Neutrino Nucleosynthesis

of radioactive nuclei in core-collapse supernovae

A. Sieverding[1], L. Huther[1], G. Martínez-Pinedo[1], K. Langanke[1,2], A. Heger[3]

[1]Technische Universität Darmstadt
[2]GSI Helmholtzzentrum, Darmstadt
[3]Monash Centre for Astrophysics, Melbourne

TECHNISCHE UNIVERSITÄT DARMSTADT

NAVI

HIC for FAIR
Helmholtz International Center

NAVI Physics Days, GSI, Darmstadt, Germany
18 Jan. 2016

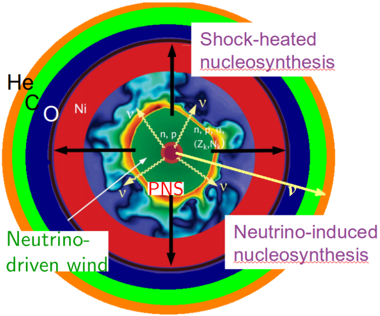
Outline

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

Neutrinos and Supernovae

Neutrinos are crucial for many aspects of Supernovae

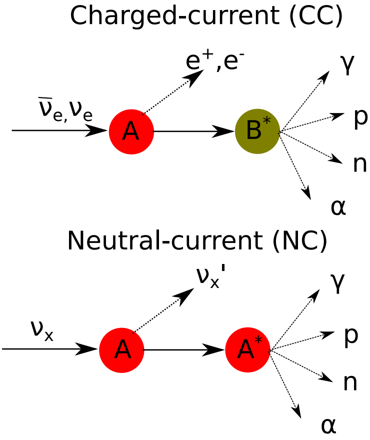
1. Deleptonization and Shock revival
   - Neutrino signal
   - Explosion dynamics
2. Neutrino driven wind
   - setting initial p/n ratio
3. ν process in the ejecta
   - Ejecta composition
   - Production of radioactive isotopes



Modified, from H.T. Janka

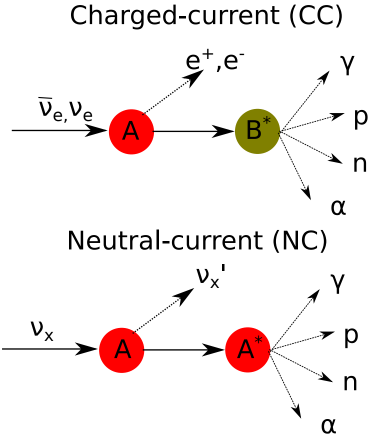
Neutrino nucleosynthesis

- Emission of 10^{58} Neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 7 - 13$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_{\mu,\tau}} \rangle$



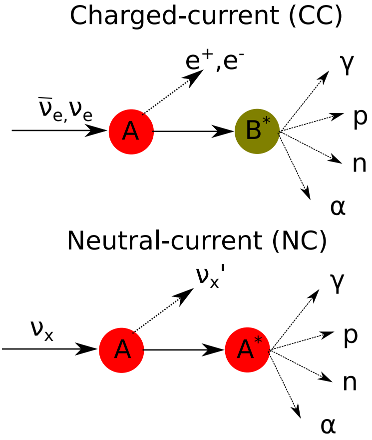
Neutrino nucleosynthesis

- Emission of 10^{58} Neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 7 - 13$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_{\mu,\tau}} \rangle$
- Inverse β-decay



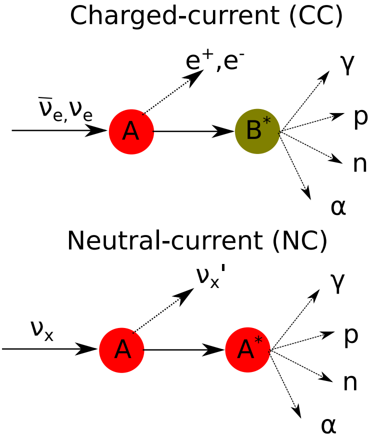
Neutrino nucleosynthesis

- Emission of 10^{58} Neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 7 - 13$ MeV
- $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle \leq \langle E_{\nu_{\mu,\tau}} \rangle$
- Inverse β-decay
- Particle evaporation



Neutrino nucleosynthesis

- Emission of 10^{58} Neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 7 - 13$ 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



Neutrino nucleosynthesis

- The supernova shock triggers photodissociation and subsequent particle capture reactions
- ν nucleosynthesis occurs mainly in regions with sufficient neutrino fluxes but still moderate post-shock temperatures

Neutrino nucleosynthesis

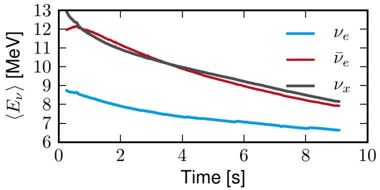
- The supernova shock triggers photodissociation and subsequent particle capture reactions
- ν nucleosynthesis occurs mainly in regions with sufficient neutrino fluxes but still moderate post-shock temperatures
- Main candidates for neutrino nucleosynthesis:

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

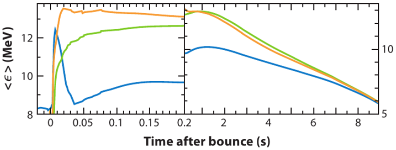
  ^{19}**F** via ^{20}Ne(ν_x,ν_x' p/n)

  ^{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 neutrino transport is included
- More channels for neutrino-matter interactions
- Inelastic channels reduce the average energies

