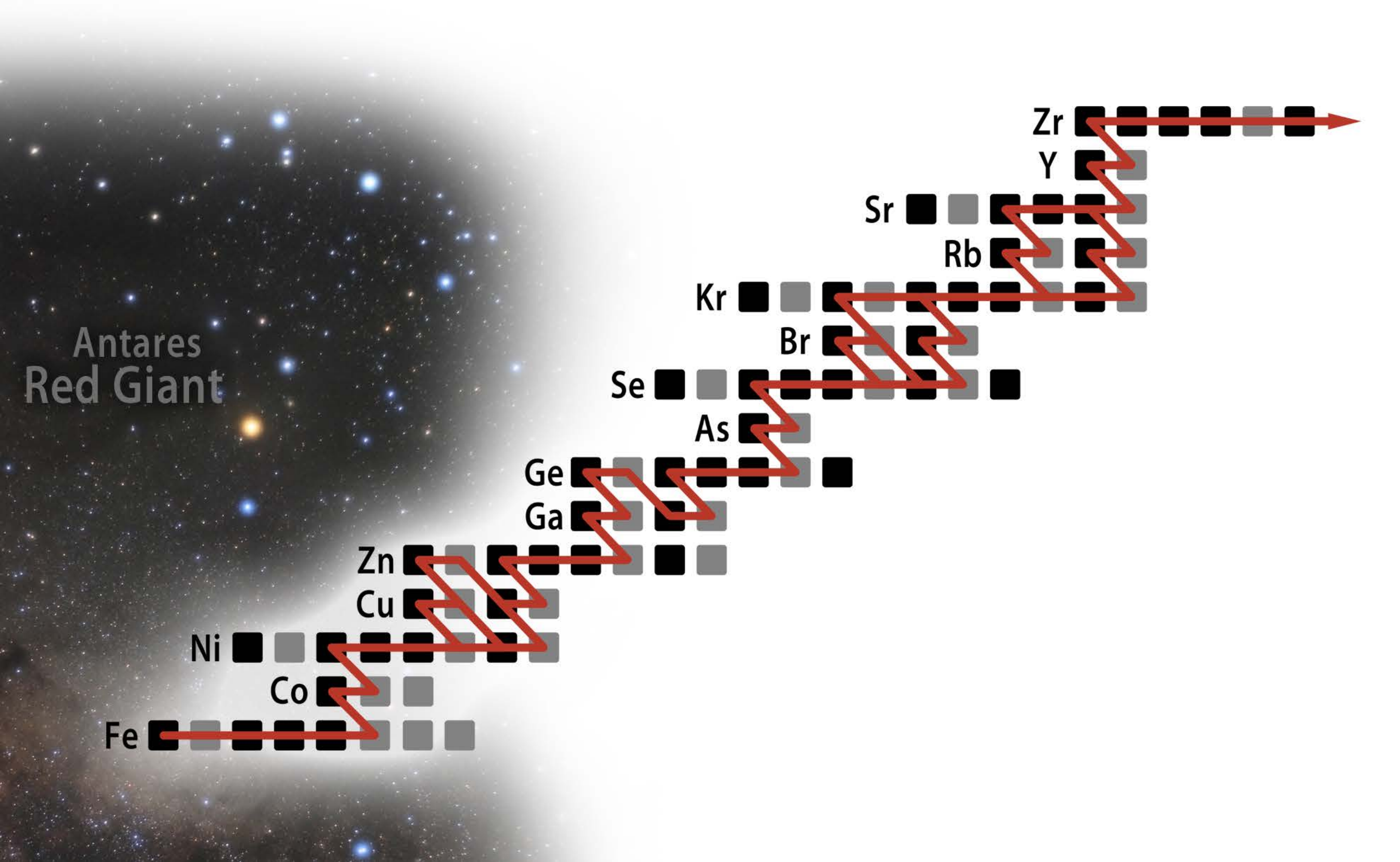
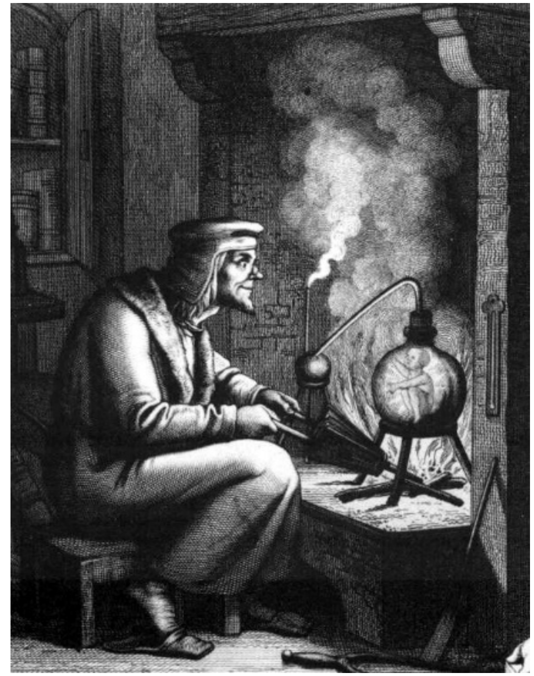
Neutron-matter interaction: nTOF for astrophysics

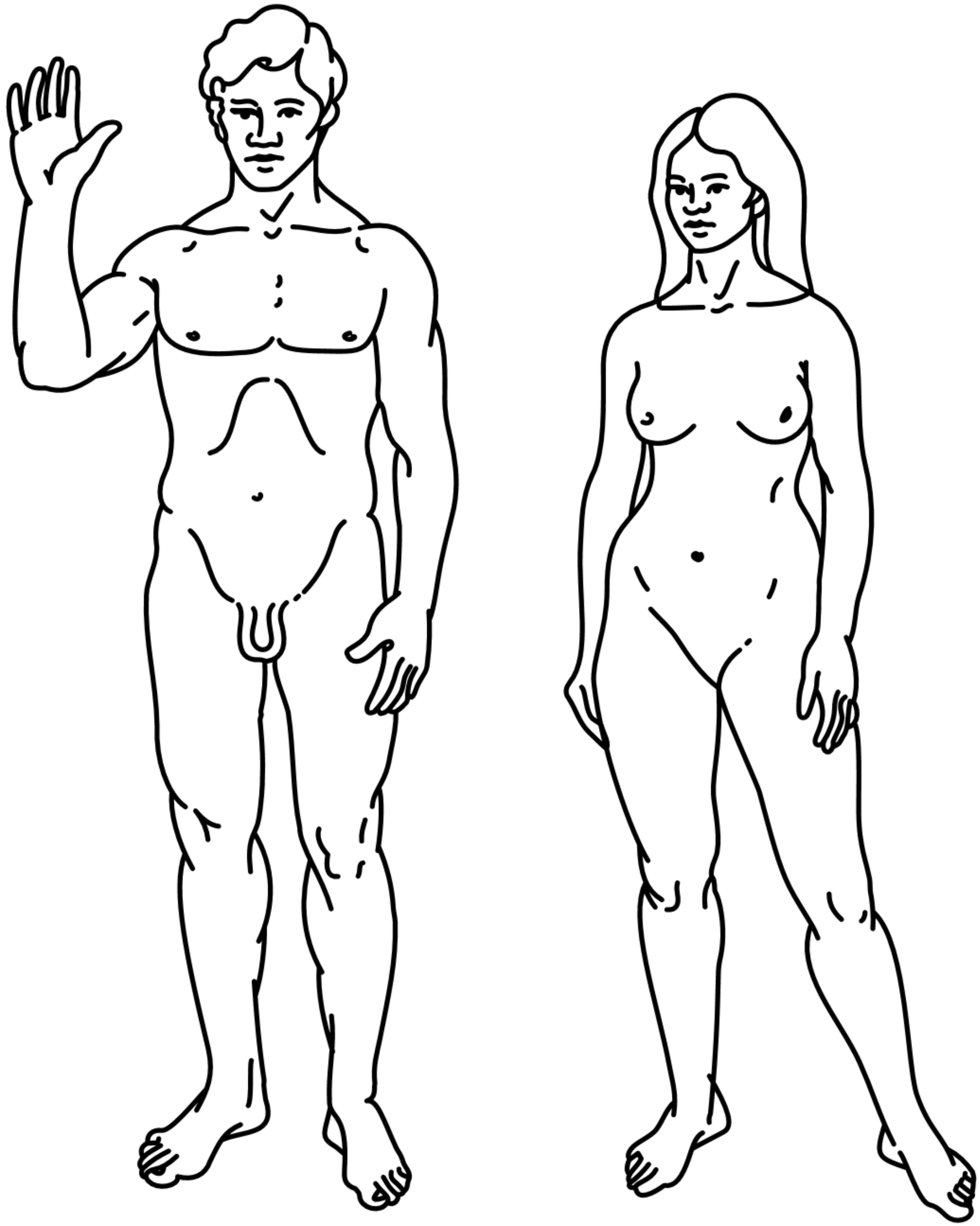
Pisa summer school on
"Rewriting Nuclear Physics Textbooks: Basic nuclear interactions and their link to nuclear processes in the cosmos and on earth"
July 1st, 2017
Pisa, Italy, July 24 –28, 2017

