Report B06

Neutrinos and Supernova Nucleosynthesis

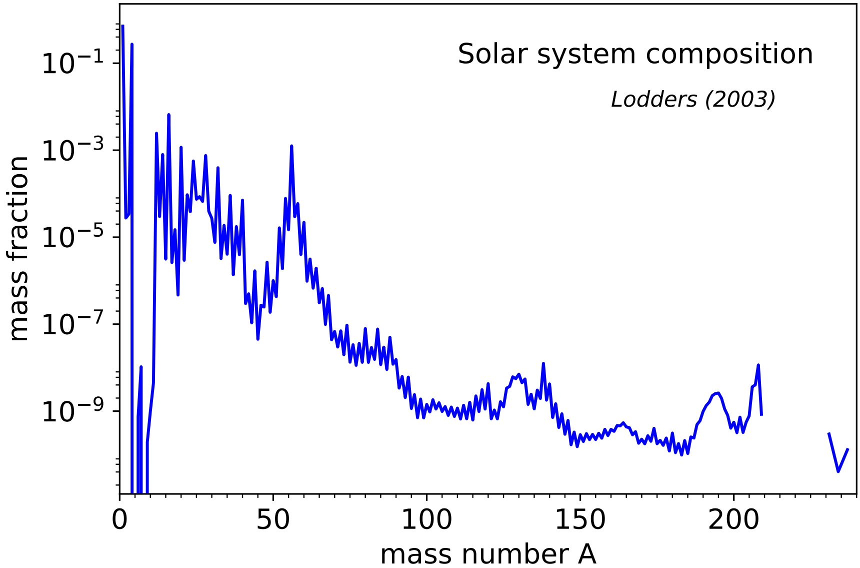
A. Sieverding

SFB 1245 Workshop
October 5th 2017

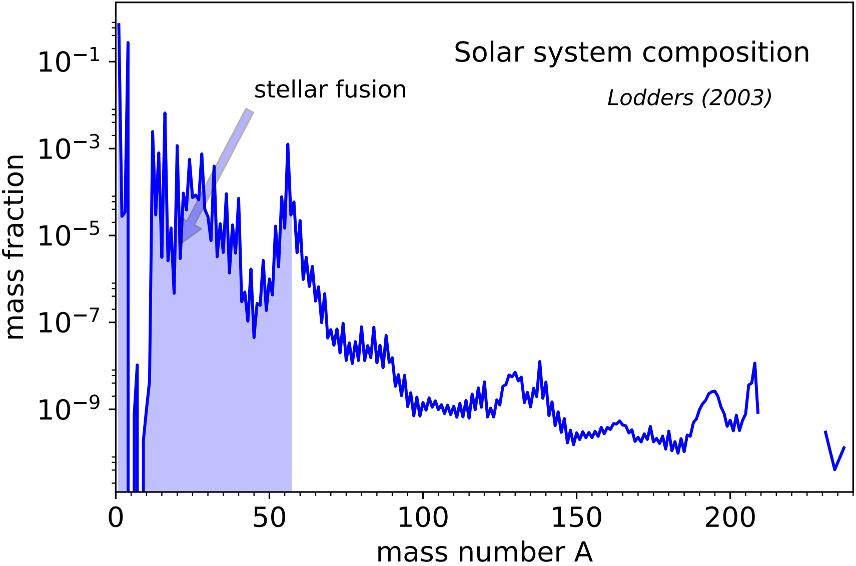
Outline

1. Introduction
   - The role of neutrinos in Supernova explosions
2. Results
   - Mircrophysics for Supernova explosions
   - Neutrino nucleosynthesis
   - The ν process in 2D
   - Nucleosynthesis in neutrino driven winds
3. Conclusions

