CCSN simulations with reduced nucleosynthesis networks

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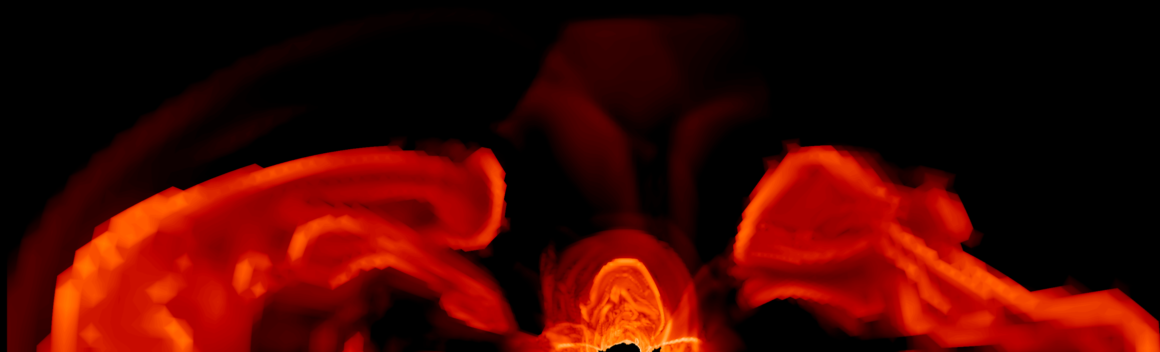
Gerard Navó

Collaborators: M. Reichert, M. Obergaulinger, A. Arcones



GN+2023 *ApJ* **951** 112

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Simulations ingredients

- Hydrodynamics
- Neutrino transport
- Gravity
- Pre-supernova model
- Nuclear EOS
- Composition at baryonic densities
- Magnetic fields
- Rotation

→ simulations →

- CCSN dynamics
- Nucleosynthesis
- Neutrinos
- Spectra, Light curves
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- Neutrino absorption
- Nuclear energy generation ($\dot{E}_{\mathrm{nuc}}$)

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(e.g., Nakamura+14)

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(e.g., Harris+17)

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- T > 5-6 GK: Nuclear Statistical equilibrium (NSE) ⟶ Given in EOS of dense matter
- T $\lesssim$ 5-6 GK: No NSE ⟶ Reduced networks.

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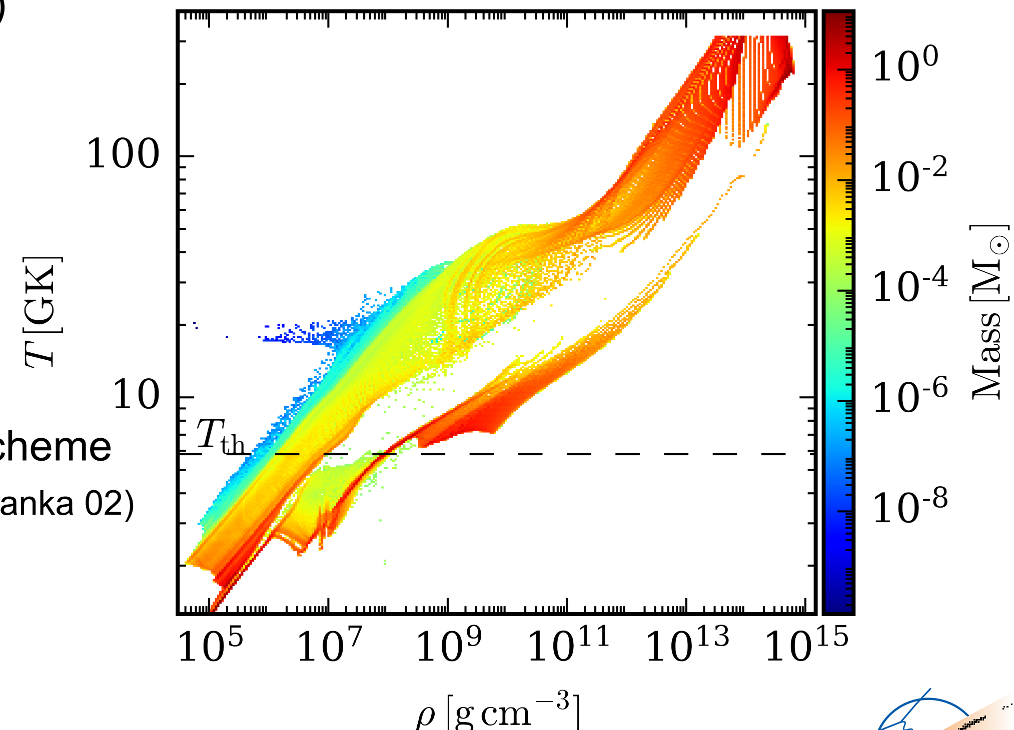
Aenus-Alcar

Special relativistic (magneto-)hydrodynamics code, two-moment (M1) neutrino transport.
(Just et al 2015, Obergaulinger & Aloy 2017)

- $T > T_{\rm th} \longrightarrow$ Nuclear EOS + NSE
- $T \leq T_{\rm th} \longrightarrow$ Helmholz EOS + flashing scheme

(Rampp & Janka 02)



