Explosions of high-mass stars with rotation and magnetic fields

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In collaboration with
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and computing time

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- and on clusters *Tirant* and *Lluisvives* at the UV.

Coconuts in times of unexpected election results

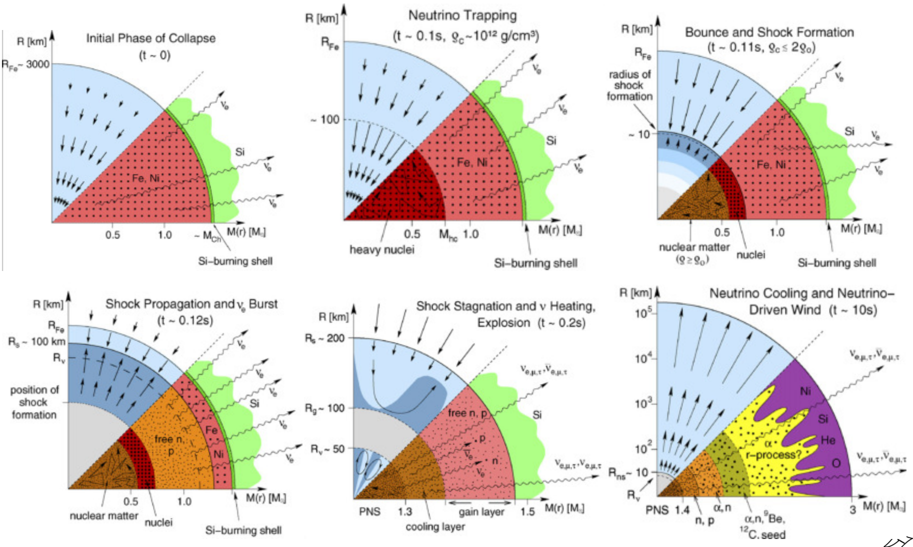
Coconut detained in Maldives over vote-rigging claims

Police take 'suspicious fruit' into their possession after claims it could have been used in black magic during elections

Coconuts are often used in black magic rituals in the Maldives. Photograph: Foodcollection/Getty Images

Jason Burke, The Guardian, 6 Sept, 2013

The basic picture



Janka et al. (2007)

Progenitor

- wide mass range: from 8 to many 10s of solar masses
- at metallicities from zero to solar
- possibly in binaries
- rotation and magnetic fields

- quite different profiles of ρ, Y_e, T
- different positions of Si,... shells
- wide variety of compactness
- widely differing rates of mass loss
- transfer of mass, angular momentum
- closely coupled: rotation allows for dynamos, magnetic fields slow down rotation
- important consequences for mixing, mass loss

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Physics of the collapse

multi-scale problem

- star: blue or red giant
- pre-collapse core: few 1000 km
- PNS: few 10 km
- stalled shock: few 100 km
- large (magnetic) Reynolds number
- many dynamical time scales

multi-physics problem

- multi-dimensional (GR)(M)HD
- turbulence
- nuclear equation of state
- neutrino transport (from optically thick to transparent), neutrino-matter interactions
- nuclear burning

The aftermath

Explosions

- "ordinary" SNe of $\sim 10^{51}$ erg showing different spectral types and light-curves
- more exotic(?) types: hypernovae, GRB-SNe, but also under-energetic ones
- all fairly asymmetric
- an unseen fraction of failed explosions

- pulsars with moderate rotation and magnetic fields
- magnetars: ultra-strong fields (dipole component), slow rotation
- remnants: strong asymmetries, mixing
- BHs, possibly with a mass gap to NSs

Theoretical uncertainties

complex physics

+ very wide range of properties of progenitors

→ wide range of outcomes: varies types of explosions as well as failures plus their respective remnants

- expensive numerical simulations only now entering 3d
- many explosions found
- some basic questions remain open: explosion criteria, contribution of different ingredients
- new, completely unexpected effects are still discovered (e.g., the LESA, Tamborra et al., 2014)
- many open parameter regimes
- do we expect one comprehensive explanation?

