Gravitational-wave probes of planetary- and asteroid-mass primordial black holes

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Miller et al. Phys.Dark Univ. 32 (2021) 100836;
Miller et al. Phys.Rev.D 105 (2022) 6, 062008;
LVK: Phys.Rev.D 106 (2022) 10, 102008

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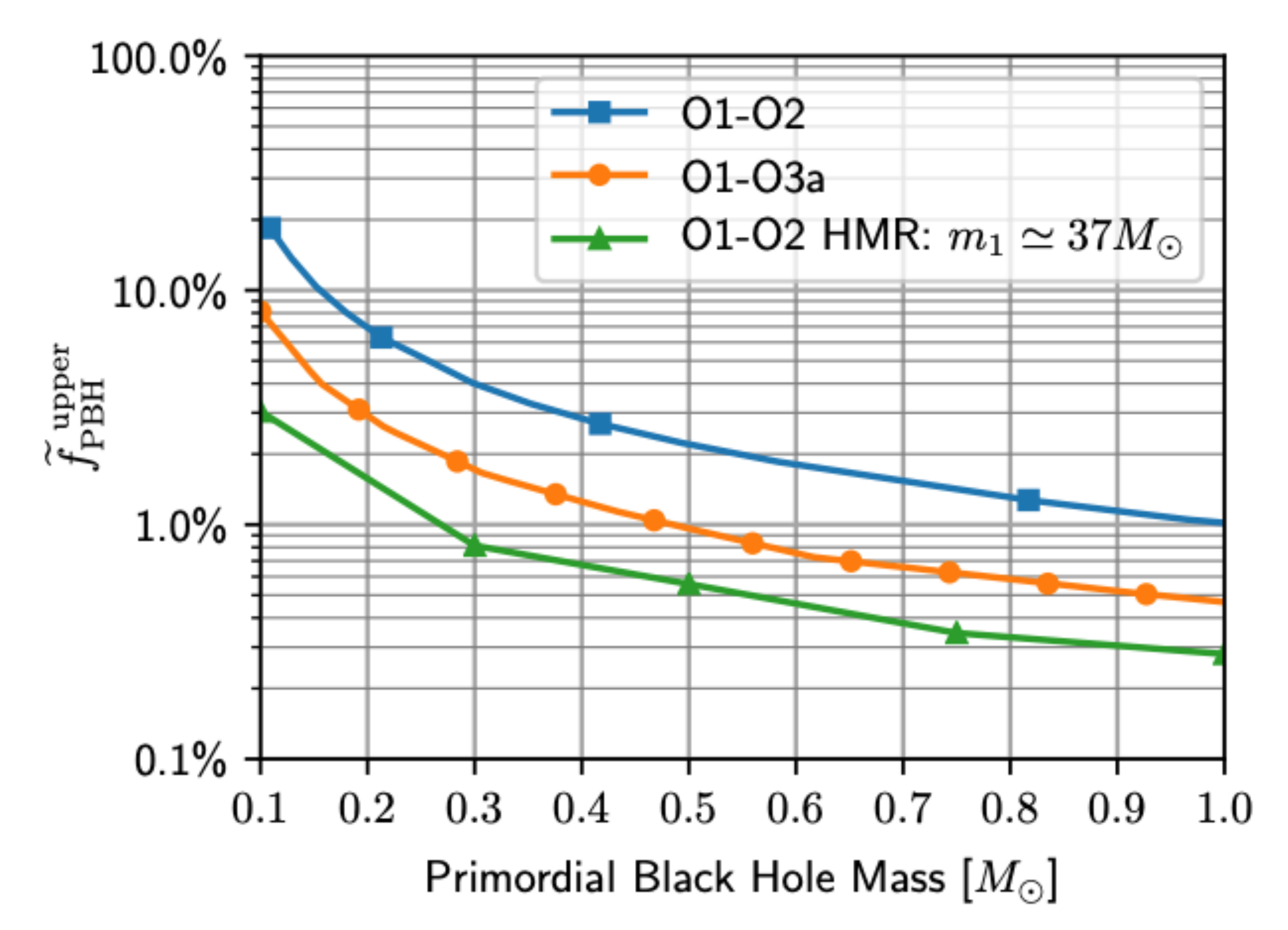
Motivation

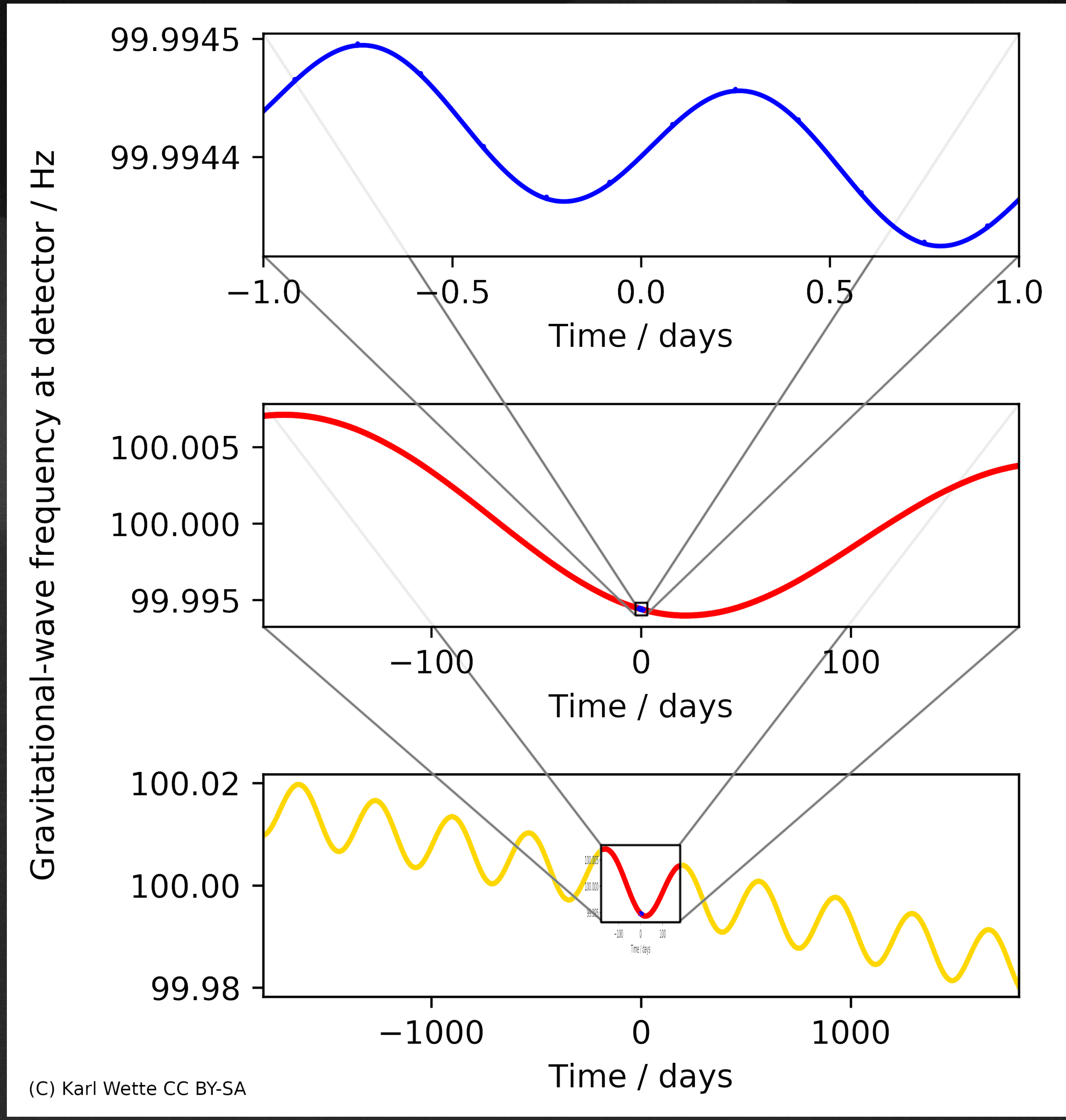
- Many GW efforts to detect PBHs focus on "sub-solar mass" regime, O(0.1 $M_\odot$)
- However, GWs from PBHs with masses [10^{-7} - 10^{-3}]$M_\odot$ have not been searched for
- Matched filtering in this mass range is extremely computationally challenging
- Signal for binaries in this mass range resemble continuous waves, since these systems will inspiral for a very long time and spin up very slowly



