ET OSB div 7
Stellar collapse and rotating neutron stars

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Coordinators (since ~March 2024)

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- Web site : https://wiki.et-gw.eu/OSB/StellarCollapseNS/WebHome
- Mailing list : https://mail.ego-gw.it/mailman/listinfo/et-osb-stellarcollapse-ns
- Blue book : https://www.overleaf.com/project/608ada23f2139b57d696cab4
- Meetings : https://wiki.et-gw.eu/OSB/StellarCollapseNS/Meetings

Many thanks to previous coordinators:
Marie-Anne Bizouard, Enrico Cappellaro and Pablo Cerda-Duran!

Div 7 activities & organisation

Meetings about every month, most recently to discuss div 7 blue book chapter but, in the long term, we aim to **discuss recent papers and ongoing work from group's members (from modeling to data analysis techniques through observational results)**

Please get in touch with div chairs to volunteer topics!

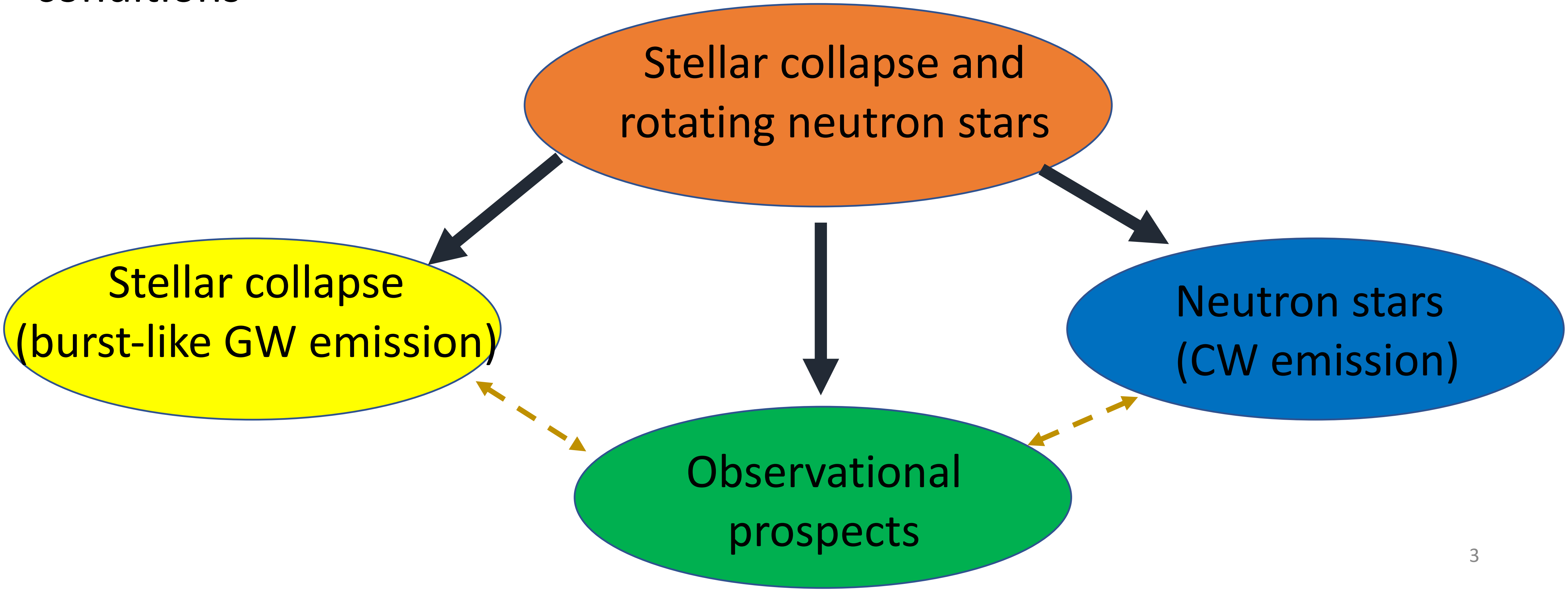
List of relevant publications: https://wiki.et-gw.eu/OSB/StellarCollapseNS/Publications

Currently, 107 people subscribed to div 7 mailing list, roughly equally divided among stellar collapse and rotating neutron stars *aficionados*

O(20) active members

What is DIV 7 about

- From progenitor stars to collapse remnants
- All available MM tracers: EM, ν, GW, cosmic rays
- Unique laboratories for the study of matter and radiation in extreme conditions



GW: Where we are – where we go

- GW from both CCSN and rotating NS have not still been detected
- With current detectors, expected strain amplitudes limit detectability horizon to the Milky Way or its neighborhoods, with few notable exceptions
- Low rate for CCSN, uncertain amplitude for CW from rotating NS
- Strong need to improve sensitivity both of detectors and of DA algorithms
- Sinergy with other messengers can be crucial to improve detection chances and science return

Stellar collapse

Stellar evolution toward stellar collapse

- Pre-supernova models
- Impact of metallicity and rotation on remnant mass
- BH maximum mass
- …

