Dark Photon Dark Matter Searches at LIGO

郭怀珂

中国科学院大学
国际理论物理中心-亚太地区

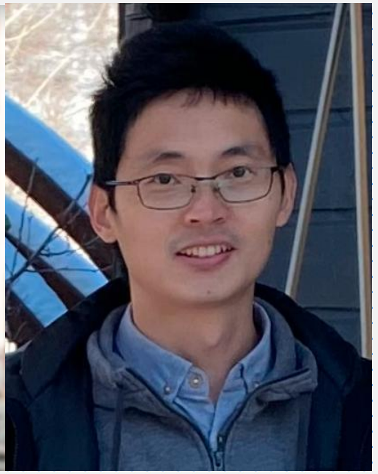
2023-12-31

Searches as of now:

- O1 Search: (Nature) Commun.Phys [1905.04316], HG, Keith Riles, Fengwei Yang, Yue Zhao
- O3 Search: LIGO-Virgo-KAGRA Collaborations, PRD [2105.13085]

The O3-Search Team

Andrew Miller



Huaike Guo

Cristiano Palomba

Ornella Piccinni

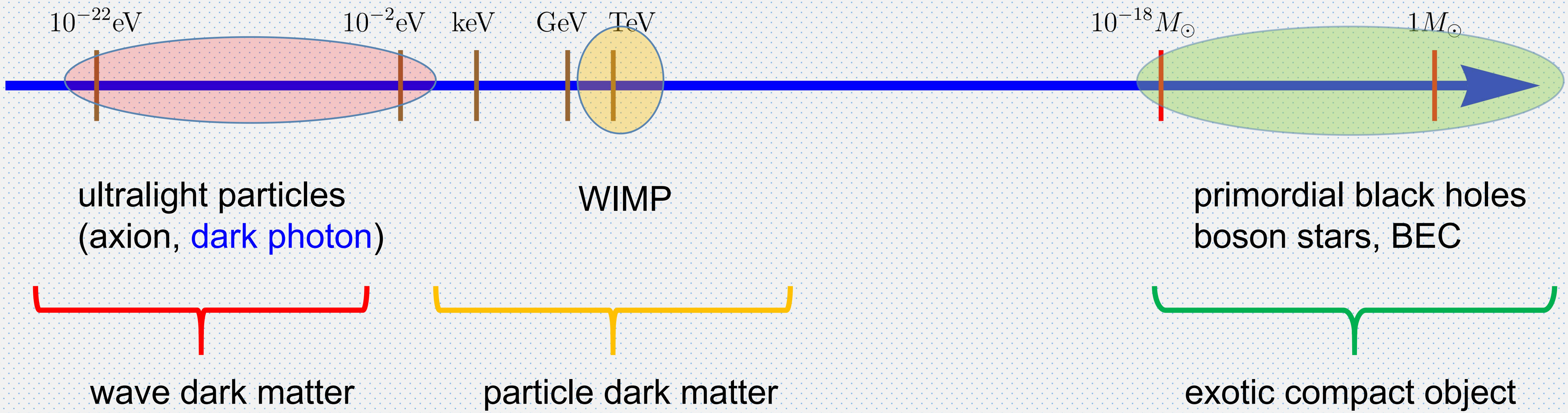
Keith Riles

Fengwei Yang

Yue Zhao

Acknowledgement: This 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: Dark Photon



- Large numer density (local DM enery density $0.4\mathrm{GeV}/cm^3$)
- Behaving like an oscillating classical field

Dark Photon

Gauge boson of a new U(1) symmetry

$U(1)_B\ (p+n)$ $\quad$ $U(1)_{B-L}(n)$

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 A^\mu A_\mu - \epsilon e J^\mu A_\mu$$

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

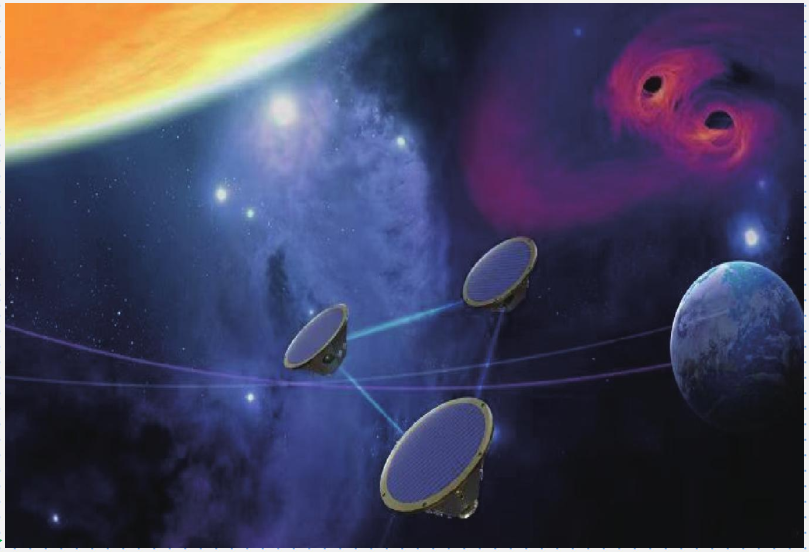
dark electric field $E_i \sim m_A A_i$

$B^i \sim m_A v_j A_k \epsilon^{ijk}$ negligible

地面

引力波探测

空间



太极计划三星编队概念（空间科学学报）

LISA、太极、天琴

Pierce, Riles, Zhao, PRL [1801.10161]

HG, Riles, Yang, Zhao, Commun.Phys [1905.04316]

Vermeulen, et al, Nature [2103.03783]

LIGO-Virgo-KAGRA Collaborations, PRD [2105.13085]

Miller, Mendes, PRD [2301.08736]
Yu,Yao,Tang,Wu [2307.09197]
Frerick et al PLB [2310.06017]

