What we can learn about supernovae using particle accelerators

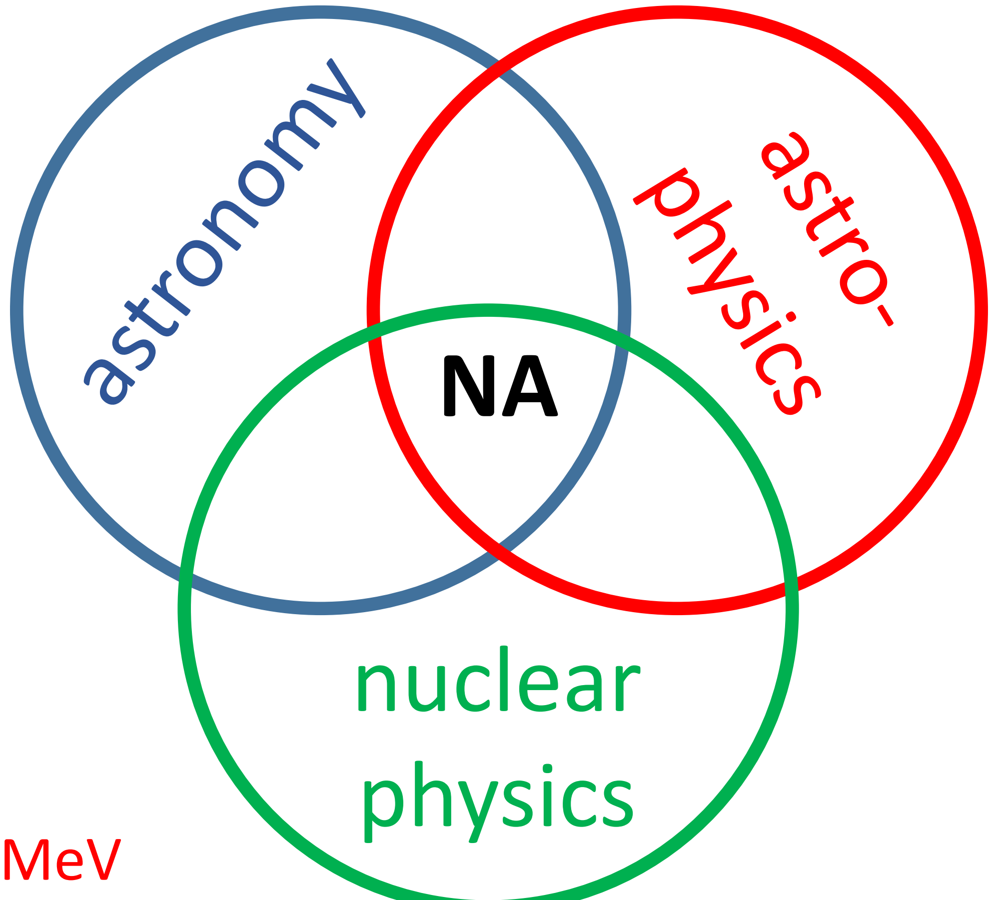
Kiss Gábor Gyula

Atomki, Debrecen

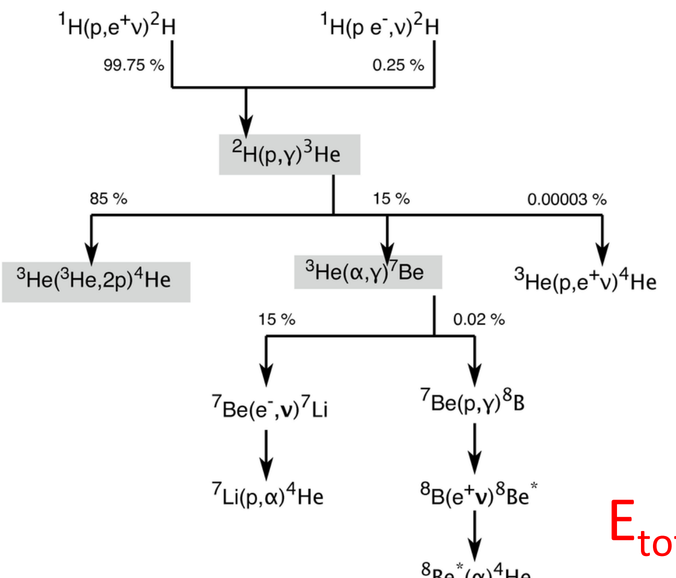
Nuclear astrophysics (NA)

- Synthesis of the chemical elements

Observation: A.C. 1054
Distance: 6523 lightyear

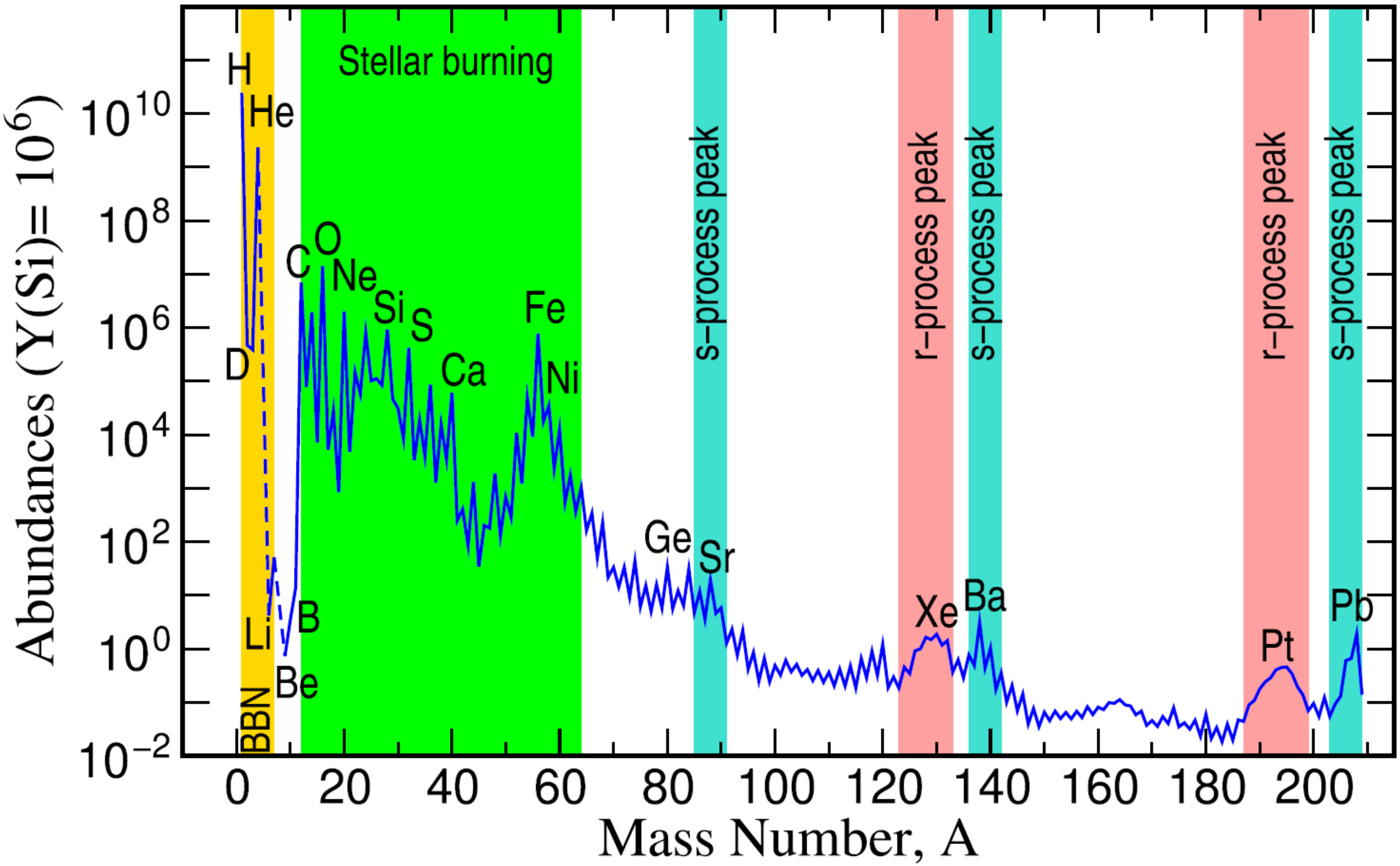


- Energy production of stars



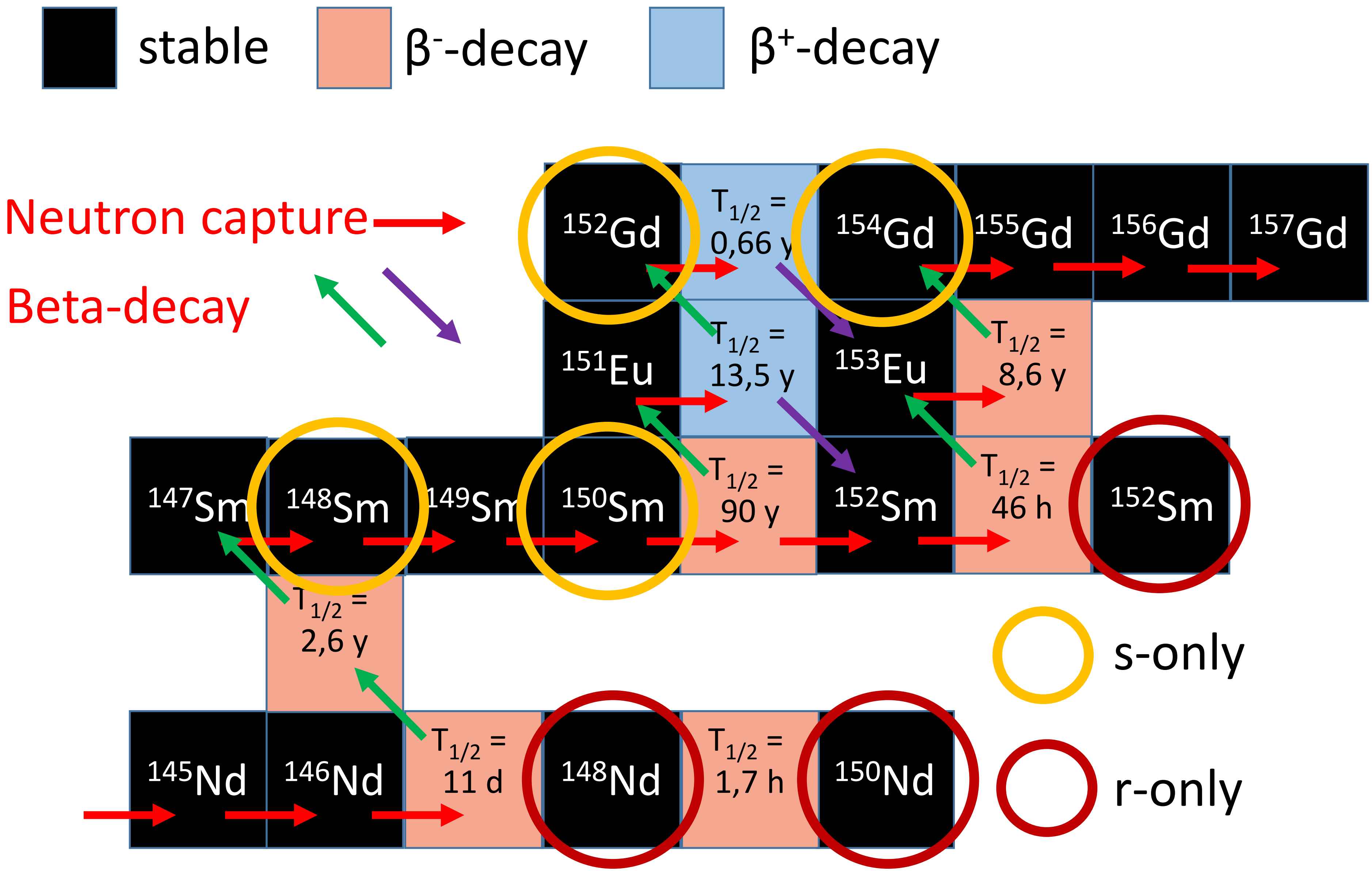
$E_{tot.} = 26{,}73$ MeV

Nucleosynthesis processes and abundances



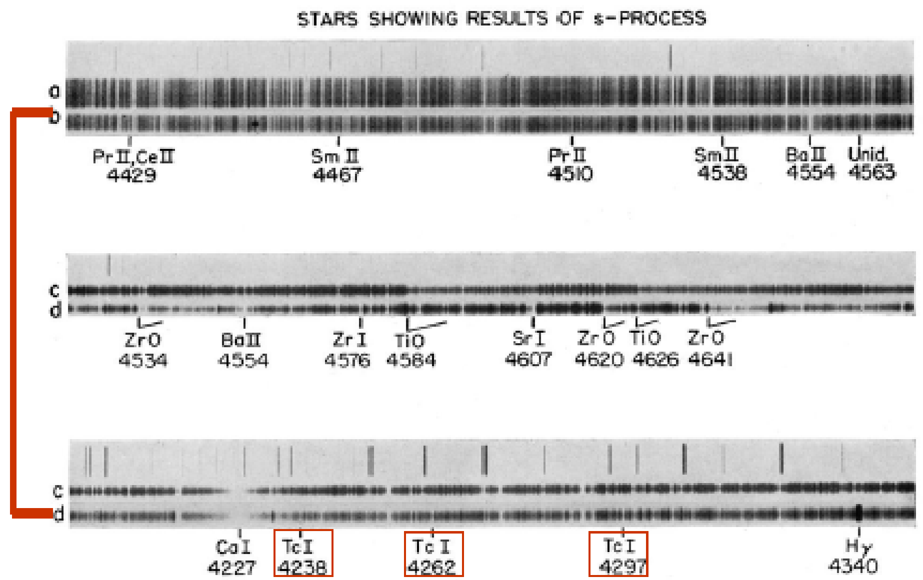
J. J. Cowan *et al*., Rev. Mod. Phys. **93** (2021) 015002.

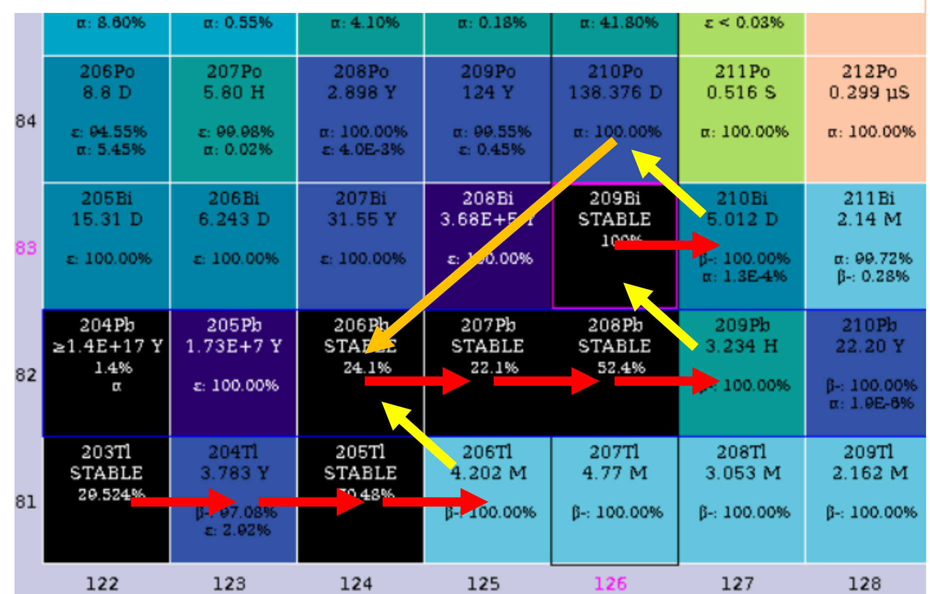
Nucleosynthesis via slow neutron capture



s-process

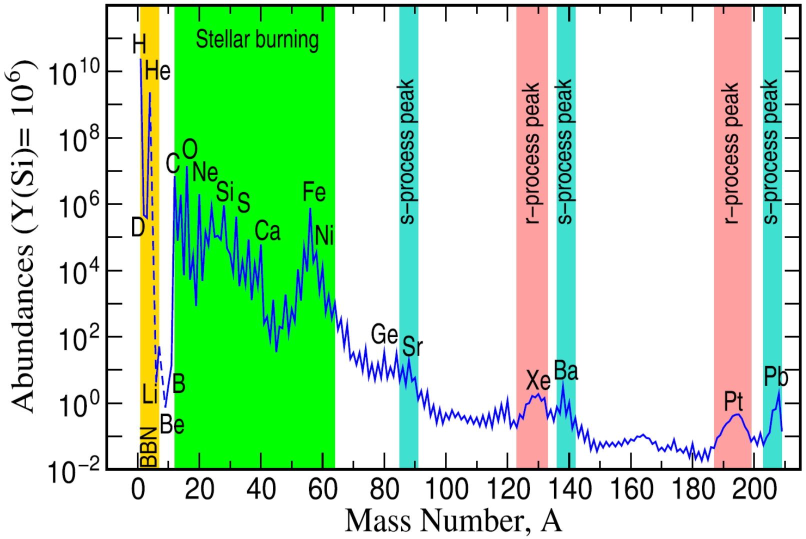
- s-process
  - 10^6-10^8 neutron/cm^3
  - 10 000+ year
  - $\lambda_{(n,\gamma)} \approx \lambda_\beta$
  - Valley of stability
  - (A,Z)max: ^{209}Bi
  - AGB stars, heavy stars
  - Key reactions are known

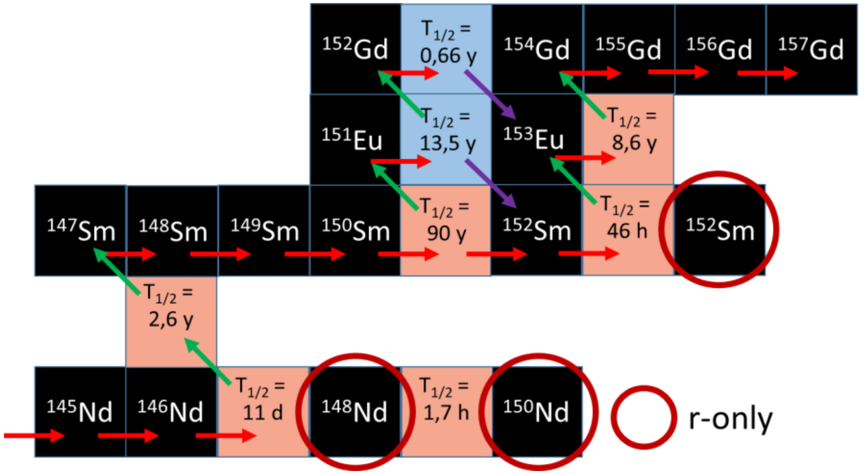




Why do we need a 2nd neutron capture process?

