ET OSB - Div. 7:

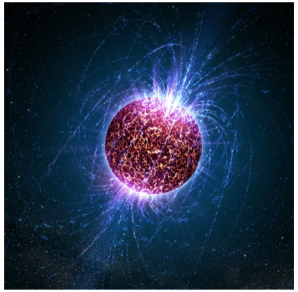
Stellar collapse and isolated neutron stars

Coordinators: Marie-Anne Bizouard, Enrico Cappellaro, Pablo Cerdá-Durán

Collapse of stellar cores / isolated neutron stars

- Core-collapse supernovae
- Long GRBs/hypernovae
- Black hole formation (unnovae)

- **Magnetars**
  - Bursts & flares in isolated magnetars (SGRs and AXPs)
  - Transients in newborn millisecond magnetars (spin-flip, bar-mode, r-mode instabilities) (CCSNs and BNS mergers)



- **Fast radio bursts**
- **Neutron star glitches**
- **Continuous waves from isolated neutron stars**

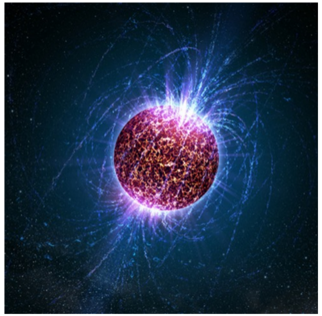
Goals

Theoretical modelling

Current observations

Observables: GW, electromagnetic, neutrinos

Rates



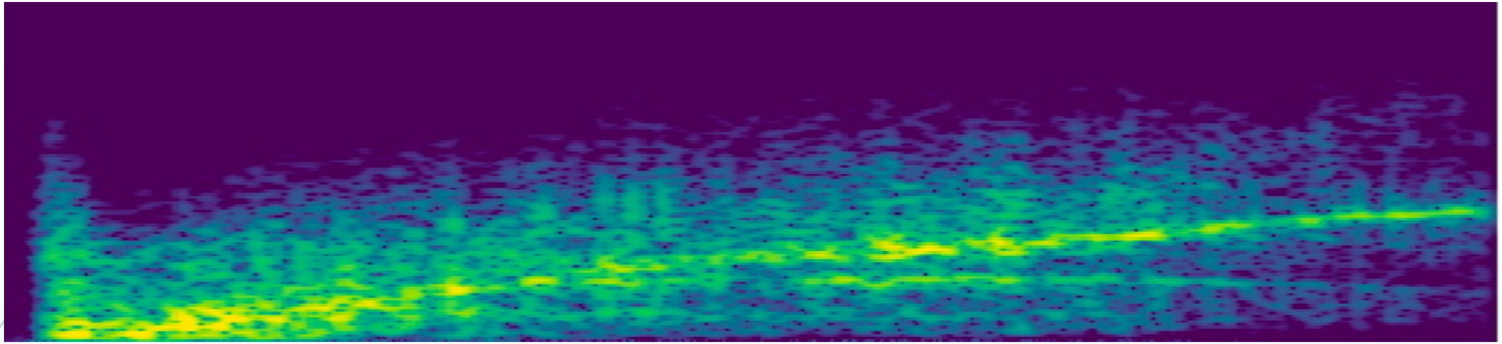
Observational prospects (GW/EM/neutrinos)	Detection scenarios	Physics	Waveforms	Data analysis needs

Div 4 (multimessenger)

Div 6 (nuclear physics)

Div 8 (waveforms)

Div 10 (data analysis)



Inference of proto-neutron star properties in core-collapse supernovae from a gravitational-wave detector network

Pablo Cerdá-Durán

University of Valencia

Collaborators:

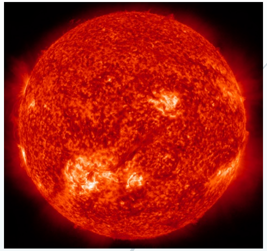
T. Bruel, M.A. Bizouard, N. Christensen (Nice)