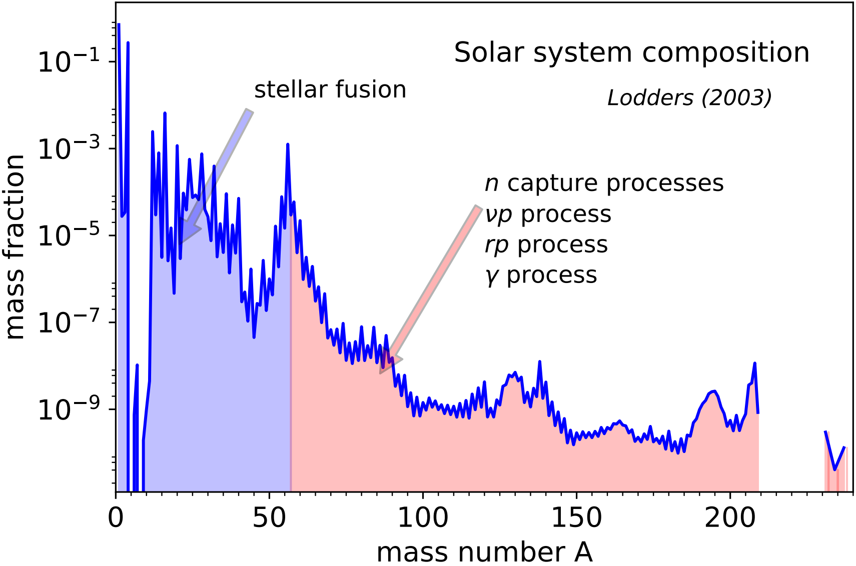
The Challenge of Nucleosynthesis



The Challenge of Nucleosynthesis

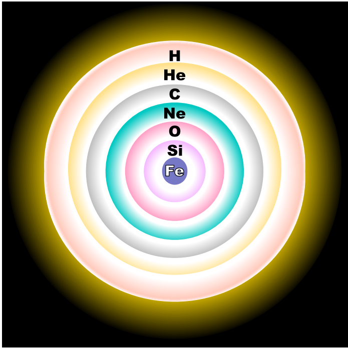


The Challenge of Nucleosynthesis



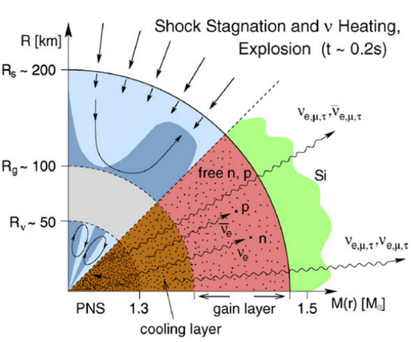
Neutrinos and Supernovae

- Massive stars form an Fe core
- Core collapse and bounce
- Bounce shock stalls
- Core emits neutrinos
- Neutrinos can revive the shock
- and influence the nucleosynthesis in outer layers of SNe



Schematic structure of a massive star

The ν driven mechanism



- Neutrinos deposit energy behind the stalled shock
- Multi-D effects and High **neutrino luminosities** L_ν favor explosions

- Three dimensional supernova simulations are very sensitive to variations of 10-20% in neutrino opacities (*Melson et al. 2015*)

Microphysics vs multidimensional supernova

- Most studies focus on neutral current neutrino-nucleon scattering:

$$\frac{1}{V}\frac{d\sigma}{d\Omega} \approx \frac{G_F^2 E_\nu^2}{16\pi^2}\left[c_a^2(3-\cos\theta)S_A + c_v^2(1+\cos\theta)S_V\right]$$

  - Reduction due to strangeness contribution to axial-vector coupling constant (*Melson et al. 2015, Hobbs et al. 2016)*:

$$c_a = \pm g_A - g_s, \quad g_s = -0.103 \pm 0.013$$

  - Reduction of structure factors due to correlations at low densities (Virial expansion *Horowitz et al. 2017*)
- Additional degrees of freedom: muons, pions, hyperons, . . .

