Searching for inspiraling planetary-mass primordial black holes in LIGO O3a data

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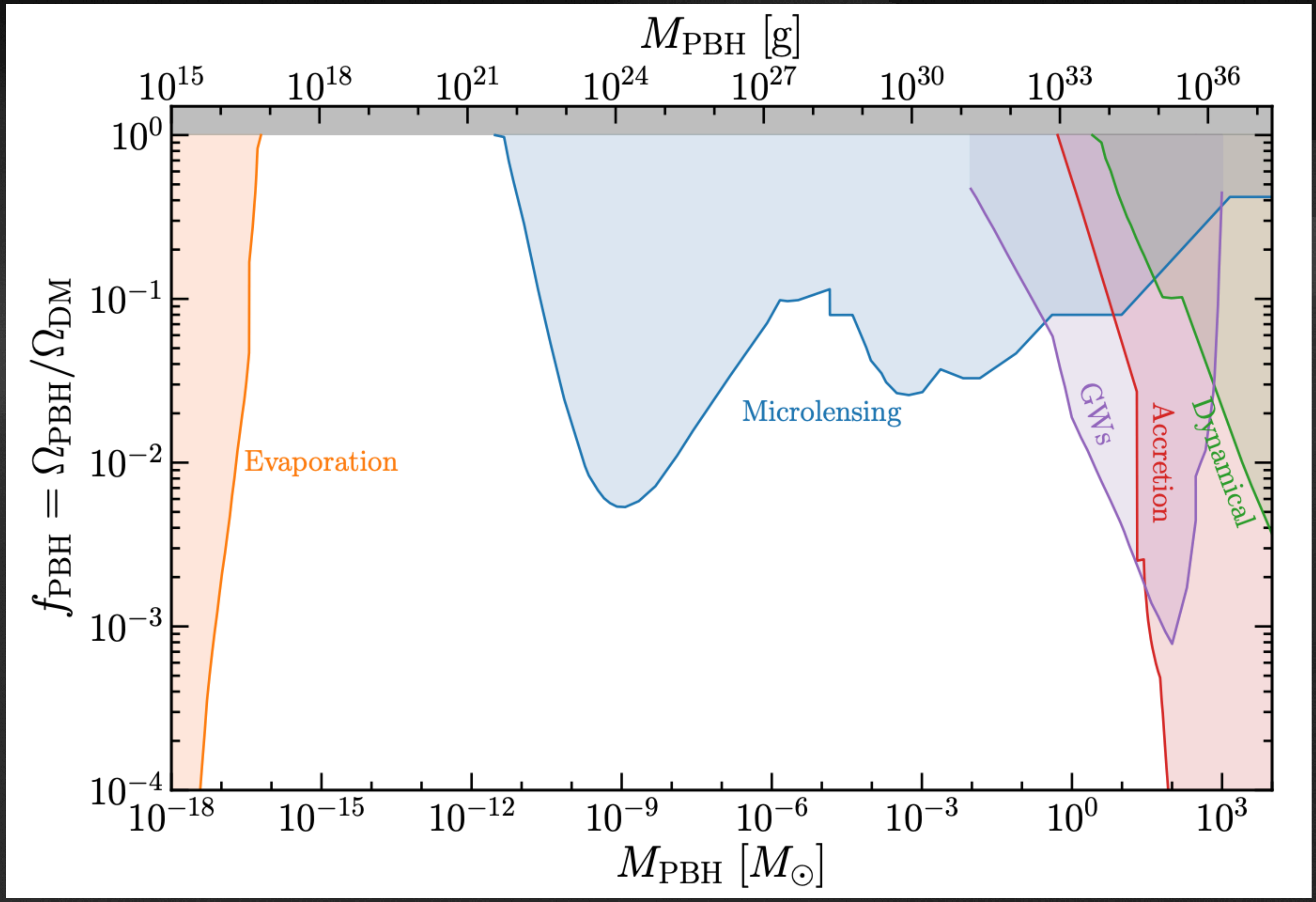
Background

Primordial Black Holes

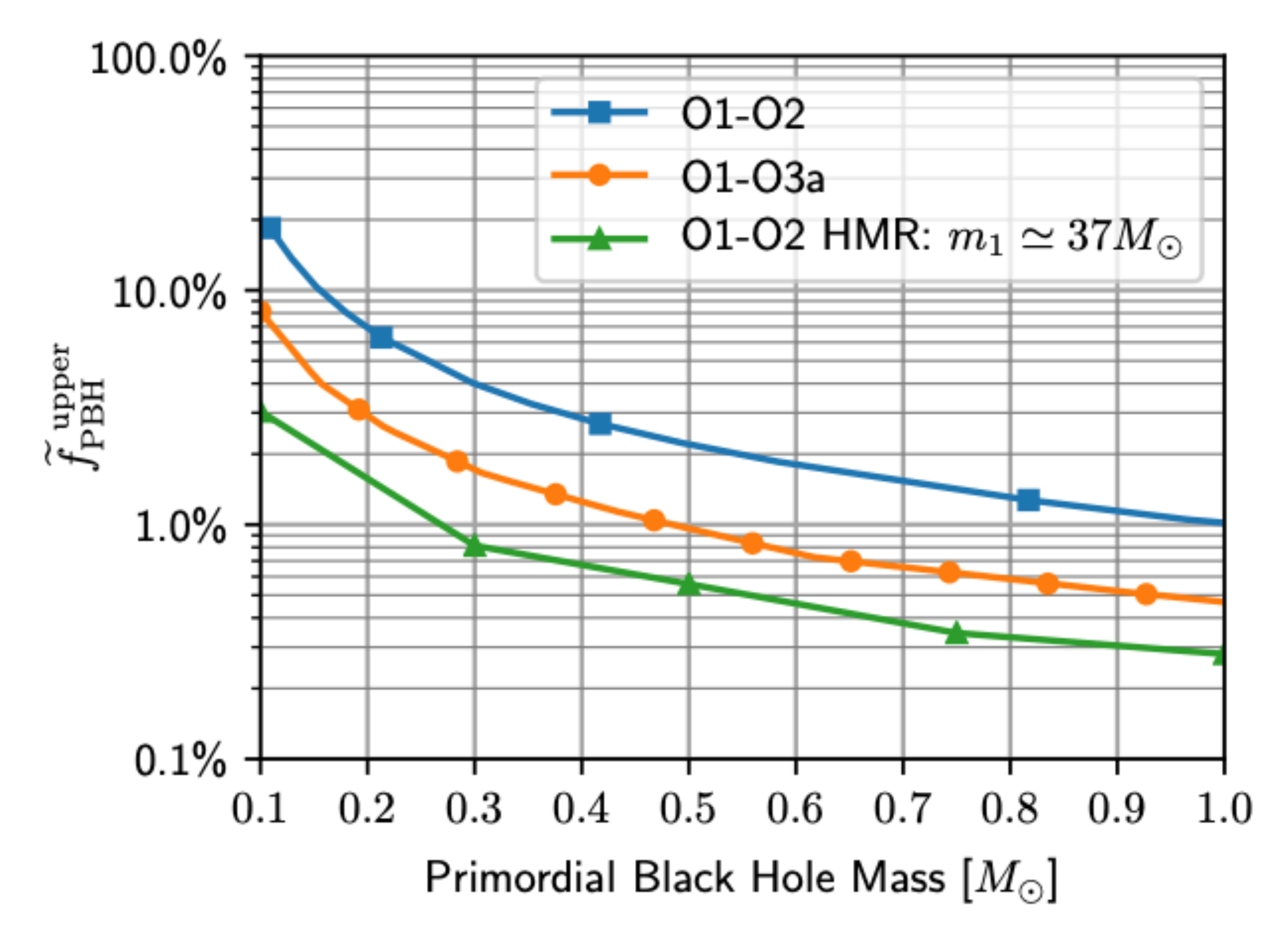
- Low spins of LIGO/Virgo black holes, and merging rate inferences have revived interest in PBHs
- BHs that formed in the early universe can take on a wide range of masses
- Possible links to dark matter



