NUMERICAL MODELING OF CORE-COLLAPSE SUPERNOVAE AND NEUTRON STAR FORMATION

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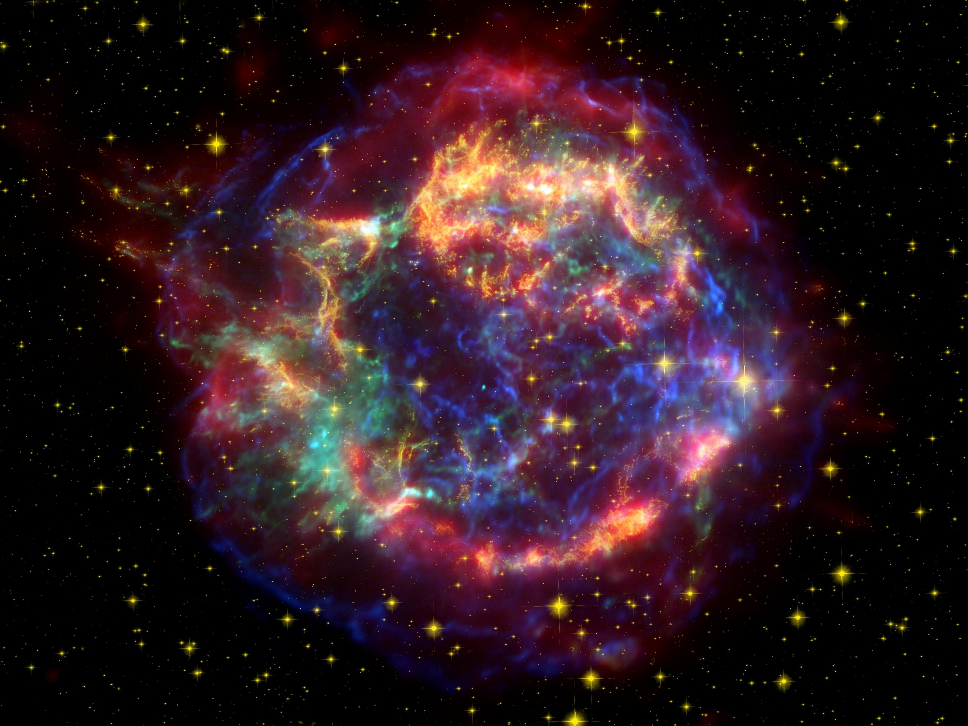

Outline of talk

1. Introduction
2. General models
3. Magneto-rotational explosions
4. Conclusions

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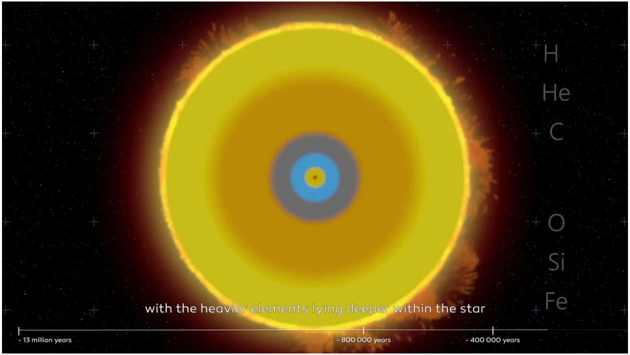
Core-collapse Supernovae

- Gravitational collapse of massive star
- Shock formation when nuclear densities are reached (stalling) ⇒ Proto Neutron Star
- Shock expansion and ejection of unbound material (explosion)
- Injection of energy and new elements

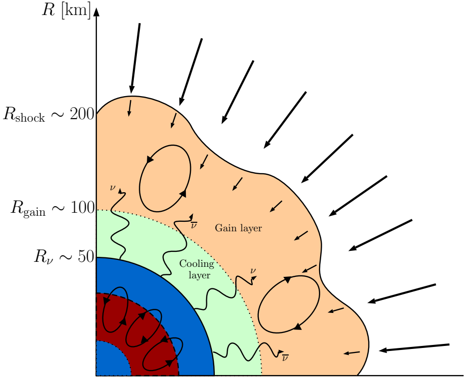
Energy budget ($\sim 10^{53}$ erg)

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



"How does a supernova explode?" (CEA-Saclay)

