Detecting Gravitational Waves from Galactic and extra-Galactic Core-Collapse Supernova

Marek Szczepańczyk
Department of Physics, University of Warsaw

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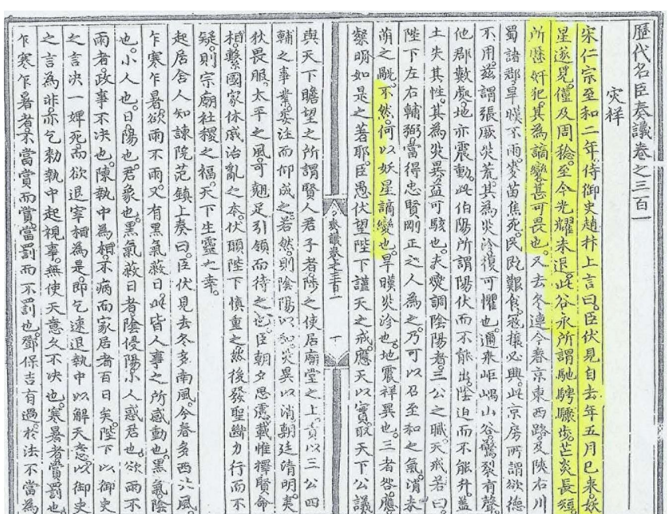
Outline

- Core-Collapse Supernova
  - Introduction
  - Gravitational Waves
- GW burst searches
  - Types
  - Low-latency
  - Optically targeted
  - Parameter Estimation

Core-Collapse Supernova

ancientpages.com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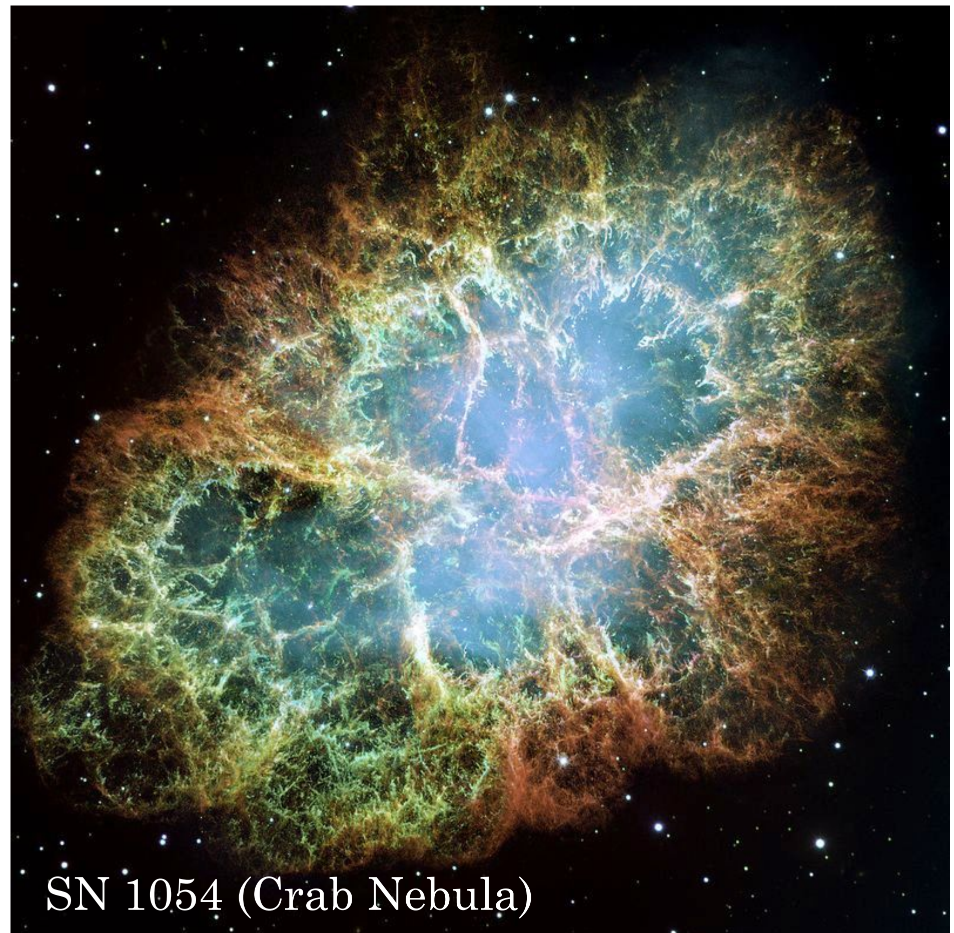
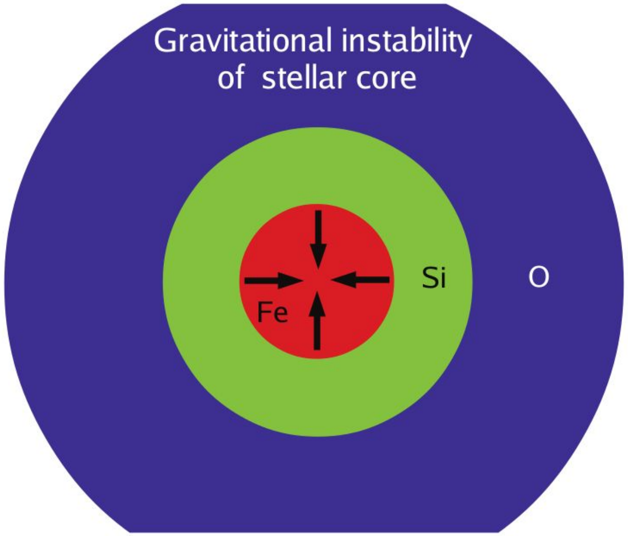
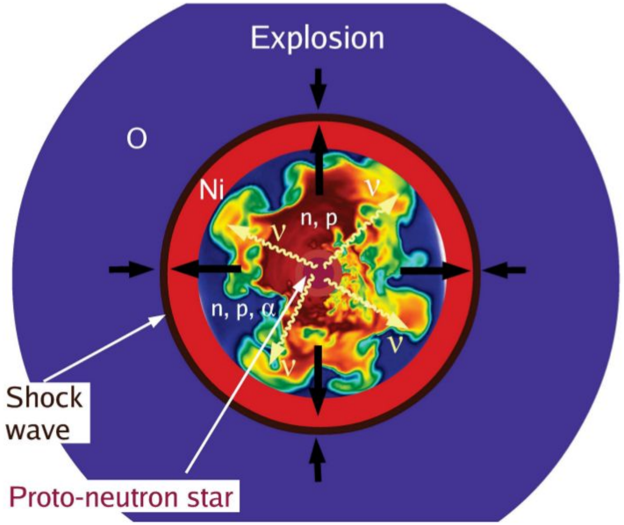
Nova on the sky!

