

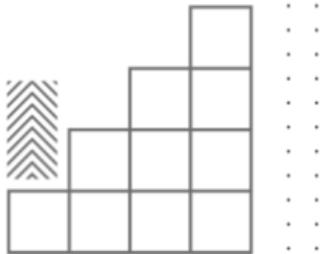
Estimating the Curvature of the CCSN GW High Frequency Feature in Interferometric Noise

Gravitational Waves and Detection Tech-
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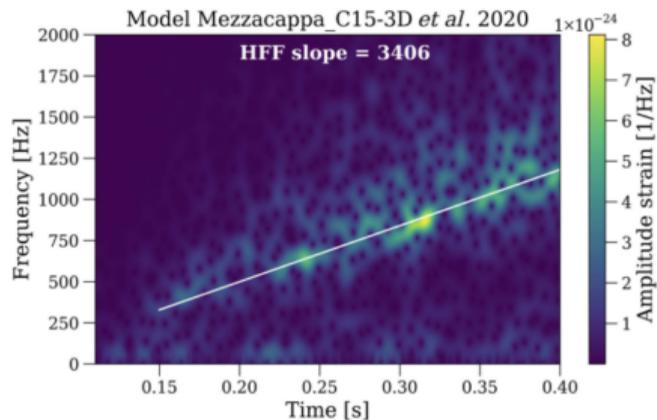
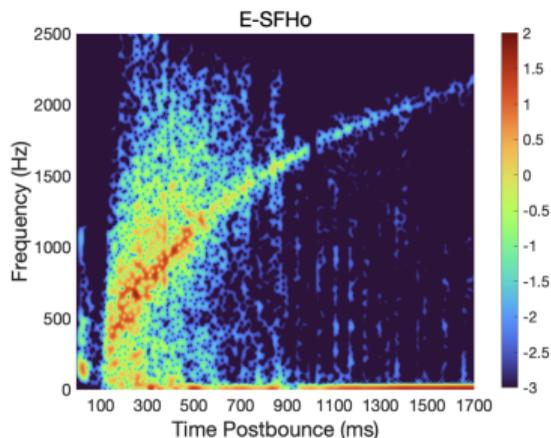
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Gravitational Waves from Core-Collapse Supernovae

- ▶ CCSN produce stochastic gravitational-wave signals.
- ▶ Several time-frequency features encode physical processes:
 - ▶ prompt convection
 - ▶ SASI
 - ▶ high-frequency feature (HFF)
- ▶ The HFF appears as an increasing frequency ridge in spectrograms.



Outline:

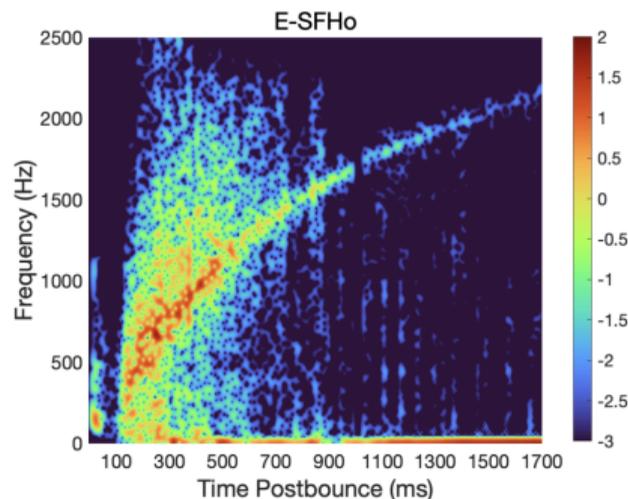
Previous papers:

<https://journals.aps.org/prd/abstract/10.1103/PhysRevD.108.084027>

<https://journals.aps.org/prd/abstract/10.1103/PhysRevD.110.083006>

<https://journals.aps.org/prd/abstract/12.1103/PhysRevD.110.083002>

In previous work, we focused on estimating the initial slope of the High-Frequency Feature (HFF), since the cWB reconstruction did not capture a sufficiently long portion of the HFF evolution. In this work, we extend the analysis by incorporating the curvature of the HFF evolution.



Goal

The HFF evolution carries information about the proto-neutron star (PNS). We would like to use it to constrain:

- ▶ Equation of state
- ▶ PNS mass
- ▶ PNS radius

1. Estimating the HFF feature using data analysis.
2. Analytical model.
3. Methodology.
4. Interpretation of the astrophysical results.
5. Parameter estimation uncertainties
6. Next steps.