- U, Th found in the Earth's crust
  - → 10^{26+} neutron/cm^3
- Peaks at the abundance distribution at A~130 & A~195
  - → process path further away from the valley of stability
- Very neutron-rich stable isotopes (e.g. ^{148,150}Nd…)



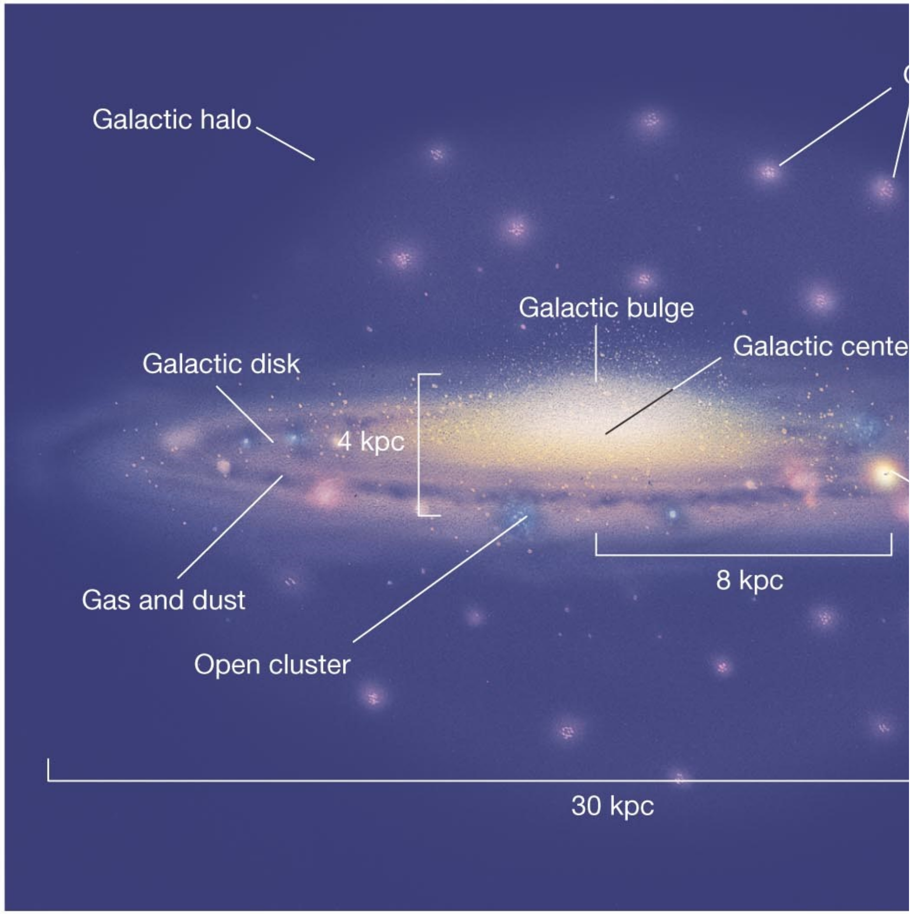


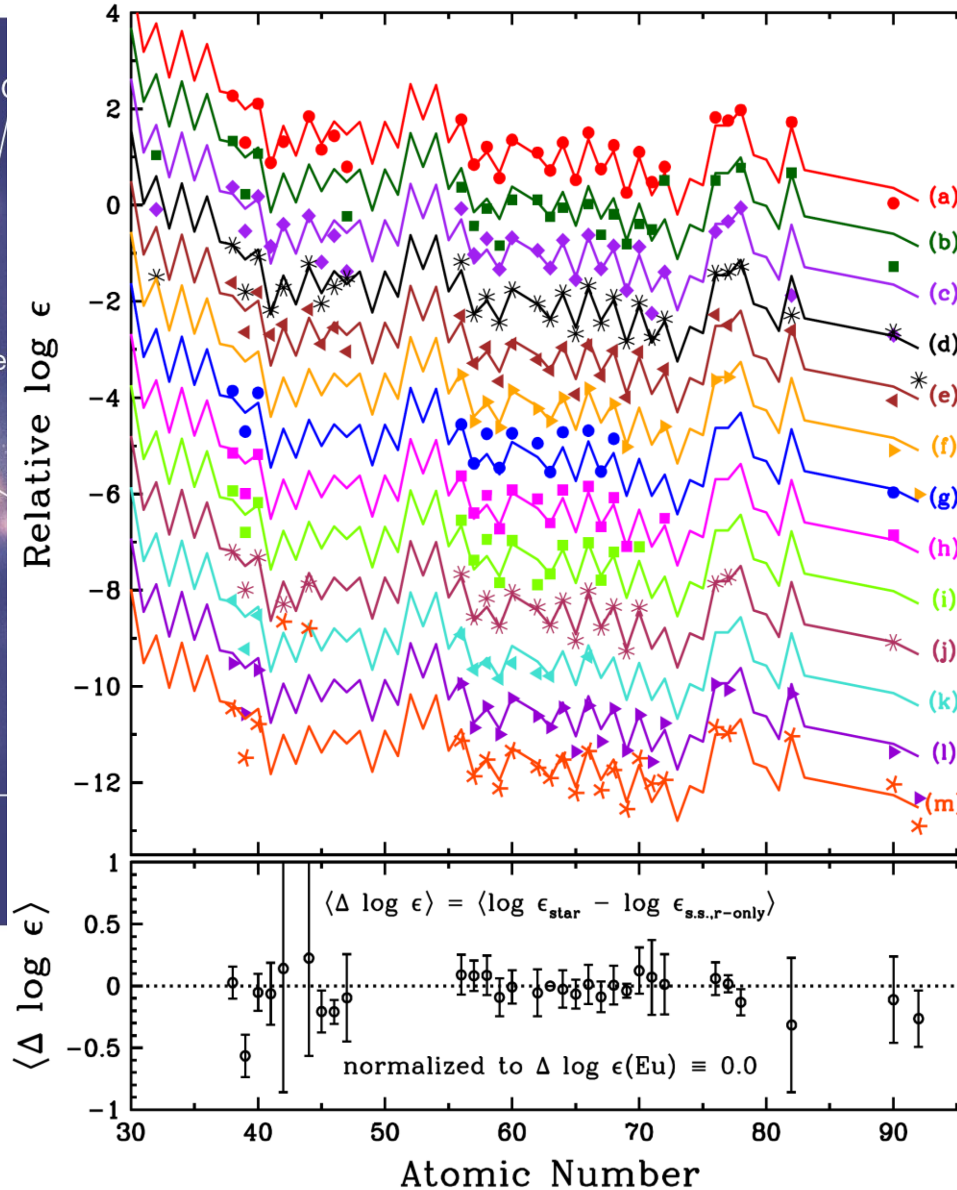
Observations: GW170817

- Direct observation of Sr in the kilonovae spectrum [Wat19]
- Lanthanide features in near-infrared spectra of kilonovae [Dom22]

B.P. Abbott *et al*., Phys. Rev. Lett. **119** (2017) 161101.
D. Watson *et al*., Nature **574** (2019) 497.
N. Domoto *et al*., Astrophys. J. **938** (2022) 8.

Observations: old halo stars





1 pc = 3.26 light year

A. P. Ji *et al*., Nature **531** (2016) 610.
D. M. Siegel *et al.,* Nature **569** (2019) 241.
J. J. Cowan *et al*., Rev. Mod. Phys. **93** (2021) 015002.

Open questions

- How common are neutron star mergers?
- How common are special supernova explosions?
- How much material escapes into interstellar space?
- What isotope distribution is created?
- How is this isotope distribution formed?

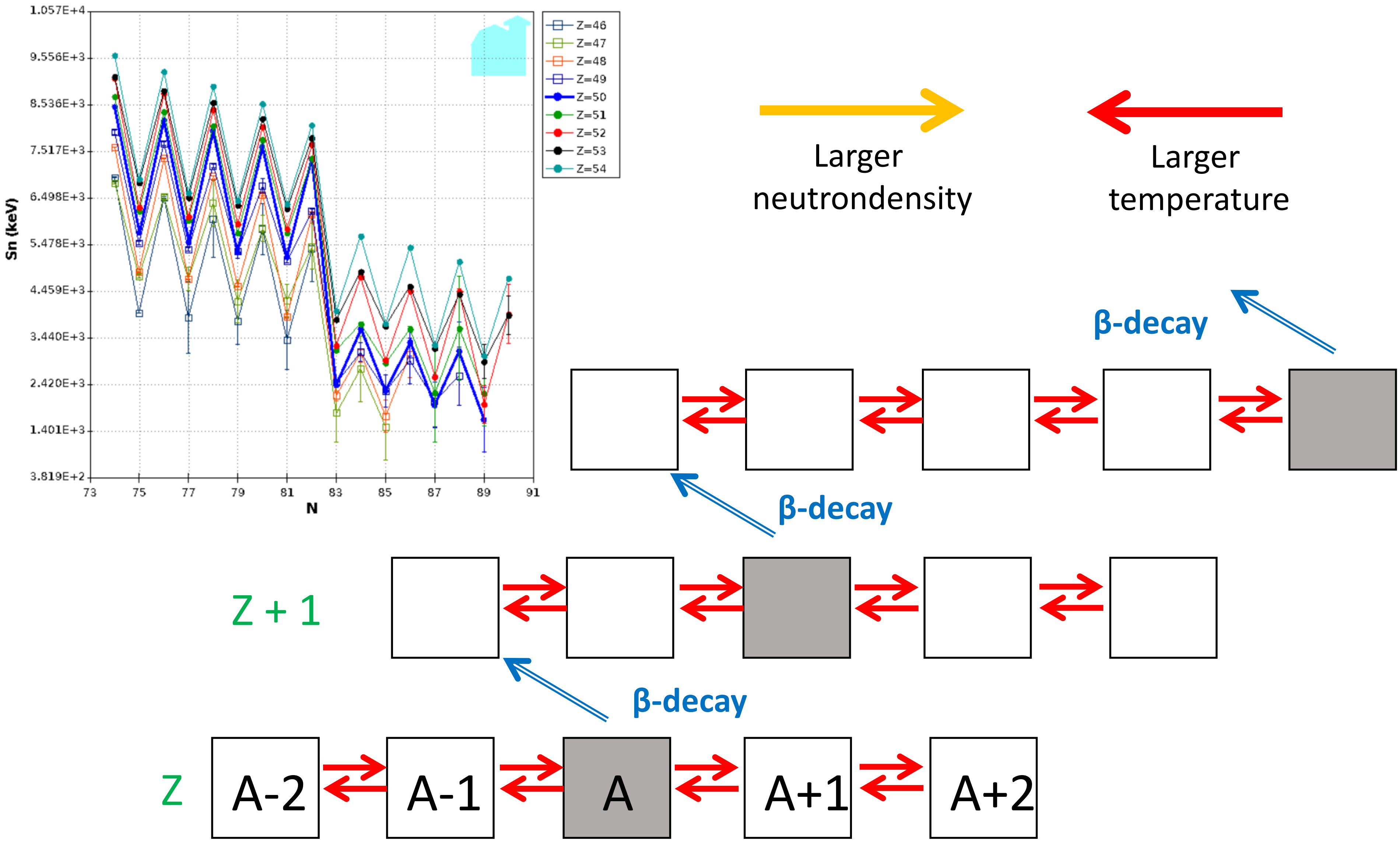
Neutron star merger scenario:
Larger neutron density
Moderate temperature
-> nucleosynthesis path closer to the drip line
-> Fission plays crucial role

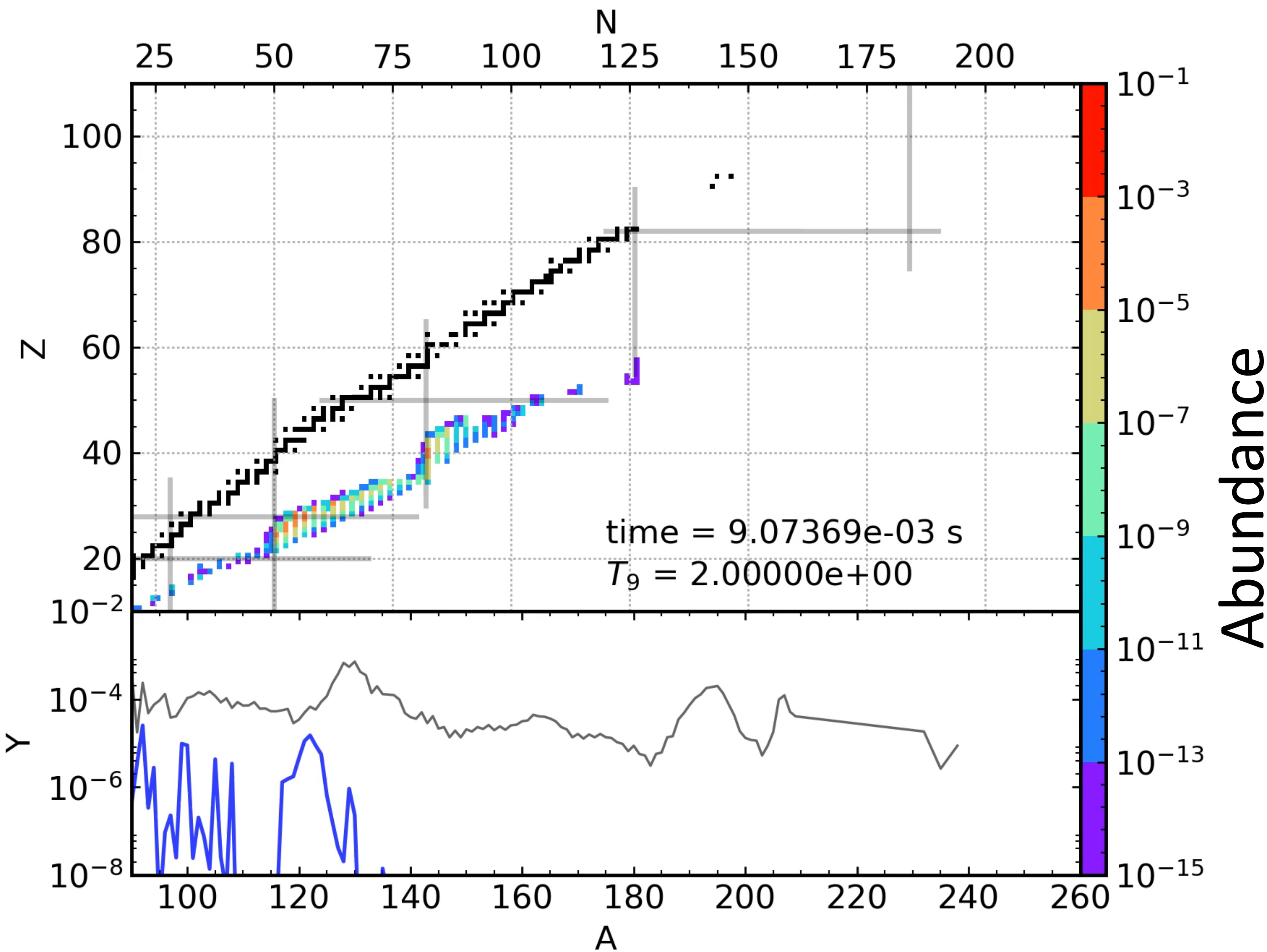
Supernovae scenario:
Moderate neutron density
Higher temperatures
-> nucleosynthesis path closer to the valley of stability
-> Fission plays less important / no role

Take home message #1

The interpretation of astronomical observations require nuclear physics knowledge

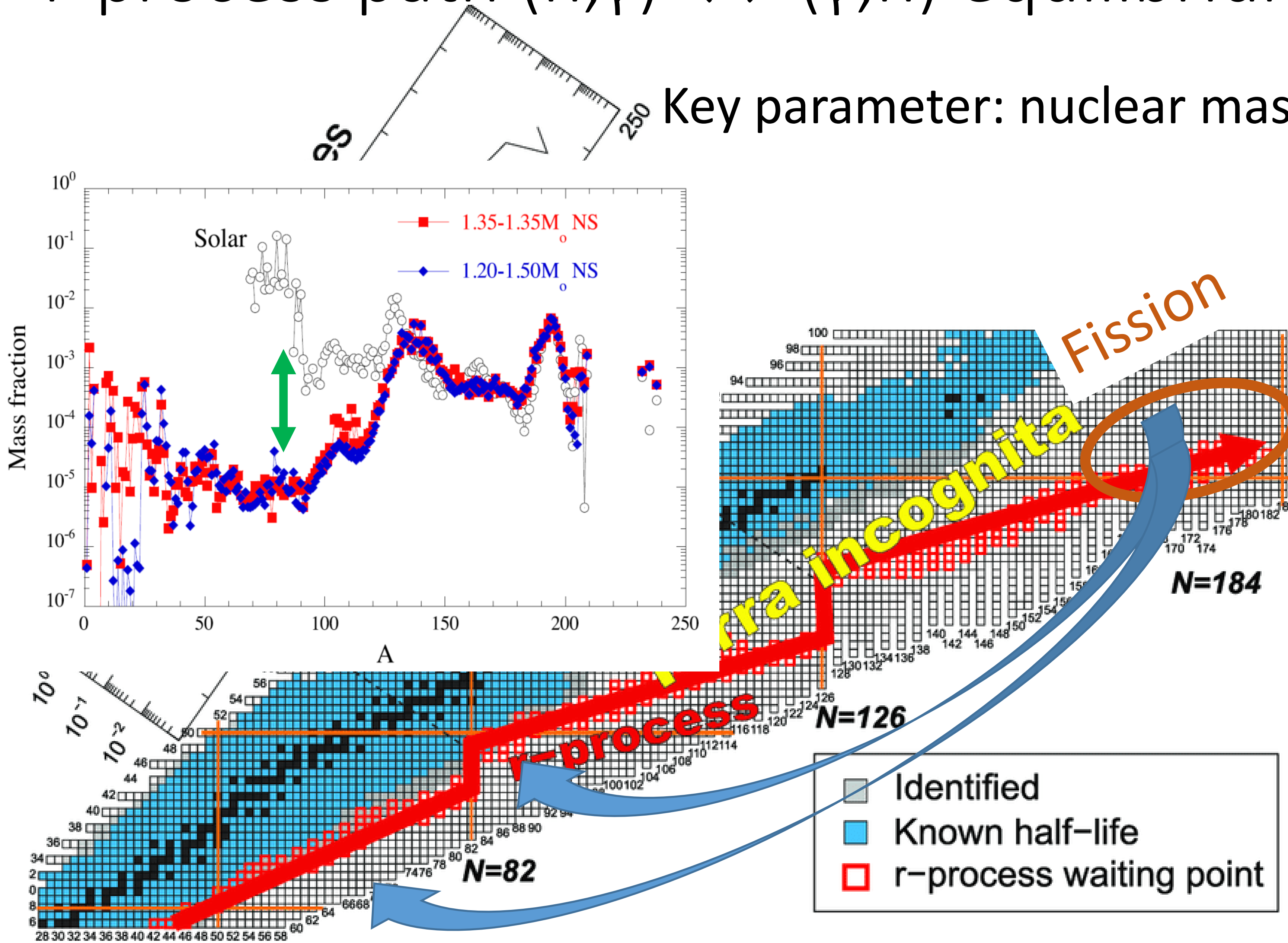
r-process: nucleosynthesis model




N
25
50
75
100
125
150
175
200
Z
100
80
60
40
20
time = 9.07369e-03 s
T_9 = 2.00000e+00
Abundance
10^{-1}
10^{-3}
10^{-5}
10^{-7}
10^{-9}
10^{-11}
10^{-13}
10^{-15}
Y
10^{-2}
10^{-4}
10^{-6}
10^{-8}
100
120
140
160
180
200
220
240
260
A