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

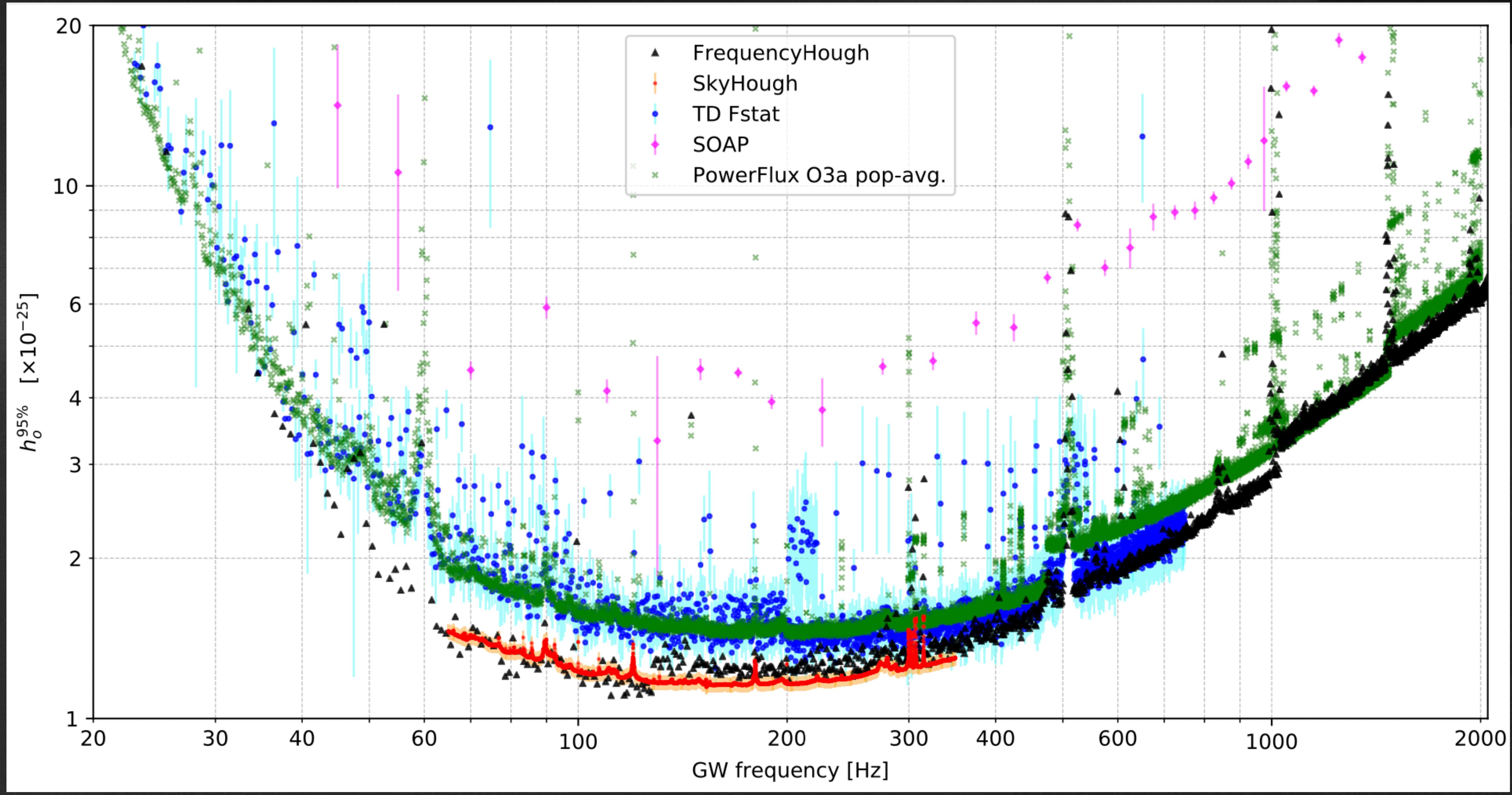
Continuous waves: what and why

- Quasi-monochromatic, persistent signals, subject to Doppler modulations
- The longer we can observe for, the more sensitive we are to these kinds of signals
- A completely new GW signal type: first detection will be another major milestone
- We can keep observing continuous-wave (CW) sources!
- So many sources, and so many algorithms not based on matched filtering!



LVK all-sky search in O3 data

- Four pipelines used
- These limits represent the minimum detectable amplitude h_0 as a function of gravitational-wave frequency, at 95% confidence
- They are generic, in the sense that they can be interpreted to be for *any* system that follows a linear frequency evolution over time



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Interpretation of upper limits

- All-sky continuous-wave upper limits give $h_0(f)$ averaged over all sky positions
- Searches specify a maximum spin-up, consider systems with linear frequency evolutions
- There could be binary systems with very small masses (PBHs) that are inspiraling and "chirping" linearly
- Reinterpret upper limits for chosen chirp masses $\mathcal{M}$

$$\dot{f}_{\rm gw} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f_{\rm gw}^{11/3}$$

$$f_{\rm gw,L}(t) = f_0 + \dot{f}_{\rm gw}\,(t - t_0)$$

$$d = \frac{4}{\underbrace{h_0}_{\text{Upper limit}}}\left(\frac{G\underbrace{\mathcal{M}}_{\text{Chosen chirp mass}}}{c^2}\right)^{5/3}\left(\frac{\pi \underbrace{f_{\rm gw}}_{\text{Frequency}}}{c}\right)^{2/3}$$

Under the conditions:

$$\dot{f}_{\rm gw} \leq 2\times 10^{-9}\ \mathrm{Hz/s}$$

Max spin-up searched

$$|f_{\rm gw,L}(T_{\rm obs}) - f_{\rm gw}(T_{\rm obs})| \leq \Delta f = \frac{1}{T_{\rm FFT}}$$

