Searching for Dark Photon Dark Matter with Gravitational Wave Detectors

Yue Zhao

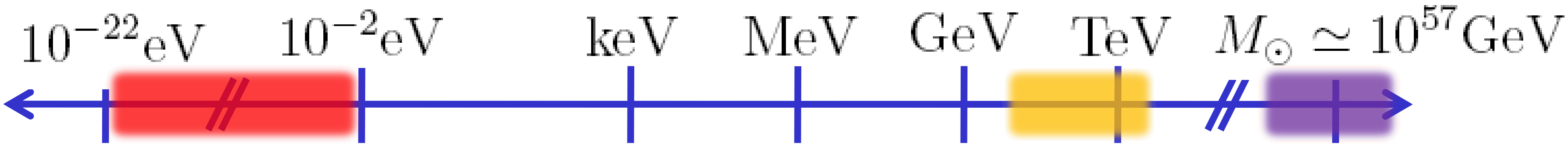
University of Utah

Aaron Pierce, Keith Riles, Y.Z.
arXiv:1801.10161 [hep-ph]
Phys.Rev.Lett. 121 (2018) no.6, 061102

Huaike Guo, Keith Riles, Fengwei Yang, Y.Z.
arXiv:1905.04316 [hep-ph]

Internally reviewed by LIGO.
O1 data analysis is done!

Popular Choices:



- Very light DM particles

  Axion and Dark "Photon"

  10^{-22} eV ~ 10^{-2} eV

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- WIMPs:

  100 GeV ~ TeV

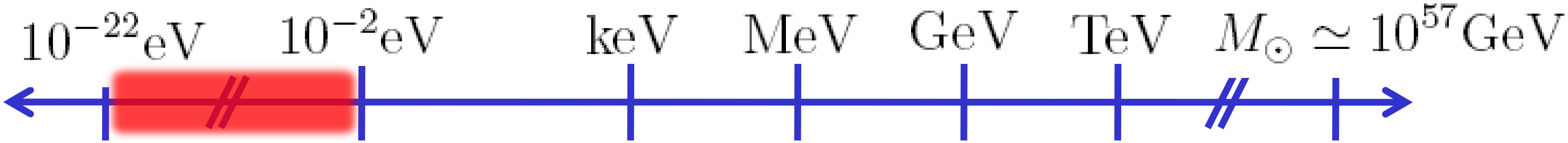
- Primordial Black Holes:

  10^{-7} ~ 100 solar mass

Huai-Ke Guo, Jing Shu, Yue Zhao
Phys.Rev. D99 (2019) no.2, 023001

Both ultra-light and ultra-heavy scenarios can be probed by GW detectors!

Popular Choices:



- Very light DM particles

  Axion and Dark "Photon"

  10^{-22} eV ~ 10^{-2} eV

gauge boson of the

$U(1)_B$ or $U(1)_{B-L}$

(p+n) (n)

DM is an oscillating background field.

Dark Photon is dominantly oscillating background dark electric field.

Driving displacements for particles charged under dark gauge group.

Ultra-light DM – Dark Photon

- Mass

  W/Z bosons get masses through the Higgs mechanism.

  A dark photon can also get a mass by a dark Higgs,
  or through the Stueckelberg mechanism.

  a special limit of the Higgs mechanism
  unique for U(1) gauge group

- Relic abundance (non-thermal production)

  Misalignment mechanism

  Light scalar decay

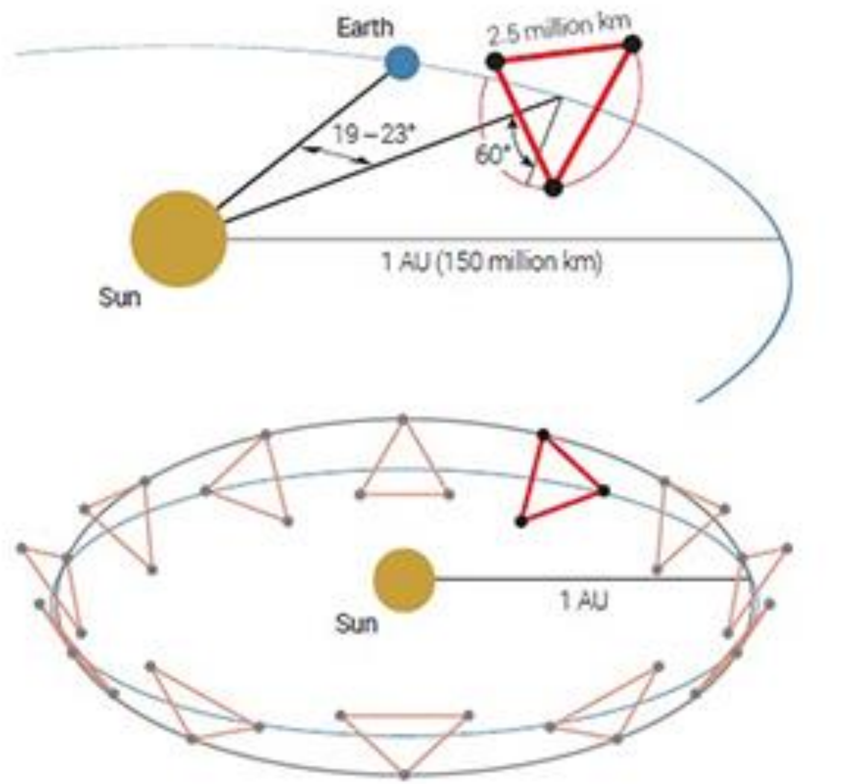
  Production from cosmic string

Ultra-light dark photon can be a good candidate of cold dark matter!

