Magneto-rotational supernovae as progenitors of lGRBs

Miguel A. Aloy

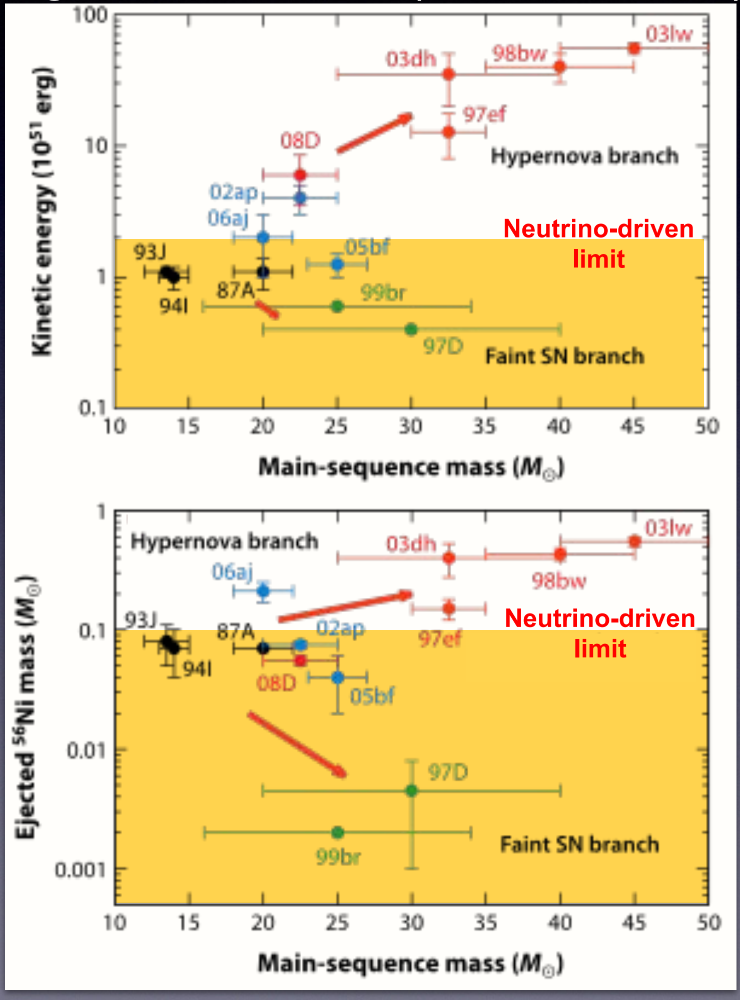
Departamento de Astronomía y Astrofísica

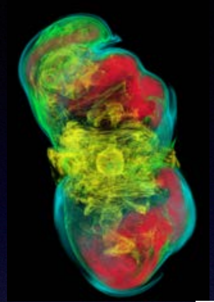
VNIVERSITAT DE VALÈNCIA

collaborators
M. Obergaulinger, M. Bugli, J. Guilet, M. Reichert, A. Arcones, A. Griffiths

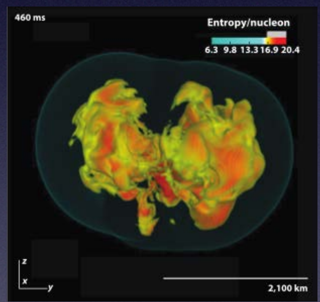
Stellar rotation and magnetic fields

Regular vs extreme SNe (Nomoto et al. 2013)

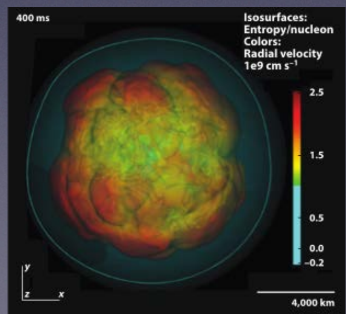




Mösta+14 $\Omega_{\rm rot} \neq 0, \vec{B} \neq 0$



Summa+18 $\Omega_{\rm rot} \neq 0$



Melson+15a $\Omega_{\rm rot} = 0$

- HN branch unlikely neutrino driven; MRSN?
- Magnetic fields + rotation allow for collimated outflows if the strength and topology are adequate
- ***Focus here***: on relatively fast rotating models with different degrees of magnetic energy and low metallicity (i.e., likely progenitors of long GRBs and SLSNe).
  - Formation of central engine.
  - Collimated ejecta.
  - Nucleosynthetic signature.

ν-*RMHD* models (2D/3D)

Originally rotating (Woosley & Heger 2006)

- **35OC**: standard collapsar progenitor; Z =0.1Z$_\odot$, fast rotating, M_{Fe} =2.02 M$_\odot$.
  - stellar evolution (SE) includes rotation and magnetic fields (TS dynamo).
  - mass @ collapse ~ 28 M$_\odot$.

