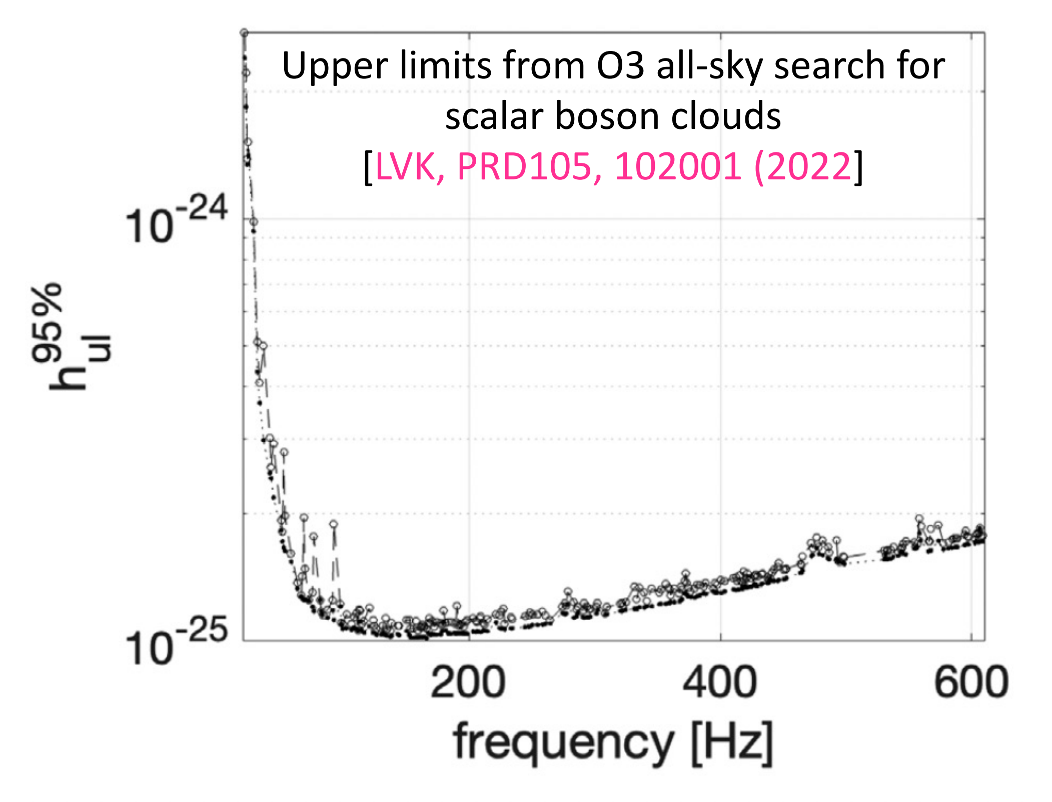
Ultralight bosons and gravitational waves: observations

Cristiano Palomba – INFN Roma



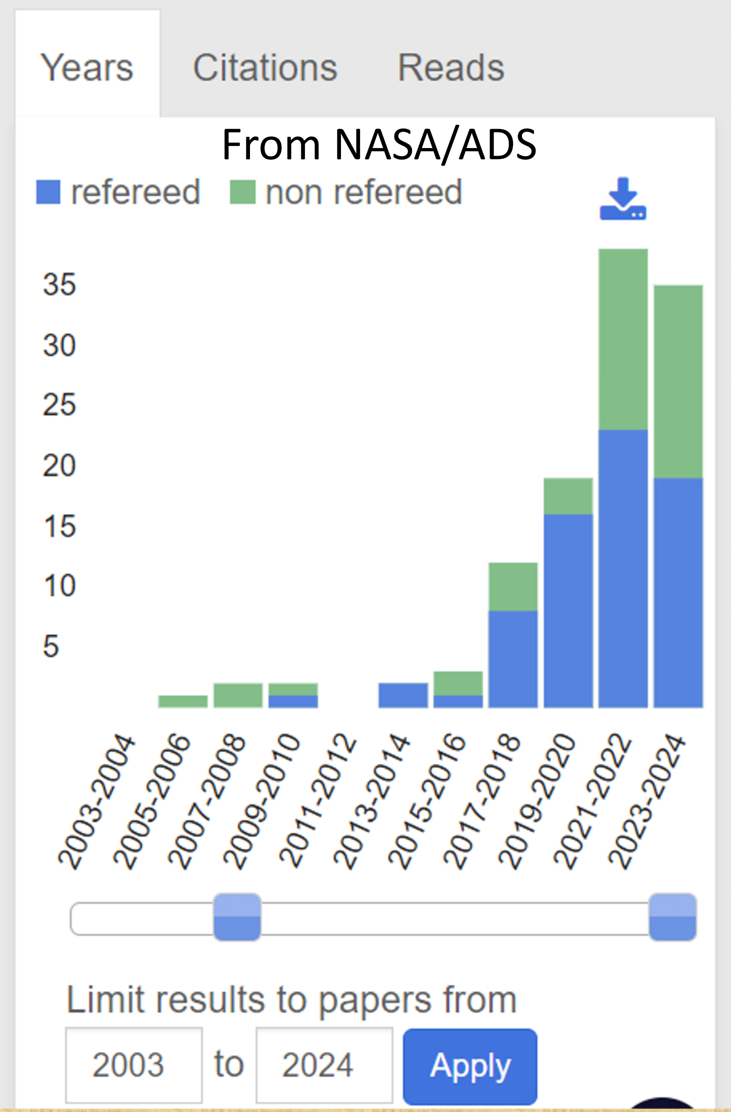
DCC: G240031

Rome, February 12-16 2024

[JENAS Initiative "Gravitational Wave Probes of Fundamental Physics"](#)

Disclaimer!

- Since a few years, tens of papers are published every year on "ultralight dark matter & gravitational wave detectors"
- I will (rather arbitrarily) choose a few examples, focusing on analyses of actual detector data
- I will not discuss in detail the great potentialities of third generation GW detectors (ET, LISA,...)
- Forgive me for not citing your preferred papers....

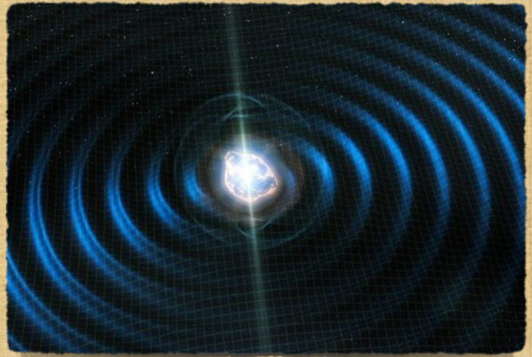


Classical source classification (from the data analysis point of view)

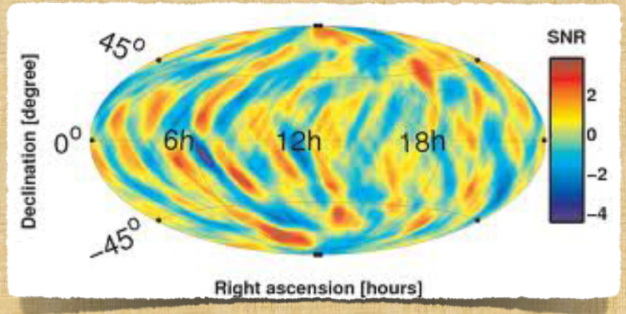
Coalescing compact binaries (black holes, neutron stars)

Supernova explosions

CW (e.g. spinning neutron stars)



Stochastic background (Astrophysical, Cosmological)



Transient signals

Persistent signals

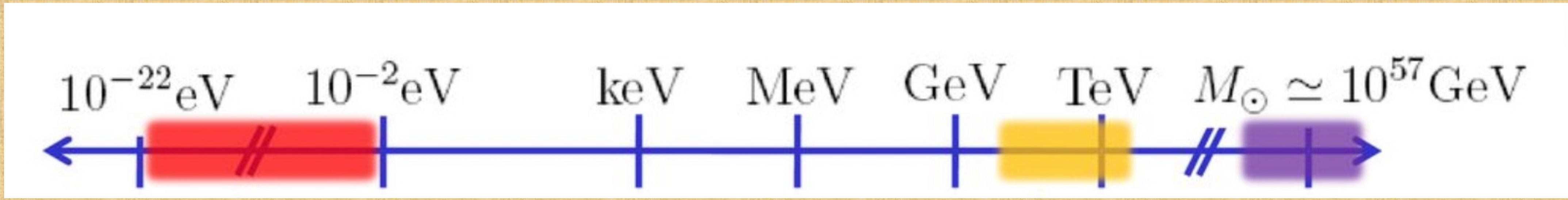
Different techniques are used in different cases, keeping in mind the three cornerstones of data analysis:

- Sensitivity: try to detect signals as small as possible
- Robustness: w.r.t. waveform uncertainties and instrumental noise
- Computational efficiency: many analyses are computationally bound

Signatures of DM in gravitational wave detectors

- In recent years a growing body of literature on the potentiality of GW detectors as tools to probe DM has been produced [see e.g. Bertone et al., arxiv 1907.10610]

- DM candidates cover ~90 orders of magnitude in mass



Ultralight particles

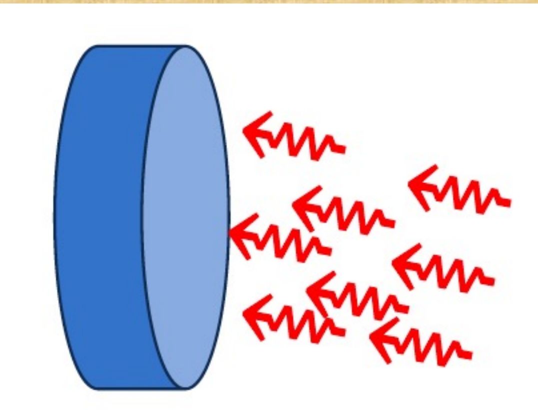
"Classical" DM candidates

Black holes

GW detectors offer an ``opportunity window" for free

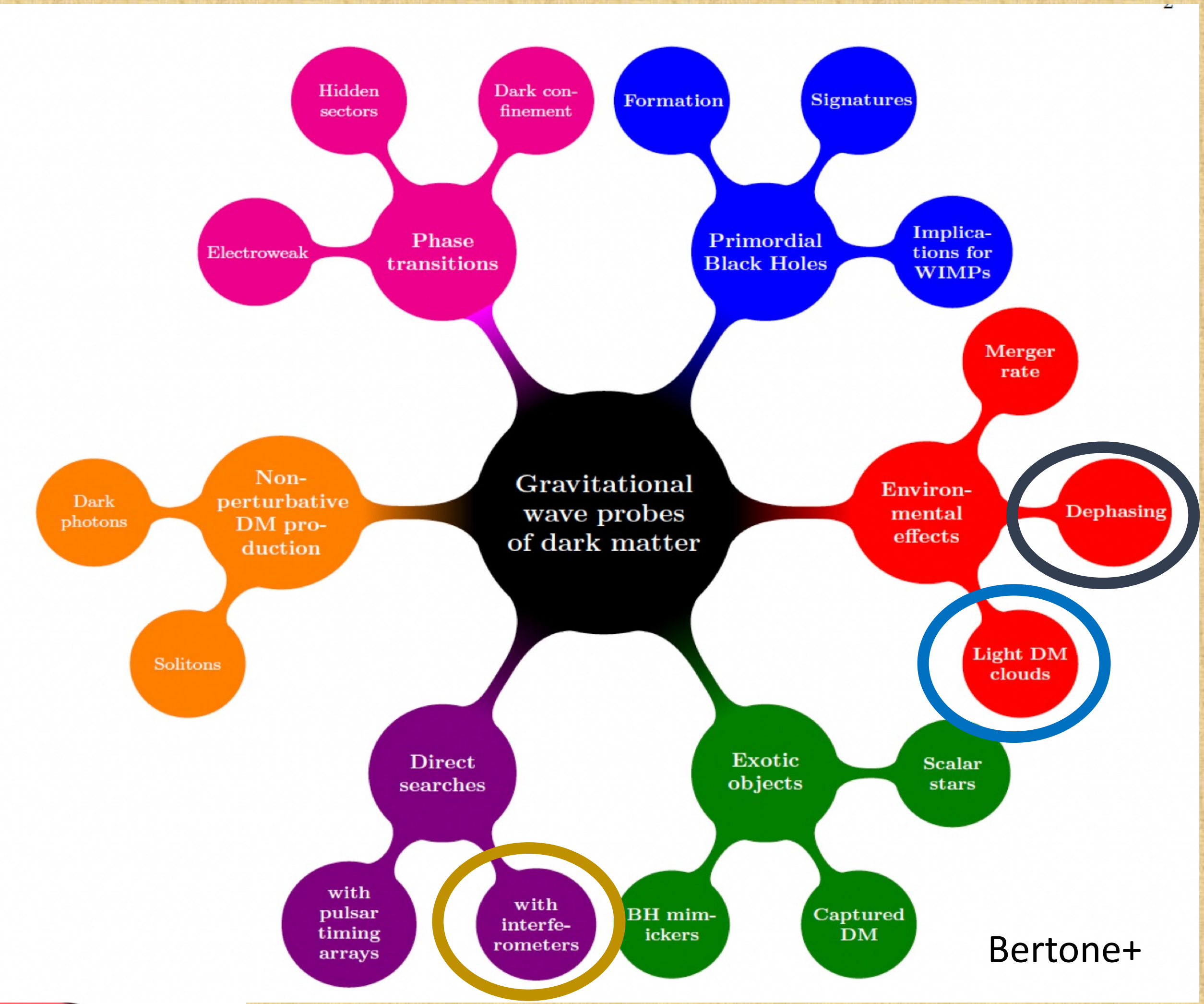
In many cases GW data analysis methods can be directly applied or adapted in a straightforward way to the search of DM fingerprints in GW data

Direct interaction of ultra-light DM (10^{-14} – 10^{-11} eV) with detector optics



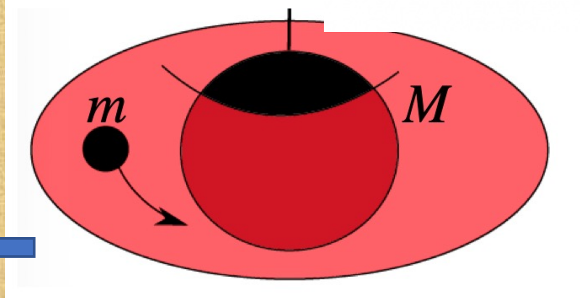
GW emission from boson clouds around spinning BHs (10^{-14} – 10^{-11} eV)

