Nucleosynthesis in core-collapse supernovae

B06

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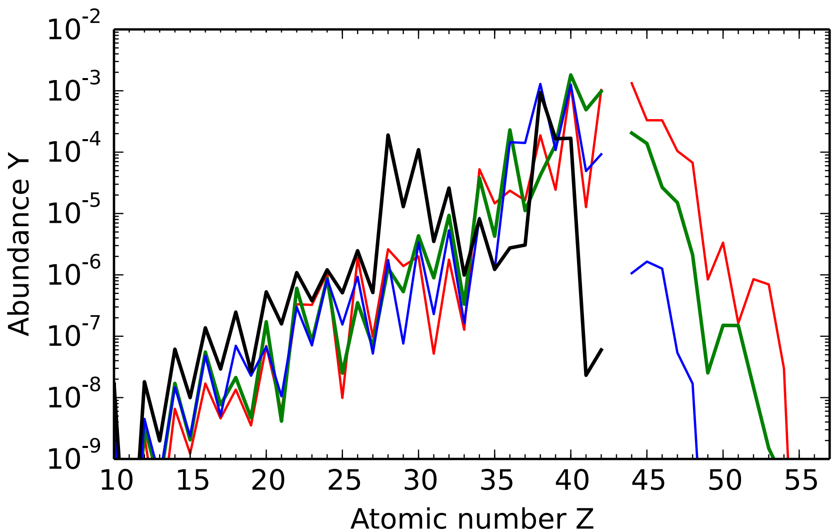


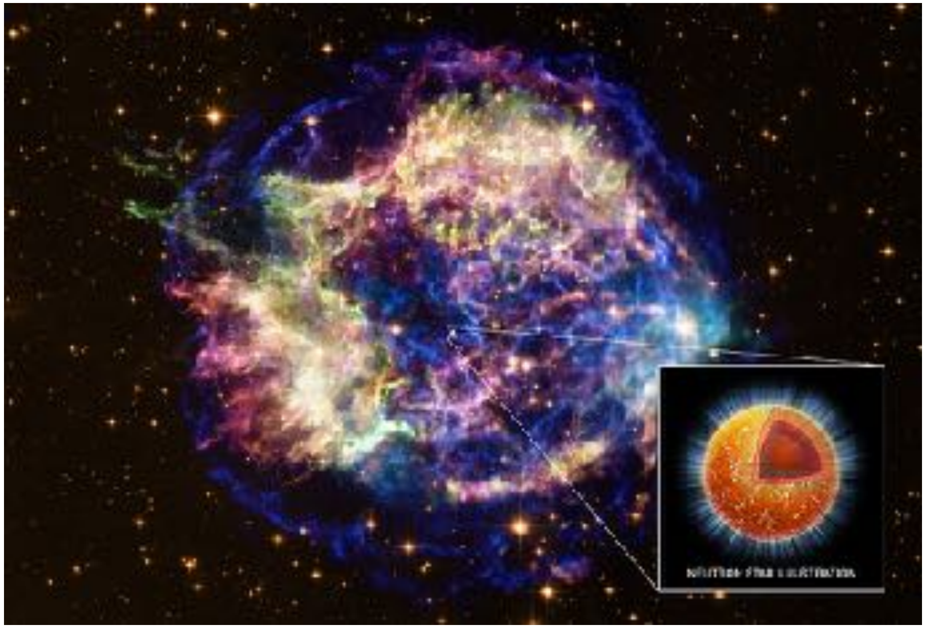
SFB 1245 workshop 2016

Core-collapse supernovae

End of massive stars, birth of neutron stars

All forces of nature are involved

Major contribution to chemical history of the universe



- Supernova simulations
- Matter properties **(B04, B05)**
- Neutrino-matter interactions **(B01)**
- Reactions on nuclei **(B02)**

↓

Nucleosynthesis

Nucleosynthesis in supernovae

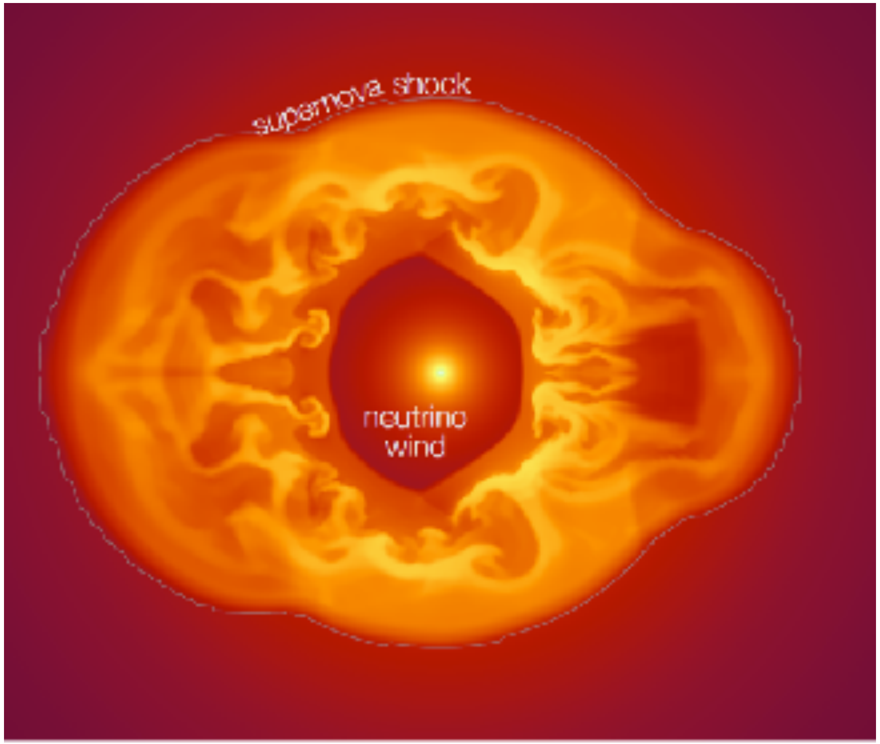
Shock:

- Fe group
- Radioactive isotopes (^{26}Al, ^{44}Ti)
- Neutrinos (~ 10^{58} ν)

➡ affect the shock-heated explosive nucleosynthesis

Neutrino-driven wind:

- Heavy elements (Sr to Ag?)



