Core-collapse supernova gravitational-wave physical inference in low-latency

(Feedback from the modeling community is essential, see the requests and questions within the slides)

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SN2025gw, Warsaw, 21-25.07.2025

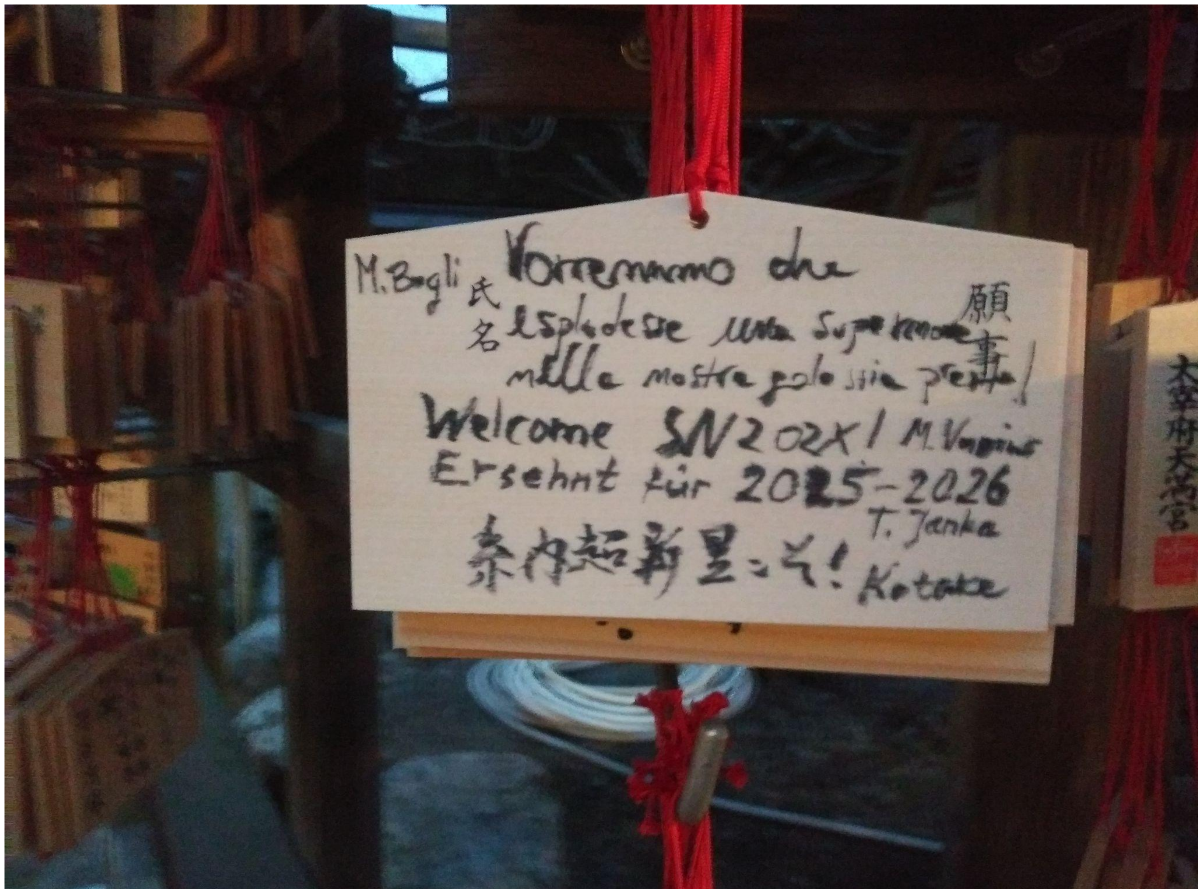
Outline

- Can LVK be scooped in case of a GW detection?
- Low-latency Physical Inference
- Warsaw Summer Projects for GW CCSN

The next Galactic CCSN is soon…

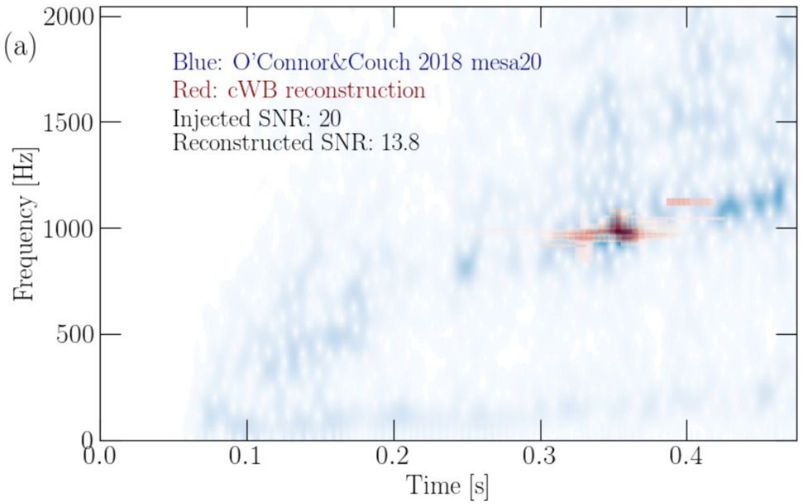
"Welcome SN 202X! Long-awaited for 2025-2026"

