Dark Photon Dark Matter Searches at LIGO

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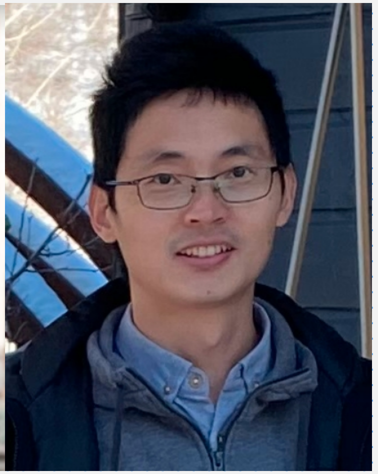
University of Utah

Searches as of now:

- O1 Search: (Nature) Commun.Phys. 2 (2019) 155 (arxiv:1905.04316), H.G, Riles, Yang, Zhao
- O3 Search: arxiv:astro-ph.CO/2105.13085, LVK Collaboration Paper

The O3-Search Team


Andrew Miller


Huaike Guo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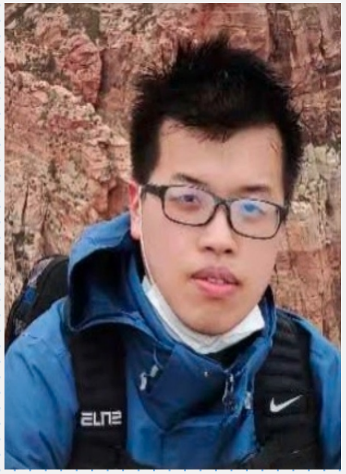
Keith Riles


Fengwei Yang


Yue Zhao

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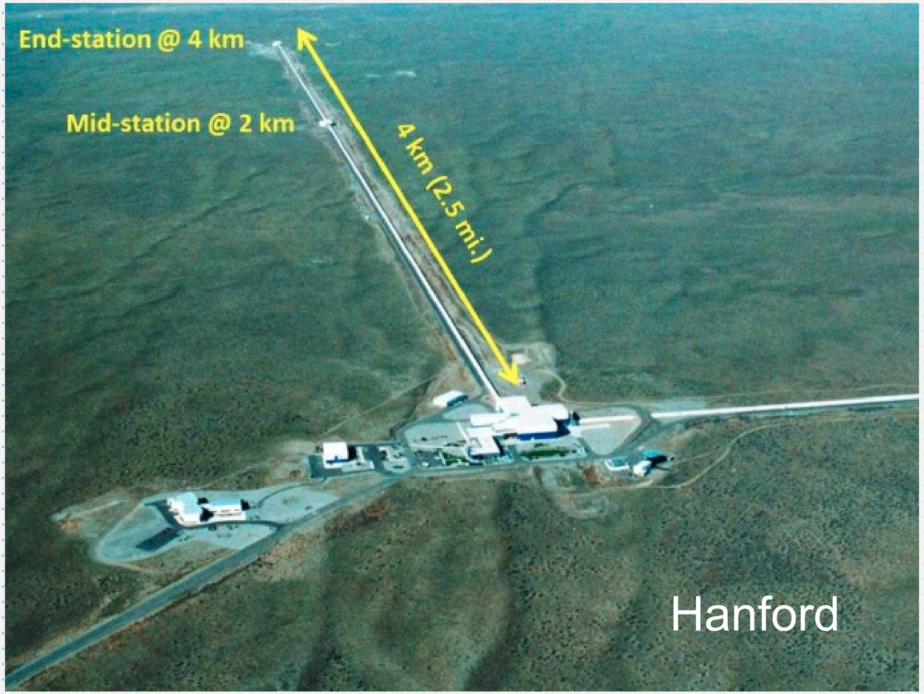
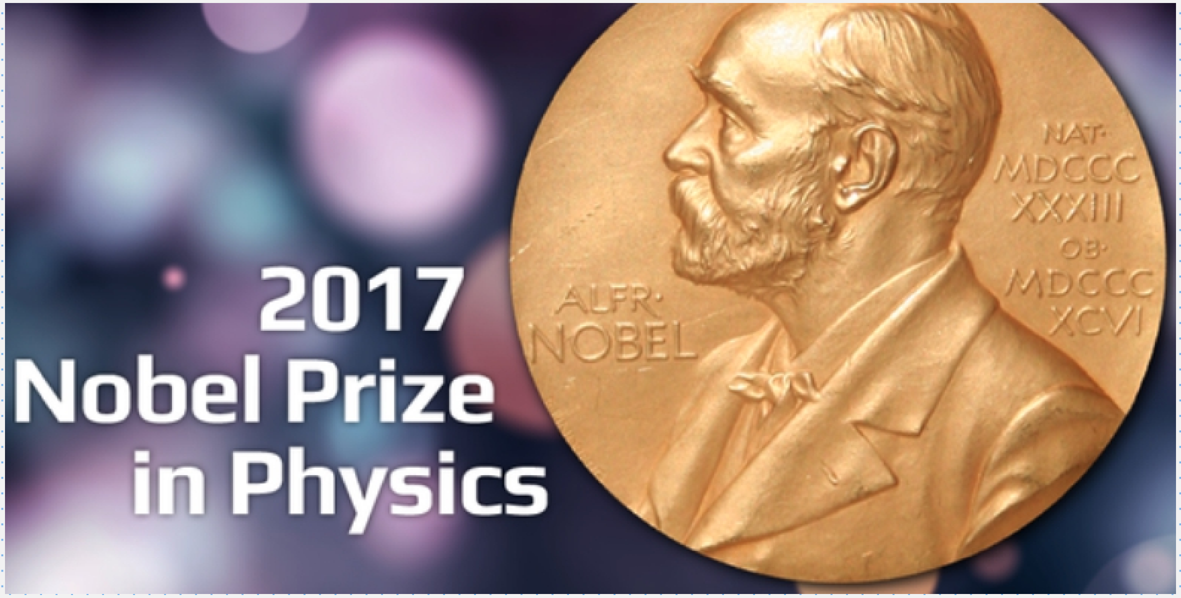
Gravitational Waves



https://www.ligo.caltech.edu



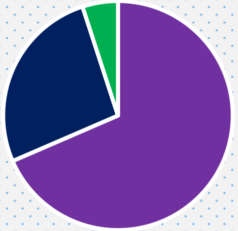
https://nobelprize.org

A new era of Gravitational Wave Astronomy

Also important for particle physics!

