Detectability and Reconstruction of the Standing Accretion Shock Instability: New results with cWB XP

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SN2025gw - First IGWN Symposium on CCSe GW Theory and Detection

SASI and Gravitational Waves

What have we learned this week?

- SASI oscillations emit GWs at f $\lesssim 200$ Hz (Mezzacappa et al., 2020; Kuroda et al., 2017; Andresen et al., 2017).
- SASI is a great multimessenger source: neutrino and GW emission (Lin et al., 2023; Drago et al., 2023).
- SASImeter: a pipeline for neutrino and GW SASI parameter estimation (Lin et al., 2023).

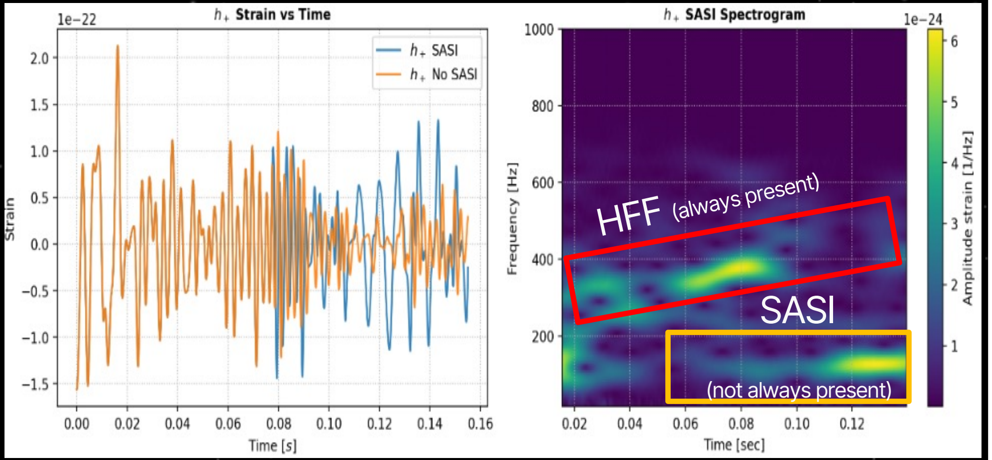


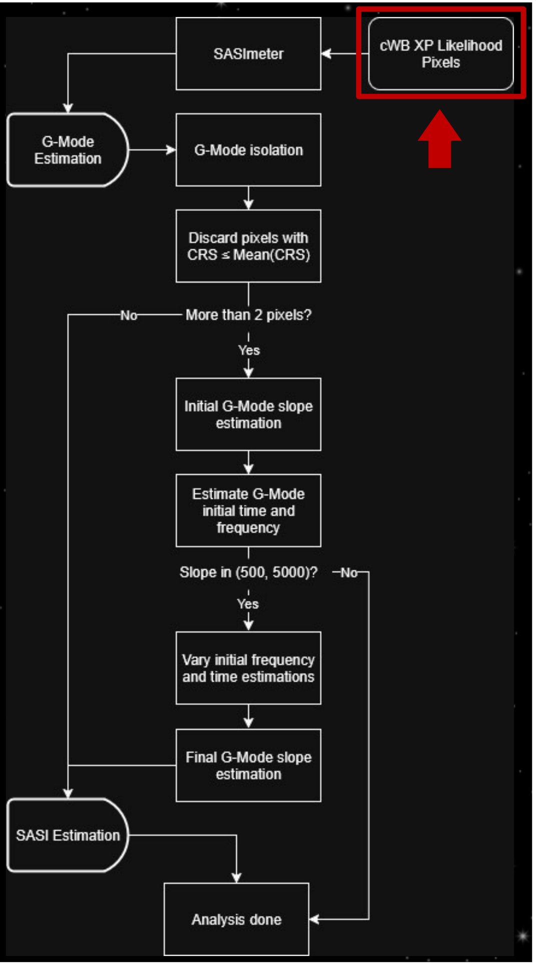
Figure 1. Kuroda 2017 s15 gravitational wave signal.

From *Correlated Signatures of Gravitational-Wave and Neutrino Emission in Three-Dimensional General-Relativistic Core-Collapse Supernova Simulations*. Kuroda et al., 2017.

How SASImeter works

cWB XP Trigger Generation

- We use cWB reconstructions of GW events.
- SASImeter is a pluggin using event wavelet components (pixels).
- cWB XP reduces spectral leakage. See Sergey Klimenko presentation.



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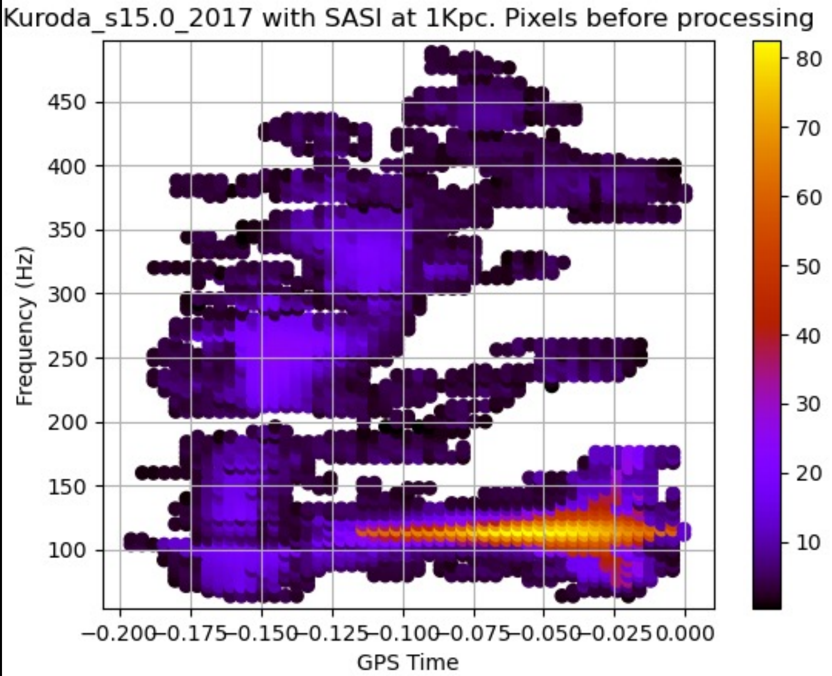
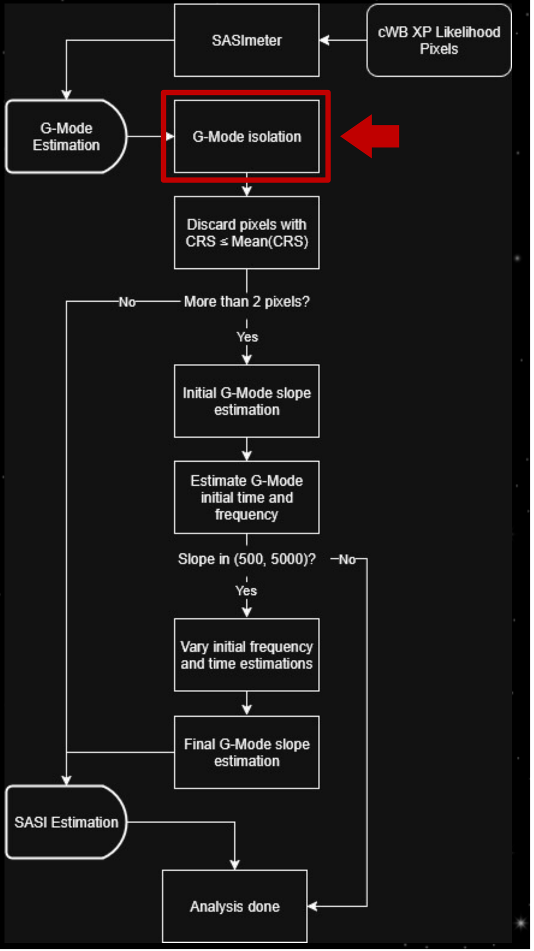