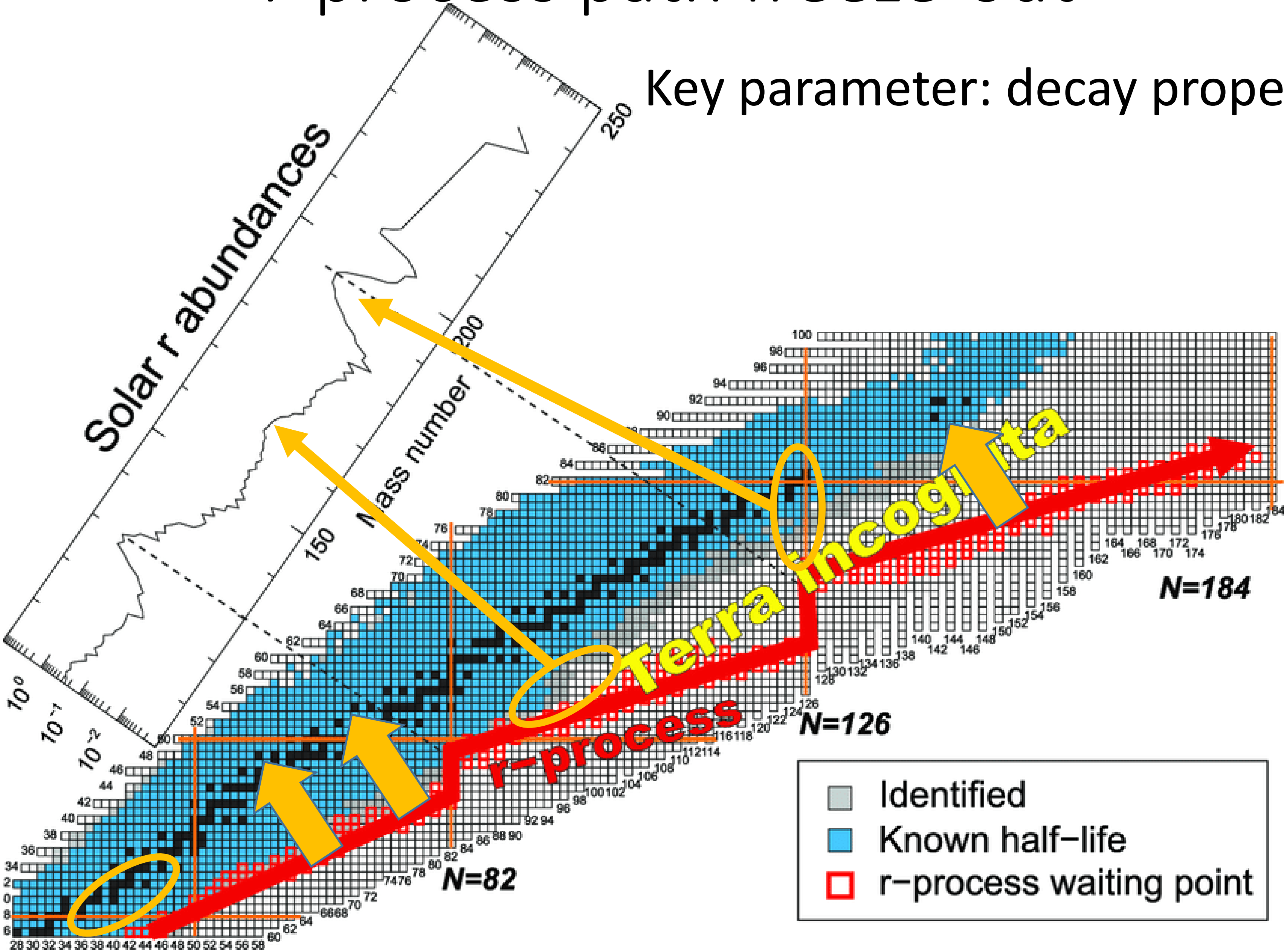
r-process path (n,γ) ↔ (γ,n) equilibrium

Key parameter: nuclear mass

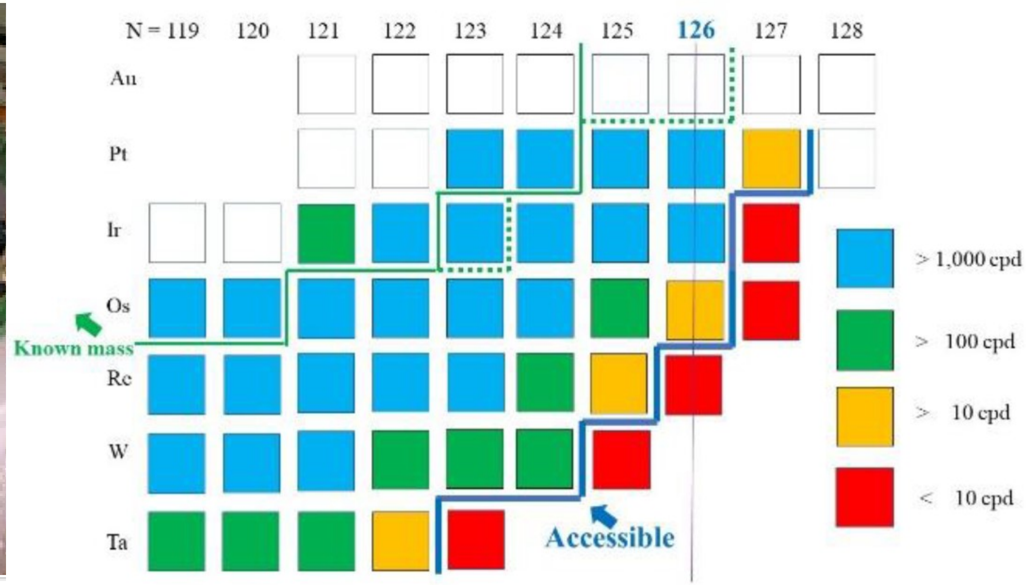


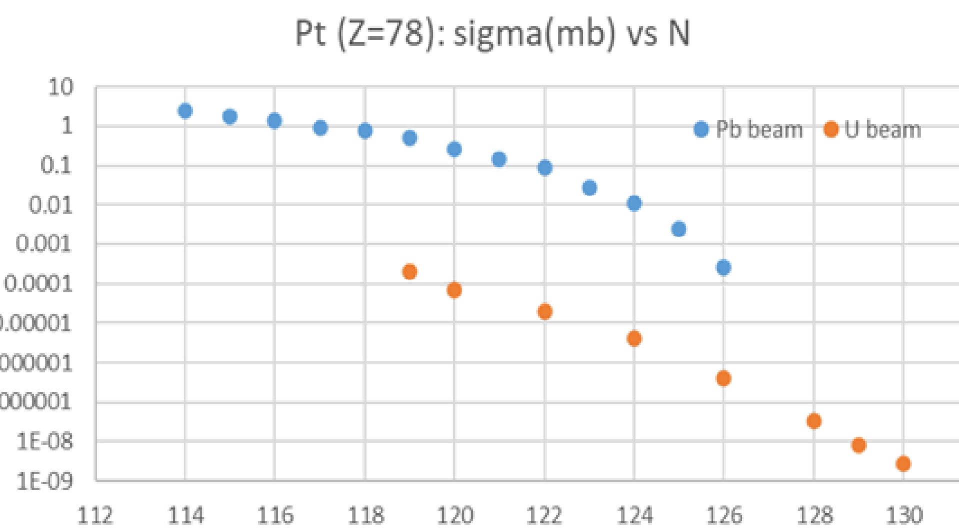
r-process path freeze-out

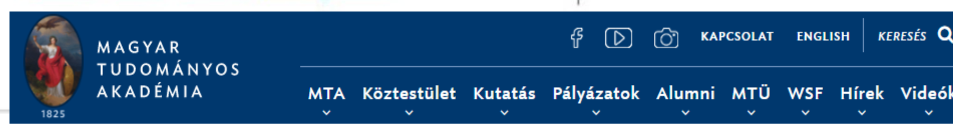
Key parameter: decay properties



Experiments at the N=126 region







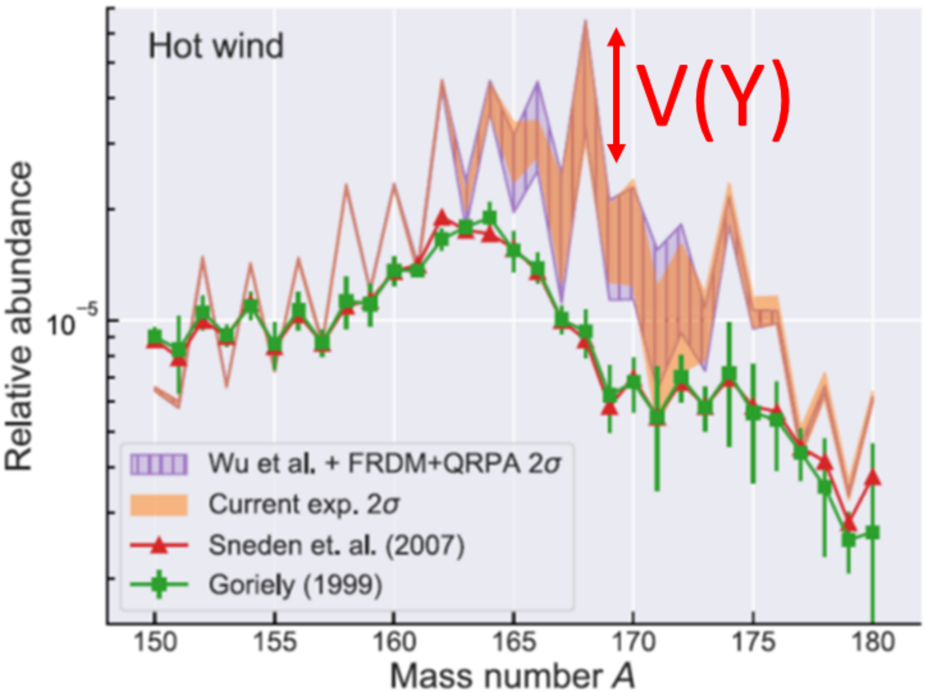
Tizenkét külföldi vendégkutató kapcsolódik be a hazai kutatásokba 2023-ban

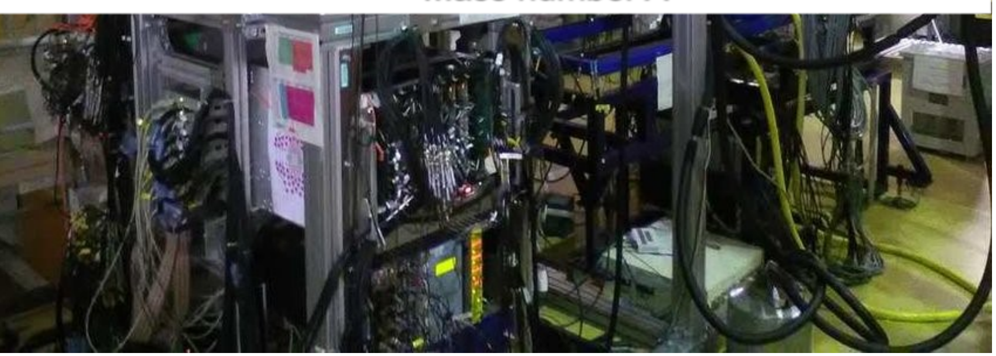
Podolyák Zsolt (Surrey)

„Strengthening the Hungarian leadership in exploring exotic atomic nuclei"

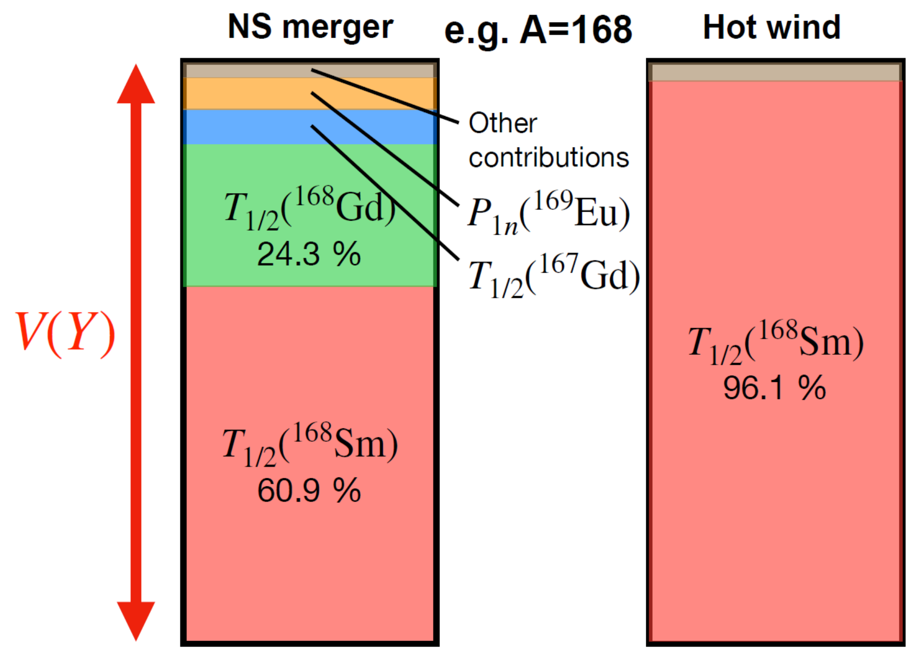
Aim: precise measurement of the decay properties and investigation of their role in nucleosynthesis

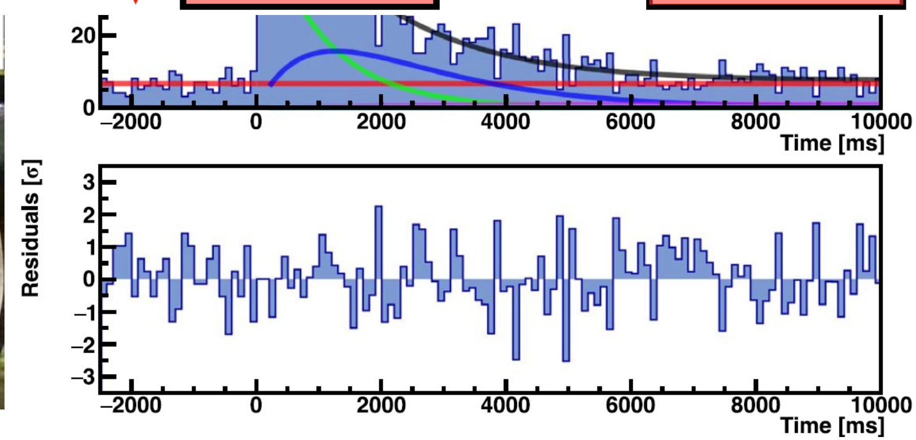
Experiments at the rare-earth region





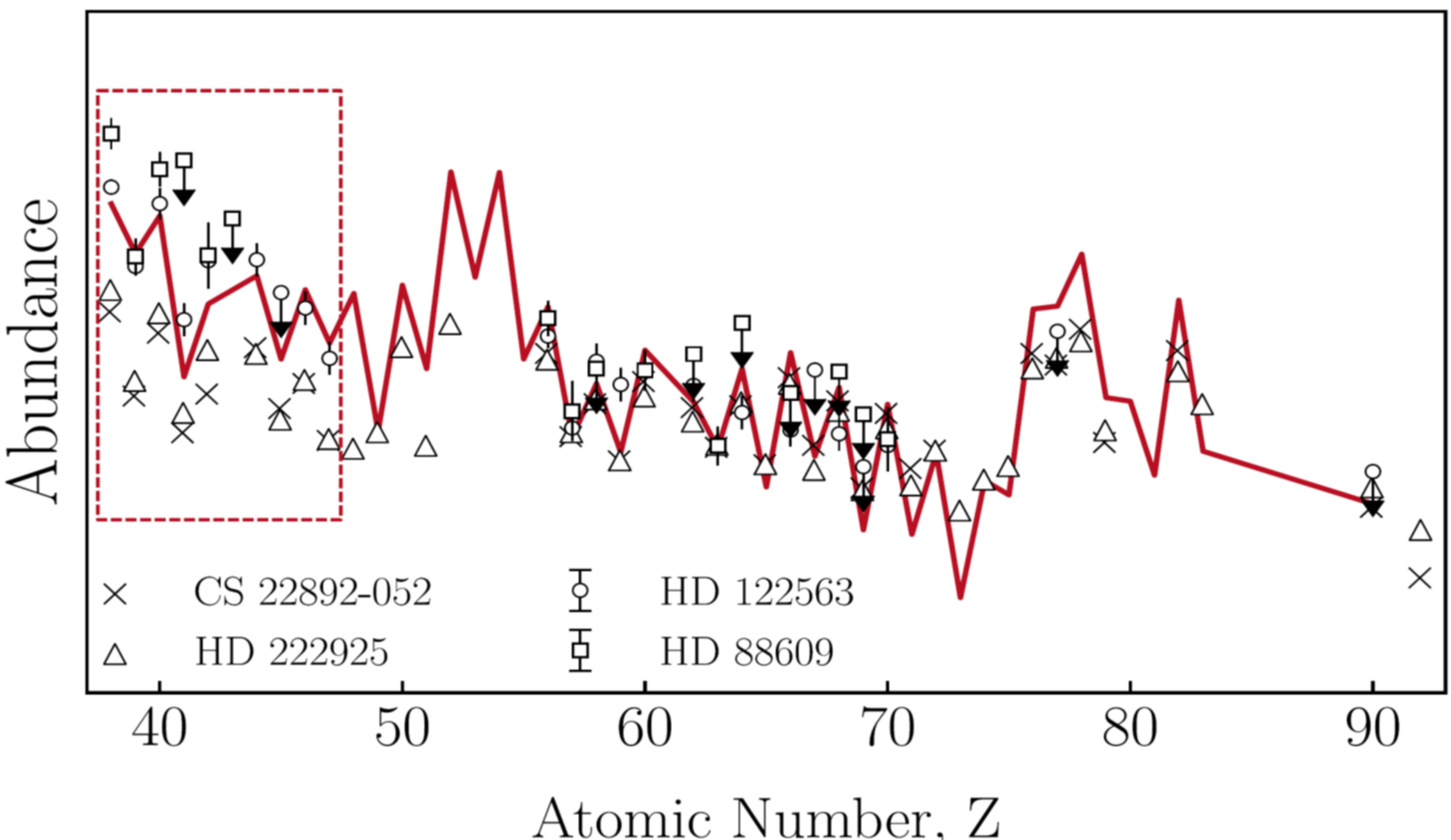
$T_{1/2}(^{168}\mathrm{Sm}) = 353^{+210}_{-164}$ [ms]