René Reifarth
Goethe Universität Frankfurt

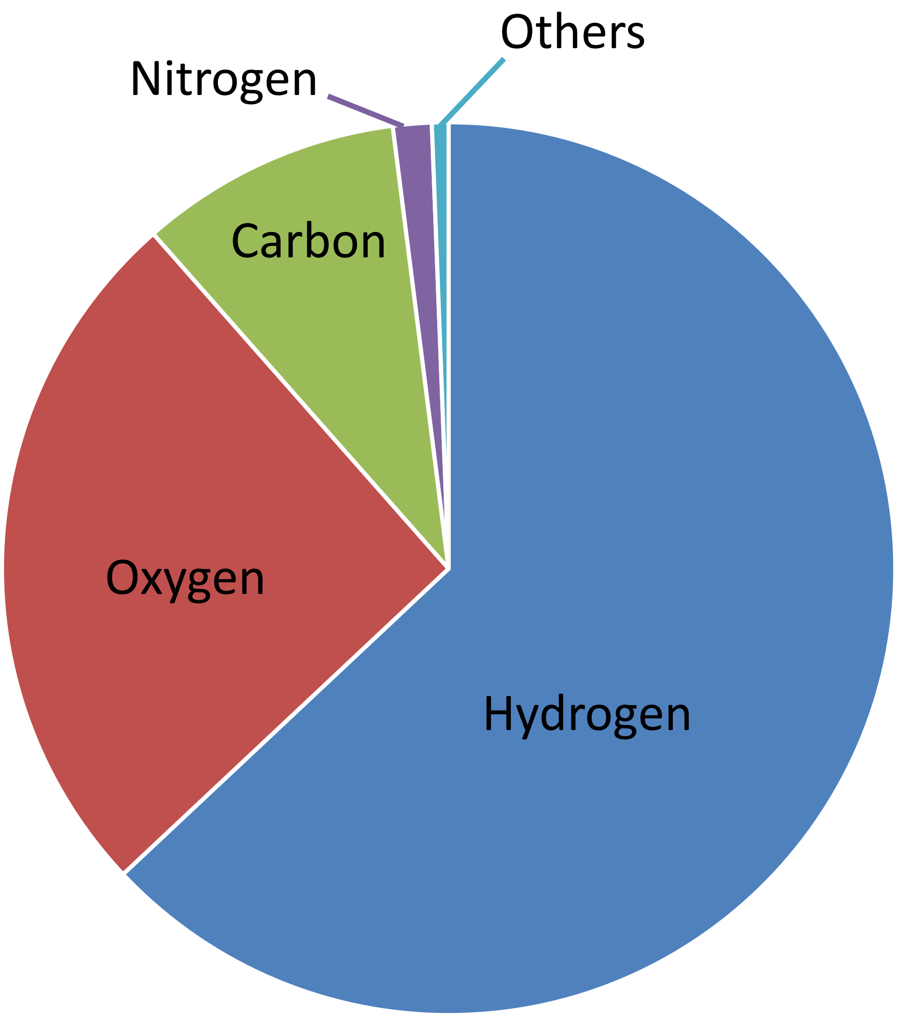
Nucleosynthesis – tales from the past



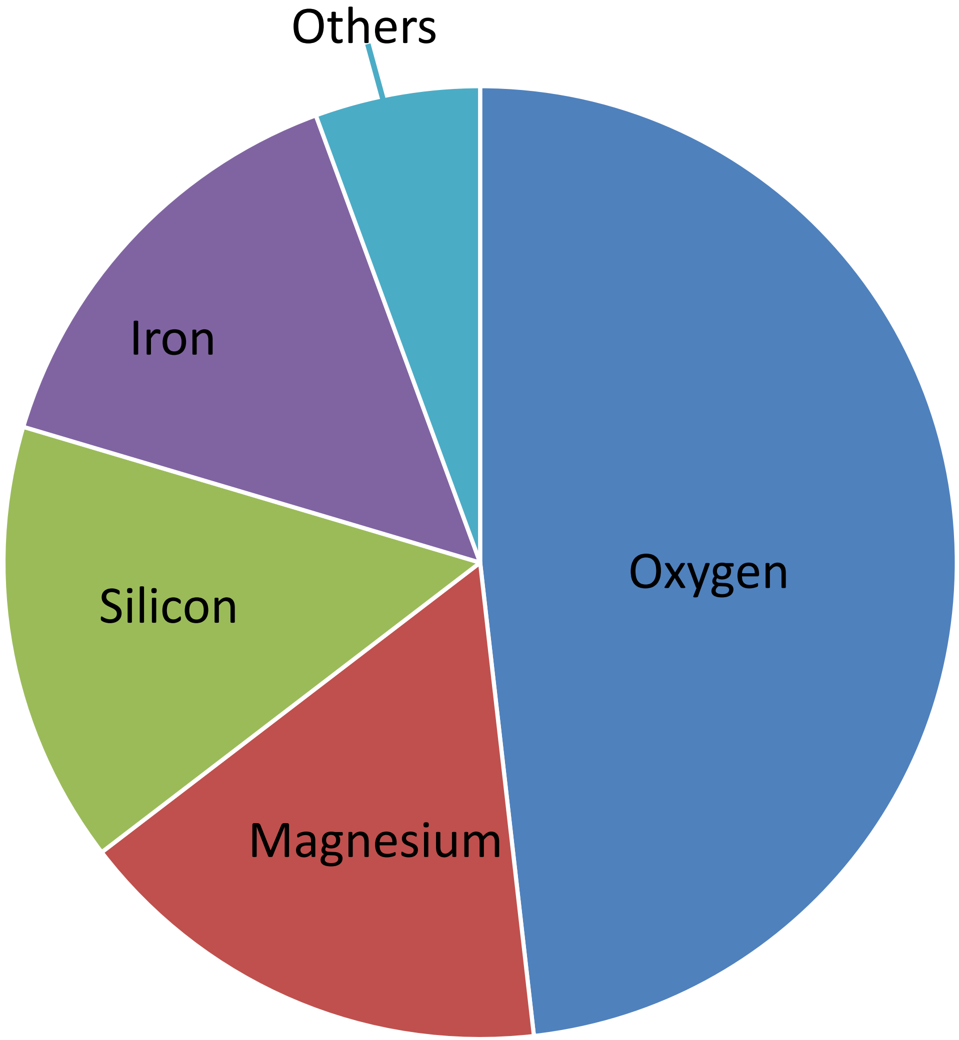




Human

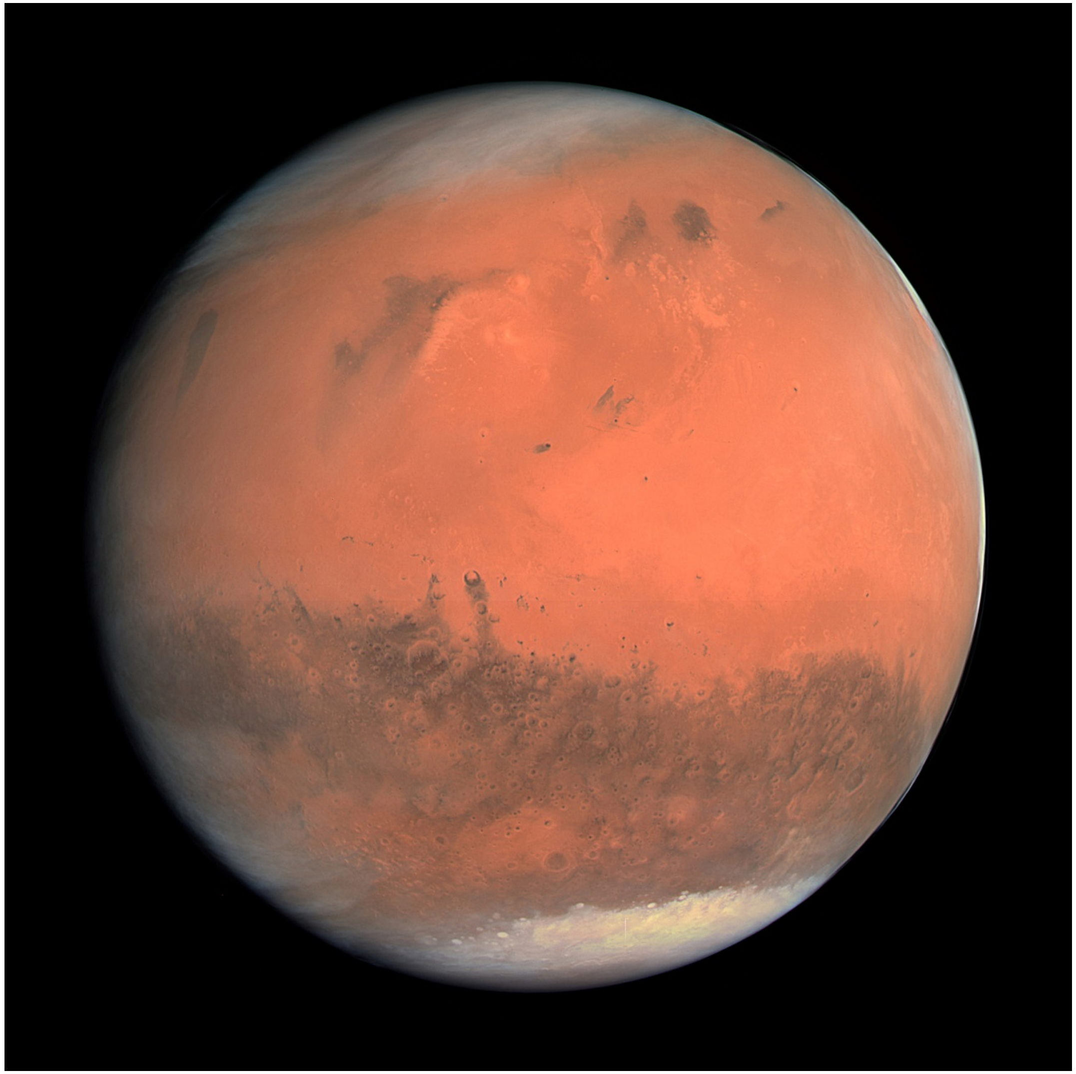


Earth

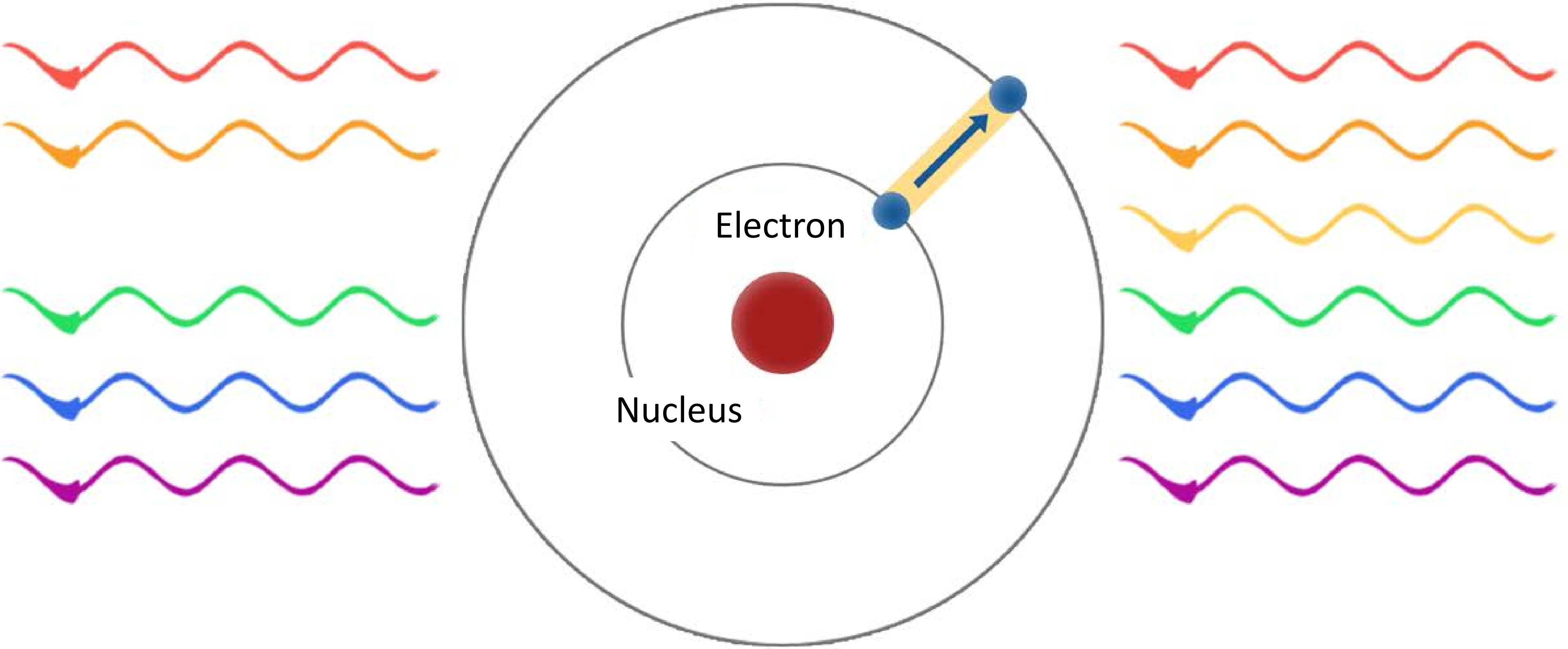


Earth – Sand & Rost

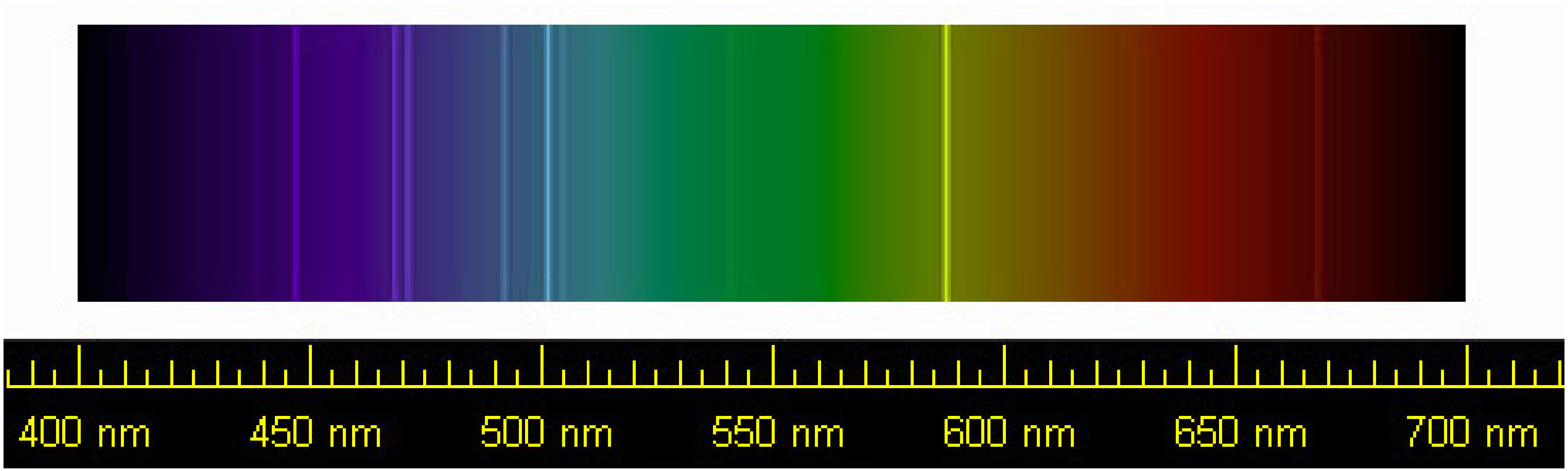
Mars – Sand & Rost



Absorption of photons

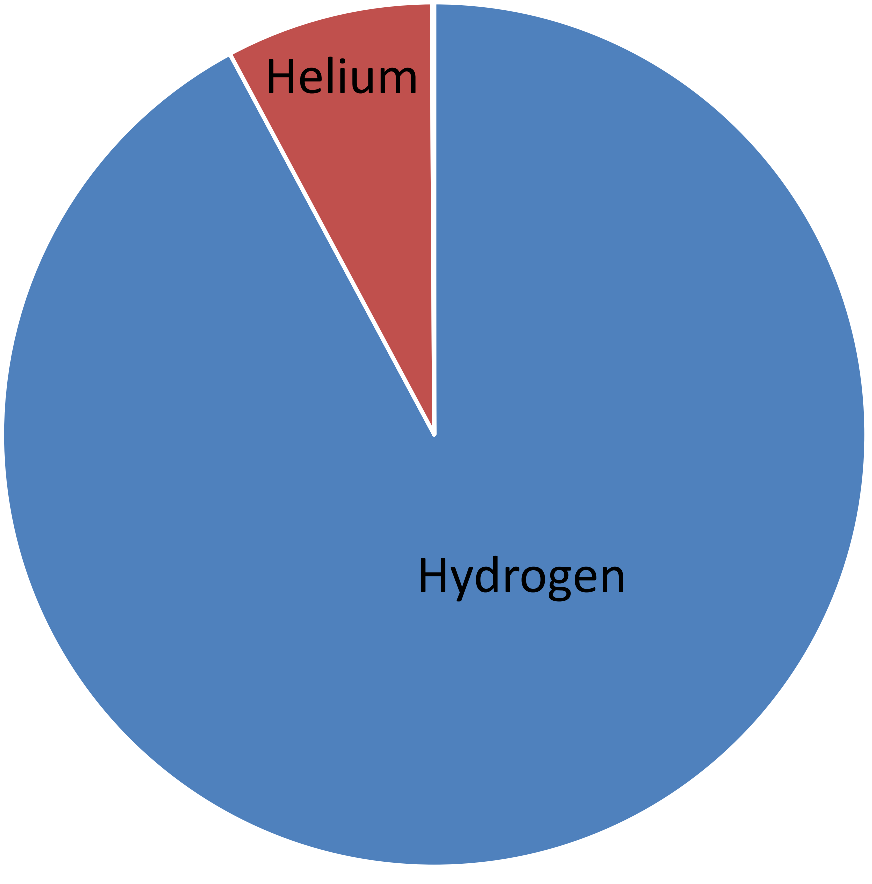


Helium – the sun‘s element

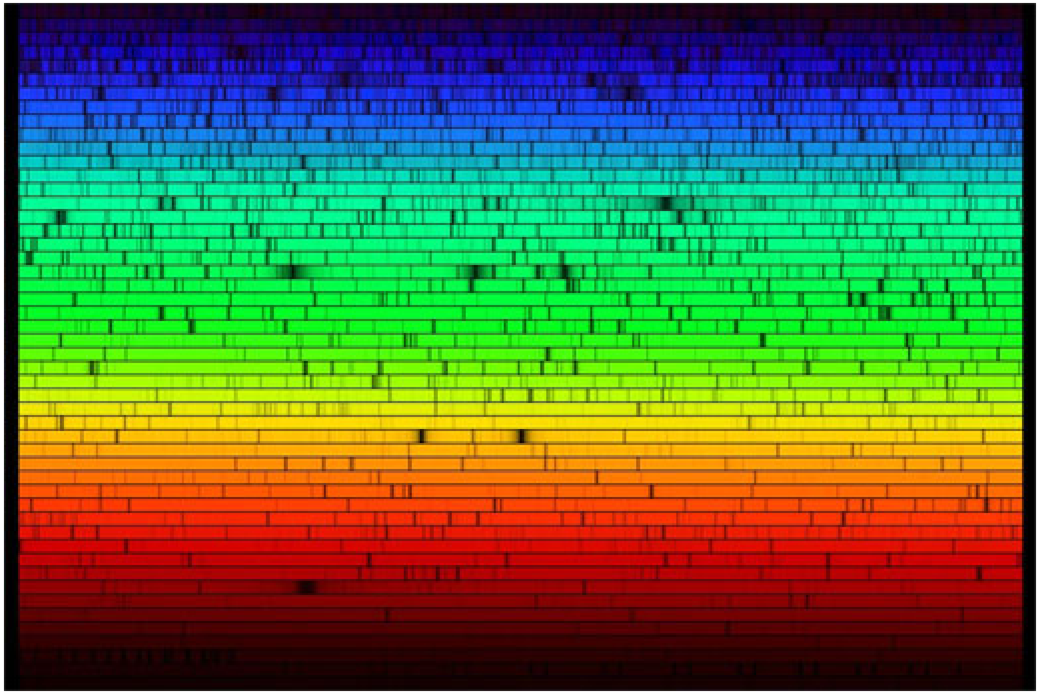


By NASA - http://imagine.gsfc.nasa.gov/docs/teachers/lessons/xray_spectra/worksheet-specgraph2-sol.html, Public Domain, https://commons.wikimedia.org/w/index.php?curid=4158610

