Multi-messenger emission and explosive nucleosynthesis from core-collapse supernovae

Matteo Bugli[1,2] (MSCA fellow)

Collaborators: J. Guilet[2], T. Foglizzo[2], M. Obergaulinger[3], M. Reichert[3], M. Bendahman[4], S. El Hedri[4], I. Goos[4]

[1]Dipartimento di Fisica, Università di Torino, Torino, Italy
[2]AIM, CEA-Saclay, CNRS, Gif-sur-Yvette, France
[3]Departament d'Astonomia i Astrofísica, Universitat de València, València, Spain
[4]Laboratoire Astroparticule et Cosmologie, Paris, France

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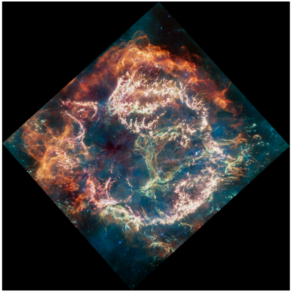
Groupement de recherche
Ondes gravitationnelles

Core-collapse Supernovae

- Formation of stellar compact object
- Dynamical feedback on galaxy evolution
- Explosive nucleosynthesis $\Rightarrow$ chemical evolution of galaxies
- Sources of gravitational waves and neutrinos

Credit: NASA, ESA, CSA



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

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

Magneto-rotational explosions

Outstanding stellar explosions

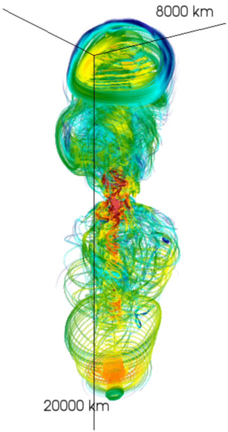
- Hypernovae and GRBs: 10^{52} erg (kinetic)
- Superluminous SN: 10^{51} erg (luminosity)
- Extended emission and X-ray plateaus (Inserra et al., 2013; Gompertz et al., 2014)

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

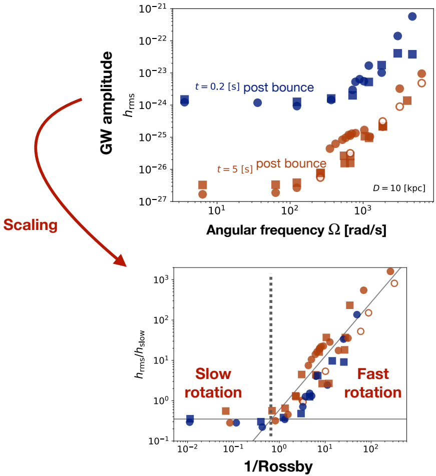
- Progenitor (Woosley and Heger, 2006; Aguilera-Dena et al., 2020)
- Stellar mergers (Schneider et al., 2019)
- PNS dynamos (Masada et al., 2015; Raynaud et al., 2020; Reboul-Salze et al., 2021; Reboul-Salze et al., 2022; Barrère et al., 2023)

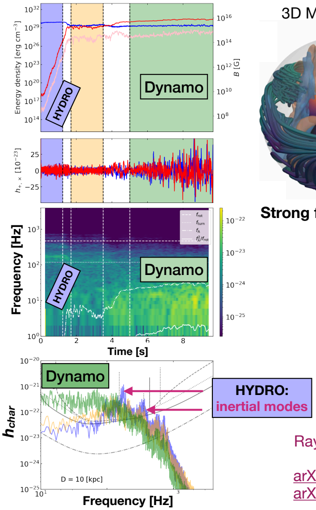


Obergaulinger and Aloy (2021)

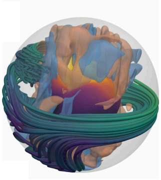
GW and PNS dynamos

GW signal of PNS convection





3D MHD models



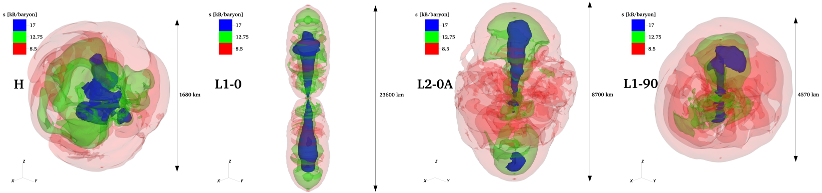
Strong field dynamo

Raynaud+20,+22

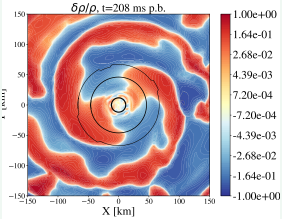
arXiv:2103.12445
arXiv:2003.06662

3D MHD explosion models

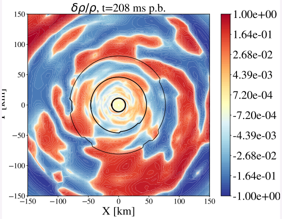
- Massive, fast rotating stellar progenitor (Woosley and Heger, 2006)
- Different magnetic configurations (Bugli et al., 2021, 2023): dipole (aligned and equatorial), quadrupole
- Higher multipoles ⇒ weaker explosions, less collimated outflows



