The ν process with time-dependent neutrino spectra

A. Sieverding[1], G. Martínez-Pinedo[3,2],
K. Langanke[3,2], A. Heger[4], R. Bollig[5], H.-T. Janka[5], W. R. Hix[6,7],
J.A. Harris[6], Y.-Z. Qian[1]

[1] *University of Minnesota, Minneapolis*
[2] *Technical University Darmstadt*
[3] *GSI Helmholtzzentrum, Darmstadt*
[4] *Monash Centre for Astrophysics, Melbourne*
[5] *Max-Planck-Institut fur Astrophysik, Garching*
[6] *Oak-Ridge National Lab*
[7] *University of Tennessee*

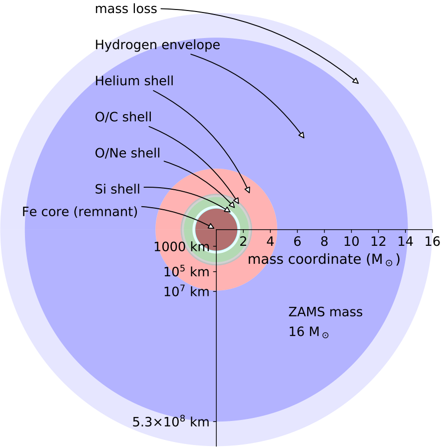
UNIVERSITY OF MINNESOTA
Driven to Discover®

GSI

SN neutrinos at the crossroads, ECT*
May 15th 2019

Neutrinos and supernovae

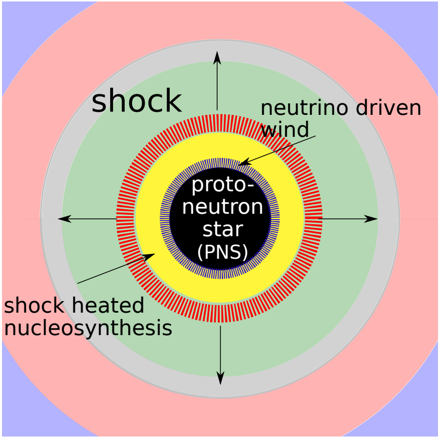
- Stellar processes and supernovae are an important site for nucleosynthesis
- During hydrostatic burning phases,energy release by nuclear reactions balances gravity
- Massive stars (> 8-$10\ M_\odot$) complete all major burning phases
- "Onion" shell structure Fe, Si, O/Ne, O/C,C/O, He, H shells



No energy release by fusion beyond iron → core-collapse

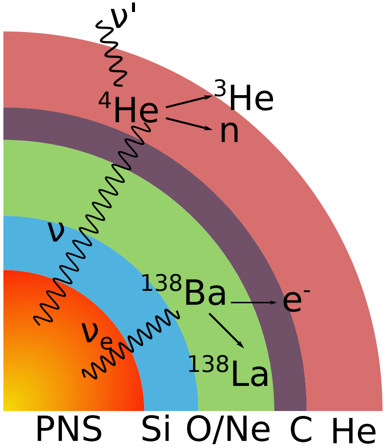
Neutrinos and supernovae

- Collapse stops when nuclear densities are reached
- Convective neutrino heating revives standing accretion shock
- Explosive nucleosynthesis and ejection
- Neutrinos influence nucleosynthesis
  - ν process
  - Conditions of the innermost ejecta



- *Inset from Pan et al. (2016)*

The ν process



- Emission of 10^{58} neutrinos from the proto-neutron star
- Produced by electron captures, pair annihilation, bremsstrahlung
- $\langle E_\nu \rangle \approx 8 - 20$ MeV
- Inverse β-decay
- Particle evaporation
- Light reaction products induce further nuclear reactions

