Exotic CWs and their detectability

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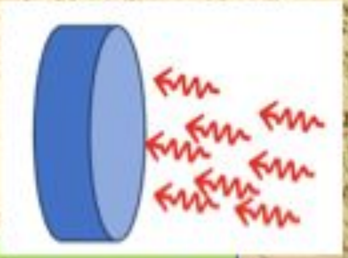


Ultra-light dark matter

Hic sunt leones

Relatively peaceful and reassuring world of rotating neutron stars

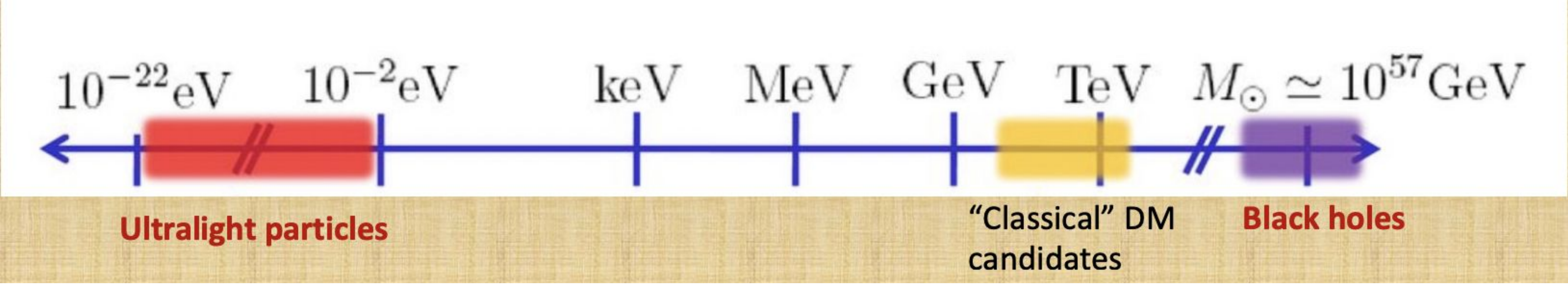
Hic sunt dracones

Primordial black holes

CW land

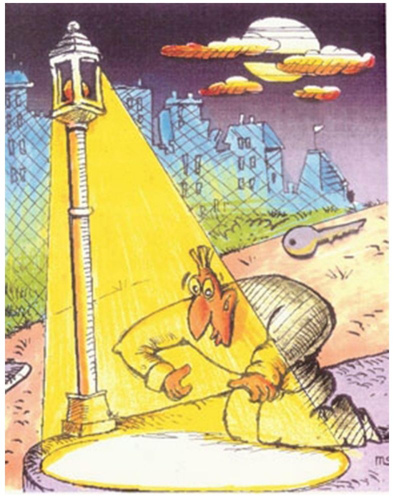
Gravitational Wave signatures of DM

- DM candidates cover ~90 orders of magnitude in mass



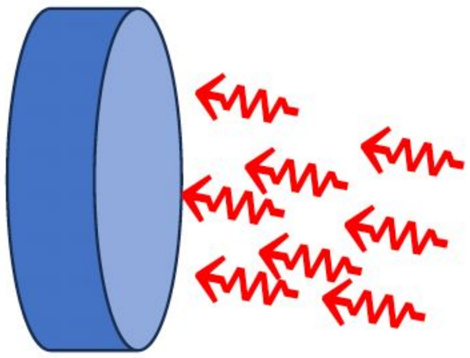
In many cases, GW data analysis methods can be directly applied, or adapted in a straightforward way, to the search of exotic source fingerprints in GW data

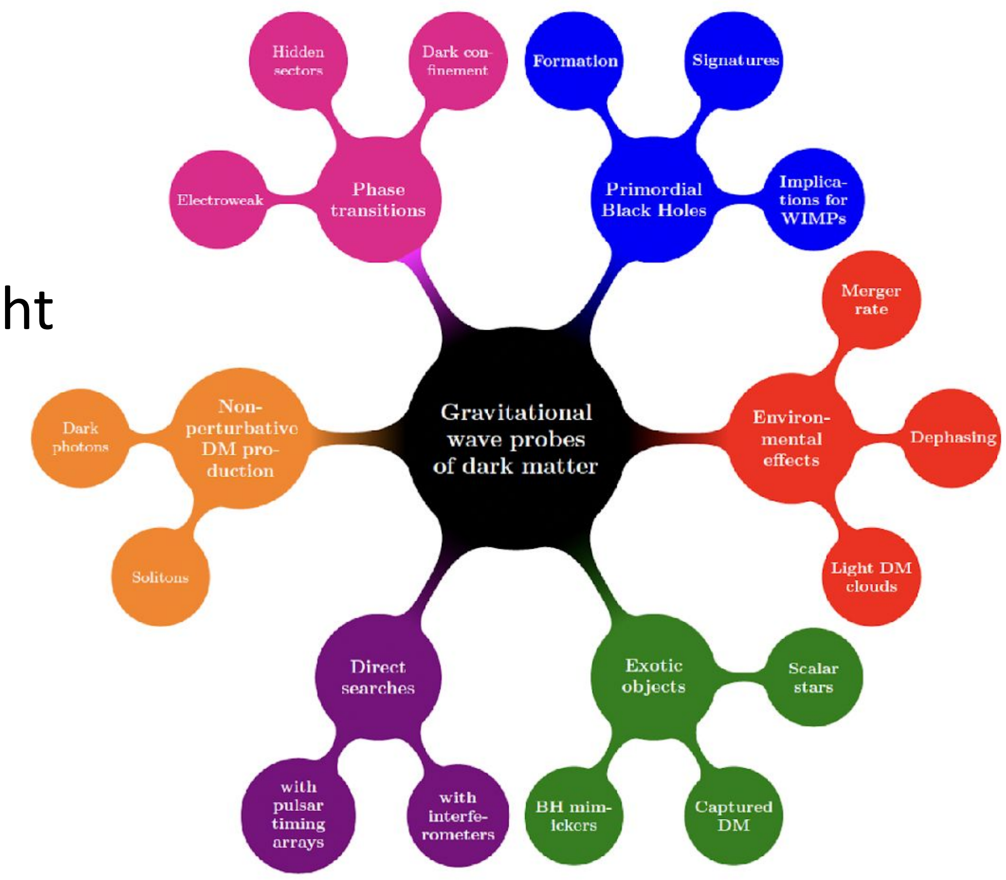
GW detectors offer an ``opportunity window" for free



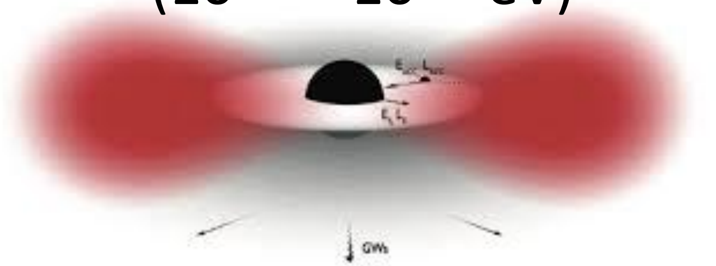
- In recent years, a growing body of literature on the potentiality of Gravitational Wave (GW) detectors as tools to probe DM has been produced (see e.g. Bertone+, arxiv:1907.10610)

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



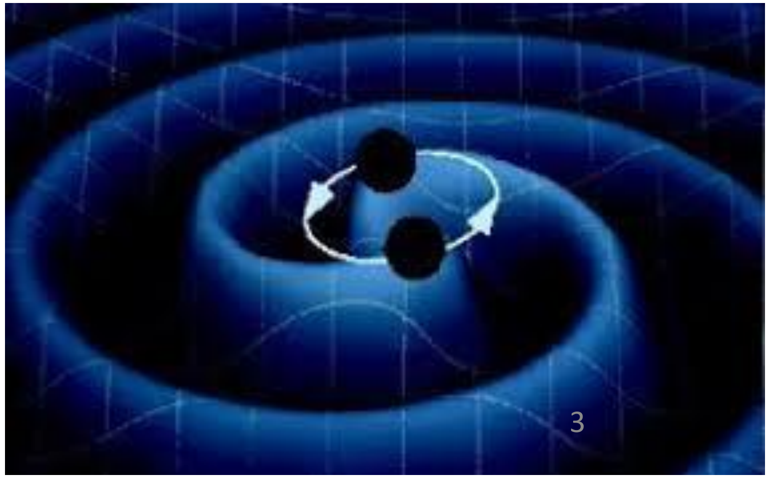


CW emission from boson clouds around Kerr BHs ($10^{-14} - 10^{-11}$ eV)



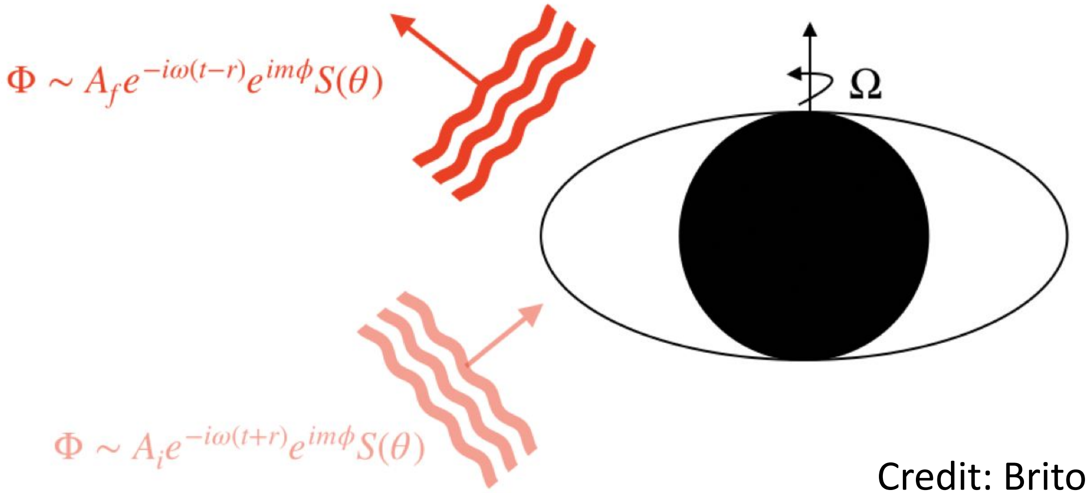
Picture credit: Ana Sousa Carvalho

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



Ultra-light boson clouds

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



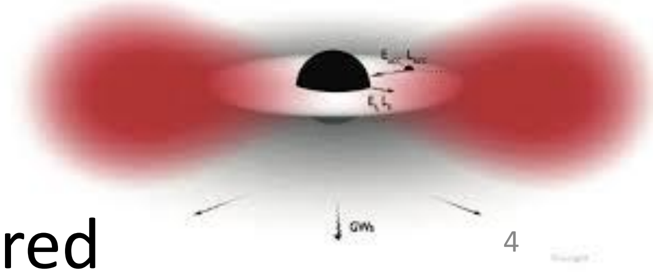
Credit: Brito

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

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

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

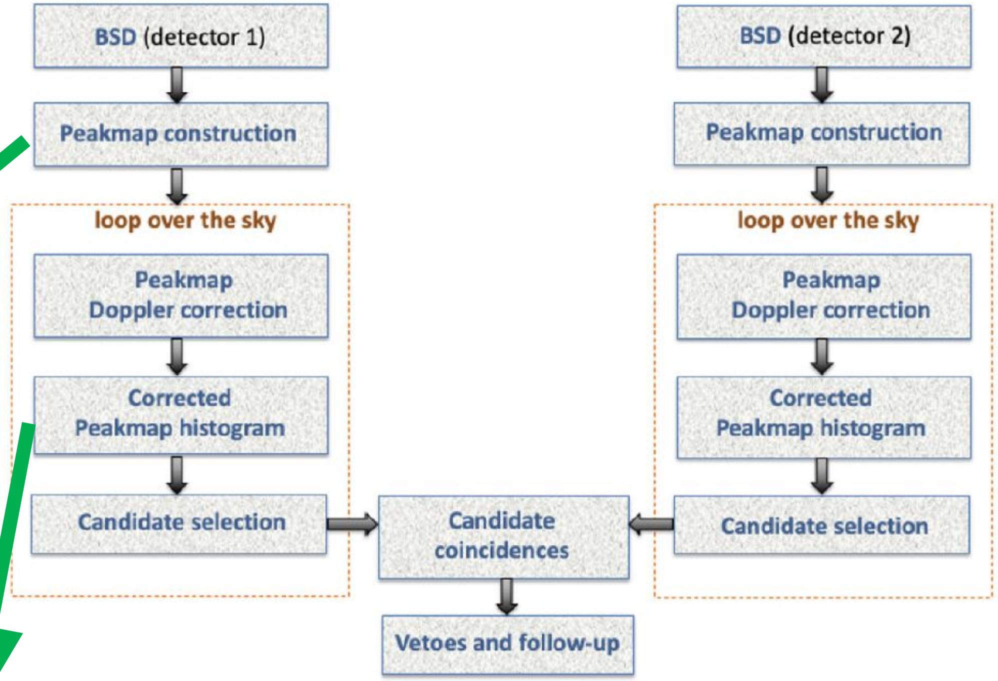
$$\alpha = \frac{G M_{\rm BH}}{c^3} \frac{m_b}{\hbar}$$