Fukuoka Temple, 2019.10.23



Can Modelers scoop LVK? Personal opinion. See also Extra Slides at the end

https://arxiv.org/abs/2104.06462

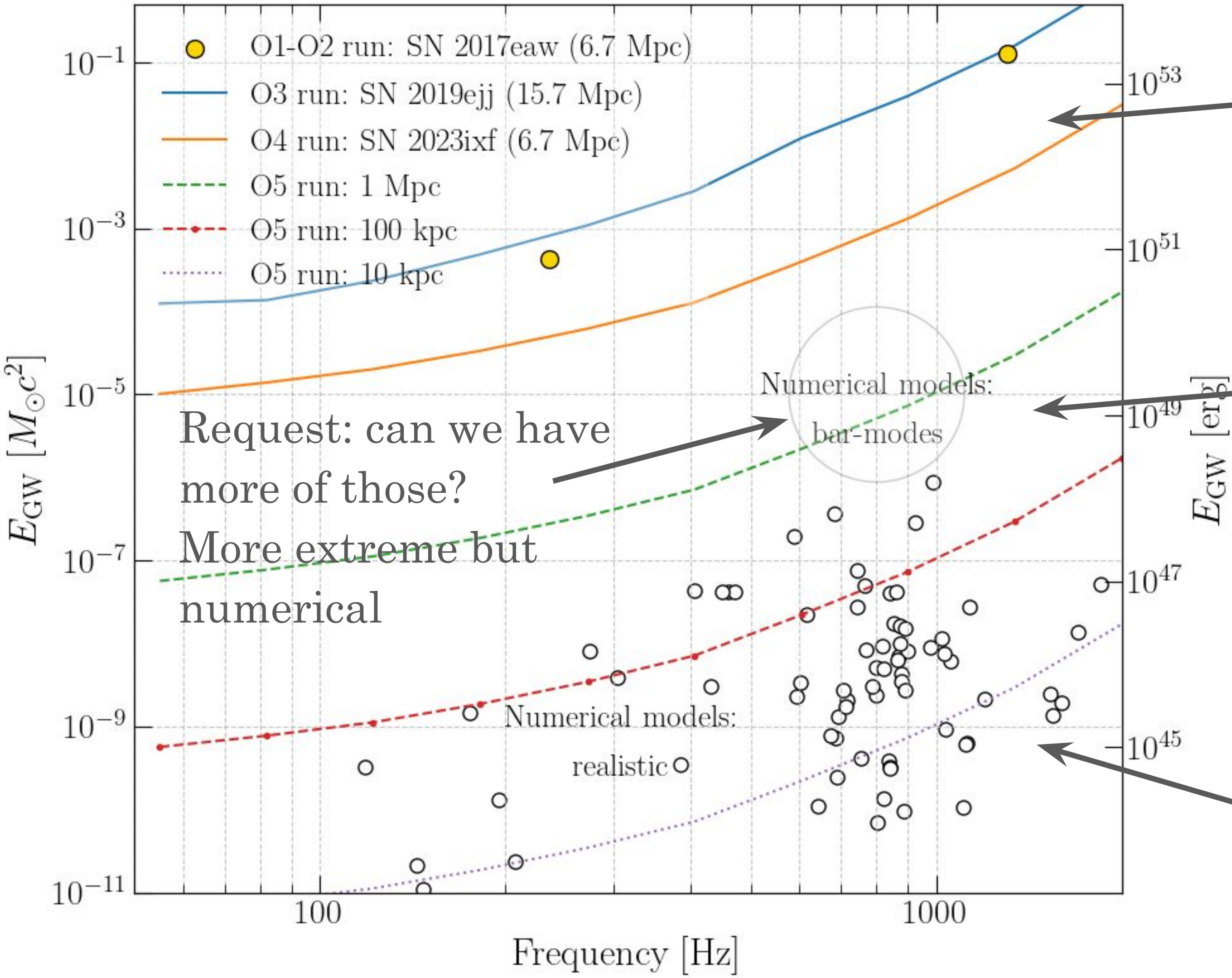


Public, within a minute:

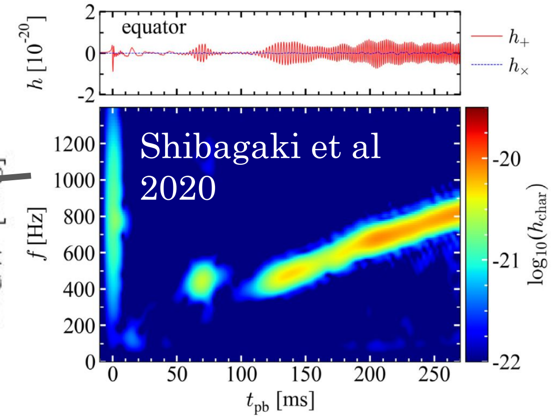
- Duration
- Central Frequency
- Fluence (~hrss)
- Central Time
- Sky location

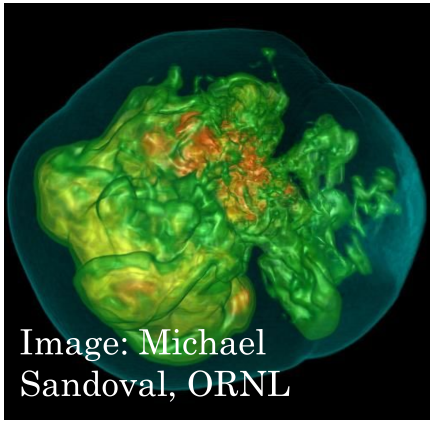
- **Can the LVK be scooped for a GW burst event?**
  - **Not likely.** For a weak burst event
  - **Maybe.** For a strong burst event
  - **Possibly for some results!** For a targeted source, especially core-collapse supernova
- Possibilities: GW energy, GW luminosity, Explosion Mechanism, Speed of sound of dense matter (if neutrino oscillations)

While waiting for a Galactic CCSN



Request: can we have more of those? More extreme but numerical

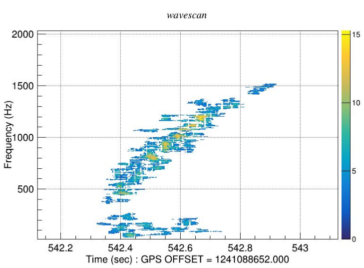




Low-latency Physical Inference

Approach:

Implement in low-latency **the existing methods**



GW burst

30-60s: LVK public alert

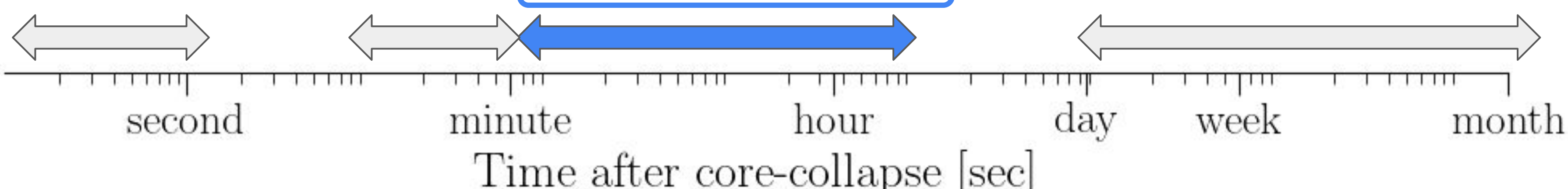
Prompt convection

PNS oscillations

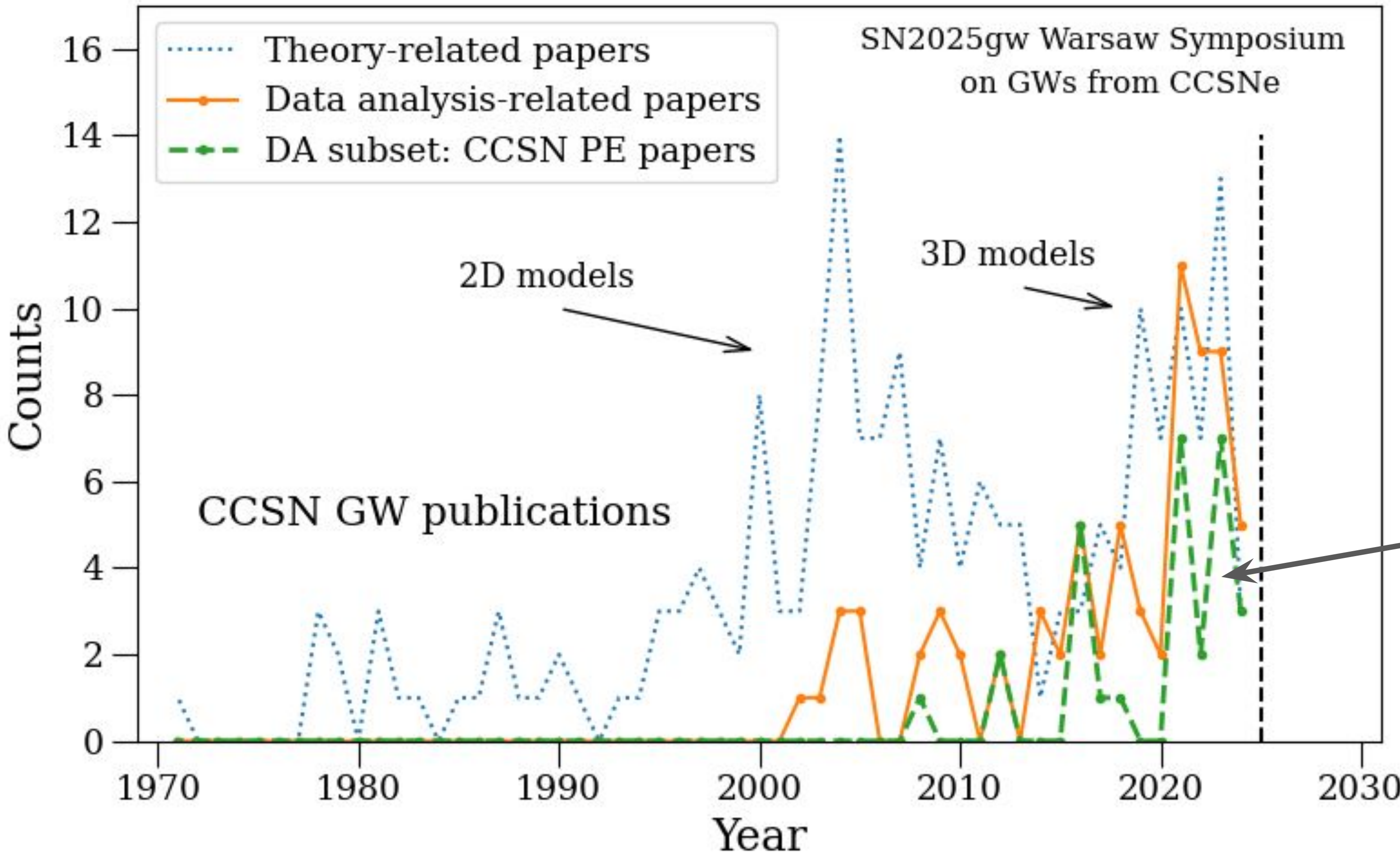
SASI/convection

Physical inference

Current infrastructure: human involvement for the physical inference



CCSN GW publications

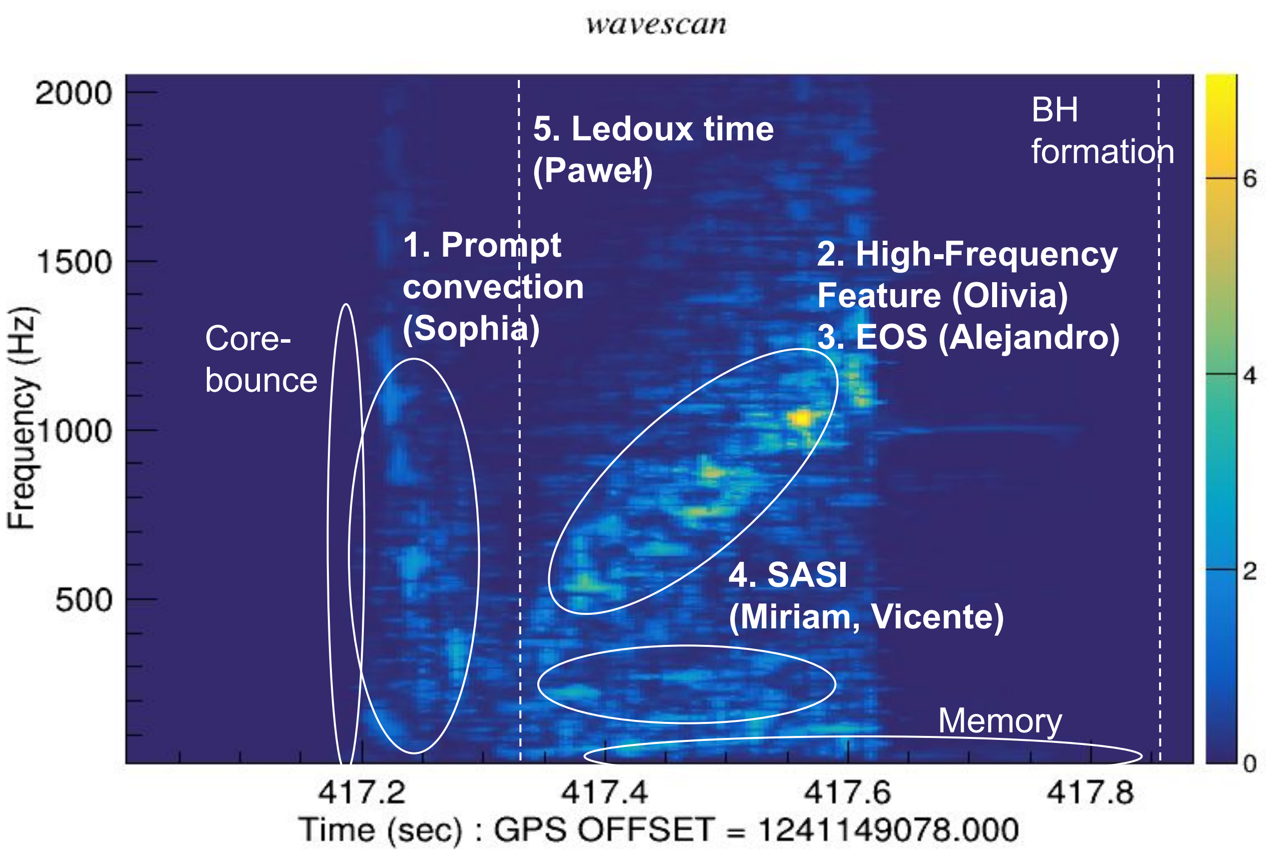


Approach:

take existing methods and implement them in low-latency

CCSN GW Literature, by Ewald Mueller:
https://wwwmpa.mpa-garching.mpg.de/rel_hydro/GWlit_catalog.shtml

CCSN PE
Warsaw Summer Projects



6. Emission Regions (Brajesh)
7. GW energy (Sreeta)
8. Source Orientation (Pratul)
9. CCSN Sound (Jan)
10. GW Representation (Stanisław)

Parameter Estimation
vs
Physical Inference

Parameters estimated during the physical inference analysis, given the GW feature present:

- t_{prompt} - beginning of the prompt convection
- ξ_{prompt} - prompt convection strength
- p_{EOS} - probability of more probable EOS (SFHx, LS etc) using HFF
- v - speed of sound using SASI frequency
- R_{stall} - radius of stalled shock using SASI frequency
- t_{Ledoux} - beginning of Ledoux convection
- E_{GW} - GW energy
- P_{GW} - GW luminosity
- $(\phi_{\text{src}}, \theta_{\text{src}})$ - source orientation

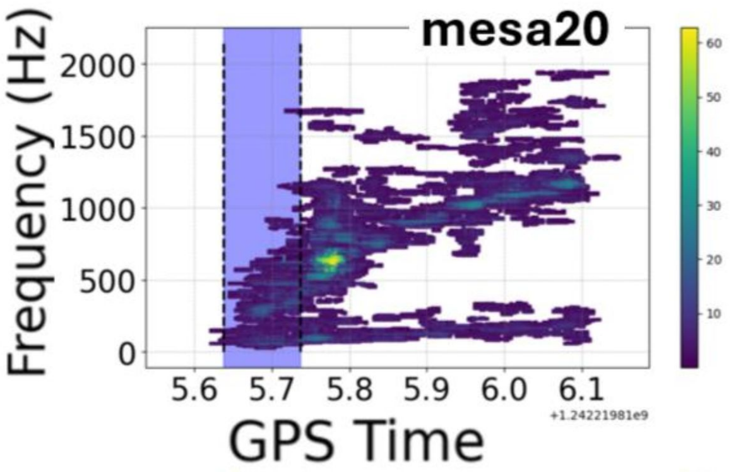
Physical Inference, even more options

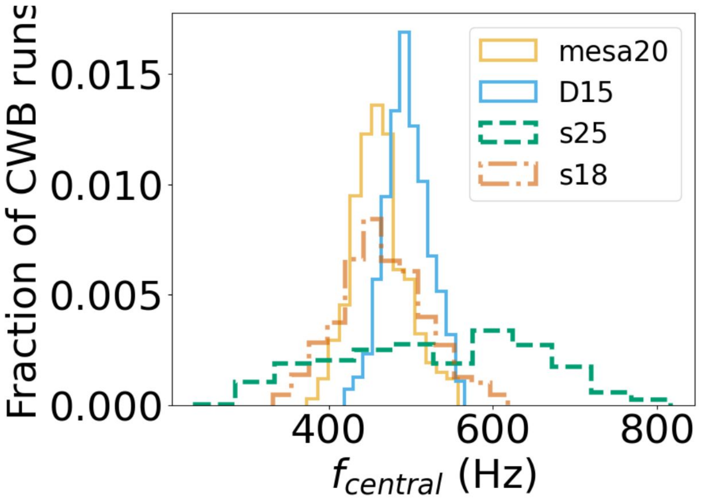
Other physical parameters that could be extracted:

- ξ - compactness (Pajkos et al 2021, ADS)
- L - angular momentum, using bounce signals
- β - kinetic to potential energy ratio, using bounce signal
- M_{PNS} and R_{PNS} - combination of PNS mass and radius
- ω_c - rotation rate using bounce signal
- ι - rotation axis orientation using GW polarization
- t_{fail} - time of BH formation
- ξ_{NFC} - neutrino flavor conversion strength
- ξ_{memory} - what physical parameter can we learn from GW memory?

1. Prompt convection (Sophia)

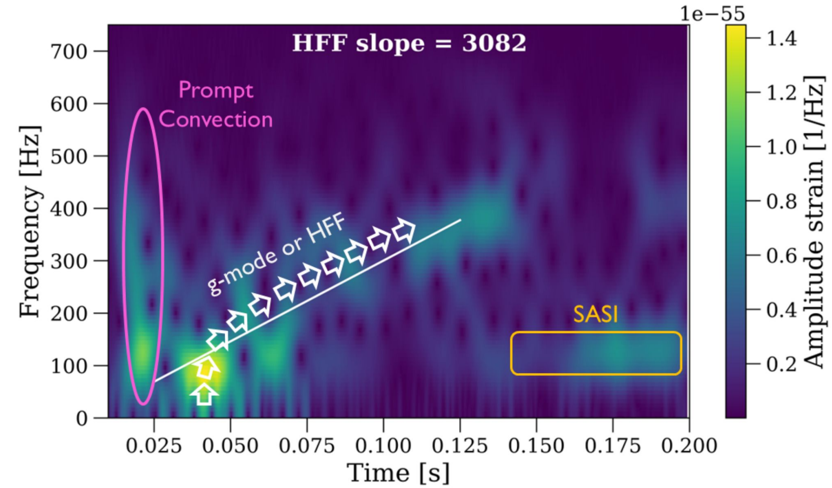
- See Sophia's poster
- No method yet developed
- Thanks to Bernhard for answering our questions
- Requests/Questions to the Modelers:
  - Request: neutrino data to learn about observational initial time.
  - Request: shock radius evolution
  - Request: prompt convection start/end in your simulation
  - Given spherical asymmetry of the progenitor stars, what are the GW amplitudes we really expect?

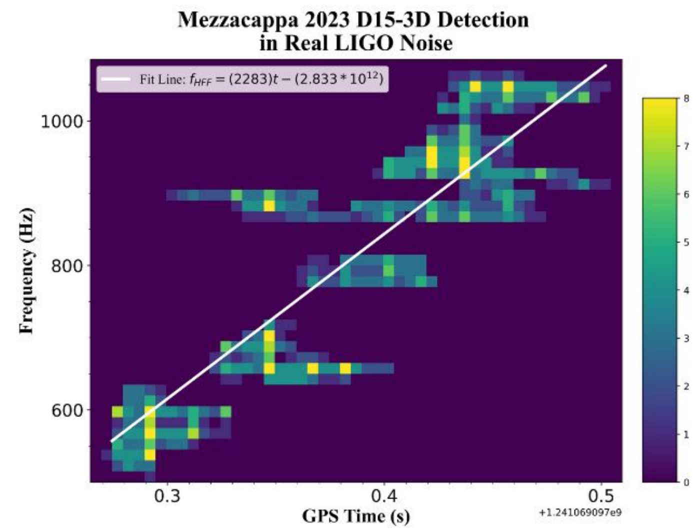




2. and 3. High-Frequency Feature (HFF) (Alejandro, Olivia)

