Analysis of gravitational wave signals from core-collapse supernovae (CCSN) with Non-Harmonic Analysis (NHA)

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Outline

- Introduction to GW and GW from CCSN
- Introduction to NHA
- Performance of NHA for test signals
- NHA time-frequency map of GW signals from CCSN
- Summary

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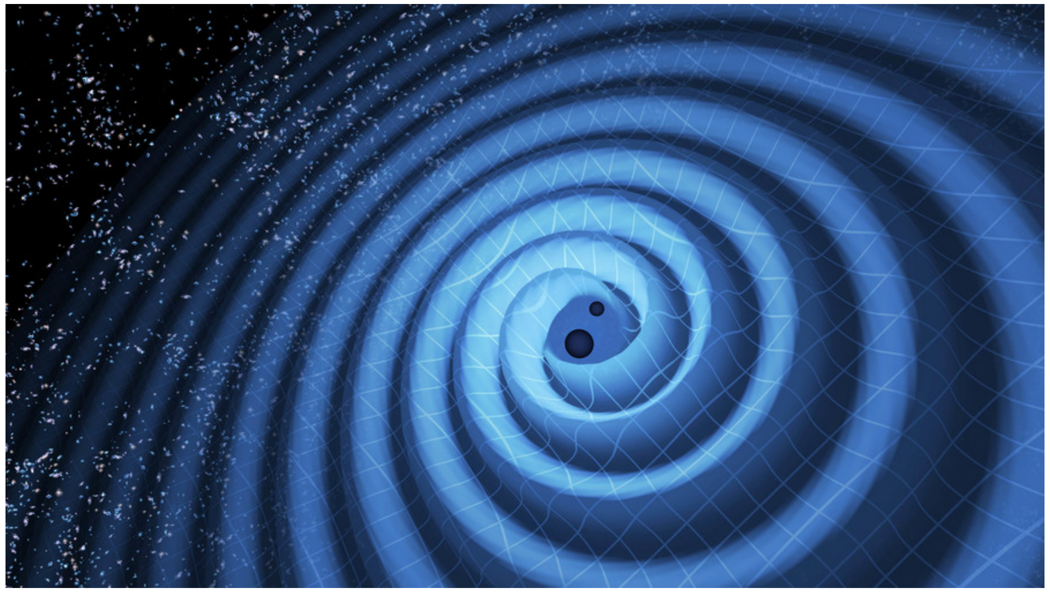
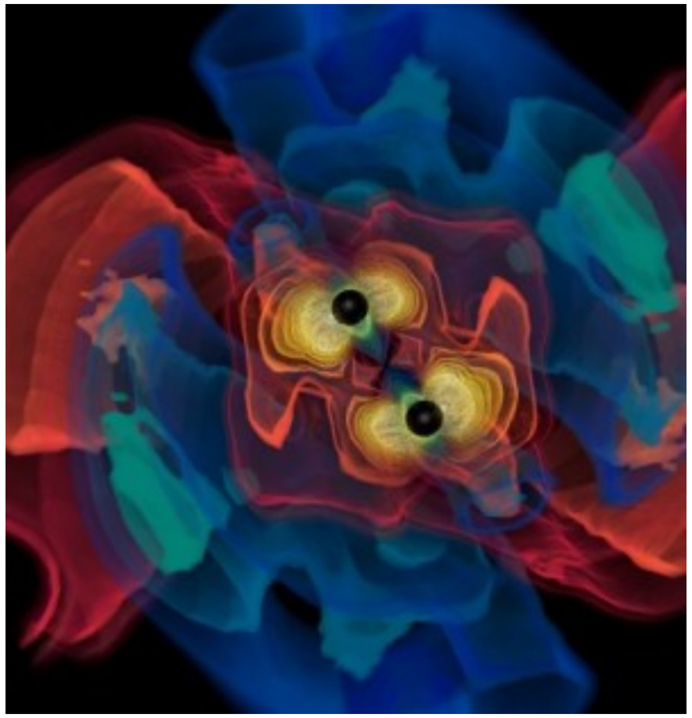
Gravitational Waves (GWs)

- Gravitational waves (GWs) are ripples in space-time traveling in light speed.
- The first detection of GWs was on September 14, 2015. Those GWs were from a binary black hole (BBH).
- Until now, ~48 GW events from BBH and two events from binary neutron star have been detected.
- All of the detected GW events are from compact binary coalescence (CBC).



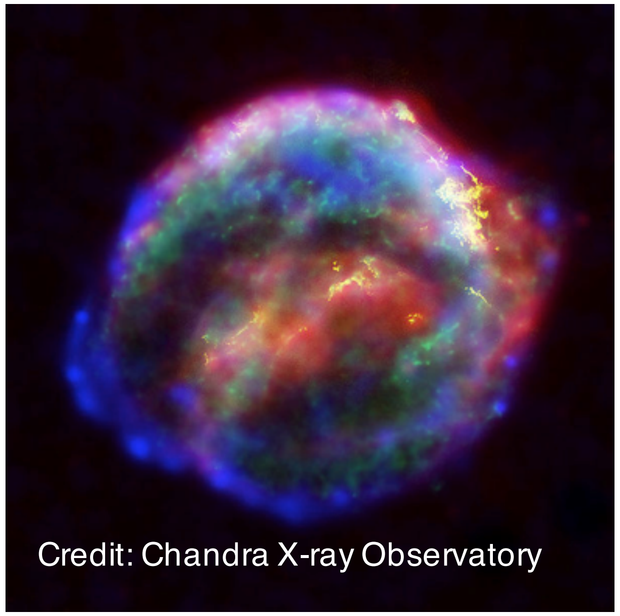
Credit: LIGO/T. Pyle

Astrophysical sources of GWs


Credit: AEI, CCT, LSU

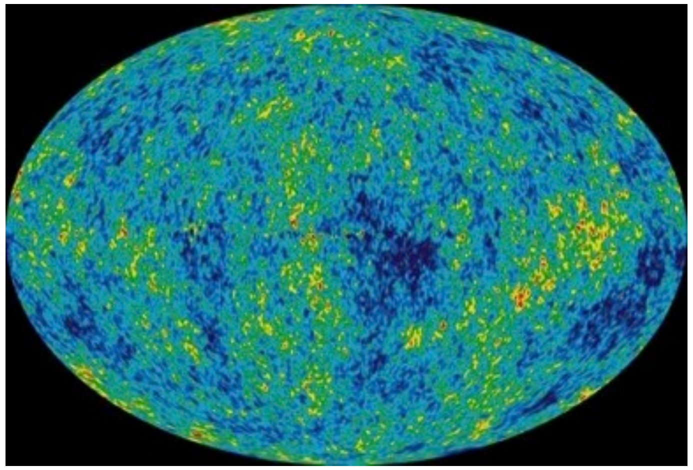
Compact Binary Coalescences (CBC):
Binary Black Hole (BBH),
Binary Neutron Star (BNS)
Neutron Star-Black Hole Binary (NS-BH)