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

P. Maturana-Rusell, R. Meier (U. Auckland)

ET symposium, May 2023

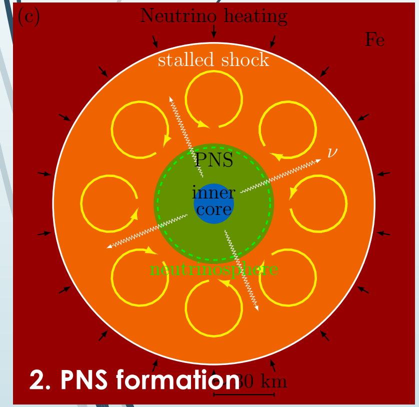
Core-collapse supernovae



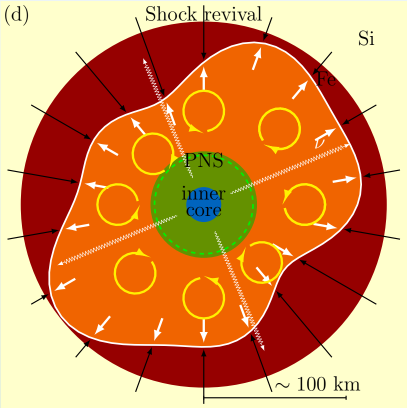
Collapse of the core of massive stars (~8-100 $M_\odot$)

- 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

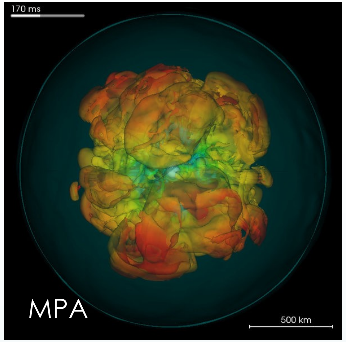
1. Collapse



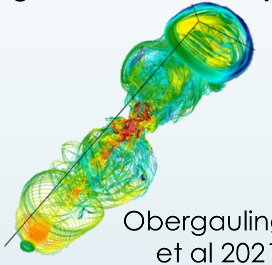
3. PNS excitation



4a. Neutrino-driven explosion

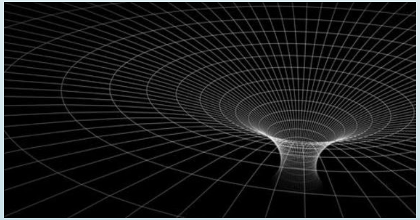


4b. Magneto-rotational explosion



Obergaulinger et al 2021

4c. Black hole formation



PNS = proto neutron star

Explosion mechanism / progenitor rotation

- **Rate of CCSNe on the Milky-way: ~2/century**
  (Adams et al 2013, $3.2^{+7.3}_{-2.6}$/century; Rozwadoska et al 2021, 1.63±0.46 / century)

- **Very fast rotators: ~1%   - magneto-rotational explosions and/or relativistic jets**
  - BL type Ic SNe: ~1% (Li et al 2011)
  - Long GRBs: ~1% (Chapman et al 2007)

$h \sim 10^{-22}$-10^{-21} @ 10 kpc

- **Magnetar progenitors (moderate/fast rotators): ~5-10% ?? – MR / neutrino-driven explosions**
  - Kouveliotou et al 1994 (10 % SN rate)
  - Gill & Heyl 2007 (0.22 / century)
  - Beniamini et al 2019 (40^{+60}_{-28}%)!!!

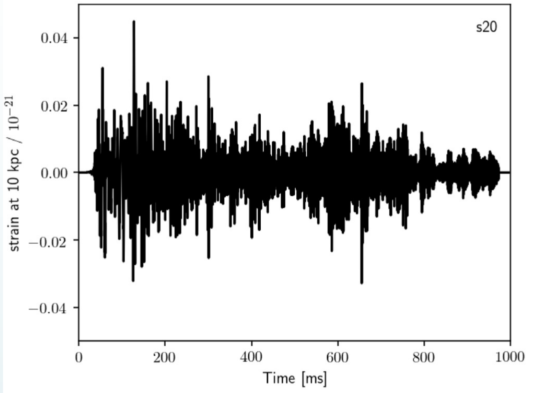
10 galactic magnetars with SNR younger tan 10 kyr ~ 0.1 / century

