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Neutrino-Driven Winds from Rotating Proto-Neutron Stars

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Outline

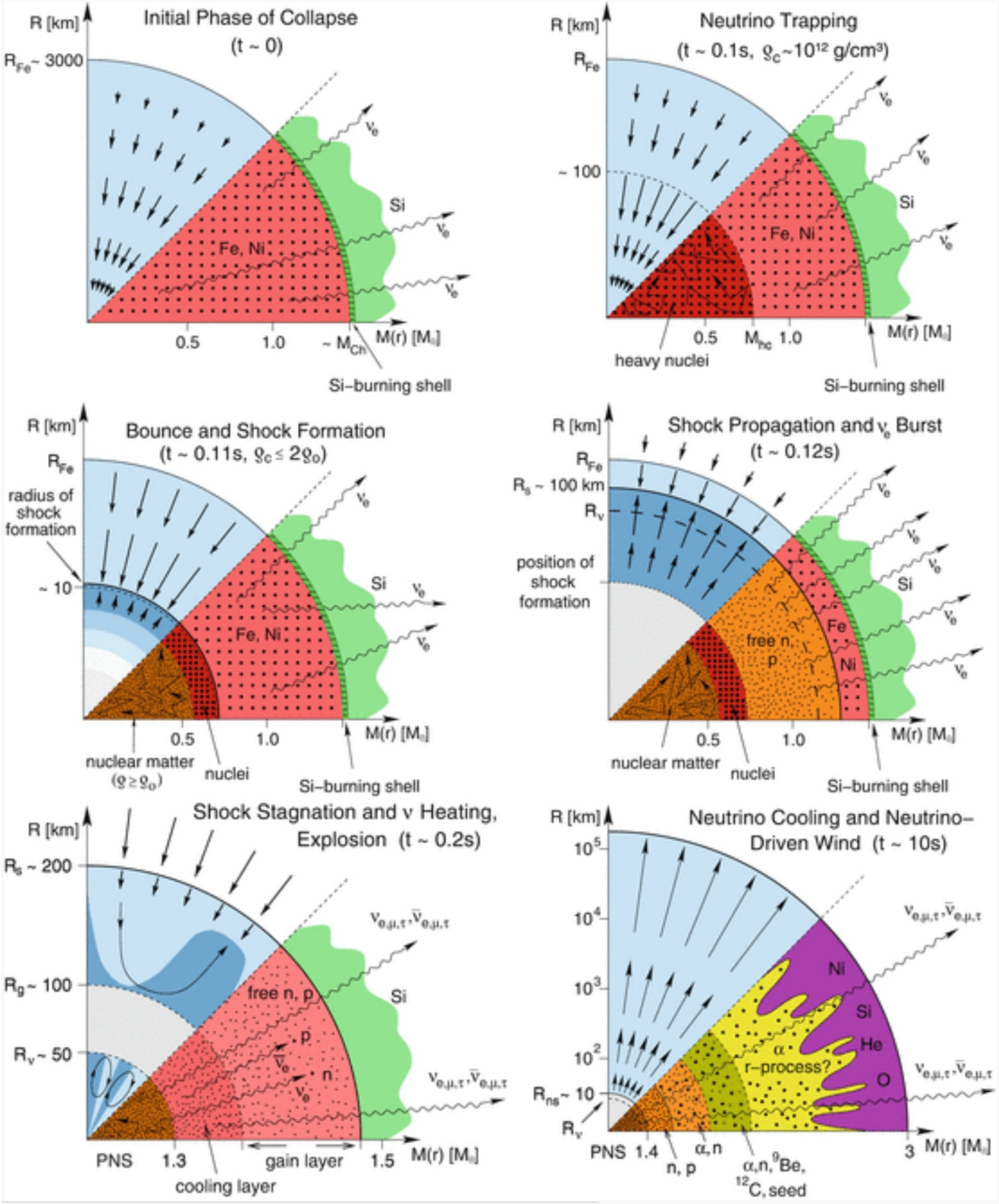
- Supernova mechanism and birth of Proto-neutron star (PNS)
- Wind launching mechanism and the gain layer
- Potential site of r-process nucleosynthesis?
- Simulation setup
- Test case: spherical winds
- Rotating PNSs
- Conclusions

Core-Collapse Supernova & PNS formation

- Core collapses, bounces; outer layers ejected
- contracting PNS formed
- Neutrinos diffuse out of PNS, free-stream from neutrinosphere, drive wind
- Remnant PNS rotating?

$$
\begin{aligned}
{}^{56}\mathrm{Fe} + \gamma &\rightarrow 13\,{}^{4}\mathrm{He} + 4n \\
{}^{4}\mathrm{He} + \gamma &\rightarrow 2p^{+} + 2n \\
p^{+} + e^{-} &\rightarrow n + \nu_e
\end{aligned}
$$

$$E_{\mathrm{SN}} \sim \frac{3GM_{\mathrm{pns}}^2}{5r_{\mathrm{NS}}} \approx 3\times10^{53}\,\mathrm{erg}\left(\frac{M_{\mathrm{pns}}}{M_\odot}\right)^2\left(\frac{r_{NS}}{12\,\mathrm{km}}\right)^{-1}$$



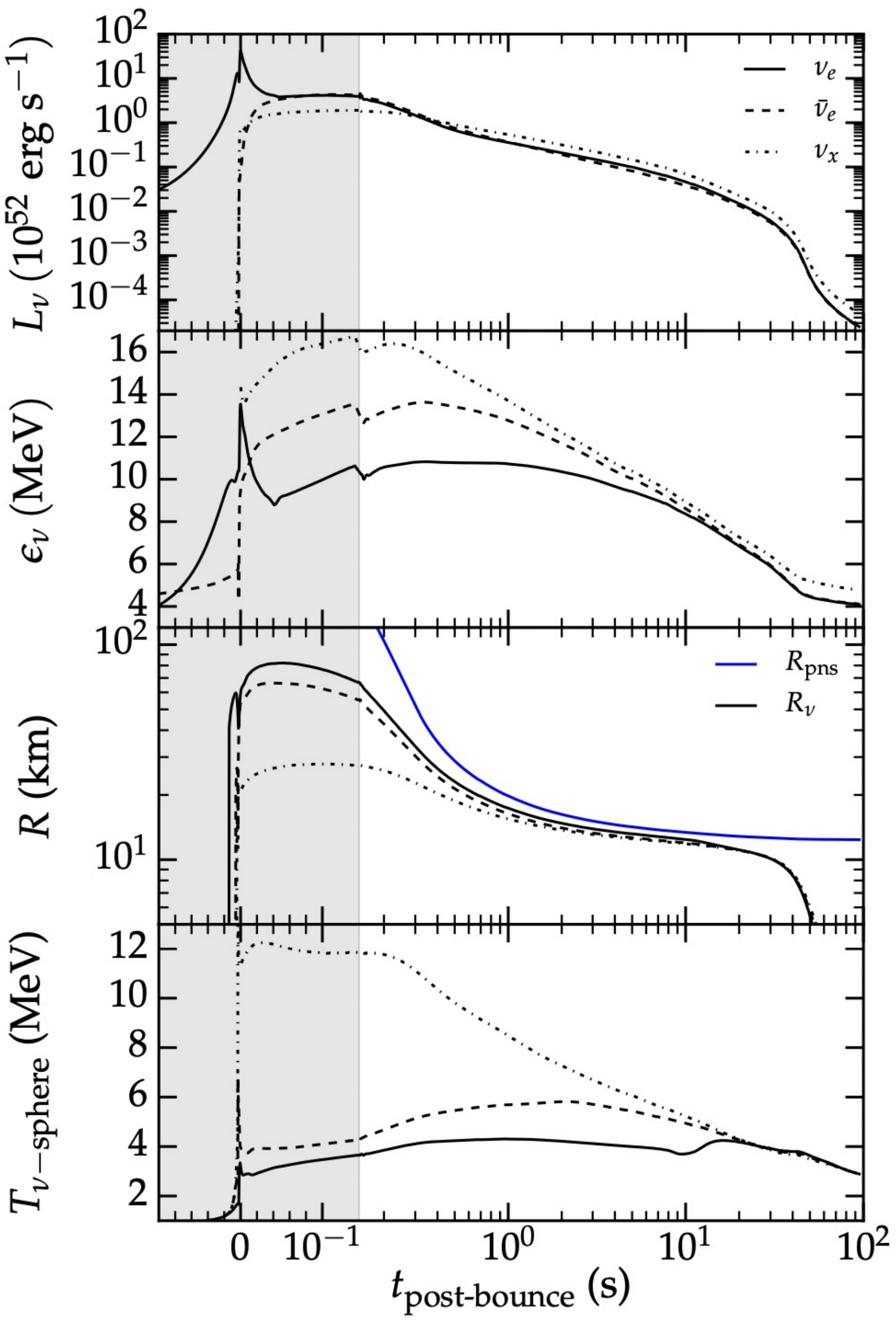
Handbook of Supernovae (2017)