Arcones & Janka, 2011

Long-time supernova simulations

Simulation requirements:

✓ Hydro code FLASH (Fryxell et al. 2000) and neutrino treatment ASL (Perego et al. 2016)

✓ Tracer particles: post-processing nucleosynthesis (M. Witt)

- EoS to low ρ and T (H. Yasin)
- Reduced reaction network into FLASH (M. Reichert)

In collaboration with S. Couch (MSU)

2D Simulation: FLASH+ASL

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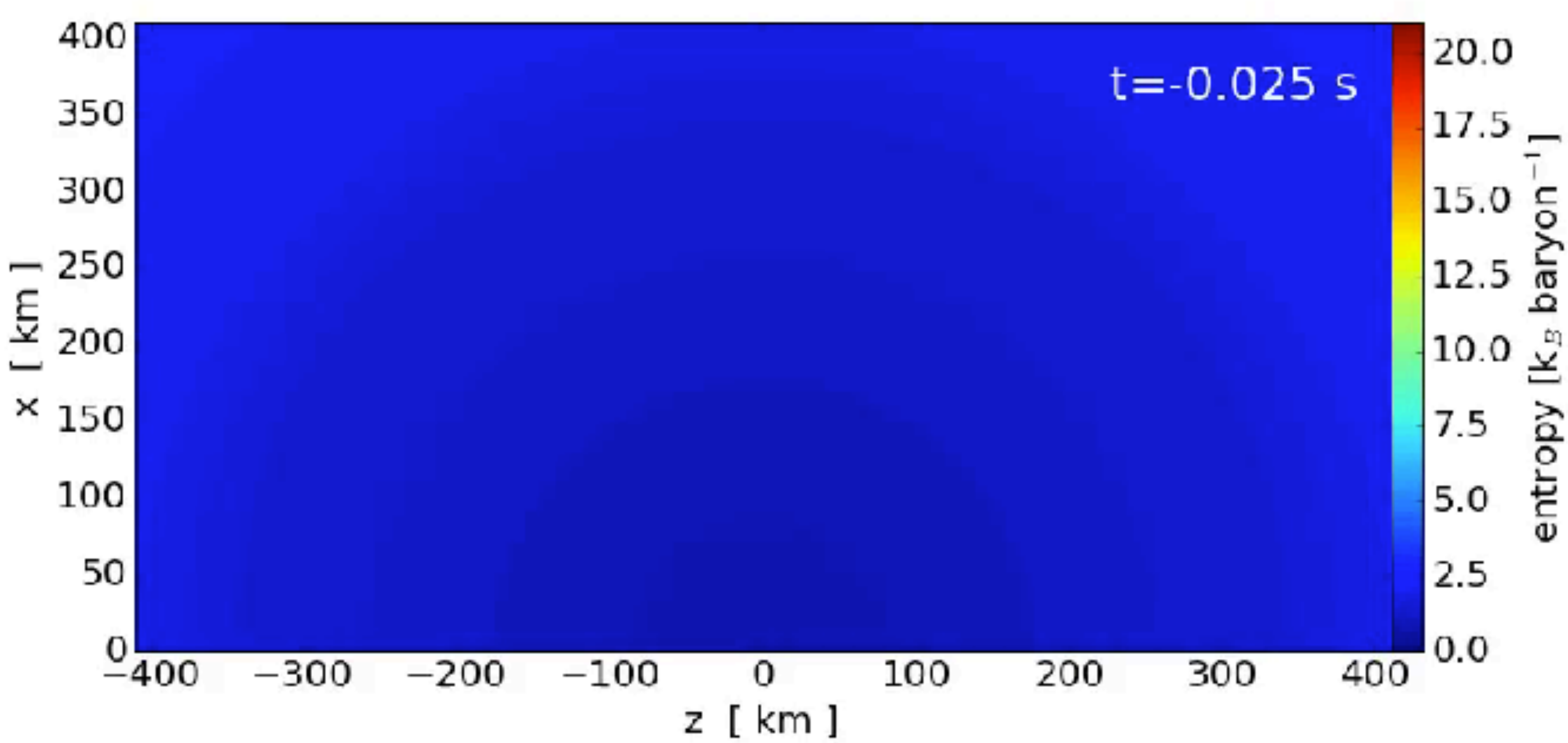

