# Localizing binary neutron star inspirals using continuous-wave methods in ET

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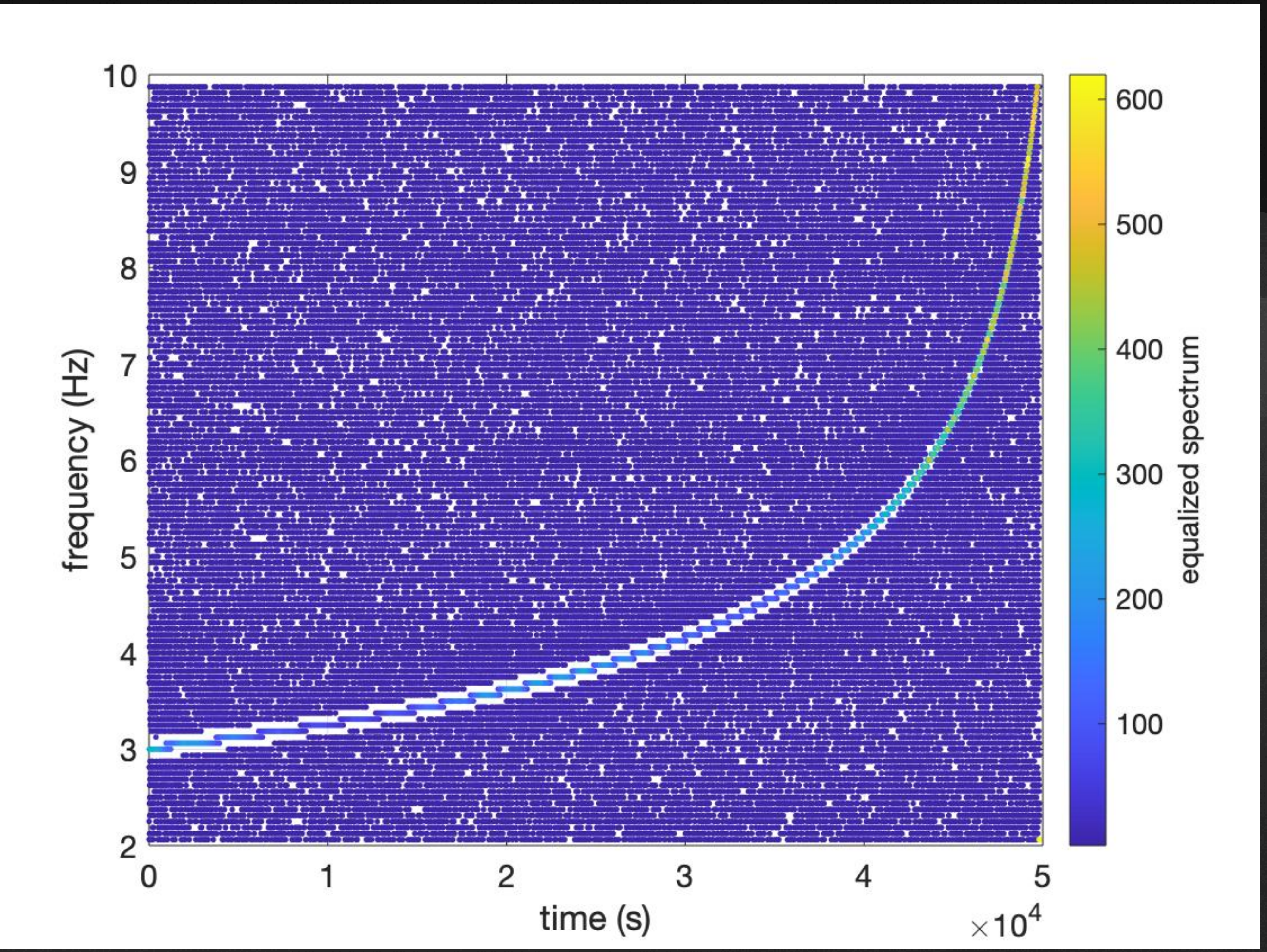
# Background and Motivation

# Binary Neutron Star Inspirals

- Inspiraling binary systems will be visible at low frequencies for a much longer time and overlap (~40-3000x longer for 5 or 1 Hz frequency floors)
- Within this time, assumptions made in matched-filtering analyses, e.g. no gaps, noise stationarity, no glitches, could break down
- Phase mismatch accumulates with longer templates —> huge computational cost for matched filtering!
- CW methods could provide early-warning sky localization, and deal with overlapping signals efficiently




- Simulated binary neutron star inspiral in white noise up to 1.5 PN, $m_1 = m_2 = 0.9M_\odot; \mathscr{M} = 0.78M_\odot$

# "Transient" continuous waves

- Signal frequency evolution over time follows a power-law and lasts $\mathcal{O}$(hours – days)

- Can describe gravitational waves from the inspiral portion of a light-enough binary system, or from a system far from coalesces

