CCSN Explosion Mechanism?

- Discussed explosion mechanisms:
  - "Enhanced" neutrino-driven explosion mechanism

    Hydro. instabilities: convection, Standing Accretion Shock Instabilities (SASI) e.g. Blondin et al. 2003, Blondin & Shaw 2007, Foglizzo et al. 2008, Iwakami et al. 2008, Marek & Janka 2009, ...
  - MHD mechanism

    Rapid rotation + Magnetic field amplification (Flux compression, winding, MRI, dynamos) e.g. Akiyama et al. 2003, Wilson et al. 2005, Kotake et al. 2006, Burrows et al. 2007, ...
  - Acoustic mechanism

    Excitation of ProtoNeutron Star (PNS) oscillations by accretion/SASI generating acoustic power to reheat the stalled shock Burrows et al. 2006,2007
  - Phase transition induced explosion mechanism

    Additional compactification of PNS due to phase transition from hadronic matter to quark matter Migdal et al. 1971, … Sagert, Fischer et al. 2009, Fischer et al. 2011, ...

Simulation of MHD CCSN

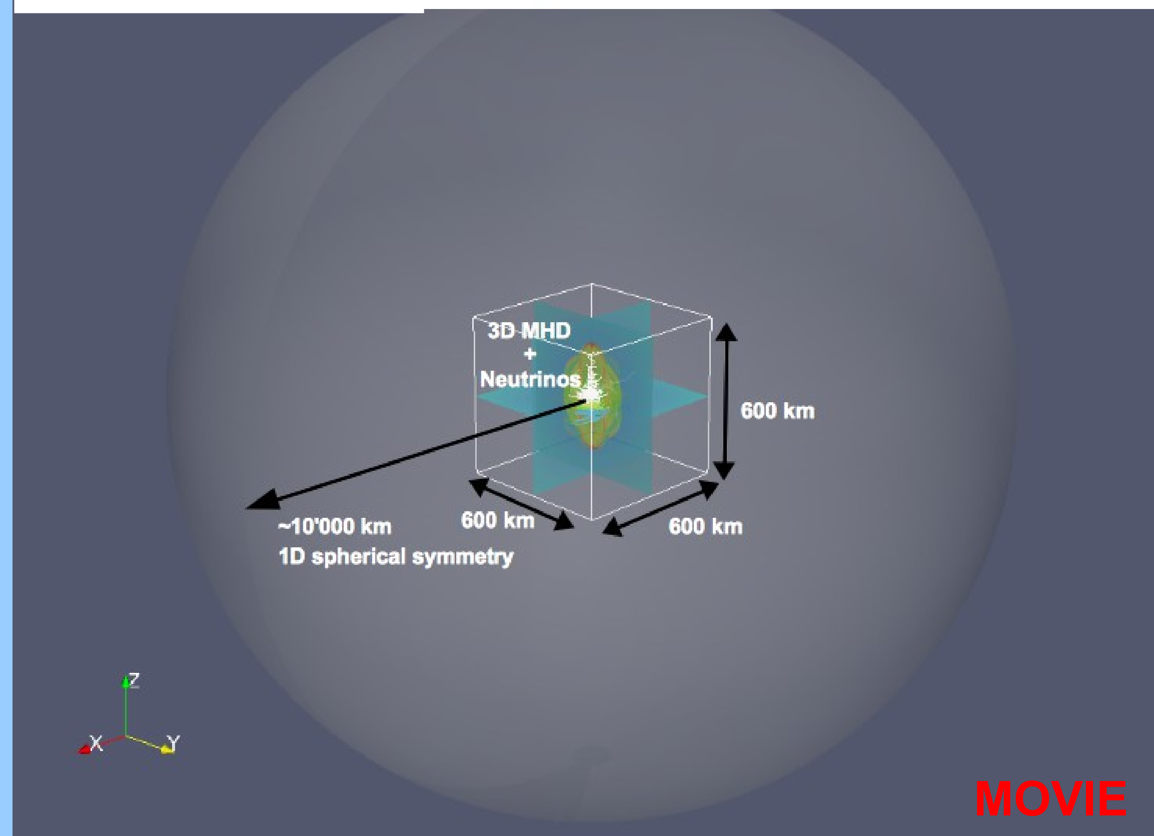
Initial conditions:

$$\Omega_{0,c} = \pi \text{ rad/s}$$

$$B_{\text{pol}} = 5 \times 10^{12}$$

Constant 1 km resolution!

