

Outline:

- 2.1 GW signal
- 2.2 Asteroseismology of PNS
- 2.3 Detection of GWs
- 2.4 Inference
- 2.5 Detection rates

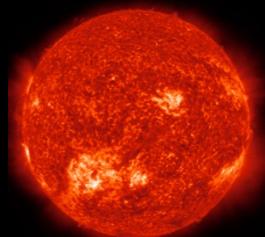
PART 2

GRAVITATIONAL WAVES FROM CCSNe

2.1 GW signal

Gravitational wave emission from CCSNe

Quadrupole-formula: GW strain in the slow-motion limit ($v/c \ll 1$)



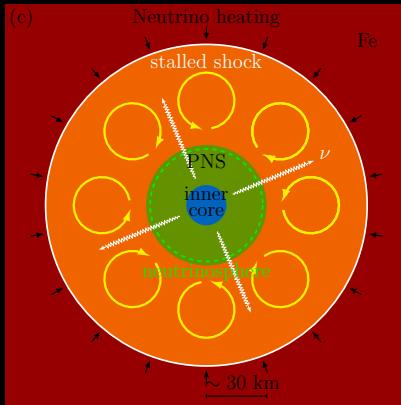
1. Collapse

$$h(\mathbf{X}, T) = \frac{1}{D} \frac{G}{c^4} \frac{8\pi}{5} \sqrt{\frac{2}{3}} \sum_{m=-2}^{+2} \ddot{Q}_{2m}(t) {}_{-2}Y^{2m}(\Theta, \Phi)$$

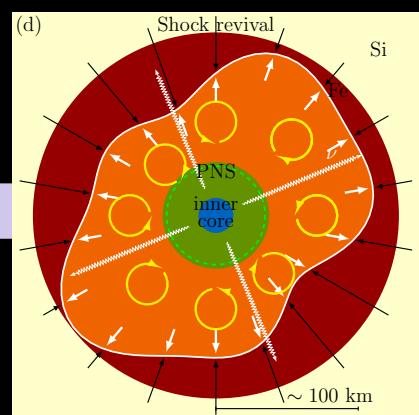
$$Q_{lm} \equiv \int \varrho(\mathbf{x}, t) r^2 Y_{lm}^\star(\theta, \varphi) d^3 \mathbf{x}$$

We need rapid variations of the quadrupole

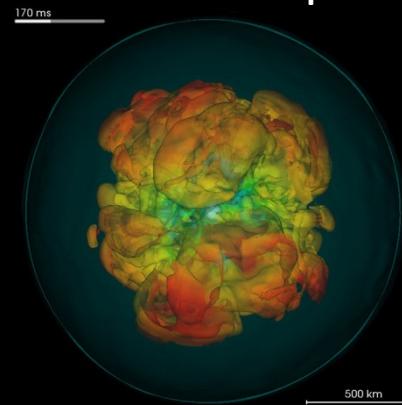
2. PNS formation



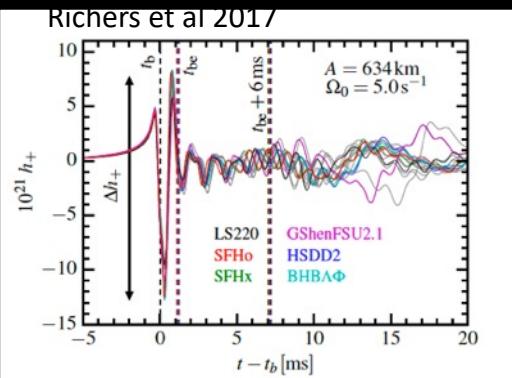
3. PNS + shock instabilities



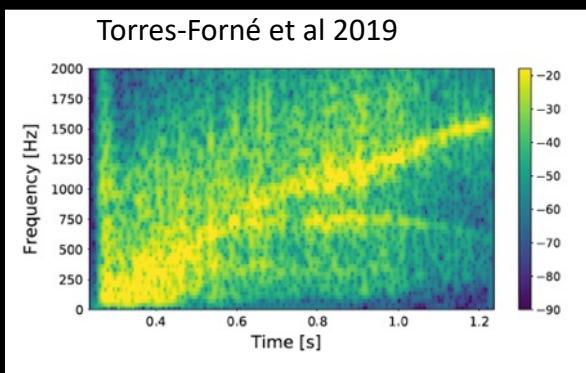
3. Neutrino-driven explosion



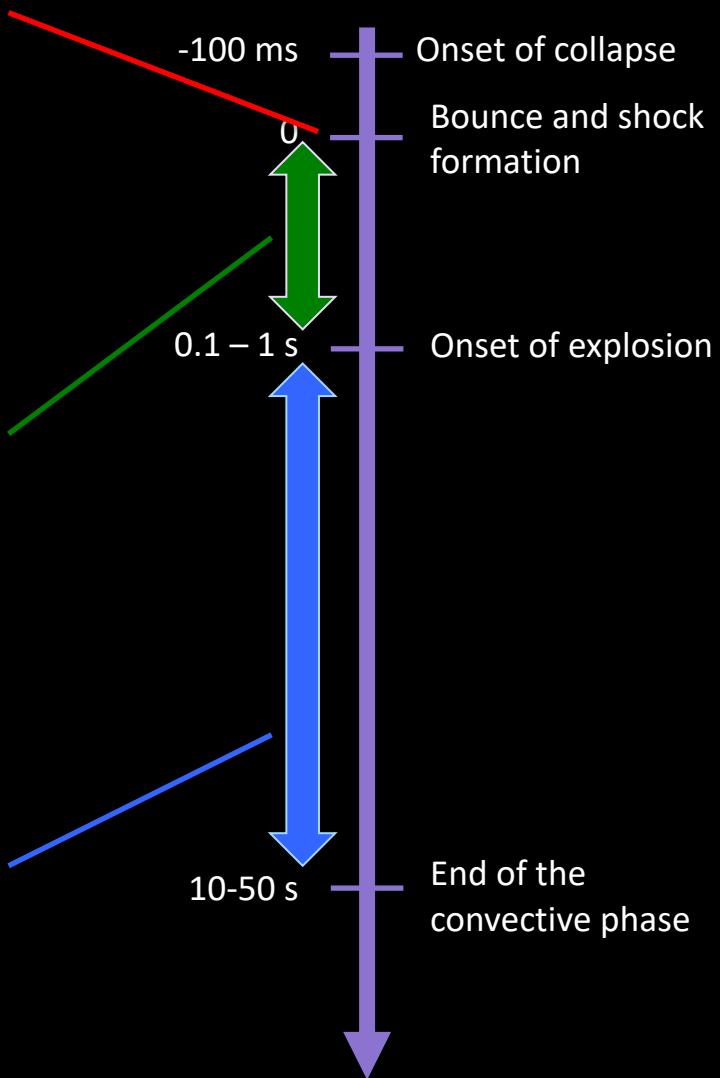
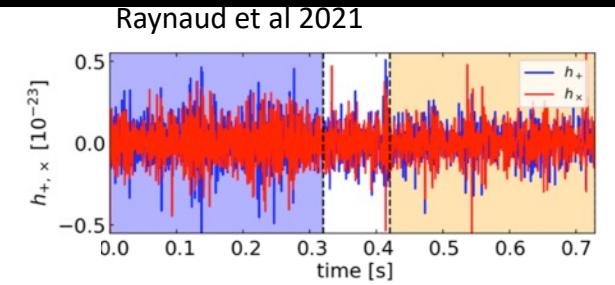
Bounce signal



Post-bounce “SN” signal



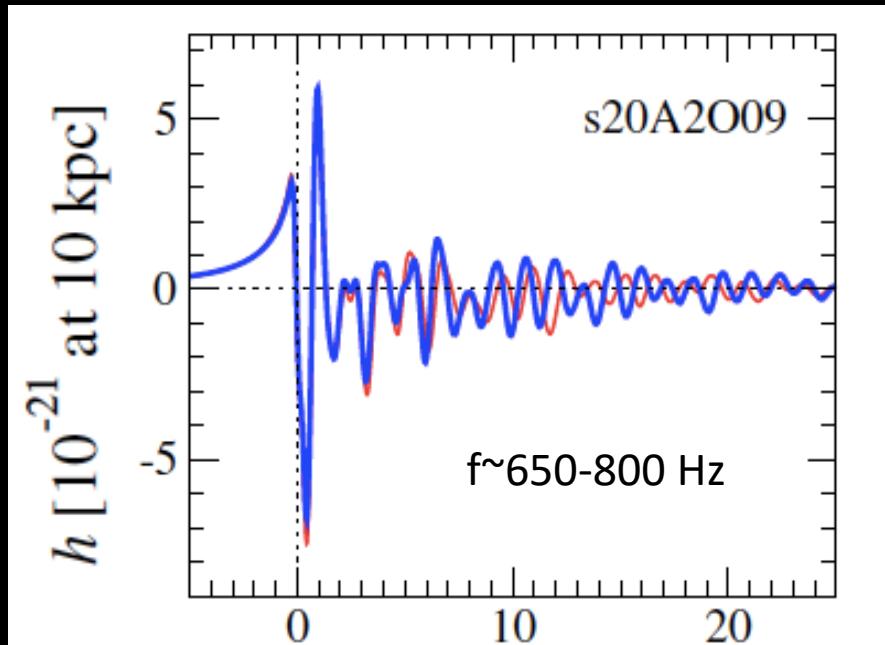
Proto-neutron star convection signal



GW emission: bounce

- Bounce of *rotating* cores:
Dimmelmeier'07,08, Abdikamalov'14,
Fuller'15, Richers'17 ...
- Short duration ~few ms
- $f \sim 650\text{-}800\text{ Hz}$
- Relevant for $\Omega > 0.1\text{ rad/s}$

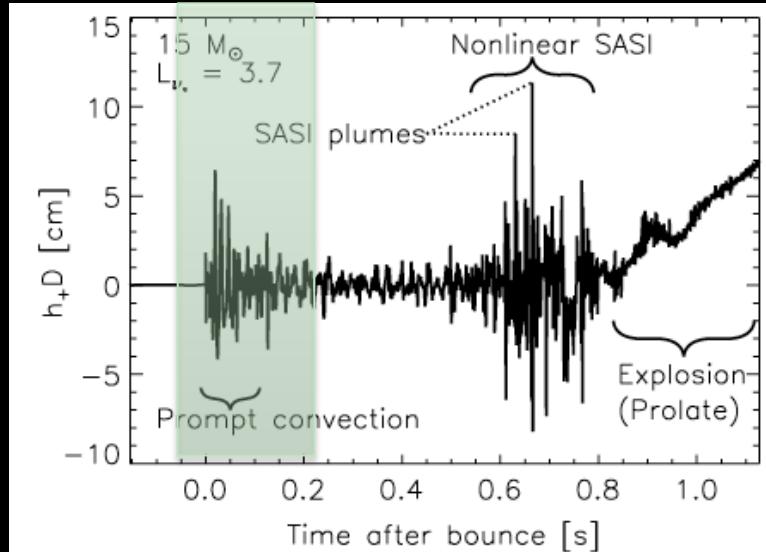
$$h_{10kpc} \sim 5 \times 10^{-21} \frac{\Omega}{1\text{ rad/s}}$$



Dimmelmeier et al 2008

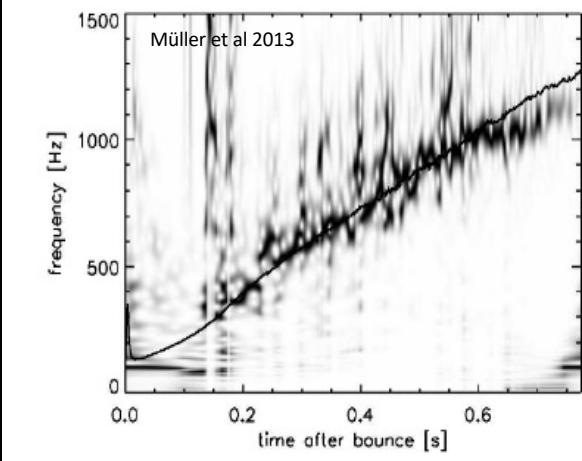
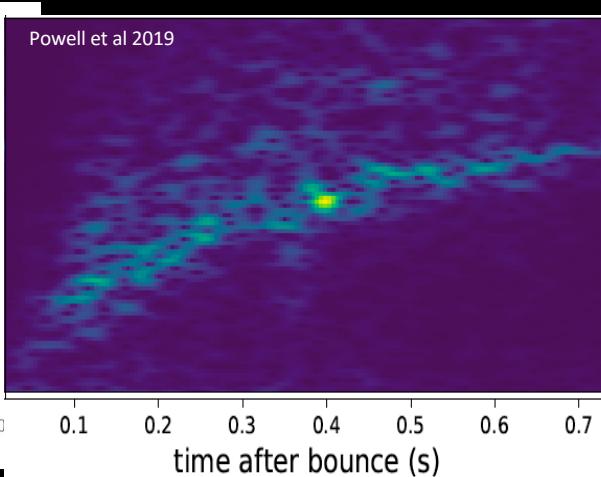
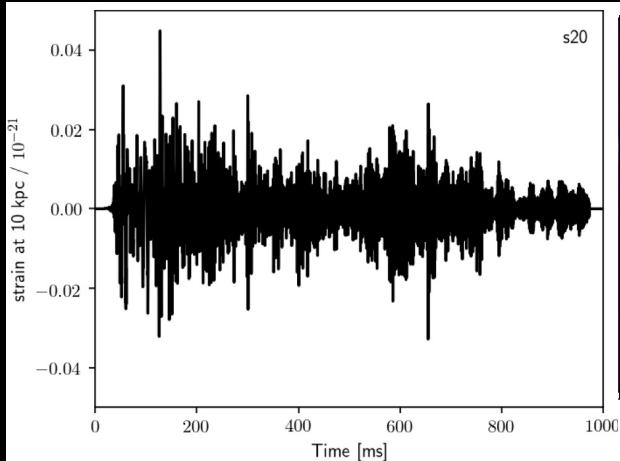
GW emission: Prompt convection

- Murphy et al. 2009; Marek & Janka 2009; Yakunin et al. 2010
- Prompt convection
 - Duration: <50 ms after bounce
 - $f \sim 100\text{-}200$ Hz
 - $h \sim 10^{-22}$ at 10 kpc
- Post-shock convection
 - Do not produce GW by itself
 - Excitation of PNS modes

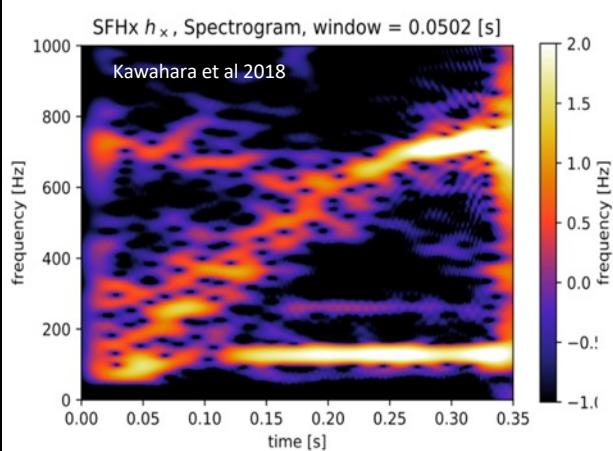
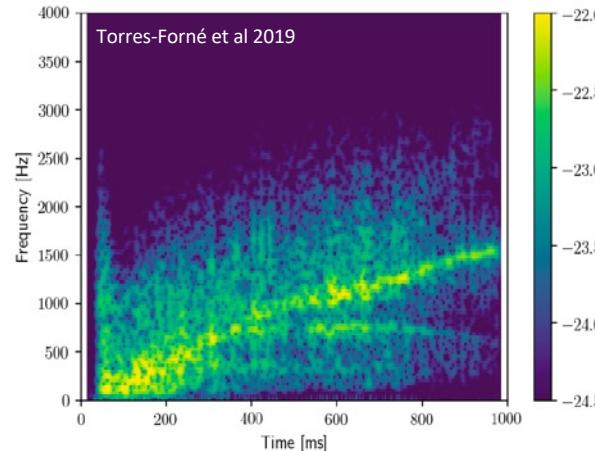


Murphy et al 2009

GW emission: PNS oscillations

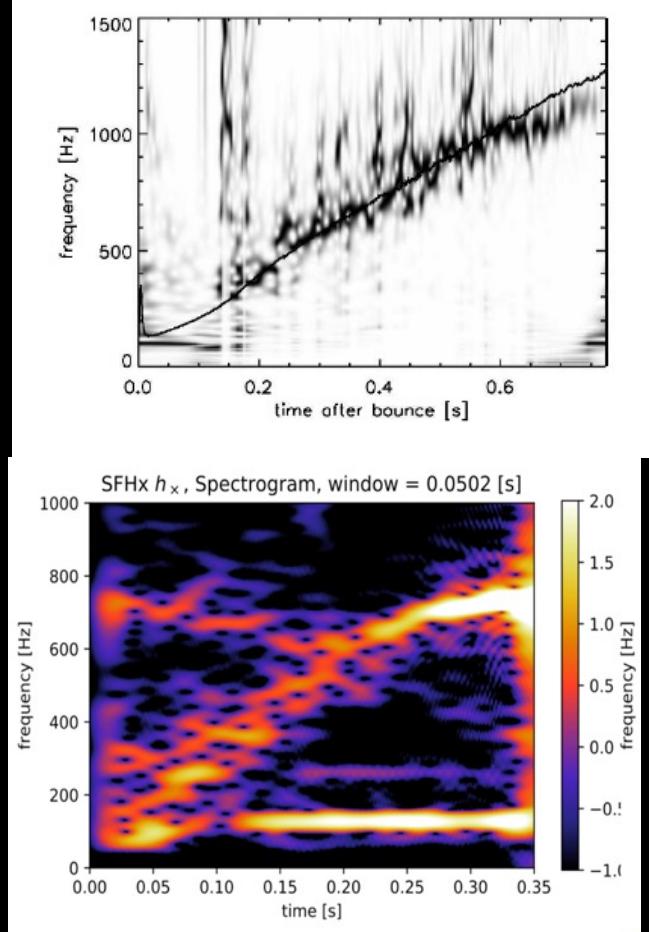


- **Highly stochastic**
- **Time evolving frequencies (g-modes, SASI)**



GW emission: PNS oscillations

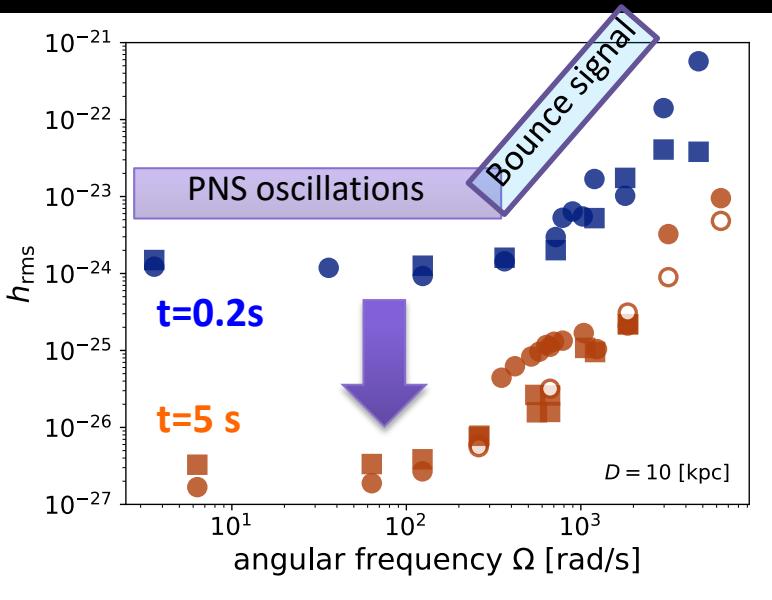
- Post-shock convection + SASI excite PNS modes
(Murphy et al. 2009; Müller et al. 2013; Cerdá-Durán et al. 2013; Yakunin et al. 2015; Kuroda et al. 2016; Andresen et al. 2017)
- Amplitude @ 10 kpc:
 - Slow rotation: $h \sim 10^{-22}$
 - Fast rotation: $h \sim 10^{-21}$
- Duration: ~ 100 ms to $\sim s$
- g/p/f-modes
 - 100-200 Hz at bounce
 - Increase at $\sim 1\text{kHz/s}$
- SASI modes
 - 50-100 Hz
 - Small increase (50-300 Hz/s)



Müller et al 2013

Kawahara et al 2018

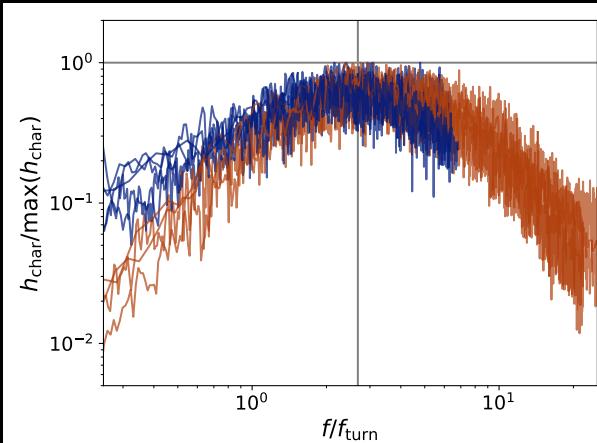
GW emission: PNS convection



- Convection layer: 10-50 s
- Convection decays with time rapidly in a time-scale of seconds

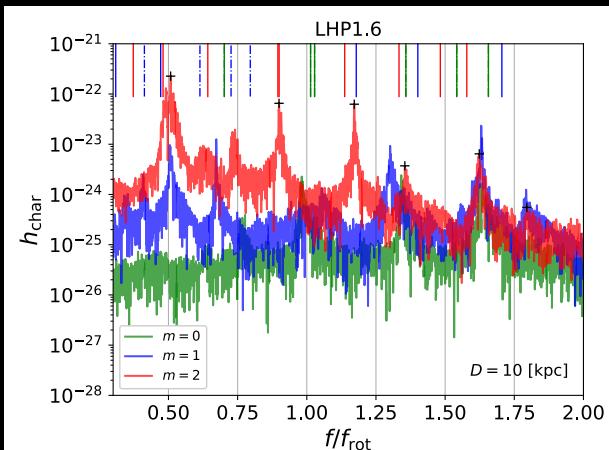
Slow rotation:

- Broad spectrum
- f scales with overturn frequency



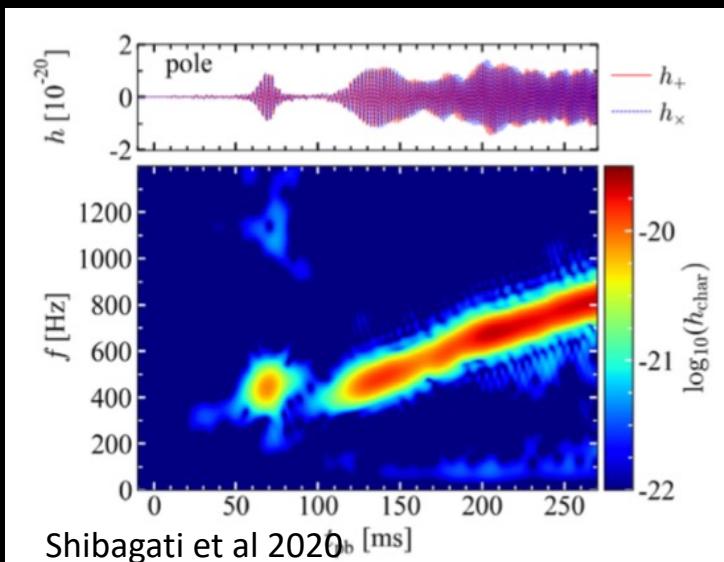
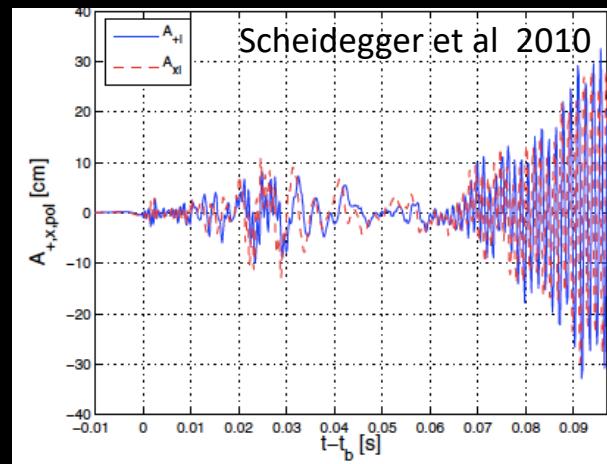
Fast rotation:

- Inertial modes
- f scales with rotation frequency



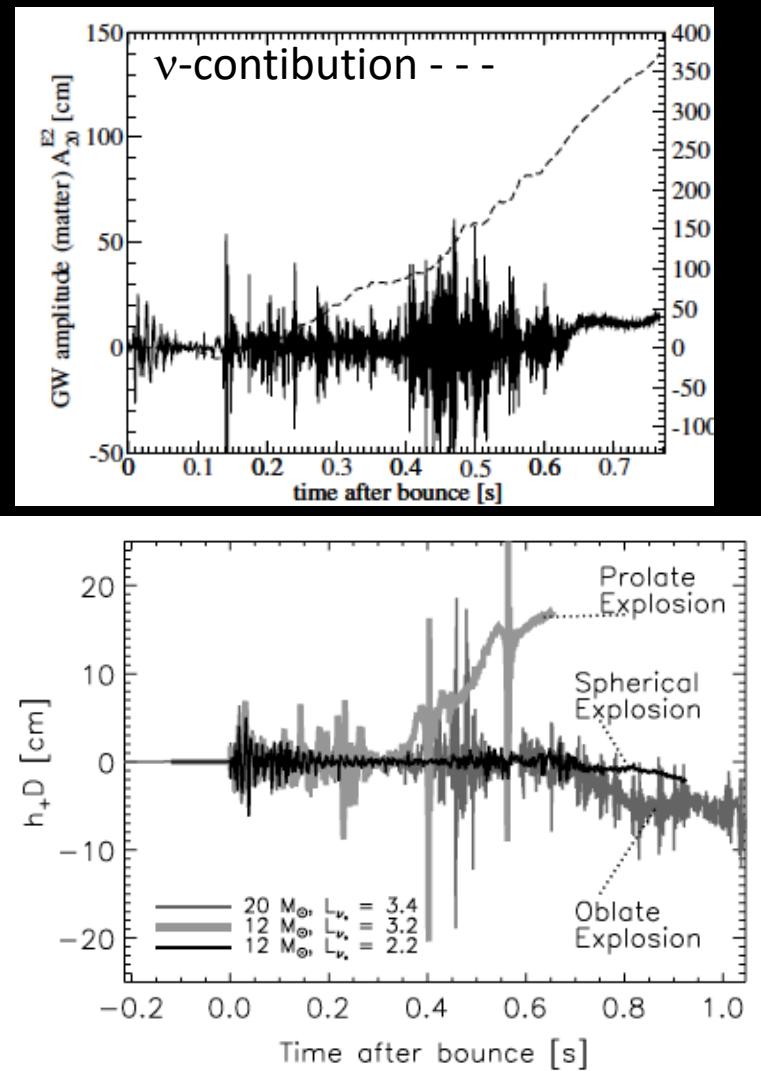
GW emission: triaxial instabilities

- Growth of bar-mode instabilities (Ott et al. 2005; Scheidegger et al. 2010; Kuroda et al. 2014, Shibagati et al 2020, Takiwaki et al 2021 ...)
 - Dynamical ($T/W > 0.27$): may be possible for very fast progenitors
 - Low T/W ($T/W > 0.01$): competing processes may not allow it (MRI, magnetic braking)
- $h \sim 10^{-20}$ at 10 kpc
- $f \sim 400\text{-}1000$ Hz
- Correlated h_+ - h_x
- Duration: unclear
 - Several processes compete: MRI, shear instabilities at the PNS surface (CD'07) \rightarrow bar destroyed in dynamical times (~ 10 ms)
 - Long-lived bars?



GW emission: memory

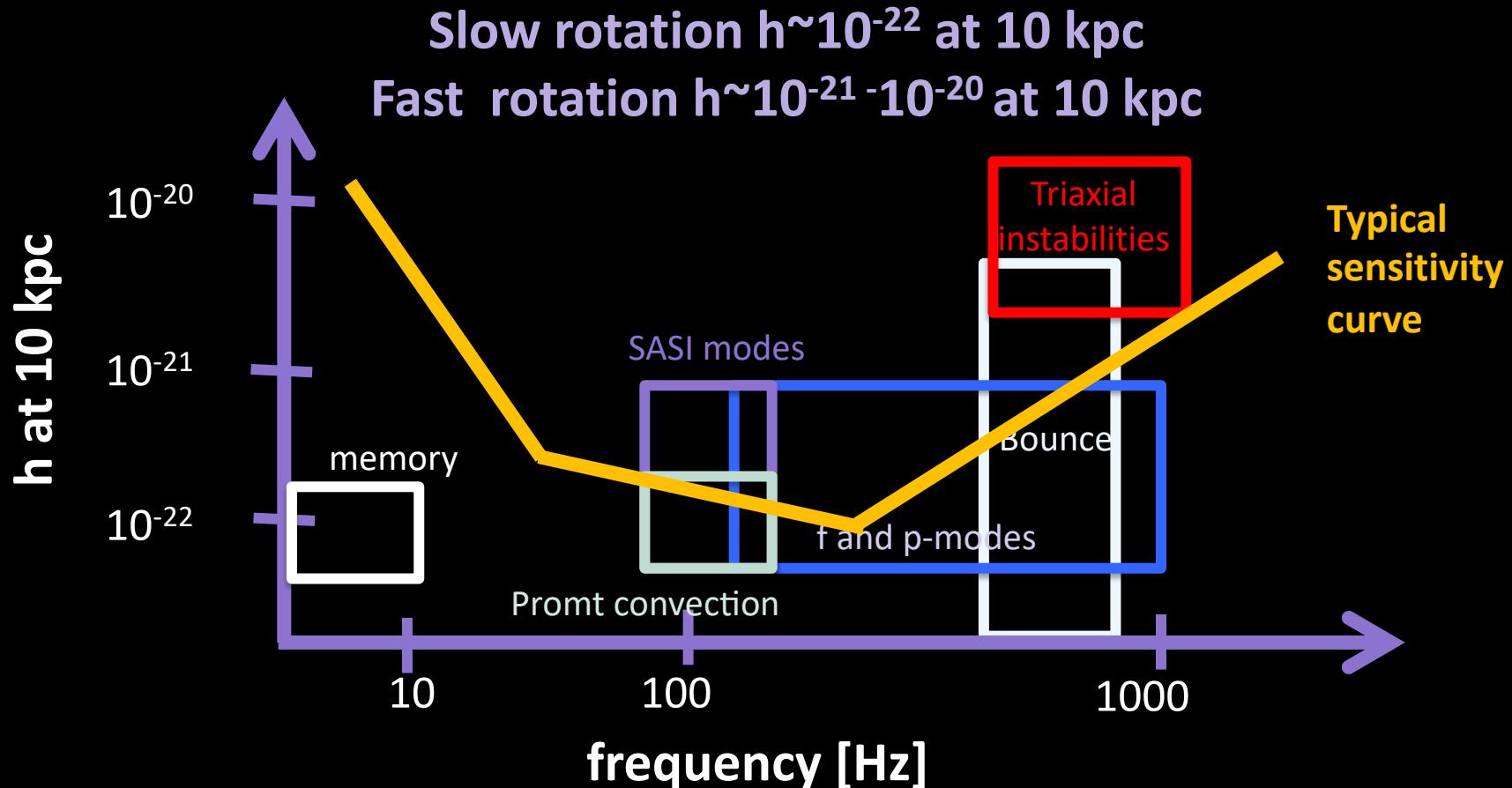
- Murphy et al. 2009; Marek & Janka 2009; Yakunin et al. 2010; Müller et al. 2004 ...
- Asymmetries:
 - In neutrino emission
 - During fast expansion (SN explosion)
- Amplitude at 10 kp $\sim 10^{-22}$
- $f \sim 1\text{-}10 \text{ Hz} \rightarrow$ too low for LIGO/Virgo/KAGRA



Murphy et al 2009

Müller et al 2013

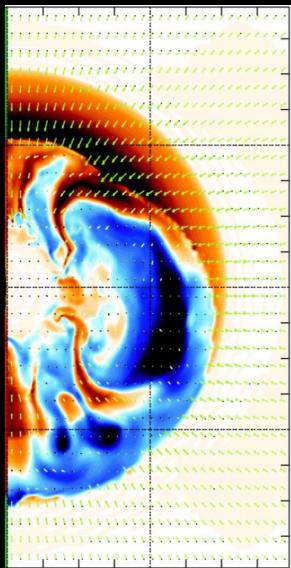
GW emission: summary



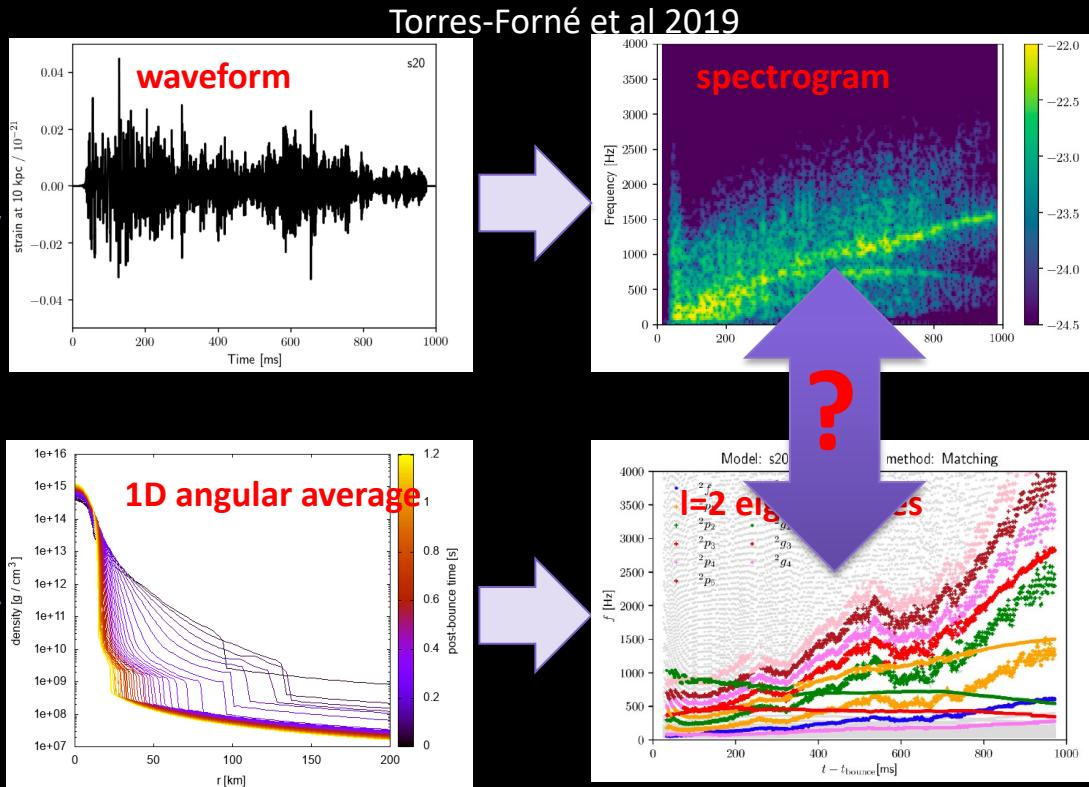
2.2 Asteroseismology of PNS

Proto-neutron star oscillations

Multi-dimensional
numerical simulation



Obergaulinger et al 2013



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

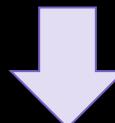
Morozova et al 2018, Radice et al 2019

Sotani et al 2019a,b

Westernacher-Schneider 2019

Our contribution:

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



GREAT = General Relativistic Eigenmode Analysis Tool

<https://www.uv.es/cerdupa/codes/GREAT/>

This afternoon ...

The GREAT hackathon

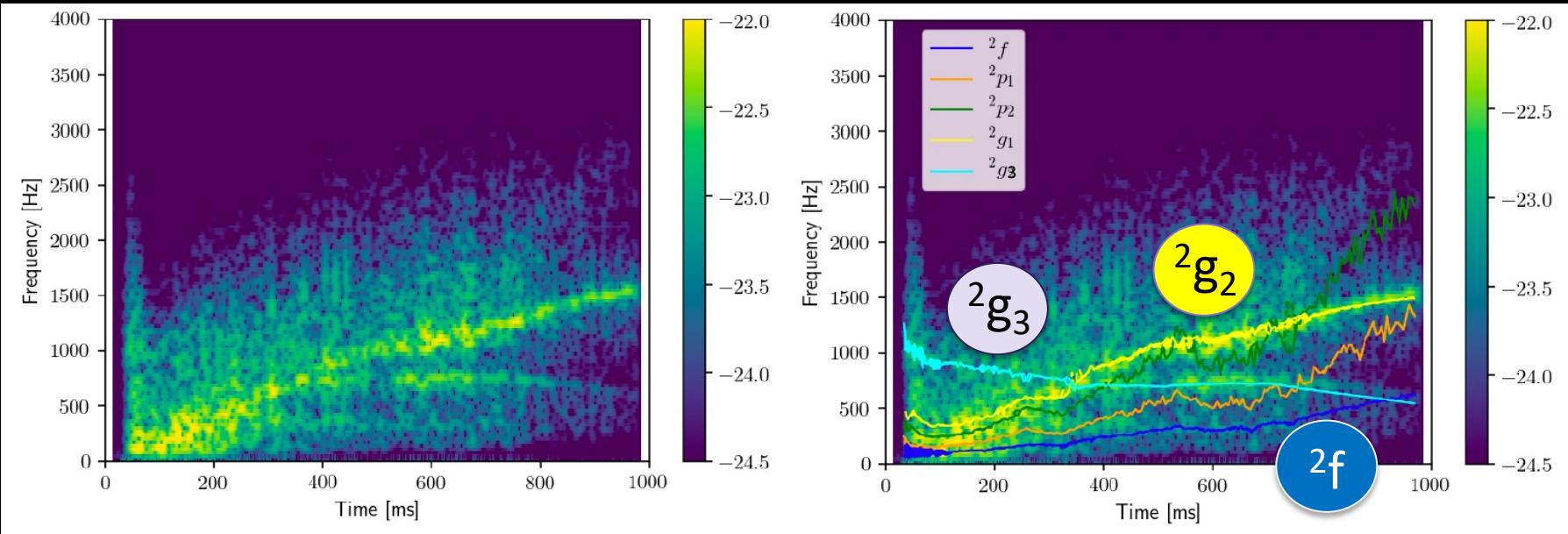
There will be prizes!!

This afternoon ...

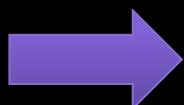
1. Download docker for GREAT(see mail with instructions)
2. Update to the latest version of GREAT (git pull)
3. Form groups of three
 - At least one fortran expert and one python expert
 - Register groups here: <https://go.uv.es/spgD3ym>

There will be prizes!!

Comparison with GWs



Which is the dominant mode?



PNS Asteroseismology

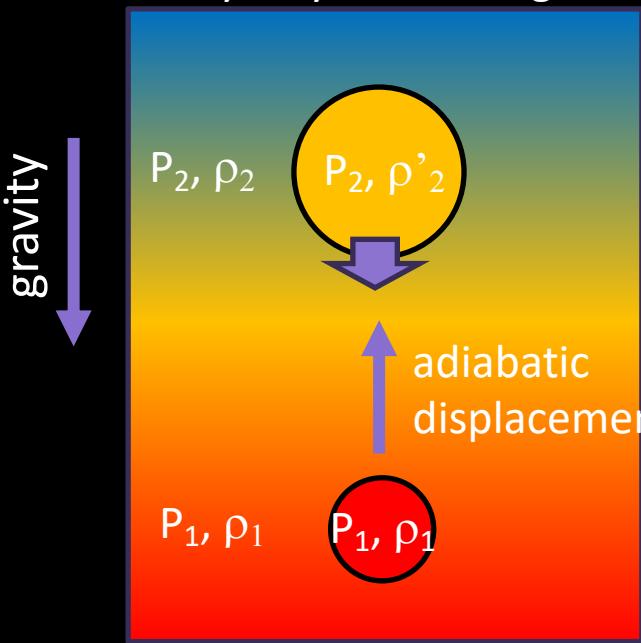
How does it depend on the PNS properties?

Buoyancy

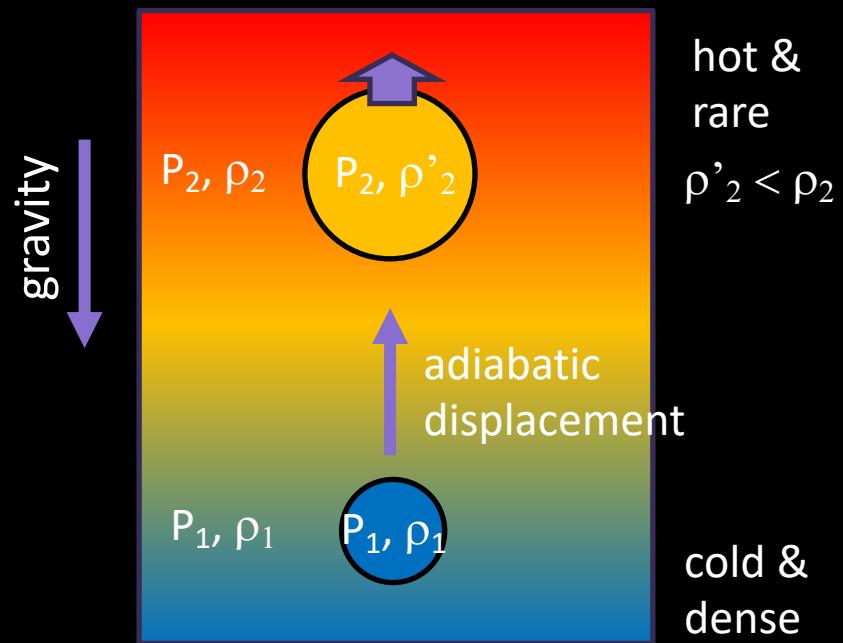
Brunt-Väisälä frequency

$$N^2 \approx \frac{\partial \Phi}{\partial r} \frac{1}{\rho} \left(\frac{1}{c_s^2} \frac{\partial P}{\partial r} - \frac{\partial \rho}{\partial r} \right)$$

$N^2 > 0$: Stability (negative buoyancy of a raising fluid)



$N^2 > 0$: Instability (positive buoyancy of a raising fluid)



Brunt-Väisälä frequency

$$N^2 \approx \frac{\partial \Phi}{\partial r} \frac{1}{\rho} \left(\frac{1}{c_s^2} \frac{\partial P}{\partial r} - \frac{\partial \rho}{\partial r} \right) = \frac{\partial \Phi}{\partial r} \frac{1}{\rho} \left(\xi \nabla s + \delta \nabla Y_e \right)$$

$$\xi = -\partial \ln P / \partial s|_{\rho, Y_e} / \Gamma_1$$

$$\delta = -\partial \ln P / \partial Y_e|_{\rho, s} / \Gamma_1$$

EOS

1st law of thermodynamics

Schwarzschild/Ledoux
criterium

$\uparrow \rho = \text{const.}$

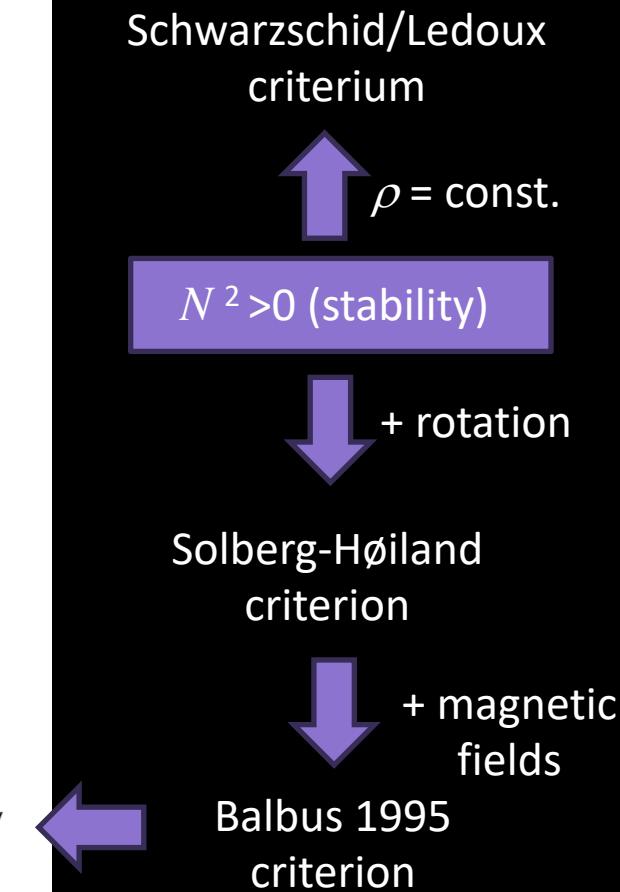
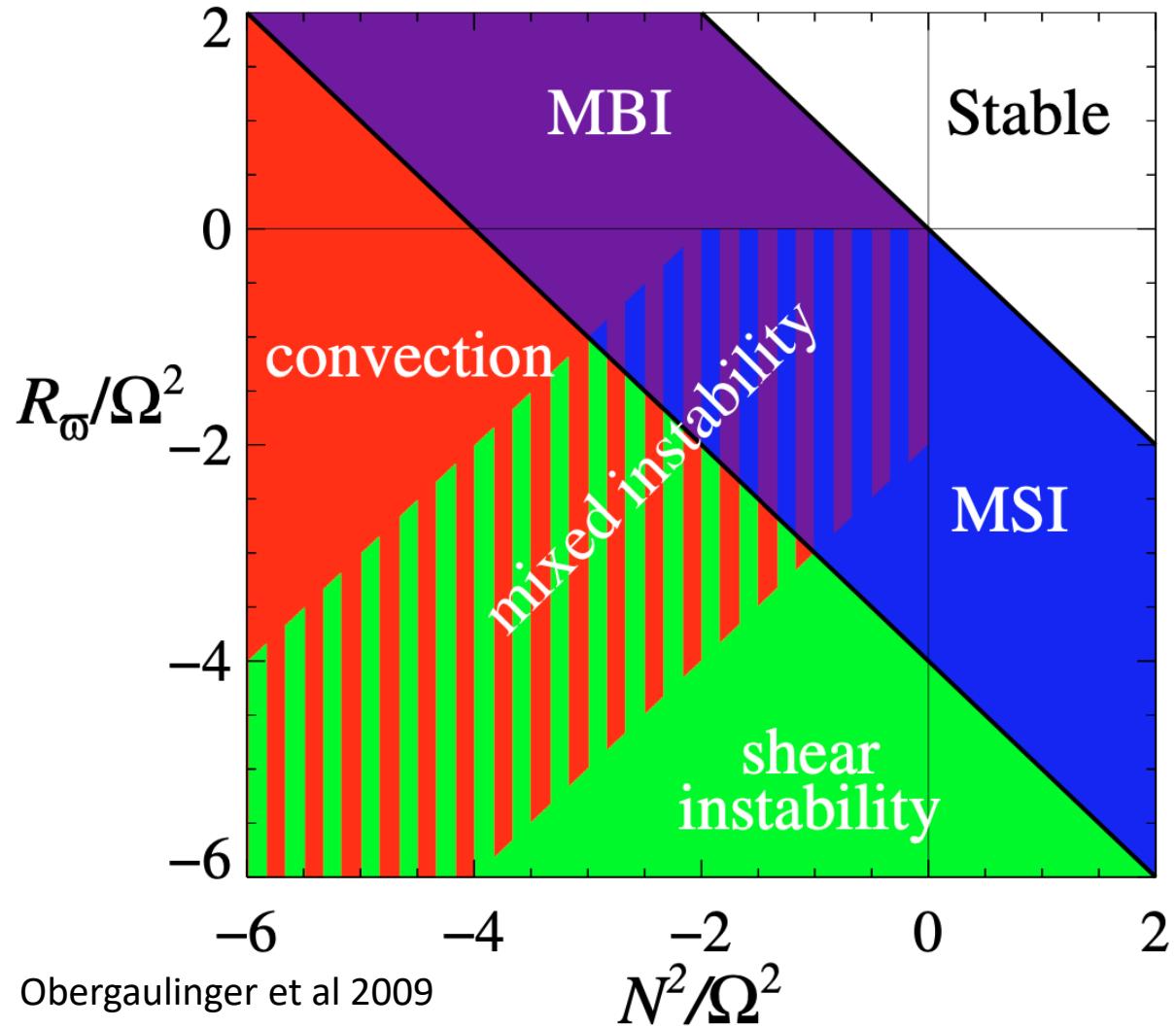
$N^2 > 0$ (stability)