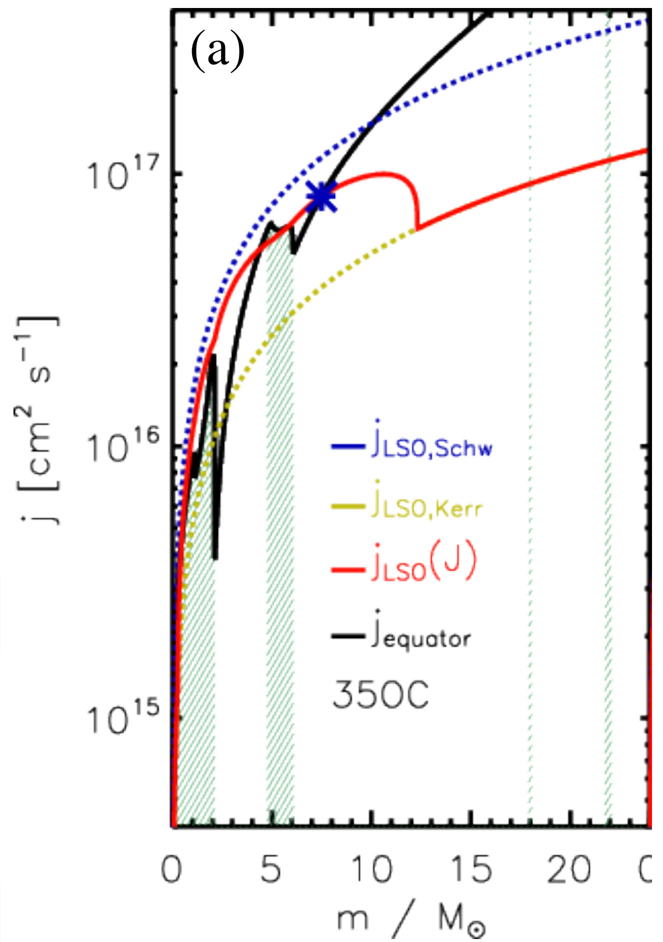
Goal 1: Impact of the variation of stellar evolution parameters of fast-rotating, cores (M_{ZAMS}=35M$_\odot$) on compact remnants and explosion types

other cores of 20M$_\odot$ in Obergaulinger, Just & Aloy (2018; JPhG)

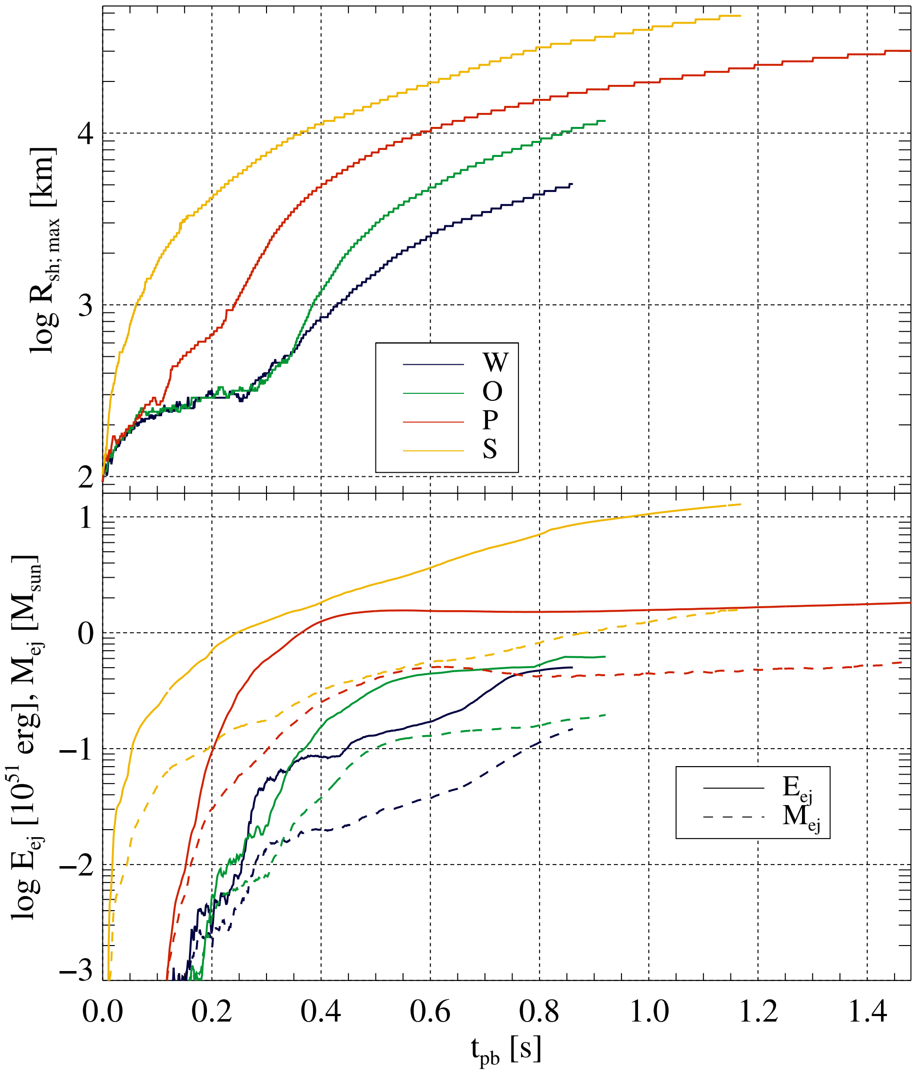
Obergaulinger & Aloy (2017, MNRAS, 469, L43)
Obergaulinger & Aloy (2020, MNRAS, 492, 4631) - P1