Credit: Ana Sousa Carvalho



Bertone+

See talks by P. Cole and V. Desjacques on Thursday



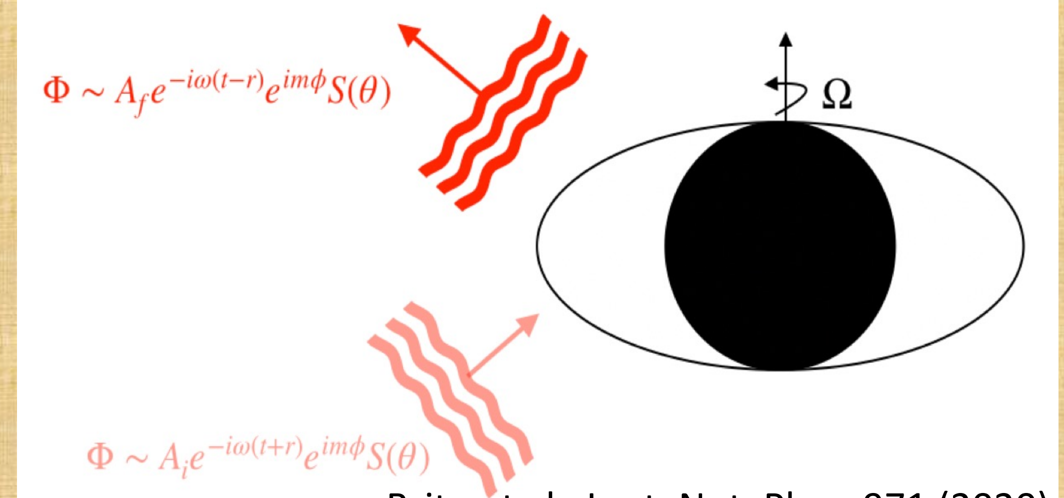
Credit: O. Hannuksela

Impact of DM on binary dynamics

[Baumann et al., PRD99, 044001 (2019); Hannuksela et al. Nature Astron. 3 447 (2019); Xue, Huang, Science China Physics, Mechanics & Astronomy, 67 210411 (2024)]

Ultra-light boson clouds around spinning BHs [Arvanitaki et al., PRD81, 123530 (2010)]

- Massive bosonic fields around a Kerr BH are amplified, due to supperradiance instability, at the expense of the BH rotational energy



Brito et al., Lect. Not. Phys. 971 (2020)

Superradiance condition: $\omega < m\Omega$

- ω: field angular frequency
- m: azimuthal quantum number
- Ω: BH angular frequency at the outer horizon

- A macroscopic boson condensate forms around the BH

- Once formed, the cloud dissipates through the emission of CWs (emission time scale >> instability time scale)

$$h_0 \approx 6 \times 10^{-24} \left(\frac{M_{\rm BH}}{10\ M_\odot}\right) \left(\frac{\alpha}{0.1}\right)^7 \left(\frac{1\ \rm kpc}{D}\right) (\chi_i - \chi_c)$$

$$\alpha = \frac{G M_{\rm BH}}{c^3} \frac{m_b}{\hbar}$$

for scalar bosons, and α << 1

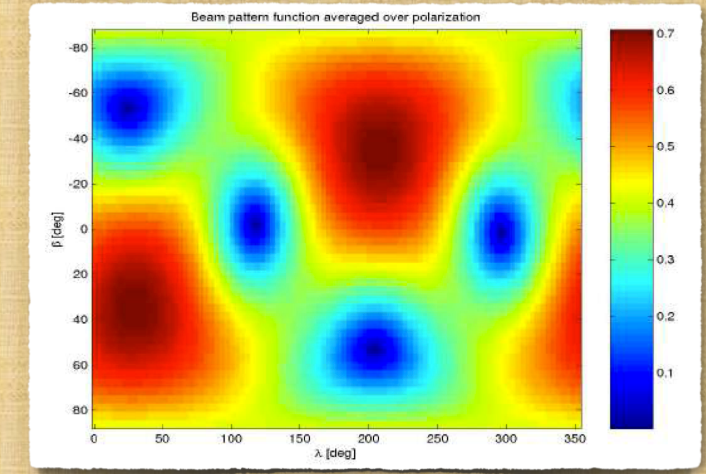
$$f_{\rm gw} \simeq 483\ \mathrm{Hz} \left(\frac{m_{\rm b}}{10^{-12}\ \mathrm{eV}}\right) \times \left[1 - 7 \times 10^{-4} \left(\frac{M_{\rm BH}}{10\ M_\odot} \frac{m_{\rm b}}{10^{-12}\ \mathrm{eV}}\right)^2\right]$$

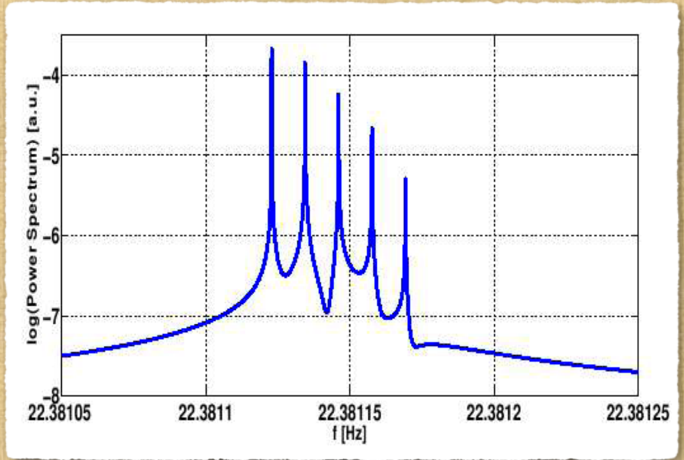
- Signal at the detector affected by various effects

$$f(t) = f_0\left(1 + \frac{\vec{\mathbf{v}} \cdot \hat{n}}{c}\right), \quad \vec{\mathbf{v}} = \vec{\mathbf{v}}_{rev} + \vec{\mathbf{v}}_{rot}$$

Doppler effect, which depends on frequency and source position

Amplitude modulation (for signal longer than ~ 1 sidereal day)



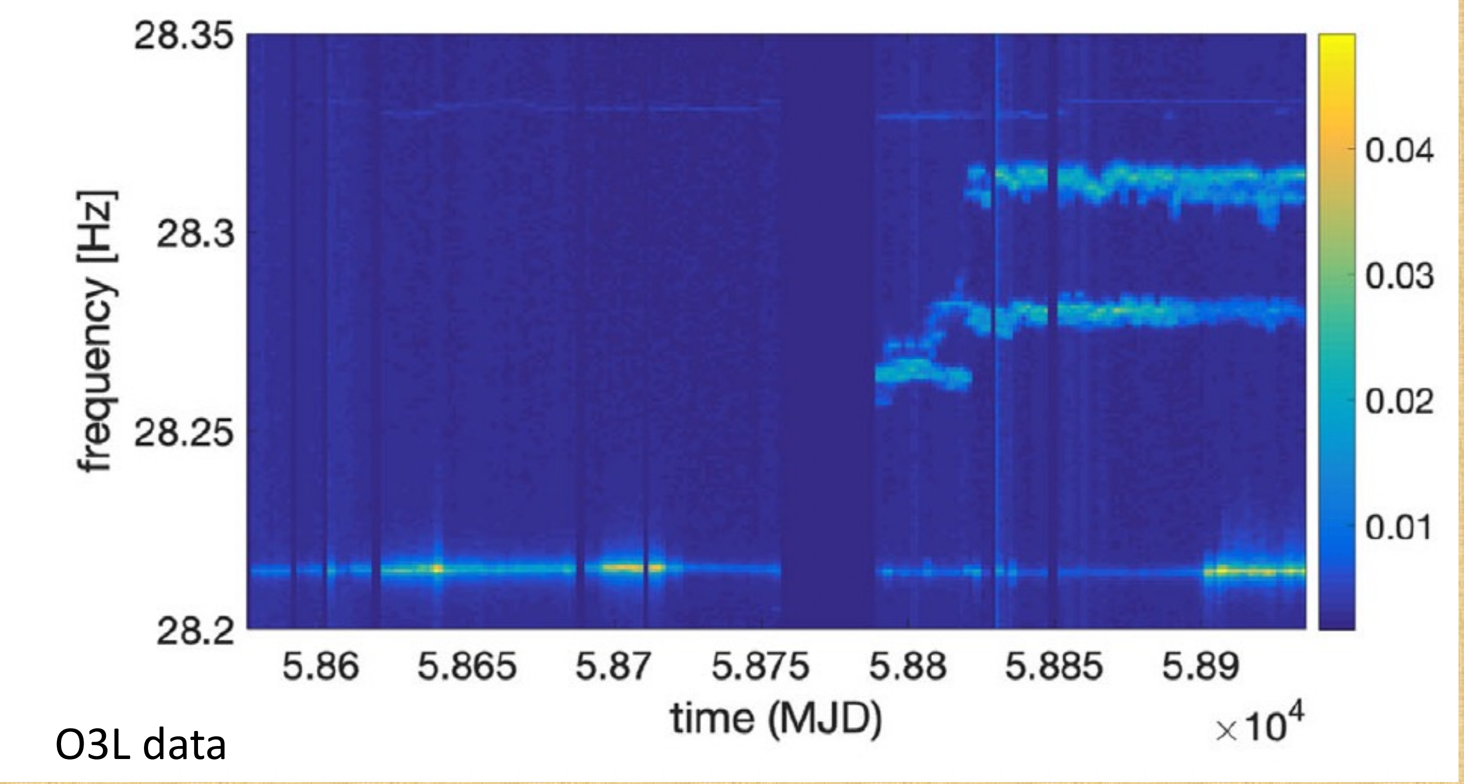


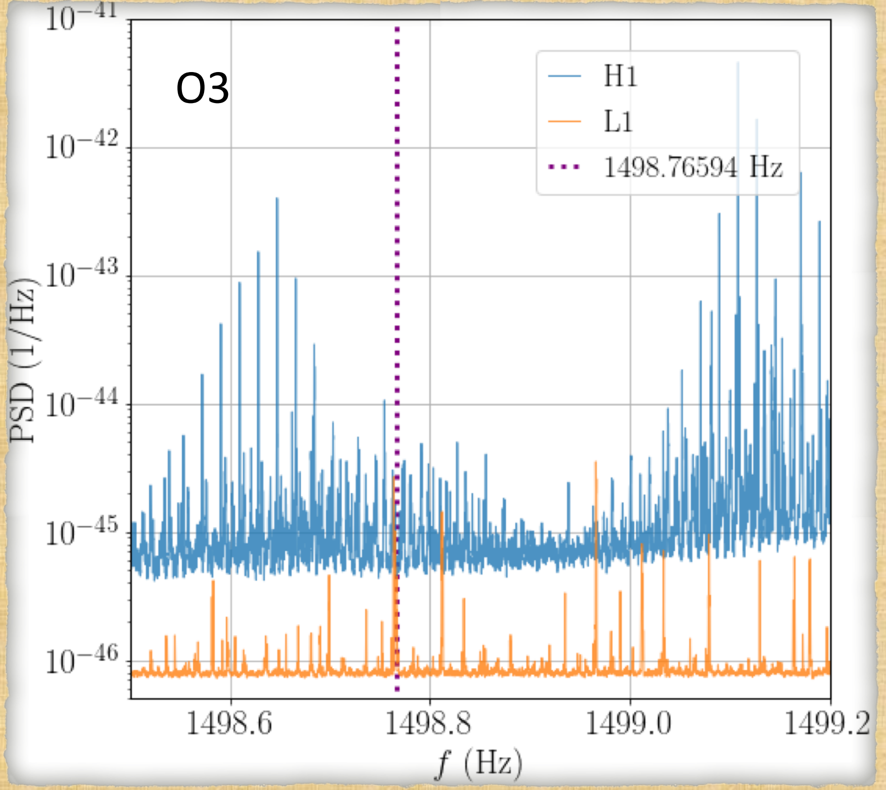
$$\Delta_E \simeq \frac{1}{c^2}\int_{t_0}^{t}\left(U_\oplus + \frac{v_\oplus^2}{2}\right) dt'$$

Relativistic effects

- **Signal processing aims at removing such effects in order to collect all the signal power in a single bin**

Real data are full of weird stuff!