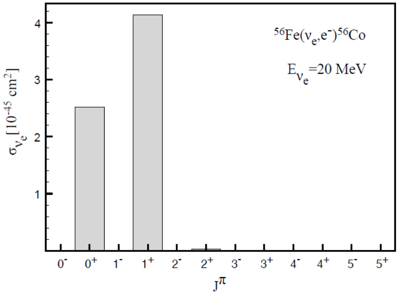
Updated physics input

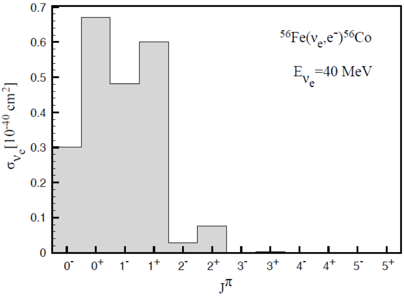
- Simulations including detailed neutrino transport give new estimates for typical neutrino energies:
  $\langle E_\nu \rangle$=**8-13 MeV** compared to 13-25 MeV
- Nuclear reaction data from *JINA Reaclib V2.0 (2013)*
- Lower neutrino energies make charged-current reactions more important
- Neutrino-nucleus cross-sections have been calculated for almost the whole nuclear chart (L. Huther 2014, PhD. Thesis)
- Where available, cross-sections have been supplemented by experimental data and/or results of shell-model calculations

Neutrino-Nucleus reaction cross sections

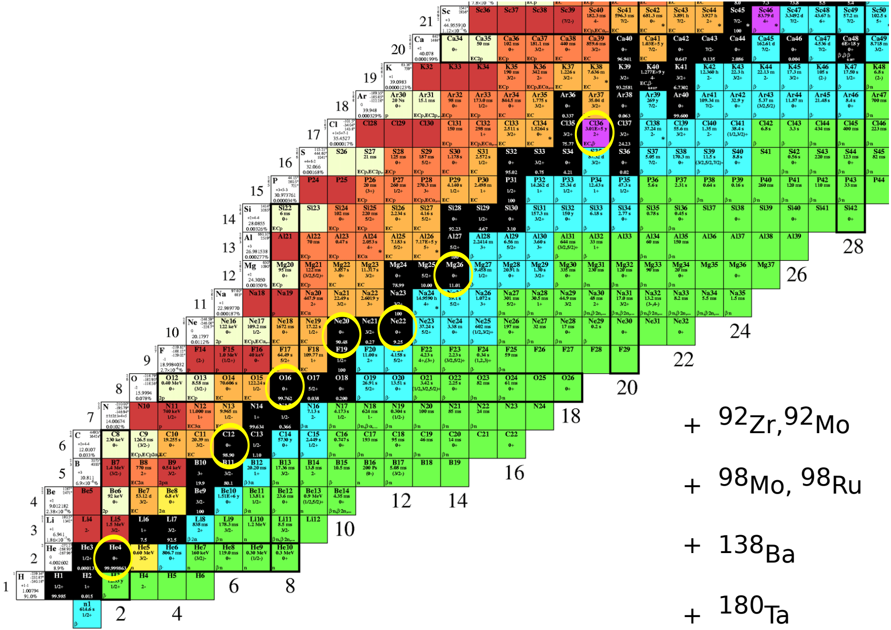
- **Charged-current neutrino absorption**
  - Transitions to bound states change the composition
  - Dominated by $J = 0^+$ and $J = 1^+$ transitions

- **Neutral-current scattering**
  - Only particle emission is relevant for nucleosynthesis
  - Mainly collective excitations at higher energies





From: Paar,Vretenar,Marketin,Ring Phys.Rev.C 77(2008) 024608



+ ^{92}Zr, ^{92}Mo

+ ^{98}Mo, ^{98}Ru

+ ^{138}Ba

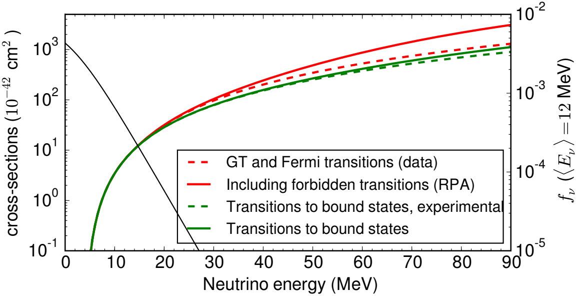
+ ^{180}Ta

Important reactions constrained by experiment

- ^{20}Ne(ν,ν'),^{20}Ne(ν_e,e$^-$),^{20}Ne($\bar{\nu}_e$,e$^+$) (*Anderson et al. 1991)*
- ^{22}Ne(ν_e,e$^-$) (from ^{22}Mg decay, *Hardy et al. 2003*)
- ^{24}Mg(ν,ν'),^{24}Mg(ν_e,e$^-$) (*Zegers et al. 2008*)
- ^{26}Mg(ν_e,e$^-$) (*Zegers et al. 2005*)
- ^{138}Ba(ν_e,e$^-$) (*Byelikov et al. 2007*)
- ^{180}Ta(ν_e,e$^-$) (*Byelikov et al. 2007*)

- ^{36}Ar($\bar{\nu}_e$,e$^+$), ^{36}S(ν_e,e$^-$) (Shell model calculations)
- ^{4}He(ν , *) (*Gazit et al., (2004), Suzuki et al. (2006)*)
- ^{12}C(ν , *) (*Woosley et al. (1990)*)