- Gravitational waves from quasi-Newtonian orbit

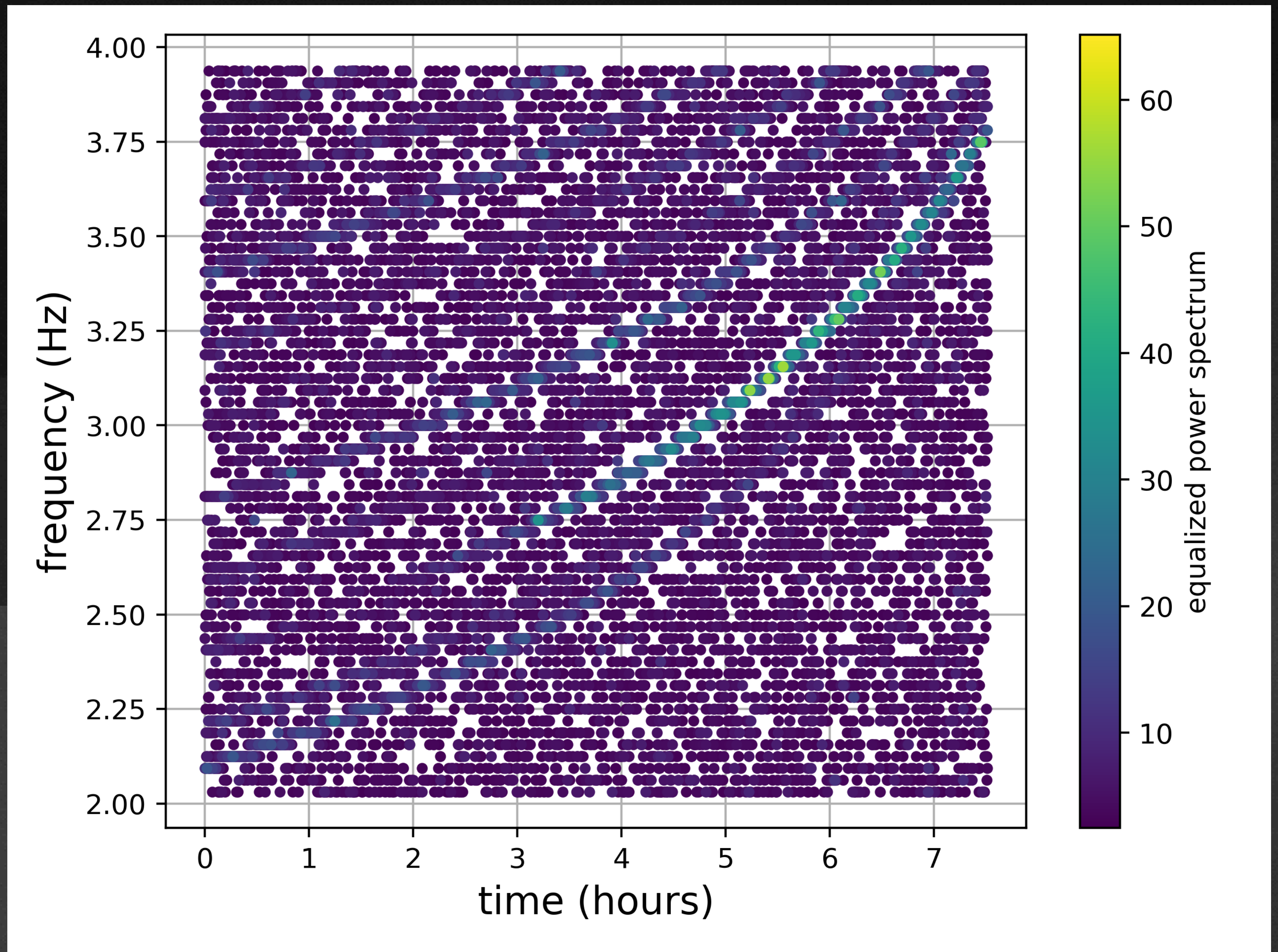
$$\dot{f} = \kappa f^n$$

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

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

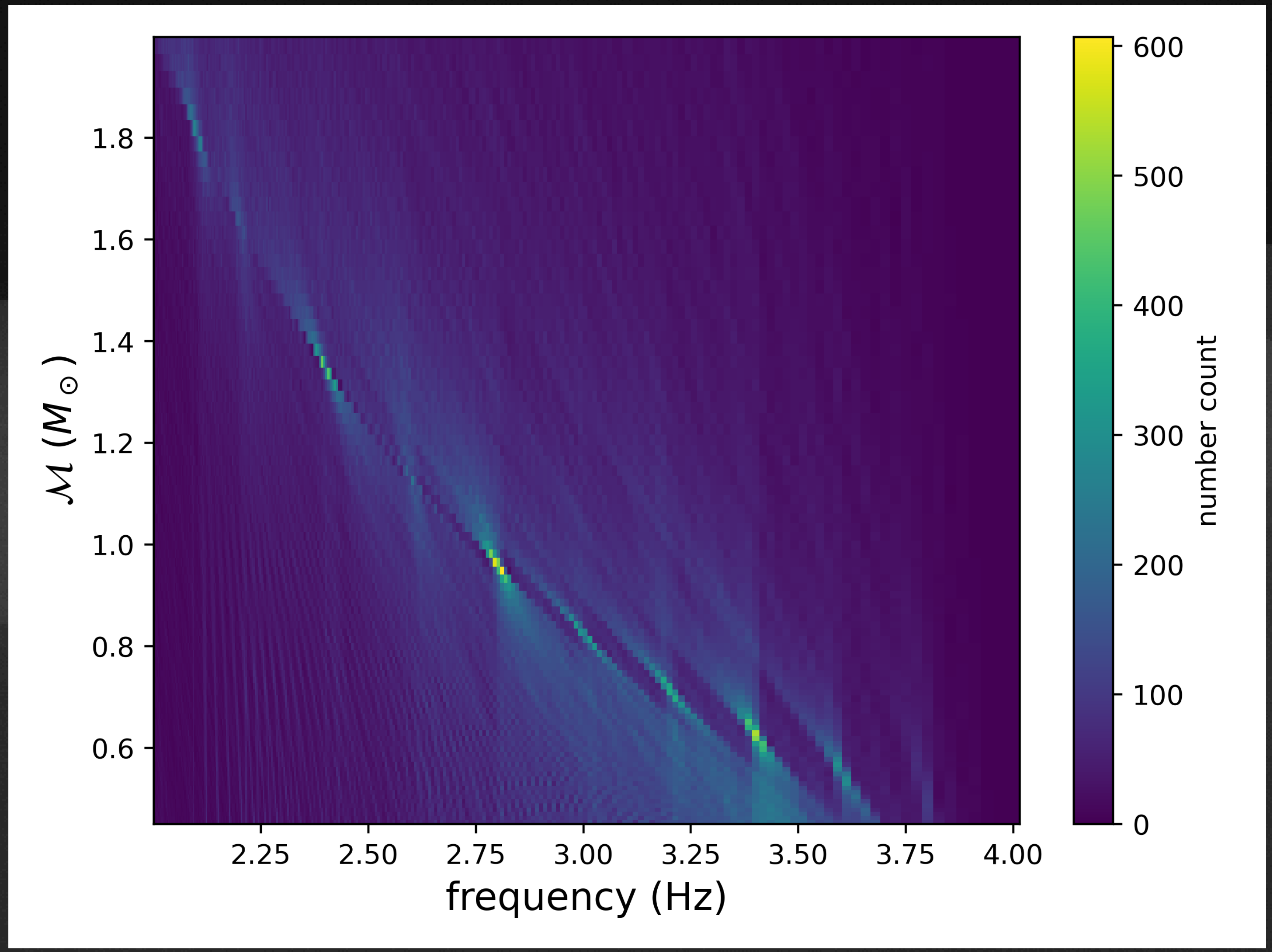
# Method

# Dealing with multiple signals




Hough Transform

$(t, f) \rightarrow (f_0, \mathcal{M})$

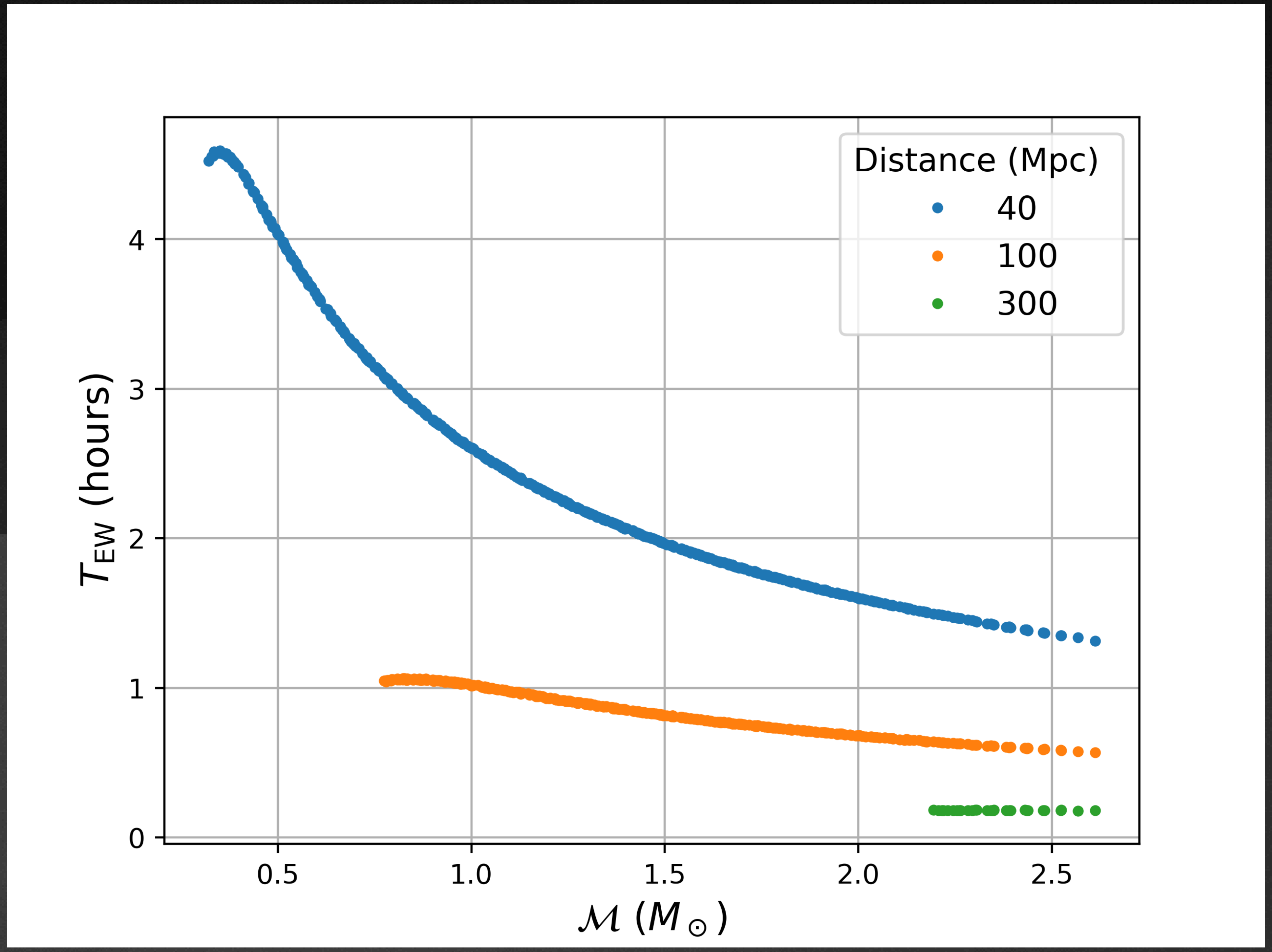


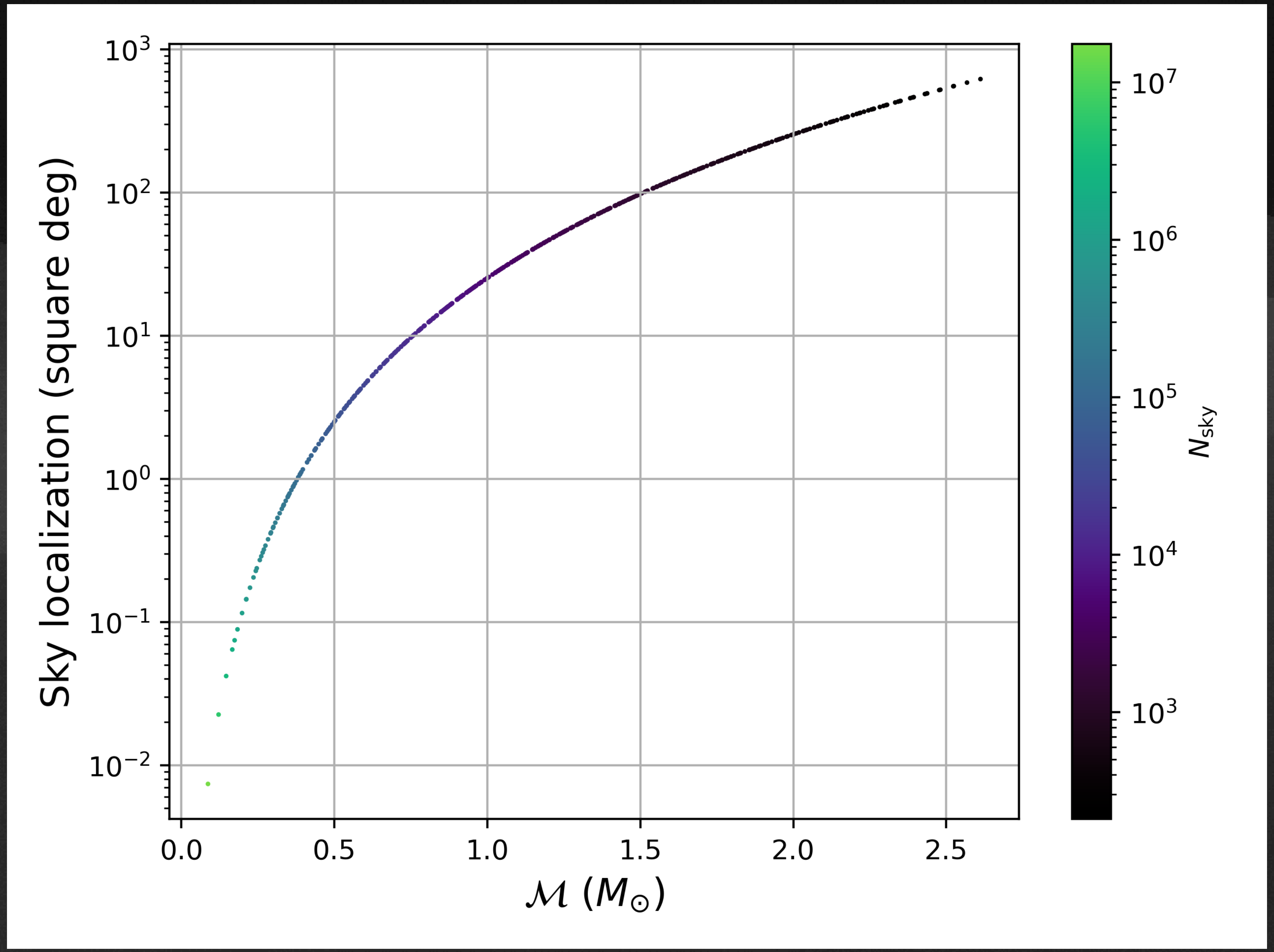