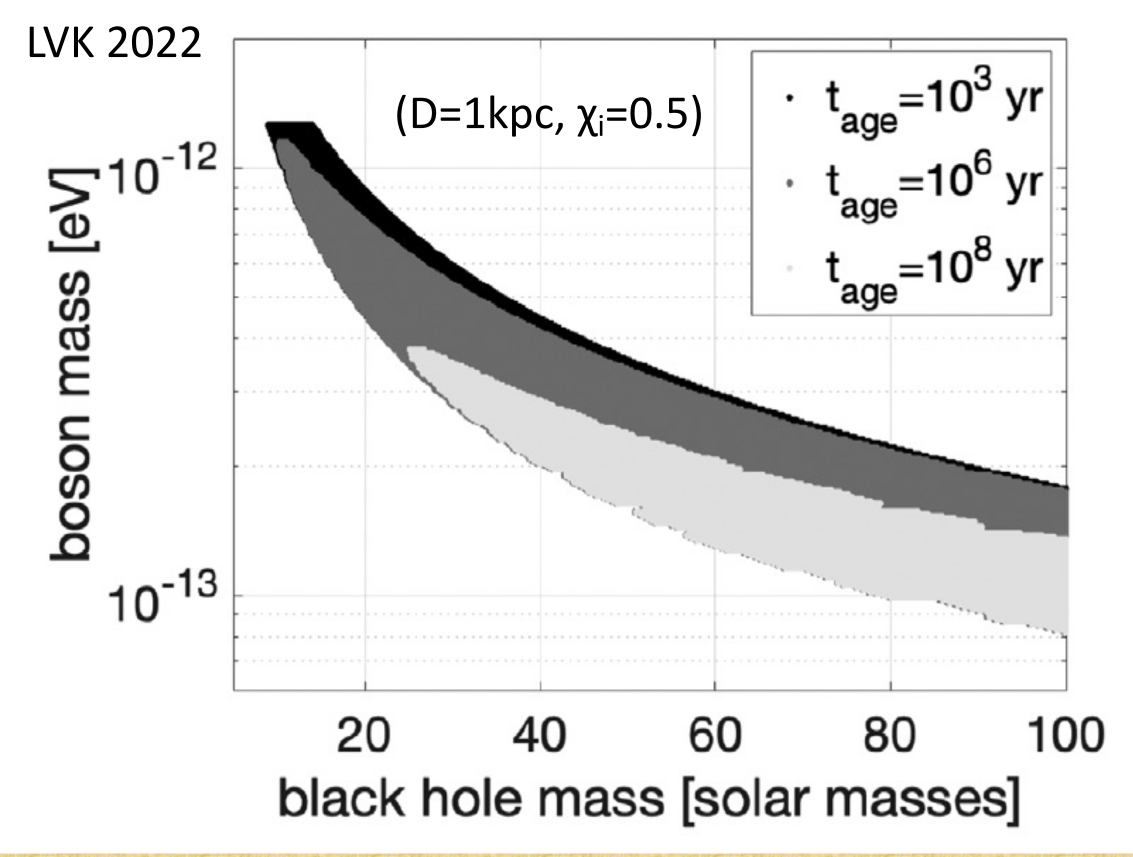




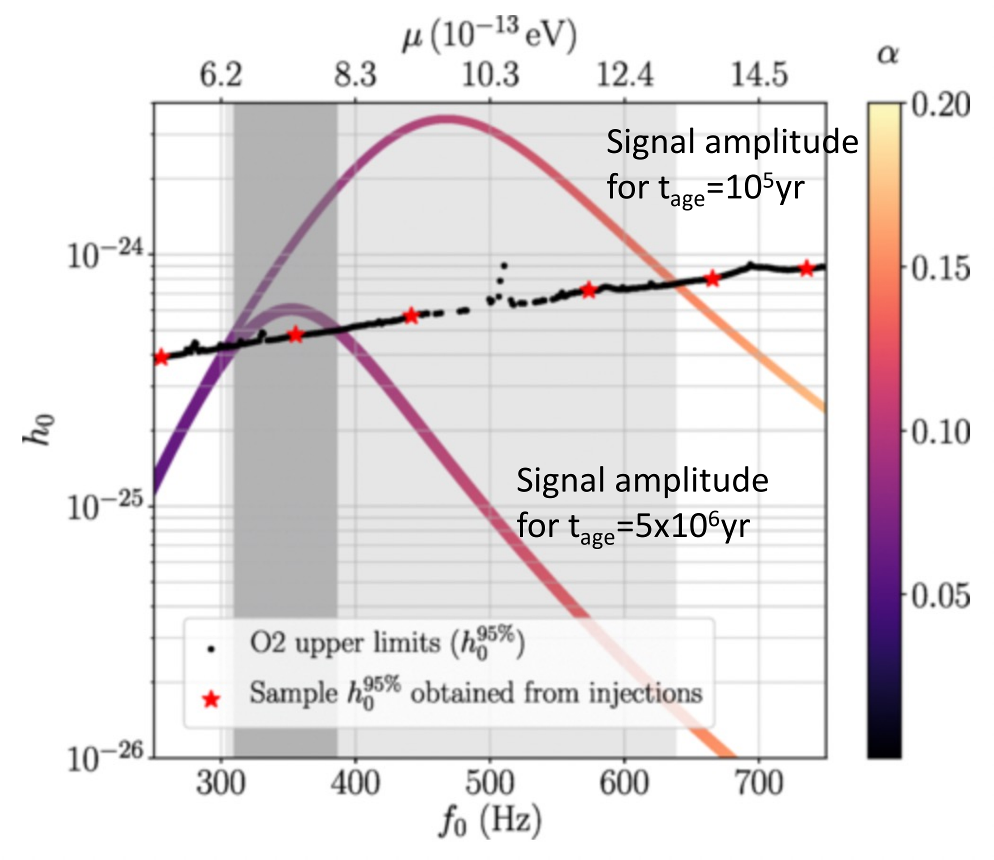
- Discrimination among real astrophysical signals and instrumental noise is an important part of the analysis: coincidences, vetos, follow-up analysis, interaction with detector experts,…

Searches for CW from boson clouds

Scalar bosons: Exclusion regions from all-sky O3 search



Scalar bosons: Search targeting Cyg X-1 in O2 [Sun+ 2020]



- All-sky searches

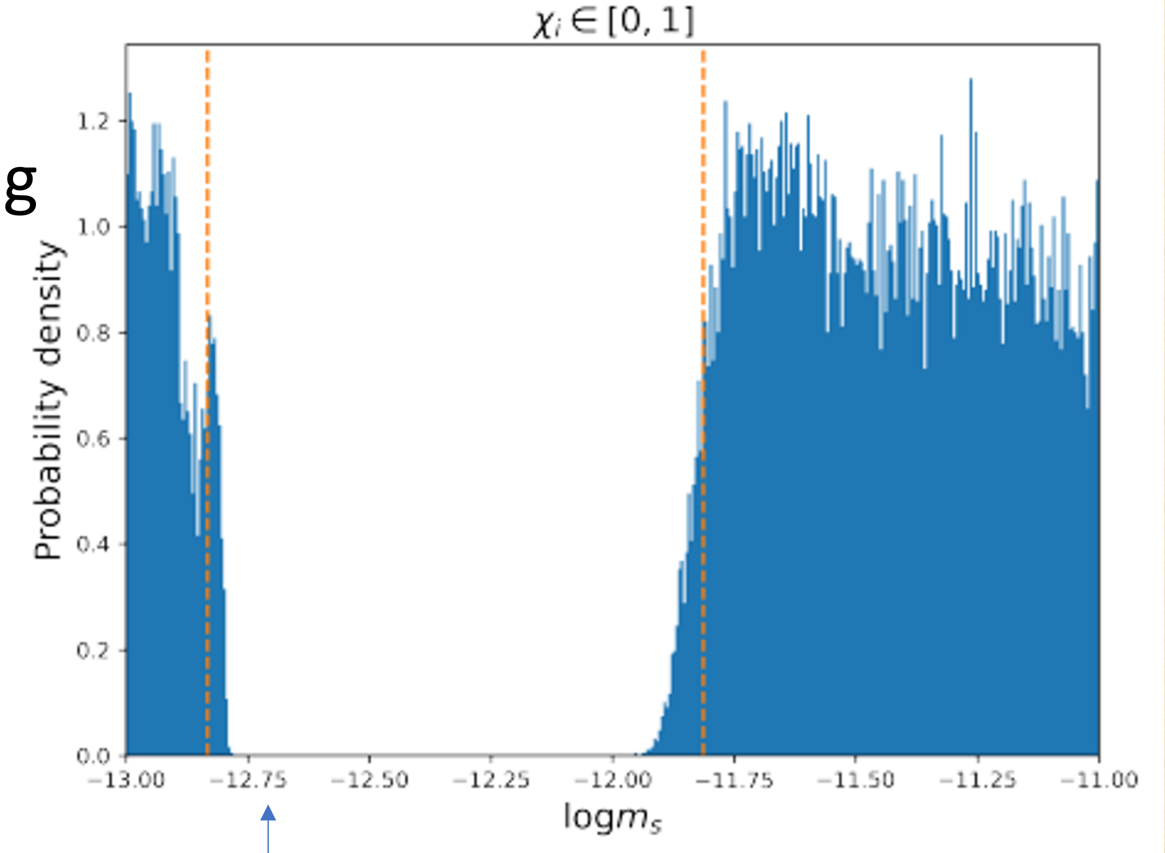
  [D'Antonio, CP et al., PRD98, 103017 (2018);
  CP, DAntonio, Astone et al., PRL123, 171101 (2019);
  LVK, PRD105, 102001 (2022)]

- Directed searches [Isi et al., PRD99, 084042 (2019);
  Sun et al., PRD101, 063020 (2020);
  Zhu, Baryakhtar et al., PRD102, 063020 (2020);
  LVK, PRD106, 042003 (2022); J
  Jones et al., PRD108, 064001 (2023)
  D'Antonio, CP, et al., PRD108, 122001 (2023)]

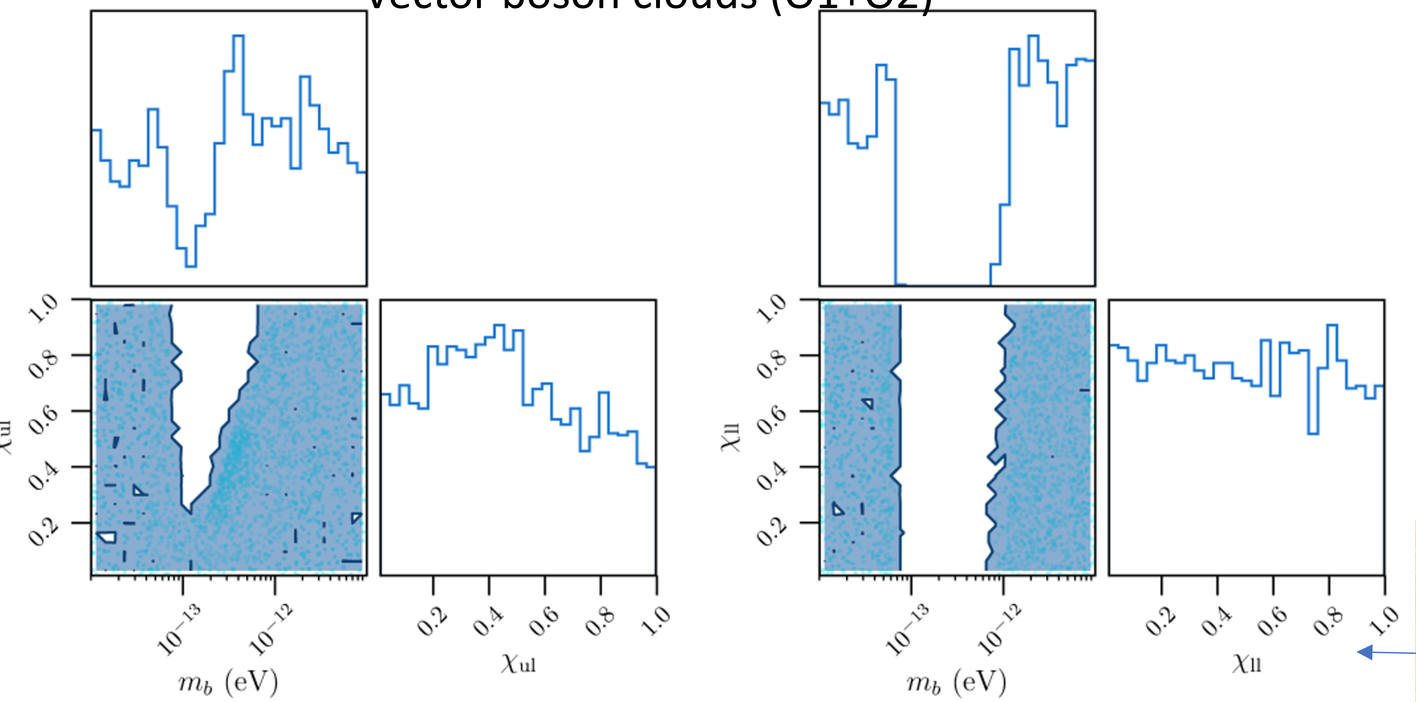
Search for stochastic background from boson clouds

- Stochastic background produced by the superposition of all scalar/vector boson cloud signals
- Assume uniform BH spin distribution
- Some mass intervals penalized (depending on the spin distribution)

Scalar boson clouds (O1+O2+O3)



Vector boson clouds (O1+O2)



[Yuan et al., PRD106, 023020 (2022)]

[Tsukada, Brito et al., PRD103, 082005 (2021)]

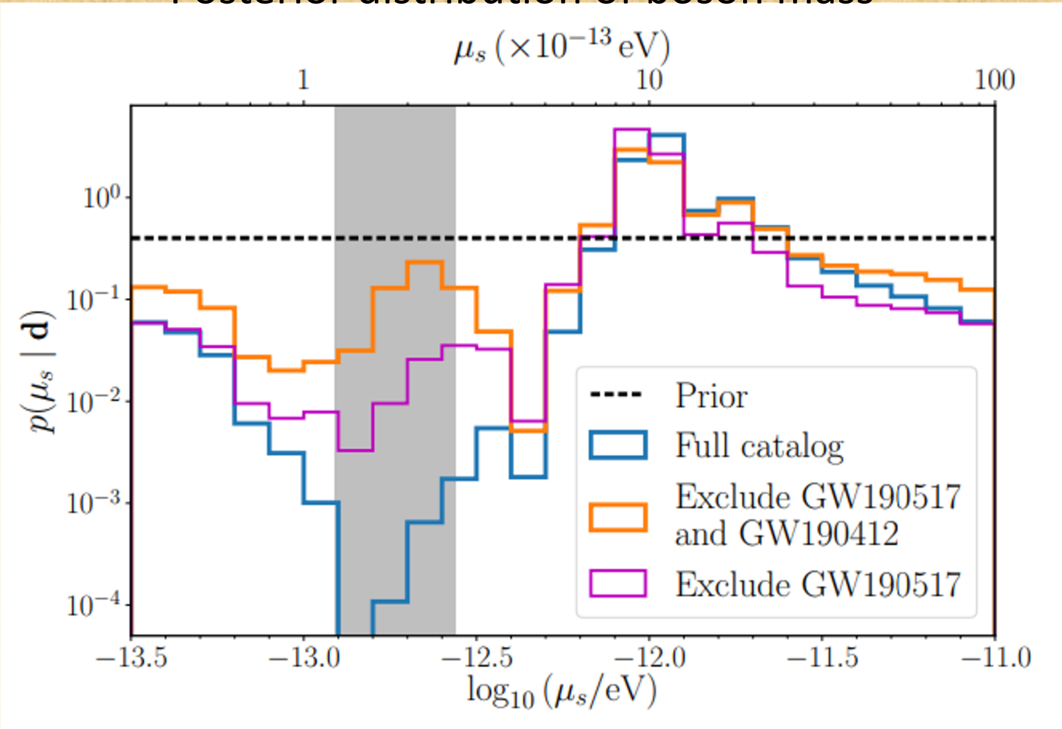
Constraints from BH spin distributions [Ng et al., PRL126, 151102 (2021)]

- Superradiance instability should limit the spin of BHs [Arvanitaki & Dubovski, PRD83, 044026 (2011), Brito et al., PRD96, 064050 (2017),….]

