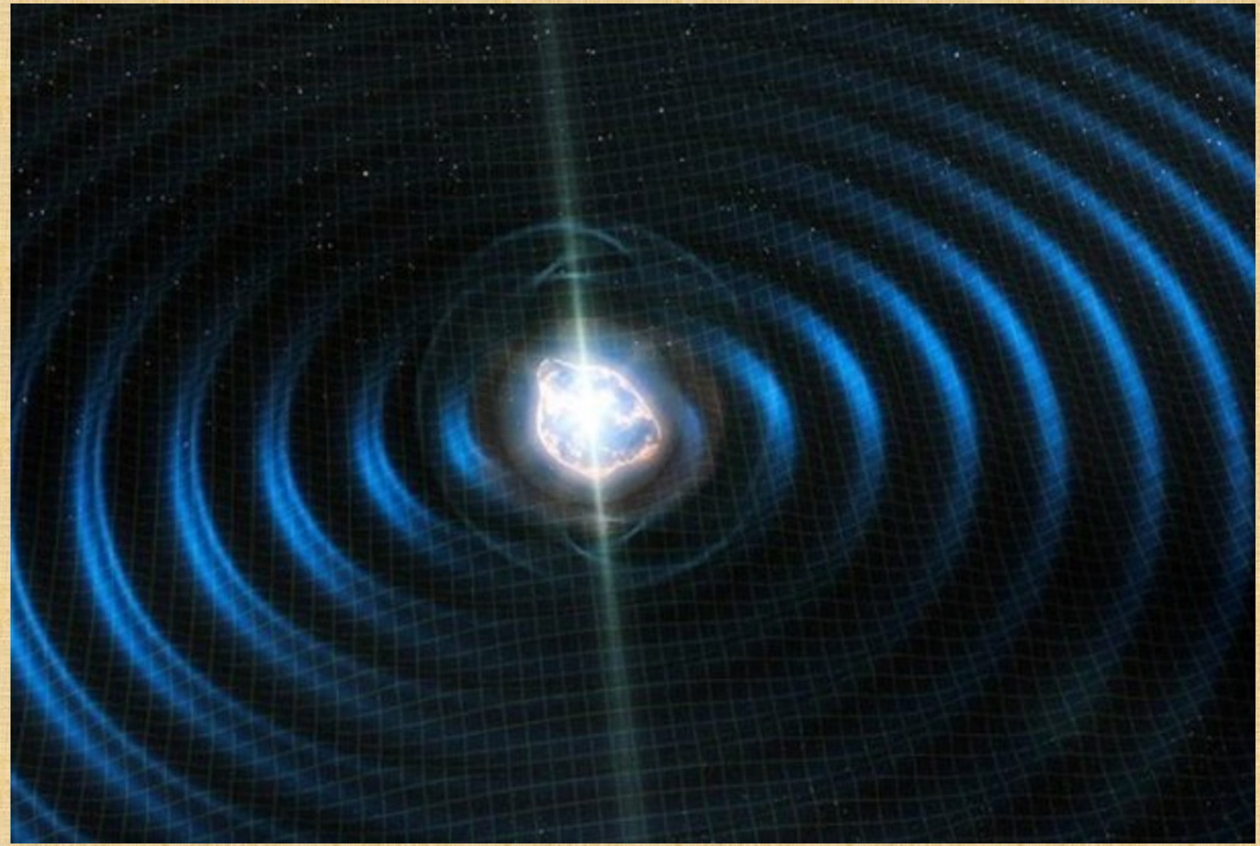
Searching for continuous gravitational waves: the remainder of the zoo

Cristiano Palomba – INFN Roma

LIGO VIRGO KAGRA



INFN
Istituto Nazionale di Fisica Nucleare

Pisa, October 24-27 2023

GraSP23 || GravityShapePisa 2023

CW land

Hic sunt leones

``Standard'' sources

Spinning neutron stars, isolated or in a binary system

- ❖ Talks by Paola Leaci (Tuesday) and Pia Astone (Thursday)
- ❖ Poster by Lorenzo Mirasola

This talk is about ``less standard'' sources

- ❖ Long-transient signals (e.g. newborn magnetars)
- ❖ Imprints of ultra-light DM
- ❖ Sub-solar mass PBH inspirals
  - Emission mechanism
  - Data analysis aspects
  - Results and perspectives

Hic sunt dracones

Gravitational Waves in a nutshell

- 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

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

$$h_{ij}^{TT} = \frac{2G}{3c^4 r} \ddot{Q}_{ij}^{TT},\quad Q_{ij}^{TT} = \int \rho \left(x^i x^j - \frac{1}{3} \delta^{ij} r^2 \right) d^3x$$

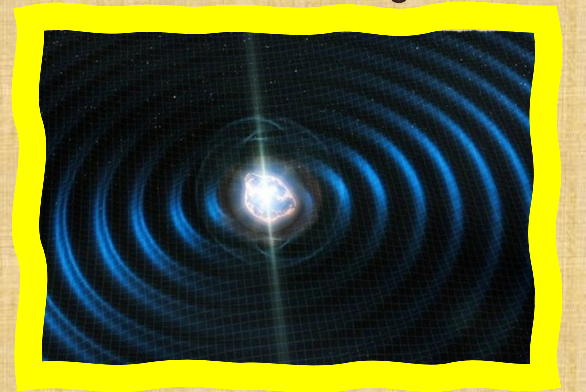
$$L_{GW} = -\frac{dE_{GW}}{dt} = \frac{G}{5c^5} \left\langle \left(\frac{\partial^3 Q_{ij}^{TT}}{\partial t^3} \right)^2 \right\rangle$$

- Produced by the bulk motion of matter. Examples:

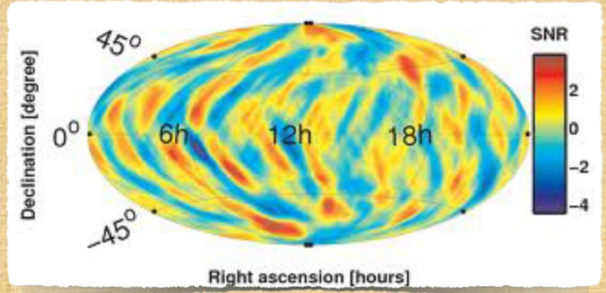
Coalescing compact binaries (black holes, neutron stars)

Supernova explosions

Continuous Waves/Long-transients



Stochastic background (Astrophysical, Cosmological)

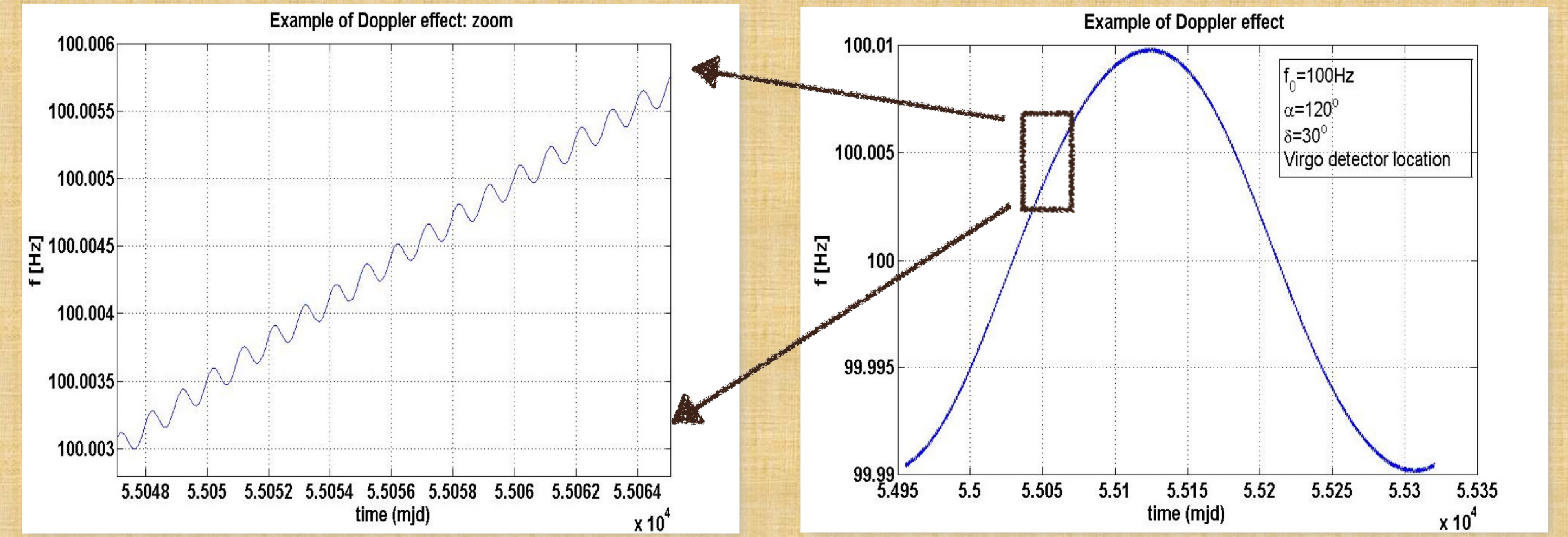


Transient signals (duration O(0.001—100) s)

Persistent or long-transient signals O(hours—days)

Basic features of CWs

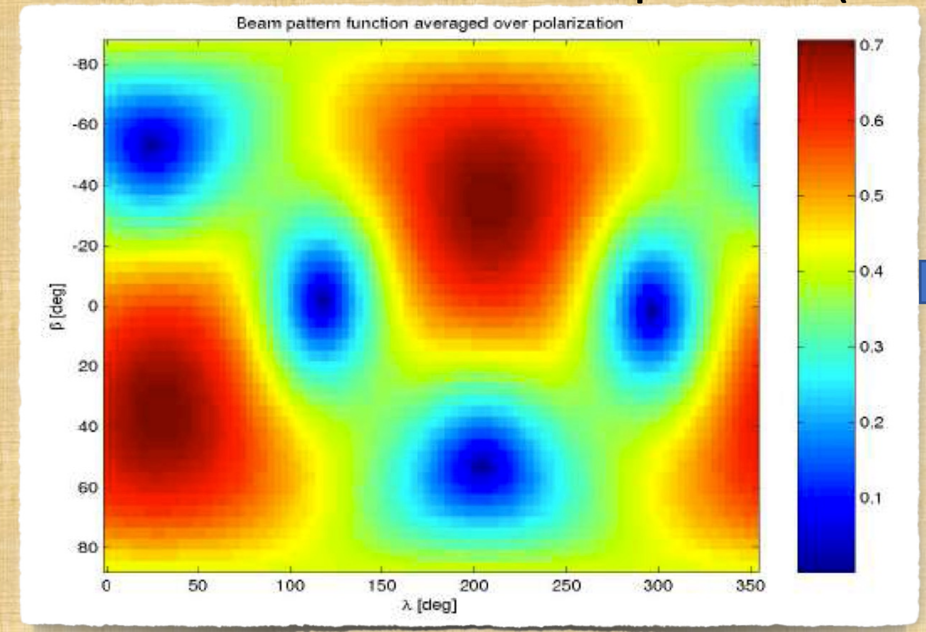
- Narrow-band, nearly periodic signals, with duration such the effect of detector motion is not negligible

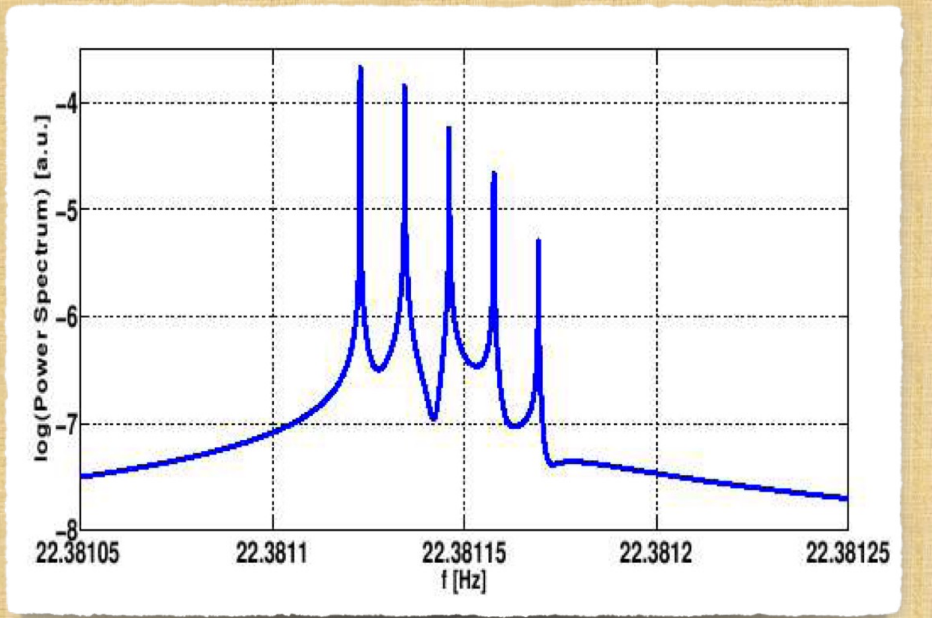


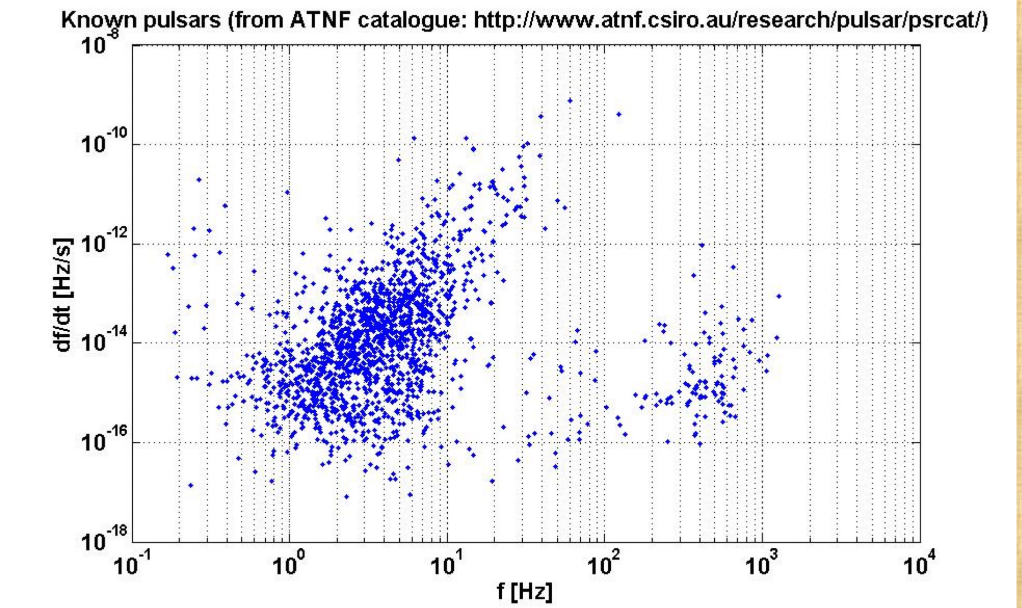
Doppler effect: $f(t) = f_0\left(1 + \frac{\vec{\mathbf{v}} \cdot \hat{n}}{c}\right), \quad \vec{\mathbf{v}} = \vec{\mathbf{v}}_{rev} + \vec{\mathbf{v}}_{rot}$

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

Amplitude (and phase) modulation







Intrinsic source secular variation of the rotational frequency: spin-down (-up)

Very specific features that help in discriminating a real signal from noise

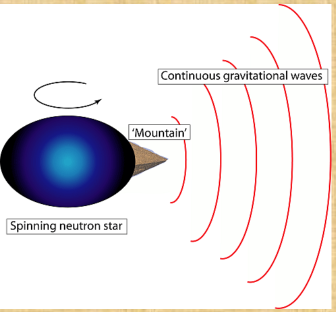
- Expected amplitude much lower than for CBC signals

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

ι : angle between star spin axis and line of sight

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

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



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

Good luck!

