Continuous gravitational waves as multi-messenger probes in third-generation gravitational-wave detectors

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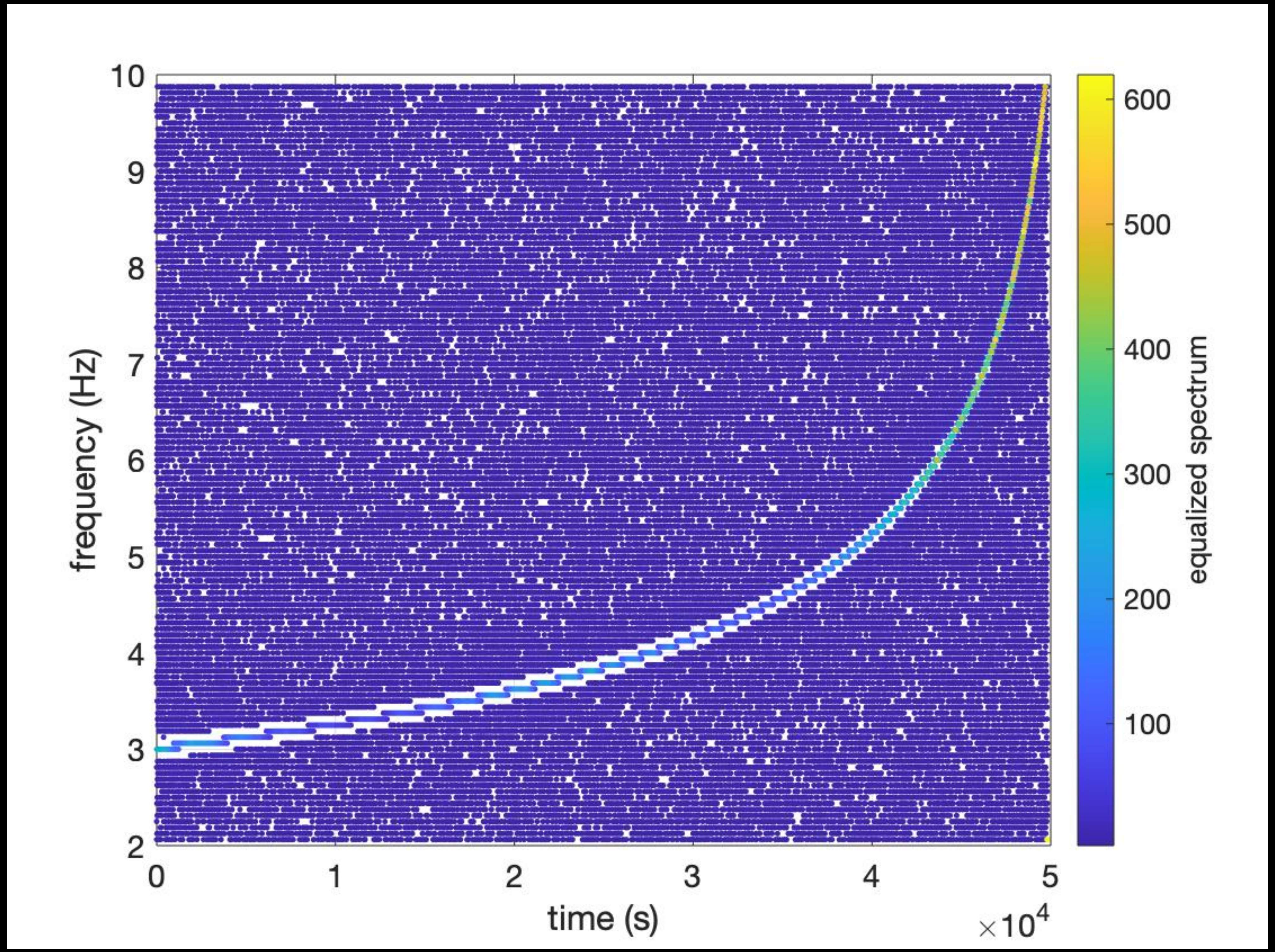
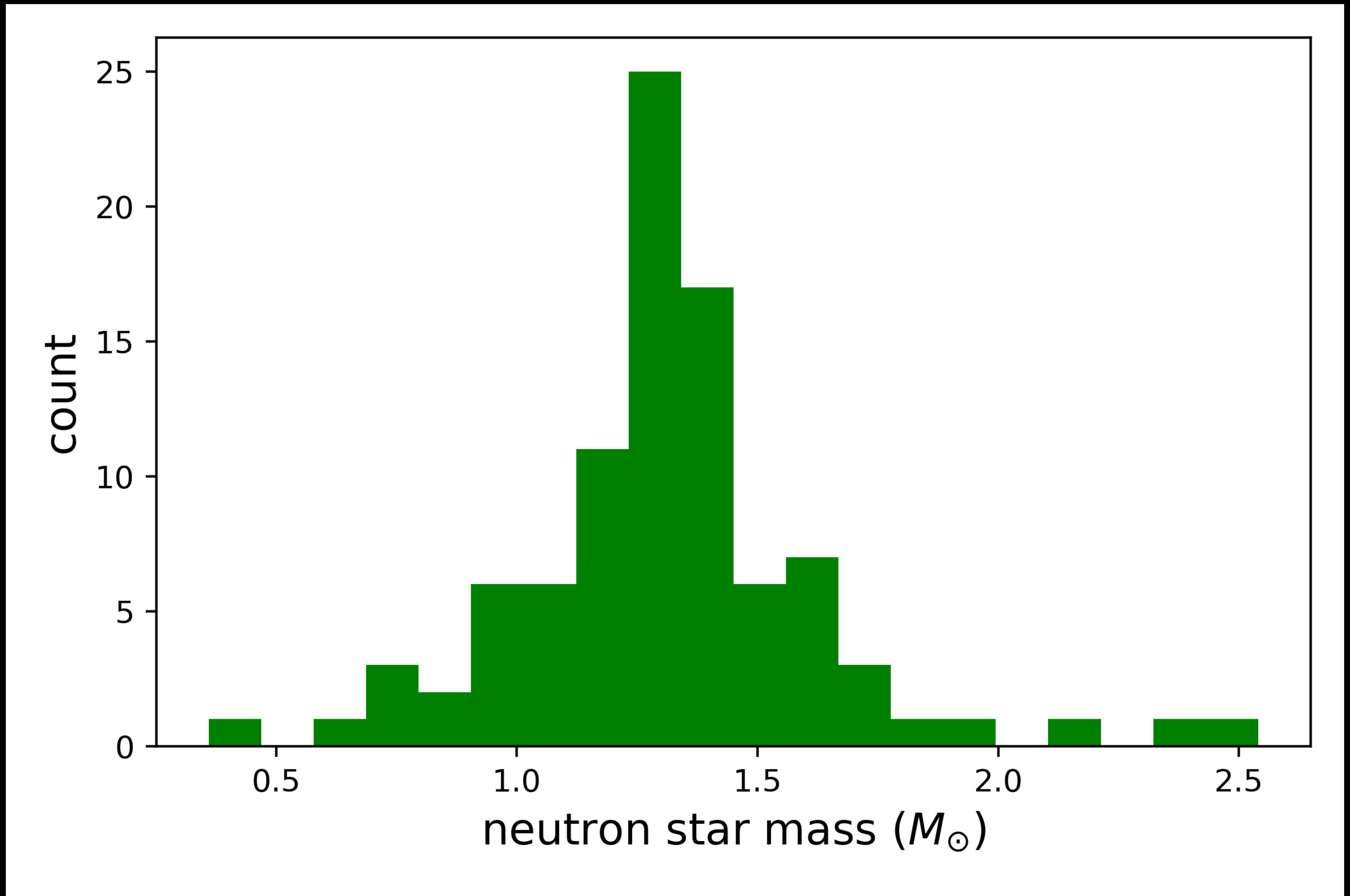
Motivation