Hydrodynamic case



Magnetized case

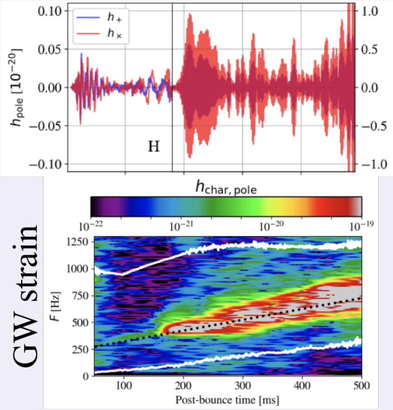


Strong B fields suppress rotational instabilities!

GW emission

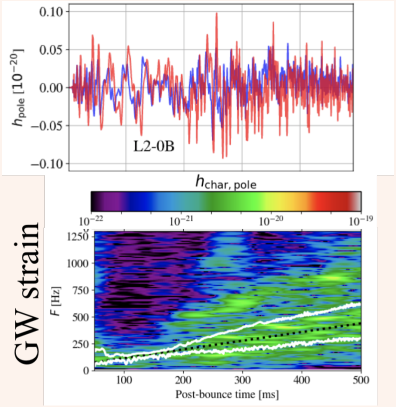
(Bugli et al., 2023)

Hydrodynamic case



- 400 Hz emission at 200 ms
- $h \sim 10^{-20}$ for $D = 10$ kpc
- Strong correlation with PNS modes
- (Shibagaki et al., 2020; Takiwaki et al., 2021)

Magnetized case (quadrupole)

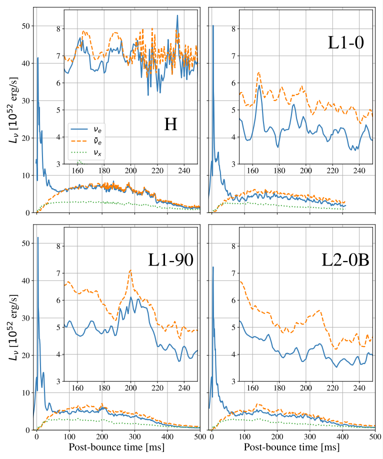


- No low $T/|W|$ signal burst
- $h \sim 5 \times 10^{-22}$ for $D = 10$ kpc
- Strong transport of AM
- (Powell et al., 2023; Shibagaki et al., 2023)

Neutrino emission

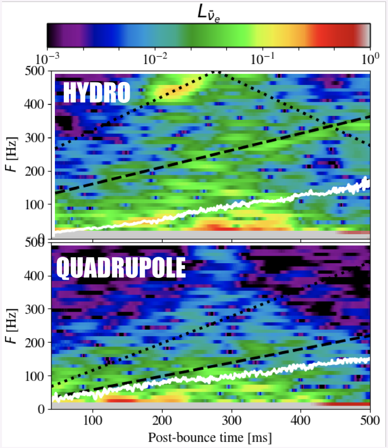
(Bugli et al., 2023)

Lightcurves (equator)



