Multi-messenger signatures of instabilities in magnetised core-collapse supernovae

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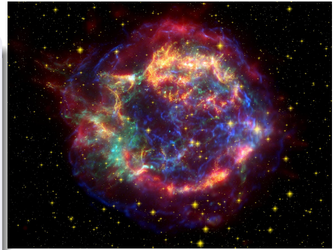
Core-collapse Supernovae

- 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)

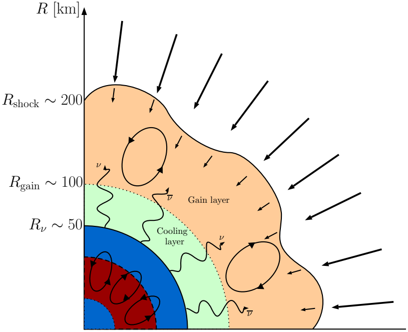


Credit: NASA/JPL-Caltech

Where does the binding energy ($\sim 10^{53}$ erg) end up?

- Neutrino emission ($\sim 99\%$)
- Ejecta ($\sim 1\%$)
- Gravitational waves ($\sim 10^{-8}$)

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)

Neutrinos and GW directly probe the explosion mechanism

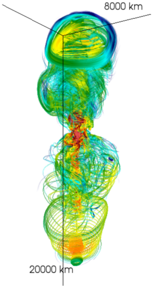
Magneto-rotational explosions

Outstanding stellar explosions

- Kinetic energy $> 10^{51}$ erg (hypernovae, GRBs)
- Total luminosity $> 10^{49}$ erg (superluminous SN)
- Lightcurve's features (e.g. X-ray plateaus)

The magneto-rotational mechanism

- Rotation $\Rightarrow$ energy reservoir
- Magnetic fields $\Rightarrow$ 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; Winteler et al., 2012; Mösta et al., 2014; Kuroda et al., 2020; Obergaulinger and Aloy, 2021; Bugli et al., 2021)

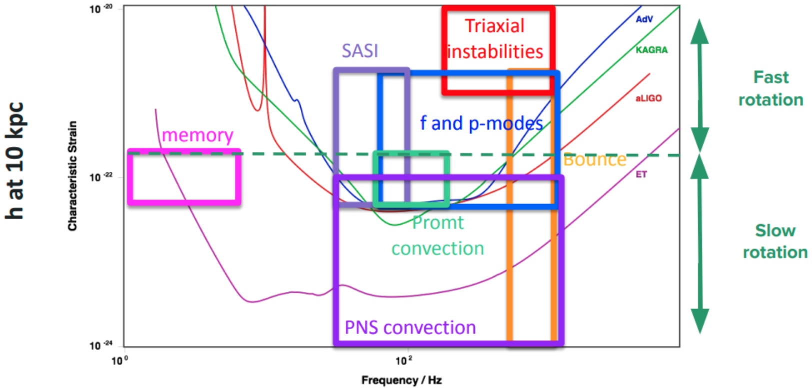


Obergaulinger and Aloy (2021)

Origin of the magnetic field

- Progenitor (Woosley and Heger, 2006; Aguilera-Dena et al., 2020)
- Stellar mergers (Schneider et al., 2019)
- PNS dynamo: convection (Raynaud et al., 2020); MRI (Reboul-Salze et al., 2021, 2022); Tayler-Spruit (Barrère et al., 2022)

Summary of physical sources of GW



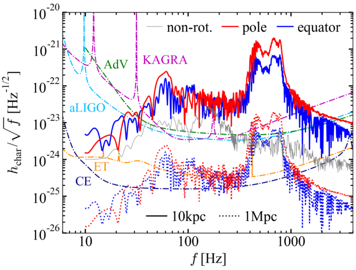
Credit: Pablo Cerdà-Duràn

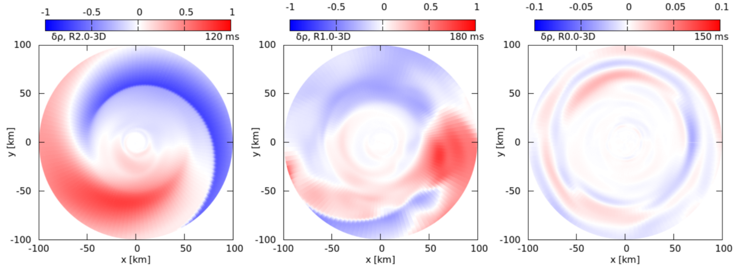
Corotational instabilities

- 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., 2021).

