Searching for Dark Photon Dark Matter with LIGO

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O1 data analysis is done!
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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.

Dark field estimation

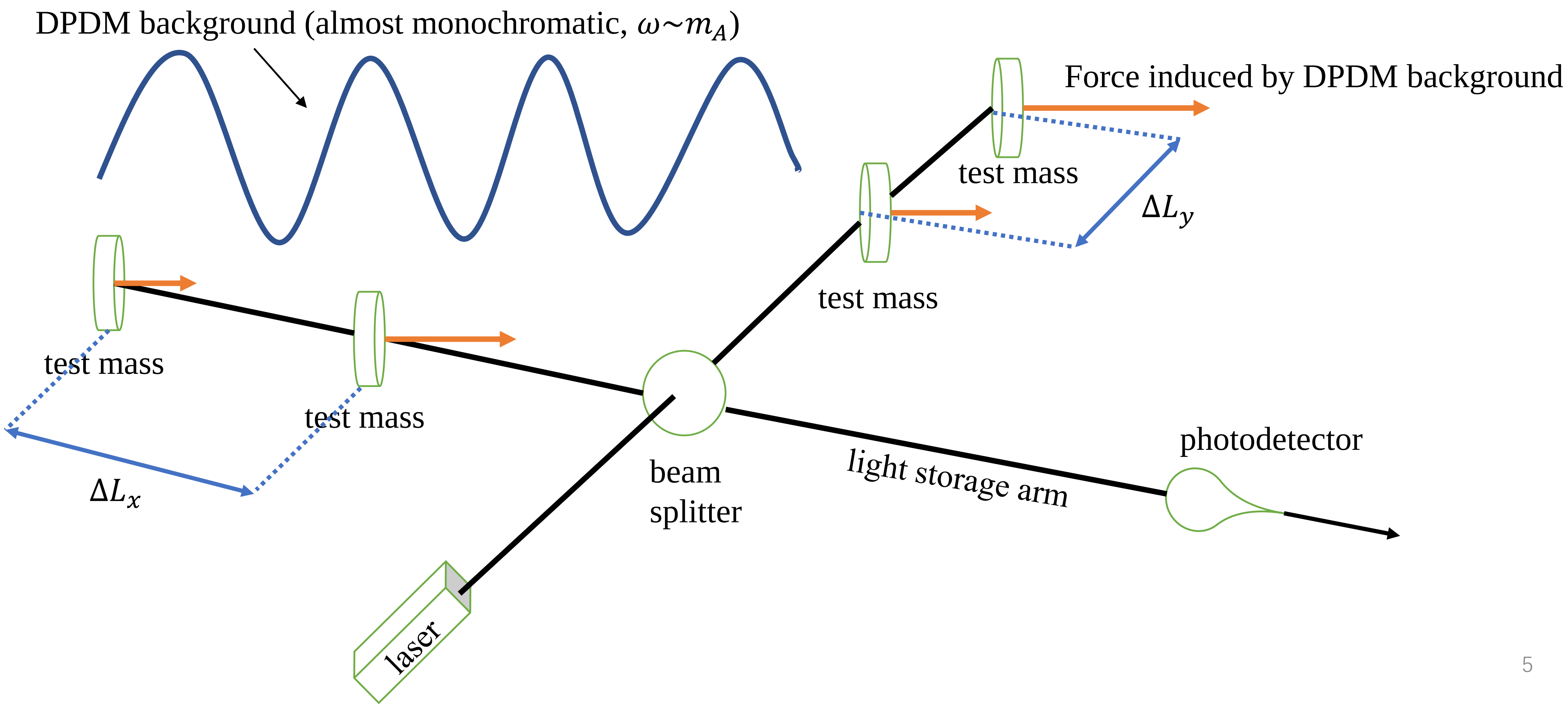
Local DM energy density:

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

In non-relativistic limit, the effect from electric component of Dark Photon background field is dominant.

How to search DPDM with LIGO?

- The most precise measurement of relative displacement $\Delta L \equiv |\Delta L_x - \Delta L_y|$ in O(1)km length scale.