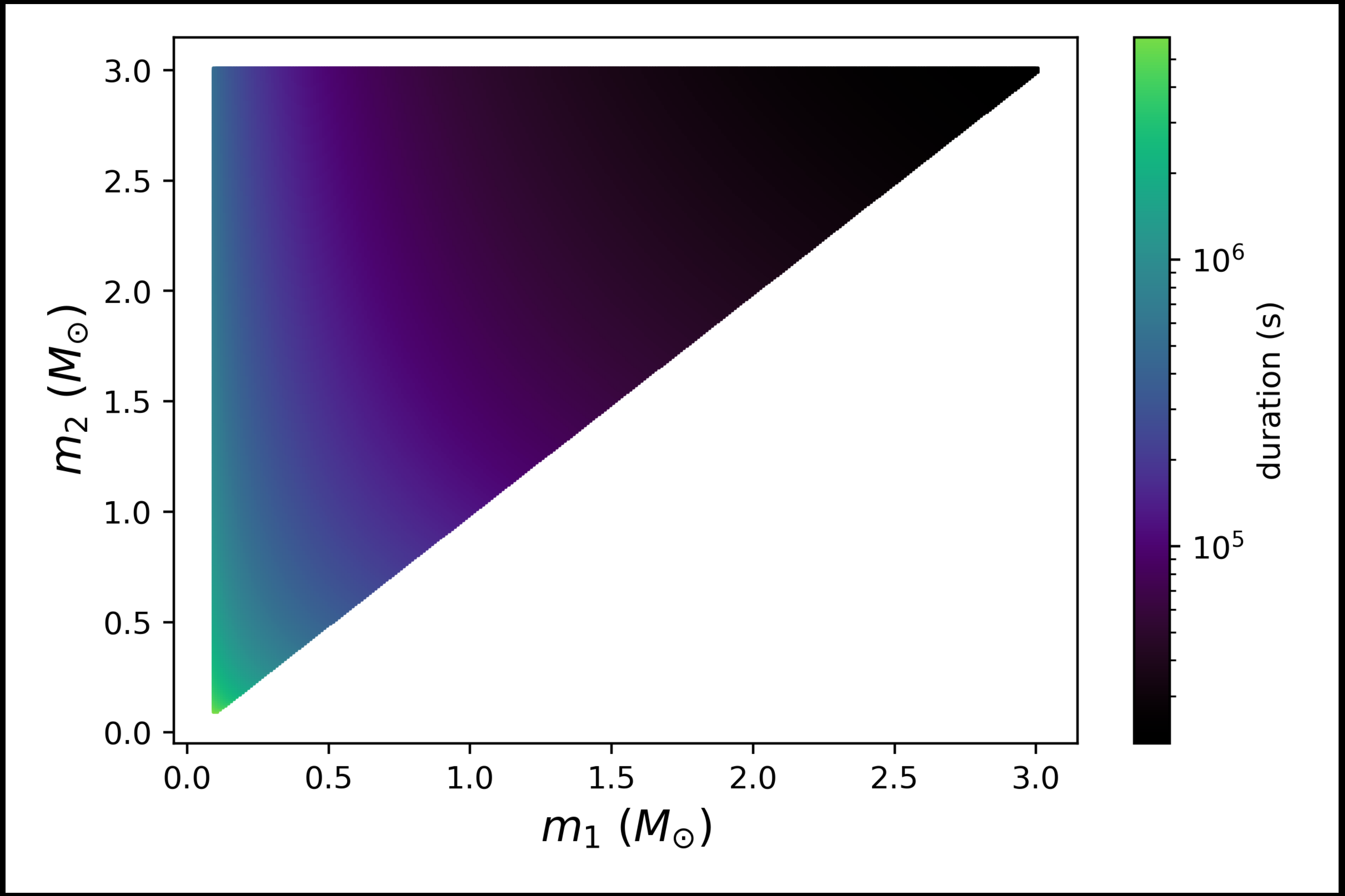
- Inspiraling binary systems will remain within the ET frequency band for a much longer time and overlap (~40-3000x longer for 5 or 1 Hz frequency floors)
- Within this time, assumptions made in matched-filtering analyses, e.g. no gaps, noise stationarity, no glitches, could break down
- Methods used in searches for (transient) continuous gravitational waves, could work here, provide early-warning sky localization, and could deal with overlapping signals