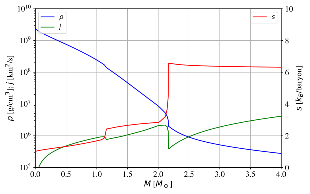
Shibagaki et al. (2020)



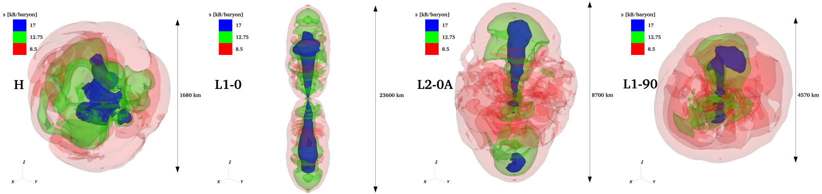


3D MHD explosion models (Bugli et al., 2021)

- 35OC: massive, fast rotating stellar progenitor (Woosley and Heger, 2006)
- Rotation profile from stellar evolution model
- Different magnetic configurations: dipole (aligned and equatorial) or quadrupole (motivated by PNS dynamos; Reboul-Salze et al. (2021, 2022))
- Qualitative impact on shock dynamics

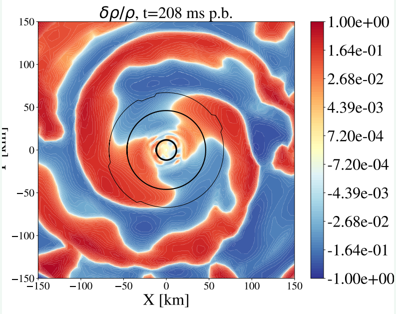


Bugli et al. (2021)



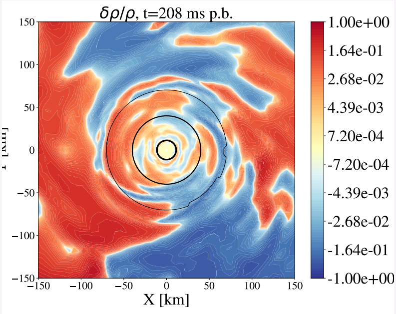
Corotational instabilities (Bugli et al, sub. to MNRAS)

Hydrodynamic case



- Spiral structures forming at ~ 200 ms p.b.
- Observed for different progenitors/rotation profiles (Takiwaki et al., 2016, 2021)

Magnetized case

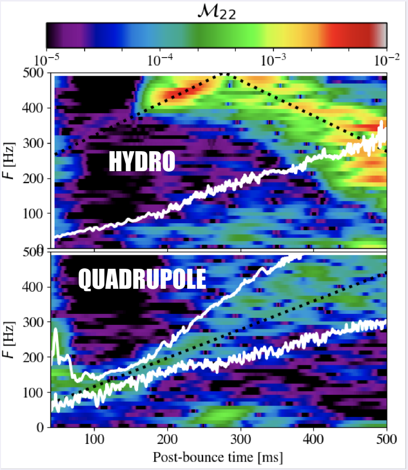


- No spiral structures
- Smaller-scale density perturbations
- Weak dependence on magnetic field

PNS oscillation modes (Bugli et al, sub. to MNRAS)