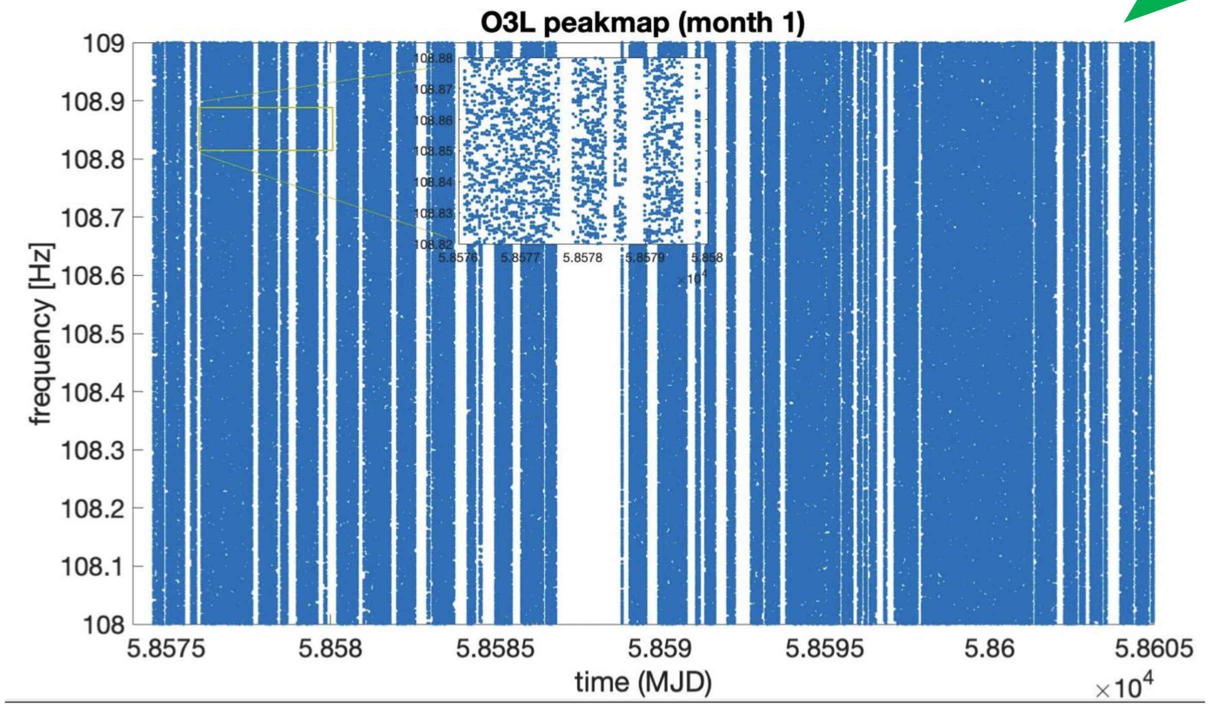
For vector bosons, stronger signals and shorter duration

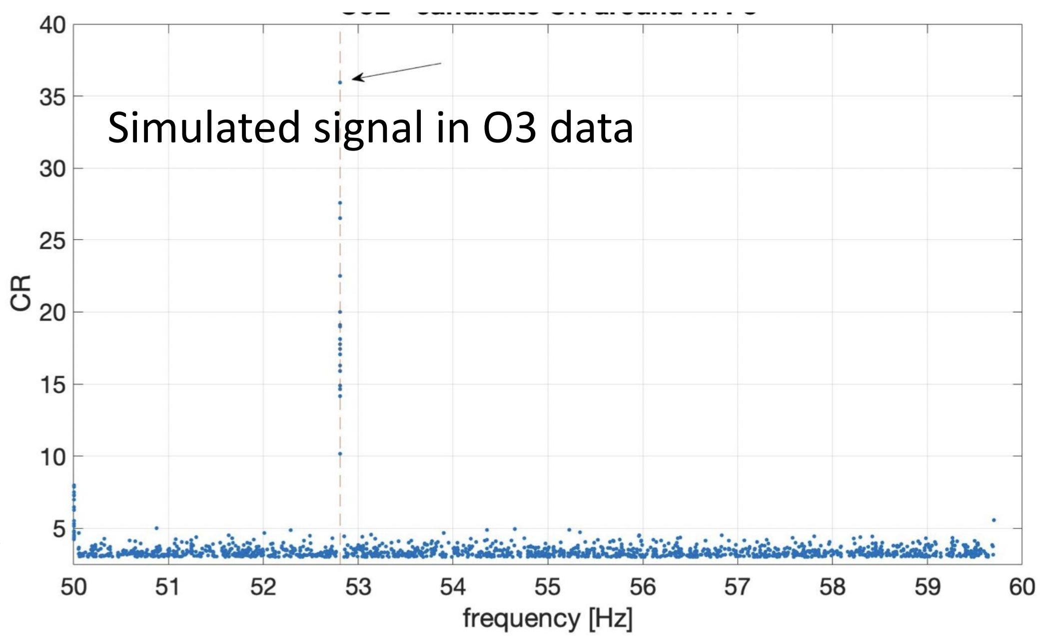
- Various DA methods have been developed and applied to search for CW-like signals from boson clouds (both for all-sky and directed searches)

Various search methods have been developed, all based on a semi-coherent combination of data segments. Here we refer to the one used e.g. in LVK, PRD105, 102001 (2022)

All-sky search scheme



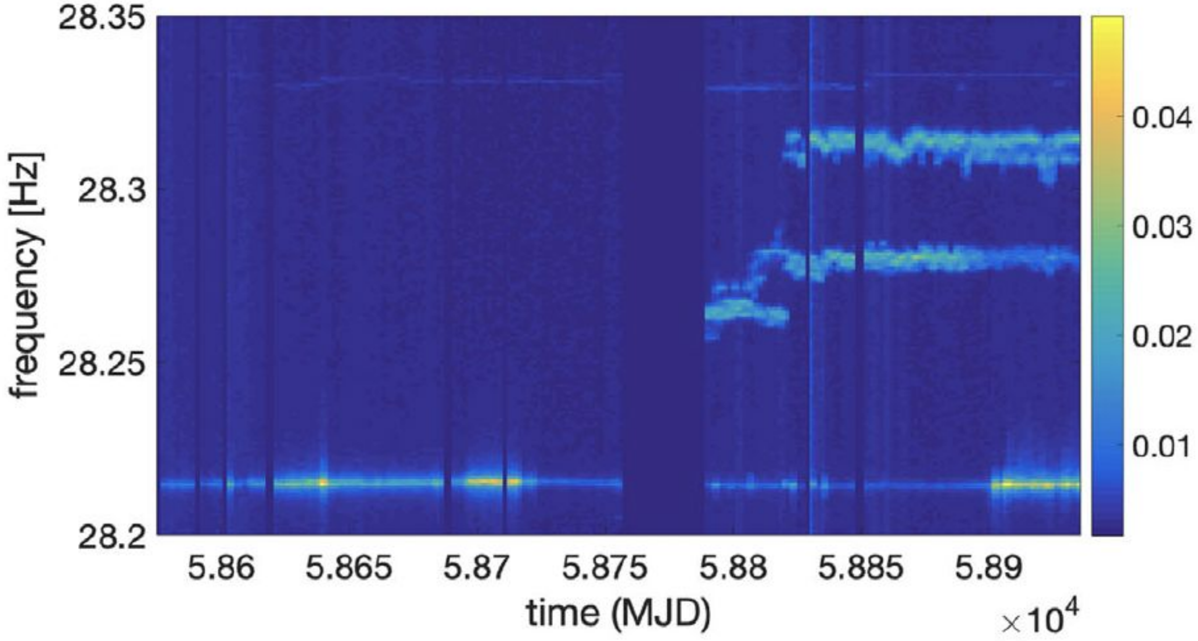




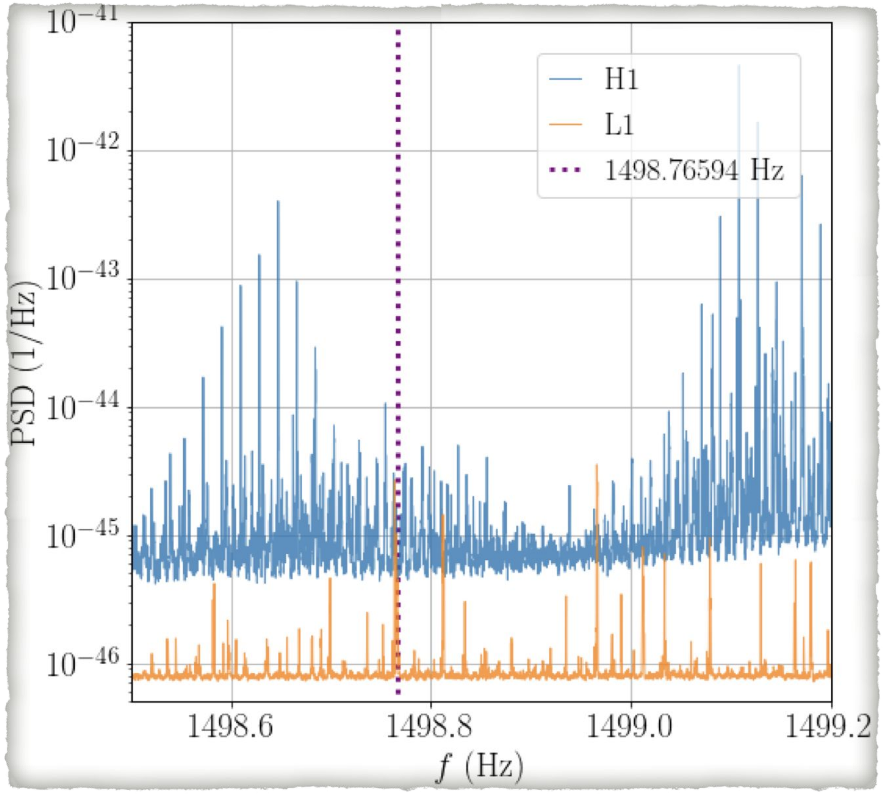
Peakmap projection after Doppler correction for a given sky location

- Real data are full of weird stuff. This is a problem especially when searching for nearly monochromatic exotic signals (which models may have uncertainties)

Spectrogram of O3L data



O3 (H, L) PSD

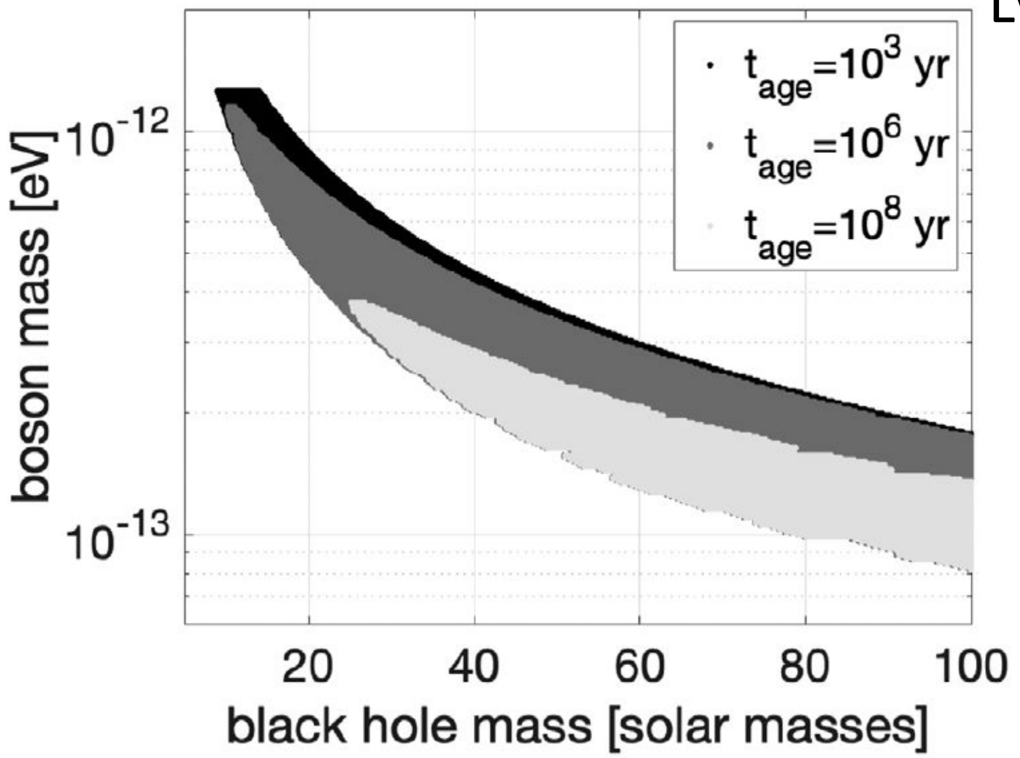


- Using longer and longer data segments is not necessarily the solution
  - Both more sensitive searches and more robust (less sensitive) searches should be done

Result example: scalar clouds, allsky

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

LVK, PRD105, 102001 (2022)



