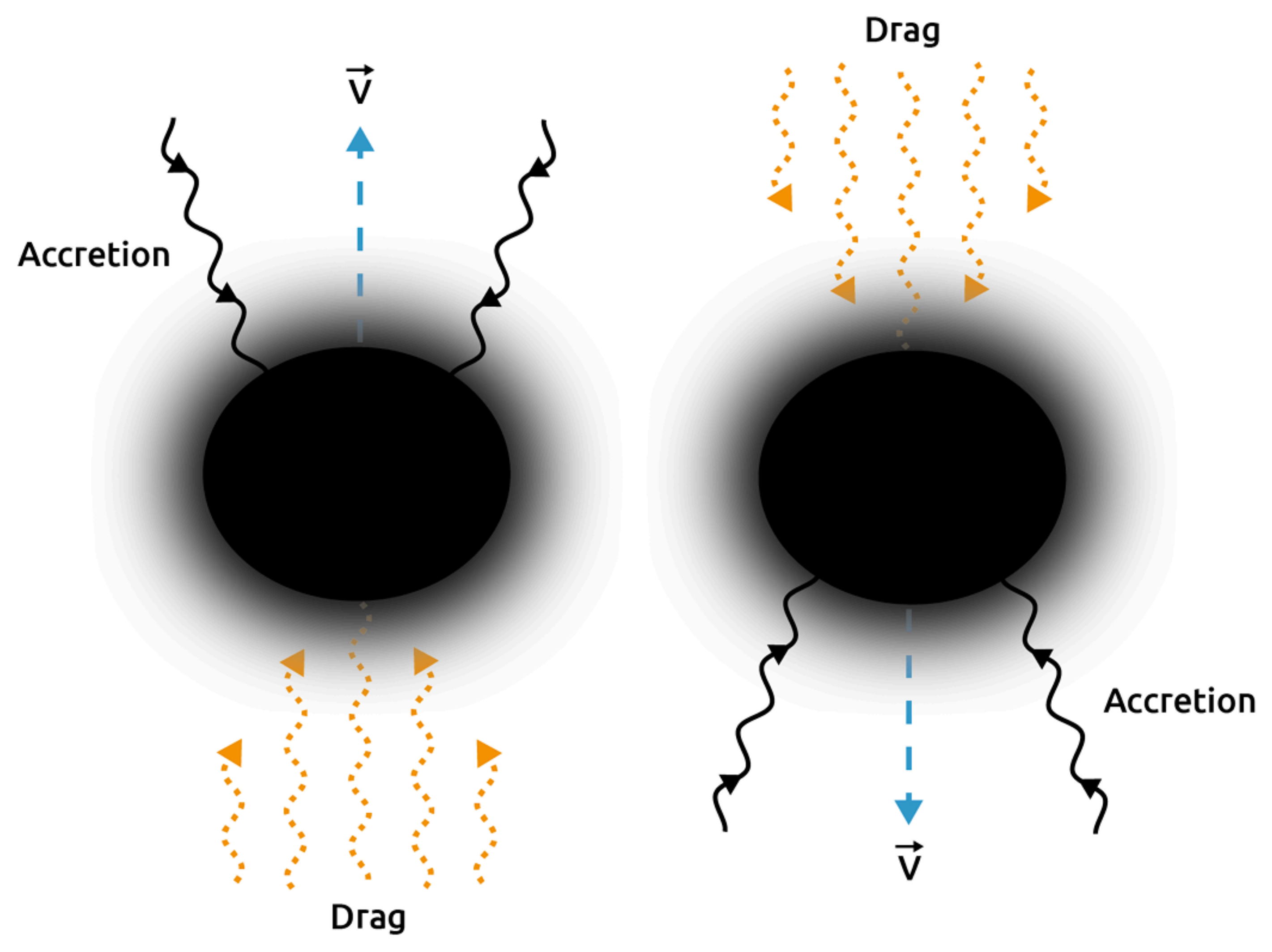


Figure 12. Depiction of a BBH evolving in a possible interstellar or DM environment. Each individual BH accretes and exherts a gravitational pull on the surrounding matter. Both effects contribute to decelerate the BHs, leading to a faster inspiral. Credit: Ana Sousa.

Cardoso et all '18

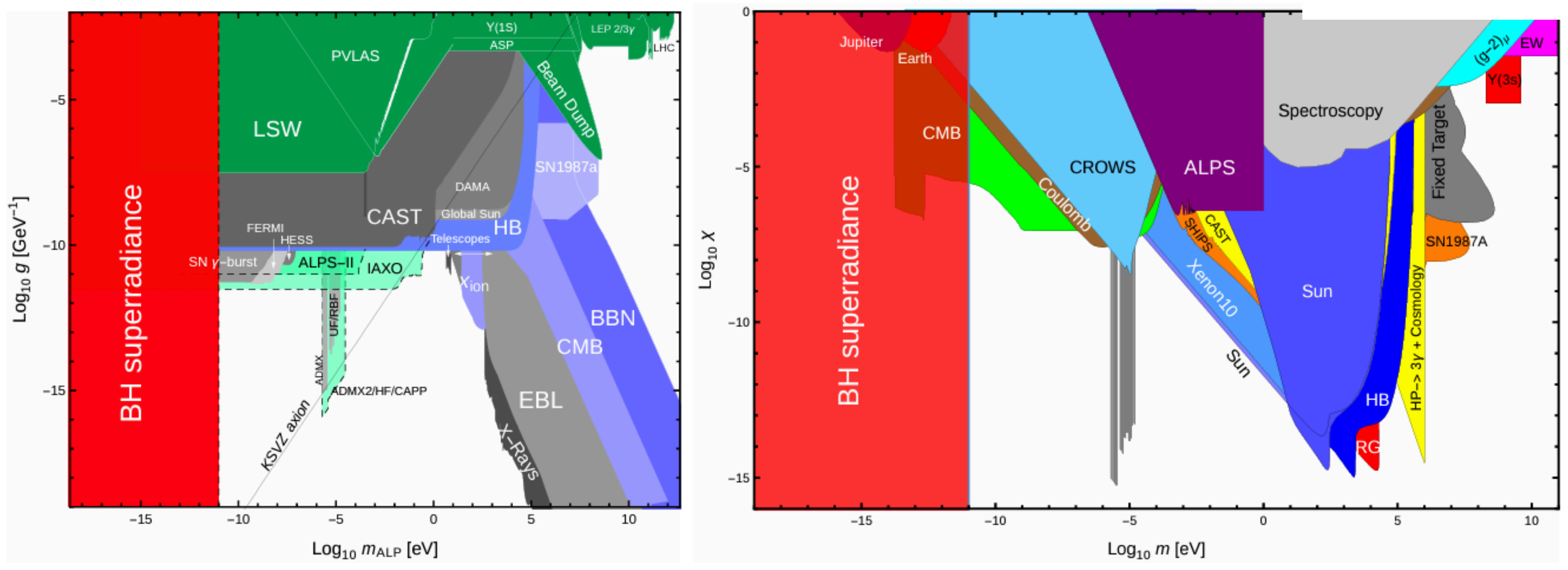


Figure 1. Current experimental limits on ALPs (left) and ULVs (right) in their corresponding mass-coupling plane (adapted from [12] and [13], respectively; courtesy of J. Redondo). The red dashed areas denote the regions that can be probed through the superradiant instability of astrophysical BHs [14–19] (cf. [20] for an overview), as discussed in this paper. These constraints do not require a direct coupling between dark matter and ordinary particles, and are complementary to other bounds.

NOT THIS TALK

Bertone et all '19

Why gravitational wave for dark sectors?

Rich sources of gravitational waves from dark sectors

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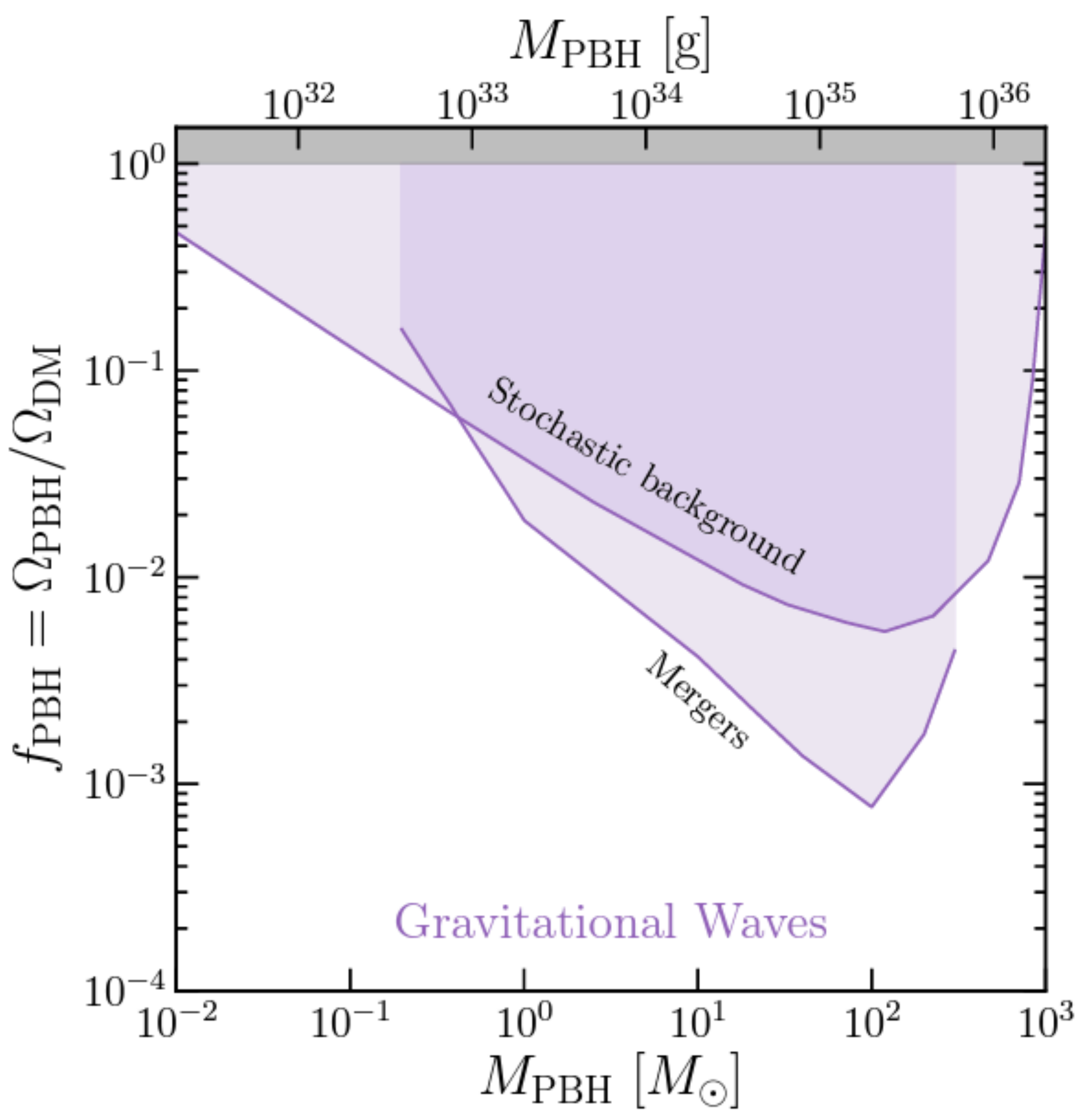
Rich sources of gravitational waves from dark sectors

Primordial black holes (PBH)

Green, Kavanagh, ‘20



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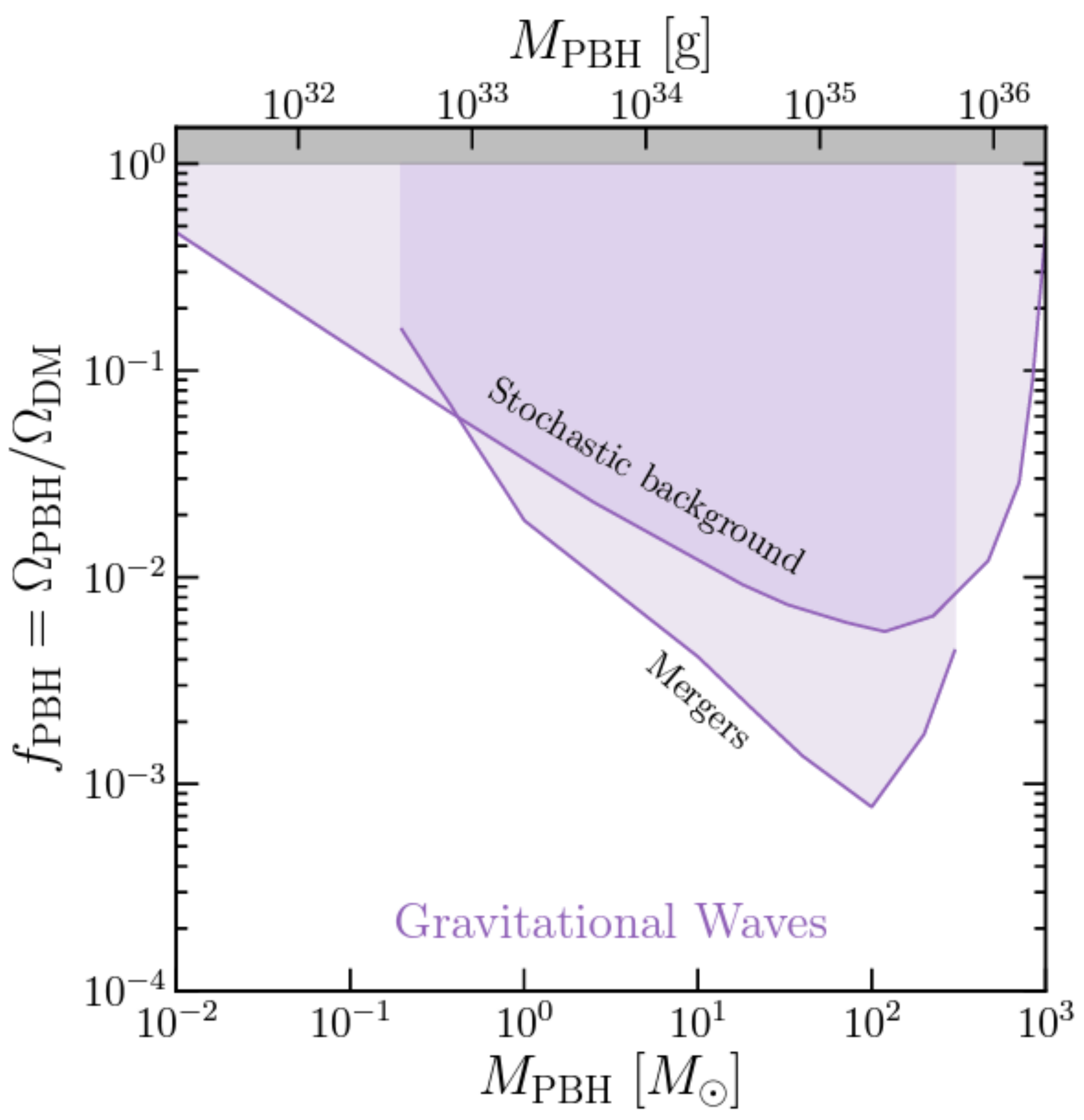

- Some randomly distributed PBHs can fall near each other and form binaries;
- PBH binaries loses energy by emitting GWs;
- Merger rate of such binaries can be used to constrain the DM fraction using GW data;
- Another constraint can be drawn by the non-detection of stochastic GW background

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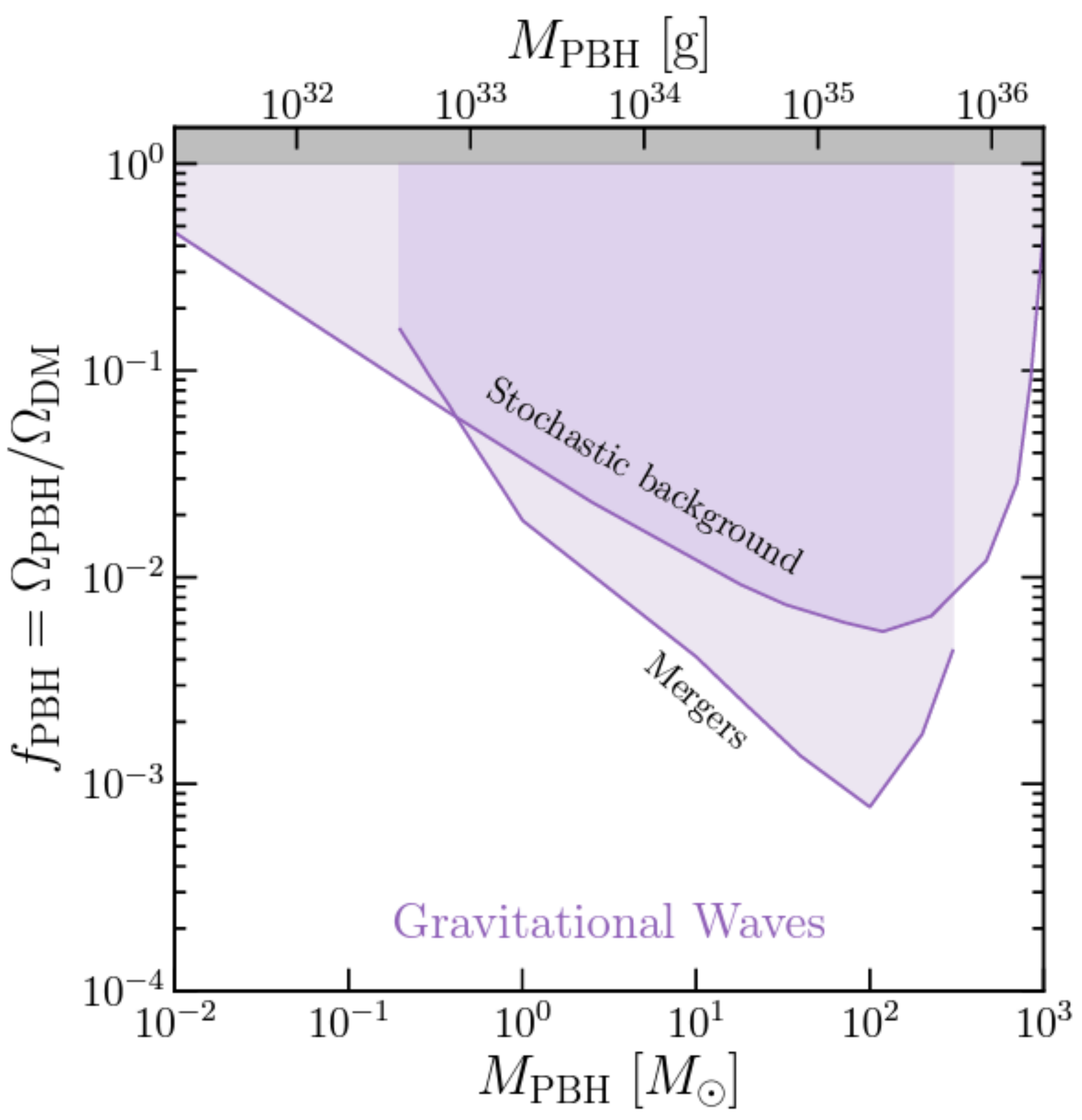

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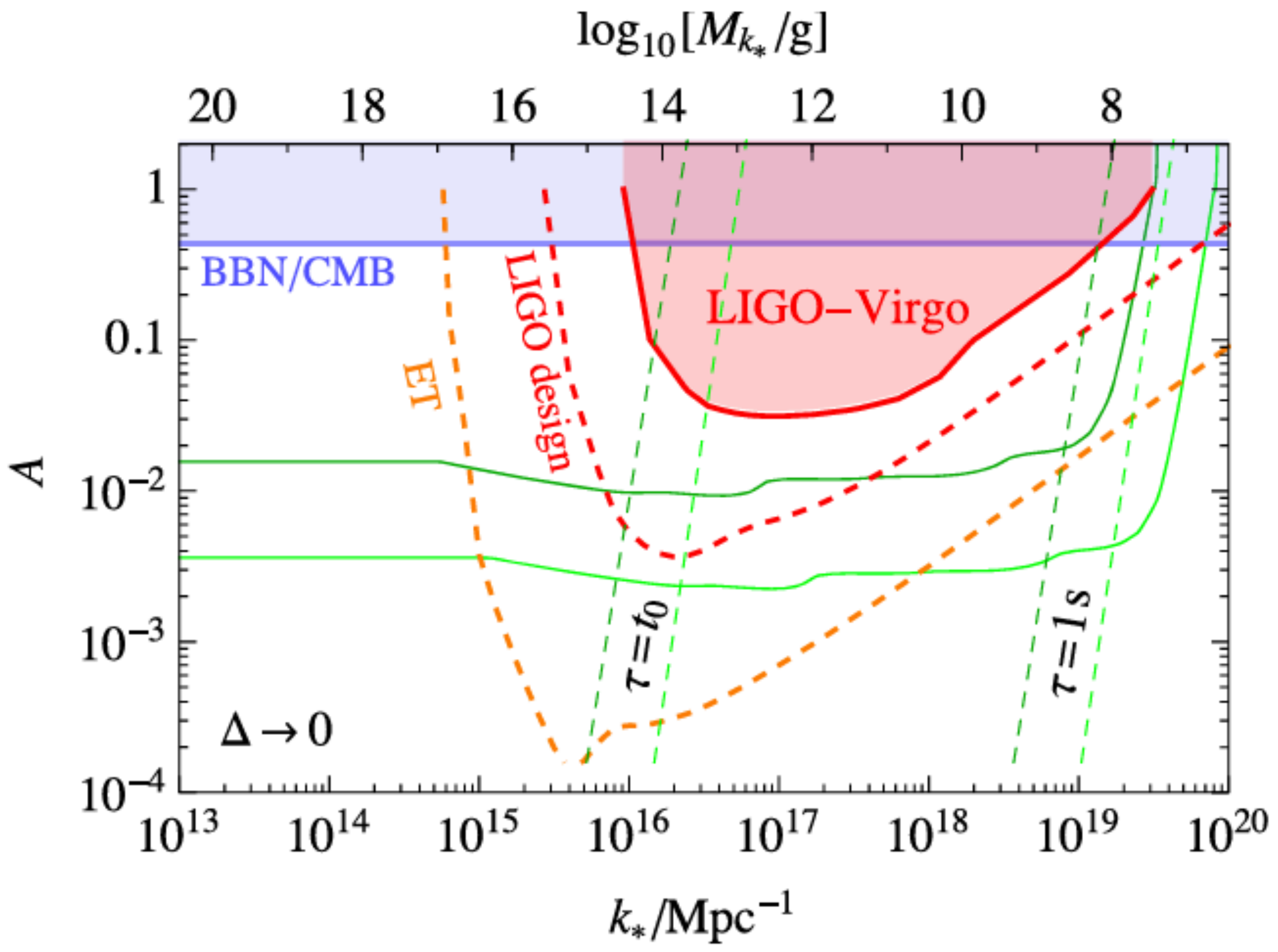
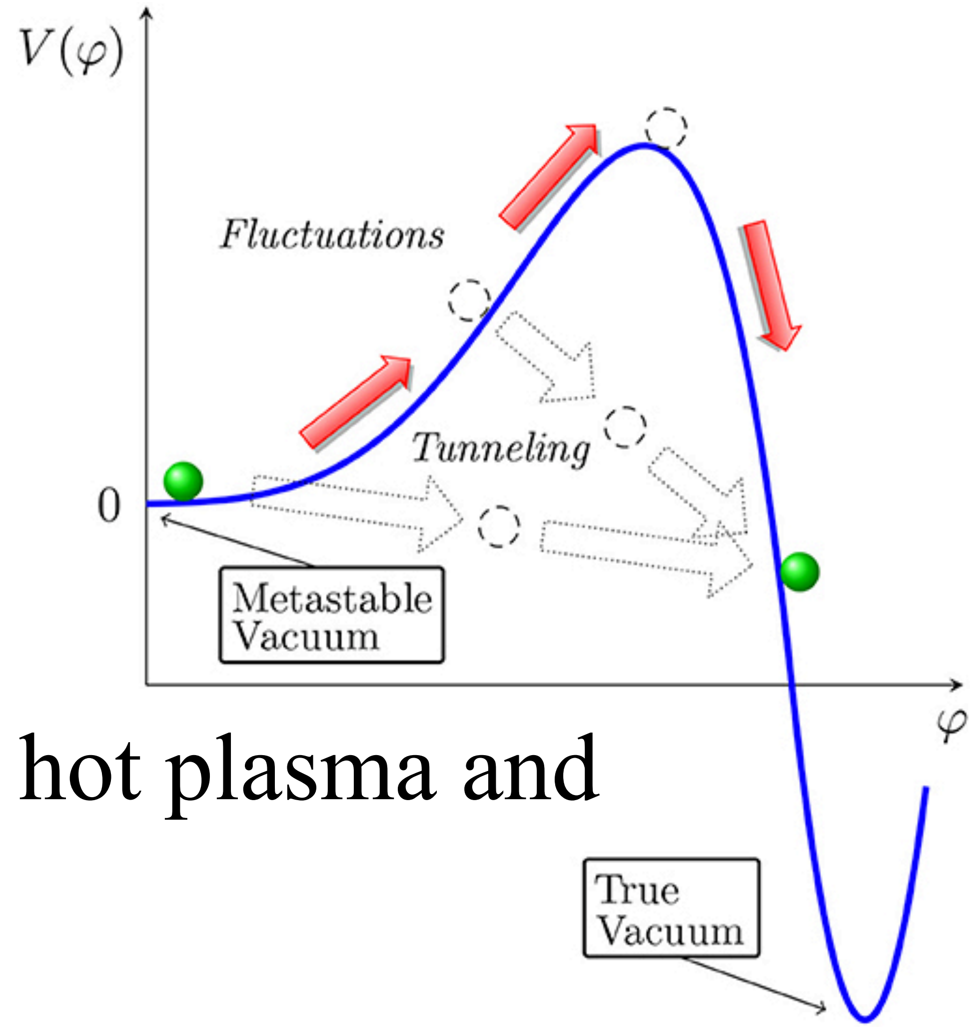


Romero-Rodríguez et al '22

Formation of PBH can be accompanied by the generation of GW background.