Analytical Model

We model the HFF frequency evolution as

$$f(t) = f_0(1 - e^{-\alpha t})$$

- ▶ f_0 : asymptotic frequency
- ▶ α^{-1} : characteristic growth timescale

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Taylor expansion at early times:

$$f(t) \approx f_0\alpha t - \frac{1}{2}f_0\alpha^2 t^2$$

- ▶ initial slope: $df/dt = f_0\alpha$
- ▶ curvature: $d^2f/dt^2 = -f_0\alpha^2$

Methodology: cWB-XP wavescan

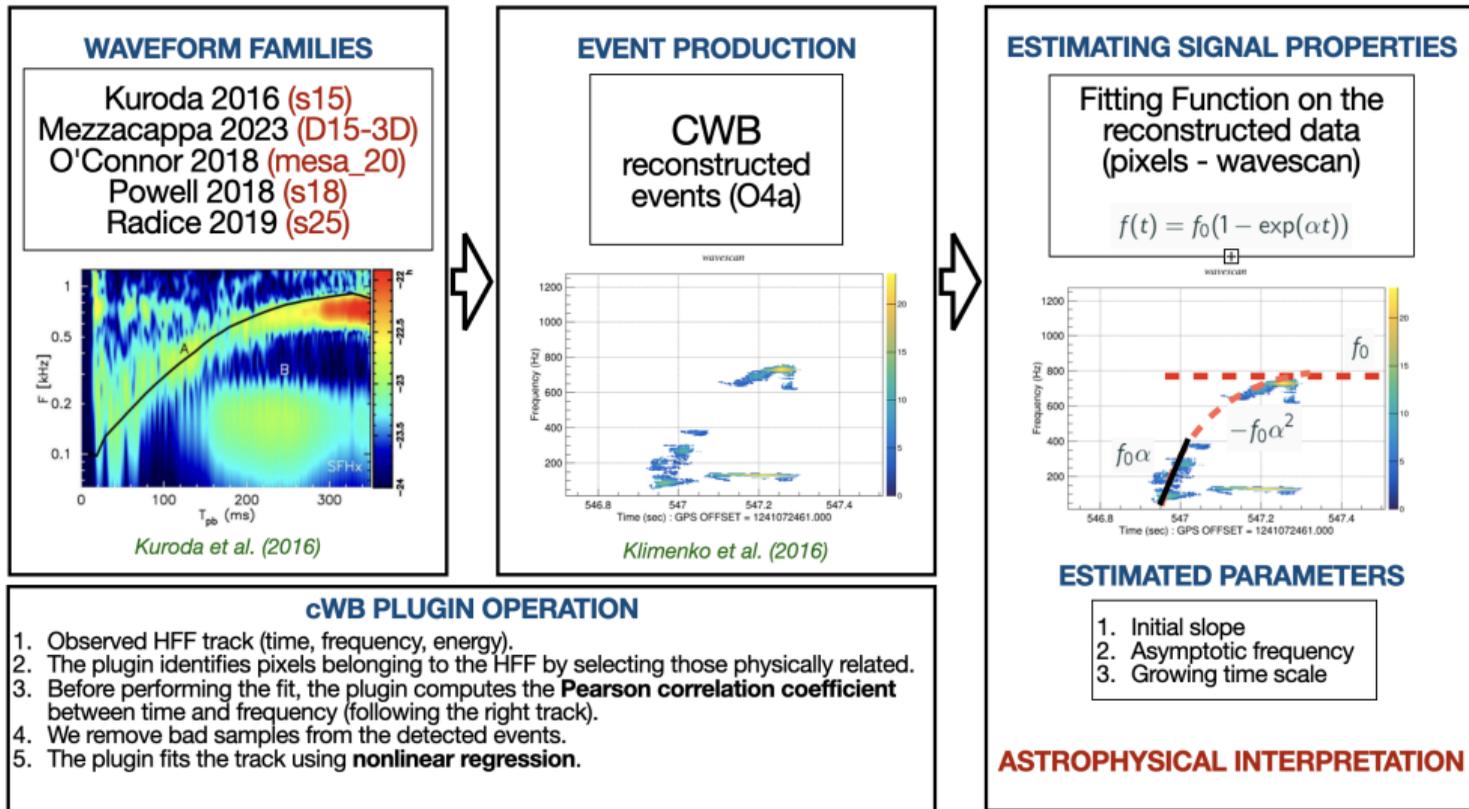


Figure: Operation steps implemented to extract from cWB-XP reconstructed events.

