MULTI-MESSENGER EMISSION FROM MAGNETISED CORE-COLLAPSE SUPERNOVAE

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Outline of talk

1. Introduction
2. GW from standard CCSN
3. GW driven by rotation
4. Magneto-rotational explosions
5. Numerical models
6. Conclusions

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Core-collapse Supernovae

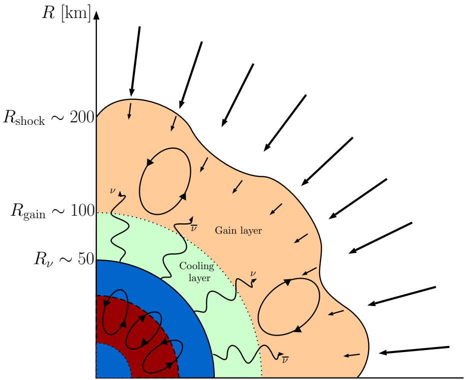
- Gravitational collapse of a massive star (unstable iron core)
- Shock formation when nuclear densities are reached (stalling) ⇒ Proto Neutron Star
- Shock expansion and ejection of unbound material (explosion)

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
- Post-shock convection; Standing Accretion Shock Instability)

Neutrinos and GW directly probe the explosion mechanism

Numerical models: (M)HD + nuclear EoS + neutrinos

Uncertain initial conditions

- Progenitor thermodynamic profiles: ρ,s,P
- Non-spherical perturbations

(Müller et al., 2017)

Explodability

- Very compact cores resist to shock revival (O'Connor and Ott, 2011);
- Combination of mass accretion and entropy profiles

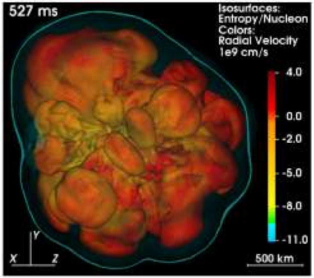
Ertl et al. (2016)

PNS proper motions

- Asymmetries and fallback accretion ⇒ PNS kick velocity and spin (Janka et al., 2021)

Hydrodynamic instabilities

- Post-shock convection (ν energy deposition) and SASI
- 3D crucial
- Longer dwelling in gain region ⇒ more efficient heating



Janka et al. (2016)

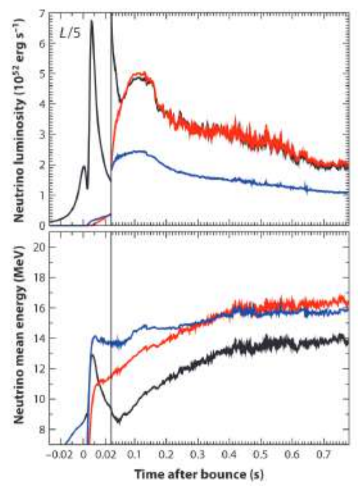
Neutrino emission

CCSN models

- Onset of collapse: ν_e released from the core, then trapped
- Neutronization burst: ν_e set free once the shock reaches low enough densities
- Accretion phase: high fluxes of ν_e and $\bar{\nu}_e$ in addition to the core luminosity

Late PNS models

- Cooling phase: residual deleptonization and loss of binding energy



Janka (2012)

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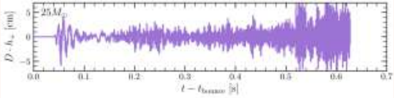
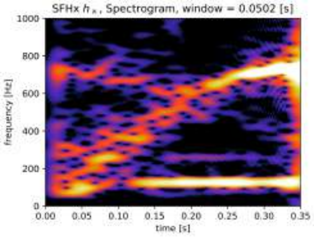
GW signals from standard CCSN

Main features

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

Radice et al. (2019)

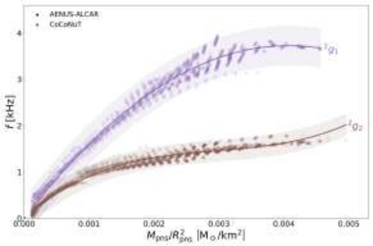




Kawahara et al. (2018)

Asteroseismology

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



Torres-Forné et al. (2019)