Laser Interferometer Gravitational-Wave Observatory

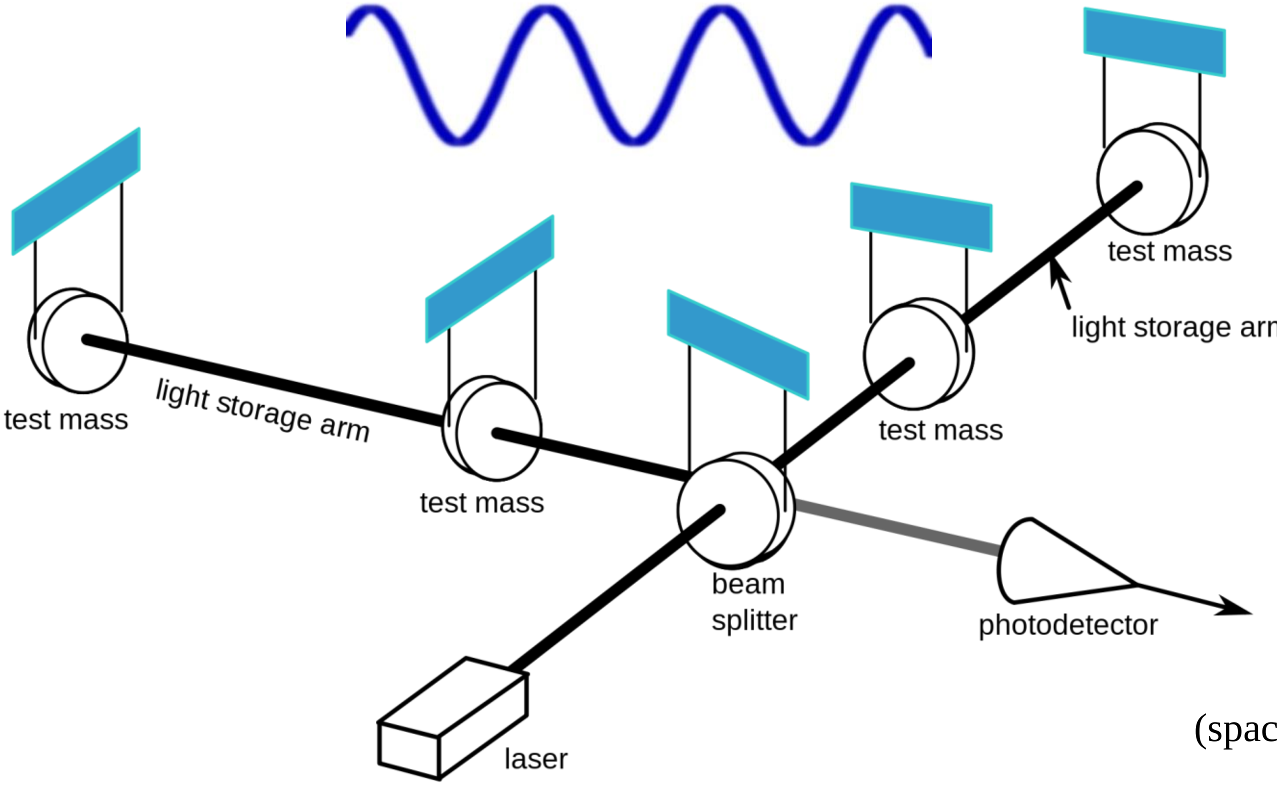
LIGO (ground-based)

LISA (space-based)



General Picture:

LIGO/LISA: advanced Michelson–Morley interferometer



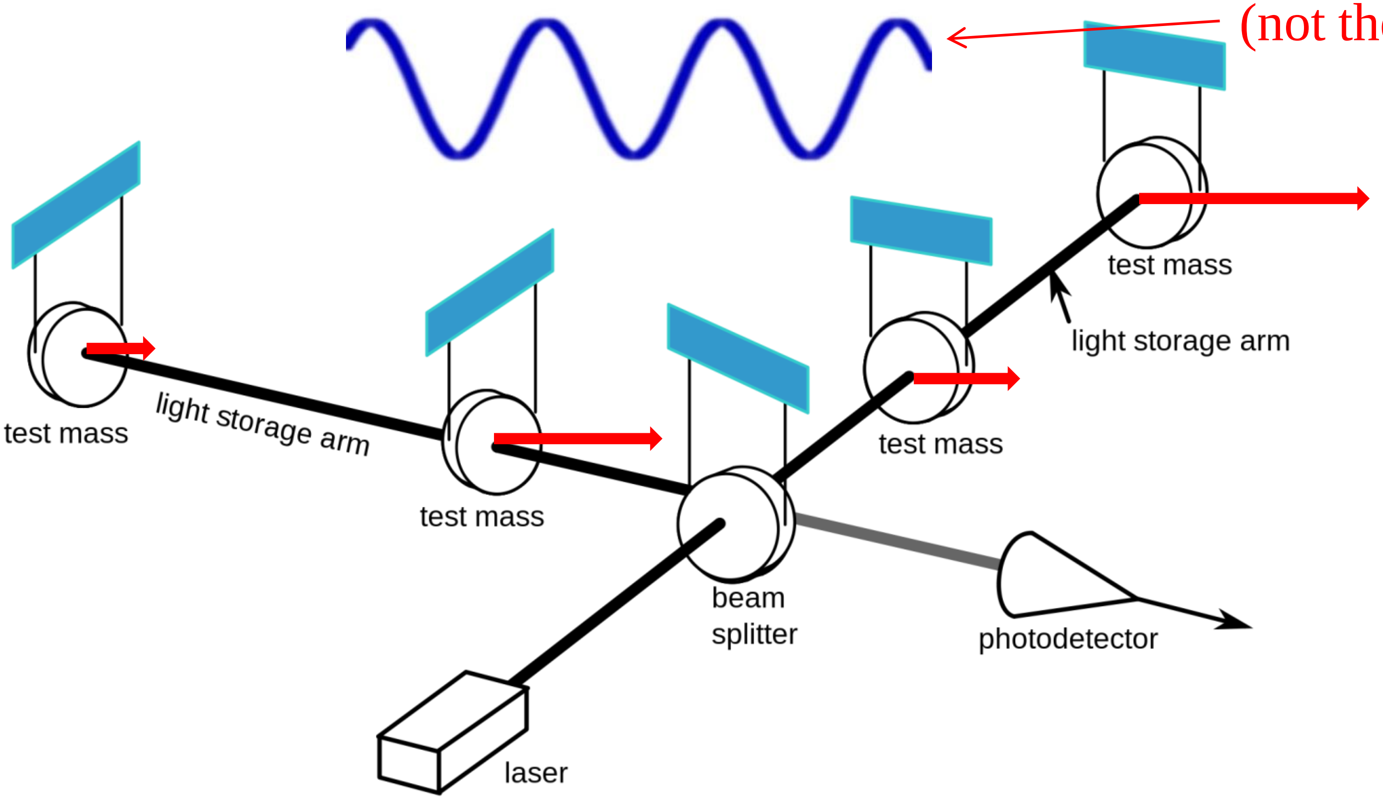
(space.com)

Gravitational wave changes the distance between mirrors. ⇨ Change photon propagation time between mirrors. ⇨ interferometer pattern

General Picture:

Ultra-light DM ⇨ background classical radio wave

(not the precise pic)



Dark photon dark matter moves mirrors. ⇨ Change photon propagation time between mirrors. ⇨ interferometer pattern

Maximal Displacement:

Local DM energy density:

$$\frac{1}{2} m_A^2 A_{\mu,0} A_0^\mu \simeq 0.4\ \mathrm{GeV/cm^3}$$

local field strength of DP

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

$$\partial^\mu A_\mu = 0$$

$E_i \sim m_A A_i$ >> $B^i \sim m_A v_j A_k \epsilon^{ijk}$

Maximal Displacement:

$$\vec{a}_i(t) = \frac{\vec{F}_i(t)}{M_i} \simeq \epsilon e \frac{q_{D,i}}{M_i} \partial_t \vec{A}(t, \vec{x}_i)$$

dark photon coupling

dark electric field

charge mass ratio of the test object

Silicon mirror:

U(1)B : 1/GeV

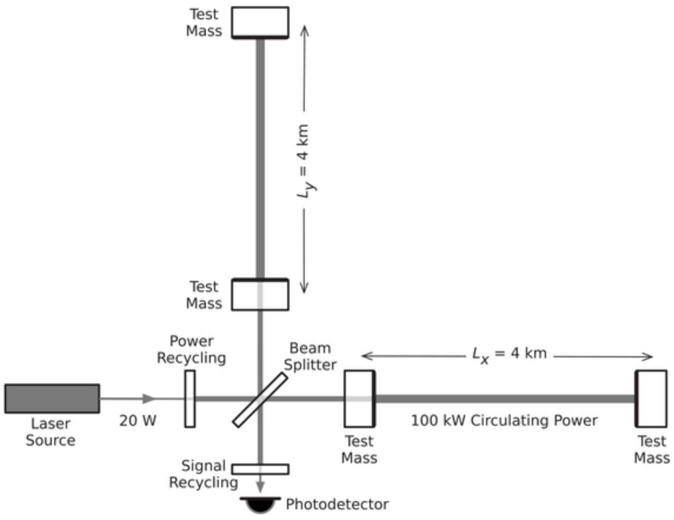
U(1)B-L : 1/(2GeV)

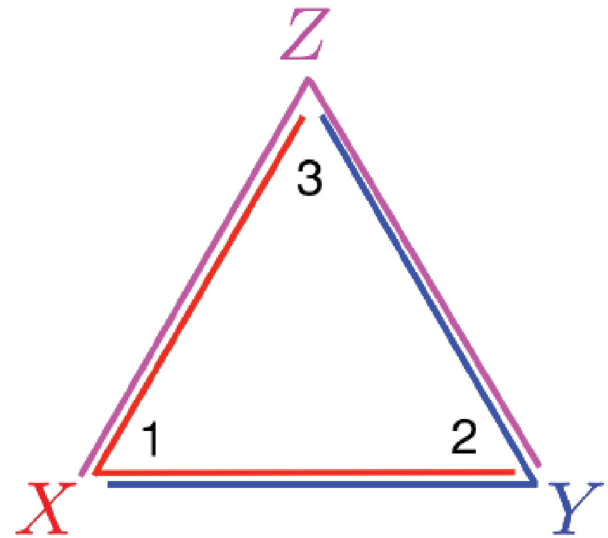
$$\Delta s_{\parallel,i} = \int dt \int dt \; a_{\parallel,i}(t)$$

projected along
the arm direction

Maximal GW-like Displacement:

$$\Delta L[t] = (x_1[t] - x_2[t]) - (y_1[t] - y_2[t])$$





$$\sqrt{\langle \Delta L^2 \rangle_{LIGO}}|_{max} = \frac{\sqrt{2}}{3} \frac{|a||k|L}{m_A^2}$$

Compare this with the sensitivity on strain h.

$$\sqrt{\langle \Delta L^2 \rangle_{LISA}}|_{max} = \frac{1}{\sqrt{6}} \frac{|a||k|L}{m_A^2}$$

v_{vir} =0 gives same force to all test objects, not observable.
Net effect is proportional to velocity.

Properties of DPDM Signals:

Signal:

- almost monochromatic

$$f \simeq \frac{m_A}{2\pi}$$

- very long coherence time

$$\Delta f / f = v_{vir}^2 \simeq 10^{-6}$$

DM velocity dispersion.
Determined by gravitational potential of our galaxy.

⇨ A bump hunting search in frequency space.

Can be further refined as a detailed template search, assuming Boltzmann distribution for DM velocity.

Once measured, we know great details of the local DM properties!

Properties of DPDM Signals:

Signal:

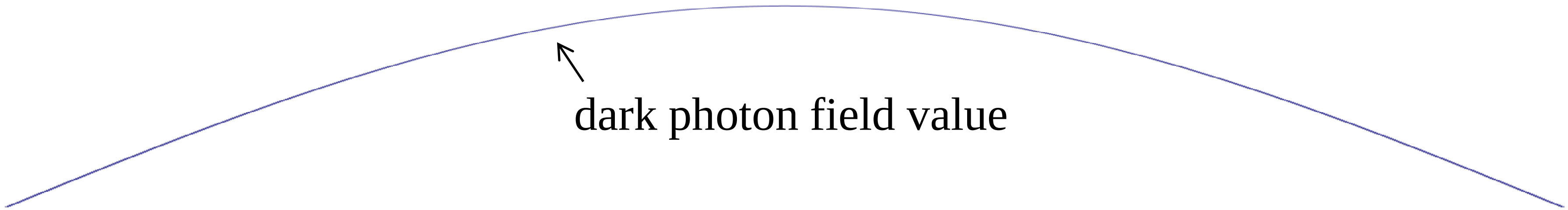
- very long coherent distance

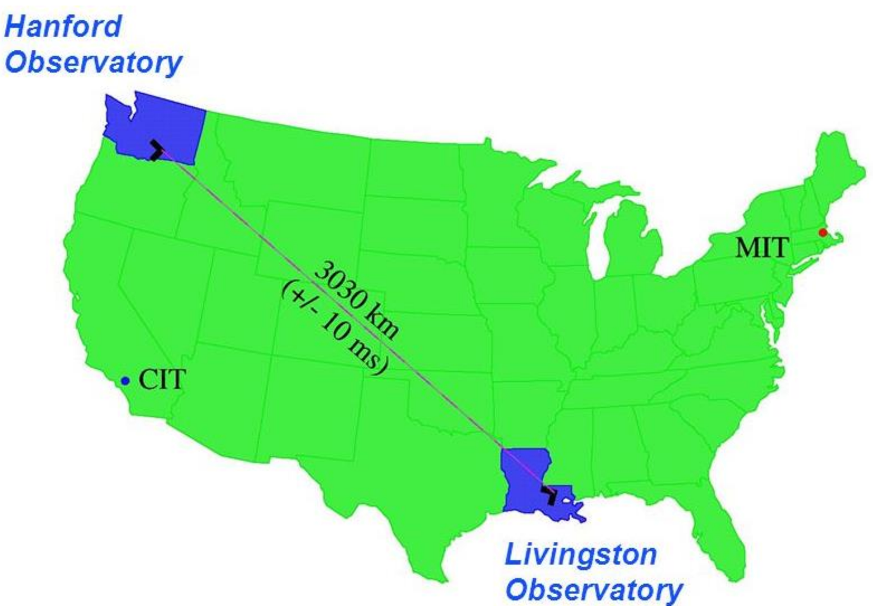
$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f} \right)$$

Propagation and polarization directions remain constant approximately.

Properties of DPDM Signals:

Correlation between two sites is important to reduce background!





Due to long coherence length, signal is almost the same for both sites.

