Searching for Dark Photon Dark Matter with Gravitational Wave Detectors

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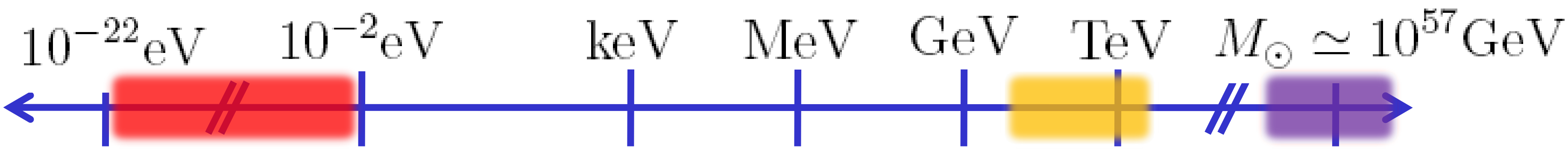
Aaron Pierce, Keith Riles, Y.Z.
arXiv:1801.10161 [hep-ph]
Phys.Rev.Lett. 121 (2018) no.6, 061102

Huaike Guo, Keith Riles, Fengwei Yang, Y.Z.
arXiv: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

Aaron Pierce, Keith Riles, Yue Zhao
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- WIMPs:

  100 GeV ~ TeV

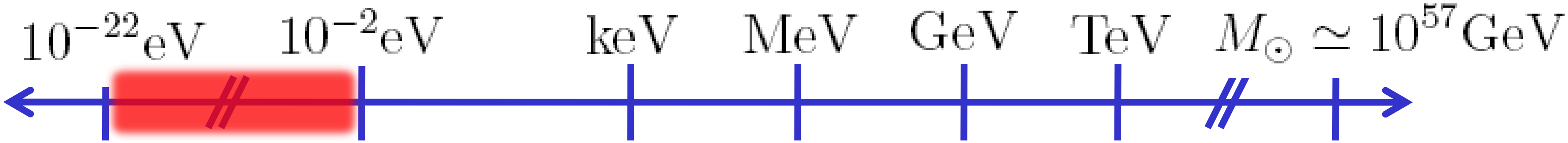
- Primordial Black Holes:

  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 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 decay

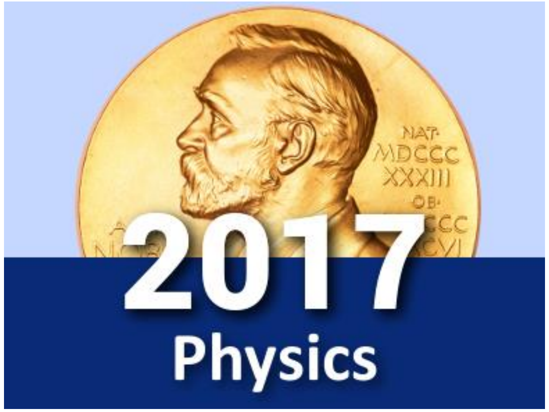
Production from cosmic string

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!

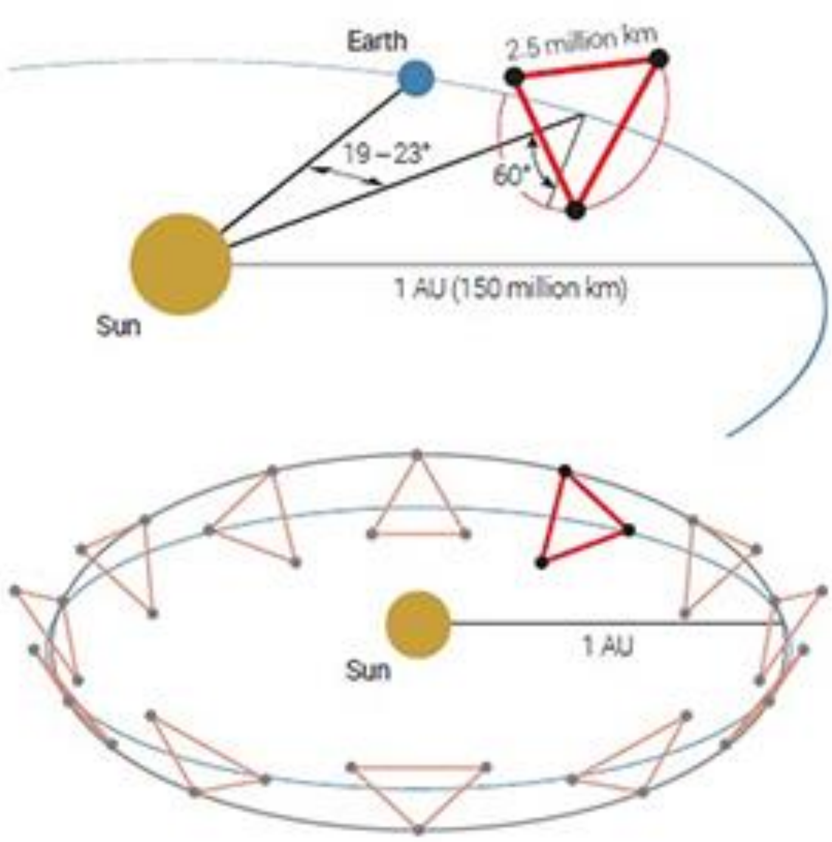


Opened a field:
Gravitational Wave Astronomy

Enrich our understanding on fundamental physics and early cosmology.

Laser Interferometer Space Antenna

LISA (space-based)



(LISA Mission Consortium)

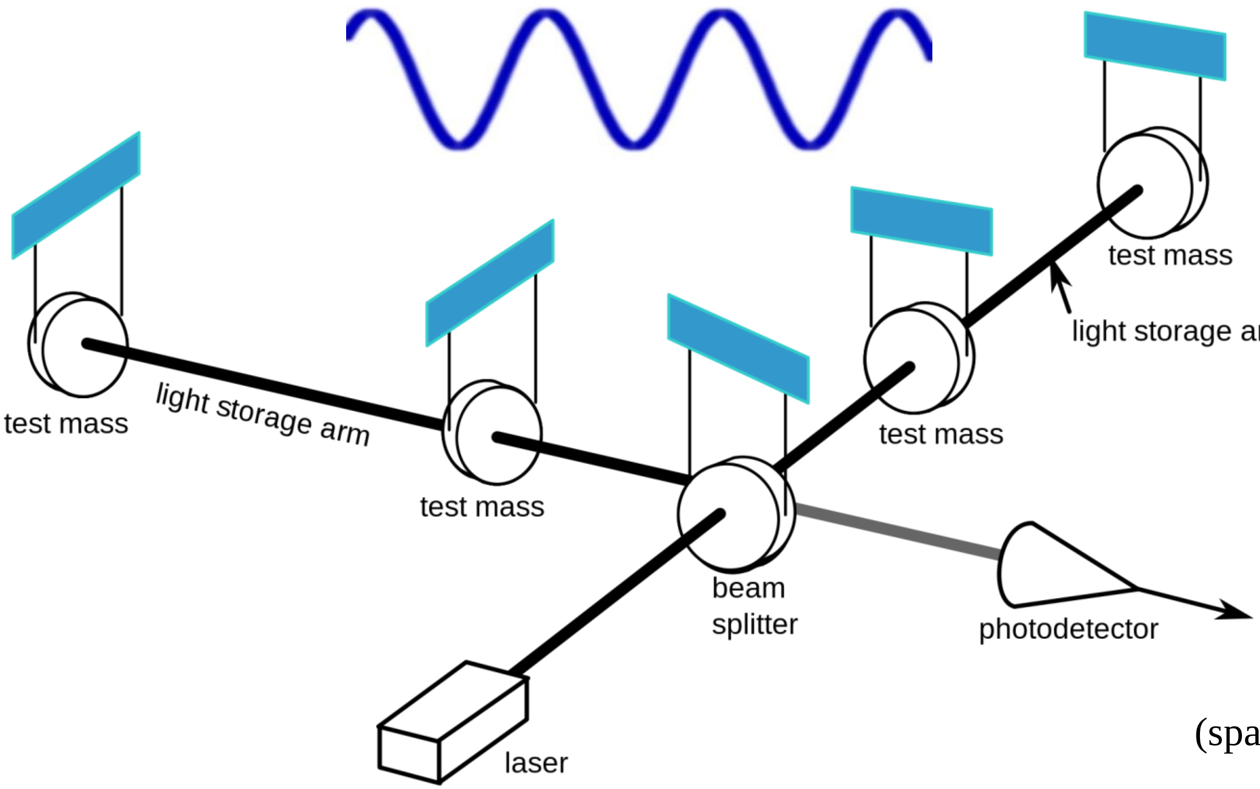
Recently approved by the European Space Agency.

