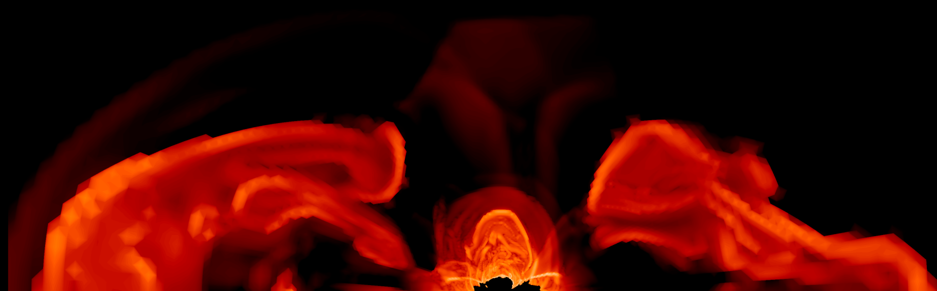
Core-collapse supernovae simulations

Nucleosynthesis network and nuclear energy generation



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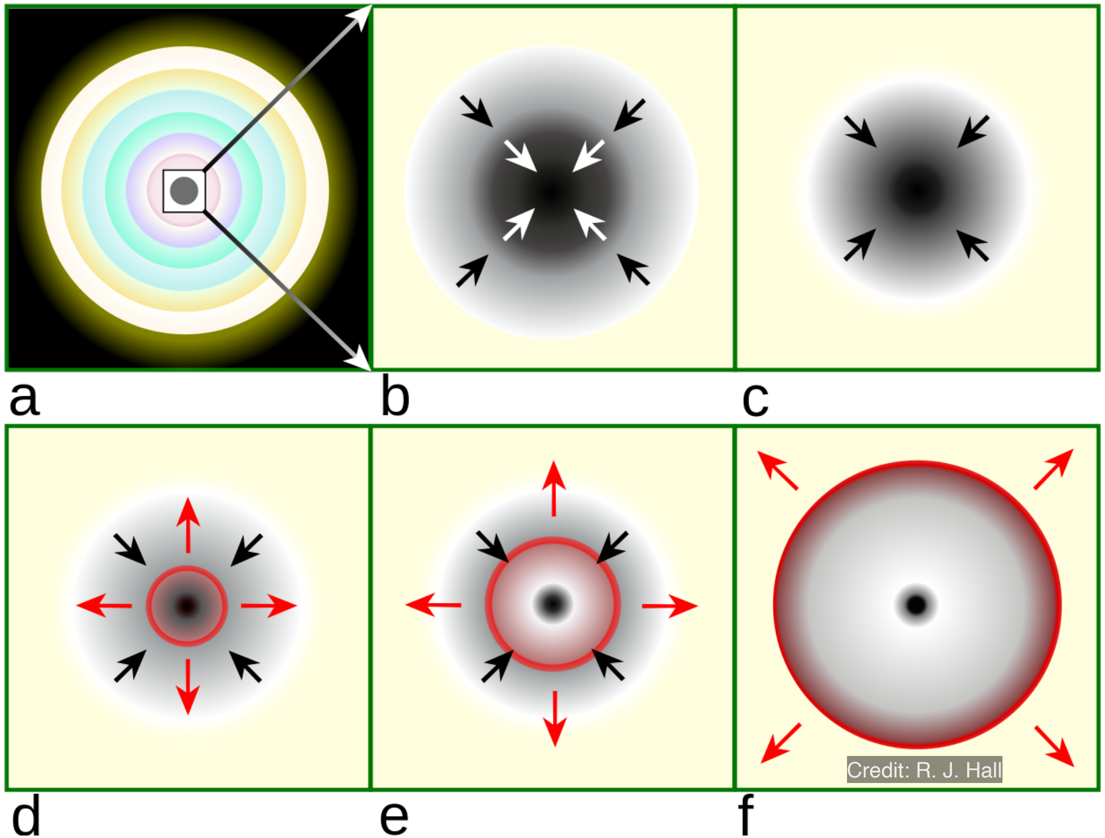
Core-collapse supernovae



Simulations ingredients

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

simulations →

- CCSN dynamics
- Nucleosynthesis.
- Neutrinos
- Spectra, Light curves
- GW

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- Baryonic EOS
- Neutrino absorption
- Nuclear energy generation

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Nucleosynthesis within simulations

- Realistic nuclear reaction network —> too computational expensive to evolve within hydro
  In post-processing with Lagrangian tracer particles
- Simplified treatments are used:
  - T > 5 GK: Nuclear Statistical equilibrium (NSE)
    $Y = Y(\rho, T, Y_e)$ —> Tabulated tables are used
  - T $\lesssim$ 5 GK: No NSE —> Reduced networks.

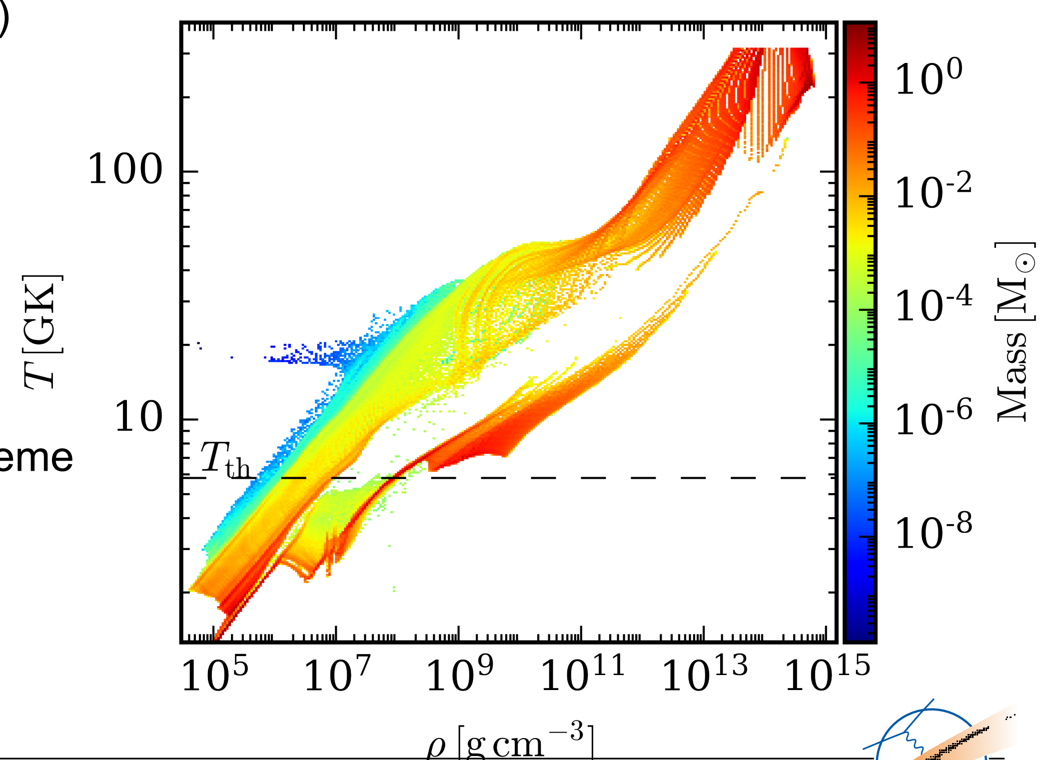
    Energy generation:

$$\dot{E}_{\mathrm{nuc}} = -\sum_i N_{\mathrm{A}} \Delta m_i c^2 \dot{Y}_i$$

Aenus-Alcar. Composition

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

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



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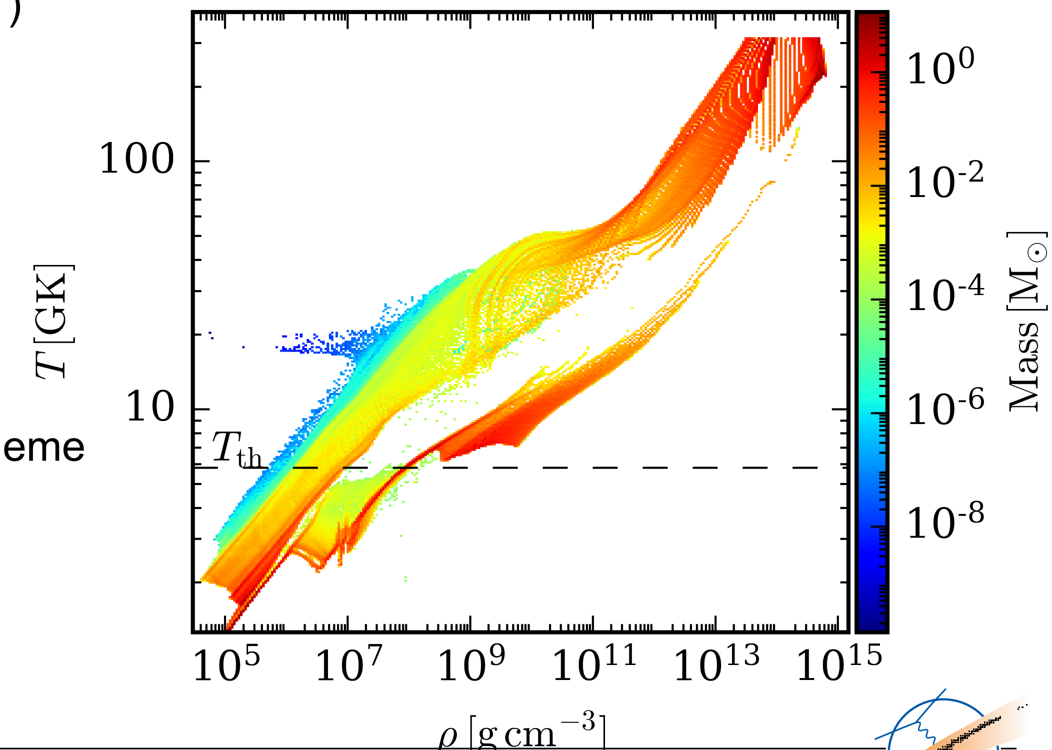
Flashing scheme:

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



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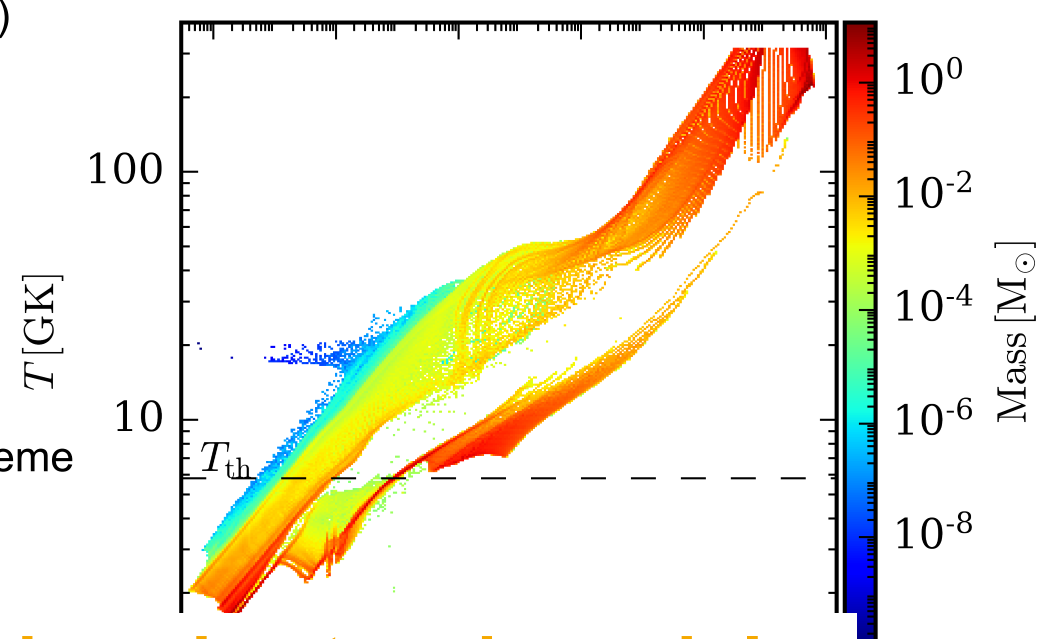

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→ **Reduced network module**

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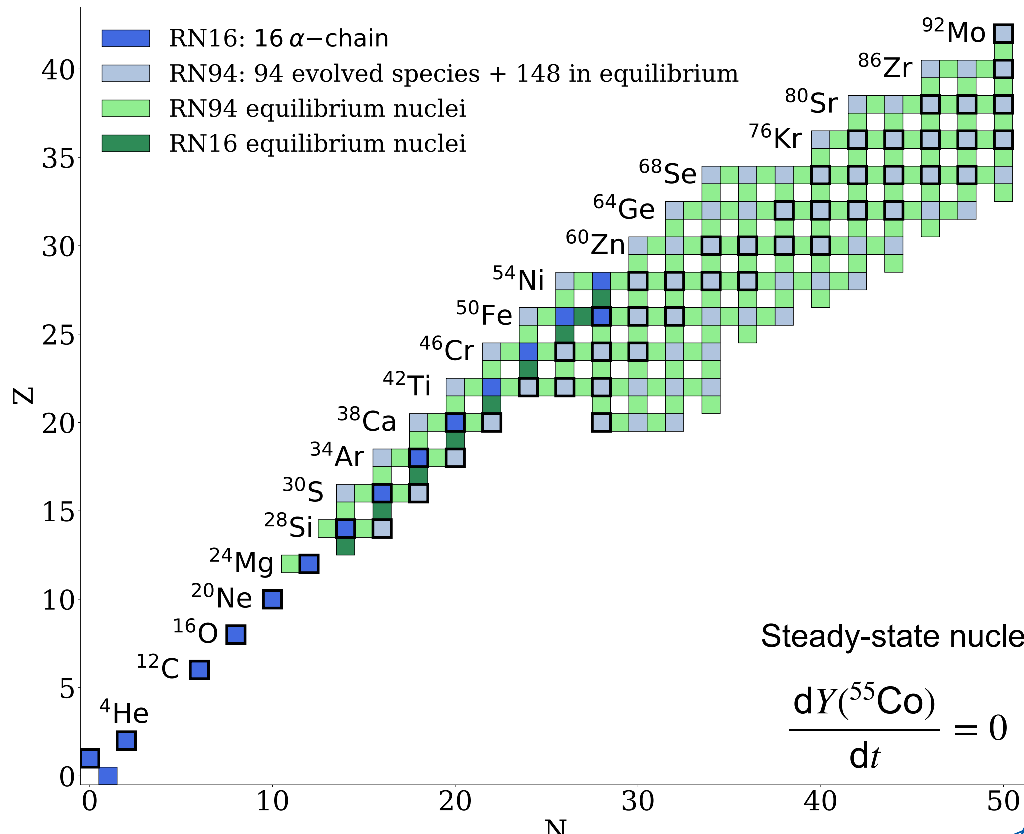
ReNet: RN16 and RN94

