Gravitational waves from core-collapse supernovae with strong rotation and magnetic fields

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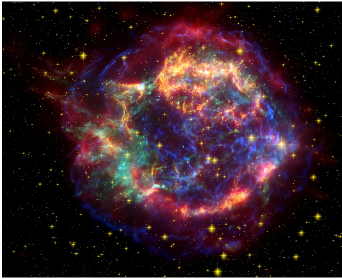
Core-collapse Supernovae

- Gravitational collapse of a massive star (unstable iron core)
- Shock formation when nuclear densities are reached (stalling) $\Rightarrow$ Proto Neutron Star
- Shock expansion and ejection of unbound material (explosion)
- 99% energy loss in neutrinos ($\sim 10^{53}$ erg)
- $\sim 10^{45}$ erg in GW

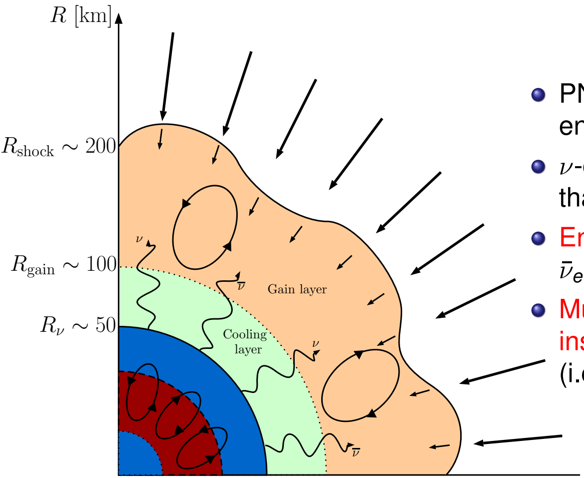


Credit: NASA/JPL-Caltech

Key questions

- How is the shock revived?
- How does the PNS evolve?
- What are the MM signatures?

Standard neutrino-driven CCSN



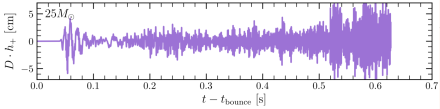
- PNS contraction $\Rightarrow$ higher ν energies
- ν-cooling rate drops faster than ν-heating $\Rightarrow$ Gain radius
- Energy deposition by ν_e and $\bar{\nu}_e$ absorption in gain layer
- Multi-D hydrodynamic instabilities aid the explosion (i.e. convection, SASI)

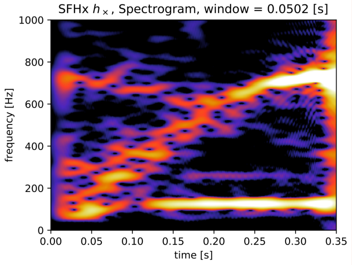
GW signals from standard CCSN

Main features

- Perturbations induced in the PNS
- Highly stochastic
- g/f modes and SASI

Radice et al. (2019)

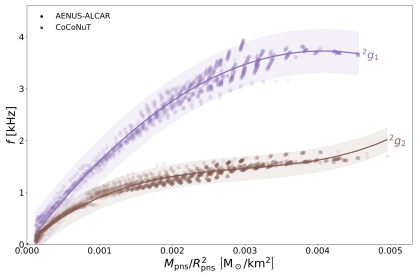




Kawahara et al. (2018)

Asteroseismology

- Universal relations between g/f modes freq. and M_{PNS}, R_{PNS}
- Same in 3D models?
- Other modes?



Torres-Forné et al. (2019)

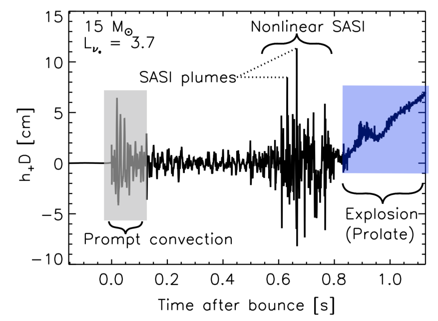
Secondary features

Prompt convection

- 50-100 Hz

Memory

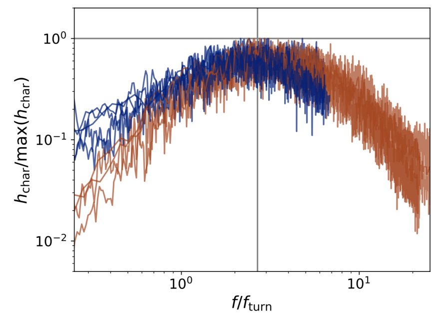
- 1-10 Hz



Murphy et al. (2009)