Linear frequency/time evolution

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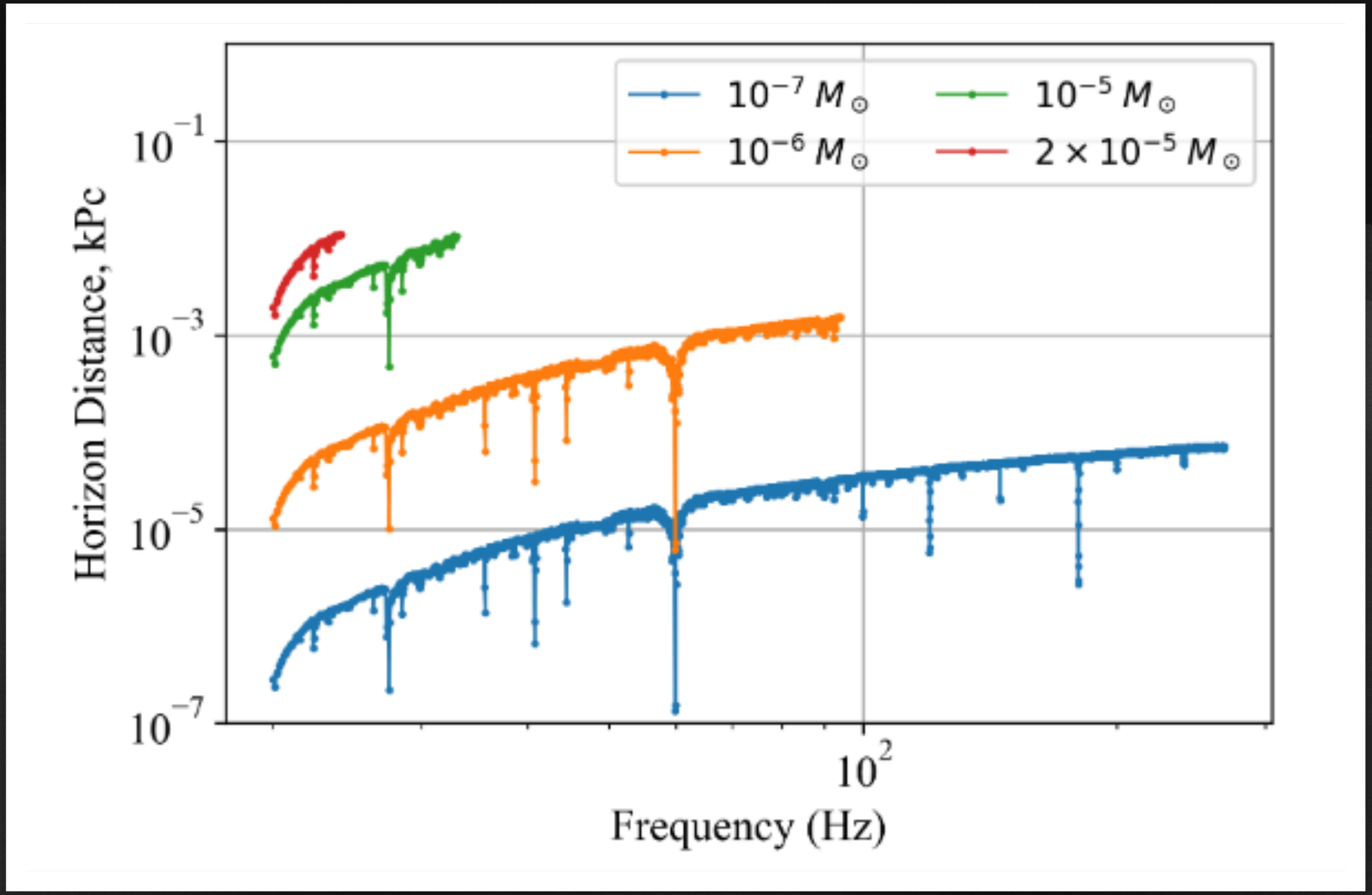
Enforcing linearity and spin-up

- Chirp mass determines spin-up
- Search ranges for spin-up and frequency restrict which upper limits we can include here
- Distance & no detection —> rates

$$N_{\text{bin}}(f) \simeq \frac{4}{3}\pi d(f)^3 RT,$$

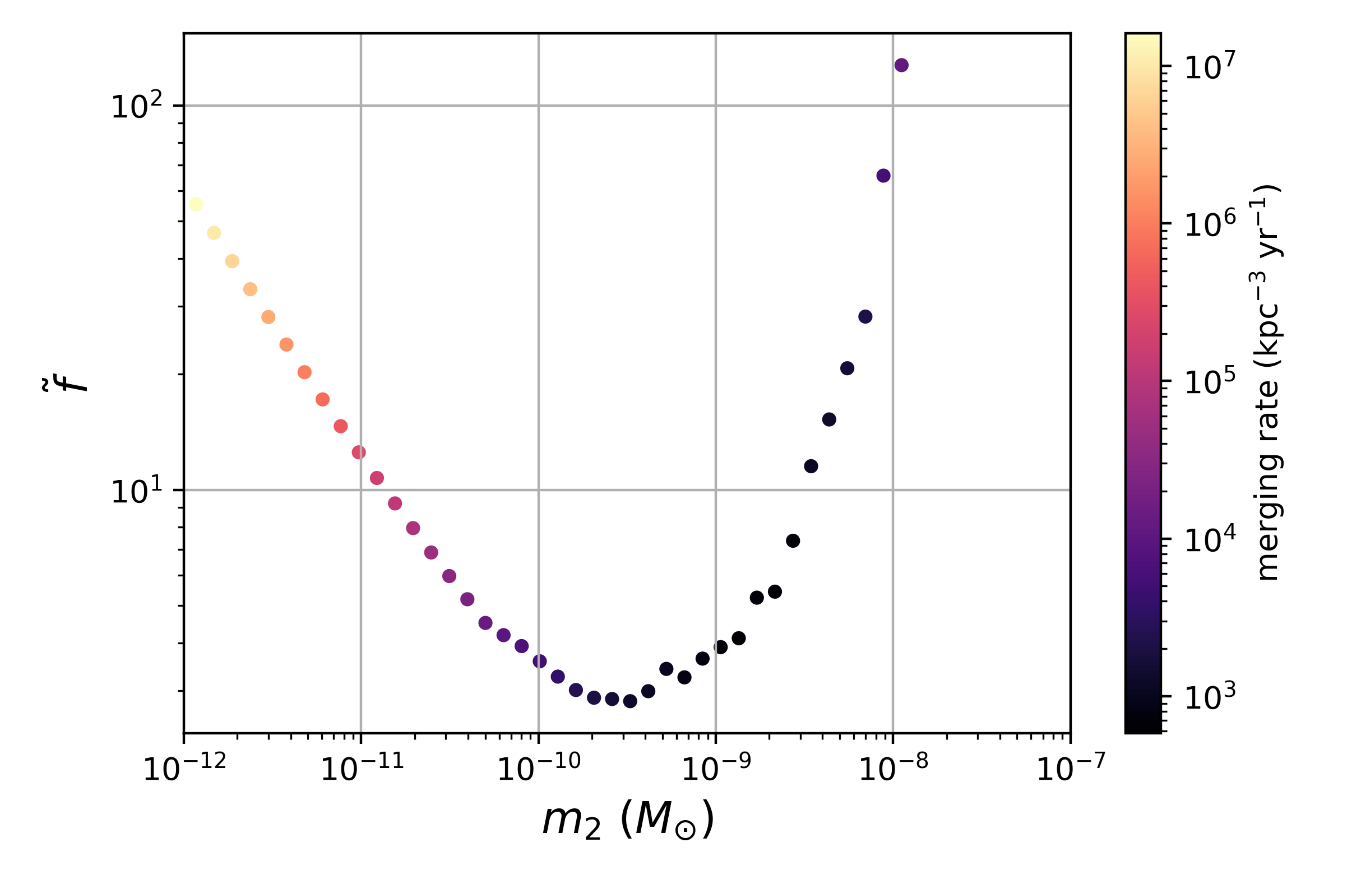
$$N_{\text{bin}}^{\text{tot}} = \sum_i N_{\text{bin}}(f_i)$$



T: how long binary spends in the band
R: rate
N_{bin} : number of detected binaries (< 1)

O3 Constraints, Asteroid-mass PBHs

- CW limits $h_0^{95\%}(f) \rightarrow d_{\rm bin}^{95\%}$
- Only allow linear frequency evolution: $f(t) = f_0 + \dot{f}(t - t_0)$
- Maximum $\dot{f}$ searched over ($\sim 1\mu$Hz/s) —> fixed ranges for $\mathcal{M}, f$
- Distance & no detection —> rates
- Constarints shown for asymmetric mass ratio binaries, $m_1 = 2.5M_\odot$