G. G. Kiss *et al.*, Astrophysical J. **936** (2022) 107

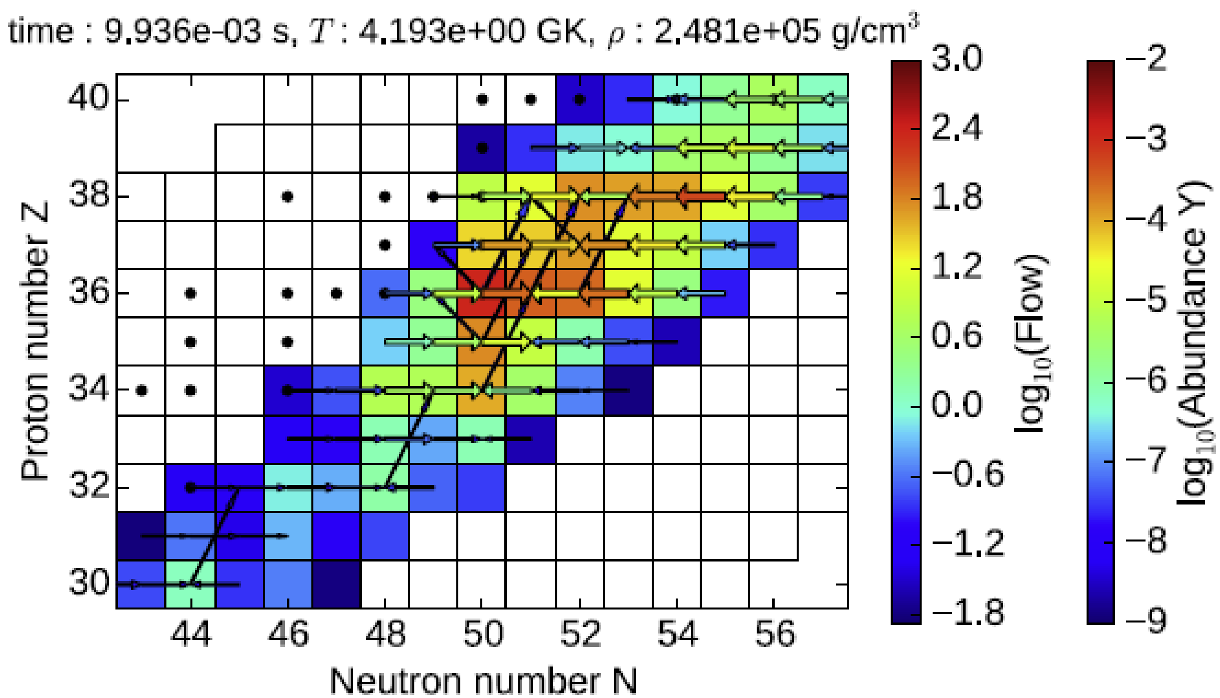
HD 122563 (and other metal-poor stars)



Nucleosynthesis in the ejected material of supernovae

- Slightly neutron-rich ejecta
- Rapid cooling
- Short timescale

- Nucleosynthesis close to the valley of stability
- Role of photodisintegration is quickly decreasing
- β-decays play no role

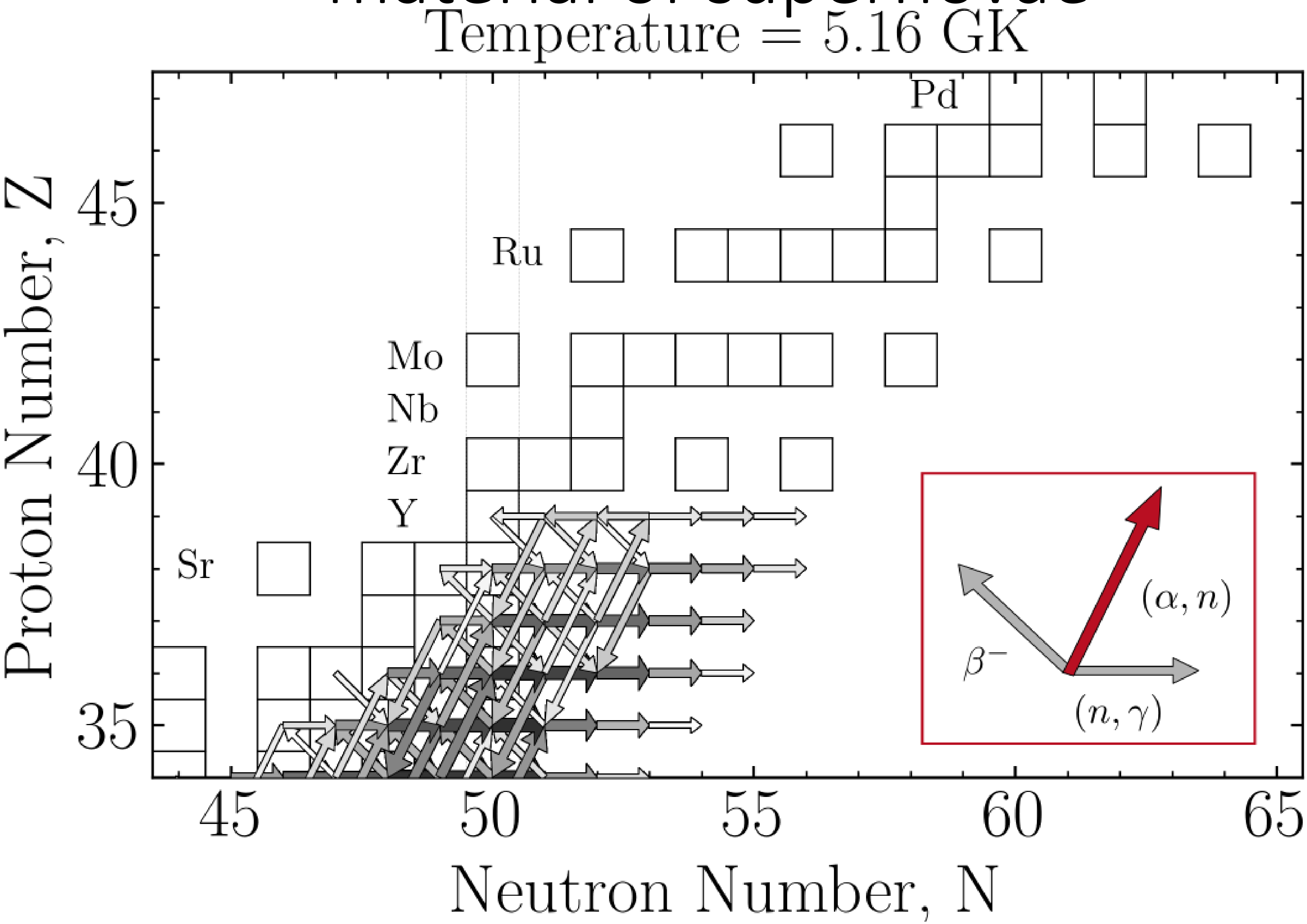


J. Bliss *et al*., J. Phys. G **44** (2017) 054003, J. Bliss *et al*., PRC **101** (2020) 055807

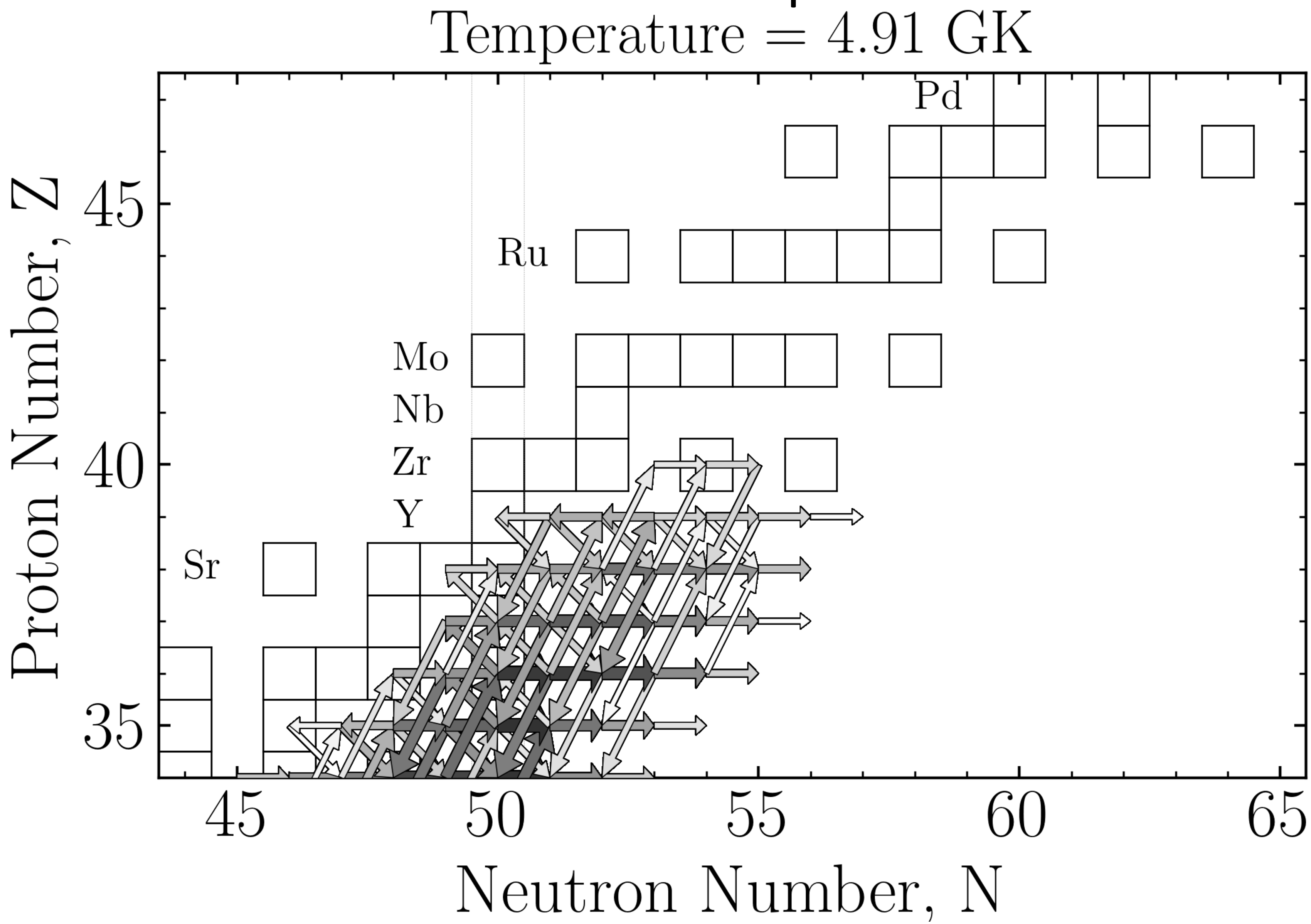
Take home message #2

- Heavy neutron-rich isotopes are formed very probably at three sites:
  - In neutron star mergers – observed
  - In special supernovae – probable
  - In the ejected material of core-collapse supernovae – I will discuss in details

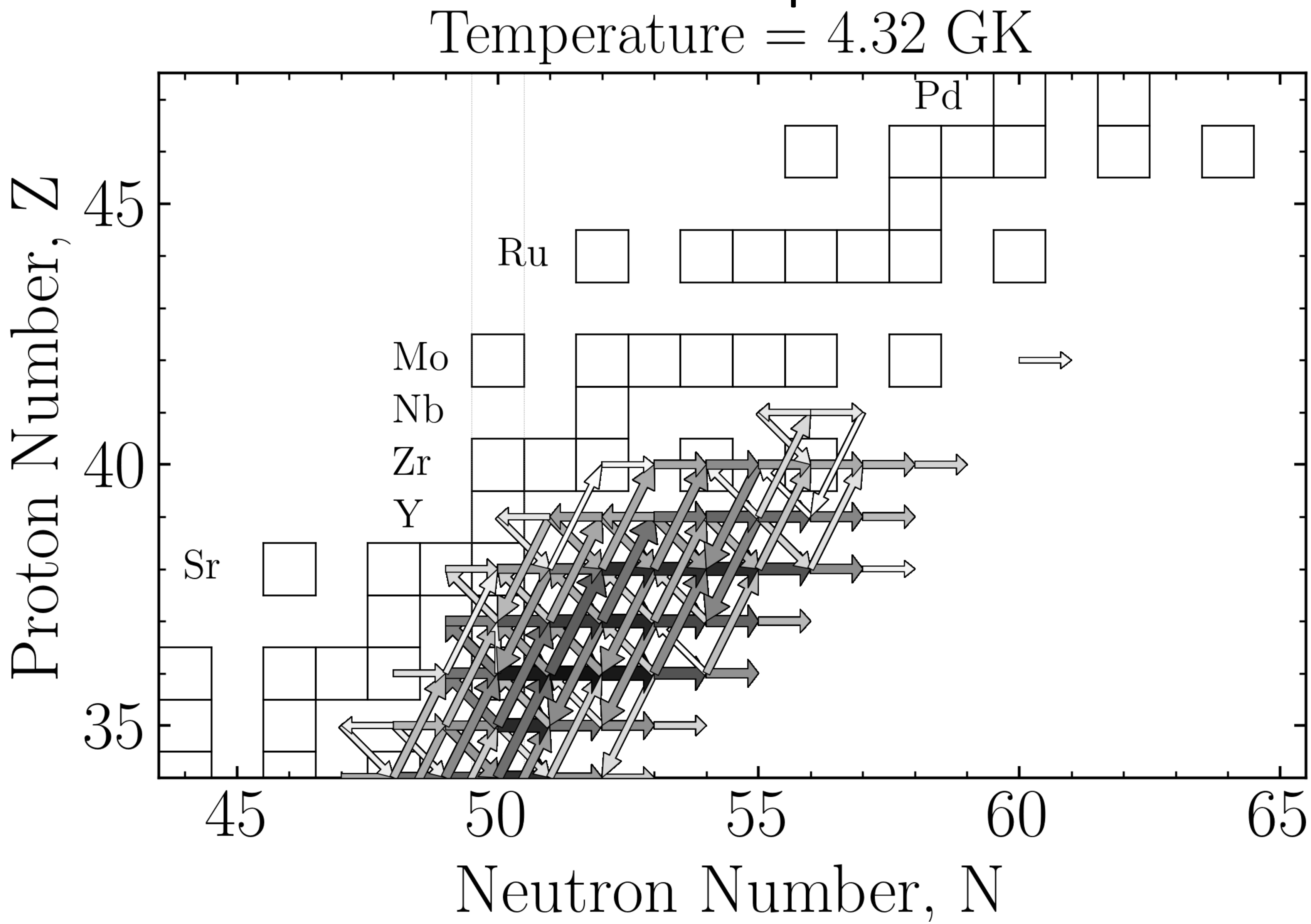
Nucleosynthesis in the ejected material of supernovae