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

Parameter space to cover



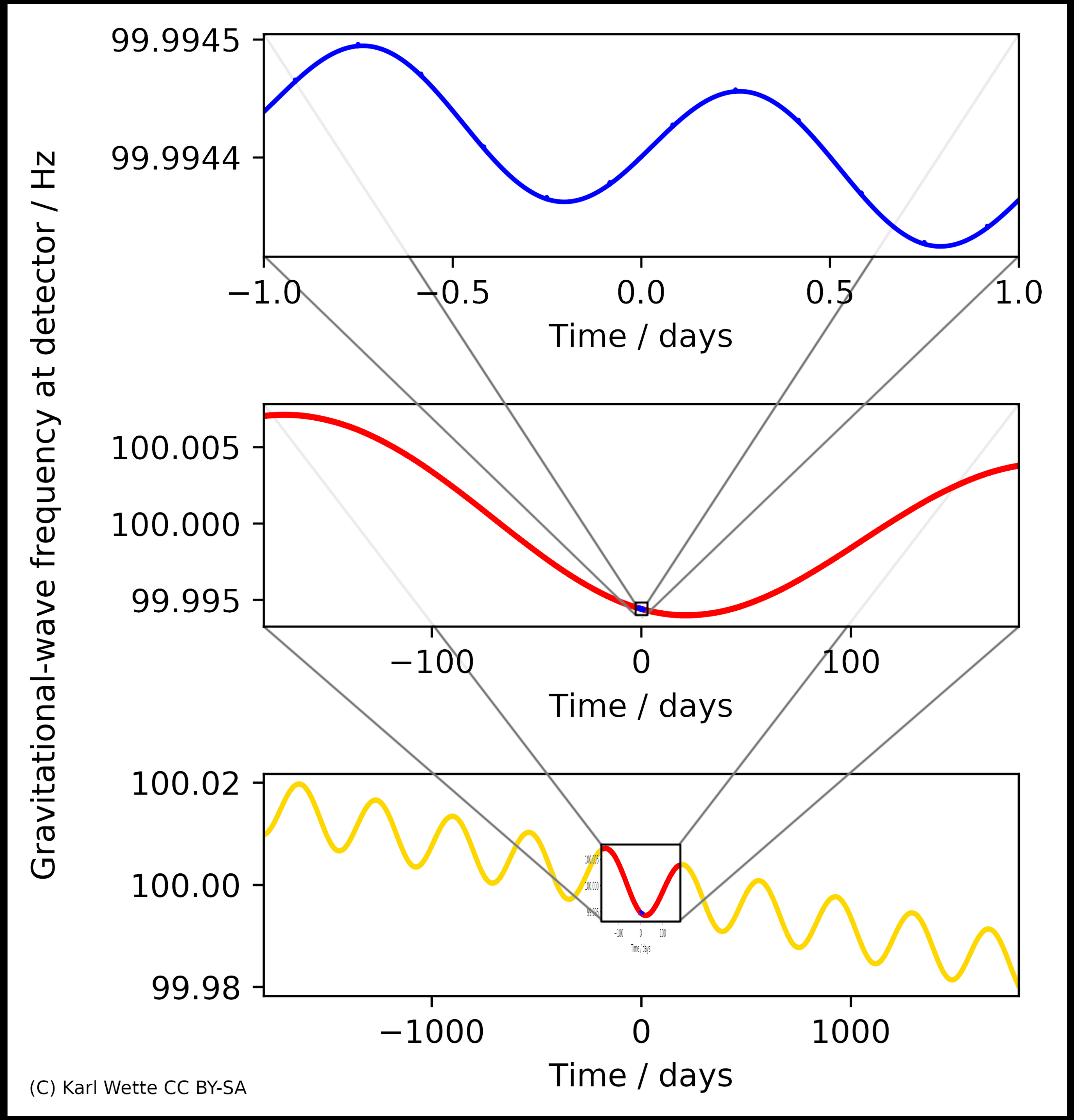


Minimum allowed mass based on 93 candidate neutron stars

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

Continuous gravitational waves

- Quasi-monochromatic, persistent, weak signals
- Modelled as a sinusoidal signal with frequency f with a small frequency drift $\dot{f}$ over time: $f = f_0 + \dot{f}(t - t_0)$, where f_0 and t_0 are the reference frequency and time, respectively
- Signals could arise from asymmetrically rotating neutron stars, but also others
- Searches for continuous waves acquire signal-to-noise ratio by observing for a long time



“Transient” continuous waves

- Signal frequency evolution over time follows a power-law and lasts O(hours-days)
- Can describe gravitational waves from the inspiral portion of a binary neutron star system
- Higher-order terms contain total mass, symmetric mass ratio at 1.5PN

- Gravitational waves from quasi-Newtonian orbit (0 PN shown)

