Searching for Dark Photon Dark Matter with Gravitational Wave Detectors

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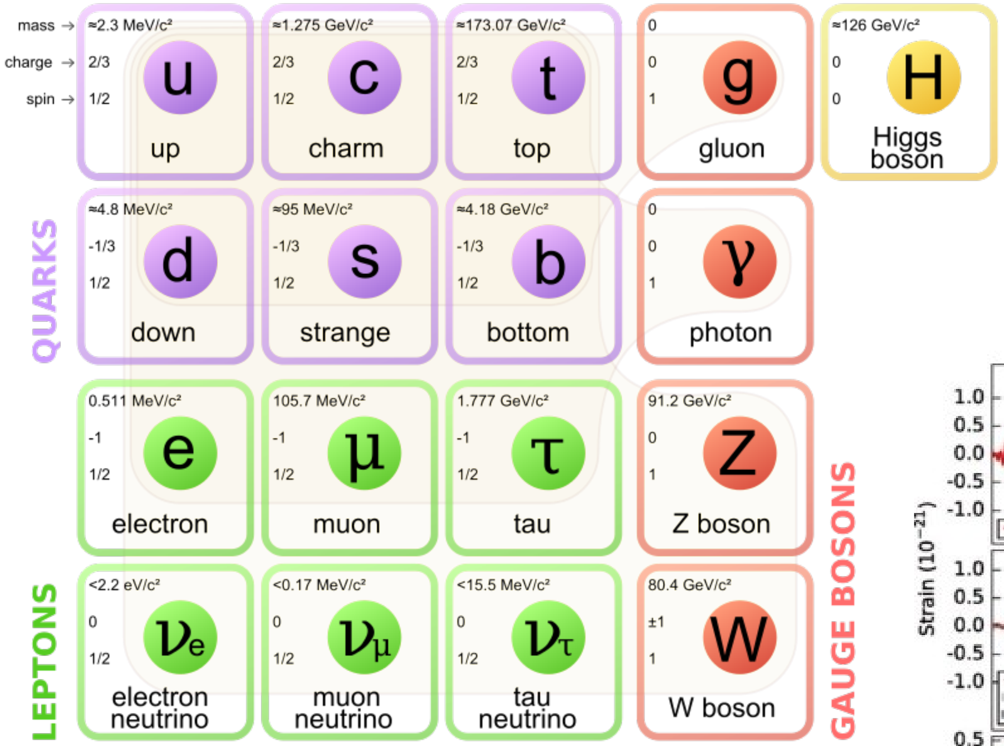
Aaron Pierce, Keith Riles, Y.Z.
arXiv:1801.10161 [hep-ph]
Phys.Rev.Lett. 121 (2018) no.6, 061102

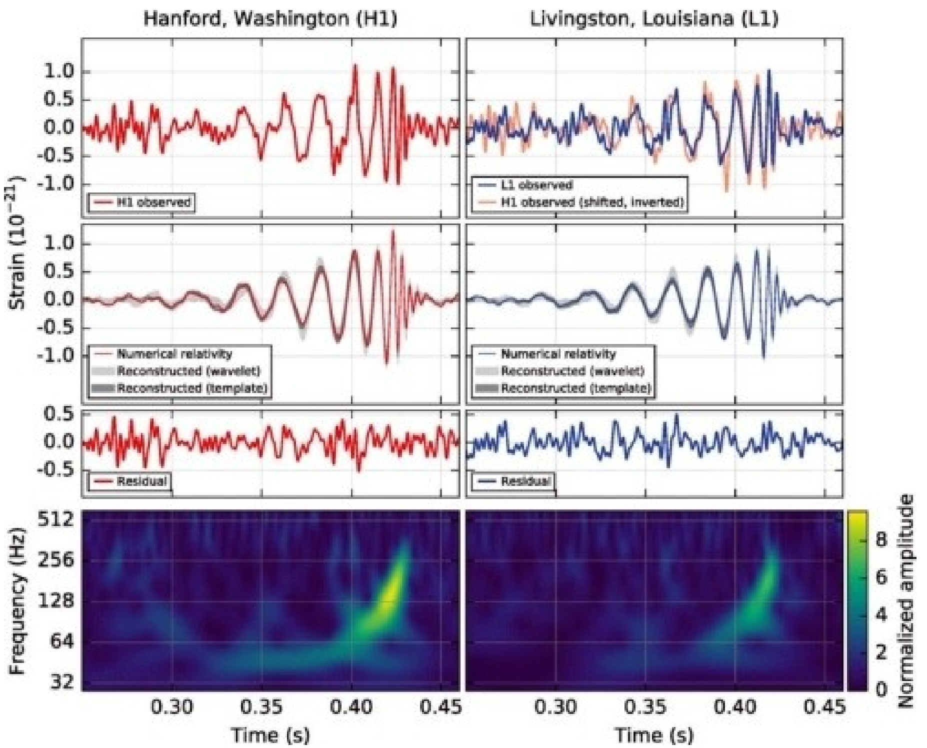
Huaike Guo, Keith Riles, Fengwei Yang, Y.Z.
arXiv:190x.xxxxx [hep-ph]

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

Current Status of Particle Physics:



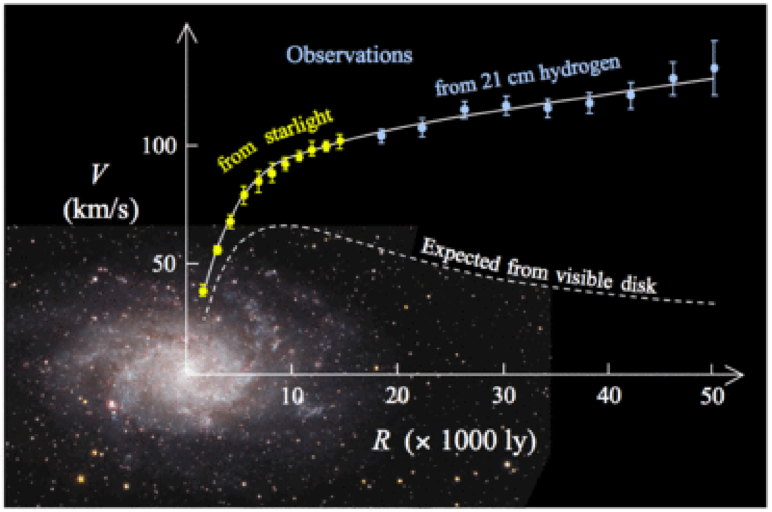
\+ Dark Sector?



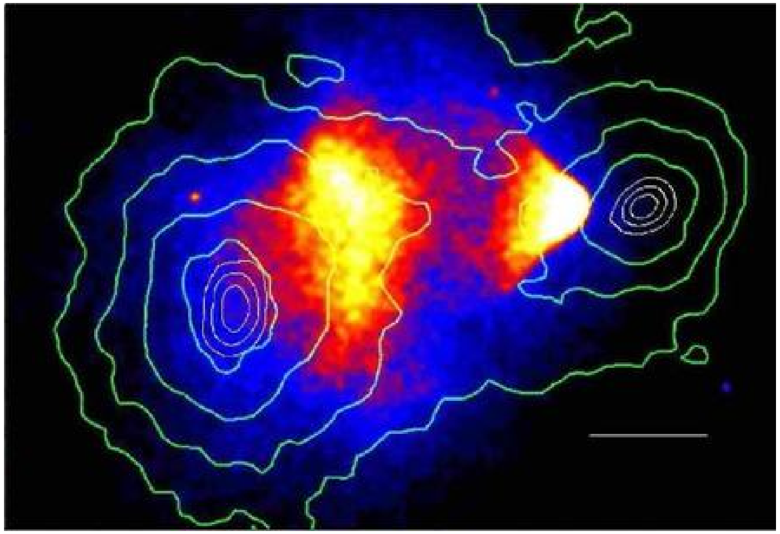
Dark Matter Overview:

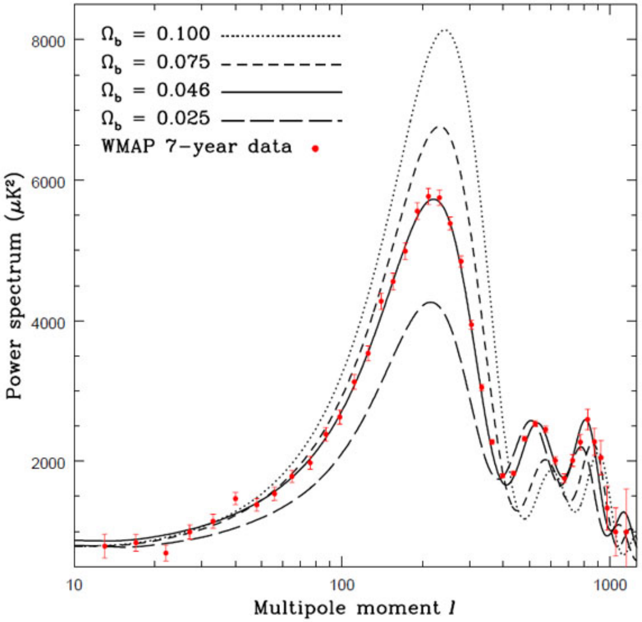
Why do we need DM?

