Core collapse supernova with 3G detectors

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Motivations

- CCSN physics has a very long history and the role of neutrinos in the explosion mechanism has been understood early.
  - GW and neutrinos are providing unique information about the explosion mechanism, the EOS of the PNS, the mass of the progenitor, etc.
- Recent breakthrough in (2D-3D) numerical simulations : almost all codes observe the same « signatures », but still not yet a complete code that includes all ingredients.
- What is required now is a galactic source or better sensitivity detectors → 3G detectors.
- What will be possible to extract from a source with 3G GW and neutrino detectors is part of this science case document.

Key questions we tried to answer

- How far can we detect a CCSN with the next generation of GW detectors ?
- Can one determine the mechanism of explosion (neutrino/MHD) ?
- What constraints can be put on the nuclear EOS ?
- Can one identify the time of bounce/explosion ?
- Can one identify PNS core oscillation modes ?
- Can one constrain the progenitor mass and/or initial internal profiles ?
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CCSN explosion mechanisms

- Neutrino driven: bounce, quiescence, neutrino convection, inner PNS convection, PNS core f, g and p modes oscillation, SASI
- MHD: Characteristic bounce / peak shape that mainly depends on T/W (rotational to gravitation energy ratio). Non axisymetric instabilities → GW emissions

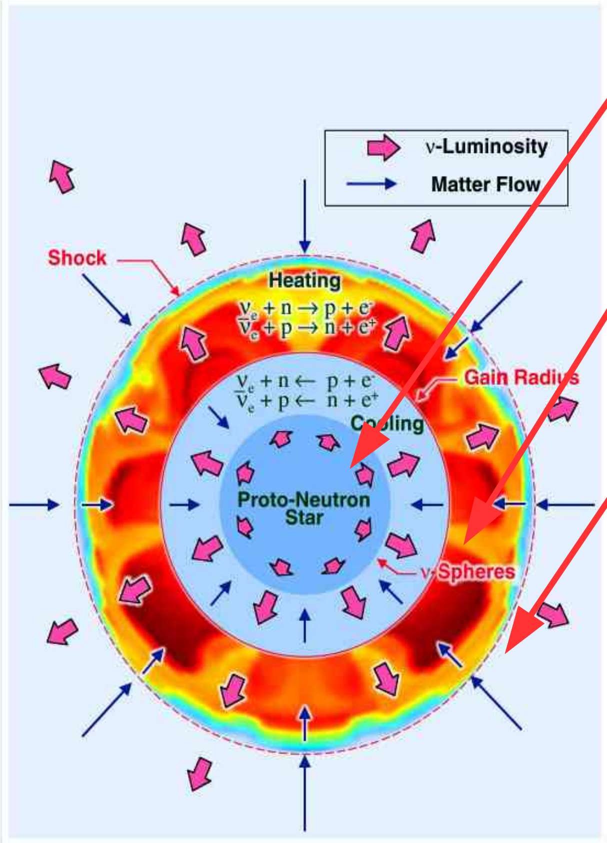


Figure credit : A. Mezzacappa

1. Trapped neutrinos diffuse out ($\tau_{\nu\text{-diff}} >> 1$) of the opaque PNS

2. Neutrinos heat matter in semi-transparant ($\tau_{\nu\text{-diff}} \sim 1$) post-shock region and drive convective flow in hot bubble region between gain radius and shock

3. Neutrinos stream freely ($\tau_{\nu\text{-diff}} << 1$) through transparent stellar envelope.

Additional key ingredients for explosion :

- Nuclear burning.
- Standing accretion shock instability (SASI) is an instability of the shock wave itself. SASI aids the explosion and determines the asphericity.

