The effect of fast neutrino flavor conversions on Neutrino-driven wind and Supernova nucleosynthesis

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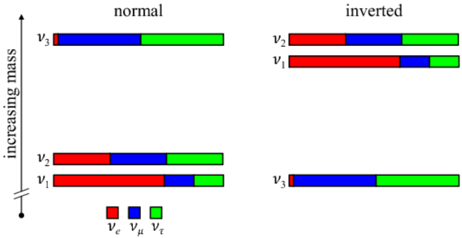
Neutrino flavor transformations

- Neutrino mass and weak interaction eigenstates are not the same
- Rich physics of neutrino flavor transformations ($\nu_e \leftrightarrow \nu_{\mu,\tau}$, $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$)
- ν-matter and $\nu - \nu$ interactions can induce flavor instabilities



- *Image credit: KM3NeT collaboration*

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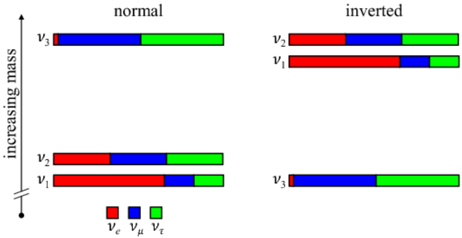
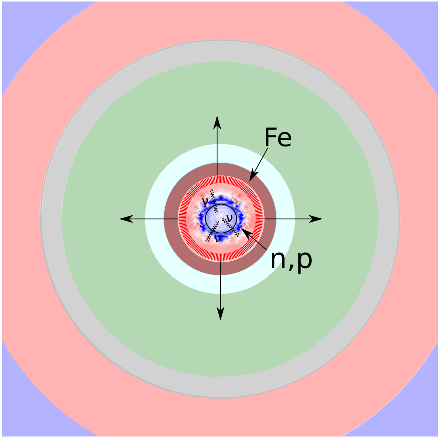
- Rich physics of neutrino flavor transformations ($\nu_e \leftrightarrow \nu_{\mu,\tau}$, $\bar{\nu}_e \leftrightarrow \bar{\nu}_{\mu,\tau}$)
- ν-matter and $\nu - \nu$ interactions can induce flavor instabilities
- **"Fast" neutrino flavor transformations may occur on very short scales and at high matter densities**



- *Image credit: KM3NeT collaboration*
- **Potential effect on the production of the elements in Supernovae**

Neutrinos and supernovae

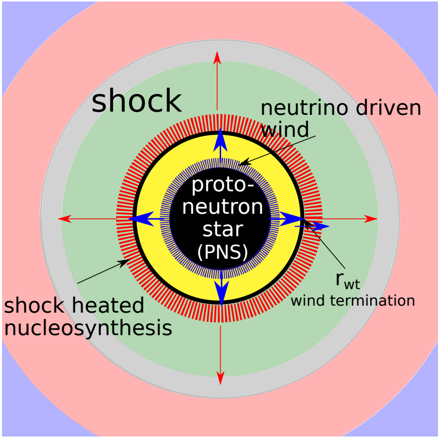
- Fe core of a massive star ($\geq 8 - 10\, M_\odot$) collapses until nuclear densities are reached
- Strong neutrino emission from electron captures and cooling ($\sim 10^{56}$/s)
- Bounce shock stalls (ν losses, nuclear dissociation)
- Neutrino heating induces turbulence and revives the explosion



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

Neutrinos and supernovae

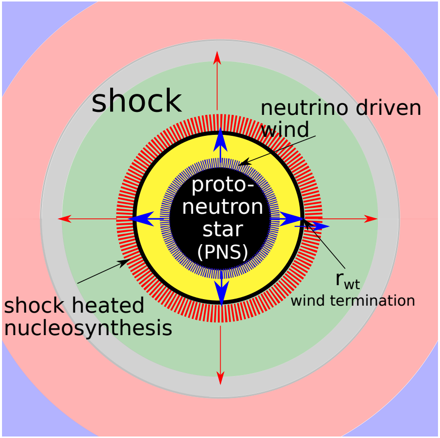
- Three sites of nucleosynthesis
  1. Inner, neutrino heated, shock-driven ejecta
  2. Outer shock-driven ejecta
  3. **Neutrino driven wind (NDW)**



Inset from Pan et al. (2016)

Neutrinos and supernovae

- Three sites of nucleosynthesis
  1. Inner, neutrino heated, shock-driven ejecta
  2. Outer shock-driven ejecta
  3. **Neutrino driven wind (NDW)**
- NDW: Fast, hot matter outflow from the PNS surface: few $10^{-3} M_\odot$
- NDW is determined by long-term neutrino cooling of the PNS, decoupled from the explosion mechanism
- Neutrinos determine Y_e of the ejecta