Cross-sections supplemented by experimental data

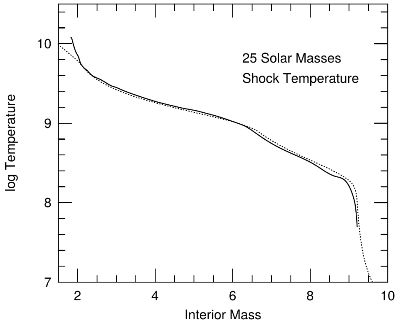


^{26}Mg(ν_e,e$^-$)

- Strength for GT and Fermi transitions is experimentally accessible in some cases
- Forbidden transitions are added from the theoretical calculations
- Branchings are calculated based on a statistical model

Supernova model

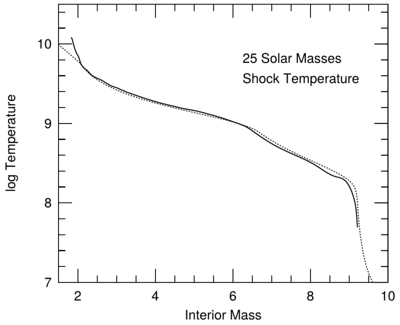
- Parametrization of temperature and density evolution during the explosion (Woosley et al. 1990)
- $T_{\mathrm{Peak}} = 2.4 \times 10^9 \mathrm{K} \times \left(\frac{E_{\mathrm{expl}}}{10^{51}\mathrm{erg}} \right)^{1/4} \times \left(\frac{R}{10^9 \mathrm{cm}} \right)^{-3/4}$



Woosley et al. 2002

Supernova model

- 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
- Fermi-Dirac distribution

Outline

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

Production factors normalized to ^{16}O

- 15 $M_\odot$ progenitor with solar metallicity

Nucleus	no ν	low energies[a]	high energies[b]
^{7}Li	0.002	0.12	1.41
^{11}B	0.01	0.30	2.07
^{19}F	1.30	1.38	1.59
^{138}La	0.10	0.68	1.33
^{180}Ta*	0.47	1.26	2.27

- a) $\langle E_{\nu_e} \rangle = 9$ MeV, $\langle E_{\bar{\nu}_e, \nu_x} \rangle = 13$ MeV
- b) $\langle E_{\nu_e, \bar{\nu}_e} \rangle = 13$ MeV, $\langle E_{\nu_x} \rangle = 19$ MeV
- *) Only about 40% of ^{180}Ta survive in the long-lived isomeric state

Production factors normalized to ^{16}O

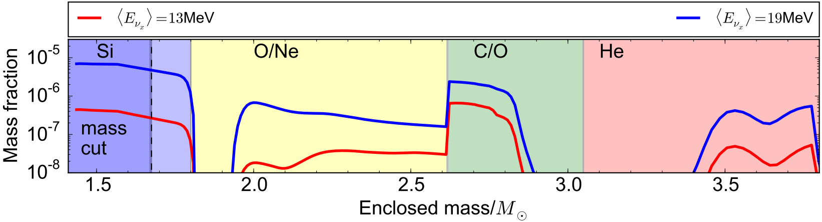
- 15 $M_\odot$ progenitor with solar metallicity

Nucleus	no ν	low energies[a]	high energies[b]
^{7}Li	0.002	0.12	1.414
^{11}B	0.01	0.30	2.07
^{19}F	1.30	1.38	1.59
^{138}La	0.10	0.68	1.33
$^{180}Ta^{*}$	0.47	1.26	2.27

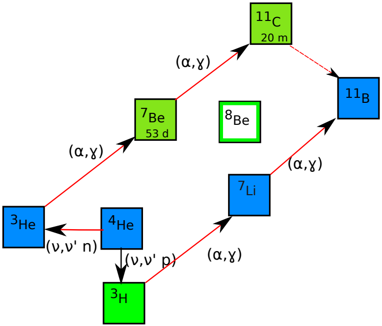
Taking into account production by Cosmic Ray spallation, only about 40% of solar ^{11}B needs to be produced by SN *(Austin et al. (2011))*

(Over)Production of ^{11}B

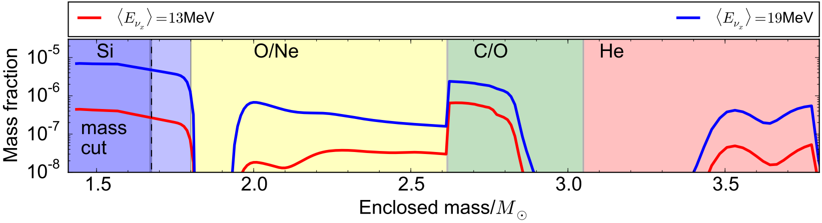
1. Si shell
2. O/Ne shell
3. C/O shell
4. He shell



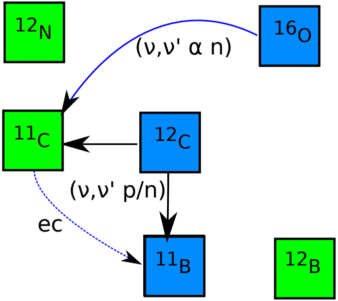
(Over)Production of ^{11}B



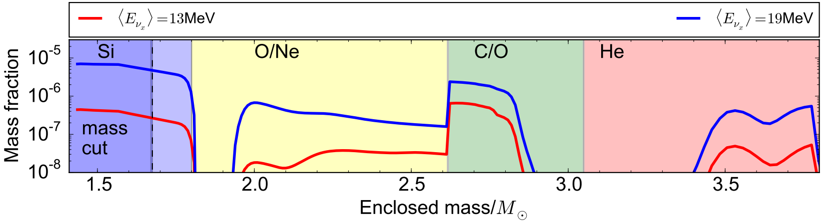
1. Si shell
   - α-rich freeze-out
   - after the SN shock
2. O/Ne shell
3. C/O shell
4. He shell