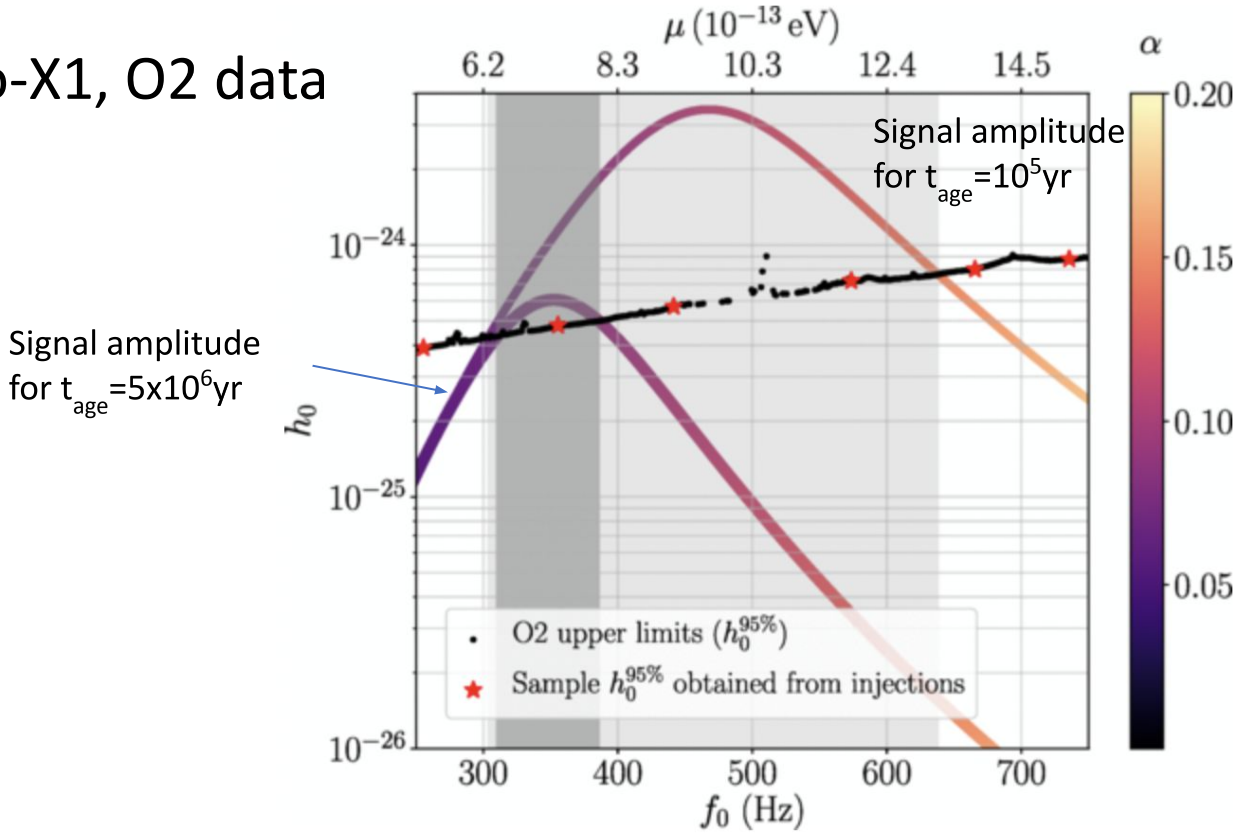
See also:
Palomba et al., PRL123, 171101 (2019)
Dergachev, Papa, PRD103, 063019 (2021)

- Interpretation of results requires assumptions
- Galactic BHs are needed
- We can have a detection even if not all BHs develop a boson cloud

Result example: scalar clouds, directed

Sco-X1, O2 data

Sun et al., PRD101, 063020 (2020)



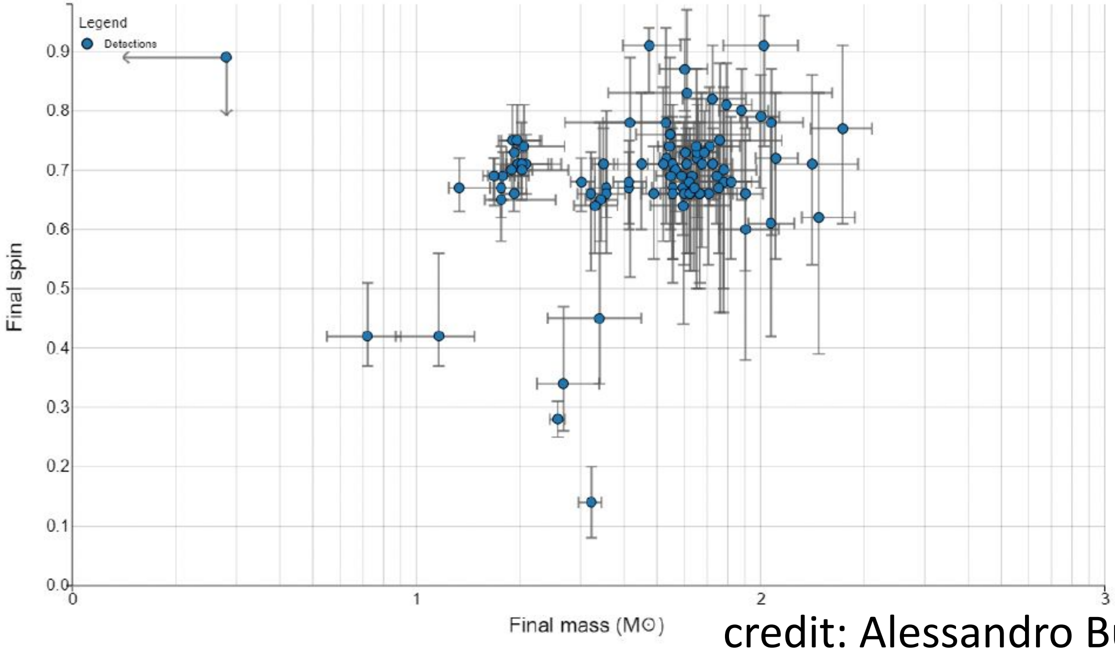
See also LVK, PRD106, 042003 (2022) for a search toward the galactic center (isolated BHs)

- HMM algorithm robust w.r.t. non exactly monochromatic signals
- Impact of mass accretion on the cloud is uncertain
- Some spin measurements (χ>0.95) disfavor cloud formation

Search for post-merger remnants

- Final BH age know, mass and spin measured to a decent accuracy
- Interpretation of null results is more direct and do not require assumptions
- Scalar clouds better suited for 3G detectors (ET, CE)
- Vector clouds are more promising already for current detectors: higher strain, shorter instability time scale

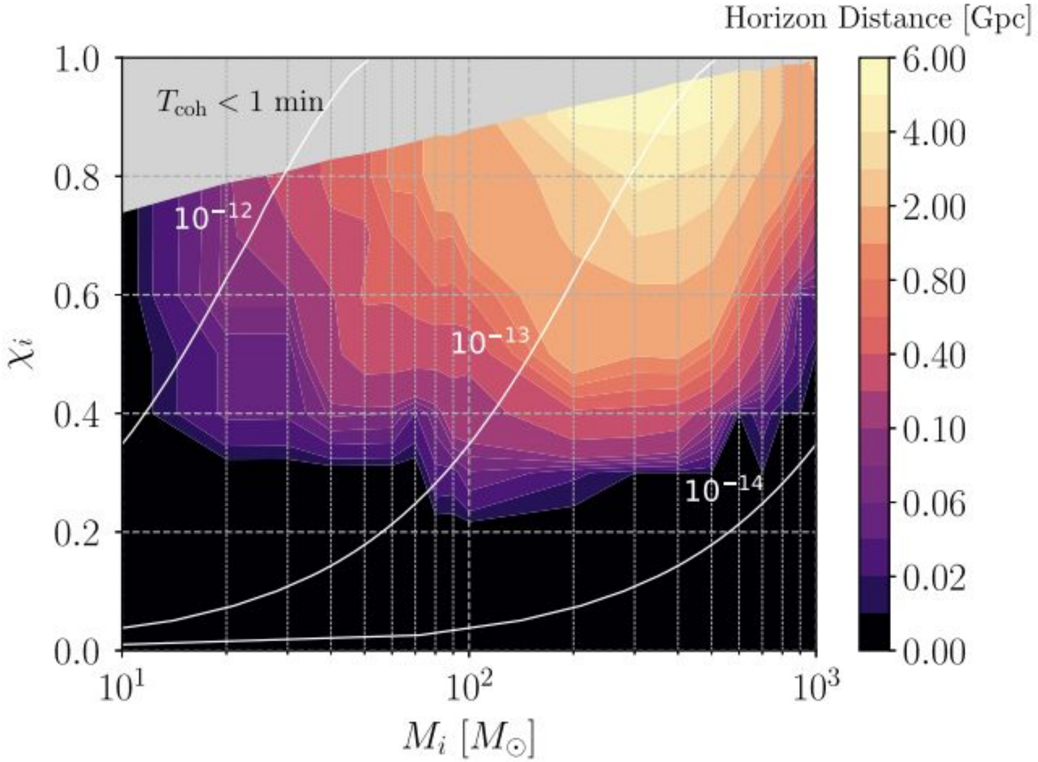
Mass and spin of final BHs (up to O3)



credit: Alessandro Buchicchio

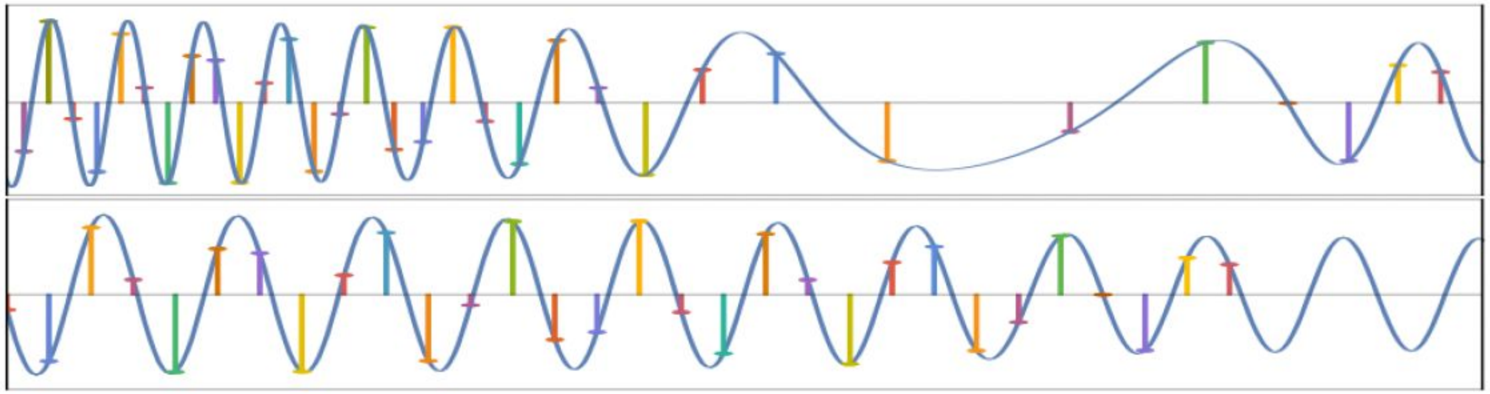
- Nevertheless, the search for vector boson clouds is challenging:
  - Sky position maybe poorly known, if there is not an EM counterpart
  - Spin-up can be much larger than for ‘standard’ CW signals

Estimated sensitivity (design Advanced LIGO) for the F-stat/HMM pipeline [D. Jones et al, PRD108, 064001 (2023)]



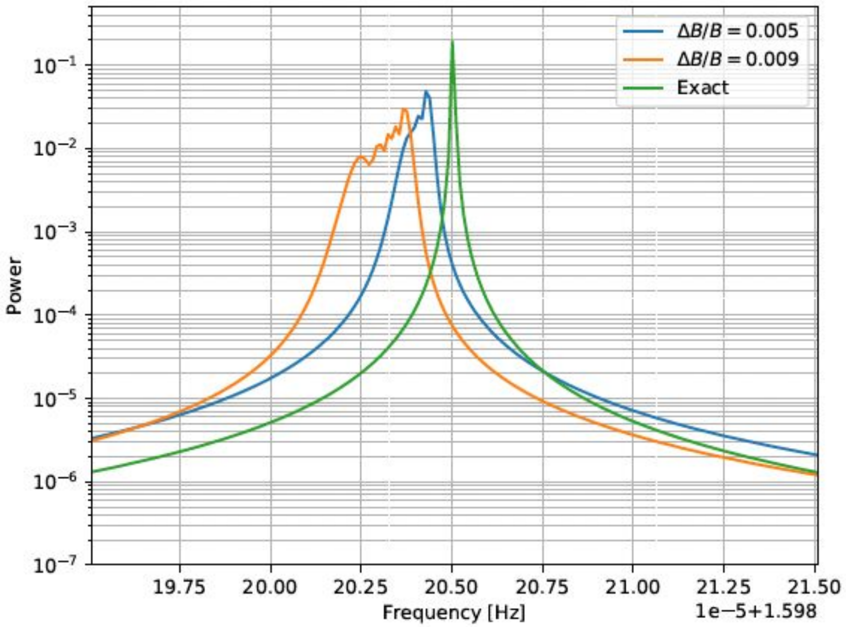
- Still no search has been done on real data

- Alternative method based on <u>resampling</u> [A. Buchicchio, Master Thesis @ Sapienza Univ. of Rome]



$$t^* = t + B \log\left(1 + \frac{t}{\tau_{GW}}\right)$$

Fit from `SuperRad` waveform



- Need to build a 2D grid in parameter space
- Potentially high sensitivity search
- But computing cost is an issue

Potential issues and opportunities

- Let us remind the three cornerstones of data analysis:
  - Sensitivity
  - Robustness w.r.t. signal uncertainties and detector artefacts
  - Computing cost