RN16

- ~ "approx19" (Weaver+1978).

RN94

- Renet242 with equilibrium/steady nuclei.
- Main species synthesized in standard CCSN



Steady-state nuclei

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

Models

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

$T > 5.8$ GK (0.5 MeV)

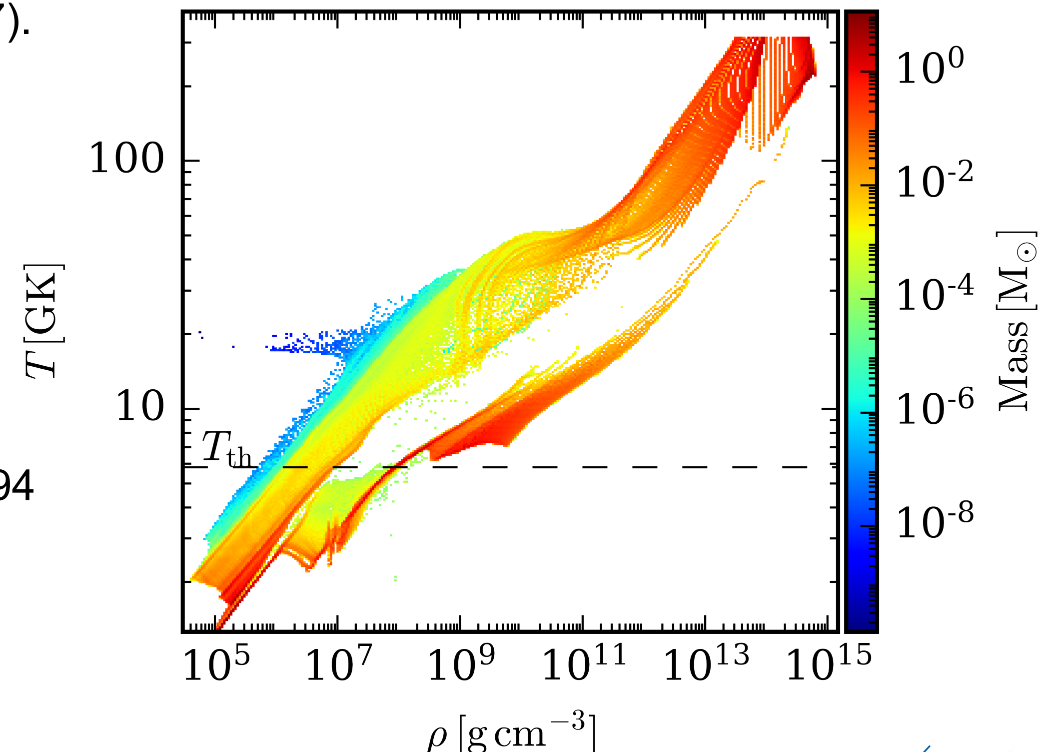
- SFHo (Steiner et al 2013)
- NSE

$T < 5.8$ GK (0.5 MeV)

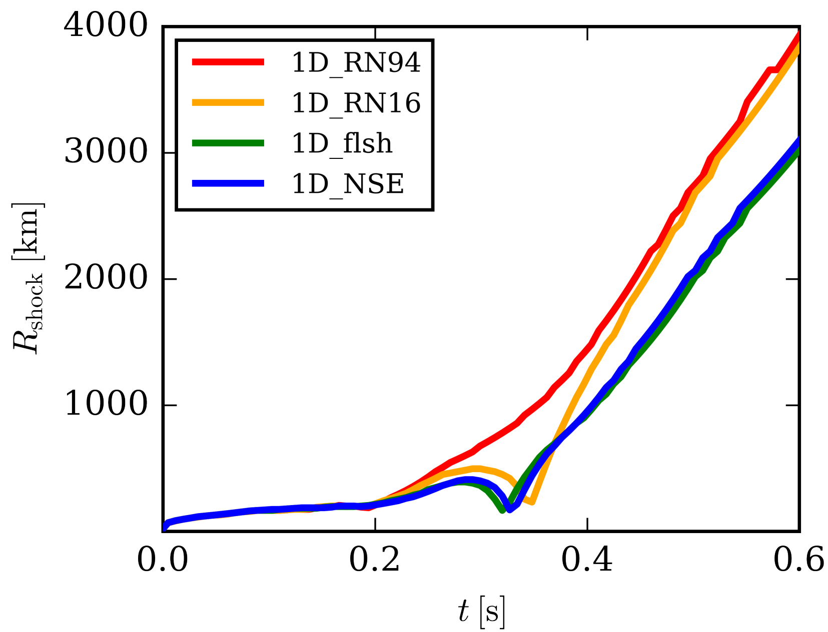
I. 1D, no $\dot{E}_{\rm nuc}$. Flashing, NSE, RN16, RN94