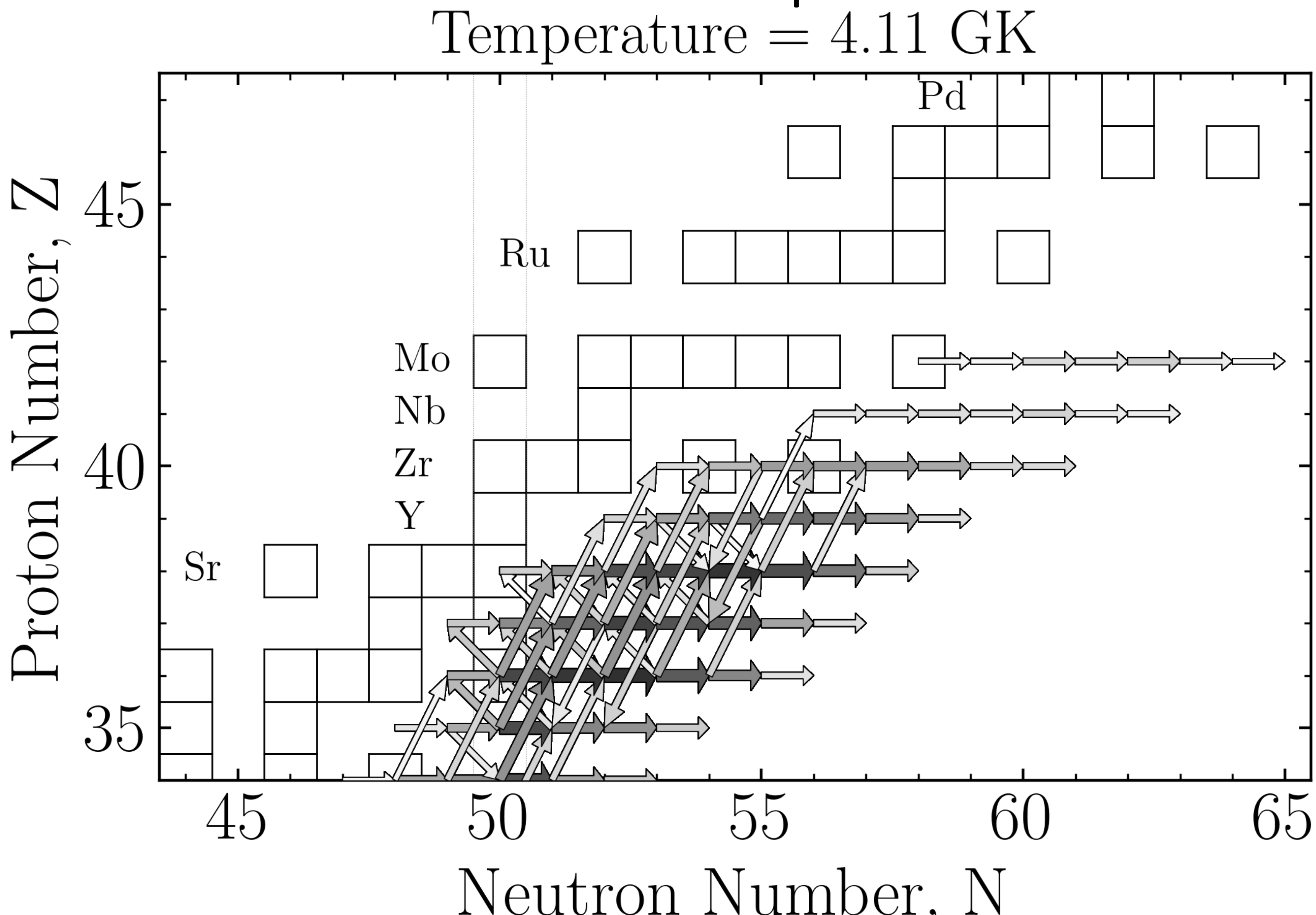
Nucleosynthesis in the ejected material of supernovae



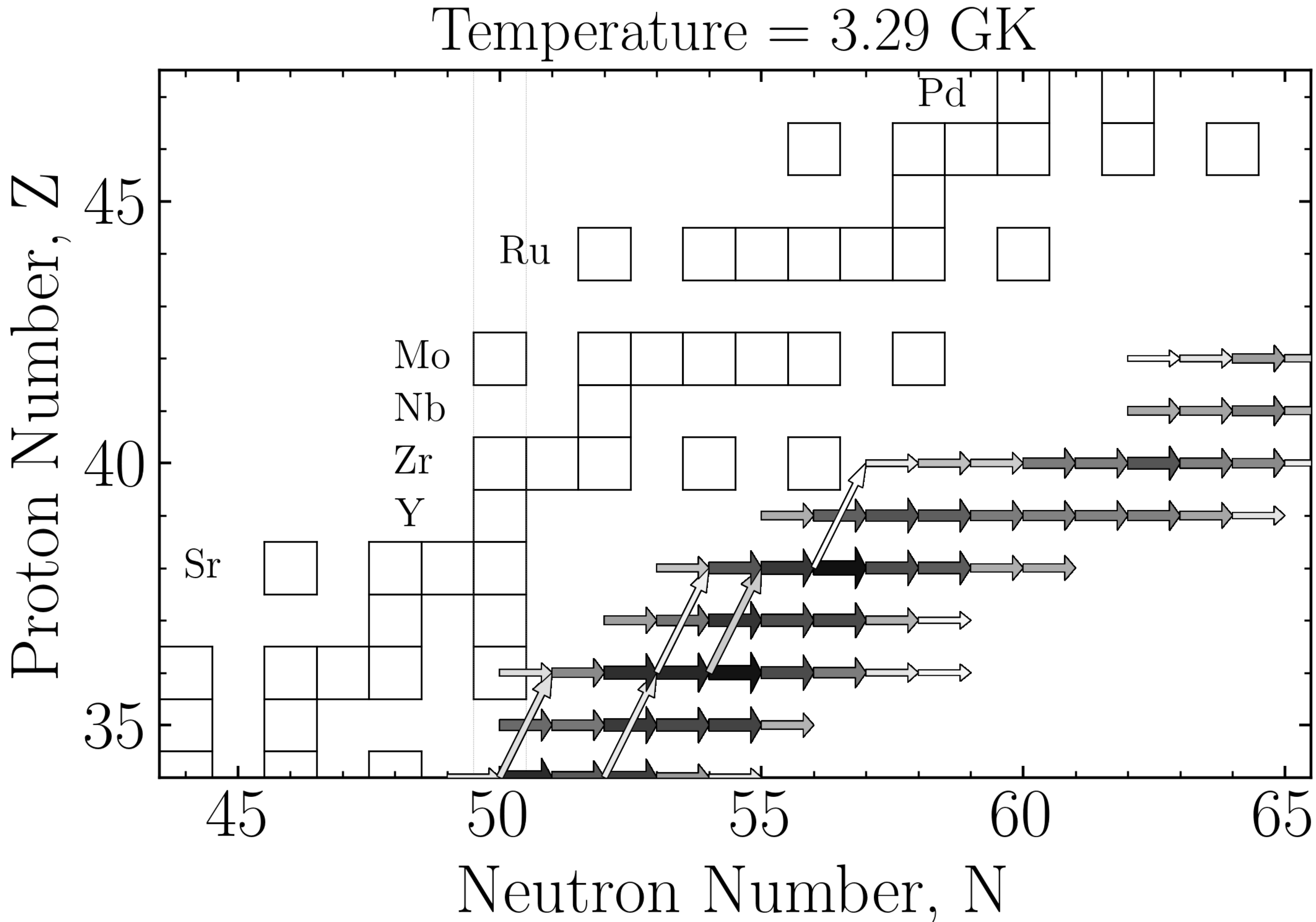
Nucleosynthesis in the ejected material of supernovae



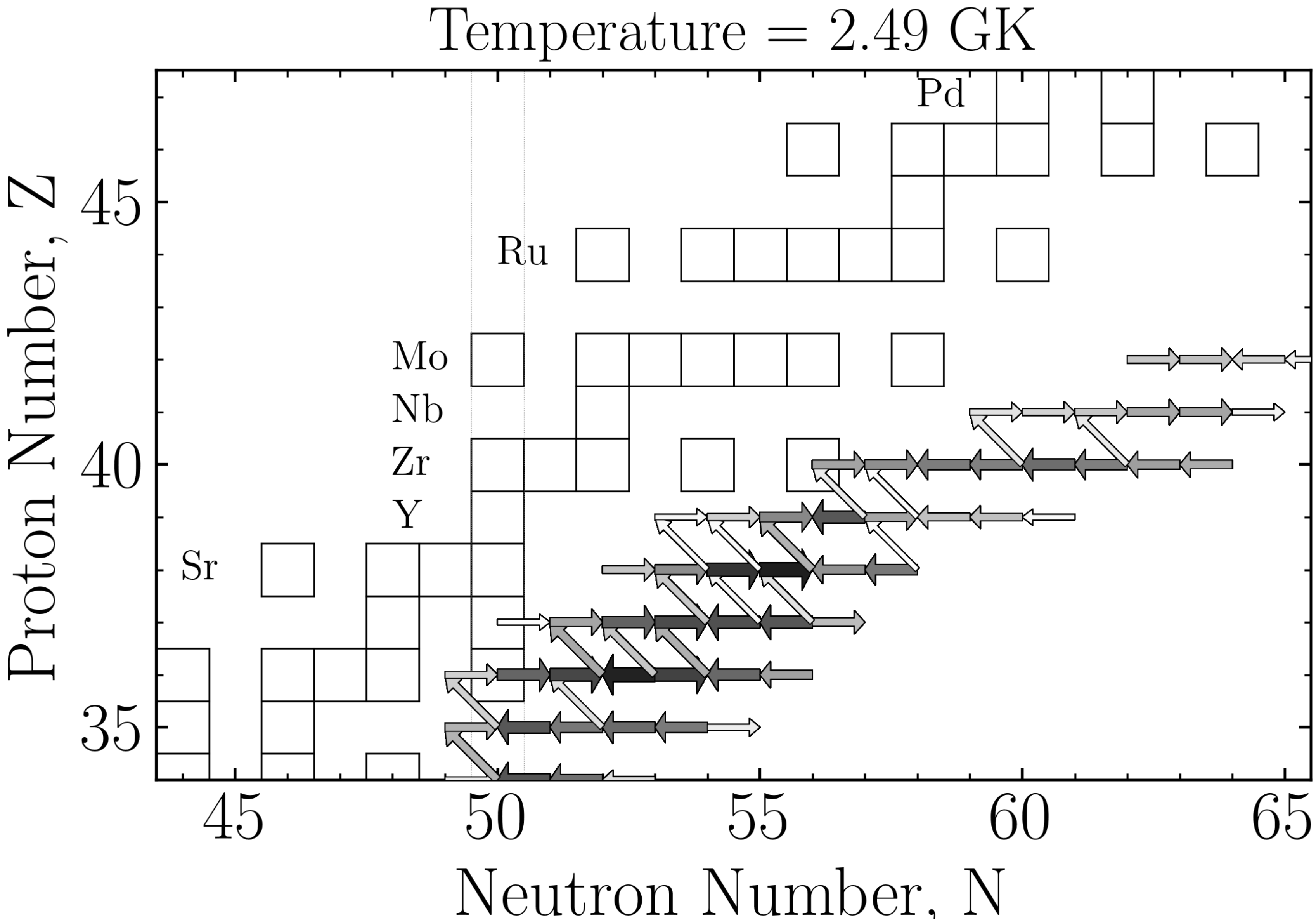
Nucleosynthesis in the ejected material of supernovae



Nucleosynthesis in the ejected material of supernovae



Nucleosynthesis in the ejected material of supernovae



Synthesis of neutron-rich Sr-Ag isotopes

- Astrophysics:
  - Timescale
  - Temperature
  - Neutron-to-seed ratio

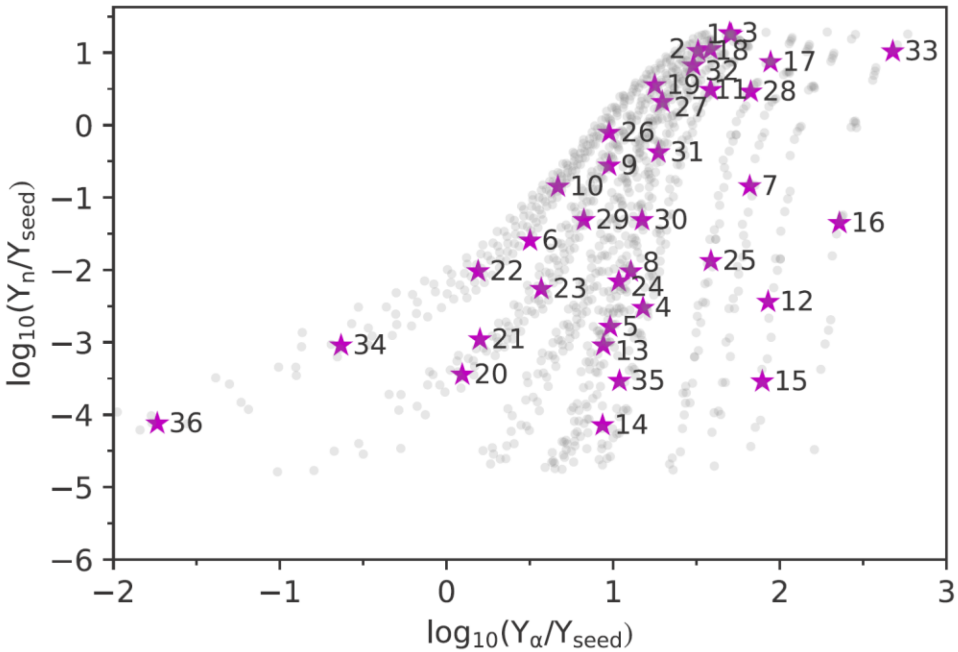


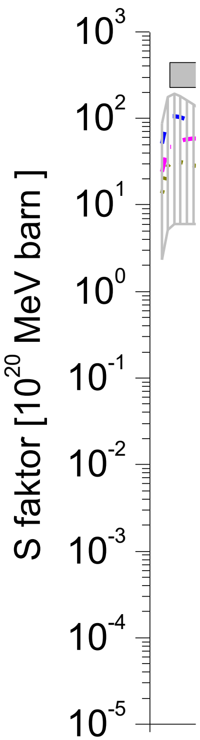
TABLE I. Astrophysical conditions associated with each trajectory.

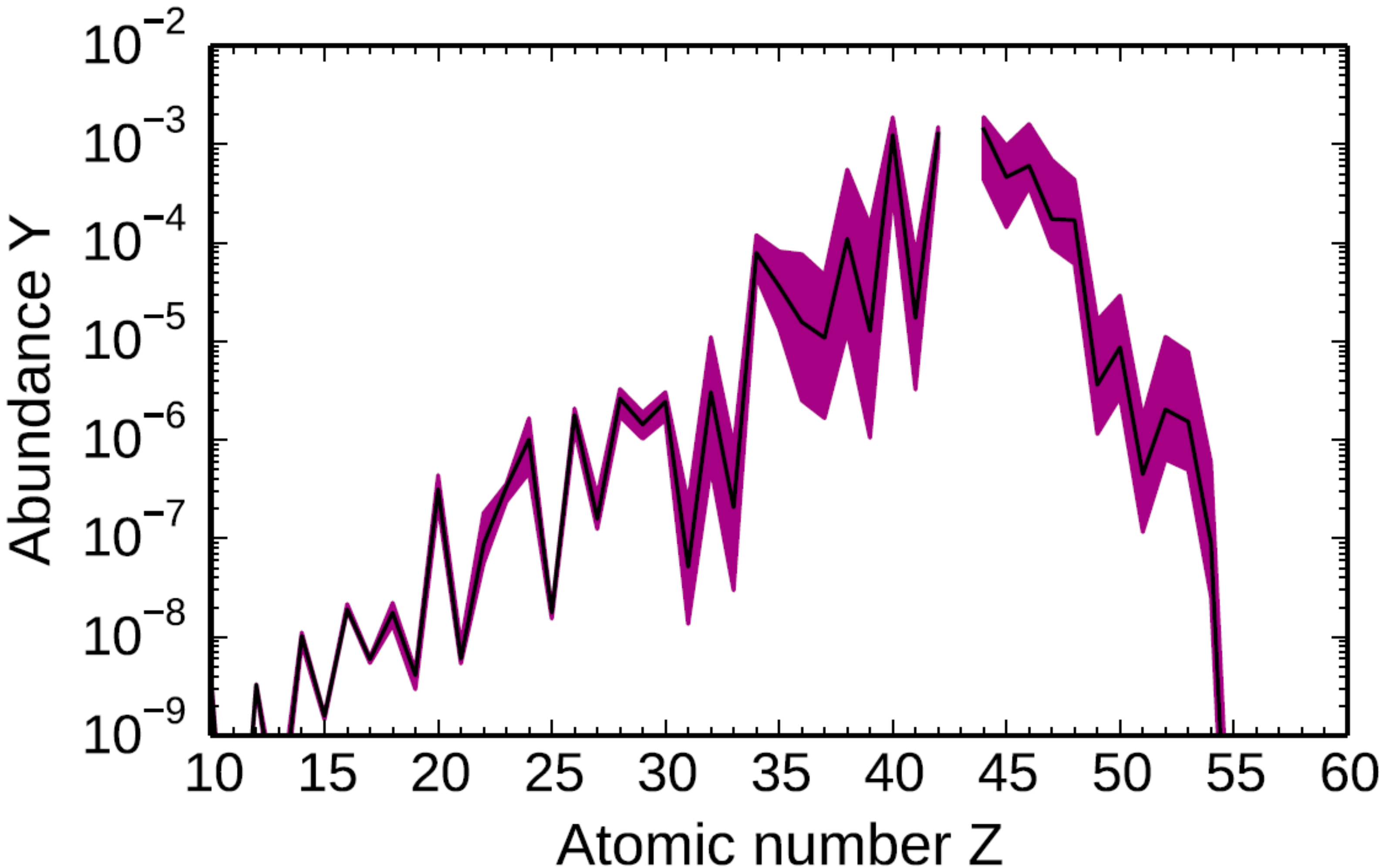
Trajectory	Y_e	Entropy k_B/nuc	Expansion time ms
MC1	0.42	129	11.7
MC2	0.45	113	11.9
MC3	0.45	122	10.3
MC4	0.44	66	19.2
MC5	0.43	66	34.3
MC6	0.4	56	63.8
MC7	0.47	96	11.6
MC8	0.43	78	35
MC9	0.40	73	28.1
MC10	0.40	54	31
MC11	0.44	104	13.2
MC12	0.48	85	9.7
MC13	0.43	64	35.9
MC14	0.45	46	14.4
MC15	0.48	103	20.4
MC16	0.49	126	15.4
MC17	0.46	132	12.4
MC18	0.45	131	21.4
MC19	0.41	75	9.8
MC20	0.41	42	59.3
MC21	0.41	31	22.2
MC22	0.40	40	46.7
MC23	0.41	48	37.5
MC24	0.43	56	16.2
MC25	0.46	96	20.9
MC26	0.40	84	36.2
MC27	0.42	76	10
MC28	0.46	113	11.9
MC29	0.41	66	41.4
MC30	0.43	79	26.3
MC31	0.43	71	11.4
MC32	0.42	103	12.7
MC33	0.49	175	14.2
MC34	0.40	34	58.7
MC35	0.44	48	13
MC36	0.40	32	63.4

