Constraints on dark photon dark matter using gravitational wave detector data

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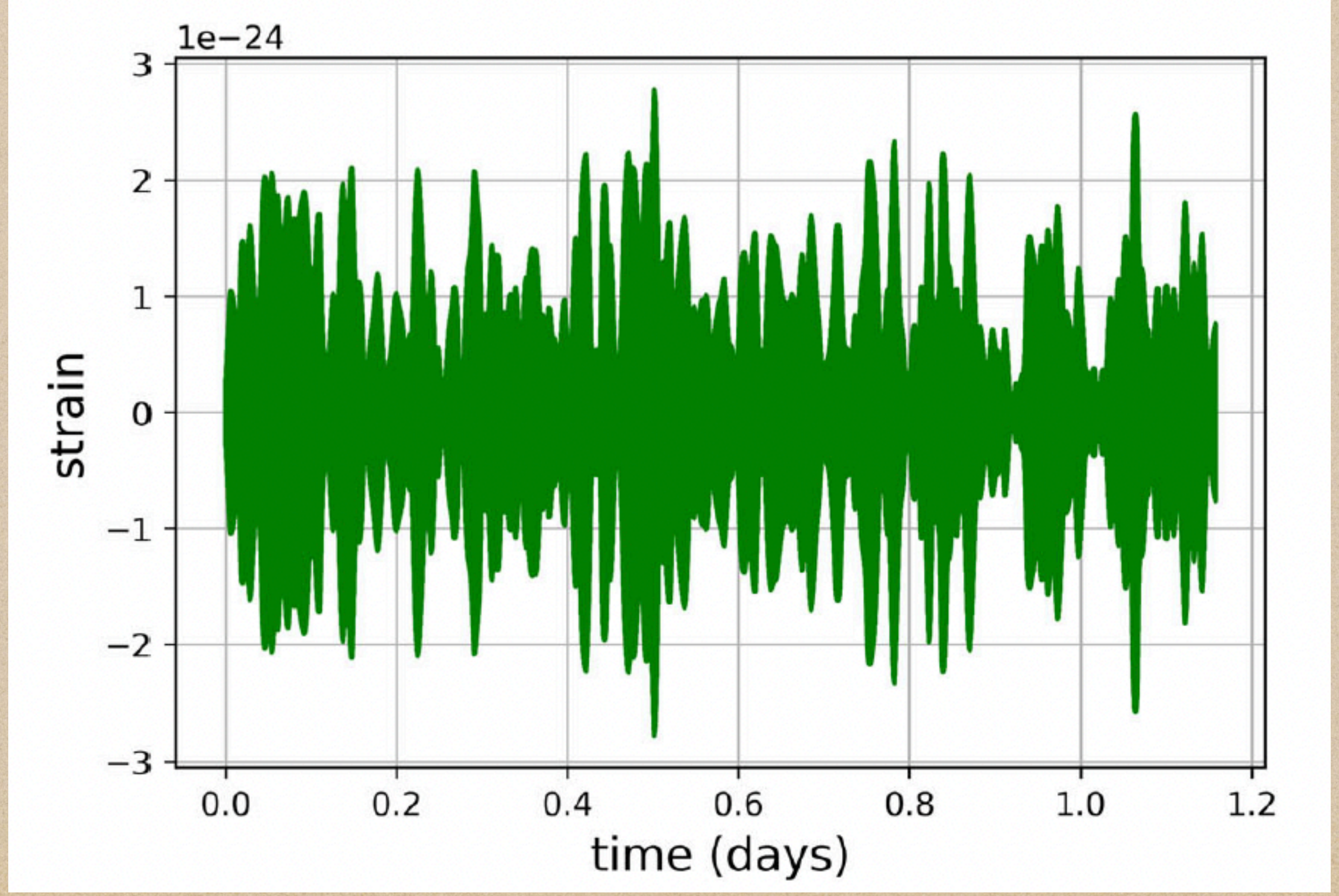
on behalf of the LIGO-Virgo-Kagra Collaborations

(Abbott et al. 2021: arXiv 2105.13085)



Gravitational Waves

- Gravitational Waves (GWs) are solutions of the linearised Einstein field equations in vacuum:

Matter

$$R_{ij} - \frac{1}{2} g_{ij} R = \frac{8\pi G}{c^4} T_{ij} \Rightarrow \Box h_{ij} = 0$$

Space-time

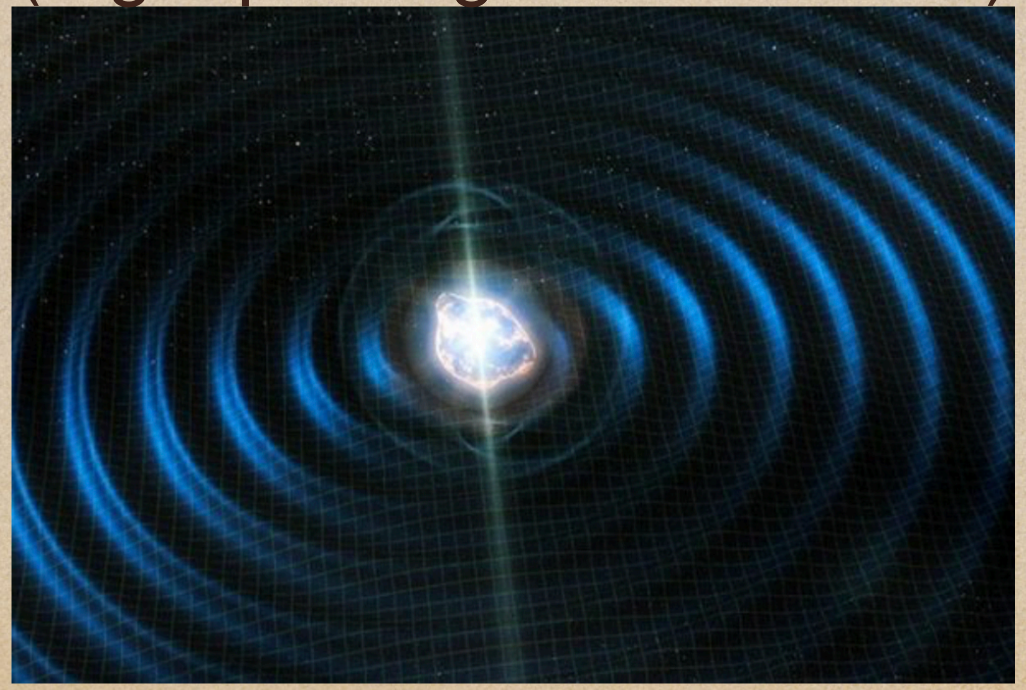
$$T_{ij} = 0,\ g_{ij} \simeq \eta_{ij} + h_{ij},\ |h_{ij}| \ll 1$$

- Produced by the bulk motion of matter. Examples:

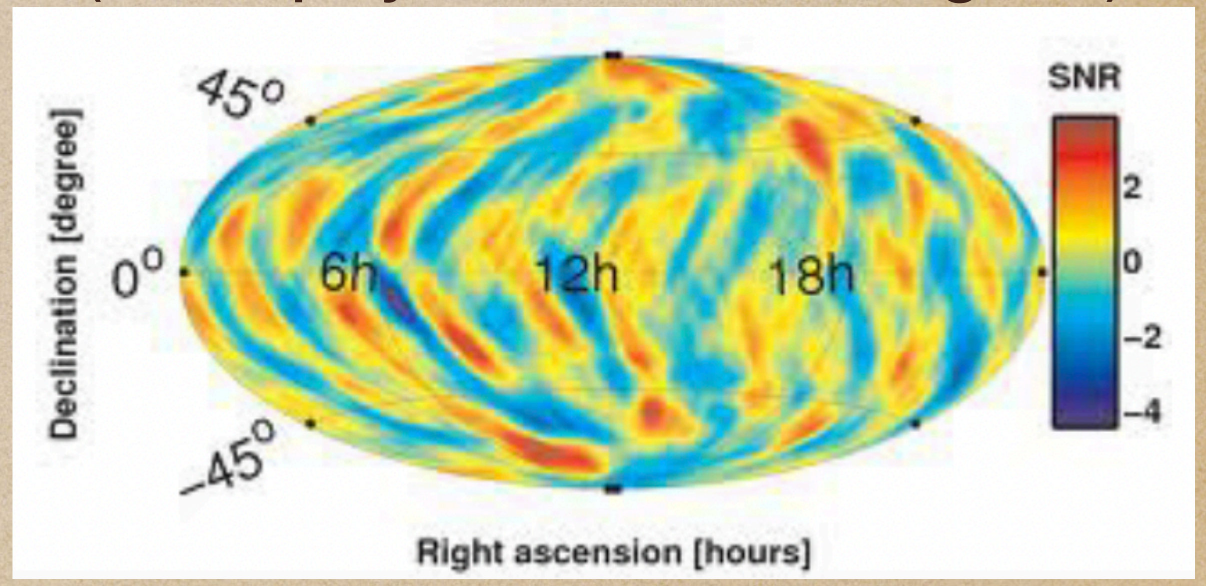
Coalescing compact binaries (black holes, neutron stars)

Supernova explosions

Continuous Waves (e.g. spinning neutron stars)



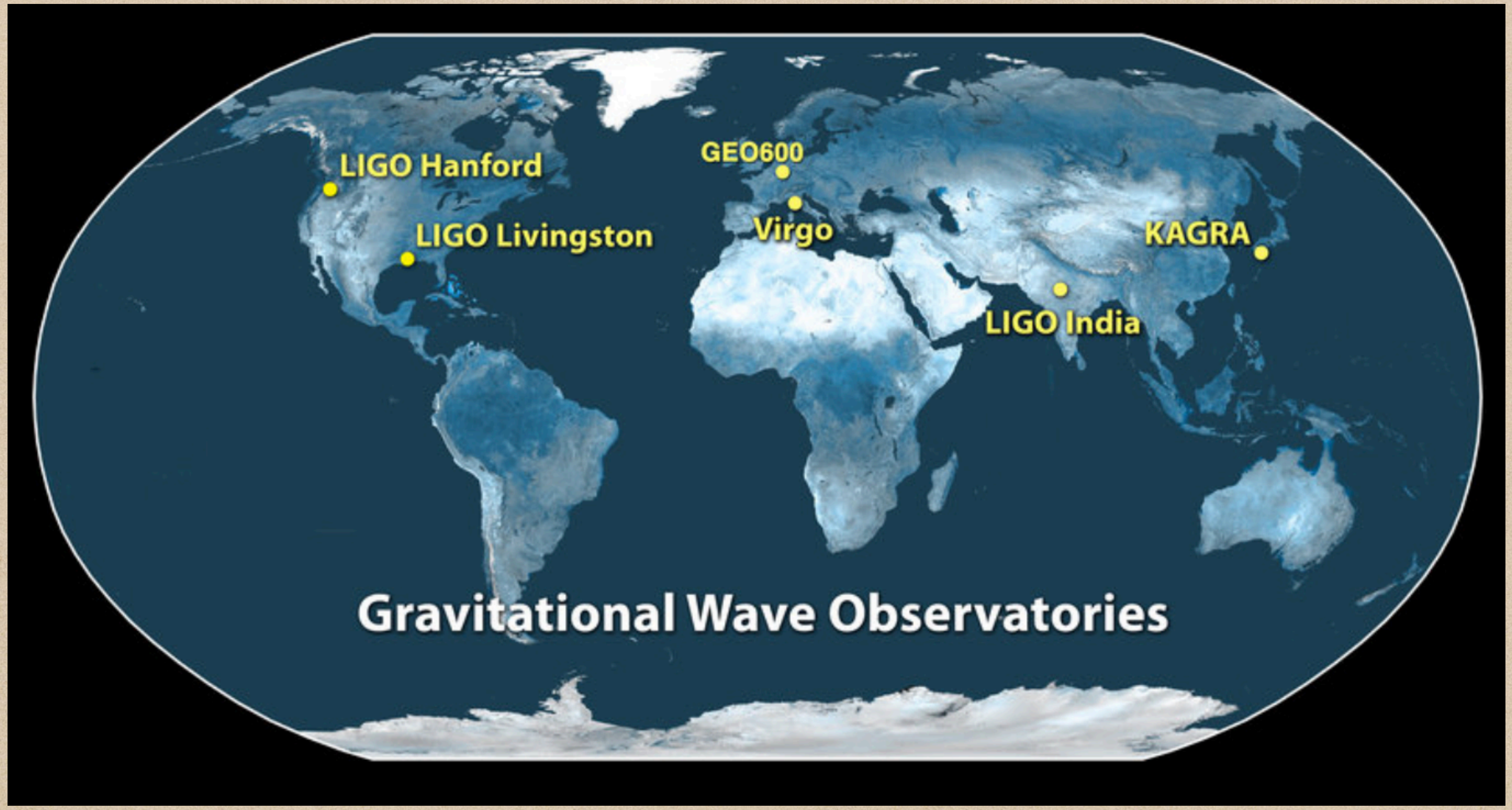
Stochastic background (Astrophysical, Cosmological)



Transient signals (duration O(0.001—100) s)

Persistent (duration much longer than observation time)

