Core-collapse supernovae simulations: explosion dynamics, multi-messenger emission, explosive nucleosynthesis

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MARIE CURIE ACTIONS

Outline of talk

1. Introduction
2. Numerical Algorithms
3. Explosion dynamics
4. Neutrino emission
5. Gravitational waves
6. Explosive nucleosynthesis
7. Summary

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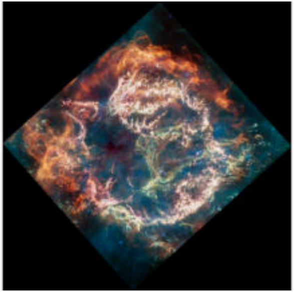
Core-collapse Supernovae

- Explosive end-of-life product of massive stars ($M \gtrsim 8 M_\odot$)
- Formation of stellar compact objects
- Dynamical feedback on galaxy evolution
- Explosive nucleosynthesis $\Rightarrow$ chemical evolution of galaxies
- Sources of gravitational waves and neutrinos

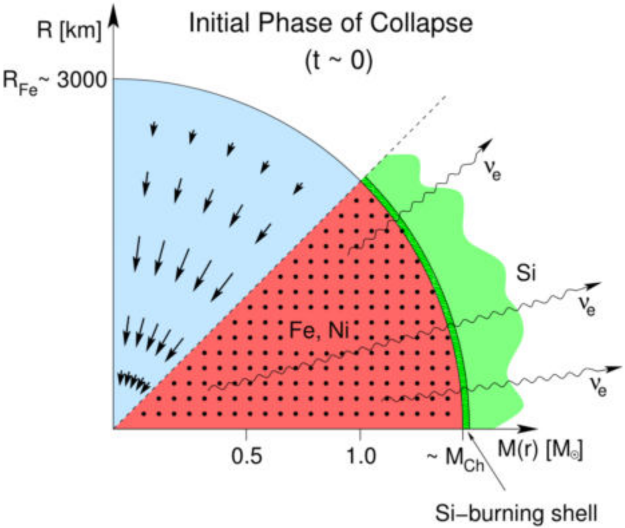
Credit: NASA, ESA, CSA



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

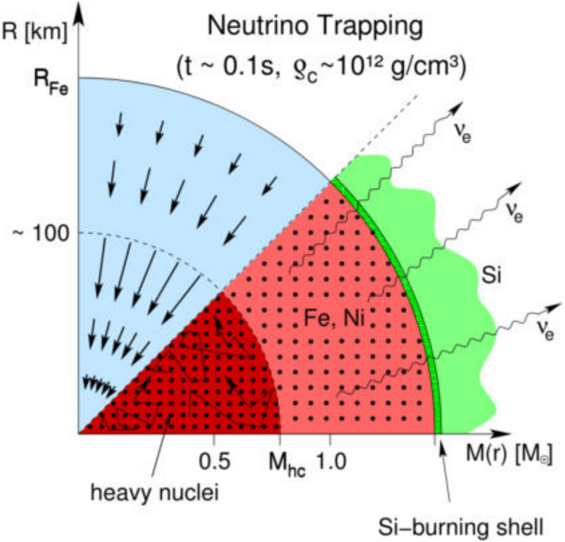
- Neutrino emission ($\sim 99\%$)
- Ejecta ($\sim 1\%$)
- Gravitational waves ($\sim 10^{-8}$)

Death of a massive star (1)



Janka (2017)

Death of a massive star (2)



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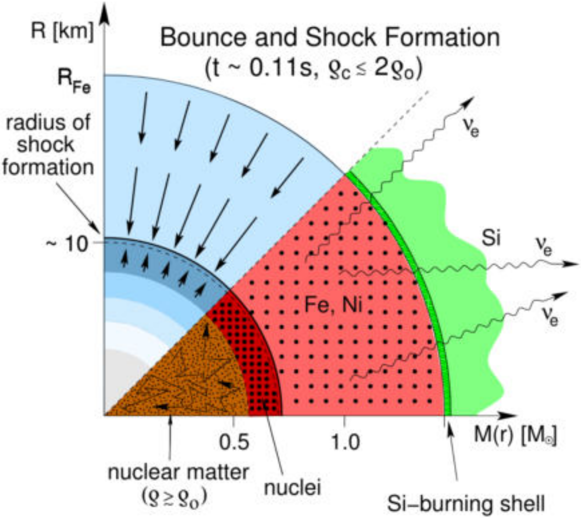
Death of a massive star (3)