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Physics and numerics

Code as documented in Just et al., 2015

- multi-D MHD
- TOV gravity
- spectral two-moment ν transport with $\mathcal{O}(v/c)$ velocity terms; no gravitational terms
- basic interactions; no pair processes
- microphysical EOS
- used in 2d simulations of collapse and of post-merger tori
- FV-UCT scheme with high-order MP reconstruction

and improvements since

- gravitational terms (redshift, observer-time correction) in transport and MHD in the $\mathcal{O}(v/c)$ plus formulation of Endeve et al. (2012)
- pair processes: NN-bremsstrahlung and electron-positron annihilation

Two-moment neutrino transport

- 0^{th} moment: conservation law for neutrino energy:

$$\partial_t E + \nabla_j (F^j + v^j E) + \mathcal{V}_0 + \mathcal{G}_0 = \mathcal{C}^0. \tag{1}$$

- 1^{st} moment: and for neutrino momentum

$$\partial_t F^i + c^2 \nabla_j (P^{ij} + v^j F^i) + \mathcal{V}_1^i + \mathcal{G}_1^i = \mathcal{C}^{1,i}. \tag{2}$$

- P, the neutrino pressure tensor, is a local function of E and $\vec{F}$, which interpolates between the limits of diffusion, $P = E/3\,\mathrm{diag}(1,1,1)$, and free streaming, $P^{ij} = E\,F^i F^j / F^2$.
- $\mathcal{V}$, $\mathcal{G}$ are the velocity and gravity terms coupling neutrino energy bins
- $\mathcal{C}$ are the neutrino-matter interaction terms: emission, absorption, scattering (potentially quite stiff).

Microphysics

Reactions with matter

- $n + \nu_e \rightleftharpoons p^+ + e^-$
- $p^+ + \bar{\nu}_e \rightleftharpoons n + e^-$
- $(A, Z) + \nu_e \rightleftharpoons (A, Z + 1) + e^-$
- $n/p + \nu_X \rightleftharpoons n/p + \nu_X$
- $(A, Z) + \nu_X \rightleftharpoons (A, Z) + \nu_X$
- $e + \nu_X \rightleftharpoons e + \nu_X$
- $e^- + e^+ \rightleftharpoons \nu_X + \bar{\nu}_X$
- $N + N \rightleftharpoons N + N + \nu_X + \bar{\nu}_X$

- implementation following Rampp & Janka (2002)
- annihilation: Pons et al. (1998)
- bremsstrahlung: Hannestad & Raffelt (1998)

- equation of state for nuclear matter of Lattimer & Swesty, 1991 with incompressibility of $K = 220\,\mathrm{MeV}$

Context and questions

Selected previous studies on collapse with rotation and magnetic fields

Meier et al. (1976), Bisnovatyi-Kogan et al. (1976), Müller & Hillebrandt (1979), Akiama et al. (2003), Thompson et al. (2005), MO et al. (2005,2009,2014), Kotake et al. (2004), Burrows et al. (2007), Dessart et al. (2007), Endeve et al. (2010,2012), Mösta et al. (2014,2015)

- field amplification by compression, winding, convection and SASI (dynamo), MRI
- turbulence and small-scale viscosity, but also large-scale coupling across scales of several turbulent eddies
- transport of angular momentum and loss of centrifugal support
- jet formation

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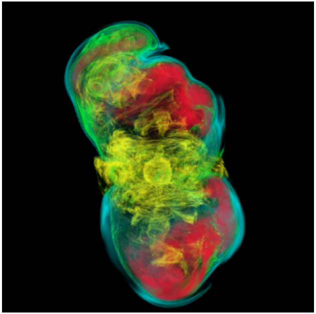
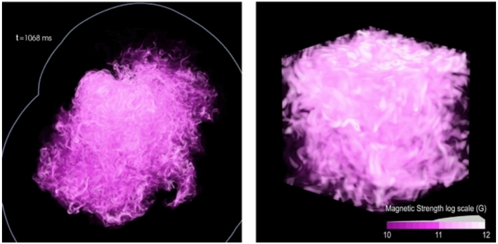


Mösta et al. (2014)



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We are interested in

- the viability of progenitors for collapsars,
- criteria for explosion or BH formation,
- and of course all the above.