$\downarrow + \text{rotation}$

Solberg-Høiland
criterion

$\downarrow + \text{magnetic fields}$

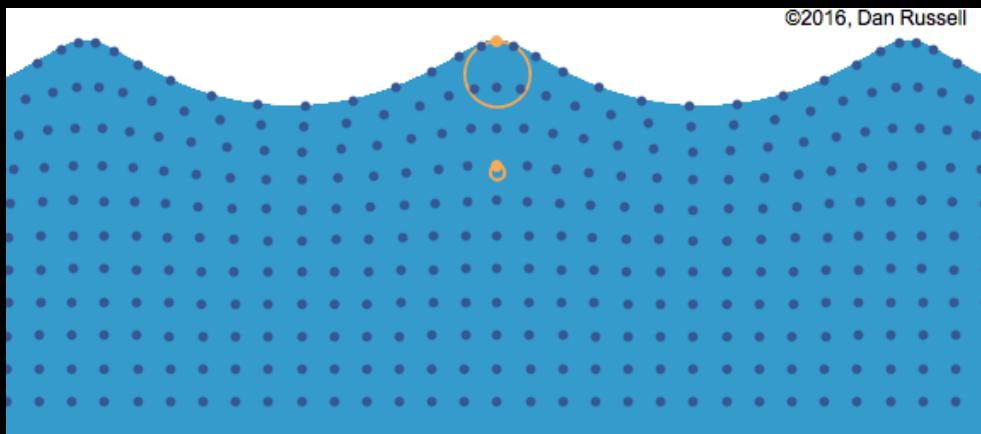
Balbus 1995
criterion



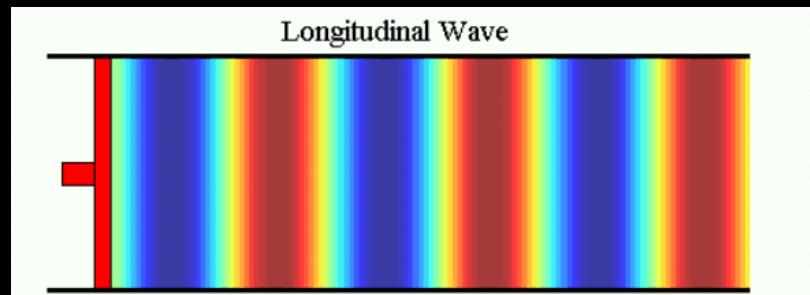
Gravity (buoyancy) waves vs pressure waves

$$N^2 > 0$$

Transverse waves



Longitudinal waves



Types of fluid modes (radial oscillations of non-rotating stars)

p-modes

- Pressure modes
- Restoring force = pressure
- Standing sound waves
- Lamb frequency (L):

$$L^2 \approx c_s^2 \frac{l(l+1)}{r^2}$$

- Mode frequency

$$f \propto c_s \propto \sqrt{\bar{\rho}} \propto \sqrt{M / R^3}$$

Types of fluid modes (non-radial oscillations of non-rotating stars)

p-modes

- Pressure modes ($l \geq 0$)
- Restoring force = pressure
- Standing sound waves
- Lamb frequency (L):

$$L^2 \approx c_s^2 \frac{l(l+1)}{r^2}$$

- Mode frequency

$$f \propto c_s \propto \sqrt{\bar{\rho}} \propto \sqrt{M / R^3}$$

f-mode

- Fundamental mode ($l \geq 2$)
- Node-less mode (simple case)
- Lowest-order p-mode?

$$L^2 \approx c_s^2 \frac{l(l+1)}{r^2}$$

- Mode frequency

$$f \propto c_s \propto \sqrt{\bar{\rho}} \propto \sqrt{M / R^3}$$

g-modes

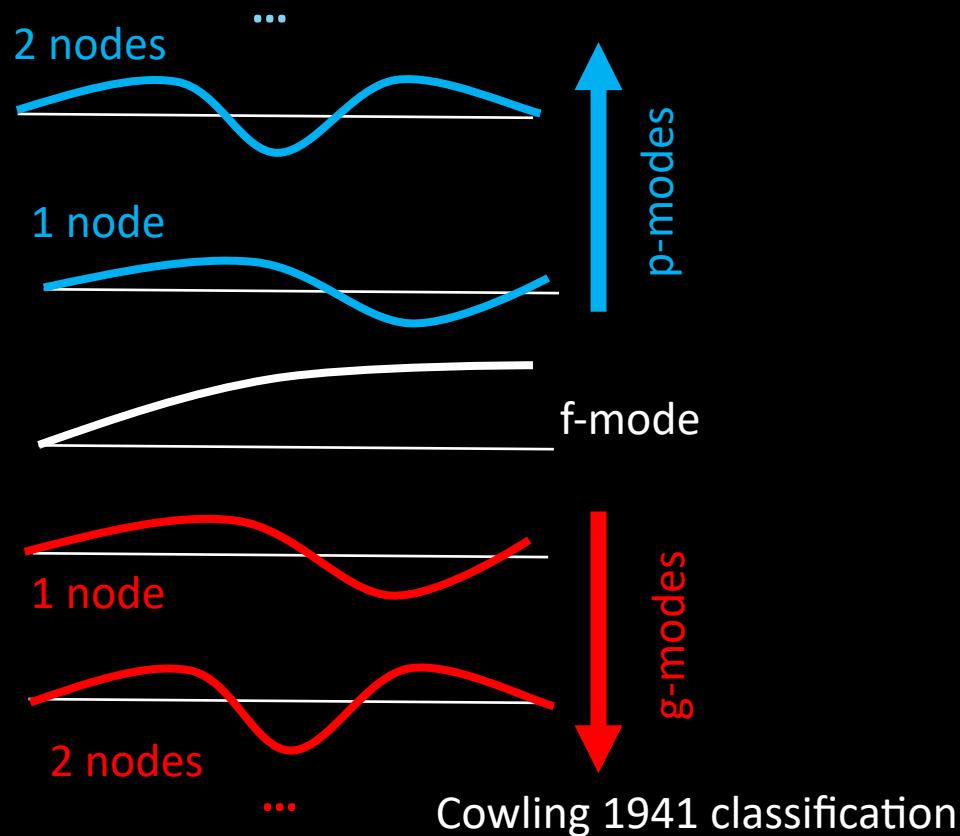
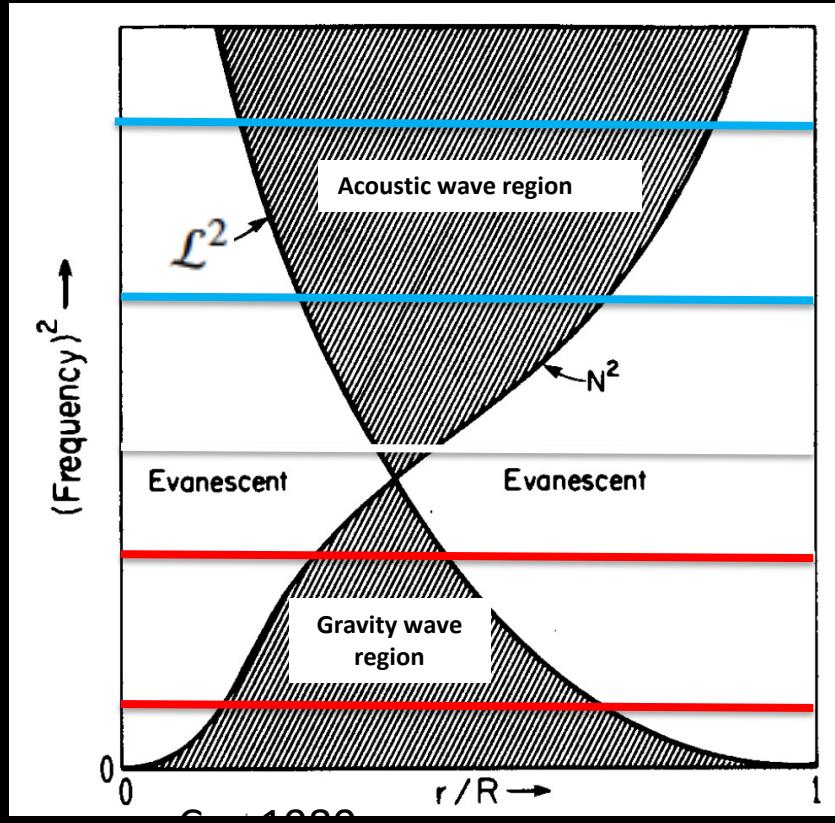
- Gravity modes ($l \geq 1$)
- Restoring force = buoyancy
- Brunt-Väisälä frequency (N)

$$N^2 \approx \frac{\partial \Phi}{\partial r} \frac{1}{\rho} \left(\frac{1}{c_s^2} \frac{\partial P}{\partial r} - \frac{\partial \rho}{\partial r} \right)$$

- Mode frequency

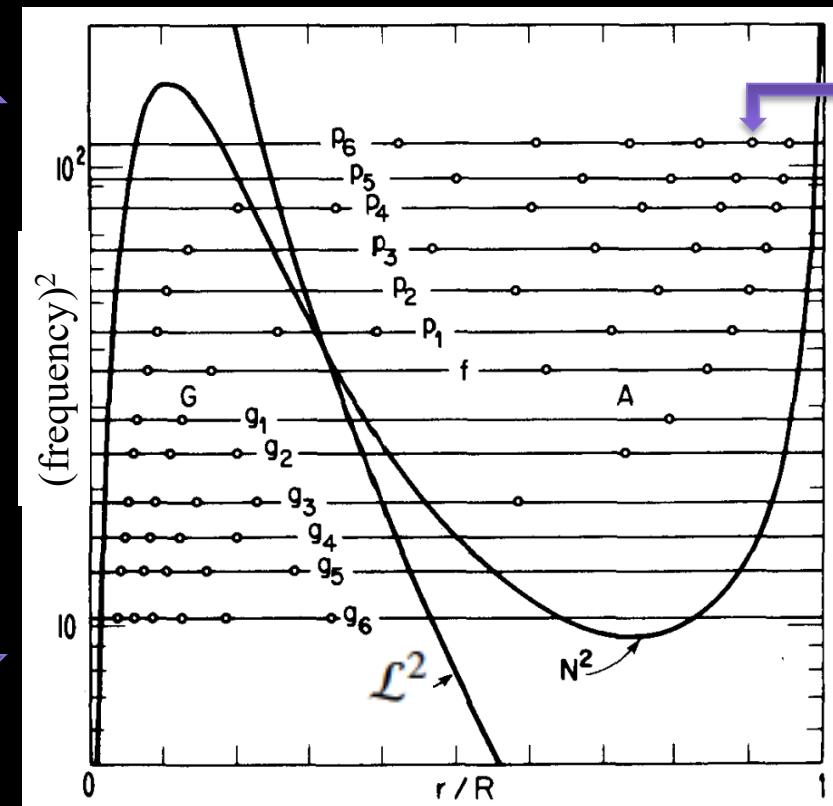
$$f \propto \frac{M}{R^2} \times \sqrt{\frac{(\Gamma-1)m_n}{\Gamma k_b T}}$$

Fluid modes - simple star



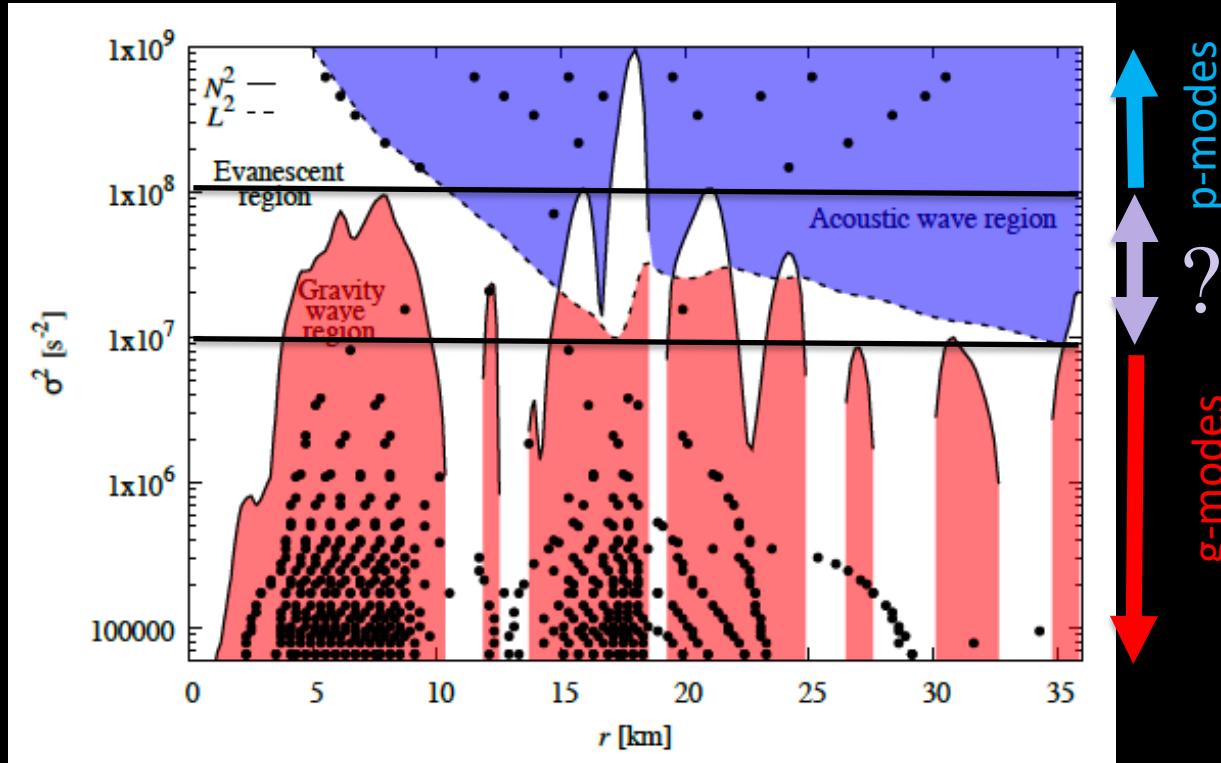
Fluid modes – increasing complexity

Acoustic and gravity region may overlap



Cox 1980

Fluid modes – proto neutron star

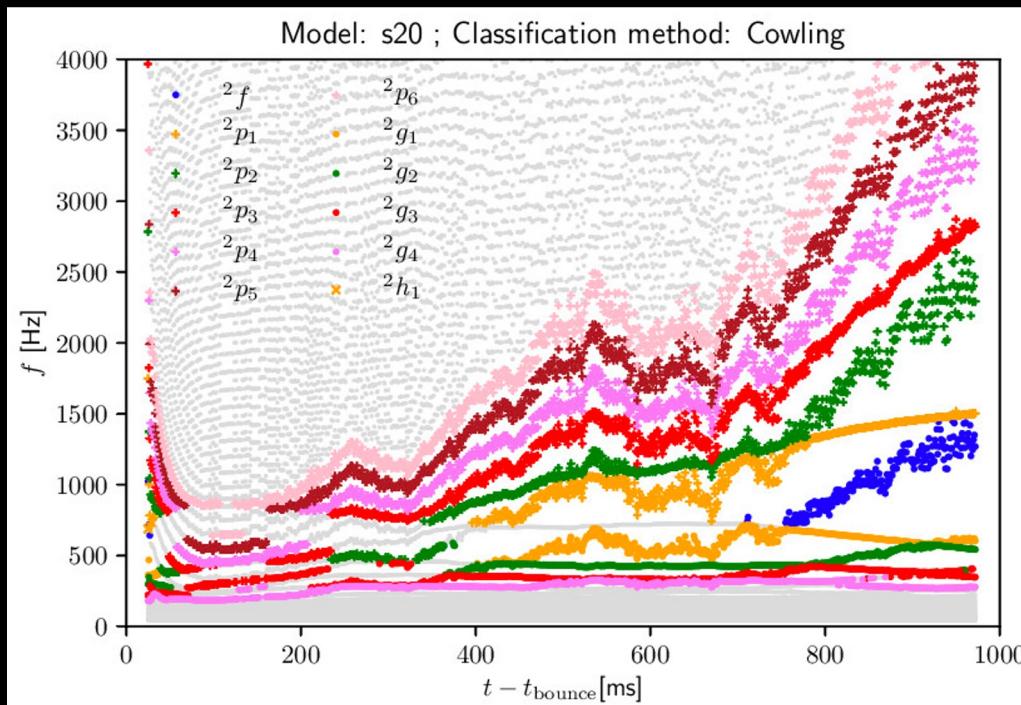


How do we classify modes?

What is a f-mode?

How are modes in the intermediate frequency range?

Open issues – mode classification (Cowling)



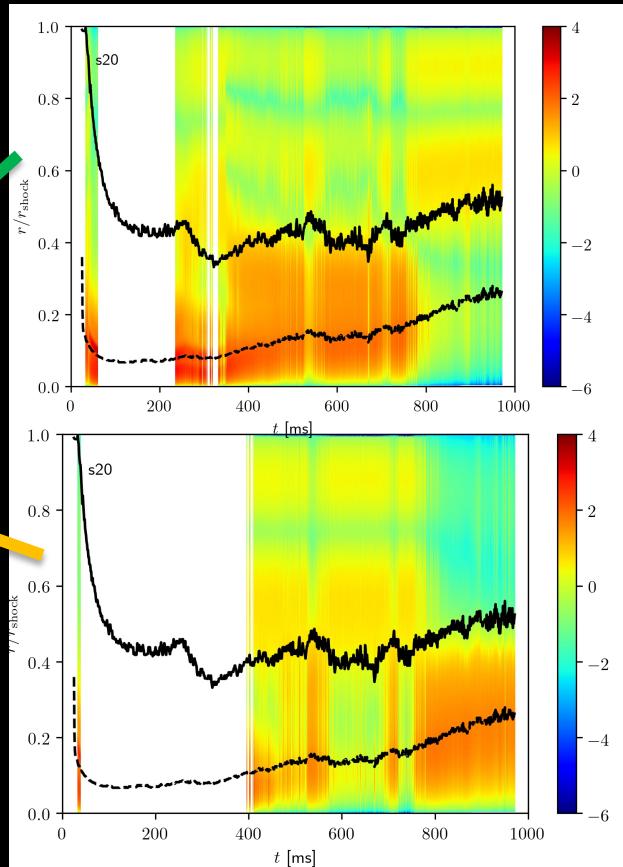
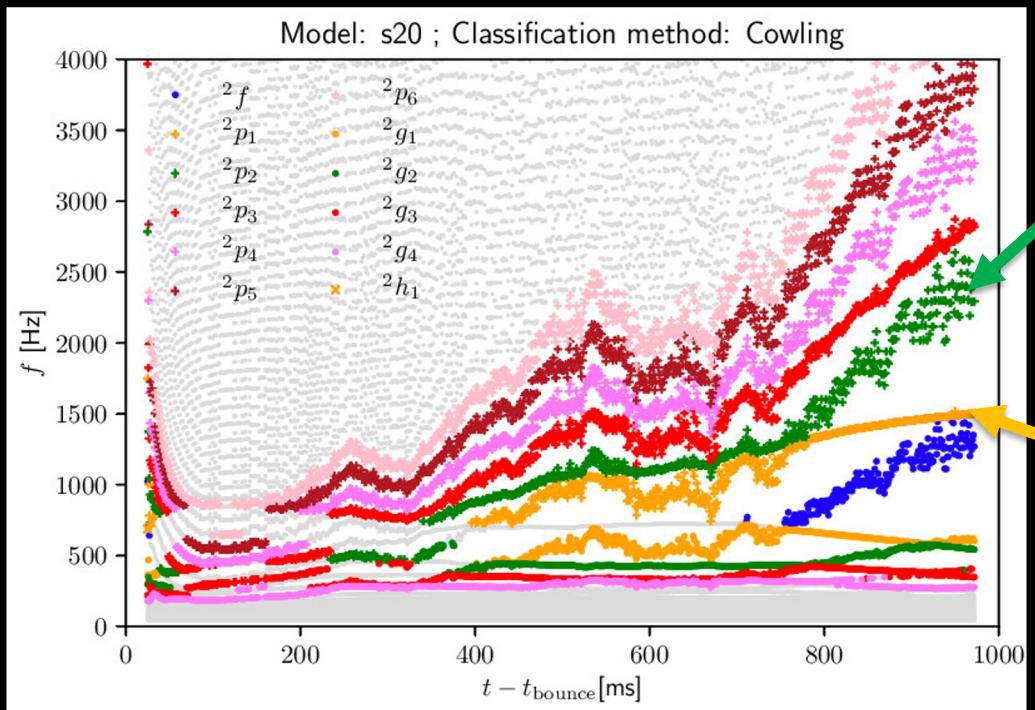
Torres-Forné et al 2019

s20, SFHo EOS

Cowling classification (Cowling 1941)

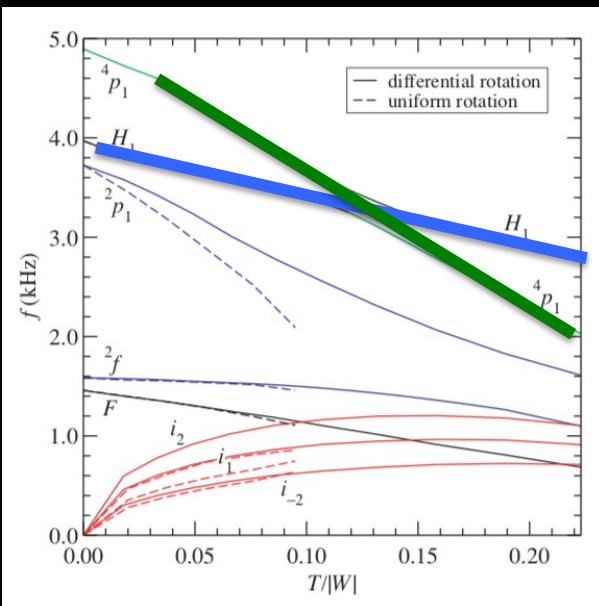
- According to the number of nodes
- Problems:
 - Eigenfunctions change at avoided crossings
 - f-mode may disappear
- Used by several authors (e.g. Sotani et al 2019, Morozova et al 2018)

Mode classification (Cowling)



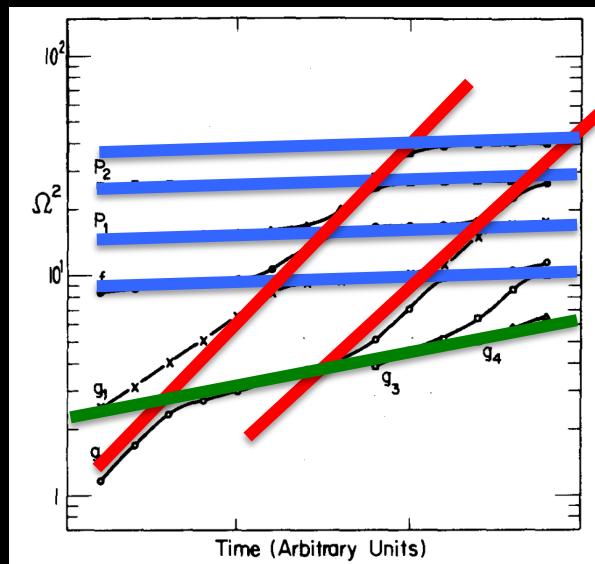
Avoided crossings

Neutron star with increasing rotation



Dimmelmeier et al 2006

Time evolution of a $10 M_\odot$ star



Osaki 1975

Background changes
(parametrized)



