Searching for Dark Photon Dark Matter with Gravitational Wave Detectors

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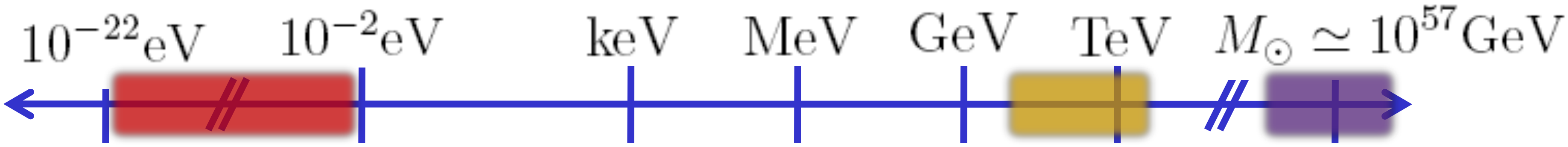
Aaron Pierce, Keith Riles, Y.Z.
arXiv:1801.10161 [hep-ph]
Phys.Rev.Lett. 121 (2018) no.6, 061102

Huaike Guo, Keith Riles, Fengwei Yang, Y.Z.
arXiv:190x.xxxxx [hep-ph]

Internally reviewed by LIGO.
O1 data analysis is almost done!

Popular Choices:



- WIMPs:

  100 GeV ~ TeV

- Very light DM particles

  Axion and Dark "Photon"

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

Aaron Pierce, Keith Riles, Yue Zhao
Phys.Rev.Lett. 121 (2018) no.6, 061102

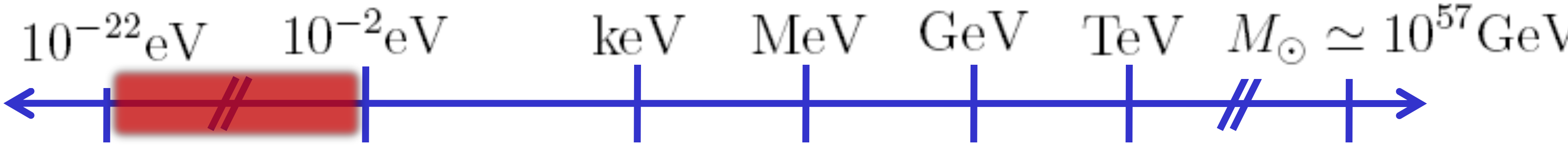
- Primordial Black Holes:

  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 proved by GW detectors!

Popular Choices:



gauge boson of the

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

(p+n) (n)

- Very light DM particles

  Axion and 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 Stueckelberg mechanism.

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

- Relic abundance (non-thermal production)

  Misalignment mechanism

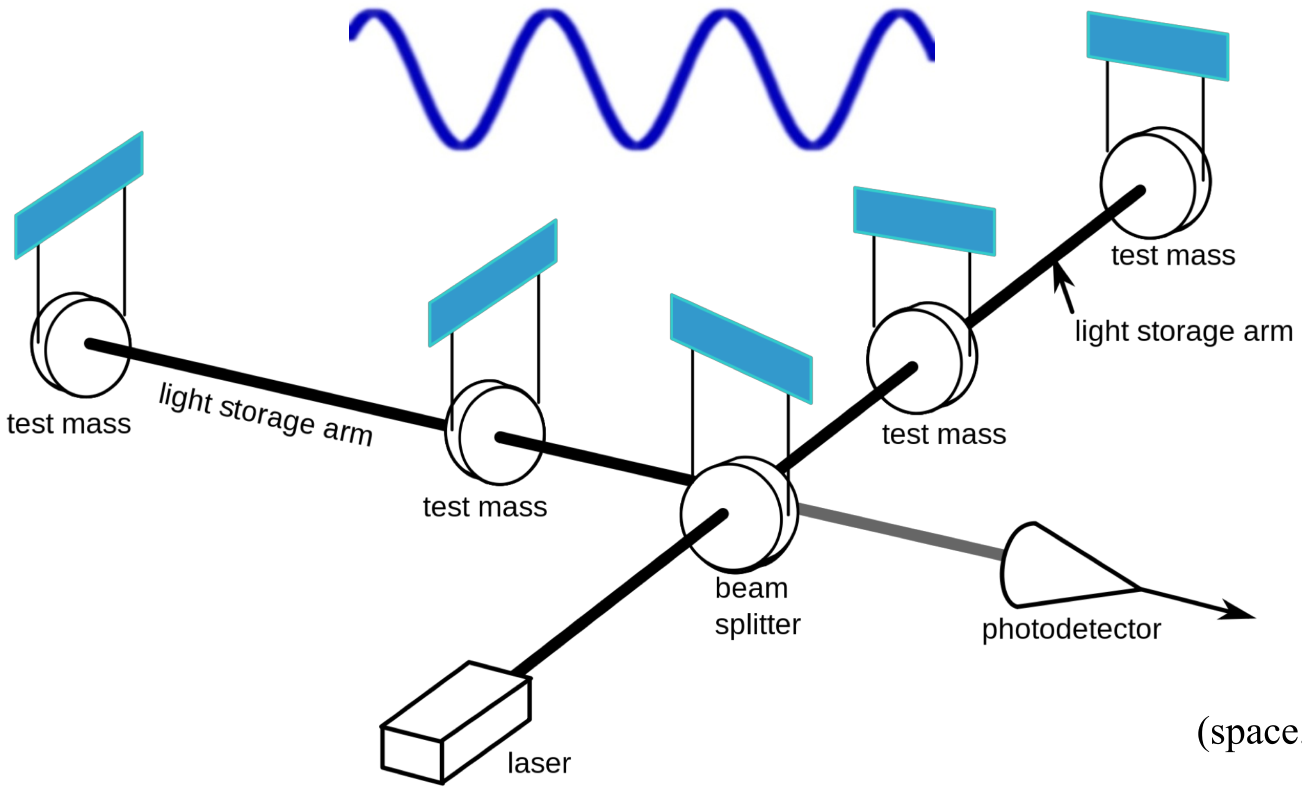
  Light scalar (moduli field) decay

  Production from cosmic string (Andrew's talk)

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

General Picture:

LIGO/LISA: advanced Michelson–Morley interferometer



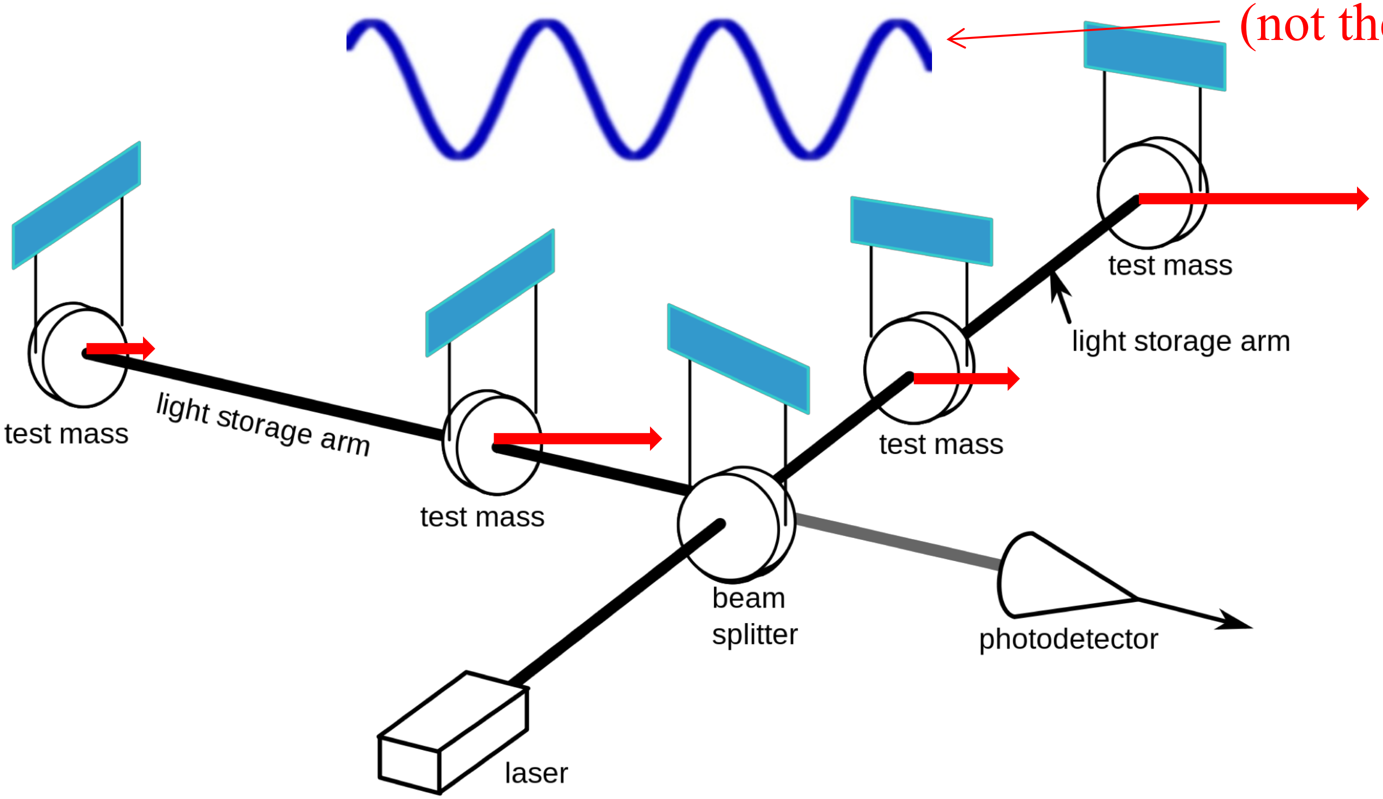
(space.com)

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

General Picture:

Ultra-light DM: coherent state ⇨ 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:

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

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

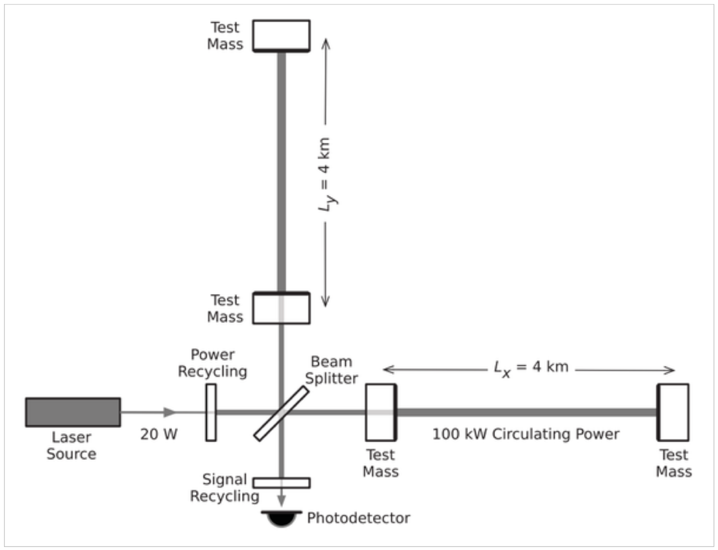
$U(1)_{B-L}$: 1/(2GeV)

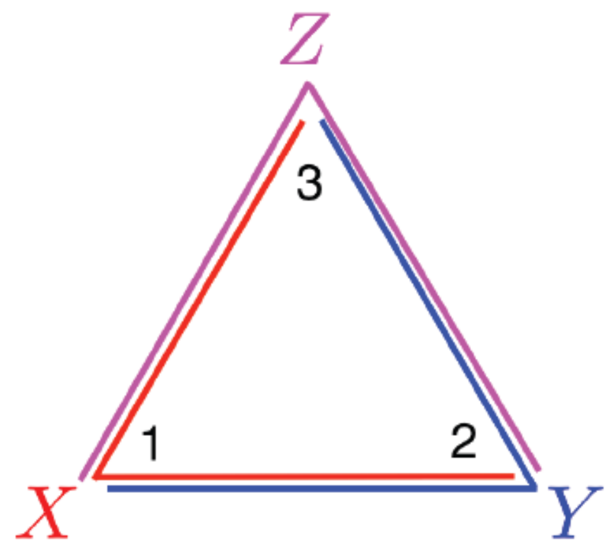
projected along the arm direction

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

Maximal GW-like Displacement:

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





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

Compare this with the sensitivity on strain h.

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

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:

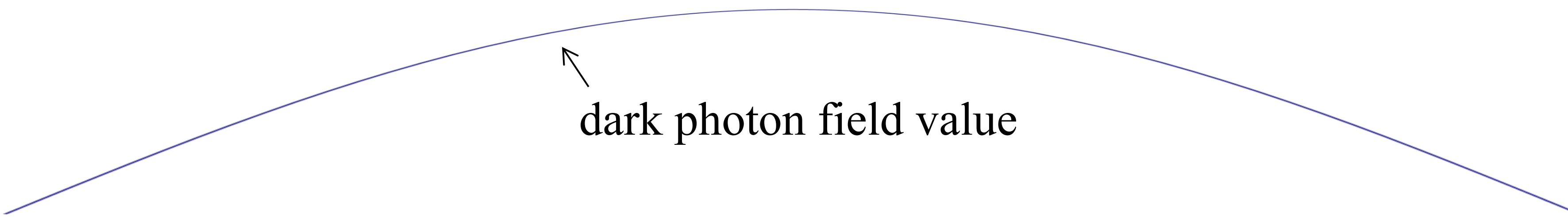
- very long coherent distance

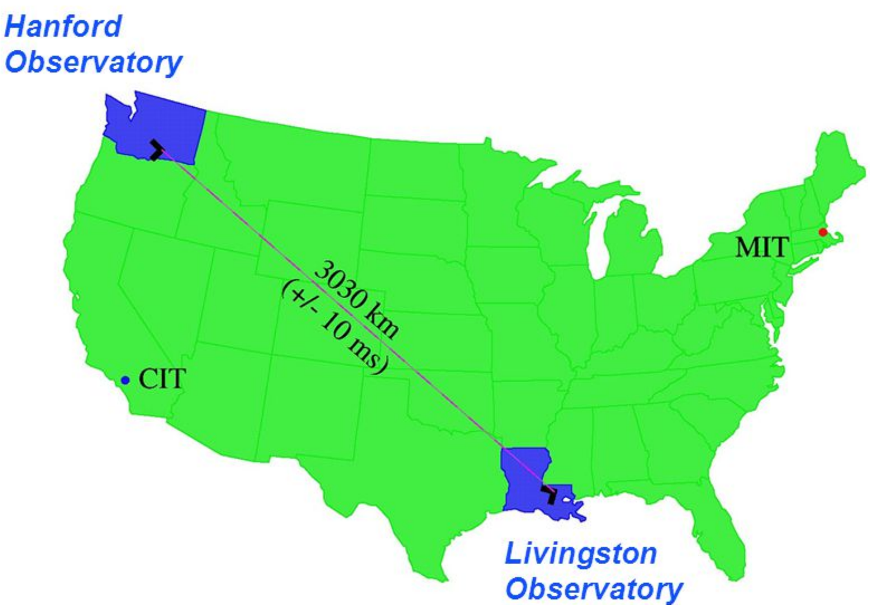
$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f} \right)$$

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:

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

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

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

Concretely predicted by
Maxwell–Boltzmann distribution!