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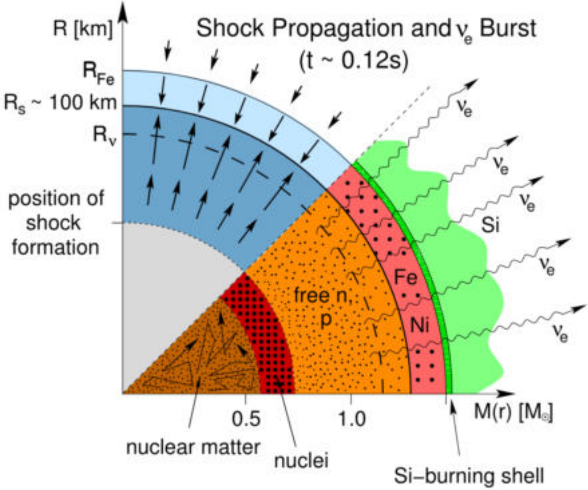
Death of a massive star (4)



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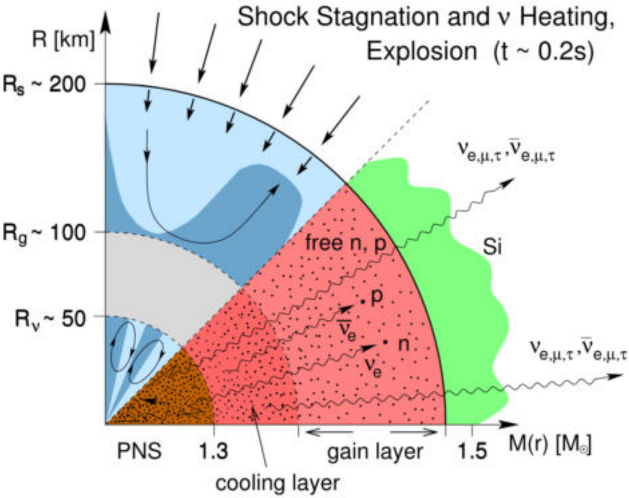
Death of a massive star (5)



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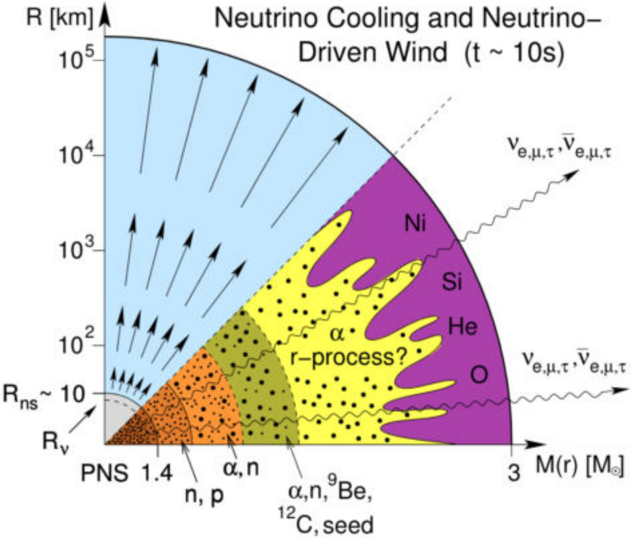
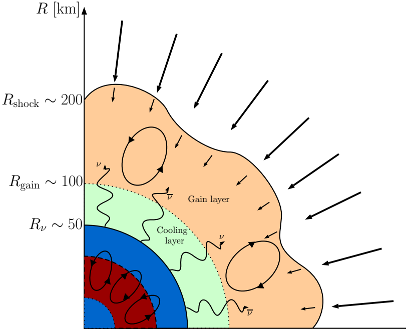
Death of a massive star (6)



Janka (2017)

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 (i.e. convection, SASI)

Neutrinos and GW directly probe the explosion mechanism

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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

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Gravitational force

Full GR

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

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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 (NSE)

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Popular choices

- LS220 (Lattimer and Swesty, 1991): compressible liquid-drop model
- Shen (STOS) (Shen et al., 1998): RMF with TM1 parameter set
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The CompOSE catalogue

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

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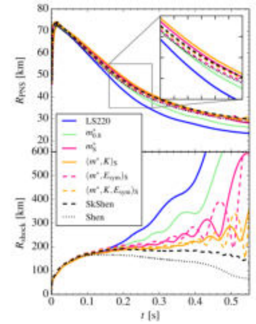
PNS and shock properties

