Core collapse with rotation and magnetic fields: explosion, compact remnants, observables

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SN2025gw: First IGWM Symposium on Core Collapse Supernova Gravitational Wave Theory and Detection, Warszawa, 2025/07/21–2025/07/25

Acknowledgements

- Collaboration with M. Reichert, M.Á. Aloy, A. Arcones, G. Navó, M. Gabler, M. Bugli, J. Guilet, M. Cusinato
- Simulations run on the Red Española de Supercomputación (Barcelona Supercomputing Centre) and at the Universitat de València
- We acknowledge support through the grant PID2021-127495NB-I00 funded by MCIN/AEI/10.13039/501100011033 and by the European Union, and the Astrophysics and High Energy Physics programme of the Generalitat Valenciana ASFAE/2022/026 funded by MCIN and the European Union NextGenerationEU (PRTR-C17.I1) as well as via the Ramón y Cajal programme (RYC2018-024938-I).

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Financiado por la Unión Europea NextGenerationEU

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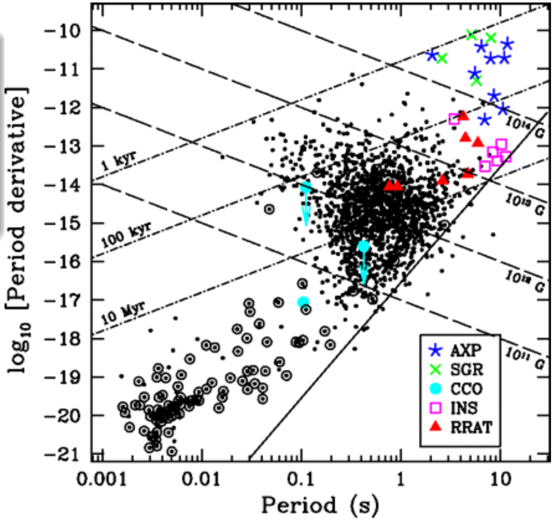
Why magnetic fields?

- pulsar $\vec{B}$-fields
- magnetars
- highly energetic or relativistic SNe



Kaspi (2010)

Context

Why magnetic fields?

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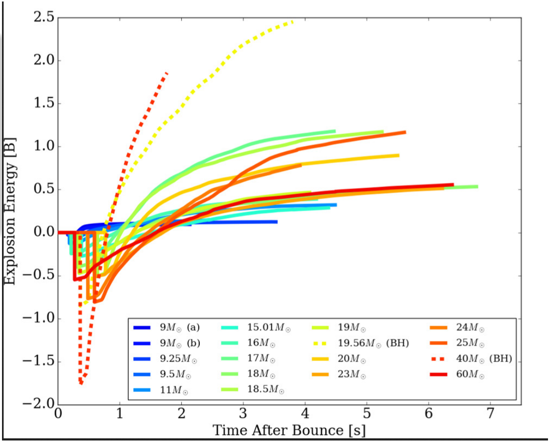
- highly energetic or relativistic SNe

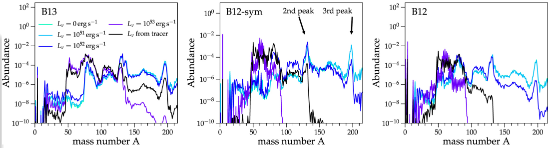


Burrows et al. (2024)

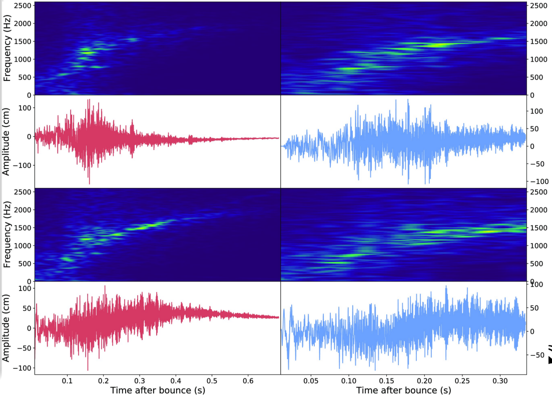
Context

Open issues

- unambiguous observation of dynamically relevant magnetic fields
- What would be characteristic observables?
- Rising number of 3d simulations with MHD show some common features. Physics or numerics?
- What do we know about progenitors?



Mösta et al. (2018)



Powell et al. (2023)

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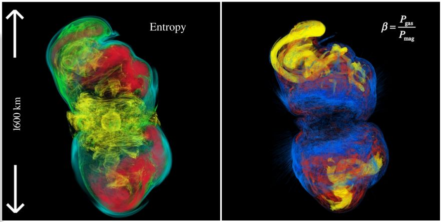
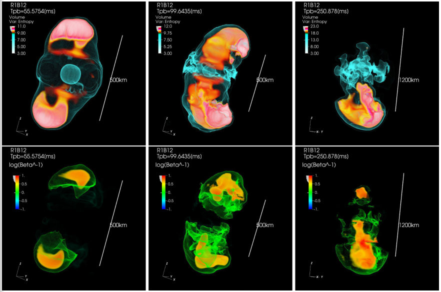


Mösta et al. (2014)



Kuroda et al. (2020)

Context

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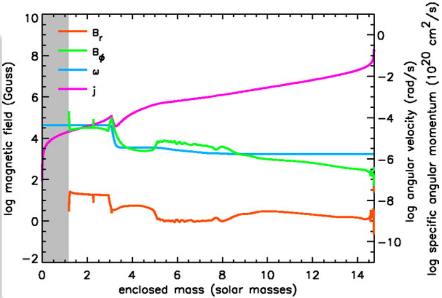
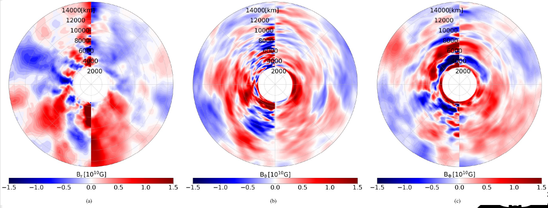