Solar system

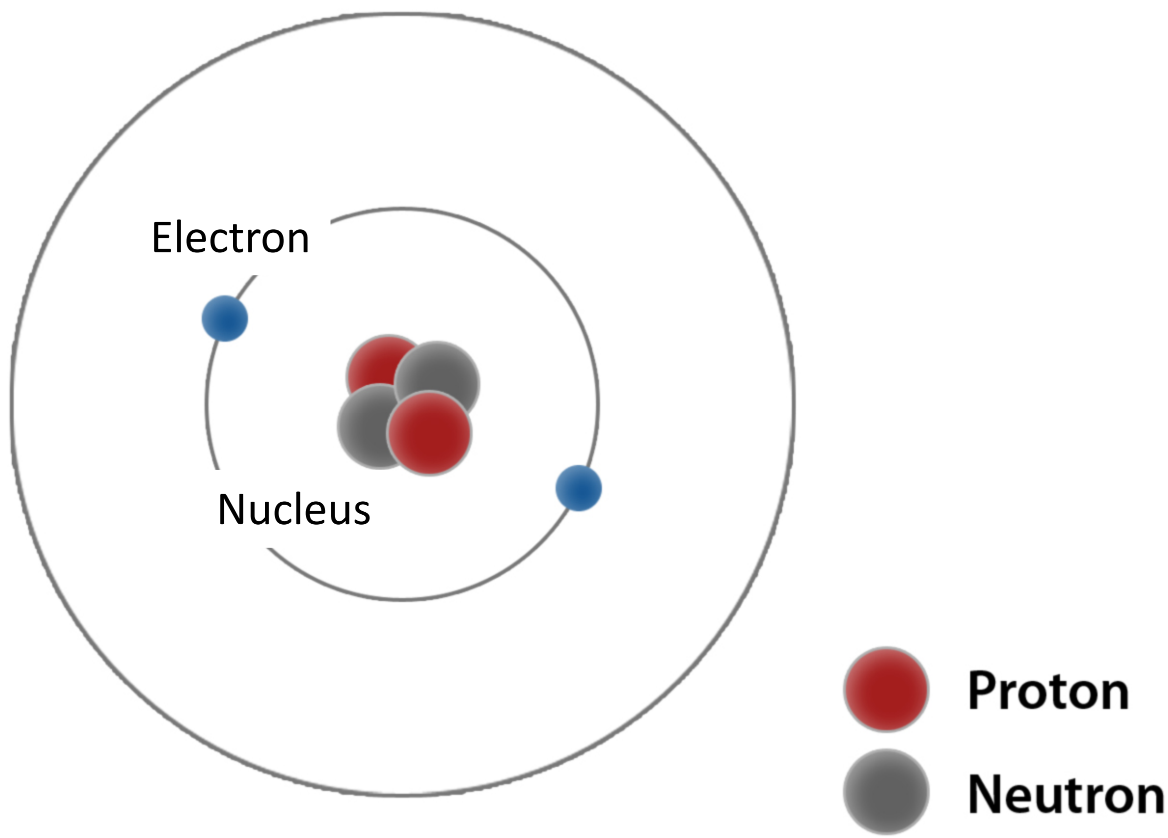


A detailed view at the sun

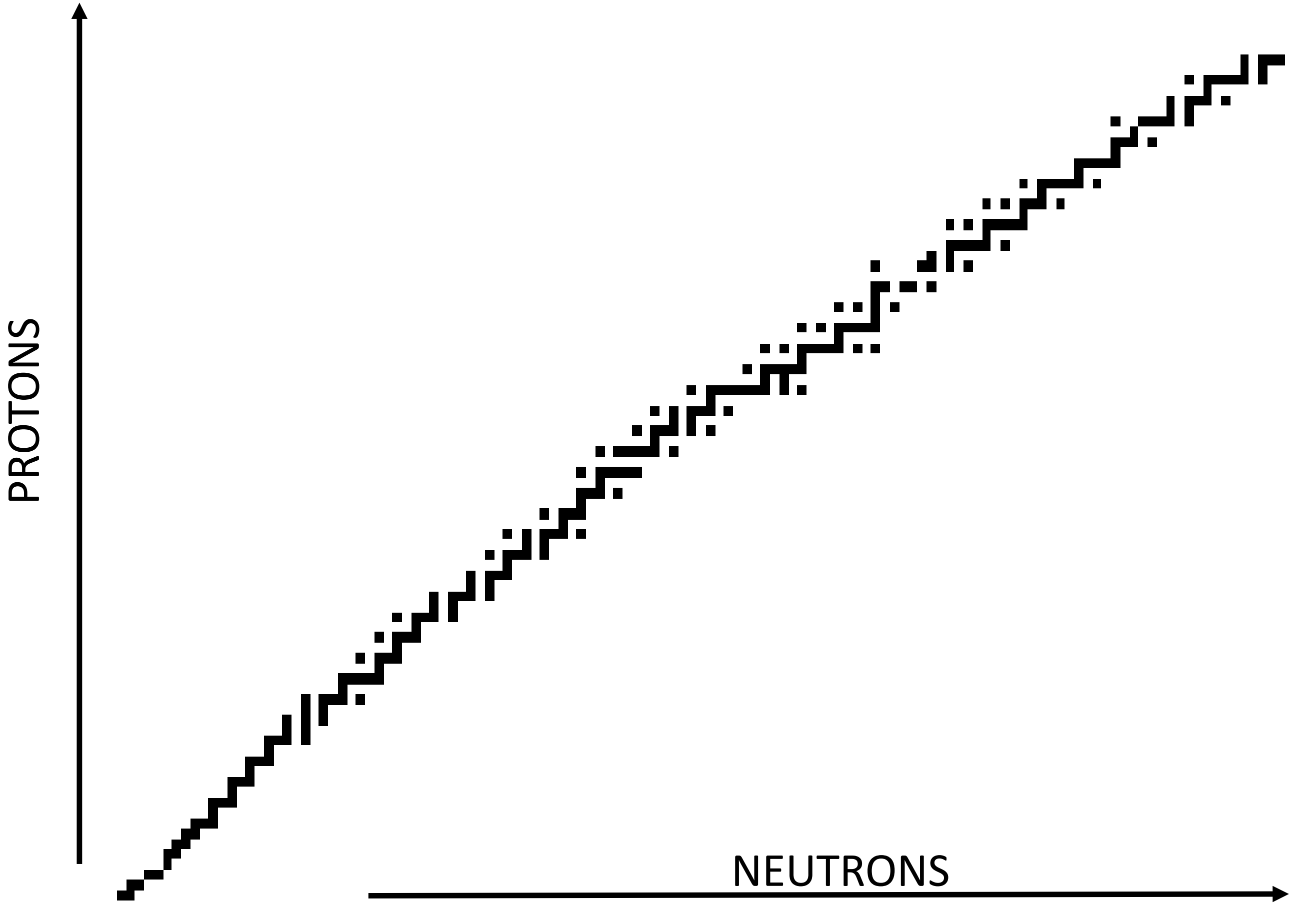


By NASA, *Nigel Sharp, National Optical Astronomical Observatories/National Solar Observatory at Kitt Peak/Association of Universities for Research in Astronomy, and the National Science Foundation.*