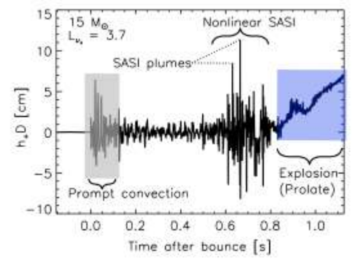
Secondary features

Prompt convection

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

Memory

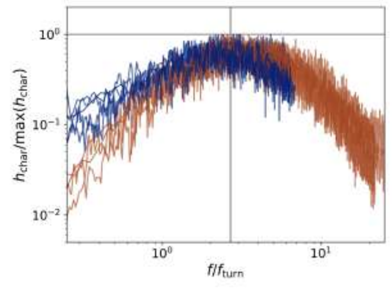
- 1-10 Hz (asymmetric explosions)



Murphy et al. (2009)

Long-term convection

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



Raynaud et al. (2022)

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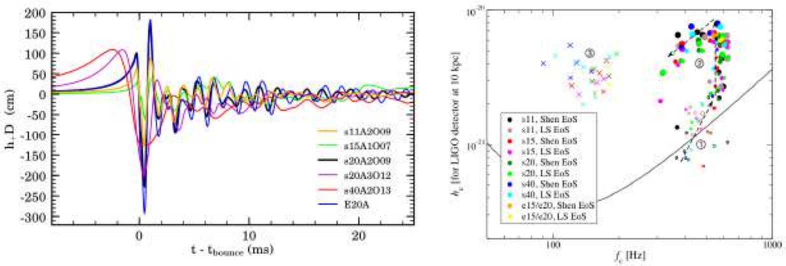
The impact of rotation

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)



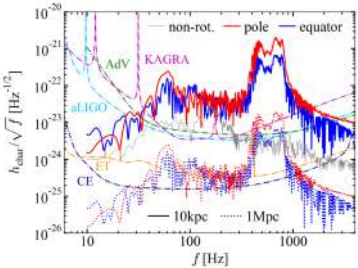
Ott (2009)

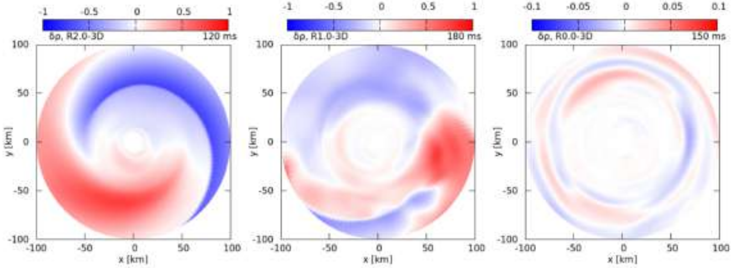
Corotational instabilities

- 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).

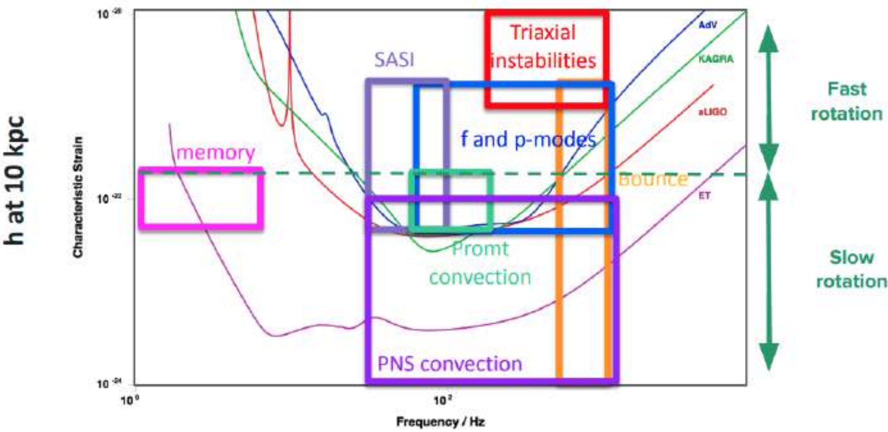
Shibagaki et al. (2020)





Takiwaki et al. (2021)

Summary of physical sources of GW



Credit: Pablo Cerdà-Duràn

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Outstanding explosions and magnetic fields