Heger et al. (2005)



Varma & Müller (2023)

Methods

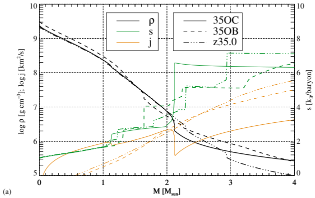
Long-term self-consistent global simulations in axisymmetry and 3d

MHD, ν-transport: Aenus/ALCAR, Just et al., 2015 and updates since

- multi-D MHD
- TOV gravity
- multi-D spectral two-moment ν transport with $\mathcal{O}(v/c)$ velocity terms and gravitational terms
- relevant interactions
- microphysical EOS: Lattimer & Swesty, 1991 with incompressibility of $K = 220\,\mathrm{MeV}$
- FV scheme with high-order MP reconstruction
- MHD: constrained transport
- angular coarsening

Progenitors

- stellar model 35OC from (Woosley & Heger, 2006)
- $M_{\mathrm{ZAMS}} = 35\,M_{\odot}$
- evolved in spherical symmetry including rotation and the Taylor-Spruit dynamo
- prescribed mass loss leads a mass at collapse of $M \approx 28\,M_{\odot}$
- compact core with $\xi_{2.5} = 0.49$
- use the magnetic field from the stellar evolution model, some variation thereof, or a global low-order (dipole, ...) field



Progenitors

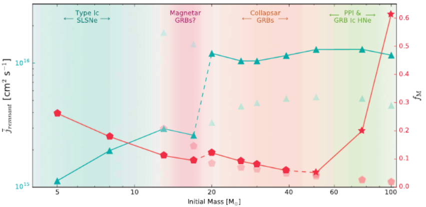


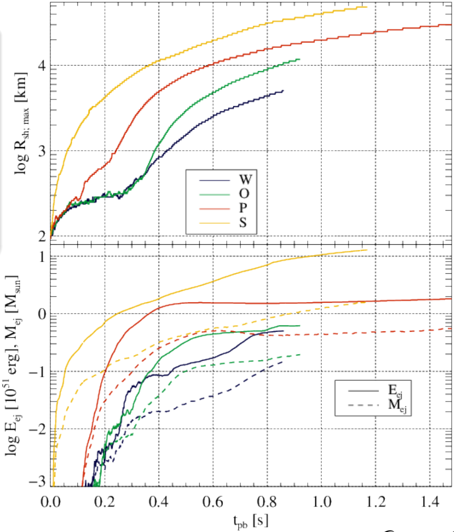
Figure 11. Average angular momentum at core O depletion of the first 1.5 $M_\odot$, for models with mass $M < 20\ M_\odot$, and first 5 $M_\odot$ for the rest (left axis, blue triangles). We also show the ratio between shell and ejecta masses for the same remnant masses (right axis, red pentagons), as a function of initial mass for Series B models. The values for converse masses are added in lower saturation for comparison. The ratio between shell and ejecta mass for models that undergo pulsational pair instability is also calculated (red stars), with ejected shell masses according to Woosley (2017).

- series of stars from 5 to 39 $M_\odot$ (Aguilera-Dena et al., 2018)
- evolved in spherical symmetry including rotation and the Taylor-Spruit dynamo
- strong rotational mixing $\rightarrow$ chemically homogeneous evolution
- possible progenitors of SLSNe and GRBs?

35 $M_\odot$ stars in 3D

Weak field

- explosion at $t \sim 0.4$ s with relatively low (seemingly saturated) energy and ejecta mass

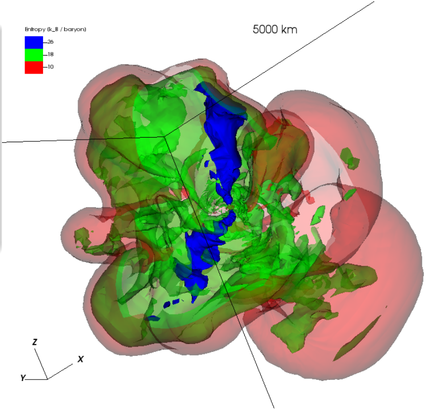


max shock radii, ejecta energies and masses of the 3d runs

35 $M_\odot$ stars in 3D

Weak field

- explosion at $t \sim 0.4$ s with relatively low (seemingly saturated) energy and ejecta mass
- complex ejecta morphology with large bubbles and a weak outflow

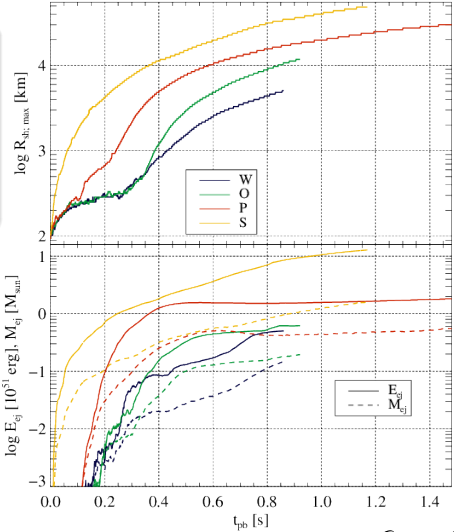


entropy contours near the end of the simulation

$35\,M_\odot$ stars in 3D

Strong field

- early and prompt explosions



max shock radii, ejecta energies and masses of the 3d runs

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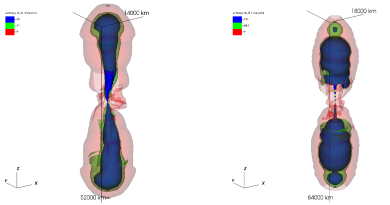
Strong field

