Neutrino-induced production of radioisotopes
in Core-Collapse Supernovae

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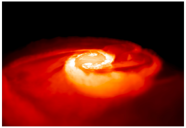
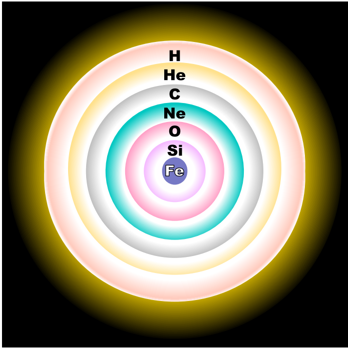


Outline

1. Introduction
   - The ν-process
2. Results with updated physics
   - Production of ^{7}Li,^{11}B,^{19}F,^{138}La,^{180}Ta
   - Radioactive nuclei relevant for γ-ray astronomy
   - Radioisotopes in meteorites
3. Summary and Outlook

Core-Collapse Supernovae

- Collapse-Collapse after hydrostatic burning turns into an explosion
- Hydrodynamic shock triggers explosive nucleosynthesis and ejection of material
- Cooling core emitts neutrinos
- Neutrinos influence the nucleosynthesis in outer layers of SNe



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- Hydrodynamic shock triggers explosive nucleosynthesis and ejection of material
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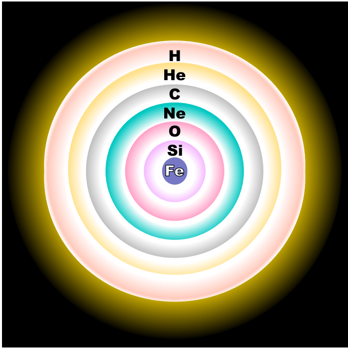
- Neutrinos influence the nucleosynthesis in outer layers of SNe
- **Impact on the composition of the ejecta**
- **Production of rare isotopes**



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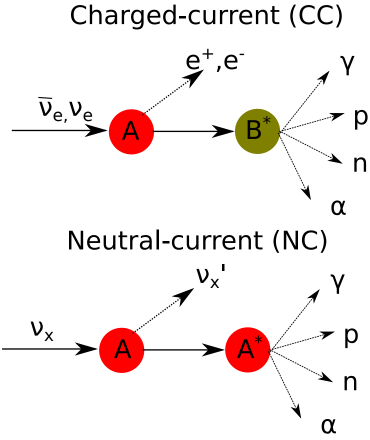
Neutrino nucleosynthesis

- Emission of 10^{58} Neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 8 - 13$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_{\mu,\tau}} \rangle$



Relevant processes

1. Inverse β-decay
2. Particle emission
3. Capture of spallation products

Neutrino nucleosynthesis

- The supernova shock leads to high temperatures and densities
- Photodissociation and particle capture reactions dominate explosive nucleosynthesis
- ν-process affects regions with sufficient neutrino fluxes and moderate post-shock temperatures
- O/Ne-,C/O- and lower He-layers

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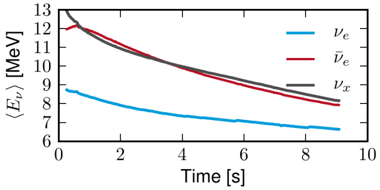
- ν-process affects regions with sufficient neutrino fluxes and moderate post-shock temperatures
- O/Ne-,C/O- and lower He-layers
- Main examples for the ν process:

  ^{7}**Li** and ^{11}**B** via ^{4}He(ν_x,ν'_x p/n) and ^{12}C(ν_x,ν'_x p) ...

