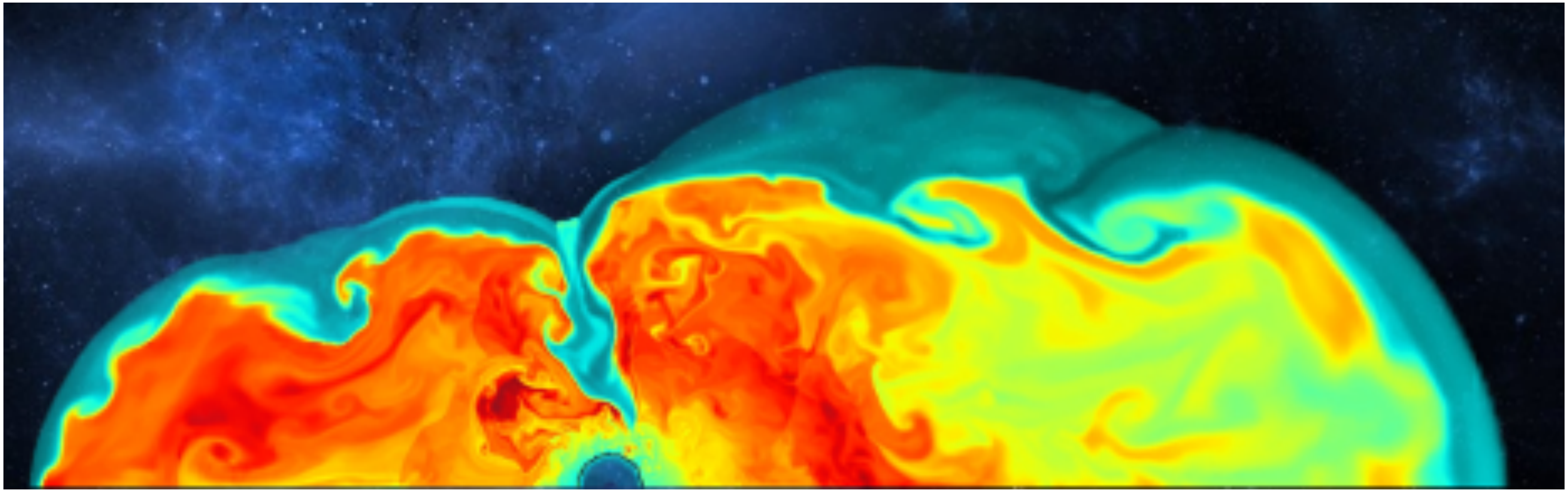
B06
Nucleosynthesis in core-collapse supernovae



PIs: Almudena Arcones and Gabriel Martinez-Pinedo
Doctoral researches:
Julia Bliss, Carlos Mattes, Andre Sieverding, Stylianos Nikas,
Hannah Yasin

Highlights

Supernova simulations:

- Comparison of neutrino transports (submitted, *arxiv:1806.10030*)
- Equation of state: synergies with B01 and B05 (in prep.)
- Long-time evolution: under development

Nucleosynthesis:

- Neutrino nucleosynthesis (submitted, *arxiv:1805.10231*)
- Neutrino-driven ejecta: impact of (α,n) reactions (*J. Phys. G, 2017,* in prep.)
  astrophysical uncertainties (*ApJ, 2018*)
- Mo & Ru: implications for presolar grains (submitted, *arxiv:1804.03947*)

Highlights

Supernova simulations:

- Comparison of neutrino transports (submitted, *arxiv:1806.10030*)
- Equation of state: synergies with B01 and B05 (in prep.)
- Long-time evolution: under development

Theory Internship

Nucleosynthesis:

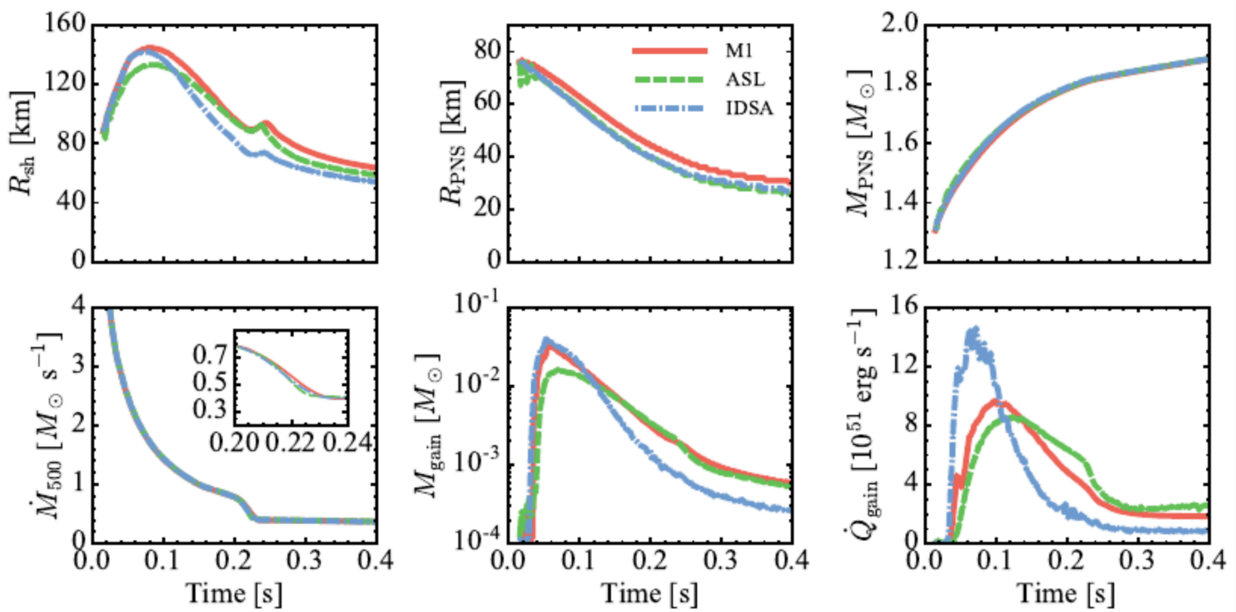
- Neutrino nucleosynthesis (submitted, *arxiv:1805.10231*)
- Neutrino-driven ejecta: impact of (α,n) reactions (*J. Phys. G, 2017,* in prep.)
  astrophysical uncertainties (*ApJ, 2018*)
- Mo & Ru: implications for presolar grains (submitted, *arxiv:1804.03947*)

Theory Internship

Neutrino transport comparison, 1D

Controlled comparison: same simulation code (FLASH) and set up different transport schemes: Fryxell et al, 2000