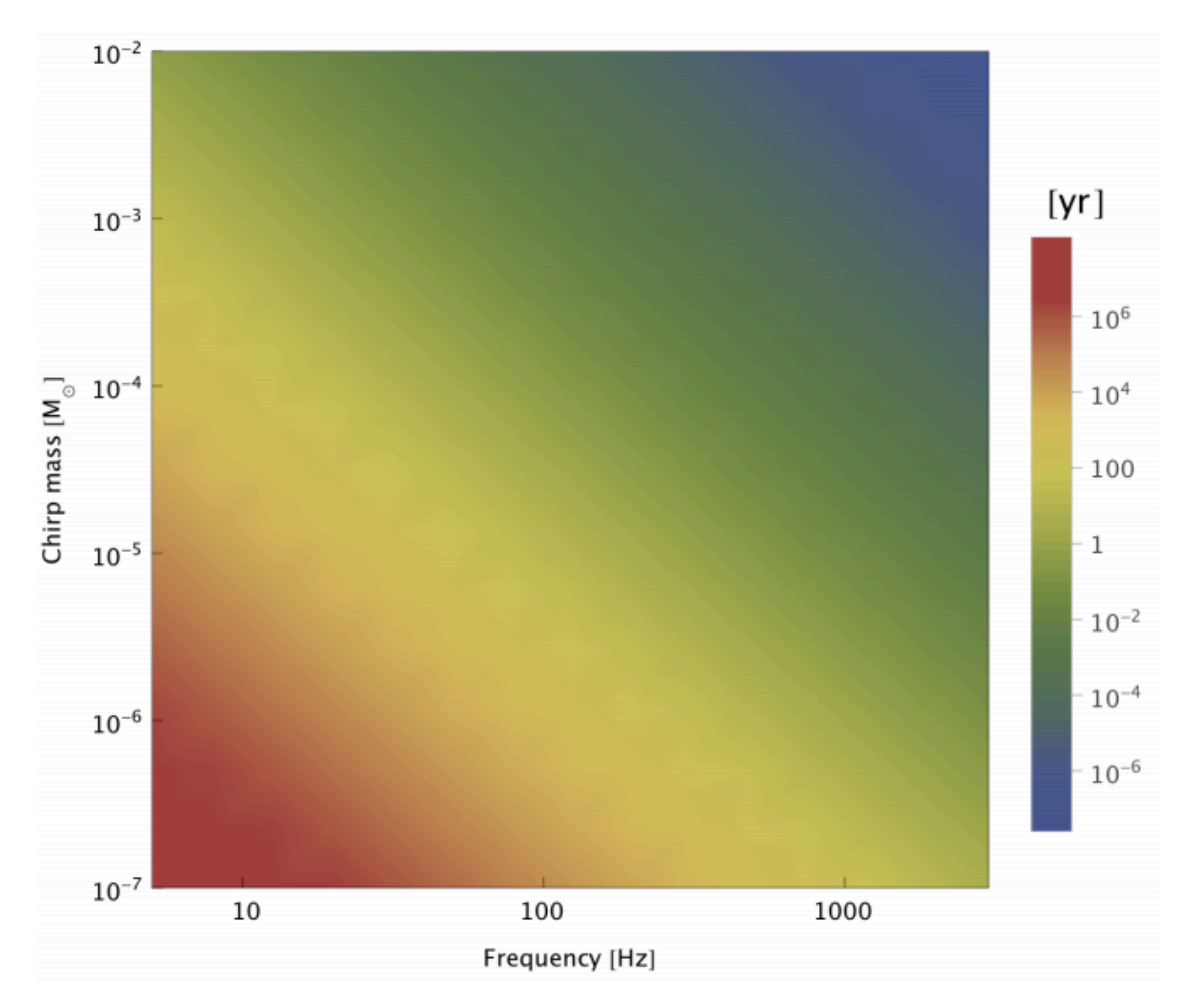
LVK: Phys.Rev.D 106 (2022) 10, 102008; arXiv:2201.00697

Constraints can be improved

- All-sky searches provide decent upper limits, but they are not the optimal way to search for inspiraling PBHs
- In fact, inspiraling compact objects with chirp masses $<\mathcal{O}(10^{-3})M_\odot$ would exhibit power-law frequency evolutions over time
- Methods to detect "transient" continuous waves, such as those used to search for a remnant of GW170817, can be tuned to search for inspiraling PBHs
- Note that searches/methods do not assume PBHs exist

GWs from inspiraling PBHs

- $\sim[10^{-7} - 10^{-3}]\ M_\odot$ give rise to signals that are *long lasting*, compared to those detected from $O(M_\odot)$ black holes
- The evolution of these binaries can be described as quasi-Newtonian circular orbits
- Techniques used in GW data analysis for quasi-monochromatic or power-law signals can also be applied to detect PBHs



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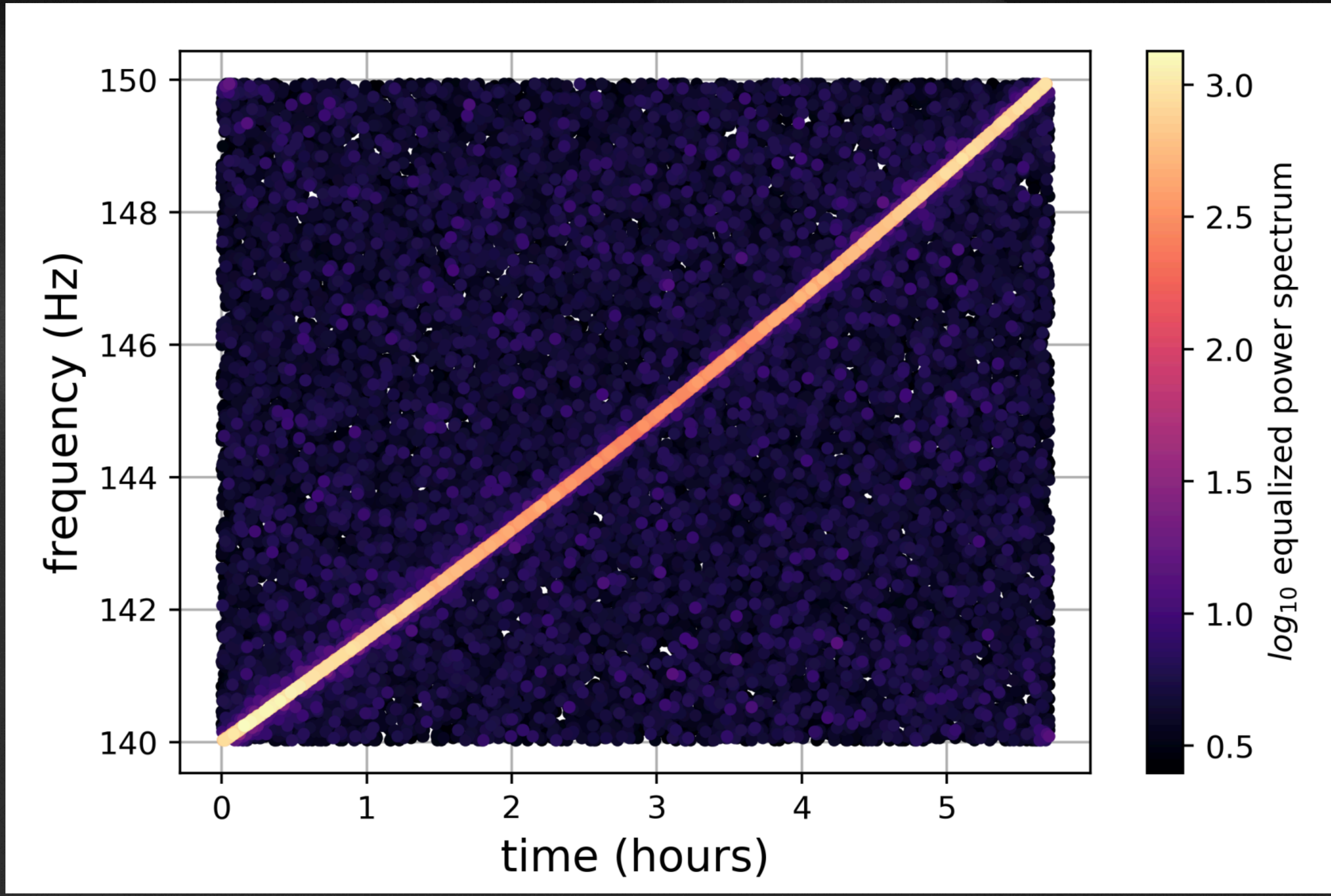
Generalized Frequency-Hough