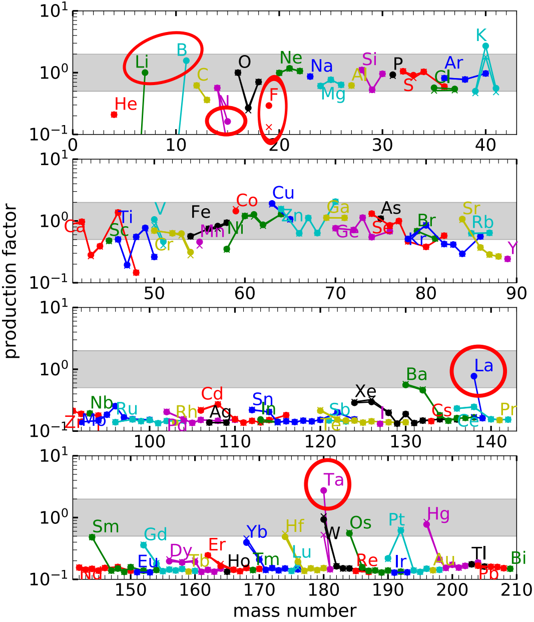
Neutrino nucleosynthesis

- Neutrino-nucleus interactions in the outer layers produce several key isotopes *Woosley et al. (1990)*
- Several studies have improved on individual reactions and included neutrino oscillations *e.g. Heger et al. (2005), Yoshida et al. (2006), Suzuki et al. (2013), AS+ (2018), Kusakabe et al. (2019), Ko et al. (2019)*

Product	Parent	Reaction
^{7}Li	^{4}He	$^{4}\mathrm{He}(\nu,\nu' p)^{3}\mathrm{H}(\alpha,\gamma)^{7}\mathrm{Li}$ $^{4}\mathrm{He}(\nu,\nu' n)^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}$
^{11}B	^{12}C	$^{12}\mathrm{C}(\nu,\nu' n)^{11}\mathrm{C}$, $^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B}$
^{19}F	^{20}Ne	$^{20}\mathrm{Ne}(\nu,\nu' n)^{19}\mathrm{Ne}(\beta^{+})^{19}\mathrm{F}$, $^{20}\mathrm{Ne}(\nu,\nu' p)^{19}\mathrm{F}$
^{138}La	^{138}Ba	$^{138}\mathrm{Ba}(\nu_e,e^{-})^{138}\mathrm{La}$
^{180}Ta	^{180}Hf	$^{180}\mathrm{Hf}(\nu_e,e^{-})^{180}\mathrm{Ta}$

Neutrinos in a nuclear reaction network

- Evolution of isotopic abundances with an nuclear reaction network including neutrino-nucleus reactions
- Rate for a neutrino induced rection:
  $r_{ij} \propto \phi_\nu(t) \int \sigma_{\nu,ij}(E_\nu) f_\nu(E_\nu, t) dE_\nu$
- Observational data on the neutrino emission spectra is very limited
- Commonly used approach:
  - Fixed spectrum $r_{ij} = \phi_\nu(t) \langle\sigma_{\nu,ij}\rangle(\langle E_\nu\rangle)$
  - Parametrized flux: $\phi_\nu(t) \propto e^{-t/\tau}/r(t)^2$
  - Motivated by the long-term PNS cooling phase (10s)



Production factor

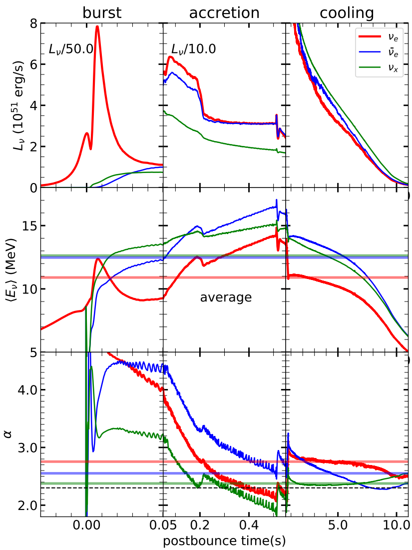
$$P_A = \left(\frac{X_A}{X_A^{\odot}}\right) / \left(\frac{X_{^{16}\mathrm{O}}}{X_{^{16}\mathrm{O}}^{\odot}}\right)$$

- Production factors averaged for stars with 13-30 $M_{\odot}$
- Piston-driven supernova models with parametrized neutrino emission
- Further contributions to radioactive isotopes *(e.g. AS+ 2018)*