PNS cooling curves

- At nuclear densities ~10^{14} g cm^{-3}, neutrinos diffuse out, resulting in such cooling curves

- Neutrino properties ~1s after bounce:
  - L ~ 10^{51} erg s^{-1}
  - E ~ 10-20 MeV
  - R_ν~10 km (where optical depth ~ 1)

- These luminosities drive a wind

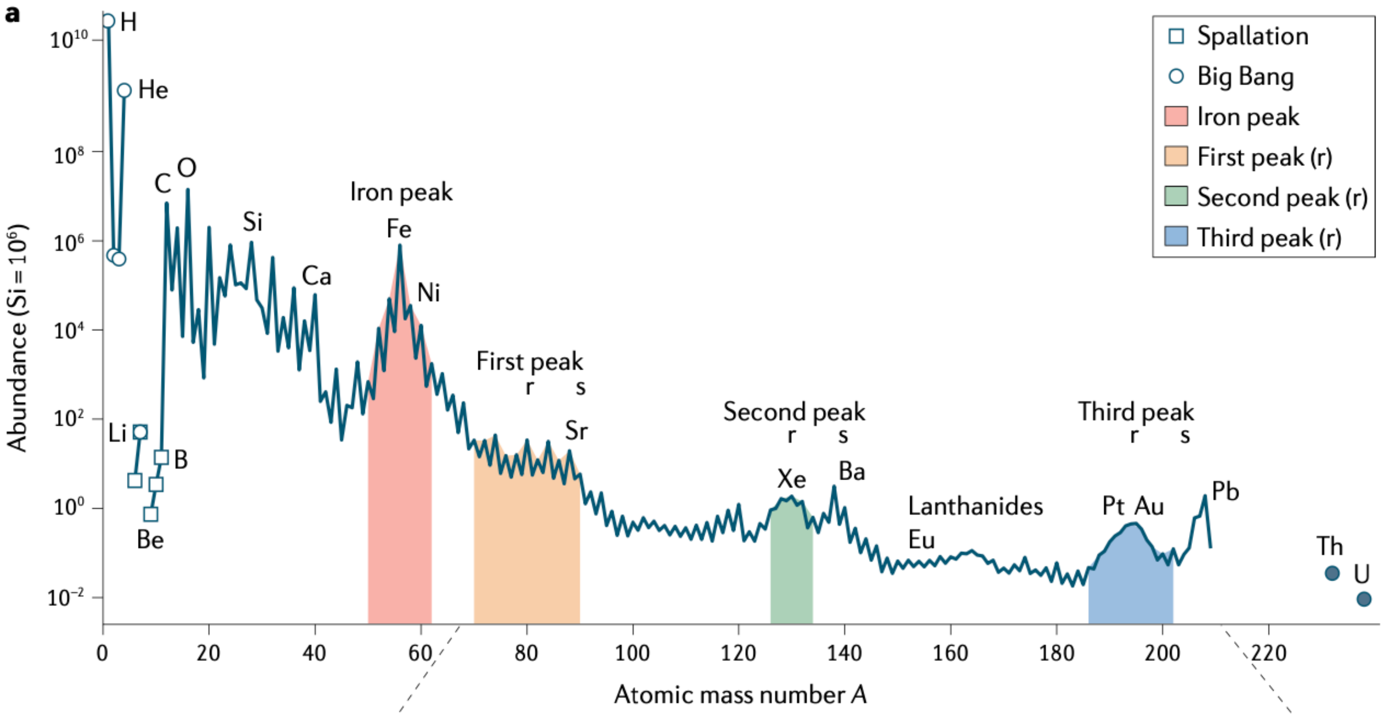


Roberts & Reddy (2017)

CCSNe as an r-process nucleosynthesis site?

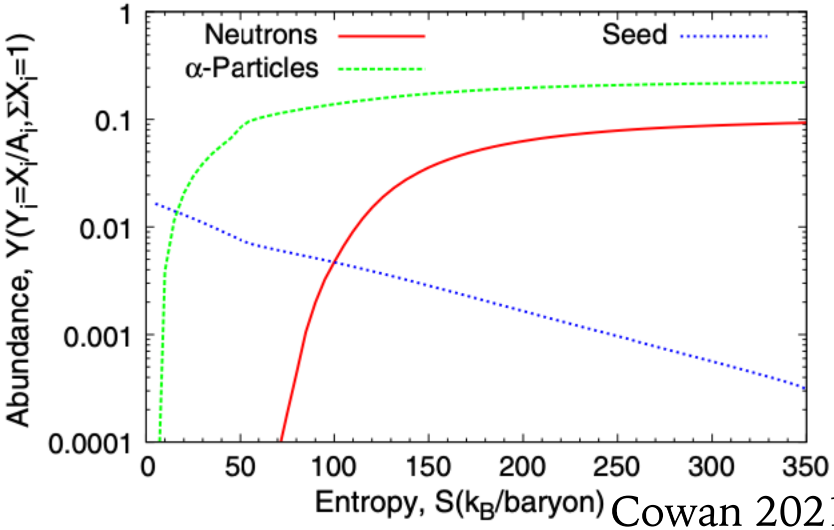
- Binary neutron star mergers/rare types of SNe as potential r-process sites

- Wind needs high neutron-to-seed ratio. 2 possibilities:
  - Y_e <0.3 (neutron-rich)
  - Alpha freeze-out (prevents formation of seeds), can occur when s > 100, and Y_e~0.45



Siegel 2022

Alpha Freeze-out suppresses seed formation



Cowan 2021

→ Under right combinations of *s*, Y_e, t_{exp} , neutron-to-seed ratio remains high; r-process occurs

Seeds form via triple alpha process (but Be decays quickly)

$$^{4}_{2}He + ^{4}_{2}He \rightarrow ^{8}_{4}Be$$

$$^{8}_{4}Be + ^{4}_{2}He \rightarrow ^{12}_{6}C + 2\gamma$$

- If $t_{alpha} < t_{exp}$, triple alpha process proceeds
- But at low densities (high entropies: $s \sim T^3/\rho \sim$ const.), reaction is suppressed

Dominant interactions:

Heating ($\boldsymbol{\nu}$-absorption) →

$$\nu_e + n \longleftrightarrow e^- + p \quad \text{and} \quad \bar{\nu}_e + p \longleftrightarrow e^+ + n$$

← Cooling ($\boldsymbol{\nu}$-emission)

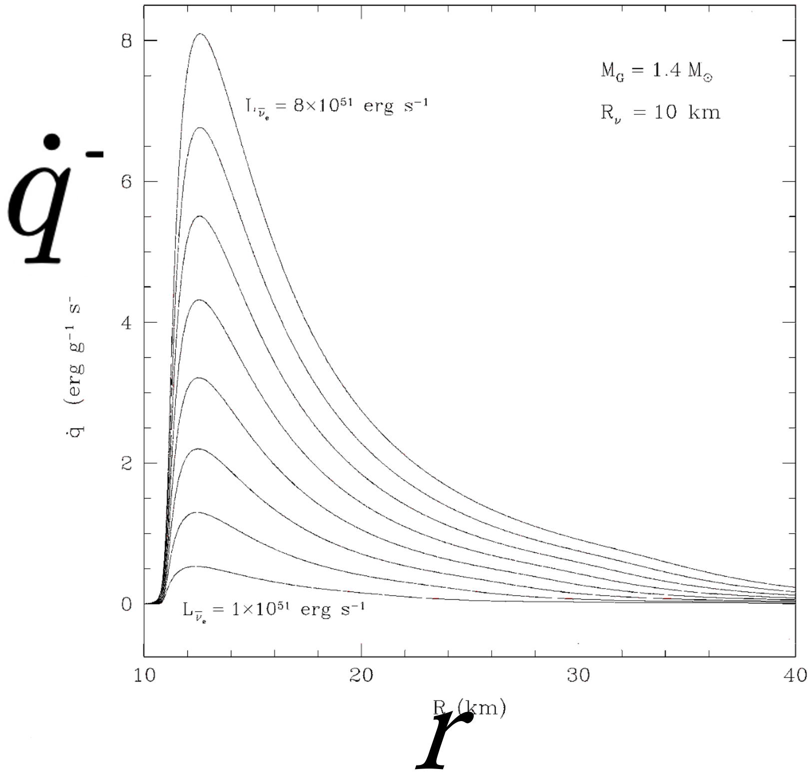
Near PNS surface, balance:

$$\dot{q}^+ \approx \dot{q}^- \quad \text{(heating} \sim \text{cooling rates)}$$

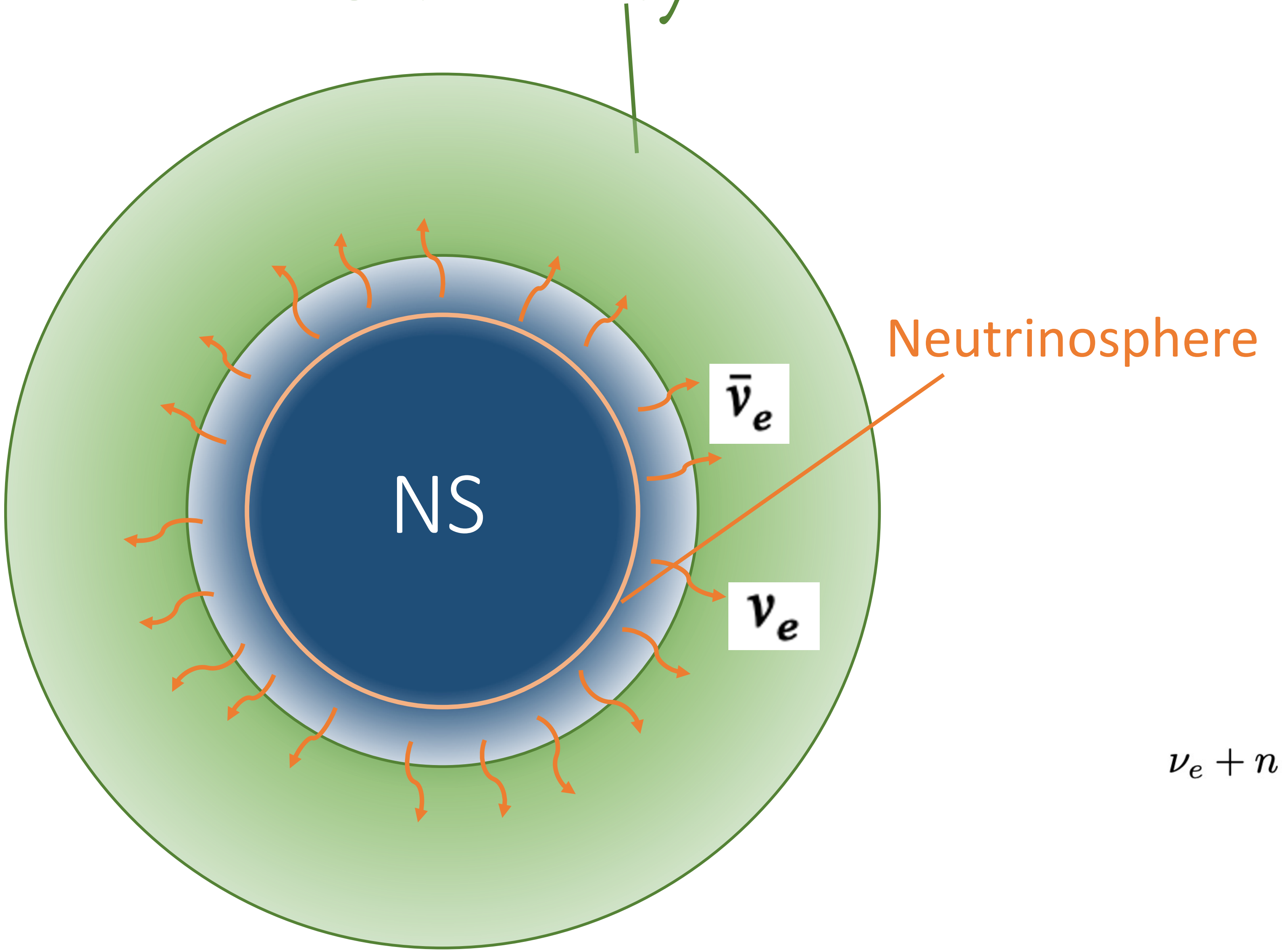
But cooling ($\sim T^6 \sim r^{-6}$) falls more rapidly than heating ($\sim r^{-2}$) with radius

> Region with net positive heating forms, the gain layer

Thompson+2001



The Gain Layer



- Gain layer: R ~ 15-50 km
- Matter (initially neutron-rich) irradiated by neutrinos,
  1. Gains energy &
  2. Protonizes ($L_{\nu_e} \sim L_{\bar{\nu}_e}$)
- Radiation-dominated, adiabatically expanding wind ($s \sim T^3/\rho \sim$ const.)

Heating (ν-absorption)

$$\nu_e + n \longleftrightarrow e^- + p \quad \text{and} \quad \bar{\nu}_e + p \longleftrightarrow e^+ + n$$

Cooling (ν-emission)

Previous works: eg. Thompson+2001, Arcones & Montes 2011, Qian & Woosley 96 etc.

- spherically symmetric, non-rotating winds
- Neutrino luminosities put in by hand
- Not in full GR

Concluded: Unable to produce 3rd peak elements (too proton-rich)

Question:

- Given neutrino luminosities/energies,
  - Wind properties (eg. Mass loss rate, entropy, Y_e etc.)?
  - Conducive to r-process?
  - Impact of rotation?

Our goal: Simulate hot NS with self-consistent neutrino transport which achieves steady-state wind solution. Study effects of rotation