- Attempt to detect power-law signals that slowly "chirp" in time
- Input: points in time/frequency plane to lines [7,11]

$$\dot{f}_{\rm gw} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f_{\rm gw}^{11/3}$$



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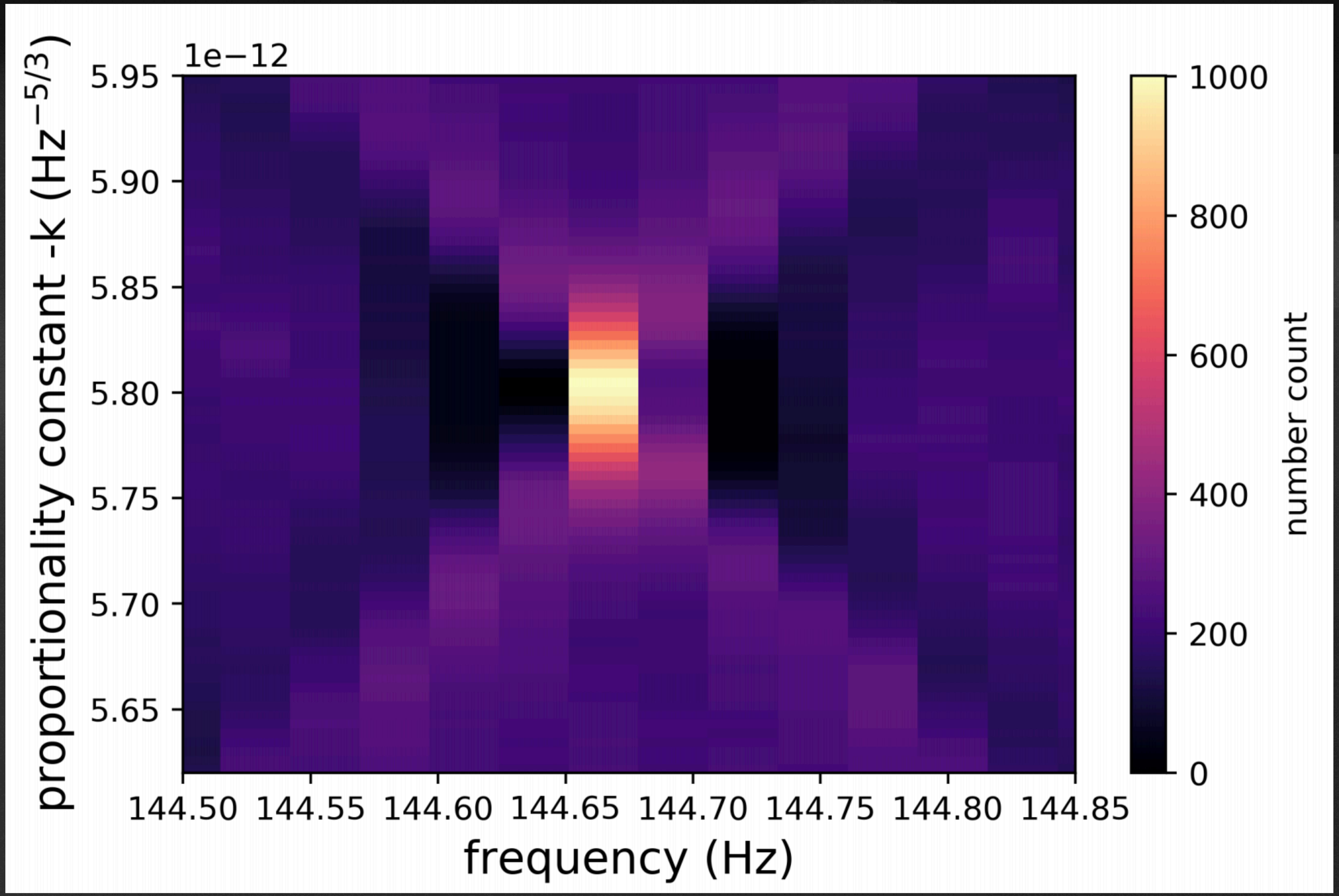
Generalized Frequency-Hough

- Generalization of method to search for isolated neutron stars
- Output: two-dimensional histogram in the frequency/chirp mass plane of the source



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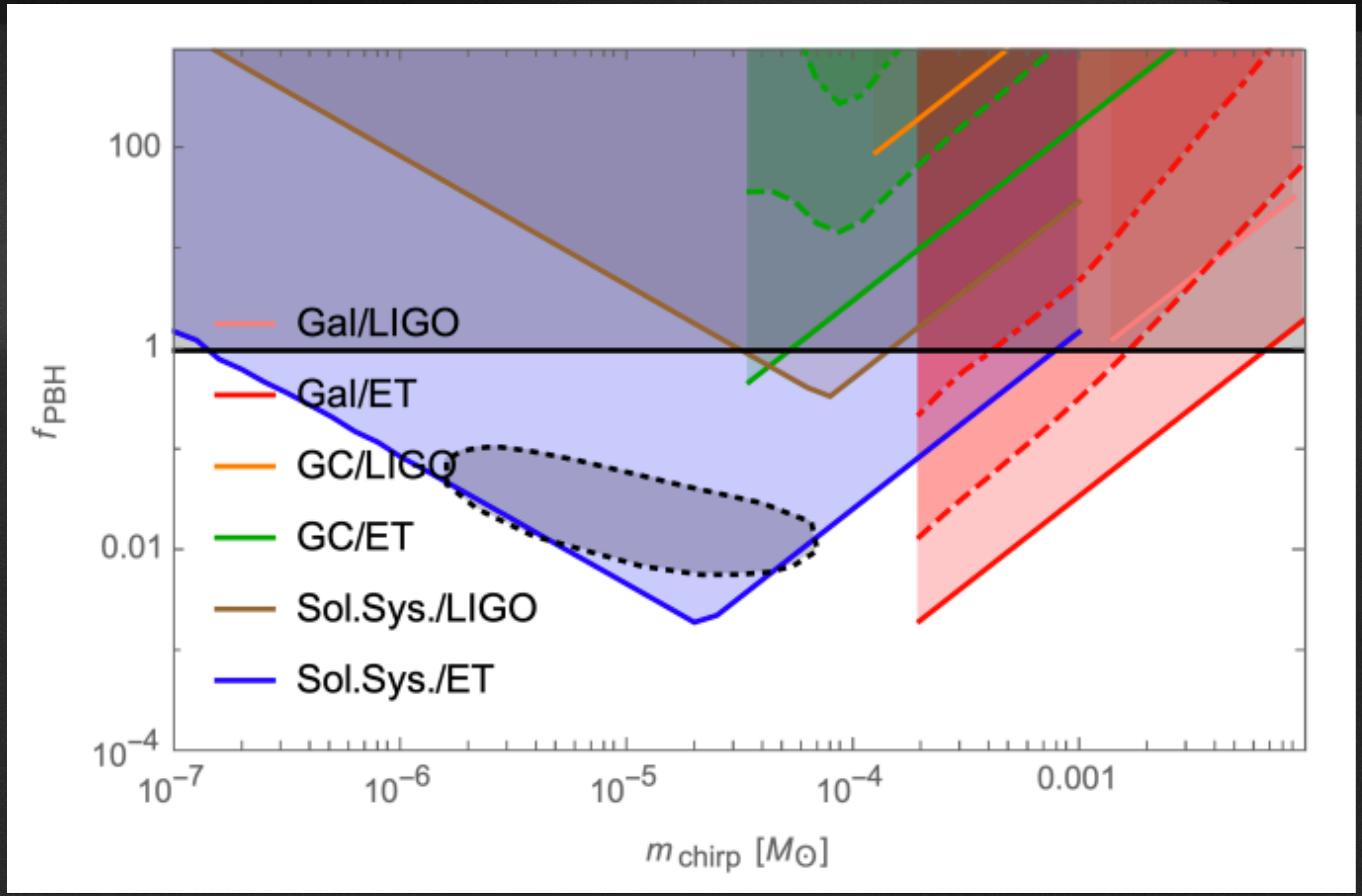
Projected constraints, PBH binaries

