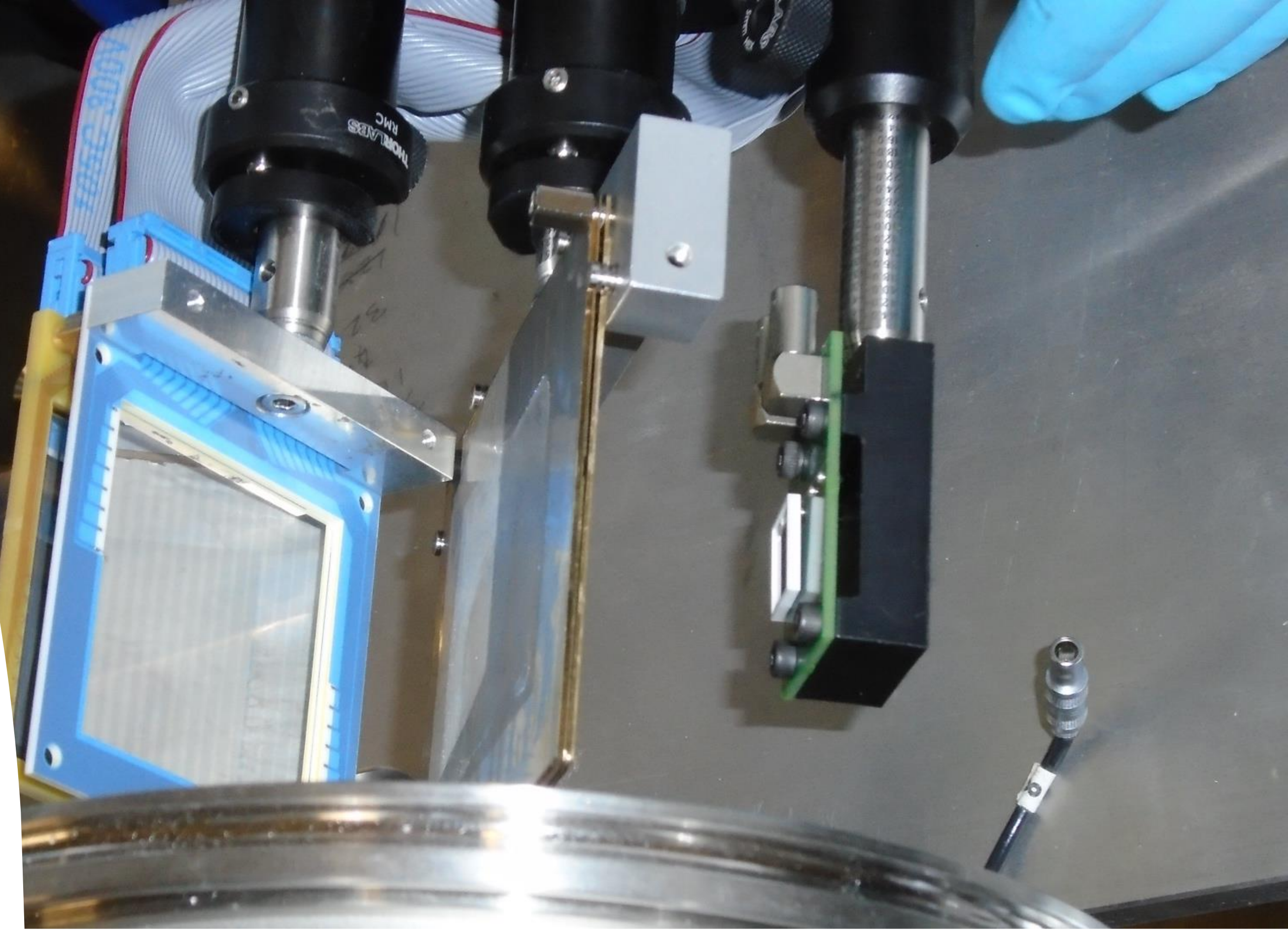
Nuclear Astrophysics at the n_TOF / CERN facility

Claudia Lederer-Woods

University of Edinburgh

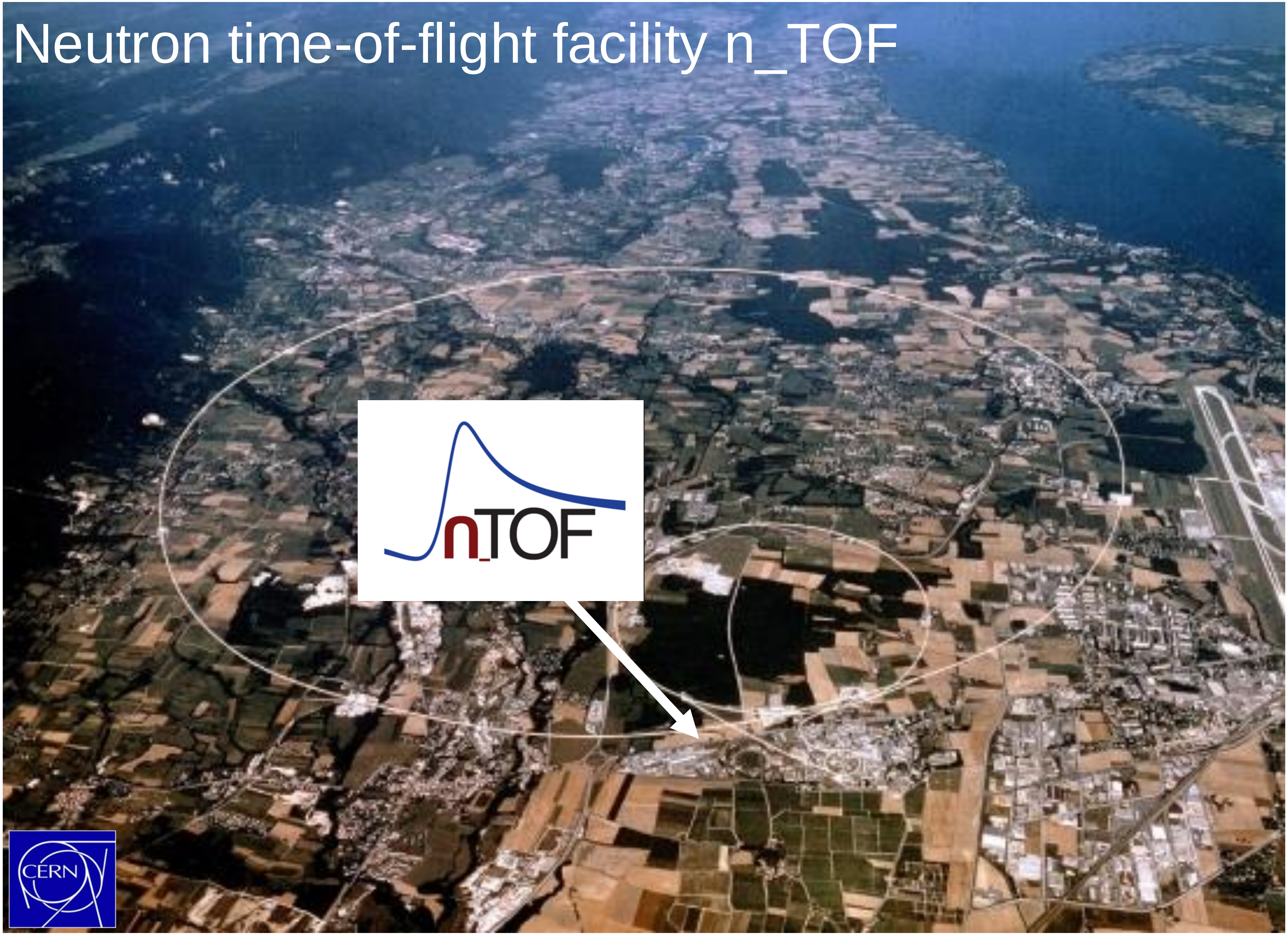
ISOLDE Users Meeting, Nov 2024



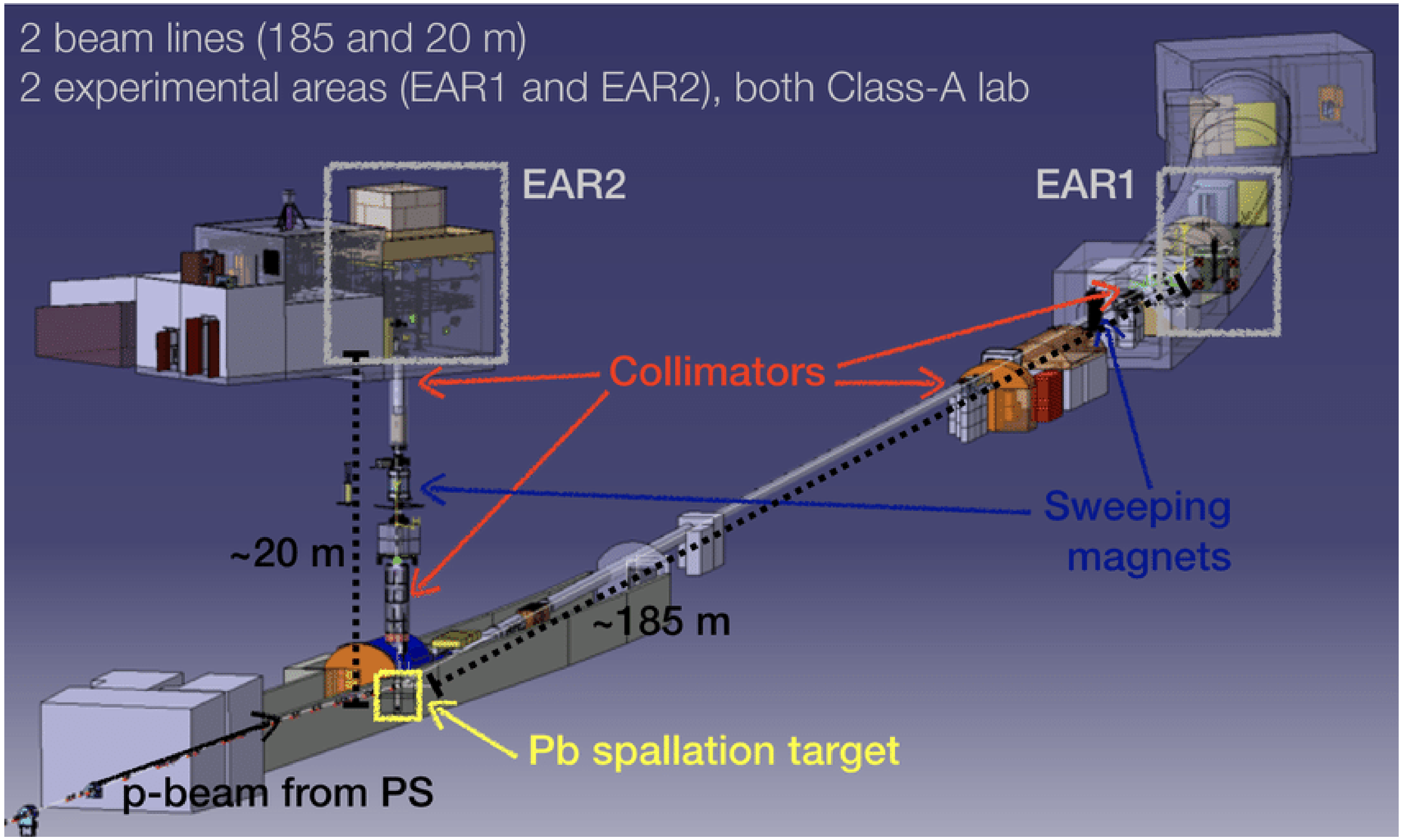
European Research Council
Established by the European Commission

