The origin of heavy elements: r-process nucleosynthesis in neutron star mergers

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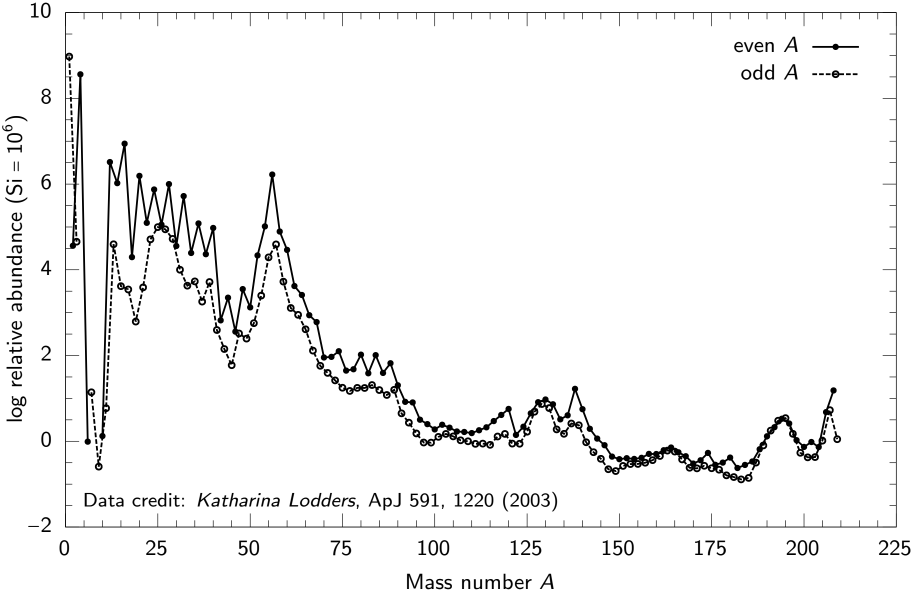
Outline

1. Origin of the elements
2. Nucleosynthesis calculations with SkyNet
3. r-Process nucleosynthesis in neutron star mergers
4. Summary

Solar system abundances



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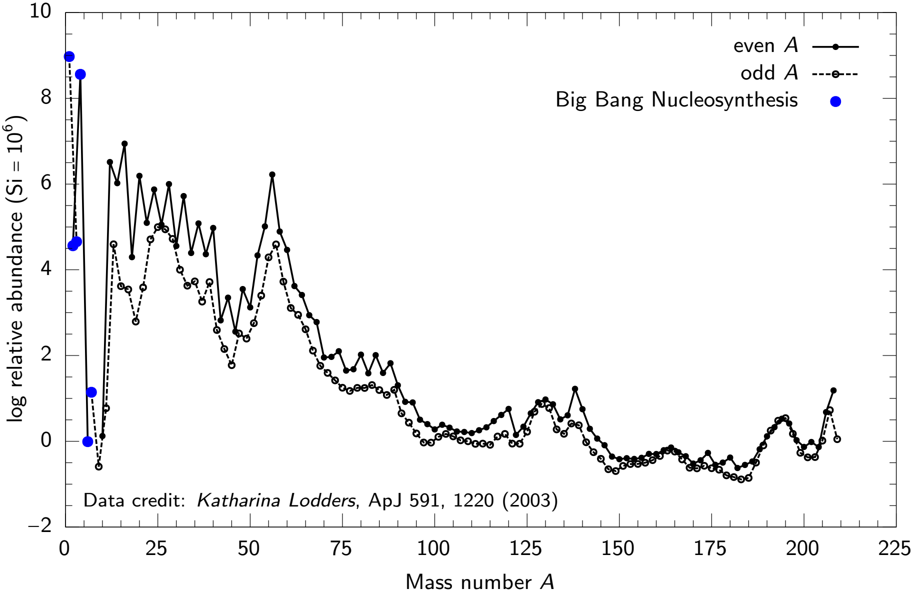

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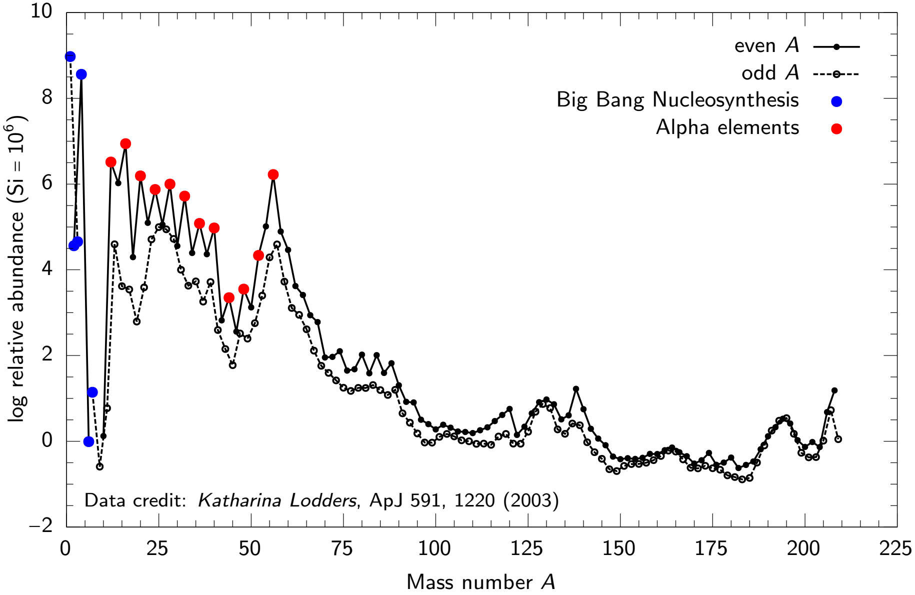

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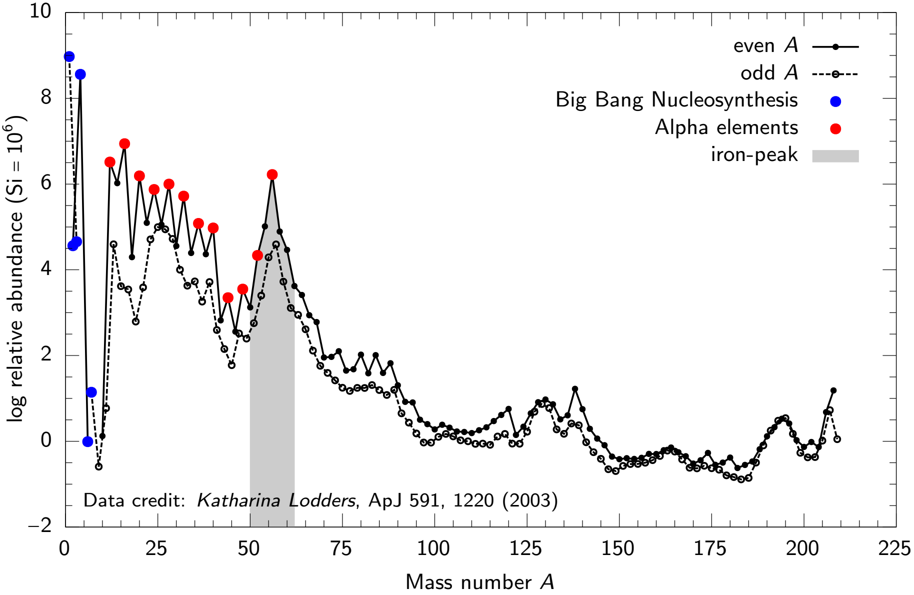

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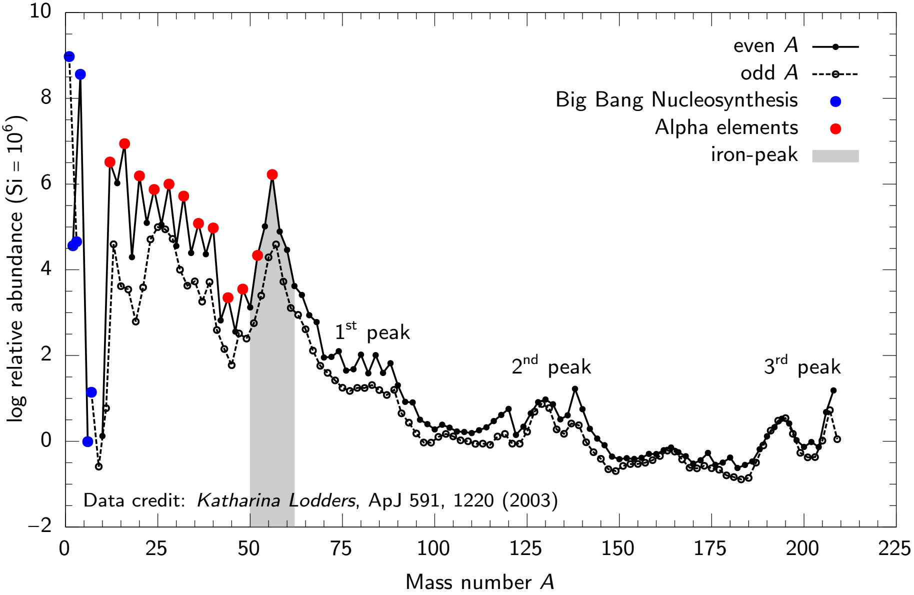
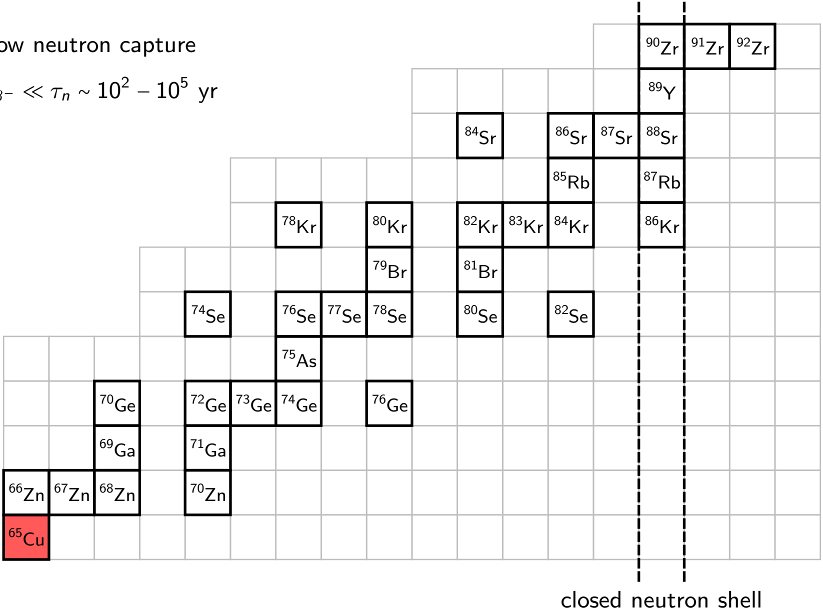


The s-process

slow neutron capture

$\tau_{\beta^-} \ll \tau_n \sim 10^2 - 10^5$ yr



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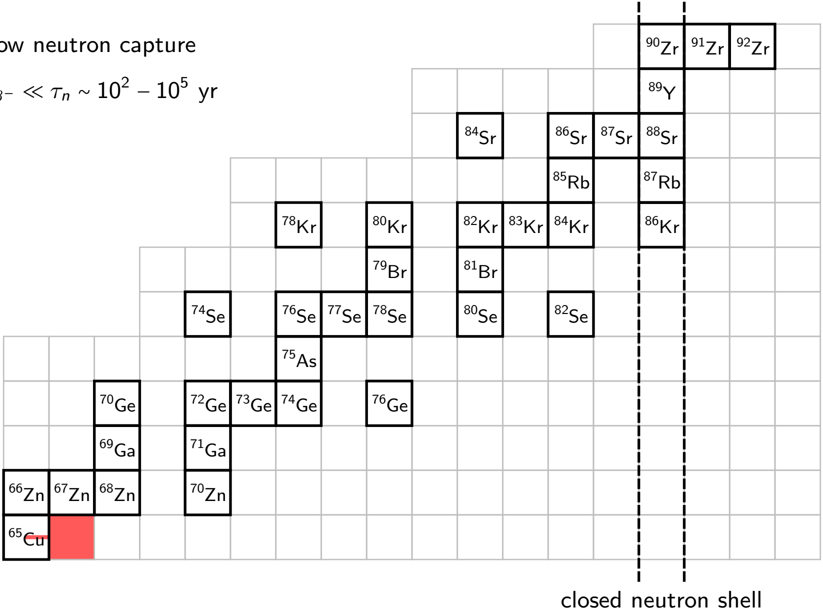

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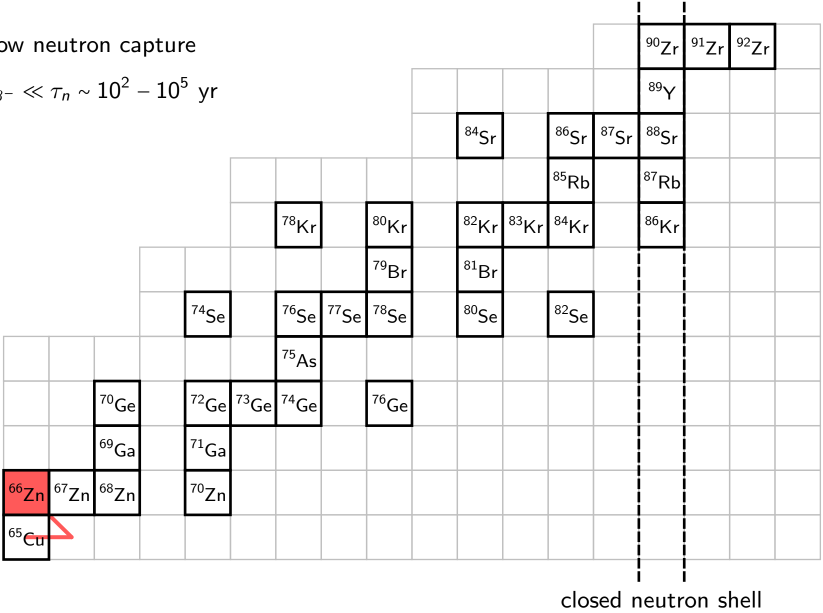

