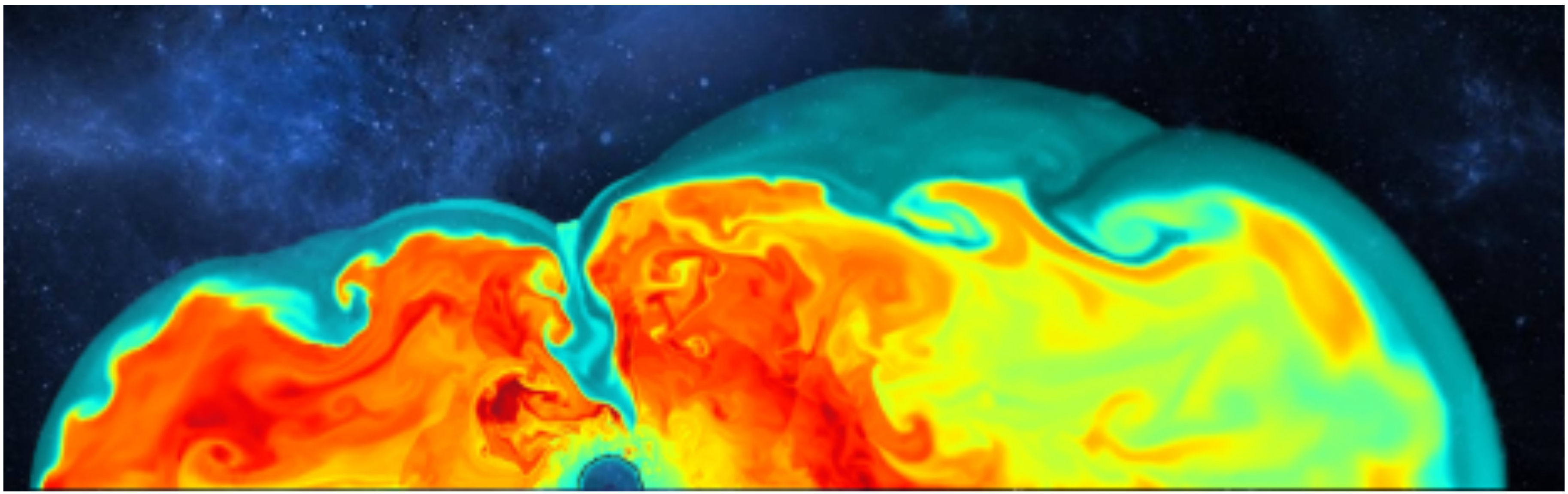
B06
Nucleosynthesis in core-collapse supernovae



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

Projects: Supernova simulations

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- Comparison of neutrino transports [J. Phys. G: Nucl. Part. Phys. **46**, 14001 (2018)]
- Equation of state with B01[submitted to Phys. Rev. Lett, arxiv:1812.02002]
- Long-time evolution: impact of explosion energy and rotation [in prep.]
- Impact of neutrino opacities [Astrophys. J. **853**, 170 (2018)]
- Muon production facilitates supernova explosions [Phys. Rev. Lett. **119**, 242702 (2017)]
- Effect of inverse neutron decay opacities [arXiv:1804.10890]

Projects: Nucleosynthesis

- Neutrino nucleosynthesis with modern neutrino spectra
  [Astrophys. J. **865**, 143 (2018)]
- Neutrino nucleosynthesis based on fully time dependent neutrino spectra
  [arXiv:1902.06643]
- Neutrino nucleosynthesis based on self-consistent 2D supernova explosions
  [in prep]
- Neutrino-driven ejecta:
  - impact of (α,n) reactions [J. Phys. G: Nucl. Part. Phys. **44**, 54003 (2017), in prep.]
  - astrophysical uncertainties [Astrophys. J. **855**, 135 (2018)]
  - proton-rich winds: astro and nuclear uncertainties [in prep.]
  - neutrino winds: supernovae vs. ns mergers [in prep.]
- Mo & Ru: implications for presolar grains [Astrophys. J. **866**, 105 (2018)]

First period

Doctoral researchers:

- Julia Bliss (2017): Nucleosynthesis of lighter heavy elements in neutrino-driven winds
- Carlos Mattes (2018): Long-time simulation of core-collapse supernovae
- Stylianos Nikas (2020): Impact of nuclear masses on neutrino wind nucleosynthesis
- Andre Sieverding (2018): Neutrinos in Core-collapse Supernova Nucleosynthesis
- Hannah Yasin (2019): Core-collapse supernovae and uncertainties of the EOS

Young researchers:

- Albino Perego: Assistant Professor at Trento University, Italy
- Meng-Ru Wu: Assistant research fellow at Academia Sinica, Taipei, Taiwan
- Andre Sieverding: PostDoc University of Minnesota
- Andre Sieverding: Giersch Excellence Award 2017

Publications

Papers: 16
Submitted: 5
In preparation: 6
Thesis: 5 PhD, 6 Master, 6 Bachelor

Top 3 publications:

Muon Creation in Supernova Matter Facilitates Neutrino-Driven Explosions,
R. Bollig, H.-T. Janka, A. Lohs, G. Martínez-Pinedo, C. J. Horowitz, and T. Melson,
Phys. Rev. Lett. 119, 242702 (2017).

Survey of astrophysical conditions in neutrino-driven supernova ejecta nucleosynthesis,
J. Bliss, M. Witt, A. Arcones, F. Montes, J. Pereira,
Astrophys. J. 855, 135 (2018).

JINA–CEE

Making the Heaviest Elements in the Universe: A Review of the Rapid Neutron Capture Process,
J. J. Cowan, C. Sneden, J. E. Lawler, A. Aprahamian, M. Wiescher, K. Langanke, G. Martínez-Pinedo, and F.-K. Thielemann,
arXiv: 1901.01410 submitted Rev. Mod. Phys.

B06 impact: workshops

- Conference Nuclear Physics in Astrophysics IX, organized by A. Arcones, R. Reifarth, K. Blaum, and Y. Litivnov, Sept. 15-20, 2019
- Nuclear Astrophysics session at Nuclear Chemistry Gordon Research Conference, organized by A. Arcones, H. Schatz and N. Alahari, June 16 - 21, 2019
- Workshop, Microphysics in computational relativistic astrophysics (MICRA), organized by A. Arcones, A. Brandenburg, S. Couch, F. Foucart, C. Frohlich, K.Kiuchi, E. Lentz, B. Messer, L. Roberts, July 17 - 21, 2017
- Workshop, Neutron star mergers: From gravitational waves to nucleosynthesis, organized by A. Arcones, H. Feldmeier, G. Martinez-Pinedo, T. Neff, R. Roth, A. Schwenk, Jan. 15 - 21, 2017
- INT Program INT-17-2b Electromagnetic Signatures of r-process Nucleosynthesis in Neutron Star Binary Mergers,
  organized by R. Fernández, D. Kasen, G. Martinez-Pinedo, and B. Metzger
- EMMI Rapid Reaction Task Force, The physics of neutron star mergers at GSI/FAIR, organized by C. Domingo Pardo, T. Galatyuk, G. Martinez Pinedo, B. Metzger, S. Nissanke, L. Rezzolla

B06 impact: outreach

Explosive synthesis: How the heavy elements are formed,
Session “The Origin of Gold, Platinum, and Other Heavy Elements in the Universe”, AAAS Annual Meeting, Washington, DC, USA (15.2.2019)

Der Ursprung der Elemente: Teil 2, Durch neutroneneinfang zu dem schwersten Atomkernen,
Franz Käppeler, Gabriel Martínez-Pinedo, Friedrich-Karl Thielemann, Sterne und Weltraum (Dec. 2018)

Estrellas de neutrones, ondas gravitatorias y kilonovas: la producción de oro en el Universo,
Arquitectura Cosmica VI, Valencia, Spain (29.11.2018)