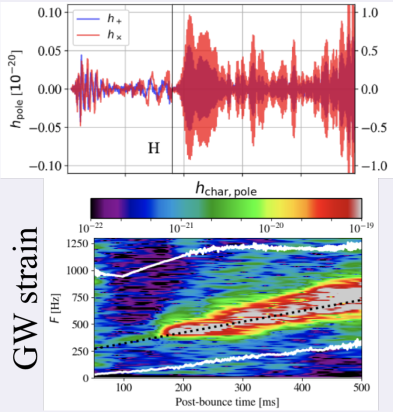
Density modes at 30 km

- Strong $l = 2$ non-axisymmetric mode in the hydrodynamic case
- Weaker mode in magnetized models
- Magnetic transport of AM
- Flat rotation profile $\Rightarrow$ stable against low $T/\|W\|$



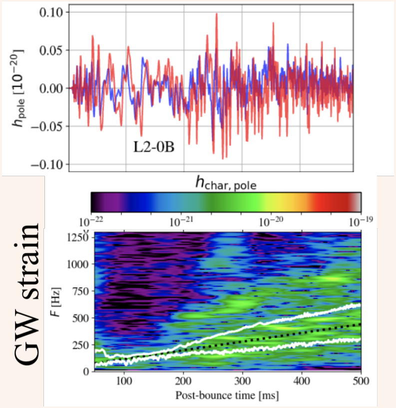
GW emission (Bugli et al, sub. to MNRAS)

Hydrodynamic case



- 400 Hz emission at 200 ms
- $h \sim 10^{-20}$ for $D = 10$ kpc
- Strong correlation with PNS modes

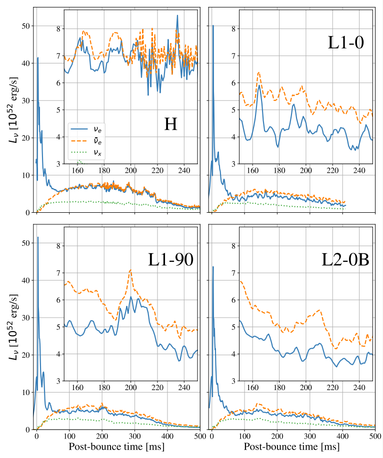
Magnetized case (quadrupole)



- No low $T/|W|$ signal burst
- $h \sim 5 \times 10^{-22}$ for $D = 10$ kpc
- Strong transport of AM

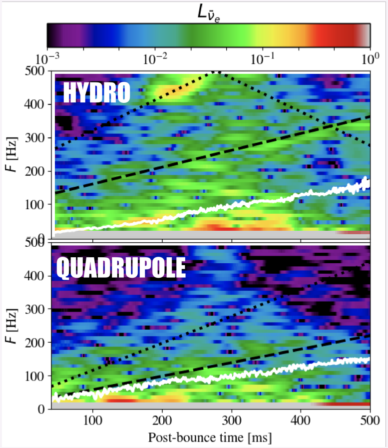
Neutrino emission (Bugli et al, sub. to MNRAS)

Lightcurves (equator)



- Lower luminosity in MHD
- ν_e-$\bar{\nu}_e$ asymmetry

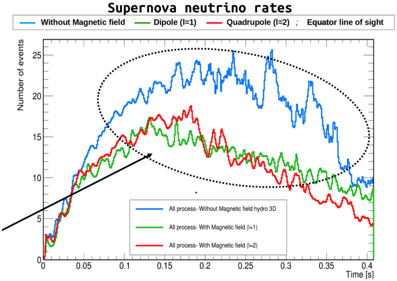
PNS modes signatures

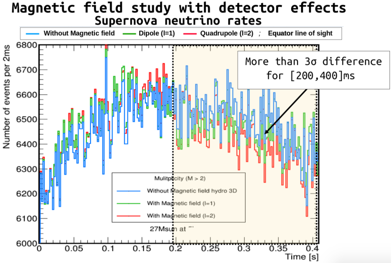


- low $T/|W|$ and SASI signatures

LEAK project

- Detection of neutrino emission from CCSN (1-100 MeV)
- Multi-detector analysis (KM3NeT+DUNE+DarkSide-20k)
- Collaboration members: APC, AIM, LUTh





