Max-Planck-Institut
für Astrophysik

SFB-TR7 SFB-TR27 Excellence Cluster Universe

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Exploring Possible Sources of r-Process Elements

Models of Supernova Explosions and Neutron-Star Mergers

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Summary & Conclusions

- Progenitors with O-Ne-Mg cores end up as e-capture SNe powered by neutrino heating. Models show robust explosions producing very little nickel (~0.001 solar masses).
- Fe-core progenitors with > 10 solar masses explode by neutrino heating, at least “marginally”, in some groups' 2D simulations.
- Supernova models have larger problems than ever to provide conditions for “strong r-processing”. Correct or fundamental problem?
- “Weak r-process” (Z < 50, A< 120) might occur in n-rich pockets ejected in e-capture SNe.
- Heaviest r-process elements in solar proportions can be robustly produced in NS-NS (or NS-BH) merger ejecta.
- NS-NS (or NS-BH) mergers are likely to be the main sources of heavy (A > 130) r-nuclei. Can they make r-material in ultra-metal poor stars?

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Neutrinos & Explosion Mechanism

Paradigm: Explosions by the convectively supported neutrino-heating mechanism

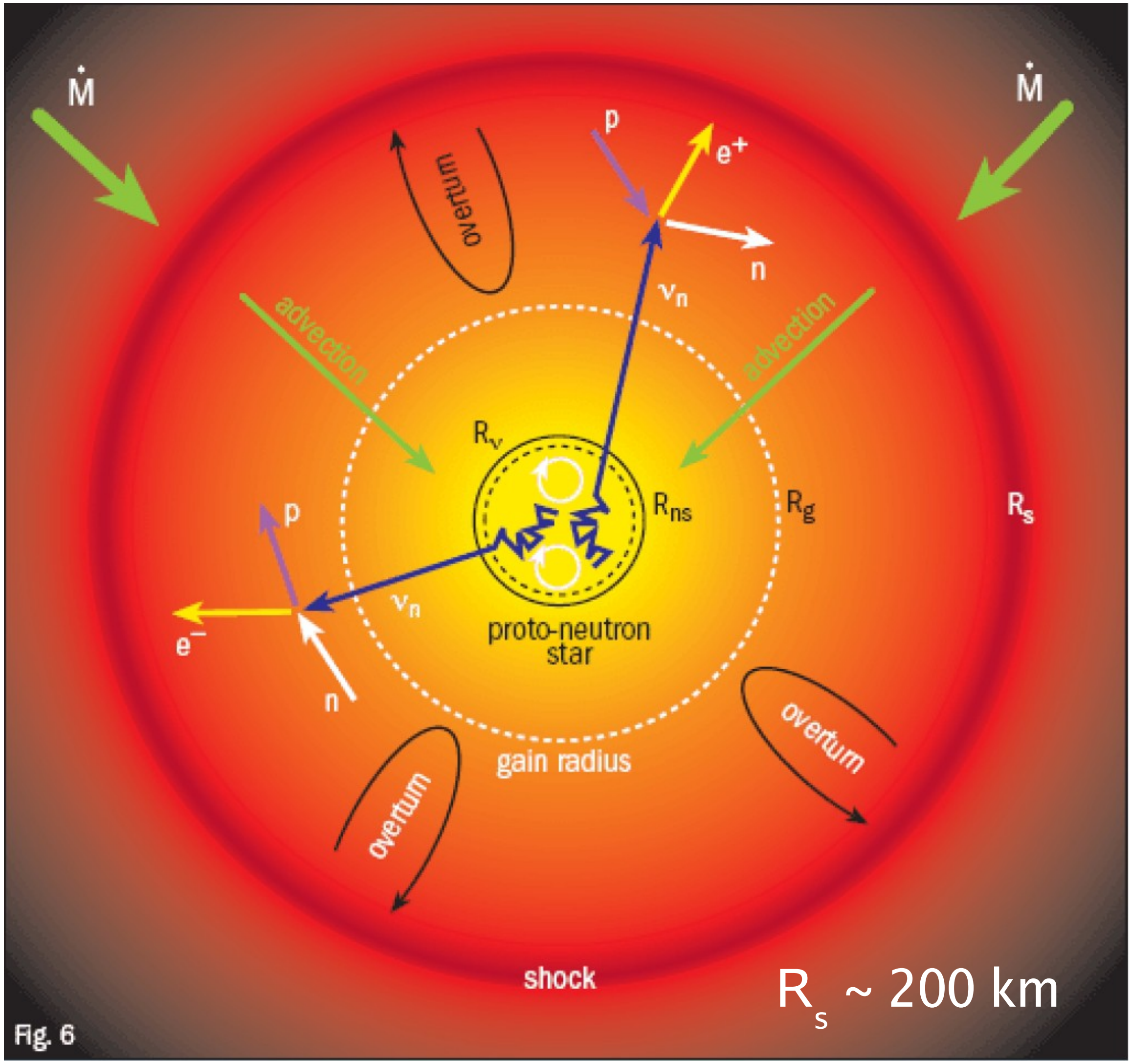


Fig. 6

- “Neutrino-heating mechanism”: Neutrinos `revive' stalled shock by energy deposition (Colgate & White 1966, Wilson 1982, Bethe & Wilson 1985);
- Convective processes & hydrodynamic instabilities enhance the heating mechanism (Herant et al. 1992, 1994; Burrows et al. 1995, Janka & Müller 1994, 1996; Fryer & Warren 2002, 2004; Blondin et al. 2003; Scheck et al. 2004,06,08).

Explosions of

$M_{star} \sim 8{-}10\ M_{sun}$ Stars

SN Progenitors: Core density profiles

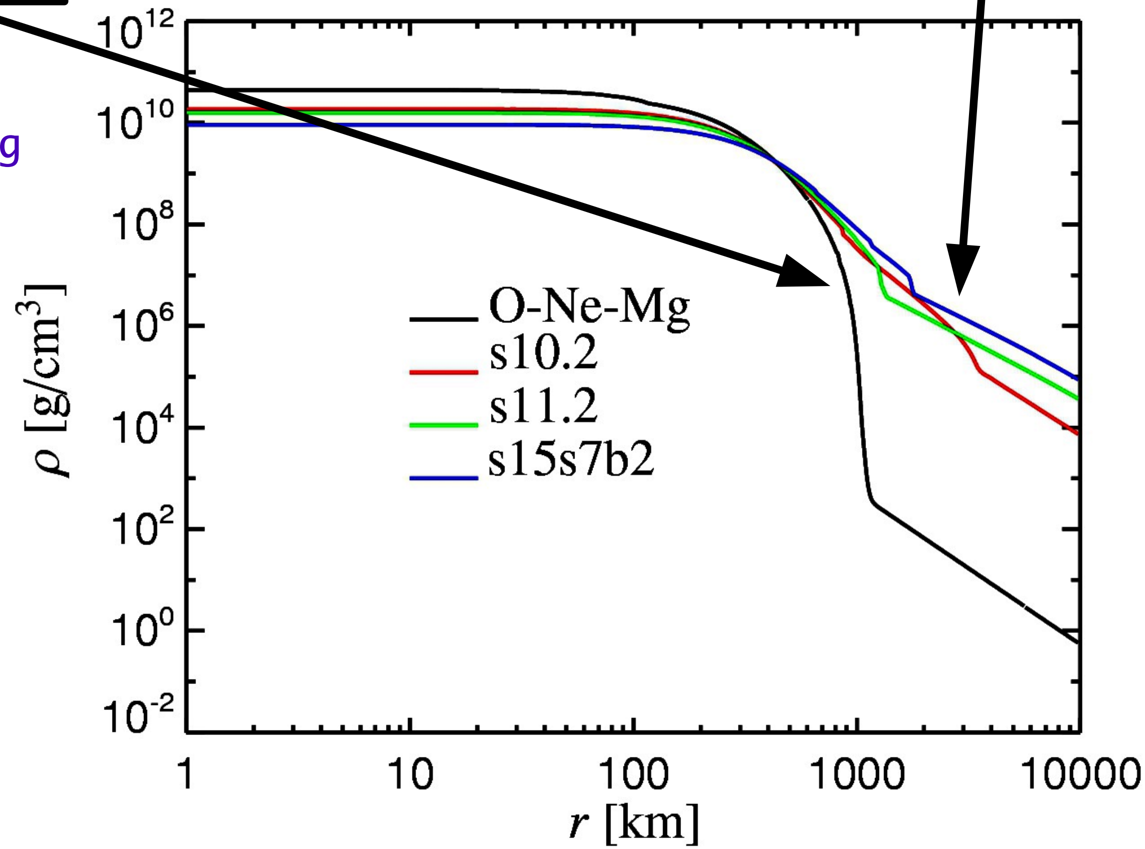
~8–10 M_{sun} (super-AGB) stars have ONeMg cores with a very steep density gradient at the surface
(====> rapidly decreasing mass accretion rate after core bounce)

>10 M_{sun} stars have much higher densities outside of their Fe cores
(e.g. Heger et al., Limongi et al.,Nomoto et al., Hirschi et al.)
(====> ram pressure of accreted mass decreases slowly after core bounce)

8.8 M_{sun} progenitor model (Nomoto 1984):
2.2 M_{sun} H+He, 1.38 M_{sun} C+O, 1.28 M_{sun} ONeMg
at the onset of core collapse

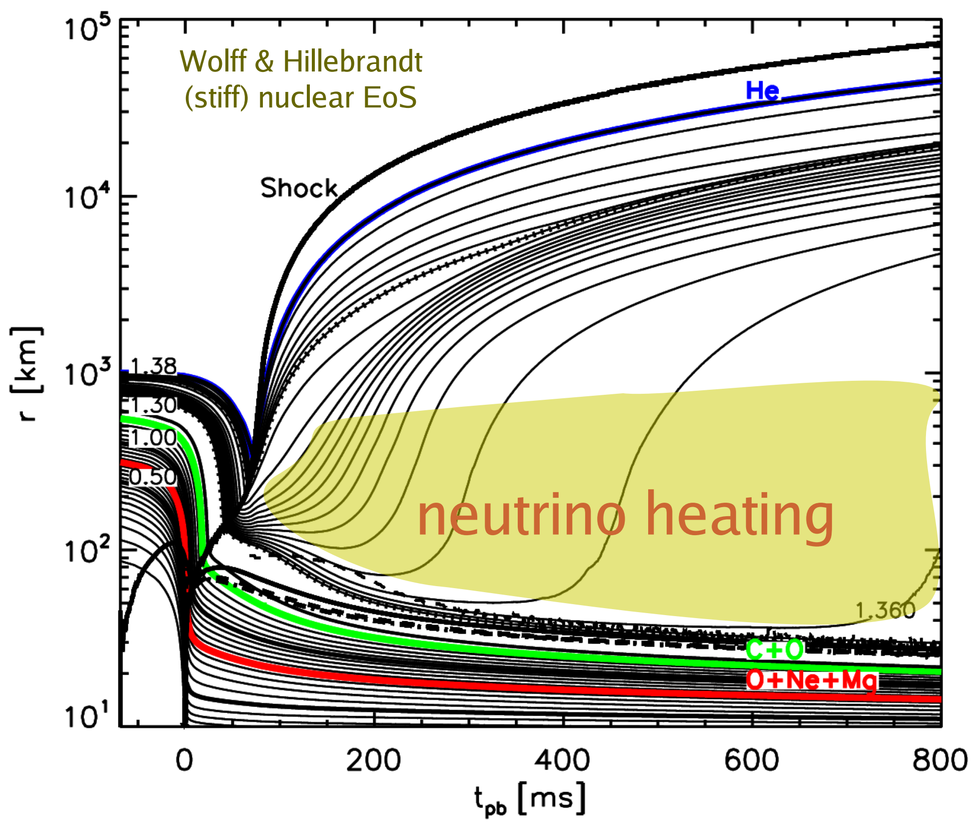
~30% of all SNe (Nomoto et al. 1981, 84, 87)

8.75 M_{sun} < M_{ZAMS} < 9.25 M_{sun}: < 20% of all SNe; (Poelarends et al., A&A 2006),
but mass range much larger at metallicities less than solar (Langer et al.)



SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

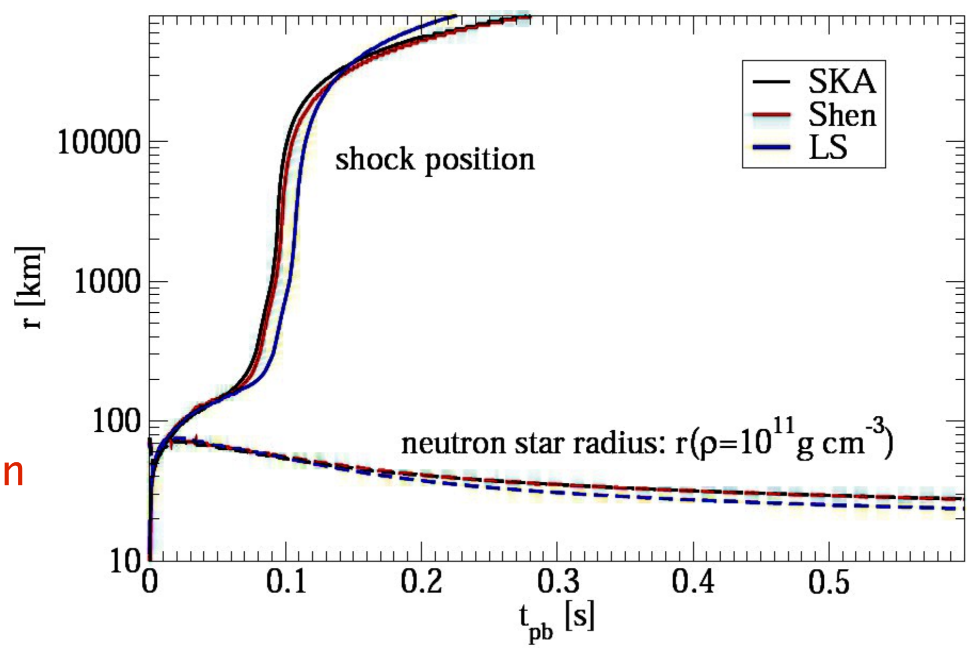
"Electron-capture supernovae"
or "ONeMg-core supernovae"



Convection is not necessary for launching explosion
but occurs in NS and in neutrino-heating layer

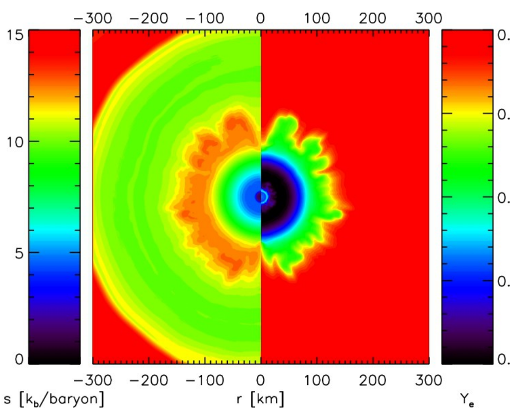
Kitaura et al., A&A 450 (2006) 345;
Janka et al., A&A 485 (2008) 199;
Fischer et al., A&A 517 (2010) A80

- No prompt explosion !
- Mass ejection by "neutrino-driven wind"
(like Mayle & Wilson 1988
and similar to AIC of WDs;
see Woosley & Baron 1992, Fryer et al. 1999;
Dessart et al. 2006)
- Explosion develops in similar way for soft nuclear EoS (i.e. compact PNS) and stiff EoS (less compact PNS)

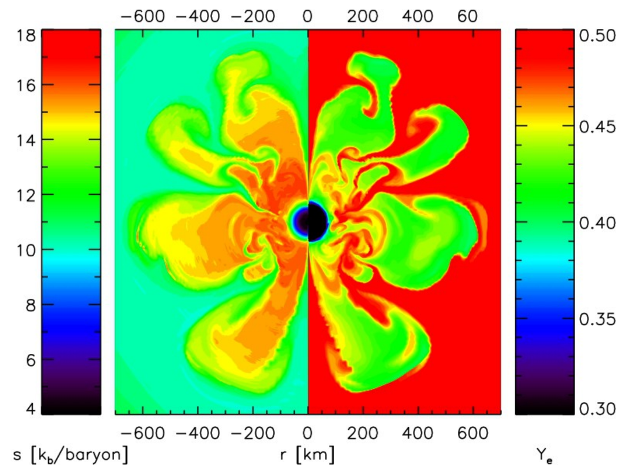


2D SN Simulations: $M_{star} \sim 8...10\ M_{sun}$

Convection leads to slight increase of explosion energy, causes explosion asymmetries, and ejects n-rich matter!

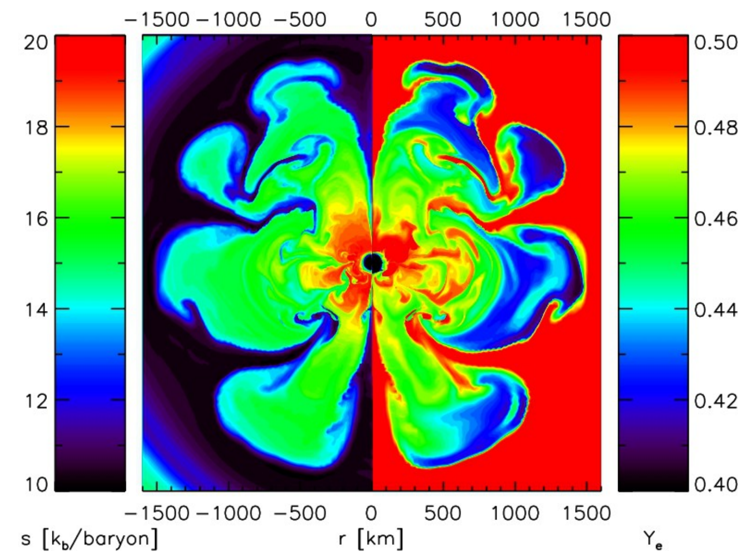


t = 0.097 s after core bounce

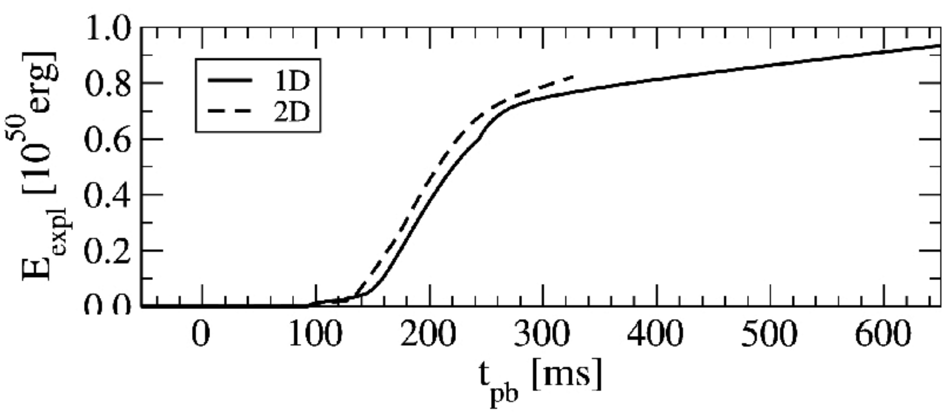


t = 0.144 s after core bounce

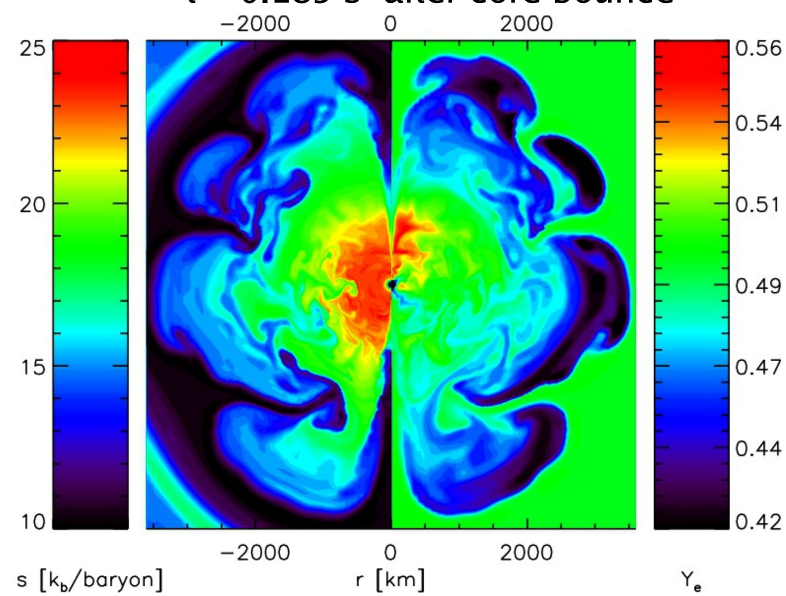
Entropy Y_e



t = 0.185 s after core bounce

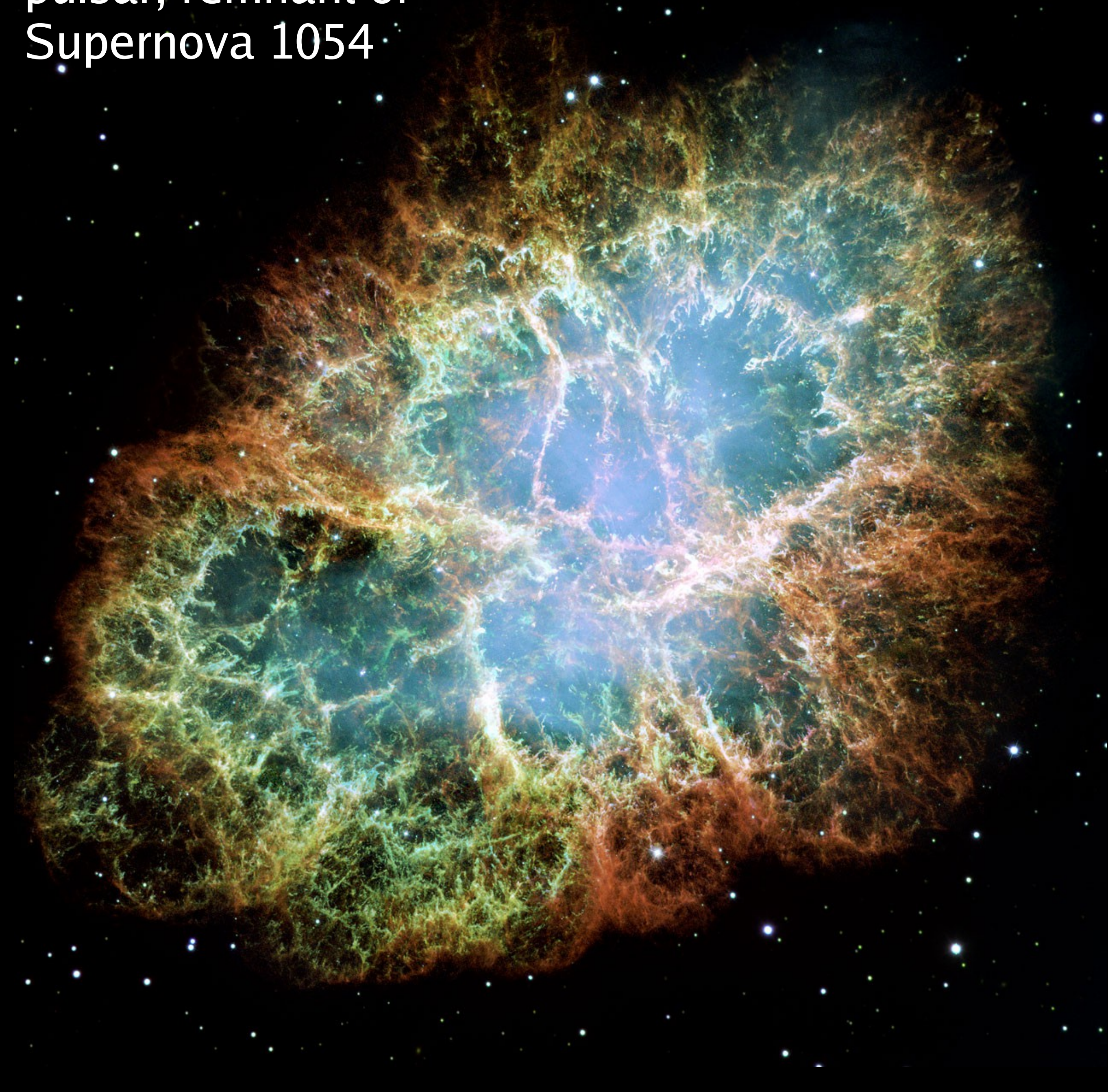


Janka et al. (2008), Müller et al. (in preparation)



t = 0.262 s after core bounce

CRAB Nebula with pulsar, remnant of Supernova 1054



Explosion properties:

$E_{exp} \sim 10^{50}$ erg $= 0.1$ bethe
$M_{Ni} \sim 0.003\ M_{sun}$

Low explosion energy and ejecta composition (little Ni, C, O) of ONeMg core explosion are compatible with CRAB (SN1054)

(Nomoto et al., Nature, 1982; Hillebrandt, A&A, 1982)

Might also explain other low-luminosity supernovae (e.g. SN1997D, 2008S, 2008HA)

Nucleosynthesis in Supernova Ejecta

Crucial parameters for nucleosynthesis in neutrino-driven outflows:

- * Electron-to-baryon ratio Y_e (<---> neutron excess)
- * Entropy (<----> ratio of (temperature)^3 to density)
- * Expansion timescale

Determined by the interaction of stellar gas with neutrinos from nascent neutron star:

$$\nu_e + n \rightarrow e^- + p$$
$$\bar{\nu}_e + p \rightarrow e^+ + n$$

$$Y_e \sim \left[1 + \frac{L_{\bar{\nu}_e}(\epsilon_{\bar{\nu}_e} - 2\Delta)}{L_{\nu_e}(\epsilon_{\nu_e} + 2\Delta)}\right]^{-1}$$

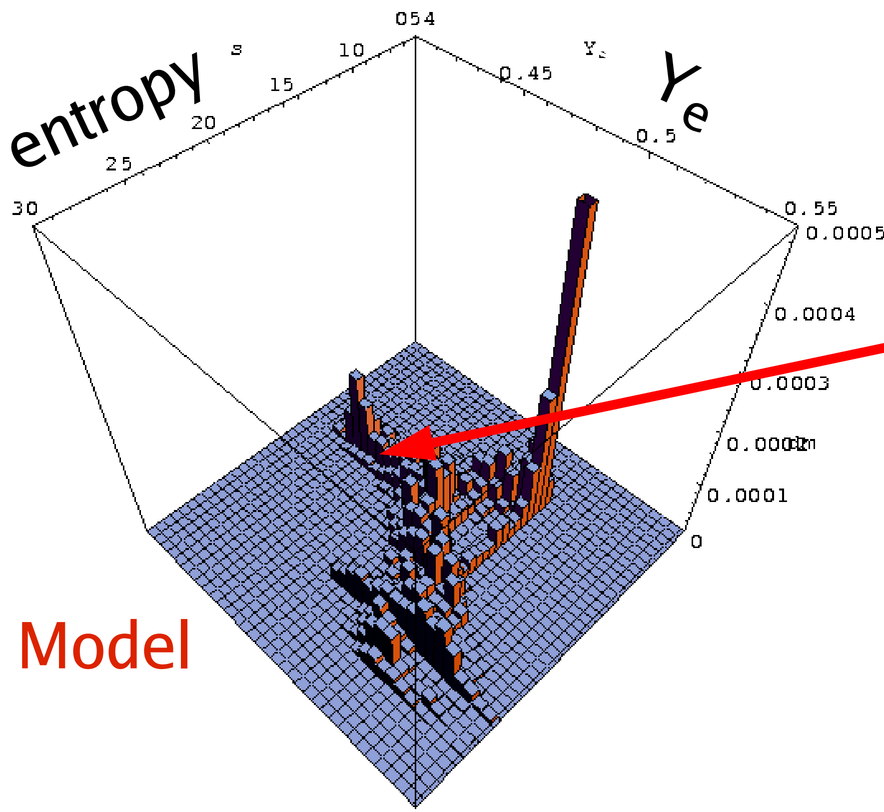
with $\epsilon_\nu = \frac{\langle \epsilon_\nu^2 \rangle}{\langle \epsilon_\nu \rangle}$ and $\Delta = (m_n - m_p)c^2 \approx 1.29\,\mathrm{MeV}.$

If $L_{\bar{\nu}_e} \approx L_{\nu_e}$, one needs for $Y_e < 0.5$ (i.e. neutron excess):

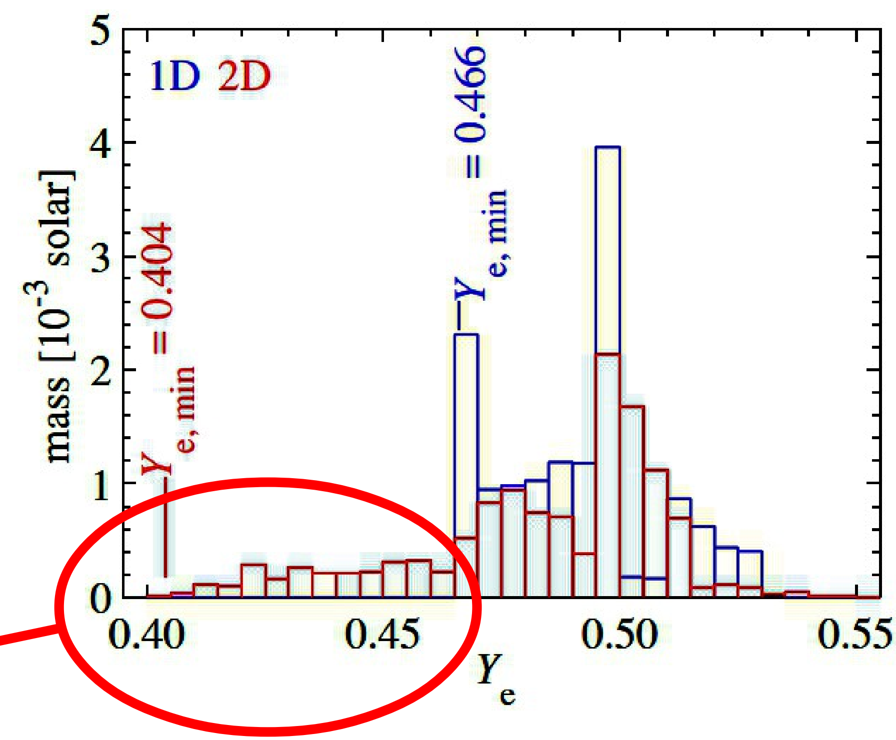
$$\epsilon_{\bar{\nu}_e} - \epsilon_{\nu_e} > 4\Delta.$$

Nucleosynthesis in O-Ne-Mg Core SNe

Convectively ejected n-rich matter with modest entropy.



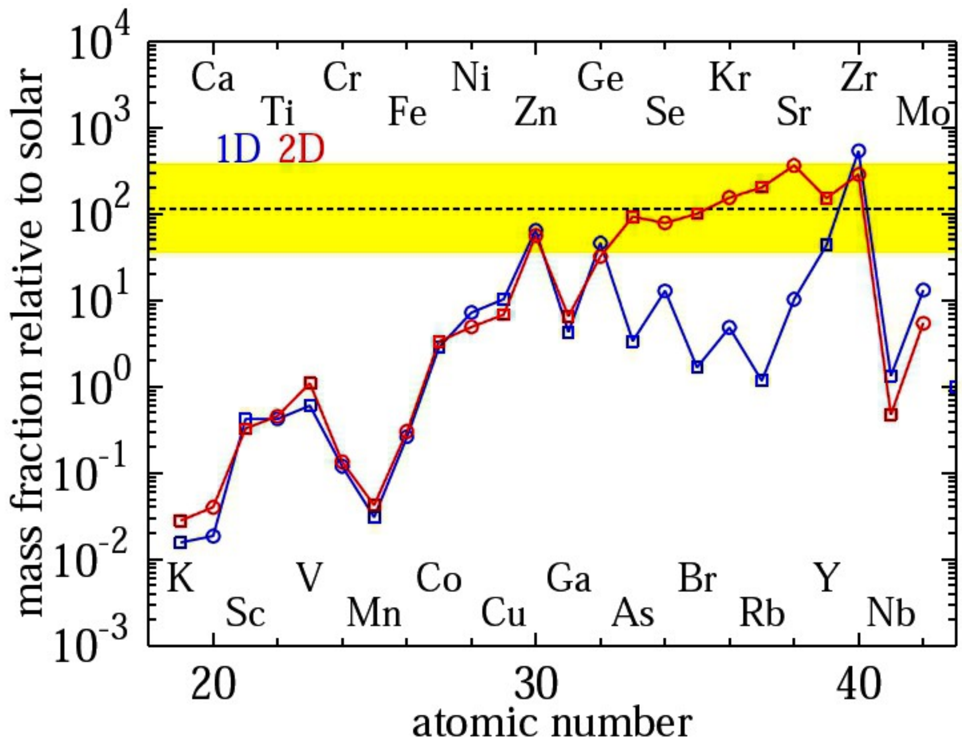
2D Model

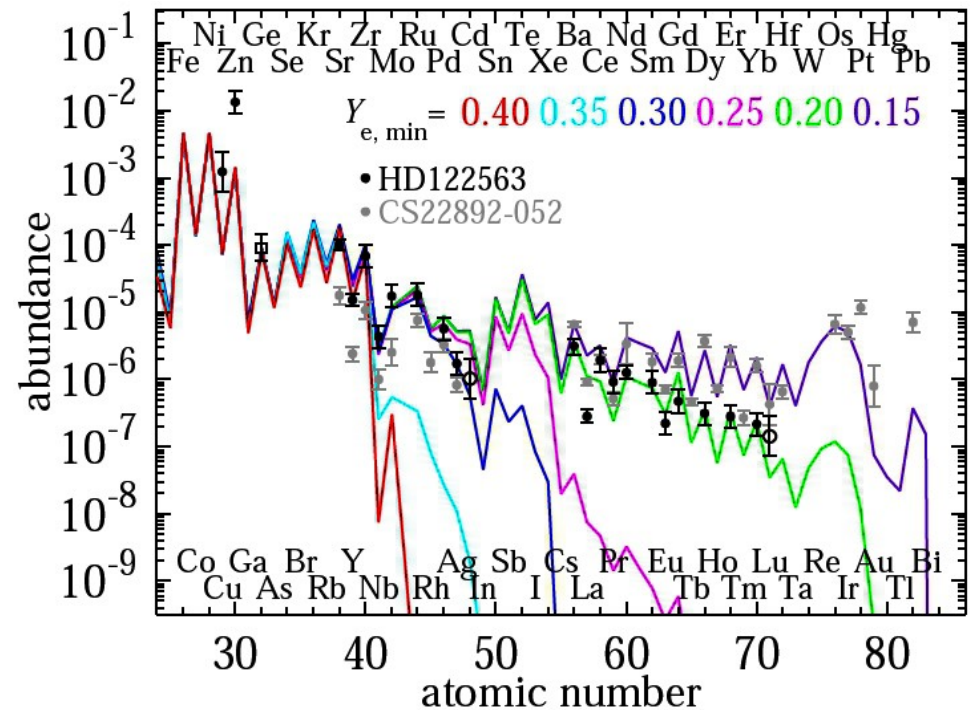


(Wanajo, Janka, & Müller, ApJ Letters 726 (2011) L15)

Nucleosynthesis in O-Ne-Mg Core SNe

Convectively ejected n-rich matter makes ONeMg-core supernovae an interesting source of nuclei between iron group and N = 50 (from Zn to Zr).



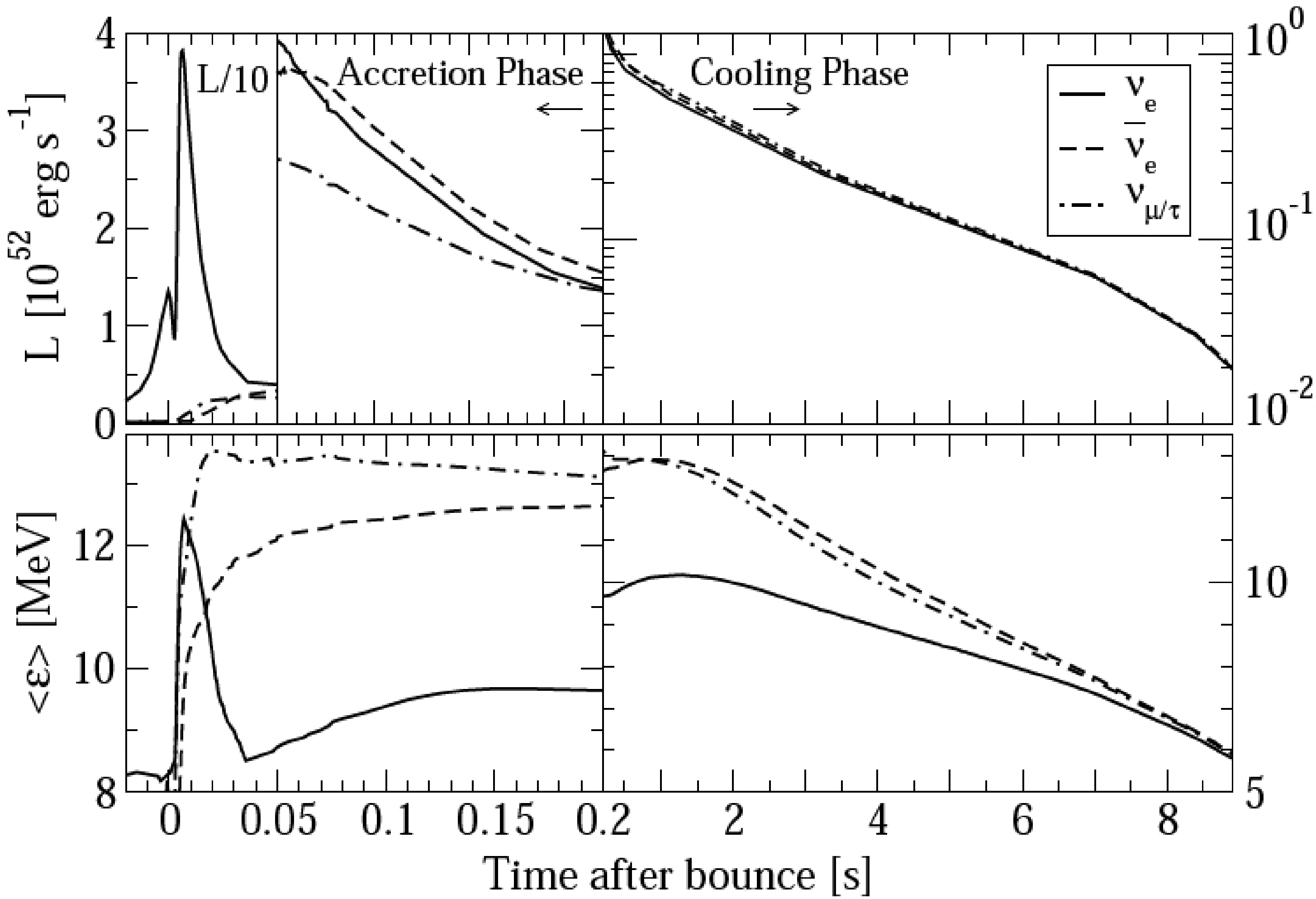


Models in very good agreement with Ge, Sr, Y, Zr abundances observed in r-process deficient Galactic halo stars.

(Wanajo, Janka, & Müller, ApJ Letters 726 (2011) L15)

If tiny amounts of matter with Y_e down to 0.30–0.35 were also ejected, a weak r-process may yield elements up to Pd, Ag, and Cd.

PNS Cooling in O-Ne-Mg-Core SNe



Hüdepohl et al. (PRL 104 (2010)); arXiv:0912:0260

Luminosities and mean energies very similar for all neutrinos during the proto-neutron star (PNS) cooling evolution.