Waveform families and their physical properties

Waveform Family	Identifier	EOS	M_{ZAMS}	f_{peak} (Hz)	Simulation duration
Mezzacappa et al. 2020	D15-3D	LS220/CHIMERA	15	718	420
Kuroda et al. 2016	SFHx	SFHx/3D-GR	15	1064	350
O'Connor – Couch 2018	mesa20_pert	SFHo/FLASH	20	1033	530
Powell – Müller 2019	s18_3d	LS220/CoCoNuT-FMT	18	872	890
Radice et al. 2019	s25	SFHo/FORNAX	25	1132	600

The frequency f_{peak} at which the GW energy spectrum peaks, the emitted GW energy EGW and approximate signal duration ([Szczepańczyk et al. \(2023\)](#)).

Model label	Dim.	Progenitor/series	Rot.	EOS	Sim. reference
Radice–s25	2D/3D	WH / Woosley–Heger	No	SFHo	Radice et al. (2019)
Kuroda–s15	3D	WH / Woosley	No	SFHx	Kuroda et al. (2016)
Powell–s18_3d	3D	WH / Woosley	No	LS220	Powell & Müller (2019)
mesa20_pert	2D/3D	MESA progenitor	No	SFHo	Burrows et al. (2020)
Mezzacappa–D15–3D	3D	MESA D-series	No	SFHo	Mezzacappa et al. (2023)

