Neutrino Nucleosynthesis

in the outer layers of supernovae

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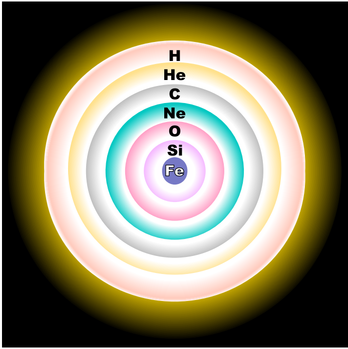
Outline

1. Introduction
   - Neutrino nucleosynthesis
   - Supernova model
2. Results
   - Production of ^{7}Li,^{11}B,^{19}F,^{138}La,^{180}Ta
   - Radioactive nuclei
3. Summary and Outlook

Neutrinos and Supernovae

- Massive stars can produce elements up to Fe in hydrostatic burning phases
- The stellar core collapses when the nuclear fuel is depleted
- Collapse stops when nuclear densities are reached
- Hydrodynamic shock triggers explosive nucleosynthesis and ejects the outer layers
- Cooling core emitts neutrinos
- Neutrinos can influence the nucleosynthesis in outer layers of SNe



(Not to scale)
from Wikimedia commons

Neutrino nucleosynthesis

- Emission of 10^{59} Neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 7 - 13$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle$
- Charged-current and neutral-current interactions
- Particle evaporation
- Capture of spallation products

Charged current (CC)

$$\begin{aligned} {}^{A}_{Z}N + \nu_e &\rightarrow {}^{A}_{Z+1}N^* + e^- \\ {}^{A}_{Z}N + \bar{\nu}_e &\rightarrow {}^{A}_{Z-1}N^* + e^+ \end{aligned}$$

Neutral current (NC)

$$\begin{aligned} {}^{A}_{Z}N + \nu_x &\rightarrow {}^{A}_{Z}N^* + \nu_x' \\ {}^{A}_{Z}N^* &\rightarrow {}^{A-1}_{Z}N + n \\ {}^{A}_{Z}N^* &\rightarrow {}^{A-1}_{Z-1}N + p \\ {}^{A}_{Z}N^* &\rightarrow {}^{A-4}_{Z-2}N + \alpha \\ {}^{A}_{Z}N^* &\rightarrow \ldots \end{aligned}$$

Neutrino nucleosynthesis

- Heating by the supernova shock triggers photodissociation and subsequent particle capture reactions
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^{19}**F** via $^{20}\mathrm{Ne}(\nu_x,\nu_x'\ \mathrm{p/n})$

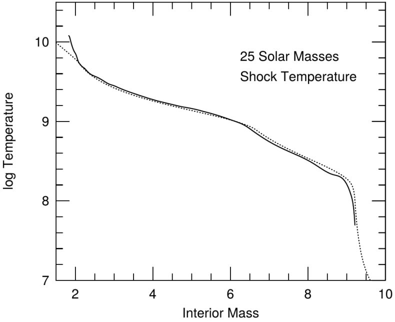
^{138}**La** and ^{180}**Ta** via $^{138}\mathrm{Ba}(\nu_e,\mathrm{e}^-)$ and $^{180}\mathrm{Hf}(\nu_e,\mathrm{e}^-)$

Updated physics input

- Neutrino-nucleus cross-sections have been calculated for almost the whole nuclear chart (L. Huther 2014, PhD. Thesis)
- Simulations including detailed neutrino transport give new estimates for typical neutrino energies:
  $\langle E_\nu \rangle$=8-13 MeV compared to 13-25 MeV
- Results from various stellar evolution calculations are available (e.g. Heger et al. 2002, Limongi et al. 2006)

Supernova model

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



Woosley et al. 2002

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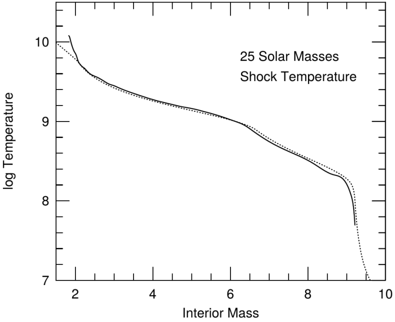

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Neutrino flux

- Exponentially decreasing neutrino luminosity
- Thermal Fermi-Dirac spectrum

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Production factors normalized to ^{16}O

- 25 $M_\odot$ progenitor with solar metallicity

Nucleus	no ν	present work	Heger et al. (2005)
^{7}Li	0.0004	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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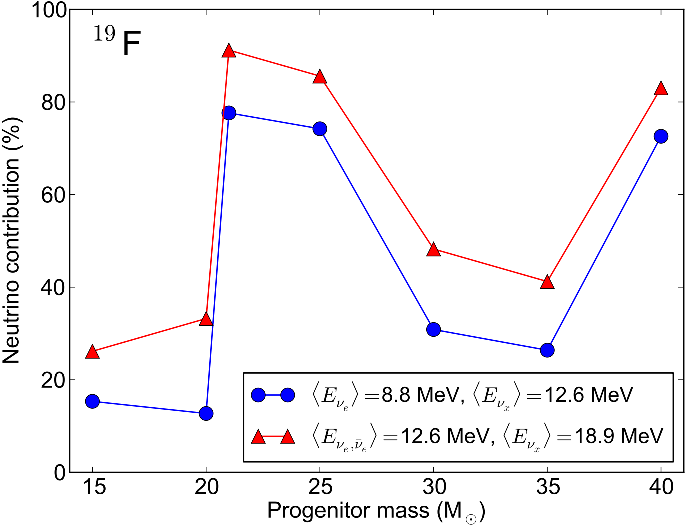
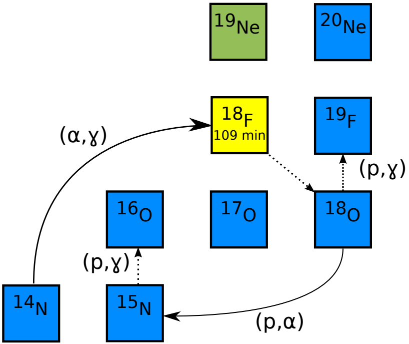
Importance of neutrinos for the production of ^{19}F