“Muonization” of the core

- Muons have a relatively high mass $m_\mu c^2 = 105.66$ MeV

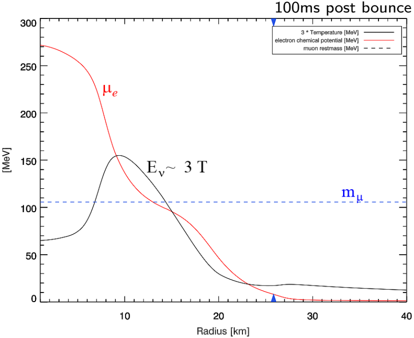
Thermal processes are subdominant

- $\gamma + \gamma \rightleftarrows \mu^+ + \mu^-$
- $e^- + e^+ \rightleftarrows \mu^+ + \mu^-$

Weak processes

- $\nu_\mu + e^- \rightleftarrows \nu_e + \mu^-$
- $\nu_\mu + e^- + \bar{\nu}_e \rightleftarrows \mu^-$
- $\bar{\nu}_e + e^- \rightleftarrows \bar{\nu}_\mu + \mu^-$
- $\nu_\mu + n \rightleftarrows p + \mu^-$
- ...

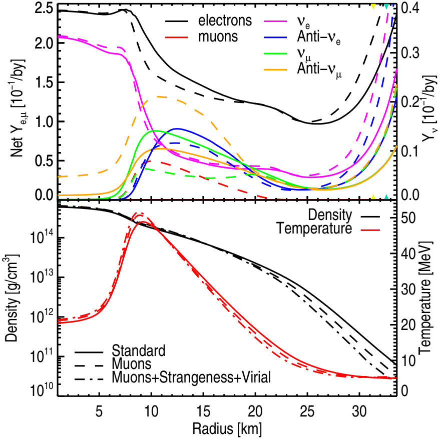
A. Lohs (2015)



- Weak processes profit from chemical potentials and mean field effects

Impact on 2D simulations

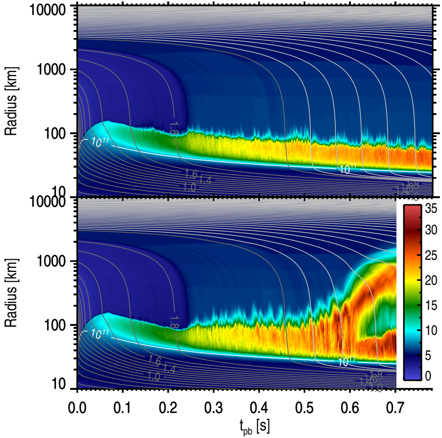
Bollig et al. 2017 (arXiv:1706.04630)



- Radial profile at 400 ms after bounce

- Six flavor neutrino transport with muonic reactions
- Appearance of net μ^- abundance

Impact on 2D simulations



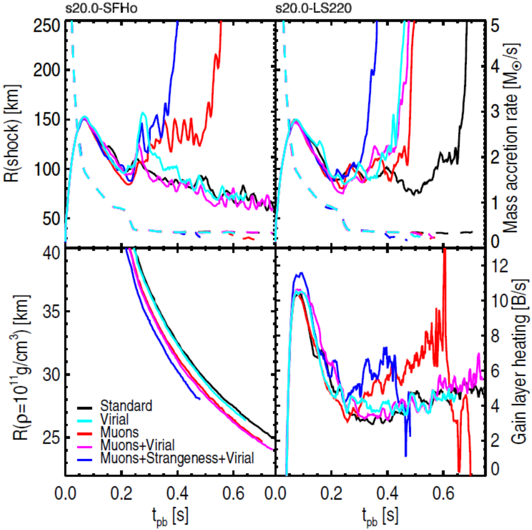
Bollig et al. 2017 (arXiv:1706.04630)

- Angle averaged entropy for a 20 $M_\odot$ star with and without muons

- Six flavor neutrino transport with muonic reactions
- Appearance of net μ^- abundance
- Thermal energy is converted into muon rest mass energy
- Electron degeneracy is reduced
- Proto-neutron star shrinks faster
- Increased neutrino luminosity and energy
- Can turn a non-exploding model into an exploding one

2D simulations: shock evolution

- Inclusion of muons favors the explosion
- Strangeness corrections also favor explosions
- Role of virial correlations uncertain.