Map of viable equations of state from nuclear physics

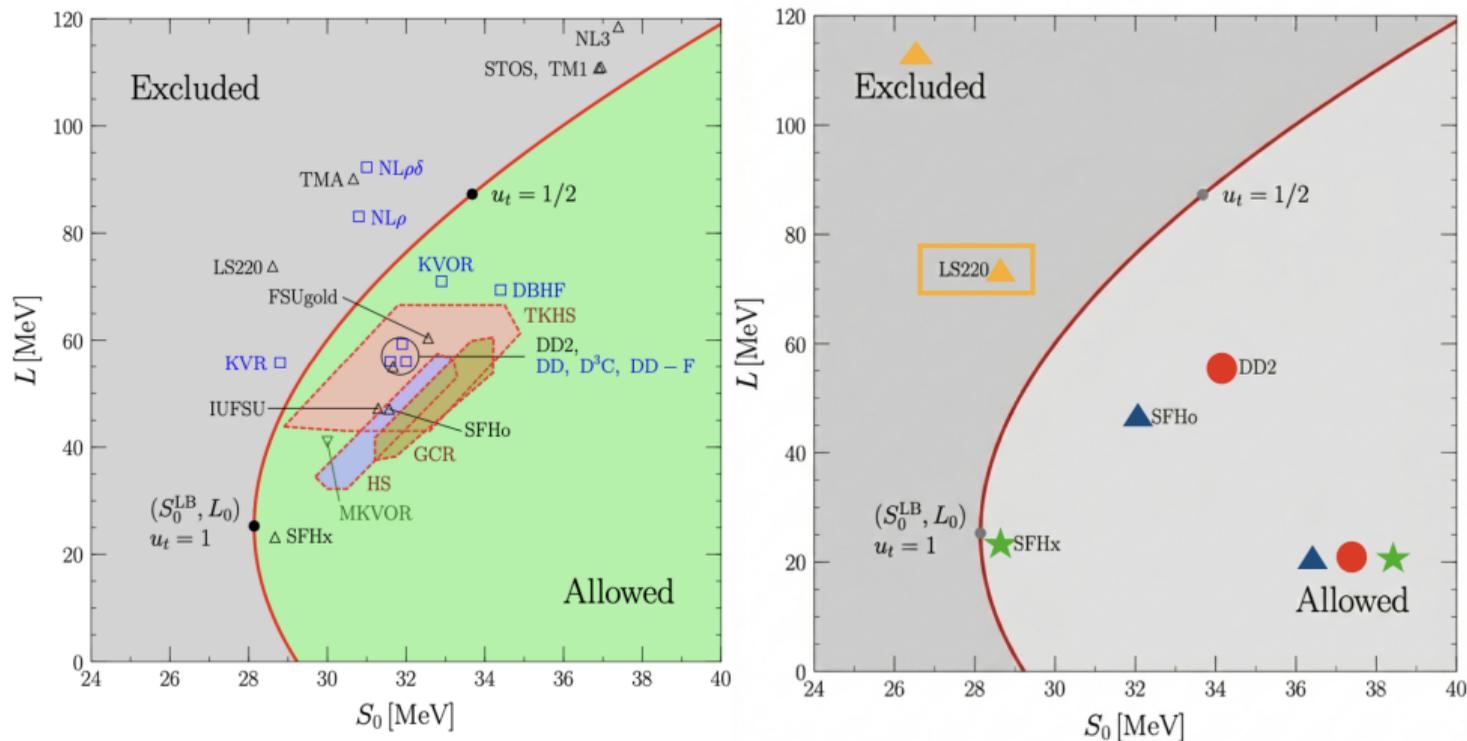


Figure: The EOS used in the CCSN waveform catalog span a region of the nuclear symmetry energy parameter space (L, S) . (Tews et al. 2017).

Results: Asymptotic frequency and time scale factor

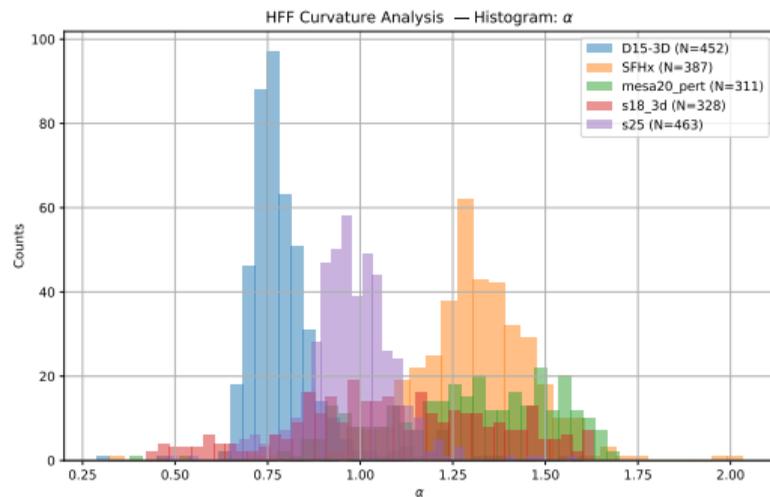
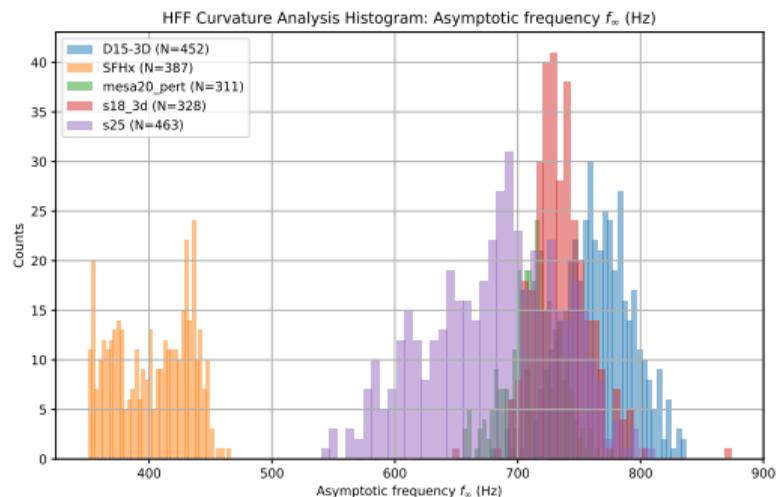


Figure: Distribution of estimated asymptotic frequencies and characteristic growth timescales for the HFF. The data set spans an SNR range of 8 to 25 per model, illustrating the reconstruction accuracy and parameter variance across the sampled population.