Computations @ CSCS Swiss National Supercomputing Centre



Explosion energy, ejected mass and its composition

- Bipolar jets quickly expand & transport energy and stellar material outward against the gravitational attraction of the PNS
- Very neutron rich matter is lifted... r-process?
- Approximately determine explosion energy and ejected mass

Specific total energy $\epsilon = e_{\text{int}} + \frac{v^2}{2} + \frac{b^2}{2\rho} + \phi > 0$ **&** $v_r > 0$

when shock reaches upper boundary of 3D domain 700 x 700 x 1400 km

$t_f = 33\text{ms}$

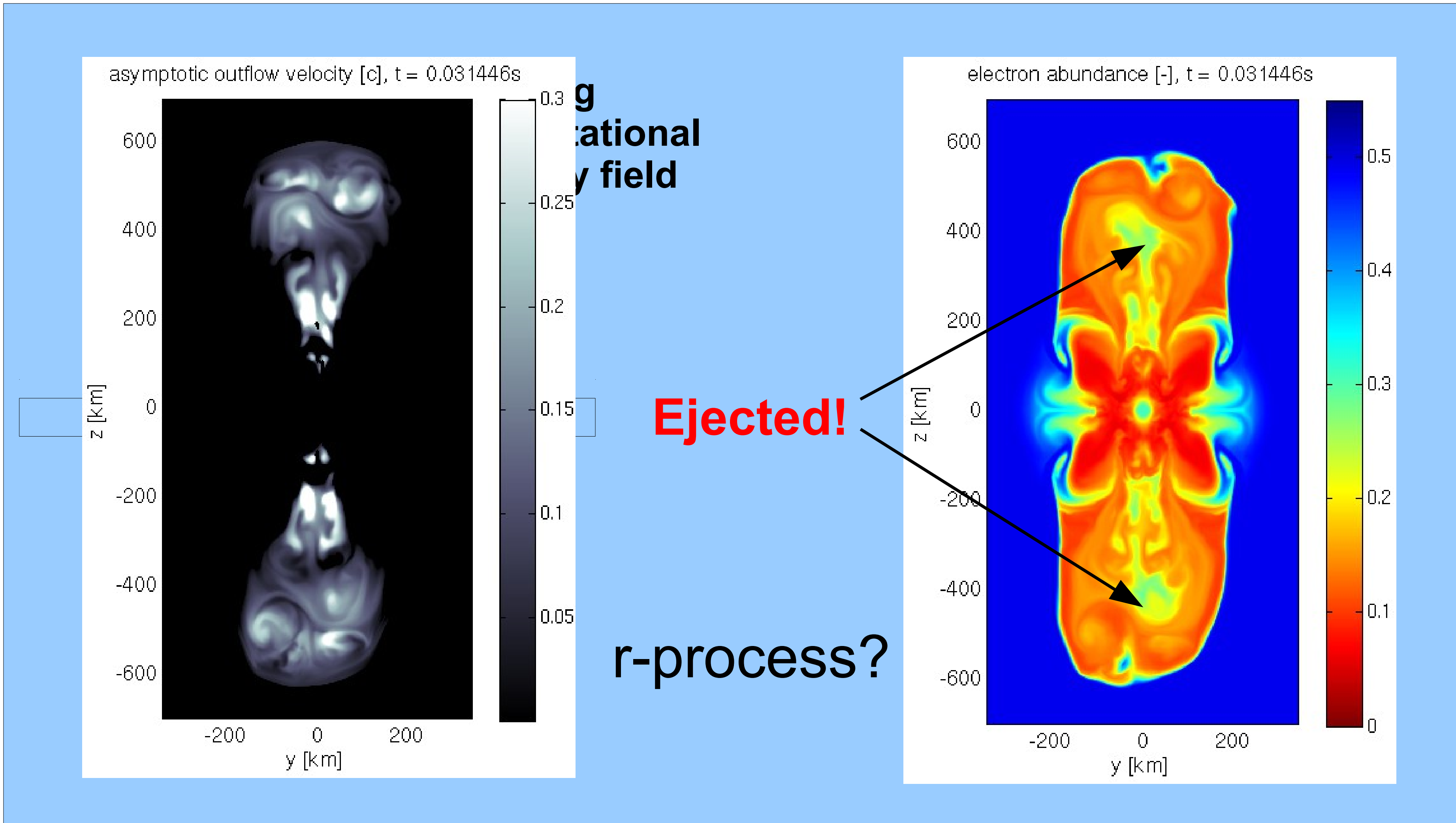
Prompt time scale...