Aloy & Obergaulinger (2021, MNRAS, 500, 4365) - P2
Obergaulinger & Aloy (2021, MNRAS, 503, 4942) - P3

models	Short name		B_p	B_ϕ	B-profile	Ω-profile	$\xi_{2.5}$
35OC-Rw	W	(=weak field)	10^{10}	10^{10}	Dipole	Original	0.49
35OC-RO	O	(=original field)	5×10^{10}	10^{12}	Original	Original	0.49
35OC-Rp3	P	(=interm. field)	1.5×10^{11}	10^{12}	Original*	Original	0.49
35OC-Rs	S	(strong field)	10^{12}	10^{12}	Dipole	Original	0.49

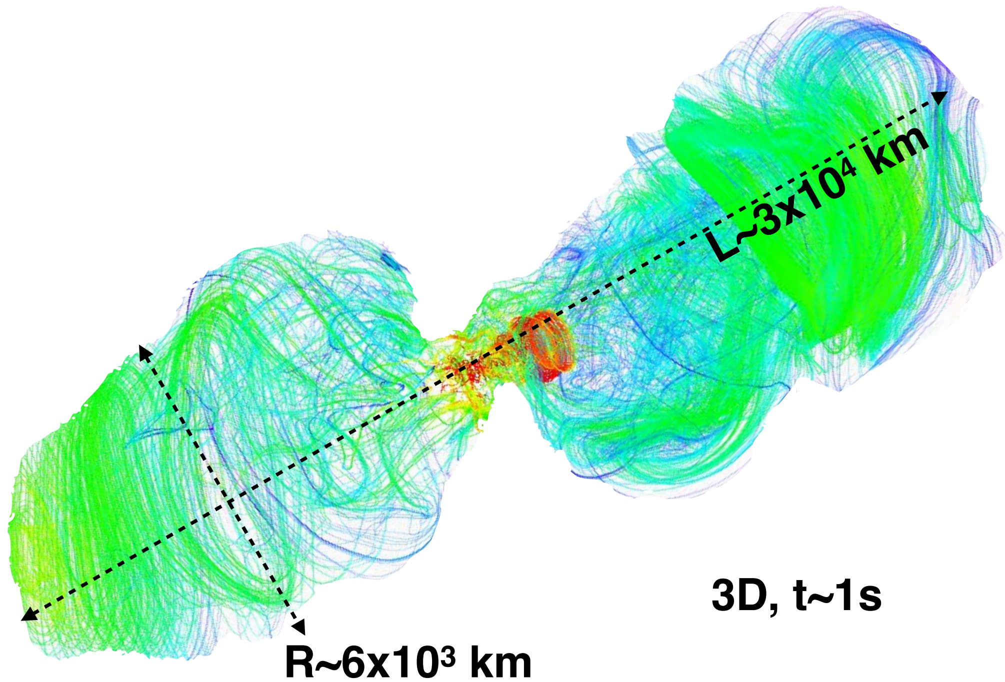


Stellar rotation + variations in B-field



Reference model O:

- ***SN mediated by ν's + B-fields + rotation***
- ***highly collimated***

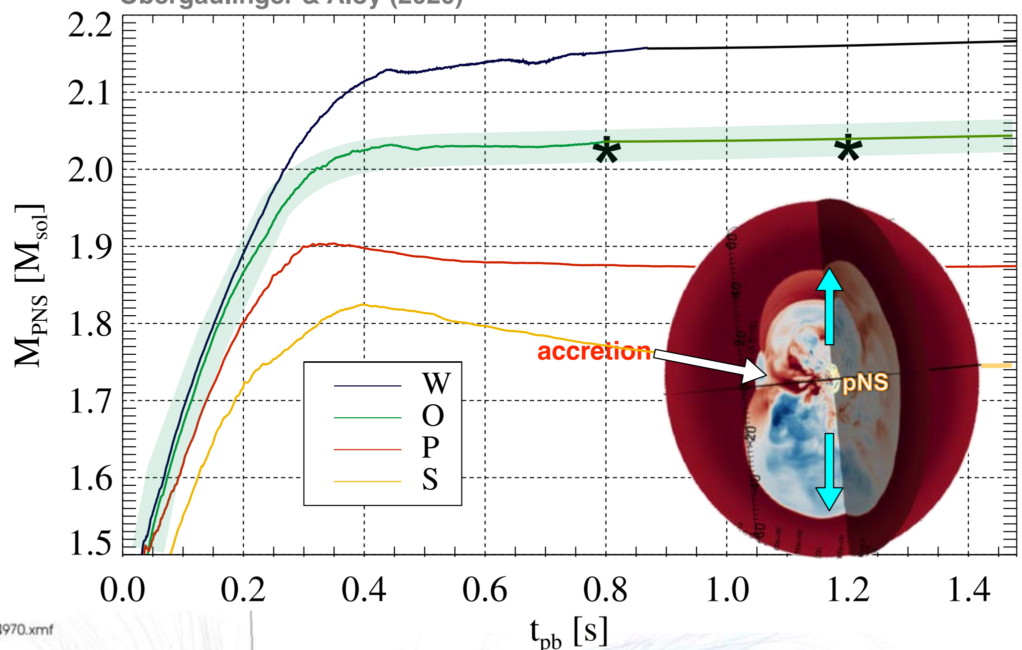


Miguel A. Aloy

VNIVERSITAT DE VALÈNCIA

Stellar rotation + variations in B-field

Obergaulinger & Aloy (2020)