Why gravitational wave for dark sectors?



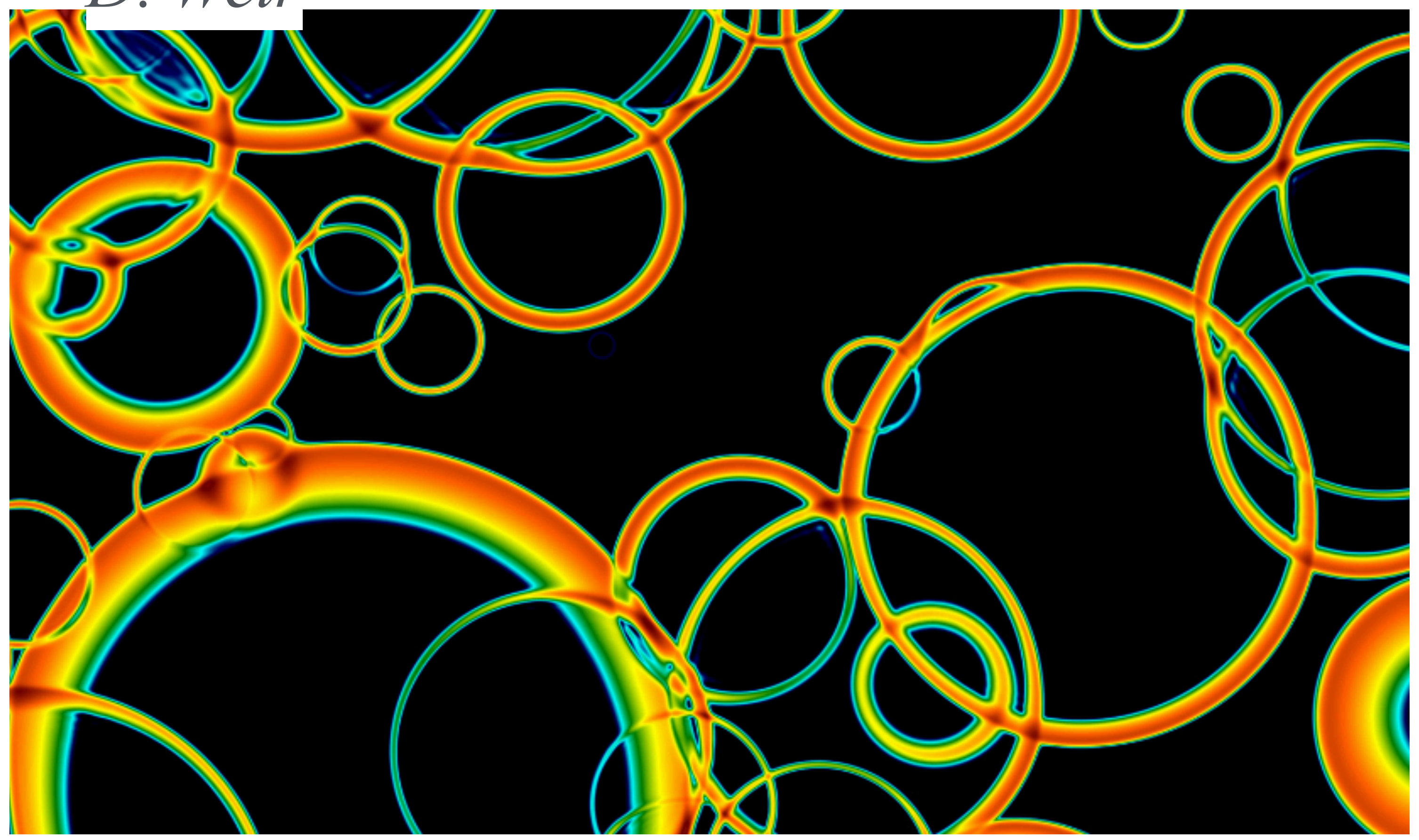
Rich sources of gravitational waves from dark sectors

Phase Transitions

A first order phase transition proceeds through bubble nucleation. The bubbles push through the hot plasma and collide, producing **stochastic gravitational wave backgrounds** via

Bubble collisions Sound waves Turbulent

D. Weir



Parameters affecting the power spectrum:

- (inverse) **duration of the phase transition** $\frac{\beta}{H_*} \sim T \left.\frac{d(S_3/T)}{dT}\right|_{T=T_*}$
- fraction of **vacuum energy released** w.r.t. the radiation bath

$$\alpha = \frac{\rho_{\tilde{v},\tilde{w}} - \rho_{v,w}}{\rho_{rad}}|_{T=T_*}$$

- **The bubble wall velocity**

For example, the power spectrum from bubble collisions can be treated by the 'envelope approximation'

$$h^2\Omega_{\text{env}}(f) = 1.67 \times 10^{-5} \left(\frac{H_*}{\beta}\right)^2 \left(\frac{\kappa\alpha}{1+\alpha}\right)^2 \left(\frac{100}{g_*}\right)^{\frac{1}{3}} \left(\frac{0.11 v_w^3}{0.42 + v_w^2}\right) S_{\text{env}}(f)$$

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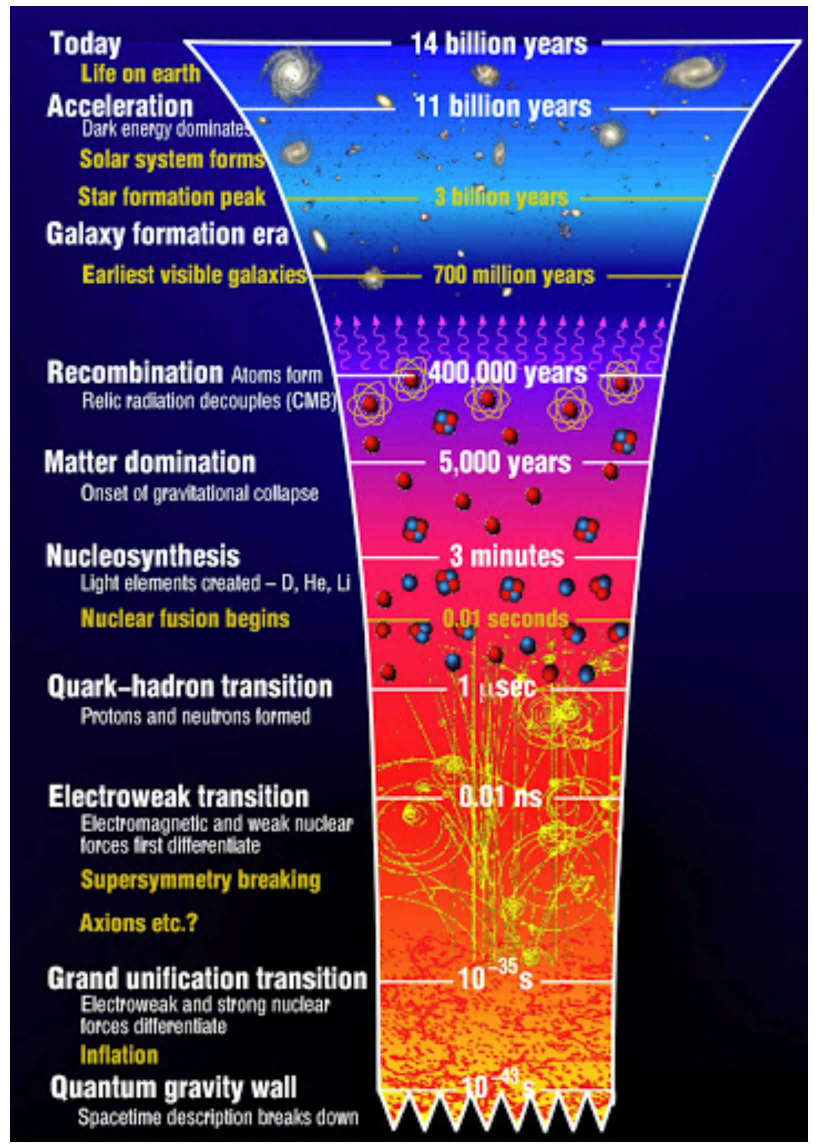
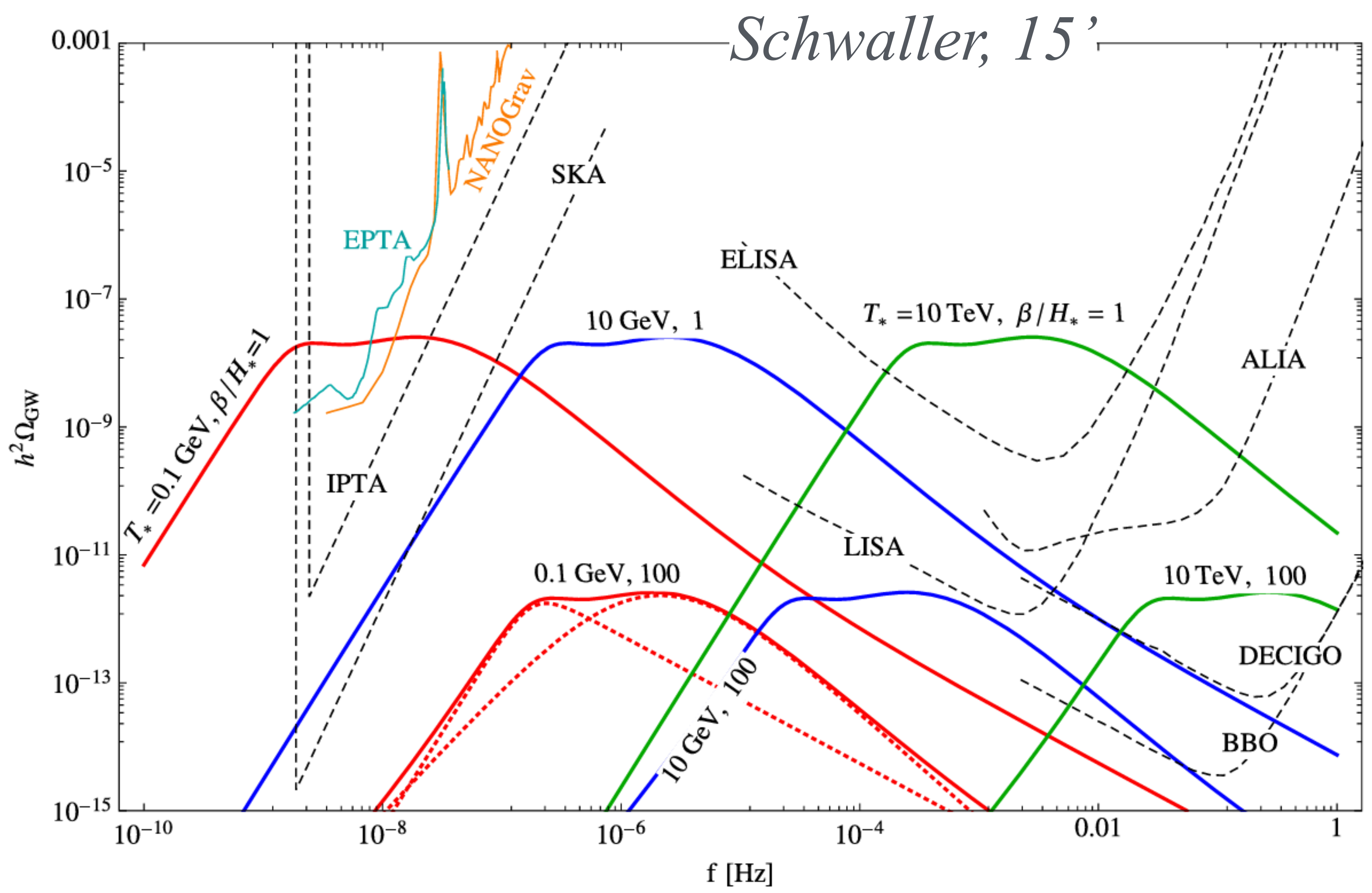
Phase Transition and dark sectors

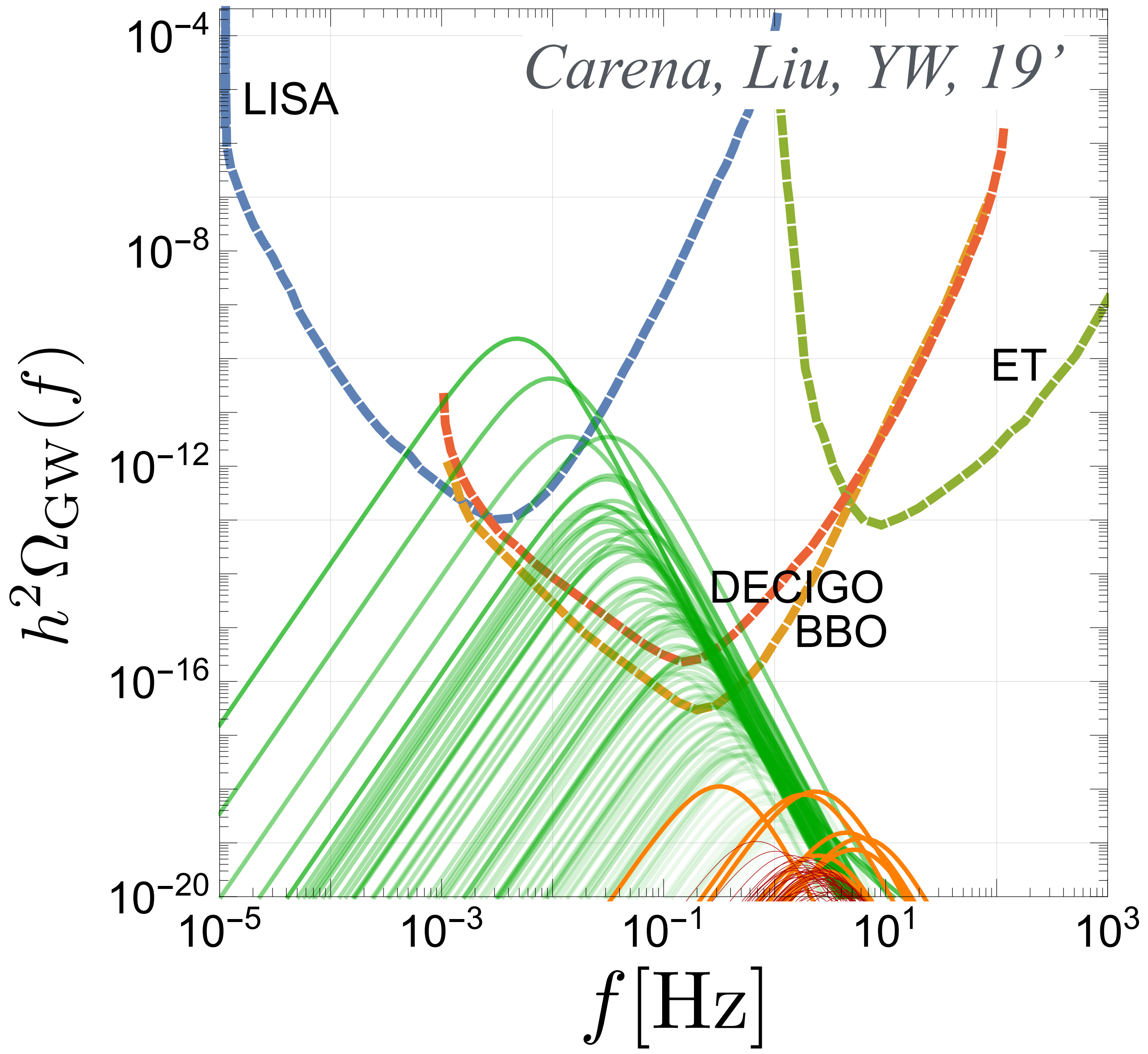
$$f_{\rm sw} = 1.9 \times 10^{-2}\,{\rm mHz}\,\frac{1}{v_w}\left(\frac{\beta}{H_*}\right)\left(\frac{T_*}{100\,{\rm GeV}}\right)\left(\frac{g_*}{100}\right)^{\frac{1}{6}}$$



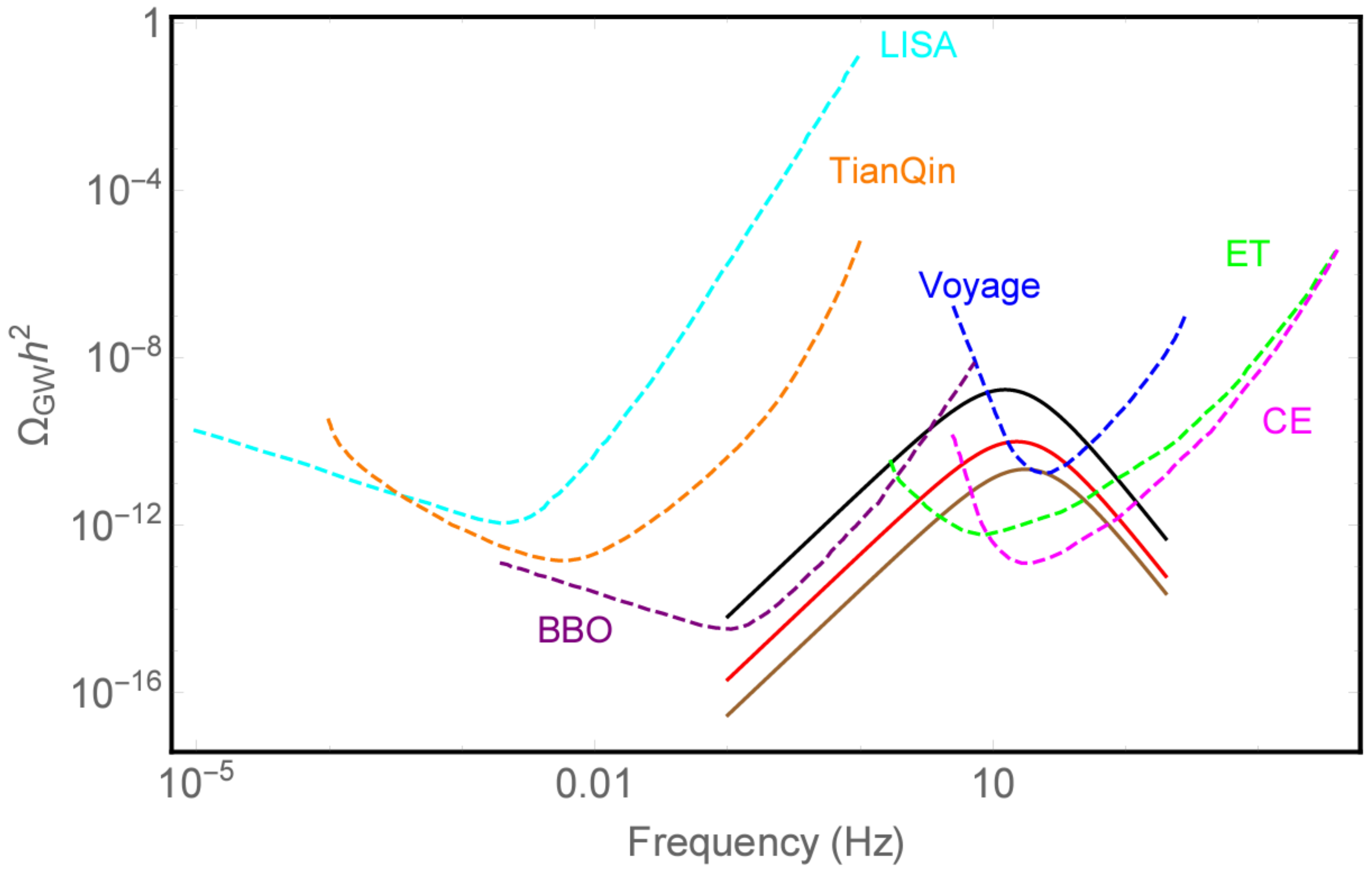
Phase Transition Scales →



Composite dark sector phase transitions



Electroweak phase transitions



Pati-Salam phase transitions

← *GW peak frequency*

Why gravitational wave for dark sectors?

Rich sources of gravitational waves from dark sectors

Phase Transition and dark sectors

- Many possibilities for a dark sector through Higgs or gauge portals;
- Playground for model building: rich DM and GW phenomenology
  Supercooling phase transition, symmetry non-restoration, inverse phase transitions
- Strong and complementary connection to collider searches;
- Theoretical development: perturbativity control, bubble wall dynamics, ….