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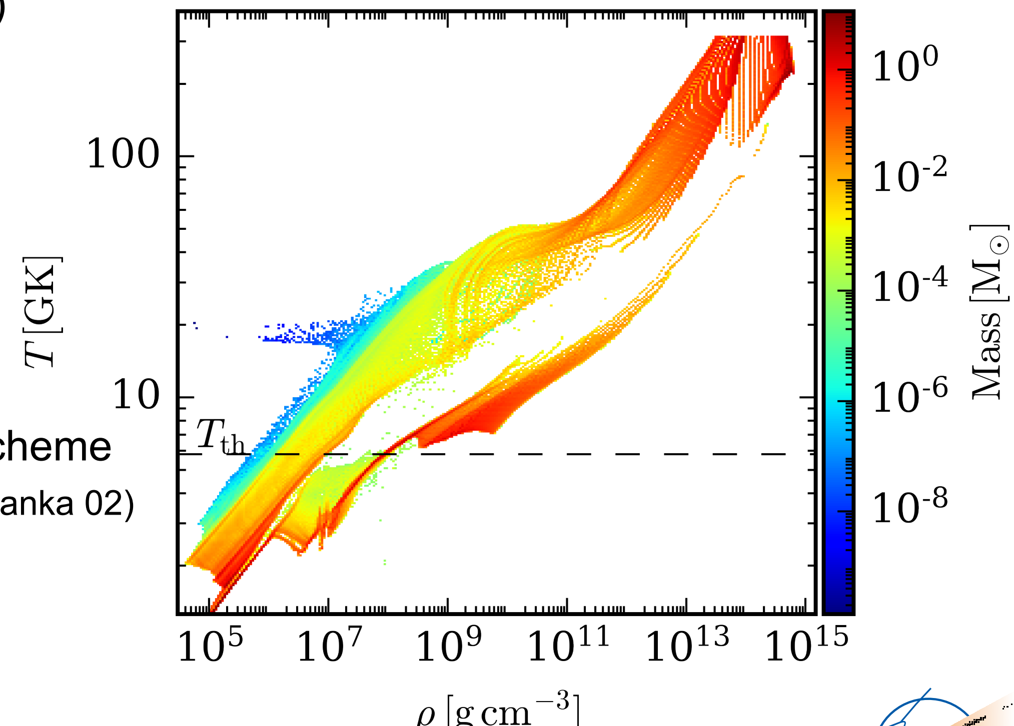
Flashing scheme:

- n, p and X_h.
- X_h = ^{28}Si or ^{56}Ni



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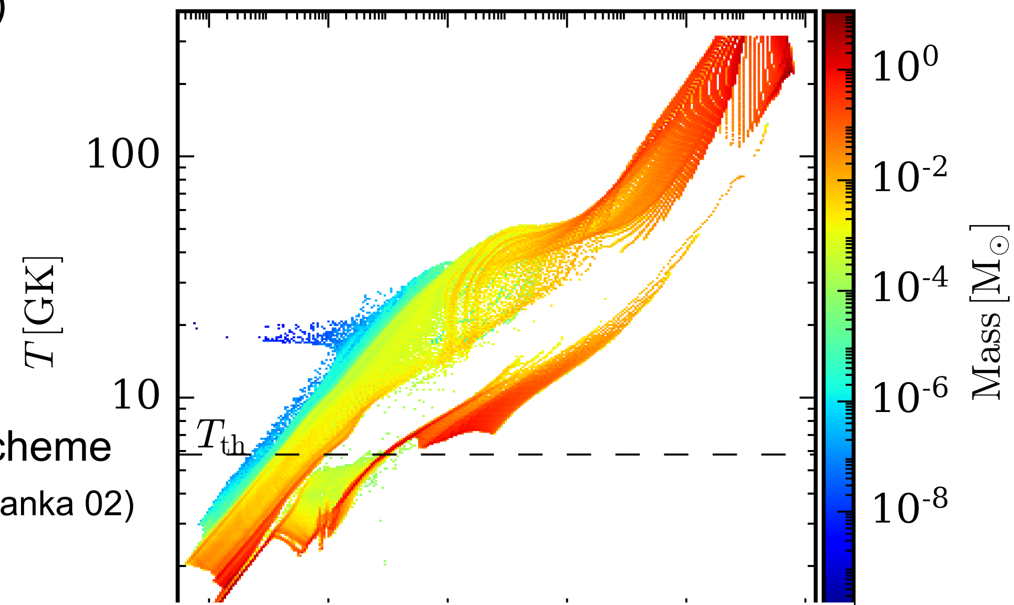

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→ **Reduced network module**

ReNet: RN16 and RN94

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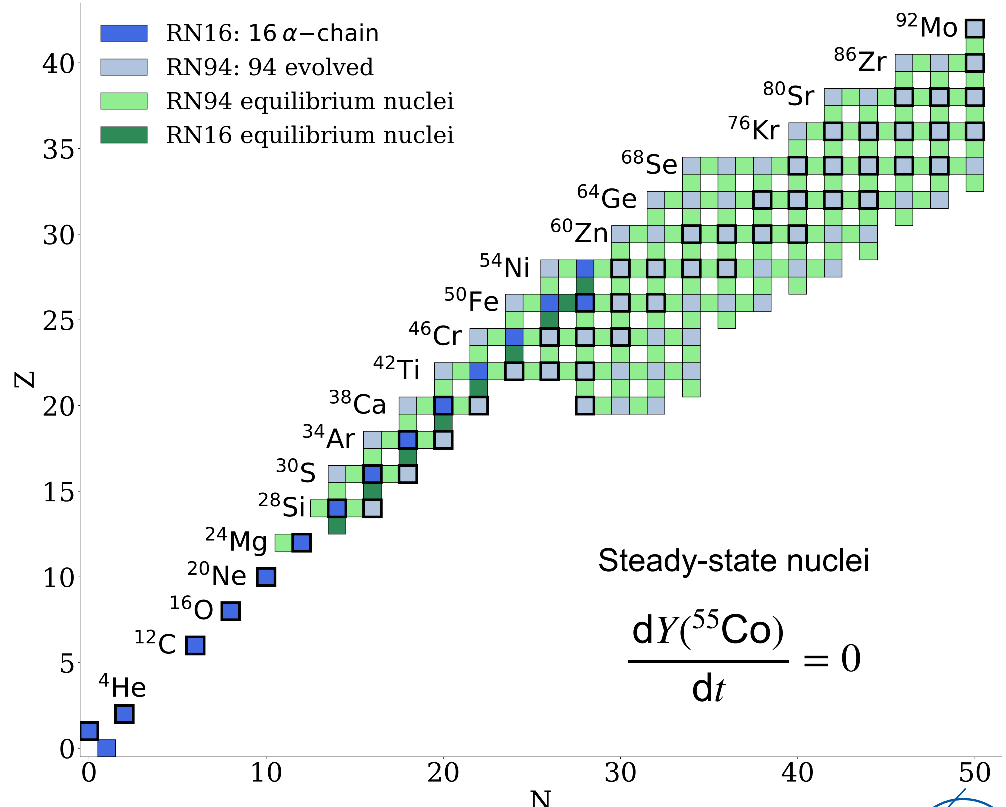
Reichert 2016