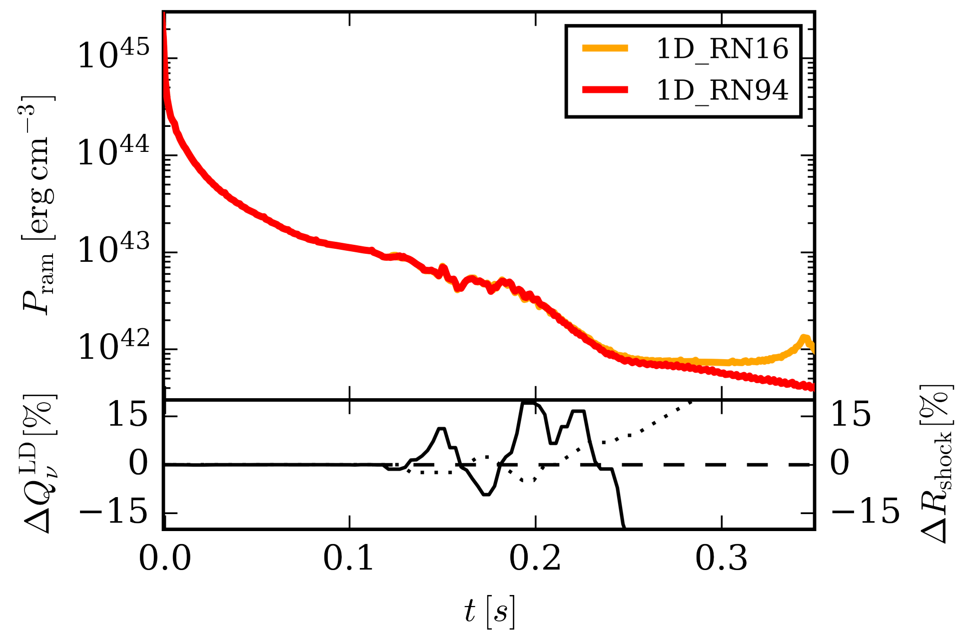
II. 1D, $\dot{E}_{\rm nuc}$. RN16 and RN94

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



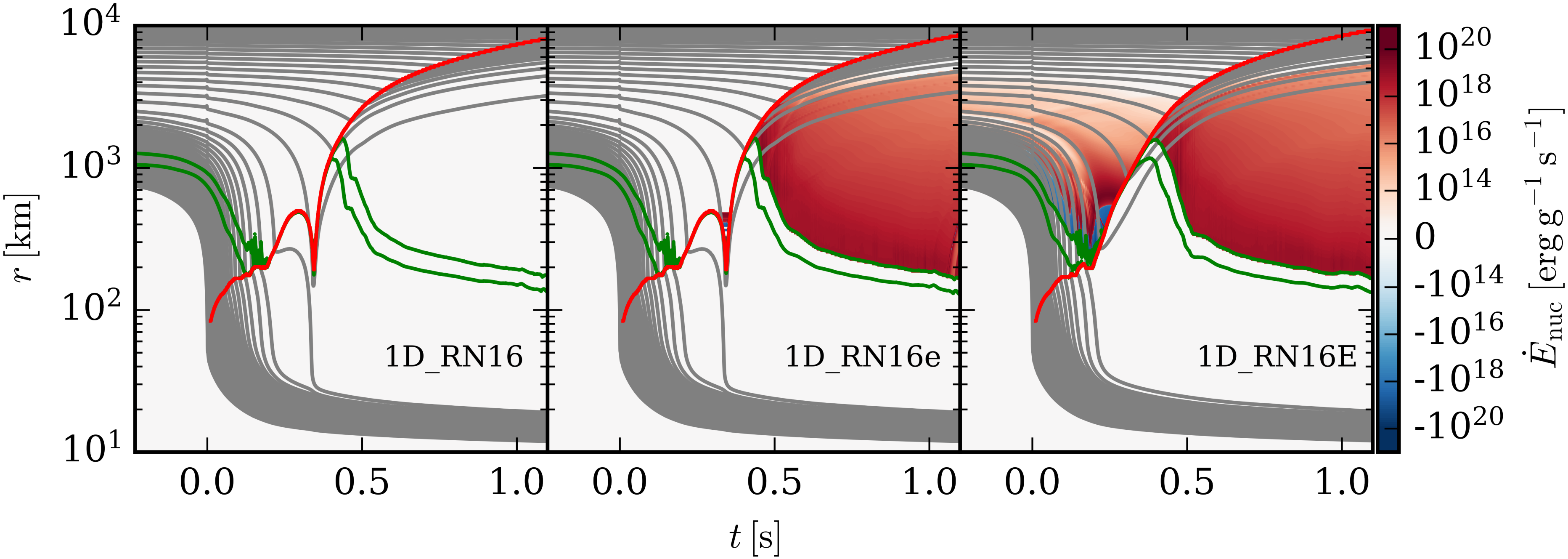
Impact on the dynamics (1D): ν energy deposition





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

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



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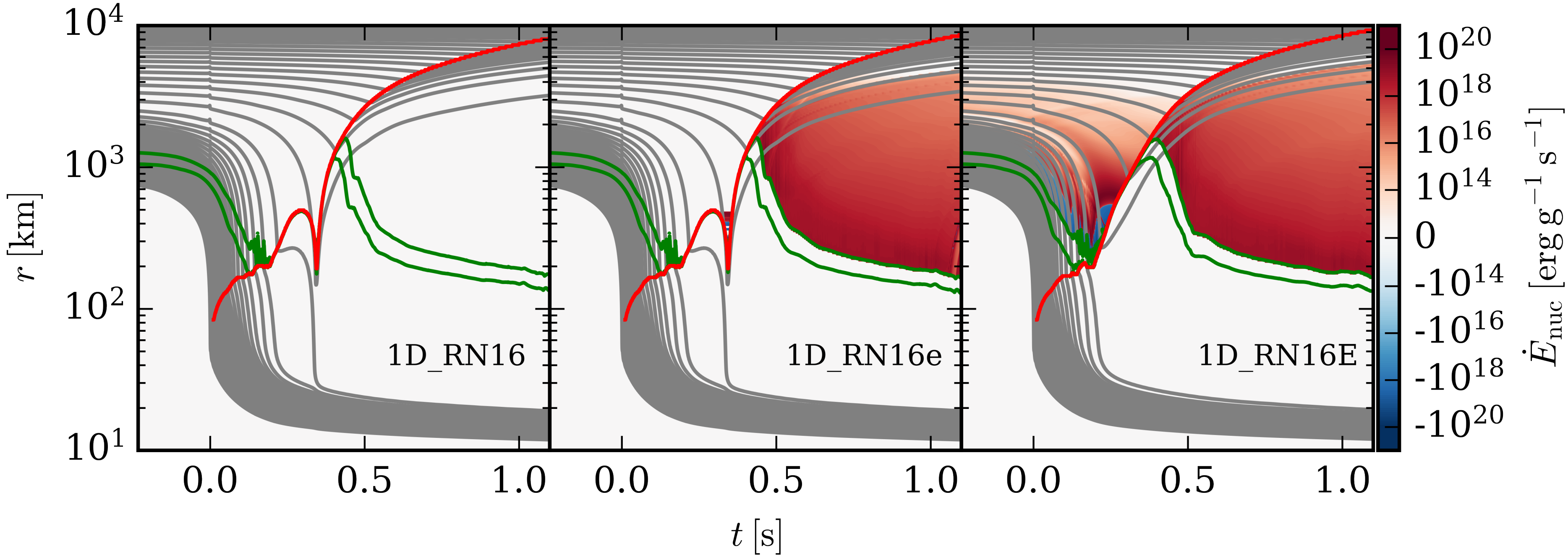
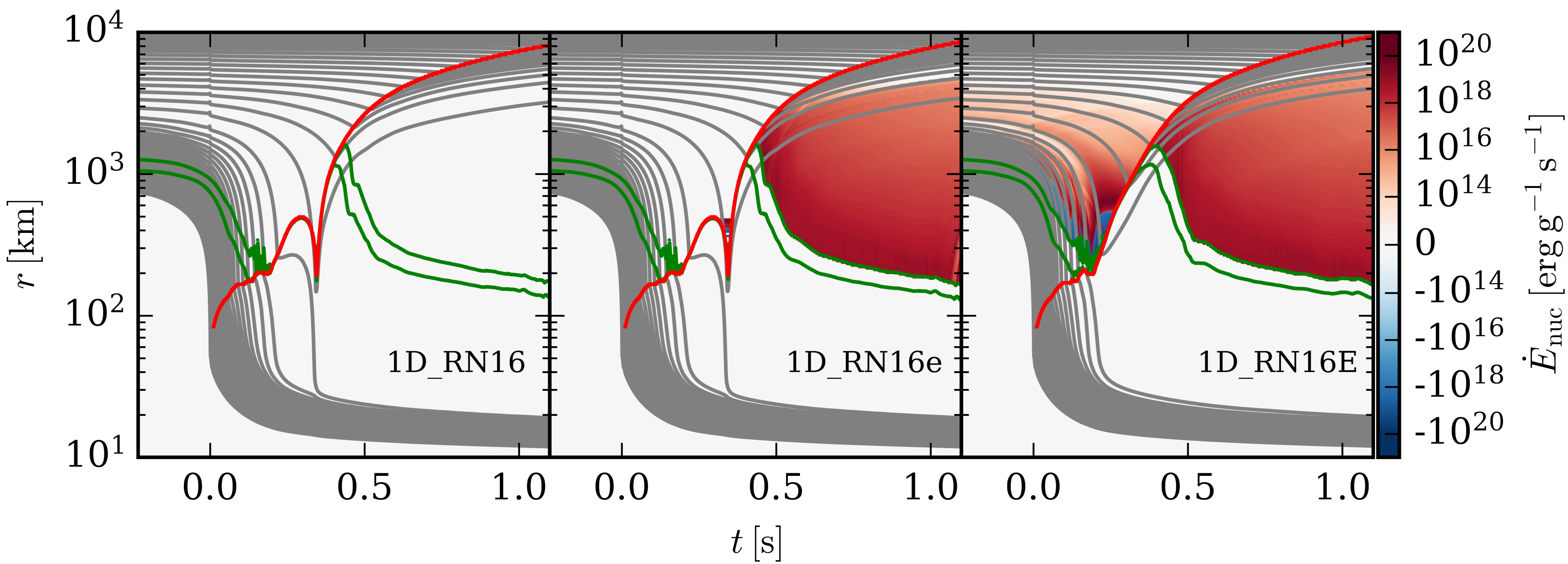