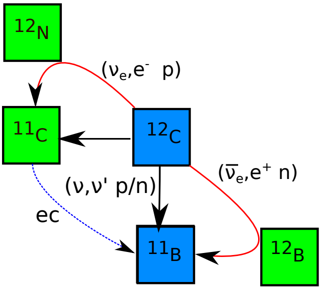
(Over)Production of ^{11}B



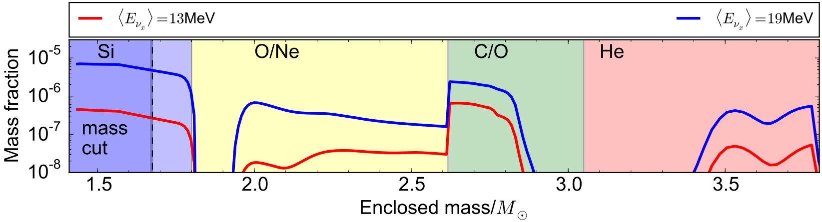
1. Si shell
   - α-rich freeze-out
   - after the SN shock
2. O/Ne shell
   - Production from ^{12}C and ^{16}O
3. C/O shell
4. He shell



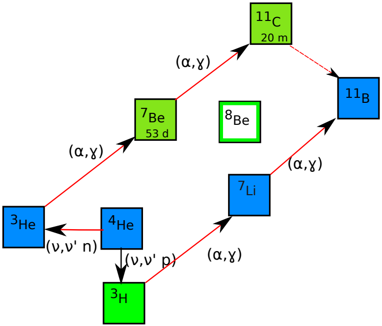
(Over)Production of ^{11}B



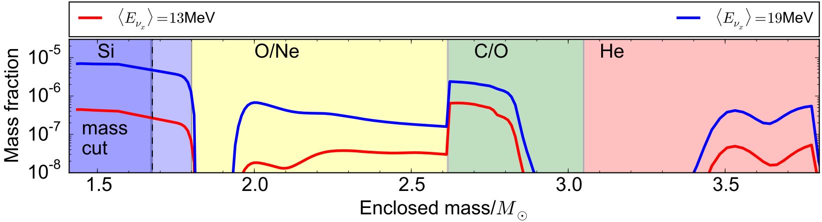
1. Si shell
   - α-rich freeze-out
   - after the SN shock
2. O/Ne shell
   - Production from ^{12}C and ^{16}O
3. C/O shell
   - Production from ^{12}C
4. He shell



(Over)Production of ^{11}B



1. Si shell
   - α-rich freeze-out
   - after the SN shock
2. O/Ne shell
   - Production from ^{12}C and ^{16}O
3. C/O shell
   - Production from ^{12}C
4. He shell
   - before the SN shock



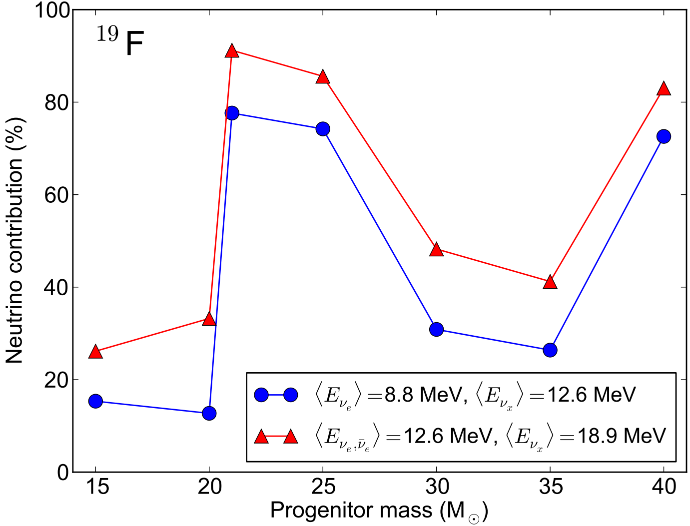
Production factors normalized to ^{16}O

- 15 $M_\odot$ progenitor with solar metallicity

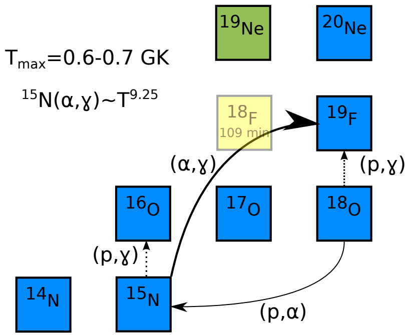
Nucleus	no ν	low energies[a]	high energies[b]
^{7}Li	0.002	0.12	1.414
^{11}B	0.01	0.30	2.07
^{19}F	1.30	1.38	1.59
^{138}La	0.10	0.68	1.33
^{180}Ta*	0.47	1.26	2.27

- a) $\langle E_{\nu_e} \rangle = 8.8$ MeV, $\langle E_{\bar{\nu}_e,\nu_x} \rangle = 12.6$ MeV
- b) $\langle E_{\nu_e,\bar{\nu}_e} \rangle = 12.6$ MeV, $\langle E_{\nu_x} \rangle = 18.9$ MeV
- *) Only about 40% of ^{180}Ta survive in the long-lived isomeric state