Bendahman et al. (2022)

Conclusions

- GW open a unique window on the central engine dynamics
- Signatures from hydrodynamic instabilities (convection, SASI, low $T/|W|$)
- Both rotation and magnetic fields deeply affects the GW emission
- Low $T/|W|$ produces high amplitude GW, but quenched by strong magnetic fields
- Important correlations between GW and neutrinos

Future goals

- Impact of weaker magnetic fields
- Dependence on the rotation profile
- Understand the fundamental physical mechanisms

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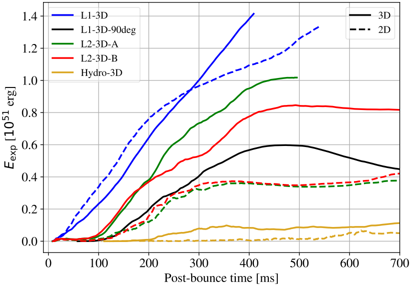
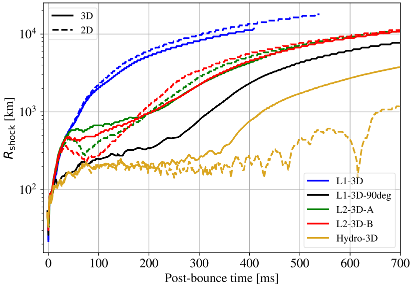
Merci pour votre attention !

BACKUP SLIDES

Explosion dynamics



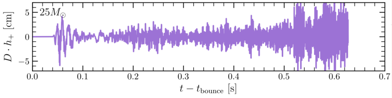


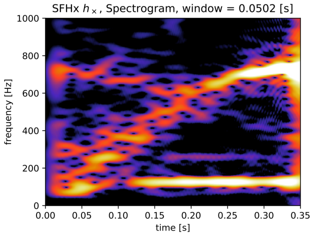
GW signals from standard CCSN

Main features

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

Radice et al. (2019)

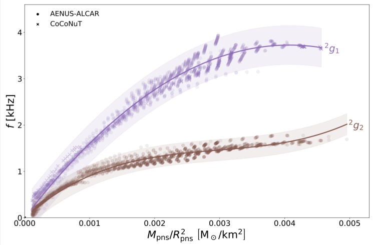




Kawahara et al. (2018)

Asteroseismology

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



Torres-Forné et al. (2019)

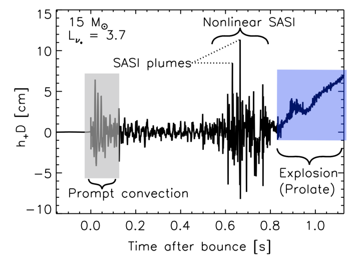
Secondary features

Prompt convection

- Onset due to shock propagation and ν_e burst
- 50-100 Hz

Memory

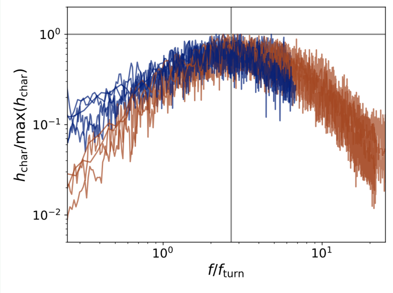
- 1-10 Hz (asymmetric explosions)



Murphy et al. (2009)

Long-term convection

- Lepton-gradient driven PNS convection
- 100-1000 Hz

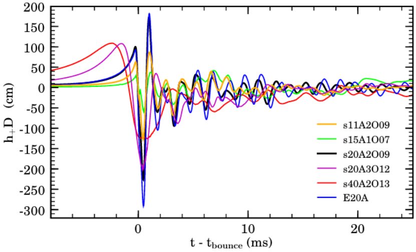


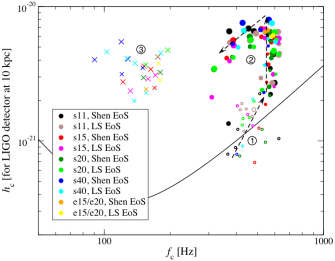
Raynaud et al. (2022)

