# GWs from CCSNe

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# Thanks to...

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# Introduction

- GW are wave-like perturbations of relativistic gravity
- two polarisation modes, $+$ and $\times$
- emitted by rapid, non-spherical accelerations of masses

$\rightarrow$ CCSNe are potential sources

- current detectors are most sensitive at $\mathcal{O}(10^{2-3})$ Hz
- no CCSN detected so far, but the waves of the first one are already on their way
- prepare for the first detection:
  - ¿Can GWs be used to detect CCSNe?
  - ¿Can we infer parameters of the explosion or its compact remnant from the GW?

$\rightarrow$ simulate CCSNe and their GW signals

# Simulation methodology and physics input

- progenitor
- collapse and engine
- later phases

- hydrostatic 1d spherical stellar evolution, potentially with approximate treatment of convection, mixing, mass loss, rotation, and magnetic fields
- detailed nuclear physics
- multi-d (magneto-)hydrodynamic simulations of brief phases before collapse

# Simulation methodology and physics input

- progenitor
- collapse and engine
- later phases

## GW-emitting phase

- 1/2/3-d (M)HD
- GR or (pseudo-GR) gravitational potential - beware impact on GW frequencies!
- EOS including nuclear regime
- various approaches to $\nu$-physics: leakage, IDSA, M0/M1, Boltzmann transport, ...; more or less up-to-date interaction rates, usually without flavour transitions; in 1d: artificial trigger for explosions
- composition and energy generation: NSE, nuclear reaction networks or approximate approaches

# Simulation methodology and physics input

- progenitor
- collapse and engine
- later phases

- 1/2/3–d (M)HD
- gradually turn off $\nu$
- ionisation
- nuclear reactions, in particular $\beta$-processes
- particle acceleration
- various processes for thermal and non-thermal photon emission, transport

# GW emission

- quadrupole formula for the GW strain at distance $D$

$$h = \frac{2G}{Dc^4} \frac{\mathrm{d}^2 Q}{\mathrm{d}t^2} \tag{1}$$

  in terms of the mass (energy) quadrupole moment $Q$
- estimate $h \sim \epsilon r_\mathrm{S} \frac{v^2}{c^2}$, with $\epsilon$ quantifying deviation from sphericity
- GW emission power:

$$\frac{\mathrm{d}E_\mathrm{GW}}{\mathrm{d}t} \sim \epsilon \frac{c^5}{G} \left(\frac{r_\mathrm{S}}{R}\right)^2 \left(\frac{v}{c}\right)^6 \tag{2}$$

  $\rightarrow$ dynamically insignificant in CCSNe, backreaction not necessary in simulations

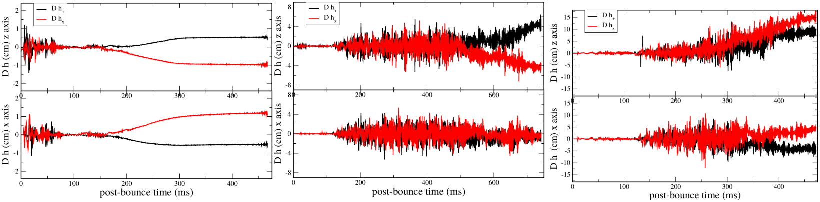
# Overview: GW emmission mechanisms

## Without rotation

- prompt convection
- hot-bubble convection, SASI
- PNS oscillations
- PNS transitions
- shock runaway
- asymmetric $\nu$ emission

## Rapid rotation

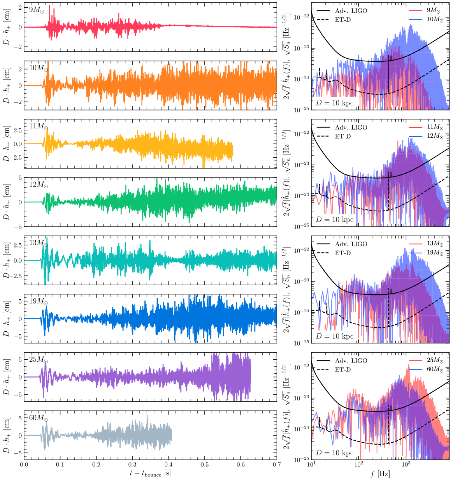
- bounce signal
- $m = 1$ instabilities
- jet signatures