RN16

- ~ "approx19" (Weaver+1978)

RN94

- 94 evolved + 148 steady nuclei
- Main species synthesized in standard CCSN



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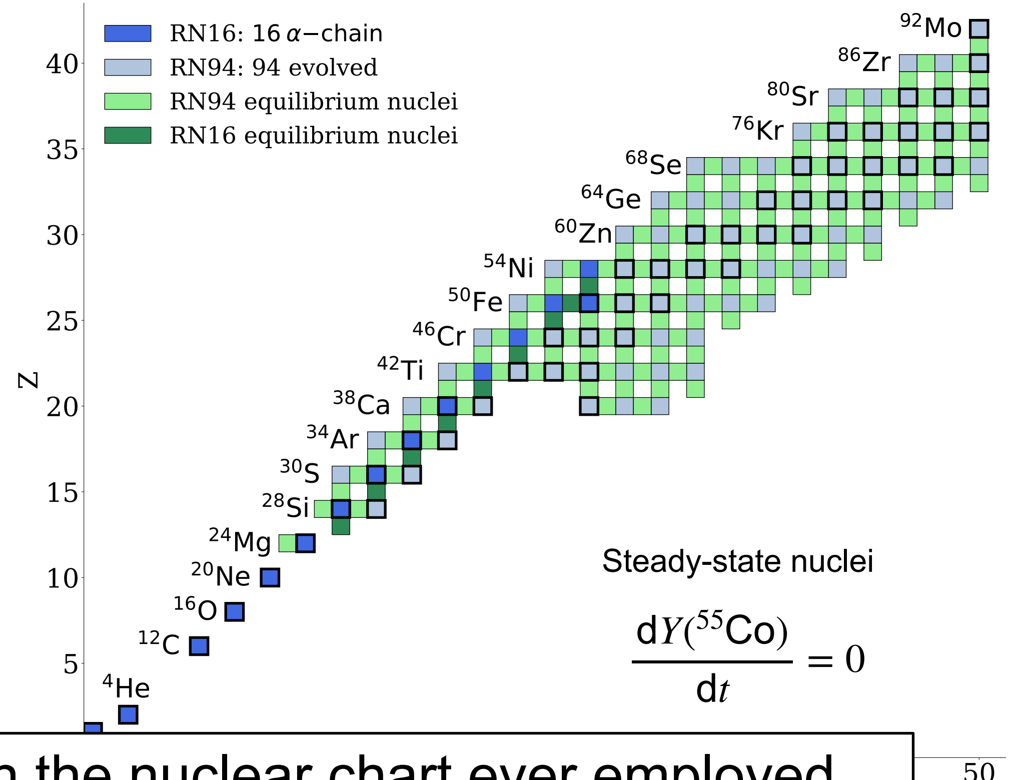


Steady-state nuclei

$$\frac{\mathrm{d}Y(^{55}\mathrm{Co})}{\mathrm{d}t} = 0$$

Most extended network in the nuclear chart ever employed

Models

- 20 $M_\odot$ progenitor (Woosley & Heger 2007).

T > 5.8 GK (0.5 MeV)

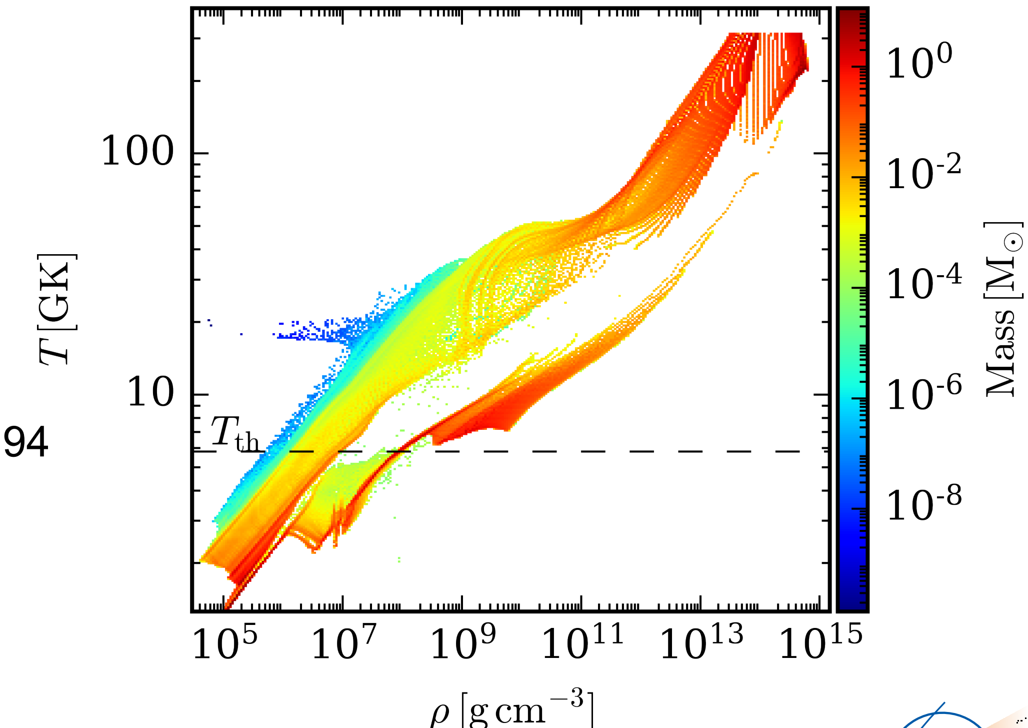
- SFHo (Steiner et al 2013)
- NSE

T ≤ 5.8 GK (0.5 MeV)