Neutrino spectra

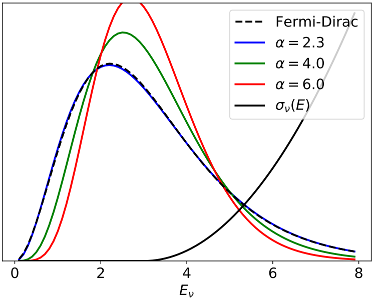
Improved treatment

- Neutrino emission as predicted by a supernova simulation with spectral neutrino transport
  (Simulation by R. Bollig, published in Mirizzi et al. 2016)
- Distinct characteristics of Deleptonization burst, accretion phase and cooling
- Time-dependent average energy
- “pinched” neutrino spectra ($\alpha(t)$)



Pinched spectra

- Neutrino spectra are expected to be pinched (e.g., Janka et al. 1989)
- Simple fit $f_\nu(E_\nu) \propto \left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^\alpha \exp\left[-(\alpha+1)E_\nu/\langle E_\nu\rangle\right]$ (e.g., Keil et al. 2003)
- with $\frac{\langle E_\nu^2 \rangle}{\langle E_\nu \rangle^2} = \frac{2+\alpha}{1+\alpha}$, $\alpha \approx 2.3$ is close to Fermi-Dirac
- Models typically find $\alpha > 2.3$, i.e., the high energy tail of the distribution is depleted



- Neutrino nucleus cross-sections are reduced

- Need to calculate $\langle \sigma_{\nu,ij} \rangle$ on the fly (for a limited set of reactions)

Production factors

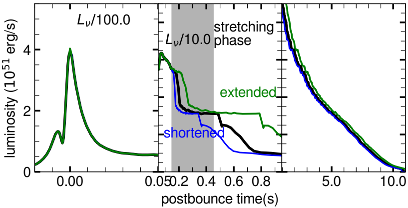
$$P = \frac{X_*(A,Z)/X_\odot(A,Z)}{X_*(^{16}\mathrm{O})/X_\odot(^{16}\mathrm{O})}$$

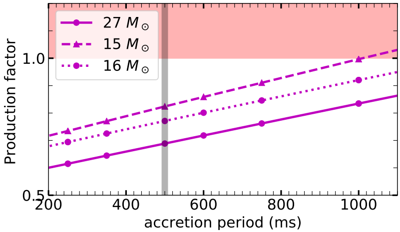
- Results for a 27 $M_\odot$ progenitor model

	parametrized PNS cooling +fixed spectrum	early phases +time-dependence	pinching
^{7}Li	0.02	0.04	0.04
^{11}B	0.18	0.31	0.30
^{19}F	0.10	0.12	0.12
^{138}La	0.41	0.74	0.69
^{180}Ta$^{\mathrm{m}}$	1.09	1.33	1.32

- Up to 40% of the ν-process production due to the first 500 ms
- Pinching leads to a small reduction, strongest for charged current reactons of ν_e

AS+ (2019)

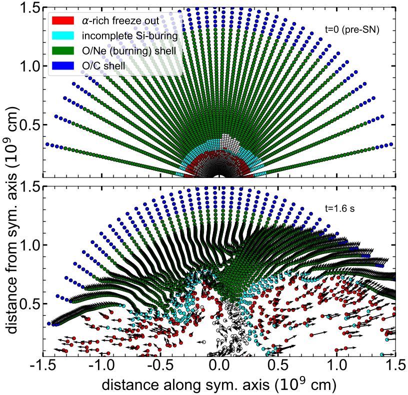




- Explore sensitivity to modifications of the accretion phase
- ^{138}La is the most sensitive
- Very fast or prompt explosions as well as very late explosions would lead to an overproduction or lack of ^{138}La compared to the solar abundances