Importance of neutrinos for the production of ^{19}F

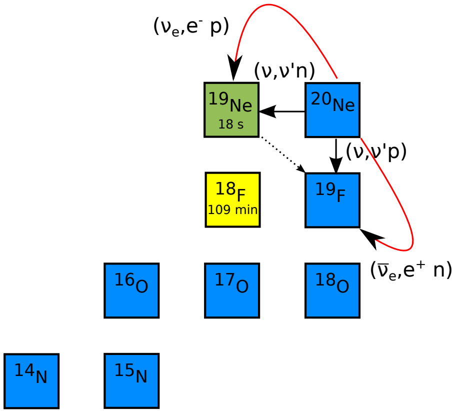


Production of ^{19}F



- Without neutrinos:
  - H- and He-shell burning create regions enriched in ^{18}O and ^{15}N
  - High shock temperatures allow^{15}N(α,γ) and ^{18}O(p,γ)

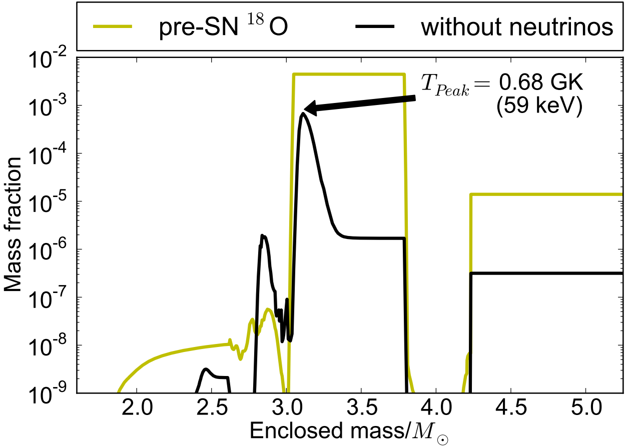
Production of ^{19}F



- Without neutrinos:
  - H- and He-shell burning create regions enriched in ^{18}O and ^{15}N
  - High shock temperatures allow^{15}N(α,γ) and ^{18}O(p,γ)
- Neutral-current and charged-current neutrino reactions on ^{20}Ne

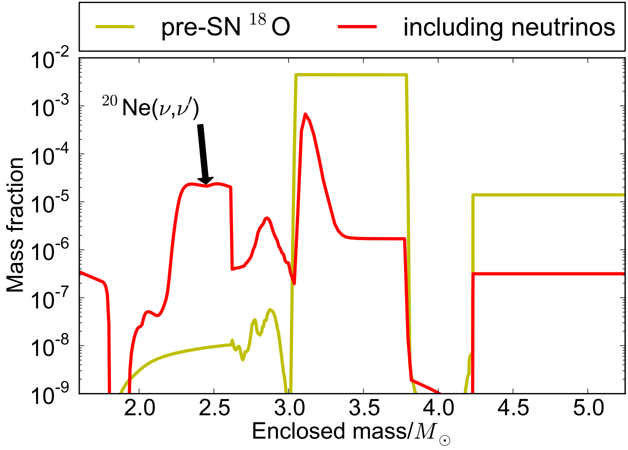
Production of ^{19}F for a 15 $M_\odot$ progenitor

- Explosive nucleosynthesis without neutrinos



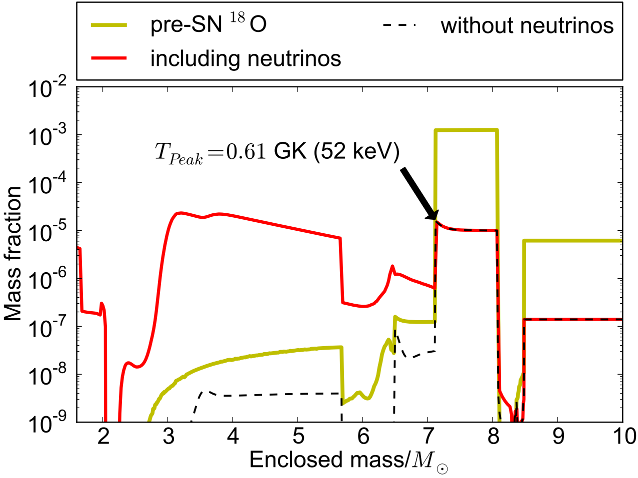
Production of ^{19}F for a 15 $M_\odot$ progenitor

- Including neutrino interactions

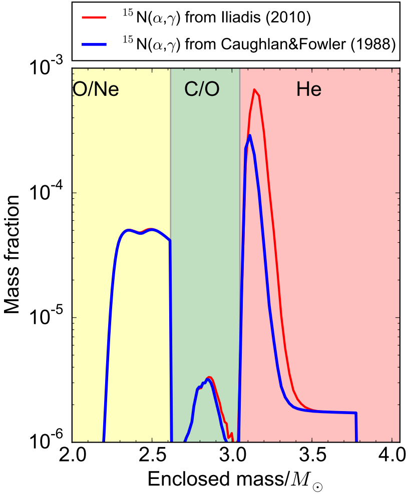


Production of ^{19}F for a 25 $M_\odot$ progenitor

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



Sensitivity to ^{15}N(α,γ) reaction rate



- Without neutrinos
  - Yield: $7.3 \times 10^{-5} M_\odot$
- High energy spectrum
  - Yield: $9.2 \times 10^{-5} M_\odot$
- High energy spectrum, ^{15}N(α,γ) from Caughlan&Fowler
  - Yield: $4.8 \times 10^{-5} M_\odot$

low energy spectra: $\langle E_{\nu_x,\bar{\nu}_e} \rangle = 13$MeV , $\langle E_{\nu_e} \rangle = 9$MeV
high energy spectra: $\langle E_{\nu_x} \rangle = 19$MeV , $\langle E_{\nu_e,\bar{\nu}_e} = 13$MeV