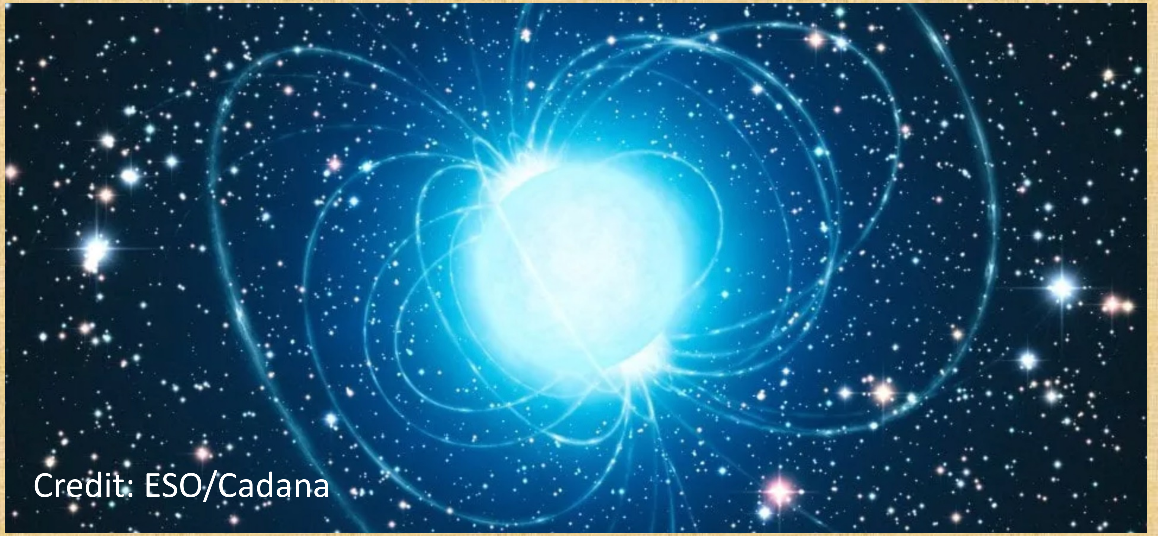
Galactic sources

Ellipticity: largely unknown

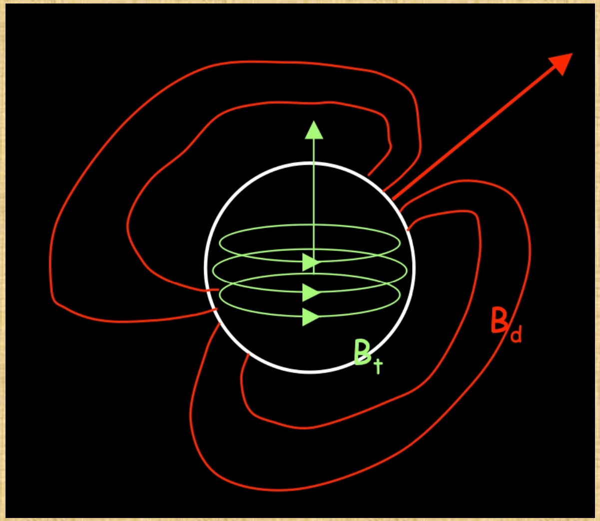
- We can exploit signal long duration to build-up SNR
- Need to develop DA pipelines to deeply dig into the detector noise. Computational efficiency is often a major issue.
- Once detected, a CW is forever! (not true in the case of long transient signals)

Long-transient signals

- Nearly periodic signals, with duration of hours – days
- Typically, |spin-down/up| >> w.r.t. standard CWs (say, >> 10^{-8} Hz/s)
- Reference source: rapidly spinning newborn magnetar



P_{rot}~O(ms)
B_{in}~10^{16} G

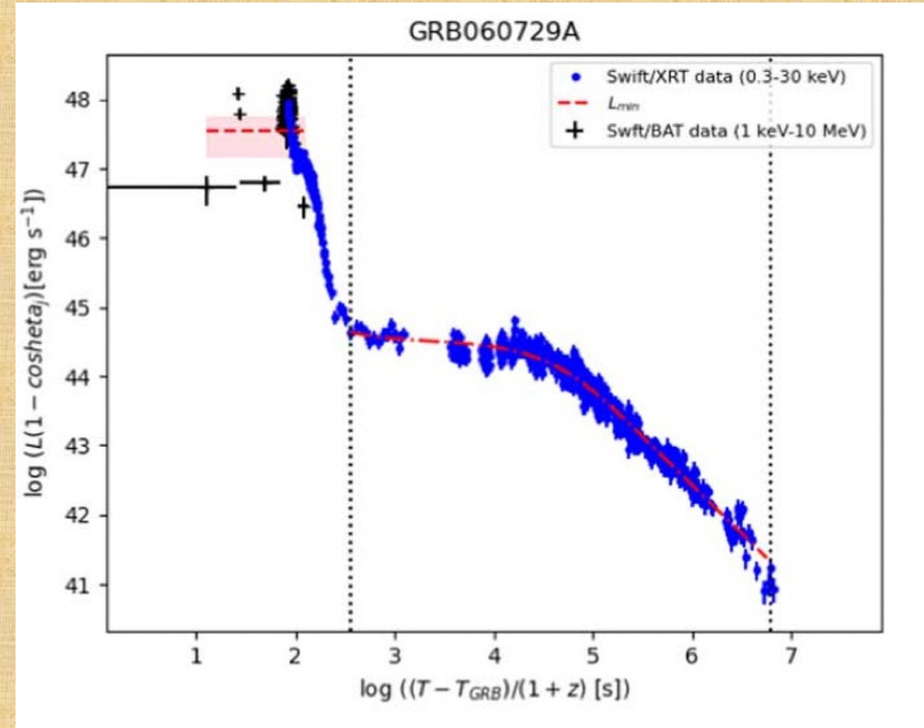


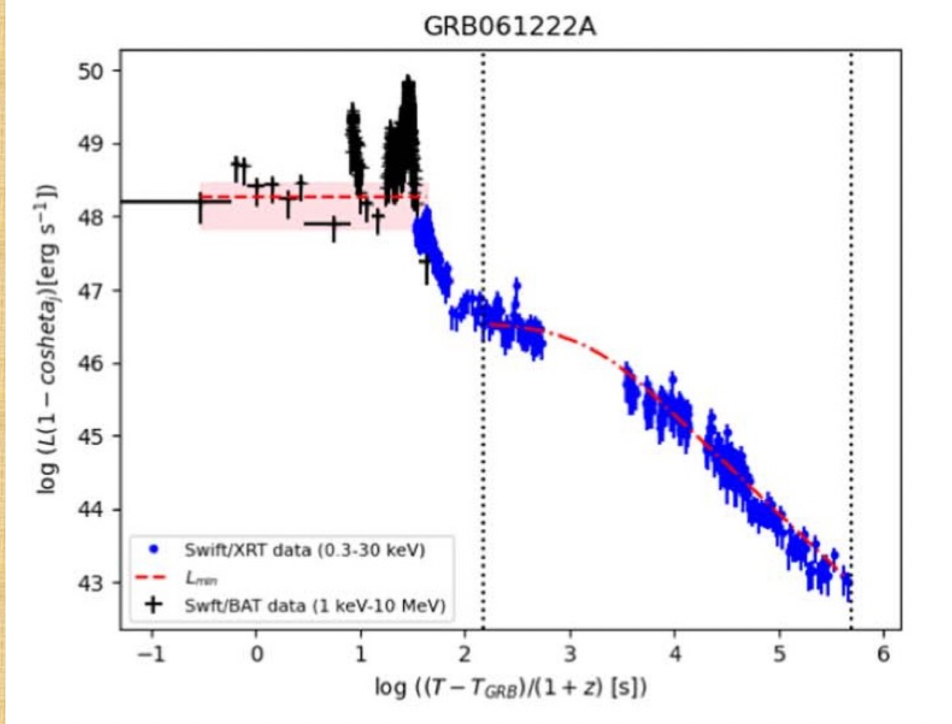
- Dynamo in fast spinning PNS: driven by differential rotation (→ toroidal magnetic field) + plasma or magneto-rotational instability

[e.g. Dall'Osso, Stella 2103.10878 for a review]

- Millisecond magnetars can form in a significant fraction of both core collapse supernovae and in NS mergers (10-40%)

- Magnetars (+ accretion disk) can also power a fraction of observed GRBs, both short and long



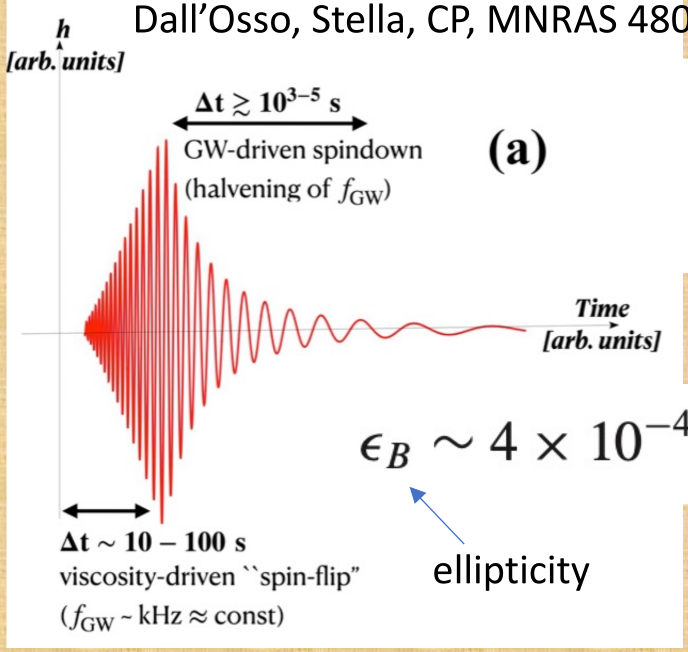


Magnetar model fit to observed GRB light curves [Dall'Osso, Stratta et al., ApJL 949 L32 (2023)]

- A newborn magnetar can be a strong GW emitter
  - The strong inner magnetic field distorts the star shape
  - Combination of GW and EM spin-down

See e.g.
CP, A&A 367, 525 (2001)
Cutler, PRD66, 084025 (2002)
Ciolfi & Rezzolla, MNRAS L43 (2013)
Dall'Osso, Stella, CP, MNRAS 480, 1353 (2018)

Dall'Osso, Stella, CP, MNRAS 480, 1353 (2018)



GW strain

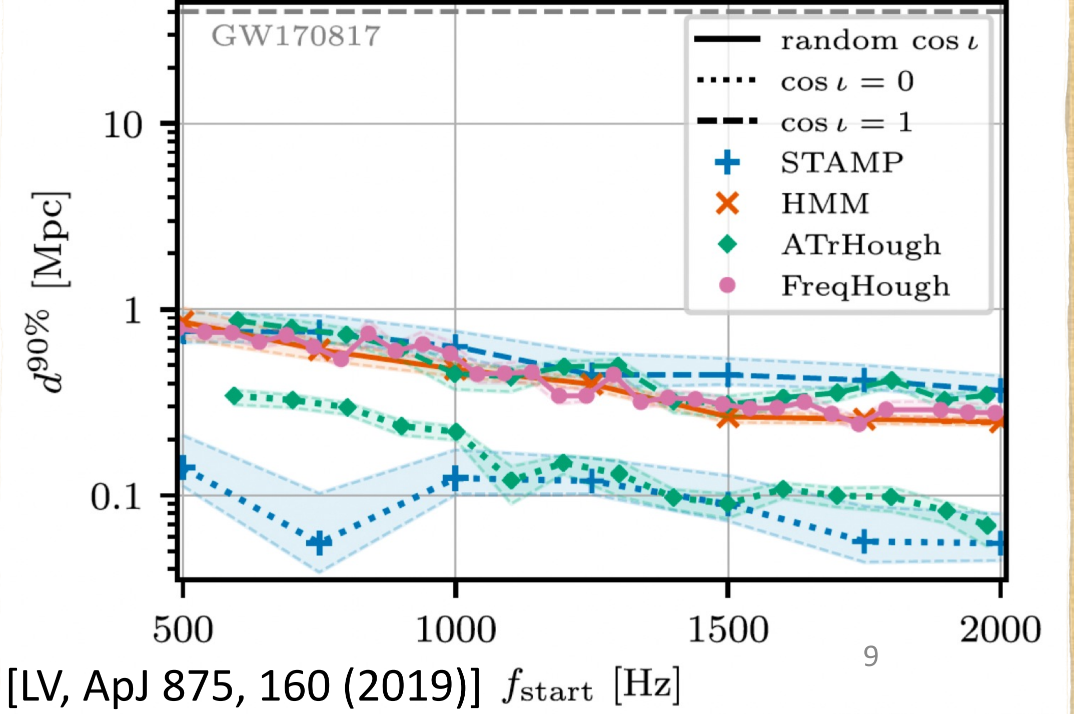
$$h_0(t) = \frac{4\pi^2 G I_{zz}}{c^4} \frac{\epsilon}{d} f_{\rm gw0}^2 \left(1 + \frac{t}{\tau}\right)^{2/(1-n)}$$

$$\epsilon_B \sim 4 \times 10^{-4} B_{t,16}^2 R_{12}^4 / M_{1.4}^2$$

ellipticity

Corrections to ε due to field geometry (e.g. toroidal-to-poloidal field ratio)

Distance reach of pipelines applied to the search of a post-merger signal from GW170817



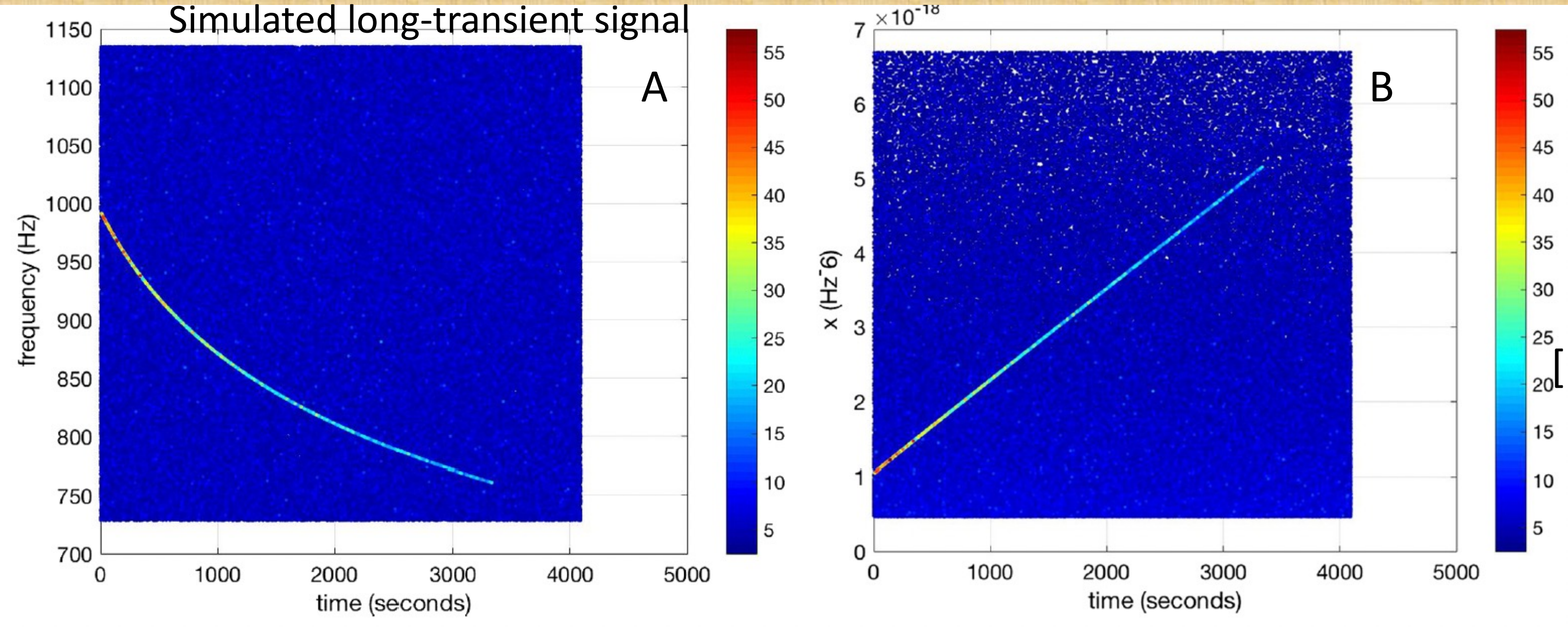
[LV, ApJ 875, 160 (2019)]

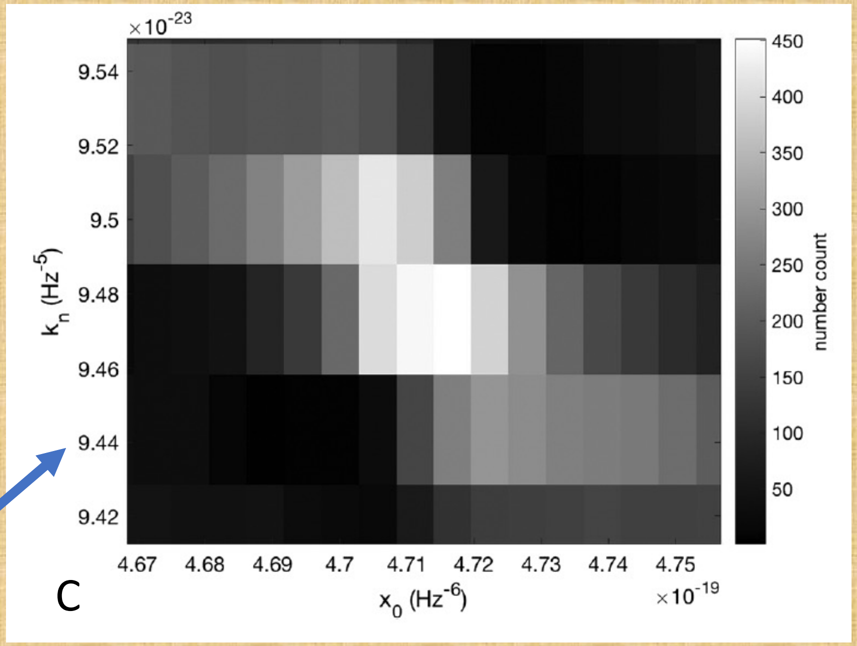
- Development of proper search methods is a very active field

- Strong need to improve the sensitivity!