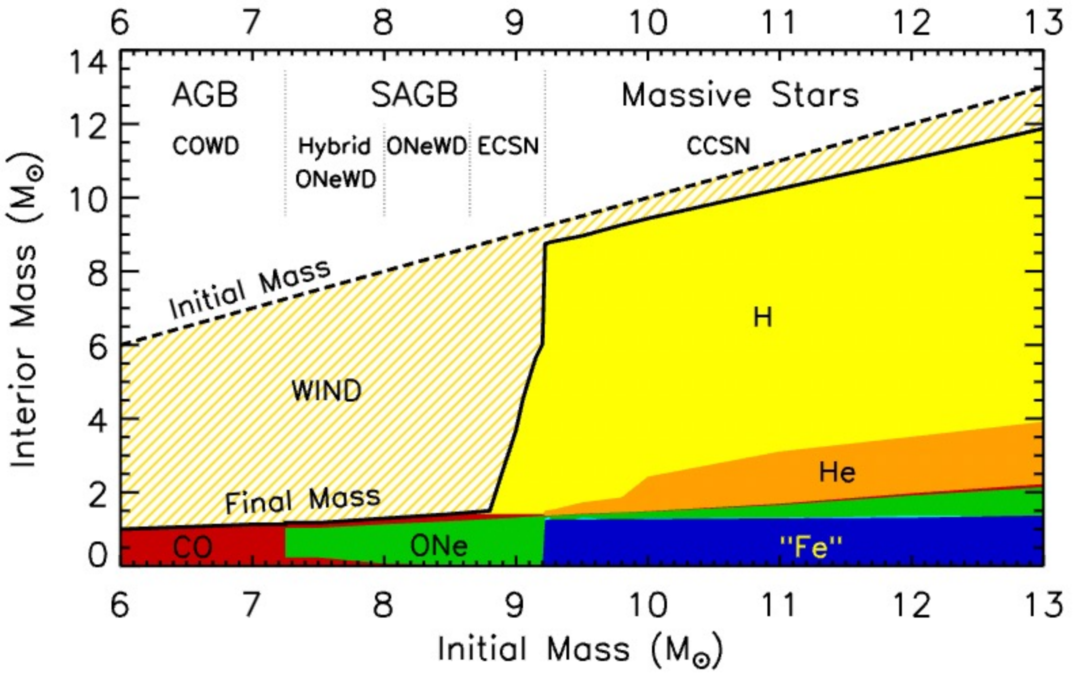


Figure 1: Final fate of stars in the mass range 7-13 $M_{\odot}$ according to [1].

Explosions mechanisms and dynamics

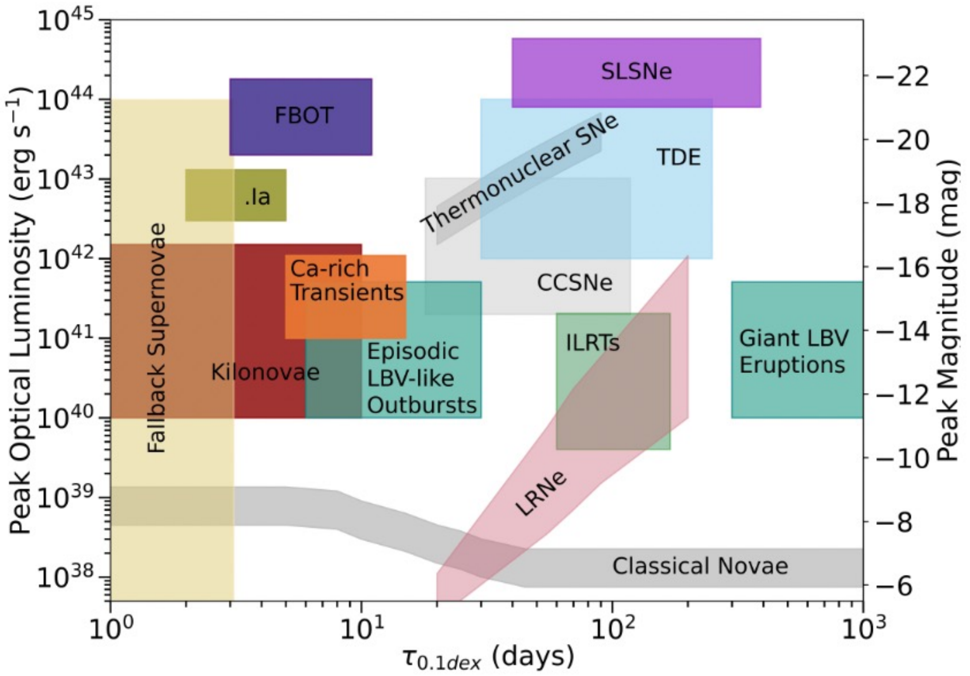
- Multi-dimensional, multi-scale numerical modelling
- Neutrino-driven vs magneto-rotational mechanisms
- Nuclear EOS
- Rotational instabilities
- …