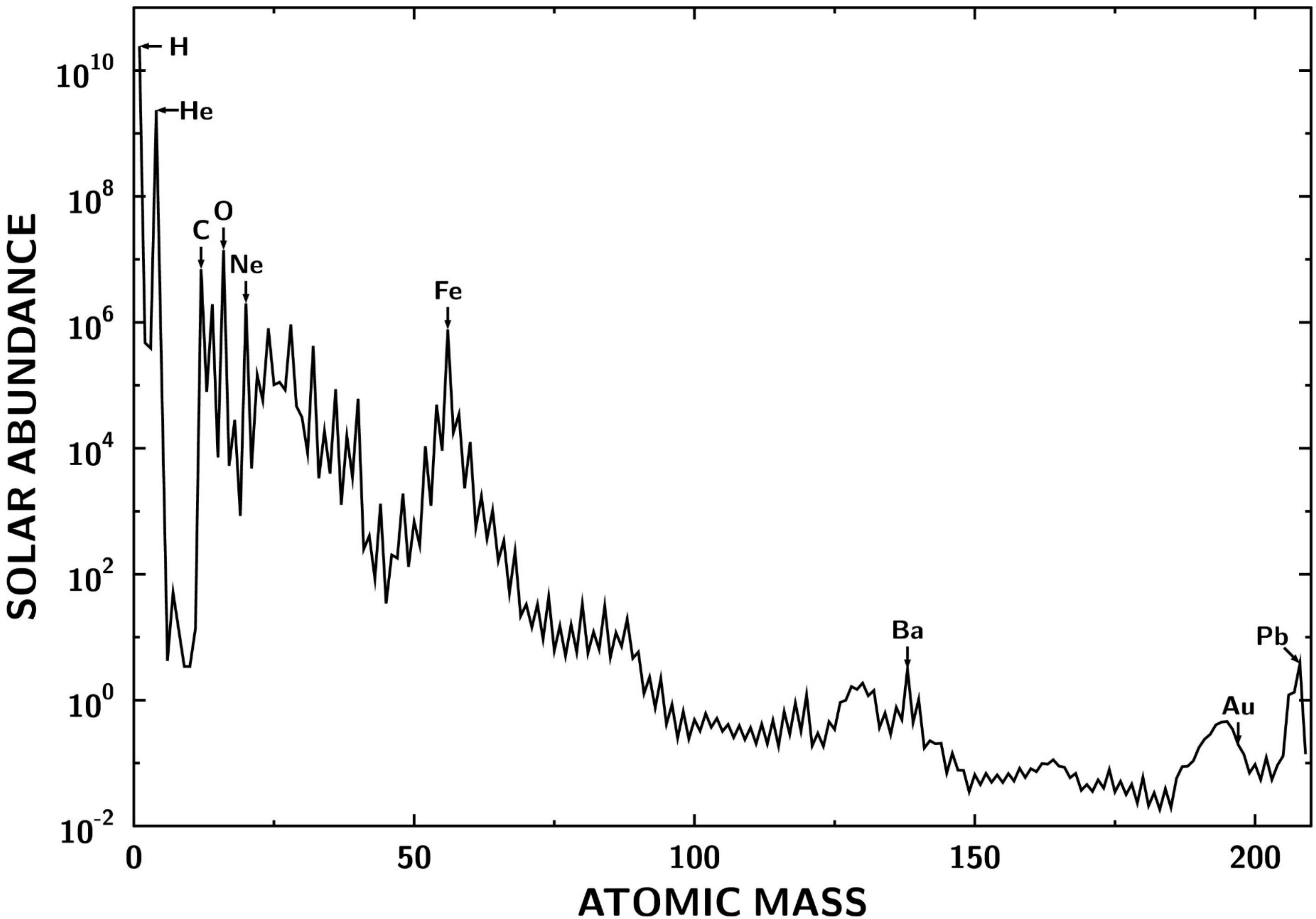
Atomic nuclei



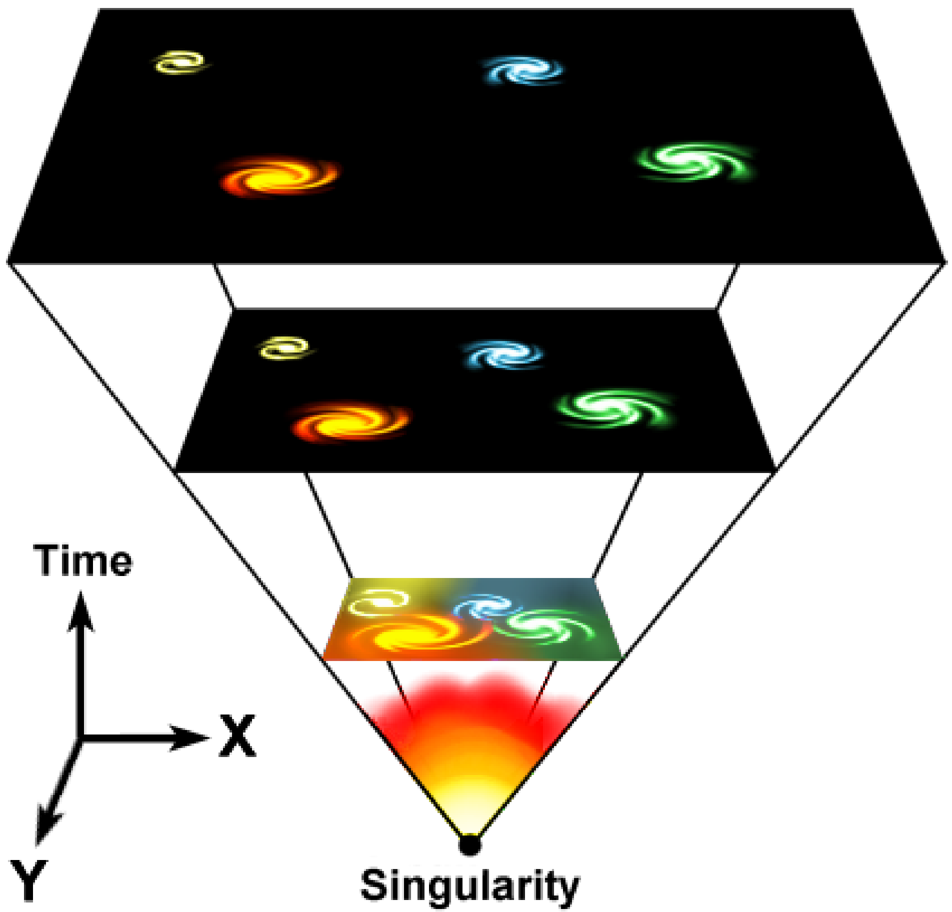
The chart of stable nuclei



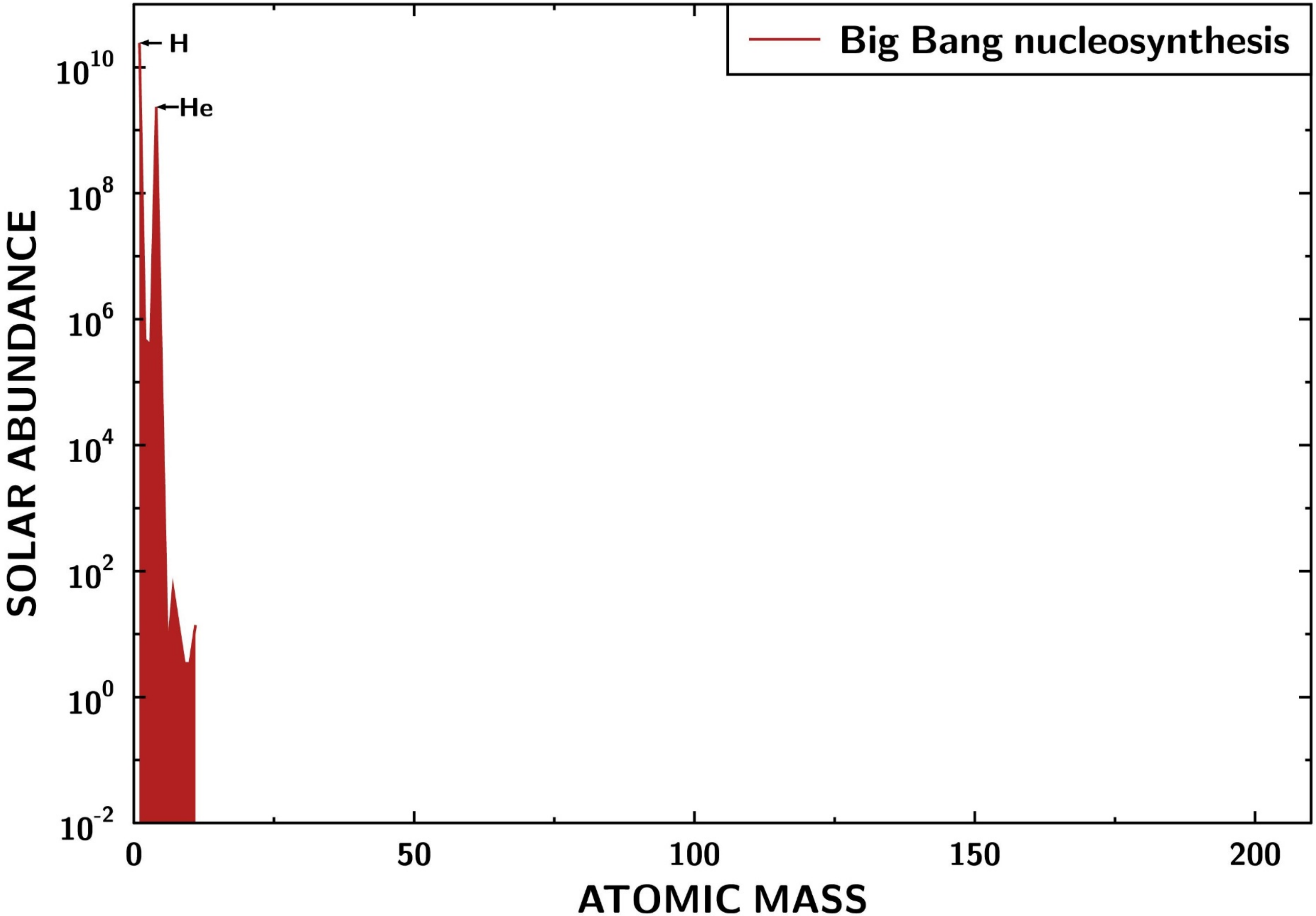
Solar abundances



The Big Bang

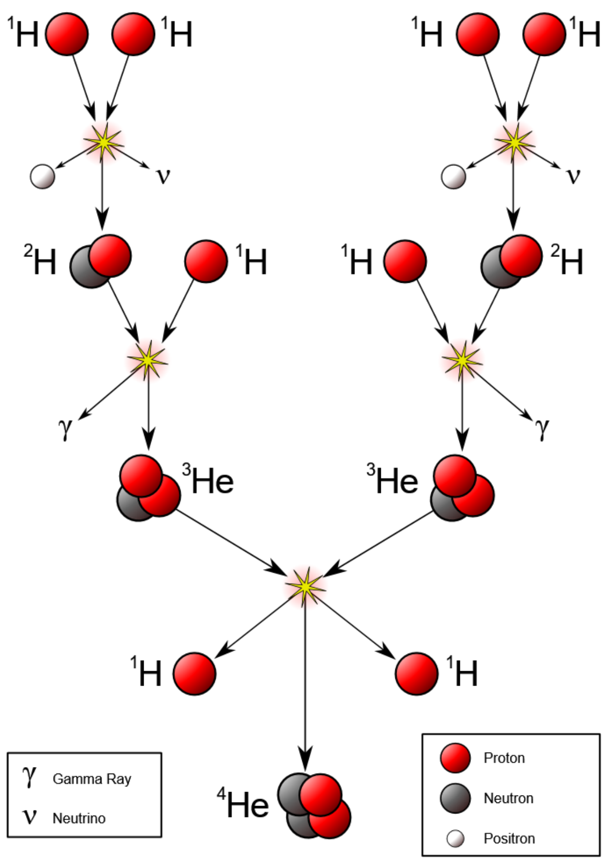


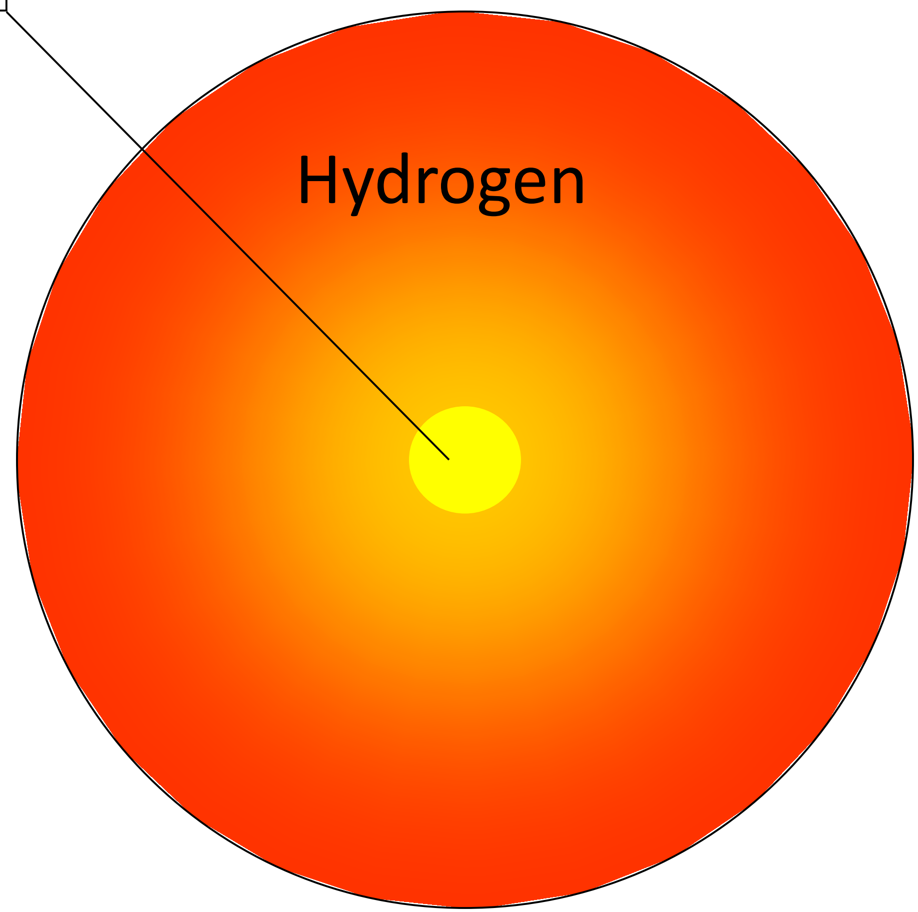
First elements – H, He



First stars after 500 million years

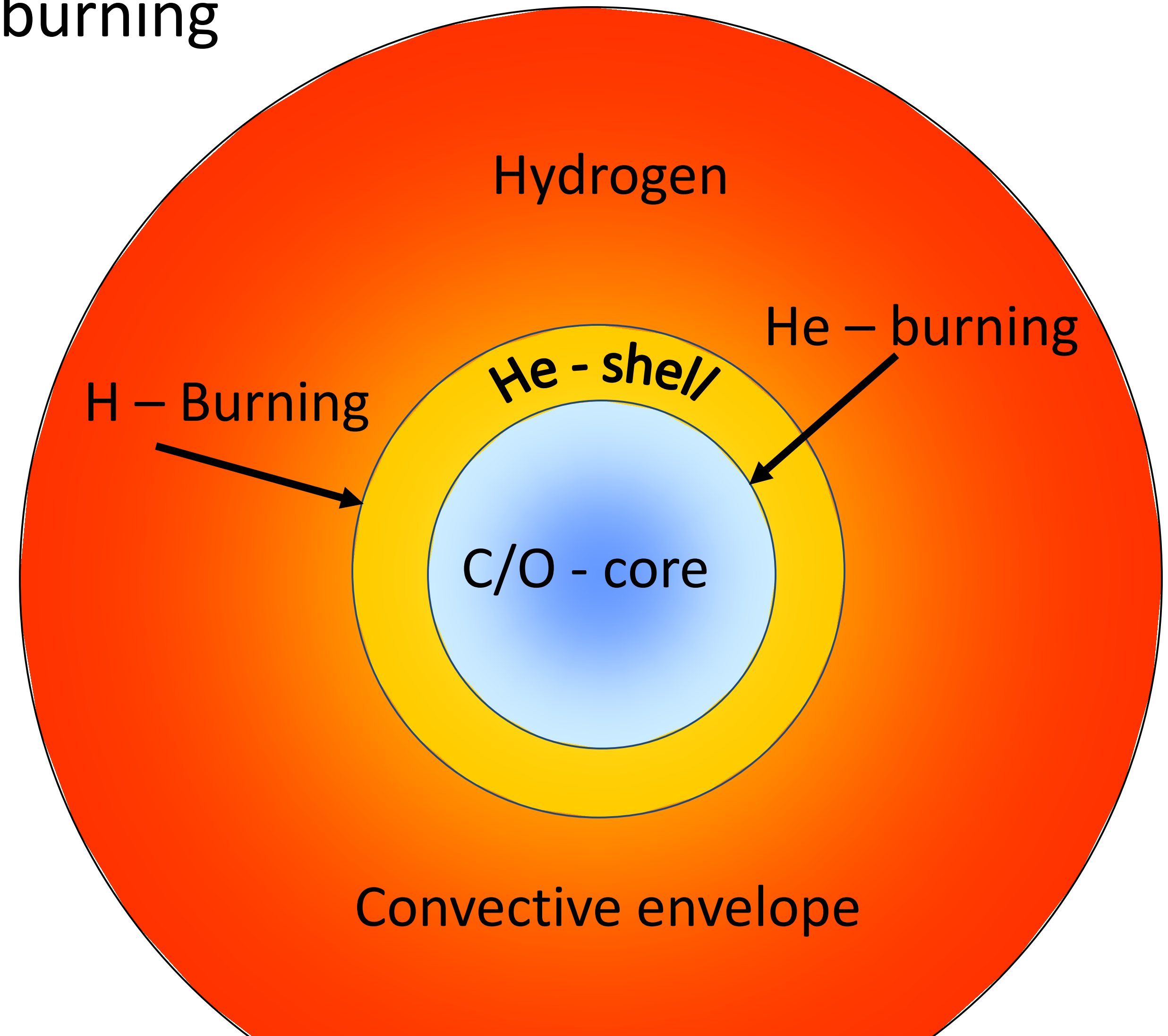
Hydrogen core burning



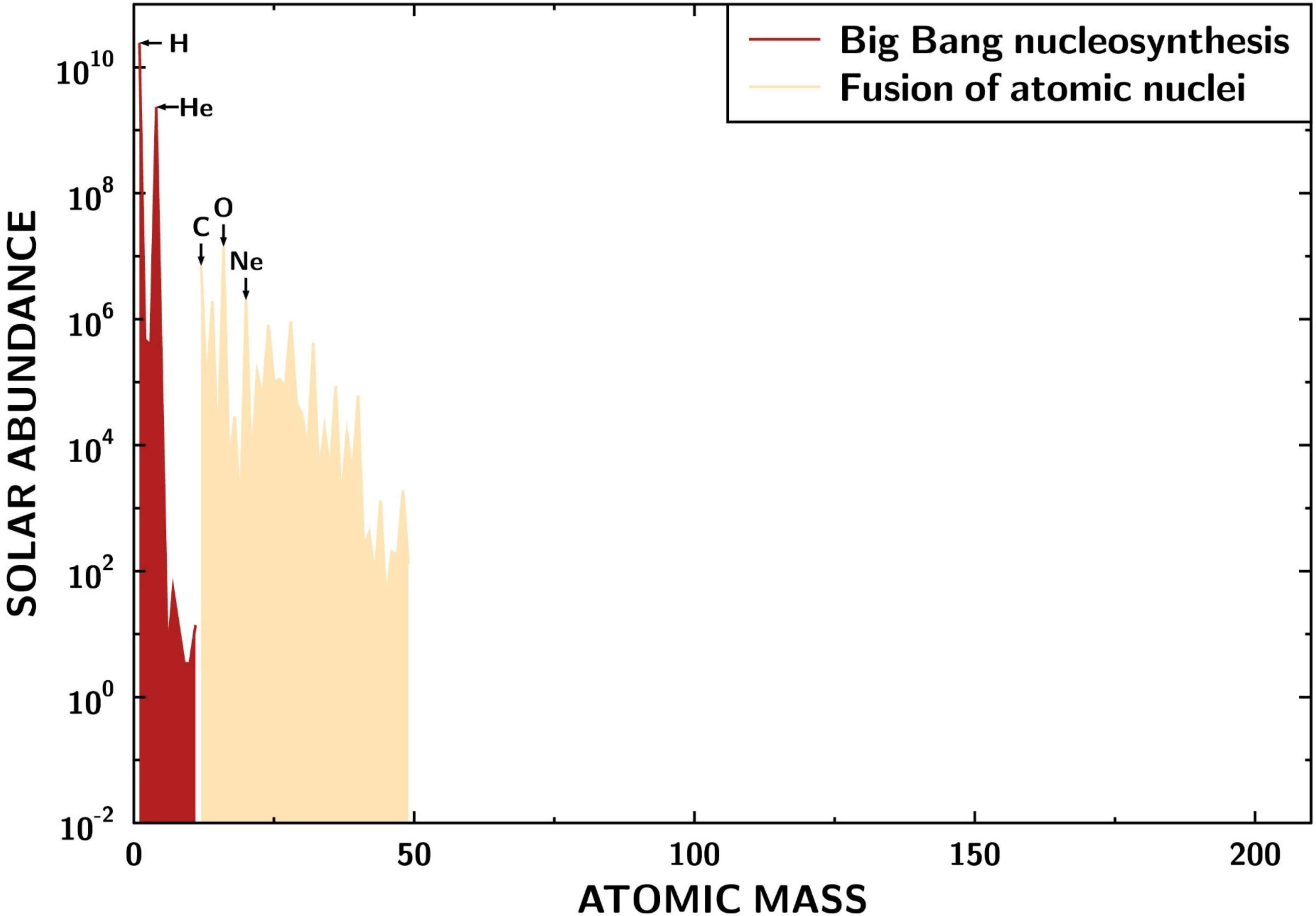


Onion structure

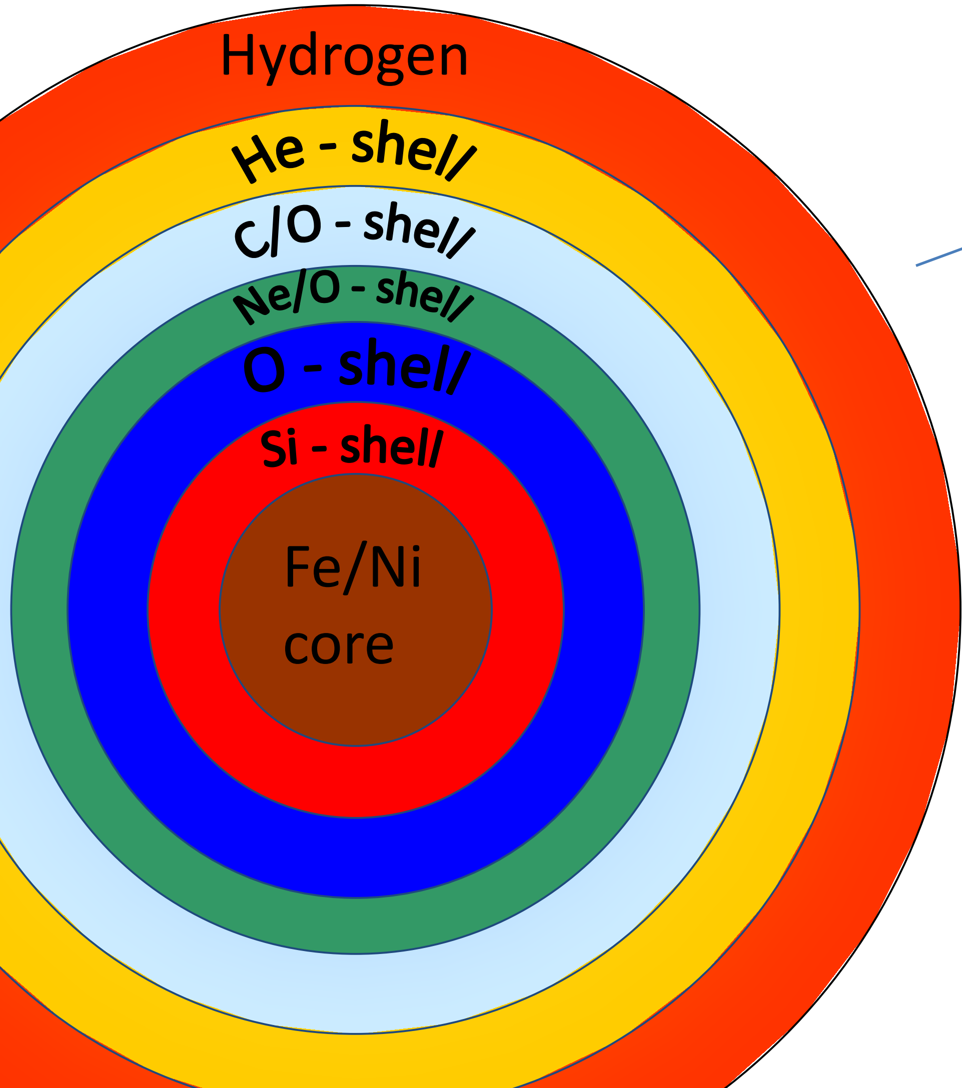
Later stages: H, He, C burning

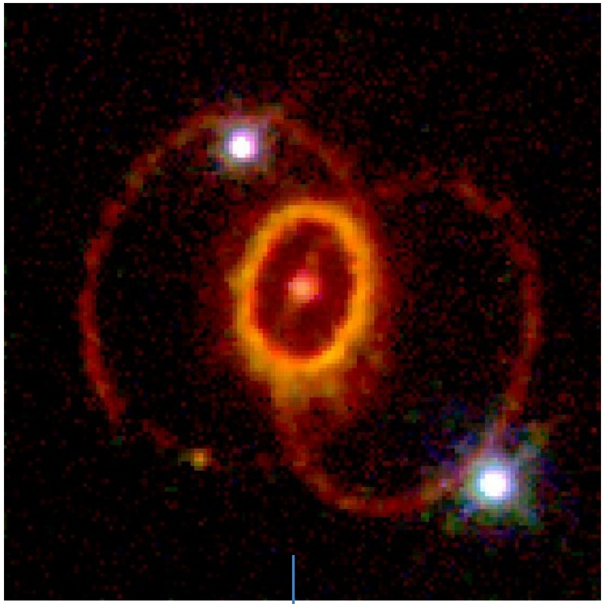


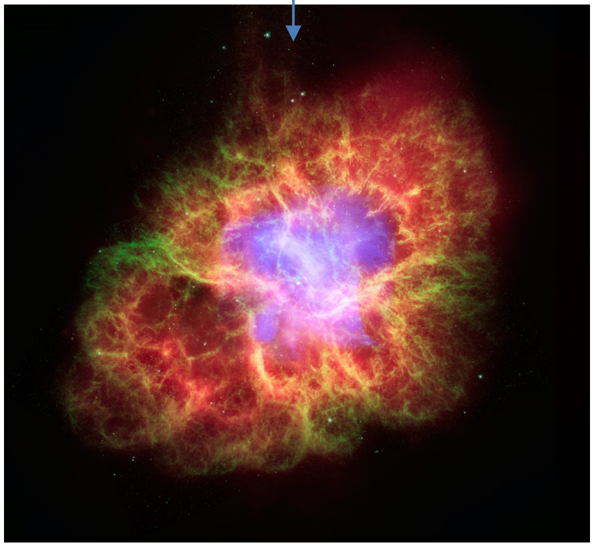
Energy source of stars