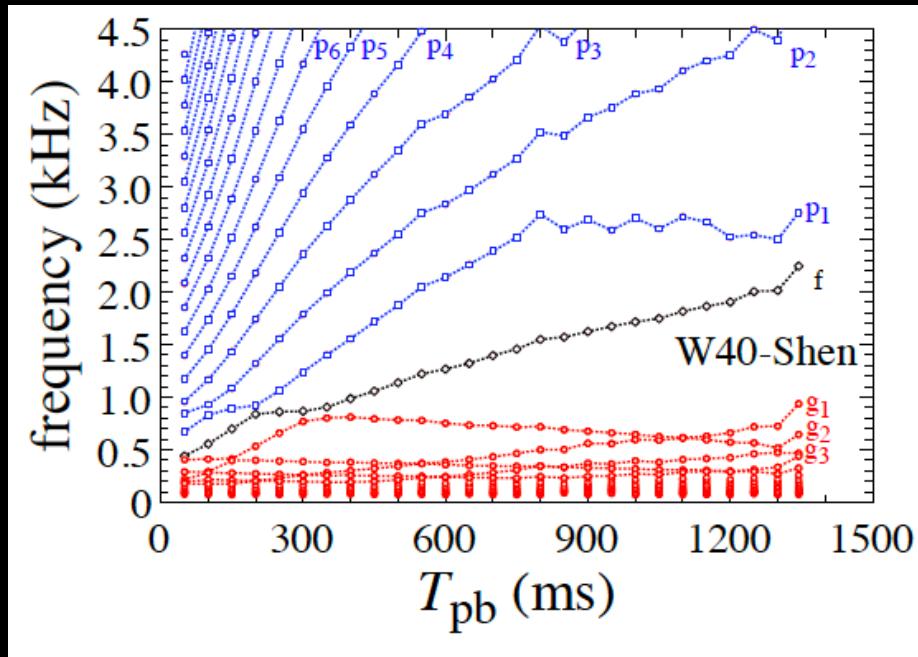
Mode frequency changes



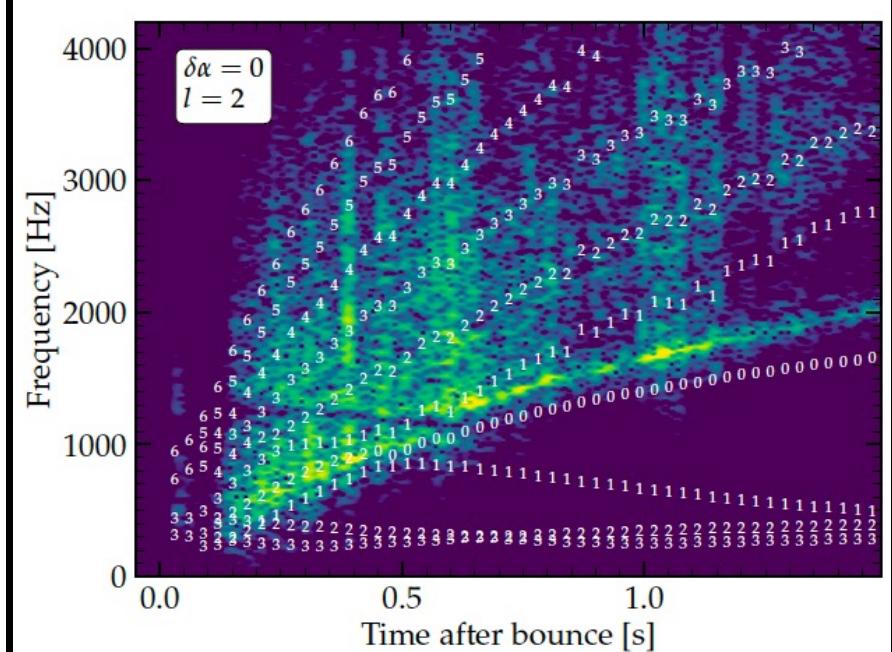
Modes coincident in frequency:

- No interaction
→ **normal crossing**
- Weak wave (linear)
interaction
→ **avoided crossing**
- Strong interaction
→ complex frequency
structure

Avoided crossing– mode classification (Cowling)

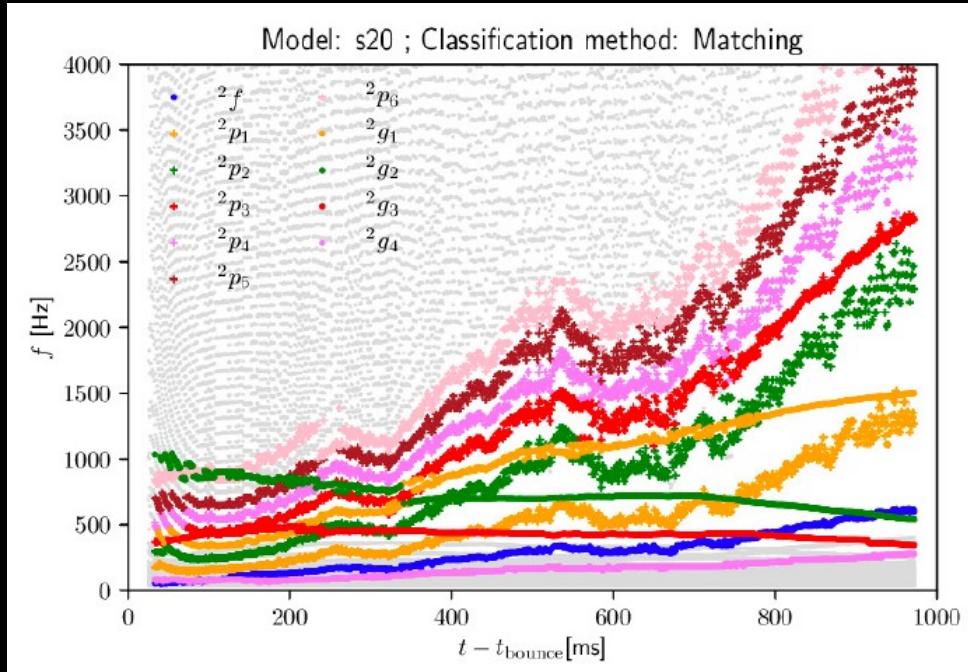


Sotani et al 2019



Morozova et al 2018

Mode classification (Matching)

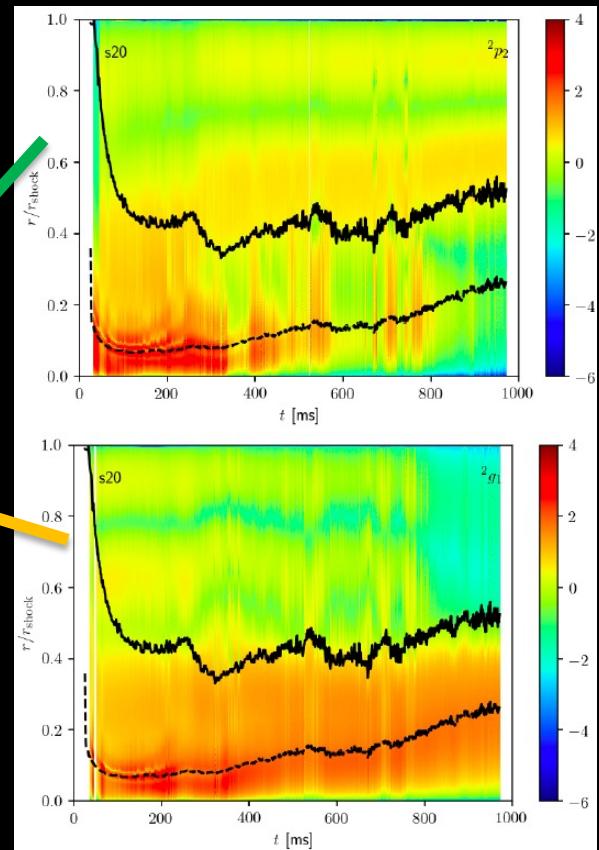
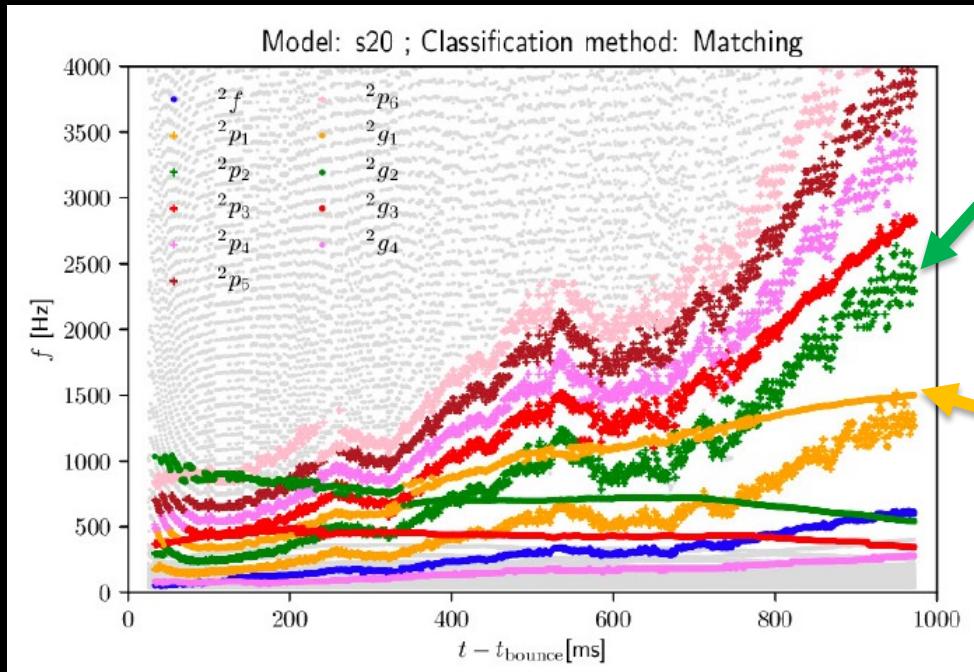


Torres-Forné et al 2019

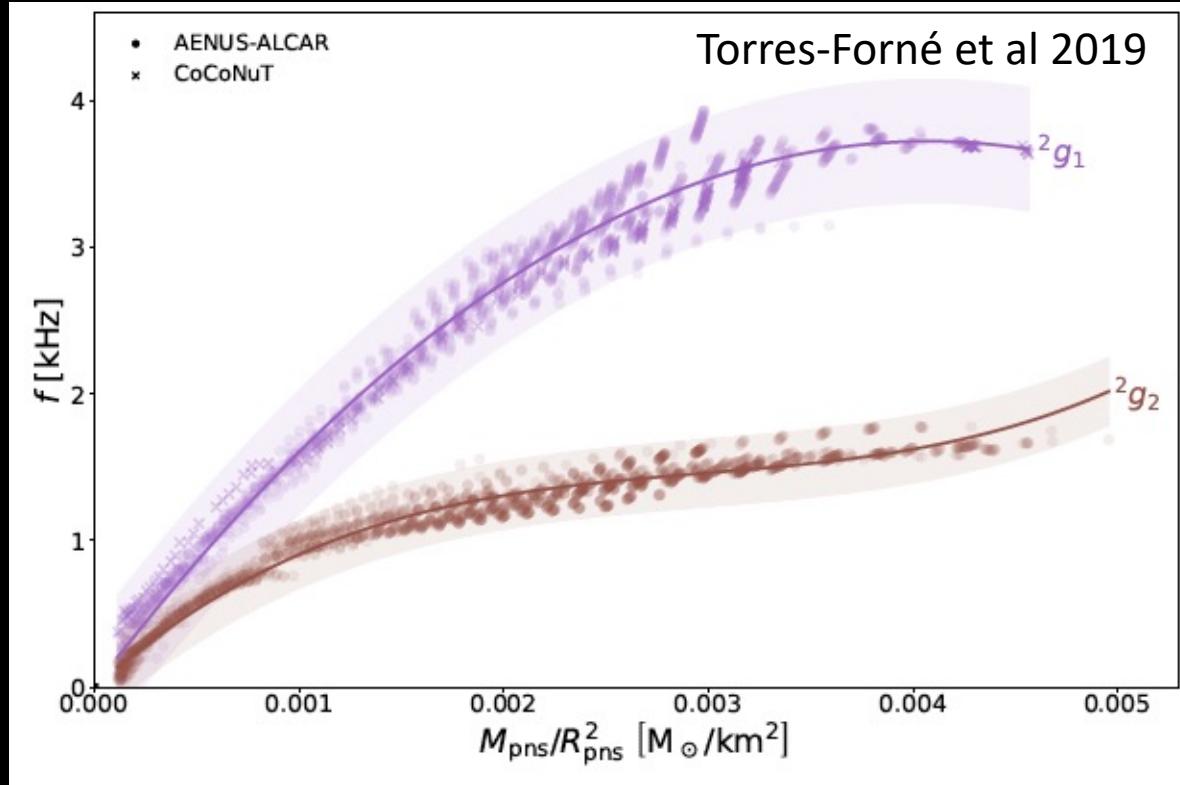
Matching classification (Torres-Forné et al 2019)

- Similarity of eigenfunctions
- f-mode always exists
- Eigenfunctions continuous at avoided crossings
- Problems:
 - Labelling of modes (f or g-mode)

Open issues – mode classification (Matching)



Universal relations



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

$$f({}^2g_2) = b x + c x^2 + d x^3$$

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

g-modes scale with PNS surface gravity

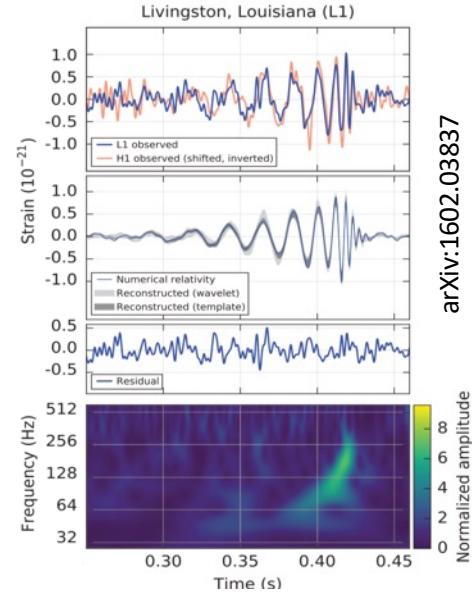
No dependence on EOS

2.3 Detection of GWs

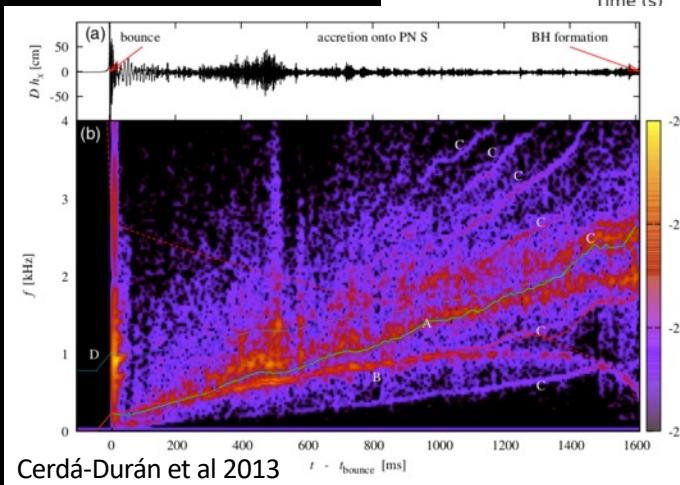
Detecting of CCSNe

- Template-based searches not possible
 - Stochastic nature of waveforms due to instabilities
 - Complexity of waveform modelling
 - Uncertainties on the progenitor stars
- Robust features in the time-frequency plane
 - g-modes
 - SASI
 - Bar-mode instabilities (rotating models)
- Parameter estimation
 - Non-trivial relation between progenitors and waveforms
 - Properties of the proto-neutron star

GW150914
and matching
template



arXiv:1602.03837



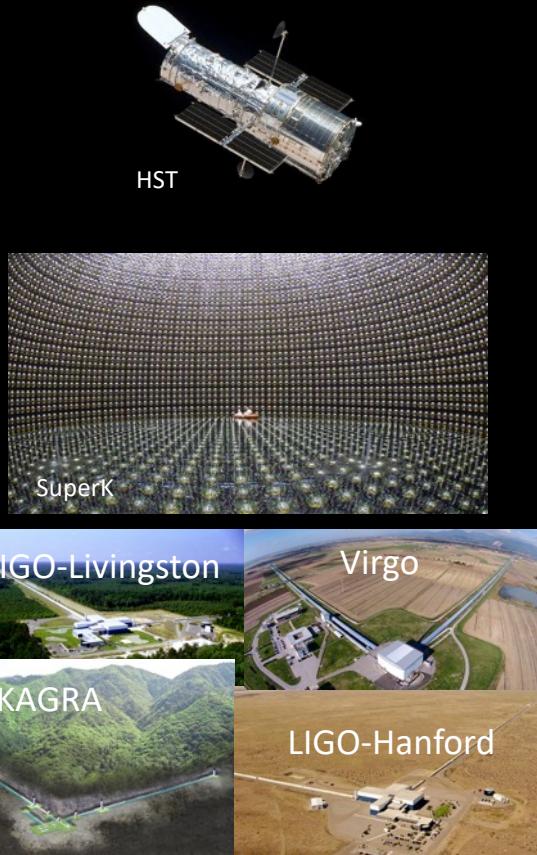
Example of
CCSN
waveform

Cerdá-Durán et al 2013

Current pipelines

- Pipeline classification
 - Coincidence methods: events generated independently for each detector → Event coincidence analysis
 - Coherent methods: Combine detector data + Combined data analysis to generate coherent events
- Searches classification
 - All-sky searches
 - Searches at all times and all sky
 - Low-latency pipelines and offline analysis
 - Targeted searches
 - Use external triggers (EM, neutrinos) ← Multimessenger information
 - Sky localization known or constrained
 - Known time (on source window = OSW)
 - Offline analysis
 - Smaller detection threshold than all-sky searches

Multimessenger observation of CCSNe



- Electromagnetic observations:
 - Historically we have missed ~5/6 of all SNe due to galactic dust obscuration.
 - Current instruments capable of observing any galactic SN (UV)
 - ~5 SNe observed per year within 20 Mpc
 - First signal hours to days after bounce.
 - Remnant will be observed several 10kyr after explosion.
- Neutrino observation:
 - Detectable by SuperK at 100-150 kpc.
 - Bounce detection within a few 10 ms.
 - Duration of ~1 s
 - SNEWS alerts
- Gravitational waves
 - Upcoming O4 run (spring 2022) of the LVK collaboration
 - Non-rotating progenitors/neutrino-driven SNe detectable up to 10 kpc (Szczepanczyk et al 2021)
 - Magnetorotational explosions detectable up to 100 kpc
 - Duration of ~1 s

Pipelines used at the LVK for CCSNe

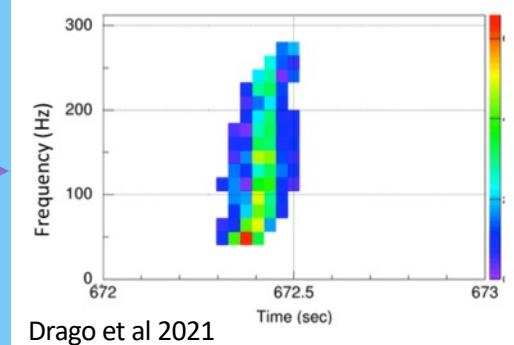
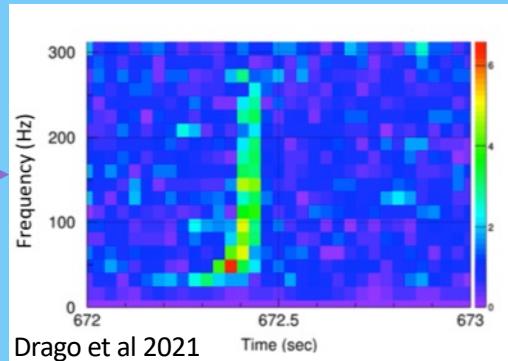
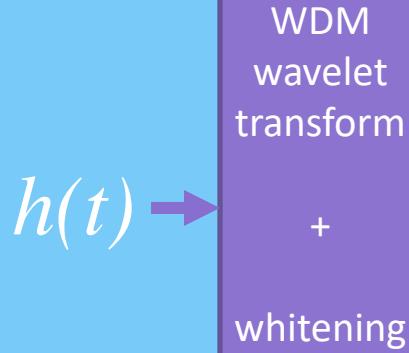
- Coherent Wave Burst (cWB, Klimenko et al 2016)
 - Coherent search analysis
 - Omicron-LIB (oLIB, Lynch et al 2016):
 - Coincidence search (Omicron) + coherent analysis (LIB)
 - BayesWave (BW, Cornish & Littenberg 2025):
 - Follow up analysis of cWB events
 - Xpipeline (Sutton et al 2010)
 - Coherent search analysis
 - Not currently in use for SNe
- 
- Excess-power searches
 - Unmodeled sources
 - All-sky and targeted

Coherent WaveBurst (cWB)

- Klimenko et al 2016 / <https://gwburst.gitlab.io>
- Pipeline for unmodeled GW data analysis
 - Minimal assumptions about waveform morphology
 - Used for a wide variety of sources (CBC, bursts ...)
 - Used both for all-sky and targeted searches
 - Detected GW150914 within 3' of the event.
- Coherent detection in a network of GW detectors
- It has been used for supernovae
 - Targeted searches (arXiv:1605.01785, arXiv:1908.03584)
 - All-sky searches for short-duration bursts (arXiv:1611.02972, arXiv:1905.03457, arXiv:2107.03701)

Coherent WaveBurst (cWB)

Detector 1

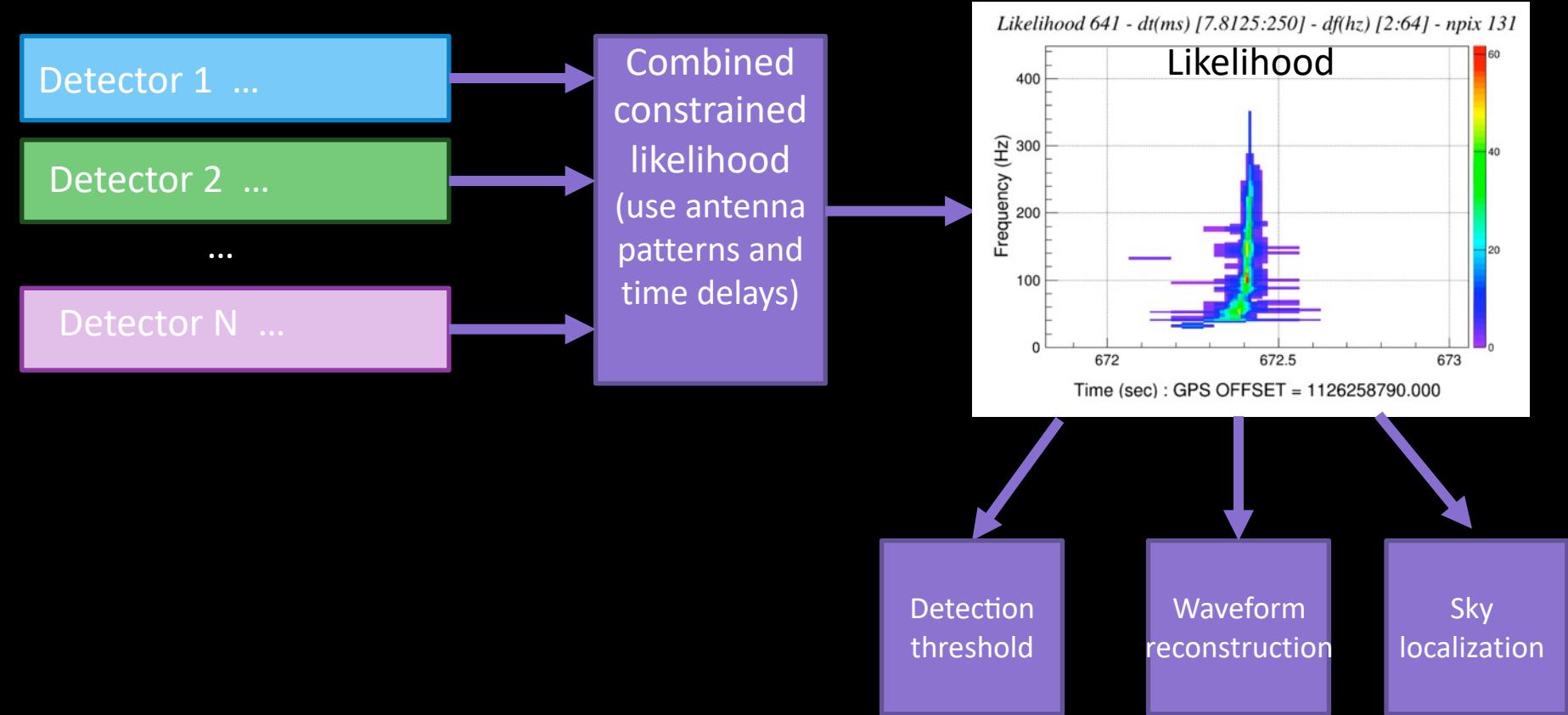


Detector 2 ...