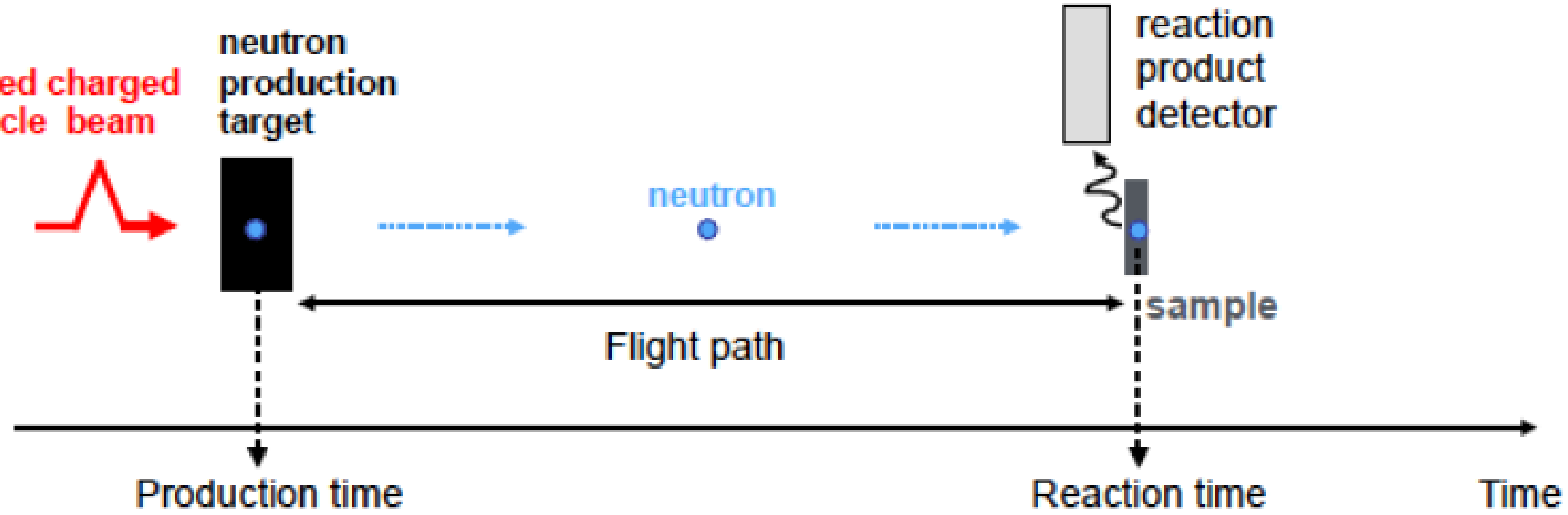
Science & Technology Facilities Council

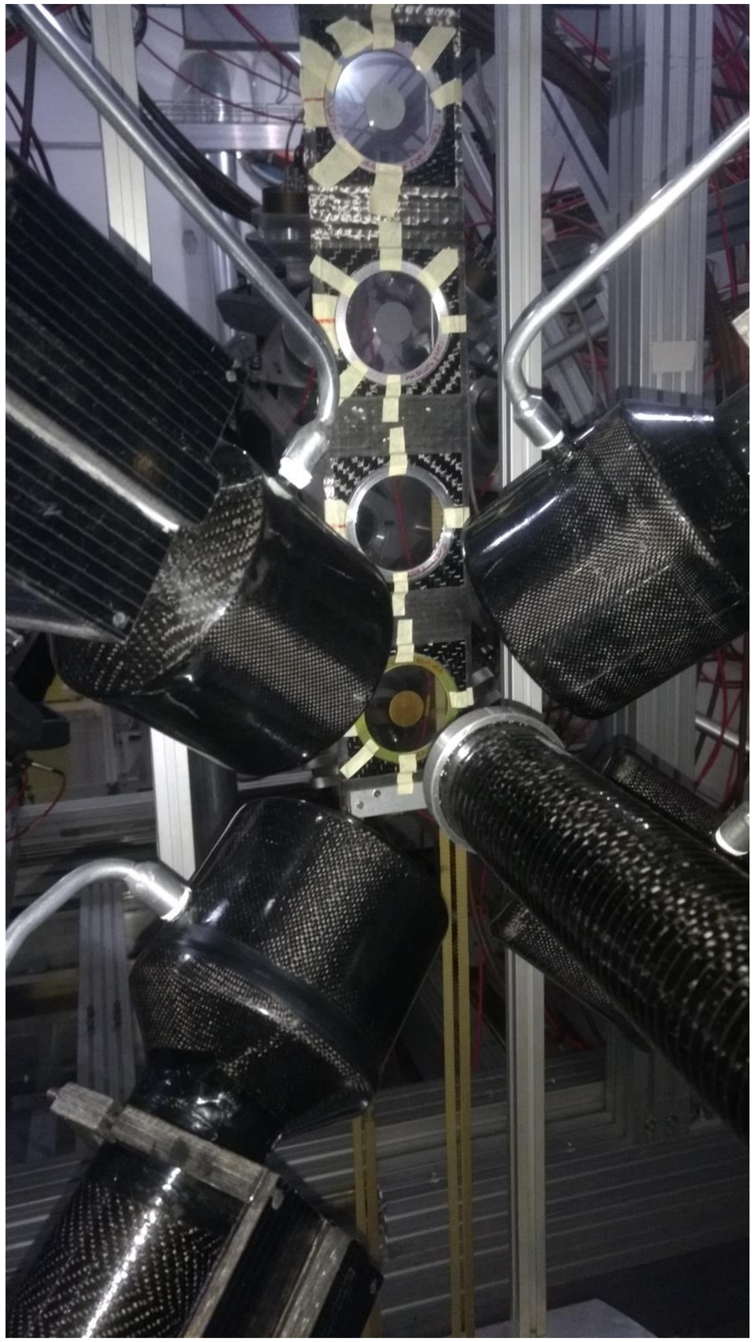
Neutron time-of-flight facility n_TOF



The n_TOF facility at CERN

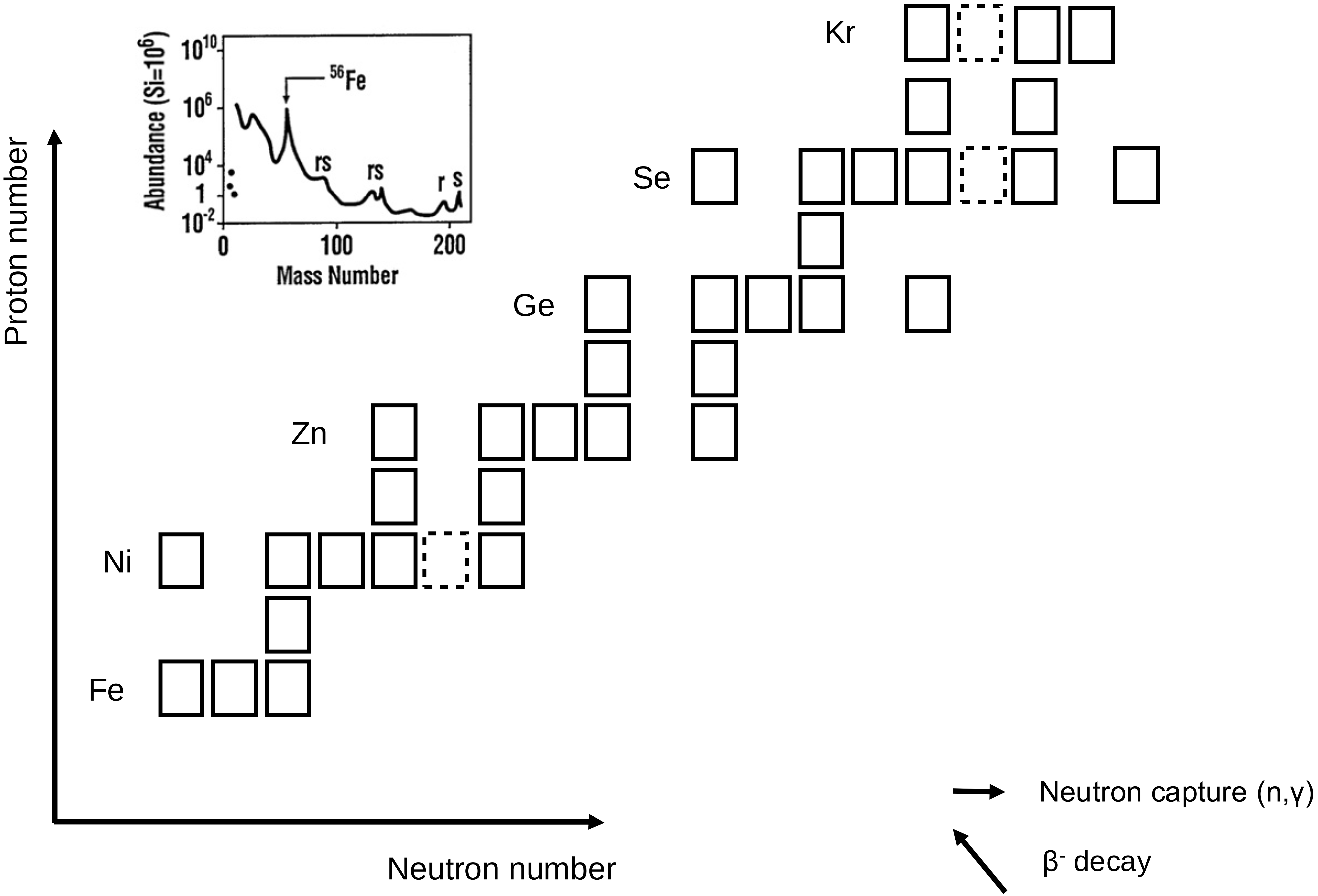




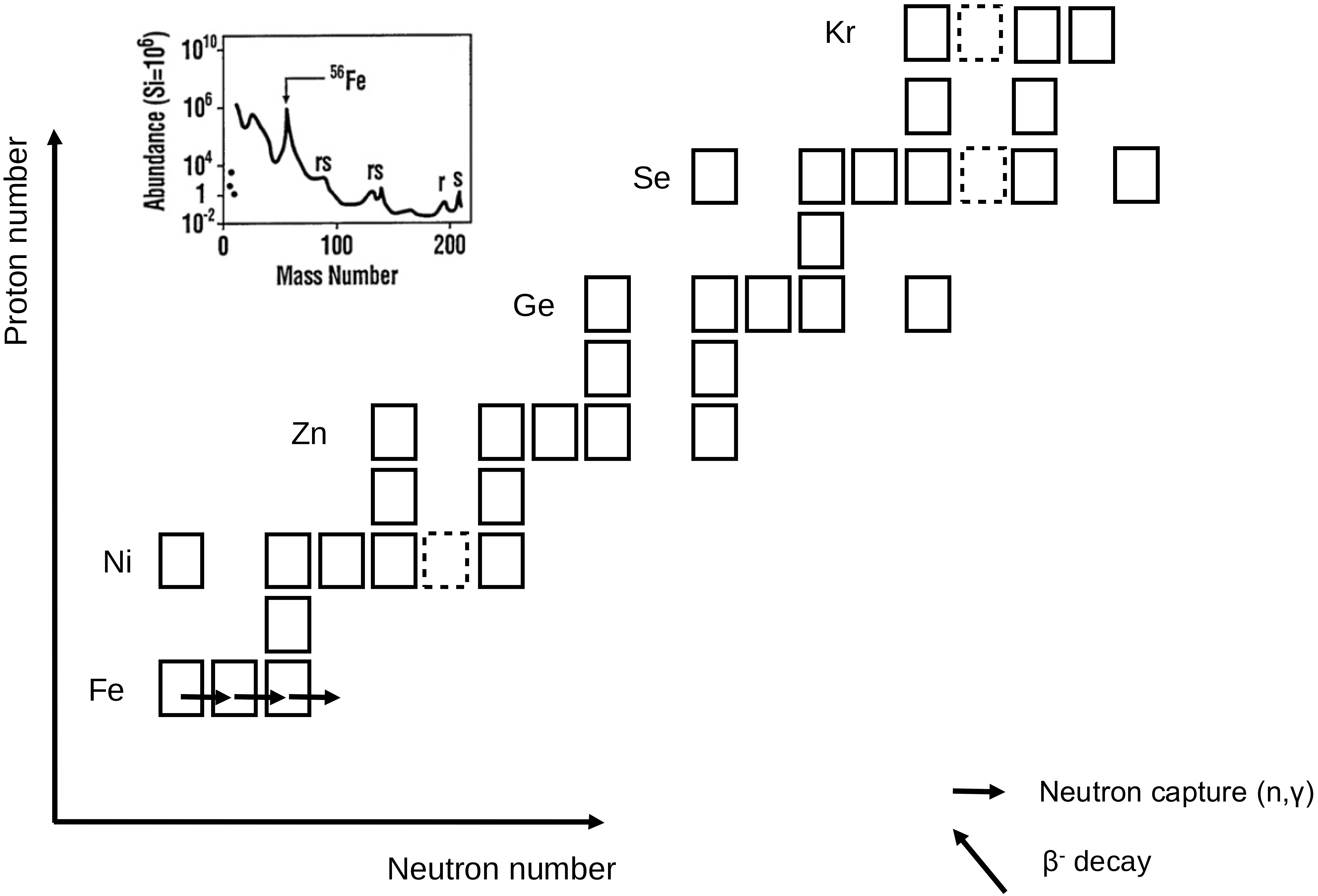


C_6D_6 Capture Setup

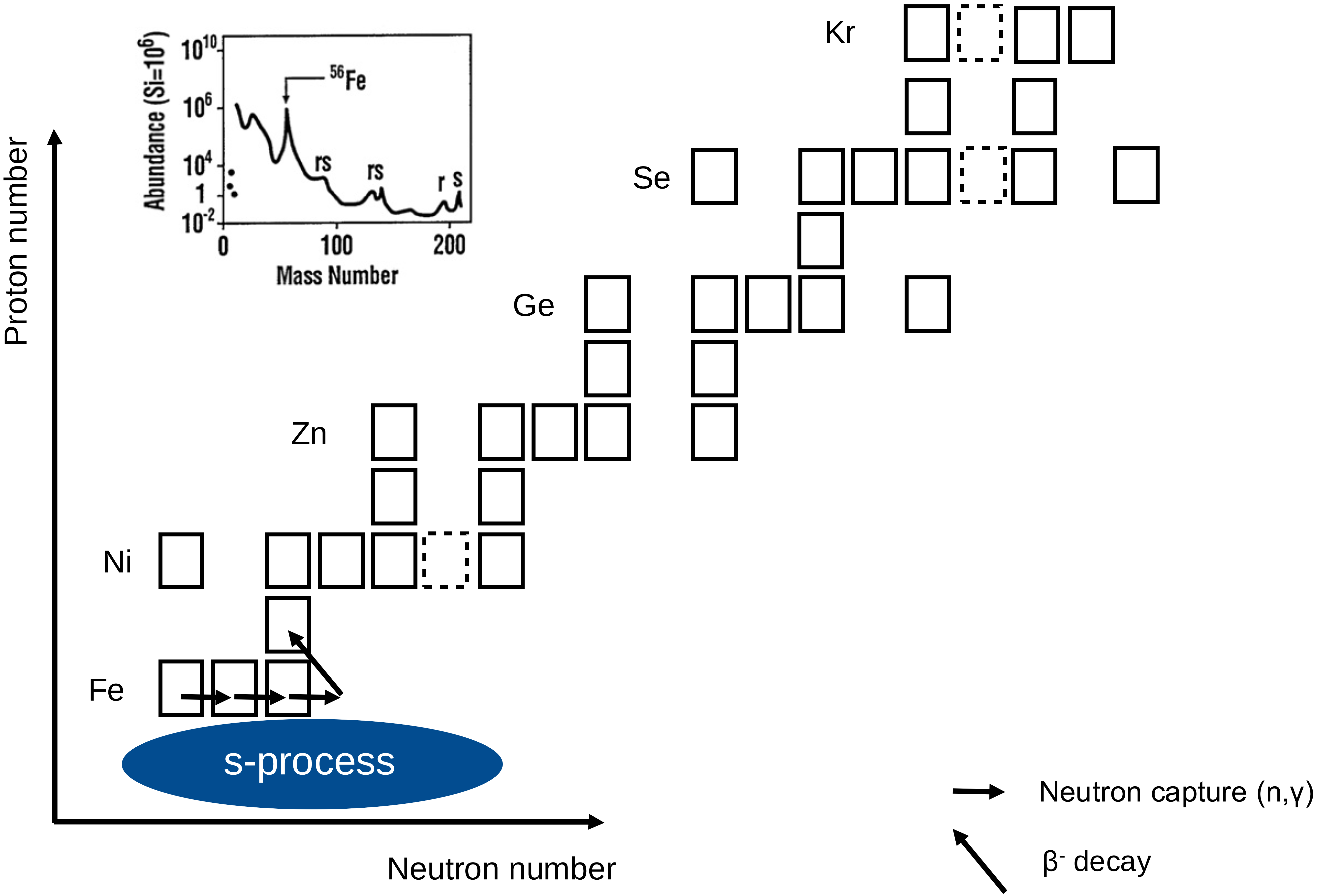
Neutron induced reactions in astrophysics



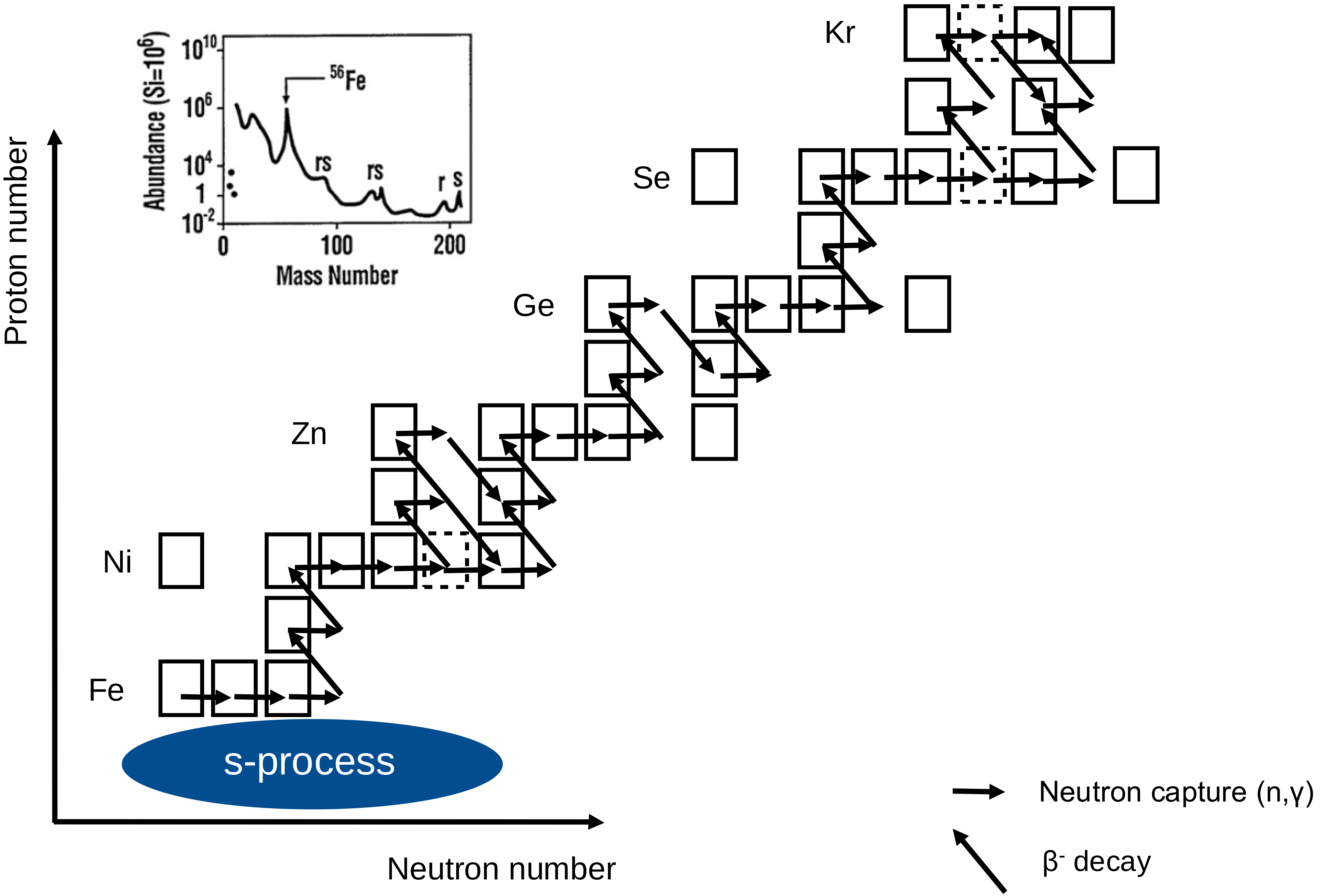
Neutron induced reactions in astrophysics