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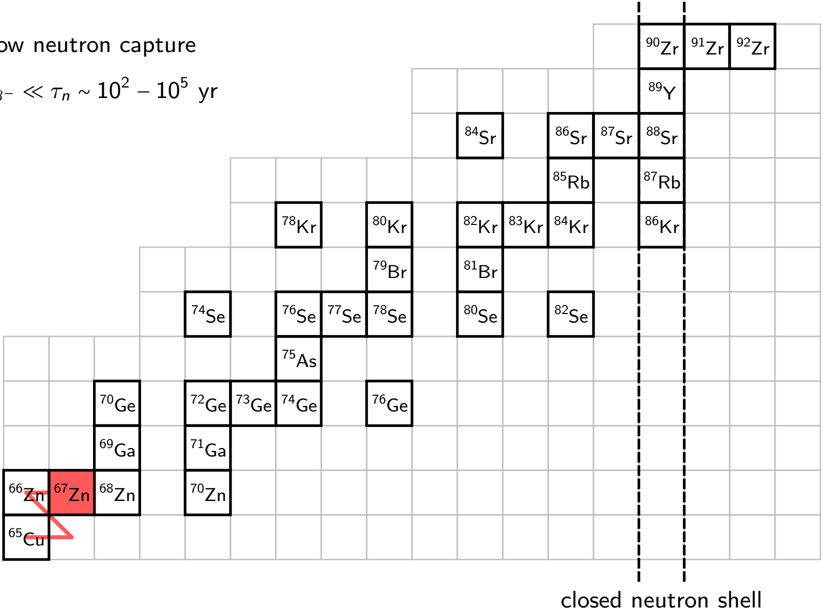

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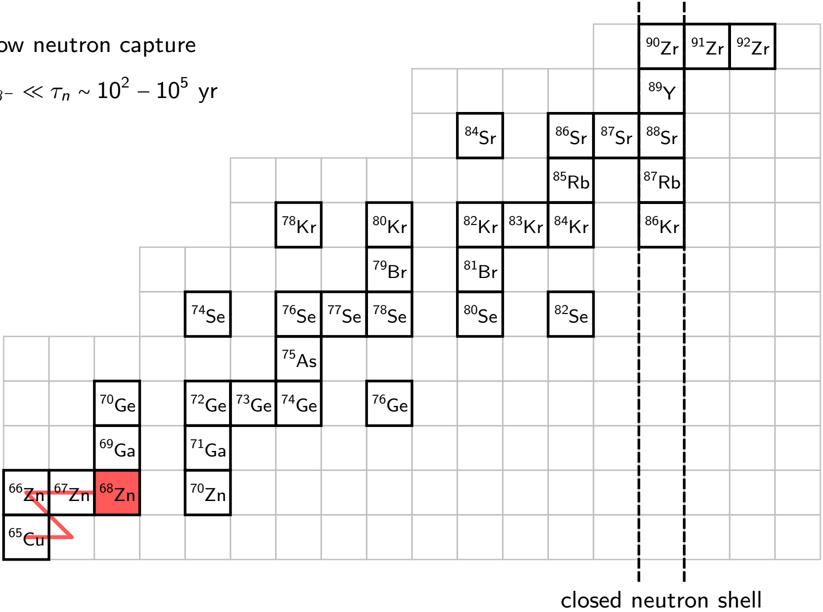

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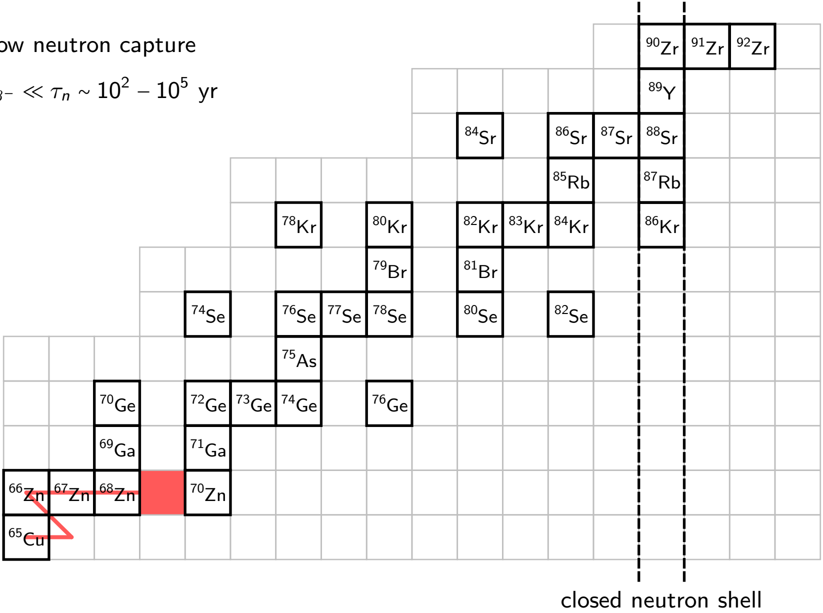

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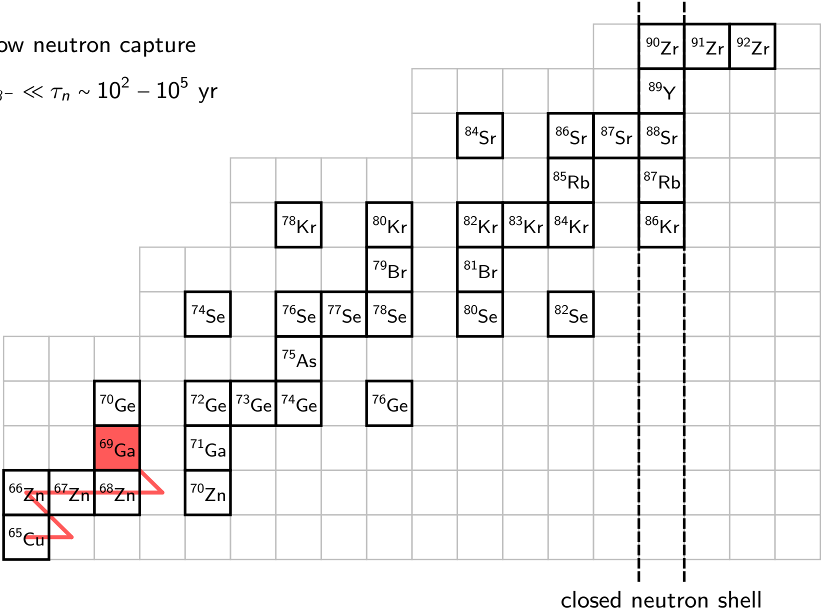

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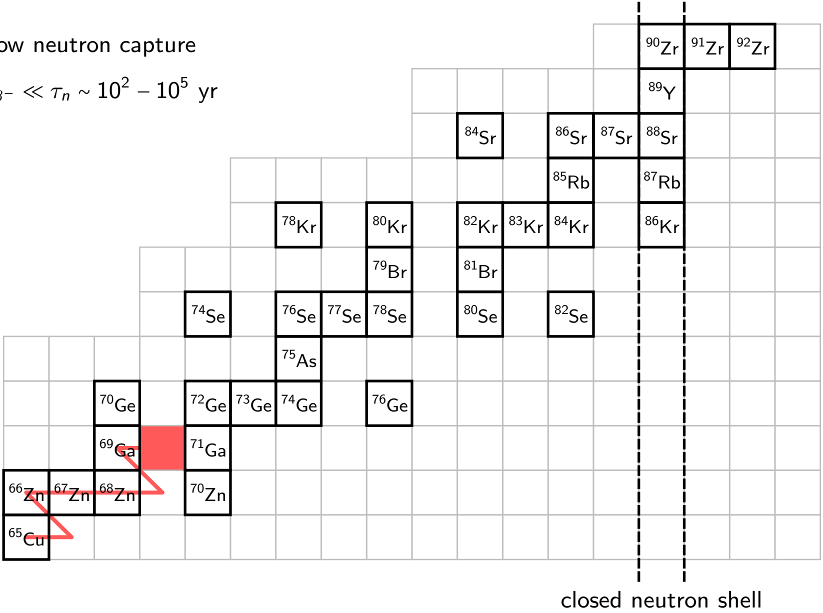

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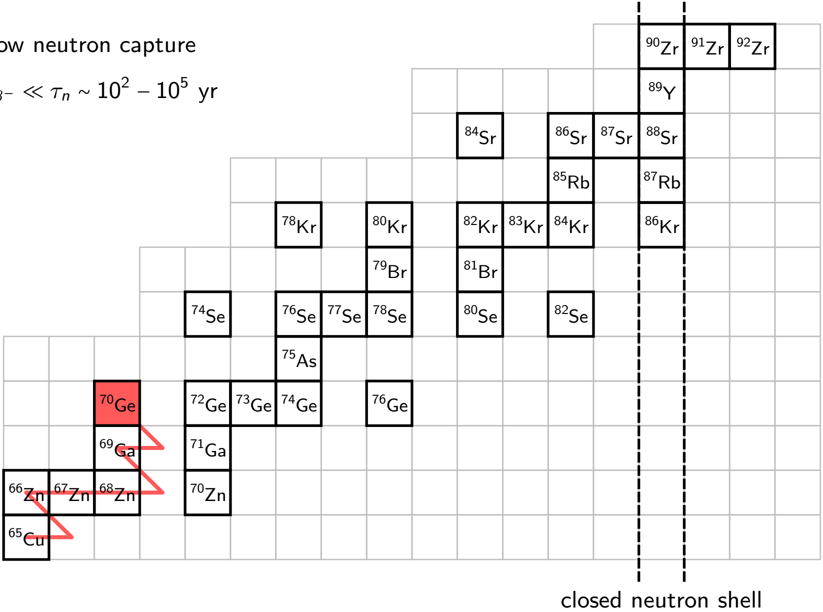

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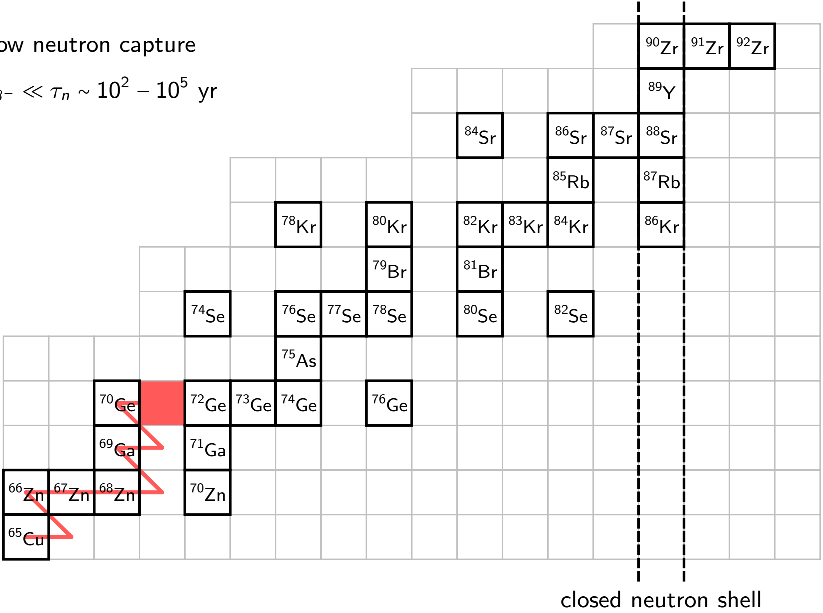

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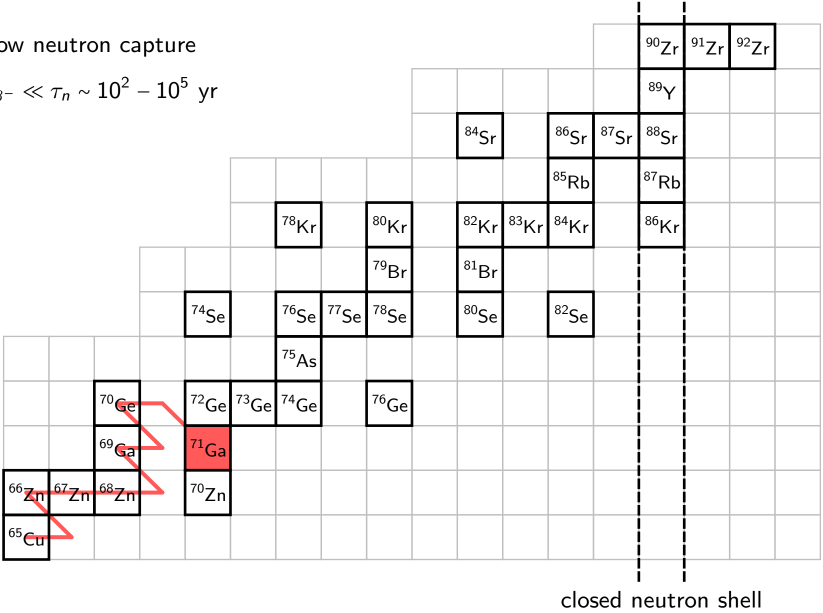

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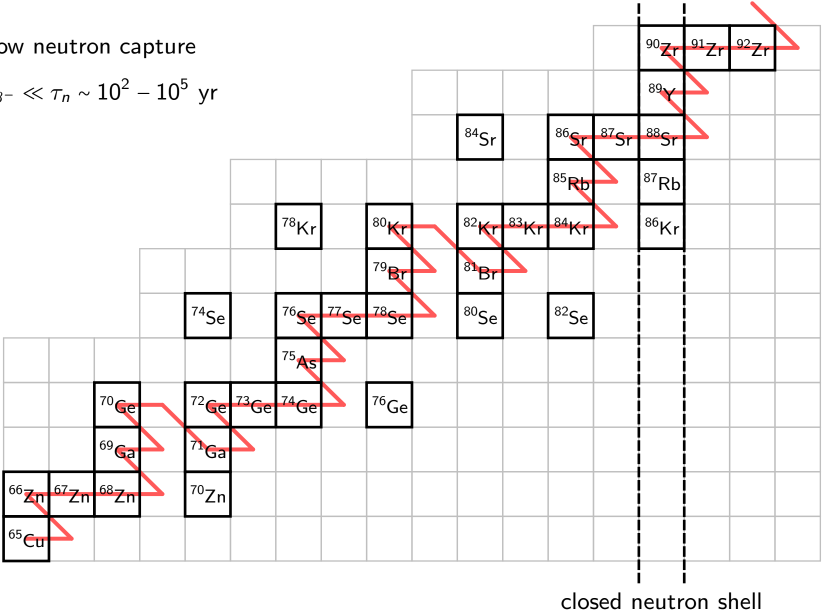