- M1 *(O'Connor & Couch 2018)*
- IDSA *(Pan et al. 2016)*
- ASL *(PhD Carlos Mattes; Pan, Mattes, et al., submitted arxiv:1806.10030)*



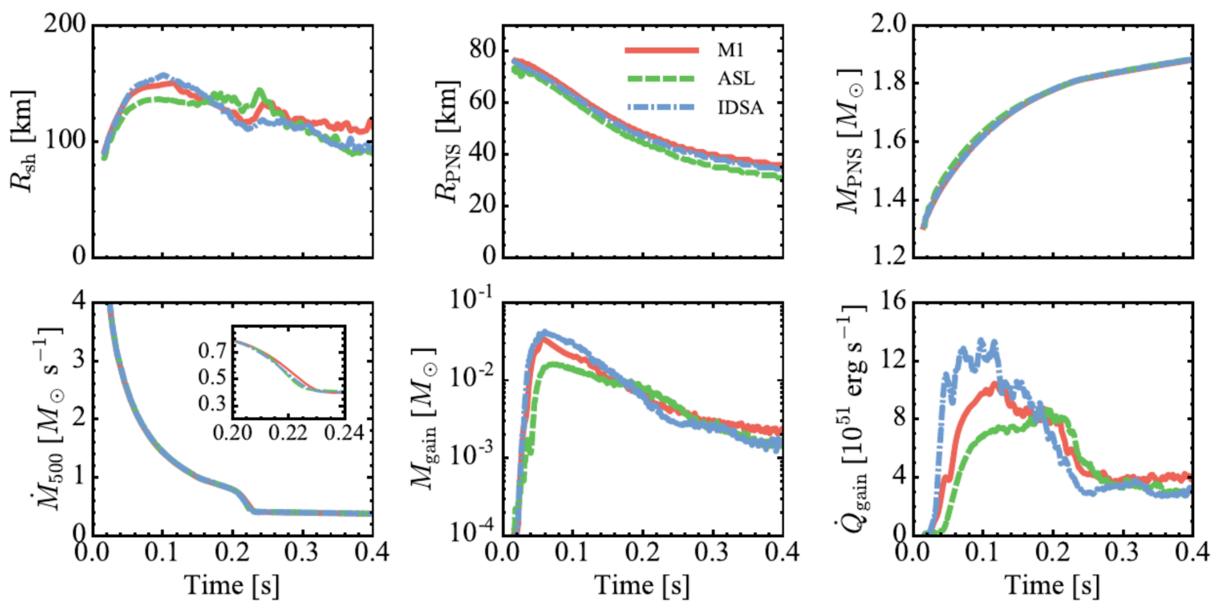
Spherical symmetry (1D)

K. C. Pan, C. Mattes, E. O'Connor, S. Couch A. Perego, A. Arcones

Neutrino transport comparison, 2D

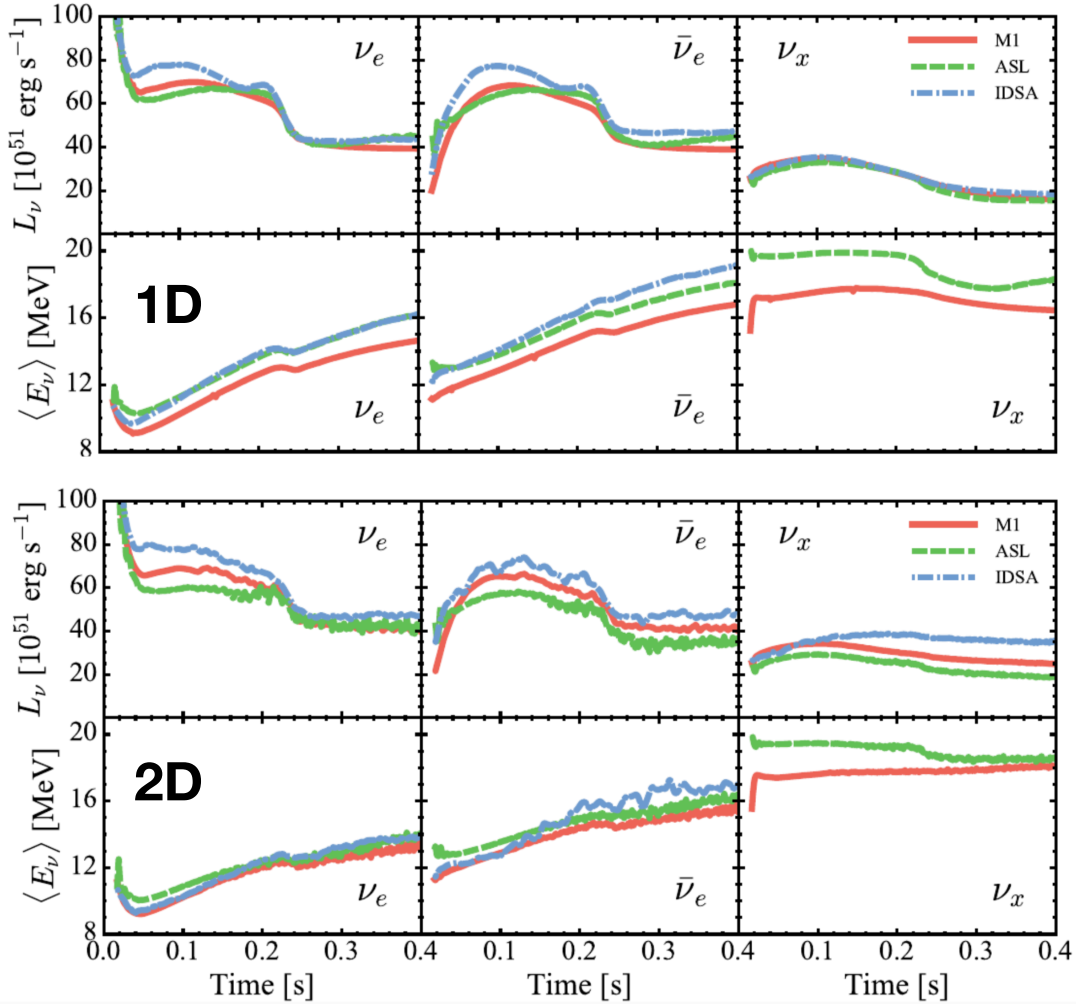
Controlled comparison: same simulation code (FLASH) and set up
Fryxell et al, 2000
different transport schemes:

- M1 *(O'Connor & Couch 2018)*
- IDSA *(Pan et al. 2016)*
- ASL *(PhD Carlos Mattes; Pan, Mattes, et al., submitted arxiv:1806.10030)*



Cylindrical symmetry (2D)

Neutrino properties



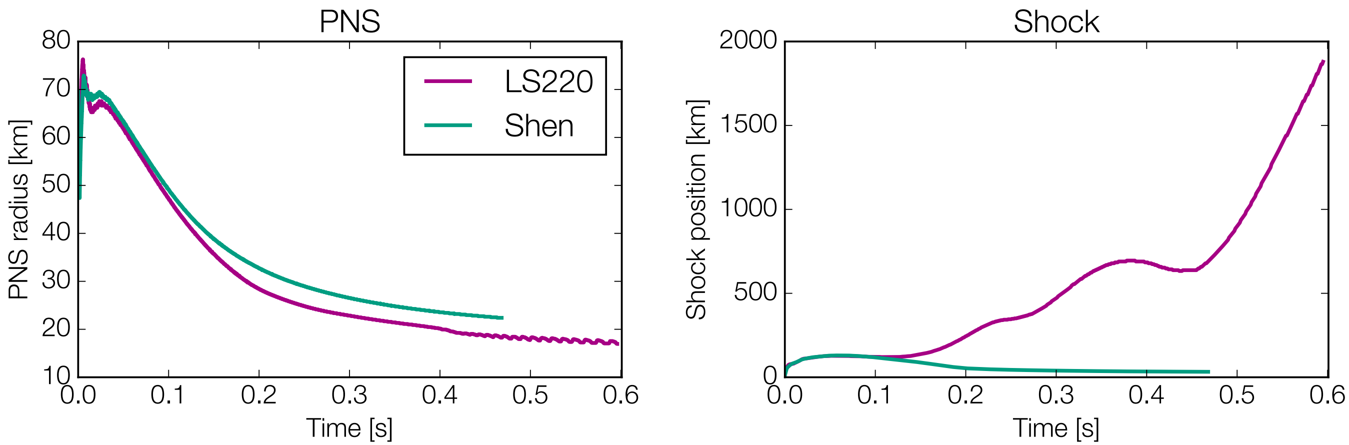
- Variations up to 10%
- Proto-neutron star convection: strong impact on 2D evolution
- ASL: qualitative good agreement and 10 times faster

Pan, Mattes, et al., submitted arxiv:1806.10030

Eos in supernova simulations

Lattimer & Swesty (1991)	H. Shen et. al. (1998)
Liquid-drop model	Relativistic mean field approach
K = 180, 220 or 375	K = 281
m* / m = 1	m* / m = 0.634

15 $M_\odot$, hf = 1.24, GR1D



EOS transition

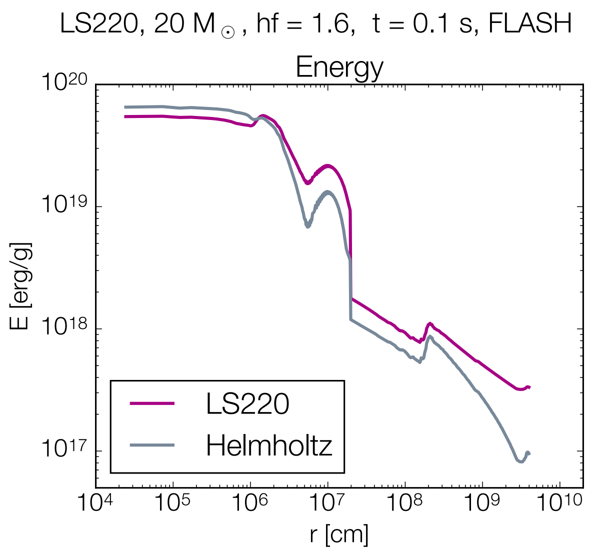
Goal: Run long-time CCSN simulations

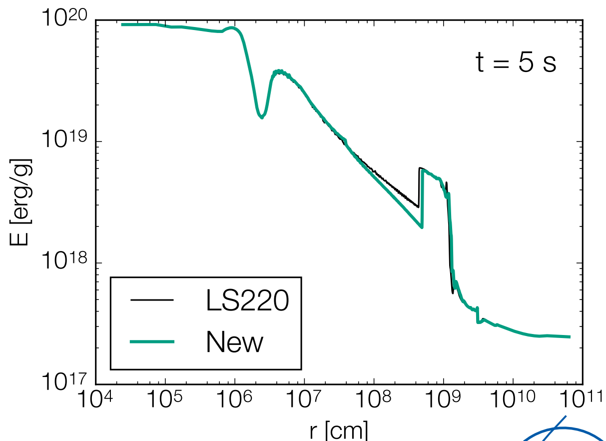
Challenges: EOS tables have limits!

- High-density EOS implement binding energies in their internal energy, low-density EOS don't
- It's not feasible to recalculate this binding energy for every EOS

We chose to:

- Make a numerical transition, for every available EOS, all available progenitors