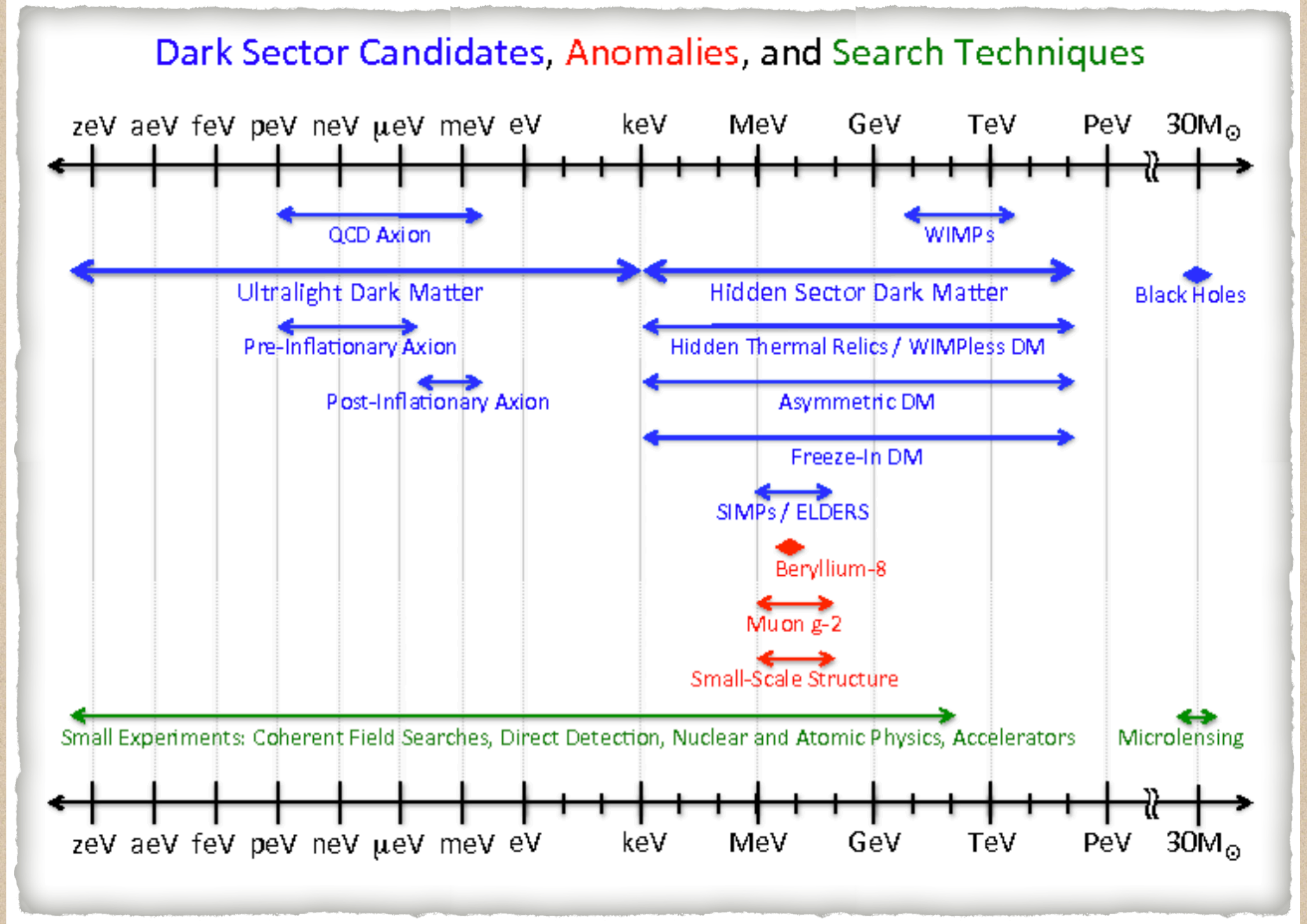
Gravitational Wave detector network



- Three runs in the Advanced configuration so far (O1-O3). Run O4 will start in Fall 2022

Dark Matter

Dark Matter (DM) candidates cover ~90 orders of magnitude in mass

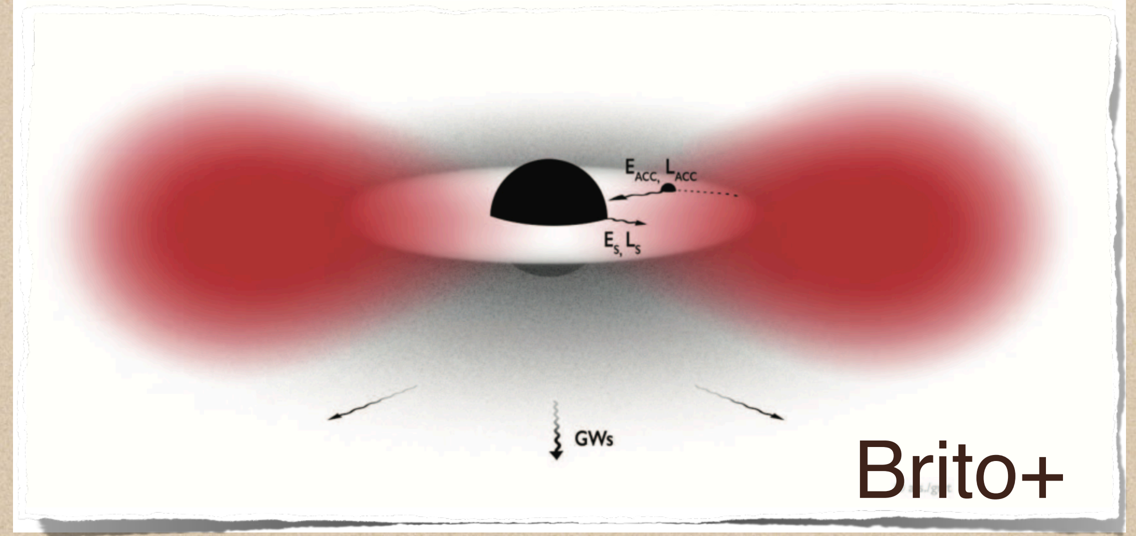


Gravitational Wave signature of Dark Matter

- In recent years, a growing body of literature on the potentiality of Gravitational Wave (GW) detectors as tools to probe DM has been produced (see e.g. Bertone+, arxiv:1907.10610)

◉ Data Analysis methods using data from GW detectors are being developed and, sometime, have already been applied in searches of Dark Matter fields.

➡ Emission of nearly-periodic persistent GWs from ultra-light boson clouds around spinning black holes



Brito+

D’Antonio et al. 2018, PRD 98, 103017
Palomba et al. 2019, PRL 123, 171101
Sun et al. 2019 PRD 101, 063020

➡ Impact of ultra-light boson clouds on binary black hole mergers

Baumann et al. 2019, PRD 99, 044001
Yang et al. 2018, Res. Astron. Astrophys. 18, 065
Choudhary et al. 2021, PRD 103, 044032

➡ Stochastic GW background from ultra-light boson clouds Tsukada et al. 2019, PRD 99, 103015

➡ Search for direct interaction of DM fields with GW detector mirrors

- Ultra-light DM can directly interact with interferometer optical components producing a potentially detectable signal

  - ➡ It is not a GW signal, but nevertheless the interaction can cause a differential strain

- The mass scale to which detectors are sensitive is set by the particle field frequency $f_0 = m_A c^2/h$:

$$10^{-14} - 10^{-11}\text{eV}$$

for Earth-bound detectors, like Virgo, LIGO, Kagra.