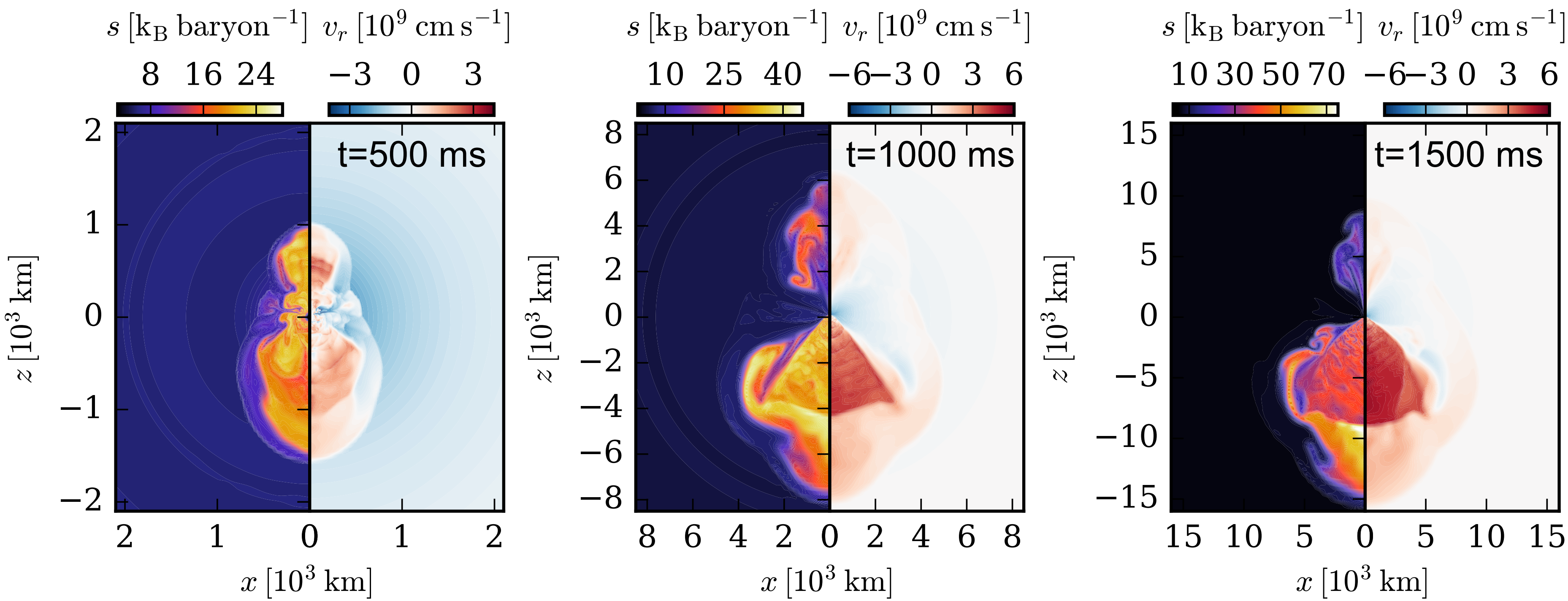
$\dot{E}_{\mathrm{nuc}}$ significant below the shock —> increases explosion energy ~ 15%