The example of the “Generalized Frequency-Hough” transform

A) Time-frequency “peak-maps” (built from “short” FFTs)
B) Variable transformation to make the signal “straight”
C) Apply classical Frequency-Hough transform to find significant peaks in a 2D histogram





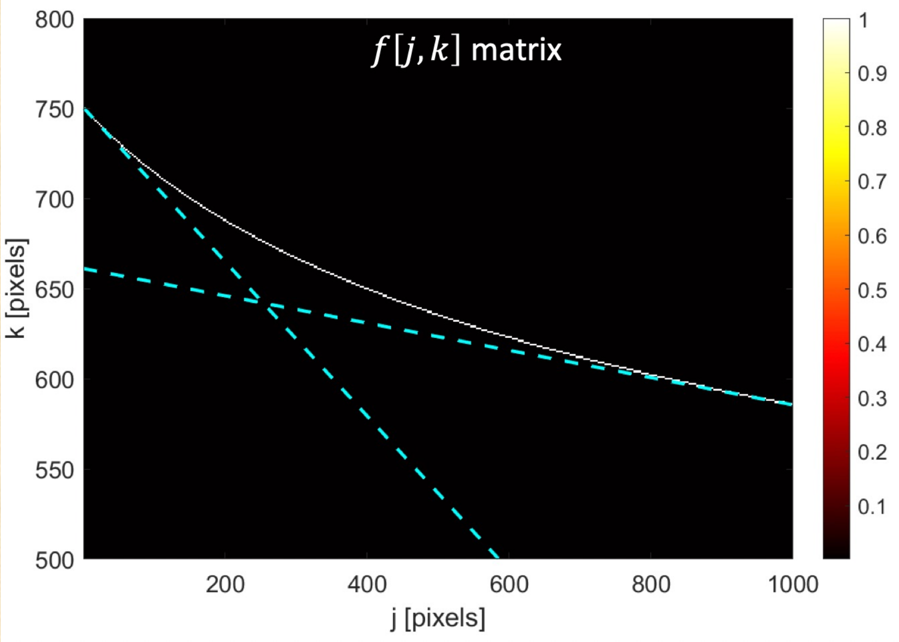
[Miller, Astone,…CP et al., PRD98, 102004 (2018)]

see P. Astone’s talk for more details on the FHT

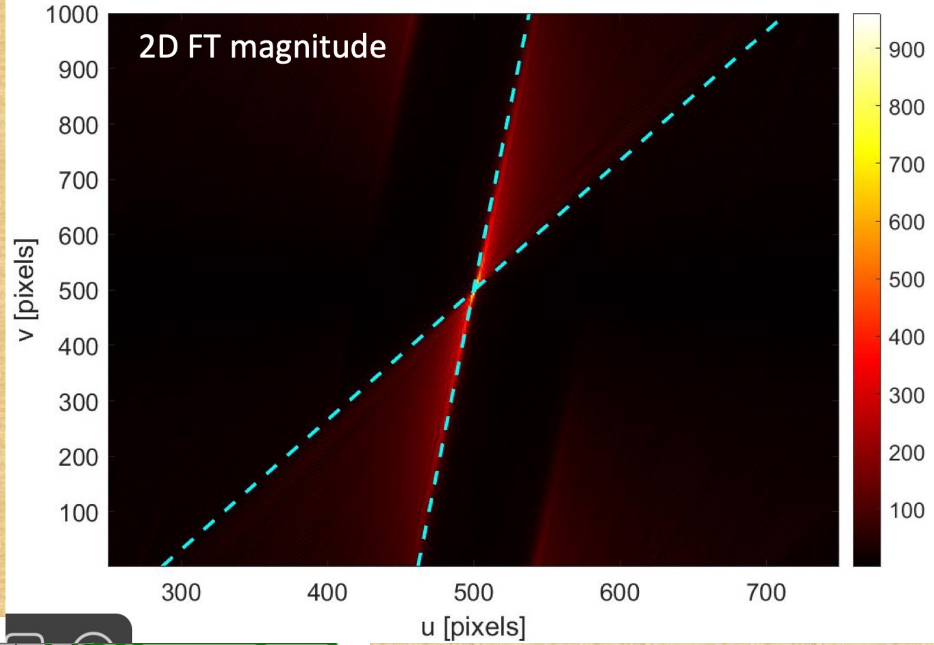
- Sensitivity of the method limited by the short data segment duration $\left(\propto T_{FFT}^{0.25}\right)$
- Computing cost is a steep function of the segment duration $(\propto T_{FFT}^{4})$

- Several efforts carried in parallel to improve search sensitivity.
  - Image processing: ”triangular filter” in 2D-Fourier domain [L. Pierini arxiv 2209.07276]

Simulated signal in the time-frequency space



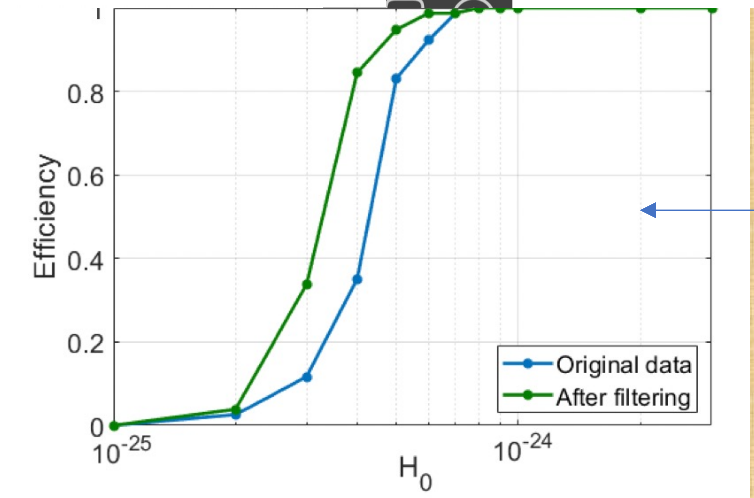
Simulated signal in the 2D FT space space



Pierini, PhD Thesis, Sapienza University of Rome (2022)

Signal power confined in a limited region

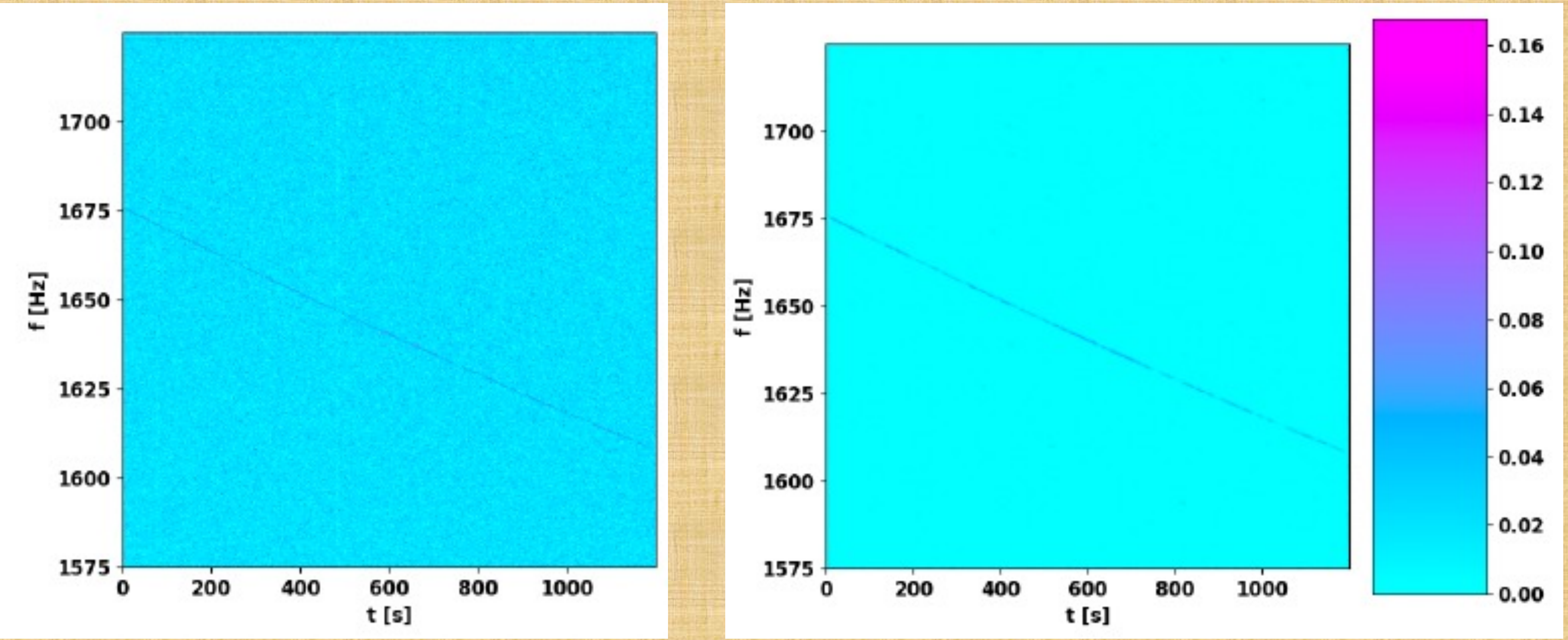
Build a filter to keep the signal and rid-off the noise



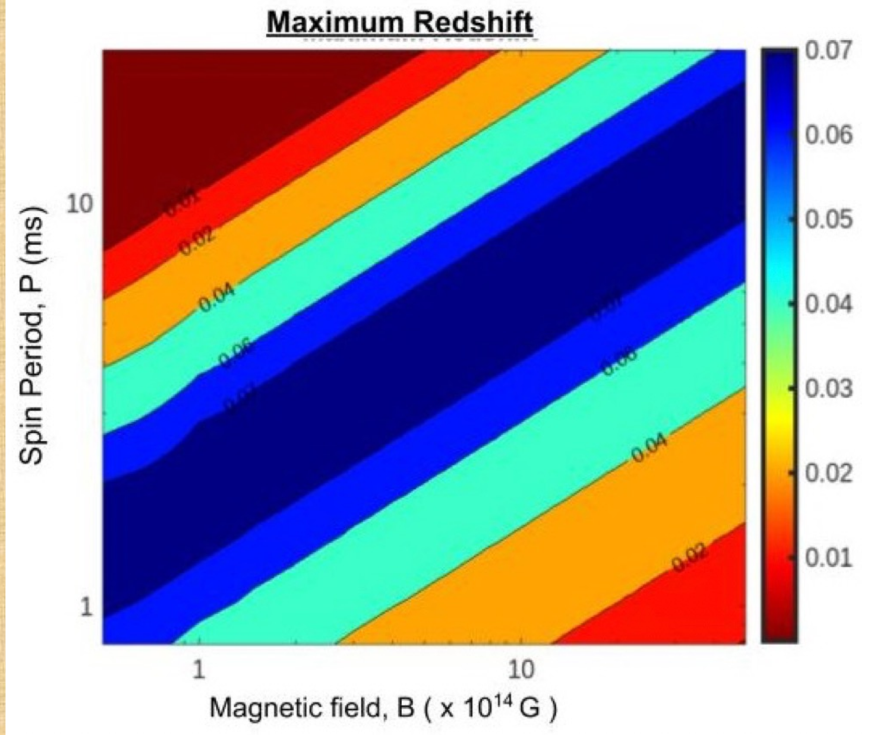
Improved signal efficiency

- ML techniques [e.g. A. Miller, P. Astone,…CP et al, PRD100, 062005 (2019); L. Modaffari et al., PRD108, 023005 (2023)]
  - To speed-up analysis (still not clear if they provide better sensitivity)
  - To reduce impact of noise (and then improve detection efficiency): denoisers

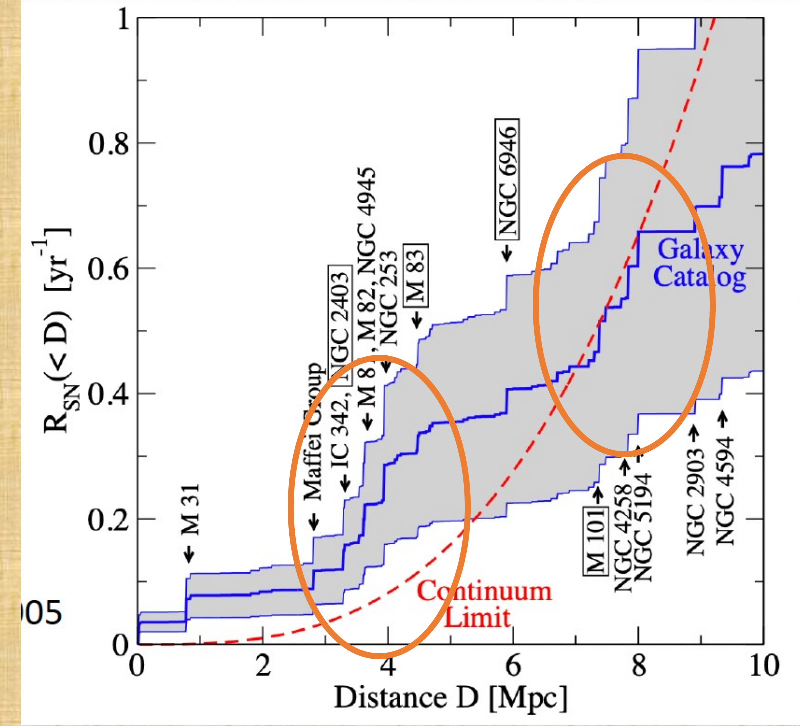
Raw and denoised spectrogram (O3 H data + simulated signal)
F. Attadio's Master Thesis – Sapienza University of Rome



- Multi-messenger approach to reduce the search parameter space
  - E.g. shock breakouts from core collapse SN
  - Early UV emission can pinpoint to the presence of a magnetar central engine
  - Light curve depends on magnetar parameters



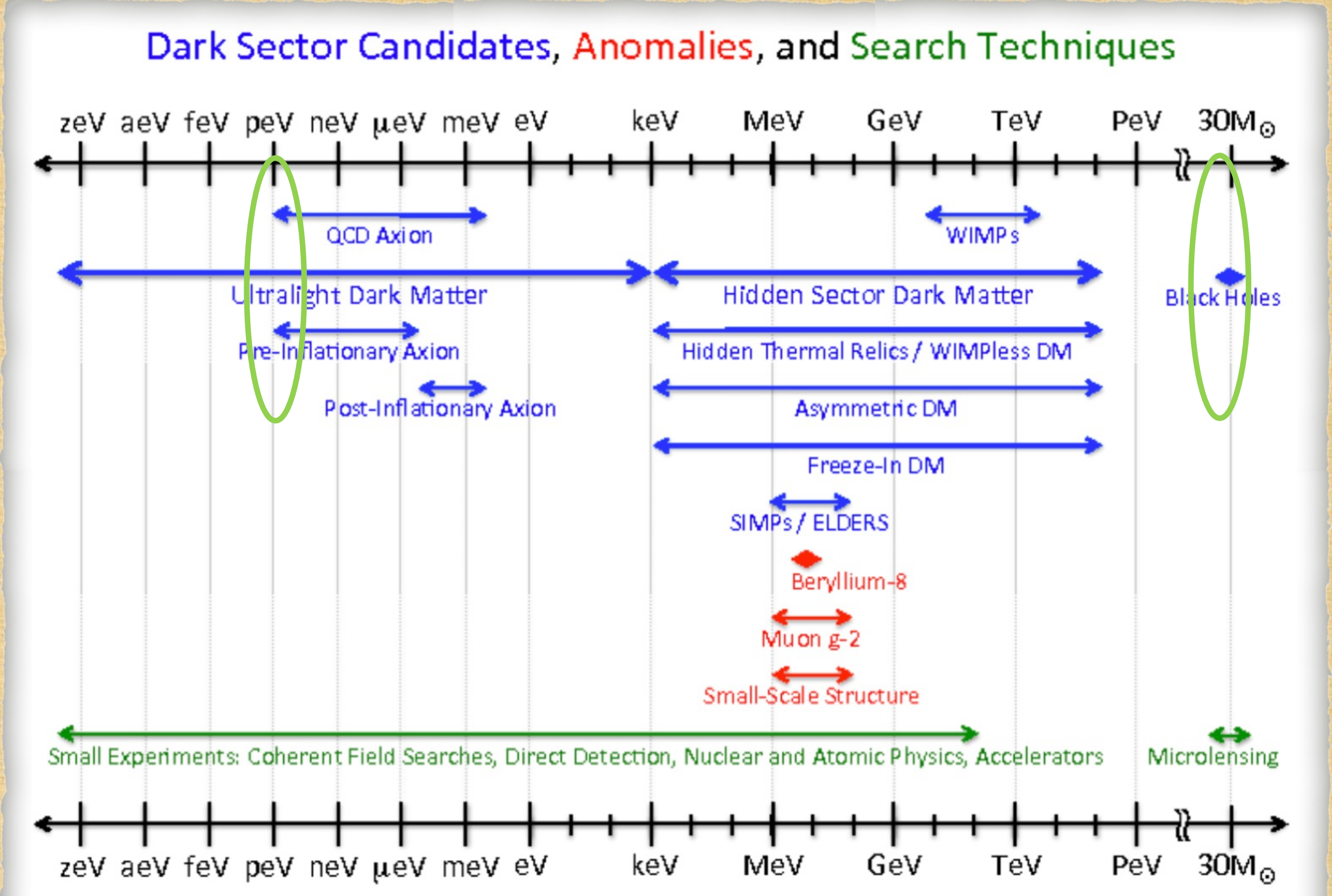
S. Menon, D. Guetta, S. Dall'Osso, ApJ 955, 6 (2023):
Maximum redshift for detection by planned ULTRASAT satellite (arxiv 2304.14482)