- Current CW search results limited —> designed new method to search for light PBHs that tracks the "chirp" inspiral

- Projected constraints on equal-mass PBHs, for monochromatic and thermal mass functions (solid and dashed lines, respectively)



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Conclusions

- CW limits can be mapped to constraints on rates as a function of chirp mass for inspiraling systems, without any model assumptions
- When assuming particular models for PBH formation rates, these limits can be translated to the fraction of dark matter that PBHs compose, for both equal-mass and asymmetric-mass ratio binaries
- Future observing runs, especially Einstein Telescope, can probe physical values for the fraction of dark matter at planet and asteroid masses

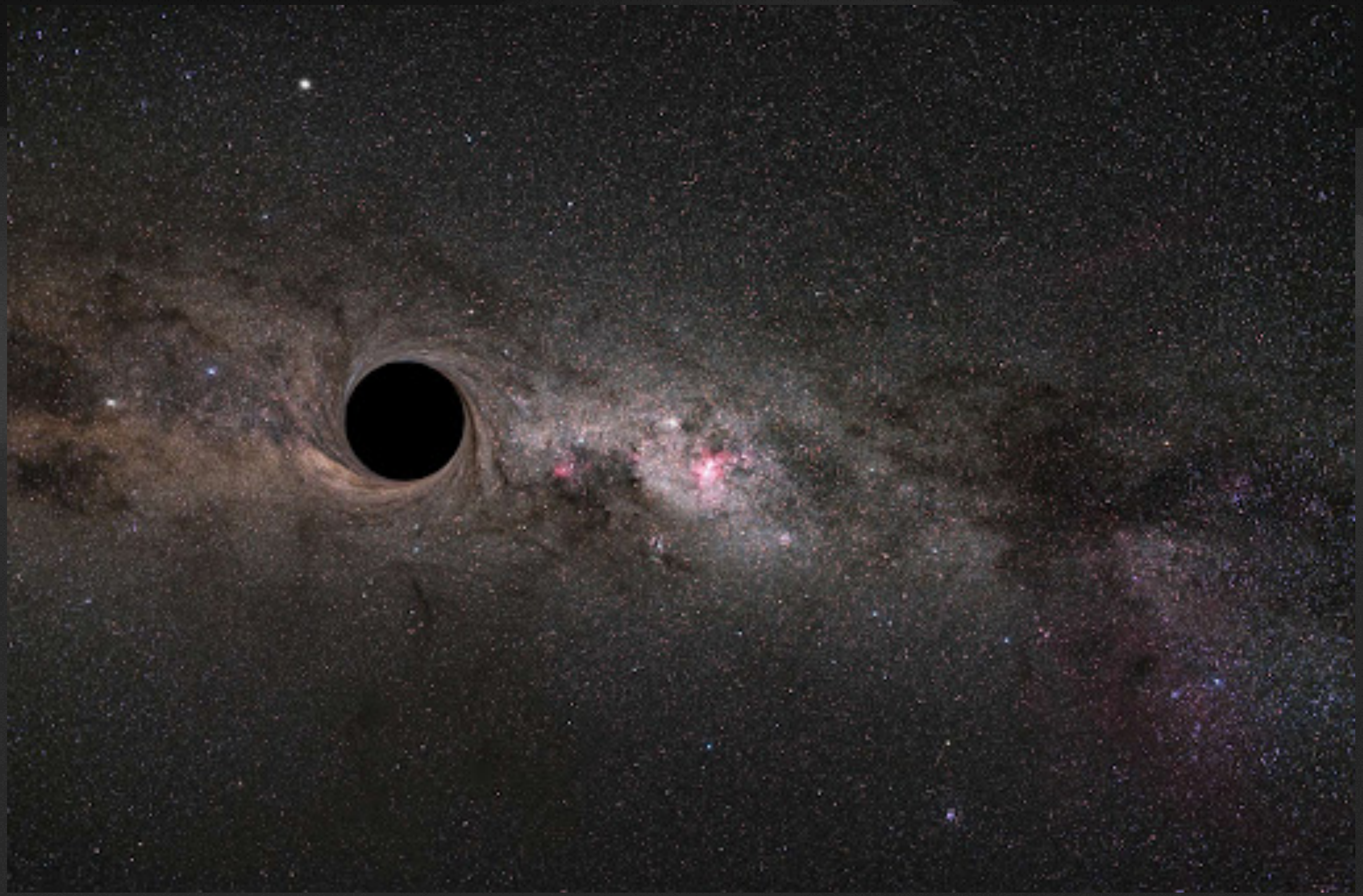
Multi-Messenger CW Workshop

- 11-13 July 2023, Amsterdam
- Registration is open!
- https://indico.nikhef.nl/e/mmcw

Back-up slides

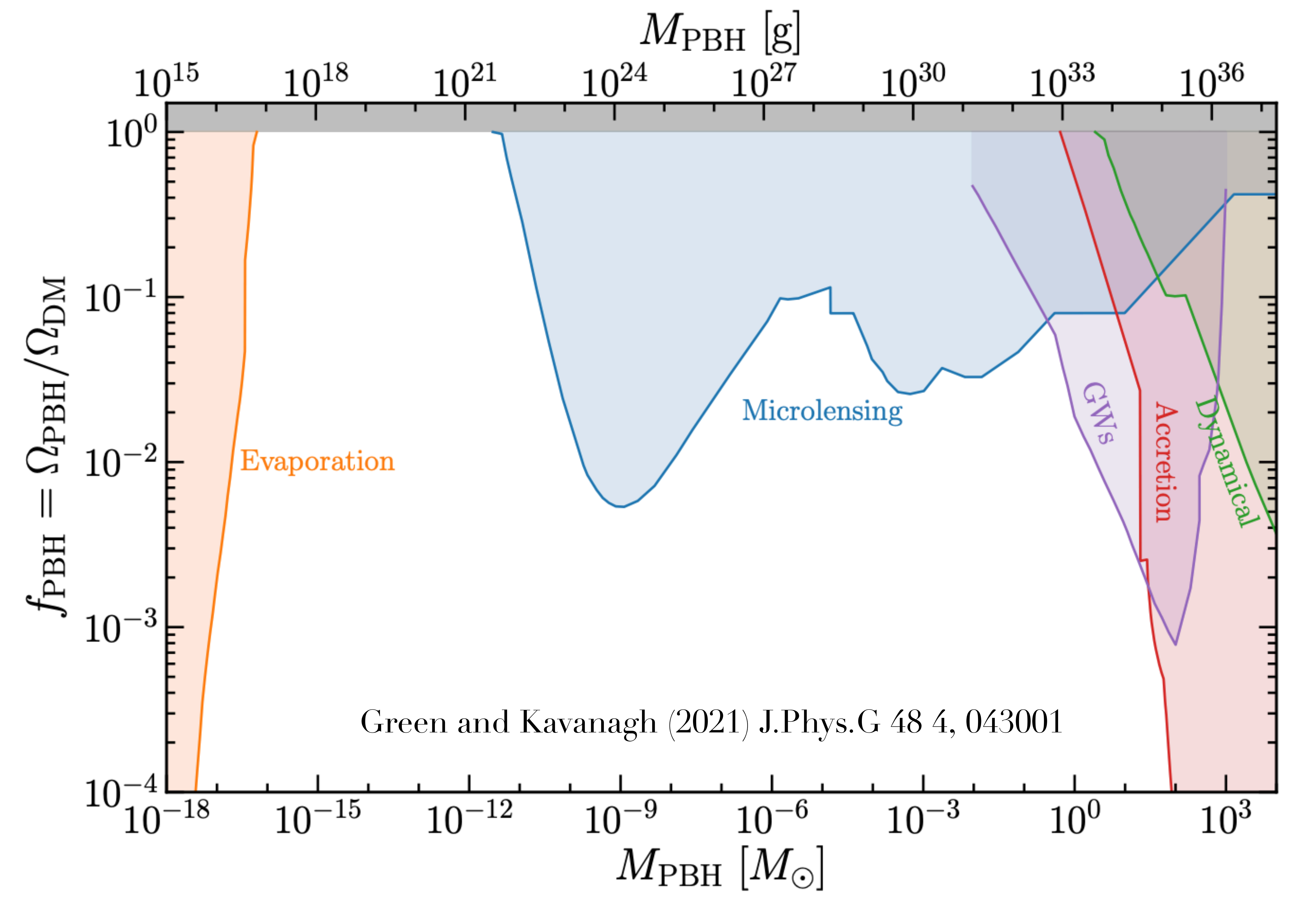
Primordial Black Holes (PBHs)