- CW methods, without much loss in sensitivity, can detect multiple signals while robust against noise disturbances (e.g. not summing raw power)

Miller et al., Phys.Rev.D 109 (2024) 4, 043021

# Results: sensitivity & early warning

# Early warning and sky localization



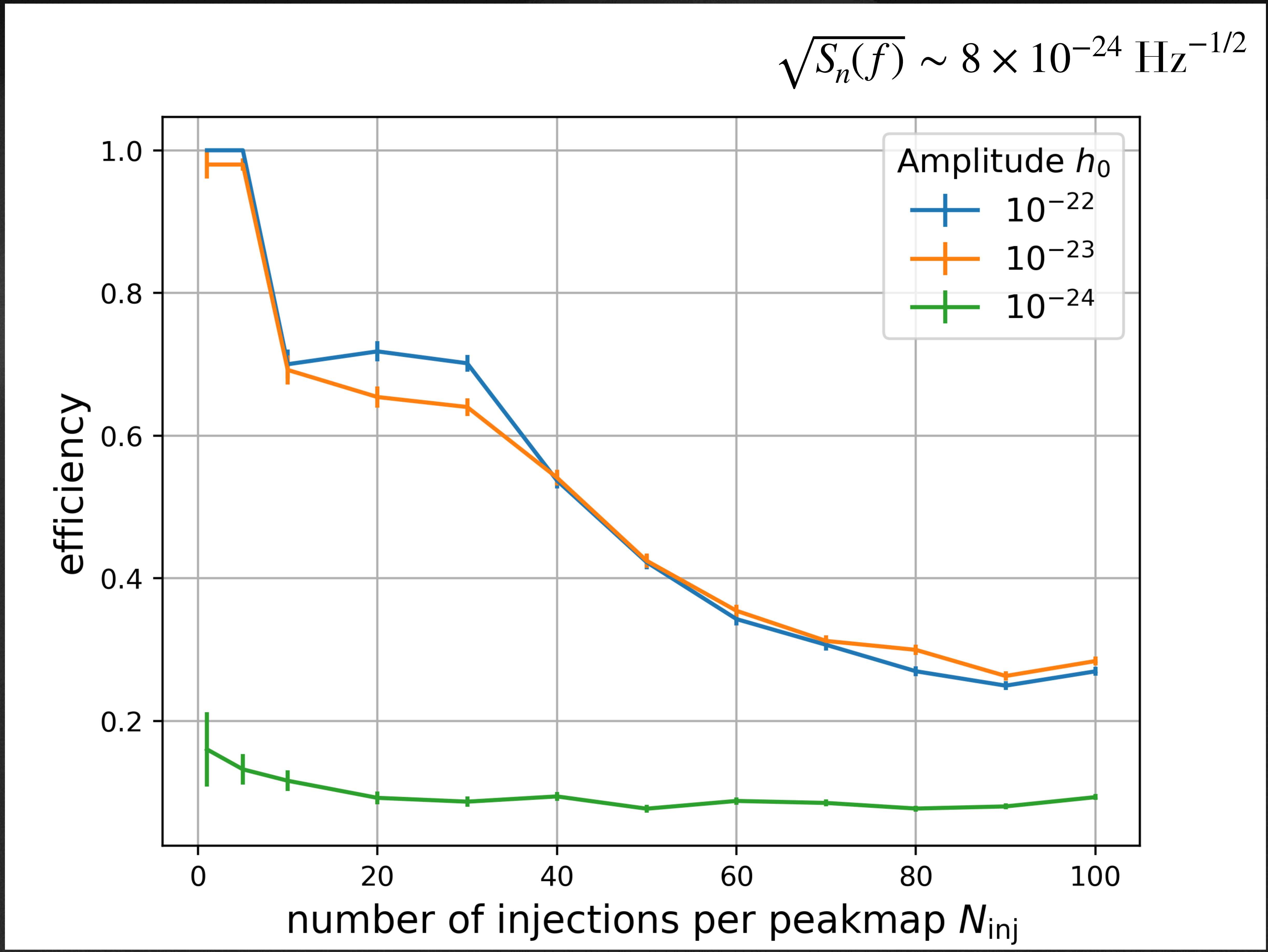




- With one detector, astronomers could be warned at most between 0.5-4 hours before merger
- Sky localization may vary.. requires more than simply a detection, but some follow-up steps

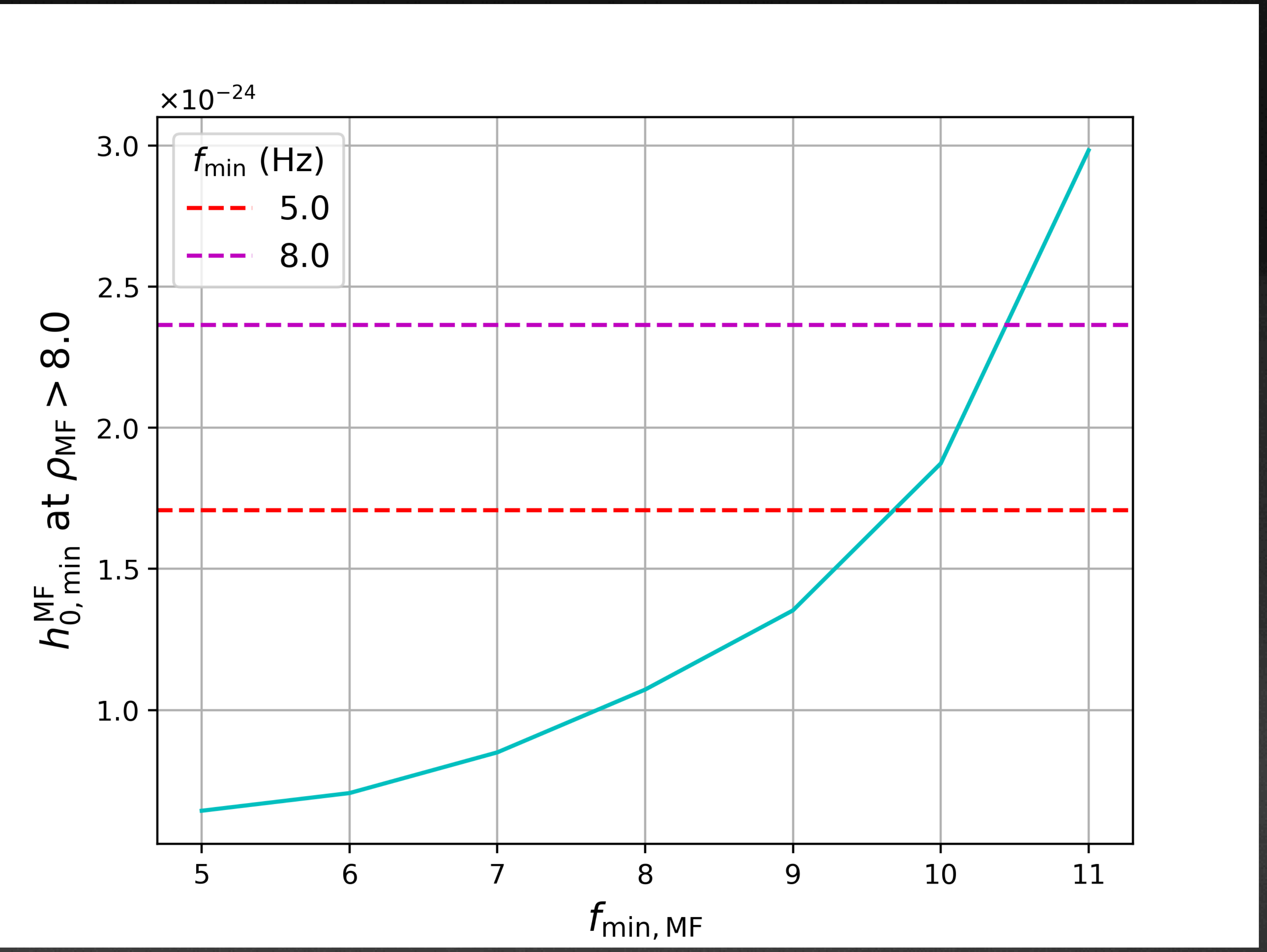
Miller et al., Phys.Rev.D 109 (2024) 4, 043021