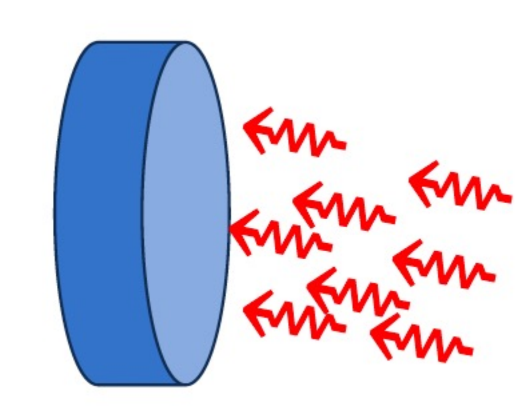
- Bayesian analysis carried using BHs from GWTC-2

- Range 1.3E-13 – 2.7E-13 eV penalized

Posterior distribution of boson mass



DM direct interactions



- 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: $f_0 = \frac{m_A c^2}{h} \rightarrow 10^{-14} - 10^{-11} eV$ for Earth-bound detectors

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

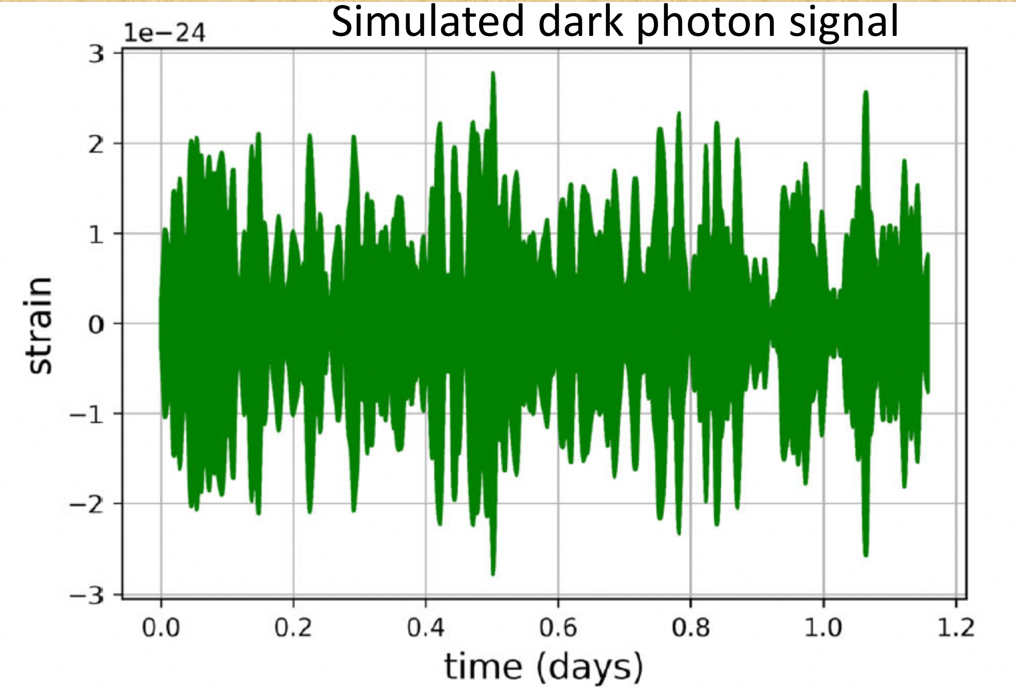
Vermeulen et al. 2021, arXiv:2103.03783

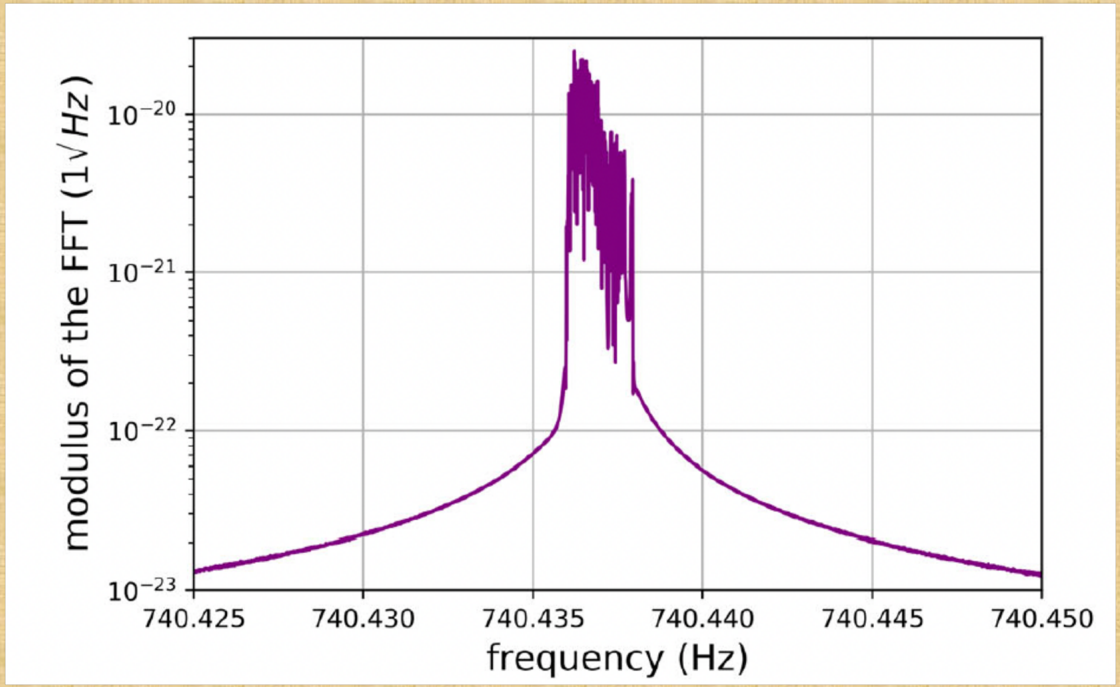
- The ultra-light DM field couples to the fields of the SM
  → Interaction terms in the SM Lagrangian → Coupling constants

- Superposition of plane waves → stochastic signal

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

- Maxwell-Boltzmann velocity distribution → narrow-band signal





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

- Such signals can be searched in detector data adapting techniques used for stochastic/continuous wave searches

- Typical analyses based on:
  - ➢ Cross-correlation [Pierce et al., PRL121, 061121 (2018)]
  - ➢ Excess power [Miller et al., PRD103, 102002 (2021), Vermeulen et al 2103.03783]

- In both methods data are divided in segments of given duration, individually processed using Fourier transforms, and then combined in order to compute a detection statistic

Cross-correlation

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

Fourier transform coefficients

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

Noise power

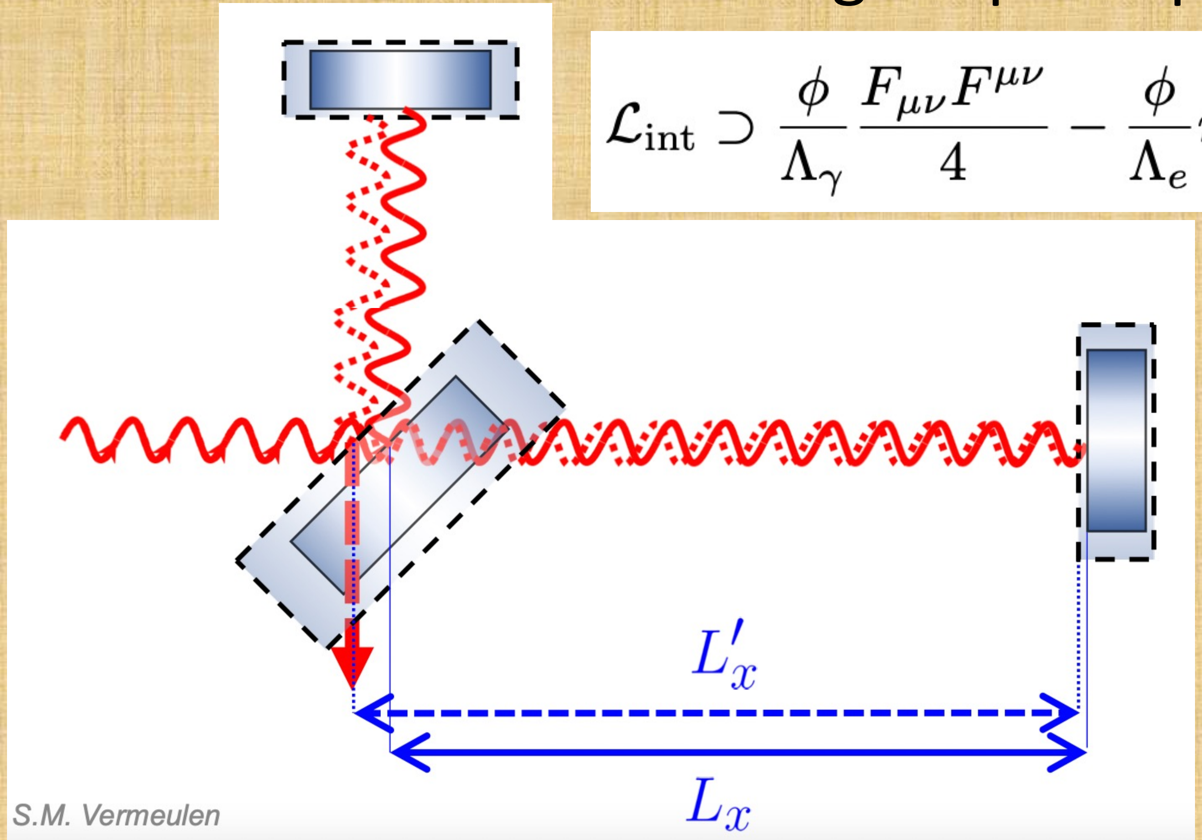
- Discrimination among signal and noise is complicate, and also among different signal models

Direct search for scalar fields [Vermeulen et al 2103.03783; Göttel et al., 2401.18076]

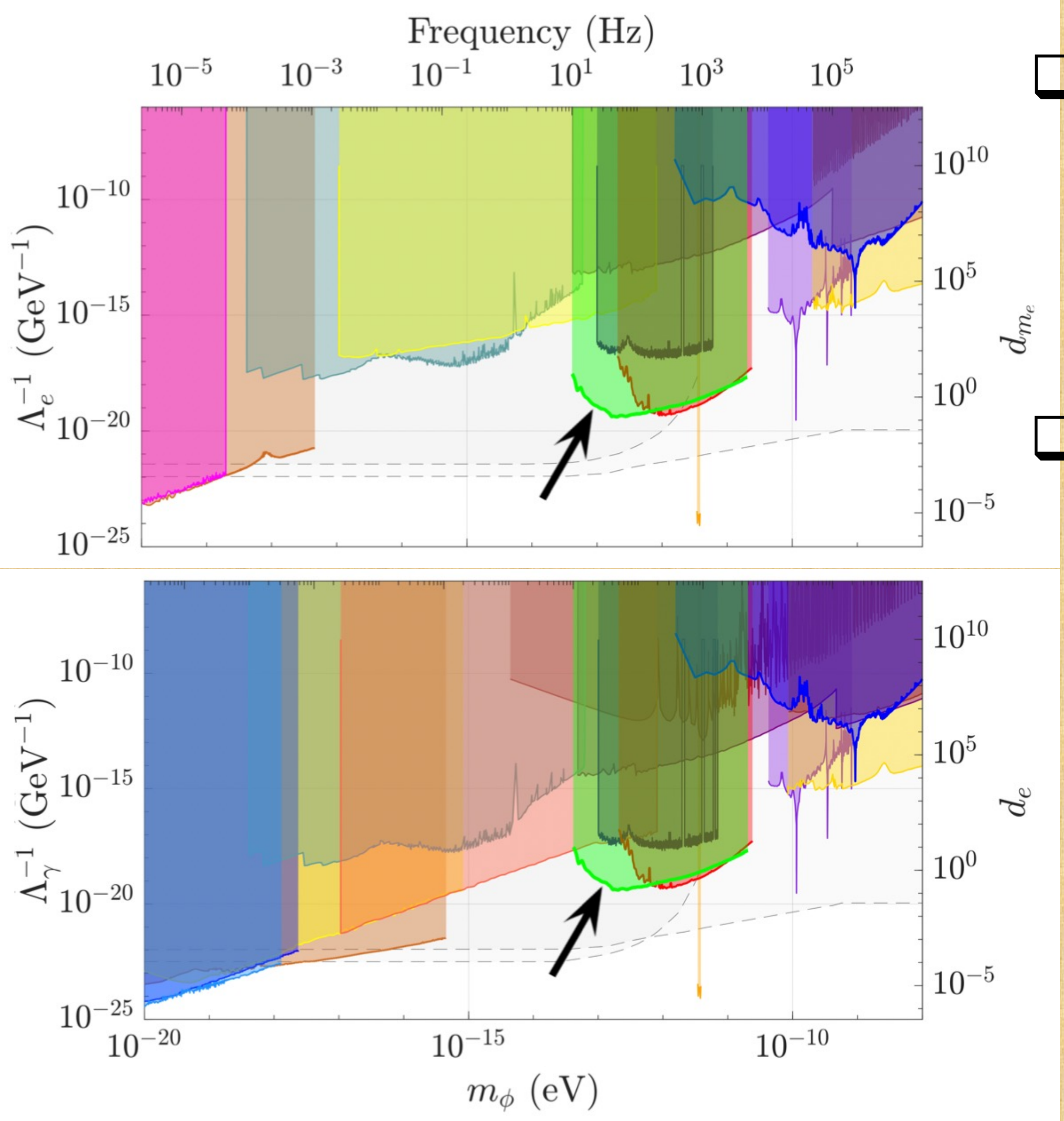
- A scalar field induces a variation of the fine structure constant α and electron rest mass m_e → variation of mirror's size ℓ and refractive index n
- Interferometer beam splitter interacts asymmetrically with light in the two arms → variation of light optical path

$$\mathcal{L}_{\text{int}} \supset \frac{\phi}{\Lambda_\gamma}\frac{F_{\mu\nu}F^{\mu\nu}}{4} - \frac{\phi}{\Lambda_e} m_e \bar{\psi}_e \psi_e$$

$$\delta(L_x - L_y) \approx \sqrt{2}\left[\left(n - \frac{1}{2}\right)\delta l + l\delta n\right]$$



- Non-negligible effects due to small thickness differences among arm test masses



- Approximation to Discrete Fourier Transform to get a FFT over logharitmic bin spacing → computational speed-up