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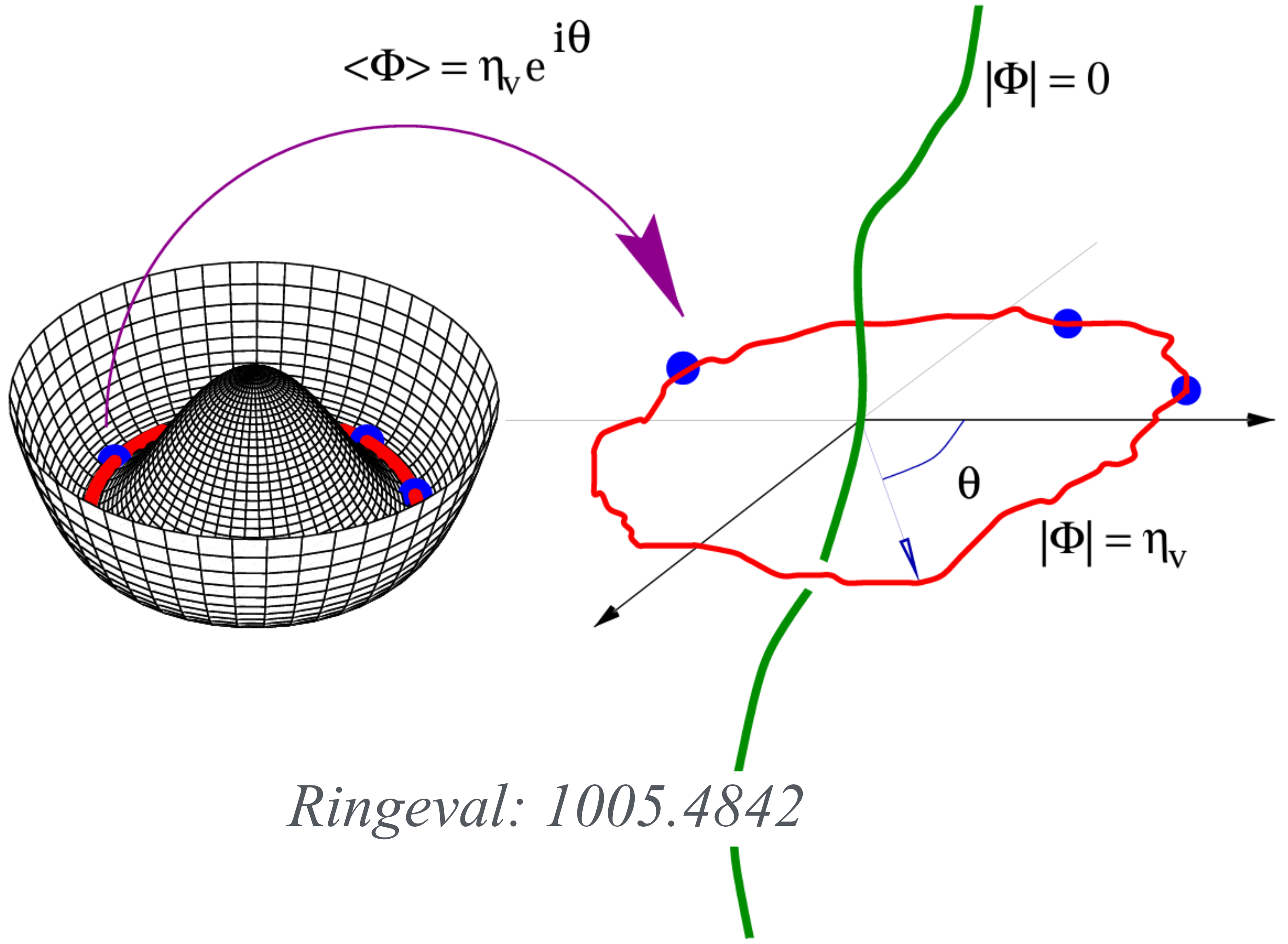
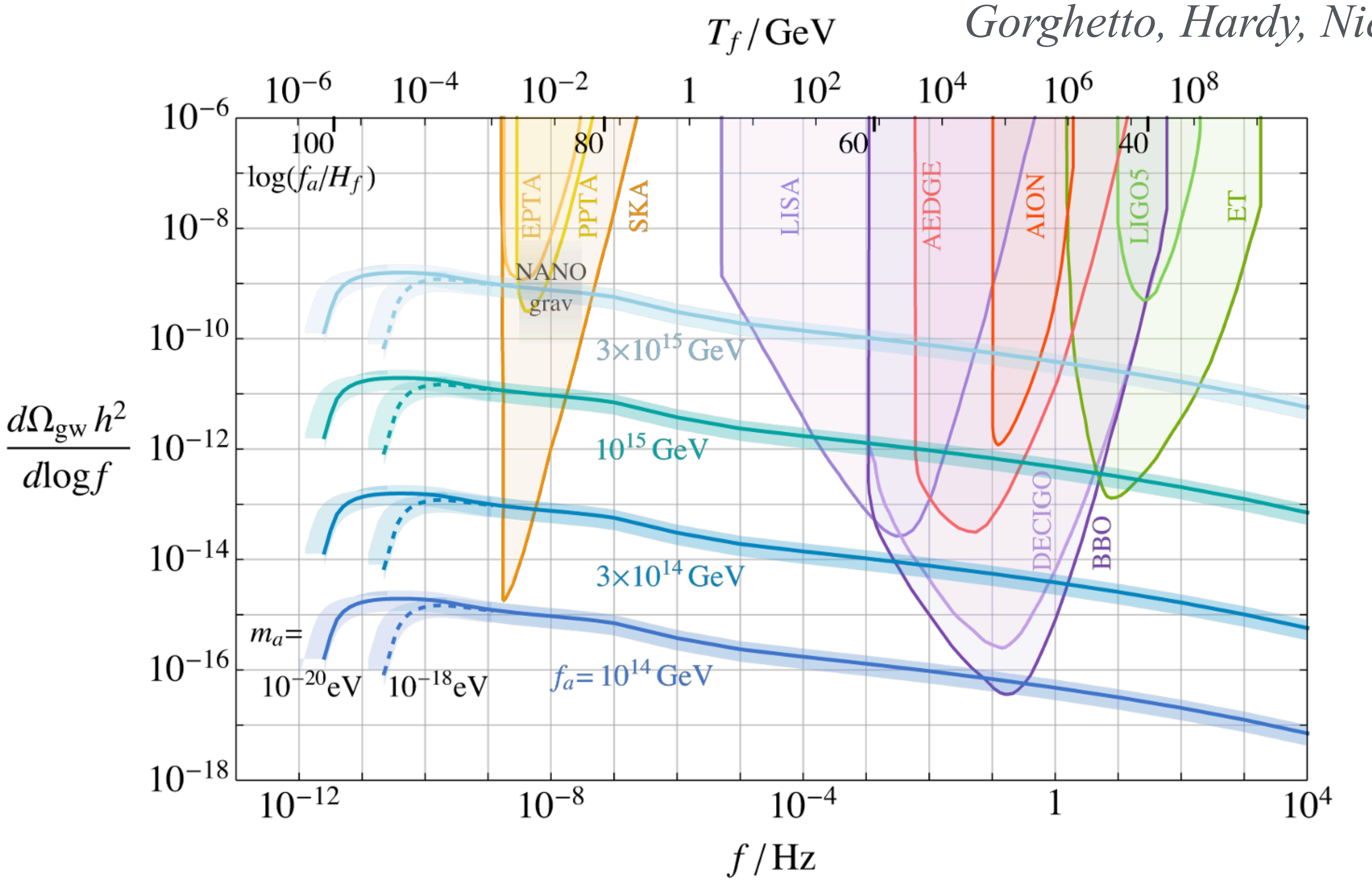
Topological Defects



Ringeval: 1005.4842

Cosmic string: topological defects after U(1) breaking

Gorghetto, Hardy, Nicolaescu, 21'



Axion strings and its GW power spectrum

And many other possible sources:

Exotic stars, captured DM, non-perturbative effects…

Why gravitational wave for dark sectors?

experiments

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Gravitational wave experiments are detectors with extreme sensitivities.

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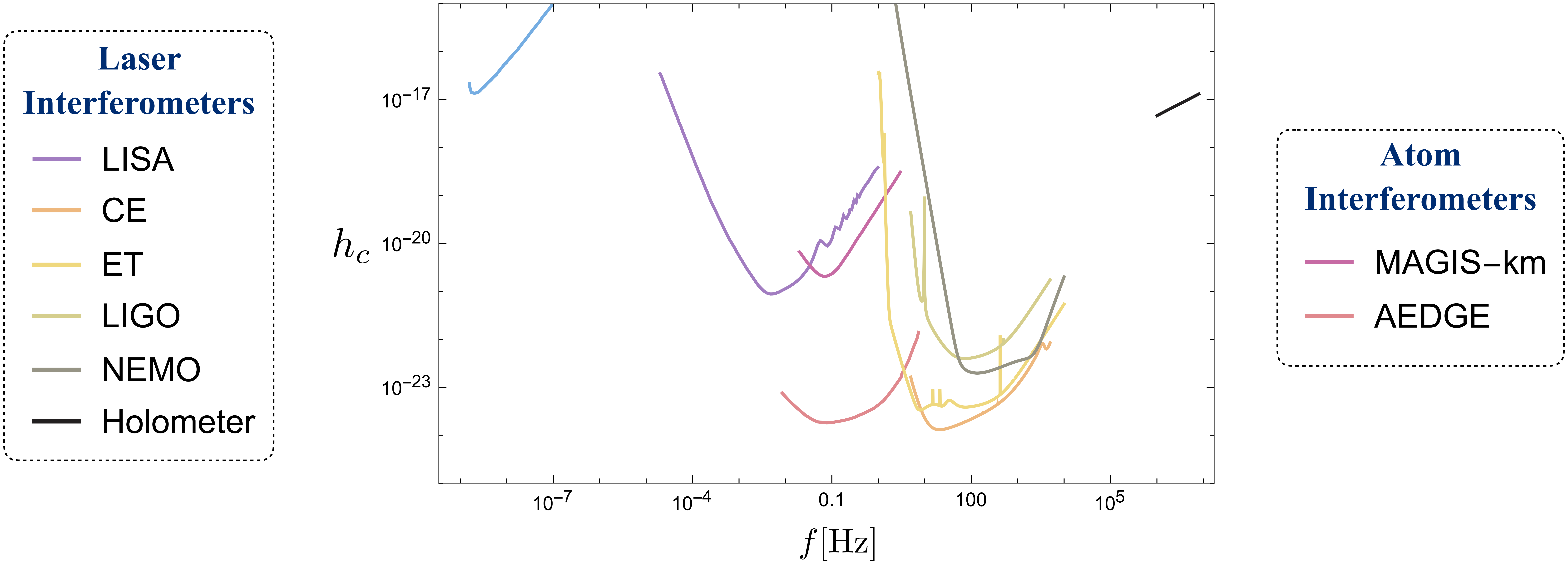


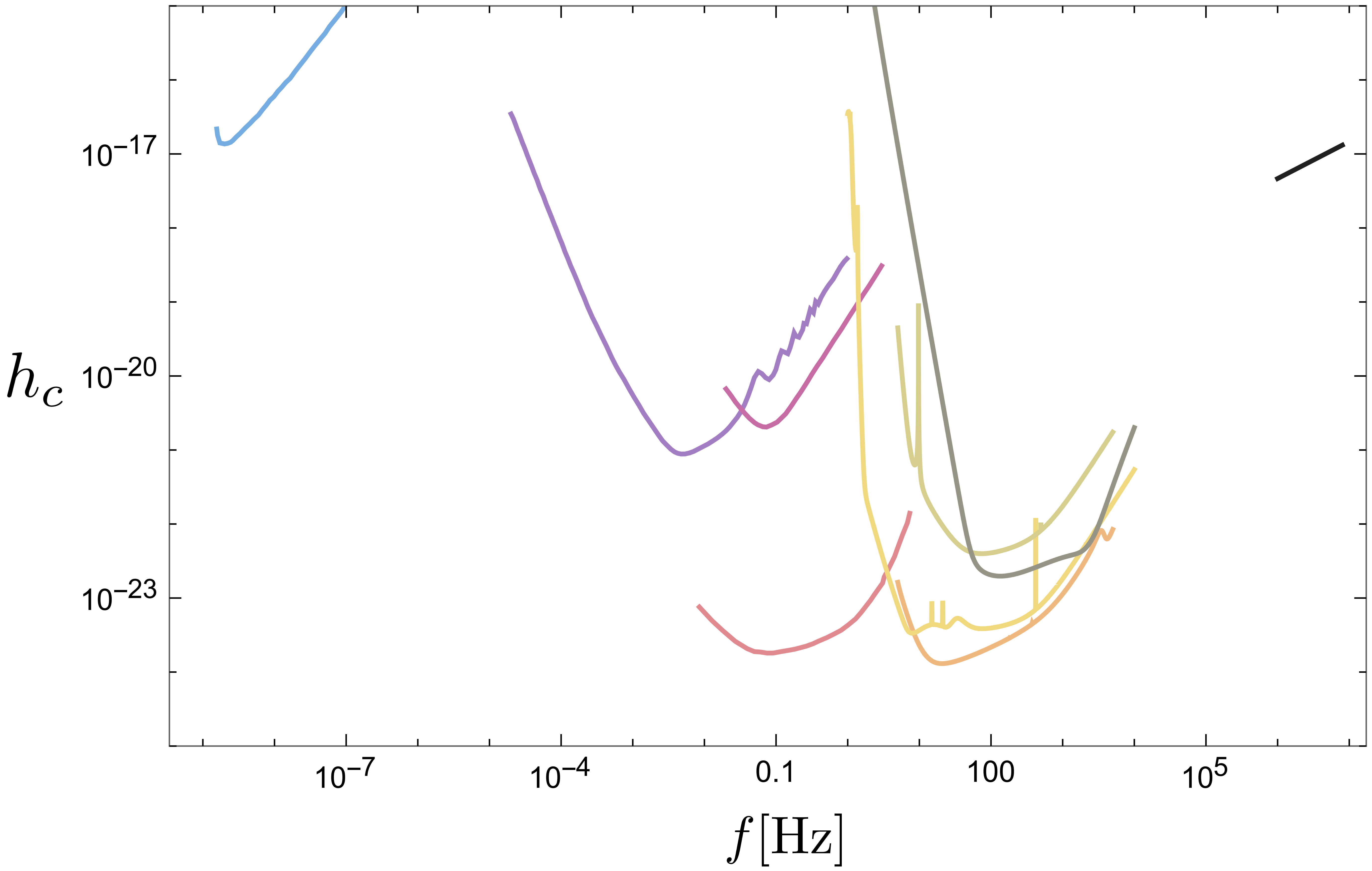
Why gravitational wave for dark sectors?

experiments

Gravitational wave experiments are detectors with extreme sensitivities.

Laser Interferometers

- LISA
- CE
- ET
- LIGO
- NEMO
- Holometer



Atom Interferometers

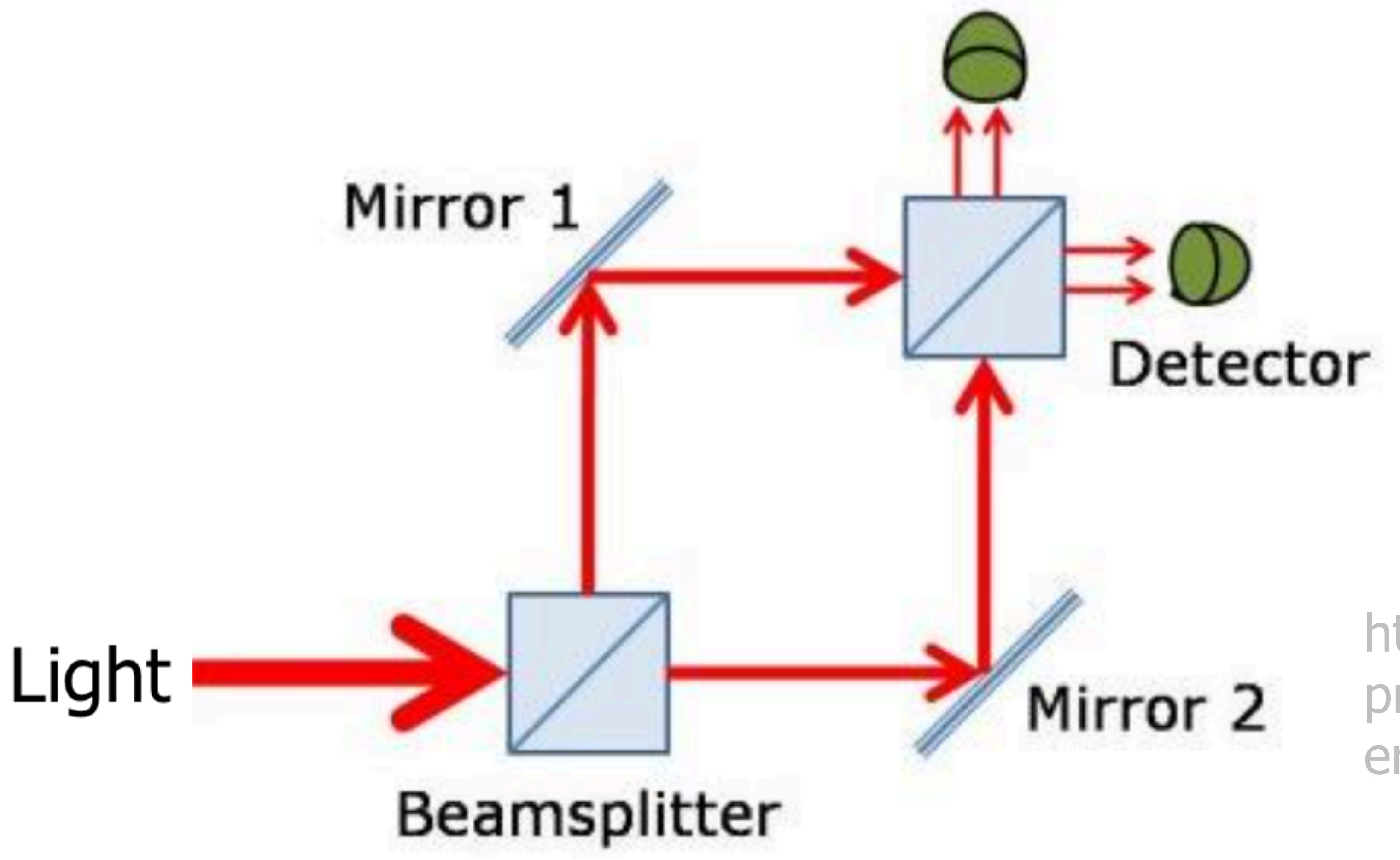
- MAGIS−km
- AEDGE

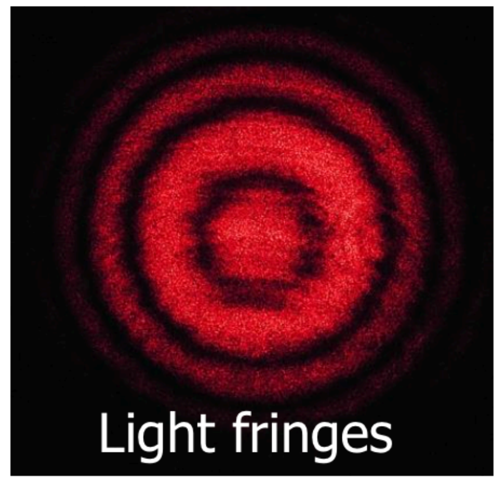
Direct Detection: dark matter can directly interact with the interferometers

Why gravitational wave experiments for dark sectors?

Gravitational wave experiments are detectors with extreme sensitivities.

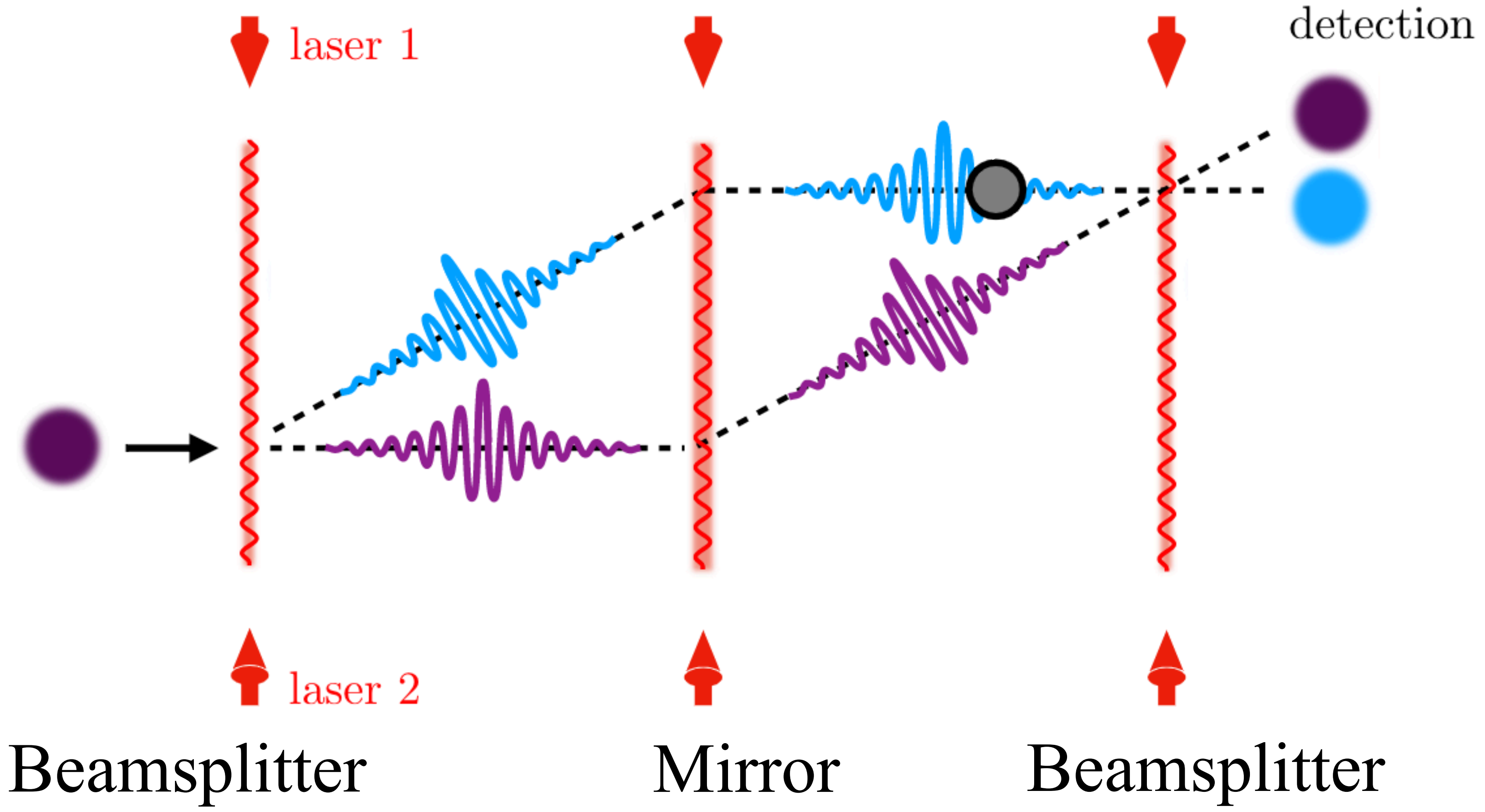
Laser Interferometers

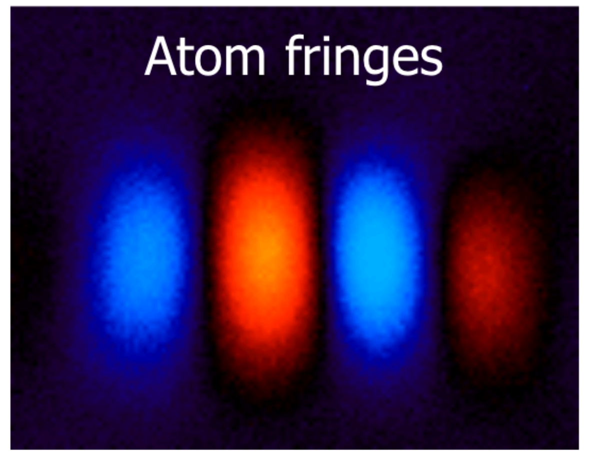




http://scienceblogs.com/principles/2013/10/22/quantum-erasure/

Atom Interferometers





http://www.cobolt.se/interferometry.html

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experiments

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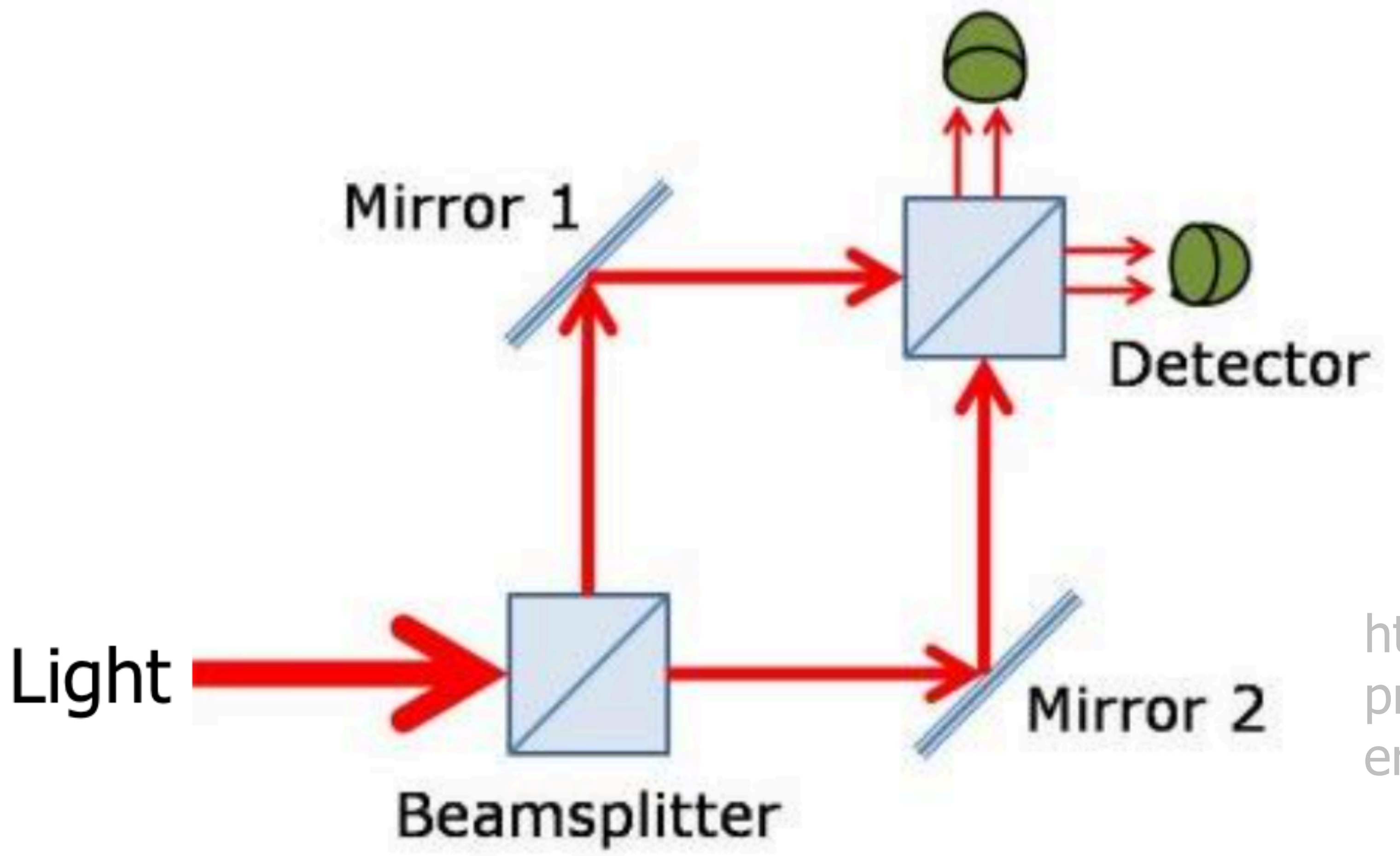
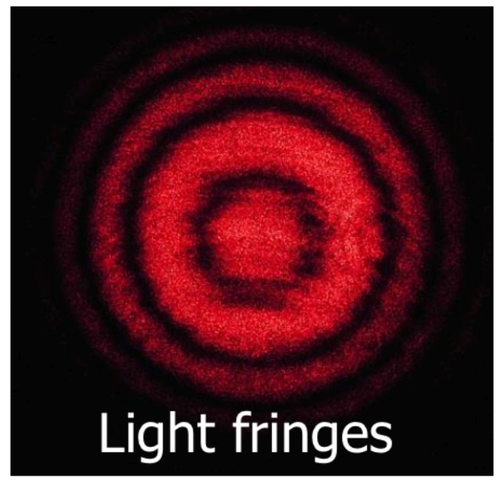
Laser Interferometers