1-2 per century in Milky Way (?)



Core-Collapse Supernova



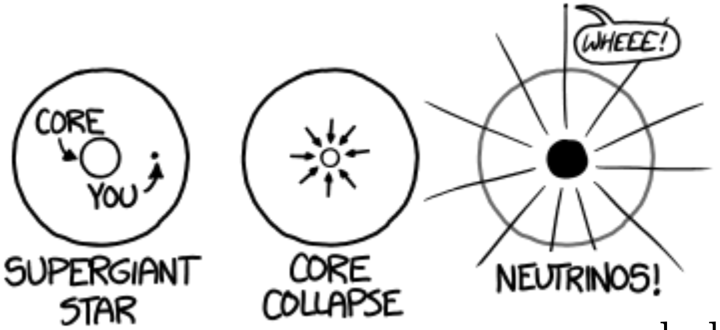


Janka+12

- Burning of the star: H → He → … → Fe
- Before collapse: Fe core of size 1000-2000 km
  After collapse: "nucleus" core of size ~50 km
- Energy available ~ 3×10^{46}J (~ 0.15 $M_\odot c^2$)
  Energy observed ~ 3-10 × 10^{44}J
- 99% of explosion energy escapes with neutrinos!

$$p + e^- \rightarrow n + \nu_e$$

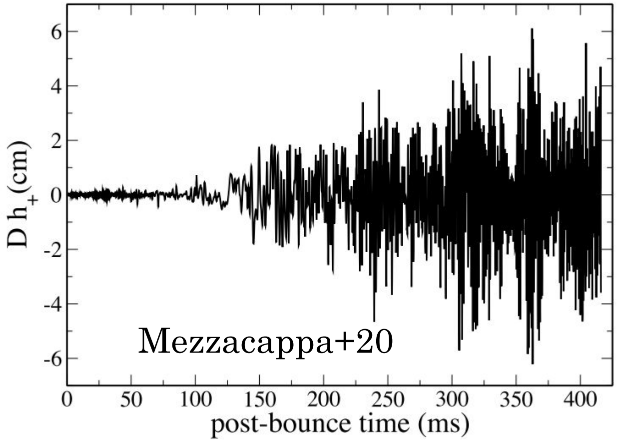
- Century-old "supernova problem":
  Why do massive stars explode?
- Gravitational-waves and neutrinos are the only signals that can help us to solve this problem.

