Searching for Dark Photon Dark Matter with Laser Interferometers and Quantum Sensors

Fengwei Yang
Department of Physics
University of Florida
Dec 14th, 2023

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

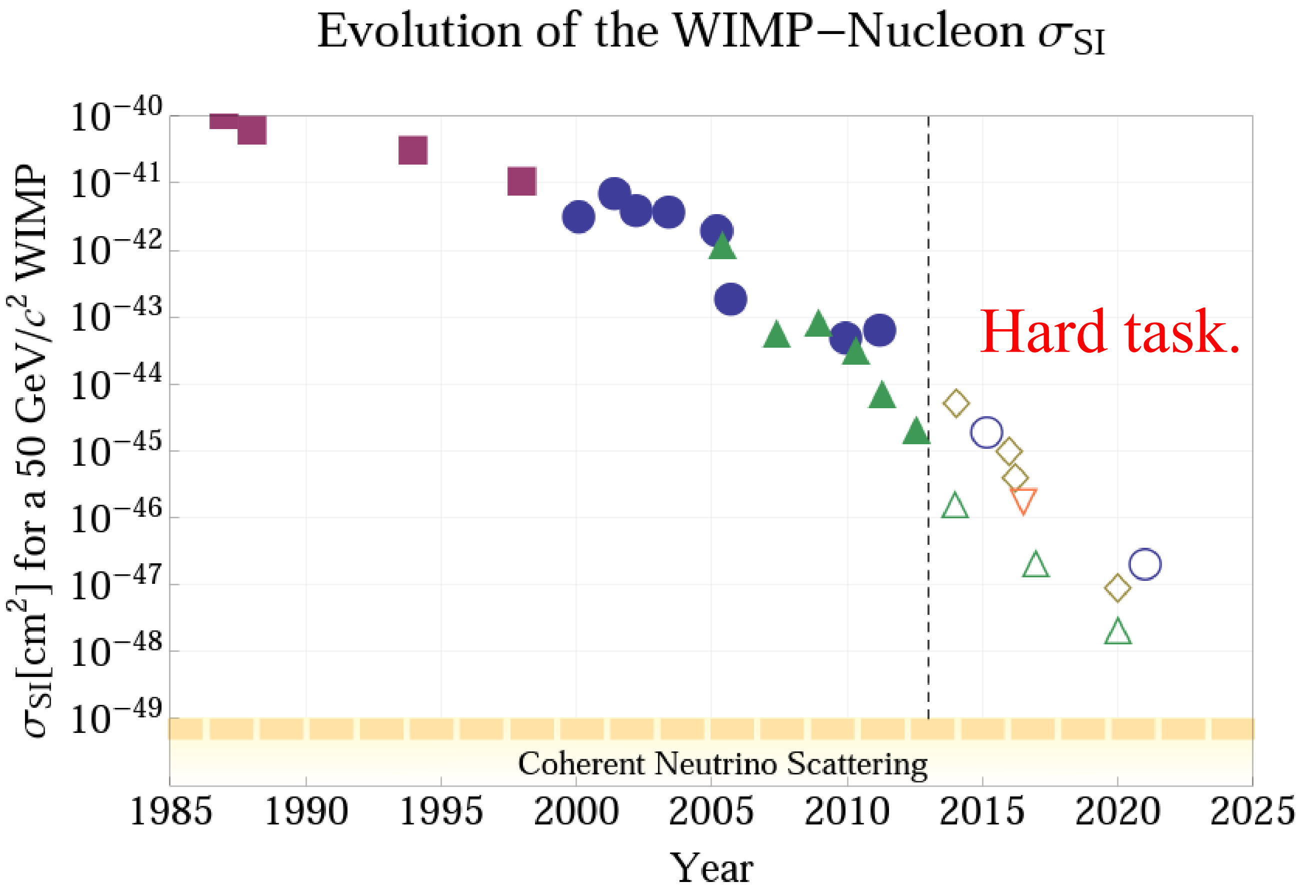
LIGO-Virgo-KAGRA Collaboration paper
arXiv: 2105.13085
***Phys.Rev.D* 105 (2022) 6, 063030**

Min Jiang, Taizhou Hong, Donddong Hu, Yifan Chen, F.W. Y., Tao Hu, Xiaodong Yang, Jing Shu, Yue Zhao, and Xinhua Peng
arXiv: 2305.00890

Acknowledgement: The part of the material is based upon work supported by NSF's LIGO Laboratory which is a major facility fully funded by the National Science Foundation.

Dark Matter Review

- Bunch of observational evidence: galaxy rotation curve, Bullet Cluster, CMB anisotropies…
- Many experiments have been performed to look for DM for the past four decades.
- However, we still have no clue about the particle nature of DM.



WIMP: Weakly interacting massive particles

Fig.1 WIMP Dark Matter Direct Detection (Community Planning Study: Snowmass 2013)

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
arXiv:1905.04316 [hep-ph]
Nature - Commun.Phys. 2 (2019) 155

- Primordial Black Holes:

  10^{-7} ~ 100 solar mass

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

Popular Choices

- Wave-like DM

  Axion and Dark "Photon"

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

Model 1: gauge boson of the $U(1)_B$ or $U(1)_{B-L}$
(p+n) (n)

Model 2: kinetically mixed dark photon (will talk later)

Dark Photon is dominantly oscillating background dark electric field. → displacements for B-charged or (B-L)-charged particles

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

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

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

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

virial velocity of DPDM $\sim 10^{-3}$

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

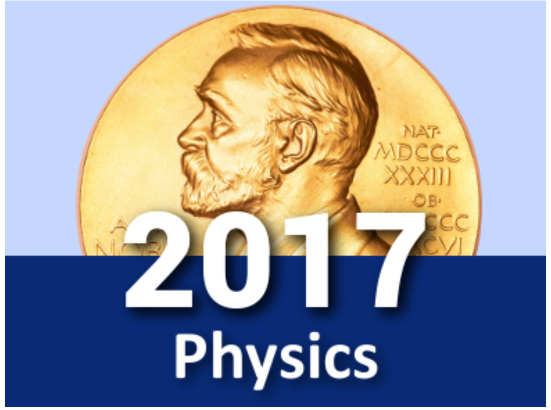
Ultra-light dark photon can be a good candidate of cold dark matter!

Chap 1: Searching for DPDM using laser interferometers

Laser Interferometer Gravitational-Wave Observatory

LIGO (ground-based)

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

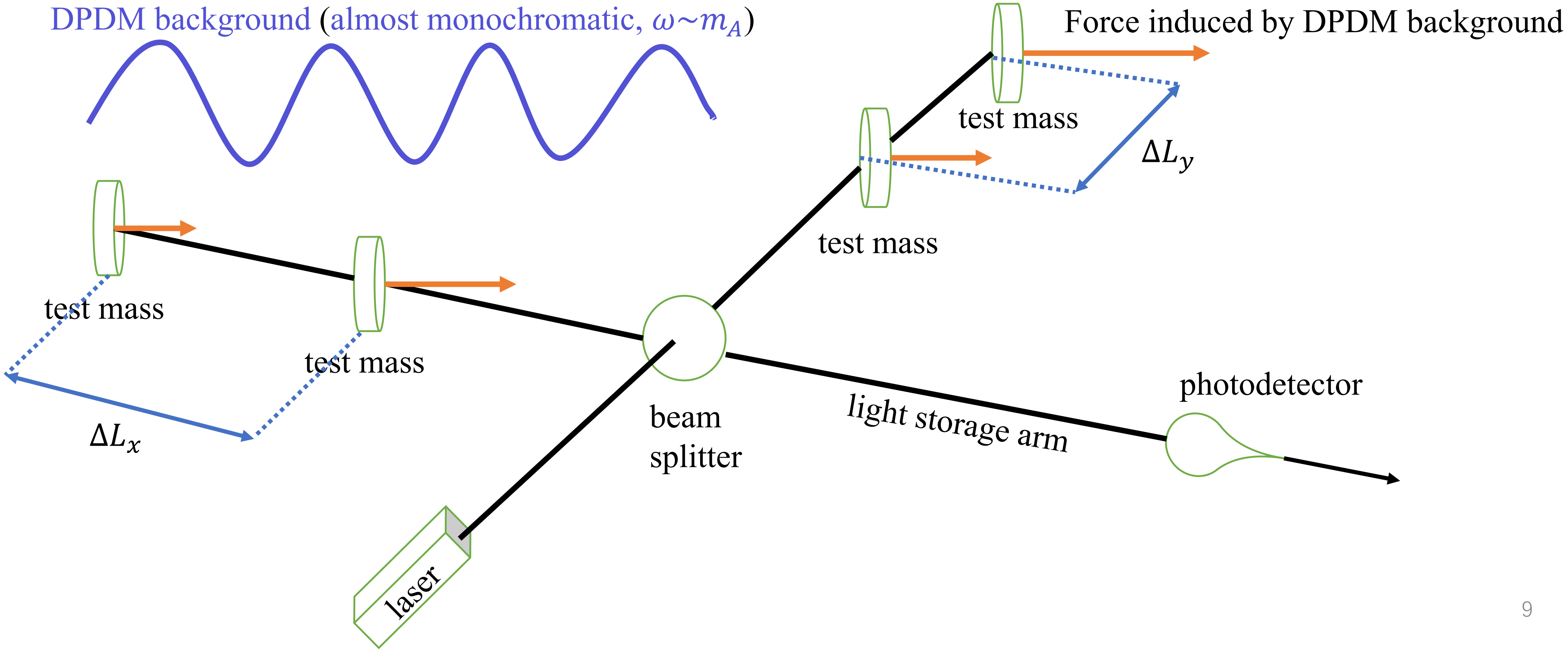


Opened a field:
Gravitational Wave Astronomy

Enrich our understanding on fundamental physics and early cosmology.

