Understanding GWs from core-collapse supernovae

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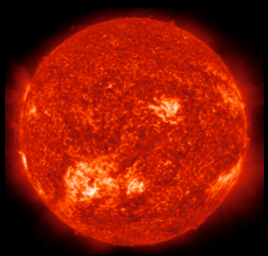
CompOSE 2021 – Feb. 24-26 2021

Core collapse supernovae

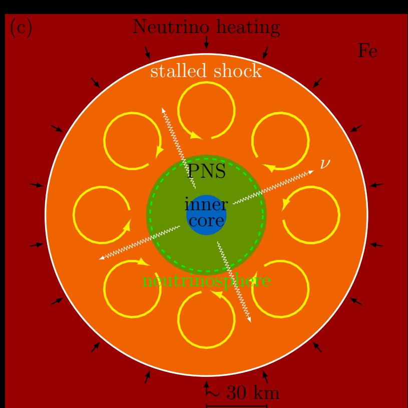


Collapse of the core of massive stars (8-100 $M_{\odot}$)

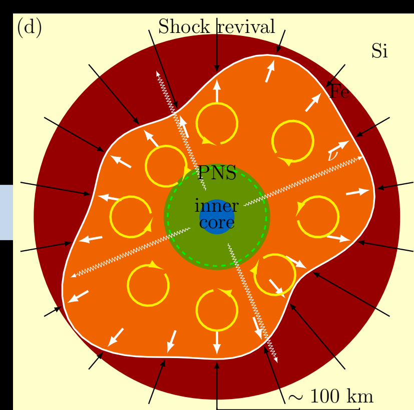
- Non-rotating progenitors (>99%) (Li et al 2011, Chapman et al 2007)
- Observable within ~10 kpc (Gossan et al 2015, Powell & Müller 2018)
- Rare events (~1/ 30 year in our galaxy) (Adams et al 2013)

1. Collapse

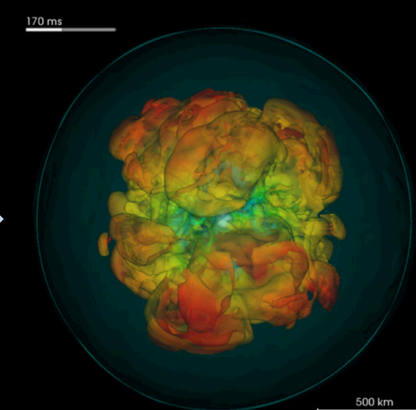
2. PNS formation



3. PNS + shock instabilities



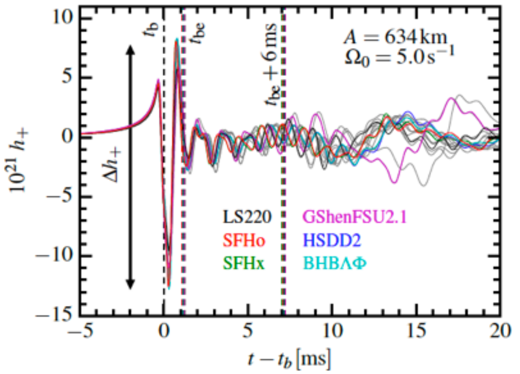
3. Neutrino-driven explosion



MPA

GW signal in CCSNe: timeline

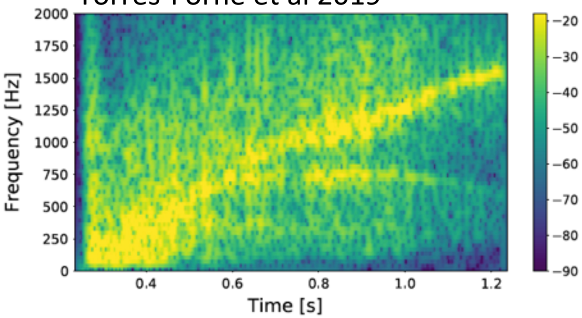
Richers et al 2017



Bounce signal:

- only fast rotating models
- *Δt* ~ 5 ms
- *f* ~ 600-900 Hz
- *h* ~10^{-21} @ 10 kpc

Torres-Forné et al 2019

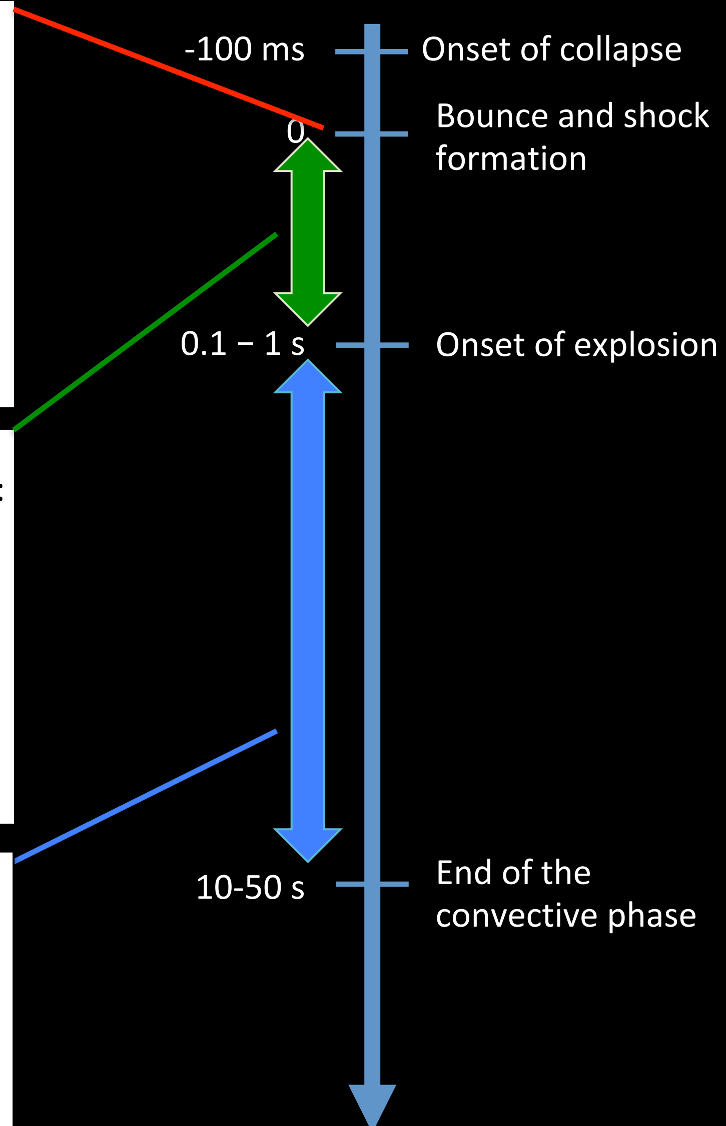


Post-bounce "SN" signal:

- g-modes, SASI, convection
- *Δt* ~ 0.1-1- s
- *f* ~ 50-2000 Hz
- *h* ~10^{-23}-10^{-22}@ 10 kpc

PNS convection signal:

- Computationally expensive
- *Δt* ~ 10-50- s
- *f* ~ ?
- *h* ~ ?