Pierce et al. 2018, Phys. Rev. Lett. 121, 061102

Guo et al. 2019 Nature Communications Physics 2

Nagano et al. 2019, PRL 123, 111301

Morisaki et al. 2021, PRD 103, L051702

Michimura et al. 2021, PRD 102, 102001

Vermeulen et al. 2021, arXiv:2103.03783

Dark Photon

- Dark Photon (DP) was originally introduced as an hypothetical vector boson that couples to SM charged particles through kinetic mixing (Holdom 1986)

- Associated to a new U(1) gauge field

$$\mathscr{L} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{1}{2}m_{\mathrm{A}}^{2}A'^{\mu}A'_{\mu} - \epsilon_{\mathrm{A}} e J^{\mu}_{\mathrm{EM}}A_{\mu}$$

$A'_{\mu\nu}$: DP field strength tensor

A'_{μ} : DP field

m_{A} : DP mass

ϵ_{A} : DP coupling strength

- It couples to baryon $(U(1)_B)$ or neutron number $(U(1)_{B-L})$

- DP is a DM candidate, with relics abundance produced by e.g. the misalignment mechanism (Nelson & Scholz, PRD 84, 103501 (2011))

- For the DP masses we are considering, and given a local DM density $\rho_{\mathrm{DM}} \approx 0.4\ GeV/cm^3$, the resulting occupation number is $O(10^{54})$

The DP field can be described as a superposition of plane waves

$$\vec{A}(\vec{x}) = \sum_i A_i \ \cos(2\pi f_i t - \vec{k}_i \cdot \vec{x} + \phi_i)$$

Frequency spread due to the Maxwell-Boltzman velocity distribution of DPs:

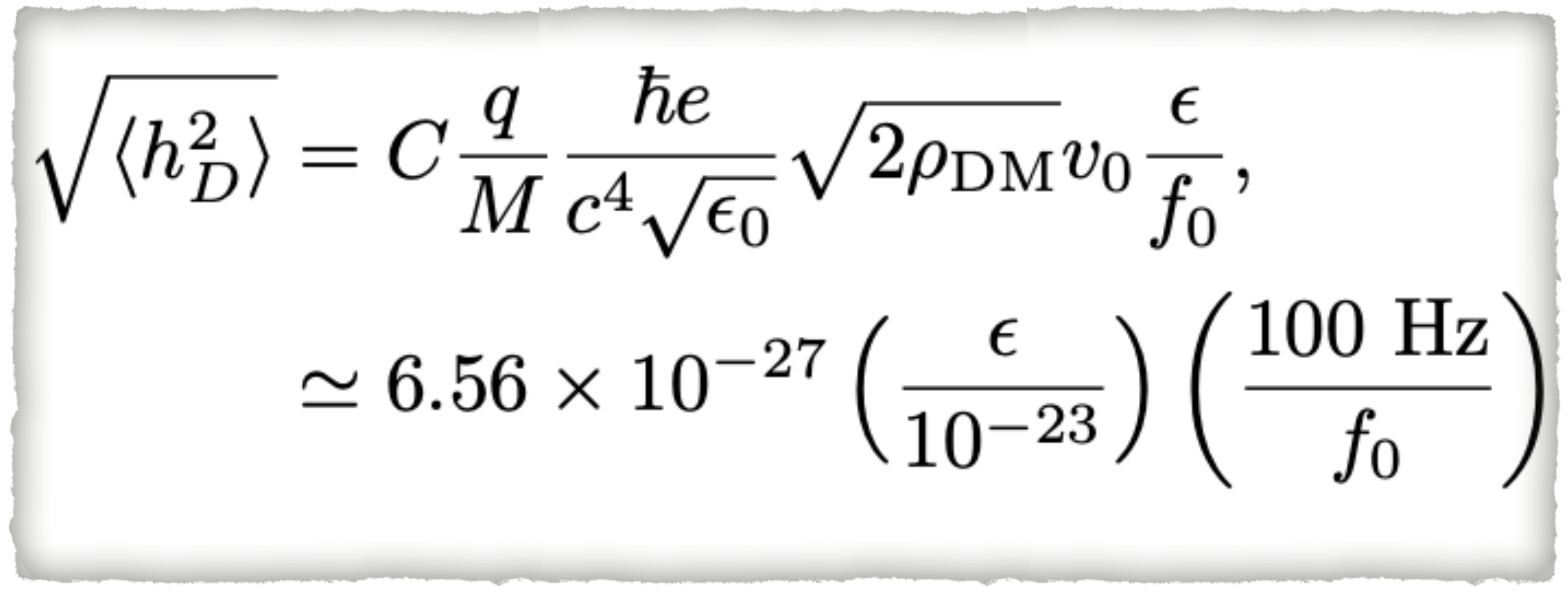
$$\Delta f = \frac{1}{2}\left(\frac{v_0}{c}\right)^2 f_0 \approx 2.94 \times 10^{-7} f_0$$

$$f_0 = \frac{m_A c^2}{2\pi\hbar}$$

- ◉ DP coupling to the protons/neutrons of the detector mirrors induces a differential strain with two components:

➡ Differential strain due to the spatial gradient of the DP field

Pierce et al. 2018, PRL 121, 061102



$$\begin{aligned}\sqrt{\langle h_D^2\rangle} &= C\frac{q}{M}\frac{\hbar e}{c^4\sqrt{\epsilon_0}}\sqrt{2\rho_{\mathrm{DM}}}v_0\frac{\epsilon}{f_0},\\ &\simeq 6.56\times 10^{-27}\left(\frac{\epsilon}{10^{-23}}\right)\left(\frac{100\ \mathrm{Hz}}{f_0}\right)\end{aligned}$$