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 $v_0 \sim 10^{-3}$.
- The wavefunction of the i−th dark photon particle,

polarization vector propagation vector

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

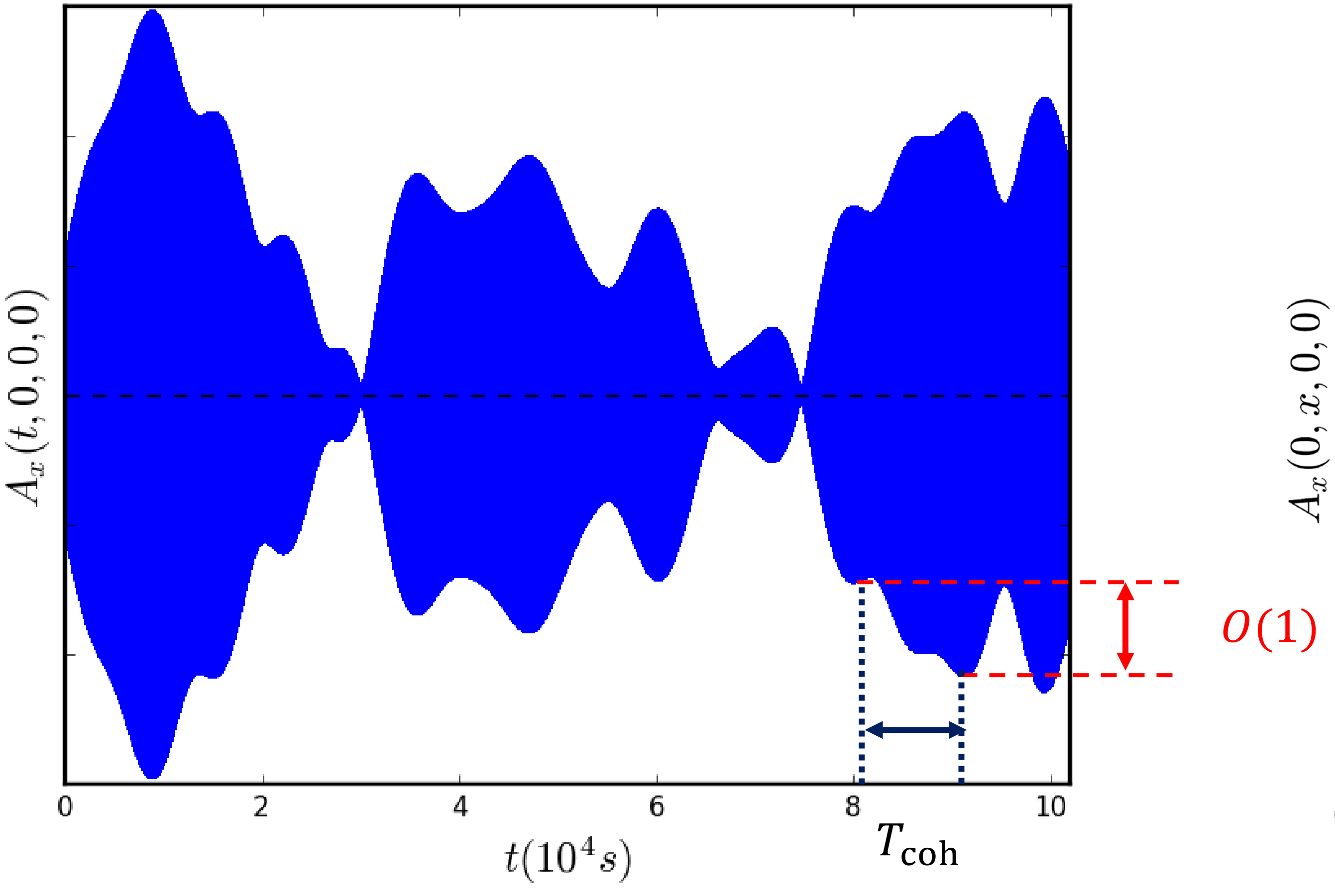
total energy random phase

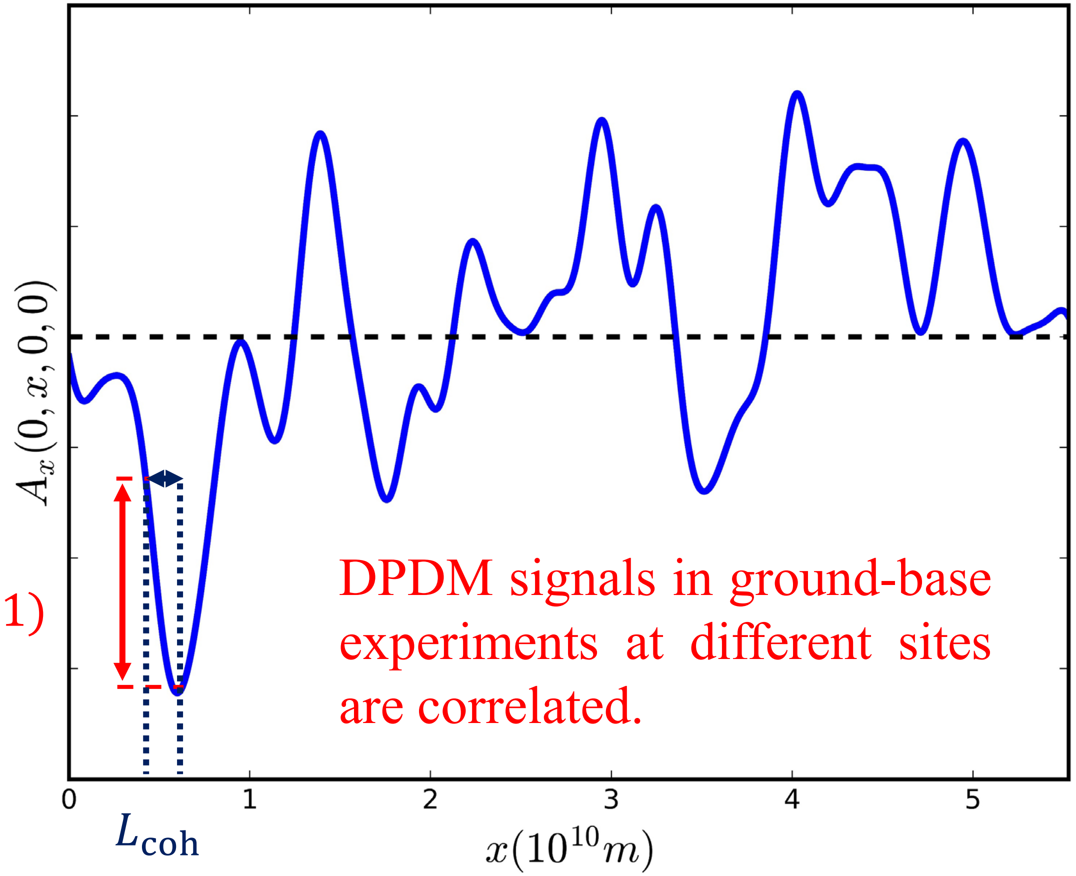
where $\omega_i = \sqrt{\mathbf{k}_i^2 + m_A^2} \equiv 2\pi f_i$ and $\mathbf{k}_i = m_A \mathbf{v}_i$.

- 100Hz $\longrightarrow$ $m_A = O(10^{-13})$eV $\longrightarrow$ Dark photon wavefunctions overlap.
- Obtain the DPDM background field:

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

Coherence time and coherence length of DPDM background field



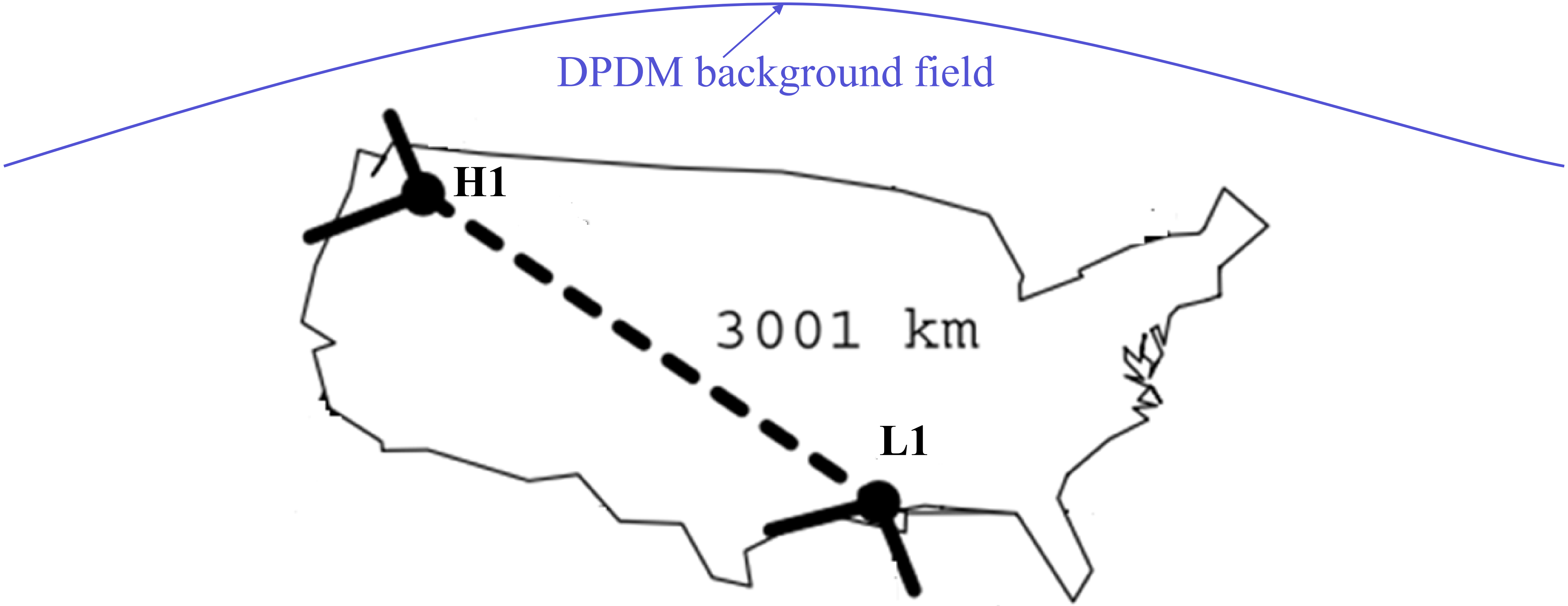


DPDM signals in ground-base experiments at different sites are correlated.

$$L_{\rm coh} \sim 3 \times 10^6 \left(\frac{100\text{Hz}}{f}\right) \text{km} \gg R_{\rm E}$$

Correlated DPDM signals

Correlation between two sites is important to reduce background!



H1 in Hanford, L1 in Livingston.

Signal modeling

- The acceleration of m-th test mass:

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

dark electric field

dark photon coupling

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

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

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

$$s_{||,m} = \int dt' \int dt'' \, a_{||,m}(t'')$$

projected along the arm direction

- Observables: strain time series $h(t) = R_L(t) = (\Delta L_x - \Delta L_y)/L$.

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

DPDM detection statistic

- The DPDM signal is approximately a peak in frequency space.
- Short-time Fourier transform (SFT), $N_{\text{SFT}} = T_{\text{obs}}/T_{\text{SFT}}$.
- 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 $P_{1(2),ij} = |z_{1(2),ij}|^2$

and the variance is

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

$$\Rightarrow \quad \text{SNR}_j \equiv \frac{S_j}{\sigma_j}.$$

Properties of DPDM signals

- Signal is almost monochromatic $f \sim \frac{m_A}{2\pi}$, $\Delta f / f \sim 10^{-6}$.

- Signal is correlated between two LIGO detectors.

- SNR value is negative since two LIGO detectors are anti-aligned.

