Understanding GWs from CCSNe

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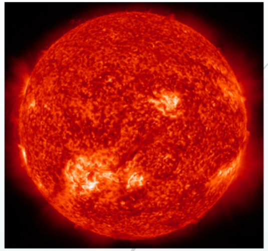
Publications:
- Torres-Forné et al 2018a,b, 2019, Astone et al 2018

4M-COCOS, Fukuoka, 23 Oct. 2019

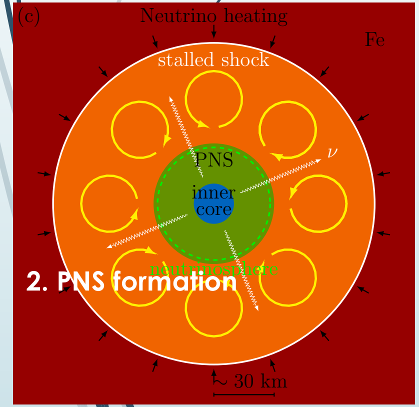
GW emission in CCSN



Collapse of the core of massive stars (8-100 $M_\odot$)

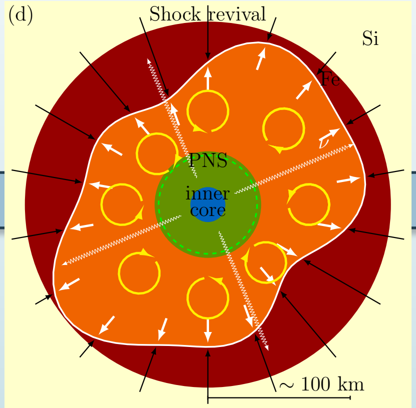
- Non-rotating progenitors (>99%) (Li et al 2011, Chapman et al 2007)
- Observable within ~10 kpc (Gossan et al 2015, Powell & Müller 2018)
- Rare events (~1/ 30 year in our galaxy) (Adams et al 2013)

1. Collapse

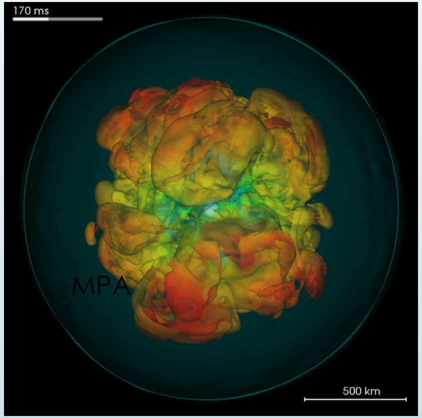


2. PNS formation

3. PNS excitation



4. Neutrino-driven explosion



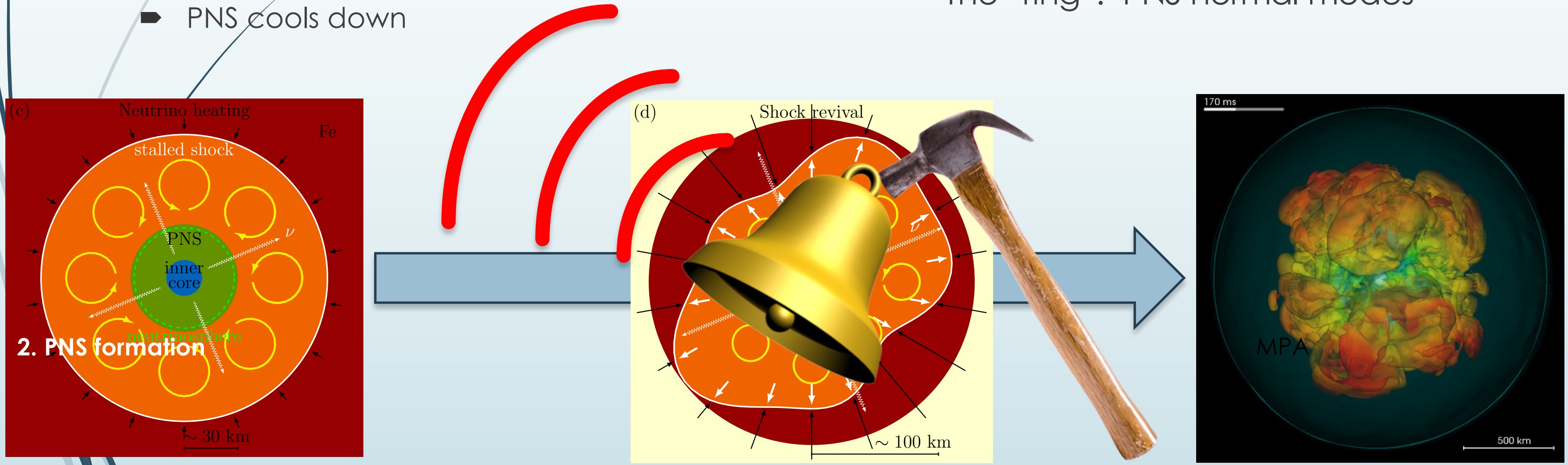
GW emission in CCSN

PNS phase (before explosion):

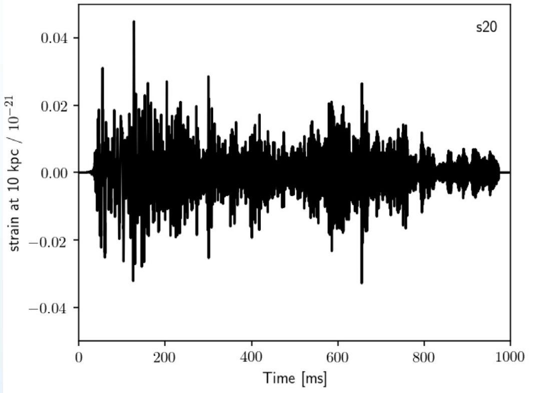
- Duration: ~ 0.1 – 1 s
- PNS mass grows: ~0.5 $M_\odot$ → 1.4 – 2 $M_\odot$
- PNS shrinks: ~30 km → ~10 km
- PNS cools down

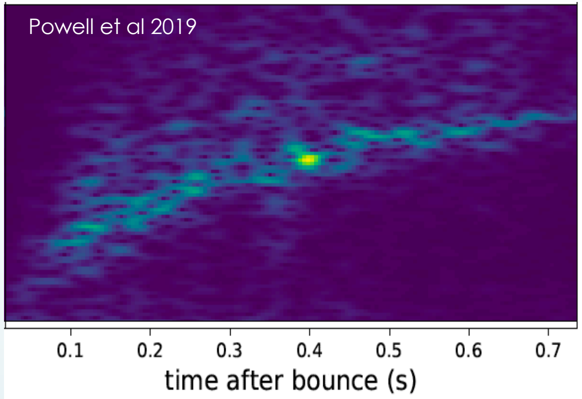
PNS excitation

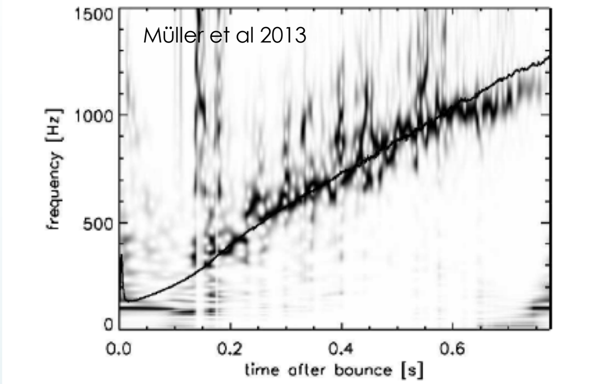
- The "hammer": convection, SASI
- The "bell": proto-neutron star
- The "ring": PNS normal modes