Probing New Physics with Gravitational Waves

New Physics



- High energy frontier (LHC, etc)
- Precision frontier (EDM, MDM, etc)
- Cosmic frontier (CMB, dark matter searches, etc)
- Gravitational waves

(cosmic phase transitions,
cosmic topological defects,
dark photons, etc)

Dark Matter: Candidates

ultralight particles
(axion, dark photon)

WIMP

primordial black holes
boson stars, BEC

field dark matter

particle dark matter

exotic compact object

- 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

$U(1)_B \ (p+n)$

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

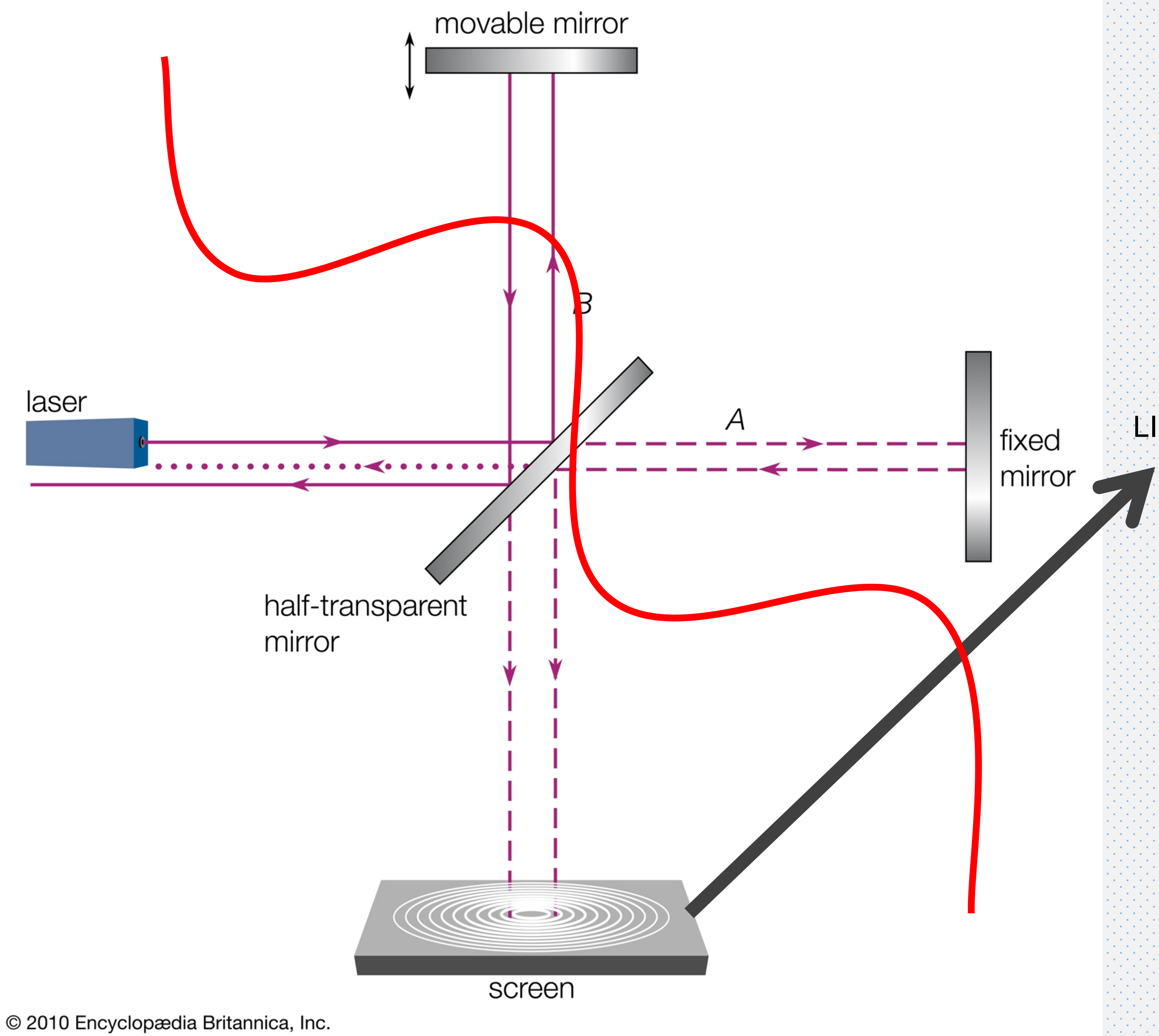
- Mass(e.g., Higgs mechanism)
- Relic abundance (e.g., misalignment mechanism)

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

dark electric field $E_i \sim m_A A_i$

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

Michelson Interferometer



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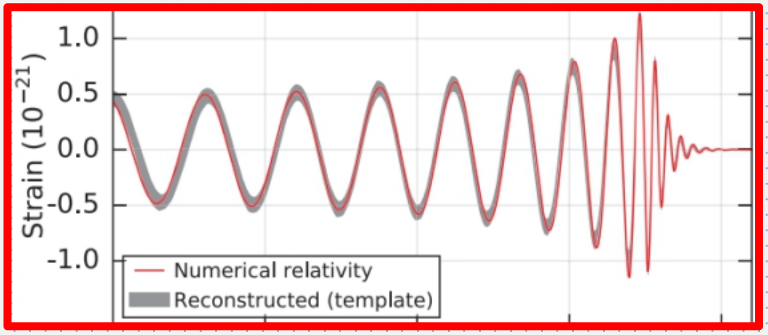
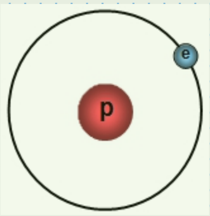


LIGO and Virgo Collaboration, PRL 116, 061102 (2016)