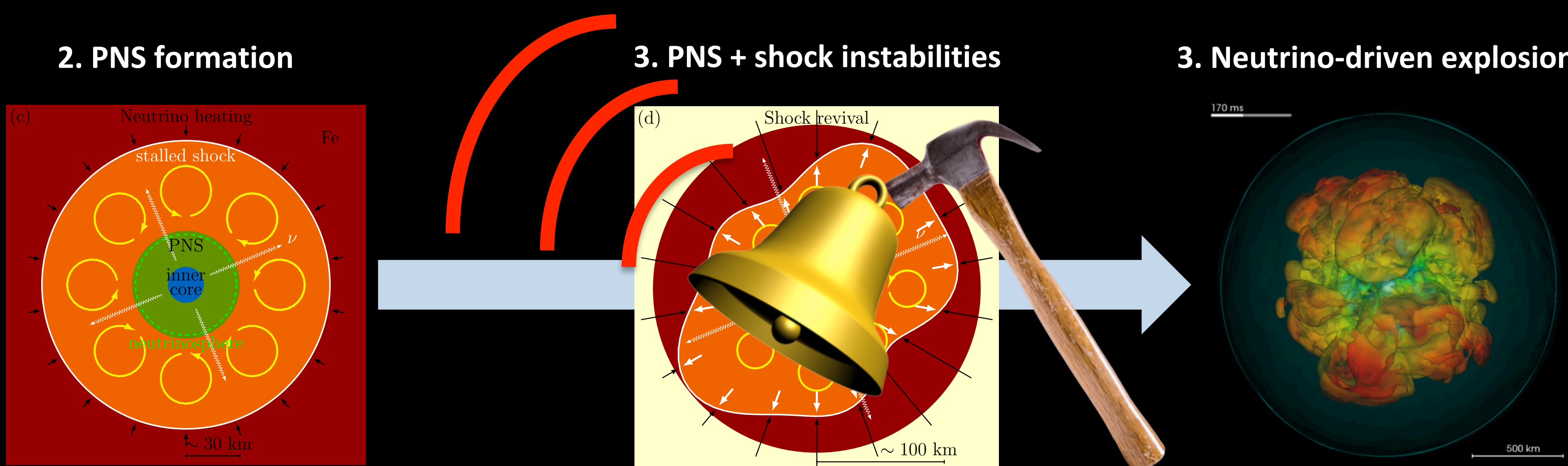
Post –bounce signal

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

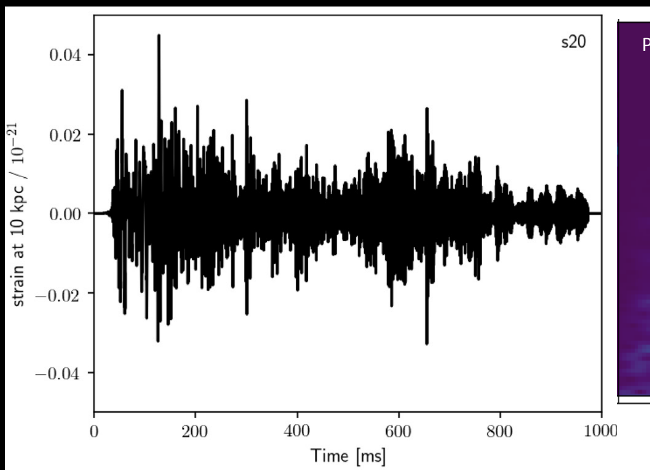
PNS excitation

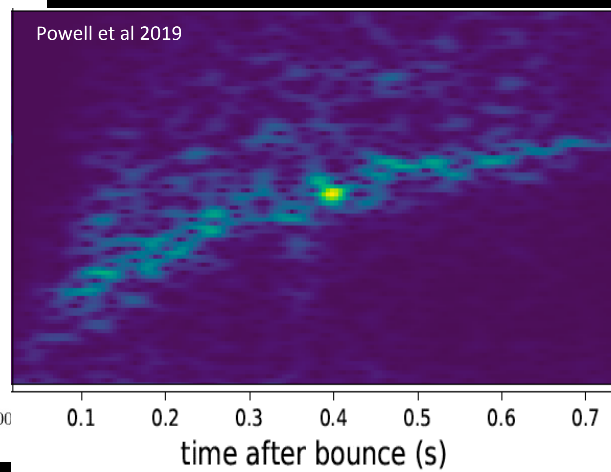
- The "hammer": convection, SASI
- The "bell": proto-neutron star
- The "ring": PNS normal modes

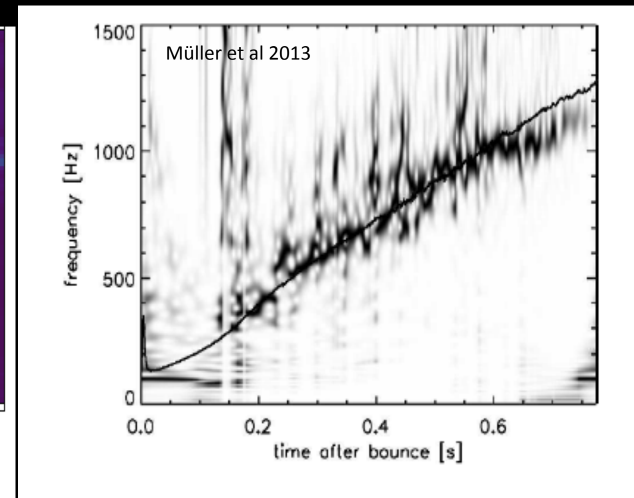


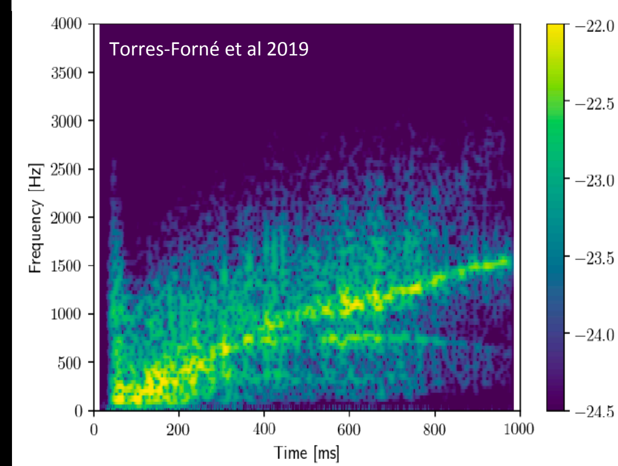
MPA

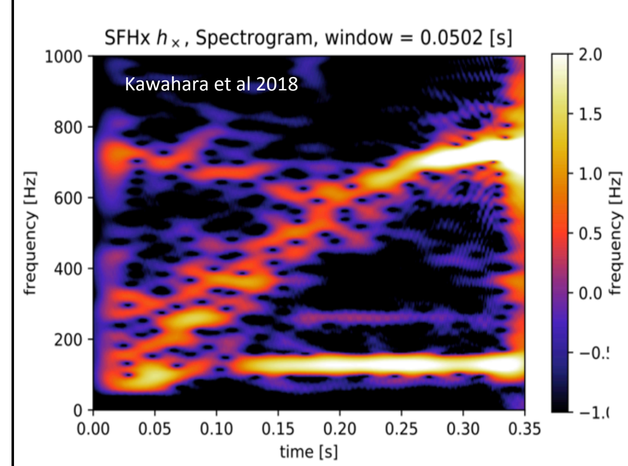
GW emission from PNS oscillations











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

What information can we extract from these modes?

PNS asteroseismology

- **Which modes can be observed?**

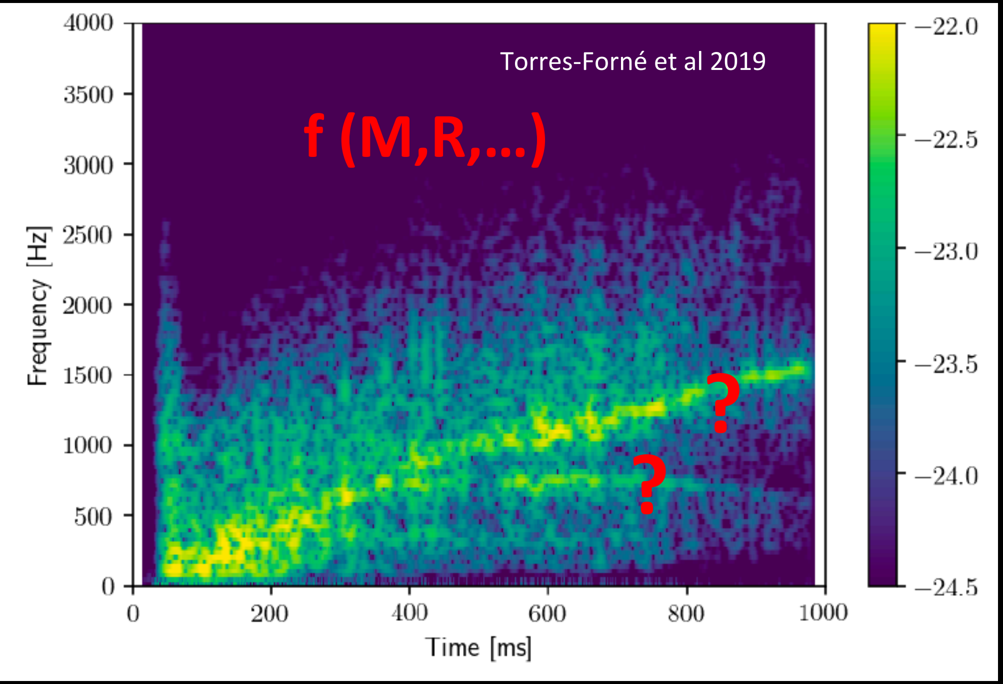
  Mode identification

- **How do mode frequencies depend of PNS properties?**

  Universal relations

- **Can we extract this information from the detectors noise?**

  Inference



Mode identification

Collaborators:

- A. Torres-Forné, M. Obergaulinger, J. A. Font (U. Valencia)
- A. Passamonti

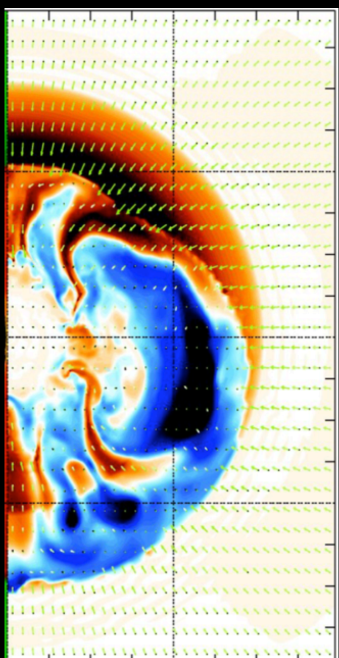
Publications:

- Torres-Forné et al 2018 (arXiv: 1806.11366)
- Torres-Forné et al 2019a (arXiv: 1708.01920)