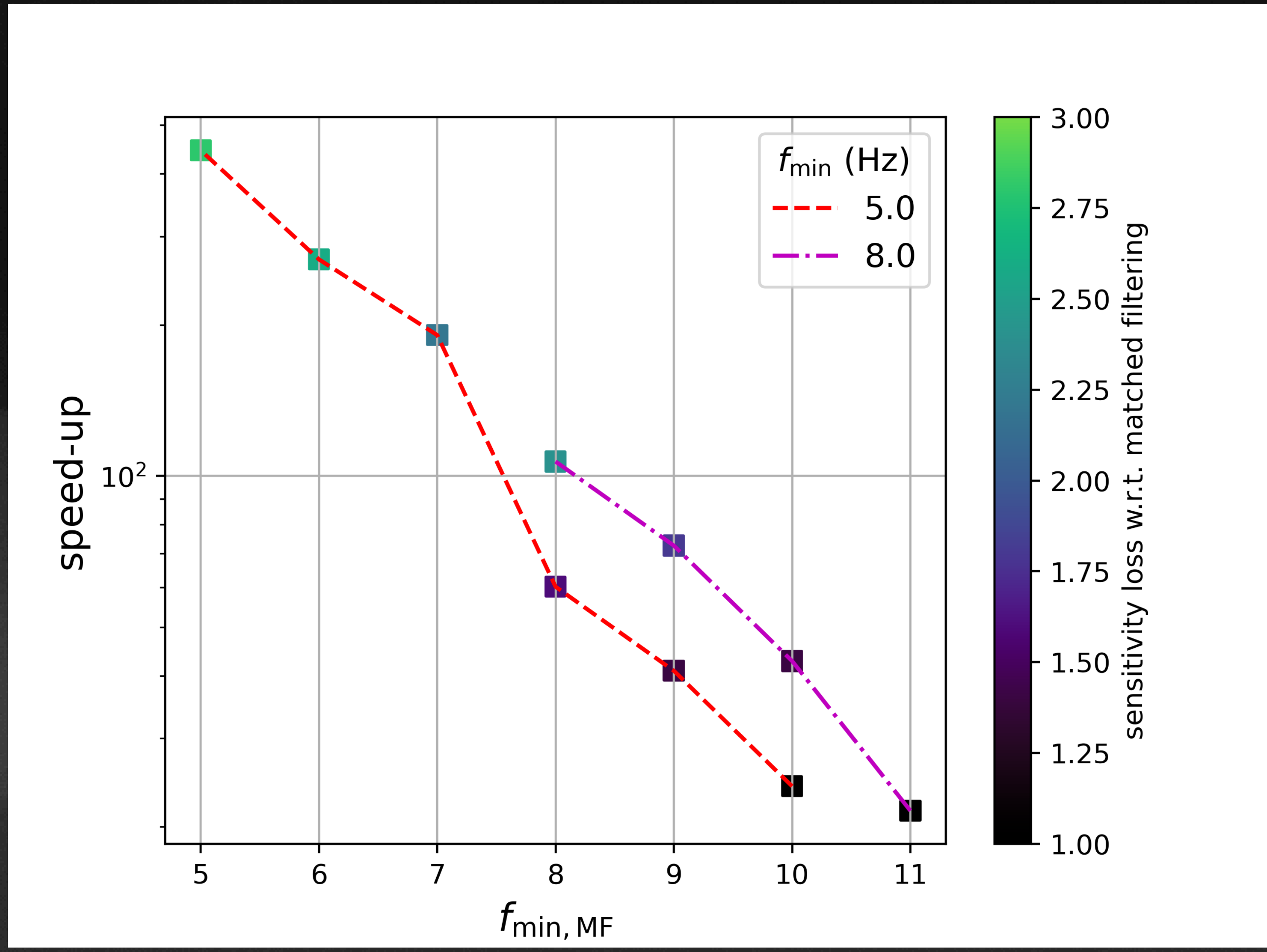
# Dealing with overlapping signals

- Injected a different number of signals with random durations, chirp masses and starting frequencies
- 50 simulations at each $N_{\mathrm{inj}}$
- Efficiency: fraction of signals recovered across *all* time/frequency maps
- This could definitely be improved… average PSD estimation not tuned to multiple signals yet - considered as well for standard CWs Pierini et al. PRD 106 (2022) 4, 042009



# Can we do better than matched filtering?




- We can quantify how much more computationally efficient our method is compared to matched filtering, at fixed sensitivity
- This depends on what the achievable minimum frequency of ET/CE will be, the number of templates necessary for matched filtering analyses, the (non-stationary) noise, among others
- Need to account for higher-order PN corrections (e.g. spins) with the continuous-wave method



Miller et al., Phys.Rev.D 109 (2024) 4, 043021

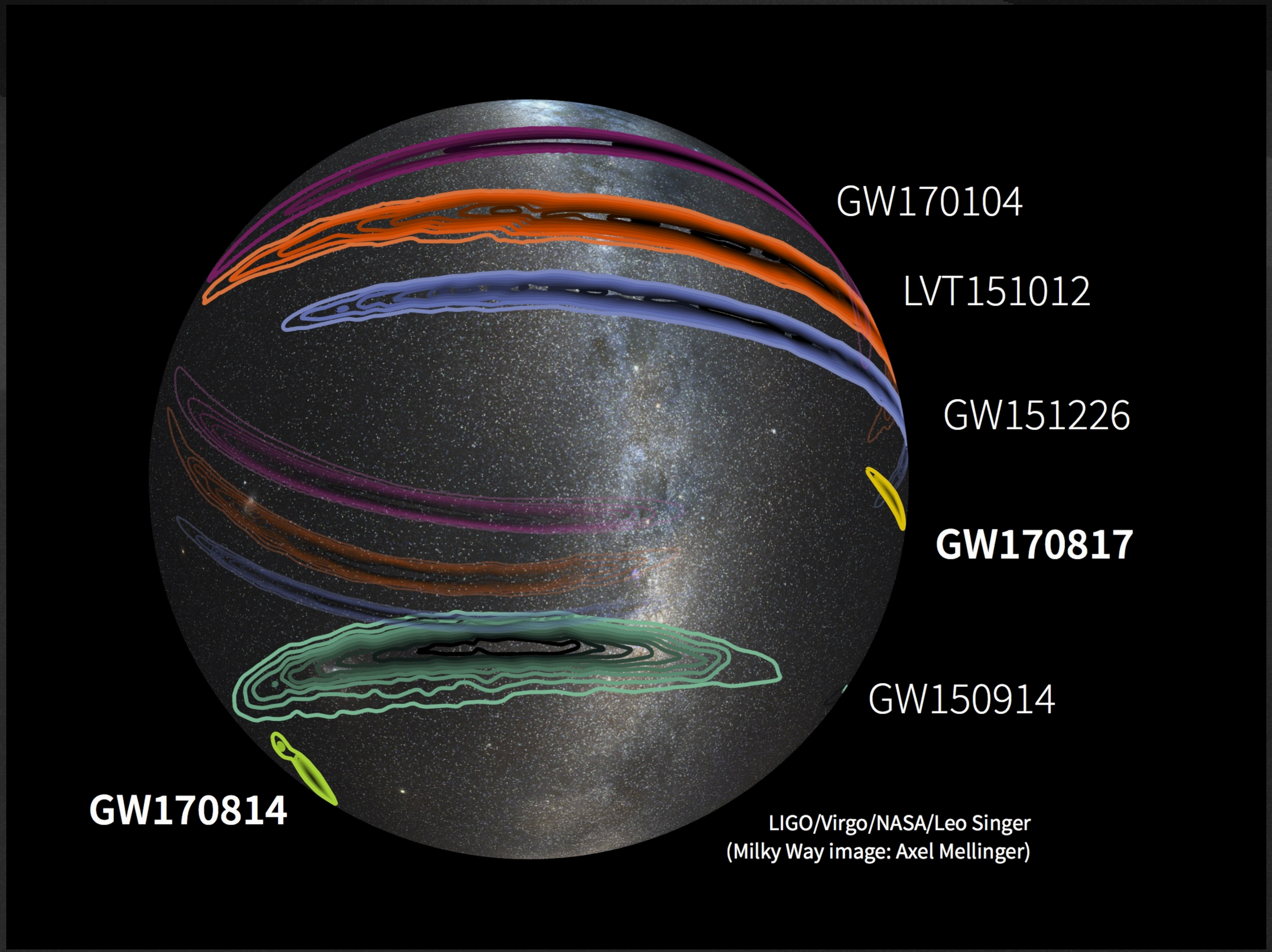
# Conclusions

- Promising that Hough could be competitive with matched-filtering searches in 3G detectors
- Early warning is possible if the Hough can iteratively run in low-latency [needs development!]
- Not sure yet if better sky localization than time-lag (needs to be studied in depth)
- Technical method development needed to apply Hough to localize and to higher-order PNs
- Primordial black hole binaries of masses up to $2.5M_{\odot}$ can also be searched for with these methods, as well as sub-solar mass ones    Miller et al. Phys.Dark Univ. 32 (2021) 100836
- Collaborations and ideas are welcome!