This is an idealized, controlled environment

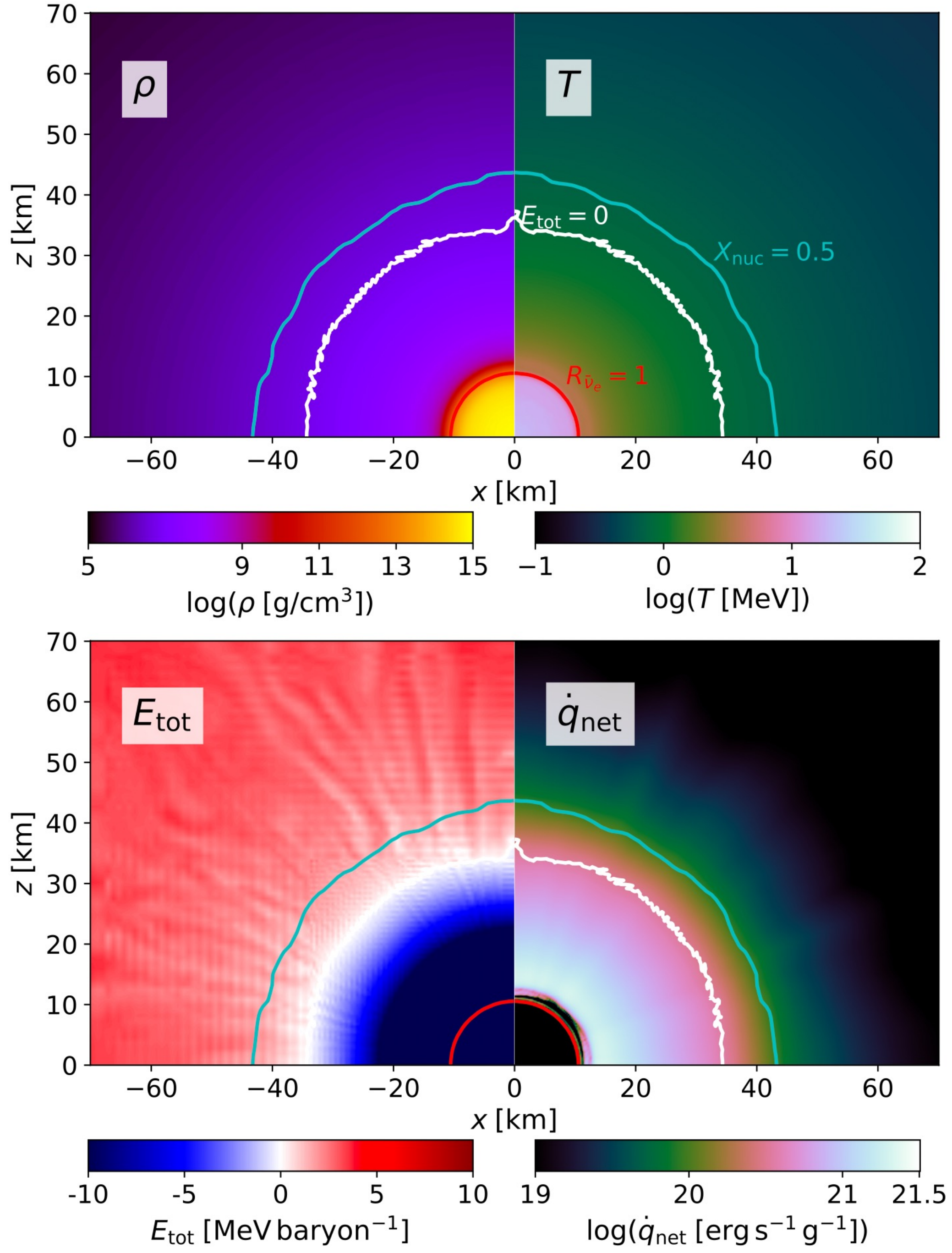
Simulation Setup

- GRMHD code ($B = 0$) (Mosta+14)
- Initial conditions: 1.4 solar mass TOV NS
- $T_c \sim 20$ MeV, Y_e profile from Kaplan+14 – Chosen to reproduce steady state neutrino emission
- Tabulated SFHo nuclear EOS (Steiner+2013)
- M0 scheme for neutrino transport (Radial equations which evolve neutrino energies/number densities along radial rays)
    - Emission and absorption included (Radice+16)
- Coarsest grid spans $\sim$1000 km
- Simulations evolved for $\sim$150ms. Steady-state achieved at $\sim$60 ms

Test case: Steady state profiles of the spherical wind

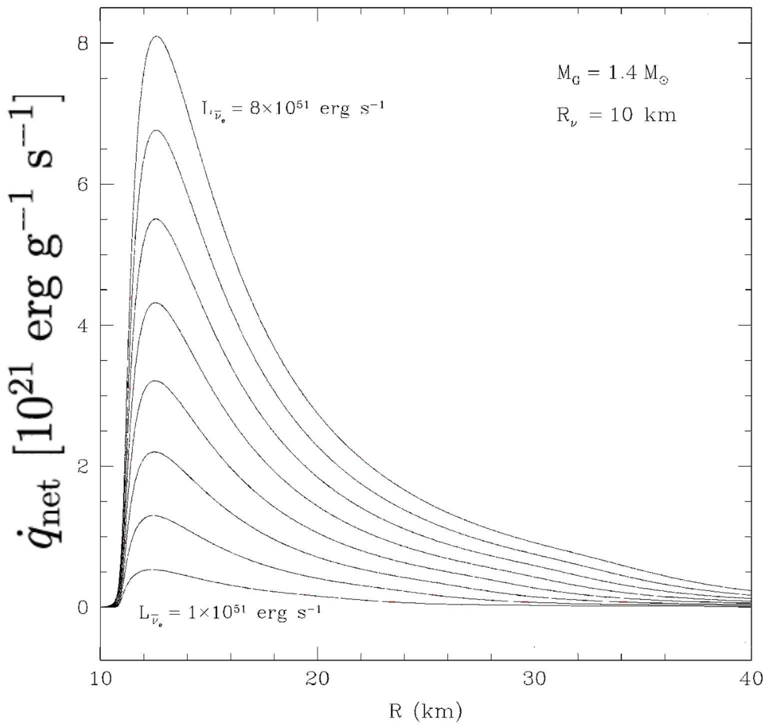
Smooth profiles in ρ, T *(top)*

Wind becomes unbound at ~35 km (white contour)
Heating ceases at alpha-formation surface (green contour)
Neutrinosphere (red contour)