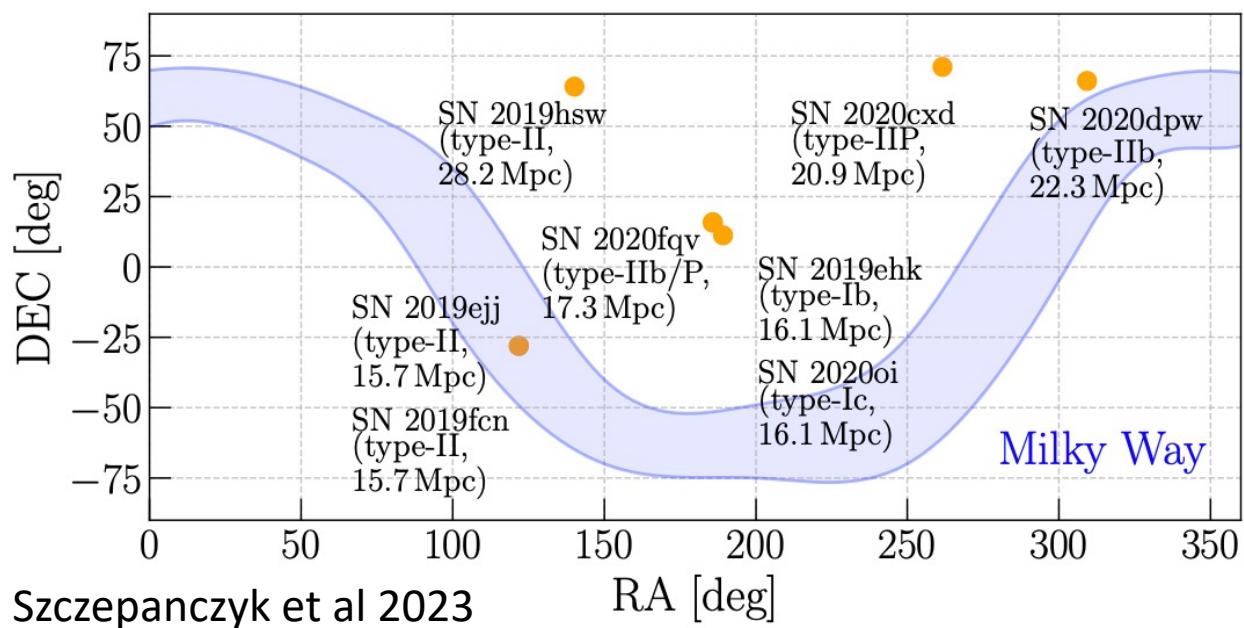
...

Detector N ...

Coherent WaveBurst (cWB)



O3 targeted search



O3: Apr. 2019 – Mar. 2020

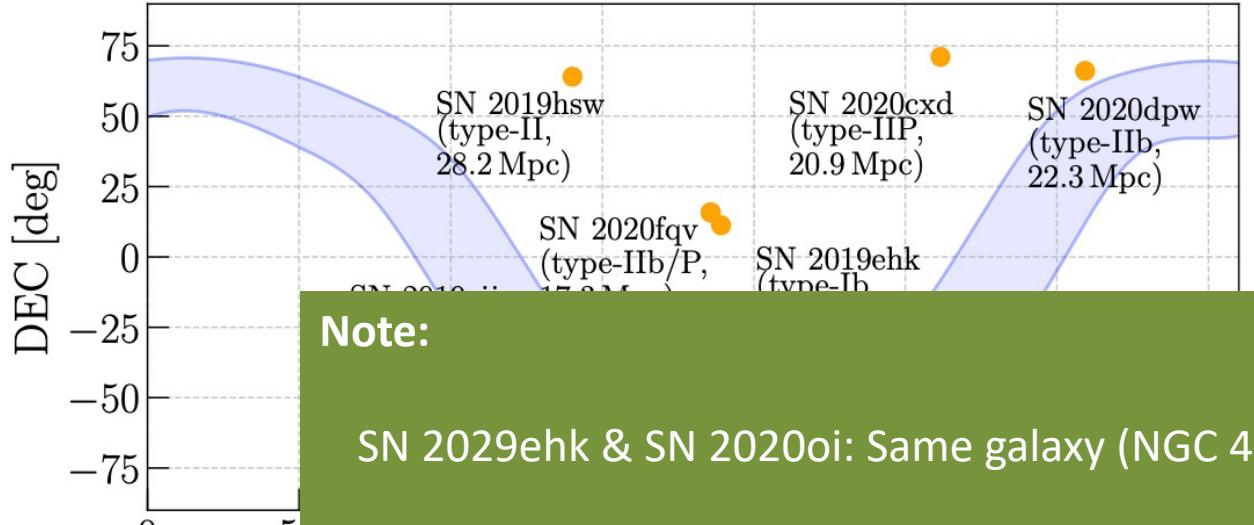
Targets: SN within 30 Mpc

9 Selected sources:

16.7 – 28.2 Mpc

Type II(3), IIb(3), IIP(2), Ic (1)

O3 targeted search



Szczepanczyk et al.

O3: Apr. 2019 – Mar. 2020

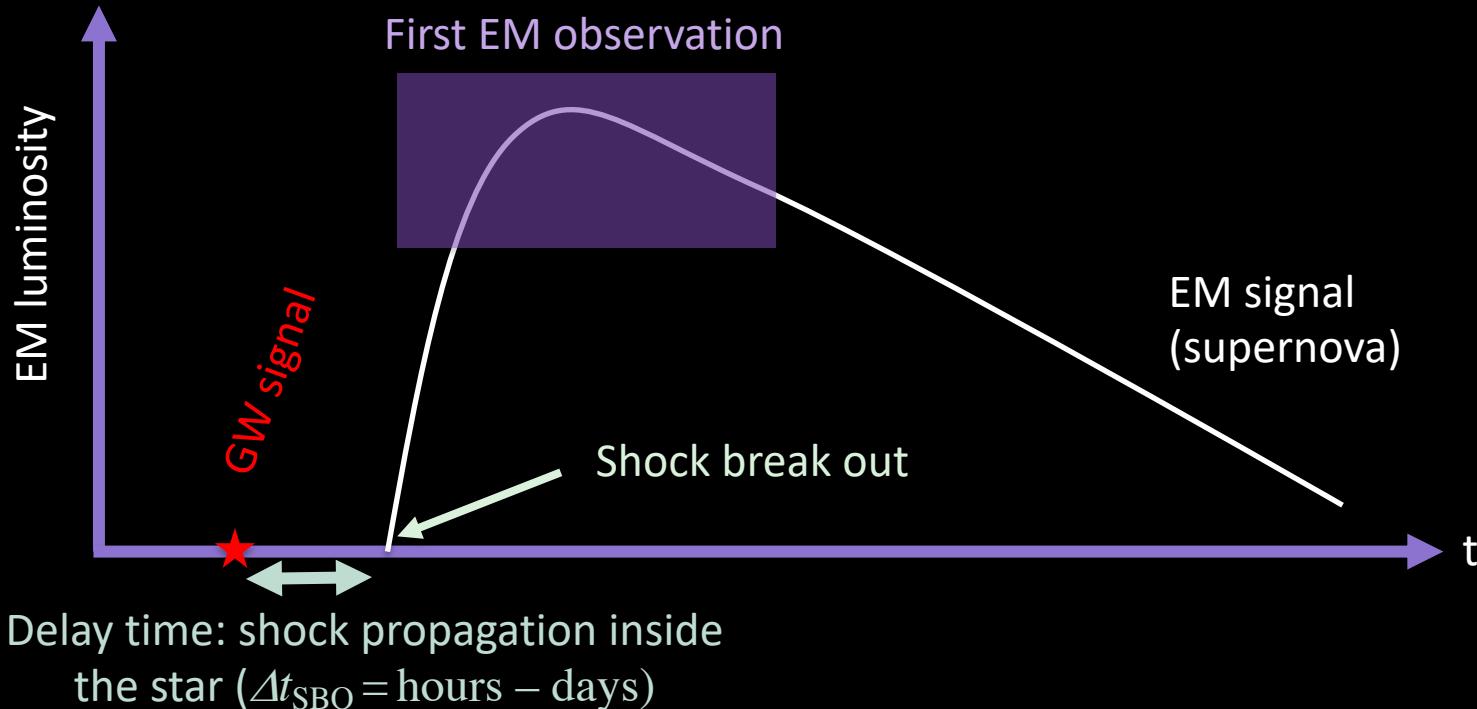
Targets: SN within 30 Mpc

9 Selected sources:

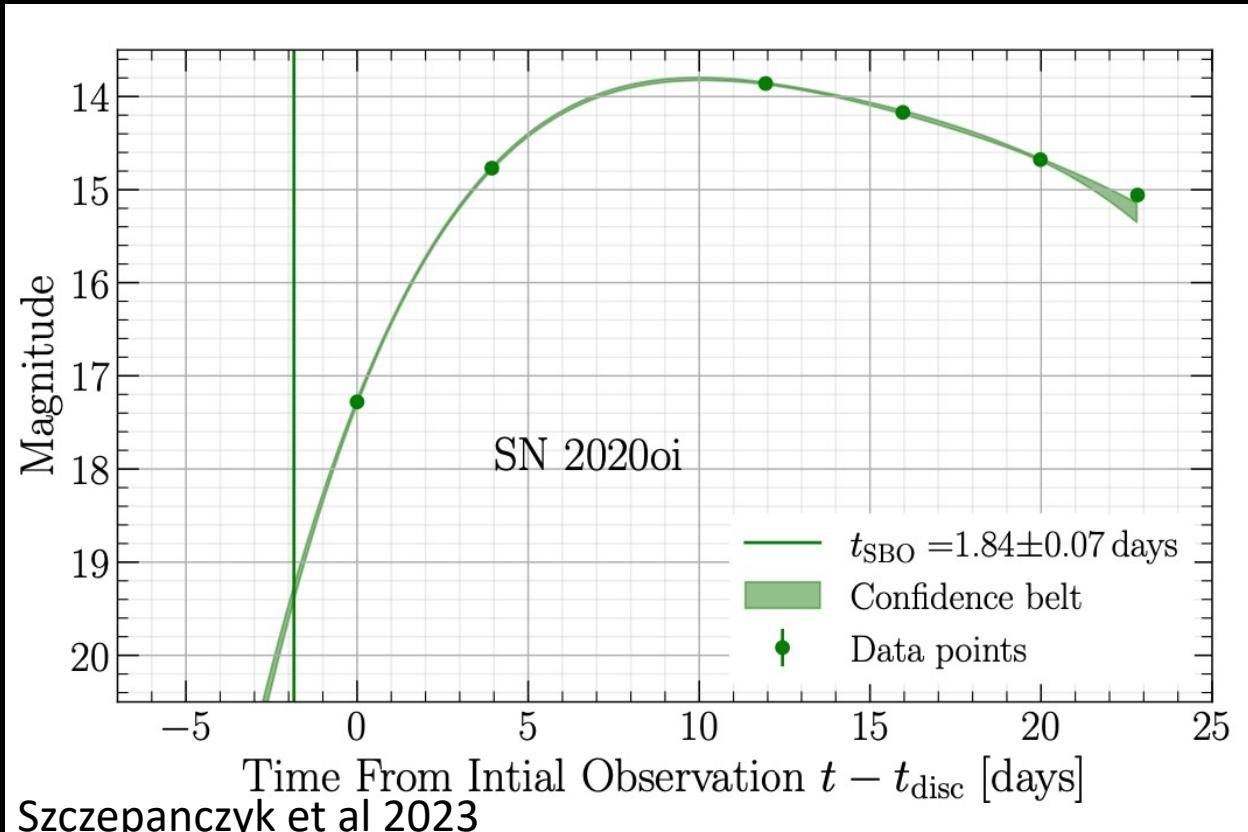
16.7 – 28.2 Mpc

Type II(3), IIb(3), IIP(2), Ic (1)

O3 targeted search – On-source window (OSW)

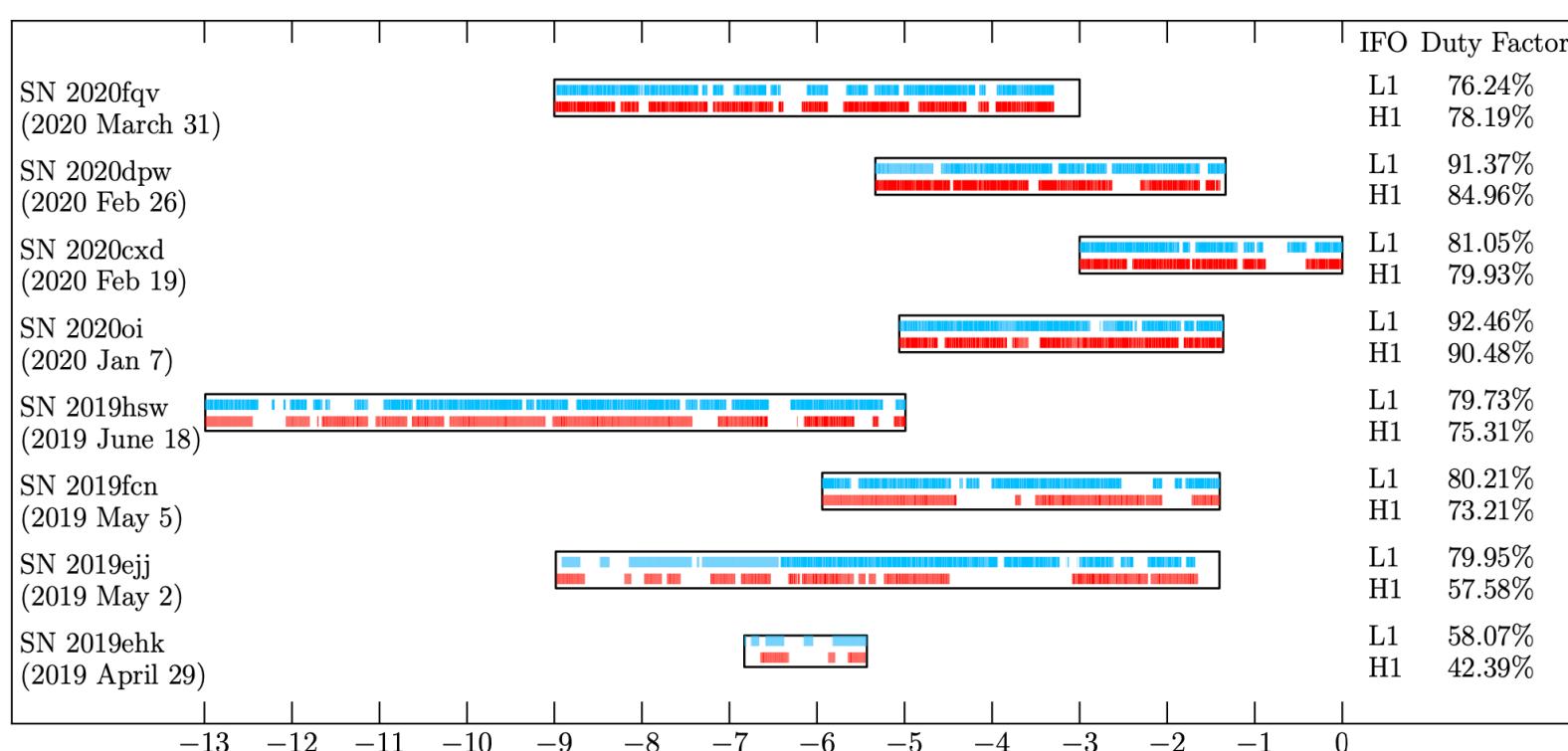


O3 targeted search – On-source window (OSW)



Modelling of the light-curve to estimate shock breakout

O3 targeted search – On-source window (OSW)



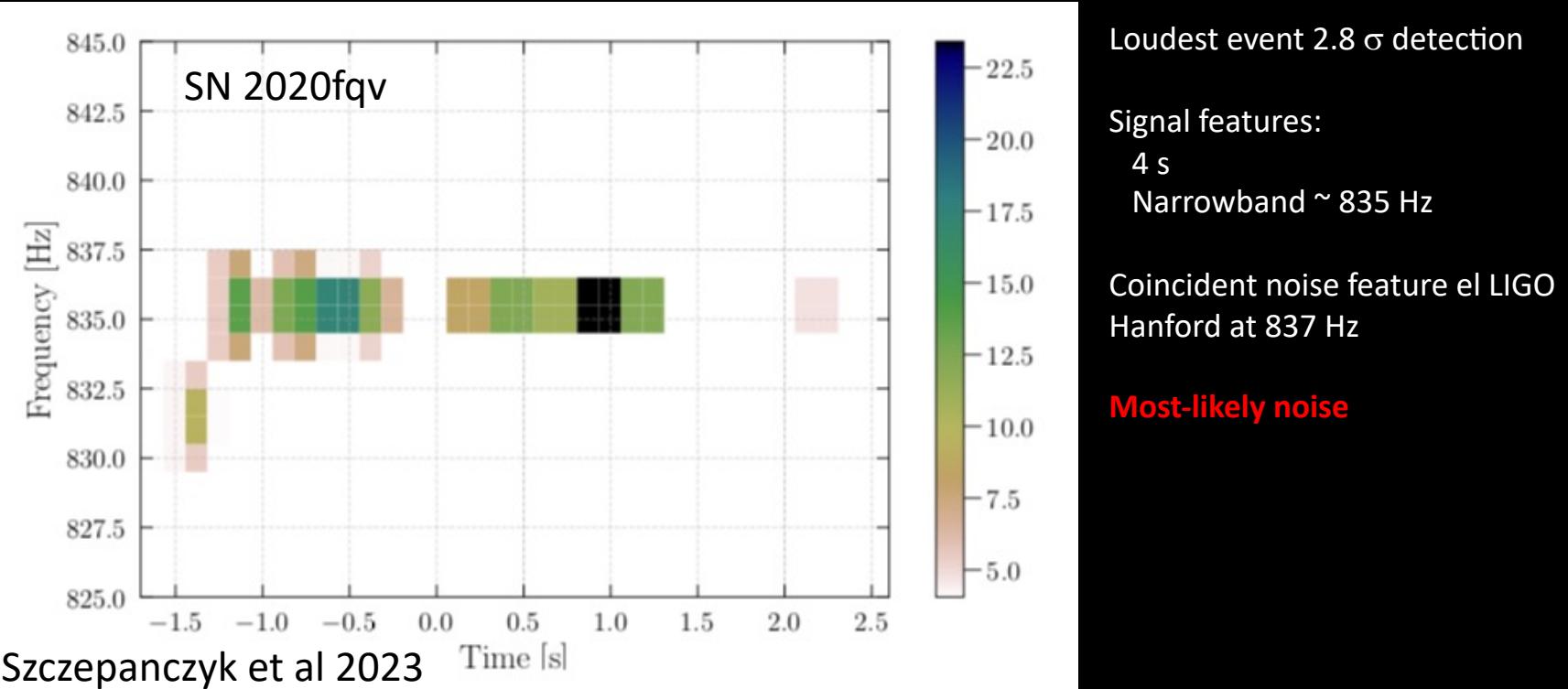
O3 targeted search – detection?

TABLE II. List of the loudest events for each CCSN. False alarm rate (FAR) and False Alarm Probability (FAP) for each of them, except SN 2020fqv, which is further analyzed, indicate that they are consistent with background noise.

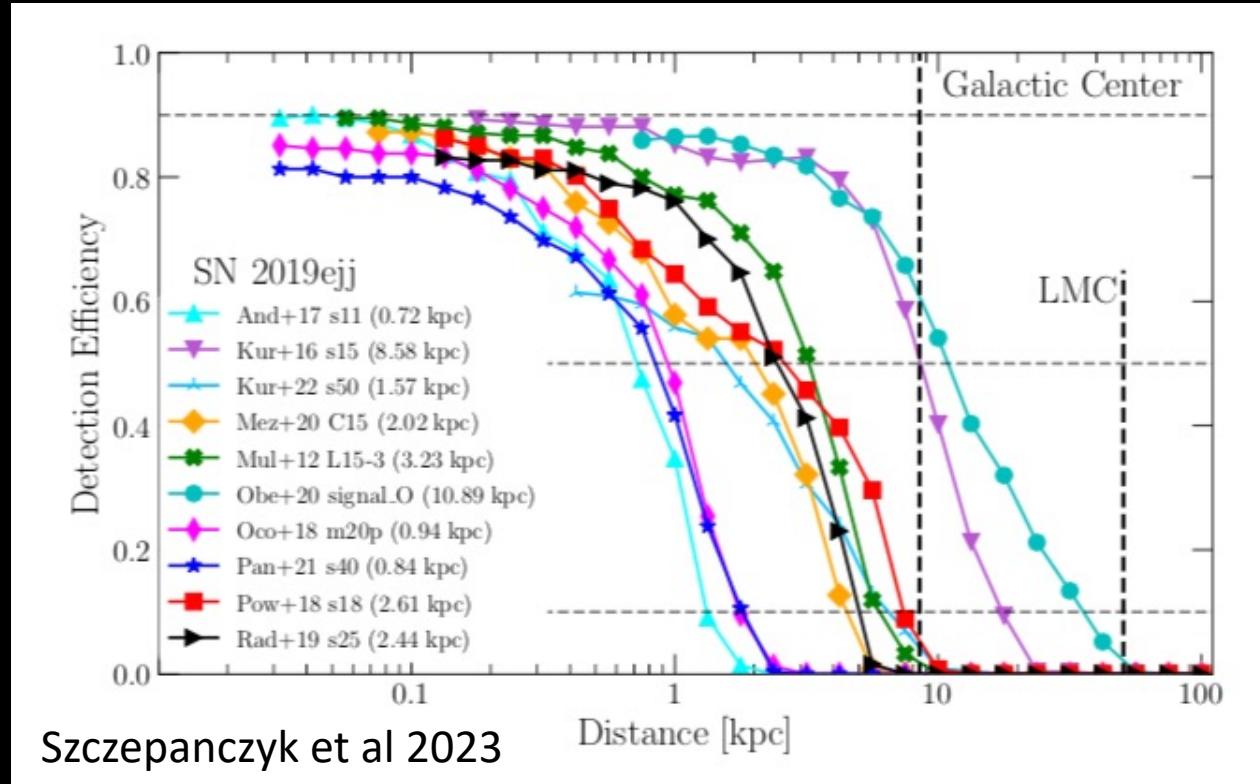
Supernova	Class	η_c	FAR [Hz]	FAP	
SN 2019ehk	<i>C2</i>	5.9	1.4e-5	0.39	(0.86σ)
SN 2019ejj	<i>C2</i>	6.7	1.1e-5	0.71	(0.38σ)
SN 2019fcn	<i>C2</i>	6.7	1.4e-5	0.95	(0.06σ)
SN 2019hsw	<i>C1</i>	5.6	4.5e-6	0.86	(0.17σ)
SN 2020oi	<i>C1</i>	5.8	2.0e-6	0.35	(0.93σ)
SN 2020cxd	<i>C1</i>	6.7	3.3e-6	0.73	(0.34σ)
SN 2020dpw	<i>C2</i>	6.2	6.3e-6	0.81	(0.23σ)
SN 2020fqv	<i>C1</i>	7.6	1.5e-8	0.005	(2.78σ)



O3 targeted search – detection?