Figure 2. cWB pixel reconstruction for Kuroda2017 s15 at 1 Kpc.

How SASImeter works

G-Mode Estimation

1. **Assumption: SASI is located at f ≤ 200 Hz; pixels below this f are removed.**
2. Mean Cross-power Root Square (CRS) is obtained. Pixels with CRS ≤ Mean(CRS) are removed..
3. Perform an initial estimation of the G-mode slope to first order via least square linear regression.



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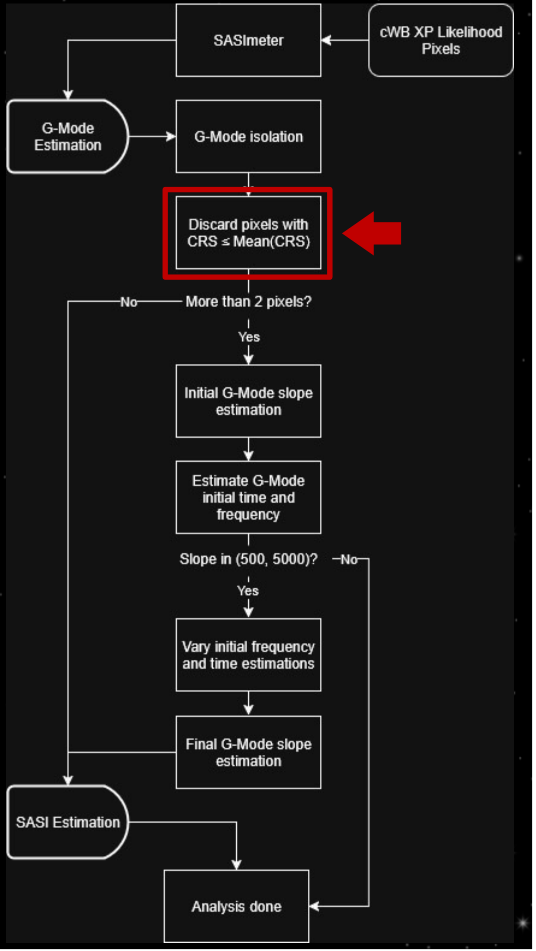

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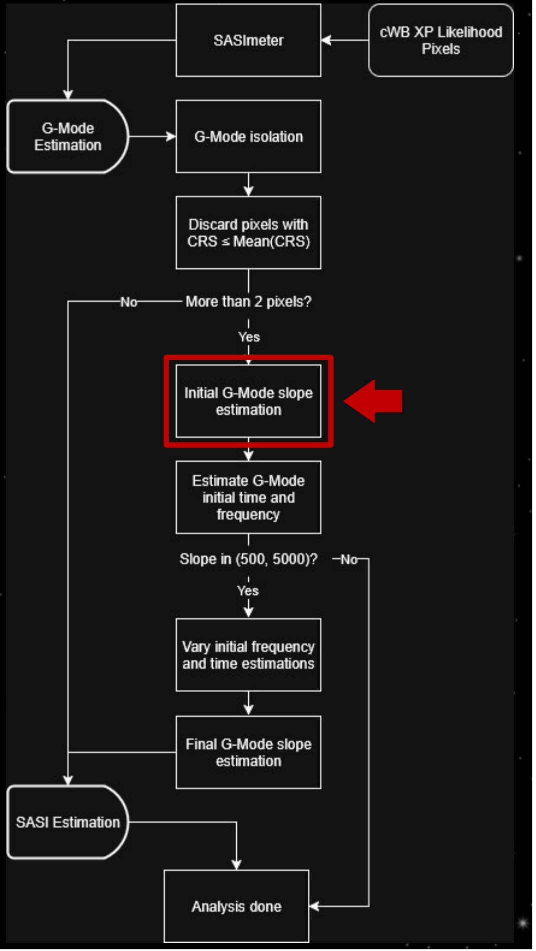

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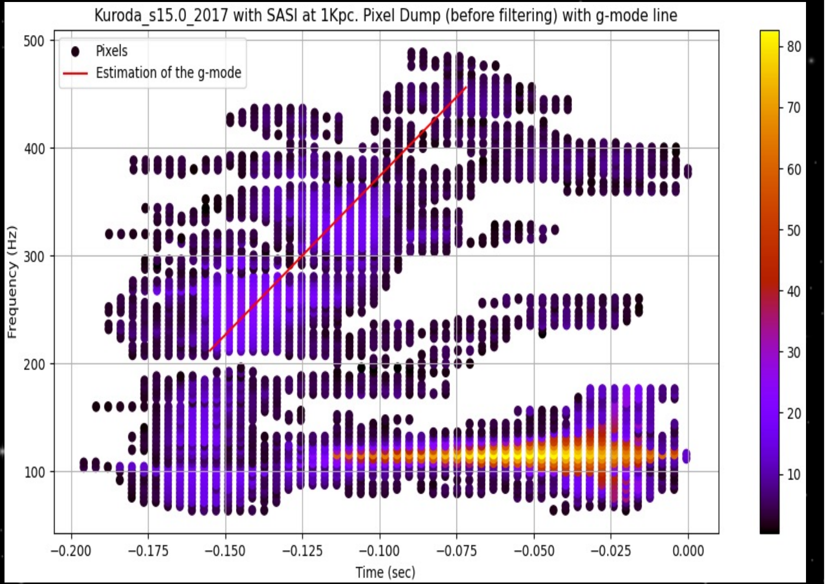

Figure 3. SASImeter G-mode slope estimation for Kuroda2017 s15 at 1 Kpc.