The DPDM background simulation

- DPDM obeys Maxwell velocity distribution $f(v) \sim v^2 e^{-v^2/v_0^2}$, where $v_0 \sim 10^{-3} c$.
- The wavefunction of the i^{th} dark photon particle,

polarization vector — $\mathbf{A}_{i,0}$; propagation vector — $\mathbf{k}_i$

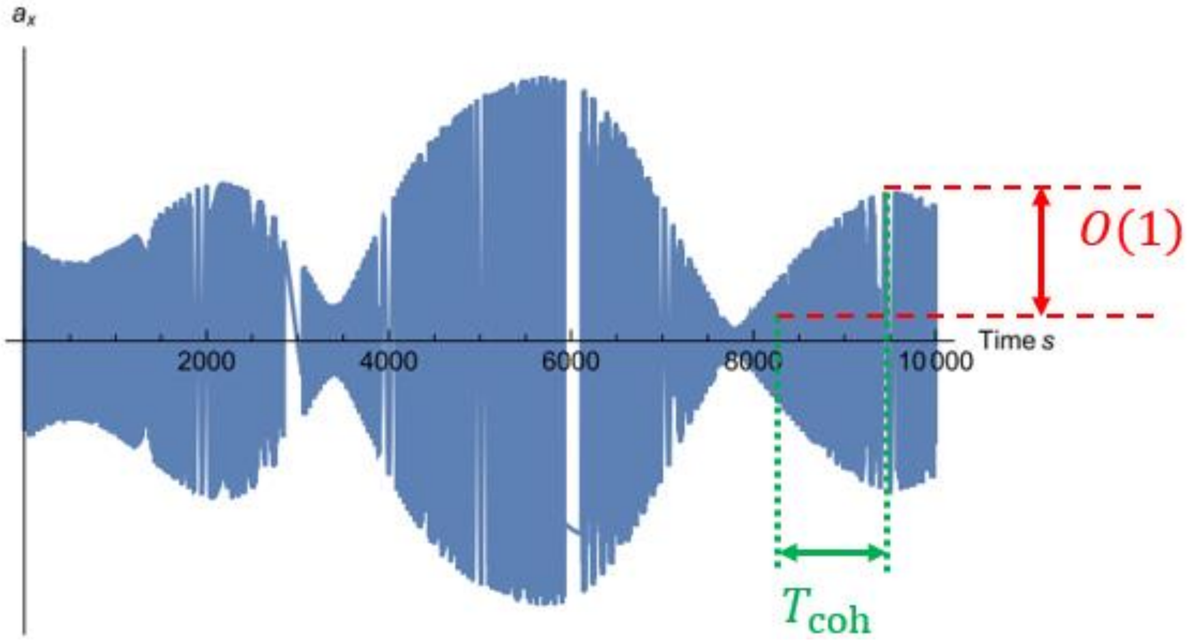
$$\mathbf{A}_i(t, \mathbf{x}) \equiv \mathbf{A}_{i,0} \sin(\omega_i t - \mathbf{k}_i \cdot \mathbf{x} + \phi_i),$$