脉冲星测时阵列

EPTA

NANOGrav
Physics Frontiers Center

PPTA

InPTA
Indian Pulsar Timing Array

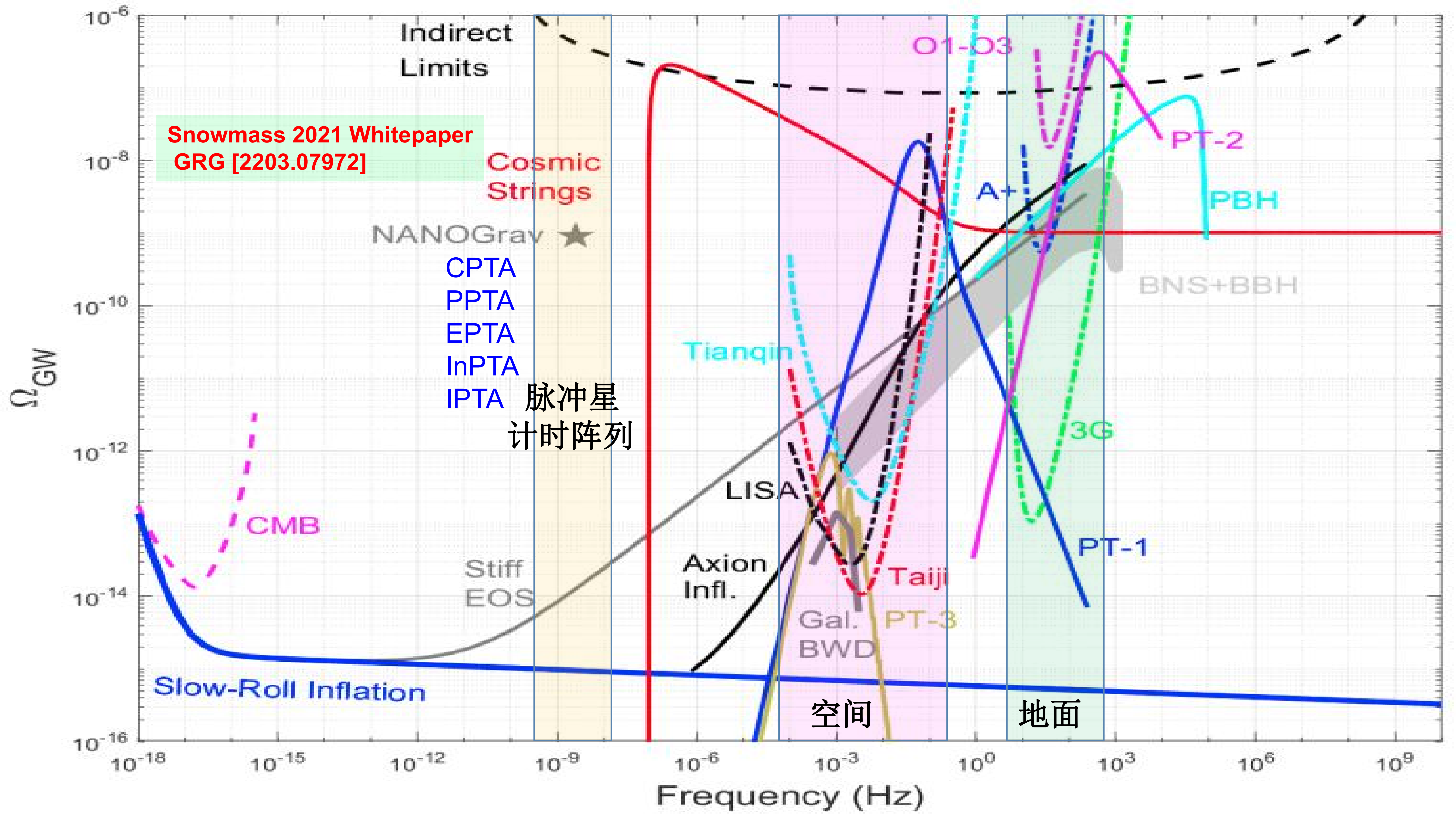
中国脉冲星测时阵列（CPTA）

原初引力波：AliCPT、BICEP...
高频引力波：Aggarwal et al, LRR [2011.12414]

NANOGrav, ApjL [2306.16219]

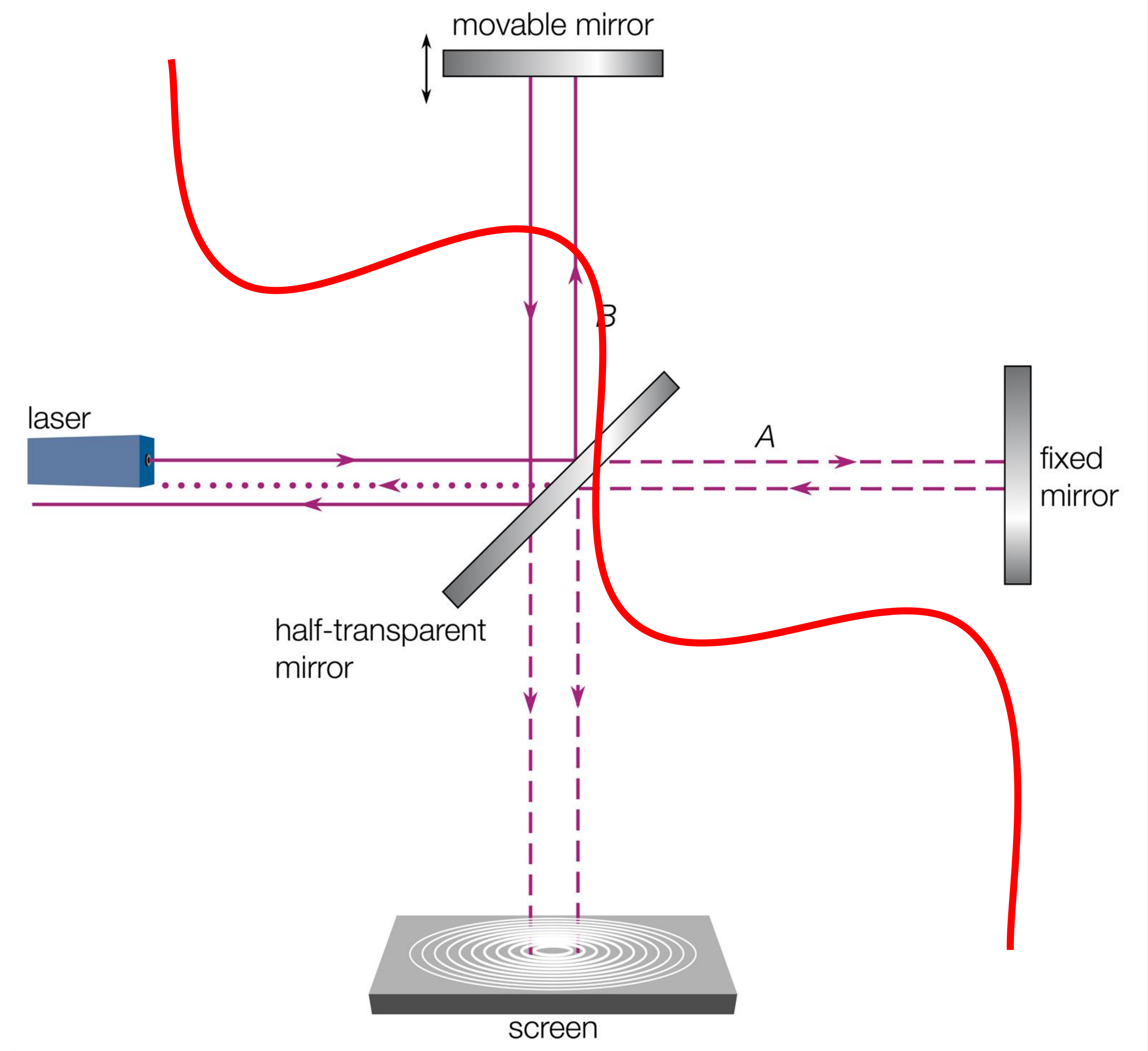
PPTA, Xue, et al, PRR [2112.07687]

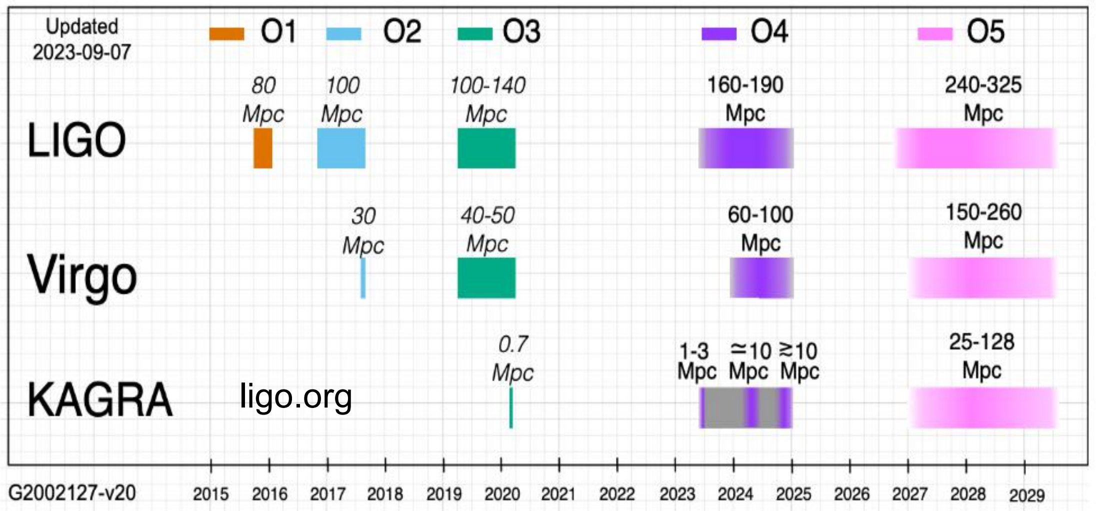
Zi-Qing Xia, et al, PRD Letter [2303.17545]