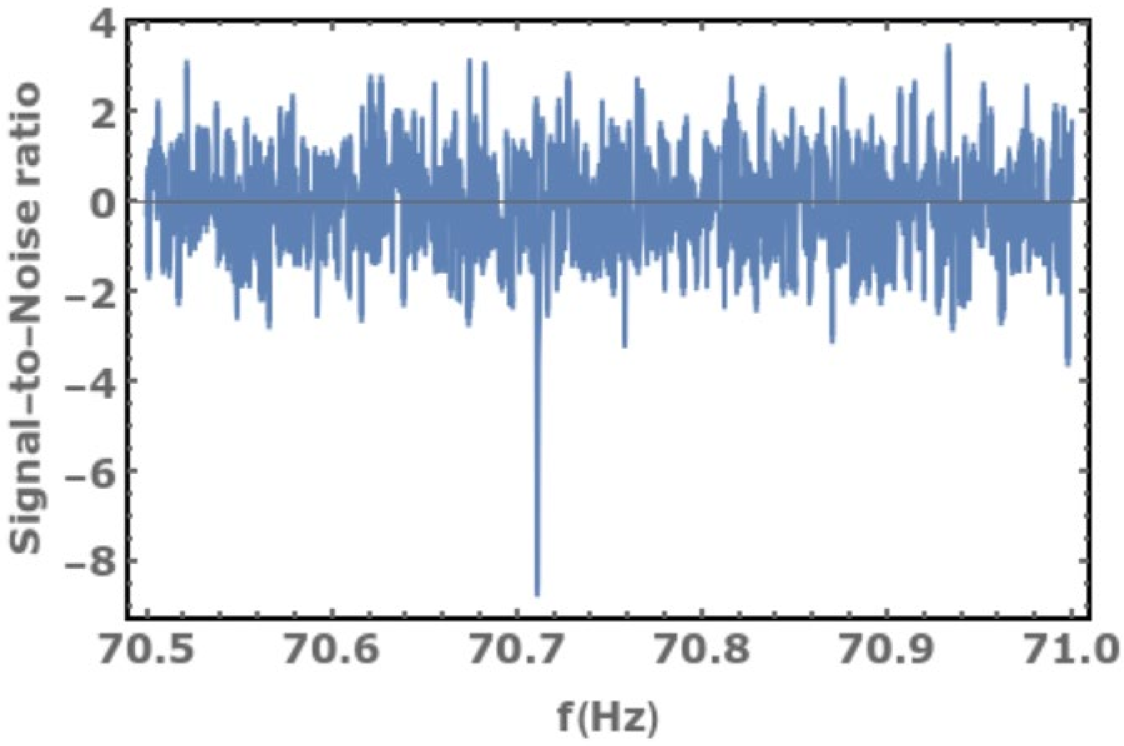
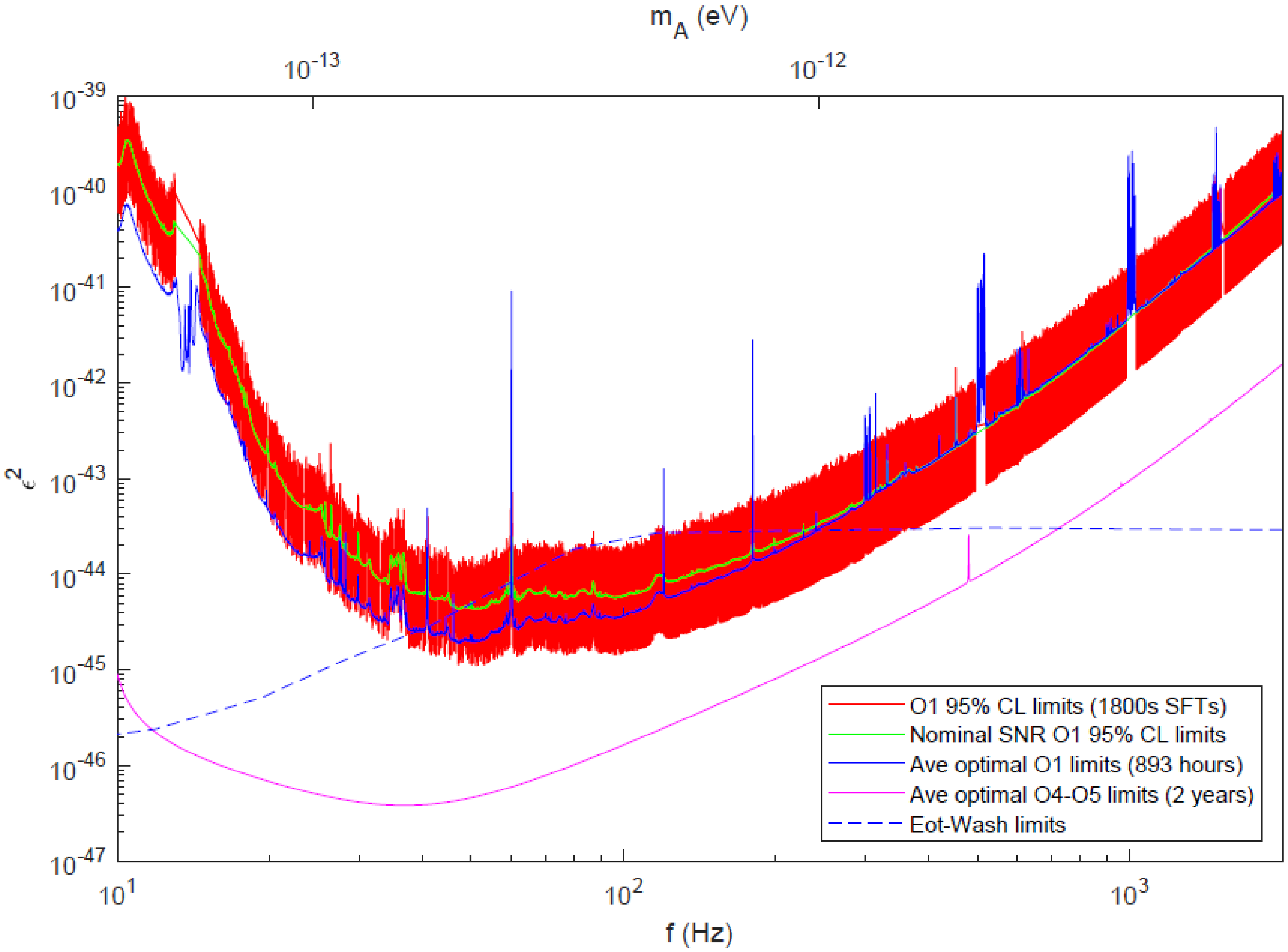


FIG. 5: The SNR v.s. frequency plot, where $f = 100/\sqrt{2}$Hz, $\epsilon^2 = 5\times10^{-44}$, $N_{\rm SFT} = 400$, $T_{\rm SFT} = 1800$s, Gaussion noise of detector set in LALSuite is 10^{-23}.