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

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

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)

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

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

optimal filter function
maximize SNR

one-sided strain noise power spectra

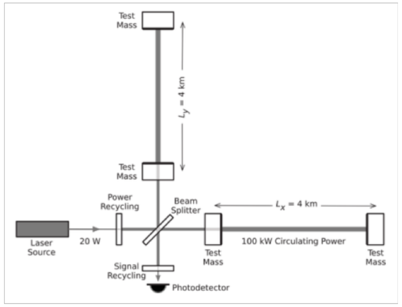
Sensitivity to DPDM signal of GW detectors:

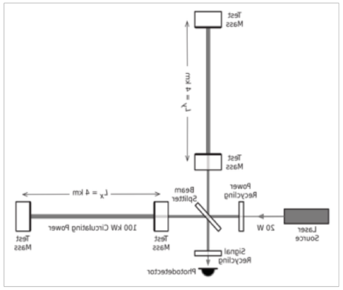
DPDM:

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:

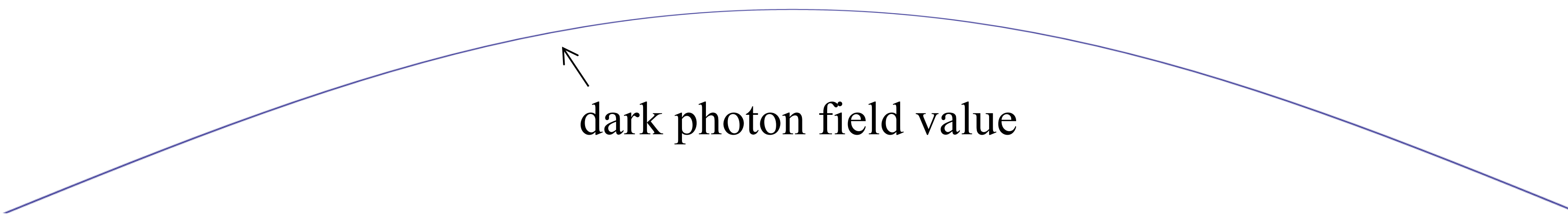
LISA

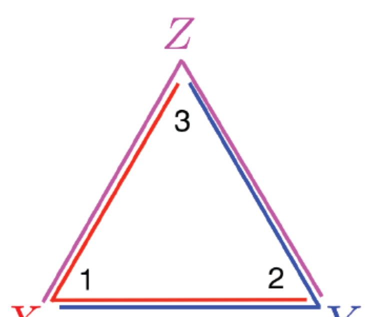
$$\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$$

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

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

$$\langle AE \rangle$$





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

Sensitivity to DPDM signal of GW detectors:

Translate strain sensitivity to parameters of DPDM:

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

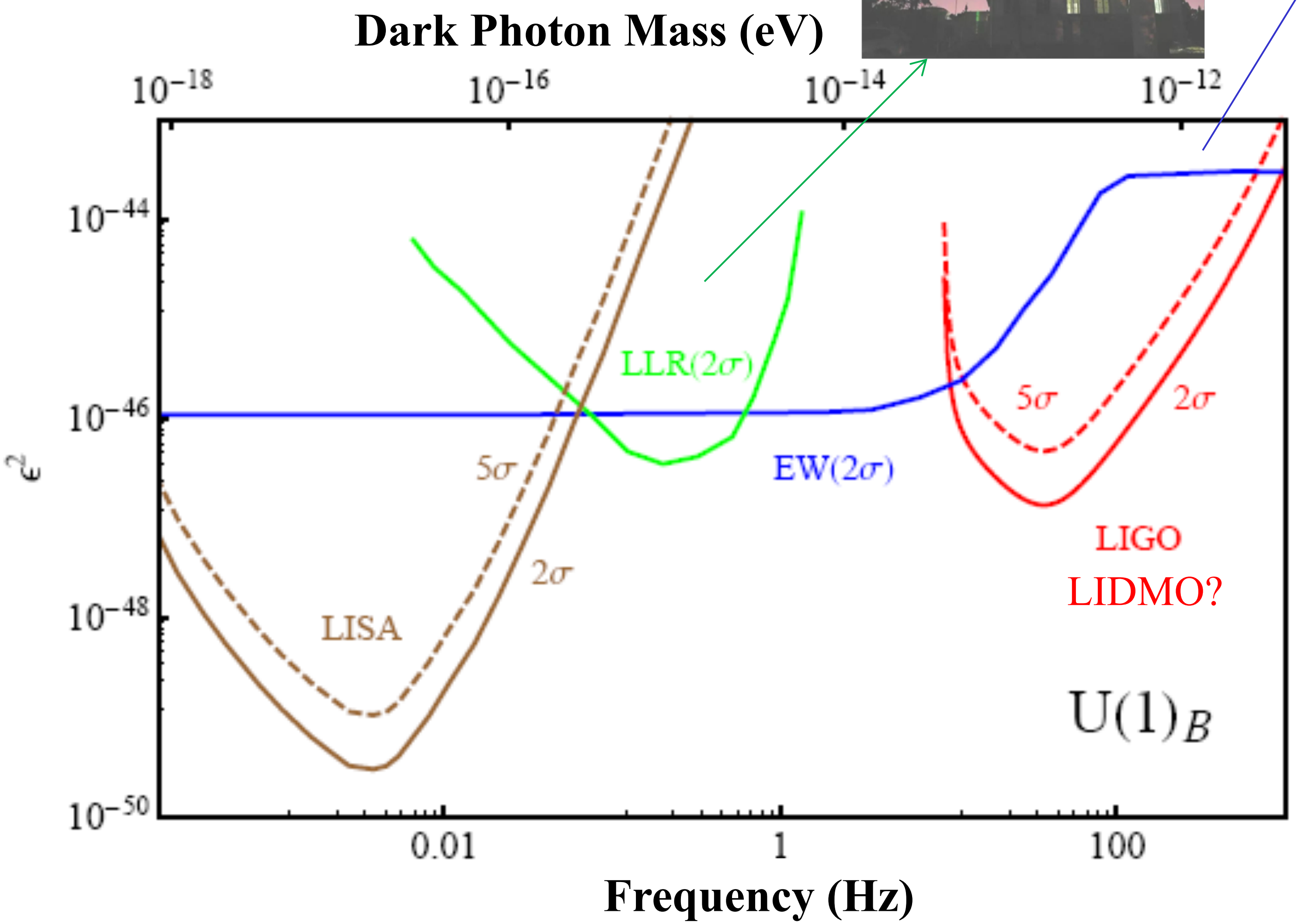
effectively the max differential displacement of two arms

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

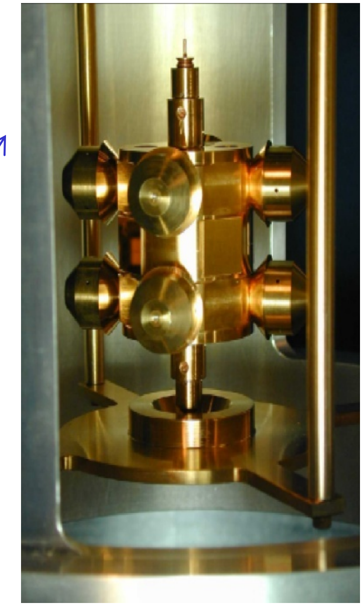
⇨ $\sqrt{\langle \Delta L^2 \rangle}_{LIGO}|_{max}$

