The impact of rotation and dynamos on the multi-messenger emission of core-collapse supernovae

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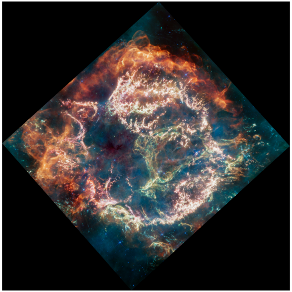
Core-collapse Supernovae

- 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)

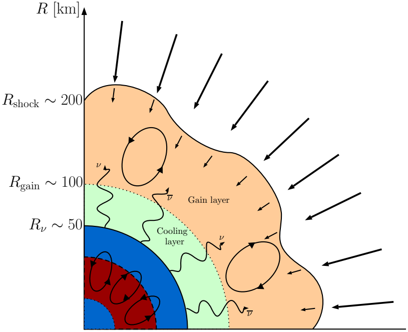
Credit: NASA, ESA, CSA



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

Outstanding explosions and magnetic fields

Explosion kinetic energy

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

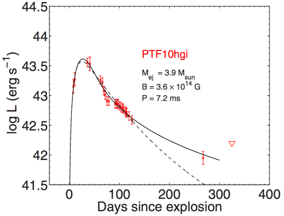
Total luminosity

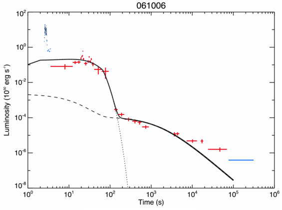
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

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)

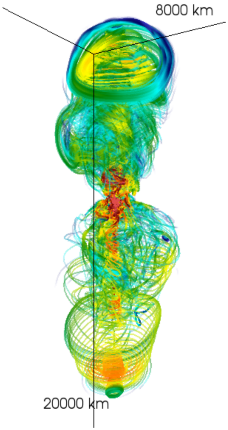
Magneto-rotational explosions

Core mechanism

- 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

- Progenitor (Woosley and Heger, 2006; Aguilera-Dena et al., 2020)
- Stellar mergers (Schneider et al., 2019)
- PNS dynamos (Masada et al., 2015, 2022)

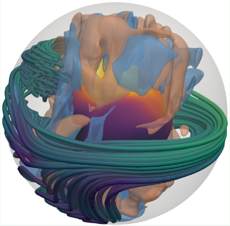


Obergaulinger and Aloy (2021)

PNS dynamos

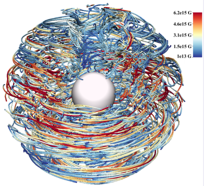
Convection

- Fast rotation leads to a magnetostrophic balance between Lorentz and Coriolis forces
- Amplification of weak magnetic seeds to **magnetar-like strength** (up to $\sim 10^{16}$ G)
- Strong toroidal field, non-axisymmetric structures (Raynaud et al., 2020, 2022)



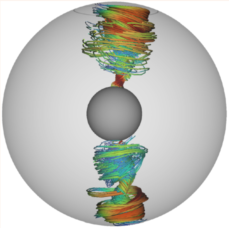
MRI

- Similar to accretion disks, but high magnetic Prandtl number $\sim 10^{12}$ (Guilet et al., 2022)
- Amplification of large-scale field from small-scale seeds
- Mean-field **$\alpha\Omega$ dynamo** behavior (periodic oscillations)
- Formation of a **highly tilted dipole** (Reboul-Salze et al., 2021; Reboul-Salze et al., 2022)



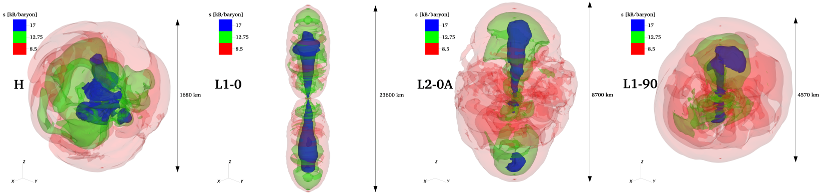
Tayler-Spruit

- Dynamo process studied in stellar evolution
- Fallback accretion onto slowly rotating PNS
- Amplification within $\sim$ 10 s from core bounce up to $\sim 10^{15}$ G
- Large-scale **non-axisymmetric modes** ($m = 1$) (Barrère et al., 2022, 2023)

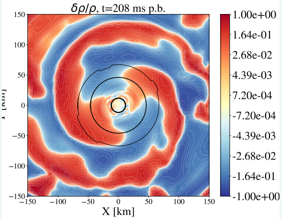


3D MHD explosion models

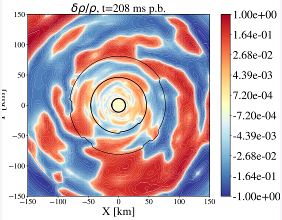
- Massive, fast rotating stellar progenitors (Woosley and Heger, 2006; ?)
- Different magnetic configurations (Bugli et al., 2021, 2023): dipole (aligned and equatorial), quadrupole
- Higher multipoles ⇒ weaker explosions, less collimated outflows



