Prospects for reconstructing the gravitational wave signal from core-collapse supernovae in Advanced LIGO-Virgo

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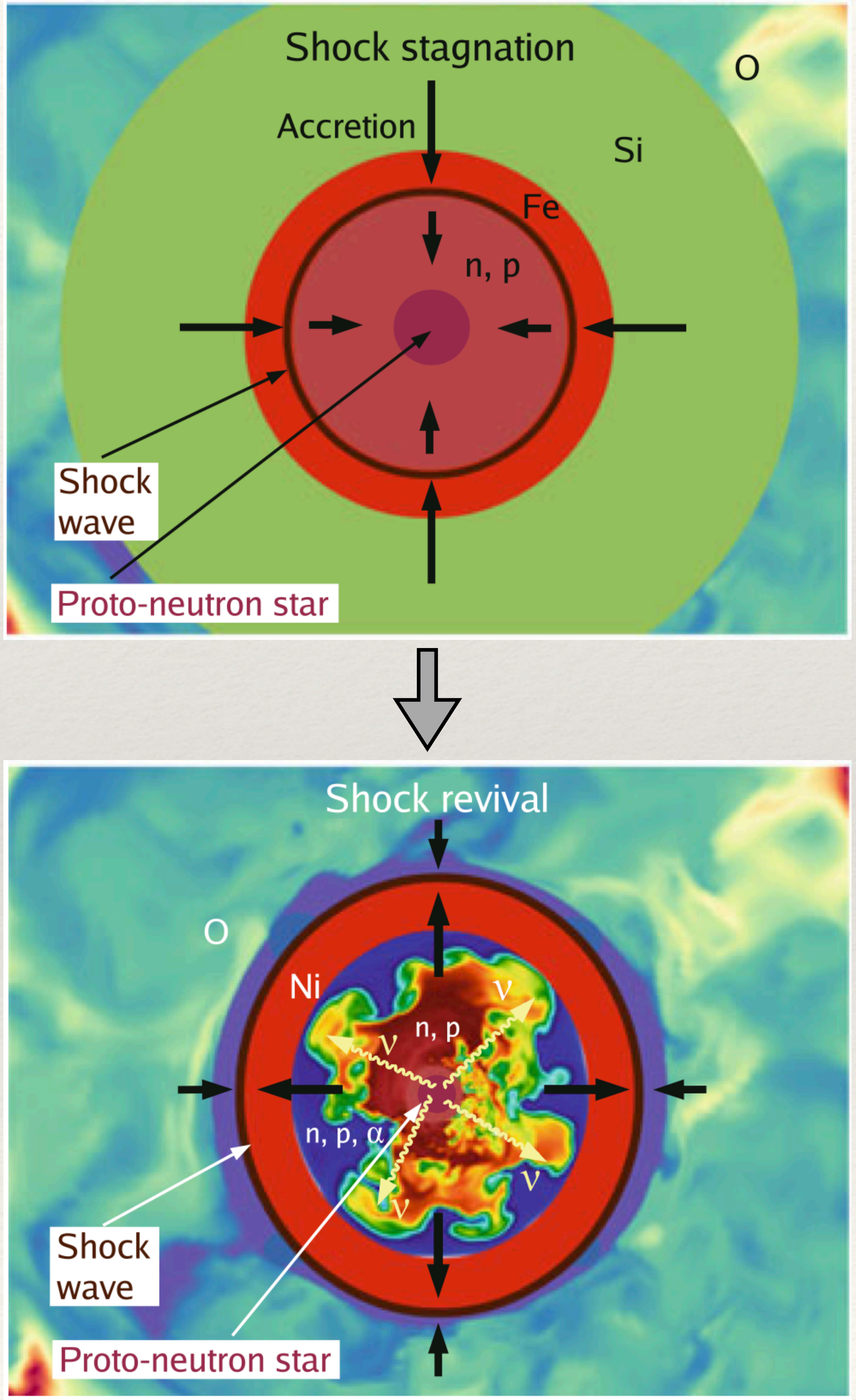
Core-collapse supernovae