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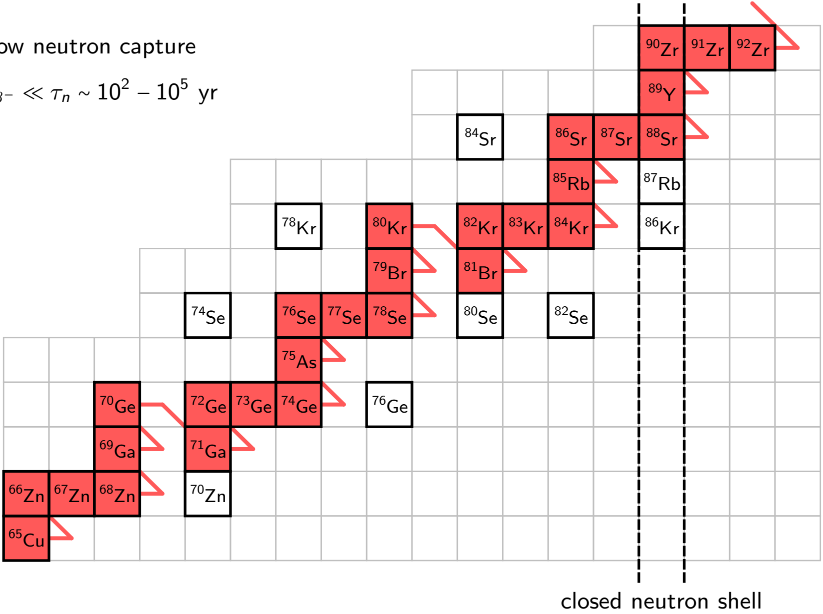

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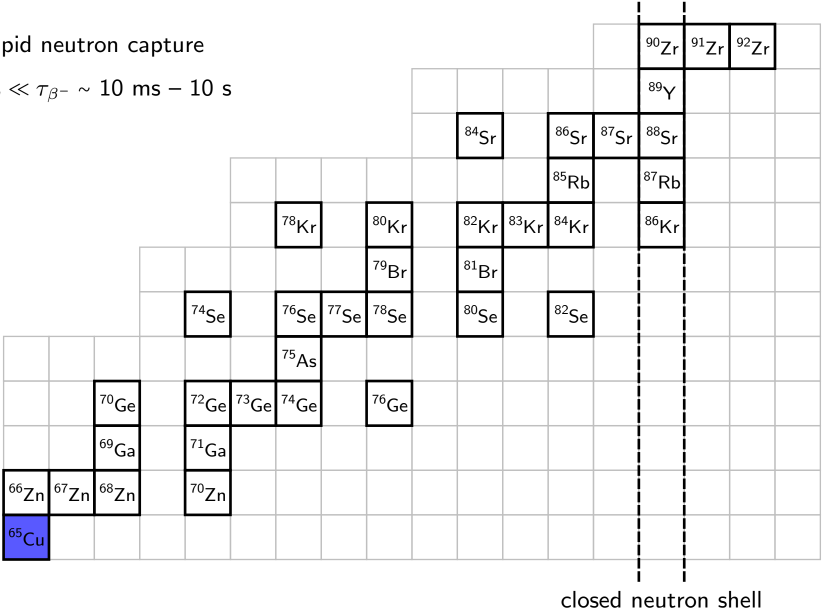

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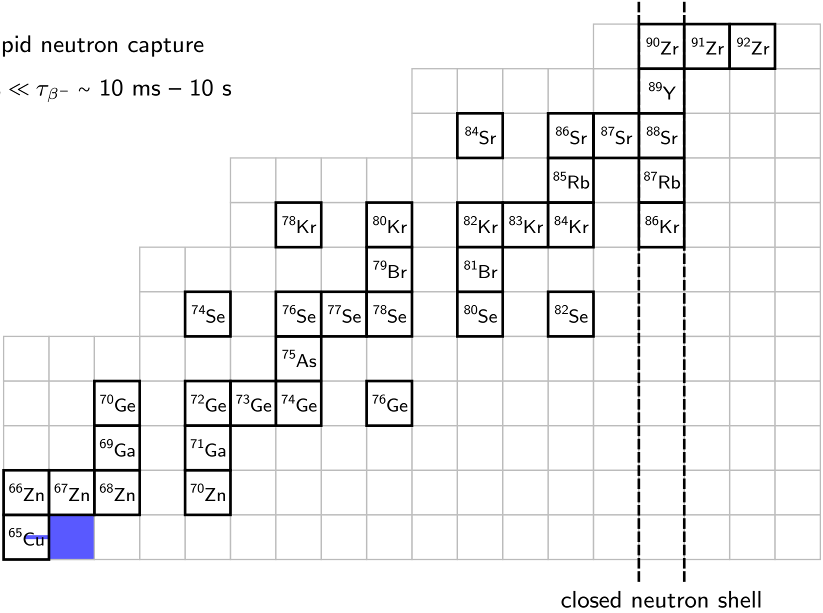

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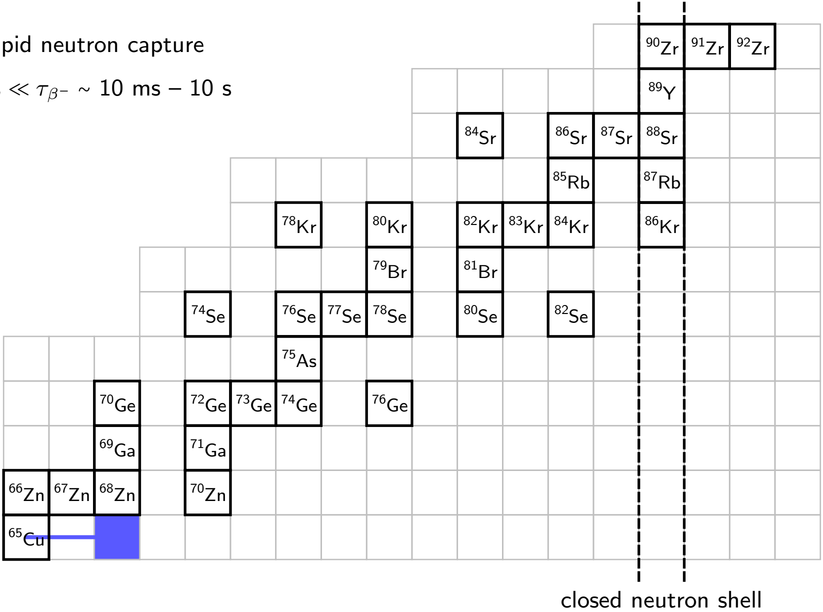

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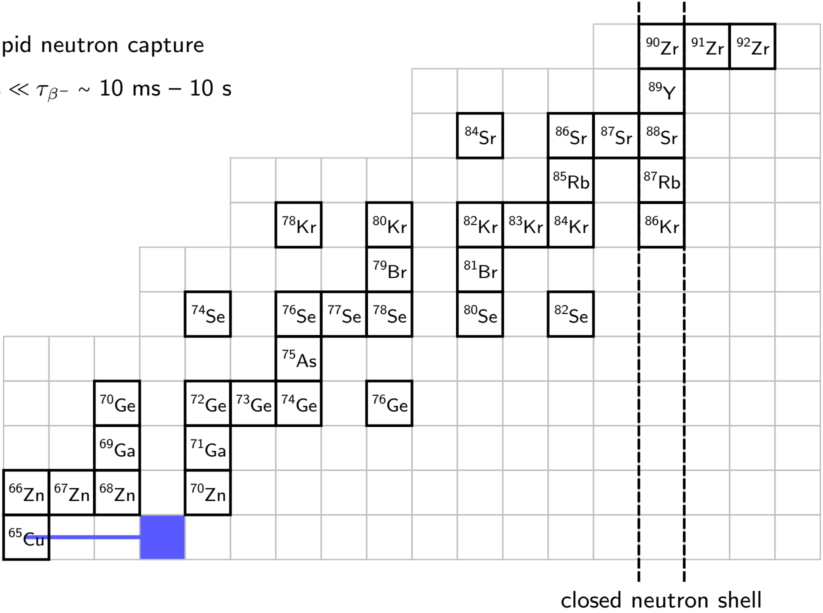

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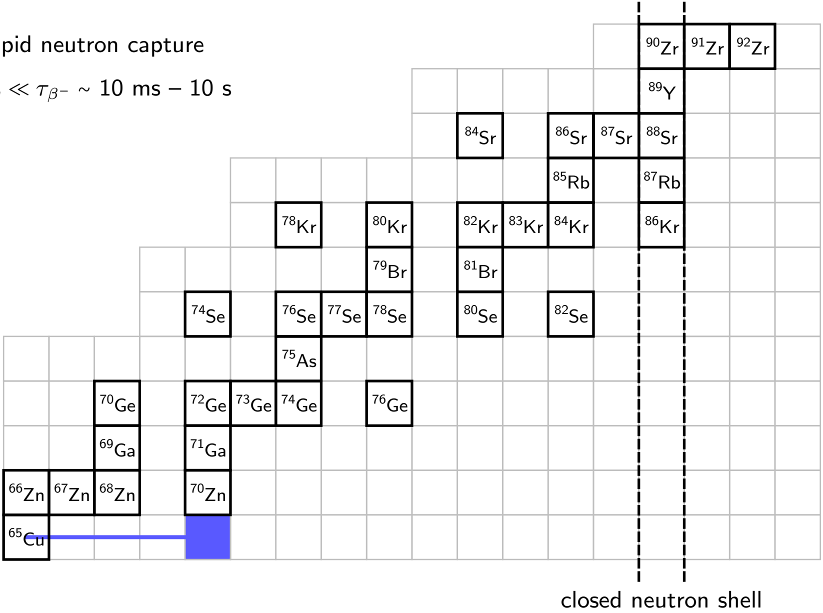

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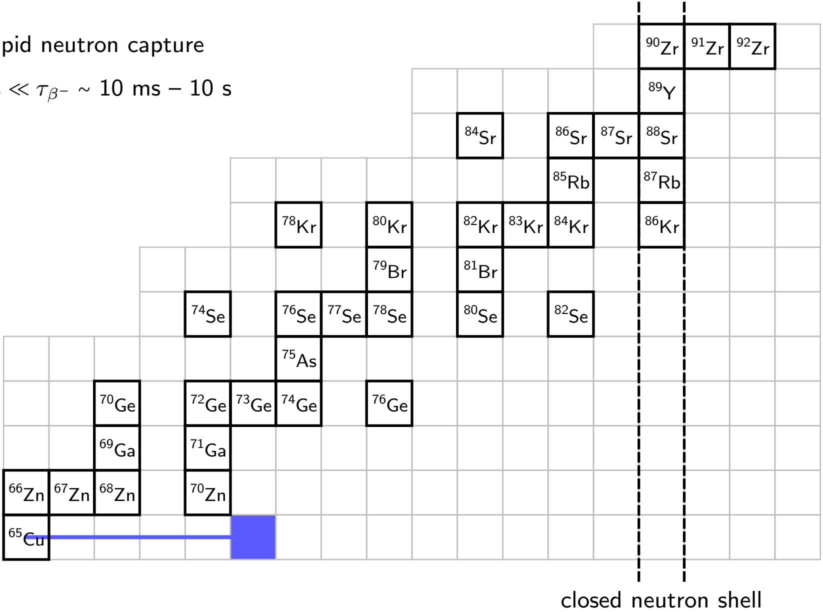

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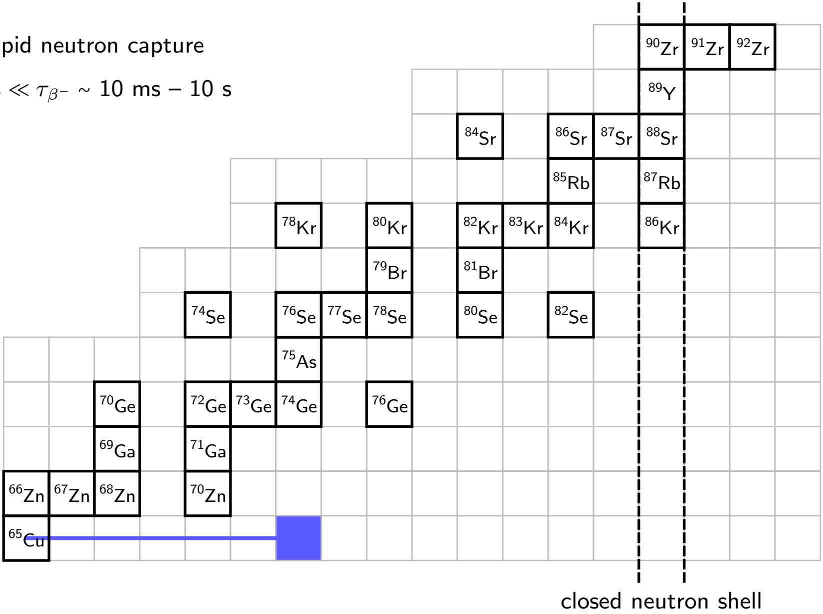

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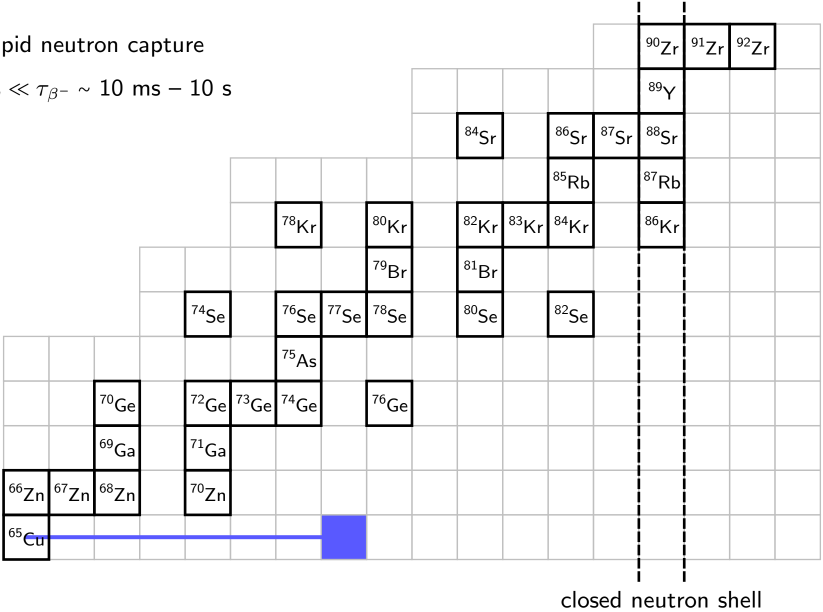