Strong emitter, well-modeled waveform, transient


Credit: Chandra X-ray Observatory

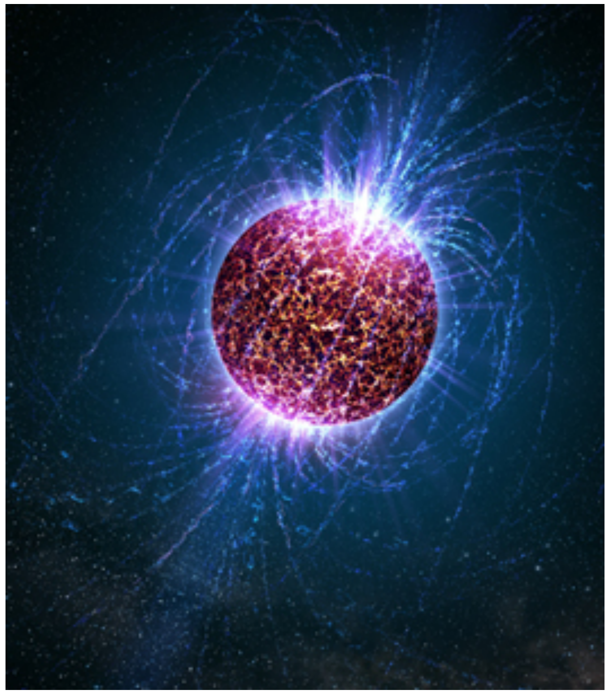
Bursts:
Supernovae

weak emitter, not well-modeled waveform, transient


NASA/WMAP Science Team

Stochastic Background:
Cosmic Gravitational-wave Background

Residue of the Big Bang,
Long duration


Casey Reed, Penn State

Continuous waves:
Spinning neutron star

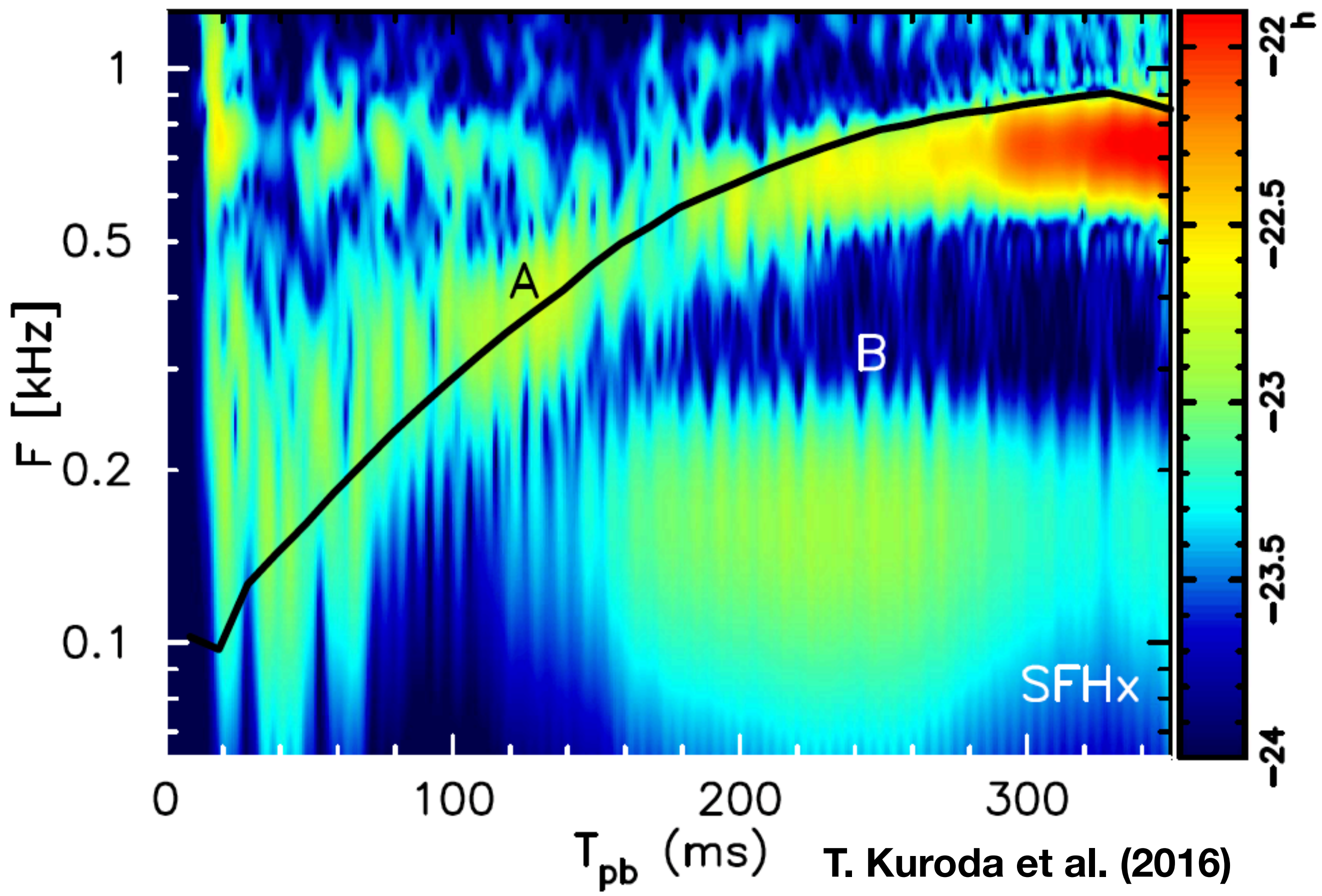
Nearly monotonic waveform,
Long duration

GWs from CCSN

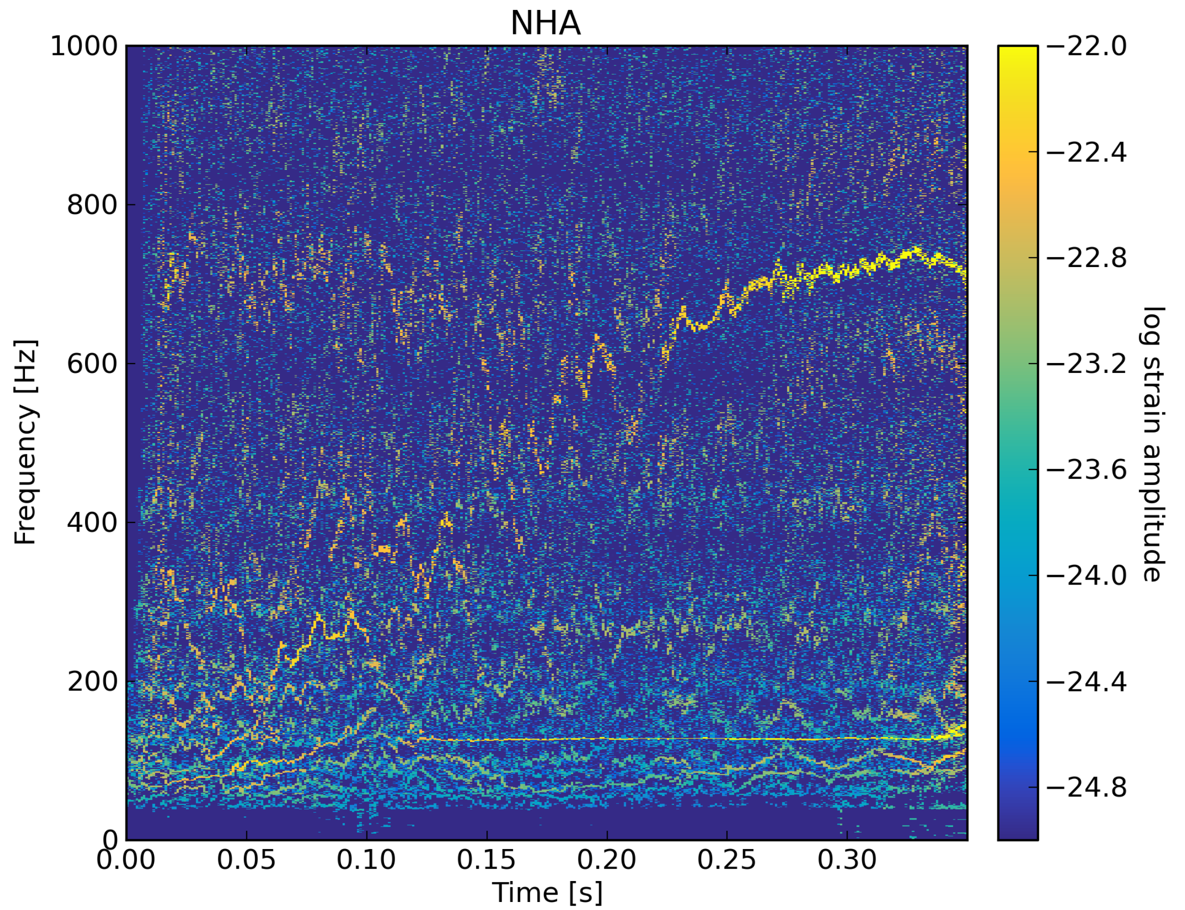
- The waveforms are affected by the turbulence in the postbounce core, which is governed by multidimensional hydrodynamics. Therefore, GWs are hard to predict accurately.
- Several numerical simulations have been performed to understand the GW emission mechanism.
- Data analysis methods of GWs from CCSN are very different from GWs from CBC.
- Since the waveform is unknown, GWs are analyzed in the time-frequency domain.

Spectrogram & NHA

Spectrogram or short-time Fourier transform (STFT) is widely used in time-frequency analysis. But one of the weak point in spectrogram is the trade-off between time resolution and frequency resolution. In order to understand the GW emission mechanism more accurately, we applied NHA on the GW signals from CCSN.



T. Kuroda et al. (2016)



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Non-Harmonic Analysis (NHA)

A time-frequency analysis method which has high clarity in both time and frequency resolution.

$$x_j = \sum_{k=1}^{k_{\max}} A_k \cos(2\pi f_k j \Delta t + \phi_k), (j = 0, ..., N-1)$$

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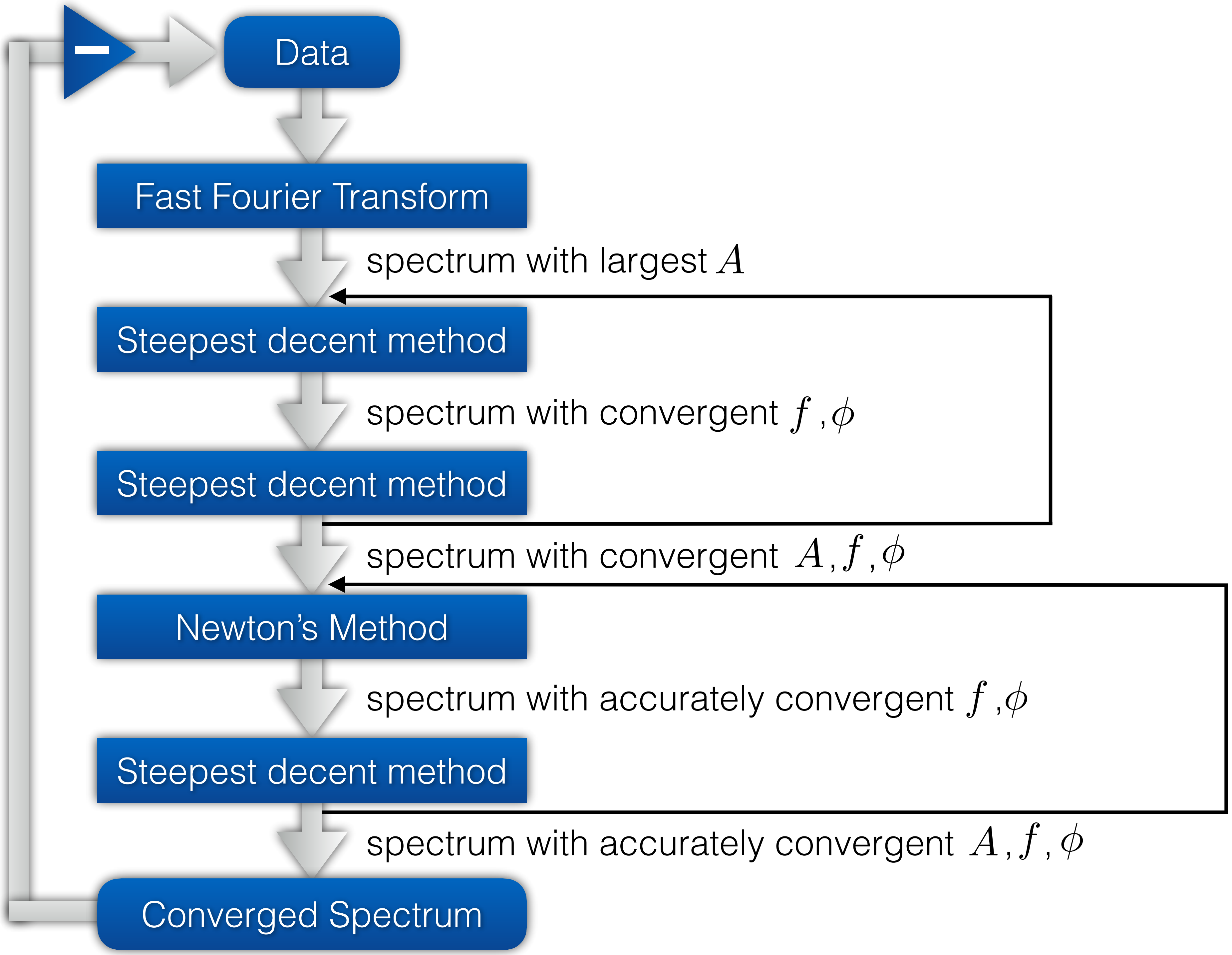
For each spectrum, we want to minimize the fitting error, which is define as

$$F_k(A, f, \phi) = \sum_{j=0}^{N-1} [x_j - A_k \cos(2\pi f_k j \Delta t + \phi_k)]^2$$