Outline

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

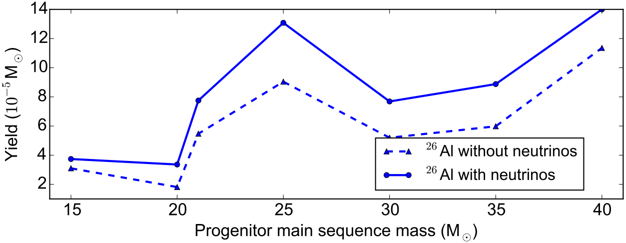
γ-ray astronomy

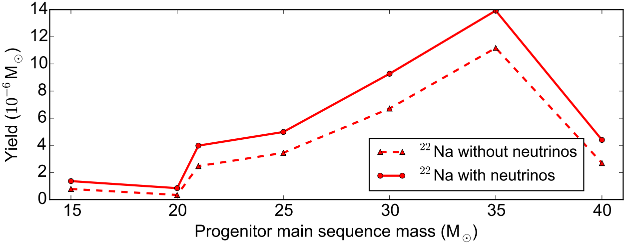
Isotope	Decaytime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti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

γ-ray astronomy

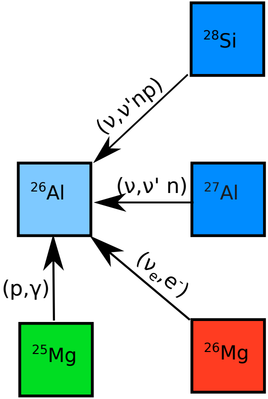
Isotope	Decaytime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	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

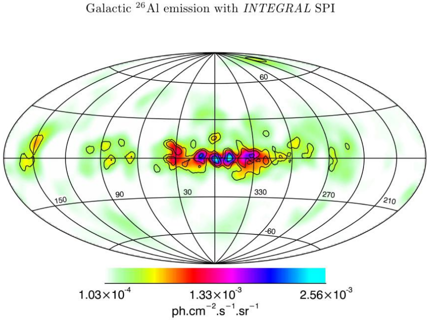
Sensitivity to the progenitor mass





Production channels for ^{26}Al

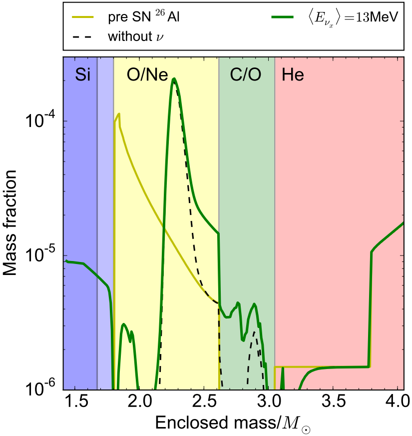




Bouchet et al. (2015)

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

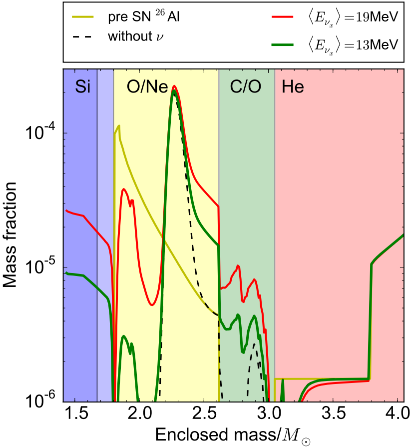
Production of ^{26}Al for a 15 $M_\odot$ progenitor



low energy spectra: $\langle E_{\nu_x, \bar{\nu}_e} \rangle = 13$MeV , $\langle E_{\nu_e} \rangle = 9$MeV
high energy spectra: $\langle E_{\nu_x} \rangle = 19$MeV , $\langle E_{\nu_e, \bar{\nu}_e} = 13$MeV

- Without neutrinos
  - Yield: $3.1 \times 10^{-5} M_\odot$
- Low energy spectrum
  - Yield: $3.8 \times 10^{-5} M_\odot$

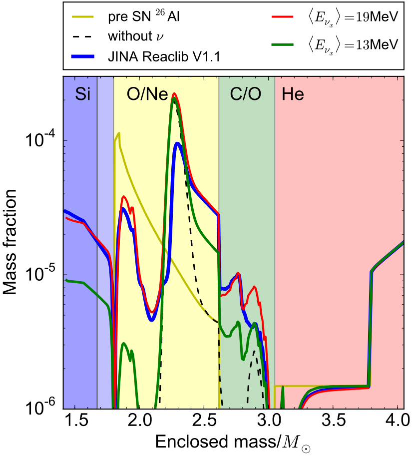
Production of ^{26}Al for a 15 $M_\odot$ progenitor



low energy spectra: $\langle E_{\nu_x, \bar{\nu}_e} \rangle = 13$MeV , $\langle E_{\nu_e} \rangle = 9$MeV
high energy spectra: $\langle E_{\nu_x} \rangle = 19$MeV , $\langle E_{\nu_e, \bar{\nu}_e} = 13$MeV