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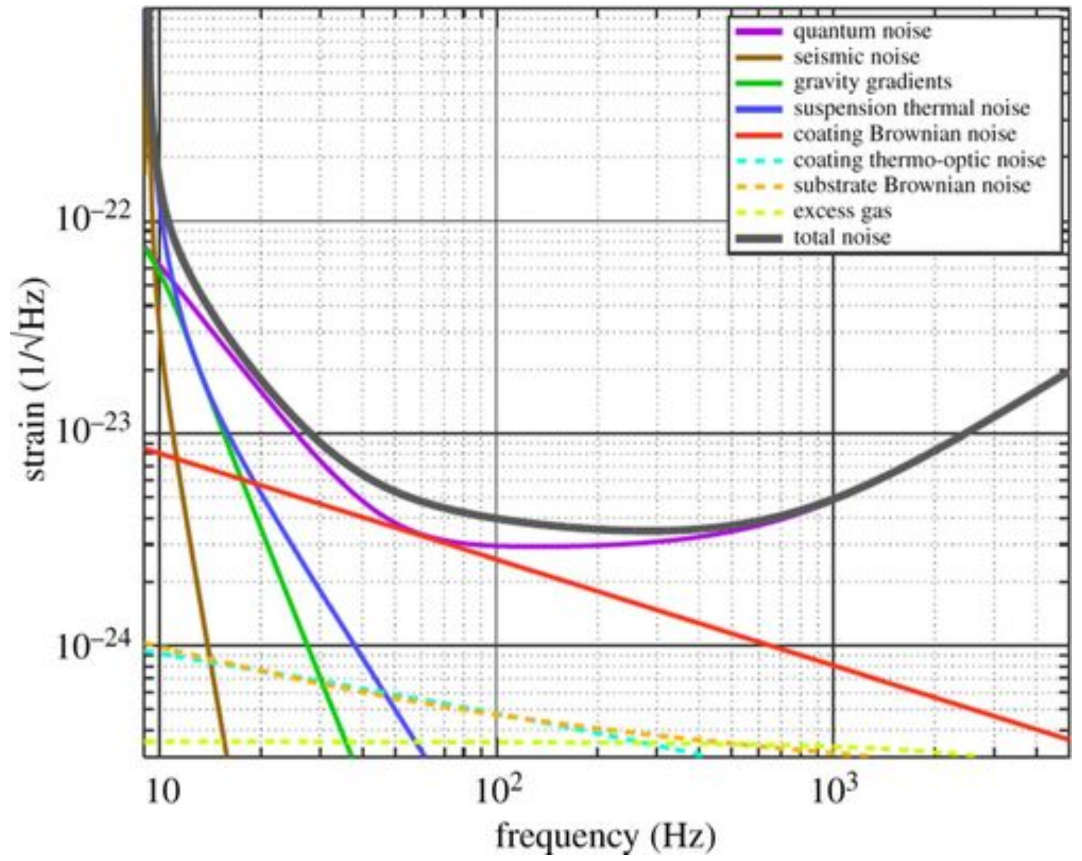
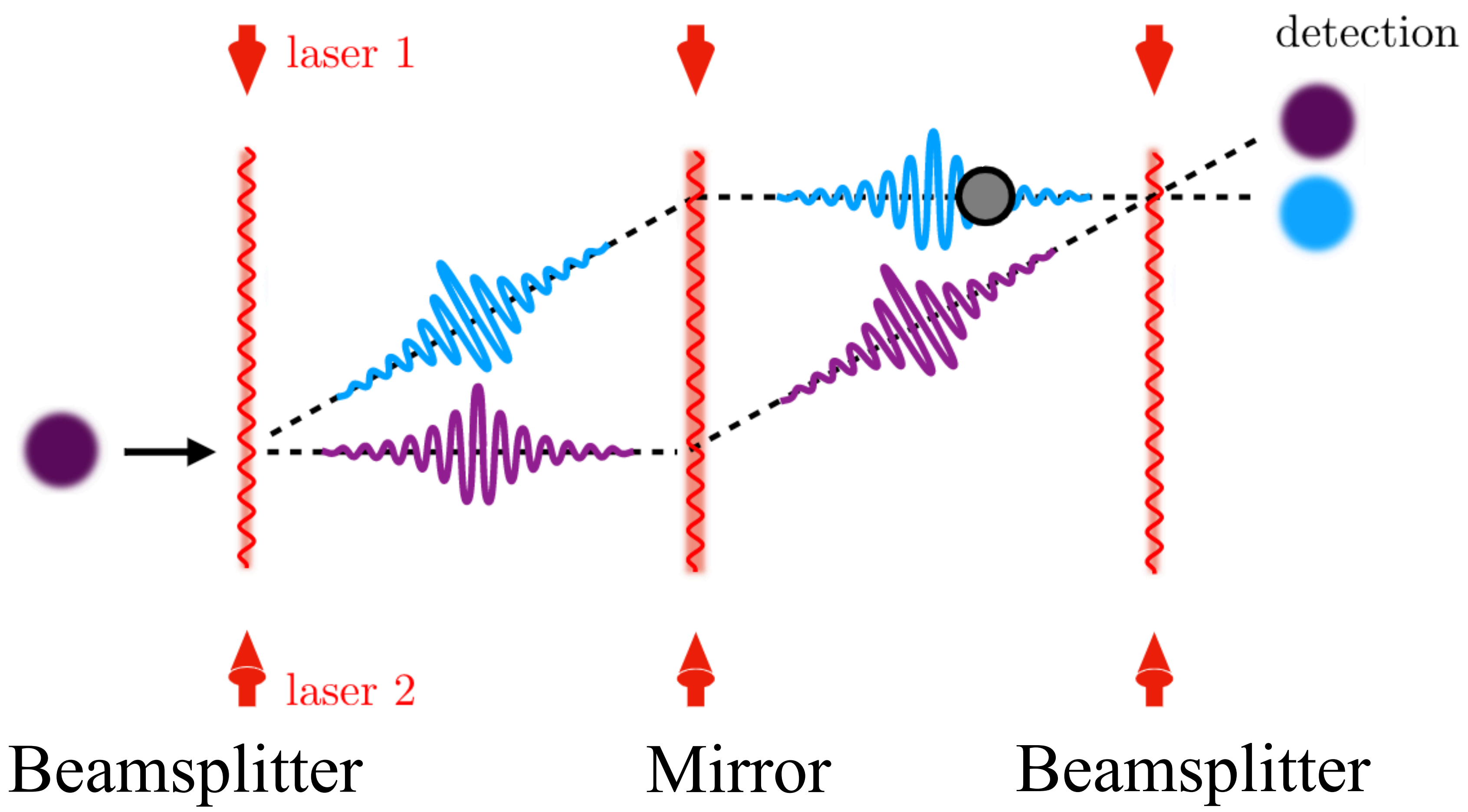
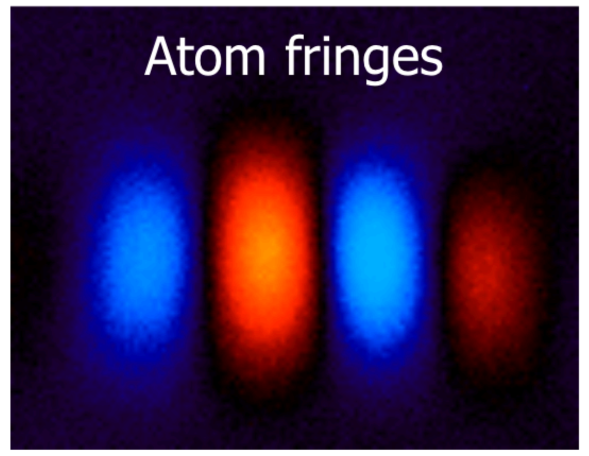


The LIGO Scientific Collaboration 2015

Atom Interferometers





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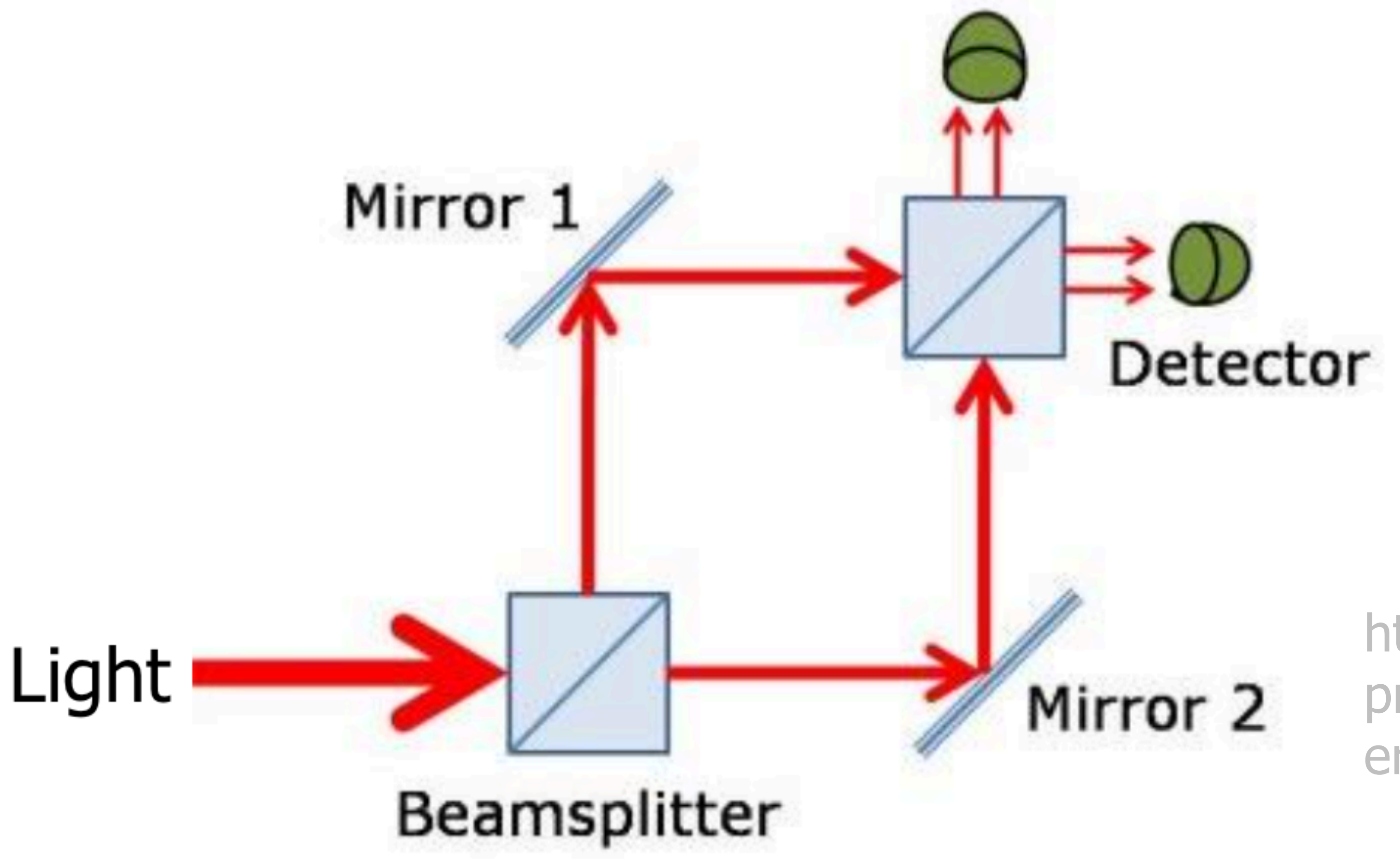

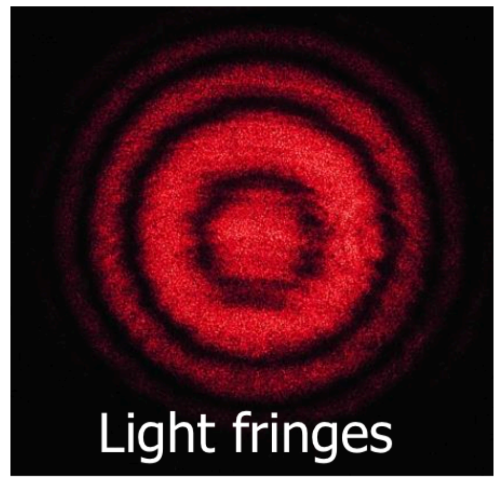

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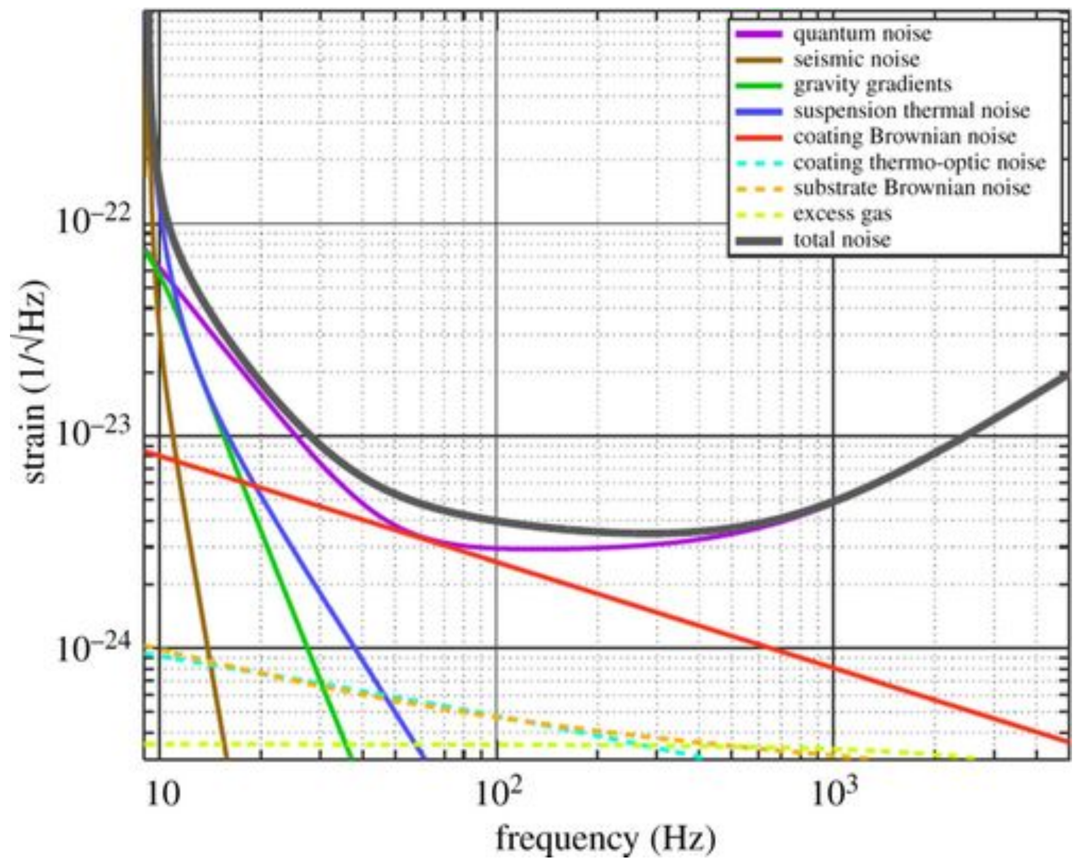

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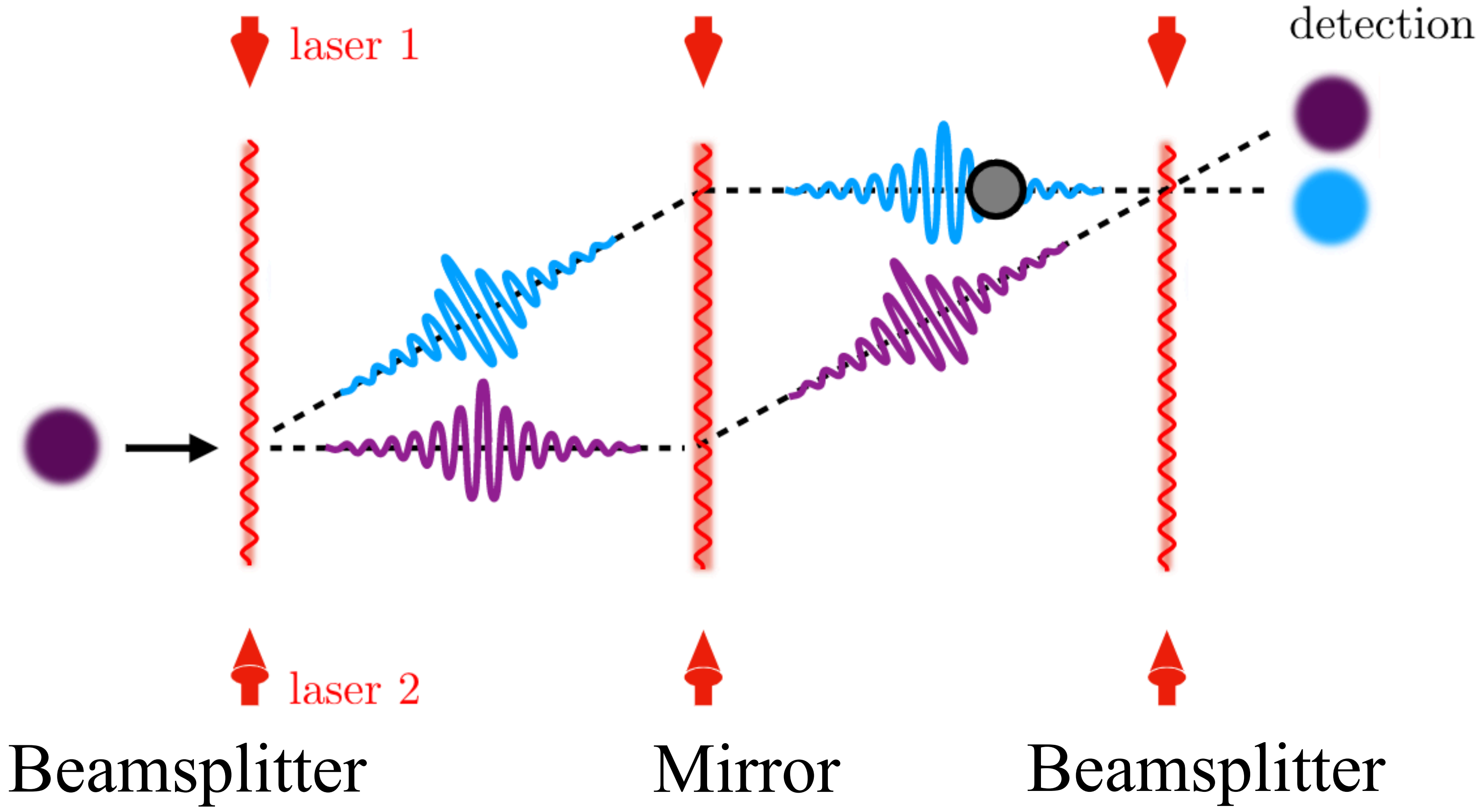

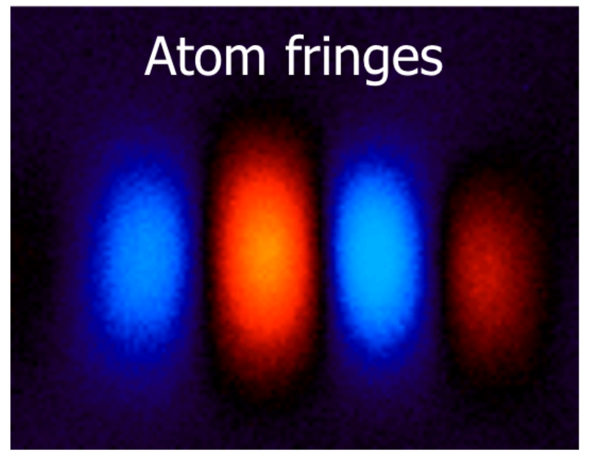

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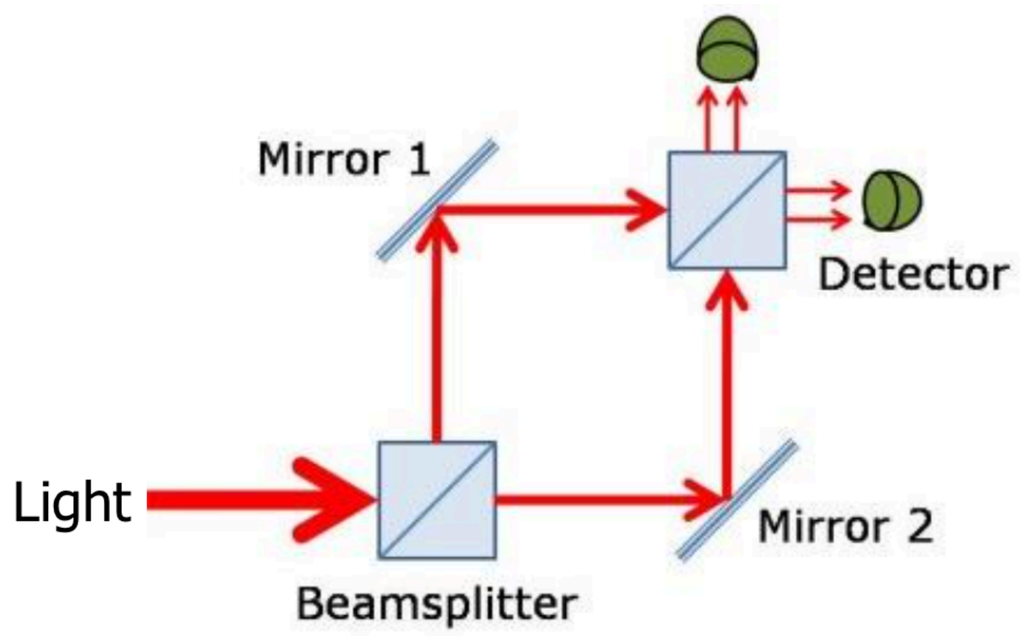
$$\sigma_\phi \equiv \frac{1\ \mathrm{rad}}{\sqrt{N_{\rm ind}}}$$

$$\sigma_\phi = \frac{1}{4} m_{\rm ind} \Delta x \, t_{\rm exp} a_{\rm min},$$

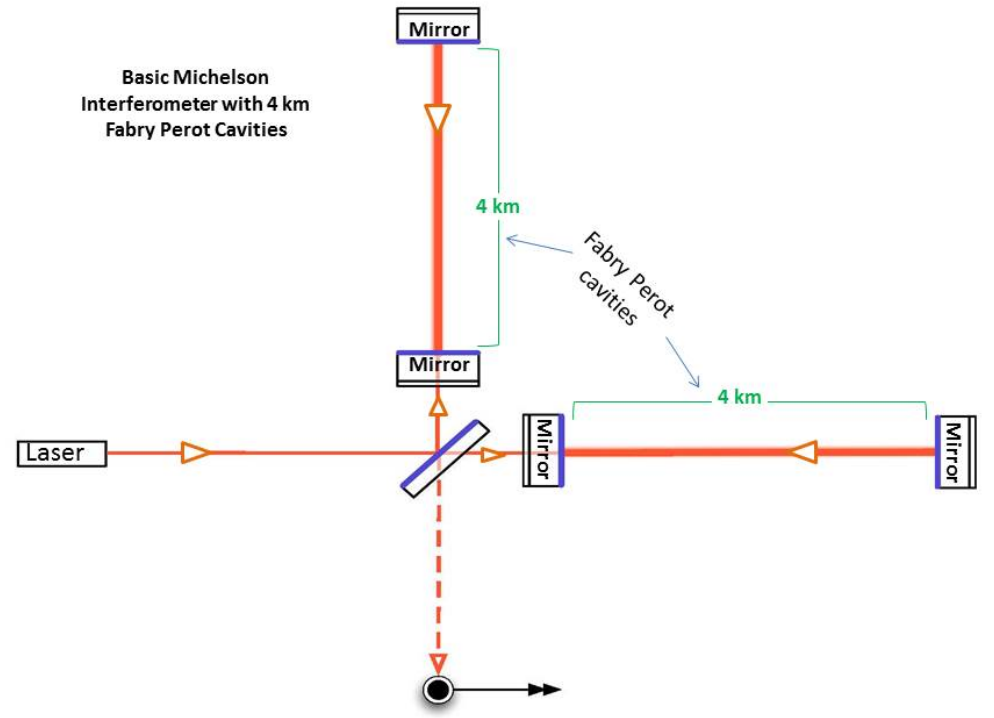


Why gravitational wave for dark sectors?