Supernovae und Neutronsternverschmelzung,
Saturday Morning Physics, TU Darmstadt, Germany (10.11.2018)

Neutronensterne, Gravitationswellen und Kilonovae: Wie im Weltall Gold entsteht,
Was Steckt Dahinter?, TU Darmstadt, Germany (12.06.2018)

Wo entstehen die Elemente im Universum?,
EXOMARS Landing: Special Event at TU Darmstadt, Germany (19.10.2016)

B06 impact: press release

JINA-CEE Newsletter, June 2017

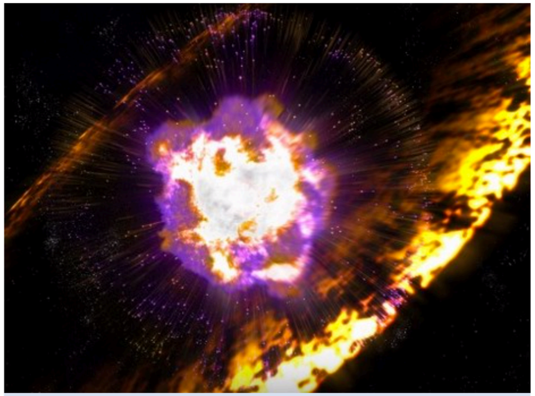
GSI: Muons influence supernova explosion mechanisms

https://www.gsi.de/en/start/news/details/2018/07/11/muons_influence_supernova_explosion_mechanisms.htm

Impact of (α, n) Reactions on Weak r-process in Neutrino-driven Winds

The origin of the heavier elements from germanium to silver is not yet fully understood even though it is currently assumed that nature may produce those elements in multiple nucleosynthesis processes and scenarios. A suitable process to create those elements is the weak rapid neutron capture process (r-process) in neutrino driven winds. These winds emerge from newly born neutron stars in the first seconds after a supernova explosion and happen frequently enough to explain the relatively large number of stars with enhanced germanium to silver abundances (Z = 32-47).

Once the wind has cooled down after a few seconds, charged particle reactions are key in the production of the heavy elements. In particular, reactions where a heavy nucleus captures an alpha particle and emits a neutron (so called (α,n) reactions) play an important role. None of the most relevant (α,n) reactions

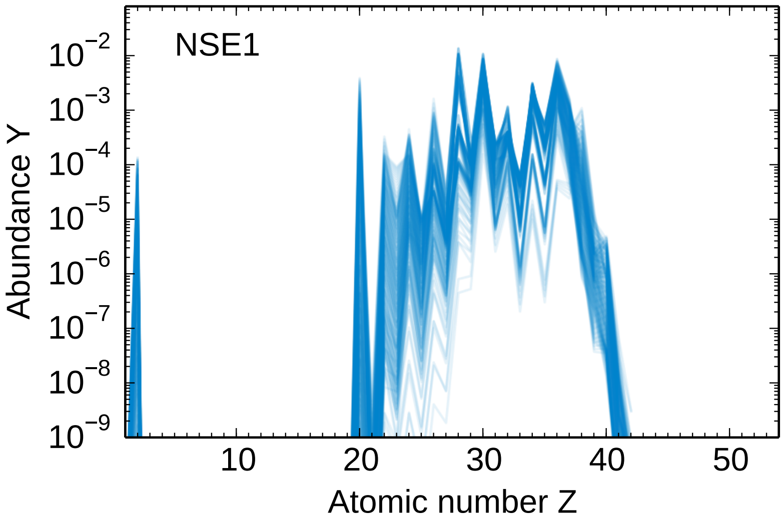


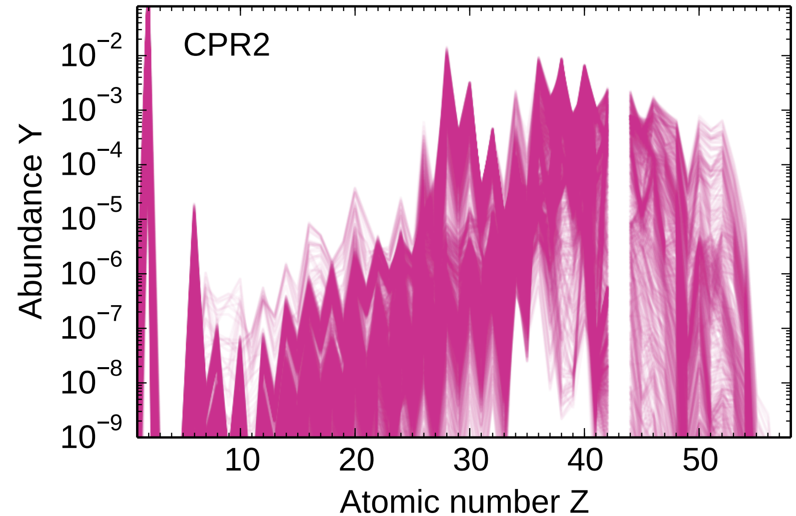
An artist's illustration of a supernova explosion.
Credit: Greg Stewart/SLAC National Accelerator Laboratory

Summary of some projects

- Nucleosynthesis in neutrino-driven ejecta
- Equation of State (EOS) in core-collapse supernovae (CCSN)
- Neutrino nucleosynthesis based on a complete set of neutrino nucleus reactions, time-dependent neutrino spectra and self-consistent 2D supernova explosions
- Demonstration that muon production facilitates supernova explosions