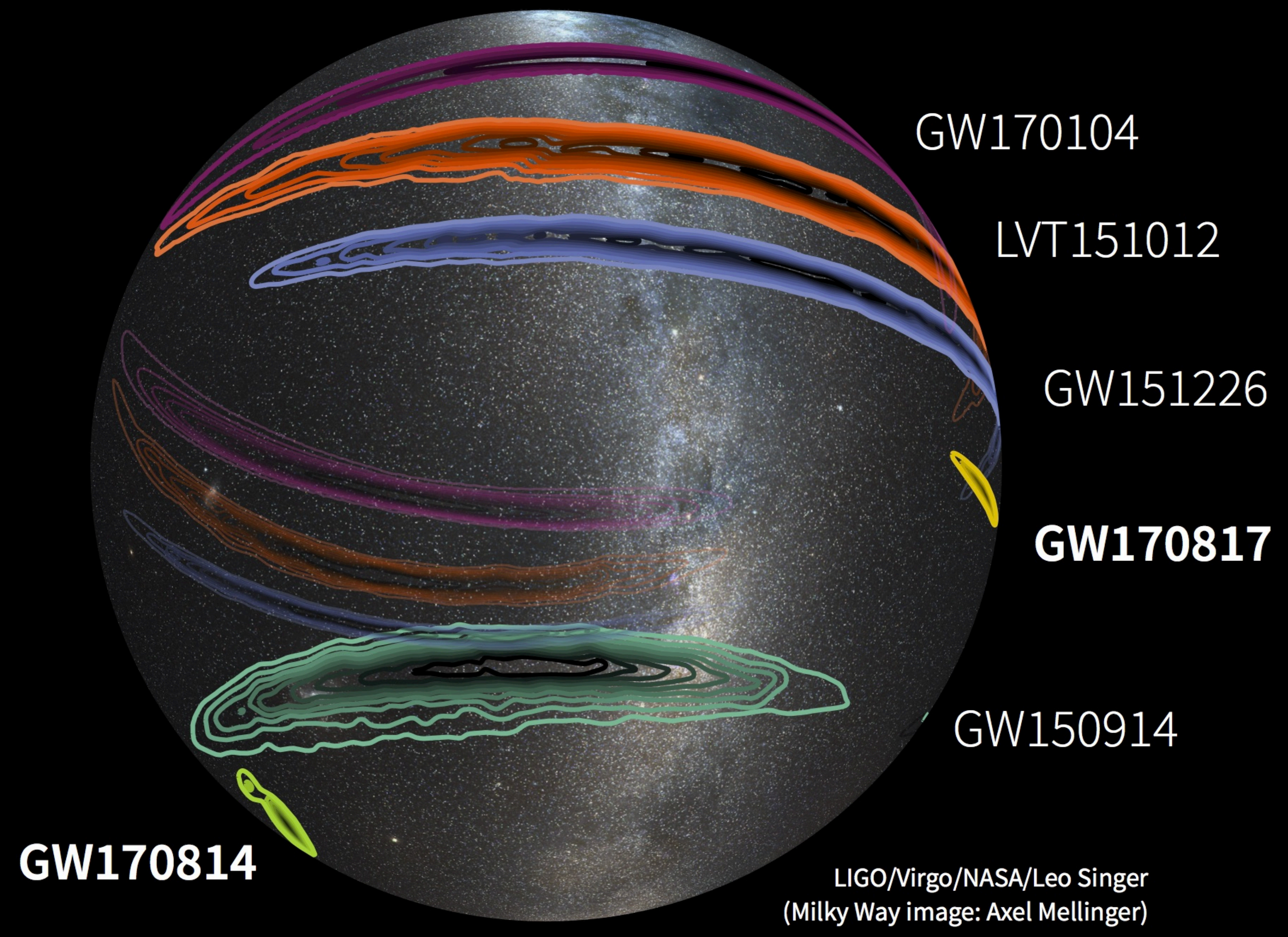
$$\dot{f} = \kappa f^n$$

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

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

Connection to multi-messengers

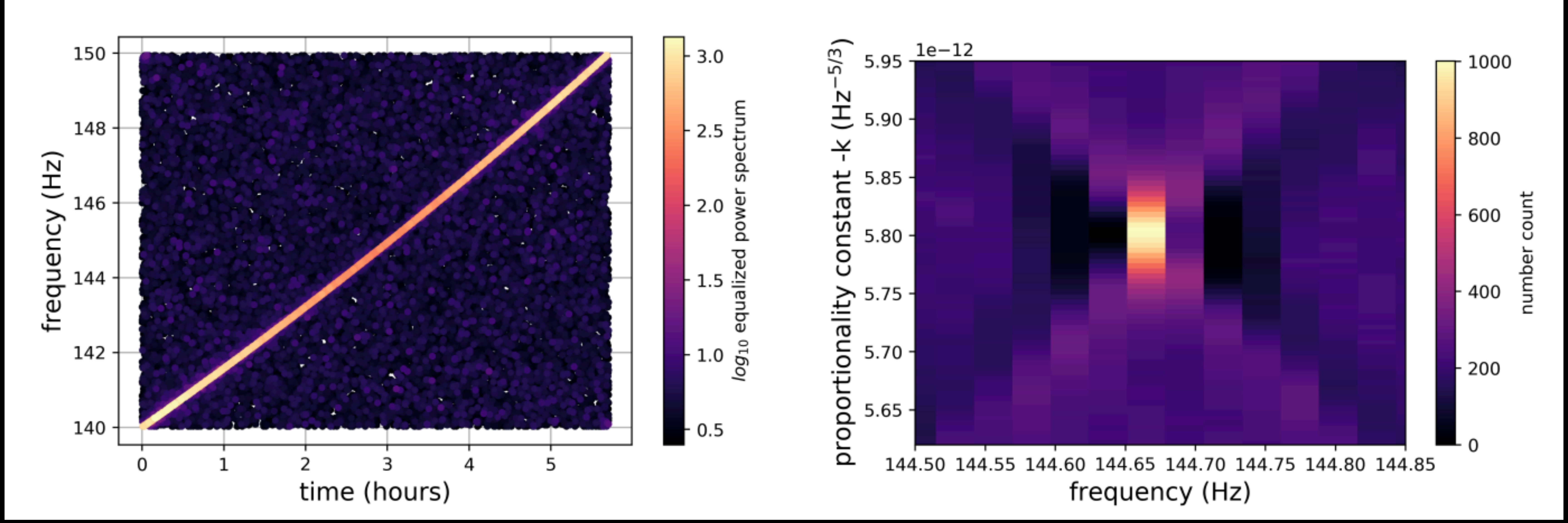
- Binary neutron star inspirals could last for O(hours-days) in future detectors, and are well-modeled by Post-Newtonian expansions
- "Early warning" for astronomers is realistic, given how long these signals could last
- We propose an alternative to matched filtering that could provide early warnings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



Hough Transform

Astone et al. Phys. Rev. D 90, 042002 (2014)