Sensitivity to DPDM signal of GW detectors:

Signal-to-Noise-Ratio can be calculated as:

$$S = < s_1, s_2 > \equiv \int_{-T/2}^{T/2} s_1(t) s_2(t) dt.$$

overlap function
describe the correlation among sites

observation time of an experiment, O(yr)

one-sided power
spectrum function

$$S = \frac{T}{2} \int df \, \gamma(|f|) \, S_{GW}(|f|) \, \tilde{Q}(f),$$

$$N^2 = \frac{T}{4} \int df \, P_1(|f|) \, |\tilde{Q}(f)|^2 \, P_2(|f|).$$

optimal filter function
maximize SNR

one-sided strain noise power spectra

Sensitivity to DPDM signal of GW detectors:

Translate strain sensitivity to parameters of DPDM:

$$\mathrm{SNR} = \frac{\gamma(|f|)h_0^2\sqrt{T}}{2\sqrt{P_1(f)P_2(f)\Delta f}}.$$

effectively the max differential displacement of two arms

a GW with strain h ⇨ change of relative displacement as h

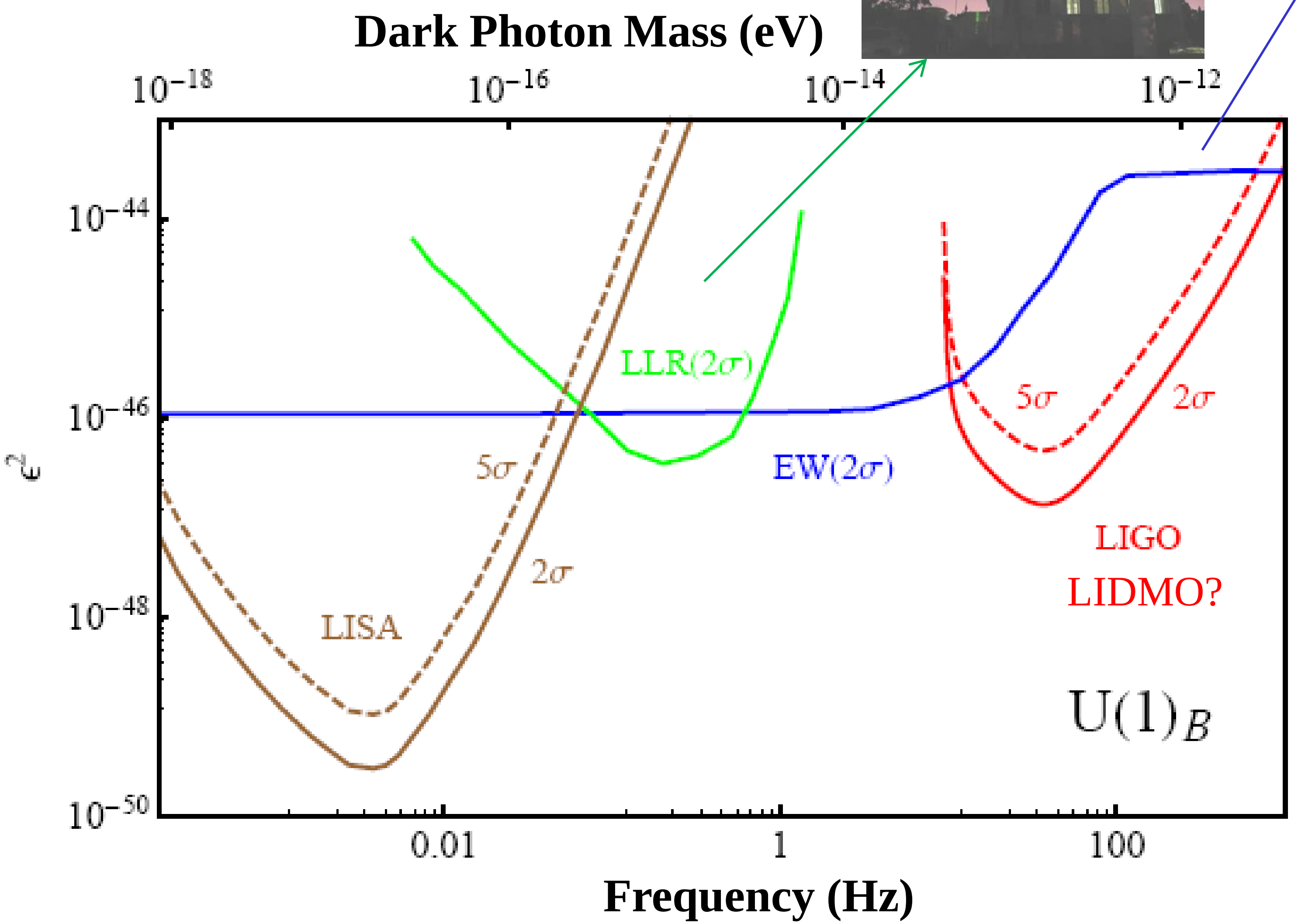
⇨ $\sqrt{\langle \Delta L^2 \rangle_{LIGO}}|_{max}$

⇨ sensitivity of DPDM parameters (mass, coupling)

Sensitivity Plot:


(People's Daily)


(Eöt-Wash web)