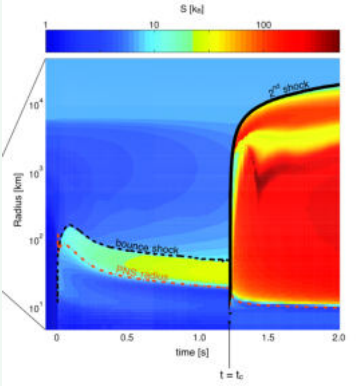
- Lower effective mass ⇒ lower contraction and ν energies
- Higher incompressibility ⇒ larger PNS radius (Yasin et al., 2018)



More specific EoS

Quark-hadron phase transition

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



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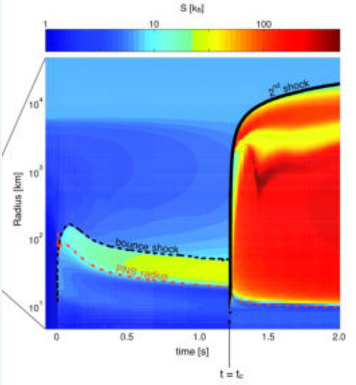
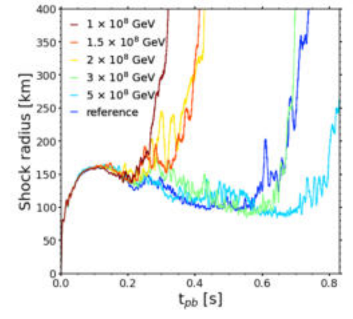


Axions in core-collapse supernovae

- Enhanced cooling (Betranhandy and O'Connor, 2022): $N + N \rightleftarrows N^* + N^* + a$
- Faster contraction ⇒ faster explosion



Neutrino Transport

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Leakage/heating schemes

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

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Isotropic Diffusion Source Approximation (IDSA)

- Diffusion at high densities, free-streaming at low ones (Liebendörfer et al., 2009)
- Particles separated into thermal/non-thermal in phase space
- Similar to Flux Limited Diffusion (FLD), but non-local sources

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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: $F_\nu^\theta = F_\nu^\phi = 0$ (Buras et al., 2006); Fast Multigroup Transport (Müller and Janka, 2015)
- 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)
- Spectral schemes (Just et al., 2015) or Grey schemes (Andresen et al., 2024).

Neutrino-matter interactions

(Bruenn85, Rampp&Janka02, Janka17)

Beta-processes (direct URCA processes)

- e^- and ν_e absorption by nuclei: $e^- + (A, Z) \leftrightarrow (A, Z-1) + \nu_e$
- e^- and ν_e captures by nucleons: $e^- + p \leftrightarrow n + \nu_e$
- e^+ and $\bar{\nu}_e$ captures by nucleons: $e^+ + n \leftrightarrow p + \bar{\nu}_e$

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"Thermal" pair production and annihilation processes

- Nucleon-nucleon bremsstrahlung: $N + N \leftrightarrow N + N + \nu + \bar{\nu}$
- e^-e^+ pair process: $e^- + e^+ \leftrightarrow \nu + \bar{\nu}$
- Plasmon pair-neutrino process: $\tilde{\gamma} \leftrightarrow \nu + \bar{\nu}$

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Reactions between neutrinos

- Neutrino-pair annihilation: $\nu_e + \bar{\nu}_e \leftrightarrow \nu_x + \bar{\nu}_x$
- Neutrino scattering: $\nu_x + \{\nu_e, \bar{\nu}_e\} \leftrightarrow \nu_x + \{\nu_e, \bar{\nu}_e\}$

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Scattering processes with medium particles

- Neutrino scattering with nuclei: $\nu + (A, Z) \leftrightarrow \nu + (A, Z)$
- Neutrino scattering with nucleons: $\nu + N \leftrightarrow \nu + N$
- Neutrino scattering with $e^\pm$: $\nu + e^\pm \leftrightarrow \nu + e^\pm$

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Standard neutrino explosions

Uncertain initial conditions

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

(Müller et al., 2017)

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Explodability

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

Ertl et al. (2016)

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PNS proper motions

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

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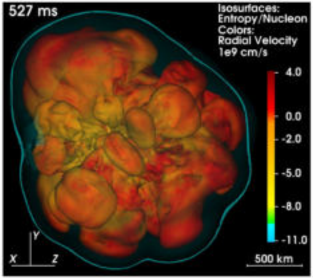
Hydrodynamic instabilities