• Galaxy rotation curve (Wikipedia)



• Bullet Cluster (Deep Chandra)





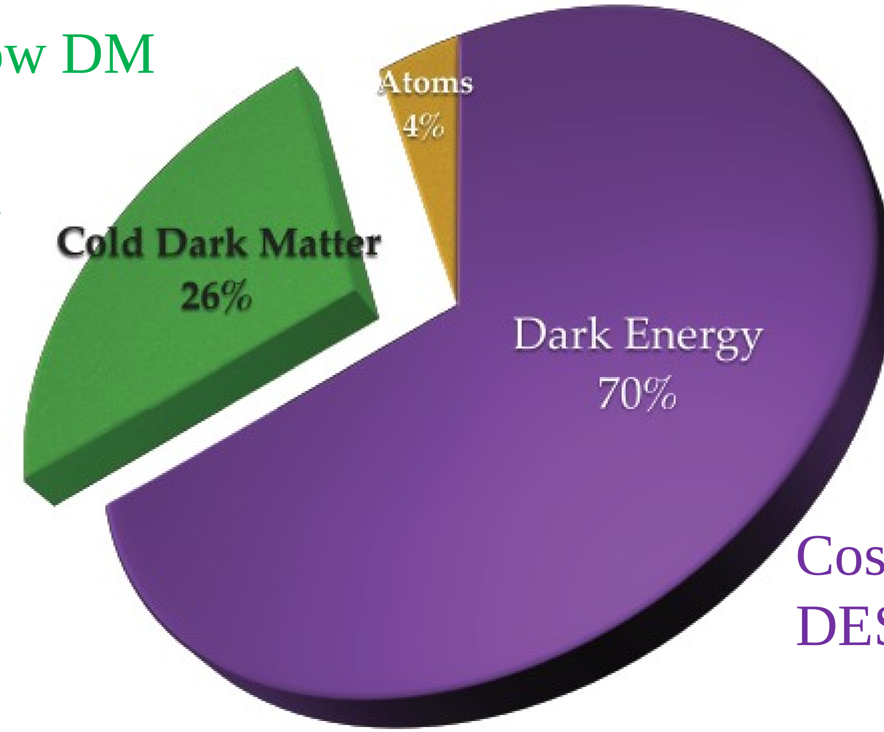
• The CMB Anisotropy Power Spectrum

(WMAP year 5 data)

Dark Matter Overview:

We only understand
~4% of the Universe!

We only know DM
through its
gravitational
interaction!



Cosmological constant?
DES, DESI, eBOSS…

Local DM
energy density:

$$\rho_{DM} = 0.4\mathrm{GeV}/\mathrm{cm}^3$$

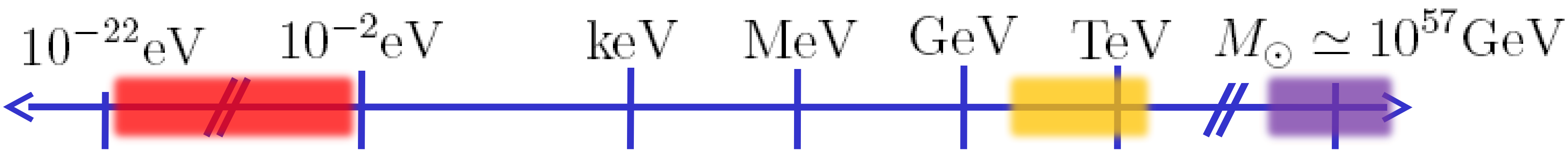
Local DM velocity:

$$v_{\mathrm{vir}} \sim 10^{-3} c$$

DM cannot be hot!

~~neutrinos~~

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

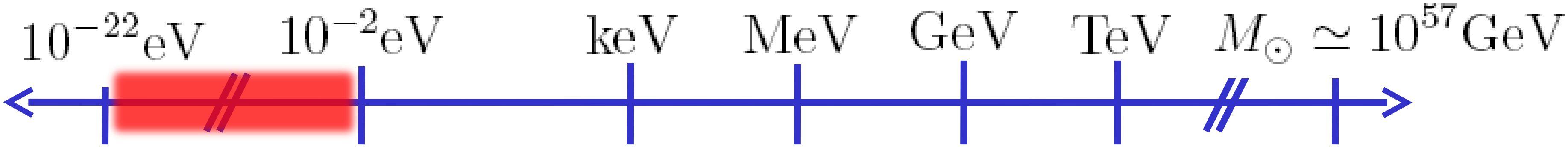
- Primordial Black Holes:

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

(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 decay

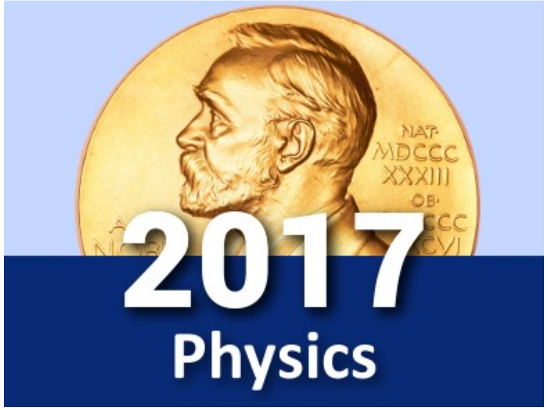
Production from cosmic string

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!

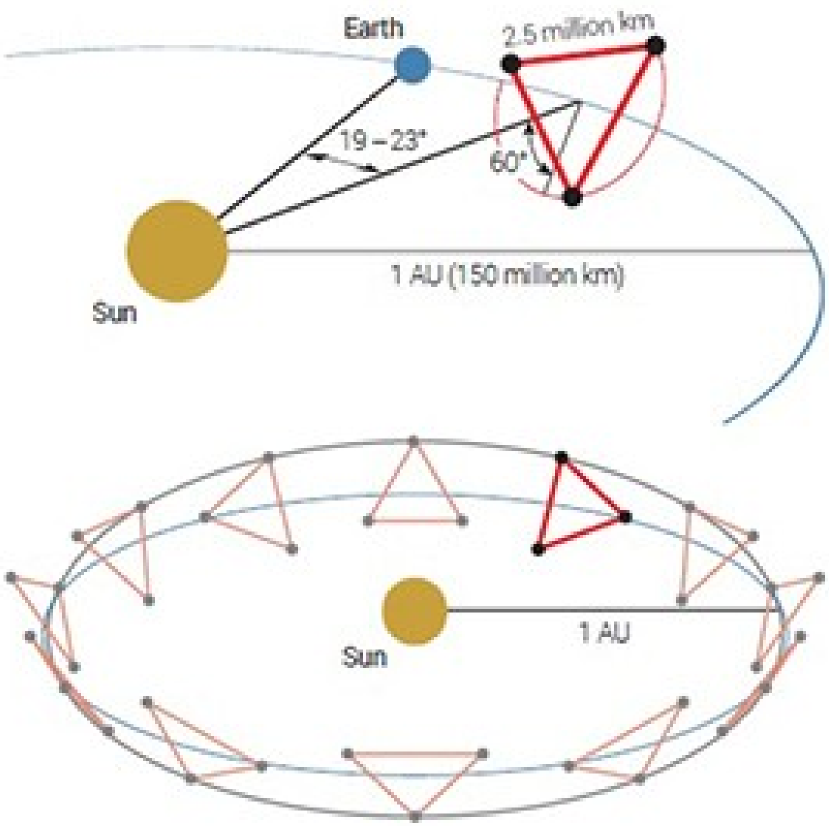


Opened a field:
Gravitational Wave Astronomy

Enrich our understanding on fundamental physics and early cosmology.

Laser Interferometer Space Antenna

LISA (space-based)



(LISA Mission Consortium)

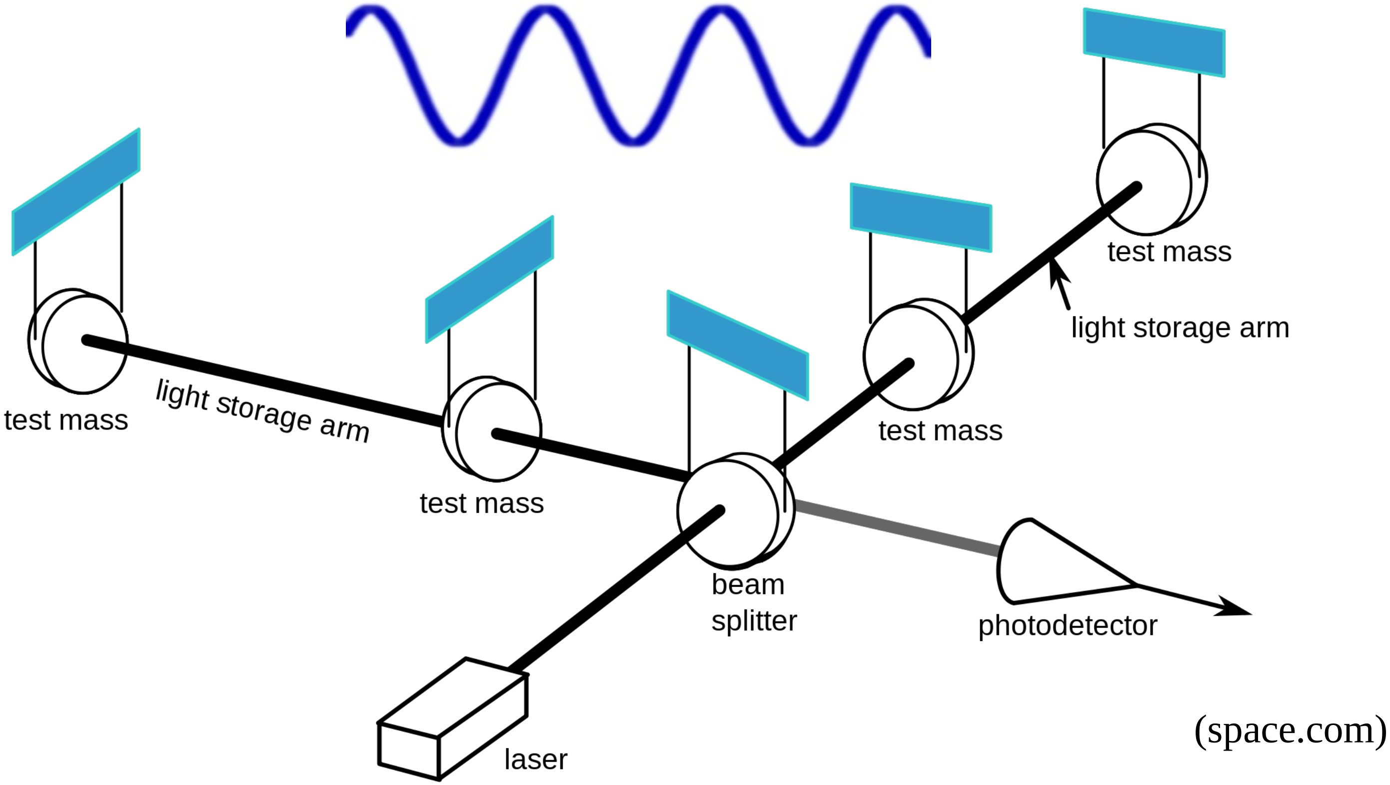
Recently approved by the European Space Agency.