Mezzacappa et al. (2022)

# Non-rotating CCSNe

no prominent signal right at bounce

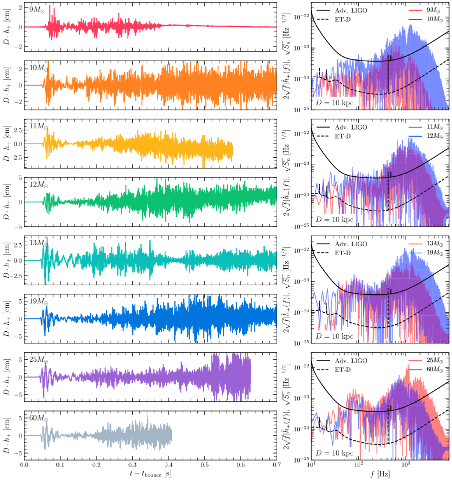



Signals and spectra for 3d models of CCSNe. $D = 10\,\mathrm{kpc}$. Radice et al. (2019)

# Non-rotating CCSNe

## Early post-bounce signal

- shock propagates out of the nascent PNS
- neutrino emission generates a convectively unstable $Y_e$-gradient
- alternative interpretation: $p$-modes (propagating waves rather than stationary eddies; Müller et al., 2013)
- moderately strong GW emission for a few 10 ms only at $f \sim 100\,\mathrm{Hz}$

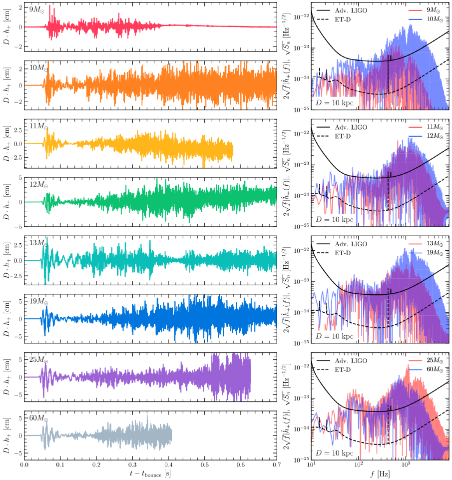



Signals and spectra for 3d models of CCSNe. $D = 10\,\mathrm{kpc}$. Radice et al. (2019)

# Non-rotating CCSNe

## PNS convection

- continues to operate on longer times
- direct contribution to GW emission found in some, though not in all, simulations

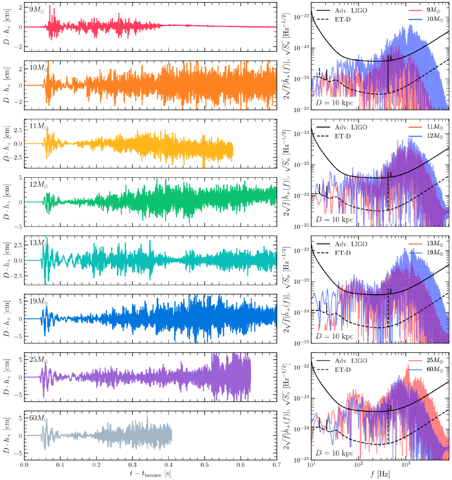



Signals and spectra for 3d models of CCSNe. $D = 10\,\mathrm{kpc}$. Radice et al. (2019)

# Non-rotating CCSNe

## Hot bubble flows

- $\nu$-driven convection behind the shock wave with intermediate to large eddies; minor contribution
- SASI: global, large-scale shock deformations; can produce a signal at low $f < 100\,\mathrm{Hz}$

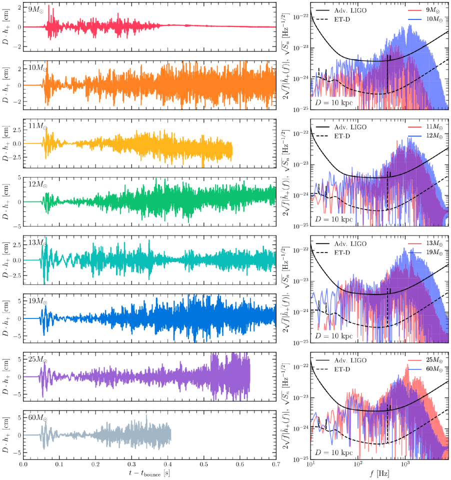



Signals and spectra for 3d models of CCSNe. $D = 10\,\mathrm{kpc}$. Radice et al. (2019)

# Non-rotating CCSNe

## PNS oscillations

- PNS, close to hydrostatic structure, admits a large spectrum of oscillations with pressure ($p$-modes) or gravity ($g$-modes) as restoring forces
- frequencies can be determined by WKB and can be expressed as functions of $M, R, (\ldots)$ of the PNS
- start at few 100 Hz and increase as PNS accretes mass and contracts
- not all possible modes are actually excited
- excitation mechanism: downflows or PNS convection? 2d-3d dichotomy?