# Back-up slides

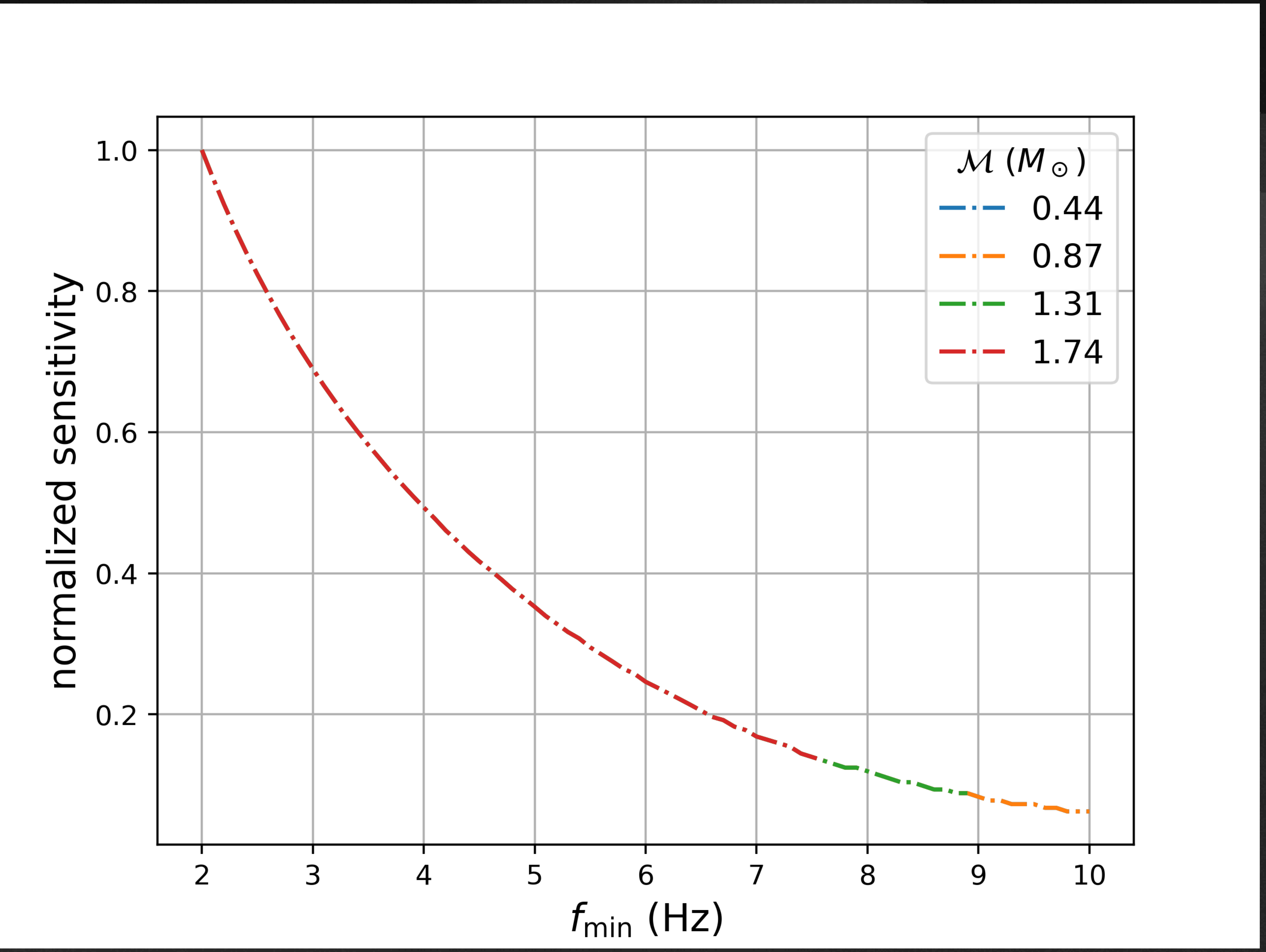
# Connection to multi-messengers

- Binary neutron star inspirals could last for O(hours-days) in future detectors, and are well-modeled by Post-Newtonian expansions
- "Early warning" for astronomers is realistic, given how long these signals could last
- We propose an alternative to matched filtering that could provide early warnings to astronomers, with excellent sky resolution



# Robustness against changing $f_{min}$

- It is not clear what will be the frequency floor achievable in ET
- We consider how our sensitivity will change if $f_{min} \neq 2$ Hz
- Normalized sensitivity defined w.r.t. the sensitivity at $f_{min} = 2$ Hz
- The curves for each chirp mass do not all extend to 10 Hz because we set a threshold of at least 10 minutes to observe, and higher chirp mass systems will not last for longer than that between $f_{min}$ and 20 Hz