Performed on Lichtenberg High Performance Computer of TU Darmstadt

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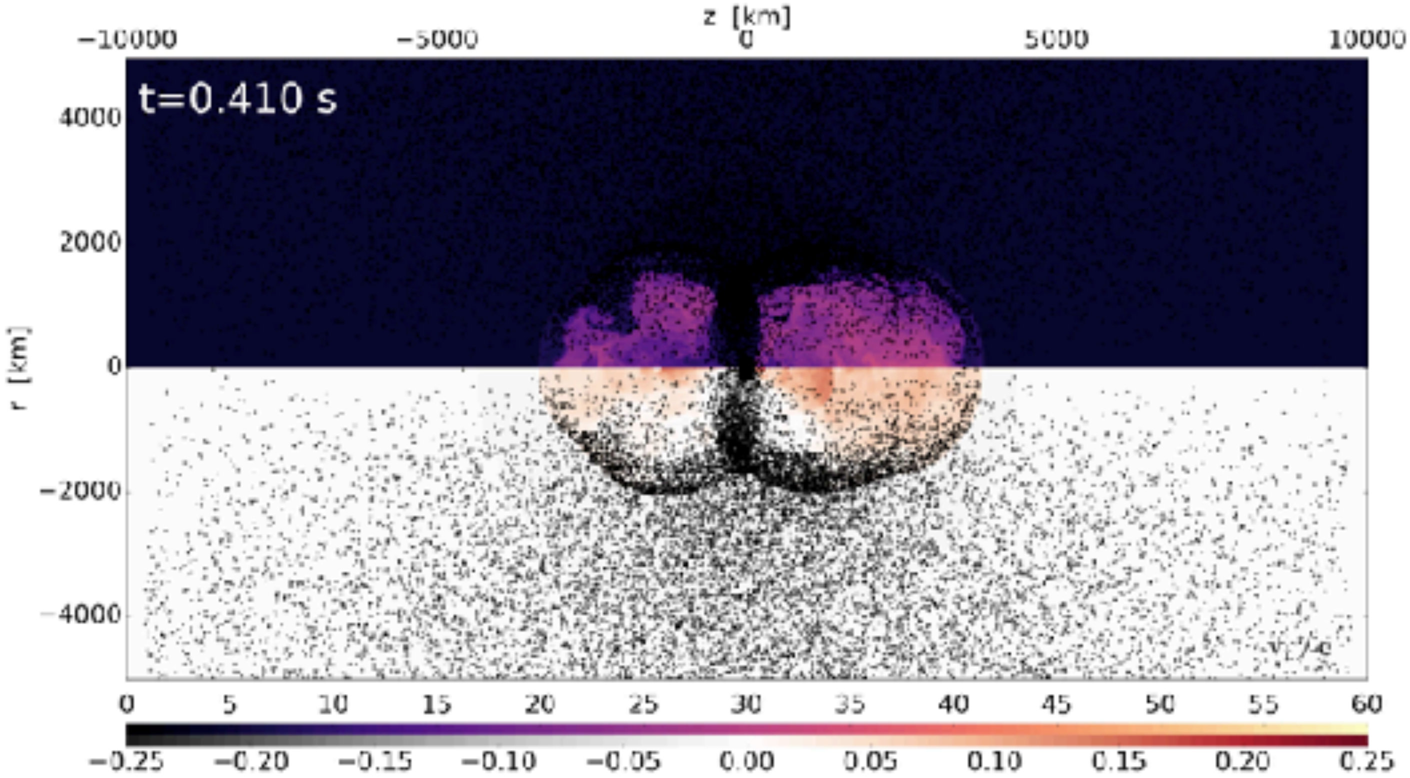
2D Simulation: tracers



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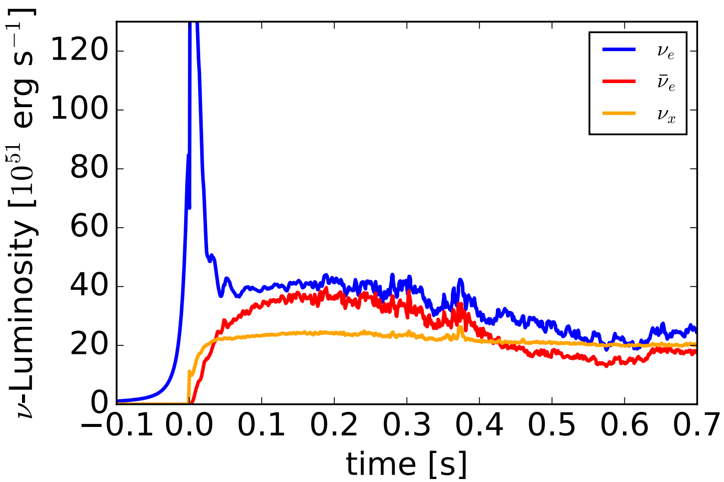
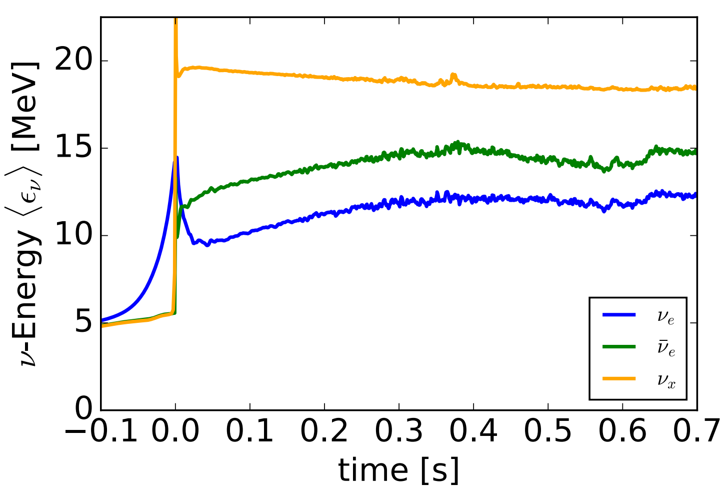
Neutrino luminosities and energies