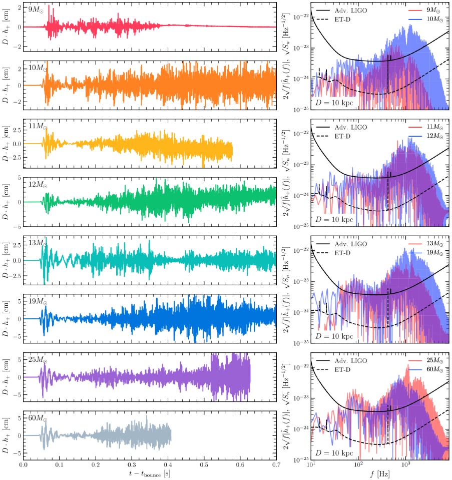



Signals and spectra for 3d models of CCSNe. $D = 10\,\text{kpc}$. Radice et al. (2019)

# Non-rotating CCSNe

## Explosion

- more or less aspherical shock expansion with a shape that varies only slowly
- low-$f$ signal (memory effect)
- weaker signals than before explosion

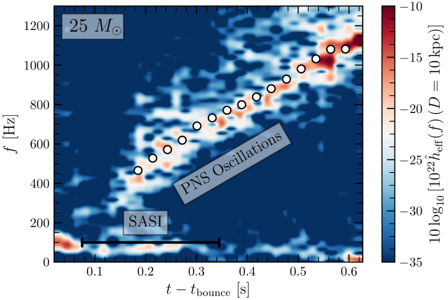



Signals and spectra for 3d models of CCSNe. $D = 10\,\mathrm{kpc}$. Radice et al. (2019)

# Non-rotating CCSNe

## Spectrogram

- LF band coming from SASI
- HF ridge from PNS oscillation modes

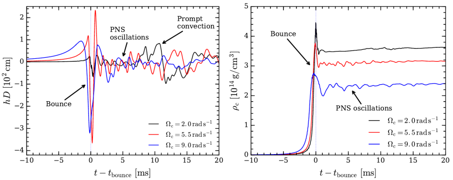



Radice et al. (2019)

# Rotating case

## Bounce signal

- fast rotation deforms the PNS at bounce oblately
- → axisymmetric oscillation with varying quadrupole moment
- bounce signal stronger for faster rotation
- but rapid rotation may stabilise via $\partial_r j > 0$ PNS convection
- could be used to constrain core rotation




Abdikamalov et al. (2014)

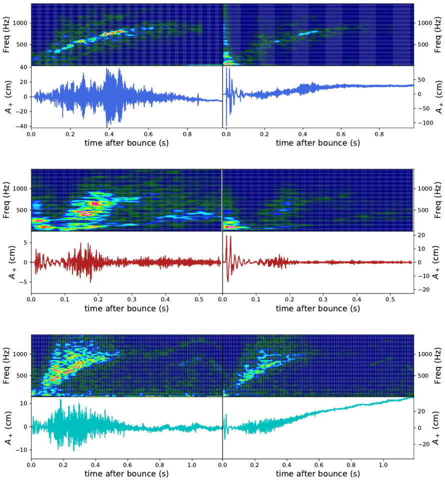
# Rotating case

## PNS oscillations

- stabilisation by positive angular-momentum gradient
- additionally, rotation can puff up the PNS

→ lower frequencies (Jardine et al., 2022)

- but: differential rotation in the progenitor can counteract this effect (Powell & Müller, 2020)

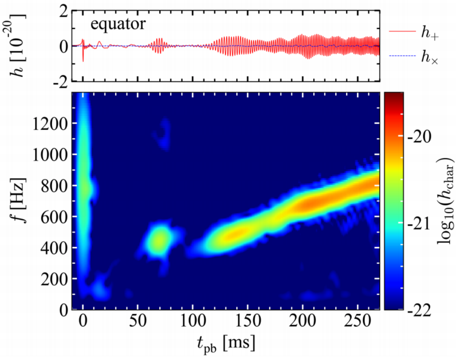



Powell & Müller (2020). Top model rotates rapidly, bottom two non-rotating.