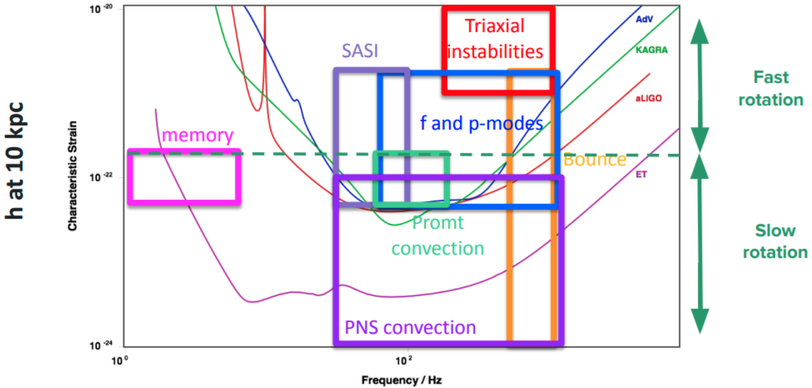
Standard neutrino-driven CCSN



- PNS contraction ⇒ higher ν energies
- ν-cooling rate drops faster than ν-heating ⇒ 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

Gravitational waves from CCSN



Credit: Pablo Cerdà-Duràn

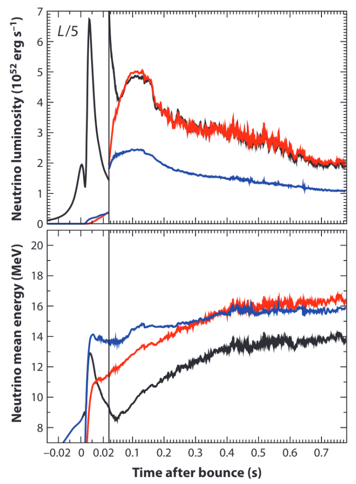
Neutrino emission

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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(Magneto)Hydrodynamics

- Godunov-type, shock-capturing, finite-volumes(differences) schemes
- Divergence-free B field: constrained transport/divergence cleaning
- Cartesian/spherical grids
- Hybrid `MPI-OpenMP` parallelization schemes (GPUs on their way...)

Gravitational force

Full GR

- Dynamical evolution of the space-time
- More accurate, higher computational cost
- Mösta et al. (2014); Kuroda et al. (2018)

Newtonian Gravity

- Relativistic corrections to Φ

  (Marek et al., 2006)
- Cheaper computational cost, less accurate
- Just et al. (2015); O'Connor and Couch (2018); Takiwaki et al. (2021)

High-density EoS

Popular choices

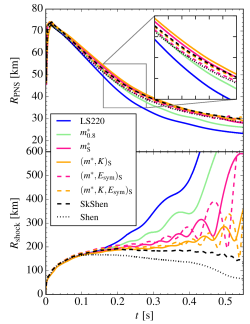
- LS220 (Lattimer and Swesty, 1991): compressible liquid-drop model
- Shen (STOS) (Shen et al., 1998): RMF with TM1 parameter set
- SFHo (Steiner et al., 2013): RMF consistent with observations

The CompOSE catalogue

- Online repo of CCSN-NS EoS
- ∼240 entries
- Free download of tables, M-R relations, references

PNS and shock properties

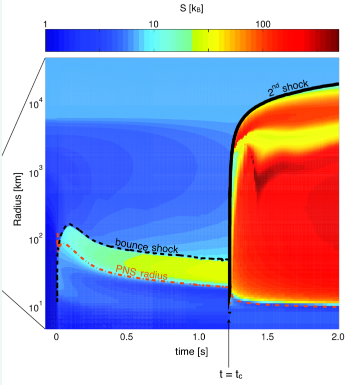
- Lower effective mass ⇒ lower contraction and ν energies
- Higher incompressibility ⇒ larger PNS radius (Yasin et al., 2018)



More recent EoS

Quark-hadron phase transition

- BBKF (DD2F-SF) (Fischer et al., 2018)
- Release of latent heat ⇒ secondary shock (Kuroda et al., 2022)

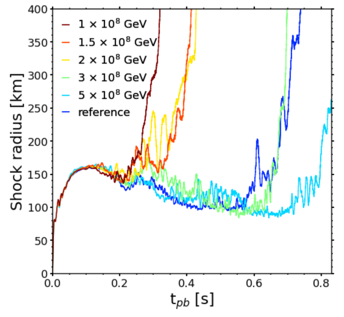


Axions in core-collapse supernovae

- Enhanced cooling (Betranhandy and O'Connor, 2022):

$$N + N \rightleftarrows N^* + N^* + a$$

- Faster contraction ⇒ faster explosion



Neutrino Transport

ν-matter interactions

- β-processes
- pair production and annihilation
- reactions between neutrinos
- scattering with medium particles