Hydrodynamic case



Magnetized case

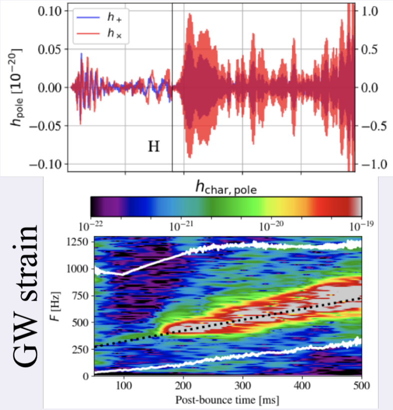


Strong B fields suppress rotational instabilities!

GW emission

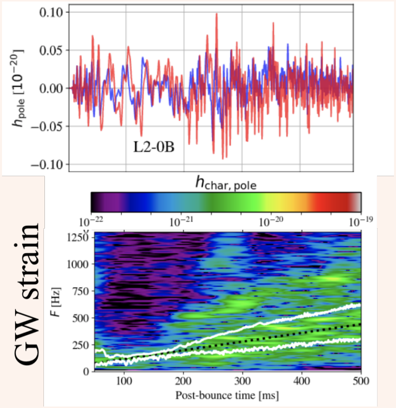
(Bugli et al., 2023)

Hydrodynamic case



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

Magnetized case (quadrupole)

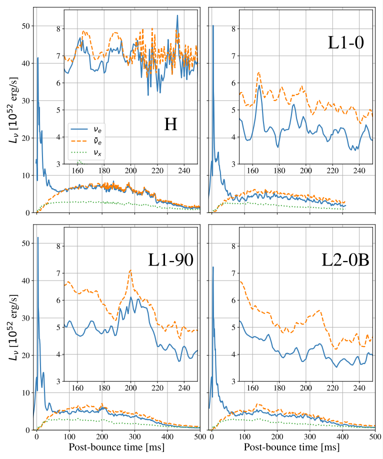


- No low $T/|W|$ signal burst
- $h \sim 5 \times 10^{-22}$ for $D = 10$ kpc
- Strong transport of AM

Neutrino emission

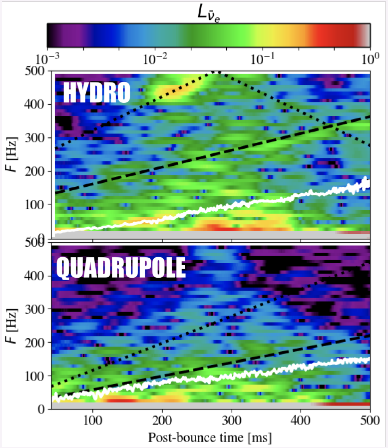
(Bugli et al., 2023)

Lightcurves (equator)



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

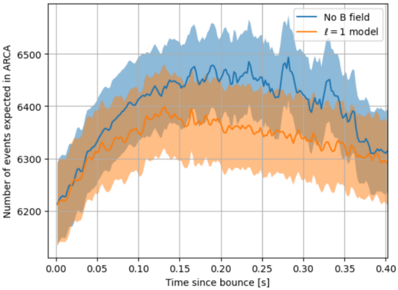
PNS modes signatures

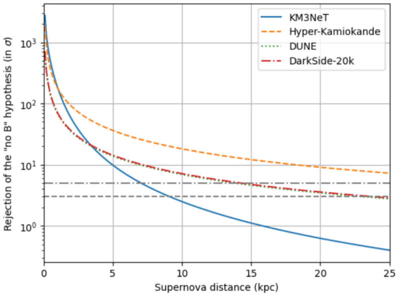


- low $T/|W|$ and SASI signatures

Constraints from neutrino observations

- Detection of low-energy neutrinos from CCSN (1-100 MeV)
- Multi-detector analysis: KM3NeT, Hyper-K ($\bar{\nu}_e$), DUNE (ν_e), DarkSide (all ν)...
- Astrophysical constraints on fundamental neutrino physics (mass hierarchy, oscillations, ...)

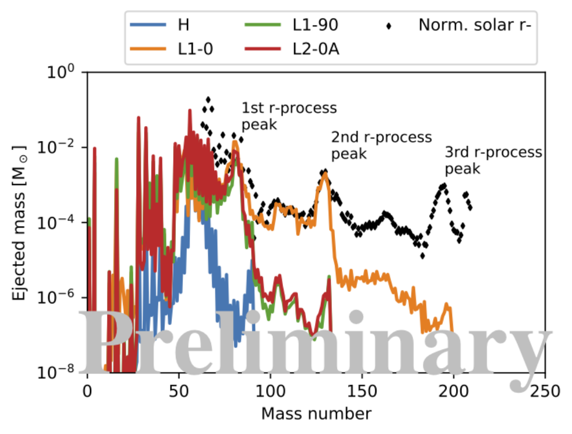




Bendahman et al. (2023)

Explosive nucleosynthesis

(Reichert et al., in prep.)