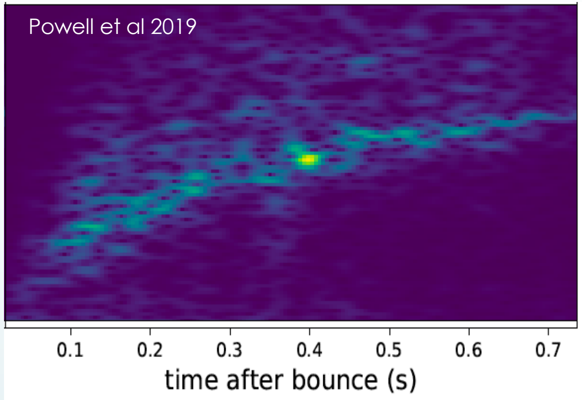
- **Non/slow rotators: 90-95%   - neutrino-driven explosions**

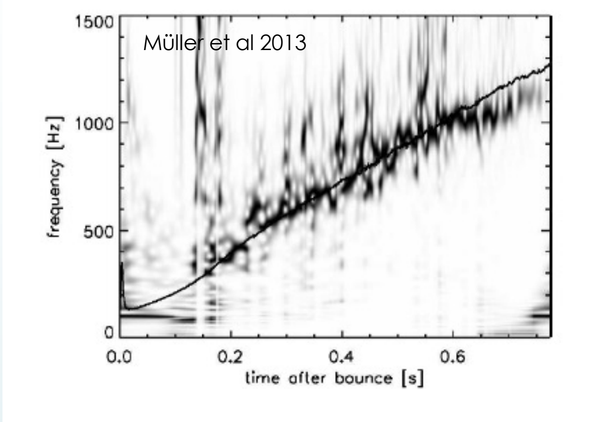
$h \sim 10^{-23}$ @ 10 kpc
(LVK: galactic SN)

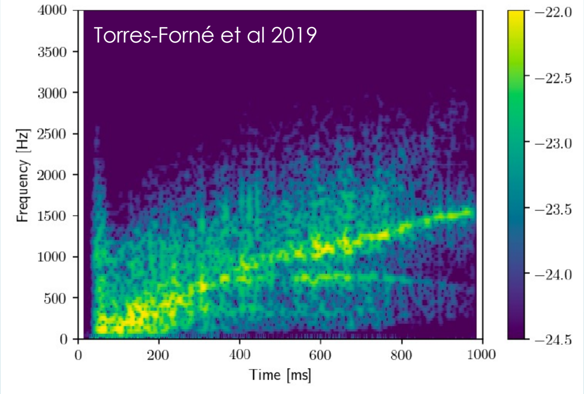
- **BH formation: 15-20% -unnovae**   (Kochanek 2014; Adams et al 2017)