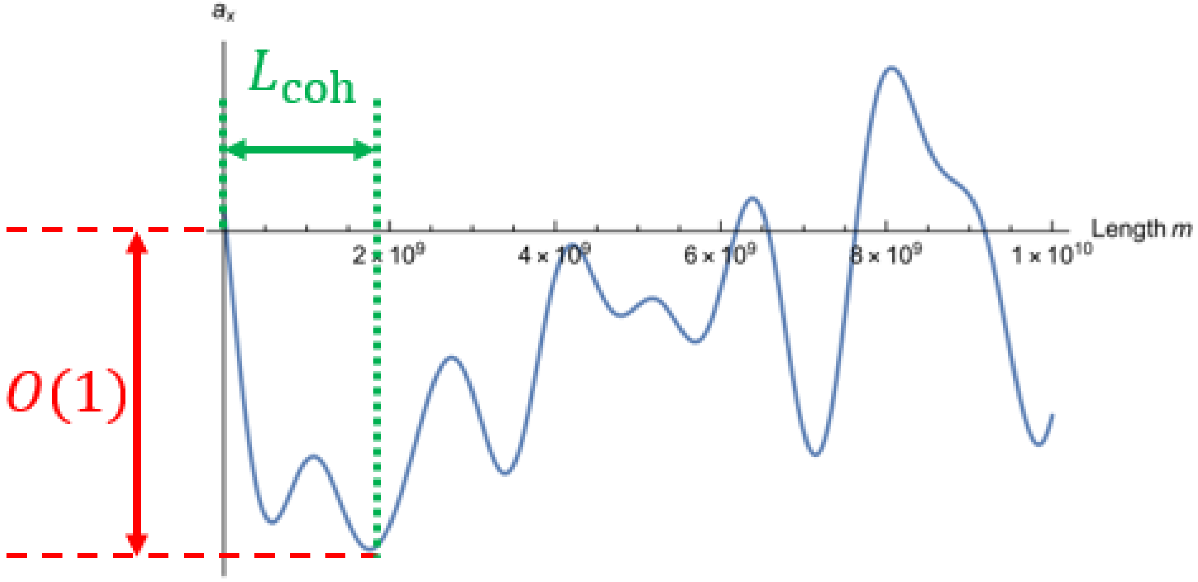
total energy — ω_i; random phase — ϕ_i

- 100Hz ⟶ $m_A \sim 4 \times 10^{-13}$eV ⟶ Dark photon wavefunctions overlap.
- Obtain the DPDM background field:

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

The DPDM background simulation





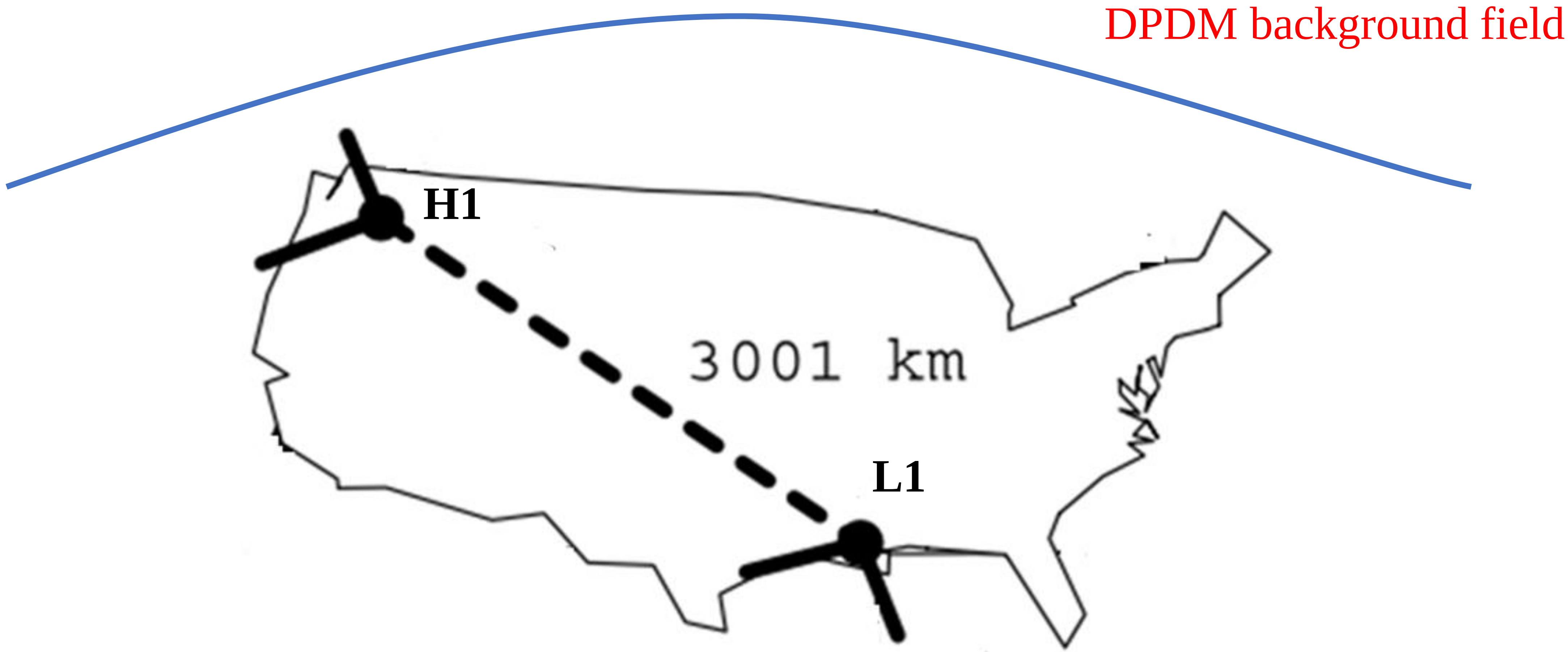
Coherence time T_{coh}:
The time when the background profile has one order of magnitude change.