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

Motivation

- Many GW efforts to detect PBHs focus on "sub-solar mass" regime, $\mathcal{O}(0.1M_\odot)$
- However, GWs from $[10^{-7}, 10^{-2}]M_\odot$ PBH binaries have not yet been searched for
- Matched filtering in this mass range is extremely computationally challenging
  - Signals are long-lasting at LIGO frequencies —> many more templates needed for the same m_1, m_2 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

GWs from inspiraling PBHs

- 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 $\mathscr{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$ and signal frequency

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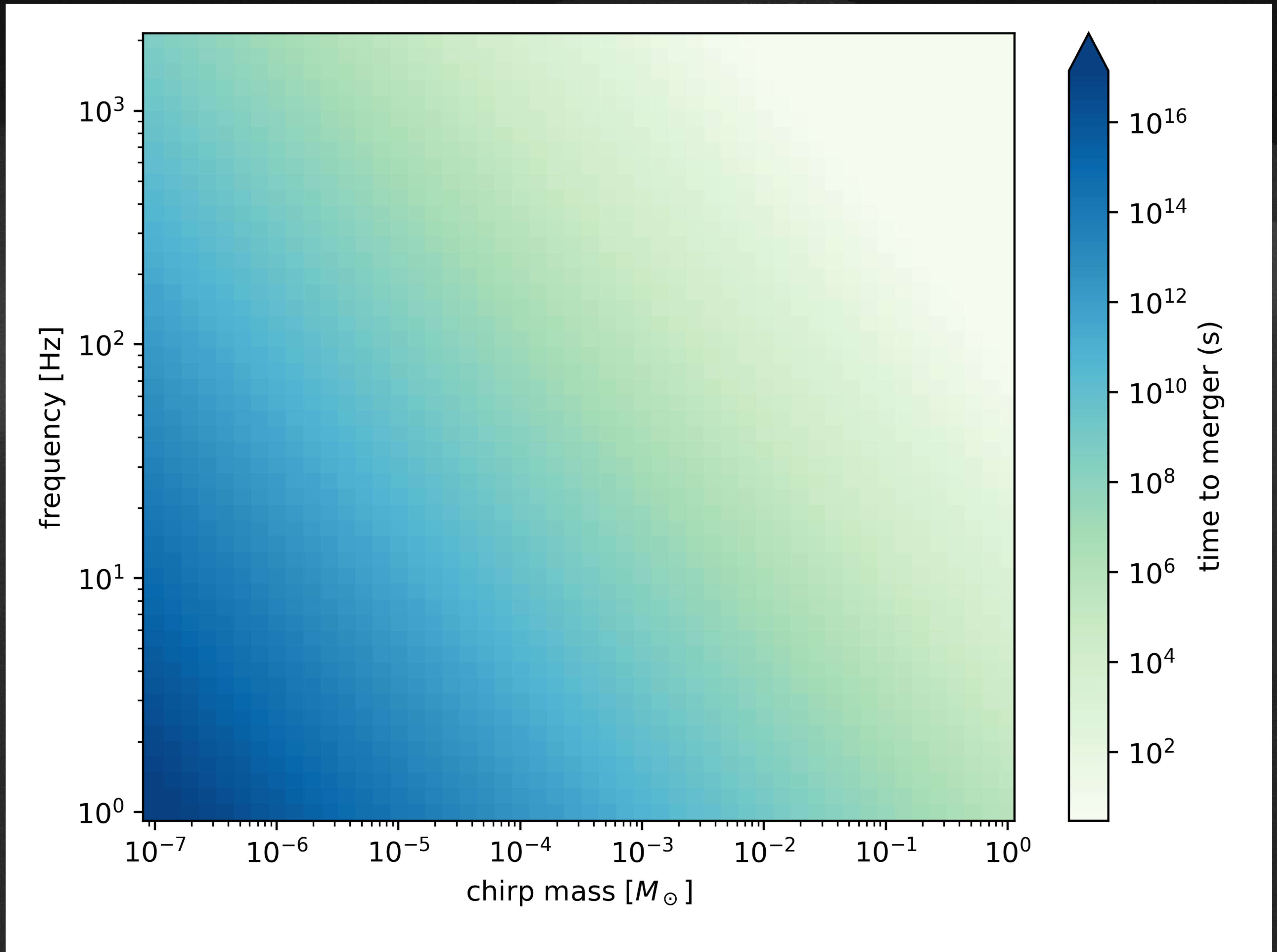


“Transient” continuous waves

- Signal frequency evolution follows a power-law and lasts hours-days at LIGO frequencies
- Can describe GWs from the inspiral portion of a light-enough binary system, or from a system far from coalescence
- How to search for these signals?

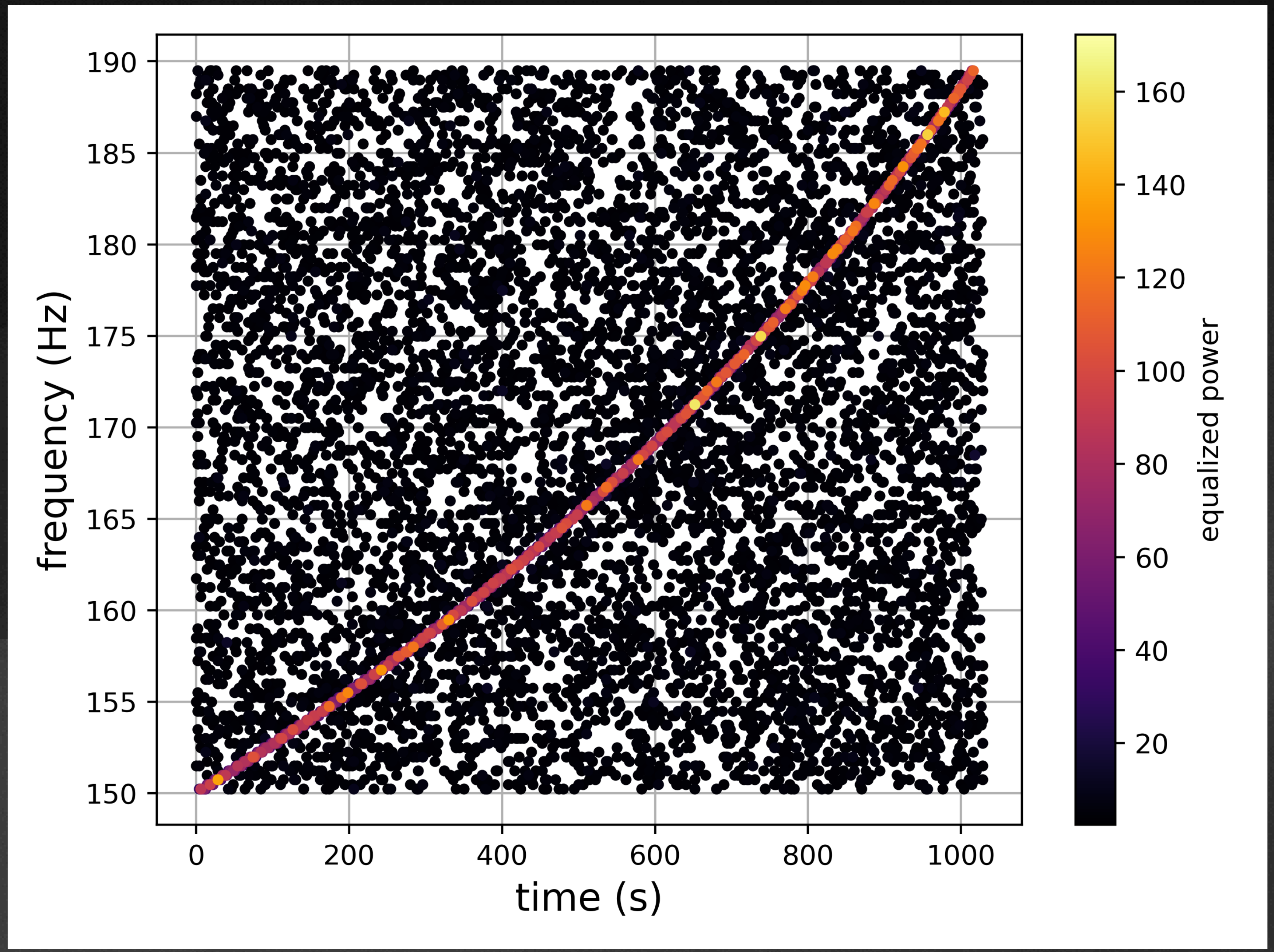
- Gravitational waves from quasi-Newtonian orbit