NHA algorithm



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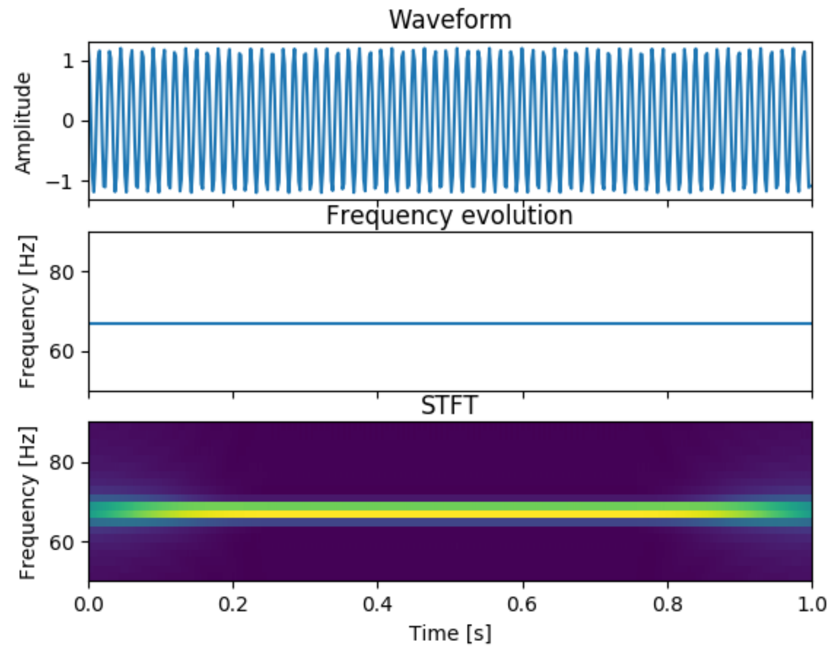
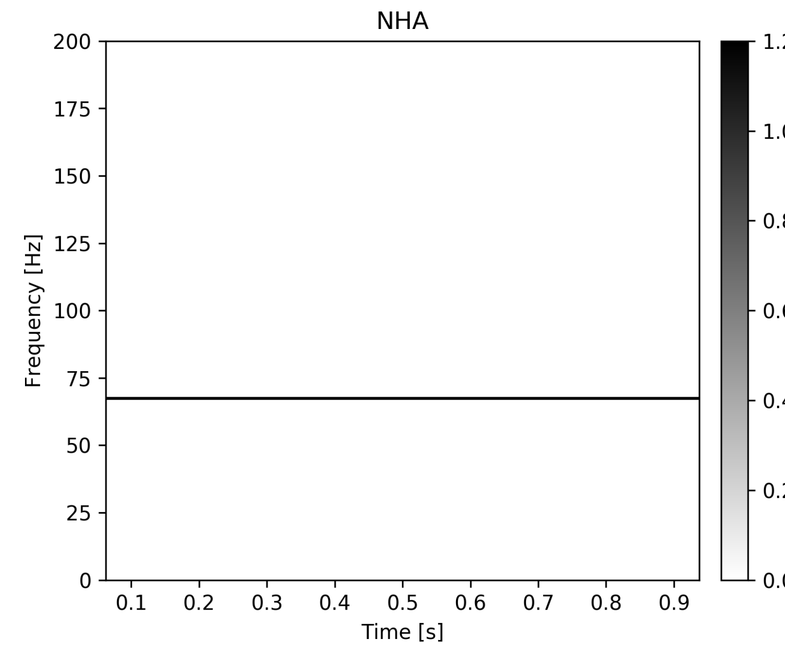
Performance of NHA for test signals

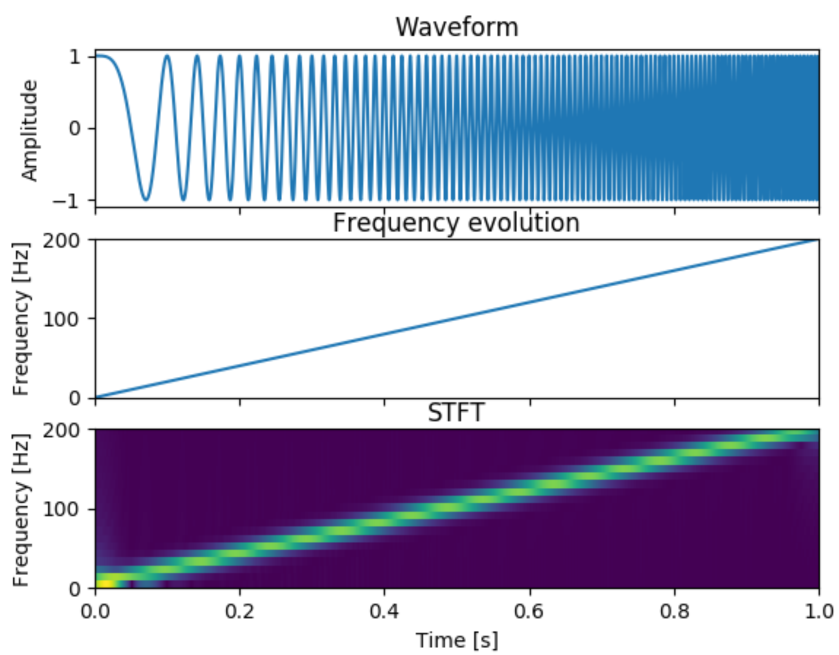
Test signal 1: $x(t) = A\cos(2\pi f t)$ $A = 1.2, f = 66.7$ Hz

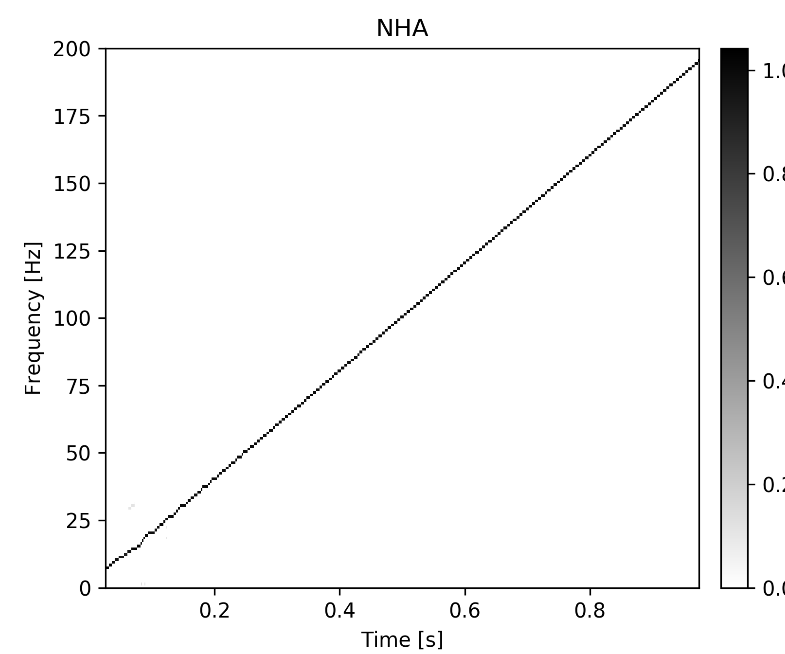




Test signal 2: $x(t) = \cos(200\pi t^2)$

K. Yanagisawa et al. (2019)





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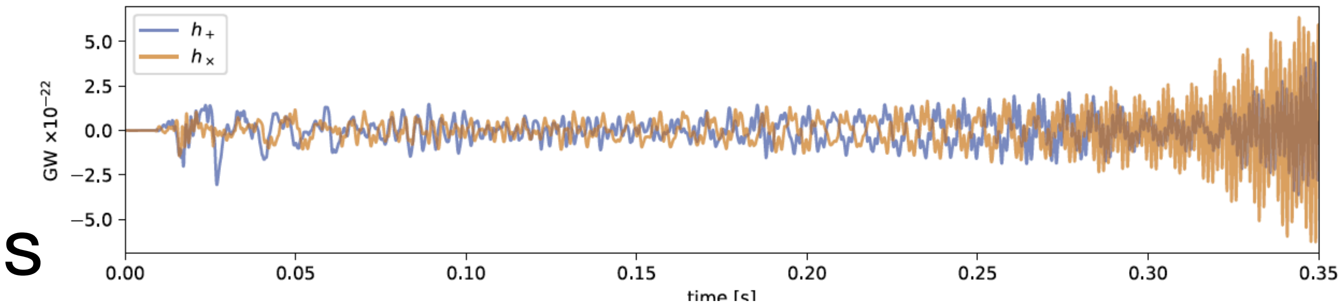
Simulated GW signals from CCSN