Neutrino Reactions in Supernovae

Beta processes:

- $e^- + p \rightleftharpoons n + \nu_e$
- $e^+ + n \rightleftharpoons p + \bar{\nu}_e$
- $e^- + A \rightleftharpoons \nu_e + A^*$

Neutrino scattering:

- $\nu + n, p \rightleftharpoons \nu + n, p$
- $\nu + A \rightleftharpoons \nu + A$
- $\nu + e^\pm \rightleftharpoons \nu + e^\pm$

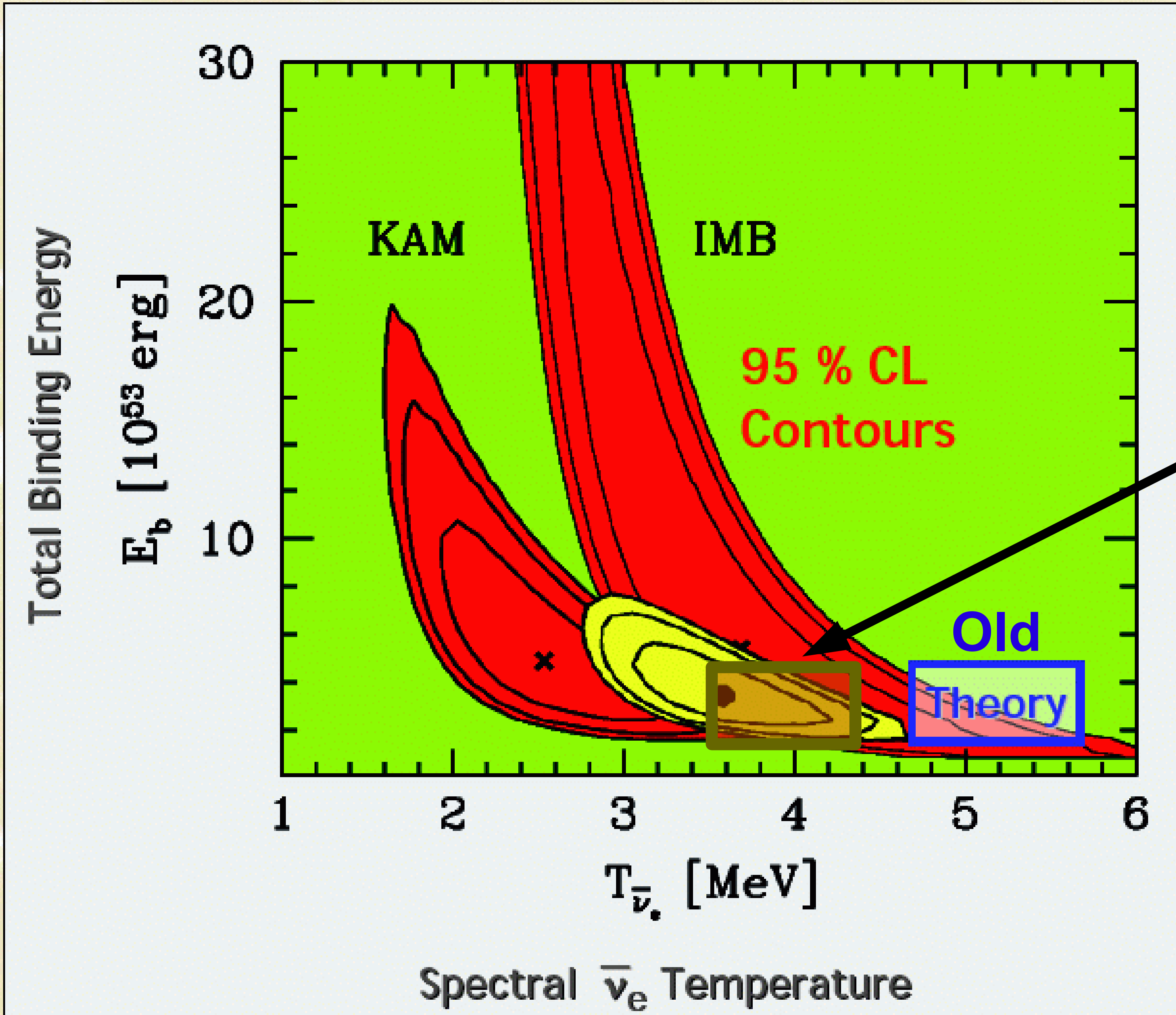
Thermal pair processes:

- $N + N \rightleftharpoons N + N + \nu + \bar{\nu}$
- $e^+ + e^- \rightleftharpoons \nu + \bar{\nu}$

Neutrino-neutrino reactions:

- $\nu_x + \nu_e, \bar{\nu}_e \rightleftharpoons \nu_x + \nu_e, \bar{\nu}_e$
  $(\nu_x = \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \text{ or } \bar{\nu}_\tau)$
- $\nu_e + \bar{\nu}_e \rightleftharpoons \nu_{\mu,\tau} + \bar{\nu}_{\mu,\tau}$

Interpreting SN 1987A Neutrinos



Jegerlehner, Neubig & Raffelt, PRD 54 (1996) 1194

New Theory Results

Assume thermal spectra and equipartition of energy between the six degrees of freedom ν_e, ν_μ, ν_τ and their antiparticles

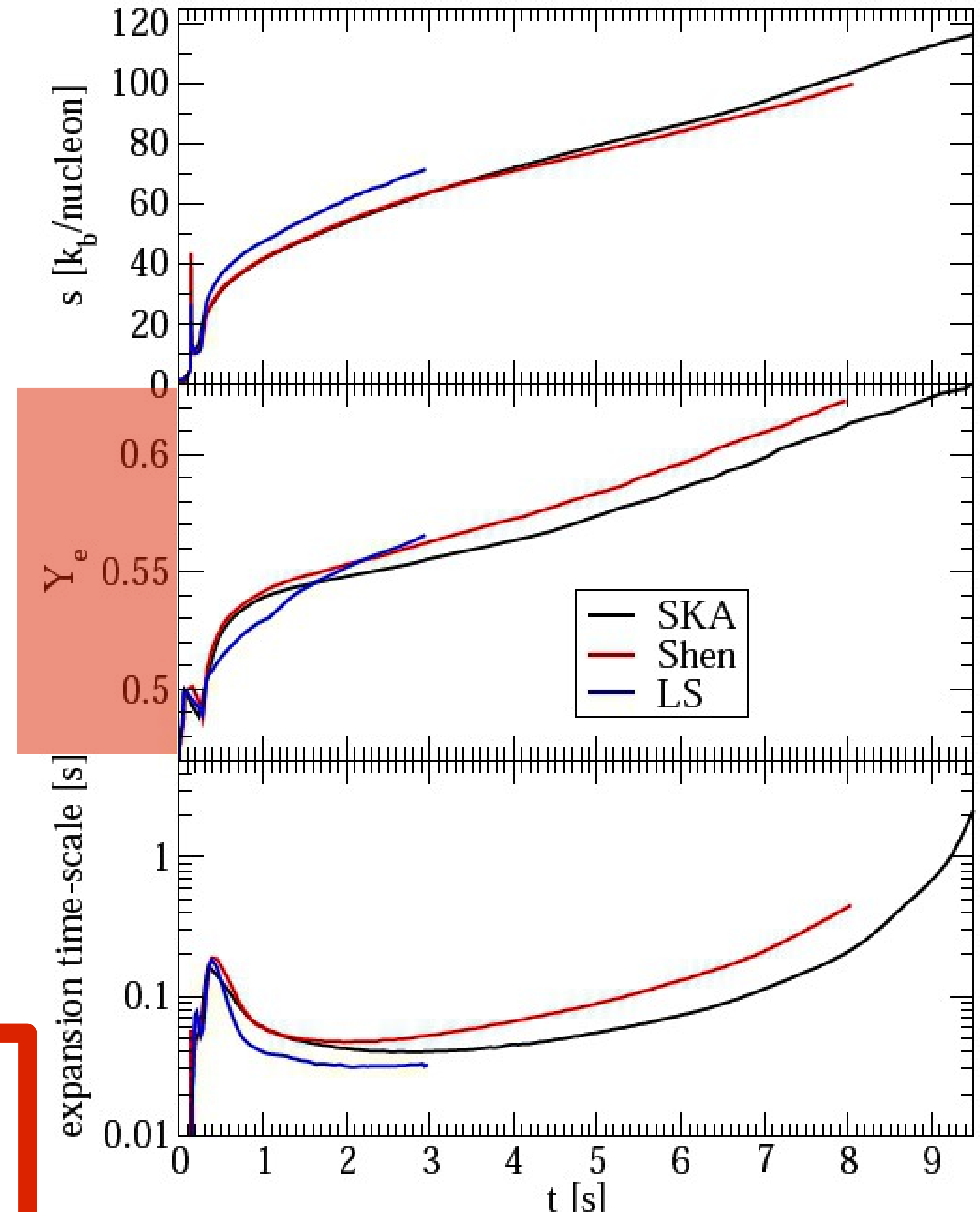
Nucleosynthesis in O-Ne-Mg Core SNe

- Neutrino-driven wind remains p-rich for >10 seconds!
- No r-process in the late neutrino-driven wind!
- Holds also for more massive progenitos (Fischer et al. 2009)

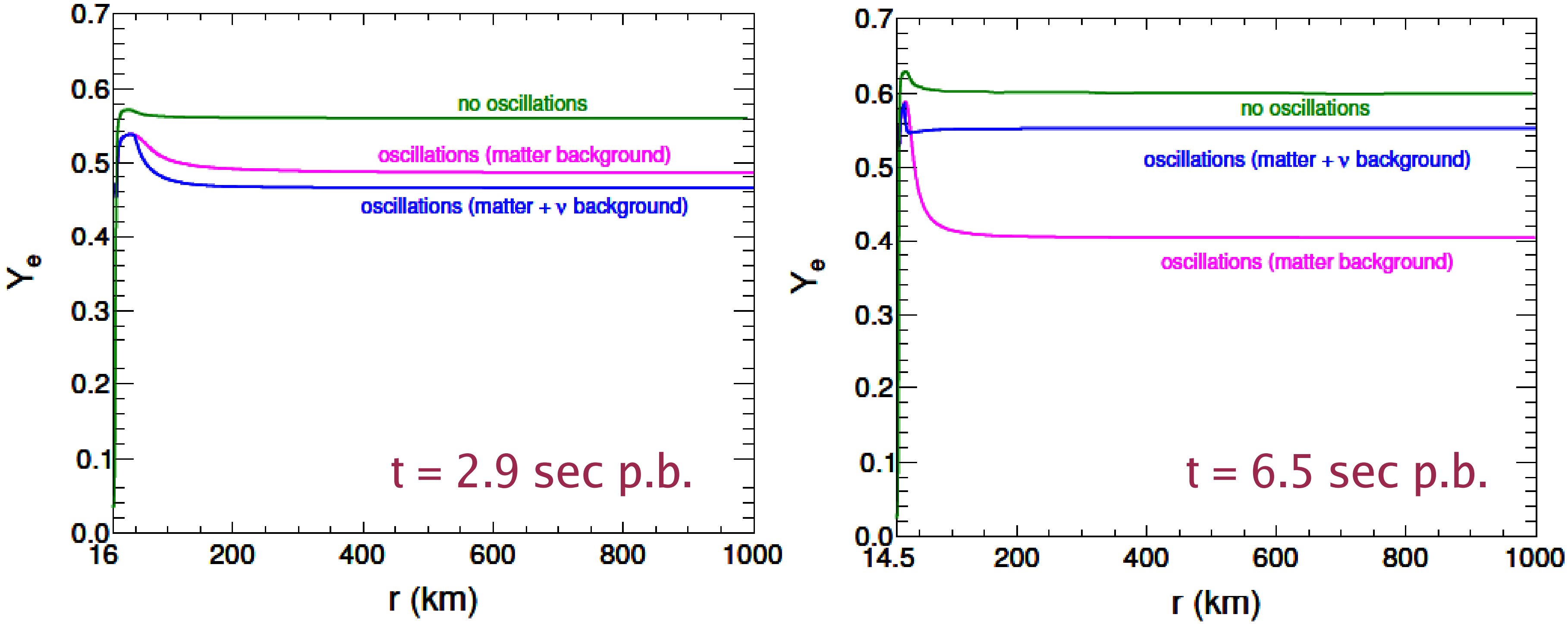
Hüdepohl (Diploma Thesis 2009);
Hüdepohl et al. (PRL 104 (2010);
in agreement with Fischer et al. (2010)

No favorable conditions for a strong r-process in ONeMg-core explosions and neutrino-driven winds of PNSs!

? What is the astrophysical site for the creation of the heaviest r-process elements (A > 130)? ?



Impact of eV-Mass Sterile Neutrino on ECSN Outflows



(Tamborra, Raffelt, Hüdepohl, THJ, JCAP, submitted; astro-ph on Oct.11, 2011)

Reactor anti-ν_e spectra motivate sterile neutrino: $\delta m^2 \sim 2.4$ eV^2, $\sin^2 2\theta \sim 0.16$

ν_e-ν_s MSW conversion swaps ν_e spectra, but is moderated by $\nu\nu$ refraction effects and ν_x-ν_e (3-1) MSW conversion.

Y_e is reduced in the neutrino-driven wind of PNS, but reduction is modest.

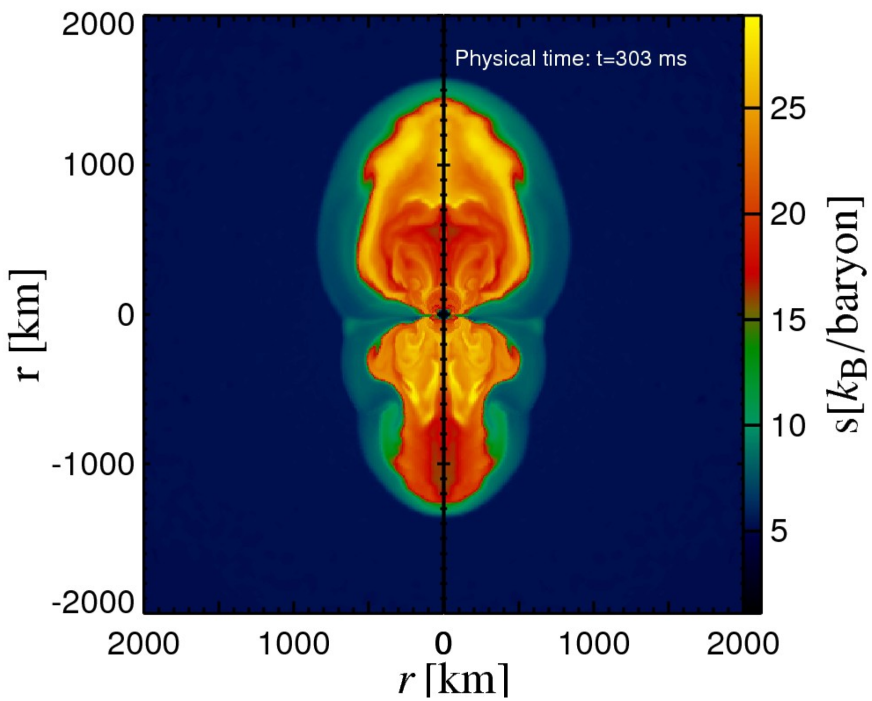
Explosions of $M_{star} > 10\ M_{sun}$ Stars

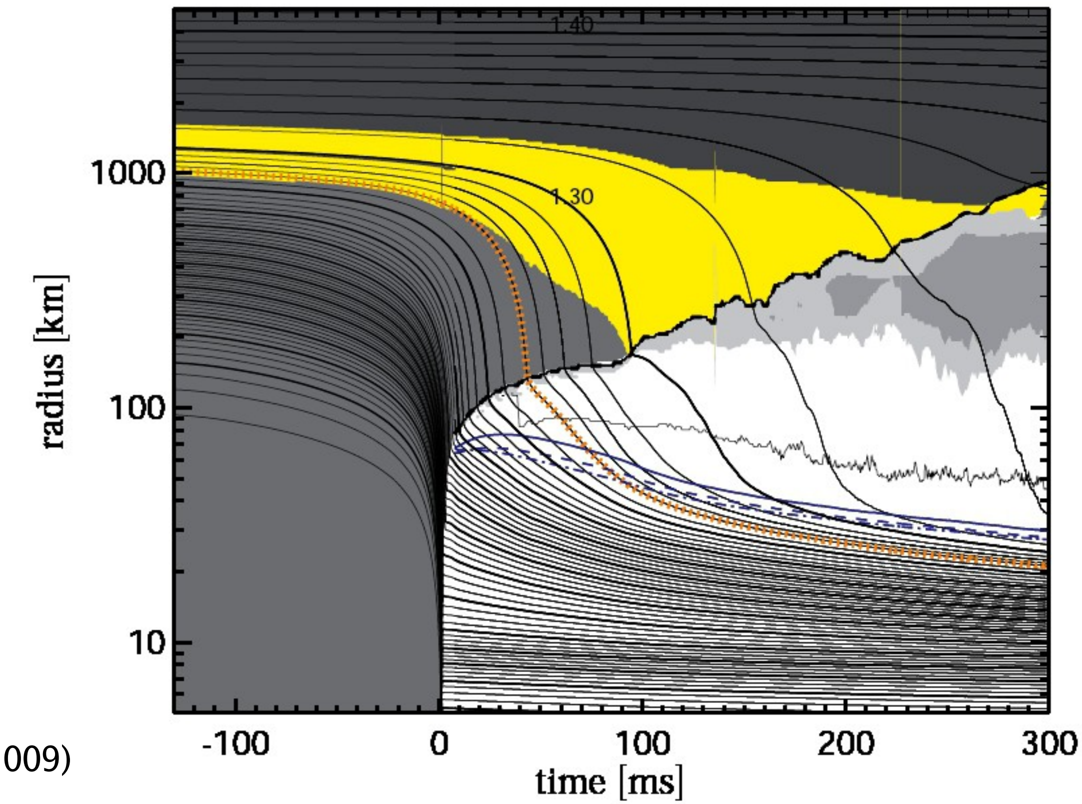
2D SN Simulations: $M_{star} \sim 11\ M_{sun}$

Nonradial hydrodynamic instabilities are crucial for the explosion !

Low-order (dipole, l=1, and quadrupole, l=2) modes of the "standing accretion shock instability" ("SASI"; Blondin et al. 2003) cause asymmetries and push shock to larger radii

===> This stretches residence time of matter in neutrino heating layer and thus increases energy absorbed by matter from neutrinos.
Leads to initiation of globally aspherical explosion even without rotation

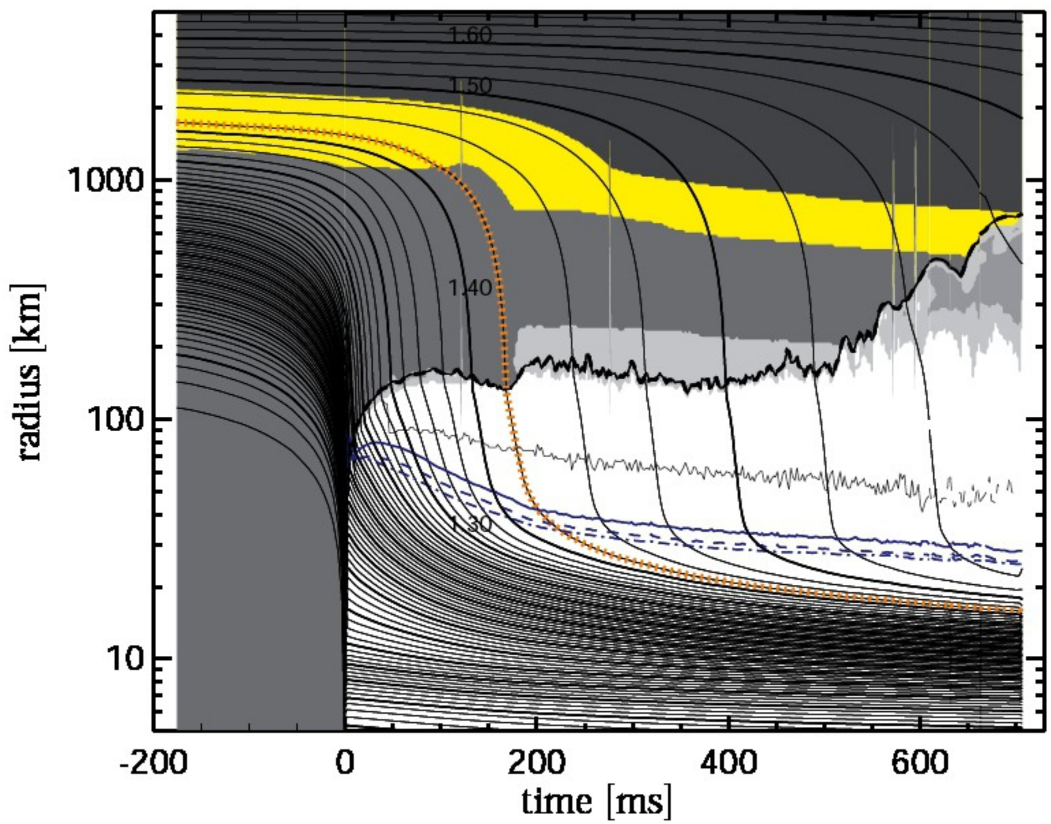


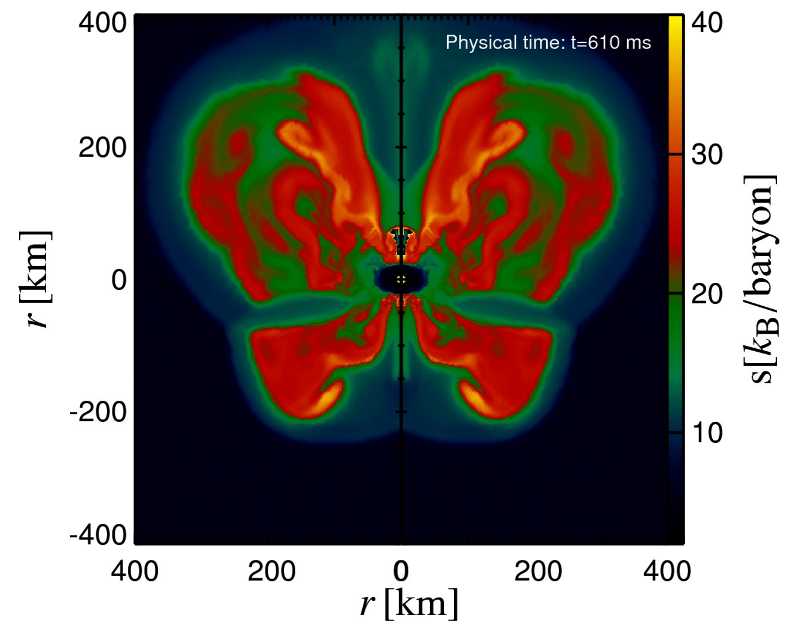


Buras et al., A&A 457 (2006) 281; Marek & Janka, ApJ (2009)

2D SN Simulations: $M_{star} = 15\ M_{sun}$

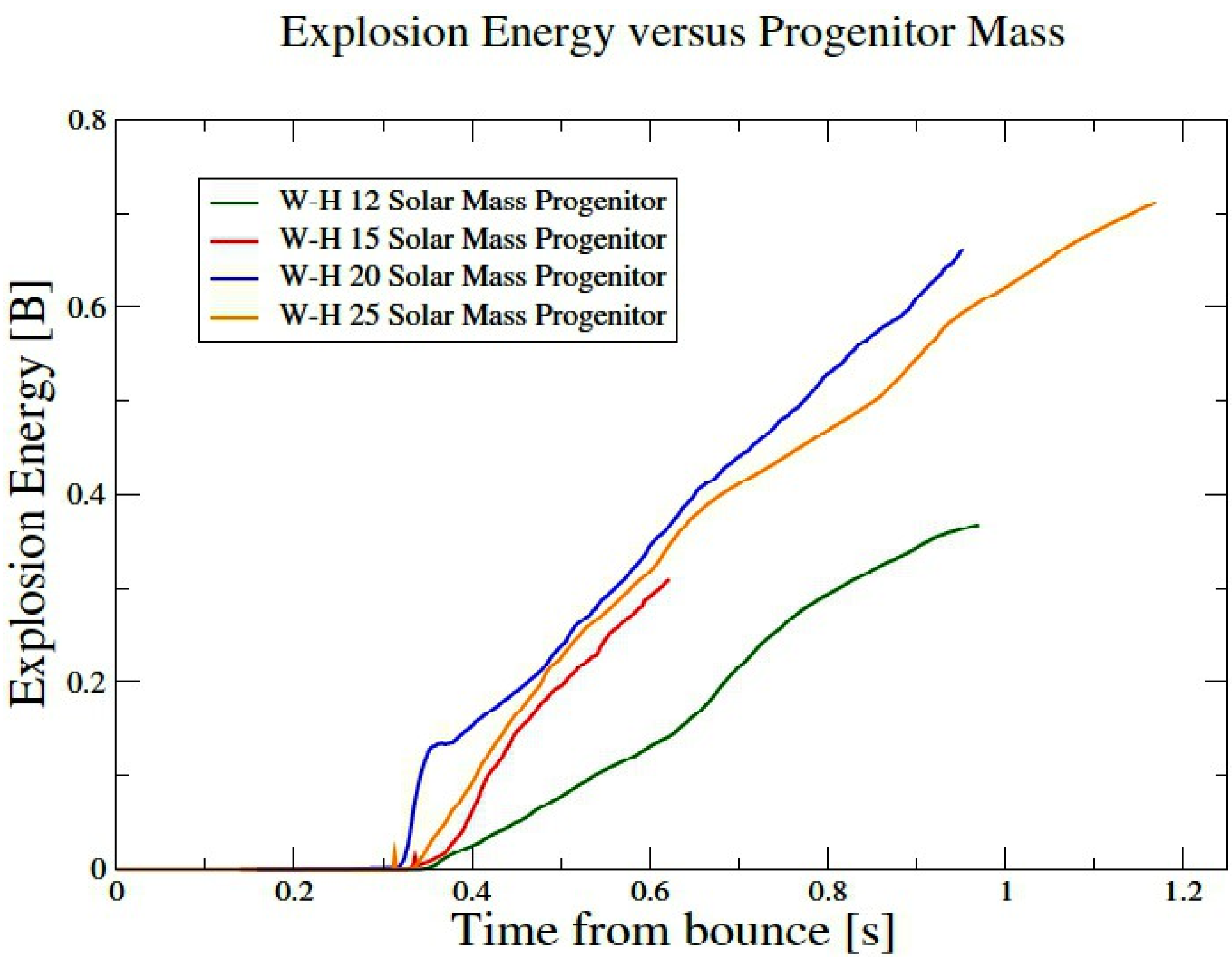
Violent SASI oscillations:
ν-driven explosion sets in
at t ~ 600 ms after bounce





(Marek, PhD Thesis 2007;
Marek & THJ, ApJ, 2009)

Explosions by Oak Ridge Group



(Bruenn et al., SciDAC2009;
JoP Conf. Ser. 180 (2009) 012018)

Simulations with CHIMERA code show faster and more energetic explosions.
Onset of explosion at essentially the same time for different progenitors (?)