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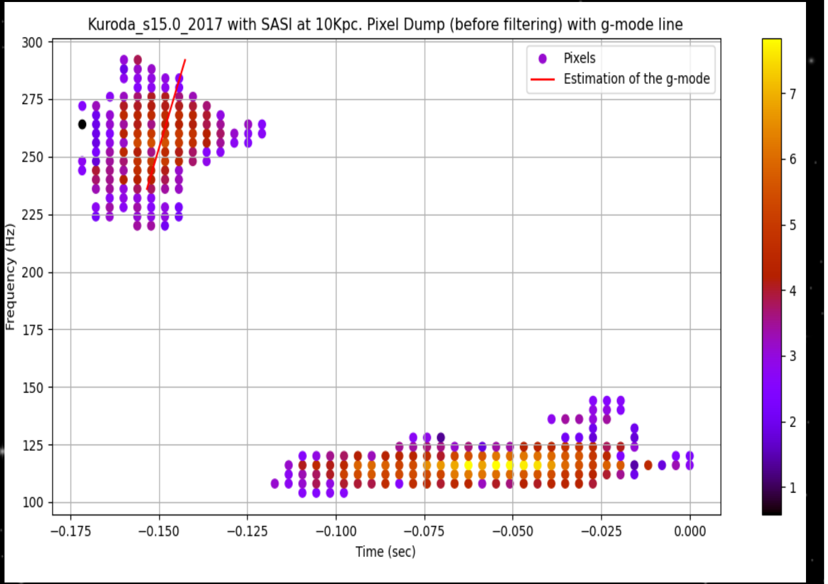


Figure 4. SASImeter G-mode slope estimation for Kuroda2017 s15 at 10 Kpc.

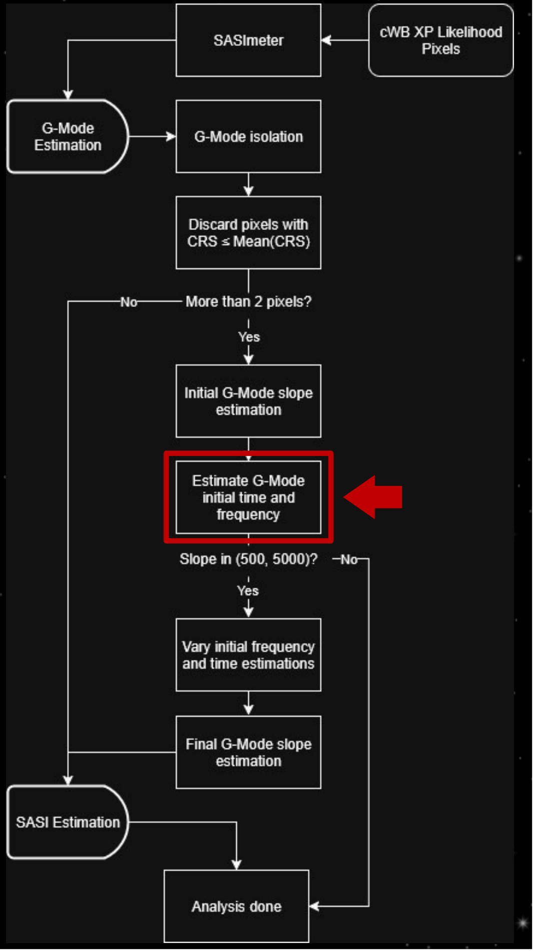
How SASImeter works

G-Mode Estimation

4. **Use slope estimation to obtain the G-mode initial time and frequency.**

    4.1 If the slope is not in the physically acceptable range, the event is discarded from the analysis.

    4.2 If the slope is in the physically acceptable range, initial slope and frequency estimates are varied 33% to generate 200 samples.



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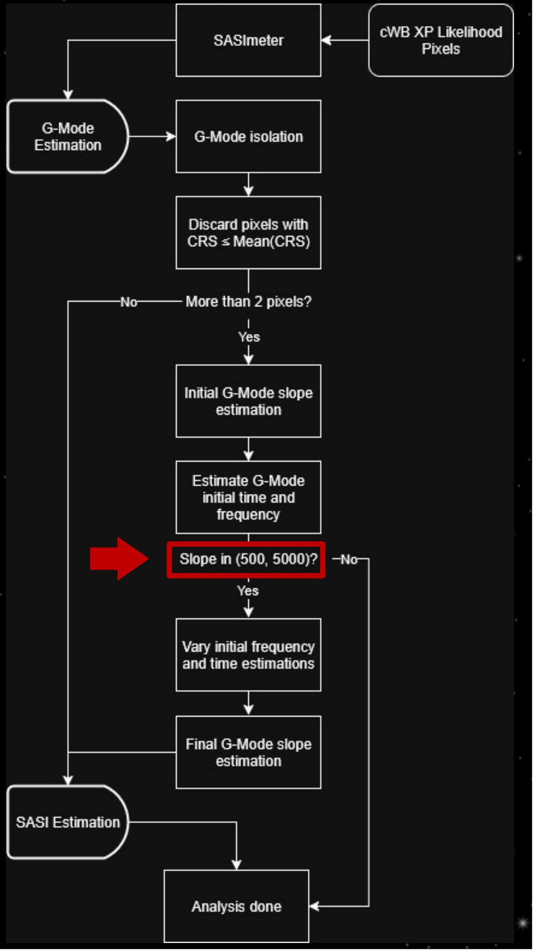

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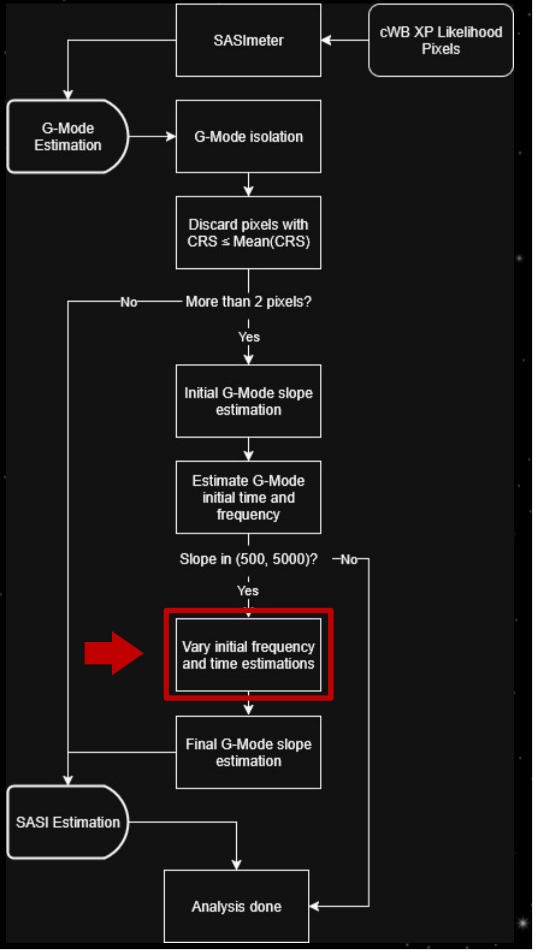