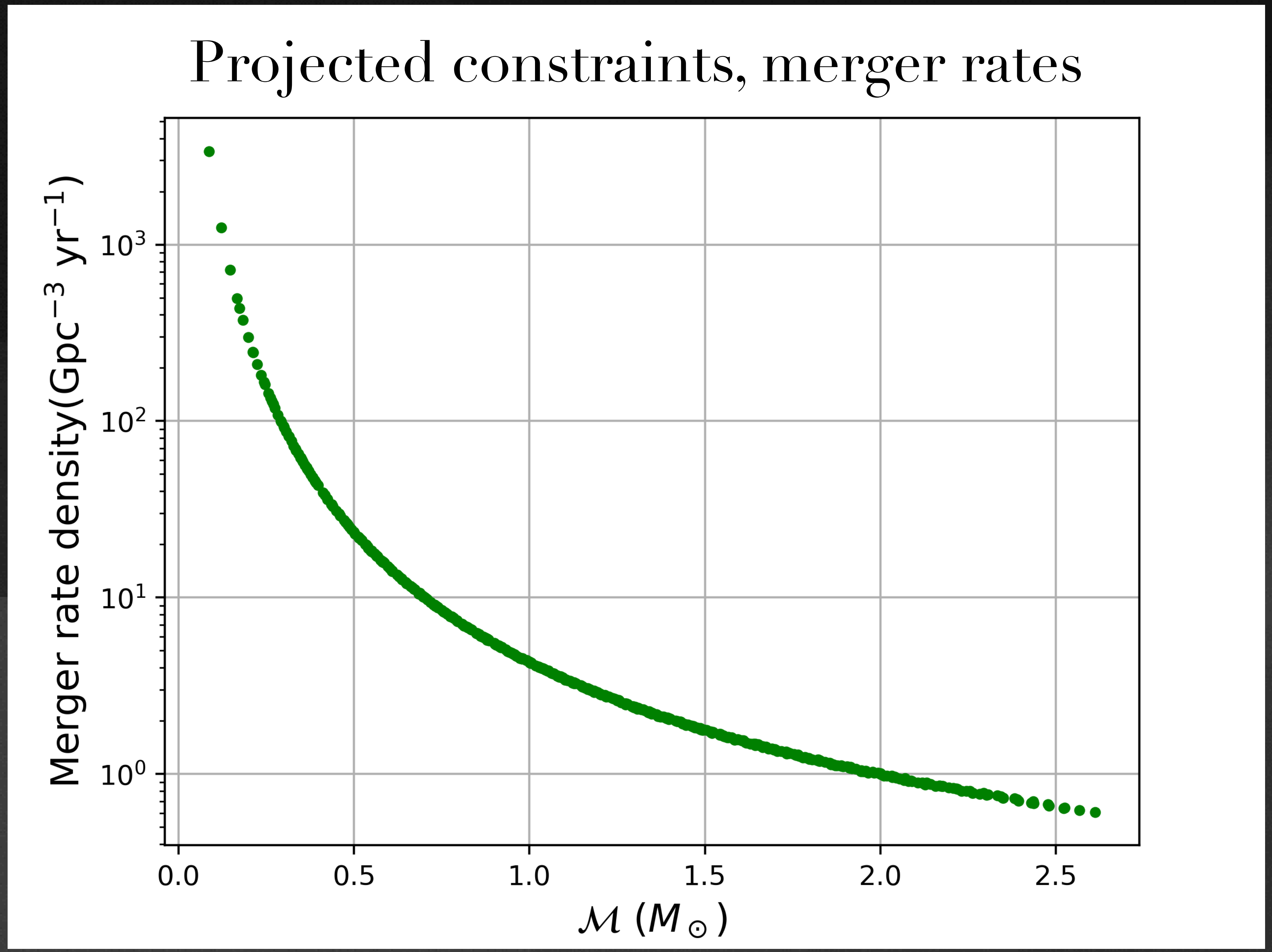


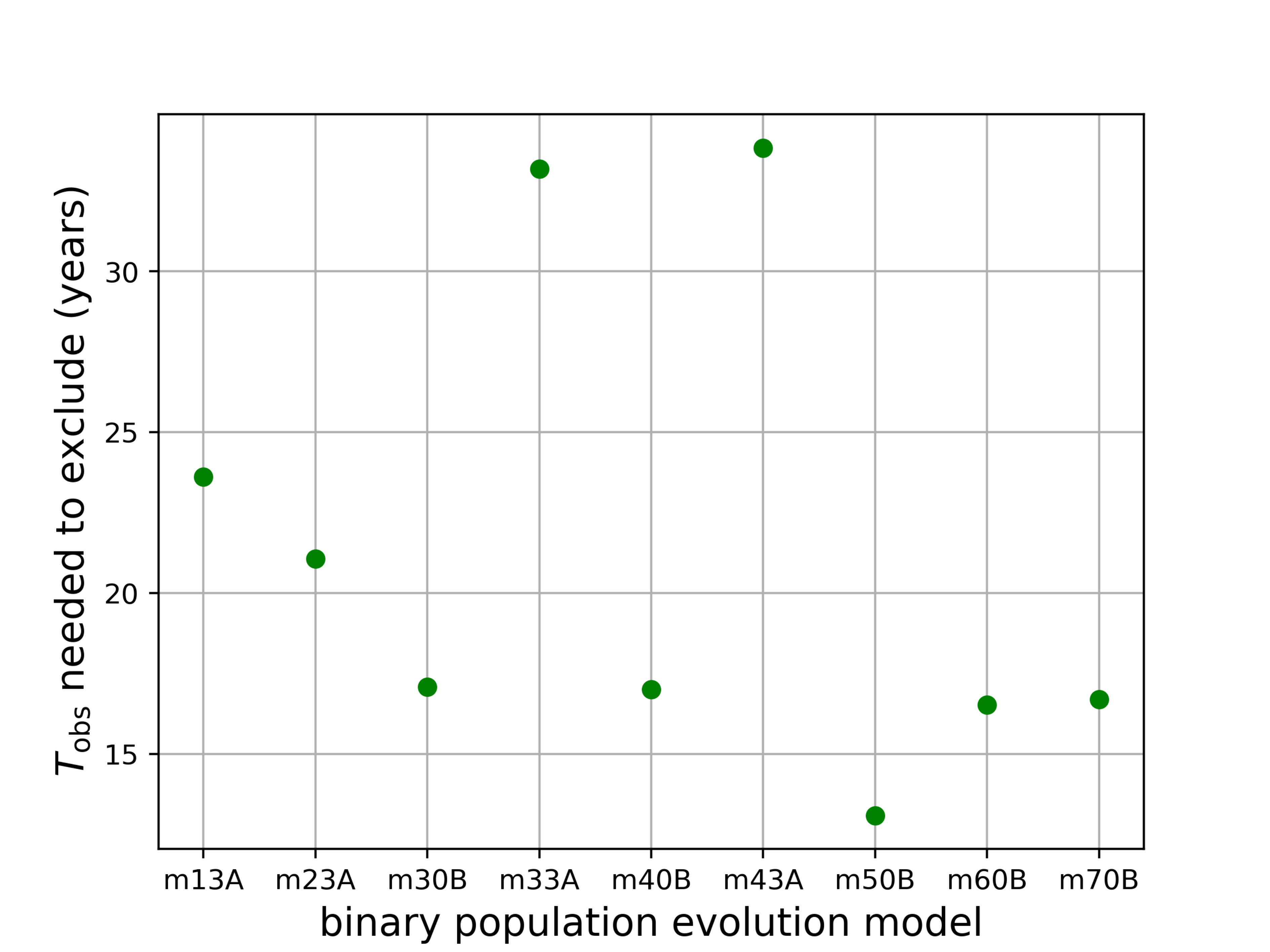
# Results: astrophysical implications

# Details of overlapping signal study

- Starting frequencies uniformally distributed between [4.01,6.97] Hz,
- chirp masses $[0.33,1.14]M_{\odot}$
- signal durations [200,10000] seconds
- Maximum frequency of peak map: 7 Hz
- 50 simulations per $N_{\mathrm{inj}}$ value

# Binary formation model constraints



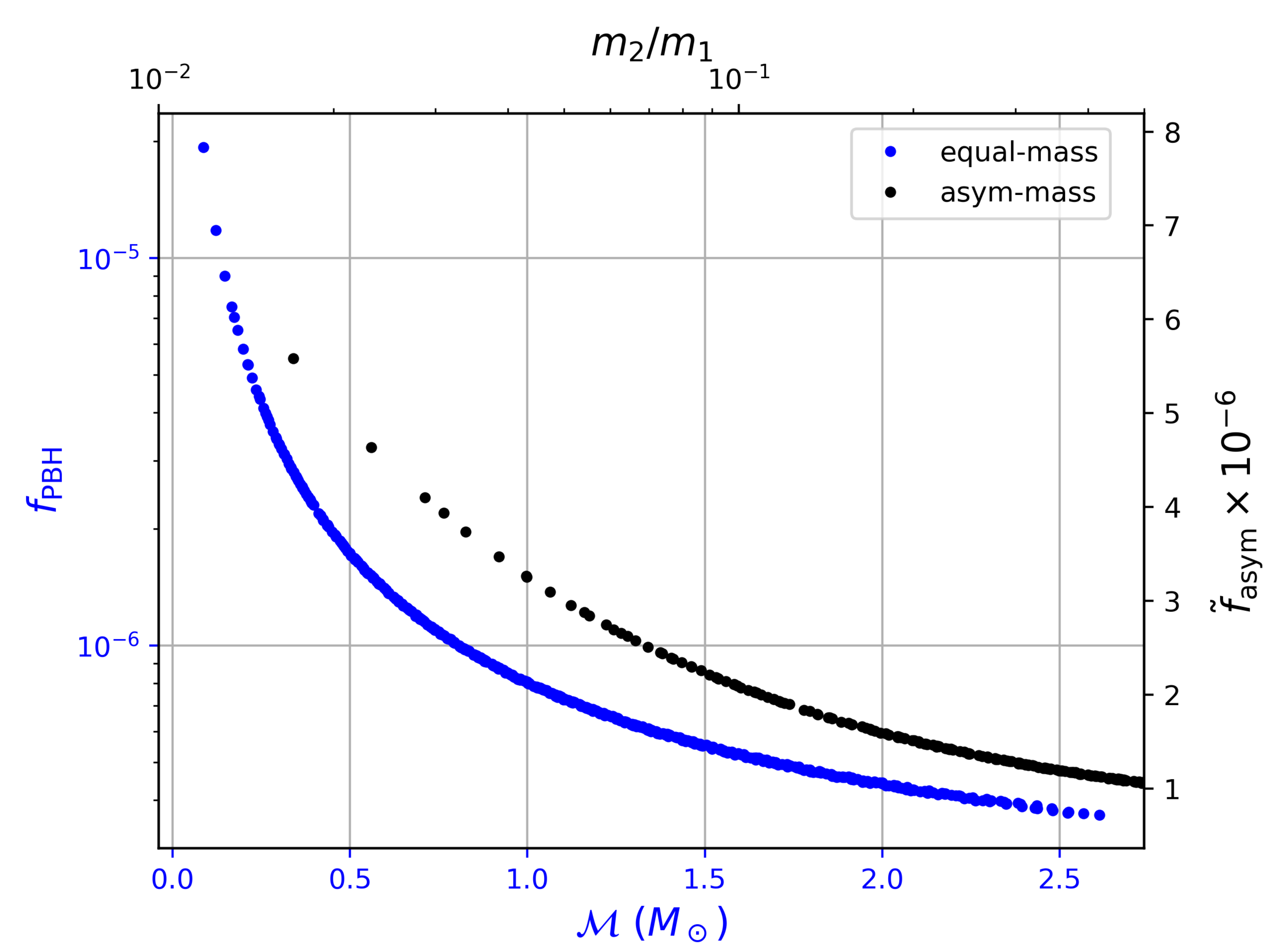




- Right: how long to observe to exclude certain population I and II field binary models (not already excluded by LVK merger rate predictions); each model predicts a merger rate density, and is compared with figure on left
- Models require assumptions on cosmic star formation, metallicity evolution, the initial binary parameters and the implied delay time (between the birth of a binary and the final merger of two compact objects) distribution

Belczynski et al., Astron. Astrophys. 636, A104 988 (2020)