# Rotating case

## Hydro instabilities

- (too) extreme rotation: non-axisymmetric bar-mode instability. Not tremendously relevant in CCSNe.
- low-$T/|W|$ instability at more moderate rotational energy
- corotation point
- formation of $m = 1, 2$ modes
- reflected in the GW emsision




Shibagaki et al. (2020). GW emission of a rotating core.

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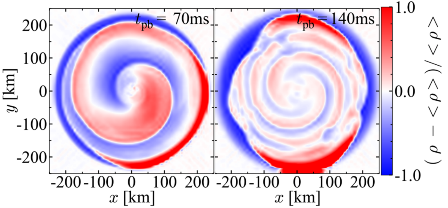
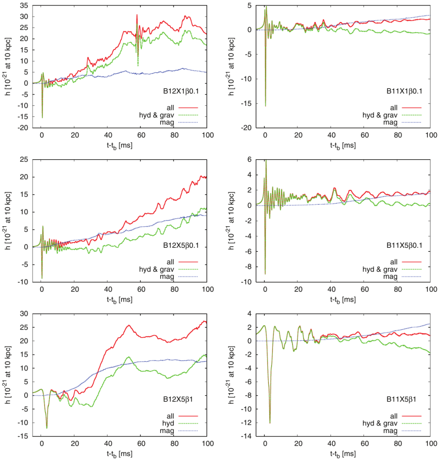



Shibagaki et al. (2020). Equatorial density distribution of a rotating core.

# Rotation and magnetic fields

## Early signal

- impact on dynamics and GW signal only for extreme field strength
- reduction of PNS rotation speed
- early jet formation → memory signal

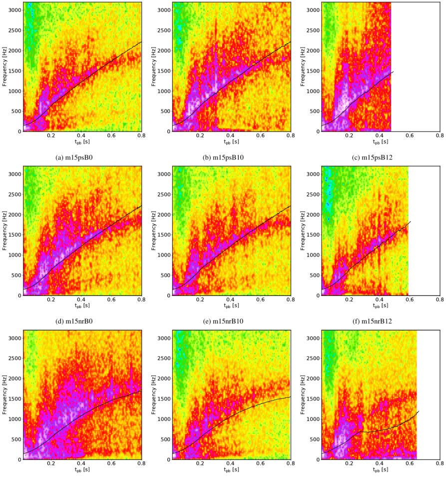



Takiwaki & Kotake (2011)

# Rotation and magnetic fields

## Long-time emission

- basically similar features as in (rotational) core collapse
- wide-band component around/above PNS oscillation modes
- jet tails more common than without magnetic fields
- ¿jittering jets? Several slowly varying tails? But have to wait for them to be found in simulations...



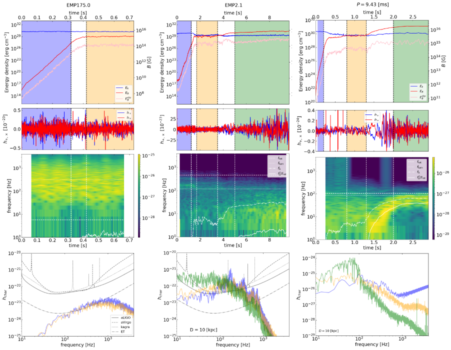

(a) m15psB0 (b) m15psB10 (c) m15psB12
(d) m15nrB0 (e) m15nrB10 (f) m15nrB12
(g) m15afB0 (h) m15afB10 (i) m15afB12

Jardine et al. (2022)