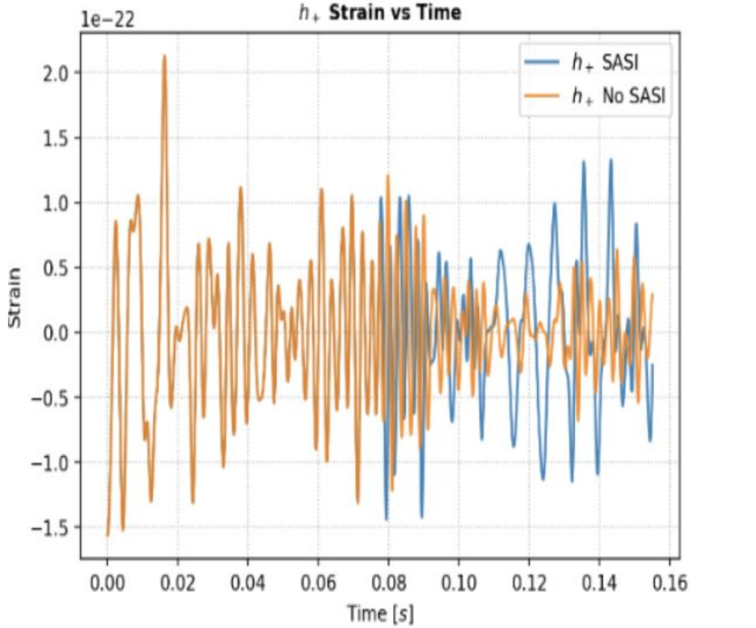
- See Alejandro's presentation (Monday)
- See Olivia's poster
- A lot of the attention in the literature
- Thanks to Alejandro and Pablo for helping with our questions
- Request/Questions to the Modelers:
  - How does it correlate with neutrinos?
  - When does the High-Frequency Feature starts/end?
  - Could you provide us with the data on how PNS radius and mass evolve?
  - How often HFF appear, every time?

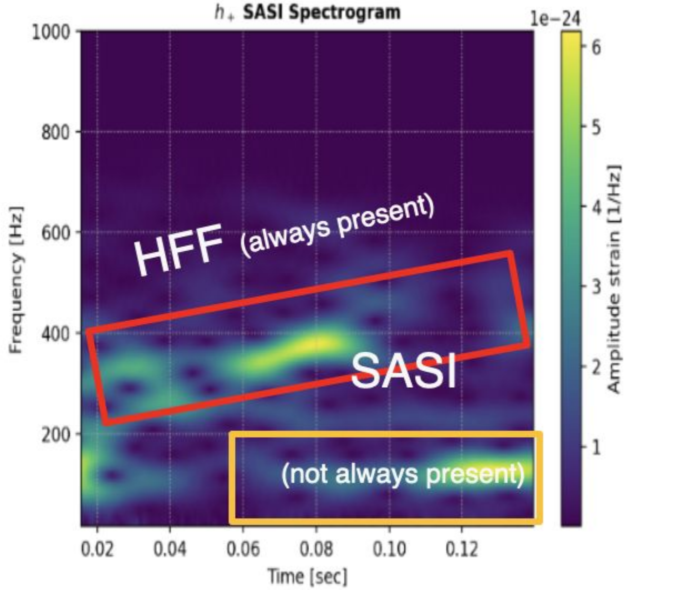




4. SASI (Vicent, Miriam)

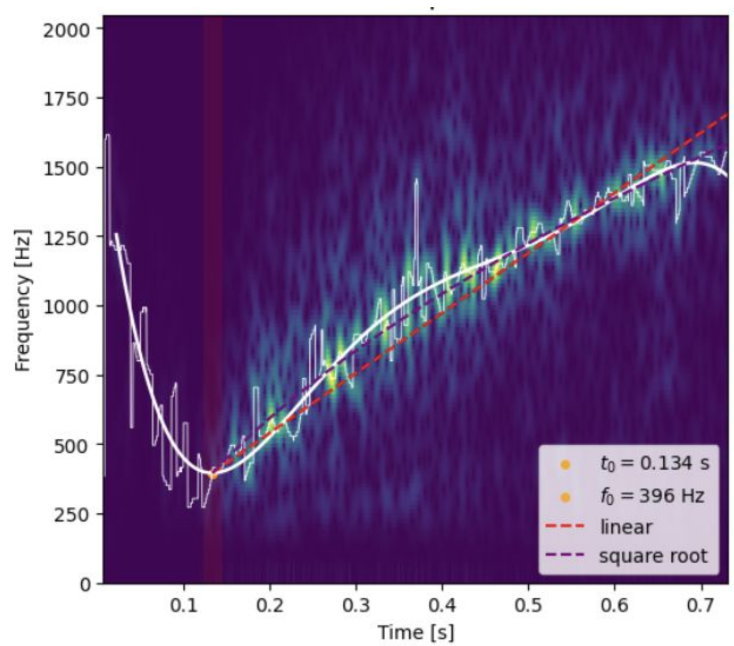
- See Vincent's presentation (Friday)
- Requests/Questions to the Modelers:
  - Request: neutrino light curves
  - What are the start/end of SASI in your simulation?
  - What is the frequency (peak/spread) in your simulation?
  - SASI vs convection, how to differentiate?
  - What physical properties (besides time stamps after bounce) can help us distinguish between all of the low-frequency features (< 300 Hz) sources?