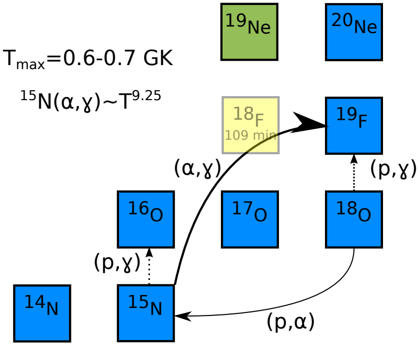


Production of ^{19}F



- Without neutrinos:
  - H- and He-shell burning create regions enriched in ^{18}O and ^{15}N

Production of ^{19}F



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  - High shock temperatures enhance ^{15}N(α,γ) and ^{18}O(p,γ)

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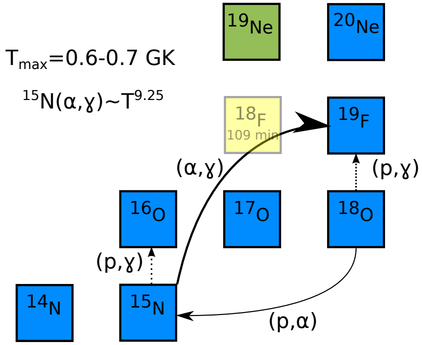

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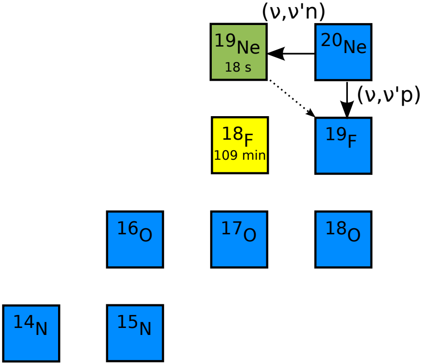

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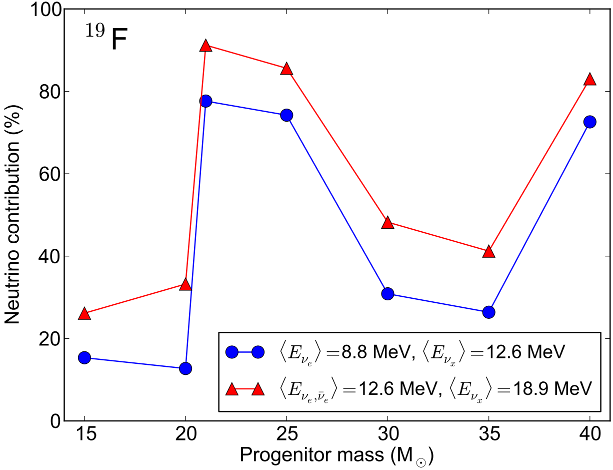
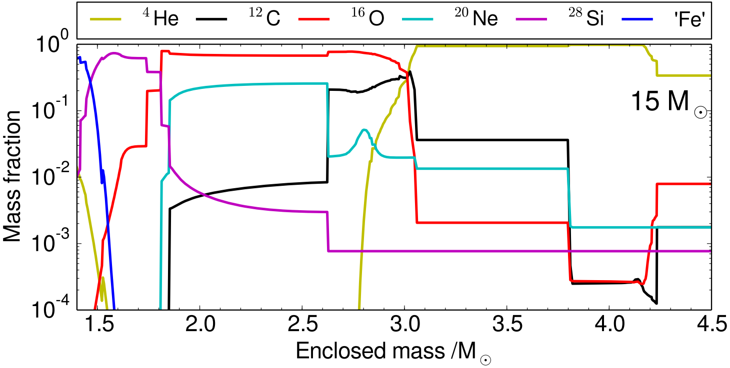
  - High shock temperatures enhance ^{15}N(α,γ) and ^{18}O(p,γ)
  - Very sensitive to temperature
- Neutral-current neutrino reactions on ^{20}Ne

Production factor of ^{19}F normalized to ^{16}O



Stellar composition



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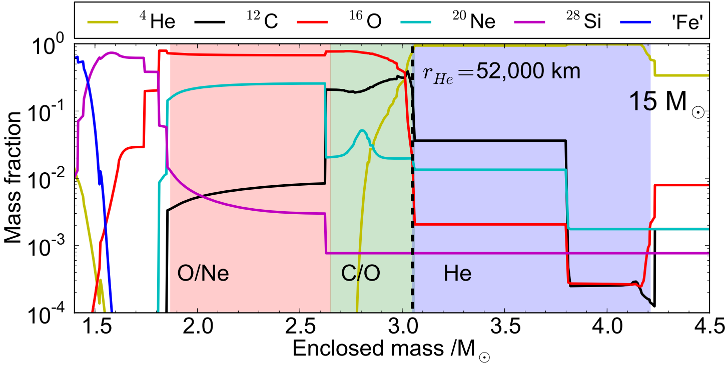