Explosion kinetic energy

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

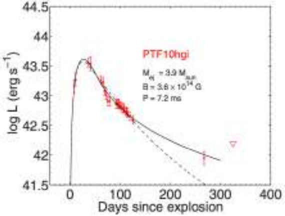
Total luminosity

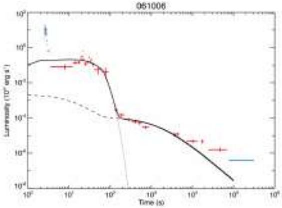
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

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)

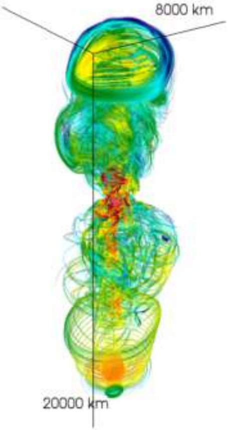
Magneto-rotational explosions

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)

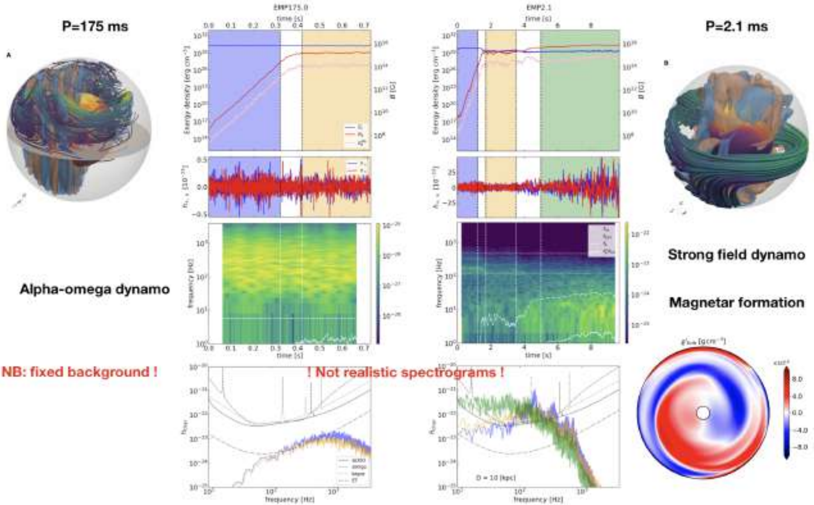
Origin of the magnetic field

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



Obergaulinger and Aloy (2021)

Convective dynamo in PNS



P=175 ms

Alpha-omega dynamo

NB: fixed background !

! Not realistic spectrograms !

P=2.1 ms

Strong field dynamo

Magnetar formation

Raynaud et al. (2022)

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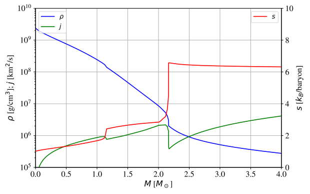
3D MHD explosion models

(Bugli et al., 2021)

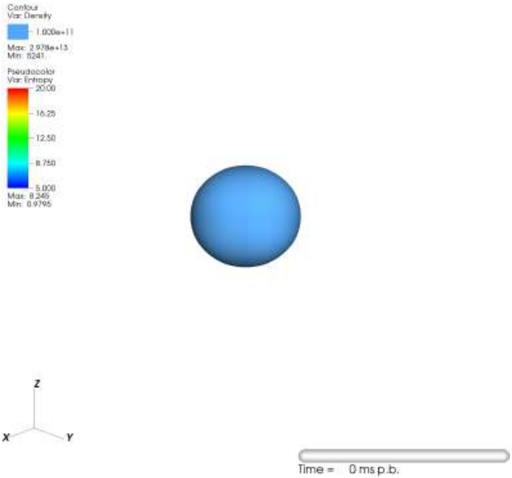
- 35OC: massive, fast rotating stellar progenitor (Woosley and Heger, 2006)
- Rotation profile from stellar evolution model
- Different magnetic configurations: dipole (aligned and equatorial) or quadrupole (motivated by PNS dynamos; Raynaud et al. (2020); Reboul-Salze et al. (2021, 2022))