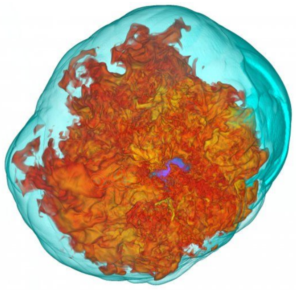


xkcd.com

CCSN explosions

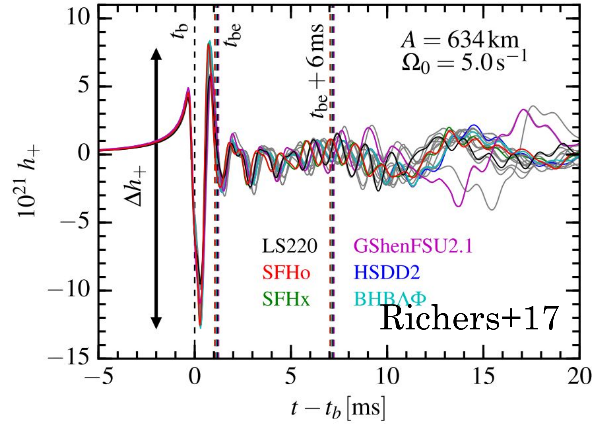
Neutrino-driven mechanism

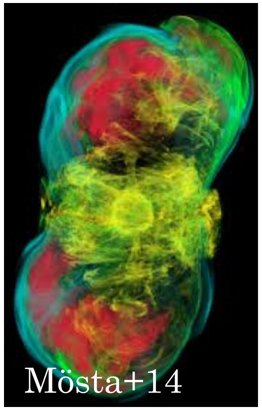




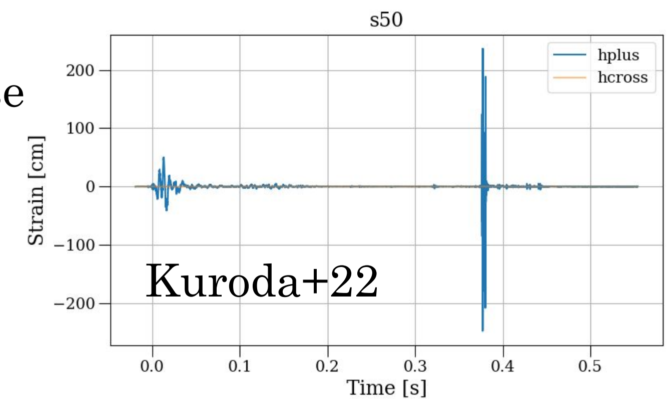
Couch+16

Magnetorotational-driven mechanism

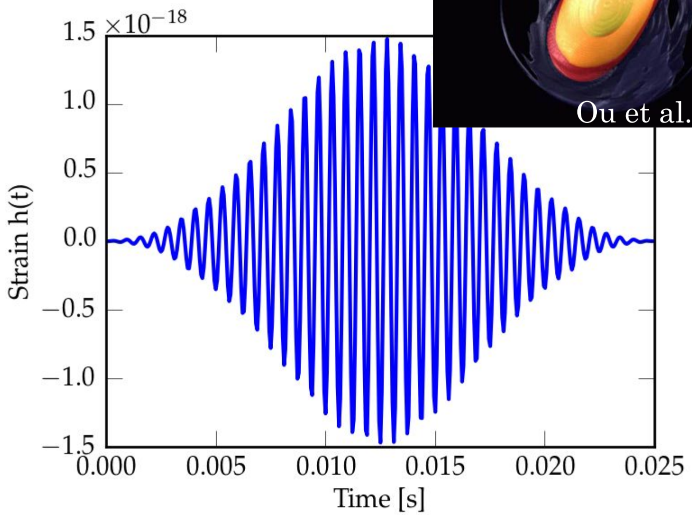




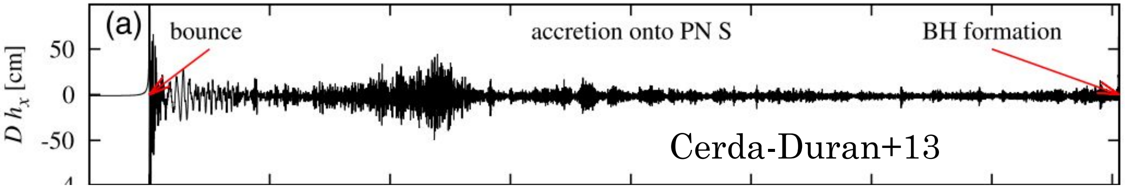
QCD Phase Transition



Extreme Emission

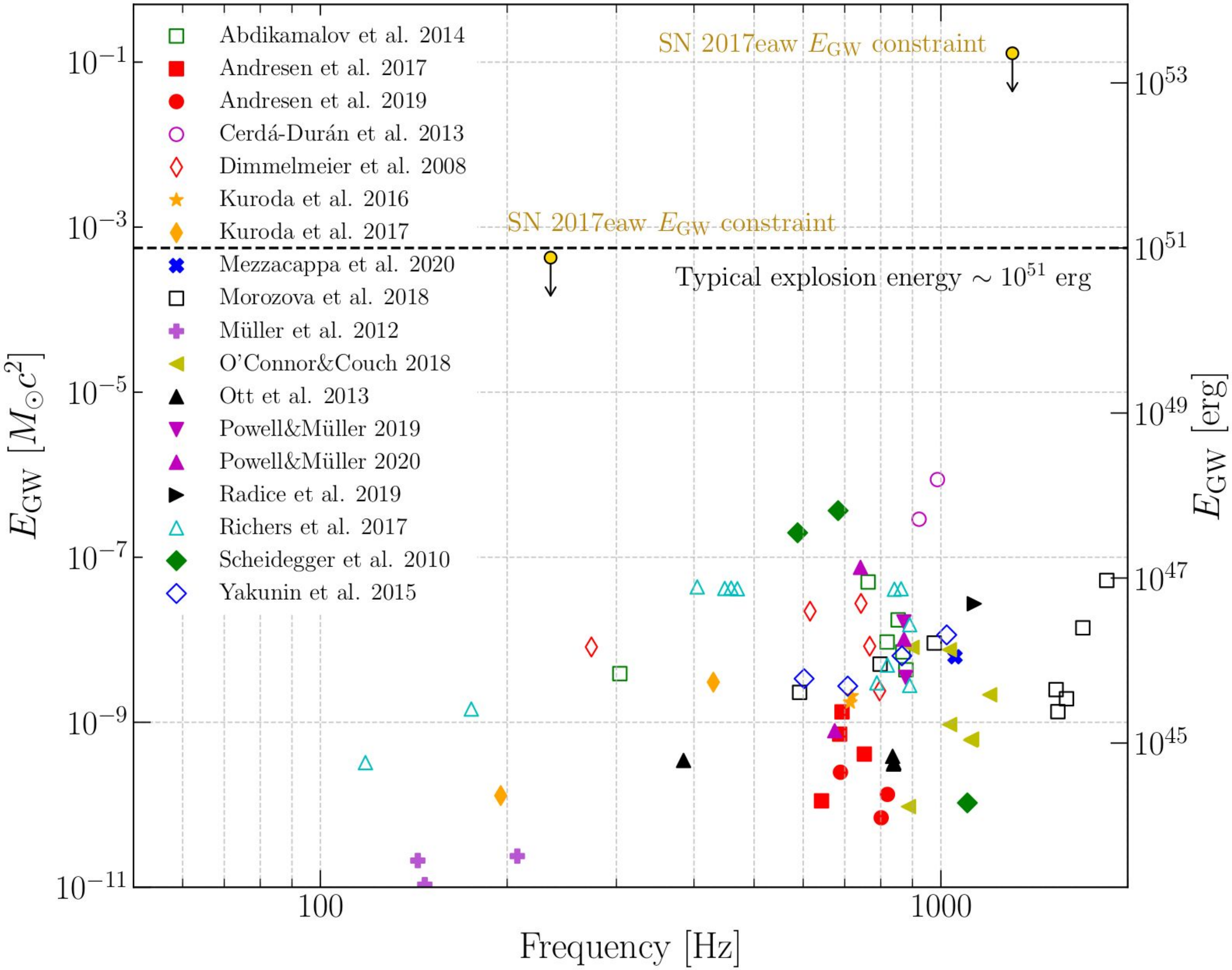


Black hole formation



Core-Collapse Supernova Properties

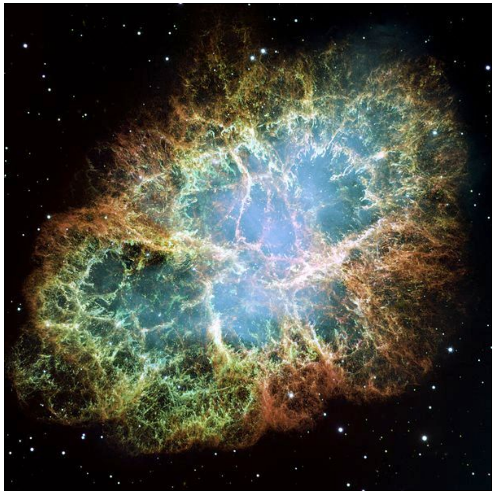
Szczepanczyk et al 2021 (2104.06462)



GW searches

- Searches:
  - **Model-dependent (template based):** binary black holes (BBH), binary neutron stars or binary black hole - neutron star