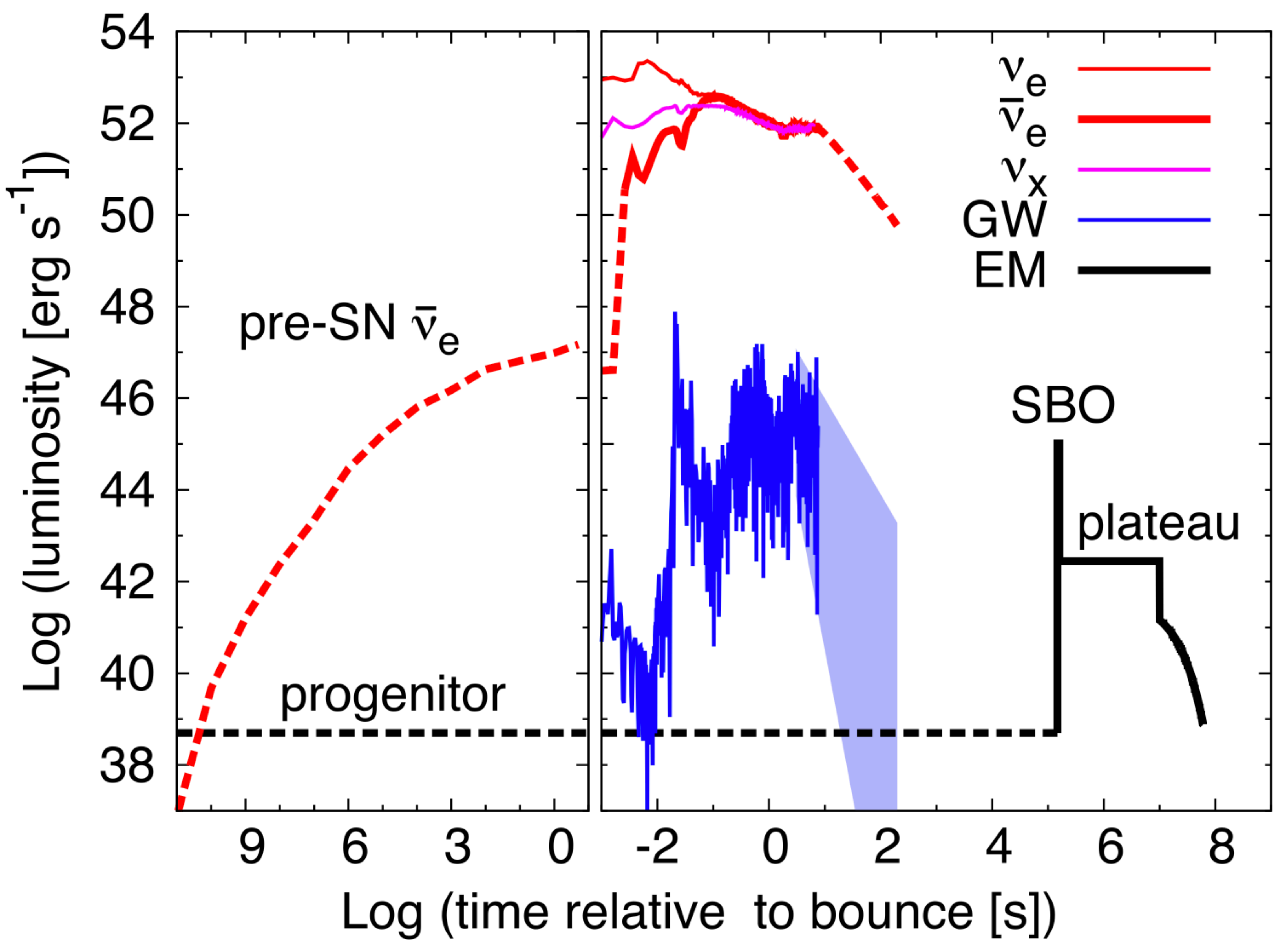
- Massive stars ($\gtrsim 8\ \mathrm{M}_{\odot}$) collapse under their own gravity at the end of their life
- Implosion turns into explosion as the inner core reaches nuclear densities, rebounds and launches a shock wave
- Initial energy of the shock is not enough to break out of the core for a successful explosion - it stalls
- How is the shock re-energized? What mechanism powers the explosion?



H.T. Janka (2017)

Gravitational waves from CCSN

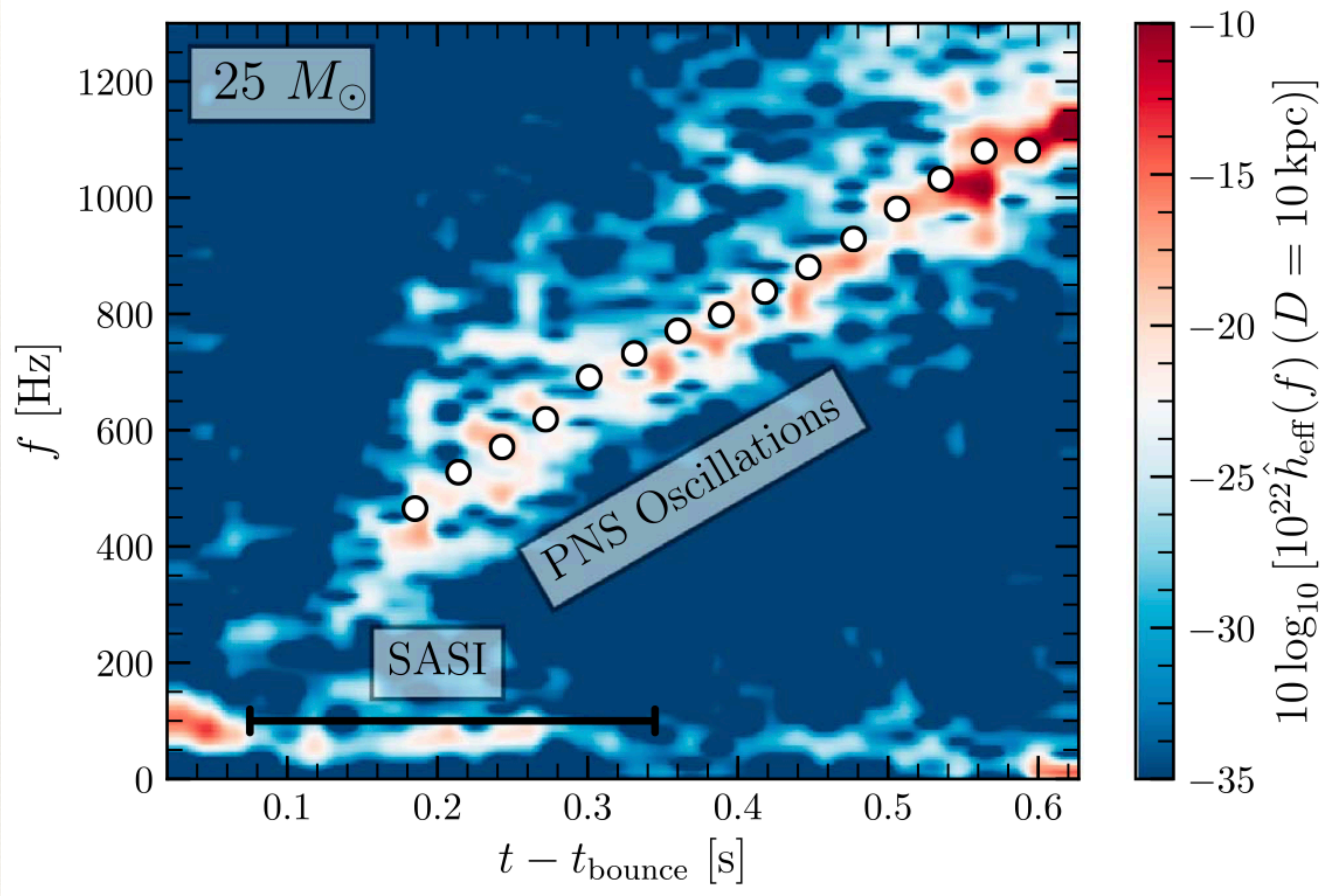
- Asymmetric explosion: Any non-spherical, accelerated mass motions in the dense SN core act as a source of GWs
- GWs (and neutrinos) from CCSN thus probe the central engine driving the explosion - not possible with EM!