The impact of rotation

Bounce signal

- Precollapse rotation ⇒ time-varying $l = 2$ deformation of bouncing core
- Most favourable for moderate/rapid rotation ($\Omega_c \in [1 - 10]$ rad/s)



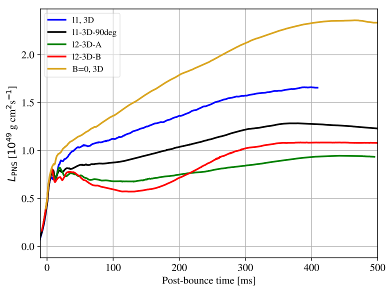


Ott (2009)

Evolution of the PNS rotation (Bugli et al., 2021)

PNS angular momentum

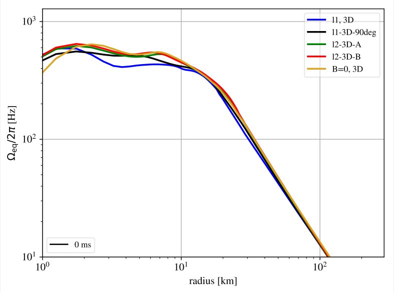
- Magnetic extraction of rotational energy
- More efficient extraction for non-dipolar fields



Angular velocity profile

- Flattened rotation profile 25 km (convective zone)
- Stable configuration against low $T/|W|$

$t = 0$ ms



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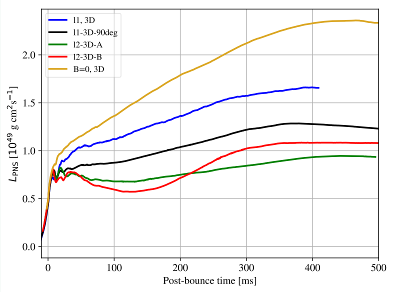
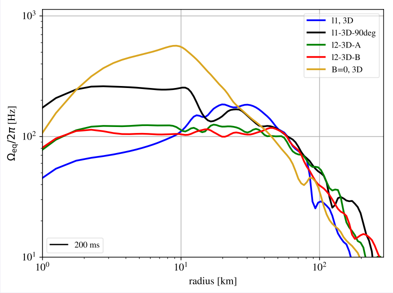


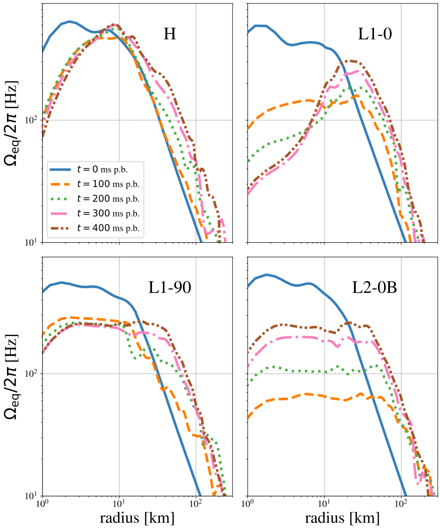
Angular velocity profile

- Flattened rotation profile 25 km (convective zone)
- Stable configuration against low $T/|W|$