~6000km

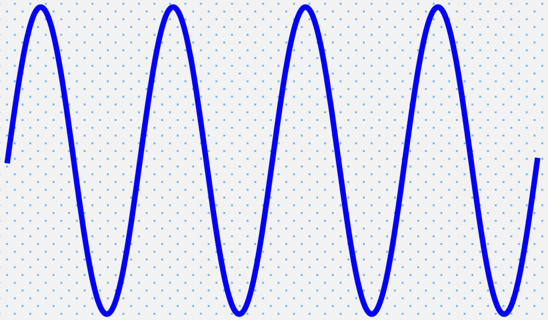
10^-15m



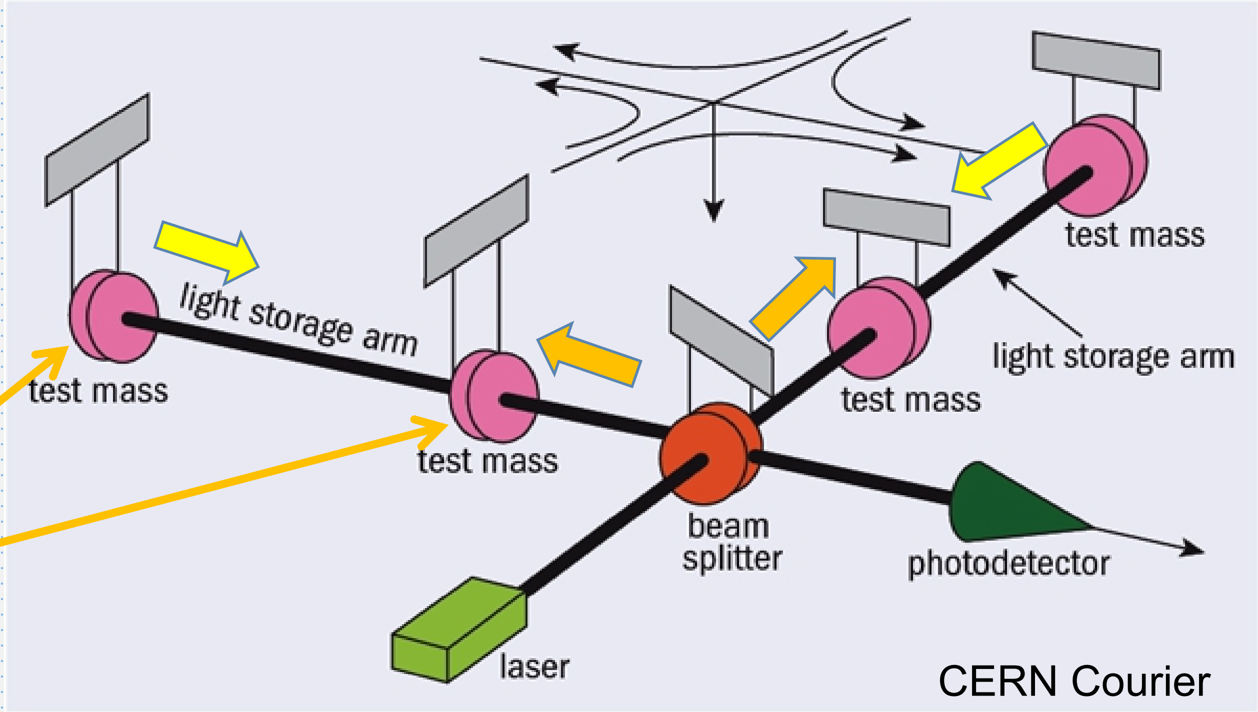
10^-15m

Dark Photon Signals at LIGO

a dark photon wave



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



CERN Courier

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

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

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

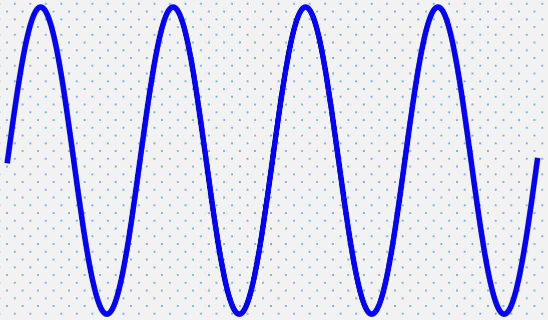
silicon mirror

$U(1)_B$: $1/\mathrm{GeV}$

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

Dark Photon Signals at LIGO

a dark photon wave



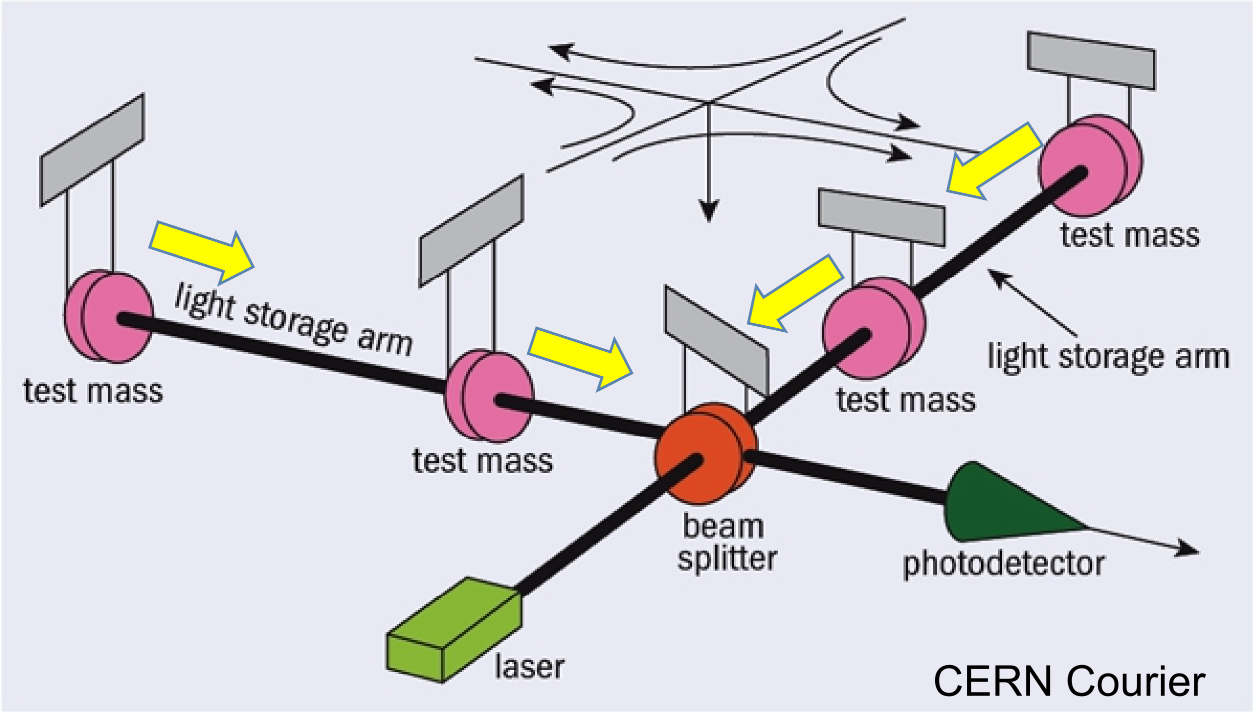
$$\vec{A}_{n,0}\sin(\omega_n t - \cancel{\mathbf{k}_n \cdot \mathbf{x}} + \phi_n)$$