ν-oscillations

- Fast Flavor Conversion (Ehring et al., 2023; Nagakura, 2023)
- Post-process data pipeline (Bendahman et al., 2021)

Leakage/heating schemes

- Sink/source terms in the HD equations (O'Connor and Ott, 2010; Mösta et al., 2014)

Spectral M1 ν-transport

- Evolution of first two moments of specific intensity $\mathcal{I}$, i.e. energy and flux.
- Full 3D fluxes (Just et al., 2015); RbR approx: $F^{\theta}_{\nu} = F^{\phi}_{\nu} = 0$ (Buras et al., 2006)
- All flavors are included: $\nu_e, \bar{\nu}_e, \nu_x \rightarrow \{\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau\}$ (Bollig et al., 2020)

(GR) (Quantum) Kinetic transport

- Solve the full Boltzmann equation (Nagakura, 2022)

Standard neutrino explosions

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

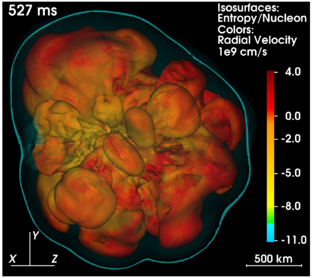
Ertl et al. (2016)

PNS proper motions

- Asymmetries and fallback accretion $\Rightarrow$ 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 $\Rightarrow$ more efficient heating



Janka et al. (2016)

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Outstanding explosions and magnetic fields

Explosion kinetic energy

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

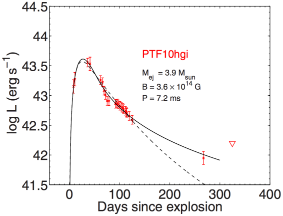
Total luminosity

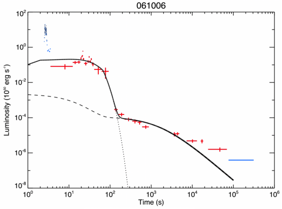
- Typical supernova: 10^{49} erg
- Superluminous SN: 10^{51} erg

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)

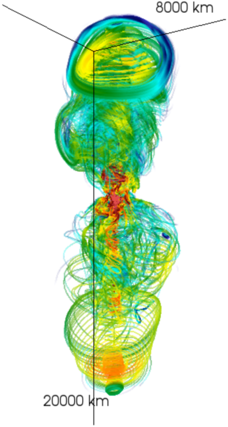
Magneto-rotational explosions

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 dynamos (Masada et al., 2015, 2022)

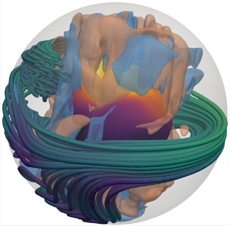


Obergaulinger and Aloy (2021)

PNS dynamos

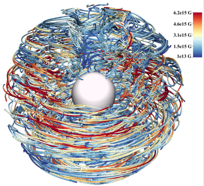
Convection

- 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)



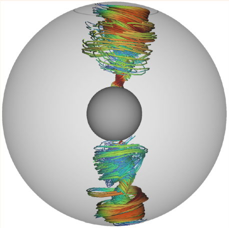
MRI

- 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)



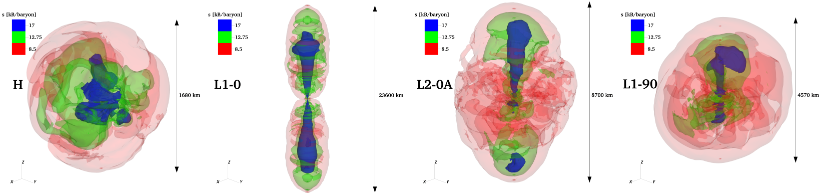
Tayler-Spruit

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

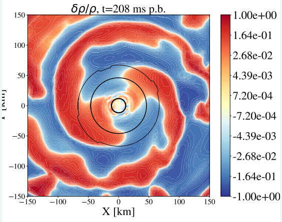


3D MHD explosion models

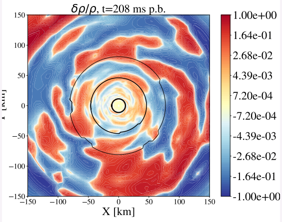
- Massive, fast rotating stellar progenitors (Woosley and Heger, 2006, 2007)
- Magnetic configurations (Bugli et al., 2021, 2023): dipole (aligned and equatorial), quadrupole
- Higher multipoles ⇒ weaker explosions, less collimated outflows