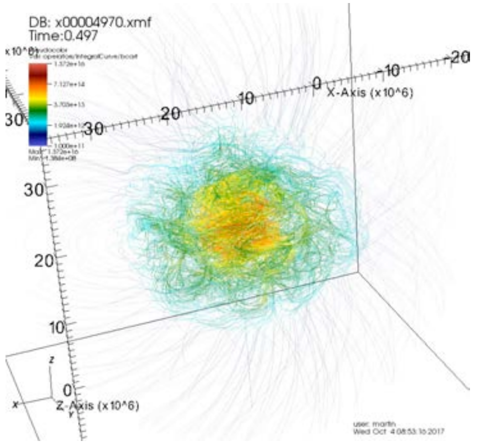
Reference model O:

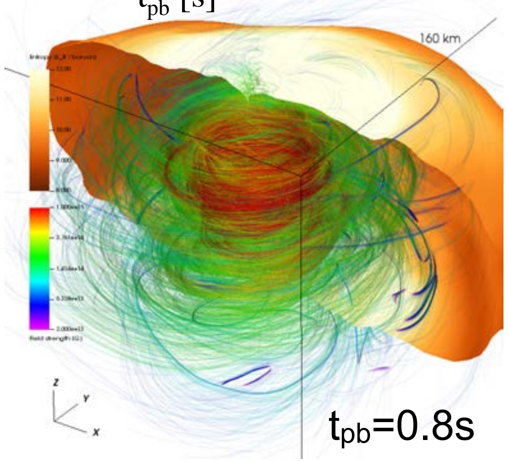
- SN mediated by ν's + B-fields + rotation
- highly collimated
- PNS reaches very high mass resulting from balance accretion/ejection
- BH collapse prevented for a long time (>1.5 s in 3D) by centrifugal forces
- ***Result: PM + SN***

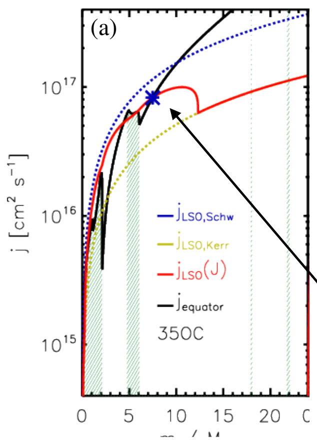
Models with smaller *j* in progenitor (W):