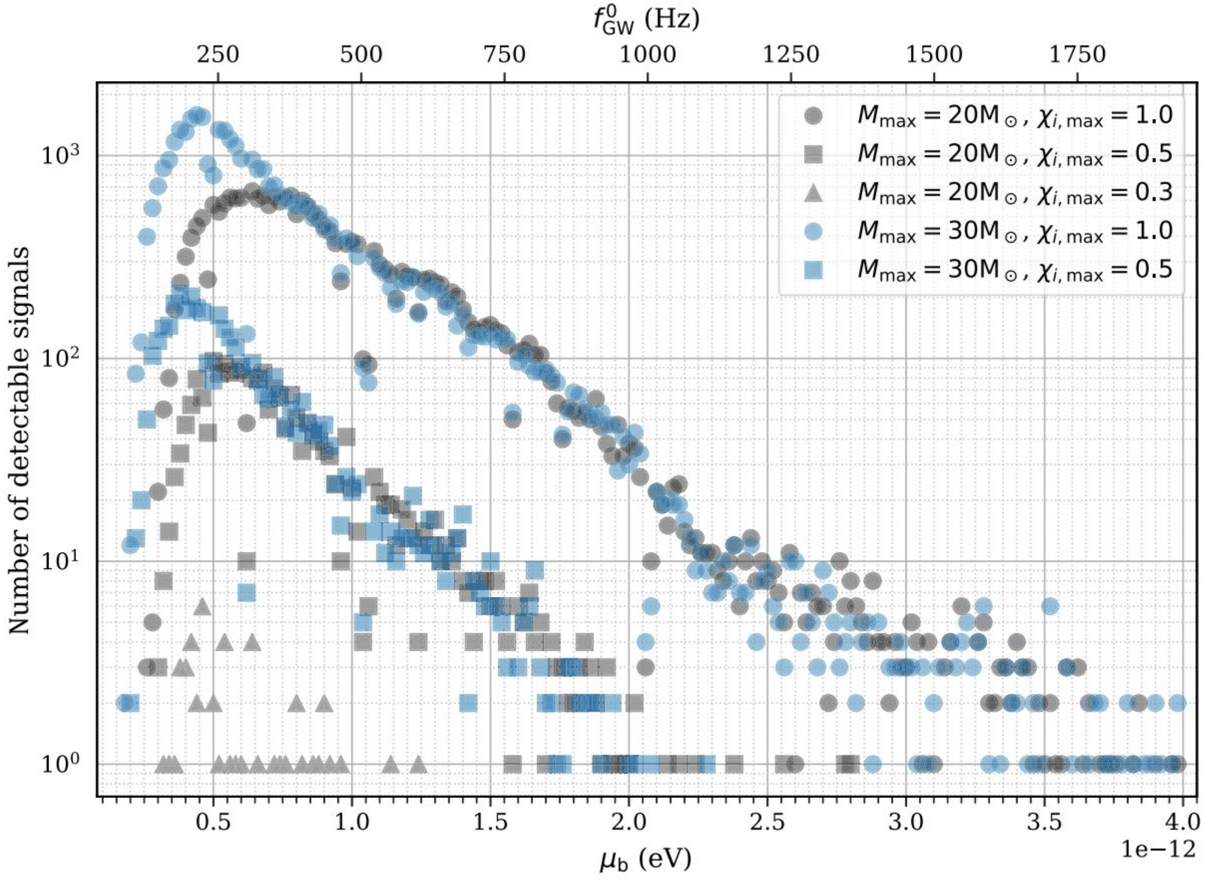
- New theoretical signal models are welcome, if they are robust!
  - Peculiar signal features may make discrimination from noise easier

- Multi-messenger and multi-band approaches can be very helpful!
  - Reduction of the parameter space

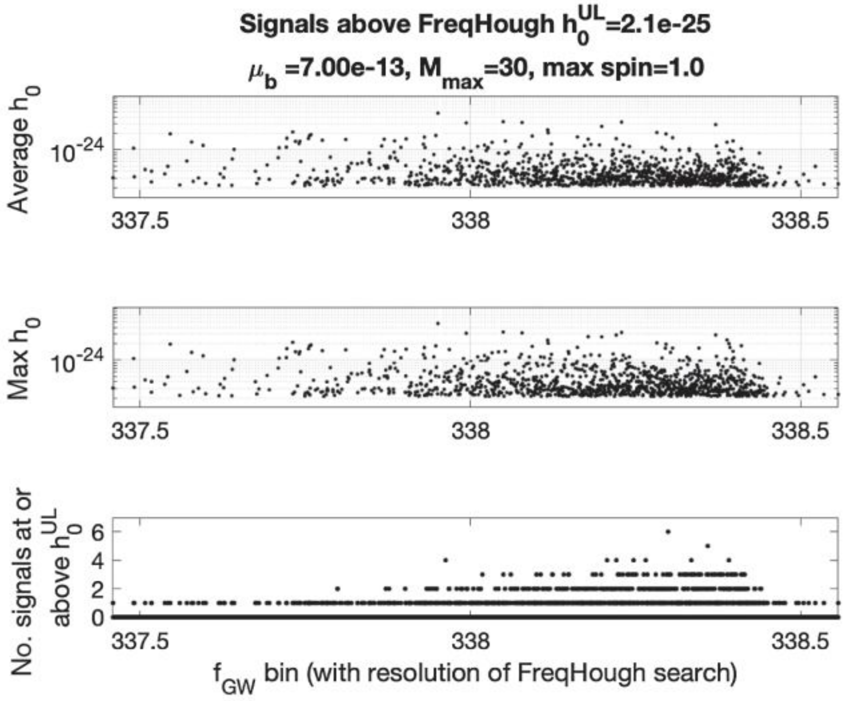
- Population studies may give some interesting hint (but must be handled with care!)

Signal superposition

- 10^7-10^8 BHs are expected to exist in the Milky Way
- If cloud formation is ubiquitous, a large number of clouds should emit CWs at the same time
- Emission frequency would lie in a fraction of Hertz band
- Detailed study in [Zhu et al., PRD102, 063020 (2020)]

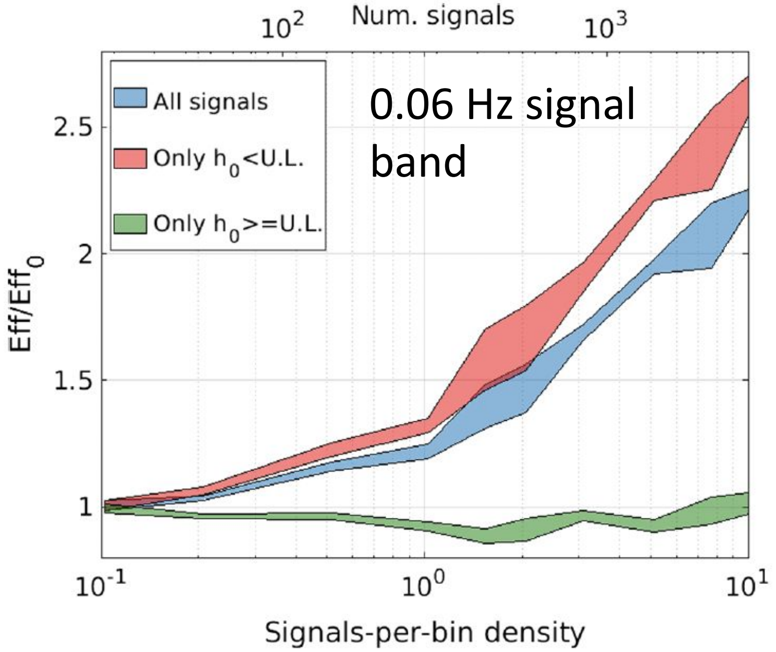


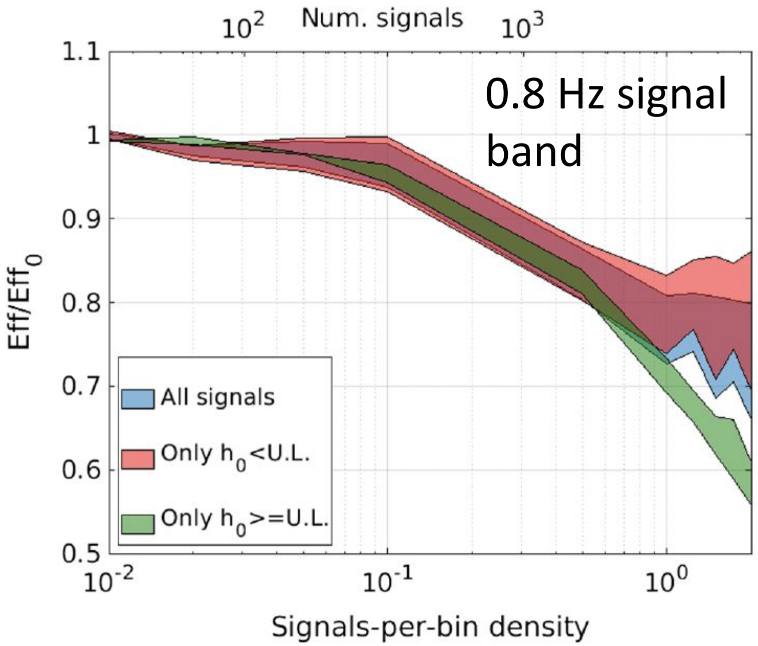
- In principle, this superposition of signals may negatively impact current CW-based search pipelines



- Indeed, it has been shown that this is not the case, at least for peakmap-based methods [L. Pierini et al., PRD106, 042009 (2022)]

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





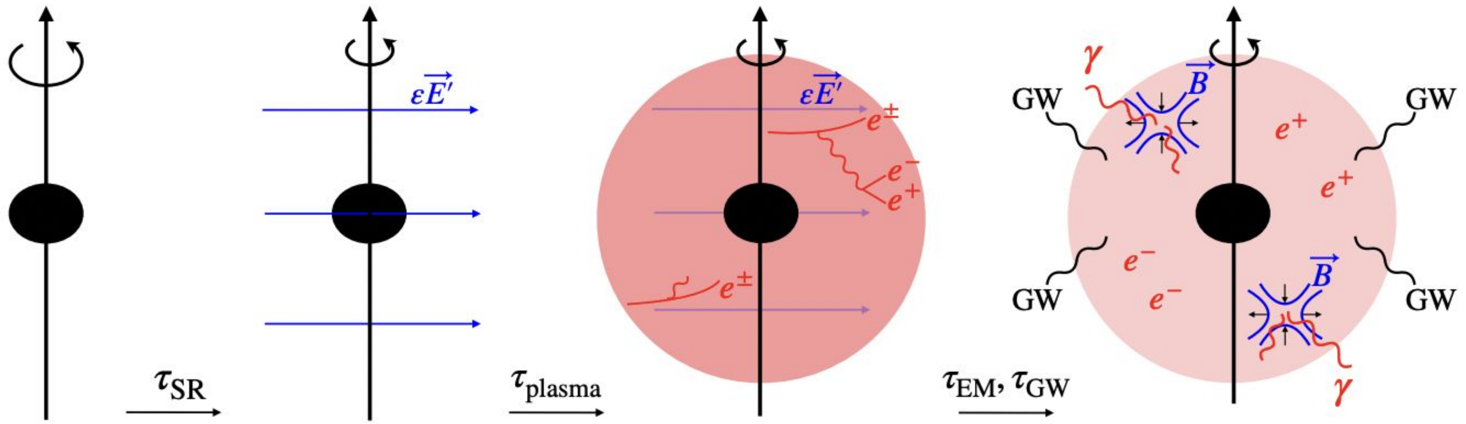
Actually, we could exploit signal superposition to our advantage!

Multi-messenger signature

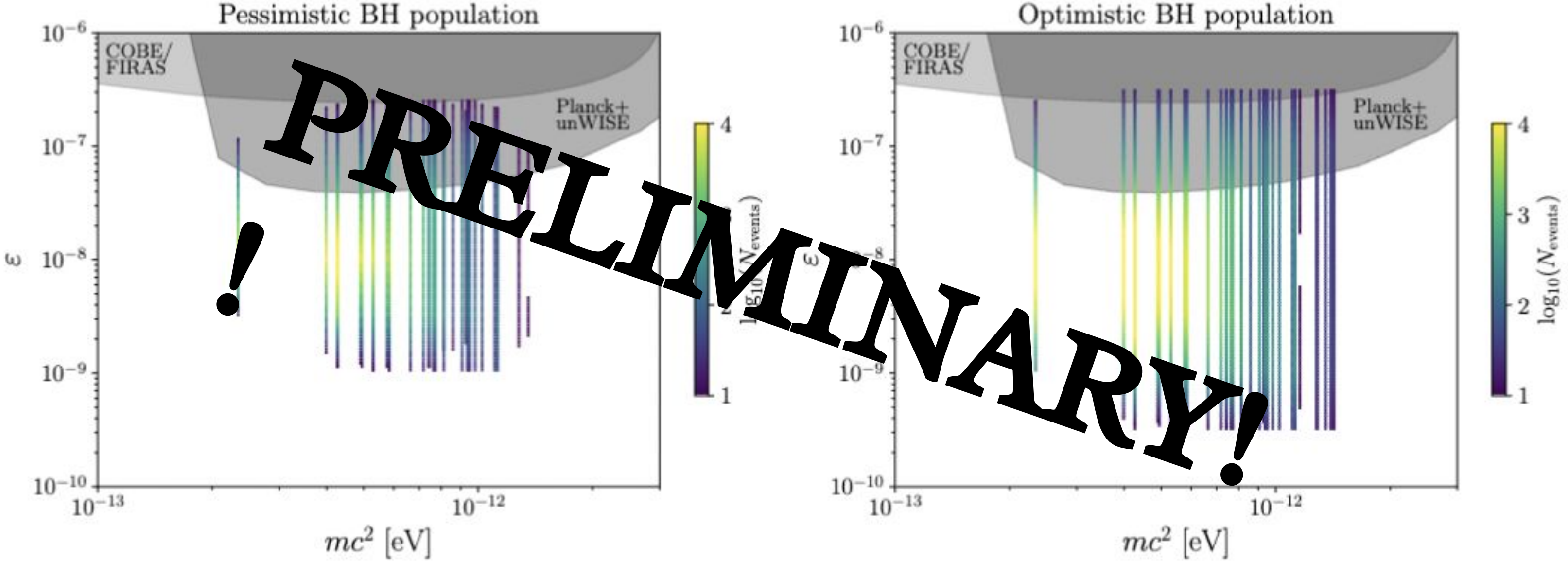
- If dark photons kinetically mix with standard model photons, the cloud is expected to emit EM radiation [N. Siemonsen et al., PRD107, 075025 (2023)]

(mixing angle ε)