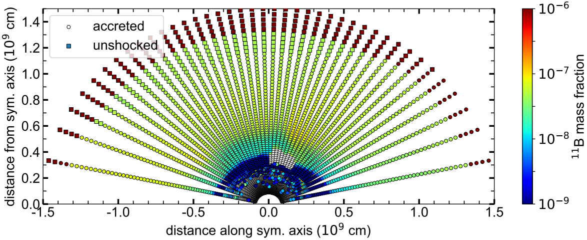
Self-consistent simulations

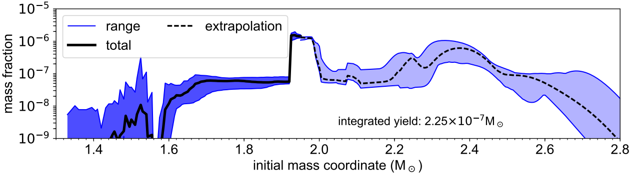
- Innermost ejecta can only be modeled self-consistently in multidimensional simulaitons
- Subject to the most intense neutrino irradiation
- Post-processing of tracer particles
- Large fraction of the innermost ejecta are α-rich and affected by the ν process
- Neutrino fluxes and energies consistent with the explosion
- Tracer particles from a 2D axisymmetric simulation with CHIMERA (Bruenn et al. 2016, Harris et al. 2017)



- based on a 12 $M_\odot$ progenitor

Production of light elements





- Small contribution from the innermost ejecta to the production of ^{7}Li and ^{11}B
- Low explosion energy gives large ν process yields (AS+ (2018))

Conclusions & Outlook

- Study of ν process nucleosynthesis for the first time using the full wealth of information from modern supernova simulations
- High energy neutrinos from the early phases of neutrino emission are important for the ν-process yields
- Spectral pinching has minor effects
- Nucleosynthesis based on self-consistent multidimensional simulations become possible
- Small contribution of the ν process from the innermost supernova ejecta (based on 2D simulations)

Neutrino oscillations

- Neutrino mass eigenstates are not the same as flavor eigenstates
- Neutrino-matter interactions lead to strong flavor conversion (MSW effect)
- Neutrino-neutrino interactions induce collective oscillations

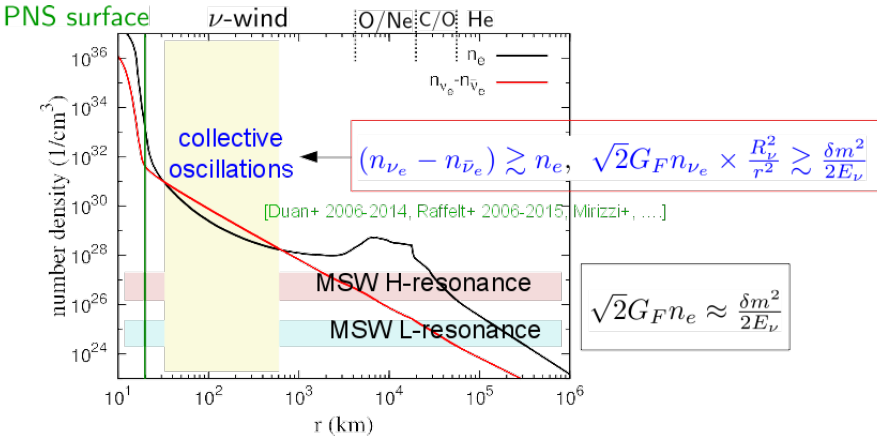
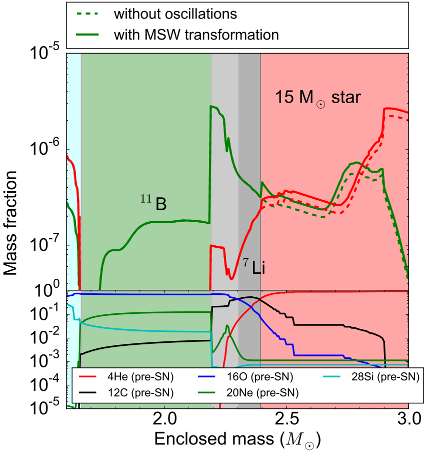


Figure: courtesy M.-R. Wu

Effects on the ν process

- Effects of MSW flavor transformations have been studied *(e.g. Yoshida et al. 2006)*
- Recent works include collective oscillations and find and increased production of ^{138}La by a factor 3 *(Ko et al. 2019)*
- Currently no fully consistent models for collective oscillations
- "Fast" oscillations may happen very close to the neutrino-sphere *(e.g. Sawyer 2016, Sen et al. 2019)*



- Minor effects on ^{7}Li and ^{11}B