Miller et al. Physics of the Dark Universe 32(7):100836



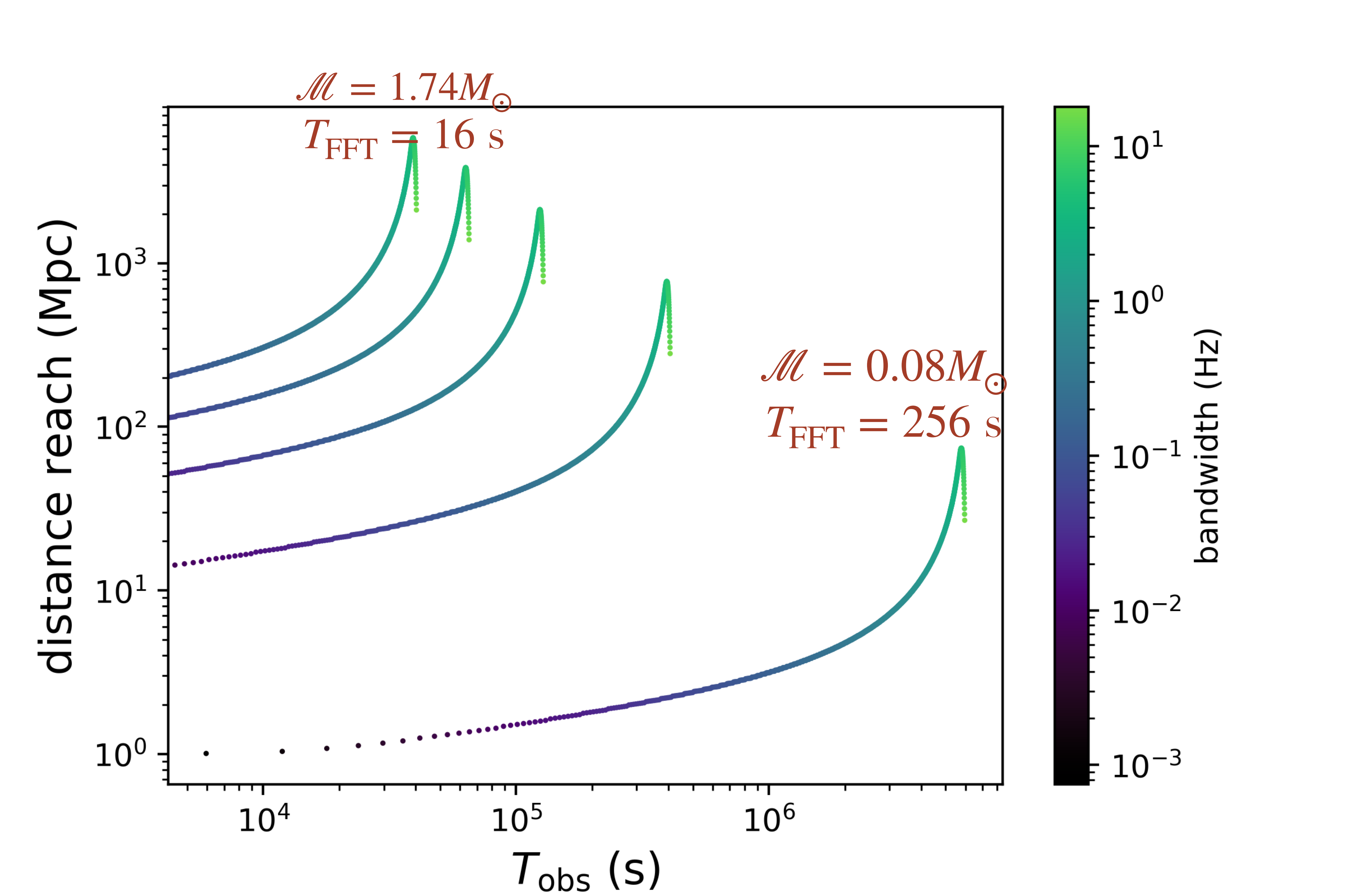
- Maps points in time/frequency plane to lines in the frequency/chirp mass plane of source
- Simulated inspiraling primordial black hole binary system and the Hough Transform of it
- Deals with gaps and non-stationarities by summing just the presence of a peak or not at each time/frequency, NOT the power

The pipeline

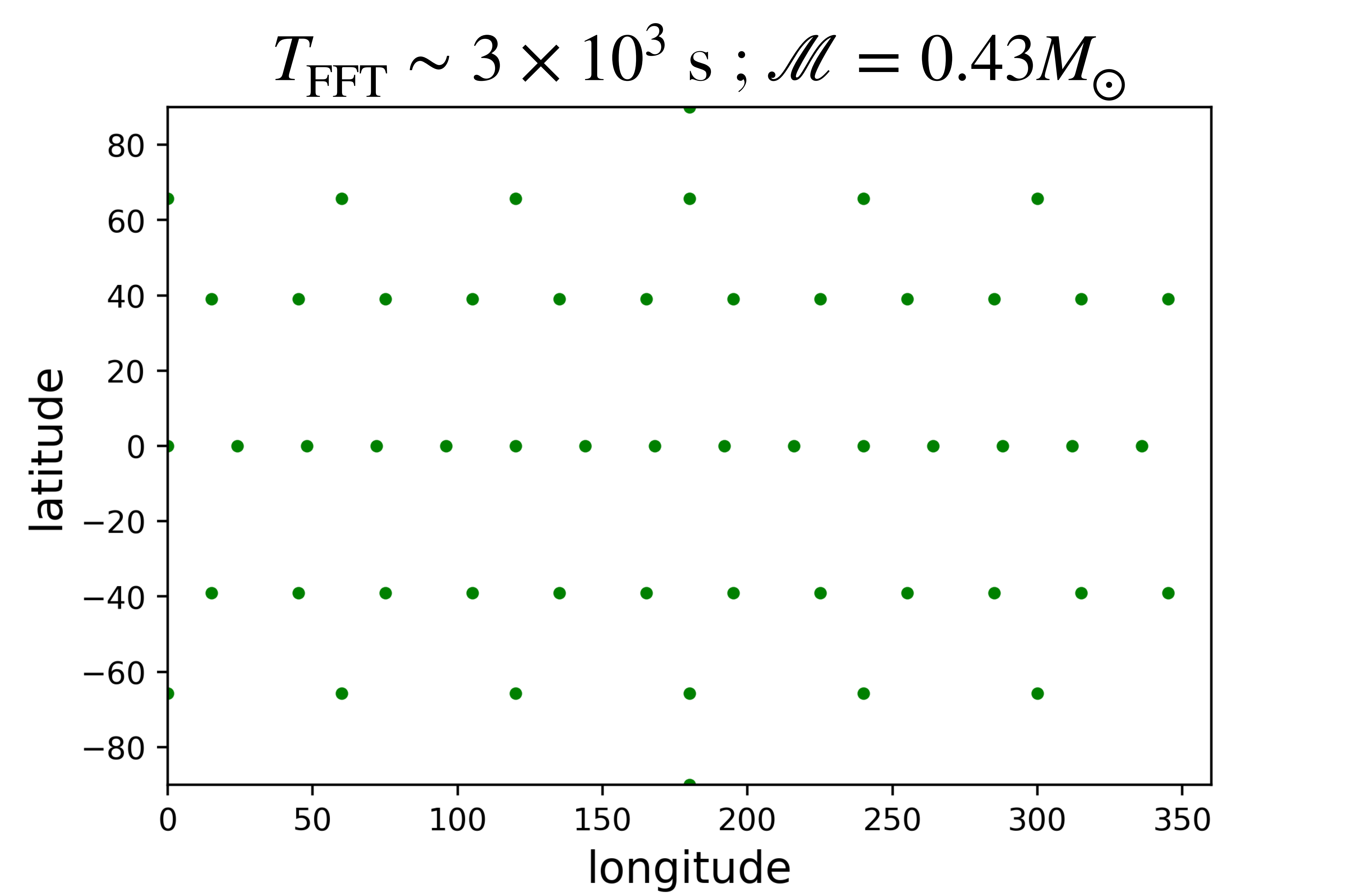
- Create time/frequency spectrograms with a given coherence time T_{FFT}
- Run the Hough Transform to obtain an estimation of the frequency and chirp mass of the system
- Demodulate the signal, leaving only the Doppler shift and Post-Newtonian corrections >0 (“Heterodyning”)
- Create sky grid, and run successive Hough Transforms to constrain the sky location, symmetric mass ratio, and total mass (up to 1.5 PN)