- Orders of magnitude improvement w.r.t. atomic spectroscopy experiments

LIGO O3 constraints on coupling parameters

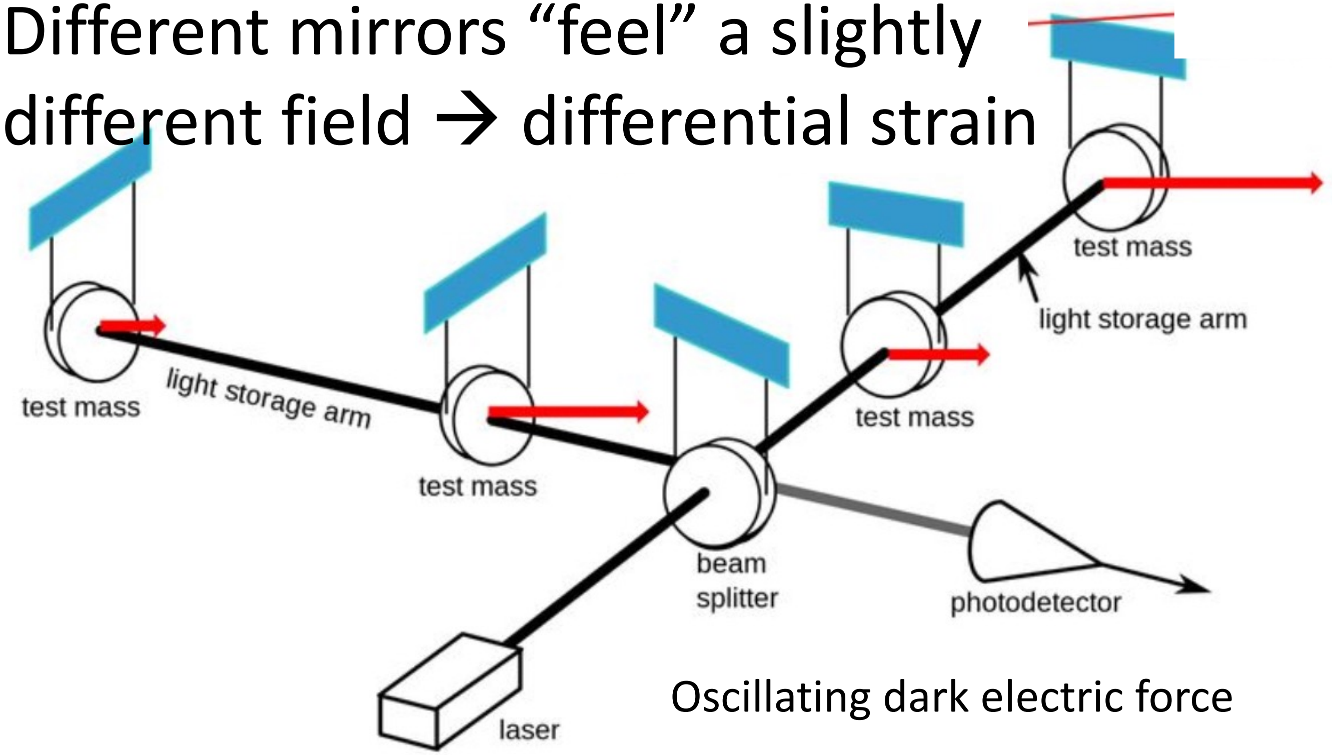
Direct search for vector fields (dark photons)

[Guo et al., Comm. Phys 2, 155 (2019), LVK PRD 105, 063030 (2022)]

- Dark photons couple to SM sector via the baryon number *B* or the baryon – lepton number *B-L*
- Associated to a new $U(1)_{B,B-L}$ gauge field

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

Different mirrors "feel" a slightly different field → differential strain



Oscillating dark electric force

Picture credit: Y. Zhao

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

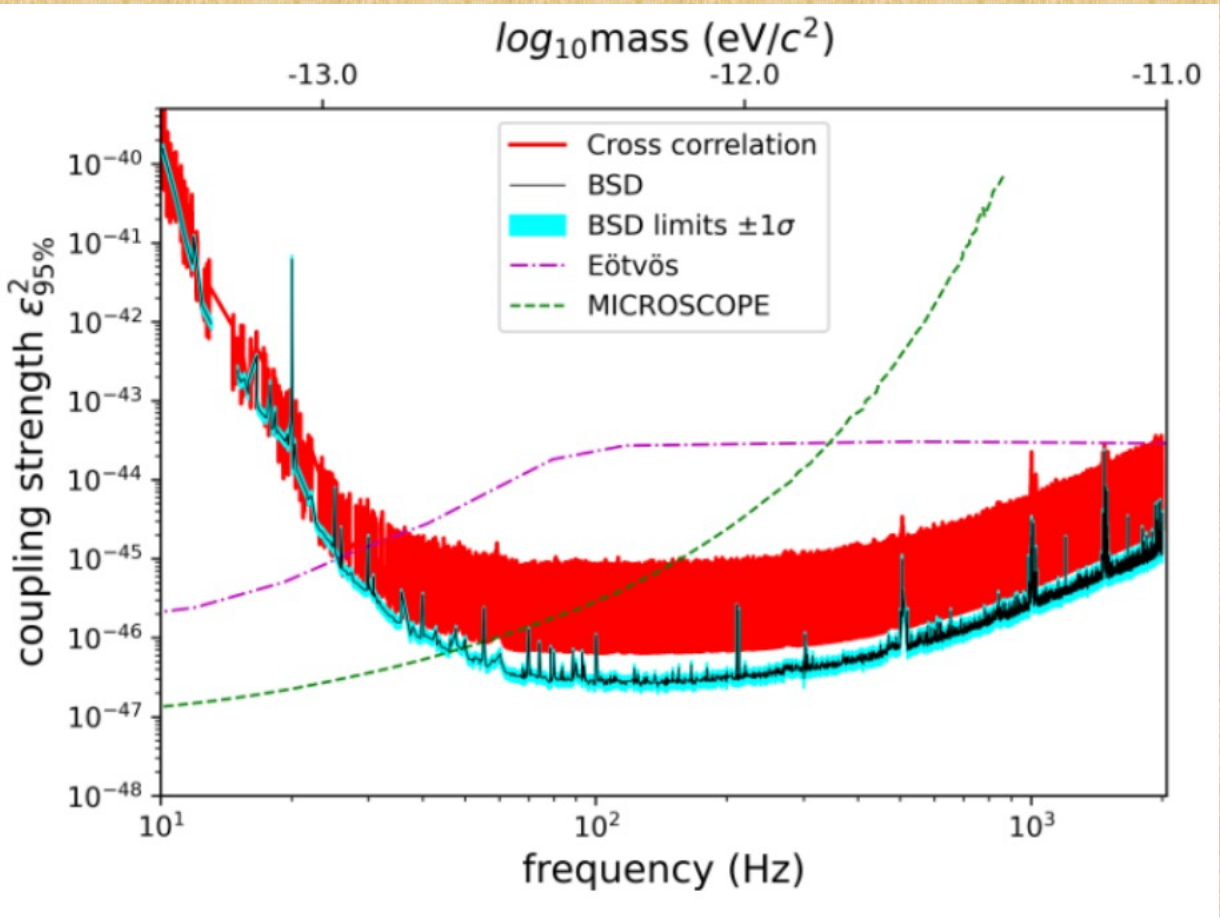
Pierce et al. 2018, PRL 121, 061102

Coupling constant

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

Morisaki et al. 2021, PRD 103, 051702

Upper limit on the coupling constant (O3 data), assuming $U(1)_B$



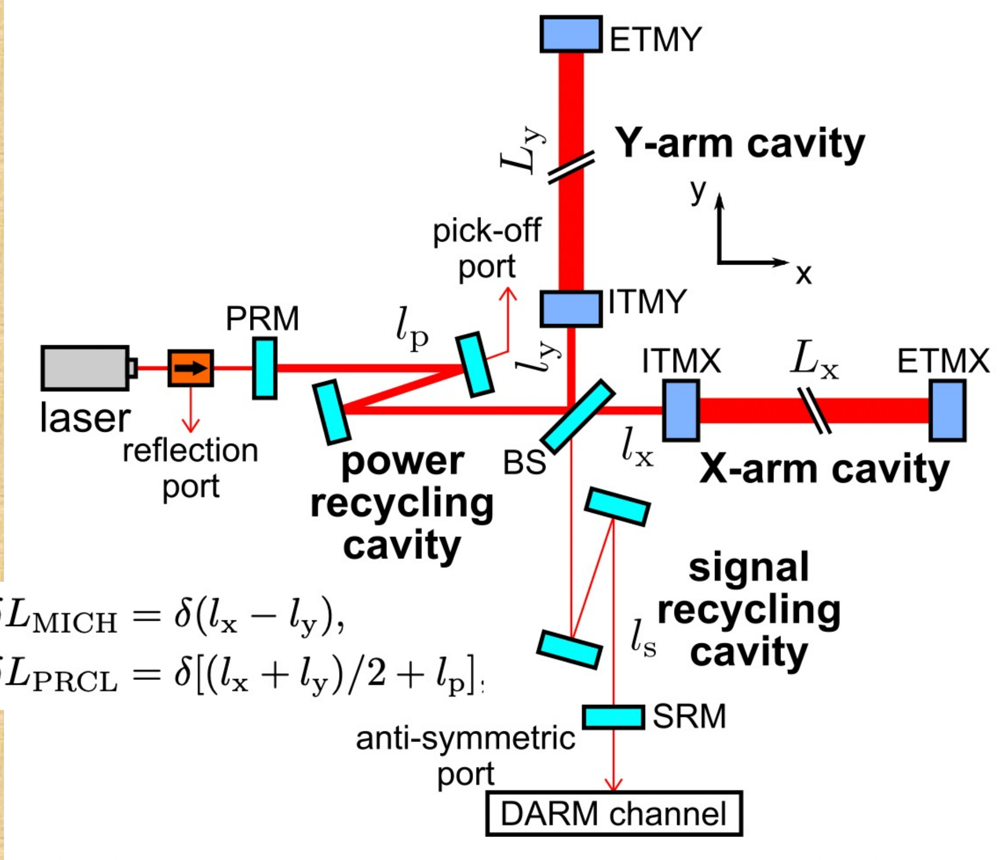
LVK PRD 105, 063030 (2022 updated in erratum https://dcc.ligo.org/LIGO-P2300439/public

❖ Improvement of up to two orders of magnitude w.r.t. direct search experiments, assuming $U(1)_B$

Direct search for vector fields (dark photons) in KAGRA

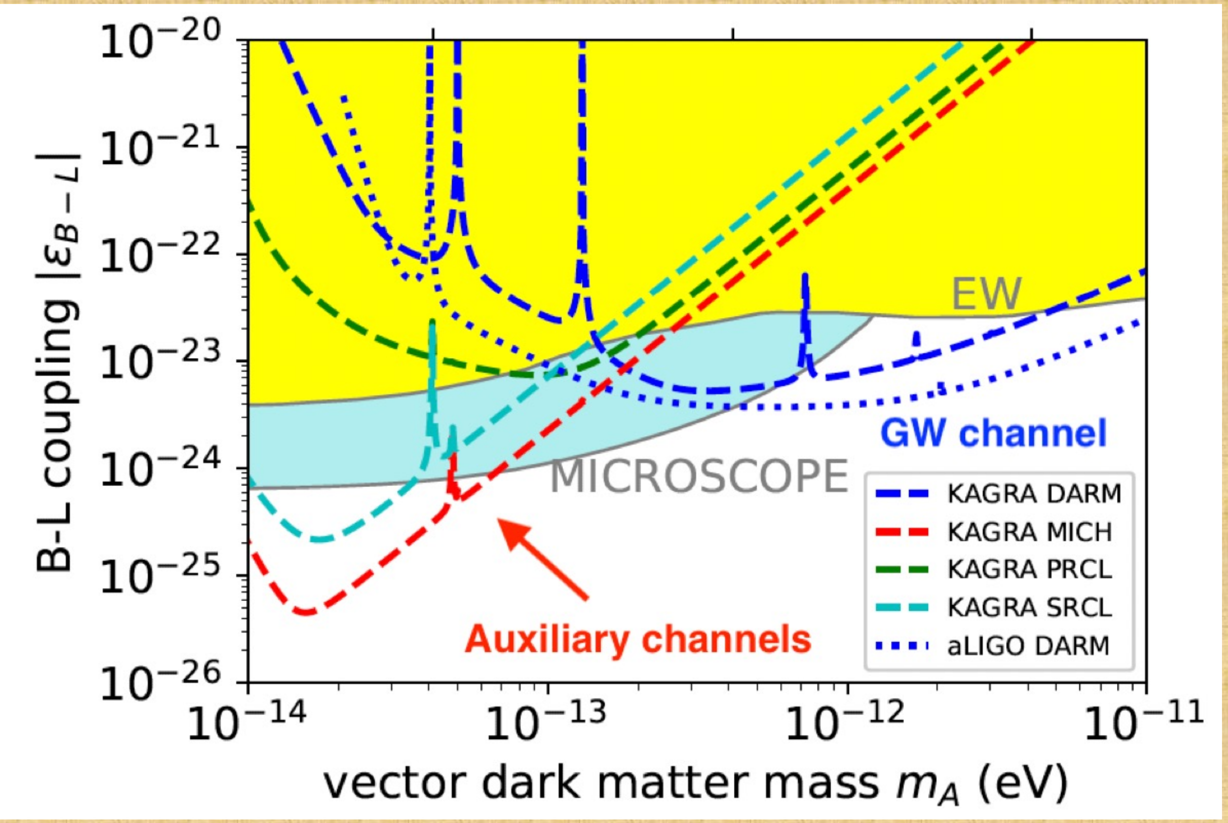
[Michimura et al., PRD102, 102001 (2020); Nakatsuka et al. PRD108, 092010 (2022); LVK, to be submitted]

- KAGRA detector has sapphire test masses, while auxiliary optics are made of fused silica → different Q/M ratios → different response to the vector field → enhanced differential length variation, especially for *U(1)*$_{B\text{-}L}$



$$\delta L_{\mathrm{MICH}} = \delta(l_x - l_y),$$
$$\delta L_{\mathrm{PRCL}} = \delta[(l_x + l_y)/2 + l_p],$$

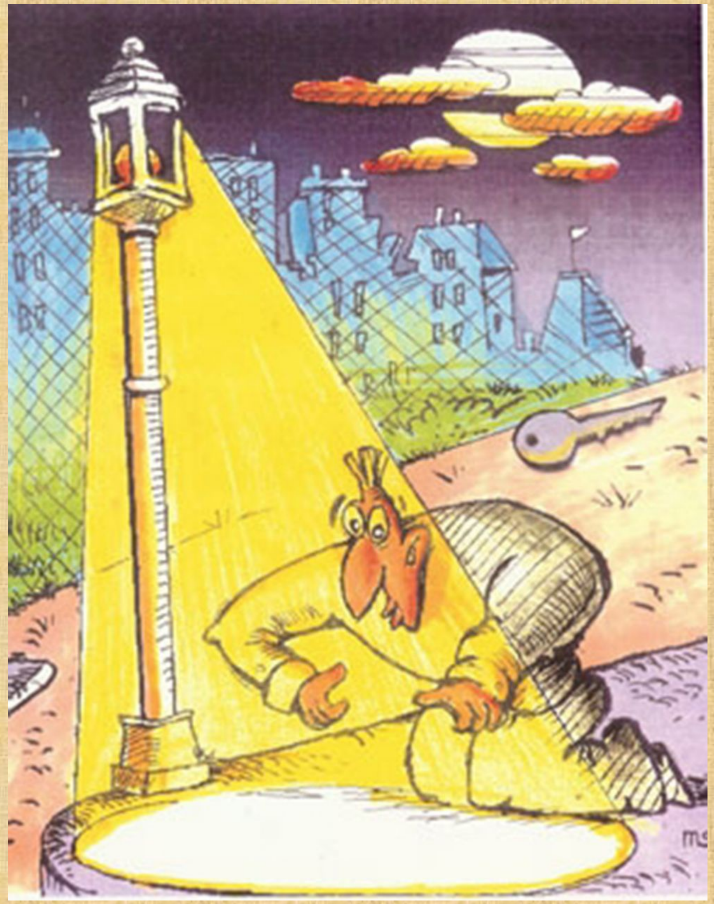
Predicted constraints assuming 1 yr of KAGRA at design sensitivity



