Neutrinos in core-collapse supernova nucleosynthesis

Neutrino-driven winds and the ν process

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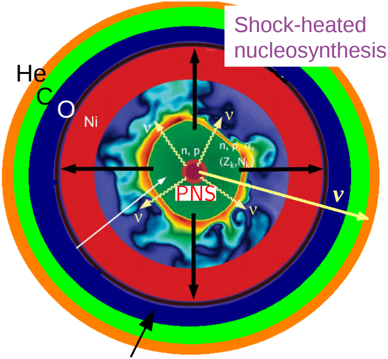
HGS-HIRe for FAIR
Helmholtz Graduate School for Hadron and Ion Research

Matter and Universe 2016
Helmholtz institute Mainz
12 Dec. 2016

Outline

Neutrinos and nucleosynthesis in supernovae

[Modified from Janka+, PTEP 01A309, 2012]



shockwave (revived mainly by ν-heating)

$\sim 10^{58}$ neutrinos of different flavors in $\sim$ 10 seconds

$$\langle E_\nu \rangle \sim 7 - 20 \text{ MeV}$$

$$\langle E_{\nu_e} \rangle \lesssim \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_{\mu,\tau}} \rangle$$

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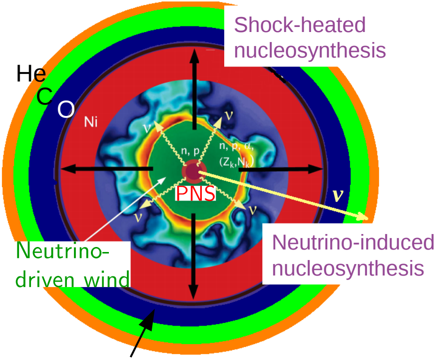

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- neutrino (induced) nucleosynthesis
  - $\rightarrow$ light elements : Li, Be, B, F
  - $\rightarrow$ radioactive nuclei : ^{22}Na, ^{26}Al
    rare isotopes : ^{138}La, ^{180}Ta

- neutrino-driven wind

$$\nu_e + n \rightarrow p + e^-$$
$$\bar{\nu}_e + p \rightarrow n + e^+$$

$\rightarrow$ determine the neutron-to-proton ratio (or equivalently, the electron number fraction per baryon, Y_e) of the ejecta

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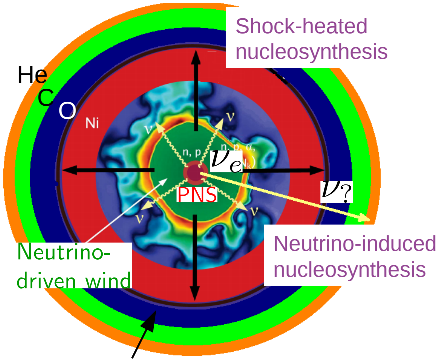

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neutrino flavor oscillations

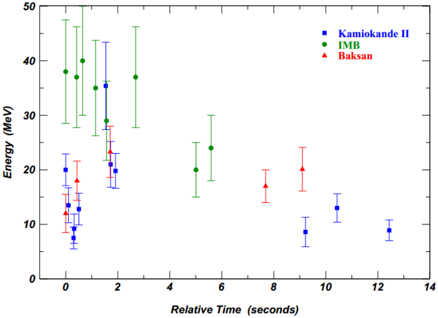
$\nu_e \leftrightarrow \nu_{\mu,\tau}$ & $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$

$\nu_e \leftrightarrow \nu_s$ & $\bar{\nu}_e \leftrightarrow \bar{\nu}_s$

when? where? how (much)?