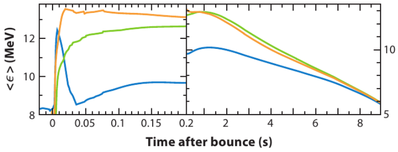
  ^{19}**F** via ^{20}Ne(ν_x,ν'_x p/n)

  ^{138}**La** and ^{180}**Ta** via ^{138}Ba(ν_e,e$^-$) and ^{180}Hf(ν_e,e$^-$)

Neutrino Spectra from state-of-the art SN simulations



Fischer et al. (2014)



Janka et al. (2012)

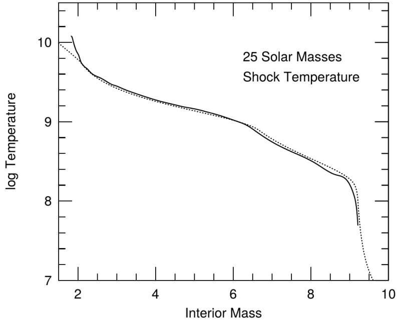
- Detailed descriptions of neutrino transport are included
- More channels for neutrino-matter interactions
- Ineslastic channels reduce the average energies

Updated physics input

- Simulations including detailed neutrino transport give new estimates for typical neutrino energies:
  $\langle E_\nu \rangle$=8-13 MeV compared to 13-25 MeV
- Neutrino-nucleus cross-sections have been calculated for almost the whole nuclear chart (L. Huther 2014, PhD. Thesis)
- Parametric description of thermodynamic and neutrino-flux quantities (Woosley et al. 1990)

Parametrization of the Supernova explosion

- Parametrization of temperature and density evolution during the explosion (Woosley et al. 1990)
- $T_{\text{Peak}} = 2.4 \times 10^9 \mathrm{K} \times \left(\frac{E_{\text{expl}}}{10^{51}\text{erg}}\right)^{1/4} \times \left(\frac{R}{10^9 \mathrm{cm}}\right)^{-3/4}$



Woosley et al. 2002

Neutrino flux

- Exponentially decreasing neutrino luminosity
- Thermal Fermi-Dirac spectrum

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Evaluation of CCSNe nucleosynthesis calculations

- The solar abundances provide oberservational infomation for nucleosynthesis results to compare with

Production factor

- $P_A = \frac{X_A}{X_A^{\odot}}$
- Assuming that CCSNe are the main source of solar ^{16}O :
- $P_{A,\text{normalized}} = \frac{P_A}{P_{^{16}\text{O}}}$

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- $P_{A,\text{normalized}} \sim 1$ indicates CCSNe as possible production site
- $P_{A,\text{normalized}} \ll 1$ hints another production site or mechanism

Production factors normalized to ^{16}O

- 25 $M_\odot$ progenitor with solar metallicity (Heger et al. 2002)

Nucleus	no ν	present work	Heger et al. (2005)
^{7}Li	10^{-4}	0.11	-
^{11}B	0.003	0.8	1.18
^{19}F	0.06	0.24	0.32
^{138}La	0.03	0.63	0.90
^{180}Ta	0.14	1.80	4.24

- present work: $\langle E_{\nu_e} \rangle = 8.8$ MeV, $\langle E_{\bar{\nu}_e,\nu_x} \rangle = 12.6$ MeV
- Heger et al.: $\langle E_{\nu_e,\bar{\nu}_e} \rangle = 12.6$ MeV, $\langle E_{\nu_x} \rangle = 18.9$ MeV

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γ-ray astronomy

Isotope	Decaytime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	1157, 78, 68
^{26}Al	1.04 10^6y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	2.0 10^6y	$^{60}Fe \rightarrow {}^{60}Co^*$	1173, 1332