$M_{\text{ej}} = 6.72 \times 10^{-3} M_\odot$

$E_{\text{exp}} = 8.45 \times 10^{+49}\text{erg} \lesssim 10^{51}\text{erg}$ **!**

Still growing!

Explosion energy, ejected mass and its composition

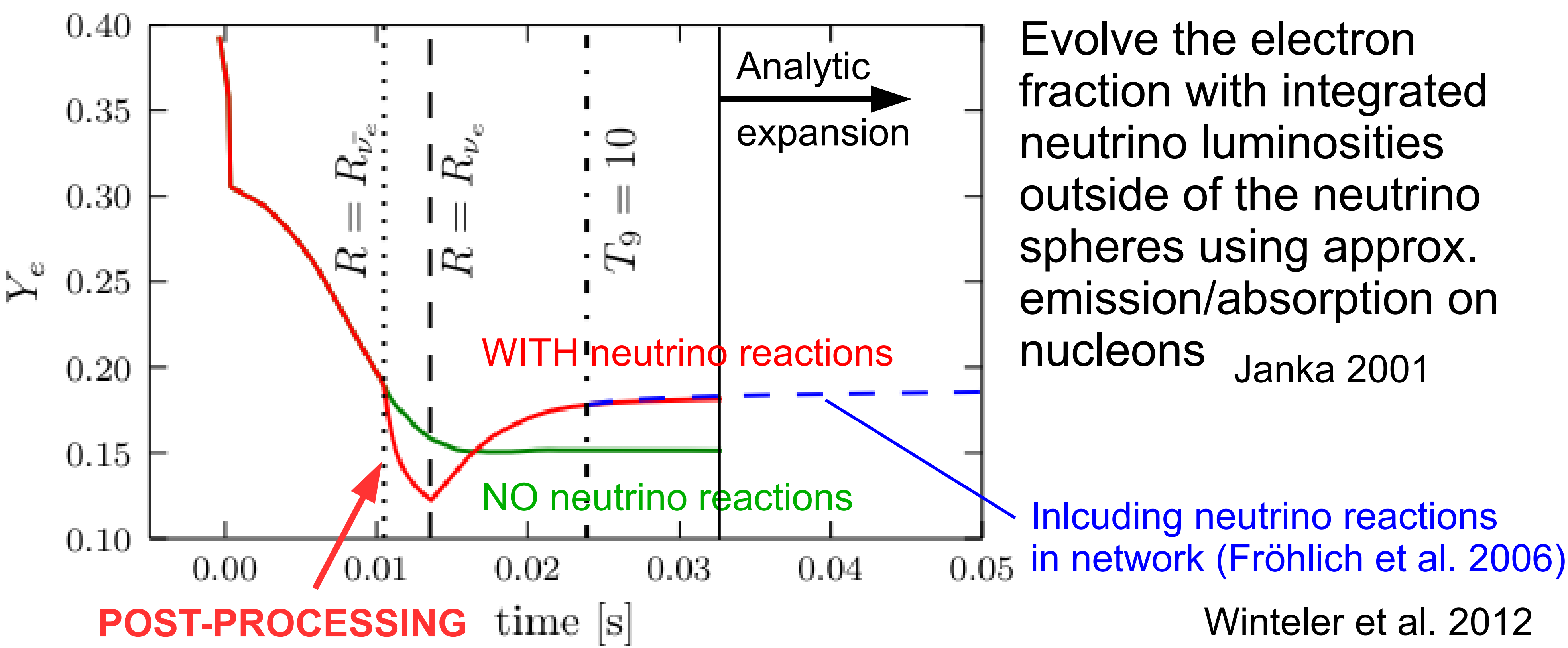


km

g!

Composition of the ejecta

- Included tracer particles to track the evolution of thermodynamic conditions in a Lagrangian manner
- Electron fraction is a key input for the nucleosynthesis and strongly depends on the challenging ν transport



Evolve the electron fraction with integrated neutrino luminosities outside of the neutrino spheres using approx. emission/absorption on nucleons Janka 2001

Winteler et al. 2012

!!! POST-PROCESSING !!!

Discussion

- (Too) Fast initial rotation rate?

  Stellar evolution with magnetic fields $\Omega \sim 0.3\ \mathrm{rad/s}$
  Heger et al. 2005

  Stellar evolution without magnetic fields $\Omega \sim \pi\ \mathrm{rad/s}$
  e.g. Heger et al. 2000, Hirschi et al. 2004

- (Too) much r-process matter ejected?

  Eject $M_{\mathrm{r,ej}} = 5.64 \times 10^{-3} M_{\odot}$ of r-process material...