O1 Result – Sensitivity curve of DPDM signal

DPDM-SM coupling strength

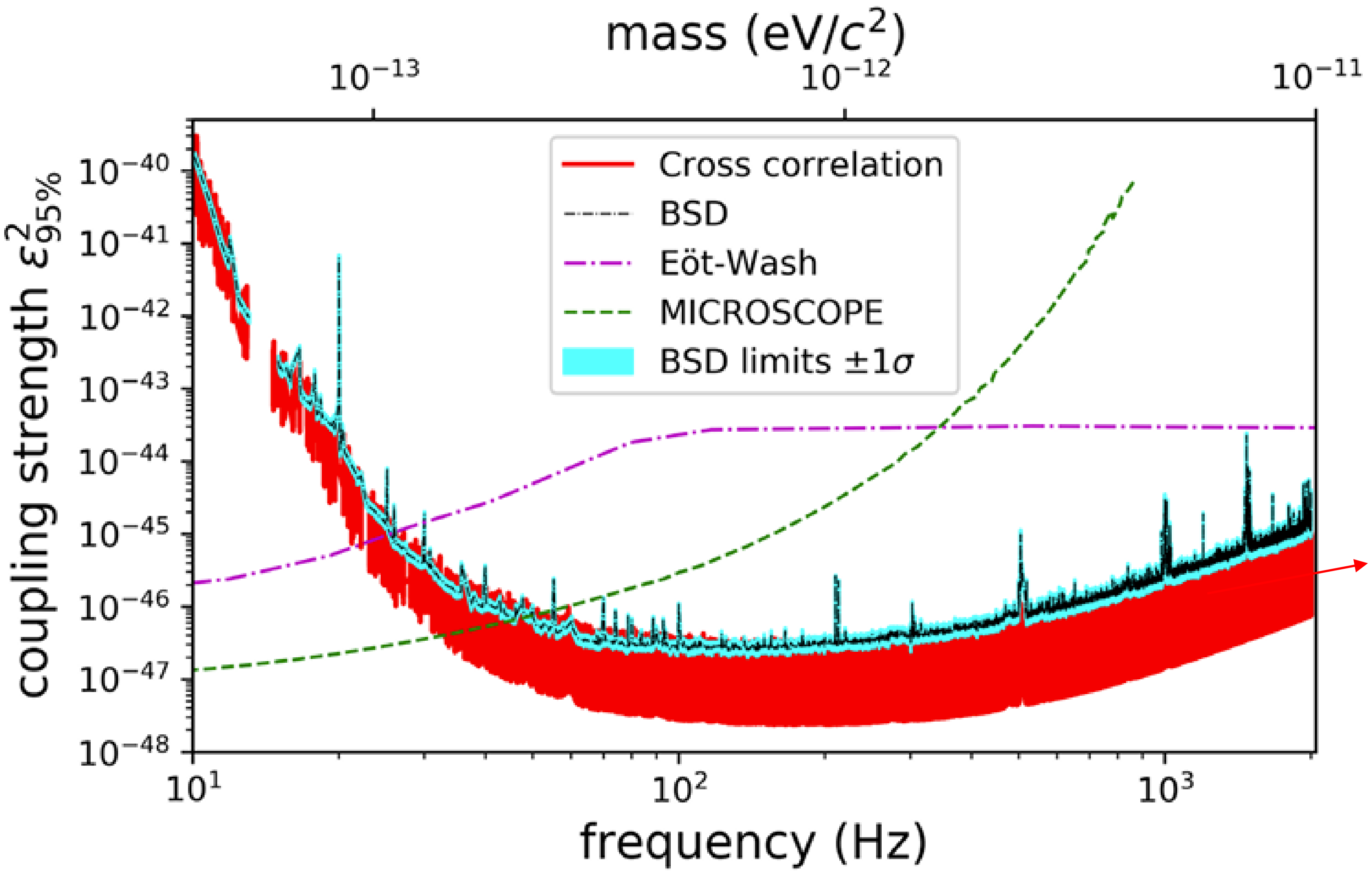
$U(1)_B$



Nature - Commun.Phys. 2 (2019) 155

LIGO and Virgo O3 Result

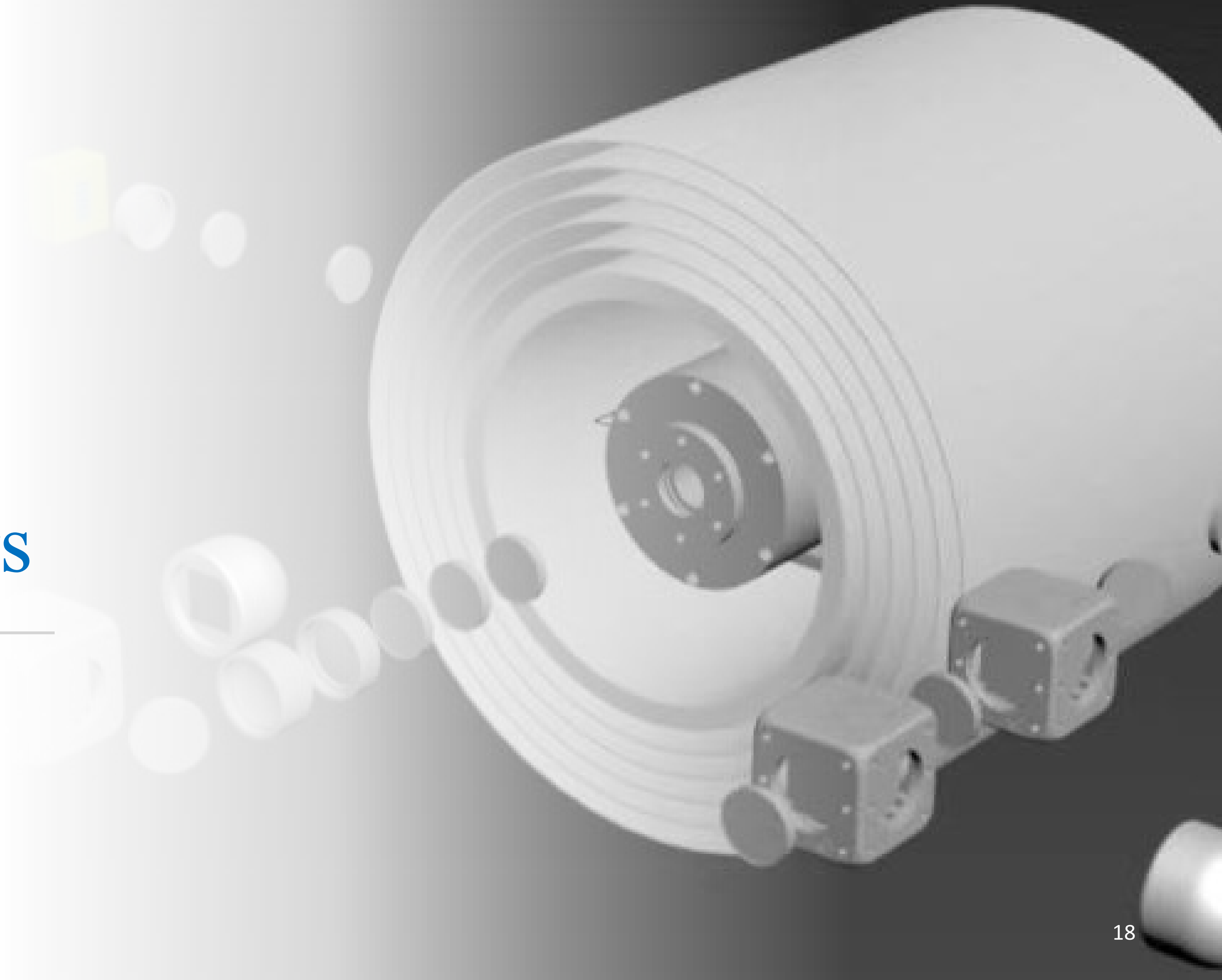
$U(1)_B$



Significant improvement: finite travel time of the laser light in the interferometer arms.

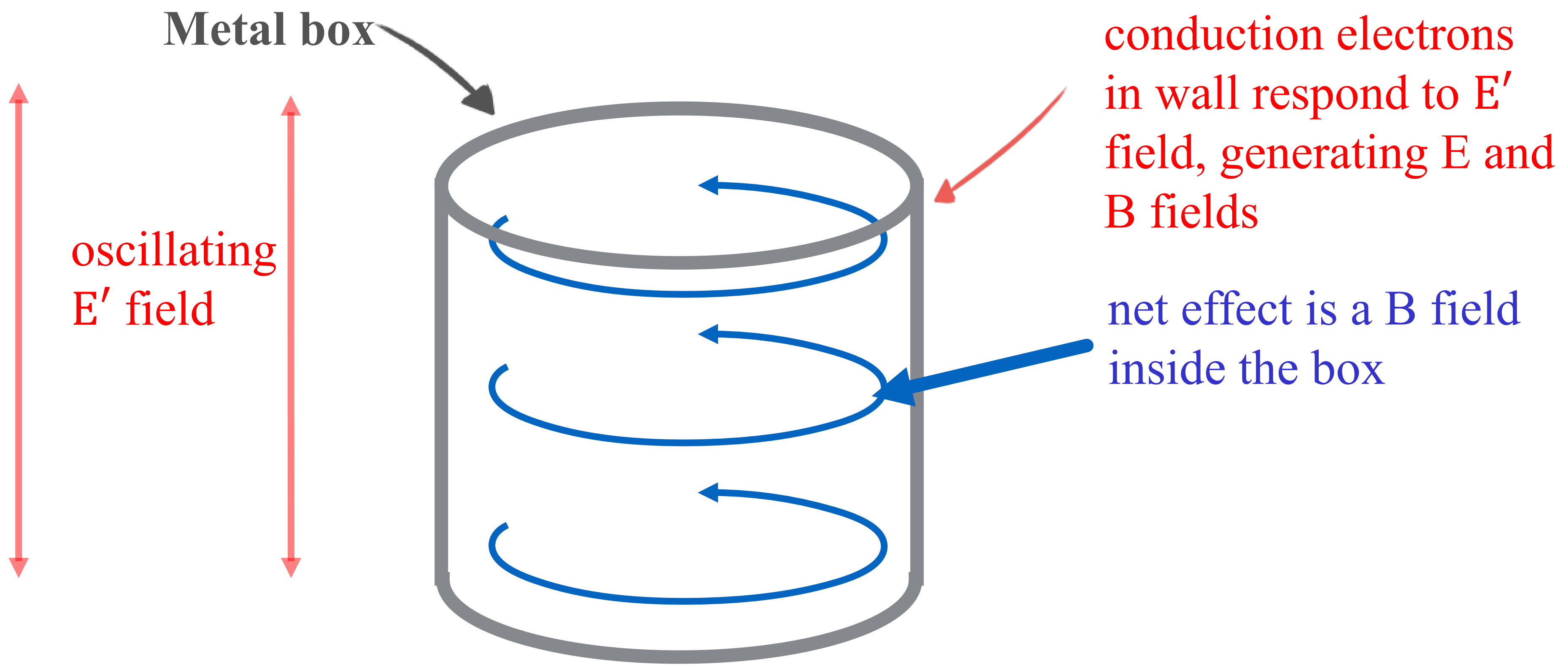
***Phys.Rev.D* 105 (2022) 6, 063030**

Chap 2: Searching for DPDM using quantum sensors



Probing DPDM signal inside a Faraday cage

kinetically mixed
dark photon: $\mathcal{L} \supset -\frac{1}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m^2_{A'}A'^{\mu}A'_{\mu} + \epsilon e A'^{\mu}J^{EM}_{\mu}$



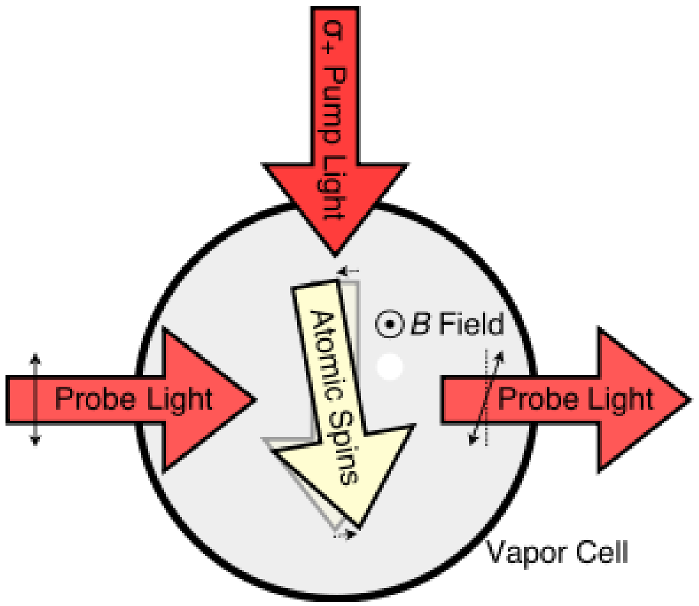
$$E_{obs} \sim \varepsilon\sqrt{\rho_{\rm DM}}e^{im_{\gamma'}t} \times \left((m_{\gamma'}R)^2 + (m_{\gamma'}Rv_{\rm DM})\right) \qquad (m'_\gamma R \ll 1)$$

$$\vec{B}_{obs} \approx -\varepsilon\sqrt{\rho_{\rm DM}}e^{im_{\gamma'}t}\hat{\phi} \times m_{\gamma'}r$$

S. Chaudhuri et al. Phys. Rev. D 92, 075012

Broad-band search at lower frequency

Spin exchange relaxation-free (SERF) magnetometer



c.f. Wikipedia

$$\vec{B}_{obs} \approx -\varepsilon\sqrt{\rho_{\rm DM}}e^{im_{\gamma'}t}\hat{\phi} \times m_{\gamma'} r$$

Operating at room temperature. (Possible to have a larger size of mag shield!)