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

LISA PathFinder is a great success!

General Picture:

LIGO/LISA: advanced Michelson–Morley interferometer

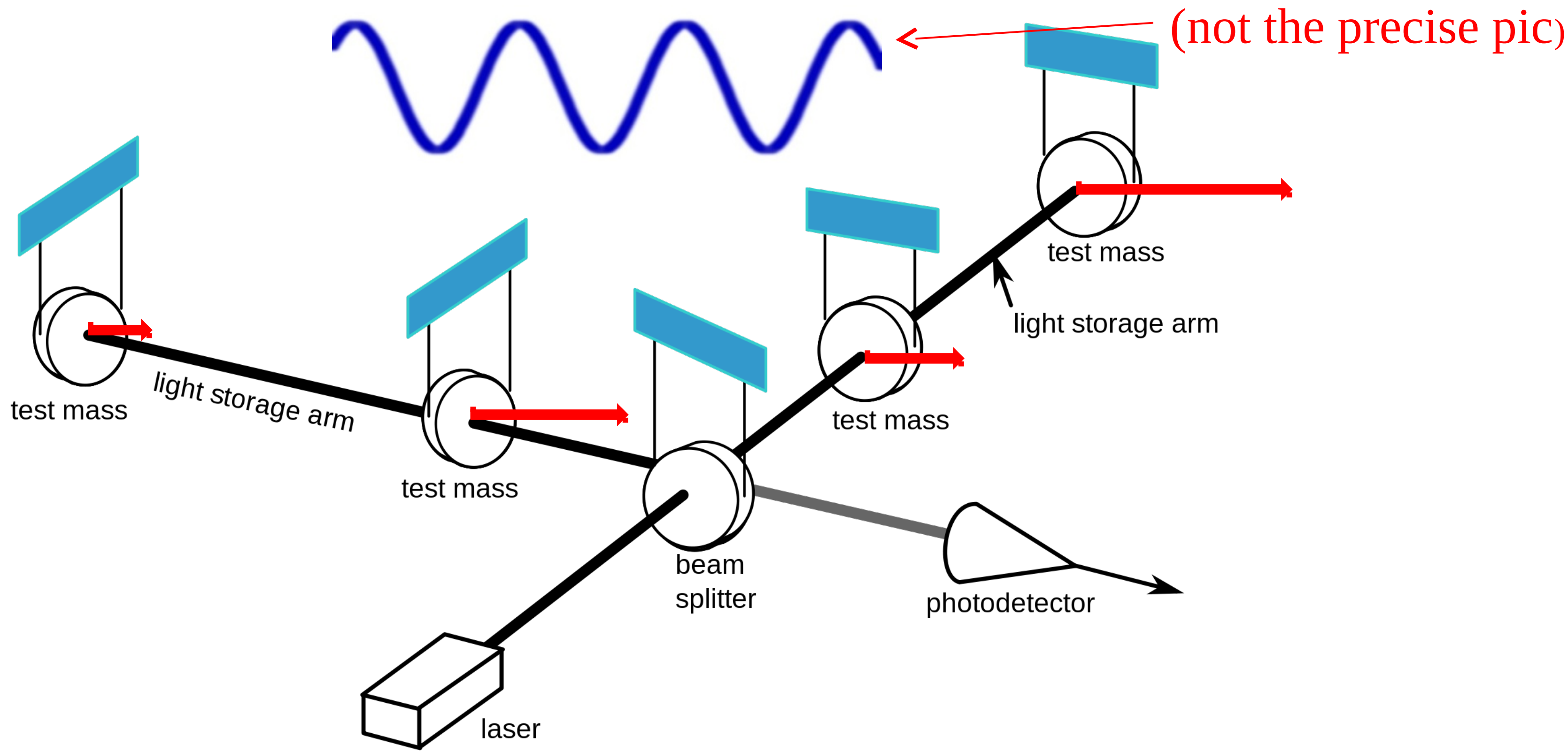


(space.com)

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

General Picture:

Ultra-light DM: coherent state ⇨ background classical radio wave



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

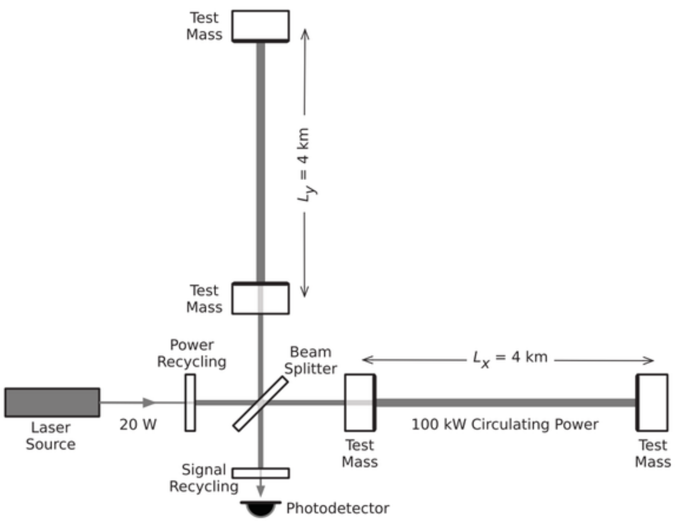
$U(1)_{B-L}$: 1/(2GeV)

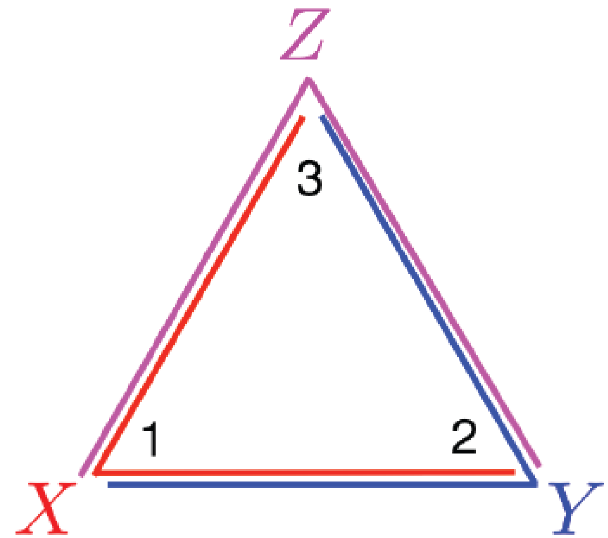
projected along
the arm direction

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

Maximal GW-like Displacement:

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





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

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.

Maximal GW-like Displacement:

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

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

Averaging on directions of
acceleration and momentum vectors.

For non-relativistic particles,
polarization vector and momentum vector are independent.

Compared with other DPDM/axion experiments (ADMX),

no resonance is required at measurement, thus no need to scan frequency!

Search for a large frequency band simultaneously!

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:

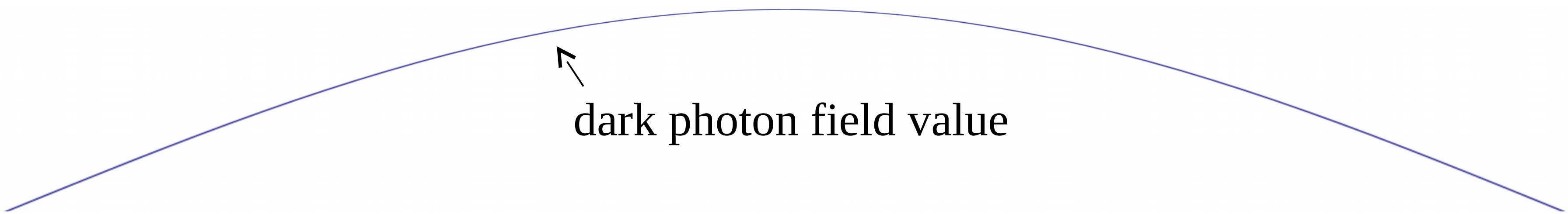
- very long coherent distance

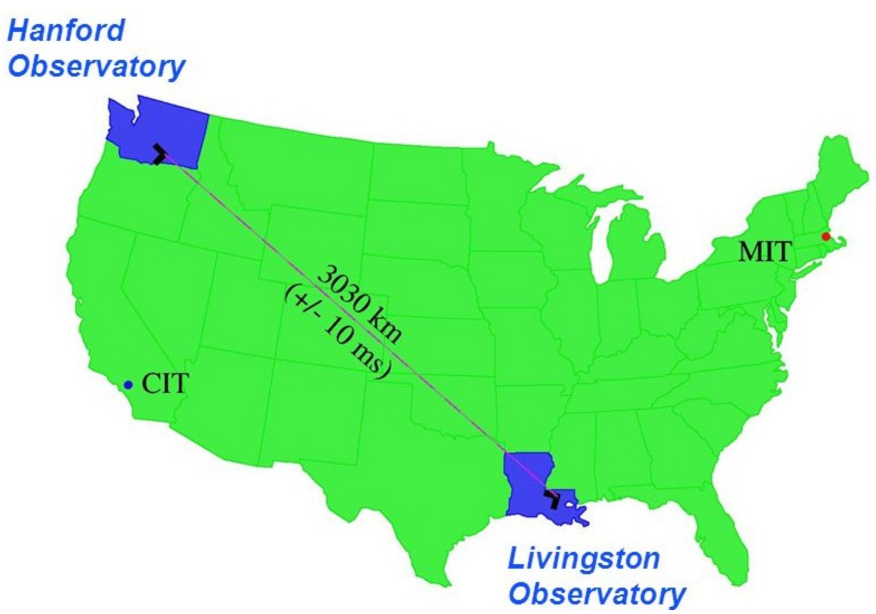
$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f} \right)$$

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.

later map to ΔL/L

(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:

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)