⇨ sensitivity of DPDM parameters (mass, coupling)

Sensitivity Plot:



(People's Daily)



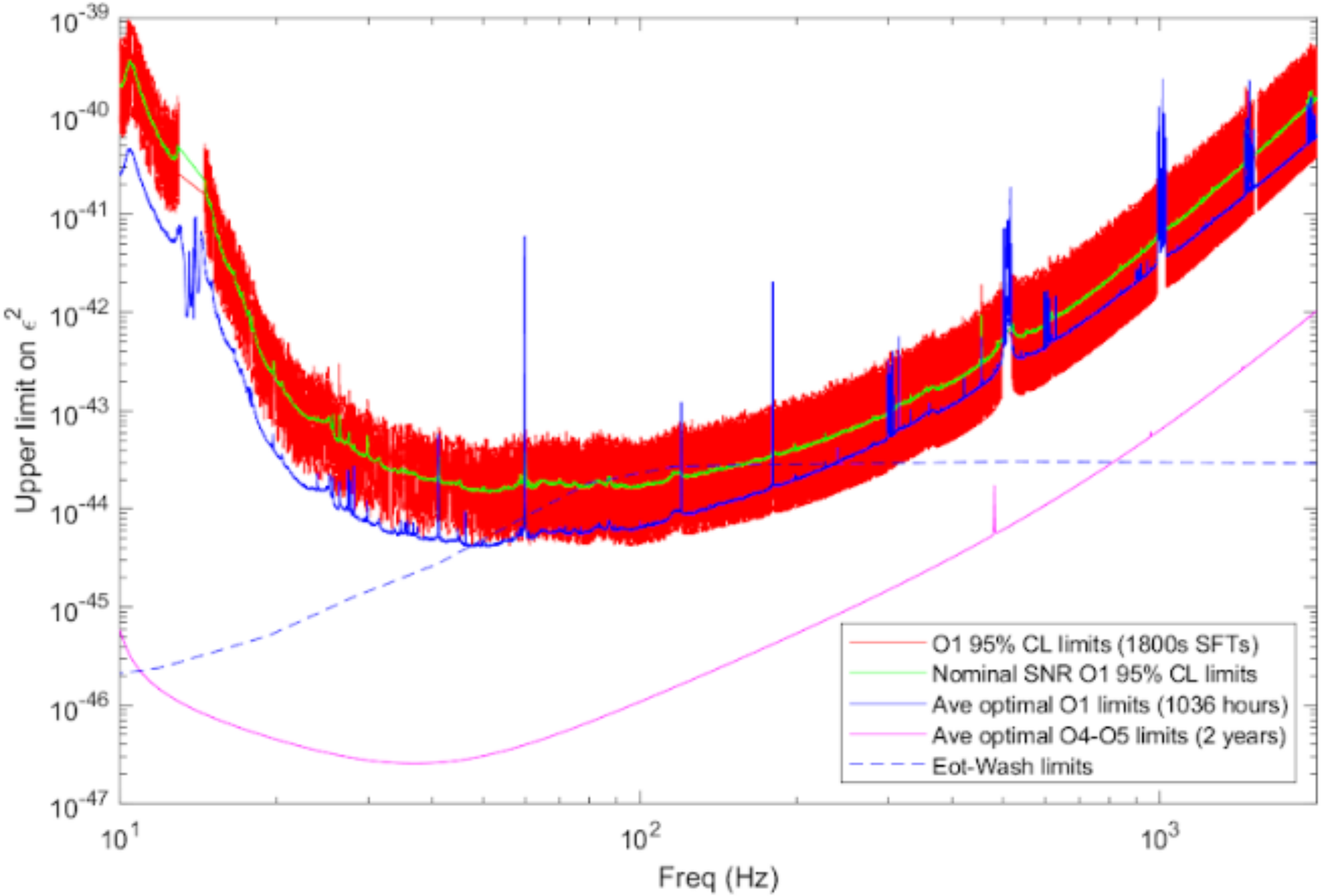
(Eöt-Wash web)

Loránd Eötvös

$\longrightarrow$ Eöt-Wash

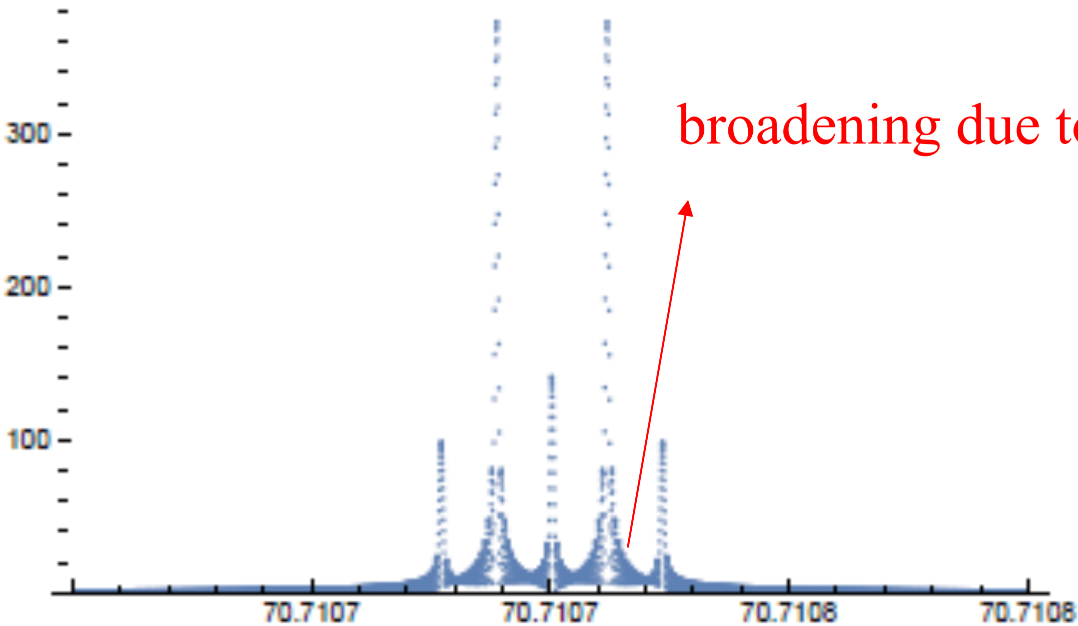
design sensitivities, 2 yrs

O1 Preliminary Result:



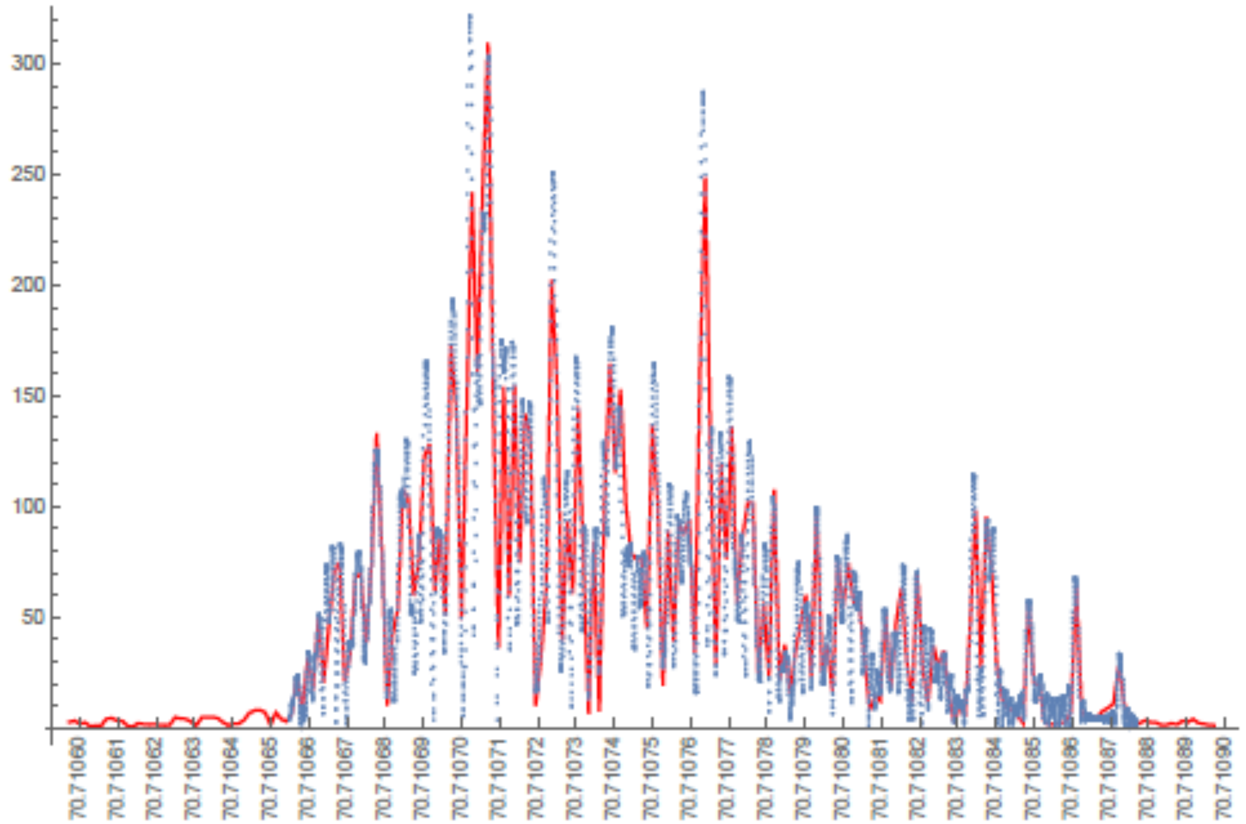
Earth Rotation Effects:

$$R_L \approx -\sum_{i=1}^{n} \frac{\cos(\omega_i t + \Phi_i)}{\omega_i^2} \Big(C_{2,1}^i \cos(2\omega_E t) + C_{2,2}^i \sin(2\omega_E t) + C_{1,1}^i \cos(\omega_E t) + C_{1,2}^i \sin(\omega_E t) + C_0^i \Big)$$



broadening due to finite T_{sft}

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.

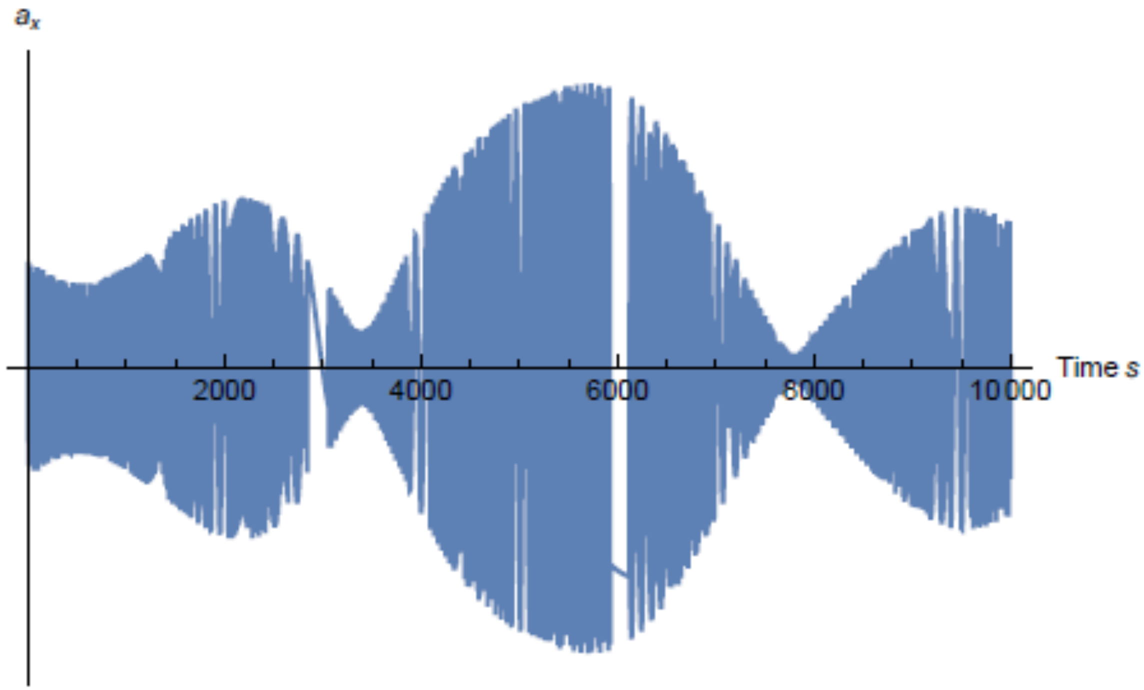
Better coherence between separated interferometers
than Stochastic GW BG.

The sensitivity can be extraordinary!

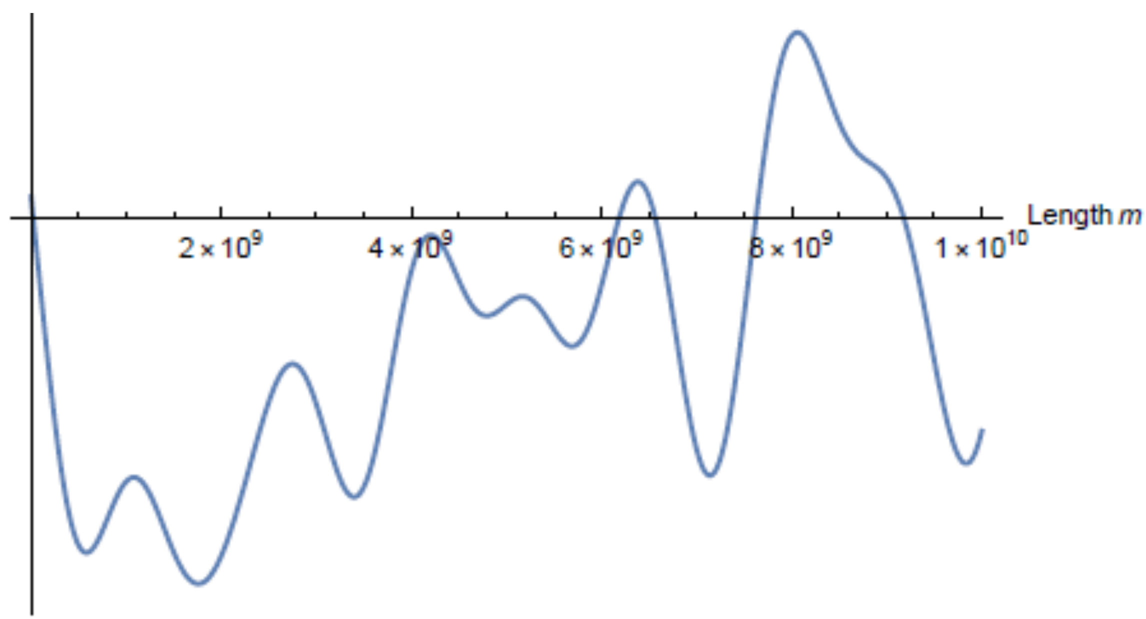
⇨ O1 data has already beaten existing experimental constraints.