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Neutrino Luminosities

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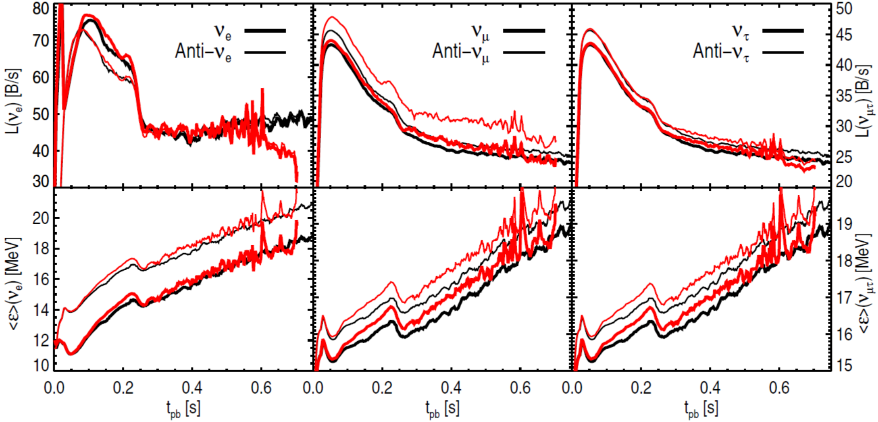
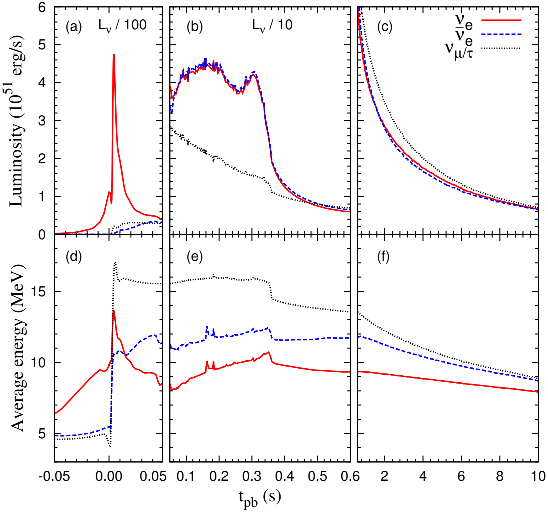


- $\bar{\nu}_\mu$ luminosities and energies are increased

Neutrino Luminosities

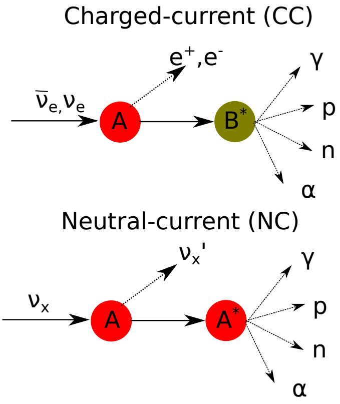


Wu et al. 2015

- High neutrino energies and Luminosities during the early phase
- Emission of 10^{58} neutrinos from the collapsing core
- Neutrino emission continues for 10s
- Energies decrease
- Neutrinos irradiate the outer layers of the star

Neutrino nucleosynthesis

- $\langle E_\nu \rangle \approx 8 - 20$ MeV
  - Inverse β-decay
  - Particle evaporation
  - Capture of spallation products
- 1D artificial explosions (Woosley et al. 2007)
- Suitable for nucleosynthesis studies
- Explosion energy $E_{\text{expl}} = 1.2 \times 10^{51}$erg



Modeling the neutrino emission

$L_\nu \propto e^{-t/\tau}$, Fermi-Dirac spectrum, constant neutrino energies

Neutrino nucleosynthesis: ν process

Neutrino-nucleus interactions in the outer layers produce several key isotopes (Woosley+ 1990, Heger+ 2005, Suzuki+ 2013)