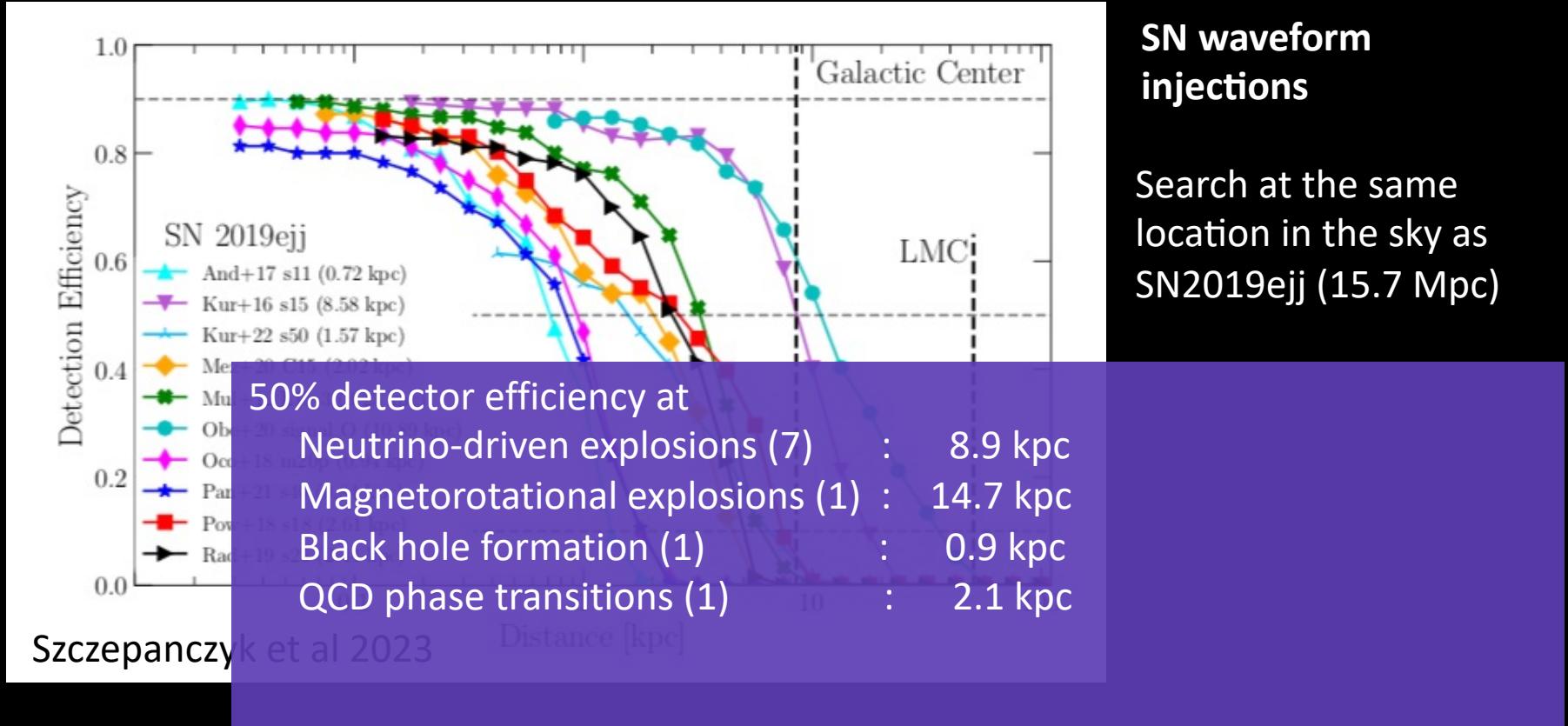
O3 targeted search – How far could have been detected?



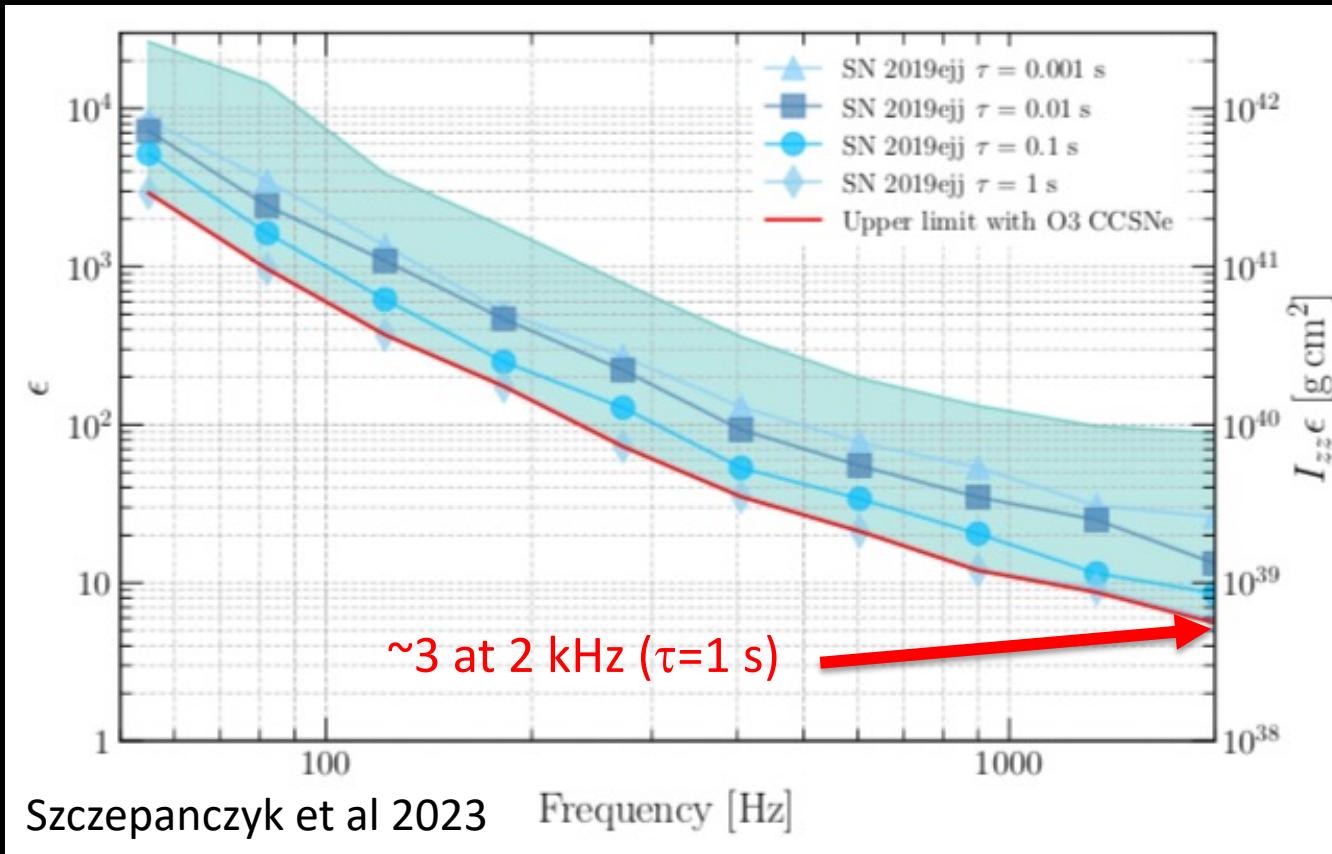
**SN waveform
injections**

Search at the same
location in the sky as
SN2019ejj (15.7 Mpc)

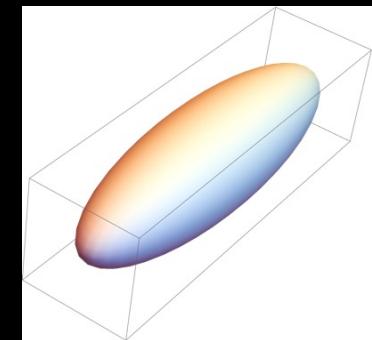
O3 targeted search – How far could have been detected?



O3 targeted search – How far could have been detected?



Bar-mode waveform injections

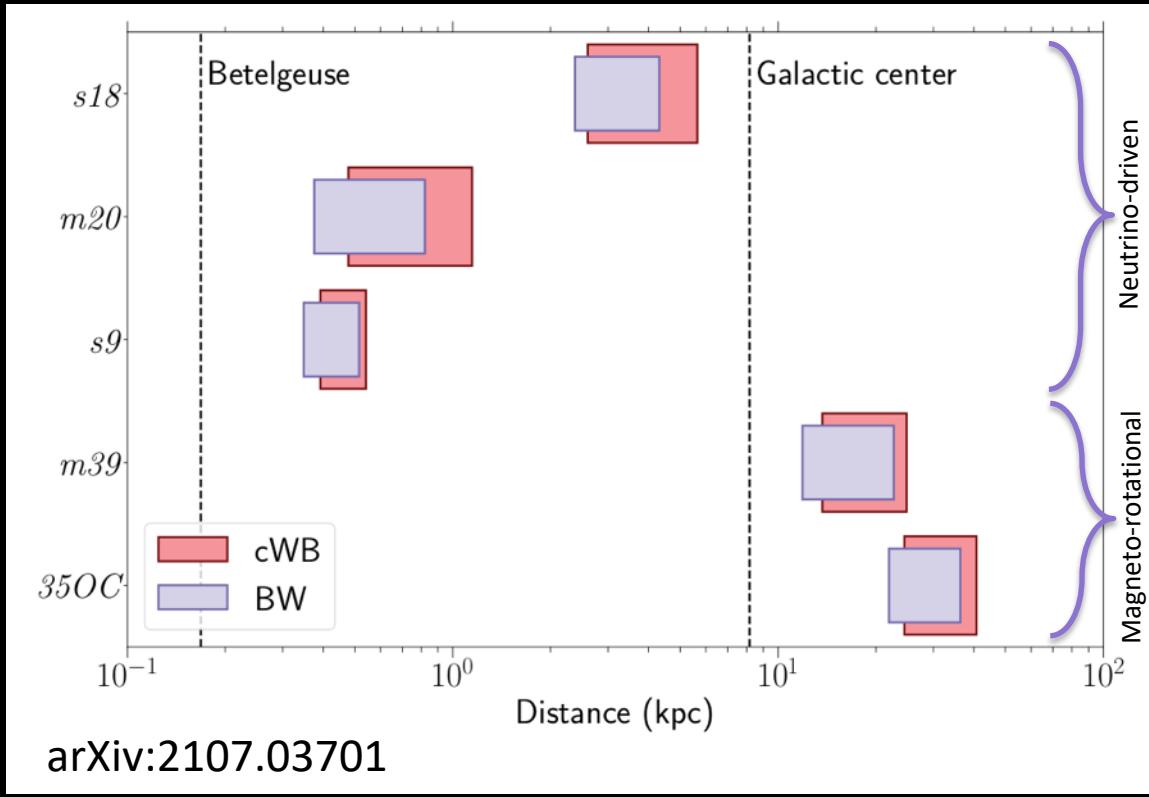


- Ellipticity

$$\epsilon \equiv \frac{I_{xx} - I_{yy}}{I_{zz}}$$

- Frequency: f
- Duration: τ

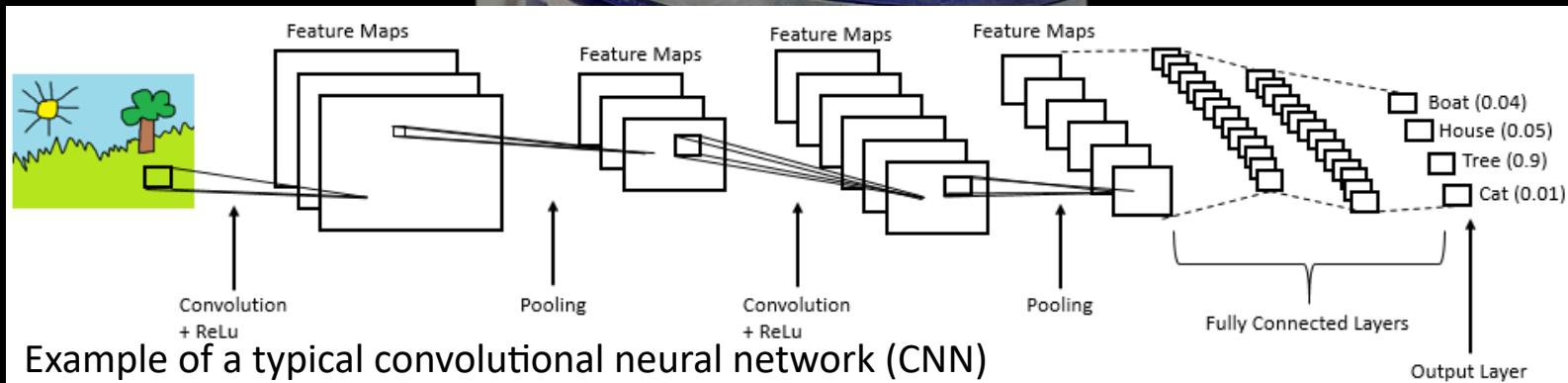
O3 all-sky search



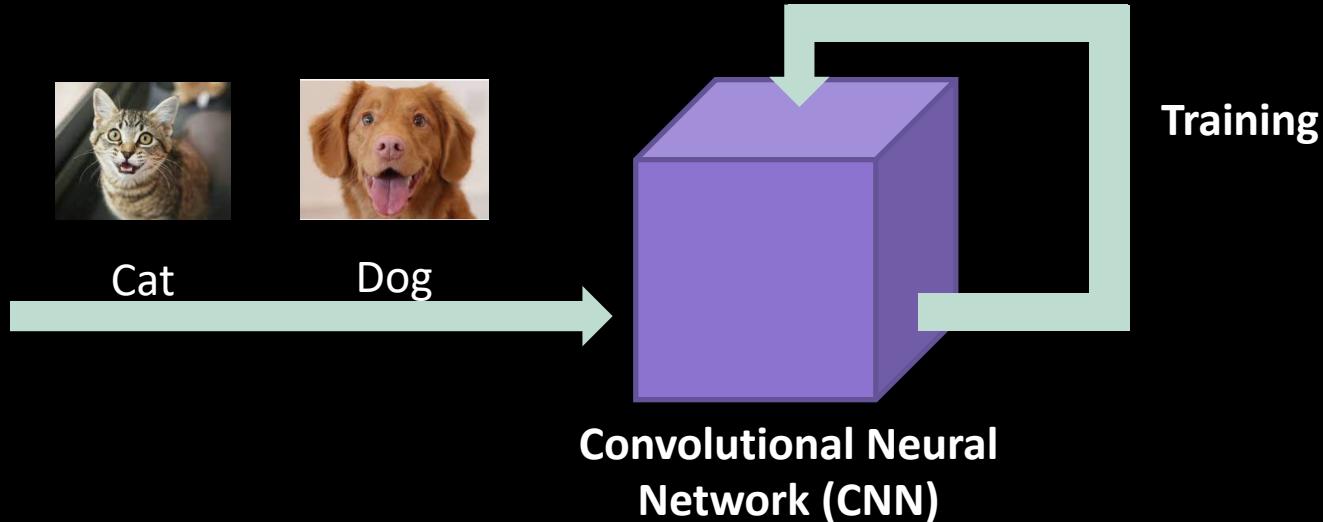
No detection

Waveform injections
allow to compute
detection horizons

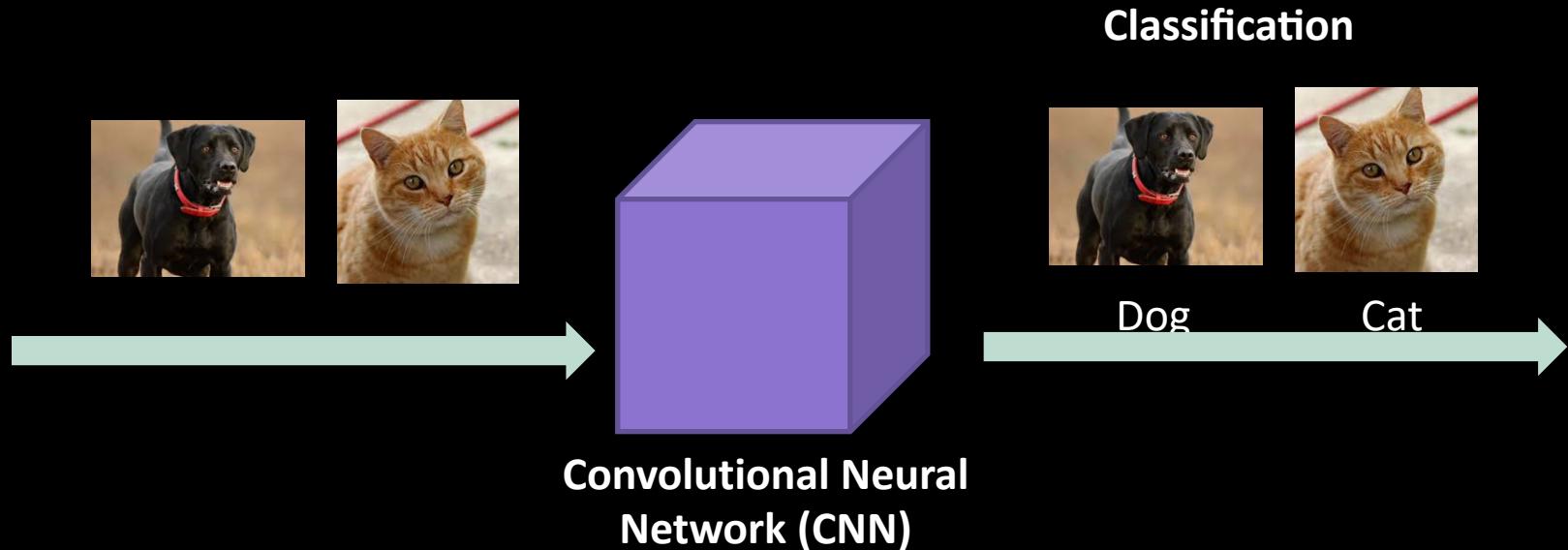
Detection using machine learning



Detection using machine learning



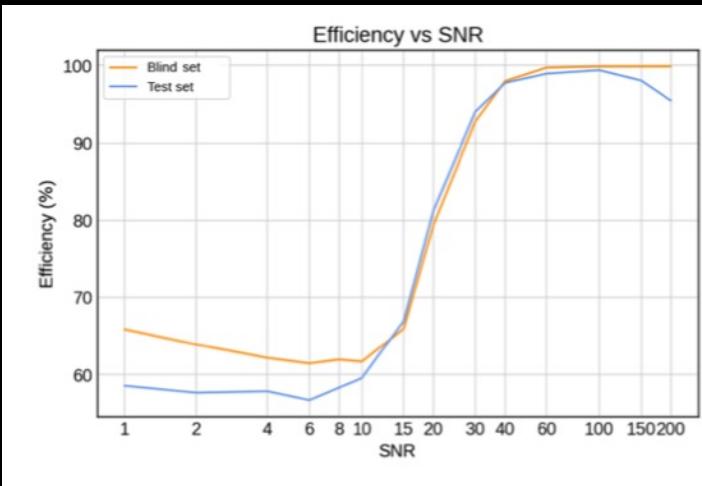
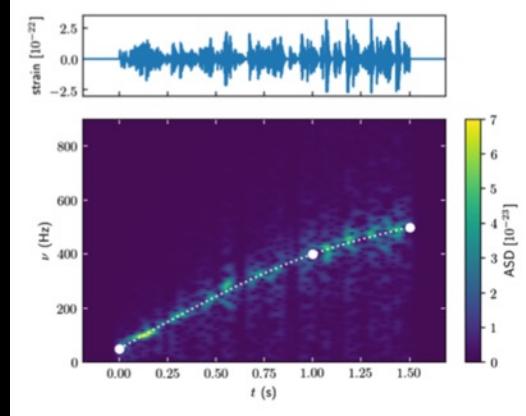
Detection using machine learning



Detection using machine learning

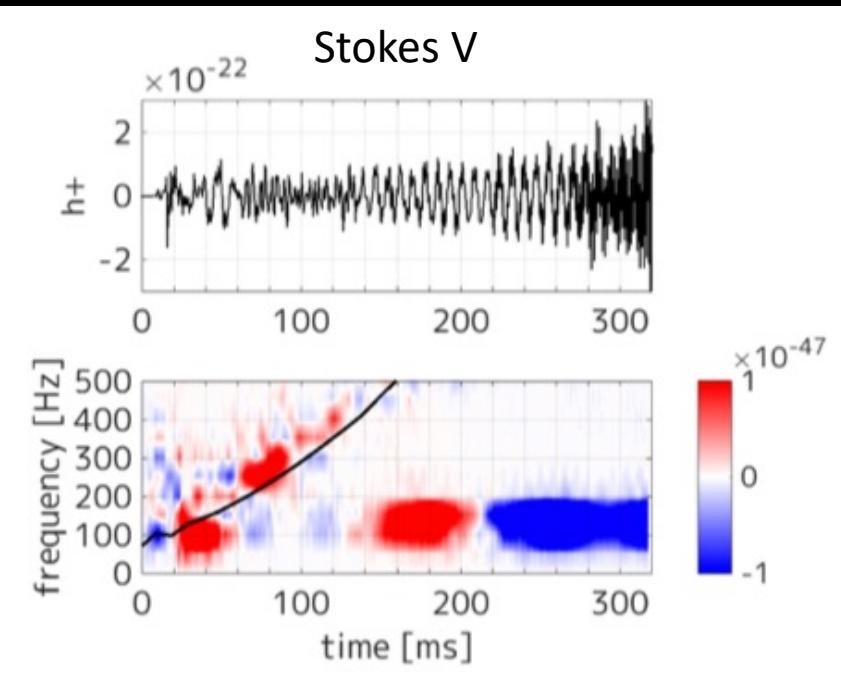
Work	Method	Waveforms	Training injections
Astone et al 2018	CNN (9 layers)	Phenomenological (100)	10 000
Chan et al 2020	CNN (14 layers)	Numerical simulations (55)	100 000
Cavaglia et al 2020	Genetic programming algorithm (300 individuals)	Numerical simulations (8)	15 000
Iess et al 2020	CNN (6-13 layers)	Numerical simulations (5)	25 000
López et al 2020	CNN (~30 layers)	Phenomenological (9072)	70 000
Mukherjee et al 2021	CNN	Numerical simulations (2)	21 000
Antelis et al 2022, Baltus et al 2022, Iess et al 2023, Casallas Lagos et al 2023, Mitra et al 2023 ...			