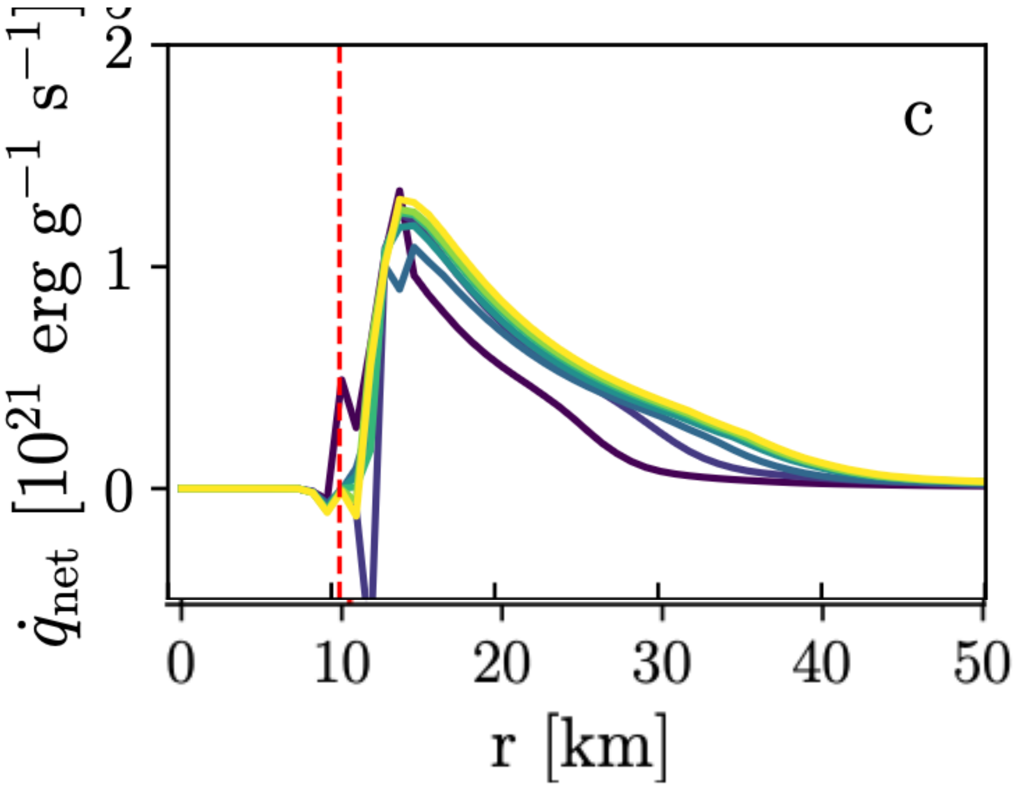


Desai+2022

Steady state profiles of the spherical wind



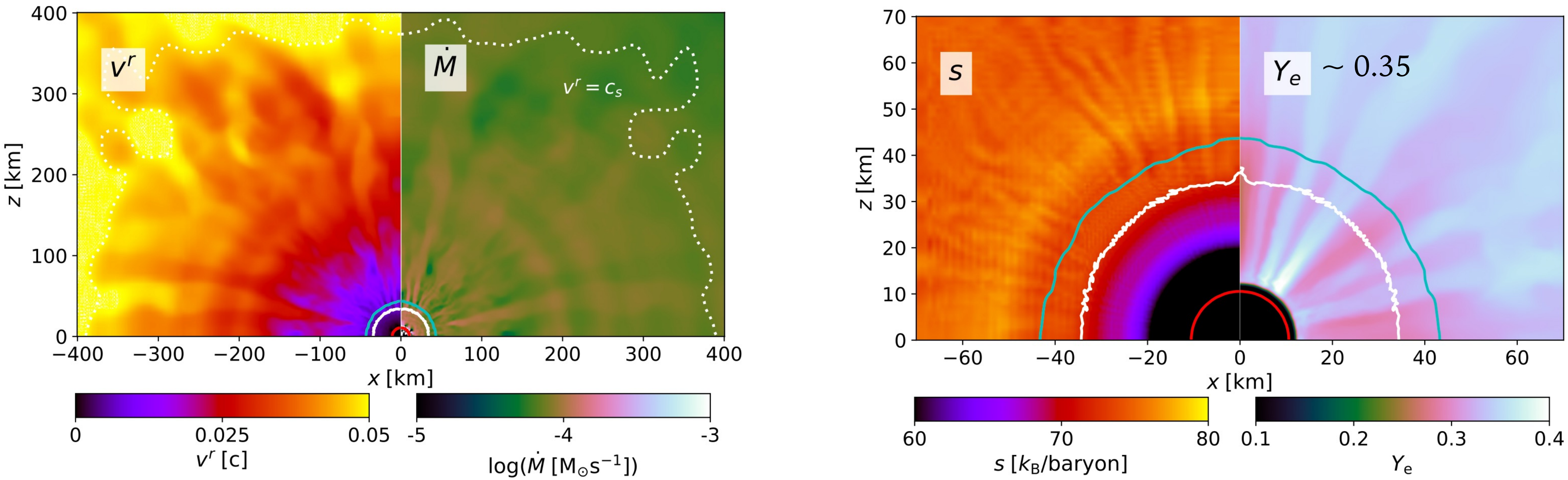
Thompson+2001



Desai+2022

Our gain region is similar to previous models

Steady state profiles of the spherical wind



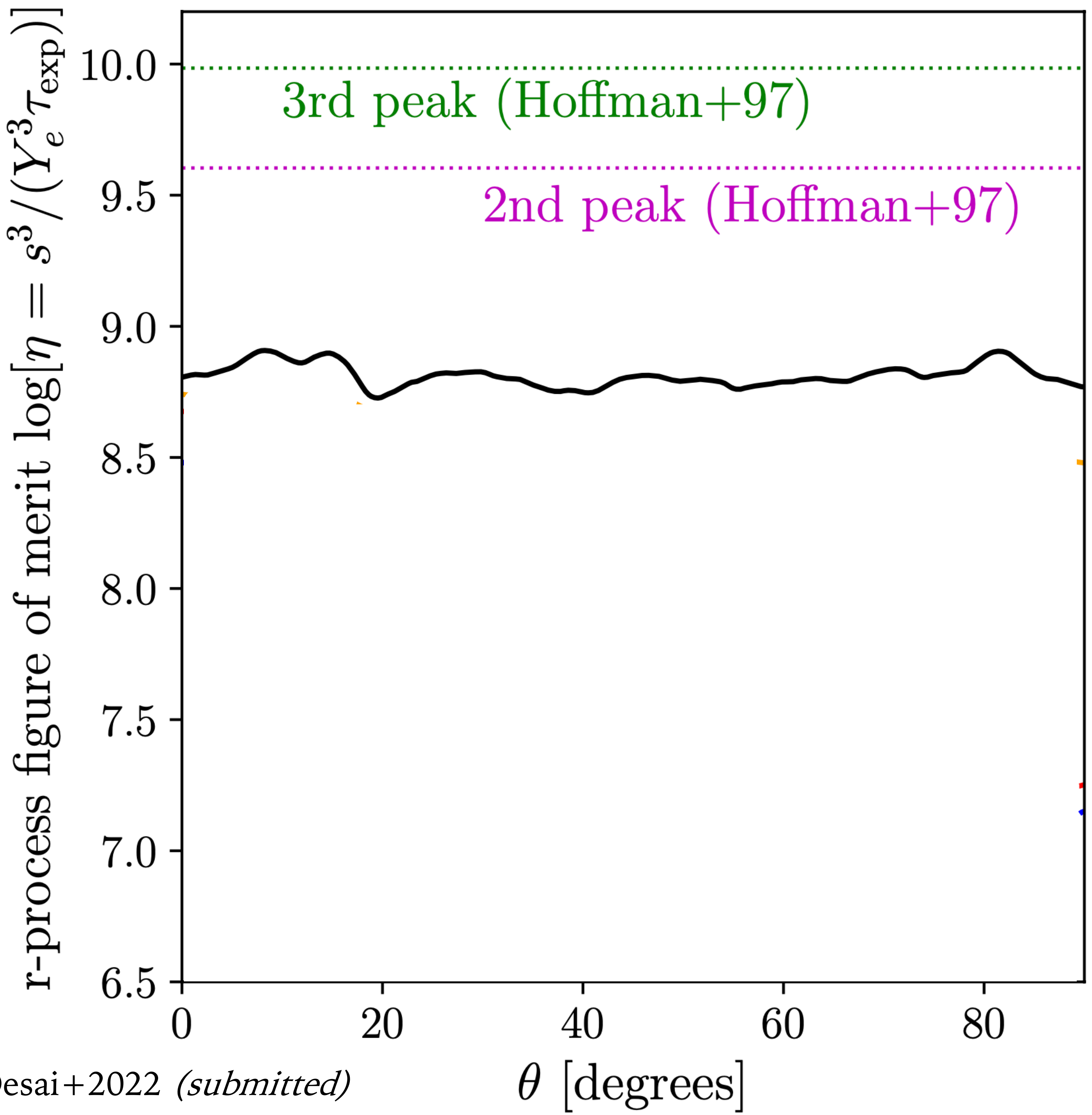
Desai+2022

Mass loss rates and entropies are rescaled to neutrino properties of Thompson et al. (2001) according to analytical relation from Qian & Woosley (1996)

Potential r-process site?

…via alpha freeze-out channel, not likely.

Consistent with previous findings.



Desai+2022 *(submitted)*

The rotating PNS wind

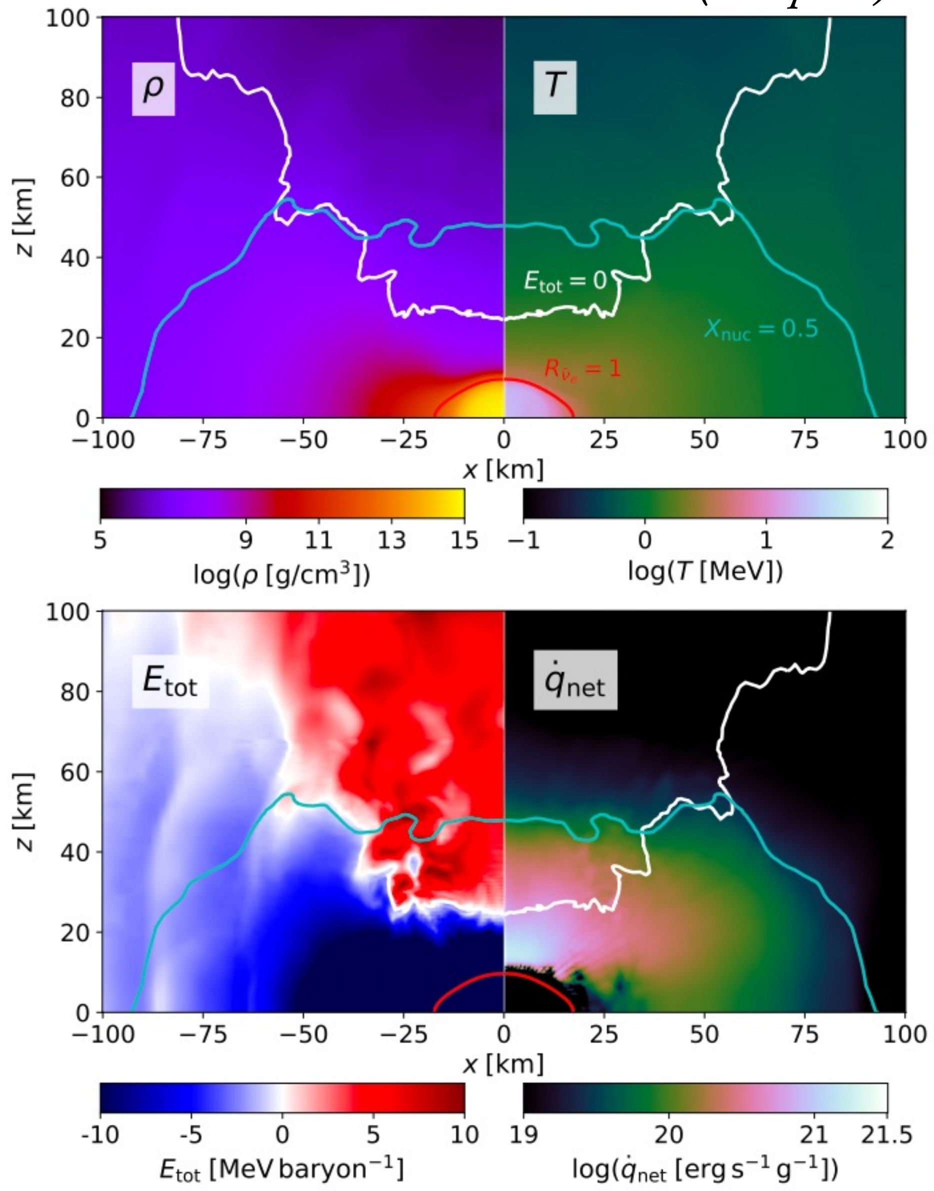
$$P_c \approx 2\pi \frac{R_\nu}{c_s} \approx 3.4\,\mathrm{ms} \left(\frac{R_\nu}{12\,\mathrm{km}}\right)^{5/4} \left(\frac{L_\nu}{10^{52}\,\mathrm{erg\,s^{-1}}}\right)^{-1/8}$$