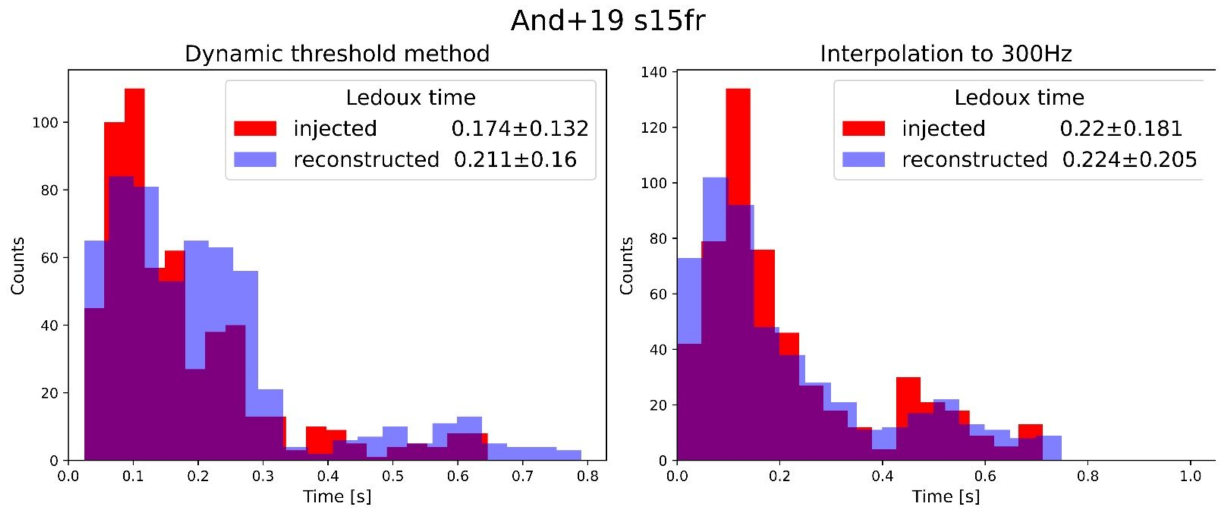




5. Ledoux convection star (Paweł)

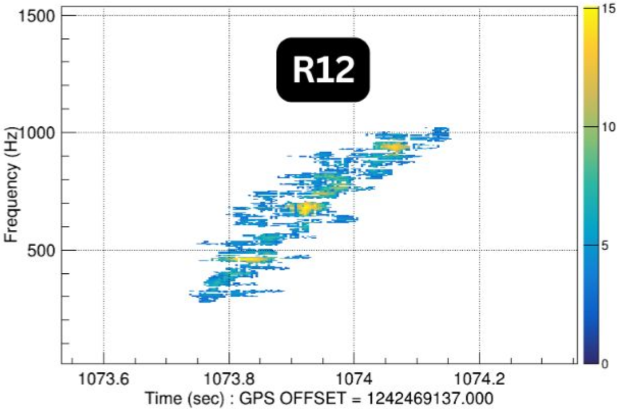
- See Paweł’s poster
- Requests/Questions to the Modelers:
  - Request: convective data mapped with GWs
  - What is the beginning of the Ledoux convection in your simulation?
  - Is this time a start of HFF?
  - How strong is prompt convection to find a minimum of peak frequencies.

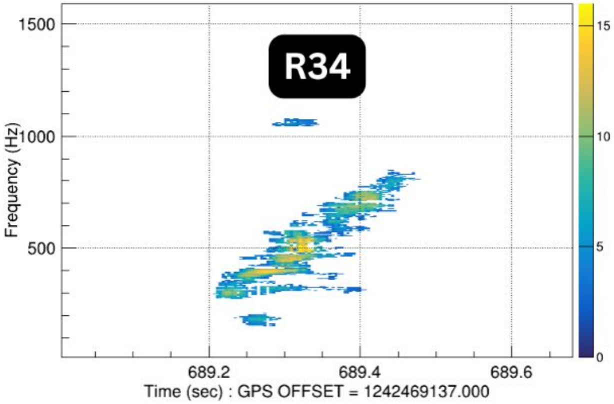


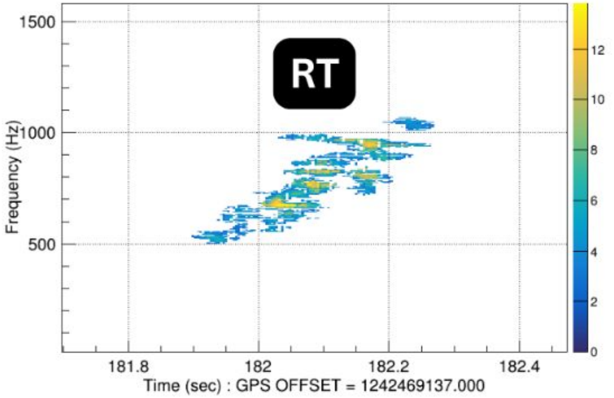


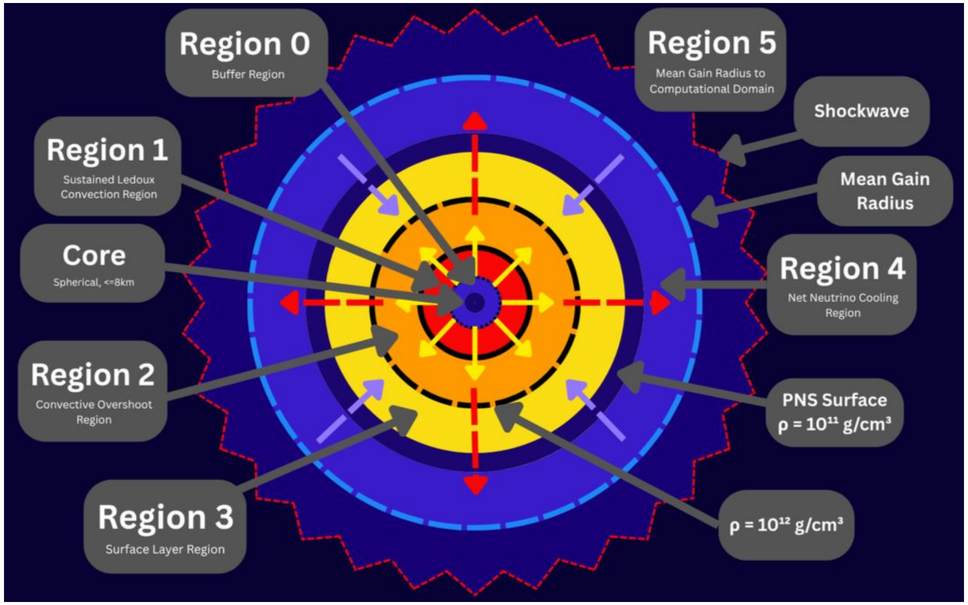
6. GW Emission Regions (Brajesh)

- See Brajesh’s poster
- Thank you do Daniel Murphy for answering our questions
- Requests/Questions to the Modelers:
  - Request: data divided into regions
  - How would you divide GWs in order to distinguish emission regions?
  - How does the metallicity of the PNS models impact various observables?