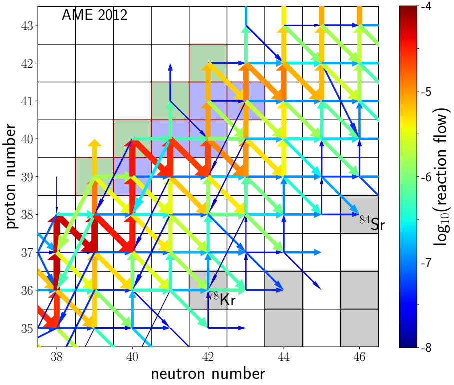


Inset from Pan et al. (2016)

- Wind slows down as it catches up with the shocked ejecta

Nucleosynthesis conditions: νp process

- NDW is expected to be proton-rich ($Y_e > 0.5$)
- Proton capture nucleosynthesis inhibited by long β^+ decay lifetimes
- If neutrons are present: (n, p) instead of β^+ decay
- $\bar{\nu}_e + p \rightleftarrows n + e^+$ as neutron source



- Important quantities:
  - Initial proton-richness (Y_e)
  - p-to-seed ratio (depends on expansion timescale, entropy)
  - $\bar{\nu}_e$ exposure while the temperature is right ($3 - 1$ GK)

Steady state model for NDW

- Time-independent eigenvalue problem for mass loss rate $\dot{M}$

$$\dot{M} = 4\pi r^2 \rho v, \tag{1a}$$

$$v\frac{dv}{dr} = -\frac{1}{\rho}\frac{dP}{dr} - \frac{GM_{\mathrm{PNS}}}{r^2}, \tag{1b}$$

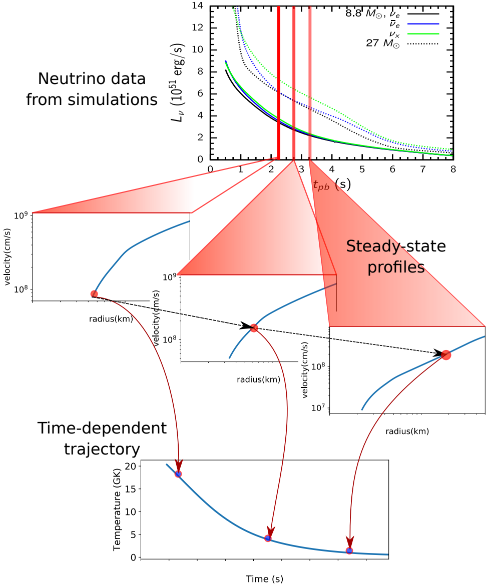
$$\frac{d\epsilon}{dr} = \frac{P}{\rho^2}\frac{d\rho}{dr} + \frac{\dot{q}}{v}, \tag{1c}$$

$$\frac{dY_e}{dr} = \frac{1}{v}[(\lambda_{\nu_e n} + \lambda_{e^+ n})Y_n - (\lambda_{\bar{\nu}_e p} + \lambda_{e^- p})Y_p], \tag{1d}$$

- Inner boundary at $R_\nu(t)$: $\dot{q} = 0$, $dY_e/dr = 0$, and $T = T_{\nu_e}$
- Outer boundary : Transonic solution, i.e., $\frac{dv}{dr} \to 0$
- **Interaction and heating based on neutrino fluxes and spectra from simulations**
- Details in *Xiong et al. (2019) ApJ* 880, *81*

Time-dependent model

- Time-dependent neutrino luminosity and spectra from simulations
- Sequence of steady state snapshots covering up to 1000 km
- Tracking "tracers" across snapshots gives time-dependent thermodynamic trajectories
- Allows to calculate total wind mass and integrated yields
- Two models: e8.8 and s27



Neutrino flavor transformations

- In a supernova, $\langle E_{\nu_{\mu,\tau}} \rangle > \langle E_{\nu_e} \rangle$
- Flavor conversion can turn high energy $\nu_{\mu,\tau}$ into ν_e
- **Two cases:**

Flavor equilibrium

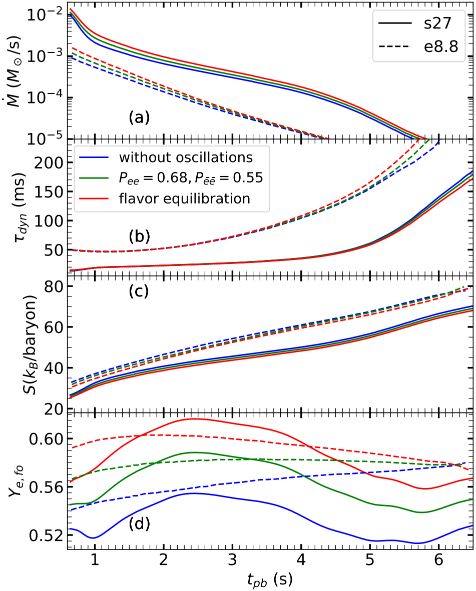
- $F_{\nu_e}^{\mathrm{osci}} = 1/3 \sum_{i=e,\mu,\tau} F_{\nu_i}^0$