# Rotation and magnetic fields

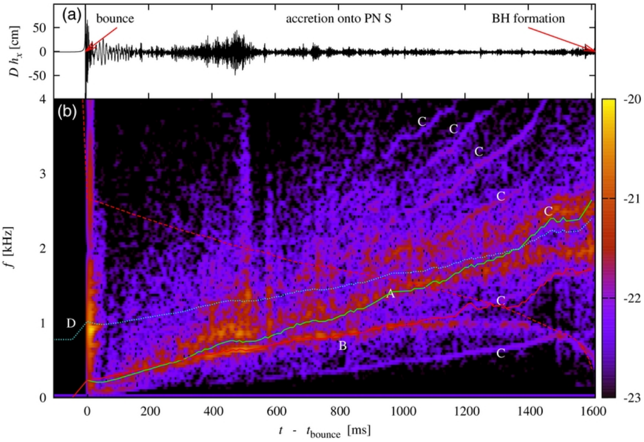
## PNS dynamo

- convection in PNS + rotation → (large-scale) dynamo
- small-scale/large-scale dynamos produce different GW signals
- feature with rising $f$ as large-scale dipole field is generated




Raynaud et al. (2022)

# Rotating BH formation

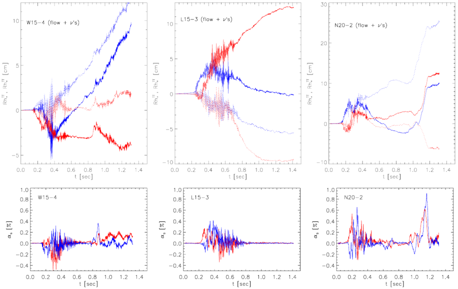



Cerdá-Durán et al. (2013): GW signal and spectrogram for an axisymmetric star with $35\,M_\odot$ collapsing to a BH.

# GWs from neutrinos

## Asymmetric $\nu$ emission

- anisotropic propagation of neutrinos $\rightarrow \ddot{Q} \neq 0$
- $h(t_1) \propto \int_{-\infty}^{t_1} \mathrm{d}t \alpha_\nu(t) L_\nu(t)$, where $\alpha_\nu$ quantifies the deviation from spherical emission
- $\int \mathrm{d}t \rightarrow$ memory effect
- an LF component of potentially very high amplitude




Müller et al. (2012)

# LVK SN searches: what can I know?

**Commemorating Immanuel Kant's 300th birthday**

Experience without theory is blind, but theory without experience is mere intellectual play.

# LVK SN searches: what can I know?

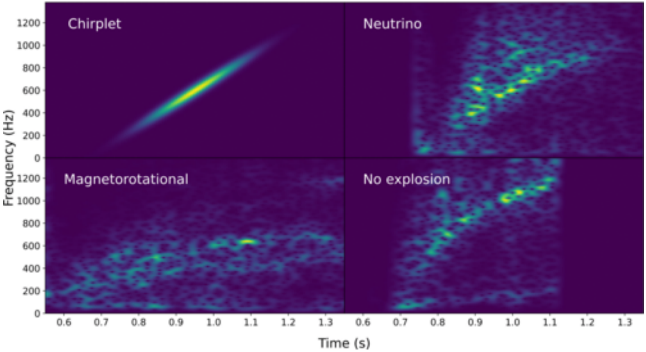
- Detection
- Parameter inference

- use GW signal as an early warning trigger
- detectors are trying to work as continuously as possible (though duty cycle is $< 100\&$)
- send alerts to neutrino, em observers
- merger events: poor sky localisation is a problem for follow-up. SNe: probably less so due to their high brightness.

# LVK SN searches: what can I know?

- Detection
- Parameter inference

explosion mechanism (e.g., Powell et al., 2024)



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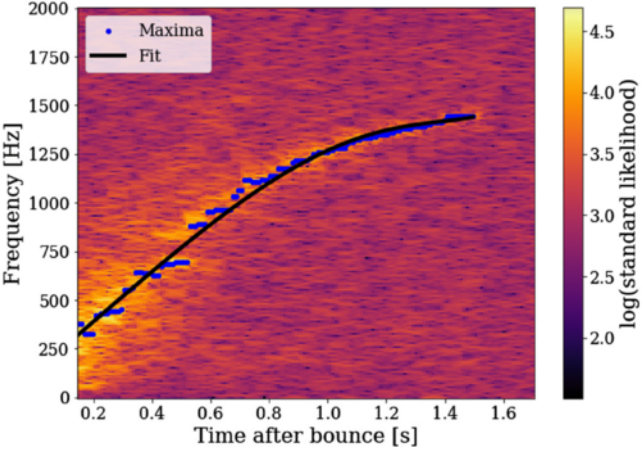
Bruel et al. (2023)