- early and prompt explosions
- rapid, collimated jets

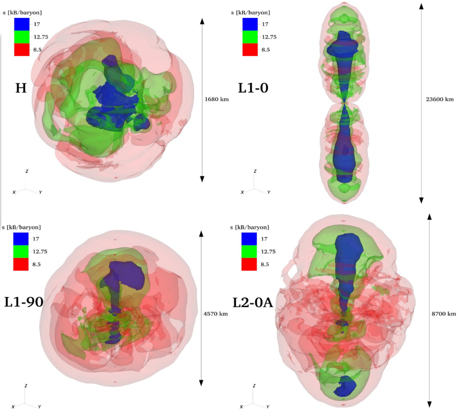


entropy contours near the end of the simulation

$35\,M_\odot$ stars in 3D

Strong field

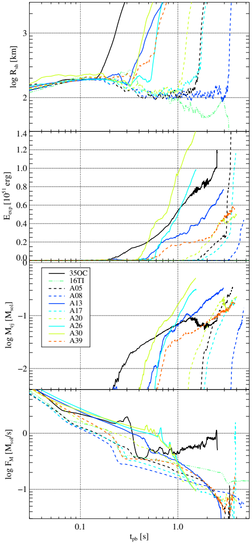
- early and prompt explosions
- rapid, collimated jets
- jets appear also for non-dipole fields, albeit weaker



Chemically homogeneous stars in axisymmetry

In axisymmetry

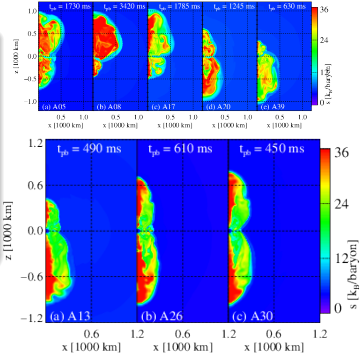
- explosions for all cores



Chemically homogeneous stars in axisymmetry

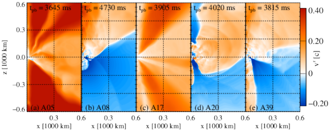
In axisymmetry

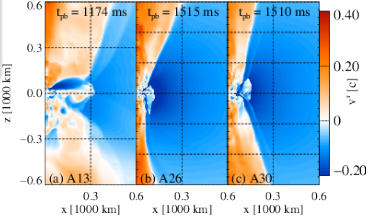
- explosions for all cores
- neutrino as well as MHD mechanisms
  directed outflows launched by the PNS



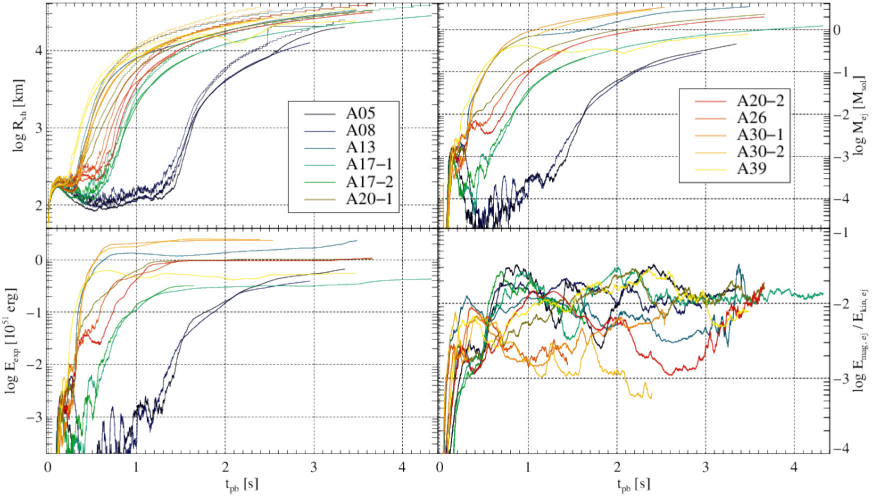
In axisymmetry

- explosions for all cores
- neutrino as well as MHD mechanisms directed outflows launched by the PNS
- rapid PNS gaining mass → NS and BH formation



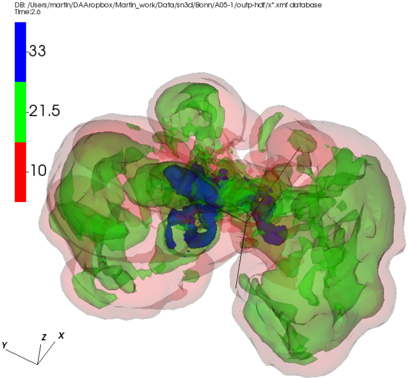


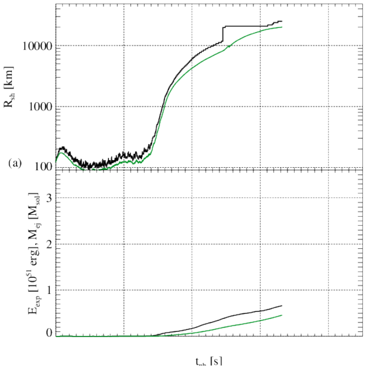
Chemically homogeneous stars exploding in 3D