  - **Model-independent (template-independent) or "burst":** for example core-collapse supernovae, strings, as well as regular or special binaries, such as heavy/eccentric BBHs
- GW sources:
  - "Vanila", e.g. stellar-mass BBHs
  - **Exceptional! -> Core-Collapse Supernova**
- Latency of GW detection:
  - **Low-latency**: rapid (within seconds to minutes) identification of the GW sources and preliminary validation (within hour) for quick astronomical follow-up.
  - **Offline**: identification of GWs after data acquisition, weeks or even years.

Image: NSF/LIGO/Sonoma/A. Simonnet



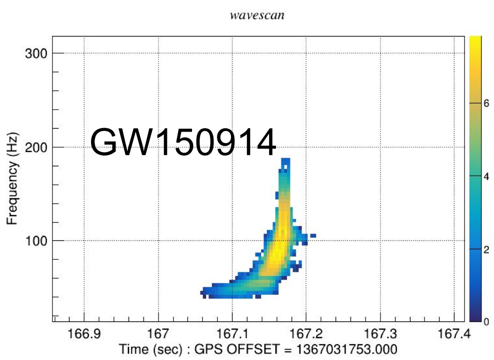
Crab Nebula

Model-independent searches

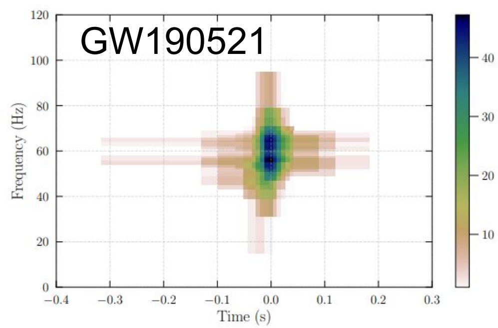
Compact binary searches (minimally modeled)