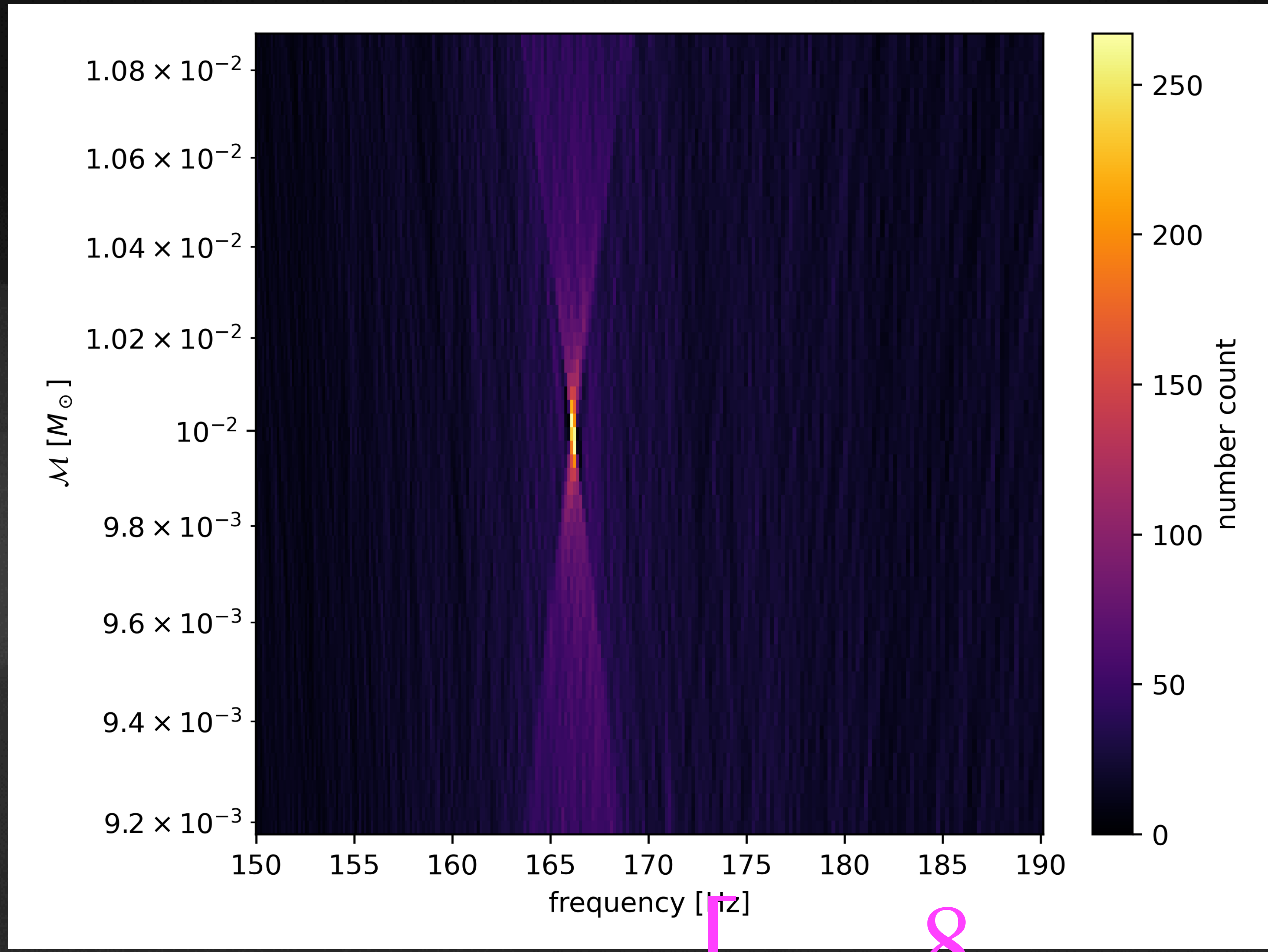
$$\dot{f} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathcal{M}}{c^3}\right)^{5/3} f^{11/3}\left[1 + \ldots\right]$$

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

$\mathcal{M}$: chirp mass
f : frequency
$\dot{f}$: spin-up

Generalized Frequency-Hough





$$f_{gw}(t) = f_0 \left[1 - \frac{8}{3}\kappa f_0^{8/3}(t - t_0)\right]^{-\frac{3}{8}}$$

- Detect power-law signals that slowly "chirp" in time
- Input: points in time/frequency detector plane ; look for power-law tracks
- Output: two-dimensional histogram in the frequency/chirp mass plane of the source