Nucleosynthesis in ν-driven ejecta



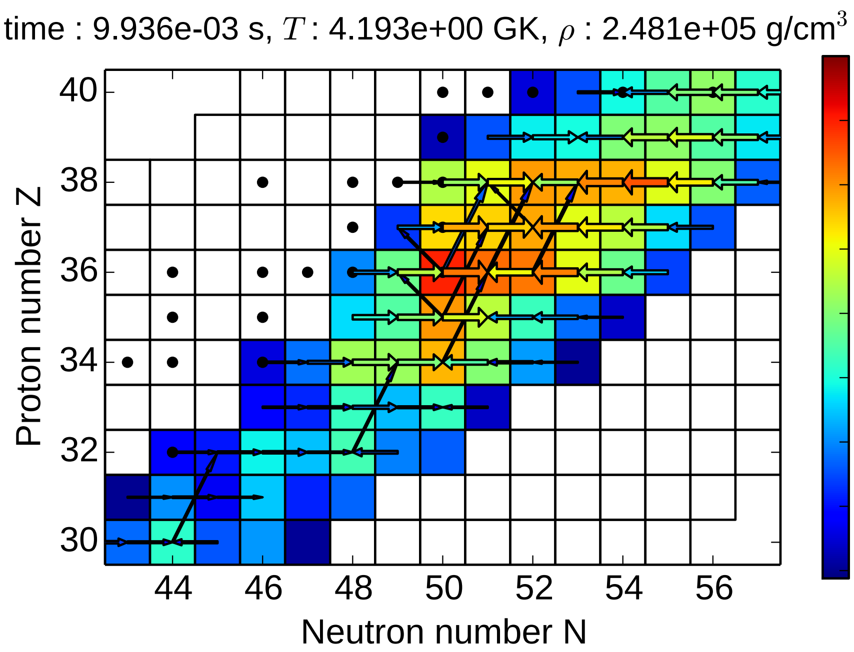


J. Bliss, M. Witt, A. Arcones, F. Montes, and J. Pereira, ApJ. 855 (2018) 135

- 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

Nucleosynthesis in ν-driven ejecta

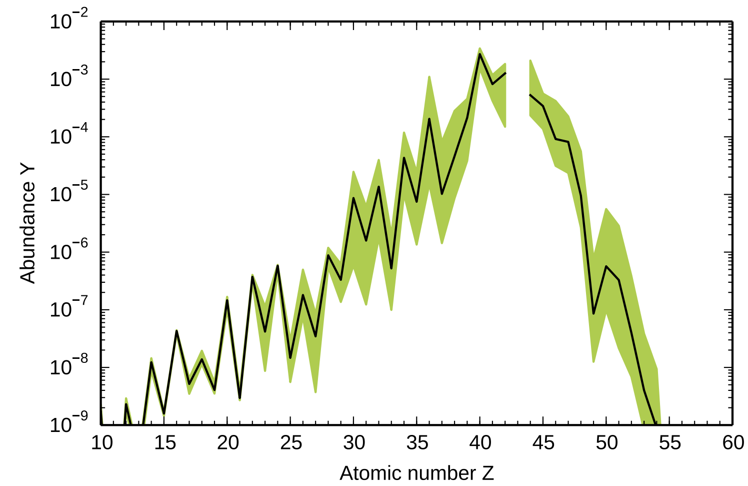
- Important reactions: α-, n-, p-capture reactions, β-decays
- $\tau_{expansion} << \tau_{\beta}$ → (α,n) are key reactions
- α-process (Hoffman & Woosley 1992)
- Absence of relevant experiments
  → theoretical reaction rates based on Hauser-Feshbach model

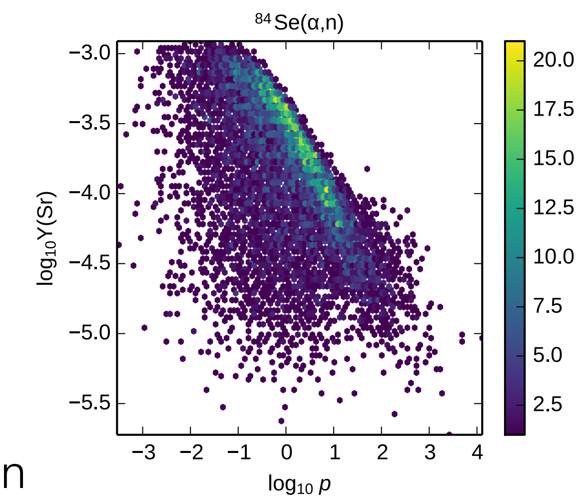


J. Bliss, A. Arcones, F. Montes, and J. Pereira, J. Phys. G. 44 (2017) 054003

Nucleosynthesis in ν-driven ejecta

- 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) done at ReA3
  → coming: ^{85}Br(α,n), ^{87}Kr(α,n)





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

EOS in CCSN

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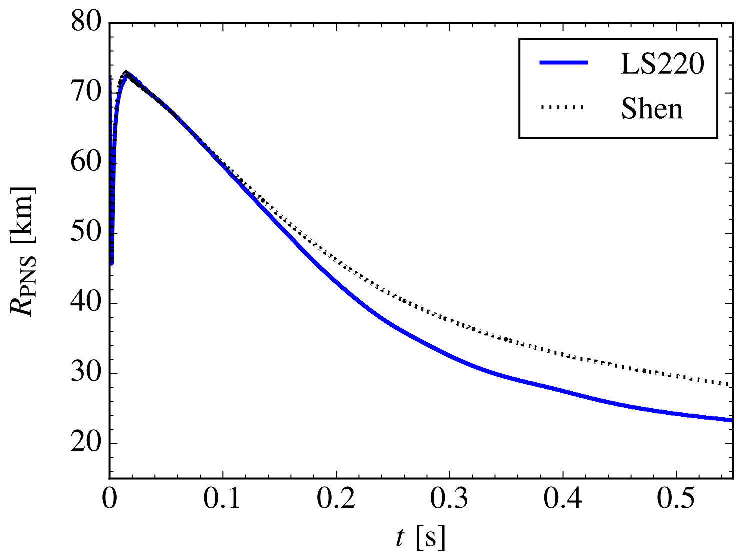
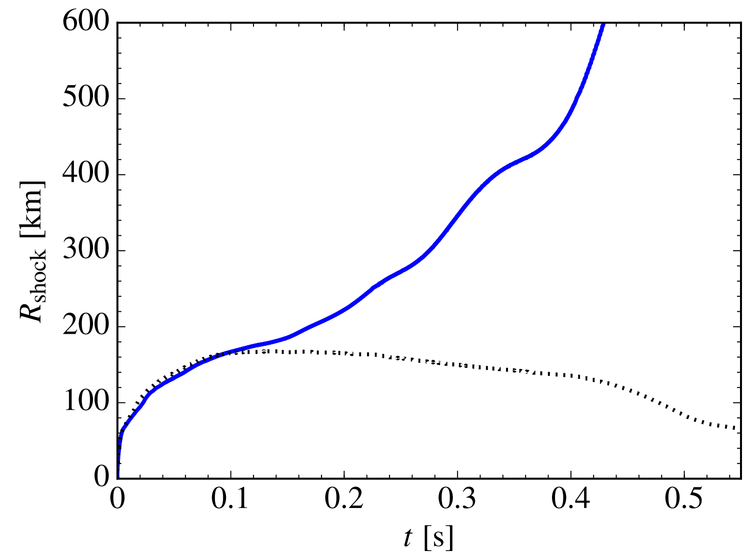
- EOS at high densities and temperature still not fully understood
- Different phenomenological models:
  - Lattimer & Swesty (LS) EOS (1991): Skyrme density functional + liquid-drop model
  - H. Shen *et al.* (Shen) EOS (1998): Relativistic mean-field approach
- Different nuclear matter properties

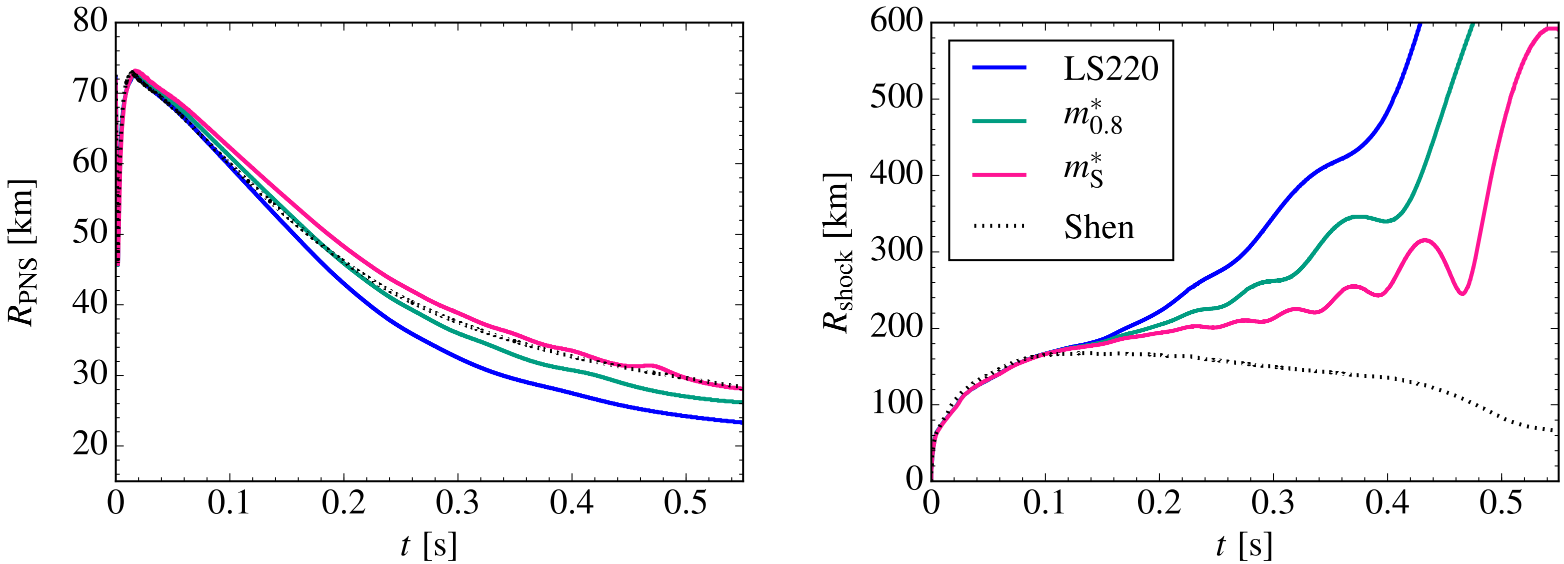
B06 & B01





H.Yassin, S. Schäfer, A. Arcones, A. Schwenk, arXiv:1812.02002

EOS in CCSN



- Simulation: 15 $M_\odot$, M1 ν-transport with enhanced energy deposition
- $m^*_S / m = 0.634$ → theory from LS220, m* value from Shen
- m* / m ↓ → P_c ↑ ($P \sim 1 / m^*$) → ρ_c ↓ → R_{PNS} ↑