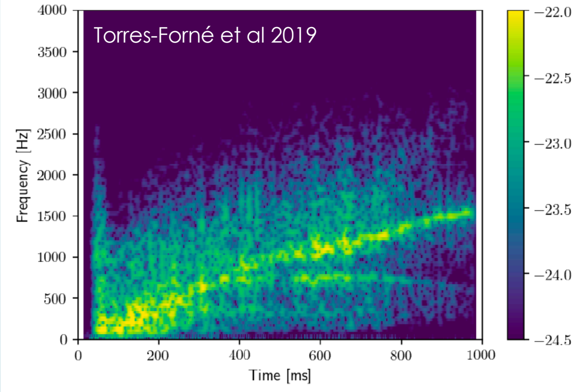


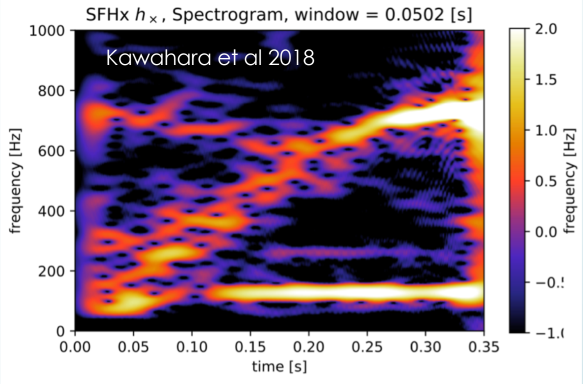
GW emission from PNS oscillations









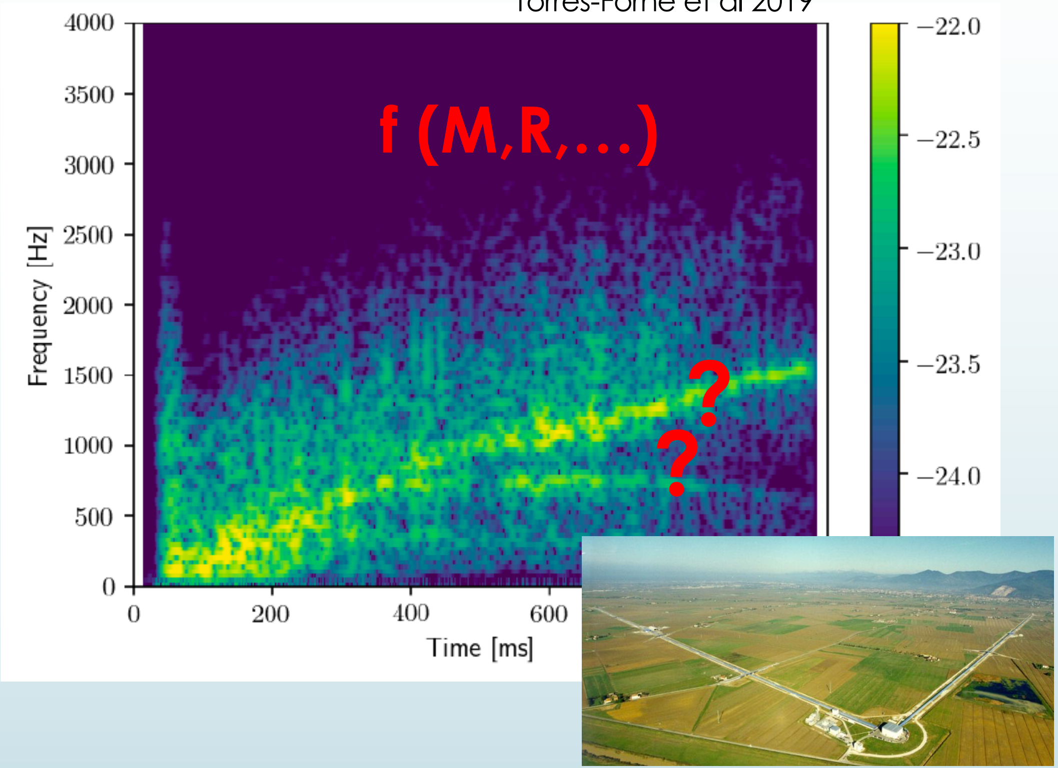


- ❑ **Highly stochastic**
- ❑ **Time evolving frequencies (g-modes, SASI)**

PNS asteroseismology

- **Which modes are observed?**→ mode identification
- **How do mode frequencies depend of PNS properties?** → universal relations
- **Can we improve detectability?** → Machine learning methods

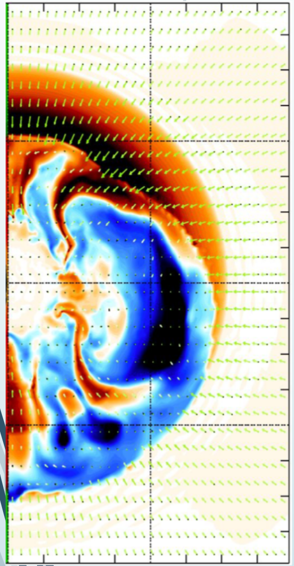
Torres-Forné et al 2019



Mode identification

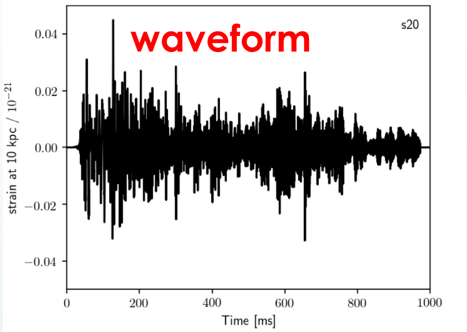
Proto-neutron star oscillations

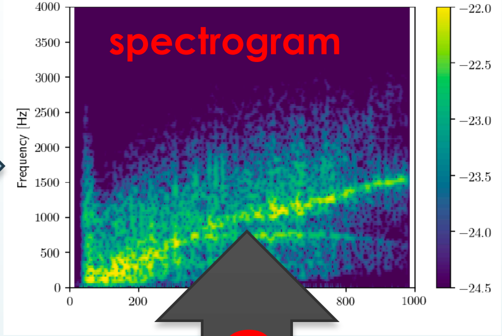
Multi-dimensional numerical simulation

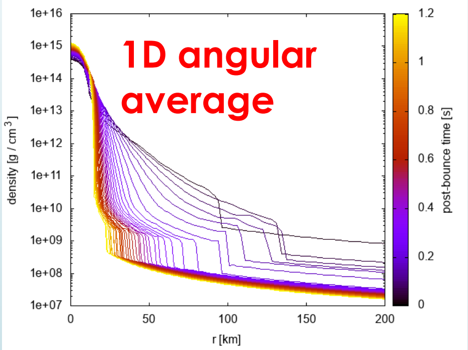


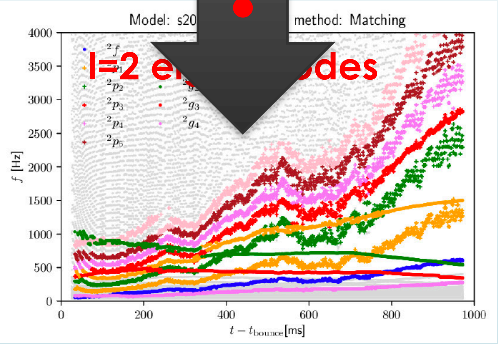
Obergaulinger et al 2013

Torres-Forné et al 2019









Torres-Forné et al 2018

Proto-neutron star oscillations

Linear perturbations of a spherical background → eigenvalue problem

Simplified background (TOV, polynomials…)

Reisenegger & Goldreich 1992
Ferrari et al 2003, 2004
Passamonti et al 2005
Krüger et al 2015
Camelio et al 2017
Sotani et al 2017

Background from simulations

Torres-Forné et al 2018, 2019a,b
Morozova et al 2018, Radice et al 2019
Sotani et al 2019a,b
Westernacher-Schneider 2