Chemically homogeneous stars exploding in 3D

A05 - weak and late explosion





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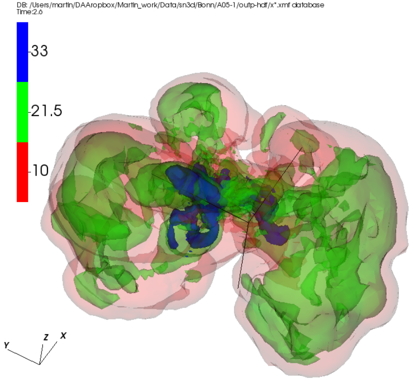
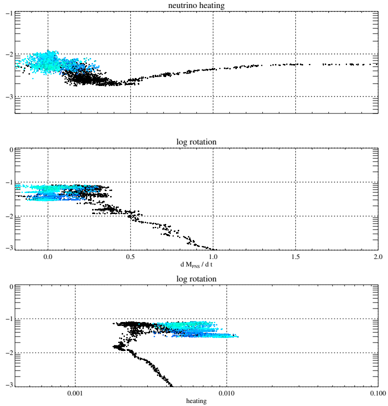
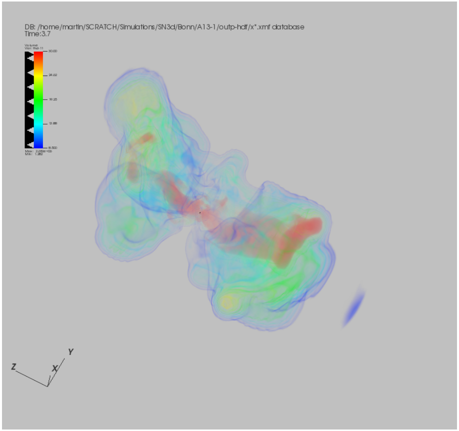
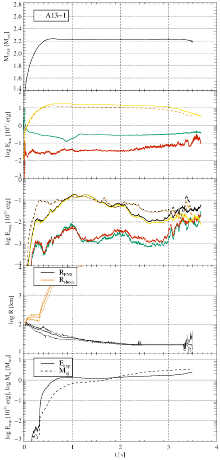




Chemically homogeneous stars exploding in 3D

A13 - early explosion with stronger magnetic imprint





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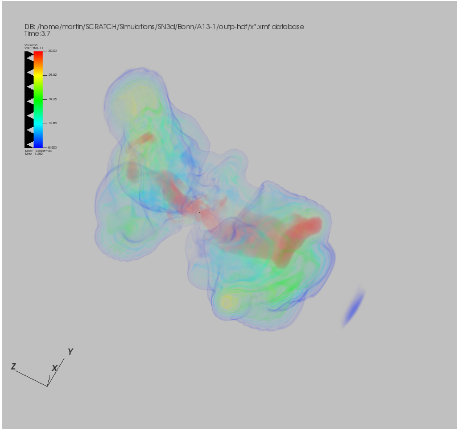
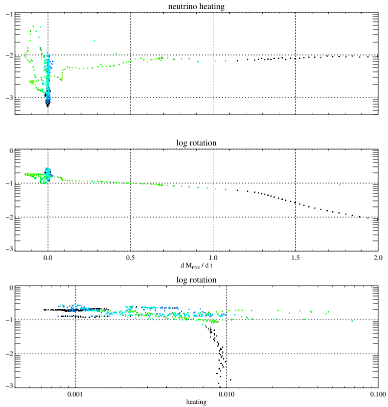
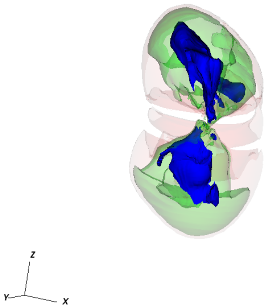
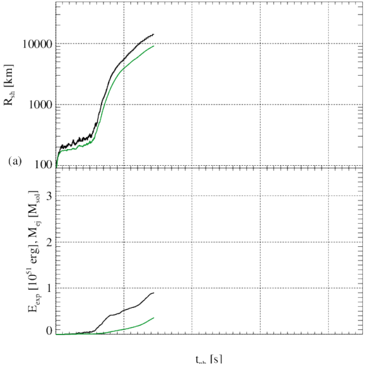




Chemically homogeneous stars exploding in 3D

A26 - strong explosion with BH formation





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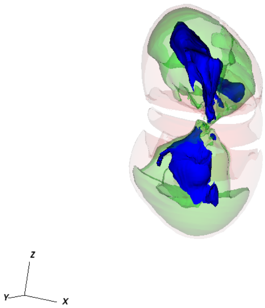
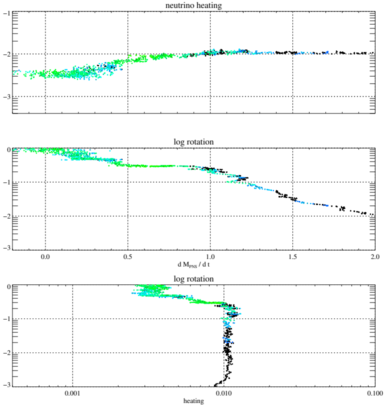
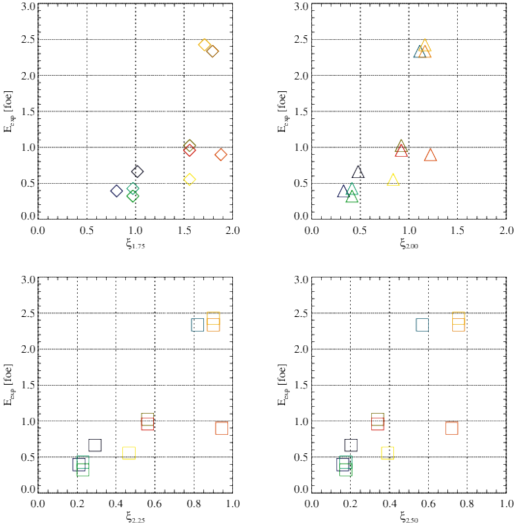