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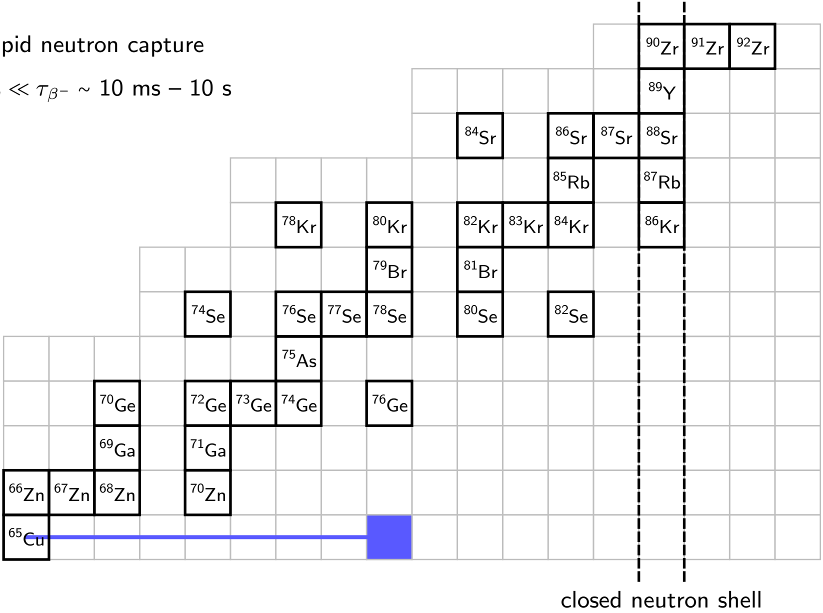

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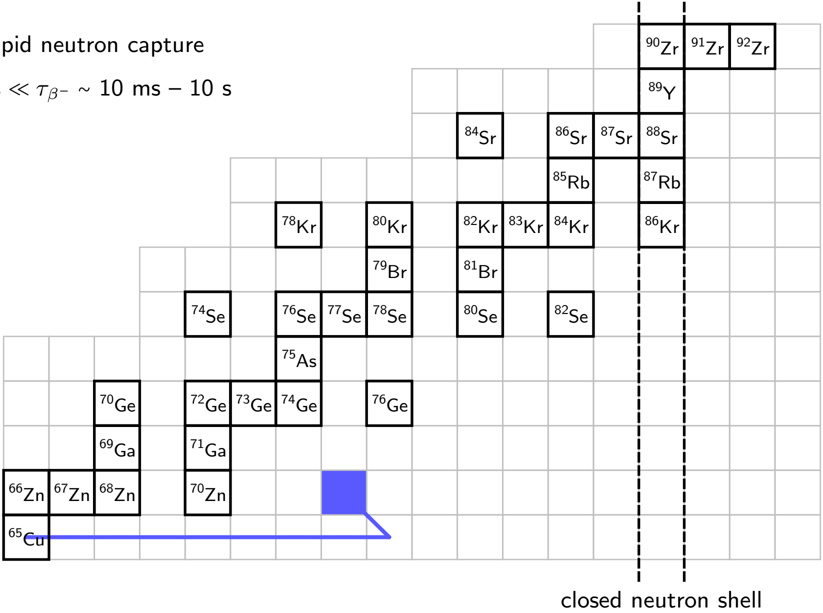

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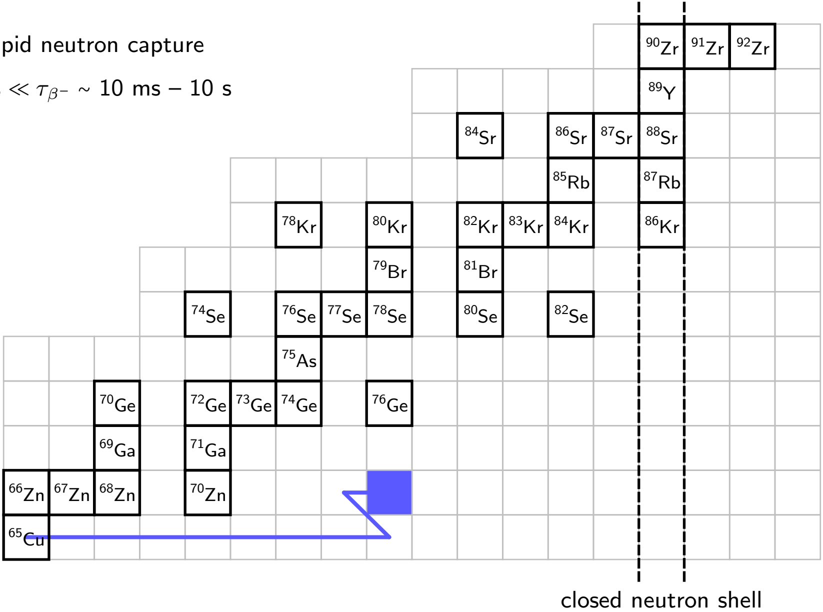

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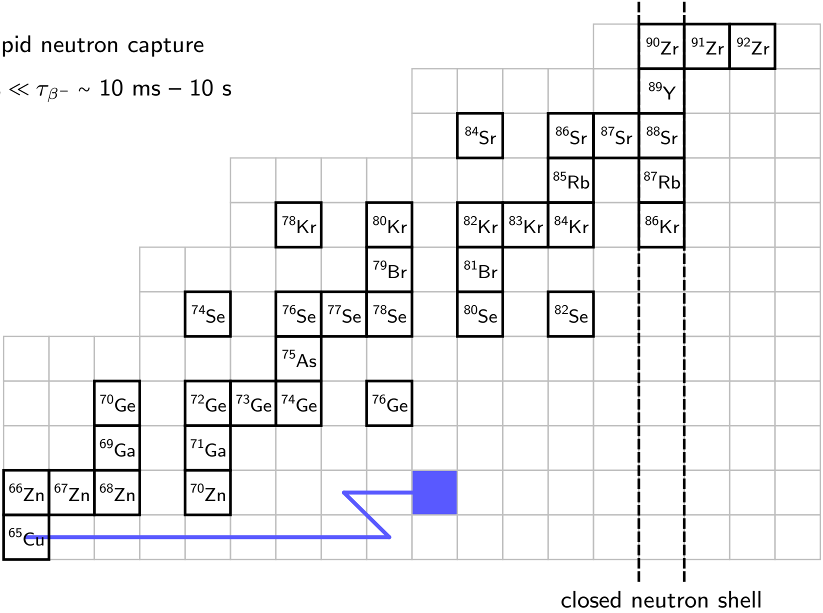

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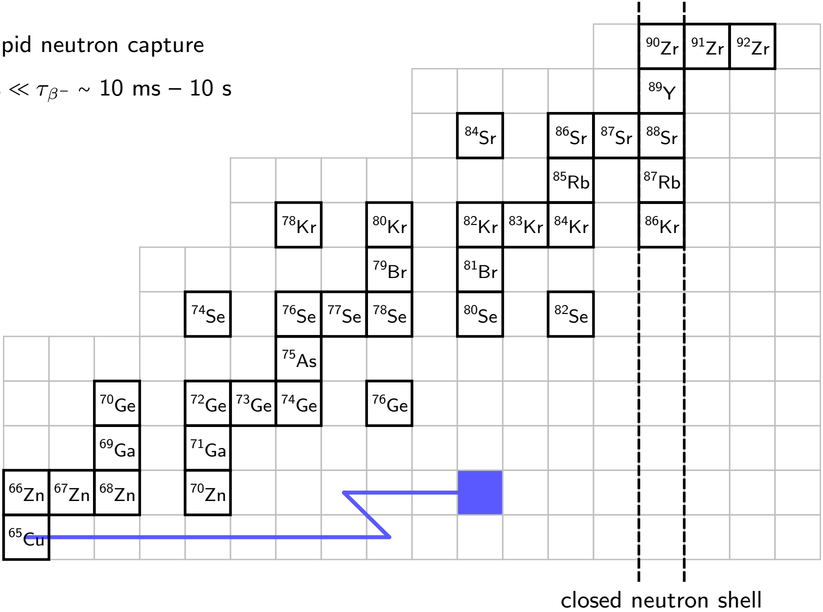

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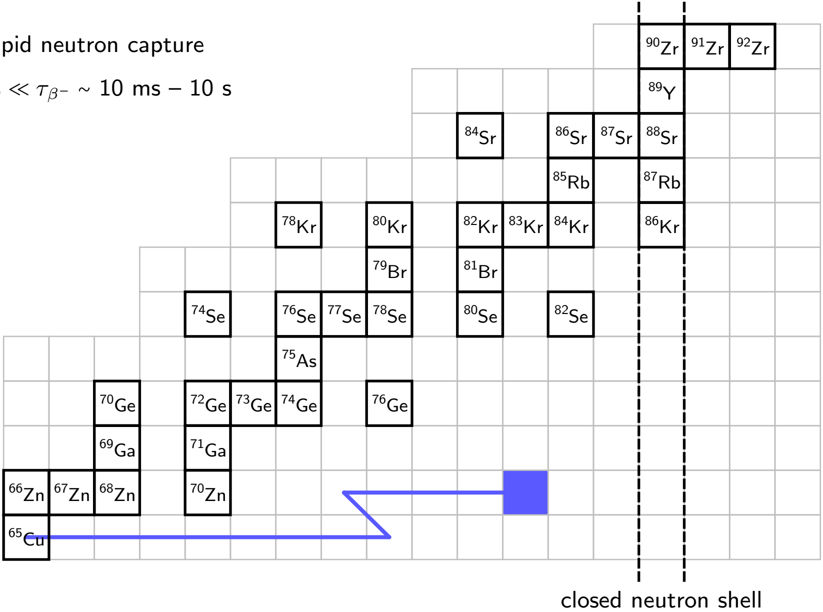

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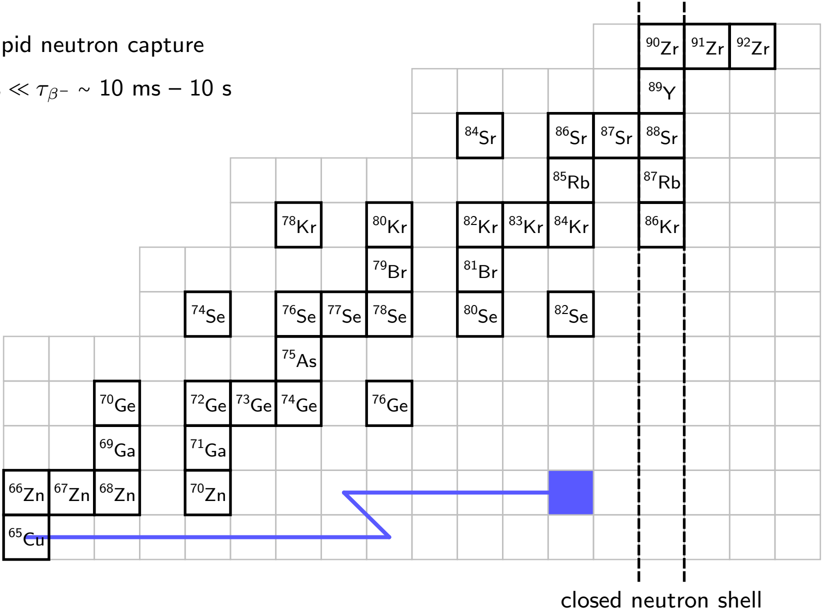

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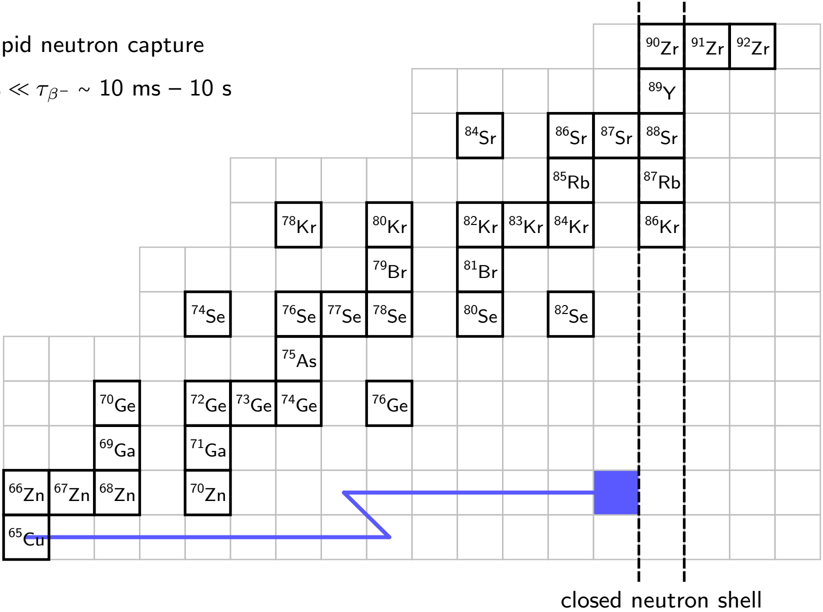

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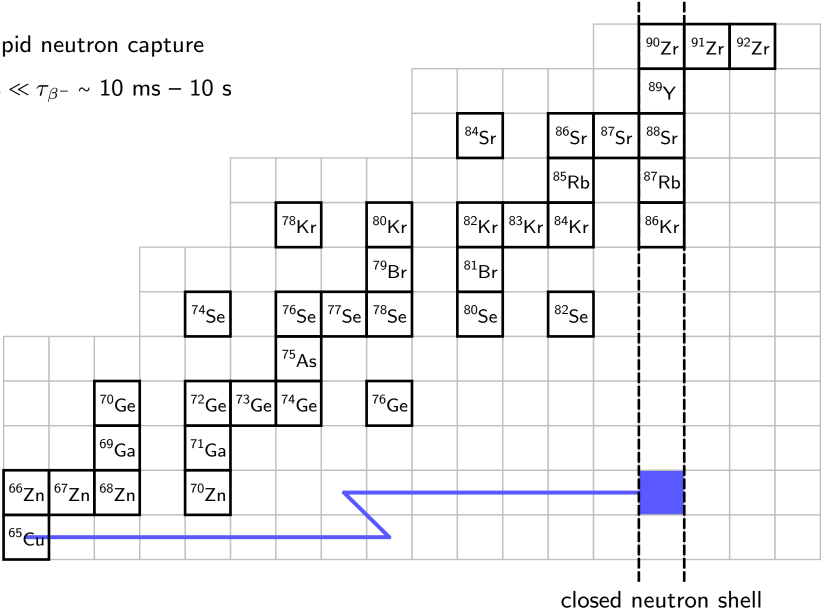