- RNS code (Stergioulas & Friedman 1995) solves GR Euler equations for uniformly rotating star in axi-symmetric spacetime

- Various spin periods tested

Result: NS deformed

Desai+2022 *(accepted)*



The rotating PNS wind

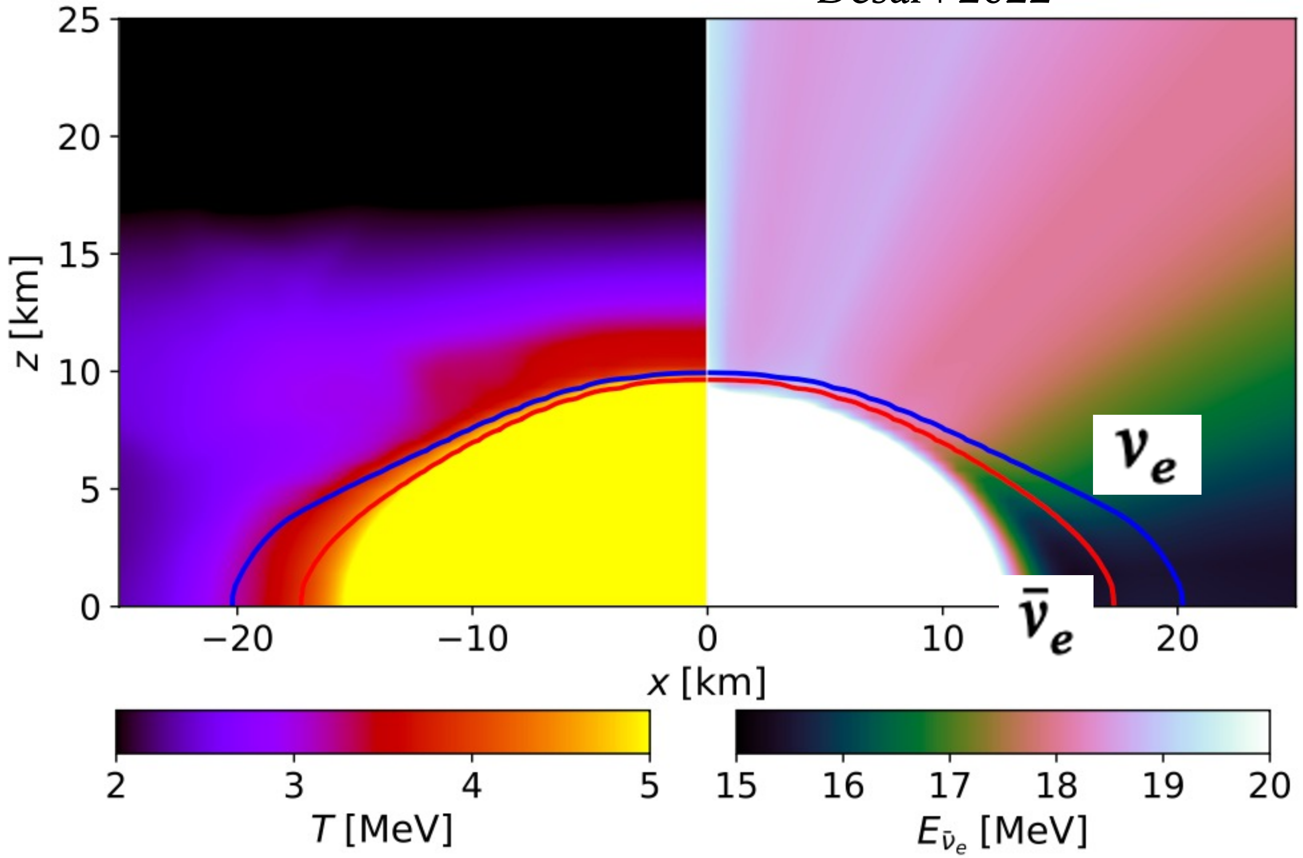
- Electron neutrino/anti-neutrinospheres are at different temperatures,

1. at equator compared to pole
2. Relative to each other at the equator

- This results in

1. More heating at the pole
2. Lower Y_e in equator (shifts balance to more neutron-rich equilibrium)

Desai+2022



Heating (ν-absorption)

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Cooling (ν-emission)

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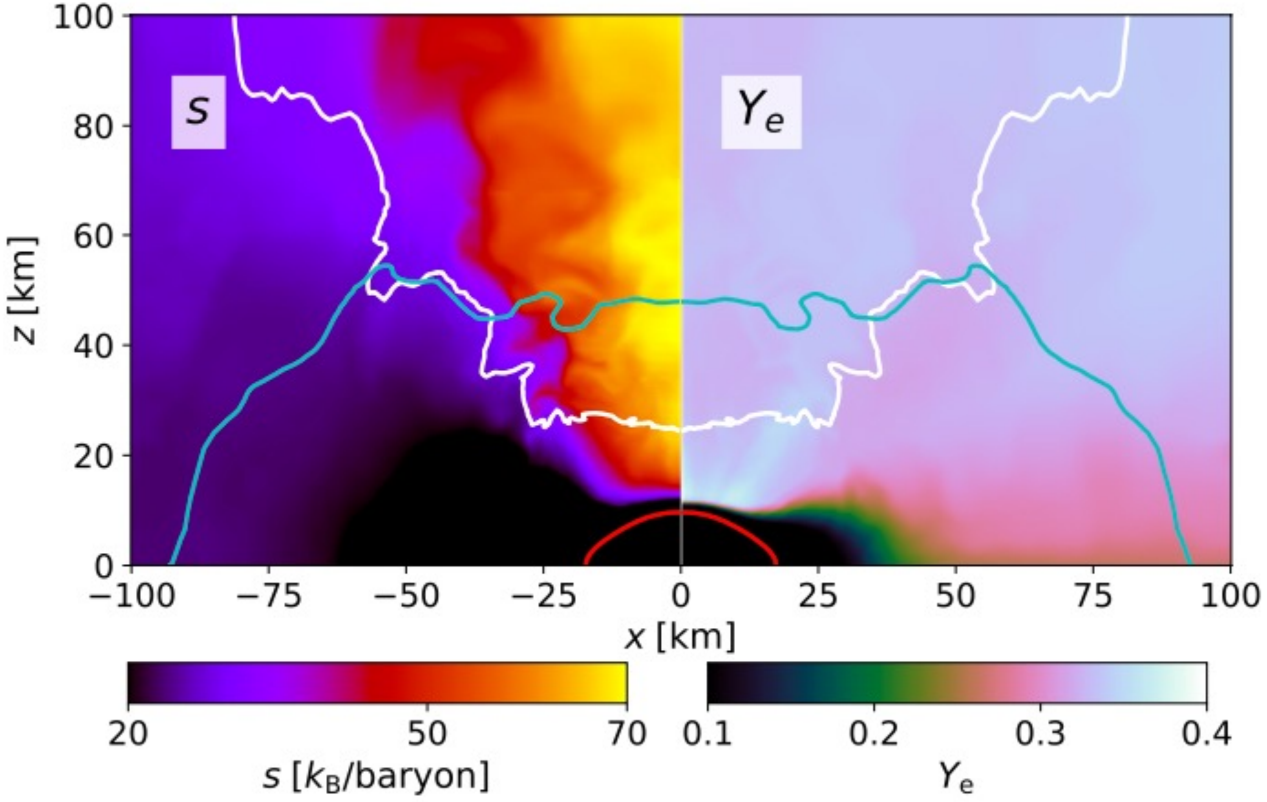
Desai+2022