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

LISA PathFinder is a great success!

General Picture:

LIGO/LISA: advanced Michelson–Morley interferometer

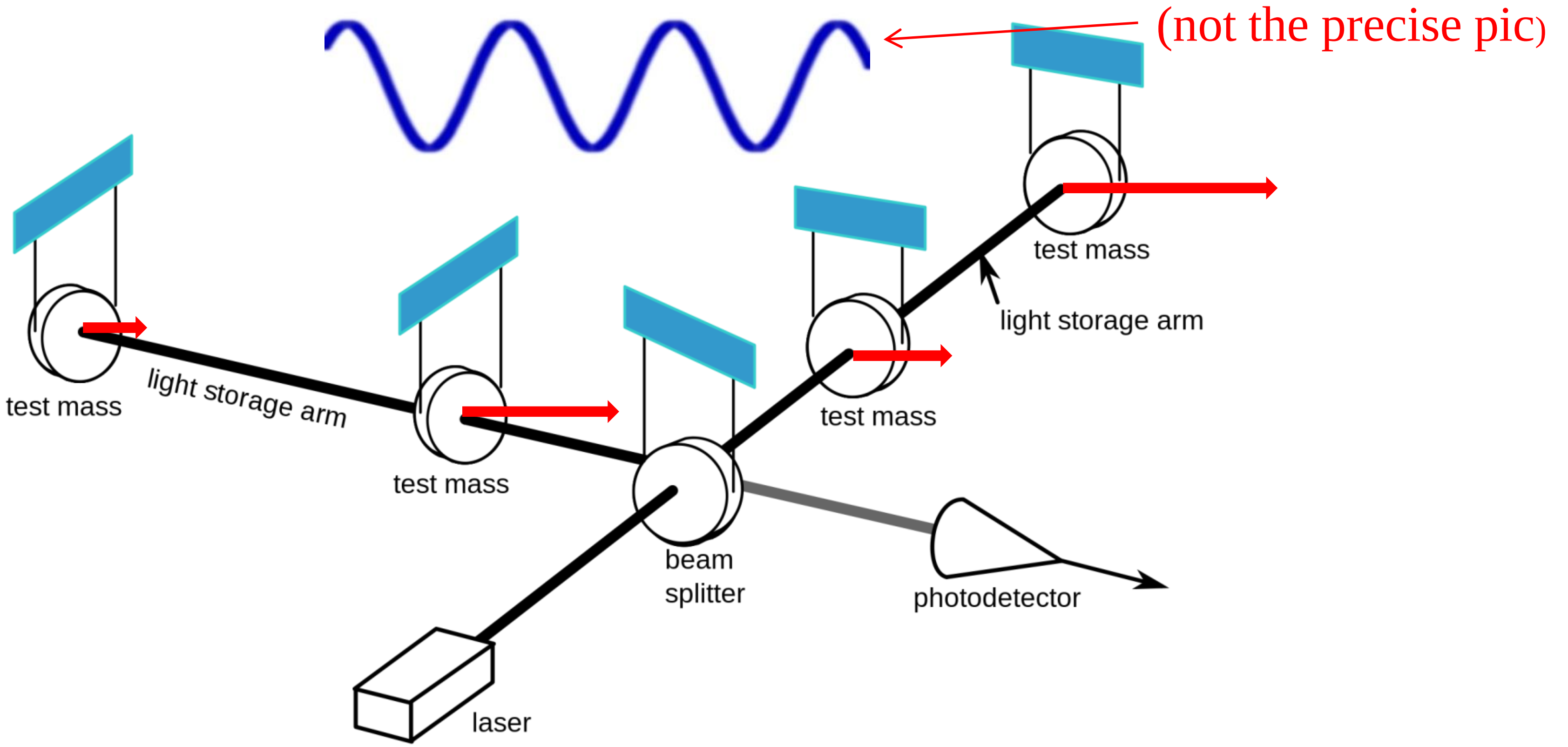


(space.com)

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

General Picture:

Ultra-light DM $\Rightarrow$ background classical radio wave



Dark photon dark matter moves mirrors. $\Rightarrow$ Change photon propagation time between mirrors. $\Rightarrow$ 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

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

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

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

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

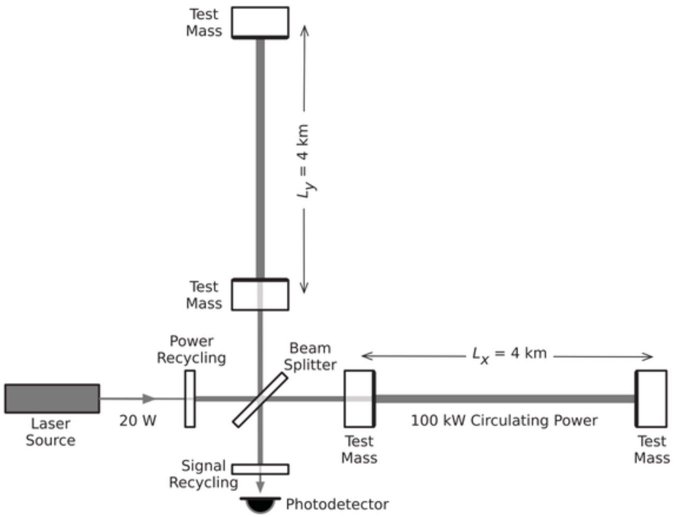
U(1)B-L : 1/(2GeV)

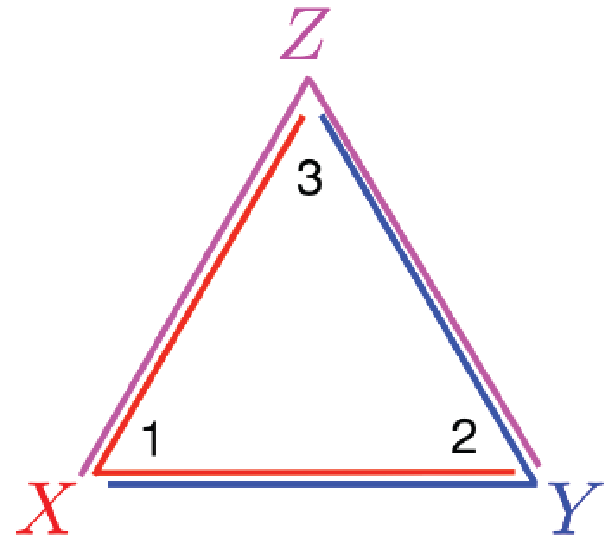
projected along
the arm direction

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

Maximal GW-like Displacement:

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





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

Compare this with the sensitivity on strain h.

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

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:

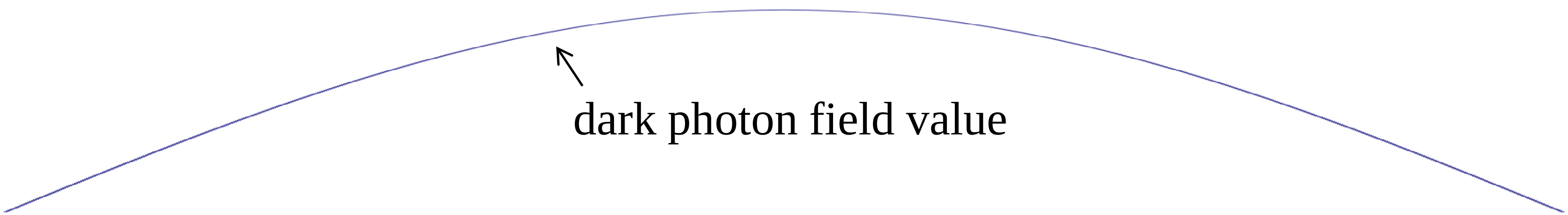
- very long coherent distance

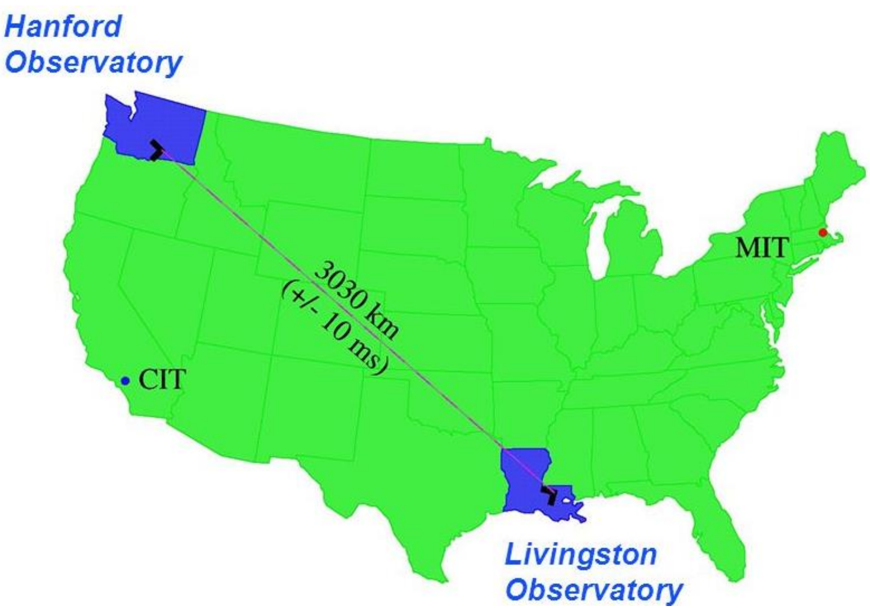
$$l_{coh} \simeq \frac{1}{m_A v_{vir}} \simeq 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f} \right)$$

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)

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

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

optimal filter function
maximize SNR

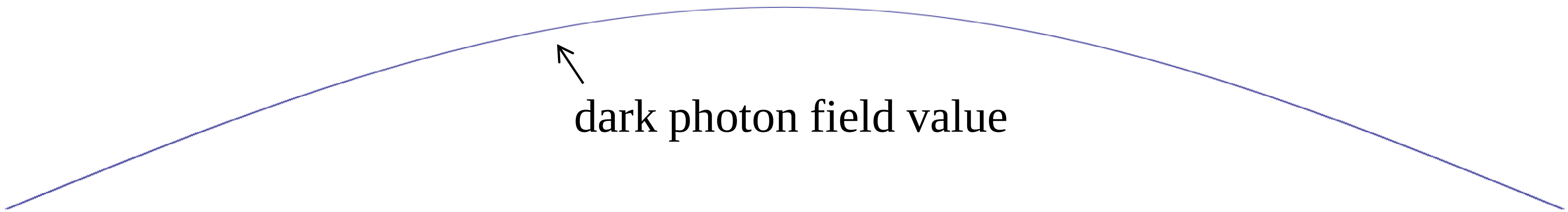
one-sided strain noise power spectra

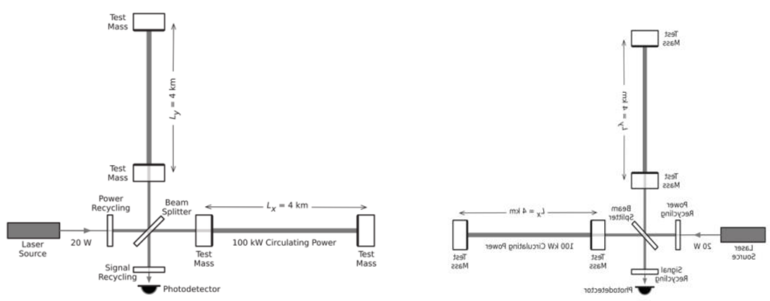
Sensitivity to DPDM signal of GW detectors:

DPDM:

LIGO

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





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:

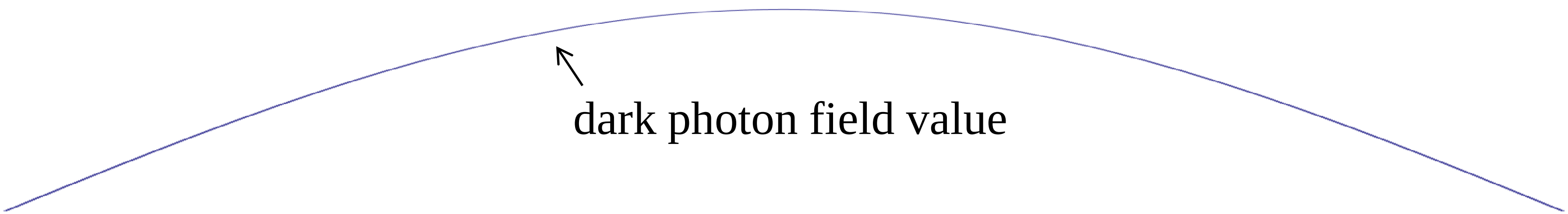
DPDM:

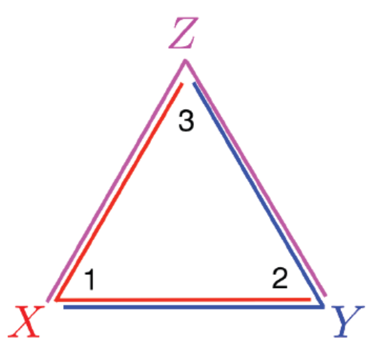
LISA

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

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

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





$\Rightarrow$ 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

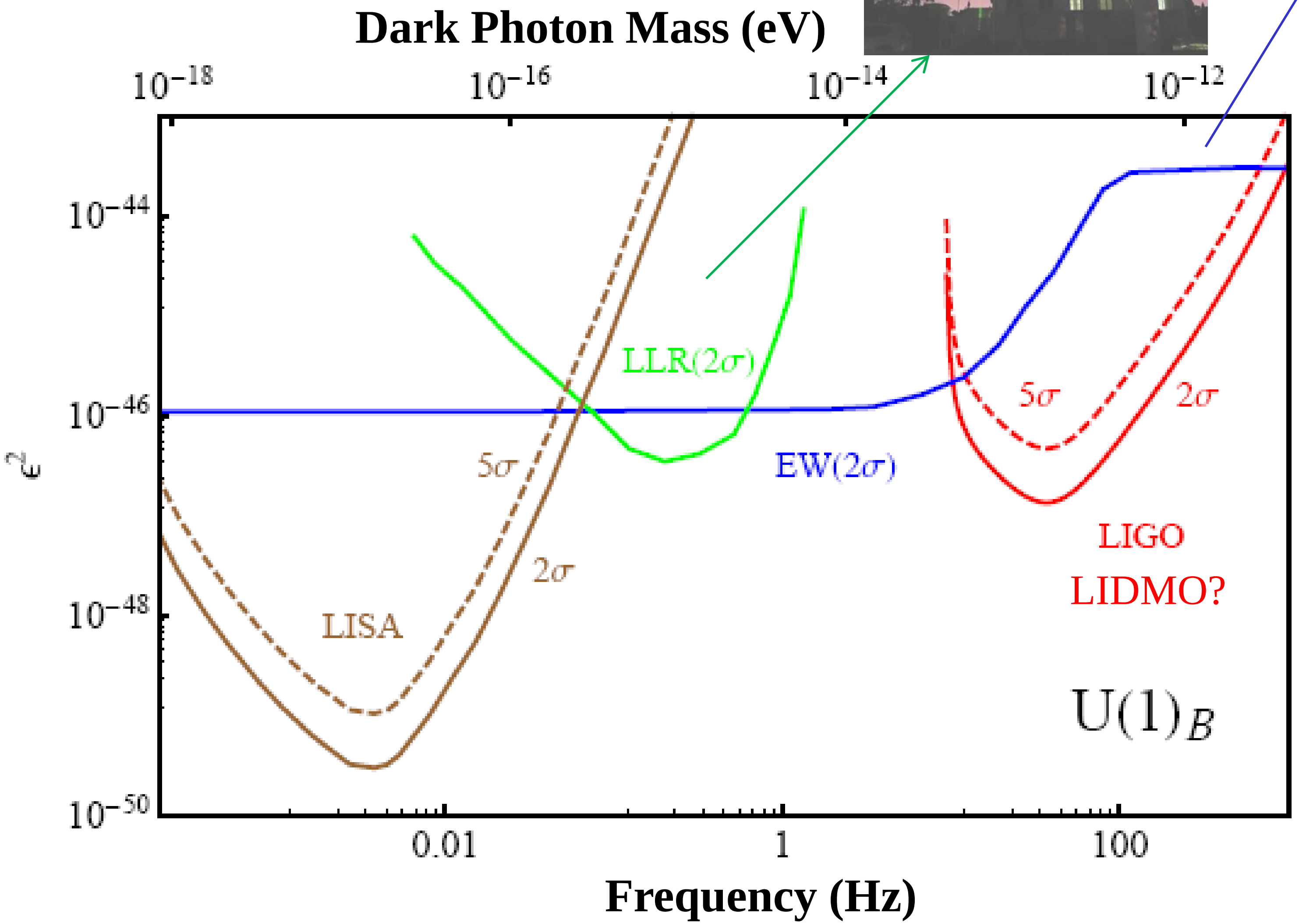
⇨ $\sqrt{\langle \Delta L^2 \rangle}_{LIGO}\Big|_{max}$