T. Kuroda et al. (2016)

The data from Kuroda et al. are simulated from

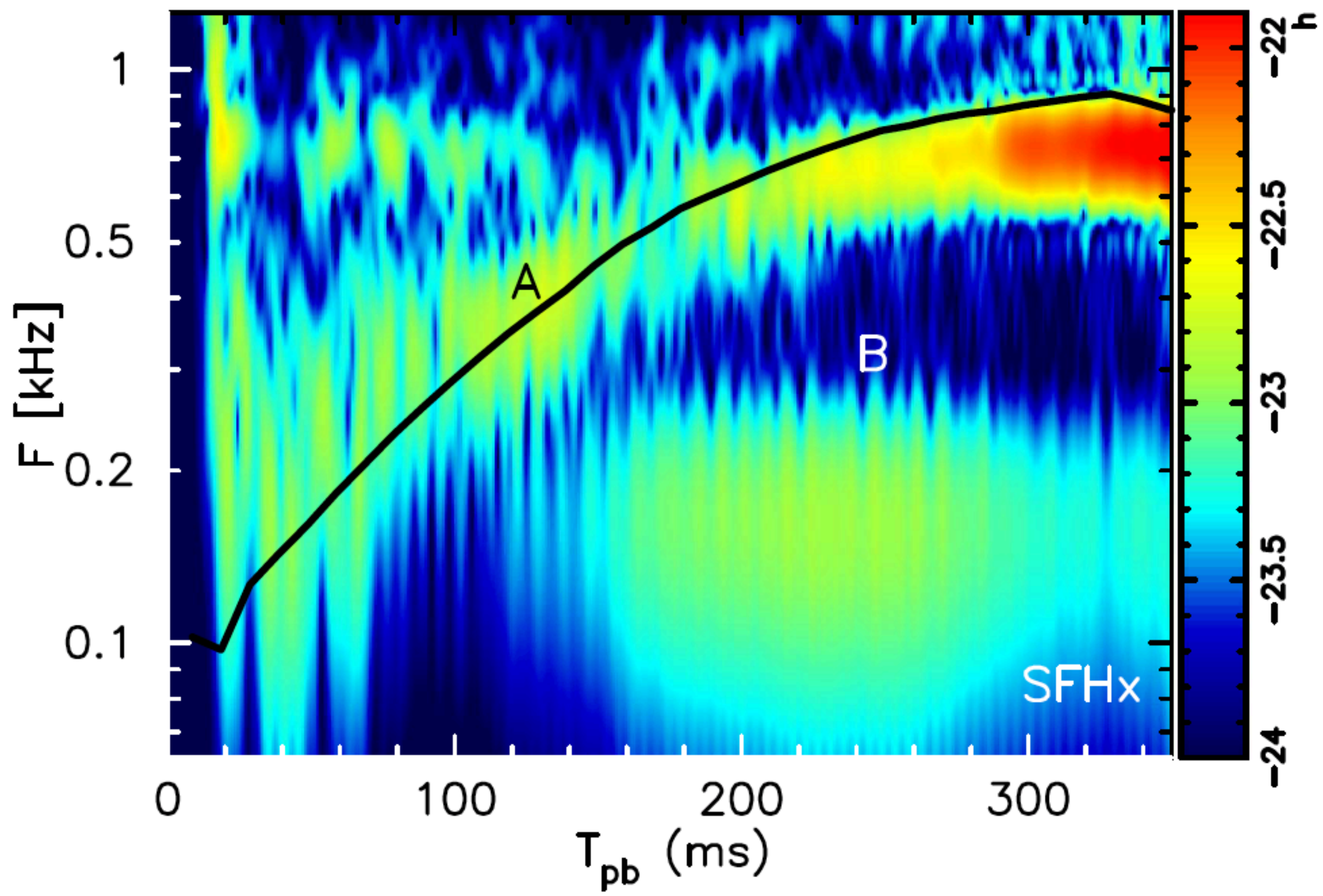
- Non-rotating 15 $M_{\odot}$ star
- Distance 10 kpc
- 3D-GR hydrodynamic simulations
- SFHx model, which is a softer EoS model, shows stronger SASI mode



$h_\times$ mode

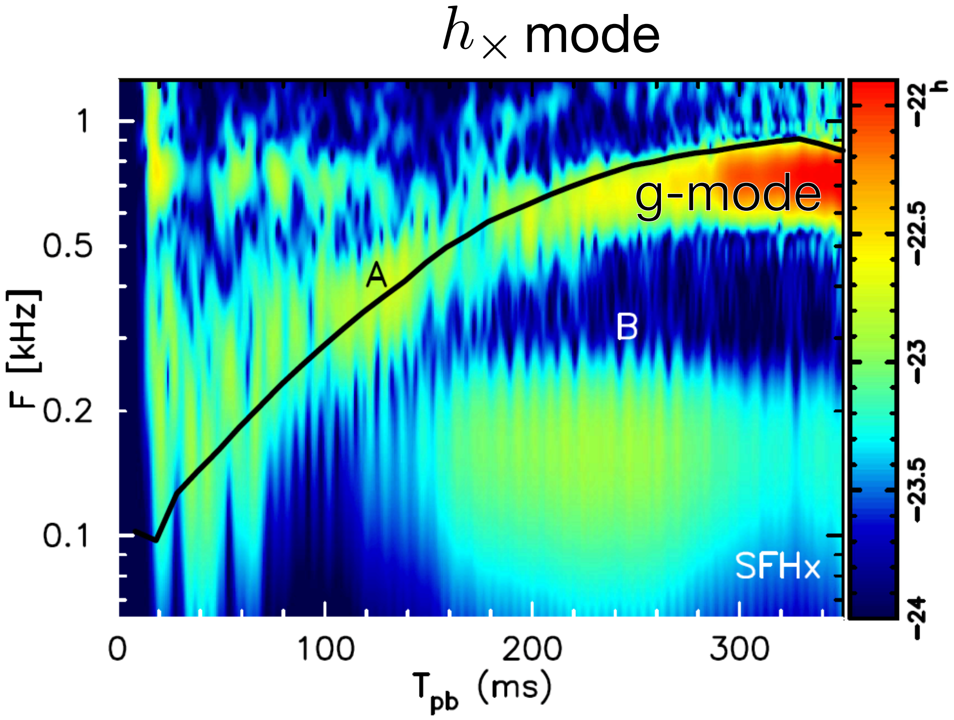
A: PNS g-mode oscillation

B: SASI activity



g-mode (Gravity mode)

- Gravity is the force to restore the thermal-induced buoyancy in the protoneutron star
- Frequency increases approximately linearly with the central temperature
- The lowest mode has approximately O(10-500) Hz



Standing Accretion Shock Instability (SASI)

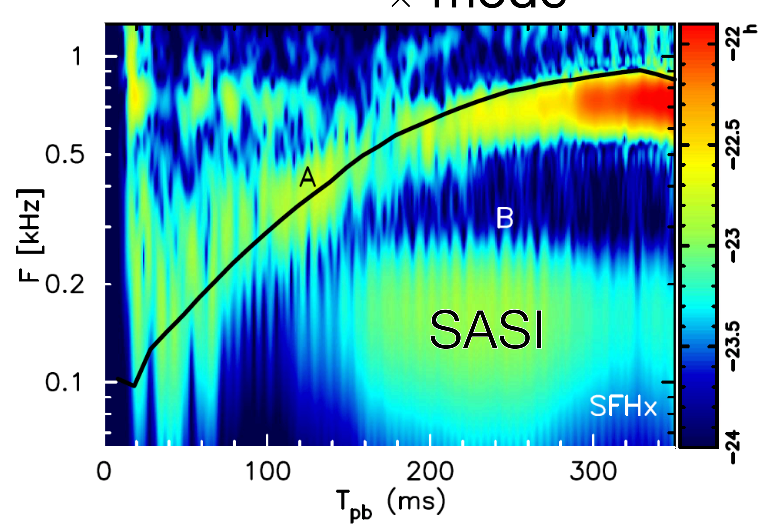
- The Fe core of a star collapse under gravitation, forming a proto-neutron star. The collapsed material bounce back from the proto-neutron star surface, producing shock and propagate outward.

- The shock collides with the collapsed Fe, and stop propagating.

- The proto-neutron star produces neutrino and heat up the surrounding materials, causing severe convection and regenerating shock.

- The standing shocks are unstable, generating gravitational waves.