Rotating dark EM field ⟶ rotating visible EM field ⟶ plasma ⟶ EM emission



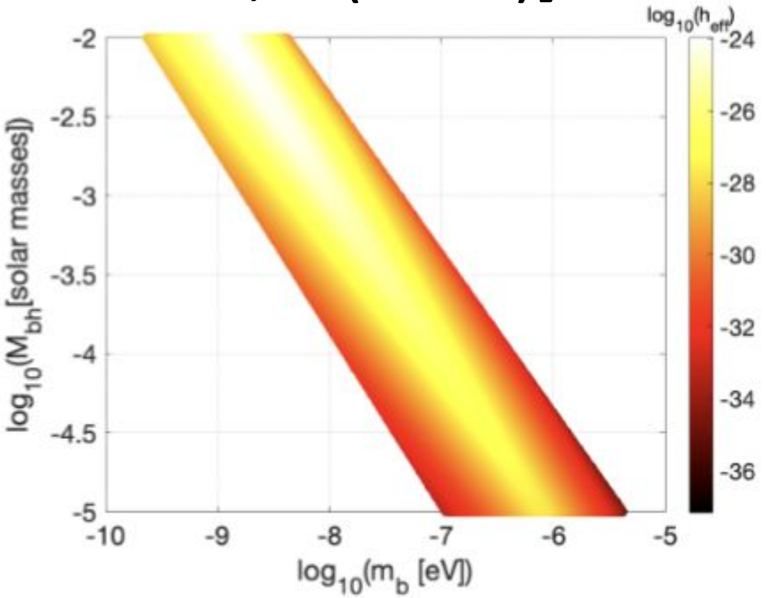
[L. Mirasola, C. Mondino + several others, in preparation]



- Some of the millisecond radio pulsars could actually be BH+cloud systems
- Search on O3 LIGO data using a sample of pulsars

UHF and multi-band approach

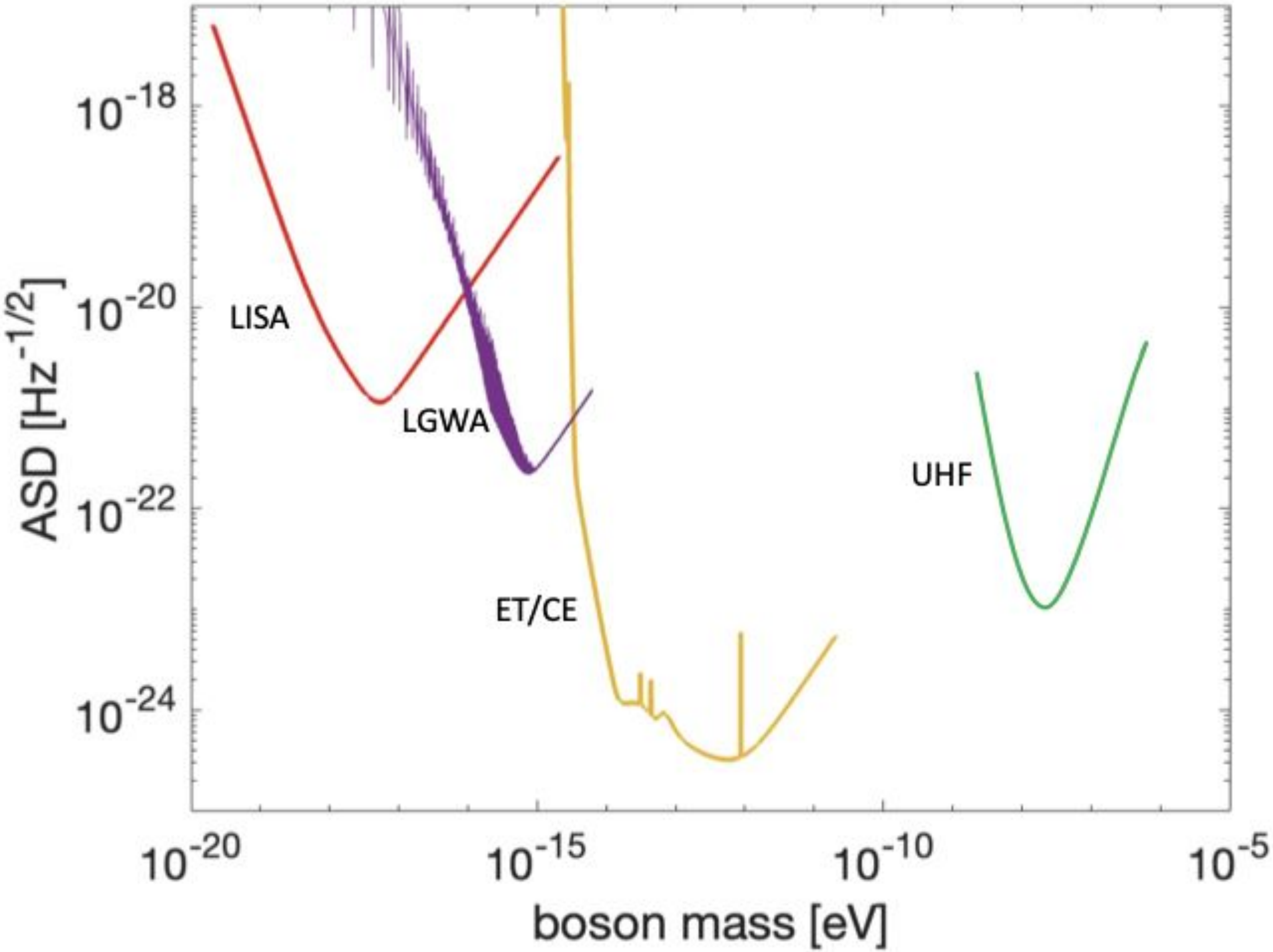
- PBHs of 10^{-5}-10^{-2} M_o can develop clouds of bosons with masses of 10^{-9}-10^{-6} eV
- The corresponding CW signal frequency is ~$50m_{1E\text{-}7\ eV}$ MHz
- In the sensitivity band of some planned future UHF-GW detectors [N. Aggarwal et al., Living Rev. Rel. 24, 4 (2021)]



[CP, Lu, Velcani, to be submitted]

- Joint detection of a binary PBH inspiral signal (e.g. by ET) and the CW signal from the cloud would provide a lot of useful information

Maybe one day, in ~15-20 years….

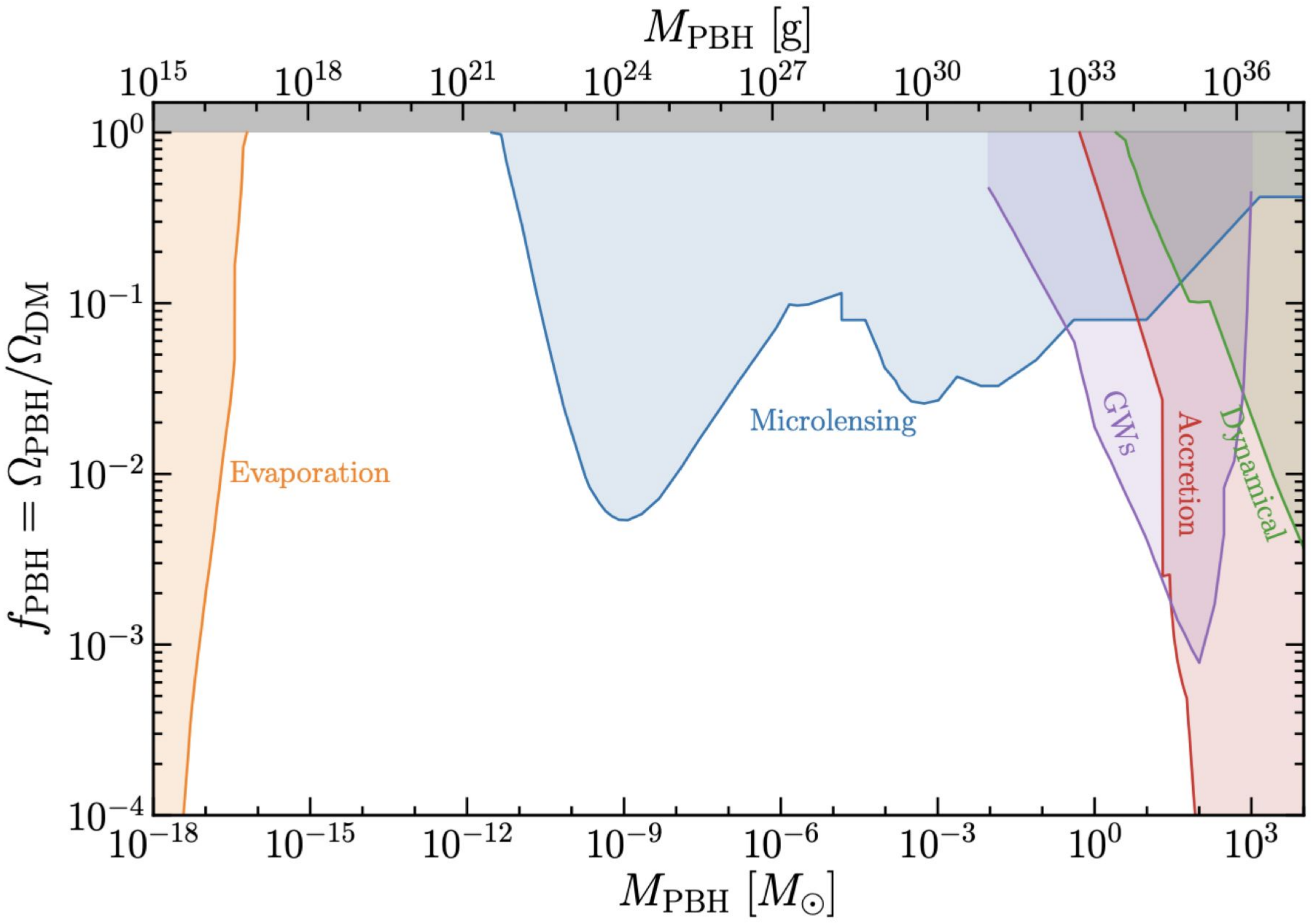


Primordial black holes

- Low spins of LIGO/Virgo black holes, and merging rate inferences have revived interest in PBHs

- BHs that formed in the early universe can take on a wide range of masses

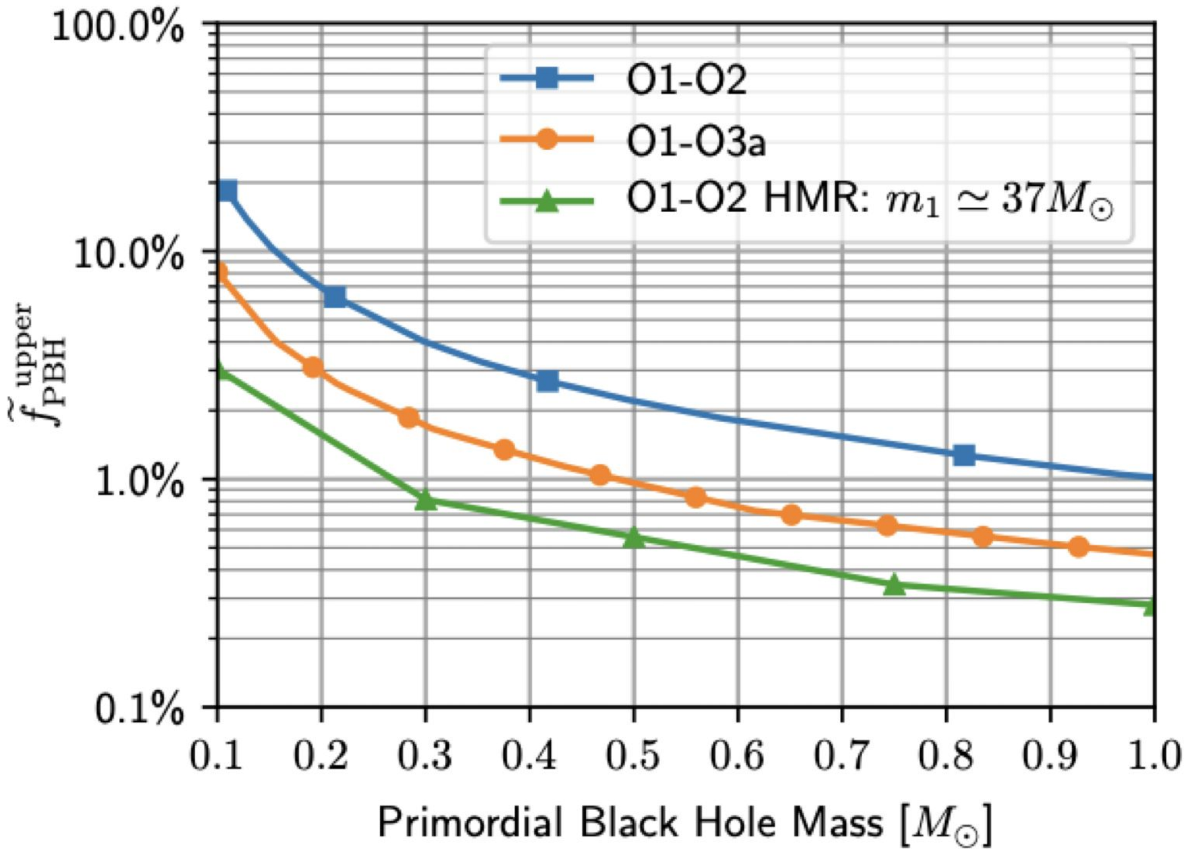
- Possible links to dark matter



- Green and Kavanagh. Journal of Physics G: Nuclear and Particle Physics 48.4 (2021): 043001.