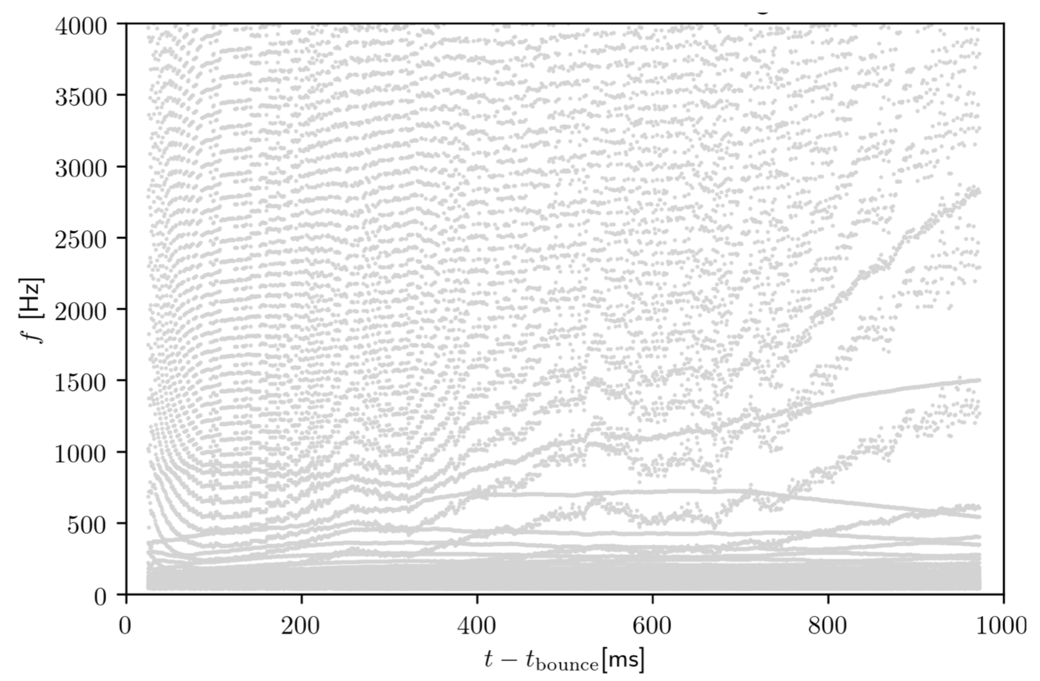
Our contribution:

- Background from simulations
- GR formalism including space-time perturbations (lapse and conformal factor)
- Global treatment (PNS + shock)

Torres-Forné et al 2018a,b, 2019

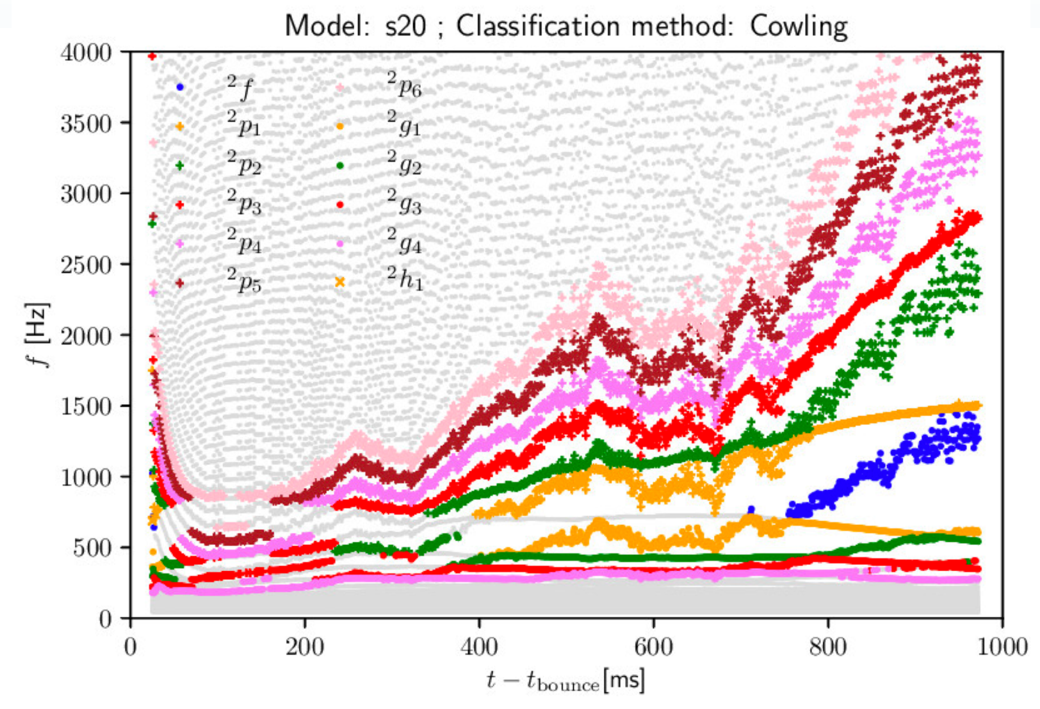
GREAT = General Relativistic Eigenmode Analysis Tool
https://www.uv.es/cerdupa/codes/GREAT/