B06 & B01

EOS in CCSN

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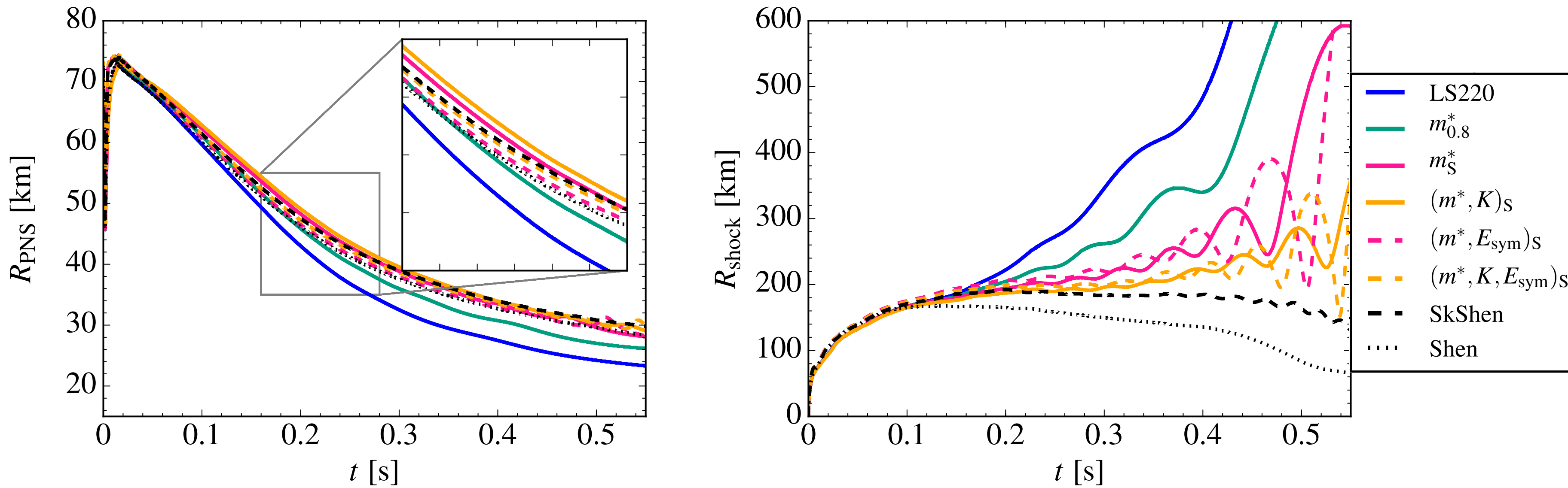


- Simulation: 15 $M_\odot$, M1 ν-transport with enhanced energy deposition
- m^*_S / m = 0.634 → theory from LS220, m* value from Shen
- m* / m ↓ → P_C ↑ (P ~ 1 / m*) → ρ_C ↓ → R_{PNS} ↑
- K ↑ → P_C ↑, E_{sym} impacts PNS interior
- SkShen model does not explode

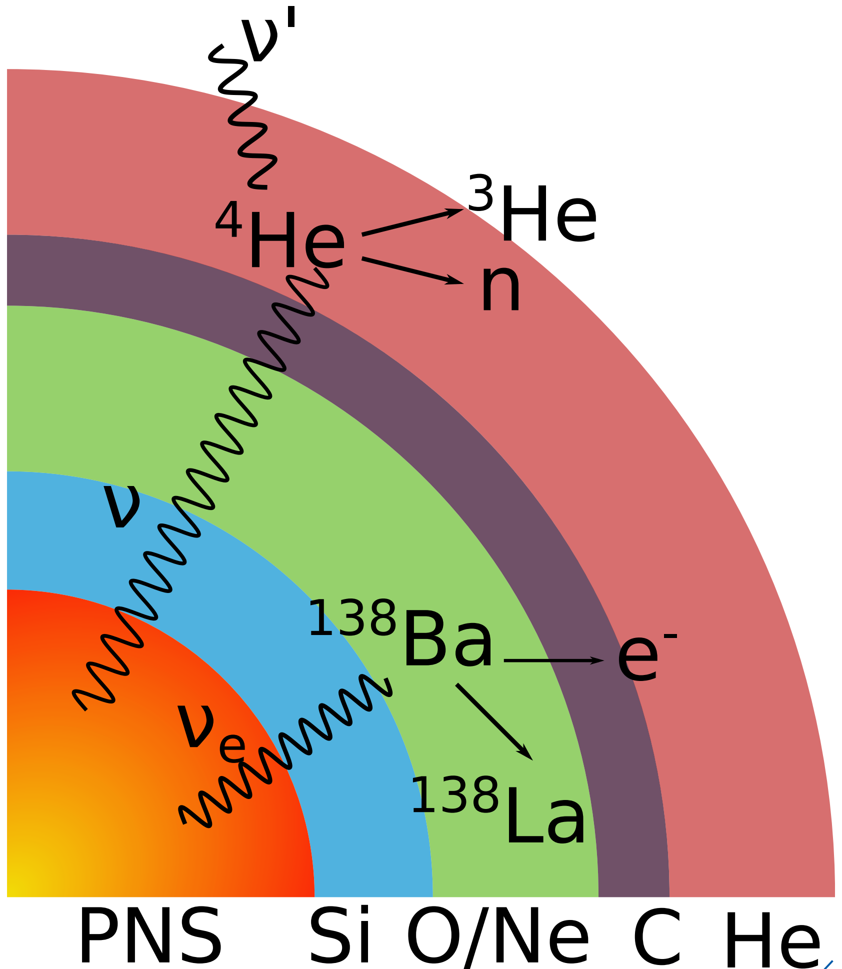
B06 & B01

H.Yassin, S. Schäfer, A. Arcones, A. Schwenk, arXiv:1812.02002

SFB 1245

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
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_{\mu,\tau}} \rangle$
- Inverse β-decay
- Particle evaporation
- Capture of spallation products