  But: if all CCSN exploded with the MHD mechanism, then r-process overproduced by factor $\sim 100 - 1000$

- (Too) strong initial magnetic field ~ 1000

  Some stars may have large field strengths... e.g. magnetars
  strong magnetic white dwarfs
  e.g. Wickramasinghe & Ferrario 2000

- (Very) Short simulation time?

  Only 33 ms !!!

MHD CCSN only rare event with special conditions

Woosley & Heger 2006

Consistent with large star-to-star scatter of r-process abundances at low metallicity

e.g. Cowan & Sneden 2006

Numerical issues...
Angular momentum conservation

Currently working on angular momentum preserving schemes

Resolution of MRI...

Discussion

- (To

Stell

Jets unstable to instability???

Moesta et al. 2014

?

Stellar evolution without magnetic fields $\Omega \sim \pi \text{ rad/s}$

e.g. Heger et al. 2000, Hirschi et al. 2004

- (T

Ej

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Neutrinos?

Currently implementing A. Perego's ASL...
(including heating approx.)

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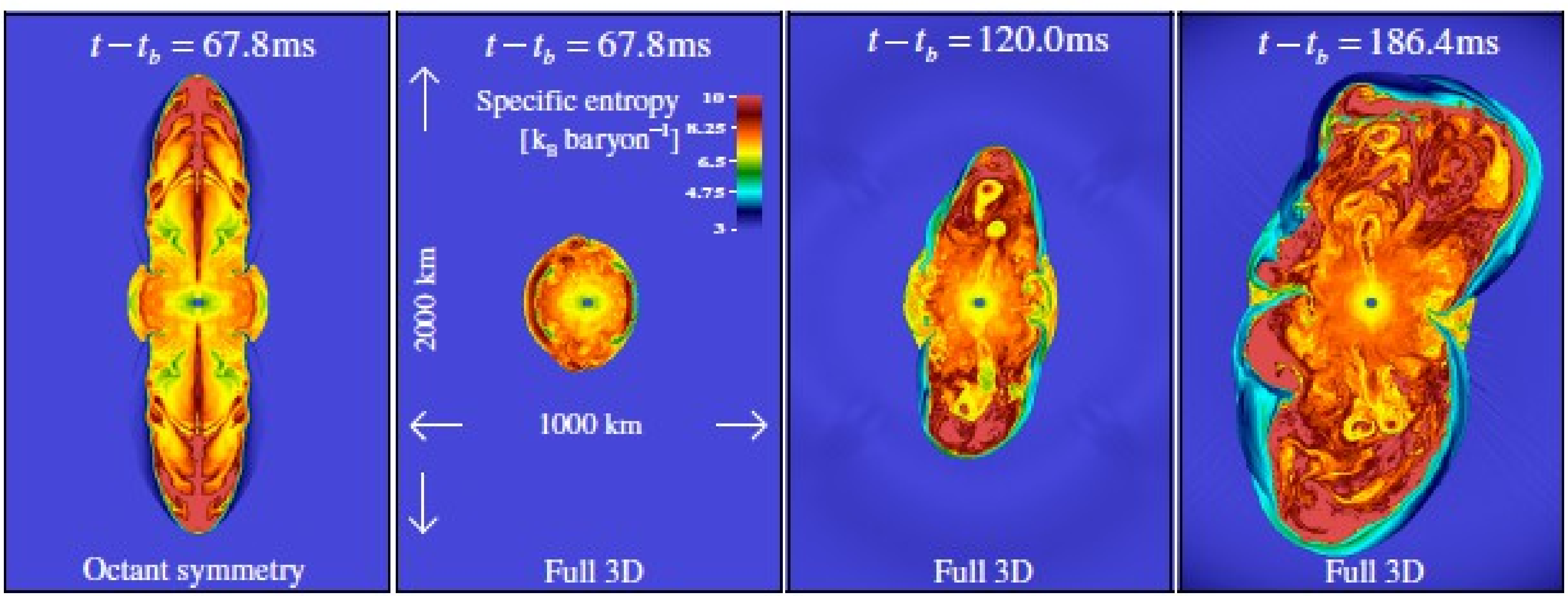

Figure 1. Meridional slices (x–z-plane; z being the vertical) of the specific entropy at various postbounce times. The "2D" (octant 3D) simulation (leftmost panel) shows a clear bipolar jet, while in the full 3D simulation (three panels to the right) the initial jet fails and the subsequent evolution results in large-scale asymmetric lobes.

Resolution of MRI...