Supernova neutrino signals

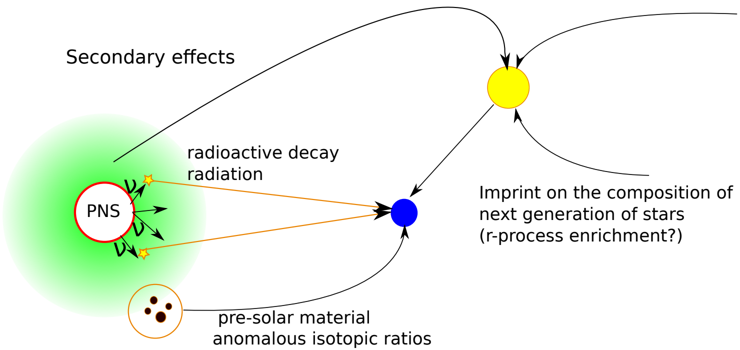
$\approx 20 \quad \bar{\nu}_e$ detected from SN1987a



- confirms the basic picture of the core-collapse SN model
- constraints on neutrino emission timescale and relevant energies

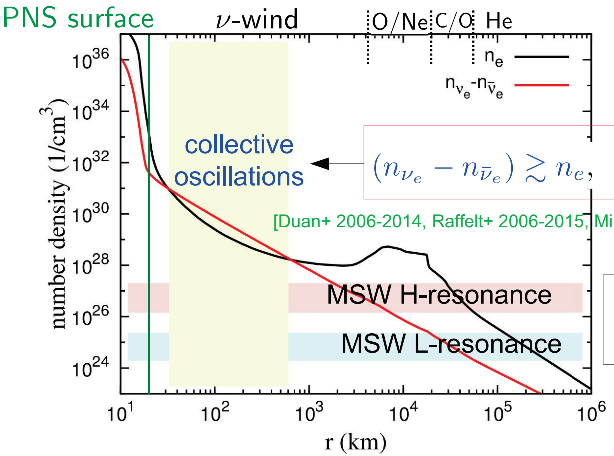
- **Thousands of events expected in multi-kiloton detectors for the next galactic supernova**

Secondary evidence from nucleosynthesis



- Enrichment of metal-poor stars
- production of rare elements (Li,Be,B,La,Ta)
- short-lived radioisotopes in pre-solar grains (Banerjee et al. 2016)
- long-lived radioactive isotopes with observed γ-ray lines (^{26}Al,^{60}Fe)

Neutrino flavor oscillations



$$(n_{\nu_e} - n_{\bar{\nu}_e}) \gtrsim n_e, \quad \sqrt{2} G_F n_{\nu_e} \times \frac{R_\nu^2}{r^2} \gtrsim \frac{\delta m^2}{2E_\nu}$$

$$\sqrt{2} G_F n_e \approx \frac{\delta m^2}{2E_\nu}$$

- Collective oscillations close to the PNS surface can affect the ν driven wind
- MSW flavor transformations can affect the ν process in the outer regions

Outline

Nucleosynthesis in neutrino driven winds

Neutrino interactions determine Y_e

$$\nu_e + n \rightleftarrows p + e^-$$
$$\bar{\nu}_e + p \rightleftarrows n + e^+$$

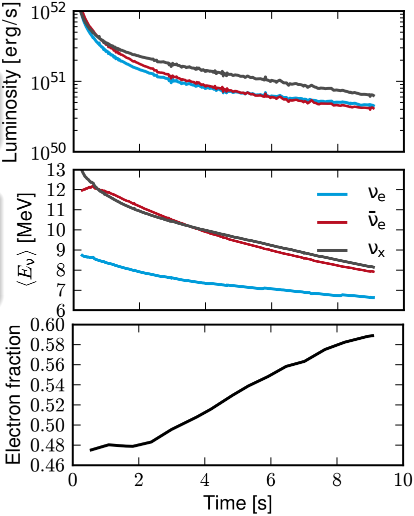
Neutron-rich ejecta:

$$\langle E_{\bar{\nu}_e}\rangle - \langle E_{\nu_e}\rangle > 4\Delta_{np} - \left[\frac{L_{\bar{\nu}_e}}{L_{\nu_e}} - 1\right]\left[\langle E_{\bar{\nu}_e}\rangle - 2\Delta_{np}\right]$$