New cross sections

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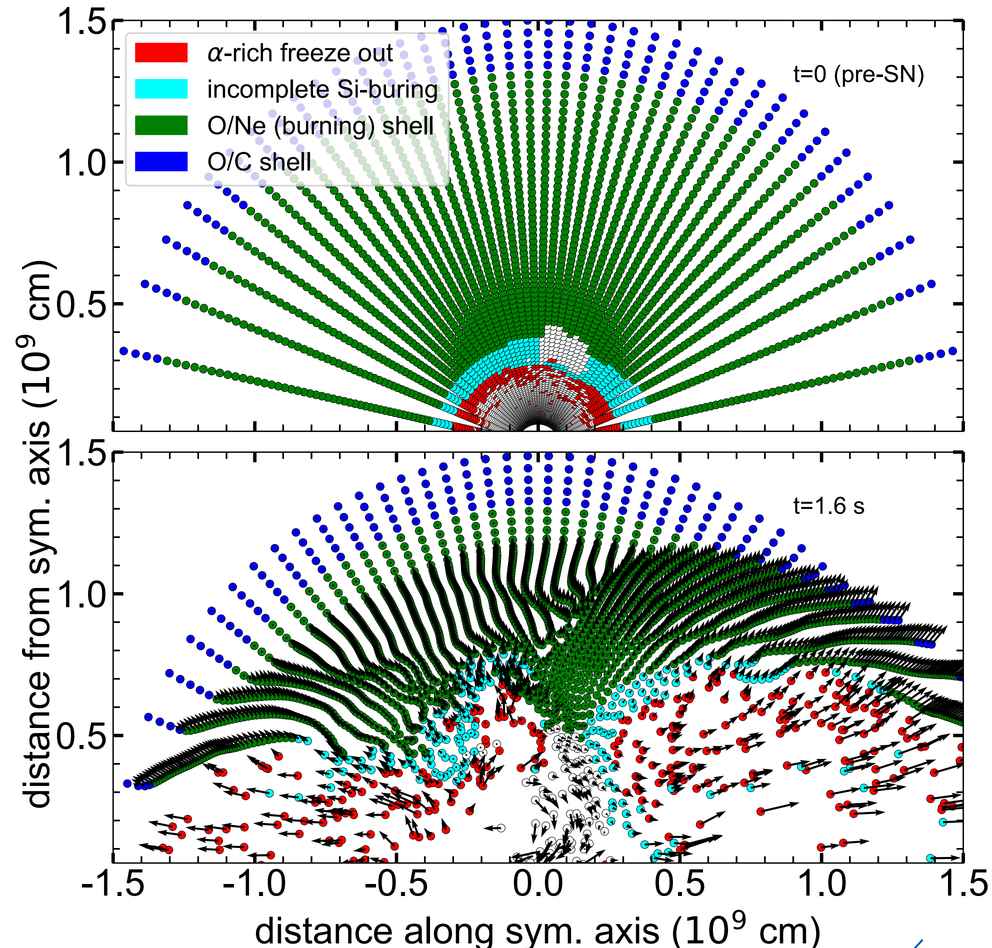
- Based on RPA from dripline to dripline up to Z=84
- Up to 5 particle emission channels *Kolbe et al. (2002)*
- Special cases:
  - $^{22}Ne + \nu_e \rightarrow {}^{22}Na$ *(mirror nucleus data)*
  - $^{26}Mg + \nu_e \rightarrow {}^{26}Al$ *(charge exchange data)*
  - $^{36}Ar + \bar{\nu}_e \rightarrow {}^{36}Cl$ *(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 $M_\odot$) arXiv:1805.10231

Self-consistent simulations

- 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)
- Tracer data until 1.6 seconds
- Production of light elements in the α-rich freeze out

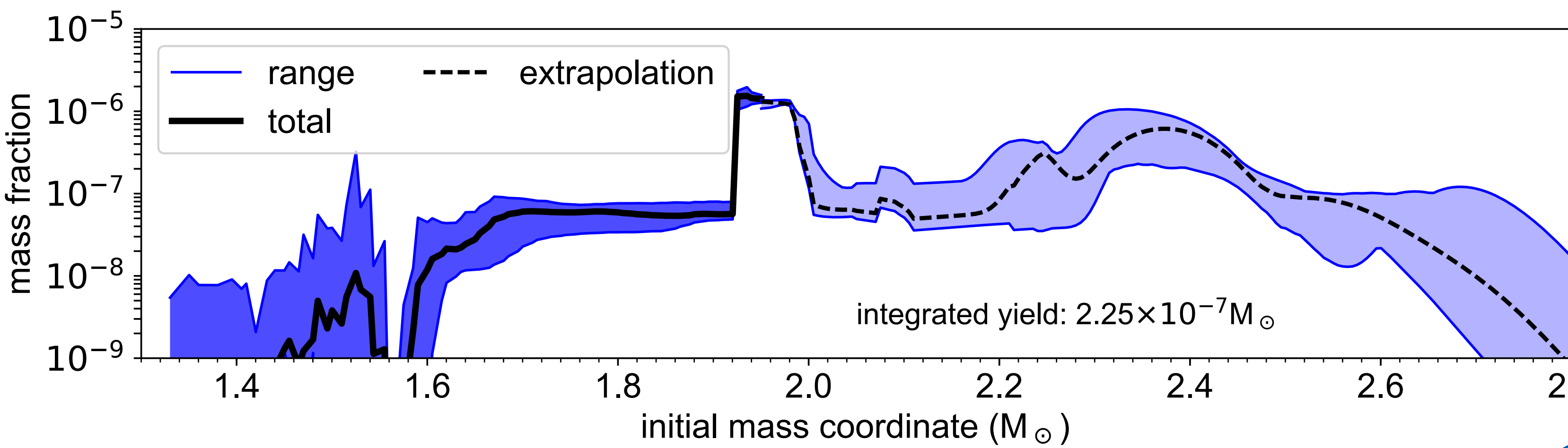


The ν process in multi-D

- 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

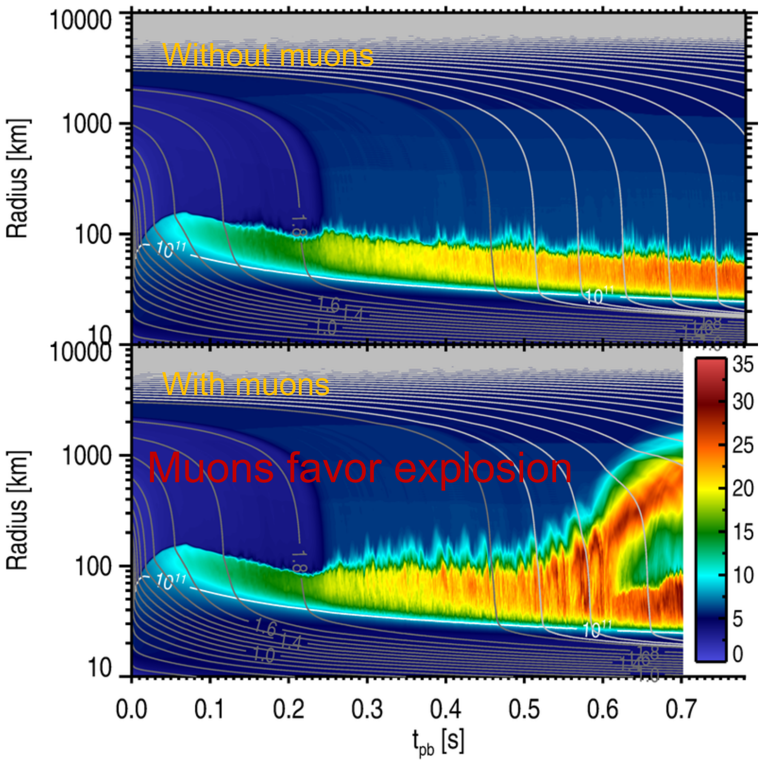
Nucleus	Production factor
^{7}Li	0.28
^{11}B	0.98
^{15}N	0.11
^{19}F	0.29
^{138}La	1.30
$^{180}Ta^{m}$	1.96

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



Muons facilitate supernova explosions

- Core-collapse supernova models require accurate physics in the neutrino and nuclear sectors coupled with multidimensional simulations
- Muon production has so far been neglected in supernova simulations
- 2D simulations show that muon production:
  - Softens the neutron star equation of state
  - Triggers faster contraction of the neutron star
  - Leads to higher luminosities and average energies of emitted neutrinos
- All these effects facilitate explosions by the neutrino-driven mechanism