Stellar collapse

Observations

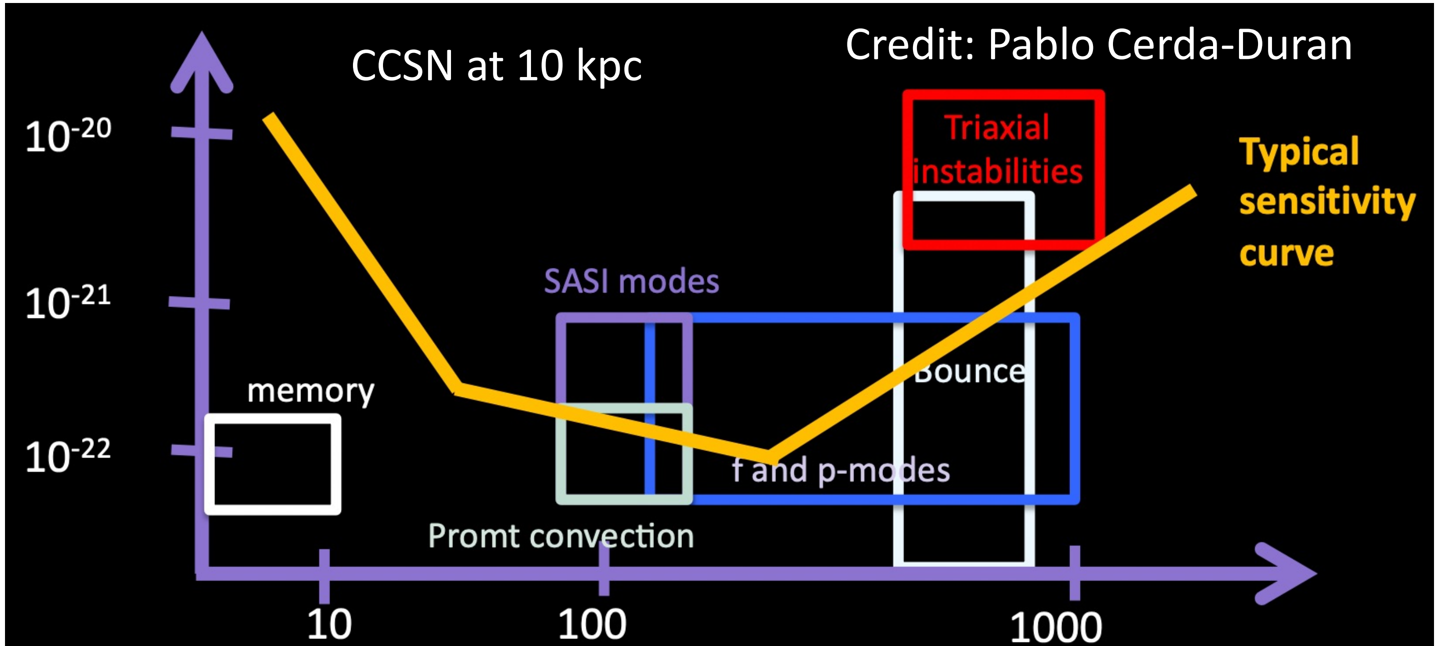
- Classification

Figure 5: Relationship between peak optical luminosity and characteristic time (defined as the duration for a luminosity decline of 0.1 dex) for optical transients within the local Universe. Different regions, denoted by various colours and shapes, indicate the typical location of some representative classes of transients such as superluminous supernovae (SLSNe), tidal disruption events (TDEs), core-collapse supernovae (CCSNe), luminous blue variables (LBVs), intermediate-luminosity red transients (ILRTs), luminous red novae (LRNe), and others. Figure adapted from [134].



GW and neutrino observables

- bounce, prompt convection, PNS oscillations



Stellar collapse

Observed and expected SN rates

- Local universe
  - SFR, CCSN observations
- Milky Way
  - Historical SN, rate from galaxies similar to MW, indirect evidence of SN

	10 Mpc		50 Mpc		100 Mpc	
	SFR ($M_\odot$ yr^{-1})	CCSNR (yr^{-1})	SFR ($M_\odot$ yr^{-1})	CCSNR (yr^{-1})	SFR ($M_\odot$ yr^{-1})	CCSNR (yr^{-1})
LOSS		$0.29^{+0.05}_{-0.04}$		$37.0^{+5.8}_{-5.7}$		295^{+47}_{-46}
Kennicutt et al.	87±4	0.40±0.02				
Lee et al.	123±8	0.59±0.04				
Bothwell et al.	75±5	0.36±0.02	9420±602	45±3	75360±4814	362±23
Hopkins & Beacom	65	0.3	8836	42	76121	365
Madau & Dickinson	63	0.3	8059	39	66568	319
Observations		$1.1^{+1.7}_{-0.6}$		38.0±2.5		153±5