Conclusions

- Analysis of GW data is already providing interesting constraints on ultralight bosons
- Data analysts are eager to tune their pipelines, or develop new ones, following advances in source/signal modelling
- Interpretation of the results is an important issue for which interaction among data analysts and theorists would be very welcome
- Discrimination among signal and noise, and among different signal models, is another hot topic

- **The key could be nearby….**

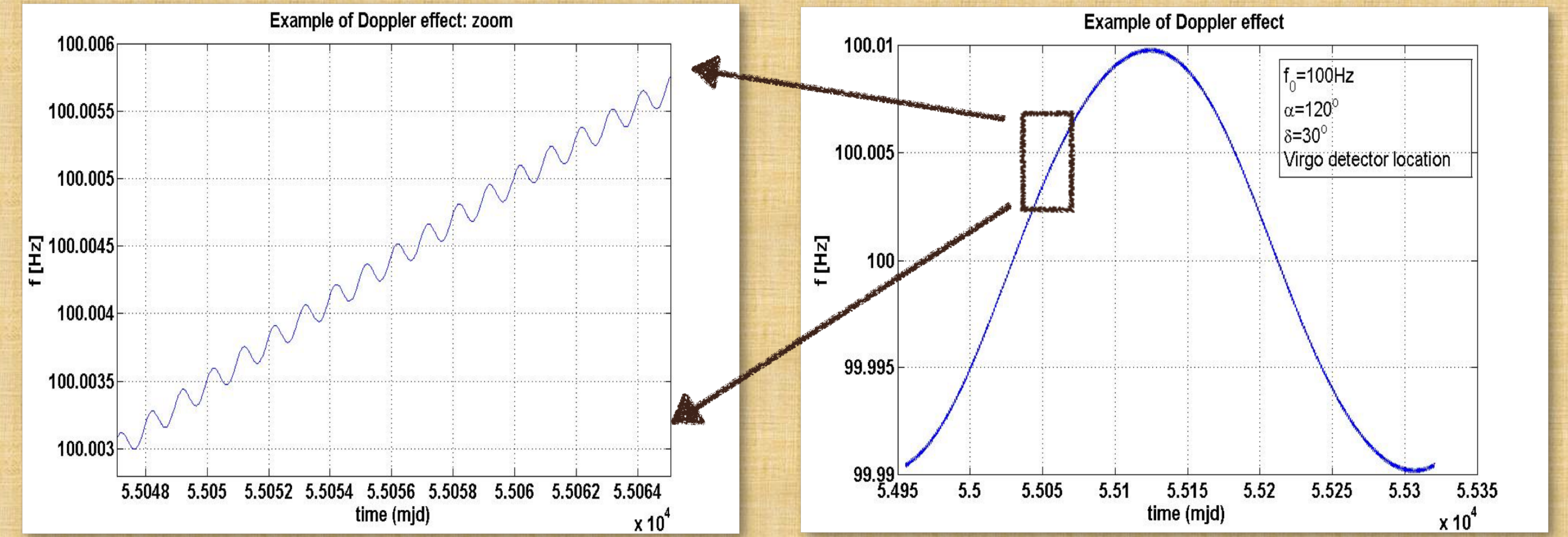


Thanks for your attention!

BACKUP SLIDES

Basic features of CWs

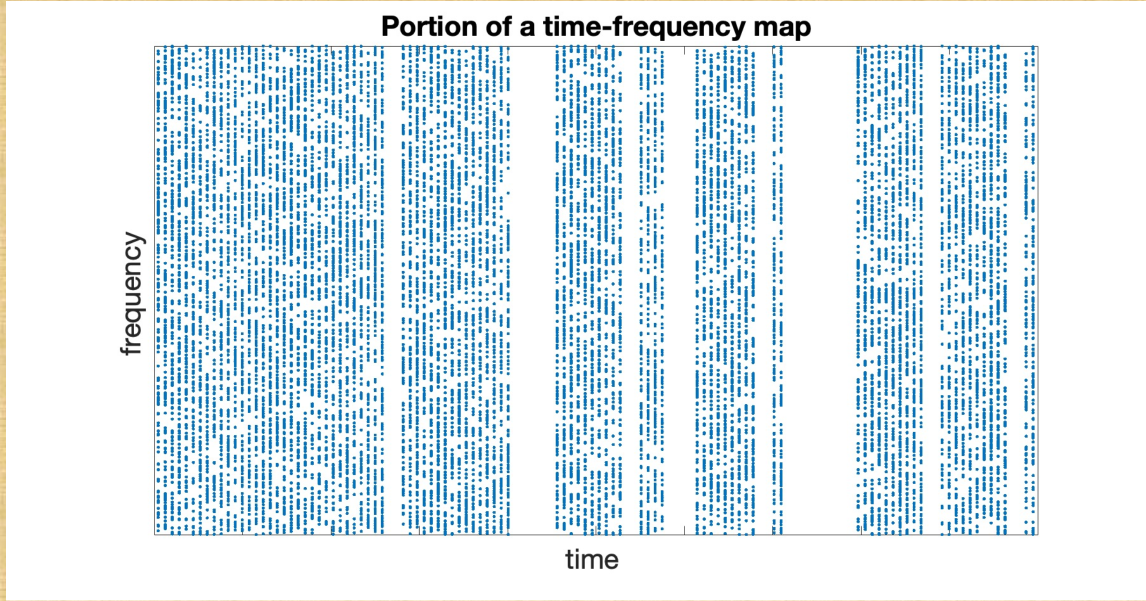
- Narrow-band, nearly periodic signals, with duration such the effect of detector motion is not negligible



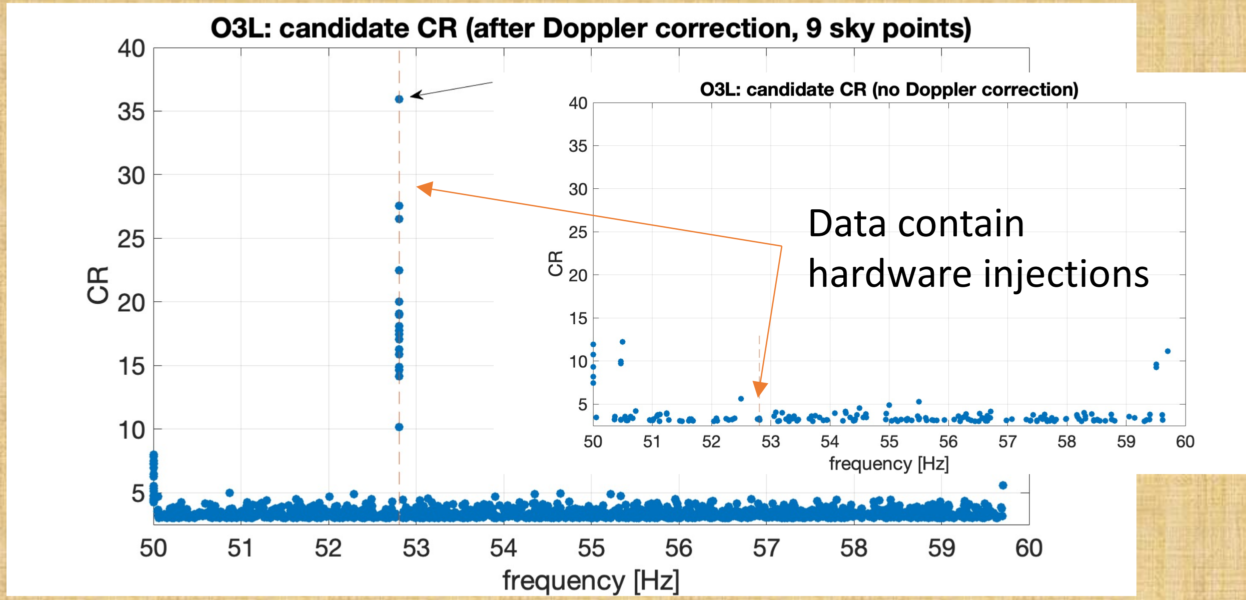
Doppler effect: $f(t) = f_0\left(1 + \frac{\vec{\mathbf{v}} \cdot \hat{n}}{c}\right), \quad \vec{\mathbf{v}} = \vec{\mathbf{v}}_{rev} + \vec{\mathbf{v}}_{rot}$

More complicated if the source is in a binary system (depends on up to 5 Keplerian parameters)

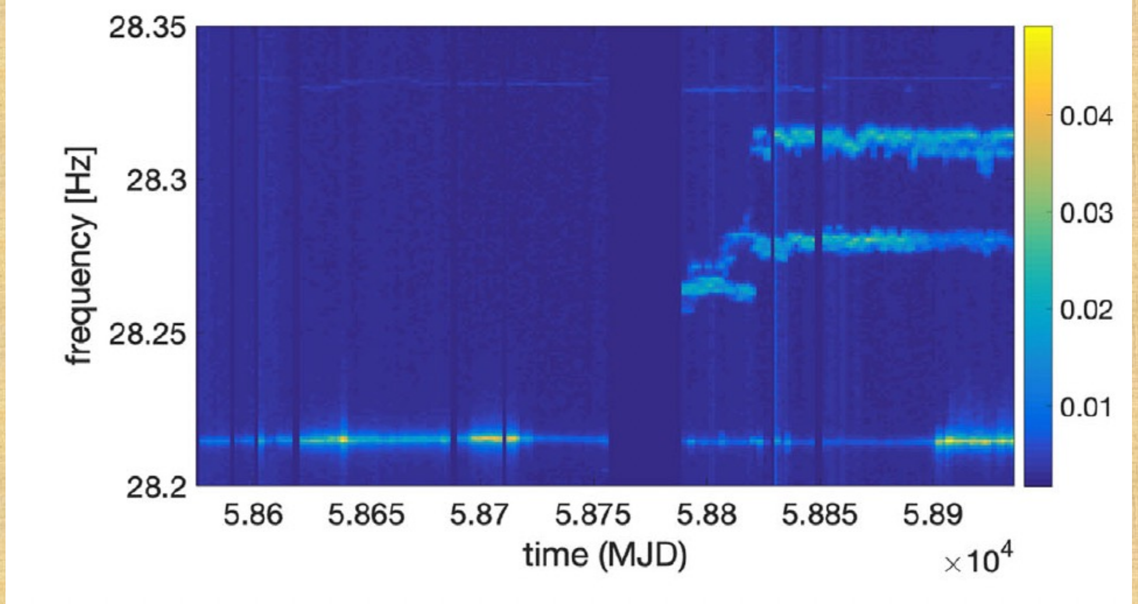
A) Time-frequency representation of the data



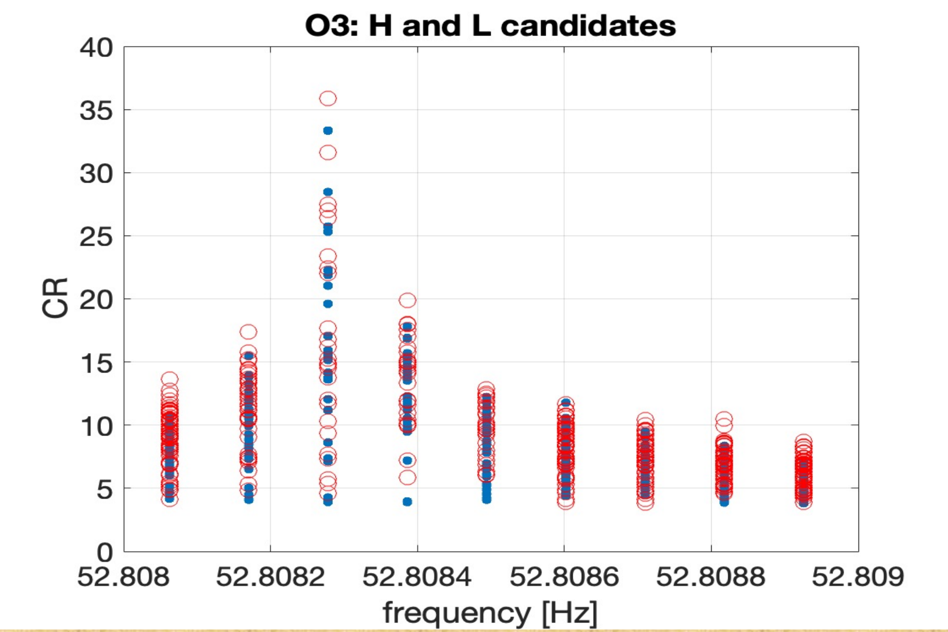
B) Doppler correction and computation of a detection statistic



Real data are full of weird stuff



C) Coincidences among candidates found in detectors + vetoes



❖ Expected amplitude much lower than for CBC signals

$$h_+ = h_0 \cdot \left(\frac{1+\cos^2 \iota}{2}\right)$$

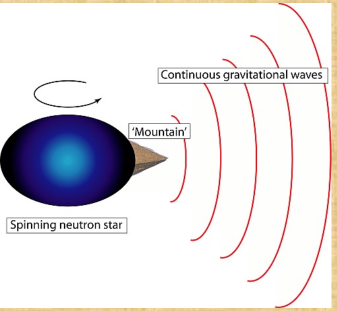
$$h_\times = h_0 \cdot \cos\iota$$

ι : angle between star spin axis and line of sight

$\varepsilon = \frac{I_{xx} - I_{yy}}{I_{zz}}$: equatorial ellipticity

$$h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} \varepsilon f_{GW}^2}{d}$$

$$f_{GW} = 2 f_{rot}$$



$$h_0 \cong 10^{-27} \left(\frac{I_{zz}}{10^{38} kg \cdot m^2}\right) \left(\frac{10kpc}{d}\right) \left(\frac{f}{100Hz}\right)^2 \left(\frac{\varepsilon}{10^{-6}}\right)$$

Good luck!