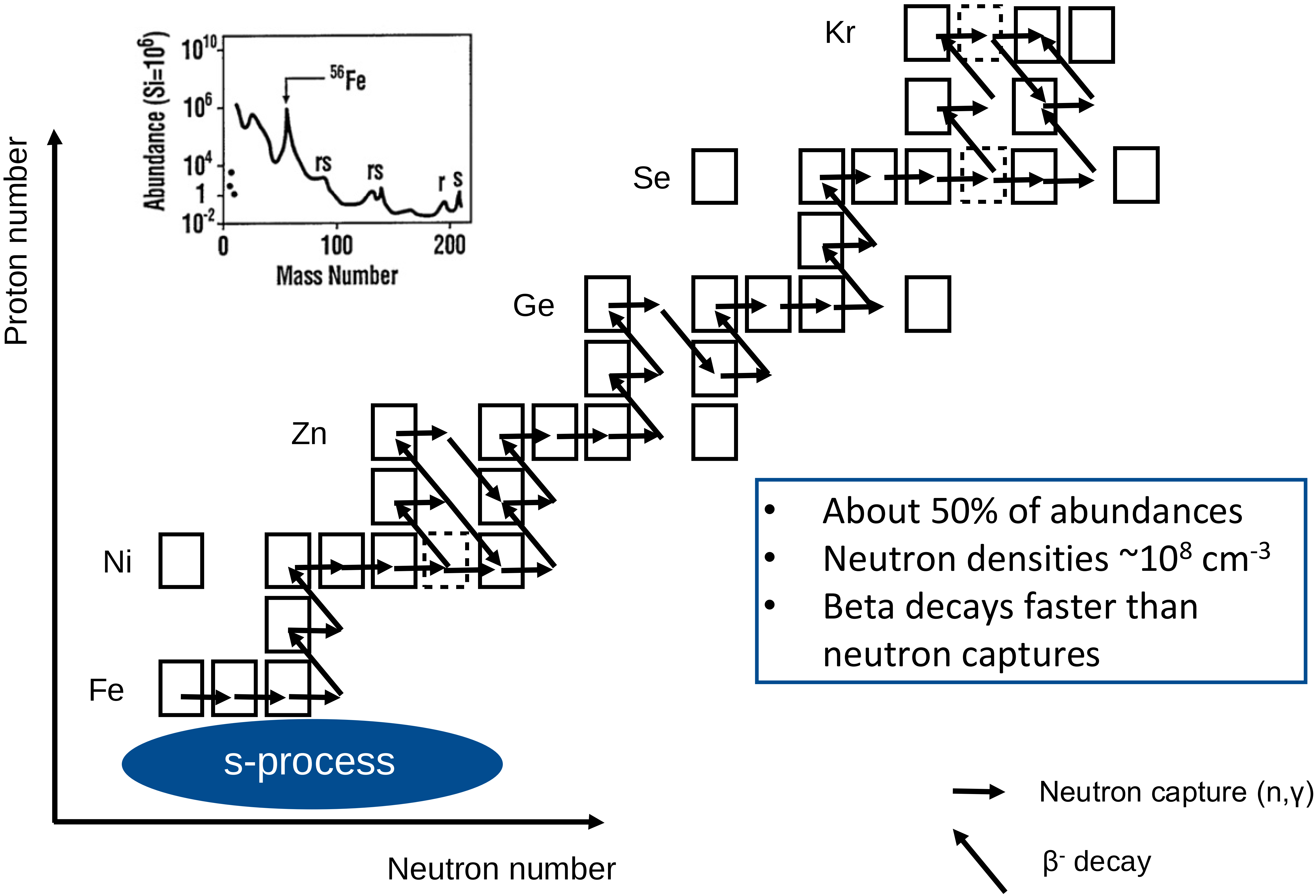
Neutron induced reactions in astrophysics



Neutron induced reactions in astrophysics

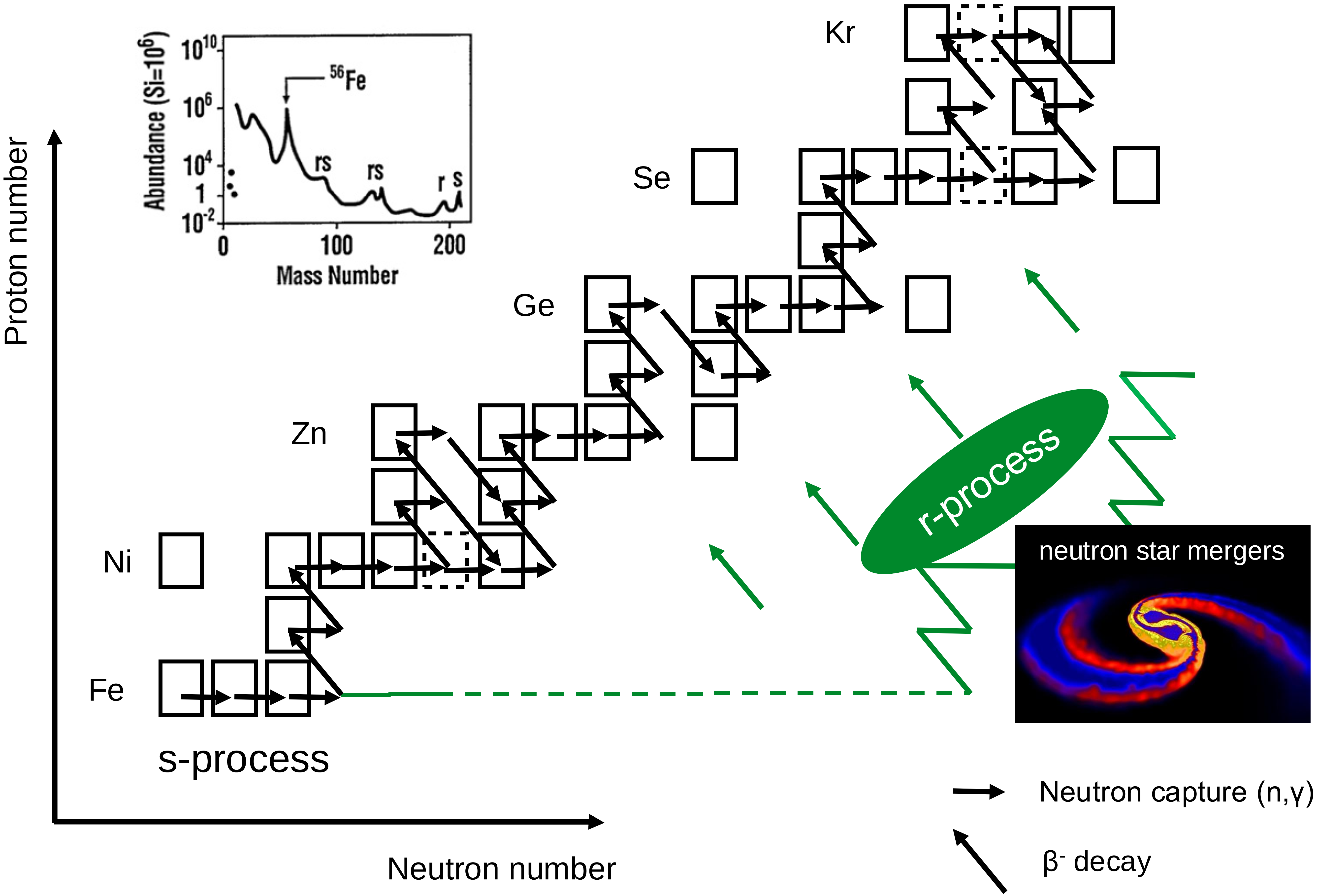


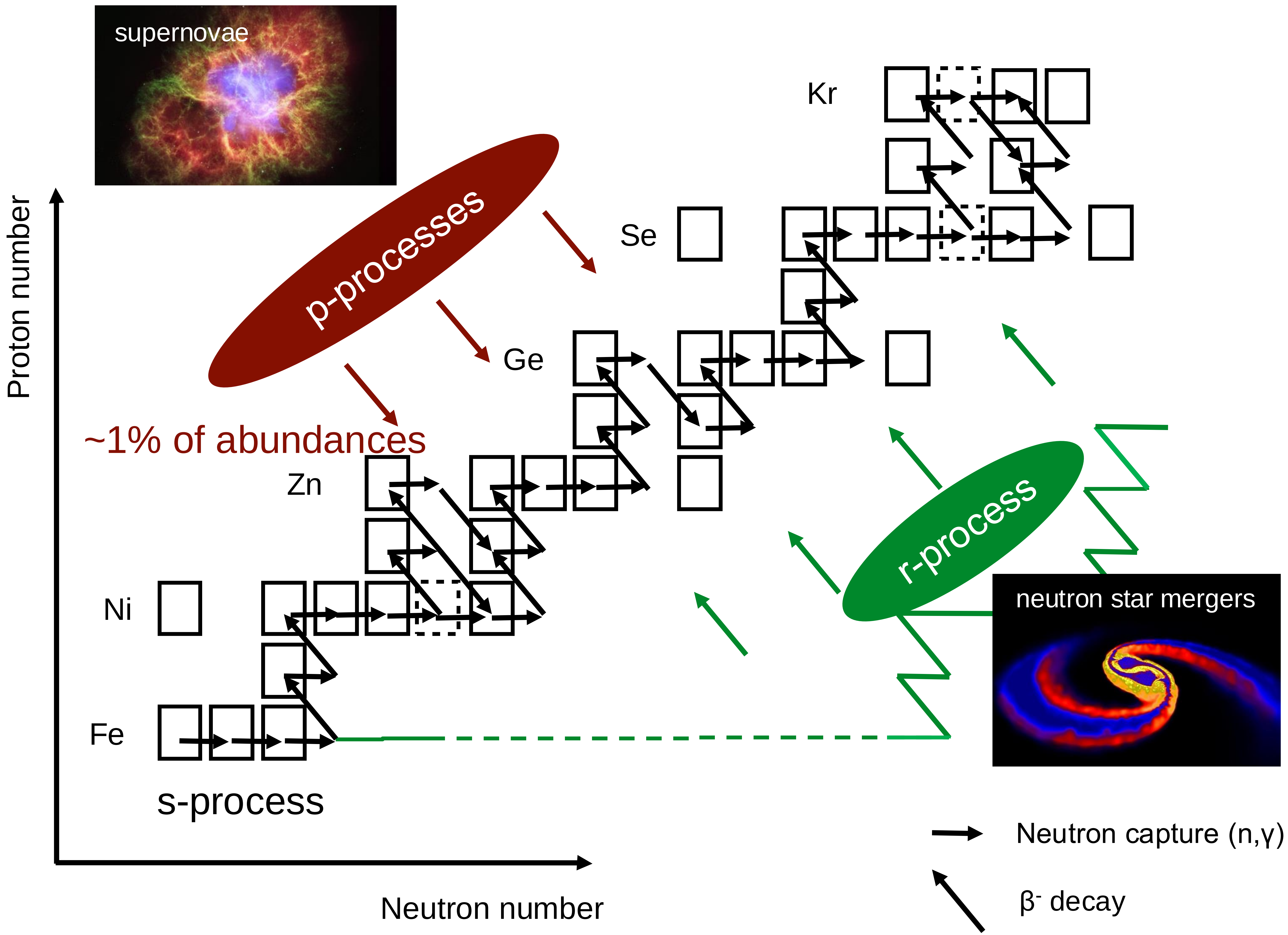
Neutron induced reactions in astrophysics

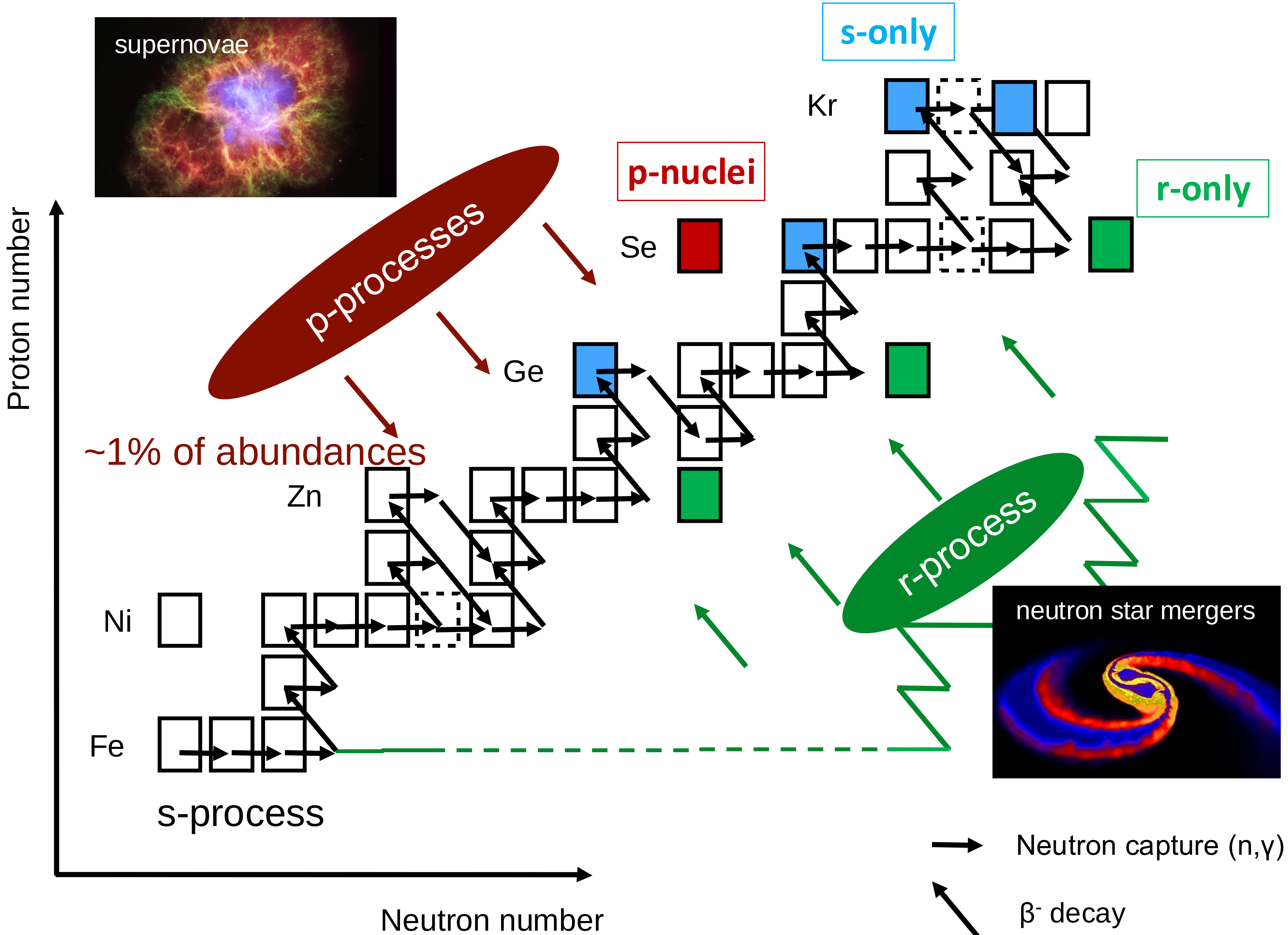


- About 50% of abundances
- Neutron densities ~10^8 cm^{-3}
- Beta decays faster than neutron captures