q : Number of protons + neutrons (or of neutrons) in each mirror

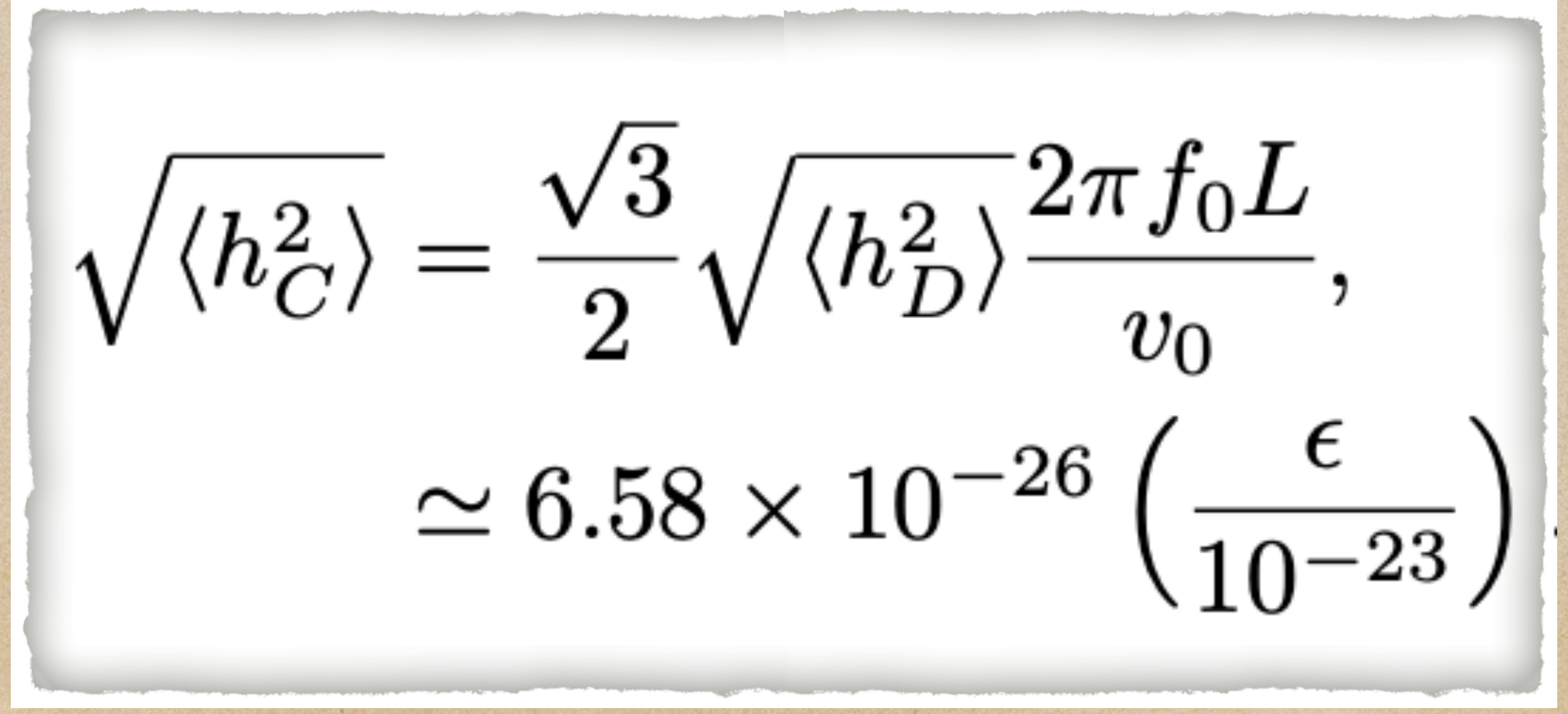
M : Mirror mass

$C = \sqrt{2}/3$: geometrical factor

ϵ : coupling constant

➡ Equivalent differential strain due to finite speed of light in detector arms

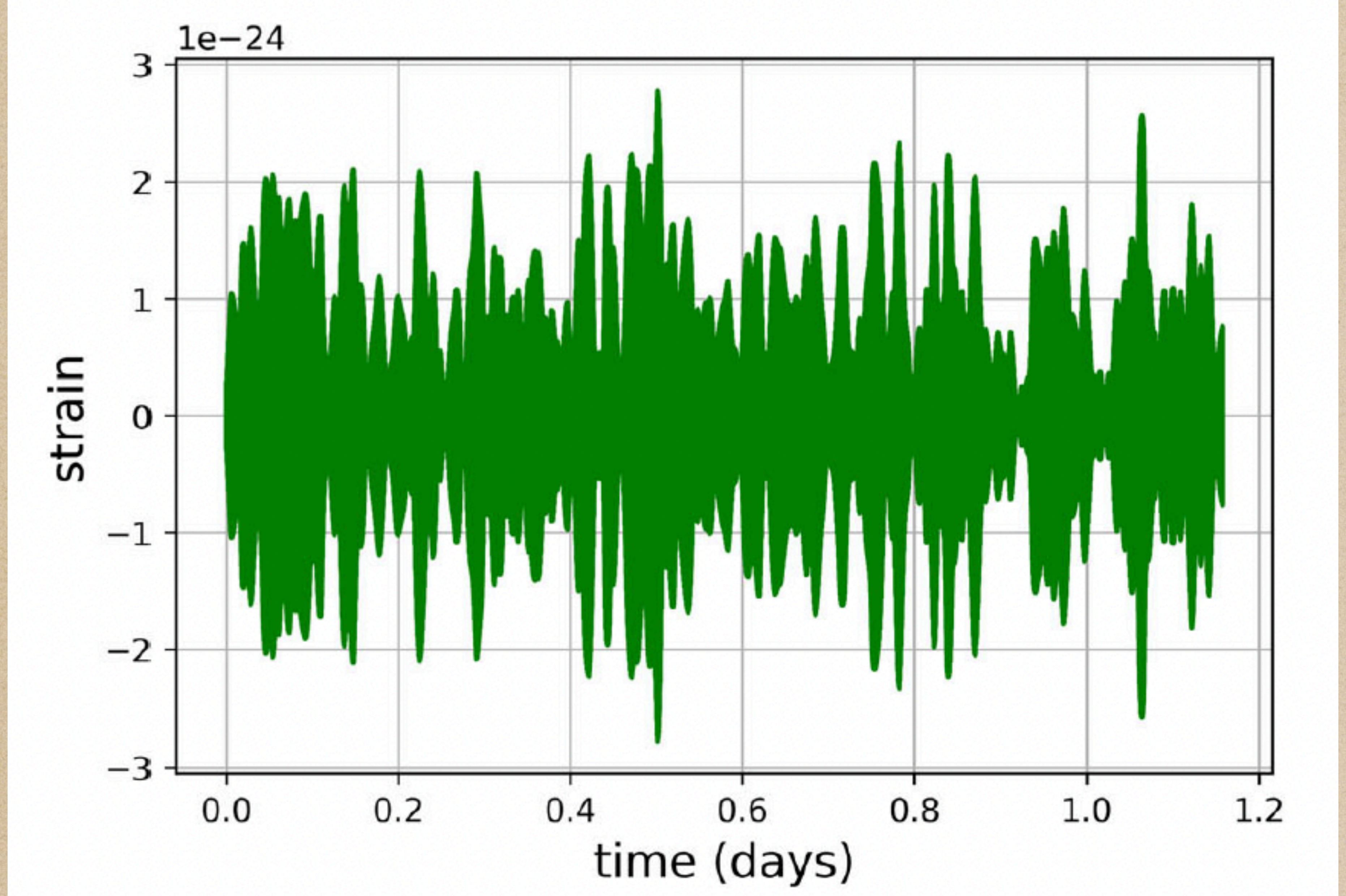
Morisaki et al. 2021, PRD 103, L051702

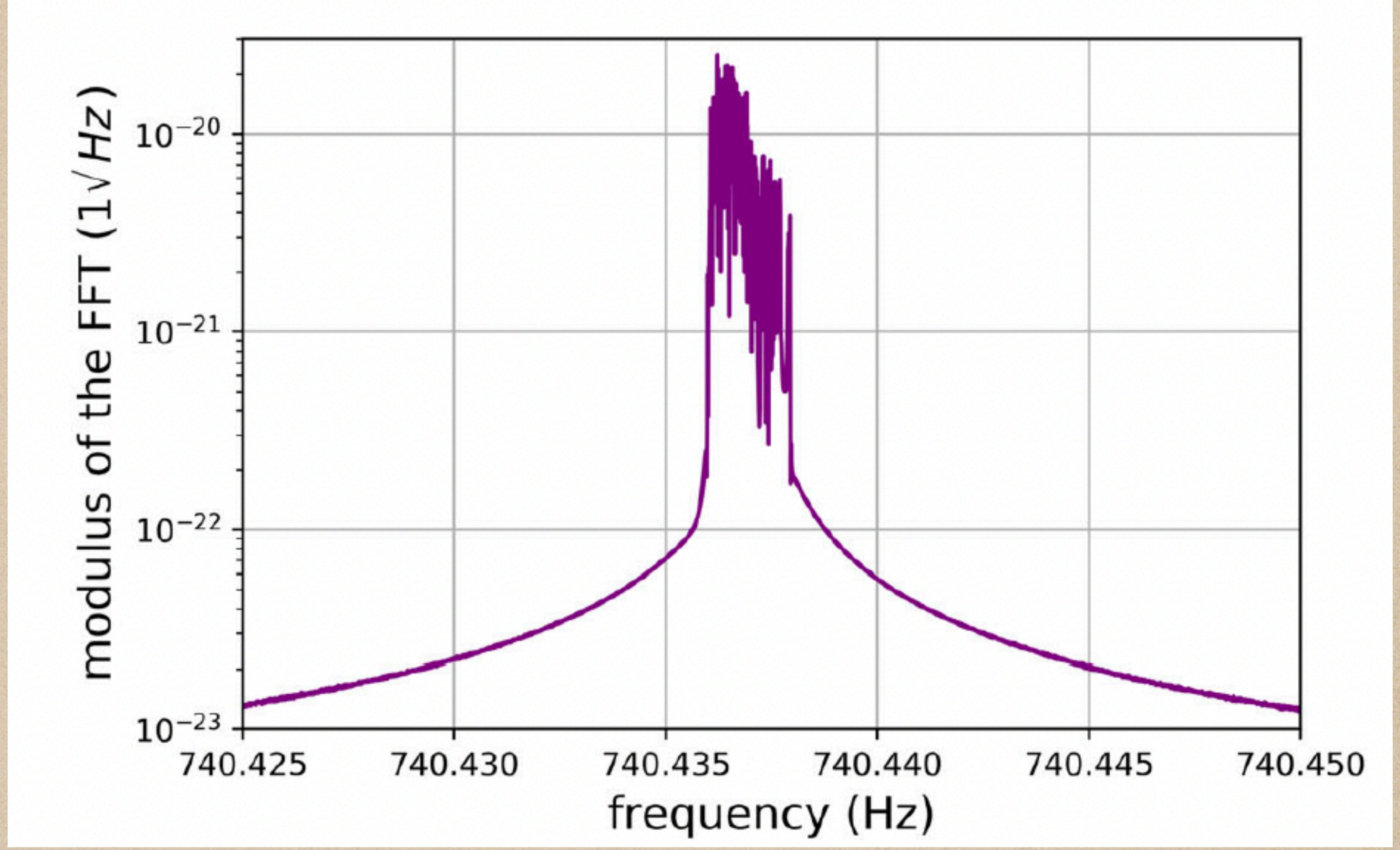


$$\begin{aligned}\sqrt{\langle h_C^2\rangle} &= \frac{\sqrt{3}}{2}\sqrt{\langle h_D^2\rangle}\frac{2\pi f_0 L}{v_0},\\ &\simeq 6.58\times 10^{-26}\left(\frac{\epsilon}{10^{-23}}\right).\end{aligned}$$

L : Detector arm length

An example of DP simulated signal





(Miller et al. 2021, Phys. Rev. D 103.103002)

- Stochastic and narrow-band signal
- It can be searched into the detector data with techniques adapted from those used in the search of “traditional” GW signals (like Continuous Waves and Stochastic Backgrounds)

Analysis methods

- Most recent analysis carried on LIGO-Virgo O3 data, using two different analysis methods:
  - ➡ Cross-correlation (Pierce et al. 2018, Phys. Rev. Lett. 121, 061102)
  - ➡ Excess power (Miller et al. 2021, Phys. Rev. D 103.103002)
- In both methods data are divided in segments of given duration, which are individually processed using Fourier transforms and properly combined in order to compute a detection statistic