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



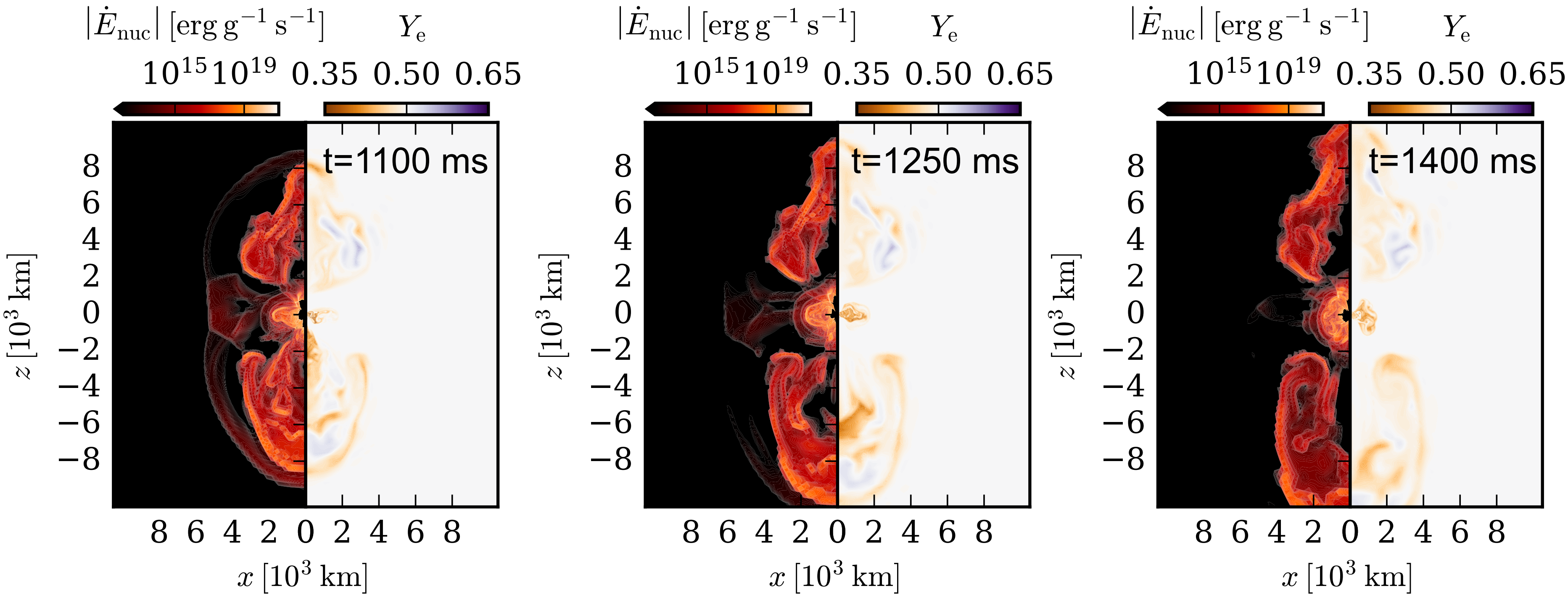
$\dot{E}_{\rm nuc}$ in progenitor accreting shells reduces accretion

Impact in the dynamics (2D): 2D_RN16



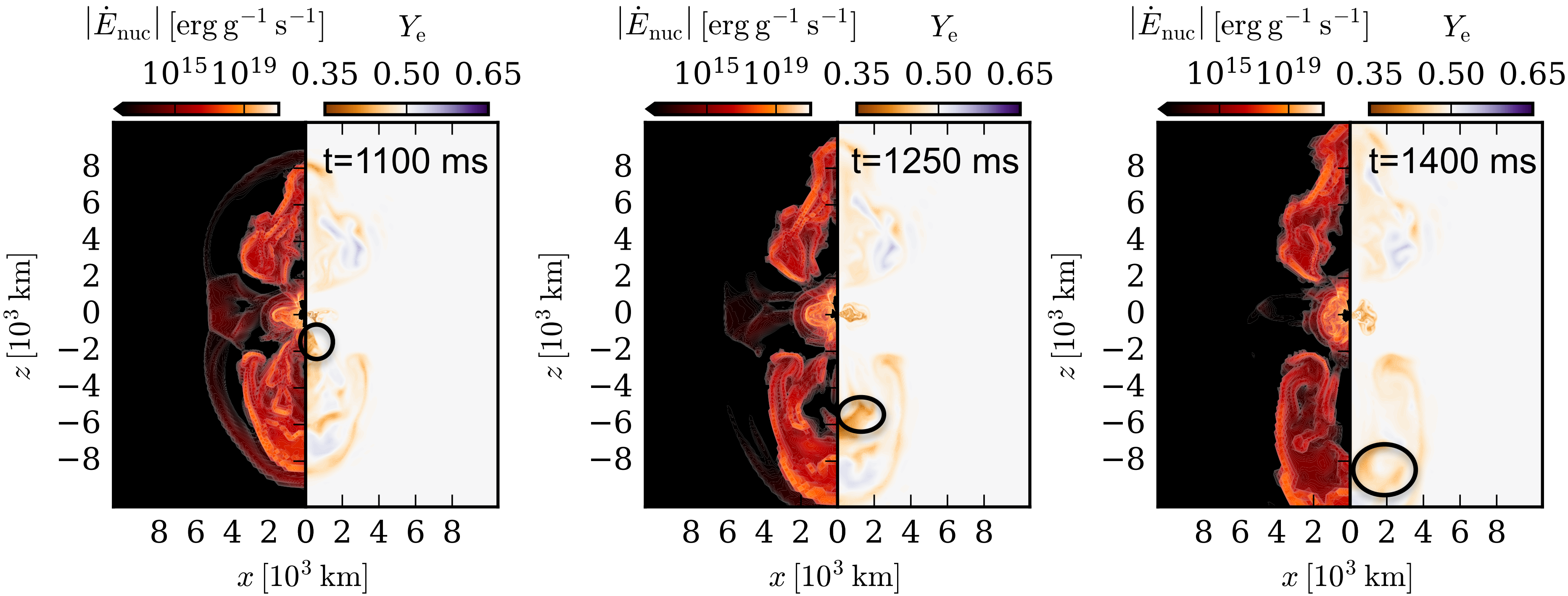
$\dot{E}_{\mathrm{nuc}}$ supports neutrino-driven winds and increase E_{expl}