Massive stars – early death

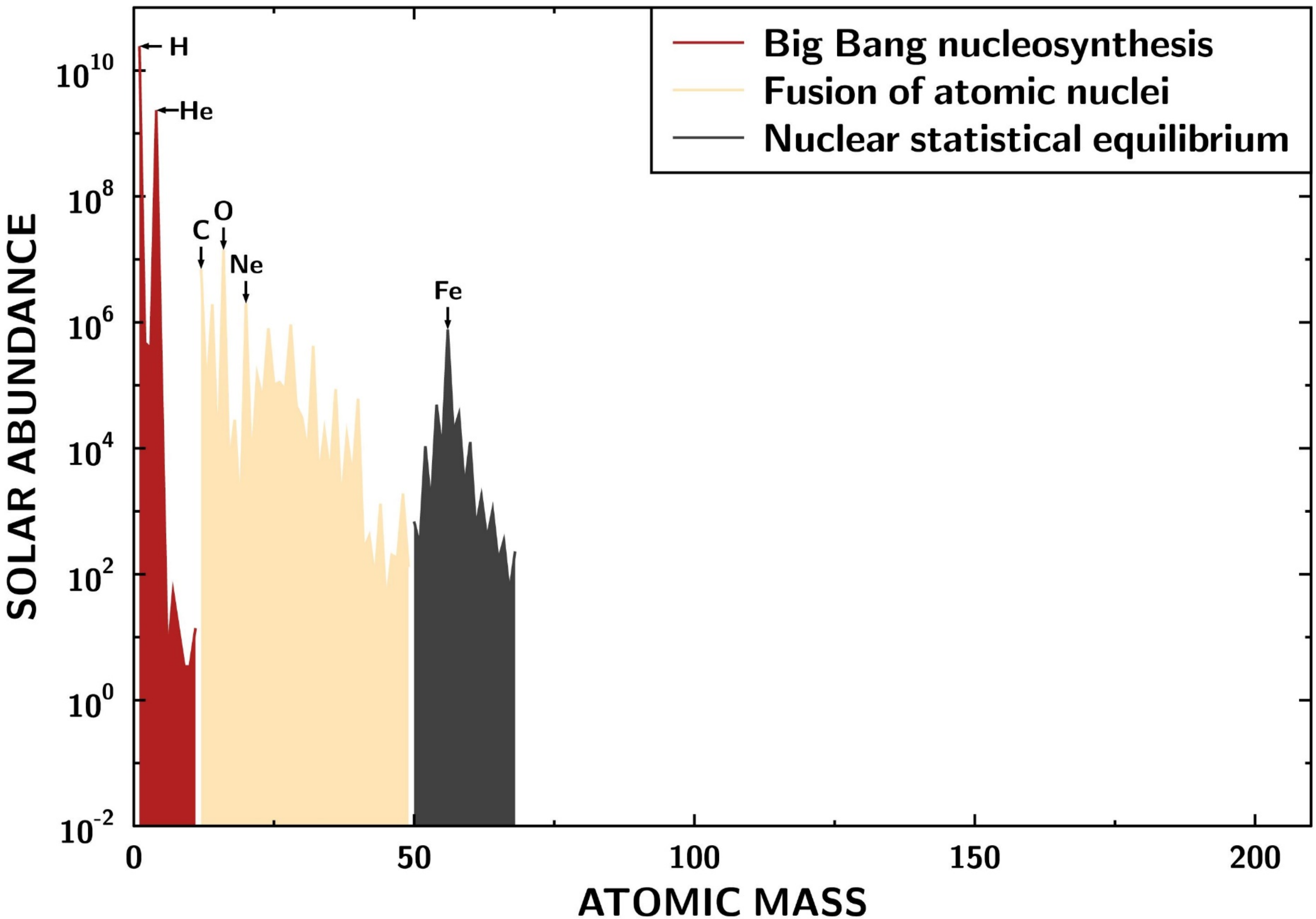




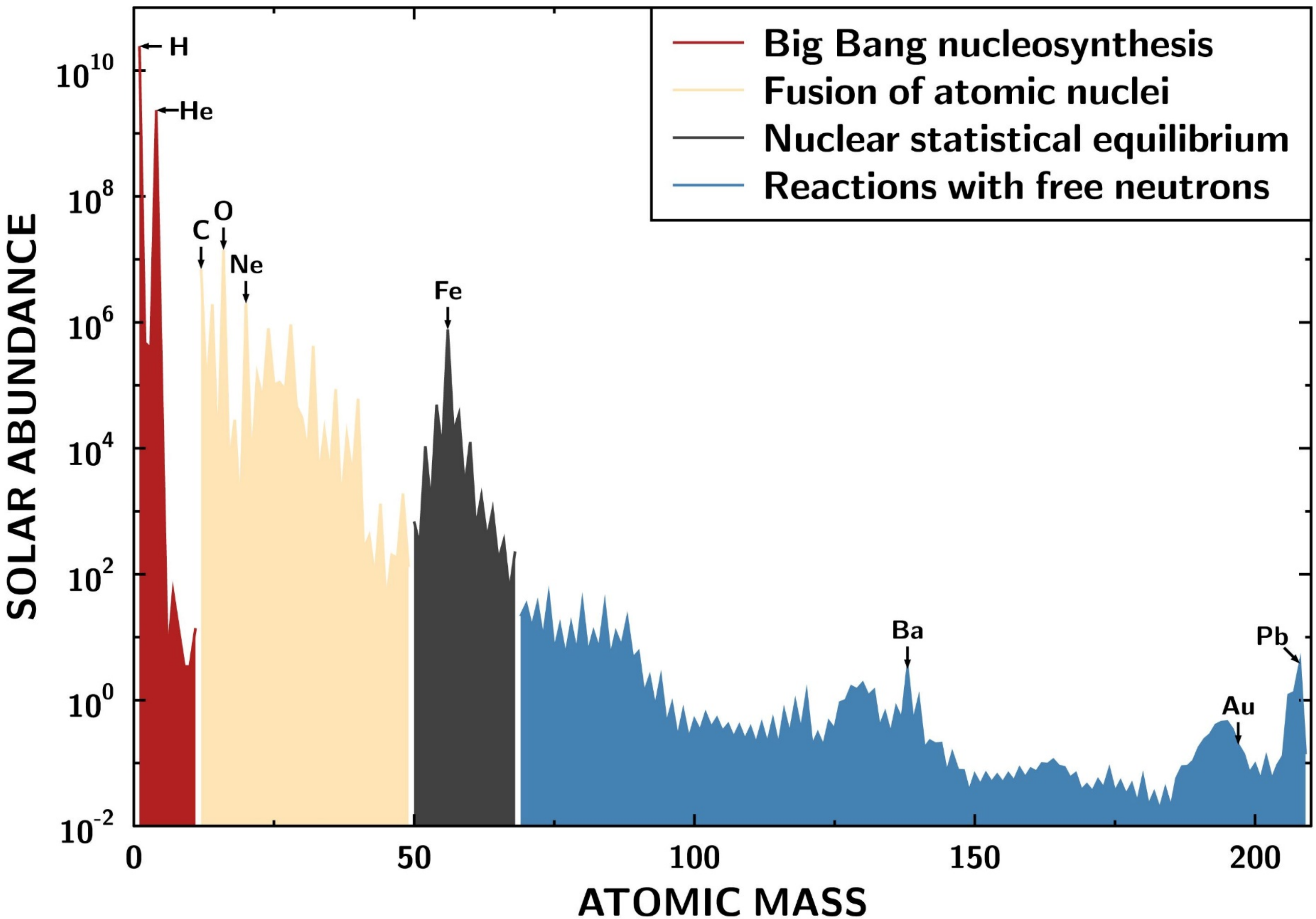


By NASA

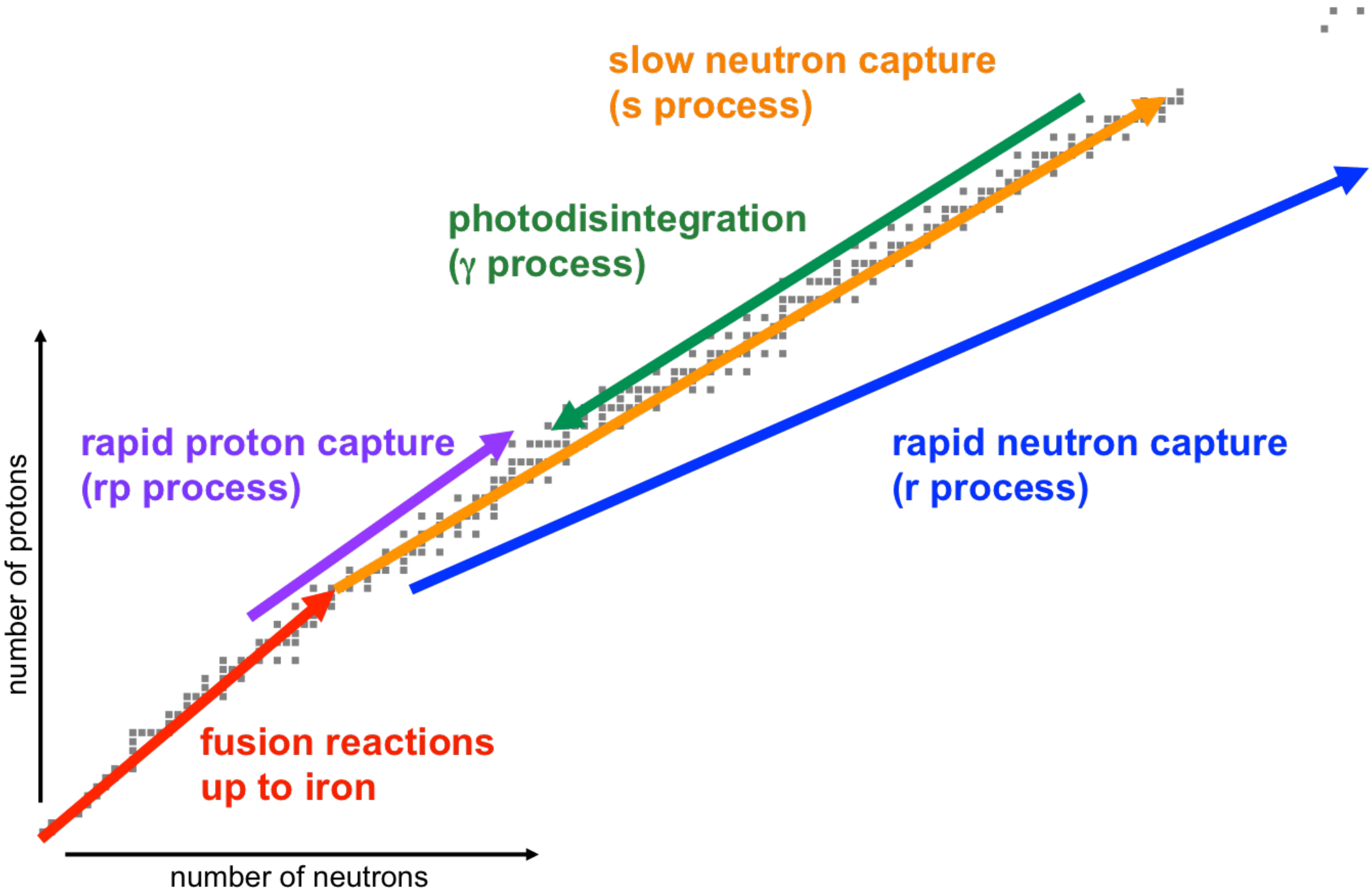
Iron – survival of the most stable



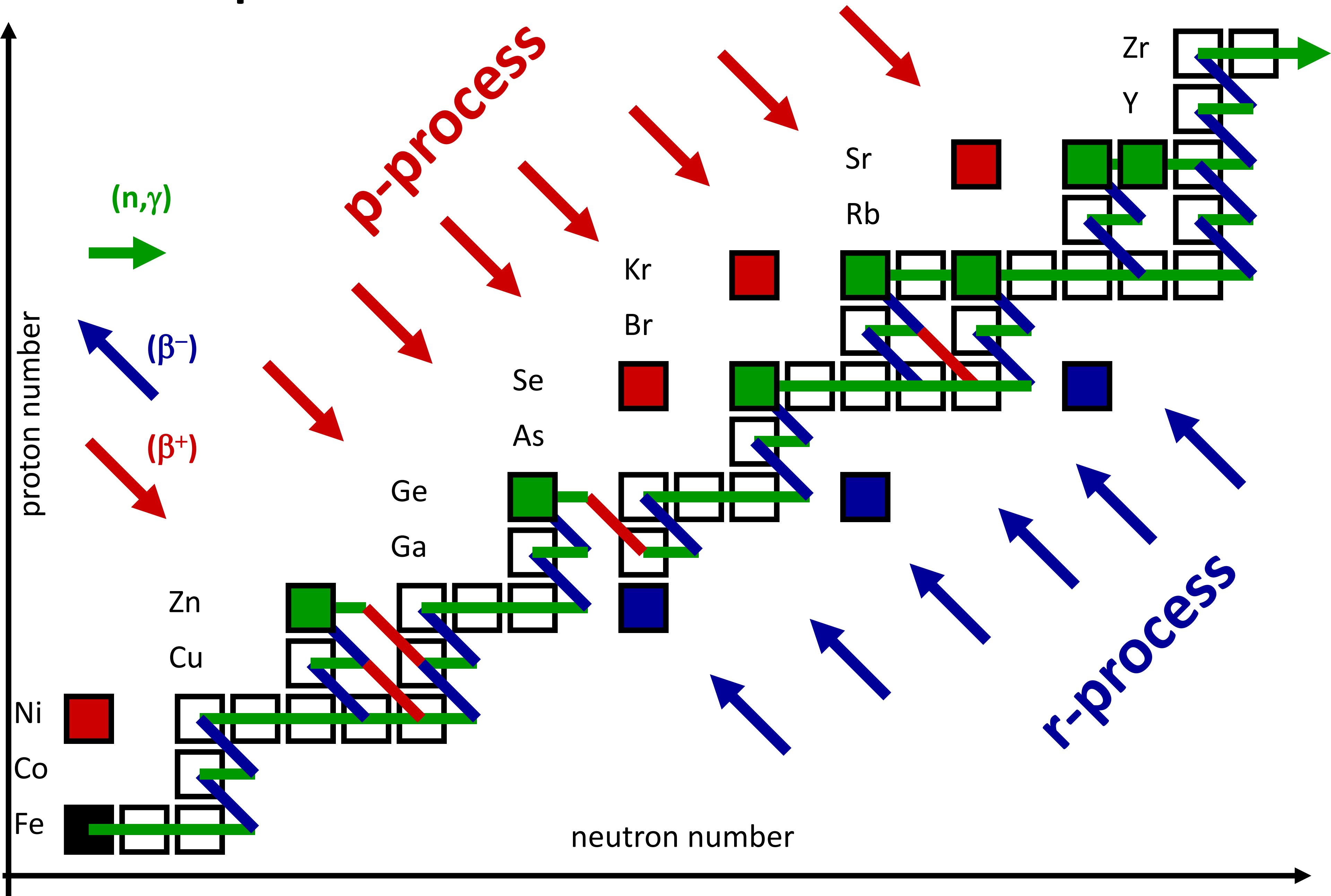
The synthesis of the elements



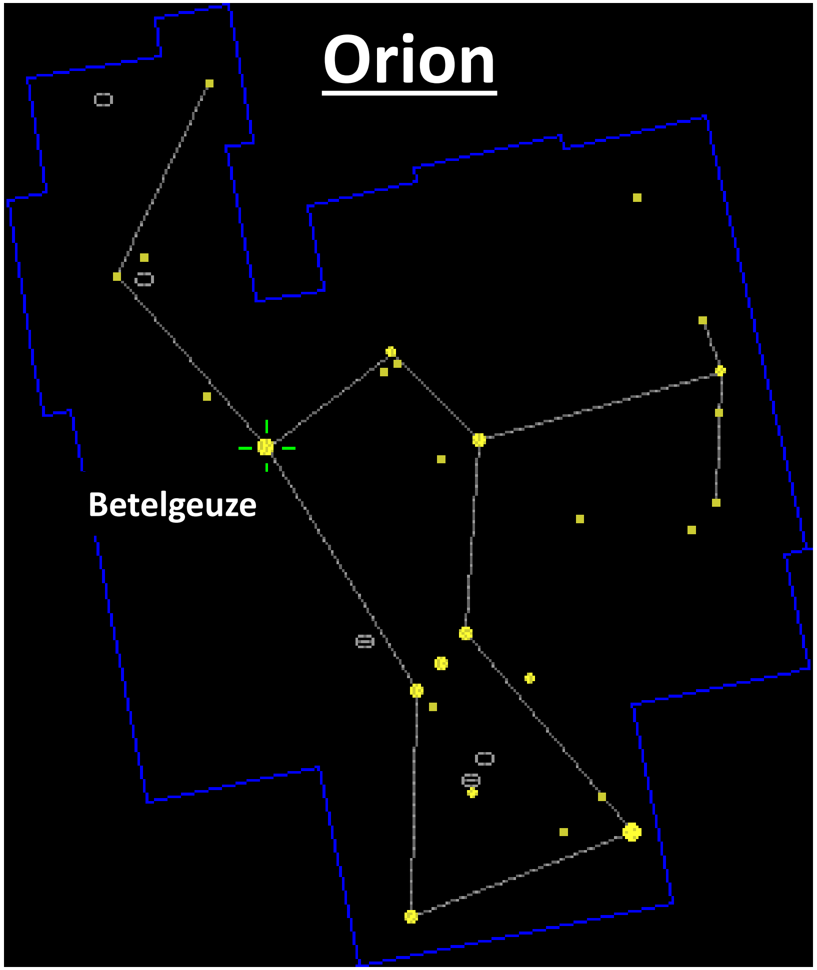
The nucleosynthesis of the elements

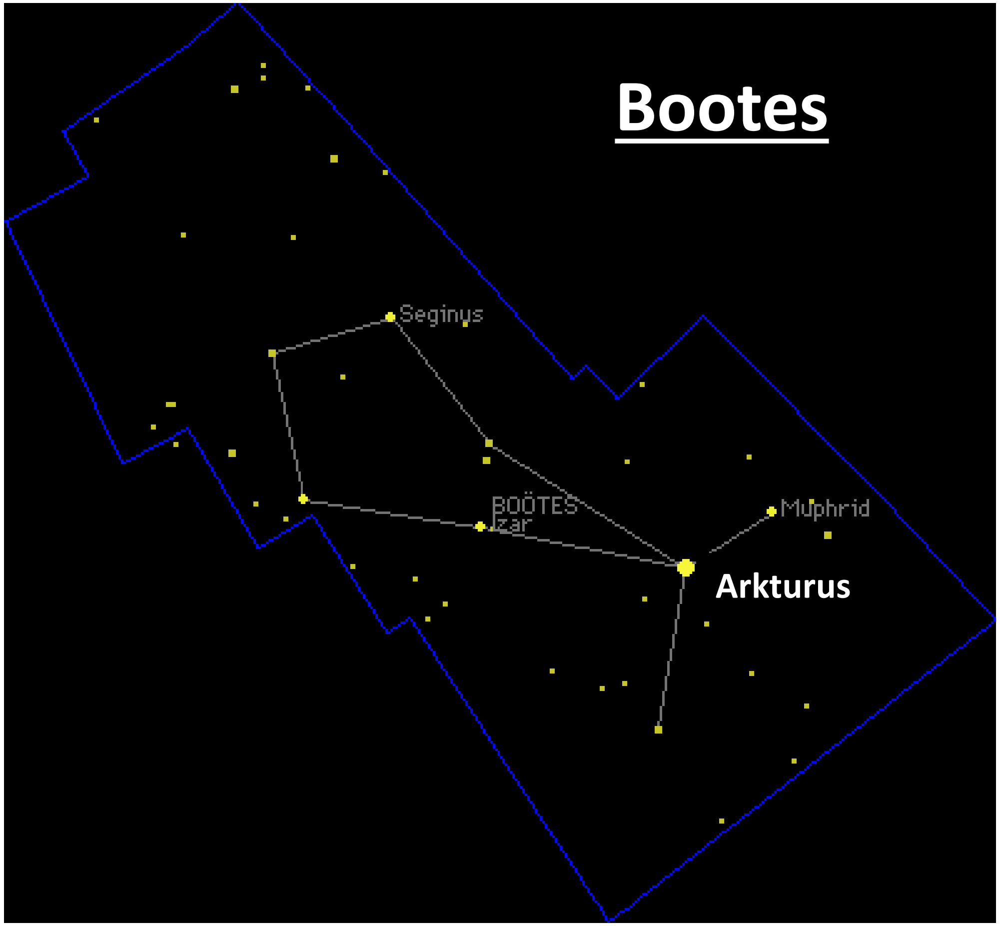


the s-process

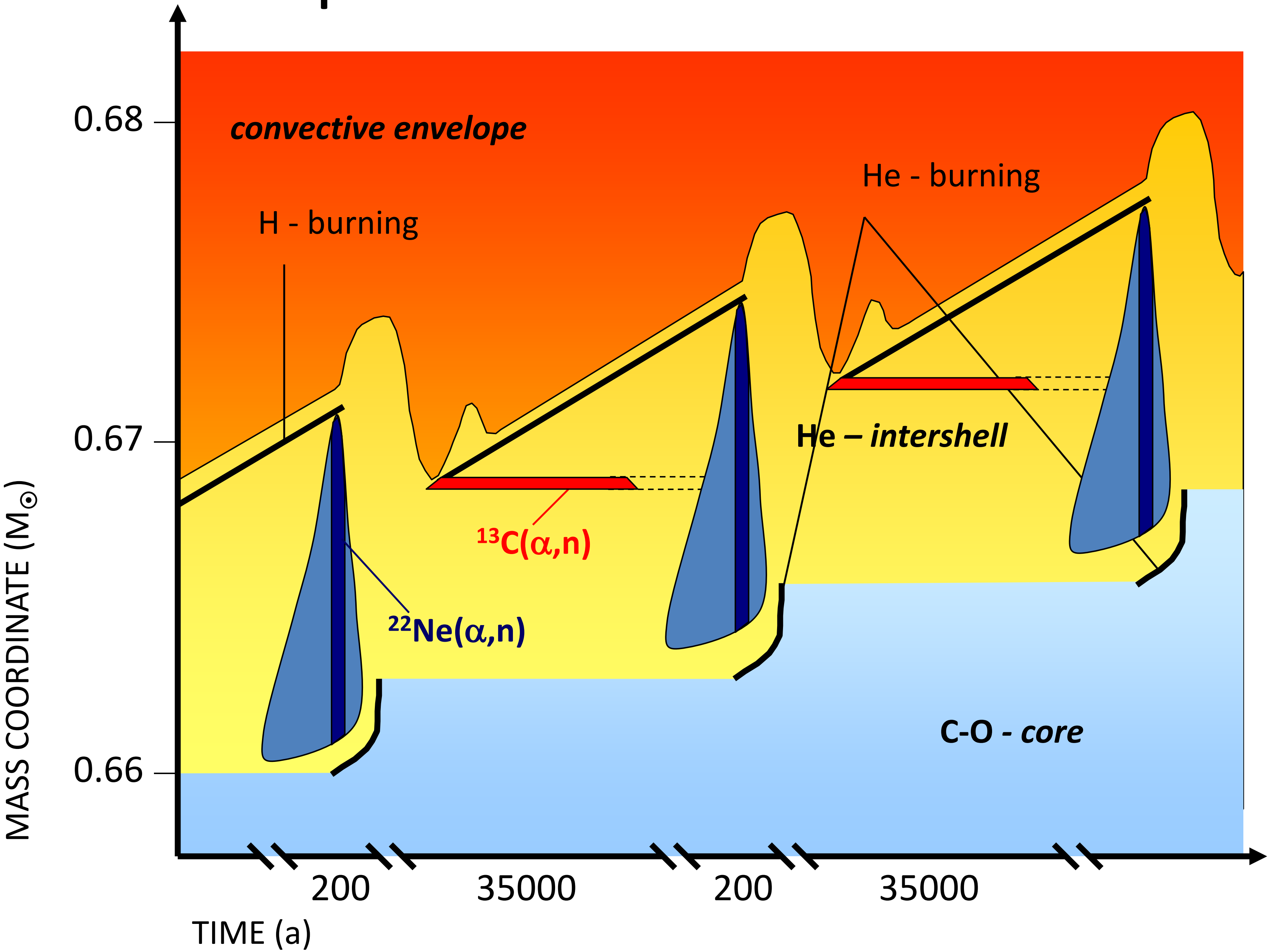


Red Giants – easy to spot

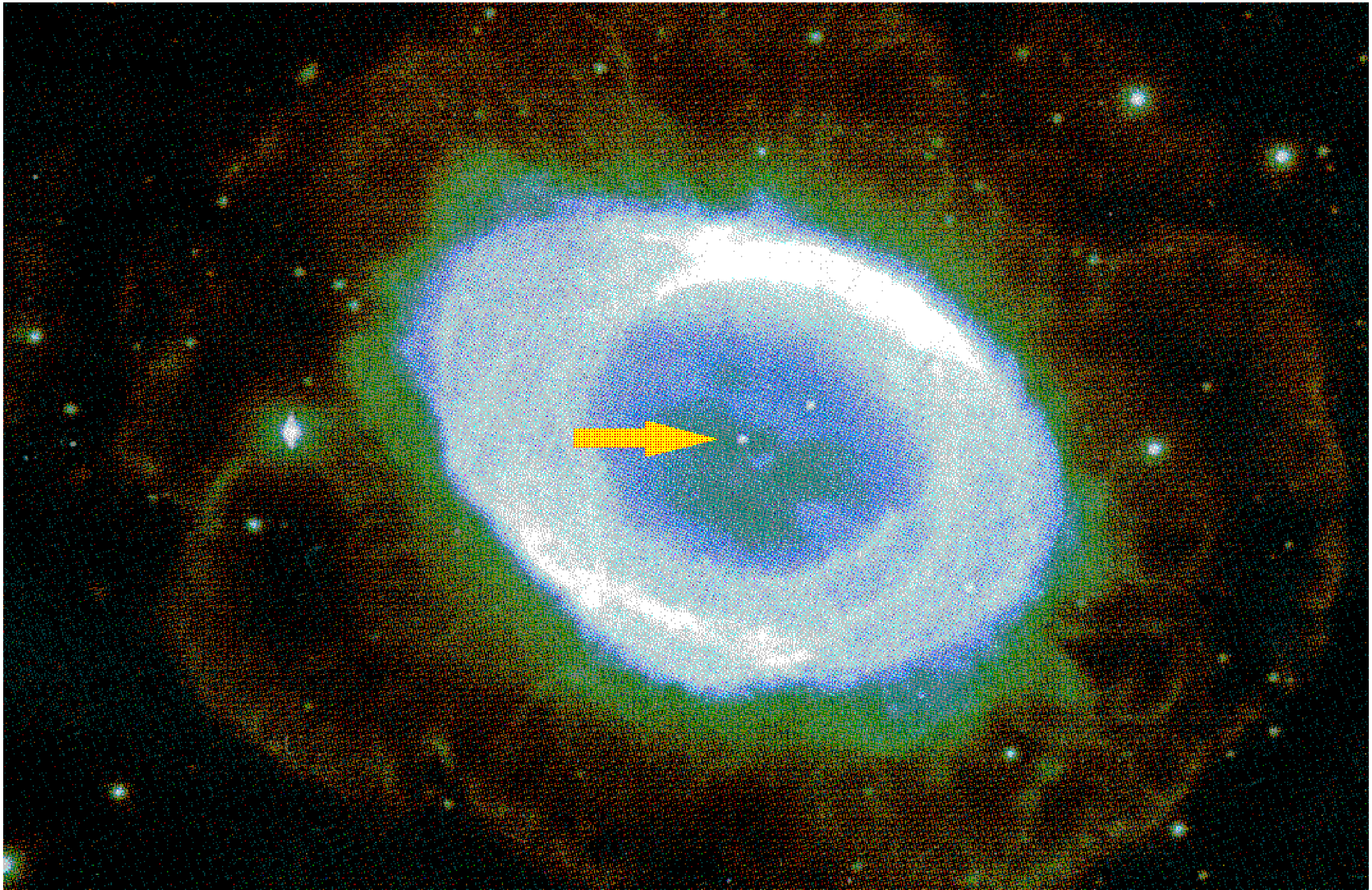




s-process in AGB stars



Red Giants become White Dwarfs

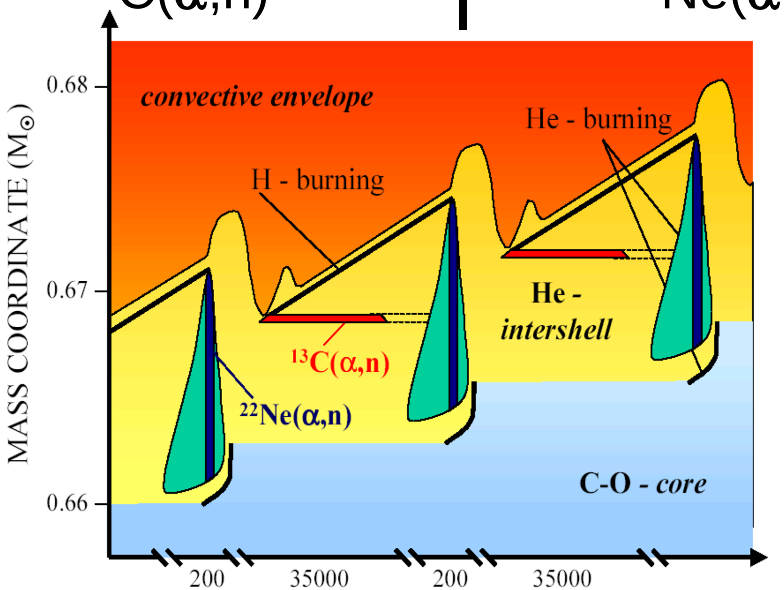


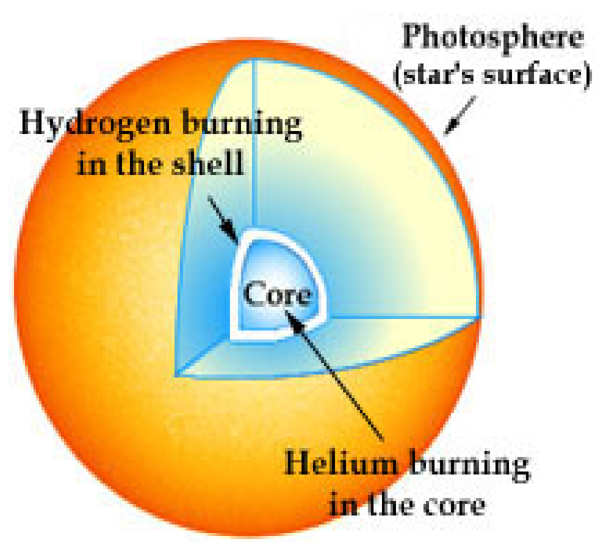