- Low spins of LIGO/Virgo black hole mergers, and merging rate inferences have revived the interest in PBHs
- Black holes that formed in the early universe can take on a wide range of masses depending on when they formed
- Could be linked to Dark Matter



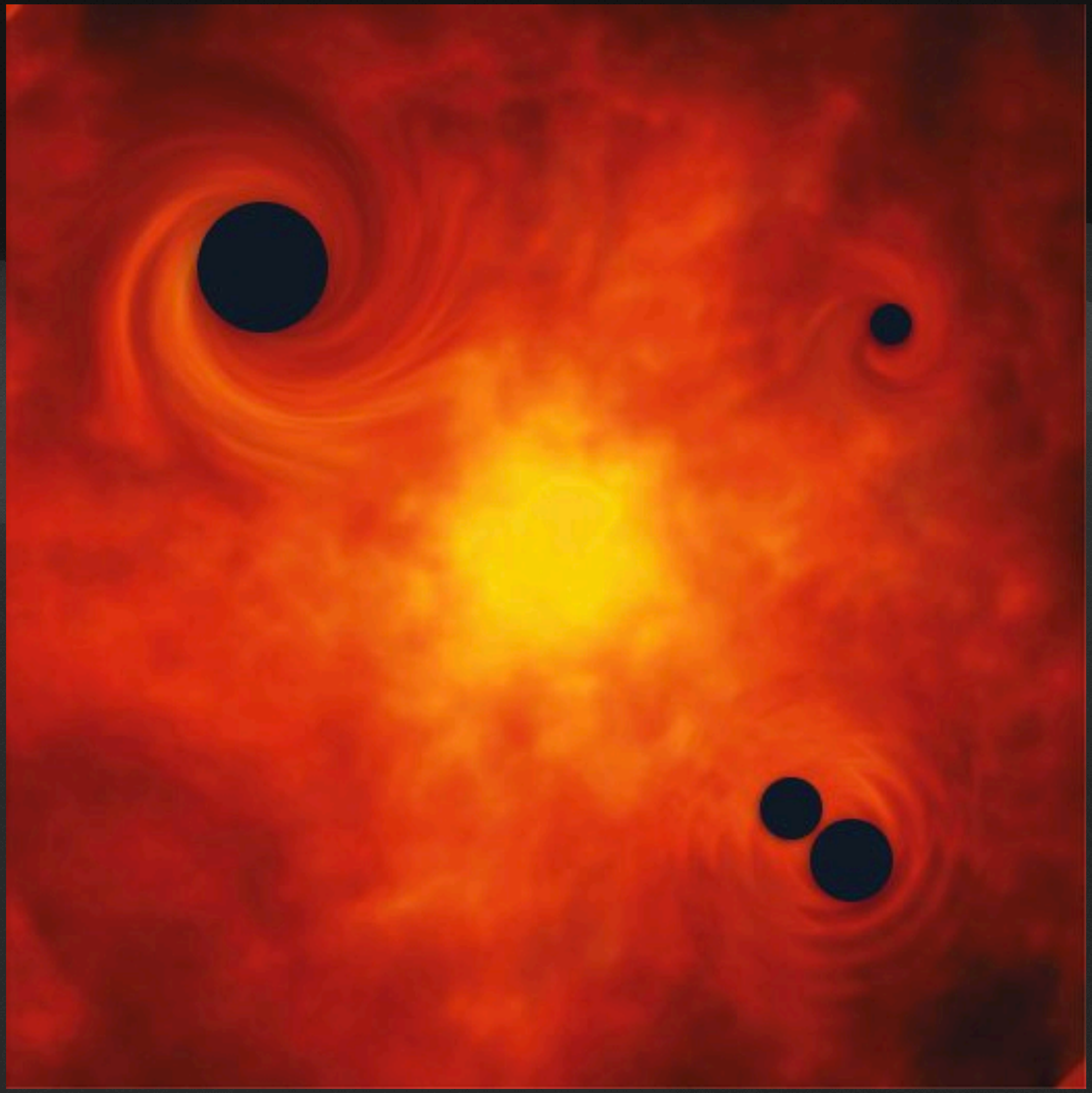
Current constraints on PBHs

- Asteroid-mass region not well constrained
- Limits based on uniform distribution of PBHs, while GWs could probe clusters of PBHs
- Constraints can be evaded in particular PBH formation models, e.g. if PBHs form in clusters
- Wide range of masses