Progenitors

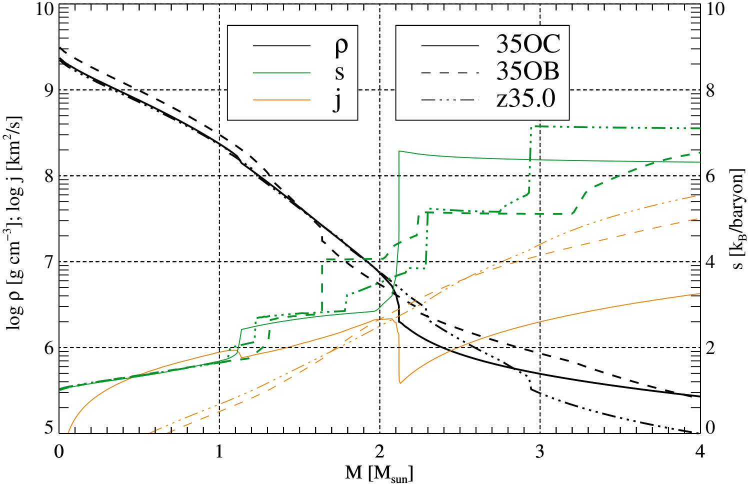
35OC/B (Woosley & Heger (2006))

- $M_{\rm ZAMS} = 35\,M_\odot$
- stellar evolution includes rotation and magnetic fields according to the Spruit (2002) dynamo
- mass loss rate is a parameter of the stellar evolution modelling $\to$ masses at collapse $\sim 28\,M_\odot$ and $\sim 21\,M_\odot$
- rapid rotation at collapse
- compactness (O'Connor & Ott, 2011) $\xi_{2.5} = 0.49$ (35OC) and $\xi_{2.5} = 0.56$ (35OB)
- models with original magnetic field and with weak and strong artificial fields

z35.0 (Woosley et al. (2002))

- $M_{\rm ZAMS} = 35\,M_\odot$
- zero metallicity
- $\xi_{2.5} = 0.56$
- neither rotation nor magnetic fields in the stellar evolution model
- artificial moderate and rapid rotation and magnetic fields

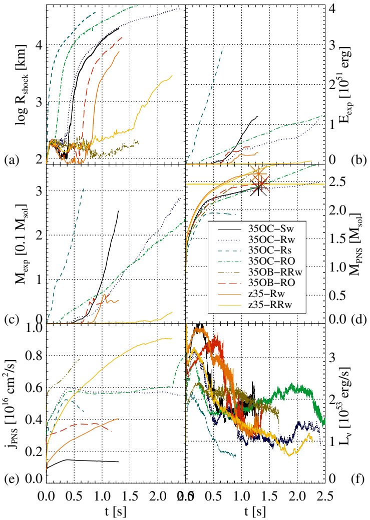
Progenitors



(a)

Pre-collapse density, entropy, and specific angular momentum profiles

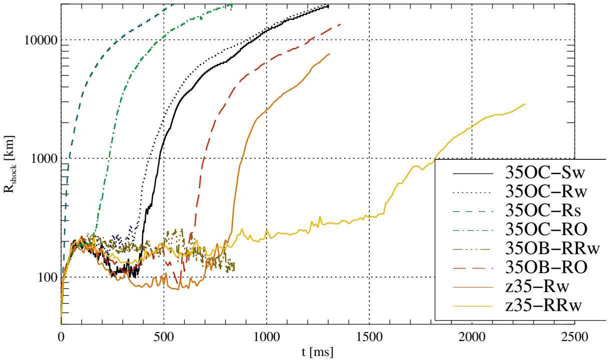
Overview



- high compactness does not completely suppress explosions
- explosions set in fairly late (correlation with the accretion of core interface)
- fairly high explosion energies; few 0.1 $M_\odot$ ejecta
- high PNS masses and high accretion rates $\rightarrow$ many collapse to BH within seconds after bounce
- rapidly rotating PNS's with strong fields
- moderately Kerr BH's
- fast rotation decreases ν luminosities
- variety of explosion mechanisms from ν-driven to magneto-rotational

Model 35OC-Sw: neutrino-driven explosion

- explosion after a phase of shock stagnation
- ejecta energy and mass increases stronger than any other model except for 35OC-Rs
- neutrino heating and hydrodynamic instabilities
- shock expansion starts when the interface of the iron core is accreted
- very oblate ejecta
- PNS (soon to be



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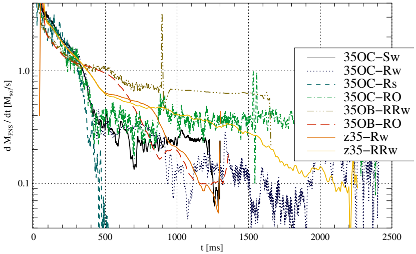