Results: Initial slope and curvature

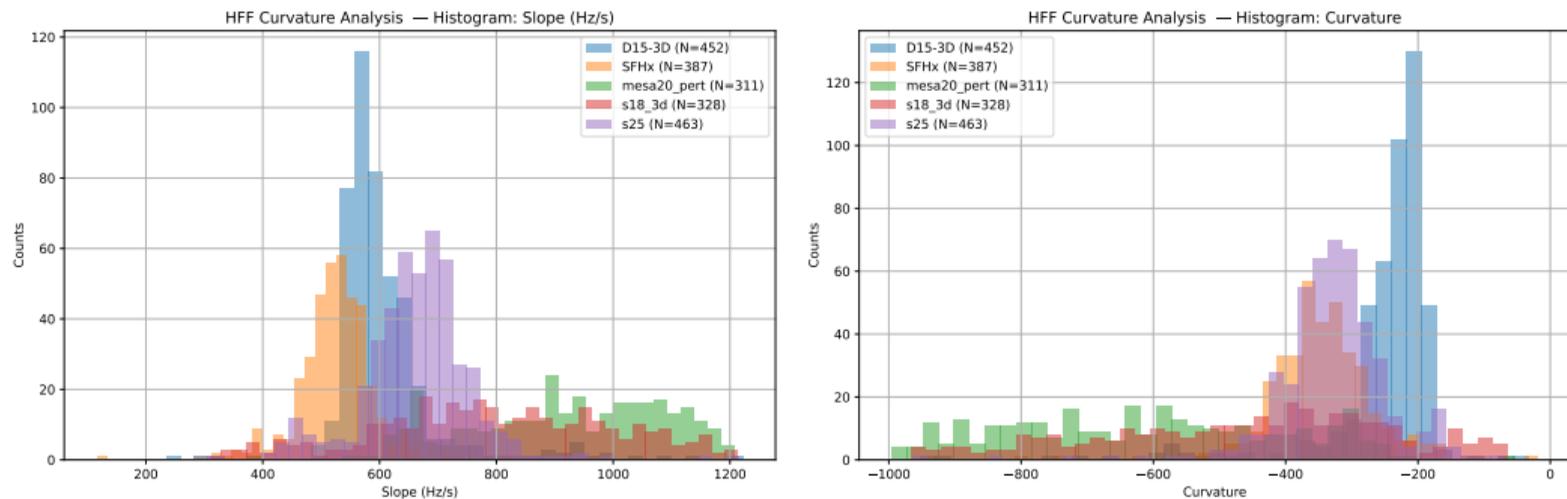


Figure: Distribution of estimated initial slope and curvature for the HFF. The data set spans an SNR range of 8 to 25 per model, illustrating the reconstruction accuracy and parameter variance across the sampled population.

Astrophysical interpretation

Pioneering work on PNS modal analyses was first conducted using perturbations of a spherically symmetric background , (Torres-Forné et al. 2018-2019).

Caveats

- ▶ Two-dimensional analyses characterize the HFF as either a low-order 2g -mode or a 2f -mode (Torres-Forné et al. 2018-2019).
- ▶ Some studies find the HFF transitions from an initial low-order 2g -mode to a fundamental 2f -mode. (Sotani et al. (2020))(Morozova et al (2018))
- ▶ Mode assignment for the emission often depends on the specific modal classification framework employed. (Rodriguez et al. (2023)) (Cowling et al. (1941))
- ▶ **This ambiguity affects HFF polynomial fits based on surface gravity or mean density; notably, g -mode peak frequencies are fundamentally tied to the source's surface gravity.** (Murphy et al. (2025), Mezzacappa et al. (2023))