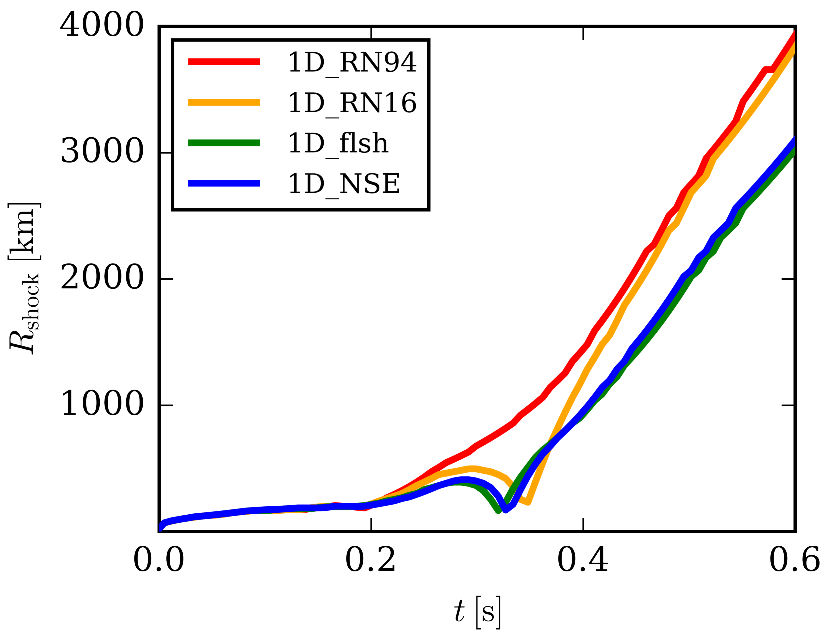
I. 1D, no $\dot{E}_{\rm nuc}$: Flashing, NSE, RN16, RN94

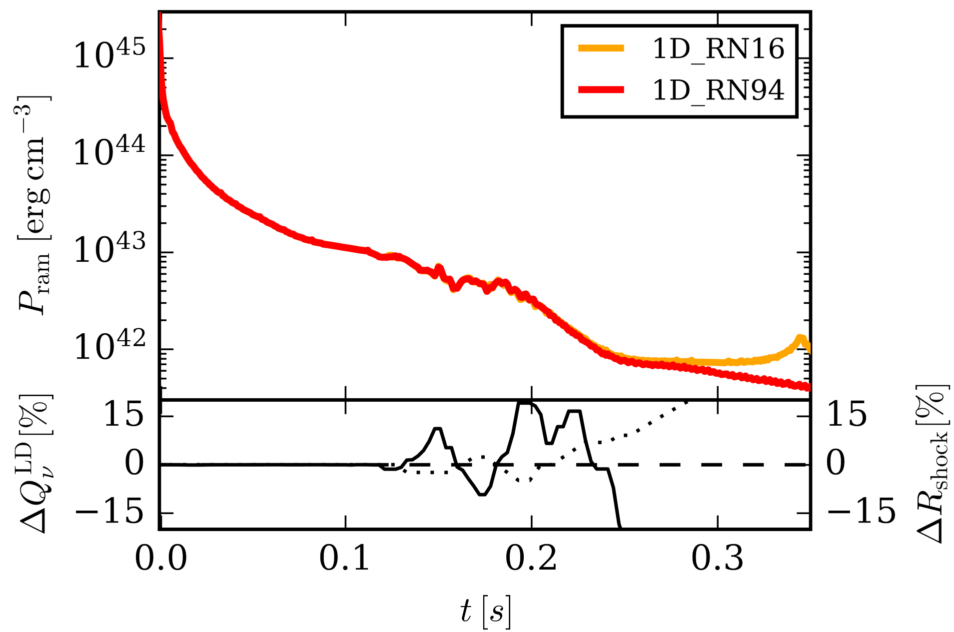
II. 1D, $\dot{E}_{\rm nuc}$: RN16 and RN94