- Without neutrinos
  - Yield: $3.1 \times 10^{-5} M_\odot$
- Low energy spectrum
  - Yield: $3.8 \times 10^{-5} M_\odot$
- High energy spectrum
  - Yield: $5.3 \times 10^{-5} M_\odot$

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



low energy spectra: $\langle E_{\nu_x,\bar{\nu}_e} \rangle = 13$MeV , $\langle E_{\nu_e} \rangle = 9$MeV
high energy spectra: $\langle E_{\nu_x} \rangle = 19$MeV , $\langle E_{\nu_e,\bar{\nu}_e} = 13$MeV

- Without neutrinos
  - Yield: $3.1 \times 10^{-5} M_\odot$
- Low energy spectrum
  - Yield: $3.8 \times 10^{-5} M_\odot$
- High energy spectrum
  - Yield: $5.3 \times 10^{-5} M_\odot$
- Reaclib V1.1, High energy spectrum
  - Yield: $3.6 \times 10^{-5} M_\odot$

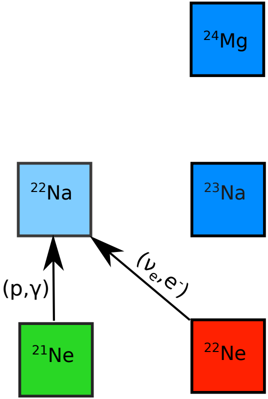
Sensitivity to reaction rates studied in Iliadis et al. (2011)

- Conclusions
  - Study of neutrino induced nucleosynthesis
  - Calculations with updated neutrino spectra
  - Important neutrino-nucleus cross-sections constrained by data
  - Study the effect on radioactive nuclei like ^{22}Na and ^{26}Al, including the sensitivity to nuclear reactions rates

- Conclusions
  - Study of neutrino induced nucleosynthesis
  - Calculations with updated neutrino spectra
  - Important neutrino-nucleus cross-sections constrained by data
  - Study the effect on radioactive nuclei like ^{22}Na and ^{26}Al, including the sensitivity to nuclear reactions rates
- Outlook
  - Study a larger range of progenitor models
  - Use trajectories from (Multi-D) SN simulations
  - Take into account time-dependent neutrino spectra

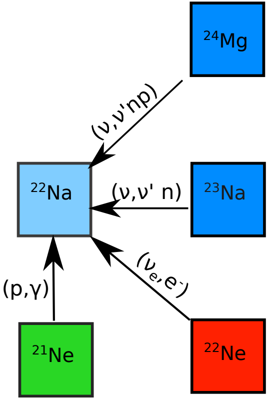
Thank you, for your attention

Production of ^{22}Na



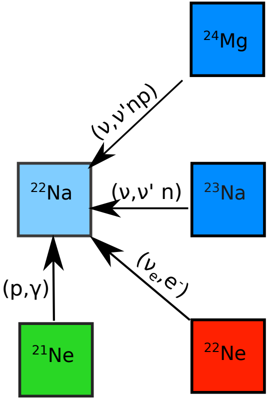
- Different mechanisms:
  - indirect enhancement of p-captures
  - direct charged-current channel