experiments

Ultralight DM

$$m_{\rm DM} \sim 4 \times 10^{-13} {\rm eV} \frac{f_{\rm GW}}{100\,{\rm Hz}}$$



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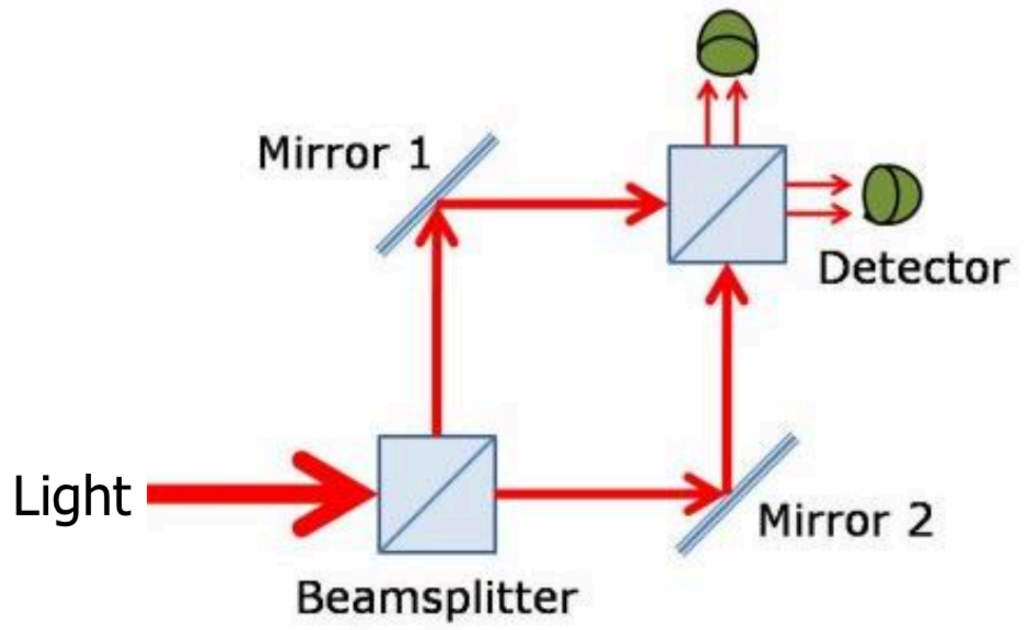

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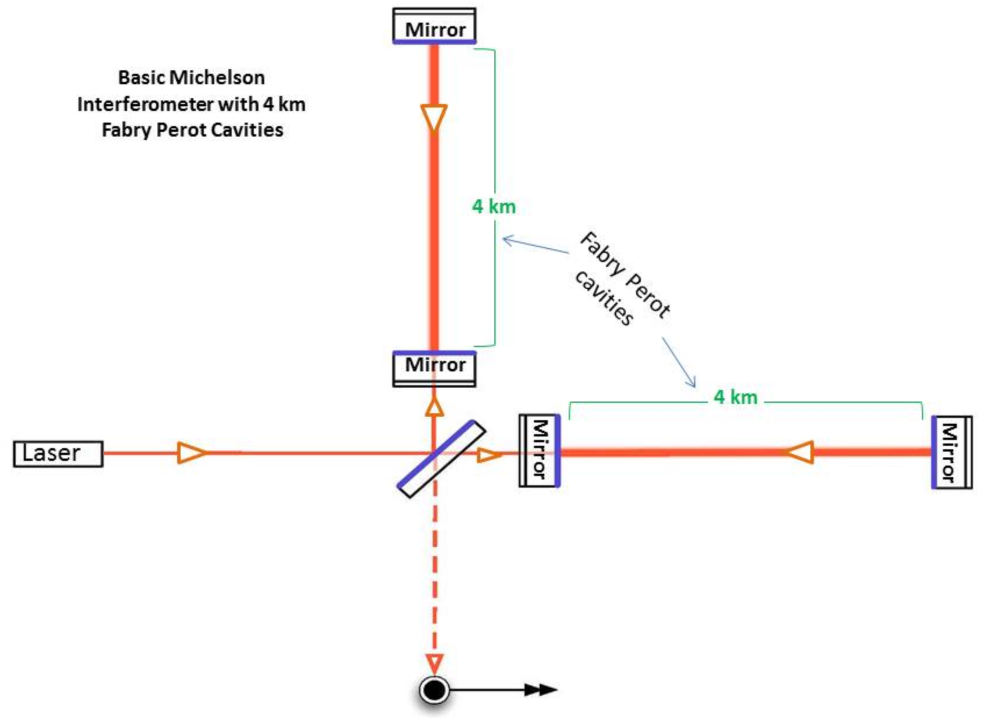
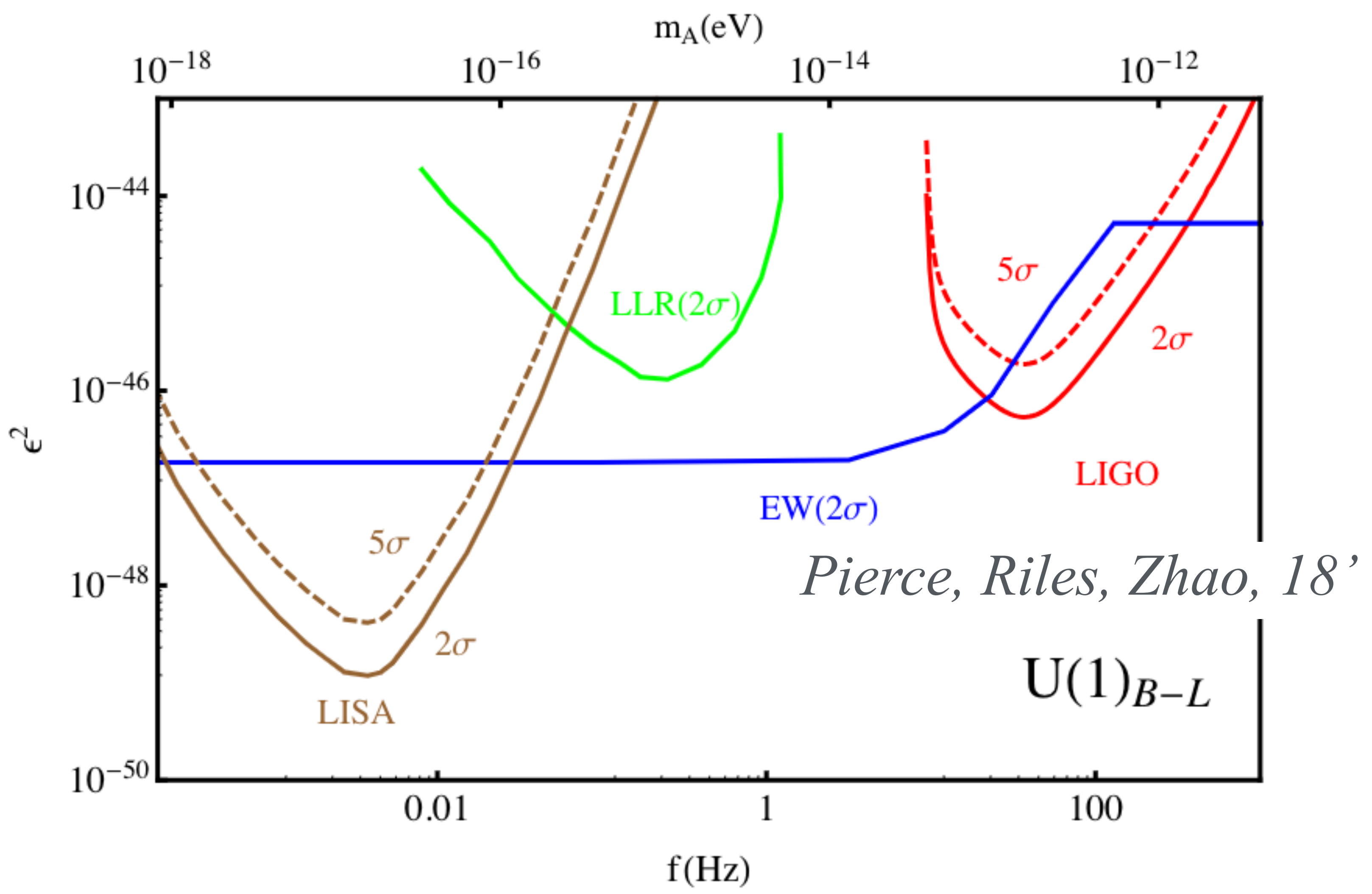
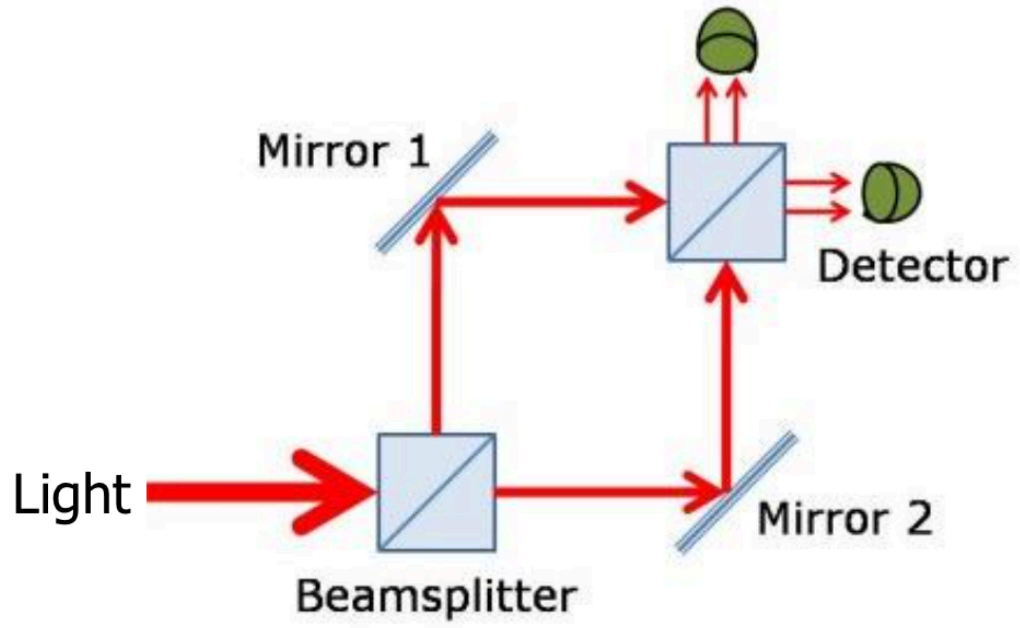




$U(1)_B$ and $U(1)_{B-L}$ dark photon DM
acts as a fifth force on mirrors.

Why gravitational wave for dark sectors?

experiments



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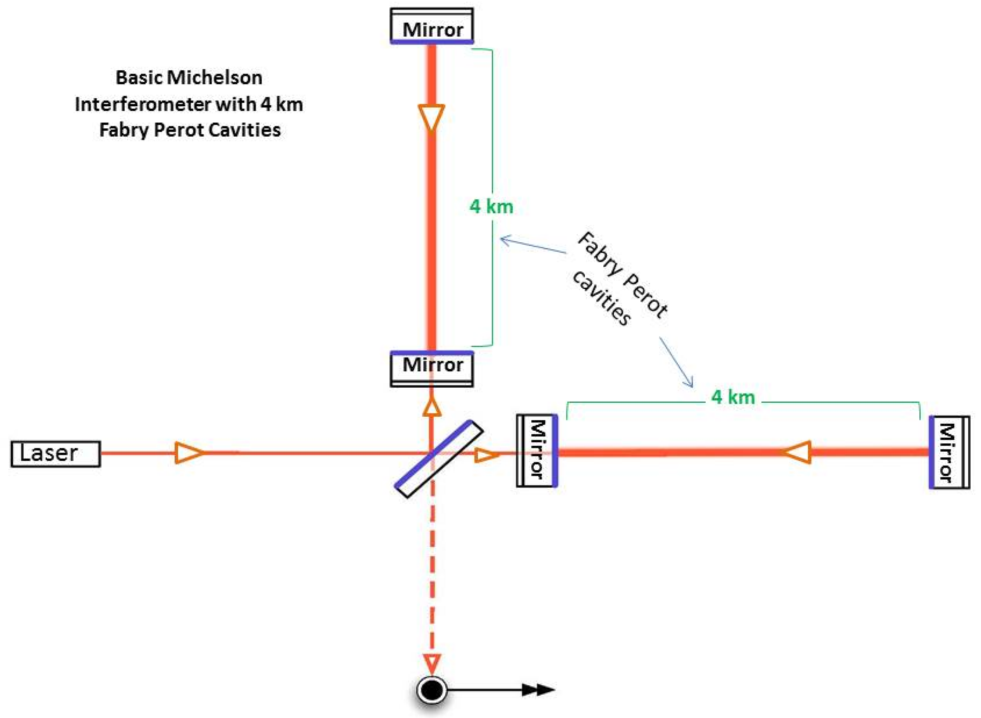

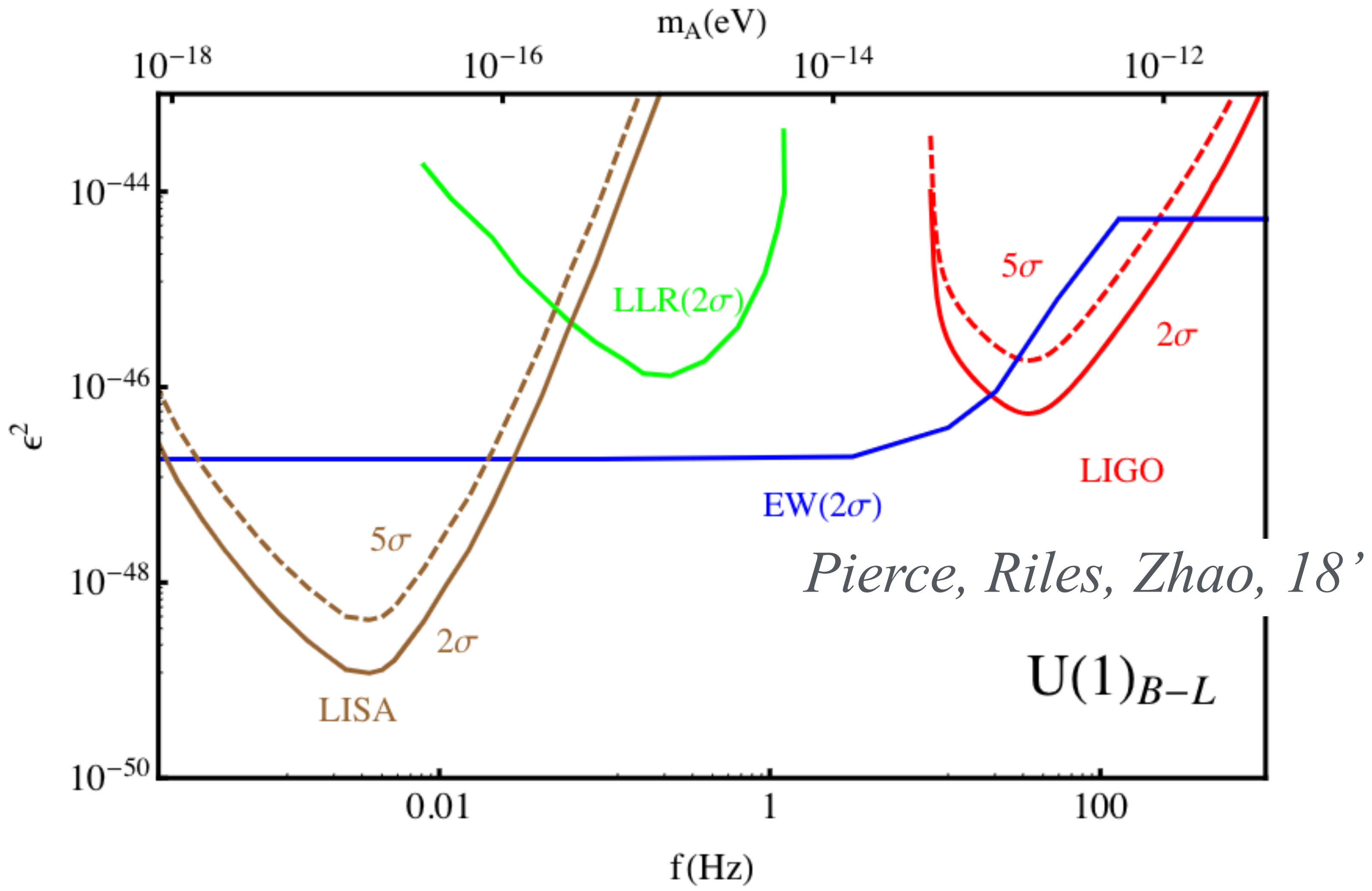

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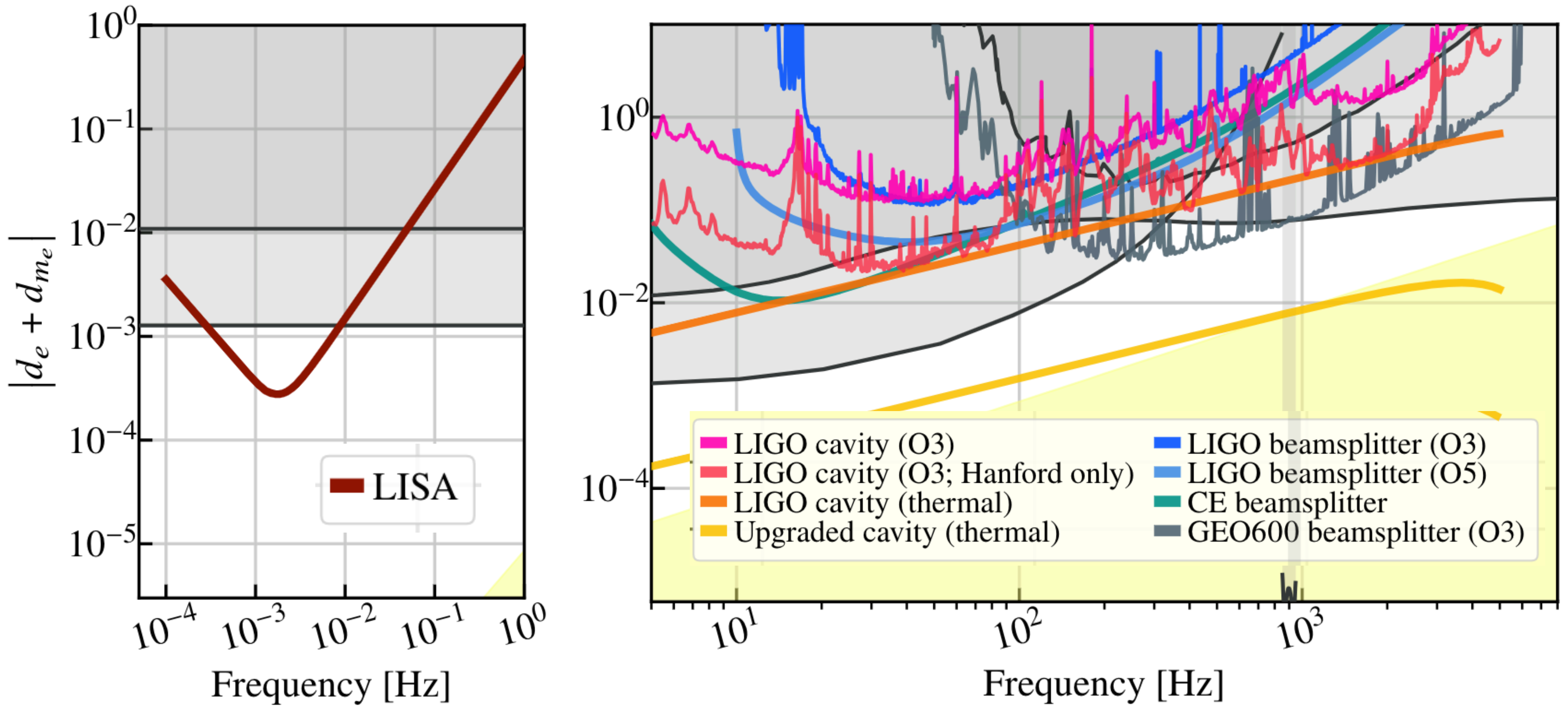


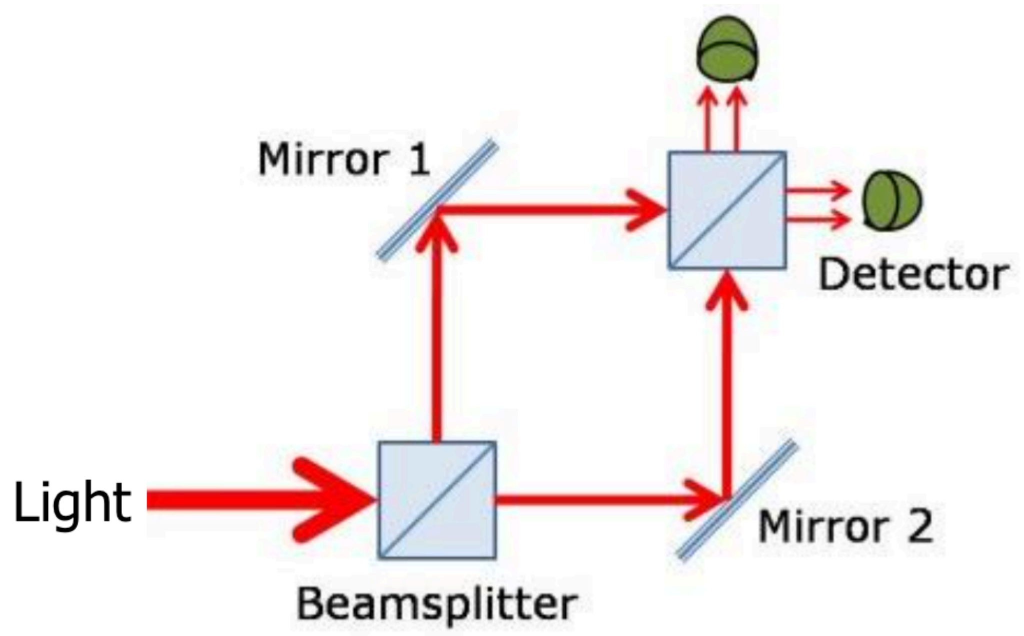
$$\frac{\Delta\alpha(t)}{\alpha} = A_e \cos(\Omega_{\rm DM} t)$$

$$\frac{\Delta m_e(t)}{m_e} = A_{m_e} \cos(\Omega_{\rm DM} t)$$

Stadnik, Flambaum '15
Morisaki1, Suyama '18
Hall, Aggarwal, '22 ...

Temporal variations on physical parameters (coupling to the photon or fermions)

Why gravitational wave *experiments* for dark sectors?