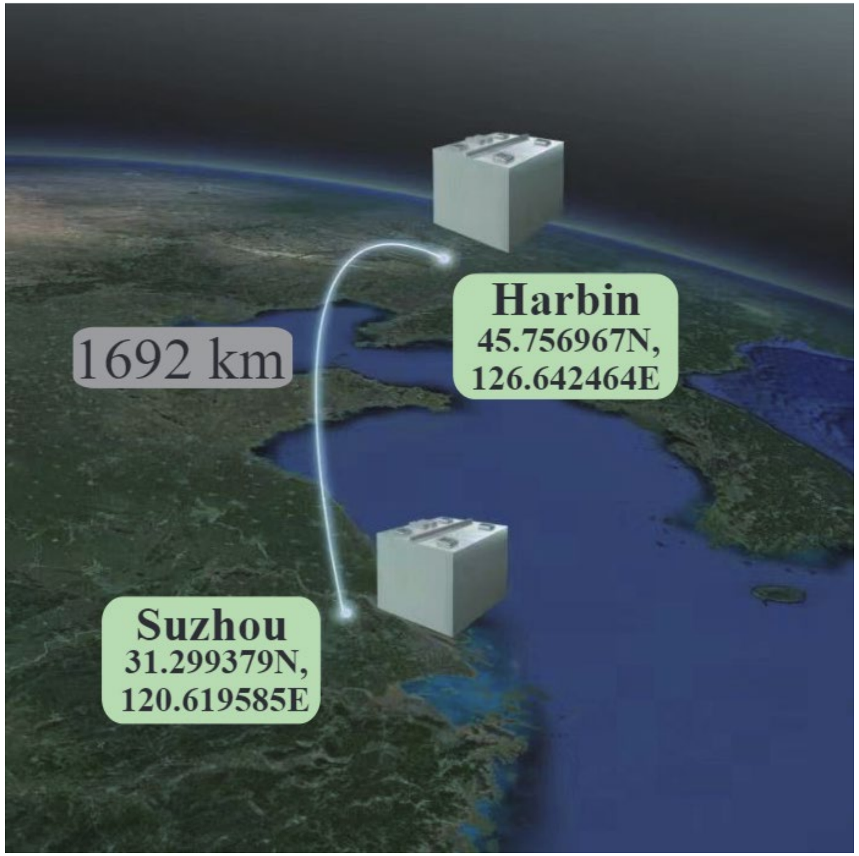
Excellent sensitivity at lower frequency (1-1000 Hz).

Broad-band: probe a large dark photon mass range simultaneously.

Experimental set-up

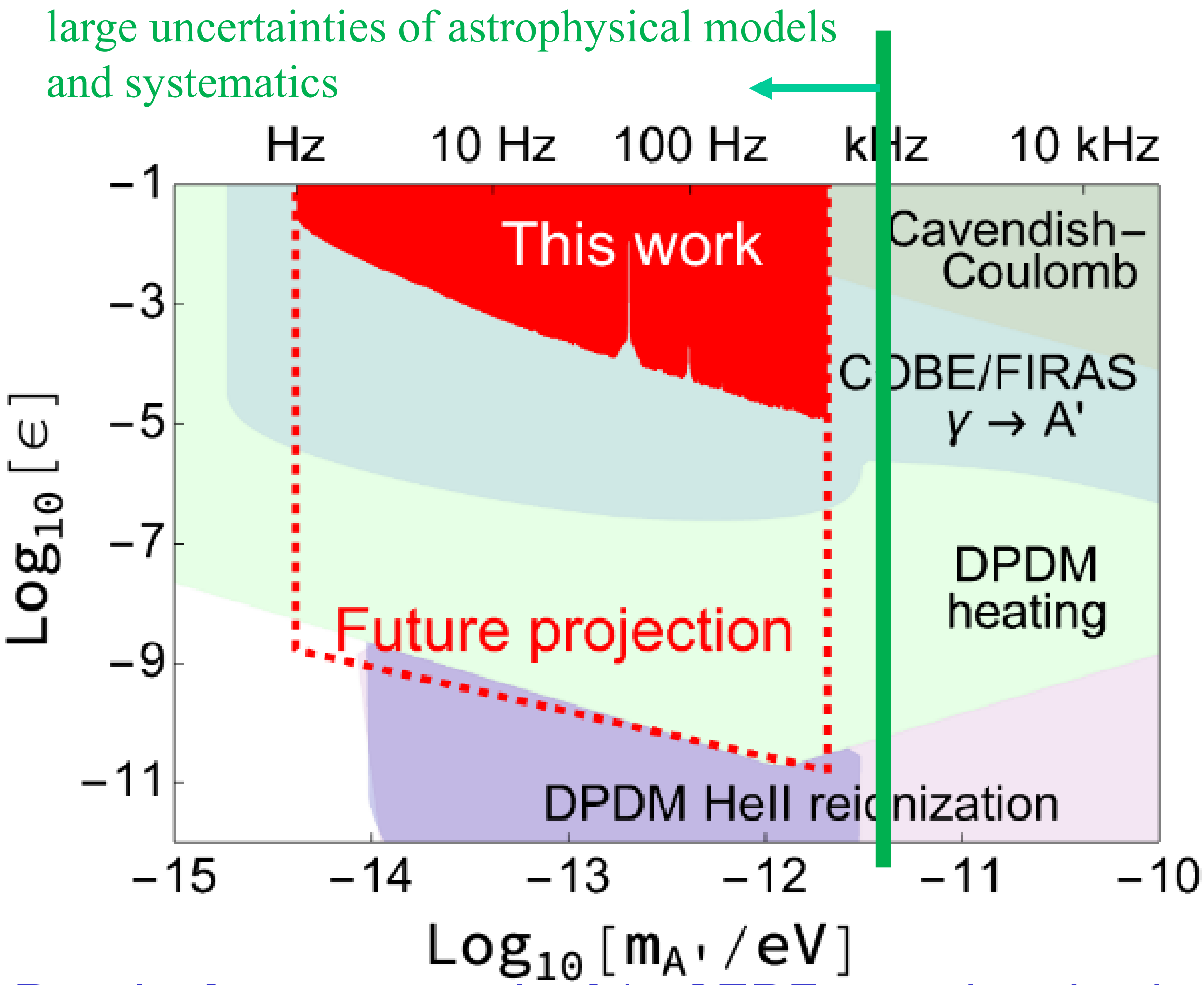
Medical imaging room provides a sizable magnetic shield!

Let's stick a bunch of SERFs on the walls.



DM generates a correlated signal to all magnetometers!

Constraints



collaboration with
a group at USTC

Results from a network of 15 SERFs synchronized with the GPS.

Installed on the edges of two meter-scale shielded rooms.

Data is taken for 2000 seconds.

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 quantum sensors can make robust measurement of low freq. DPDM signal!

⇨ SERF atomic magnetometers can probe 1-1000Hz magnetic field.
Kinetically mixed DPDM sources the signal within the metal shield.

The analysis is straightforward!

⇨ Cross correlation

The sensitivity can be extraordinary!

⇨ LIGO-Virgo O3 data has already beaten existing experimental constraints.

⇨ SERF magnetometers provide competitive terrestrial constraints

Back up slides

Back-up: Stueckelberg limit

Stueckelberg action:

$$\mathcal{L} = -\frac{1}{4}(\partial^\mu A^\nu - \partial^\nu A^\mu)(\partial_\mu A_\nu - \partial_\nu A_\mu) + \frac{1}{2}(\partial^\mu \phi + m A^\mu)(\partial_\mu \phi + m A_\mu)$$

$A_\mu \to A_\mu + \partial_\mu \alpha(x)$, $\phi \to \phi - \alpha(x)$ -- remaining local symmetry

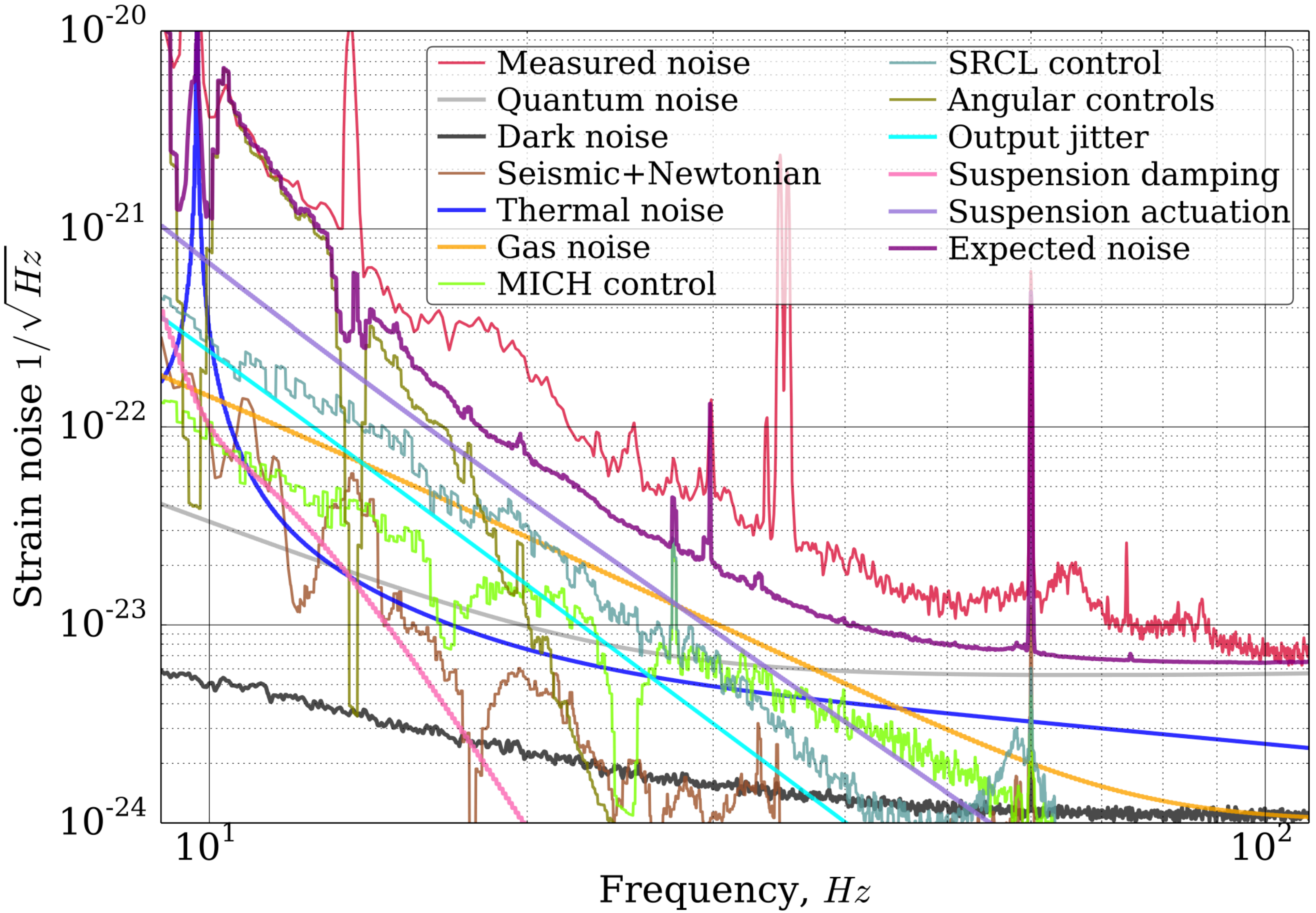
By taking Lorenz gauge, $\partial_\mu A^\mu = 0$, and doing field redefinition, ϕ will decouple from A^μ.
Integration by part:

$$m A^\mu \partial_\mu \phi = m \partial_\mu (A^\mu \phi) - m\phi(\partial_\mu A^\mu)$$