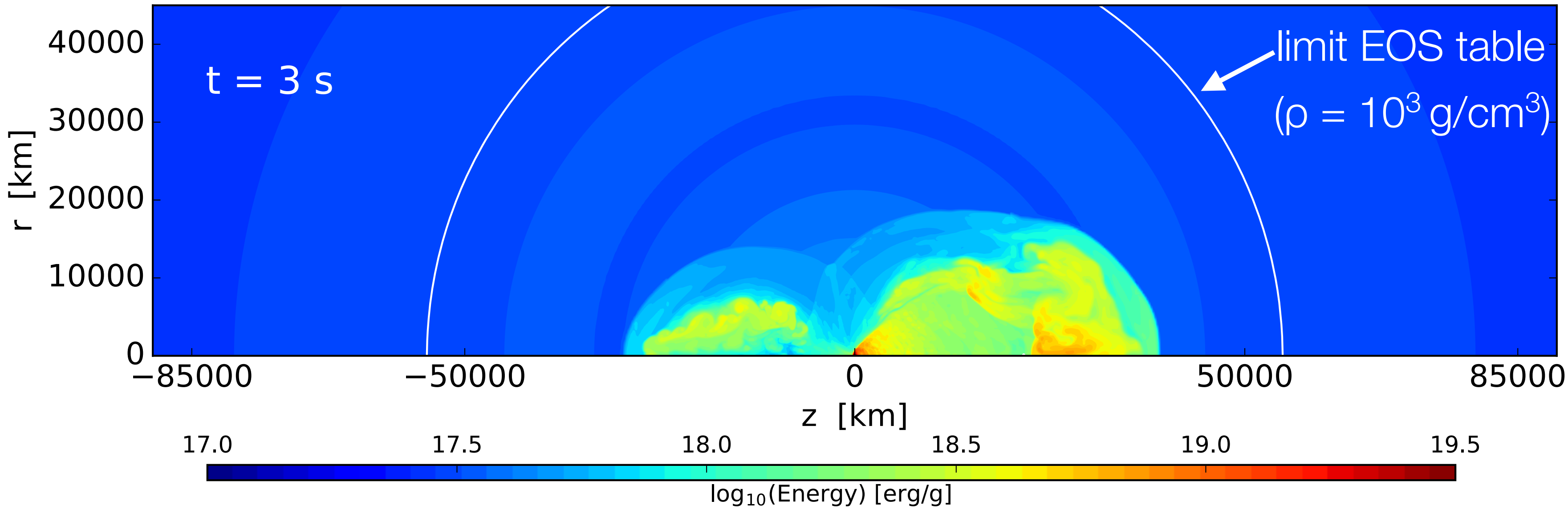




H. Yasin, C. Mattes, M. Witt, A. Arcones, S. Couch

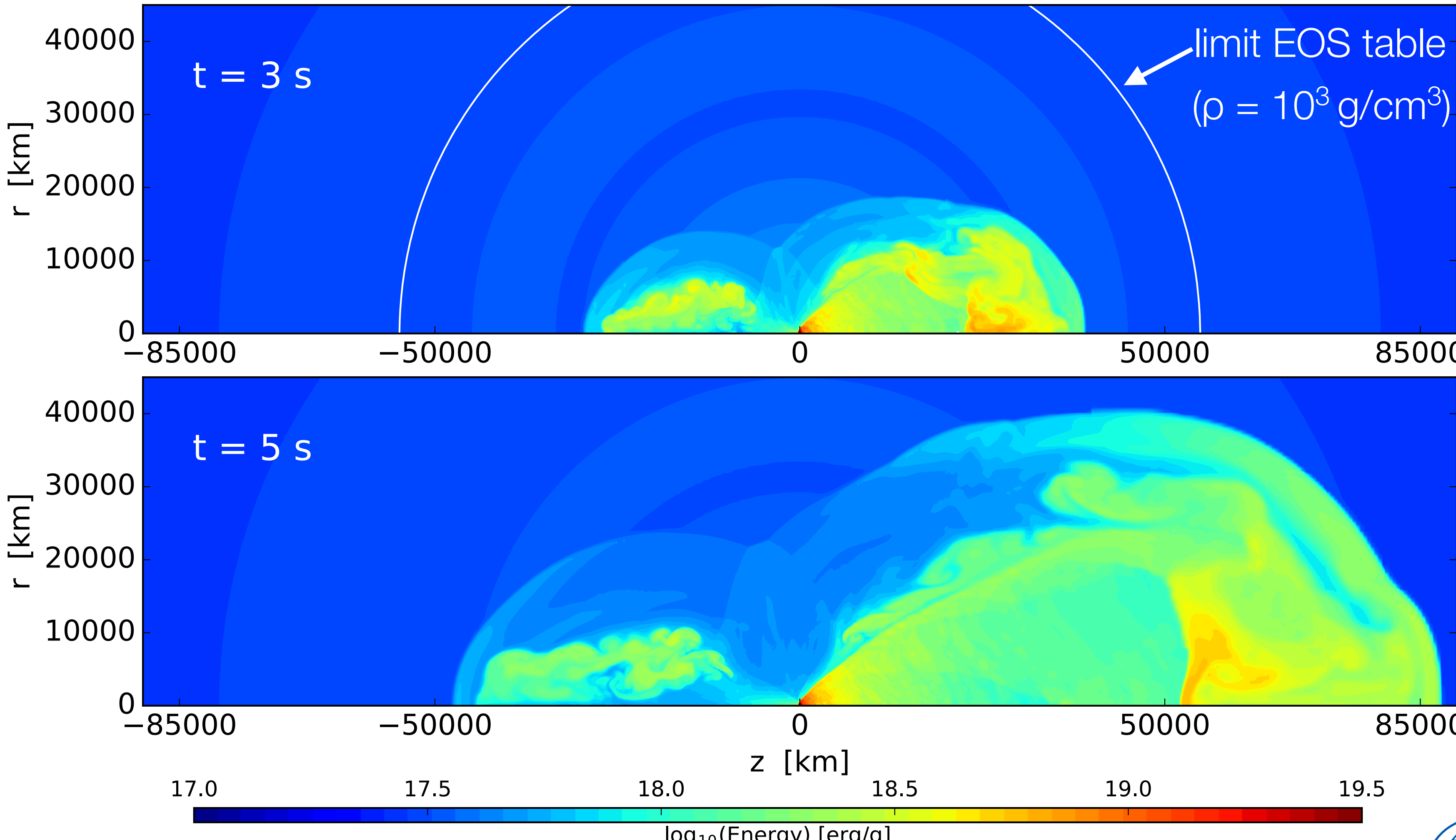
2d: LS220 + Helmholtz with ASL, 20 $M_{\odot}$, hf = 1.0

TECHNISCHE UNIVERSITÄT DARMSTADT



2d: LS220 + Helmholtz with ASL, 20 $M_\odot$, hf = 1.0

TECHNISCHE UNIVERSITÄT DARMSTADT



Effective mass m^*

Skyrme–type effective mass for a nucleon with isospin t:

$$\frac{\hbar^2}{2m_t^*} = \frac{\hbar^2}{2m} + \lambda_1 n_t + \lambda_2 n_{-t}$$

Lattimer & Swesty, 1991

Label	$m/m^* \|_{PNM,\, n_0}$	$m/m^* \|_{SM,\, n_0}$	$\lambda_1 \left[10^{-3} \frac{fm^3}{MeV}\right]$	$\lambda_2 \left[10^{-3} \frac{fm^3}{MeV}\right]$
$m^*_{1.0}$ (LS)	1	1	0	0
$m^*_{0.8}$	0.8	0.8	0.831	0.831
$m^*_{0.634}$ (Shen)	0.634	0.634	1.920	1.920