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

O3a search for planetary-mass PBH binaries

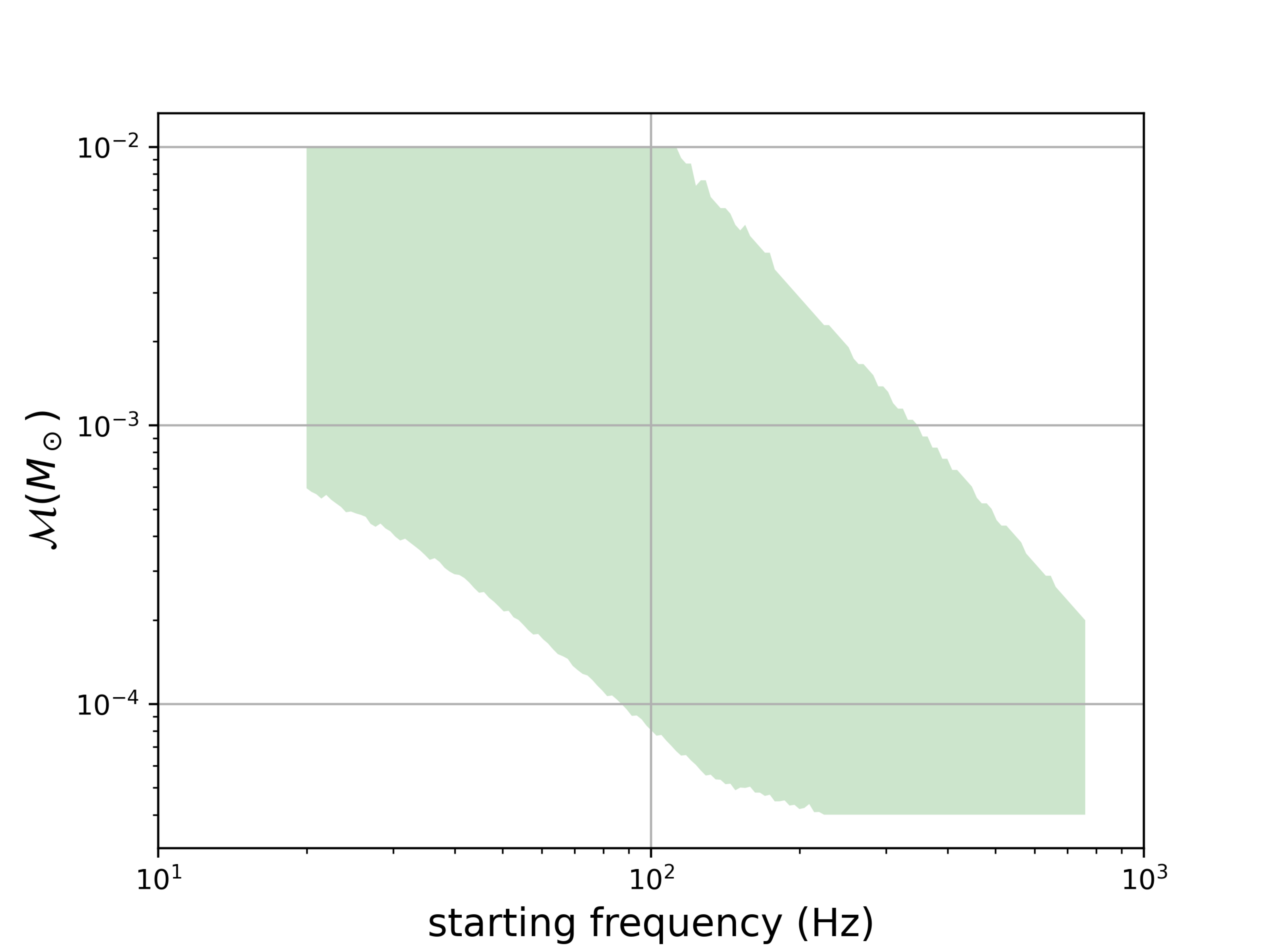
Miller et al., arXiv: 2402.19468

Parameter Space

- Constructed by considering equal-mass systems with: $\mathscr{M} \in [4 \times 10^{-5}, 10^{-2}]M_\odot;\ T_{\rm PM} \in [1\text{ h},\ 7\text{ d}]$; $T_{\rm FFT} \in [2, 30]$ s

- Sensitive to asymmetric mass-ratio systems $q = m_2/m_1 \approx \eta \in [10^{-7}, 10^{-4}]$ for $m_1 \sim \mathcal{O}(M_\odot)$ as long as: $$|f_{0PN}(t) - f_{3.5PN}(t)| \leq \frac{1}{T_{\rm FFT}},$$

- We found ~300 candidates at 7σ but these were due to noise disturbances



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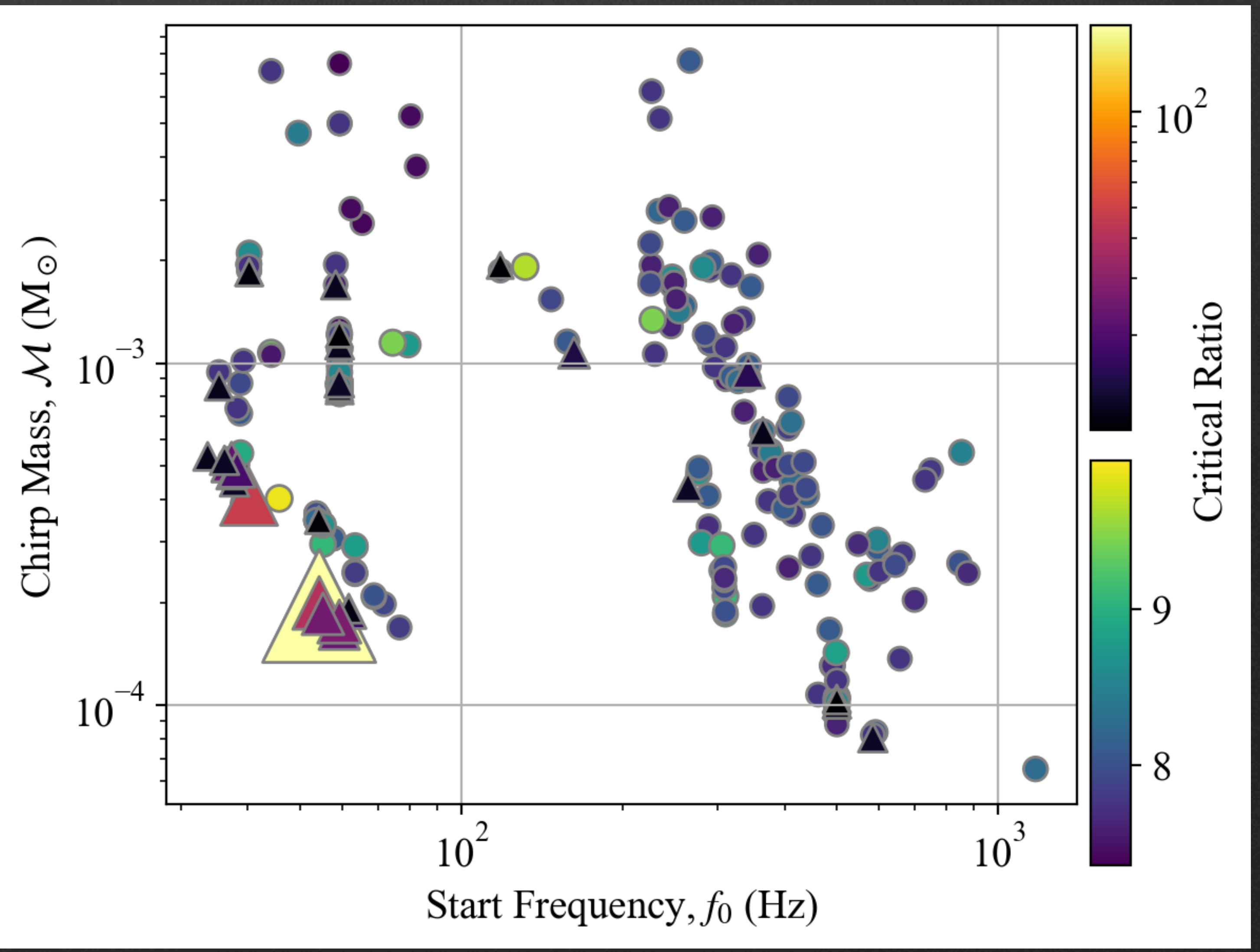
Search details and results

- ~ 100 search configurations cover the parameter space, decided based on maximizing expect distance reach as a function of the source and search parameters
- We analyze each frequency band for given observation time and FFT length over all of LIGO O3a data (SFDBs used)
- 10^7 coincident candidates before any vetos
- Apply threshold on average *CR* (accounting for trials factor) and line veto —> only 334 candidates with $CR_{\text{thr}} > 7$ with f_0 at least 1 bin away from noise line

$f_{\min}$ (Hz)	$f_{\max}$ (Hz)	T_{obs} (s)	T_{FFT}(s)	$\mathcal{M}_{\min}$ ($M_\odot$)	$\mathcal{M}_{\max}$ ($M_\odot$)
20	68	572600	29	5.9469×10^{-4}	8.7096×10^{-3}
20	121	54700	9	1.0823×10^{-3}	8.7096×10^{-3}
43	123	51400	9	1.0929×10^{-3}	1×10^{-2}
44	126	48300	8	1.1031×10^{-3}	1×10^{-2}
45	128	45400	8	1.1105×10^{-3}	1×10^{-2}
46	131	42700	8	1.1105×10^{-3}	1×10^{-2}
47	133	40100	7	1.1265×10^{-3}	1×10^{-2}