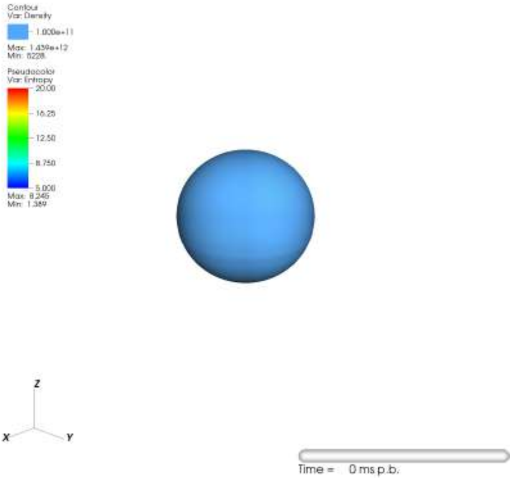
Multipolar poloidal field

$$A_{\phi,l} = r B_0 \frac{\sqrt{l}}{2l+1} \frac{{r_0}^3}{r^3+{r_0}^3} \frac{P_{l-1}(\cos\theta) - P_{l+1}(\cos\theta)}{\sin\theta}$$

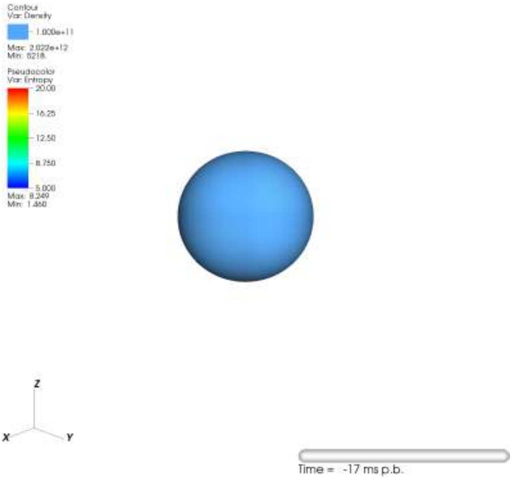
Hydrodynamic model



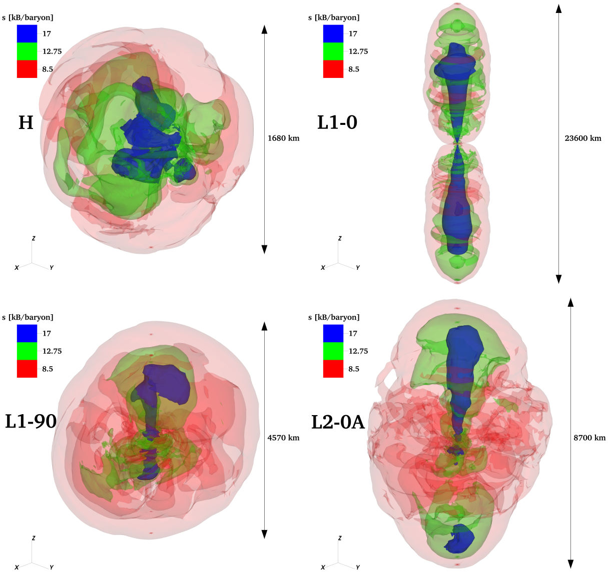
Aligned dipole



Equatorial dipole



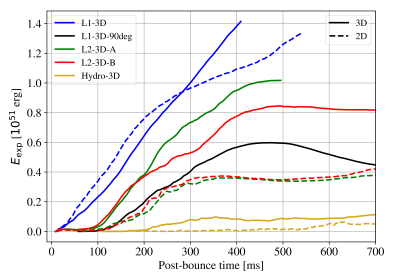
Explosion Morphology



Explosion dynamics

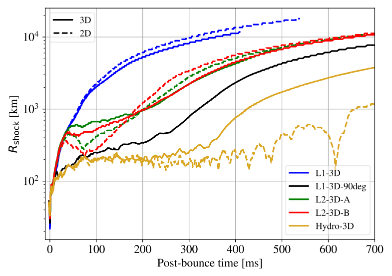
(Bugli et al., 2021)

Ejecta energy



- Stronger explosions for lower multipoles and aligned configurations
- 3D generally more energetic

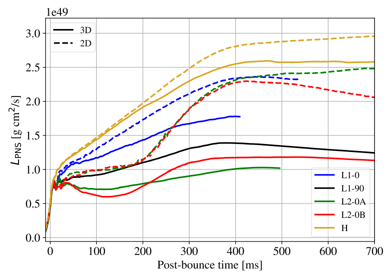
Shock expansion



- Faster shock expansion for stronger explosions
- 2D faster than 3D in magnetized models