III. 2D, $\dot{E}_{\rm nuc}$: Flashing, RN16, RN94



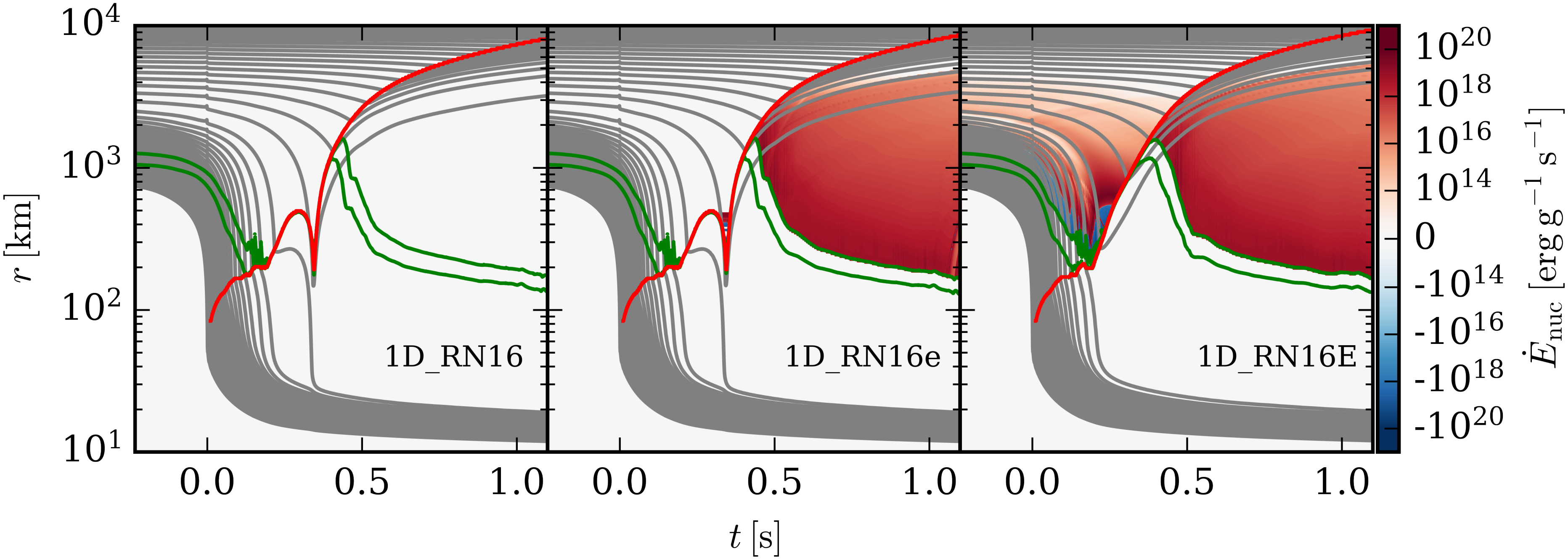
Impact on the dynamics (1D): no $\dot{E}_{\rm nuc}$





Larger number of free nucleons ⟶ Larger ν energy deposition

Impact on the dynamics (1D): $\dot{E}_{\rm nuc}$



$\dot{E}_{\rm nuc}$ in progenitor accreting shells favors shock expansion (Bruenn+06, Nakamura+14)

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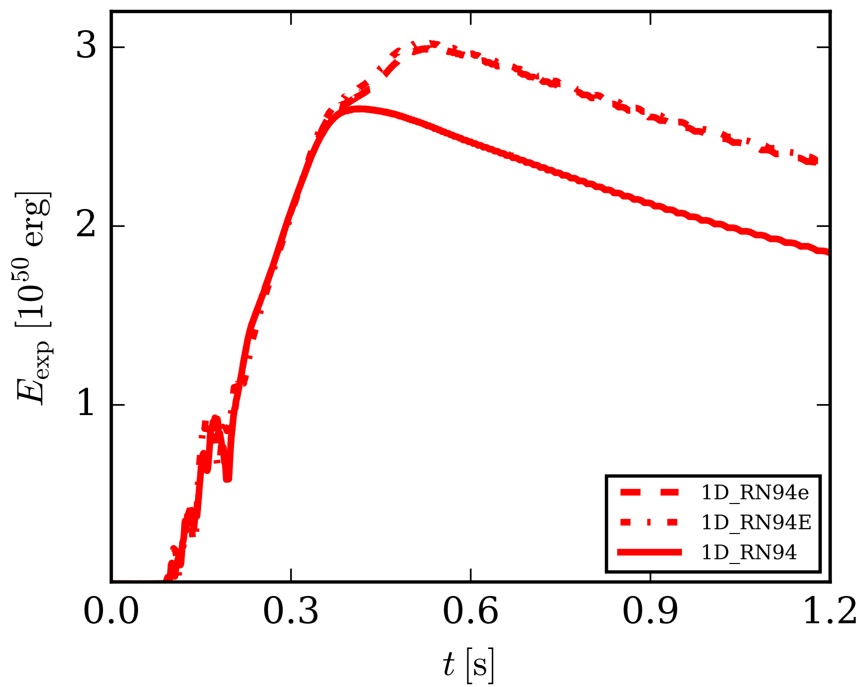
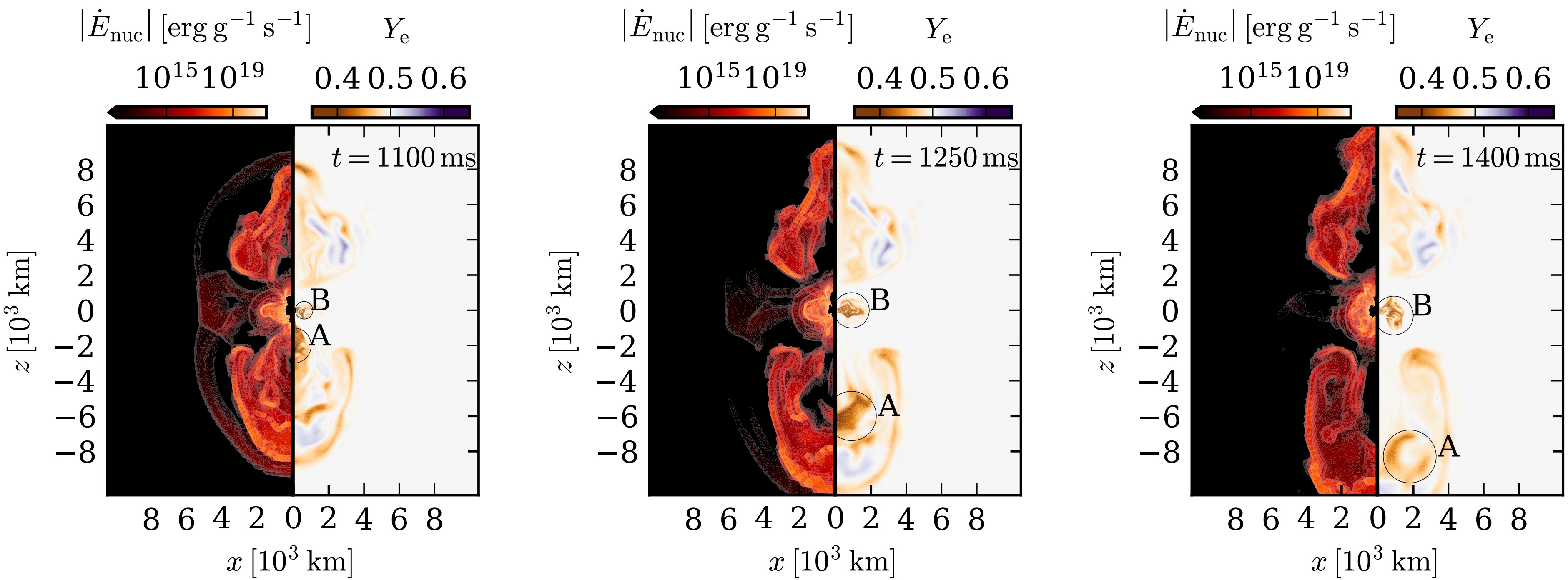