Production of ^{22}Na



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

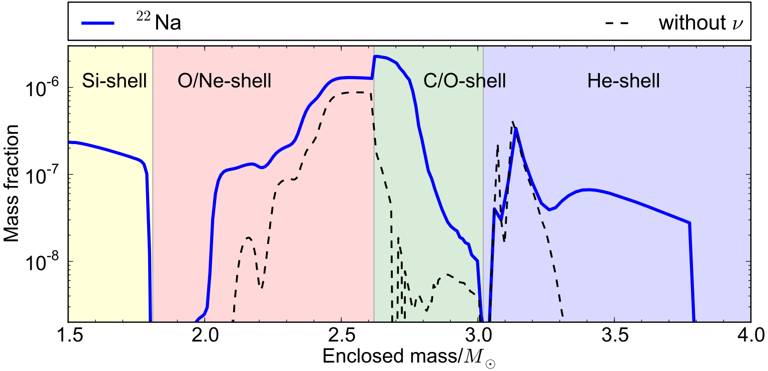
Production of ^{22}Na



- 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

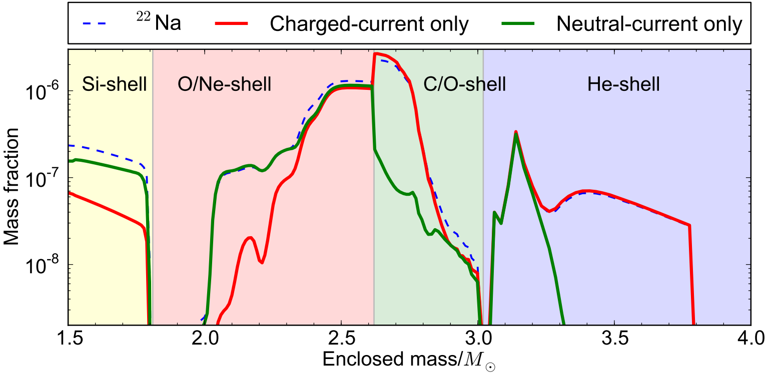
Production of ^{22}Na

- For a 15 $M_\odot$ progenitor



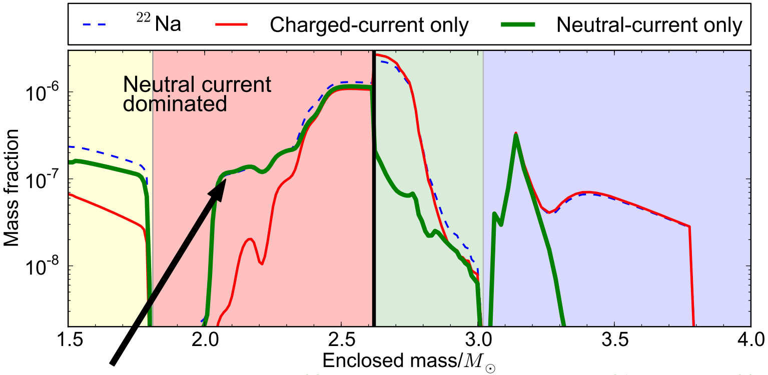
Production of ^{22}Na

- For a 15 $M_\odot$ progenitor



Production of ^{22}Na

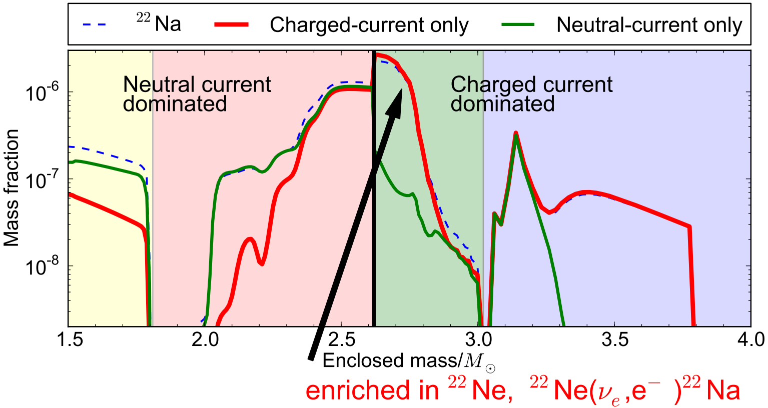
- For a 15 $M_\odot$ progenitor



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

Production of ^{22}Na

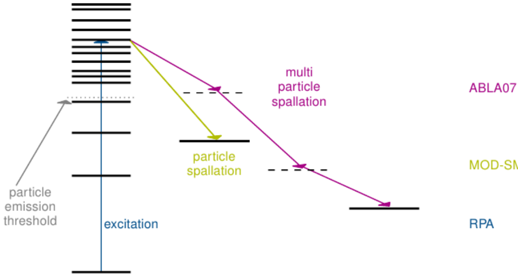
- For a 15 $M_{\odot}$ progenitor



Neutrino cross sections

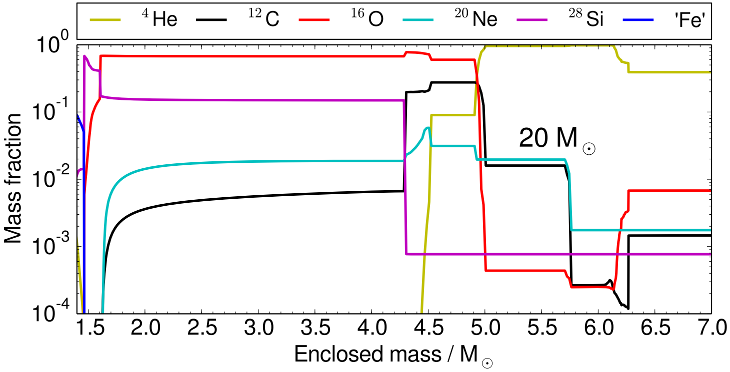
- Two step process: Excitation and decay
- $\sigma^k_{X\to Y}(E_\nu) = \sum_i \sigma_i^{RPA}(X) \times P_k(Y)$

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



L. Huther, PhD ThesisTU Darmstadt, 2014

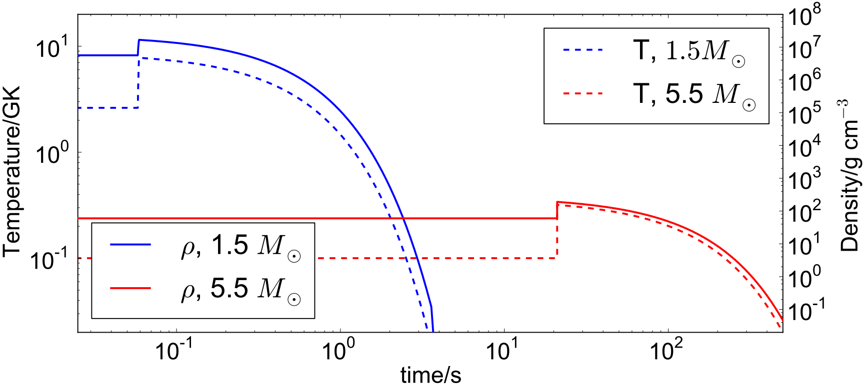
Stellar composition



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

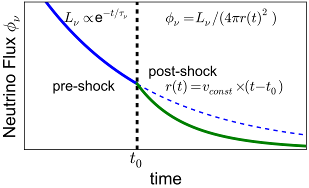
Parametrization of the supernova event



- 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, $\langle E_\nu \rangle = 3.15 \times T_\nu$
  - $T_{\nu_e} = 4$ MeV
  - $T_{\bar{\nu}_e} = 4$ MeV
  - $T_{\nu_{\mu,\tau}} = 8$ MeV



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