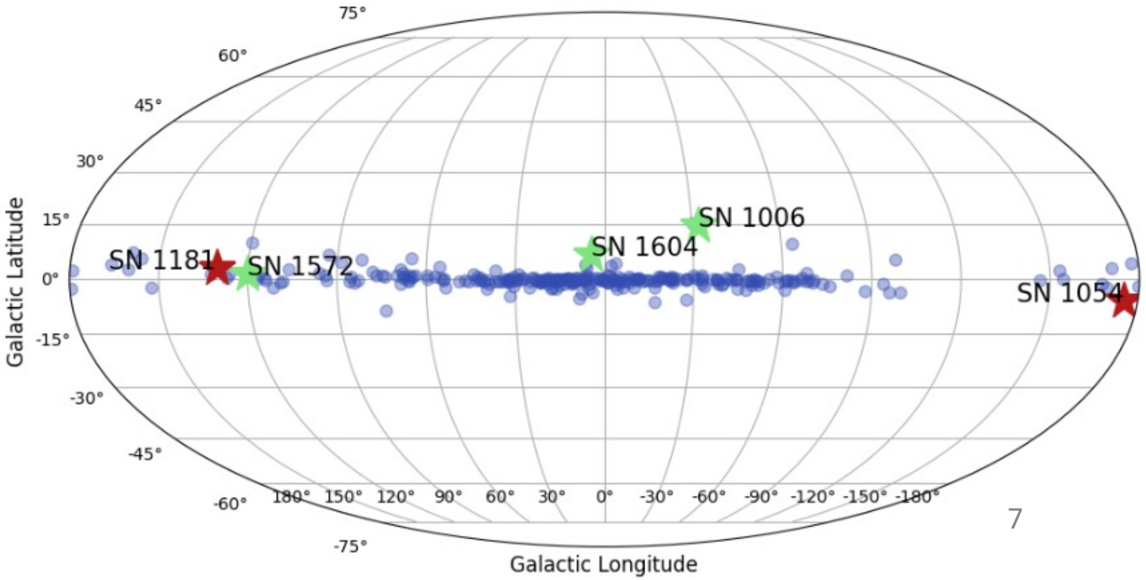
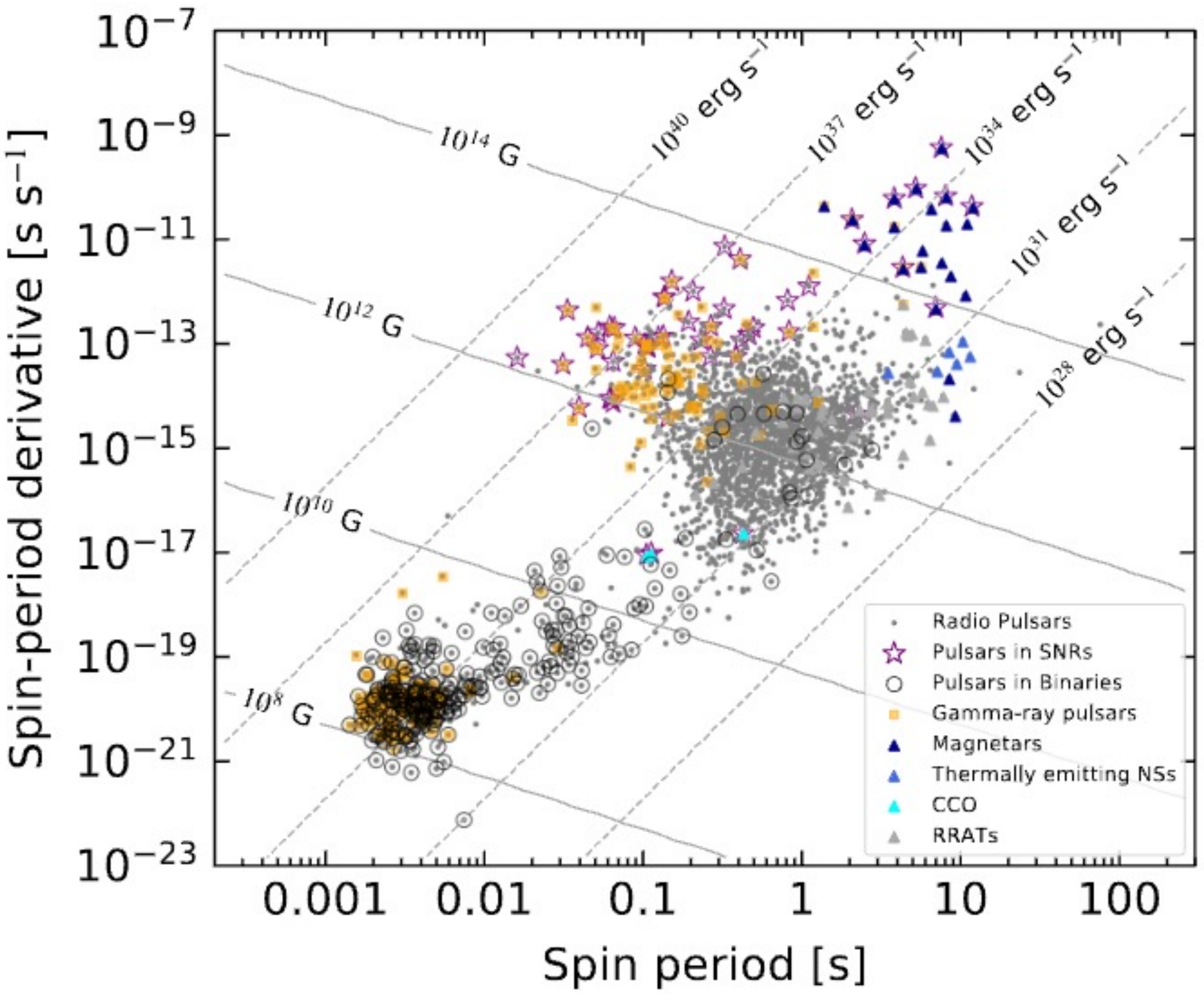


Figure 10: The distribution of the historical SNe and the supernova remnants in the galactic coordinate system. The blue dots are the 294 remnants from the Green et al. catalogue[256], the red stars are the observed CCSNe and the green stars are the observed SN Ia.

Neutron stars

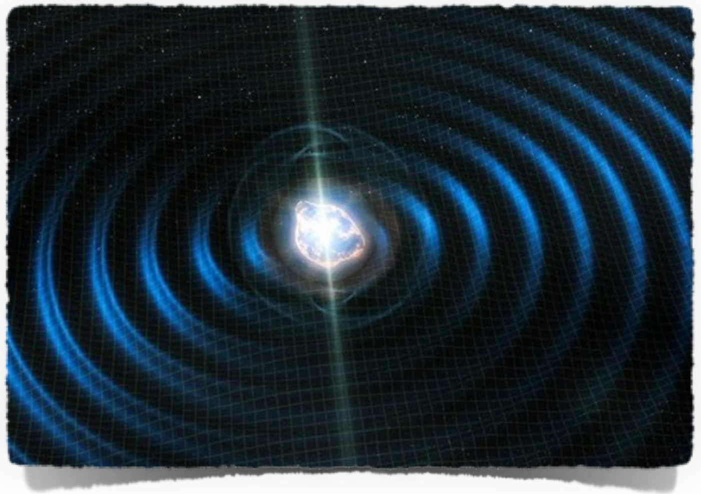
Observed neutron star population

- ~2500 isolated radio/gamma pulsars
  - some experiences rotational glitches
- ~1500 NS in binaries (radio/gamma/X/optic, transitional)
  - Some accretes matter from a companion star (LMXBs)
- Magnetars/XDINS/CCOs: different evolutionary stages of high-B NSs