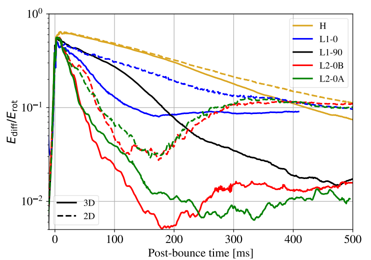
Angular momentum transport

PNS angular momentum



- Magnetic stresses slow down the PNS

PNS differential rotation

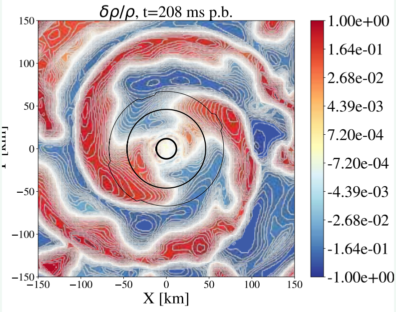


- Fast redistribution of differential rotation in magnetized models

- Quadrupolar fields more efficient than dipolar ones
- 3D more efficient than 2D

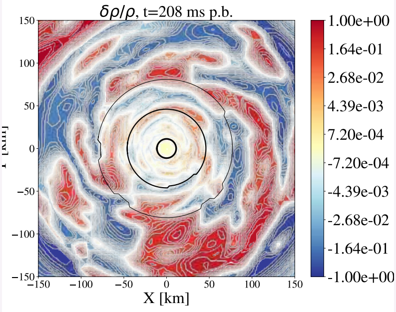
The low $T/|W|$ instability (Bugli et al., sub. to MNRAS)

Hydrodynamic case



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

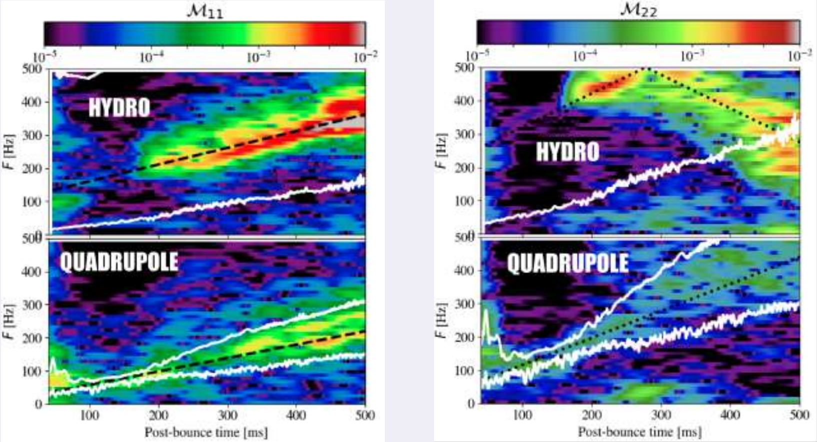
Magnetized case



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

PNS oscillation modes

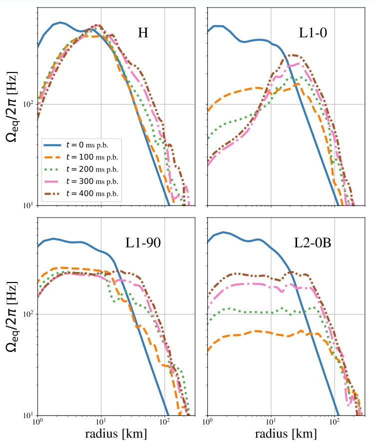
Density modes at 30 km ($\{l, m\} = \{1, 1\}$ and $\{2, 2\}$)



- Strong $l = 1, 2$ non-axisymmetric modes in the hydrodynamic case
- Weaker modes in magnetized models

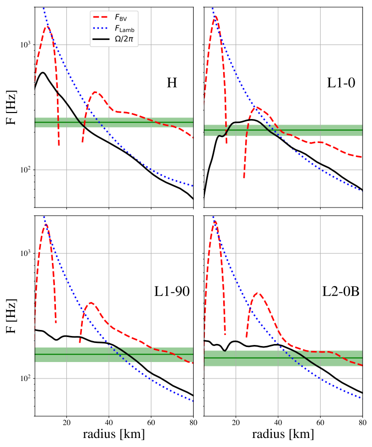
Magnetic transport of angular momentum

Rotation profile evolution



- Distinctive dynamics for each model
- Strongest flattening for quadrupolar fields