Nakamura et al. (2016)

Gravitational waves from CCSN

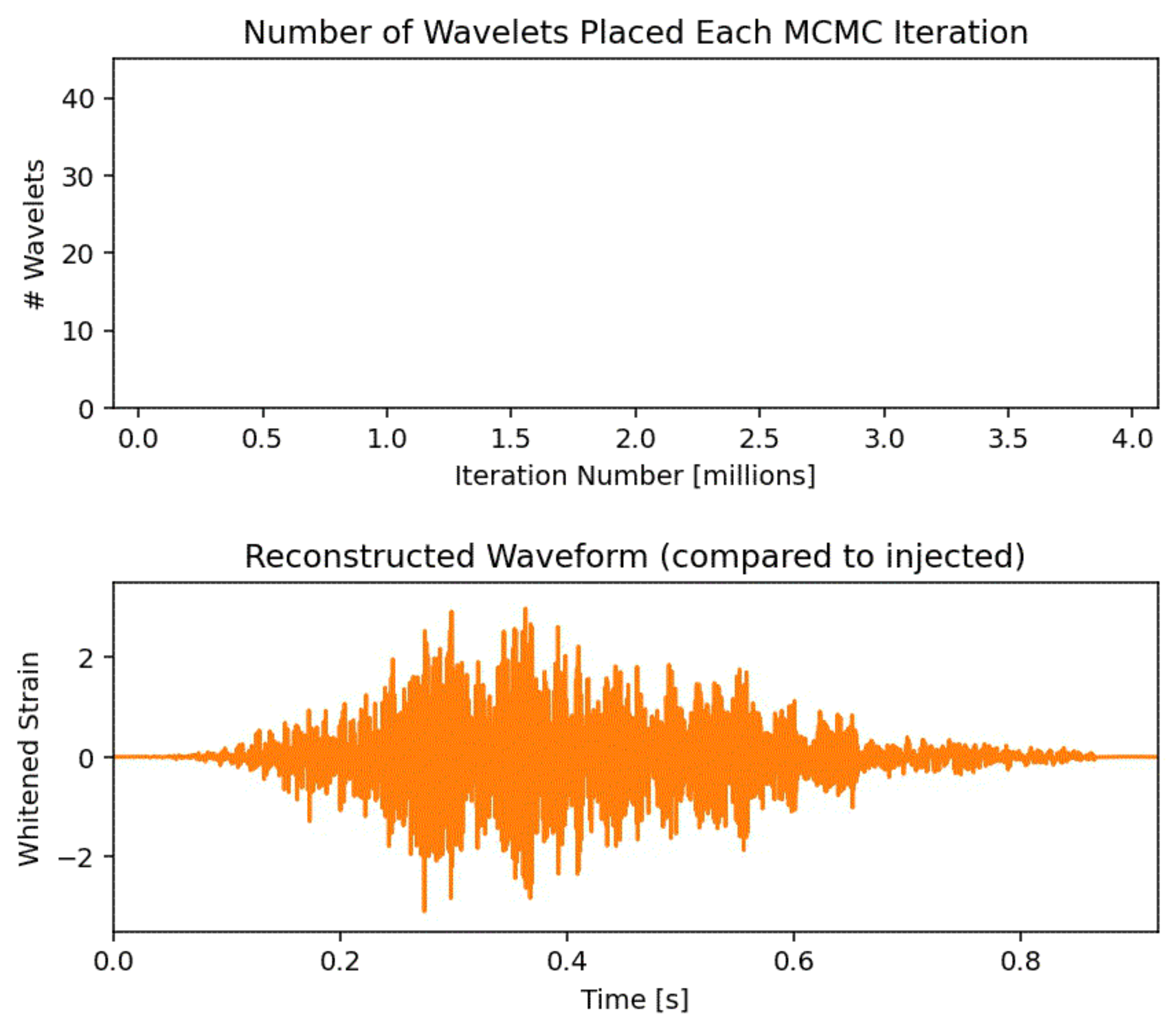
- Dominant emission from surface oscillations of Proto Neutron Star - (g and f modes)
- Hydrodynamic instabilities - highly asymmetric turbulent flow and SASI
- Detection will allow us to use GW features to distinguish between different explosion models and mechanisms, extract astrophysical parameters



Radice et al. (2019)

The BayesWave algorithm

- A GW signal reconstruction algorithm for short bursts ($\lesssim 1$ s) that makes no assumptions about the signal morphology (Cornish & Littenberg 2015)
- Uses a trans-dimensional reversible jump MCMC to model both the signal and instrumental noise
- Places a variable number of Morlet-Gabor (sine-Gaussian) wavelets, the linear combination of which forms the whole reconstructed signal