Picture credit: N. Rea

Neutron stars



GW emission from rotating NS

- ‘mountains’: supported by crustal rigidity or magnetic field
- Oscillation modes: f-modes (mass quadrupole), r-modes (current quadrupole)

$$h_0 = \frac{4G}{c^4}\frac{\epsilon I_3 \Omega^2}{d} \approx 10^{-25}\left(\frac{10\text{kpc}}{d}\right)\left(\frac{\epsilon}{10^{-6}}\right)\left(\frac{I_3}{10^{45}\,\text{g}\,\text{cm}^2}\right)\left(\frac{\nu}{500\,\text{Hz}}\right)^2$$

Mechanisms of mountain formation and r-mode excitation already described in DIV 6 (which is focused on implication of GW observation on EOS)

We mainly focus on GWs from: LMXBs, newborn magnetars, pulsar glitches

Observational prospects

GW from CCSN

- Targeted searches (EM/nu counterpart) with standard DA methods
  - Detection horizon ~0.1-1 Mpc for generic excess power methods
  - ~ few Mpc for bar-mode instability in PNS (assuming ε~0.1)

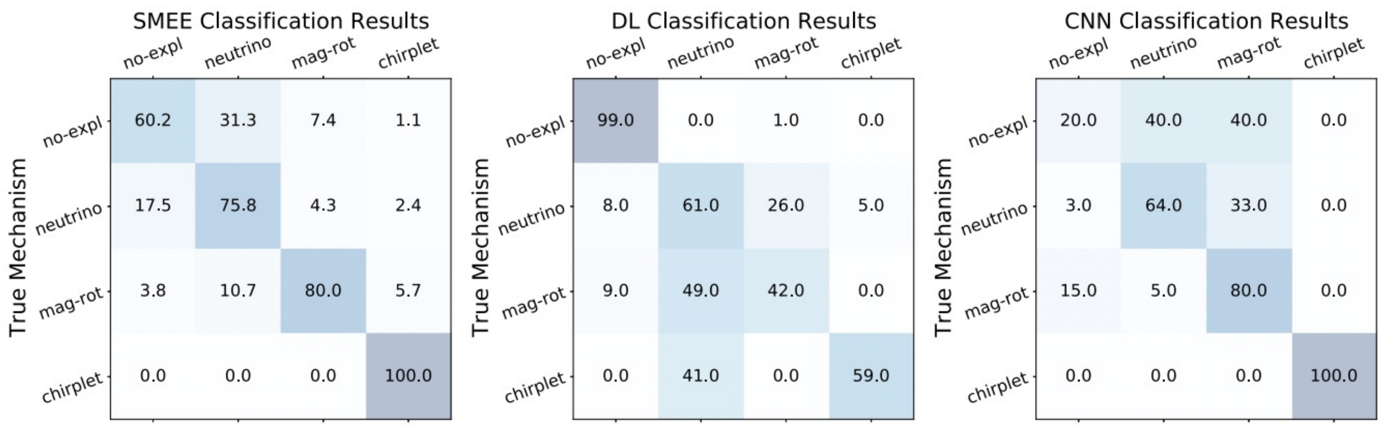
- All-sky burst searches (no counterpart)
  - Faint CCSN (BH collapse, dust exstinction,…)

- For galactic SN, possibility to detect weaker emission from SASI, PNS convection, quasi-radial oscillations

- Impact of CBC background: needs for MDC (synergy with div 10)

Observational prospects

New methods/open issues



Powell+ (2024): ML classification of explosion mechanisms using ET

- Machine Learning methods
  - Detailed comparison with standard excess method still to be done
  - Properly training of the network (phenomenological templates, dimensionality reduction)
  - Use ML as a post-processing step of classical excess power methods

- Waveform reconstruction (if SNR is high enough)

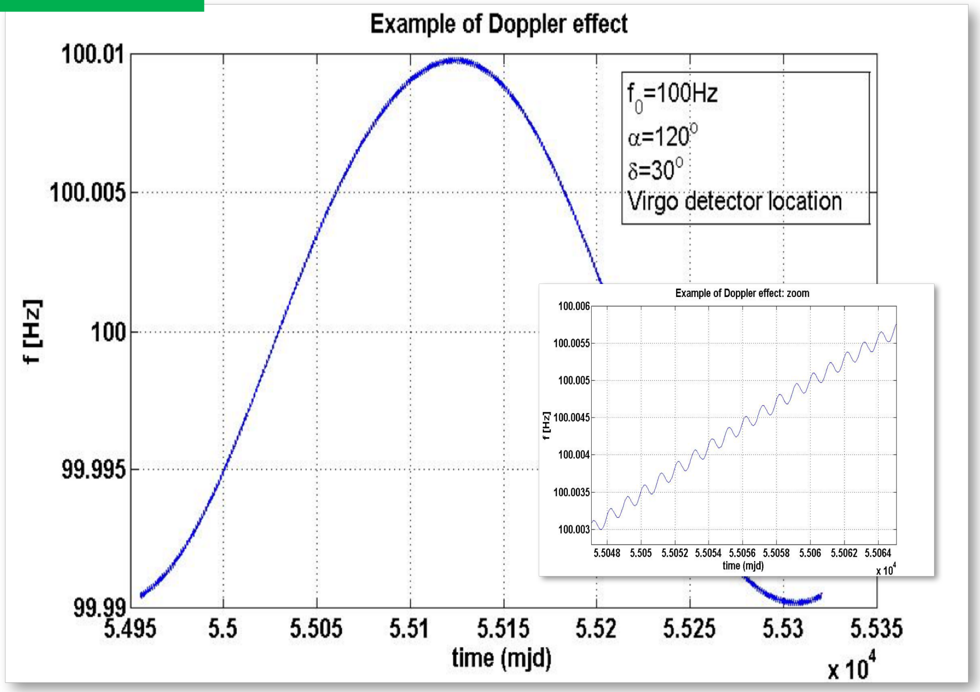
- Model classification (discriminate ν-driven and magneto-rotational up to ~Mpc)