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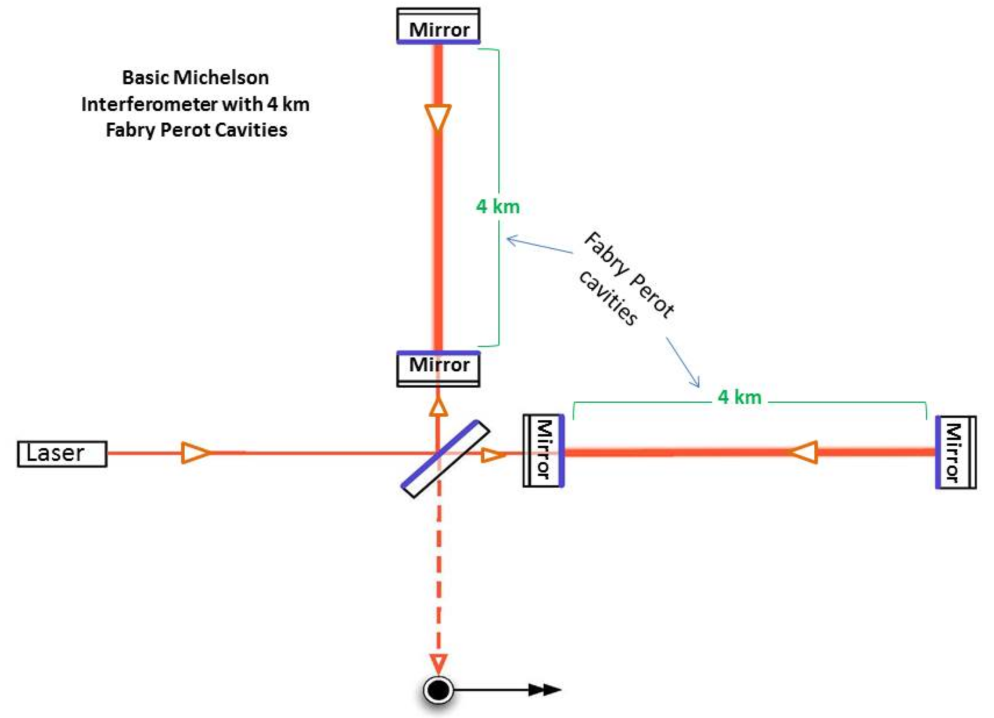
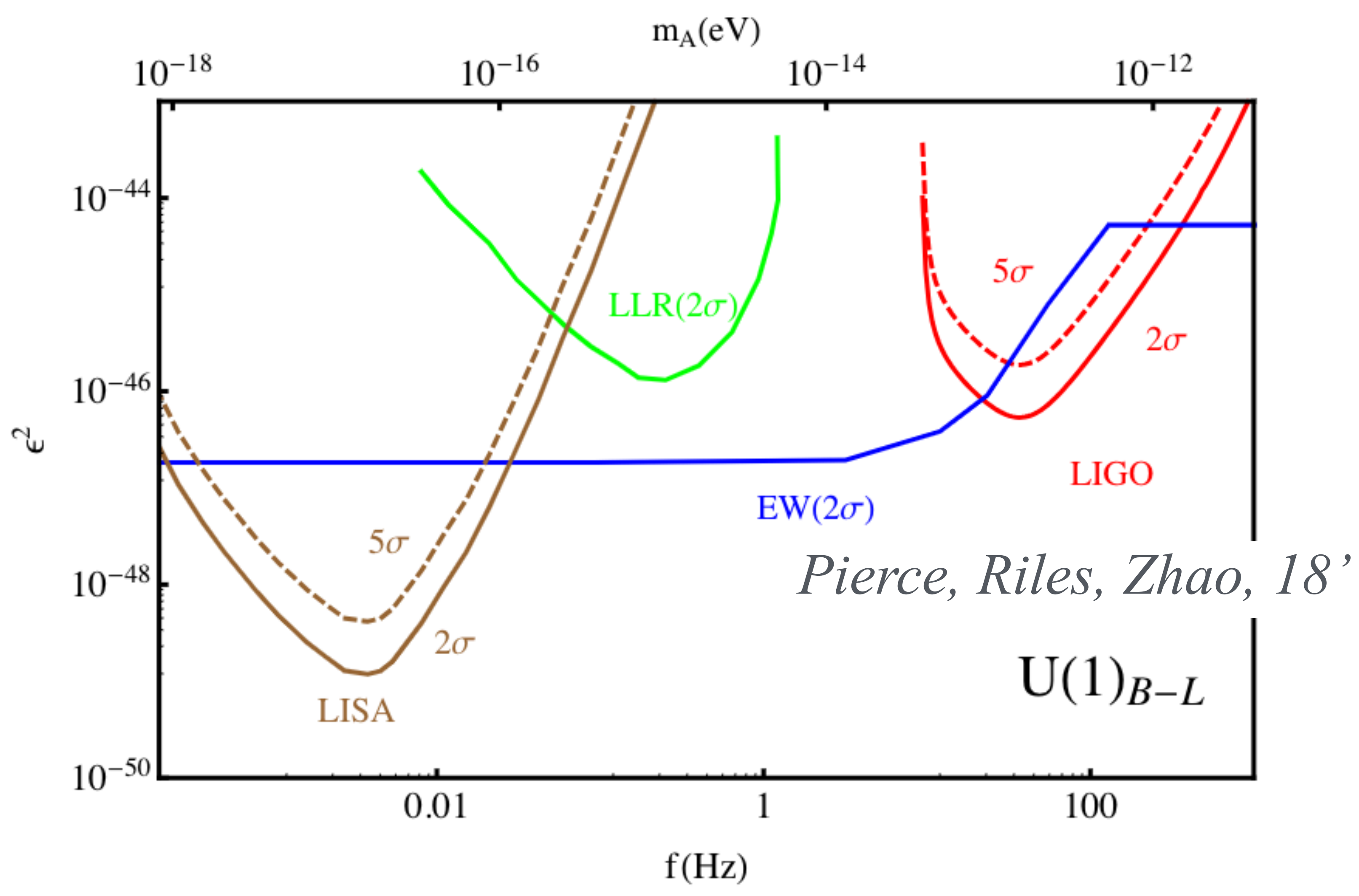


Nagano, Fujita, Michimura, Obata '19



Pierce, Riles, Zhao, 18'

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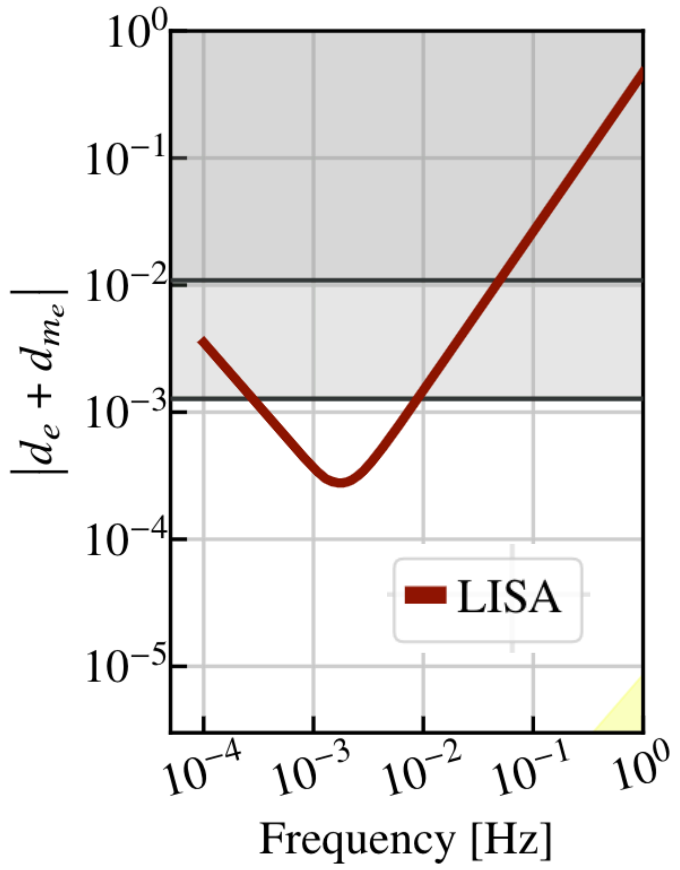

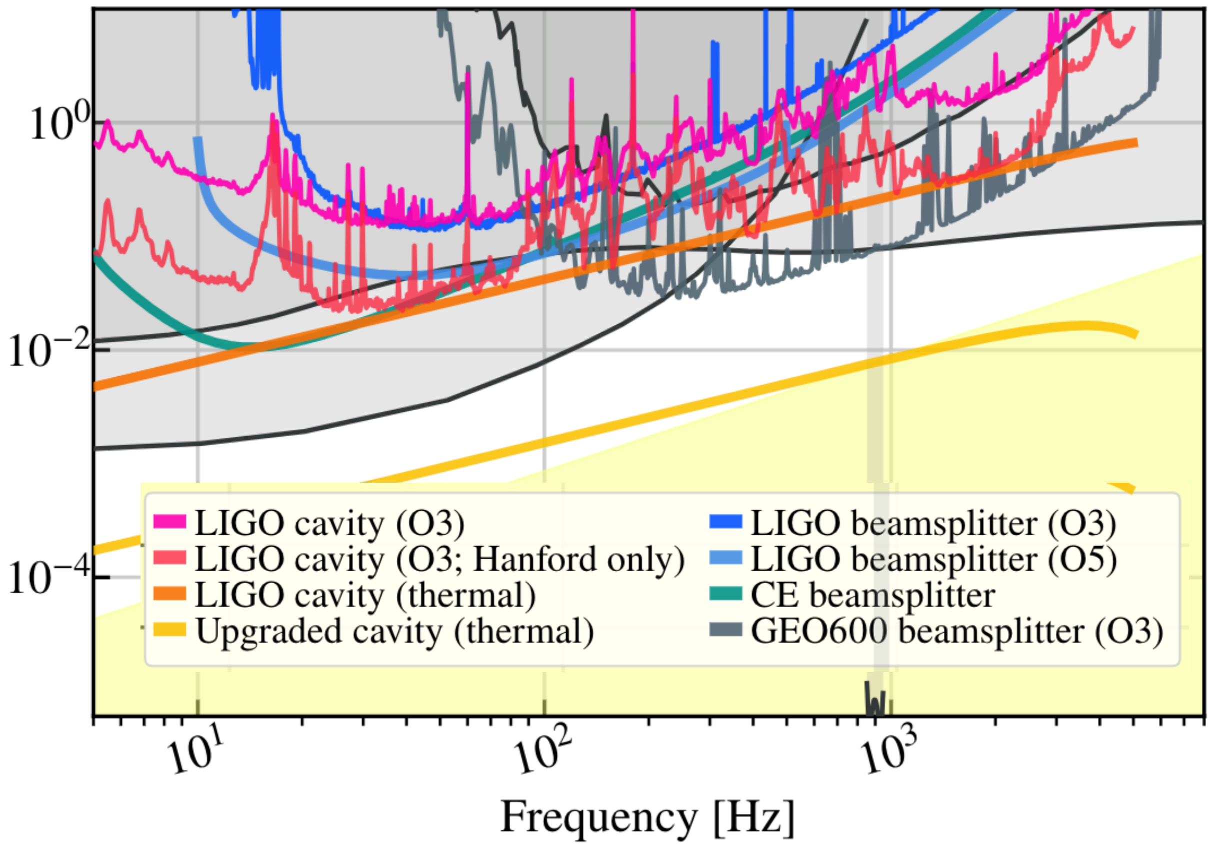

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Stadnik, Flambaum '15
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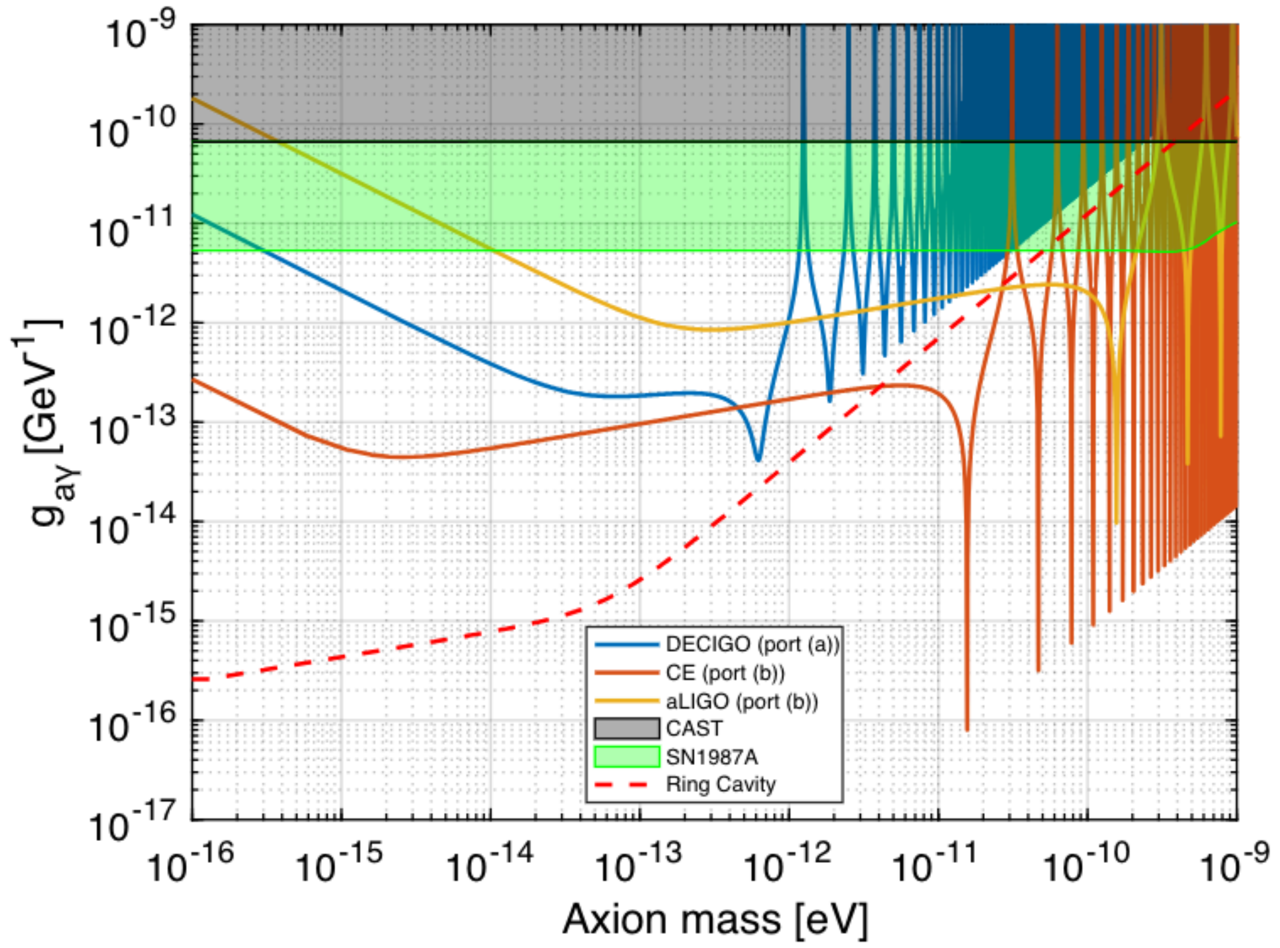

Axions can induce polarization change of photons circulating in FP cavities.

Why gravitational wave experiments for dark sectors?

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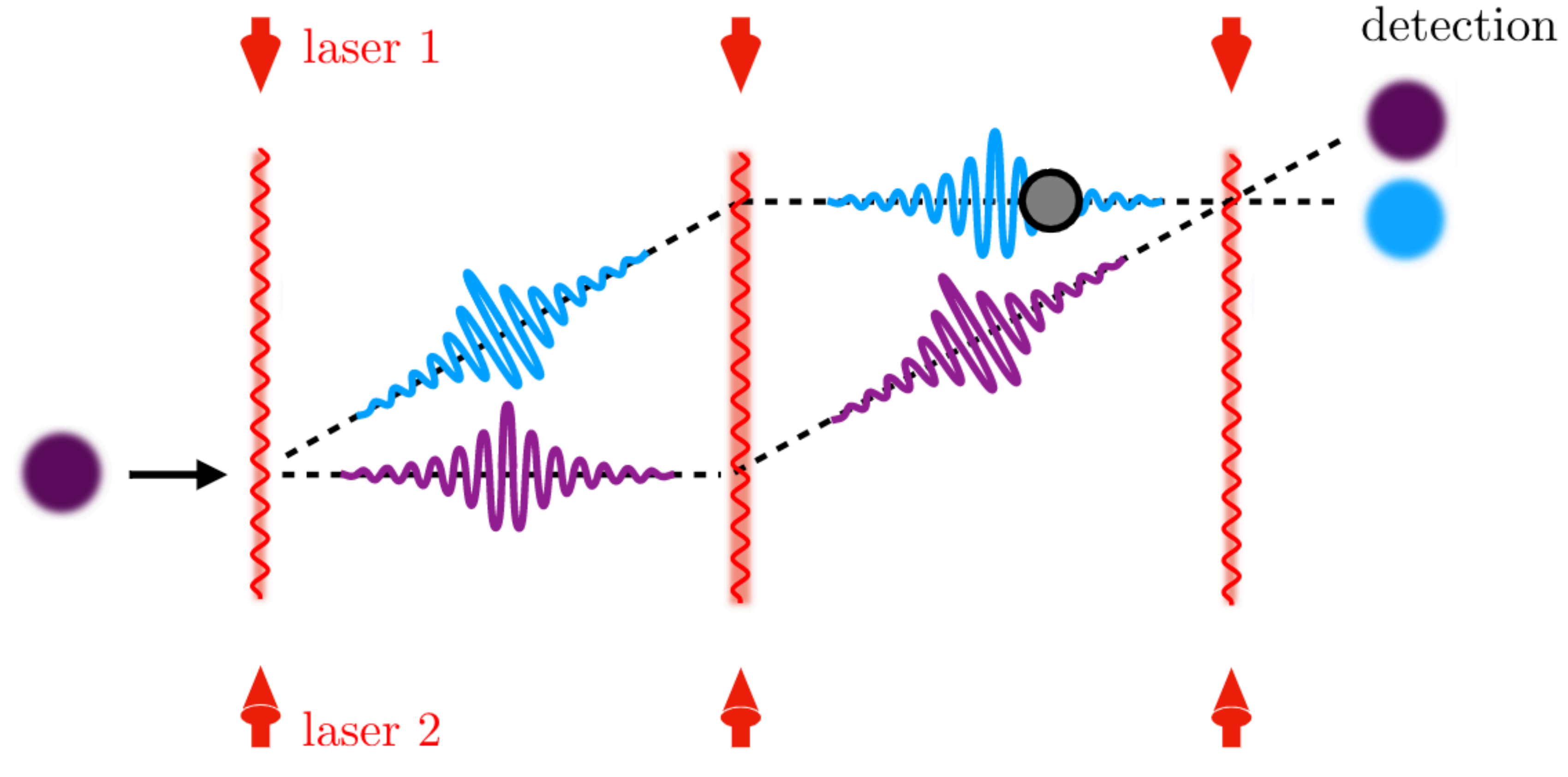
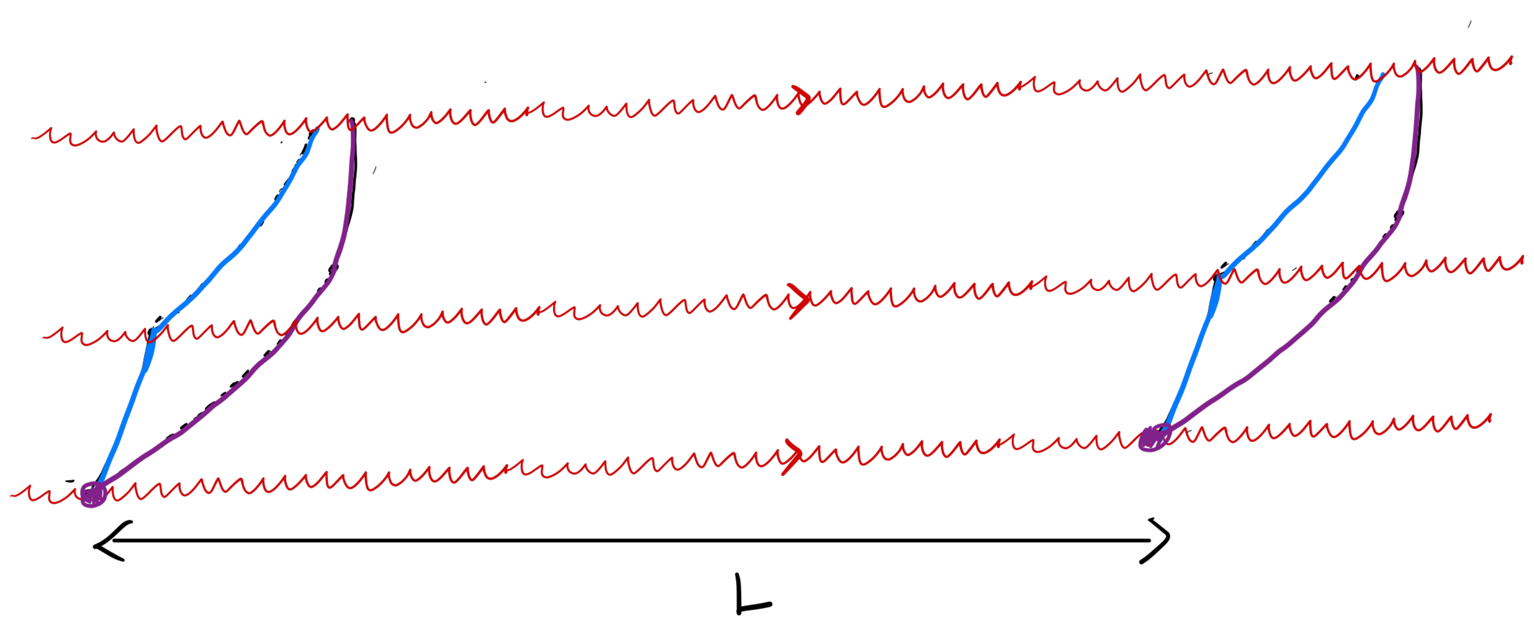
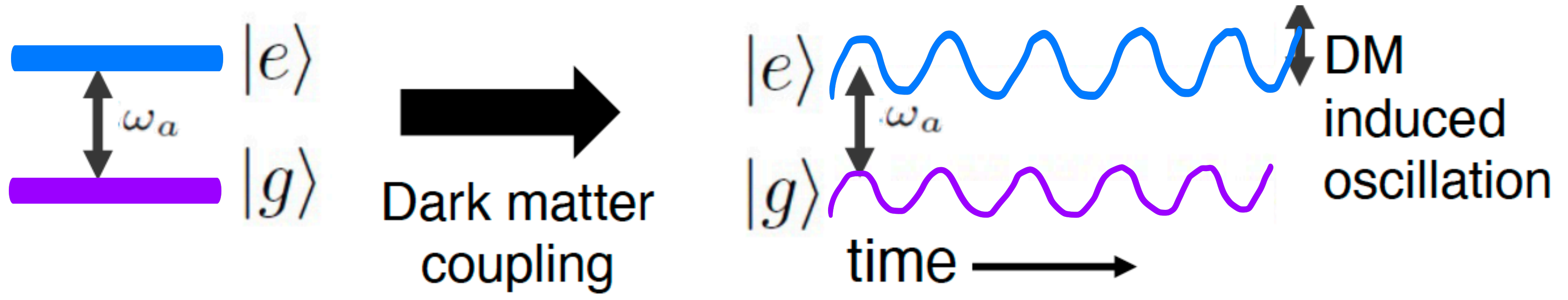


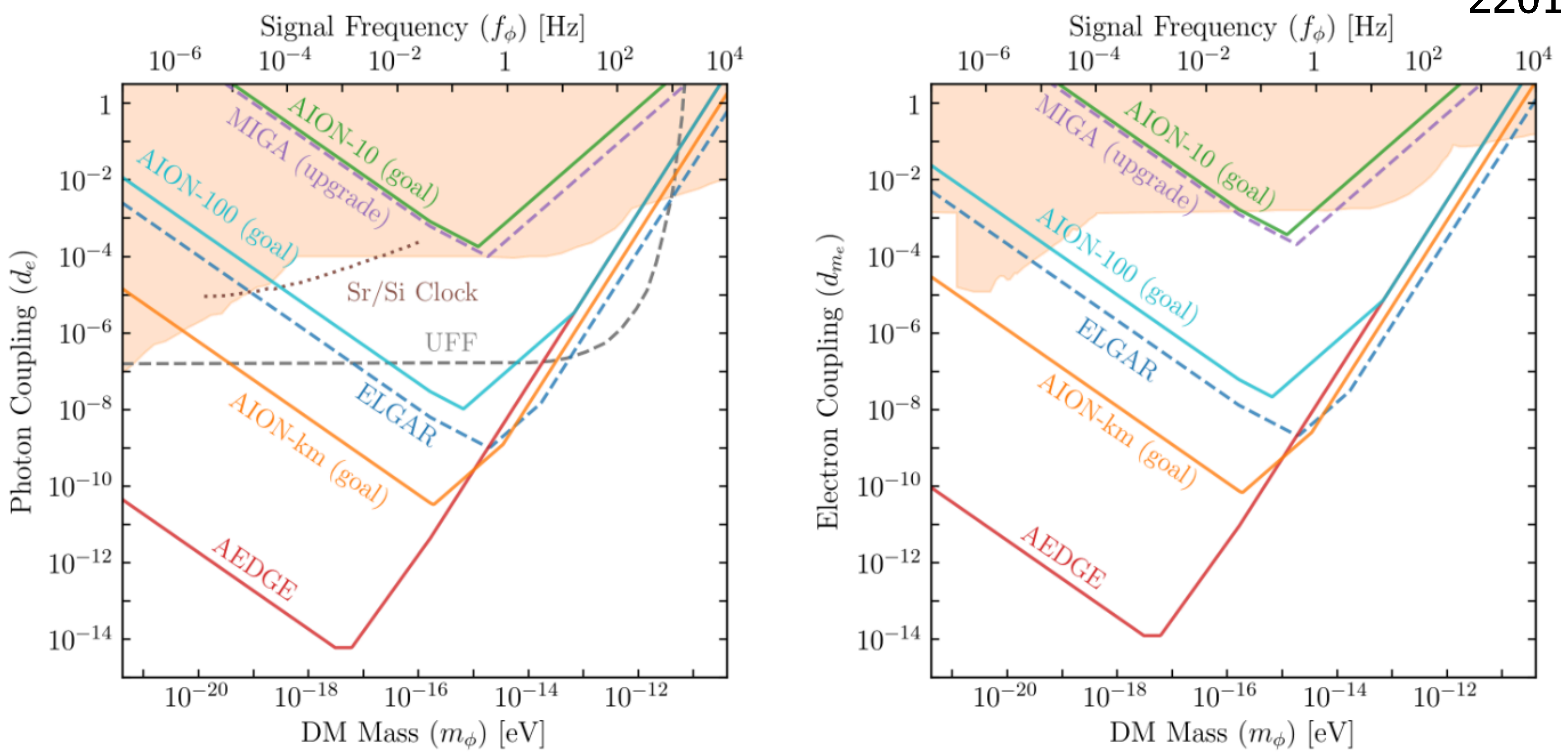


Long baseline experiment



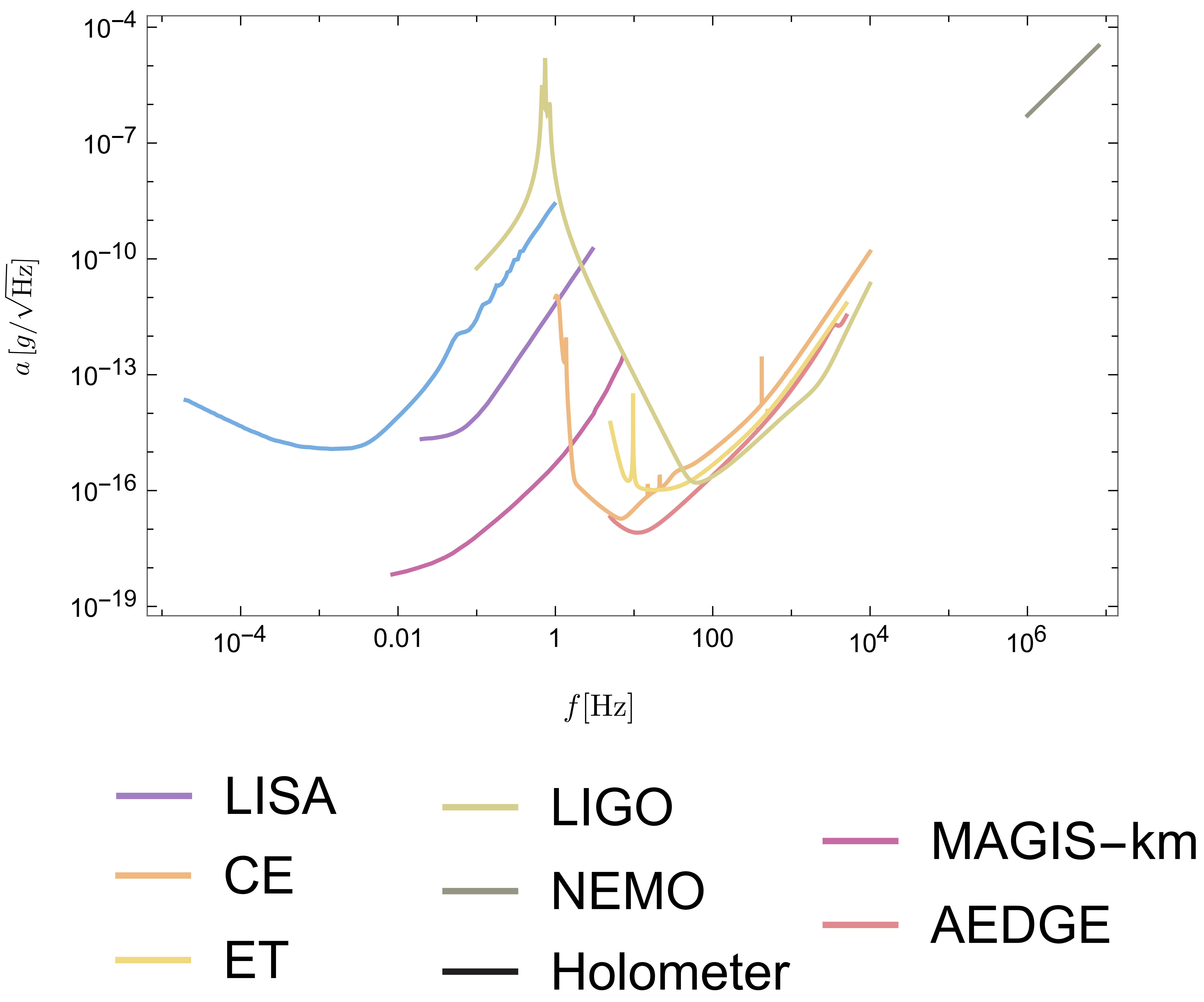
From Oliver Buchmueller's talk

Snowmass
2203.07250
2201.07789



Why gravitational wave *experiments* for dark sectors?