How SASImeter works

G-Mode Estimation

5. Estimate the g-mode slope by minimizing

$$\chi^2 = \sum_i \rho^i (f_c^i)^2 \Xi^i \left[t_c^i - \frac{f_c^i - c}{m} \right]^2$$

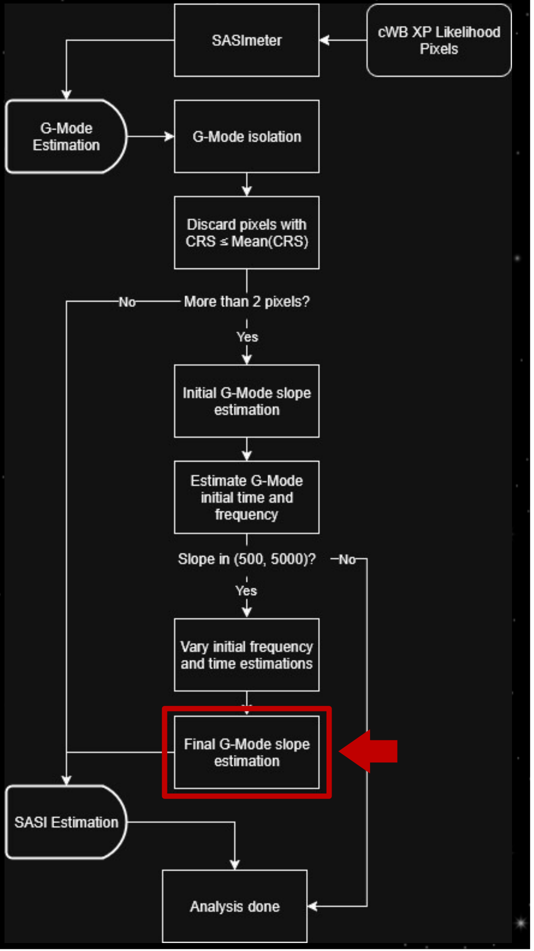
c, m: intercept and slope.

t_c^i, f_c^i: time and frequency of the i-th pixel.

ρ^i: CRS of the i-th pixel.

f_c^i: weight function to compensate for the detectors noise curve.

Ξ^i: density of pixels around the i-th pixel.



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Crude, but fast and sufficiently accurate!

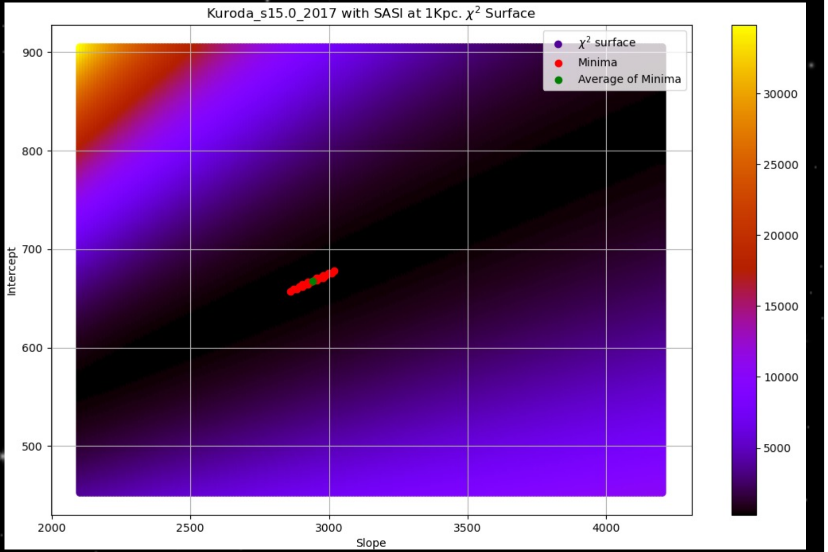


Figure 5. χ^2 surface minimization for Kuroda2017 s15 at 1 Kpc.

How SASImeter works

SASI Estimation

1. Select pixels with $f < 200$ Hz and $t > 50$ ms after the initial time of the G-mode.

2. Select pixels with CRS values greater than $\frac{Max(All\ CRS\ values)}{2}$.

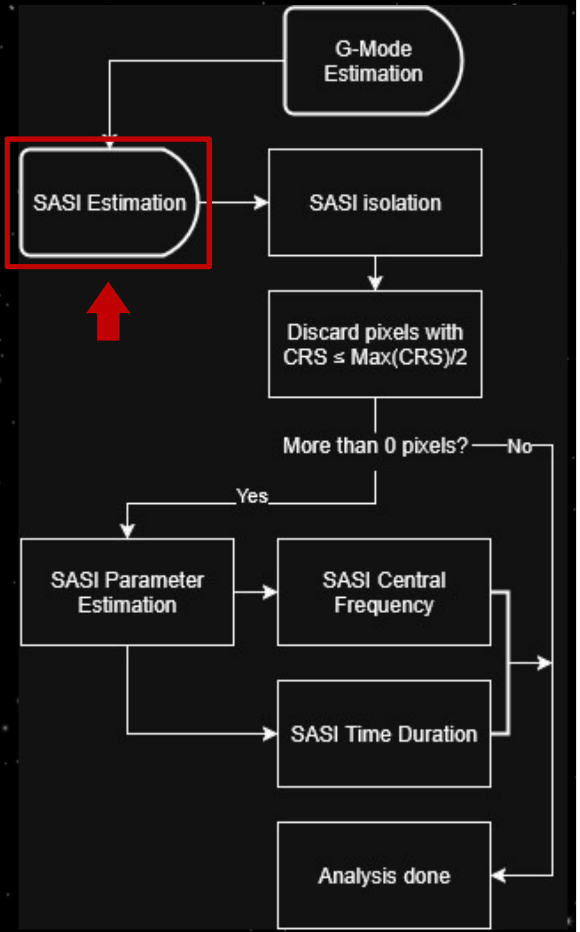
3. Estimate SASI parameters.