Generic searches (unmodeled)

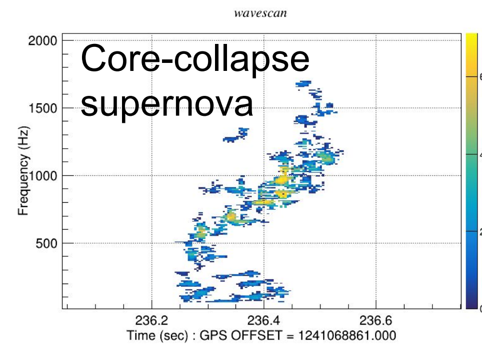
Binary black holes
Binary neutron stars
Black hole - neutron star



Binaries with eccentric orbits
Intermediate-mass black holes
Hyperbolic encounters
Extreme mass-ratio



Core-collapse supernovae
Pulsar glitches
Cosmic strings
Unknown



Low-latency searches

Public alerts for multi-messenger observations: electromagnetic, cosmic rays, and neutrino

Searches for new phenomena

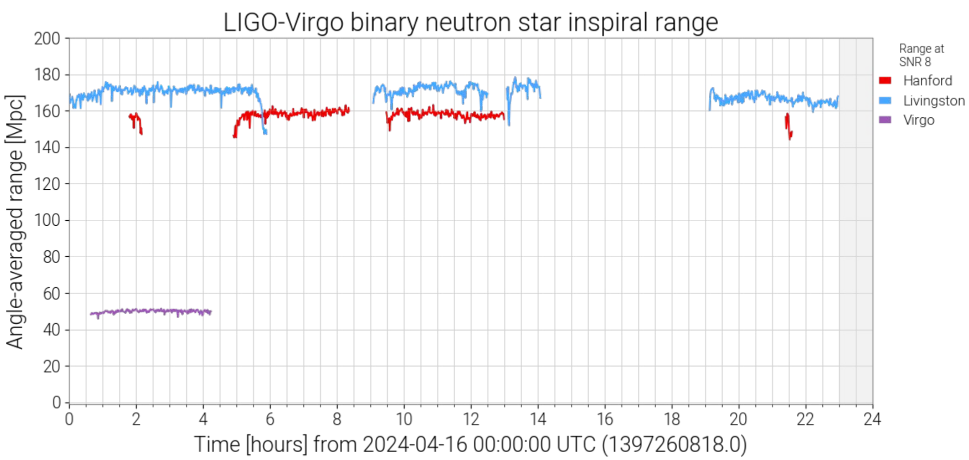
CCSN Parameter Estimation:
Proto-neutron star evolution, shock properties, rotational rate etc.

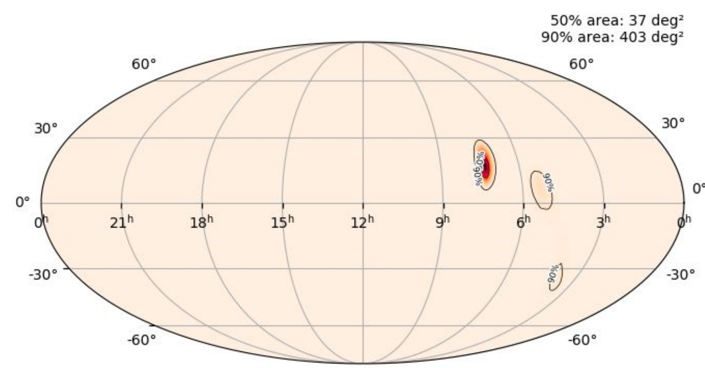
O4 and low-latency searches

- O4: 20 months total, until Feb 2025
- GW candidates: 81 (O4a, 3 per week) and 2 (O4b so far)
- BNS ranges: 155-175 Mpc (LIGO), 55-60 Mpc (Virgo)
- Public alert for GW bursts (cWB, oLIB):
  - False Alarm Rate, sky localization (cWB),
  - “Fluence” (~luminosity), peak frequency, duration

Useful resources:

- https://gracedb.ligo.org/superevents/public/O4/
- https://emfollow.docs.ligo.org/userguide/
- https://wiki.gw-astronomy.org/OpenLVEM
- https://gwosc.org/detector_status/
- https://observing.docs.ligo.org/plan/
- https://online.igwn.org/