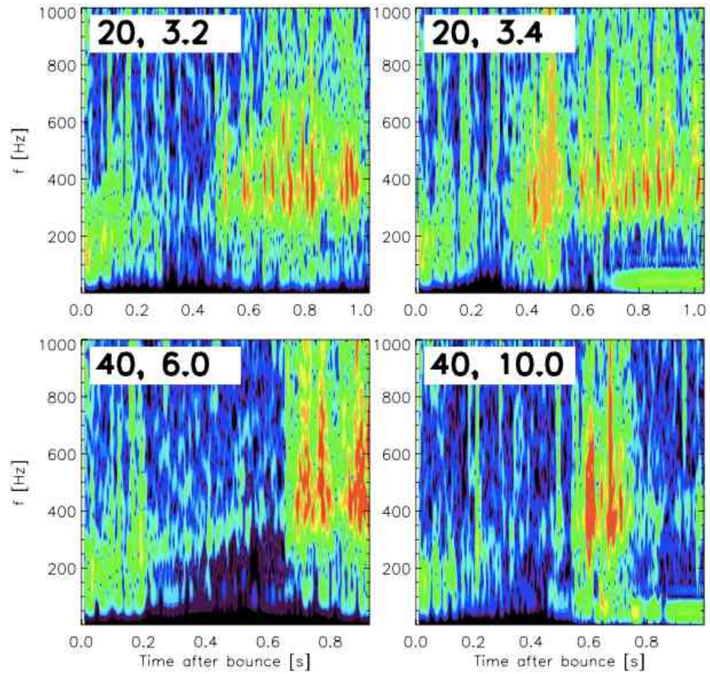
Identified/discussed signal features

- Rotational bounce spike (rapid rotation?); differential rotation
- Initial Progenitor perturbation spike
- Outer PNS convection (early, non-rotating)
- Quiescent phase (altered by progenitor perturbations?)
- Ramp up and saturation of turbulent convection and SASI
- Infall plume excitation of PNS oscillations
- Inner PNS convection
- Transition to explosion, leading to decreased accretion, occasioning signal turnover (near time of frequency peak?)
- Neutrino component
- Christodoulou Memory (low frequency): asymmetric explosion, neutrinos

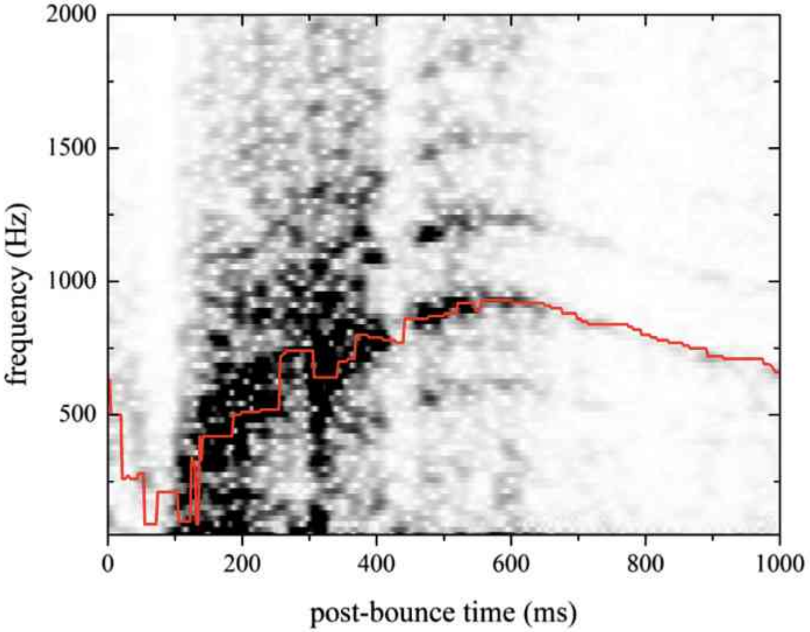
- Progenitor, rotation, orientation, explosion energy dependences?
- Duration of phases; frequency spectra; signal phase?

Neutrino-driven explosion GW waveforms

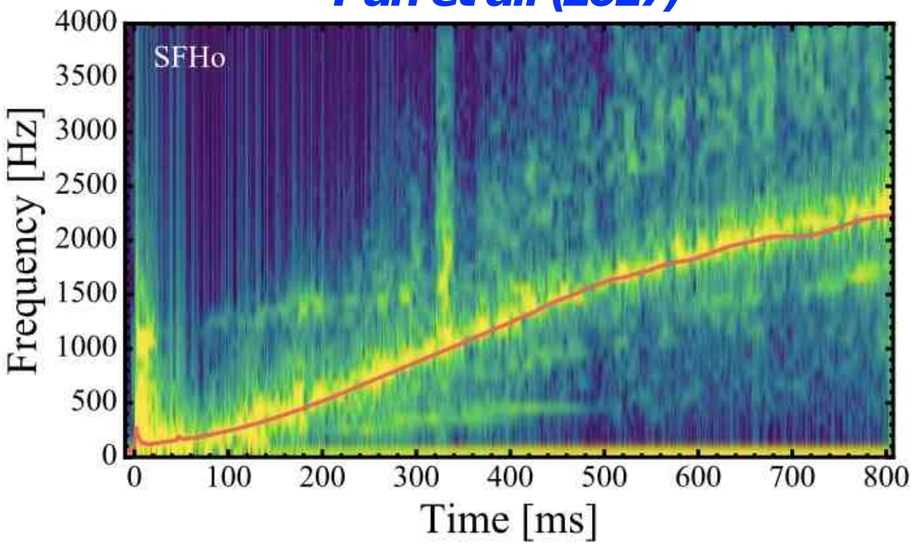
Murphy et al. (2009)