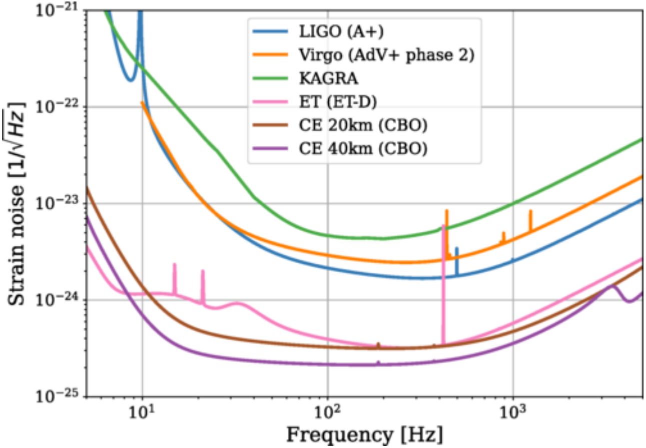


# LVK SN searches: what ought I do?

What can I know?

- Build a detector (network)
- write analysis pipelines

Bruel et al. (2023)



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Bruel et al. (2023)

| Waveform | HL | HLV | HLVK | HLVA | HLVKA |
|---|---|---|---|---|---|
| s15-3De | 0.63 | 0.77 | 0.77 | 0.90 | 0.98 |
| s15-3Dp | 0.67 | 0.85 | 0.77 | 0.92 | 0.94 |
| s11 | 0.52 | 0.65 | 0.65 | 0.81 | 0.81 |
| s15 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| s15S | 0.96 | 0.98 | 0.98 | 1.0 | 1.0 |
| s15G | 0.96 | 0.98 | 1.0 | 1.0 | 1.0 |
| s20 | 0.88 | 0.94 | 0.98 | 0.98 | 1.0 |
| s20S | 0.60 | 0.73 | 0.75 | 0.90 | 0.90 |
| s25 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |
| s40 | 1.0 | 1.0 | 1.0 | 1.0 | 1.0 |

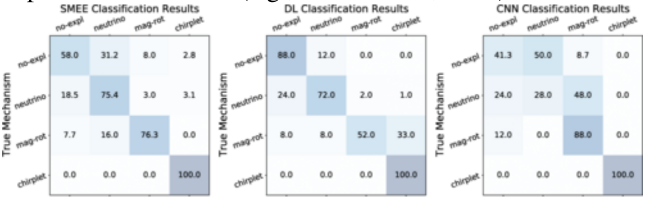
TABLE IV. Fraction of the coverage greater than 0.8 for arrival times of the GWs spanning a 24-hour period with different network configurations. For each arrival time and each network configuration the CCSN is simulated at the center of the Milky Way (RA=$17^{h}45^{m}$, dec=$-29^{\circ}00'$, d=8.2 kpc).

# LVK SN searches: what ought I do?

What can I know?

- Build a detector (network)
- write analysis pipelines

explosion mechanism (e.g., Powell et al., 2024)



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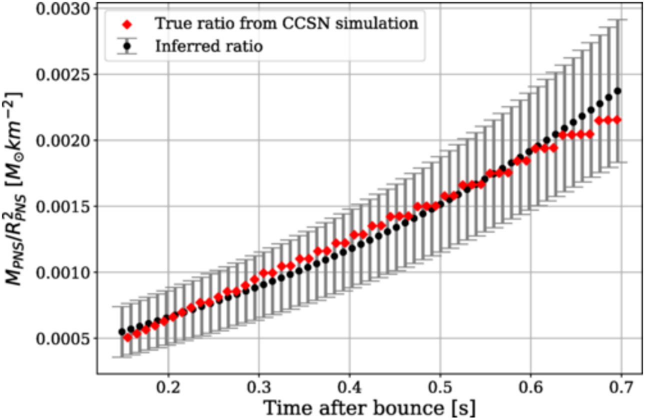
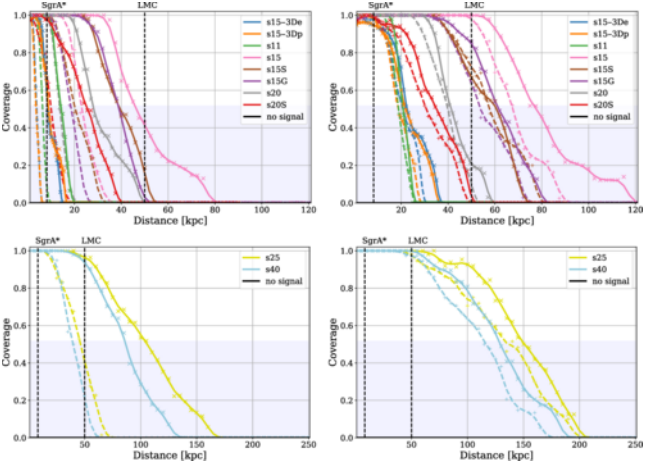
Bruel et al. (2023)