Intermediate mixing

- $F_{\nu_e}^{\mathrm{osci}} = P_{ee} F_{\nu_e}^0 + (1 - P_{ee}) F_{\nu_x}^0$
- $F_{\bar{\nu}_e}^{\mathrm{osci}} = P_{\bar{e}\bar{e}} F_{\bar{\nu}_e}^0 + (1 - P_{\bar{e}\bar{e}}) F_{\bar{\nu}_x}^0$
- $P_{ee} = 0.68,\ P_{\bar{e}\bar{e}} = 0.55$

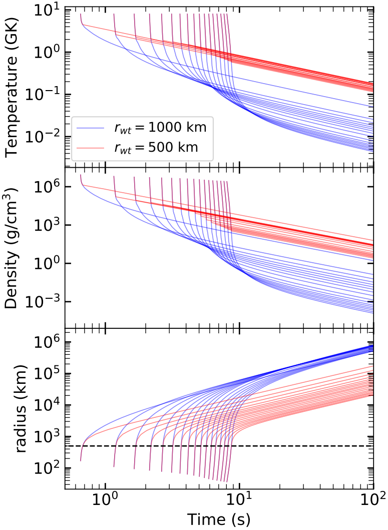
Effects on dynamics

- Flavor oscillations effectively make ν_e and $\bar{\nu}_e$ more energetic
- Charged current reacions are the main heating mechanism
- Increased wind outflow rate $\dot{M}$, increased total wind mass by up to 40%
- Otherwise, only minor changes of the dynamics
- More energetic ν_e lead to an increase of Y_e



Wind termination radius

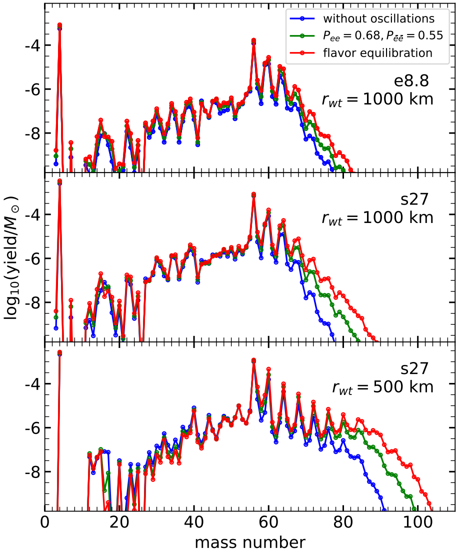
- Wind slows down when it catches up with the SN ejecta at r_{wt}
- Material spends more time in the relevant temperature range (*Wanajo et al. 2011*)
- Consistent model requires full simulation
- Simple model: switch to parametric expansion at smaller r_{wt}
- additional model: s27 with $r_{\rm wt} = 500$ km



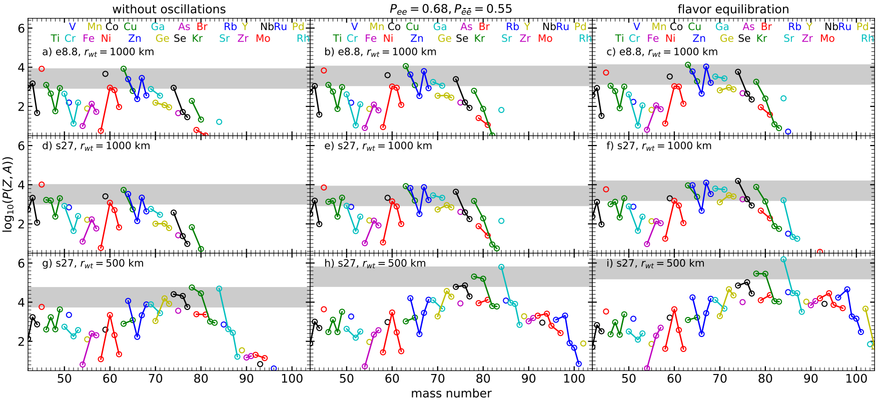
<u>In total: 3 models x 3 oscillation cases</u>

Effects on nucleosynthesis

- Standard e8.8 and s27 models ($r_{wt} = 1000$ km) show little effect of the νp process
- With $r_{wt} = 500$ km, the production of heavier nuclei is enhanced
- More energetic $\bar{\nu}_e$ favor νp process by providing more neutrons
- More energetic ν_e favor lead to higher Y_e at freeze-out
  - higher Y_e at freeze-out
  - more neutrons