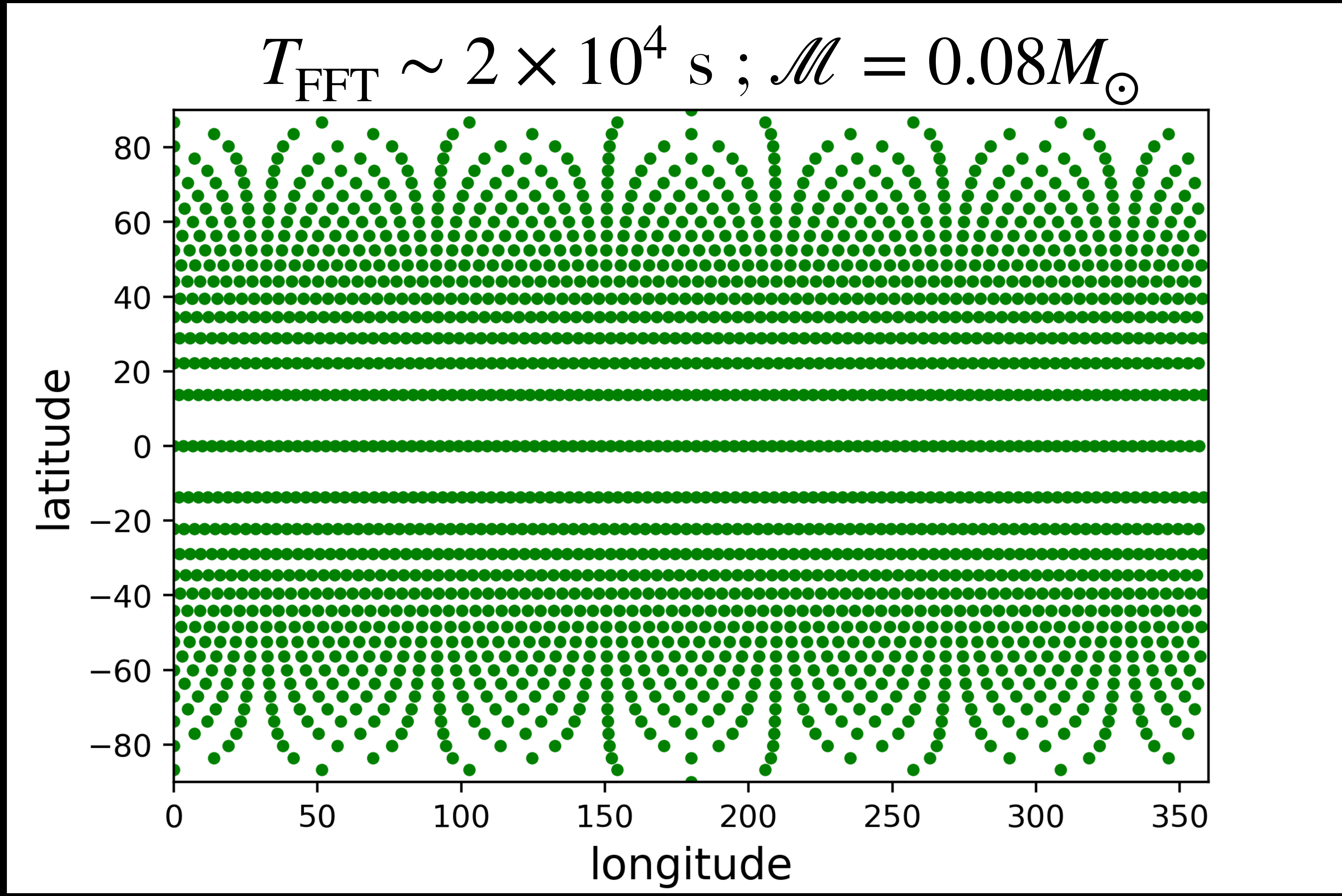
Optimal distance reach

- 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 T_{FFT} decreases
  - This is actually ok for early-warning
- Sensitivity level is fixed in first pass of Hough



Sky grid in successive Houghs





- Trade-off between better sky localization and increasing computational cost
- Low chirp-mass systems can be better localized, but will emit weaker gravitational waves than high chirp-mass ones

Conclusions

- Methods to detect (transient) continuous gravitational waves can be generalized to search for inspiraling binary neutron stars in third- generation detectors
- Our method relies on treating each PN term as a separate power-law, performing the analysis *hierarchically*, correcting for each frequency modulation
- The Hough's sensitivity depends on the chirp mass of the system, and ranges from 10 Mpc to 1 Gpc for $\mathscr{M} = [0.08, 1.74] M_{\odot}$, respectively
- The Hough could also inform matched-filtering analyses, greatly reducing the computational cost by constraining the chirp mass, mass ratio and total mass