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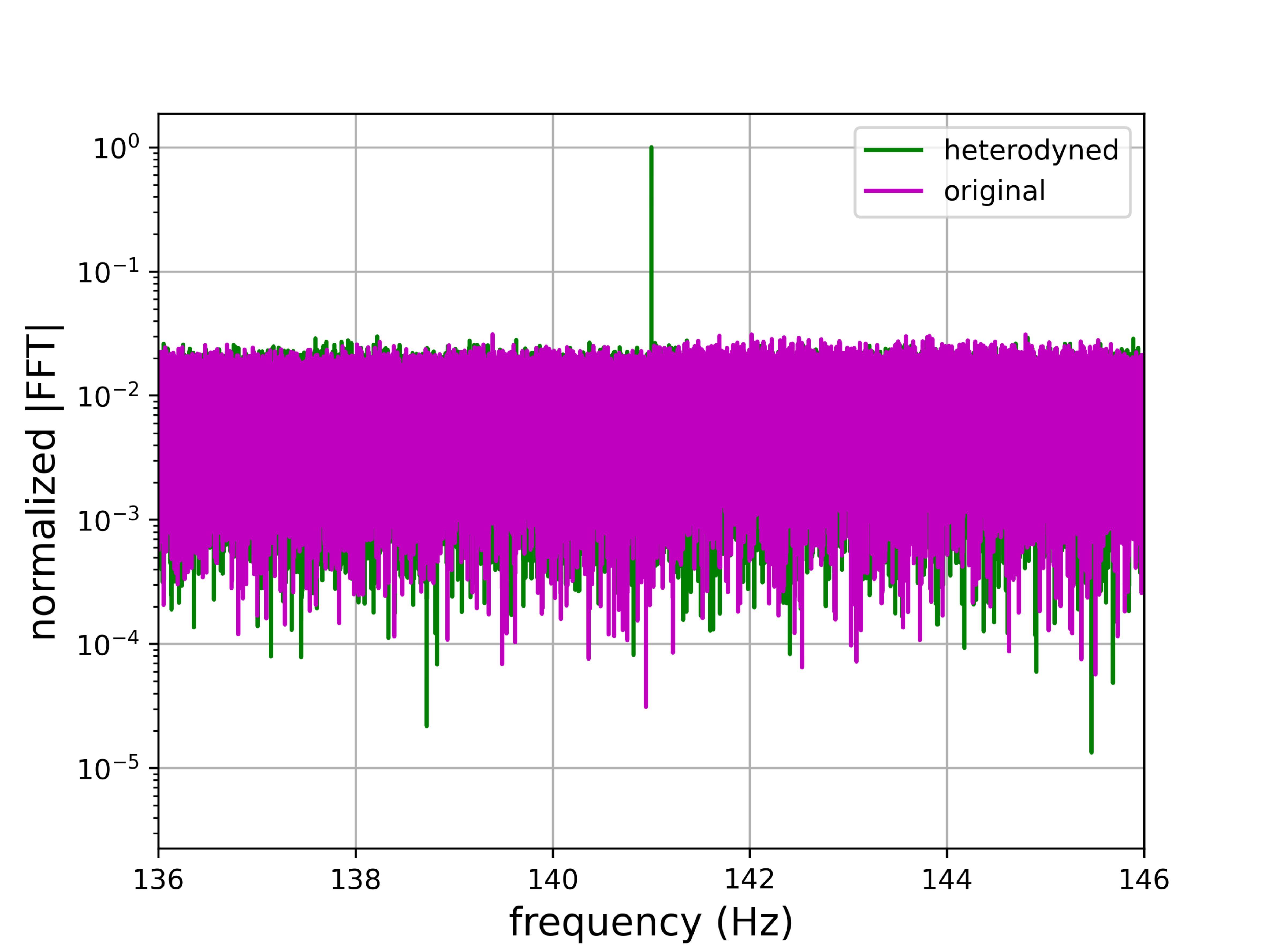
Follow-up procedure

- Consider a grid around each candidate $f_0, \mathcal{M}$ based on uncertainty ($\propto \delta f$)
- Demodulate data via heterodyning $h^{het}(t) = \mathrm{Re}[h(t)e^{-i\phi}]; \phi = \phi(f_0, \mathcal{M}, t)$
- Double T_{FFT}
- Apply original Frequency-Hough in a narrow-band around candidate
- Obtain new CR ; check if $CR_{\mathrm{new}} > CR_{\mathrm{old}}$
- No candidates survived this procedure



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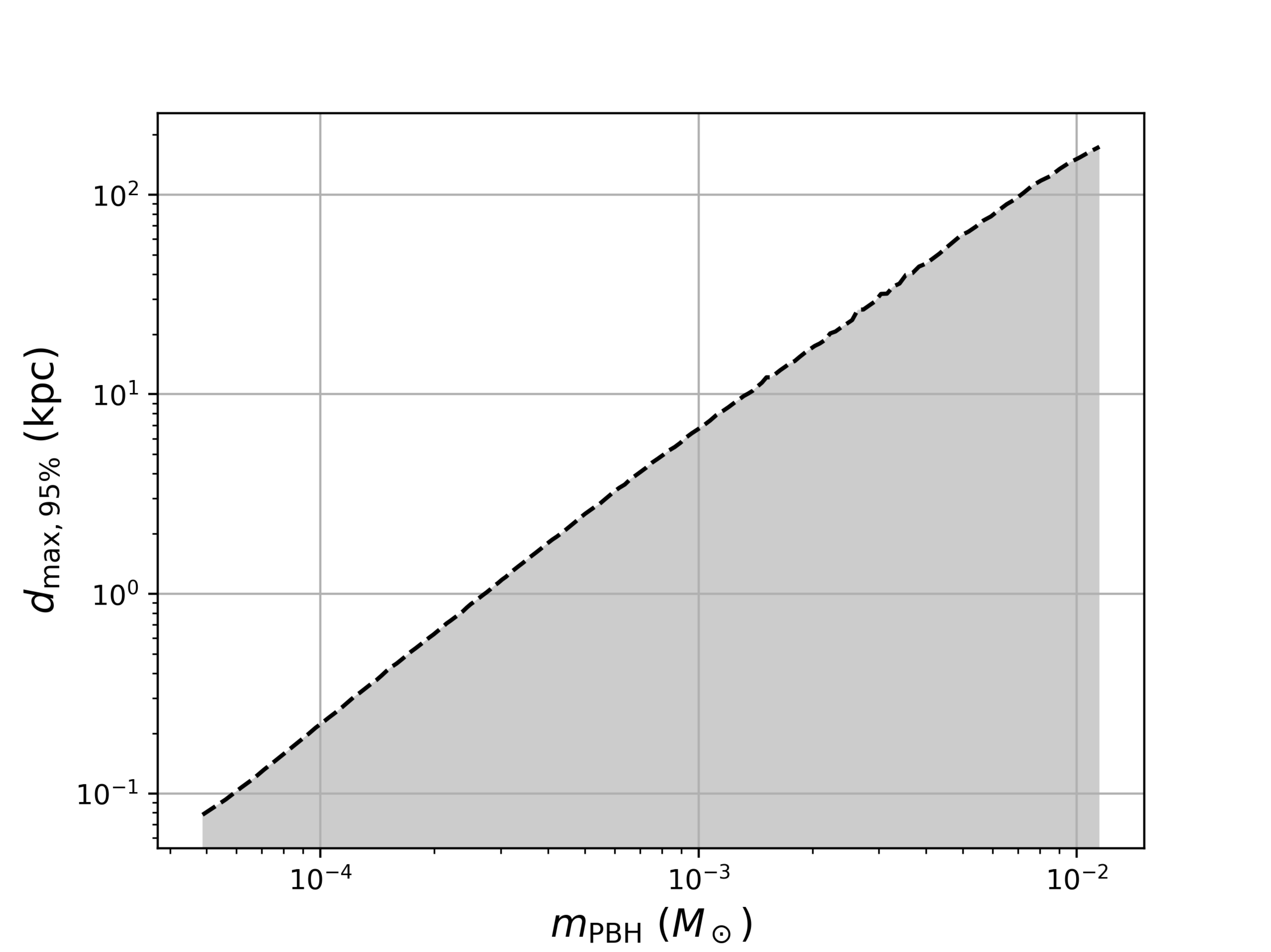
Upper limits procedure