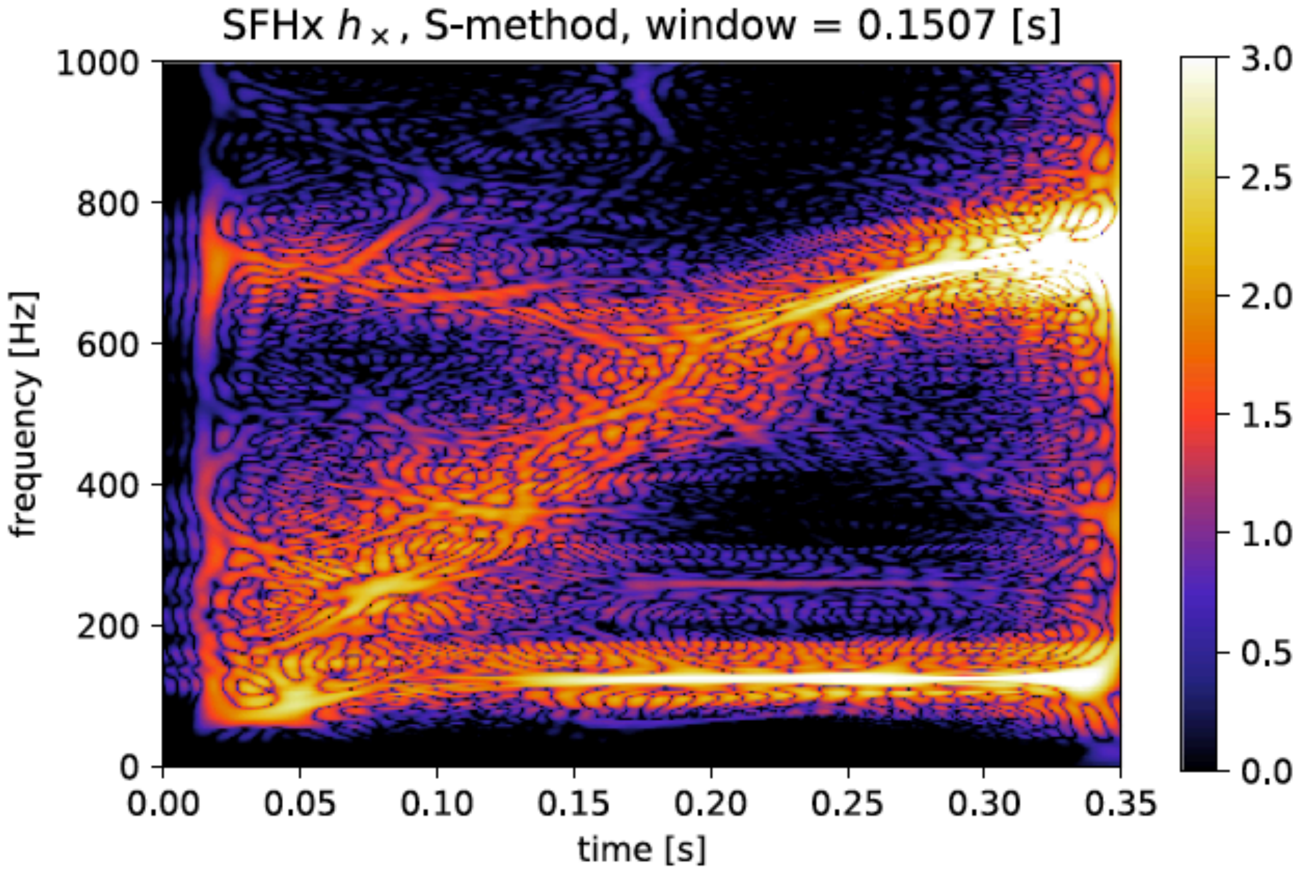
$h_\times$ mode

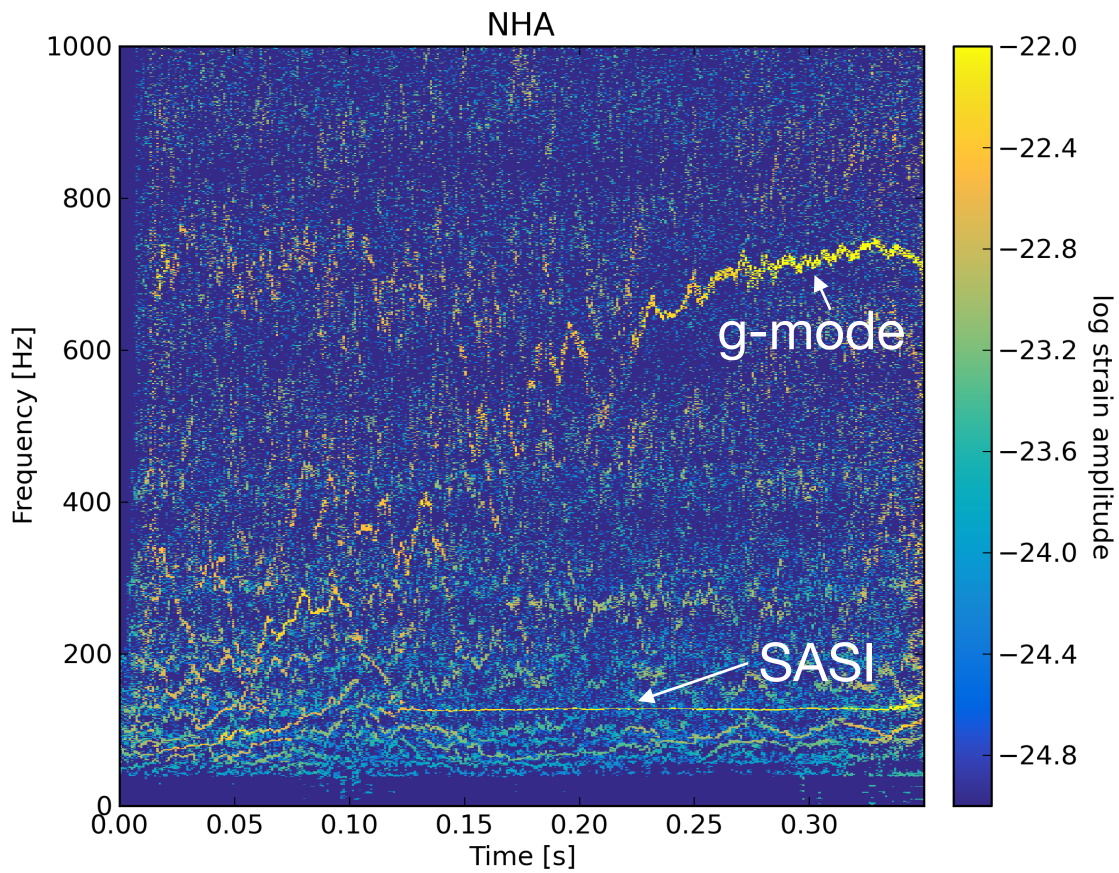


NHA of Simulated GW signals from CCSN

We analyzed a simulated GW signal from CCSN using NHA, and compared the result with spectrogram and Kawahara et al..

- g-mode: we found some oscillations of frequencies. The oscillations are larger in lower frequency between 300-600 Hz.
- SASI mode: frequency can be resolved very sharply.
- below SASI mode: some possible oscillation mode. Physical nature of these modes are under investigation.





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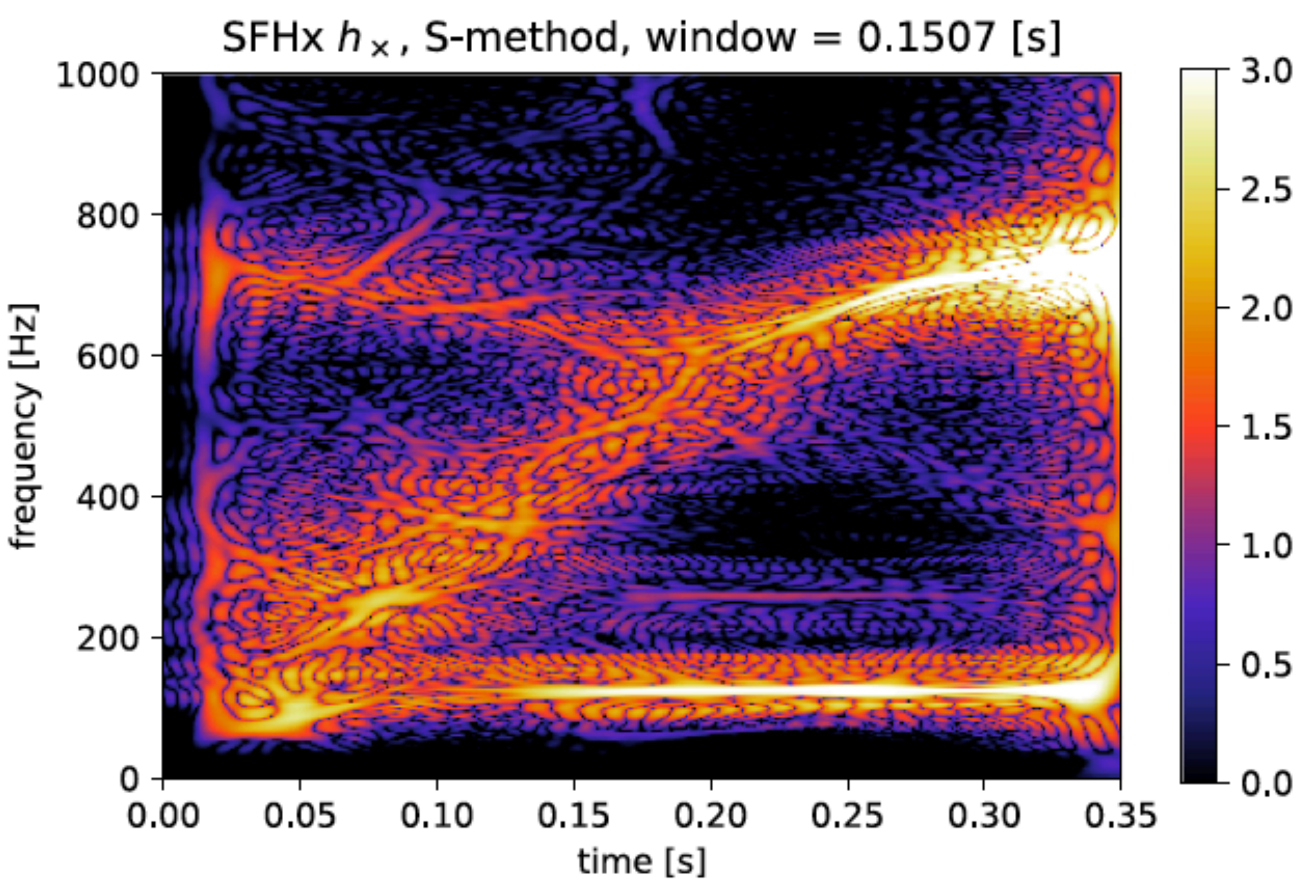
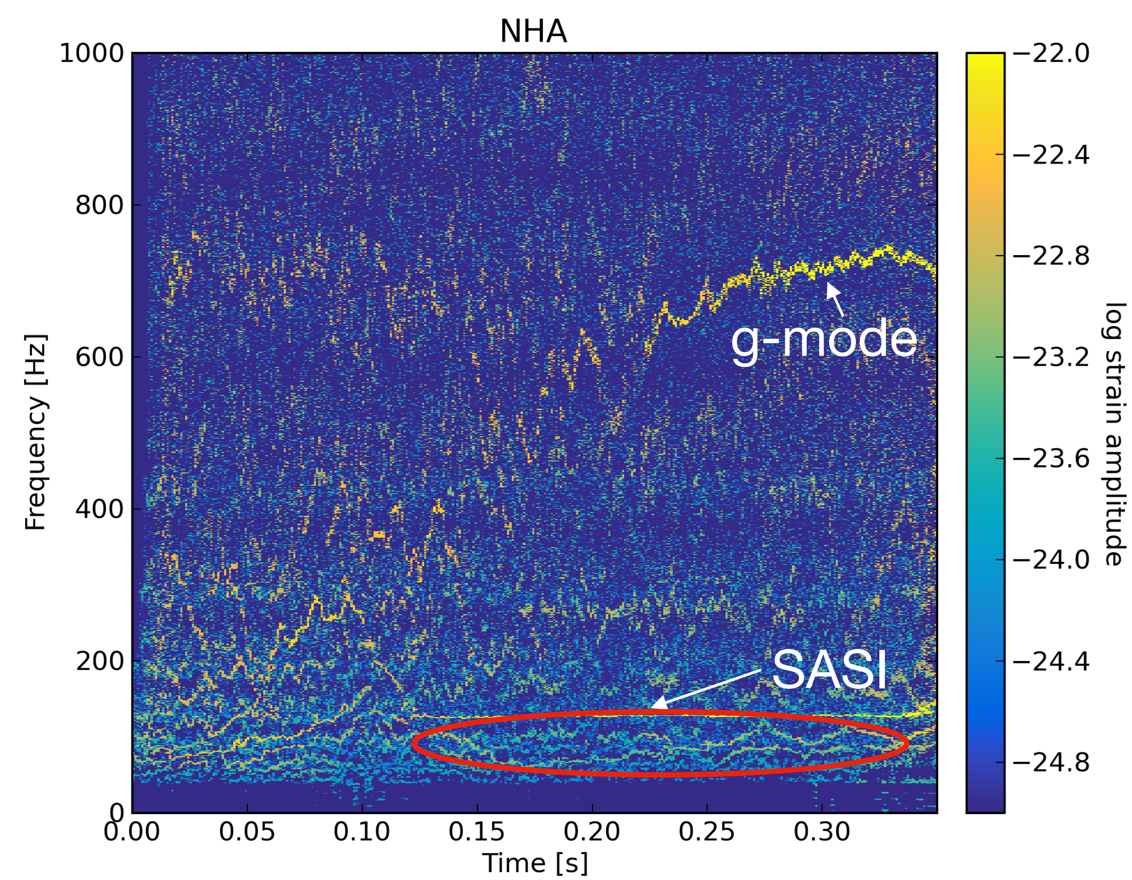