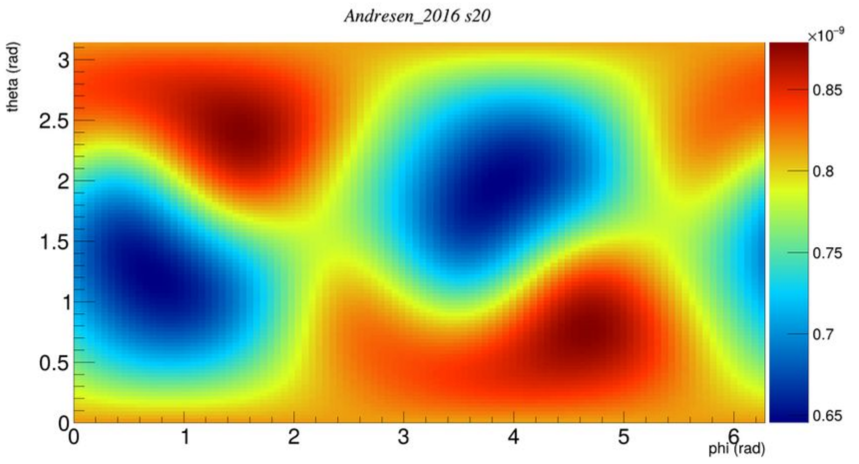


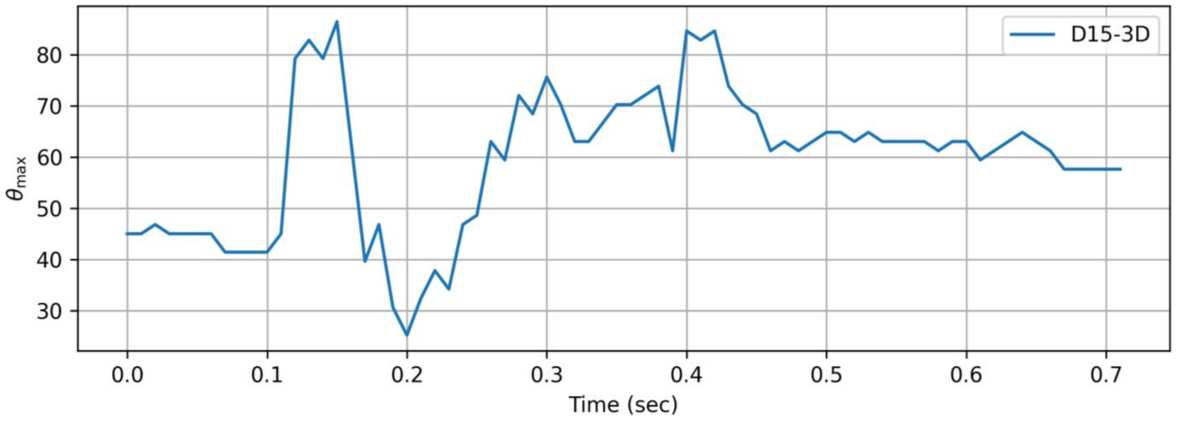




7. GW Energy (Sreeta)
8. Source orientation (Pratul)

- See Pratul's poster
- Requests/Questions to the Modelers:
  - Request: PNS rotation axis evolution.
  - What does the maximum GW emission mean?
  - How does the PNS axis evolve?





9. CCSN GW Sounds (Jan)
10. GW Data Representation (Stasiek)

- What formalism is preferred?
- Quadrupole approximation:

$$\mathbf{h}_{ij}^{TT}(t, \mathbf{x}) = \frac{1}{D}\ddot{Q}_{ij}(t - D/c, \mathbf{x})$$

- Newman-Pearson notation
(why is M=1.41, does it change between simulations?)

$$h_{+} + ih_{\times} = \frac{M}{r}\sum_{l=2}^{\infty}\sum_{m=-l}^{l} H_{lm}(t)^{-2}Y_{lm}(\theta, \phi)$$

- We are building tools to go between these two data representations.

- We are building a webpage with the GW sounds from SN simulations.
  - Request: feel free to send us your beautiful pictures and movies of your simulations

Summary

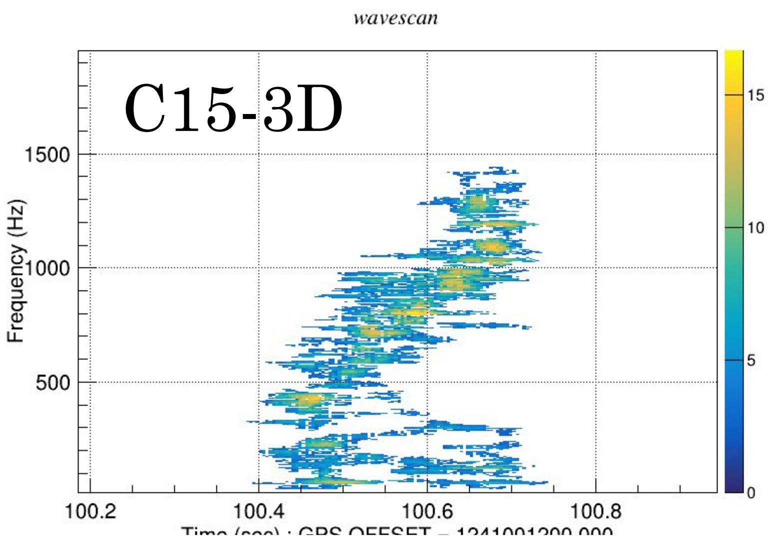
- A global CCSN Physical Inference is challenging
- Having waveforms is not enough
    - Feedback from the Modelers community is essential