Product	Parent	Reaction
^{7}Li	^{4}He	$^{4}\mathrm{He}(\nu,\nu' p)^{3}\mathrm{H}(\alpha,\gamma)^{7}\mathrm{Li}$ $^{4}\mathrm{He}(\nu,\nu' n)^{3}\mathrm{He}(\alpha,\gamma)^{7}\mathrm{Be}(e^{-},\nu_e)^{7}\mathrm{Li}$
^{11}B	^{12}C	$^{12}\mathrm{C}(\nu,\nu' n)^{11}\mathrm{C}(\beta^{+})^{11}\mathrm{B}$, $^{12}\mathrm{C}(\nu,\nu' p)^{11}\mathrm{B}$
^{15}N	^{16}O	$^{16}\mathrm{O}(\nu,\nu' n)^{15}\mathrm{O}(\beta^{+})^{15}\mathrm{N}$, $^{16}\mathrm{O}(\nu,\nu' p)^{15}\mathrm{N}$
^{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	$^{138}\mathrm{Ba}(\nu_e,e^{-})^{138}\mathrm{La}$, $^{138}\mathrm{Ba}(\nu_e,e^{-} n)^{137}\mathrm{La}(n,\gamma)^{138}\mathrm{La}$
^{180}Ta	^{180}Hf	$^{180}\mathrm{Hf}(\nu_e,e^{-})^{180}\mathrm{Ta}$

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^{180}Ta	^{180}Hf	$^{180}\mathrm{Hf}(\nu_{e},e^{-})^{180}\mathrm{Ta}$

Nucleosynthesis yields

- So far studies have assumed large average neutrino energies
- Modern supernova simulations predict lower average energies

High energies	Low energies
$\langle E_{\nu_e} \rangle = 12.6$ MeV	$\langle E_{\nu_e} \rangle = 8.8$ MeV
$\langle E_{\bar{\nu}_e} \rangle = 15.8$ MeV	$\langle E_{\bar{\nu}_e} \rangle = 12.6$ MeV
$\langle E_{\nu_{\mu,\tau}} \rangle = 18.9$ MeV	$\langle E_{\nu_{\mu,\tau}} \rangle = 12.6$ MeV

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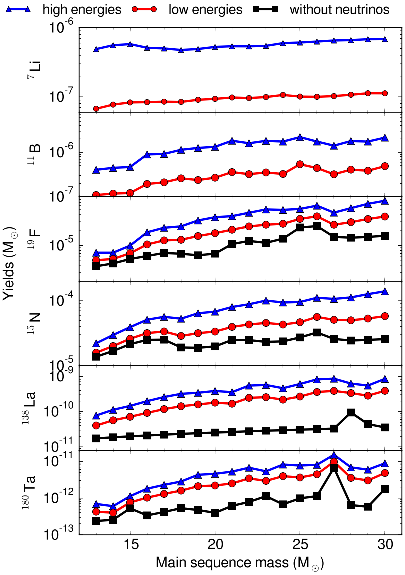

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Yields normalized to ^{16}O and averaged over initial mass function.

Nucleus	no ν	Low energies	High energies
^{7}Li	0.002	0.07	0.45
^{11}B	0.008	0.36	1.54
^{15}N	0.05	0.07	0.13
^{19}F	0.12	0.19	0.33
^{138}La	0.12	0.59	1.29
^{180}Ta	0.19	0.49	0.88

Sieverding et al., in preparation

Production factor

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

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- ^{7}Li and ^{15}N barely produced by the ν process
- ^{11}B consistent with expected yields from cosmic rays (Austin et al. 2011)
- ^{19}F is expected to be produced mainly in AGB stars
- ^{138}La and ^{180}Ta have also contributions from s process.

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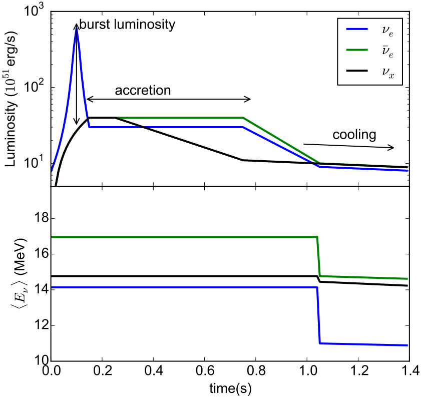
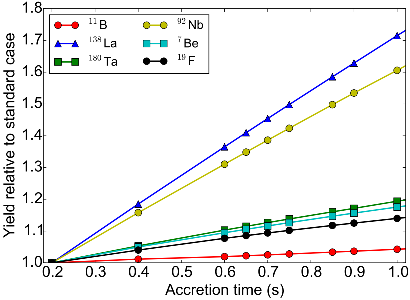
Sensitivity to Supernova dynamics