- ***PNS may collapse to a BH (but after long time)***

➡ ***If a BH forms: two stage scenario (spinar + collapsar)***





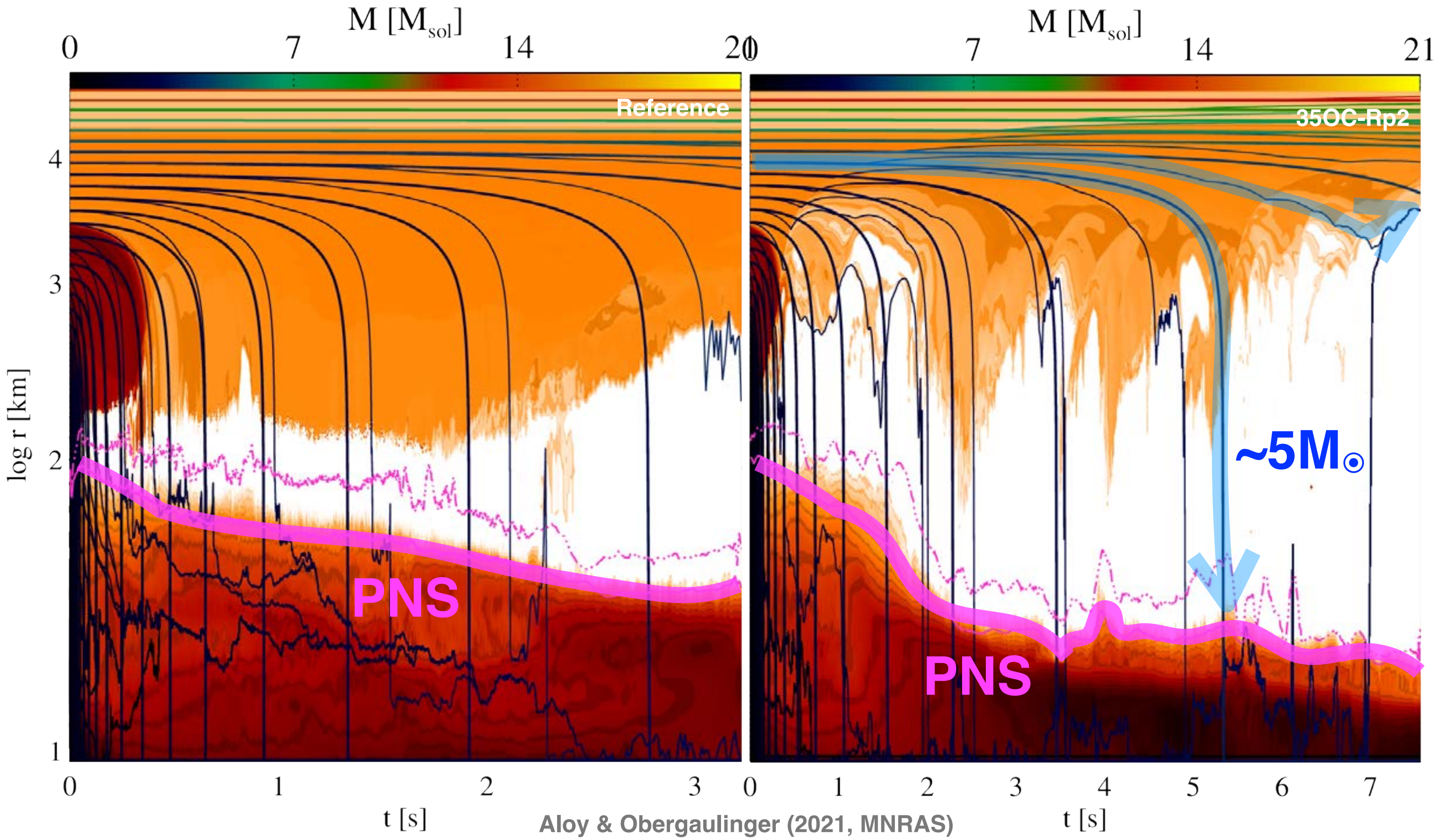


Disagreement with Woosley & Heger (2006).

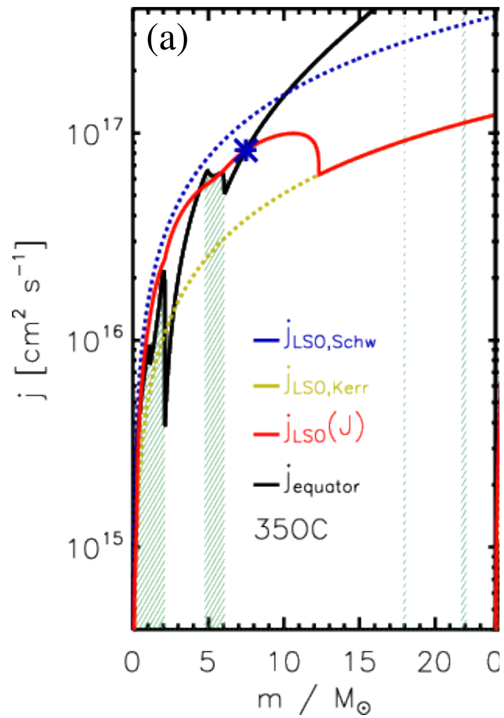
Qualitative agreement with Dessart+08 find that *35OC is very susceptible to early MR-explosion inhibiting the PNS growth and making a later BH collapse unlikely* (diminishing the prospects of a collapsar progenitor)

CAVEAT: t_{DF} ~ 9.3s will BH form before disc?