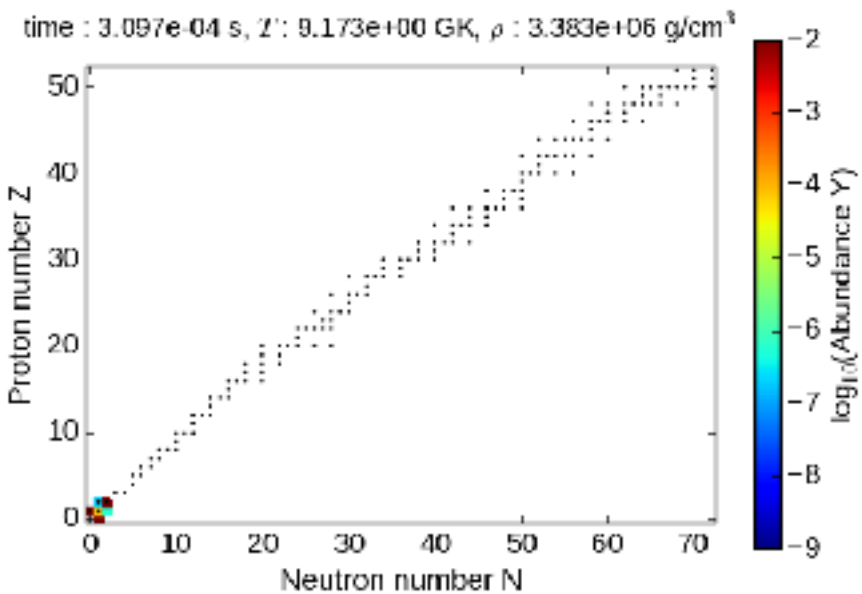




- Goal: explosive nucleosynthesis for different explosion energies
- Vary neutrino heating (Couch et al. 2015)
- Problem: neutrino treatment and neutrino-matter reactions (B01)
- Comparison of neutrino transports
- Strategy:
  - neutrino-driven wind simulations with improved transport
  - post-processing nucleosynthesis varying Y_e

Nucleosynthesis in neutrino-driven winds

- Goal: study astrophysical and nuclear uncertainties
- Based on existing simulations
- Neutrino uncertainties: variation of wind parameters (Y_e)

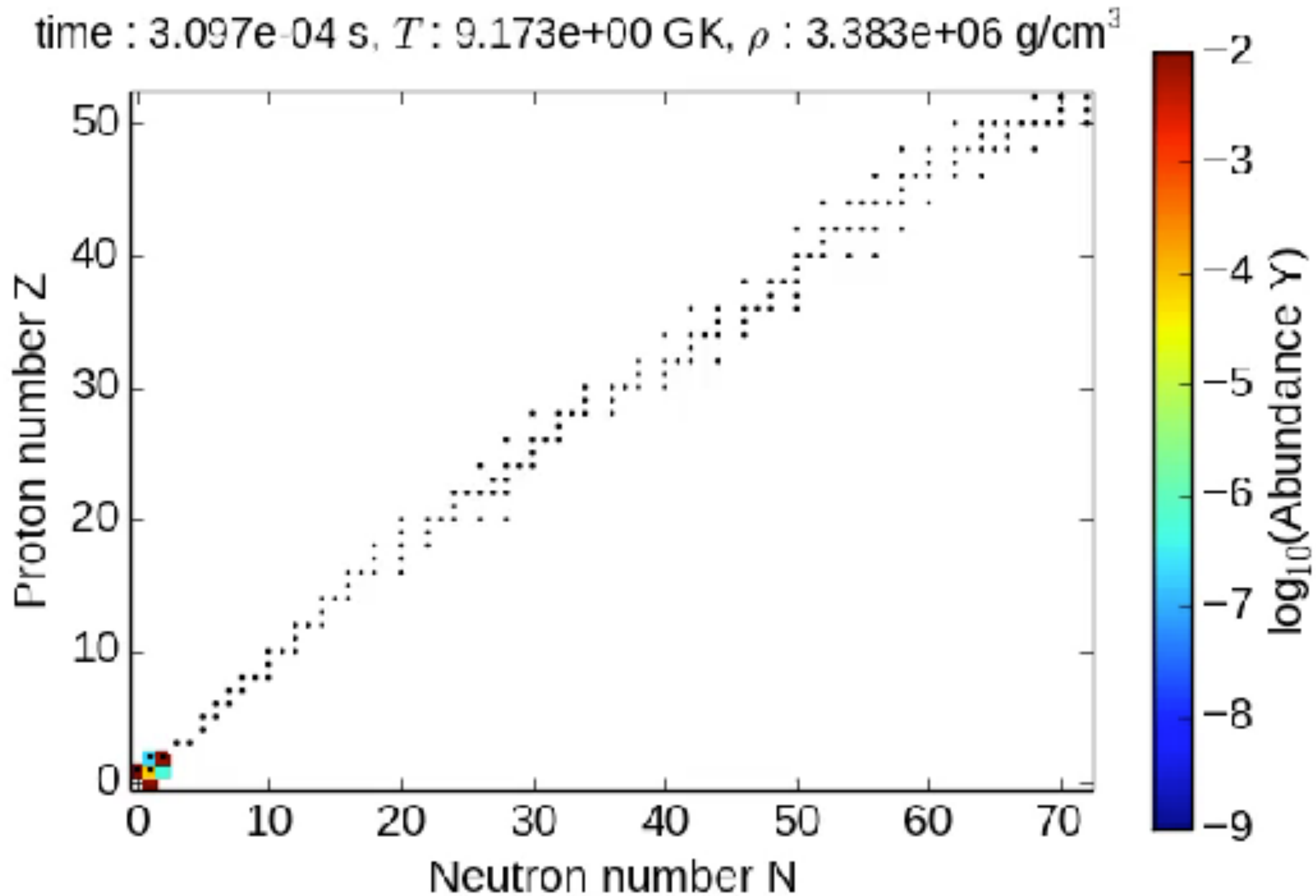


- Initial conditions:

  Nuclear statistical equilibrium **(NSE)**
- **Alpha-rich** freeze out
- Slightly neutron-rich conditions:

  weak r-process
- Close to stability: slow beta decay

Nucleosynthesis in neutrino-driven winds



Astrophysical uncertainties

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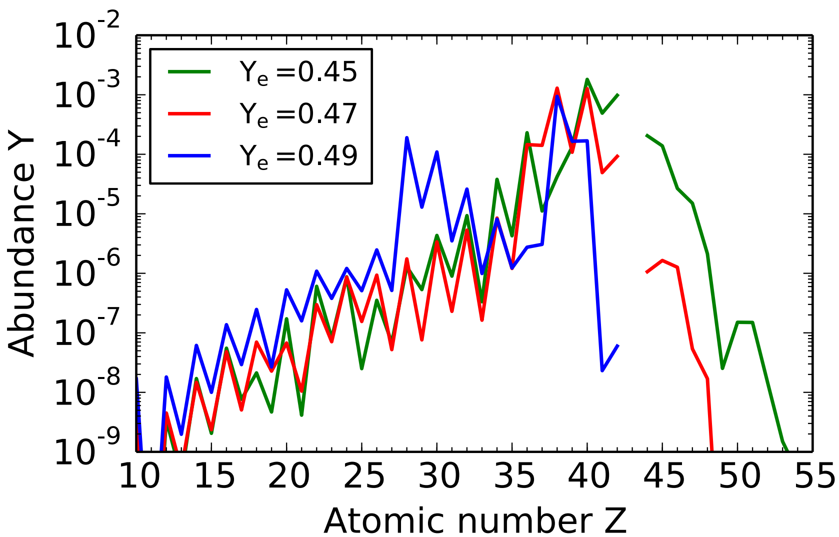
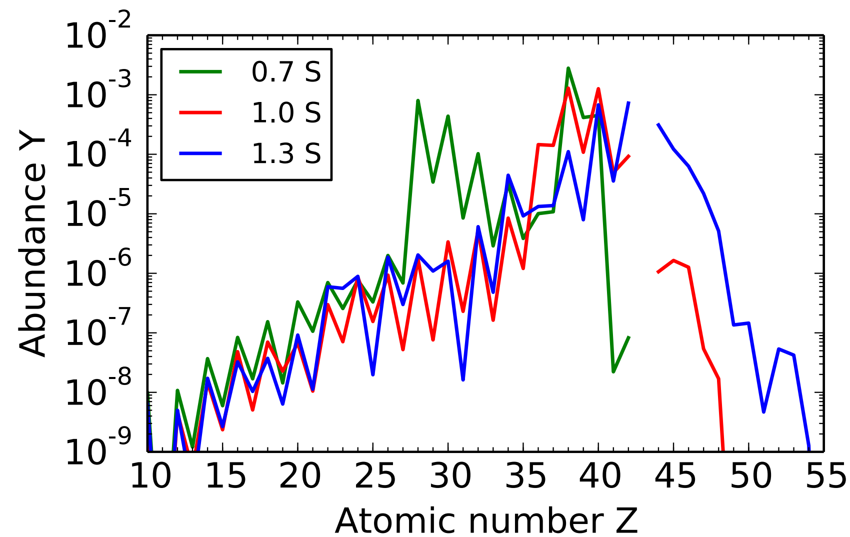
Reference case from simulations: S=86 k_B/nuc, Y_e=0.47, τ=11 ms





- Key nucleosynthesis quantity → **neutron-to-seed ratio**
- Formation of lighter heavy elements including Sr, Y, Zr up to Ag
  (Hoffman 1996, Arcones & Bliss 2014)

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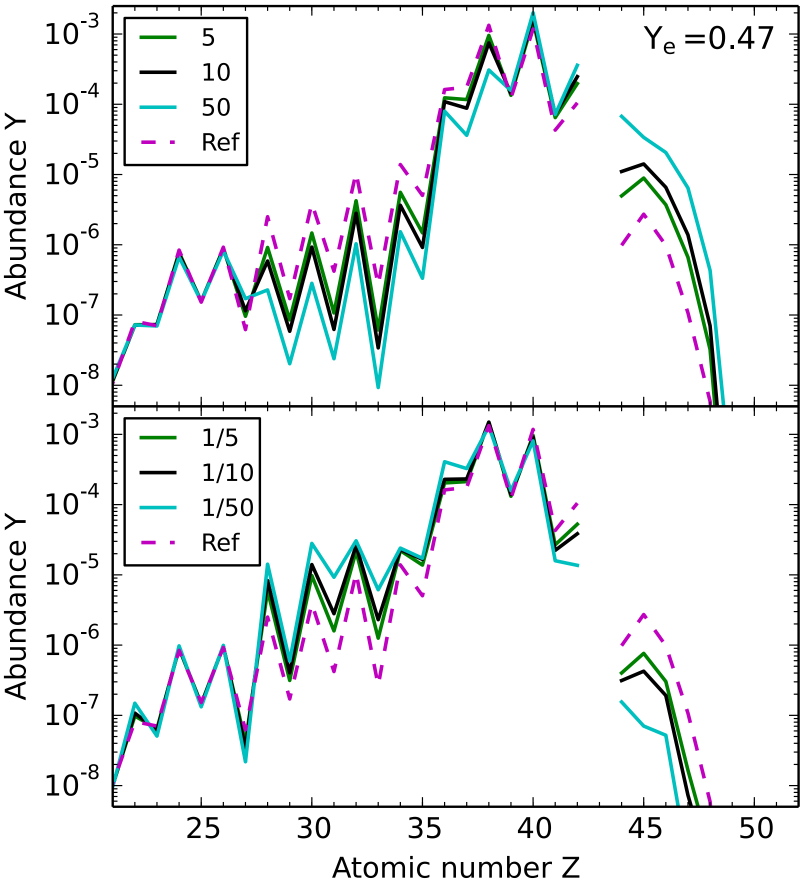
Nuclear physics uncertainties: (α,n) reaction rates