- So far, only cooling phase taken into account for the ν process



- 3D simulations show delayed explosions
- High neutrino energies during burst and accretion



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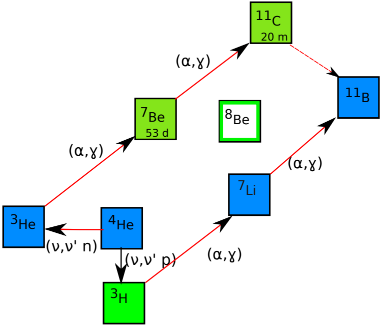
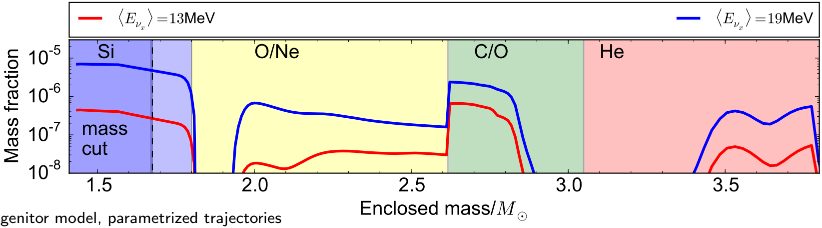
Production of ^{11}B



1. Si shell (NSE)
    - α-rich freeze-out
    - Spallation of ^{4}He
2. O/Ne shell
    - Production from ^{12}C and ^{16}O
3. C/O shell
    - Production from ^{12}C
4. He shell
    - Spallation of ^{4}He



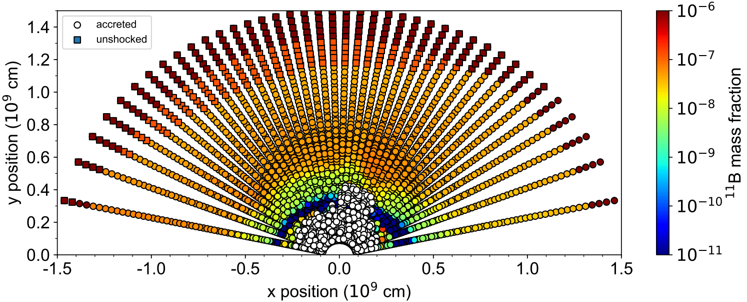
15 $M_\odot$ progenitor model, parametrized trajectories

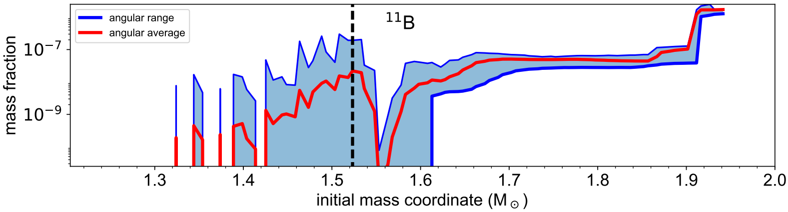
The ν process in 2D

- Possibly stronger exposure due to convective motion

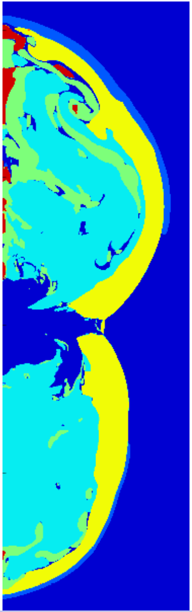
- 2D axisymmetric simulation with CHIMERA (ORNL group, Bruenn et al. 2016, Harris et al. 2017)
- Nucleosynthesis calculations with lagrangian tracer particles
- based on a non-rotating 12 $M_\odot$ progenitor of solar metallicity (Woosley et al. 2007)
- Neutrino fluxes and energies from the simulation calculated with a multi-group flux-limited diffusion method

2D effects on ^{11}B production





Status CCSN Simulations



- Implement Approximate Neutrino scheme ASL (Perego et al 2016) — Done!
- Extend Simulation Domain to low temperature and density (Yasin) — Done!
- Place tracers on output (Witt) — Done!
- Cut inner zone — in preparation
- Comparison ASL vs M1 (Mattes et al. in preparation)
- Simulations up to several seconds in production