- neutron-rich ejecta: weak r-process
- proton-rich ejecta: νp-process

Energy difference related to symmetry energy (Martínez Pinedo et al. 2012, Roberts et al. 2012)

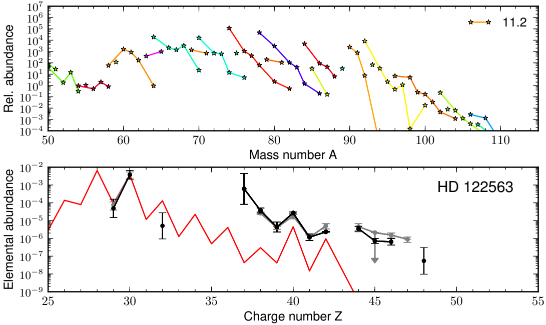
1D Boltzmann transport simulation



Martínez Pinedo et al. 2013

Nucleosynthesis in neutrino driven winds

Neutron-deficient isotopes of elements between Zn and Mo



Uncertainties:

- Neutrino-matter interactions
- Flavor oscillations:
  - Collective oscillations shown to have only minor impact (Wu et al 2015)
  - Active-sterile ($\sim$ eV) transformations (Wu et al 2013).
- Multi-D effects (Wanajo et al. 2011)

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Neutrino nucleosynthesis

- Emission of 10^{58} neutrinos from the collapsing core
- $\langle E_\nu \rangle \approx 8 - 20$ MeV
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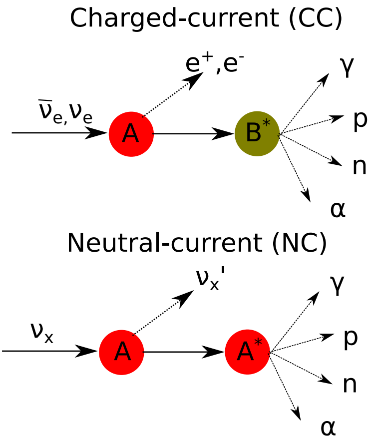

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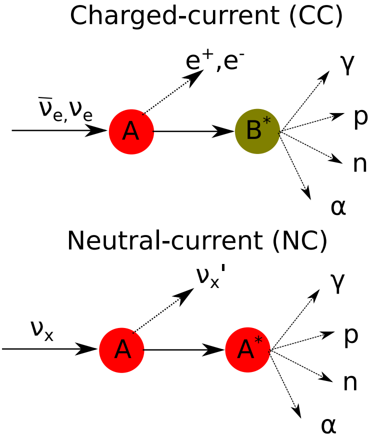

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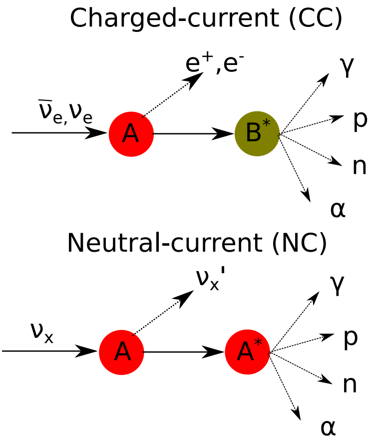
- Particle evaporation



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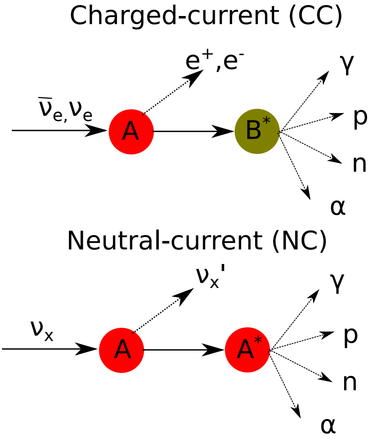