Neutron induced reactions in astrophysics




supernovae
p-processes
~1% of abundances
Kr
Se
Ge
Zn
Ni
Fe
s-process
r-process
neutron star mergers
Proton number
Neutron number
Neutron capture (n,γ)
β^- decay

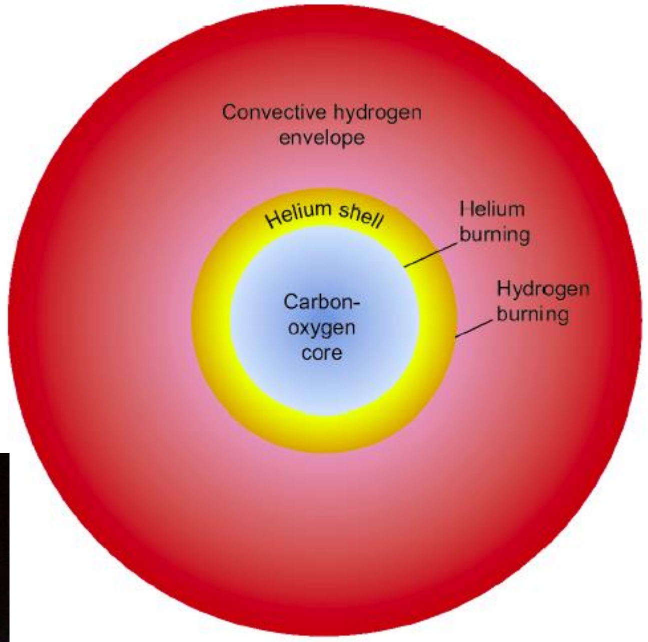


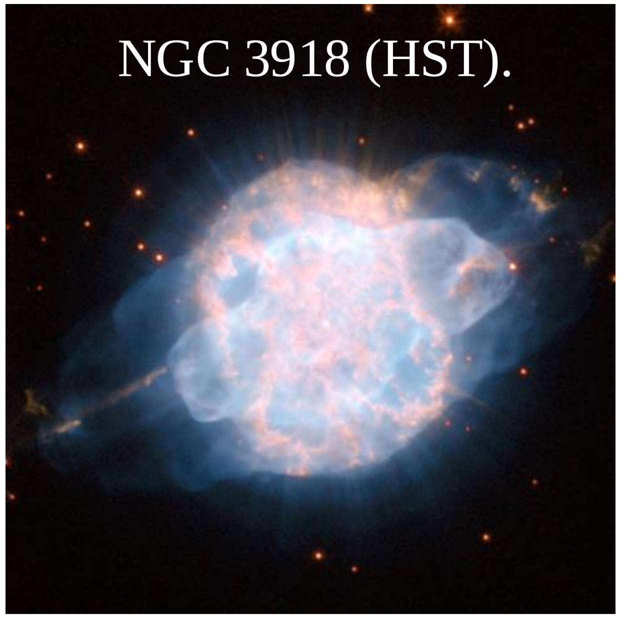
supernovae
s-only
Kr
p-nuclei
r-only
p-processes
Se
Ge
~1% of abundances
Zn
Ni
Fe
r-process
neutron star mergers
s-process
Proton number
Neutron number
Neutron capture (n,γ)
β- decay

Slow Neutron Capture Process Sites

Low mass red giants

1-3 solar mass

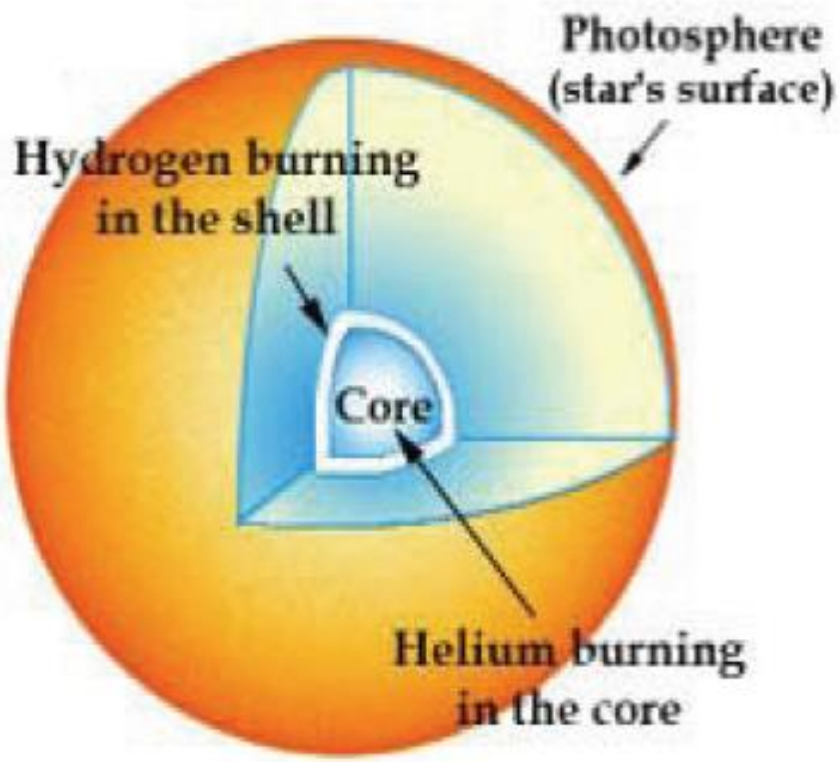




Production of Zr to Pb

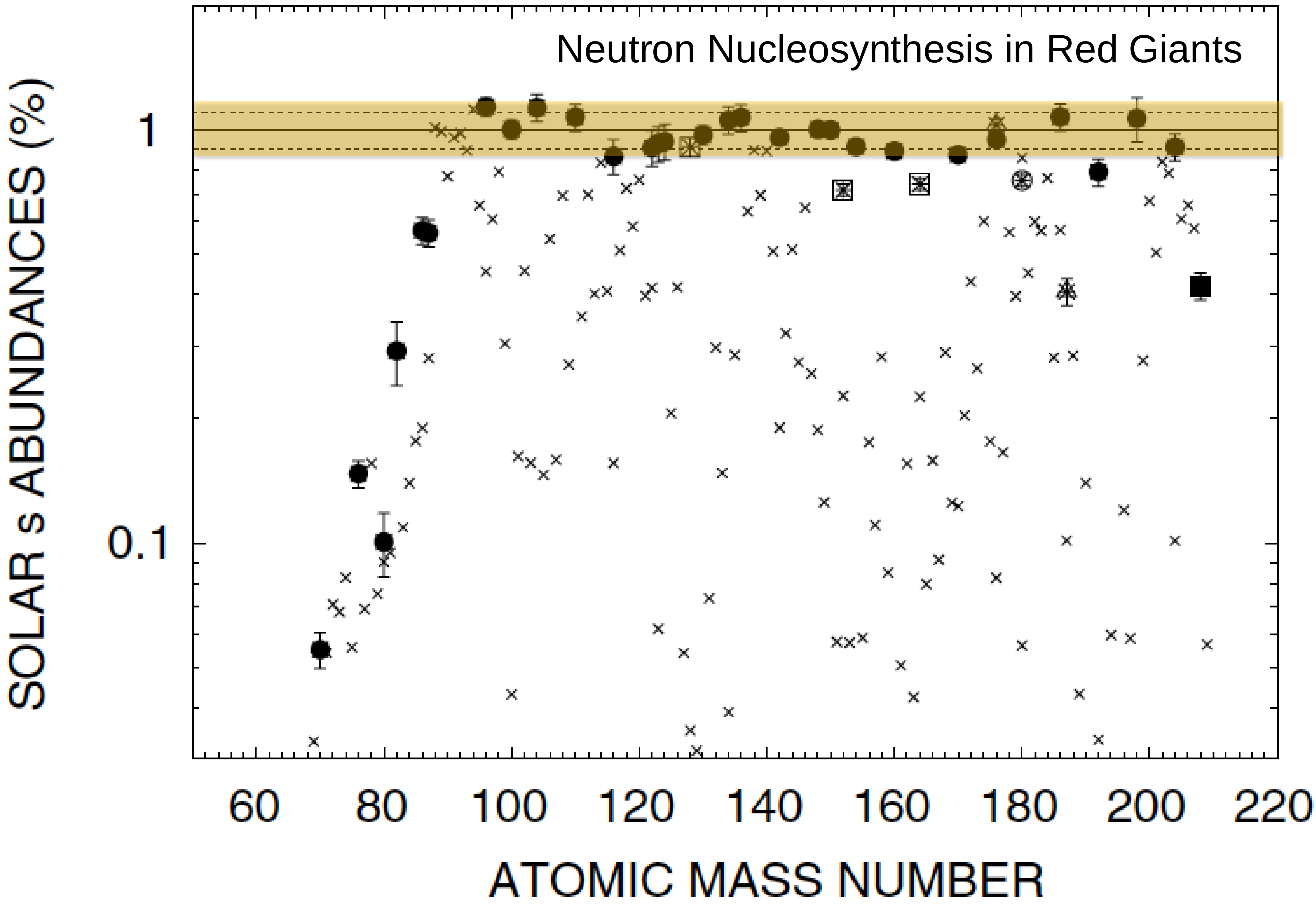
Massive Stars

>8 solar mass



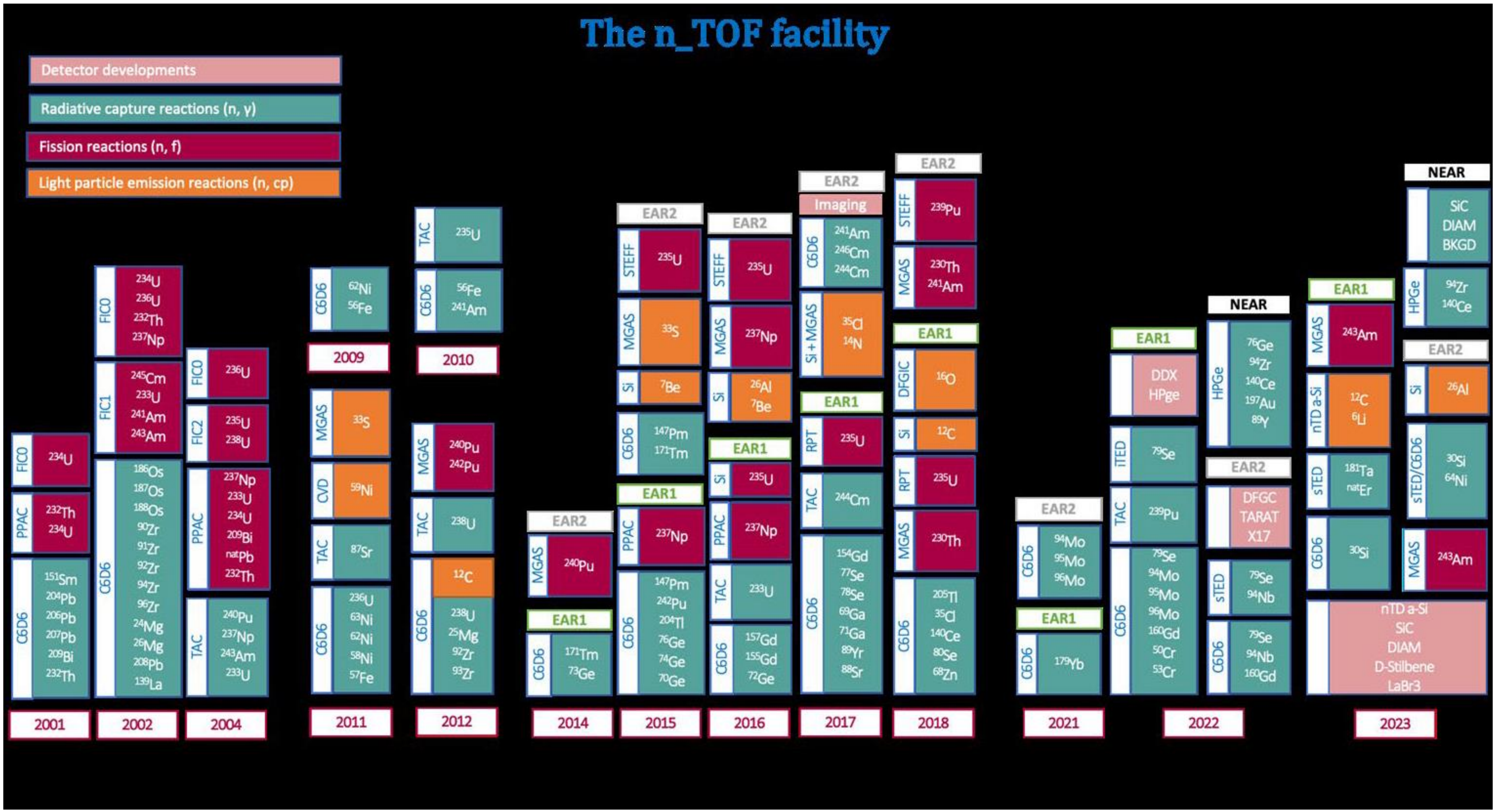
Production up to Zr

Success of modelling the slow process using nuclear data input

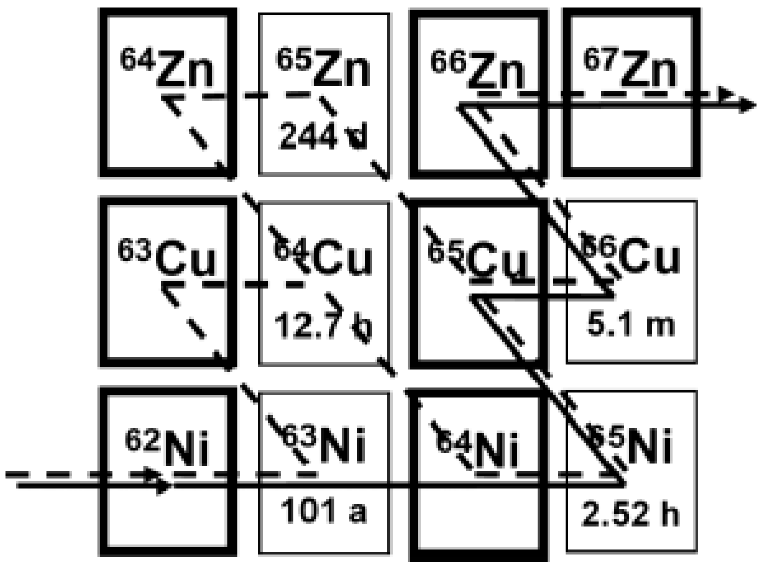


J. Phys. G: Nucl. Part. Phys. 41 (2014) 053101

Measurements at n_TOF: 2001-present



s-process branching ^{63}Ni(n,γ)