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Nucleosynthesis in neutrino driven winds

Neutrino interactions determine Y_e

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

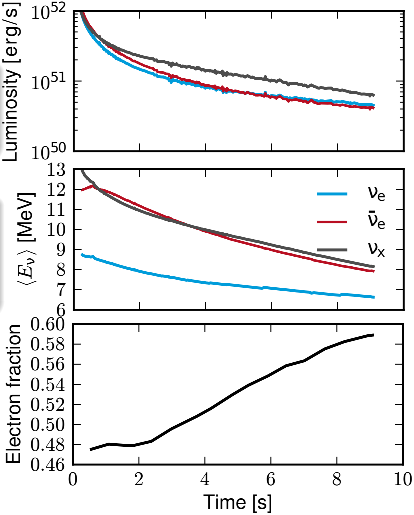
Neutron-rich ejecta:

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

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

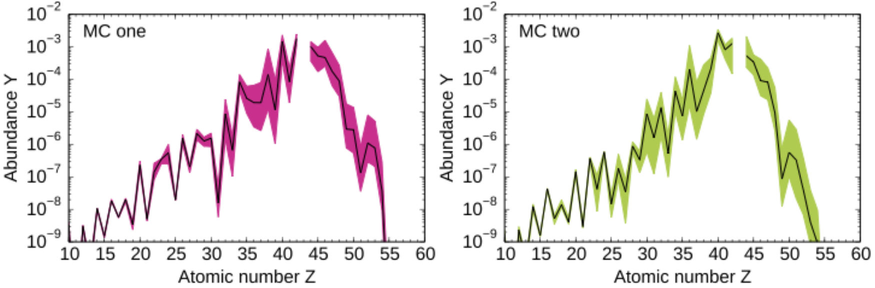
Energy difference related to symmetry energy (Martínez Pinedo et al. 2012, Roberts et al. 2012)

1D Boltzmann transport simulation



Martínez Pinedo et al. 2013

MC Sensitivity study in neutron rich winds

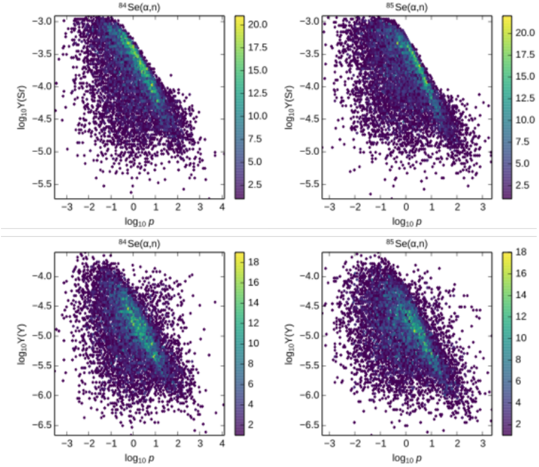


J. Bliss et al. in preparation

- Independently vary each (α, n) reaction rate between Fe and Rh by a random factor
- 10,000 Monte Carlo runs
- Representative trajectory for ν driven winds
- **MC one & MC two**: impact on **Z=36-39**
  - → **important for wind nucleosynthesis**
- **MC three**: impact on **Z=28-35**
  - → **relevant for explosive nucleosynthesis**

Monte Carlo Sensitivity study in neutron rich winds

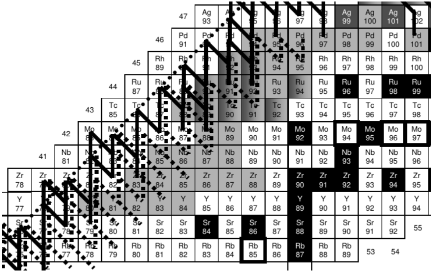
- ^{82}Ge(α, *n*), ^{84}Se(α, *n*), ^{85}Se(α, *n*) significantly influence the abundances for **Z=36-39**
- Measurement of ^{85}Ga(α, *n*) at ReA3 (NSCL/MSU) in July 2016
- Accepted proposal for measurement of ^{85}Br(α, *n*)