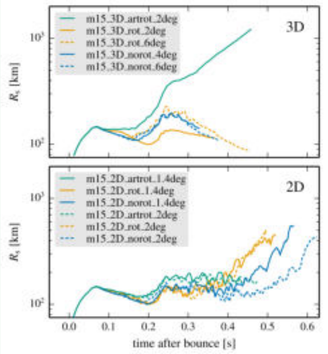
- Post-shock convection (ν energy deposition) and SASI
- 3D crucial
- Longer dwelling in gain region $\Rightarrow$ more efficient heating



Janka et al. (2016)

The impact of rotation

- Small fraction of fast rotating progenitors
- Rotation favors the explosion in 3D models (Summa et al., 2018)
- Development of spiral SASI modes (Foglizzo et al., 2015; Kazeroni et al., 2017)
- Enhanced neutrino heating (longer dwelling times in the gain region)
- Qualitatively different results in axisymmetry



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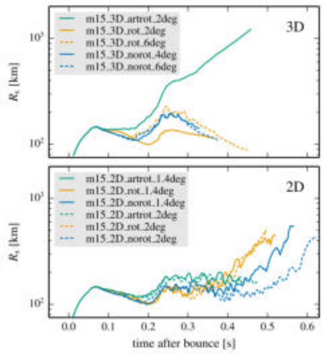


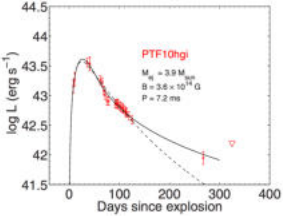
Summa et al. (2018)

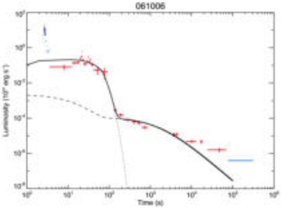
Rotation at collapse is one the most uncertain parameters!

- Stellar evolution models need to cover $\sim$ 10 Myrs (Heger and Langer, 2000)
- Magnetic fields (dynamos), angular momentum transport, winds, mass-loss,. . .

Outstanding explosions and magnetic fields

Inserra et al. (2013)





Gompertz et al. (2014)

Explosion kinetic energy

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

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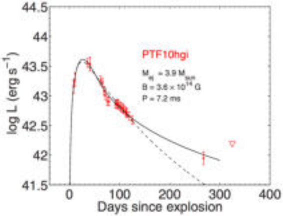

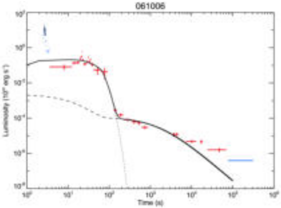

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Total luminosity

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

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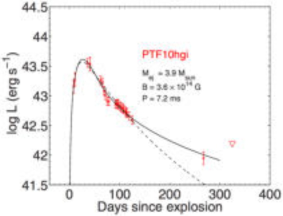

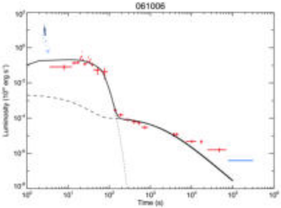

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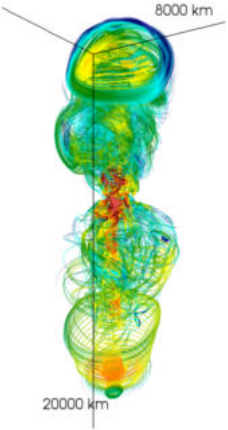
Lightcurves and X-ray plateaus

- 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)

Magneto-rotational explosions



Obergaulinger and Aloy (2021)

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; Winteler et al., 2012; Kuroda et al., 2020; Obergaulinger and Aloy, 2021; Bugli et al., 2021)

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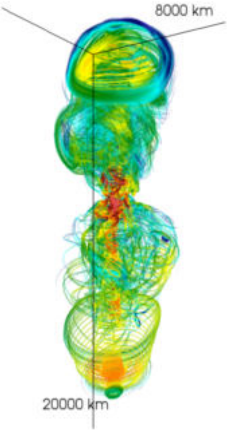