Impact in the dynamics (2D): 2D_RN94



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

Impact in the dynamics (2D): 2D_RN94



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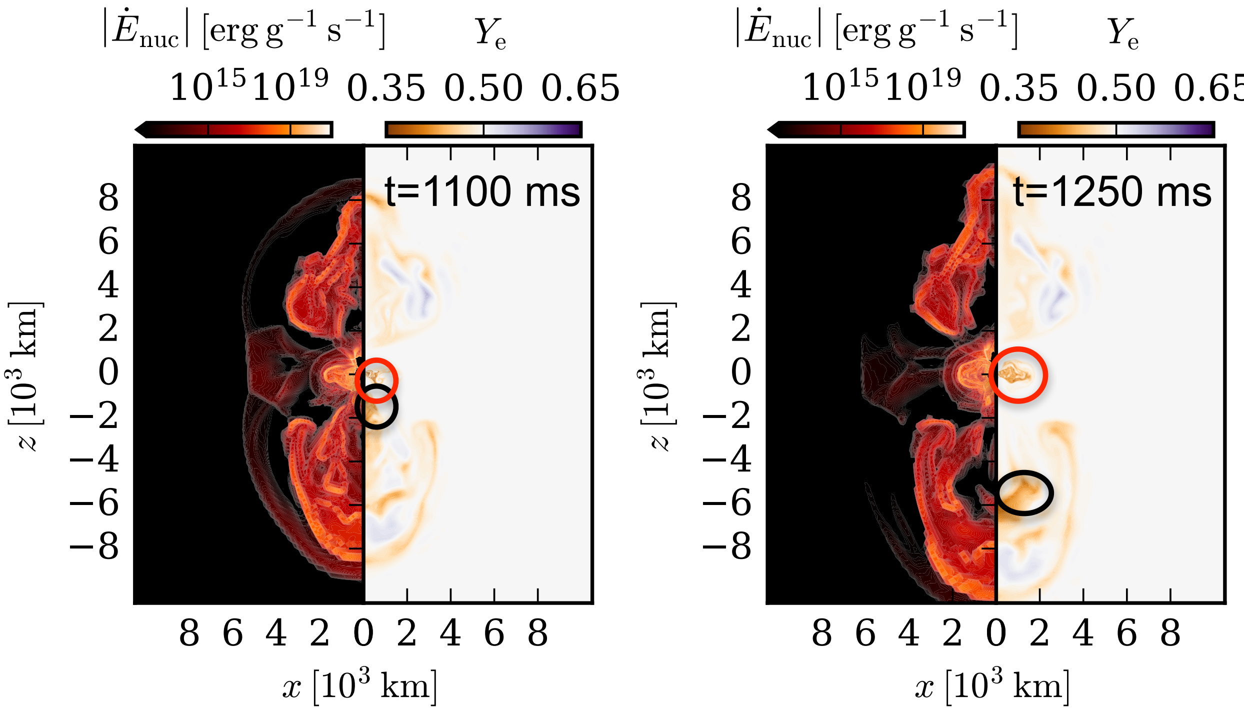

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Impact on the composition (2D)

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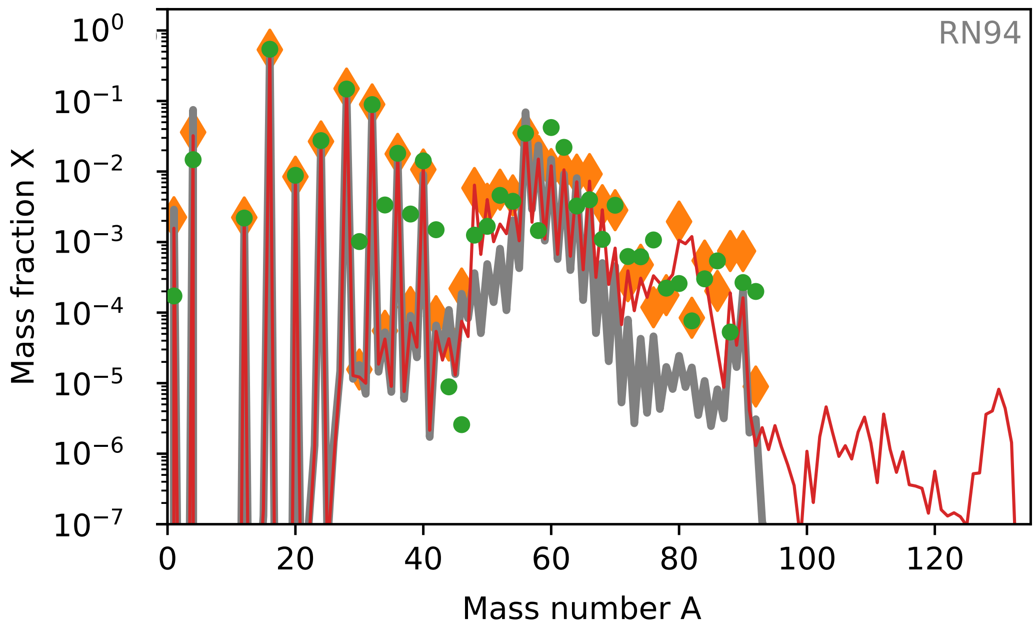
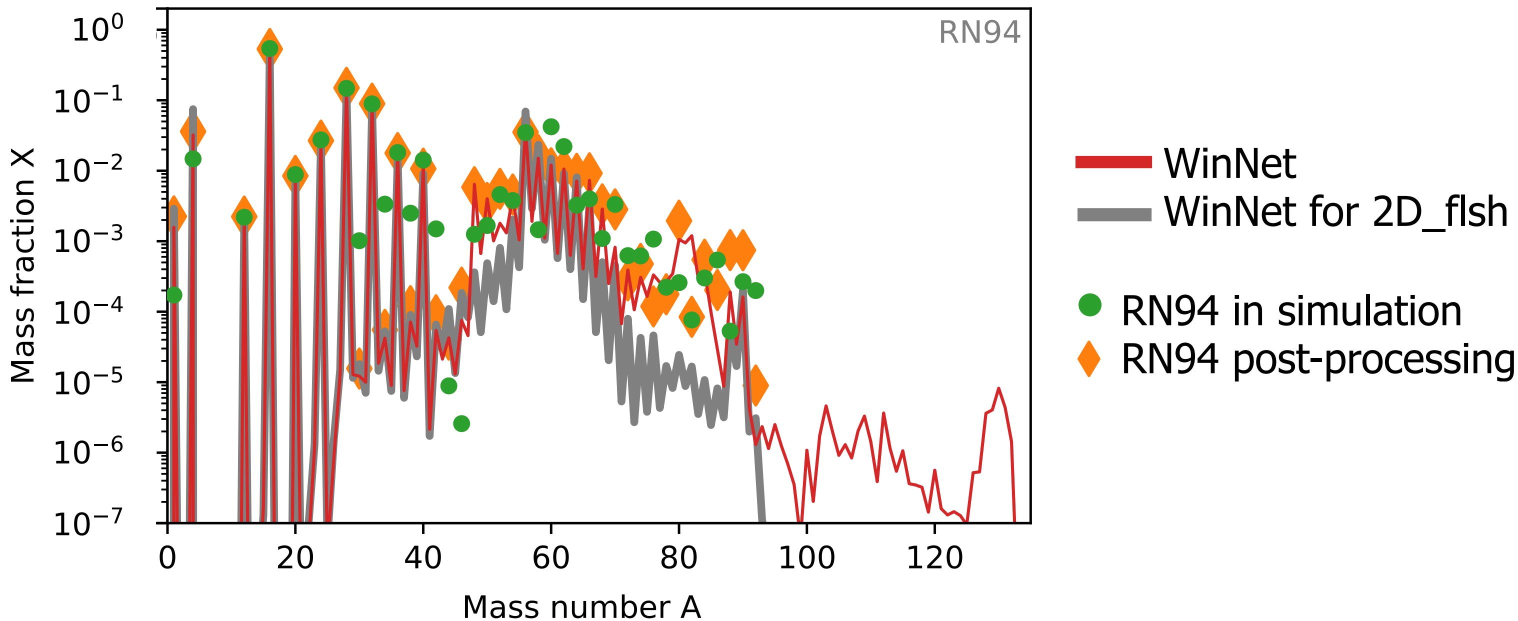