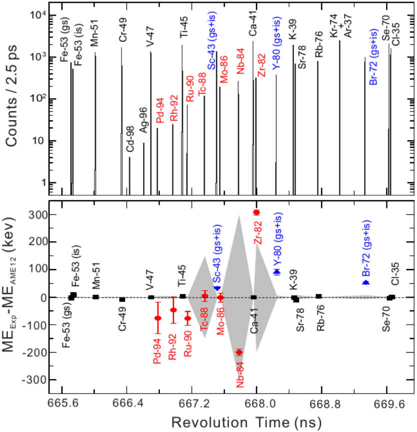


J. Bliss et al. in preparation

New experimental masses for the νp process

Weber et al. (2008)



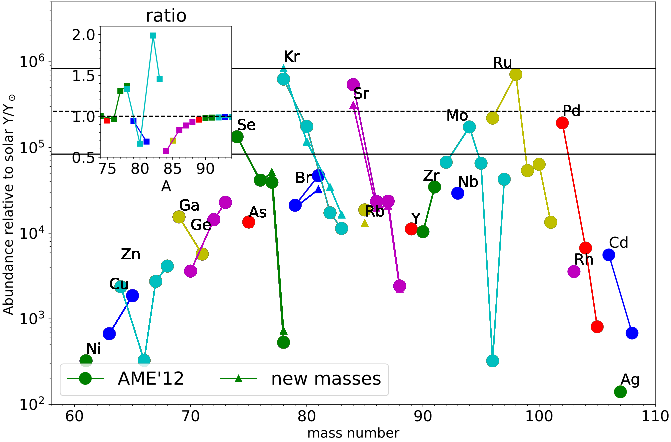


- νp process produces p-nuclei
- Measurement of ^{79}Y, ^{81}Zr, ^{82}Zr, ^{83}Nb, ^{84}Nb at the Cooler Storage Ring (CSR) in Lanzhou

Y. M. Xing et al. (submitted)

νp with updated experimental masses

- Masses of ^{82}Zr and ^{84}Nb measured for the first time
- Improved values for ^{79}Y, ^{81}Zr and ^{83}Nb
- Impact on the reaction rates relevant for the νp process



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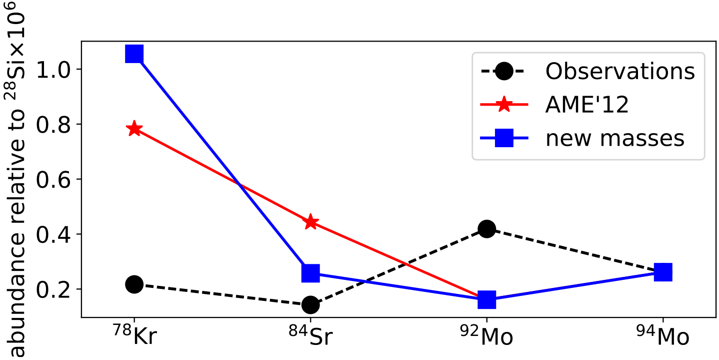

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- Study of neutrino induced nucleosynthesis for piston driven explosions in 1D with improved neutrino-nucleus cross-sections and modern estimates for neutrino energies
- Study of the ν process with neutrino properties consistent with the underlying explosion model in 2D

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- Muon creation in the core helps the explosion
- Study of neutrino induced nucleosynthesis for piston driven explosions in 1D with improved neutrino-nucleus cross-sections and modern estimates for neutrino energies
- Study of the ν process with neutrino properties consistent with the underlying explosion model in 2D
- Monte Carlo Sensitivity study for (α, n) reaction rates to guide future experiments
- Study the effect of nuclear masses on νp process nucleosynthesis in neutrino driven winds

B06: Nucleosynthesis in core-collapse supernovae

Thanks for your Attention

A. Arcones, G. Martínez-Pinedo
J. Bliss, M. Eichler, J. Keller, D. Martin, C. Mattes, M. Reichert,
A. Sieverding, M. Witt, H. Yasin