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

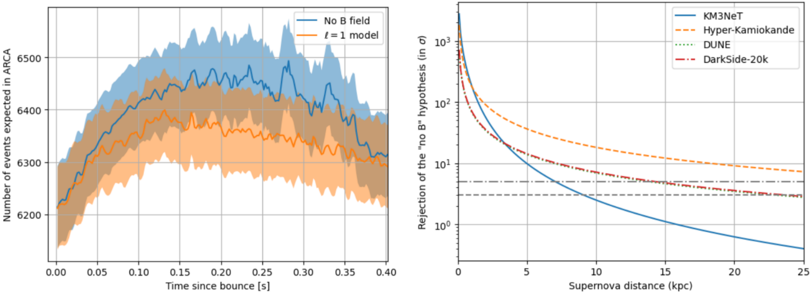
PNS modes signatures



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

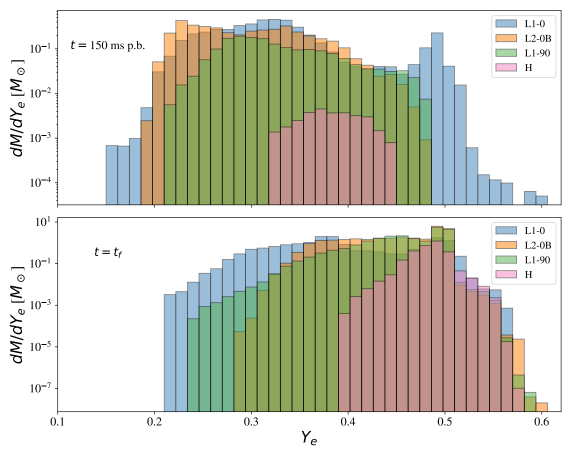
Constraints from neutrino observations (Bendahman et al. 2021)

- 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)

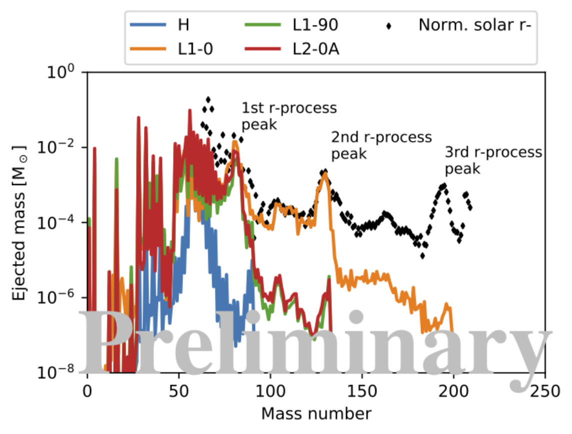
Nuclear composition of the ejecta (Bugli et al., 2023)



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

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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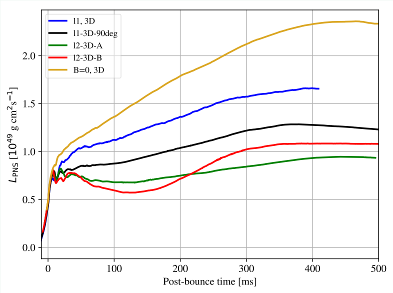
Merci de votre attention !

Backup slides

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

PNS angular momentum

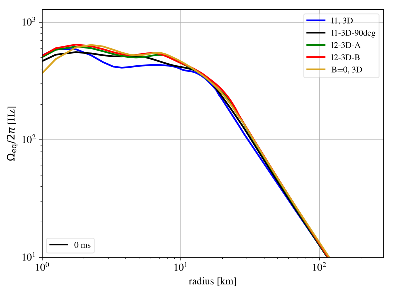
- Magnetic extraction of rotational energy
- More efficient extraction for non-dipolar fields



Angular velocity profile

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

$t = 0$ ms



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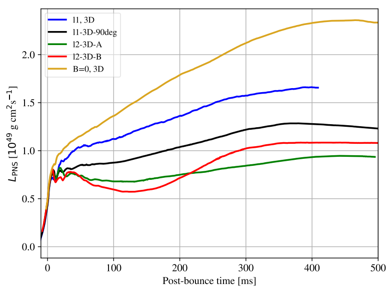

Angular velocity profile

- Flattened rotation profile 25 km (convective zone)
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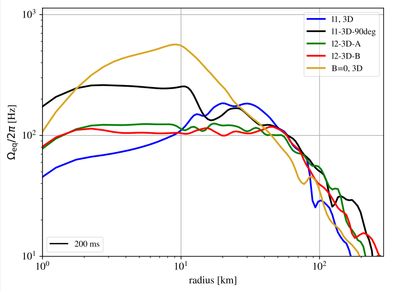
$t = 200$ ms

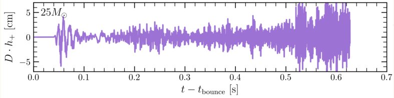


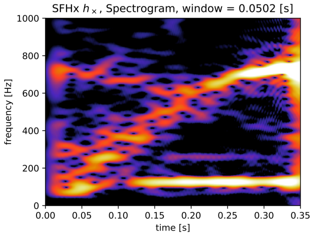
GW signals from standard CCSN

Main features

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

Radice et al. (2019)

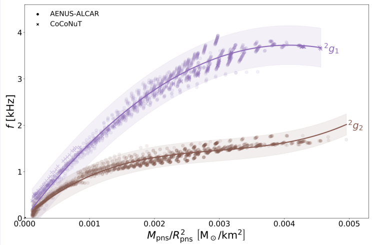




Kawahara et al. (2018)