- No detection, but competitive upper limits are computed

Cross-correlation search

Signal strength:

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

Fourier transform coefficients

(j: frequency bin index; i: FFT index)

Noise power

Variance:

$$\sigma_j^2 = \frac{1}{N_{\mathrm{FFT}}} \left\langle \frac{1}{2 P_{1,ij} P_{2,ij}} \right\rangle_{N_{\mathrm{FFT}}}$$

Fixed segment length: 1800 seconds

Detection statistic:

$$\mathrm{SNR}_j = \frac{S_j}{\sigma_j}.$$

- ◉ Removal of noise artefacts (background estimation based on the computation of frequency lags)
- ◉ Selection of significant outliers

Excess power search

- Based on the so-called “Band Sampled Data” framework, widely used in Continuous Waves searches (e.g. from spinning asymmetric neutron stars)

- Time/frequency maps (over 10-Hz bands) are built, with an optimal choice of the segment length
  ➡ Frequency dependent, such that signal power is confined in a frequency bin

- Maps are projected on the frequency axis and a number of the most significant outliers are selected (D’Antonio et al. 2018 Phys. Rev. D 98, 103017)

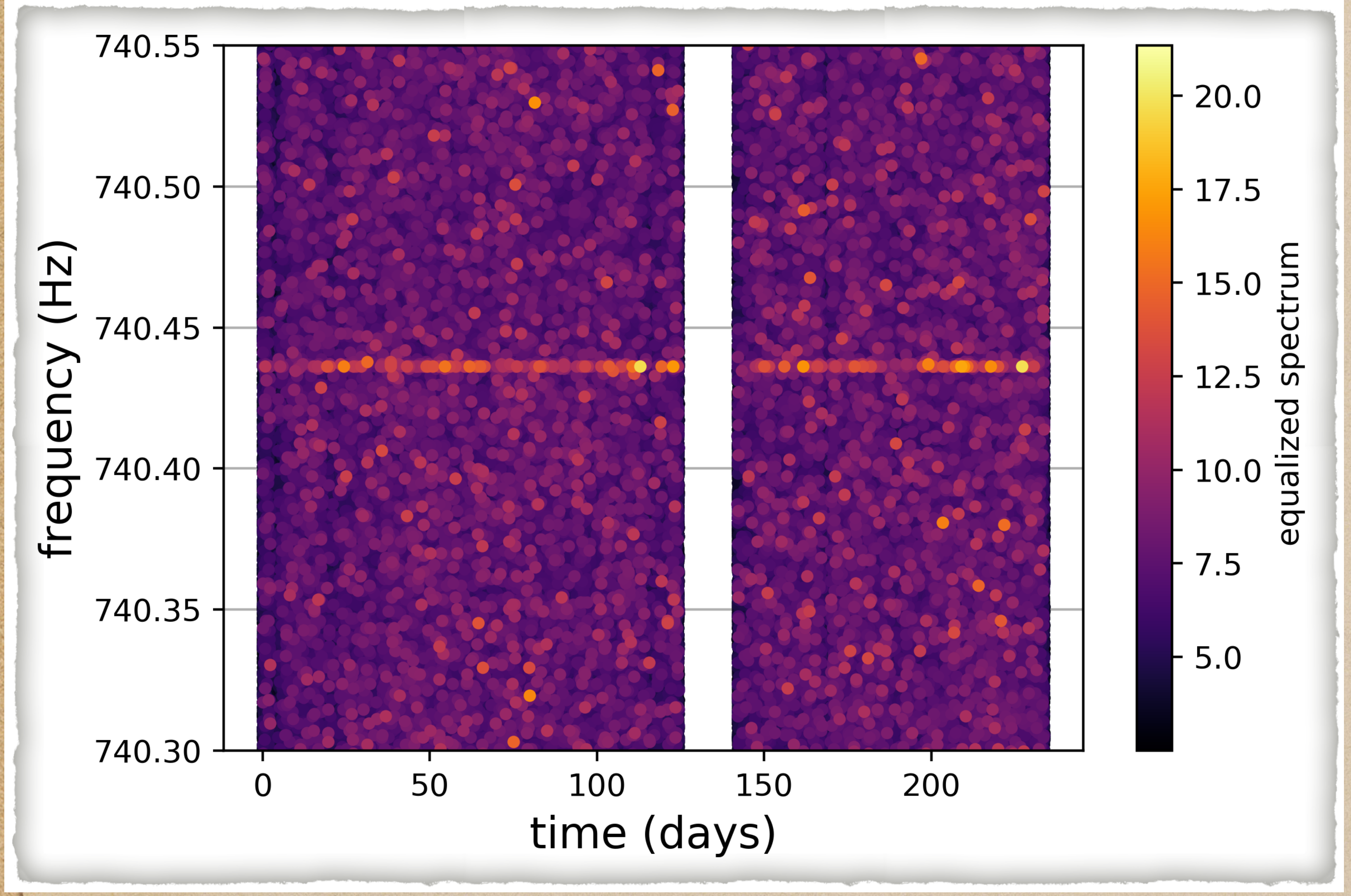
- Coincidences among outliers found in different detectors