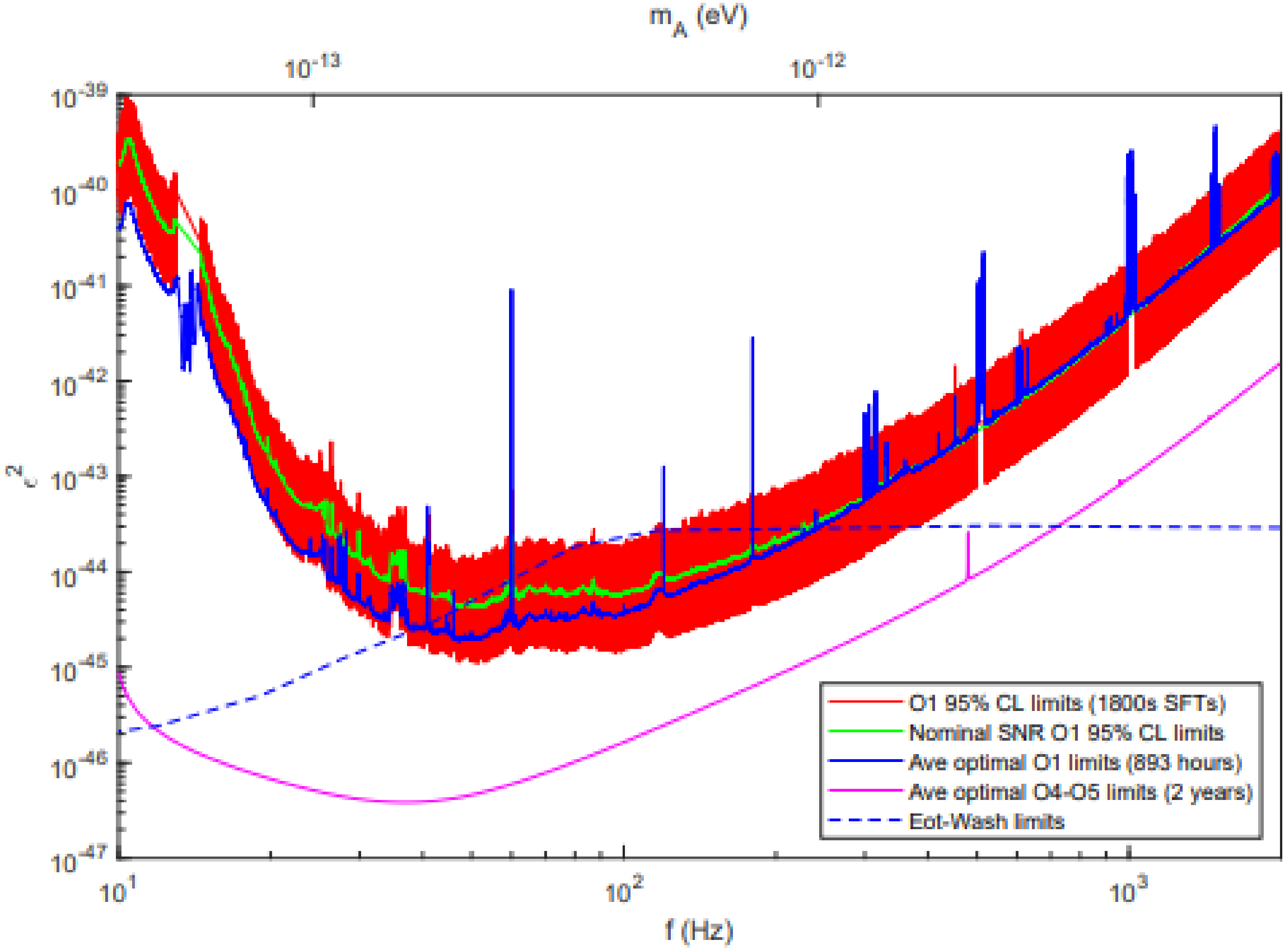


Loránd Eötvös

⟶ Eöt-Wash

design sensitivities, 2 yrs

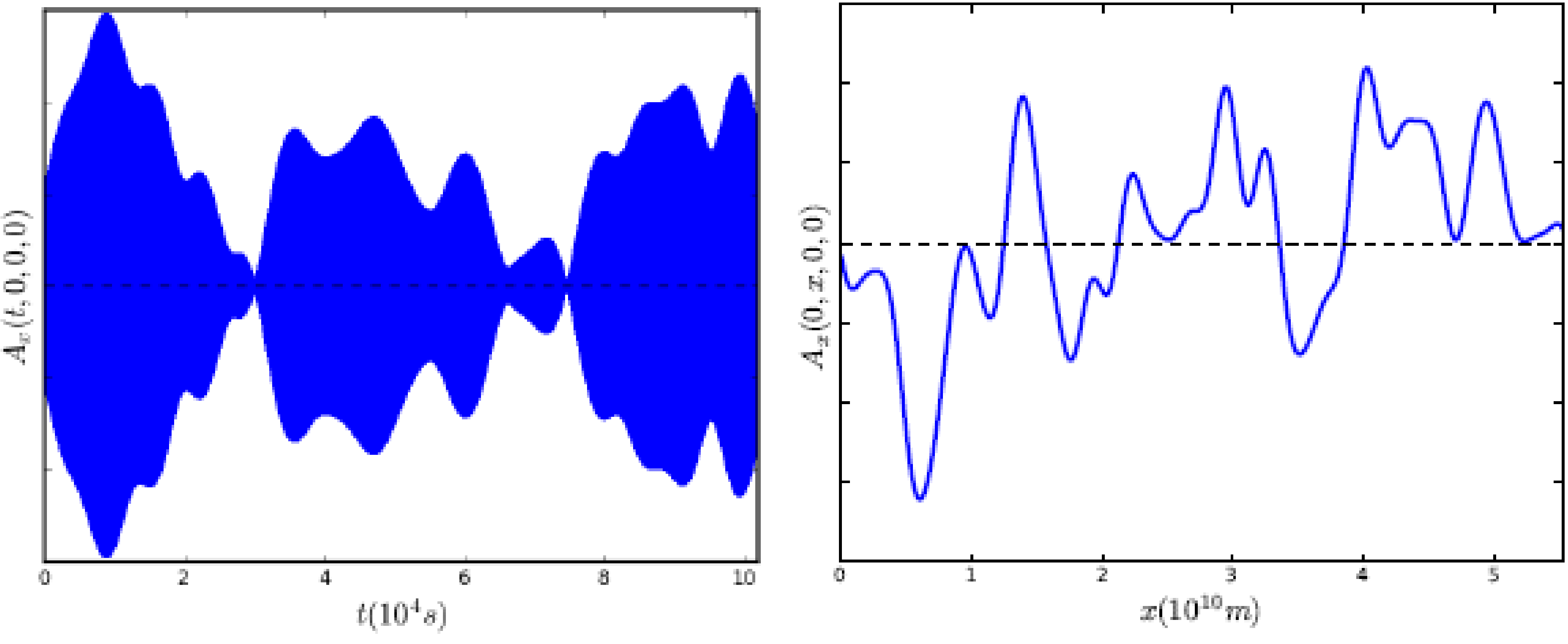
O1 Result:



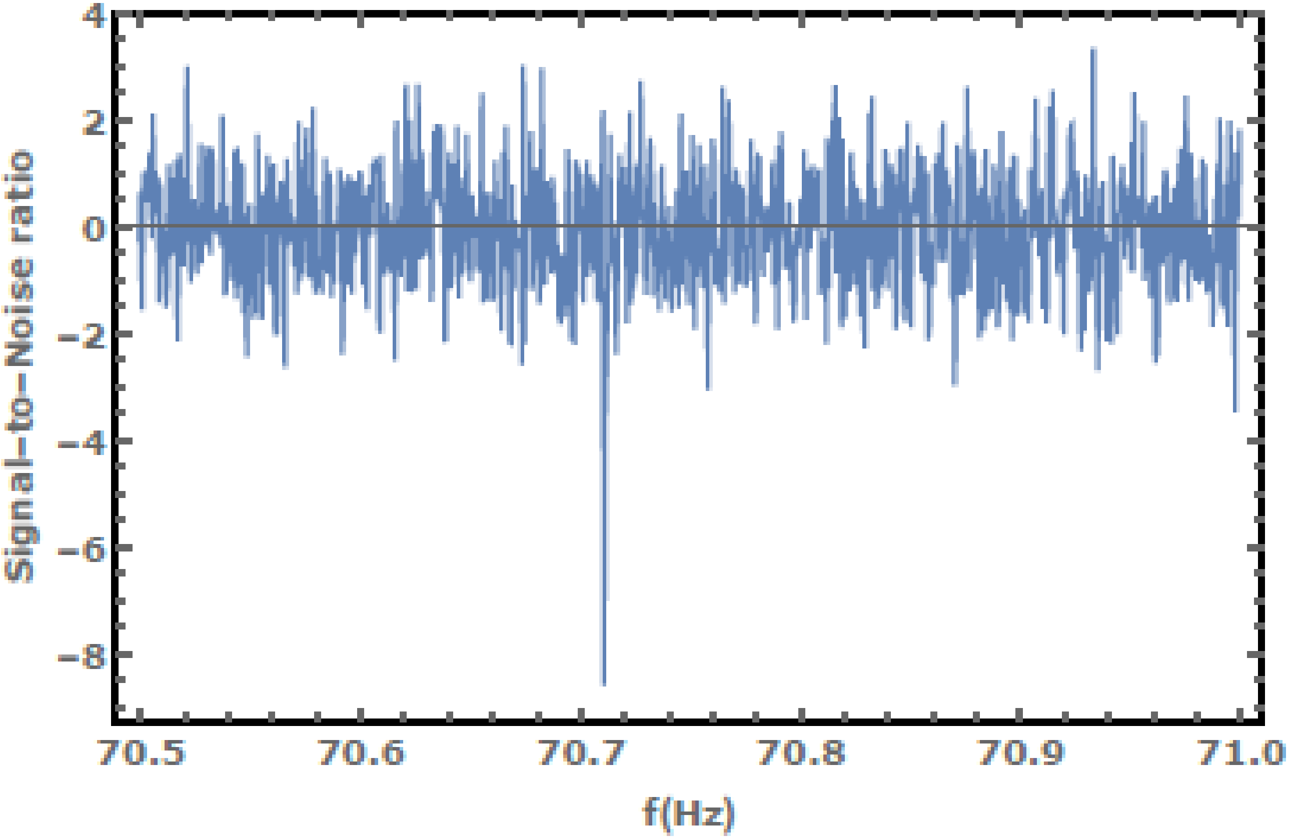
m_A (eV)
10^{-13}
10^{-12}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
ϵ^2
10^1
10^2
10^3
f (Hz)
O1 95% CL limits (1800s SFTs)
Nominal SNR O1 95% CL limits
Ave optimal O1 limits (893 hours)
Ave optimal O4-O5 limits (2 years)
Eot-Wash limits

Modeling DPDM background:

$$\vec{A}_{total}(t, \mathrm{x}) = \sum_{i=1}^{N} \vec{A}_{i,0} \sin(\omega_i t - \vec{k}_i \cdot \vec{x} + \phi_i)$$



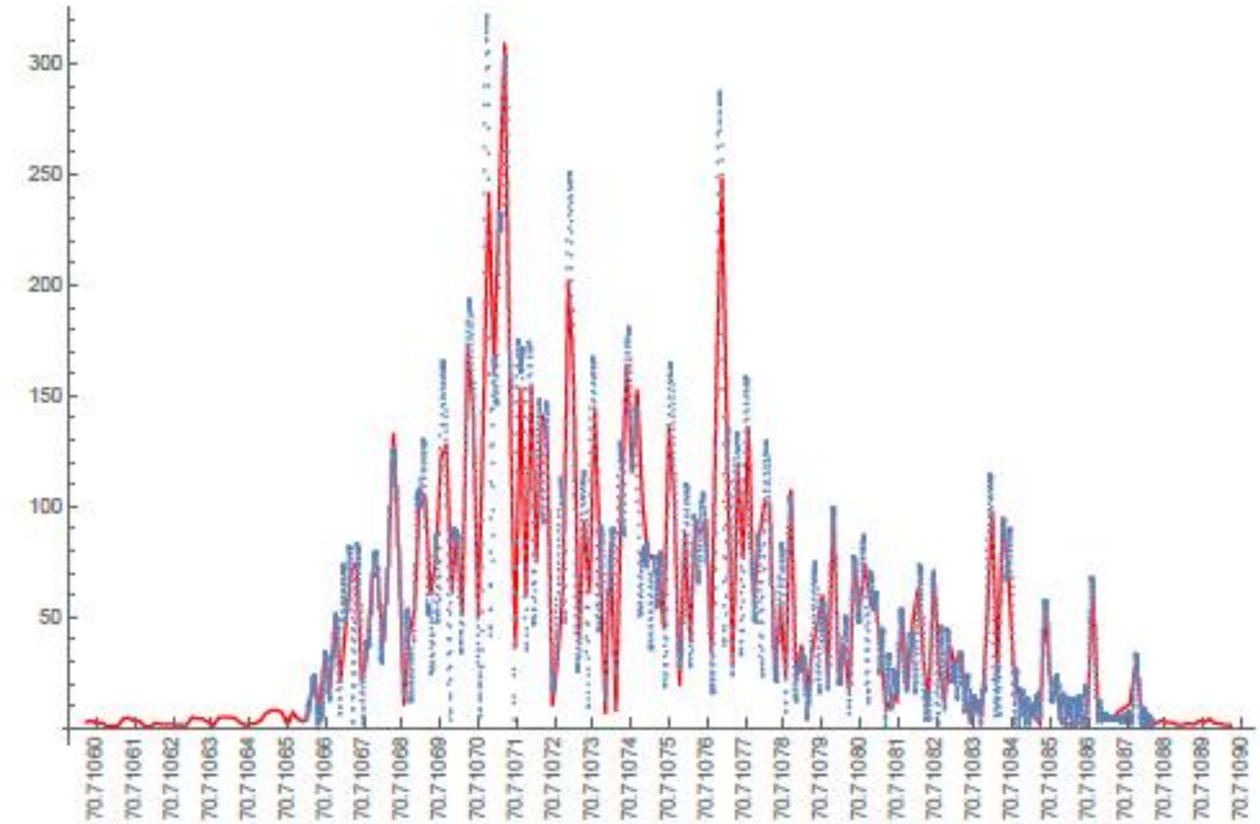
LIGO simulation output:



$\epsilon^2 = 5\times 10^{-44}$ $f = 70.71$ Hz T_{SFT} = 1800 s T_{tot} = 200 hr

⇨ SNR $\simeq -8$.