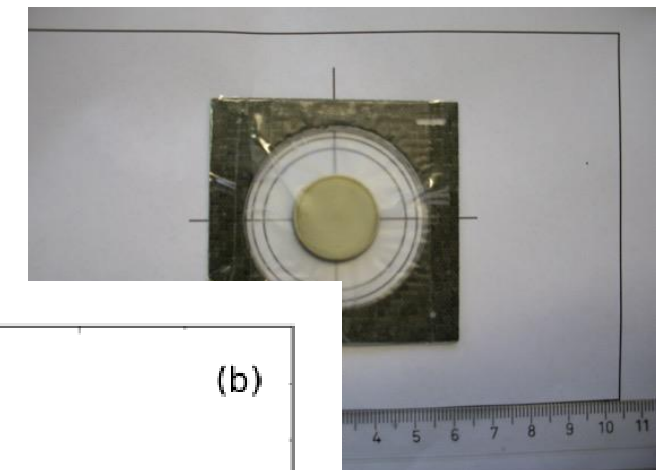


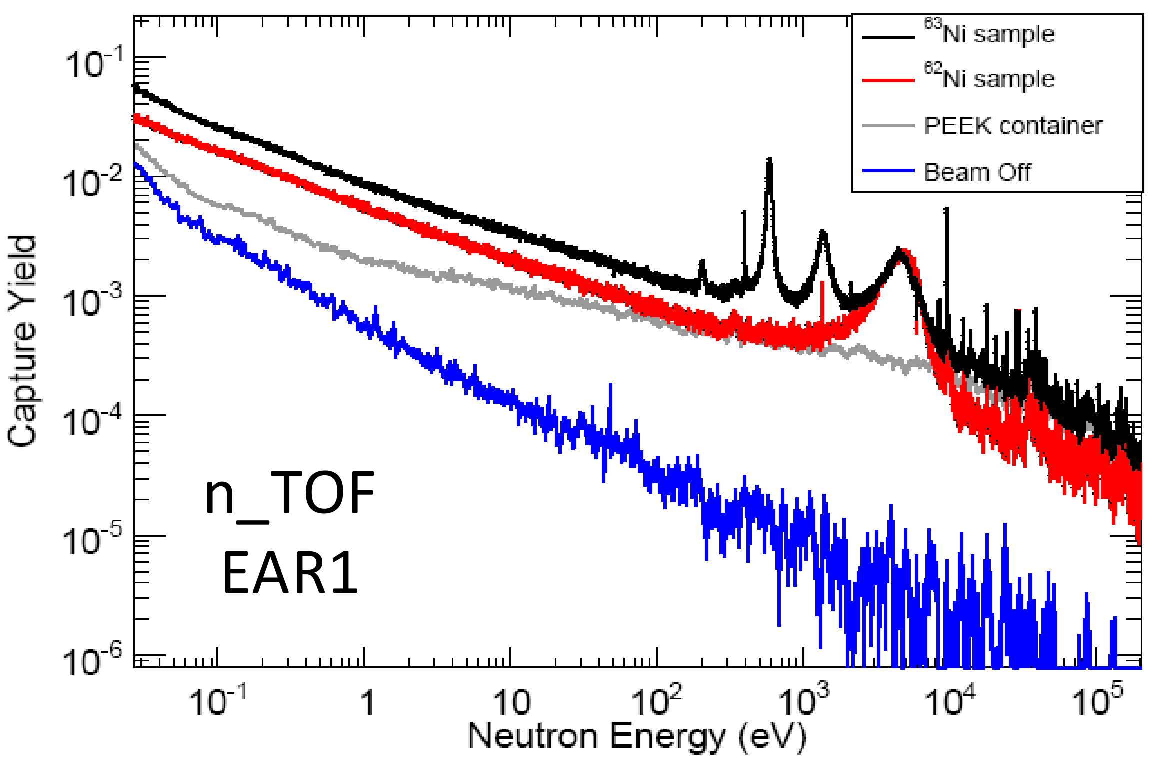
^{63}Ni is **radioactive** ($t_{1/2}$~100 y)

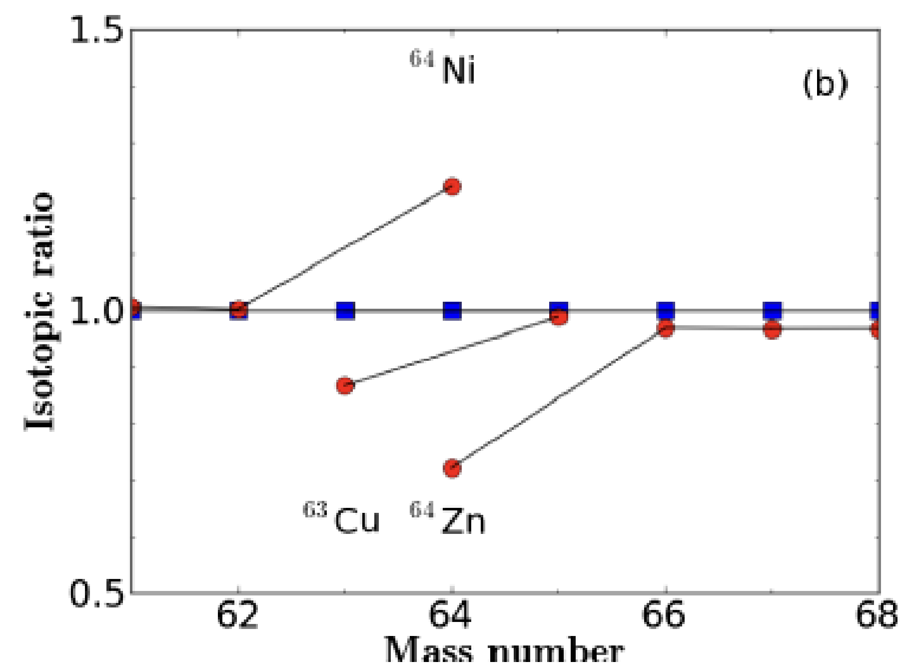
1) irradiation of ^{62}Ni in the ILL thermal reactor (high cross sections and neutron flux)

2) chemical separation of contaminants at PSI (other elements)

→ resulting target: ~100 mg ^{63}Ni, 900 mg ^{62}Ni







→ Constrain the weak s-process inventory in ^{63}Cu, ^{64}Ni and ^{64}Zn before SN explosion

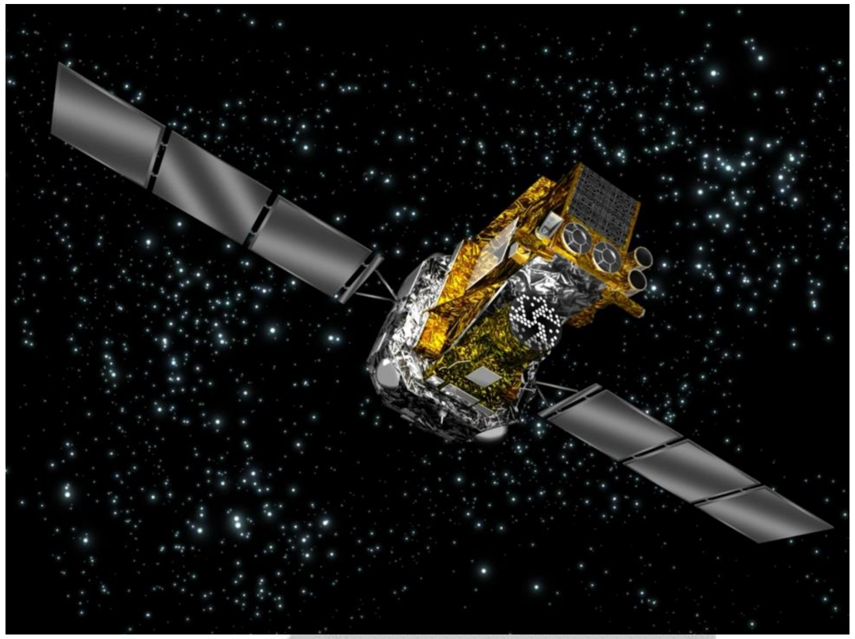
Measurement with DANCE (LANL) agrees (M. Weigand, et al., Phys. Rev. C **92** (2015) 045810.)

Lederer et al. PRL 110, 022501 (2013)

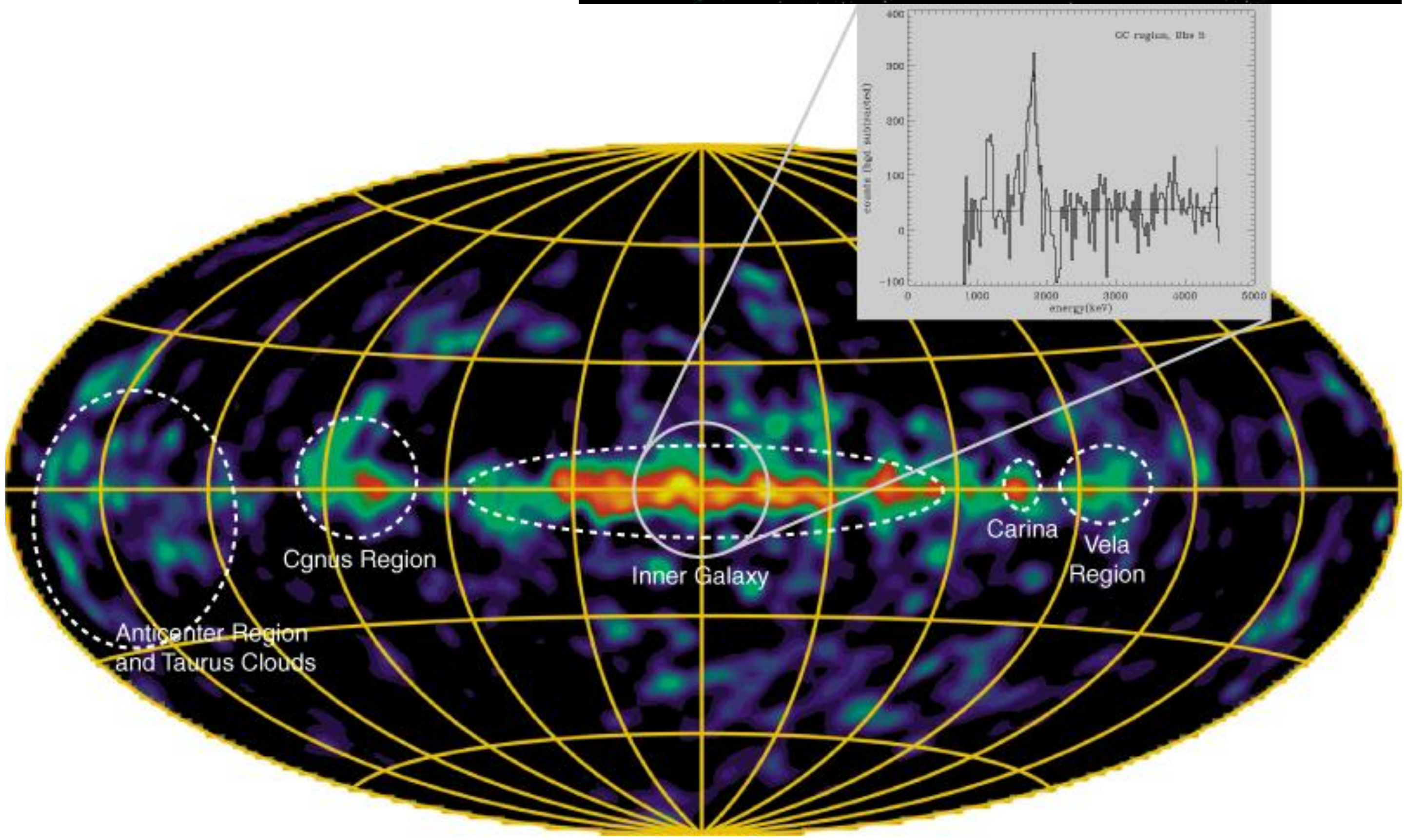
Branching points measured at n_TOF

Branching	Terrestrial $T_{1/2}$	Mass	n_TOF Publication
^{63}Ni	101 y	100 mg	Lederer et al., PRL 110 (2013)
^{79}Se	3E5 y	3 mg	under analysis (*J. Lerendegui-Marco, C. Domingo-Pardo, et al)*
^{93}Zr	1E6 y	1 g	Tagliente et al. PRC 87 (2013)
^{94}Nb	2E4 y	1 mg	under analysis, Balibrea-Corret et al., EPJ Web of Conferences 279, 06004 (2023)
^{151}Sm	93 y	200 mg	Abbondanno et al. PRL 93 (2004)
^{171}Tm	1.9 y	5 mg	Guerrero et al. PRL 125(2020)
^{204}Tl	3.87 y	9 mg	Casanovas et al., Phys. Rev. Lett. 133, (2024)

Cosmic γ-ray emitter ^{26}Al



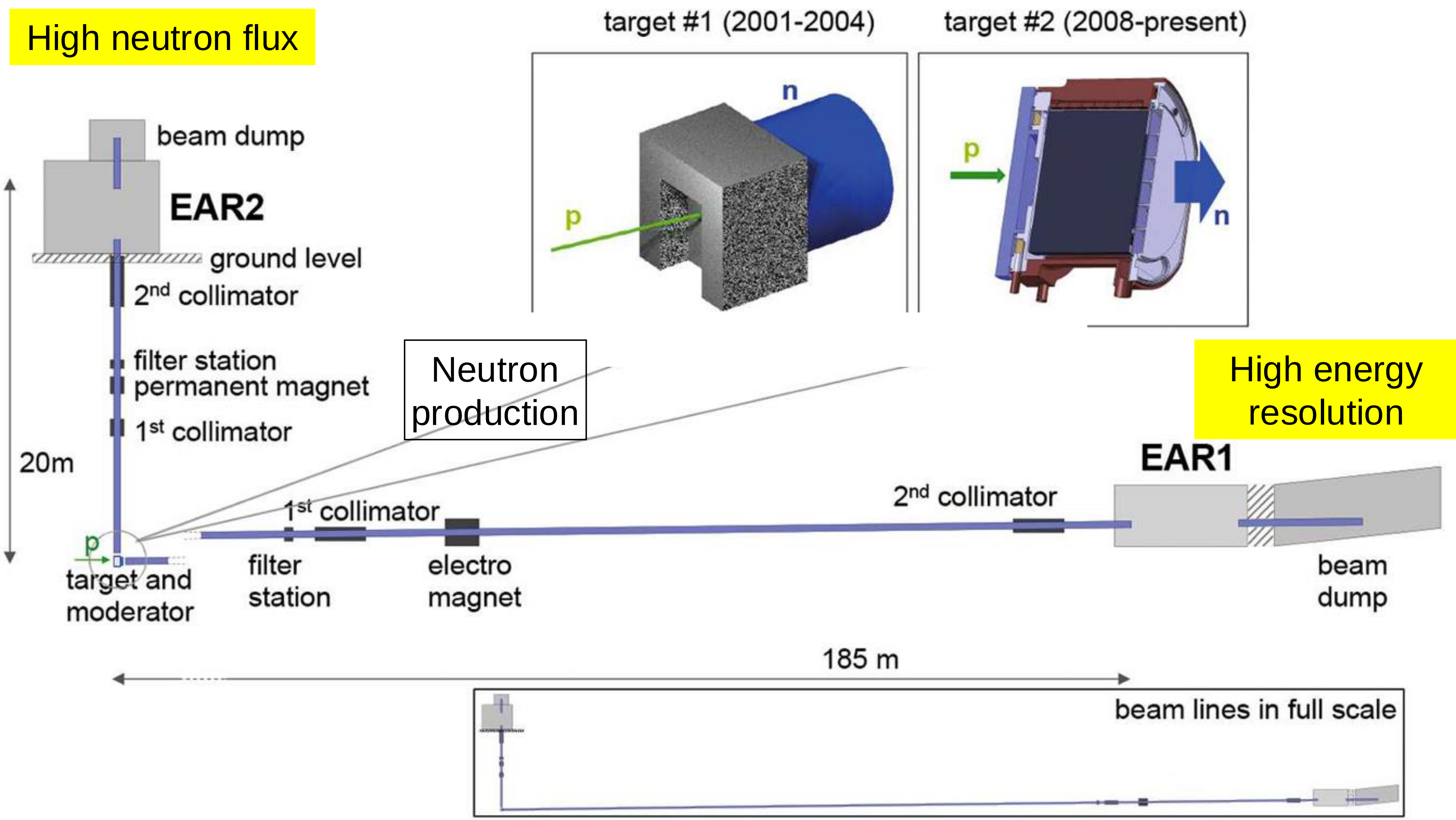
Galactic ^{26}Al ($T_{1/2}$~7×10^5 y) can be detected by satellite telescopes via its characteristic γ-ray emission