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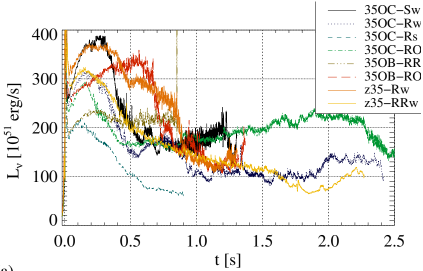

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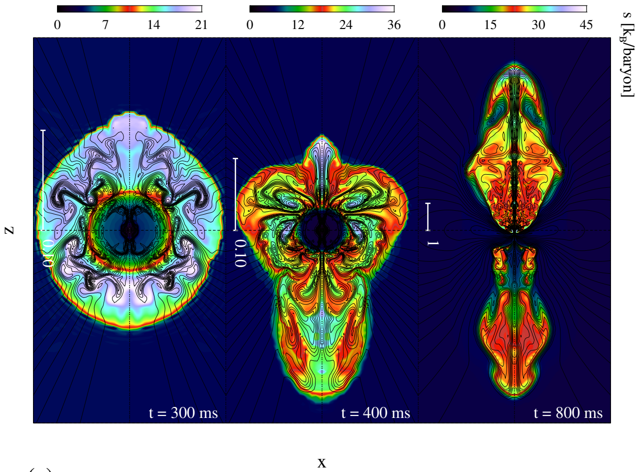

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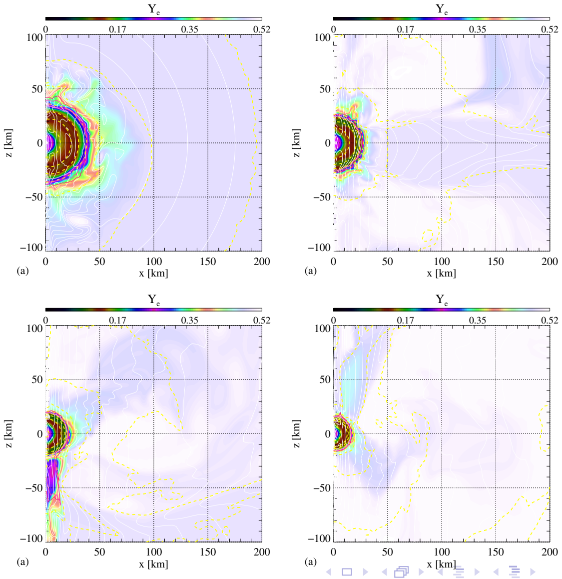
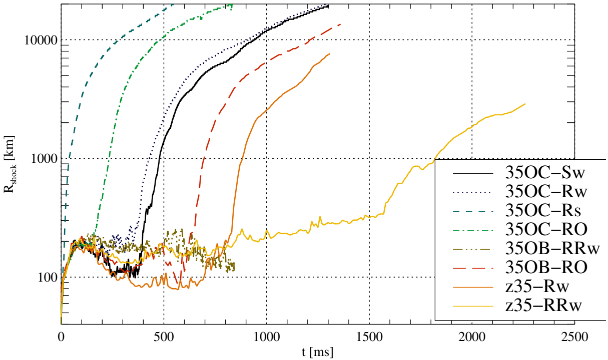


35OC-Rw: faster rotation

- explosion after a phase of shock stagnation
- very asymmetric neutrino heating
- again, interface triggers shock expansion
- quite jet-like ejecta
- PNS very prolate



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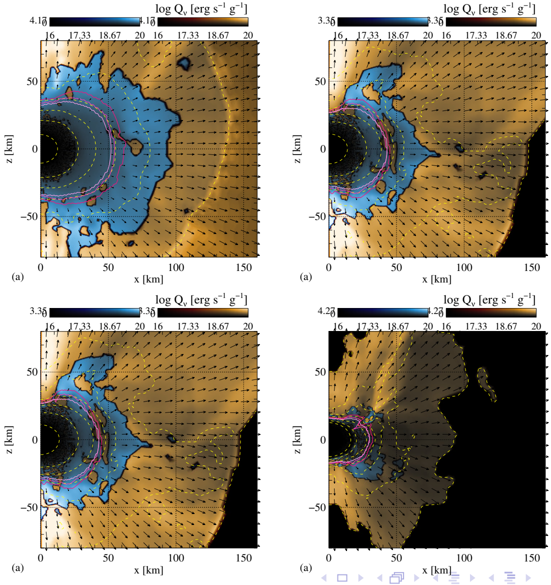