# LVK SN searches: what may I hope?

- Distance range for PE
- Results of O3 search

Bruel et al. (2023)



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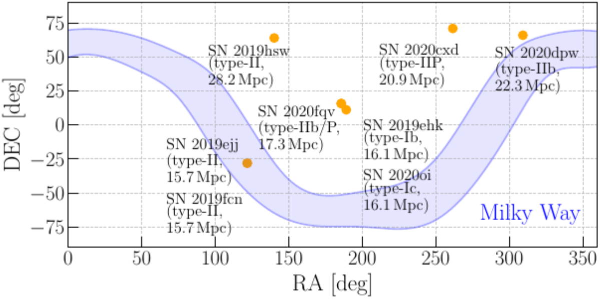


FIG. 1. Sky locations of CCSNe analyzed in this paper. All were recorded within 30 Mpc during the third observing run of LIGO, Virgo, and KAGRA.

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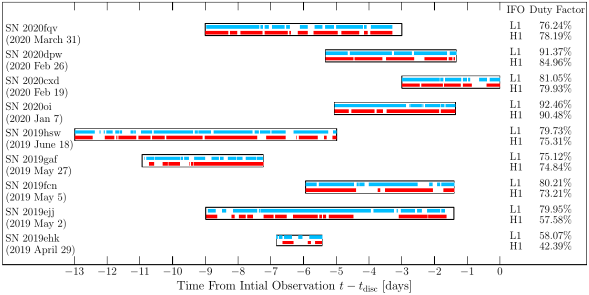

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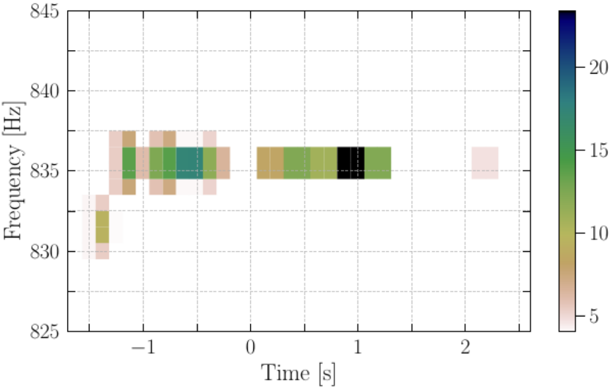

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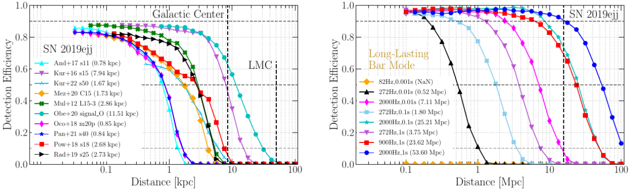

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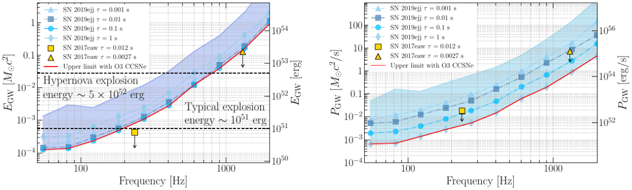

# LVK SN searches: what is the human being?

**Kant**

Space and time are the framework within which the mind is constrained to construct its experience of reality.

# Summary

- GW detection should be possible for galactic SN, with rotation beyond the MW
- features such as PNS oscillations in the right frequency range
- interpretation of signal, in particular with rotation and magnetic fields, more difficult than merger chirps due to stochasticity
- long-term simulations can show features, production of templates limited
- detection and parameter analysis techniques are maturing $\rightarrow$ a nearby event would be very much appreciated to go beyond the current upper limits