Long-term convection

- 100-1000 Hz

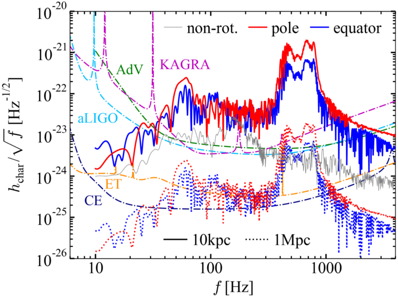


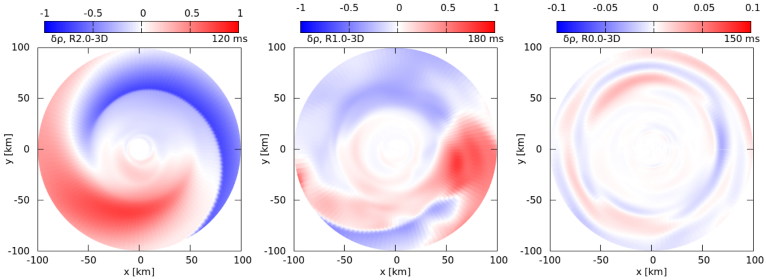
Raynaud et al. (2021)

Corotational instabilities

- Growing non-axisymmetric large-scale modes with fast rotation
- Low $T/|W|$ instability associated to GW emission (Shibagaki et al., 2020; Takiwaki et al., 2021).

Shibagaki et al. (2020)





Takiwaki et al. (2021)

Outstanding explosions and magnetic fields

Explosion kinetic energy

- Typical supernova: 10^{51} erg
- Rare hypernovae and GRBs: 10^{52} erg

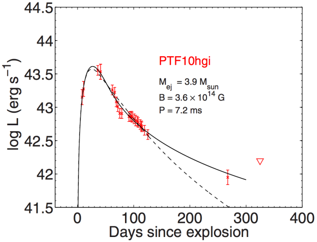
Total luminosity

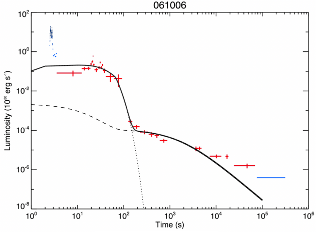
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

Lightcurves and X-ray plateaus

- Strong dipolar magnetic field: $B \sim 10^{14} - 10^{15}$ G
- Fast rotation: $P \sim 1 - 10$ ms
- Kasen and Bildsten (2010); Dessart et al. (2012); Nicholl et al. (2013); Zhang and Mészáros (2001); Metzger et al. (2008); Lü et al. (2015); Gao et al. (2016)

Inserra et al. (2013)

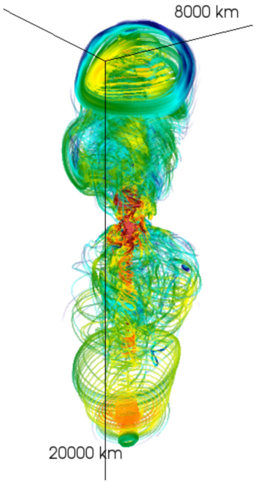




Gompertz et al. (2014)

Impact of strong magnetic fields

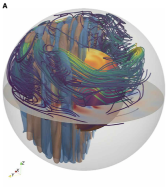
- Rotation ⇒ energy reservoir
- Magnetic fields ⇒ means to extract that energy through magnetic stresses
- Powerful jet-driven explosions (Shibata et al., 2006; Burrows et al., 2007; Dessart et al., 2008; Takiwaki et al., 2009; Kuroda and Umeda, 2010; Winteler et al., 2012; Obergaulinger and á. Aloy, 2017)
- Origin of the magnetic field uncertain:
  - Progenitor?(Woosley and Heger, 2006; Aguilera-Dena et al., 2020)
  - Stellar mergers? (Schneider et al., 2019)
  - PNS dynamo? (Raynaud et al., 2020; Reboul-Salze et al., 2021)



Obergaulinger and Aloy (2021)

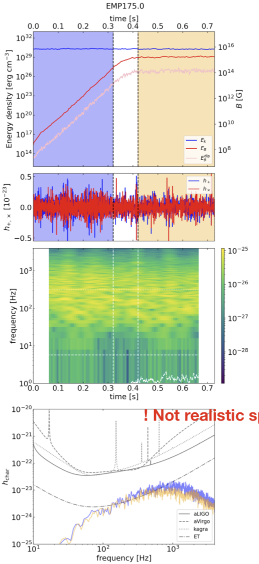
Convective dynamo in PNS (Raynaud et al. 2021, sub. to MNRAS)

P=175 ms

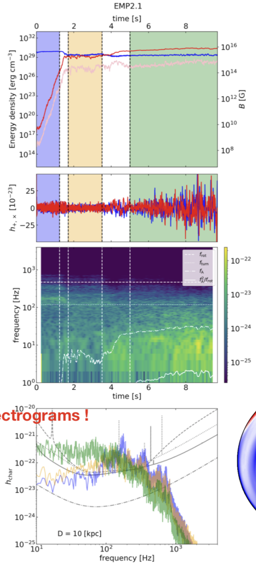


Alpha-omega dynamo

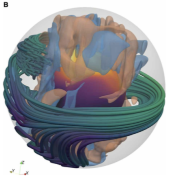
NB: fixed background !