General-Relativistic 2D Supernova Models

(Müller B., PhD Thesis (2009); Müller & THJ, ApJS, (2010))

$$\frac{\partial\sqrt{\gamma}\rho W}{\partial t} + \frac{\partial\sqrt{-g}\rho W\hat{v}^i}{\partial x^i} = 0, \quad (2.5)$$

$$\frac{\partial\sqrt{\gamma}\rho h W^2 v_j}{\partial t} + \frac{\partial\sqrt{-g}\left(\rho h W^2 v_j \hat{v}^i + \delta^i_j P\right)}{\partial x^i} = \frac{1}{2}\sqrt{-g}T^{\mu\nu}\frac{\partial g_{\mu\nu}}{\partial x^j} + \left(\frac{\partial\sqrt{\gamma}S_j}{\partial t}\right)_C, \quad (2.6)$$

$$\frac{\partial\sqrt{\gamma}\tau}{\partial t} + \frac{\partial\sqrt{-g}\left(\tau\hat{v}^i + P v^i\right)}{\partial x^i} = \alpha\sqrt{-g}\left(T^{\mu 0}\frac{\partial\ln\alpha}{\partial x^\mu} - T^{\mu\nu}\Gamma^0_{\mu\nu}\right) + \left(\frac{\partial\sqrt{\gamma}\tau}{\partial t}\right)_C. \quad (2.7)$$

$$\frac{\partial\sqrt{\gamma}\rho W Y_e}{\partial t} + \frac{\partial\sqrt{-g}\rho W Y_e\hat{v}^i}{\partial x^i} = \left(\frac{\partial\sqrt{\gamma}\rho W Y_e}{\partial t}\right)_C, \quad (2.8)$$

$$\frac{\partial\sqrt{\gamma}\rho W X_k}{\partial t} + \frac{\partial\sqrt{-g}\rho W X_k\hat{v}^i}{\partial x^i} = 0. \quad (2.9)$$

GR hydrodynamics

CFC metric equations

$$\hat{\Delta}\Phi = -2\pi\phi^5\left(E + \frac{K_{ij}K^{ij}}{16\pi}\right), \quad (2.10)$$

$$\hat{\Delta}(\alpha\Phi) = 2\pi\alpha\phi^5\left(E + 2S + \frac{7K_{ij}K^{ij}}{16\pi}\right), \quad (2.11)$$

$$\hat{\Delta}\beta^i = 16\pi\alpha\phi^4 S^i + 2\phi^{10}K^{ij}\hat{\nabla}_j\left(\frac{\alpha}{\Phi^6}\right) - \frac{1}{3}\hat{\nabla}^i\hat{\nabla}_j\beta^j, \quad (2.12)$$

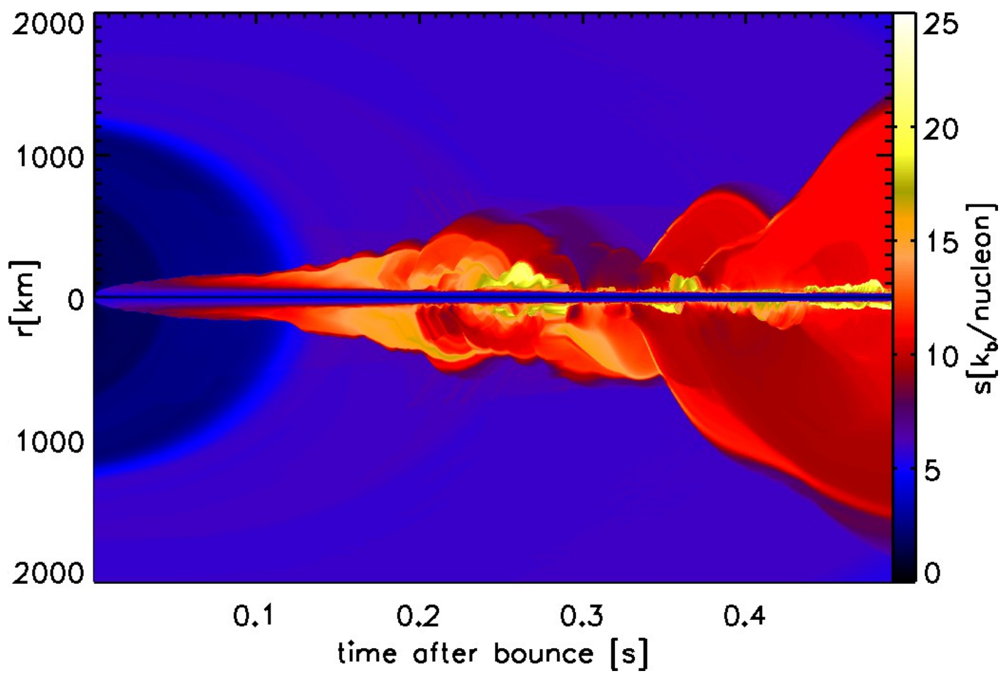
$$\begin{aligned}
&\frac{\partial W\left(\hat{J} + v_r\hat{H}\right)}{\partial t} + \frac{\partial}{\partial r}\left[\left(W\frac{\alpha}{\phi^2} - \beta_r v_r\right)\hat{H} + \left(W v_r\frac{\alpha}{\phi^2} - \beta_r\right)\hat{J}\right] - \quad (2.28)\\
&\frac{\partial}{\partial\varepsilon}\left\{W\varepsilon\hat{J}\left[\frac{1}{r}\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right) + 2\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right] + \right.\\
&W\varepsilon\hat{H}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right) - \frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r} + \alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r} - \frac{\partial v_r}{\partial t}\right)\right] -\\
&\left.\varepsilon\hat{K}\left[\frac{\beta_r W}{r} - \frac{\partial\beta_r W}{\partial r} + W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + v_r\frac{\partial v_r}{\partial t}\right)\right]\right\} -\\
&W\hat{J}\left[\frac{1}{r}\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right) + 2\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right] -\\
&W\hat{H}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right) - \frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r} + \alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r} - \frac{\partial v_r}{\partial t}\right)\right] +\\
&\hat{K}\left[\frac{\beta_r W}{r} - \frac{\partial\beta_r W}{\partial r} + W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + v_r\frac{\partial v_r}{\partial t}\right)\right] = \alpha\hat{C}^{(0)},
\end{aligned}$$

Neutrino transport

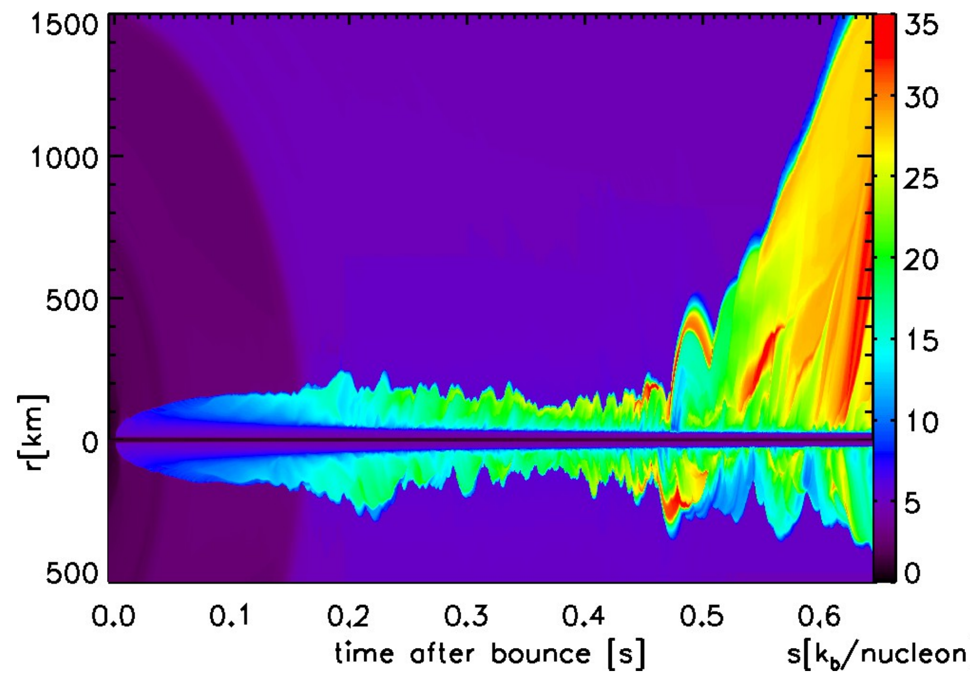
$$\begin{aligned}
&\frac{\partial W\left(\hat{H} + v_r\hat{K}\right)}{\partial t} + \frac{\partial}{\partial r}\left[\left(W\frac{\alpha}{\phi^2} - \beta_r v_r\right)\hat{K} + \left(W v_r\frac{\alpha}{\phi^2} - \beta_r\right)\hat{H}\right] - \quad (2.29)\\
&\frac{\partial}{\partial\varepsilon}\left\{W\varepsilon\hat{H}\left[\frac{1}{r}\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right) + 2\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right] + \right.\\
&W\varepsilon\hat{K}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right) - \frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r} + \alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r} - \frac{\partial v_r}{\partial t}\right)\right] -\\
&\left.\varepsilon\hat{L}\left[\frac{\beta_r W}{r} - \frac{\partial\beta_r W}{\partial r} + W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + v_r\frac{\partial v_r}{\partial t}\right)\right]\right\} +\\
&\left(\hat{J} - \hat{K}\right)\left[v_r\left(\frac{\beta_r}{r} - \frac{\partial\beta_r}{\partial r}\right) + \frac{\partial}{\partial r}\left(\frac{W\alpha}{\phi^2}\right) - \frac{W\alpha}{r\phi^2} + W^3\left(\frac{\partial v_r}{\partial t} - \beta_r\frac{\partial v_r}{\partial r}\right)\right] +\\
&\left(\hat{H} - \hat{L}\right)\left[\frac{W^3\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + \frac{\beta W}{r} - \frac{\partial\beta W}{\partial r} - W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + \frac{\partial W}{\partial t}\right] -\\
&W\hat{H}\left[\frac{1}{r}\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right) + 2\left(\beta_r - \frac{\alpha v_r}{\phi^2}\right)\frac{\partial\ln\phi}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right] -\\
&W\hat{K}\left[v_r\left(\frac{\partial\beta_r\phi^2}{\partial r} - 2\frac{\partial\ln\phi}{\partial t}\right) - \frac{\alpha}{\phi^2}\frac{\partial\ln\alpha W}{\partial r} + \alpha W^2\left(\beta_r\frac{\partial v_r}{\partial r} - \frac{\partial v_r}{\partial t}\right)\right] +\\
&\hat{L}\left[\frac{\beta_r W}{r} - \frac{\partial\beta_r W}{\partial r} + W v_r r\frac{\partial}{\partial r}\left(\frac{\alpha}{r\phi^2}\right) + W^3\left(\frac{\alpha}{\phi^2}\frac{\partial v_r}{\partial r} + v_r\frac{\partial v_r}{\partial t}\right)\right] = \alpha\hat{C}^{(1)}.
\end{aligned}$$

Relativistic 2D SN Models: 11.2 and 15 M_{sun} Stars

11.2 M_{sun}



15 M_{sun}

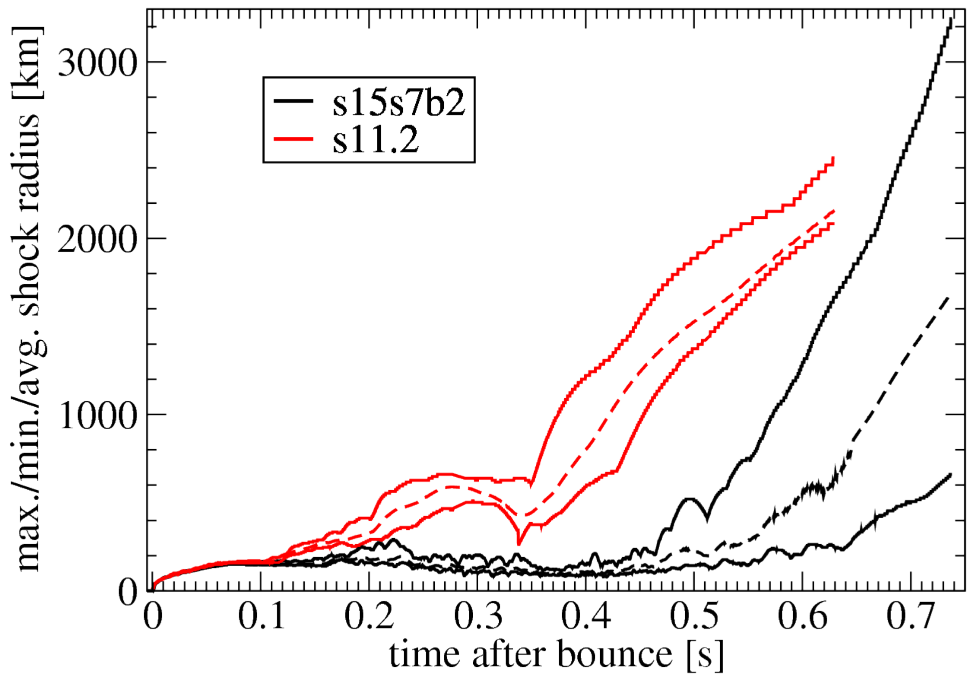


(Müller, THJ, Marek & Dimmelmeier, to be submitted)

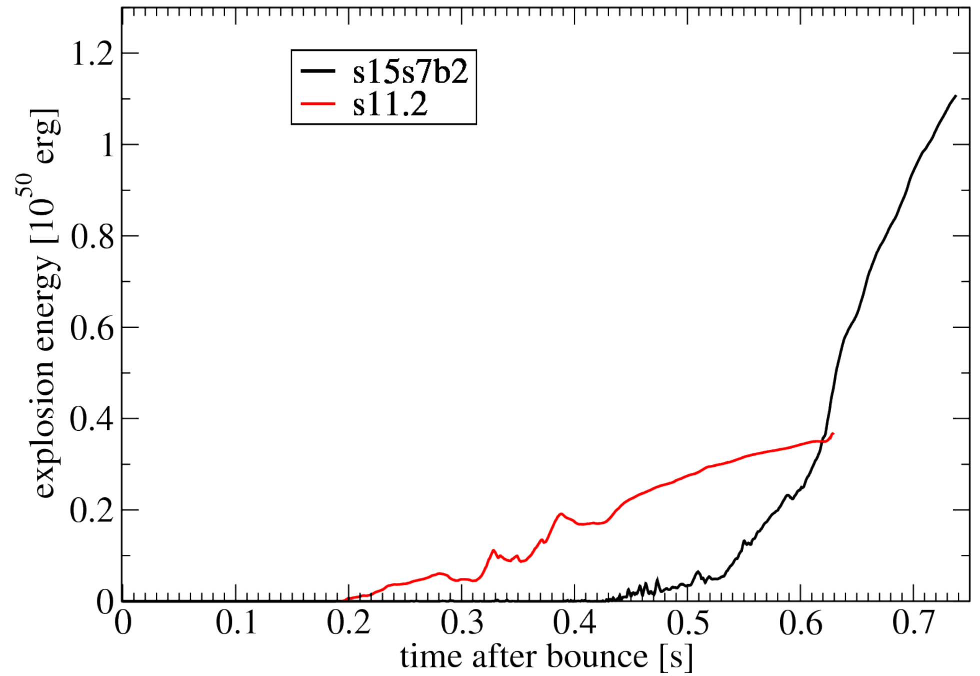
Violent, long lasting shock oscillations produce quasi-periodic variations of neutrino emission and gravitational-wave signal.

Relativistic 2D SN Simulations

Shock radii



Explosion energies

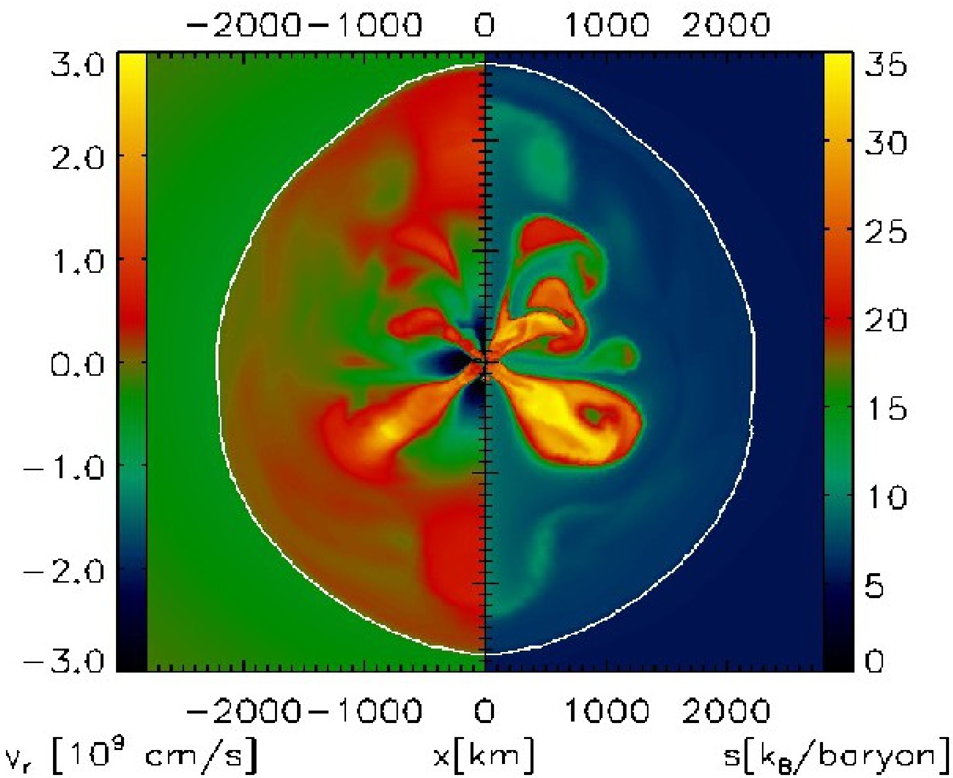


(Müller, THJ, Marek & Dimmelmeier, to be submitted)

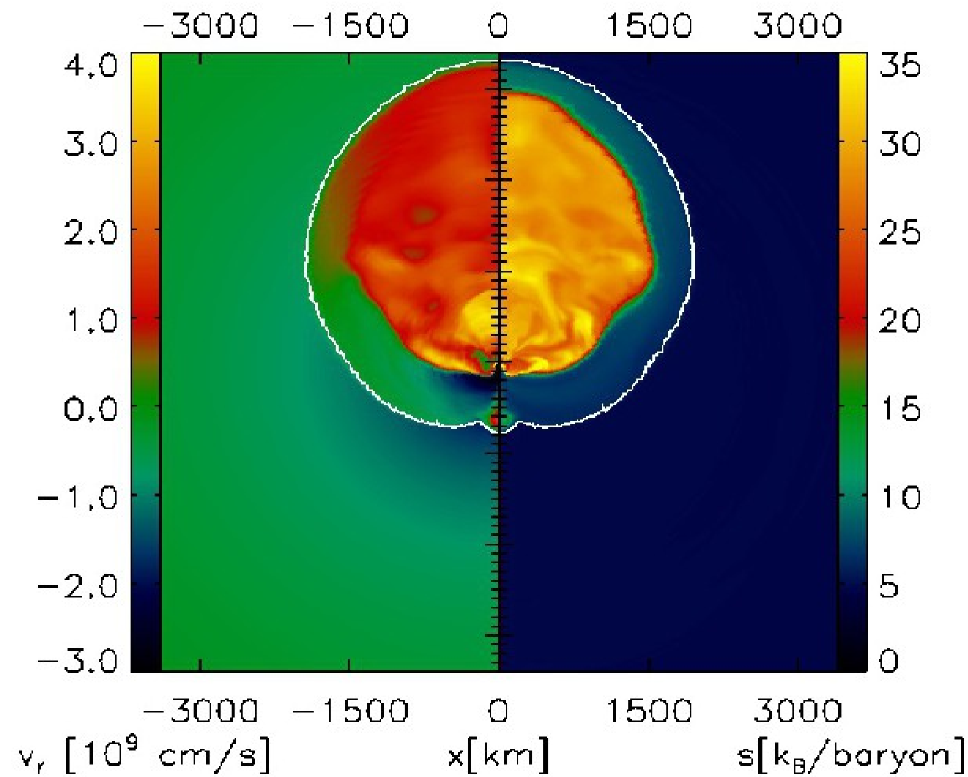
- Relativistic (GR) 2D calculations basically confirm our "post-Newtonian" results.
- Explosions with GR develop somewhat faster and earlier. GR effects help!
- 2D explosions are seemingly "marginal", i.e., tend to set in late and to be relatively weak and highly deformed.