⇨ sensitivity of DPDM parameters (mass, coupling)

Sensitivity Plot:

(People's Daily)

(Eöt-Wash web)

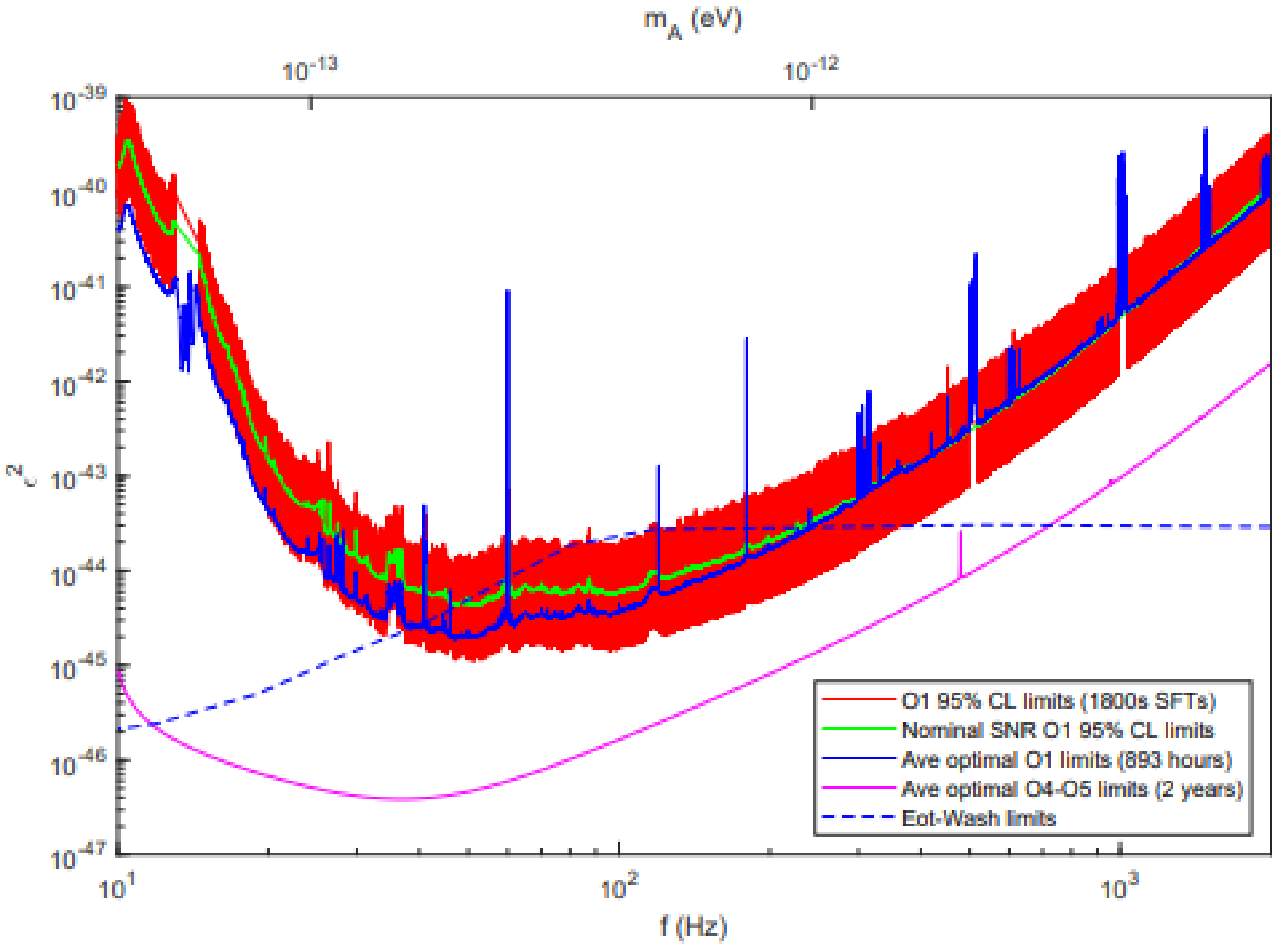


Loránd Eötvös

$\longrightarrow$ Eöt-Wash

design sensitivities, 2 yrs

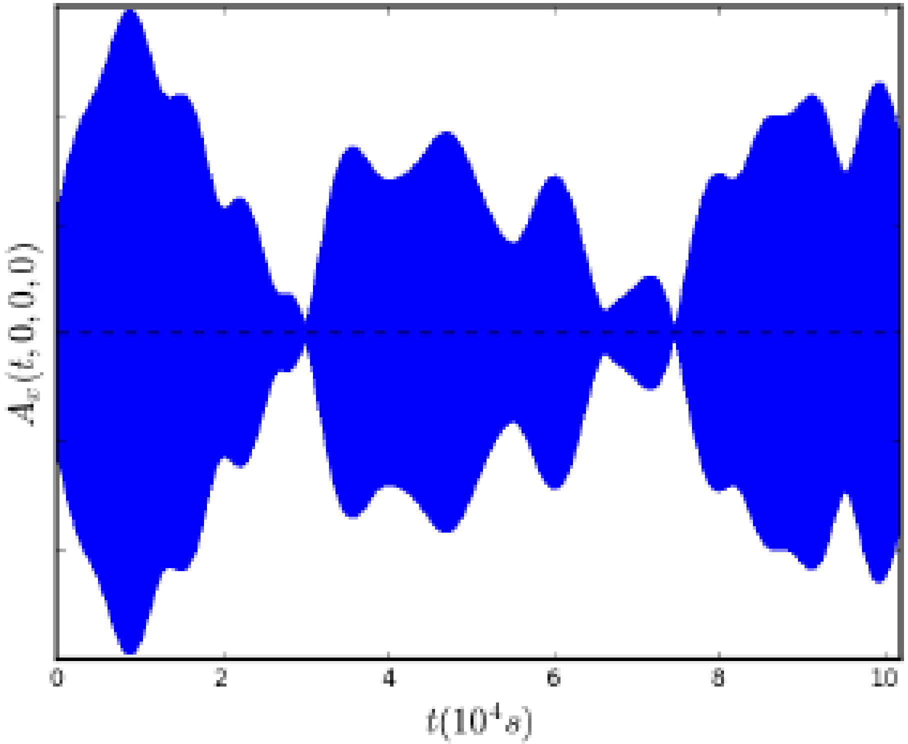
O1 Result:

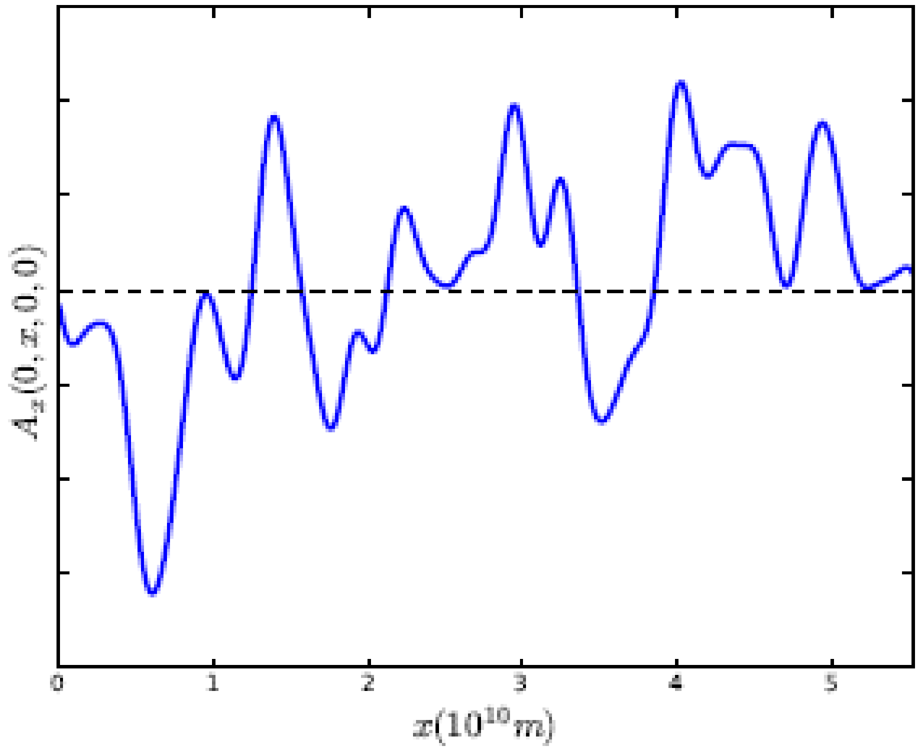


m_A (eV)
10^{-13}
10^{-12}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
ϵ^2
10^1
10^2
10^3
f (Hz)
O1 95% CL limits (1800s SFTs)
Nominal SNR O1 95% CL limits
Ave optimal O1 limits (893 hours)
Ave optimal O4-O5 limits (2 years)
Eot-Wash limits

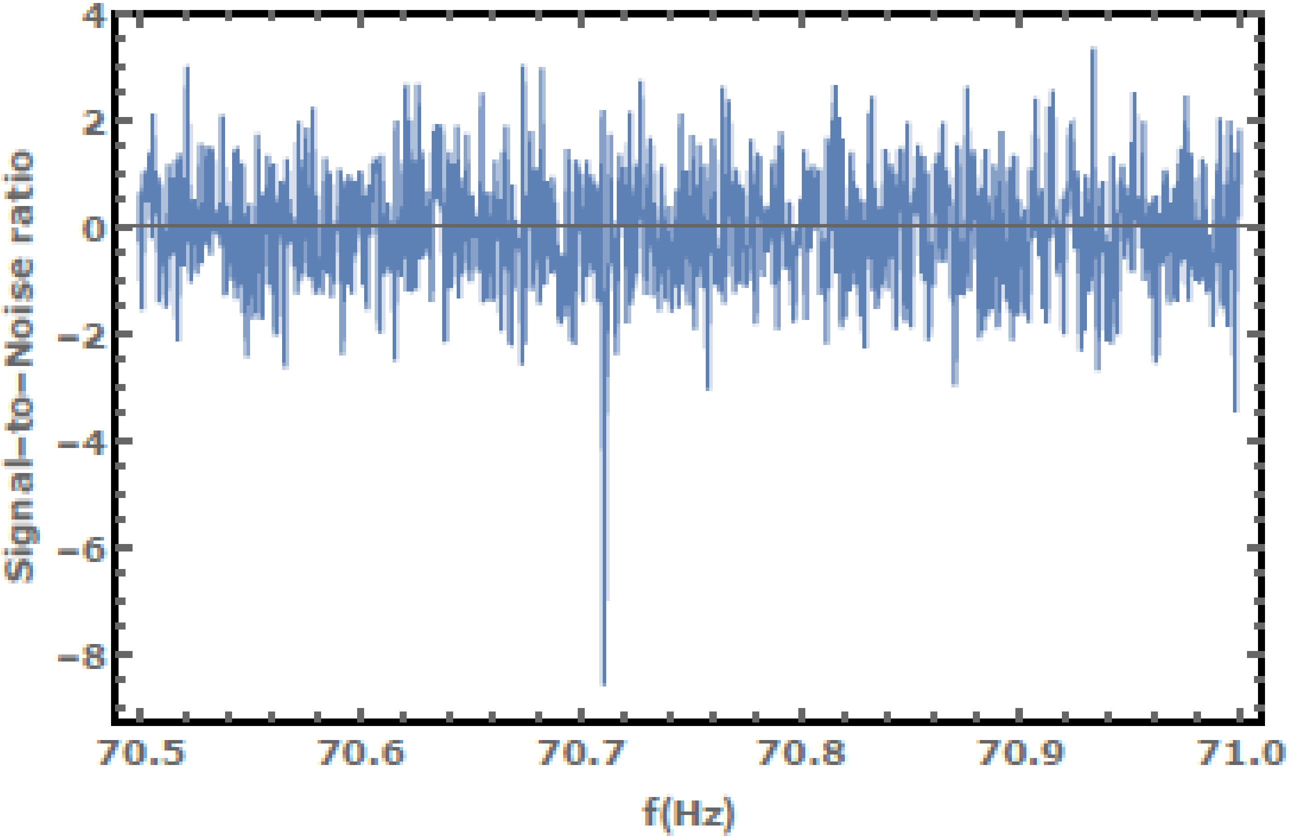
Modeling DPDM background:

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





LIGO simulation output:

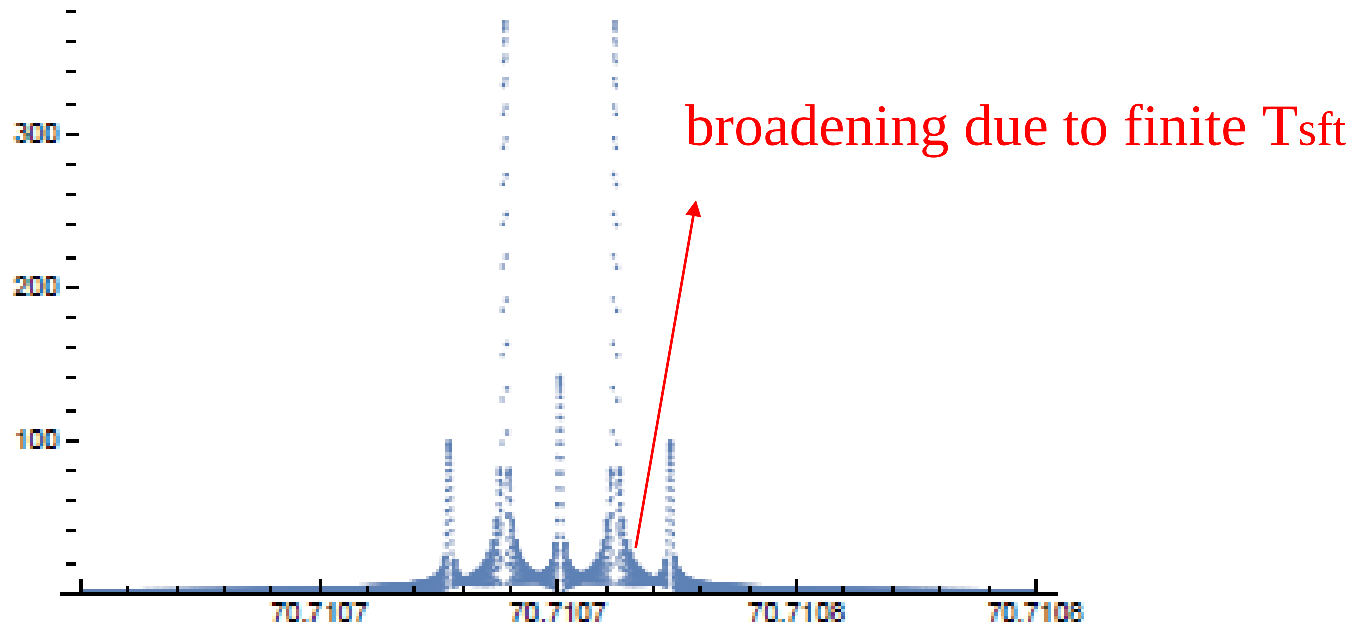


$\epsilon^2 = 5\times10^{-44}$ $f = 70.71$ Hz $T_{SFT} = 1800$ s $T_{tot} = 200$ hr