Non-classified modes



s20, SFHo EOS

Modes classified according to the number of nodes

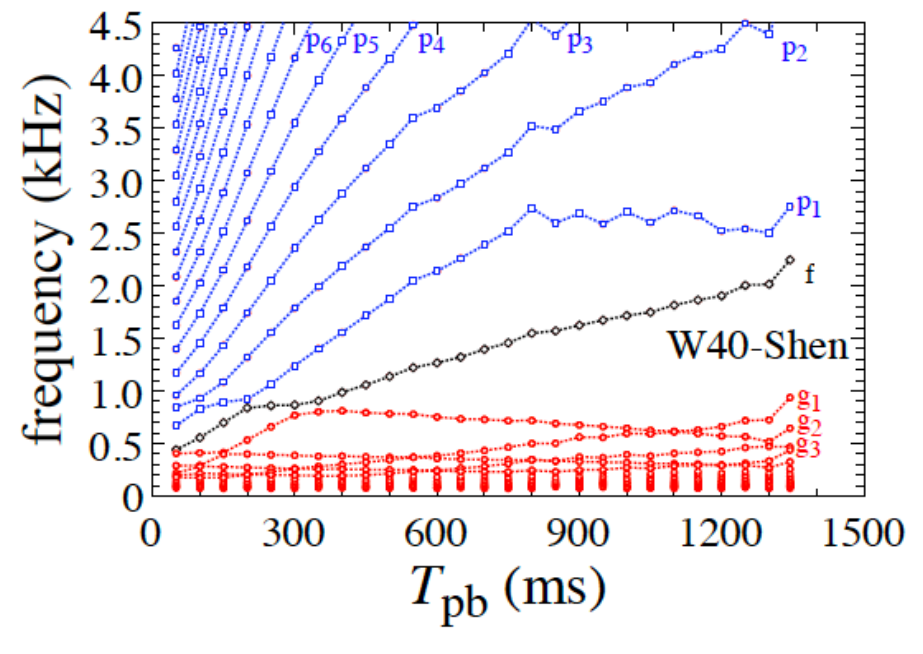


s20, SFHo EOS

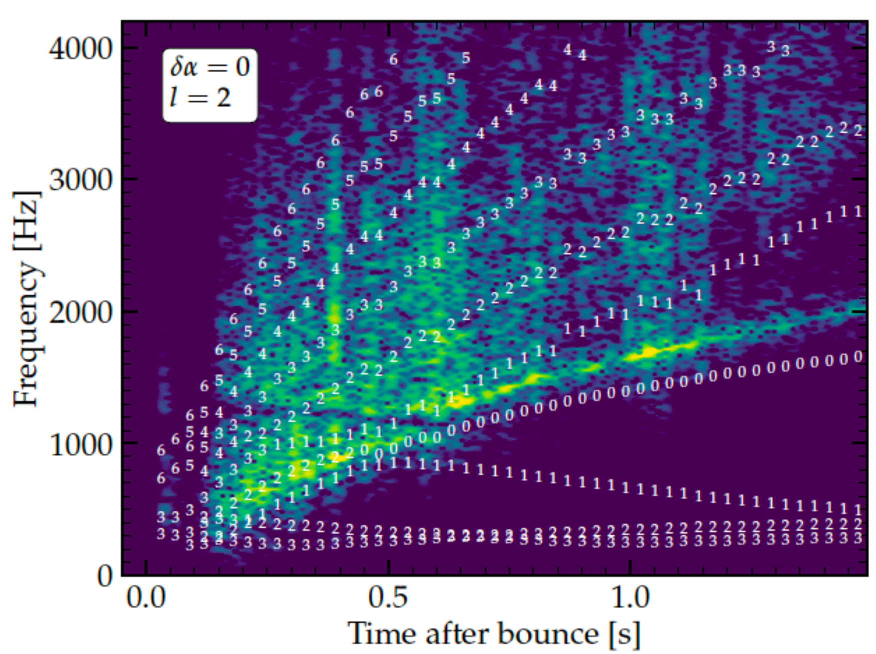
Other groups use this classification

- Morozova et al 2018
- Sotani et al 2017,2019

Modes classified according to the number of nodes

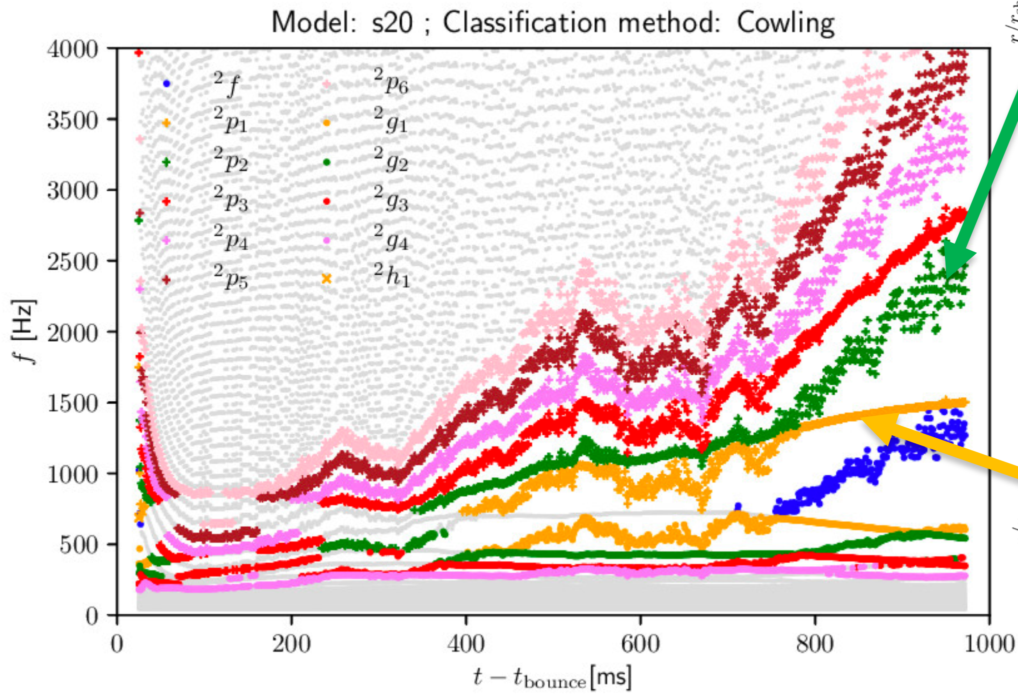


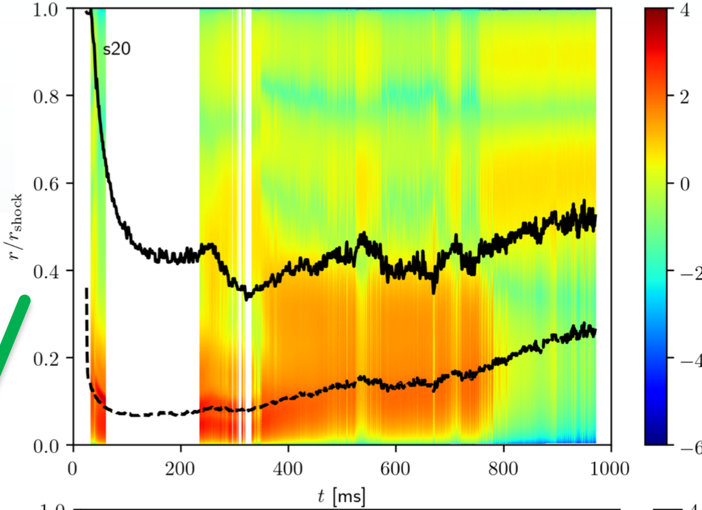
Sotani et al 2019

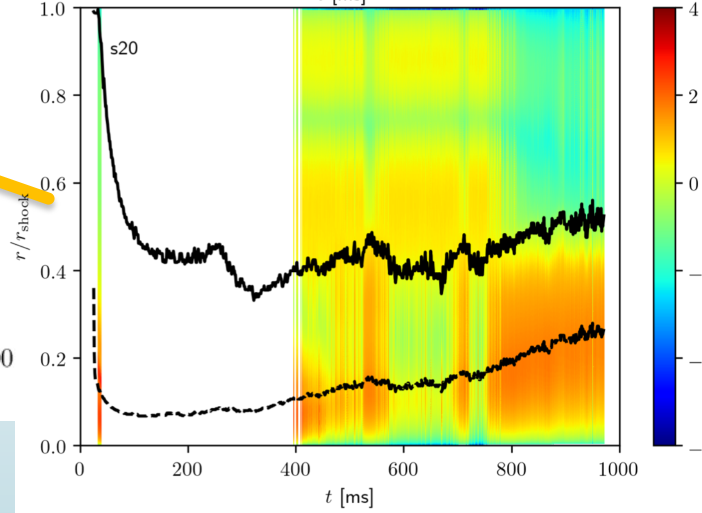


Morozova et al 2018

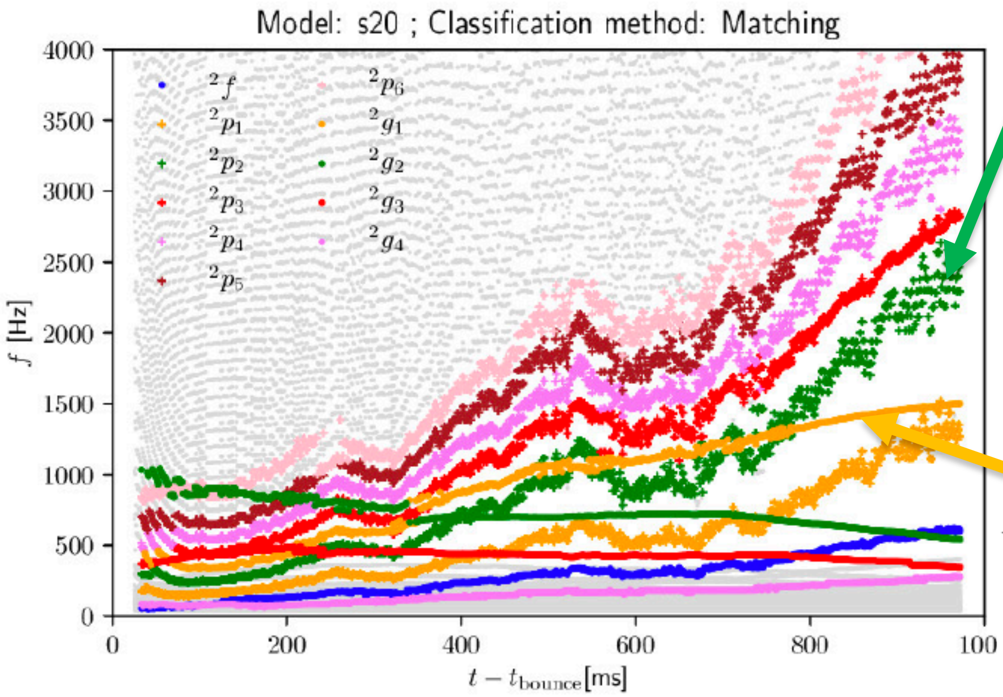
Modes classified according to the number of nodes