Indirect Limits
Snowmass 2021 Whitepaper
GRG [2203.07972]
Cosmic Strings
NANOGrav
CPTA
PPTA
EPTA
InPTA
IPTA
脉冲星
计时阵列
O1-O3
A+
PT-2
PBH
BNS+BBH
Tianqin
LISA
3G
CMB
PT-1
Stiff EOS
Axion Infl.
Taiji
Gal. BWD
PT-3
Slow-Roll Inflation
空间
地面
Ω_{GW}
Frequency (Hz)

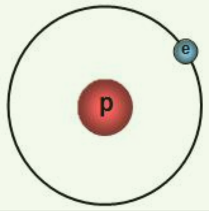
Michelson Interferometer





~6000km

10^-15m

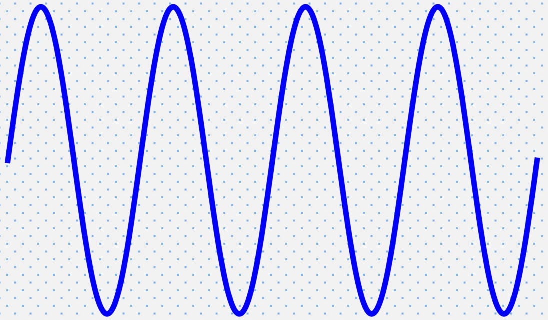


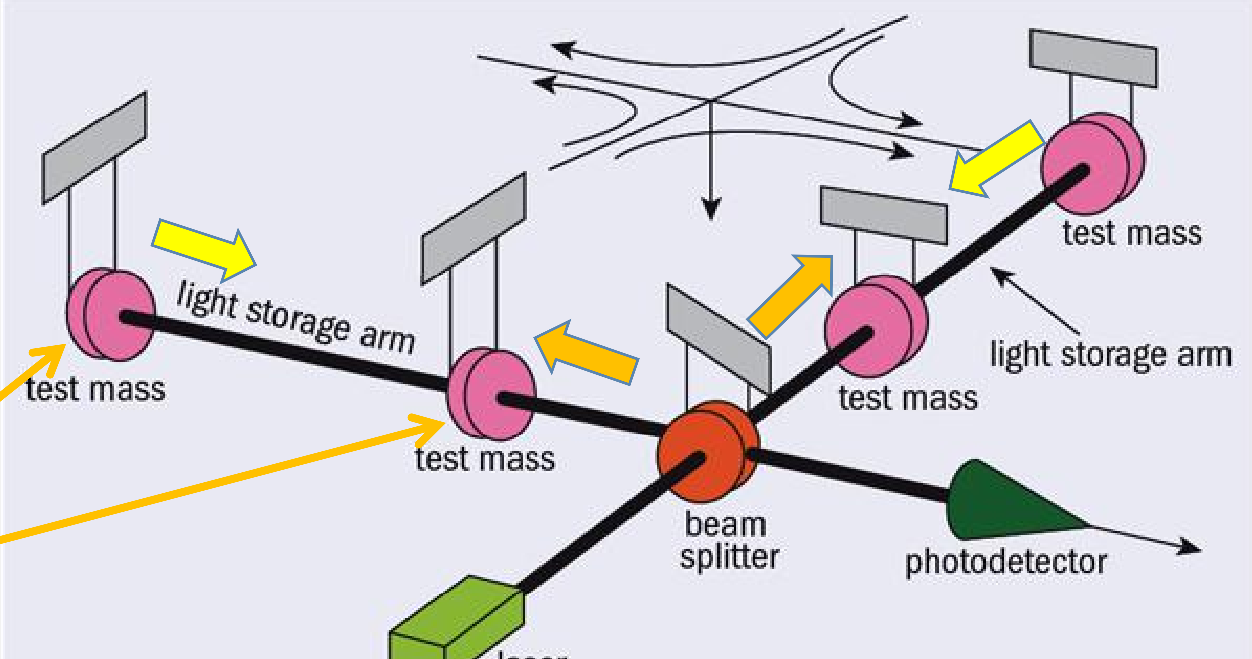
10^-15m

Dark Photon Signals at LIGO

Pierce, Riles, Zhao, PRL [1801.10161]

a dark photon wave





CERN Courier

$$\vec{A}_{n,0}\sin(\omega_n t - \mathbf{k}_n \cdot \mathbf{x} + \phi_n)$$

$A_0 \frac{1}{\sqrt{N}}\mathbf{e}(\mathbf{A}_n)$

$m_A v_n \mathbf{e}(\mathbf{k}_n)$

random phase

dark electric field

acceleration $\mathbf{a}_i(t, \mathbf{x}_i) \simeq \epsilon e \frac{q_{\mathrm{D},i}}{M_i} \boxed{\partial_t \mathbf{A}(t, \mathbf{x}_i)}$

coupling

charge mass ratio for test object

dark electric field

silicon mirror

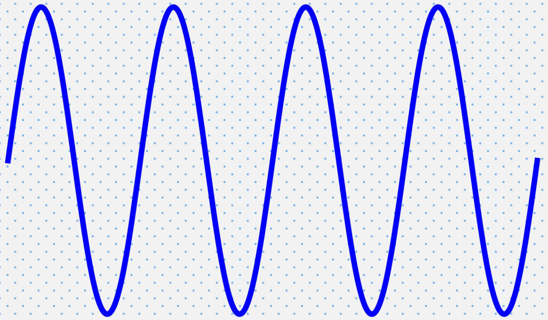
$U(1)_B$: 1/GeV

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

Dark Photon Signals at LIGO

Pierce, Riles, Zhao, PRL [1801.10161]

a dark photon wave



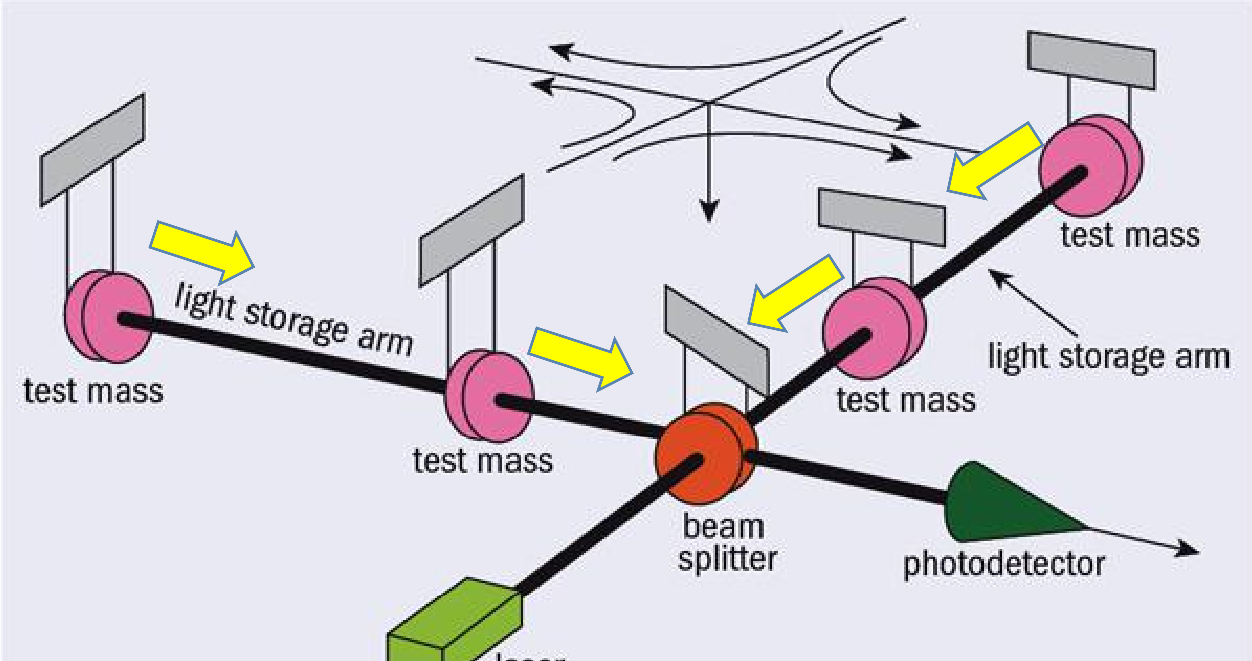
$$\vec{A}_{n,0}\sin(\omega_n t - \cancel{\mathbf{k}_n \cdot \mathbf{x}} + \phi_n)$$