   3.1 SASI Central Frequency:

$$f_{\mathrm{SASI}} = \frac{\sum_{i\in \mathrm{SASI}} \rho^i f_c^i}{\sum_{i\in \mathrm{SASI}} \rho^i}$$

   3.2 SASI Time Duration:

$$\tau_{\mathrm{SASI}} = \left(t_{\max} + \frac{\delta t_{\max}}{2}\right) - \left(t_{\min} + \frac{\delta t_{\min}}{2}\right)$$



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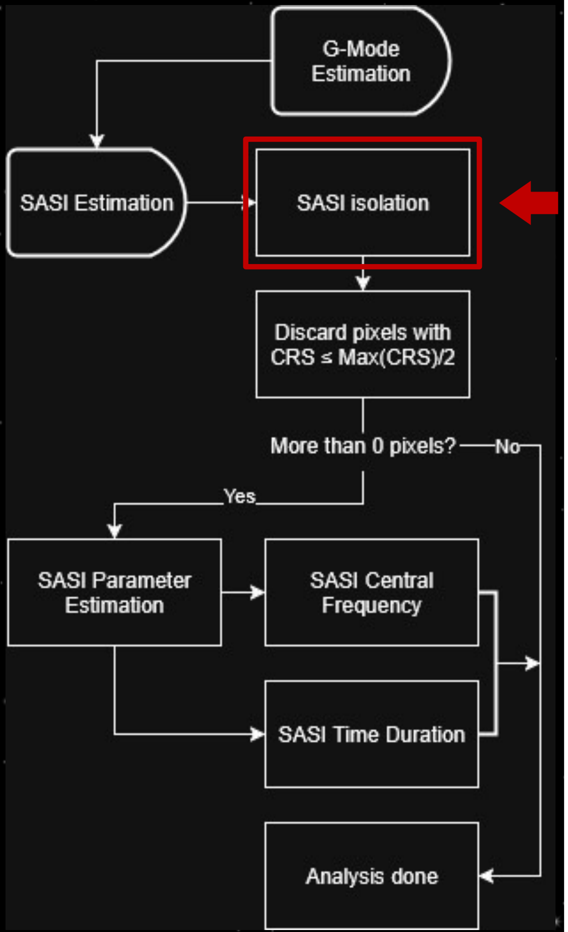

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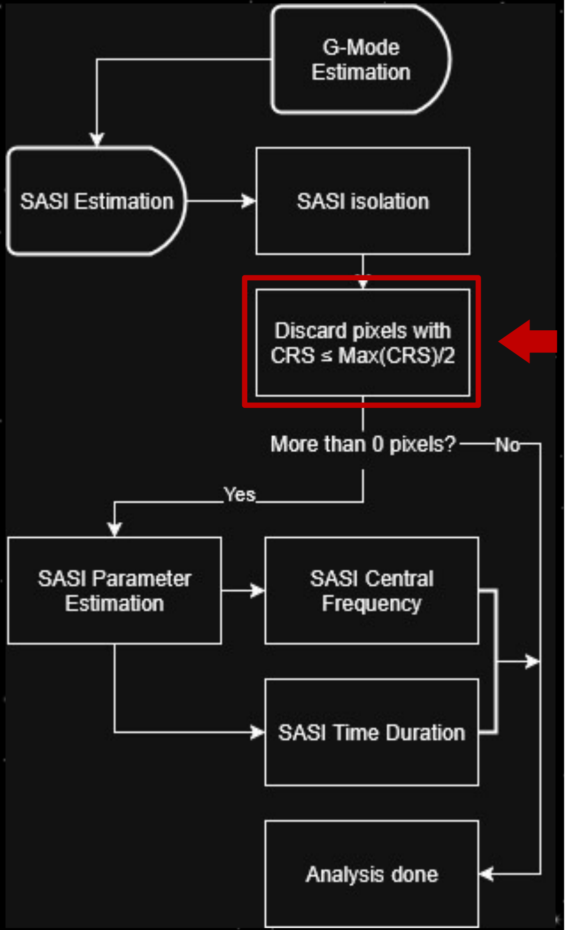

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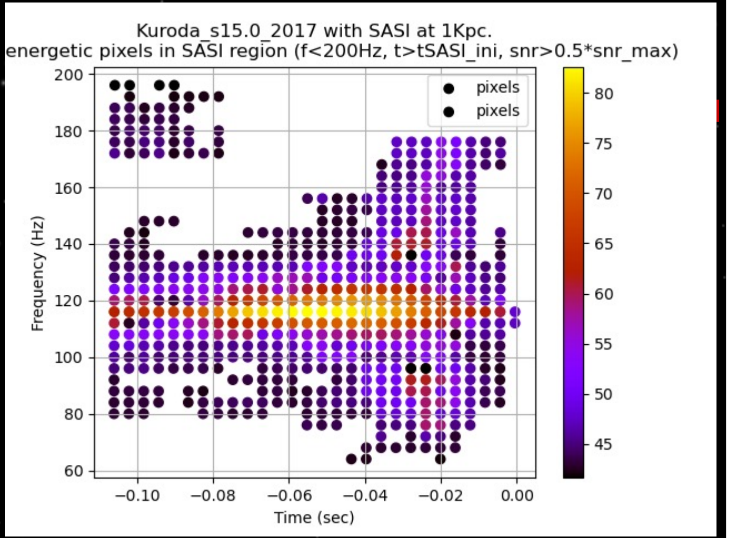

Figure 6. Pixels in the SASI region for Kuroda2017 s15 at 1 Kpc.

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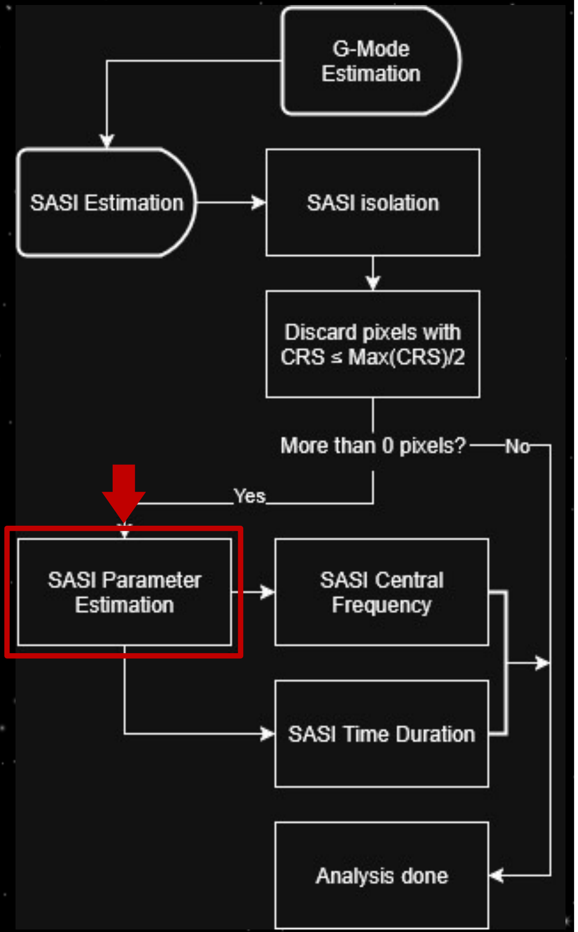