Ring nebula illuminated by the White Dwarf in the center.

s-process nucleosynthesis

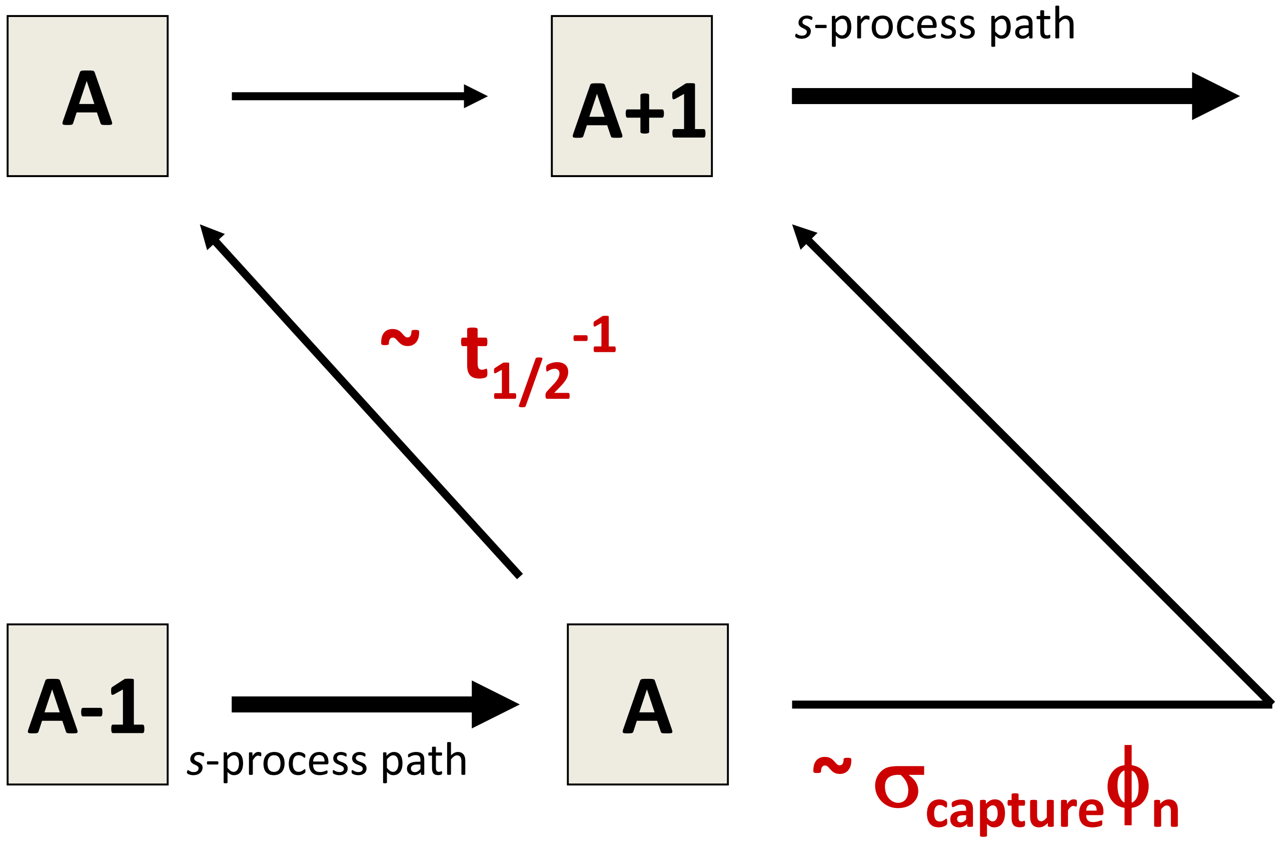
Two components were identified and connected to stellar sites:

Main s-process 90<A<210		**Weak s-process A<90**	
TP-AGB stars 1-3 $M_\odot$		massive stars > 8 $M_\odot$	
shell H-burning $0.9\cdot10^8$ K	He-flash $3\text{-}3.5\cdot10^8$ K	core He-burning $3\text{-}3.5\cdot10^8$ K	shell C-burning $\sim1\cdot10^9$ K
kT=8 keV $10^7\text{-}10^8$ cm^{-3}	kT=25 keV $10^{10}\text{-}10^{11}$ cm^{-3}	kT=25 keV 10^6 cm^{-3}	kT=90 keV $10^{11}\text{-}10^{12}$ cm^{-3}
$^{13}C(\alpha,n)$	$^{22}Ne(\alpha,n)$	$^{22}Ne(\alpha,n)$	