Primordial black holes

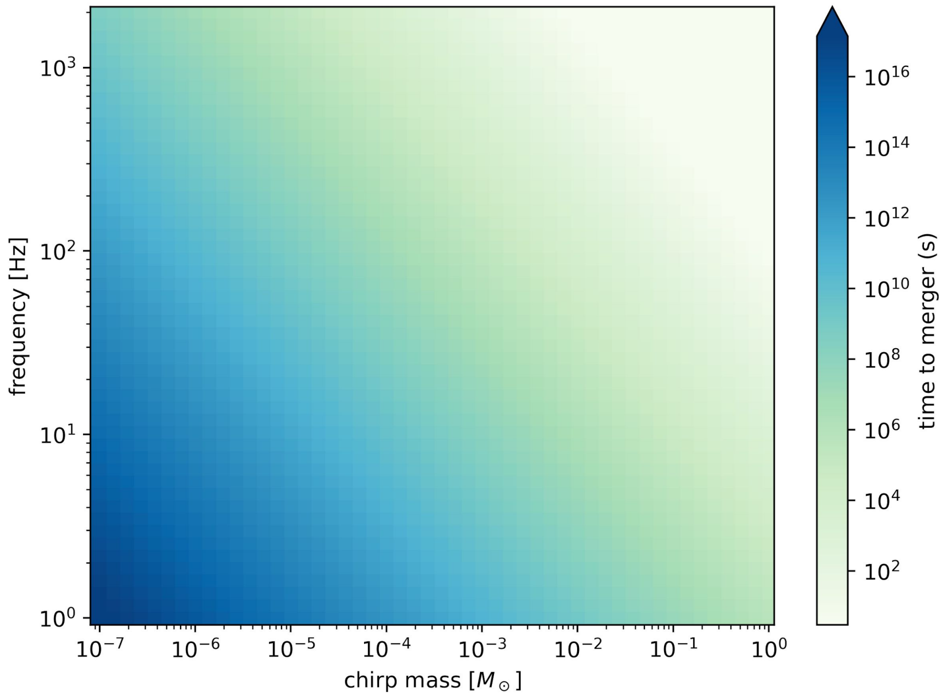
- Many GW efforts to detect PBHs focus on “sub-solar mass” regime, ￼
- However, GWs from planetary-mass PBH binaries have only recently been been thought about
- Matched filtering in this mass range is extremely computationally challenging
- Signals are long-lasting at LIGO frequencies—> many more templates needed for the same ￼ system if the system inspirals for longer



- Nitz & Wang: Phys.Rev.Lett. 127 (2021) 15, 151101.
- LVK: Phys.Rev.Lett. 129 (2022) 6, 061104
- LVK: arXiv: 2212.01477

Primordial black holes

- The phase evolution of two objects far enough away from merger can be described by quasi-Newtonian circular orbits
- We analyze GW data looking for the phase evolution of the signal, characterized entirely by the chirp mass and signal frequency

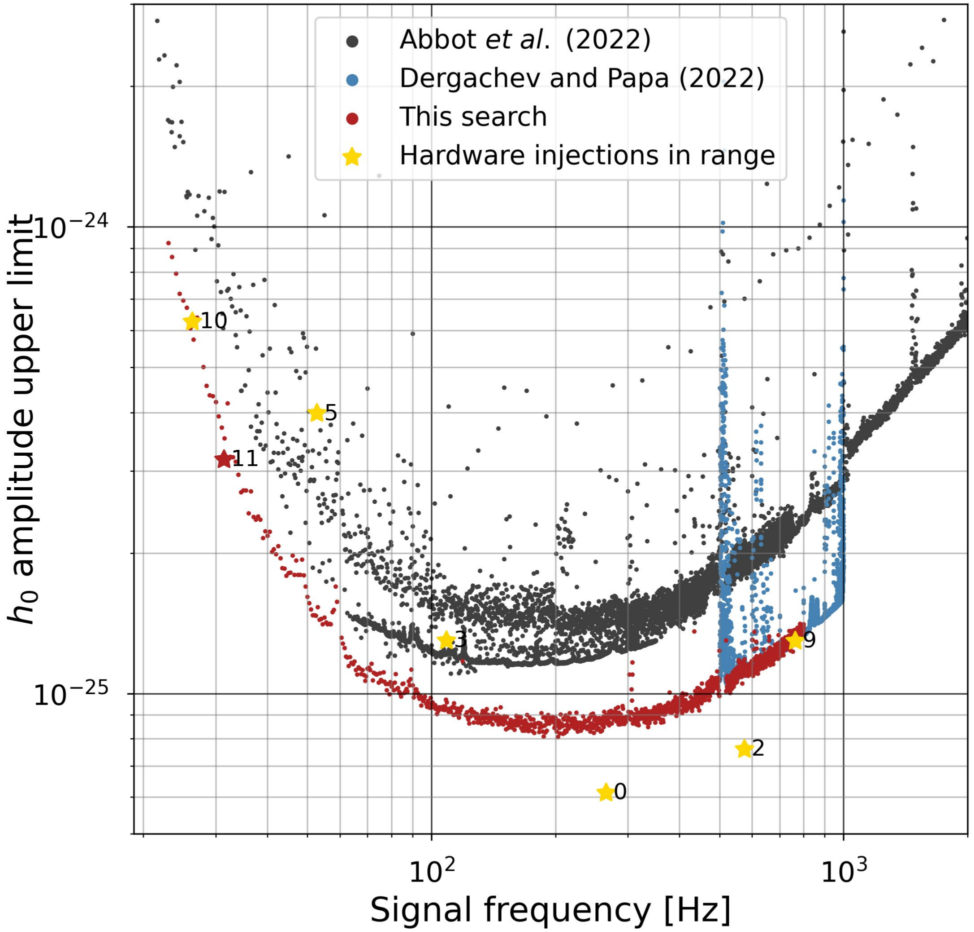


- Miller et al. Phys.Dark Univ. 32 (2021) 100836
- Miller, Andrew L. arXiv:2404.11601 (2024).

The pure CW approach to PBHs

Steltner, B., et al. ApJ 952.1 (2023): 55.

- For small chirp masses, the inspiral GW frequency is almost monochromatic
- The small frequency drift, however, is positive
- Without thinking too much, standard CW all-sky search results can be mapped to constraints on PBH inspirals
- Practical considerations: maximum $\dot{f}$ of search, frequency range, *eccentricity*, how "monochromatic" are we talking

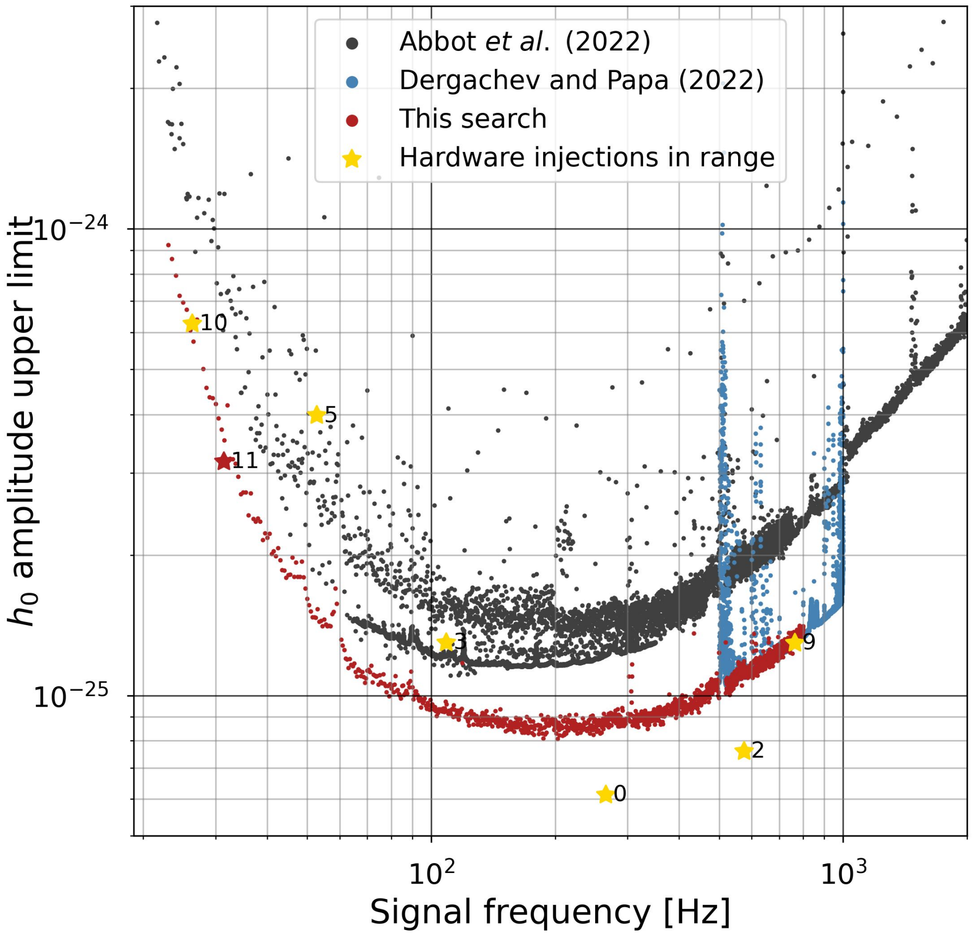


- Upper limits on CWs need not be interpreted as coming from deformed NSs!

How to set upper limits on PBH abundance

Steltner, B., et al. ApJ 952.1 (2023): 55.

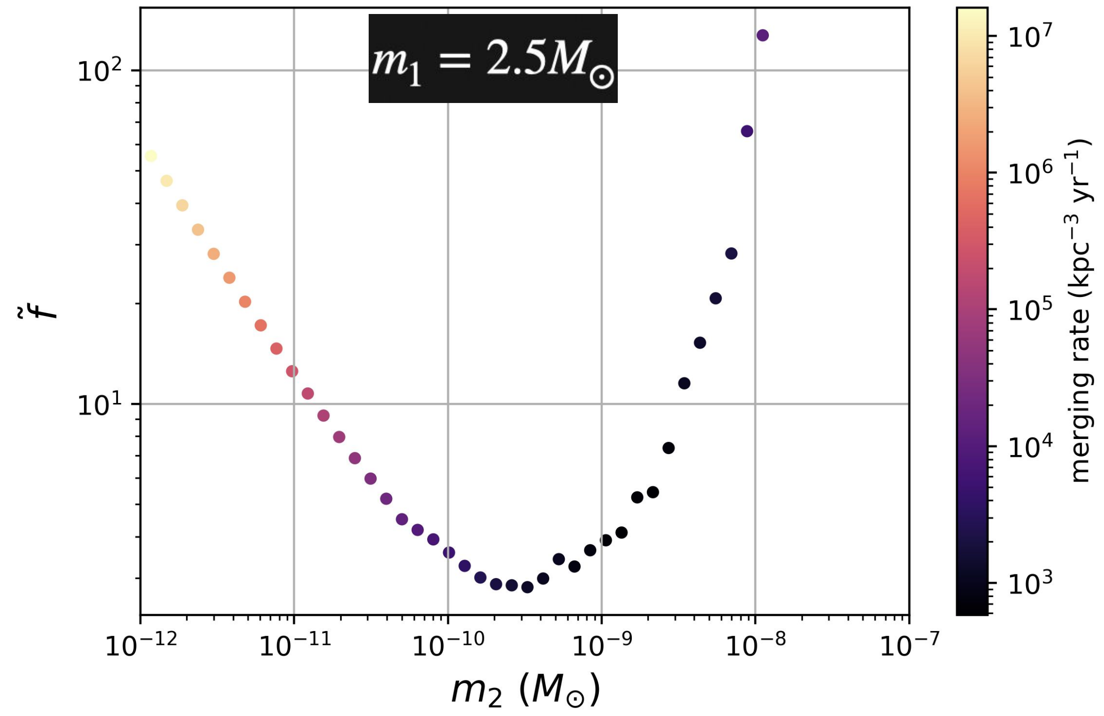
- CW upper limits $h(f) \rightarrow d(f)$ for an inspiraling system
- Volume we probe is just a sphere
  - But it need not be isotropic!
- We typically don't find anything, so the number of detectable binaries < 1, which allows us to estimate a rate density
- Assume PBHs compose these sub-solar mass objects, we can constrain f_{PBH}



- Upper limits on CWs need not be interpreted as coming from deformed NSs!

O3 limits on PBH abundance

- The chirp mass drives the spin-up of the binary system
- We are thus free to pick m_1 and m_2 so long as the combination gives the same chirp mass
- CW searches can thus be sensitive to highly asymmetric mass ratio systems, if we ignore eccentricity (and even if we don't)
  - Miller (2024): arXiv:2410.01348



- BUT: we can't physically constrain anything yet, we don't know the mass functions of PBHs, nor if binary formation is suppressed

Miller et al. Phys.Rev.D 105 (2022) 6, 062008
LVK: Phys.Rev.D 106 (2022) 10, 102008

Can we do better??

What about developing methods to search for long-lived inspiraling PBHs with higher sub-solar masses?