All these efforts aim at reaching an horizon of at least 4-8 Mpc by LVK run O5

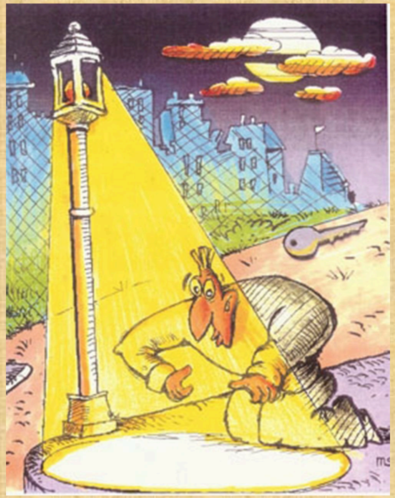
Gravitational Wave signatures of DM

- DM candidates cover ~90 orders of magnitude in mass



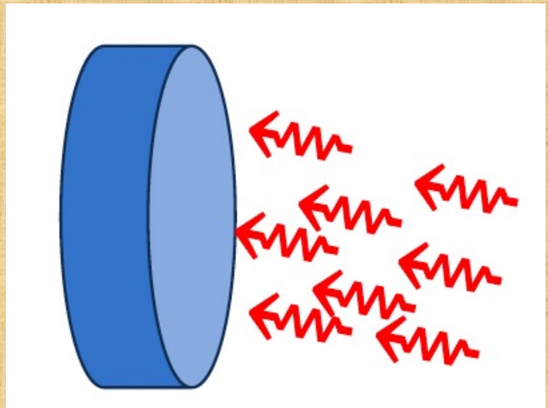
Credit: Battaglieri+, arxiv:1707.04591

GW detectors offer an ``opportunity window" for free

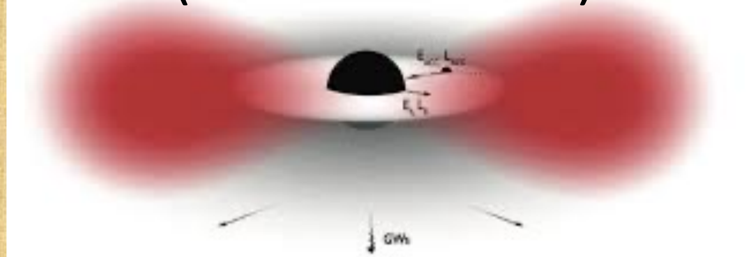


- In recent years, a growing body of literature on the potentiality of Gravitational Wave (GW) detectors as tools to probe DM has been produced (see e.g. Bertone+, arxiv:1907.10610)

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

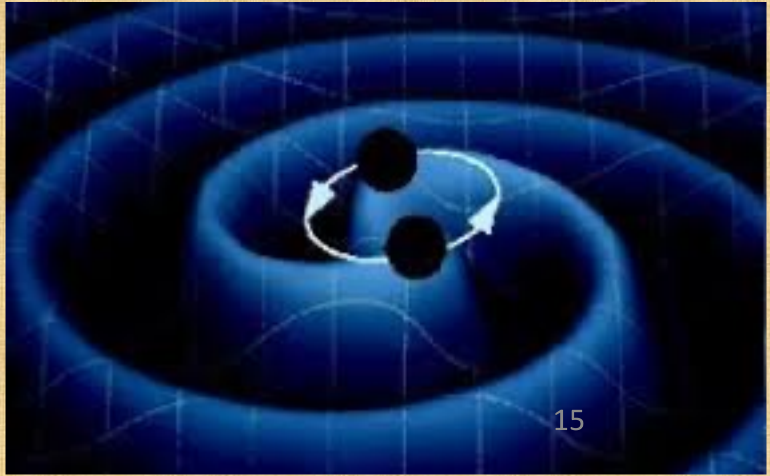


CW emission from boson clouds around Kerr BHs (10^{-14} – 10^{-11} eV)



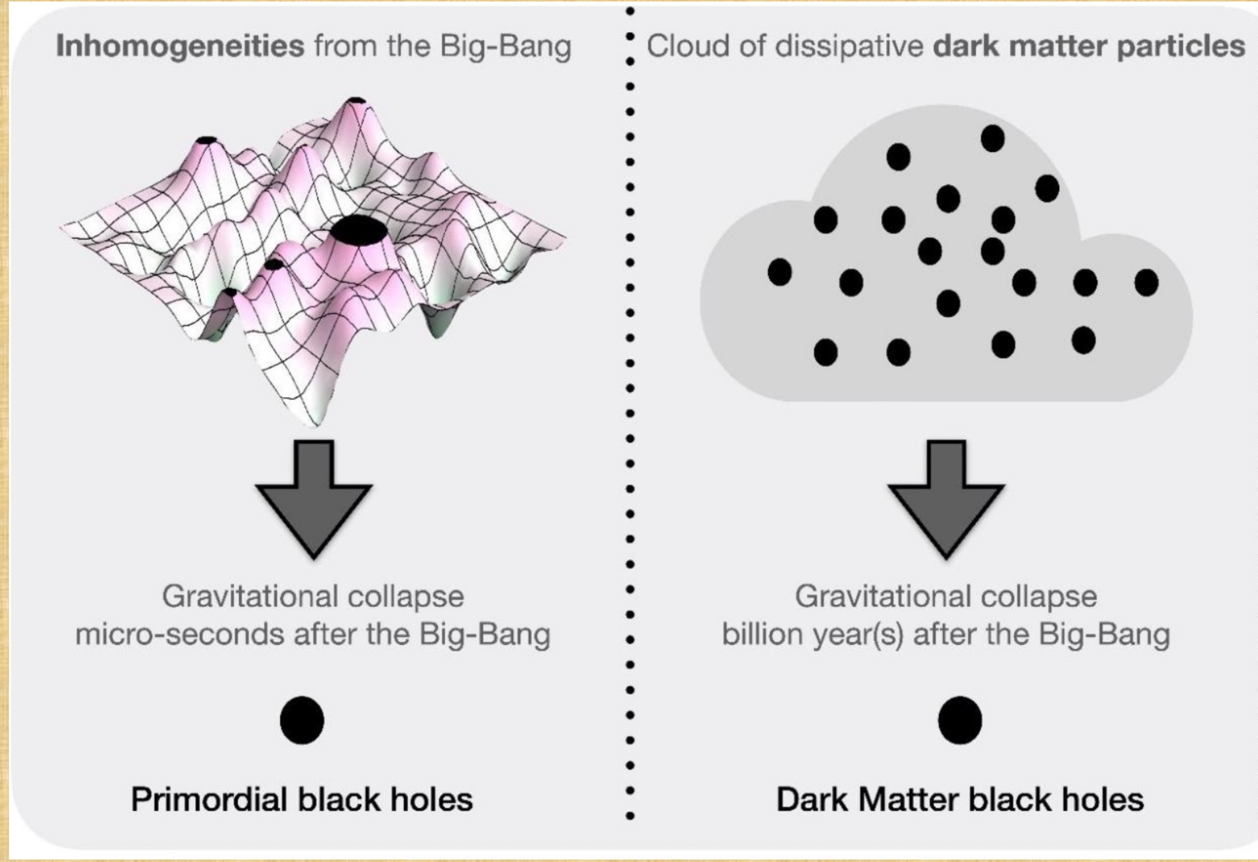
Picture credit: Ana Sousa Carvalho

Sub-solar mass BH inspirals ($M<0.01M_{sun}$)

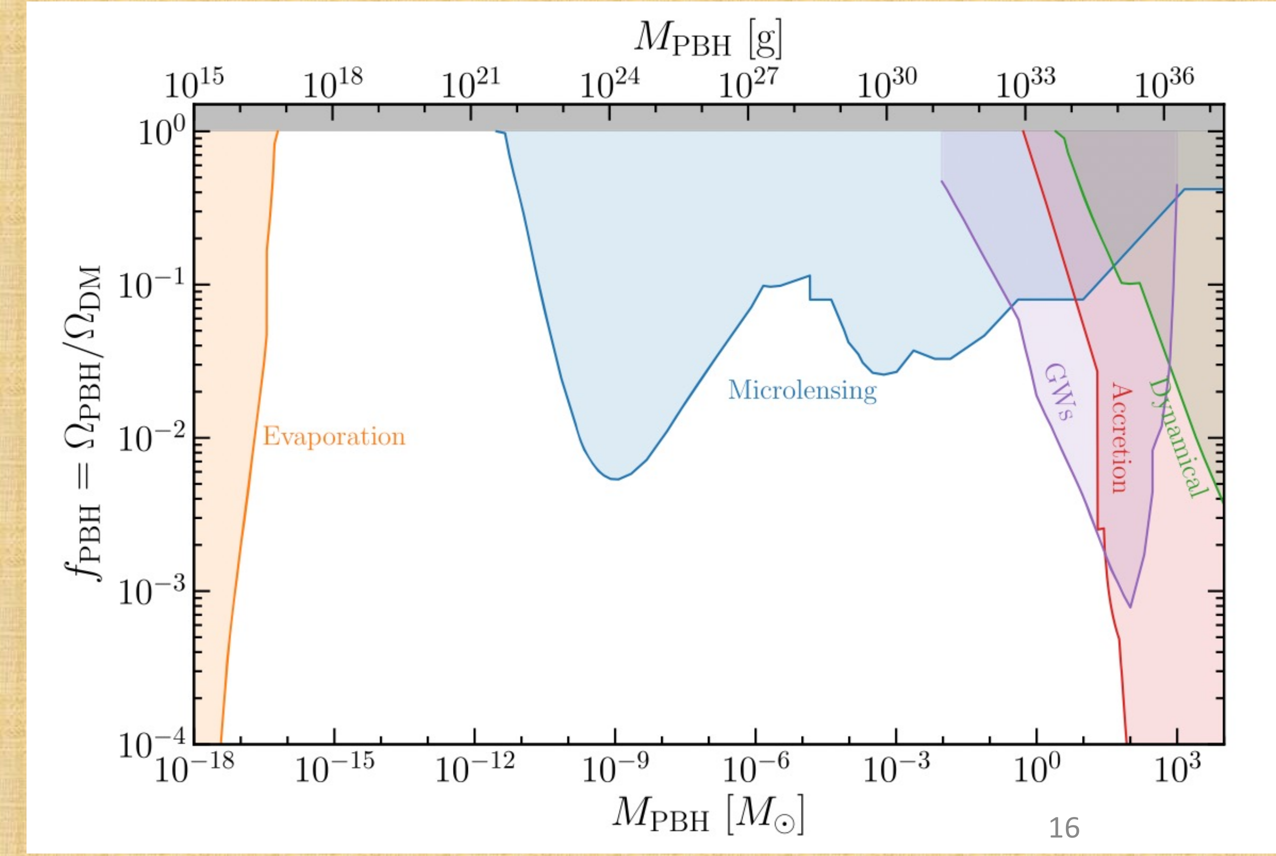


Sub-solar mass BH binaries

Formation mechanisms (very qualitative!)



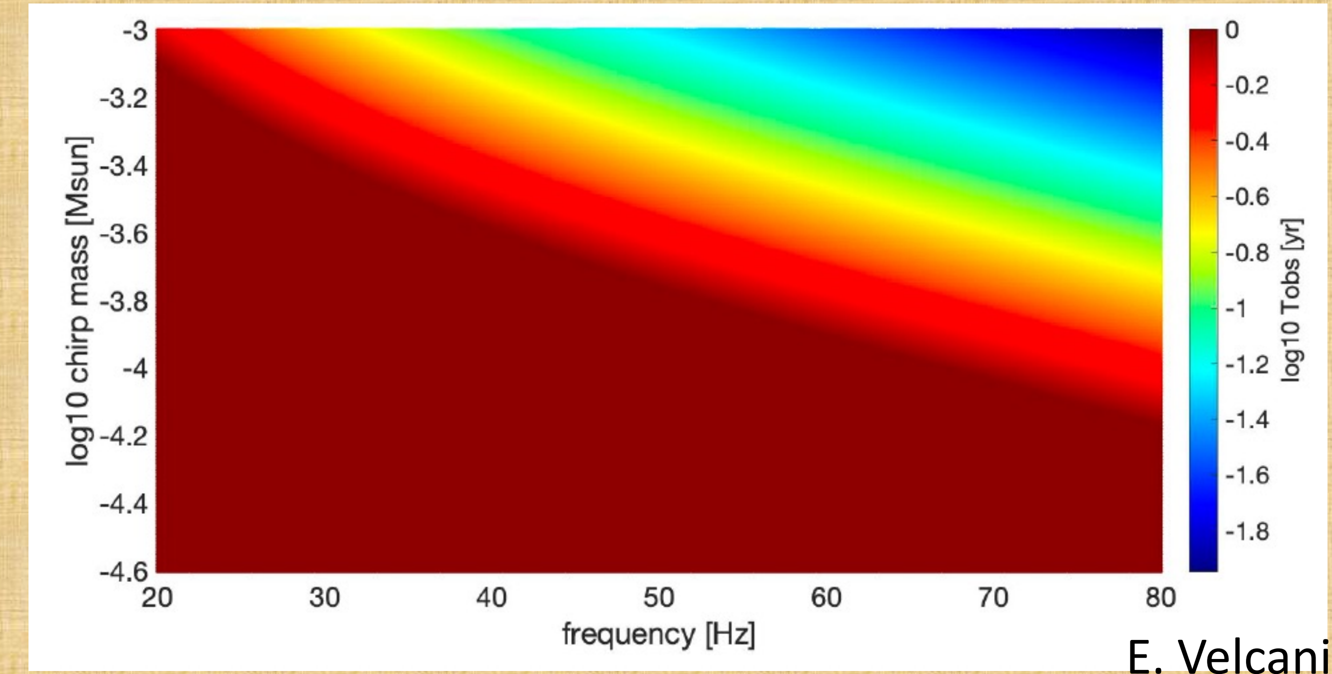
Current constraints on PBH abundance (with caveats!)



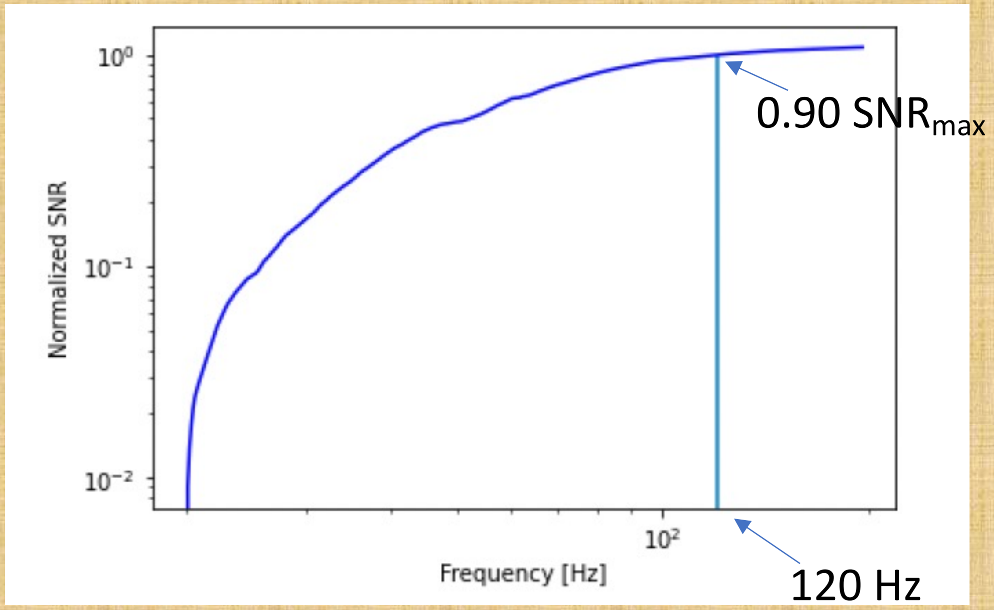
- For masses < 0.01 M_{sun} and just considering the early inspiral, PN0 waveforms are sufficiently accurate

- Moreover, limiting the search at the early inspiral significantly reduces the computing cost in front of a small sensitivity loss

Signal duration (for f_{max}=120 Hz), with T_{obs}=1 yr



SNR fraction as a function of the maximum search frequency (O3 L data)