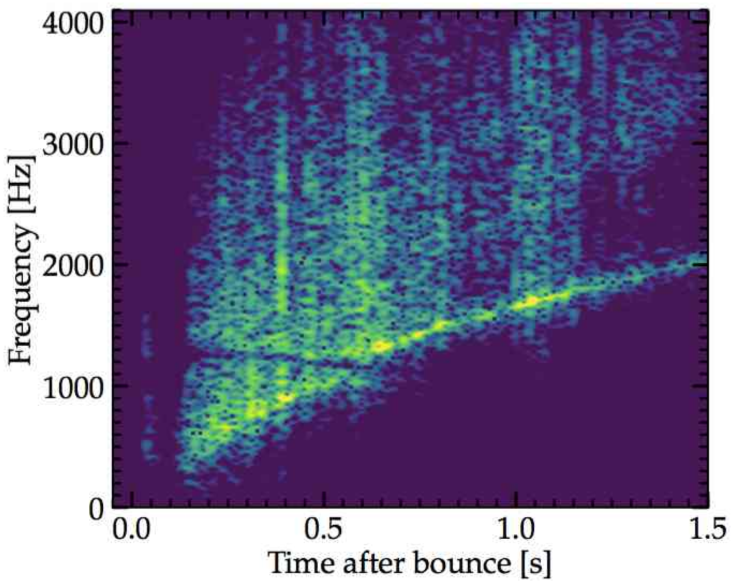
Yakunin et al. (2015)



Pan et al. (2017)