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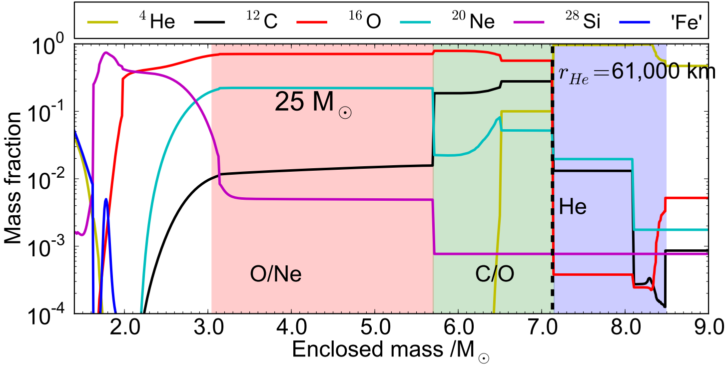

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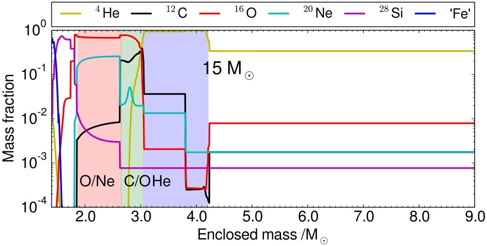
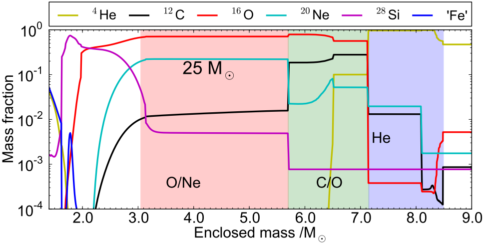
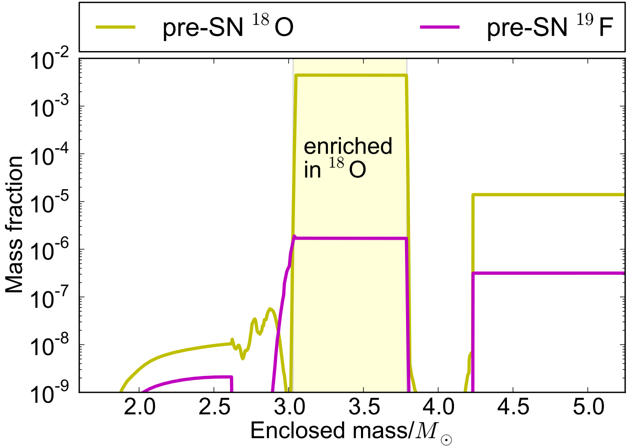




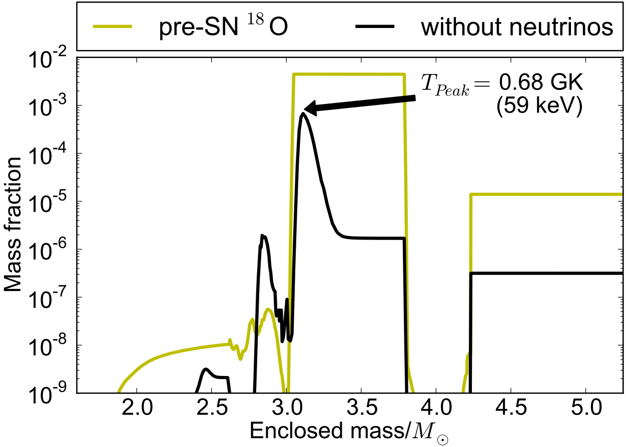
Production of ^{19}F for a 15 $M_\odot$ progenitor

- Initial conditions



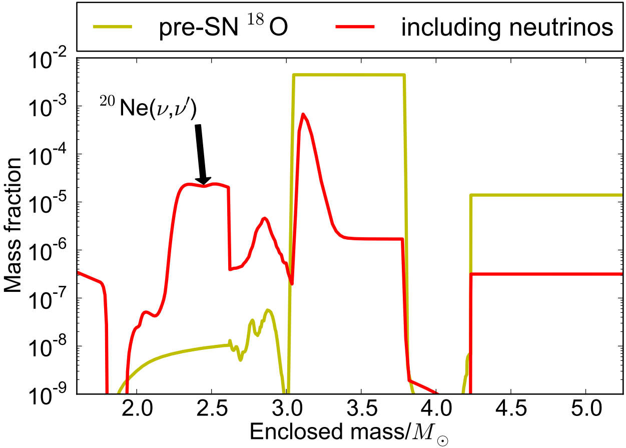
Production of ^{19}F for a 15 $M_\odot$ progenitor