Can achieve 5-sigma discovery at unexplored parameter regimes.

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



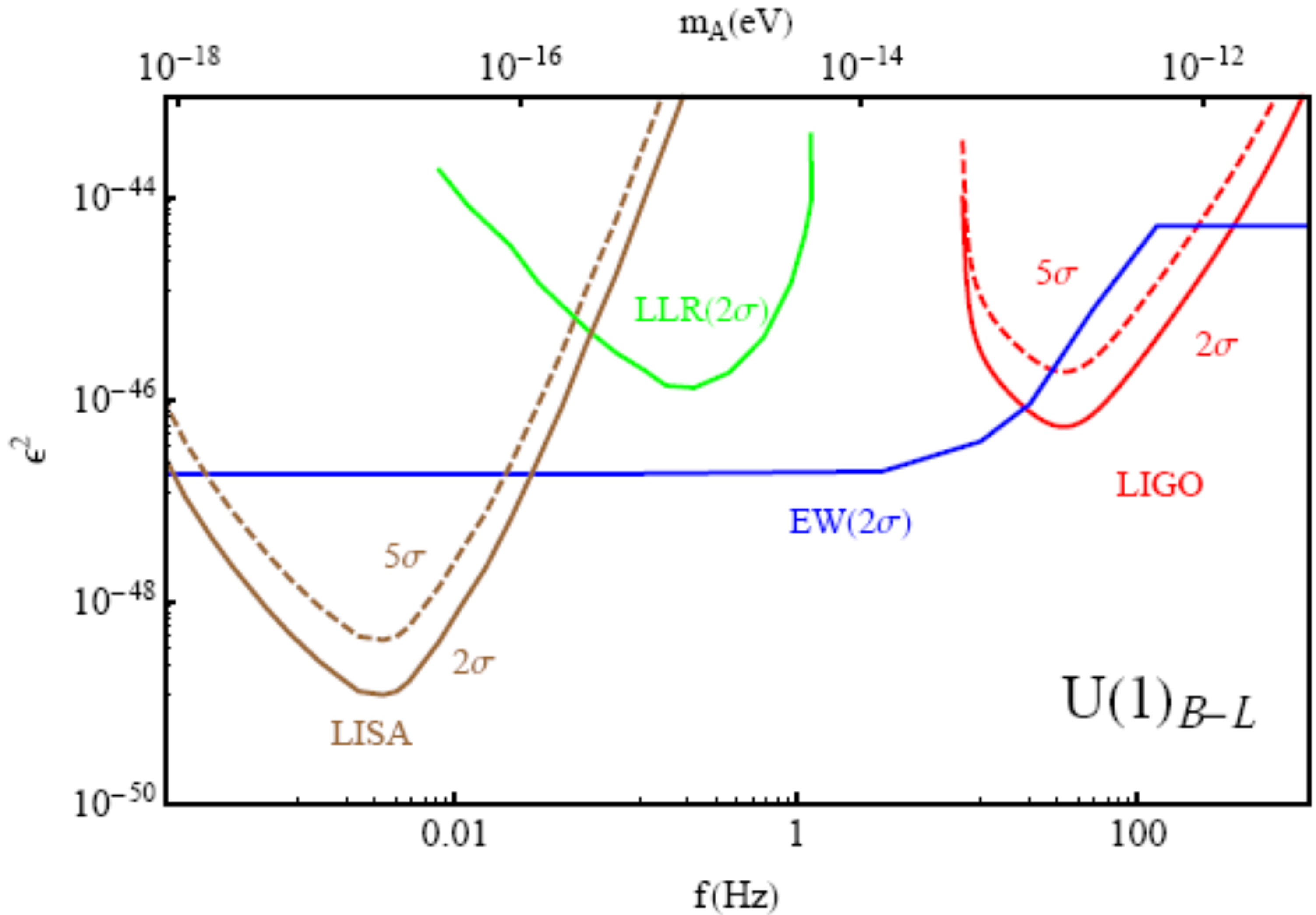
a_x
Time s
2000
4000
6000
8000
10 000



Length m
2×10^9
4×10^9
6×10^9
8×10^9
1×10^{10}

Sensitivity Plot:

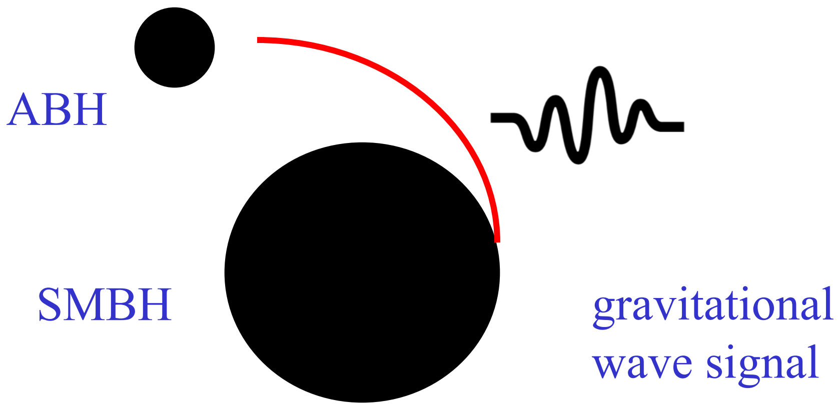
$U(1)_{B-L}$ charge mass ratio: 1/2GeV

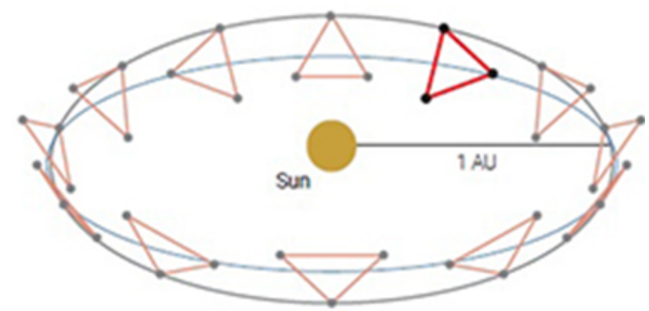


design sensitivities operating for 2 years

LISA-like GW exp for PBH

Extreme Mass Ratio Inspirals

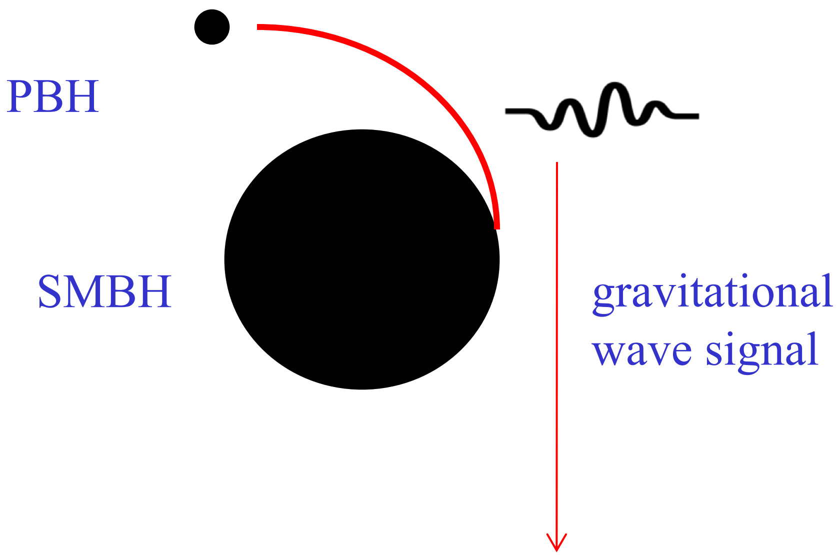


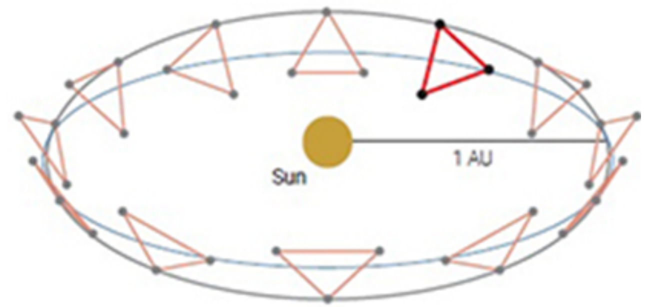


LISA

LISA-like GW exp for PBH

Extreme Mass Ratio Inspirals





LISA

Same frequency, but smaller amplitude!

Master Formula:

$$\Gamma = \int \boxed{\mathcal{R}(M,\mu)} \boxed{\left(\frac{dn(M,z)}{dM}dM\right)} \boxed{(p(s,z)ds)} \boxed{\left(\frac{dV_c}{dz}dz\right)}$$

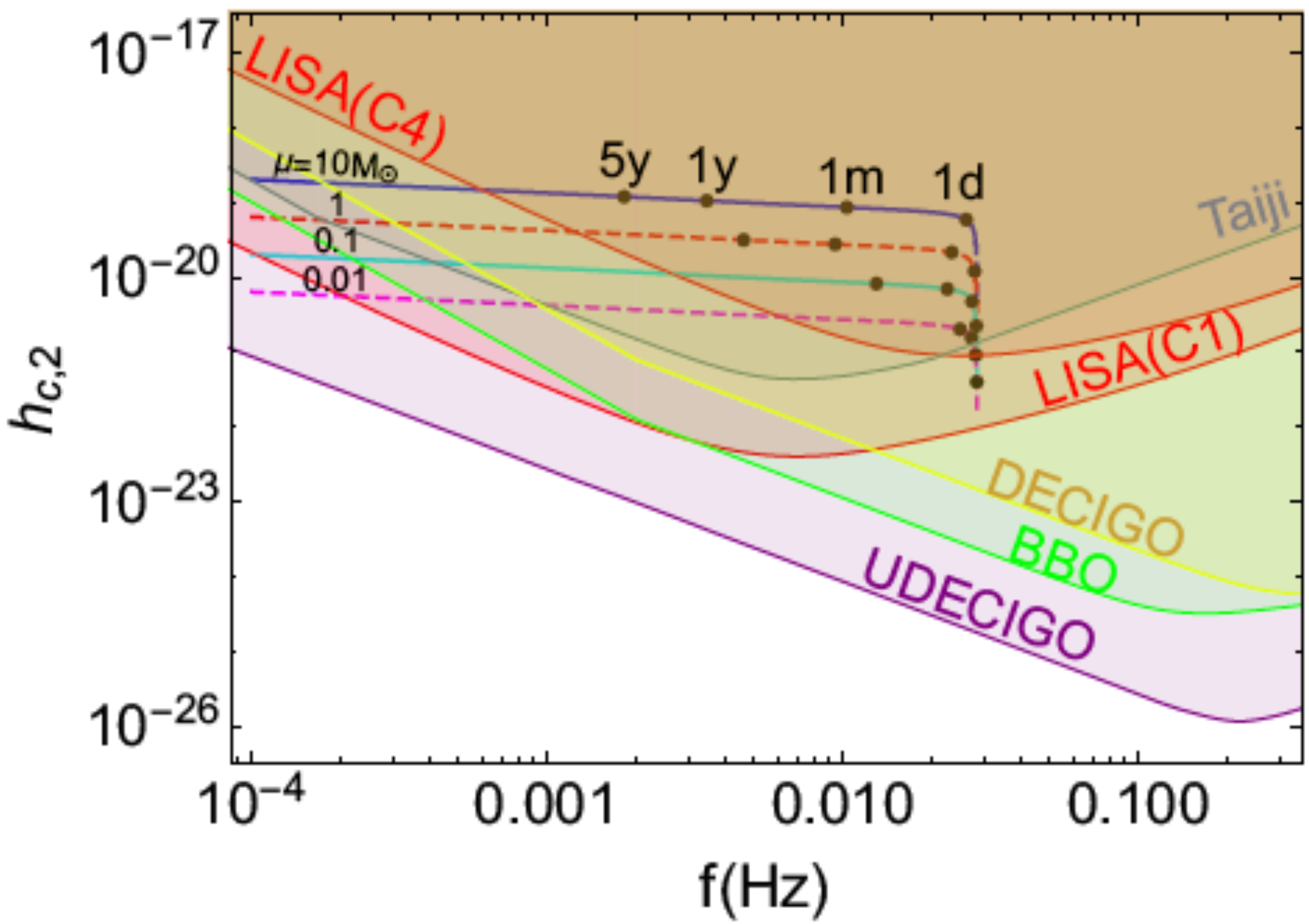
intrinsic EMRI rate
well studied for SMBH-ABH
rescale for PBH mass and density

SMBH mass spectrum
10^4 - 10^7 $M_\odot$
provided in astrophysics

volume integral
truncated by SNR

SMBH spin distribution
likely to be almost extremal
little effects to final results