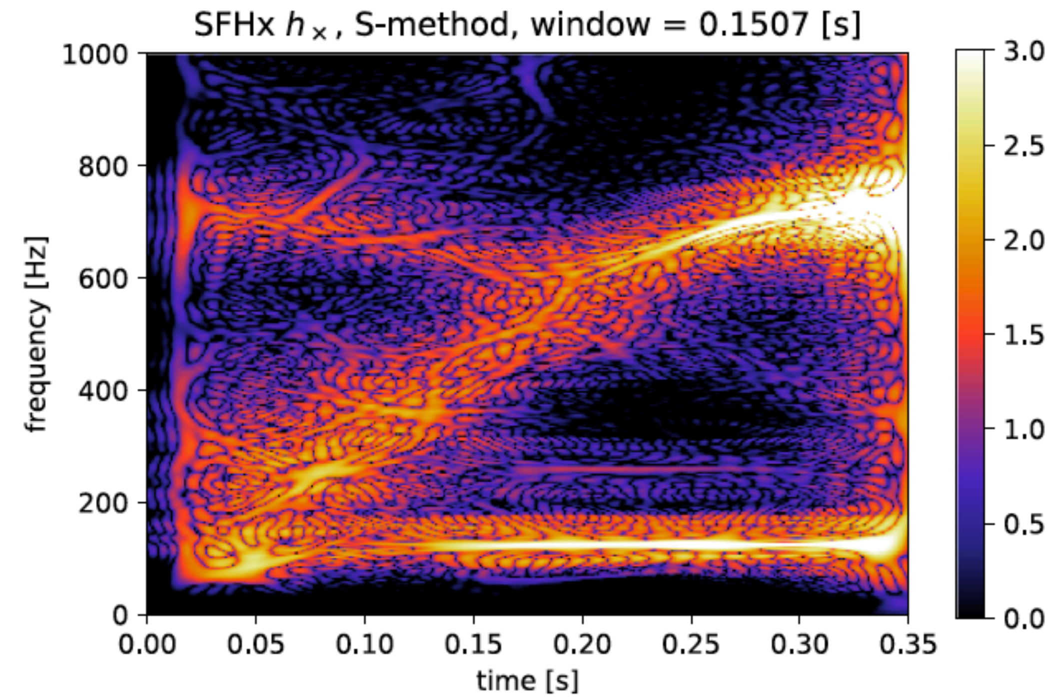
NHA of Simulated GW signals from CCSN

PNS g-mode

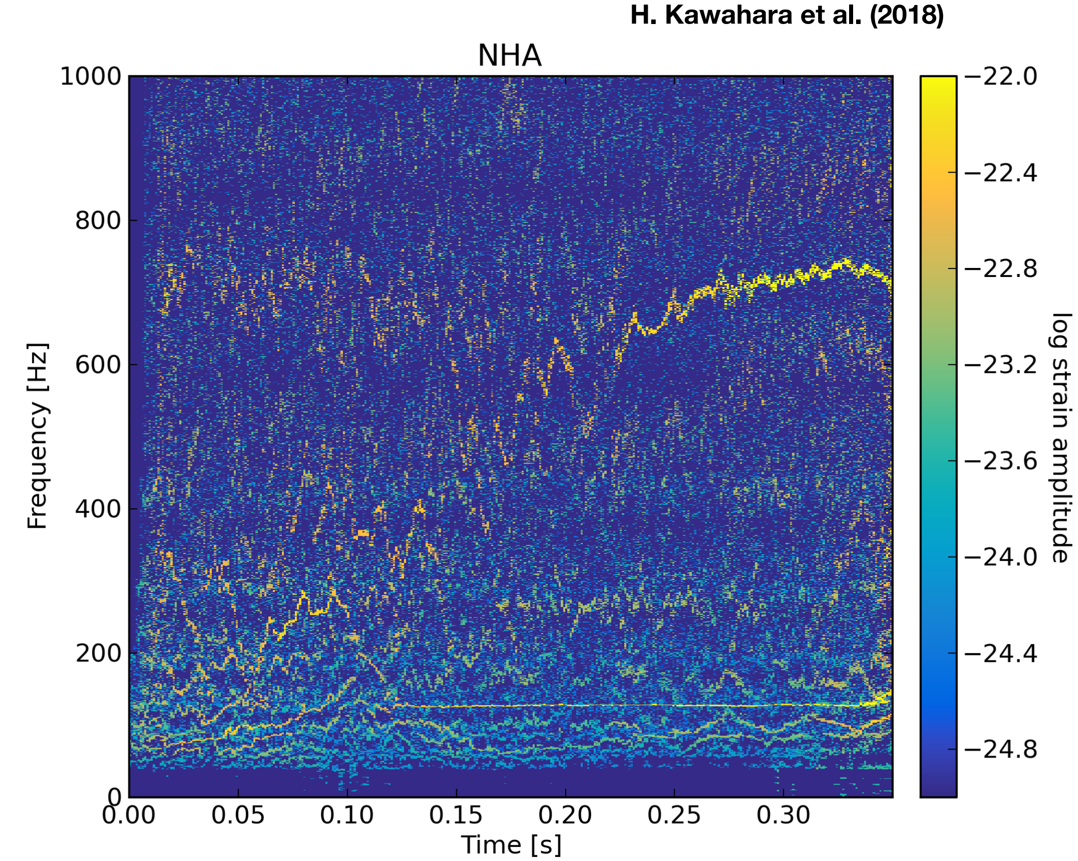
Time	Frequency [Hz]	Amplitude (log)
0.00-0.05	100~200	-22.8~-22.6
0.05-0.10	200~300	-22.5~-22.2
0.10-0.15	300~420	-22.8~-22.2
0.15-0.20	420~630	-22.5~-22.2
0.20-0.25	500~700	-22.5~-22.1
0.25-0.30	660~730	-22.4~-21.6
0.30-0.35	705~750	-21.8~-21.2

SASI mode Kawahara et al. (130Hz)

Time	Frequency [Hz]	Amplitude (log)
0.15-0.20	125~129	-22.2~-22.1
0.20-0.25	127~129	-22.1~-22.0
0.25-0.30	126~129	-22.2~-22.0
0.30-0.35	126~134	-22.2~-21.9



H. Kawahara et al. (2018)



Summary

- NHA is a time-frequency analysis tool which does not have trade-off between time and frequency resolution.
- We performed NHA on test signals, and showed that NHA can show clear GW modes in time-frequency map.
- We analyzed simulated GW signals from CCSN with NHA
  - We obtained frequency evolution more precisely than spectrogram and S-method.
  - SASI mode: we obtain precise value of frequency of SASI mode.
  - g-mode: frequency oscillates. The oscillation is larger in lower frequency between 300-600 Hz. This is consistent with the results with S-method (Kawahara et al.)

References

1. K. Yanagisawa, D. Jia, S. Hirobayashi, N. Uchikata, T. Narikawa, K. Ueno, H. Takahashi, H. Tagoshi, PTEP, 2019, 6, 063F01

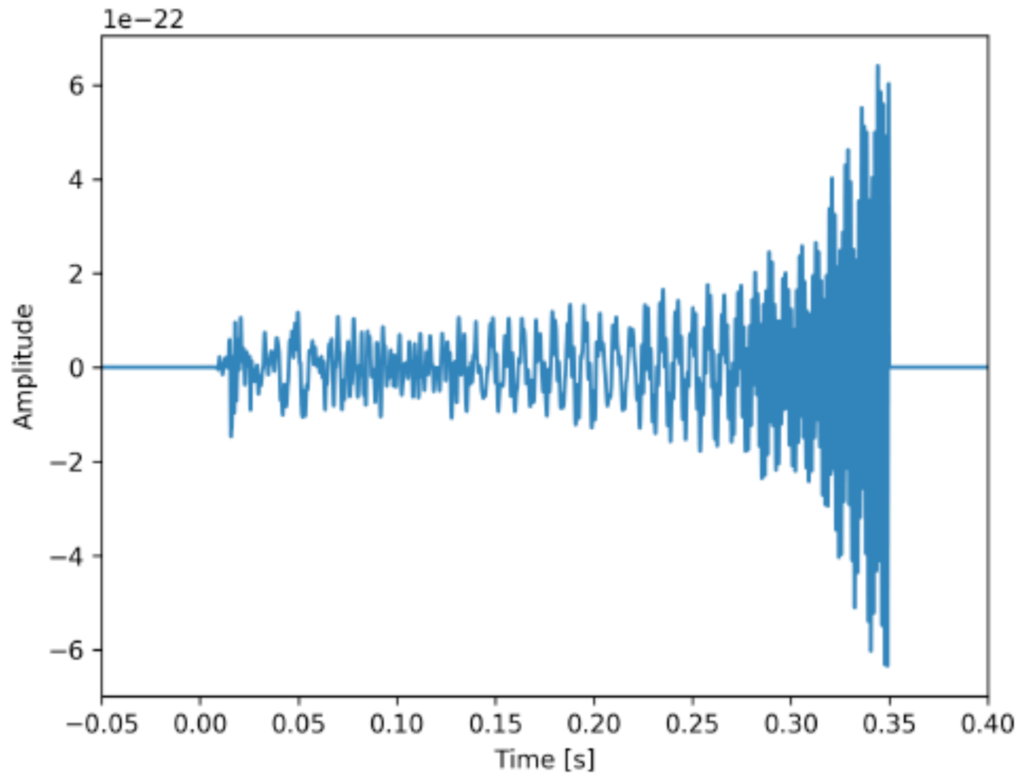
2. T. Kuroda, K. Kotake, T. Takiwaki, 2016, ApJL, 829, 1, L14