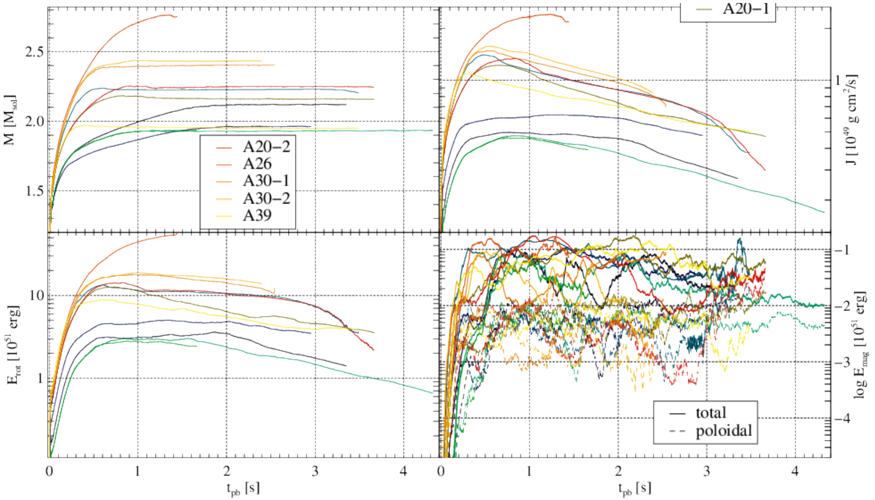


Chemically homogeneous stars exploding in 3D

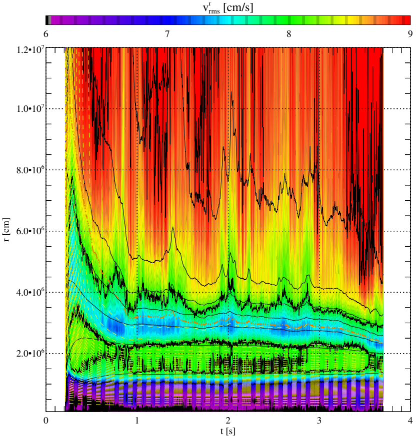


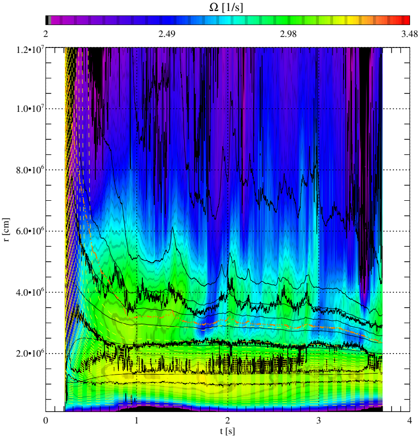
loose correlation between compactness parameters, $\xi_M = M/R(M)$, and explosion energy

Chemically homogeneous stars exploding in 3D



Evolution of the PNS: A39

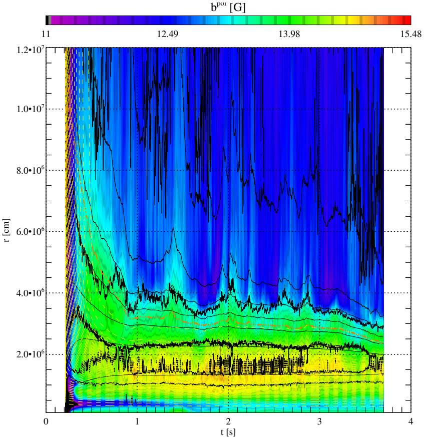


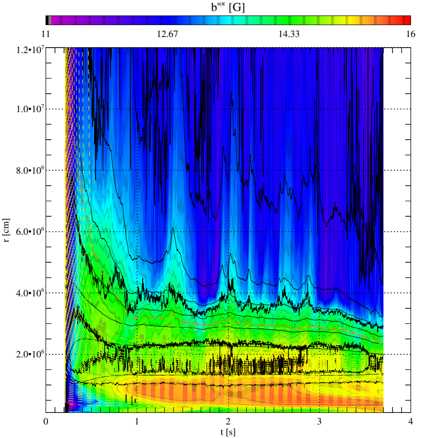


very long lasting convective layer in the PNS

... and differential rotation

Evolution of the PNS: A39



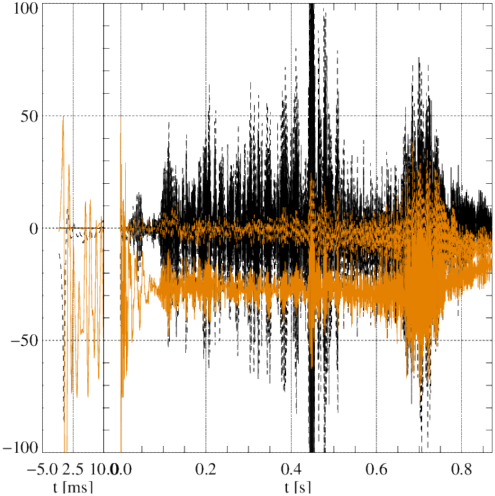


poloidal magnetic field at the bottom of the convective layer...