- Evaluate maximum distance reach based on coincident candidates' CR, $\mathcal{M}$, and f_0
- Apply Feldman-Cousins' approach and map CR to larger CR (assuming Gaussian noise)

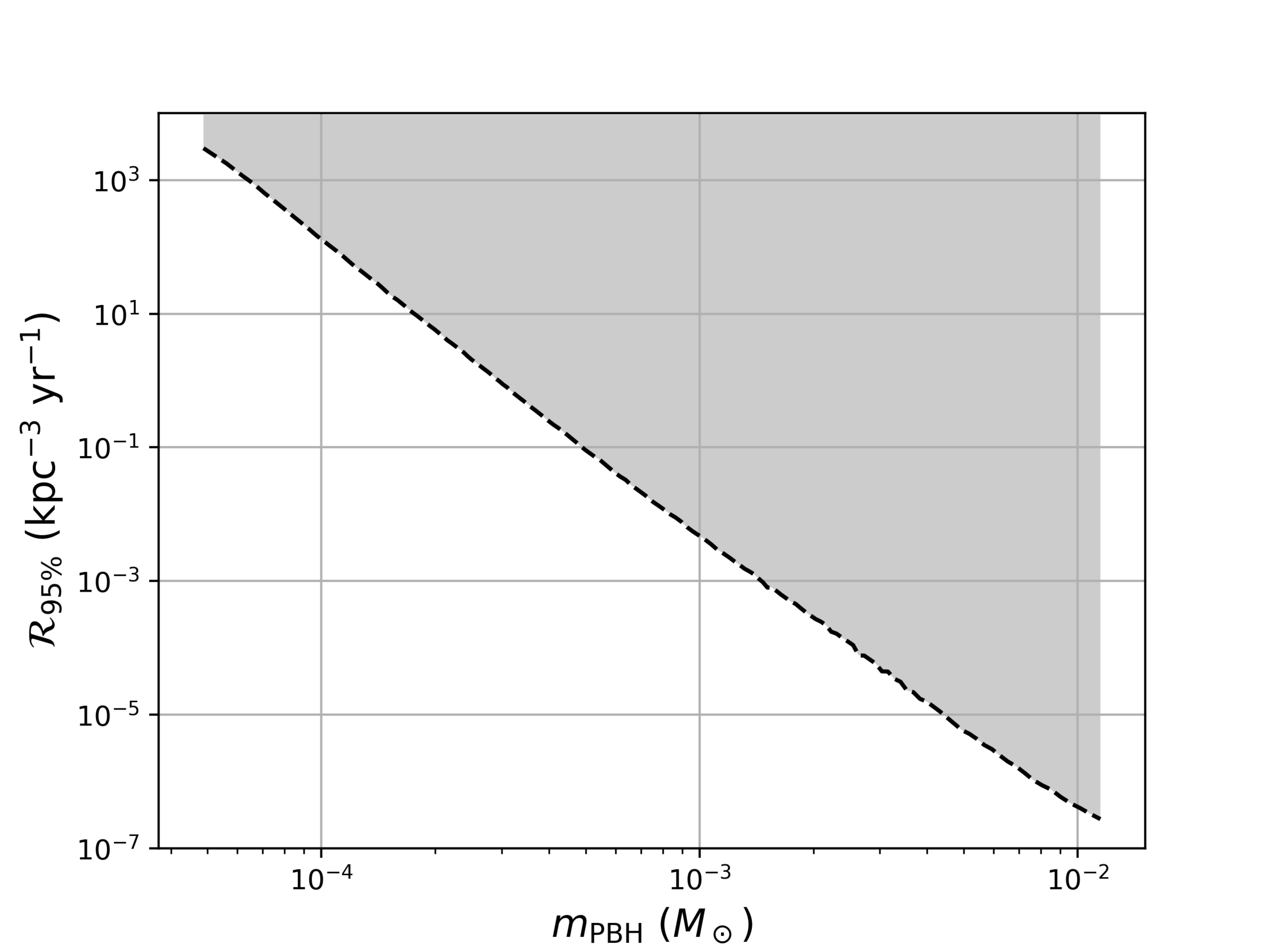
$$d_{\rm max}^{95\%} \propto \mathcal{M}^{5/3} T_{\rm FFT}^{3/4} T_{\rm obs}^{-1/4} \left(\sum_i^N \frac{f_i^{4/3}}{S_n(f_i)} \right)^{1/2} \left(CR - \sqrt{2}\,{\rm erfc}^{-1}(2\Gamma) \right)^{-1/2}$$

- We compute $d_{\rm max}$ for each of the 10 million coincident candidates, in each configuration, at each time, and average them at each chirp mass



Upper limit procedure

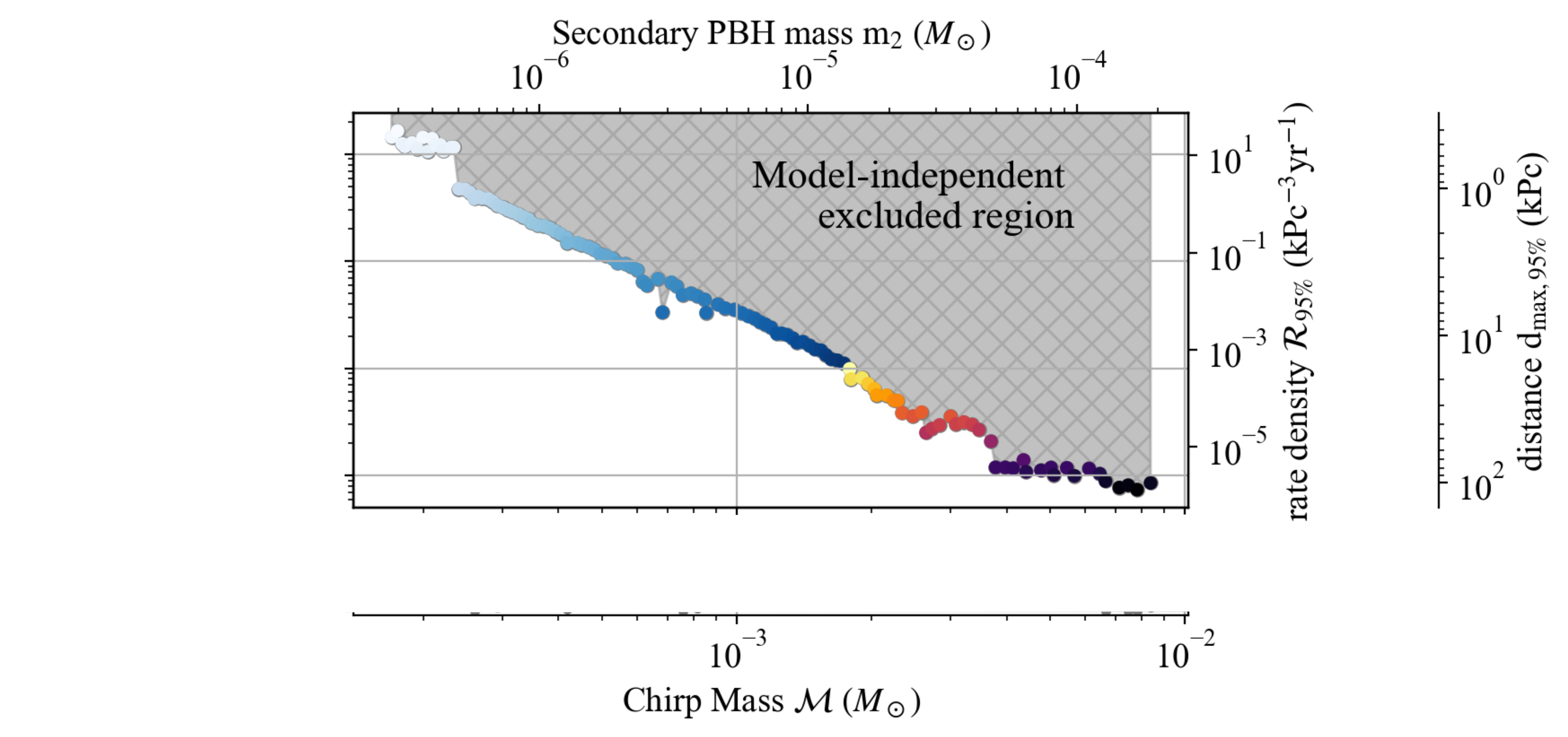
- We ensure $|f_{0PN}(t) - f_{3.5PN}(t)| \leq \frac{1}{T_{\mathrm{FFT}}}$
- From $d_{\max}$, compute the reachable space-time volume and rate density: $\langle VT \rangle = \frac{4}{3}\pi d_{\max}^3 T_{\mathrm{obs}}$; $\mathcal{R}_{95\%} = \frac{3.0}{\langle VT \rangle}$
- Since we are sensitive to systems at $\lesssim 100$ kpc, $\langle VT \rangle_{\mathrm{comoving}} = \langle VT \rangle_{\mathrm{euclidean}}$