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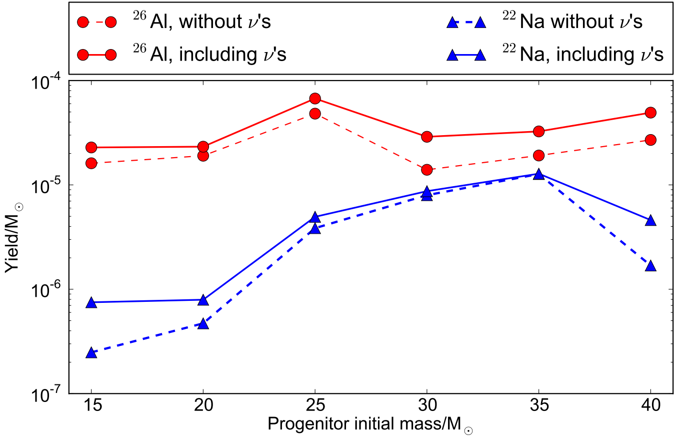
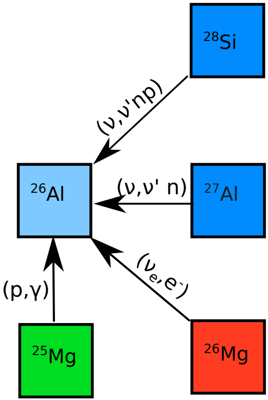
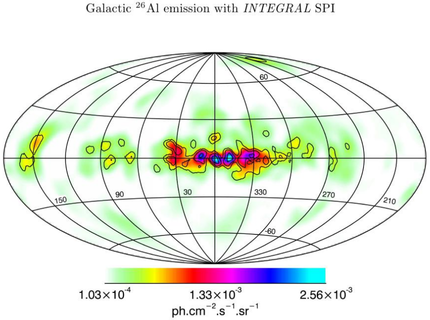
^{22}Na and ^{26}Al for a set of progenitor models



- ^{26}Al yields are modified by factors beween 1.4 and 2.2
- ^{22}Na increased by factors up to 2.9

Production channels for ^{26} Al

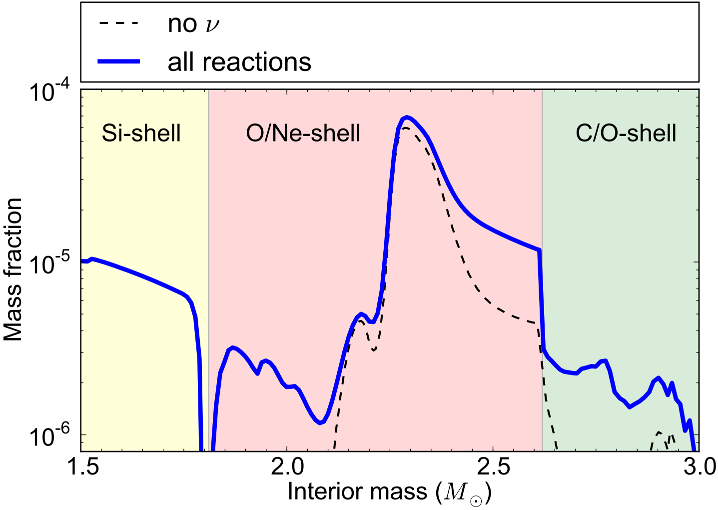




Bouchet et al. (2015)

- Different mechanisms:
  - enhancement of p-captures
  - charged-current channel
  - neutral-current channels

Production of ^{26}Al for a 15 $M_\odot$ progenitor



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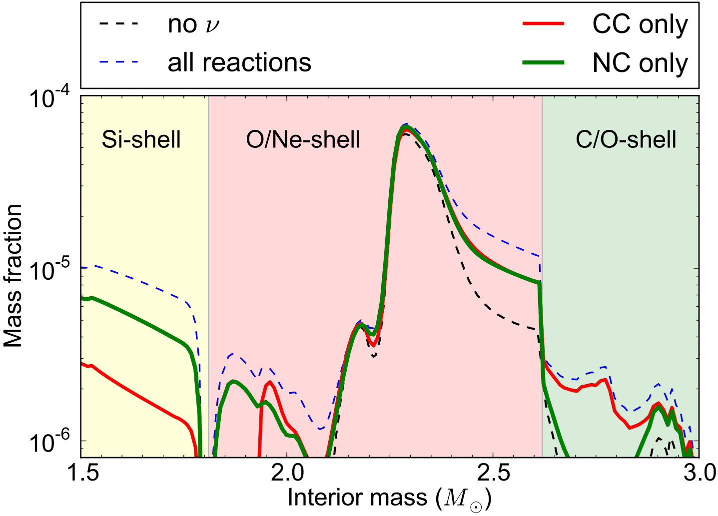