... and toroidal field further inside still

35 $M_\odot$: 3d GW signals

- model W (ν-driven, later weak jets)



GW signal: $h_{+/\times}$ (solid/dashed) along polar/equatorial line of sight (black/orange)

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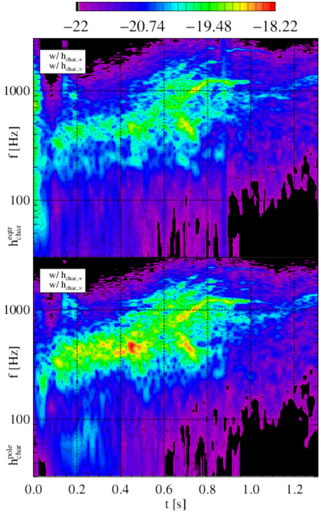
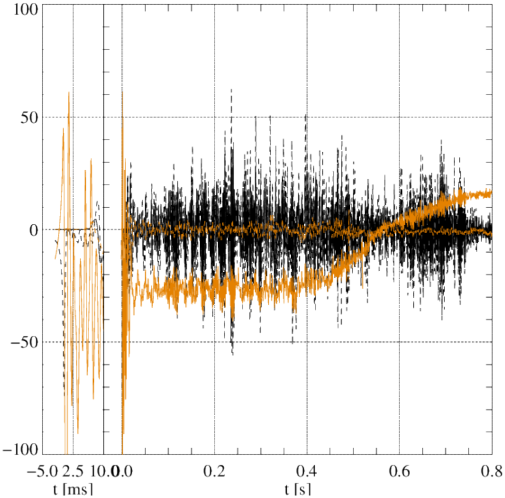


spectrograms of the characteristic strain

- model W (ν-driven, later weak jets)
- model O



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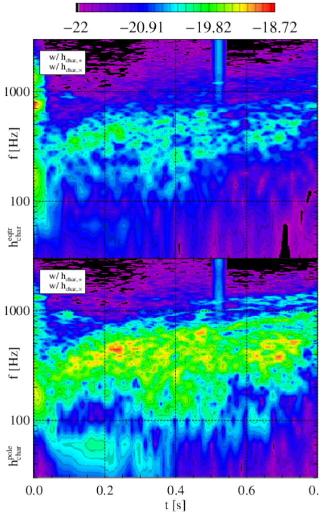

spectrograms of the characteristic strain

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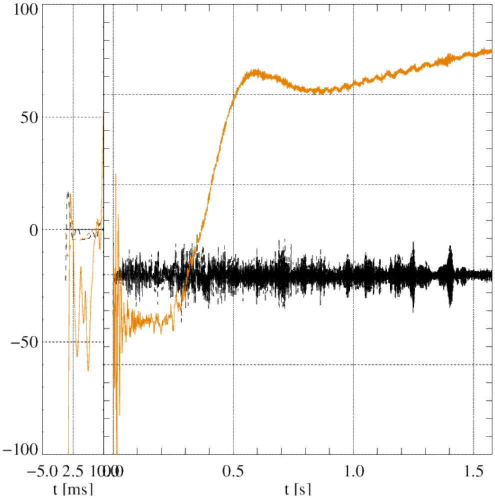
- model O
- model P



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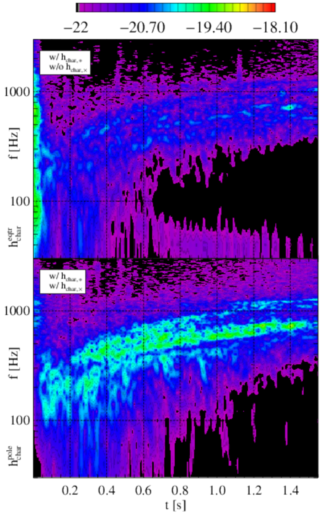
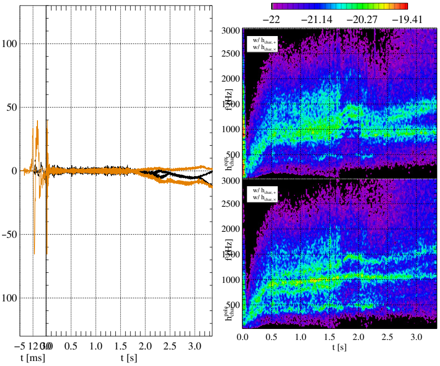
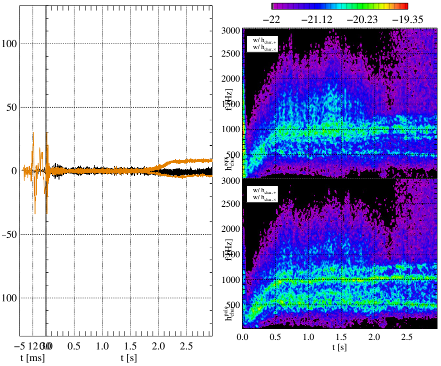