$\vec{A}_{n,0} \rightarrow A_0 \frac{1}{\sqrt{N}} \mathbf{e}(\mathbf{A}_n)$

$\mathbf{k}_n \rightarrow m_A v_n \mathbf{e}(\mathbf{k}_n)$

$\phi_n \rightarrow$ random phase

dark electric field



CERN Courier

Light travel time effect

New in O3

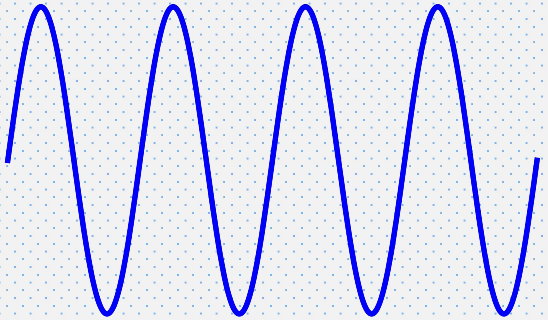
(Morisaki, et al Phys. Rev. D 103, L051702)

- Signal exists even when mirrors are in common motion
- Unsuppressed by dark photon velocity

Dark Photon Signals at LIGO

Pierce, Riles, Zhao, PRL [1801.10161]

a dark photon wave



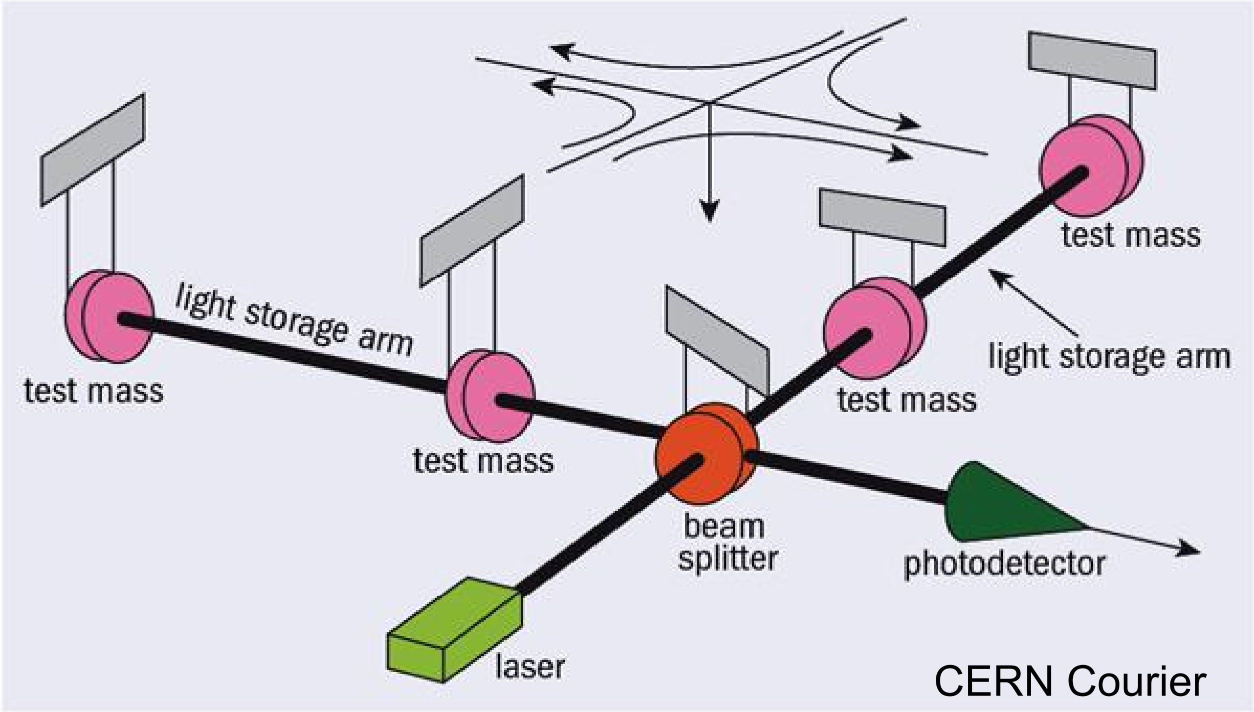
$$\vec{A}_{n,0} \sin(\omega_n t - \mathbf{k}_n \cdot \mathbf{x} + \phi_n)$$