Relativistic 2D SN Simulations

11.2 M_{sun}

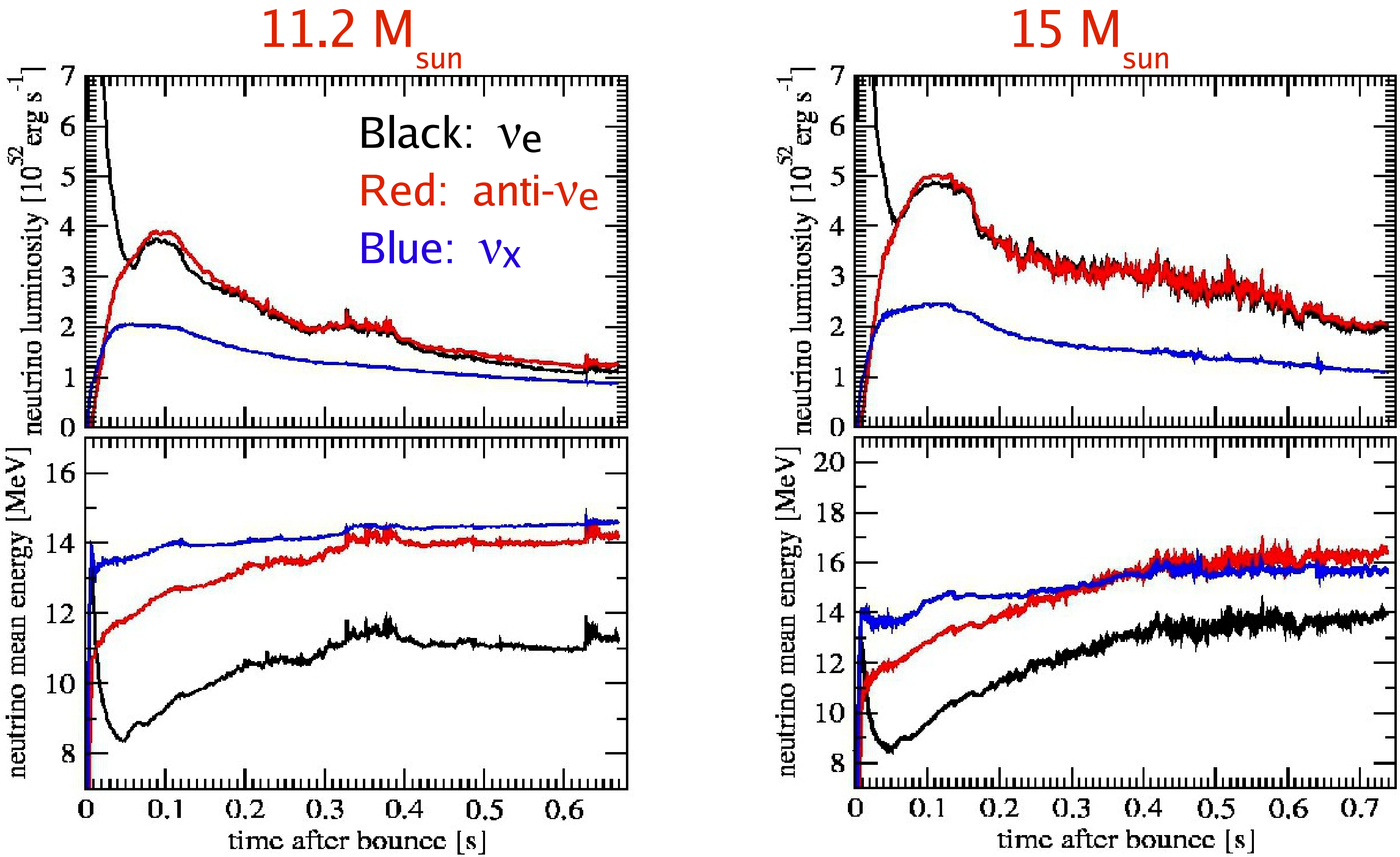


15 M_{sun}



(Müller, THJ, Marek & Dimmelmeier, to be submitted)

Relativistic 2D SN Simulations

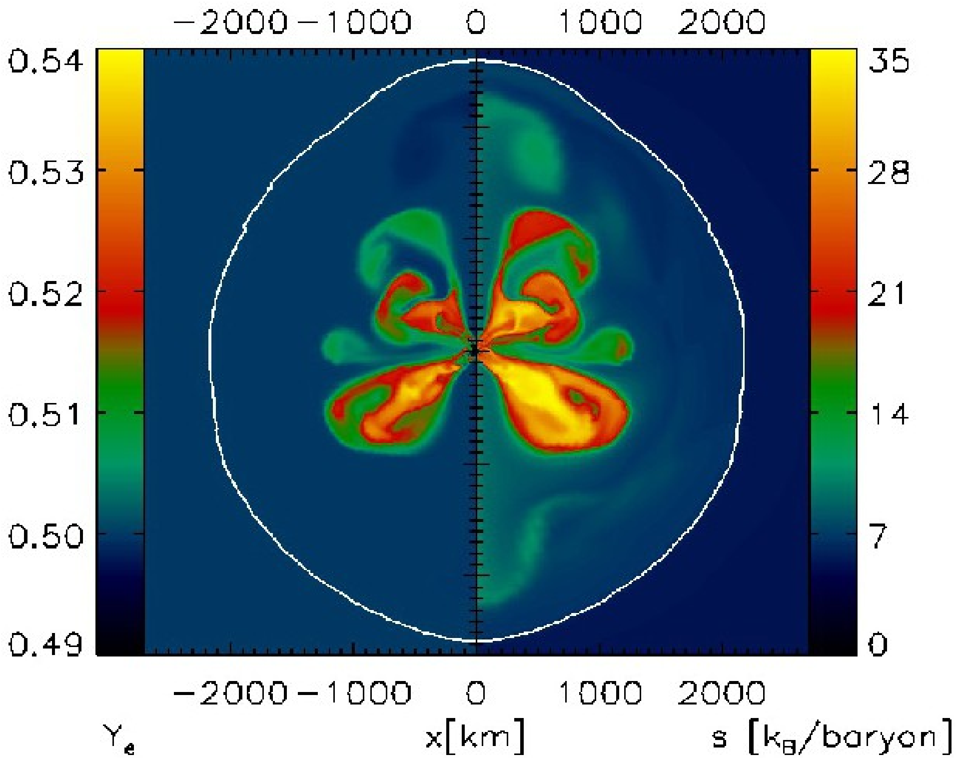


(Müller, THJ, Marek & Dimmelmeier, to be submitted)

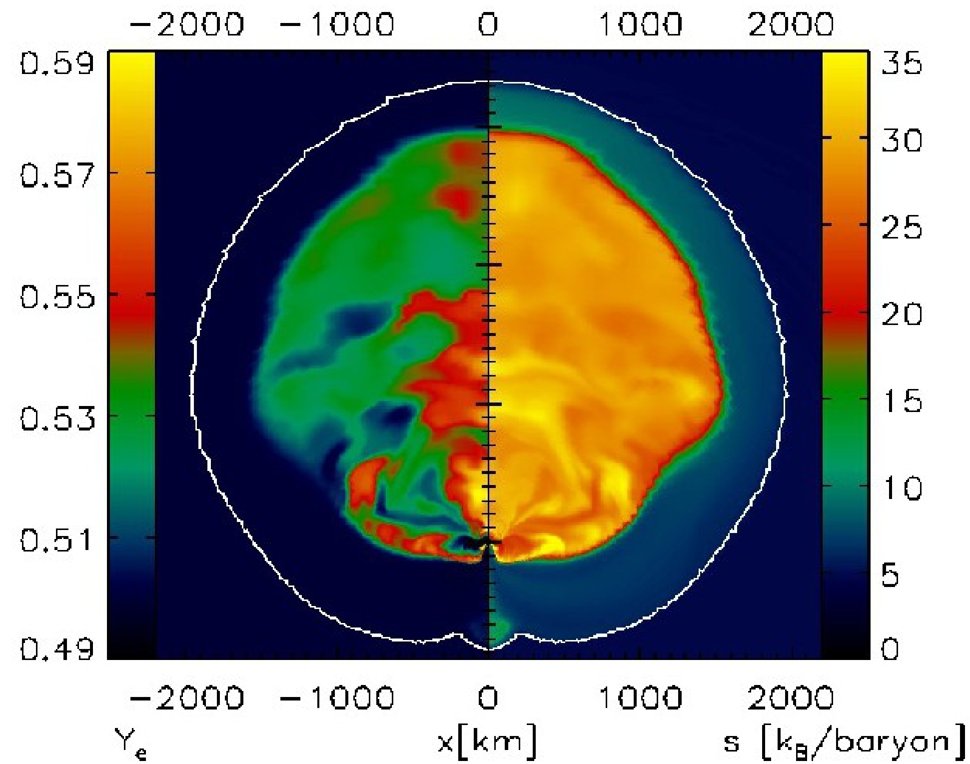
- All neutrino-processed ejecta are proton-rich.
- ν_e and anti-ν_e luminosities stay high due to simultaneous explosion and accretion!
- May be favorable condition for neutrino-p process.

Relativistic 2D SN Simulations

$11.2\ M_{sun}$



$15\ M_{sun}$



(Müller, THJ, Marek & Dimmelmeier, to be submitted)

Self-Induced (Collective) Neutrino Flavor Transformations

(Sarikas, Raffelt, Hüdepohl, THJ, PRL, submitted; arXiv:1109.3601)

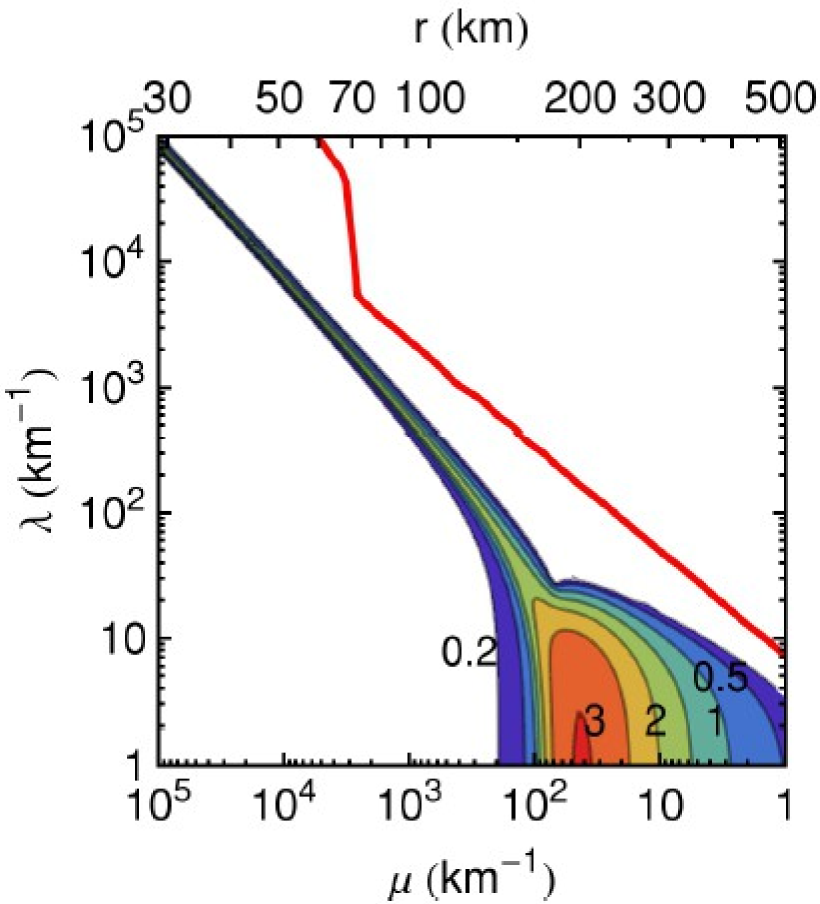


FIG. 4: Contours for the growth rate κ in km^{-1}. Also shown is the profile for our 280 ms SN model. The vertical axis essentially denotes the density, the horizontal axis the radius ($\mu \propto r^{-4}$).

Linearized flavor stability analysis (1D, multi-angle and multi-energy effects included) proves neutrino flavor stability in SN core during the post-bounce accretion phase.

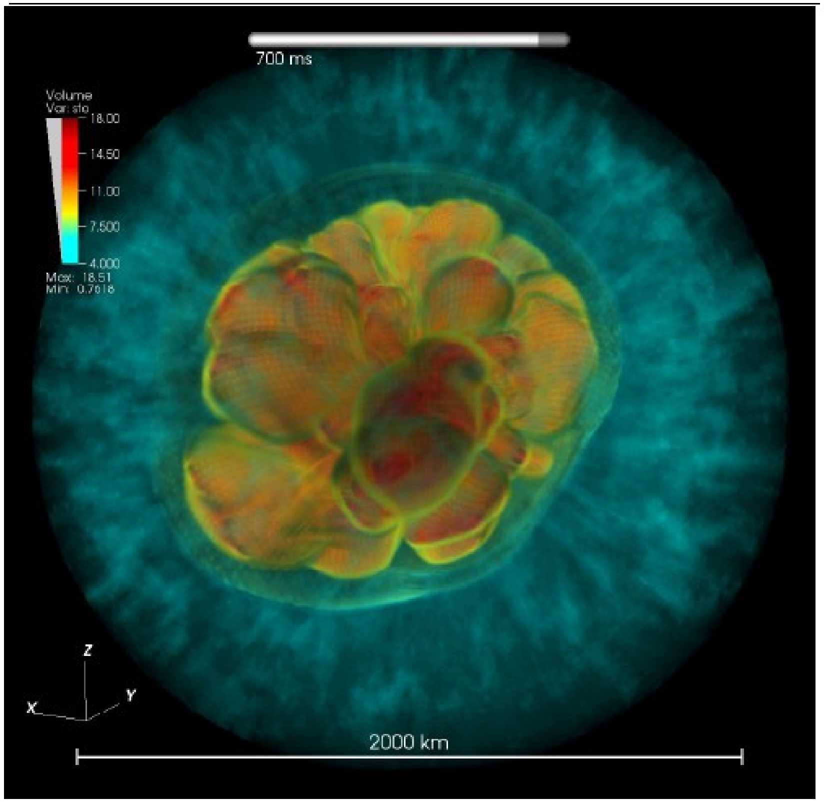
Collective flavor conversions are therefore not relevant for neutrino heating behind SN shock.

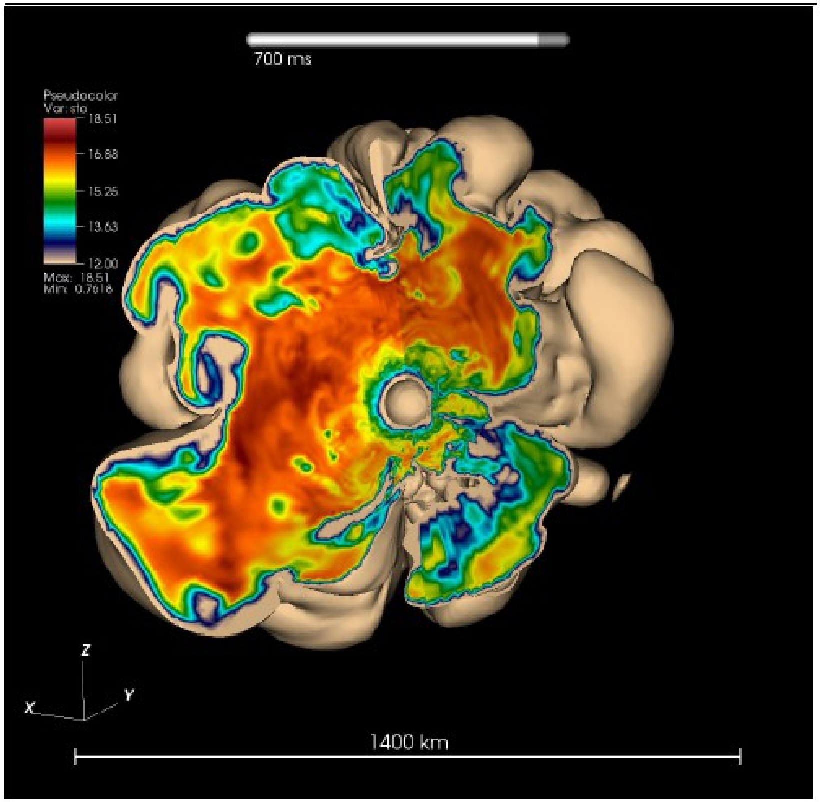
In agreement with conclusions drawn by Dasgupta, O'Connor & Ott, arXiv:1106.1167, Chakraborti et al., PRD 84 (2011) 025002.

3D vs. 2D Differences ?

3D Supernova Simulations are Needed!

- 3D code version is presently constructed and in test phase (F. Hanke, L. Hüdepohl, B. Müller; Andreas Marek (RZG)).
- We are beginning to explore 3D phenomena and effects (F. Hanke).