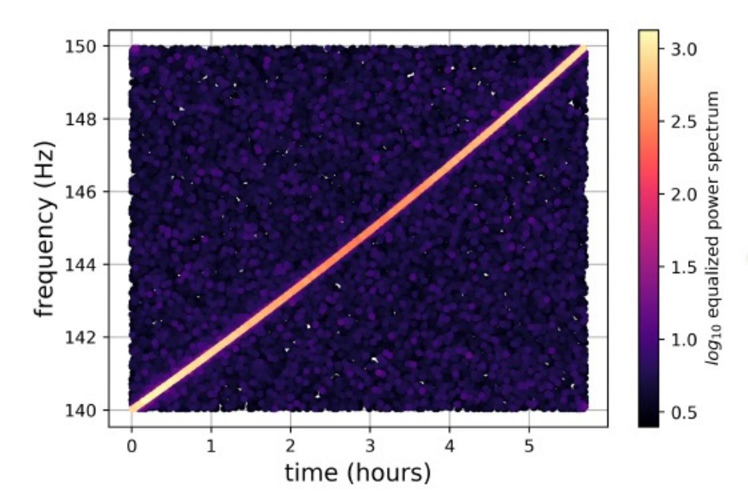


E. Velcani's Master Thesis – Sapienza University of Rome (2022)

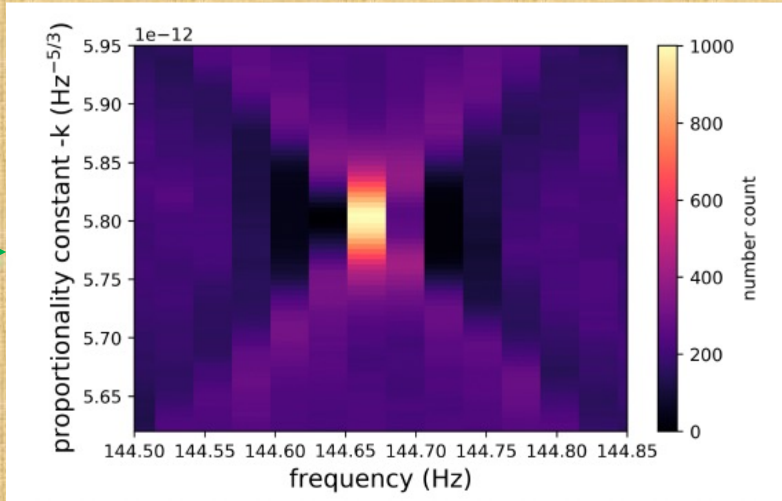
- Long-transient/CW signal, depending on parameters

- Methods for the search of long-transient signals from newborn NSs can be adapted to light PBH inspirals
  - * E.g. GFH algorithm [A. Miller, S. Clesse et al., 2012.12983]

Simulated PBH inspiral in O3 L data



GFH histogram



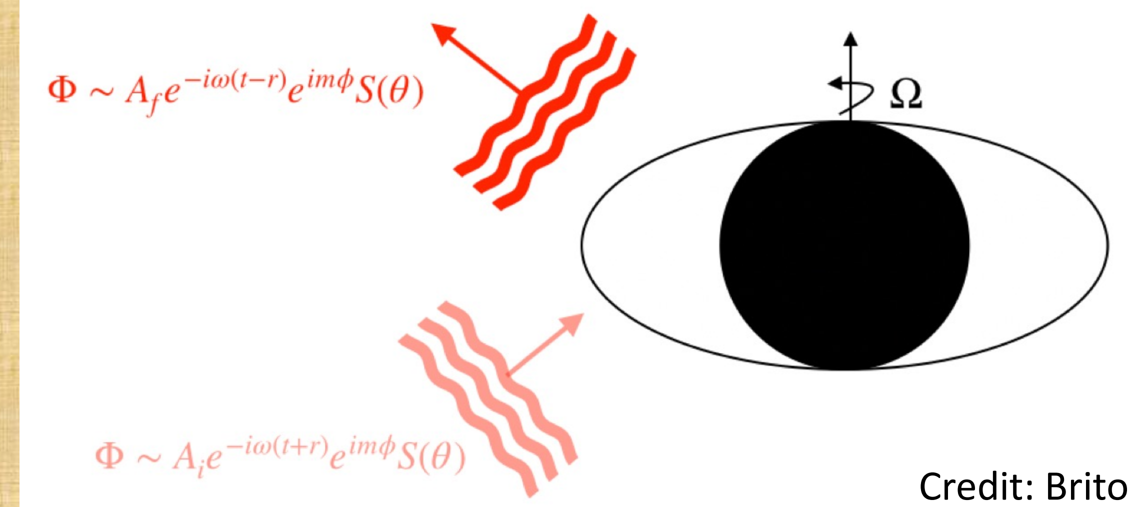
Sensitivity limited by short allowed FFT length

- Methods to boost the sensitivity are being explored:
  - “smart” construction of the parameter space grid [Rome, IFAE Barcelona groups]
  - resampling [joint Rome/ANU project]
    - define a new time variable in which the signal is nearly monochromatic

→ Poster by Neil Lu on display on Thursday

Ultra-light boson clouds

- Massive bosonic fields around a Kerr BH induce a superradiance instability, in which the field is amplified, at the expense of the BH rotational energy



Credit: Brito

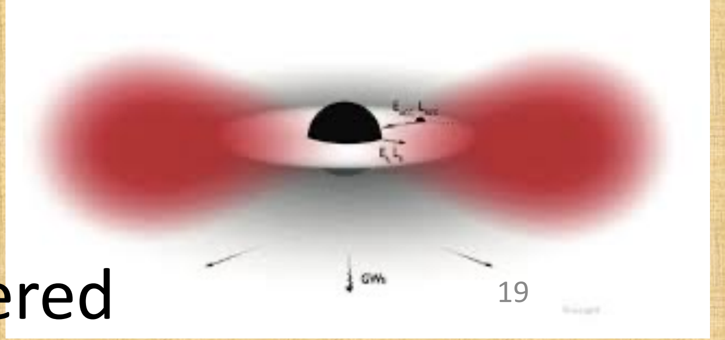
Possible candidates:
QCD axion
Axion-like particles from string theory
Dark photon
……

field angular frequency — azimuthal quantum number

Superradiance condition: $\omega < m\Omega$

BH angular frequency at the outer horizon

- A macroscopic boson condensate forms around the BH



- Scalar, vector and also tensor bosons have been considered

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

[Arvanitaki et al., PRD81, 123530 (2010); Yoshino & Kodama, Prog. Rep. Theor. Phys. 043E02 (2014); Arvanitaki et al., PRD91, 084011 (2015); Brito et al., PRD96, 064050 (2017); East, PRL121, 131104 (2018); Baryakhtar et al., PRD103, 095019 (2021);

signal frequency:

$$f_{\rm gw} \simeq 483\ \text{Hz} \left(\frac{m_{\rm b}}{10^{-12}\ \text{eV}}\right) \times \left[1 - 7\times10^{-4}\left(\frac{M_{\rm BH}}{10\ M_\odot}\frac{m_{\rm b}}{10^{-12}\ \text{eV}}\right)^2\right]$$

$f_{gw} \in [10, 10^4]$ Hz for $m_b \in [10^{-14}, 10^{-11}]$ eV

$$h_0 \approx 6\times10^{-24}\left(\frac{M_{\rm BH}}{10\ M_\odot}\right)\left(\frac{\alpha}{0.1}\right)^7\left(\frac{1\ \text{kpc}}{D}\right)(\chi_i - \chi_c)$$

for scalar bosons, and $\alpha \ll 1$

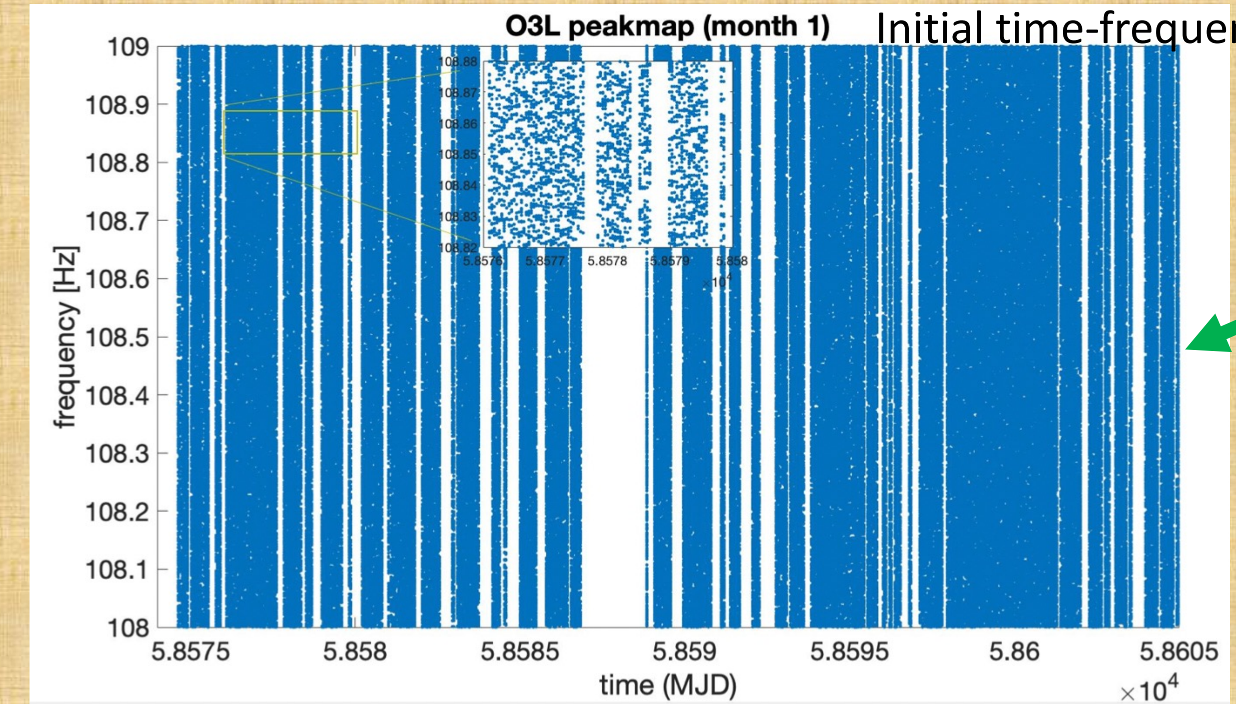
$$\alpha = \frac{GM_{\rm BH}}{c^3}\frac{m_b}{\hbar}$$

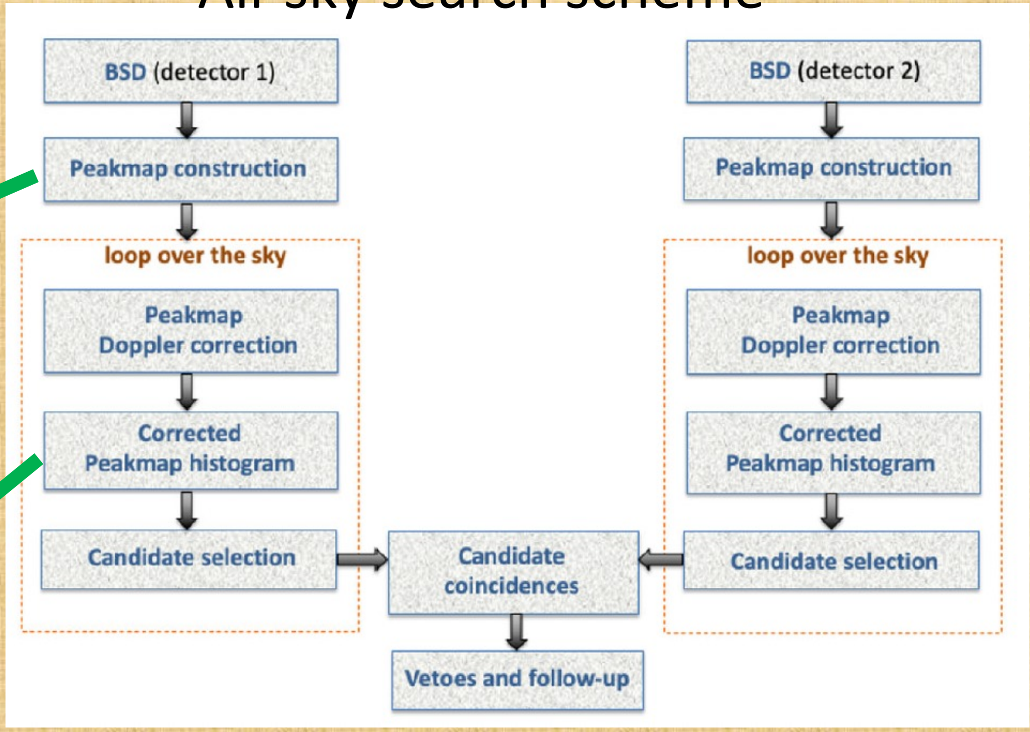
For vector bosons, stronger signals and shorter duration

- Various DA methods have been developed and applied to search for CW-like signals from boson clouds (both for all-sky and directed searches)