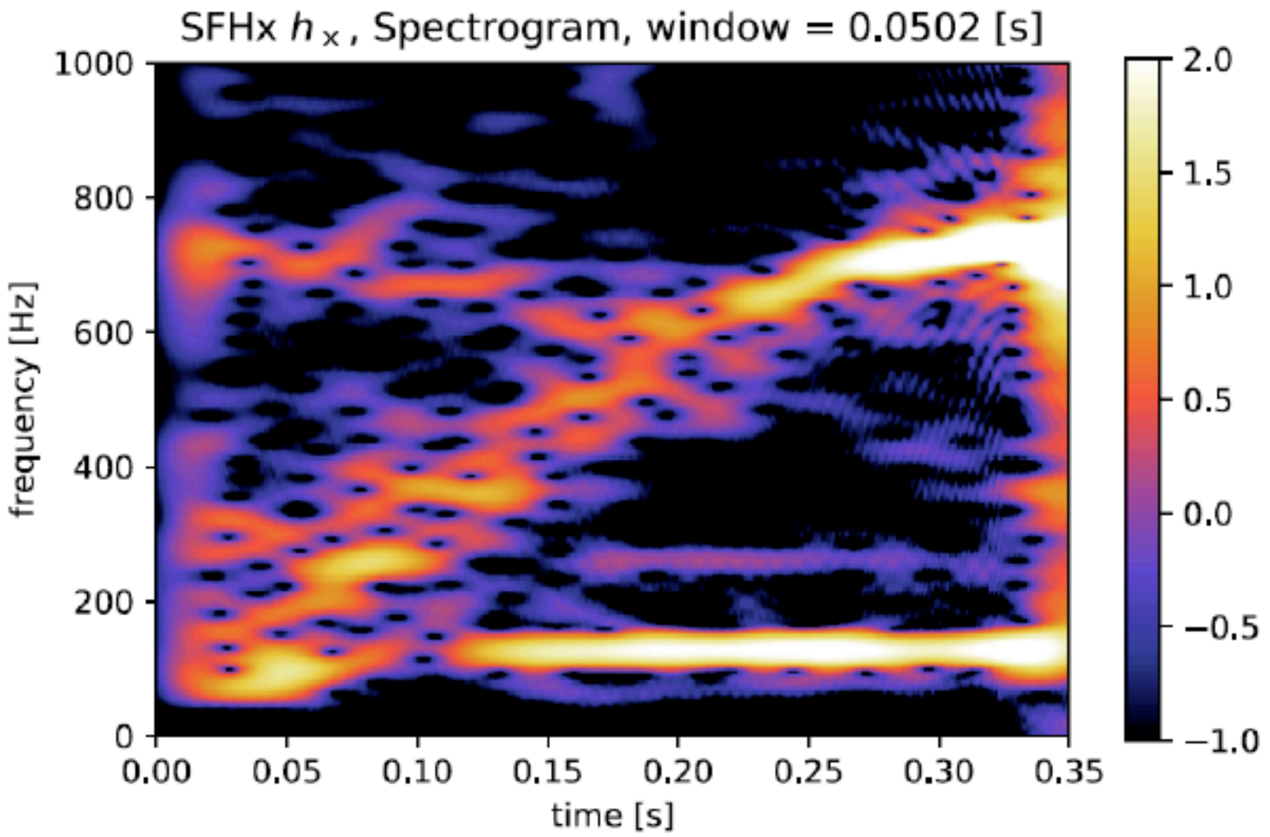
3. H. Kawahara, T. Kuroda, T. Takiwaki, K. Hayama, K. Kotake, 2018 APJ, 867, 2

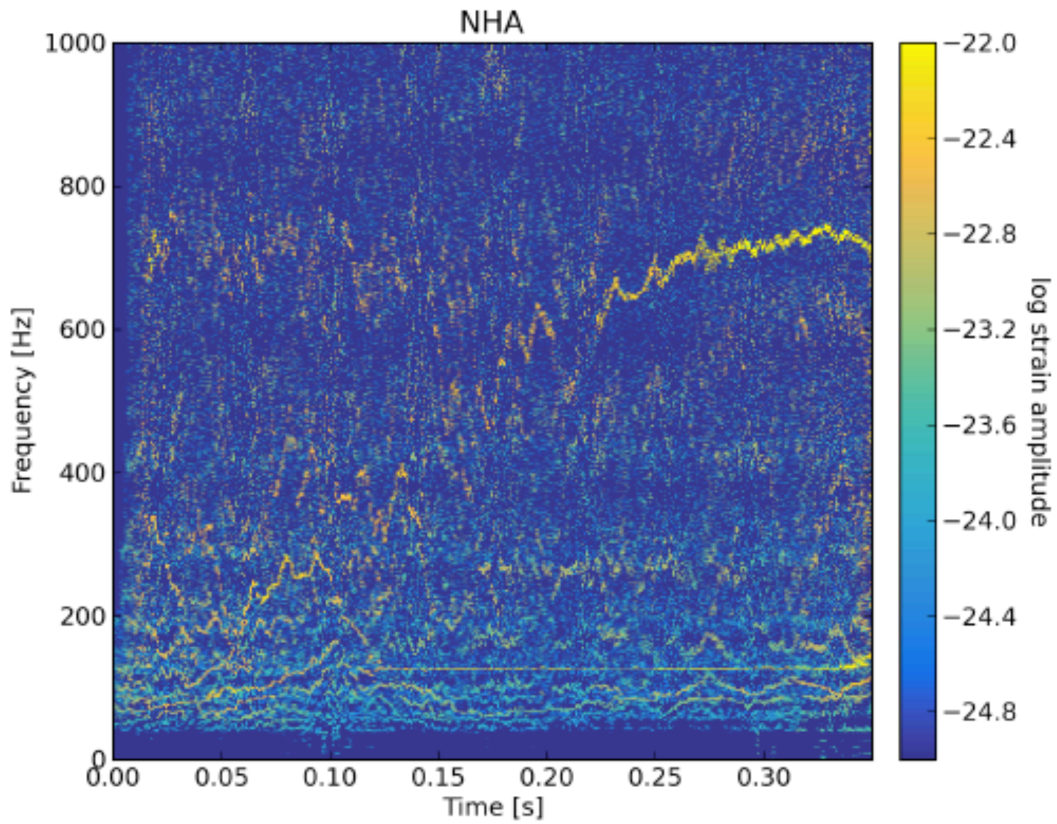
Backup

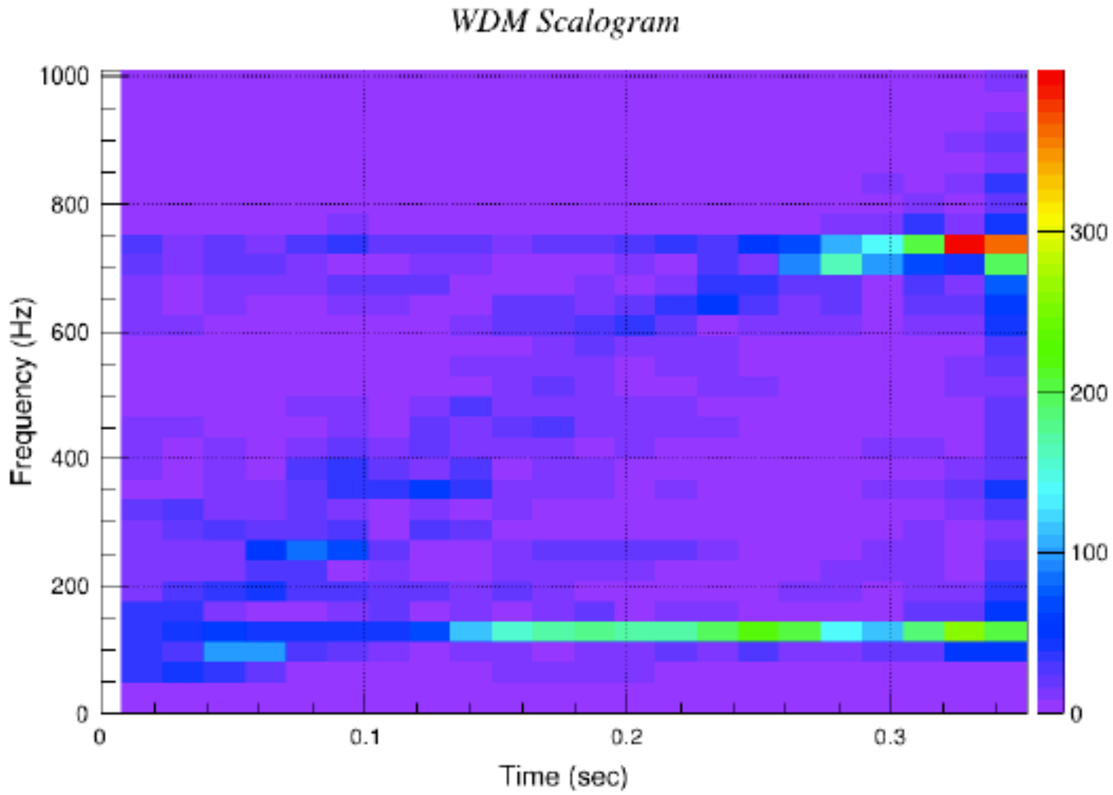
Burst analysis

- Coherent WaveBurst (cWB) pipeline is used in the burst GW analysis.
- It combines data streams from multiple detectors into one coherent statistics.
- Wavelet transform is performed to produce time-frequency map.
- Use clustering algorithm to detect the signal.