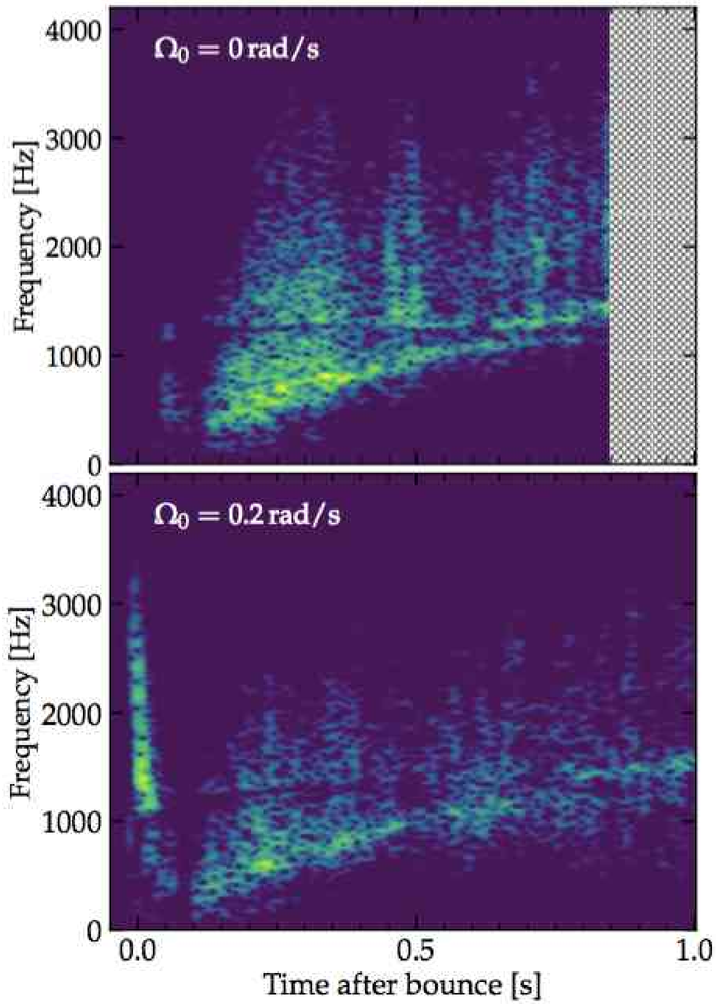


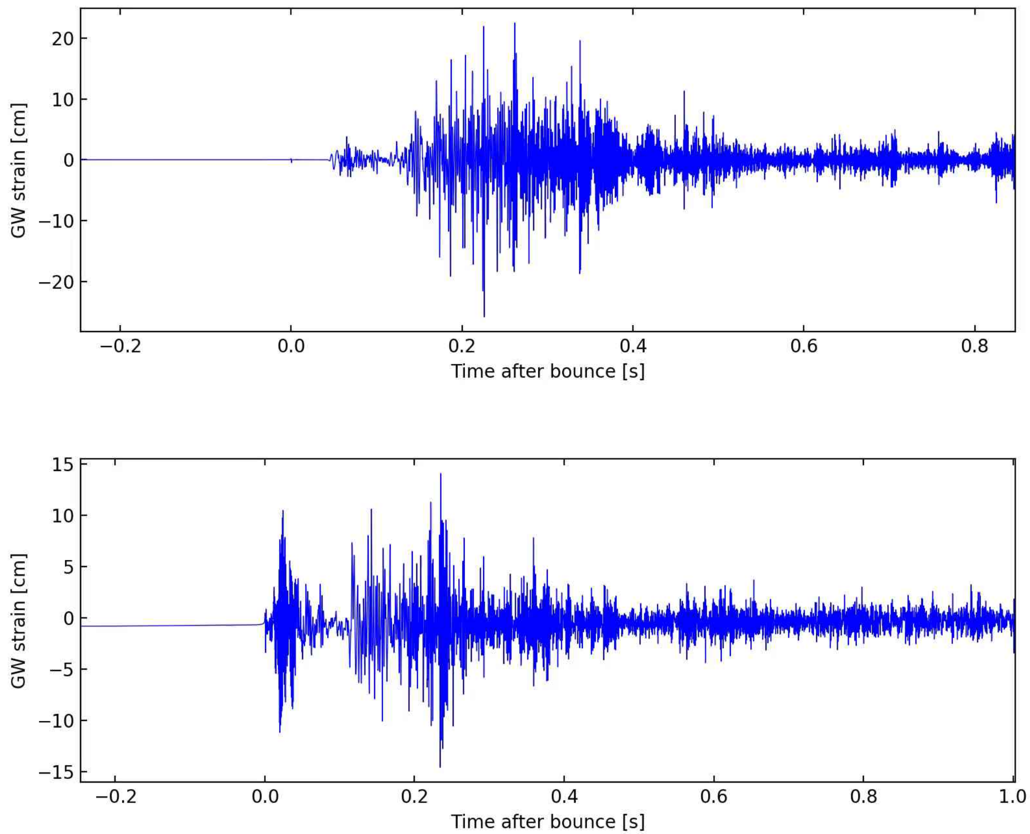
Morozova et al. (2018)