$$T_{coh} \cong \frac{2\pi}{E_k} = \frac{4\pi}{m_A v_0^2}$$

Coherence length L_{coh}:
The length where the profile has one order of magnitude change.

$$L_{coh} \cong \frac{2\pi}{k} = \frac{2\pi}{m_A v_0} \sim 3 \times 10^9 \mathrm{m} \left(\frac{100\mathrm{Hz}}{f}\right)$$

Correlated DPDM signals



H1 in Hanford, L1 in Livingston.

Properties of DPDM signals

- Signal is almost monochromatic $f \cong \frac{m_A}{2\pi}$.
- Signal is correlated between two LIGO detectors due to the board coherence region of DPDM background.
- SNR value is negative since there is 90° rotation between two LIGO detectors. The sign of the signal flips.

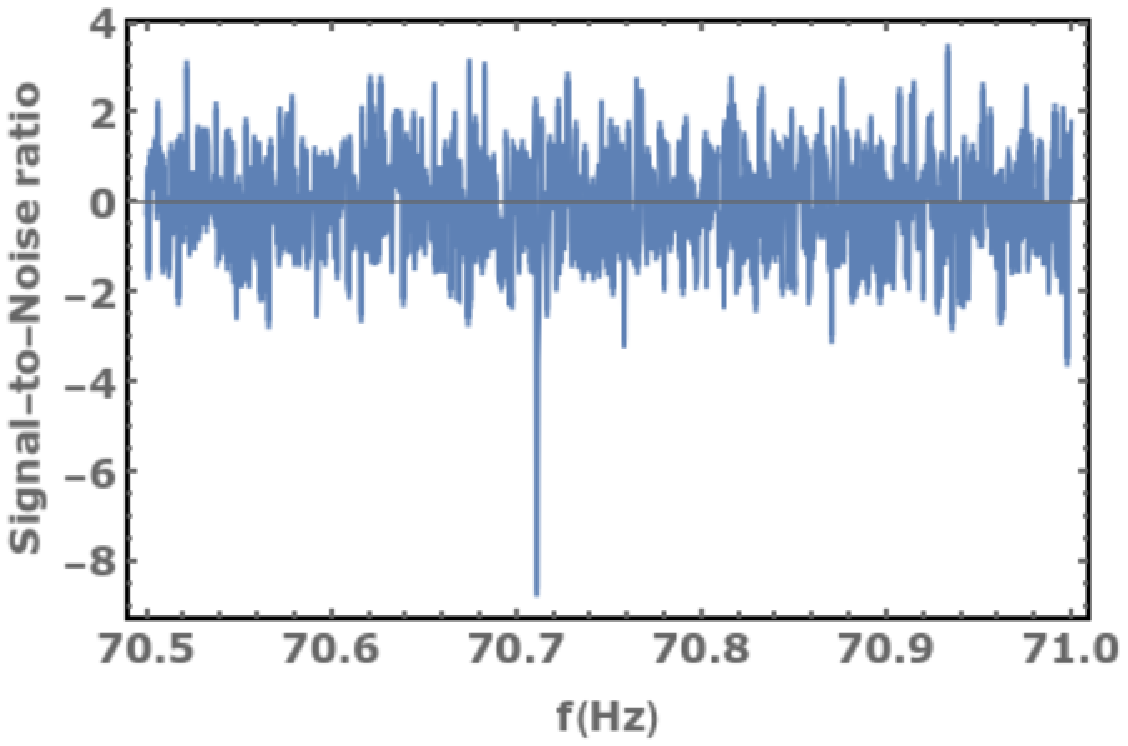


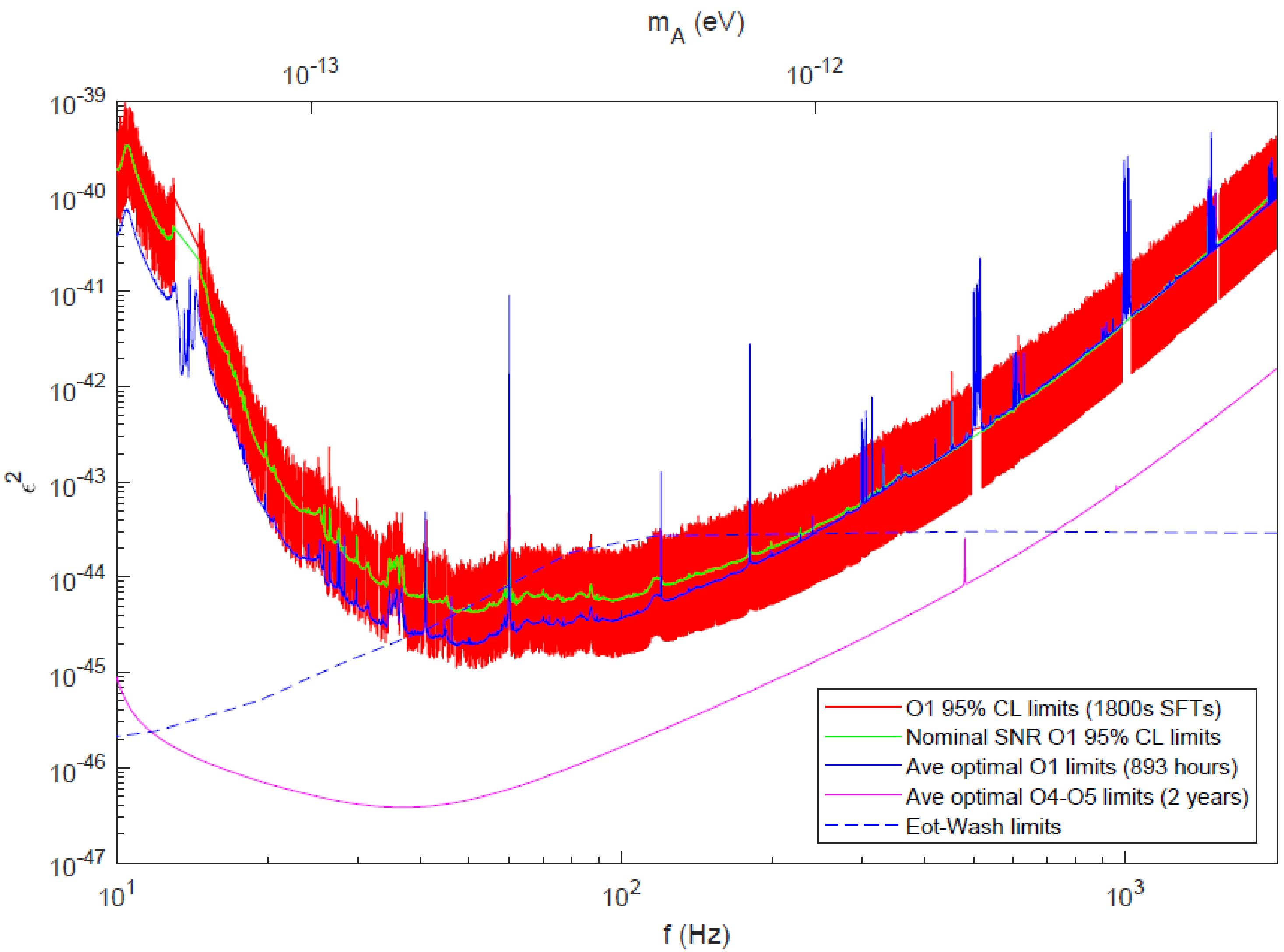
FIG. 5: The SNR v.s. frequency plot, where $f = 100/\sqrt{2}$Hz, $\epsilon^2 = 5\times10^{-44}$, $N_{\rm SFT} = 400$, $T_{\rm SFT} = 1800$s, Gaussion noise of detector set in LALSuite is 10^{-23}.