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

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

optimal filter function
maximize SNR

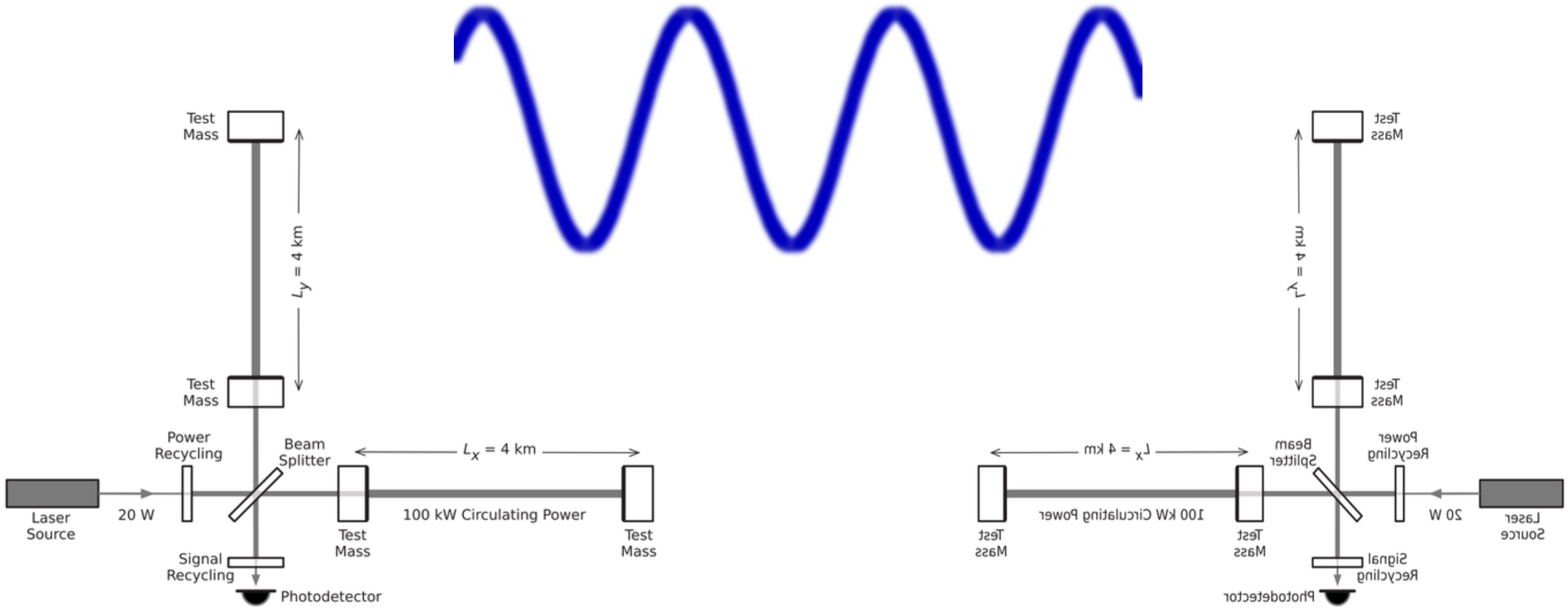
one-sided strain noise power spectra

Sensitivity to DPDM signal of GW detectors:

Stochastic GW:

LIGO

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



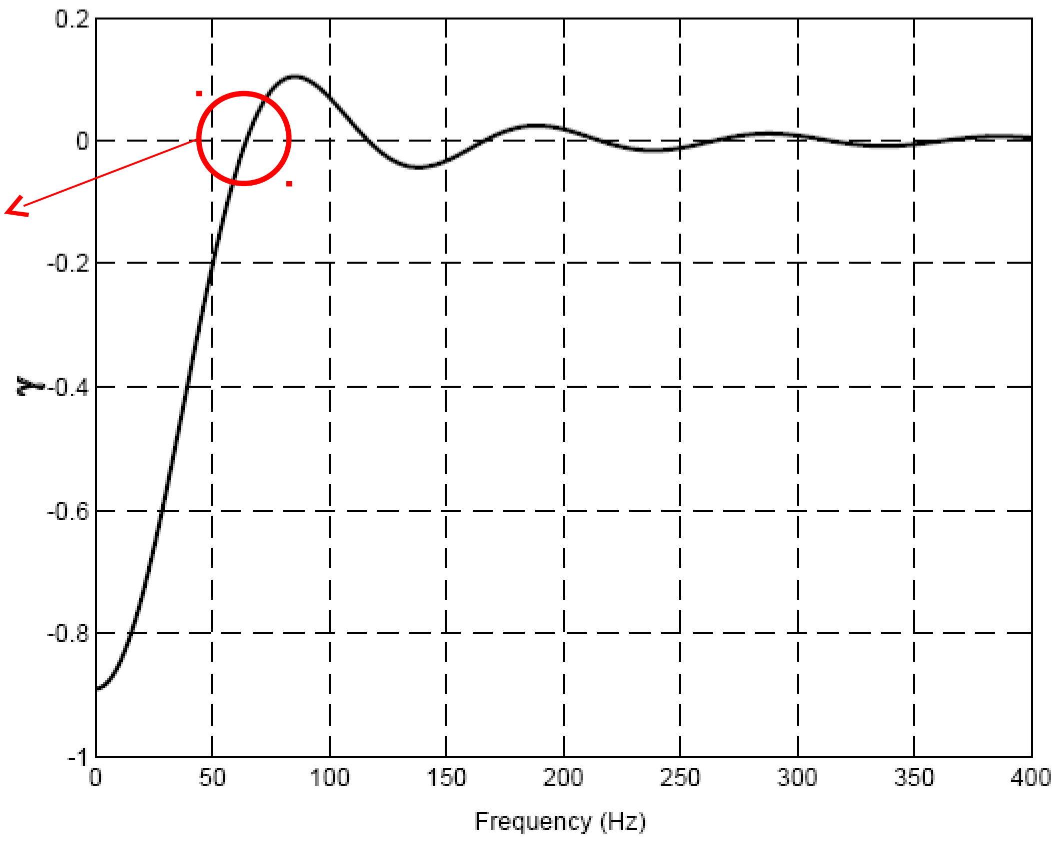
Sensitivity to DPDM signal of GW detectors:

Stochastic GW:

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

Signal correlation between two sites is lost when the separation is comparable to one wavelength.

LIGO

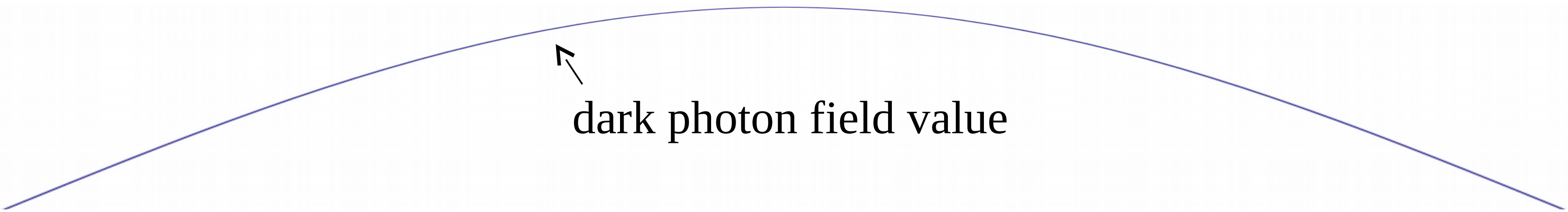


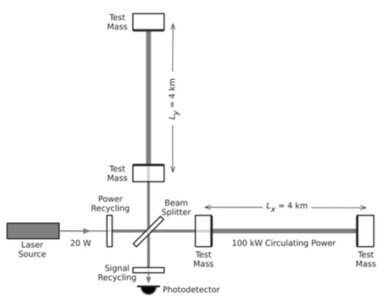
Sensitivity to DPDM signal of GW detectors:

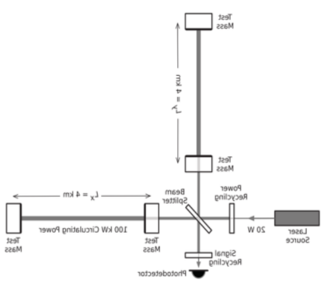
DPDM:

LIGO

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







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:

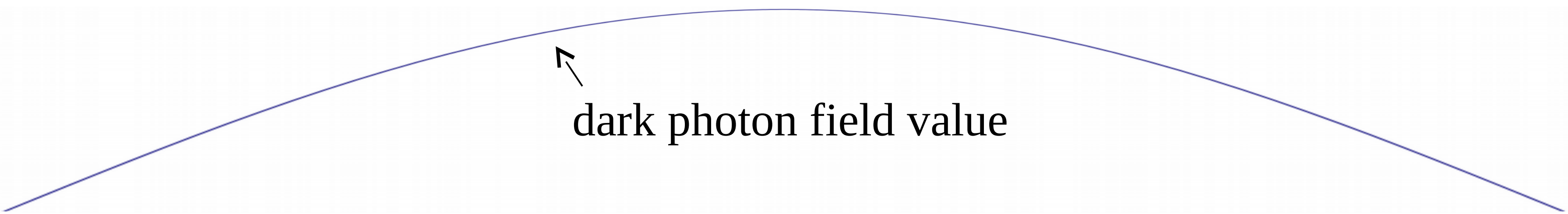
LISA

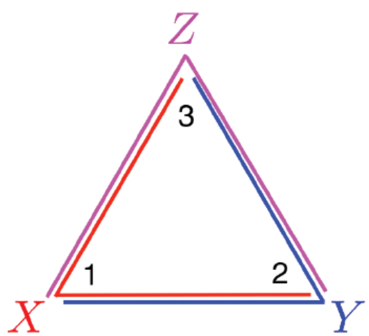
$$\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$$

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

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

$$\langle AE \rangle$$





⇨

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:

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

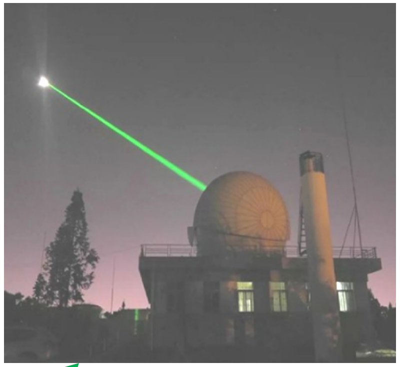
effectively the max differential displacement of two arms

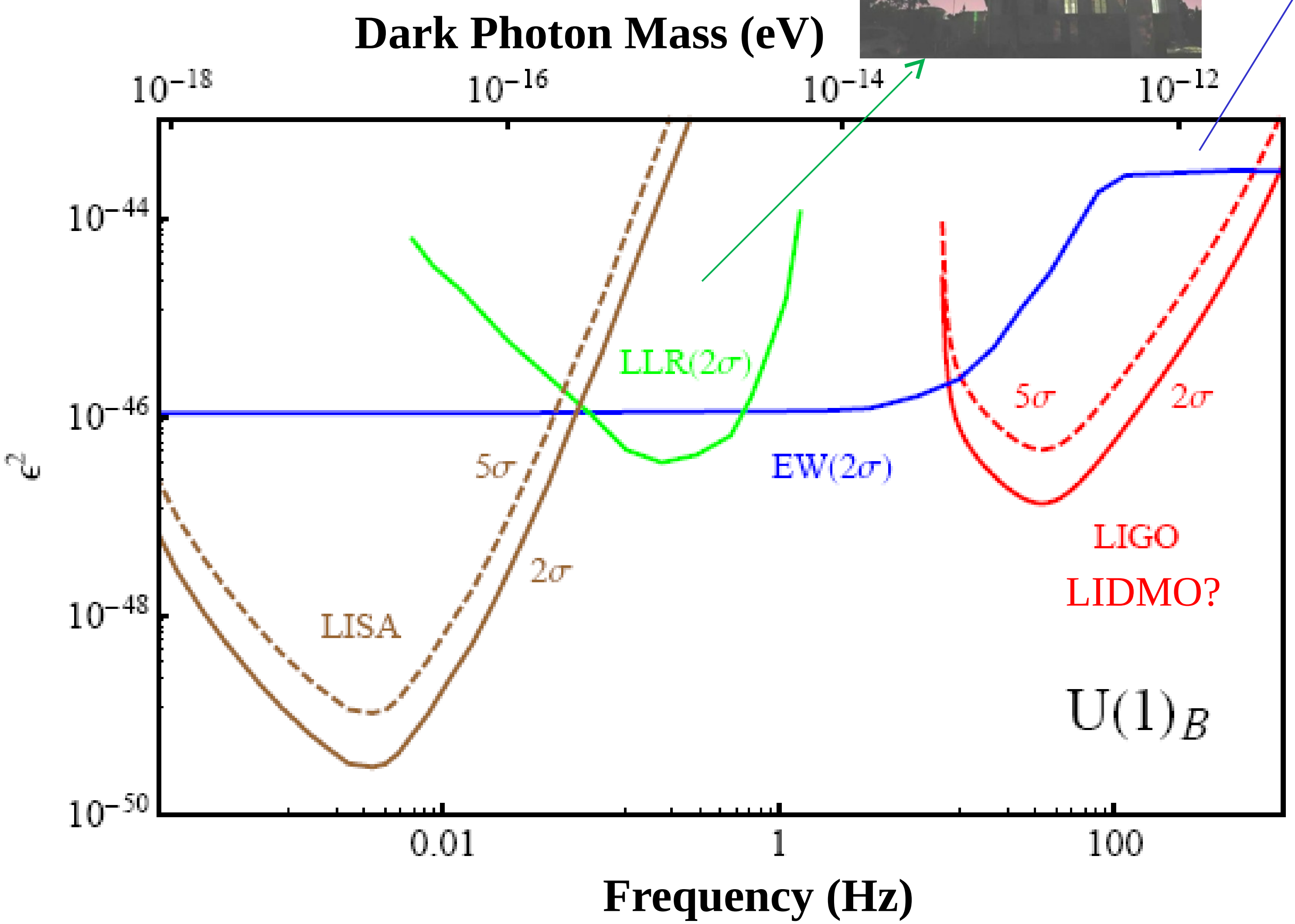
a GW with strain h ⇨ change of relative displacement as h

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

⇨ sensitivity of DPDM parameters (mass, coupling)

Sensitivity Plot:


(People's Daily)




(Eöt-Wash web)

Loránd Eötvös

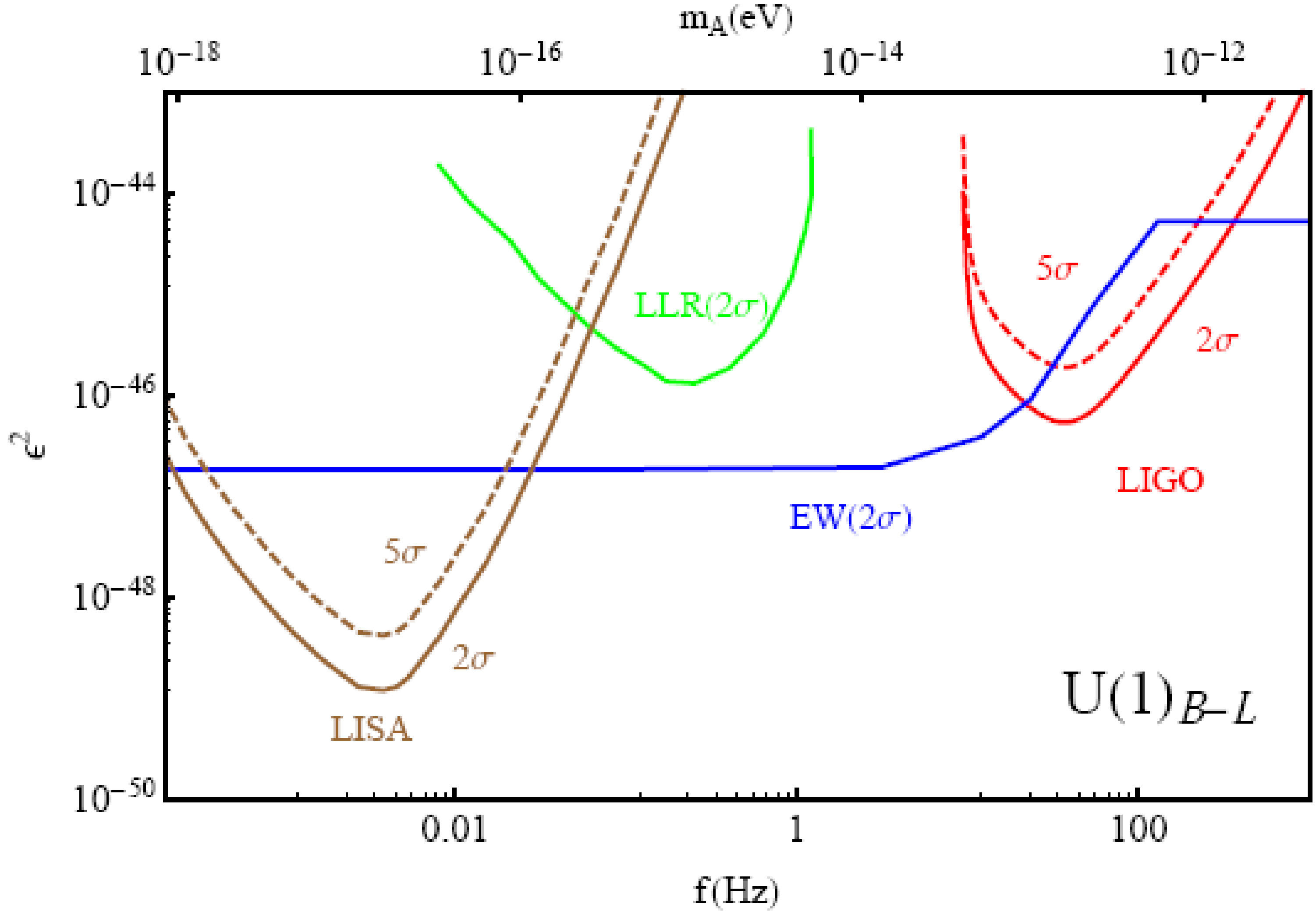
→ Eöt-Wash

design sensitivities, 2 yrs

Sensitivity Plot:

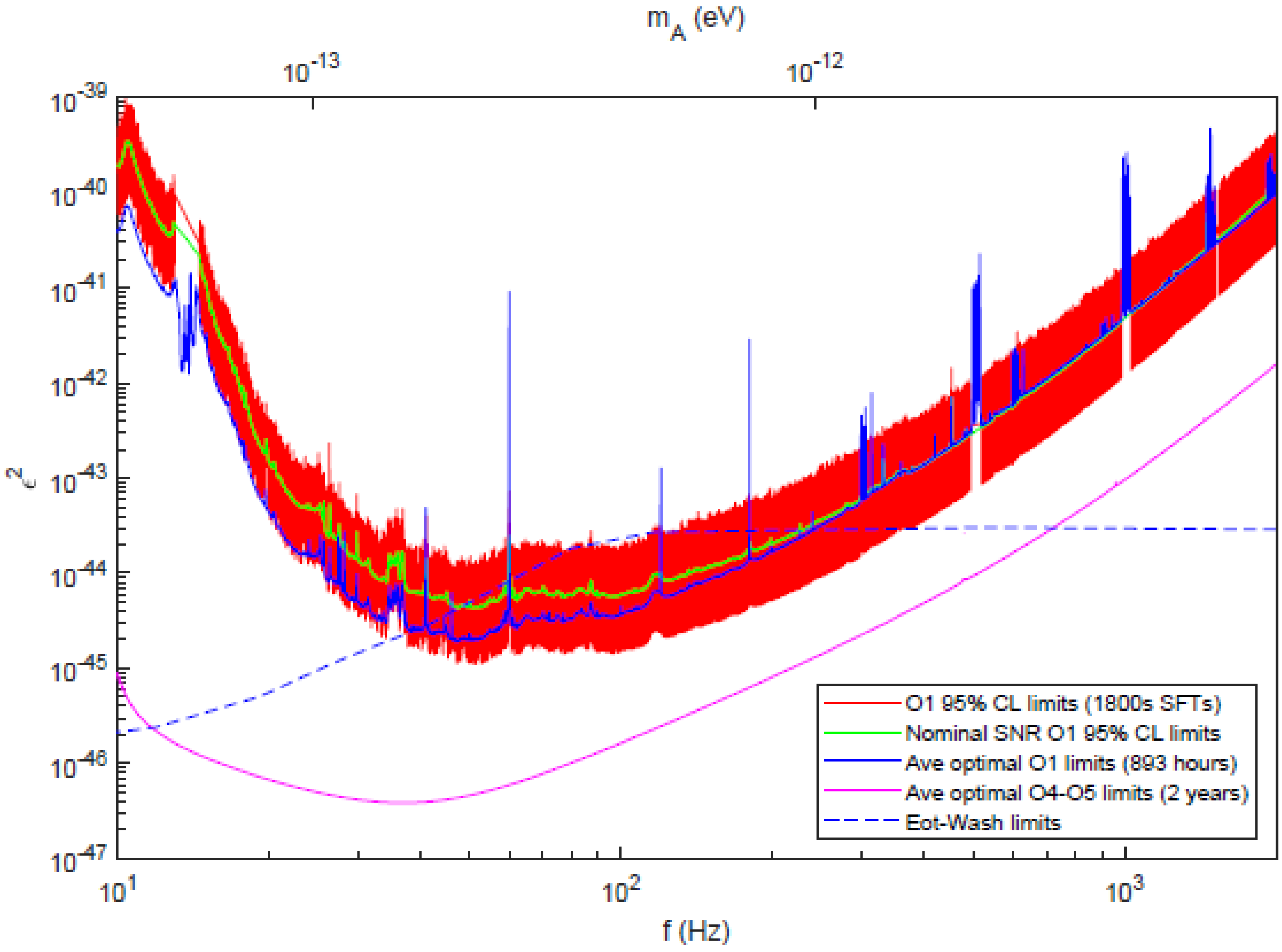
U(1) B-L

charge mass ratio: 1/2GeV



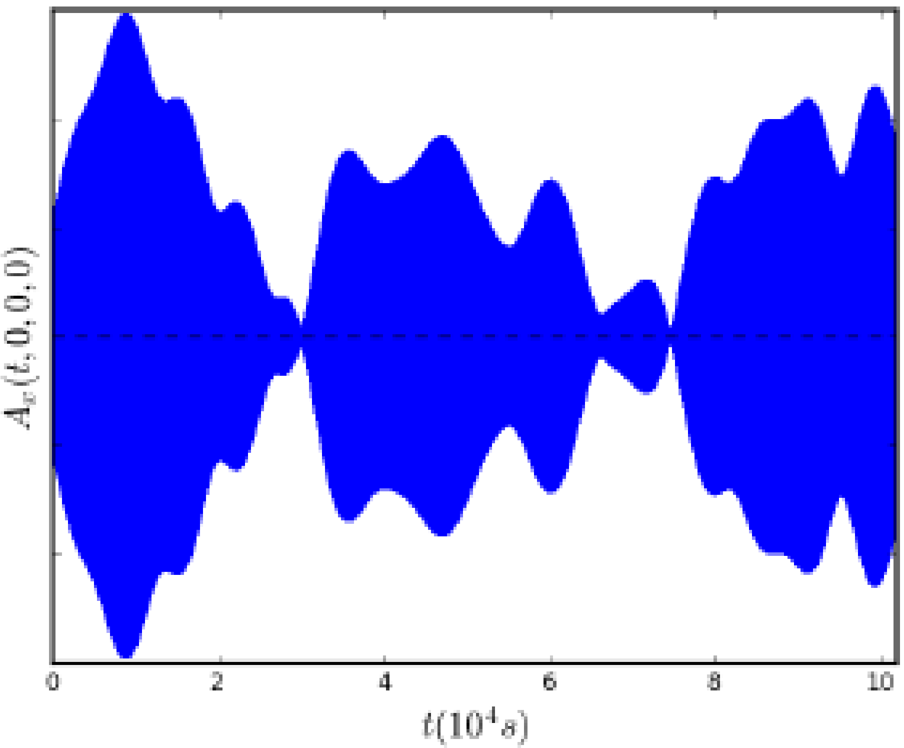
design sensitivities operating for 2 years

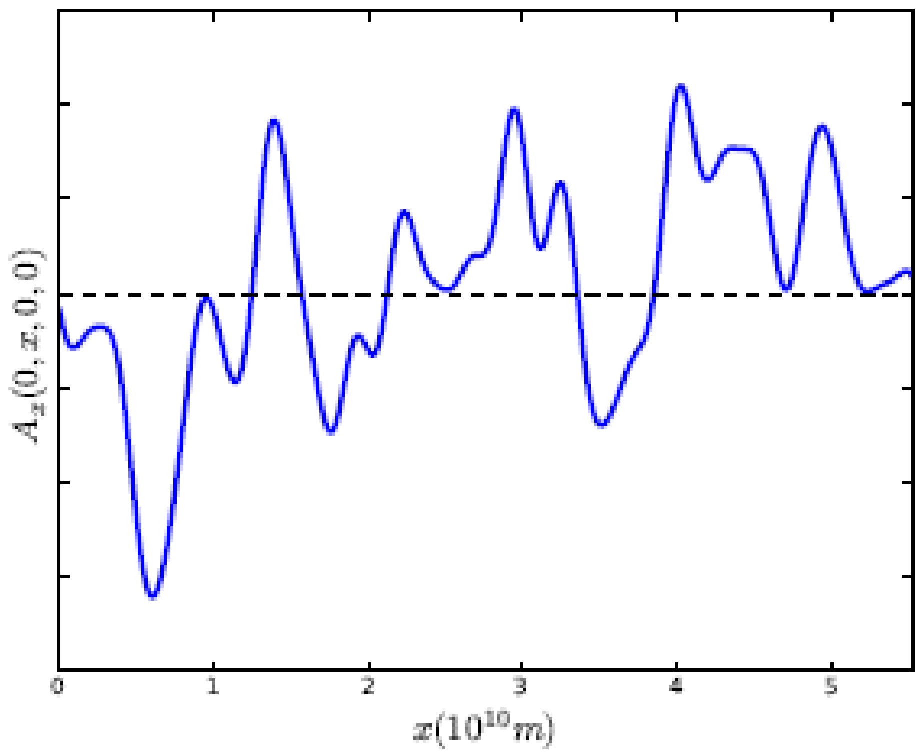
O1 Preliminary Result:



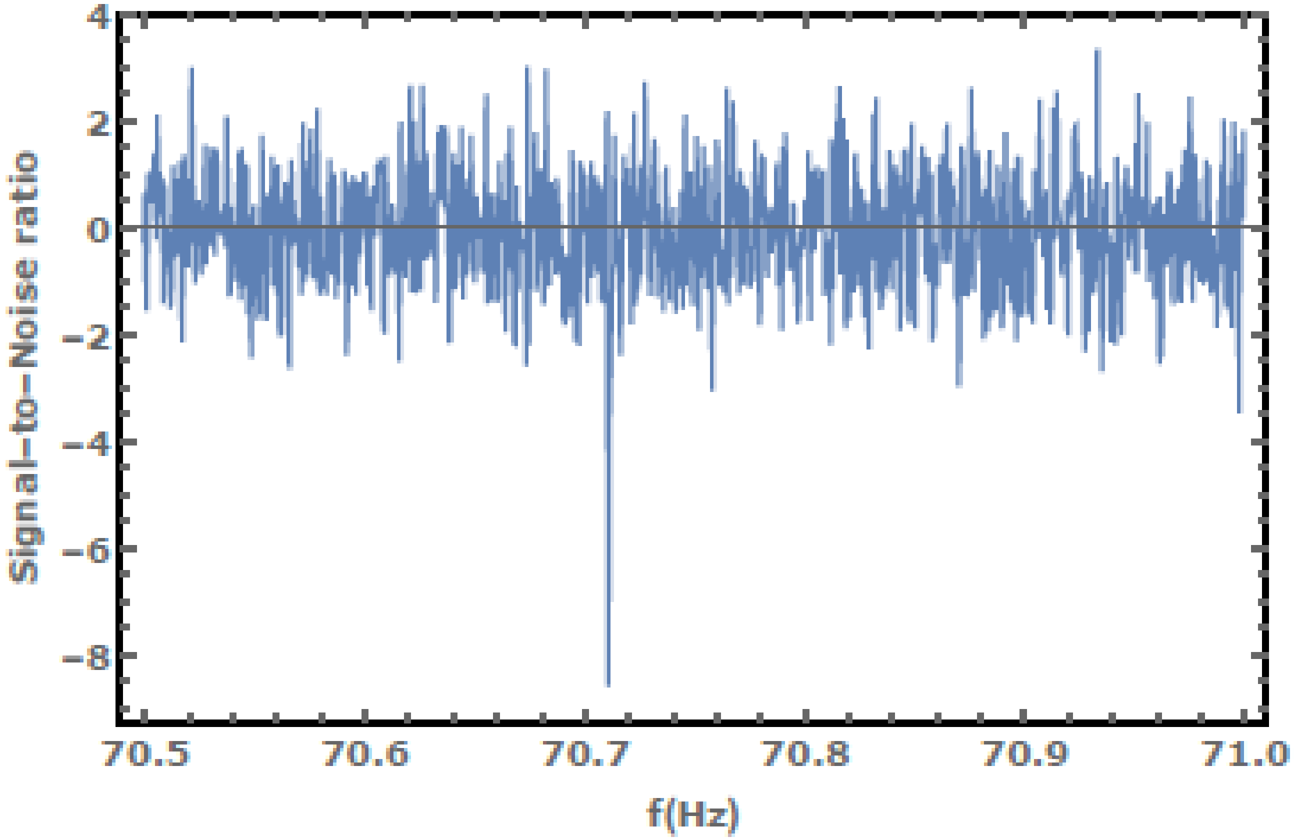
Modeling DPDM background:

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





LIGO simulation output:



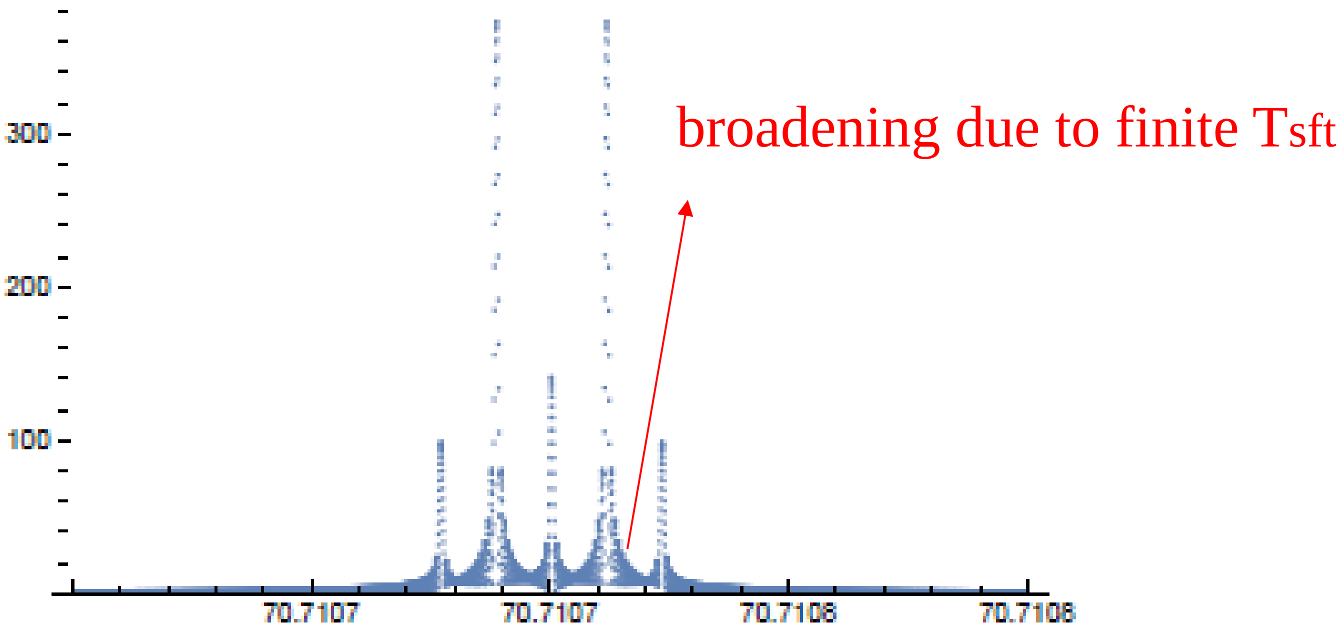
$\epsilon^2 = 5\times 10^{-44}$ $f = 70.71$ Hz $T_{SFT} = 1800$ s $T_{tot} = 200$ hr

⇨ $\mathrm{SNR} \simeq -8.$

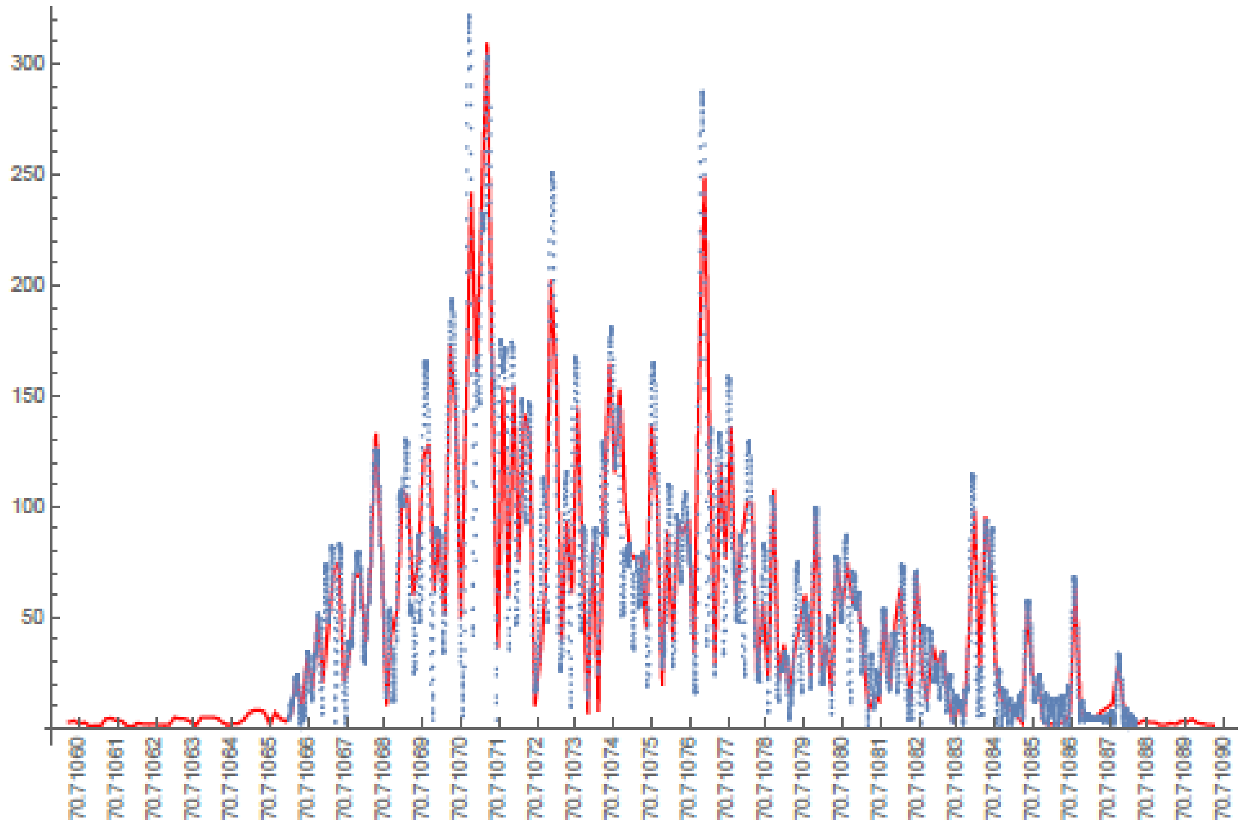
Earth Rotation Effects:

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

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



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 BG.

The sensitivity can be extraordinary!

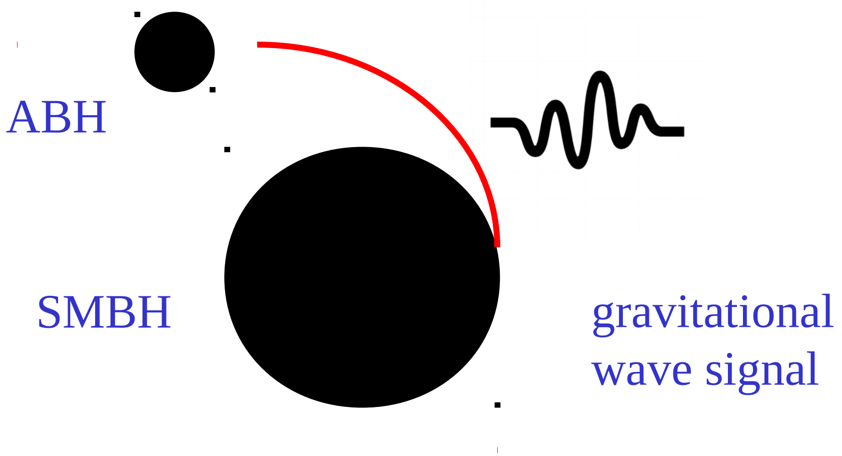
⇨ O1 data has already beaten existing experimental constraints.

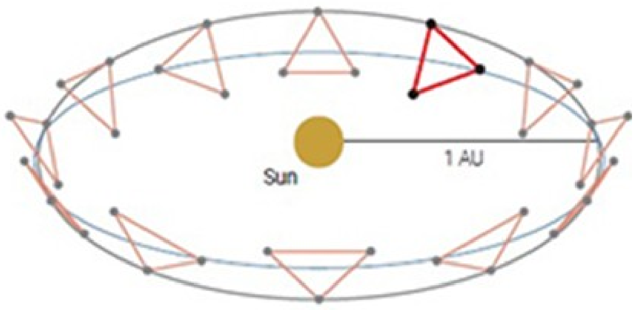
Can achieve 5-sigma discovery at unexplored parameter regimes.

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

LISA-like GW exp for PBH

Extreme Mass Ratio Inspirals

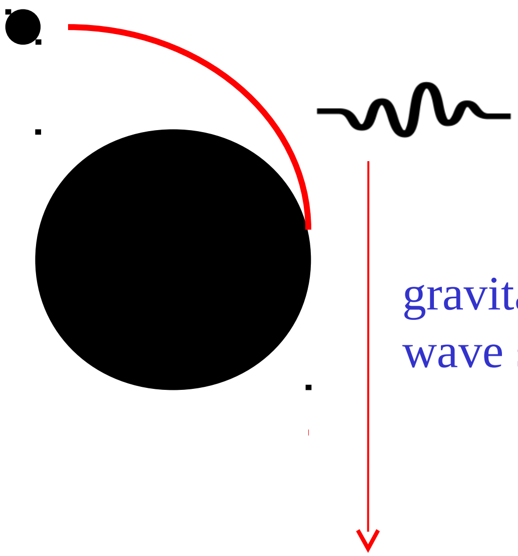


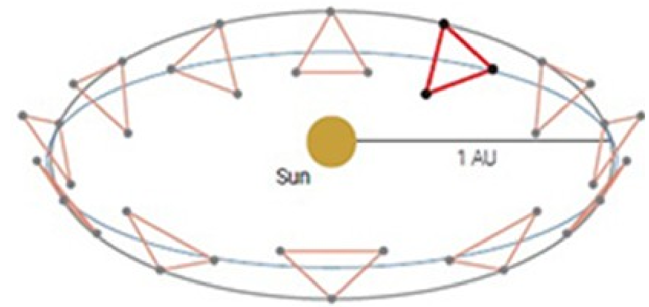


LISA

LISA-like GW exp for PBH

Extreme Mass Ratio Inspirals





LISA

Same frequency, but smaller amplitude!