A. Arcones & J. Bliss, Phys. G **41** (2014) 044005, J. Bliss *et al.*, J. Phys. G **44** (2017) 054003, J. Bliss *et al.*, PRC **101** (2020) 055807

Synthesis of neutron-rich Sr-Ag isotopes

- Nucl
  - R



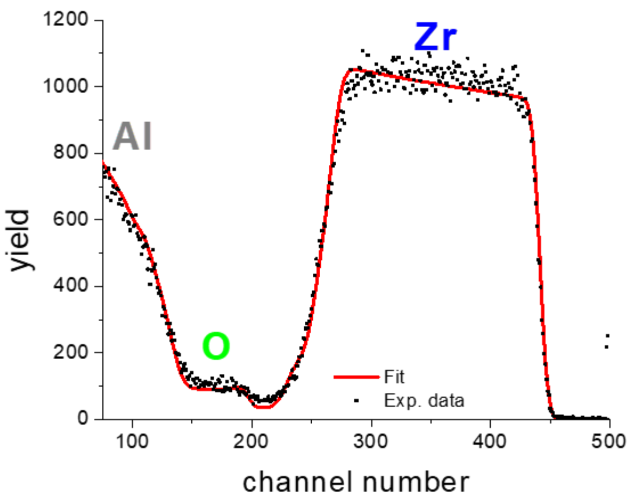


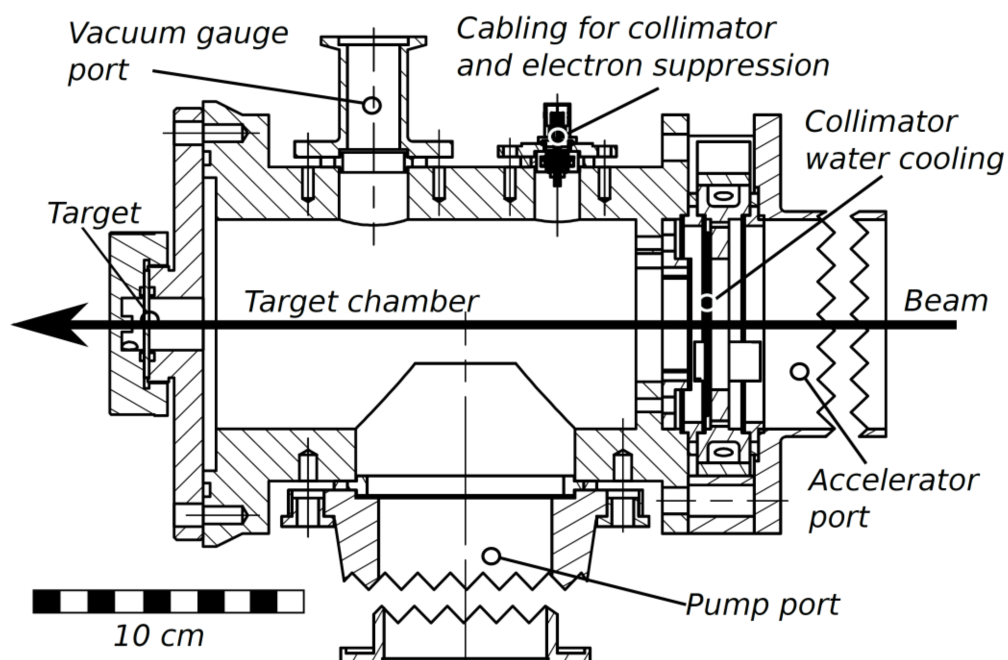
$$S(E) \equiv \frac{E}{\exp(-2\pi\eta)}\sigma(E)$$

P. Mohr, Phys. Rev. C **94** (2016) 035801.
J. Pereira and F. Montes, Phys. Rev. C **93** (2016) 034611.

Activation cross section measurements

6.5 MeV ≤ E_α ≤ 13 MeV;
Vacuum evaporation of high purity ZrO_2
Target properties (thickness, uniformity, composition):
Backscattering spectroscopy
Number of impinging particles:
current measurement
multichannel scaling mode





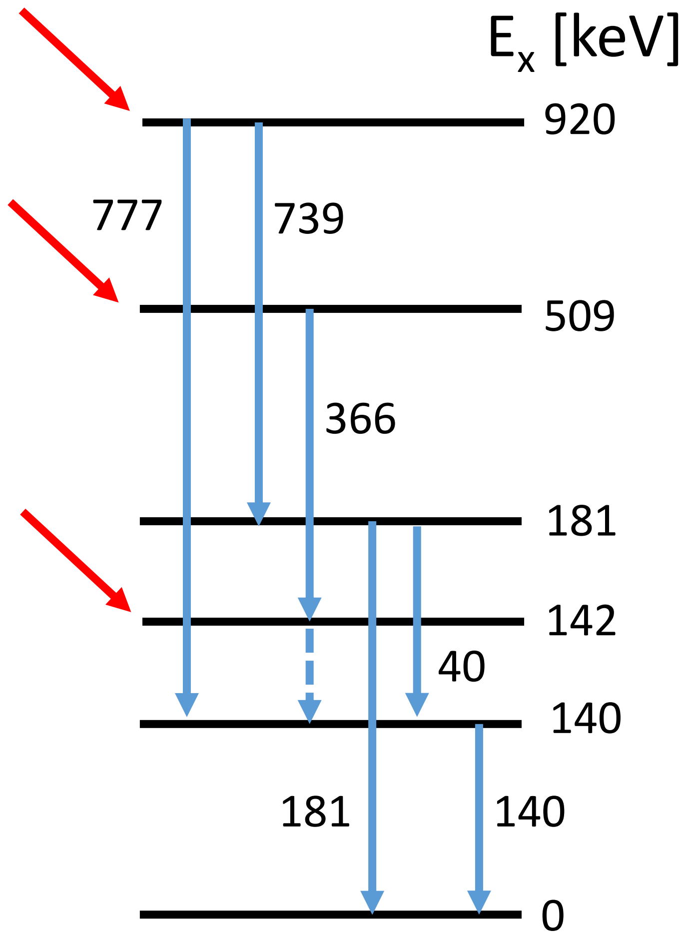
G. G. Kiss *et al.,* Astrophys. J. **90**8 (2021) 202

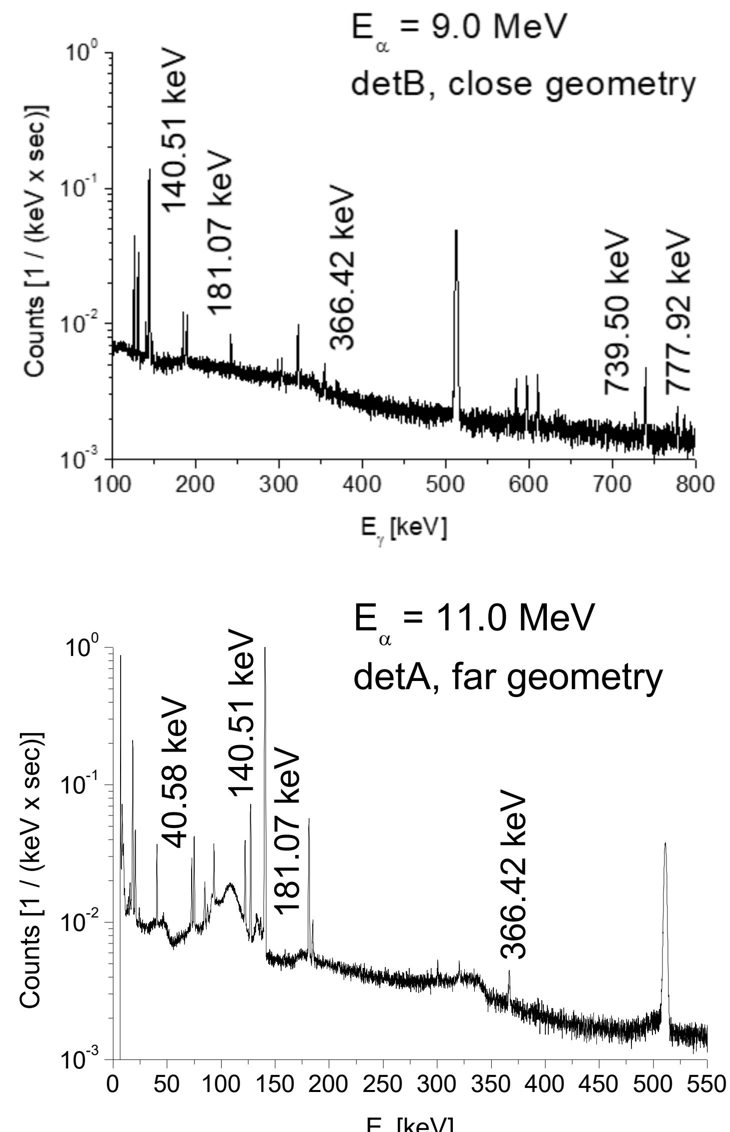
Measurement of the induced activity

^{99}Mo

$t_{1/2}$ = 65.924 ± 0.06 h

Q_{β} = 1357.8 keV





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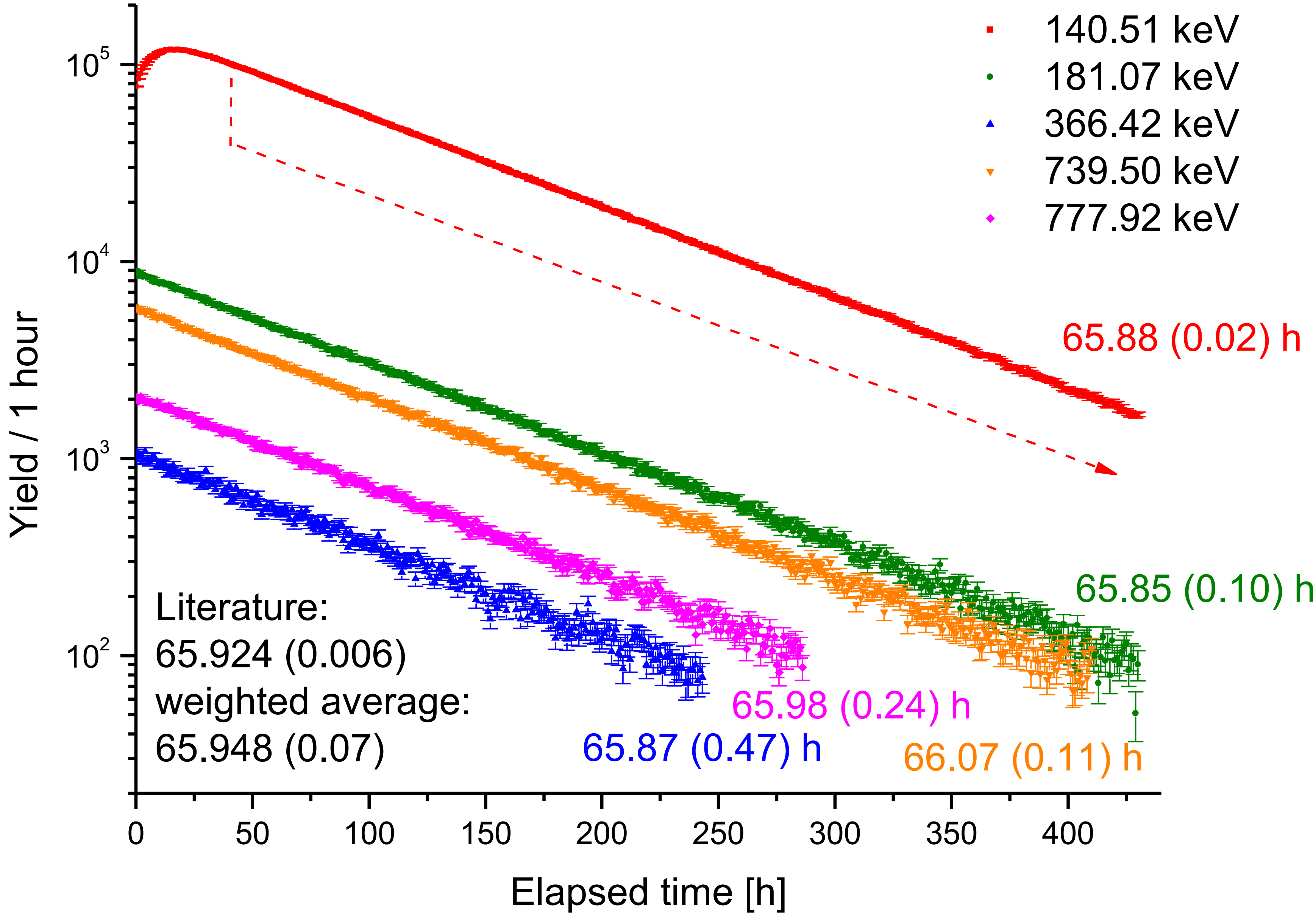

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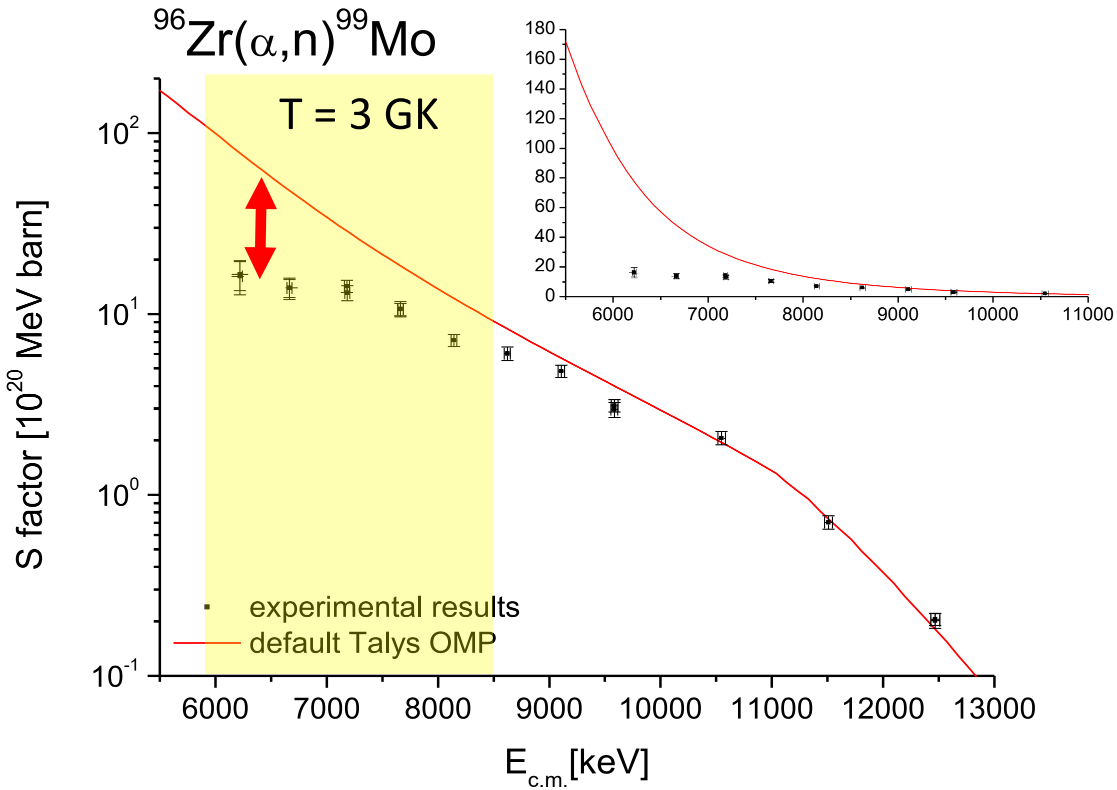
Experimental results

Uncertainties:

Statistical:	≤ 15.3%
Target thickness:	5%
Detection efficiency:	5%
Current measurement:	3%
Decay parameters:	≤ 4%
TOTAL:	≤ 21%
Beam energy:	0.3%
Energy loss calculation	5%
TYPICAL:	25-48 keV



Default α-OMP used in the network calculations overestimates the cross sections by an order of magnitude!