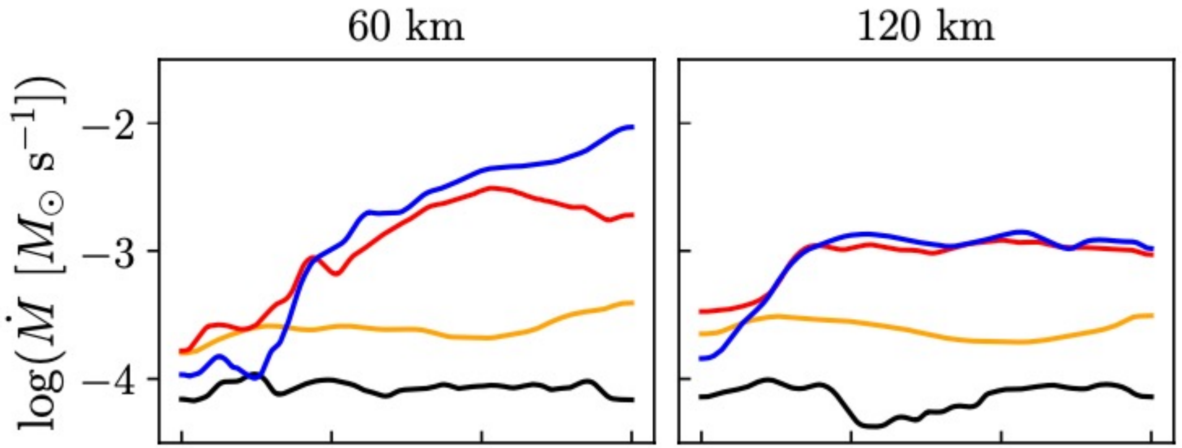
Heating ($\boldsymbol{\nu}$-absorption)

$$\nu_e + n \longleftrightarrow e^- + p \quad \text{and} \quad \bar{\nu}_e + p \longleftrightarrow e^+ + n$$

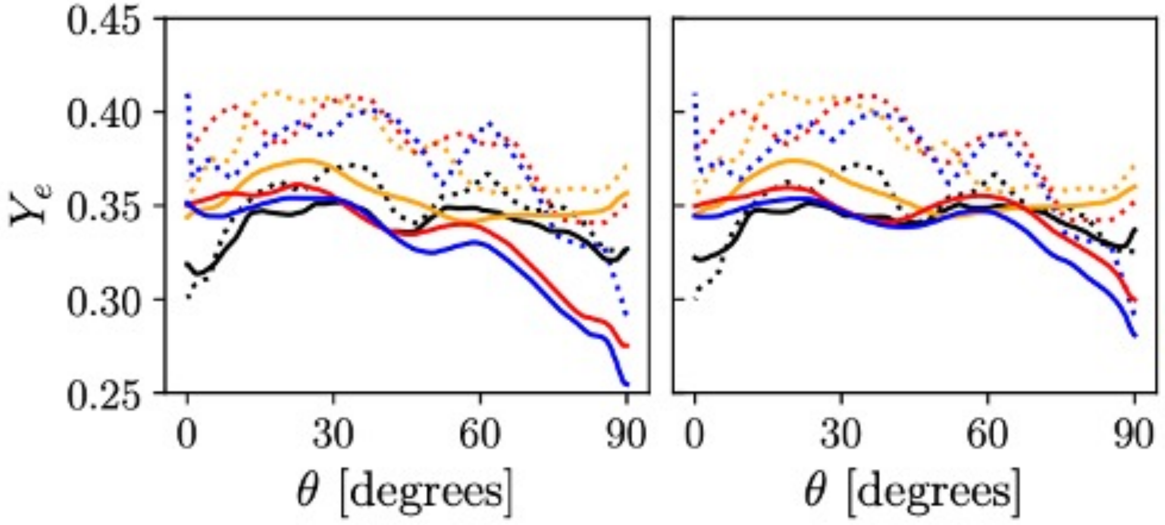
Cooling ($\boldsymbol{\nu}$-emission)

The rotating PNS wind: angular properties

- Polar quantities are similar, independent of spin period (centrifugal effects minimal)
- Y_e reduced in equator! Hope for r-process
- High equatorial mass loss rate



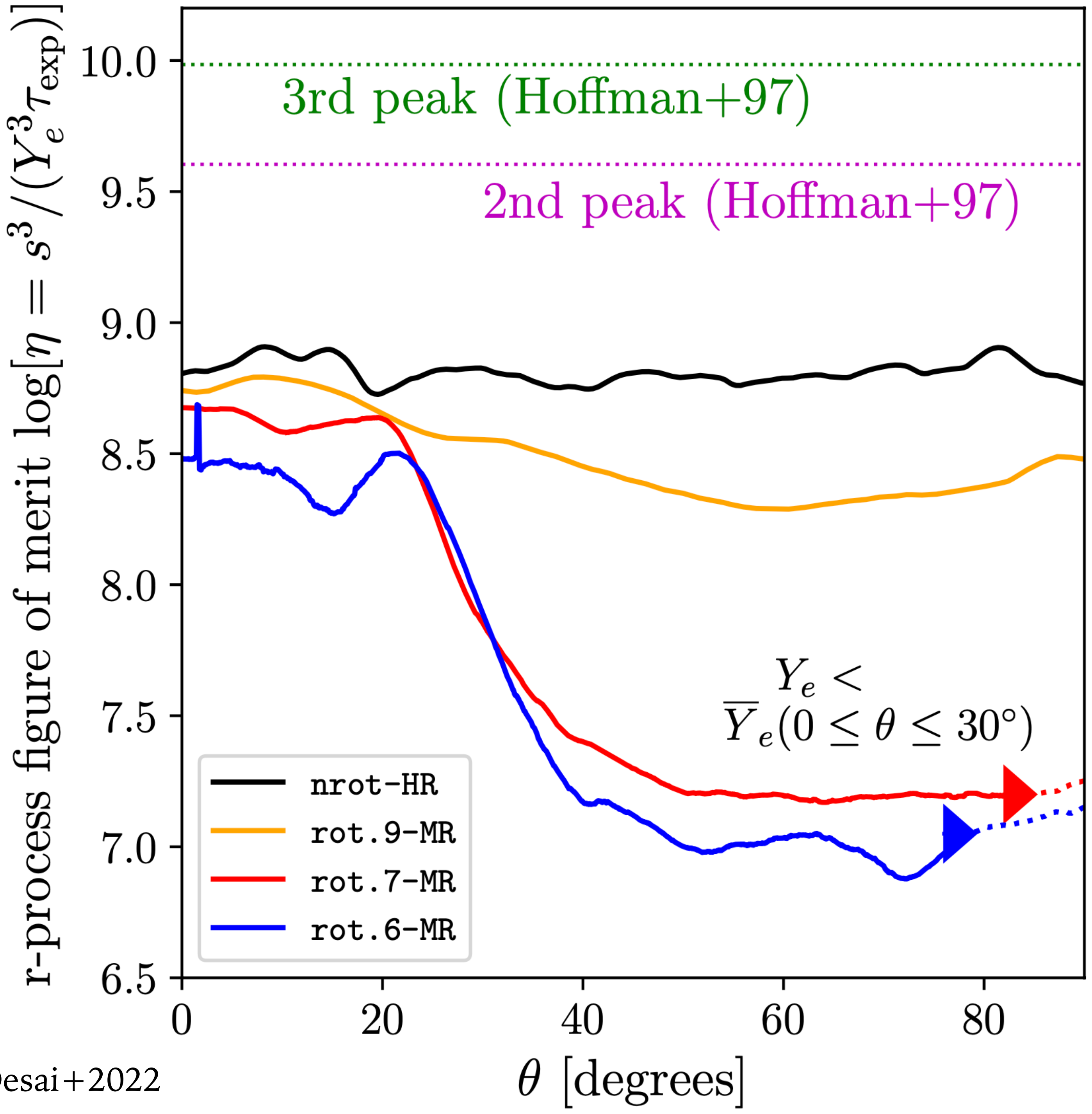
Desai+2022



Potential r-process site?

…via alpha freeze-out channel, again not likely.