PNS oscillations

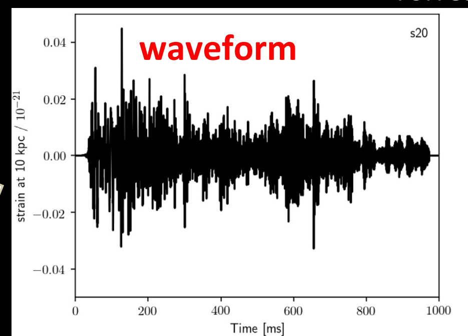
Analysis of GW signal from simulation

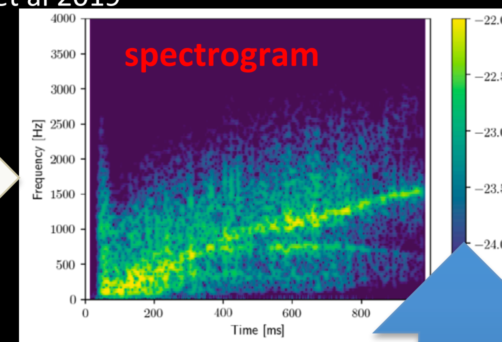
Multi-dimensional numerical simulation

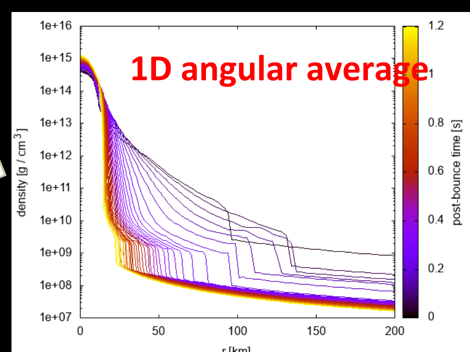


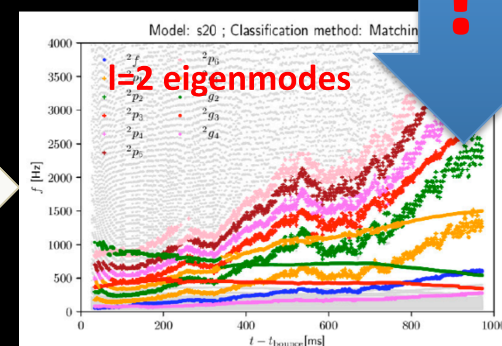
Obergaulinger et al 2013

Torres-Forné et al 2019









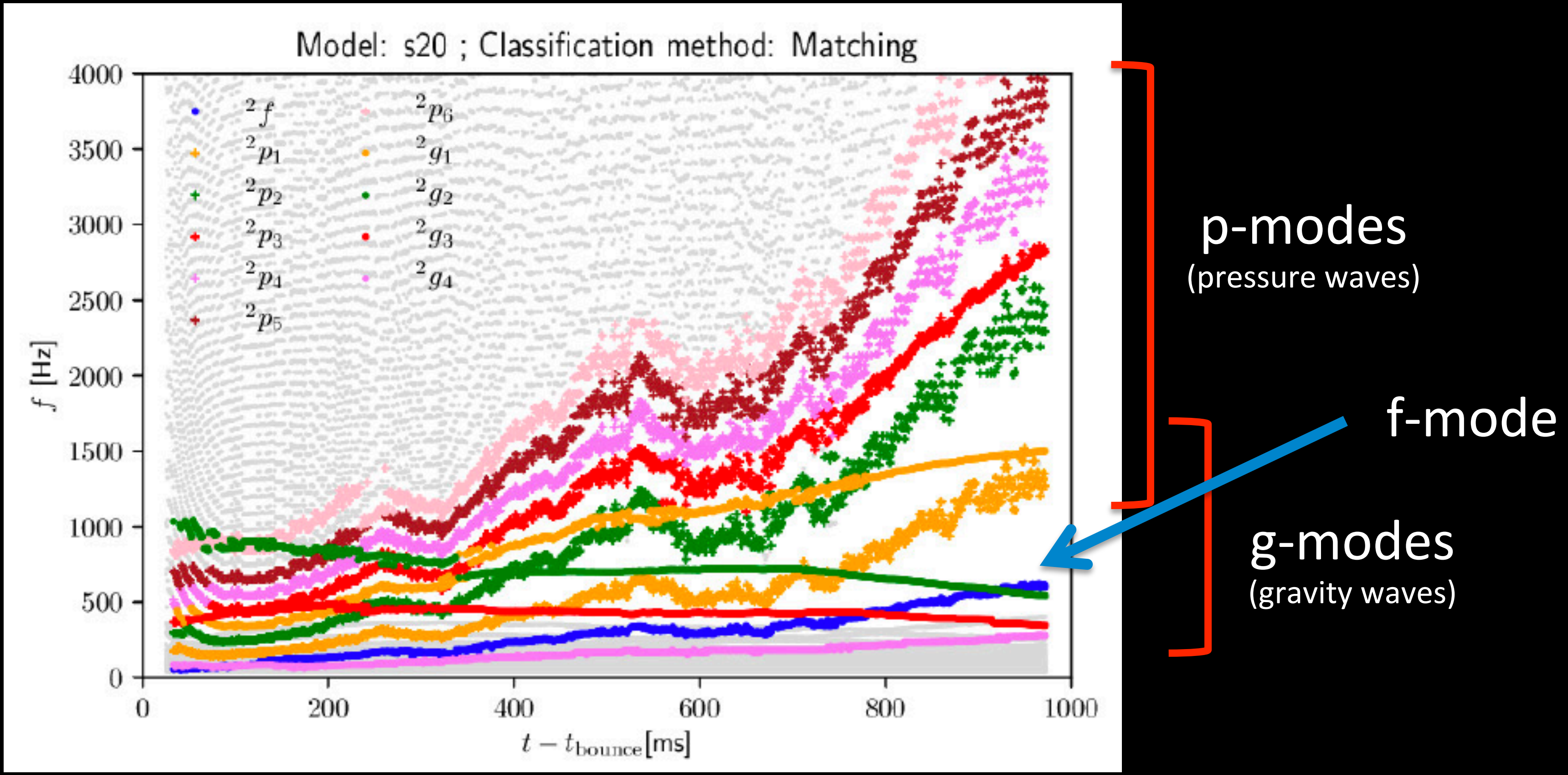
?

Torres-Forné et al 2018

Linear perturbation analysis of 1d background

Classified modes

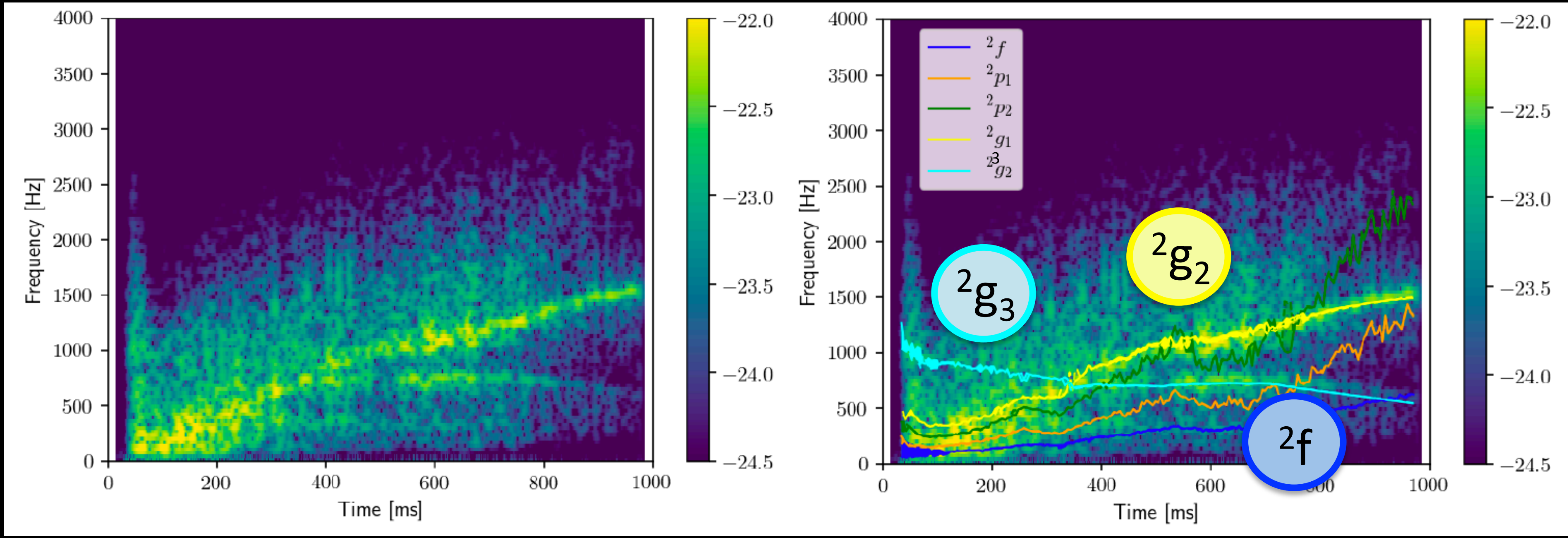
Computed using GREAT (General Relativistic Eigenmode Analysis Tool)



Torres-Forné et a 2018b

s20, SFHo EOS

Comparison with GWs



The main feature in all CCSN simulations is related to the excitation of a particular g-mode ($^2g_2$ in our notation)

Universal relations

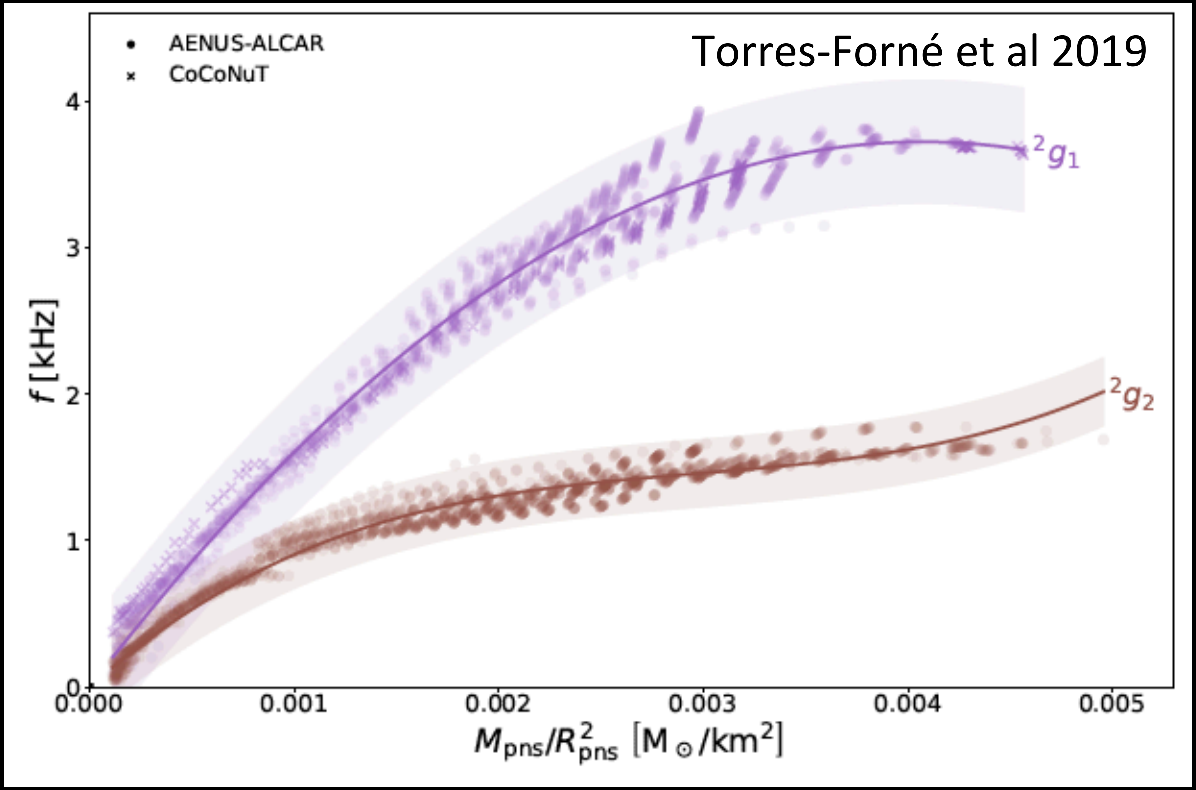
Collaborators:

- A. Torres-Forné, M. Obergaulinger, J. A. Font (University of Valencia)
- B. Müller (Monash University)

Publications:

- Torres-Forné et al 2019b (arXiv: 1902.10048)

Universal relations: g-modes



- 26 1D simulations
- 2 codes
  - Alcar-Aenus
  - CoCoNuT
- 6 EOS:
  - LS220
  - Gshen-NL3
  - Hshen
  - SFHo
  - BHB-Λ
  - Hshen-Λ
- 8 progenitors (11.2 − 75 $M_\odot$)

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

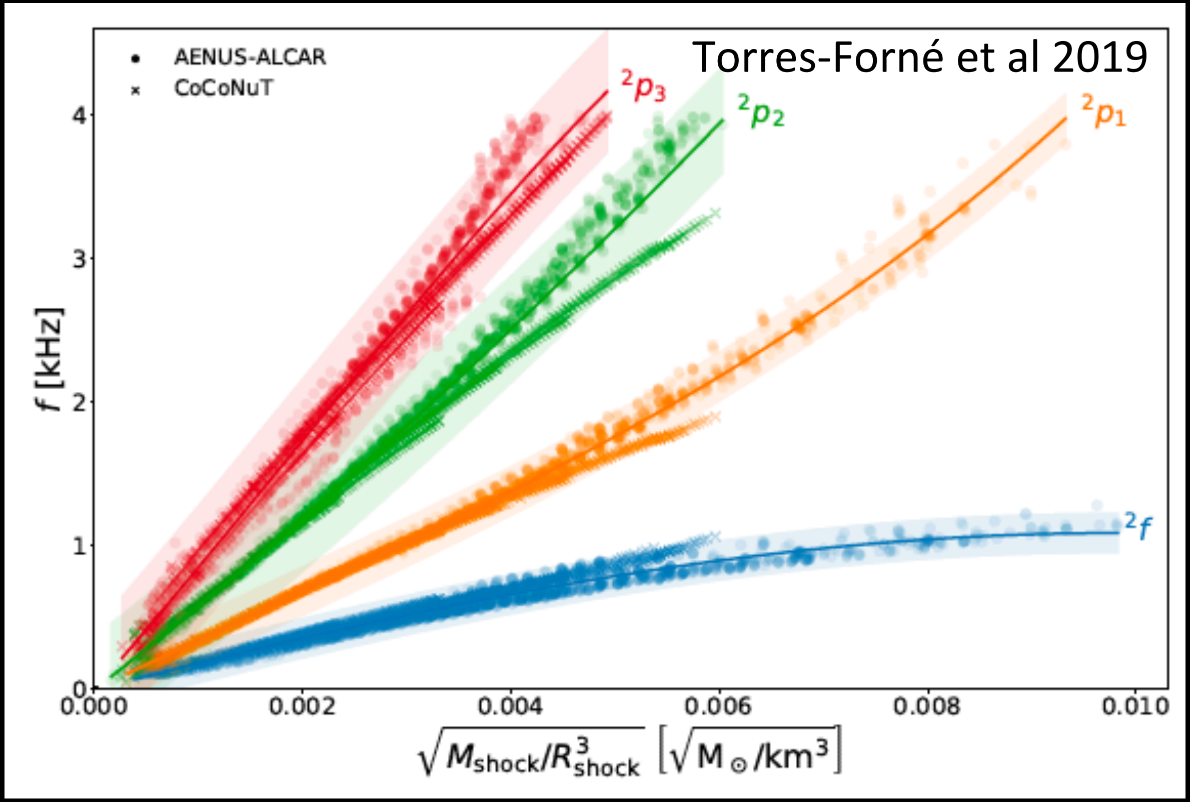
$x = M_{PNS}/R_{PNS}^2$

g-modes scale with PNS surface gravity

No dependence on EOS

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

Universal relations: f and p-modes



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

$x^2 = M_{shock}/R_{shock}{}^3$

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

Their frequency traces (mainly) the location of the shock

Inference

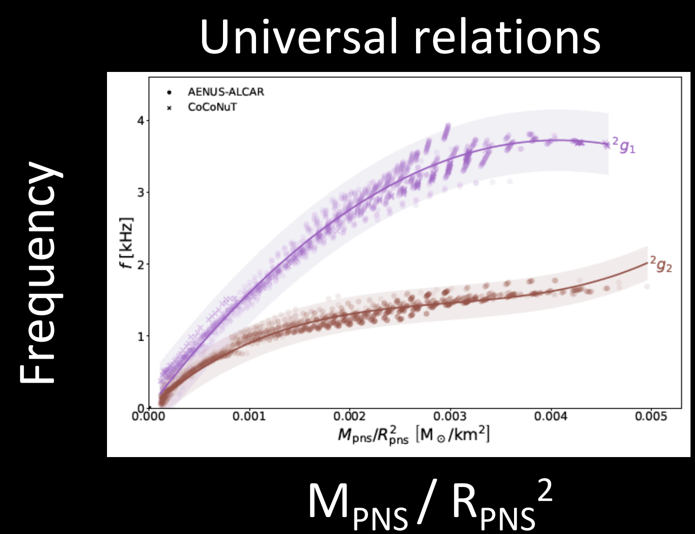
Collaborators:

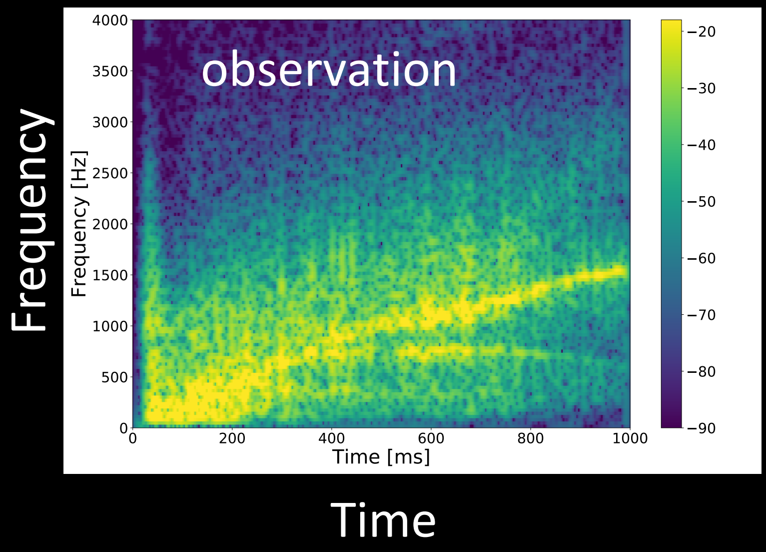
- A. Torres-Forné, M. Obergaulinger, J. A. Font (University of Valencia)
- M.A. Bizouard, N. Christensen (Observatoire Côte d'Azur)
- P. Maturana, R. Meyer (University of Auckland)

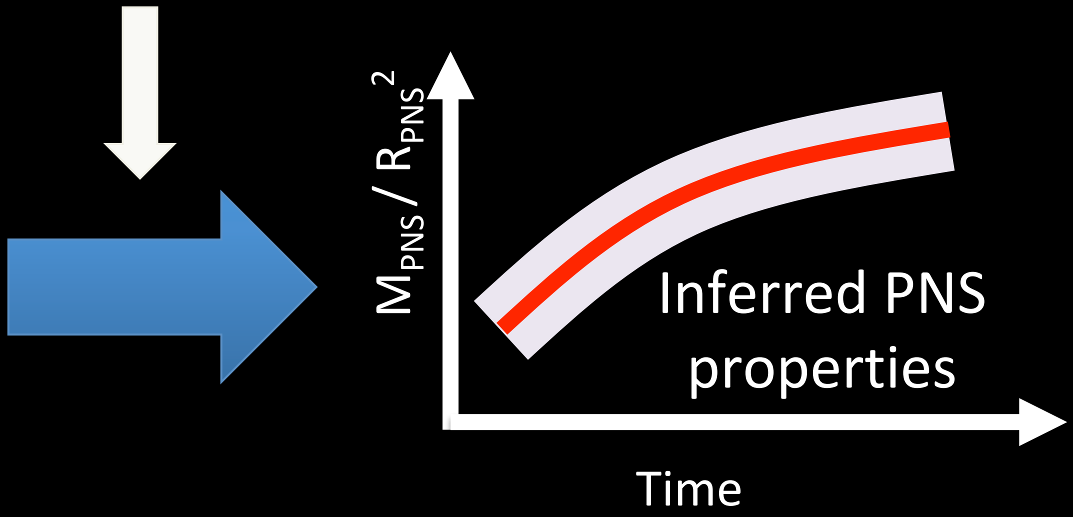
Publications:

- Bizouard et al 2020 (arXiv: 2012.00846)

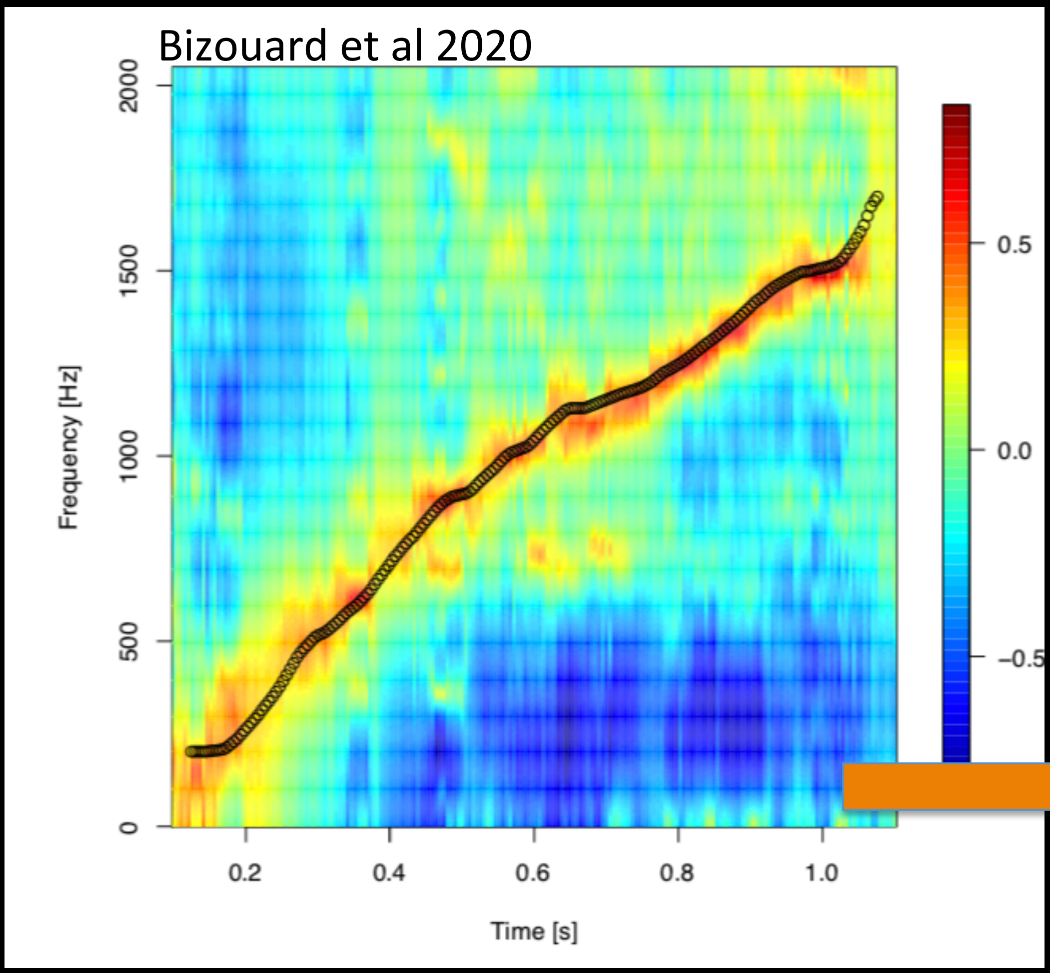
Inference (inverse problem)







Mode extraction



Test GW data:

- Simulations: 8 x 2D
- Code: Aenus-Alcar
- Progenitors: 11.2-40 $M_{\odot}$
- EOS: LS220 and Gshen

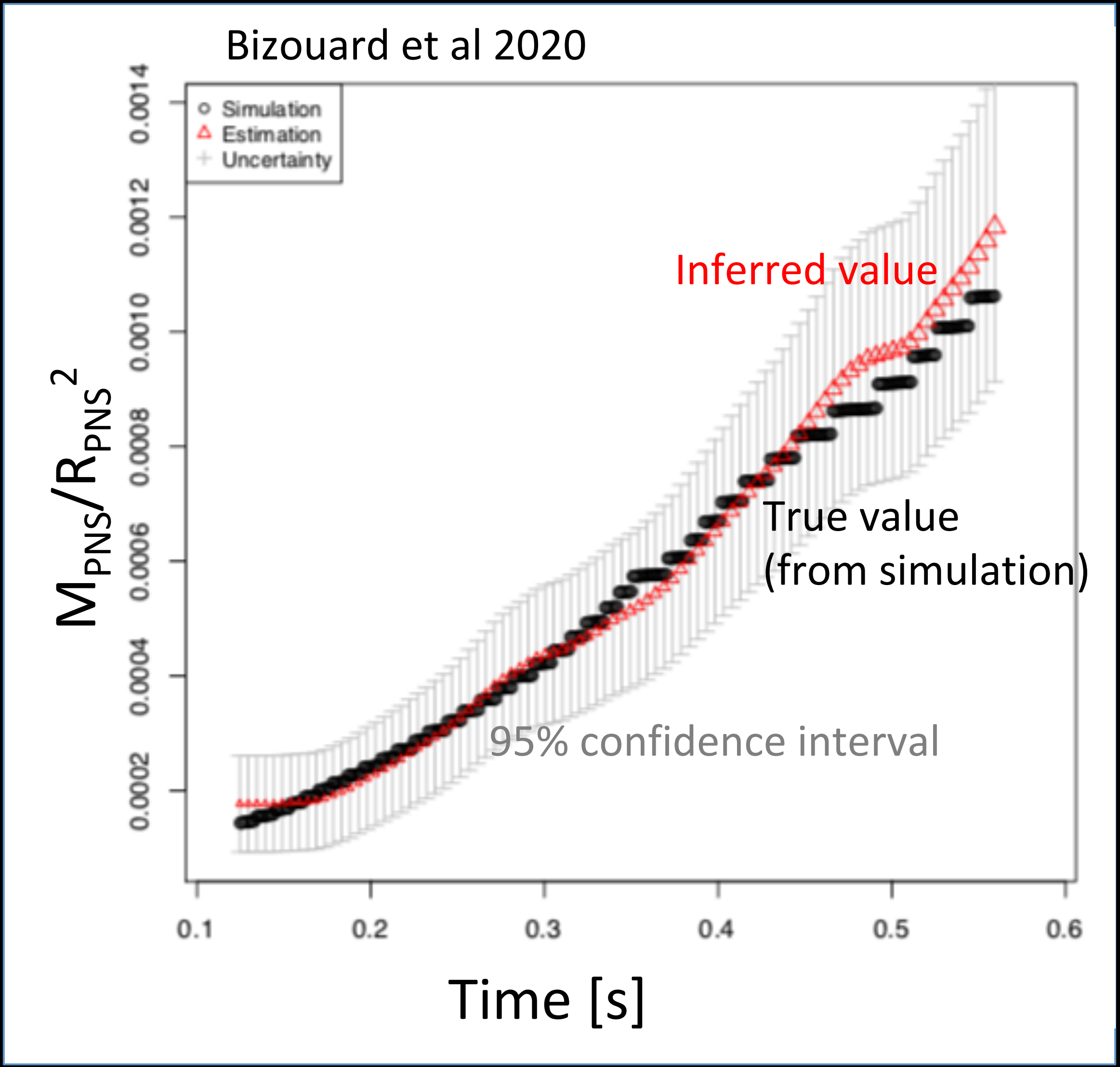
Injections in detector noise:

- Single detector: aLIGO, aVirgo, ET or CE.
- Gaussian colored noise

Time-frequency tracking of the main ridge

f(t)