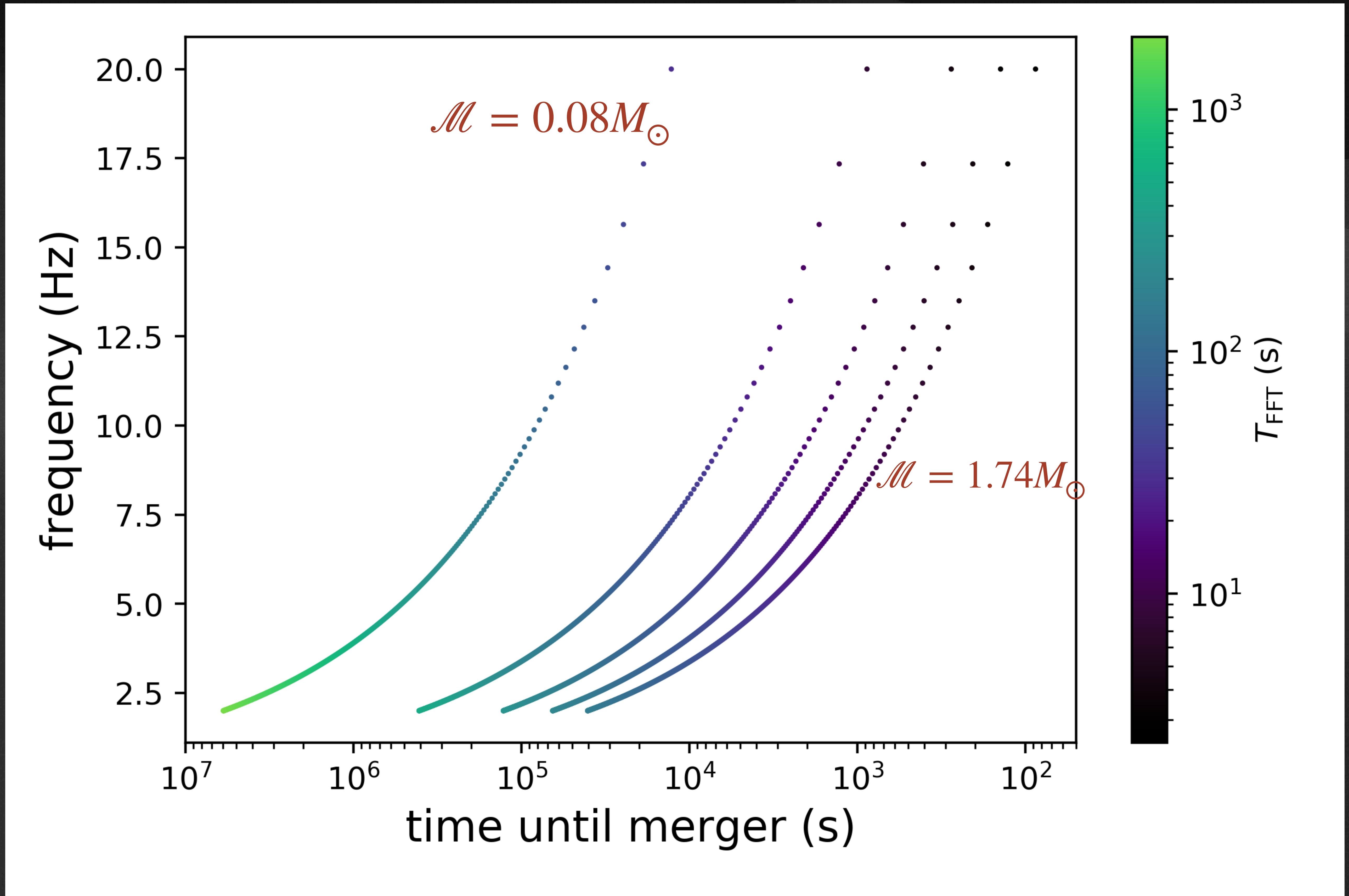
# Primordial Black Hole Binaries

- Can constrain the fraction of dark matter that PBHs could compose, in both equal-mass (blue) and asymmetric mass ratio (black) cases
- Blue: $f_{\rm PBH}$ calculated with $f_{\rm sup} = 2.5 \times 10^{-3}$ & monochromatic mass function
- $\tilde{f}^{53/37} \equiv f_{\rm sup} f(m_1) f(m_2) f_{\rm PBH}^{53/37}$ with $m_1 = 2.5 M_\odot$



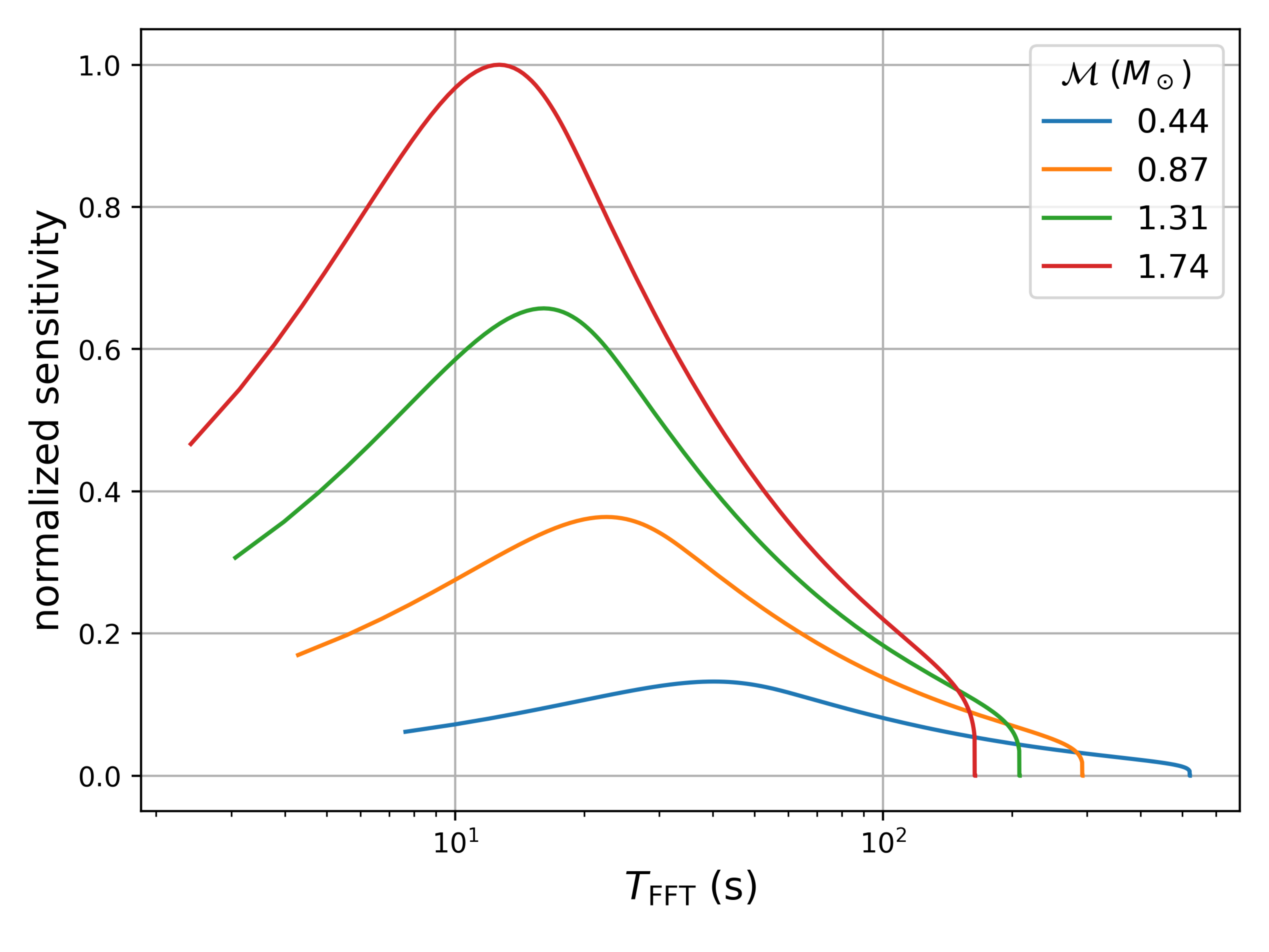
# With which $T_{\mathrm{FFT}}$?

- The gravitational-wave frequencies of systems with different chirp masses evolve at different rates, with smaller chirp masses having slower frequency drifts
- This is also a function of the time to merger
- Should be an "optimal one"



# Optimal Sensitivity

- Sensitivity estimation using ET power spectrum as a function of the observation time and frequency range to analyze, starting with a signal at 2 Hz
- At some point, it is no longer beneficial to observe the signal, since  decreases
- This is actually ok for early-warning
- Sensitivity level is fixed in first pass of Hough