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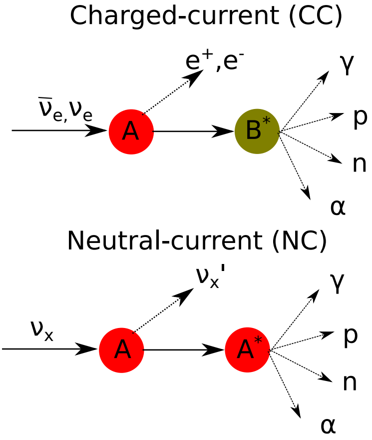
- Sensitive to all neutrino flavors (also those without direct detection)



Neutrino nucleosynthesis

- The supernova shock triggers photo dissociation and subsequent particle capture reactions
- ν nucleosynthesis occurs mainly in regions with sufficient neutrino fluxes but still moderate post-shock temperatures $\rightarrow$ Ne,C,He shells
- In this regions neutrinos can have been affected by **MSW flavor transformations**

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^{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$^-$)

Supernova model

- 1D parametrized explosions (KEPLER code, e.g. Heger et al. 2007)
- kinetic explosion energy $E_{\text{expl}} = 1.2 \times 10^{51}$erg

Neutrino flux

- Large nuclear network
- Exponentially decreasing neutrino luminosity
- Two sets of neutrino energies
- Thermal Fermi-Dirac spectrum, time independent
- Extended set of ν-nucleus cross-sections

High energies

- $\langle E_{\nu_e} \rangle = 12$ MeV
- $\langle E_{\bar{\nu}_e} \rangle = 15$ MeV
- $\langle E_{\nu,\bar{\nu}_{\mu,\tau}} \rangle = 19$MeV

Low energies

- $\langle E_{\nu_e} \rangle = 9$ MeV
- $\langle E_{\bar{\nu}_e} \rangle = 13$ MeV
- $\langle E_{\nu_{\mu,\tau}} \rangle = 13$ MeV

Evaluation of CCSNe nucleosynthesis calculations

- The solar abundances provide observational information for nucleosynthesis results to compare with

Production factor

- $P_{A,\text{normalized}} = \left(\frac{X_A}{X_A^{\odot}}\right) / \left(\frac{X_{^{16}\text{O}}}{X_{^{16}\text{O}}^{\odot}}\right)$

Assuming that CCSNe are the main source of solar ^{16}O

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

Production factors normalized to ^{16}O

- Averaged production factor for 13-30 $M_\odot$ stars (solar metallicity)

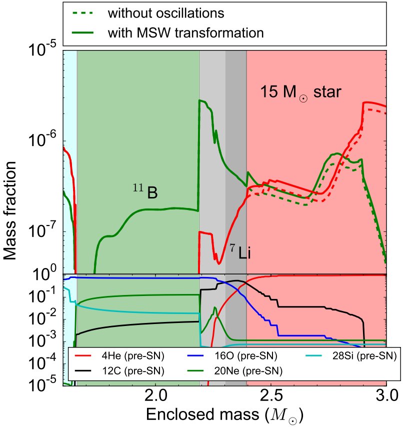
Nucleus	no ν	Low energies[1]	High energies[2]	
^{7}Li	0.001	0.07	0.91	^{4}He(ν,ν' p/n)
^{11}B	0.005	0.45	1.81	^{12}C(ν,ν' p/n)
^{15}N	0.06	0.09	0.15	^{16}O(ν,ν' p/n)
^{19}F	0.12	0.25	0.40	^{20}Ne(ν,ν' p/n)
^{138}La	0.12	0.86	1.70	^{138}Ba(ν_e,e$^-$)
^{180}Ta*	0.6	1.49	2.67	^{180}Hf(ν_e,e$^-$)