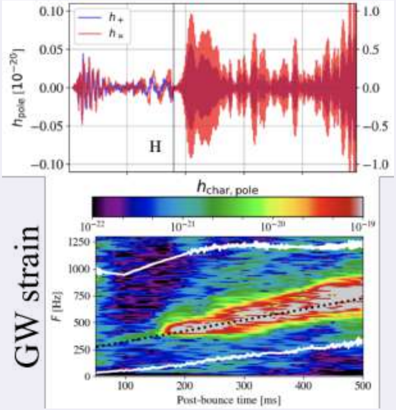
Mode's frequency



- Corotation radius outside the convective zone ⇒ stable against low $T/\|W\|$ (Takiwaki et al., 2021)

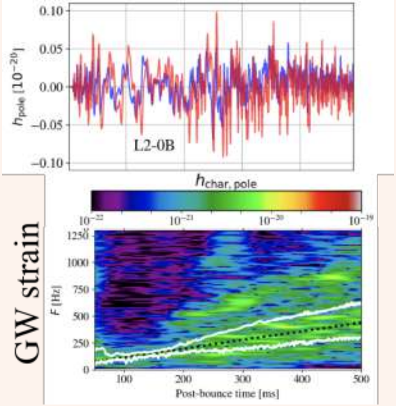
GW emission

Hydrodynamic case



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

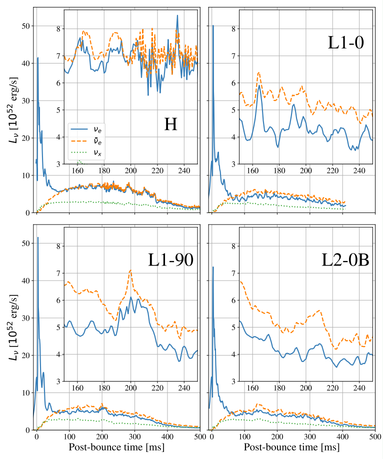
Magnetized case (quadrupole)



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

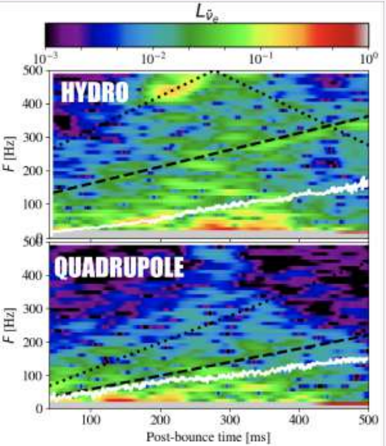
Neutrino emission

Lightcurves (equator)



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

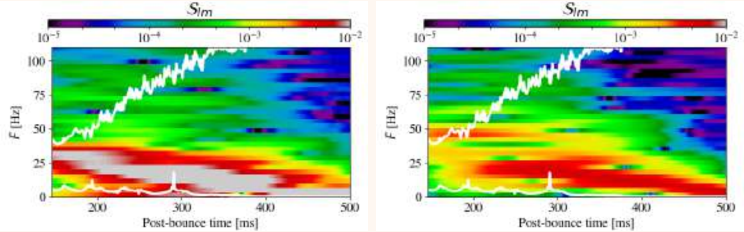
PNS modes signatures

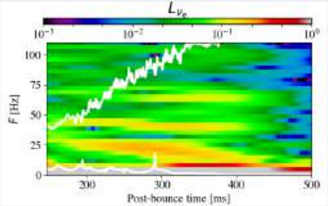


- low $T/|W|$ and SASI signatures

Neutrino SASI signature

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

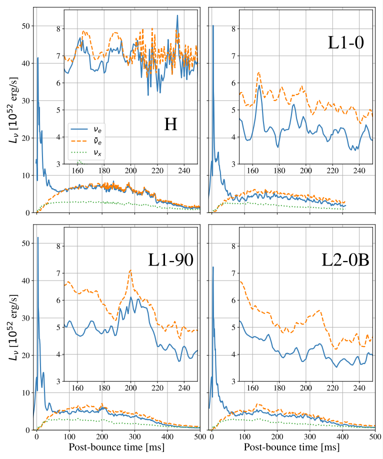




- Low-frequency signature of spiral SASI modes $\sim 20 - 30$ Hz
- Decreasing frequency and short duration for exploding models