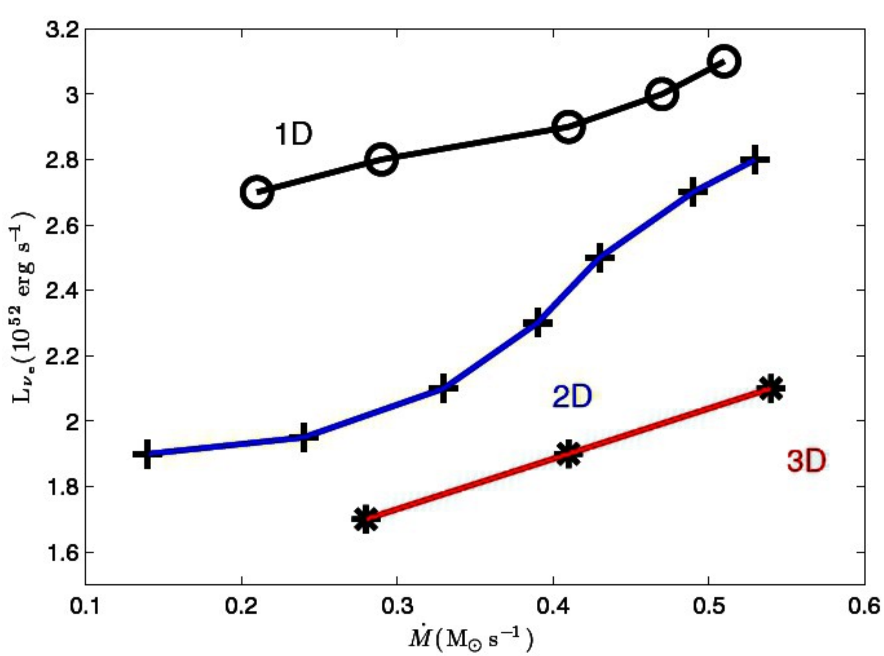
Simulations: Florian Hanke;
Visualization: Elena Erastova, Markus Rampp (RZG)

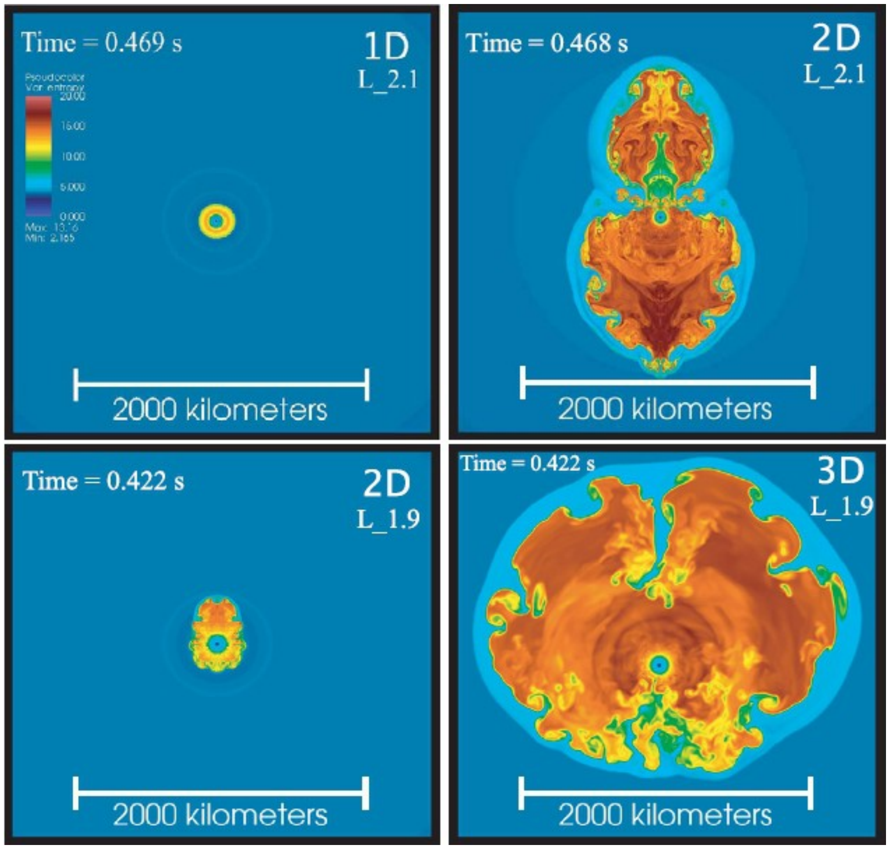
2D-3D Differences in Parametric Explosion Models

- Nordhaus, Burrows et al. performed 2D & 3D simulations with simple neutrino-heating and cooling terms and found 15–25% improvement in 3D for 15 M_{sun} progenitor star (ApJ 720 (2010) 694)

$$\mathcal{H} = 1.544 \times 10^{20} \left(\frac{L_{\nu_e}}{10^{52}\ \mathrm{erg\ s^{-1}}}\right)\left(\frac{T_{\nu_e}}{4\ \mathrm{MeV}}\right)^2 \times \left(\frac{100\ \mathrm{km}}{r}\right)^2 (Y_\mathrm{n} + Y_\mathrm{p}) e^{-\tau_{\nu_e}} \left[\frac{\mathrm{erg}}{\mathrm{g\ s}}\right]$$

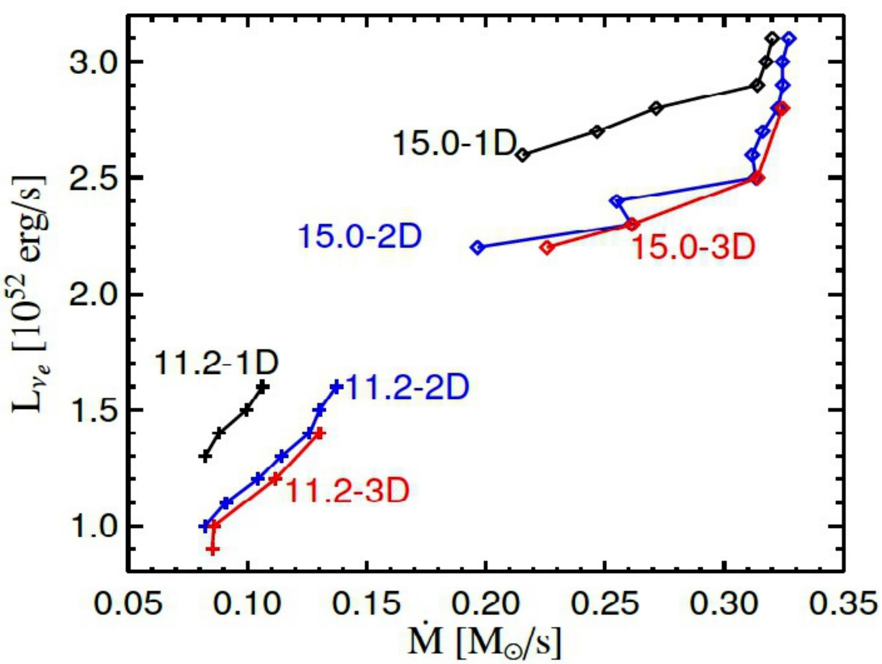
$$\mathcal{C} = 1.399 \times 10^{20} \left(\frac{T}{2\ \mathrm{MeV}}\right)^6 (Y_\mathrm{n} + Y_\mathrm{p}) e^{-\tau_{\nu_e}} \left[\frac{\mathrm{erg}}{\mathrm{g\ s}}\right]$$

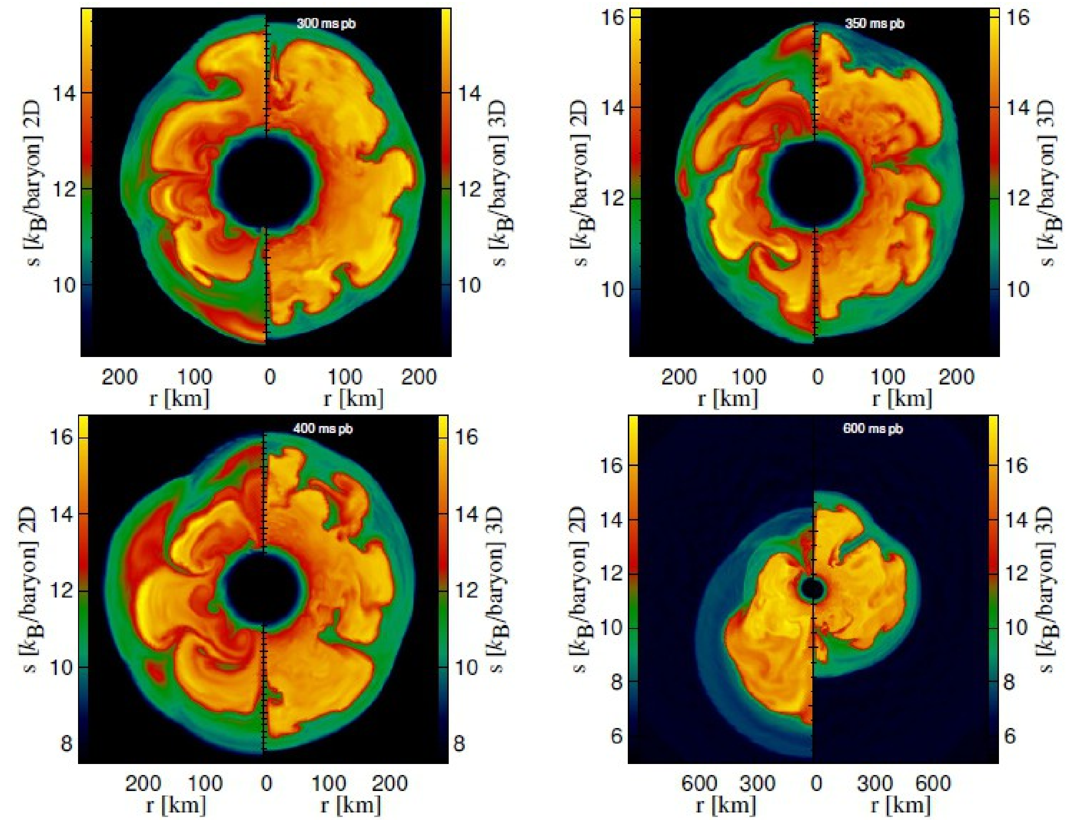




2D-3D Differences in Parametric Explosion Models

- F. Hanke (Diploma Thesis, MPA, Garching, 2010) in agreement with L. Scheck (PhD Thesis, MPA, 2007) cannot confirm the findings by Nordhaus et al. (2010) ! 2D and 3D simulations for 11.2 M_{sun} and 15 M_{sun} progenitors are very similar!





2D & 3D slices for 11.2 M_{sun} model, L = 1.0*10^{52} erg/s

2D-3D Differences in Parametric Explosion Models

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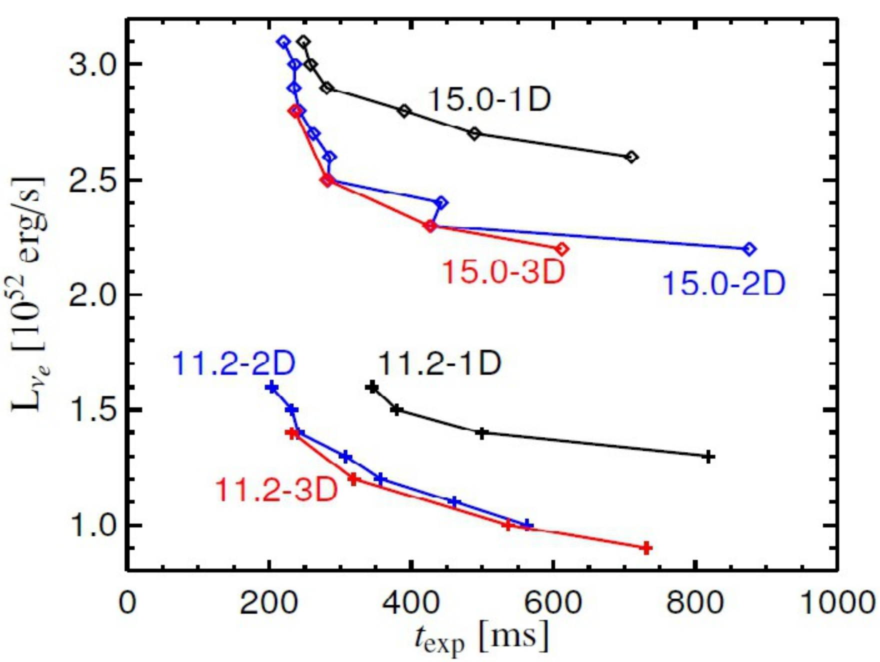
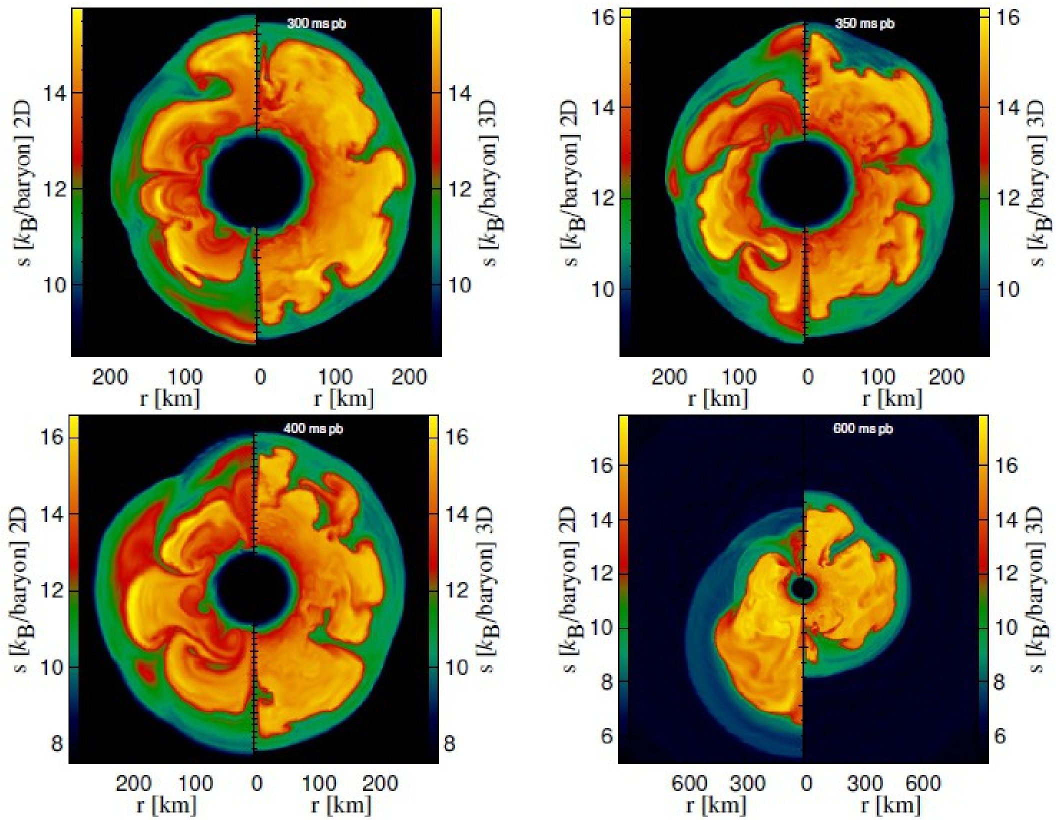




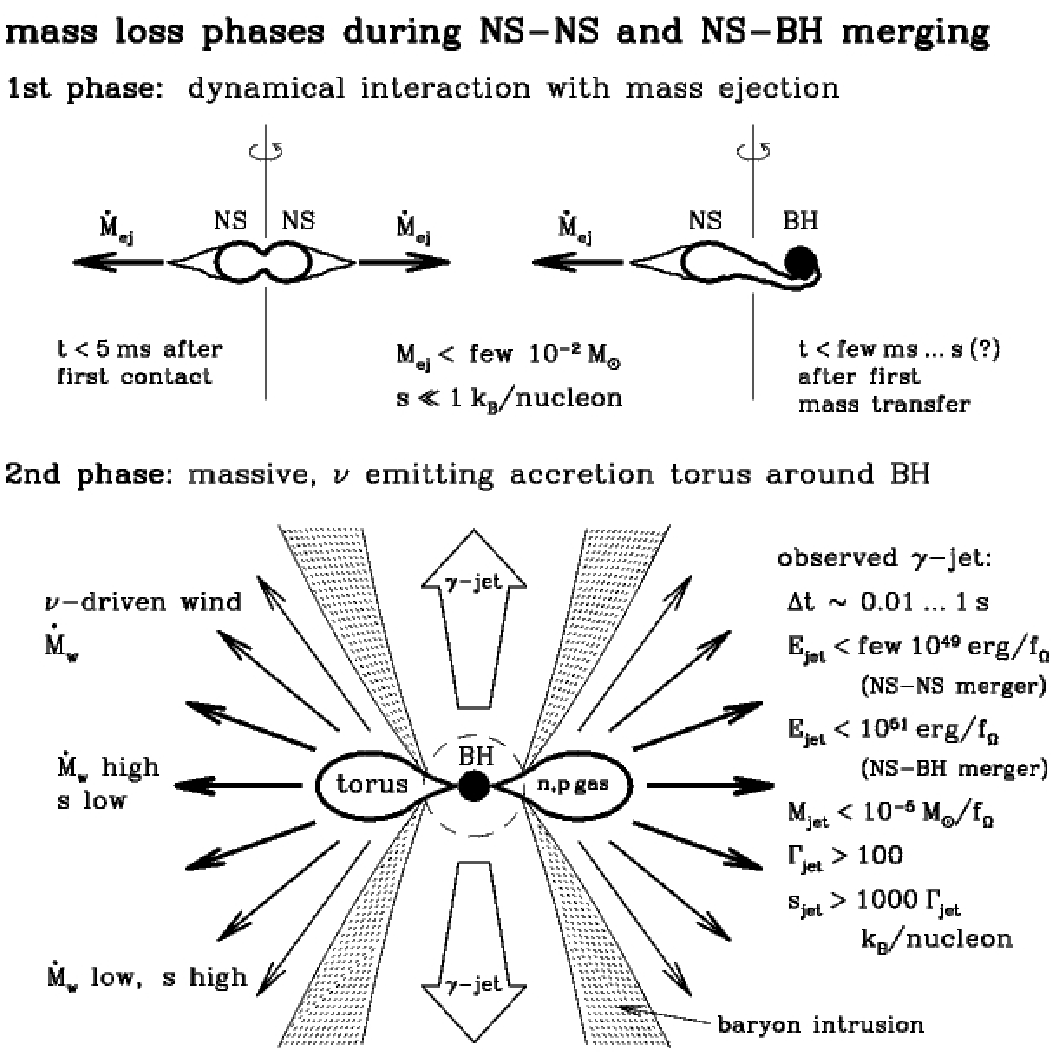
2D & 3D slices for 11.2 M_{sun} model, L = 1.0*10^{52} erg/s

Neutron Star Mergers
and
Their Remnants

Neutron Star Mergers as Production Sites of Heavy Elements

Compact binary mergers

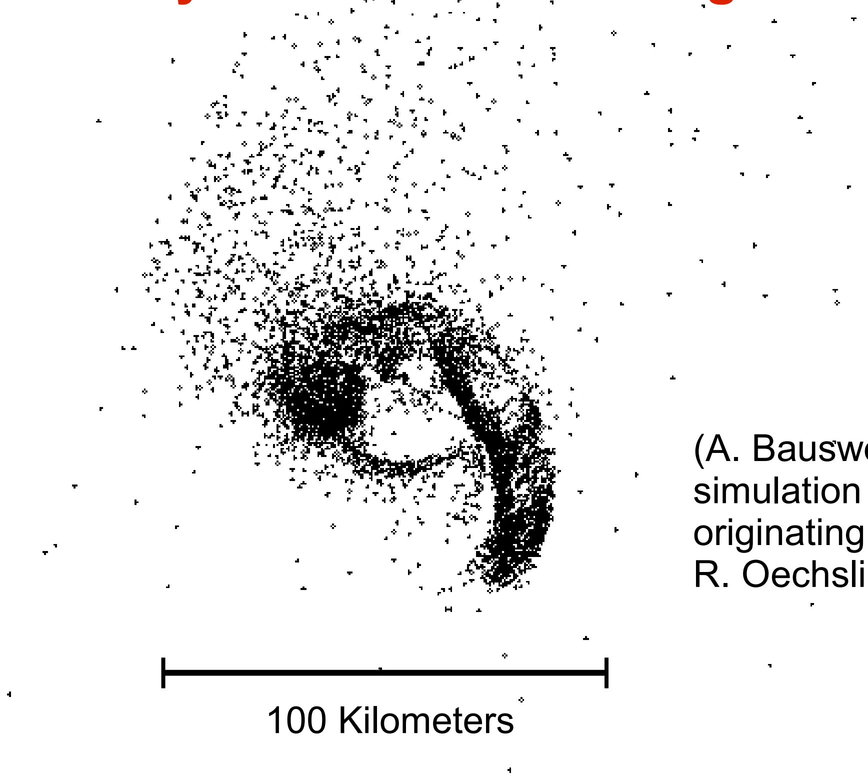
- are likely sources of short gamma-ray bursts
  (Paczynski, Jaroszynski, etc.)
- are among strongest sources of gravitational waves
- are potential production sites of r-process nuclei
  (Lattimer & Schramm & Arnett 1974, 1976; Lattimer et al. 1977; Meyer 1989)
- May be observable transient sources of optical radiation
  (Li & Paczynski 1998, Kulkarni 2005, Metzger et al. 2010, Roberts et al. 2011)



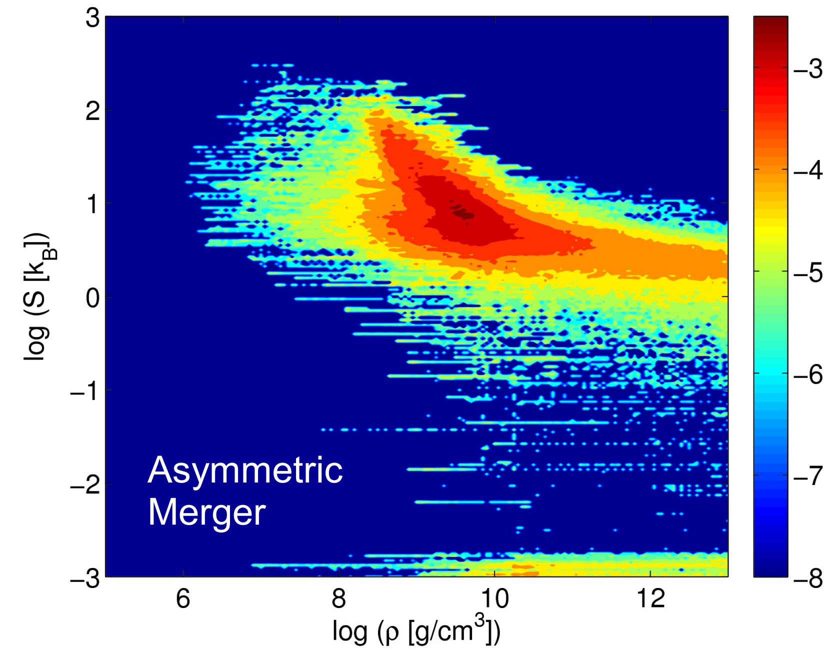
(Ruffert & Janka 1999)