O1 Result – sensitivity curve of DPDM signal in LIGO:

Dark Photon Mass

DPDM-SM
coupling strength

$U(1)_B$



Frequency of DPDM signal

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!

⇨ Cross correlation

The sensitivity can be extraordinary!

⇨ O1 data has already beaten existing experimental constraints.

Can probe the unexplored parameter regimes.

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

Backup 1: Dark field estimation

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

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

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

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

the typical velocity of DPDM $v \sim 10^{-3} c$
(the virial velocity of DM halo in the Milky Way)

Backup 2: Signal modeling

- The acceleration of m^{th} test mass $\mathbf{a}_m$ is

$$\mathbf{a}_m \approx \epsilon e \frac{q_{D,m}}{M_m} \frac{\partial \mathbf{A}_{total}(t, \mathbf{x}_m)}{\partial t}.$$

dark electric field

dark photon coupling

charge – mass ratio of m^{th} test mass

Silicon mirror:
$\mathrm{U}(1)_{\mathrm{B}}$: 1/GeV
$\mathrm{U}(1)_{\mathrm{B}-L}$: 1/(2GeV)

- The displacement of m^{th} test mass projected along the arm direction:

$$s_{||,m} = \int dt \int dt \, \mathrm{a}_{||,m}(t)$$

projected along the arm direction

- One subtlety: If Earth rotation effect is included, the direction of polarization vector and propagation vector will rotate around the Earth rotation axis.