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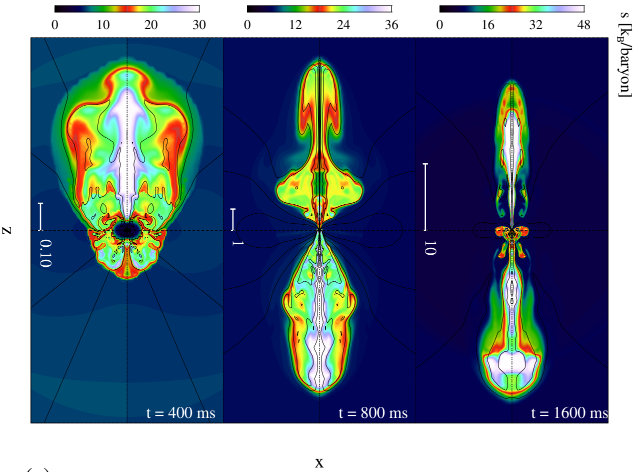

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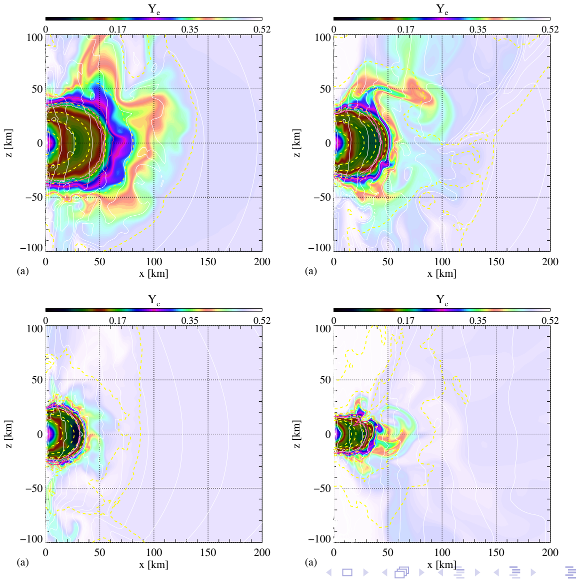
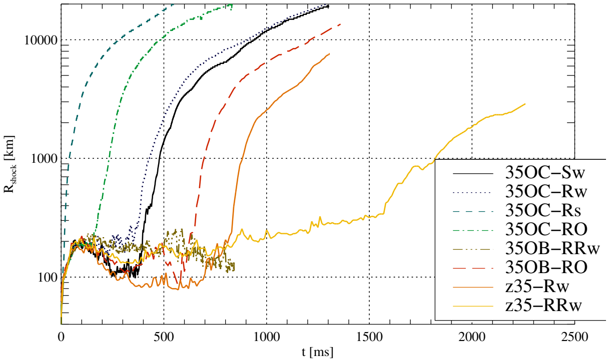


35OB-RRw: failed explosion

- no explosion occurs at all
- very asymmetric neutrino emission, but insufficient to overcome high mass accretion rate
- intense activity of convection
- PNS very prolate, almost a torus



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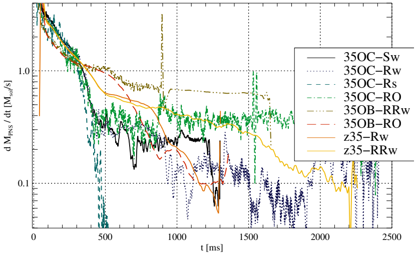

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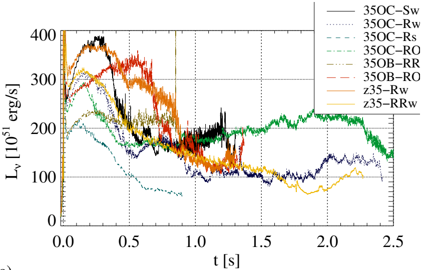