R. Bollig, H.-T. Janka, A. Lohs, G. Martínez-Pinedo, C. J. Horowitz, and T. Melson, PRL **119**, 242702 (2017)

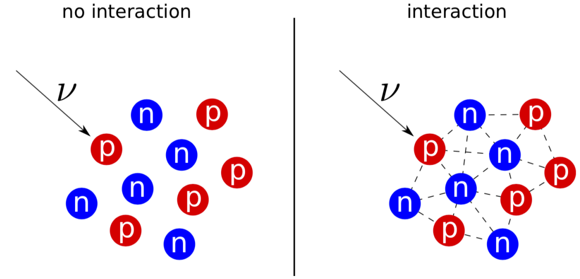
Future

Multi-dimensional simulations and nucleosynthesis calculations:

- Impact of EOS and neutrino-matter interactions on neutron star, shock and nucleosynthesis evolution
- Complete nucleosynthesis study including astro and nuclear uncertainties
- Impact of neutrino processes producing muons on dynamics and nucleosynthesis

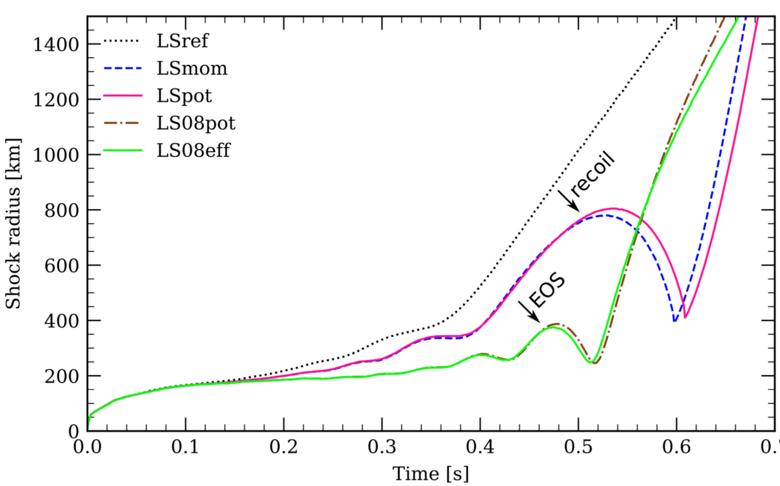
EOS and neutrinos in supernovae

- Continue project on EOS in core-collapse supernovae
- Include consistently calculated neutrino interactions

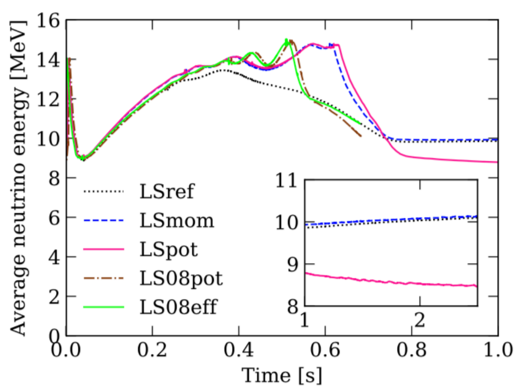


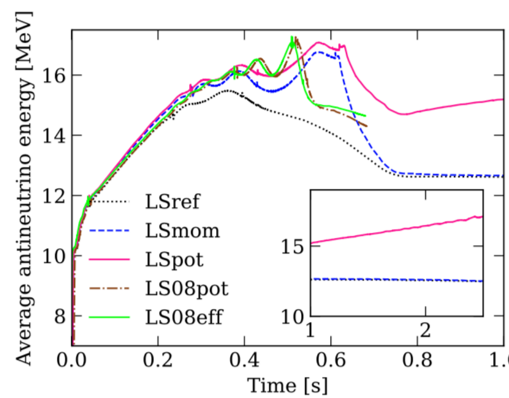
$$E_i = \underbrace{m_i + \frac{p_i^2}{2m_i}}_{\text{free particle}} + \underbrace{\Sigma_i(p_i, E_i)}_{\text{interaction}} \approx m_i + \frac{p_i^2}{2\mathbf{m_i^*}} - \mathbf{U_i}$$

B06 & B01



Jonas Keller



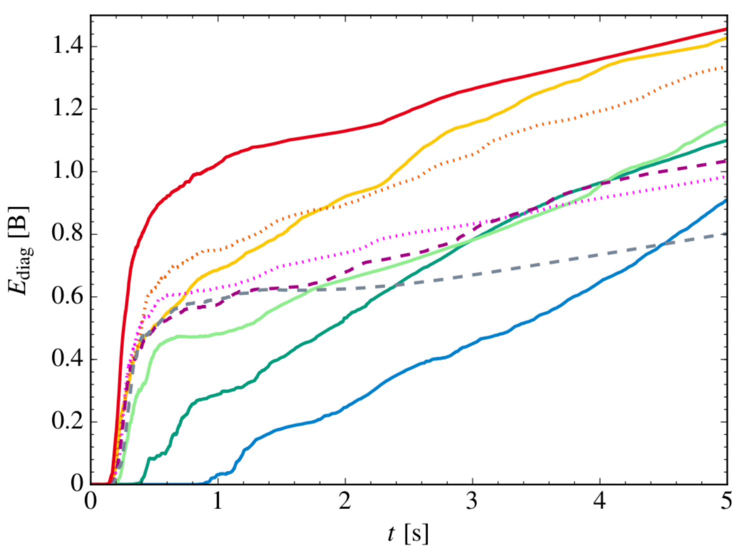


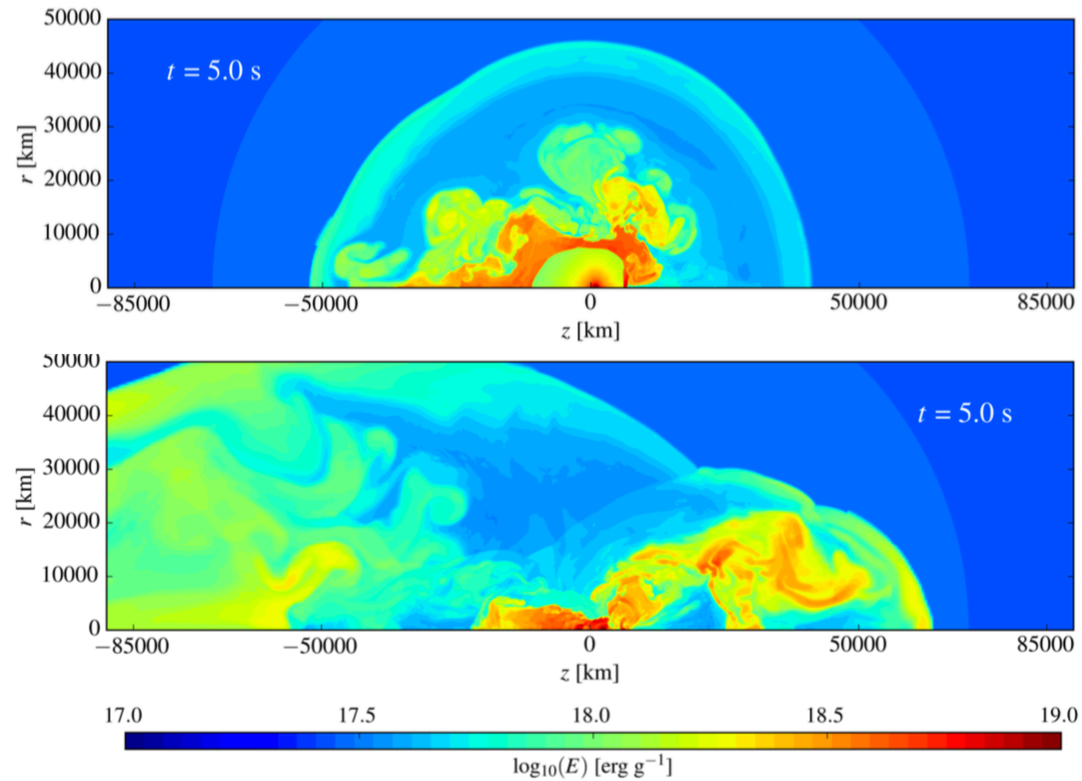
Nucleosynthesis from simulations

2D simulations for 15M progenitor, different explosion energy and rotation

Plan:

- Calculate nucleosynthesis (use better neutrino transport to benchmark Ye)
- Extend simulations to various progenitors
- Astro uncertainties: microphysics in simulations, explosions, rotation
- Nuclear uncertainties





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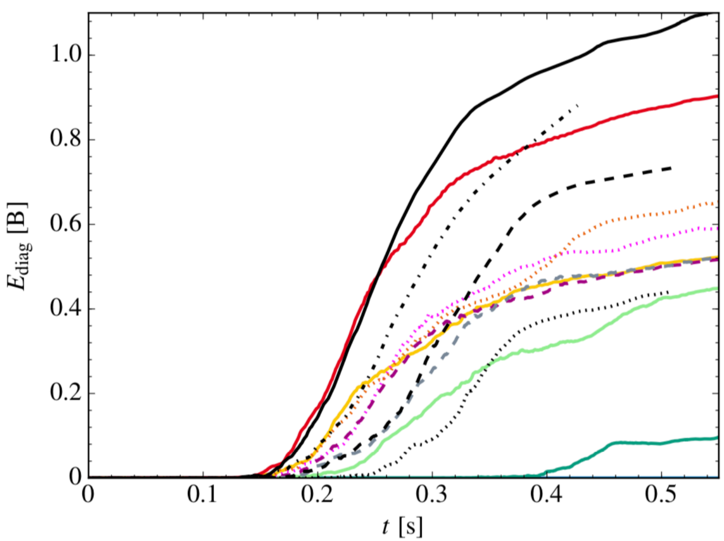
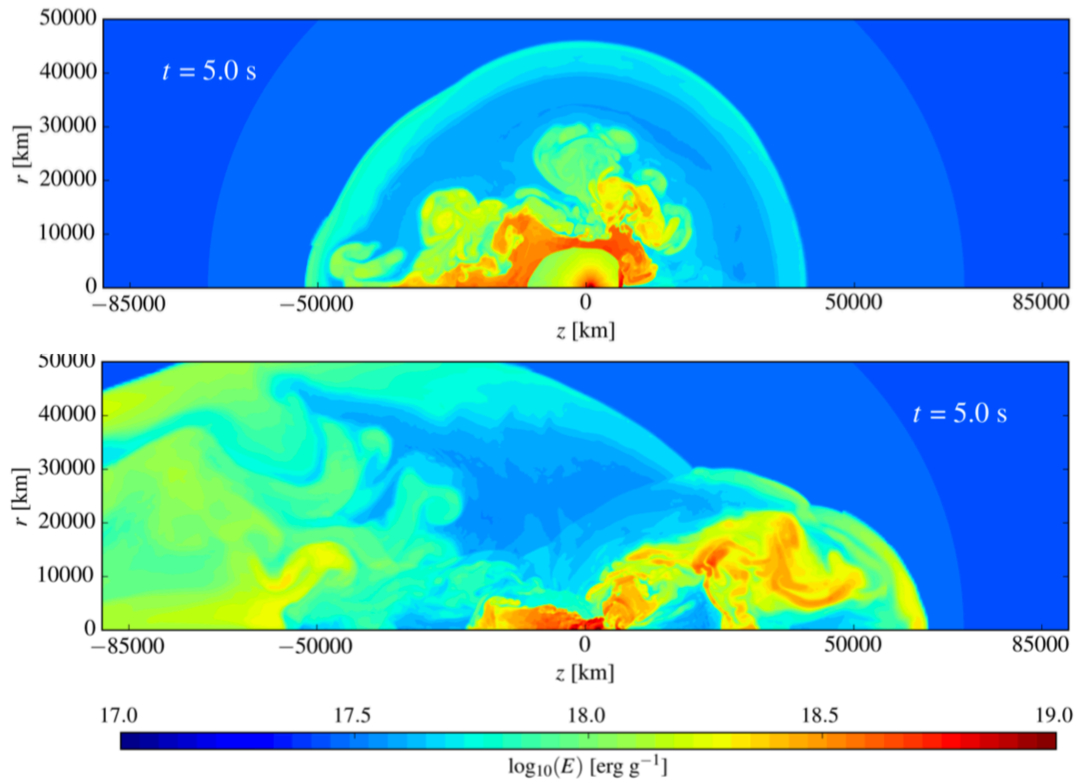
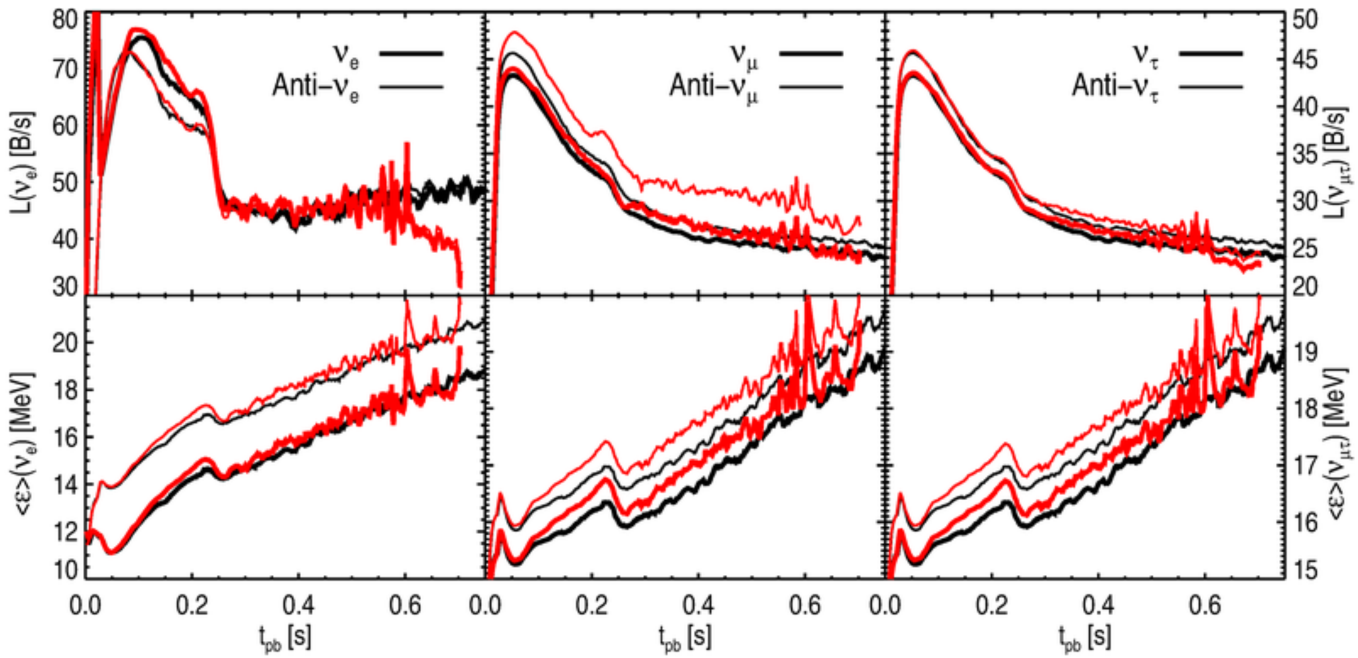