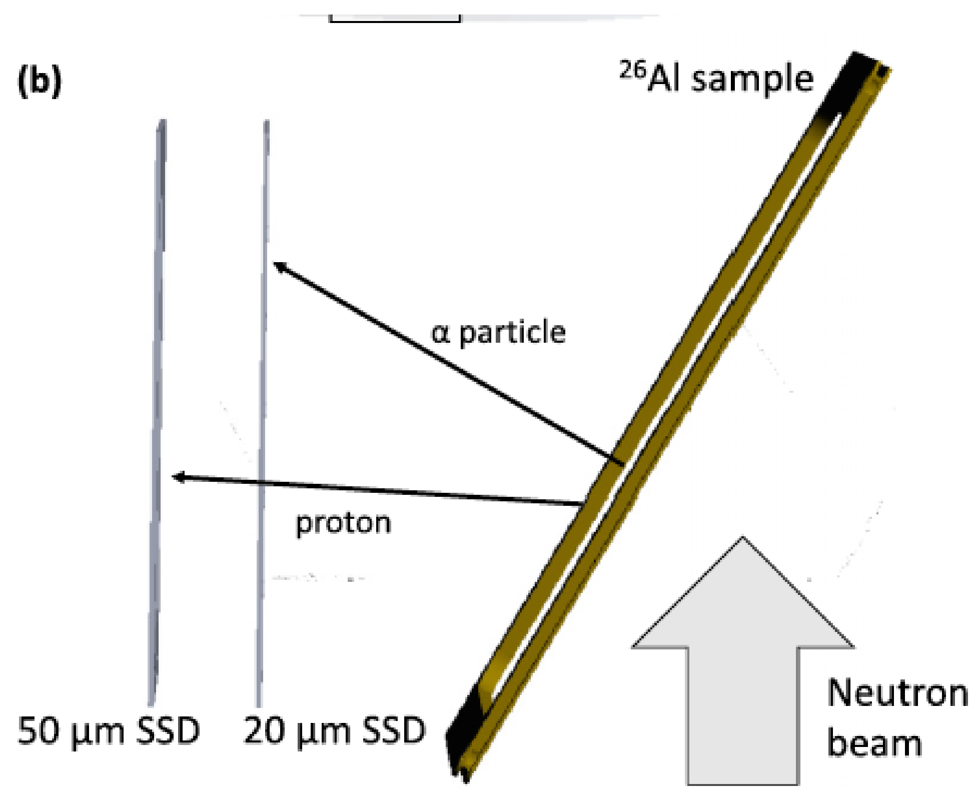
Main Origin of ^{26}Al in massive stars (Diehl et al, Nature 439 (2006))

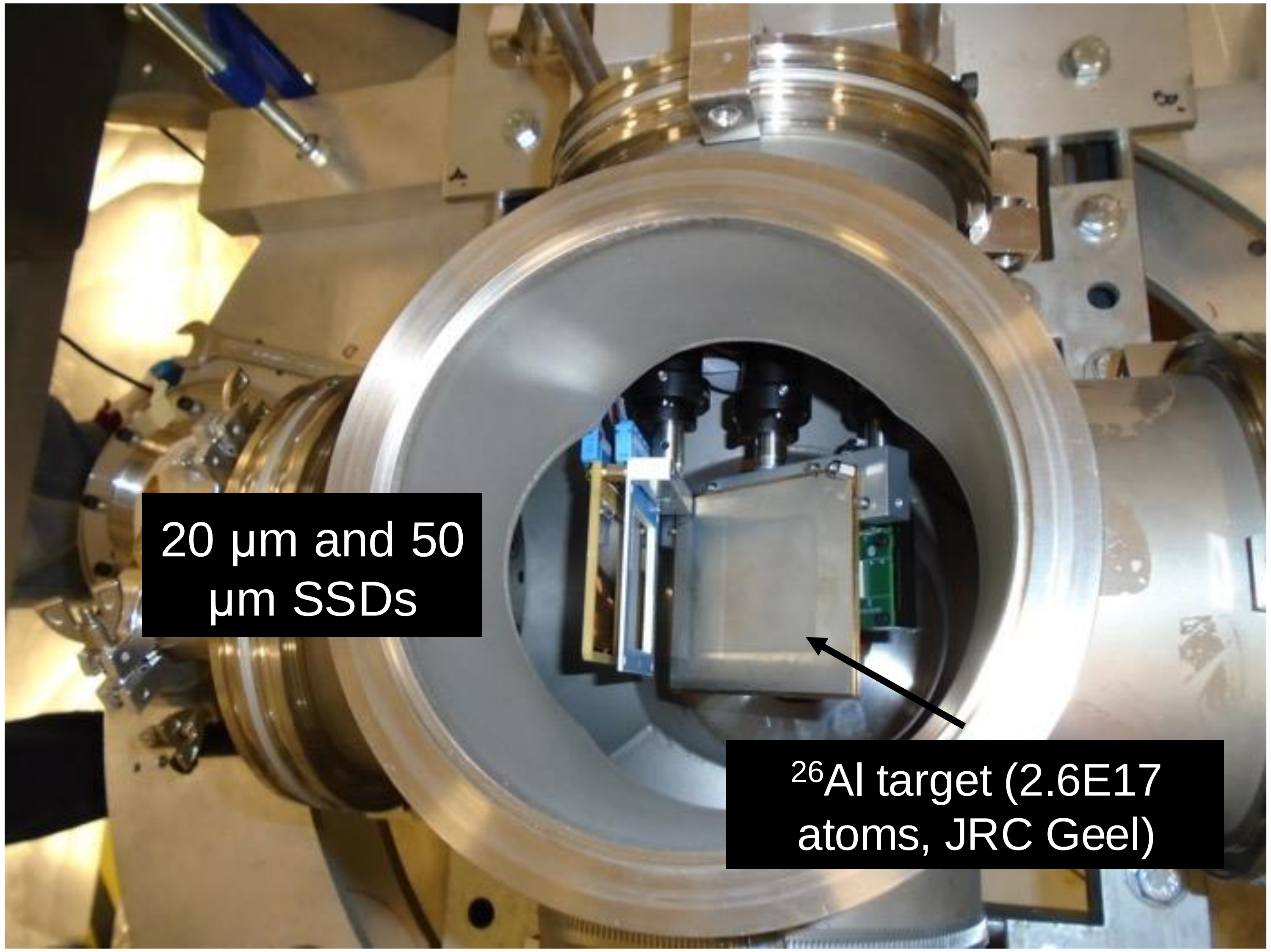
Key nuclear uncertainties for theoretical predictions of abundances: **^{26}Al(n,p)** and **^{26}Al(n,α)** reaction rates [Iliadis et al., Astrophys. J. Supp. 193, 16 (2011)]

n_TOF EAR-2

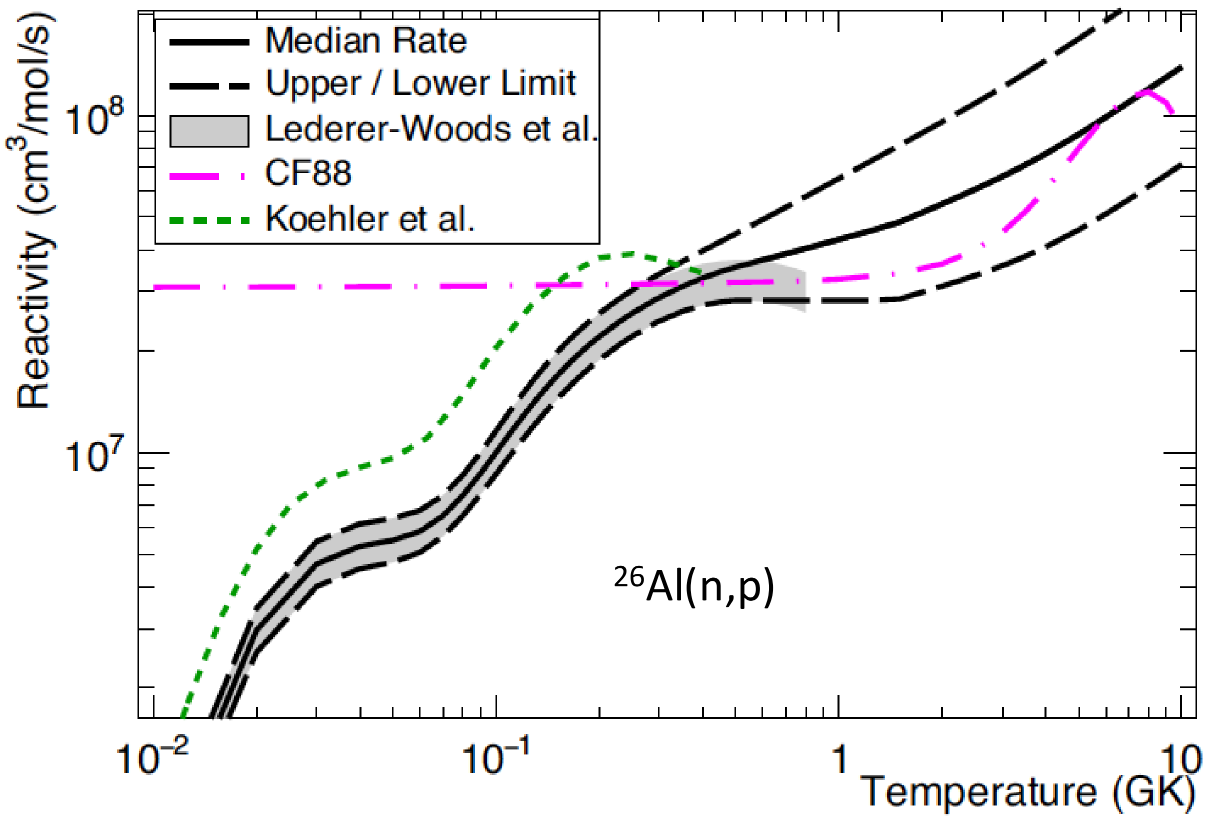

High neutron flux
target #1 (2001-2004)
target #2 (2008-present)
n
p
p
n
beam dump
EAR2
ground level
2nd collimator
filter station
permanent magnet
1st collimator
20m
Neutron production
High energy resolution
EAR1
2nd collimator
1st collimator
p
target and moderator
filter station
electro magnet
beam dump
185 m
beam lines in full scale

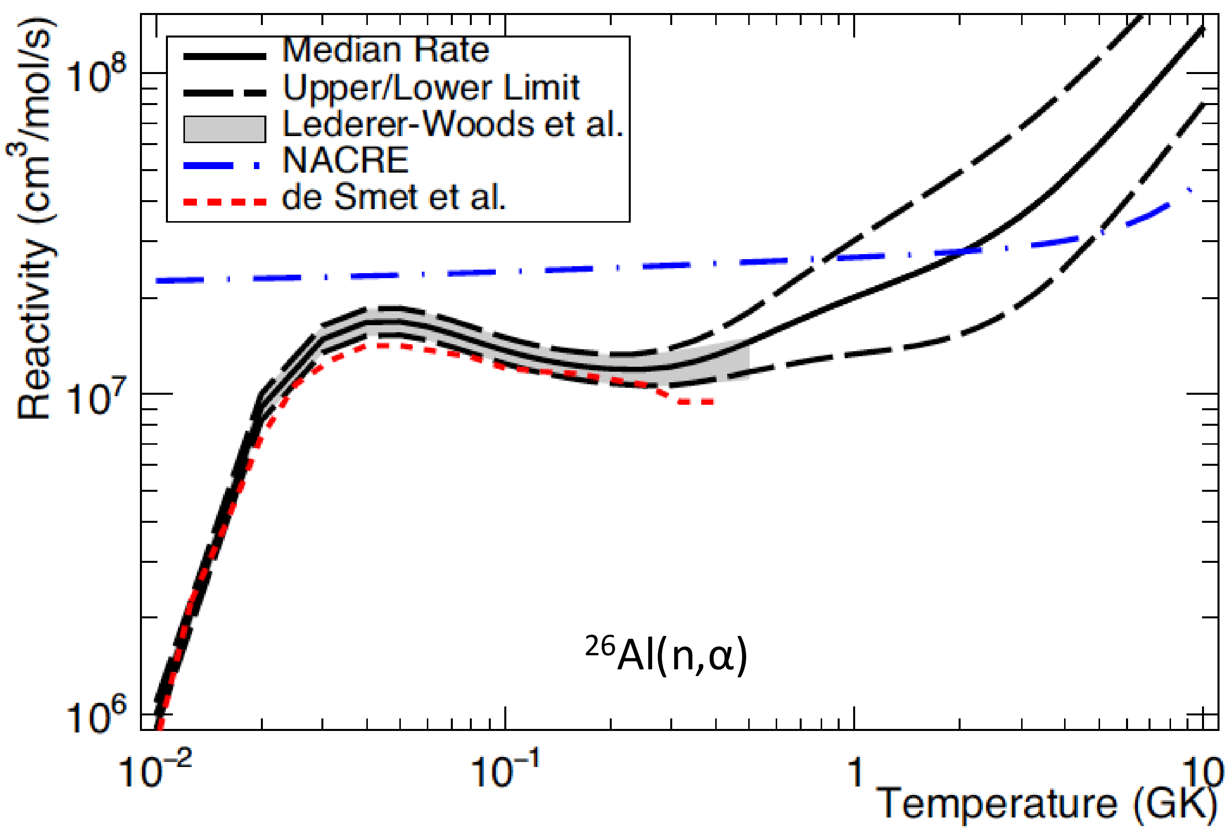
^{26}Al(n,α) and ^{26}Al(n,p) measurement detection setup at EAR-2