- Explosive nucleosynthesis without neutrinos



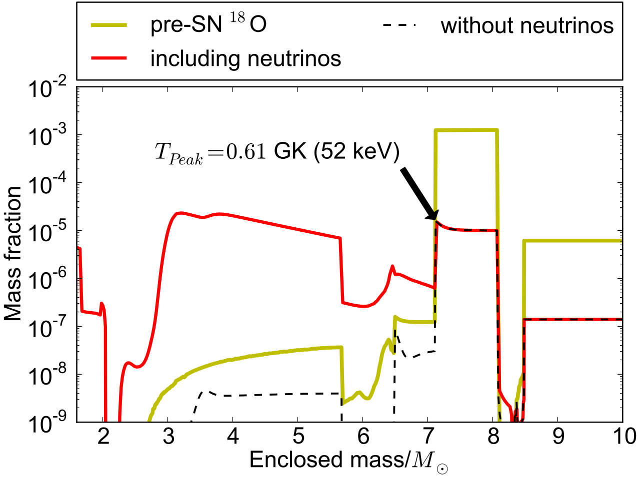
Production of ^{19}F for a 15 $M_\odot$ progenitor

- Including neutrino interactions

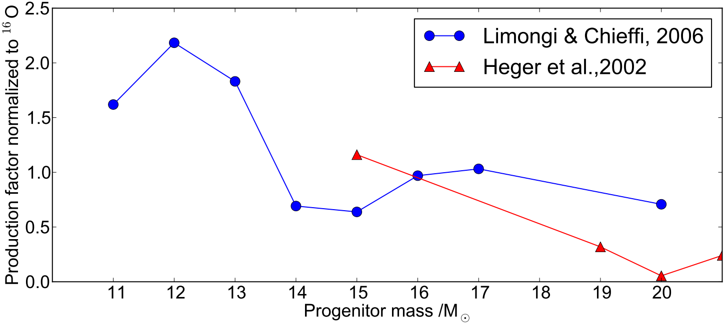


Production of ^{19}F for a 25 $M_\odot$ progenitor

- With the 25 $M_\odot$ progenitor the neutrino-induced production dominates



Comparision with other progenitor models



- Less massive stars tend to produce more ^{19}F by thermonuclear processes
- while neutrinos become more important with increasing mass

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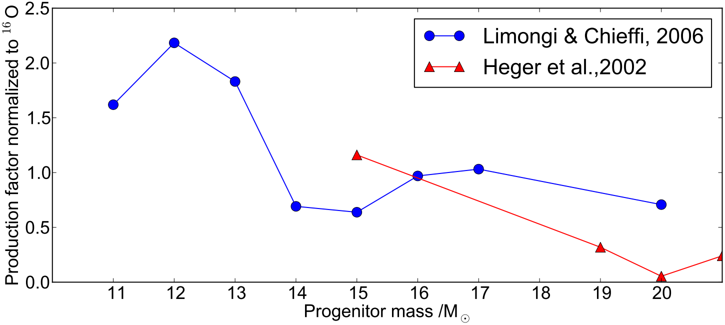

- Less massive stars tend to produce more ^{19}F by thermonuclear processes
- while neutrinos become more important with increasing mass
- Large sensitivity to stellar modelling and, neutrino fluxes and spectra

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γ-ray astronomy

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

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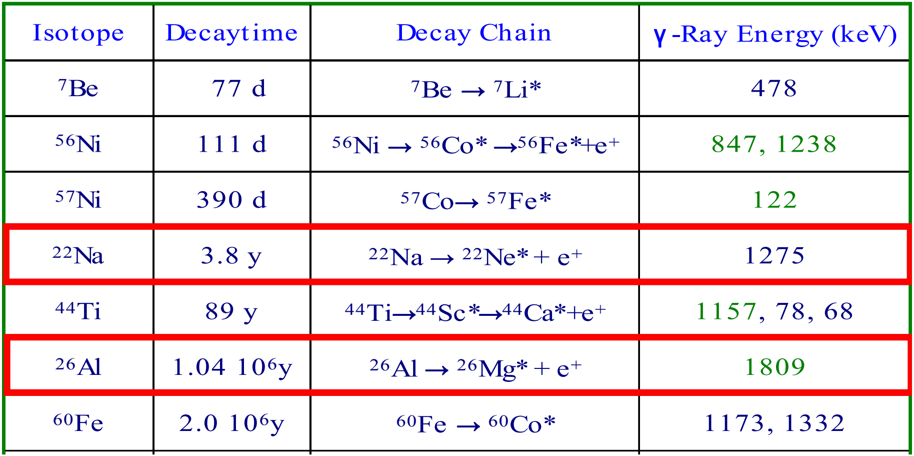

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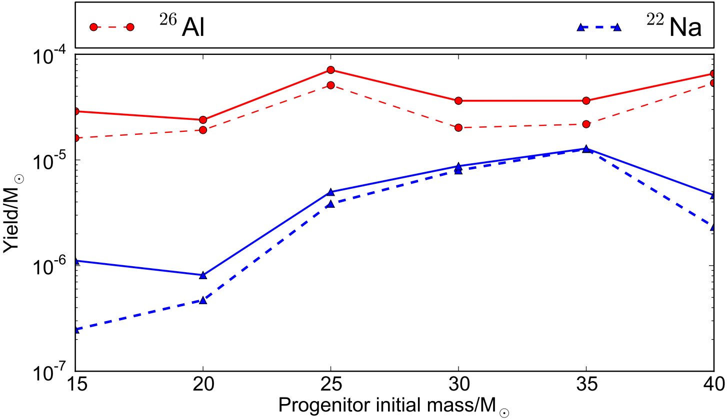
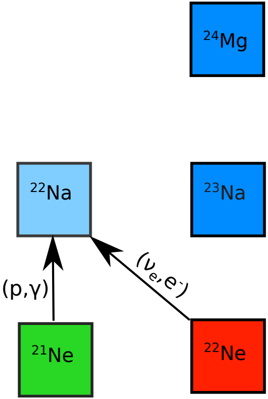
Sensitivity to the progenitor mass