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

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

random phase

dark electric field



CERN Courier

Light travel time effect

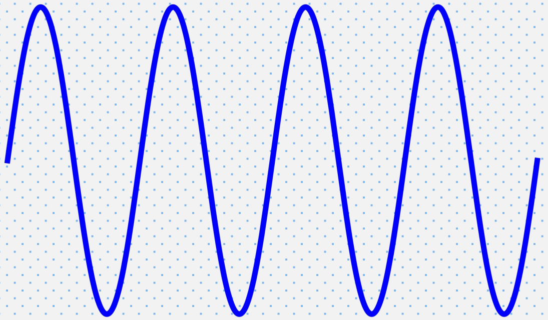
New in O3

(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

a dark photon wave



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

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

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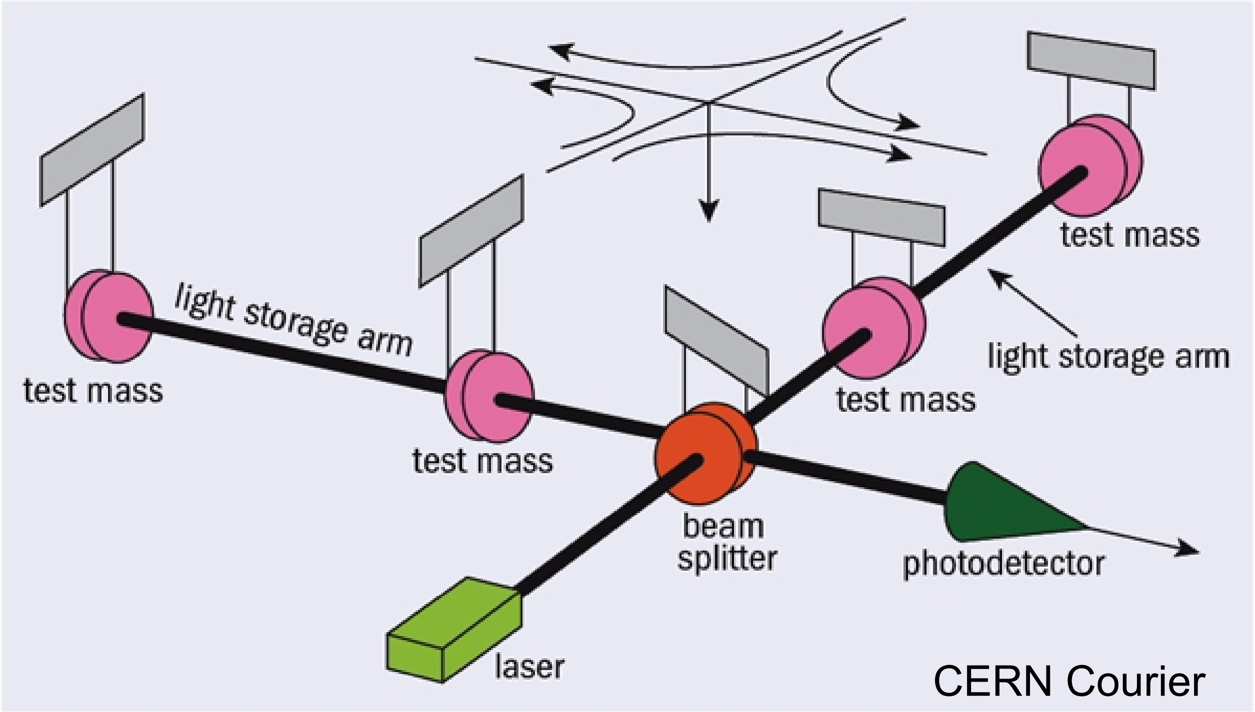
random phase

dark electric field



CERN Courier

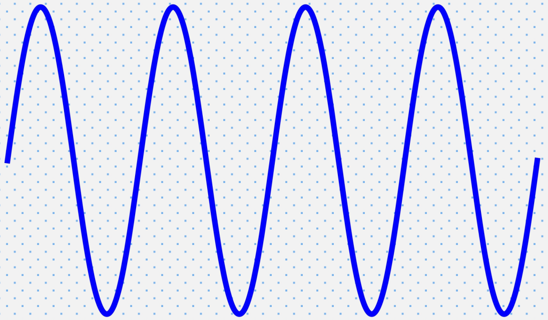
$$\omega_n = m_A\left(1+\frac{1}{2}v_n^2\right) = 2\pi \times (100\mathrm{Hz}) \approx 4 \times 10^{-13}\mathrm{ev}$$

non-relativistic

mass LIGO is sensitive to

Dark Photon Signals at LIGO

a population



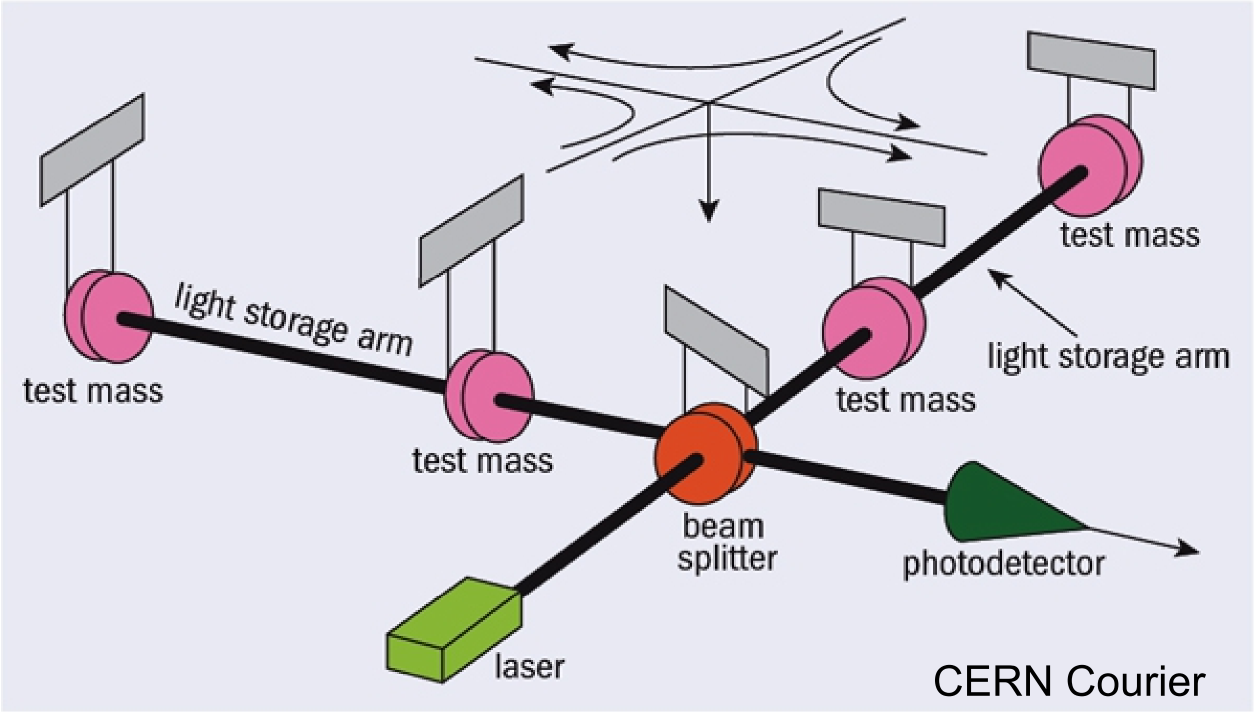
$$\vec{A}_{n,0}\sin(\omega_n t - \mathbf{k}_n \cdot \mathbf{x} + \phi_n)$$