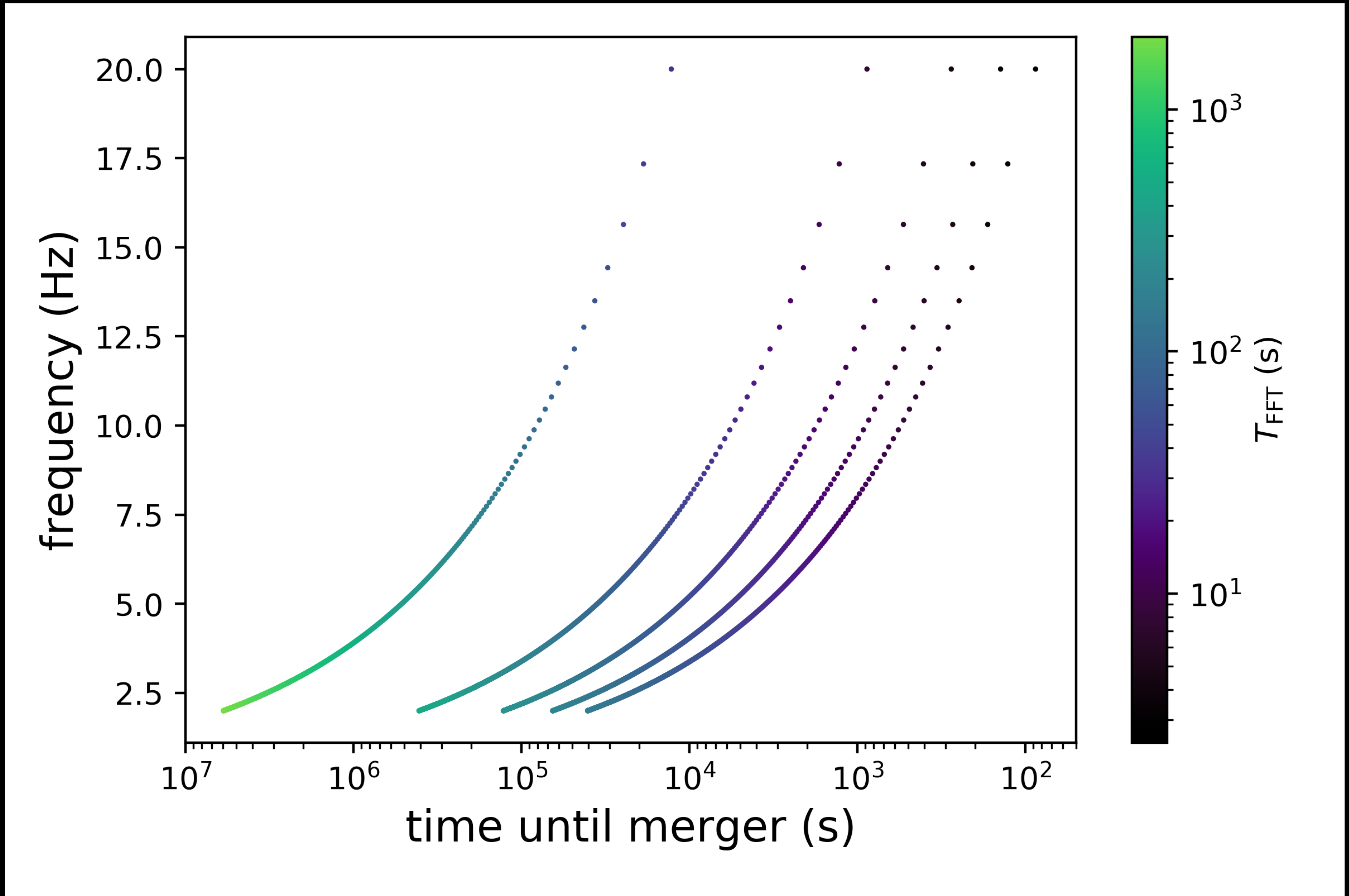
Back-up slides

With which T_{FFT}?

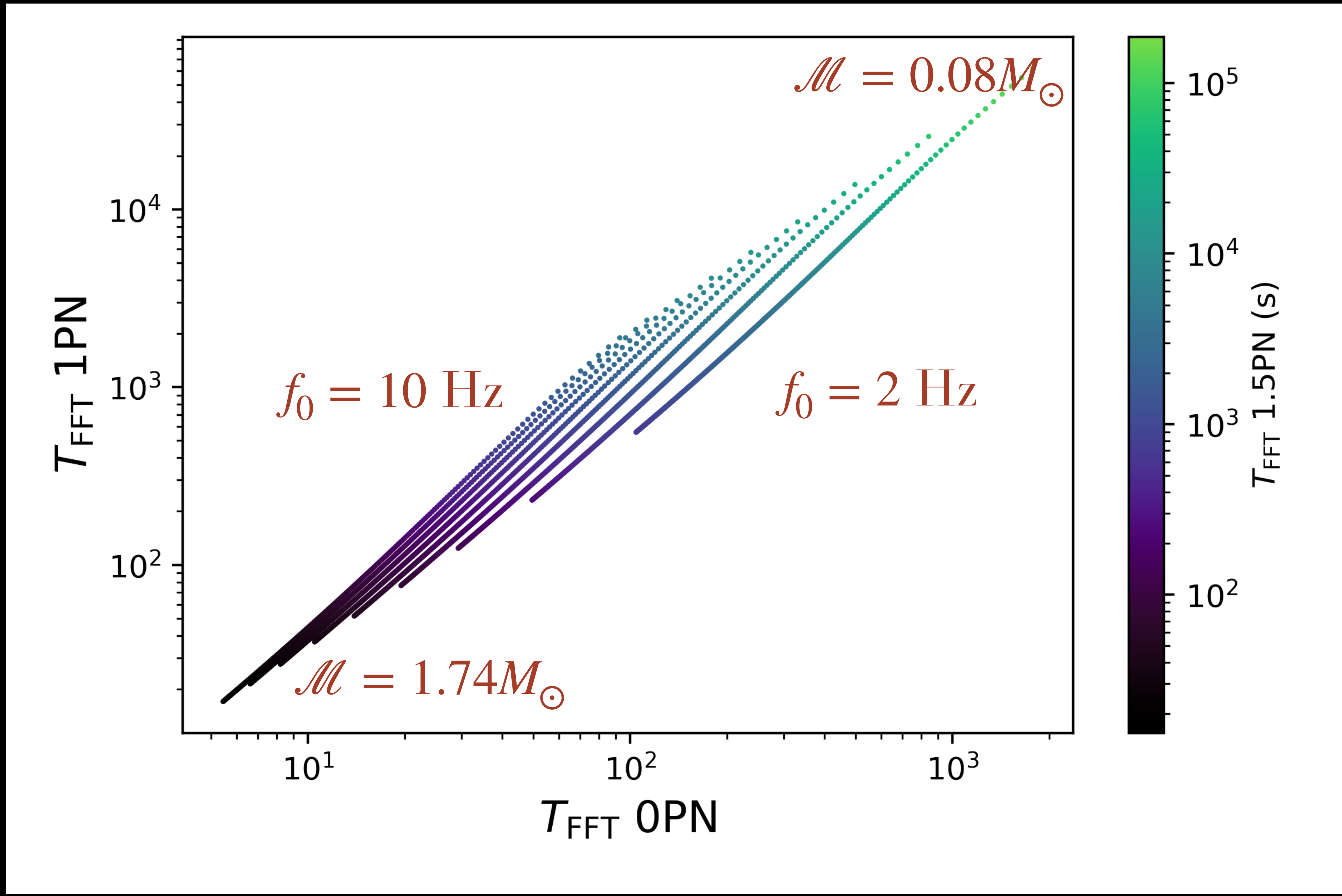
- The gravitational-wave frequencies of systems with different chirp masses evolve at different rates, with smaller chirp masses having slower frequency drifts