- All magnetized models produce 1st r-process peak elements
- 2nd peak only for the aligned dipole
- No 3rd peak, consistent with recent 3d models (Reichert et al., 2022) and in contrast to 2d models (Reichert et al., 2021).
- Crucial estimates for chemical evolution models (Dvorkin et al., 2020)

Conclusions

- GW-ν open a unique window on the central engine of CCSN
- 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
- MR-CCSN possible sites of r-process elements (but no third peak)

Future goals

- Impact of moderate rotation and B field (most progenitors)
- PNS dynamo subgrid model to bridge the small and large scales
- Long-term modeling of the magnetized jets $\Rightarrow$ EM emission?

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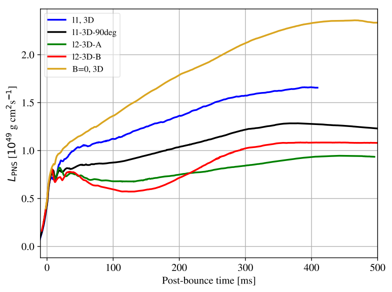
Merci de votre attention !

Backup slides

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

PNS angular momentum

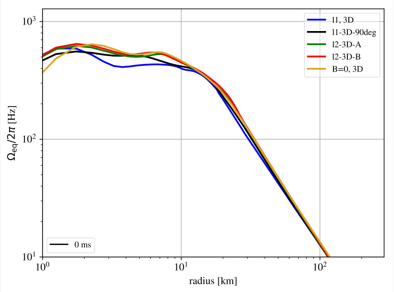
- Magnetic extraction of rotational energy
- More efficient extraction for non-dipolar fields



Angular velocity profile

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

$t = 0$ ms



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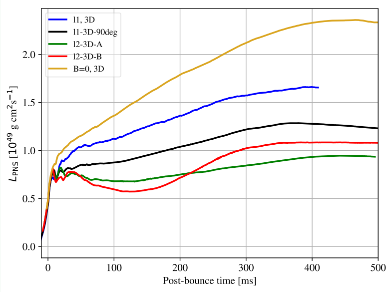

Angular velocity profile

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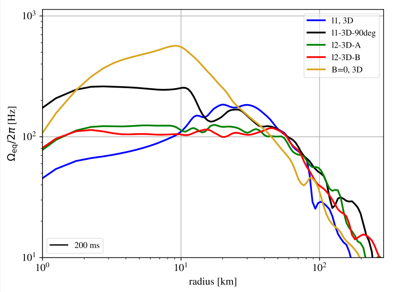
$t = 200$ ms

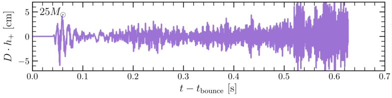


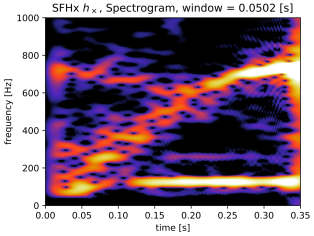
GW signals from standard CCSN

Main features

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

Radice et al. (2019)

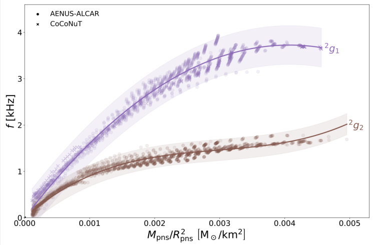




Kawahara et al. (2018)

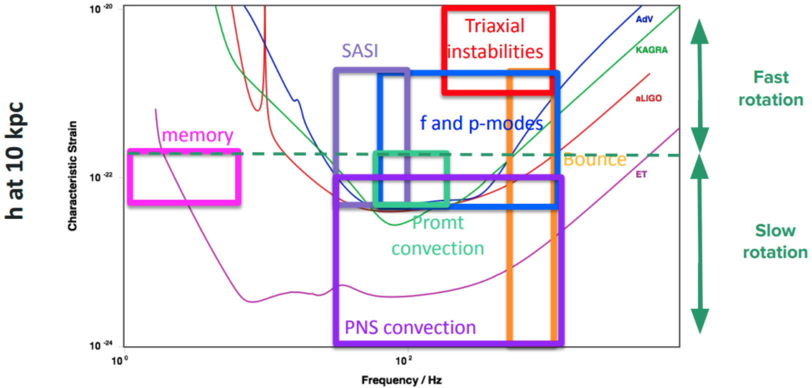
Asteroseismology

- 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)