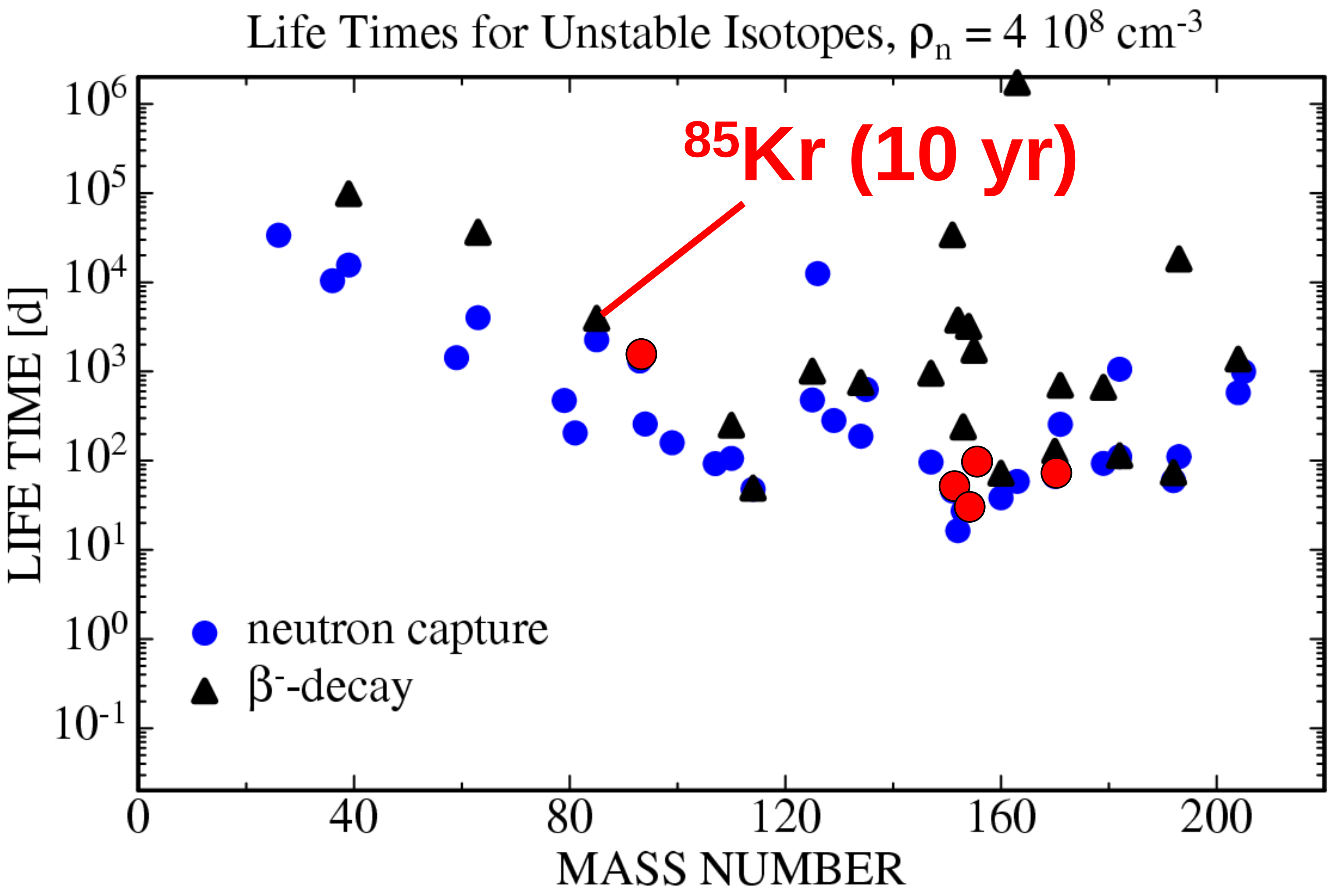




branch point in the s-process path

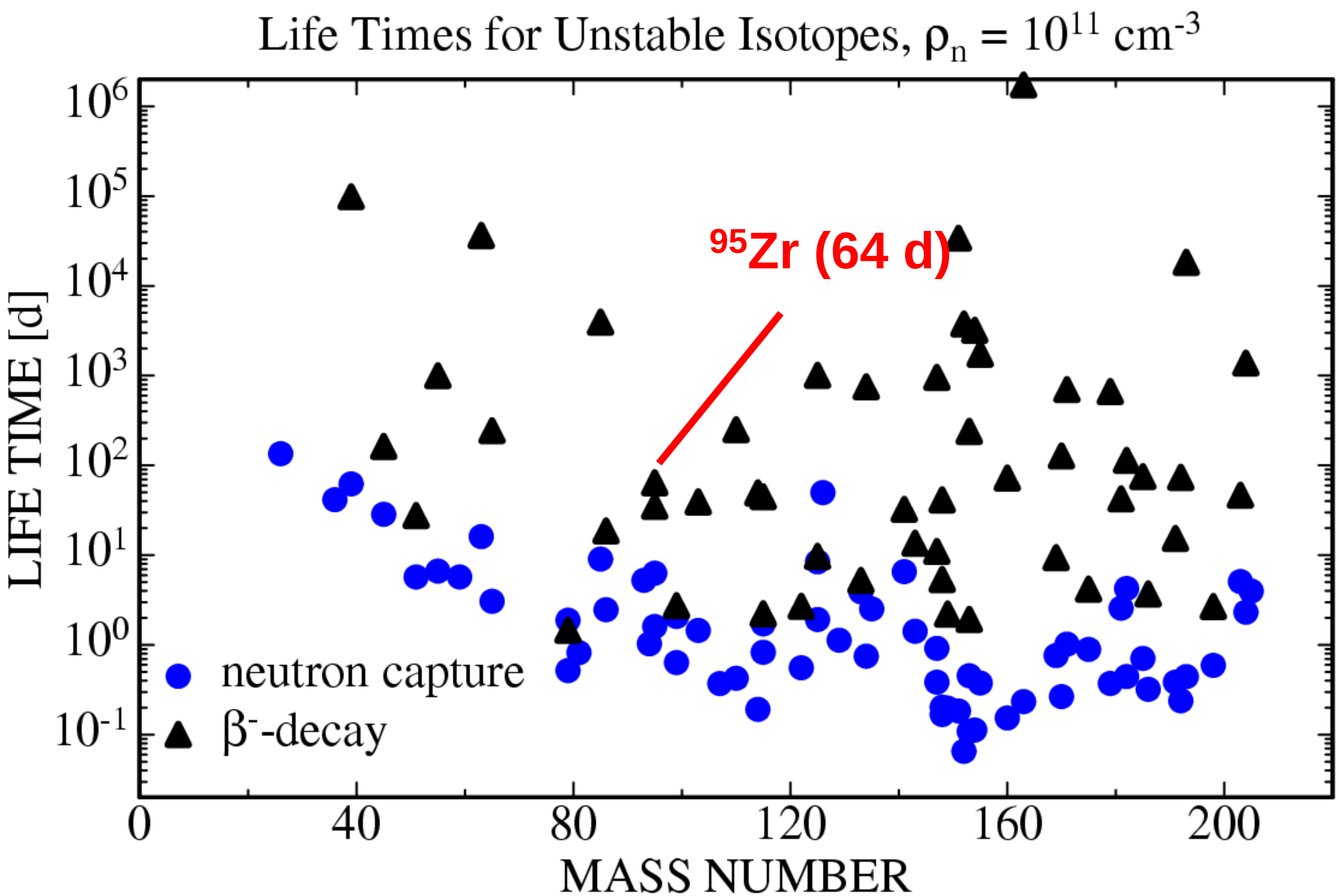


s-process models - classical s-process



$$\lambda_n > \lambda_\beta$$

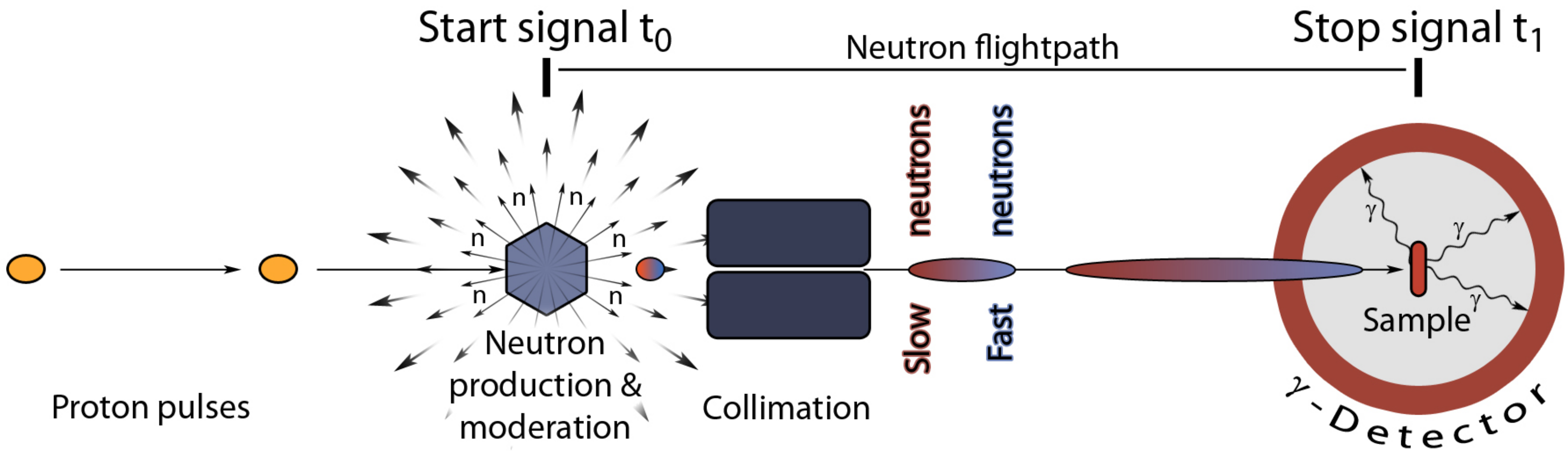
s-process models – T-AGB stars, ^{22}Ne phase



$$\lambda_n > \lambda_\beta$$

Couture & Reifarth, ADNDT, 93 (2007) 807

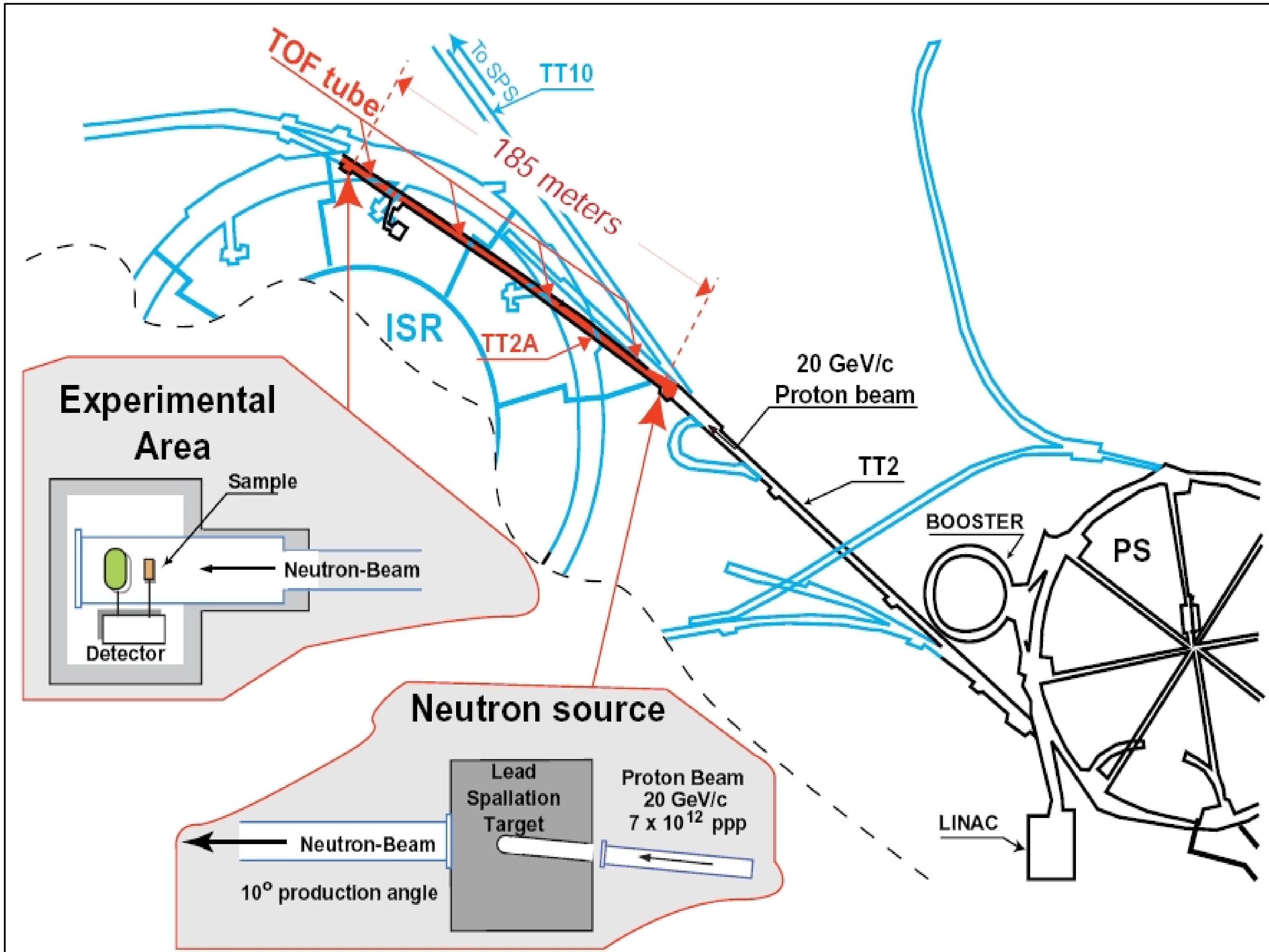
Neutron Captures
time-of-flight technique