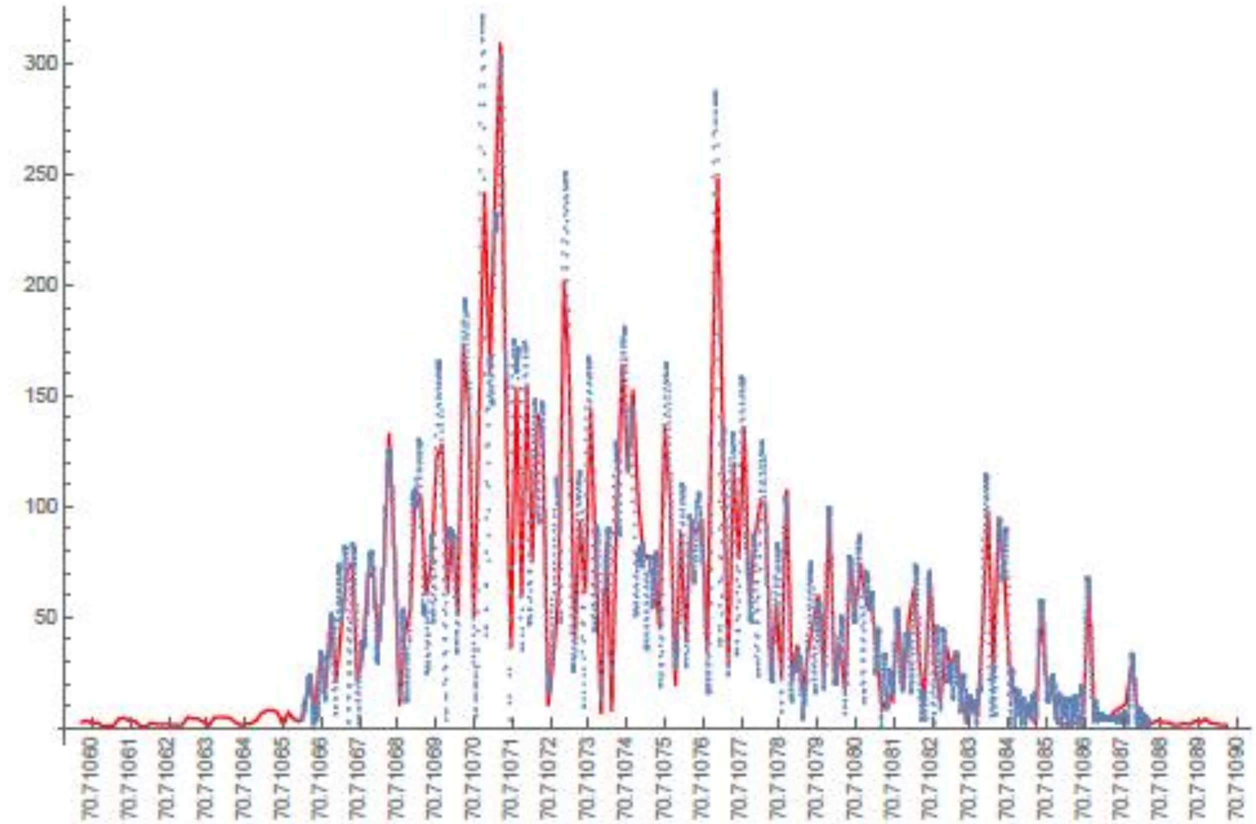
⇨ $\mathrm{SNR} \simeq -8.$

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!

Facial mask: prevent the damage to your skin from gravitational wave radiation.

GS-mechanism for massive U(1):

Lagrangian for a massive photon with GS-term:

$$\mathcal{L}_\alpha \;=\; -\frac{1}{4g_A^2}F^AF^A - \frac{1}{4g_a^2}Tr[G^aG^a] - \frac{1}{2}\left(\partial^\mu\alpha - MA^\mu\right)^2 - \frac{1}{2}\,c_1\;\alpha\;Tr[G^a\wedge G^a]$$

U(1) gauge transformation:

$$A^\mu \rightarrow A^\mu + \partial^\mu\epsilon \quad , \qquad\qquad \alpha \rightarrow \alpha + M\epsilon$$

GS term can be chosen so that the anomaly from fermions are cancelled:

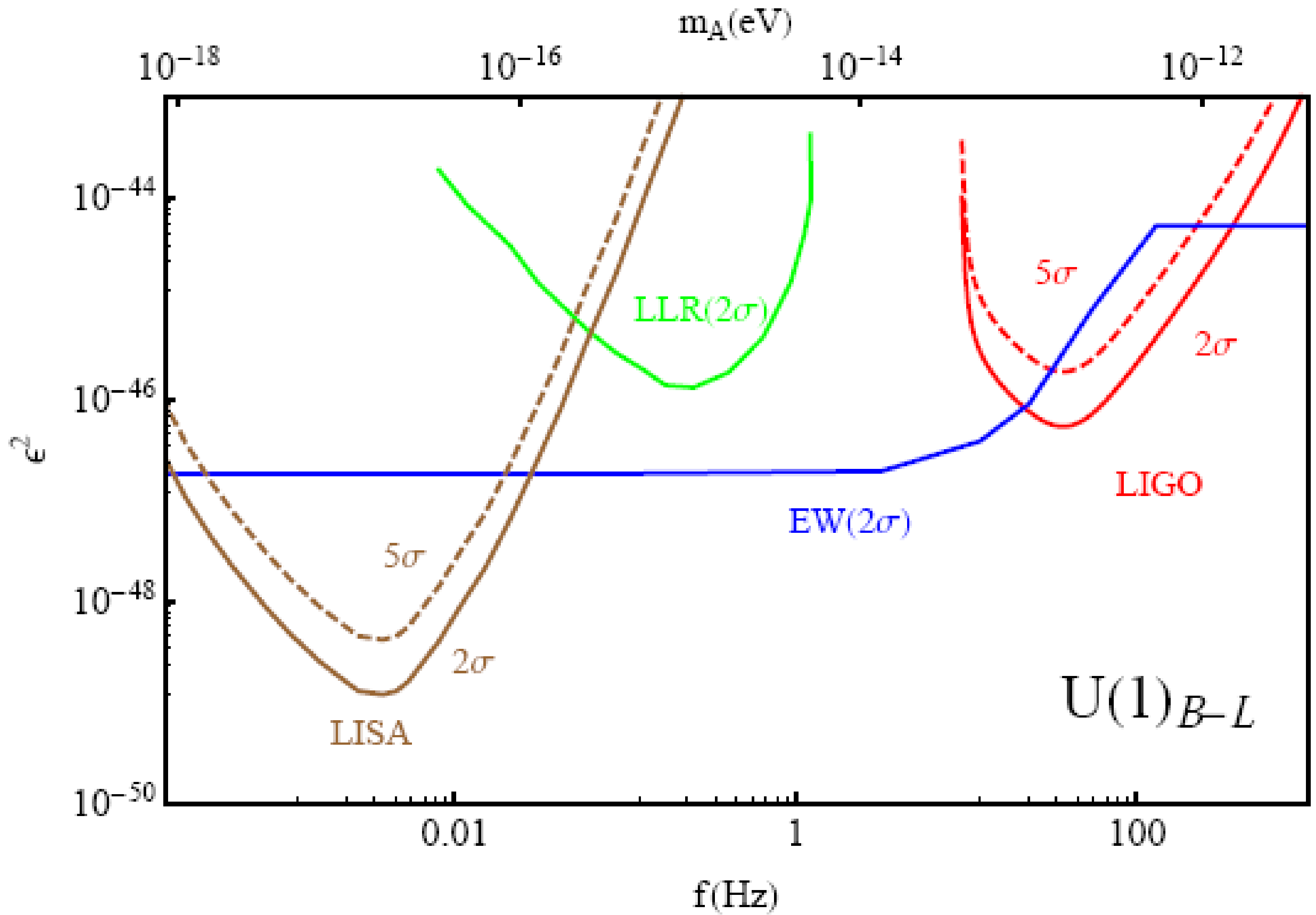
$$\delta_\epsilon\mathcal{L}_{total} = -\frac{1}{2}\left(Mc_1 - \frac{\mathcal{A}}{16\pi^2}\right)\epsilon\;Tr[G^a\wedge G^a]$$

$$\mathcal{A} = 16\pi^2Mc_1$$

Sensitivity Plot:

U(1) B-L

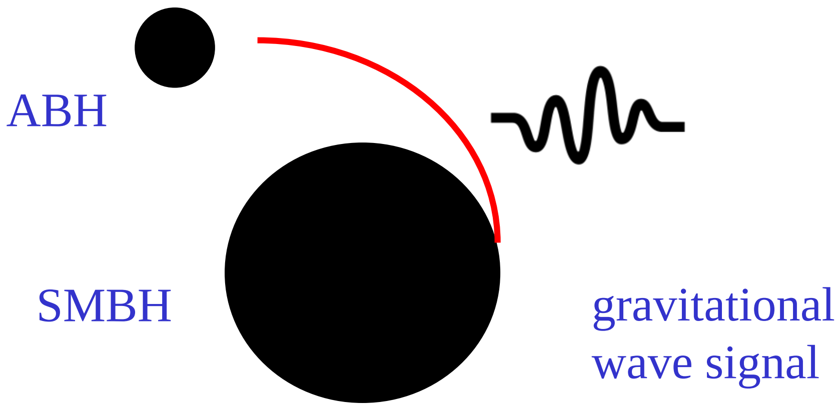
charge mass ratio: 1/2GeV

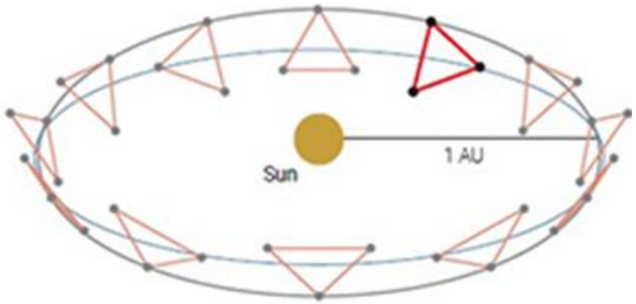


design sensitivities operating for 2 years

LISA-like GW exp for PBH

Extreme Mass Ratio Inspirals





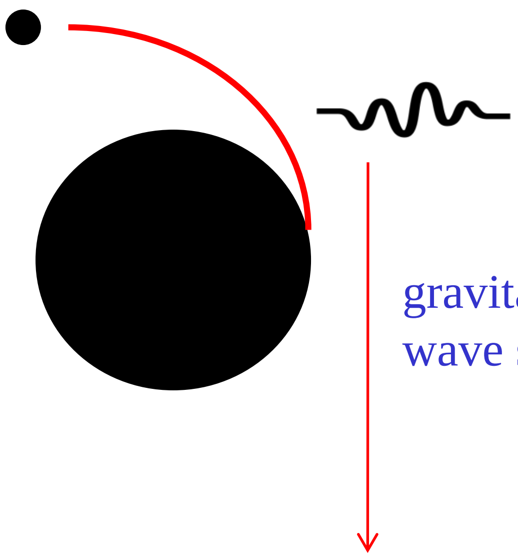
LISA

LISA-like GW exp for PBH

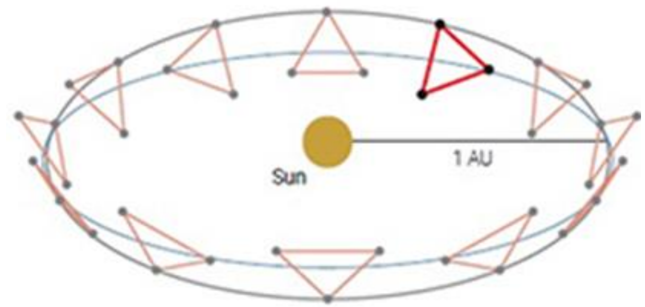
Extreme Mass Ratio Inspirals

PBH

SMBH



gravitational
wave signal



LISA

Same frequency, but smaller amplitude!

Master Formula:

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

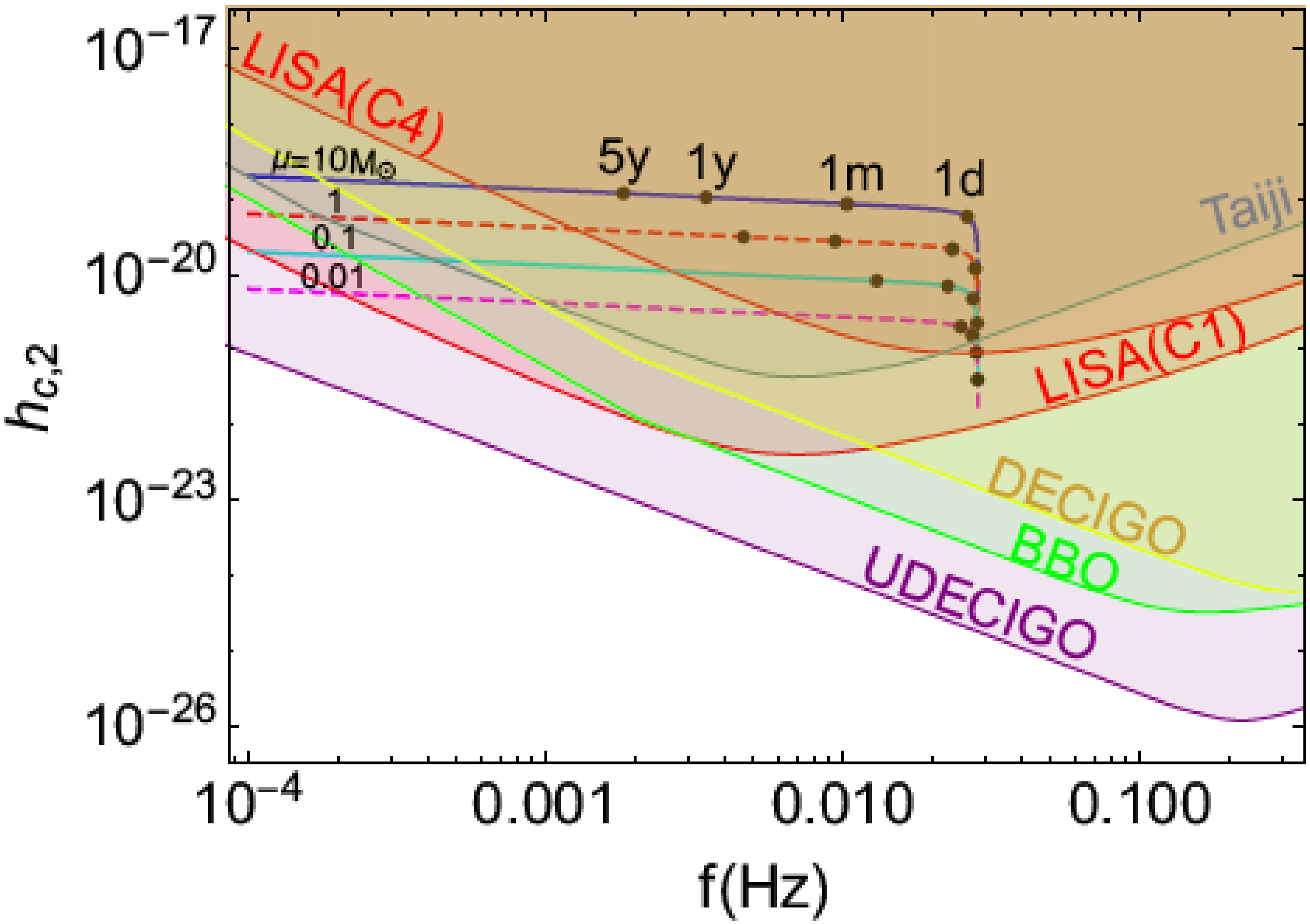
intrinsic EMRI rate
well studied for SMBH-ABH
rescale for PBH mass and density