Rotation

Morozova et al. 2018

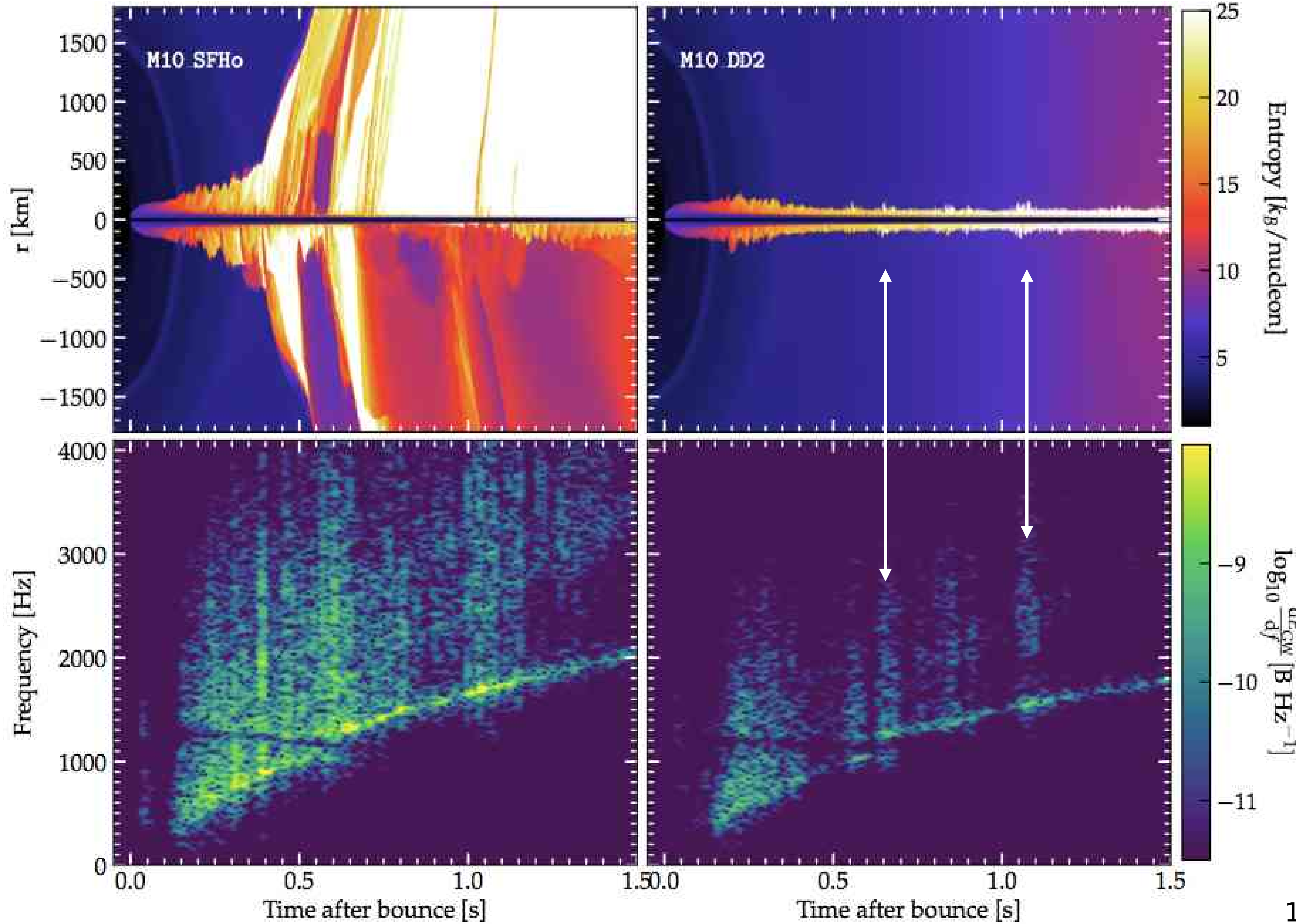




* The bounce signal is stronger, because the collapse is not symmetric
* The dominant frequency is nearly the same