Inference of surface gravity



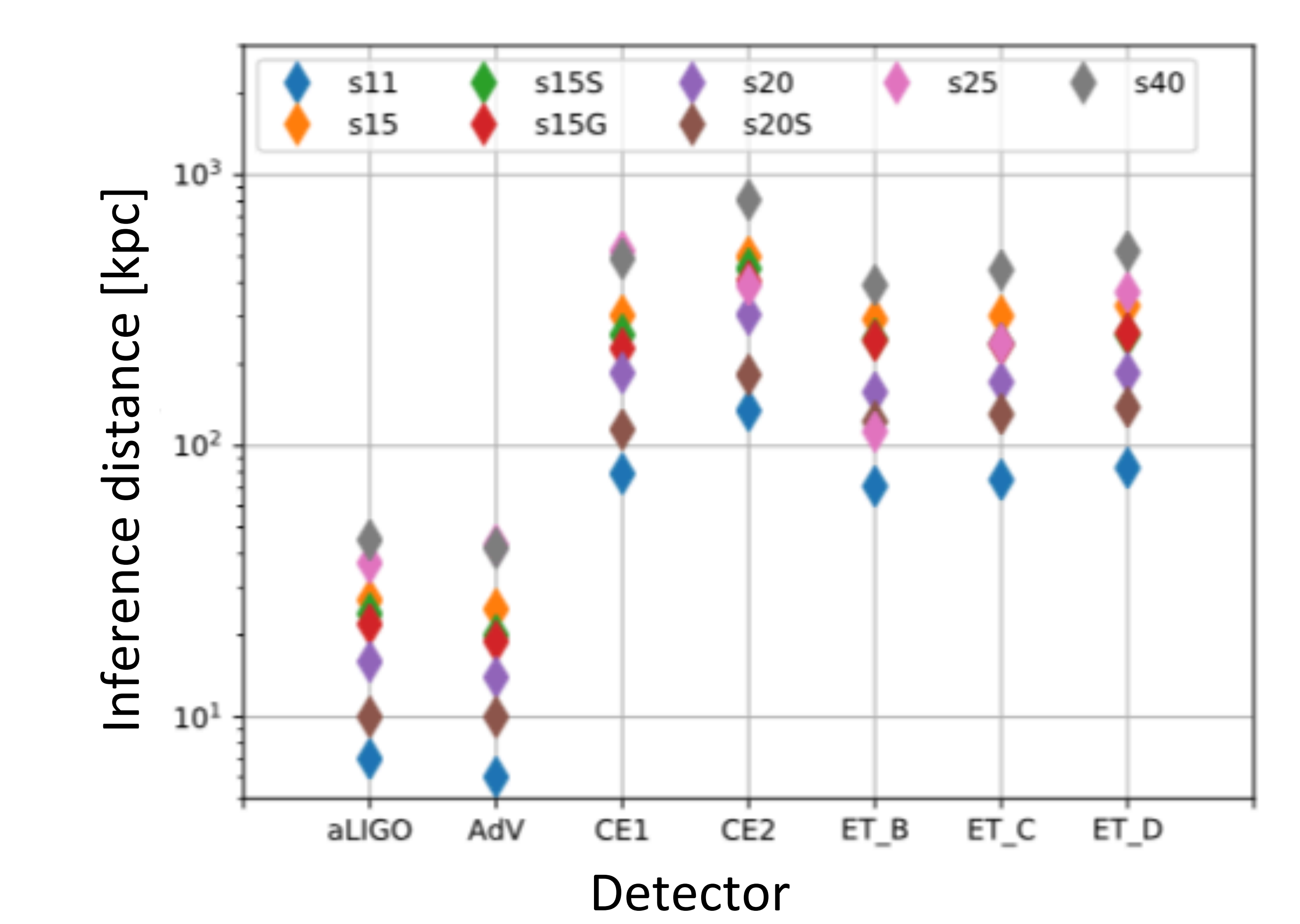
For sufficiently close sources we can measure the surface gravity only from GW data

Errors estimated using the dispersion in the universal relations (do not include errors due to detector's noise)

The inference is as good as the model: Alcar-Aenus was used for both the 2D simulations and to build the universal relations (1D simulations).

Inference distance

Bizouard et al 2020



Inference from the bounce signal

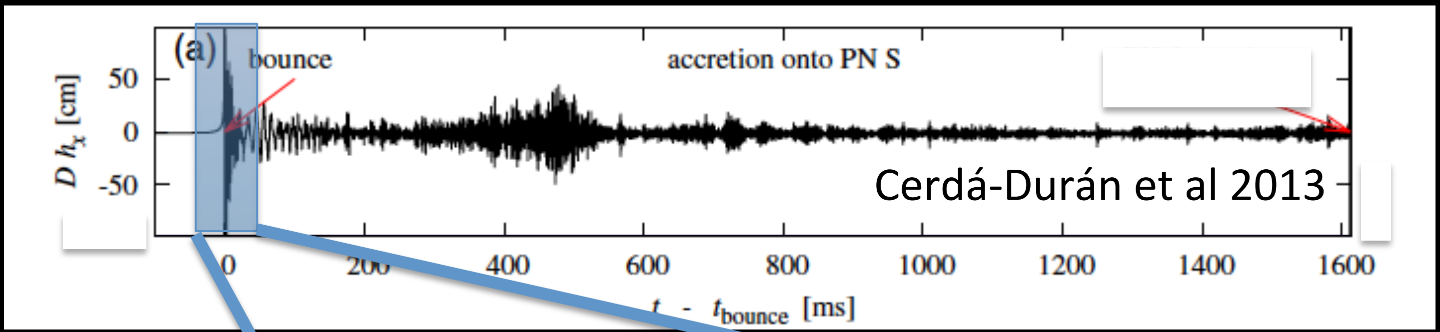
Collaborators:

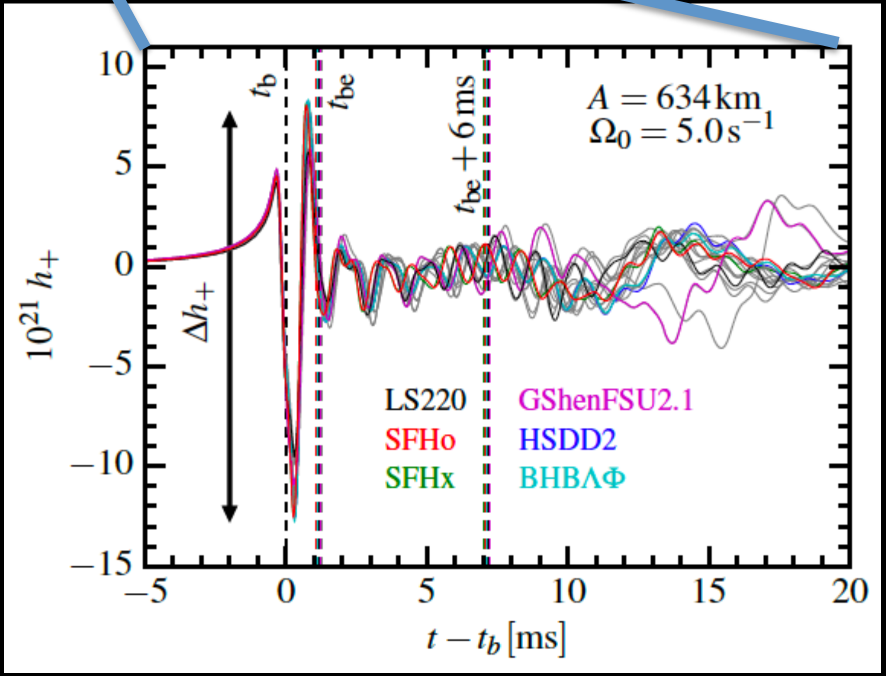
- C. Pastor-Marcos (University of Valencia / University of Heiledberg)
- A. Torres-Forné, J. A. Font (University of Valencia)
- E. Abdikamalov (Nazarbayev University)
- S. Richers (UC Berkeley)

Publications:

- Pastor-Marcos et al (in preparation)

Bounce GW signal



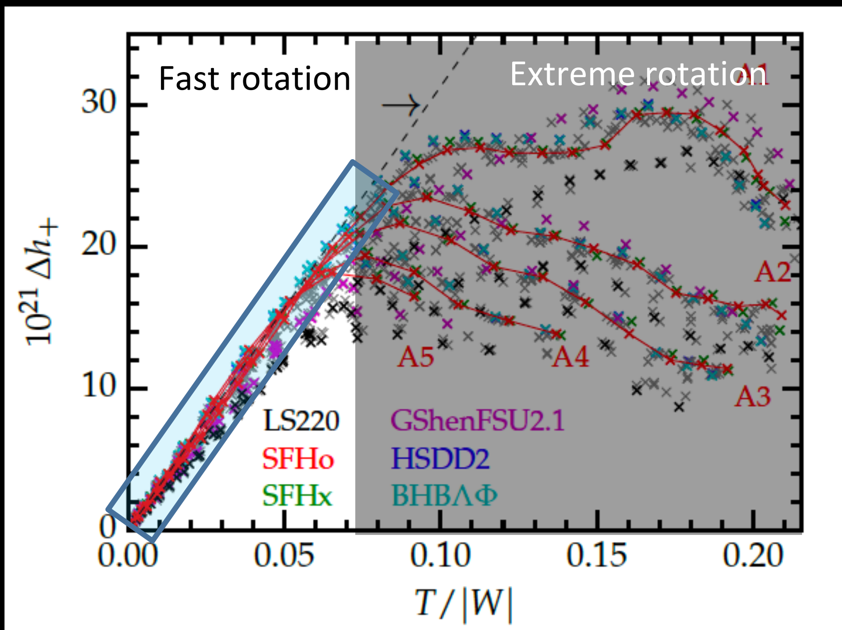


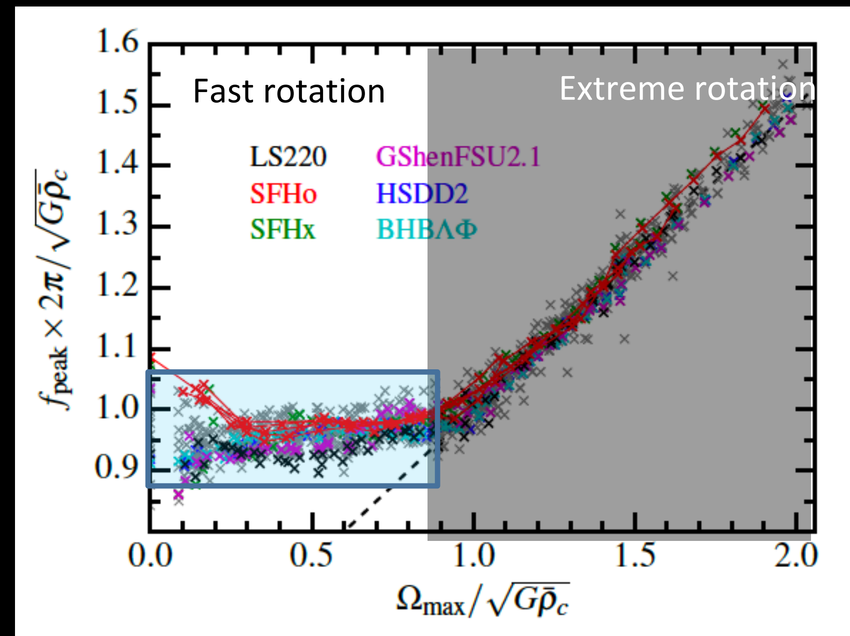
Richers et al 2017

- Only first few ms
- Only rotating models (zero for non-rotating): <1% SNe
- Main features:
  - Peak with amplitude Δh_+
  - Several oscillations with frequency f_{peak}
- Richers et al catalogue
  - 2D GR simulations
  - 1824 waveforms
  - 18 different EOS

What can we learn from Δh_+ and f_{peak}?