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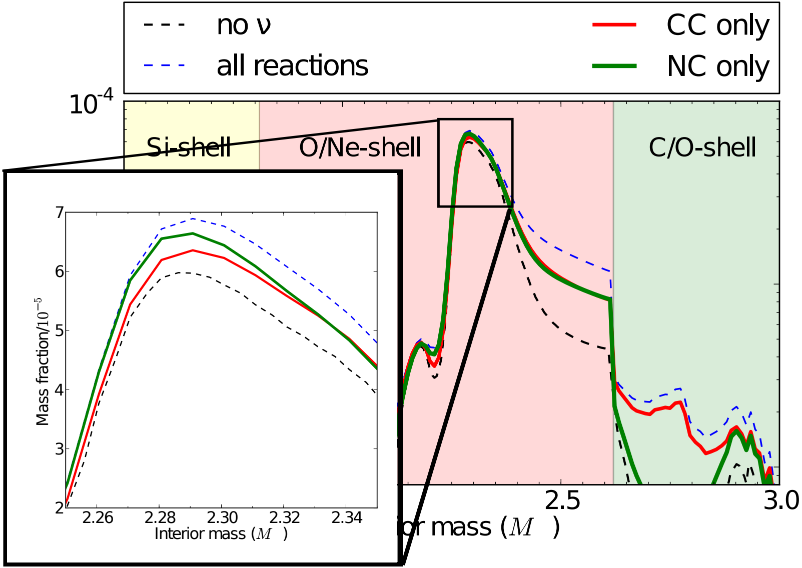
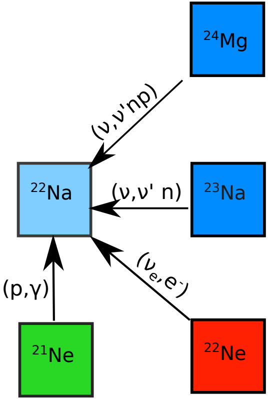
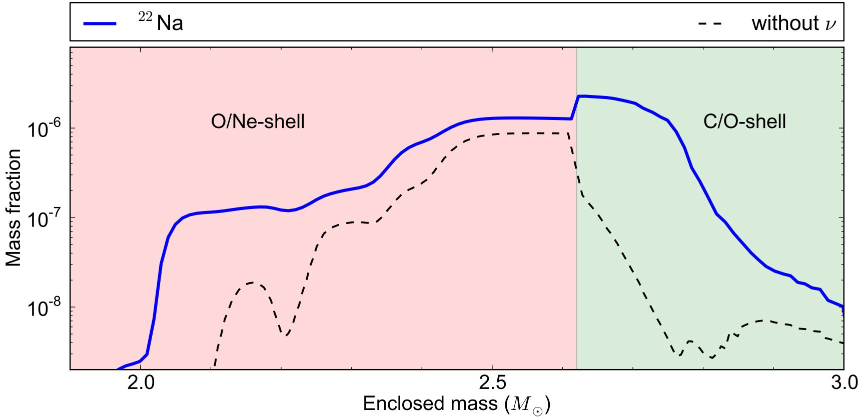


Production of ^{22}Na



- Different mechanisms:
  - indirect enhancement of p-captures
  - direct charged-current channel
  - direct neutral-current channels
- Balance of the different channels is sensitive to stellar structure and neutrino spectra