Detection using machine learning – phenomenological templates



- Phenomenological templates:
 - Parametric
 - Stochastic
 - Mimic CCSNe waveforms
- Training:
 - no limitation in number of templates
 - Exploration of the parameter space homogeneously
- CNN's can recognize signals from numerical simulations

Detecting circular polarization



Hayama et al 2018

- Stokes V parameter shows signatures of circular polarization
- Fast rotation or rotating modes (e.g. SASi spiral modes) emit circularly polarized GWs
- Hayama et al 2018, Chang & Hayama 2021
- Detectable within 5 kpc (Chang & Hayama 2021, for 2nd generation network)

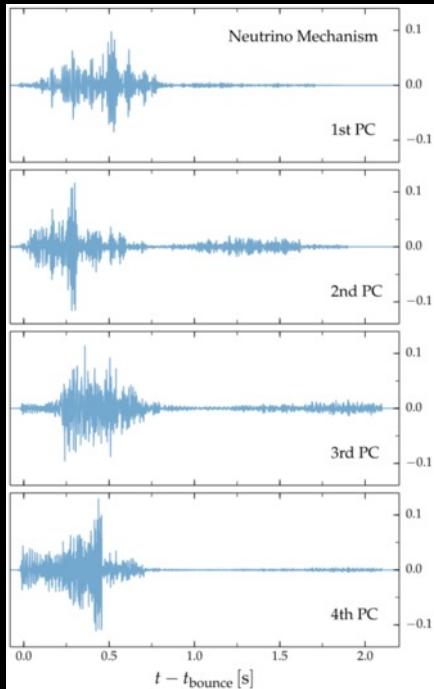
2.4 Inference

Parameter estimation

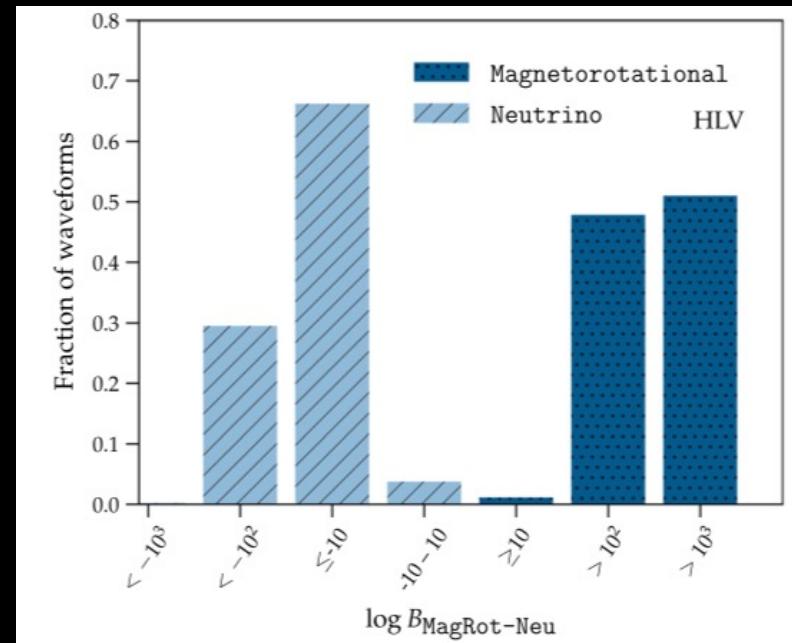
- Blind waveform reconstruction
 - no model assumed
 - Summerscales et al 2008, Klimenko et al 2016, Cornish et al 2016
- Waveform reconstruction based on PCA model
 - Heng et al 2009, Röver et al 2009
- Classification
 - SMEE (based on PCA): Powell et al 2016, 2017, Roma et al 2019
 - Machine learning: Edwards et al 2014
 - Classifies in general categories: neutrino-driven vs magetorotational
- Asteroseismology:
 - g-mode tracking: Bizouard et al 2020, Bruel et al 2023
 - g-mode features: Powell & Müller 2022, Casallas Lagos et al 2023

SMEE (Supernova Model Evidence Extractor)

Principal component analysis
(for a catalogue of SN waveforms)



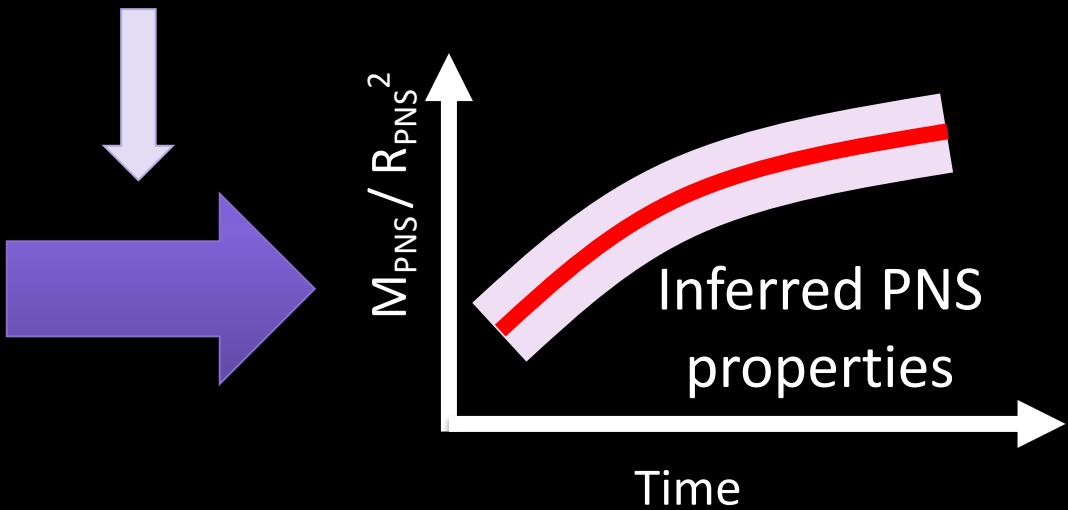
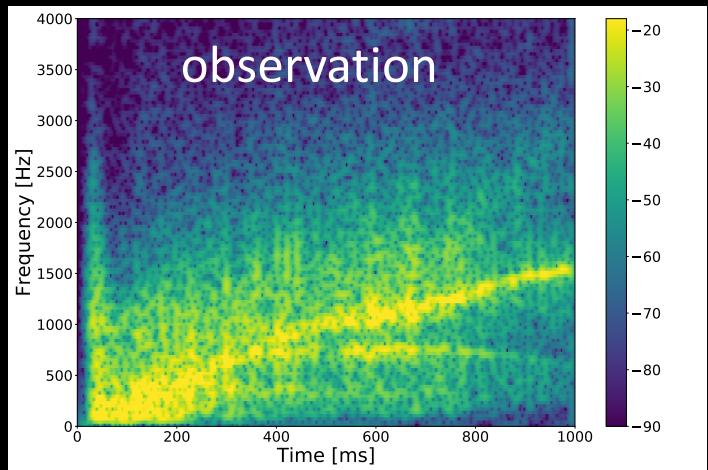
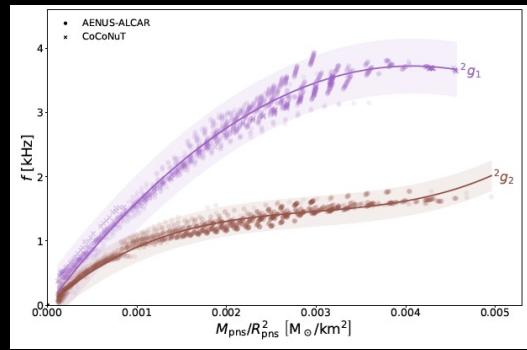
Results after decomposing
injections into PCAs



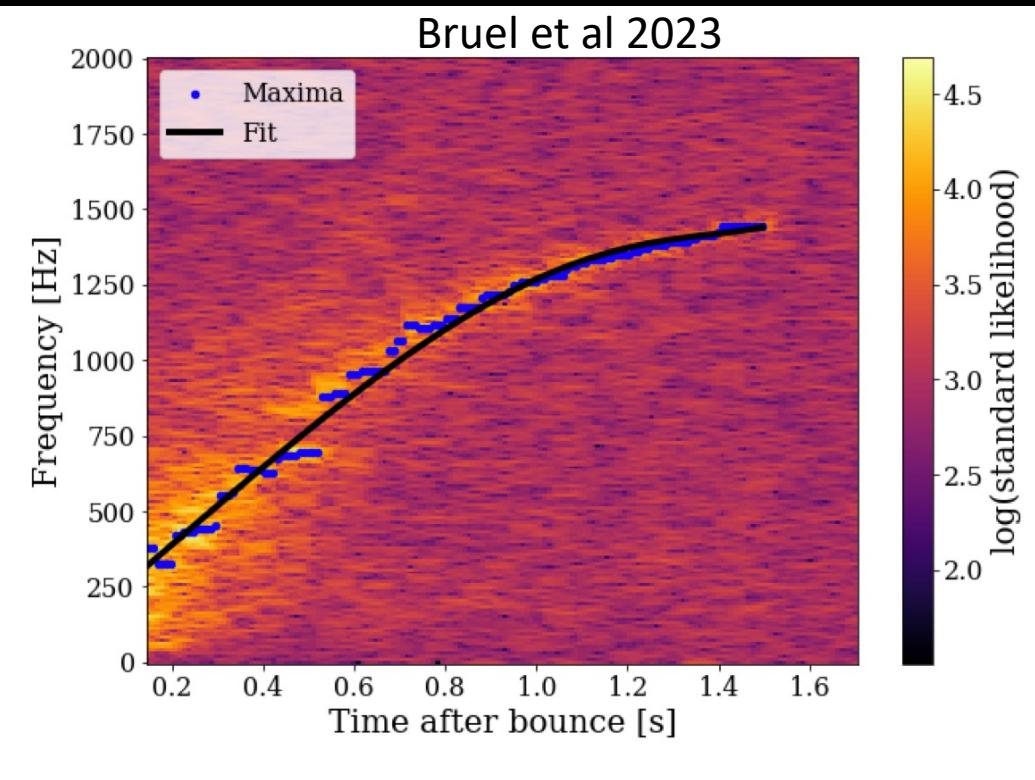
Powell et al 2017

Asteroseismology

Universal relations



Asteroseismology



LVK network, source at 5 kpc

Injections:

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

Noise:

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

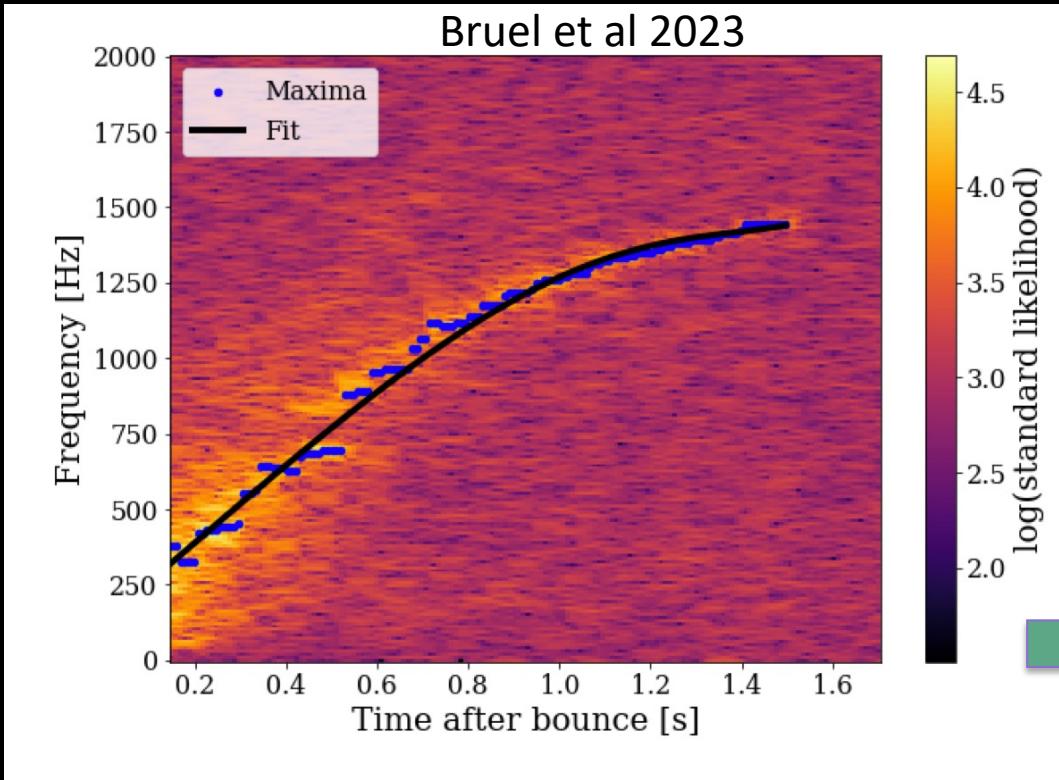
Observational scenario

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

Spectrograms:

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

Asteroseismology



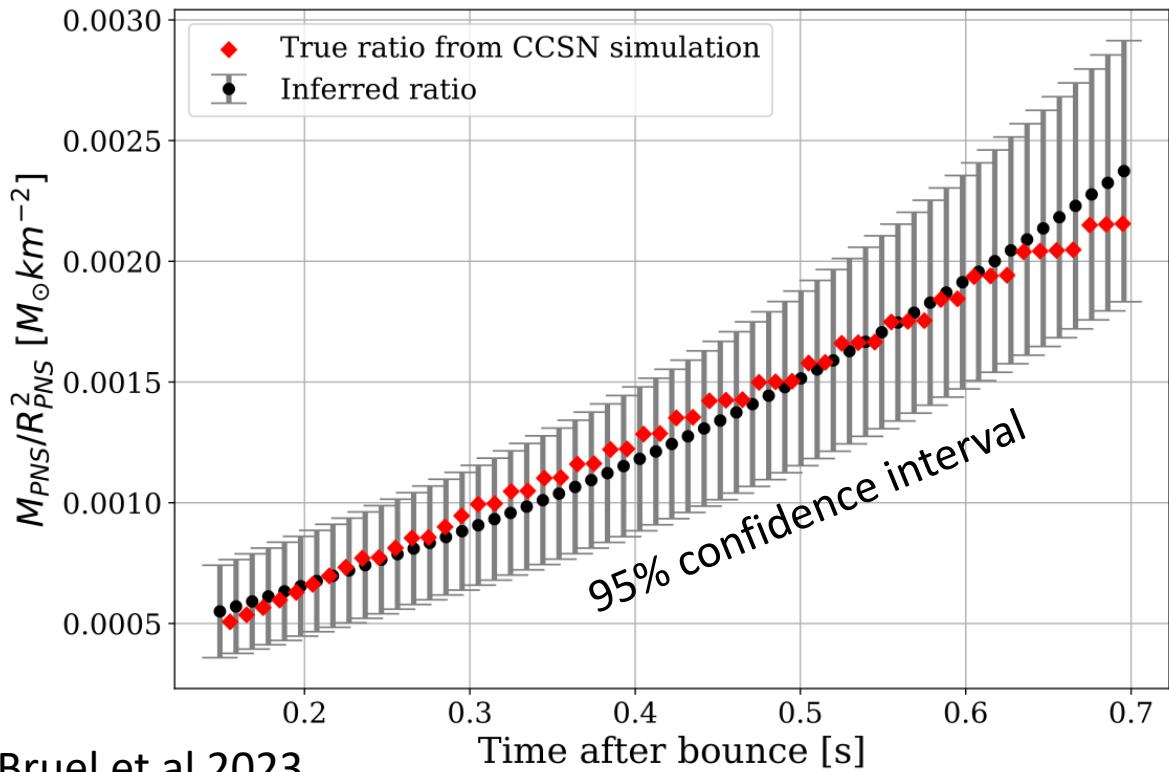
Tracking algorithm:

- Maximum identification
- Polynomial fit (LASSO regression)

Time-frequency tracking
of the main ridge

$$f(t)$$

Asteroseismology

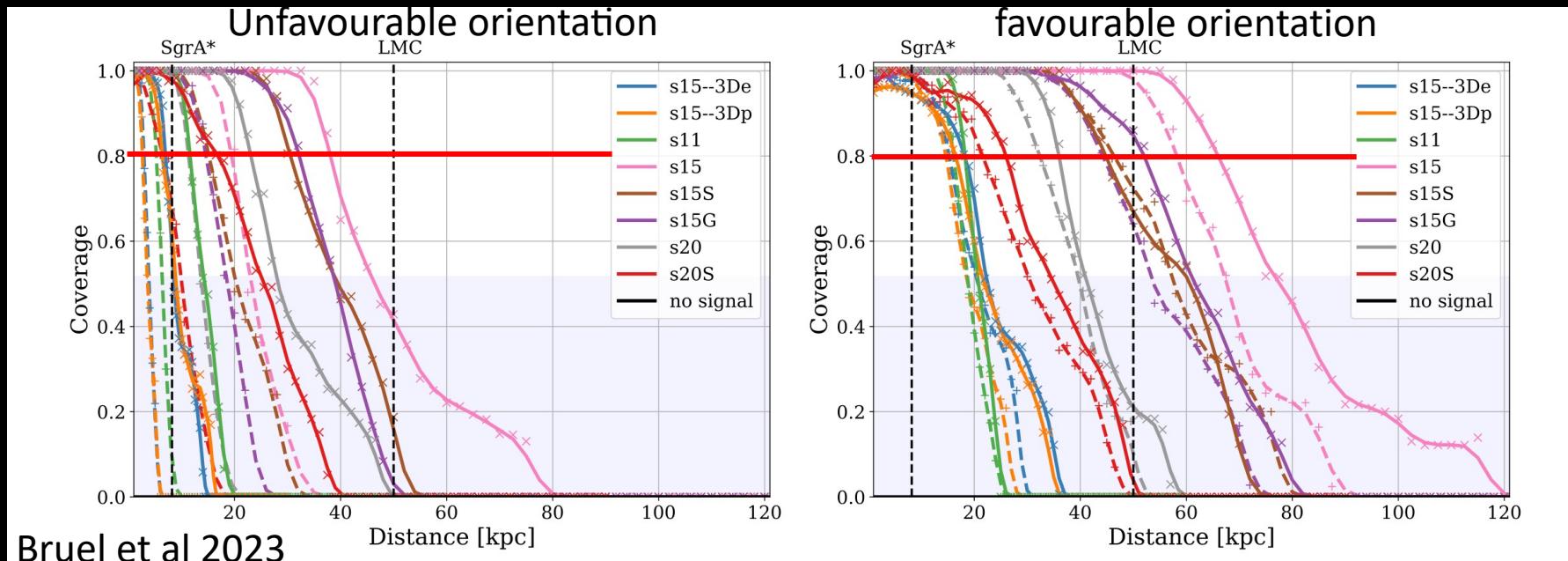


Inference of surface gravity

HLVKA network,
source at 5 kpc

Asteroseismology with 2nd generation detectors

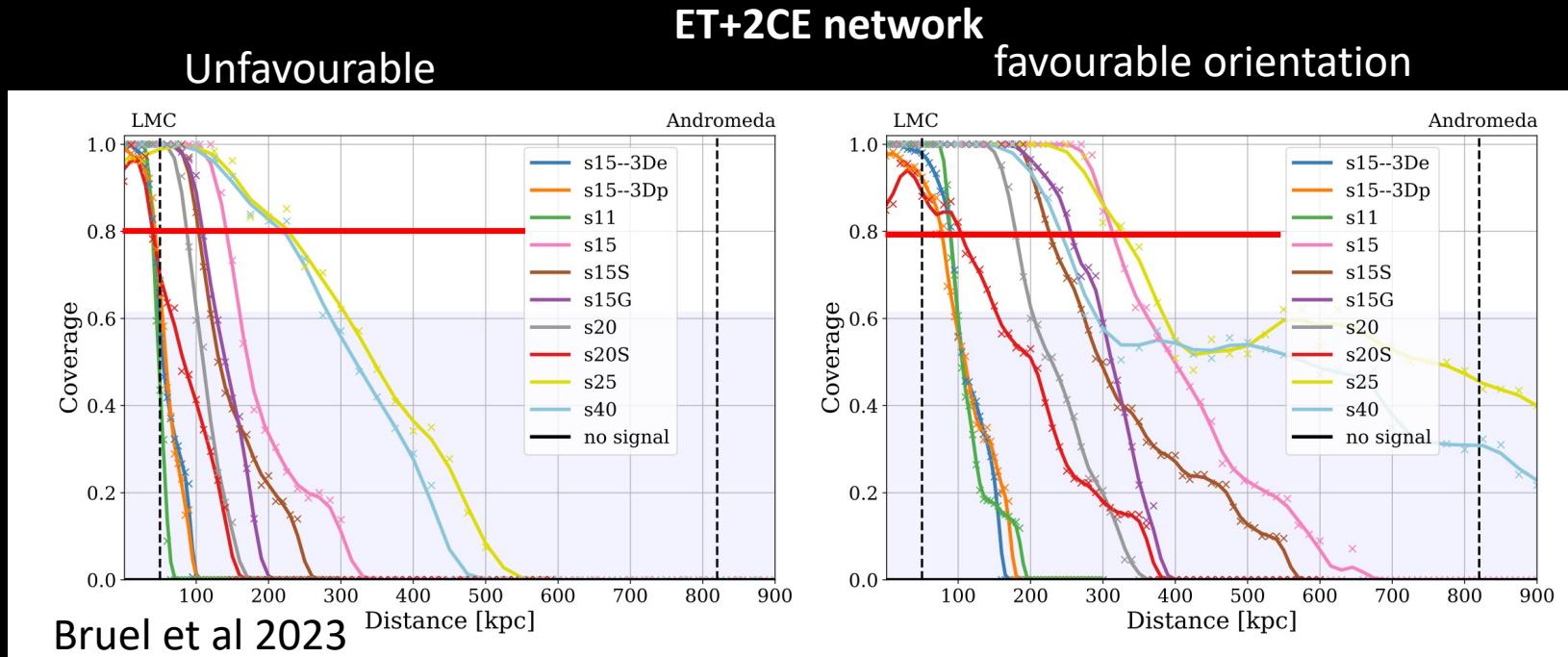
Coverage for 2nd gen detectors (fraction of the real surface gravity inside the 95% interval of the inferred values) **HLVKA and HL network** (solid and dashed lines)



Bruel et al 2023

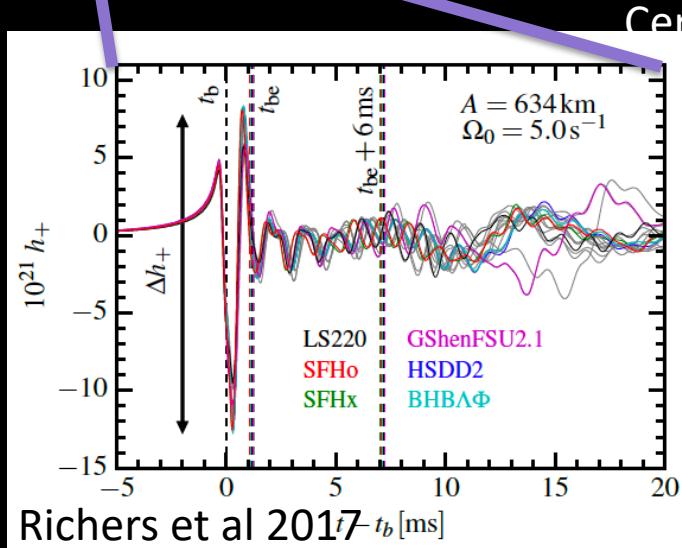
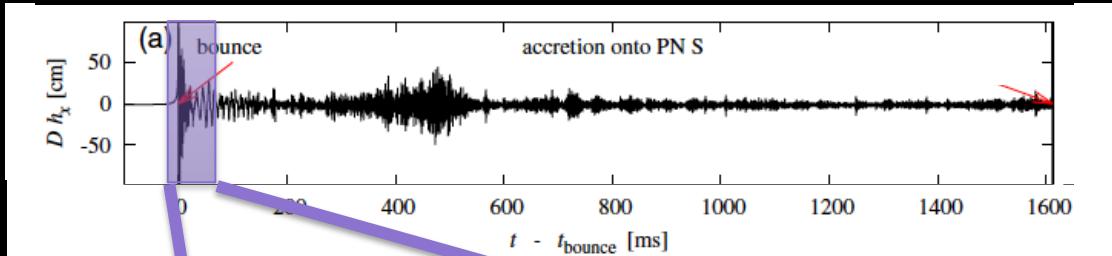
Galactic supernovae well reconstructed (coverage>0.8)

Asteroseismology with 3rd generation detectors



Possible up to a few 100 kpc

Bounce signal



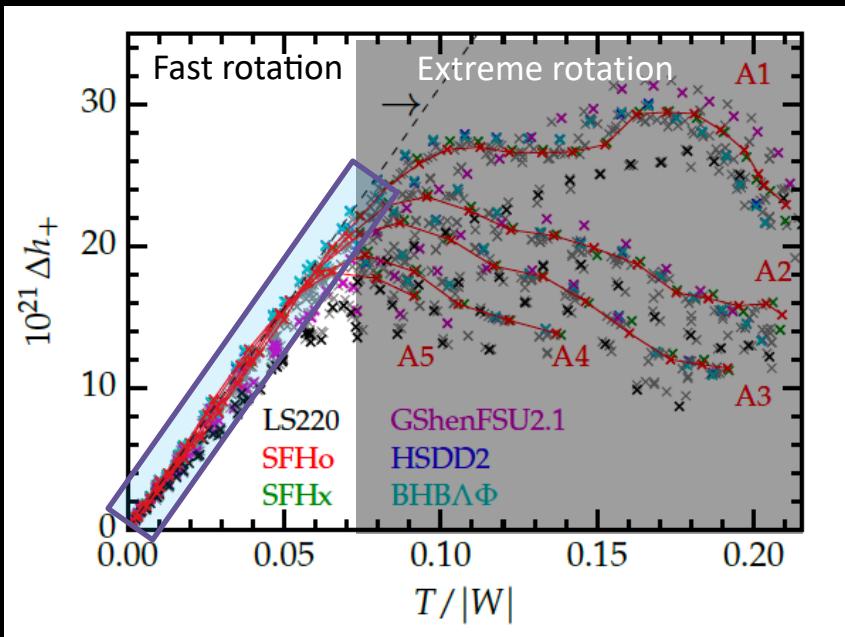
- ▶ Only first few ms
- ▶ Only rotating models (zero for non-rotating): $\sim 1\%$ SNe?
- ▶ Main features:
 - ▶ Peak with amplitude Δh_+
 - ▶ Several oscillations with frequency f_{peak}
- ▶ Richers et al catalogue
 - ▶ 2D GR simulations
 - ▶ 1824 waveforms
 - ▶ 18 different EOS

$$\Delta h_+ \propto T / |W| \quad (\text{rotation})$$

$$f_{peak} \propto \sqrt{\rho_c} \quad (\text{central density})$$

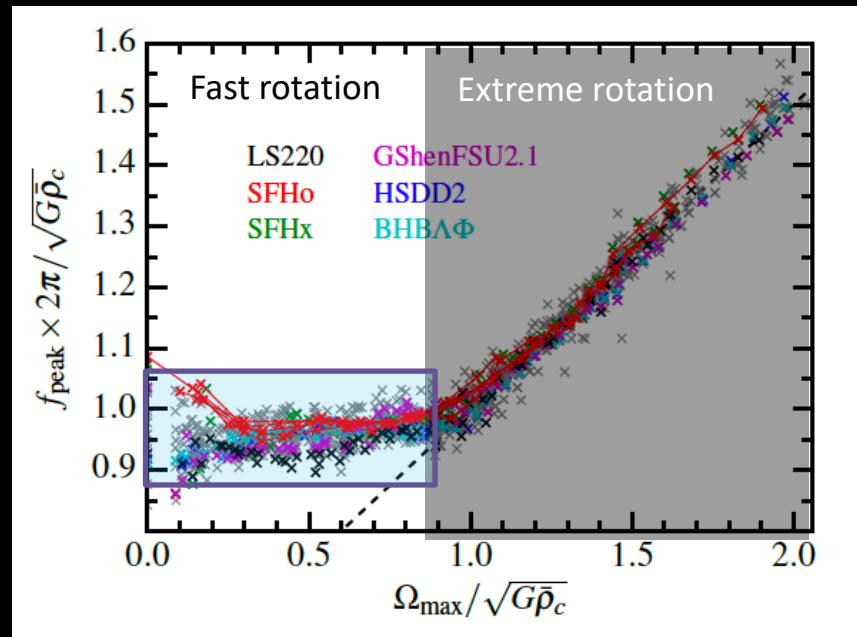
Bounce signal: What can we learn from Δh_+ and f_{peak} ?