Richers et al 2017





$$\Delta h_+ \propto T/|W|$$

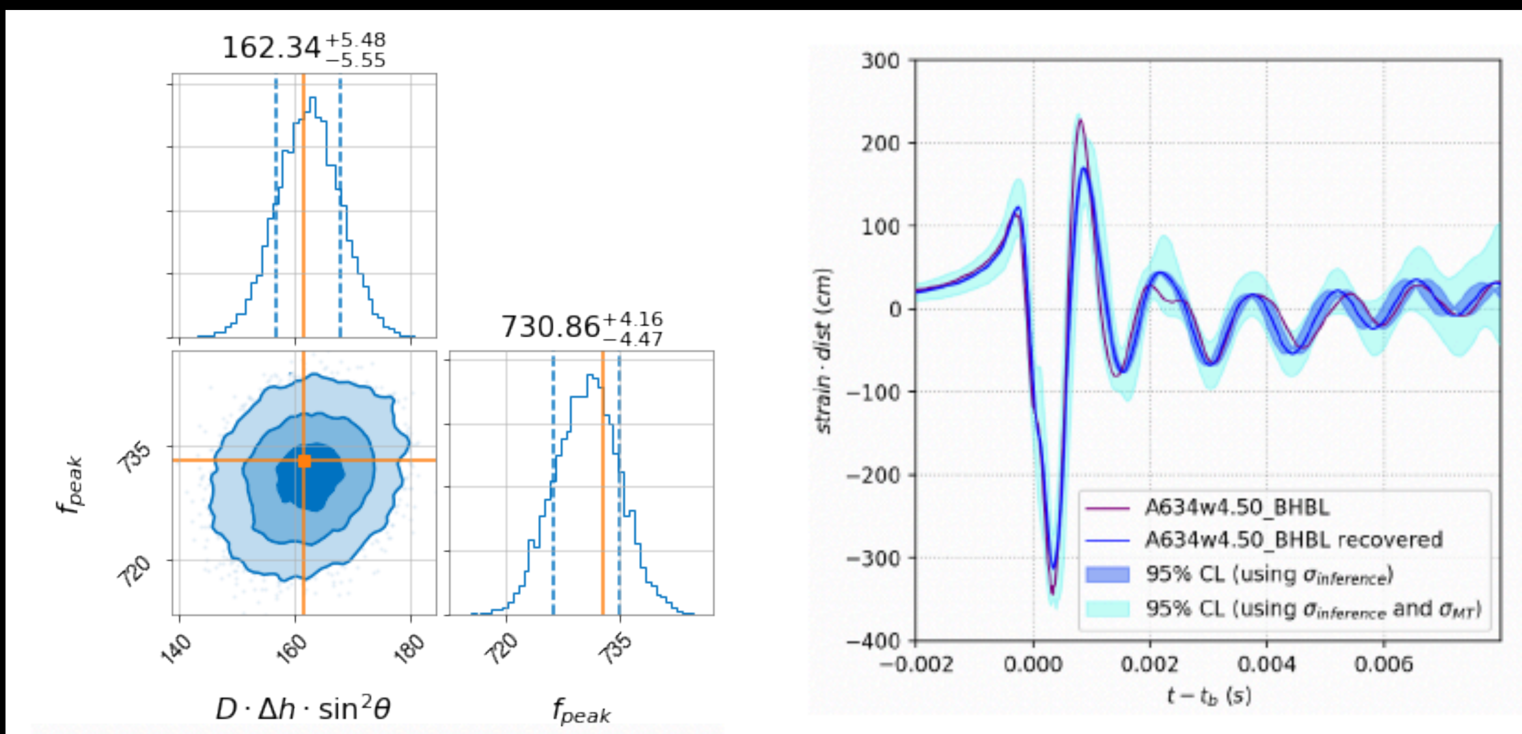
$$f_{peak} \propto \sqrt{\rho_c}$$

Kinetic rotational to potential energy ratio (measure of rotation)

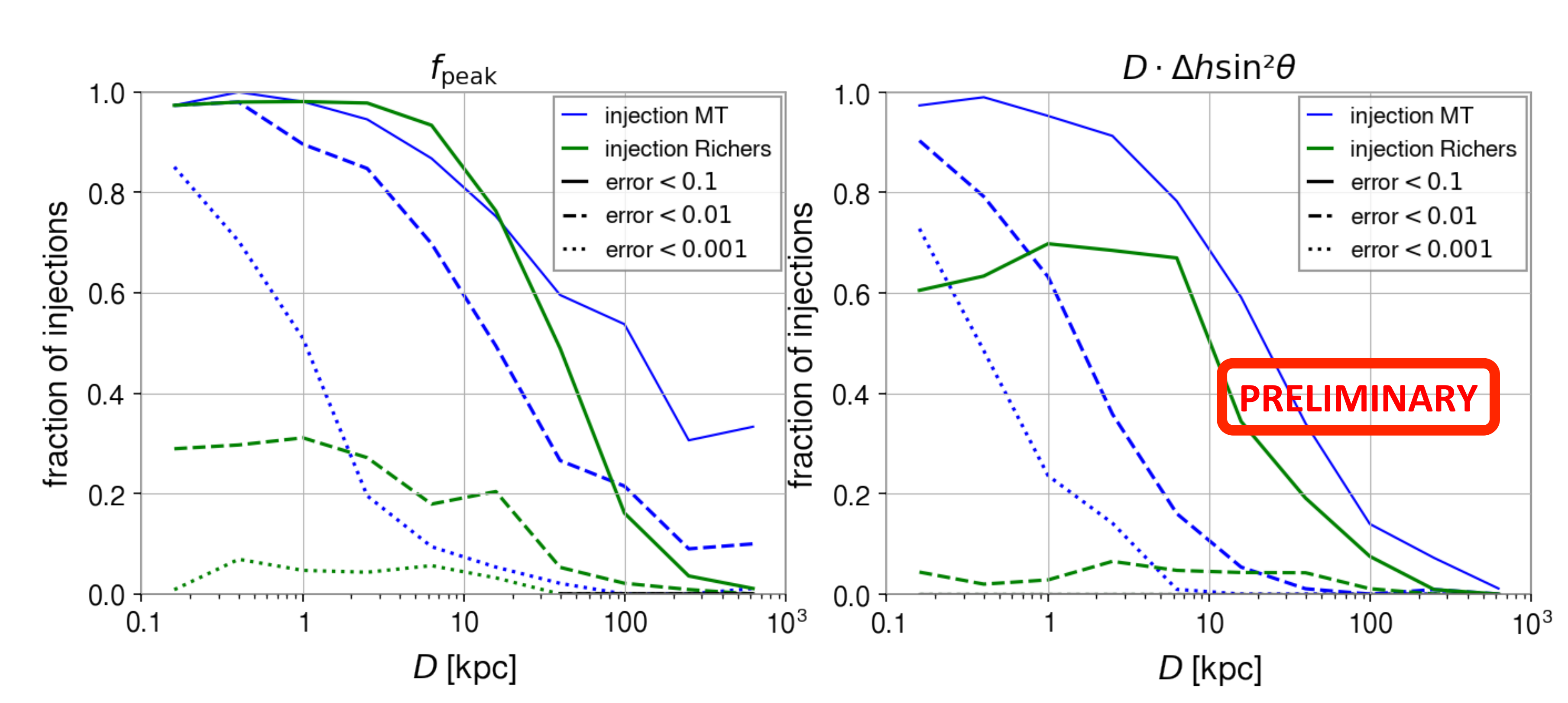
Central density

Bayesian inference with BILBY

- Injections in Gaussian colored noise
- 3 detector network (2 x aLigo + aVirgo)
- 1000 random injections in the sky wit D = [0.1,1000] kpc



Inference distance



- Inference with ~10% errors is possible within 10-50 kpc (only fast rotating progenitors)
- Value of Δh is degenerated with inclination angle

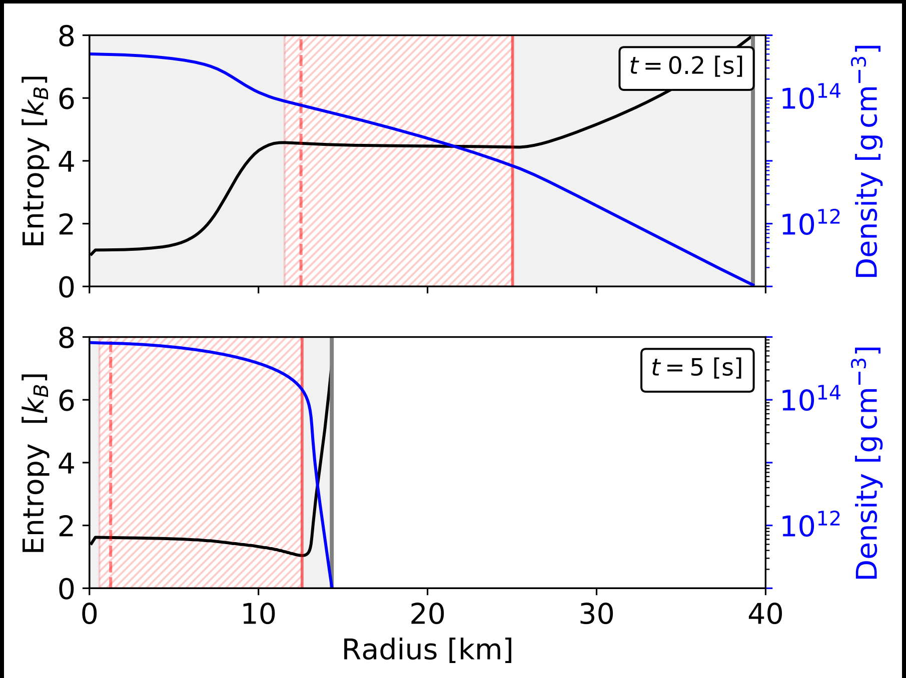
GWs from the long term evolution of a PNS