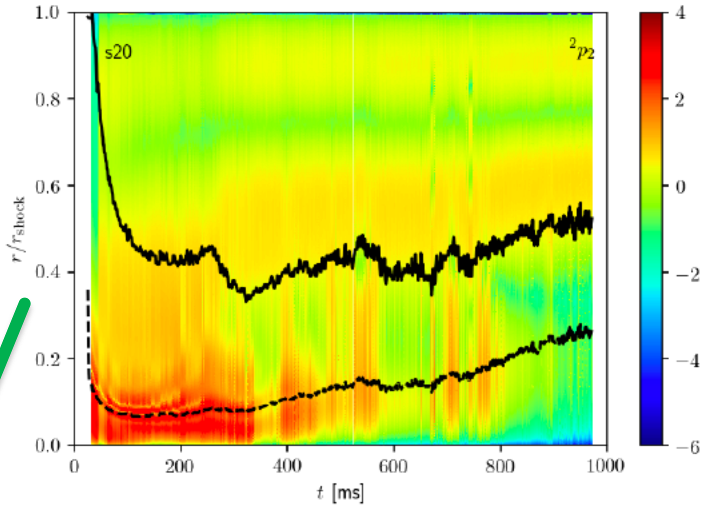


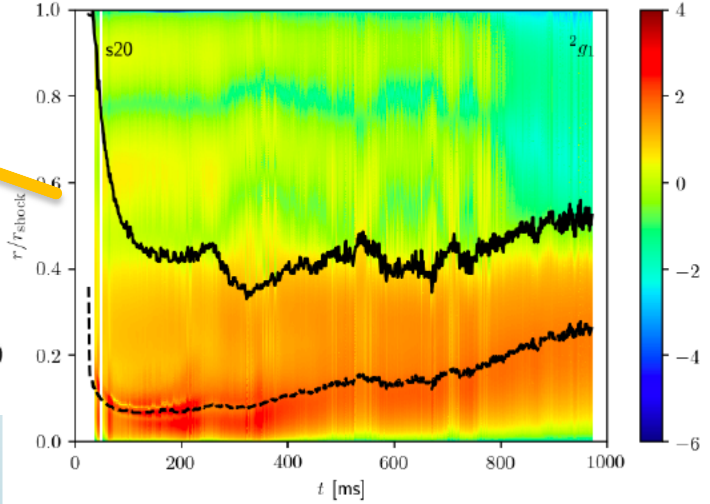




Matching classification

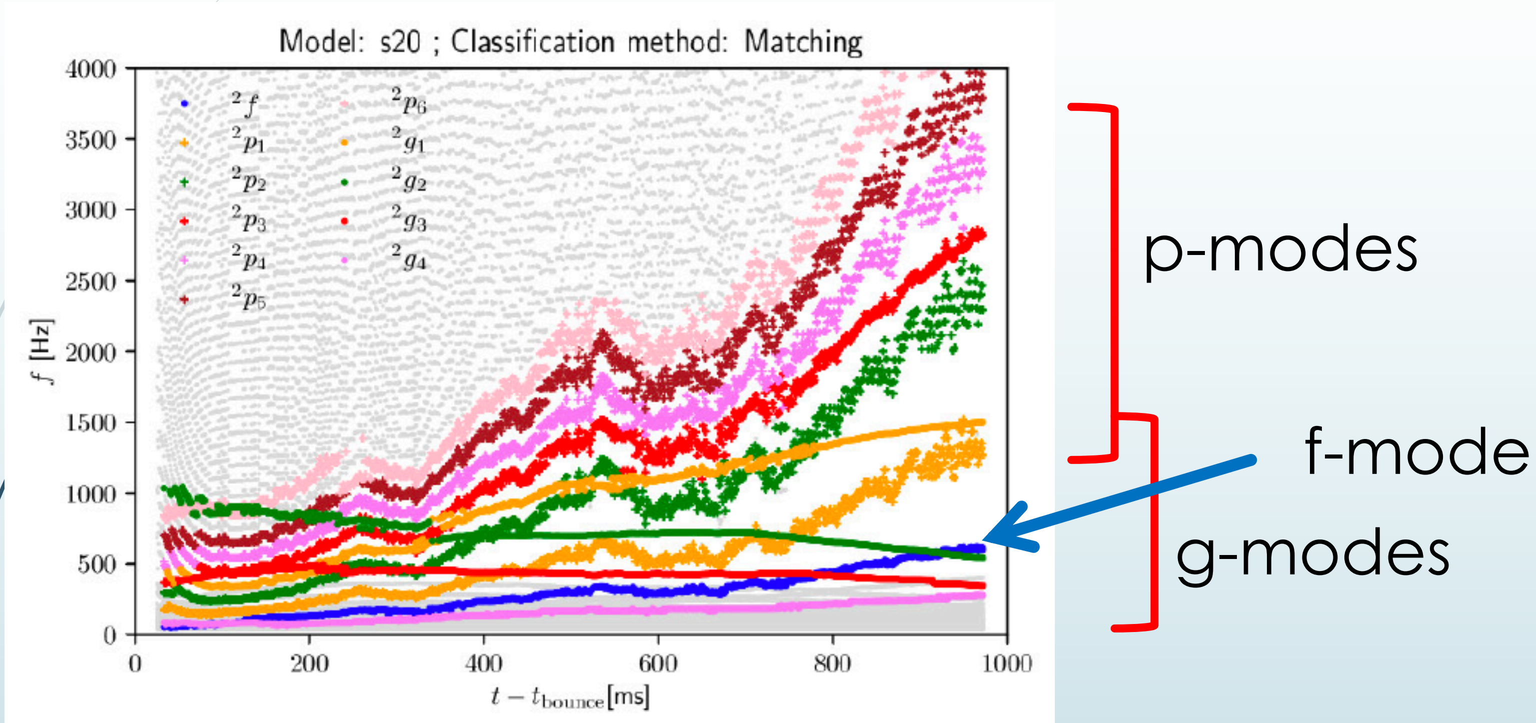






Torres-Forné et a 2018b

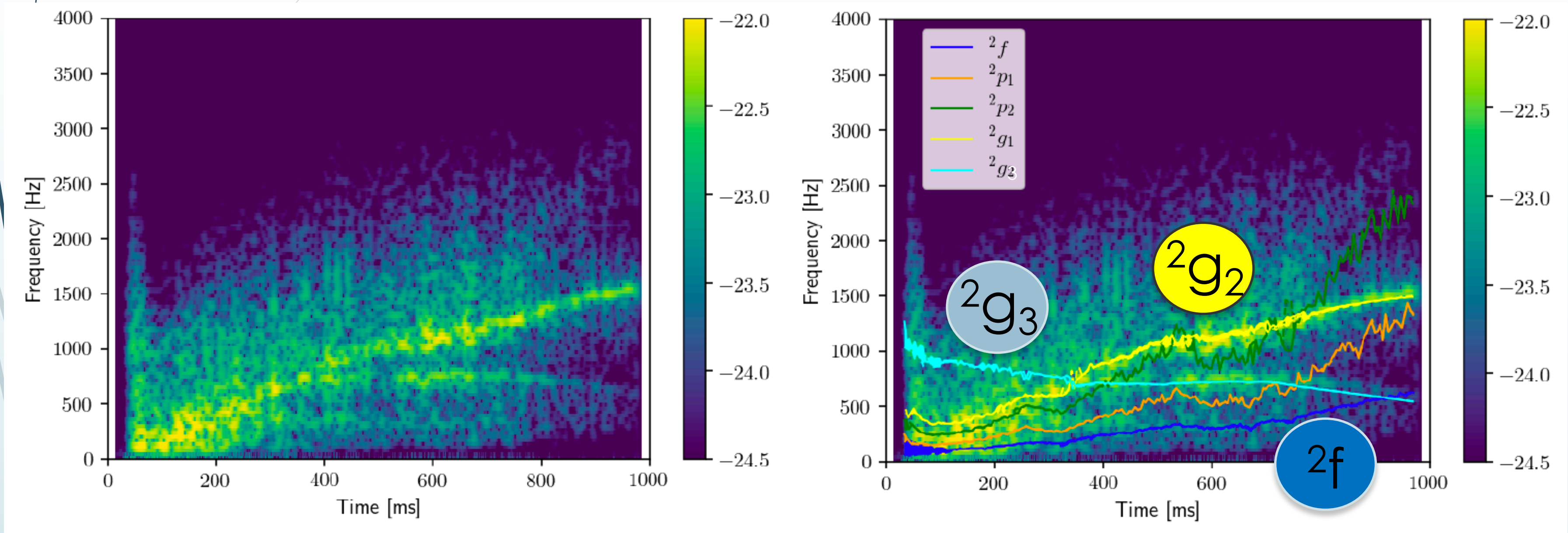
Classified modes



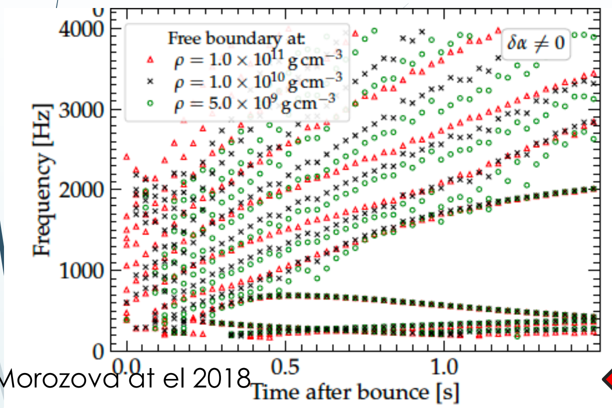
Torres-Forné et a 2018b

s20, SFHo EOS

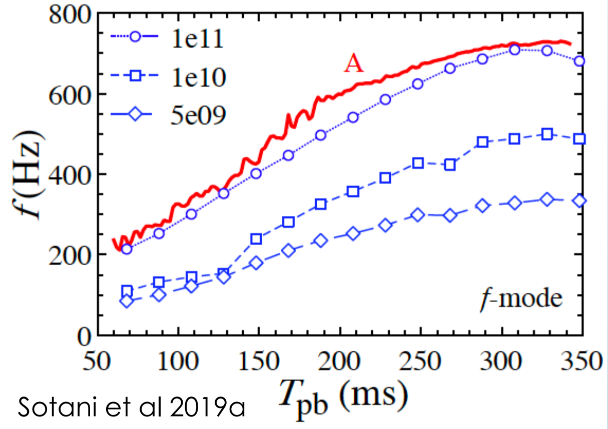
Comparison with GWs



Boundary conditions



Morozova at el 2018



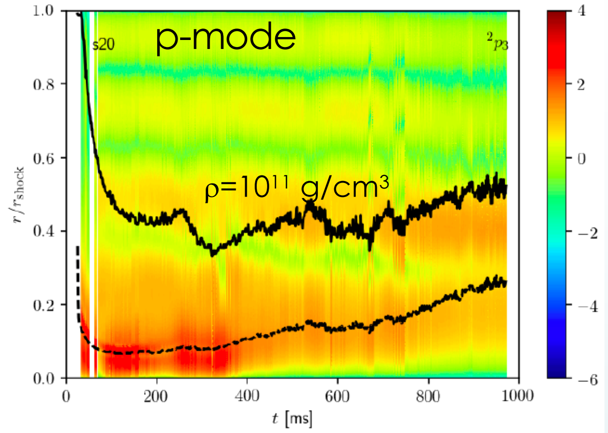
Sotani et al 2019a

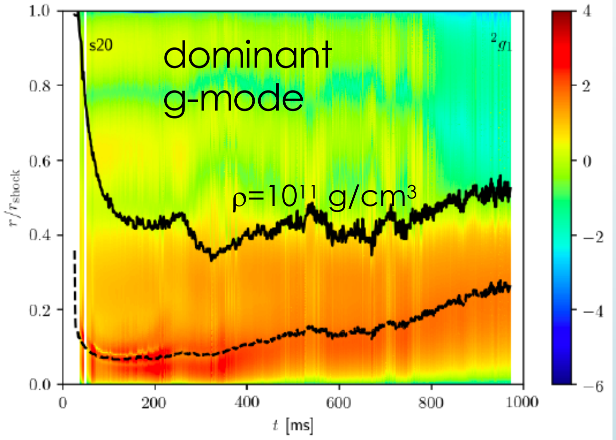
At the shock location

- TF et al 2018, 2019a,b
- Shock is a sonic point
- Well defined boundary
- f-mode at 100-500 Hz

At the PNS surface

- Morozova et al 2018, Radice et al 2019, Sotani et al 2019a,b, Westernacher-Schneider 2019)
- ΔP=0 at fixed density
- Neglects sound waves outside PNS
- Depends on threshold density