Simulating supernova signals in Adv. LIGO-Virgo

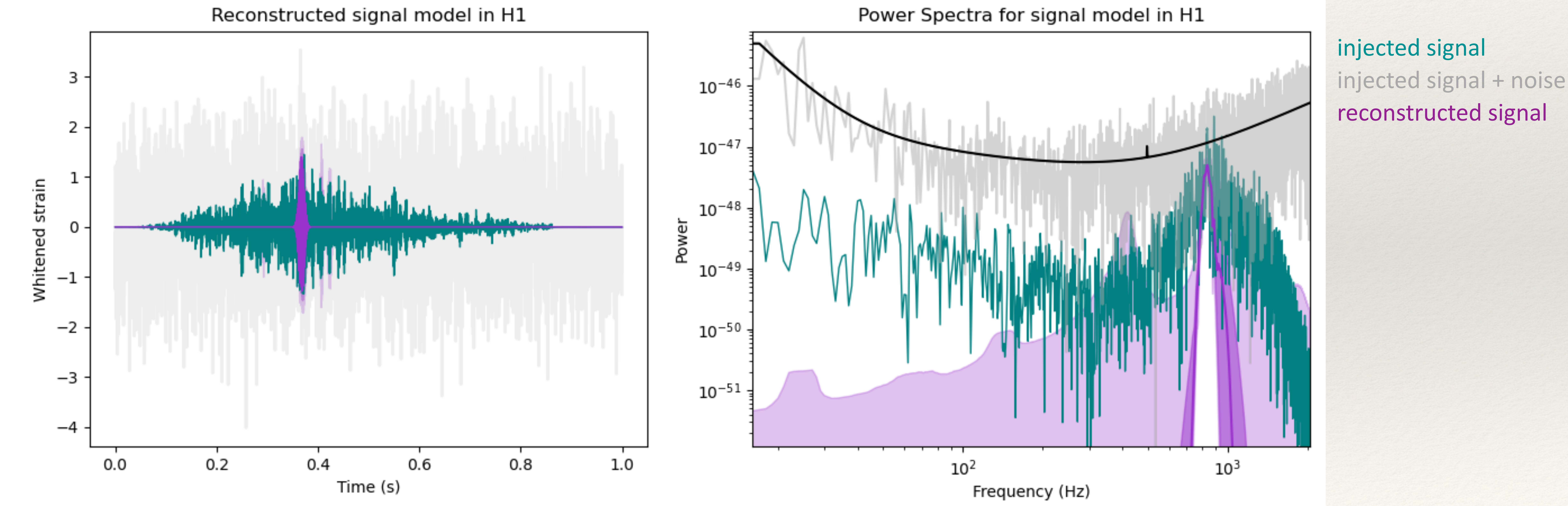
- Use GW waveforms generated from the latest 3D GRMHD simulations of CCSN
- Inject the waveform into simulated design sensitivity Advanced LIGO and Advanced Virgo noise for the Hanford, Livingston and Virgo detectors
- For each model do many injections while varying extrinsic parameters:
  - sky positions
  - source orientations
  - distances

Recovering supernova signals

- Perform waveform reconstruction of the GW signal with BayesWave
- Tune the BayesWave algorithm to maximize waveform recovery
- Preliminary results from one model in this talk: **Powell 2019 s18** neutrino-driven explosion of $18\ \mathrm{M}_{\odot}$ non-rotating progenitor star (Powell & Muller 2019)

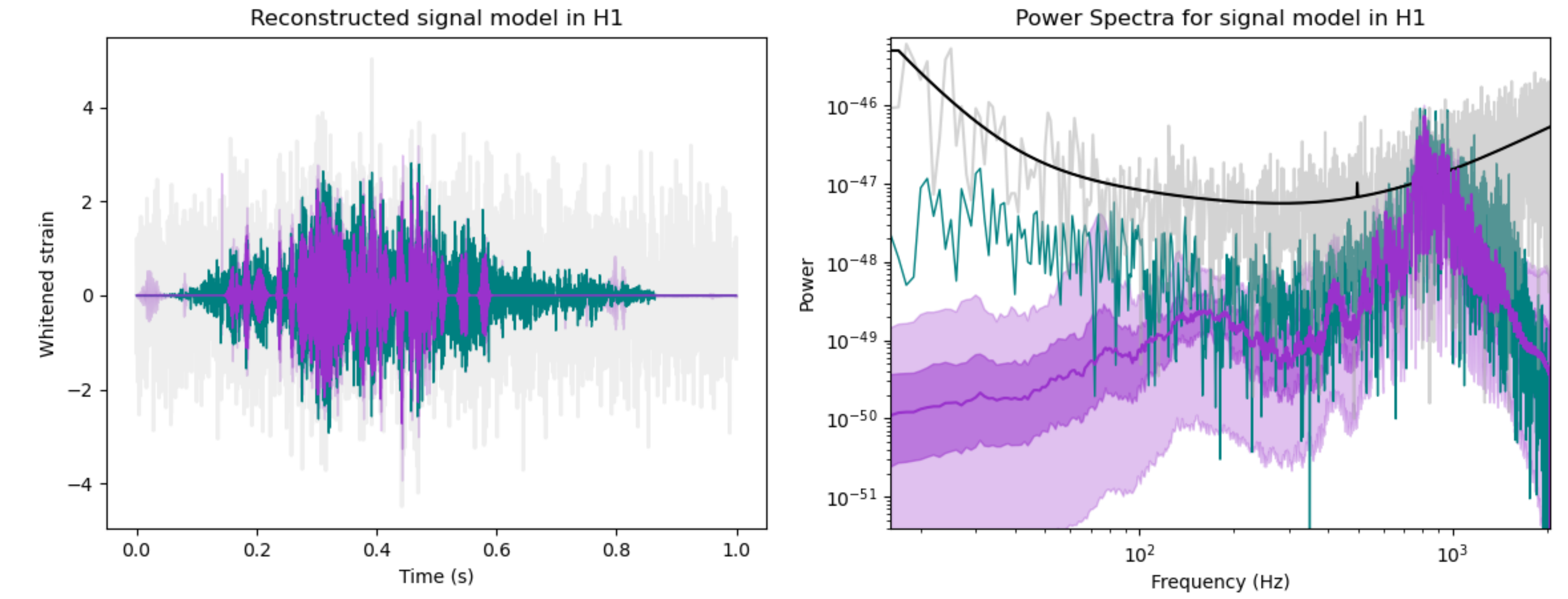
Some typical reconstructions (Powell 2019)