Collaborators:
- R. Raynaud, J. Guilet (CEA-Saclay)

Publications:
- Raynaud et al (in preparation)

Long term evolution of the PNS (>1 s)

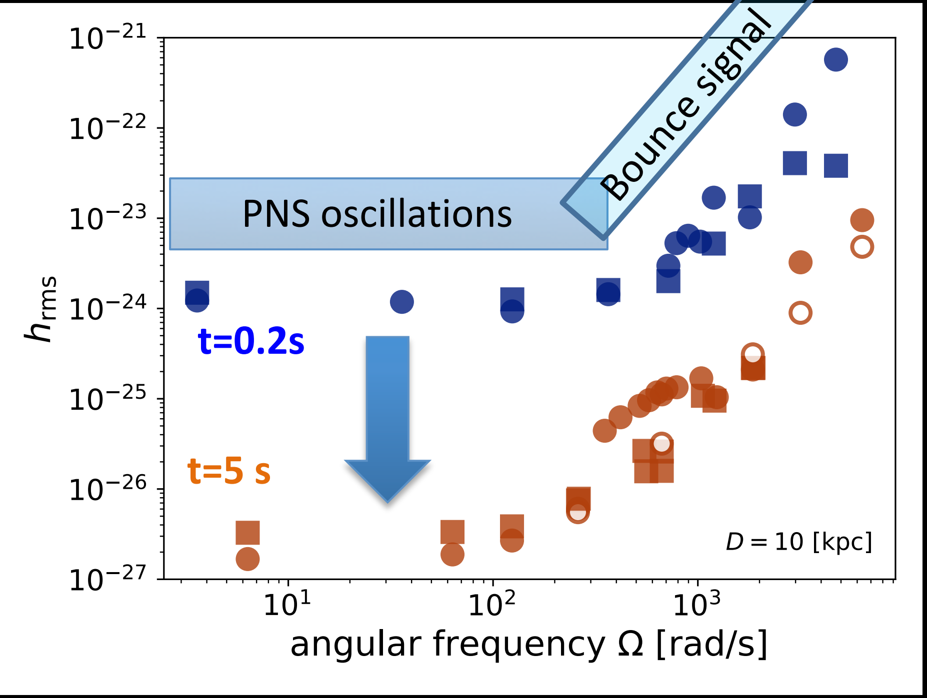
- MHD 3D simulations in the anelastic approximation (sound waves filtered)
- MagIC pseudo-spectral code (magic-sph.github.io)
- Recent application to proto-neutron star dynamos (Raynaud et al 2020)



1. 1D background simulation:
- 7 s post-bounce
- PROMETHEOS-VERTEX code
- Energy-dependent 3-neutrino flavour transport
- Progenitor: s27.0 of Woosley et al 2002
- EOS: LS220

2. 3D simulation of the convection zone
- Density and temperature of the background model at 0.2 and 5 s
- Simple gray neutrino transport: constant flux at the base of the convection zone.

Gravitational wave amplitude

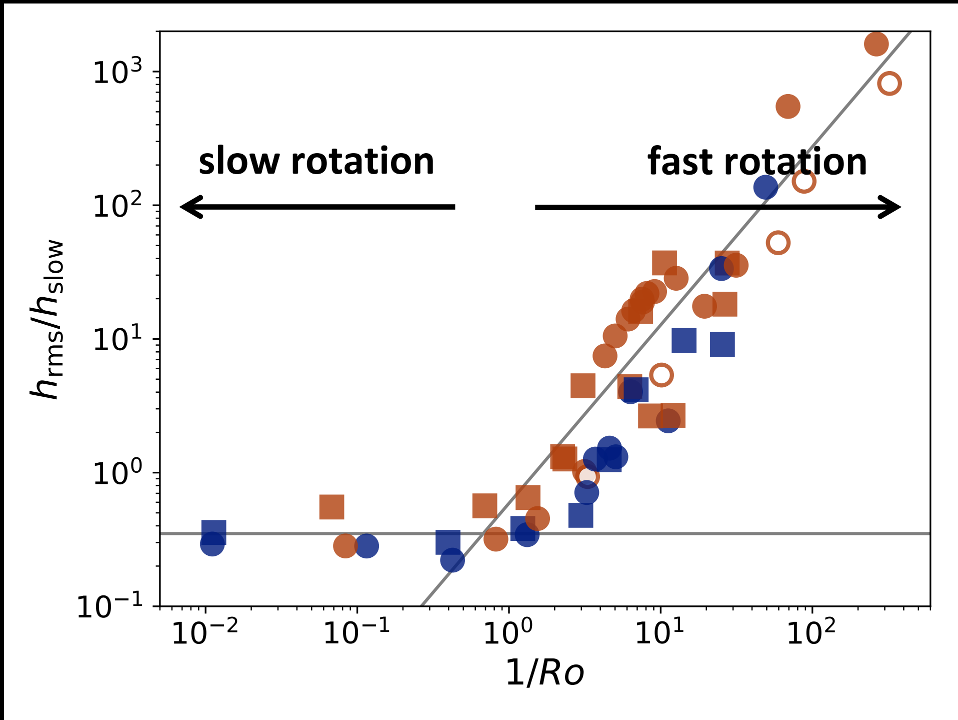


Convection decays with time rapidly in a time-scale of seconds

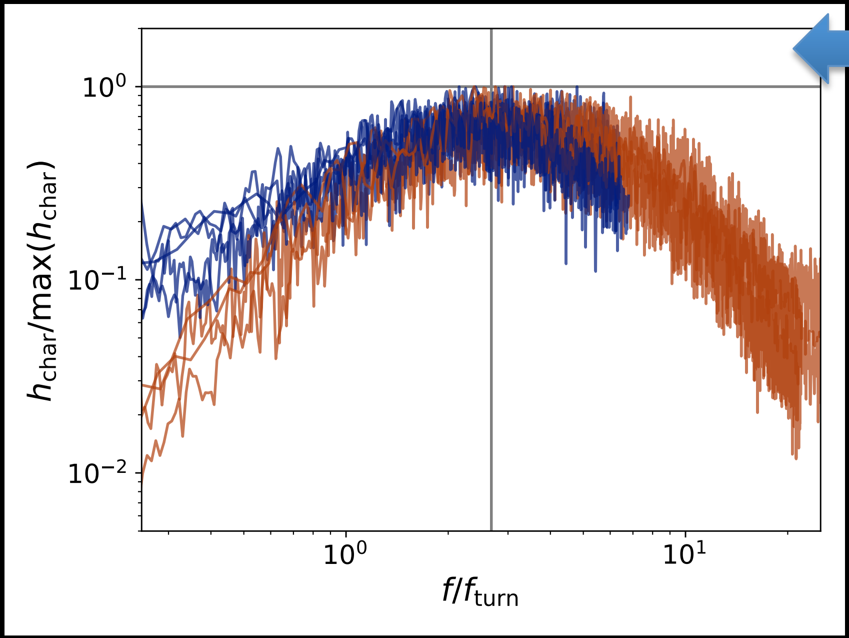
Decay can be modelled with simple scaling relations in two limits:

- Slow rotation (Ro>>1)
- Fast rotation (Ro<<1)

Ro = f_{turn} / $f_{rotation}$ → Rosssby number



GW frequency



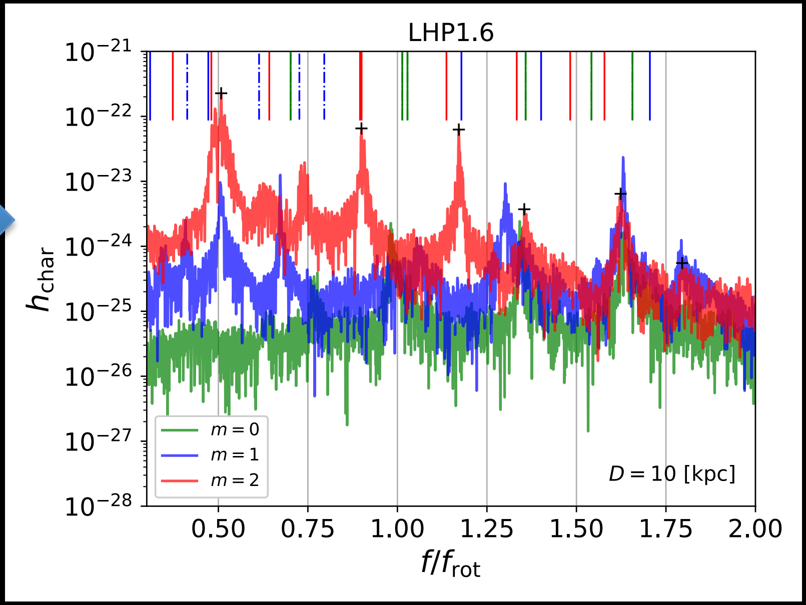
Slow rotation (Ro>1)

Broad spectrum due to convection

Peak frequency scales with overturn (convection) frequency

Fast rotation (Ro<1)

- Appearance of inertial modes
- GW frequency scales with rotation frequency.



Conclusions

- GW signals offer multiple possibilities to infer properties of the PNS
  - g-modes and p-modes
  - peak frequency at bounce (only fast rotation)
  - inertial modes (only fast rotation)
- The observation of these features would confirm the CCSN model
- It is unclear which kind of information about the hot EOS could be extracted (none? Edwan et al 2021)