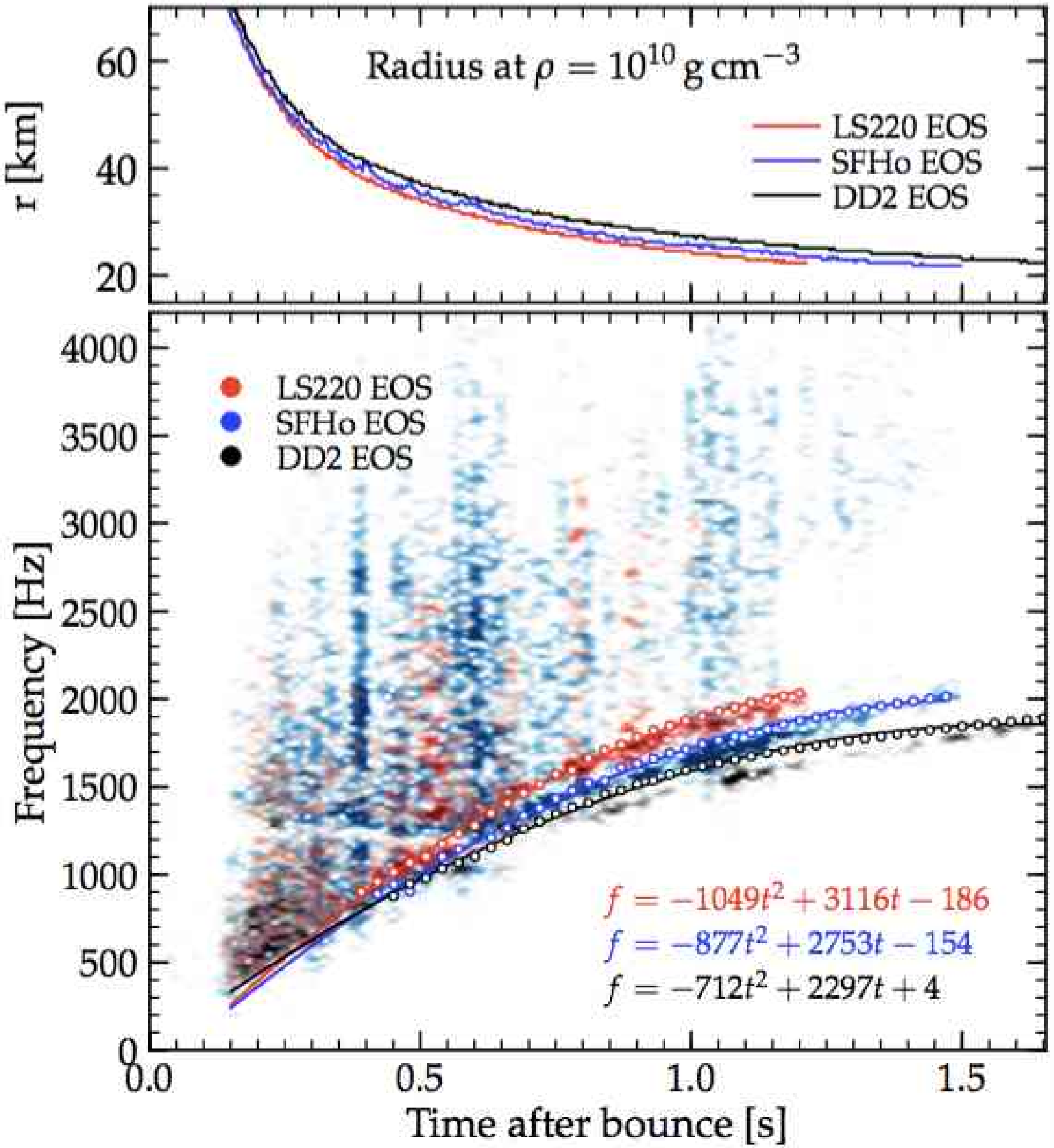
Characteristic bounce / peak shape that mainly depends on T/W (rotational to gravitation energy ratio)

Weaker convection leads to weaker signal



Morozova et al. 2018

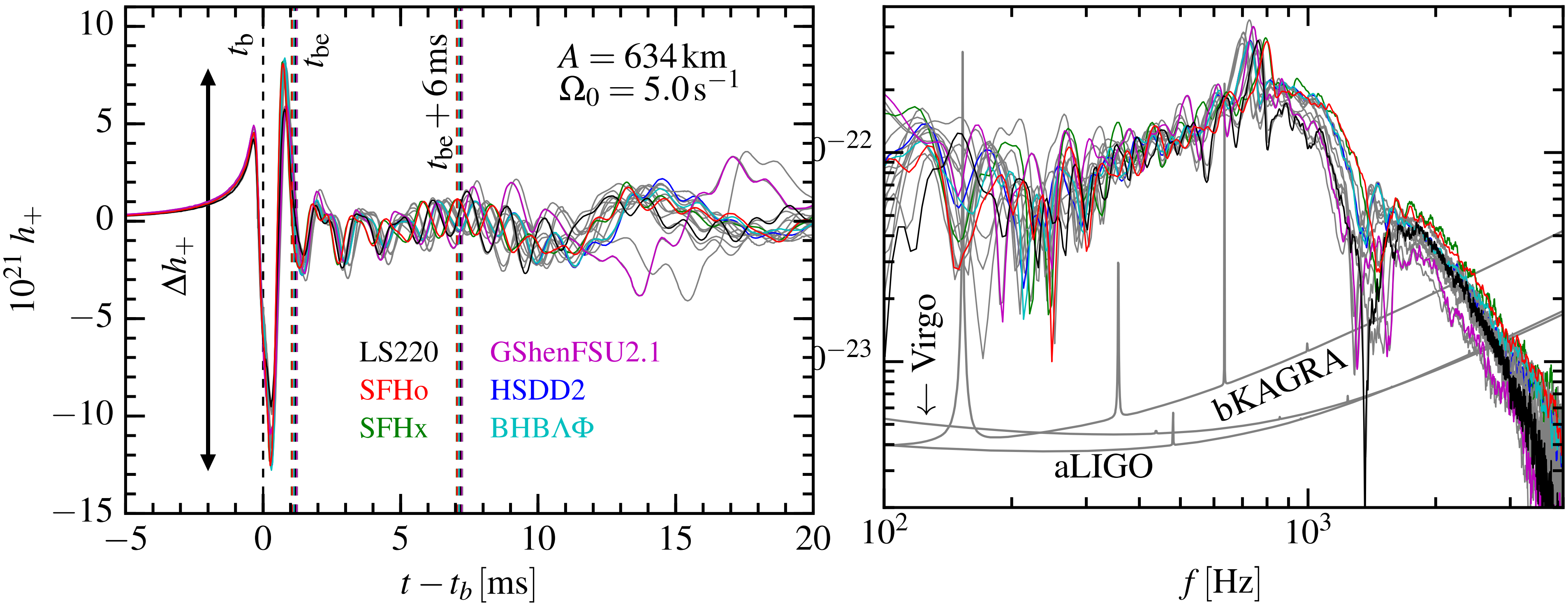
Dependence of the dominant GW frequency on the EOS