Results: Curvature estimated parameters

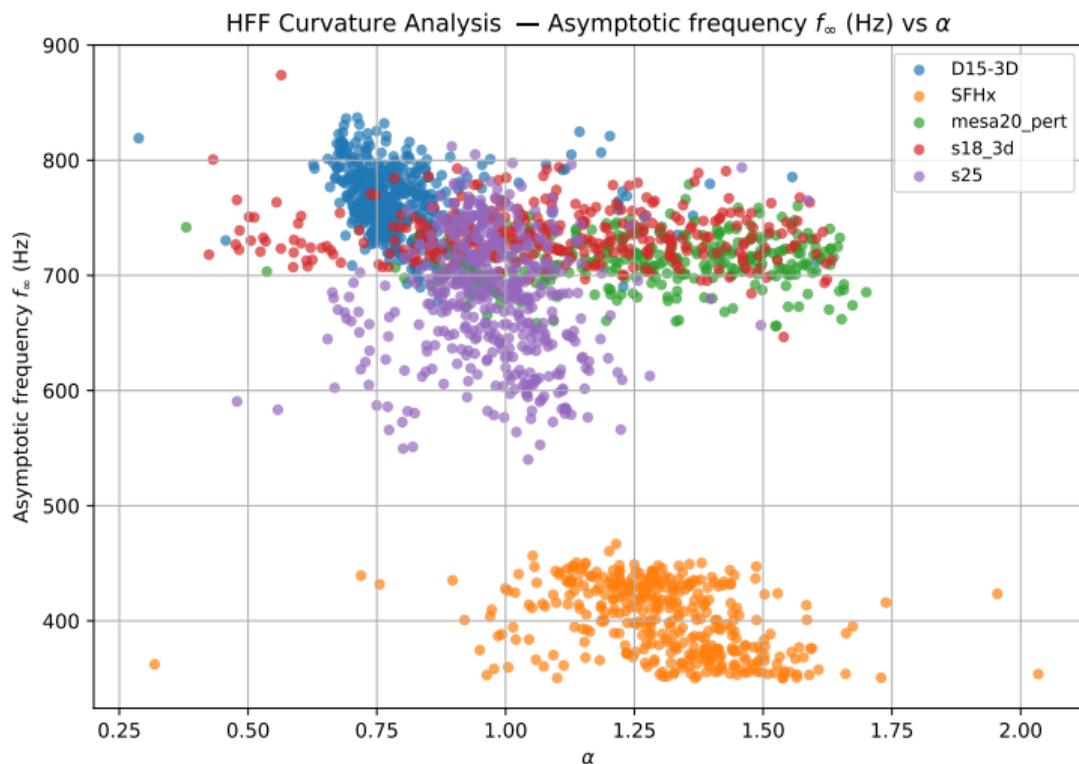


Figure: Scatter plot of the signal asymptotic frequency versus growth timescale across all models. This distribution illustrates the physical correlation between the initial rise of the HFF 12 / 18

Results: Initial slope correlations

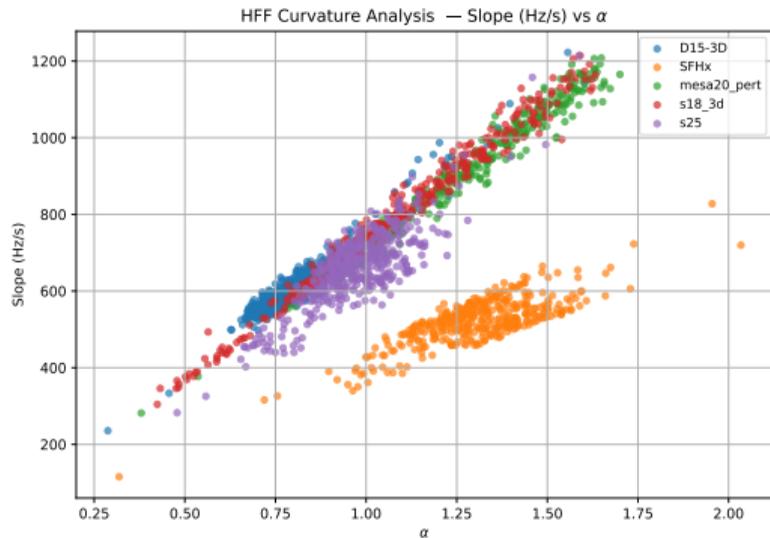
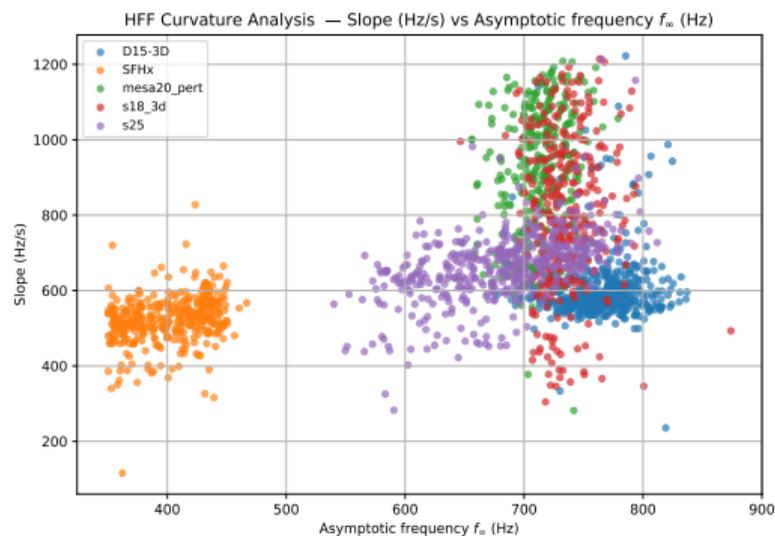


Figure: Scatter plot of the signal slope versus asymptotic frequency and growth timescale across all models. This distribution illustrates the physical correlation between the initial rise of the HFF and its asymptotic stabilization.