However, low Y_e promising (~10% reduction from polar region, to the right of arrows)

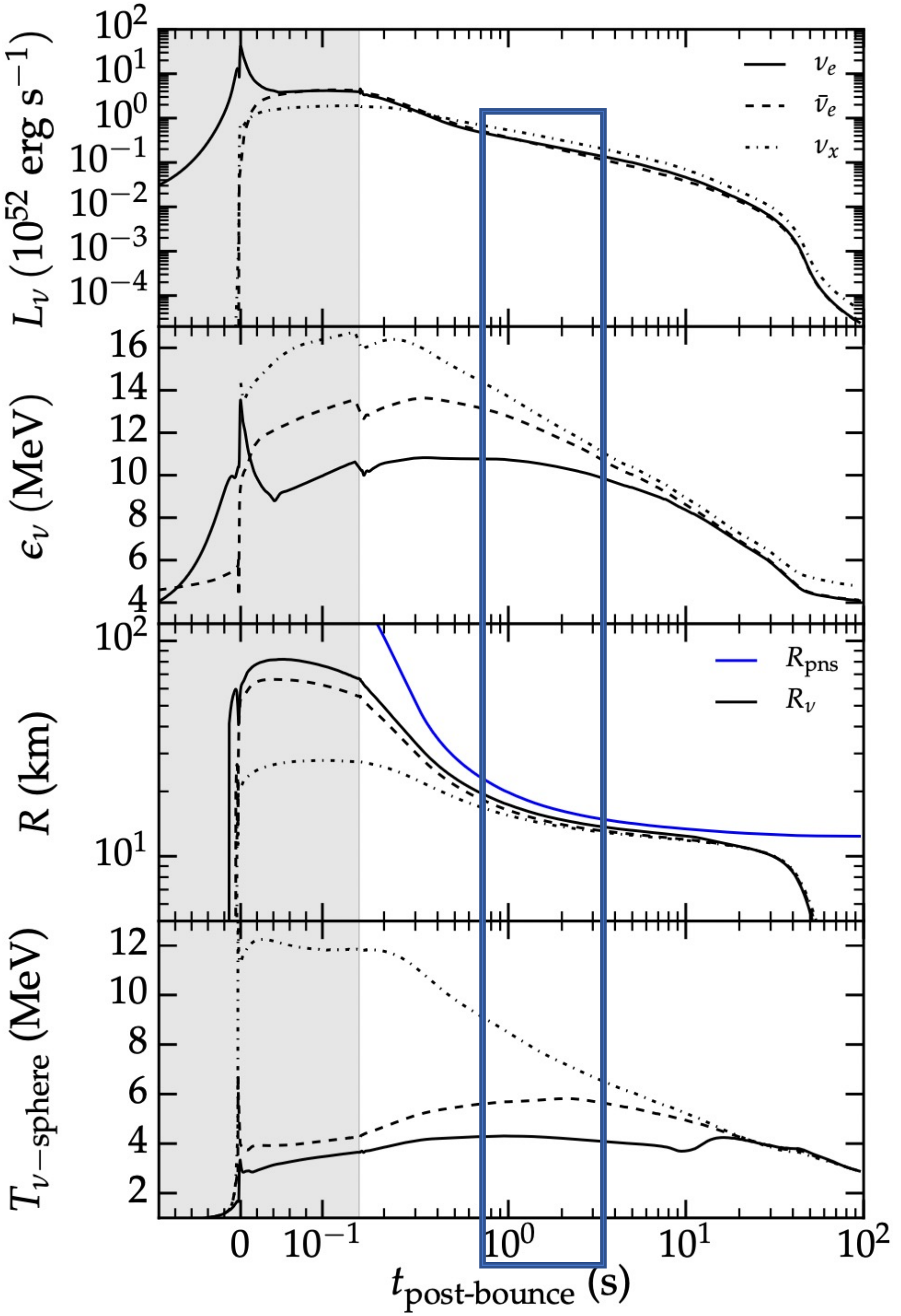


Desai+2022

Back to the cooling curve

- Reflects true luminosities/energies post CCSN
- Significant outflows in the equator
- L_ν ~few 10^{51} erg s^{-1} lasts ~3 s so M_{ej} ~ dM/dt*3 ~ 1e-3 solar masses

→ Conclusion:
High mass loss rate → Competitive with ordinary supernova yields even if rapidly rotating NSs are formed in ~10% of CCSNe



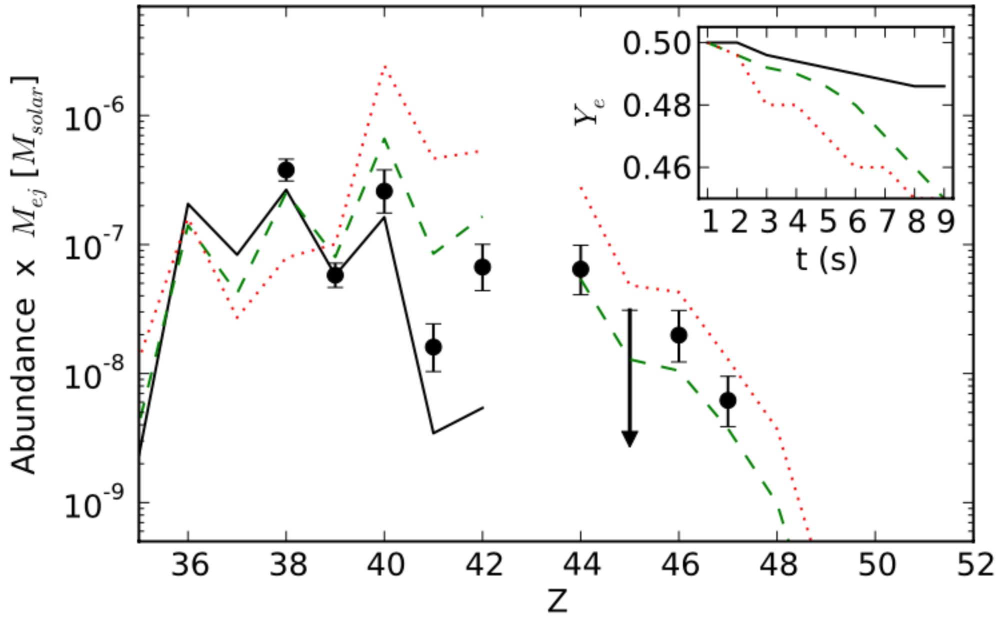
Roberts & Reddy (2017)

PNS wind as a source of LEPP elements?

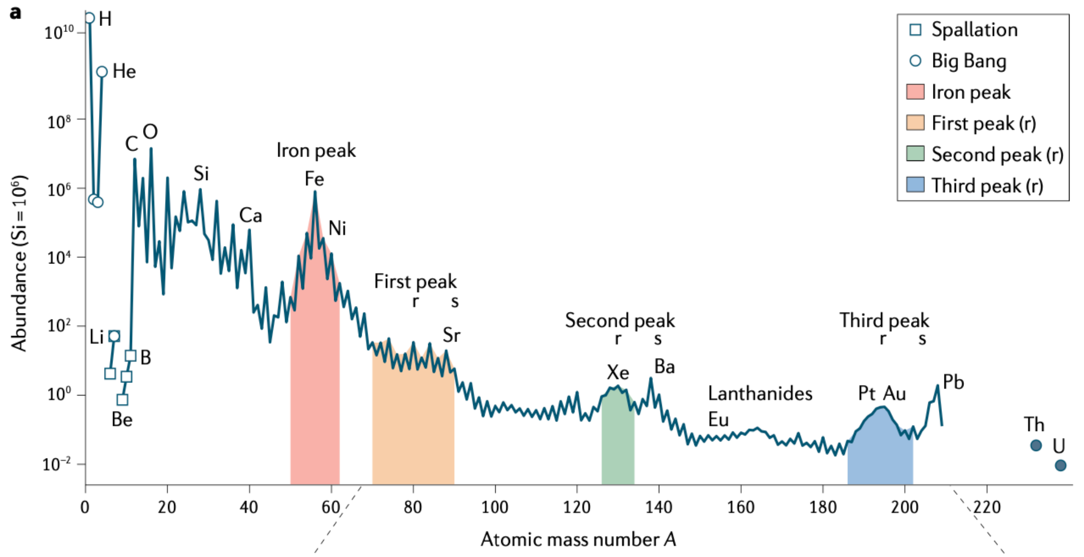
- “Lighter Element Primary Process”. Set of elements between Fe and 2nd r-process peak

- Found in ultra metal-poor stars

Conclusion: Even if non-rotating PNS winds not conducive to r-process, 10% reduction in Y_e in rotating winds **may allow for LEPP production**



Arcones & Montes 2011



Siegel 2022

Conclusions

With Rotation:

- True Y_e unknown, but rotation reduces Y_e by 10% in equatorial plane compared to non-rotating case
  - LEPP elements? (Arcones & Montes 2011)

- Mass loss rate boosted by factor of 10 → competitive with ordinary CCSN yields

Next:

Add magnetic fields

- low Y_e retained in material flung out?
- Magnetar may explain extended emission?