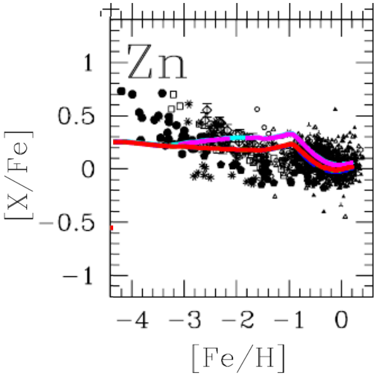


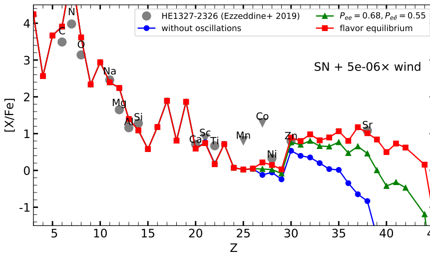
Effects on nucleosynthesis



- Significantly increased production of ^{64}Zn, ^{78}Kr, ^{84}Sr
- At most 3% of SN should produce conditions as in model s27, $r_{\rm wt} = 500$ km and flavor equilibrium to avoid overproduction of ^{84}Sr

Implications





Model s27 with $r_{wt} = 500$ km, combined with SN yields from Heger et al. (2010)

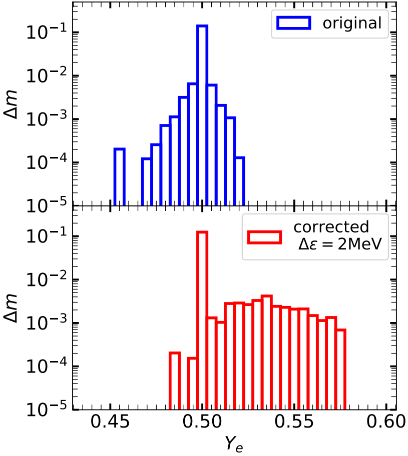
Kobayashi et al. (2020)

- High Zn abundances in metal poor stars are challenging for most supernova models
- Promising for Zn and Sr abundances in HE1327-2326

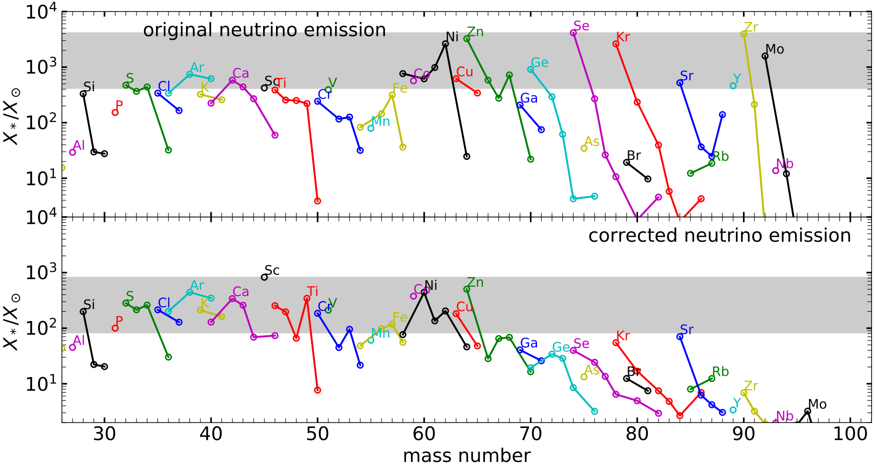
Outline

Supernova simulation

- Composition of the inner, neutrino heated supernova ejecta are also strongly affected by neutrino irradiation
- 3D Simulation for a 11.8 $M_\odot$ star (Müller+ 2019, Janka+ 2015)
- Nucleosynthesis of the innermost 0.1 $M_\odot$
- $\Delta\varepsilon = \langle \varepsilon_{\bar{\nu}_e} \rangle - \langle \varepsilon_{\nu_e} \rangle$
- Original: $\Delta\varepsilon \approx 4$ MeV
- Corrected: $\Delta\varepsilon \approx 2$ MeV (artificially increased $\langle \varepsilon_{\nu_e} \rangle$)
- Flavor conversions would have similar effects on the spectra



Nucleosynthesis results



- Flavor equilibrium would suppress production of *p* isotopes
- Enhanced yields of Sc
- Change pattern of Ti,Fe,Ni chains

Conclusions & Outlook

- Fast flavor transformation favor the νp process in neutrino driven winds
- Make NDWs more likely to be a major source of *p*-isotopes
- Overproduction is only problematic if the most favorable conditions are assumed
- Major effects also on the inner supernova ejecta, may suppress heavy element production
- (not in this talk) Affects the production of isotopes due to the ν-process (^{26}Al, ^{36}Cl, ^{138}La, ^{180}Ta)