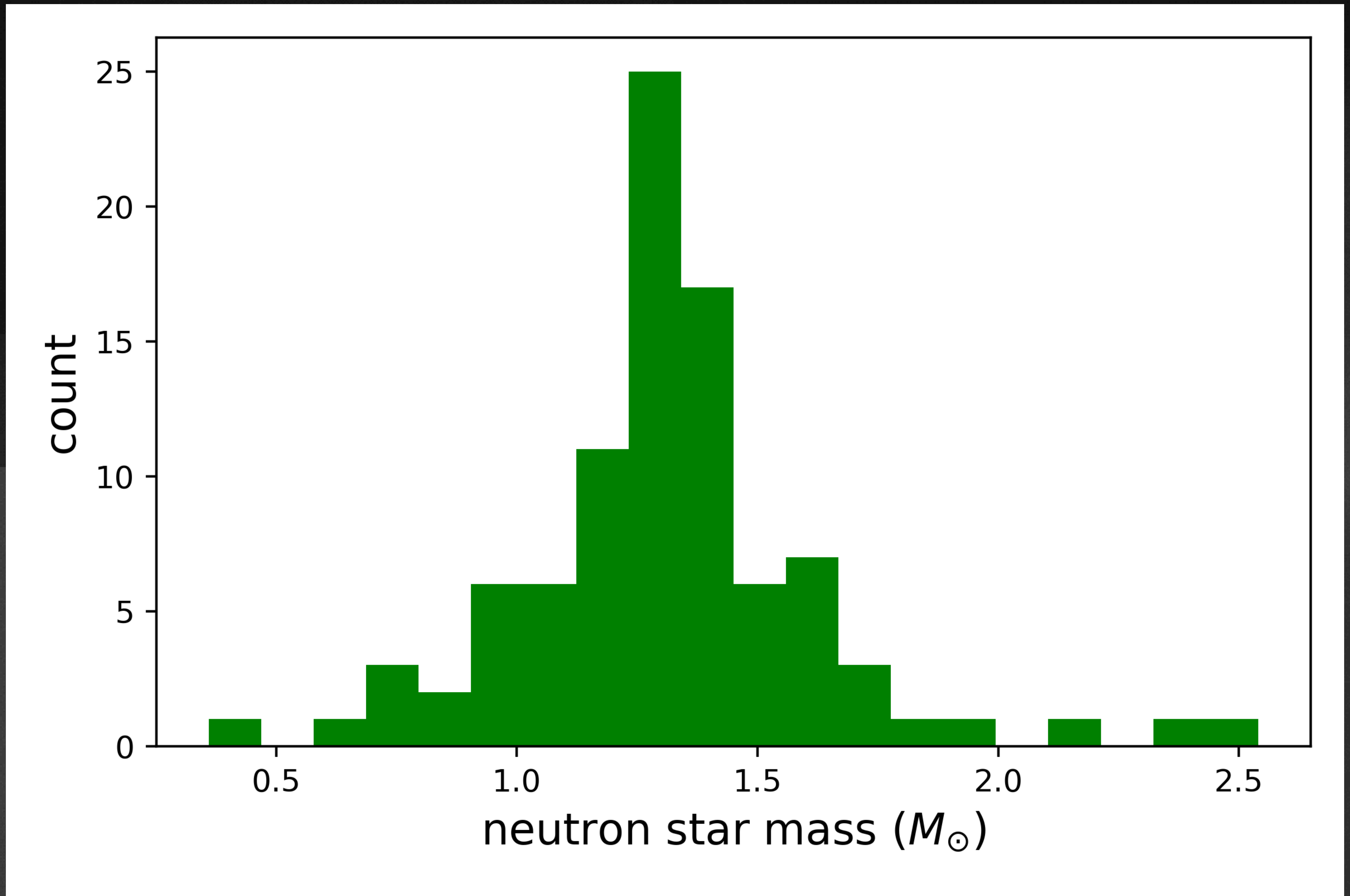
# Spin-up evolution, 1.5 PN

$$\frac{df}{dt} = \frac{96}{5}\pi^{8/3}\left(\frac{G\mathscr{M}}{c^3}\right)^{5/3} f^{11/3}\left[1 - \left(\frac{743}{336} + \frac{11}{4}\nu\right)\left(\pi\frac{GM}{c^3}f\right)^{2/3} + 4\pi\left(\pi\frac{GM}{c^3}f\right)\right]$$

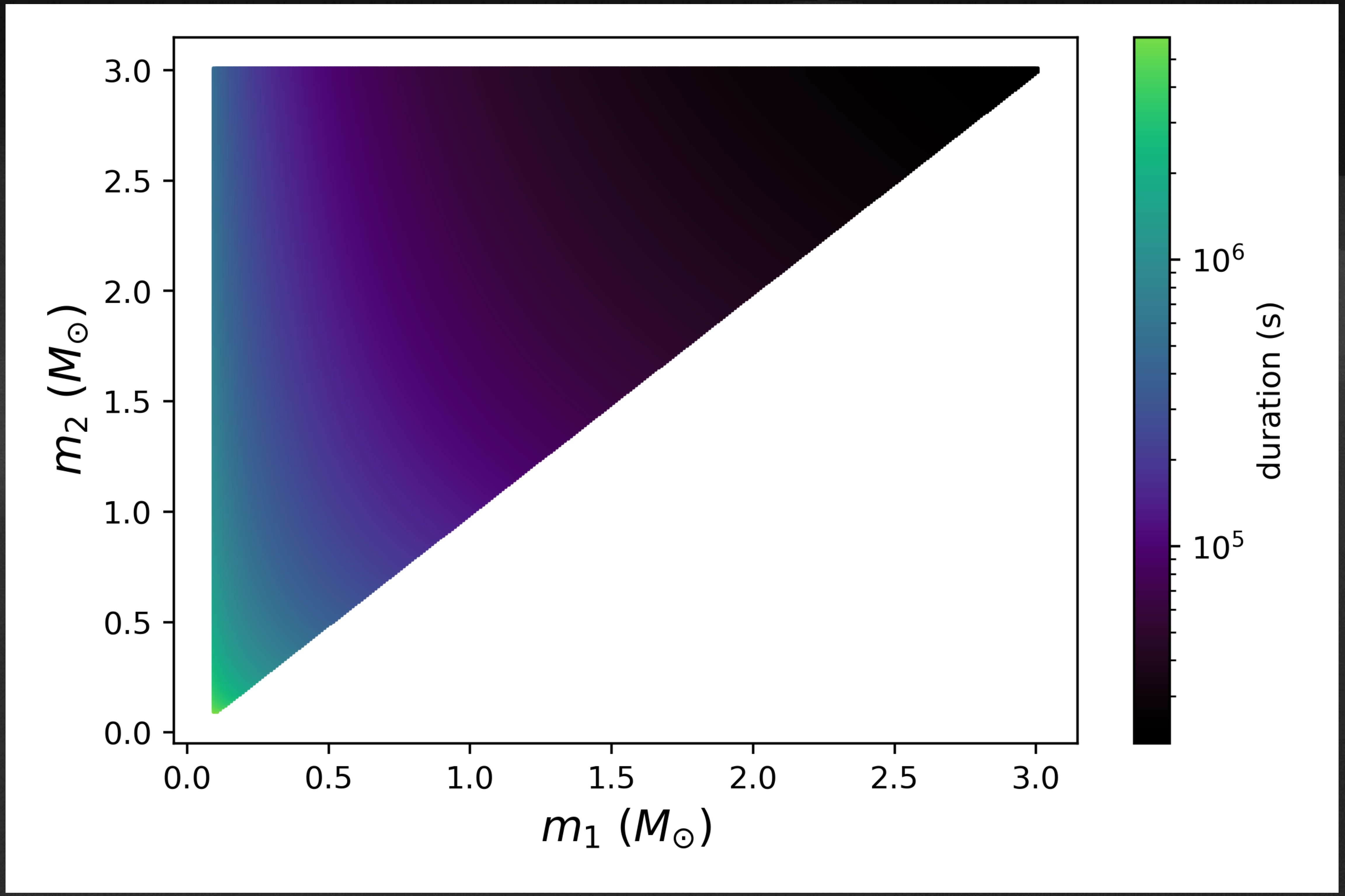
$$\frac{df}{dt} = 1.02 \times 10^{-5}\ \mathrm{Hz/s}\left(\frac{\mathscr{M}}{1.22M_\odot}\right)^{5/3}\left(\frac{f}{2\ \mathrm{Hz}}\right)^{11/3}\left[1 - 4.3\times10^{-3}\left(\frac{M}{2.8M_\odot}\right)^{2/3}\left(\frac{f}{2\ \mathrm{Hz}}\right)^{2/3} + 1.1\times10^{-3}\left(\frac{M}{2.8M_\odot}\right)\left(\frac{f}{2\ \mathrm{Hz}}\right)\right]$$

$$\frac{df}{dt} = \kappa_0 f^{11/3} - \kappa_1 f^{13/3} + \kappa_{1.5} f^{14/3}$$

# Parameter space to cover




Minimum allowed mass based on 93 candidate neutron stars




Durations of potential neutron-star binaries between 2-20 Hz

# How to compute sensitivity loss?

- $\lambda \equiv 4 \int_{f_{min}}^{f_{max}} df \frac{|\tilde{h}(f)|^2}{S_n(f)}, \quad ; |\tilde{h}(f)|^2 = \frac{5}{6} \frac{4}{25} \frac{1}{4\pi^{4/3}} \frac{c^2}{d^2} \left( \frac{G\mathcal{M}}{c^3} \right)^{5/3} f^{-7/3}.$
- $P(S > S_{thr}; \lambda) = \int_{S_{thr}}^{\infty} dS e^{-S-\frac{\lambda}{2}} I_0 \left( \sqrt{2S\lambda} \right), > 0.95$ ; solve for $\lambda$ ;
  - Means: spectrum distribution in presence of signal is a non-central $\chi^2$ with 2 dof
- $S_{thr} = -\log \left( \frac{N_{cand}}{N_{tot}} \right), \quad -> \frac{N_{cand}}{N_{tot}} = FAP$ ;
  - Means: spectral power is exponential in absence of a signal
- Calculate the minimum detectable $h_0$ for MF as a function of $\lambda$:
- $h_{0,min}^{MF} = \sqrt{120\pi^{8/3} \lambda_{min} \left( \frac{G\mathcal{M}}{c^3} \right)^{5/3} \left( \int_{f_{min}}^{f_{max}} df \frac{f^{-11/3}}{S_n(f)} \right)^{-1}}$ . compare to Generalized FH, compute ratio