Results: Curvature correlations

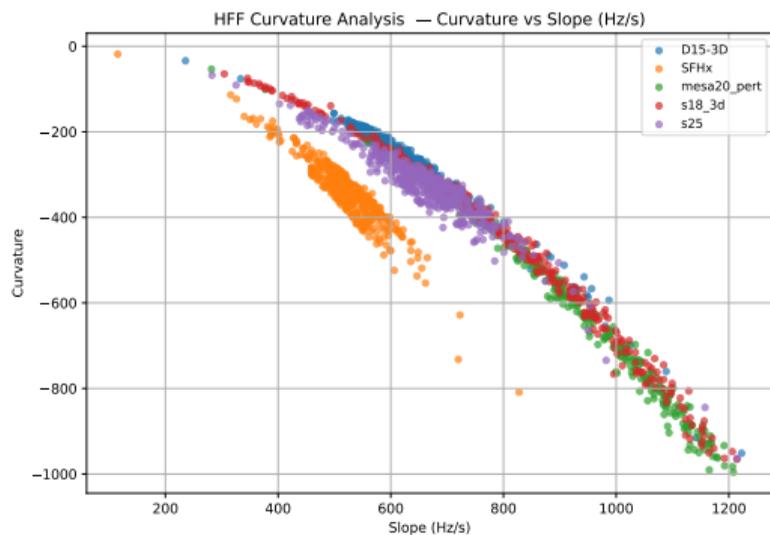
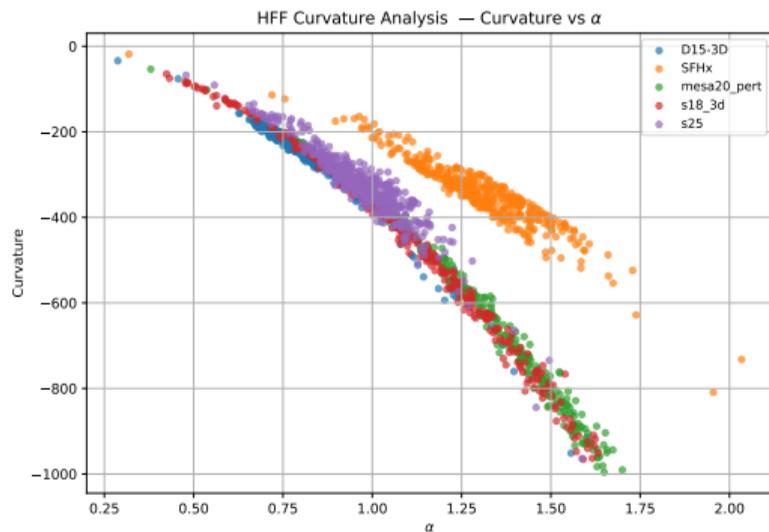
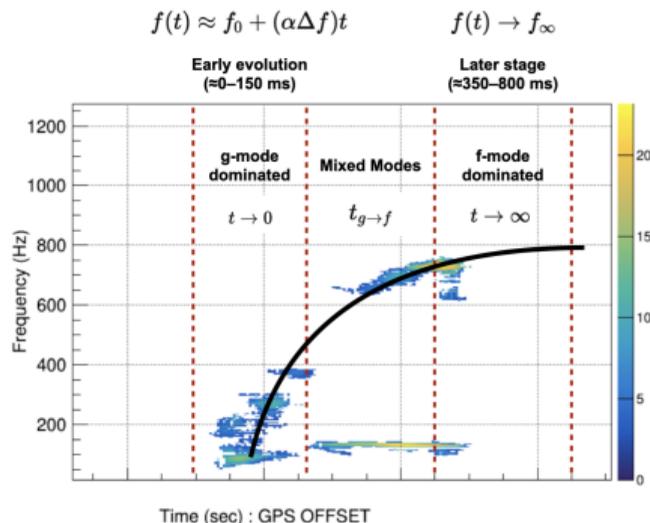


Figure: Scatter plot of the curvature vs asymptotic frequency and time scale factor per model..

Conclusions and prospects:

1. Methodology independent of the mode switching.
2. Enlarging the number of estimated parameters provides new tools for astrophysical interpretation.



Our fit extracts information from the **two extremes of the signal**.

3. Astrophysical parameters estimation by splitting the physics?
4. For the paper: The waveform families will be enlarge including all models available to the date.

THANK YOU!