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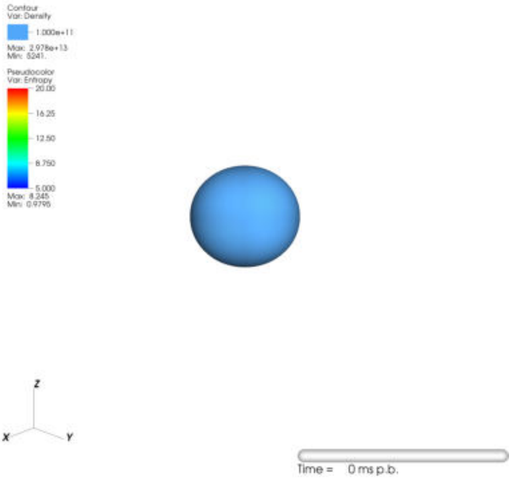
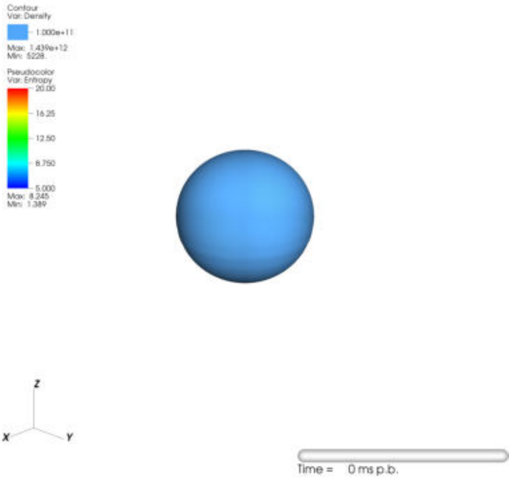
Origin of the magnetic field

- 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; Reboul-Salze et al., 2022)
  - Tayler-Spruit (Barrère et al., 2022, 2023)

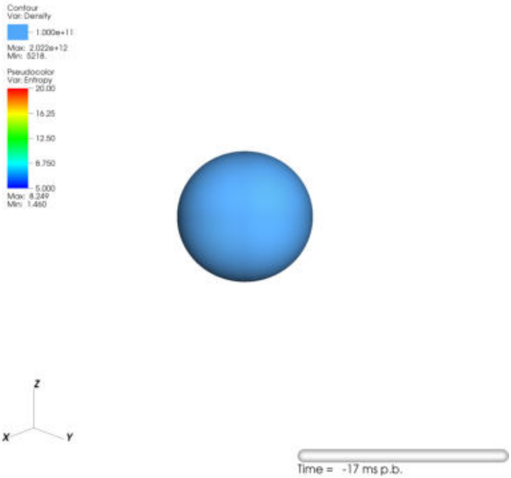
Hydrodynamic model



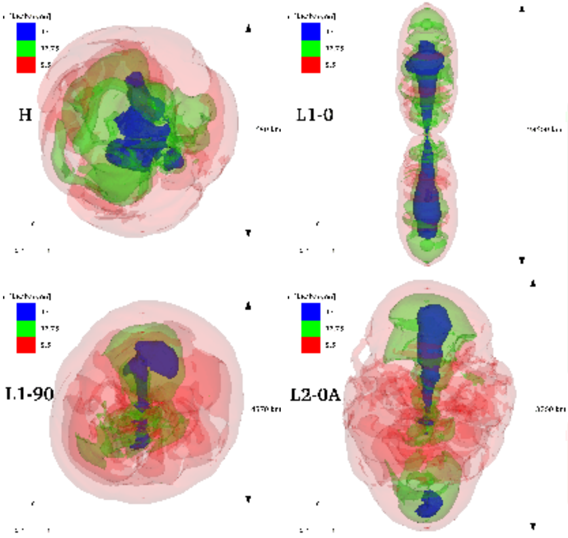
Aligned dipole



Equatorial dipole



Explosion Morphology



Bugli et al. (2021)

- Wide range of explosion energies, degree of ejecta collimation, and shock propagation speed
- Qualitative impact of rotation, field strength and topology
- All of them are highly uncertain!

Aligned dipolar magnetic fields are a magneto-rotational supernova best friend

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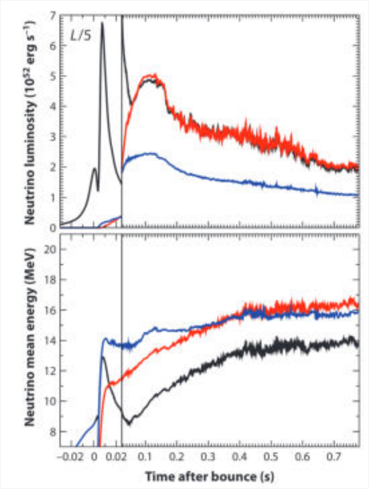
Neutrino emission