1e−22
Amplitude
Time [s]


SFHx $h_\times$, Spectrogram, window = 0.0502 [s]
frequency [Hz]
time [s]

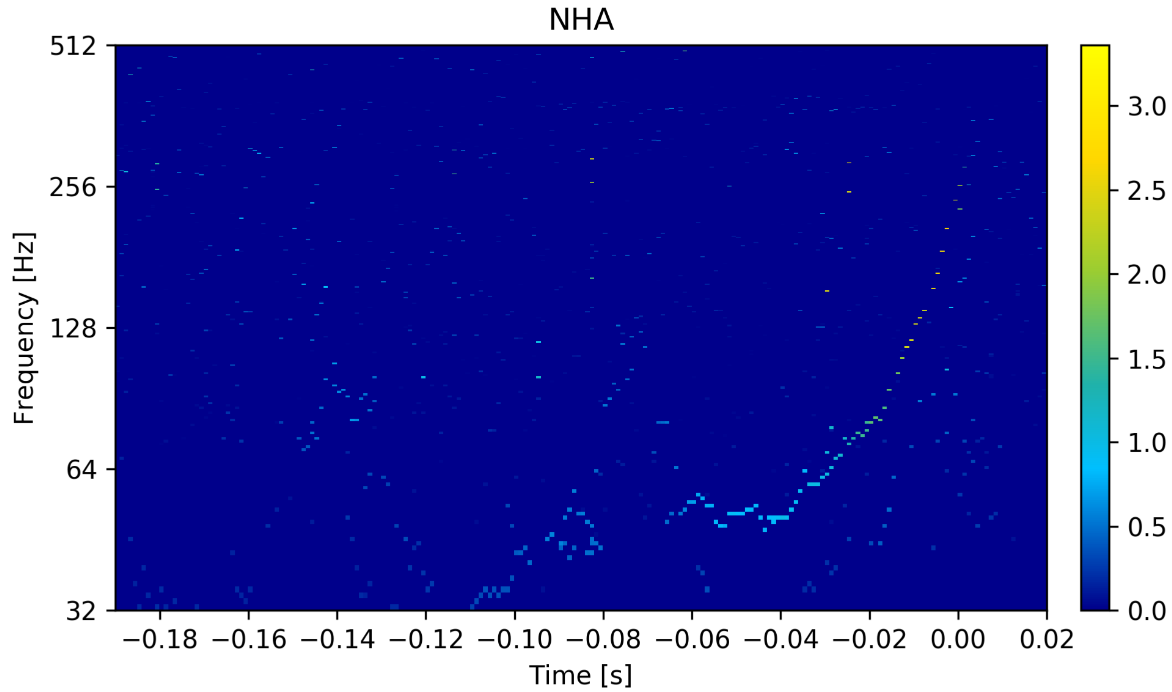

NHA
Frequency [Hz]
Time [s]
log strain amplitude


WDM Scalogram
Frequency (Hz)
Time (sec)

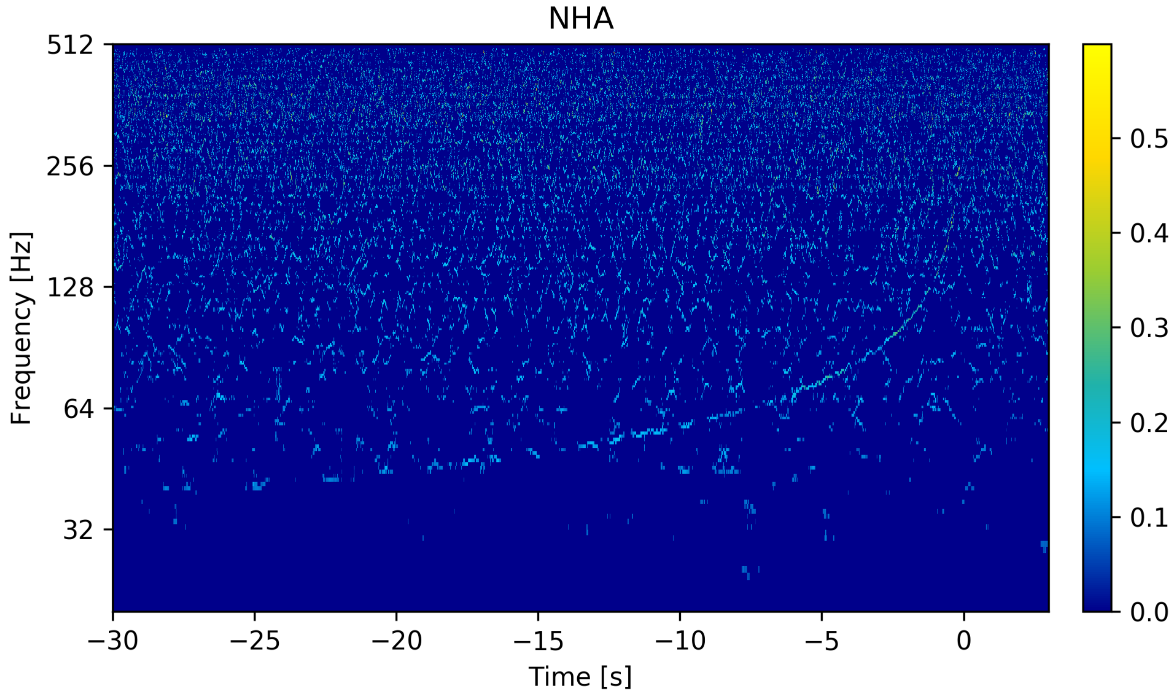
NHA of LIGO events

K. Yanagisawa et al. (2019)

GW150914 LIGO Hanford



GW170817 LIGO Livingston



GW mode tracking

H. Kawahara et al. (2018)

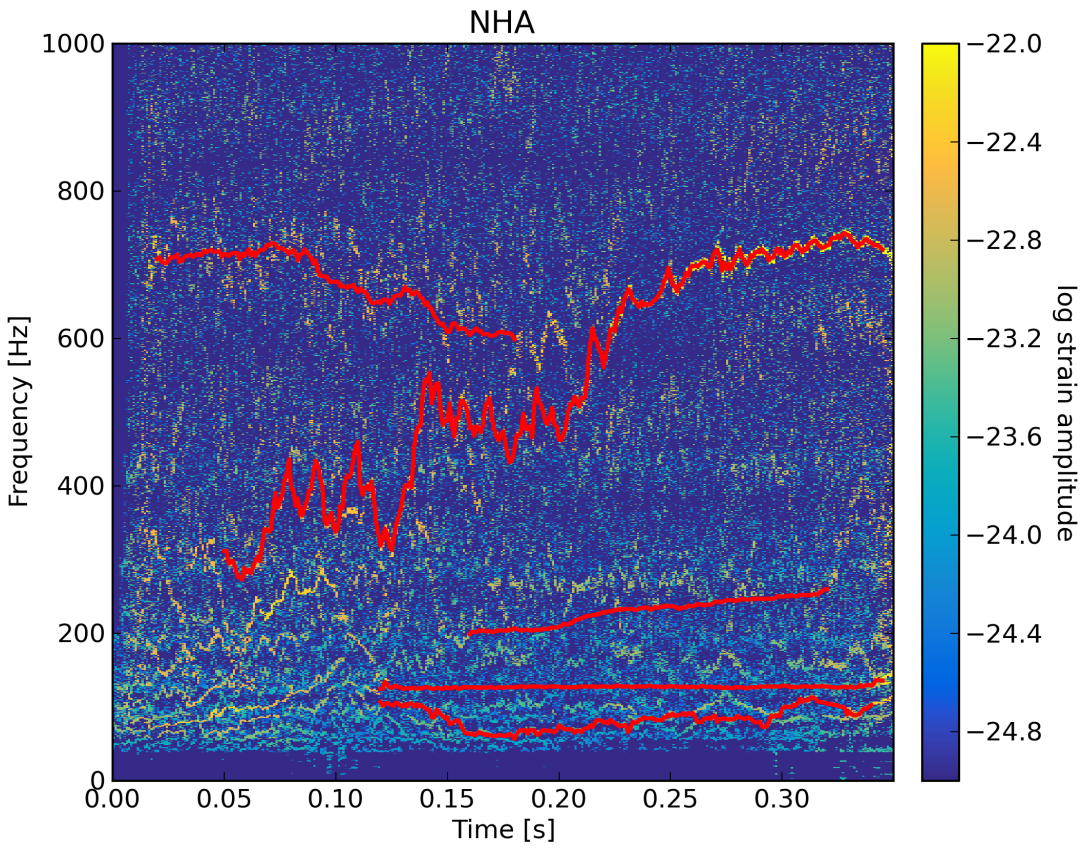
GW modes are tracked by frequency weighted average. The starting points are chosen from the clear peaks in the time-frequency map, and derive the next points by iterating equation.

Iterating equation:

$$f_c^{i+1}(t) = \frac{\int_{f_c^i(t)-w/2}^{f_c^i(t)+w/2} f X(f,t) df}{\int_{f_c^i(t)-w/2}^{f_c^i(t)+w/2} X(f,t) df}$$

Next time step:

$$f_c^0(t_{j+1}) = f_c^{\mathrm{final}}(t_j)$$



S-method

H. Kawahara et al. (2018)

S-method is a modification from Pseudo Wigner Ville distribution, which is not a linear but quadratic transformation.

$$\rho_s(f,t) = 2\int_{-\infty}^{\infty} P(\theta) s(f+\theta/2, t) s^*(f-\theta/2, t) d\theta$$

$$= 2\int_{-\theta_{\rm L}}^{\theta_{\rm L}} s(f+\theta/2, t) s^*(f-\theta/2, t) d\theta$$

$\theta_{\rm L} \to 0$: Spectrogram

$\theta_{\rm L} \to \infty$: PWV distribution