Upper limits interpretation

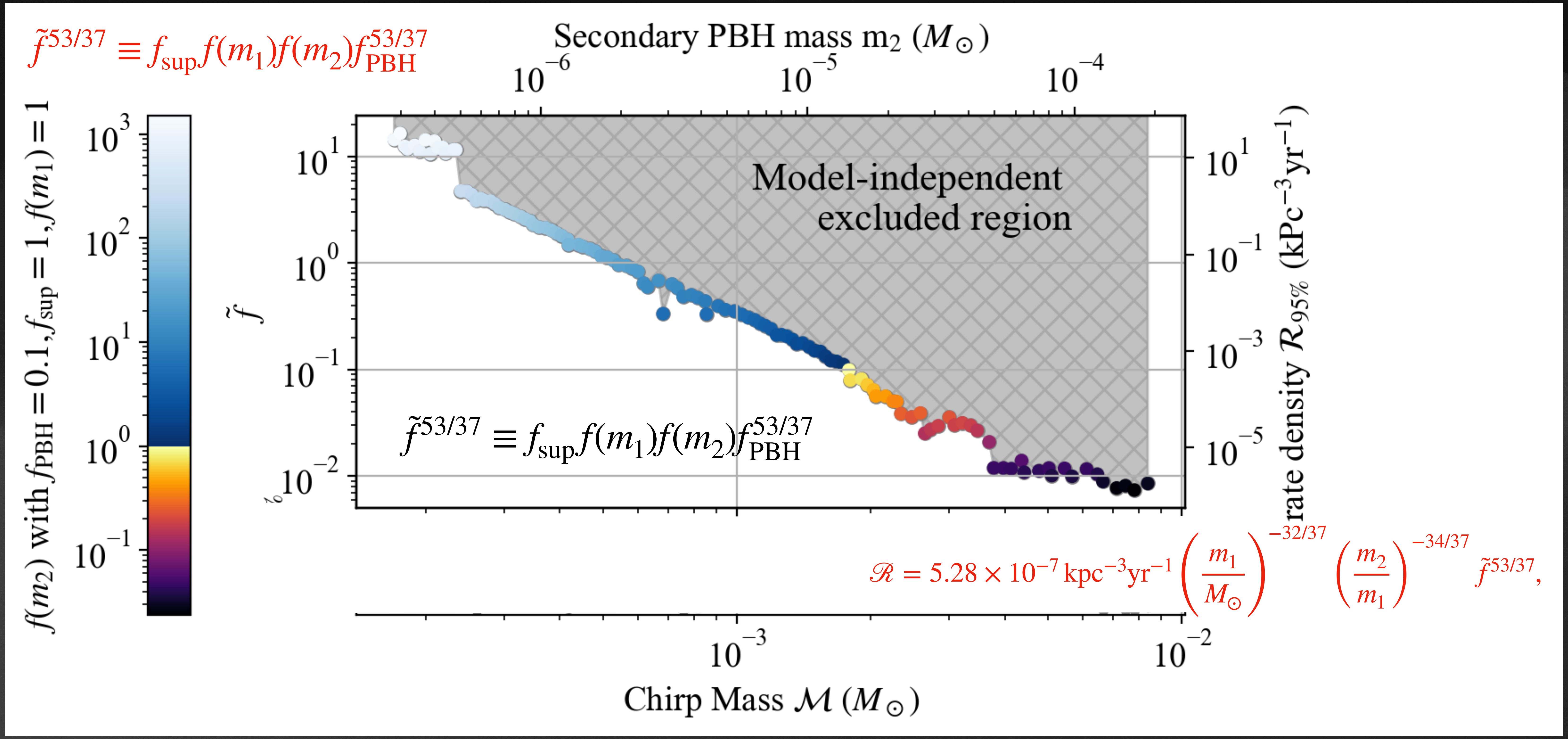
- Our method only looks for the inspiral of two compact objects with masses m_1, m_2. They make no assumptions about how they formed
- After placing rate density upper limits, we assume that m_1, m_2 are PBHs, and constrain the fraction of DM that PBHs compose
- Since we are sensitive to $\mathscr{M}$, we have the freedom to pick m_1, m_2 so long as higher-order contributions to $\dot{f}$ are still small

Asymmetric-mass ratio PBHs



- First, we compute the maximum distance at which we could have seen a signal at 95% confidence
- Then, we assume a uniform distribution of sources, and compute a rate density $\mathscr{R} \sim \left[\frac{4}{3}\pi d^3 T_{\mathrm{obs}}\right]^{-1}$