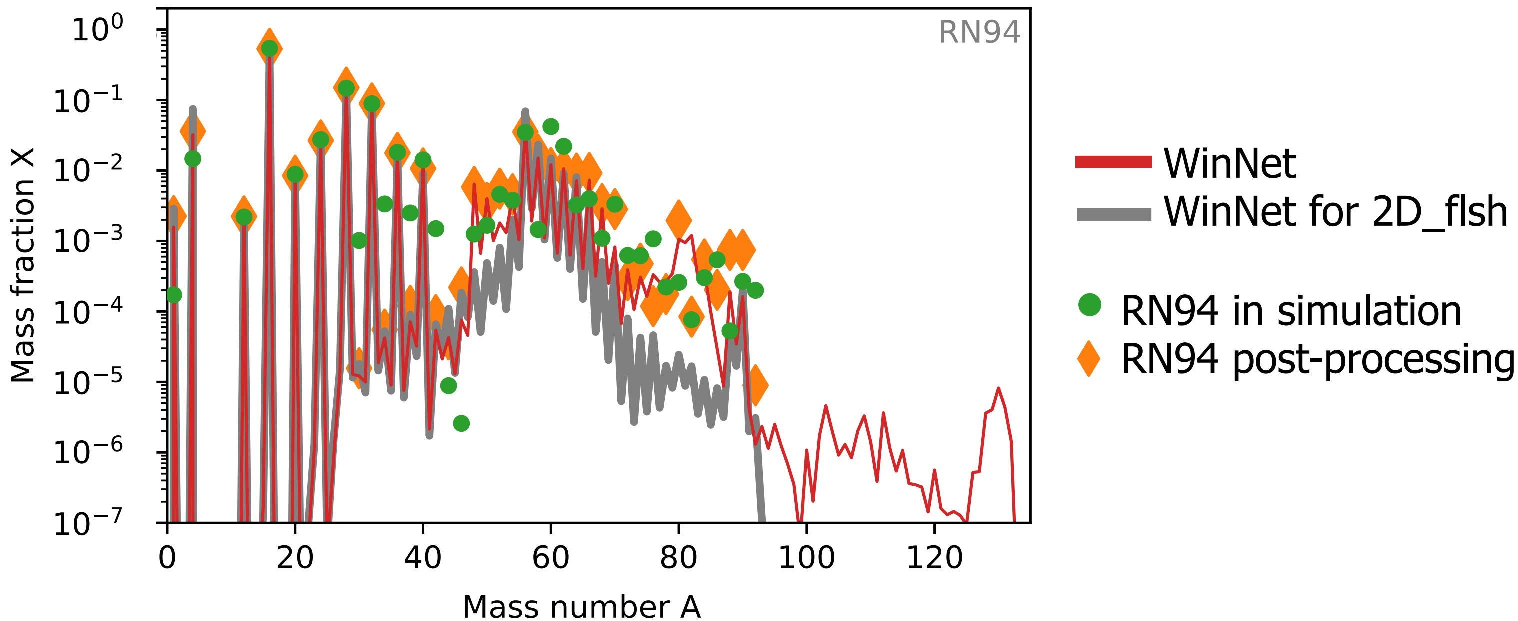
- Reduced network in simulation
- Reduced network post-processing
- WinNet (Winteler et al 2012) post-processing
- WinNet for 2D_flsh trajectories

Impact on the composition (2D)



Agreement between the post-processing RN94 and Winnet

Impact on the composition (2D)



Post-processing underproduction w.r.t. in-situ: ^{44}Ti, ^{46}Ti, 544 ^{48}Ti, ^{48}Cr, ^{50}Cr, ^{52}Cr, ^{54}Fe, ^{56}Fe

Lagrangian particles fail to reproduce products of low density regions (Harris+17)

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

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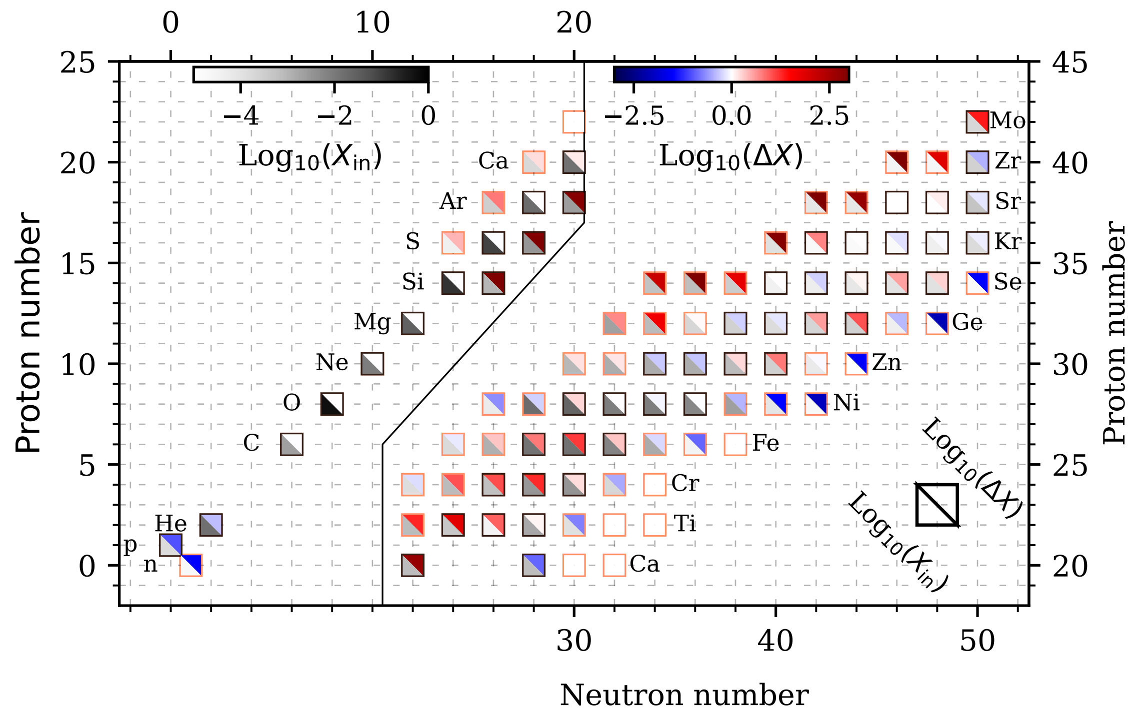

The change in the production of Ti, Cr, Fe isotopes lead to different nucleosynthesis pathways —> Impact abundances

Summary

- Composition impacts amount of n,p —> changes Q_ν^{LD} and modifies accretion.
- Energy generation $\dot{E}_{\mathrm{nuc}}$:
    i. In accretion layers: faster shock evolution
    ii. Behind the shock: larger explosion energy
- $\dot{E}_{\mathrm{nuc}}$ on explosion dynamics affects final nucleosynthesis
- Post-processing calculations fail to reproduce low-density regions (in agrement with Harris+17)

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<u>In situ networks provide more accurate dynamics and nucleosynthesis</u>