- Injected Network SNR ~ 20 (distance ~ 8 kpc)



Some typical reconstructions (Powell 2019)

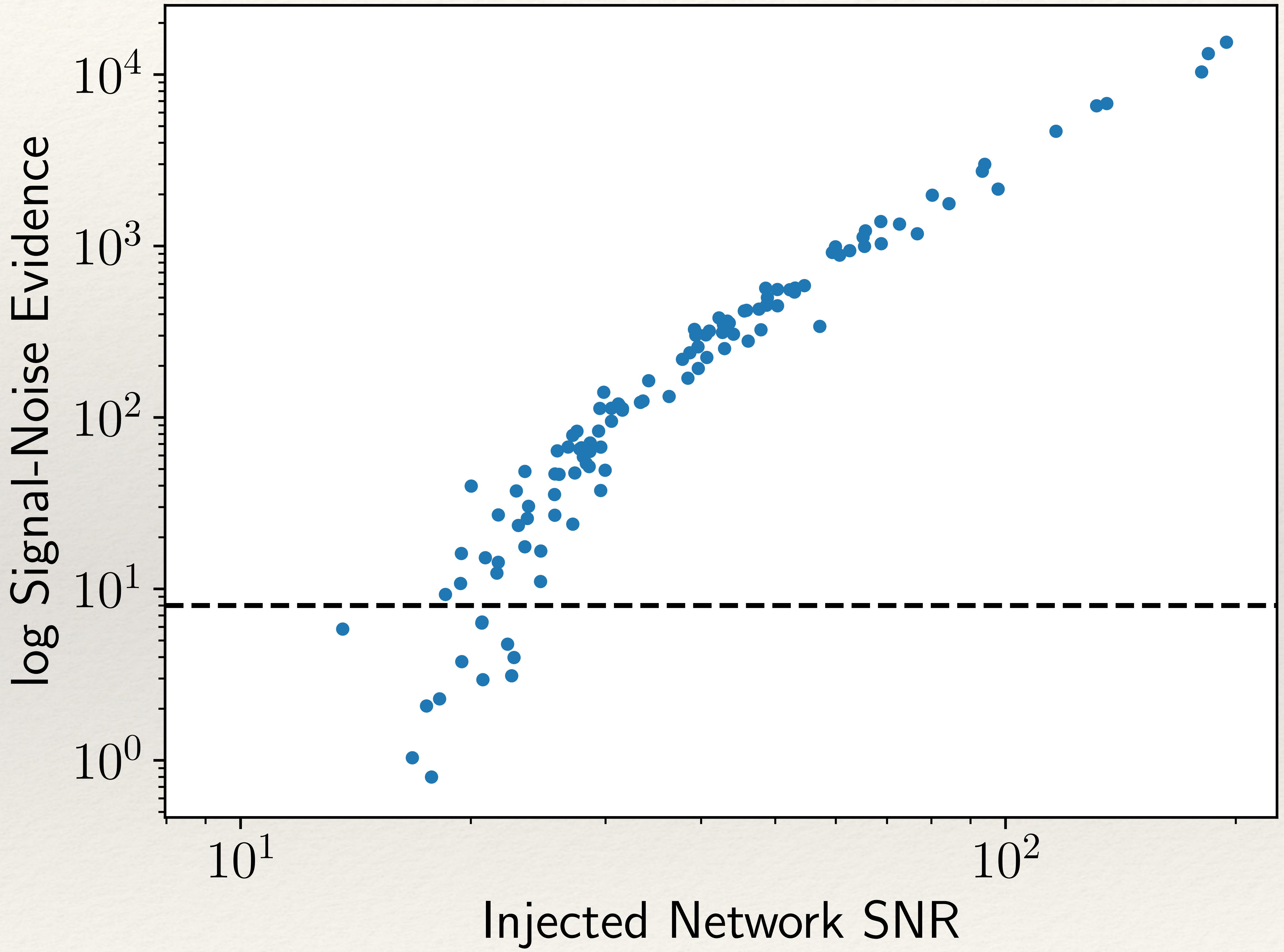
- Injected Network SNR ~ 55 (distance ~ 4 kpc)



