Searching for Dark Photon DM with GW Detectors, O1 and beyond

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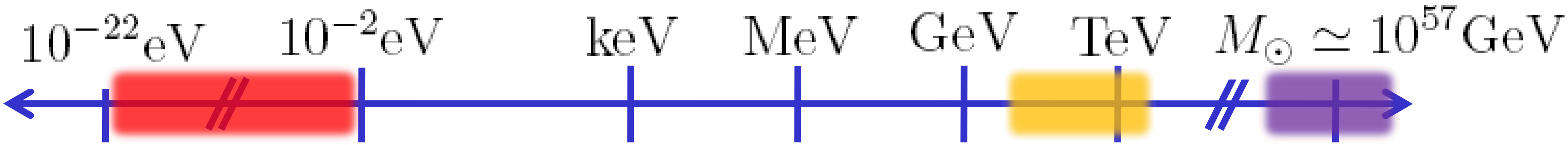
Aaron Pierce, Keith Riles, Yue Zhao
arXiv:1801.10161 [hep-ph]
Phys.Rev.Lett. 121 (2018) no.6, 061102

Huaike Guo, Keith Riles, F.W. Y., Yue Zhao
arXiv:1905.04316 [hep-ph]
Nature - Commun.Phys. 2 (2019) 155

Popular Choices:



- WIMPs:

  100 GeV ~ TeV

- Very light DM particles

  Axion and Dark "Photon"

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

Huaike Guo, Keith Riles, F.W. Y., Yue Zhao
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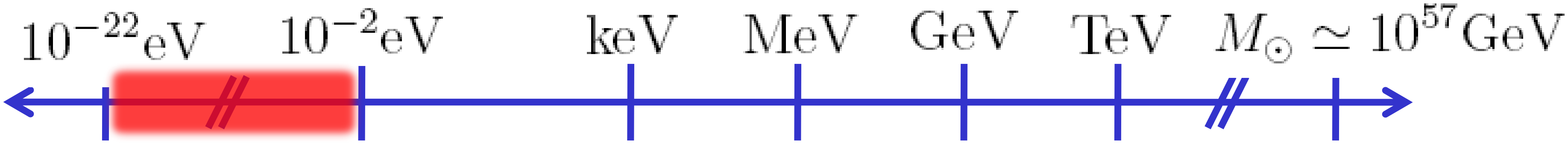
- Primordial Black Holes:

  10^{-7} ~ 100 solar mass

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

Popular Choices:



gauge boson of the

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

(p+n) (n)

- Very light DM particles

  Axion and $\boxed{\text{Dark "Photon"}}$

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

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 $\boxed{\text{Stueckelberg mechanism.}}$

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

- Relic abundance (non-thermal production)

Misalignment mechanism

Light scalar decay

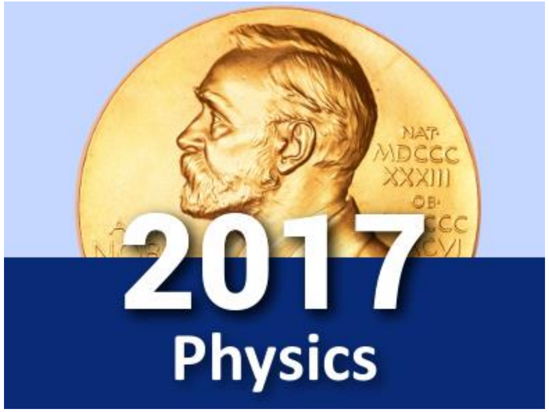
Production from cosmic string

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

Laser Interferometer Gravitational-Wave Observatory

LIGO (ground-based)

Amazing precision at LIGO:
O(1/1000) the radius of a single proton!

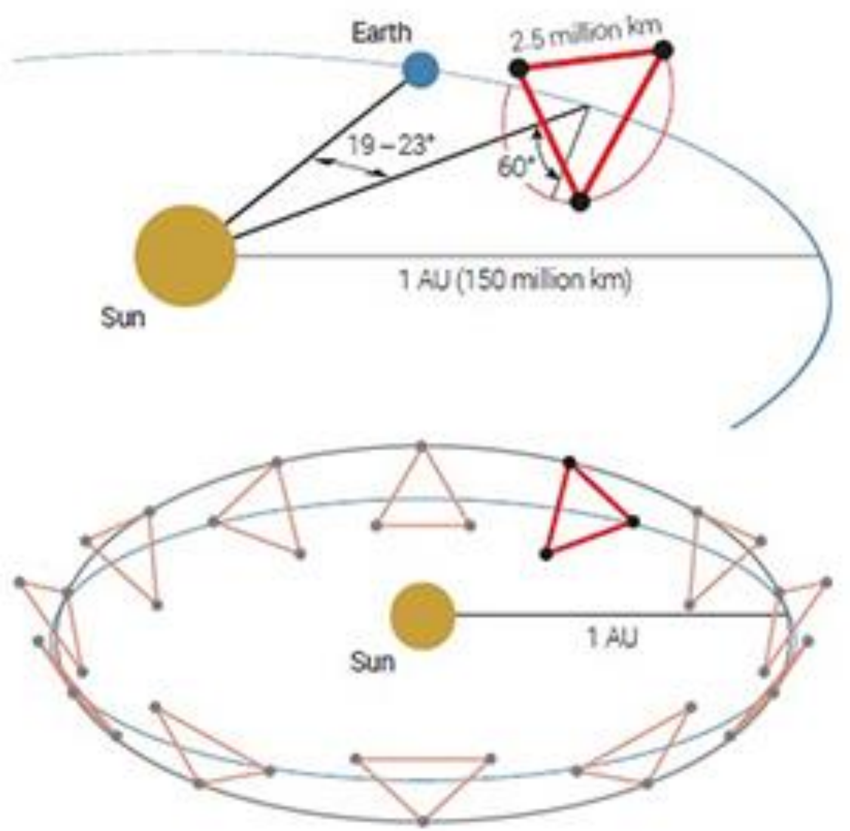


Opened a field:
Gravitational Wave Astronomy

Enrich our understanding on fundamental physics and early cosmology.