Transient CWs

- Signal frequency evolution over time follows a power-law and lasts hours-days
- Can describe gravitational waves from the inspiral portion of a light-enough binary system, or from a system far from coalesces
- For us, n=11/3

$$\dot{f} = \kappa f^n$$

$$f_{\mathrm{gw}}(t) = f_0 \left[1 - (n-1)\kappa f_0^{n-1}(t - t_0)\right]^{-\frac{1}{n-1}}$$

$\kappa \propto \mathcal{M}$: chirp mass

f : frequency

$\dot{f}$: spin-up

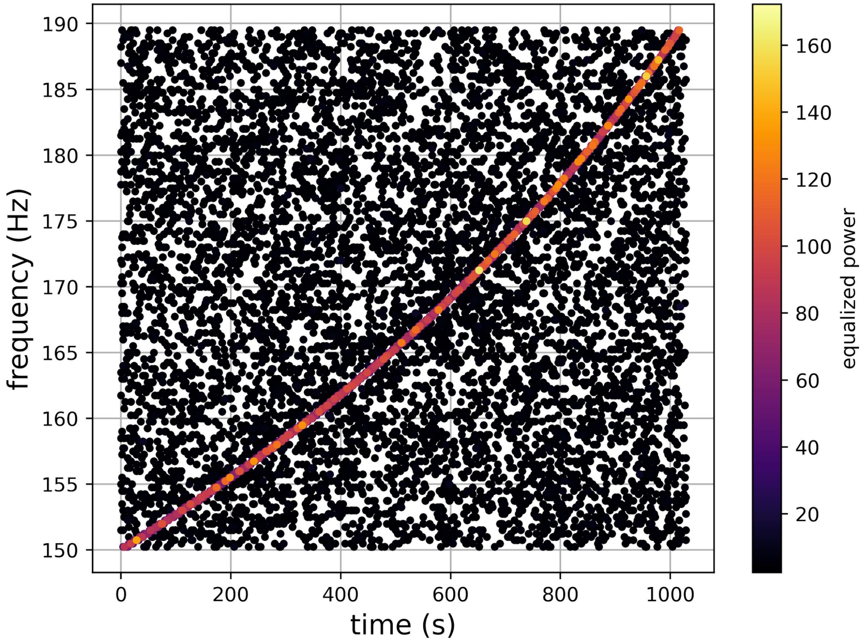
How to search for long-lived PBHs

- Find “tracks” in the time-frequency spectrogram, where each track corresponds to a particular chirp mass and reference time (merger time) or reference frequency

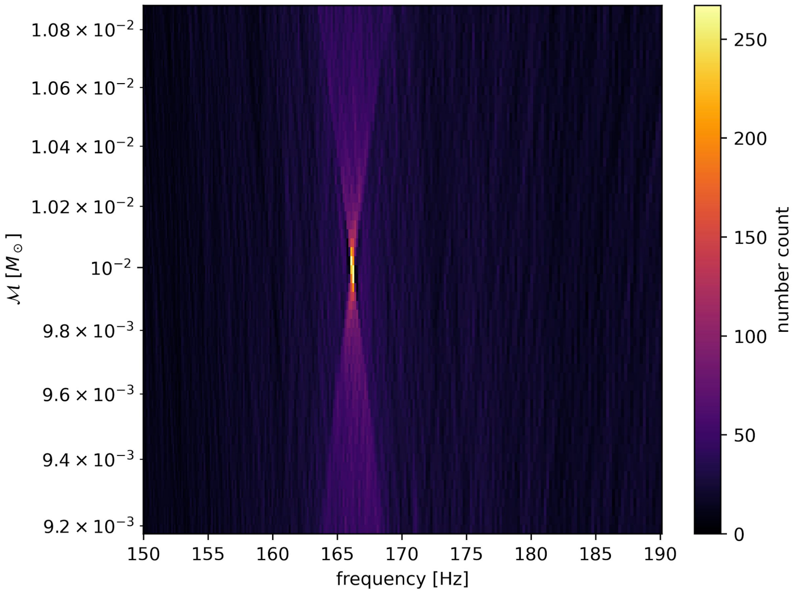
- Sum the power, or the number of points above a certain threshold, along each track

- Repeat for each chirp mass, and histogram the result

Input:



Output:

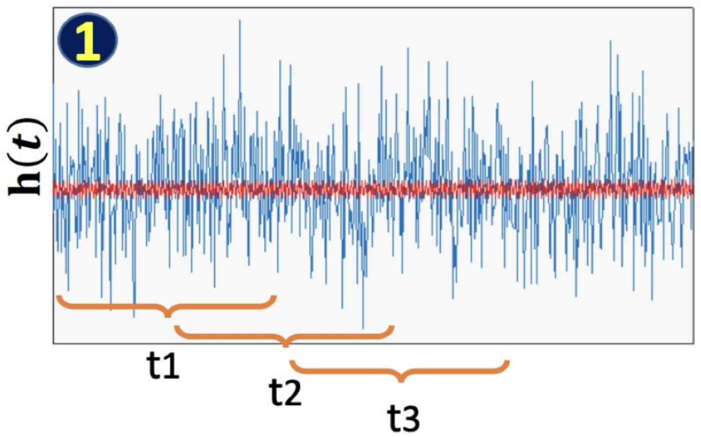


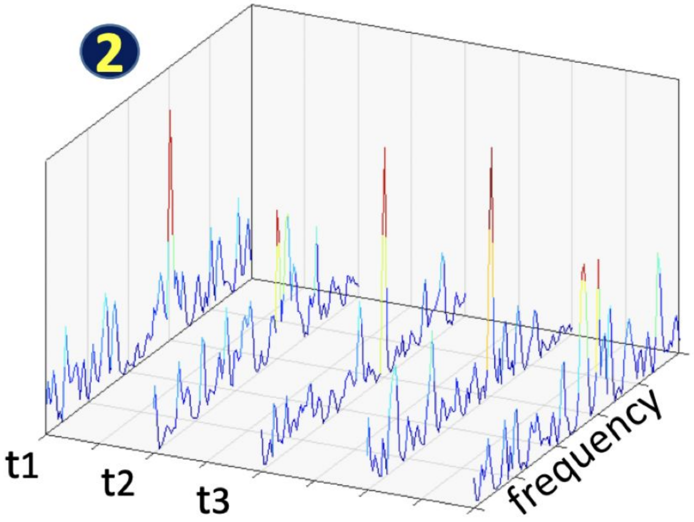
Miller et al. Phys.Dark Univ. 32 (2021) 100836

See also: Carcasona et al., arxiv:2411.04498; Lu, CP et al. in preparation

What do we actually do?