$m\partial_\mu(A^\mu\phi)$ ↓ surface term; $m\phi(\partial_\mu A^\mu)$ ↓ 0

Back-up: Example of LIGO detector noise

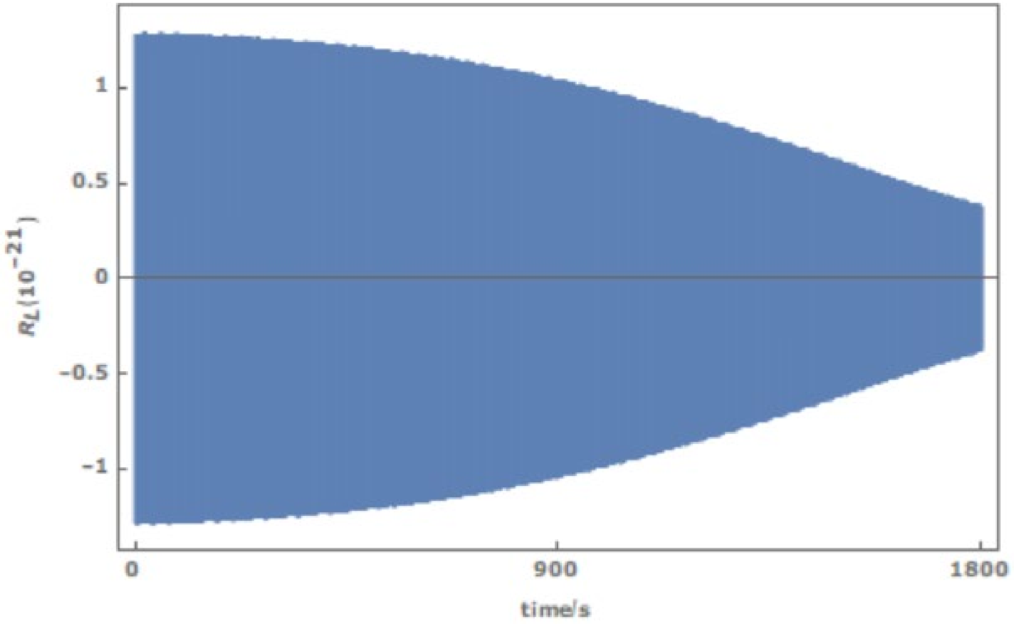
L1



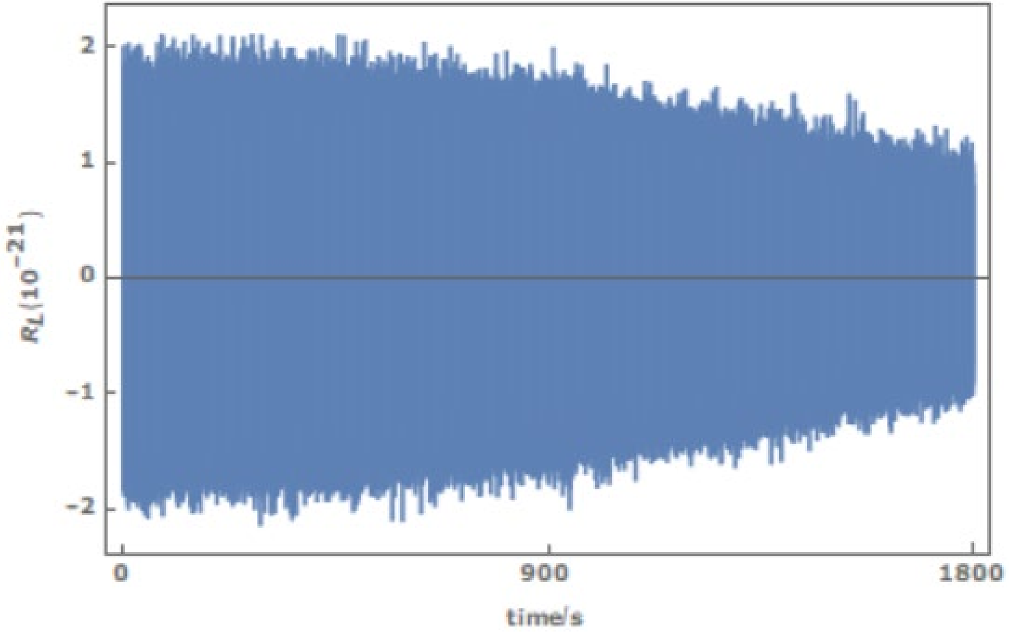
Detector response (simulation)

- The relative arm length change is

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



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



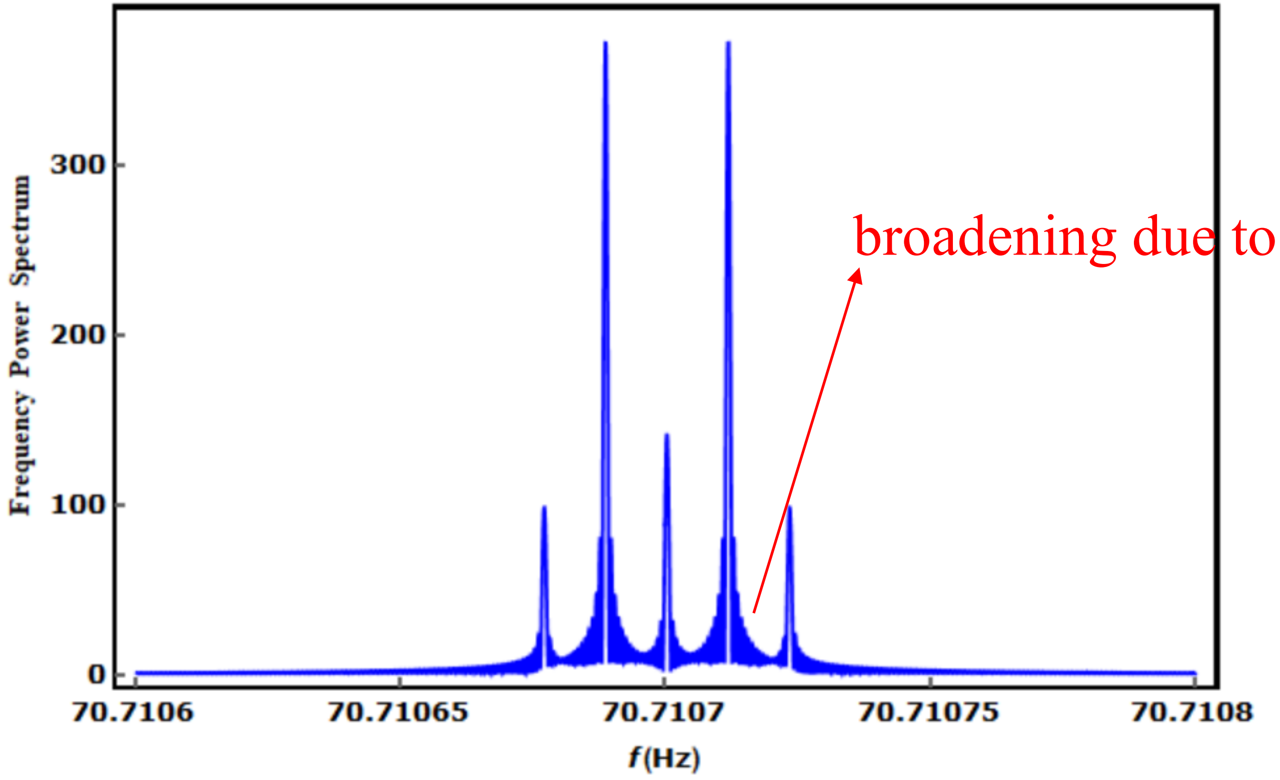
Earth Rotation Effect

Dark photon oscillation frequency

$$\frac{R_L}{\mathcal{N}} = \sum_{i=1}^{n} e^{j\Phi_i}\Big(c_{2,i}e^{j(\omega_i+2\omega_E)t} + c_{1,i}e^{j(\omega_i+\omega_E)t}$$

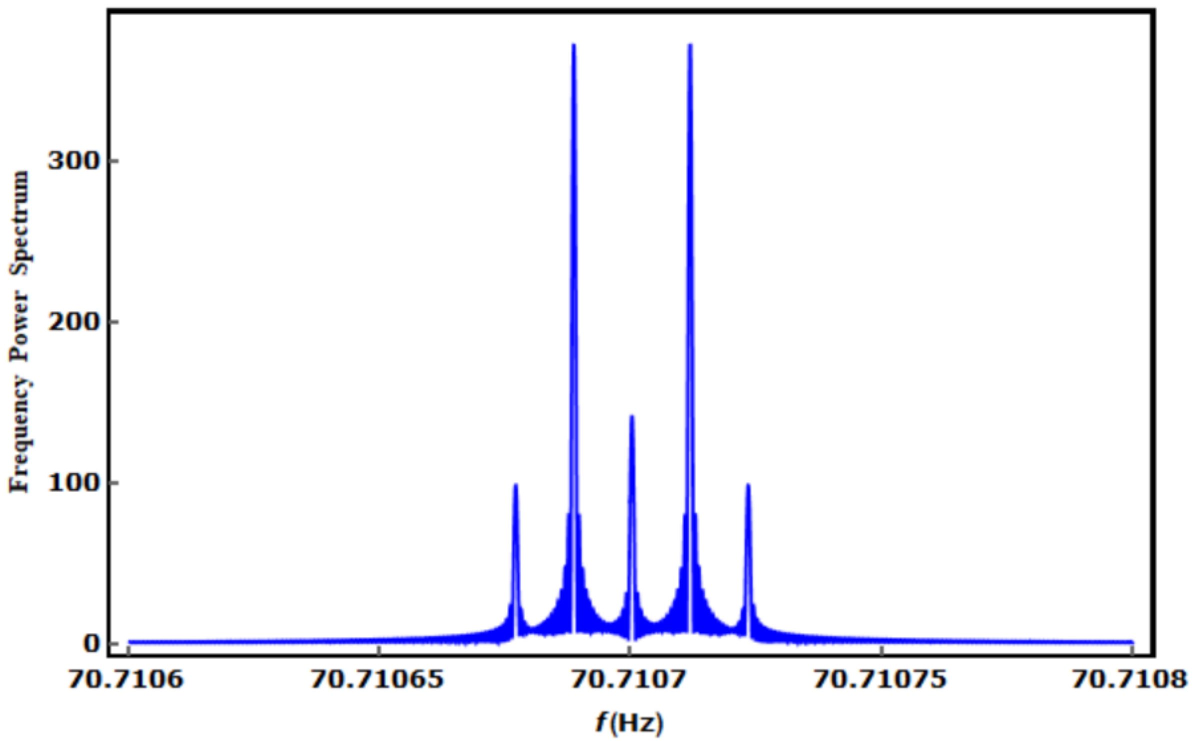
Earth rotation frequency

$$+\ c_{0,i}e^{j\omega_i t} + c_{-1,i}e^{j(\omega_i-\omega_E)t} + c_{-2,i}e^{j(\omega_i-2\omega_E)t}\Big) + \mathcal{C.C.}$$



Back-up: Earth Rotation Effect

1. The relative heights among these peaks are determined by the coefficient c_k, which is related to directions of polarization vector A, propagation vector k and the DP mass.
2. The overall height is determined by the normalization factor $\mathcal{N}$.
3. The random phase in the DP planewave only shifts the real and imaginary parts of the signal, and dose not affect the modulus of the signal.
4. The width of each peak is determined by T_{SFT}.