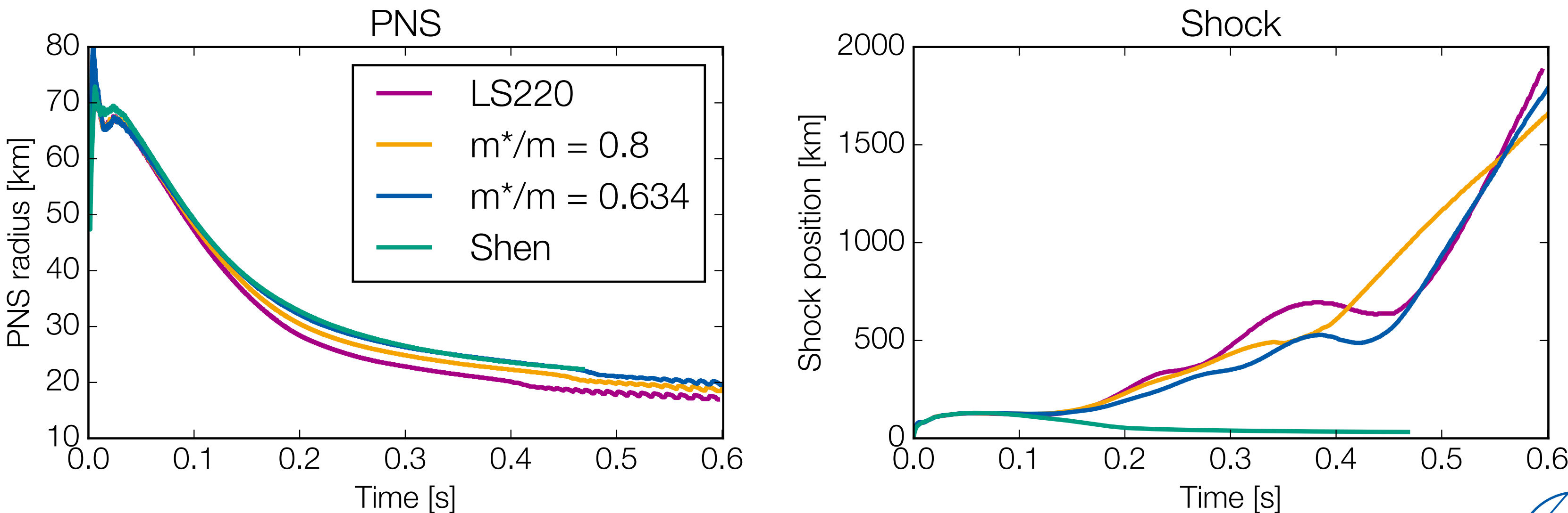
$P \sim {}^1/_m$, we expect m^* with $m^* / m < 1$ to decrease the central density

H. Yasin, S. Schäfer, A. Arcones, A. Schwenk: strong synergy B06, B01, B05

Impact on proto-neutron star and shock

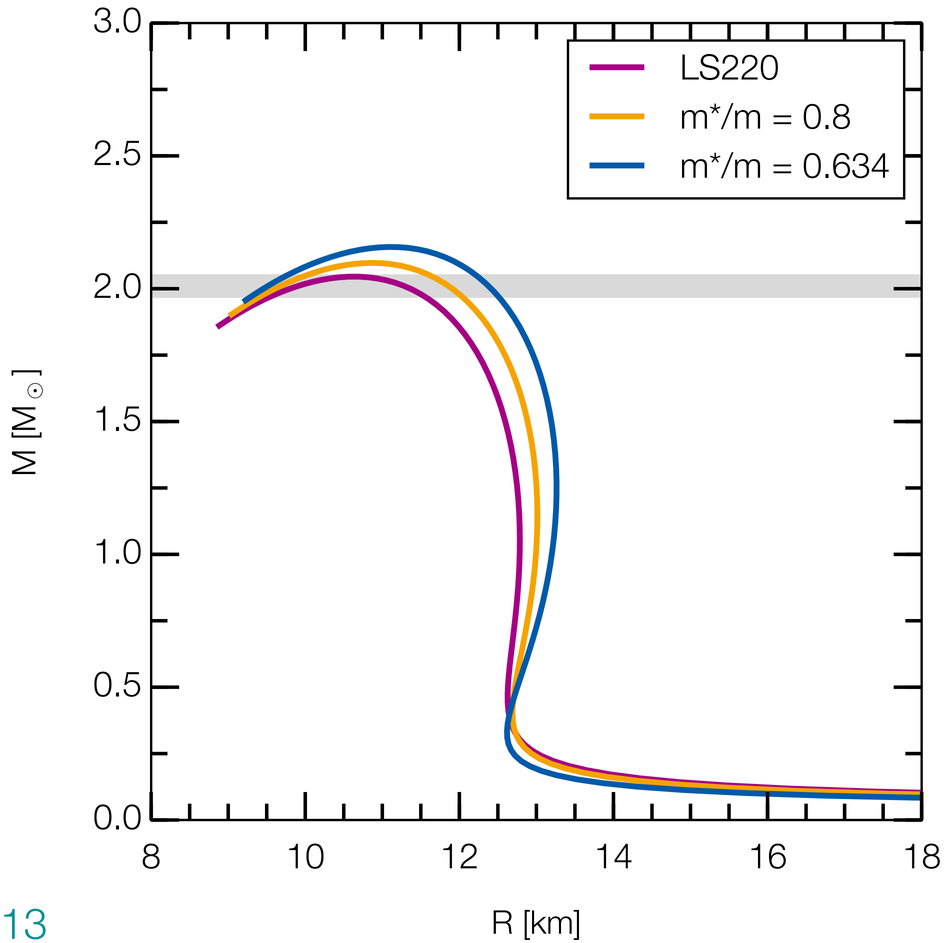
- Proto-neutron star (PNS) radius increases for m* / m < 1
- $m^*_{0.634}$ reproduces the PNS radius obtained with original Shen EOS
- Explosion evolution strongly affected

15 $M_\odot$, hf = 1.24, GR1D



Mass-radius relationship

- Solve Tolman-Oppenheimer-Volkoff equations at T = 0
- $m^* / m < 1$ lead to higher maximum mass and larger radii (pressure)
- $2M_\odot$ constraint fulfilled
  Antoniadis et al, 2015
- Chiral EFT provides an uncertainty band for the radii of NS Hebeler et al, 2013



Highlights

Supernova simulations:

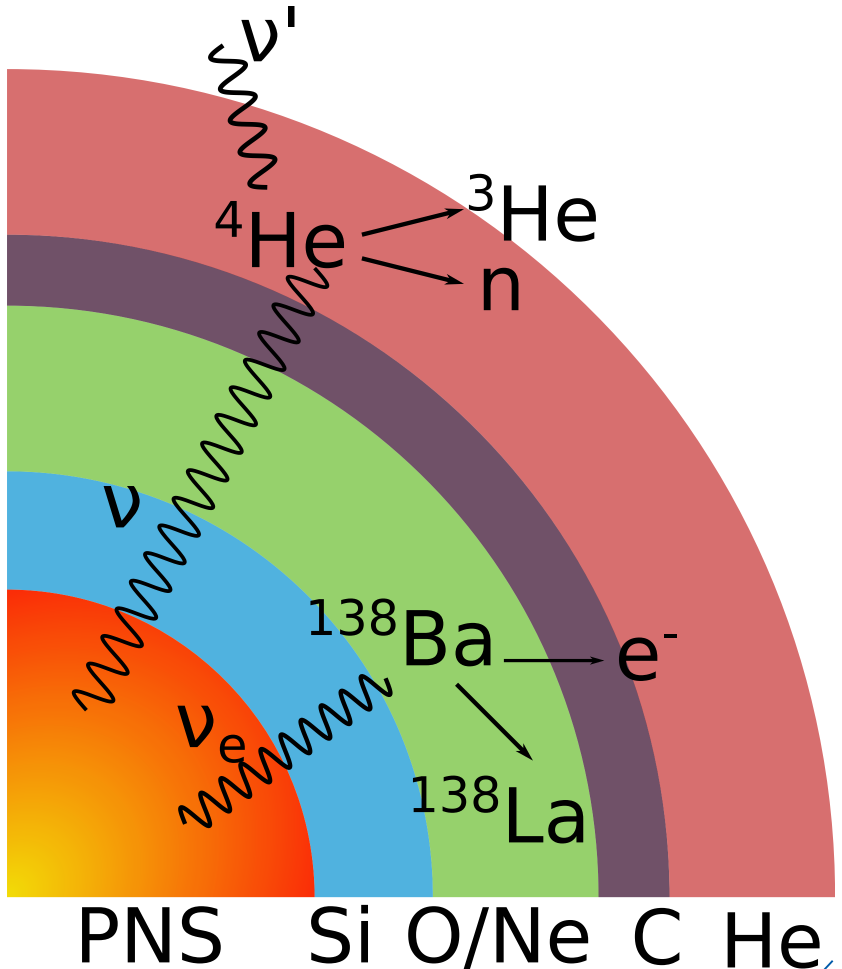
- Comparison of neutrino transports (submitted, *arxiv:1806.10030*)
- Equation of state: synergies with B01 and B05 (in prep.)
- Long-time evolution: under development

Nucleosynthesis:

- Neutrino nucleosynthesis (submitted, *arxiv:1805.10231*)
- Neutrino-driven ejecta: impact of (α,n) reactions (*J. Phys. G, 2017,* in prep.)
  astrophysical uncertainties (*ApJ, 2018*)
- Mo & Ru: implications for presolar grains (submitted, *arxiv:1804.03947*)

Neutrino nucleosynthesis

- Neutrinos are crucial for supernova explosions and have a direct impact on the nucleosynthesis in the ν process
- Emission of 10^{58} neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 8 - 20$ MeV
- Inverse β-decay
- Particle evaporation
- Capture of spallation products
- Significant production of e.g. ^{11}B



New cross section compilation

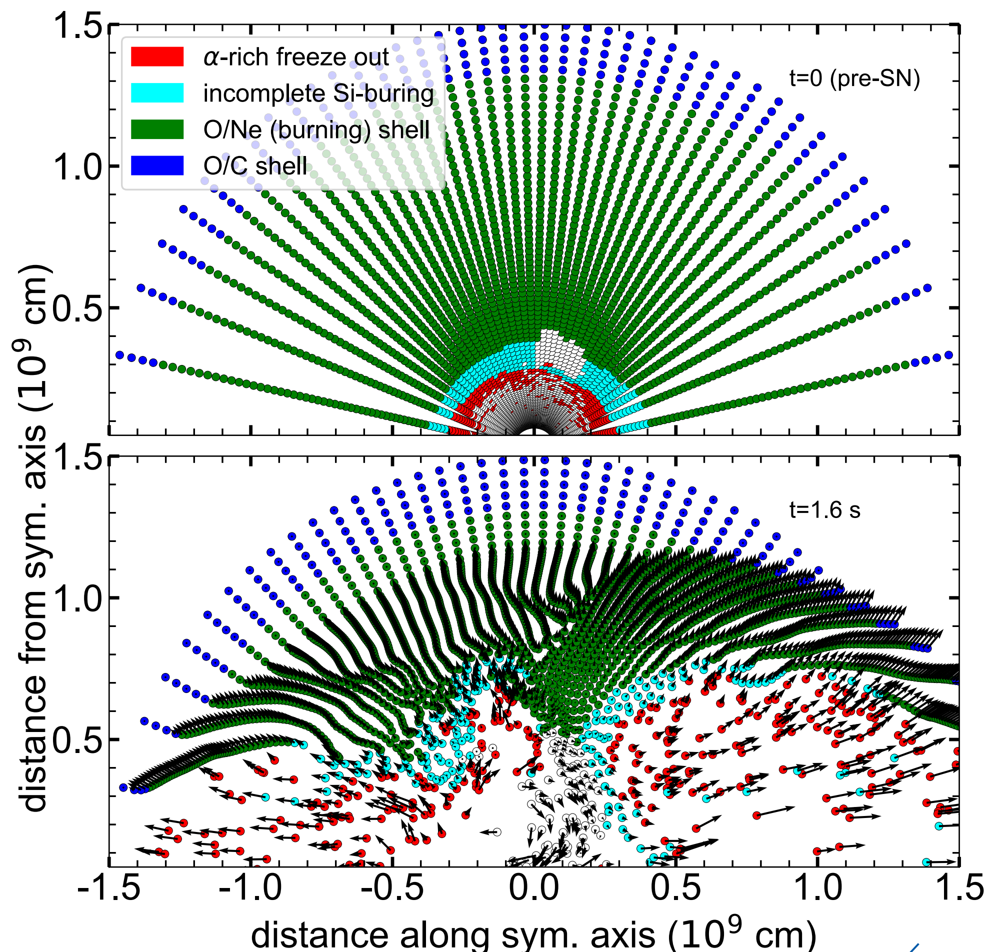
- Based on RPA from dripline to dripline up to Z=84
- Additionally derived from experimental data and shell model calculations:
  - $^{22}Ne + \nu_e \rightarrow {}^{22}Na$ *(mirror nucleus data)*
  - $^{26}Mg + \nu_e \rightarrow {}^{26}Al$ *(charge exchange data)*
  - $^{36}Ar + \bar{\nu}_e \rightarrow {}^{36}Cl$ *(Shell model)*
  - $^{36}S + \nu_e \rightarrow {}^{36}Cl$ *(Shell model)*
- From the literature:
  - $^{138}Ba + \nu_e \rightarrow {}^{138}La$ *Byelikov et al. (2007)*
  - $^{180}Hf + \nu_e \rightarrow {}^{180}Ta$
  - ^{4}He spallation *Gazit et al. (2007)*
  - …