Production of ^{22}Na for 15 $M_\odot$ progenitor



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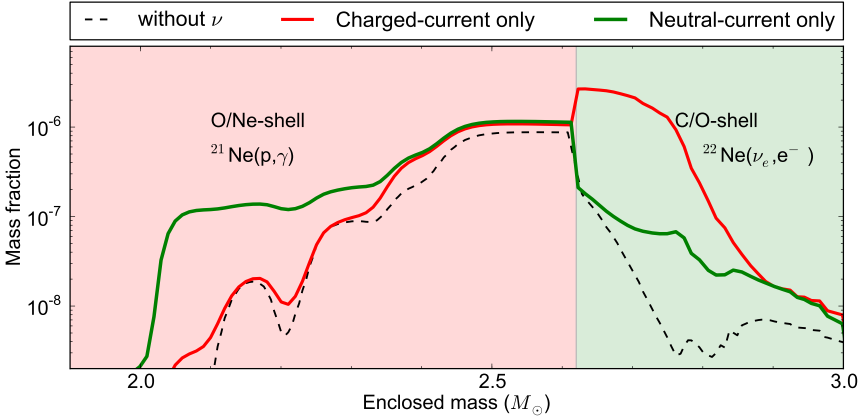
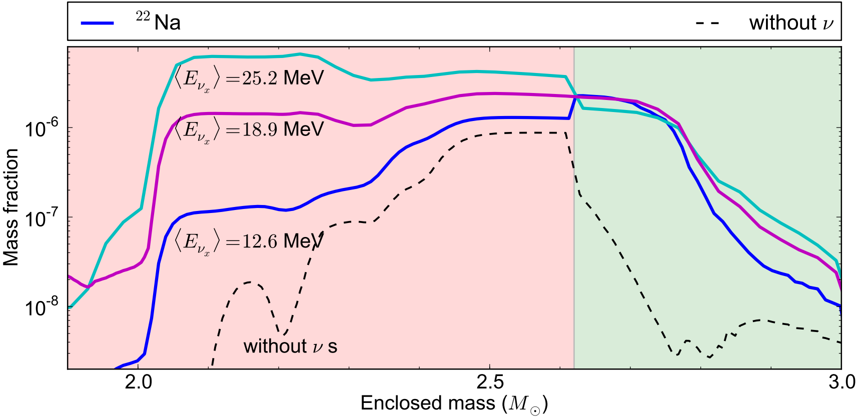


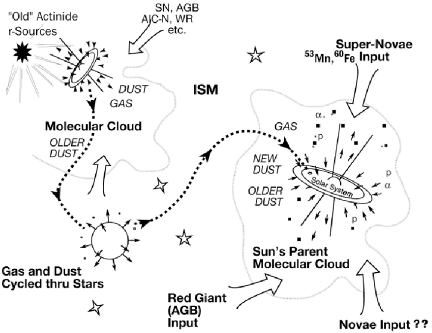
Production of ^{22}Na for 15 $M_\odot$ progenitor

- **Updated ν-spectra increase the relative importance of CC reactions**



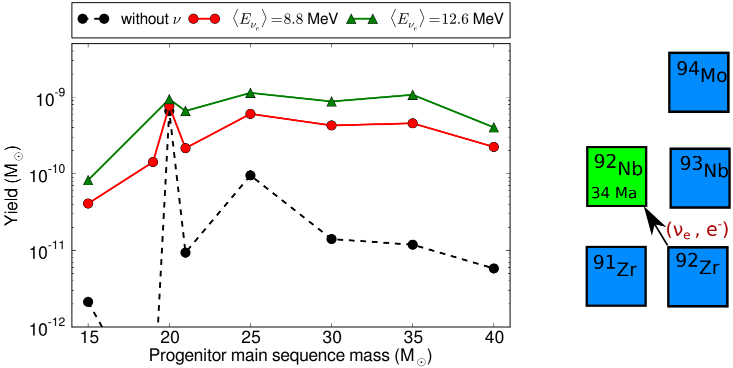
Isotopic ratios from meteorites

- Meteorites contain material that represents the composition of the early solar system (ESS) and the pre-solar molecular cloud
- A combination of nucleosynthesis events is necessary to reproduce the measured composition
- Isotopic ratios can be determined with high precision