$\vec{A}_{n,0} \rightarrow A_0 \frac{1}{\sqrt{N}} \mathbf{e}(\mathbf{A}_n)$

$\mathbf{k}_n \rightarrow m_A v_n \mathbf{e}(\mathbf{k}_n)$

$\phi_n \rightarrow$ random phase

dark electric field



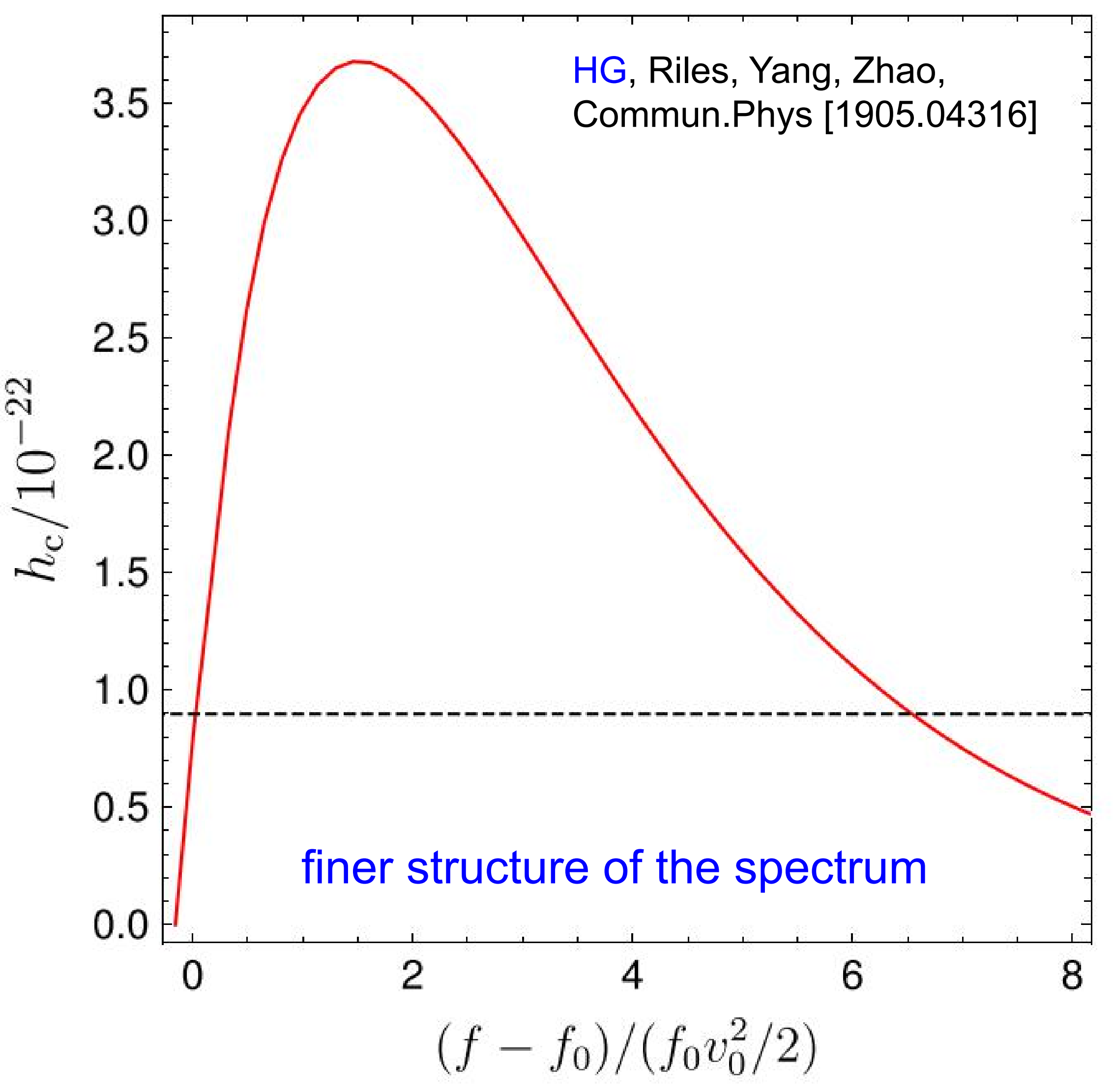
CERN Courier

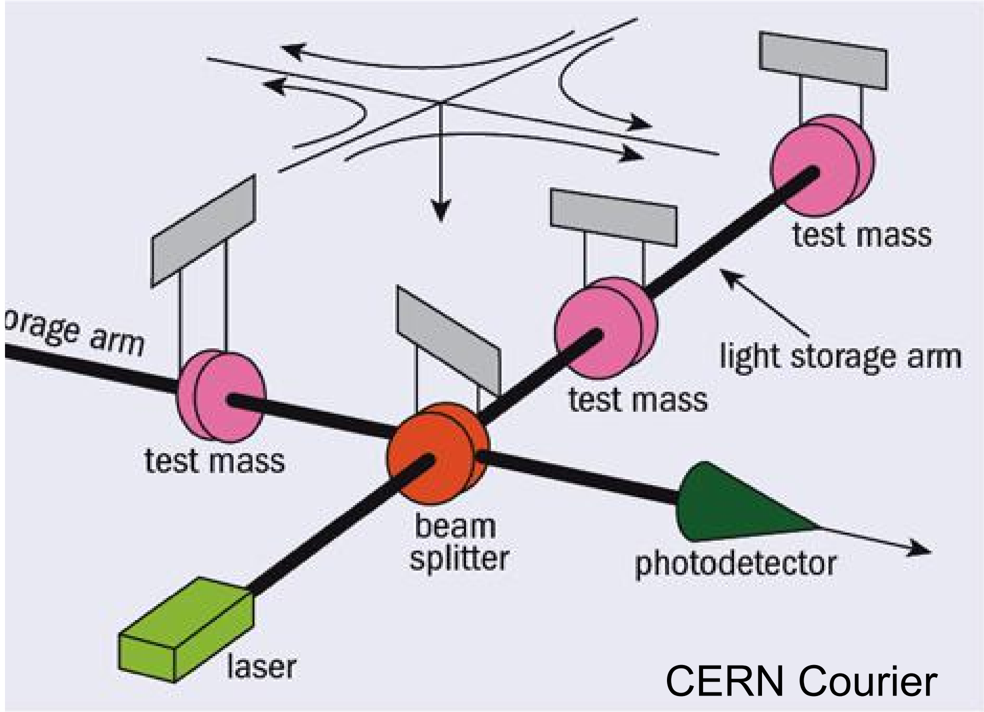
$$\omega_n = m_A(1 + \frac{1}{2}v_n^2) = 2\pi \times (100\text{Hz}) \approx 4 \times 10^{-13}\text{ev}$$

non-relativistic

mass LIGO is sensitive to

Dark Photon Signals at LIGO





- Maxwell distribution $v_0 \sim \mathcal{O}(10^{-3})$
- polarization: isotropic (Galaxy frame)

$$\Delta f/f = 10^{-6}$$

very narrow band ⇒ Fourier analysis

Cross-Correlation

Benefits:

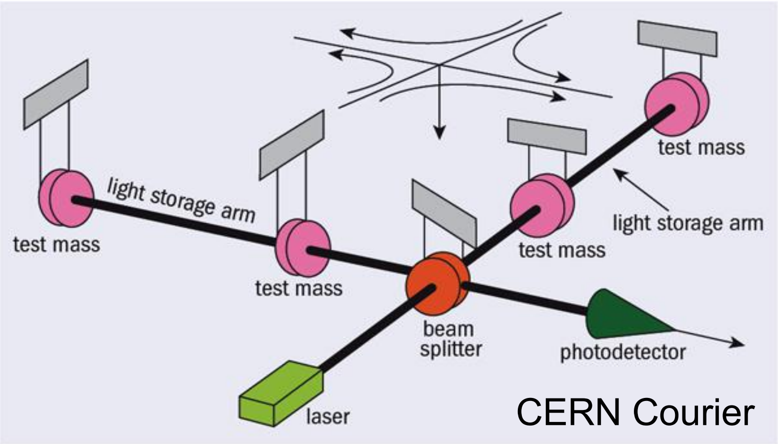
- Significantly reduce noise
- Larger SNR for longer observation time

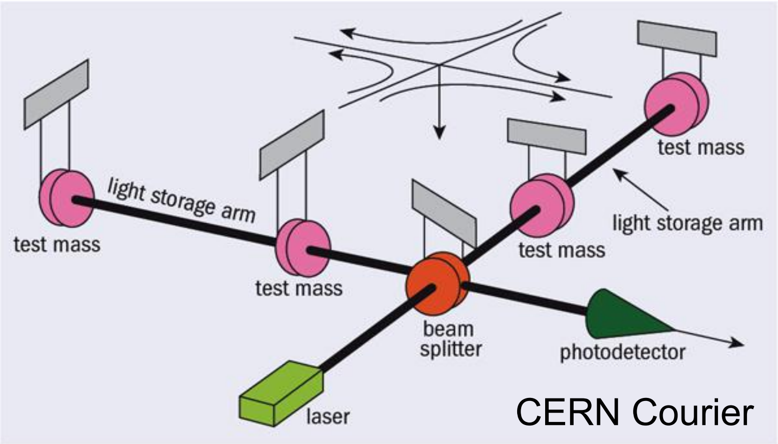
Overlap reduction: $\gamma(f) = \frac{\langle \Delta L_1 \Delta L_2 \rangle}{\langle \Delta L_1^2 \rangle}$