Collapsar disc formation

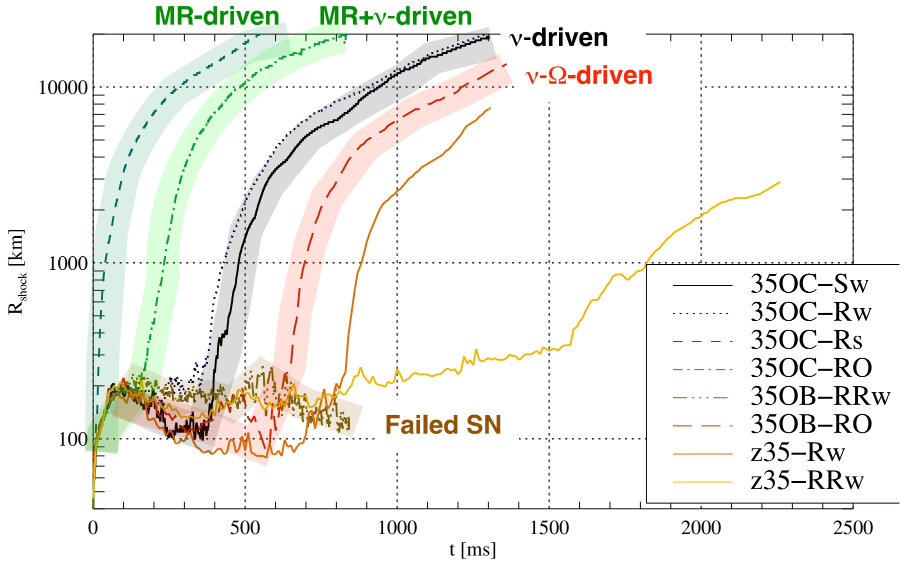


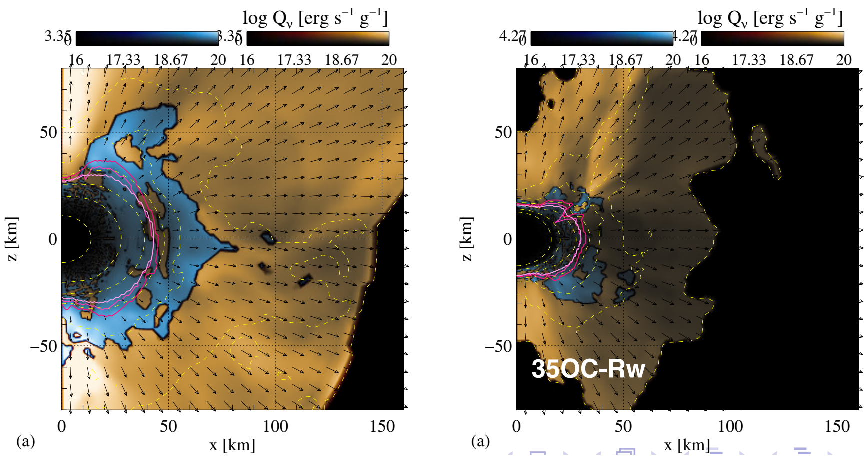
Aloy & Obergaulinger (2021, MNRAS)



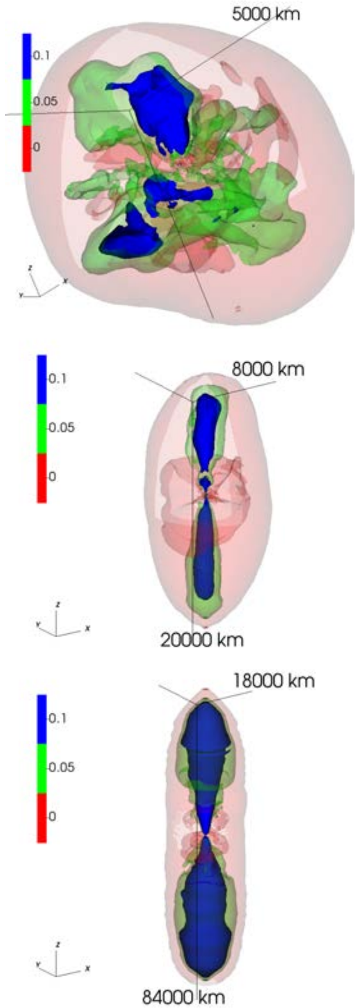
- Expected formation @ t_{DF} ~ 9.3 s; M_{DF} ~ 7.5 $M_\odot$ (ref. model).
- However, *(partly) inhibited by explosion* (also along the equator!)
- Longer simulations needed to fully cover disk formation.
- Disk may form once the polar ejecta breaks out of the stellar surface.
- A collapsar may form, but the delay between SN ejecta and (posterior) ultrarelativistic ejecta could be significant.

Diversity of explosions (I)





2D
Obergaulinger & Aloy (2017)



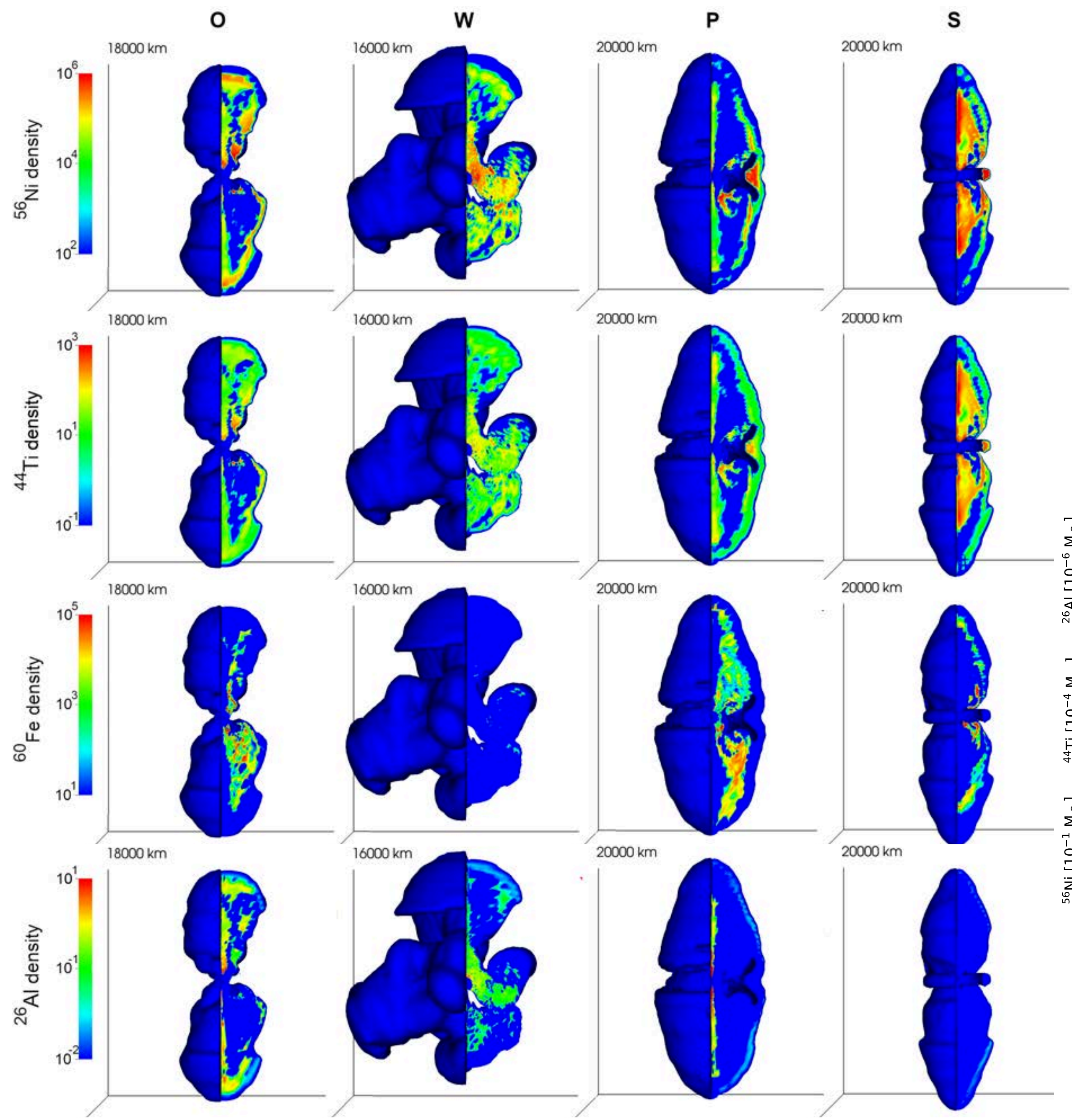
3D
Obergaulinger & Aloy (2021)