spectrograms of the characteristic strain

3d chemically homogeneous stars: GW signal

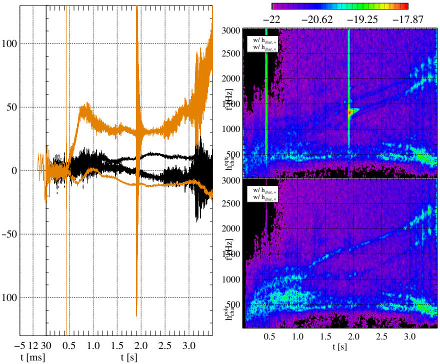


$5\,M_{\odot}$

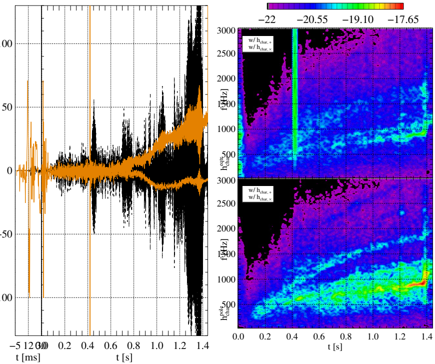


$8\,M_{\odot}$

3d chemically homogeneous stars: GW signal

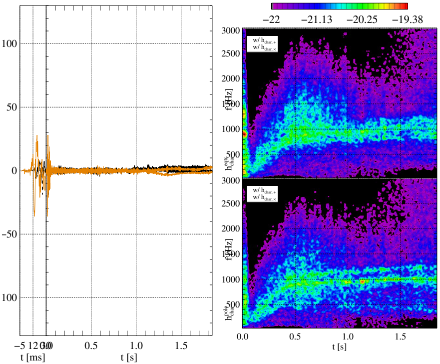


$13\,M_\odot$

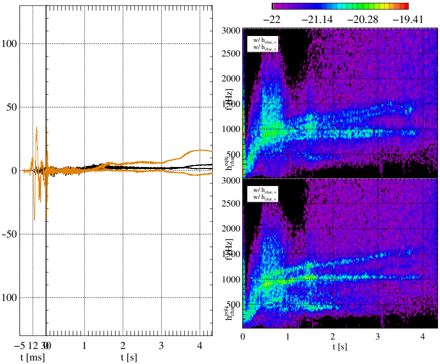


$26\,M_\odot$

3d chemically homogeneous stars: GW signal

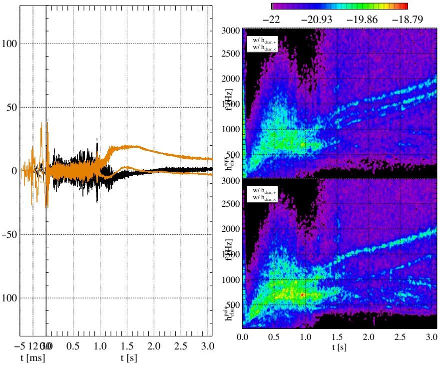


$17\,M_\odot$

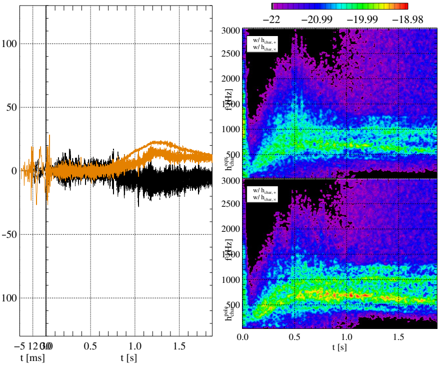


$17\,M_\odot$

3d chemically homogeneous stars: GW signal

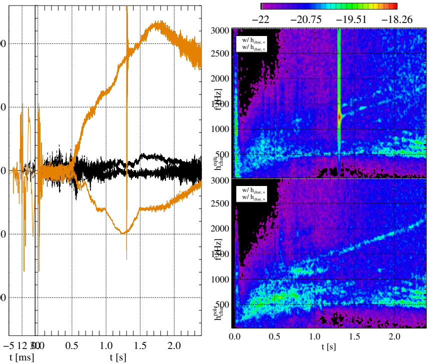


$20\,M_\odot$

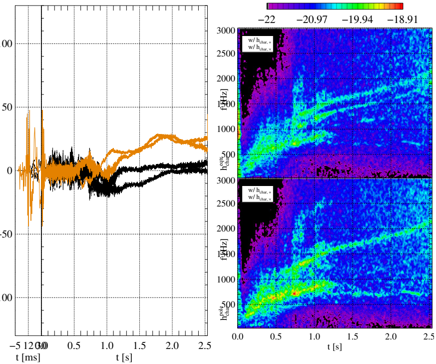


$20\,M_\odot$

3d chemically homogeneous stars: GW signal

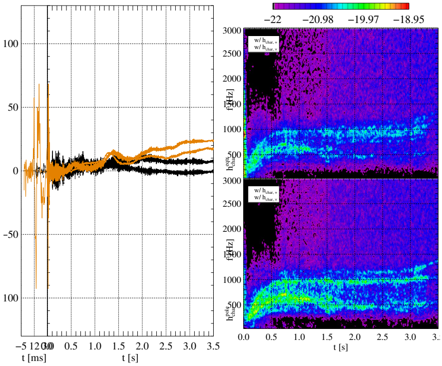


$30\,M_\odot$



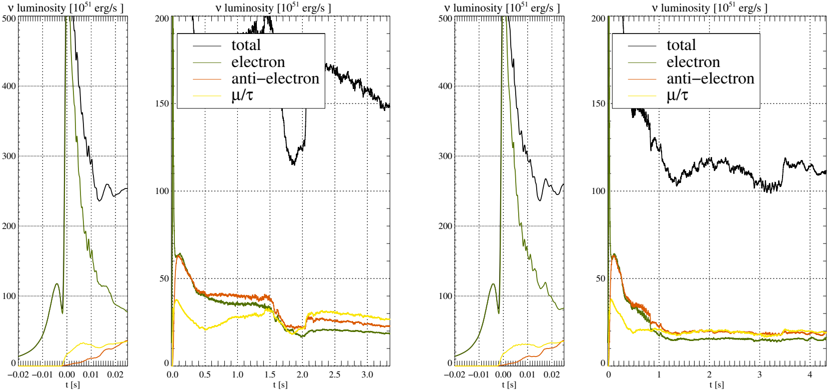
$30\,M_\odot$

3d chemically homogeneous stars: GW signal

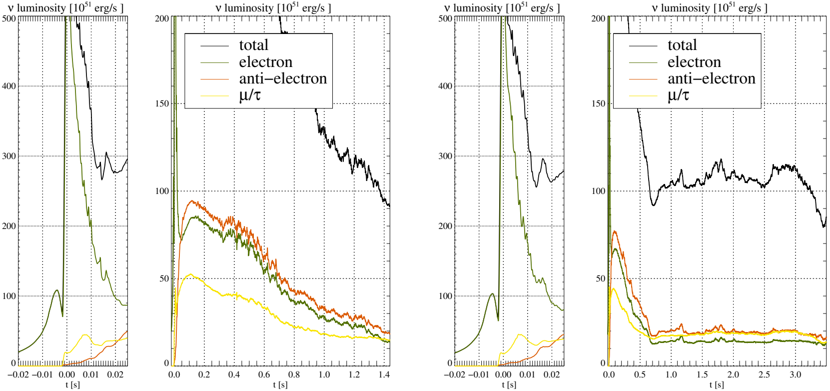


$39\, M_{\odot}$

Neutrino emission

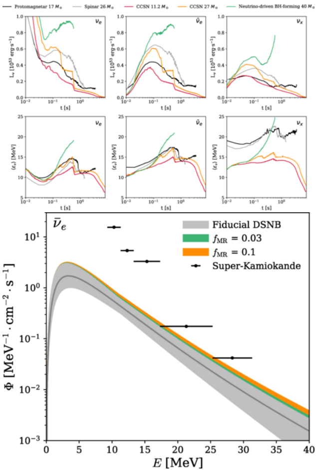


Neutrino emission



Diffuse SN neutrino background?

- how would a population of SNe with long-lasting neutrino emission modify the diffuse neutrino background?
- relatively high neutrino energies, as seen in some cases, might increase detection chances