Signal is similar to stochastic GWs

Livingston - Hanford
$\gamma \sim -0.9$
very good coincidence

dark photon field value





Method 1: Cross-Correlation

Hanford + Livingston
O1: 1786 pairs (1800s)
O3: 7539 pairs (1800s)

- Signal is approximately a peak in frequency space
- Data analyzed using coincident short-time Fourier transforms (SFTs)

$N_{SFT} = T_{\mathrm{obs}}/T_{\mathrm{SFT}}$, where $T_{\mathrm{SFT}} = 1800s$

- Signal:

$$S_j = \frac{1}{N_{\mathrm{SFT}}} \Sigma_{i=1}^{N_{\mathrm{SFT}}} \Re \left\{ \frac{\boxed{z_{1,ij}}\boxed{z^*_{2,ij}}}{\boxed{\mathrm{P}_{1,ij}}\mathrm{P}_{2,ij}} \right\}$$

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

The signal is correlated!

the noise power

- Noise:

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

(background might not be ideally Gaussian)

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

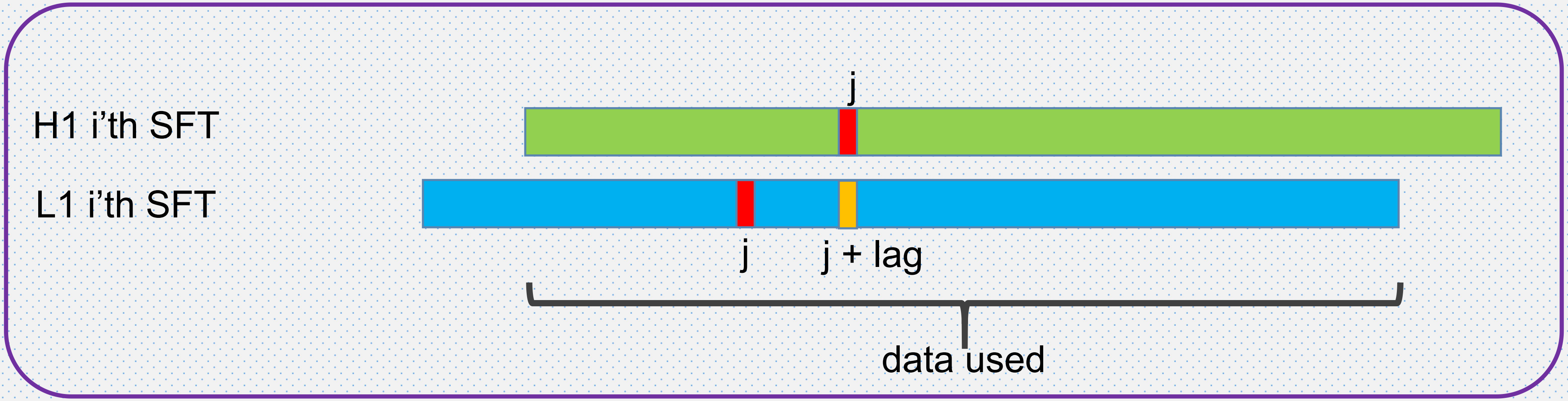
~ sqrt(T)

Method 1: Background Estimation

Background is estimated using frequency offset (lags) when calculating cross-correlation statistics.

Ideally, the SNR from the background should follow a Gaussian distribution with mean=0 and variance = 1.

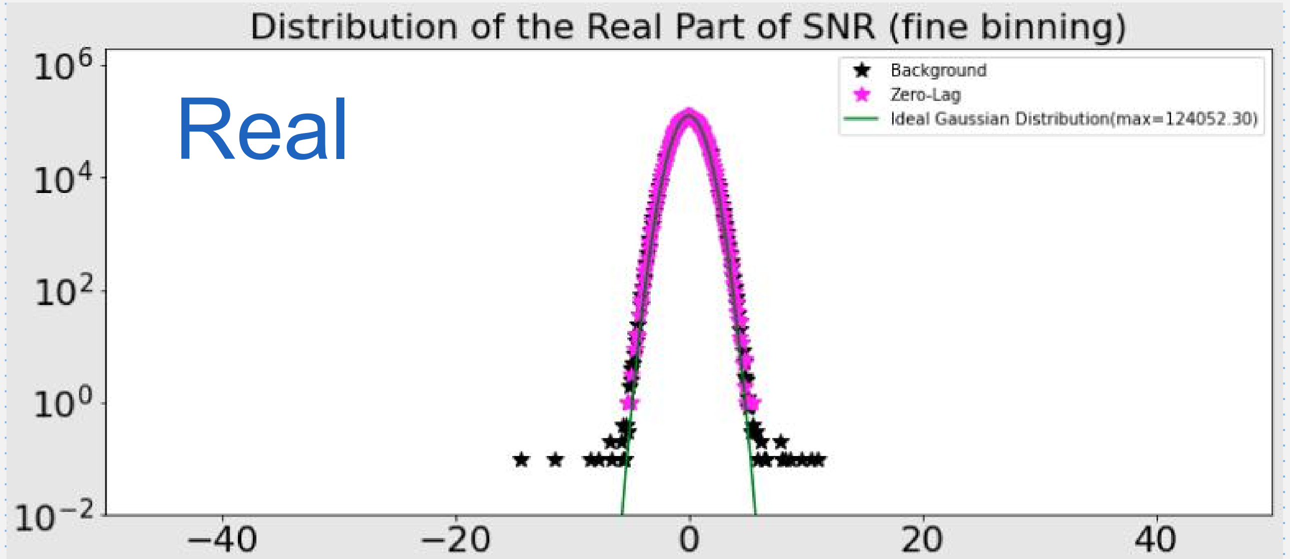
1 pair of SFTs with offset of amount "lag"



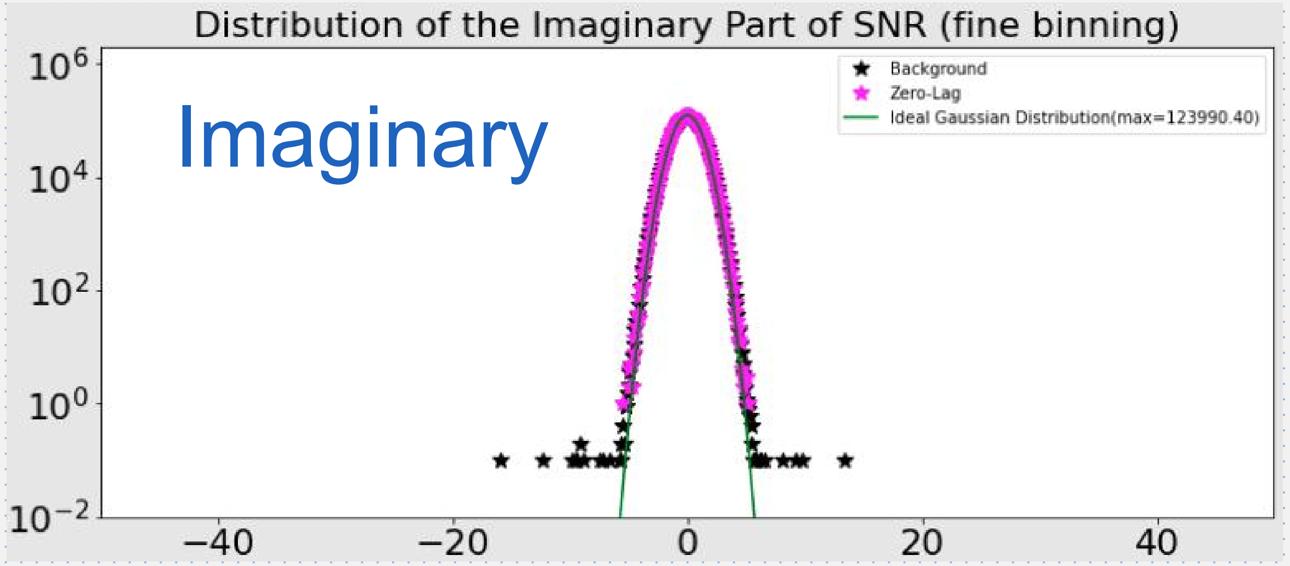
10 lag choices: (-50, -40, -30, -20, -10, 10, 20, 30, 40, 50)
(bin size = 1/1800 Hz = 0.556 mHz)