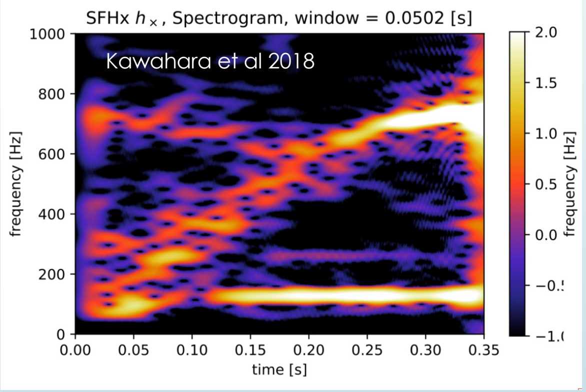
GW signal





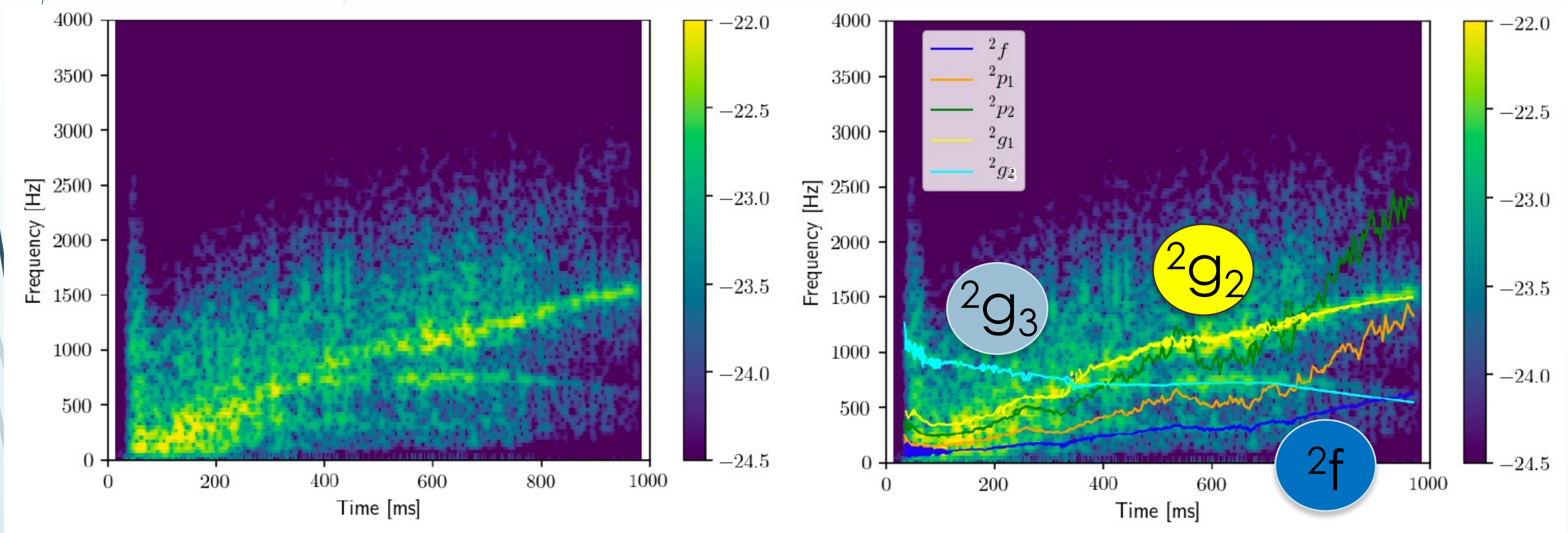






- ❑ **Highly stochastic**
- ❑ **Time evolving frequencies (g-modes, SASI)**

PNS oscillations

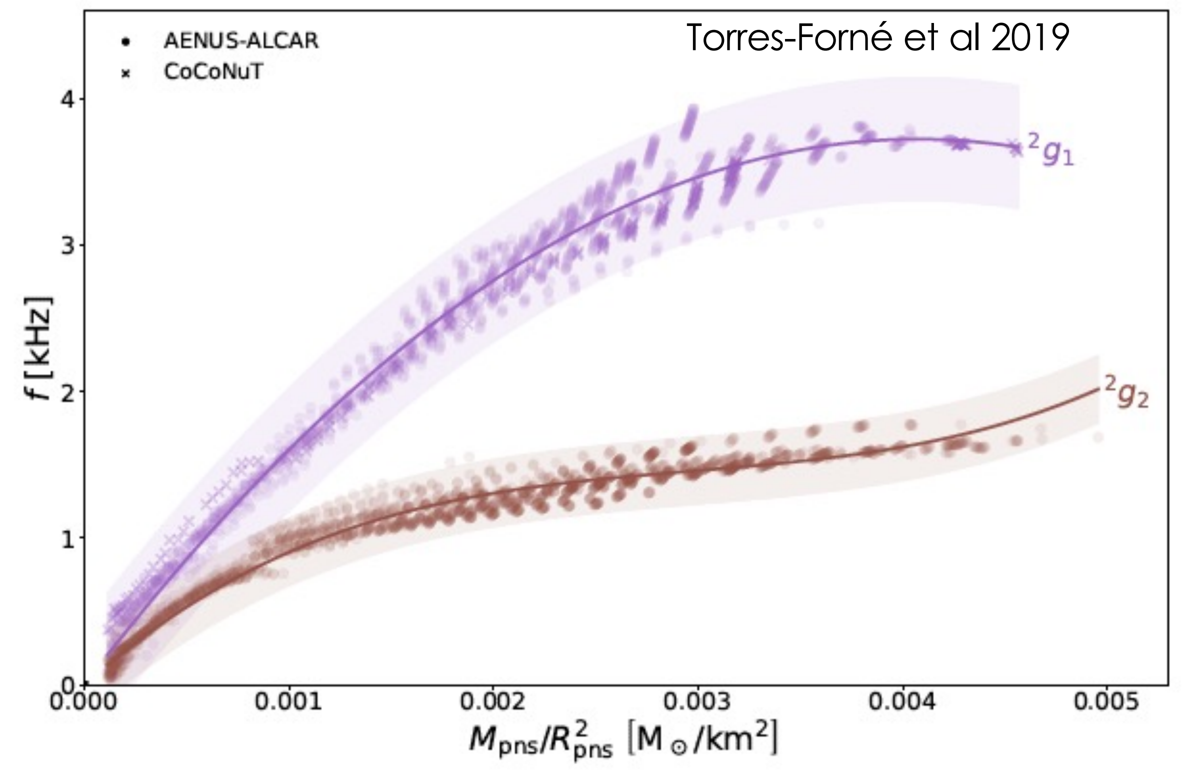


Which is the dominant mode?