Accelerometers of ultra high sensitivity.



Why gravitational wave ~~for~~ experiments for dark sectors?

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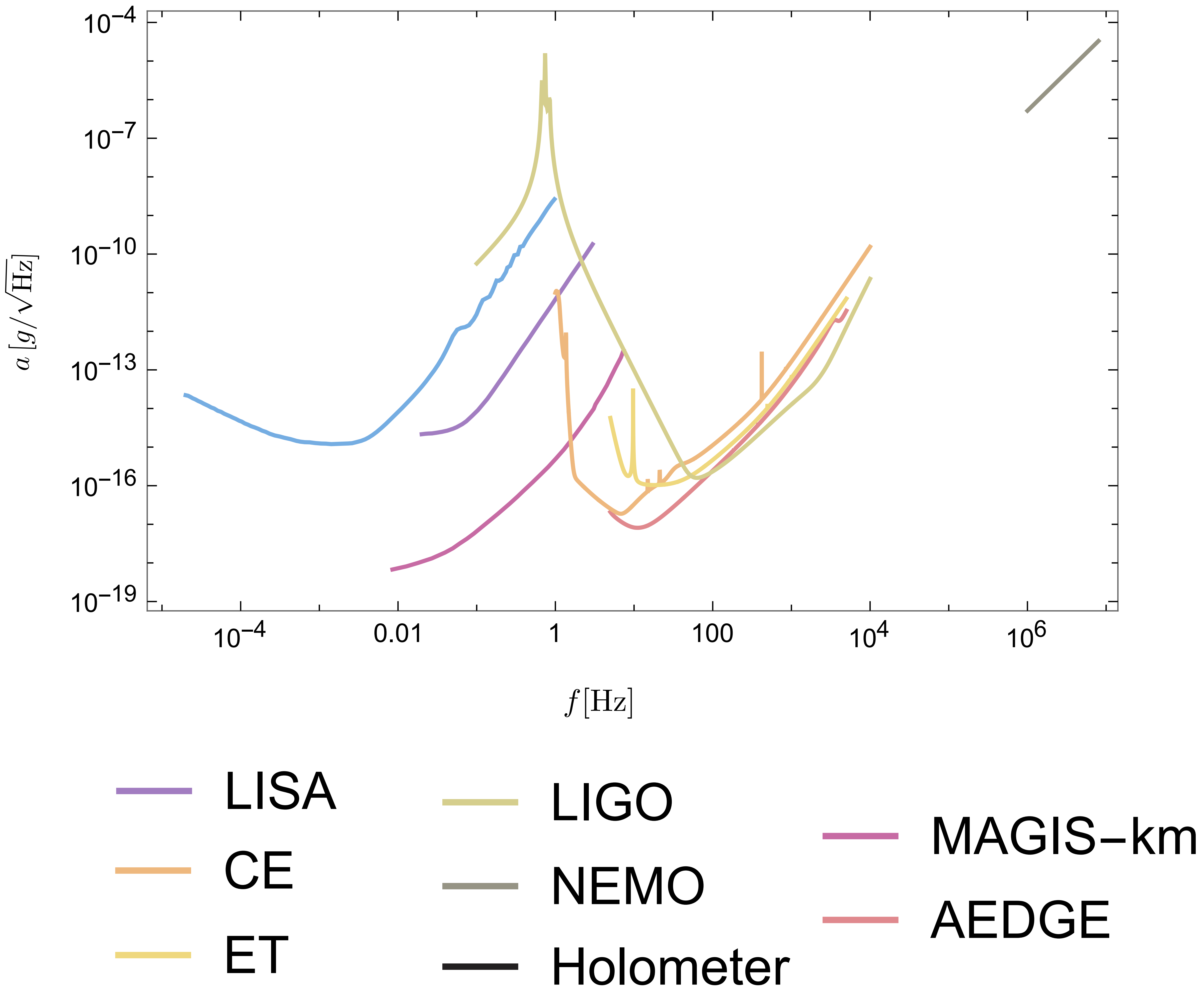
$$a_{\rm DM} \sim 10^{-18}{\rm m/s^2}\,\frac{G}{6.7\times10^{-11}\,{\rm N\,m^2/kg^2}}\,\frac{M}{10^7\,{\rm kg}}\left(\frac{4.4\times10^7\,{\rm m}}{L}\right)^2$$

$$R \sim (\rho_{\rm DM}/M)L^2 v_{\rm DM} \sim 1/{\rm year}$$



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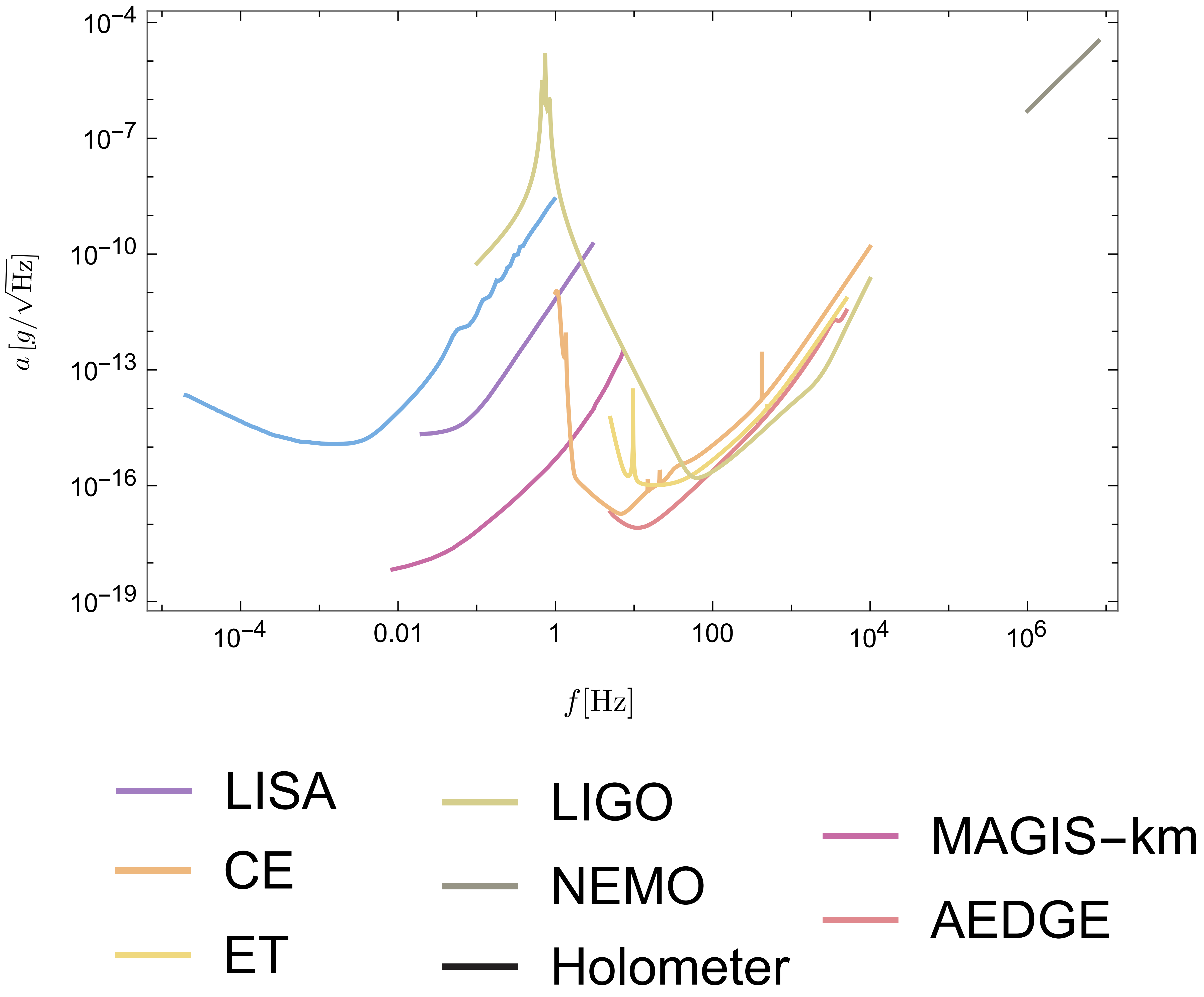


$$a_{\rm DM} \sim 10^{-18}{\rm m/s}^2 \, \frac{G}{6.7\times 10^{-11}\,{\rm N\,m^2/kg^2}} \, \frac{M}{10^7\,{\rm kg}} \left(\frac{4.4\times 10^7\,{\rm m}}{L}\right)^2$$

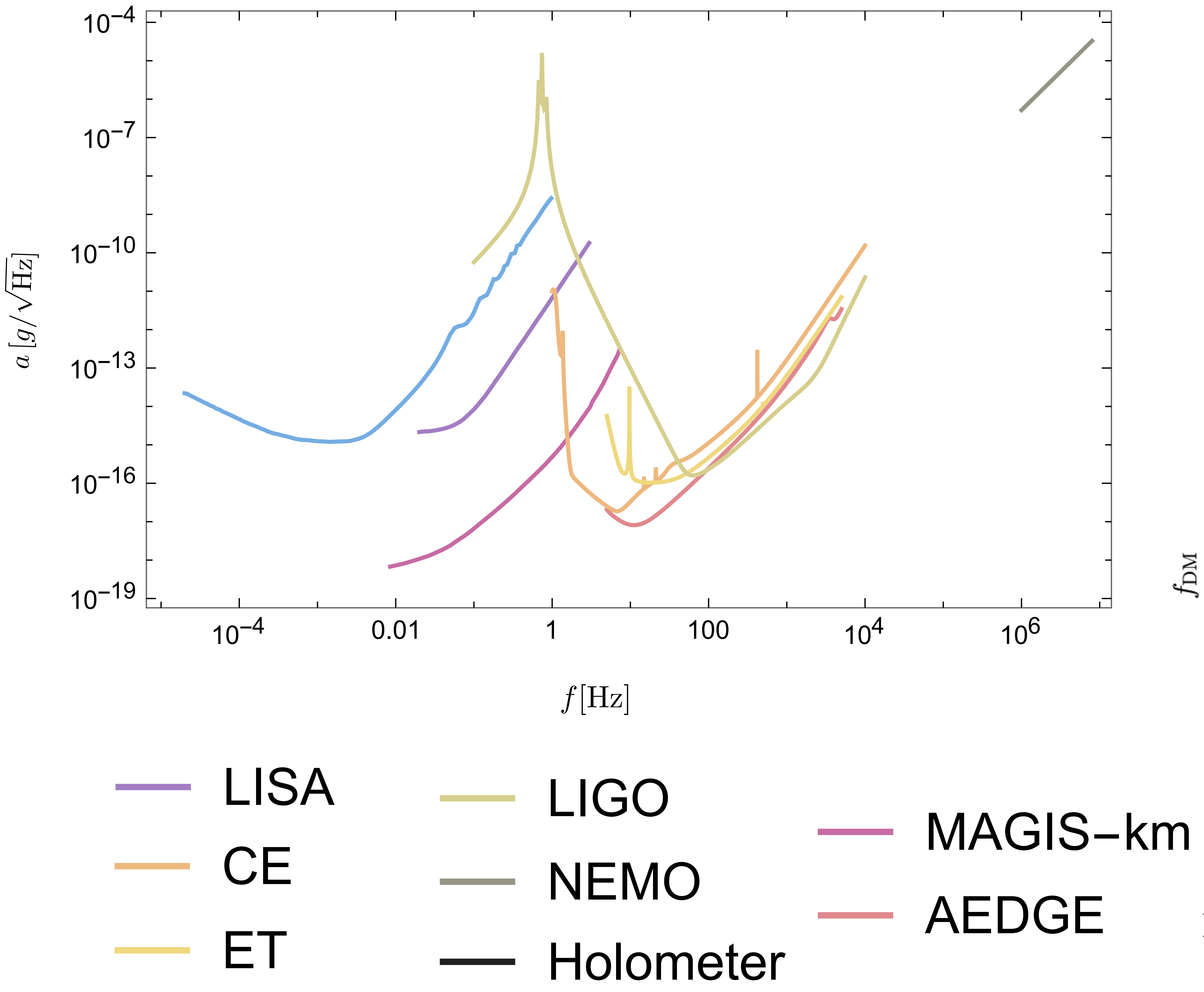
$$R \sim (\rho_{\rm DM}/M) L^2 v_{\rm DM} \sim 1/{\rm year}$$

Ultra-heavy clumpy DM can induce acceleration through pure **gravity**.

Why gravitational wave for dark sectors?

experiments

Accelerometers of ultra high sensitivity.



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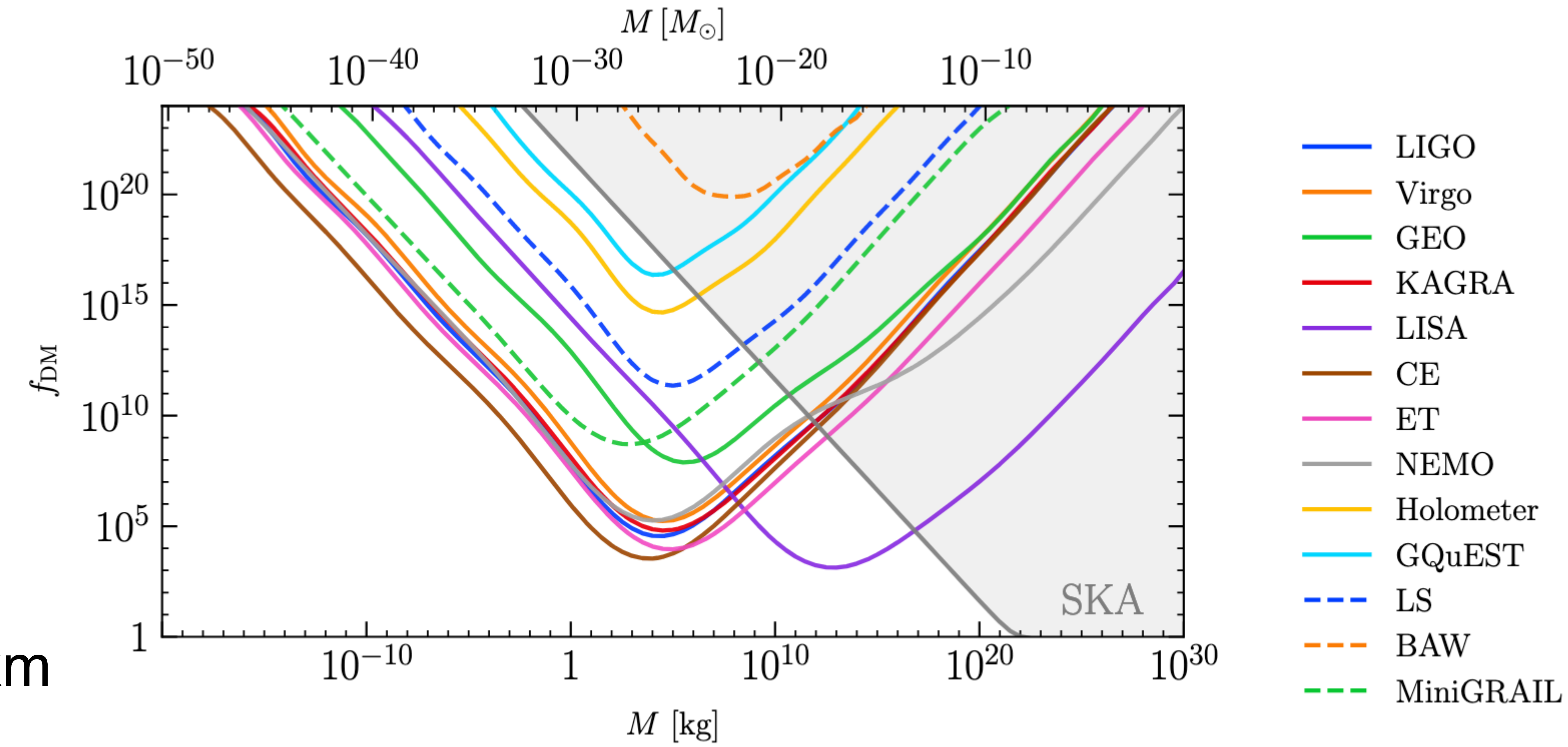

Projected 90th-percentile upper limits on transiting DM fraction. One year observation time.

Du, Lee, YW, Zurek 23'

Why gravitational wave experiments for dark sectors?

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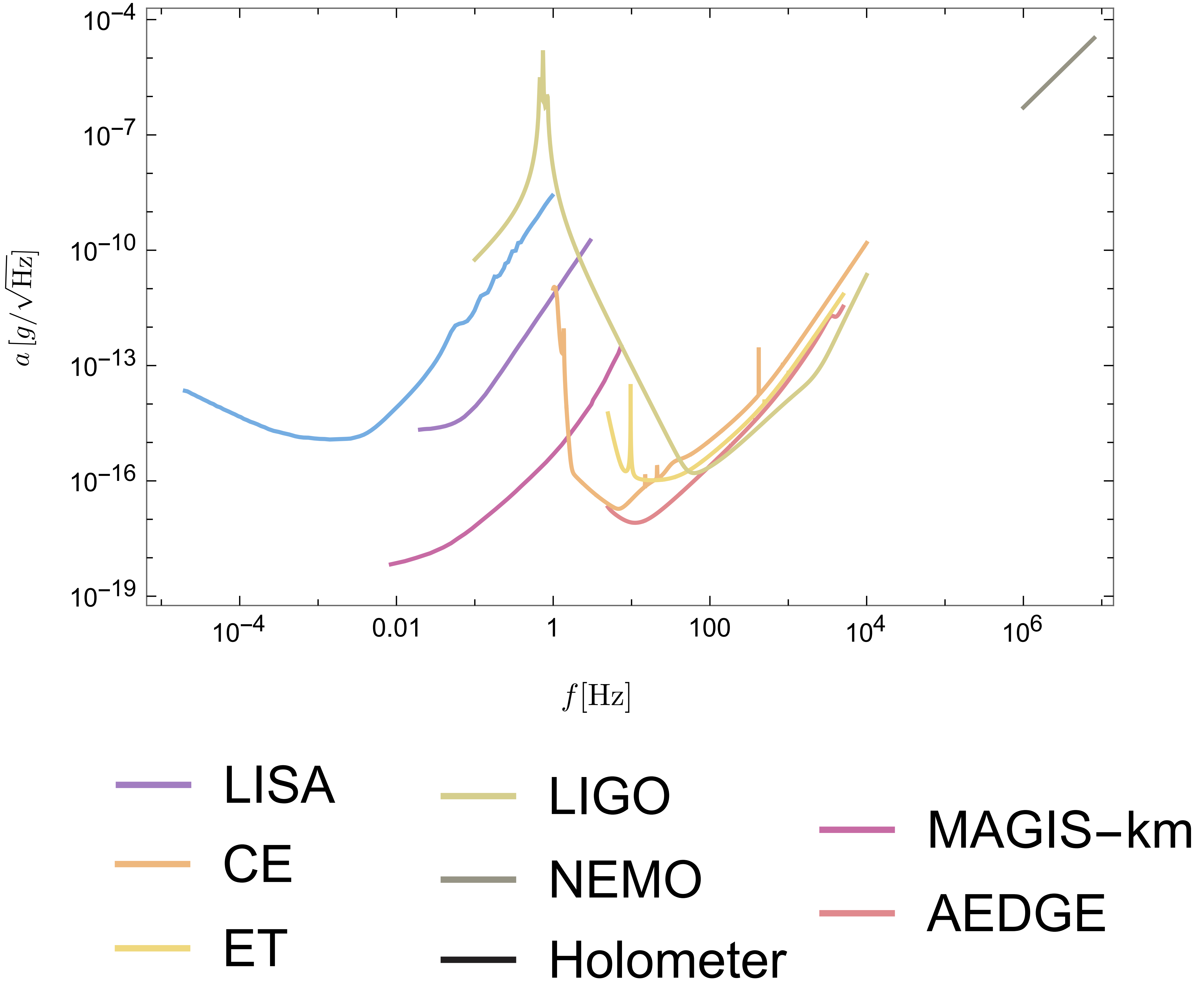