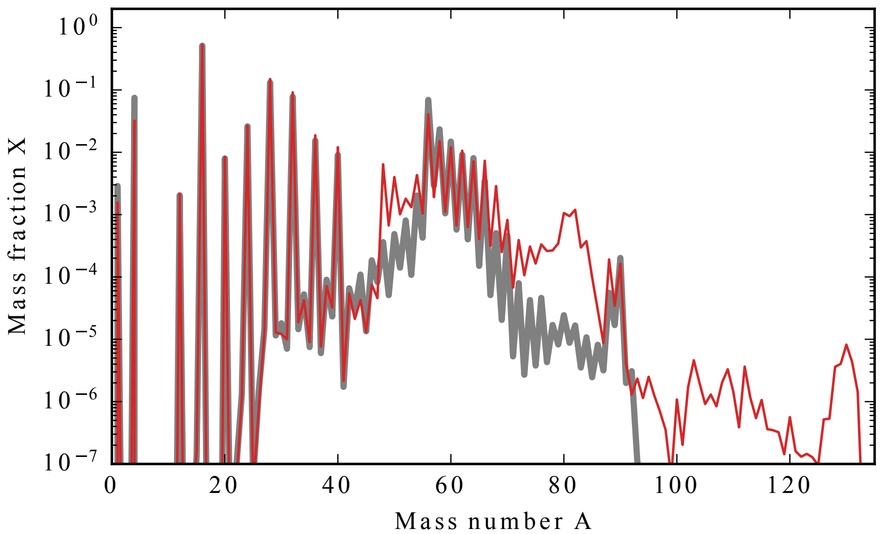
$\dot{E}_{\rm nuc}$ significant below the shock ⟶ increases explosion energy ~ 15%

Impact in the dynamics (2D): 2D_RN94



$\dot{E}_{\rm nuc}$ sustain low-Ye outflows from the PNS vicinity —> synthesis of heavier nuclei

Impact on the composition (2D)



- **2D_RN94E** shows heavier nucleosynthesis than **2D_flsh**

WinNet (Winteler+12, Reichert+23) post-processing
WinNet for 2D_flsh trajectories

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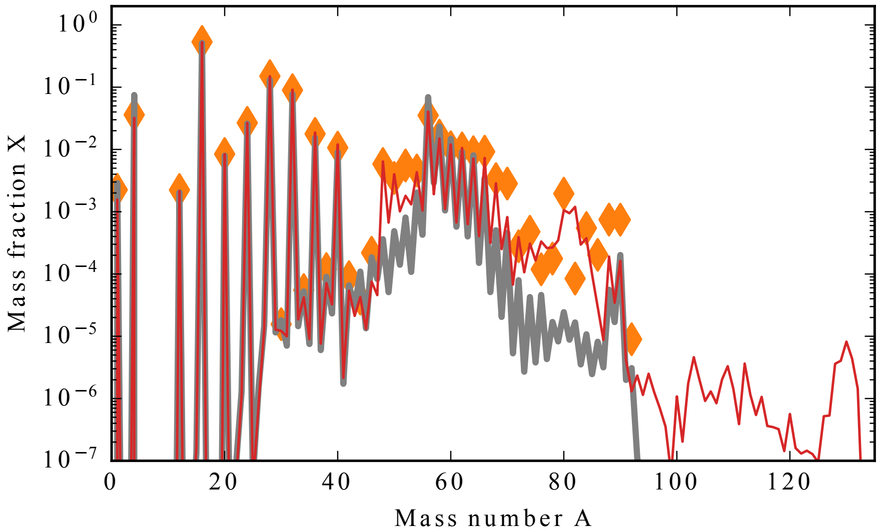