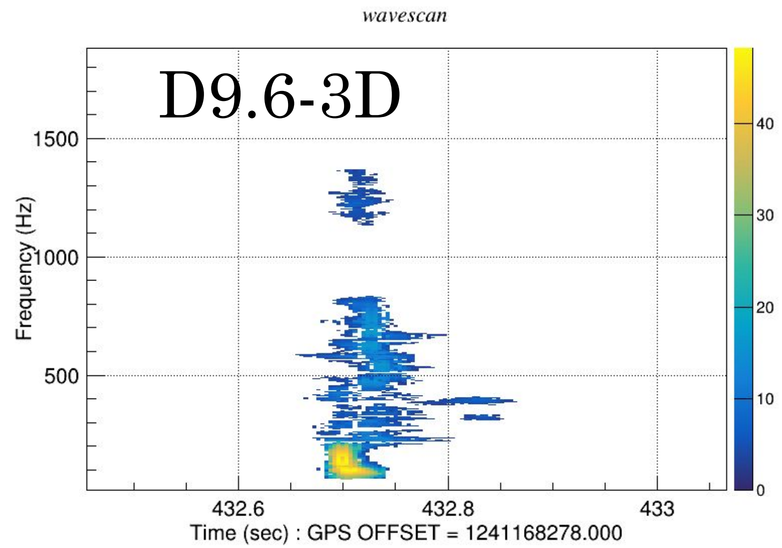
Extra Slides

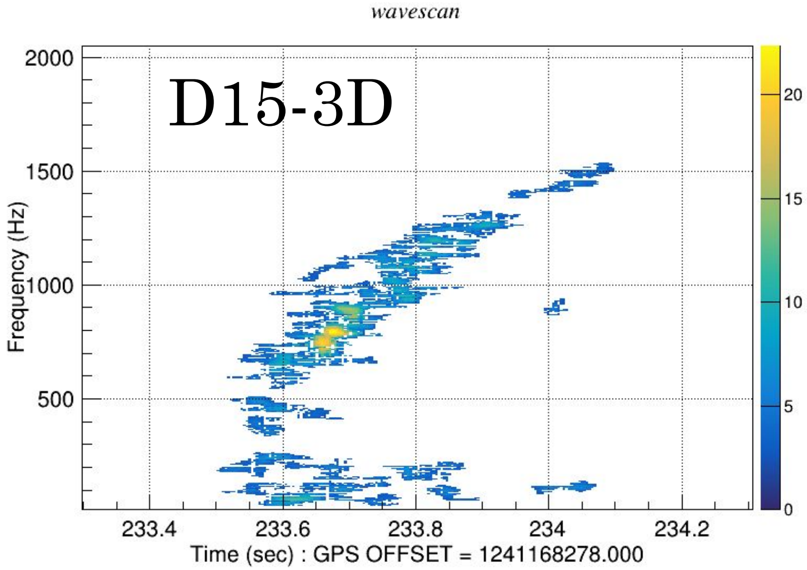
Other Notes

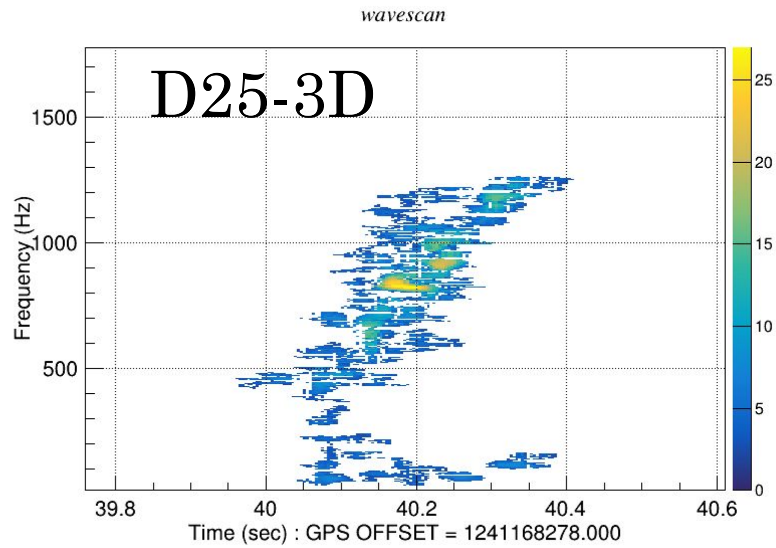
- What is the global effort to probe the parameter space?
- How to systematically explore GW features, is it possible to isolate them?
- How would you probe the physical parameter space?

Challenge, the models may be very different the waveforms, not. Example for SNR=80









Can Modelers scoop LVK?

O4 public information for bursts - notes

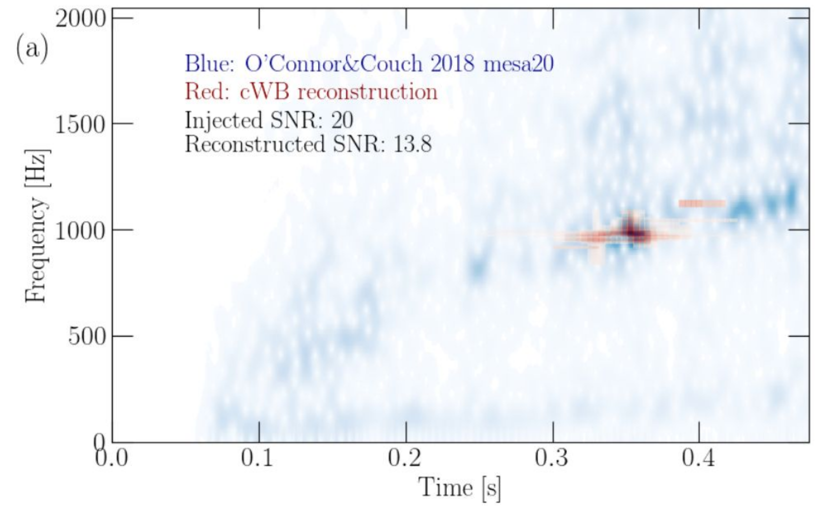
Marek Szczepańczyk

- O3 lesson learned: S200114f was weak and did not bring much attention.
- O3 public information: duration, peak frequency and hrss.
- O4: a weak burst event might not bring much attention.
- **Can the LVK be scooped?**
  - **Not likely.** For a weak burst event
  - **Maybe.** For a strong burst event
  - **Possible for some results!** For a targeted source, especially core-collapse supernova
- Core-collapse supernova:
  - High-profile physical properties can be estimated from a few publicly released information. It's not guaranteed, but very possible. Even if they are conservative, they are novel. Results published later by LVK will be rather corrections.
- **Possible solution** for burst public alerts, a condition:
  - No EM and/or neutrino counterpart: duration, peak frequency, hrss
  - EM and/or neutrino counterpart: none, or just peak frequency?

Core-collapse supernova

- How can the LVK be scooped?
- Examples of what people outside the LVK can assume:
  - GW signals of low-SNR events are typically reconstructed first around the peak frequency.
  - LVK papers provide energy limit estimates as a function of peak frequency.
- EM observations:
  - GWs and EM are not correlated but EM can teach us a lot about a CCSN
  - What can be estimated:sky location, source distance, progenitor star, rotation, supernova type etc.
- Neutrino:
  - GWs and neutrino are correlated
  - Neutrino like curves will be available to many observers (not public data)

https://arxiv.org/abs/2104.06462



Core-collapse supernova

- Examples of physical properties that can be estimated quickly from currently released publicly information:
  - **Source energy**, it can be estimates from the hrss. Current constraint is 10^-3 Msun, publicly released hrss can provide consevative estimate that is a few orders of magnitude lower.
  - **Source power** = energy/duration. This quantity provides the dynamics of a CCSN source, important for CCSN modelling.
  - **Explosion mechanism**, it can be roughly estimated. Neutrino-driven explosions are typically weaker.
  - **Dominant emission process**, peak frequency plays an important role: SASI/convection dominated (low-frequency, below 300 Hz) or protoneutron star oscillation dominated (higher frequency)
  - **Oscillations of the shock or speed of sound** from GW peak frequency and neutrino light curve oscillations.
  - Etc.

Core-collapse supernova

- Table below shows examples of the CCSN models and basic properties of the waveforms
- The public information can be matched with the models, and model-dependent quantities can be further explored.

https://arxiv.org/abs/2104.06462

Waveform Family	Numerical Method	GW Features	Waveform Identifier	$M_{\rm star}$ [$M_\odot$]	Ω_c [rad/s]	$f_{\rm peak}$ [Hz]	$E_{\rm GW}$ [$M_\odot c^2$]	Duration [ms]
Abdikamalov et al. 2014, 2D [76]	LS220, Shen CoCoNuT	bounce prompt-conv.	A1O01.0	12	1.0	819	9.4×10^{-9}	50*
			A2O01.0	12	1.0	854	1.7×10^{-8}	50*
			A3O01.0	12	1.0	867	7.0×10^{-9}	50*
			A4O01.0	12	1.0	873	4.2×10^{-9}	50*
Andresen et al. 2017, 3D [51]	LS220 CoCoNuT PROMETHEUS	g-modes SASI (spiral) convection	s11	11.2	-	642	1.1×10^{-10}	350*
			s20	20	-	687	7.4×10^{-10}	430*
			s20s	20	-	693	1.4×10^{-9}	530*
			s27	27	-	753	4.4×10^{-10}	570*
Andresen et al. 2019, 3D [77]	LS220 PROMETHEUS	SASI (spiral) g-modes	m15fr	15	0.5	689	2.7×10^{-10}	460*
			m15nr	15	-	820	1.5×10^{-10}	350*
			m15r	15	0.2	801	7.1×10^{-11}	380*
Cerdá-Durán et al. 2013, 2D [59]	LS220 CoCoNuT	BH formation g-modes, SASI/conv.	fiducial	35	2.0	922	3.3×10^{-7}	1620
			slow	35	1.0	987	9.4×10^{-7}	1050