- Asteroseismology to study PNS structure up to O(100 kpc): inference of PNS parameters
  - Active field for new DA algorithms

Observational prospects

Continuous GW

- Persistent and weak signals: exploit long duration to build SNR
- Need to take into account various phase and frequency modulations (Doppler, sidereal response,…)
- Impact of CBC background on searches (div 10)



Estimated number of detections for targeted searches toward known pulsars

Configuration	2L 15km	2L 15km HF-only
n_1	959 $(2.0 \times 10^{-10},\ 1.2 \times 10^{-4})$	451 $(2.0 \times 10^{-10},\ 5.6 \times 10^{-6})$
n_2	206 $(2.0 \times 10^{-10},\ 4.2 \times 10^{-9})$	203 $(2.0 \times 10^{-10},\ 4.0 \times 10^{-9})$
n_3	29 $(2.0 \times 10^{-10},\ 8.1 \times 10^{-10})$	29 $(2.0 \times 10^{-10},\ 8.1 \times 10^{-10})$

Table 3: Expected number of detectable sources, including binaries, assuming three different conditions for the ellipticity: $\epsilon = \epsilon_{sd}$ (n_1), $\epsilon = min(\epsilon_{sd},\ 10^{-6})$ (n_2), $\epsilon = min(\epsilon_{sd},\ 10^{-9})$ (n_3), assuming a total observation time $T_{\rm obs} = 1$ year and a duty cycle of 85%. For each case, we give in parentheses the minimum and median values of ellipticity for detectable signals.

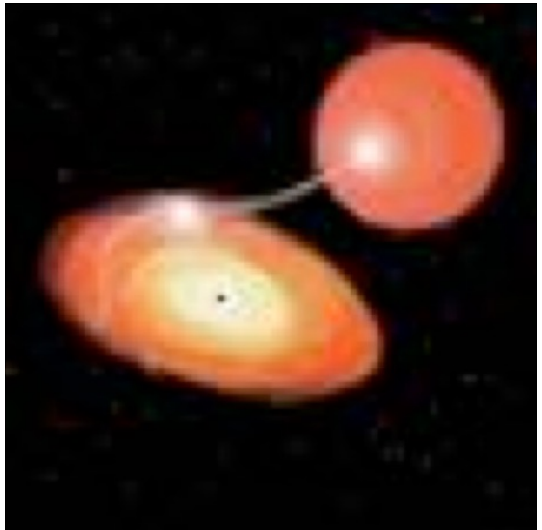
Observational prospects

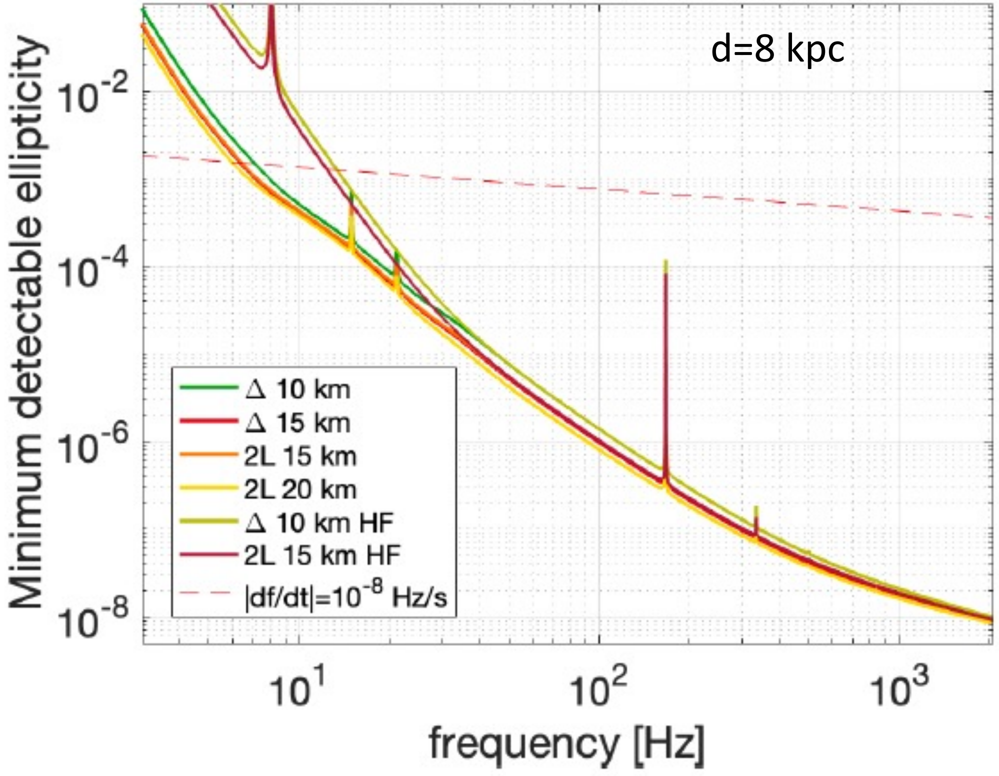
All-sky searches

- Computationally heavy, need to improve sensitivity keeping computing cost under control