How does it depend on the PNS properties?

PNS Asteroseismology

PNS oscillations - Universal relations



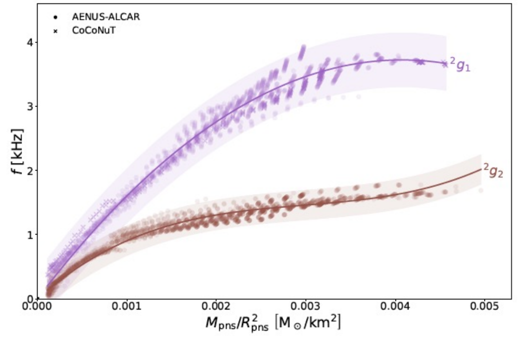
- 26 1D simulations
- 2 codes (Alcar-Aenus and CoCoNuT)
- 6 EOS (LS220, Gshen-NL3, Hshen, SFHo, BHB-Λ, Hshen-Λ)
- 8 progenitors (11.2 – 75 $M_\odot$)

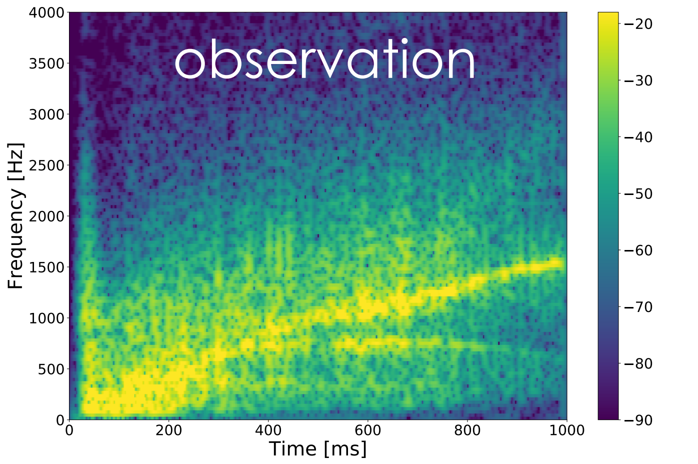
g-modes scale with PNS surface gravity

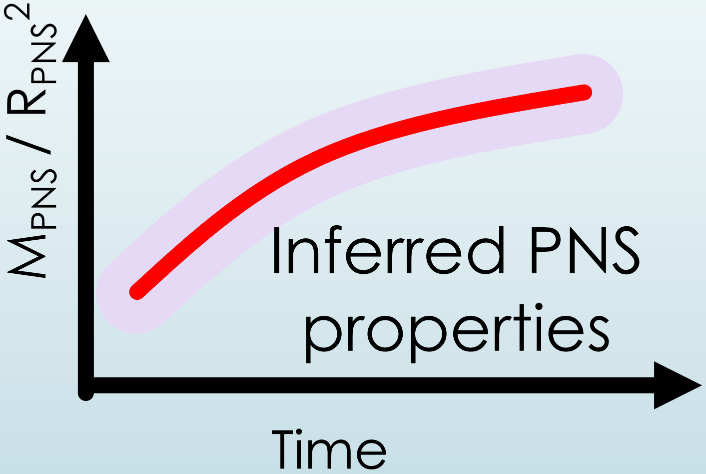
No dependence on EOS

PNS oscillations - Inference (inverse problem)