Laser Interferometer Space Antenna

LISA (space-based)



(LISA Mission Consortium)

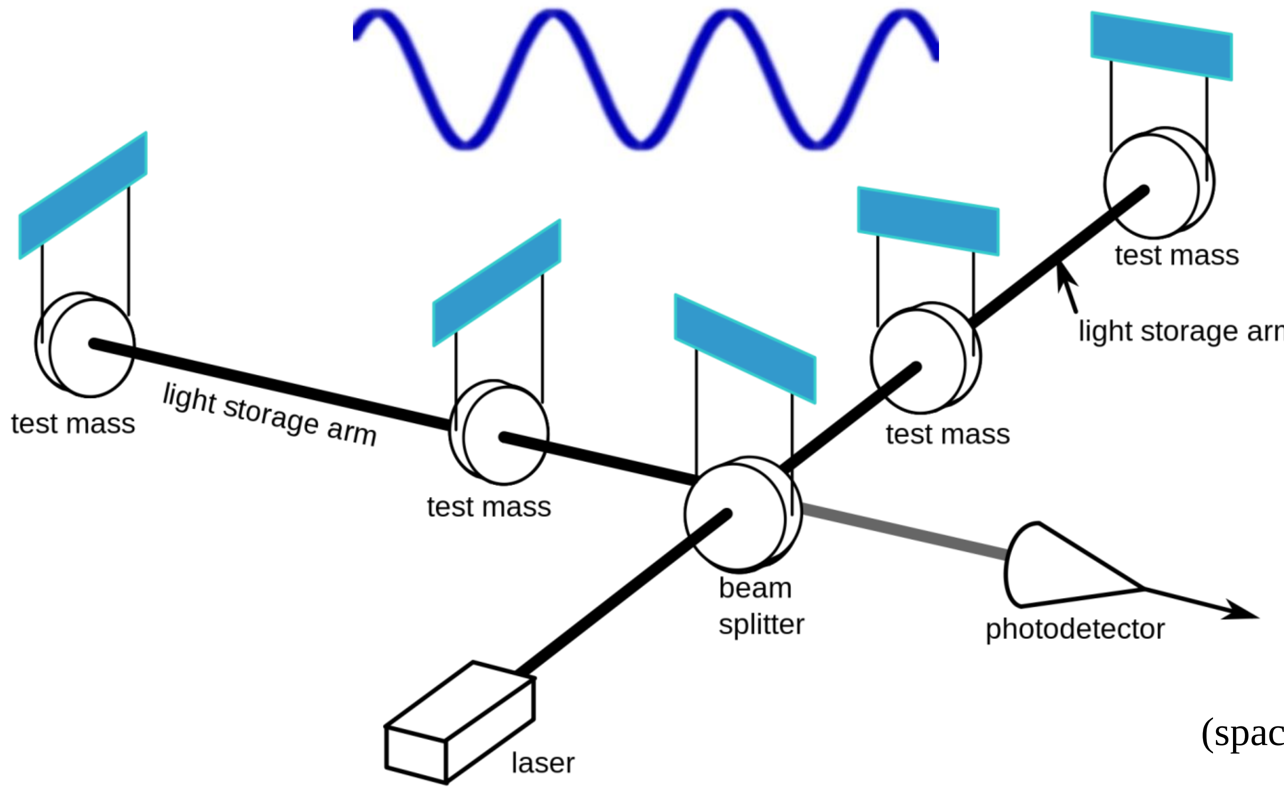
Recently approved by the European Space Agency.

U.S. (NASA) just rejoined the program.

LISA PathFinder is a great success!

General Picture:

LIGO/LISA: advanced Michelson–Morley interferometer

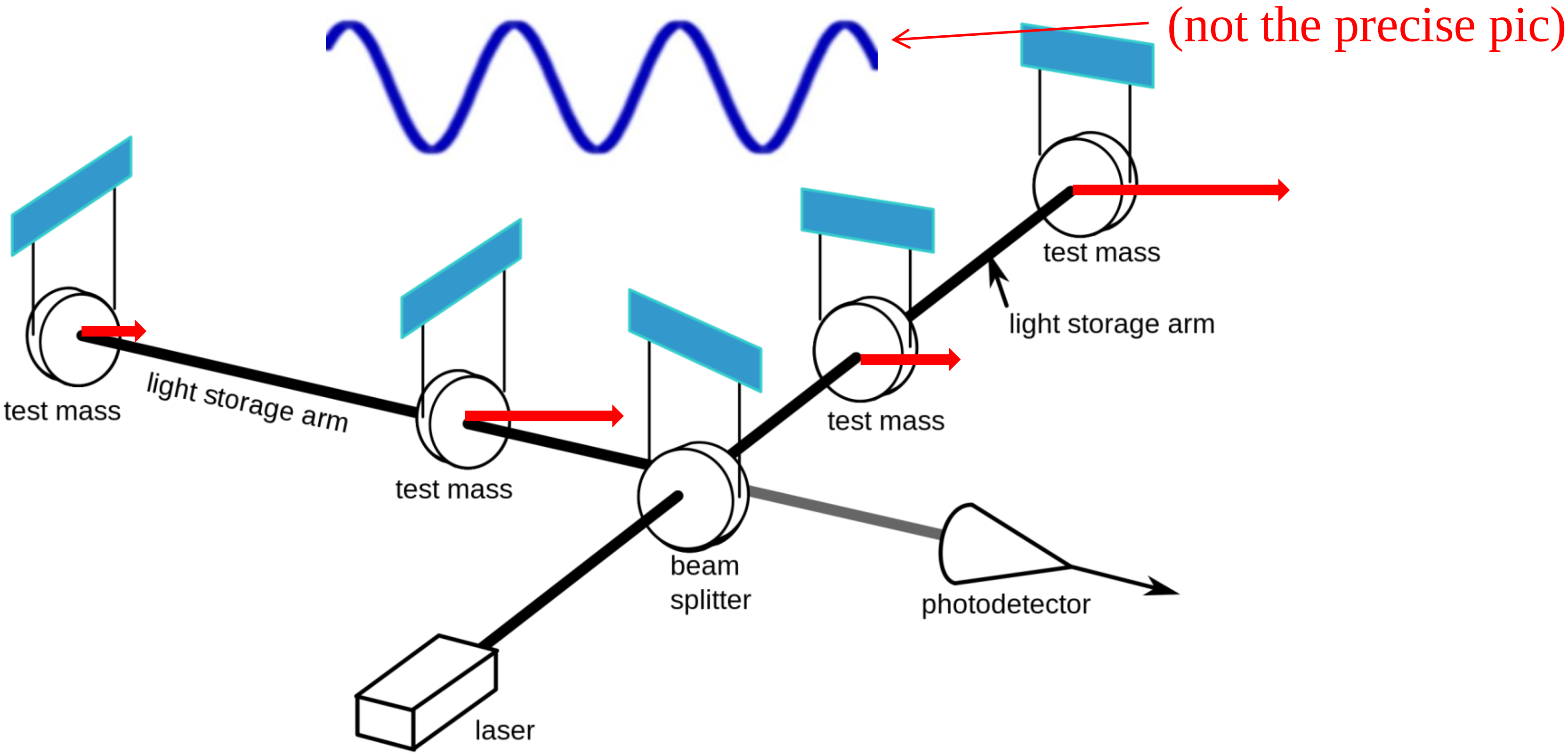


(space.com)

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

General Picture:

Ultra-light DM ⇨ classical oscillating background field



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

Maximal Displacement:

Local DM energy density:

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

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:

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

dark photon coupling

dark electric field

charge mass ratio of the test object

Silicon mirror:

U(1)B : 1/GeV

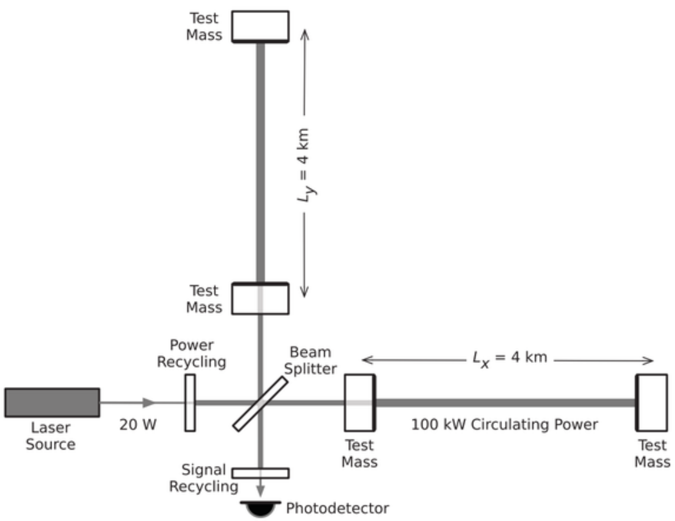
U(1)B-L : 1/(2GeV)

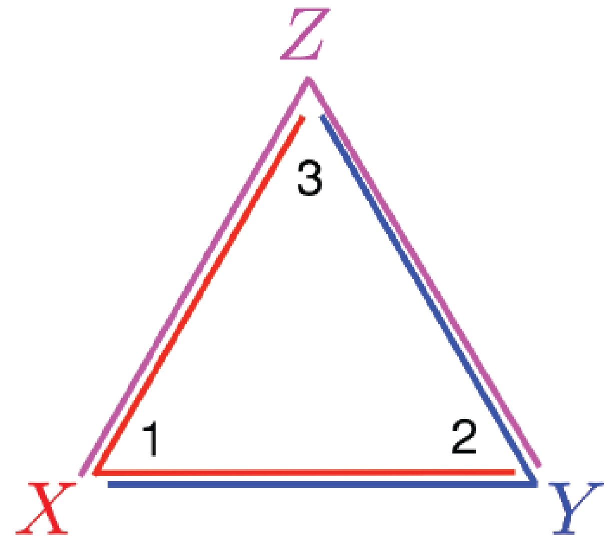
projected along
the arm direction

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

Maximal GW-like Displacement:

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





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

Averaging on directions of acceleration and momentum vectors.