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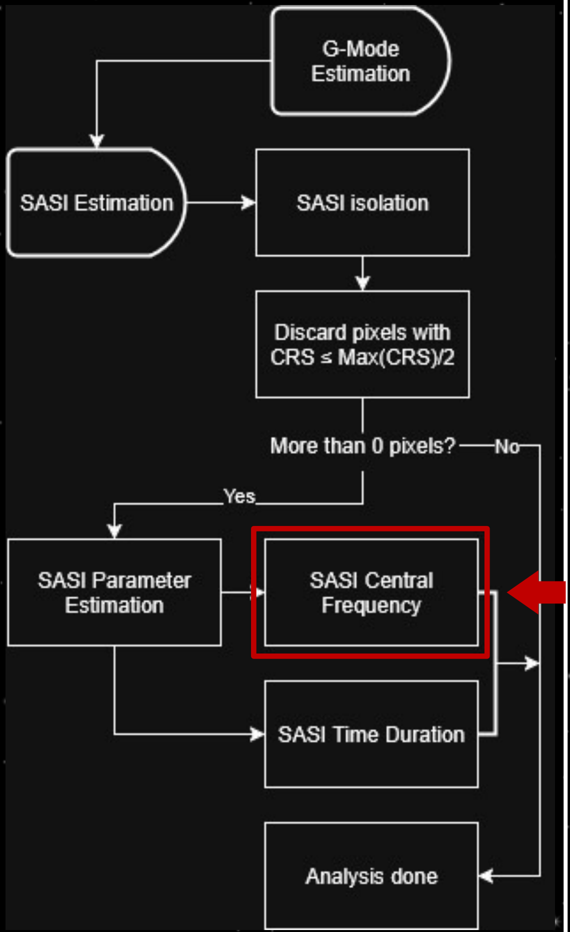

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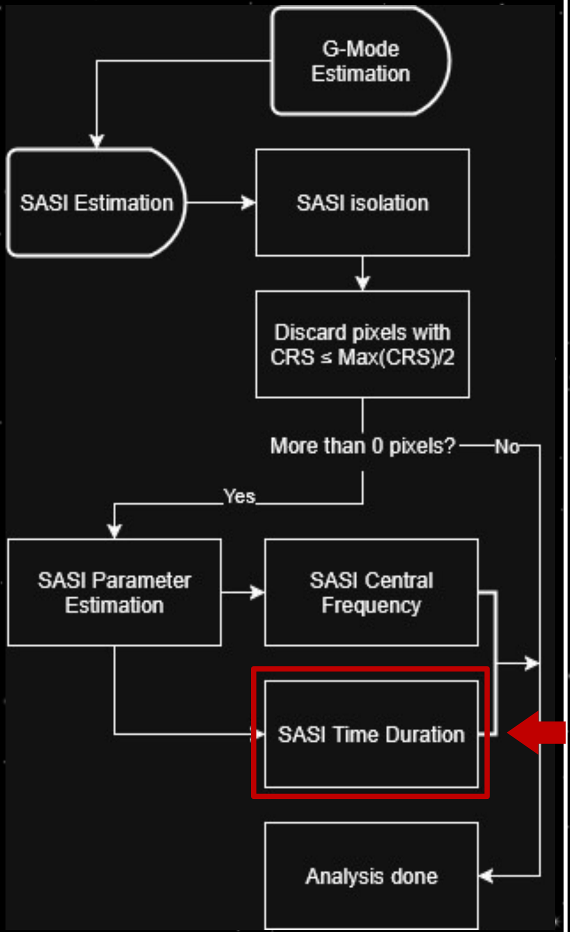

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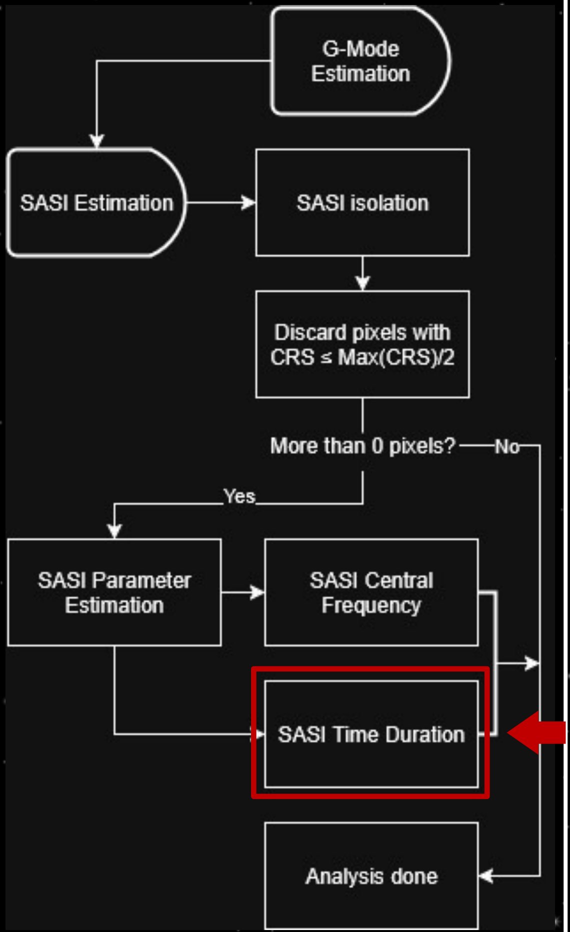

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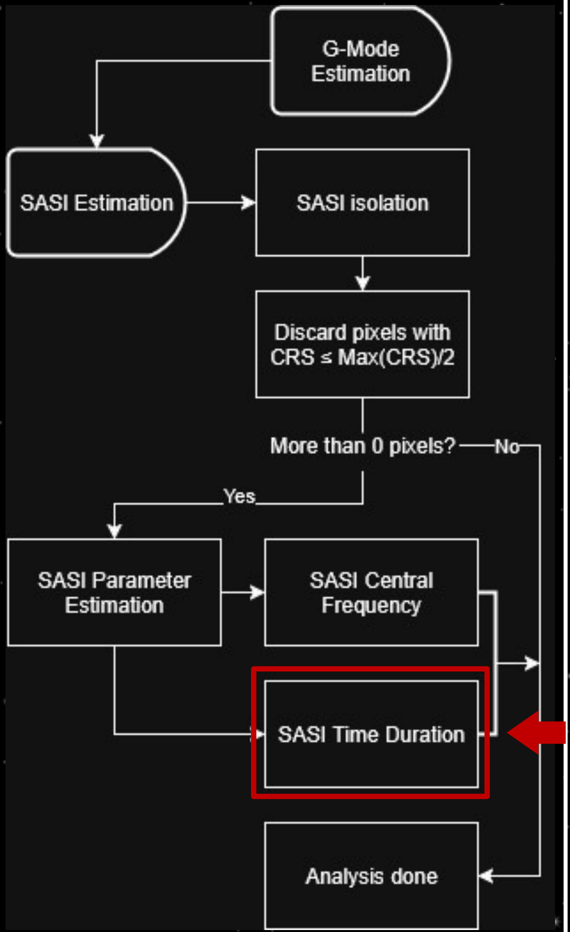
   3.2 SASI Time Duration (next implementation):

$$\tau_{\text{SASI}} = t \in (0.05 \cdot CRS, 0.95 \cdot CRS)$$



SASImeter Results

Kuroda 2017 S15 on O3 Data

Central Frequency	cWB 2G		cWB XP	
	Mean (Hz)	Std. Dev. (Hz)	Mean (Hz)	Std. Dev. (Hz)
10 Kpc	120.08	18.65	117.292	3.501
5 Kpc	120.42	13.80	123.590	6.075
1 Kpc	122.36	5.48	120.928	4.695