injected signal
injected signal + noise
reconstructed signal

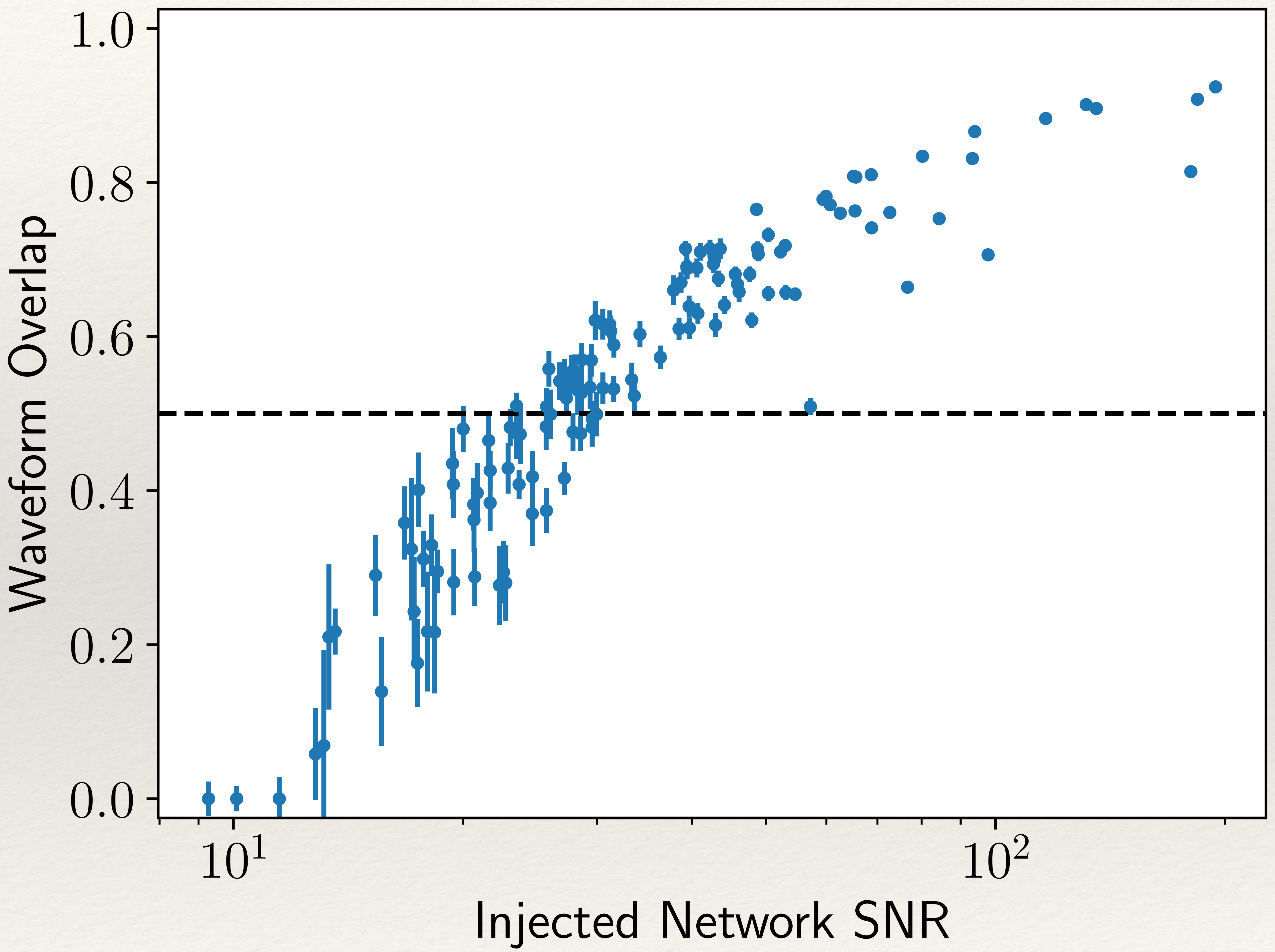
Population detection prospects

- **Signal-Noise Evidence**: Bayes factor or likelihood ratio of the signal model compared to noise given the data
- Classifying signal as confidently **detected** by BayesWave if reconstructed model log Signal-Noise Evidence > 8
- CCSN signals with $\mathrm{SNR} \gtrsim 20$ detected