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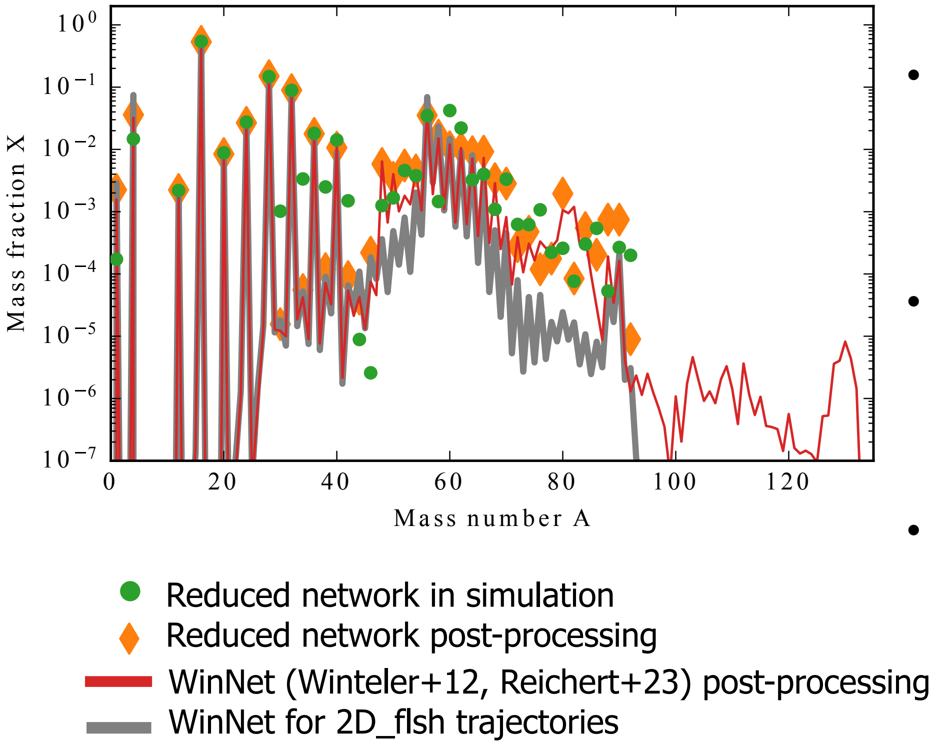

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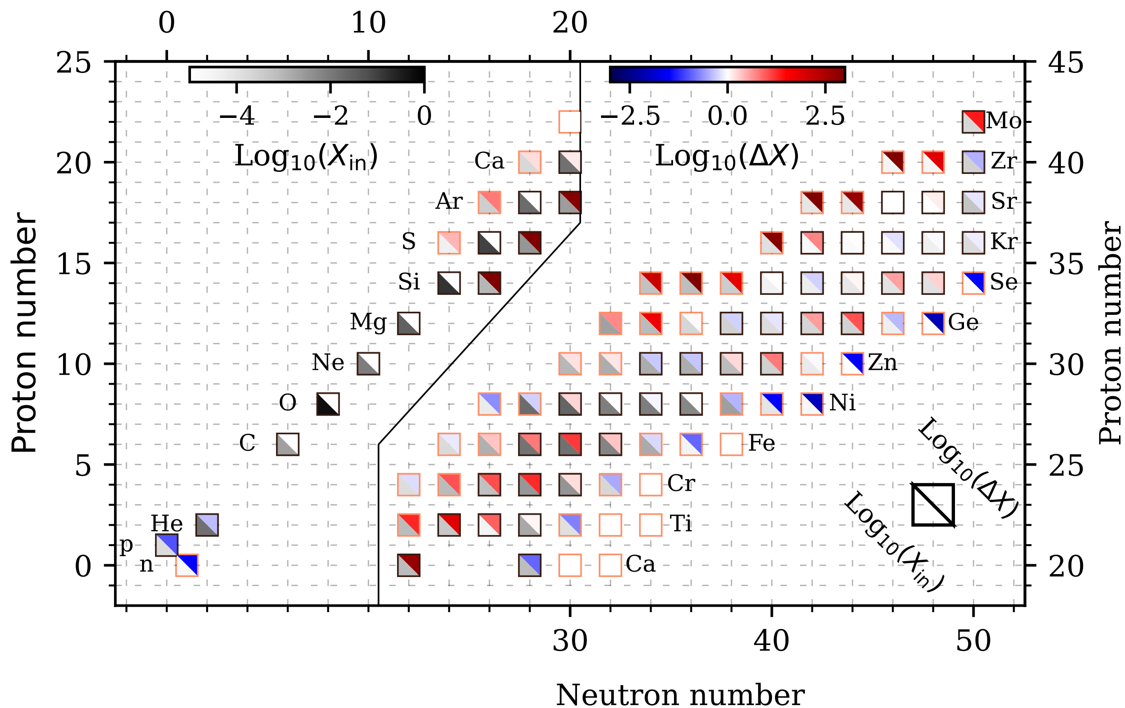
- **Post-processing** underproduction w.r.t. **in-situ**: ^{44}Ti, ^{46}Ti, ^{48}Ti, ^{48}Cr, ^{50}Cr, ^{52}Cr, ^{54}Fe, ^{56}Fe

Impact on the composition (2D): In situ vs Ex situ



Change in production of Ti, Cr, Fe isotopes lead to different nucleosynthesis pathways → Impact final abundances

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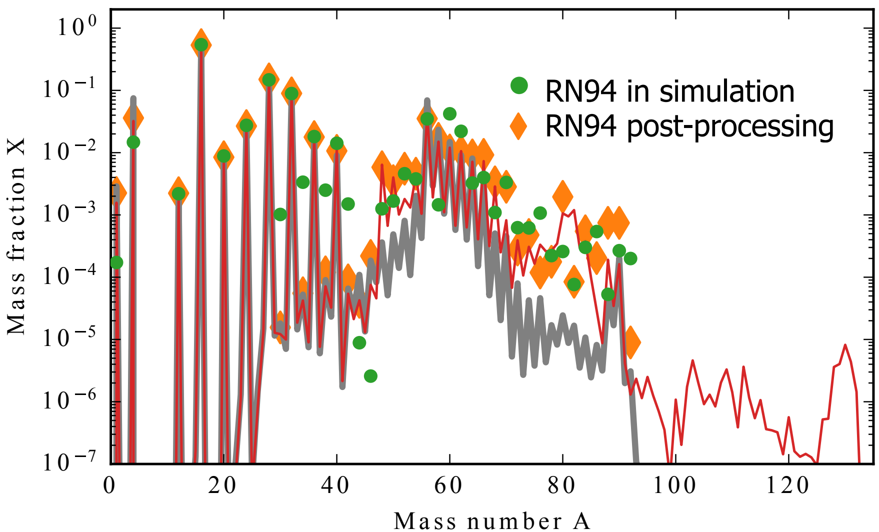