- Reflects the evolution of the PNS radius
- Captured reasonably well by the analysis
- Can be described by a quadratic function

Morozova et al. 2018

EOS dependence



Richers et al. 2017

Neutrino/GW/optical synergies

- Timing :
  - Neutrino burst timing measurement provides a O(10ms) precision of the time of the bounce
  - Optical trigger : hours – days precision
- Sky localization accuracy :
  - Optical trigger : ~arcminutes.
  - Super-K : ~ 5deg.
  - GW detectors : ~100 deg^2

3G neutrino detectors: gain of a factor 10

- Correlation between GW & neutrino signal :
  - Burst & GW signal modulated by the same accretion plumes associated with the instabilities in the post-shock flow.
  - SASI is expected to generate modulation in the neutrino signal close to fundamental SASI frequencies (100-200Hz)

Neutrino detectors panorama

Galactic sensitivity

Current supernova neutrino detectors

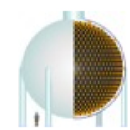
Detector	Type	Location	Mass (kton)	Events @ 8 kpc	Status
Super-K	Water	Japan	32	8000	Running (SK IV)
LVD	Scintillator	Italy	1	300	Running
KamLAND	Scintillator	Japan	1	300	Running
Borexino	Scintillator	Italy	0.3	100	Running
IceCube	Long string	South Pole	0.4/PMT	N/A	Running
Baksan	Scintillator	Russia	0.33	50	Running
Mini-BOONE	Scintillator	USA	0.7	200	Running

@ K. Scholberg









Primary sensitivity is to electron antineutrinos via inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$

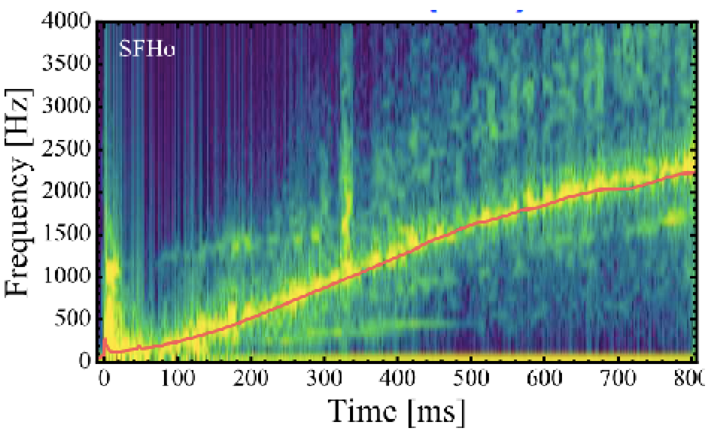
Next generation neutrino detectors :

extragalatic sensitivity with JUNO (2019), DUNE, Hyper-K (>100 000 ν), ...