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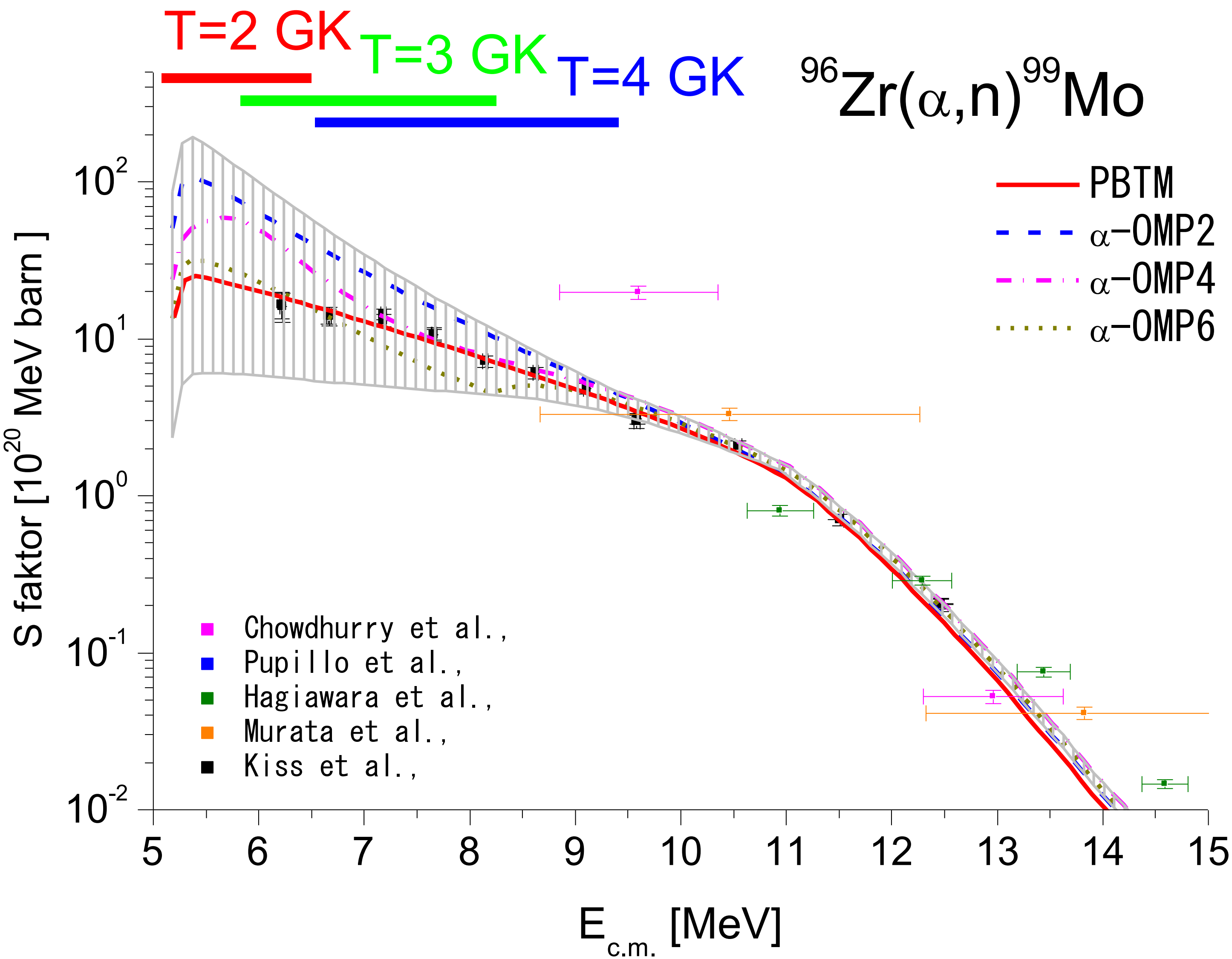
Experimental results



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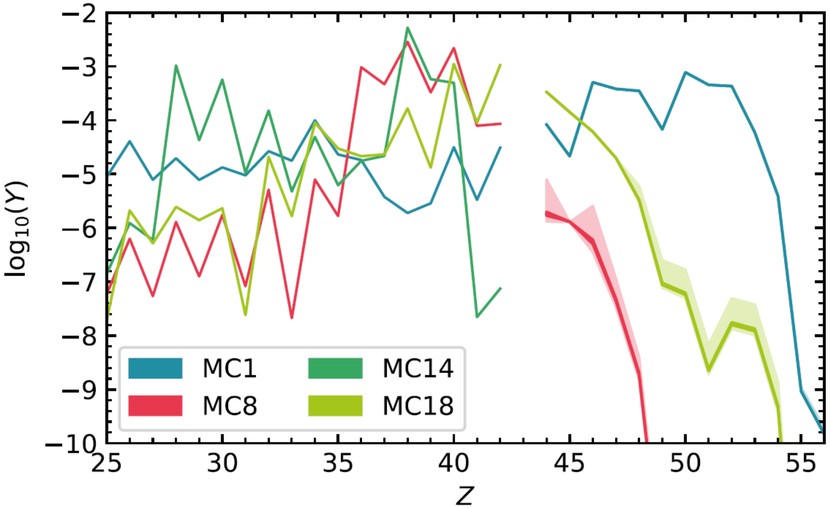
Astrophysical analysis

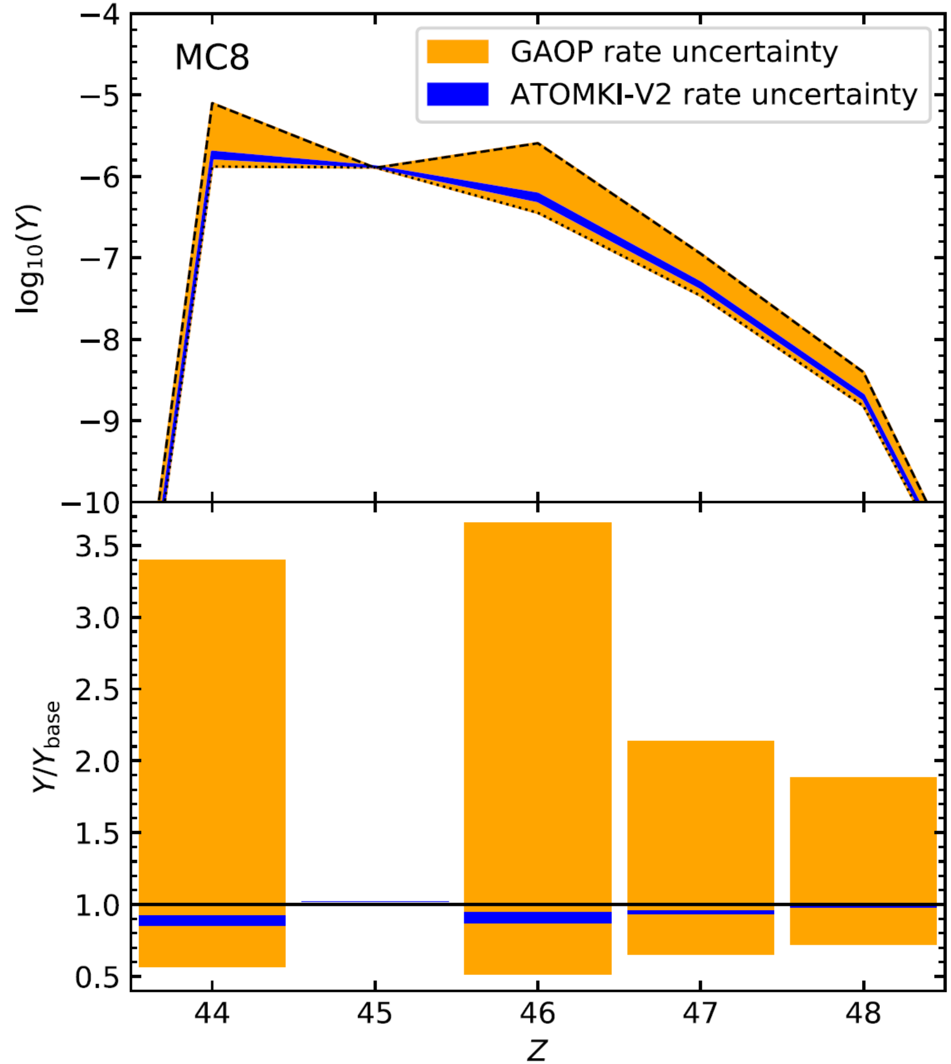


	Ye	Entropy	Timescale
MC1	0.42	129 k_B / nuc.	11.7 ms
MC8	0.43	78 k_B / nuc.	35 ms
MC14	0.45	46 k_B / nuc.	14.4 ms
MC18	0.45	131 k_B / nuc.	21.4 ms

Rate determined by our experimental data; uncertainty (even at 2 GK) is 30%

↓

very well constrained nucleosynthesis yields for the Z = 44–47 range



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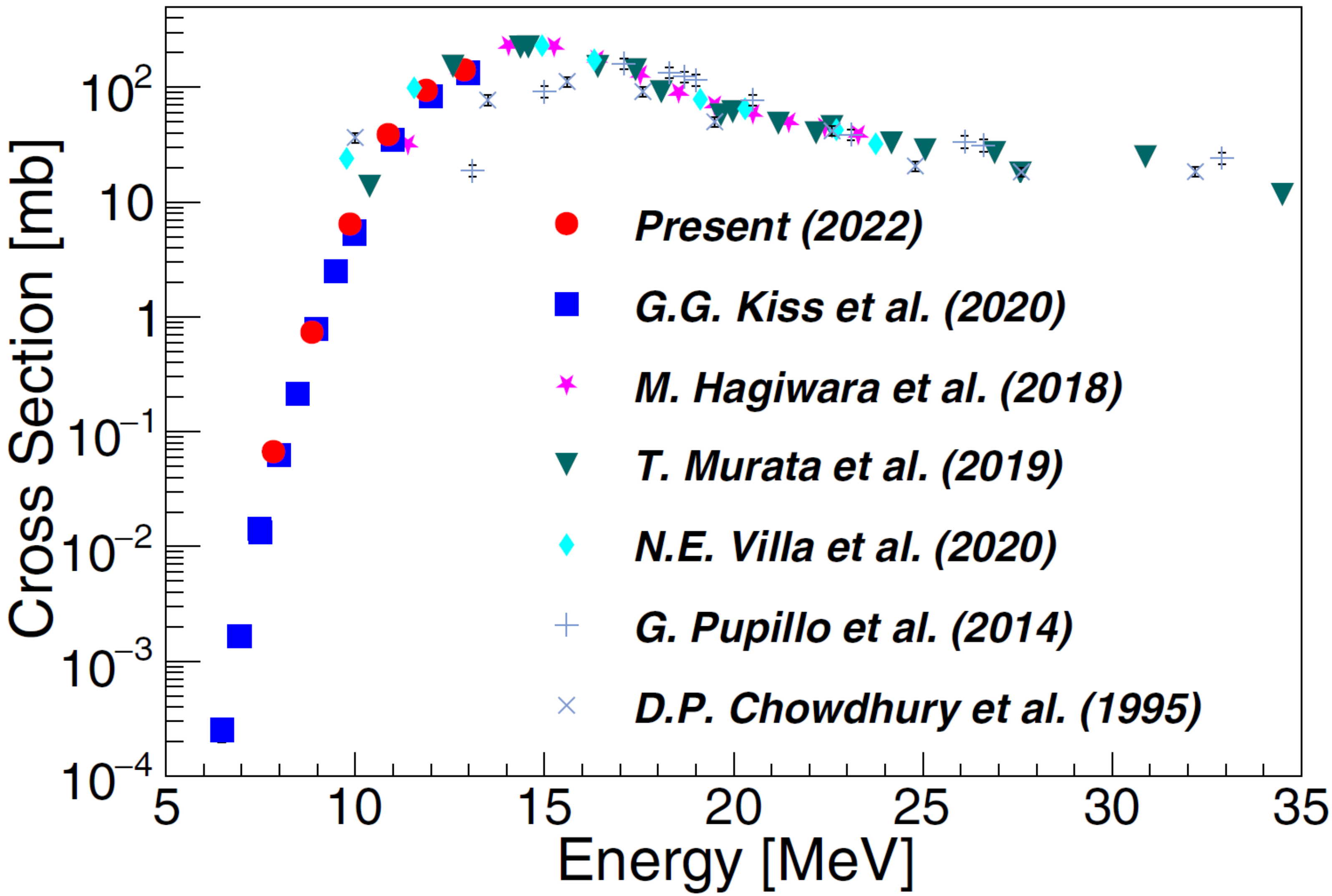
Confirmation of our results



Edwards Lab. @ Ohio University (US)

G. Hamad *et al.*, PRC **106** (2022) 025804

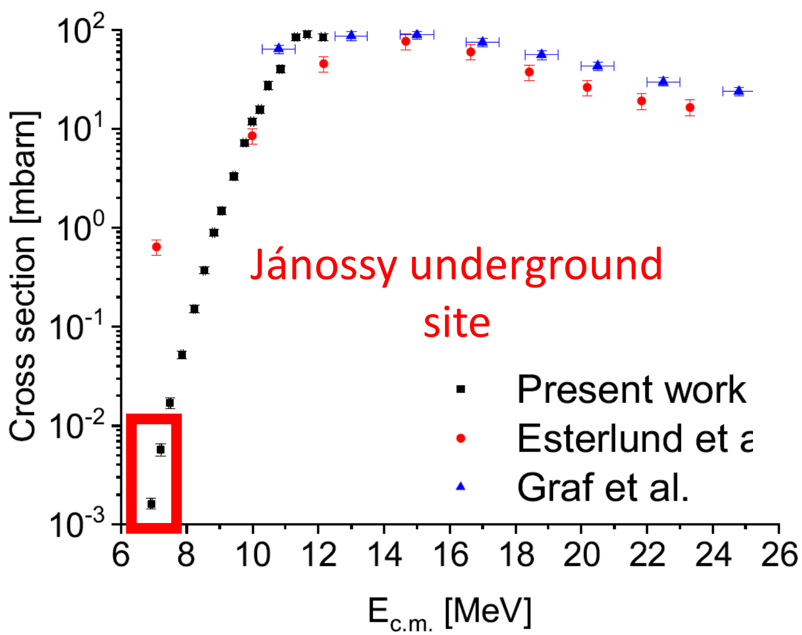
Study of the $^{100}Mo(\alpha,n)^{103}Ru$ reaction

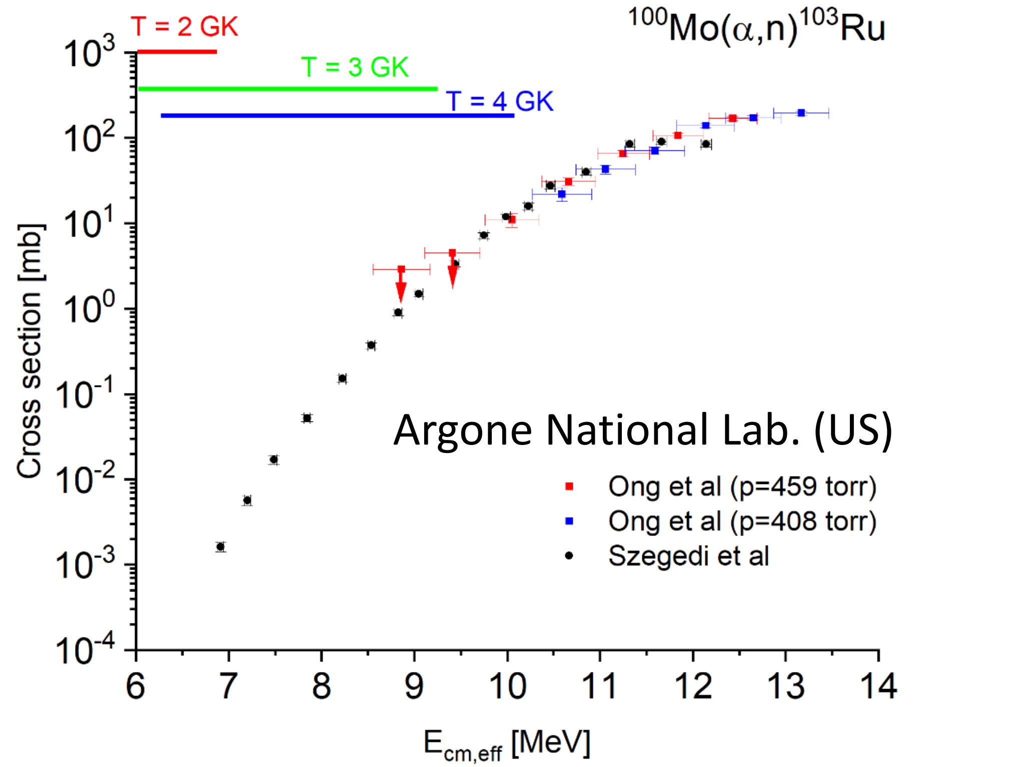
Thick target yield (Y_{TT}) technique:

Reactions take place with all the energies between the initial beam energy (E) and the threshold energy

$$Y_{TT}(E) = \int_{E_{th}}^{E} \frac{\sigma(E')}{\epsilon_{eff}(E')} dE'$$

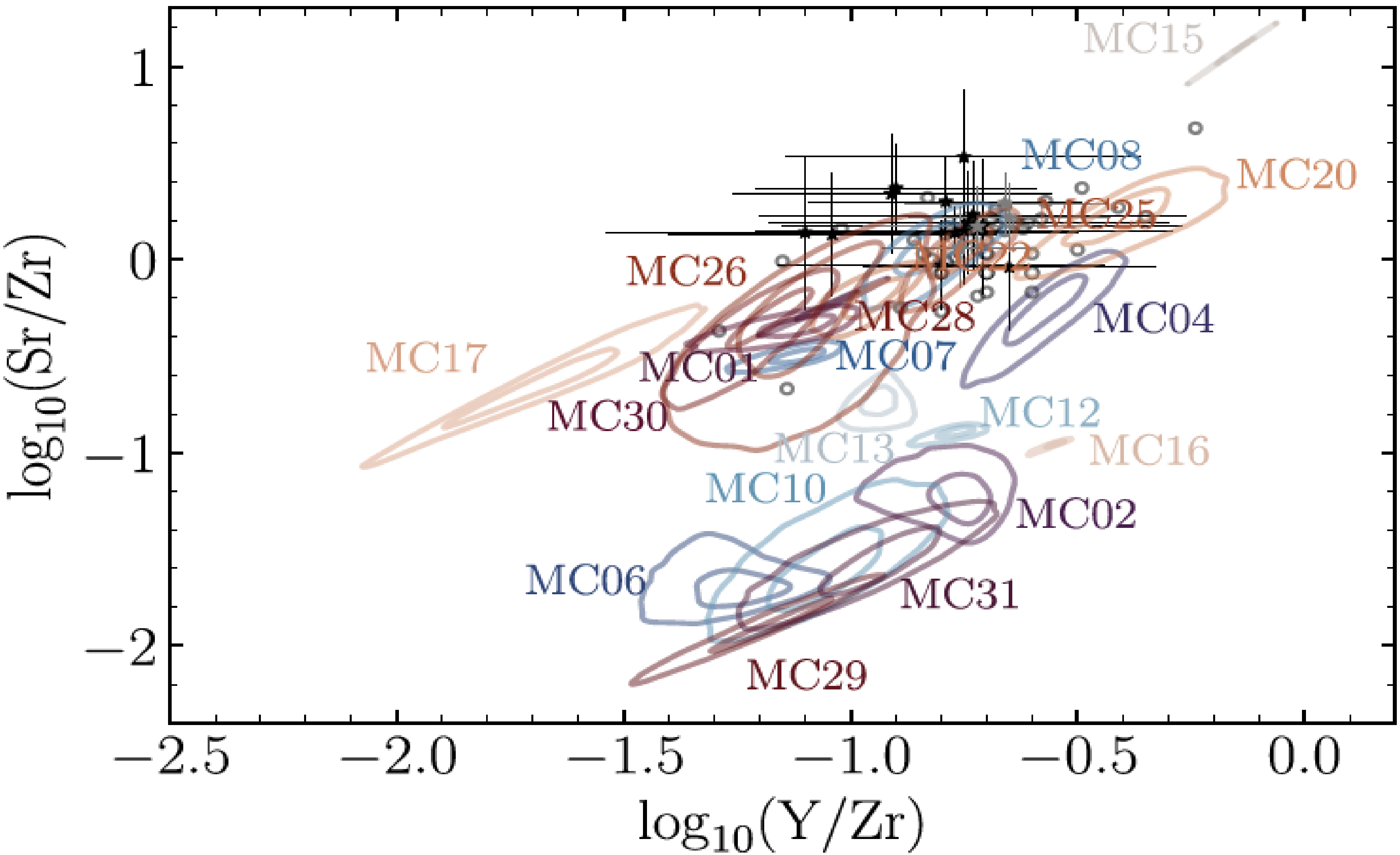
$$\sigma(E_{eff}) = \frac{[Y_{TT}(E_2) - Y_{TT}(E_1)] \cdot \overline{\epsilon_{eff}}(E_1;E_2)}{E_2 - E_1}$$