Galactic sources

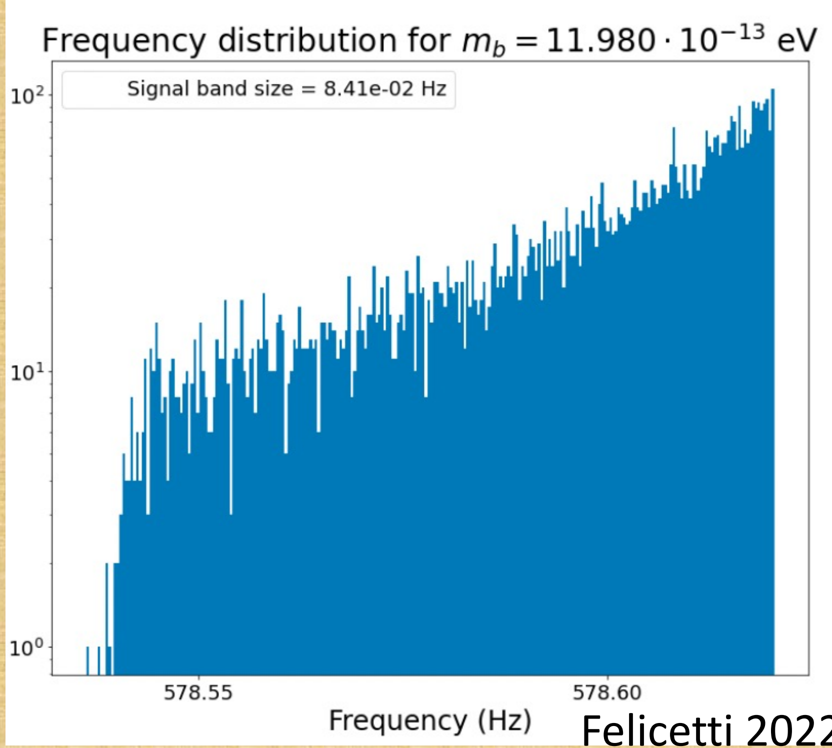
Ellipticity: largely unknown

❖ We can exploit signal long duration to build-up SNR

❖ Need to develop DA pipelines to deeply dig into the detector noise. Computational efficiency is often a major issue.

❖ Once detected, a CW is forever! (not true in the case of long transient signals)

- $10^7 - 10^8$ BHs are expected to exist in the Milky Way

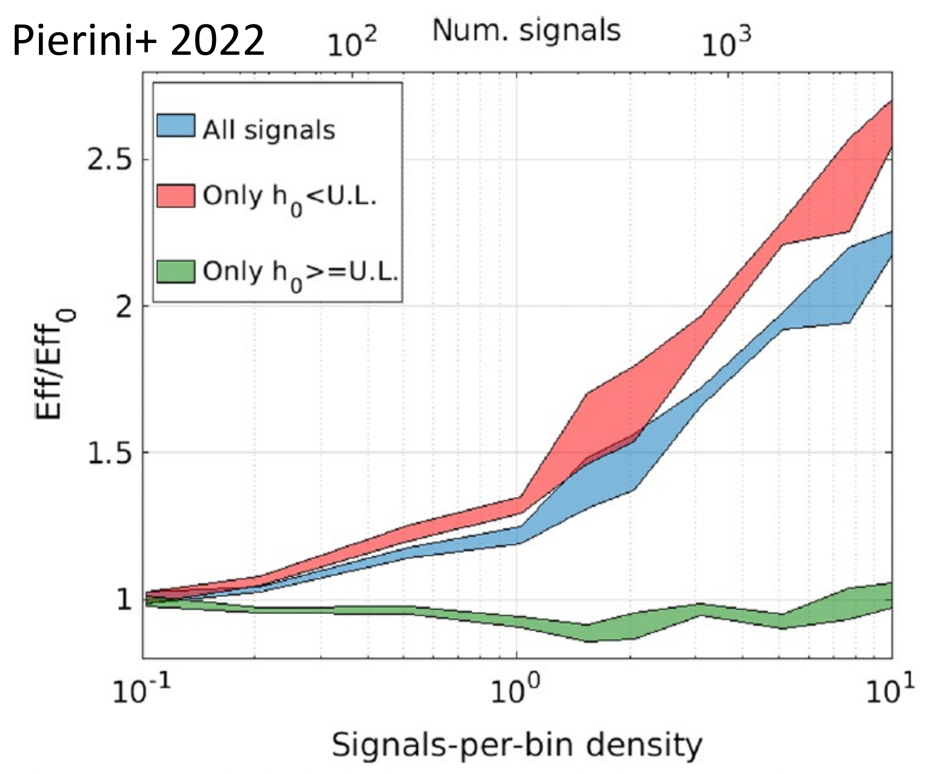


Felicetti 2022

- Signal superposition in all-sky searches, if most BHs are sorrounded by a boson cloud

Relative detection efficiency as a function of the signal-per-bin density

Pierini+ 2022

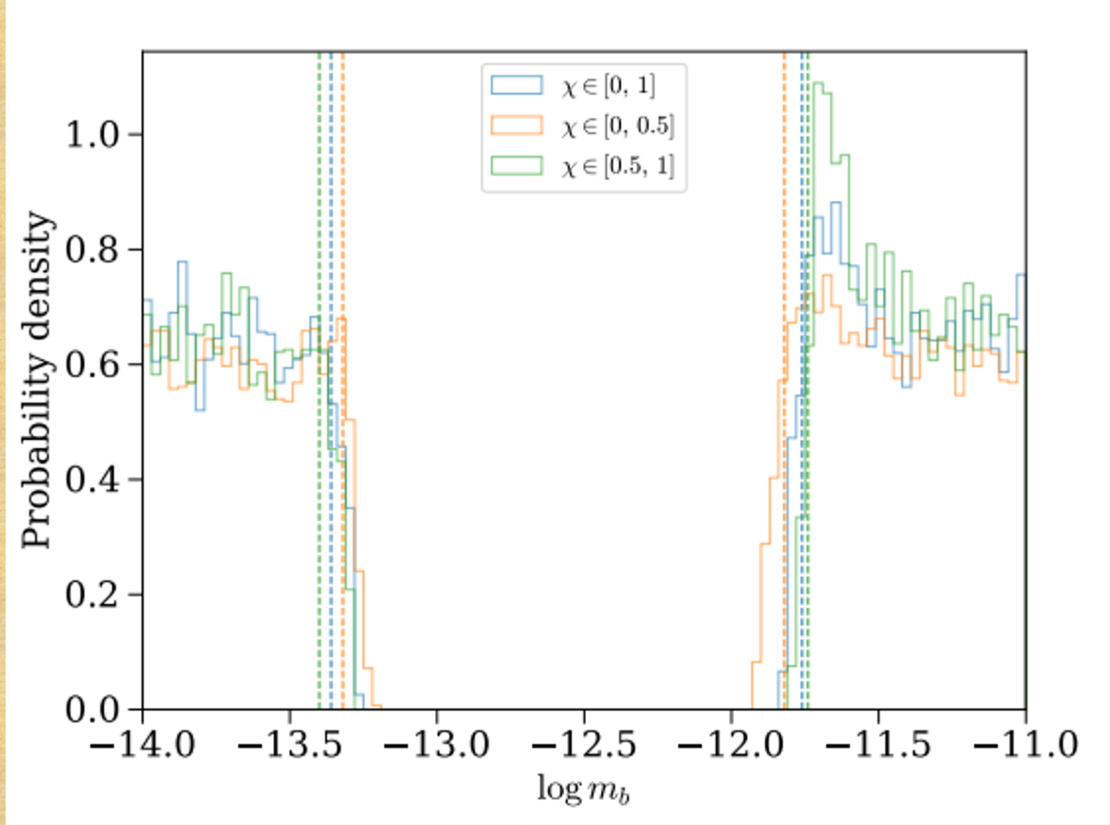


- Robustness of current search method has been demonstrated in [Pierini, Astone, CP et al. PRD106, 042009 (2022)]
- Possible sensitivity improvement by tuning FFT duration in semi-coherent searches [R. Felicetti, Master Thesis, Sapienza University of Rome 2022]

SGWB from tensor boson clouds [Guo et al. Arxiv 2312.16435]

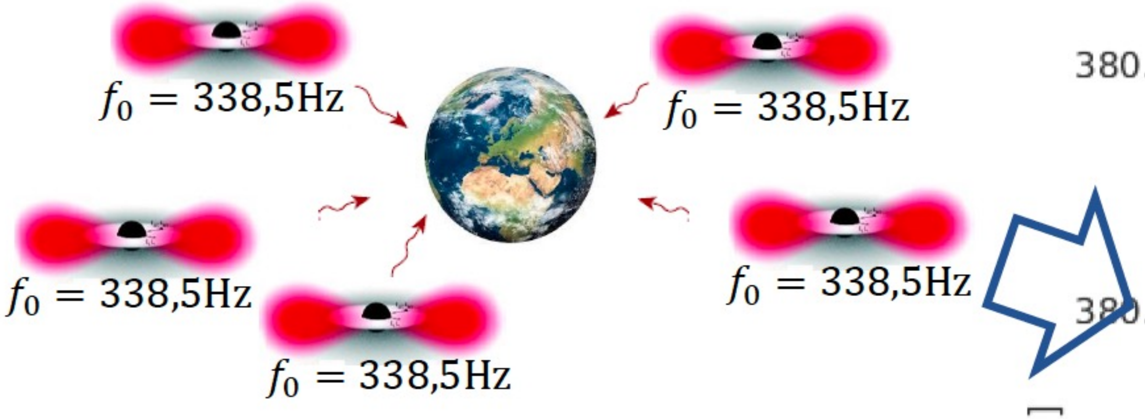
Assume uniform spin distribution

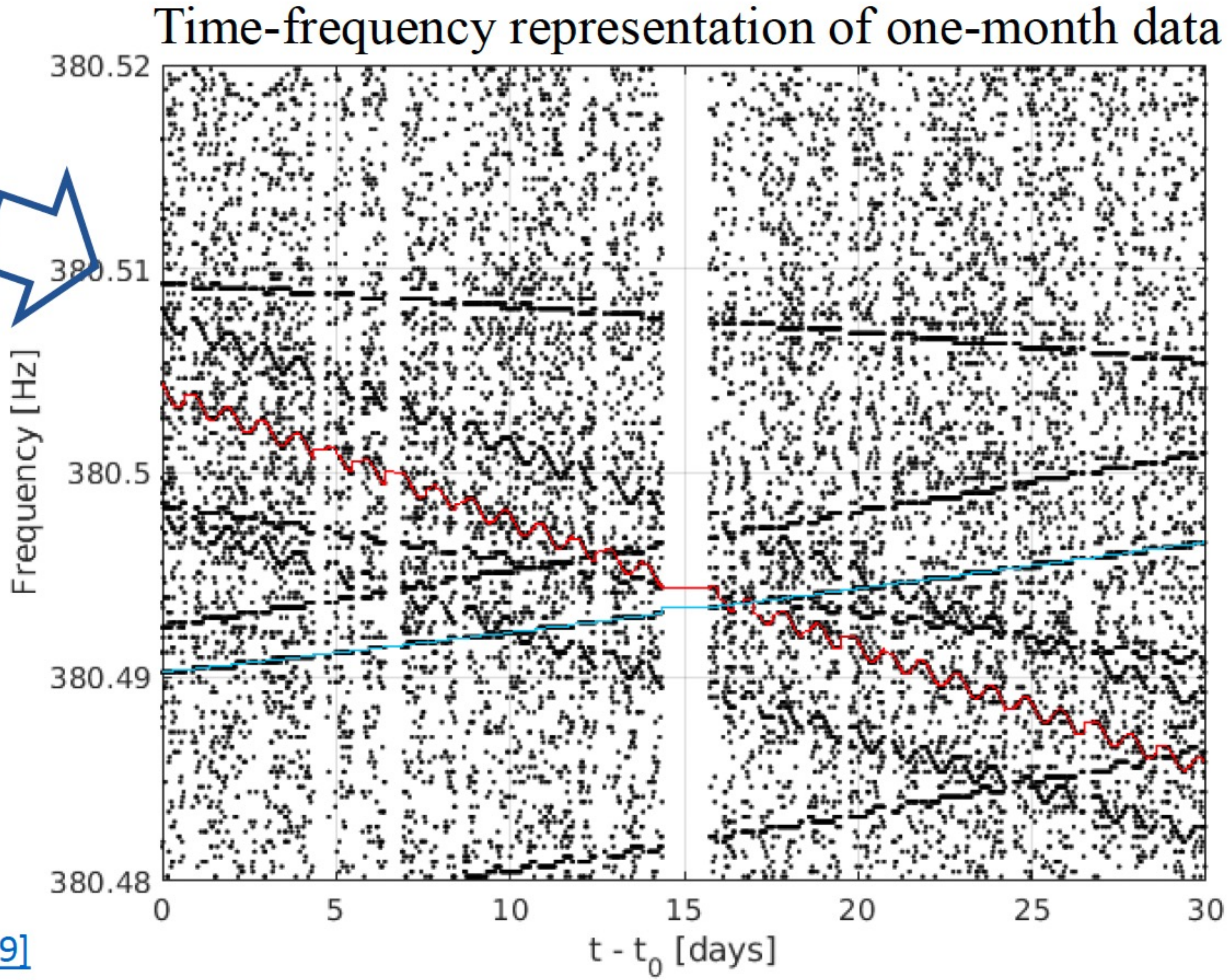
Tensors: faster timescales – stronger signals



Multiple signals can be resolved!