- f-mode at higher frequencies





- Most of the GW signal in CCSN can be modelled as PNS oscillations
- It is possible to identify PNS modes in GW data

Asteroseismology

Universal relations and inference

1D CCSN simulations

Aenus-ALCAR code

- "M1" neutrino transport: algebraic Eddington factor method with M_1 closure (Just et al 2015).
- 3 neutrino flavours + multigroup
- Newtonian / Pseudo-relativistic gravity (Marek et al 2006)

CoCoNuT code

- "FMT" neutrino transport: stationary neutrino solution with a closure. (Müller el at 2015)
- 3 neutrino flavours + multigroup
- GR in the XCFC approximation (Cordero-Carrión et al 2009)

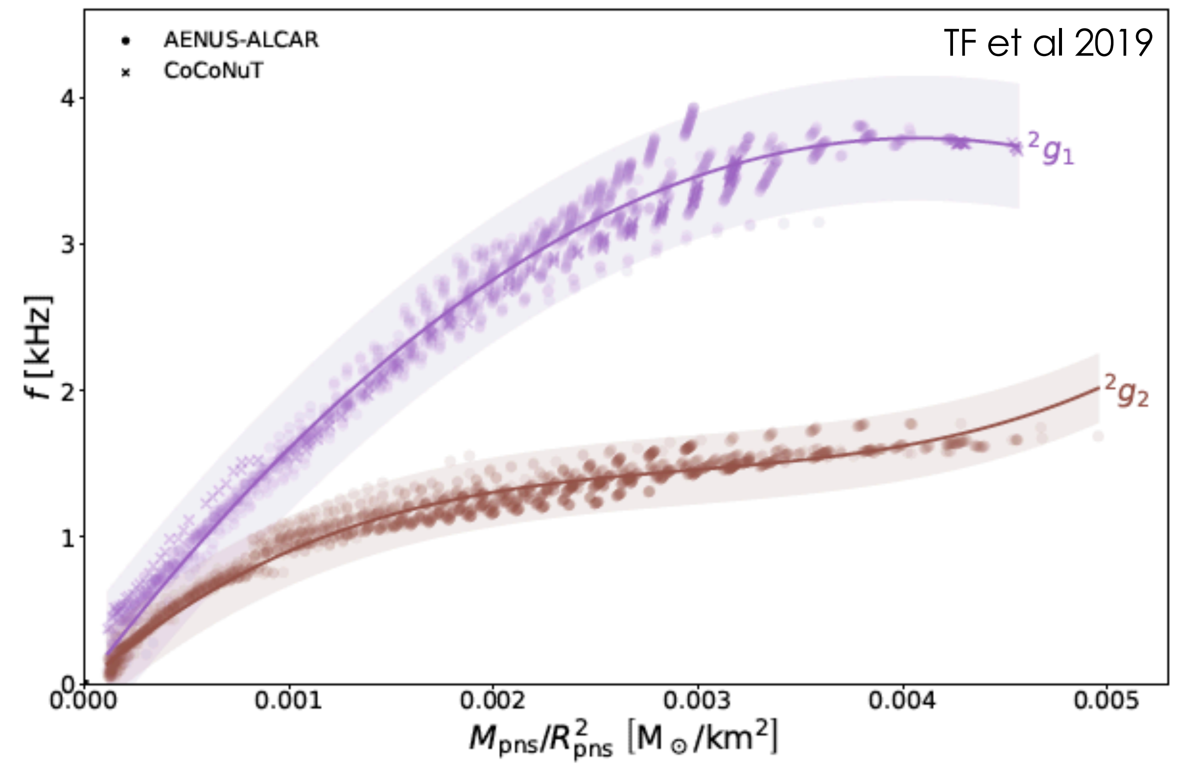
Progenitor models

- Woosley et al 2002
- 11.2 - 75 $M_\odot$ (ZAMS), solar metallicity + u20 model

Equation of state

- 6 EOS: LS220, HShen, SFHo, BBH-Λ and Hshen-Λ.