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

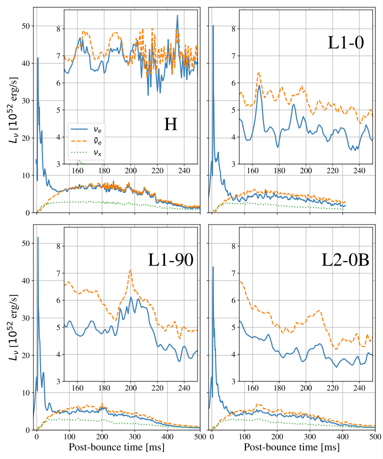


Janka (2012)

Magnetized models

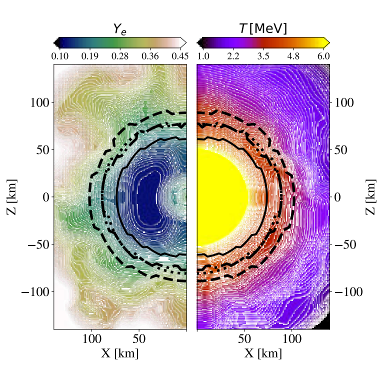
(MB+2023)

Lightcurves (equator)



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

Y_e distribution (hydro)



Hydrodynamic model

- More compact PNS ⇒ higher mean energies

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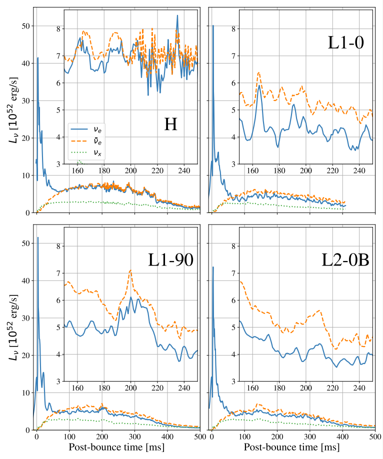

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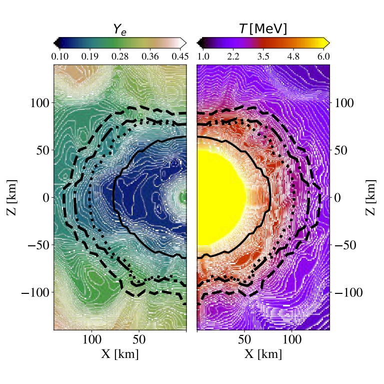
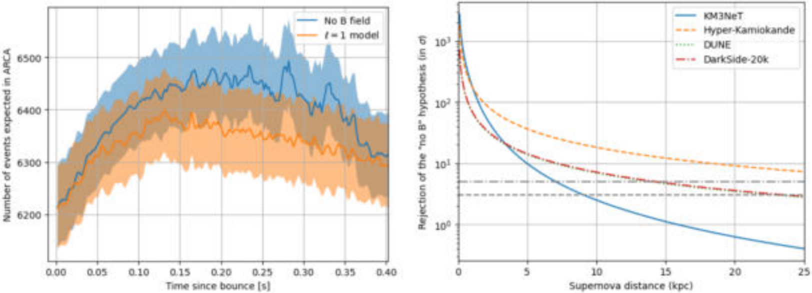


Quadrupolar model

- Outward transport of a.m. $\Rightarrow$ lower Y_e

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)

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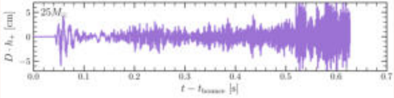
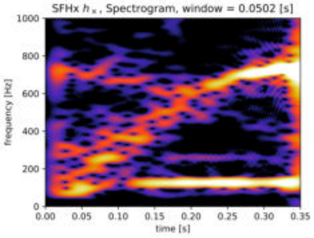
GW signals from standard CCSN

Main features

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

Radice et al. (2019)

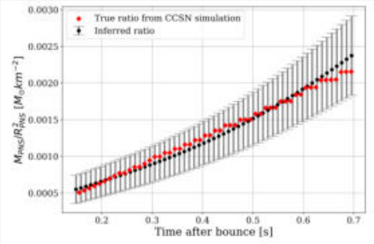




Kawahara et al. (2018)

Asteroseismology

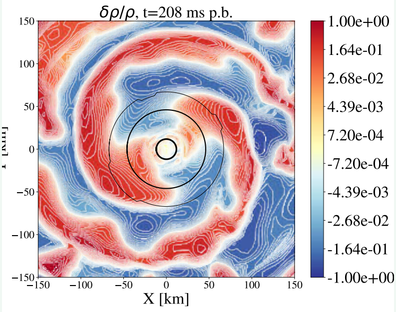
- Universal relations between g/f modes and M_{PNS}, R_{PNS} (Torres-Forné et al., 2019)
- Inference of PNS properties from GW signal (Bizouard et al., 2021)
- Impact of 3D models? Disentangle M_{PNS} from R_{PNS}?