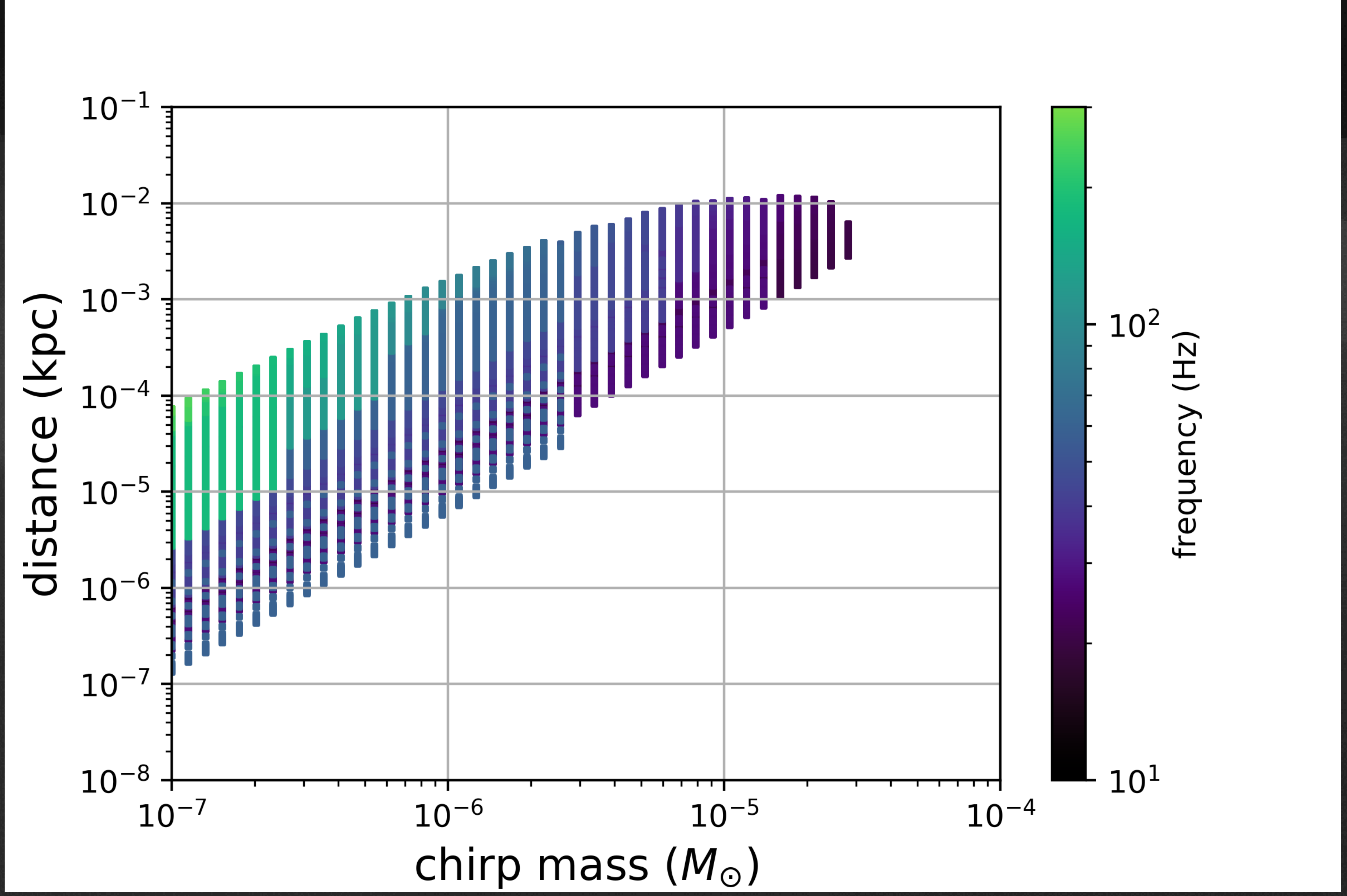
PBH Formation

- Could have formed in early universe which contained inhomogenities that stopped too dense regions from expanding, causing collapses
- Quantum fluctuations in various inflation theories
- A binary could form if two PBHs form independently but are kept from merging by the gravitational pull of other nearby PBH
  - Binaries would take age of the universe to merge
- Also, formation could occur through capture in a PBH halo
- Many more….



Distance reach

$$h_0 = \frac{4}{d}\left(\frac{G\mathcal{M}}{c^2}\right)^{5/3}\left(\frac{\pi f_{\mathrm{gw}}}{c}\right)^{2/3}$$



- For chosen chirp masses, compute the distance reach at each frequency in the upper limit
- Frequencies > ~250 Hz give rise to signals with spin-ups greater than the maximum allowed by the search
- Typically, at a fixed chirp mass, higher frequencies →larger distance reach

PBH merging rates constraints

- T is the time that a binary system would spend in a frequency range f to $f + \delta f$, where $\delta f = \dot{f}_{max} T_{obs}$;
  $T = max(\Delta T, T_{obs})$

- To obtain constraints, sum over binaries present at each frequency, and demand that the total number of binaries observed is less than one

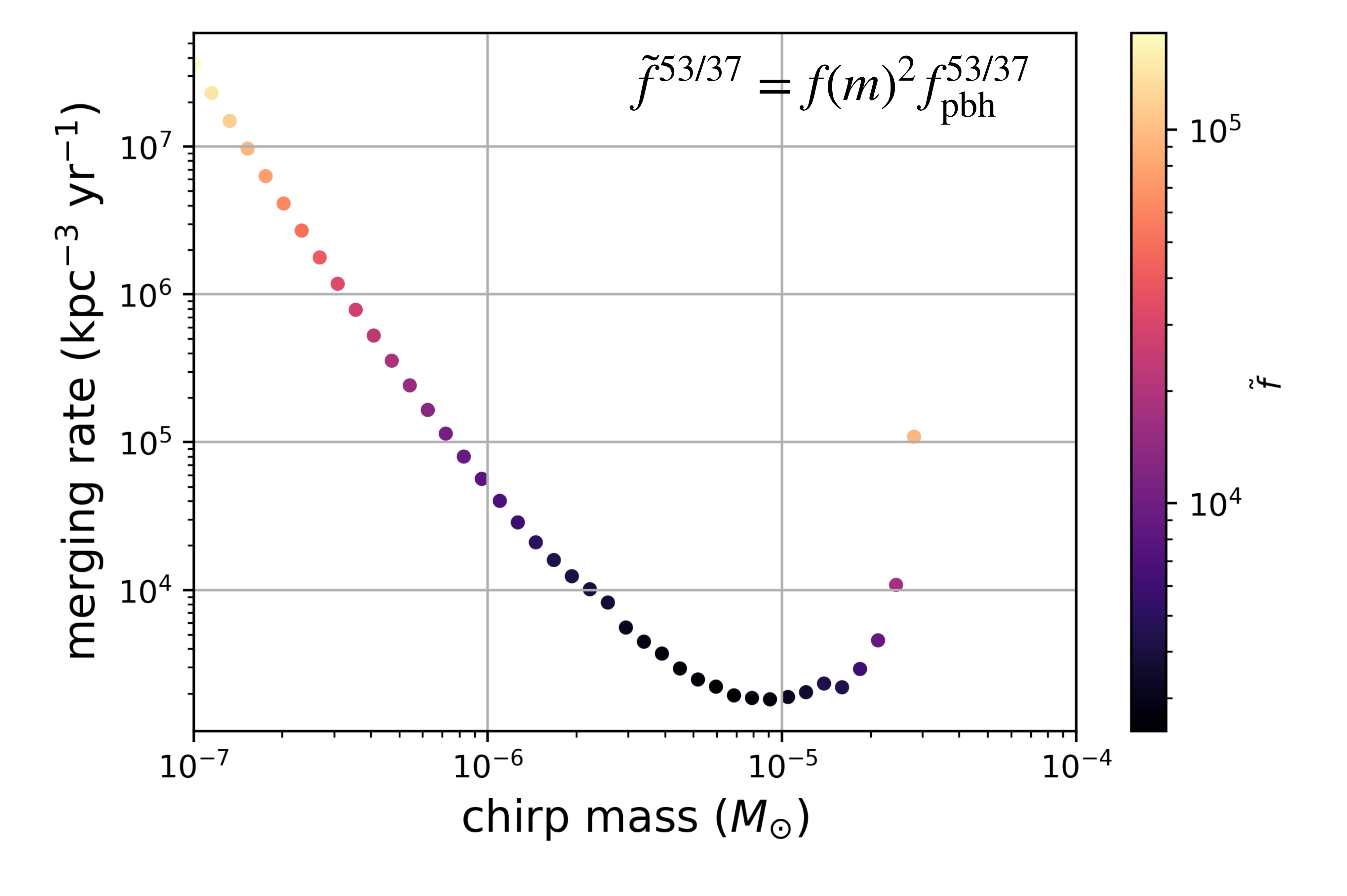
$$N_{\rm bin}(f) \simeq \frac{4}{3}\pi d(f)^3 RT,$$

$$N_{\rm bin}^{\rm tot} = \sum_i N_{\rm bin}(f_i)$$

$$\Delta T = \frac{5}{256}\pi^{-8/3}\left(\frac{c^3}{G\mathcal{M}}\right)^{5/3}\left[f^{-8/3} - (f+\delta f)^{-8/3}\right]$$

Constraints for equal-mass binaries

- Can derive model-independent rates on the basis of upper limits
- Constraints are made on effective parameter $\tilde{f}$ that equals f_{pbh} for a monochromatic mass function
- Assume rate model from G. Hutsi+ (2021) & Raidal (2019)



$$R = 1.04 \times 10^{-6} \mathrm{kpc}^{-3} \mathrm{yr}^{-1} f(m)^2 \left(\frac{m}{M_\odot}\right)^{-32/37} \left(f_{\rm PBH}\right)^{53/37}$$