Production of ^{22}Na



- Different mechanisms:
  - indirect enhancement of p-captures
  - direct charged-current channel

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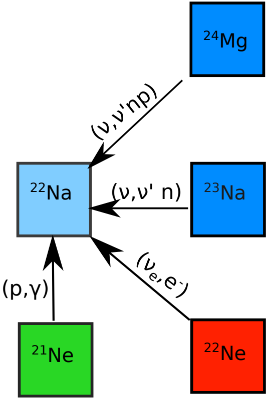

- Different mechanisms:
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  - direct neutral-current channels

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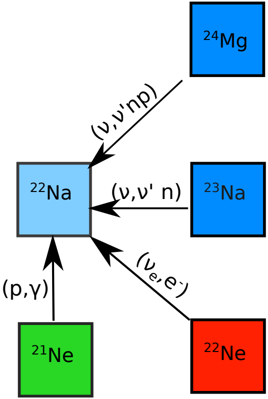

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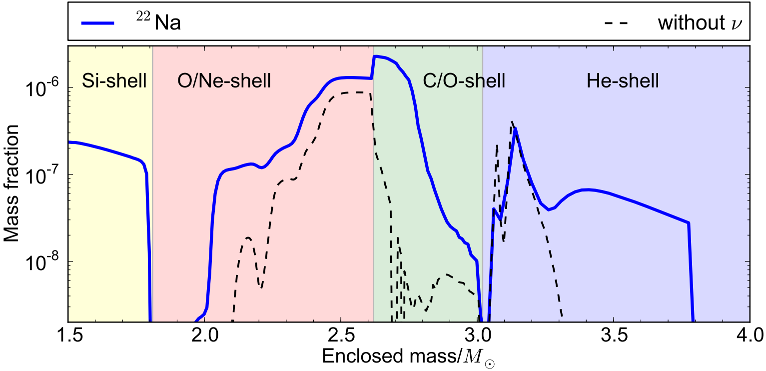
  - direct charged-current channel
  - direct neutral-current channels
- Balance of the different channels is sensitive to stellar structure and neutrino spectra

Production of ^{22}Na

- For a 15 $M_\odot$ progenitor



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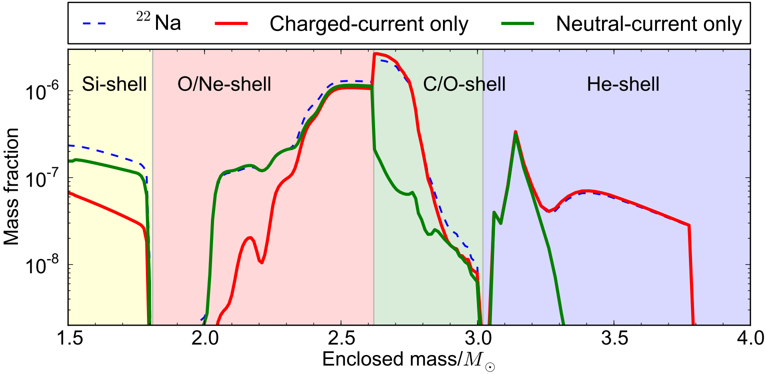

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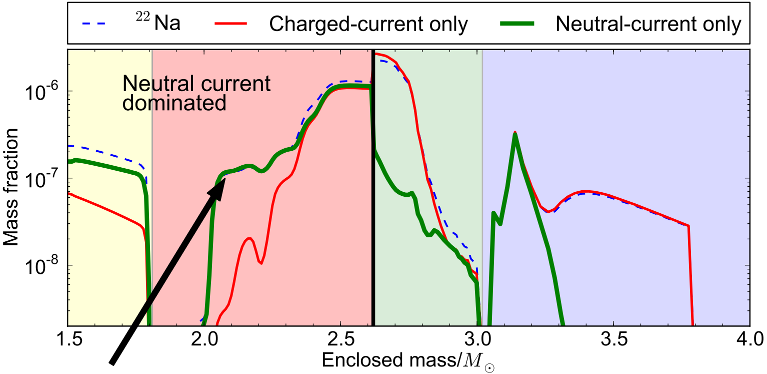