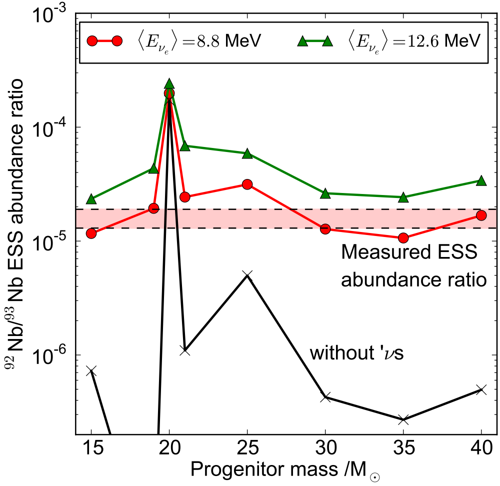
Wasserburg et al (2006)

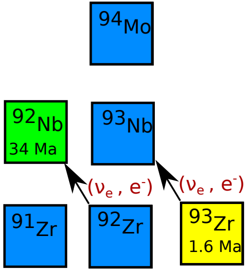
Production of ^{92}Nb



^{92}Nb/^{93}Nb ratio in the early solar system (ESS)

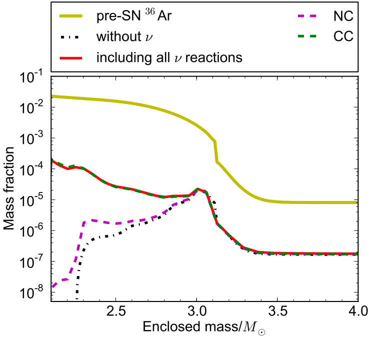
- Assuming uniform production over 10 Gyr

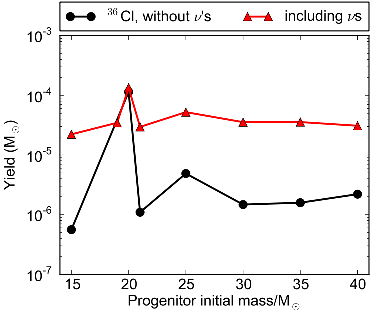




Short-lived radionuclides from a recent event

- Short-lived radioactive isotopes (^{10}Be, ^{26}Al, ^{36}Cl, ^{41}Ca, ^{53}Mn, ^{60}Fe) in the ESS could explained by a recent low-mass supernova

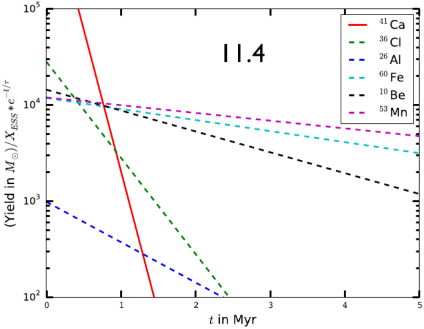




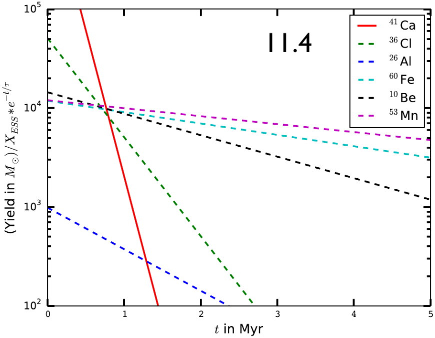
- In the Si-shell, the production of ^{36}Cl is increased by ^{36}Ar($\bar{\nu}_e$,e^+)

Short-lived radioactive isotopes

- A single event needs to reproduce the abundances of all relevant isotopes at the same time



- Haxton et al. ν cross-sections (1990)



- Huther et al. ν cross-sections (2014)

courtesy of P. Banerjee

- Summary
  - ν nucleosynthesis affects the abundances of radioactive nuclei
  - Important for the comparison of high-precision observations (meteorites and γ-ray astronomy) with predicitons from simulations
  - Uncertainties in neutrino spectra add to the uncertainties of nucleosynthesis calculations, that can be comparable to the uncertainties due to nuclear physics.

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- Outlook
  - Fallback and innermost ejecta
  - Non-thermal and time-dependent ν-spectra
  - Effects of neutrino oscillations

Thank you, for your attention