Electron fraction distribution

Lightcurves (equator)



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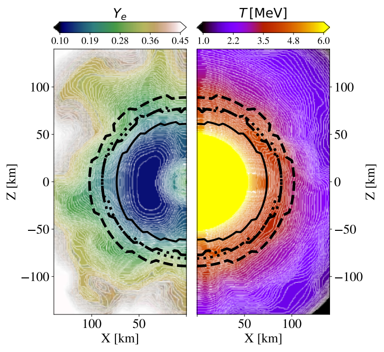
Y_e distribution

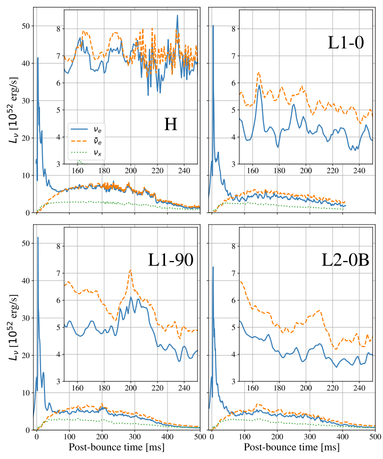


Hydrodynamic model

- More compact PNS ⇒ higher mean energies

Electron fraction distribution

Lightcurves (equator)



- Lower luminosity in MHD
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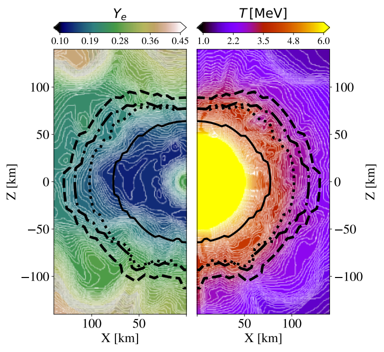
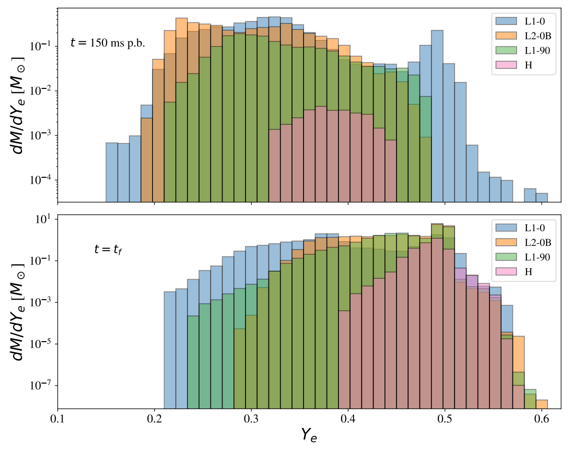
Y_e distribution



Quadrupolar model

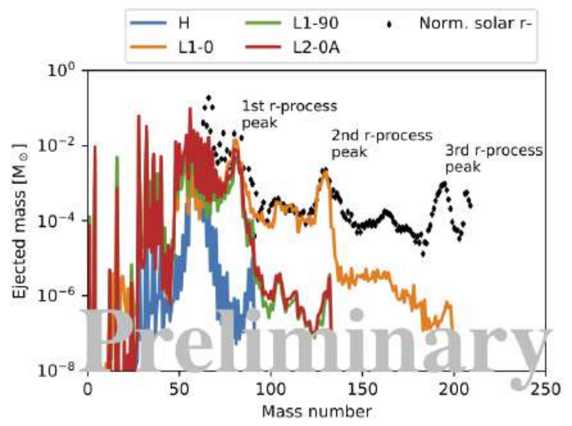
- Outward transport of a.m. ⇒ lower Y_e

Nuclear composition of the ejecta



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

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)

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Conclusions

- GW open a unique window on the central engine dynamics
- Signatures from fluid 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

`https://arxiv.org/pdf/2210.05012.pdf`

Future goals

- Impact of weaker magnetic fields
- Dependence on the rotation profile
- Fundamental physical mechanism behind low $T/|W|$
- Impact on explosive nucleosynthesis

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