Complete nucleosynthesis study with 1D parametric explosion models (13 - 30 $M_\odot$) and updated neutrino properties *arXiv:1805.10231*

Self-consistent simulations

TECHNISCHE UNIVERSITÄT DARMSTADT

- Innermost supernova ejecta are affected by the details of the explosion
- Nucleosynthesis with tracer particles from a 2D axisymmetric simulation from the ORNL group *(Bruenn et. al, 2016)* (LS220 + 12 $M_{\odot}$)
- Tracer data until 1.6 seconds
- Production of light elements in the α-rich freeze out



SFB 1245

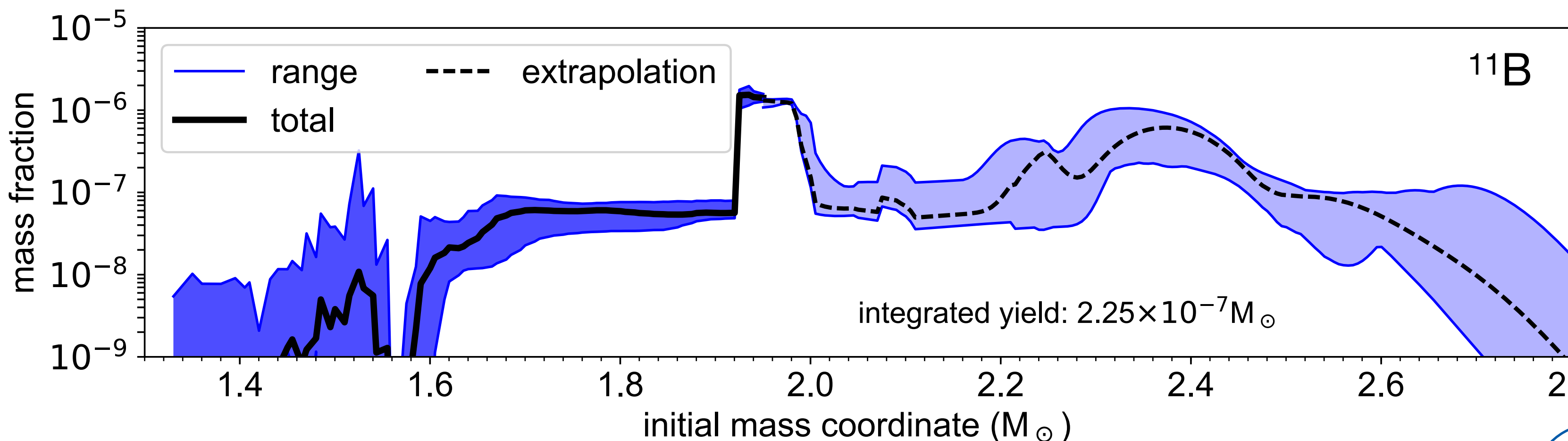
The ν process in multi-D

For this case:

- Production of light elements in the innermost ejecta is negligible
- Qualitative agreement with 1D calculations
- Longer evolution time and other progenitor models are now being studied

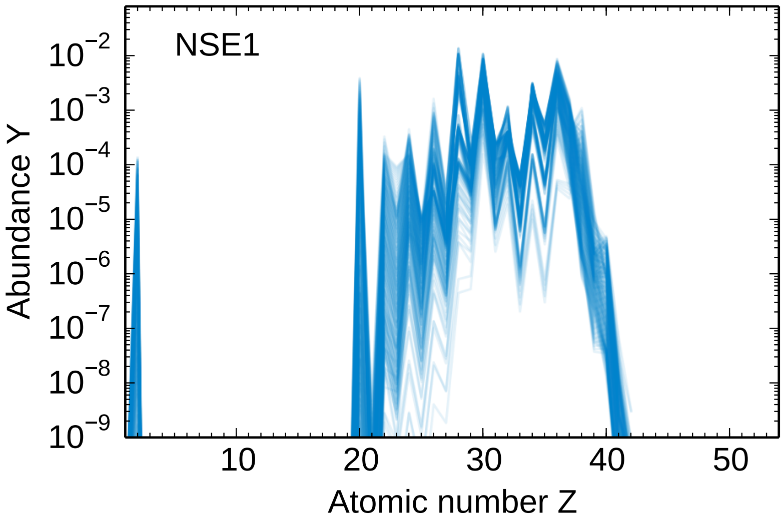
Nucleus	Production factor
^{7}Li	0.28
^{11}B	0.98
^{15}N	0.11
^{19}F	0.29
^{138}La	1.30
^{180}Ta^{m}	1.96

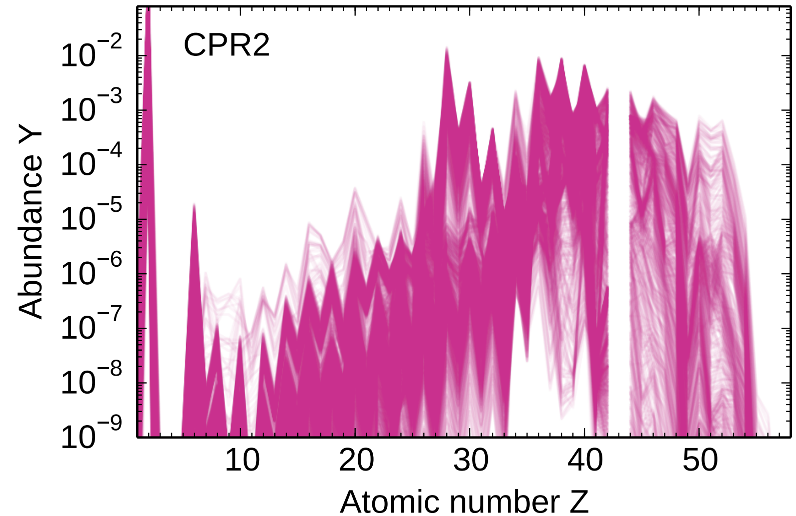
Production factors for the 12 $M_\odot$ model (Progenitor model from Woosley et al. 2007)