Richers et al 2017



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

Kinetic rotational to potential energy ratio
(measure of rotation)



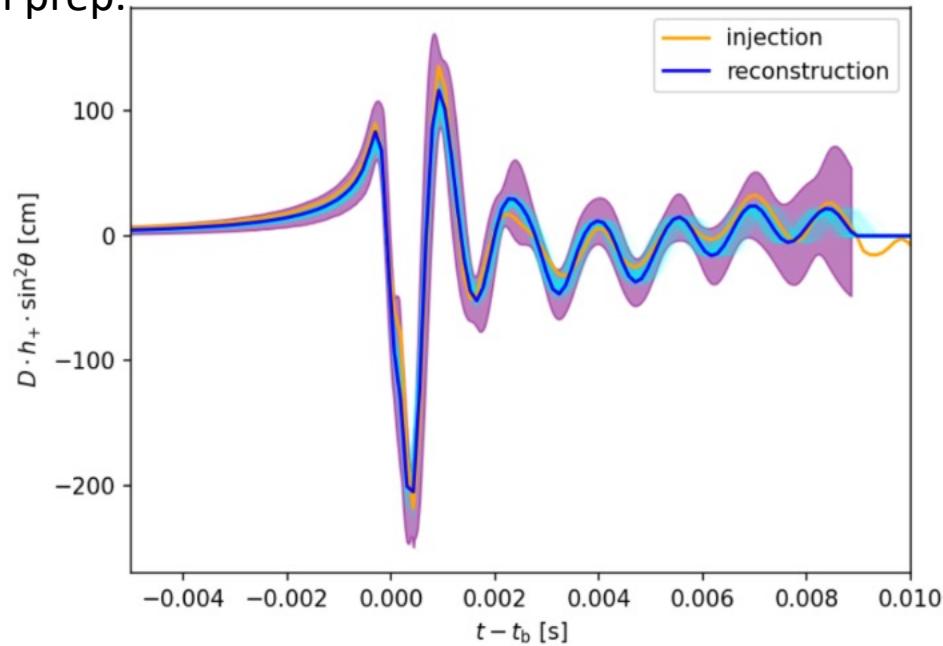
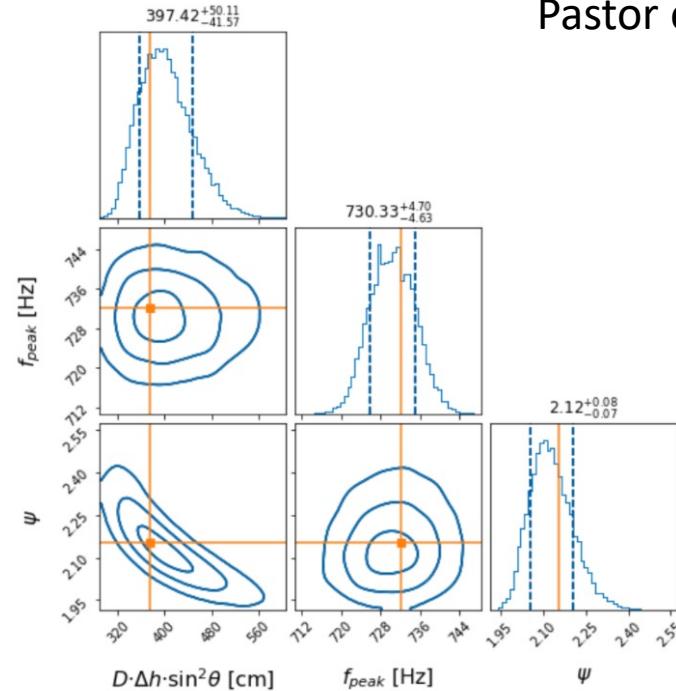
$$f_{\text{peak}} \propto \sqrt{\rho_c}$$

Central density

Bounce signal: Bayesian inference with **BILBY**

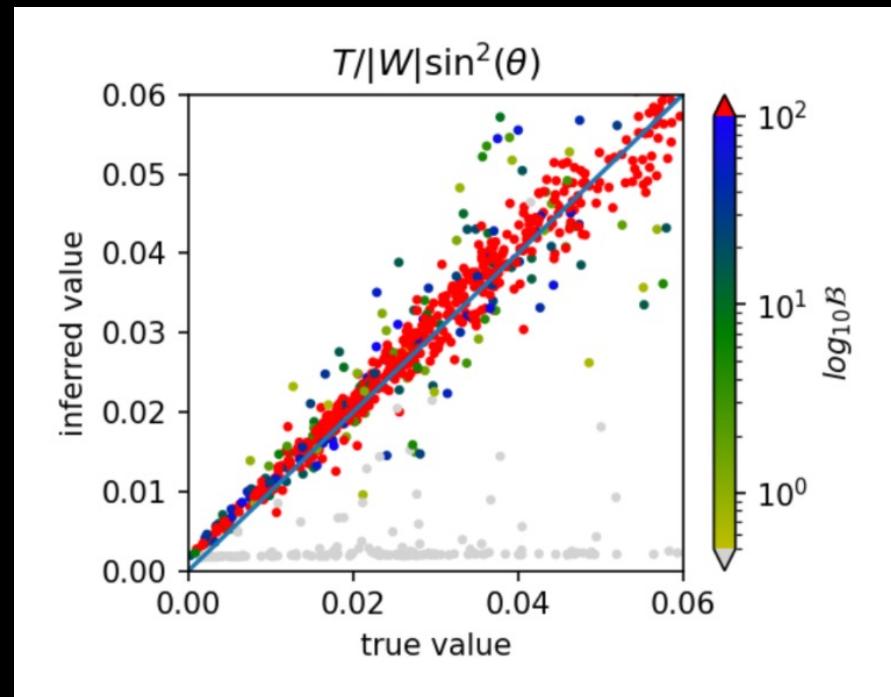
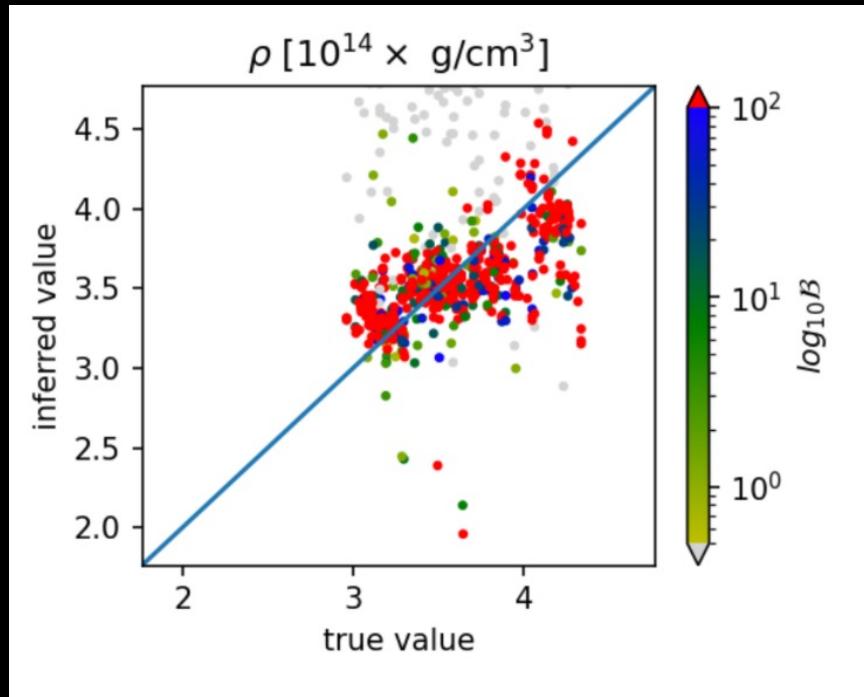
- Injections in Gaussian colored noise
- 3 detector network (2 x aLigo + aVirgo)
- 1000 random injections in the sky with $D = [0.1, 1000]$ kpc

Pastor et al in prep.



Bounce signal: Inferred values

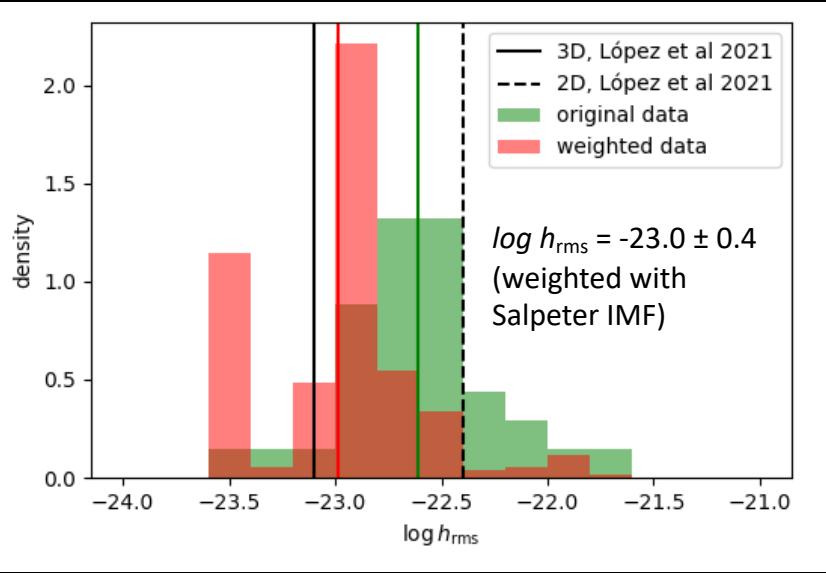
Pastor et al in prep.



Δh is degenerated with inclination angle \rightarrow Can EM observations constrain the inclination?

2.5 Detection rates

Gravitational wave emission from CCSNe



Fast rotating progenitors:

Rms strain increases with rotation.

Can reach $\sim 10^{-21}$ (amplitude x100).

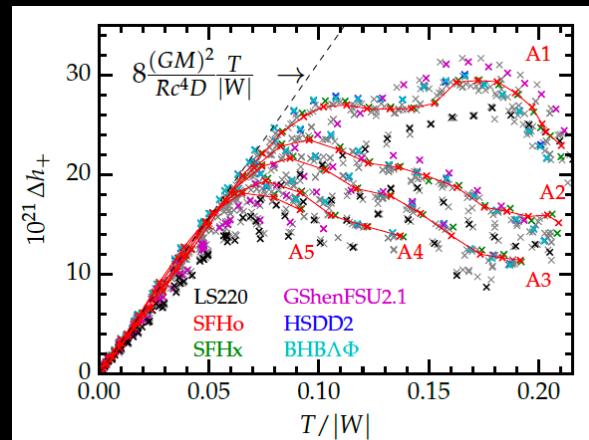
Fast rotating progenitors can be observed at distances x100 of non-rotating progenitors.

Non-rotating progenitors:

rms strain at 10 kpc (f>200 Hz)

34 waveforms: Andresen et al 2016 (4), Andresen et al 2019 (1), Kuroda et al 2016 (2), Kuoda et al 2017 (2), Mezzacappa et al 2020 (1), O'Connor & Couch 2018 (6), Pan et al 2020 (1), Powell et al 2018 (1), Powell et al 2020 (2), Powell et al 2021 (5), Radice et al 2019 (8), Yakunin et al 2017 (1)

Selection criteria: 3D + Non rotating + Non magnetic + Only standard progenitors (no ultra-stripped models) + Advanced neutrino transport: MGFLD, ray-by-ray+, M1, IDSA (no leakage or light-bulbs) + Relativistic gravity (BSSN, CFC, TOV)

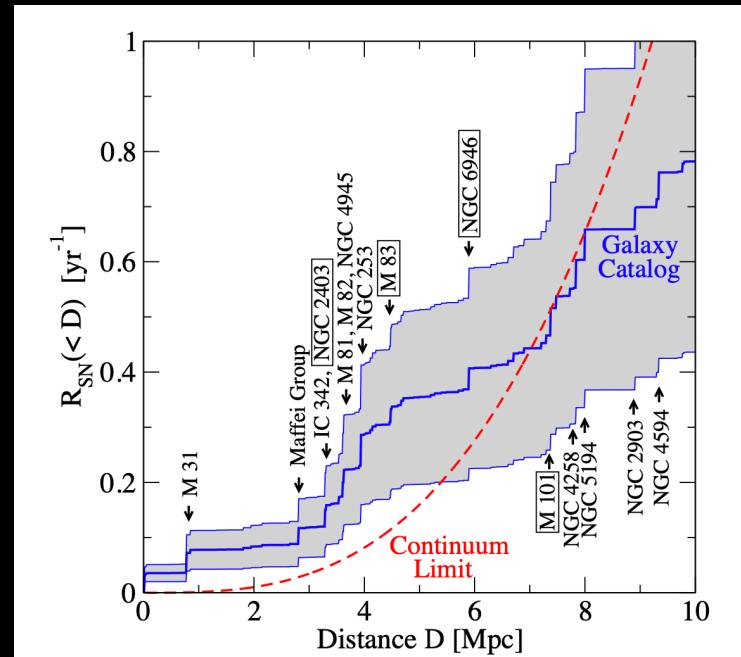


Rates of CCSNe

- **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)
- **Rate within 20 Mpc: ~4/yr** (5 during O1+O2)
(Gill et al 2017, 4.2±2/yr at 20 Mpc, ~1/yr at 10 Mpc)

Observational uncertainties and biases??

Ando et al 2005



Rates of CCSNe

- **Rate of CCSNe on the Milky-way: ~2/century**
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- **Rate within 20 Mpc: ~4/yr** (5 during O1+O2)
(Gill et al 2017, 4.2 ± 2 /yr at 20 Mpc, ~ 1 /yr at 10 Mpc) **Observational uncertainties and biases??**
- **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)
- **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 ($40^{+60}_{-28}\%$)!!!
- **Non/slow rotators: 90-95%? - neutrino-driven explosions**
- **BH formation: 15-20% -unnovae** (Kochanek 2014; Adams et al 2017)

Magnetar birth rate?

Simple estimate:

10 galactic magnetars with SNR younger than 10 kyr → magnetar formation rate = 0.1 / century ($\sim 5\%$ SN rate)

Uncertainties:

- Completeness of the observed sample of young galactic magnetars?
 - 24 confirmed + 6 candidates, McGill Online Magnetar Catalogue
 - Bright objects, almost all young magnetars should be visible.
 - Buried field in some cases? Very slow rotating NS?
- Age of magnetars?
 - Can be measured dating associated supernova remnants (SNR)
 - Association not always possible/sure
 - Expansion transversal velocities only measured in young SNR (a few kyr)
 - Ages in older SNR are model dependent → ages may have large uncertainties
 - General disagreement with ages measured from spin-down.

At which distance can we observe SNe in GWs?

LVK – Estimations for O4 & O5 (Szczepanczyk et al 2021):

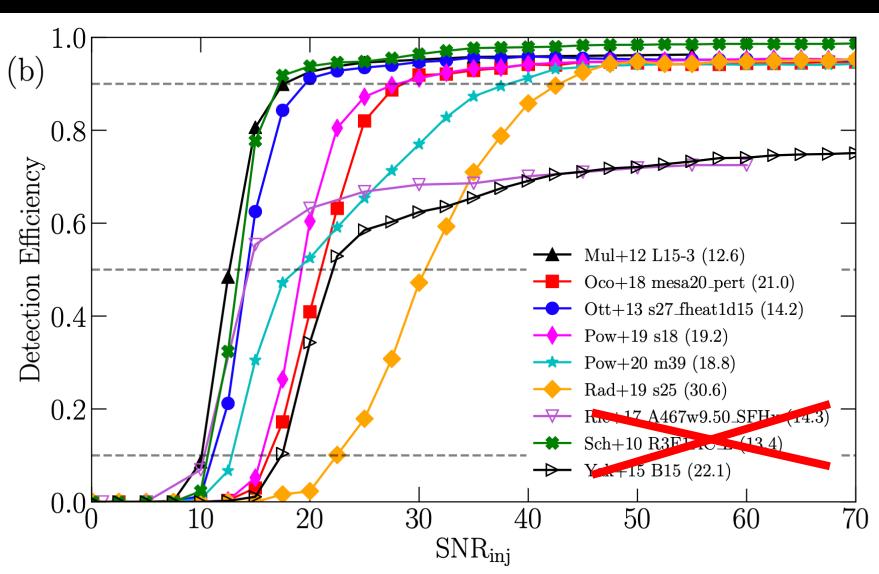
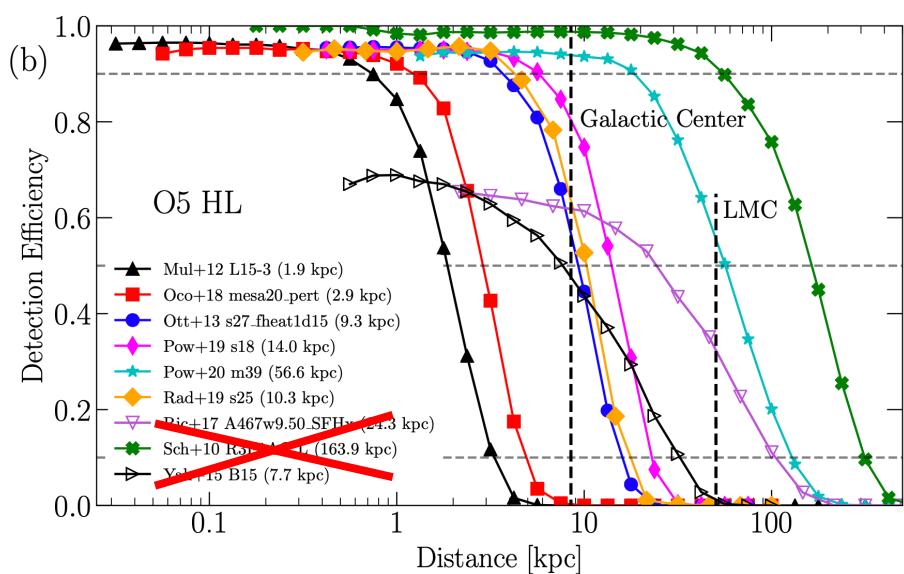
~10 kpc for non-rotating progenitors

~100 kpc for fast-rotating progenitors

Minimum SNR~15-20

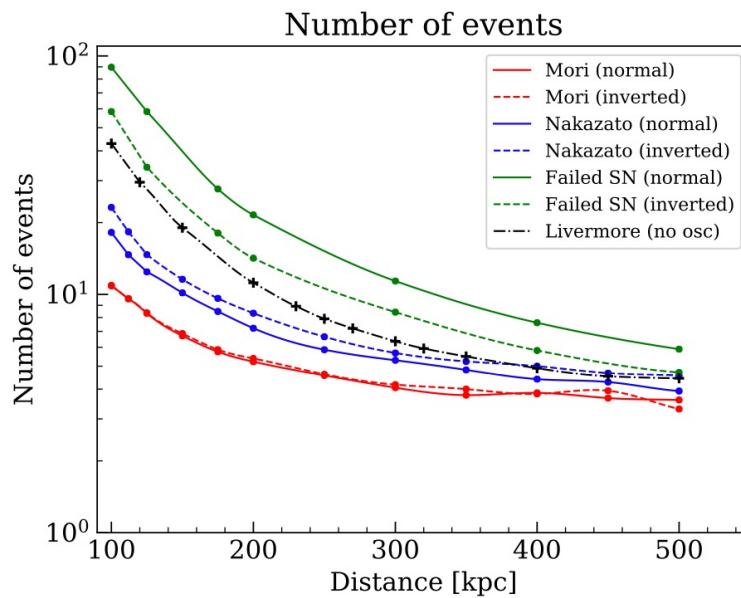
Most realistic waveforms require higher SNR

Current data analysis techniques are not optimal (matched filtering is optimal, achieving SNR~8)



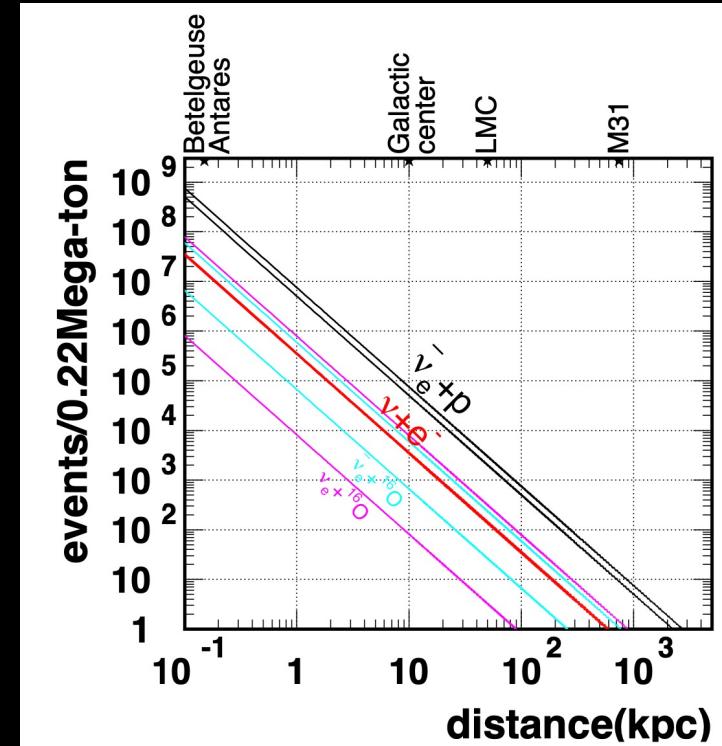
At which distance can we observe neutrino counterparts?

Super-kamiokande (50 kton, Gd): 10 v at 100 kpc



Mori et al 2022

Hyper-kamiokande (258 kton): 10 v at 1 Mpc



Abe et al 2018

Importance of a counterpart

FAP= False Alarm Probability
(probability of having a false alarm in a given observing window)

On-source
window

FAR= False Alarm Rate
(how often do you detect false alarms)

$$\text{FAP} = 1 - \exp(-T_{\text{coinc}} \times \text{FAR})$$

Example: FAR=1 / 5 yr

- $T_{\text{coinc}}=1 \text{ s}$ (v counterpart) $\rightarrow \text{FAP}=1.5 \times 10^{-7}$ ($5-\sigma$)
- $T_{\text{coinc}}=3 \text{ d}$ (EM counterpart) $\rightarrow \text{FAP}=0.038$ ($\sim 2-\sigma$)

Rate of observed SNe with ET

- Increased sensitivity (x10)
 - ~100 kpc for non-rotating
 - ~1 Mpc for fast-rotating
 - Improved data analysis
(optimal detection w. SNR~8)
→ detection range x 2 (~200 kpc/ ~2Mpc)
 - If a large fraction of SN have fast rotating progenitors (~100%)
 - ~ 4 fast rotating SNe within 20 Mpc per year.
 - ~ 1 fast rotating SNe within 10 Mpc per year.
 - ~ 2 nearby (galactic) SNe per century.
- 
- 1 every few years?
(optimistic)**
- 1 every few
decades?
(pesimistic)**