Distribution of effective pixels for estimating curvature according to the EOS

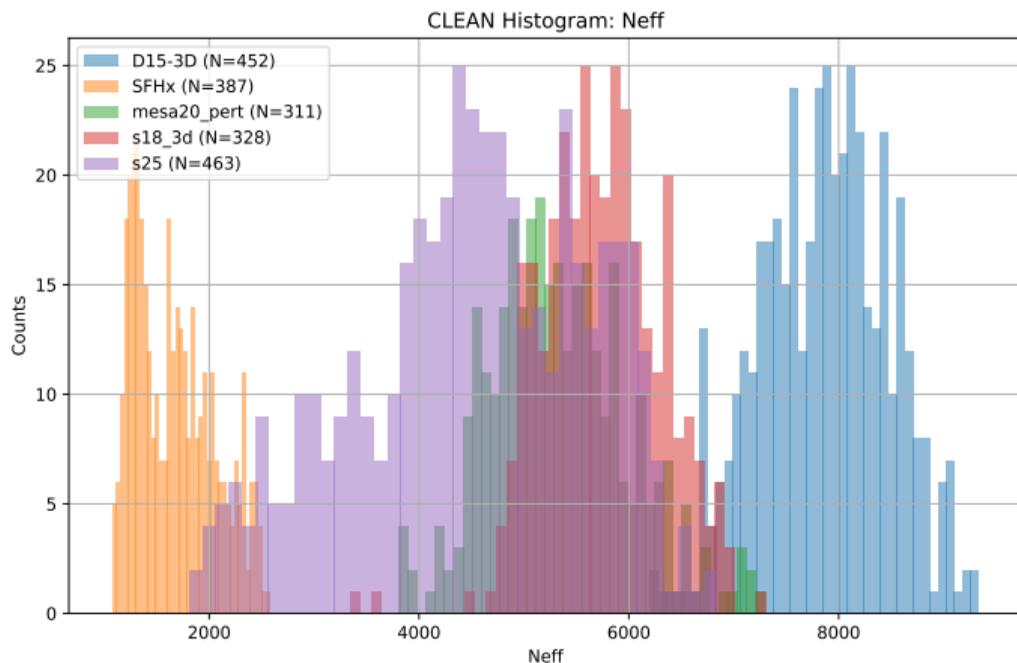


Figure: Distribution of estimated pixels for each EOS.

RESULTS

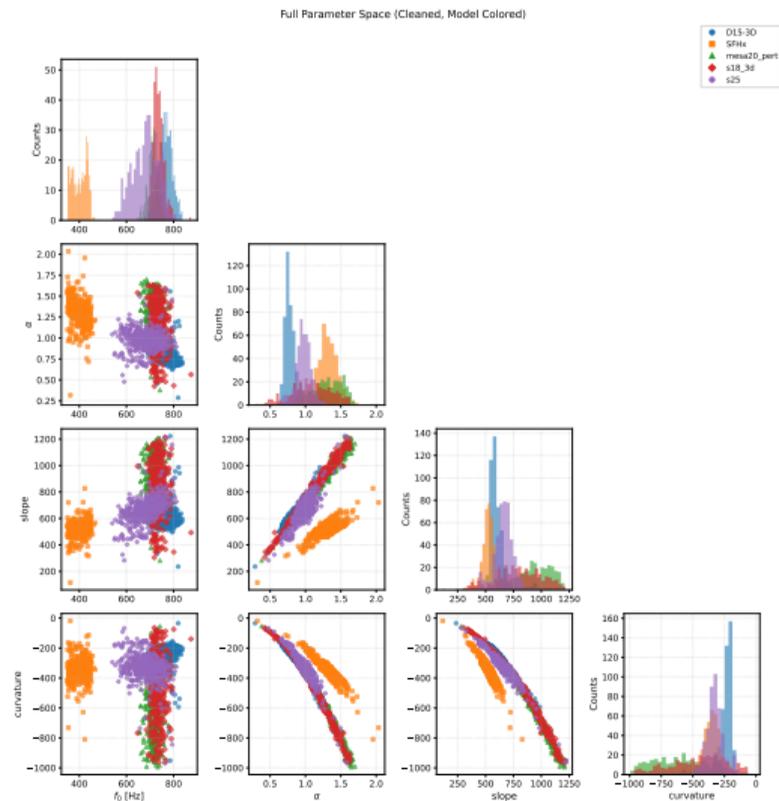


Figure: A CCSN GW HFF parameter space.