- Most abundant species are within range **26 ≤ Z ≤ 45**
- **weak r-process:** Slow β-decay → (α,n) move matter to high *Z*
- Theoretical uncertainties: **alpha optical potential**
- (α,n) rates modified by constant factors

In collaboration with
F. Montes and J. Pereira (MSU)

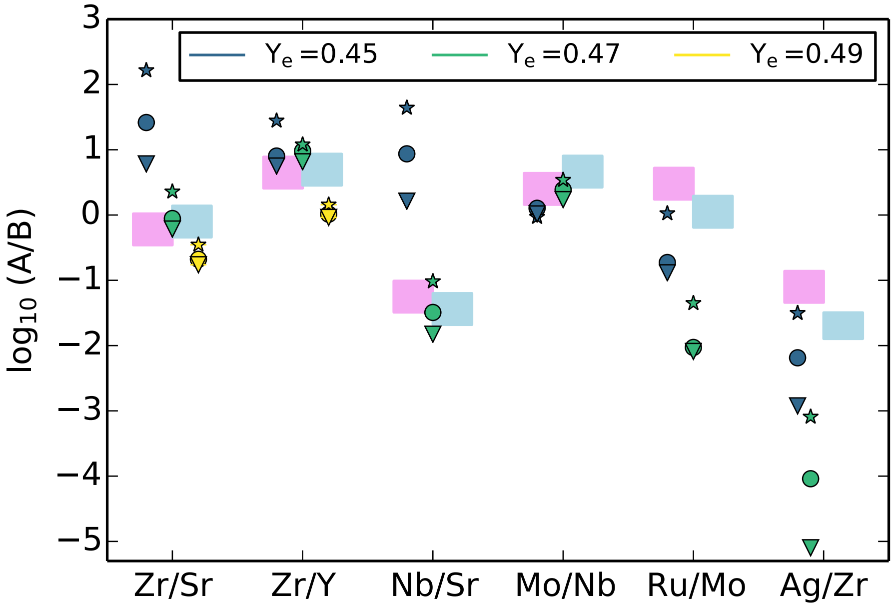
➡ Measurement of ^{75}Ga(α,n) at ReA3 (NSCL/MSU) on July 5-15, 2016

Bliss et al. (to be submitted)



Astrophysical and nuclear physics uncertainties

- Variation of astrophysical conditions (Y_e) and nuclear physics uncertainties (★ ≡ 10, ▼ ≡ 1/10)
- Important to **reduce** nuclear physics **uncertainties**
- Use **observations** to constrain astrophysical conditions

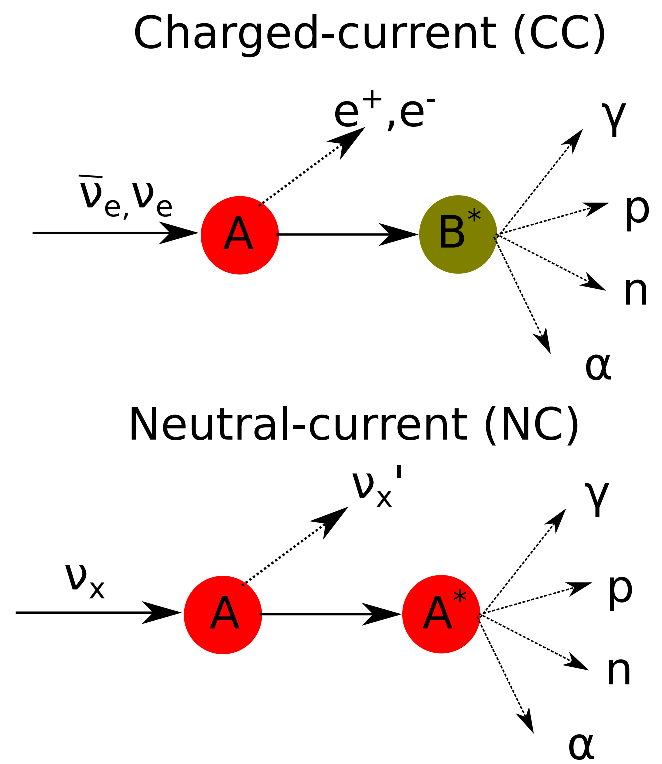


Bliss et al. (to be submitted)