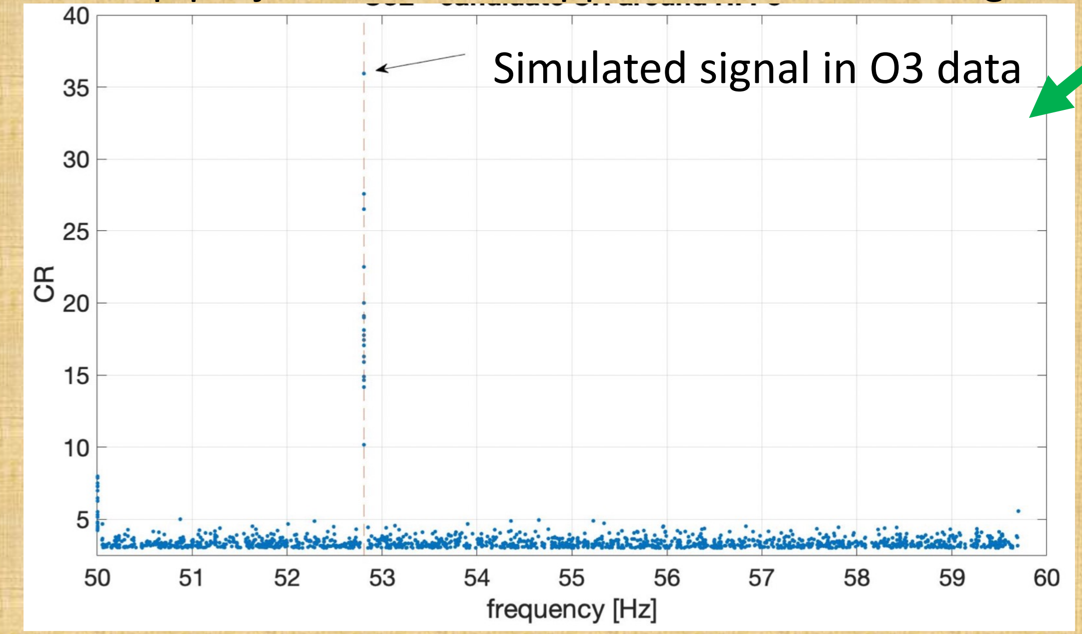
All-sky search scheme

Initial time-frequency map

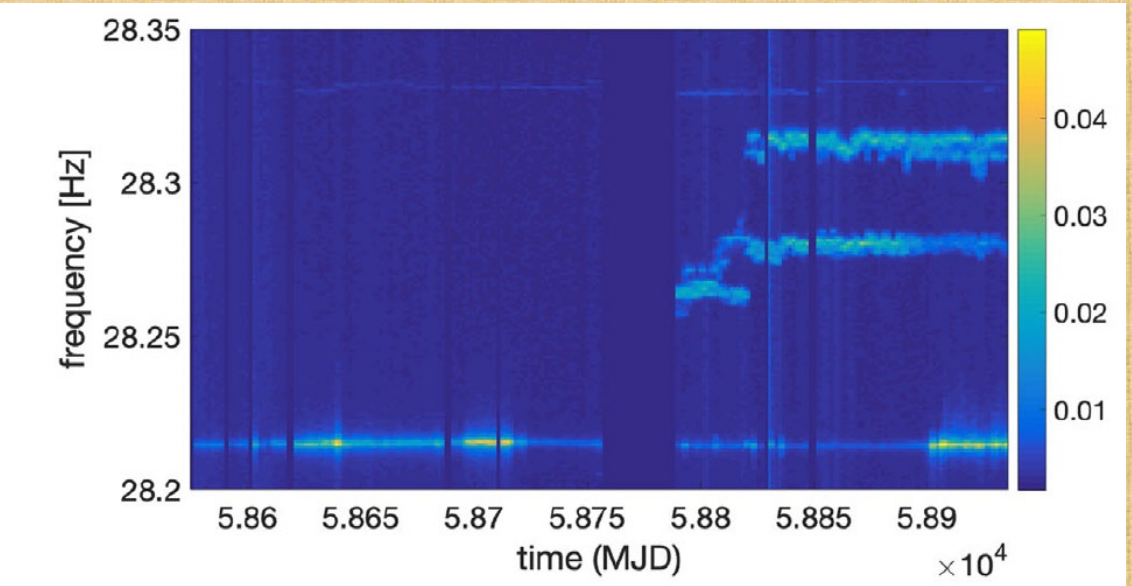




Peakmap projection after Doppler correction for a given sky location

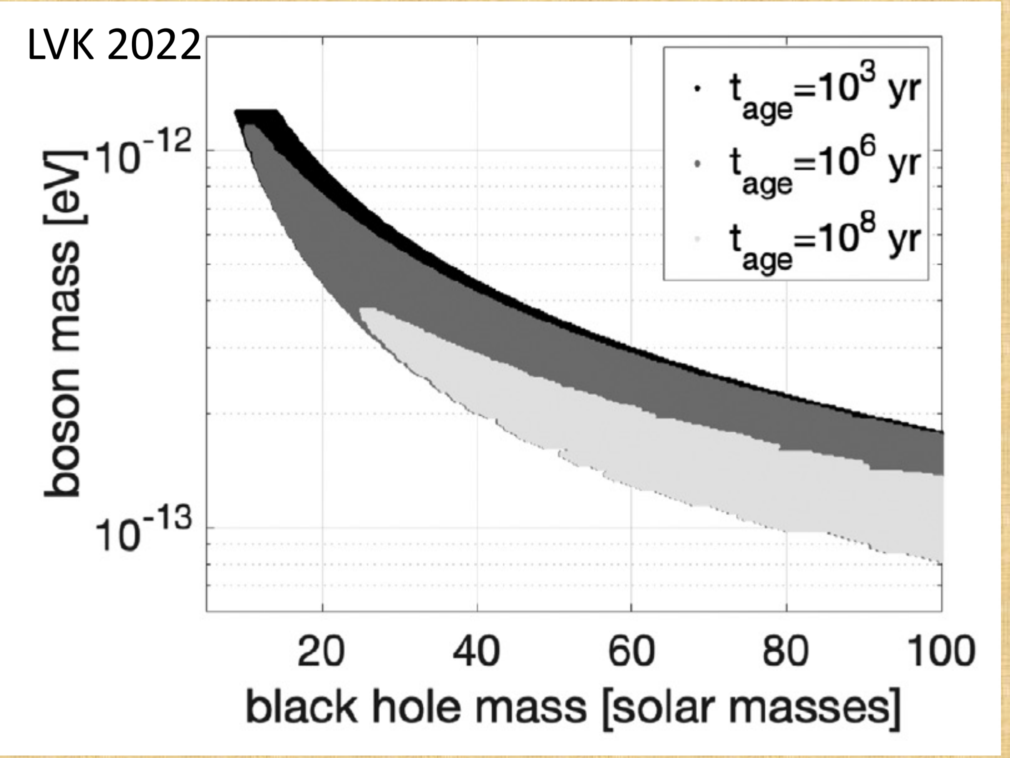


Real data are full of weird stuff

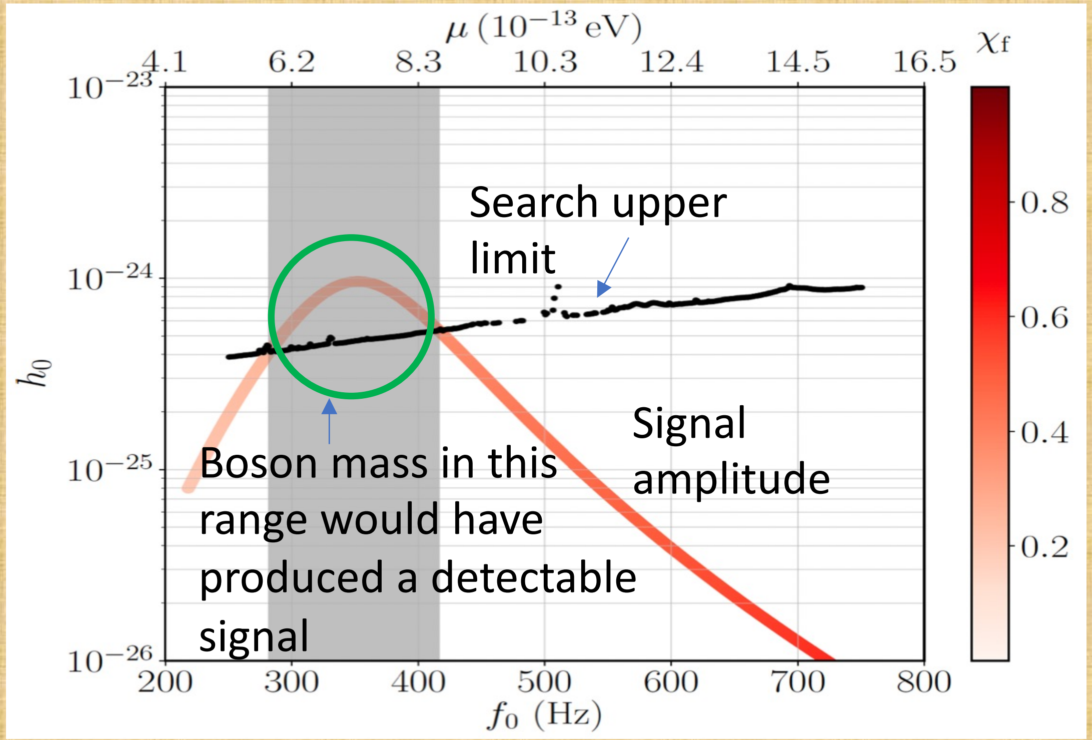


Result examples (scalar clouds)

Exclusion regions from all-sky O3 analysis (D=1kpc, χ_i=0.5)



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



- All-sky searches (scalar bosons)

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

- Directed, post-merger BHs (vector bosons)

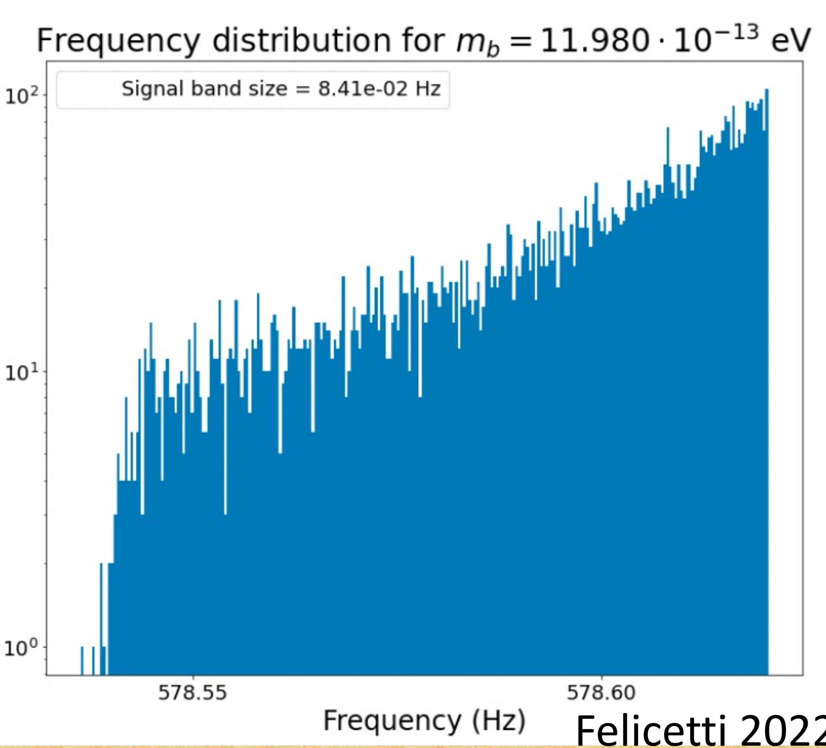
  [Jones, Sun et al., PRD108, 064001 (2023)]

- Directed searches (scalar bosons)

  [Sun et al., PRD101, 063020 (2020);
  Zhu, Baryakhtar et al., PRD102, 063020 (2020);
  LVK, PRD106, 042003 (2022);
  D'Antonio, CP, Astone et al., accepted in PRD (2023)]

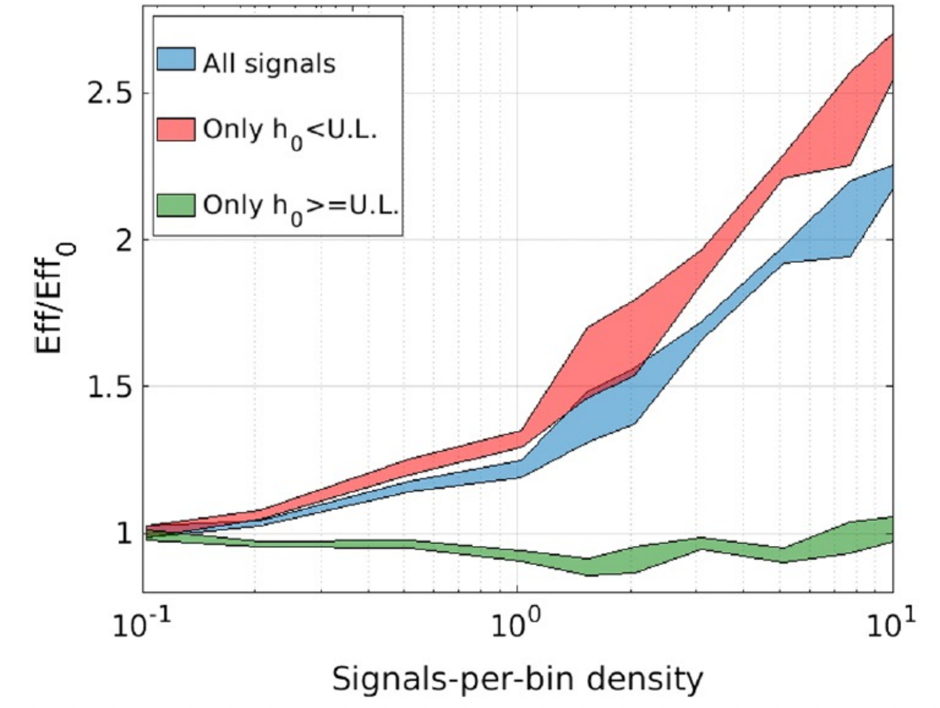
- $10^7 - 10^8$ BHs are expected to exist in the Milky Way

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



Felicetti 2022

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

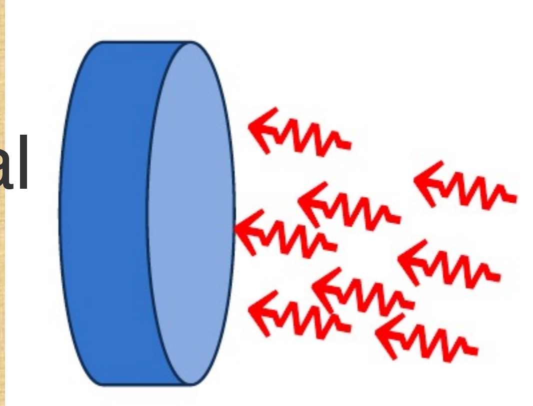


Pierini+ 2022

- 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]

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

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

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

◉ 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

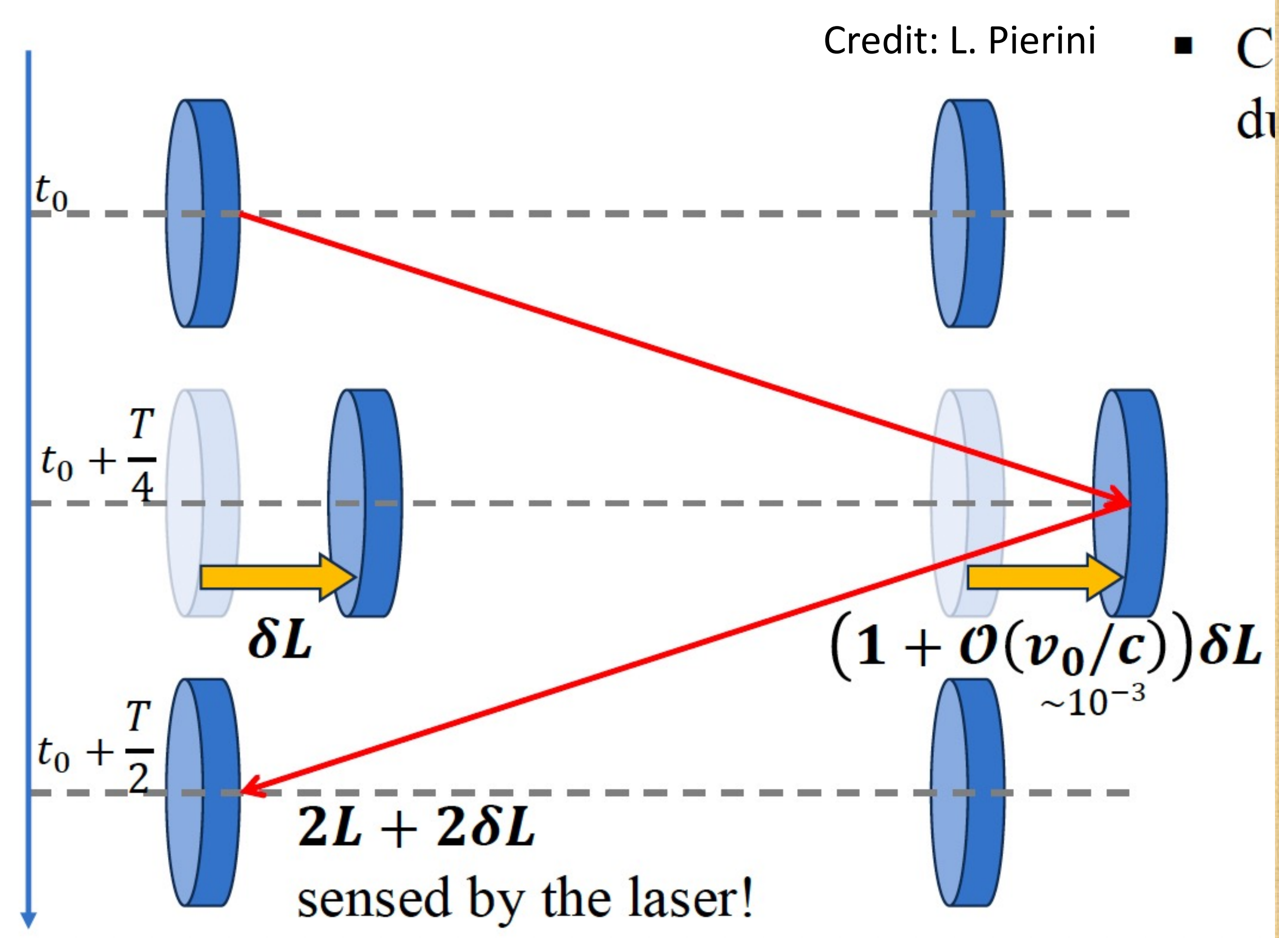
$$\sqrt{\langle h_D^2 \rangle} = C \frac{q}{M} \frac{\hbar e}{c^4 \sqrt{\epsilon_0}} \sqrt{2\rho_{\rm DM}} v_0 \frac{\epsilon}{f_0},$$
$$\simeq 6.56 \times 10^{-27} \left(\frac{\epsilon}{10^{-23}}\right) \left(\frac{100 \text{ Hz}}{f_0}\right)$$

Pierce+ 2018

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

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

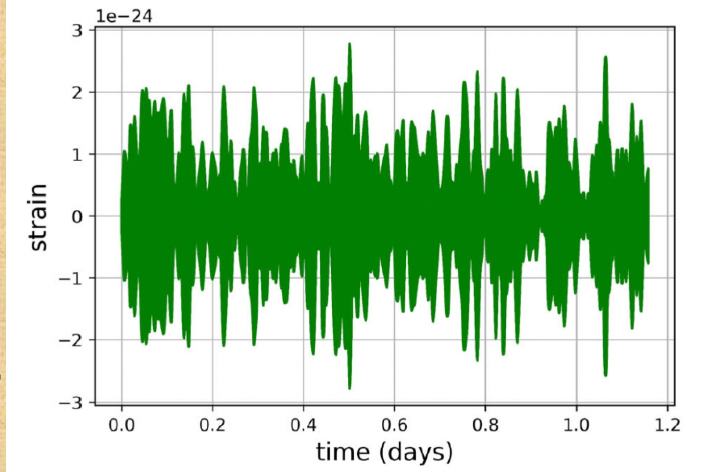
Morisaki+ 2021

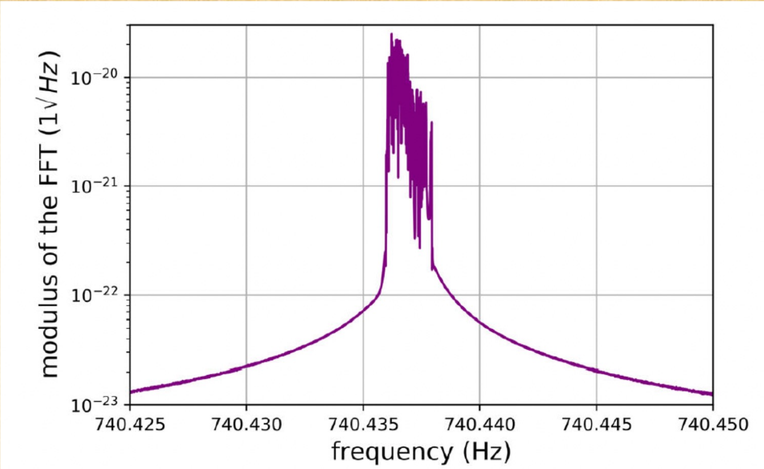


◉ Stochastic and narrow-band signal

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

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





[Miller,…CP et al., PRD 103, 103002 (2021)]