Fundamental relations

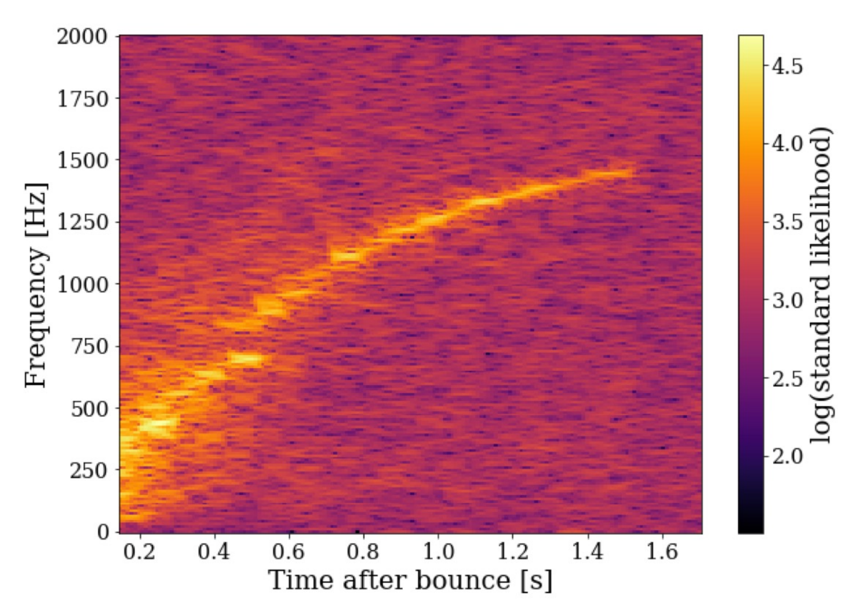






PNS oscillations from GW data

Bruel et al 2023



LVK network, source at 5 kpc

Injections:

- Simulations: 10 x 2D & 3D
- Code: Aenus-Alcar
- Progenitors: 11.2-40 $M_\odot$
- EOS: LS220, Gshen, SFHo

Noise:

- Detector network 2nd gen (HL, HLV, HLVK, HLVKA..) and 3rd gen (ET, CE)
- Simulated noise

Observational scenario

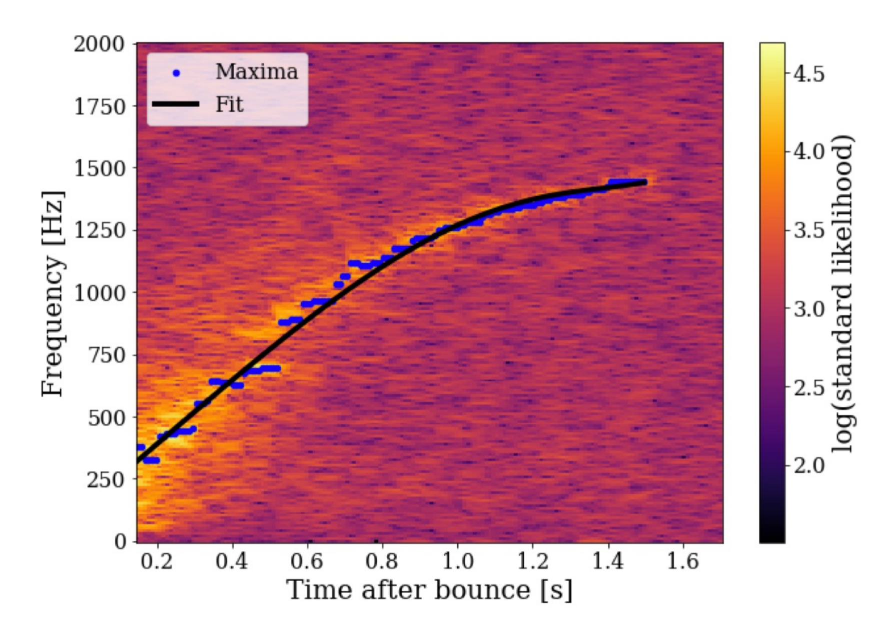
- Neutrino trigger (time of bounce within ~10 ms)
- EM observation → accurate sky localization

Spectrograms:

- Dominant polarization frame (similar to X-pipeline)
- Time shifted data

PNS oscillations from GW data

Bruel et al 2023



LVK network, source at 5 kpc

Tracking algorithm:

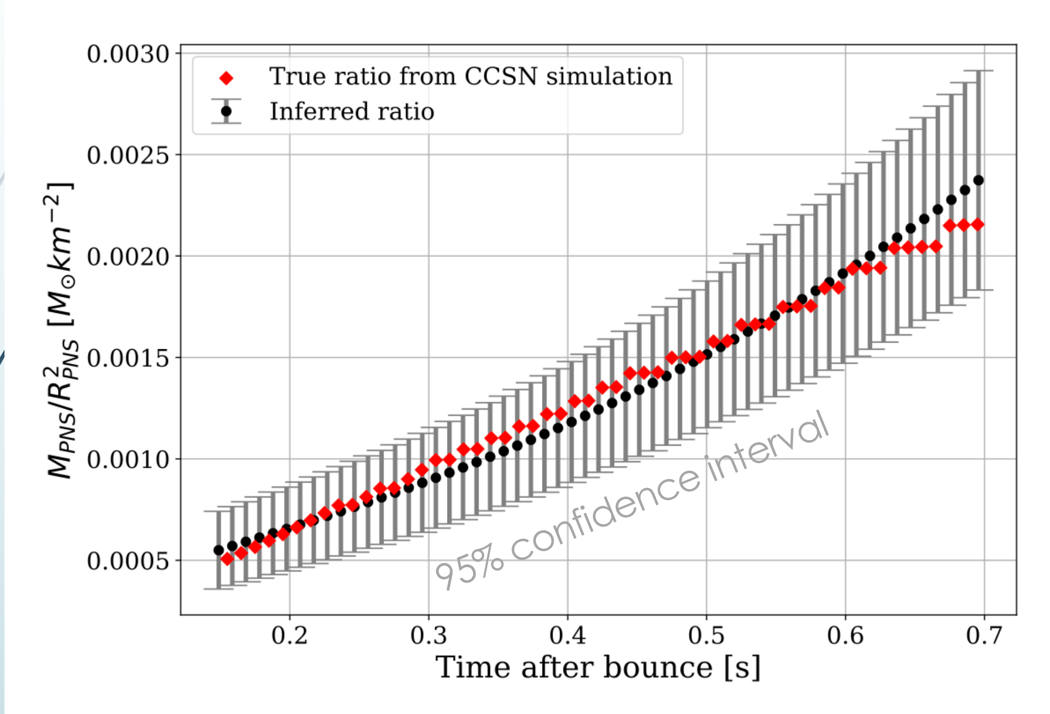
- Maximum identification
- Polynomial fit (LASSO regression)