Fine structure of the signal:



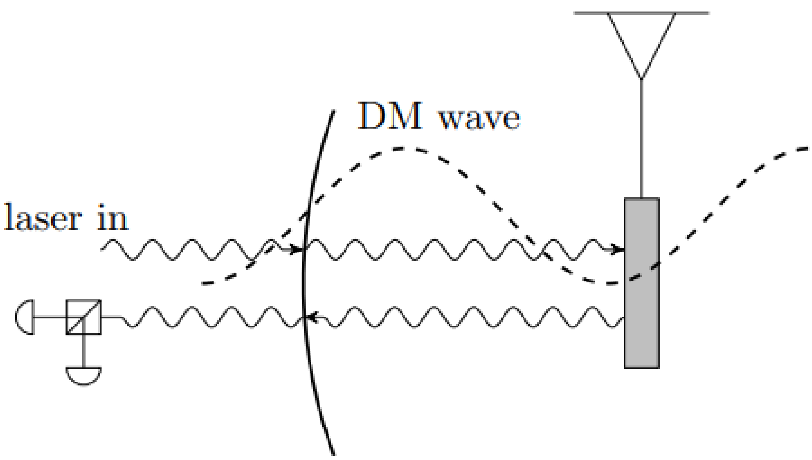
Analytic understanding matches very well with numerical result!

A quick digression: mechanical quantum sensors

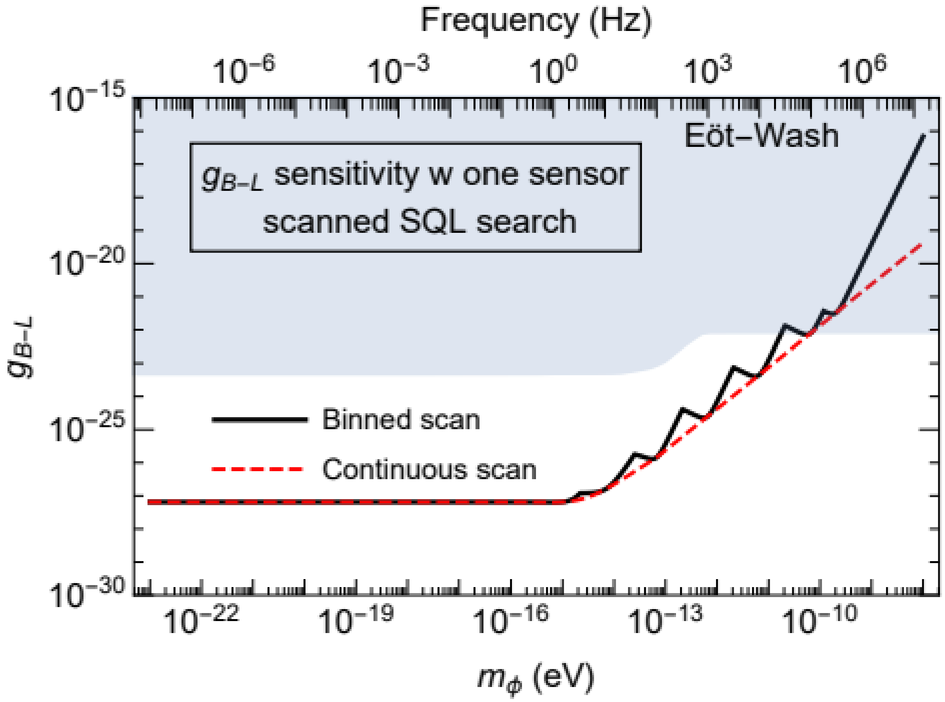
arXiv:1908.04797 D. Carney, A. Hook, Z. Liu, J. M. Taylor, Y. Z.

Laser: shot noise (SN) & backaction noise (BA)

(Standard Quantum Limit) SQL: optimization between SN and BA



milli-gram test object



Scan: optimize lase power for each frequency bin

1-hour integration time for each bin

Sensitivity grows with sqrt[N_{det}]!

Conclusion

The applications of GW experiments can be extended!

⇨ Particularly sensitive to relative displacements.

Coherently oscillating DPDM generates such displacements.

It can be used as a DM direct detection experiment.

The analysis is straightforward!

⇨ Very similar to stochastic GW searches.

Better coherence between separated interferometers than Stochastic GW BG.

The sensitivity can be extraordinary!

⇨ O1 data has already beaten existing experimental constraints.

Can achieve 5-sigma discovery at unexplored parameter regimes.

Once measured, great amount of DM information can be extracted!

Sensitivity to DPDM signal of GW detectors:

First we estimate the sensitivity in terms of GW strain.

(Allen & Romano, Phys.Rev.D59:102001,1999)

One-sided power spectrum function:

$$S_{GW}(f) = \frac{3H_0^2}{2\pi^2} f^{-3} \Omega_{GW}(f)$$

energy density carried by a GW planewave $\rho_{GW}(f) = \frac{\langle \dot{h}^2 \rangle}{16\pi G}$

$$\Omega_{GW}(f) \equiv \frac{f}{\rho_c}\frac{d\rho_{GW}}{df} = \frac{f}{\rho_c}\frac{\rho_{GW}(f)}{\Delta f}$$

$$\Delta f / f = v_{vir}^2 \simeq 10^{-6}$$

Concretely predicted by Maxwell–Boltzmann distribution!

A template search is possible, and a better reach is expected!

We make simple estimation based on delta function as a guideline.

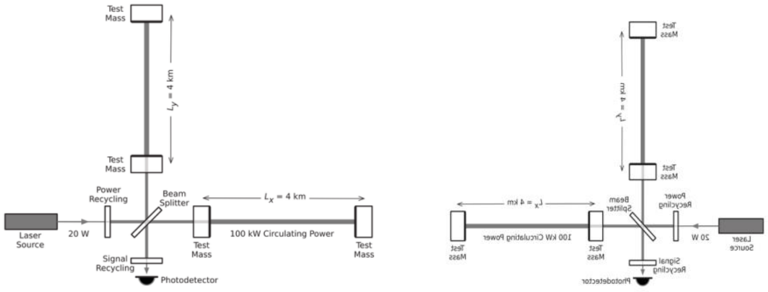
Sensitivity to DPDM signal of GW detectors:

DPDM:

LIGO

$$\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$$

dark photon field value



Livingston/Hanford:
Approximately a constant (-0.9) for all frequencies we are interested.

Virgo (-0.25) may be useful for cross checks.

Sensitivity to DPDM signal of GW detectors:

DPDM:

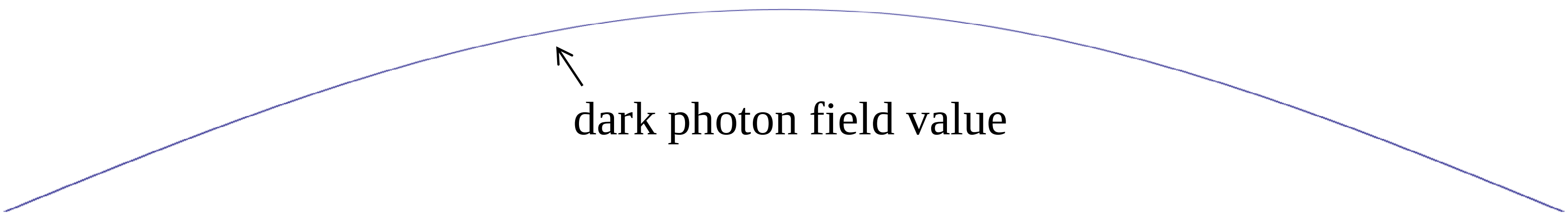
LISA

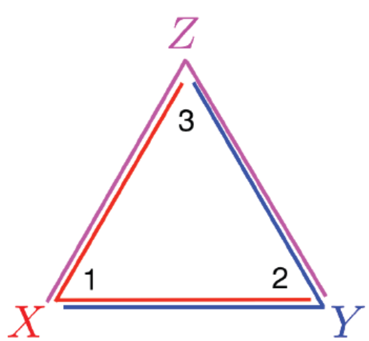
$$\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$$

$$A \equiv \frac{1}{3}(2X - Y - Z)\,,$$

$$E \equiv \frac{1}{\sqrt{3}}(Z - Y)\,,$$

$$\langle AE \rangle$$

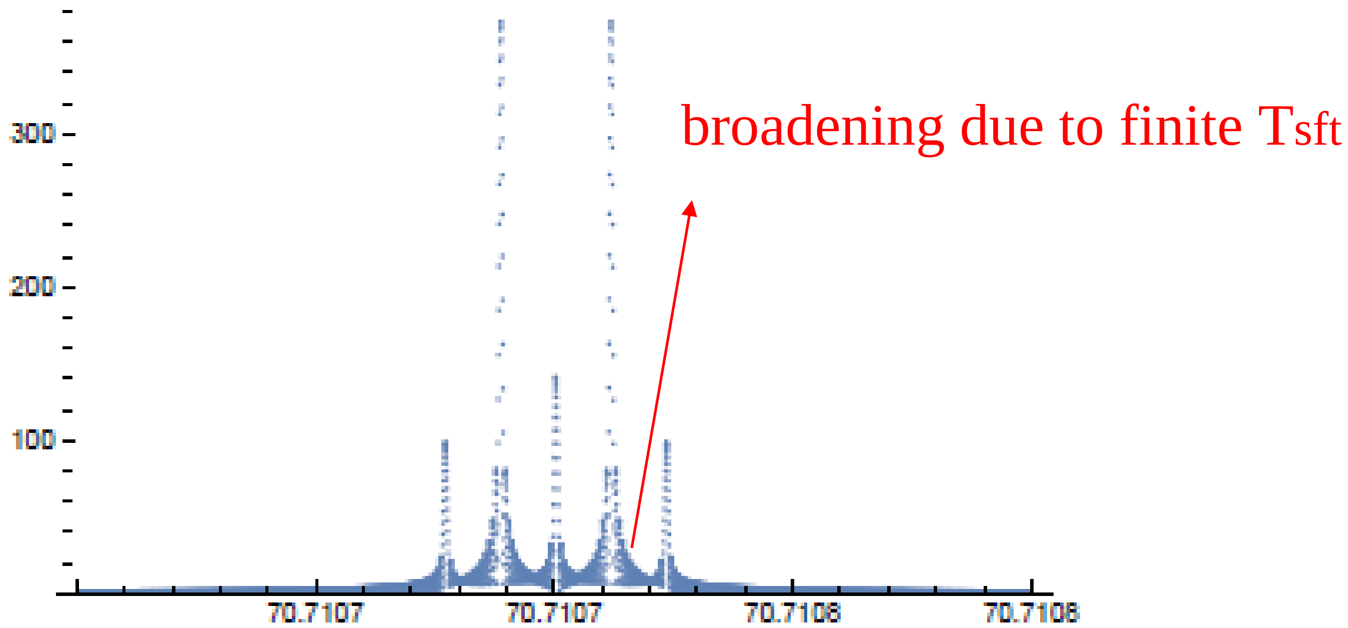




⇨ Approximately a constant (-0.3) for all frequencies we are interested.

Earth Rotation Effects:

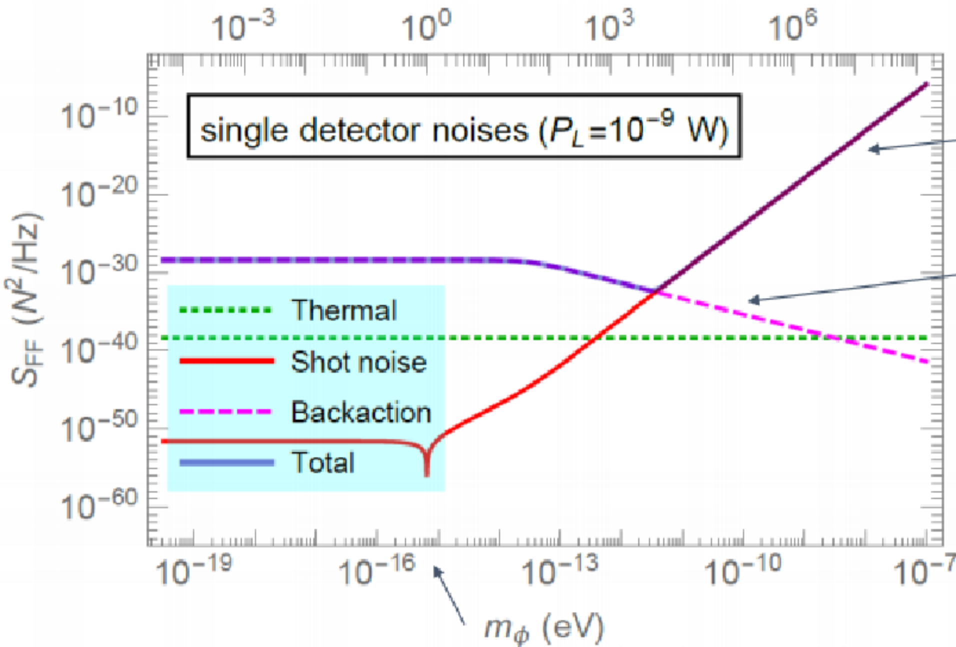
$$R_L \approx -\sum_{i=1}^{n} \frac{\cos(\omega_i t + \Phi_i)}{\omega_i^2} \Big(C^i_{2,1} \cos(2\omega_E t) + C^i_{2,2} \sin(2\omega_E t) + C^i_{1,1} \cos(\omega_E t) + C^i_{1,2} \sin(\omega_E t) + C^i_0 \Big)$$



Detecting monochromatic forces

Minimum force amplitude detectable:

$$F_* = \sqrt{S_{FF}(\omega_s)/T_{int}}$$



Detector fundamental frequency

Fluctuations in laser phase (~1/P_L)

Fluctuations in laser amplitude (~P_L)

$$S_{FF}^T = \gamma m_s kT + PA_s\sqrt{m_a kT}$$

$$S_{FF}^{M,SQL}(\omega_s) = 2m_s\sqrt{(\omega_s^2-\omega_m^2)^2+\gamma^2\omega_m^2}$$

$$S_{FF}^M = S_{FF}^{BA} + S_{FF}^{SN}$$