Credit: L. Pierini

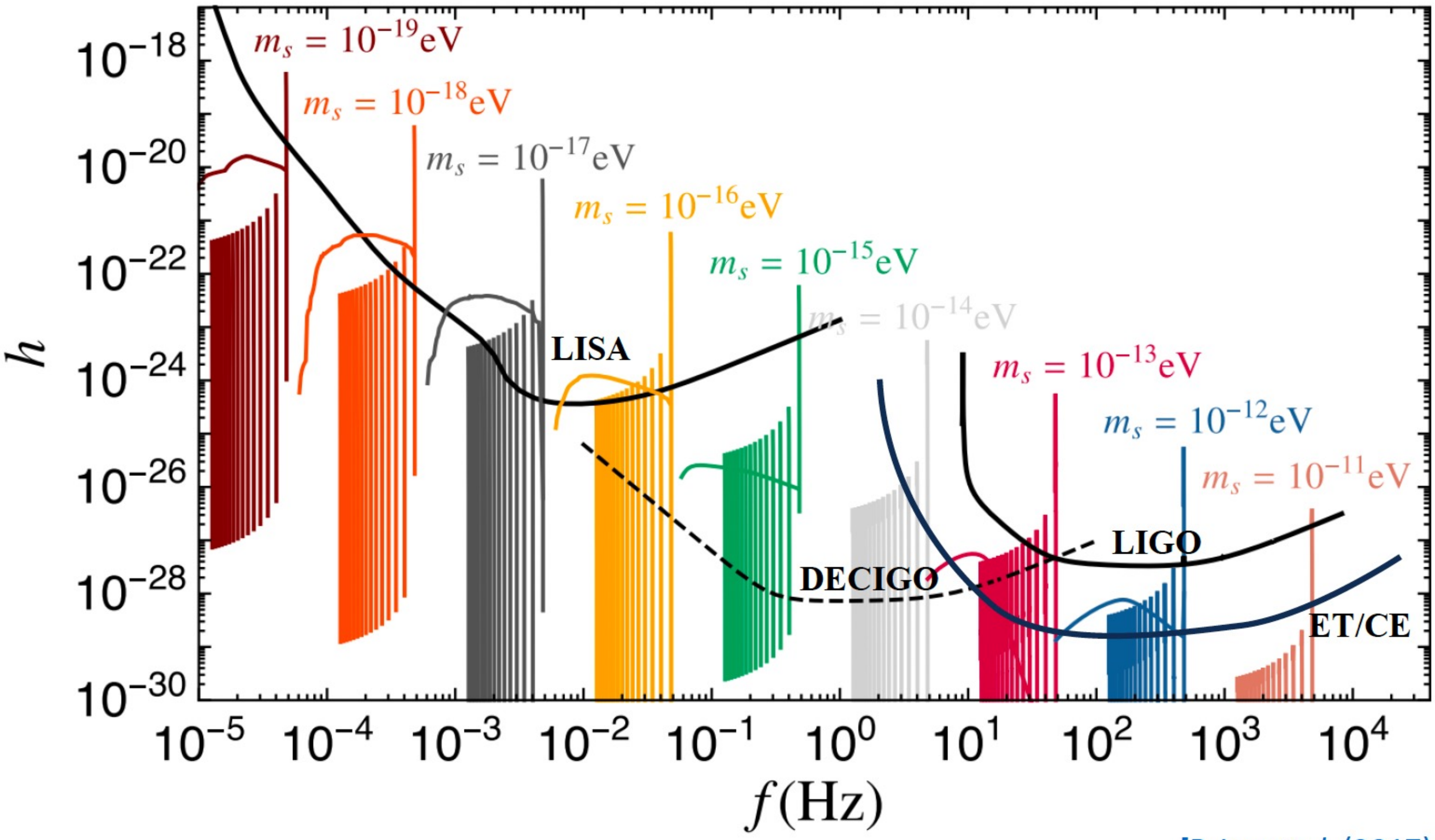




- The daily and annual Doppler effect due to the Earth motion modulates the observed signal.
- Exploiting the Doppler, we can resolve individual signals up to the sky resolution.

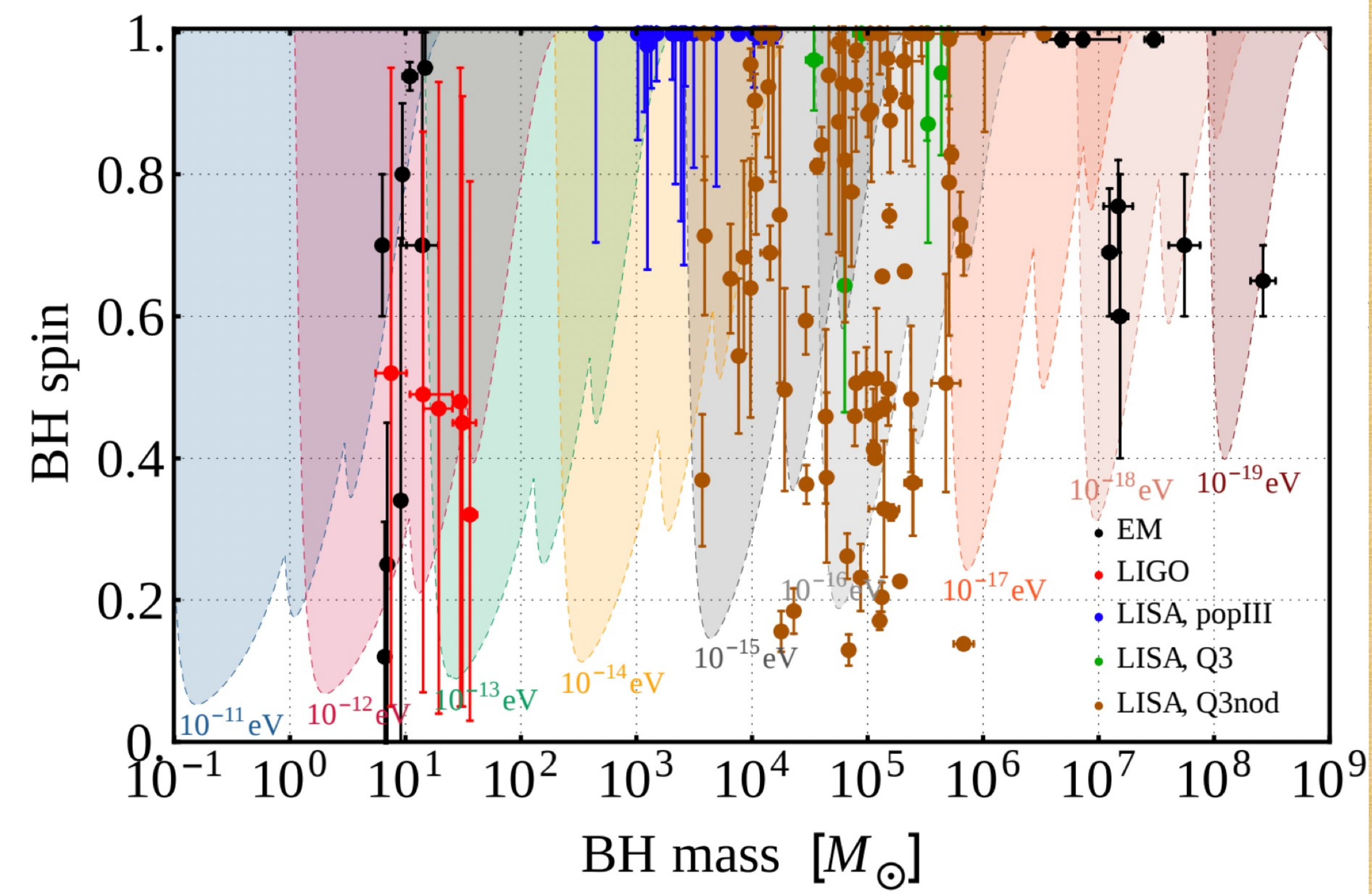
[Pierini et al. (2022) PRD 106(4), 042009]

Future observations

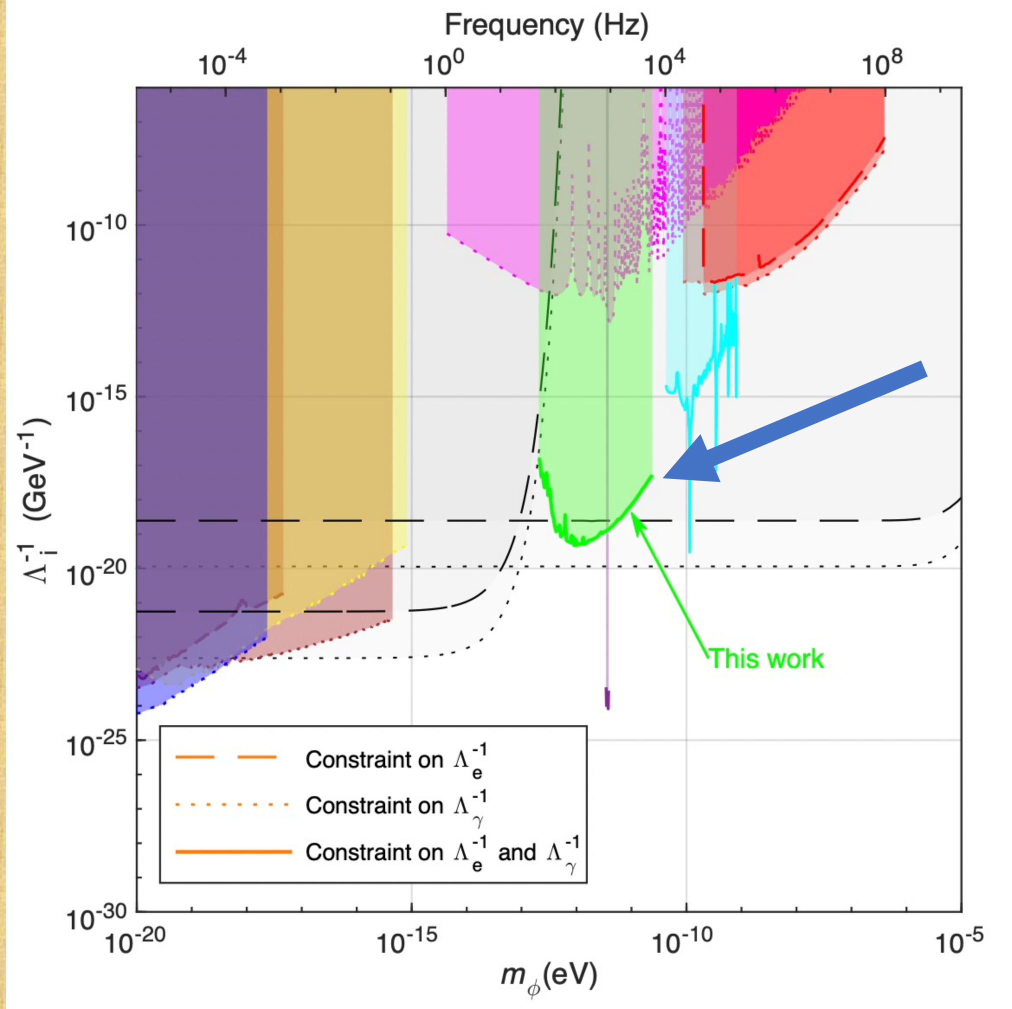


[Brito *et al.* (2017) **PRL 119**, 131101]

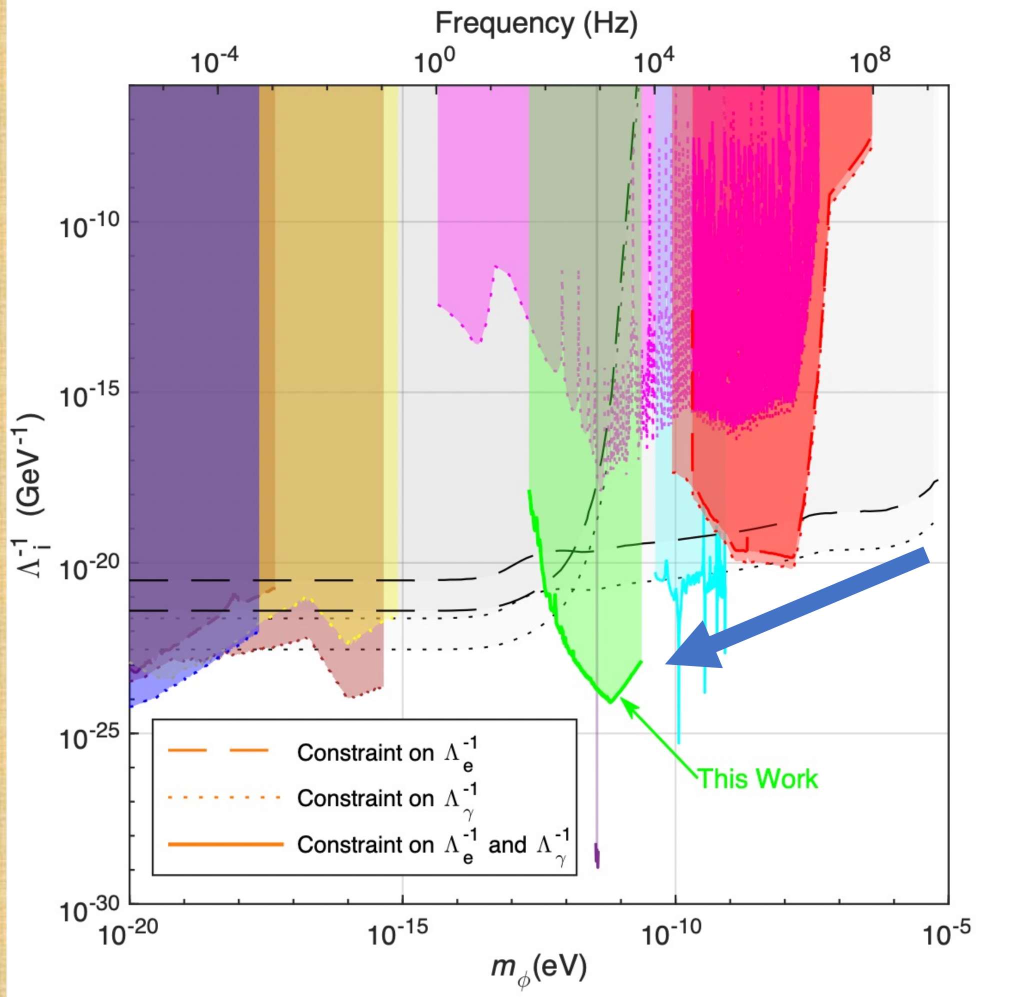
Indirect search looking at gaps in the BH mass-spin plane (Brito+ 2018, see also Ng+ 2021)



Standard scenario: coupling to EM sector + standard DM Halo model



Additional coupling to QCD sector + Relaxation Halo model



Orders of magnitude improvement w.r.t. atomic spectroscopy experiments and, for some model, w.r.t. fifth force experiments

◉ 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

$$\sqrt{\langle h_D^2 \rangle} = C \frac{q}{M} \frac{\hbar e}{c^4 \sqrt{\epsilon_0}} \sqrt{2\rho_{\rm DM}} v_0 \frac{\epsilon}{f_0},$$

$$\simeq 6.56 \times 10^{-27} \left(\frac{\epsilon}{10^{-23}}\right) \left(\frac{100\ \text{Hz}}{f_0}\right)$$

Pierce+ 2018

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

$$\sqrt{\langle h_C^2 \rangle} = \frac{\sqrt{3}}{2} \sqrt{\langle h_D^2 \rangle} \frac{2\pi f_0 L}{v_0},$$

$$\simeq 6.58 \times 10^{-26} \left(\frac{\epsilon}{10^{-23}}\right)$$

Morisaki+ 2021