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

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

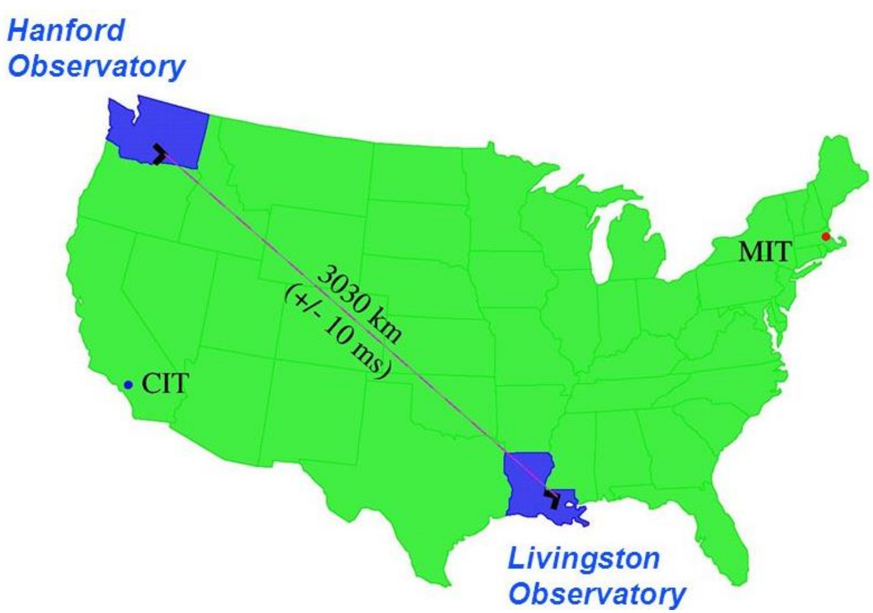
$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f} \right)$$

Within the coherent distance, the detectors will experience almost the same DPDM background field.

Properties of DPDM Signals:

Correlation between two sites is important to reduce background!

dark photon field value



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

Virgo is not very well aligned with two LIGO GW detectors. The correlation for Virgo-LIGO is not significant.

Sensitivity to DPDM signal of GW detectors:

First we estimate the sensitivity in terms of GW strain.

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

later map to ΔL/L

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 $\rho_{GW}(f) = \frac{\langle \dot{h}^2 \rangle}{16\pi G}$

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

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

Concretely predicted by
Maxwell–Boltzmann distribution!

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

Sensitivity to DPDM signal of GW detectors:

Translate strain sensitivity to parameters of DPDM:

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

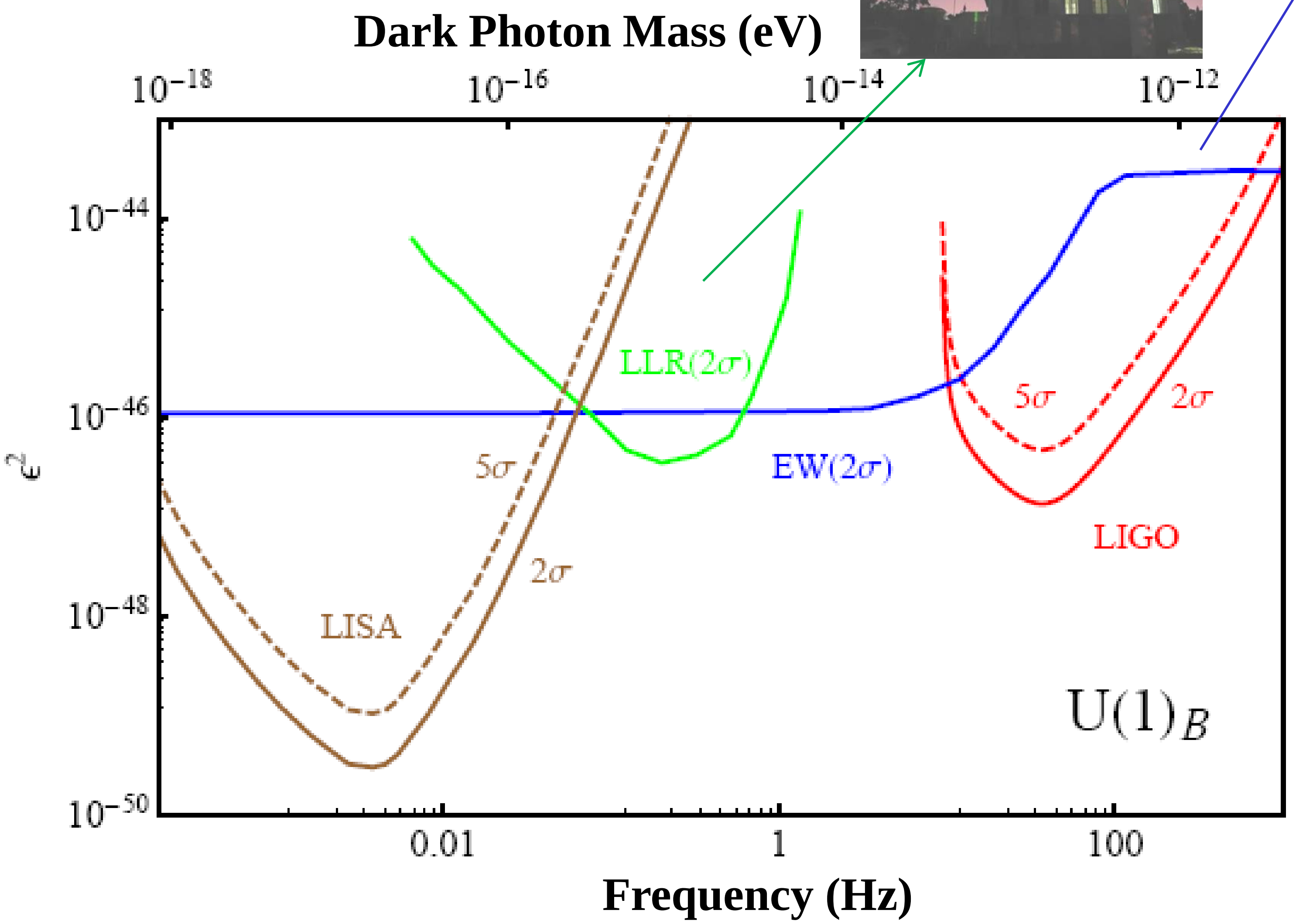
effectively the max differential displacement of two arms