Time Duration	cWB 2G		cWB XP	
	Mean (ms)	Std. Dev. (ms)	Mean (ms)	Std. Dev. (ms)
10 Kpc	259	347	71	21
5 Kpc	494	552	83	27
1 Kpc	166	261	95	16

SASImeter Results

Kuroda 2017 S15 on O3 Data

cWB 2G

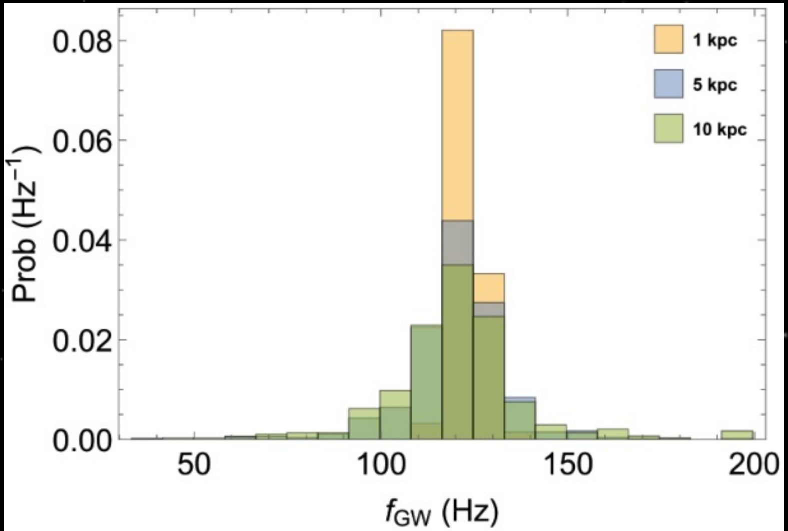


Figure 7A. Probability density distribution of the SASI central frequency for cWB 2G.

From *Characterizing a supernova's Standing Accretion Shock Instability with neutrinos and gravitational waves*. Lin et al., 2023.

cWB XP

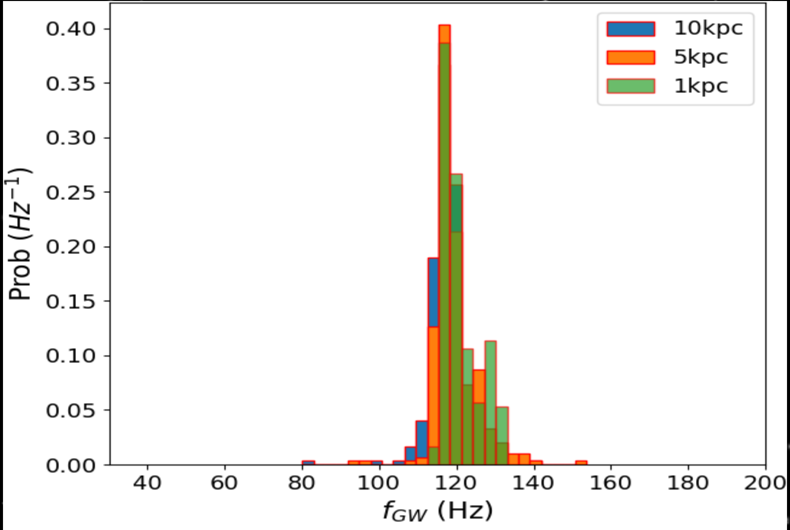


Figure 7B. Probability density distribution of the SASI central frequency for cWB XP.

SASImeter Results

Kuroda 2017 S15 on O3 Data

cWB 2G

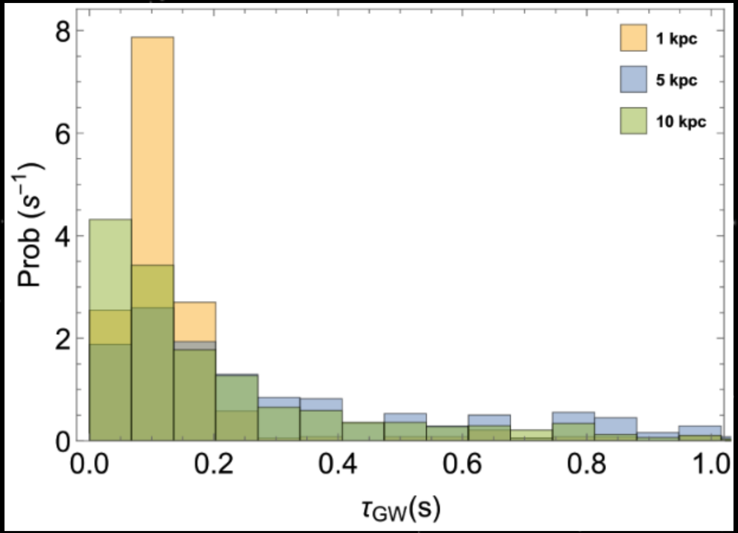


Figure 8A. Probability density distribution of the SASI time duration for cWB 2G.

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cWB XP

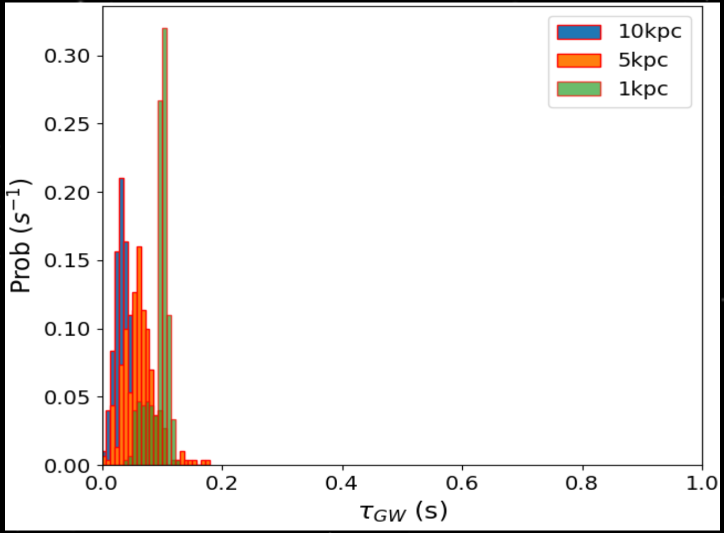

Figure 8B. Probability density distribution of the SASI time duration for cWB XP.