'Directed' searches

- toward specific directions (e.g. Galactic center, globular clusters, SNR,…) or sources (e.g Sco X-1) for which rotational parameters are poorly known



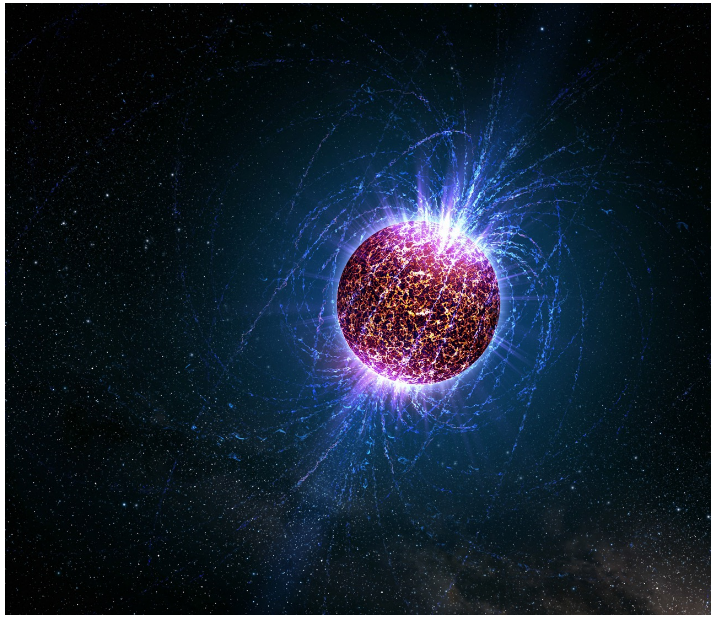


Plot from CoBa paper. A version specific for the BB will be done

Observational prospects

Long-transient signals (or tCWs)

- duration: O(hours-days)
- Associated e.g. to newborn magnetars
- Estimated distance reach assumes robust improvement in DA methods



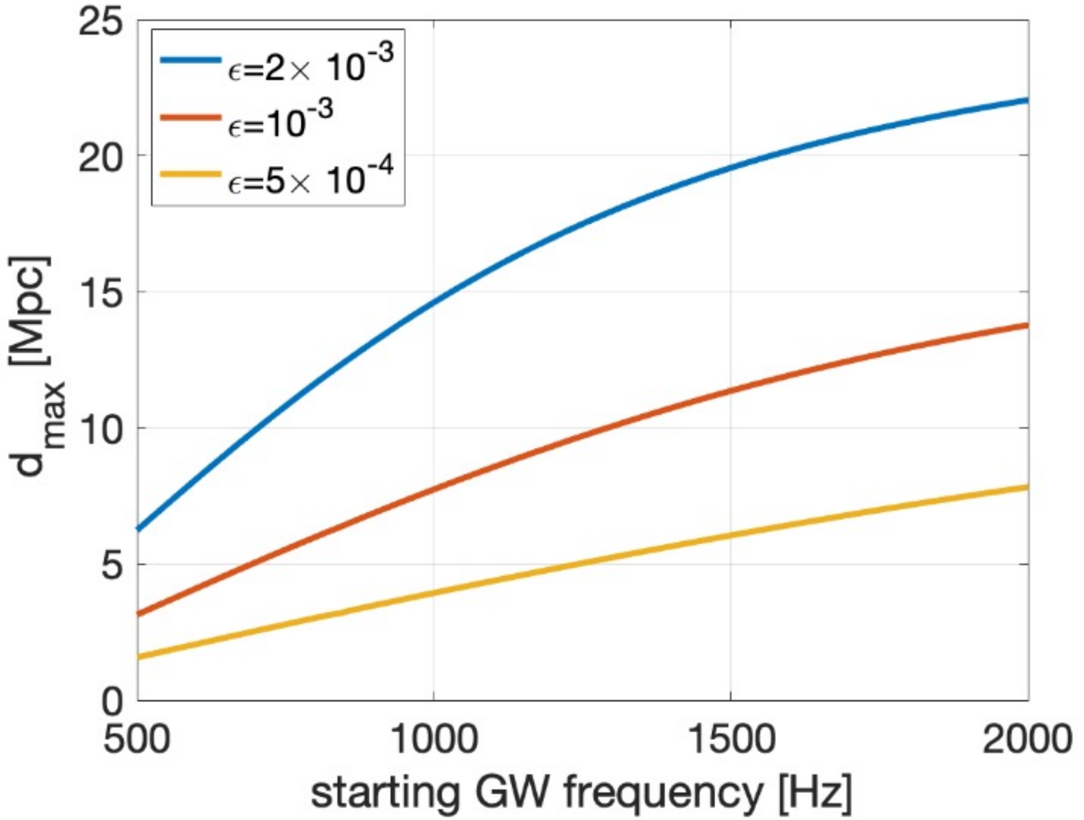
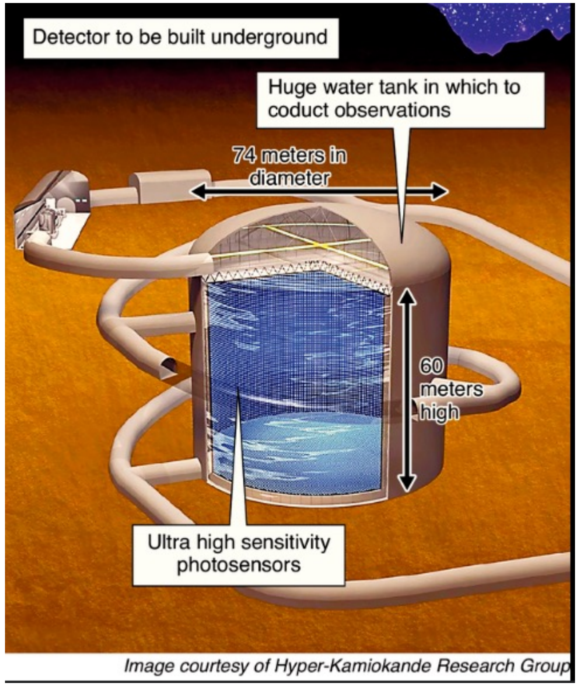