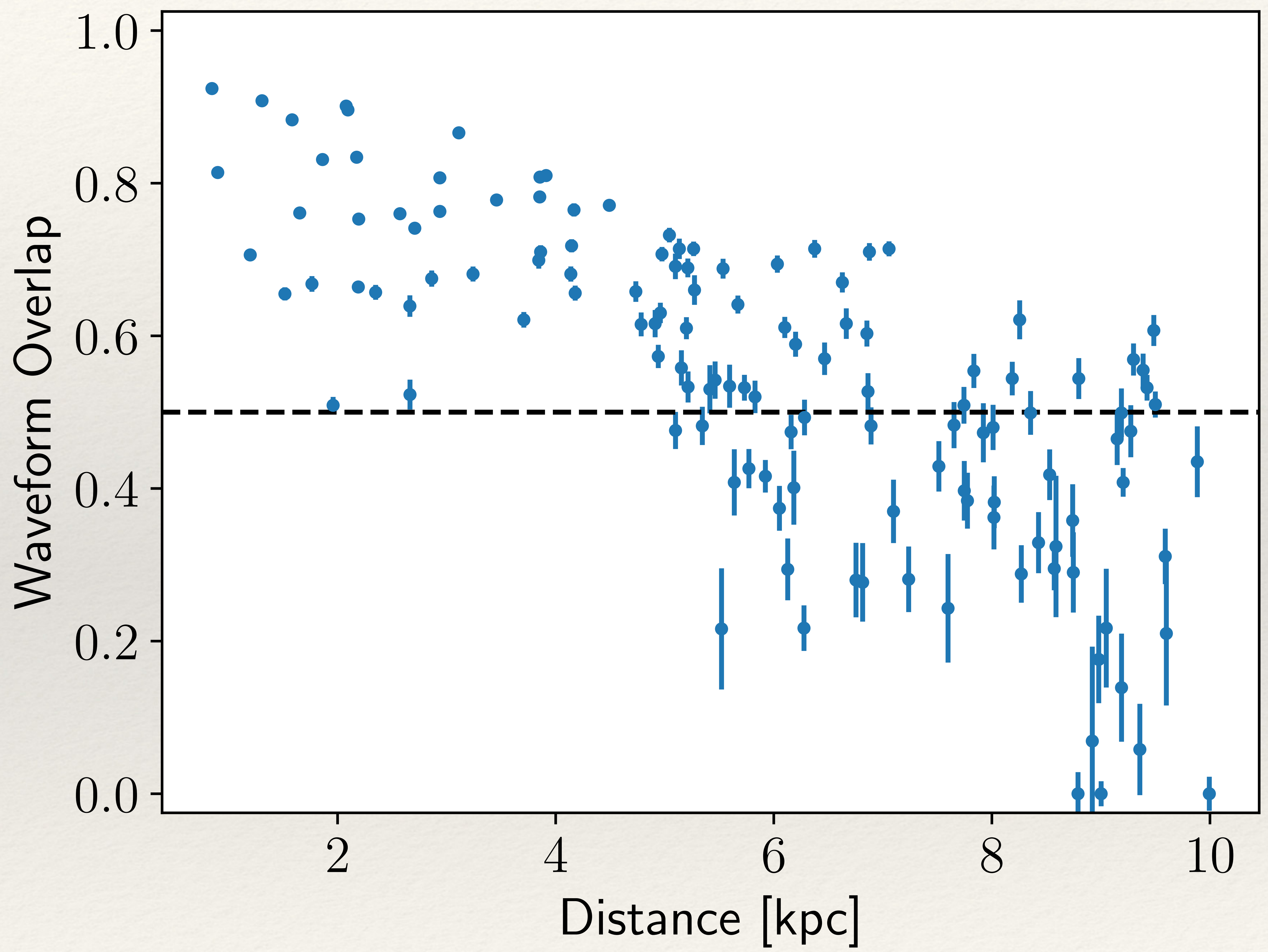
Population reconstruction prospects

- **Overlap**: normalized inner product of injected and reconstructed waveforms (characterizes quality of reconstruction)
- Classifying signal as confidently **recovered** by BayesWave if Waveform Overlap > 0.5
- Signals with $\mathrm{SNR} \gtrsim 30$ confidently recovered - loudest signals reach an overlap accuracy of $\sim 90\,\%$



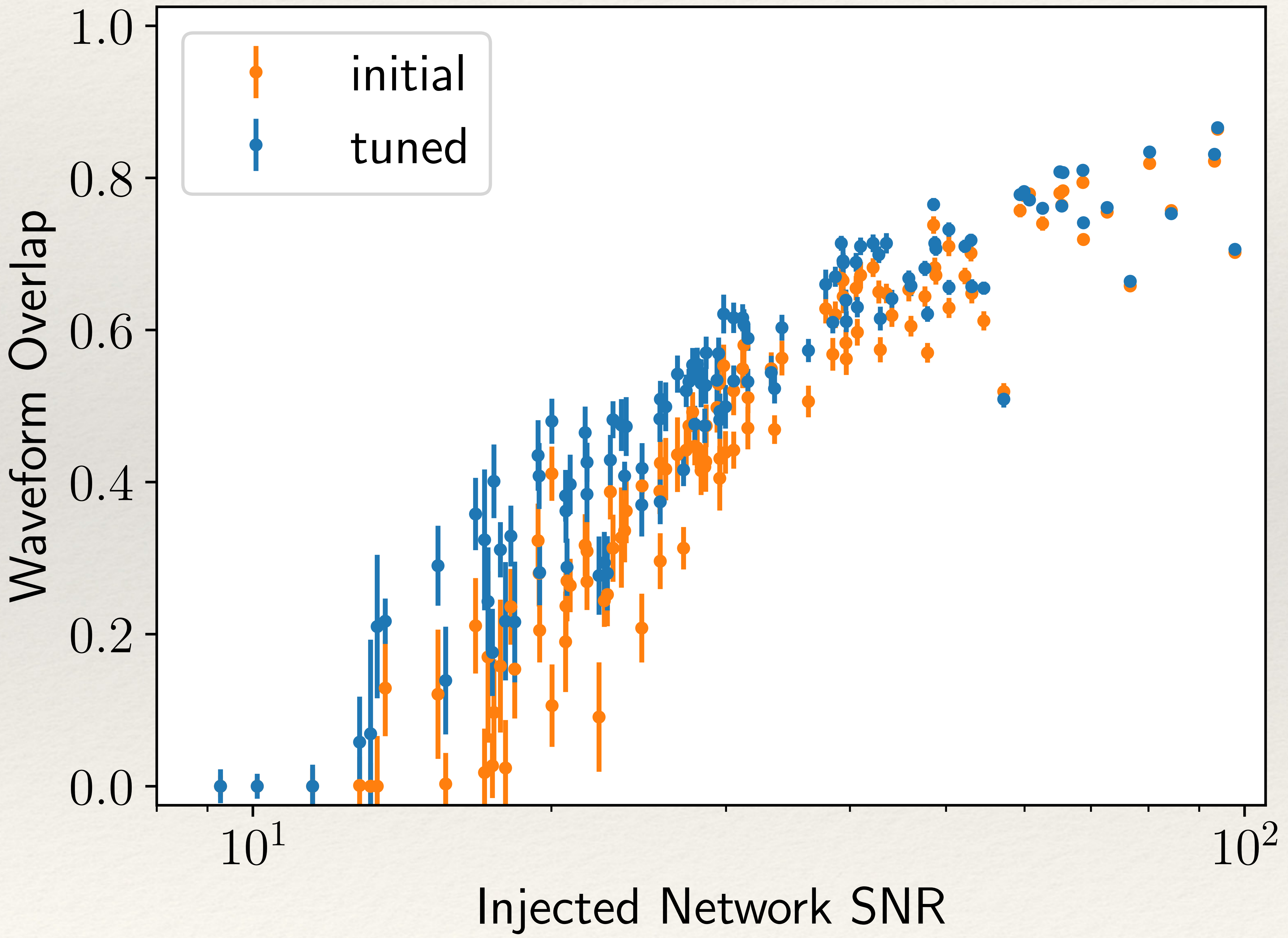
Population reconstruction prospects - distance