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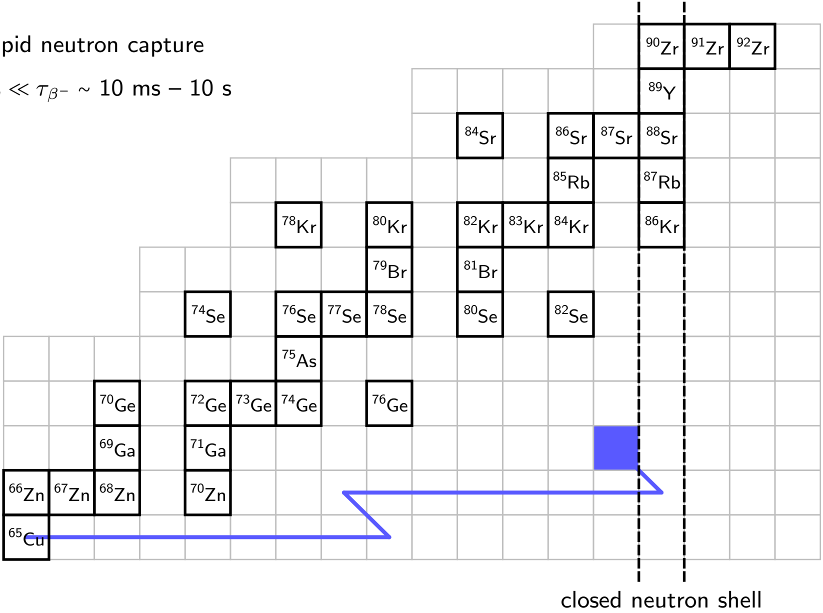

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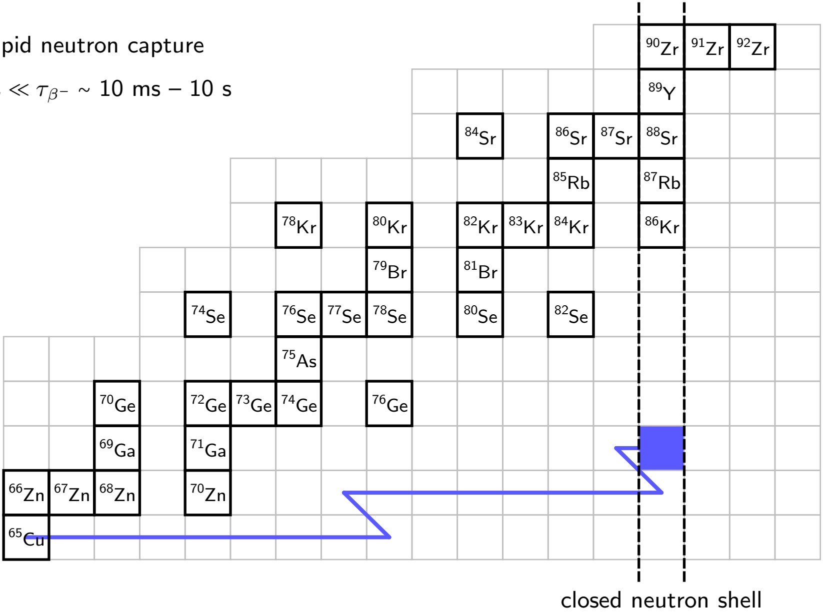

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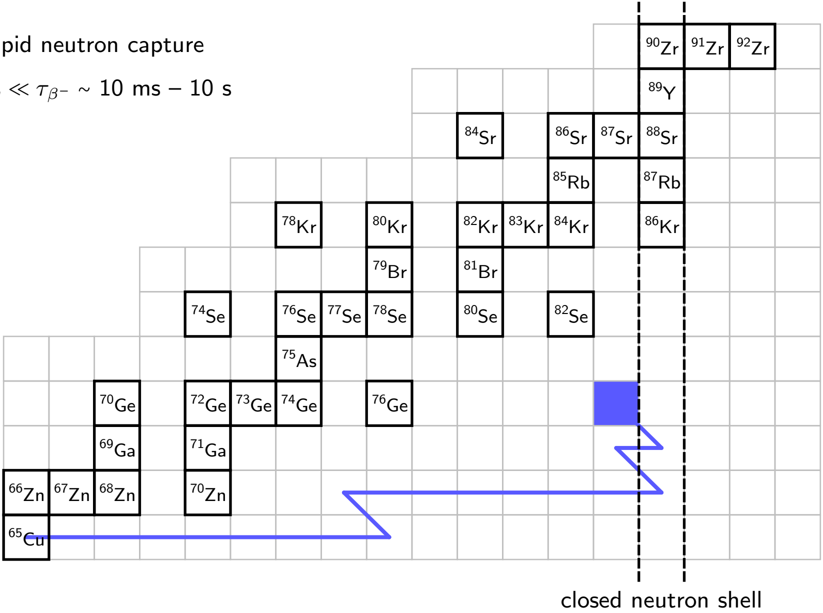

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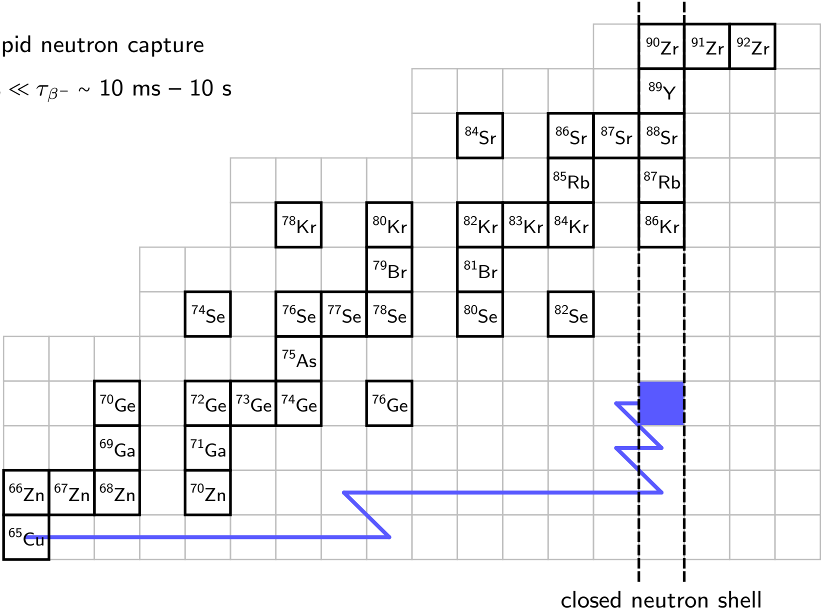

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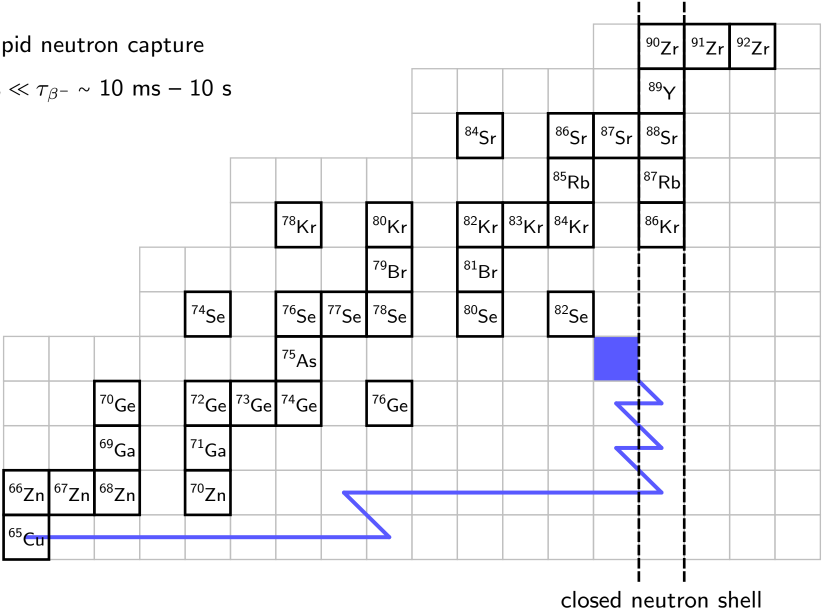

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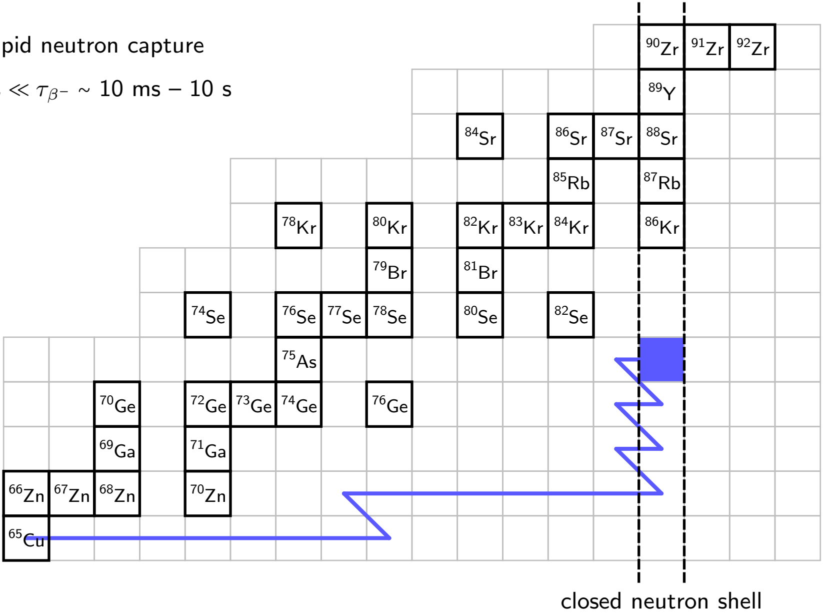

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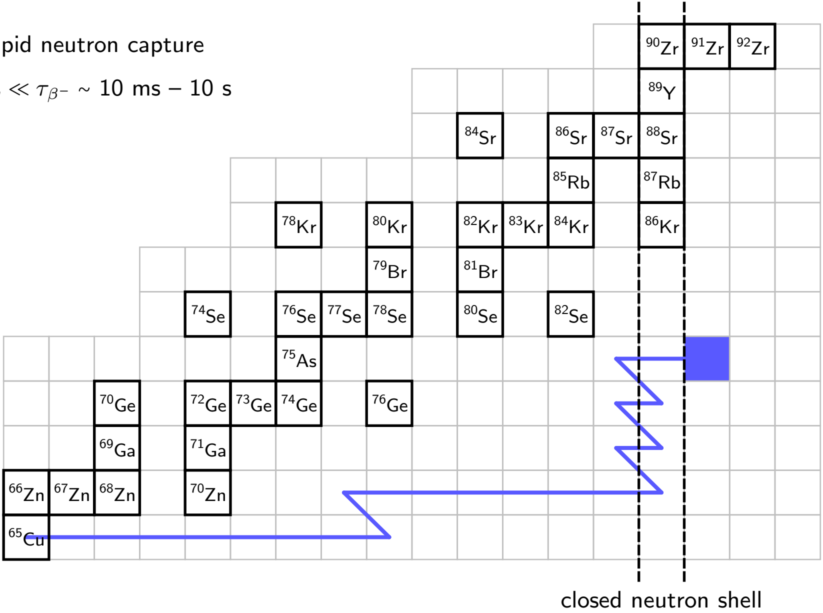

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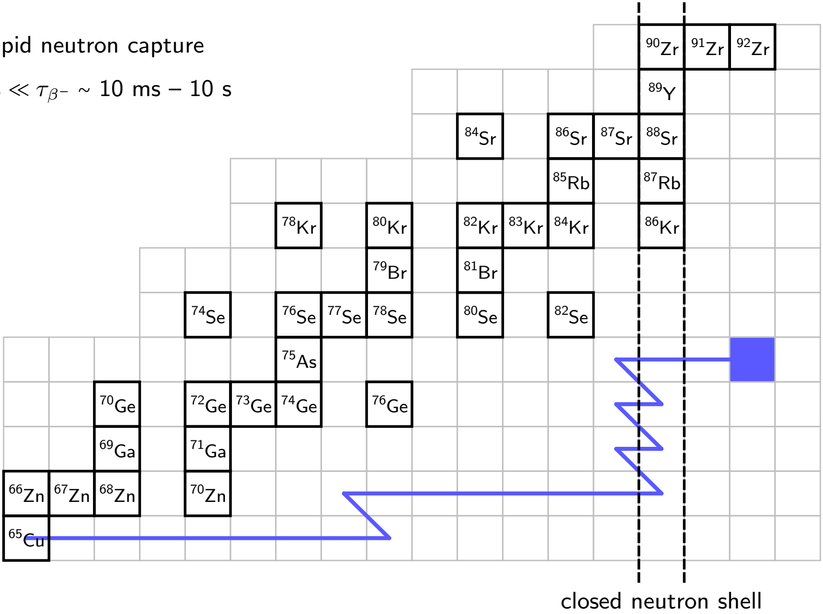

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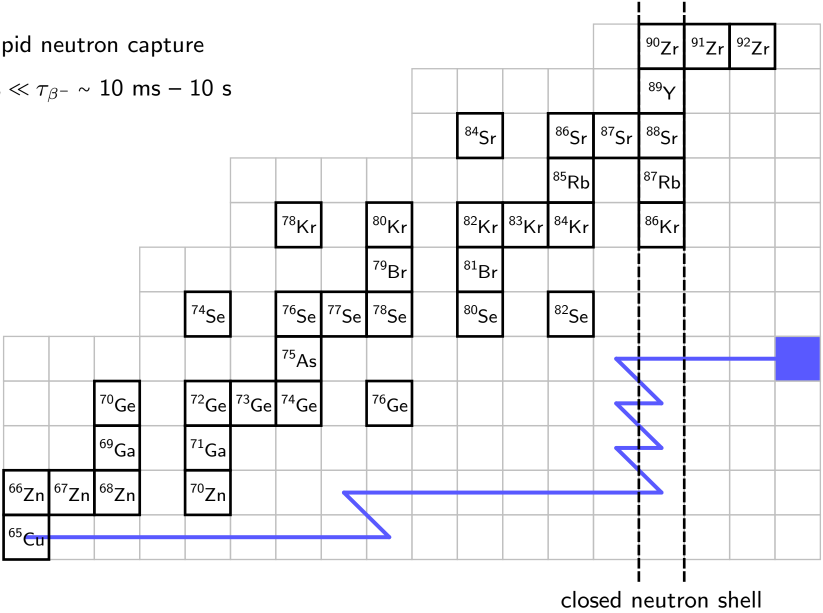