Hydrodynamic case



Magnetized case

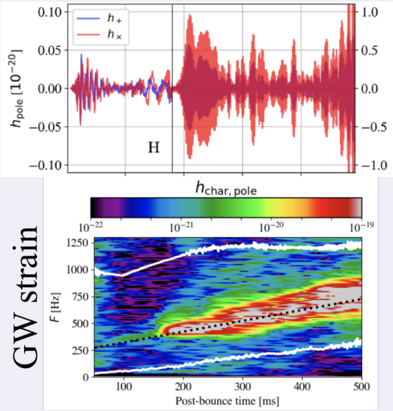


Strong B fields suppress rotational instabilities!

GW emission

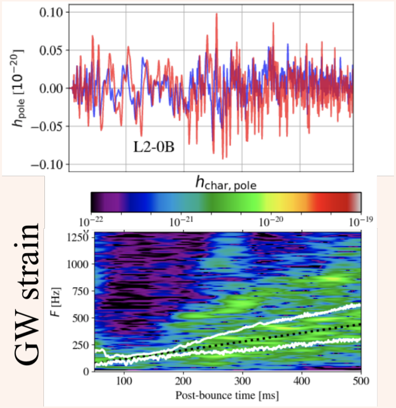
(Bugli et al., 2023)

Hydrodynamic case



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

Magnetized case (quadrupole)

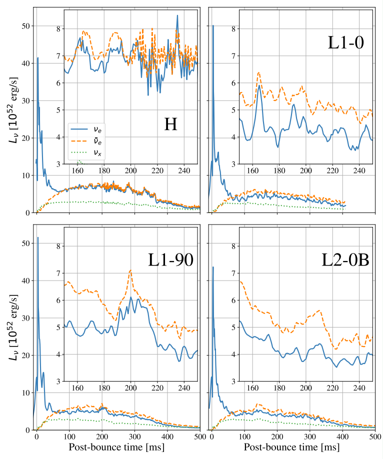


- No low $T/|W|$ signal burst
- $h \sim 5 \times 10^{-22}$ for $D = 10$ kpc
- Strong transport of AM
- 3rd generation GW interferometers required

Neutrino emission

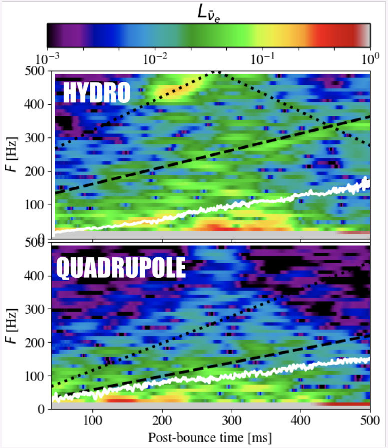
(Bugli et al., 2023)

Lightcurves (equator)



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

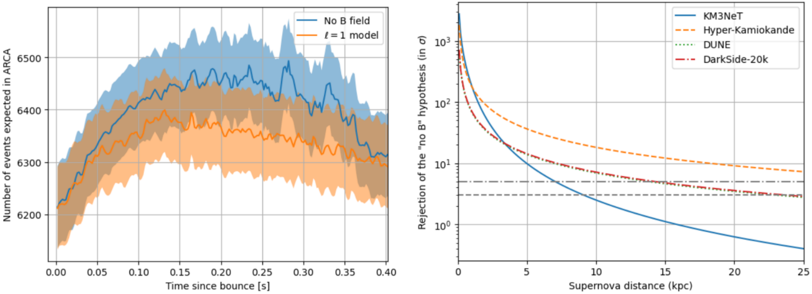
PNS modes signatures



- 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)

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Conclusions

- CCSN modeling is a multiphysics, multiscale problem
- Strong impact of microphysics on the large-scale dynamics
- GW and neutrinos open a unique window on the central engine dynamics
- 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

Perspectives

- Improve the state-of-the-art EoS used in CCSN models
- Probe more combinations of EoS and stellar progenitors
- Impact on nucleosynthesis yields
- Improve transport schemes and microphysics

Merci de votre attention !

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