Figure 13: Maximum distance at which long-transient GW emission from a newborn magnetar could be detected by ET for three different plausible values of the ellipticity (and realistic analysis setup). A configuration consisting of two L-sphape 15km arms detectors is considered. Similar results would be obtained for other realistic configurations.

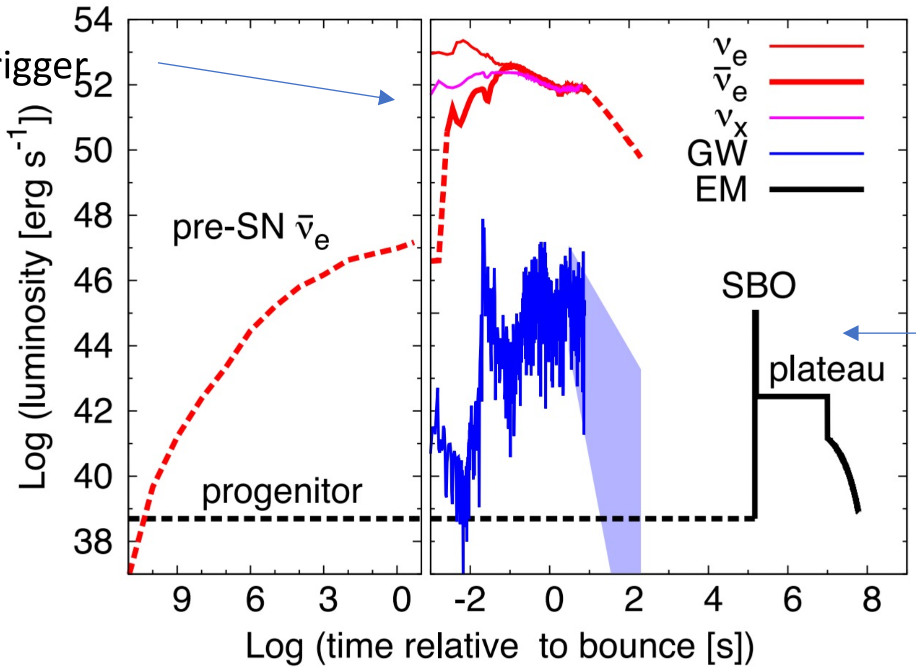
Observational prospects

Future MM facilities

- Secure multi-wavelength EM follow-up after GW/ν burst
- EM transient → GW/ν search
  - Time of the event and sky localization
  - Possible information on the GW source dynamics (e.g. in the case of newborn magnetars)
- Systematic study of all events to get insight on SN diversity/classification



ν : temporal trigger



EM alert

Time evolution of multi-messenger signals from a CCSN (Nakamura+ 2016)

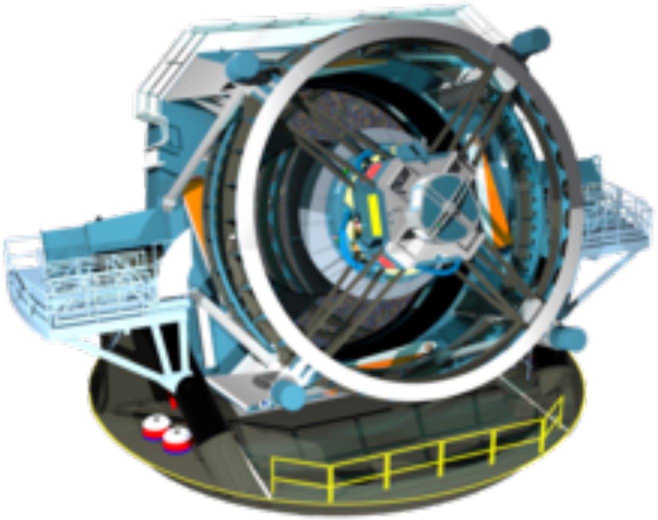
Observational prospects

EM follow-up/search

- Prompt wide-field observations (tens of deg^2 field of view), contaminants removal
- High cadence search for EM transients (with possible GW/ν follow-up)
- ZTF --> GOTO, Vera Rubin

- Spectroscopic analysis of promising candidates

- EM characterization of
  - Massive star populartion
  - Nearby CCSNR



Vera Rubin

Status of the bluebook

- No more empty sections (thanks to the effort of many contributors!), but some sections still in a rather rough state
- ~70 pages of text (+70 of bibliography)
- Division chairs have started to work on the chapter
- Still a considerable amount of work to have a good draft
- Contributors will be asked to expand/contract some parts
- We are committed to release our draft by the end of the month