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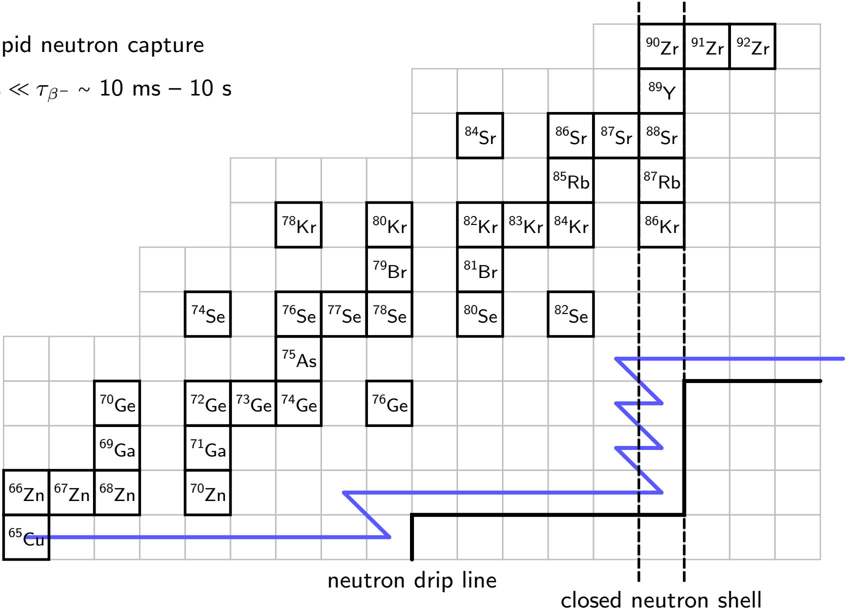

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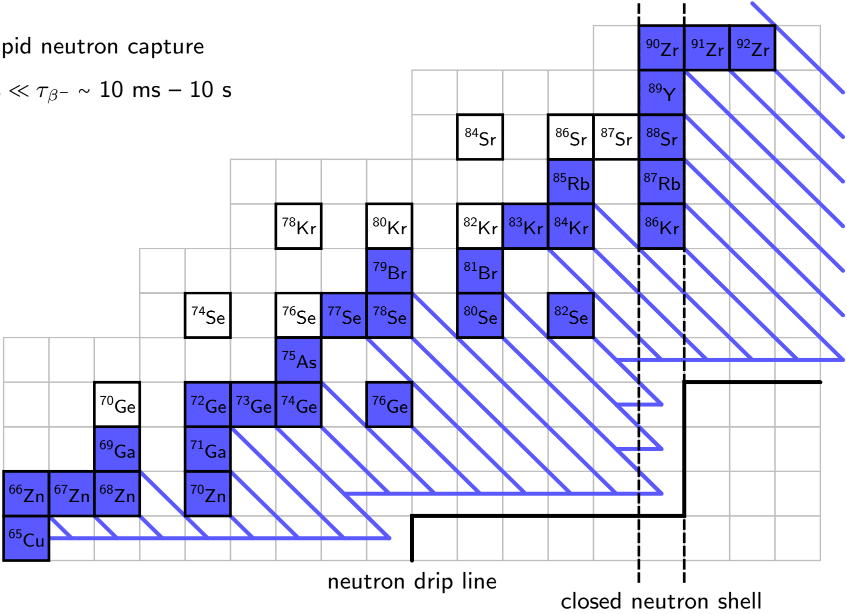

Double peaks due to closed neutron shells

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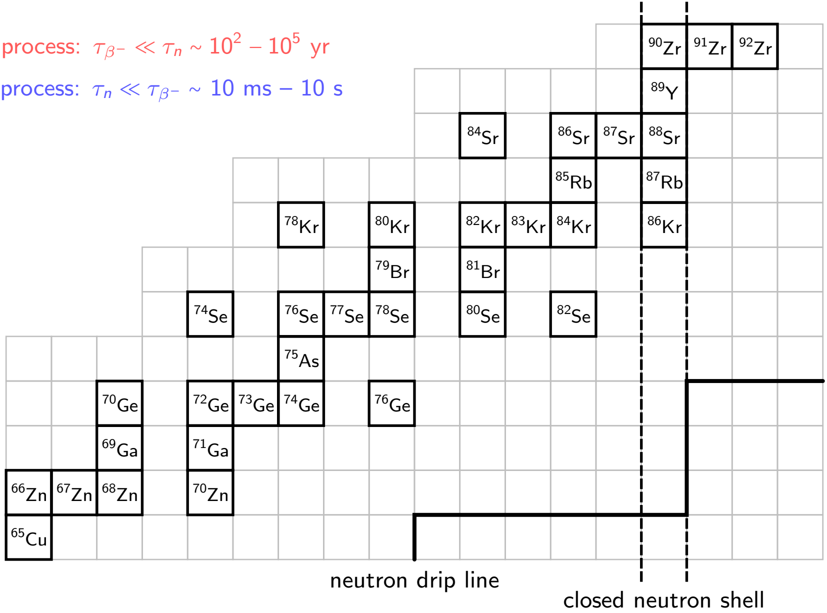

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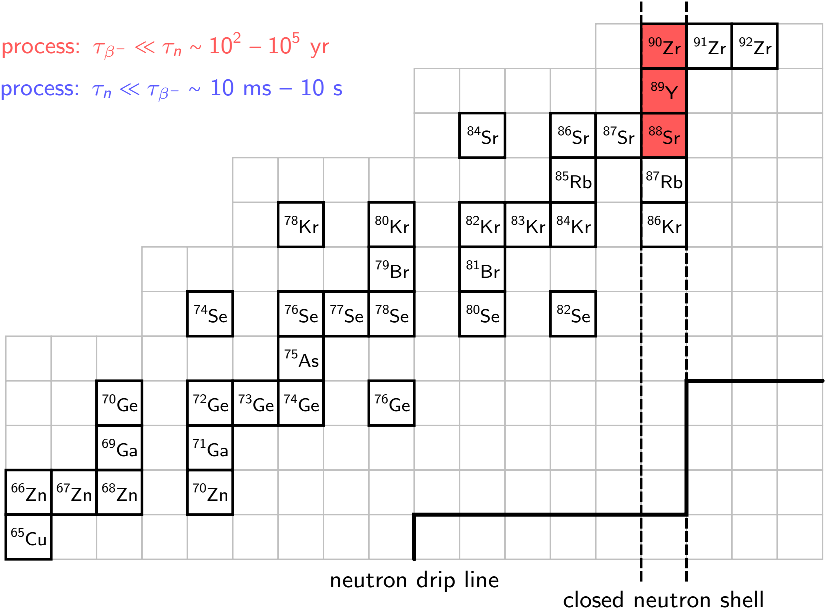

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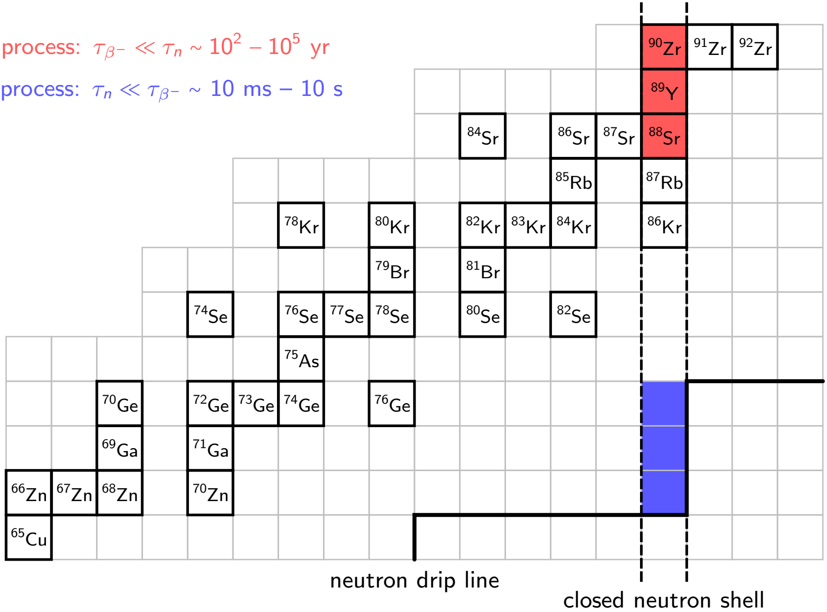

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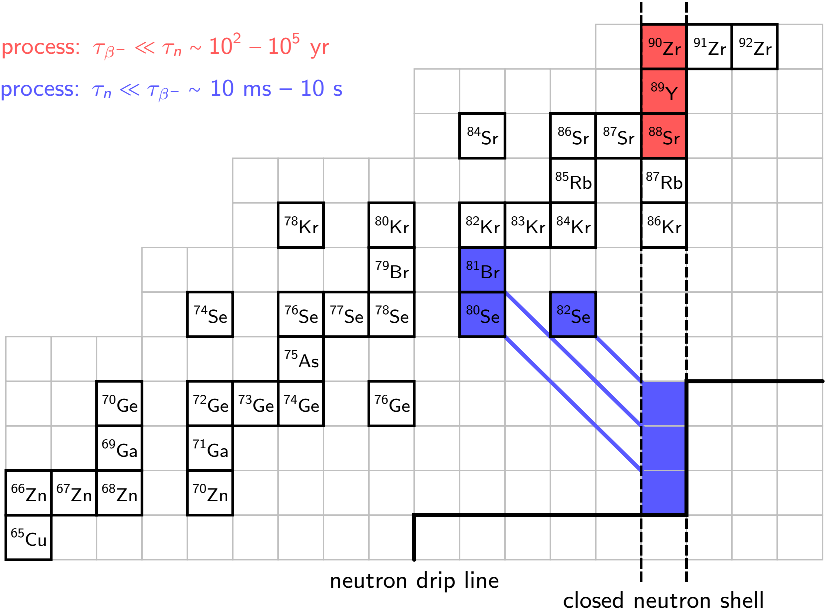
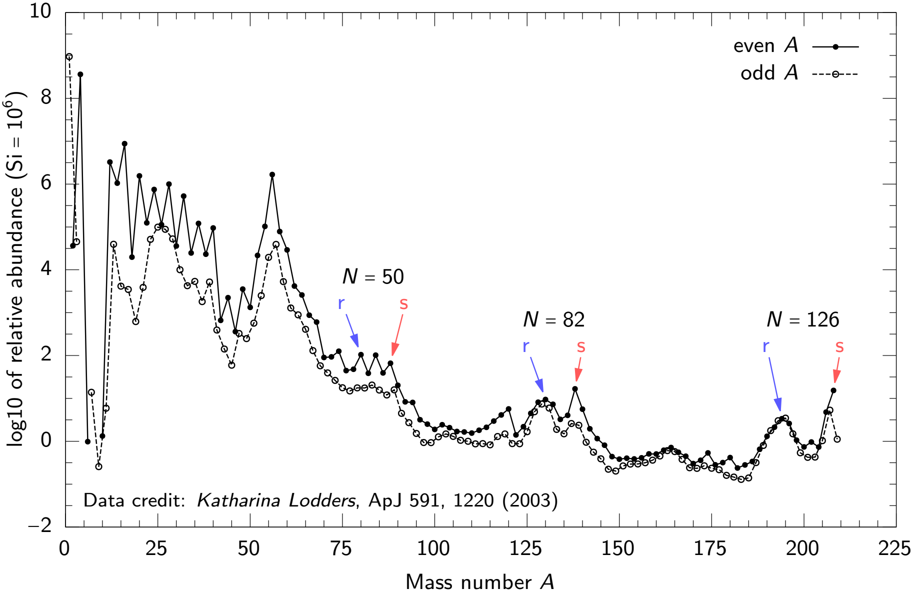
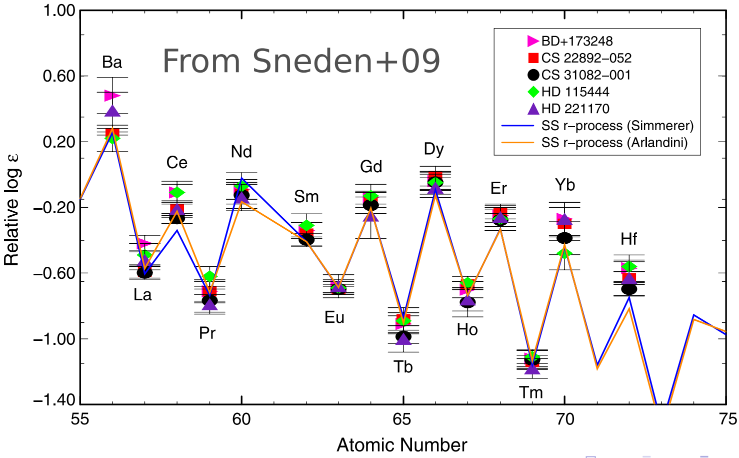


Solar system abundances



Universal r-process pattern

- Metal-poor stars ([Fe/H] $\lesssim -2$) formed early (first few 100 Myr)
- s-Process starts later as stars evolve
- Observed r-process pattern agrees with present solar system abundances
- **Conclusion:** robust and early r-process mechanism



r-Process site

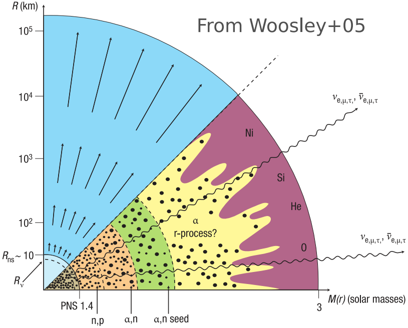
Astrophysical site of r-process nucleosynthesis is still an open question, favored site is neutron star mergers

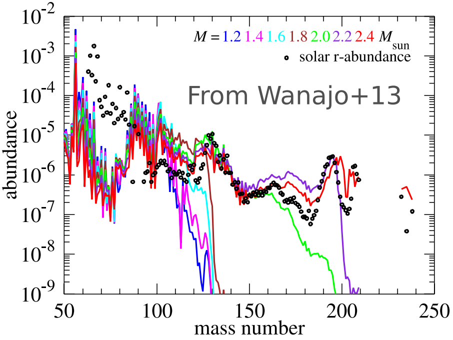
	core-collapse supernovae	neutron star mergers
rate $[\mathrm{MW}^{-1}\,\mathrm{Myr}^{-1}]$	5000 – 12,000 ? ? ?	NS–NS: 1 – 1000, NS–BH: 0.05 – 100 ? ? ?
ejecta	few $\times 10^{-4}\,M_\odot$, $Y_e \gtrsim 0.4$ e.g. **?**	$\sim 10^{-3} - 10^{-2}\,M_\odot$, $Y_e \sim 0.05 - 0.45$ see refs below *
challenges	not neutron-rich enough for full r-process (e.g. **? ? ?**)	heavy elements present at early times, mixing (e.g. **? ? ?** , but maybe no problem: e.g. **? ?**)

* **? ? ? ? ? ? ? ? ? ? ? ?**

Neutrino driven wind in core-collapse supernovae

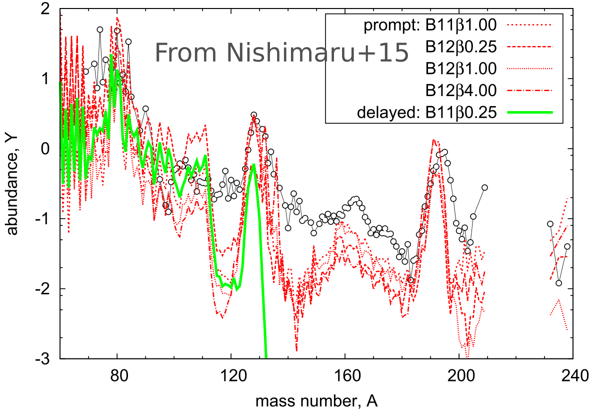
- Neutrinos emitted from hot proto-neutron star can drive outflow of n and p
- Neutrino driven wind is mildly neutron-rich → r-process?