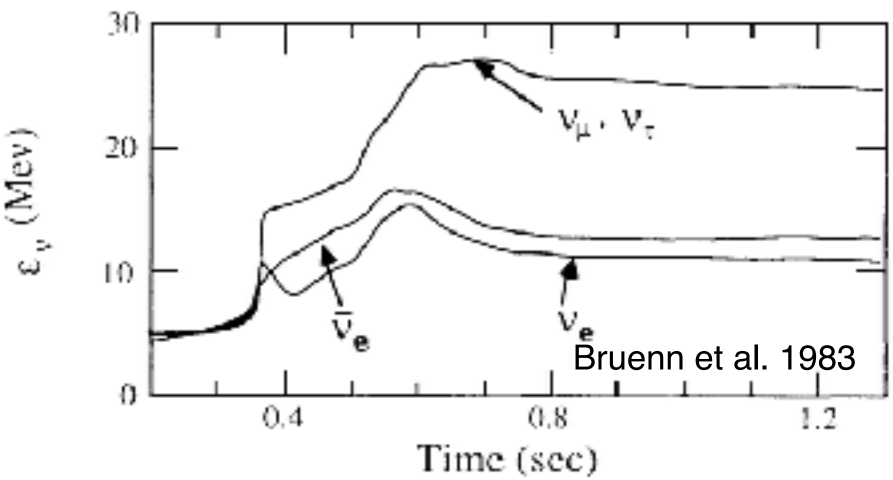
Neutrino nucleosynthesis

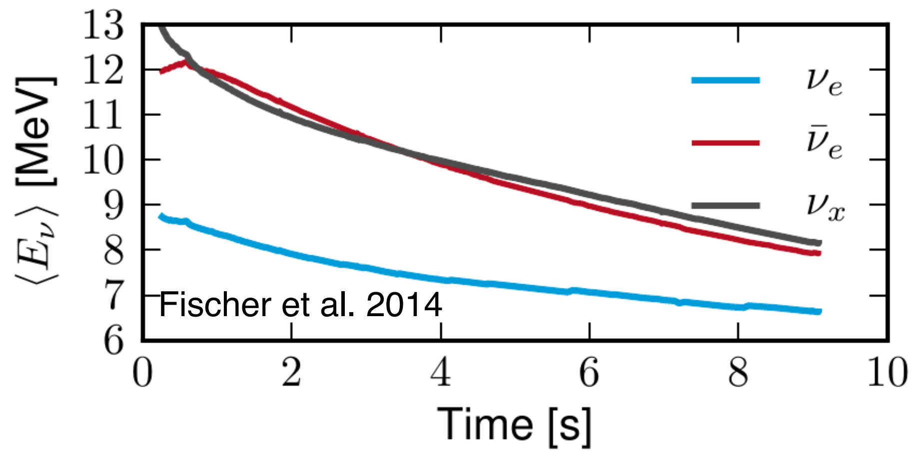
- Emission of 10^{58} neutrinos
- $\langle E_\nu \rangle \approx 8$ - 20 MeV
- **Inverse β-decay**
- **Particle evaporation**
- **Capture of spallation products**

Set of cross sections based on RPA and a statistical model (L. Huther)



Neutrino spectra from state-of-the art SN simulations





- Improved treatment of neutrino transport (B01,B05): lower ν energies

Current standard:

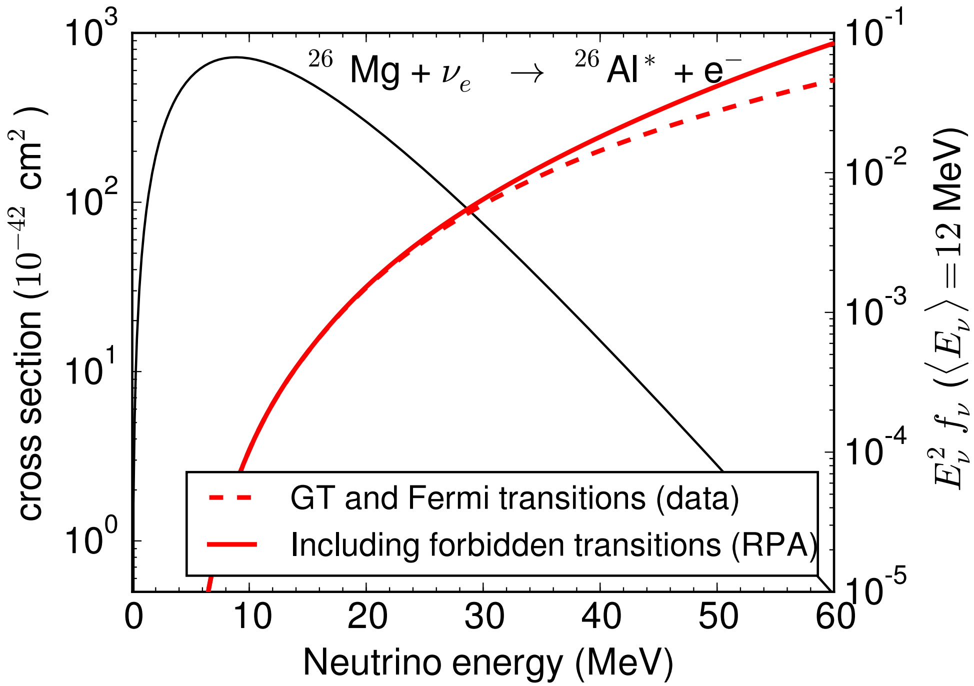
$$\langle E_{\nu_e} \rangle = 12 \text{ MeV}$$
$$\langle E_{\bar{\nu}_e} \rangle = 15 \text{ MeV}$$
$$\langle E_{\nu,\bar{\nu}_{\mu,\tau}} \rangle = 19 \text{ MeV}$$

Low ν energies:

$$\langle E_{\nu_e} \rangle = 9 \text{ MeV}$$
$$\langle E_{\bar{\nu}_e} \rangle = 13 \text{ MeV}$$
$$\langle E_{\nu_{\mu,\tau}} \rangle = 13 \text{ MeV}$$