Bruel et al. (2023)

Corotational instabilities

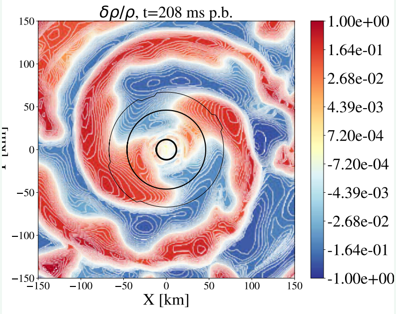
Hydrodynamic case



- Spiral structures forming with fast rotation
- Onset of the low $T/|W|$ instability
- Observed for different progenitors/rotation profiles (Takiwaki et al., 2016, 2021; Bugli et al., 2023)

Corotational instabilities

Hydrodynamic case



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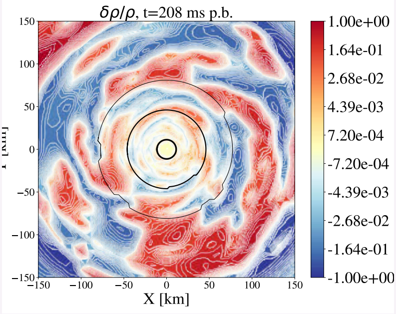
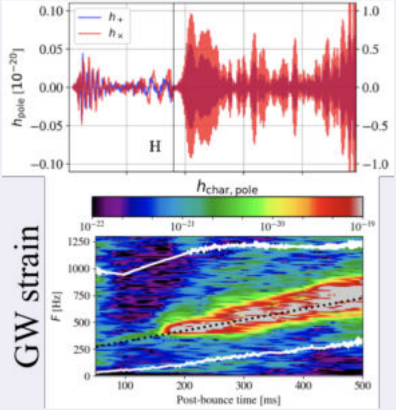
Magnetized case



- No spiral structures
- Smaller-scale density perturbations
- Weak dependence on magnetic field
- B field stabilizes against low $T/|W|$

GW emission from low $T/|W|$

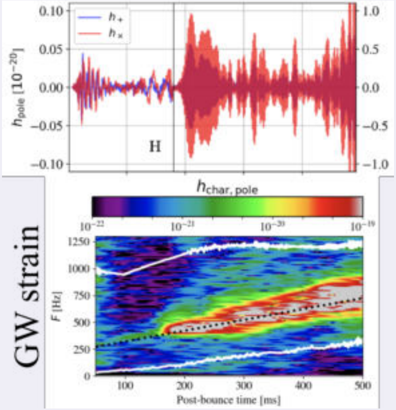
Hydrodynamic case



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

GW emission from low $T/|W|$

Hydrodynamic case



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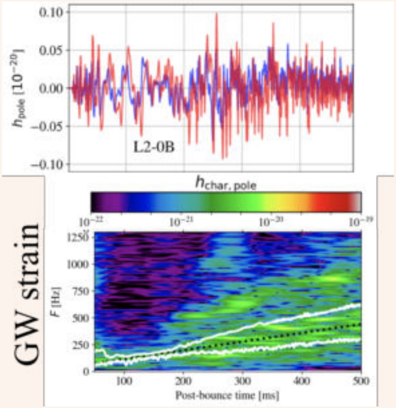
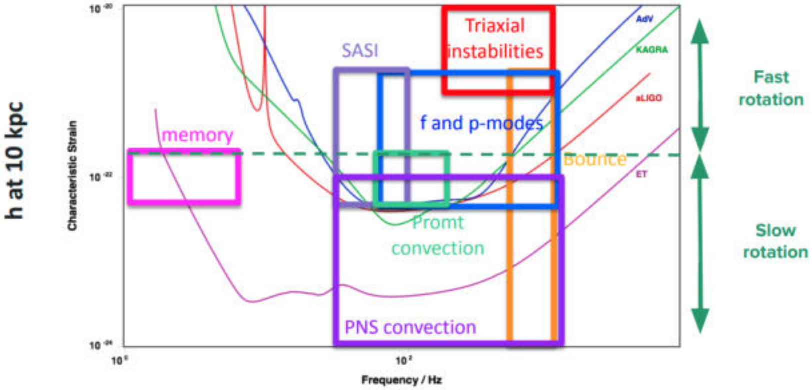
Magnetized case (quadrupole)