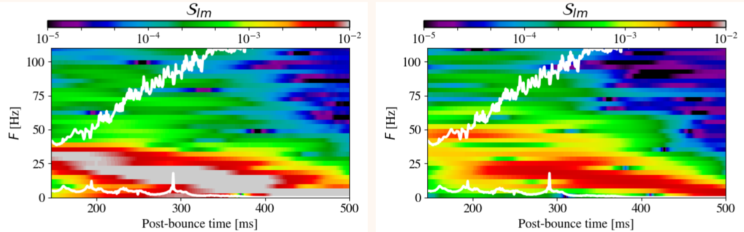
Summary of physical sources of GW

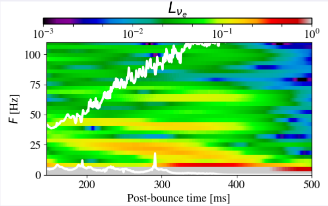


Credit: Pablo Cerdà-Duràn

Neutrino SASI signature

Shock's surface modes: (1,1), (2,2)

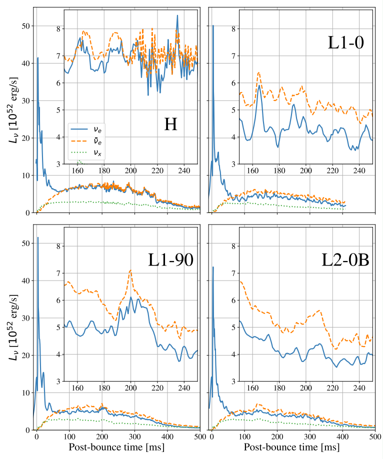




- Low-frequency signature of spiral SASI modes $\sim 20-30$ Hz
- Decreasing frequency and short duration for exploding models

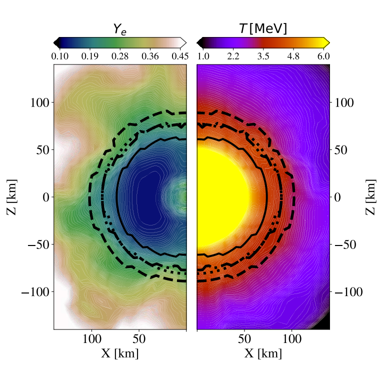
Electron fraction distribution

Lightcurves (equator)



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

Y_e distribution

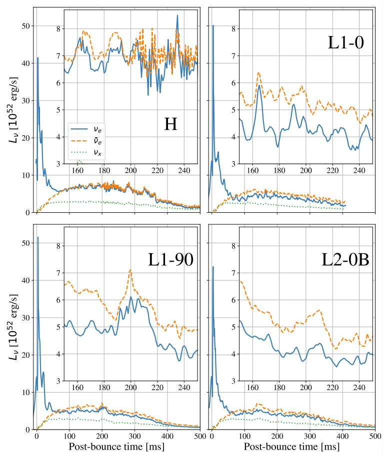


Hydrodynamic model

- More compact PNS ⇒ higher mean energies

Electron fraction distribution

Lightcurves (equator)



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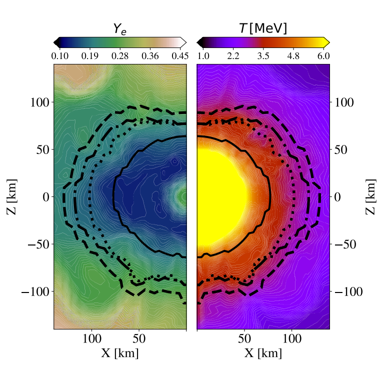
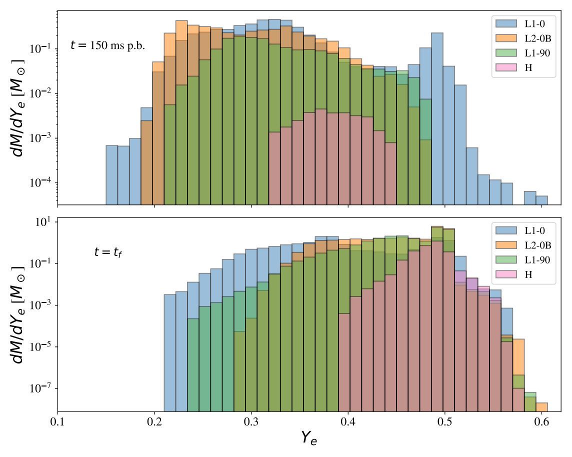


Quadrupolar model

- Outward transport of a.m. ⇒ lower Y_e

Nuclear composition of the ejecta



- More neutron-rich material for magnetized models
  - Lowest Y_e for dipolar fields
- Longer simulations required to reduce uncertainties

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