GW signal detection and source parameter estimation

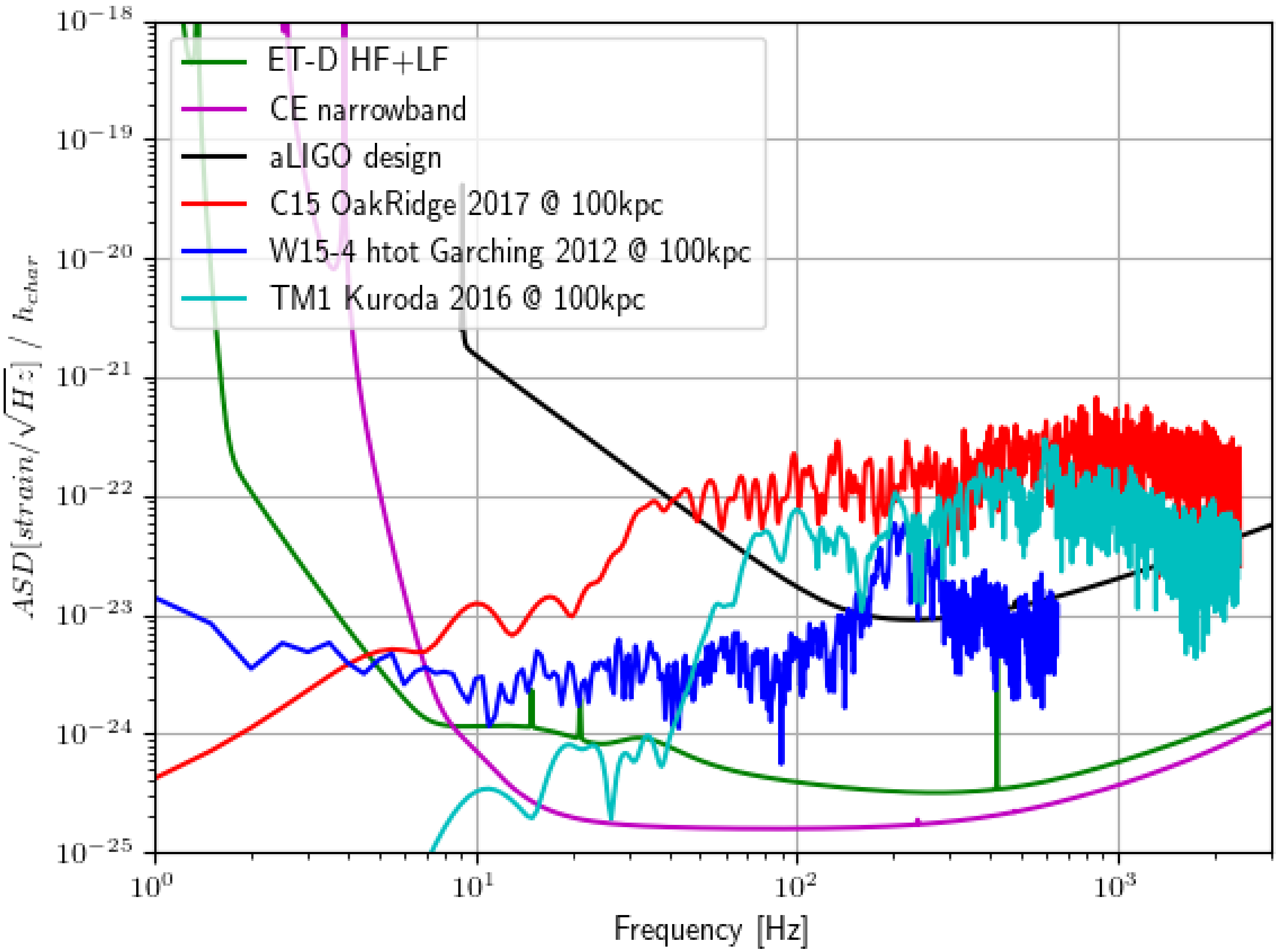
- Detection : All-sky/ all-time searches (silent supernova) & targetted searches :
  - False alarm rate significantly reduced.
  - A short on source window allows to use signal extraction methods that are computing time limited (Bayesian methods using CCSN waveforms or simplified models).

- Source parameter estimation :
  - Agnostic waveform reconstruction using the coherence of the GW polarizations in 2 or more GW detectors data.
  - Identify some of the (loudest) features expected in the different phases : rotation at bounce, quiessence phase, SASI, PNS oscillation modes, …
  - Determine the explosion mechanism : neutrinos or MHD.
  - Constrain EOS, progenitor mass, ...



Still lots of developments that require theoritical inputs

Figure in the document



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