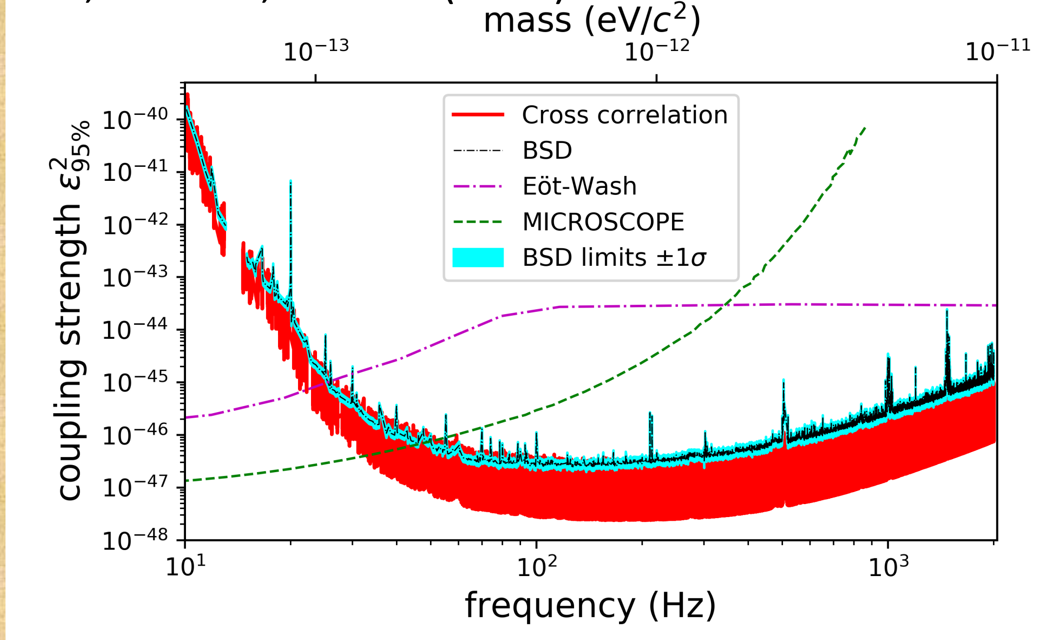
◉ It can be searched into the detector data with techniques adapted from those used in the search of "traditional" CW and/or stochastic signals

O3 analysis with:

* Cross-correlation

* Excess power (BSD)

LVK, PRD105, 063030 (2022)



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

See also very interesting results on scalar DM coupled to GEO600 beam-splitter [Vermeulen+, Nature 2021]

Conclusions

- Search methods developed for ``standard'' CW signals (from spinning NSs) can be used/adapted to search for ``less standard'' sources

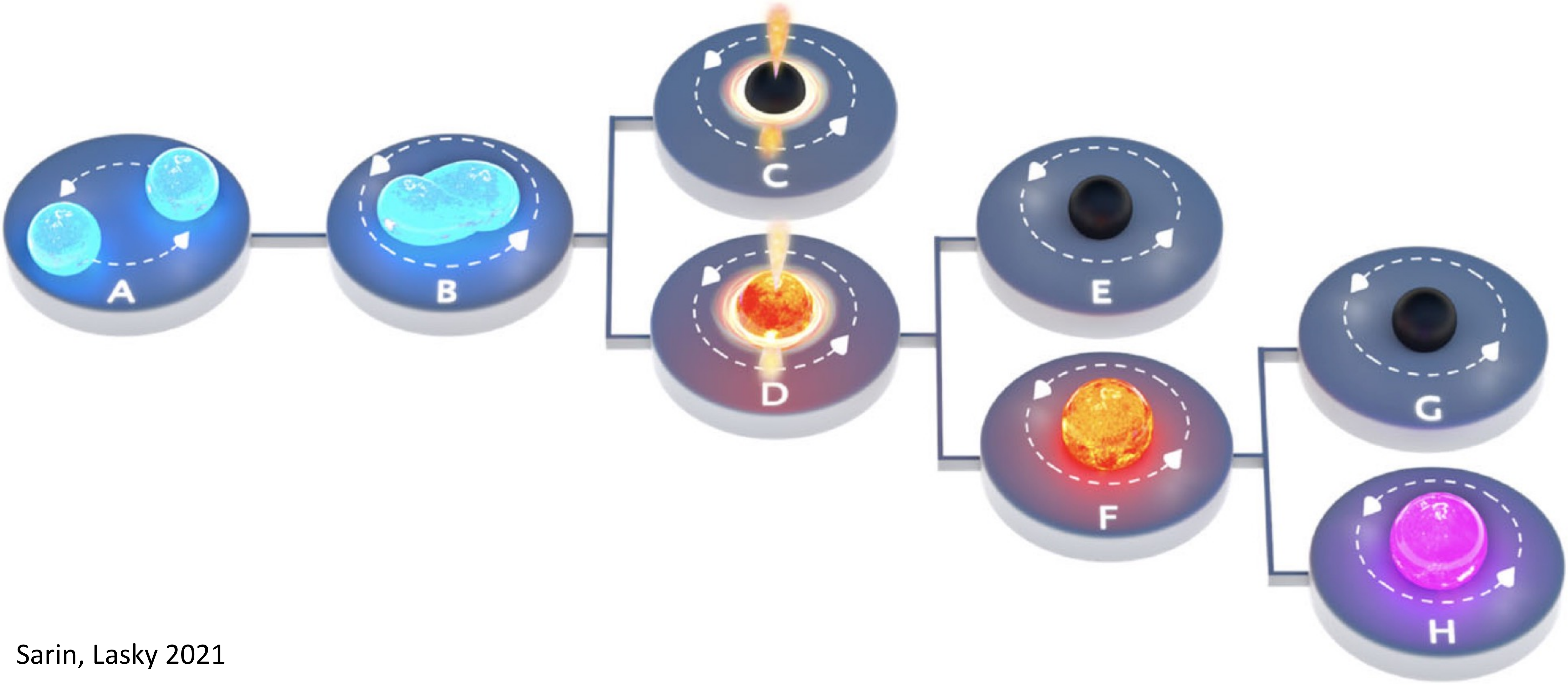
- GW detectors can be also used as ``particle detectors", basically for free

- A detection from exotic CW sources could well be possible right NOW

- In the worst case, we are paving the way for enhanced DA methods to be used with 3rd generation detectors, like Einstein Telescope and Cosmic Explorer

BACKUP SLIDES

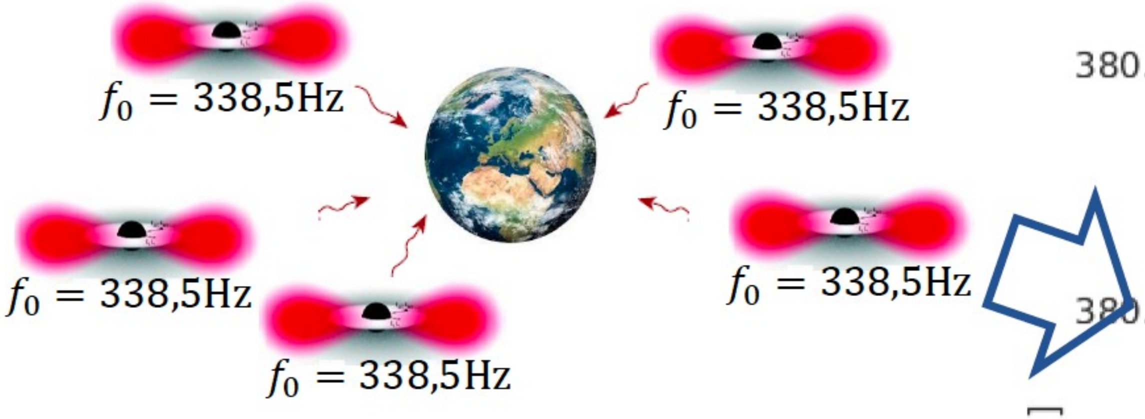
The fate of NSNS coalescence

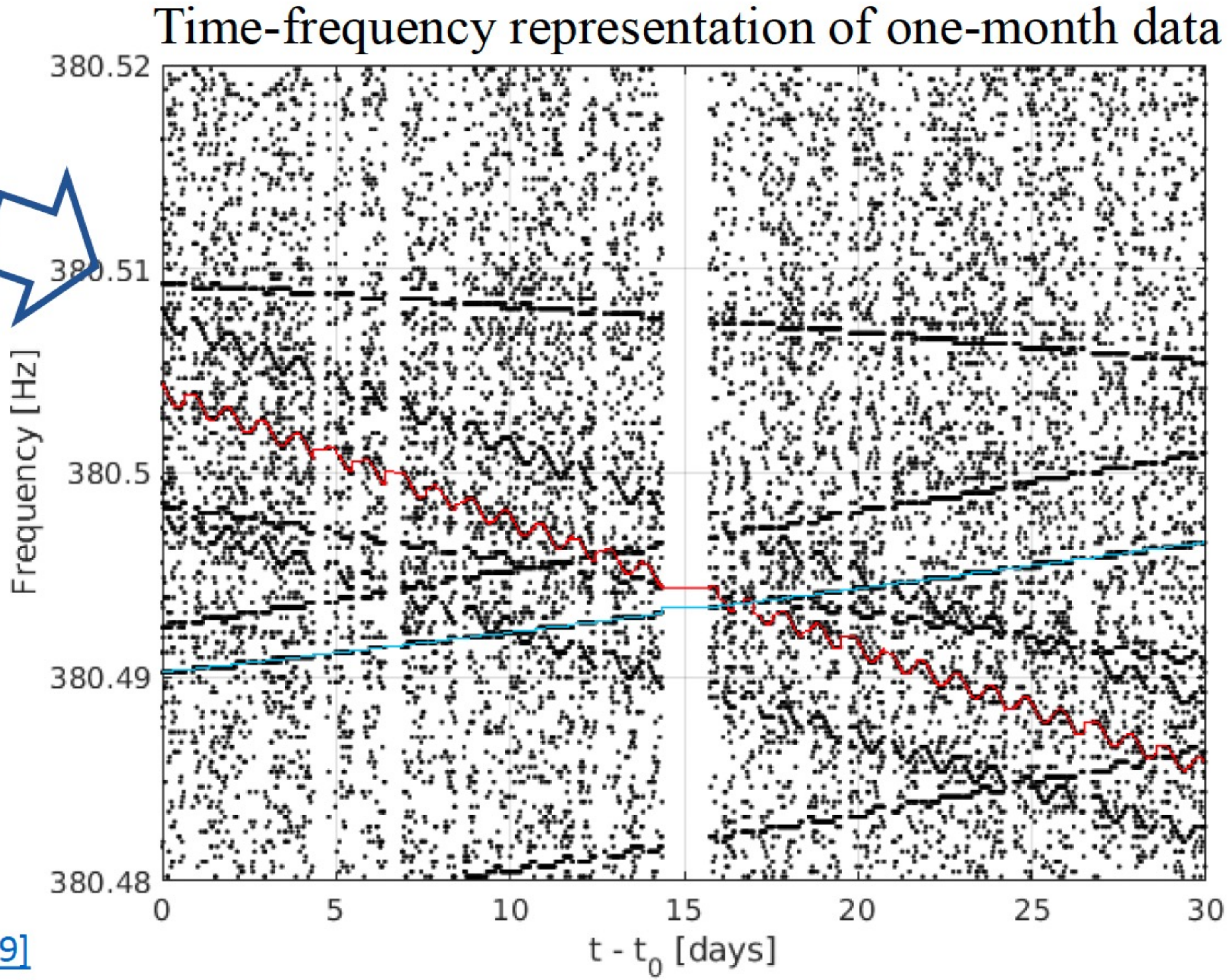


Sarin, Lasky 2021

Multiple signals can be resolved!

Credit: L. Pierini

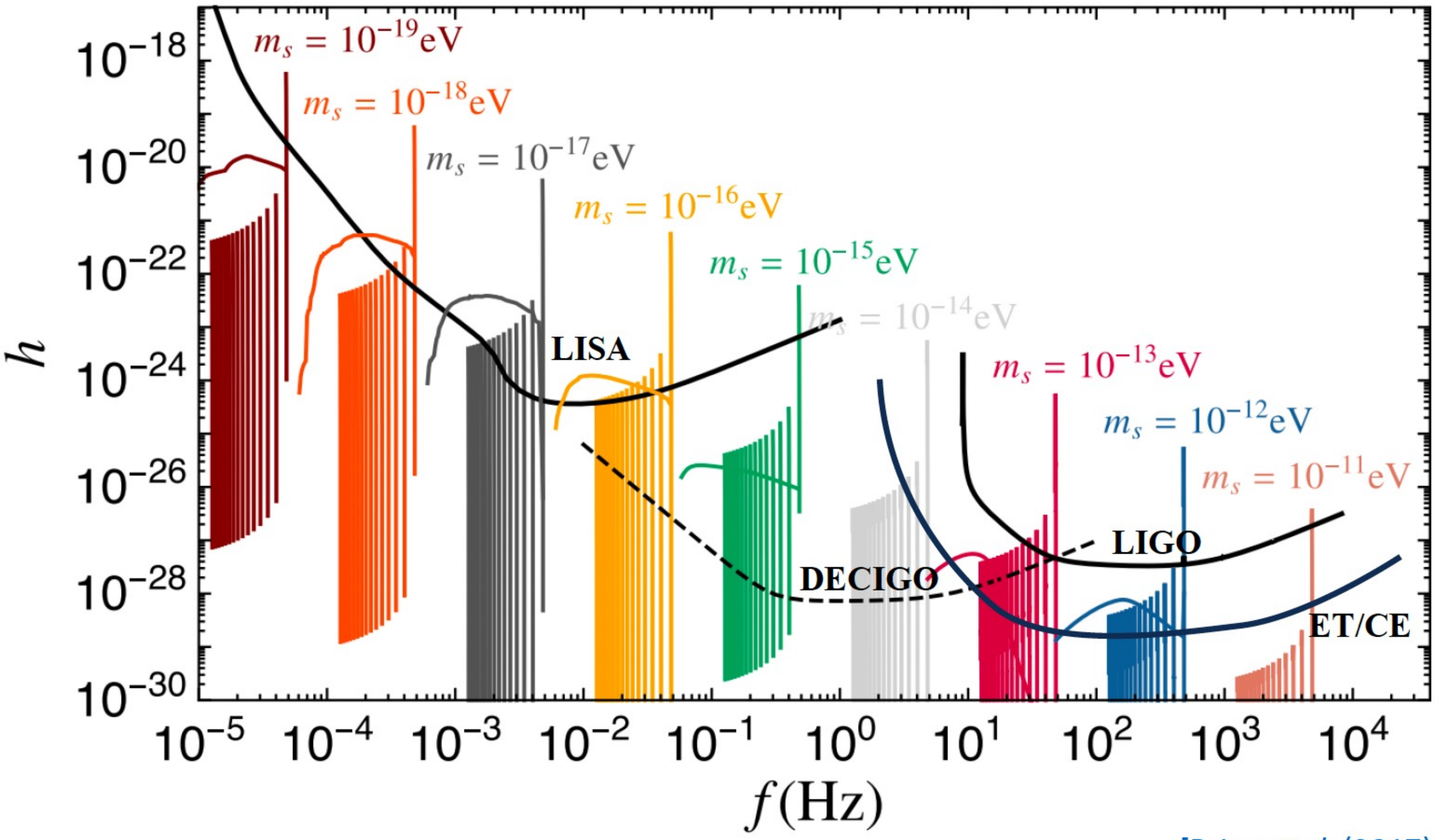




- The daily and annual Doppler effect due to the Earth motion modulates the observed signal.
- Exploiting the Doppler, we can resolve individual signals up to the sky resolution.