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

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

⇨ sensitivity of DPDM parameters (mass, coupling)

Sensitivity Plot:



(Eöt-Wash web)

Loránd Eötvös

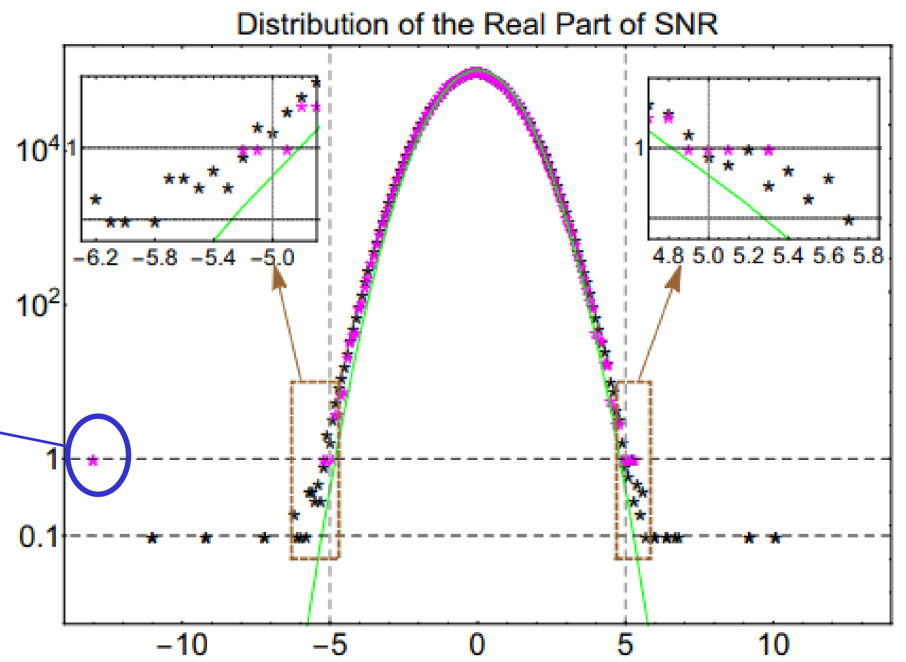
⟶ Eöt-Wash

design sensitivities, 2 yrs

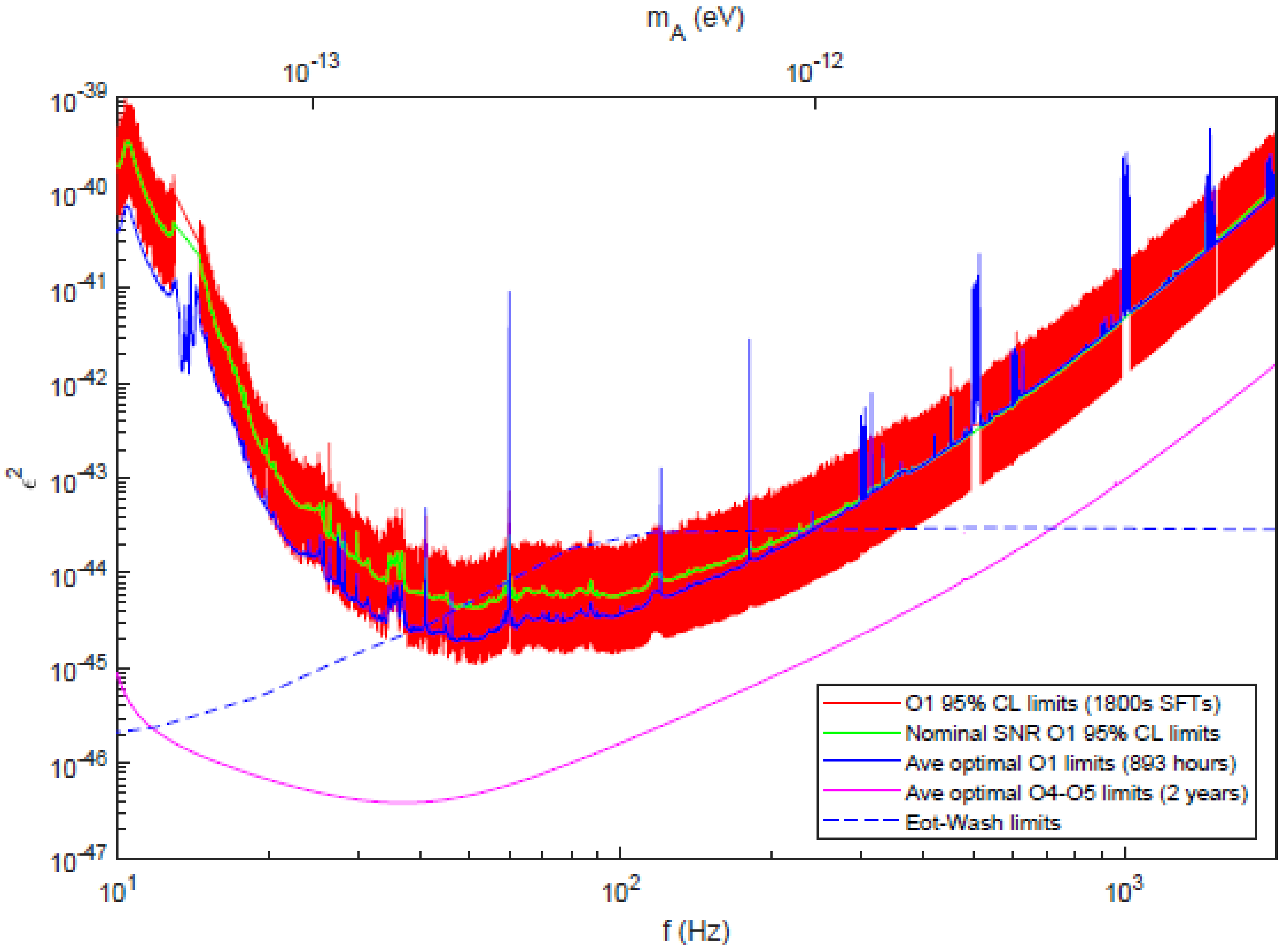
O1 Result:

- 1800s FT: optimized for a signal at f~500 Hz
- Remove known noise bins and their neighbor bins
- Within 10-2000 Hz frequency band, require Re[SNR] < −5.8
  ~ 1% false alarm probability after including trial factors.
- Frequency lags: to deal with non-Gaussian noise
  offset bins (−50, −40, ..., −10, +10, ..., +50)
  Remove single interferometer
  artifacts and broadband
  correlated artifacts

known continuous wave
“hardware injections”
with random phase



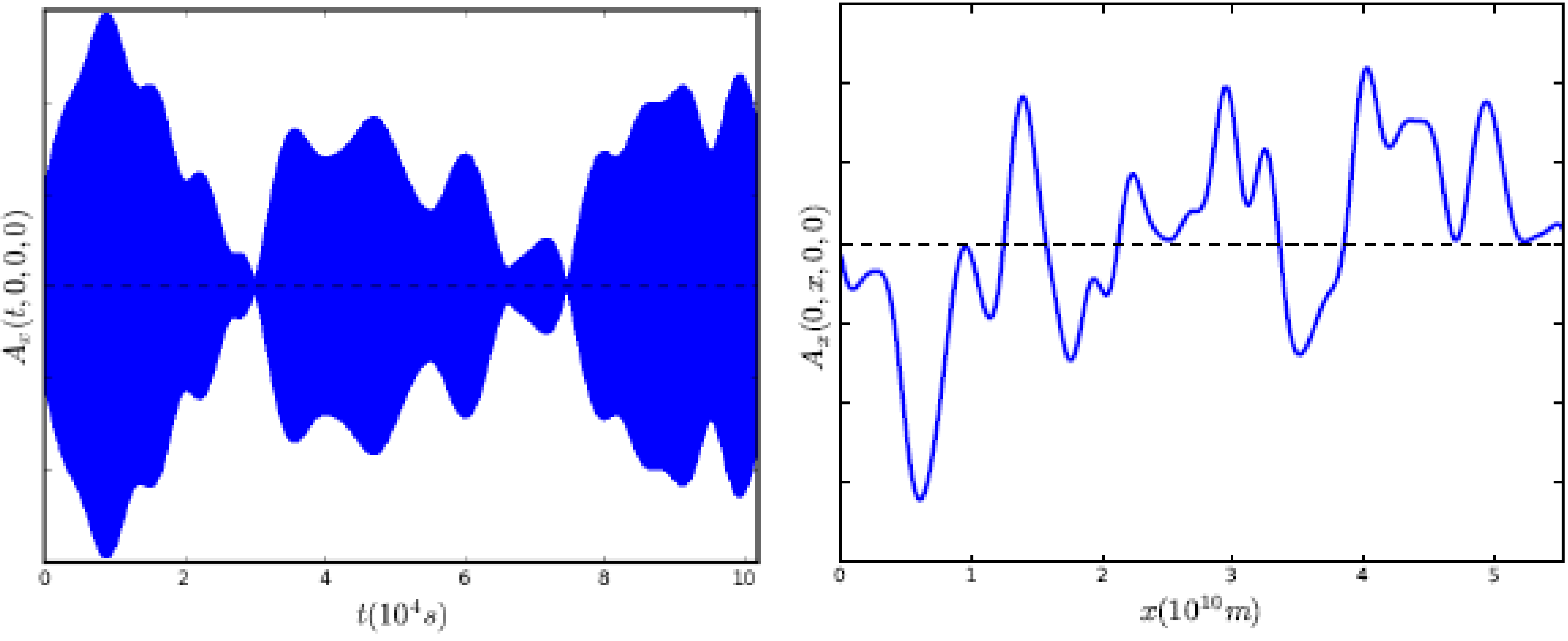
O1 Result:



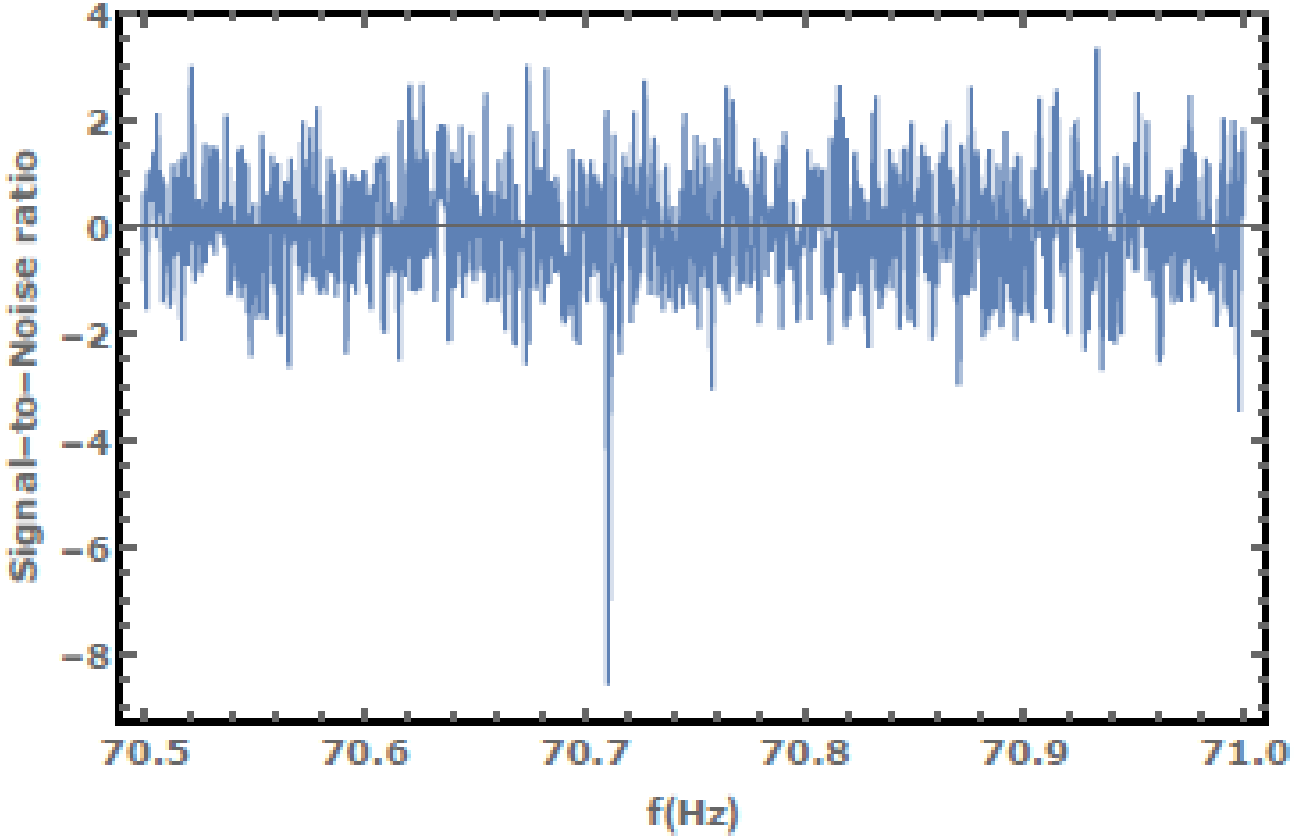
m_A (eV)
10^{-13}
10^{-12}
ϵ^2
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{1}
10^{2}
10^{3}
f (Hz)
O1 95% CL limits (1800s SFTs)
Nominal SNR O1 95% CL limits
Ave optimal O1 limits (893 hours)
Ave optimal O4-O5 limits (2 years)
Eot-Wash limits

Modeling DPDM background:

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



LIGO simulation output:



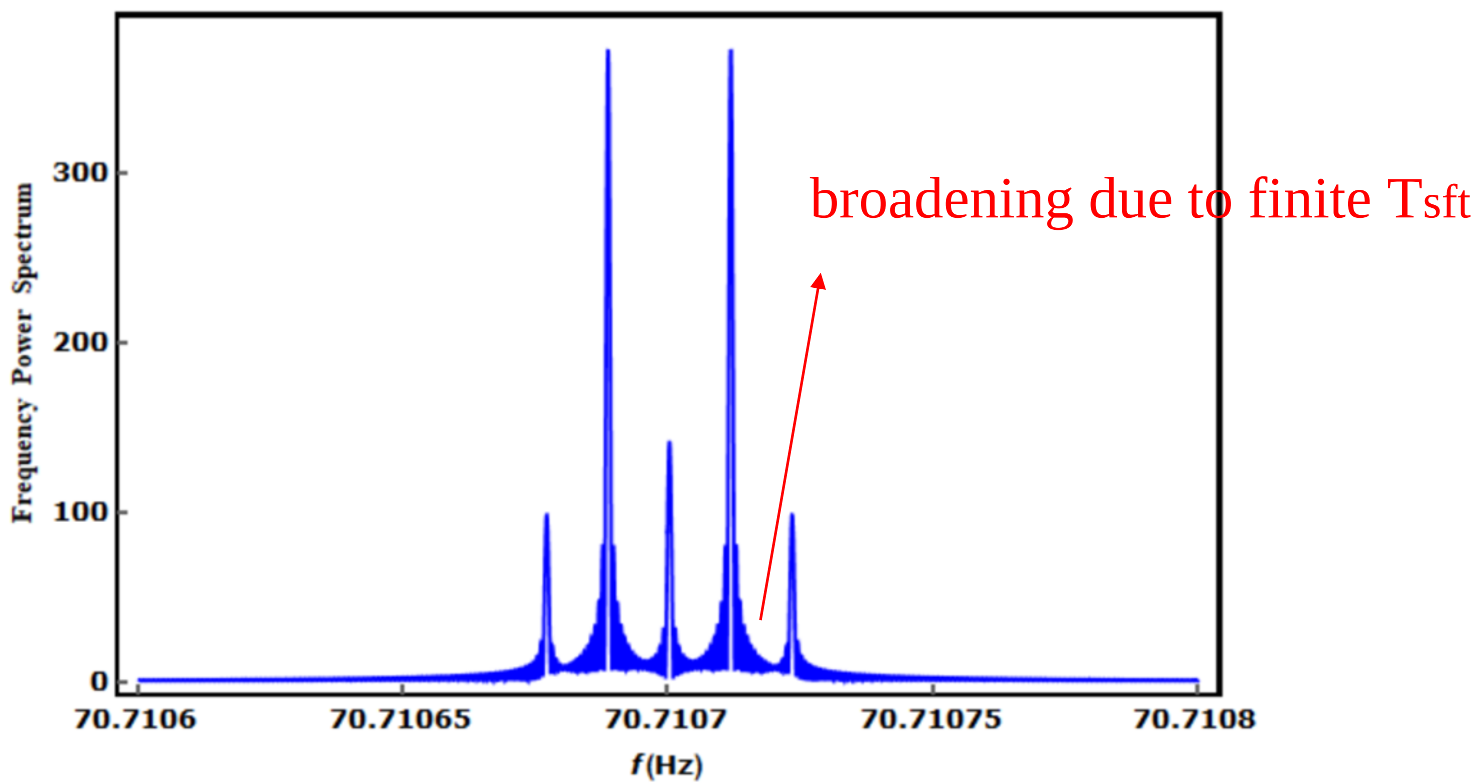
$\epsilon^2 = 5\times10^{-44}$ $f = 70.71$ Hz $T_{SFT} = 1800$ s $T_{tot} = 200$ hr