Asymmetric-mass ratio PBHs



$f(m)$: mass function

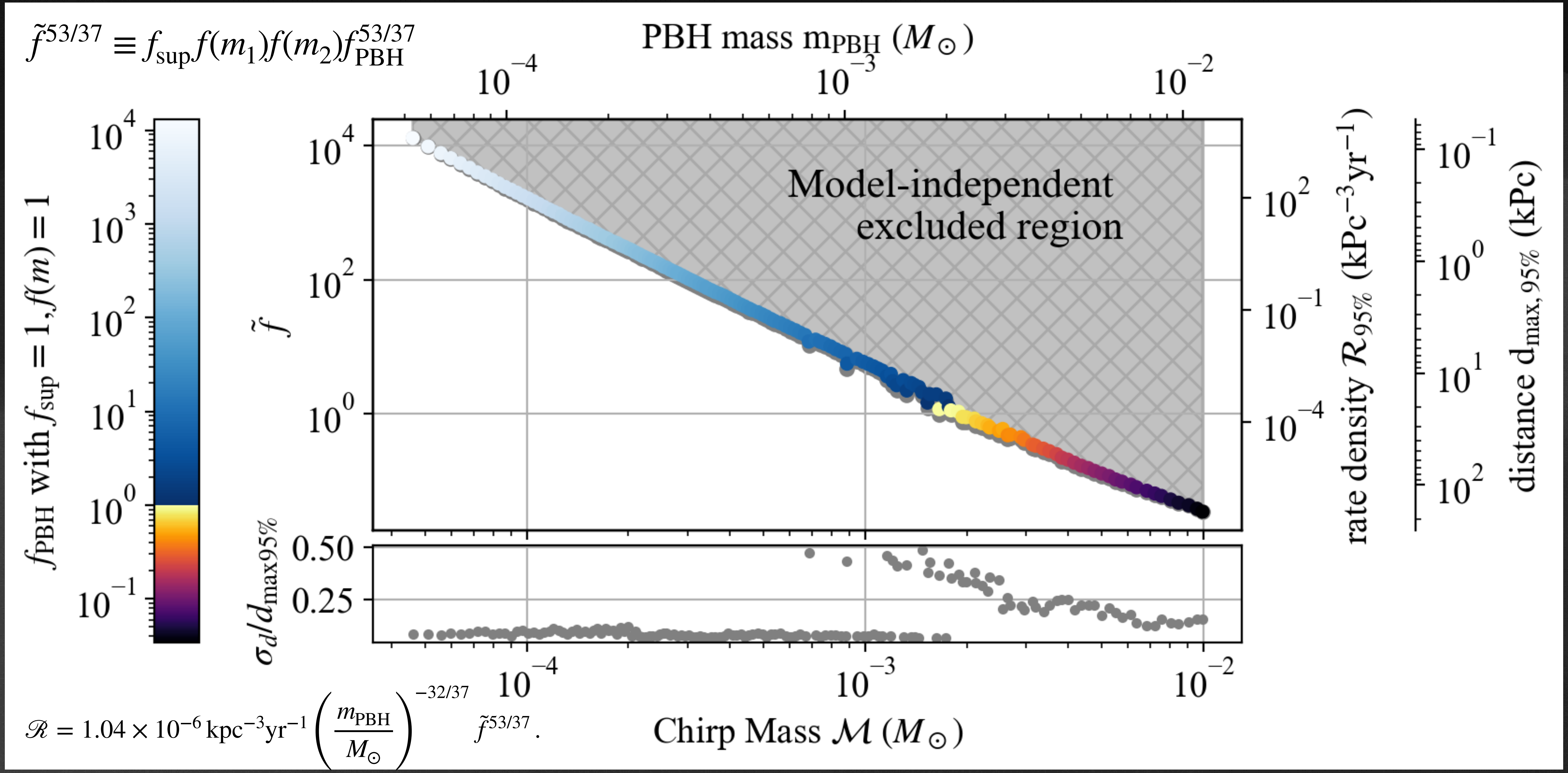
f_{PBH}: fraction of DM that PBHs could compose

f_{sup}: binary suppression factor

- Merger rates enhanced for PBHs in asymmetric mass ratio binaries
- We can constrain $\tilde{f}$, or assuming $m_1 = 2.5 M_\odot$, $f(m_1) \sim 1$, $f_{sup} = 1$, we can put upper limit on $f(m_2)$

Miller et al., arXiv: 2402.19468

Equal-mass PBH interpretation



- We can convert the constraint on rate density to an upper limit on the fraction of DM that PBHs could compose
- Assuming monochromatic mass functions ($f(m_{\rm PBH}) = 1$) and no rate suppression ($f_{\rm sup} = 1$), we can constrain $f_{\rm PBH}$

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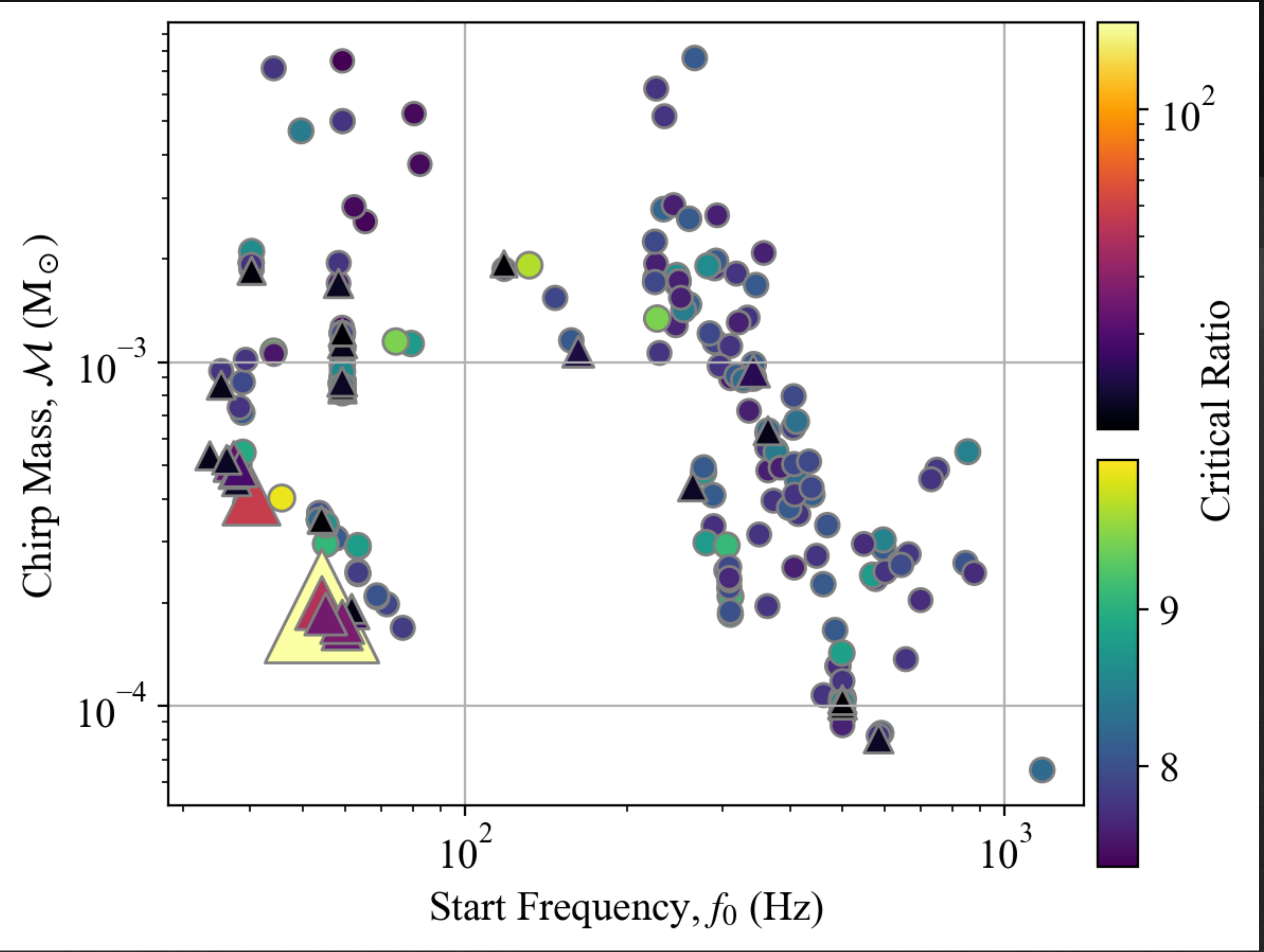
Conclusions

- A simple quasi-monochromatic or power-law signal model describes many types of sources
- Dark matter can be probed directly via its interactions with GW detectors without the need to design new instruments!
- GW detectors can constrain the existence of dark matter in the form of planetary-mass primordial black holes
- There is plenty of work to do on improving these results — if interested, please contact me!

Backup slides

Search results

- Some candidates were found with high significance, but ultimately were due to noise disturbances
- In absence of detection, place upper limits
- Determine the maximum distance away that we could have seen a signal, and then use that to obtain a rate density estimate



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Additional parameter space plots