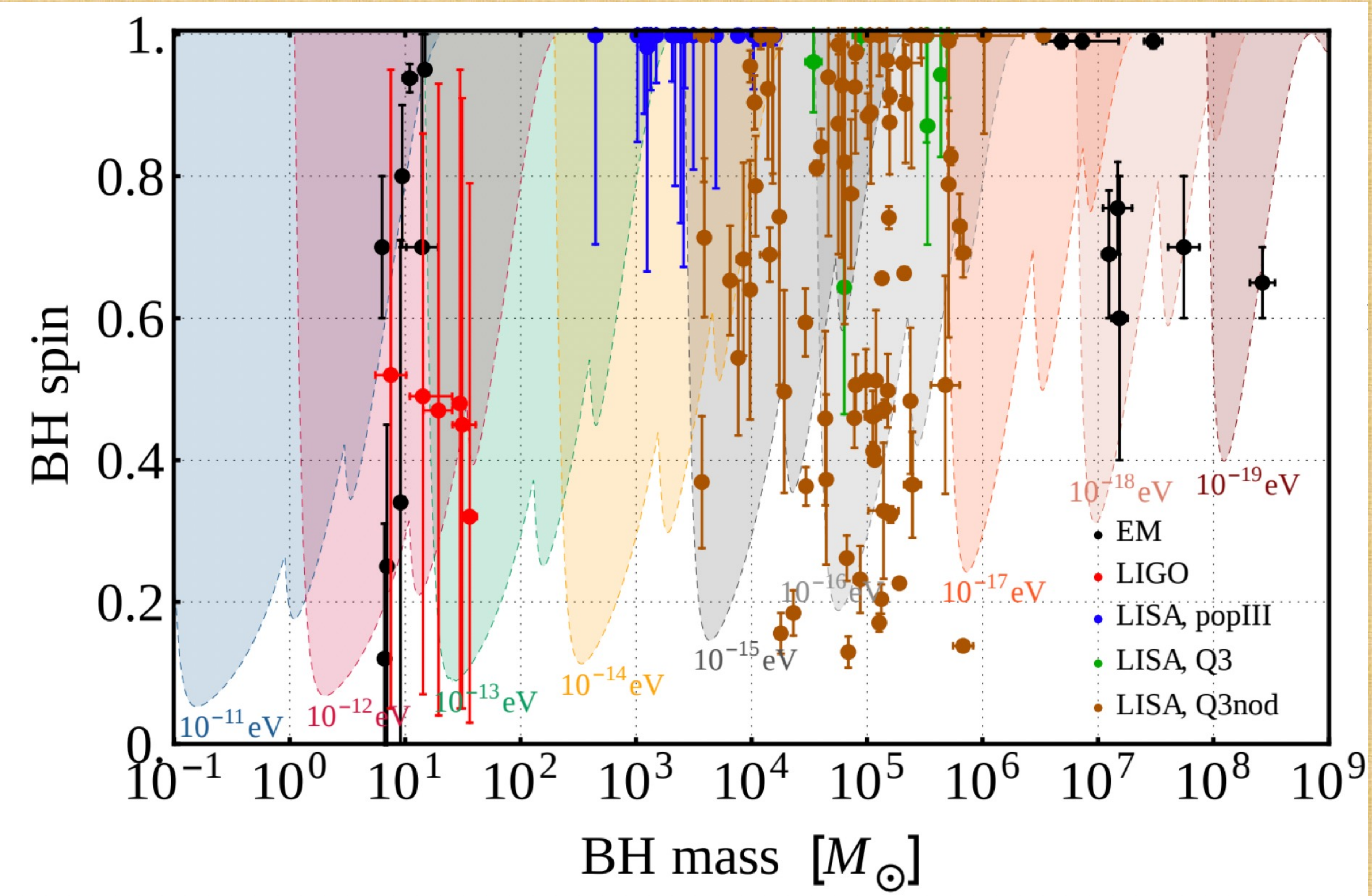
[Pierini et al. (2022) PRD 106(4), 042009]

Future observations

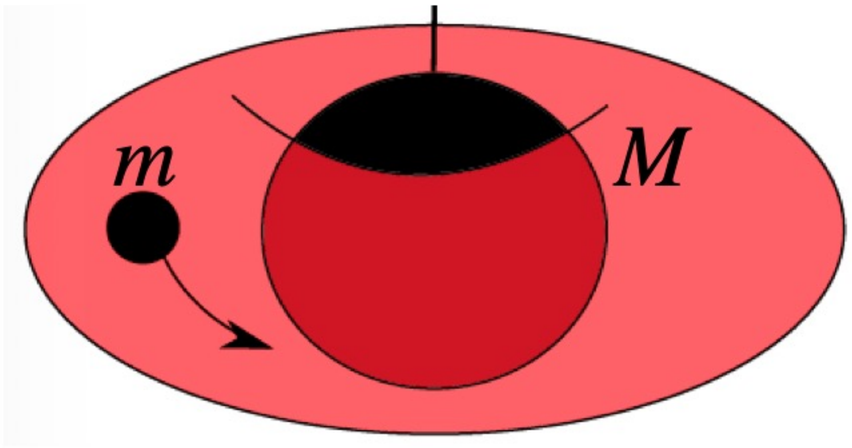


[Brito *et al*. (2017) **PRL 119**, 131101]

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



Impact of boson clouds on binary dynamics (and viceversa)



Credit: O. Hannuksela

Yang+ 2018
Hannuksela+ 2018
Baumann+ 2019
Choudhary+ 2021
De Luca, Pani 2021
…..

⊙ 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

$$\mathcal{L} = -\frac{1}{4}A'_{\mu\nu}A'^{\mu\nu} + \frac{1}{2}m_A^2 A'^{\mu}A'_{\mu} - \epsilon_A e J^{\mu}_{EM} A'_{\mu}$$

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

A'_{μ} : DP field

m_A : DP mass

ϵ_A : DP coupling strength

⊙ It couples to baryon or neutron number

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

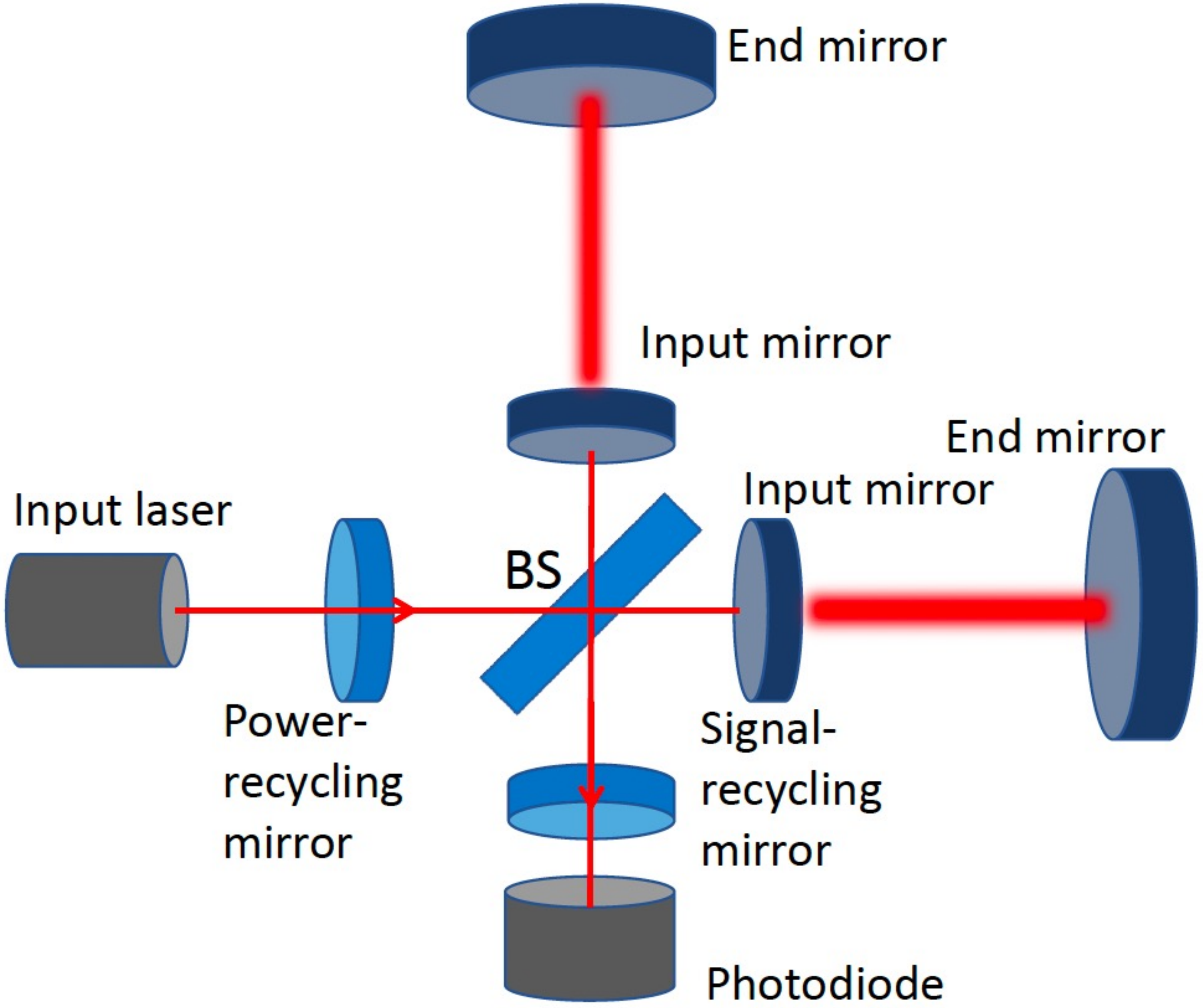
The DP field can be described as a superposition of plane waves →

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

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

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

The peculiarity of KAGRA



- End and Input mirrors are made by **sapphire**.
- Beam-splitter and recycling mirrors are made by **fused-silica**.
- The force on the optics is composition-dependent!
- The effect can be observed by the auxiliary channels, which monitor the intra-optics distances.
- Will provide meaningful results in the next observing runs.

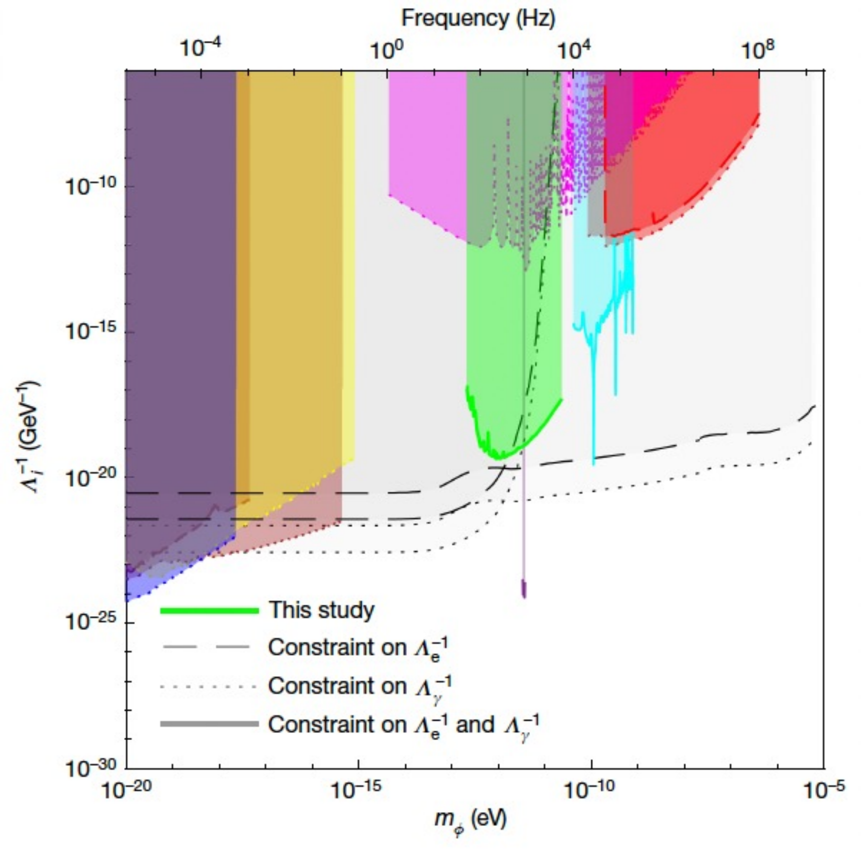
Slide credit: L. Pierini

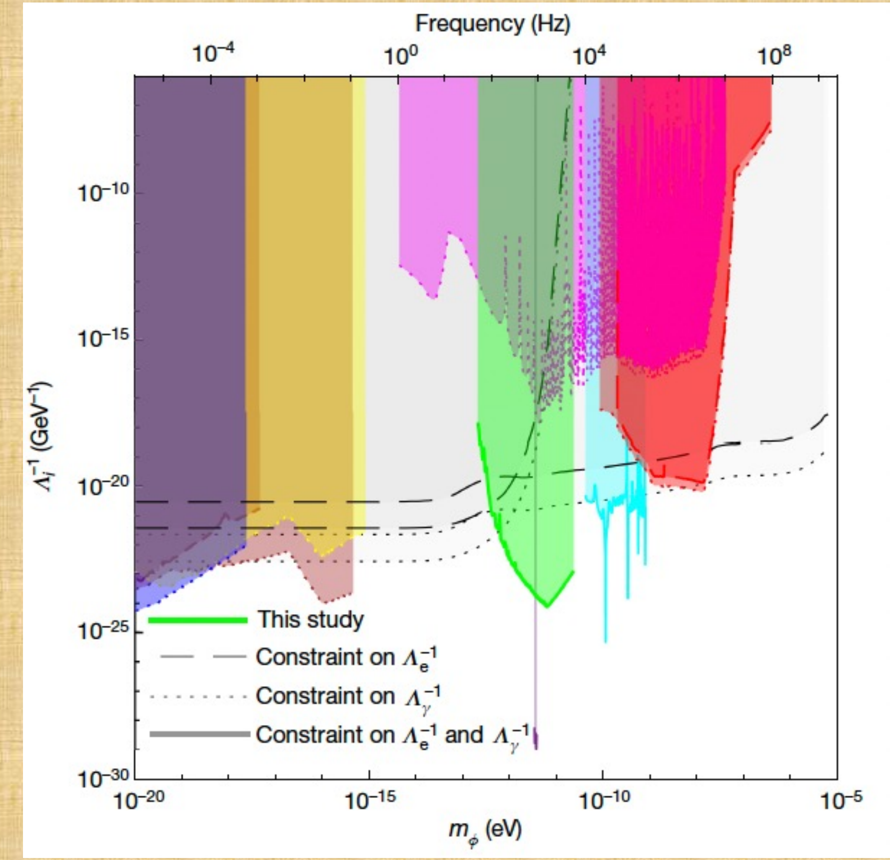
[Michimura *et al*. (2020) **PRD 102**, 102001]

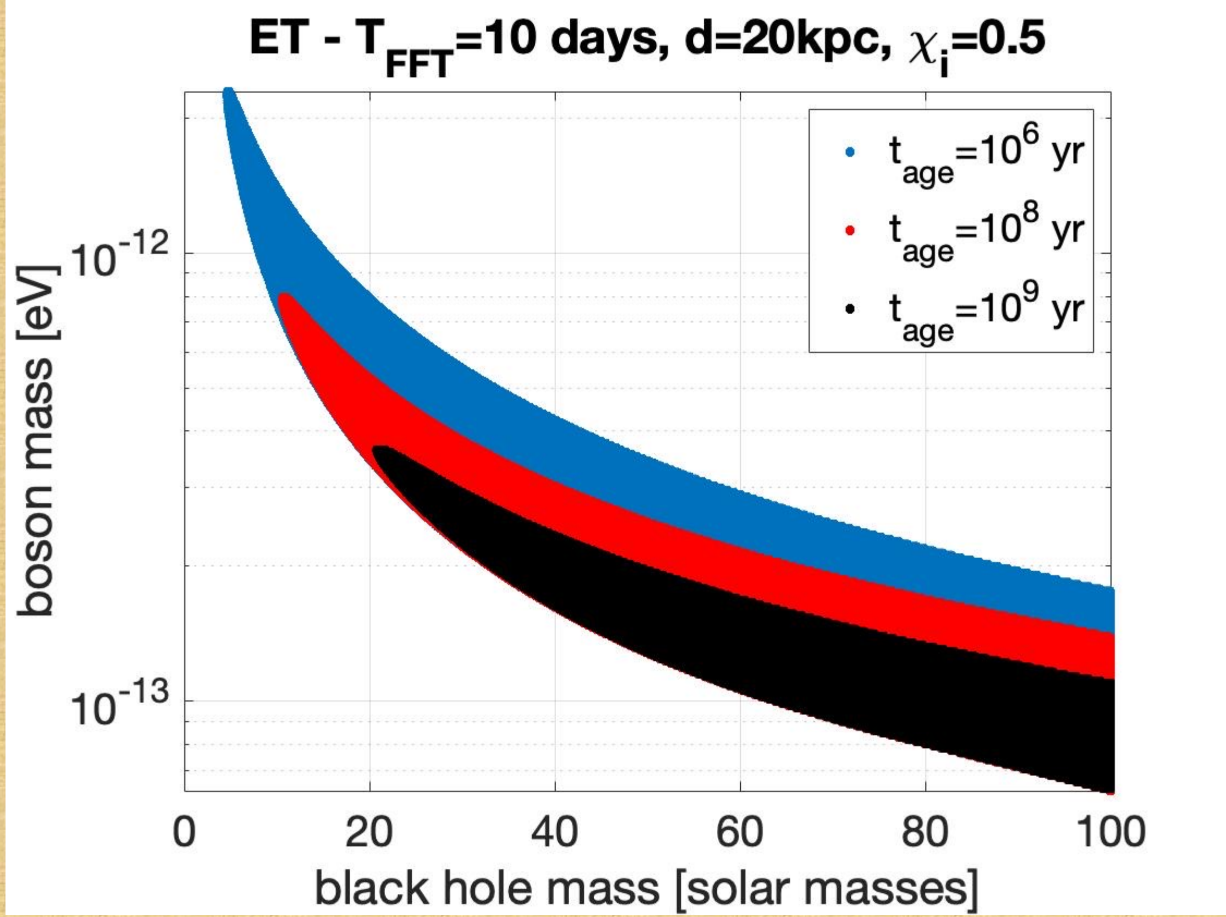
Scalar DM coupling to GW detector beam-splitter → change in size and refraction index

Vermeulen et al, Nature 600, 424 (2021)

GEO600 best suited thanks to its sensitivity to optical phase differences (squeezing)






ET - T_{FFT}=10 days, d=20kpc, χ_i=0.5
$t_{age}=10^6$ yr
$t_{age}=10^8$ yr
$t_{age}=10^9$ yr
boson mass [eV]
10^{-12}
10^{-13}
0
20
40
60
80
100
black hole mass [solar masses]