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

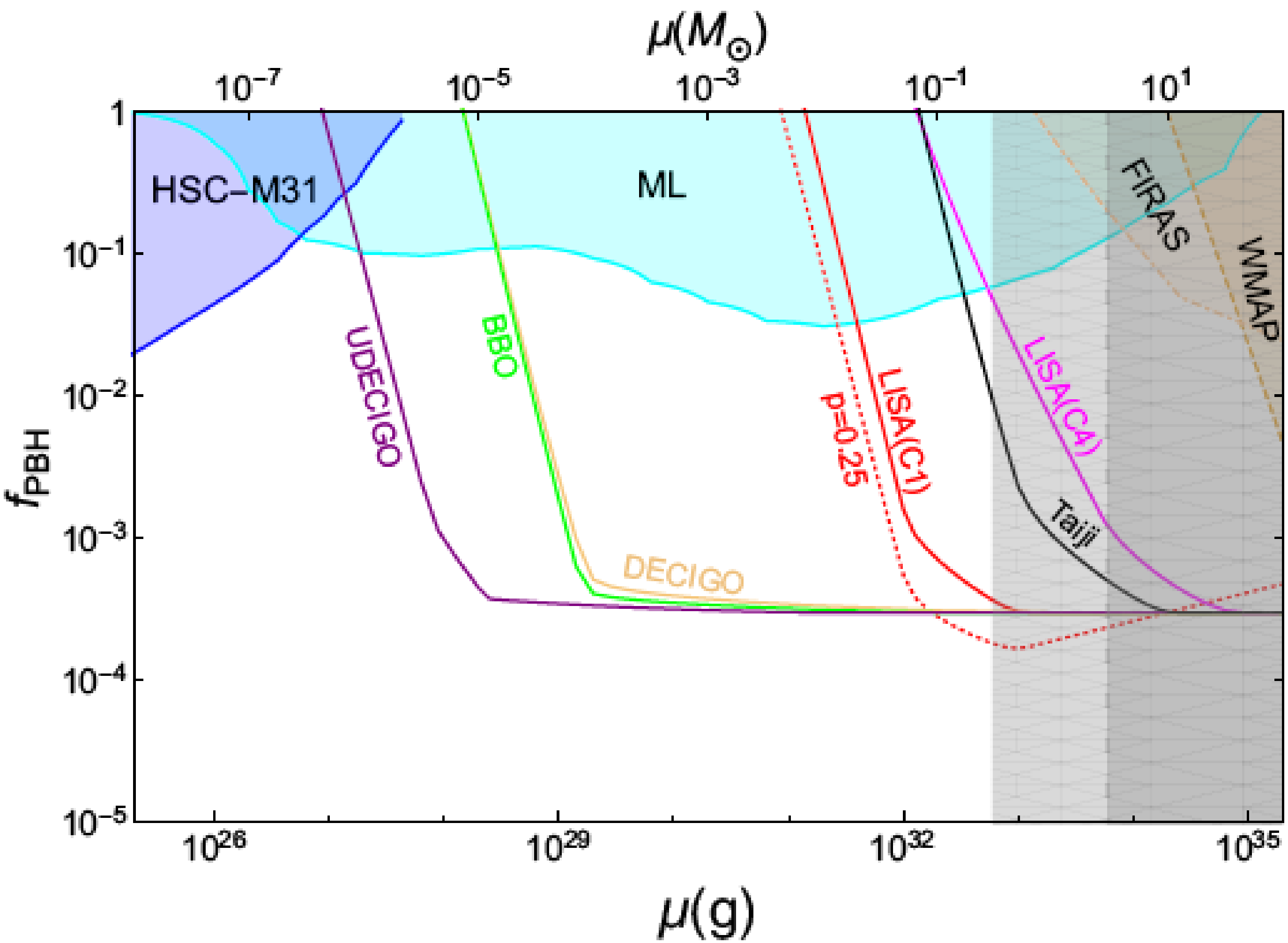
GW Strain:

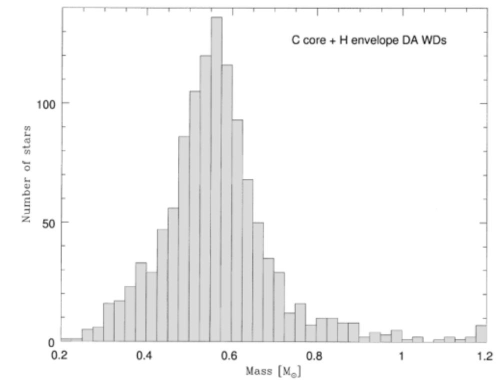


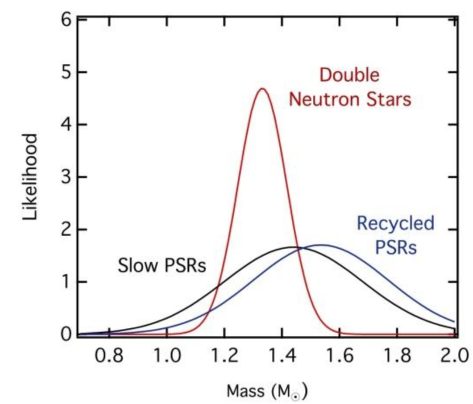
M = $10^6\,M_\odot$; Spin = 0.999 ; 1 Gpc

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

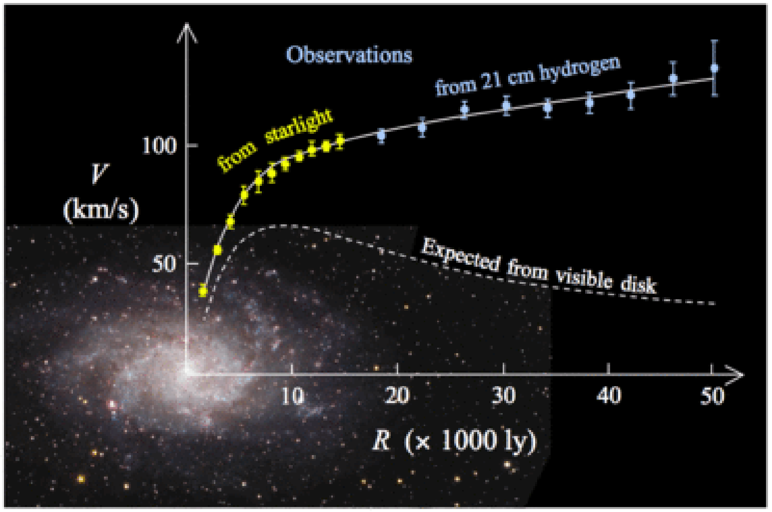
LIGO opens the era of GW astronomy. (Similar to the time when CMB is observed.)

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

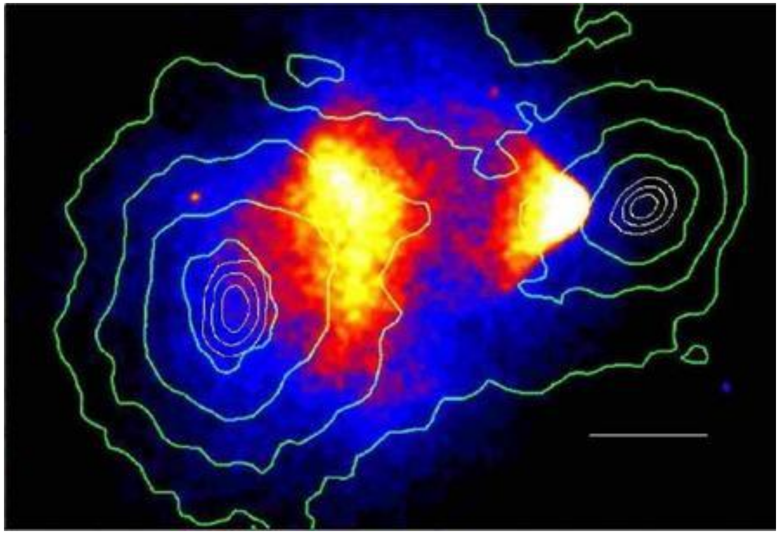
Dark Matter Overview:

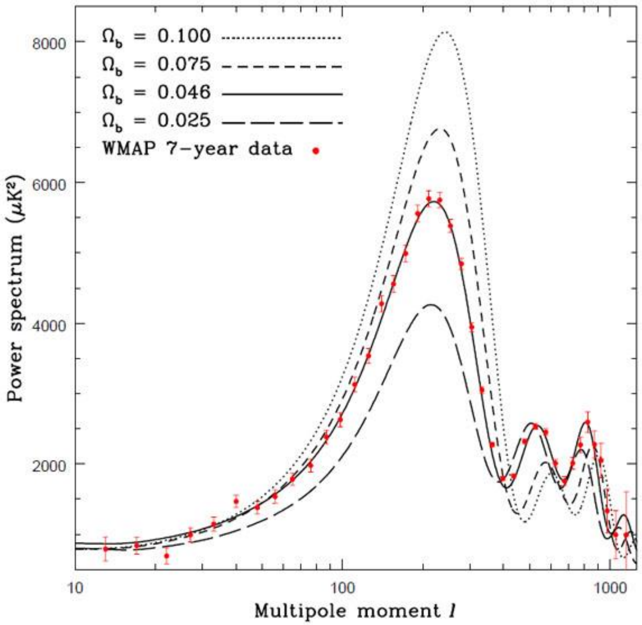
Why do we need DM?

• Galaxy rotation curve (Wikipedia)



• Bullet Cluster (Deep Chandra)





• The CMB Anisotropy Power Spectrum

(WMAP year 5 data)