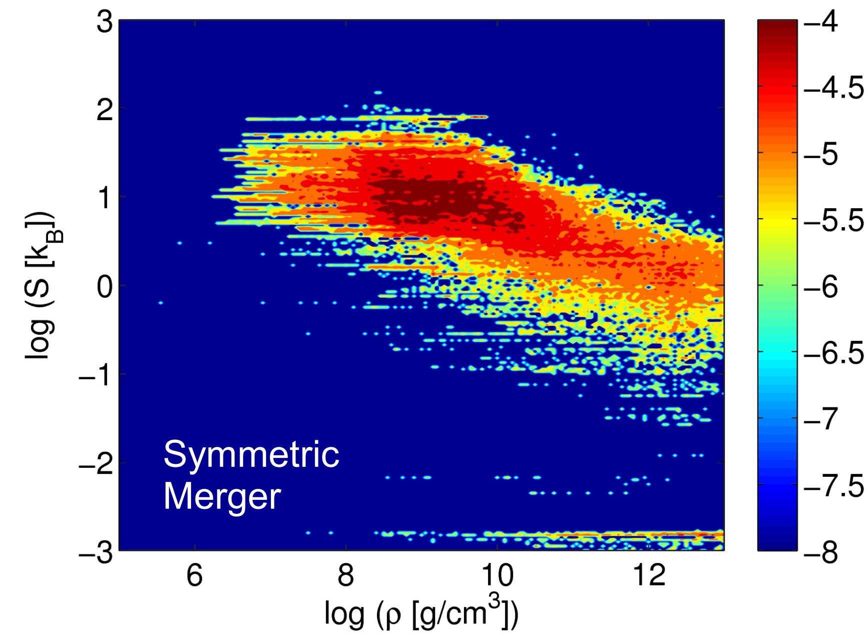
Properties of Dynamical Merger Ejecta

Asymmetric NS-NS merger



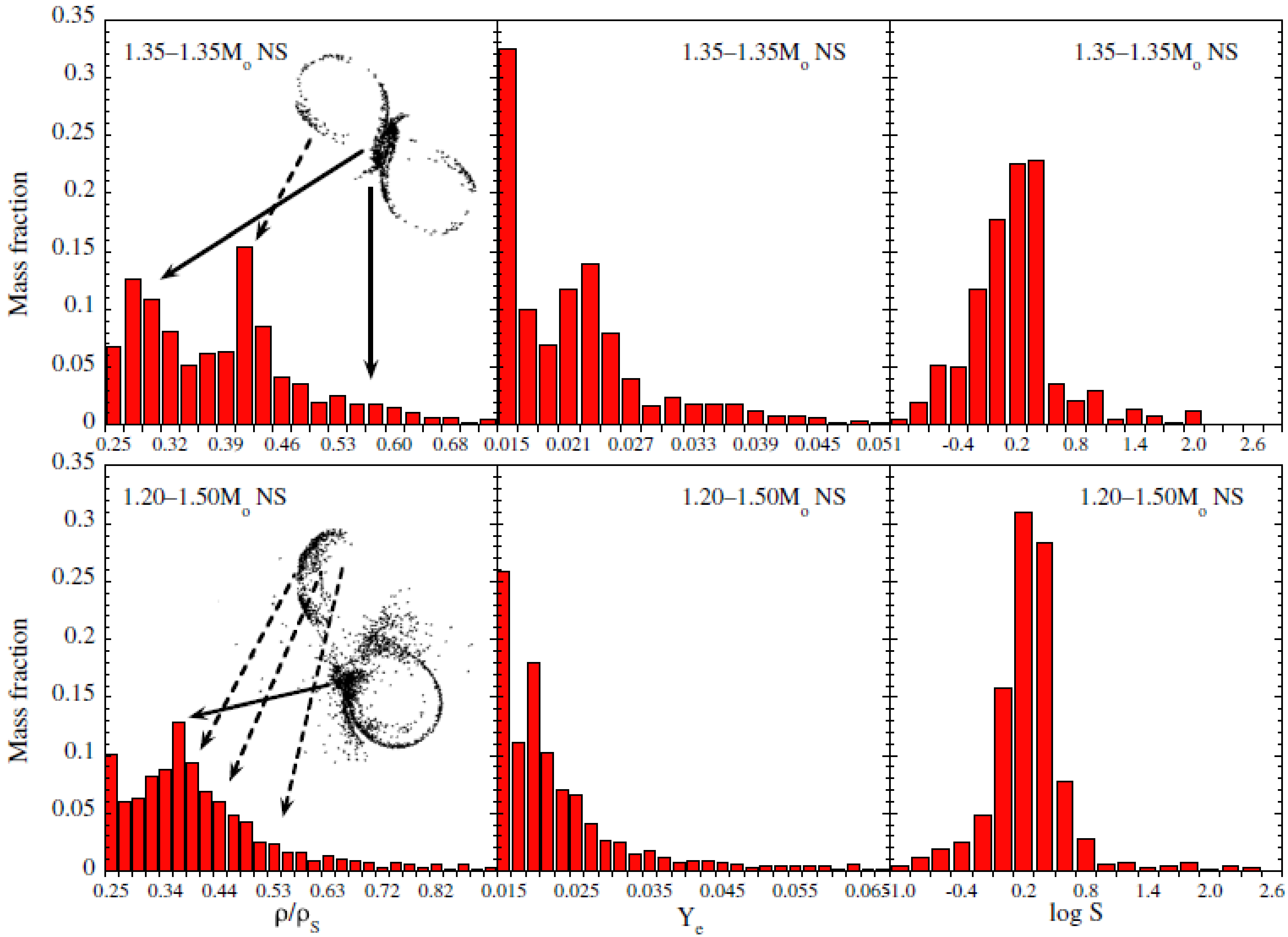
(A. Bauswein 2011; simulation code originating from R. Oechslin)





- Detailed conditions of ejecta depend on merger dynamics.
- Cold and hot (shocked) ejecta components.
- Significant differences dependent on binary parameters ! Models needed!

Properties of Dynamical Merger Ejecta



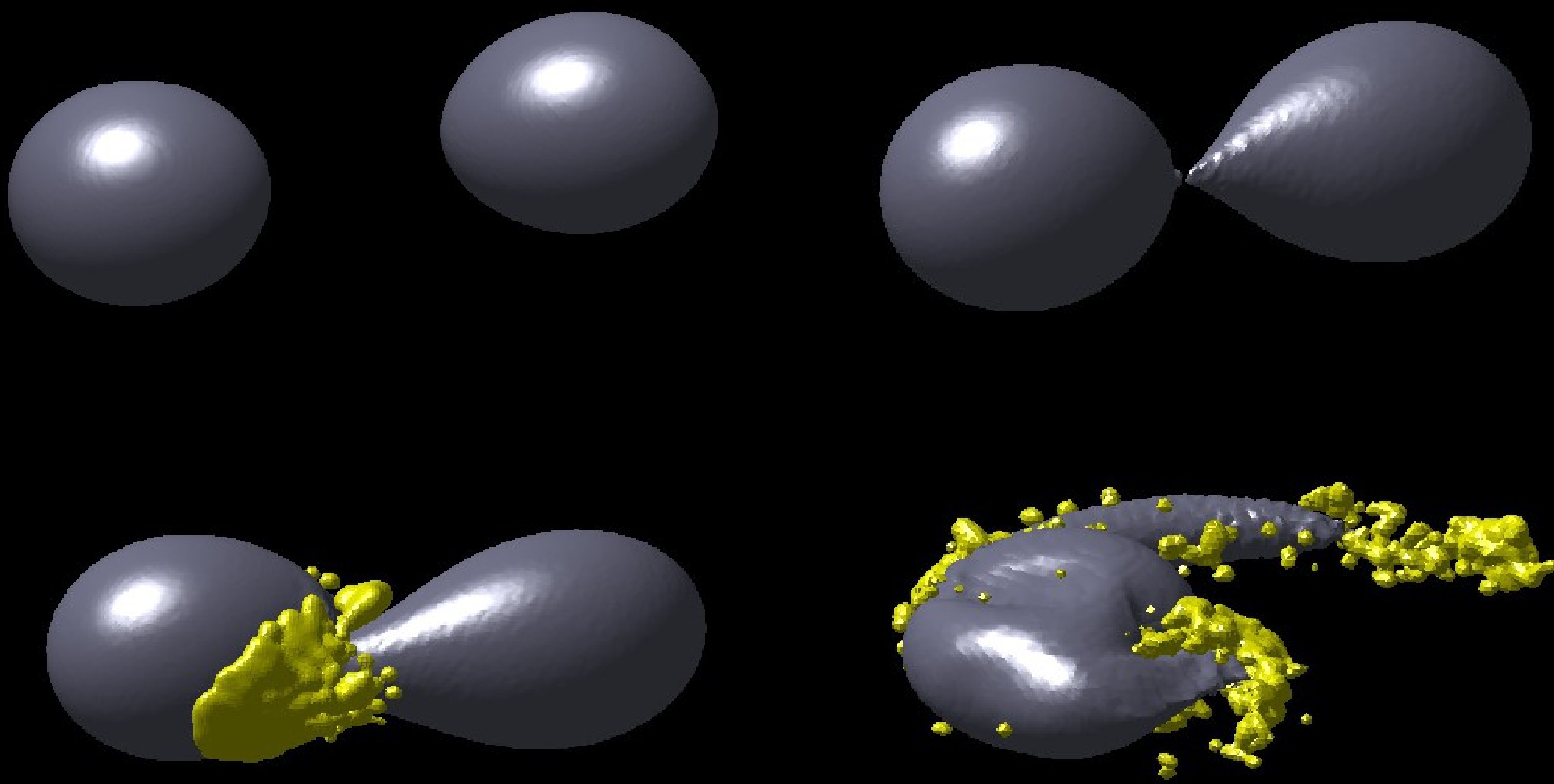
Symmetric NS-NS merger

Asymmetric NS-NS merger

(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

Mass distributions of initial density and Y_e and final entropy S per nucleon (at beginning of free expansion) of ejecta from NS-NS merger with Shen et al. (1998) EoS.

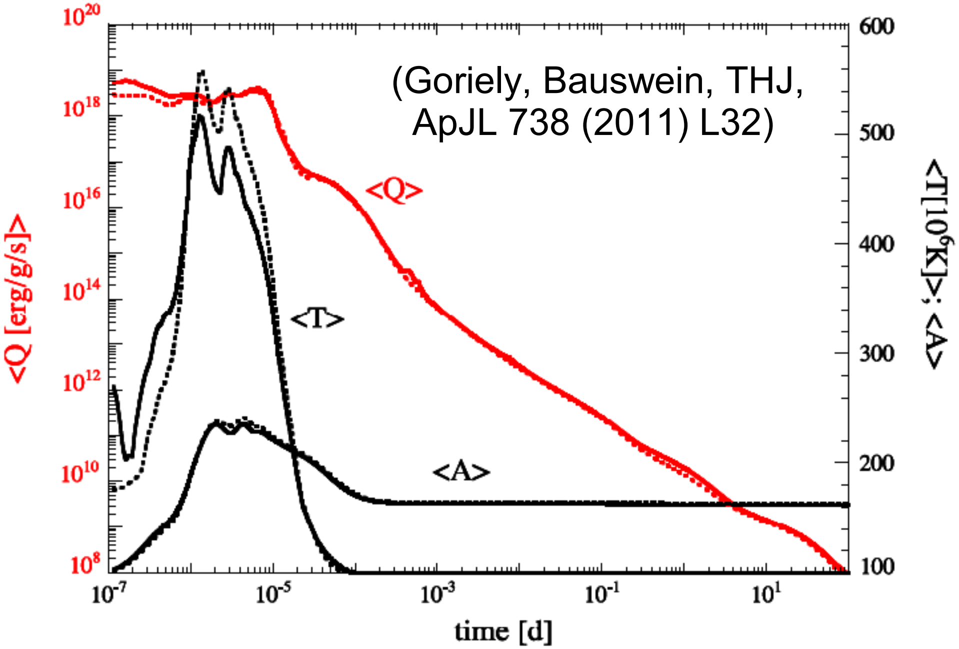
Properties of Dynamical Merger Ejecta



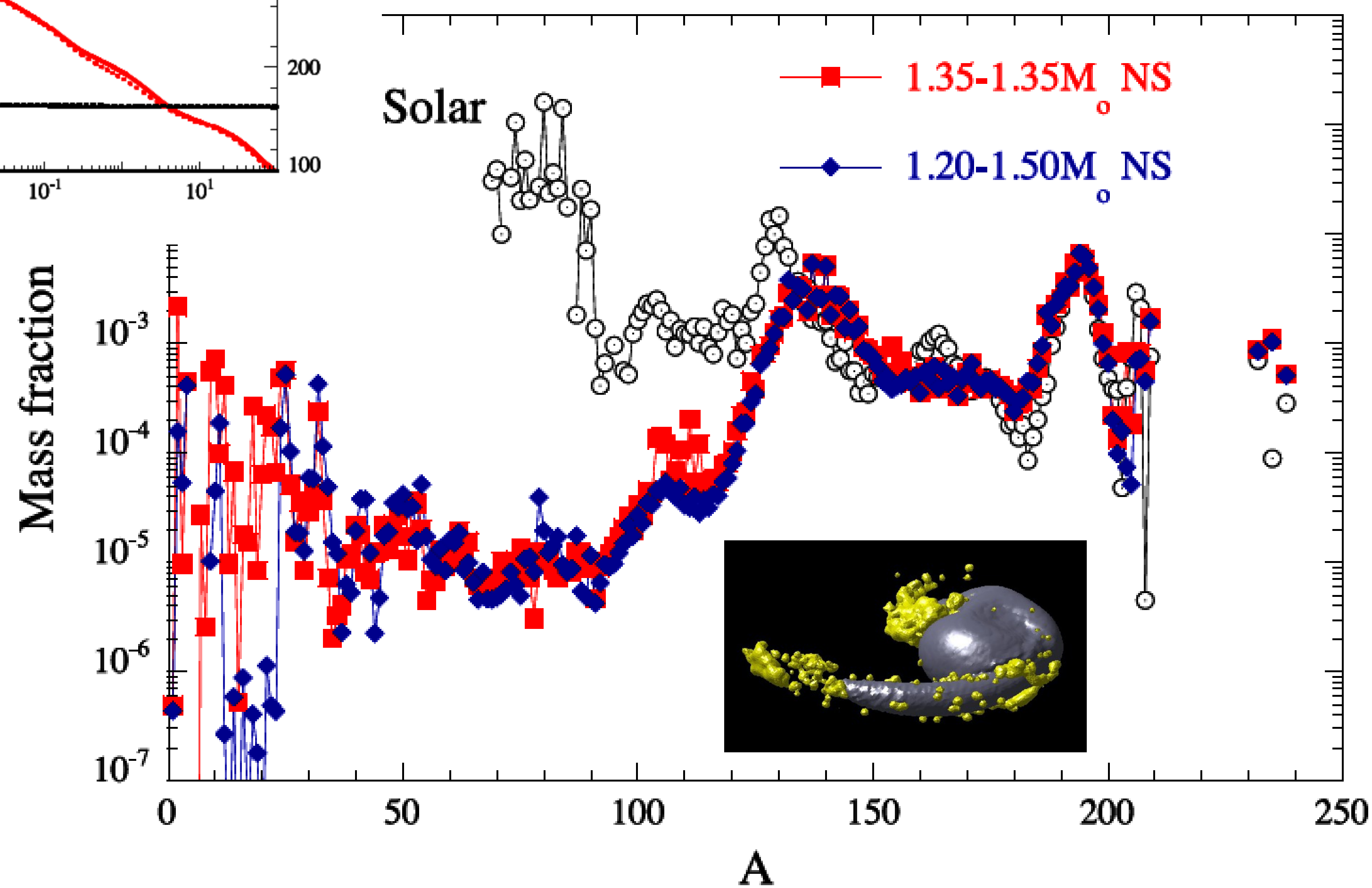
Asymmetric NS-NS merger

(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

Nucleosynthesis in Dynamical Merger Ejecta



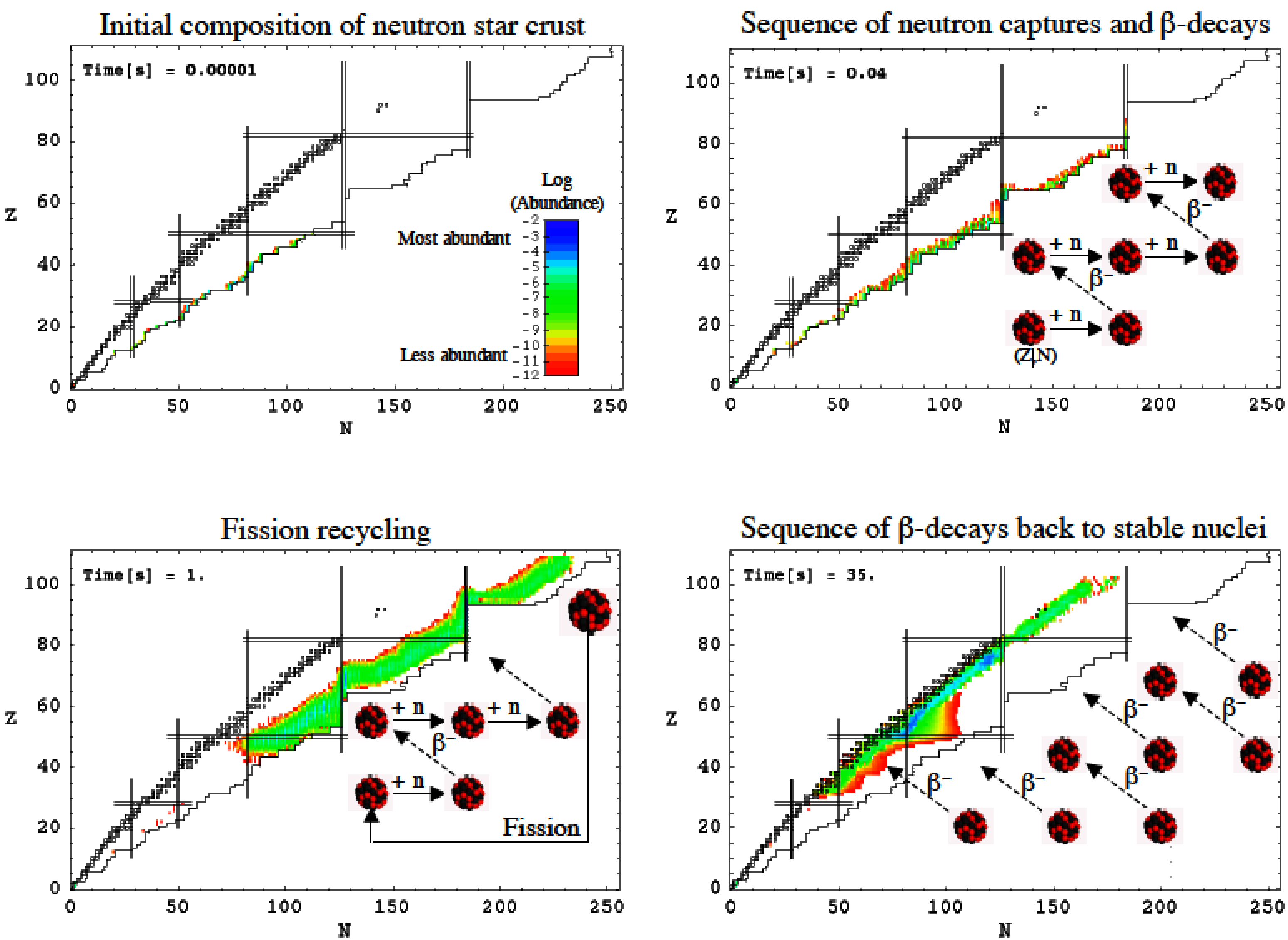
During r-processing fission recycling takes place and produces roughly solar abundances for A > 130.



Per merger event 10^{-3}–10^{-2} M_{sun} are ejected.

With rate of 10^{-5} events per year and galaxy, NS mergers could be the main source of heavy r-process material.

Nucleosynthesis in Dynamical Merger Ejecta



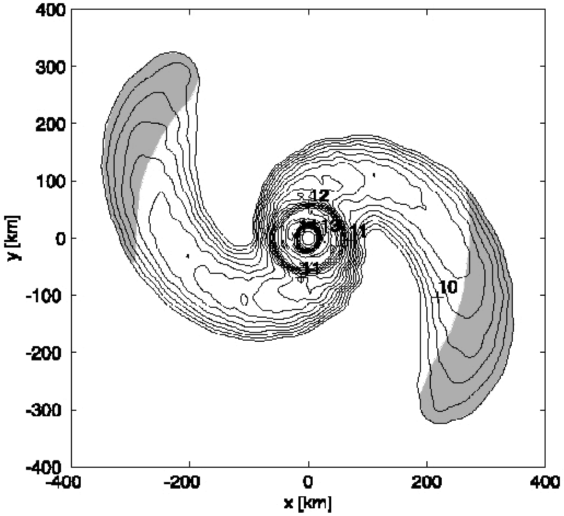
(Goriely, Bauswein, THJ, ApJL 738 (2011) L32)

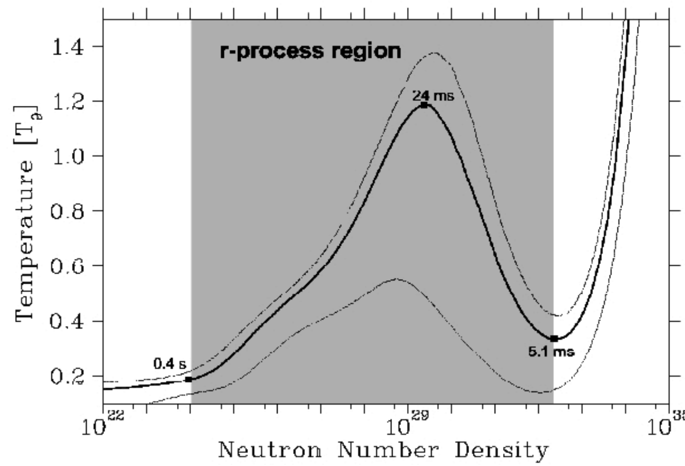
Fission recycling leads to robust abundance distribution.