Fundamental relations: g-modes



- 2D simulations
- 2 codes
- 6 EOS
- 8 progenitors

g-modes scale with PNS surface gravity

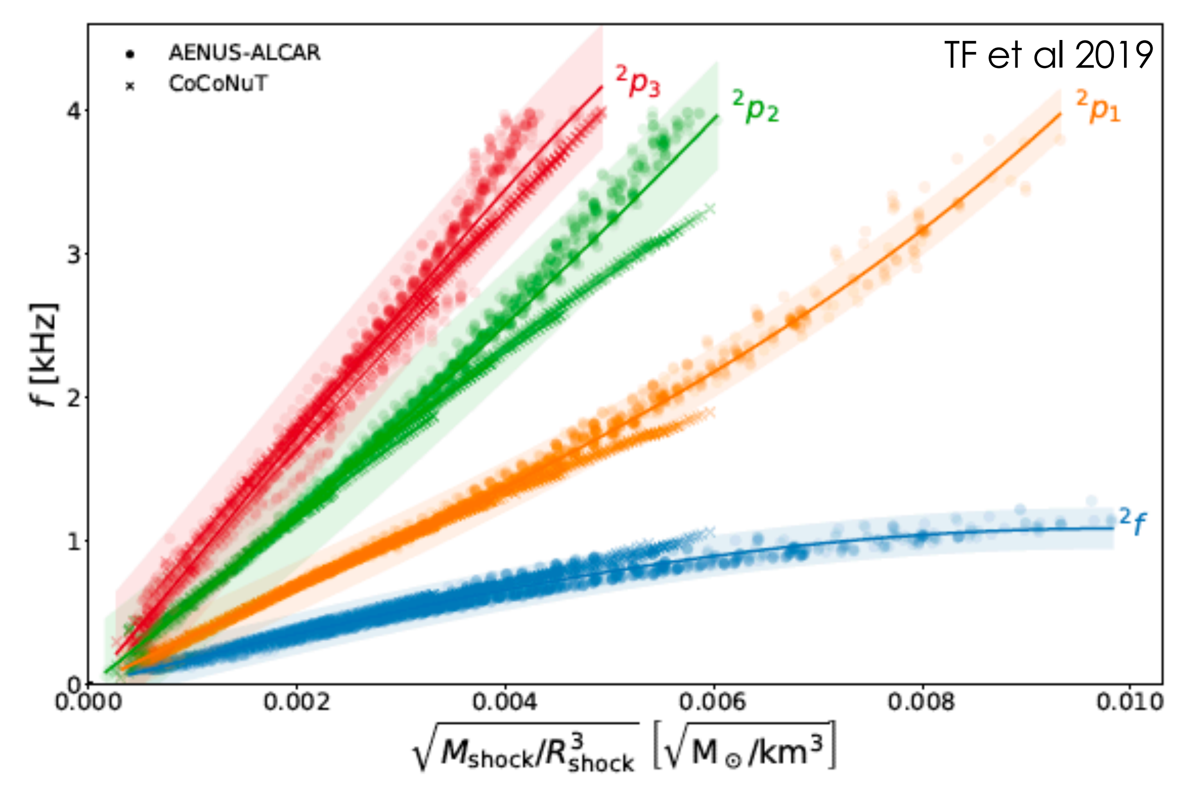
$f\,(^2g_2) = b\,x + c\,x^2 + d\,x^3$

$x = M_{PNS}/R_{PNS}^2$

$R^2 = 0.967$
$\sigma = 76$ Hz

PNS definition: $\rho > 10^{11}$ g/cm^3

Fundamental relations: f and p-modes



f and p-modes scale with sqrt. of mean density inside the shock

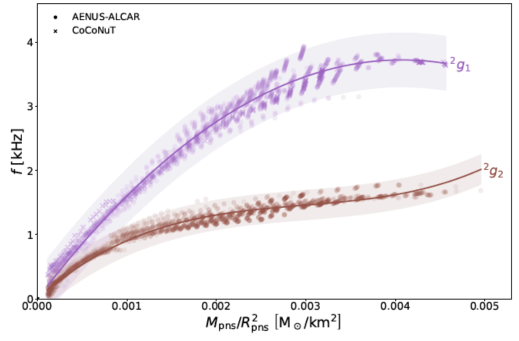
$f\,(^2f) = b\,x + c\,x^2$

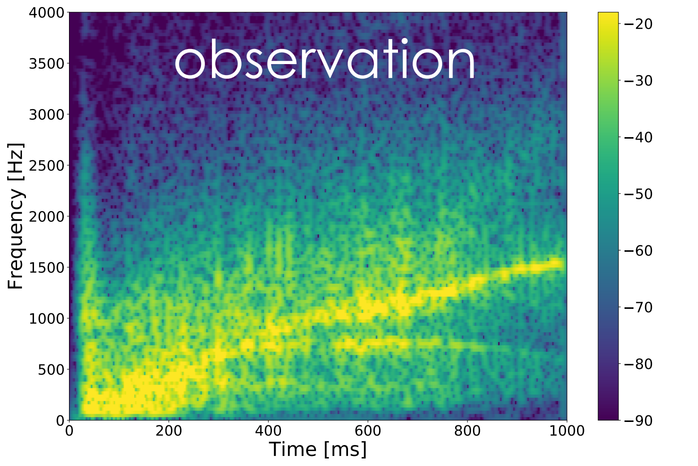
$x^2 = M_{shock}/R_{shock}^3$
$R^2 = 0.967$
$\sigma = 45$ Hz

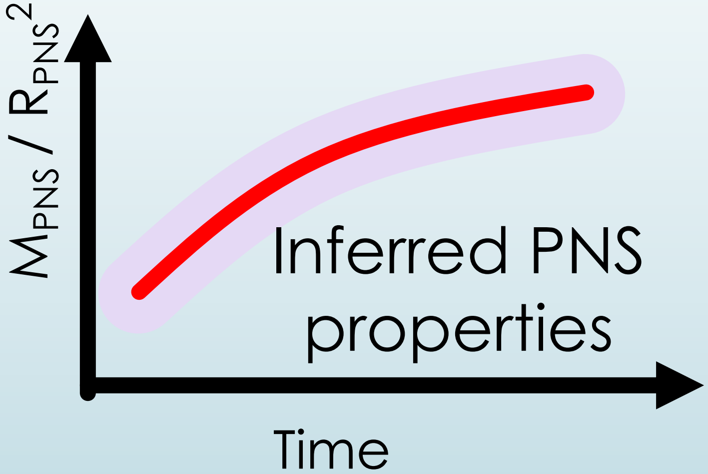
PNS definition: $\rho > 10^{11}$ g/cm^3

Inference (inverse problem)

Fundamental relations

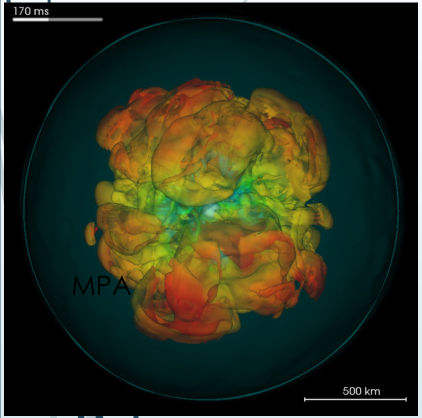


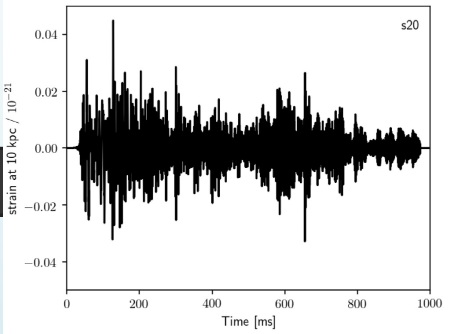




Improving detectability

Can we use this to help with GW detection?