C. Lederer-Woods et al., PRC 104, L032803 (2021)
C. Lederer-Woods et al., PRC 104, L022803 (2021)



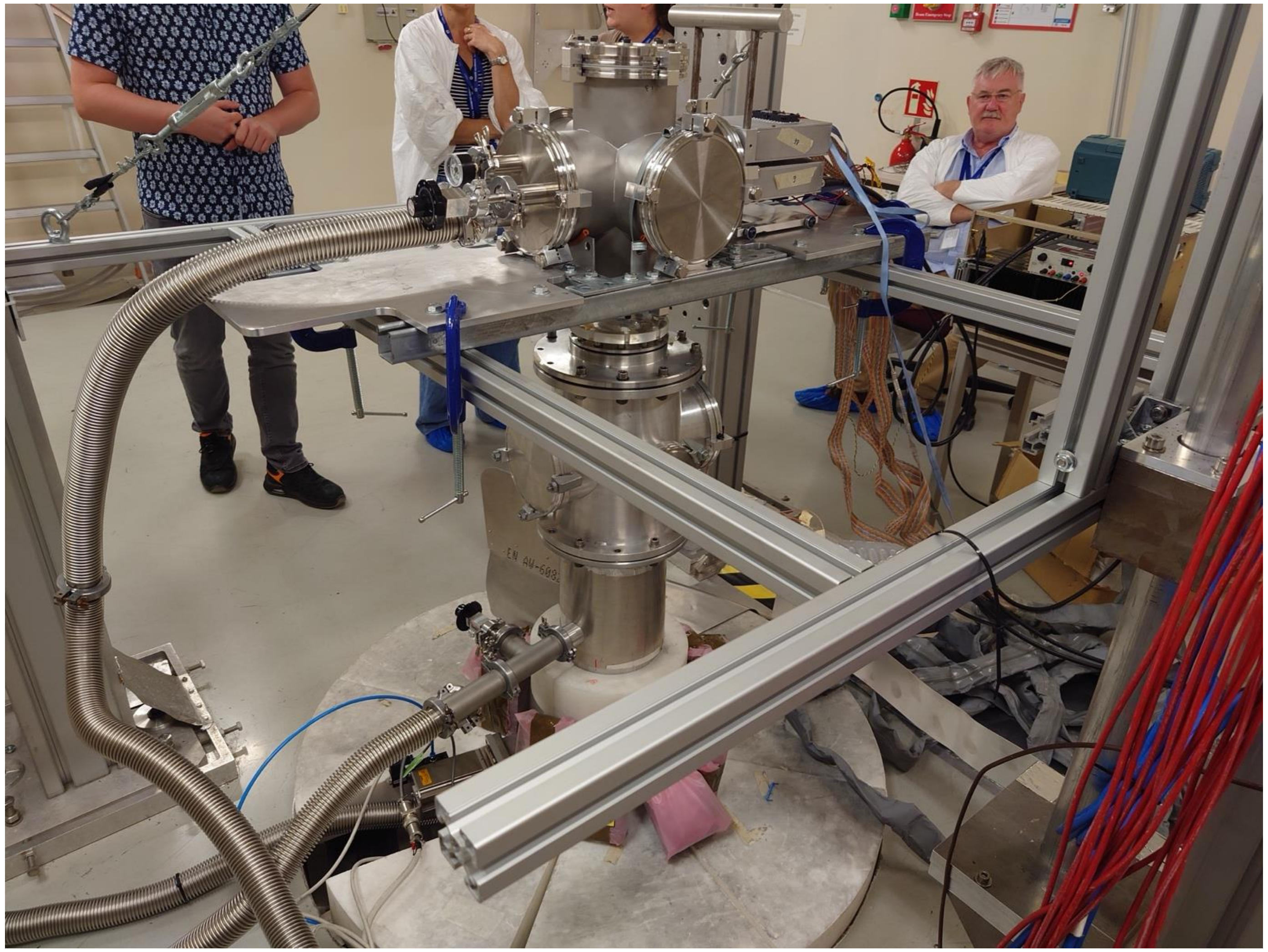


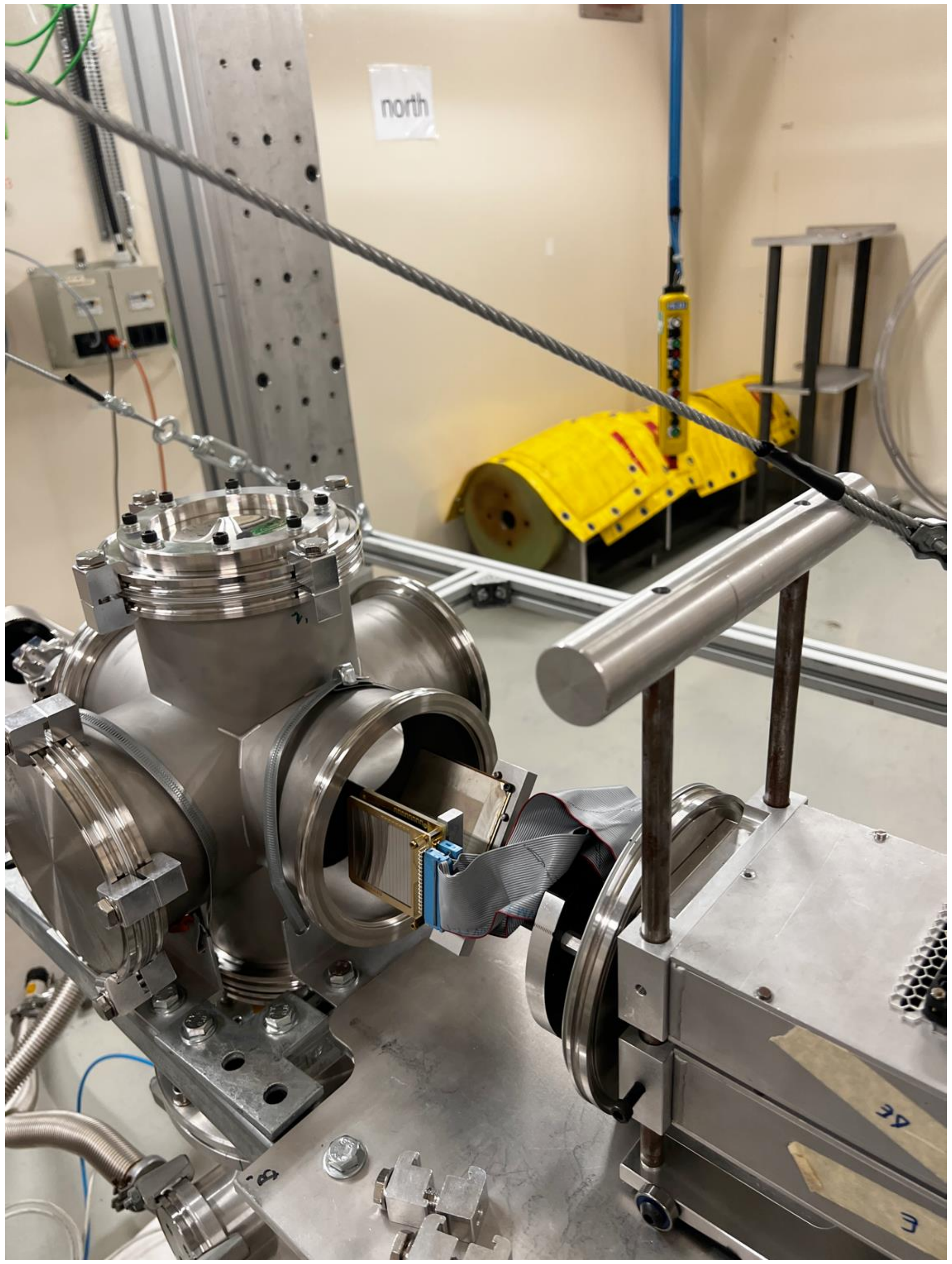
- Cross sections measured up to ~150 keV neutron energy, reaction rates reliable up to ~0.5 GK (PRC 104, L032803 (2021), PRC 104, L022803 (2021))
- Data allow accurate predictions of ^{26}Al destruction in low mass AGB.
- Good agreement with presolar grain abundances using n_TOF data (Battino et al., MNRAS **520,** 2436–2444 (2023))

BUT more accurate data are still needed at high neutron energy, relevant to ^{26}Al abundances in massive stars (T~1GK)

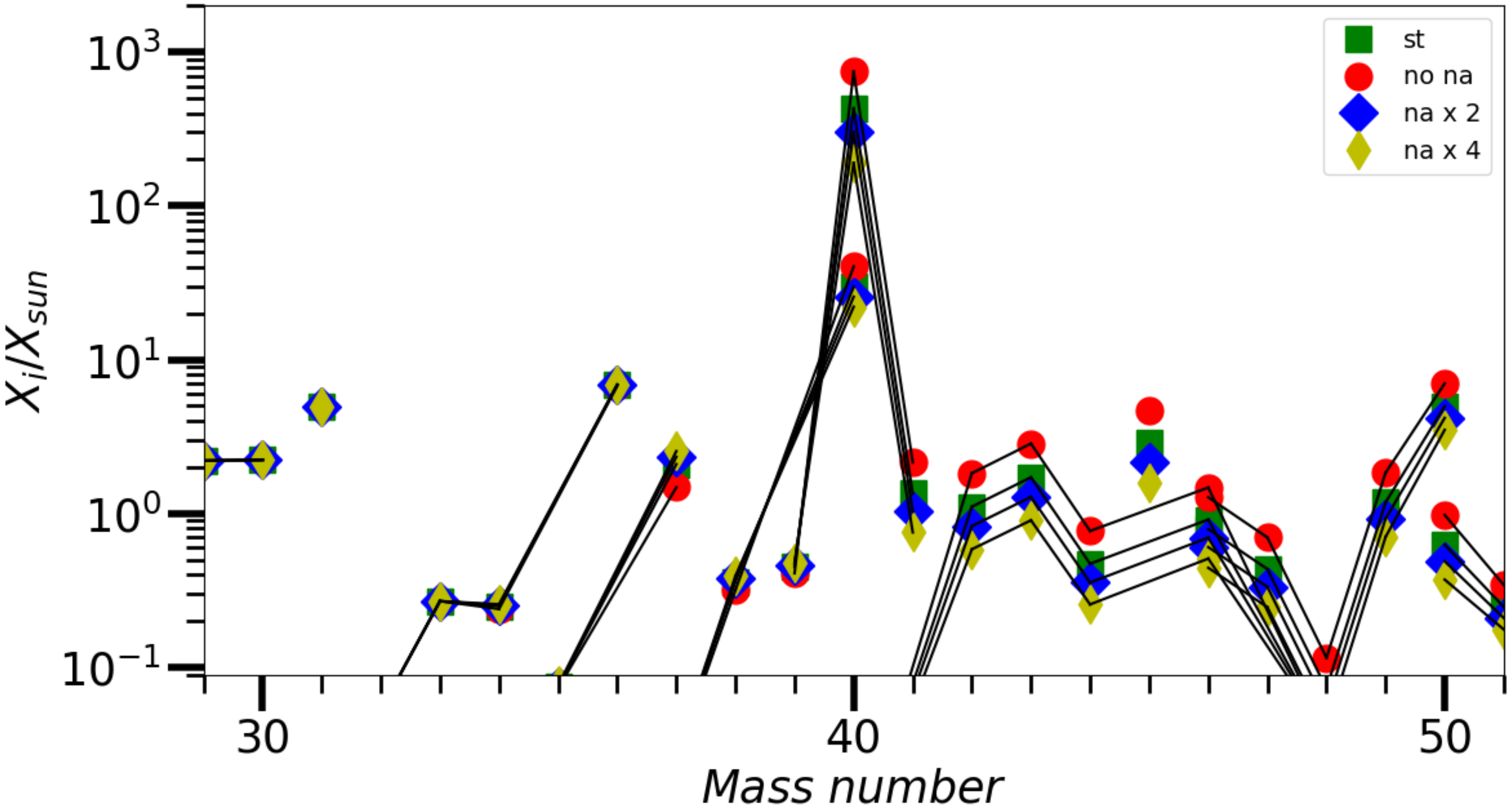
New Run at for high neutron energy 2023

… taking advantage of higher flux which allows use of better collimated neutron beam



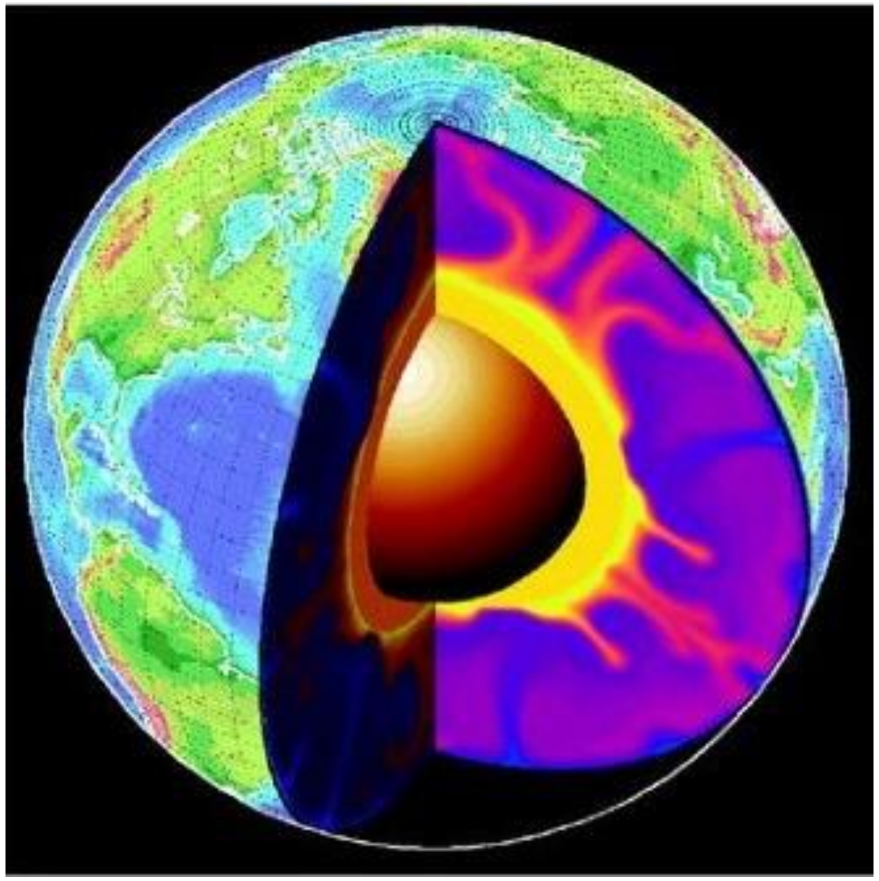


$^{40}K(n,\alpha)$ and $^{40}K(n,p)$



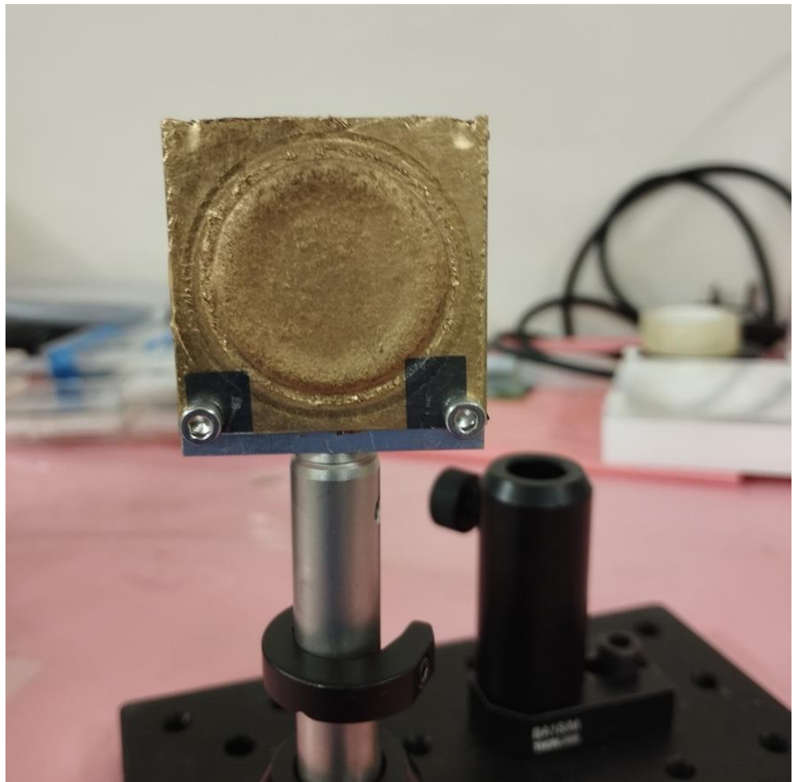
- ^{40}K efficiently produced in massive stars
- destroyed by (n,γ), (n,α) and (n,p) reactions

- ^{40}K abundances impact on radiogenic heating, most important in young exoplants (Frank et al, Icarus (2014))
- Scarce cross section data