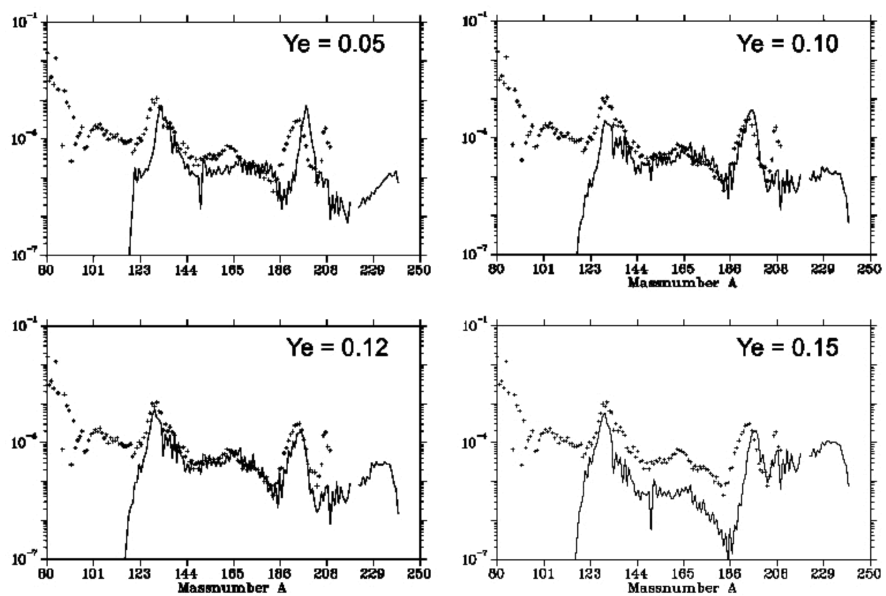
Nucleosynthesis in Dynamical Merger Ejecta

Previous calculations based on parametrized approaches, in particular for Y_e.

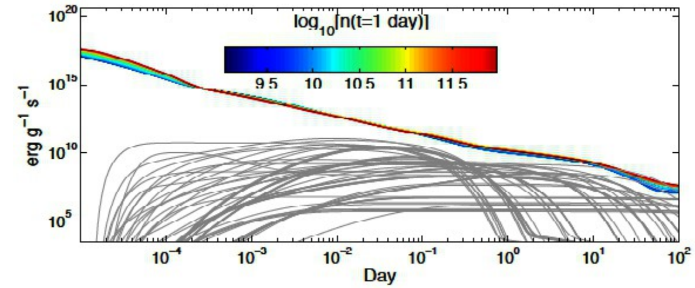
(Freiburghaus et al. 1999)

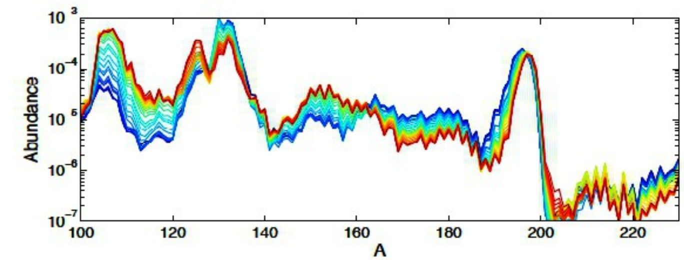


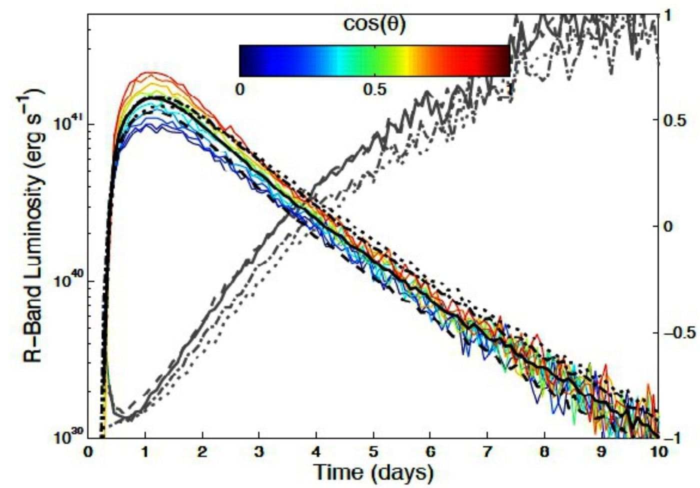




(Roberts et al. 2011)



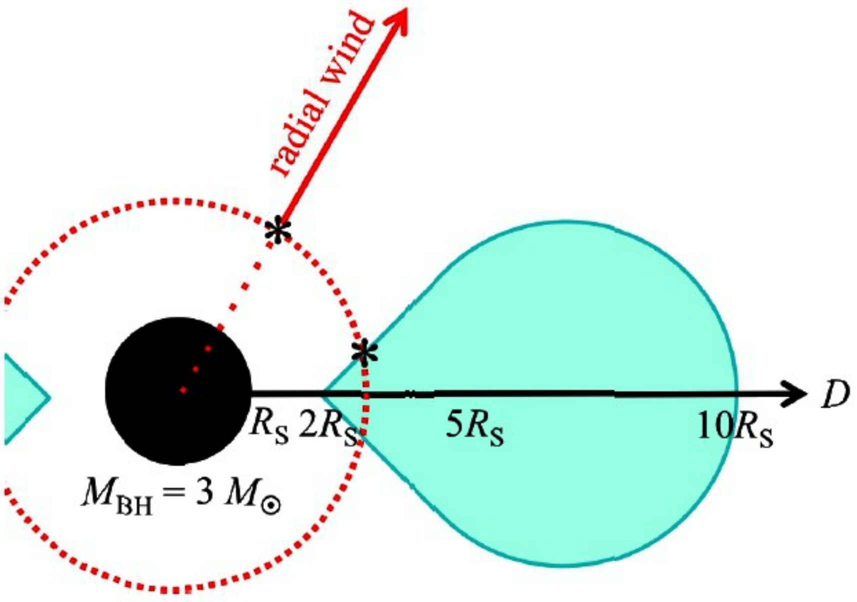




Outflows from Postmerger BH-Tori

- Post-merger accretion tori lose mass by neutrino-driven, viscously driven, and MHD-driven winds.
- Wanajo & THJ consider analytic, time-dependent torus evolution model.
- Neutrino-driven wind is described by spherical, stationary, general relativistic solutions.
- Neutron-rich matter is ejected.

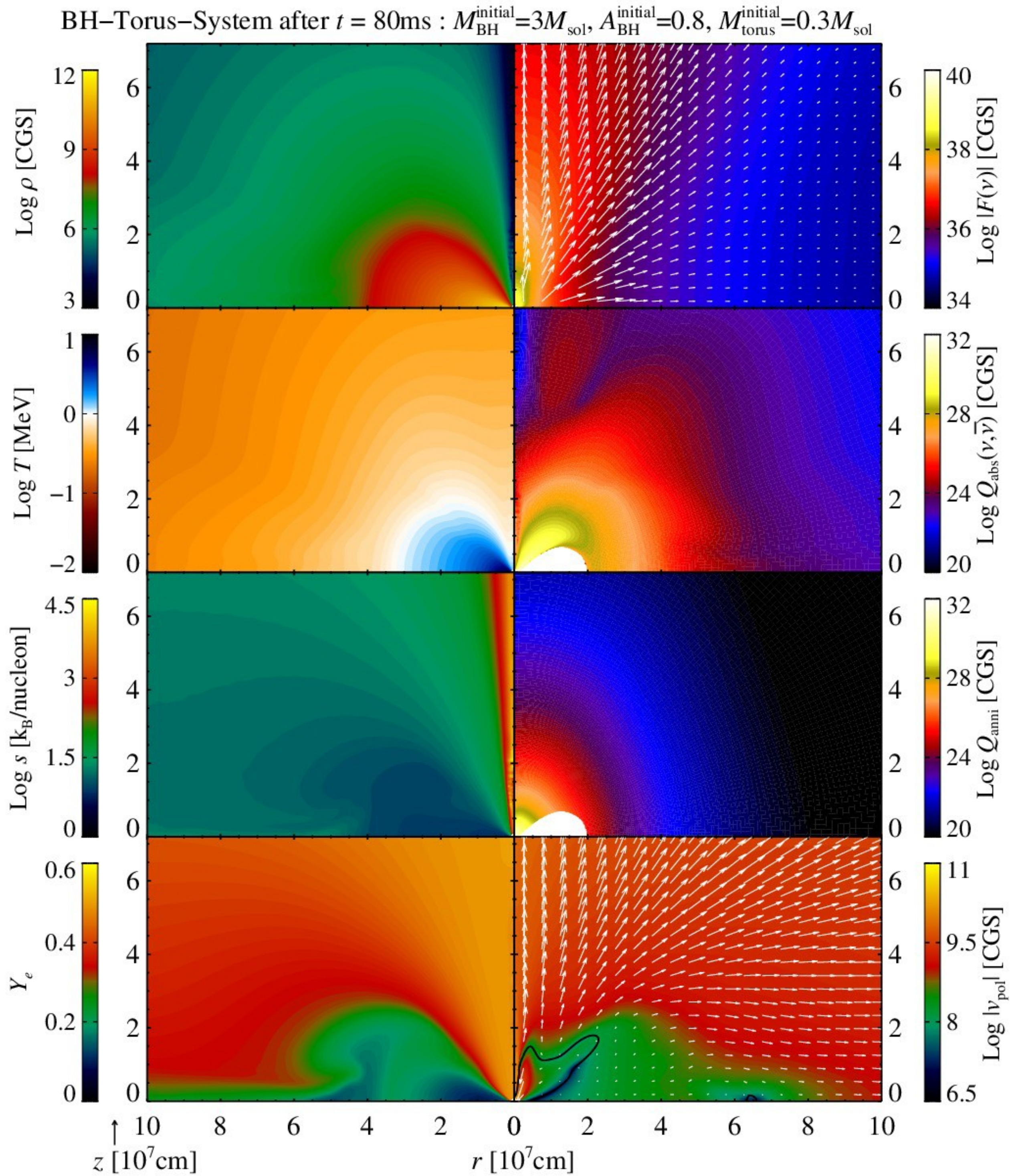
- Results agree qualitatively well with very recent, hydrodynamical simulations.
(Just, PhD Thesis 2011;
Just, Obergaulinger, THJ)



(Wanajo & Janka,
NIC Proceedings 2010;
ApJ, to be sumbitted)

BH-Torus Outflows

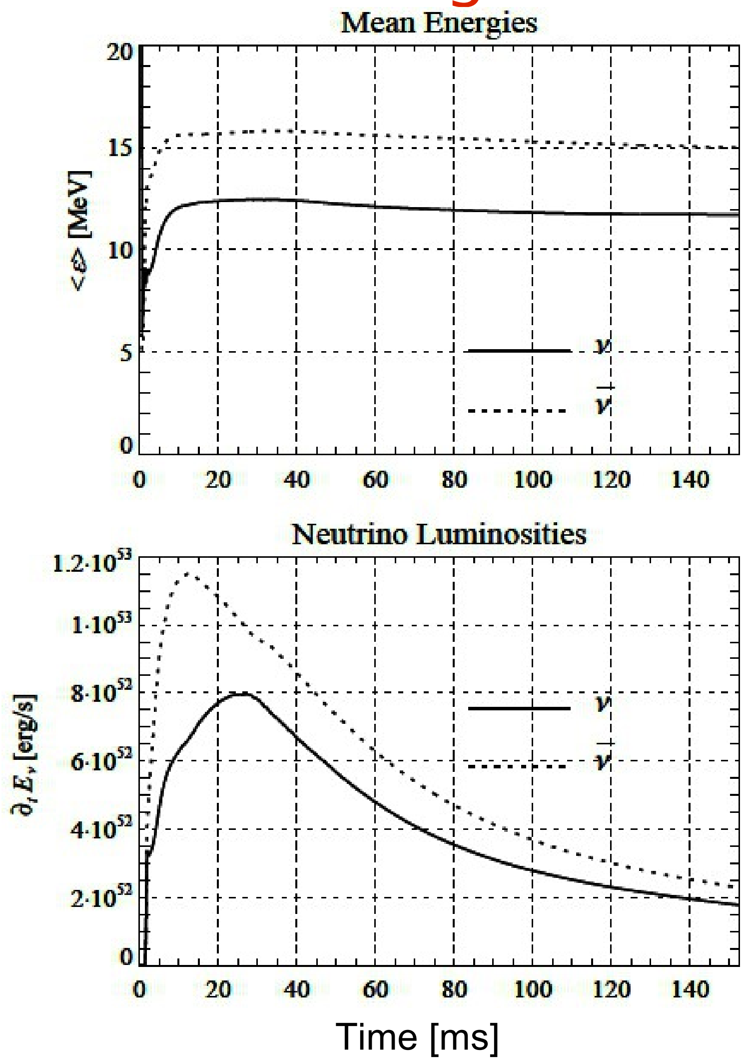
- Hydrodynamical 2D models of BH-torus evolution.
  (Just, PhD Thesis 2011;
  Just, Obergaulinger, THJ, in prep.)
- New Newtonian MHD-code with 2D, energy-dependent neutrino transport based on two-moment closure scheme.
  (Obergaulinger, PhD Thesis 2008;
  Just, Obergaulinger, THJ, in prep.)
- BH treated by Artemova-Novikov potential.
- Present models based on Shakura-Sunyaev α-viscosity.



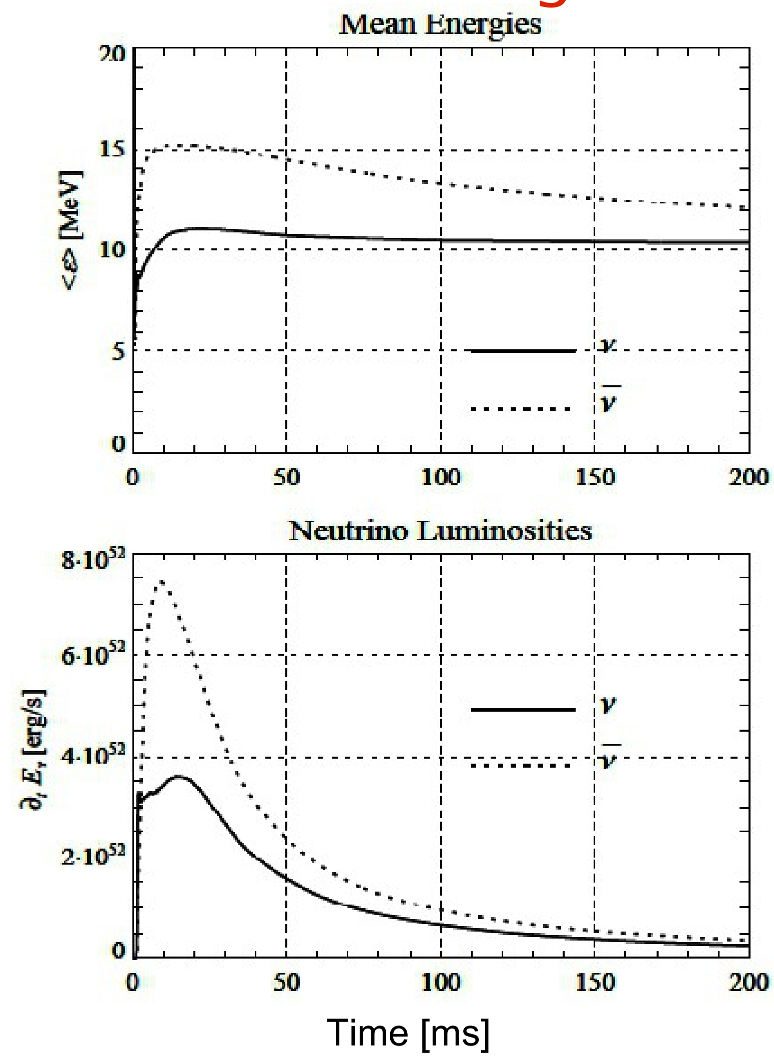
(Just, PhD Thesis, 2011)

Postmerger BH-Tori: Neutrino Emission

Rotating BH



Nonrotating BH

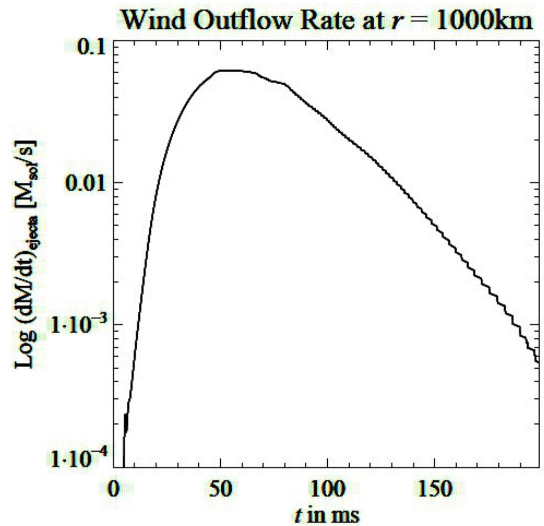


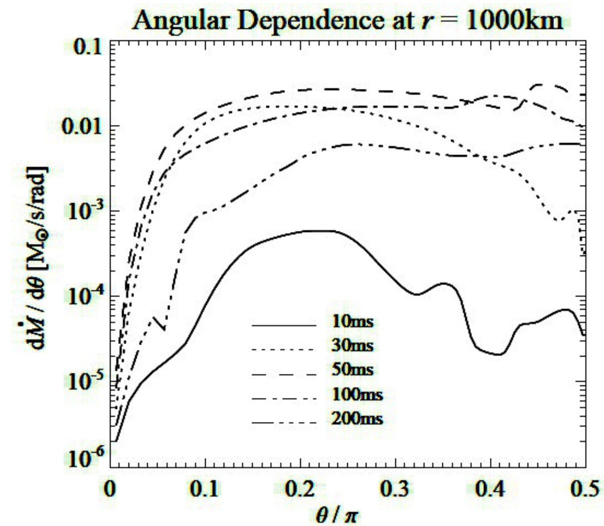
movie

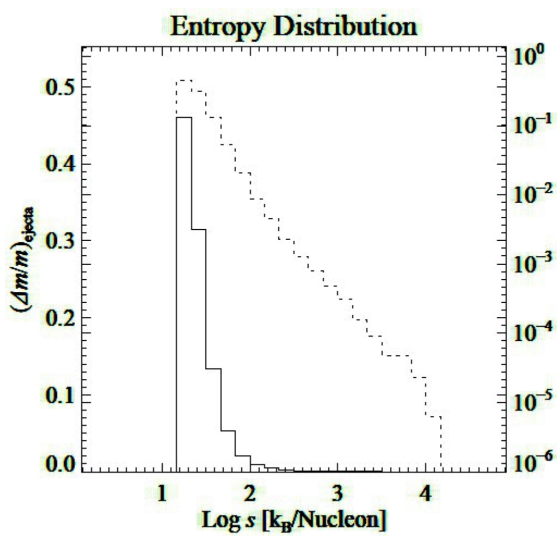
- Post-merger torus is initially n-rich and "protonizes" !
- Emitted anti-ν_e have higher luminosity and more energetic spectra than ν_e.

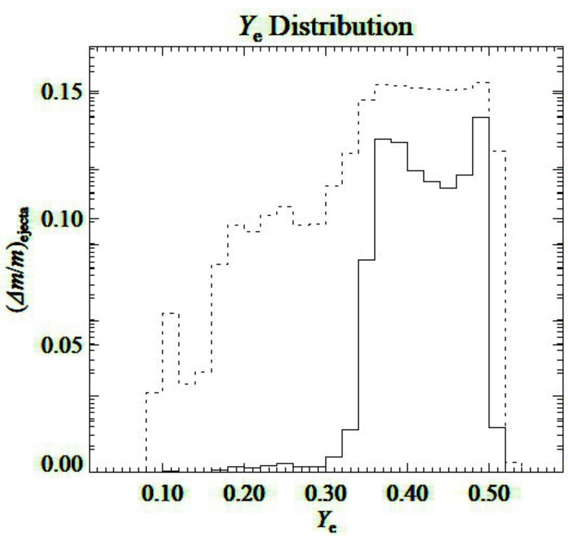
Postmerger BH-Tori: Outflow Properties

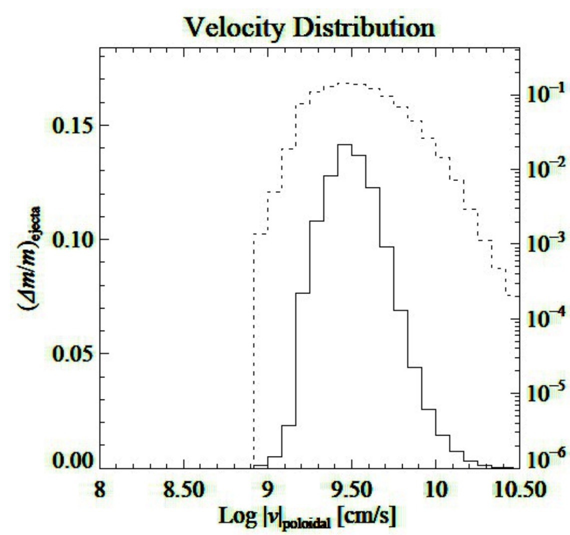
- Hydro models yield time-dependent, direction-dependent information.
- Qualitative agreement with analytic torus-evolution model of Wanajo & THJ.











Summary & Conclusions

- Progenitors with O-Ne-Mg cores end up as e-capture SNe powered by neutrino heating. Models show robust explosions producing very little nickel (~0.001 solar masses).
- Fe-core progenitors with > 10 solar masses explode by neutrino heating, at least "marginally", in some groups' 2D simulations.
- Supernova models have larger problems than ever to provide conditions for "strong r-processing". Correct or fundamental problem?
- "Weak r-process" ($Z < 50$, $A < 120$) might occur in n-rich pockets ejected in e-capture SNe.
- Heaviest r-process elements in solar proportions can be robustly produced in NS-NS (or NS-BH) merger ejecta.
- NS-NS (or NS-BH) mergers are likely to be the main sources of heavy ($A > 130$) r-nuclei. Can they make r-material in ultra-metal poor stars?