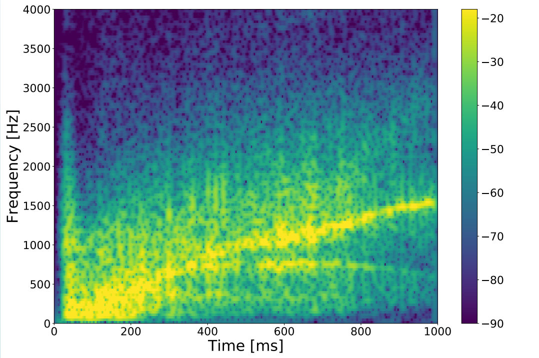


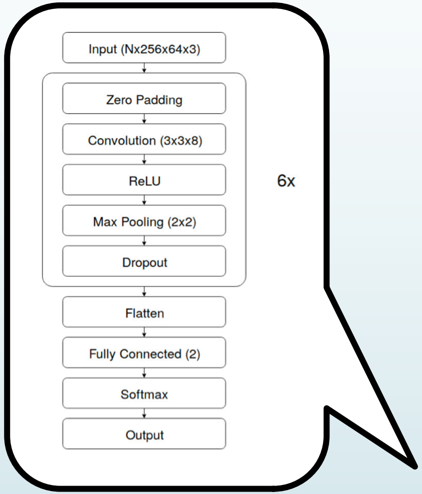


SNe GW detection in LIGO/Virgo

- Current methods: unmodelled burst searches
- Can we improve these by adding information about the SN signal (g-modes)?

Train a convolutional neural network (CNN) to recognize GW patterns

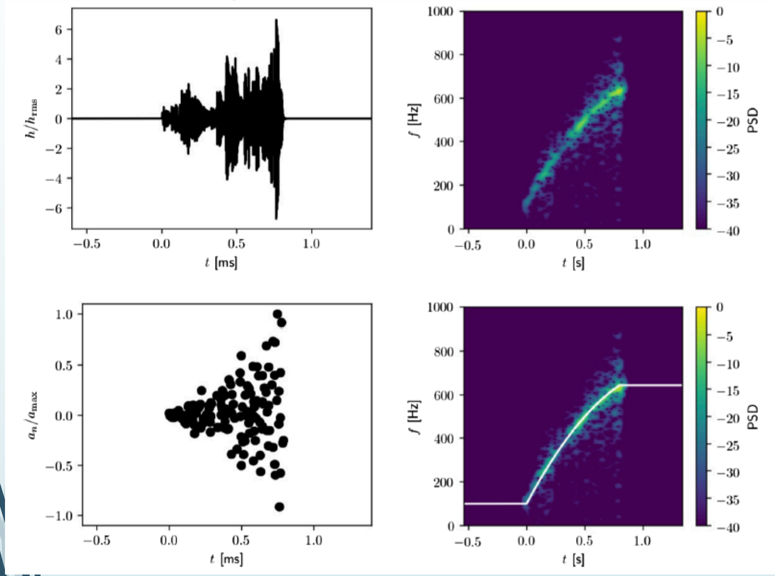




SNe GW detection in LIGO/Virgo

- Train CNN with SN-like waveforms → phenomenological templates
- Modify coherent waveburst pipeline (CWB, Klimenko et al 2008, 2016) to include the CNN
- Compare results with original CWB

Parametrized phenomenological templates



Astone et al 2018

- Mimics PNS modes
- Model: damped harmonic oscillator
- 7 free parameters (ccphenv2)
- Stochastic excitation: different realizations possible

Automatic generation of templates to train CNN (800 in this work)

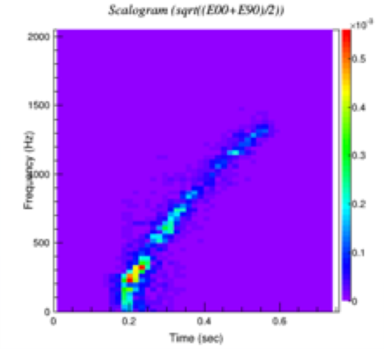
Pipeline

waveform

+ Detector Gaussian noise

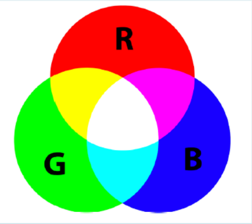
CWB

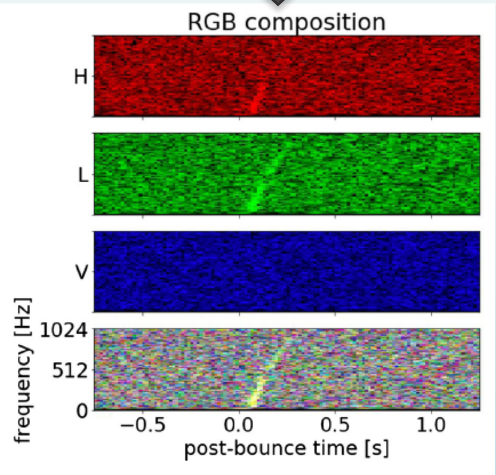
time-freq. likelihood



CWB

SIGNAL / NOISE



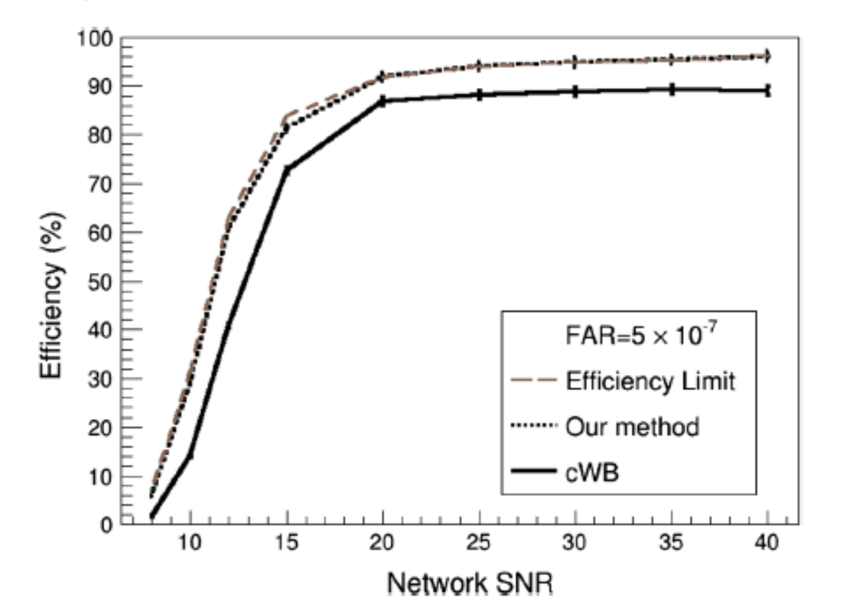


CNN

SIGNAL / NOISE

Detection efficiency

Astone et al 2018



- 10000 signal images & 10000 noise images
- Improved efficiency over CWB
- Proof-of-concept: more realistic setup needed.

It is possible to improve detectability using CNN and phenomenological templates

Conclusions

- Asteroseismology
  - It is possible to identify PNS eigenmodes in GW signals from neutrino-driven CCSN.
  - Observation of eigenmode frequencies allow to infer the properties of the PNS.
- Detection
  - Machine learning could improve detectability of GWs from CCSNe.

Thank you