- *For a fixed stellar progenitor (fixed mass) and variations of Ω / B:* most models eventually achieve shock revival, but driven by distinct mechanisms (cf. Burrows+20)

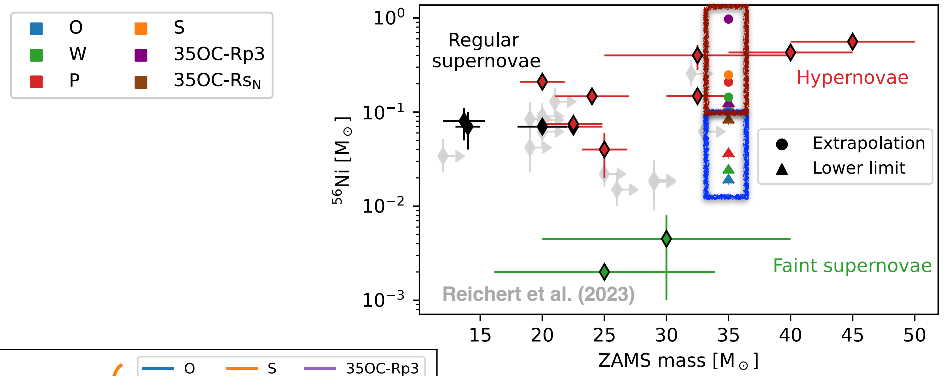
  1. Standard ν-driven SN + hydro-instabilities, but followed by collapse to a BH; 35OC-Sw/W.
  2. Rapid rotation creates the conditions for bipolar explosion, namely, ***anisotropic*** ν-emission concentrated along the rotational axis; 35OC-{Rw, RRw, RO} / O.
  3. Early magneto-rotational explosions launching moderately relativistic outflows (v ~ c/3) and producing hypernovae; 35OC-Rs/S (jetted explosions are a solid result in 3D Winteler+12, Mösta+14,15, 18; Kuroda+20).

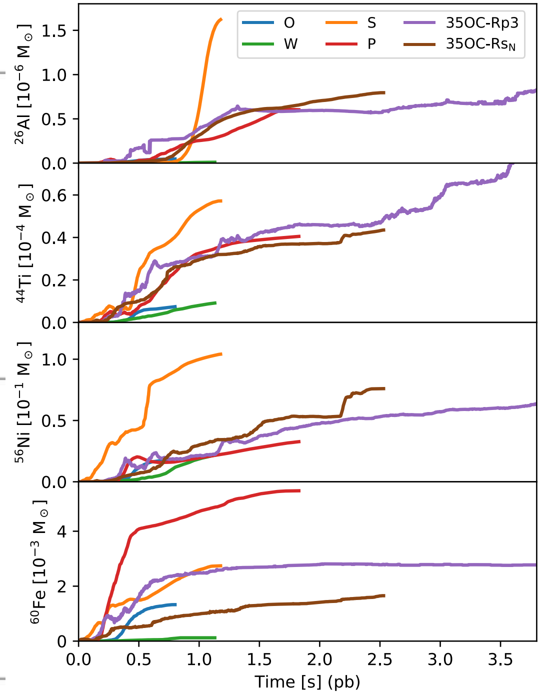
- ***Ejecta collimation correlates with magneto-rotational energy in the progenitor***