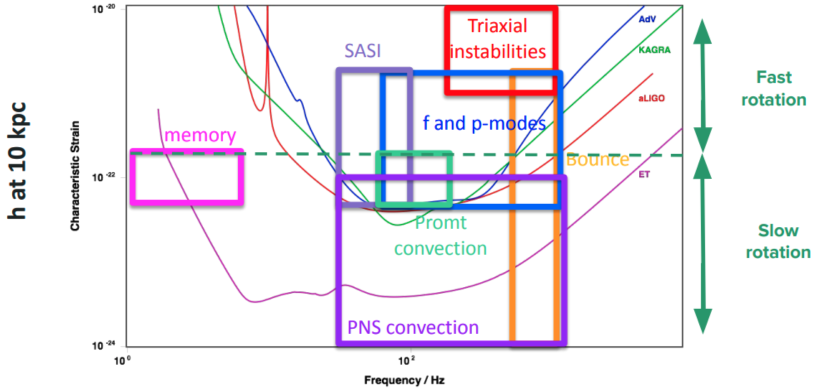
Asteroseismology

- 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)

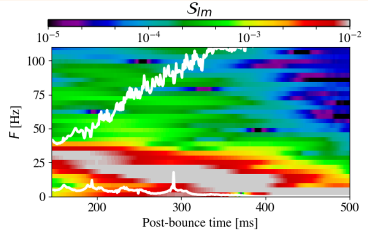
Summary of physical sources of GW

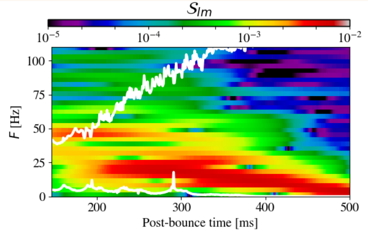


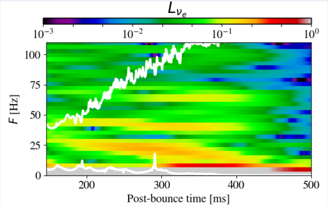
Credit: Pablo Cerdà-Duràn

Neutrino SASI signature

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



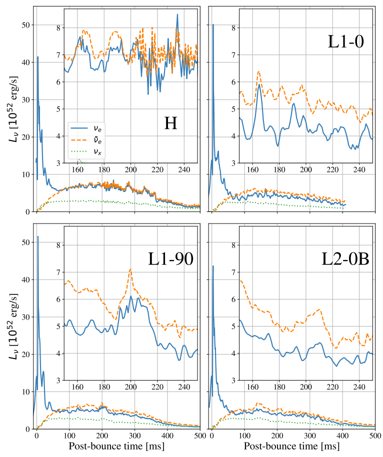




- Low-frequency signature of spiral SASI modes $\sim 20 - 30$ Hz
- Decreasing frequency and short duration for exploding models

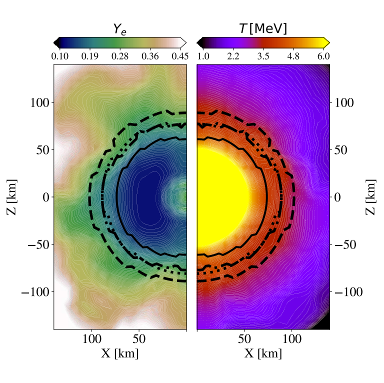
Electron fraction distribution

Lightcurves (equator)



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

Y_e distribution

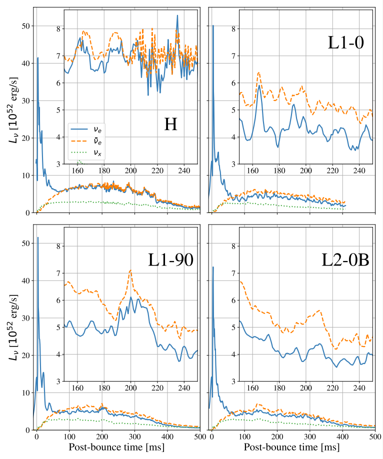


Hydrodynamic model

- More compact PNS ⇒ higher mean energies

Electron fraction distribution

Lightcurves (equator)



- Lower luminosity in MHD
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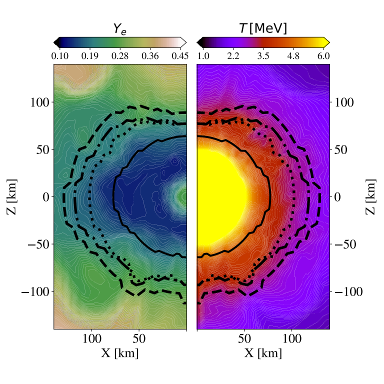

Quadrupolar model

- Outward transport of a.m. ⇒ lower Y_e

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