Survey of astrophysical conditions in ν-driven supernova ejecta

TECHNISCHE UNIVERSITÄT DARMSTADT





J. Bliss, M. Witt, A. Arcones, F. Montes, and J. Pereira, ApJ. 855 (2018) 135

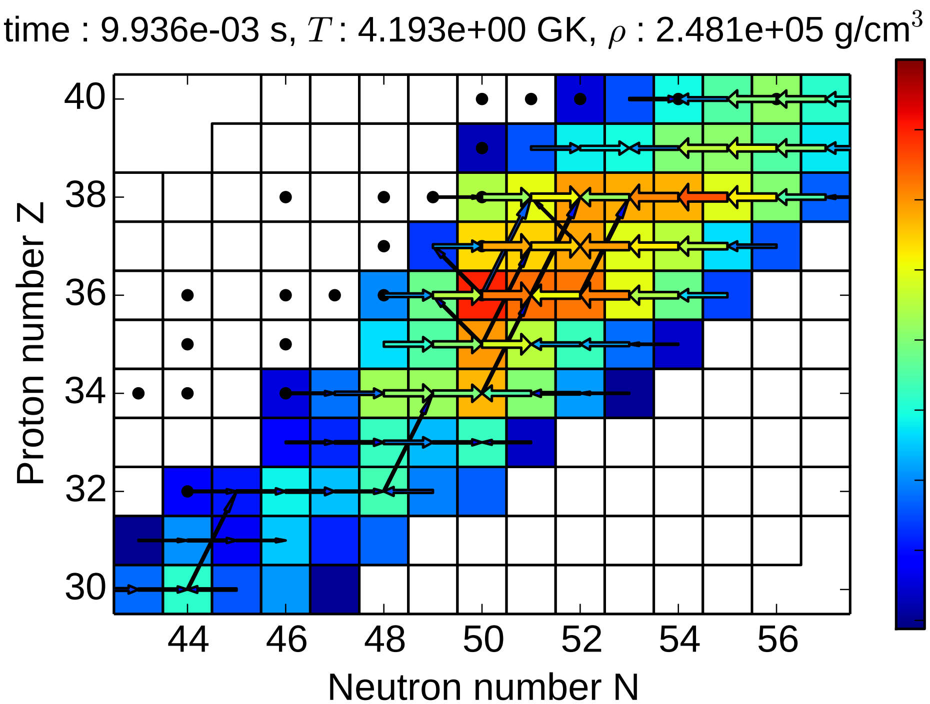
- Systematic study of nucleosynthesis conditions based on steady-state models
- Identification of four characteristic abundance patterns:
  - ✳ NSE1 & NSE2 → binding energies and partition functions
  - ✳ CPR1 → Q-values of (α,n) reactions
  - ✳ CPR2 → individual reactions are critical

JINA-CEE

SFB 1245

Reactions in ν-driven supernova ejecta

- Important reactions: α-, n-, p-capture reactions, β-decays
- $\tau_{expansion} << \tau_{\beta}$ → (α,n) are key reactions
- α-process *(Hoffman & Woosley 1992)*
- Absence of relevant experiments
  → theoretical reaction rates based on Hauser-Feshbach model

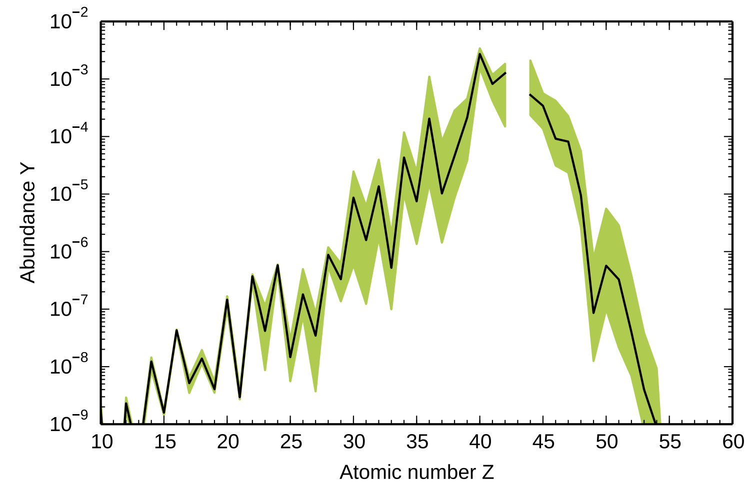


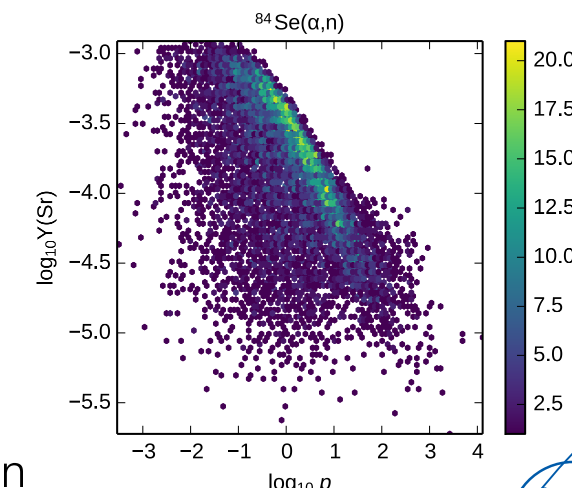
J. Bliss, A. Arcones, F. Montes, and J. Pereira, J. Phys. G. 44 (2017) 054003

Sensitivity study of (α,n) reactions in neutrino-driven supernova ejecta

TECHNISCHE UNIVERSITÄT DARMSTADT

- Independently vary each (α,n) rate between Fe and Rh by a random factor
- Identification of key reactions → large correlation and abundance change
- ^{82}Ge, ^{84,85}Se, ^{85}Br(α,n) strongly affect abundance of Z=36–39
- Measurement of important (α,n) reactions will reduce nuclear physics uncertainties:
  → ^{75}Ga(α,n) and ^{85}Br(α,n) at ReA3
  → need more experiments





J. Bliss, A. Arcones, F. Montes, and J. Pereira in preparation

SFB 1245

Highlights

Supernova simulations:

- Comparison of neutrino transports (submitted, *arxiv:1806.10030*)
- Equation of state: synergies with B01 and B05 (in prep.)
- Long-time evolution: under development

Nucleosynthesis:

- Neutrino nucleosynthesis (submitted, *arxiv:1805.10231*)
- Neutrino-driven ejecta: impact of (α,n) reactions (*J. Phys. G, 2017,* in prep.)
  astrophysical uncertainties (*ApJ, 2018*)
- Mo & Ru: implications for presolar grains (submitted, *arxiv:1804.03947*)