Master Formula:

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

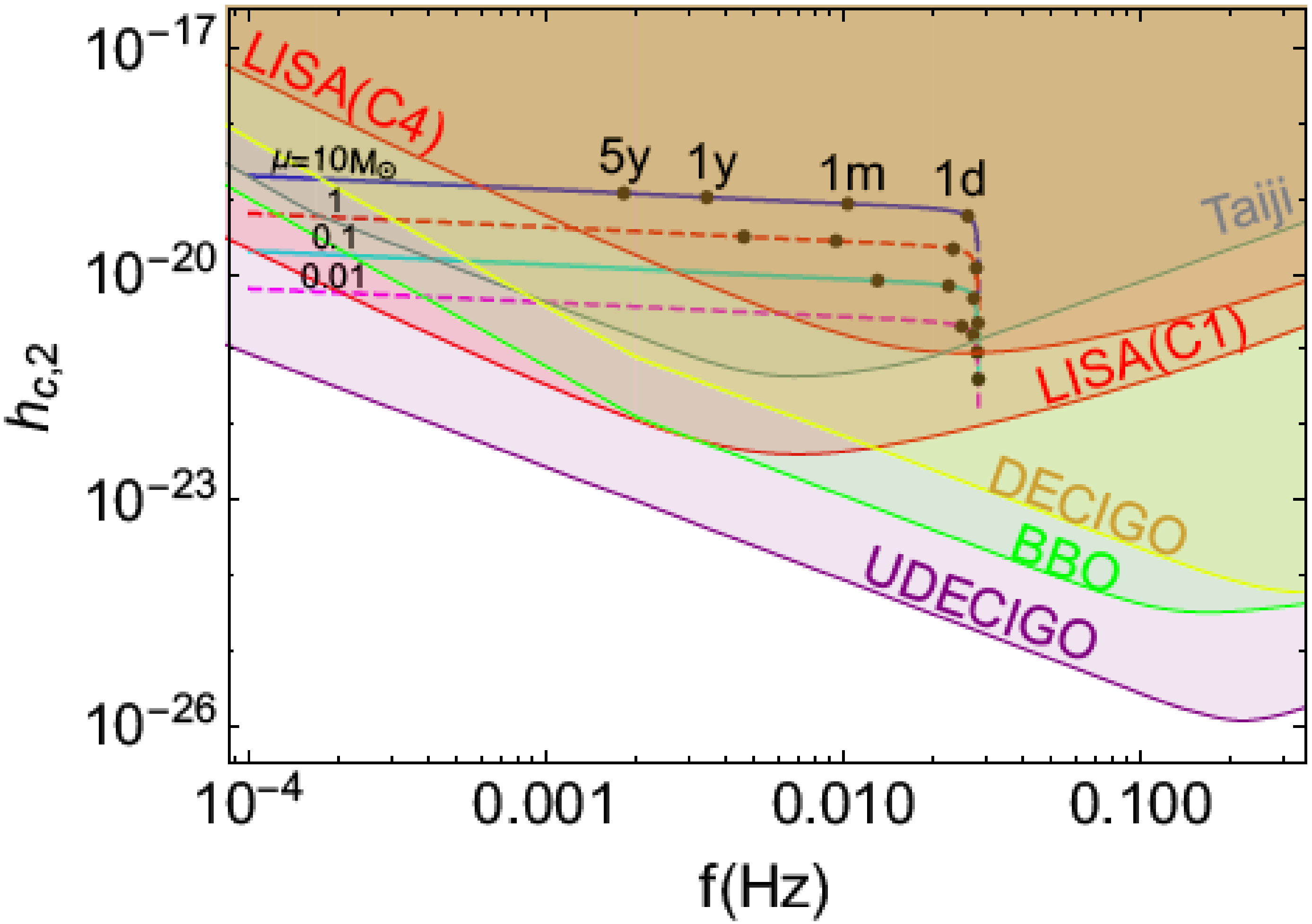
intrinsic EMRI rate
well studied for SMBH-ABH
rescale for PBH mass and density

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

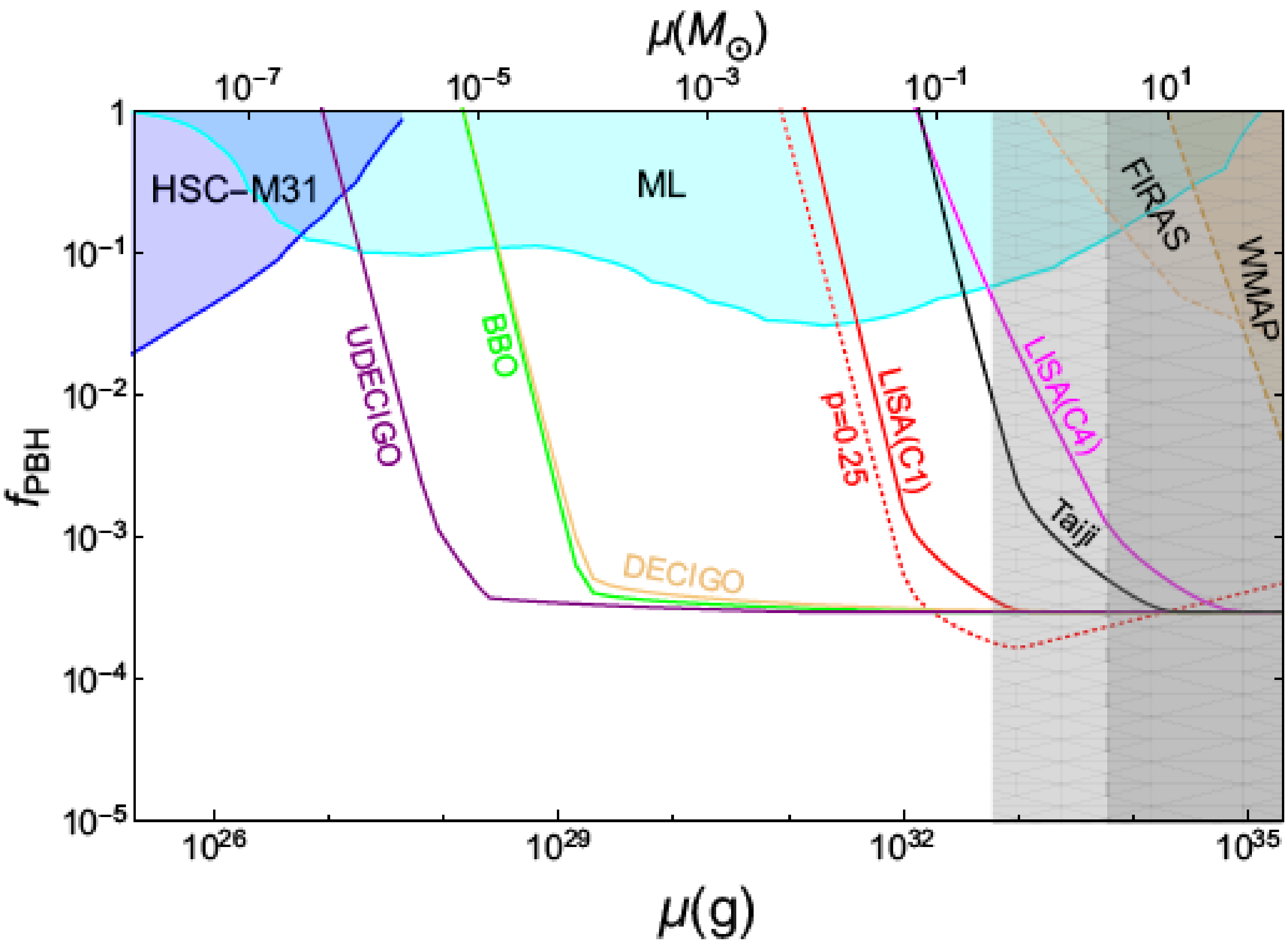
GW Strain:

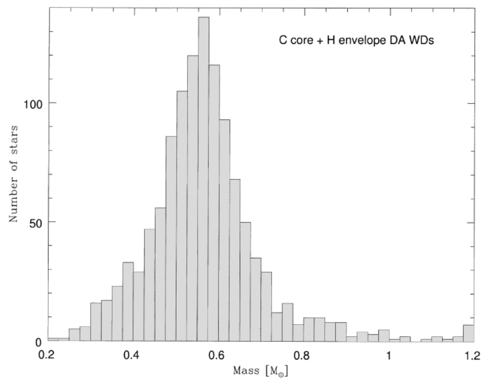


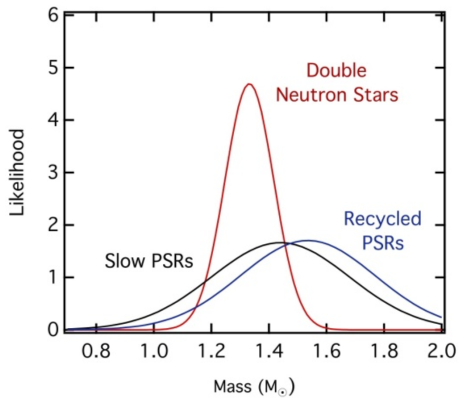
M = $10^6\, M_\odot$; Spin = 0.999 ; 1 Gpc

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.

Relation to stochastic GW searches:

Stochastic GW: (Abbott et. al. Phys.Rev. D69 (2004) 122004)

Correlation is lost every oscillation period.

DPDM signal:

Dominated by single plane wave for a long period of time.

Correlation is maintained for millions of oscillation periods.

Directions of polarization and propagation are fixed over each coherence time and length, but randomly vary over longer time scales.

⇨ Signal well suited to stochastic search techniques exploiting correlations between interferometers
(despite signal's being more monochromatic than continuous waves)