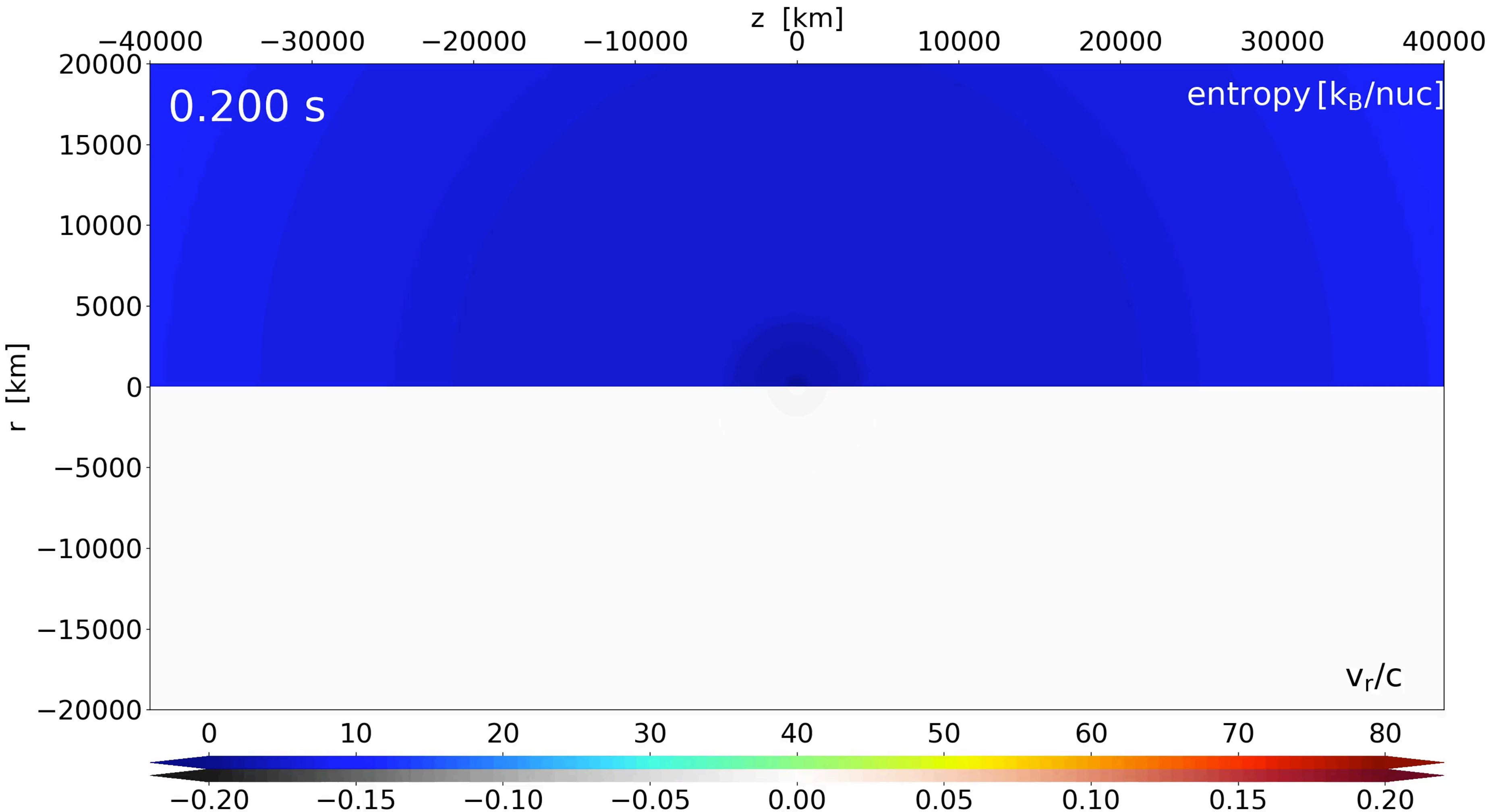
Future: Muon reactions and supernova nucleosynthesis

Goal: Ascertain the role of charged current processes producing muons on proto-neutron star cooling and nucleosynthesis:

- Consistent description of neutrino opacities including weak-magnetism, pseudo scalar corrections and RPA correlations
- Long term proto-neutron star simulations
- Neutrino wind and nu-process nucleosynthesis



With muons
Without muons



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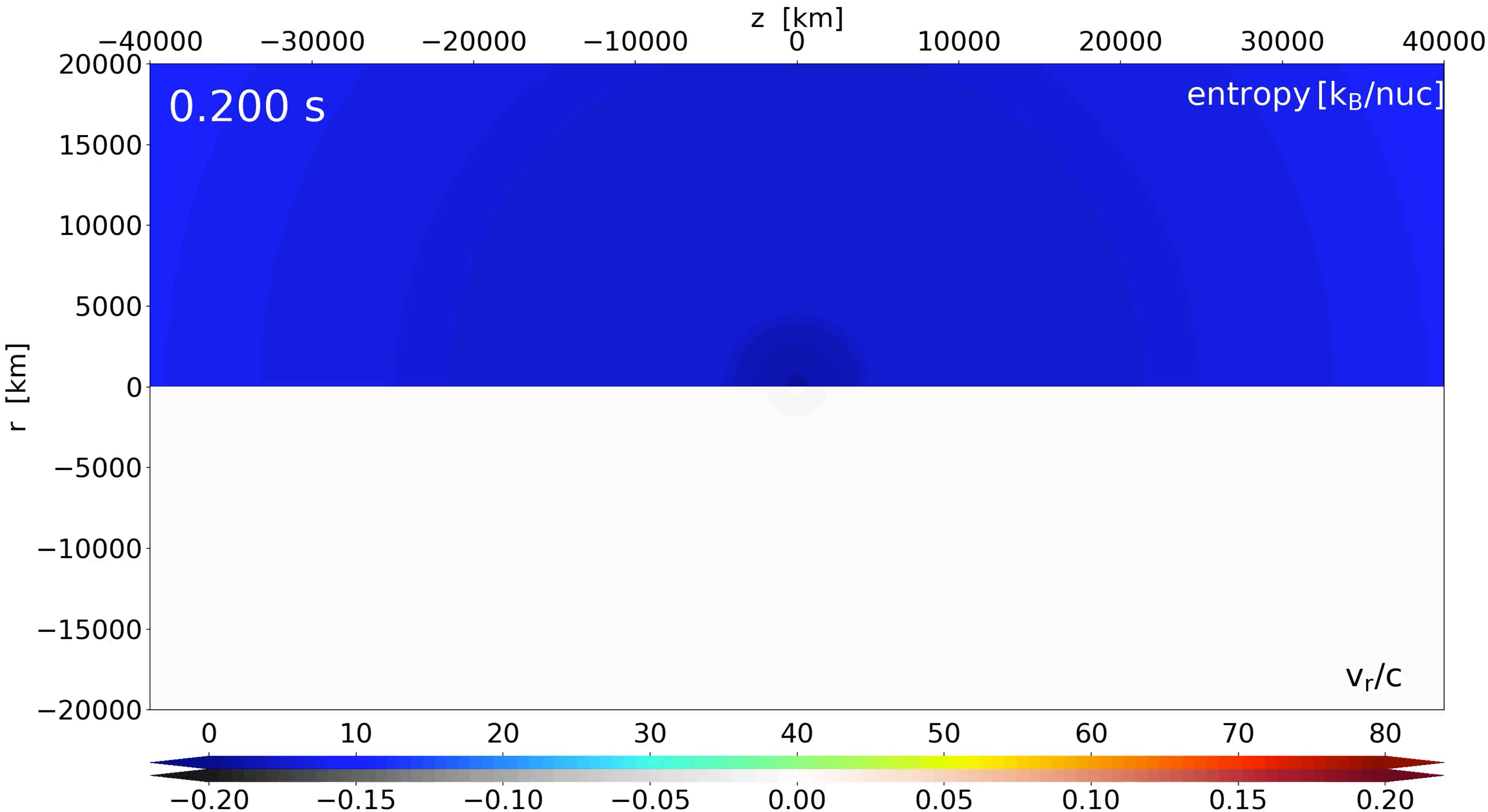

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