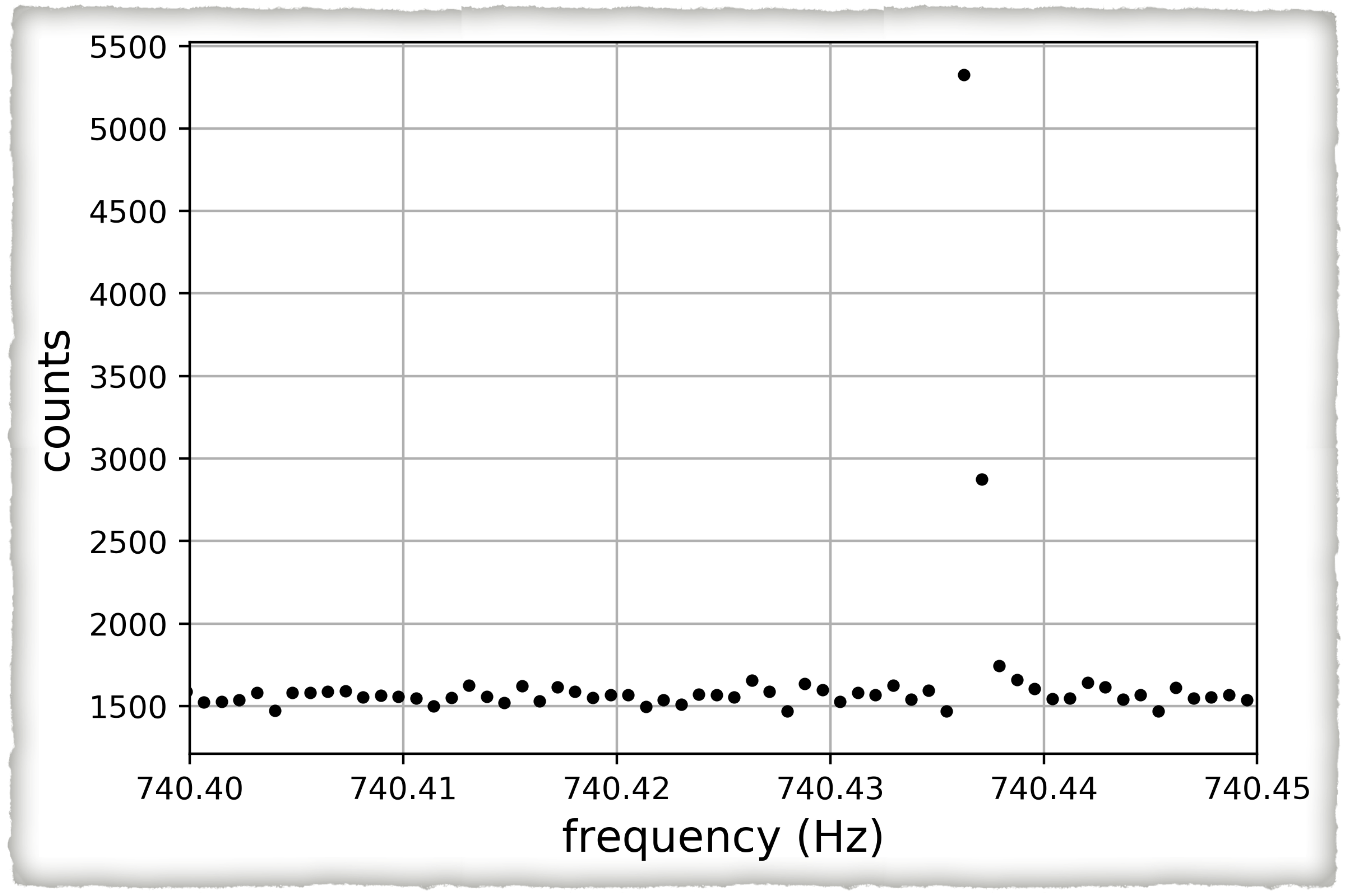
Detection statistic:

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

y: map projection in a given frequency bin
μ: mean value of the map projection
σ: standard deviation of the map