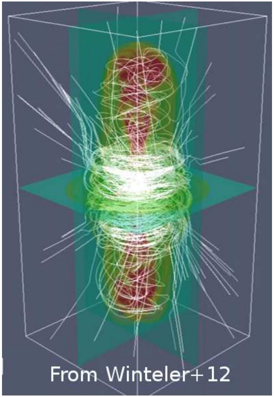




Jet in MHD-driven supernova

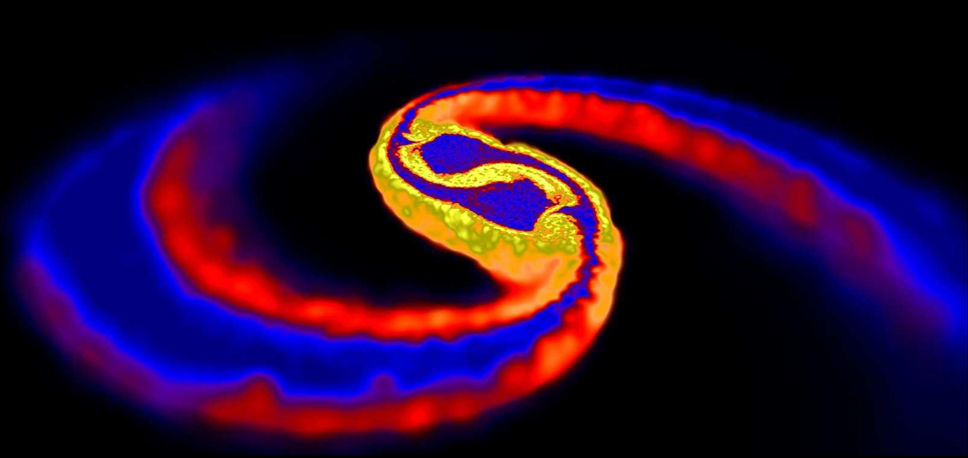
- Requires very high magnetic field ($B \sim 10^{12} - 10^{13}$ G) and rapid rotation
- Maybe $0.1 - 1\%$ of all core-collapse supernovae





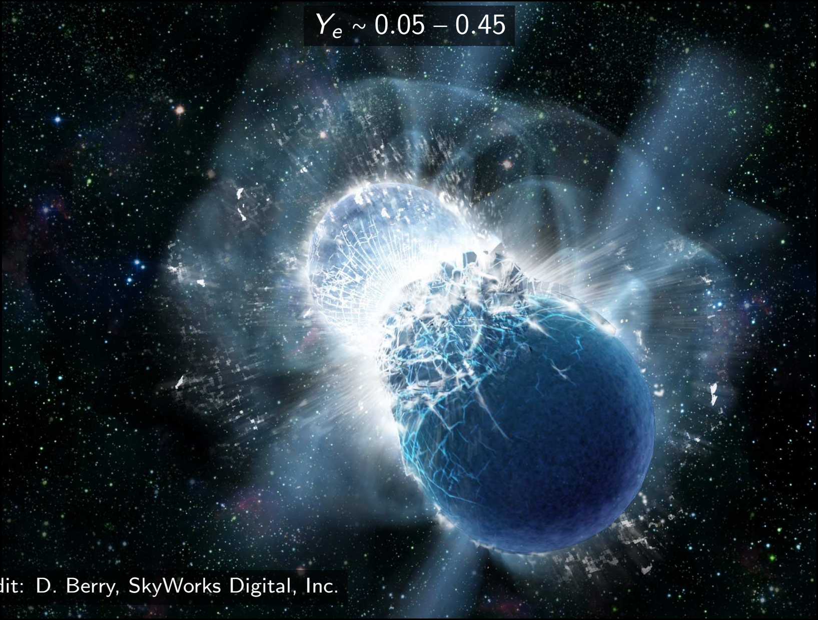
NS–NS ejecta sources: Tidal tails

$Y_e \sim 0.05 - 0.45$



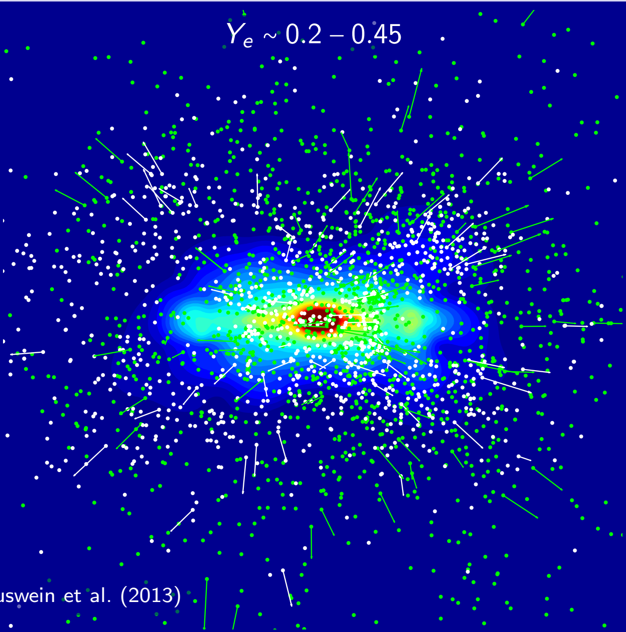
Credit: D. J. Price et al. (2006)

NS–NS ejecta sources: Collision interface



Credit: D. Berry, SkyWorks Digital, Inc.

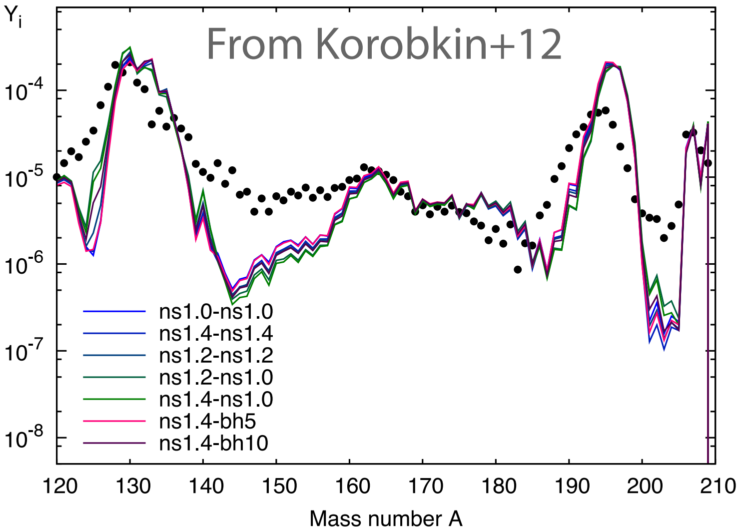
NS–NS ejecta sources: Disk outflow



Credit: A. Bauswein et al. (2013)

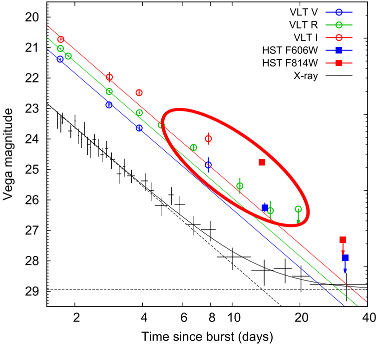
Neutron star mergers

- Robustly produces full r-process

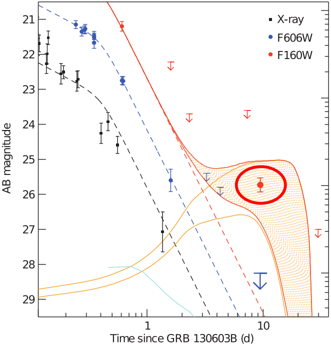


Kilonova

- Radioactively powered transient after r-process nucleosynthesis (e.g. ? ? ? ?)
- Triple coincidence: GW + sGRB + kilonova (e.g. ? ? ?)
- Lanthanides/actinides → opacity ~ 100 κ_{Fe} (e.g. ? ?)



GRB060614, from ?



GRB130603B, from ?

Nucleosynthesis calculations with SkyNet

SkyNet

github.com/jlippuner/SkyNet

- General-purpose nuclear reaction network
- ~8000 isotopes, ~140,000 nuclear reactions
- Evolves temperature and entropy based on nuclear reactions
- Input: $\rho(t)$, initial composition, initial entropy or temperature
- Open source (soon)

JL, Roberts 2017, *in prep.*

SkyNet

Define abundance

$$Y_i = \frac{n_i}{n_B}. \tag{1}$$

Consider reaction

$$\mathrm{p} + {}^{7}\mathrm{Li} \to 2\,{}^{4}\mathrm{He} \tag{2}$$

with rate $\lambda = \lambda(T, \rho)$. Then

$$\begin{aligned} \dot{Y}_{^4\mathrm{He}} &= 2\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots, \\ \dot{Y}_\mathrm{p} &= -\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots, \\ \dot{Y}_{^7\mathrm{Li}} &= -\lambda Y_\mathrm{p} Y_{^7\mathrm{Li}} + \cdots \end{aligned} \tag{3}$$

Huge system of coupled, first-order, non-linear ODEs.

SkyNet additional features

Science

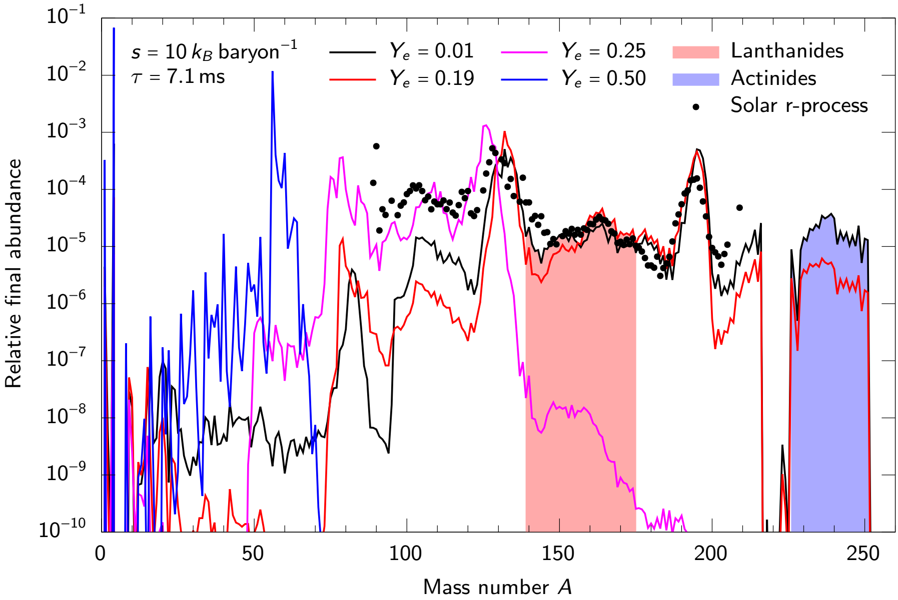
- Expanded Timmes equation of state (Timmes+00)
- Calculate nuclear statistical equilibrium (NSE)
- Calculate inverse rates from *detailed balance* to be consistent with NSE
- NSE evolution mode
- Implementing screening with chemical potential corrections