Differences stem from the intrinsic characteristics of evolving the composition in situ or ex situ

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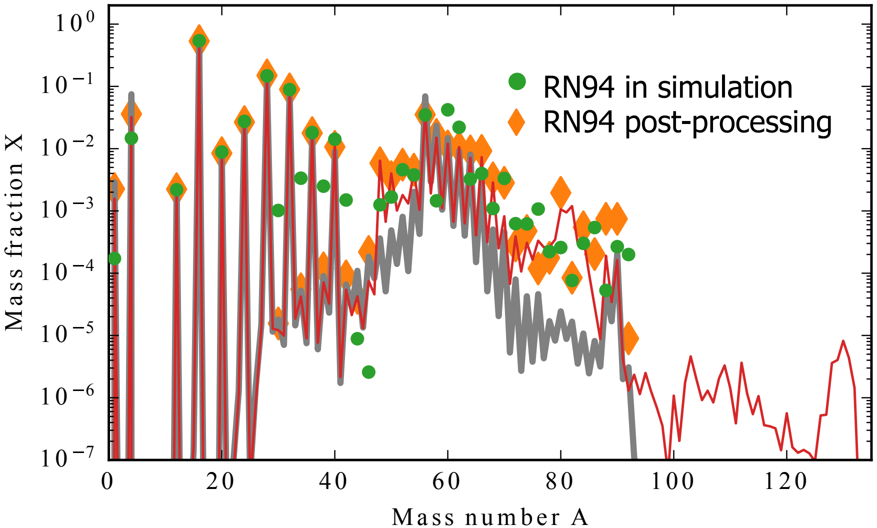

Disadvantages ex situ networks

- Lagrangian tracer particles more uncertain to reproduce products of low density regions (Harris+17)
- Tracers lack of mixing

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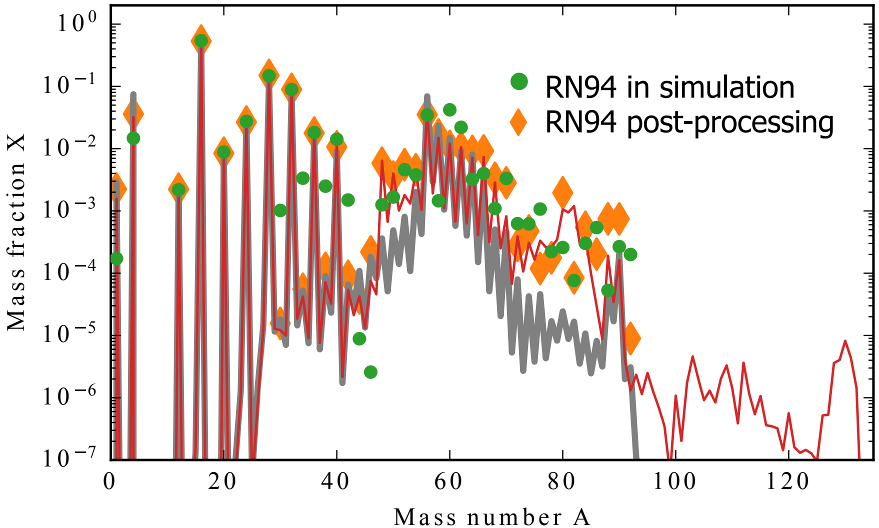

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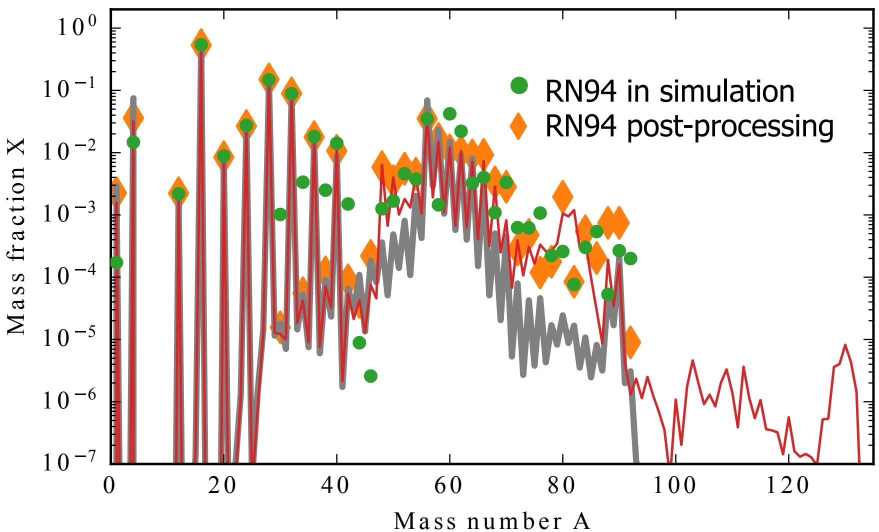

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Disadvantages in situ networks

- Numerical diffusion in eulerian grids leads to artificial mixing
  - Increase resolution (much finer than feasible)
  - Modify advection scheme (Plewa & Müller 1999)

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Summary

- Composition impacts amount of n,p $\longrightarrow$ changes Q_ν^{LD} and modifies accretion
- Energy generation $\dot{E}_{\mathrm{nuc}}$:
  i. In accretion layers: faster shock evolution
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