T. Szegedi *et al.*, Phys. Rev. C **104** (2021) 035804
W.-J. Ong *et al.*, Phys. Rev. C **105** (2022) 055803

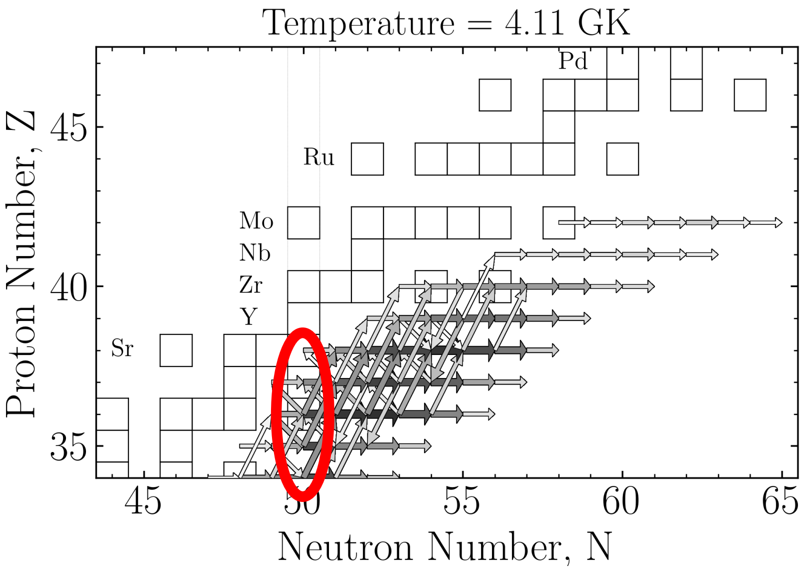
Nucleosynthesis calculations and observations

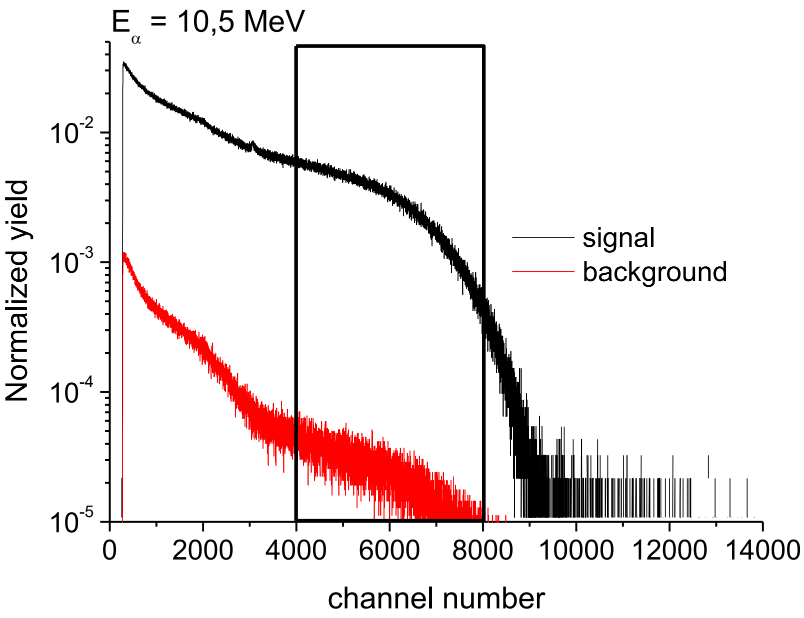


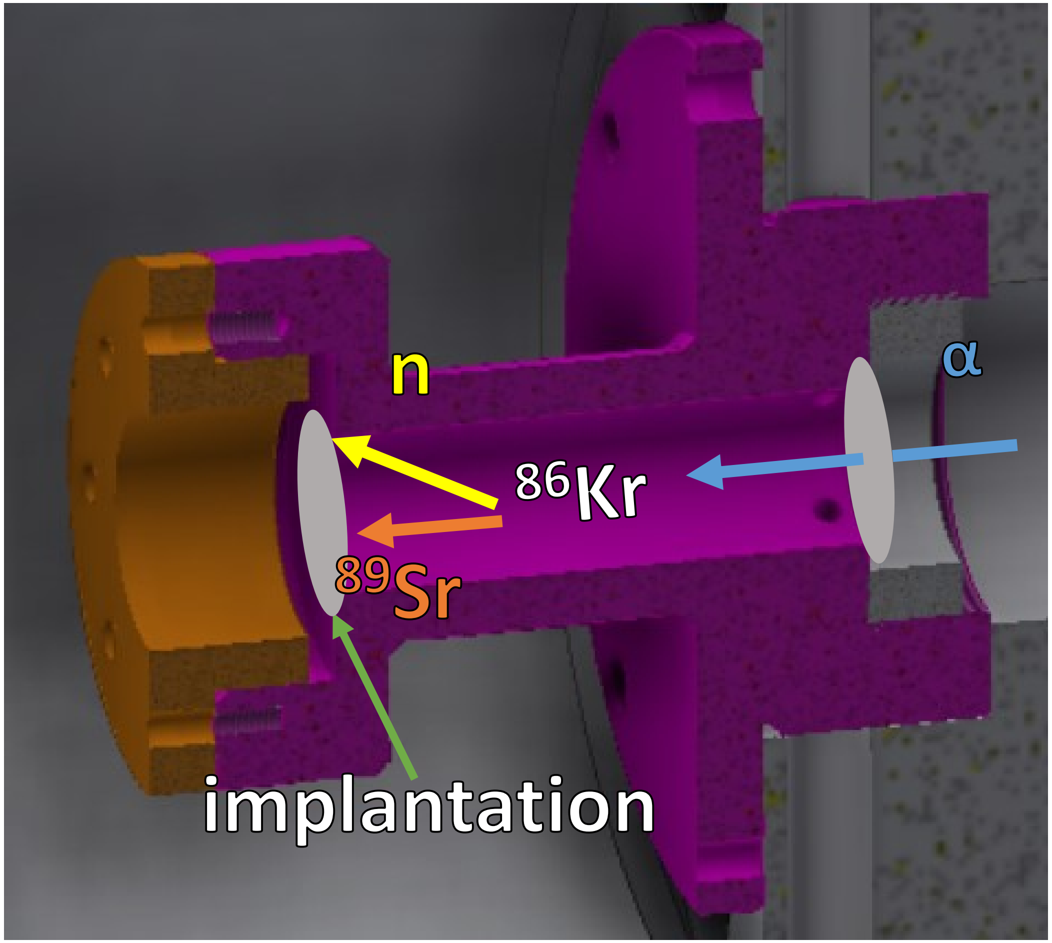
Take home message #3

With high-precision nuclear physics data and astronomical observations, we can obtain information about the properties of supernovae.

Ongoing work: $^{86}Kr(\alpha,n)^{89}Sr$

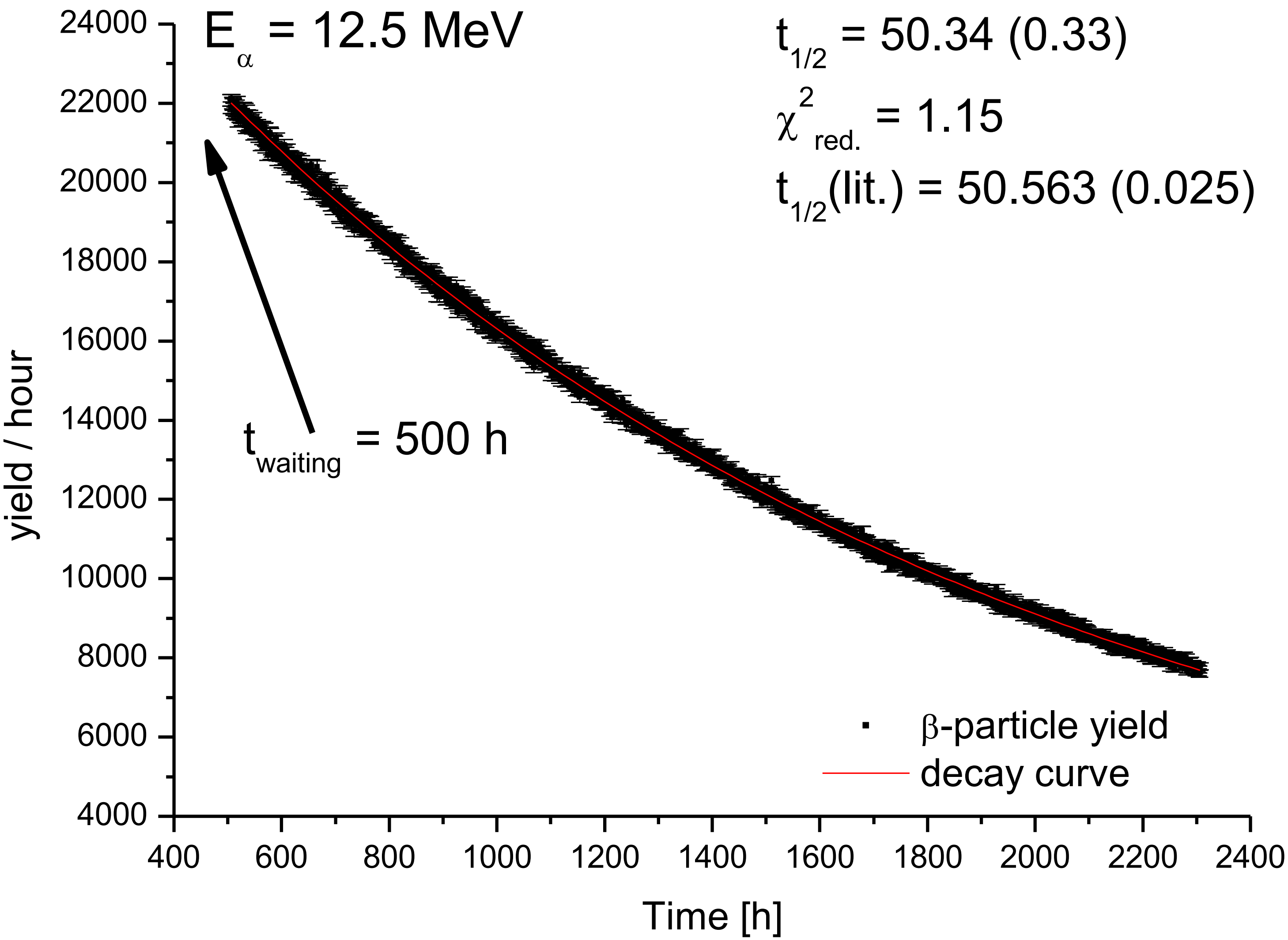




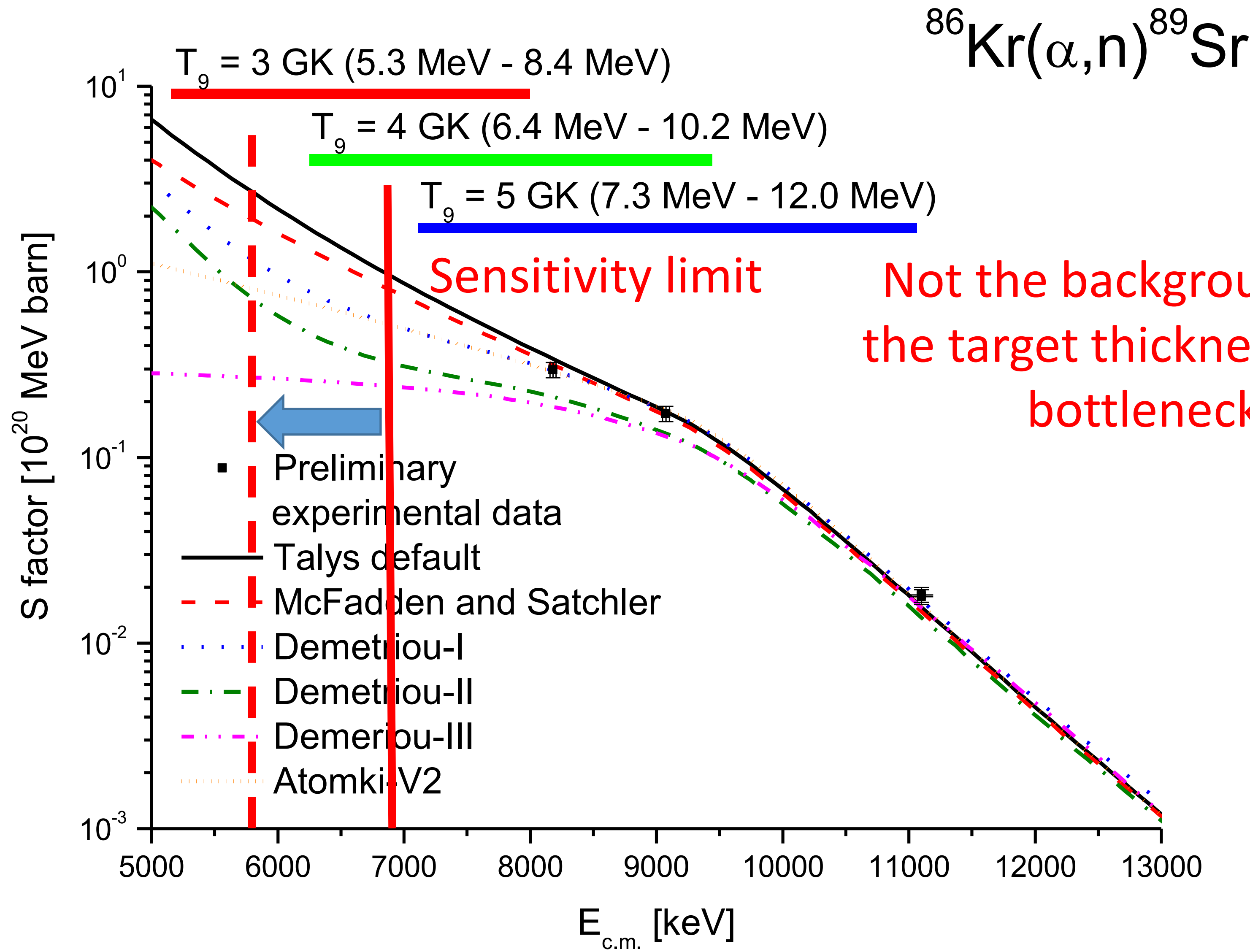


Competition with TRIUMF (CA) & MSU (US)

Half-life of ^{89}Sr

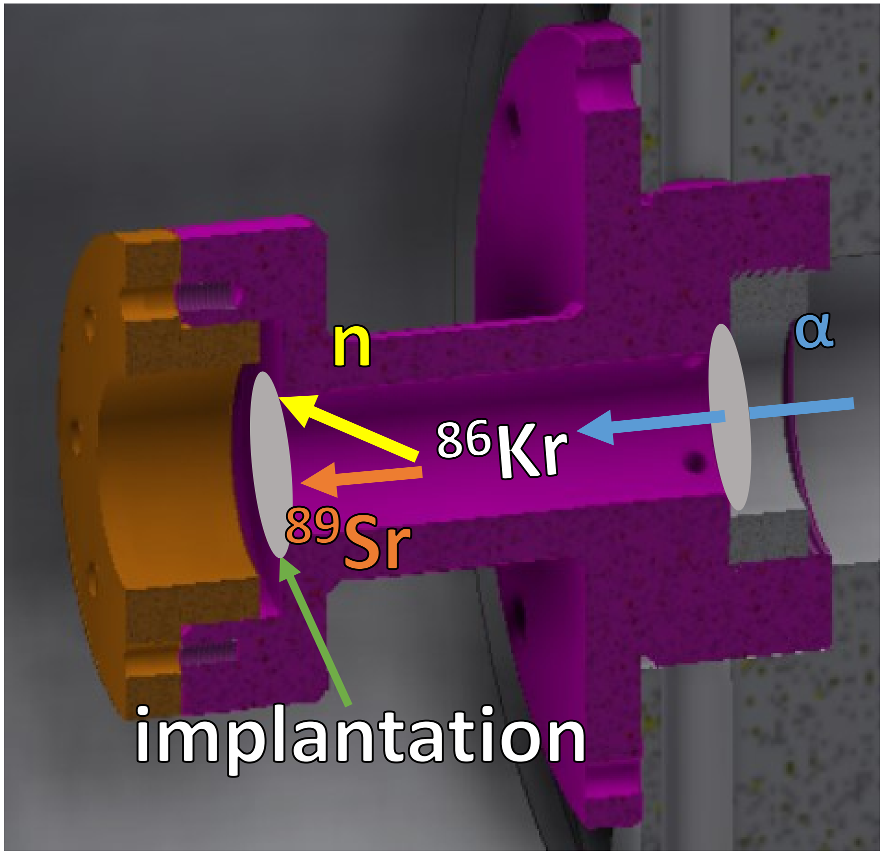


Ongoing work: $^{86}Kr(\alpha,n)^{89}Sr$



Not the background but the target thickness is the bottleneck

Ongoing work: ^{86}Kr(α,n)^{89}Sr



Problem: this experimental approach works only with low pressures

Solution: solid ^{86}Kr targets, produced by implantation. Target thickness: x 20!

Thank you very much for your attention!