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

Gravitational waves from CCSN



Credit: Pablo Cerdà-Duràn

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From CCSN models to nucleosynthetic yields

Nuclear reaction networks

- Large set of coupled ODEs tracking nuclear abundances over time
- NSE ($T \gtrsim 6$ GK) $\Rightarrow$ set of algebraic Saha equations
- Several 10^3 isotopes tracked in post-processing

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In-situ MHD-network coupling

- Isotopes advected by the flow $\Rightarrow$ from ODEs to PDEs
- Direct feedback on the flow, direct thermodynamic conditions
- Highly expensive, typically $\sim$100 species (Harris et al., 2017; Sandoval et al., 2021)

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Input from CCSN models

- Lagrangian tracer particles providing density, temperature, electron fraction
- Accurate neutrino transport schemes are crucial!
- Nishimura et al. (2015); Bovard et al. (2017); Reichert et al. (2023)
- Recent review: Obergaulinger and Reichert (2023)

Nucleosynthesis and B field topology (Reichert,MB+2024)

- Analysis of 3D MHD models with different B field configurations (Bugli et al., 2023)
- WinNet nuclear reaction network (Winteler et al., 2012; Reichert et al., 2023) $\sim$ 6500 nuclei

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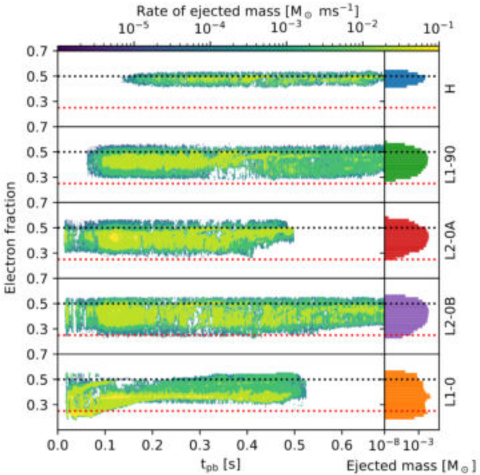
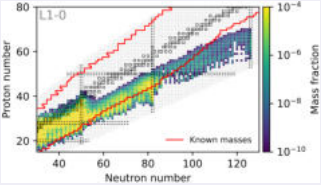
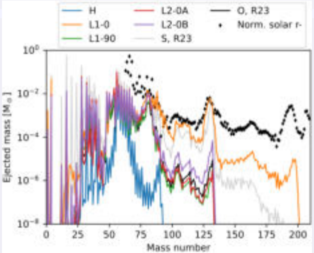


- More neutron-rich material for magnetized models
- Lowest Y_e for dipolar fields
- Neutron-rich material is expelled promptly only for strong MR explosions
- Rotation supports against the accretion onto the PNS
- Longer simulations required to reduce uncertainties



Ejecta composition

(Reichert,MB+2024)



- All magnetized models produce 1st r-process peak elements
- 2nd peak reproduced only for the aligned dipole
- No 3rd peak nor actinides, consistent with recent 3d models (Reichert et al., 2023) and in contrast to 2d models (Reichert et al., 2021).
- Crucial estimates for chemical evolution models (Dvorkin et al., 2020)

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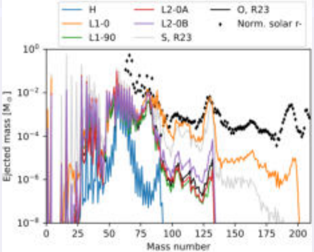

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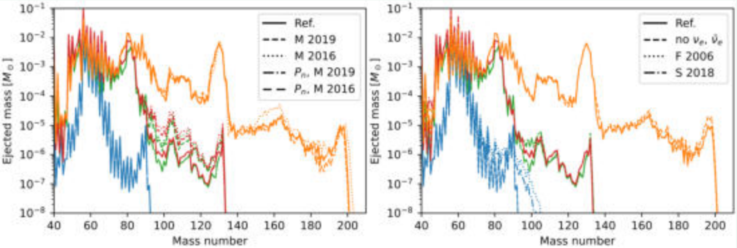
Dynamical uncertainties can dominate over nuclear network details!



Ejecta masses for different β-decays (left) and neutrino treatments (right).

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Summary

- 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 engine's dynamics
- Both rotation and magnetic fields qualitatively affect the explosion
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Perspectives

- Constraints from stellar evolution models
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Questions?

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