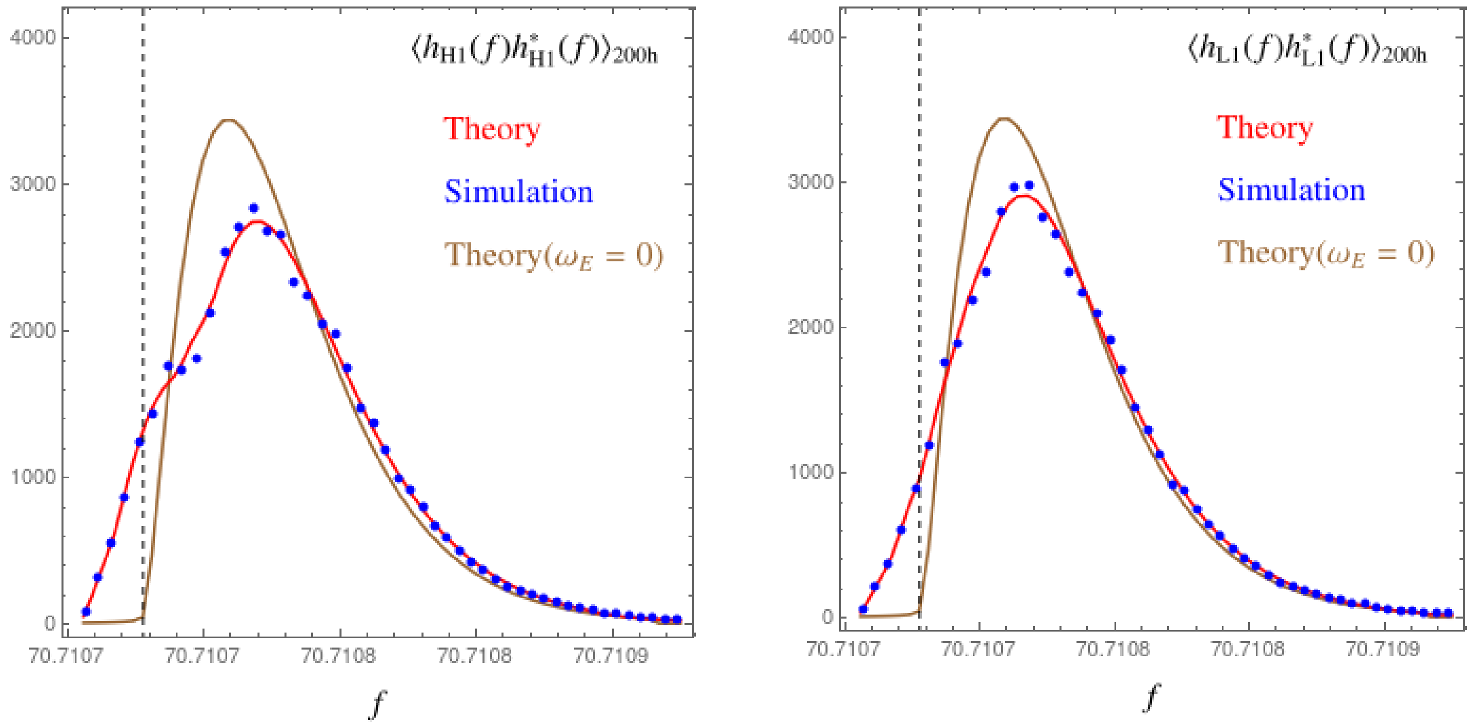


The averaged signal power spectrum

$$\langle \frac{\widetilde{\Delta L_1}(f)^*}{L} \frac{\widetilde{\Delta L_2}(f')}{L} \rangle = \frac{1}{16} \left[(\epsilon e \frac{q_{D,i}}{M_i}) A_0 m_A \right]^2 \sum_k X_{12}^{kk}$$

$$\left(\frac{dv}{d\omega_v} f(v) \left[\frac{v}{\omega_v} \right]^2 \right) \Big|_{\omega_v = \omega - k\omega_E} \frac{1}{2\pi} \delta_T(f - f').$$

DPDM velocity distribution



O1 Result:

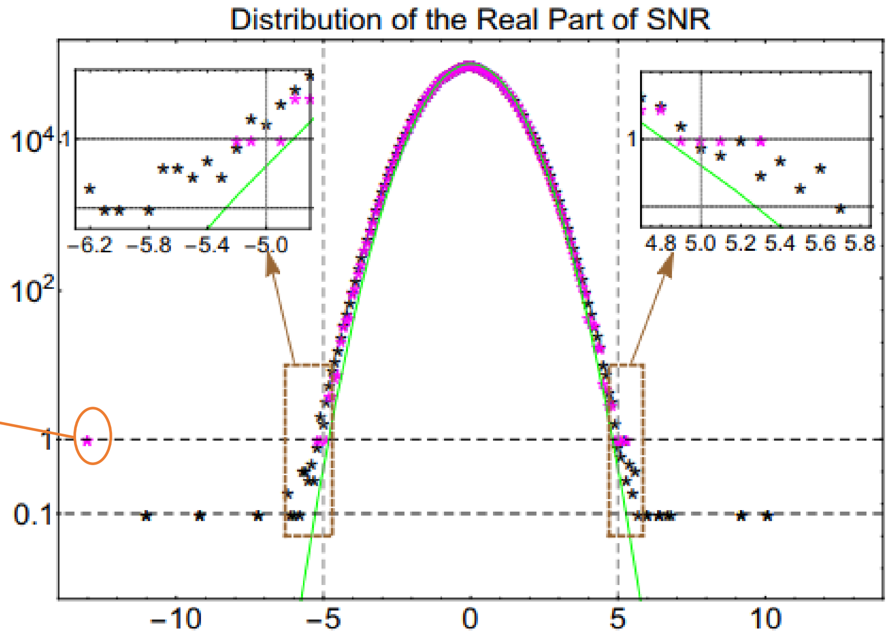
- 1800s FT: optimized for a signal at f~500 Hz
- Remove known noise bins and their neighbor bins
- Within 10-2000 Hz frequency band, require Re[SNR] < −5.8

  ~ 1% false alarm probability after including trial factors.
- Frequency lags: to deal with non-Gaussian noise

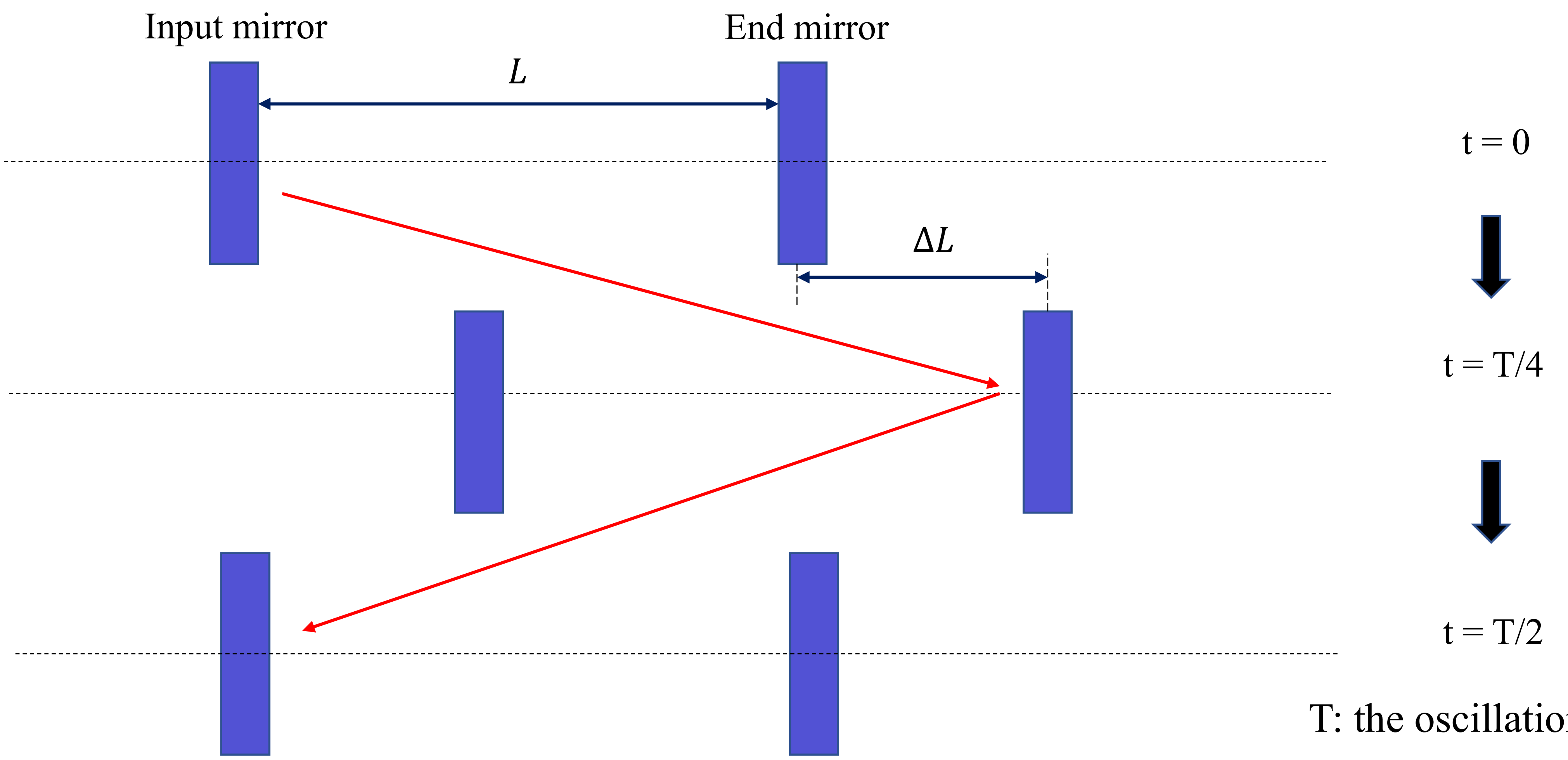
  offset bins (−50, −40, ..., −10, +10, ..., +50)

  Remove single interferometer artifacts and broadband correlated artifacts

known continuous wave "hardware injections" with random phase



Common motion



T: the oscillation period.