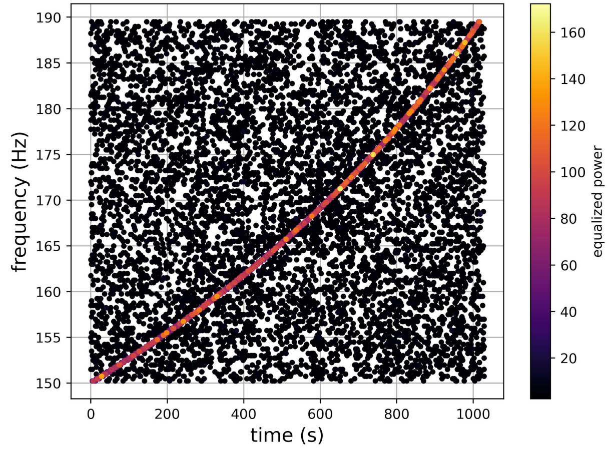
Make spectrograms

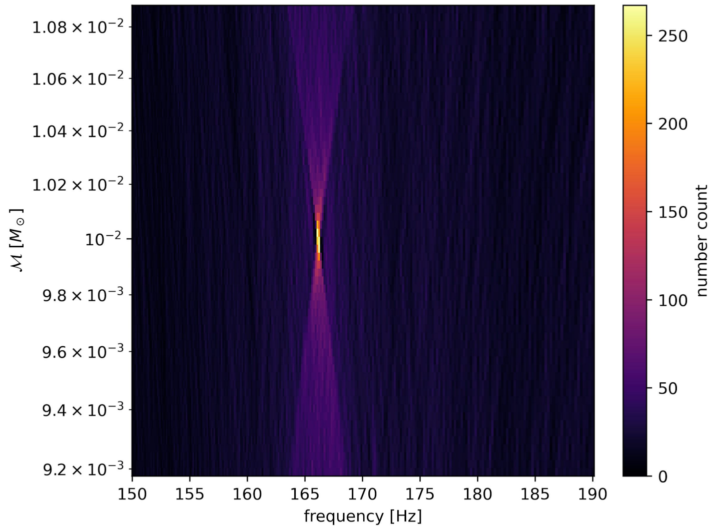




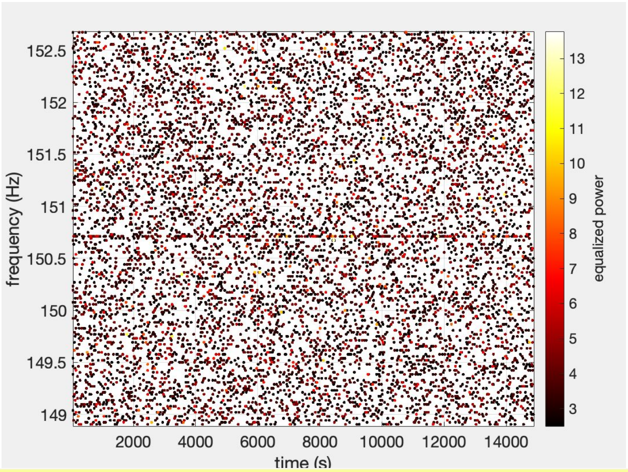
Credit: L. Pierini

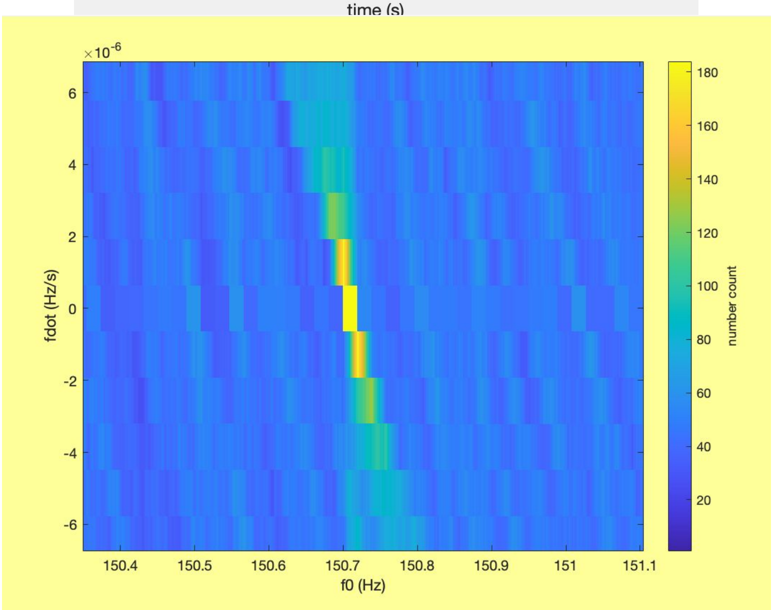
Make histograms



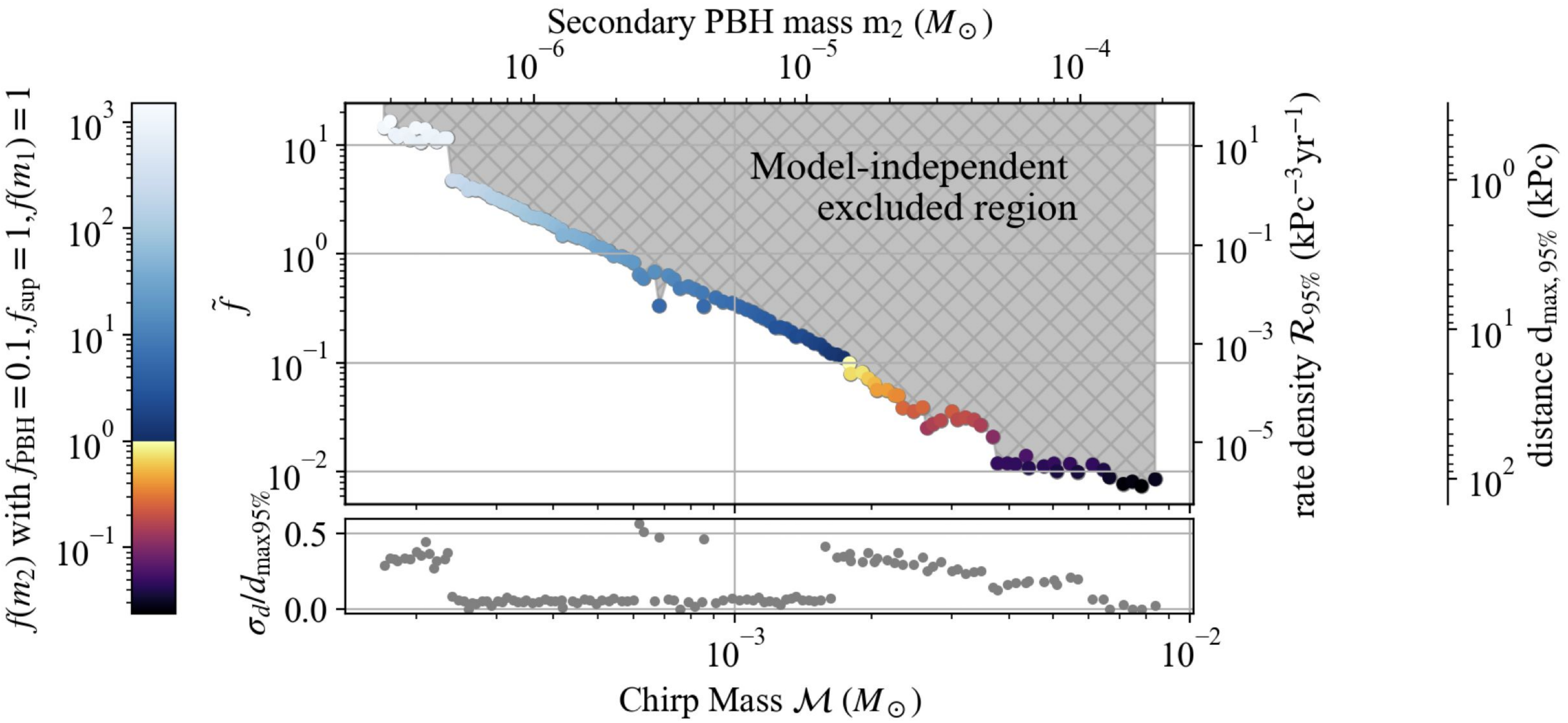


Demodulate, increase coherence time, and repeat





O3a search for planetary-mass PBHs

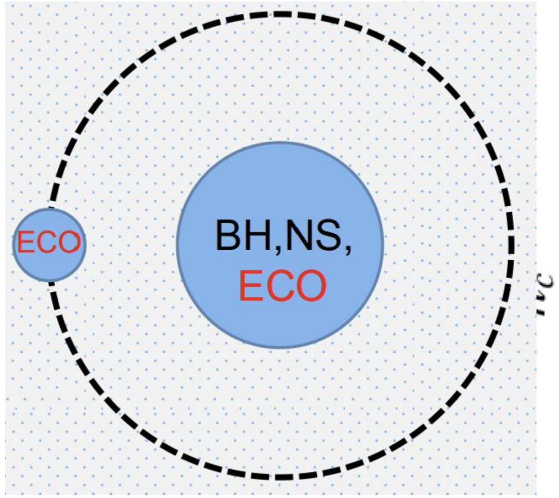


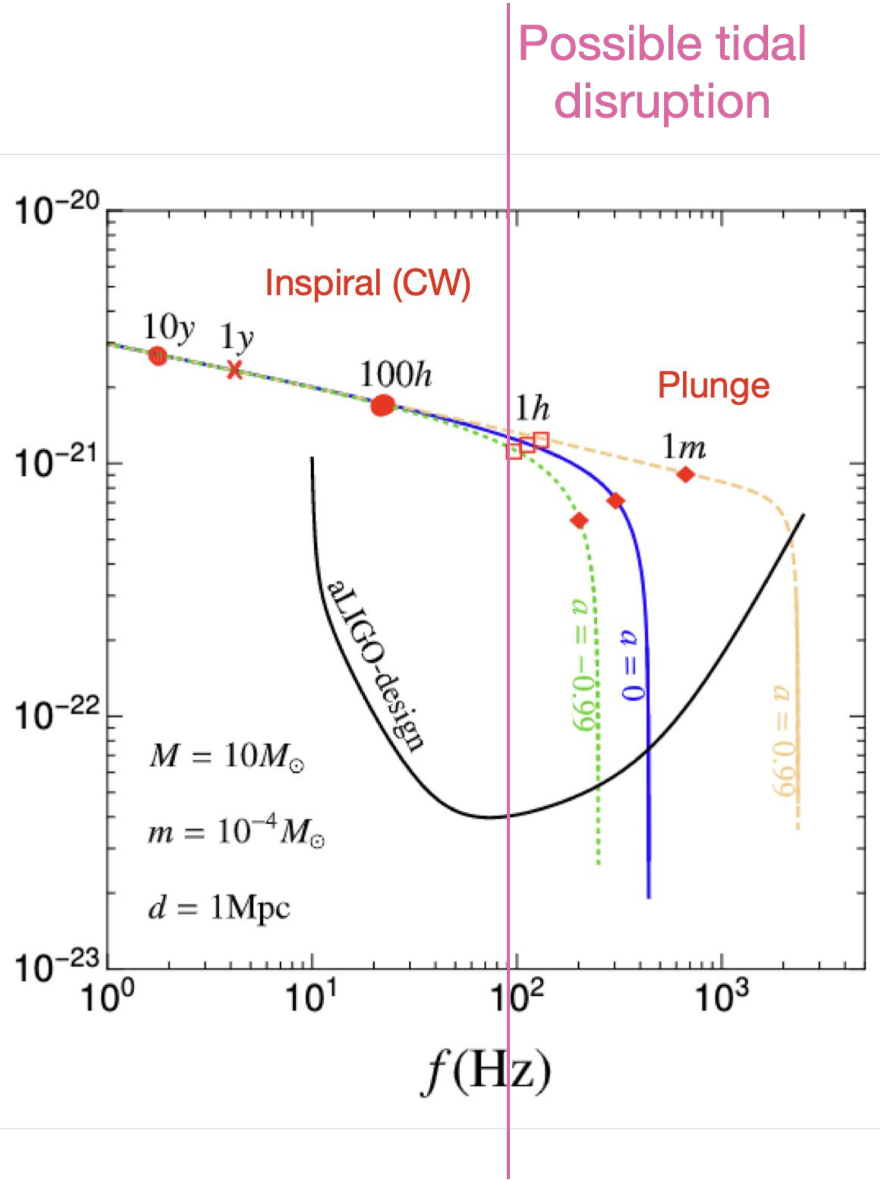
- Assume 2.5 solar mass primary object
- Distance reach is of O(kpcs) for most systems

Miller et al., PRL 133.11 (2024): 111401

How about (mini-) EMRIs?

- Extreme mass ratio inspirals (EMRIs) typically describe a solar-mass object plunging into a supermassive black hole, which should be visible in space-based GW detectors
- *mini*-EMRIs, on the other hand, refer to an exotic sub-solar mass object inspiraling around a heavier one
- Could they exist? Sure. But do they?



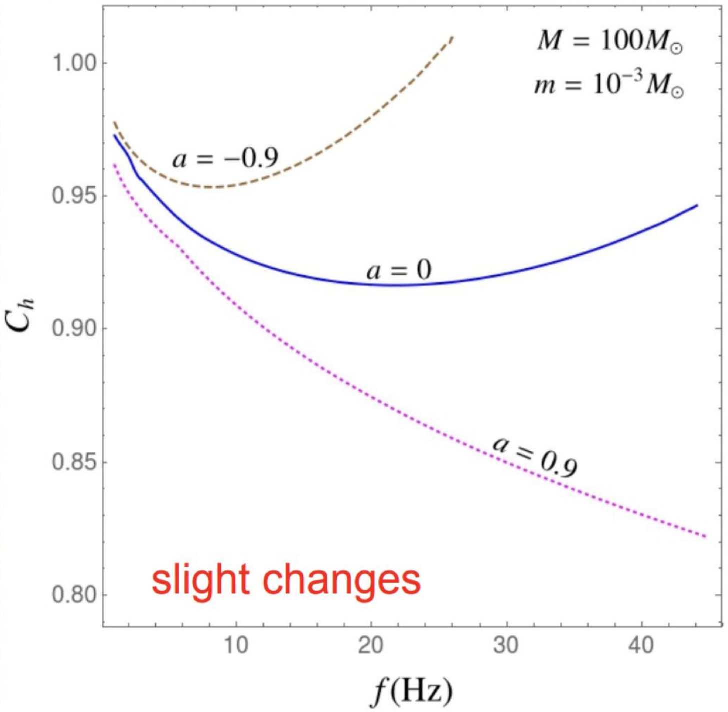


Guo and Miller arXiv: 2205.10359

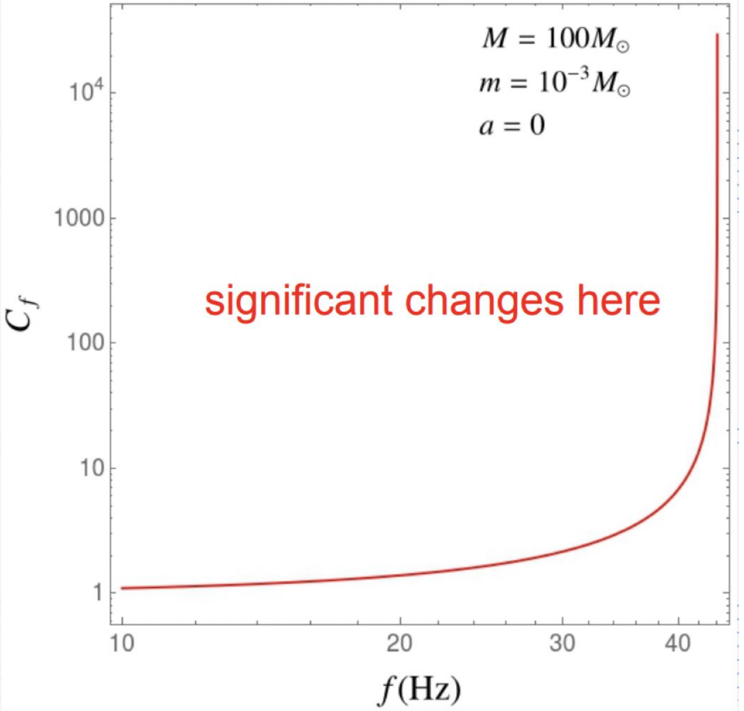
Waveforms for mini-EMRIs

- For particular chirp masses, we can ignore "EMRI" effects
- For others, we cannot. Must account for spin of the primary object
- Not even considering eccentricity, and already things get complicated

$$h_0 = \frac{4}{d}\left(\frac{GM_c}{c^2}\right)^{5/3}\left(\frac{\pi f}{c}\right)^{2/3} C_h(a, f)$$



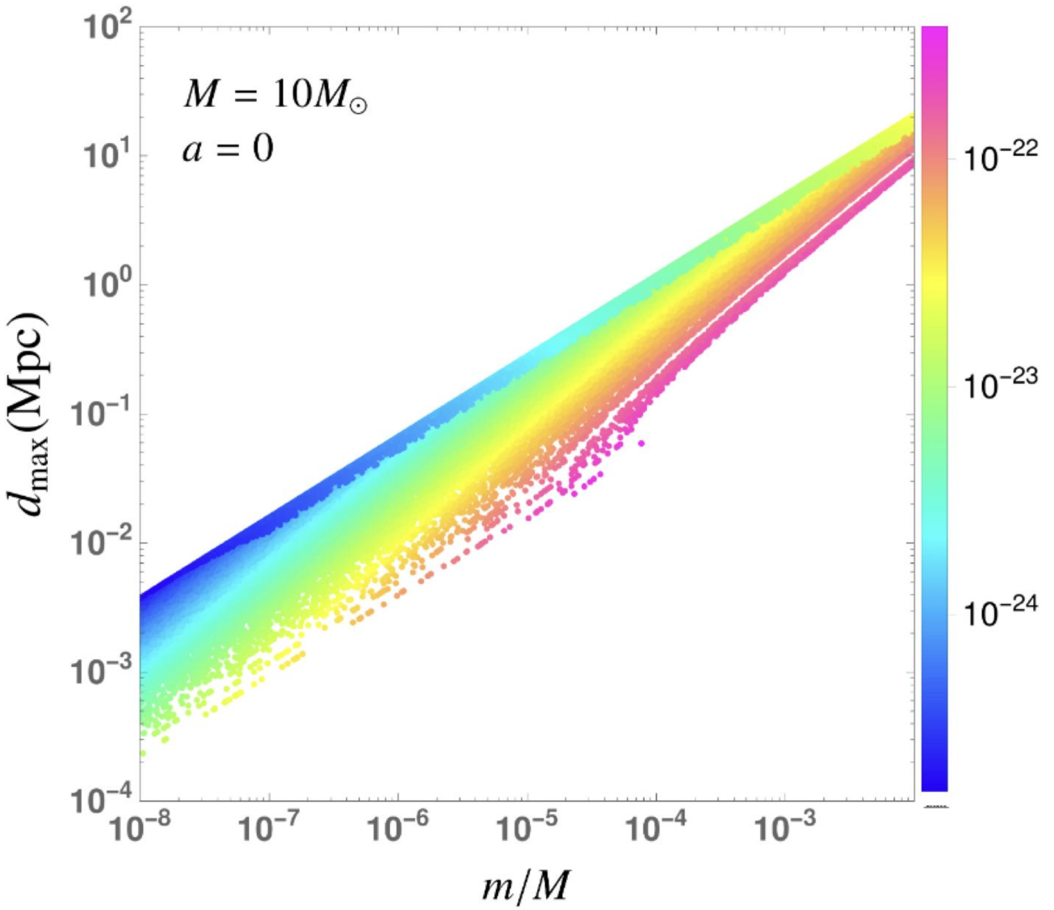
$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{GM_c}{c^3}\right)^{5/3} f^{11/3} C_f(a, f)$$



Waveforms from: Finn & Thorne (2000) PRD, 62, 124021

Could we see mini-EMRIs in LIGO?

- We certainly hope so, but we may need to move beyond purely analytic time-frequency relations of the signal
- Simplicity is great, but only considering PN0 won't let us see close to the plunge
- Time-frequency sums along the track of any waveform of your choosing?
  - "Matched filter" in time/frequency plane
  - Implications for long-lived BNSs?



Guo and Miller arXiv: 2205.10359

Could we see *any* sub-solar mass systems with LIGO?

- As Pippa Cole said, PBHs will be accompanied by some kind of dark matter cloud
- This will distort the vanilla inspiral/merger/ringdown signal, and maybe even for comparable mass systems Cole, Philippa S. et al., PRD 107.8 (2023): 083006; Aurrekoetxea, Josu C., et al. PRL 132.21 (2024):211401.
- The signal model changes to, optimistically: $\dot{f} = k_1 f^{11/3} + k_2 f^{3/2}$
- Other effects? Eccentricity?
- Are model-independent methods that find arbitrary time-frequency tracks better? Alestas, George, et al. PRD 109.12 (2024): 123516.
- Or: can we sum different time-frequency tracks according to numerical time-frequency relations? Major computational cost? How to place templates?

What is the meaning of all these constraints?

- There are so many assumptions that go into constraining PBH abundance – how can we compare constraints?
- What's the mass function of PBHs, and how does this impact constraints?
- Can binary formation be suppressed?
- What is a constraint in the first place? A null search result (microlensing, GWs) or a theoretical limit (evaporation)?
- And finally: can we do more work to *find,* rather than just constrain, PBHs?