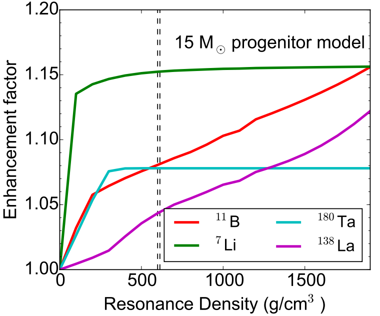
- 1) $\langle E_{\nu_e} \rangle = 9$ MeV, $\langle E_{\bar{\nu}_e,\nu_x} \rangle = 13$ MeV
- 2) $\langle E_{\nu_e} = 13$MeV ,$\langle E_{\bar{\nu}_e} \rangle = 16$ MeV, $\langle E_{\nu_x} \rangle = 19$ MeV
- *) Only about 40% of ^{180}Ta survive in the long-lived isomeric state

Effect of MSW flavor transformations

MSW flavor transformations can lead to an almost complete conversion of $\nu_e \leftrightarrow \nu_{\mu,\tau}$ (Normal mass hierarchy)

- $\rho_{\text{res}} Y_e \propto \Delta m_{13}^2 \cos 2\theta_{13} \, E_\nu^{-1} \approx 630 \text{ g cm}^3$ for $E_\nu = 50\text{MeV}$

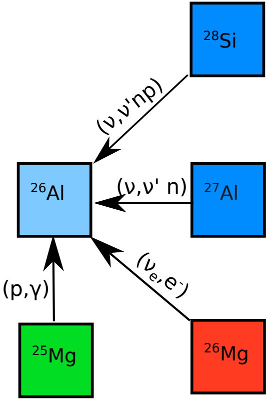


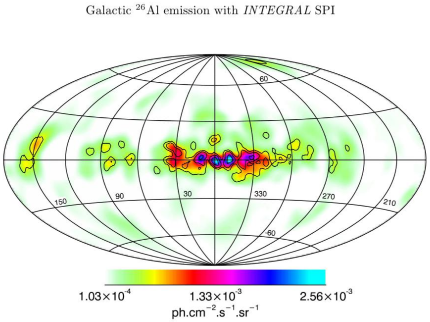


- Sensitive to θ_{13}
- Very small effect

Outline

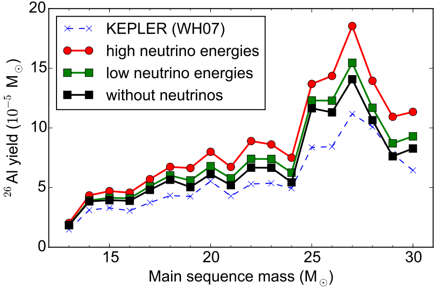
Production channels for ^{26}Al in the ν process

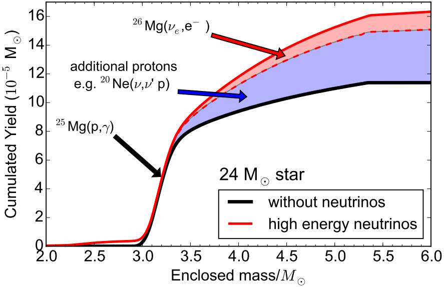




- Different mechanisms:
  - enhancement of p-captures
  - charged-current channel
  - neutral-current channels

Contribution to the production of radioactive nuclei





- ^{60}Fe/^{26}Al $\approx$ 1.25 (Observations give $\approx$ 0.35)
- Further contributions from less massive stars, Wolf-Rayet stars, rotating stars

Isotope	without ν	low energy ν	high energy ν
^{26}Al	5.19	5.64	6.56
^{22}Na	0.20	0.27	0.39

- ^{22}Na with a half life of 2.6 yr is affected similarly

Conclusions

- Core-Collapse supernovae are an ideal laboratory to study neutrino properties
- Impact on nucleosynthesis in the neutrino driven wind and the ν process
    - Production of nuclei between Zn and Mo in NDW
    - Light elements in the ν process
    - Increased production of radioactive nuclei (e.g. ^{26}Al)
- Neutrino Oscillations seem to have a minor impact on nucleosynthesis results, but the impact of newly discovered instabilities need to be explored

Neutrino properties are important to understand astrophysical phenomena