Code

- Adaptive time stepping
- Python bindings
- Extendible reaction class
- Make movie with chart of nuclides

r-Process nucleosynthesis in neutron star mergers

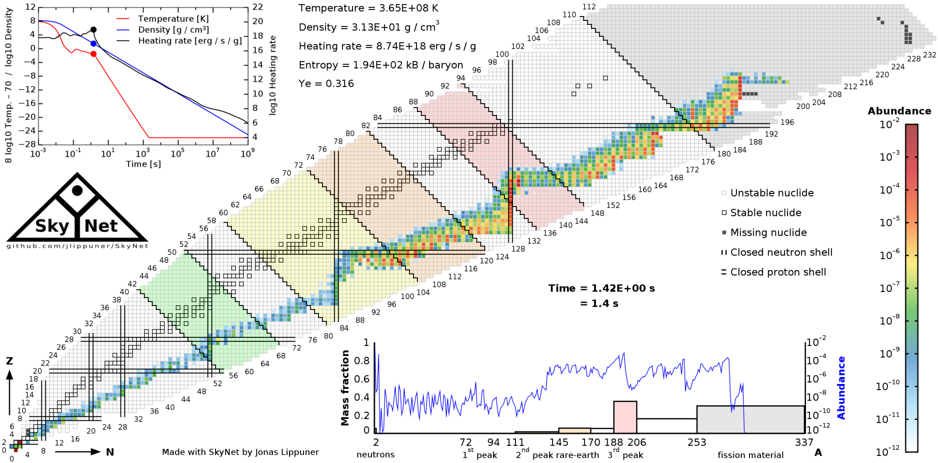
Final abundances vs. electron fraction



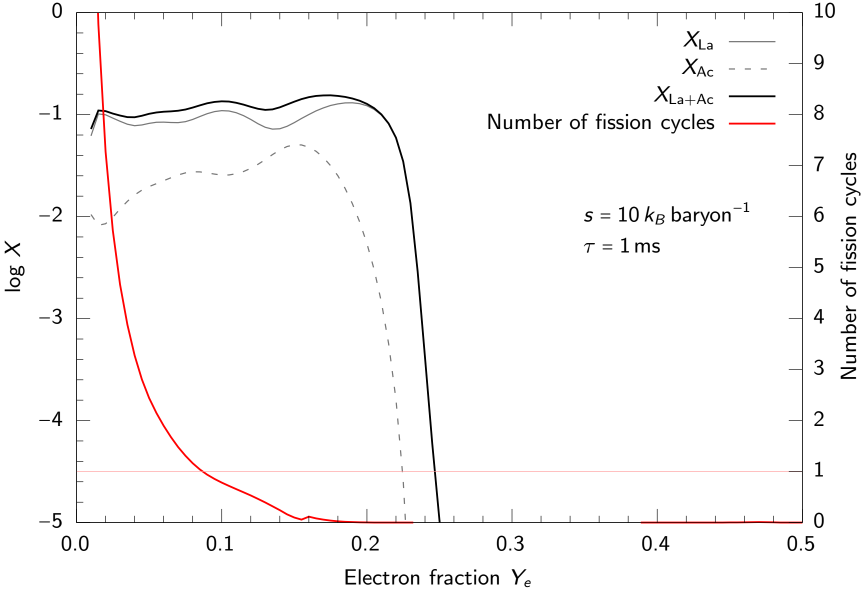
Movies

http://lippuner.ca/skynet/SkyNet_Ye_0.010_s_010.000_tau_007.100.mp4

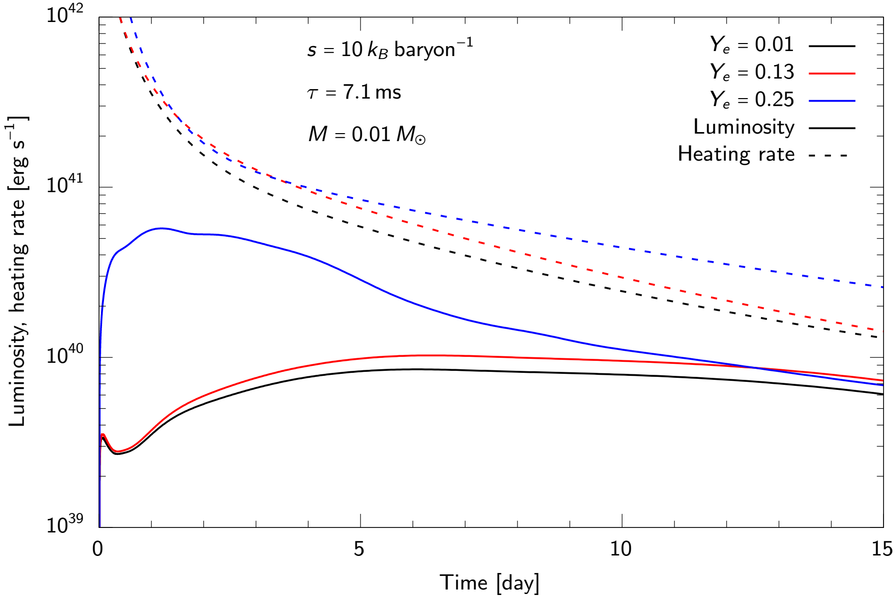
http://lippuner.ca/skynet/SkyNet_Ye_0.250_s_010.000_tau_007.100.mp4



Impact of electron fraction



Example light curves



Neutron star–black hole merger

1. Full GR simulation of NS–BH
   Francois Foucart (LBL), Foucart+14
2. Ejecta in SPH code,
   Matt Duez (WSU)
3. Nucleosynthesis with SkyNet and varying neutrino luminosity
   JL and Luke Roberts (Caltech)

Roberts, JL, Duez, et al., 2016, *MNRAS*, 464, 3907, arXiv:1601.07942

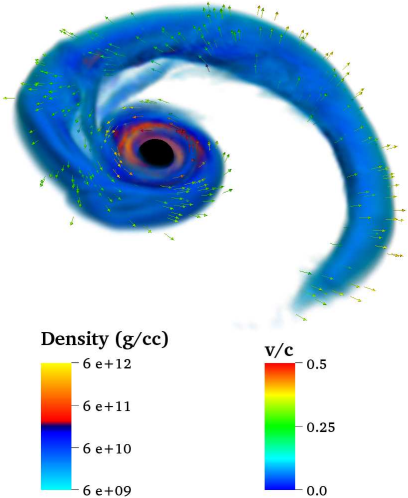
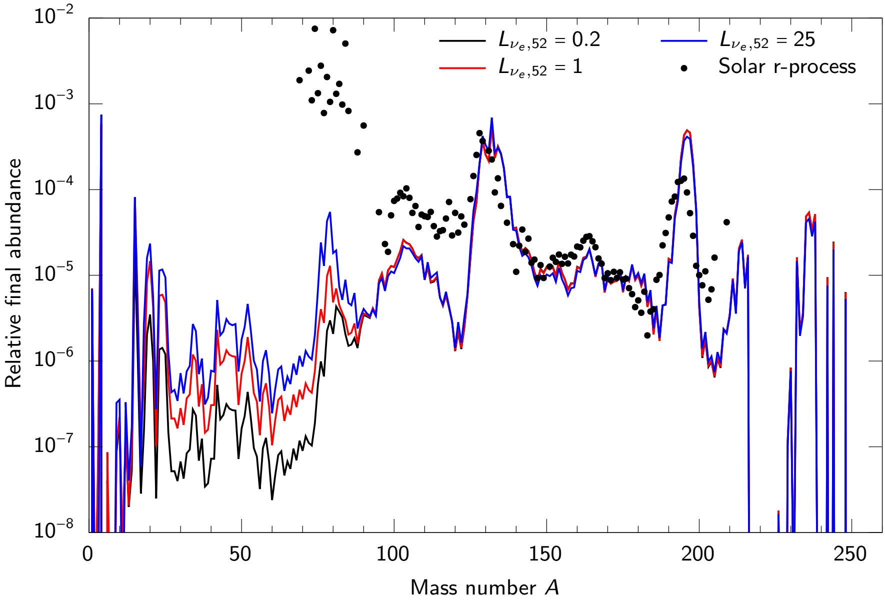
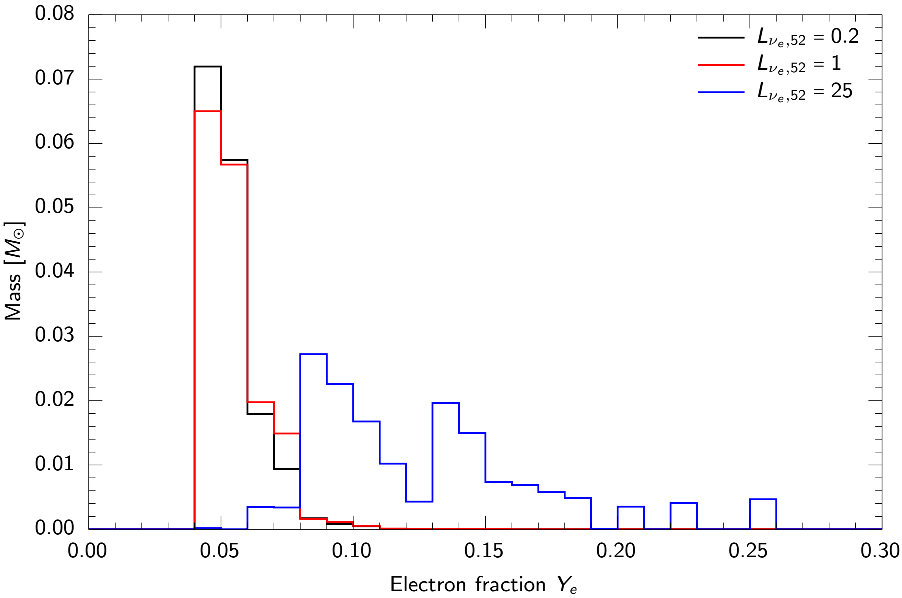


Figure credit: F. Foucart

BHNS: Final abundances vs. neutrino luminosity



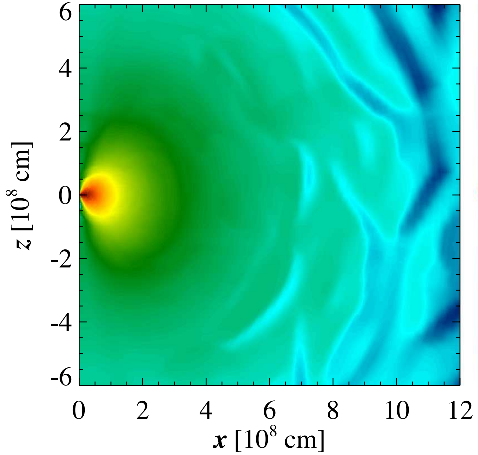
BHNS: Electron fraction distribution



BHNS: New first peak production mechanism

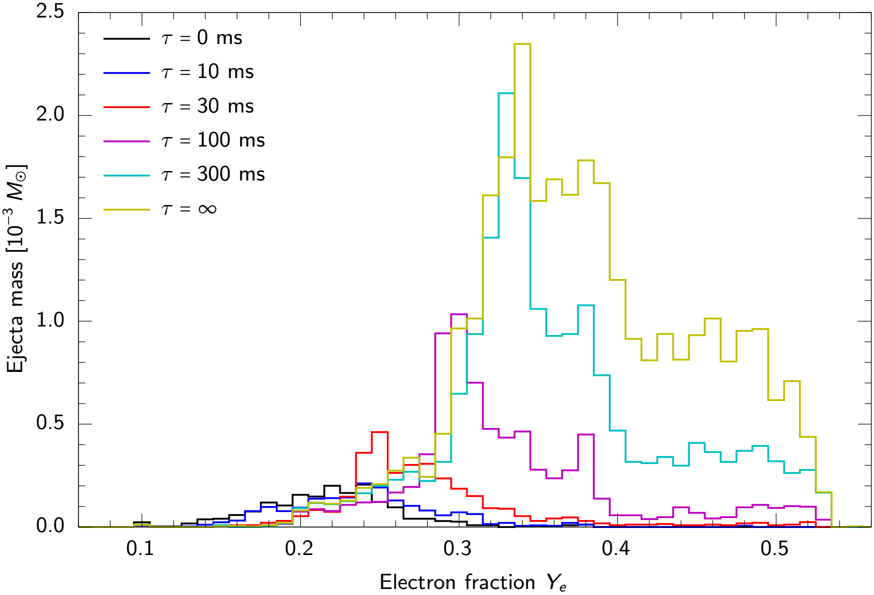
- Original seeds: $A \sim 80 \rightarrow$ full r-process
- With neutrinos:
  - $\nu_e + \mathrm{n} \rightarrow \mathrm{p} + \mathrm{e}^-$
  - $2\,\mathrm{p} + 2\,\mathrm{n} \rightarrow {}^4\mathrm{He}$
  - $3\,{}^4\mathrm{He} + \mathrm{n} \rightarrow {}^{12}\mathrm{C} + \mathrm{n}$
- Additional low-mass seed nuclei → enhanced 1st peak
- No combination of complete and incomplete r-process

JL, Fernández, Roberts, et al., 2016, *in prep.*

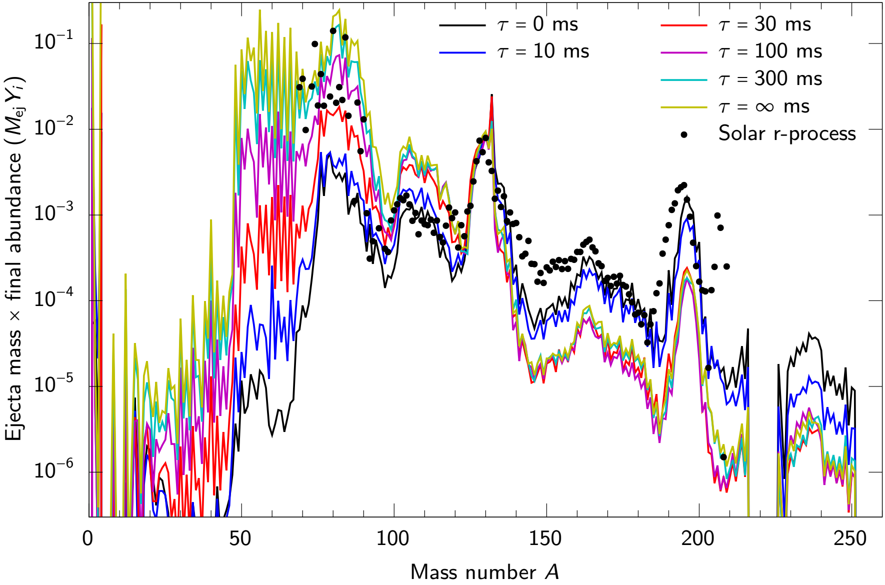


τ [ms]	M_{ej} [10^{-3} $M_\odot$]	$M_{ej, Y_e \leq 0.25}$ [10^{-3} $M_\odot$]
0	1.8	1.36
10	1.9	1.07
30	3.3	0.83
100	7.8	0.52
300	18.0	0.67
∞	29.6	0.69

Y_e distribution vs. HMNS lifetime



Final abundances vs. HMNS lifetime



Summary

- Supernova do not seem to produce right conditions for full r-process
- Neutron star mergers easily make full r-process
- SkyNet is a flexible reaction network that will be open source
- $Y_e \sim 0.25$ is the critical value for lanthanide production, does not correlate with heating rate
- Black hole-neutron star merger produces very strong 3rd peak $\rightarrow$ red kilonova
- Disk outflow can produce (weak) 3rd peak $\rightarrow$ blue kilonova