Indirect effect: ^{20}Ne(ν,ν' p) enhances ^{21}Ne(p,γ)^{22}Na

Production of ^{22}Na

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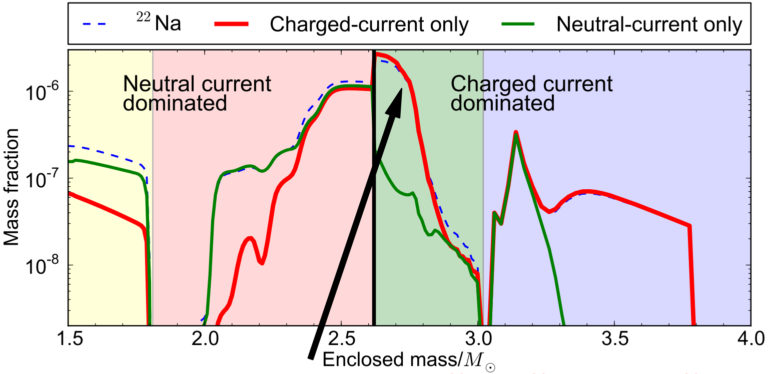
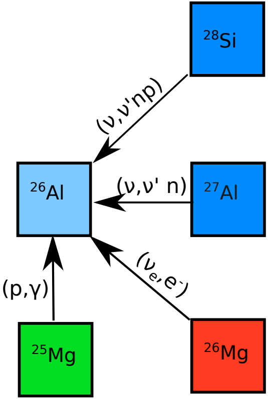
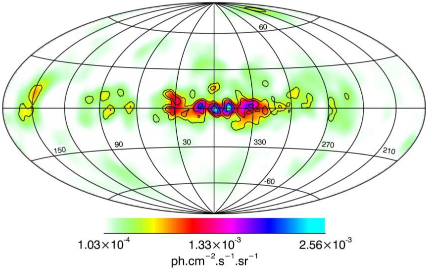


enriched in ^{22}Ne, $^{22}\mathrm{Ne}(\nu_e, e^-)^{22}\mathrm{Na}$

Production channels for ^{26}Al



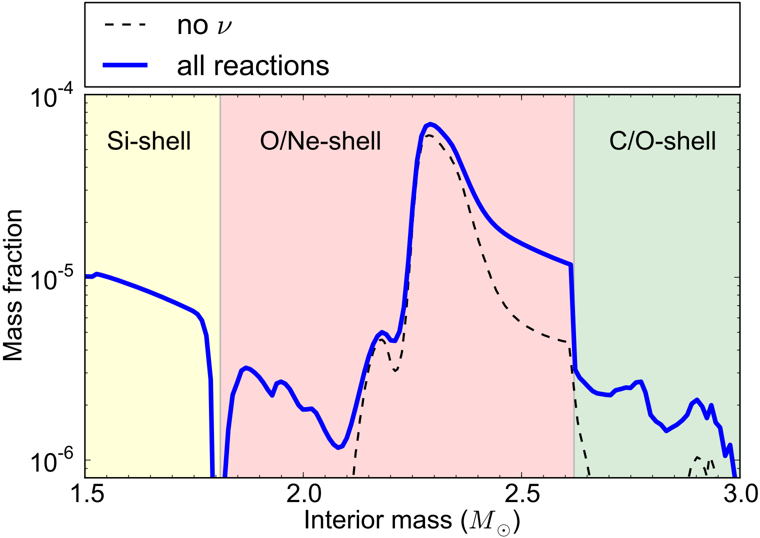
Galactic ^{26}Al emission with *INTEGRAL* SPI



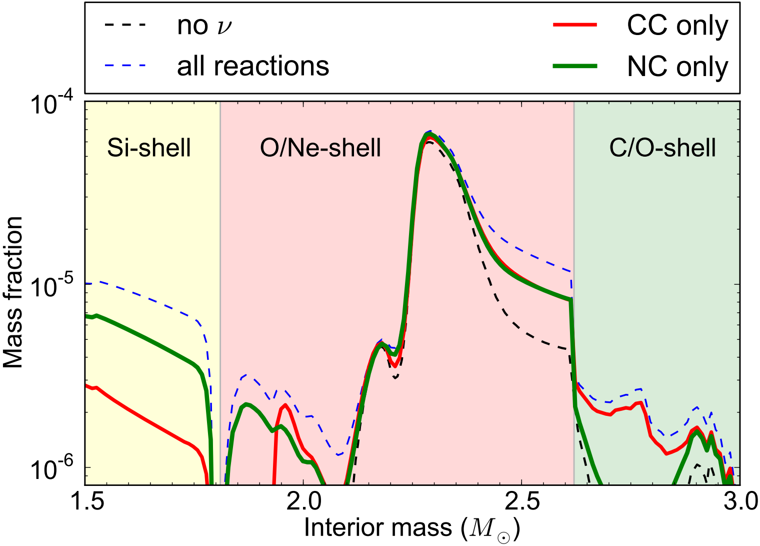
Bouchet et al. (2015)

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

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



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



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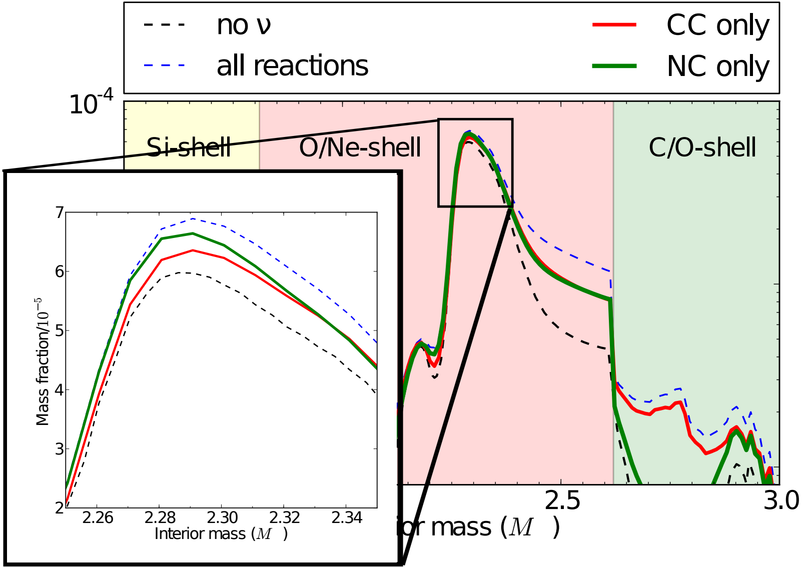