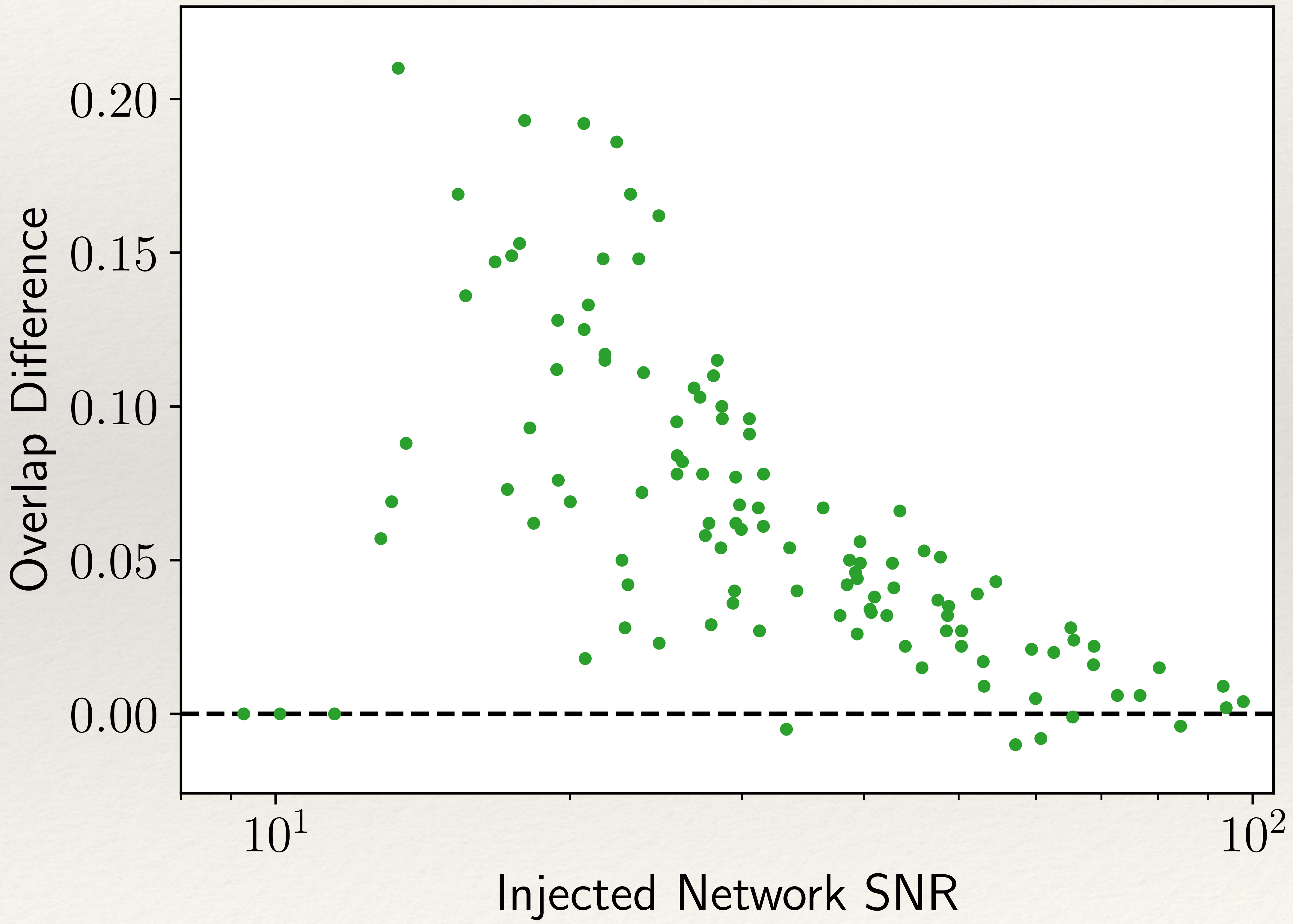
- All signals originating at Galactic distances of $\lesssim 5$ kpc are confidently recovered, and some up to ~ 10 kpc away



Reconstruction gains from tuning

- Current tuning giving up to $\sim 20\,\%$ better reconstruction overlap at lower SNR





Summary

- Can confidently detect and recover GW signals from Powell 2019 like neutrino driven supernova explosions in Advanced LIGO-Virgo for $\mathrm{SNR} \gtrsim 30$

- Correspondingly all signals originating at Galactic distances of $\lesssim 5\ \mathrm{kpc}$ are confidently recovered, and some up to $\sim 10\ \mathrm{kpc}$ away

- Tuning increases the reconstructed accuracy significantly, up to 20% for lower SNR signals - correspondingly many more events are confidently recovered

Next steps

- Relaxing polarization constraints (Cornish et al. 2021), tweaking and tuning of more BayesWave settings
- Results for other supernova models, especially stronger magneto-rotationally driven explosions
- Comparison of astrophysical features recovered between different models

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