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Optically Targeted searches

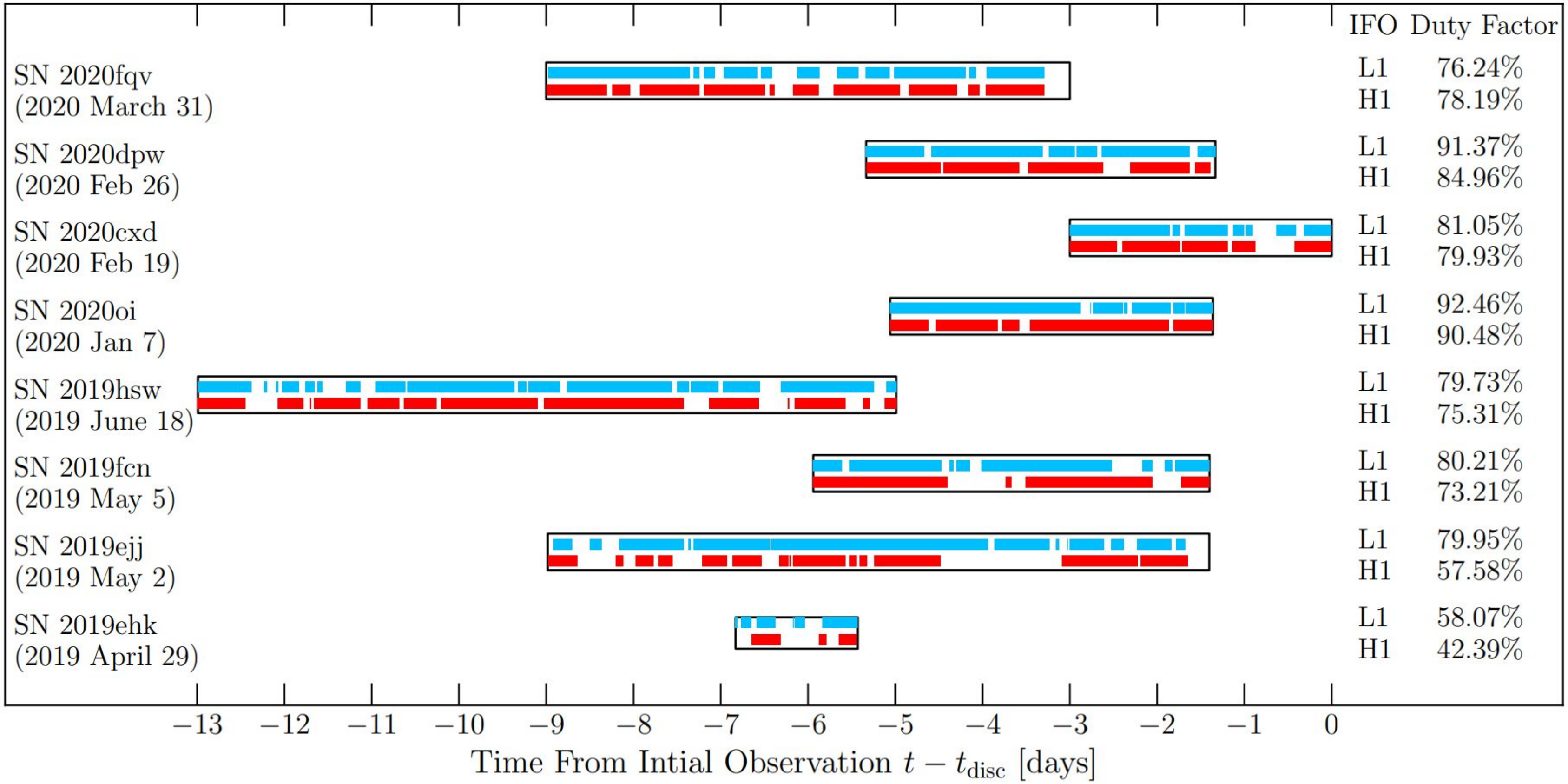
While waiting for the Galactic event, we search for GWs from extra-Galactic CCSNe (targets).

O1-O2 data (5 CCSN up to 20 Mpc, [1908.03584]):

- First constraints of CCSN engine

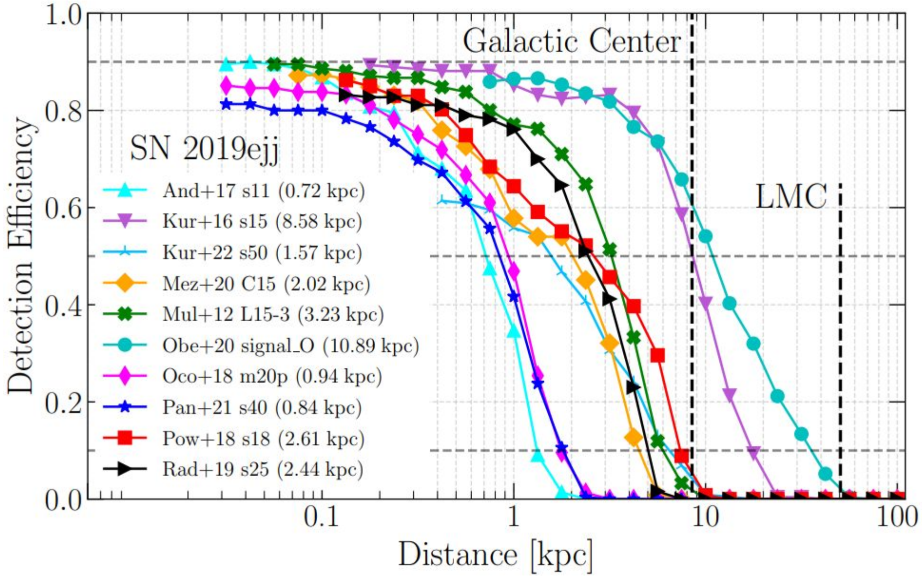
O3 data (9 CCSN up to 30 Mpc, [2305.16146]):