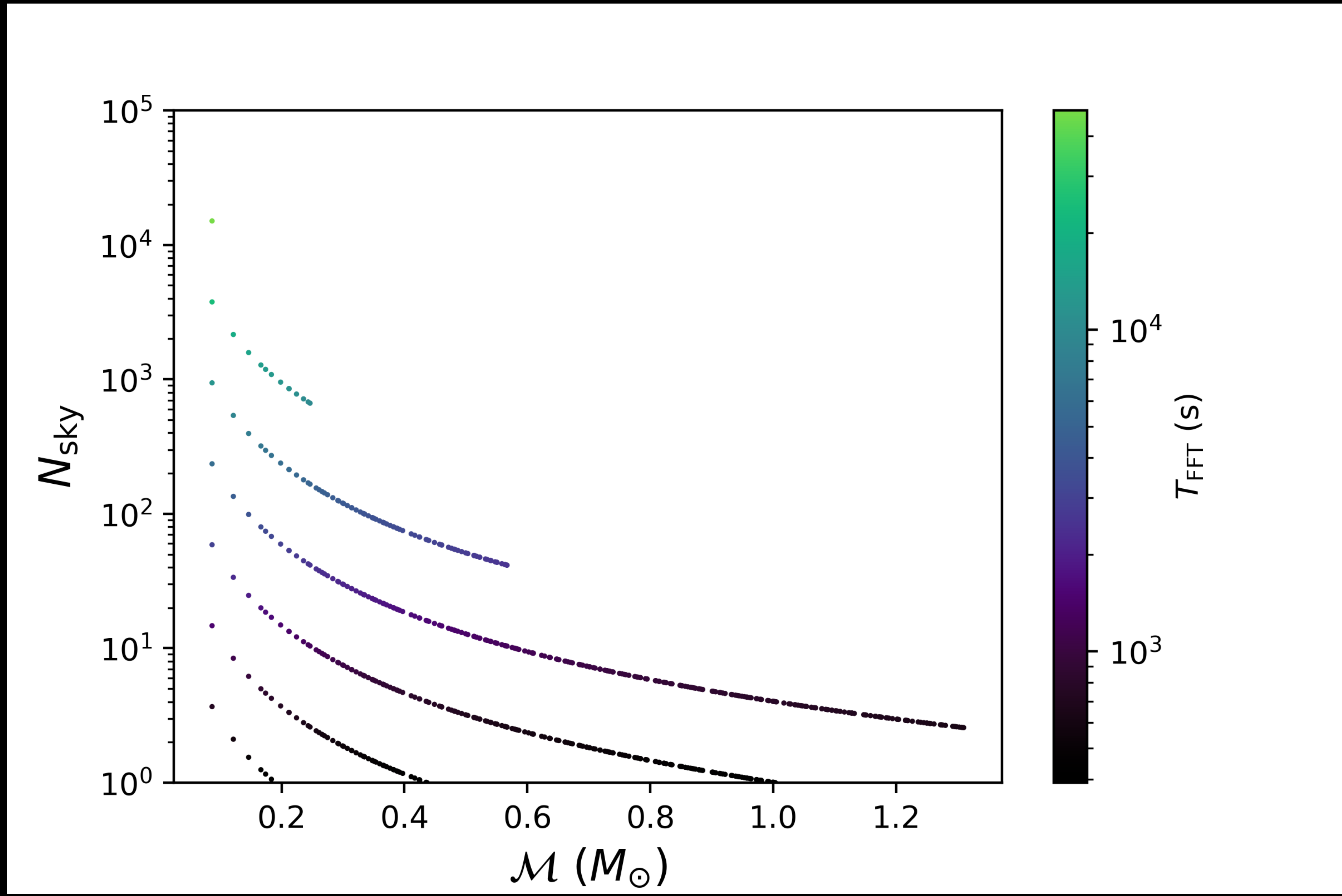
- This is also a function of the time to merger

- Should be an "optimal one"



Sky localization





- In first Hough: T_{FFT} too short, f too low, to localize
- But, after phase correction, T_{FFT} can be increased, to match that of frequency drift from higher PNs
- Different lines correspond to increasing T_{FFT} at a fixed chirp mass
- N_{sky} : number of sky points to analyze

Spin-up evolution, 1.5 PN

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

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

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

Future work

- Show that the Hough is robust towards overlapping signals
- Quantify the reduction in computational cost for a matched-filter analysis that is informed by the chirp mass, mass ratio and total mass of the system
- Low-latency implantation of the Hough Transform
- Enable early-warning alerts: quantify how early we can inform astronomers with this method, as a function of sensitivity loss
    - The earlier we inform, the less we can observe and accumulate signal-to-noise ratio