SASImeter Results

Kuroda 2017 S15 on O3 Data

G-Mode Slope	cWB 2G		cWB XP	
	Mean (s^{-2})	Std. Dev. (s^{-2})	Mean (s^{-2})	Std. Dev. (s^{-2})
10 Kpc	2564.84	1301.08	2985.75	1342.36
5 Kpc	2645.02	1132.72	2567.88	948.99
1 Kpc	3190.68	929.62	2502.56	451.77

SASImeter Results

Kuroda 2017 S15 on O3 Data

cWB 2G

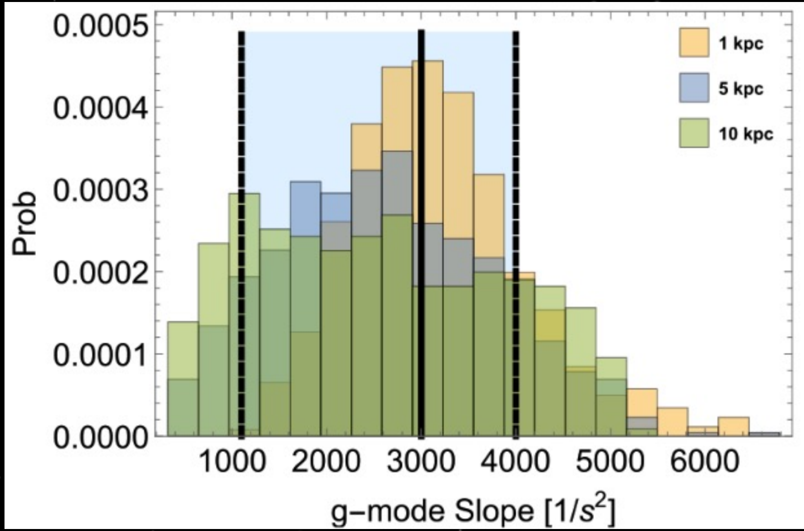

Figure 9A. Probability density distribution of the SASI G-Mode slope for cWB 2G.

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cWB XP

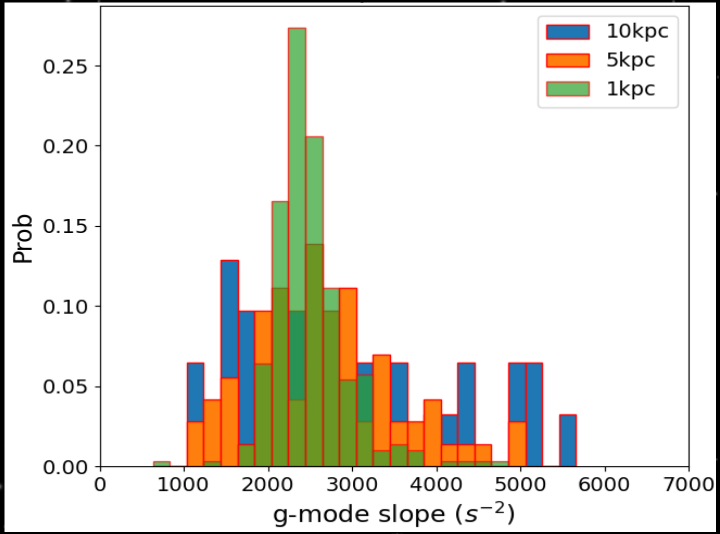

Figure 9B. Probability density distribution of the SASI G-Mode slope for cWB XP.

SASImeter Results

Kuroda 2017 S15 on O3 Data

cWB 2G

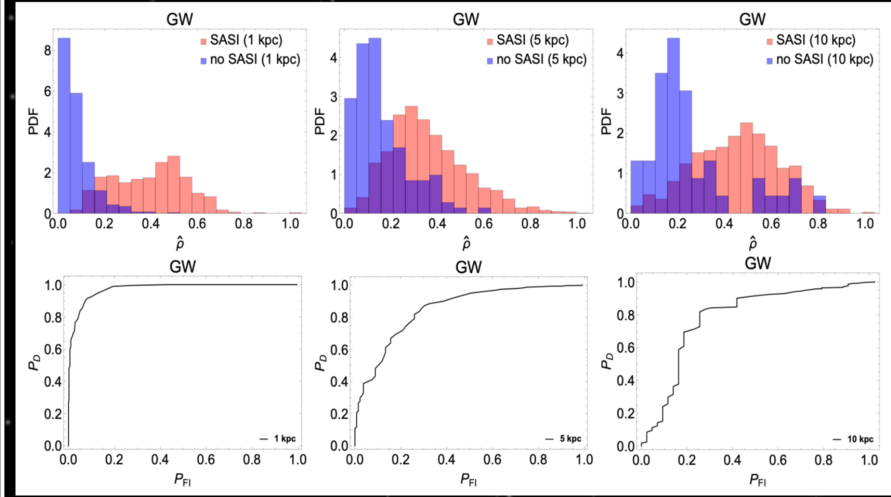

Figure 10A. Top: histograms for the estimation of the ρ statistic for 1, 5 and 10 Kpc. Right: Receiving Operating Characteristic Curves. cWB 2G version.

From *Characterizing a supernova's Standing Accretion Shock Instability with neutrinos and gravitational waves*. Lin et al., 2023.

cWB XP

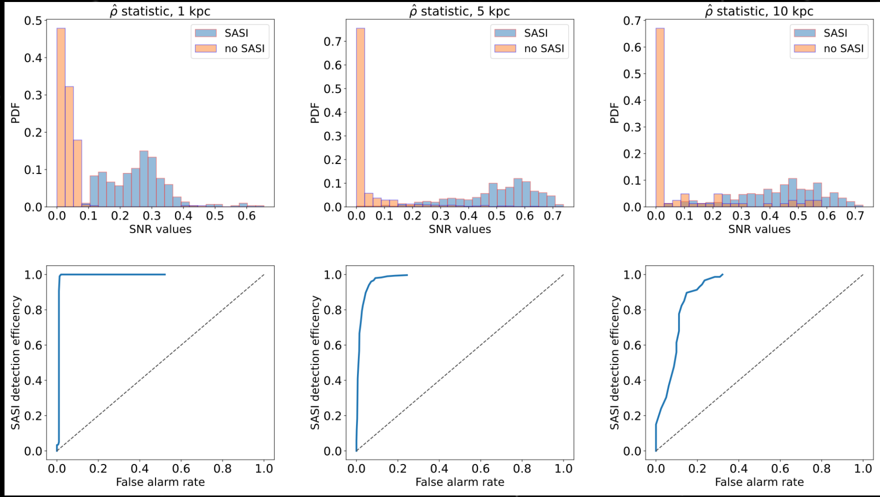

Figure 10B. Top: histograms for the estimation of the ρ statistic for 1, 5 and 10 Kpc. Bottom: Receiving Operating Characteristic Curves. cWB XP version.

Next Steps for SASImeter

- Explore Spiral SASI case.
- SASI time-frequency region was estimated from literature 3 years ago. Suggested updates are welcome!
- Test with more and more diverse GW simulations: some have already been added to our list during this week, **thank you**!!
- Joint pipelines: neutrino and GW SASImeter.