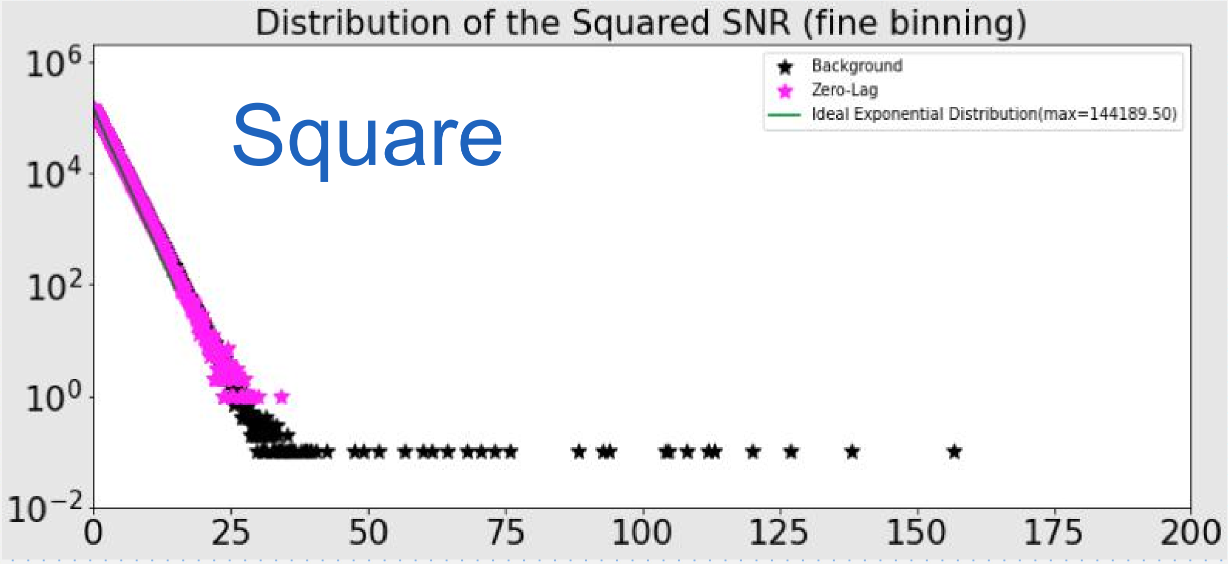
Also veto the marked lines and combs provided by the CW group.

Method 1: O3 Search Summary



Similar to Fig.3 in O1 paper.





Method 1: O3 Search Summary

A total of 21 are found with SNR larger than 5, but no interesting candidates for DPDM.

- 11 are due to loud artifacts from one detector (inspecting the single detector PSD)
- 6 have elevated noise (with real or imaginary SNR exceeding 4 in magnitude for background)

  For 1800s SFT, 0.2 Hz control band, real and imaginary SNR, there are a total of 7200 measurements.
  Expect less than 1 event with real or imaginary SNR greater than 3.8.
  Existence of backgrounds with real or imaginary SNR greater than 3.8 suggests non-Gaussian artifacts.

- 4 remaining are consistent with Gaussian expectation

frequency (Hz)	SNR	SNR(Bkg)
483.872	$0.53+5.03i$	Re: [-3.62, 3.62] Im: [-3.52, 3.51]
853.389	$-0.18+5.02i$	Re: [-3.85, 3.85] Im: [-3.55, 3.90]
1139.590	$-5.21+0.67i$	Re: [-3.54, 3.39] Im: [-3.61, 3.58]
1686.598	$5.01+1.63i$	Re: [-3.50, 3.70] Im: [-3.65, 3.89]

Method 2: Excess Power

- BSD (banded sampled data) excess power method

New in O3

Optimized Fourier Transform coherence time

Signal power is confined to one frequency bin

- Time/frequency map in 10-Hz bands over all of O3

Projected to frequency axis

- Candidates selection

On average one coincident candidate per 1Hz band in Gaussian noise.

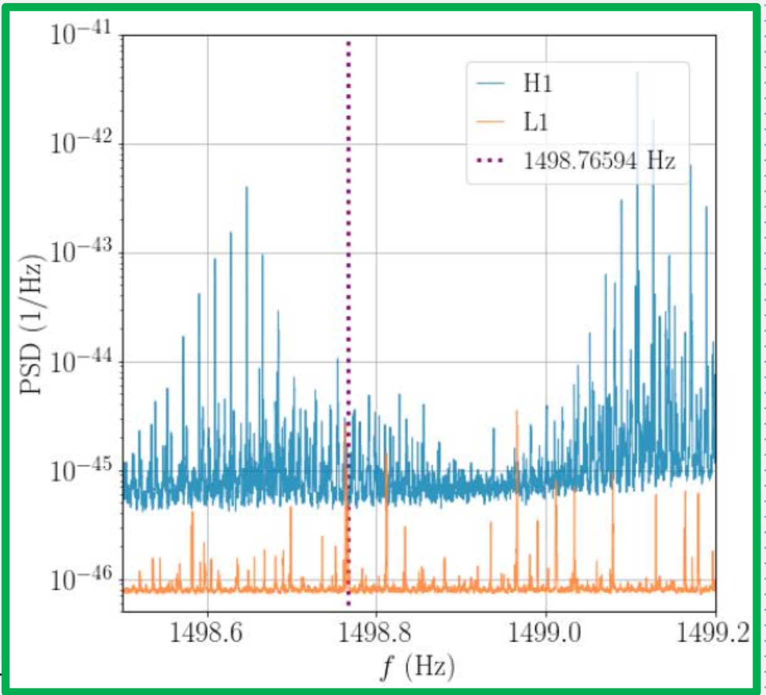
$$CR = \frac{y - \mu}{\sigma}$$

- Coincidence check

Vetoed if CR<5 and if they are farther than 1 frequency bin from each other.

Method 2: Outliers

Outliers (all vetoed, none exists for triple coincidence)