! Not realistic spectrograms !

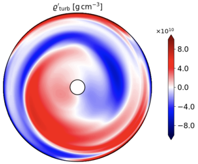


P=2.1 ms



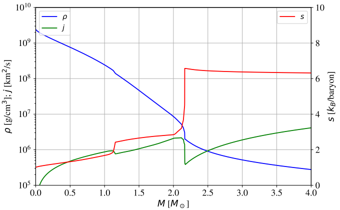
Strong field dynamo

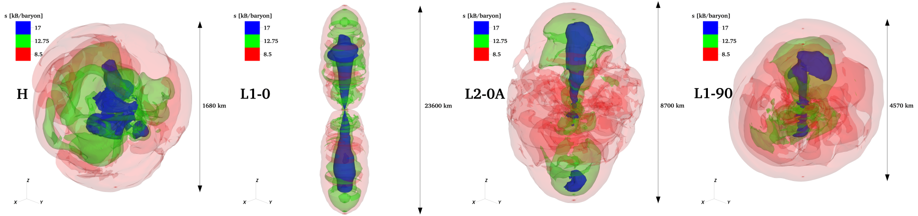
Magnetar formation



3D MHD explosion models (Bugli et al., 2021)

- Stellar progenitor: 35OC (Woosley and Heger, 2006)
- Different magnetic configurations: dipole (aligned and equatorial) or quadrupole
- Qualitative impact on shock dynamics

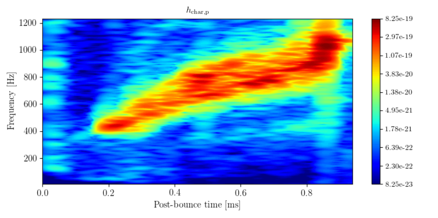


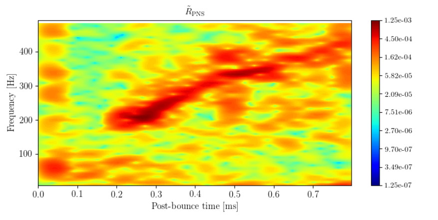


GW signatures

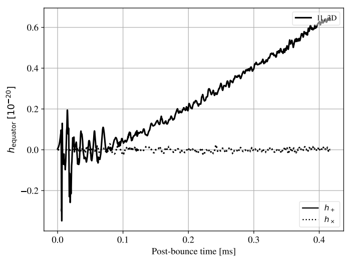
Surface modes of the PNS

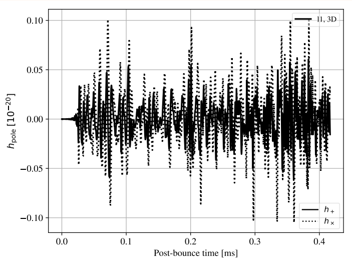
- Strong correlation with $m = 1$ mode in R_{PNS}



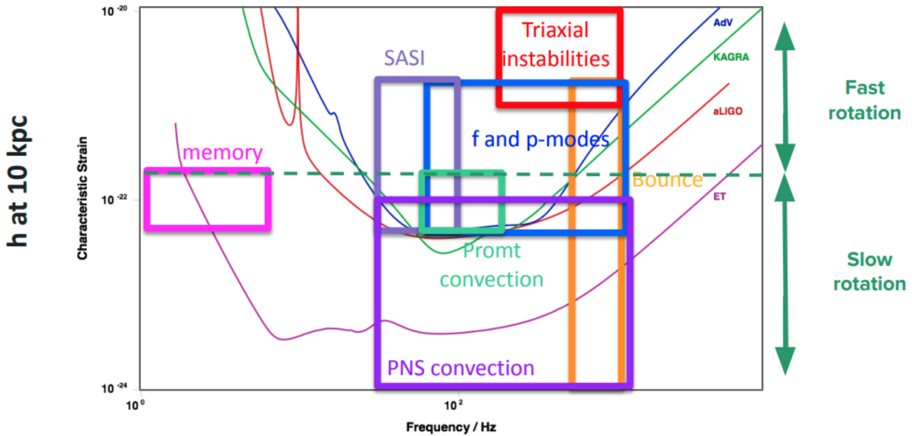


Aligned dipole





Summary of physical sources of GW



Credit: Pablo Cerdà-Duràn

Conclusions

- Both rotation and magnetic fields deeply affects the GW emission
- PNS dynamo action possibly detectable at low frequencies
- Low $T/|W|$ produces high amplitude, connection to corotation period
- Strong magnetic fields might change this scenario

Future goals

- Probe more stellar progenitors
- Identify of possible rotation/B field thresholds
- Understand the fundamental physical mechanisms
- Signal detection (neutrinos quasi-coincidence)

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