Backup 3: Detector response

- The relative arm length change is

$$R_L \equiv \frac{\Delta L_x - \Delta L_y}{L}.$$

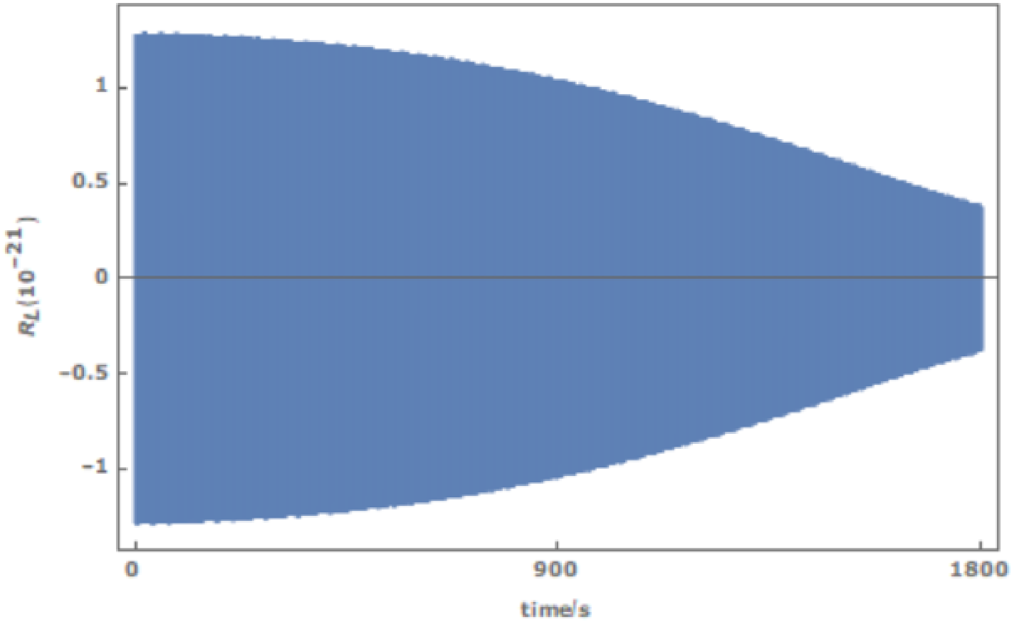


FIG. 3: Signal input to the LIGO similation package. We set $f = 100\sqrt{2}$Hz, $\epsilon = 10^{-18}$. The DPDM profile is obtained by superposing 10^3 DPDM particles.

- Inject the signal into LALSuite (LIGO simulation package) to obtain the detector response.

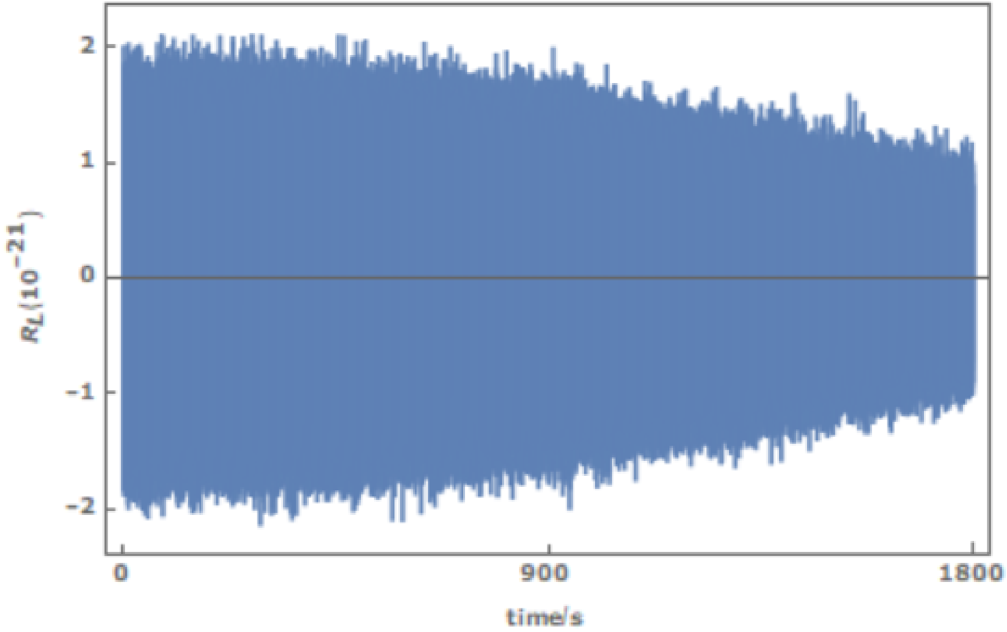


FIG. 4: The output of the LIGO simulation package, after noise is added. We set $f = 100\sqrt{2}$Hz, $\epsilon = 10^{-18}$. The DPDM profile is obtained by superposing 10^3 DPDM particles.

Backup 4: DPDM detection statistic

- The DPDM signal is approximately a peak in frequency space.
- We use short-time Fourier transform (SFT). Given fixed observation time T_{obs}, $N_{SFT} = T_{\mathrm{obs}}/T_{\mathrm{SFT}}$.
- The measure of signal strength:

$$S_j = \frac{1}{N_{SFT}} \sum_{i=1}^{N_{SFT}} \frac{z_{1,ij} z_{2,ij}^*}{P_{1,ij} P_{2,ij}}$$

complex SFT coefficient for SFT i and frequency bin j and interferometer 1, 2

The signal is correlated!

the noise power

and the variance is

$$\sigma_j^2 = \frac{1}{N_{SFT}} \left\langle \frac{1}{2P_{1,j}P_{2,j}} \right\rangle_{N_{SFT}}$$

- The signal-to-noise ratio obtained from measurement:

$$\mathrm{SNR} \equiv \frac{S_j}{\sigma_j}.$$