Explosive nucleosynthesis



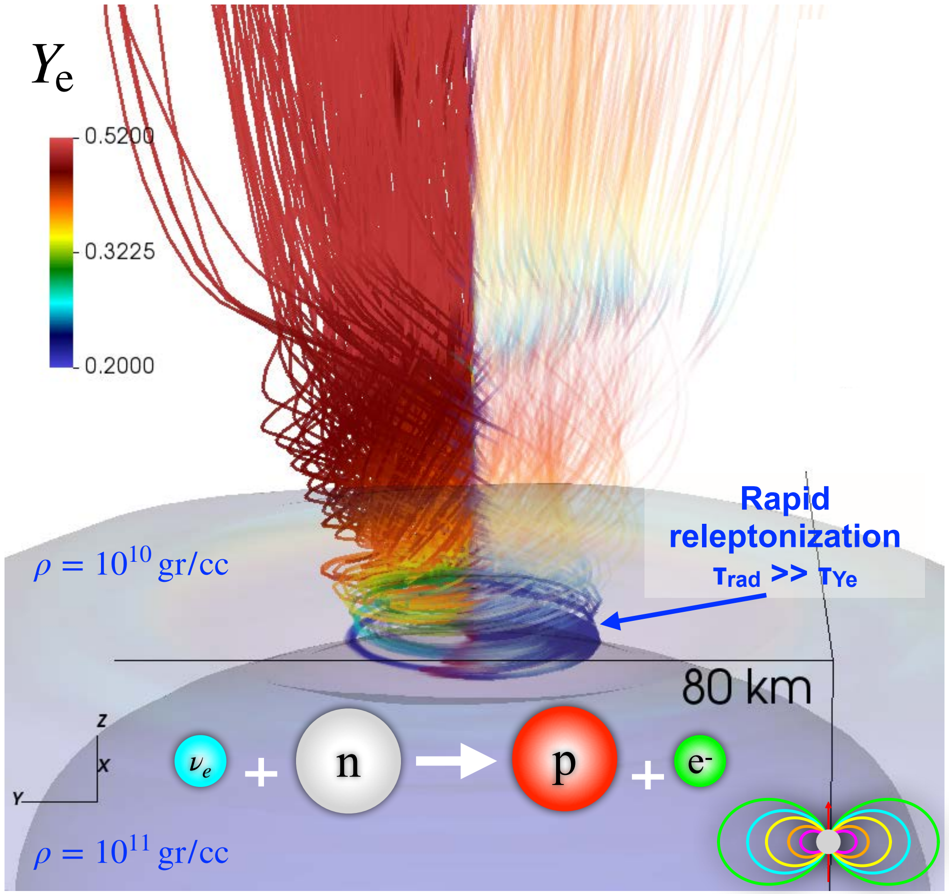
Low M_{Ni} in ejecta; compatible with regular SNe





- Ejecta mass of unstable nuclei still growing
- *Extrapolation of M_{Ni} in ejecta agrees with HN branch*
- ^{60}Fe nearly absent in ordinary SN; large in MR-SNe
- ^{26}Al synthesised @ shock! Correlates with E_{exp}

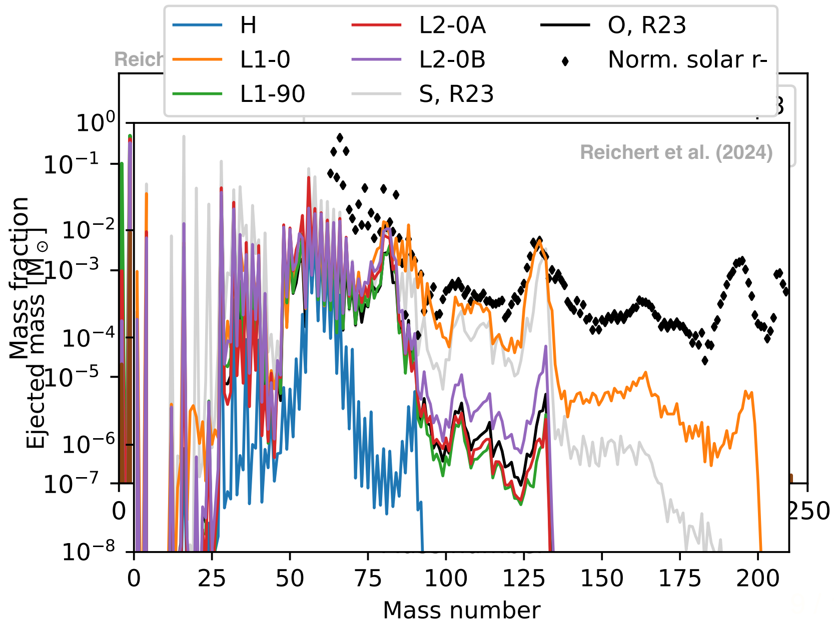
Production of r-process yields



Trajectories of particles close to the PNS north pole for model S @ t_{pb} =0.8s

2D/3D models confirm magneto-rotational SN as additional sources of r-process nuclei

- Magnetic fields favor the creation of heavy elements while rotation acts against it
- Early MRSNe may yield up to 3rd process peak
- Critical phenomenon occurring in the first tens ms with matter close to PNS and strong enough B



Summary and conclusions

- Explosion success and type (ν-/ MHD-driven) tightly linked to rotation profile and magnetic topology/strength.
- Feedback of the explosion dynamics on the compact remnant: PNS mass growth due to equatorial accretion - PNS mass reduction by mass ejection.
- MRSNe intrinsically anisotropy: strong dependence on the B-field topology.
- Nucleosynthesis calculations of 2D/3D models confirm MRSN as additional sources of r-process nuclei (complementary to NS-mergers).
- R-process 3rd-peak yields on reach of the most magnetised, dipolar-B models.
- Formation of the central engine of a LGRB including feedback from explosion dynamics