Time-frequency tracking of the main ridge

$f(t)$

PNS oscillations - Inference of surface gravity

Bruel et al 2023



HLVKA network, source at 5 kpc

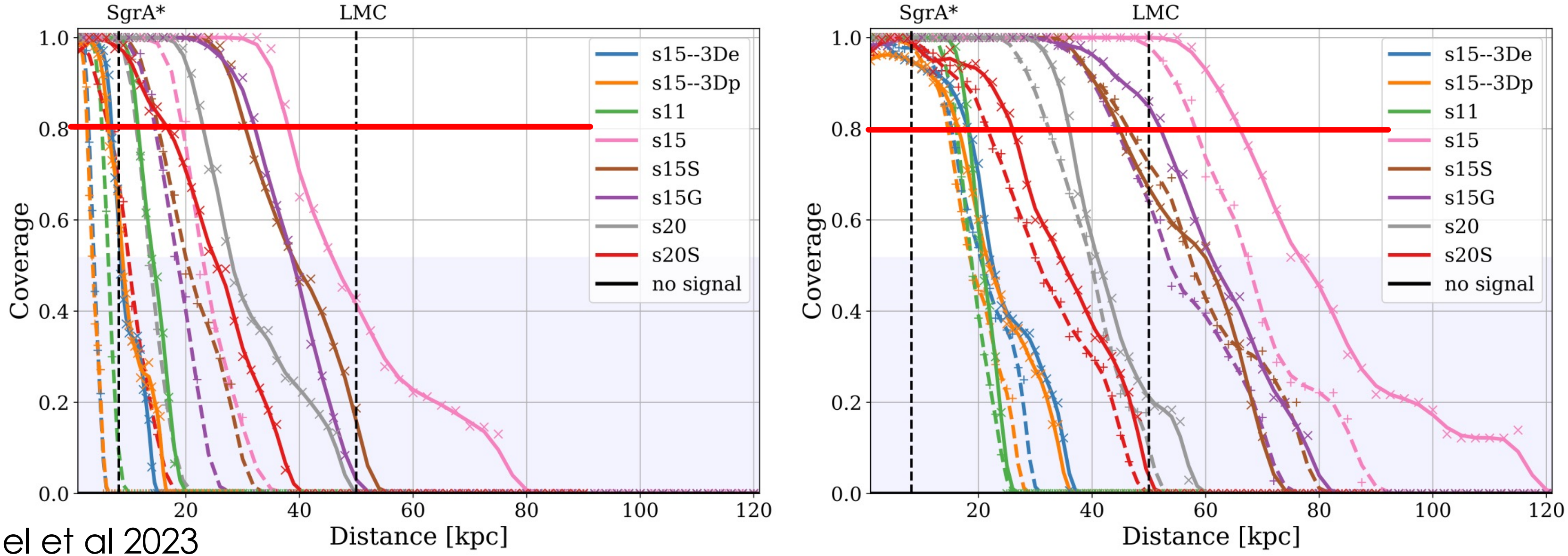
Coverage for 2nd gen detectors

(fraction of the real surface gravity inside the 95% interval of the inferred values)

HLVKA and HL network (solid and dashed lines)

Unfavourable orientation

favourable orientation



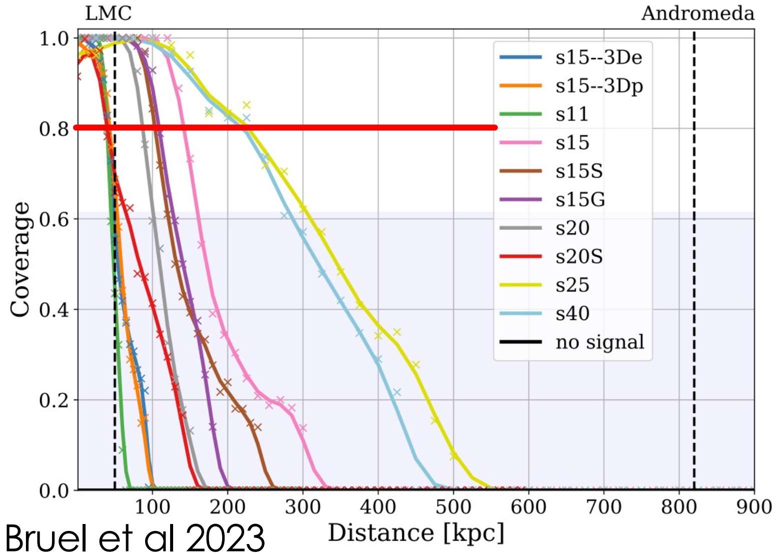
Bruel et al 2023

Galactic supernovae well reconstructed (coverage>0.8)

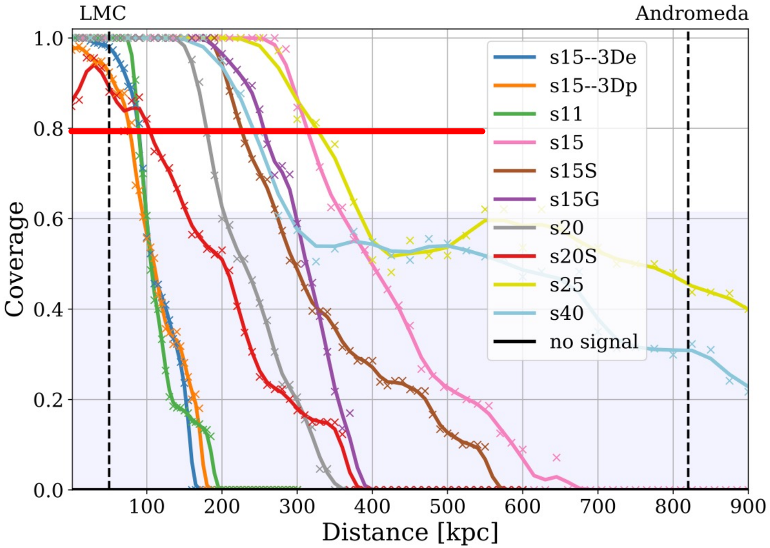
Coverage for 3rd gen detectors

ET+2CE network

Unfavourable orientation



favourable orientation



Bruel et al 2023

Possible up to a few 100 kpc

Conclusions

- It is possible to infer surface gravity of the nascent PNS from GW data
- ET will be able to do PNS asteroseismology at ~100 kpc