Laser light experiences $2L + 2\Delta L$!

Credit to Soichiro Morisaki's presentation in 2020.

Soichiro Morisaki et al. (Phys. Rev. D **103**, L051702)

Fine structures of the signal

1. $\{v, \theta_A, \phi_A, \theta_k, \phi_k, \phi\}$ analytically determine the signal frequency spectrum.

2. Interference of different dark photons with random phase induces spiky features.

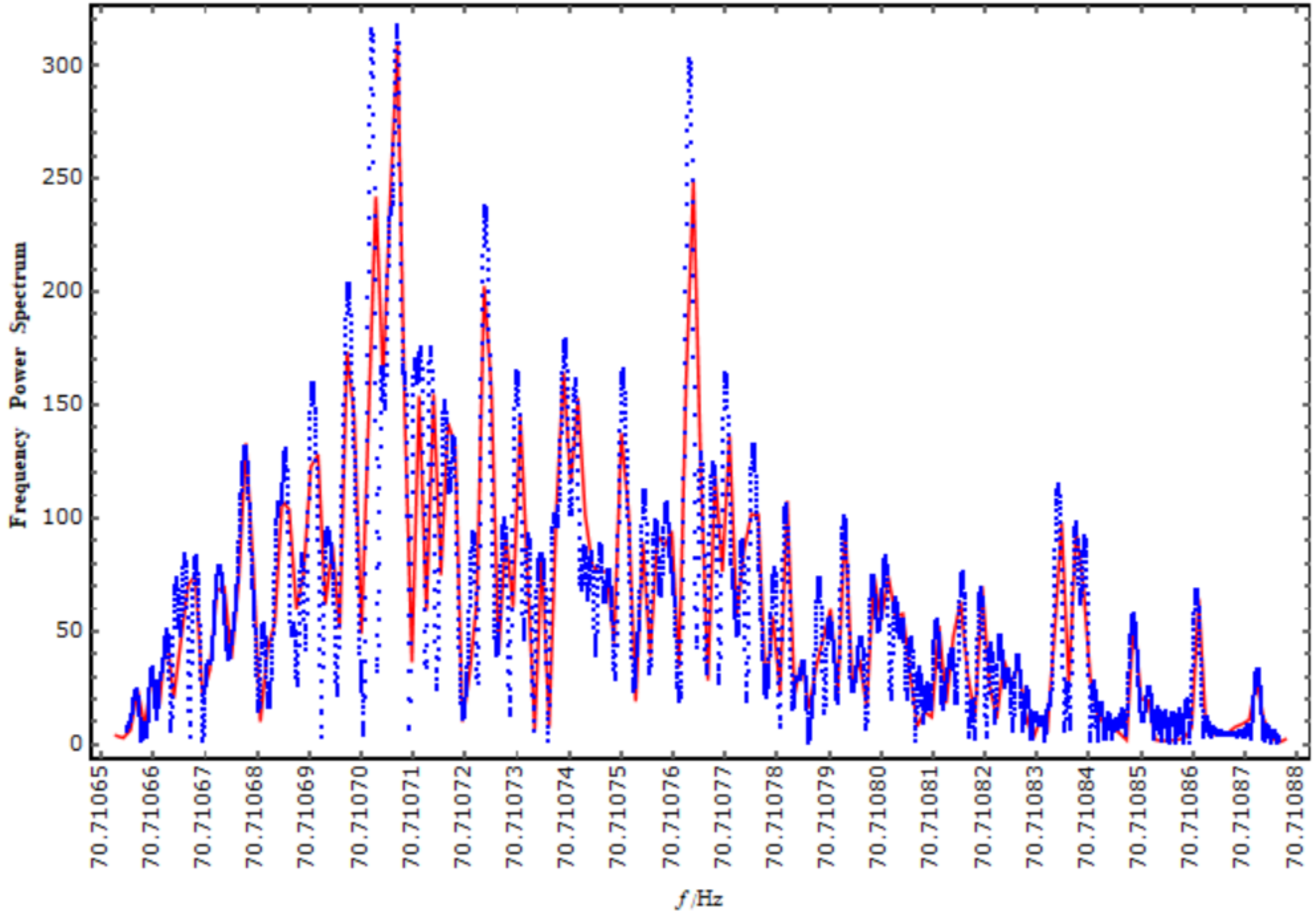
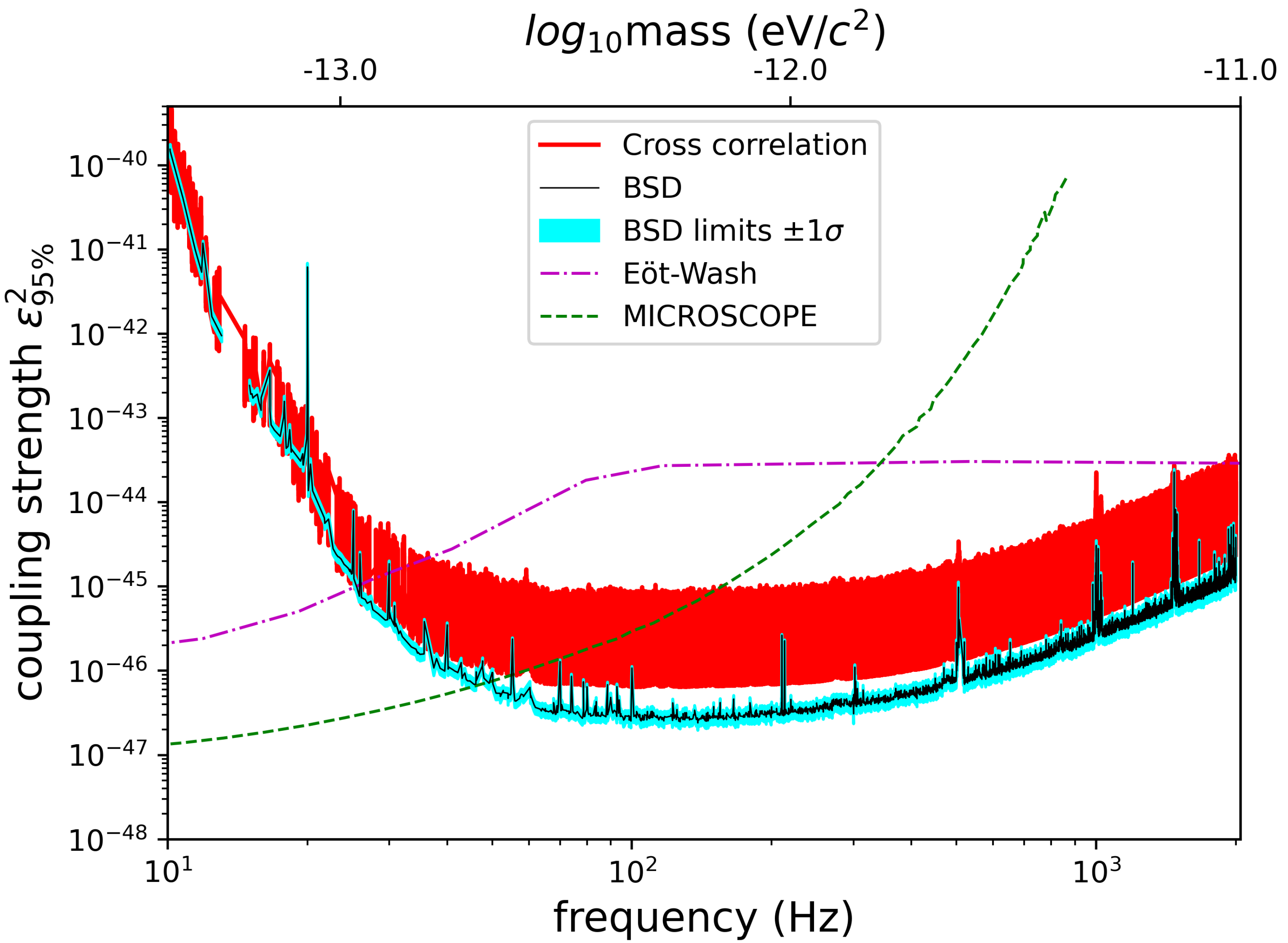


FIG: The signal power spectrum using 800 plane waves. $T_{\rm sft}$=200 hours.

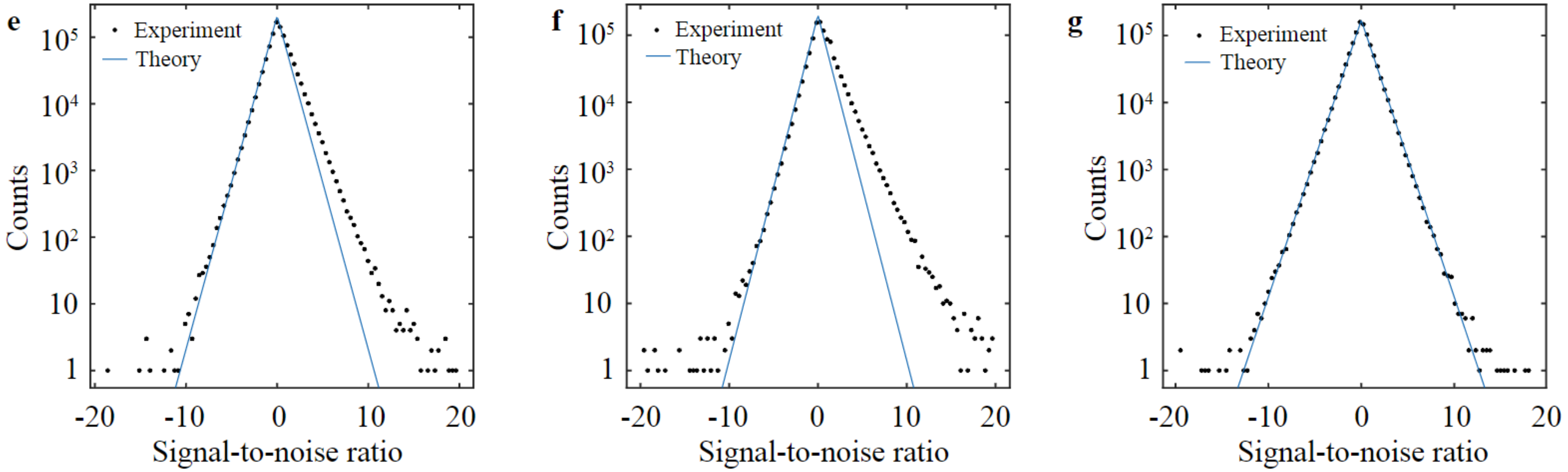
Analytic understanding matches very well with numerical result!

LIGO and Virgo O3 Result: corrected ORF



Correlated background noise

- Similar analysis method used in GW data can be applied
- New subtlety: common mode noise in same detection site → non-Gaussian SNR.



Suzhou-Suzhou Harbin-Harbin Suzhou-Harbin