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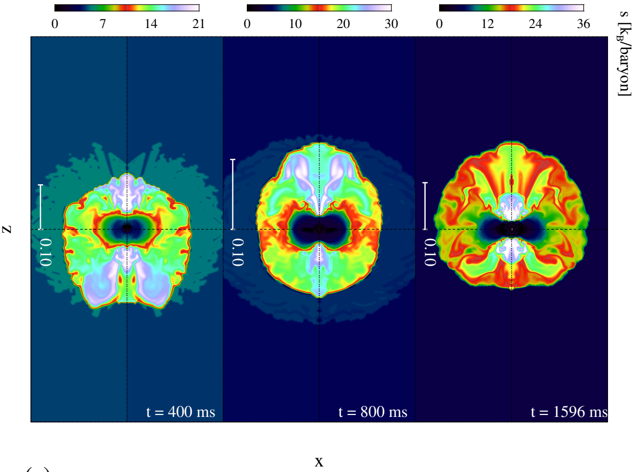

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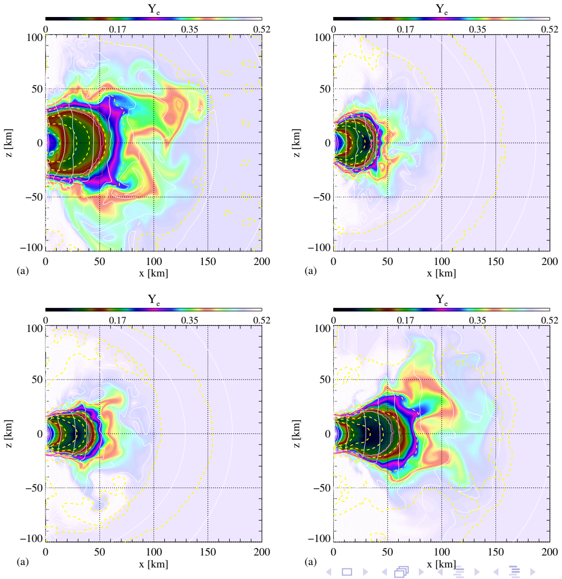
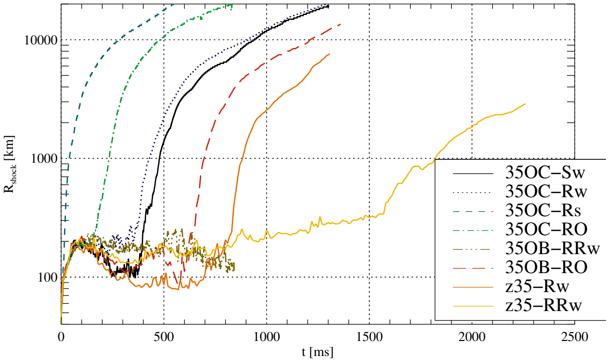


35OC-Rs: magneto-rotational explosion

- very prompt explosion
- magnetic fields launch jets long before neutrinos can achieve anything
- PNS very prolate
- PNS stops to grow and even loses mass after 400 ms, i.e., no BH collapse anytime soon



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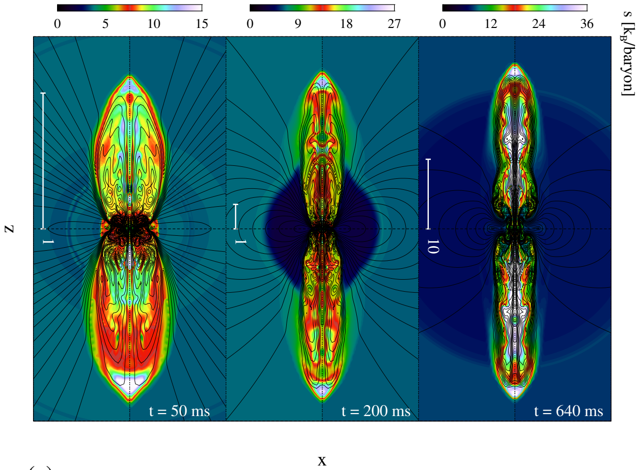

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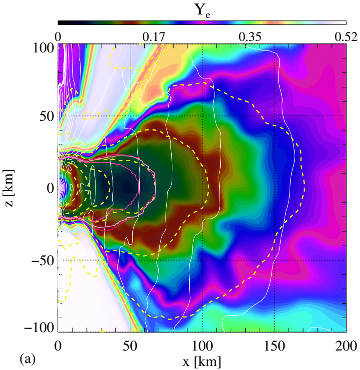