Simulated signal in Livingston detector O2 data



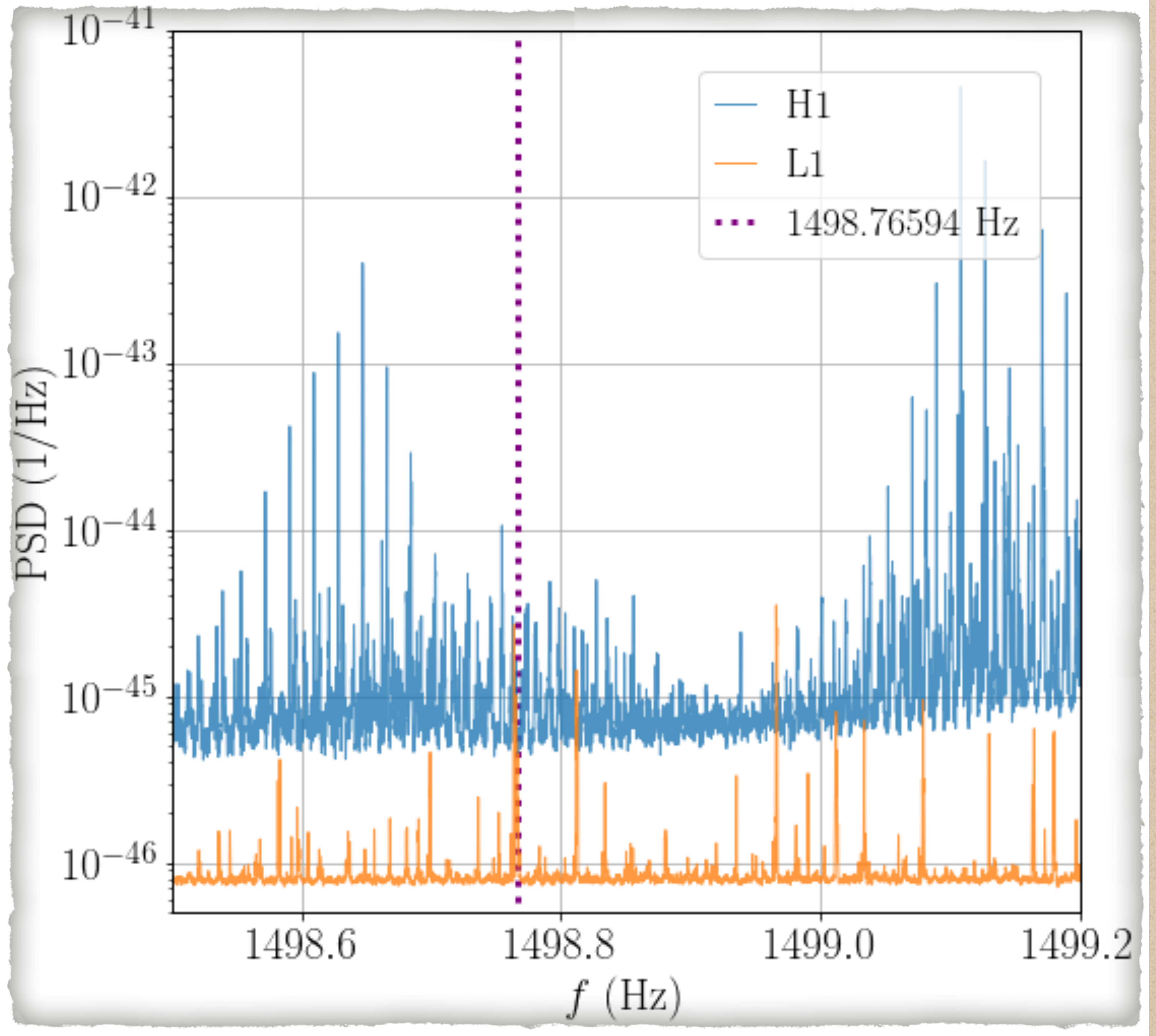


O3 results

- Cross-correlation search
  - ➡ no outliers with $\mathrm{Re(SNR)} < -5.8$ (threshold corresponding to 1% false alarm probability, after taking into account the trial factor)
  - ➡ Number of sub-threshold outliers with $|\mathrm{Re(SNR)}|$ or $|\mathrm{Im(SNR)}|$ in the range [5,5.8] consistent with Gaussian noise expectation

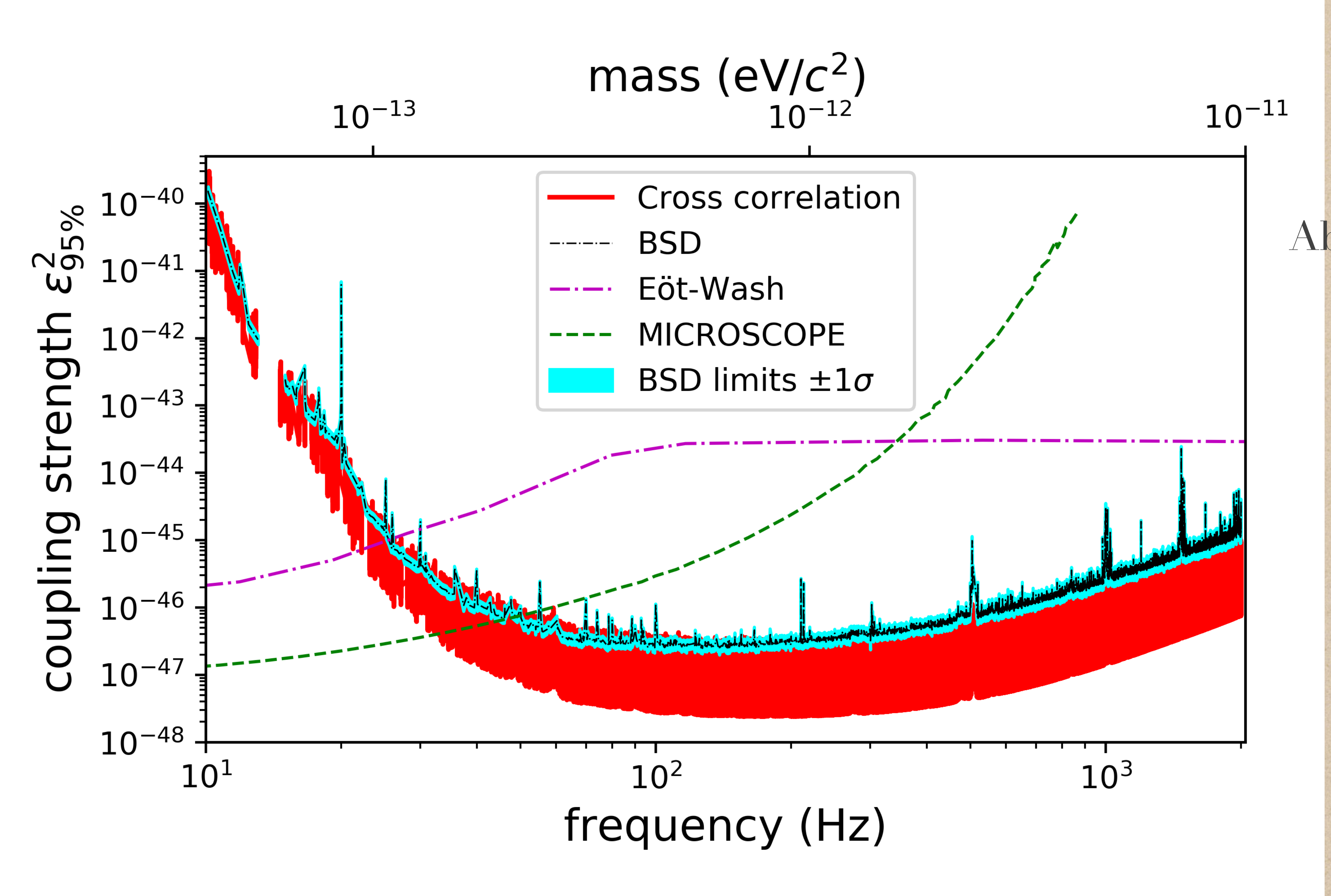
- Excess power search: 11 coincident outliers among the three baselines (HL, HV, LV), all found to be due to noise disturbances
  - ➡ Vetoed by computing higher resolution spectra, which revealed noise artefacts

PSD around one outlier, in a frequency region affected by large noise line combs



Upper limits on the coupling strength

- Both common and differential mode taken into account in the computation



Abbott et al. (LVK) 2021: arXiv 2105.13085

- Improvement of two order of magnitude w.r.t. direct search experiments, assuming $U(1)_B$

- For $U(1)_{B-L}$ upper limits are comparable to direct search experiments

Other searches

- Other searches for ultra-light fields interacting with GW detectors have been carried or proposed. For example:

- ➡ Search for *scalar* field Dark Matter in GEO detector (exploiting change in the refraction index of the beam-splitter (Vermeulen et al. 2021, arXiv:2103.03783)

- ➡ Proposed search for vector Dark Matter in Kagra detector (exploiting difference in the material of mirrors) (Michimura et al. 2021, PRD 102, 102001)

Conclusions

- Gravitational-wave detectors are promising tools for particle physics
- In particular, they allow to probe or constrain ultra-light Dark Matter fields
- Already able to produce competitive constraints w.r.t. other direct search experiments
- Future LIGO-Virgo-Kagra runs and detectors (ET, LISA, DECIGO, TianQin) will allow to set stricter constraints and to probe different mass ranges