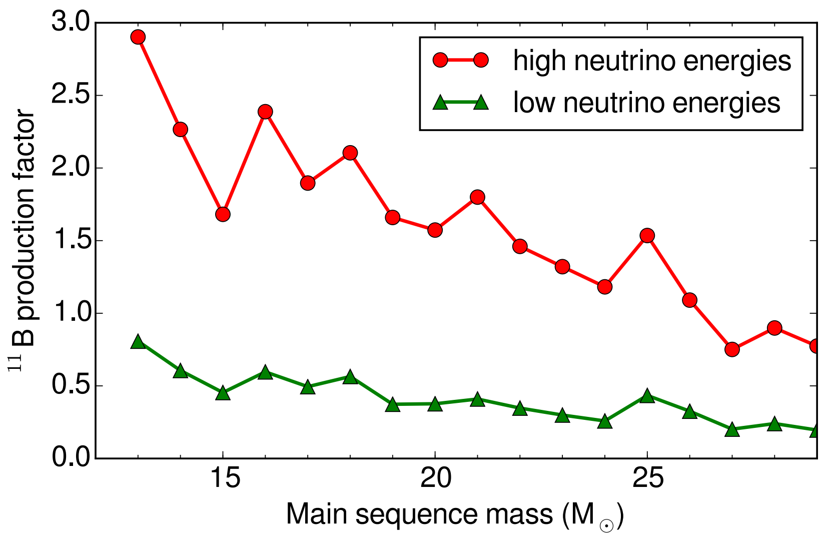
Neutrino spectra from state-of-the art SN simulations

- **ν cross sections** are more sensitive to details of **nuclear structure at low energies**
- Charged-current ν-nucleus cross sections based on measured Gamow-Teller strengths for key nuclei (e.g., ^{26}Al)



Neutrino nucleosynthesis results

Nucleosynthesis calculation for **1D piston driven explosion models** performed with the **KEPLER** hydrodynamics code (Heger et al.)



Averaged production factors:

	No ν	Low E_ν [1]	High E_ν [2]
^{7}Li	0.001	0.07	0.91
^{11}B	0.005	0.45	1.81
^{15}N	0.06	0.09	0.15
^{19}F	0.12	0.25	0.40
^{138}La	0.12	0.86	1.70
^{180}Ta*	0.6	1.49	2.67

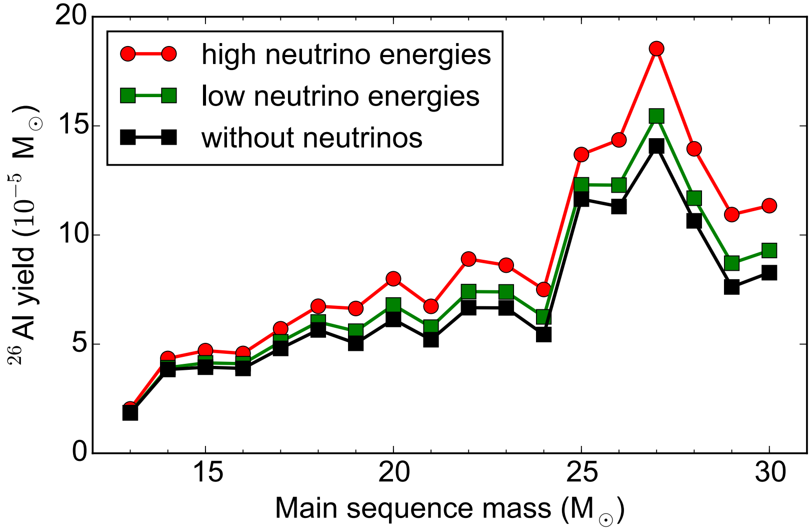
1) $\langle E_{\nu_e} \rangle = 9\,\mathrm{MeV}, \langle E_{\bar{\nu}_e,\nu_x} \rangle = 13\,\mathrm{MeV}$

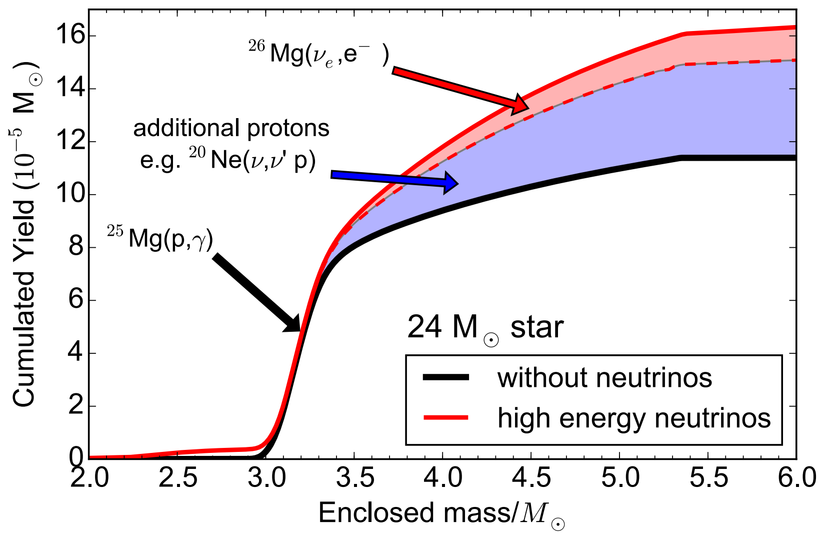
2) $\langle E_{\nu_e} \rangle = 13\,\mathrm{MeV}, \langle E_{\bar{\nu}_e} \rangle = 16\,\mathrm{MeV}, \langle E_{\nu_x} \rangle = 19\,\mathrm{MeV}$

*) Only about 40% of ^{180}Ta survives in the long − lived isomeric state

- **Reduced but still significant** enhancement of production factors
- More consistent with estimates for contributions from cosmic rays

Effects on radioactive nuclei





^{60}Fe/^{26}Al ≈ 1.25 (observations give ≈ 0.35)

Production factors

Isotope	Without ν	Low energy ν	High energy ν
^{26}Al	5.19	5.64	6.56
^{22}Na	0.20	0.27	0.39

Outlook: Extension to **neutrino-driven** (e.g., Janka et al.) and **multidimensional** (e.g., Hix et al.) explosion models

B06: Project goals

- Long-time multidimensional simulations
- Explosive shock nucleosynthesis based on neutrino-driven explosions
- Wind nucleosynthesis and its dependency on neutrino opacities and EoS