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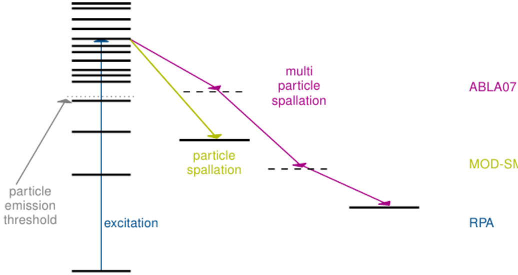
- Outlook
  - Include the neutrino interactions in Hydrodynamic Simulation
  - Study a larger range of progenitor models, especially lower mass
  - Explore effects of metallicity
  - Use time-dependent neutrino spectra
  - Effects of neutrino oscillations

Thank you, for your attention

Neutrino cross sections

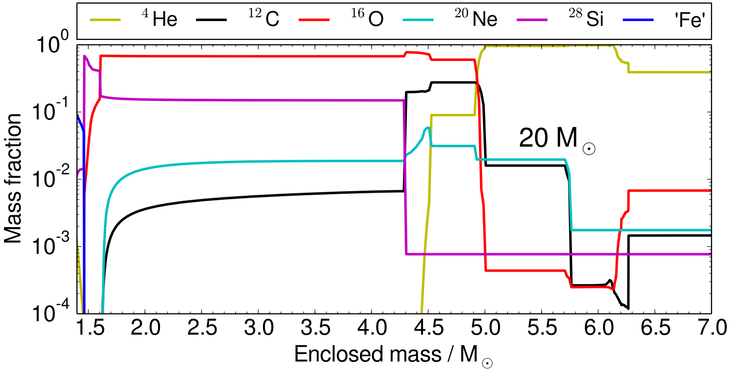
- Two step process: Excitation and decay
- $\sigma^k_{X\to Y}(E_\nu) = \sum_i \sigma_i^{RPA}(X) \times P_k(Y)$

- Excitation spectra from RPA
- Decay rates from Hauser-Feshbach statistical models
- Including evaporation of up to 4 particles



L. Huther, PhD Thesis
TU Darmstadt, 2014

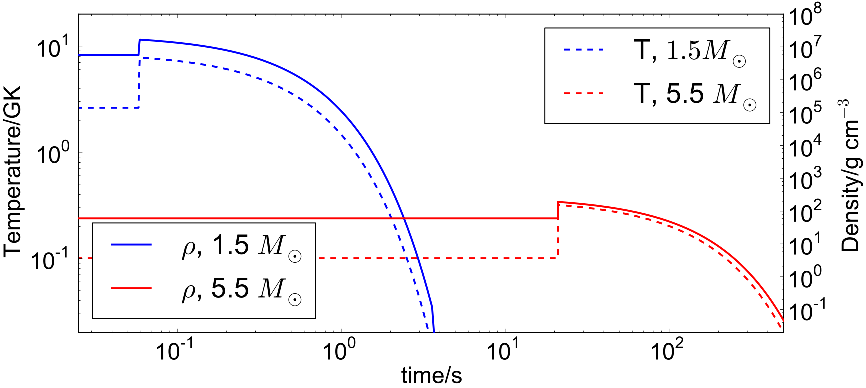
Stellar composition



Supernova model

- Thermodynamic parametrization
- Temperature and density constant until the passage of the shock at t_0
- Peak temperature in the shock: $T_P = E_{\text{expl}}^{1/4} \times R^{-3/4}$
- Exponential decrease of temperature with time scale $\tau_{dyn} \propto \frac{1}{\sqrt{\rho_{\text{initial}}}}$
- Expansion with constant velocity of 5000 km/s
- Explosion energy of 10^{51} ergs