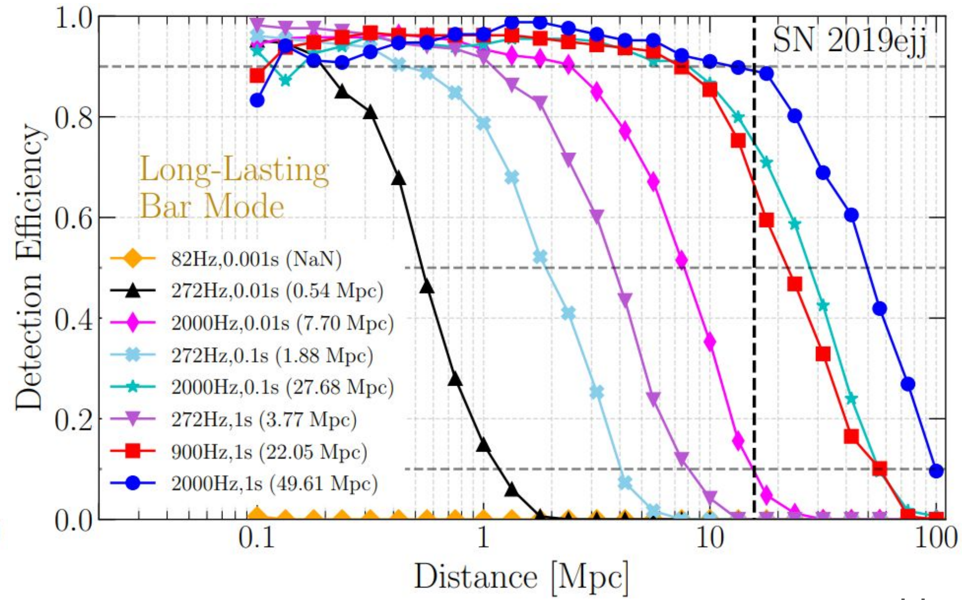
- First upper limits on GW power and ellipticity
- Continuation of constraining extreme emission models



O3 Optically Targeted search
(Szczepanczyk et al. 2023)

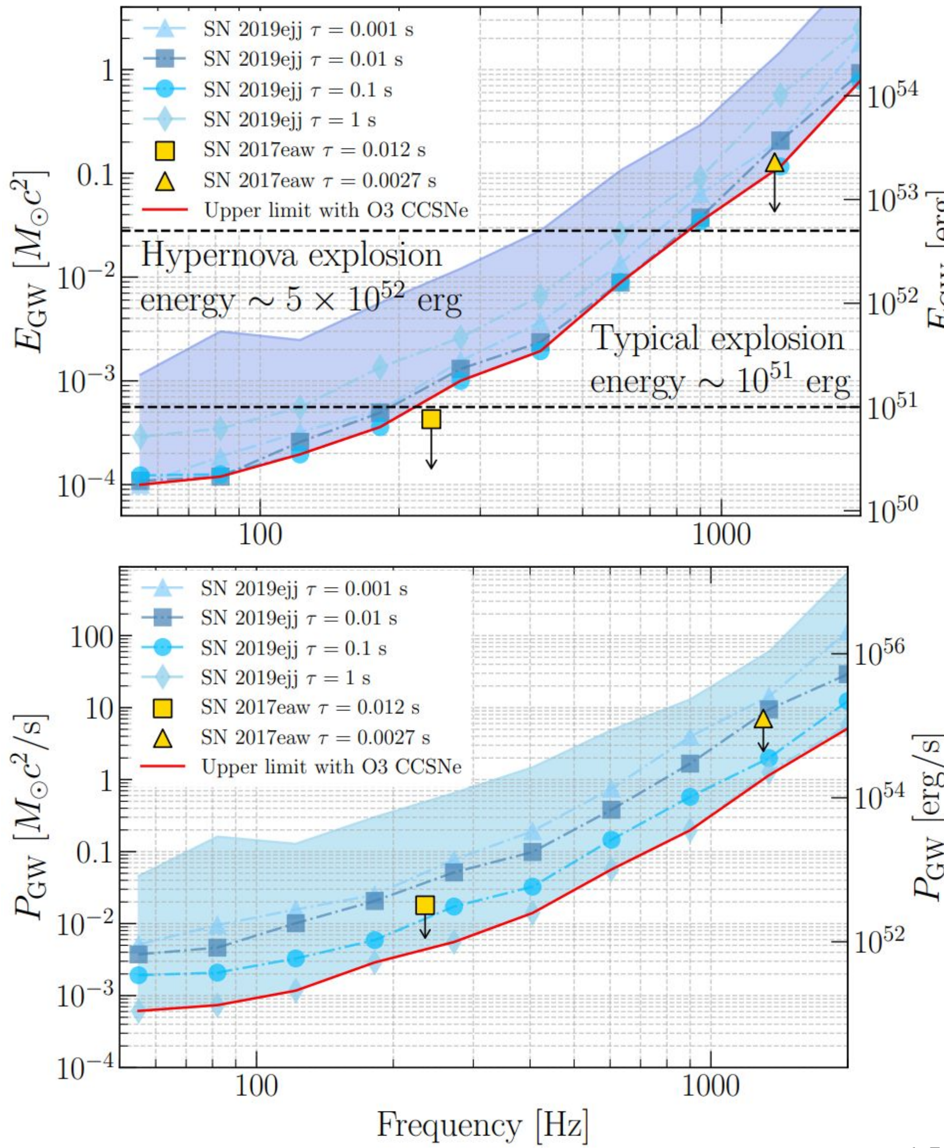
- No GW detection so far
- Most significant event for SN 2020fqv: 2.8 sigma significance
- Detection range: distance at 50% detection efficiency
  - Neutrino-driven explosions: up to 13.7 kpc
  - Magnetorotationally-driven explosions: up to 15.9 kpc
  - QCD phase transition: up to 2.1 kpc
  - Black hole formation: up to 0.8 kpc
  - Extreme emission models: several Mpc