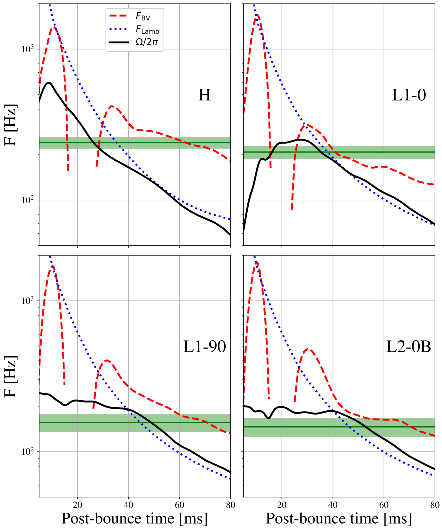
$t = 200$ ms



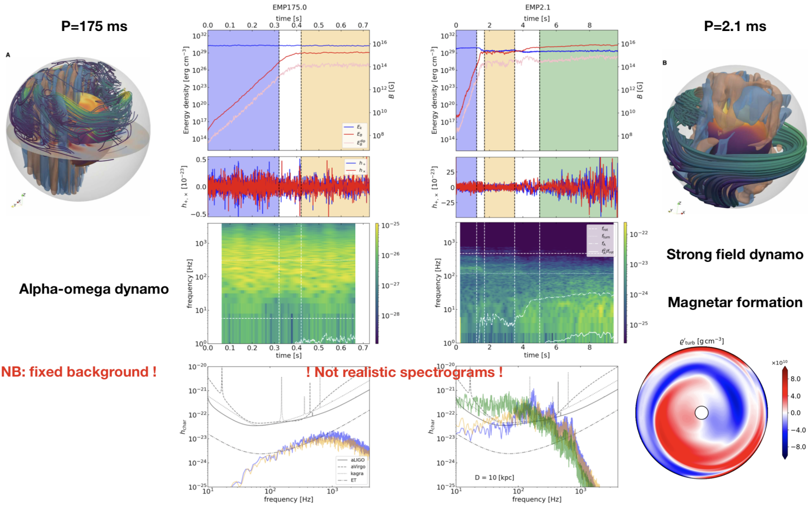
Evolution of Ω



Characteristic frequencies

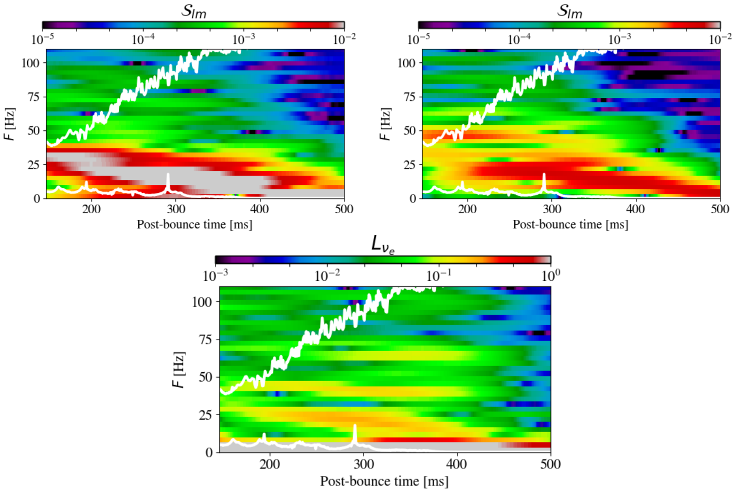


Convective dynamo in PNS

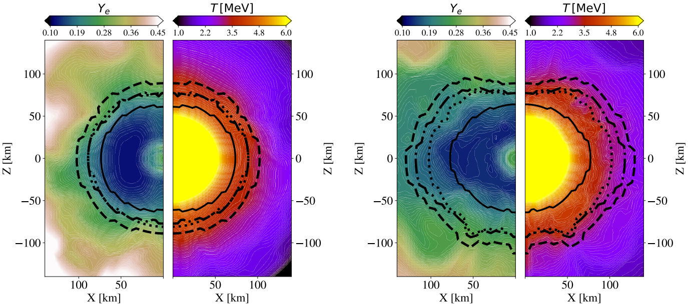


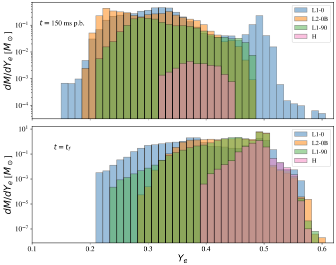
Raynaud et al. (2022)

Neutrino SASI signature



Matter composition





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