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

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

$\phi_n \rightarrow$ random phase

dark electric field



CERN Courier

- 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

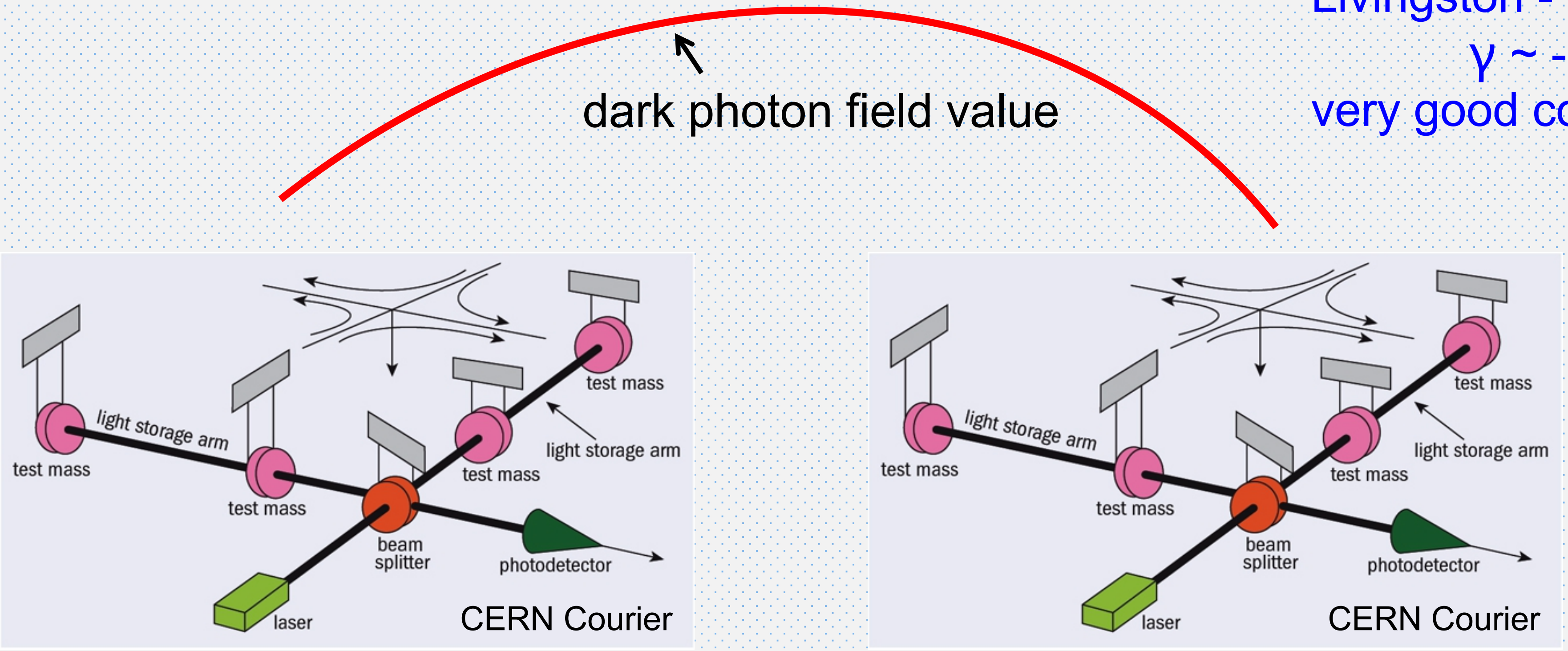
Benefits:

- 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
γ ~ -0.9
very good coincidence



dark photon field value

CERN Courier

CERN Courier

Method 1: Cross-Correlation

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

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

- Signal:

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

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)

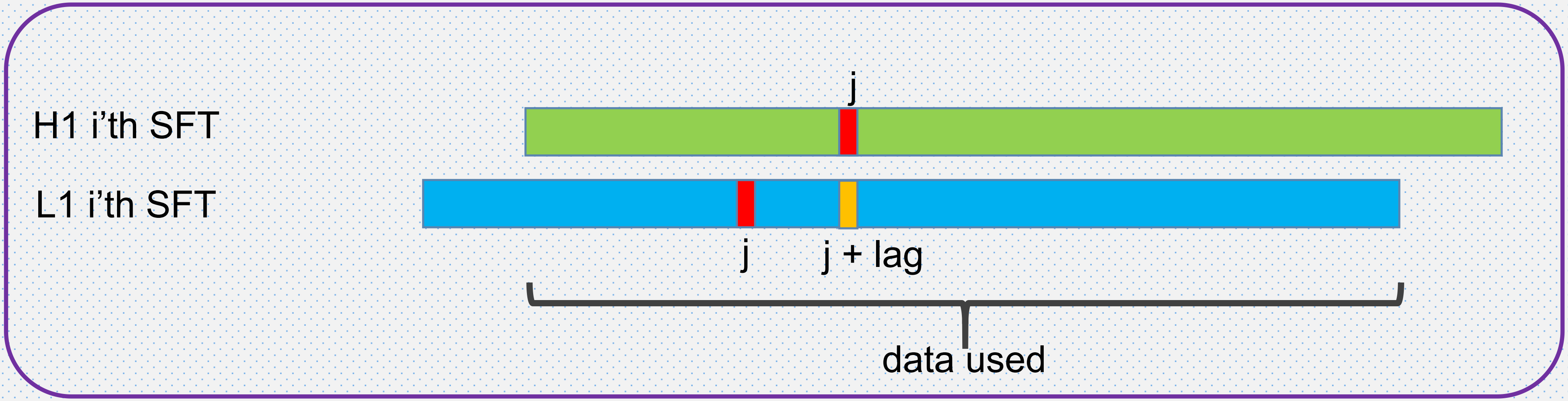
$$\mathrm{SNR} \equiv \frac{S_j}{\sigma_j}.$$

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.

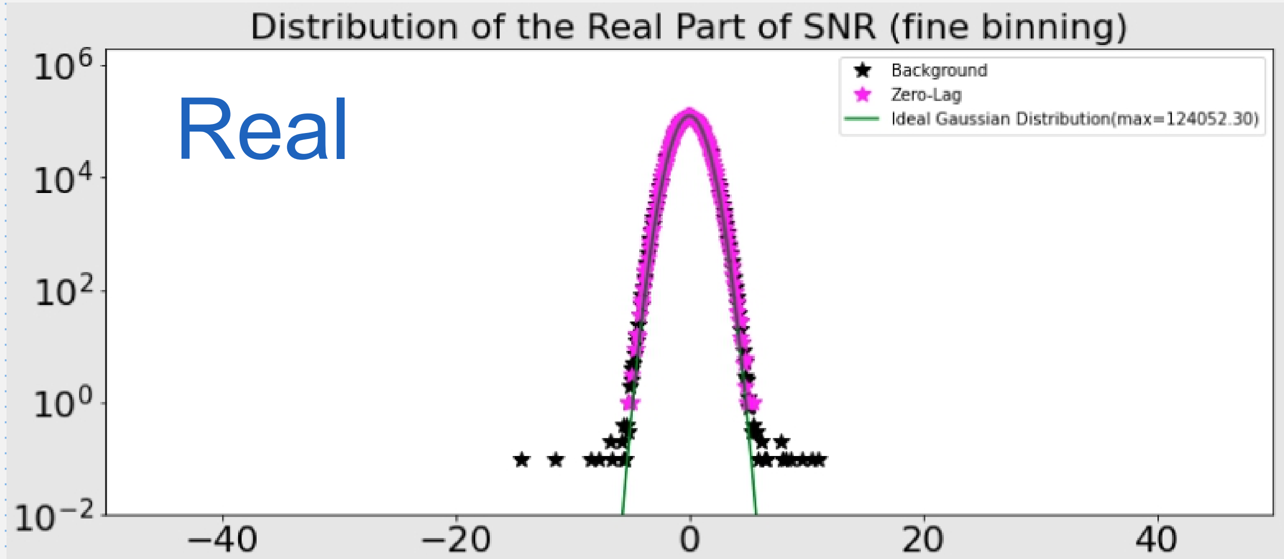
1 pair of SFTs with offset of amount “lag”