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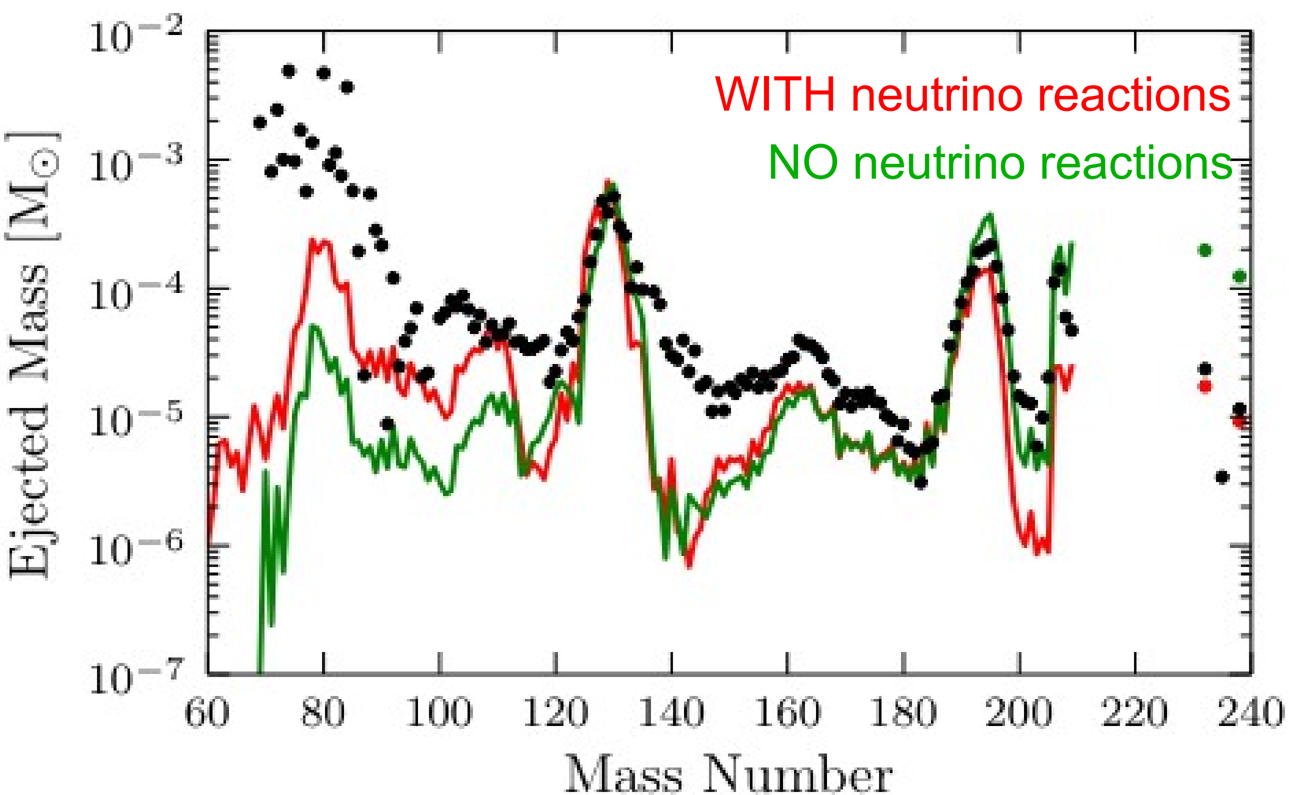

Mass integrated abundances

Winteler et al. 2012

!!! POST-PROCESSING !!!

Solution Algorithm: Neutrinos

- In principle, should solve the relativistic Boltzmann eq

4-vector 4-momentum Distribution function

Cercignani
emer 2002

n

For eac nt c.)

F

Spectral Leakage scheme: only cooling

Electron or positron capture on nucleons and nuclei

$$e^- + p \leftrightarrow n + \nu_e$$
$$e^+ + n \leftrightarrow p + \overline{\nu}_e$$
$$e^- + (A,Z) \leftrightarrow (A,Z-1) + \nu_e$$

Elastic coherent scattering of neutrinos on nucleons and nuclei

$$\nu + N \leftrightarrow \nu + N$$
$$\nu + (A,Z) \leftrightarrow \nu + (A,Z)$$

- Appr

Computational cost

- Parametrisation scheme: only collapse phase Liebendörfer 2005
- Spectral Leakage scheme: only cooling A. Perego et al. in prep.

Epstein & Pethick 1981, van Riper & Lattimer 1981, ..., Ruffert et al. 1996, Rosswog & Liebendörfer 2003

- Isotropic Diffusion Source Approx. (IDSA) Liebendörfer et al. 2009