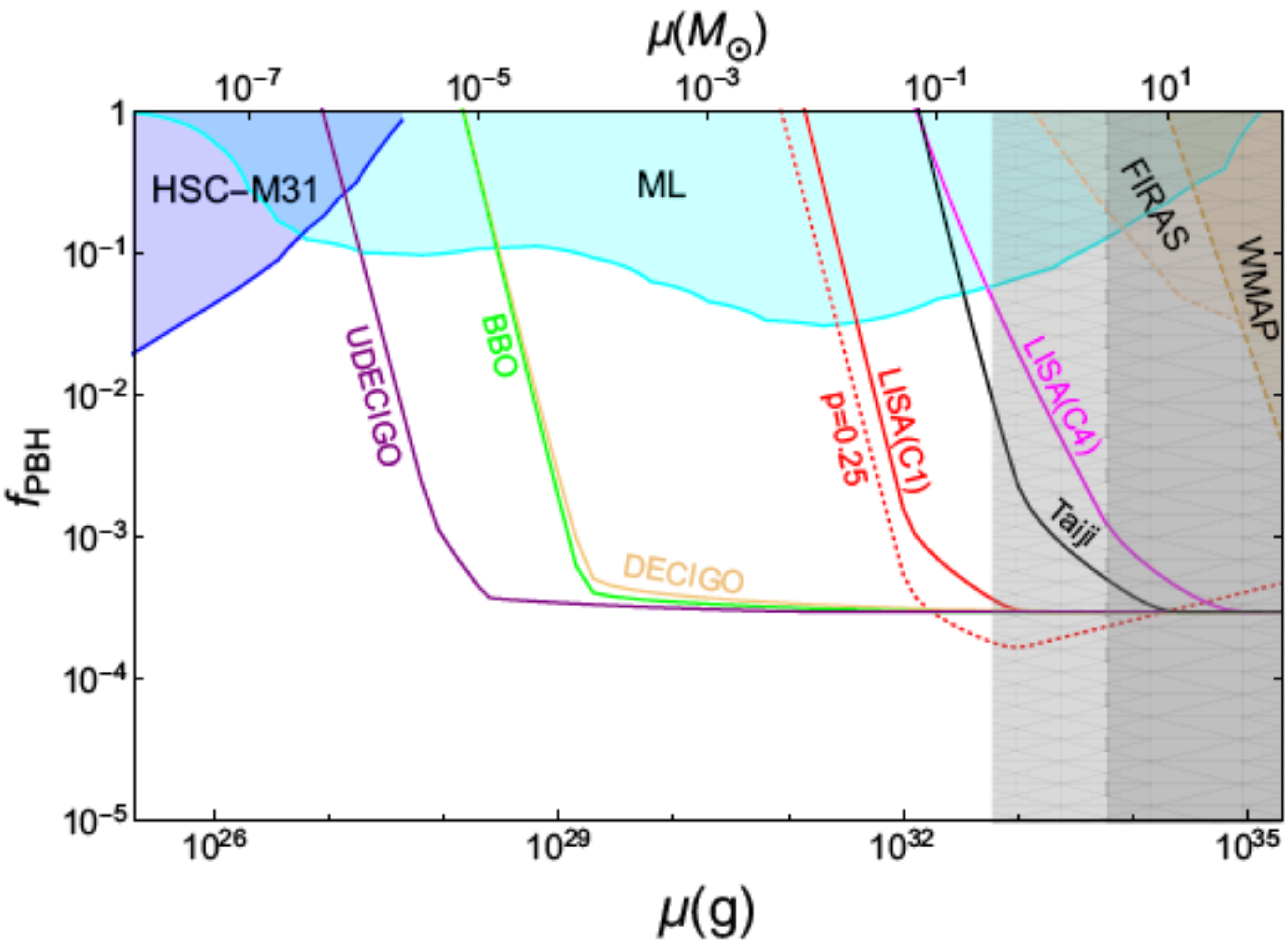
GW Strain:

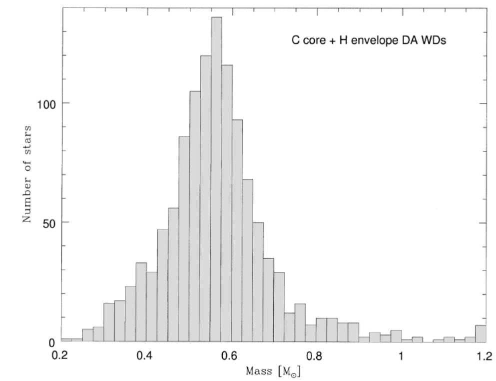


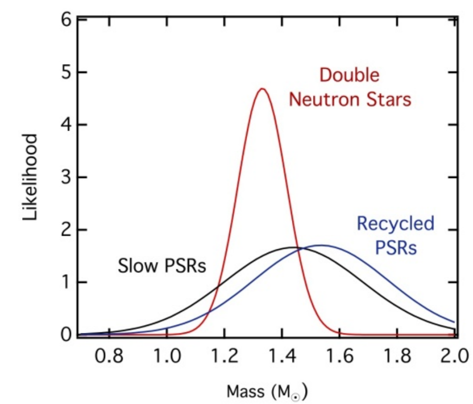
$M = 10^6\, M_\odot$; Spin = 0.999 ; 1 Gpc

Sensitivity:

One observation may be good enough to claim discovery!







Conclusion

LISA-like GW detectors is powerful to search for PBHs!

⇨ Large unexplored parameter space can be probed.

PBH mass: $10^{-7} \sim 10\ M_\odot$

Fraction can be as small as 10^{-4}.

⇨ One or few signal events are good enough to declare discovery, if PBH is out of the mass regime of astrophysical COs.

Non-COs (planets) are destroyed by tidal force before ISCO.

Conclusion

- Astrophysical uncertainties can be largely reduced by measurements on ABH-SMBH EMRIs.

  Mass spectrum and spin distribution of SMBHs.

  Help to remove hard cut-off at z=1.

- Lighter SMBH may be more useful to look for smaller PBHs.

  Larger Frequency Integration Regime (SNR)

  Guideline in future LISA-like GW experiments

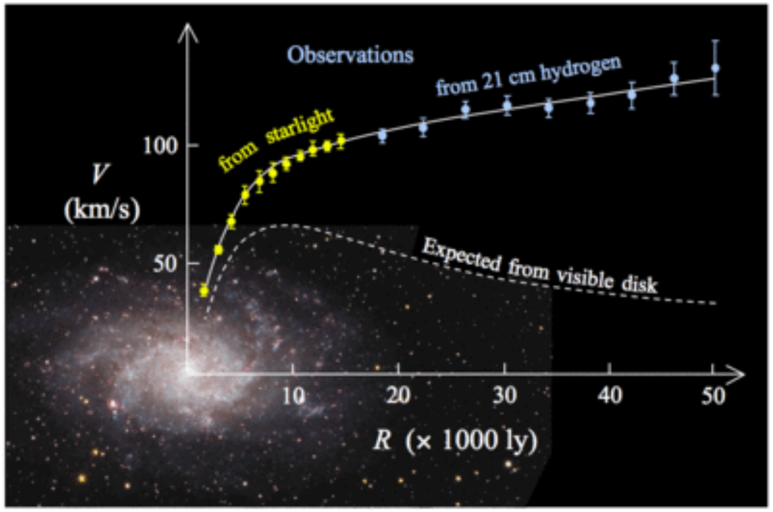
LIGO opens the era of GW astronomy. (Similar to the time when CMB is observed.)

Plenty astrophysics can be studied, as well as non-SM physics.

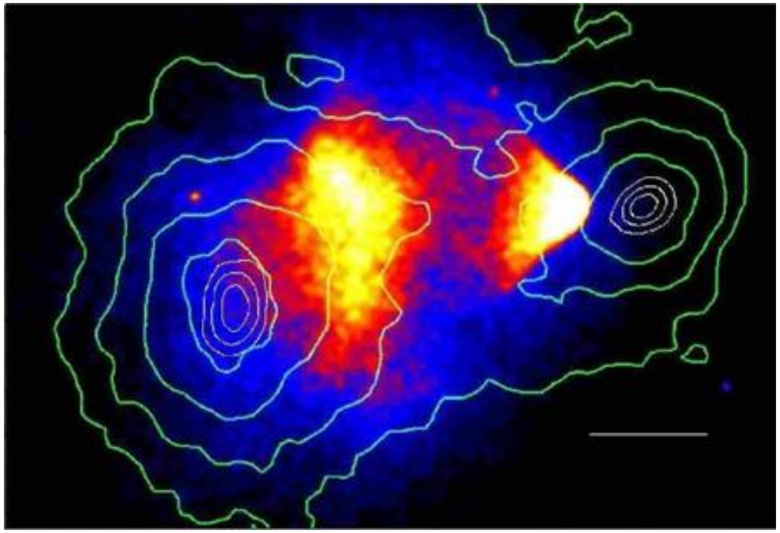
Dark Matter Overview:

Why do we need DM?

• Galaxy rotation curve (Wikipedia)



• Bullet Cluster (Deep Chandra)



• The CMB Anisotropy Power Spectrum

(WMAP year 5 data)