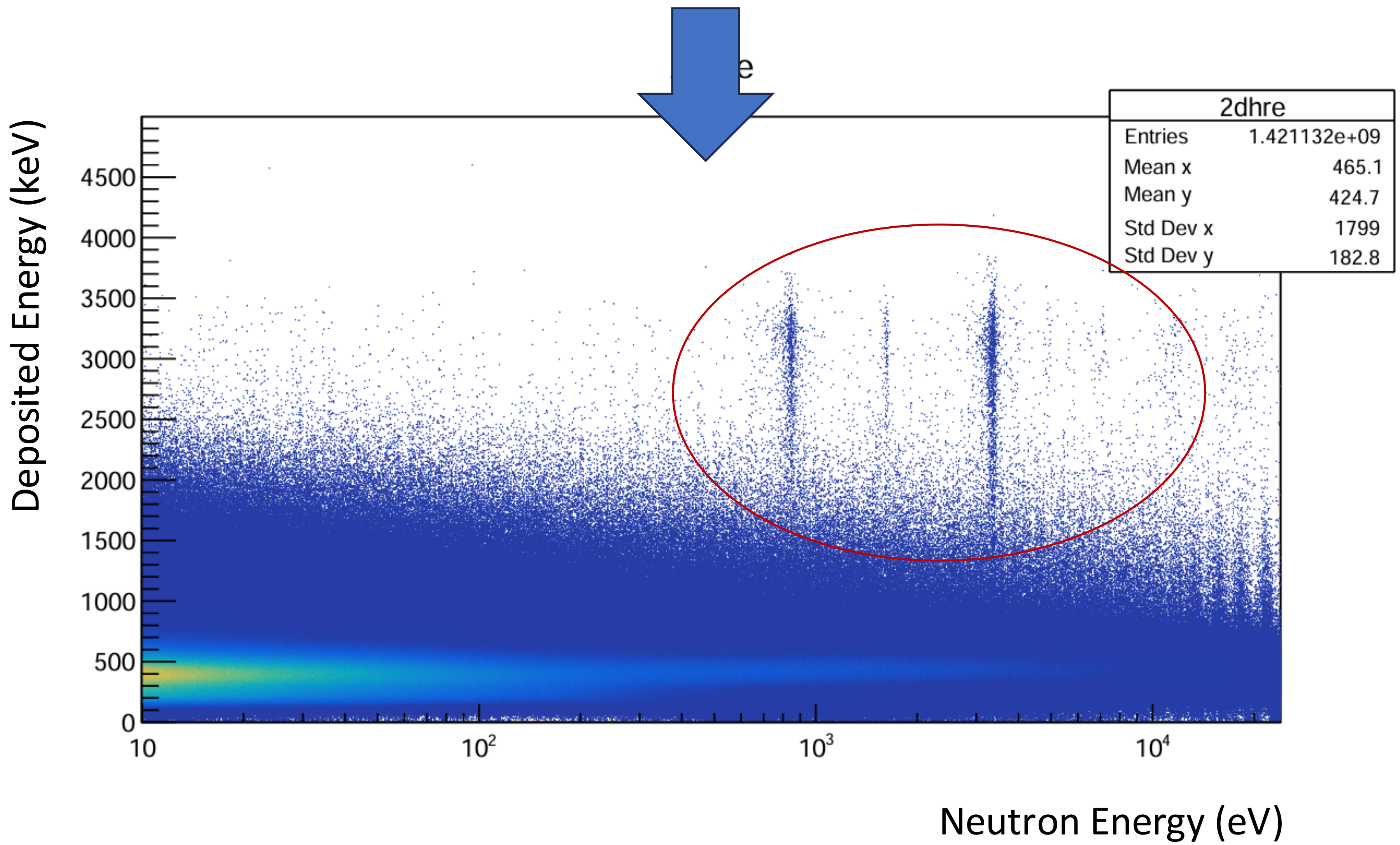


Bercovici, David. "Mantle convection." (2010).

Measurement at n_TOF EAR-2

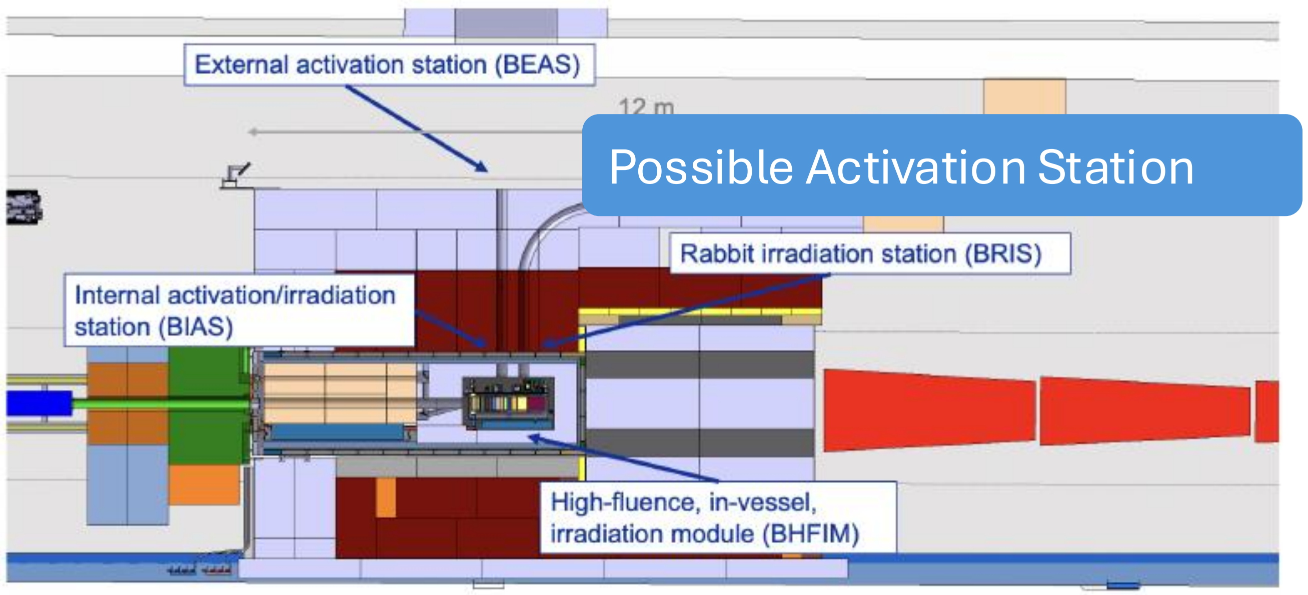


- Sample 0.5 mg, 16% enriched in ^{40}K coated in 100 nm Au (produced at PSI)
- dE-E setup for proton and alpha detection
- First data from dE detector



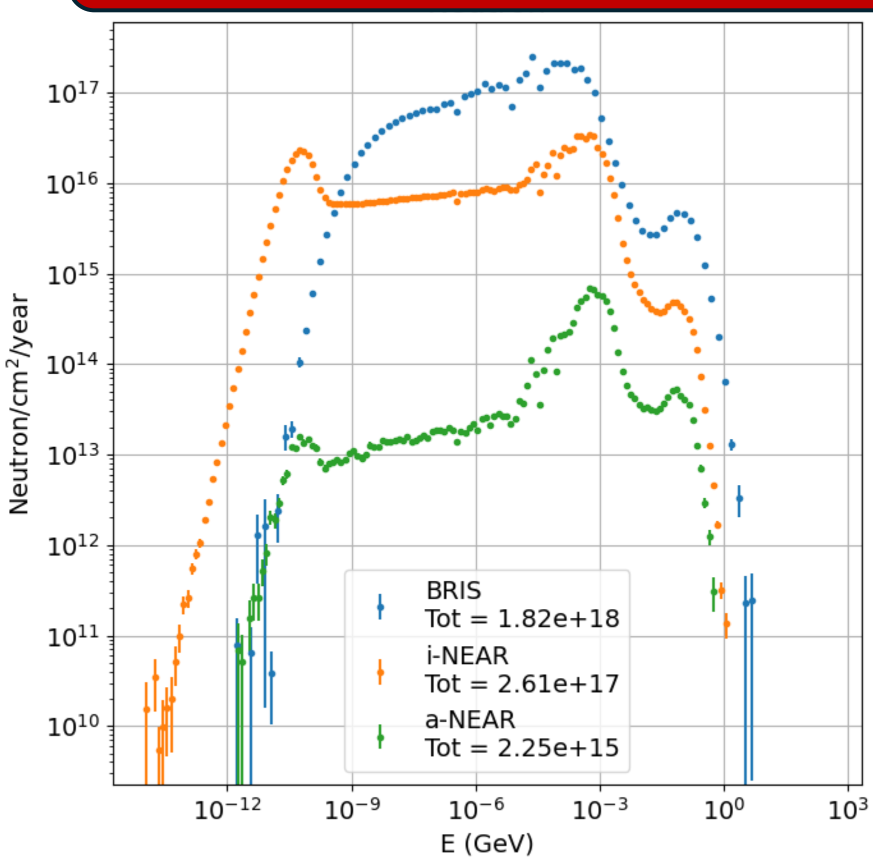
n_Act@BDF – Neutron Activation Station at the SPS Beam Dump Facility

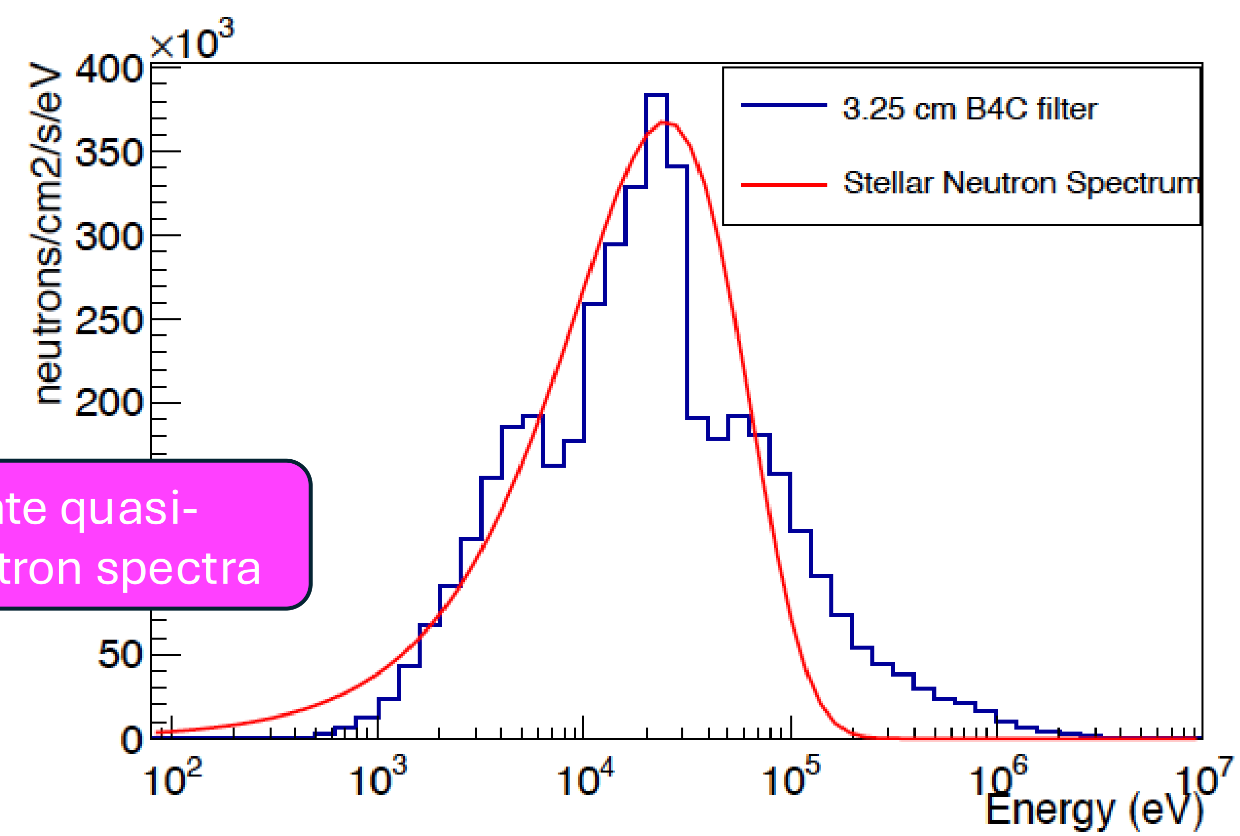
CERN-SPSC-2024-027 / SPSC-EOI-023



- Parasitic use for **neutron cross section measurements**
- **Unique** installation providing **ultra high neutron fluxes** over a wide energy range for activation measurements – complementary to n_TOF capabilities
- Proximity to ISOLDE – measurements on **radioactive** nuclei
- **World-first measurements** of key reactions for nuclear astrophysics and nuclear applications

Flux 3-4 orders of magnitudes higher than at present n_TOF NEAR





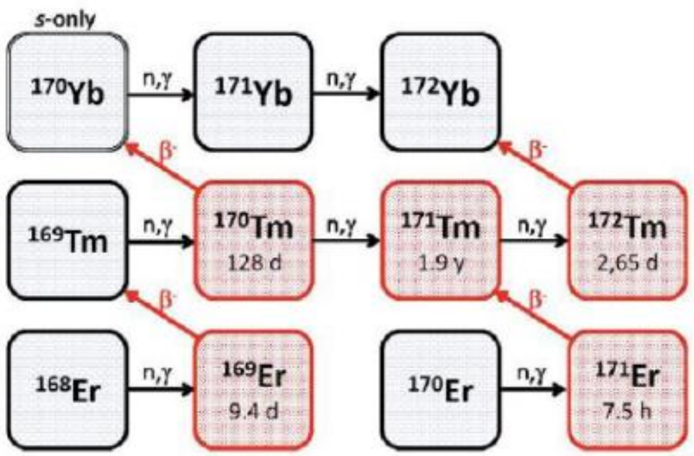
Filters create quasi-stellar neutron spectra

n_Act@BDF – Neutron Activation Station at the SPS Beam Dump Facility

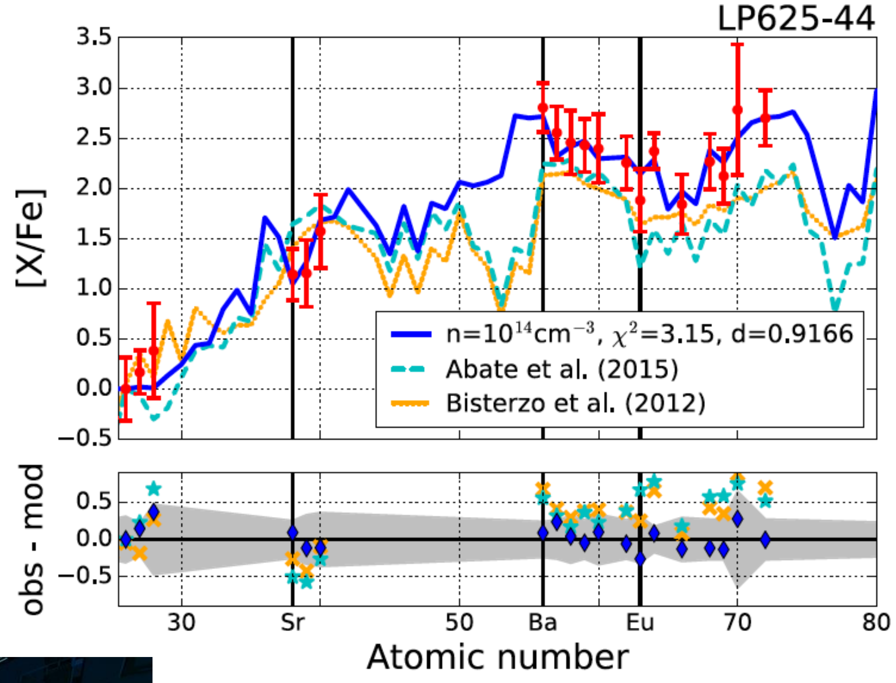
CERN-SPSC-2024-027 / SPSC-EOI-023

Science Examples:

Measurements to determine neutron densities and temperature in stellar interiors e.g. (n,γ) on ^{94}Nb, ^{147}Pm, ^{163}Ho and ^{171}Tm



Measurements to explain peculiar abundances in old stars e.g. (n,γ) on ^{125}Sb, ^{137}Cs, ^{144}Ce



Measurements for next generation fission and fusion reactors e.g. (n,2n) on ^{109}Ag, ^{151,153}Eu

Thanks for listening!