O3 Optically Targeted search
(Szczepanczyk et al. 2023)

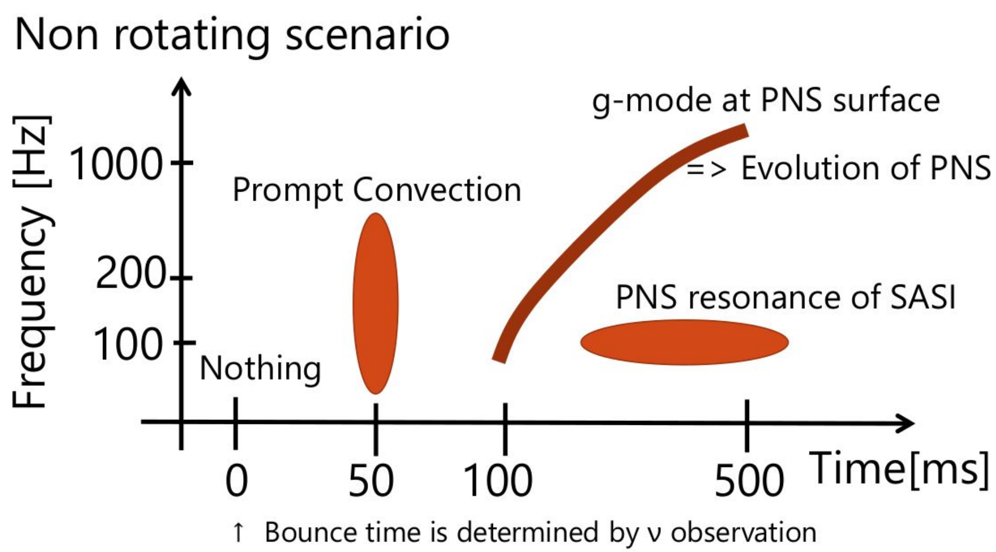
- Extensive constraints of the CCSN engine.
  - Assuming monochromatic (narrowband) emission
- GW energy constraints
  - Isotropic emission
  - Stringest: **$1x10^{-4}\ M_{\odot}c^2$**
- GW power (luminosity) constraints
  - First observational constraints
  - Stringest: **$5x10^{-4}\ M_{\odot}c^2/s$**



Parameter Estimation

Recently a lot of efforts to extract physical parameters from CCSN. See review in Mezzacappa&Zanolin+24 (2401.11635), examples:

- Proto-neutron star (PNS) evolution: Casallas-Lagos+23 (2304.11498), Bizouard+21 (2012.00846),
- Equation of State: Edwards+21 (2009.07367),
- SN kicks (GW memory): Richardson+21 (2109.01582)
- Standing Accretion Shock Instability: Takeda+21 (2107.05213)
- PNS rotation: Chan+21 (ADS), Hayama+18 (1802.03842)
- Rotation properties: Pastor-Marcos+23 (2308.03456), Villegas+23 (2304.01267)



Credit: Takiwaki

Summary

- Core-Collapse Supernova
  - "Supernova problem": why do the stars explode?
  - Gravitational Waves can bring an answer!
- GW burst searches
  - Optically targeted searches: constraining SN engine
  - Parameter Estimation - a lot of effort