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

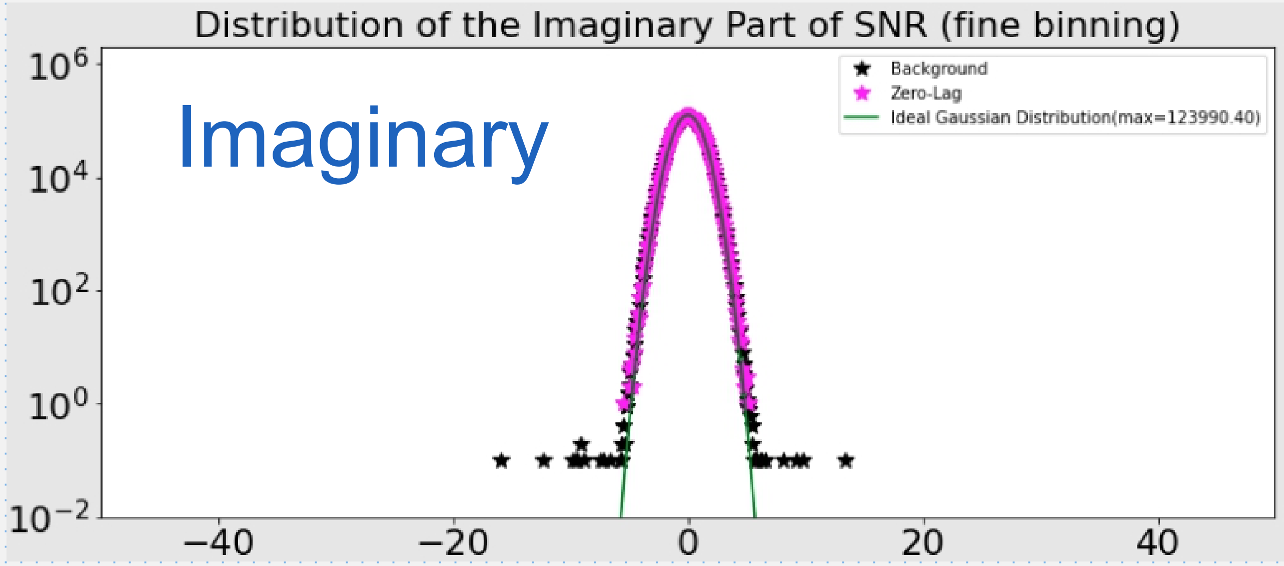
Also veto the marked lines and combs provided by the CW group.

Method 1: O3 Search Summary

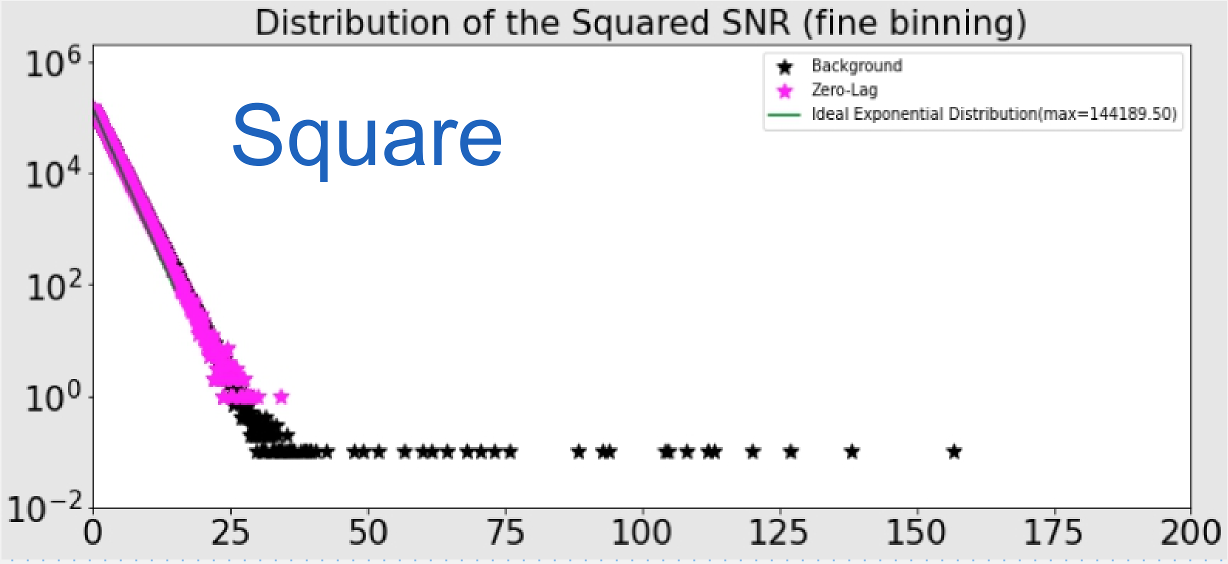

Distribution of the Real Part of SNR (fine binning)

Real

Similar to Fig.3 in O1 paper.


Distribution of the Imaginary Part of SNR (fine binning)

Imaginary


Distribution of the Squared SNR (fine binning)

Square

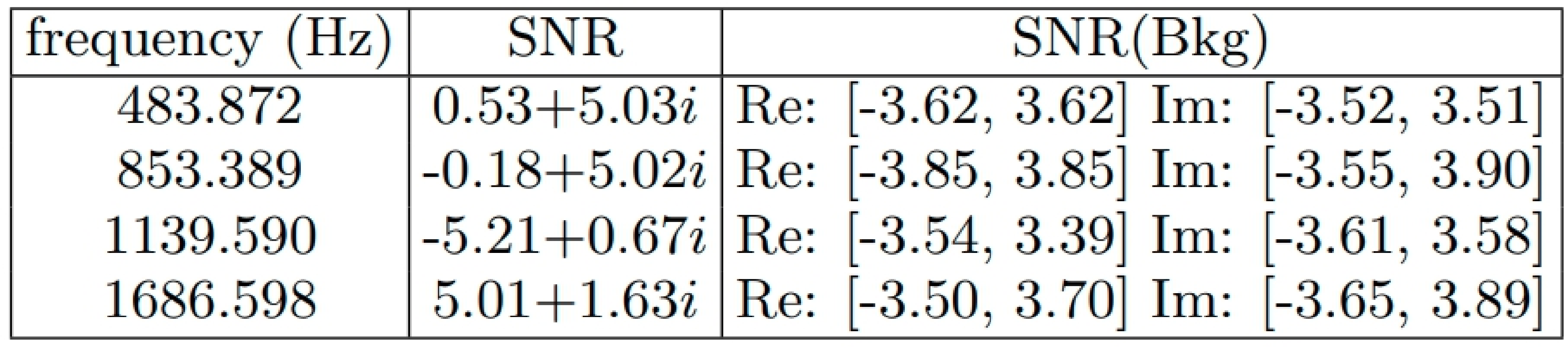
Method 1: O3 Search Summary

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

  Optimized Fourier Transform coherence time

  Signal power is confined to one frequency bin

New in O3

- 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.