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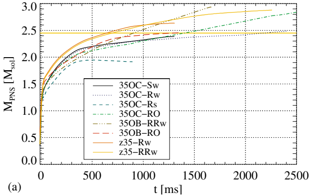
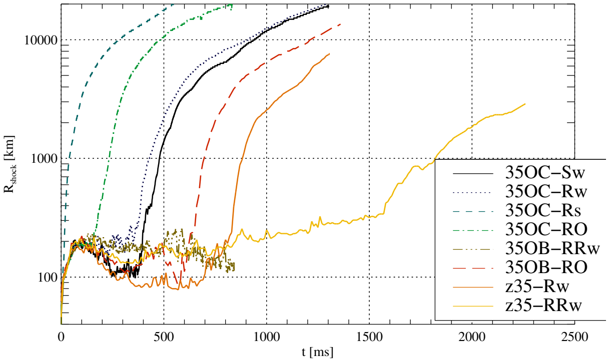


(a)

35OC-RO: the original magnetic field

- intermediate case between 35OC-Rs and 35OC-Rw
- explosion has a considerable magnetic contribution
- indications of MRI
- PNS reaches very high masses but prevented from collapse for a long time by centrifugal forces



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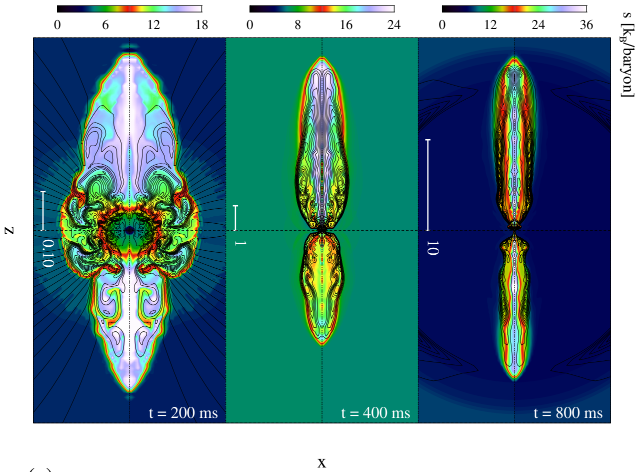

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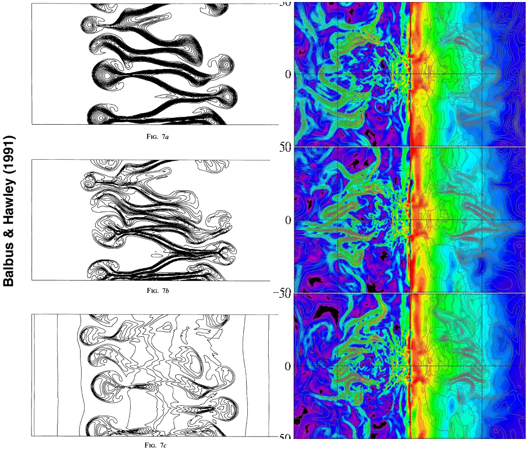

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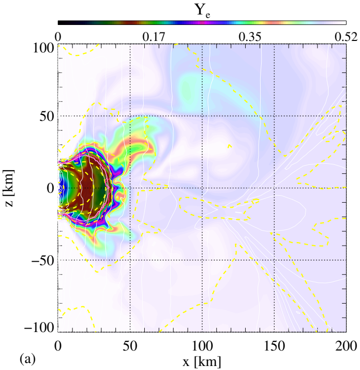

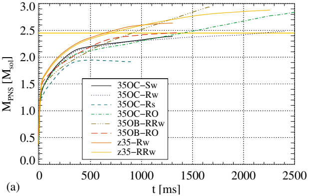

Summary

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- less compact model easier to explode, accretion of interfaces where the mass flux drops facilitate explosions
- rotation decreases the ν luminosity, but leads to predominantly polar emission and enhances heating there,
- which of the two opposite effects wins depends on the model
- magnetic fields do what they do best, namely produce jets
- possibility of GRB's: collapsars or proto-magnetars?

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Follow-up work

- quite different thermodynamical conditions $\rightarrow$ differences in nucleosynthesis
- very strong emitters of GW
- long-term evolution: propagation through the envelope and break-out signal
- the elephant in the room, of course, is 3d