- neutrino emission + assumptions on population $\rightarrow$ we might get there...



Nucleosynthesis

Method

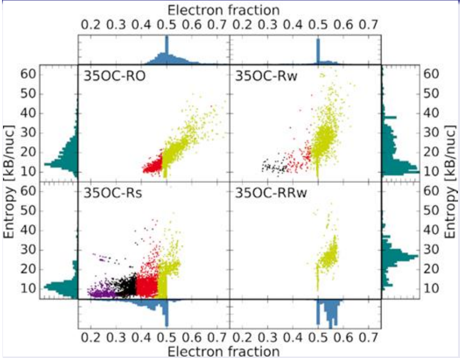
- no nuclear network at simulation run-time

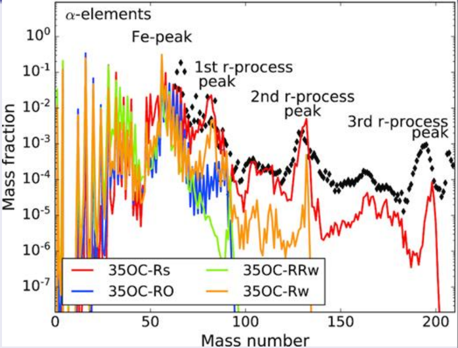
→ sampling the evolution of the ejecta via Lagrangian tracer particles

- apply WinNet (Winteler et al, 2012) with 6545 nuclei up to $Z = 111$ to the tracers
- reactions from JINA Reaclib and NSE above $T = 0.5\,\mathrm{GK}$

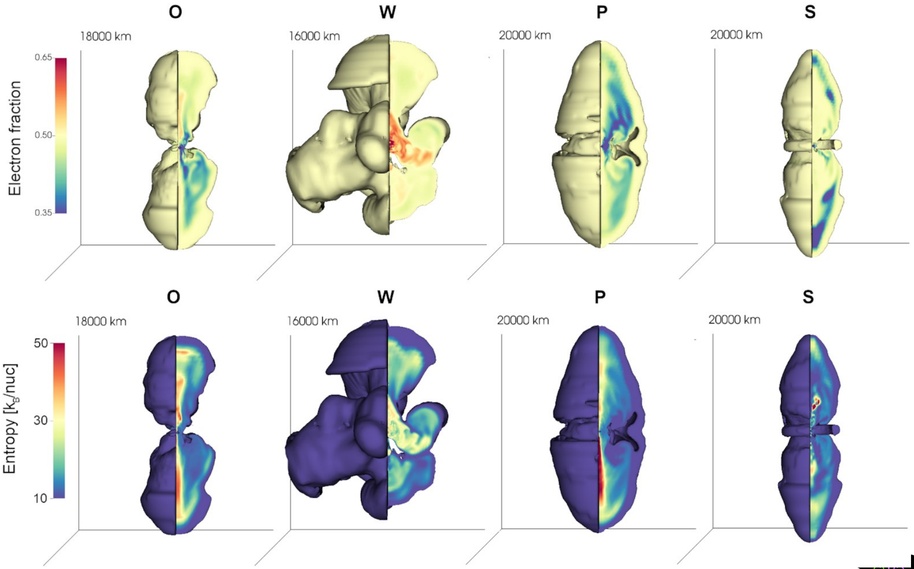
Nucleosynthesis

35OC: axisymmetry

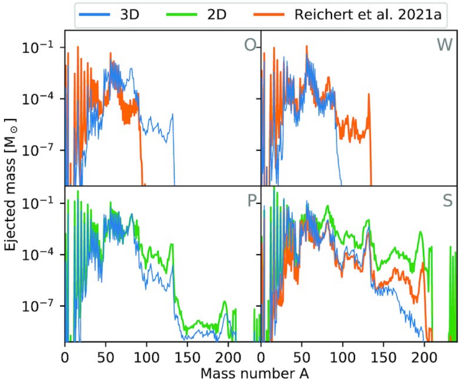




Nucleosynthesis



Nucleosynthesis



- differences in conditions and yields between 2d and 3d
- but not necessarily a unique trend
- less r-process in 3d, but strong fields still reach $A \gtrsim 200$

Summary

- set of long-term simulations in 3d across mass range from 5 to 39 $M_\odot$
- neutrino-driven and MHD explosions with energies below and above the 10^{51} erg mark and with high degrees f asymmetry
- neutron stars and black holes
- GW and neutrino emission lasting for seconds
- potential for r-process?

TBD

The MOLT$\vec{B}$E catalogue: Models and Observables of Luminous, Turbulent, Magnetic Explosions