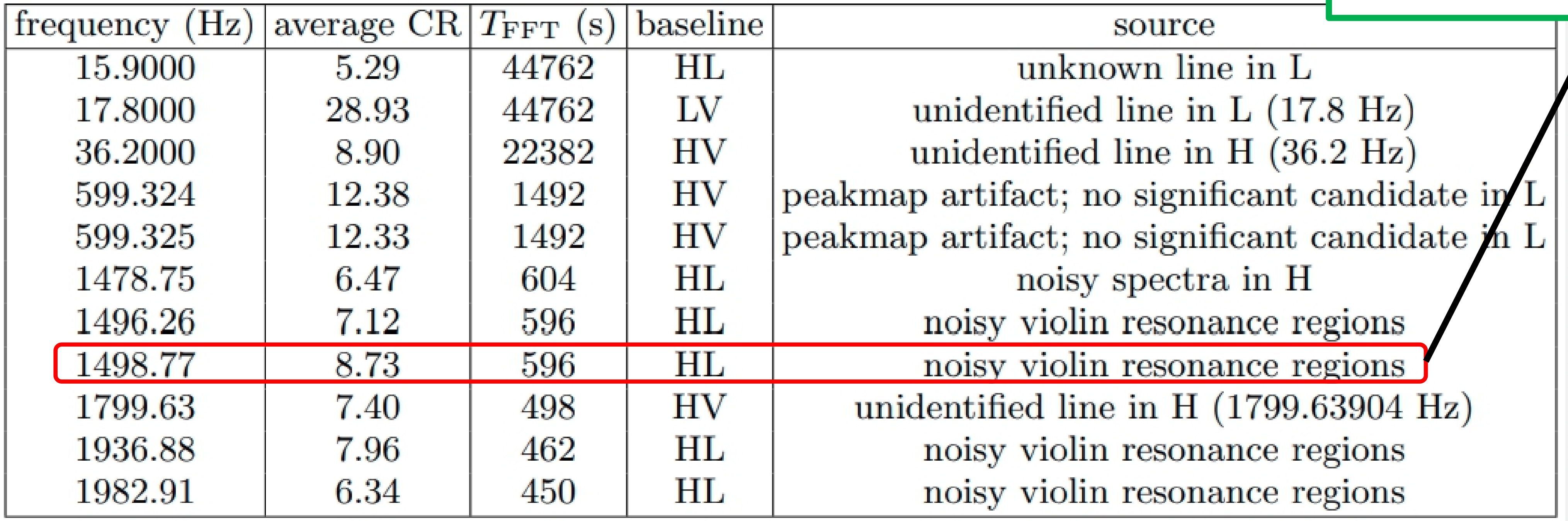
$$CR = \frac{y - \mu}{\sigma}$$

- Coincidence check

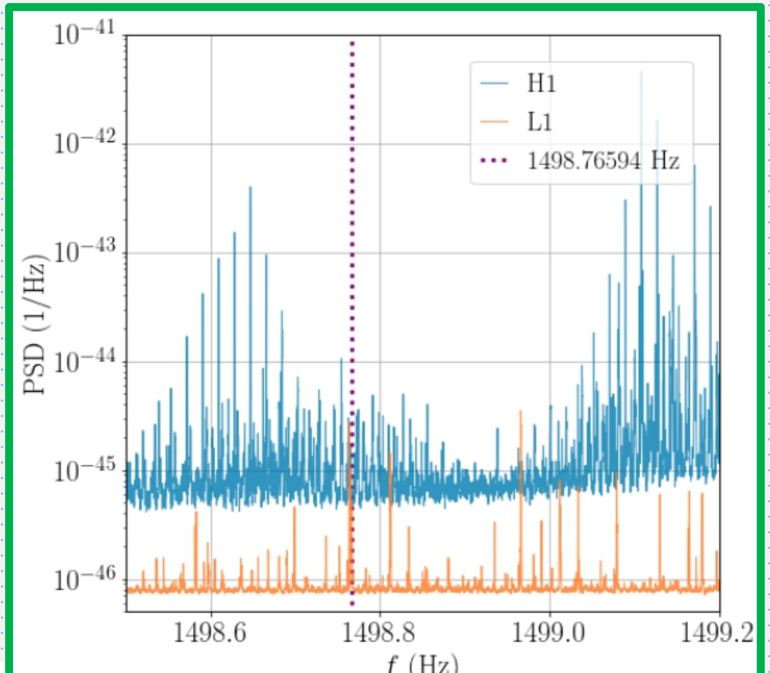
  Vetoed if CR<5 and if they are farther than 1 frequency bin from each other.

Method 2: Outliers

Outliers (all vetoed, none exists for triple coincidence)