$\Rightarrow$ SNR $\simeq -8$.

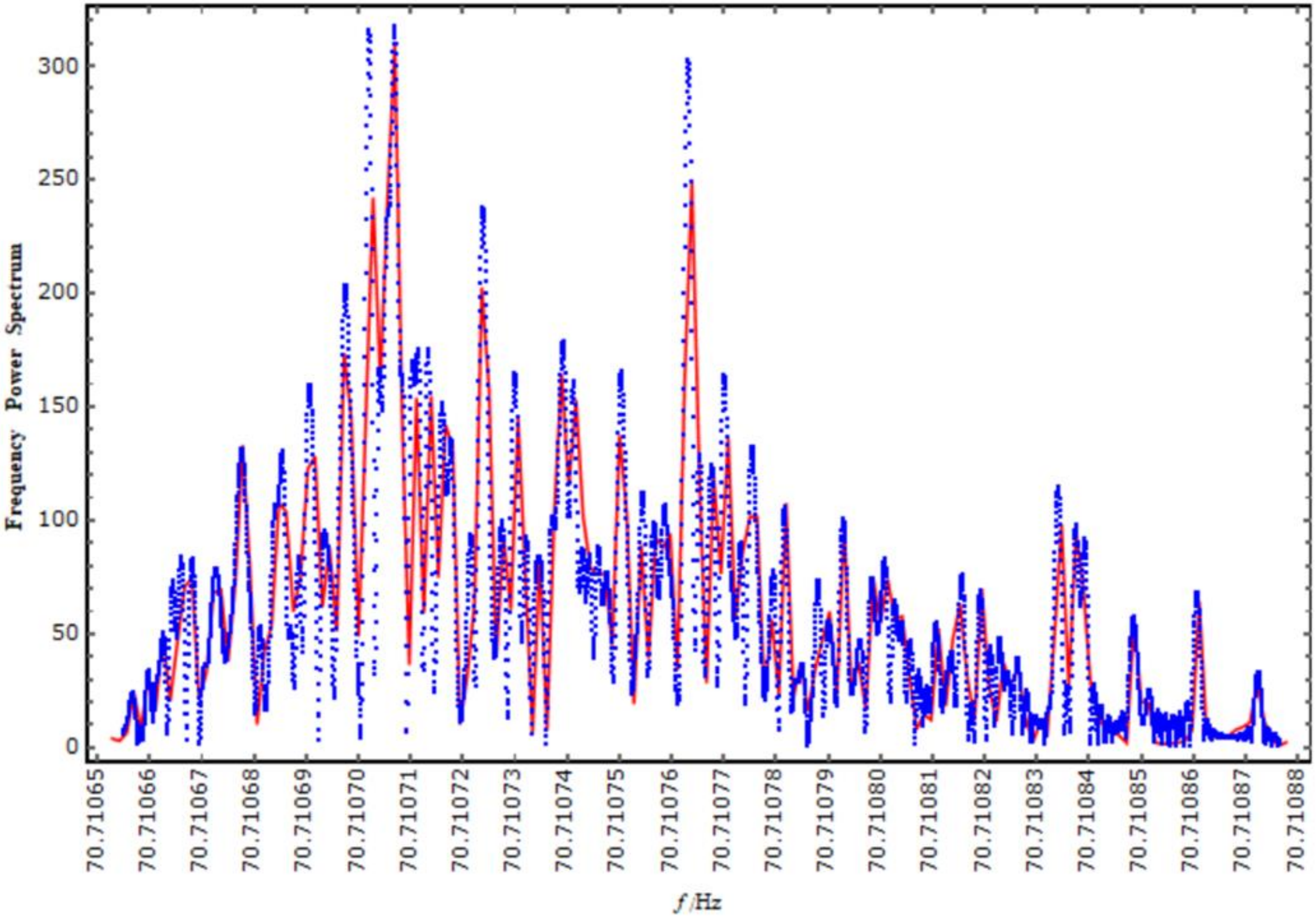
Earth Rotation Effects:

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

$$C^i_{2,2} \sin(2\omega_E t) + C^i_{1,1} \cos(\omega_E t) + C^i_{1,2} \sin(\omega_E t) + C^i_0 \Big)$$



Fine structure of the signal:



Analytic understanding matches very well with numerical result!

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 background.

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!