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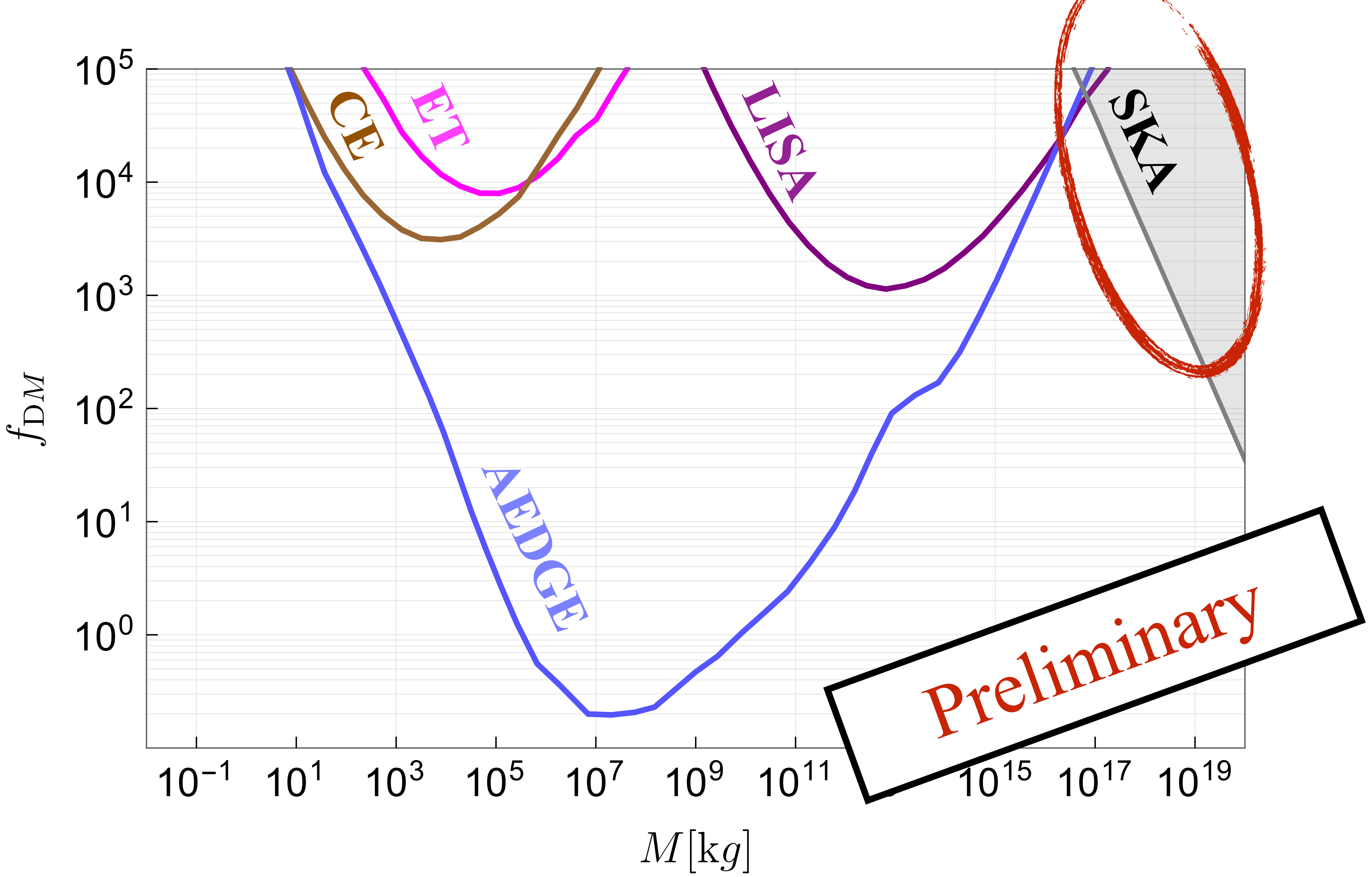

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Laser interferometer as Dark Matter Detectors

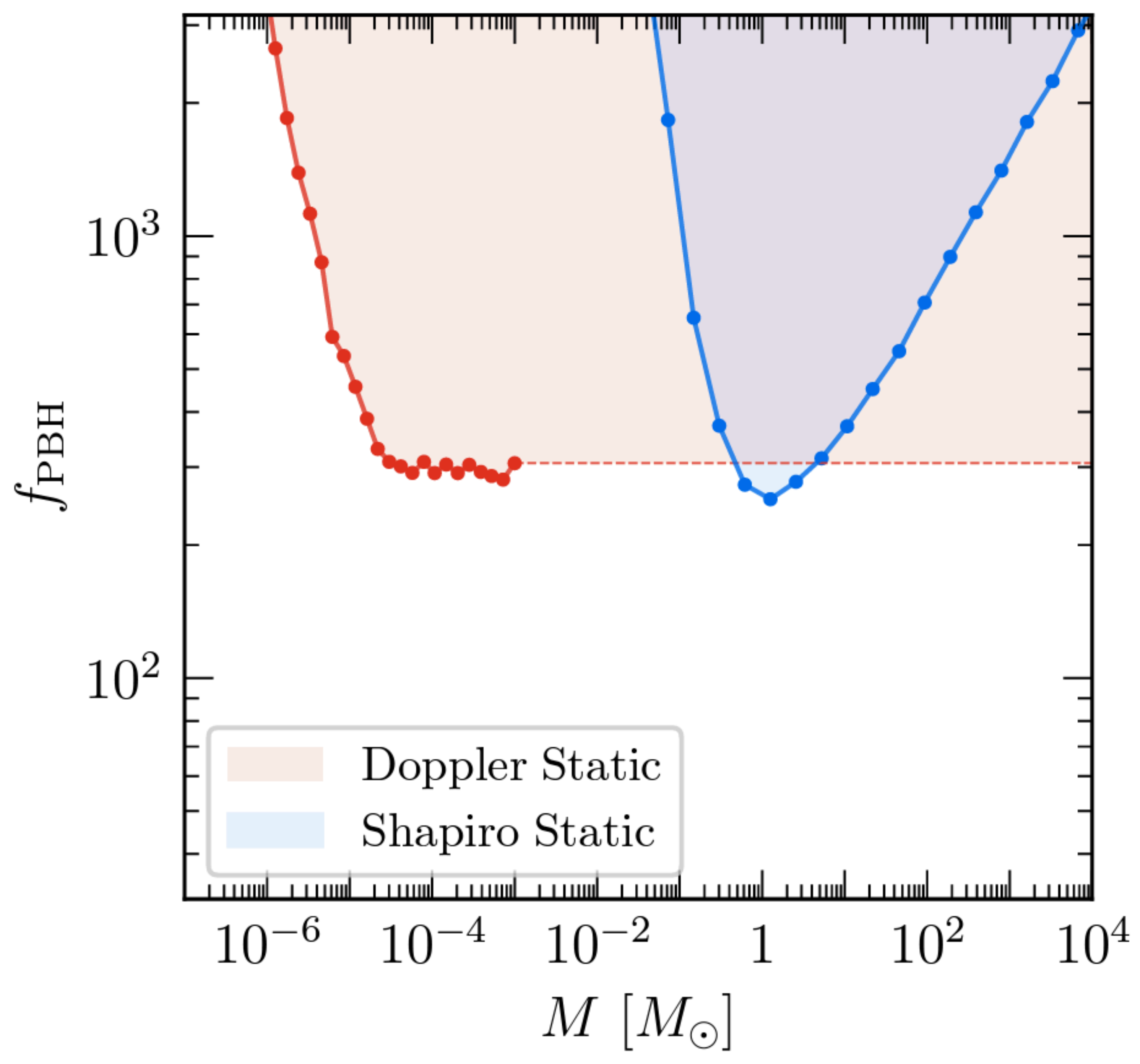
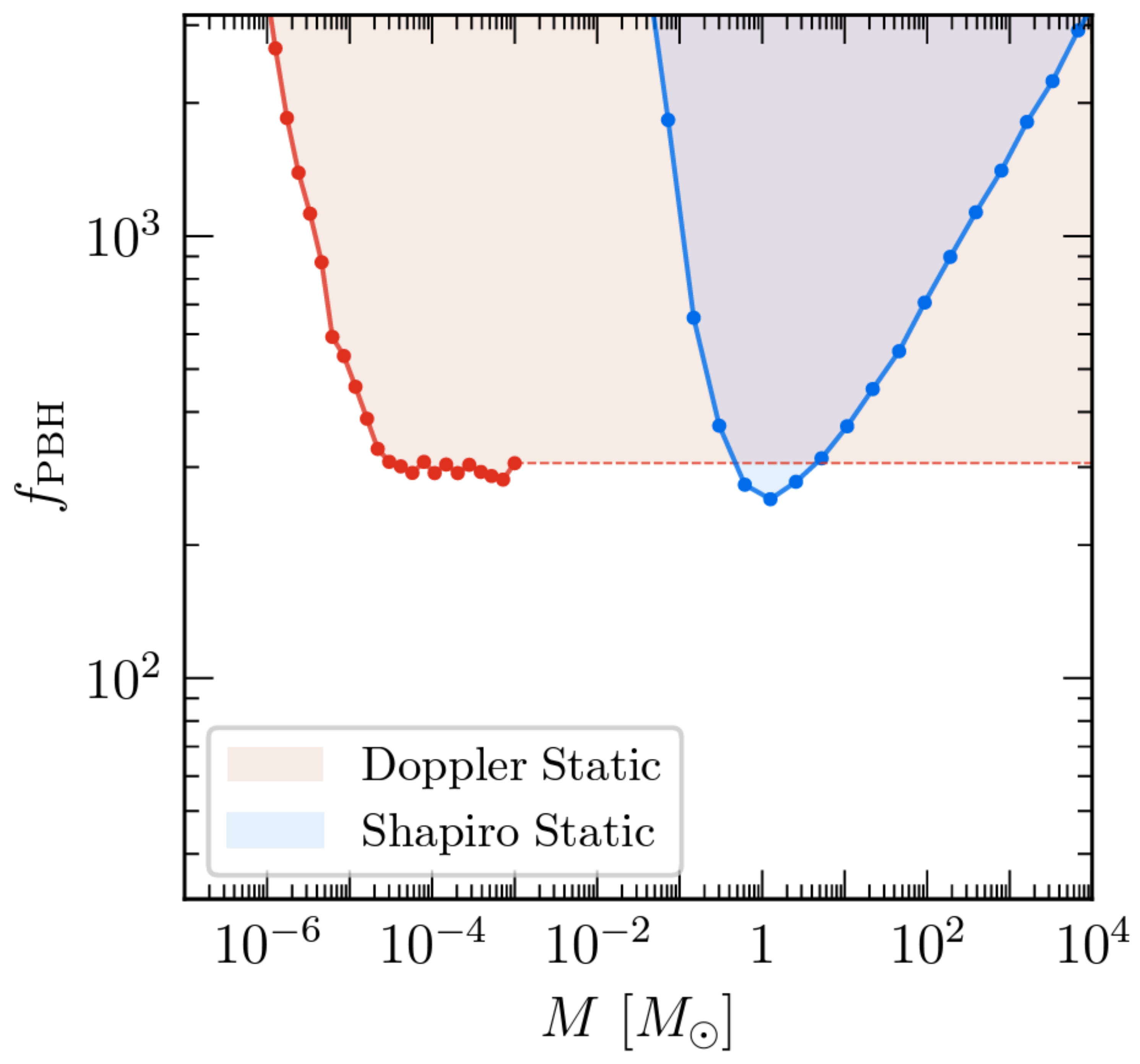


Figure 17. Constraints at the 95% credible level on the local PBH abundance derived from the search for static Doppler (red shaded region) and static Shapiro signals (blue shaded region). The solid lines interpolate between the PBH masses simulated in this work, while the red dashed line shows an extrapolation of the constraints to higher masses.

[NANOGrav15-yearNew-PhysicsSignals]

Laser interferometer as Dark Matter Detectors

Du, Lee, YW, Zurek 23'



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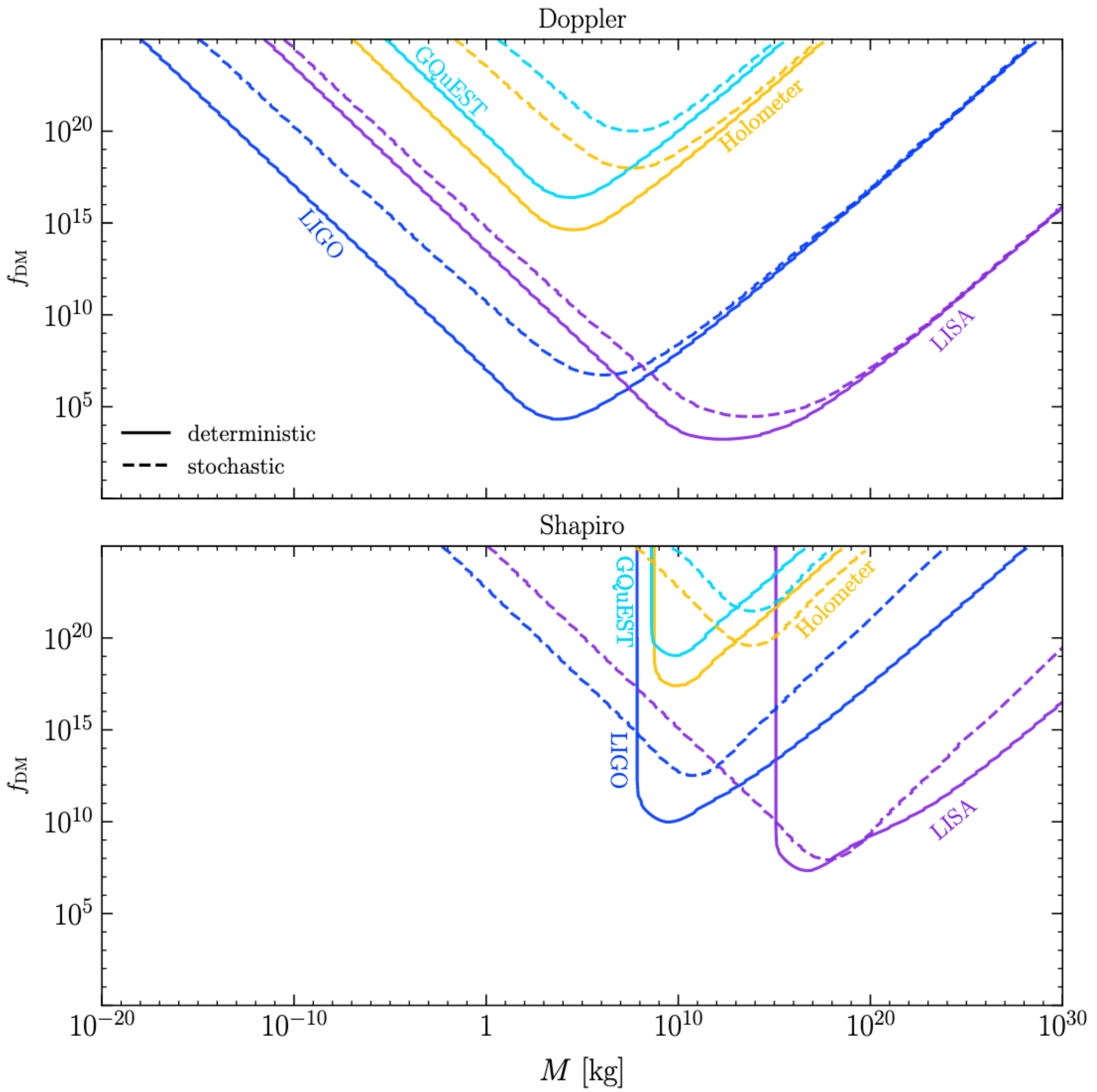
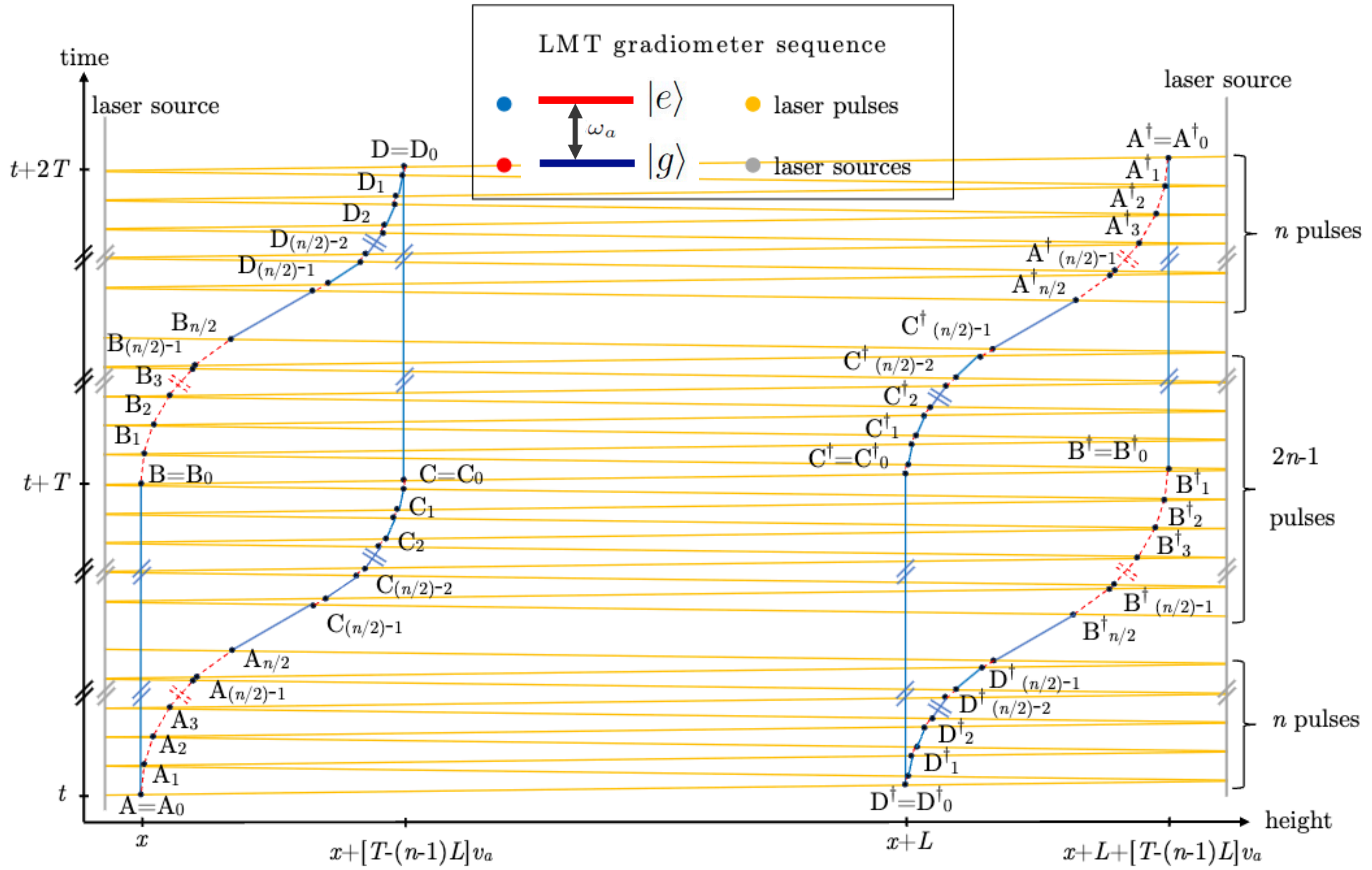
$$c\delta T_\gamma \equiv cT_\gamma - 2L = \underbrace{c\delta\tau}_{\text{Einstein}} + \underbrace{2r_{\rm M}\left(t+\frac{L}{c},L\right) - r_{\rm M}(t,0) - r_{\rm M}\left(t+\frac{2L}{c},0\right)}_{\text{Doppler}}$$
$$+\underbrace{\frac{1}{2}\int_0^L dr\mathcal{H}^{\rm out}\left(t+\frac{r}{c},r\right) - \frac{1}{2}\int_L^0 dr\mathcal{H}^{\rm in}\left(t+\frac{2L-r}{c},r\right)}_{\text{Shapiro}}.$$



Projected 90th-percentile upper limits on DM fraction. One year observation time.

Atom interferometer phase shift from linearized gravity and a weak potential

Long-baseline Atom Interferometer Gradiometer



$$\Delta\phi_{\rm tot} = \oint m\sqrt{-g_{\mu\nu}\frac{dx^\mu}{dt}\frac{dx^\nu}{dt}}\,dt$$

[Dimopoulos, Graham, Hogan, and Kasevich1, 08'] [Roura, 20']

Badurina, Du, Lee, YW, Zurek 23'

$$\Delta\phi_{\rm tot} = -\frac{1}{2}\oint m\left(1+\int dt'\,\mathbf{v}_a\cdot\nabla\right)h_{00}\,dt \;+\omega_a\int_{|e\rangle} dt\; +\mathcal{O}(h^2 v_a, h v_a^2)$$

Einstein delay **Doppler shift, Shapiro delay**

Example: a weak potential

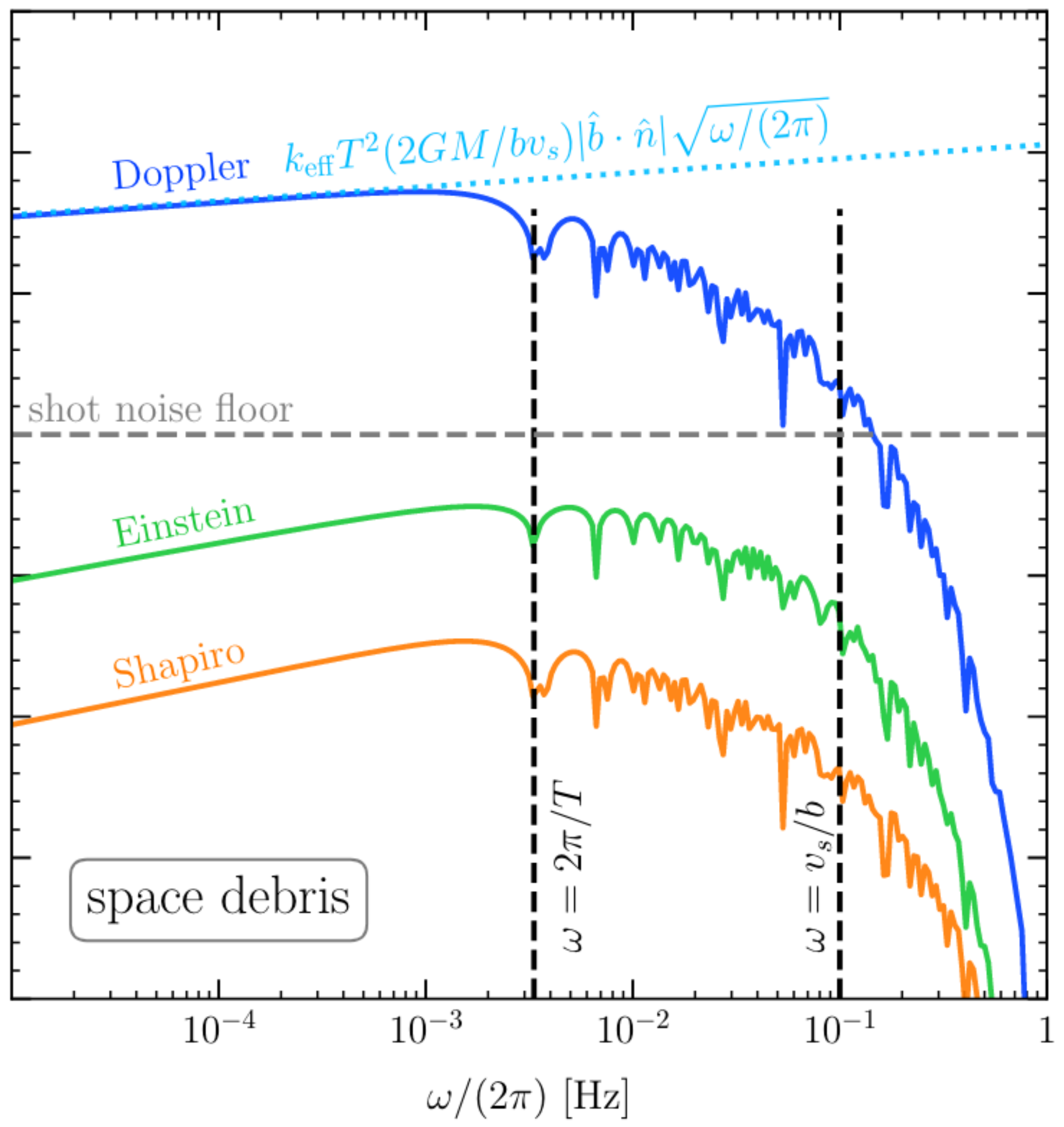
$$ds^2 = -(1+2\Phi)dt^2 - 8\Phi v_i dx_i dt + (1-2\Phi)dx_i dx_i$$

gives

$$\widetilde{\Delta\phi}_{\mathcal{E}}(\omega,\mathbf{x}_0) = T^2\,\mathbf{k}_{\rm eff}\cdot\nabla\tilde{\Phi}(\omega,\mathbf{x}_0)\,K_1(\omega) + T^2\,\omega_a\tilde{\Phi}(\omega,\mathbf{x}_0)\,K_2(\omega)$$

$$\widetilde{\Delta\phi}_{\mathcal{D}}(\omega,\mathbf{x}_0) \simeq T^2\,\mathbf{k}_{\rm eff}\cdot\nabla\tilde{\Phi}(\omega,\mathbf{x}_0)\,K_D(\omega)$$

$$\widetilde{\Delta\phi}_{\mathcal{S}}(\omega,\mathbf{x}_1\to\mathbf{x}_2) \simeq T^2\,|\mathbf{k}_{\rm eff}|\mathcal{FT}_{t\to\omega}\left\{\int_{|\mathbf{x}_2-\mathbf{x}_1|/2}^{-|\mathbf{x}_2-\mathbf{x}_1|/2} dx\,\Phi\left(t\pm x, \frac{\mathbf{x}_1+\mathbf{x}_2}{2}+x\frac{\mathbf{x}_2-\mathbf{x}_1}{|\mathbf{x}_2+\mathbf{x}_1|}\right)\right\}K_S(\omega)$$



Different contributions to the phase shift of a benchmark space debri.

Conclusion

* Gravitational wave astrophysics is the next venue for dark matter indirect detection
* Rich sources for gradational wave signatures from the dark sectors
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Thank you!