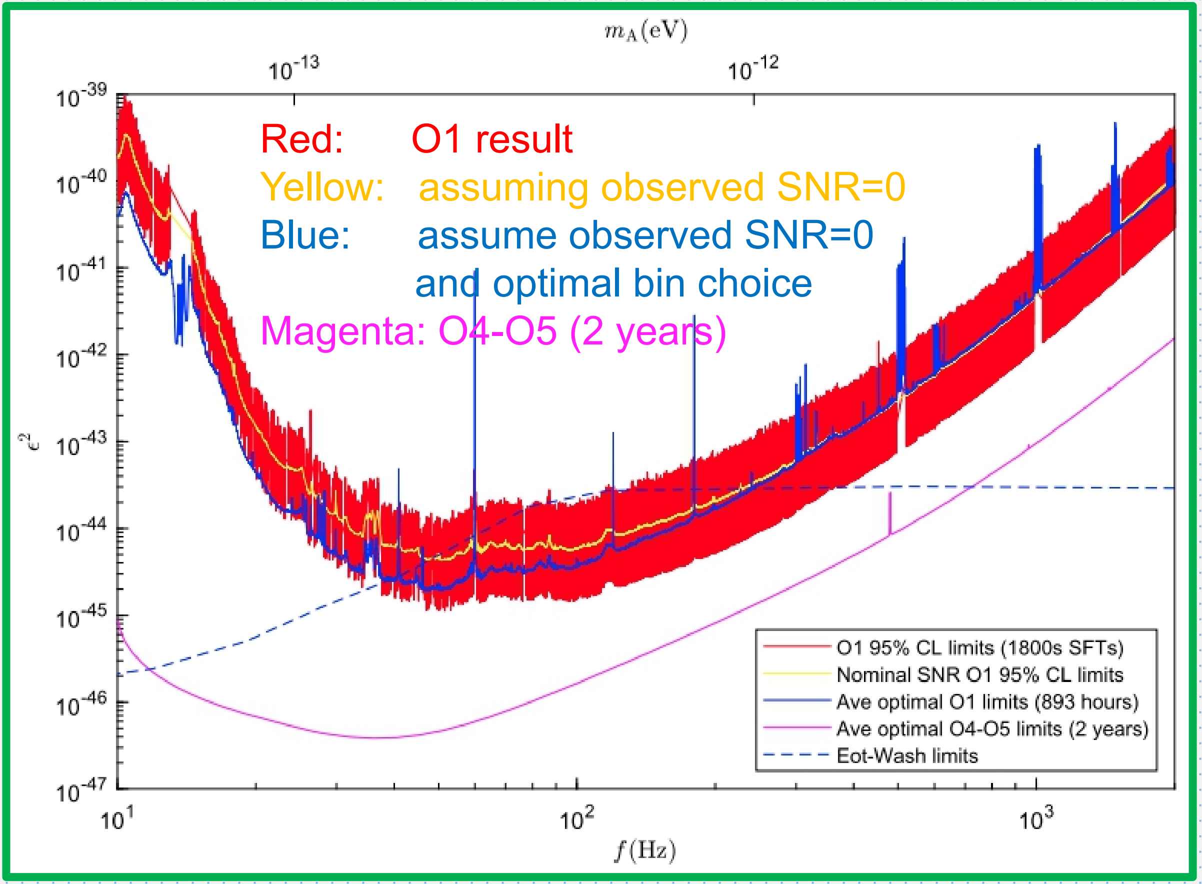


frequency (Hz)	average CR	T_{FFT} (s)	baseline	source
15.9000	5.29	44762	HL	unknown line in L
17.8000	28.93	44762	LV	unidentified line in L (17.8 Hz)
36.2000	8.90	22382	HV	unidentified line in H (36.2 Hz)
599.324	12.38	1492	HV	peakmap artifact; no significant candidate in L
599.325	12.33	1492	HV	peakmap 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



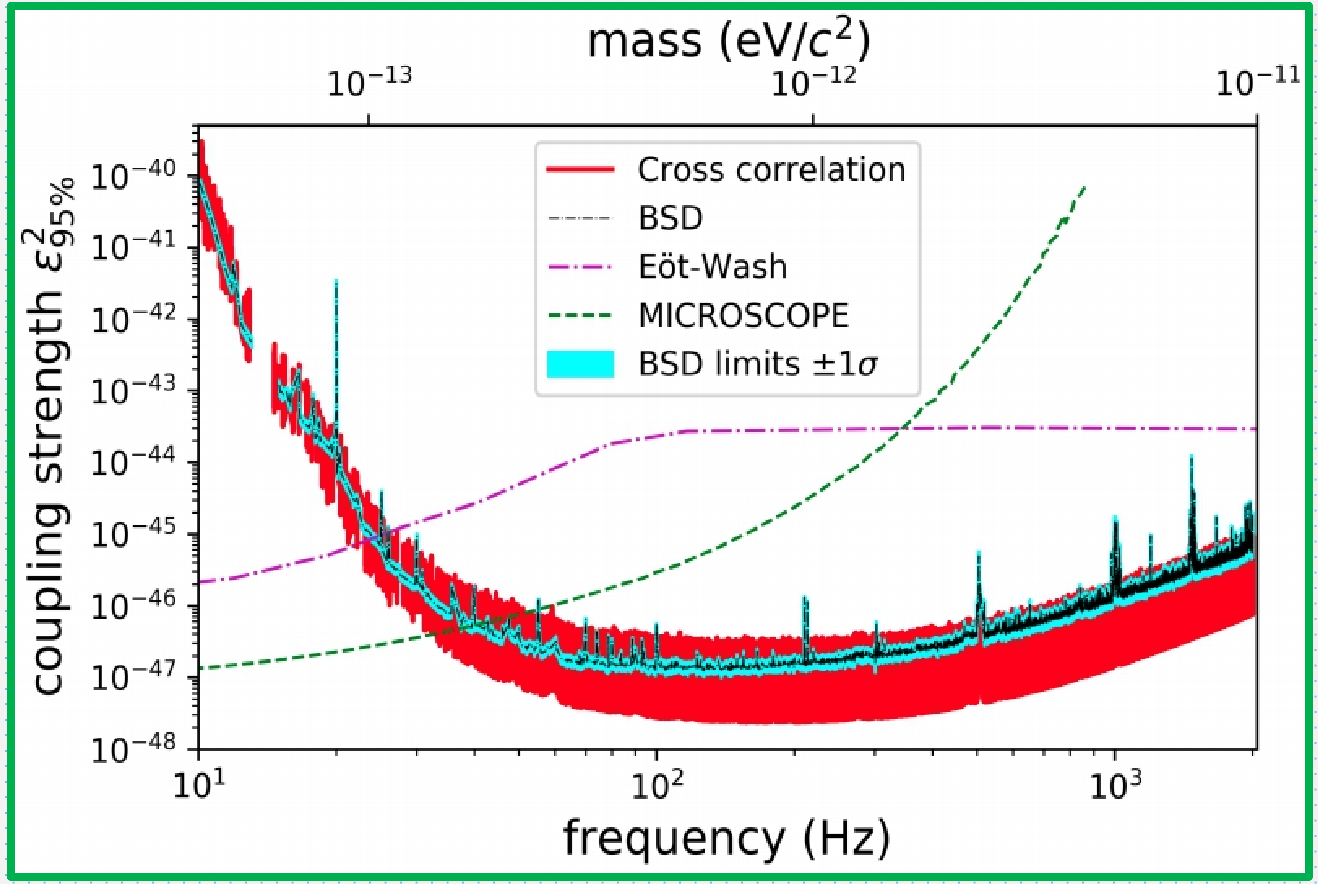
example

O1 Result



(Nature) Commun.Phys. 2 (2019) 155, H.G, Riles, Yang, Zhao

O3 Result



arxiv:astro-ph.CO/2105.13085, LVK Collaboration Paper

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 search for dark matter

  GW detector as a dark matter direct detection experiment

- O1 data has already beaten existing experimental constraints

- O3 data gives much better result

  Possibly achieve 5-sigma discovery at unexplored parameter regimes

Thanks!