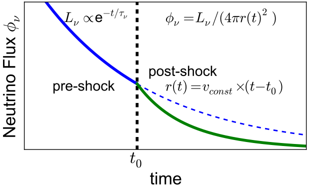
Parametrization of the supernova event



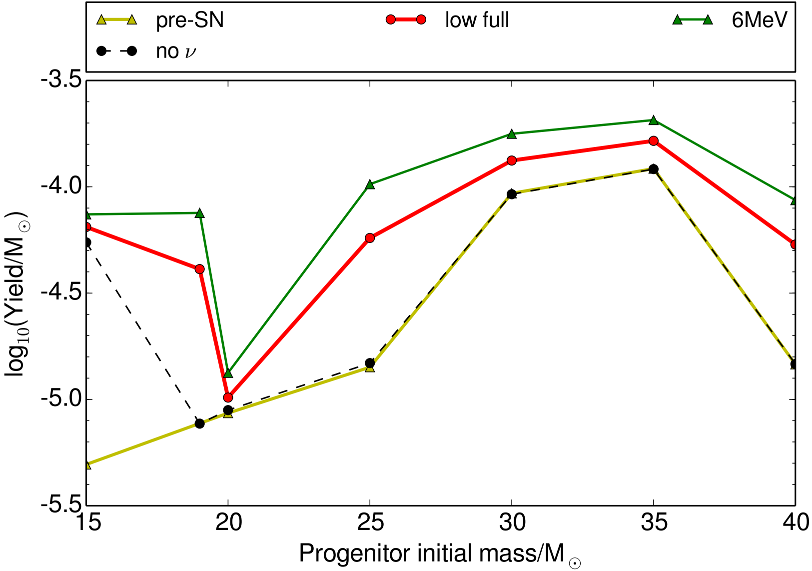
- Example for thermodynamic trajectory

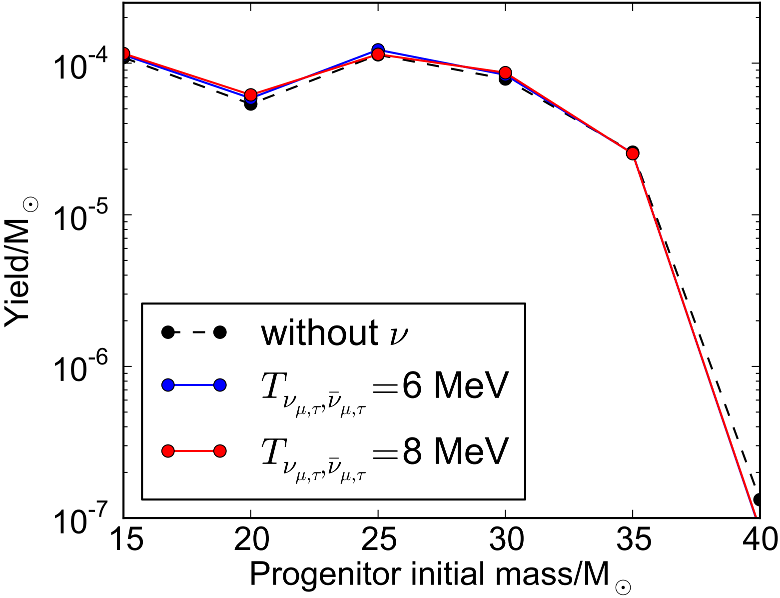
Description of ν emission

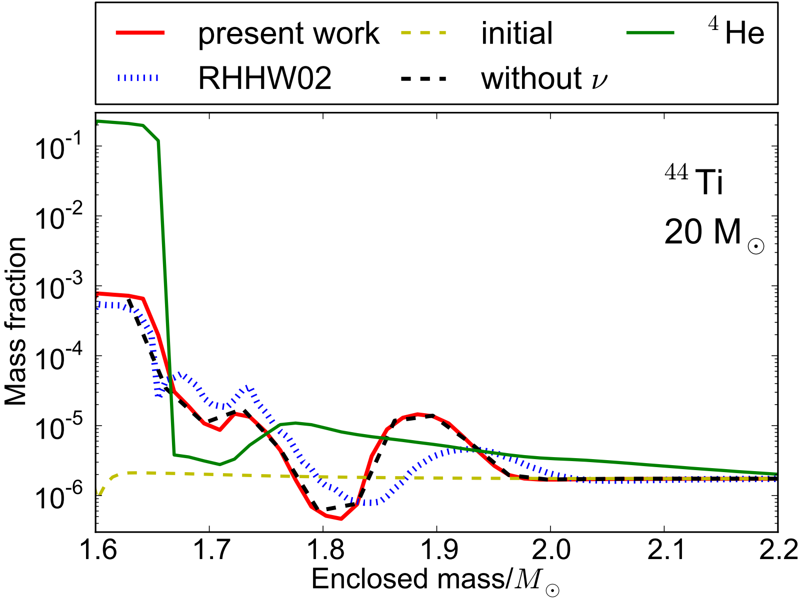
- Decreasing Luminosity $L_\nu \propto \exp\left(-\frac{t}{\tau_\nu}\right)$
- Isotropic emission
- Emission of 10^{53} ergs for each flavour
- Fermi-Dirac distributed energies, $\langle E_\nu \rangle = 3.15 \times T_\nu$
    - $T_{\nu_e} = 4\ \mathrm{MeV}$
    - $T_{\bar{\nu}_e} = 4\ \mathrm{MeV}$
    - $T_{\nu_{\mu,\tau}} = 8\ \mathrm{MeV}$



- Description taken from Woosley and Weaver 1990 (*The ν-process*, ApJ:356,272)


pre-SN
low full
6MeV
no ν
-3.5
-4.0
-4.5
-5.0
-5.5
15
20
25
30
35
40
$\log_{10}$(Yield/M$_\odot$)
Progenitor initial mass/M$_\odot$


Yield/M$_\odot$
10^{-4}
10^{-5}
10^{-6}
10^{-7}
15
20
25
30
35
40
Progenitor initial mass/M$_\odot$
without ν
$T_{\nu_{\mu,\tau},\bar{\nu}_{\mu,\tau}}$=6 MeV
$T_{\nu_{\mu,\tau},\bar{\nu}_{\mu,\tau}}$=8 MeV


present work
initial
^{4}He
RHHW02
without ν
^{44}Ti
20 $M_\odot$
Mass fraction
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1.6
1.7
1.8
1.9
2.0
2.1
2.2
Enclosed mass/$M_\odot$