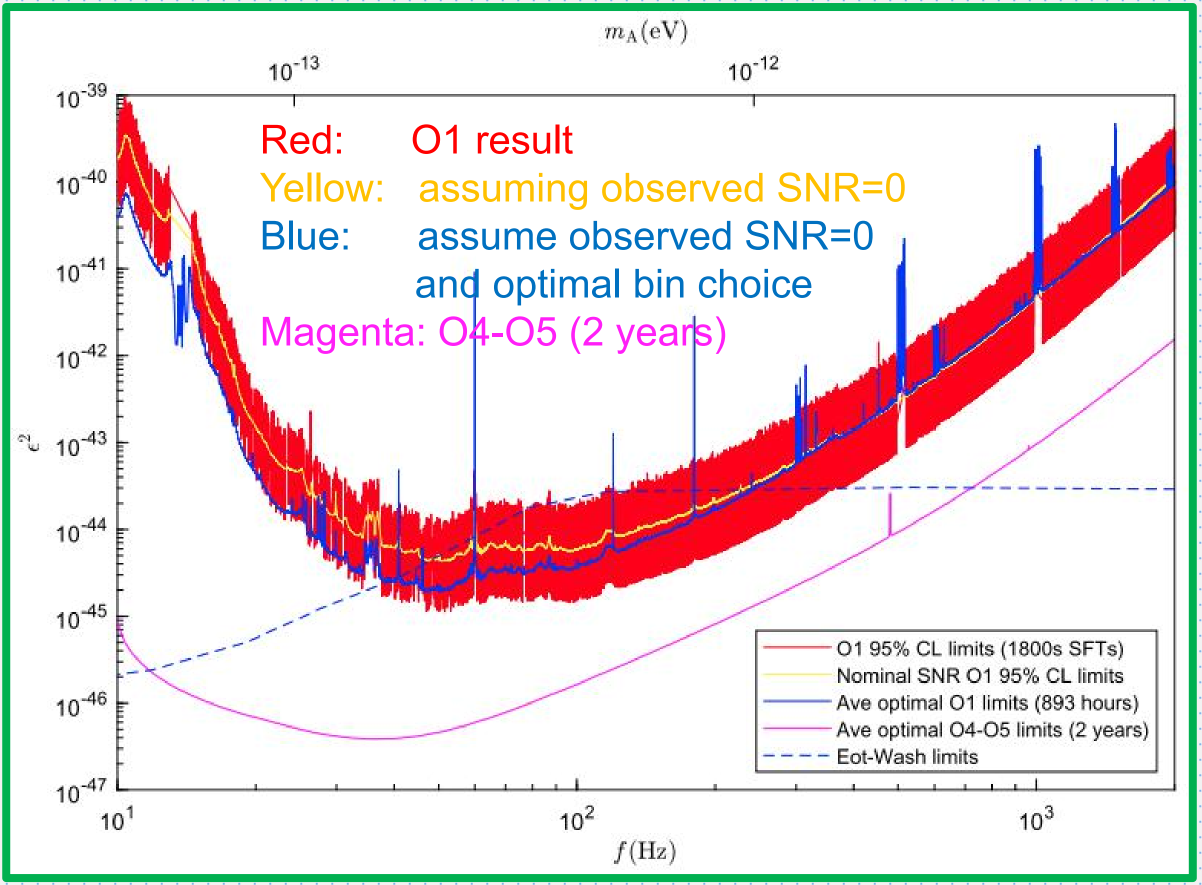


example

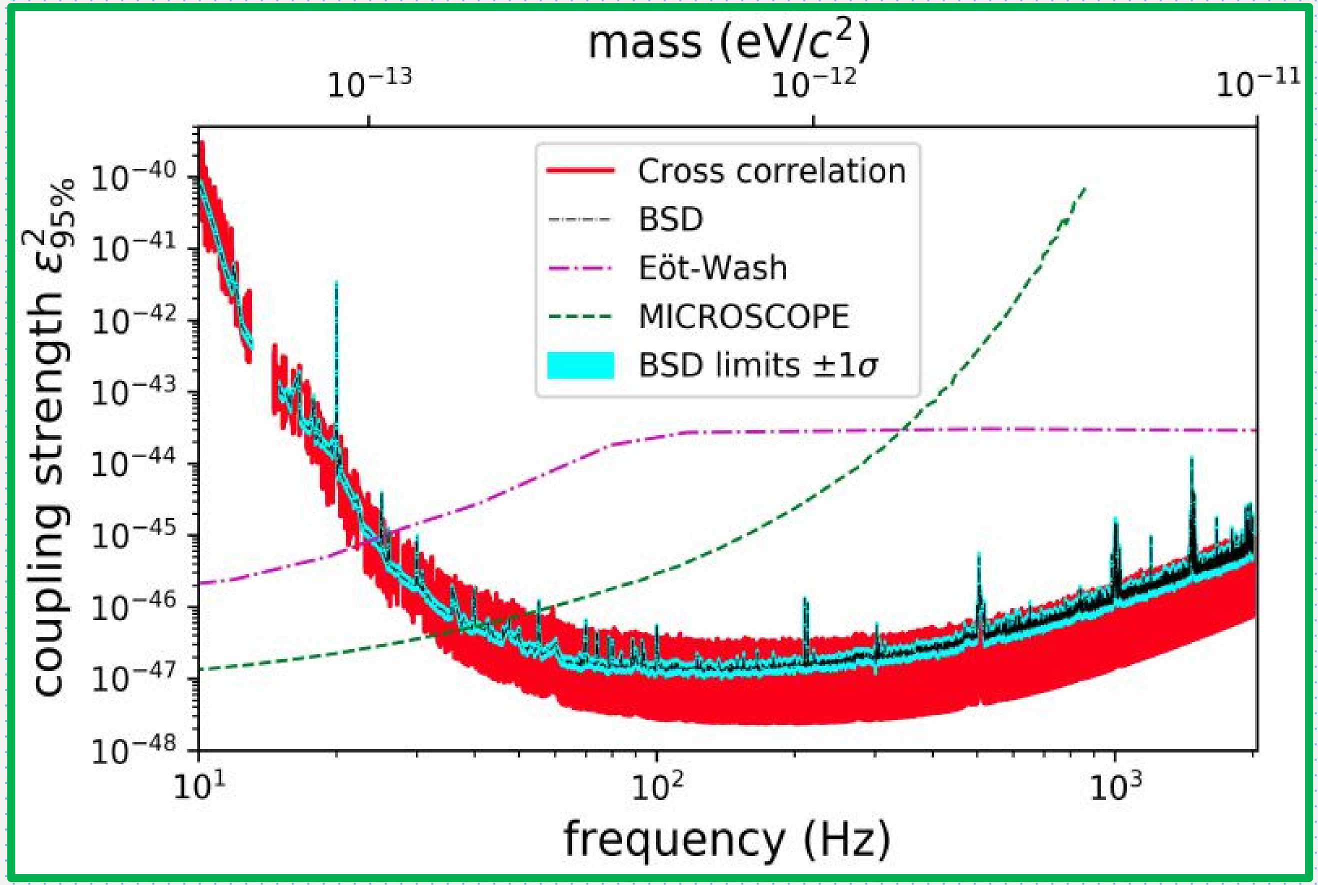
frequency (Hz)	average CR	$T_{\rm FFT}$ (s)	baseline	source
15.9000	5.29	44762	HL	unknown line in L
17.8000	28.93	44762	LV	unidentified line in L (17.8 Hz)
36.2000	8.90	22382	HV	unidentified line in H (36.2 Hz)
599.324	12.38	1492	HV	peakmap artifact; no significant candidate in L
599.325	12.33	1492	HV	peakmap artifact; no significant candidate in L
1478.75	6.47	604	HL	noisy spectra in H
1496.26	7.12	596	HL	noisy violin resonance regions
1498.77	8.73	596	HL	noisy violin resonance regions
1799.63	7.40	498	HV	unidentified line in H (1799.63904 Hz)
1936.88	7.96	462	HL	noisy violin resonance regions
1982.91	6.34	450	HL	noisy violin resonance regions

O1 Result

O3 Result



(Nature) Commun.Phys [1905.04316], HG, Riles, Yang, Zhao



LIGO-VIRGO-KAGRA Collaborations, PRD [2105.13085]

New in O3 search:

1. Another search performed by the continuous wave group with a different method
2. An improvement factor included from finite light travel time (PRD.103.L051702, Morisaki, et al)

Summary

- GW experiments can be extended to directly search for dark matter
- Searches have been performed with LIGO-Virgo-KAGRA’s O1 and O3 data
- Constraints set on dark photon coupling (best in relevant mass range)

  Possibly achieve 5-sigma discovery at unexplored parameter regimes

Thanks!