Reifarth et al, Journal of Physics G 41 (2014) 53101

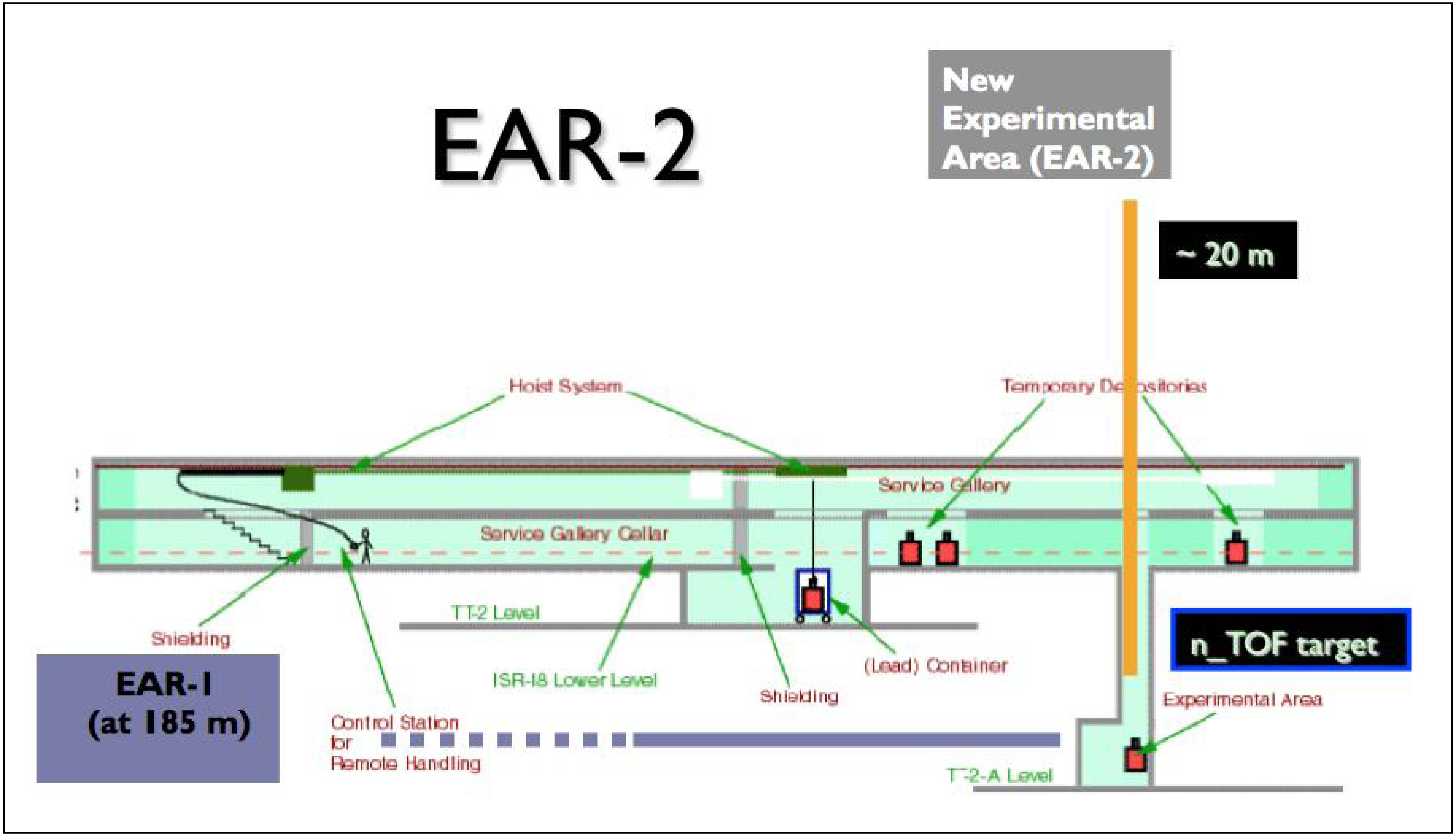
nTOF @ CERN - spallation neutron source

- Δt = 7 ns
- 1-10 s between pulses

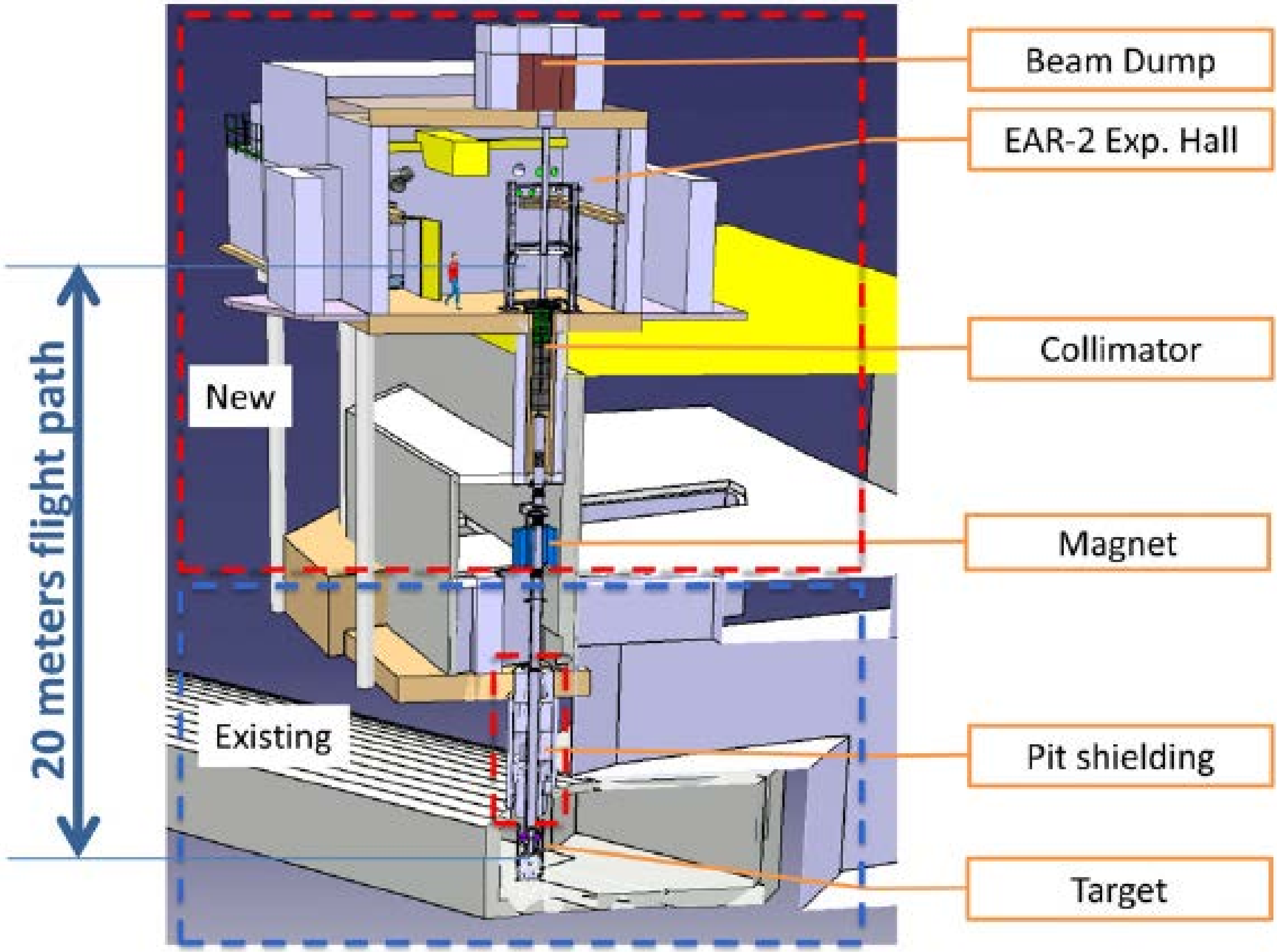


C. Guerrero et al, Eur. Phys. J. A (2013) 49: 27

nTOF @ CERN : 20 m & 200 m

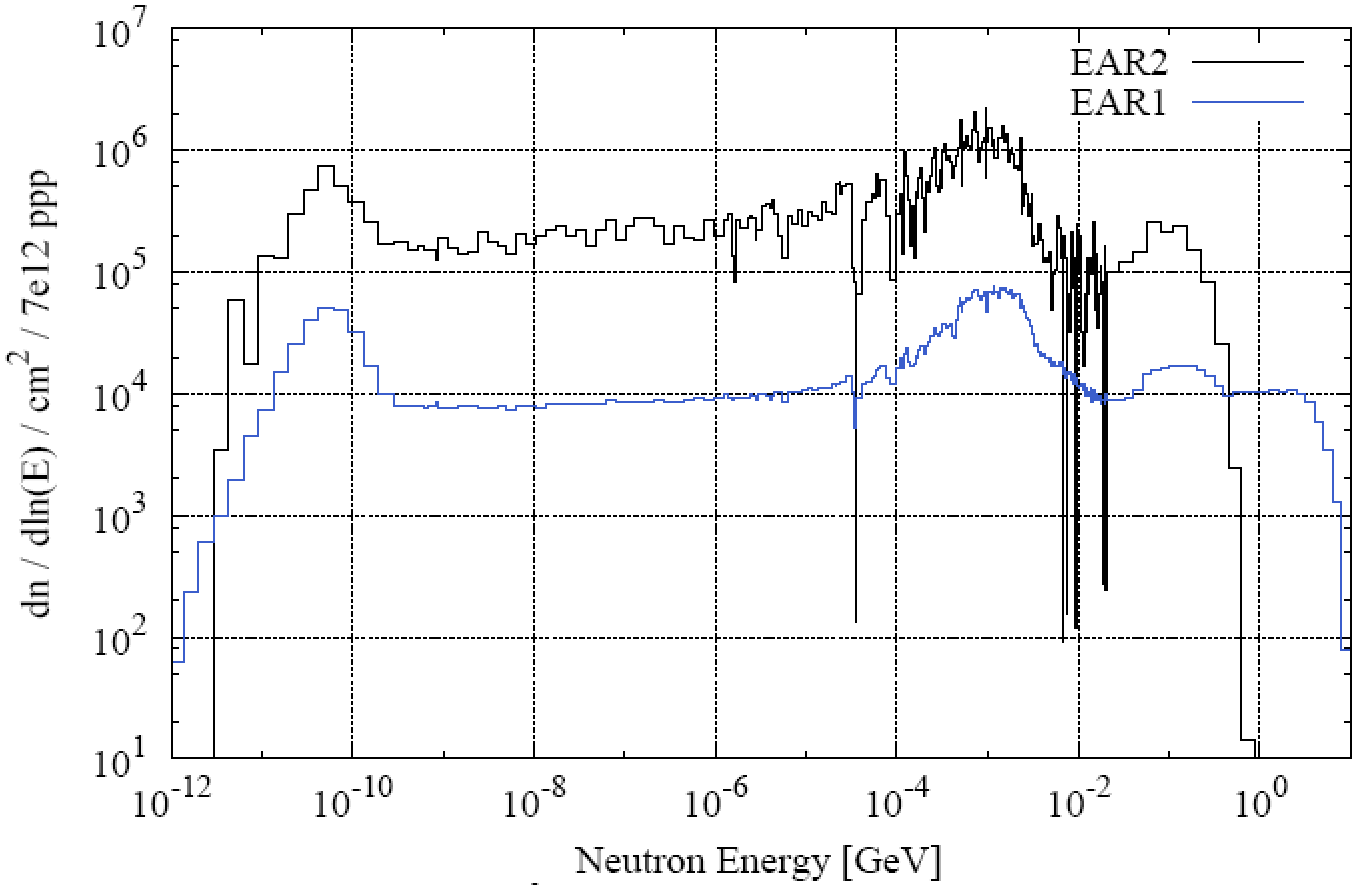


nTOF @ CERN -> EAR2

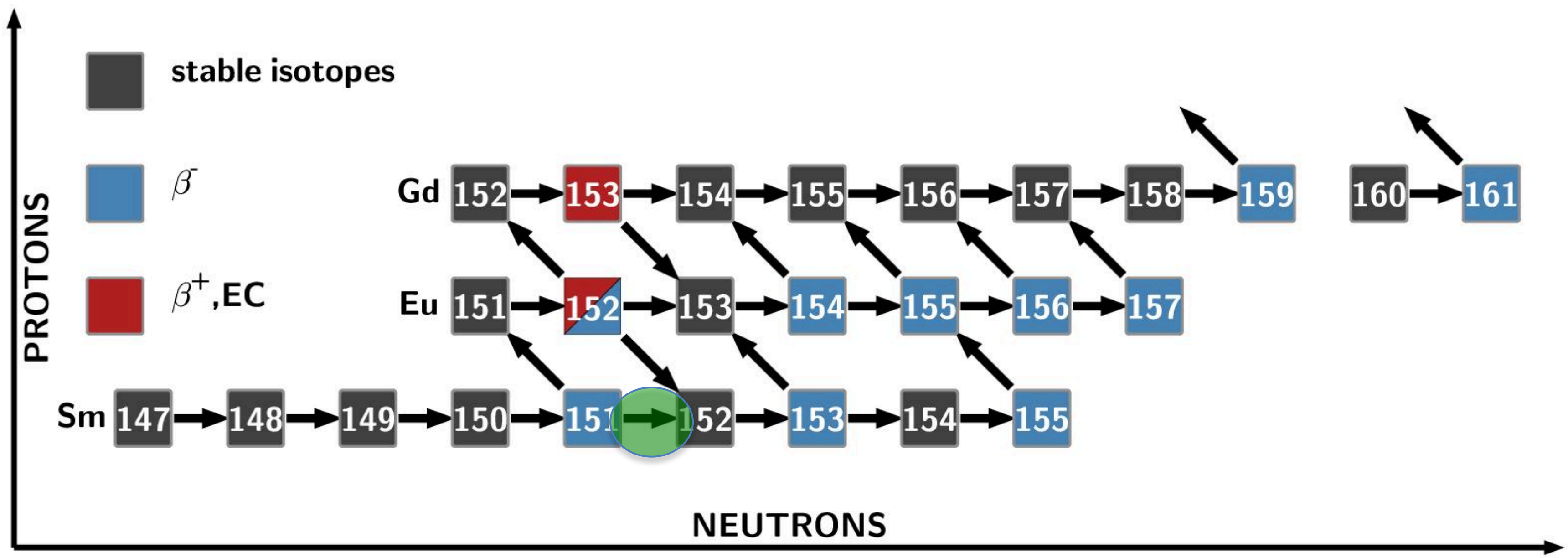


C. Weiß et al, NIM A 799 (2015) 90-98

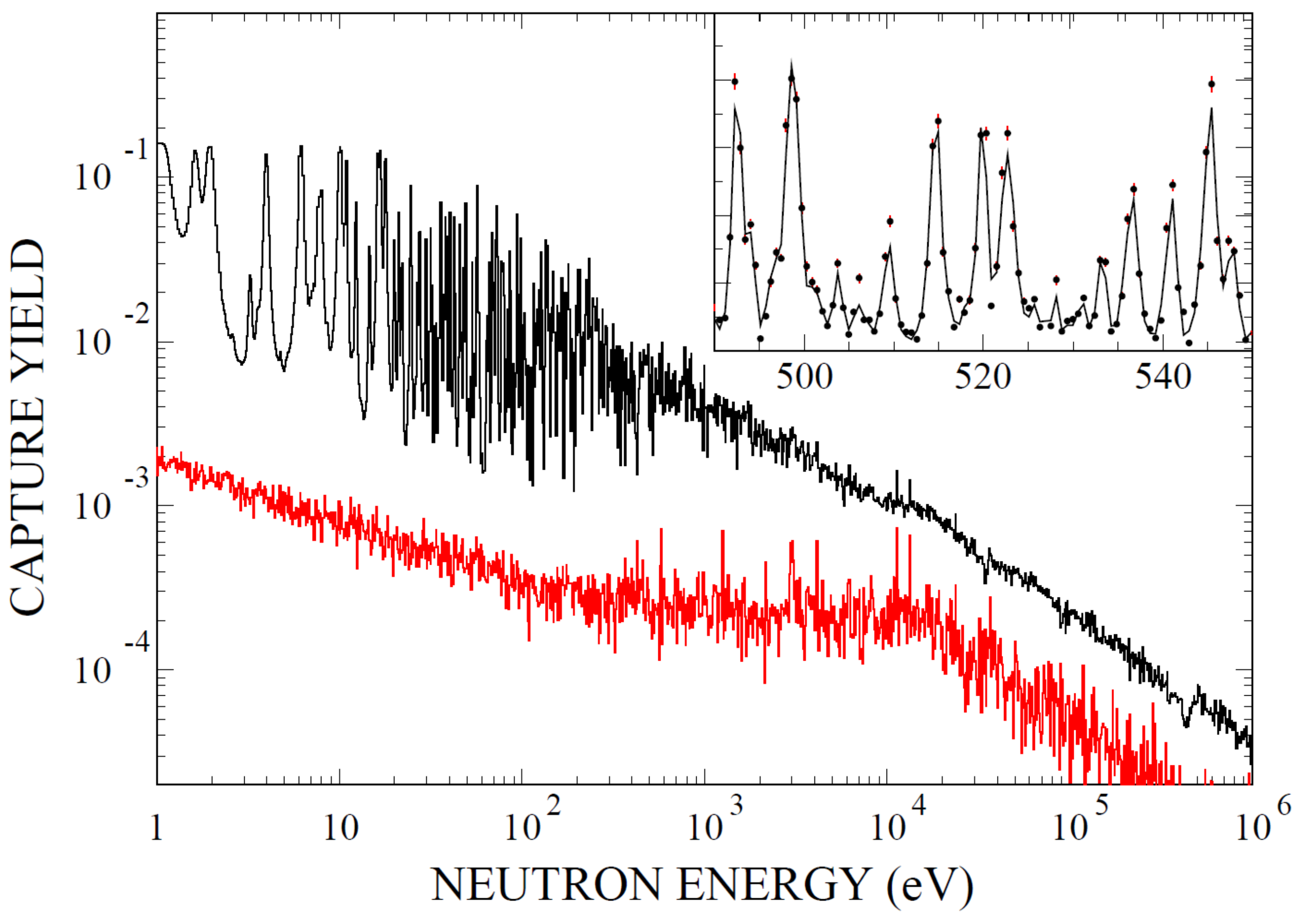
nTOF @ CERN – neutron flux



^{151}Sm – a s-process branch point

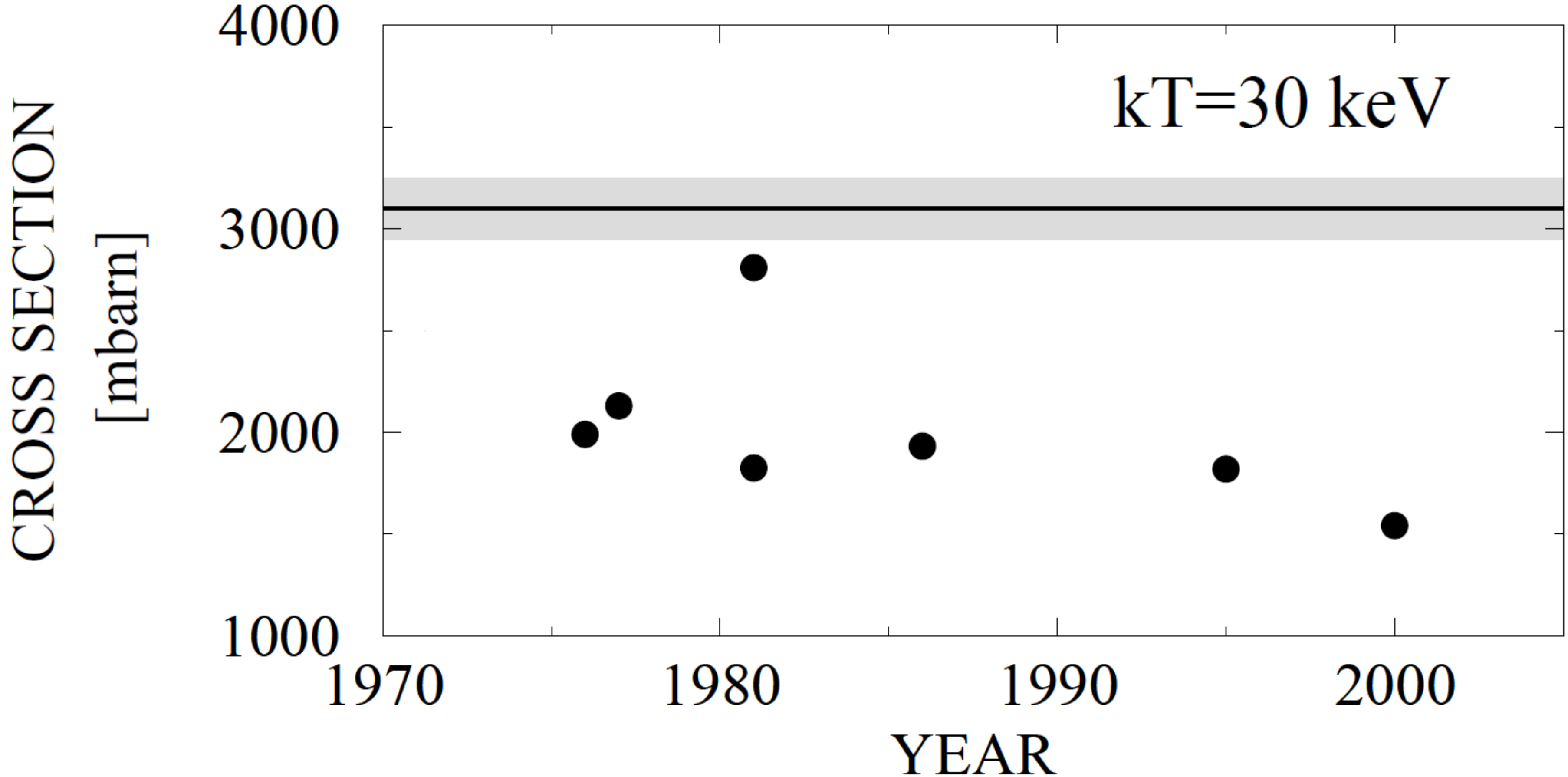


^{151}Sm – measured at nTOF

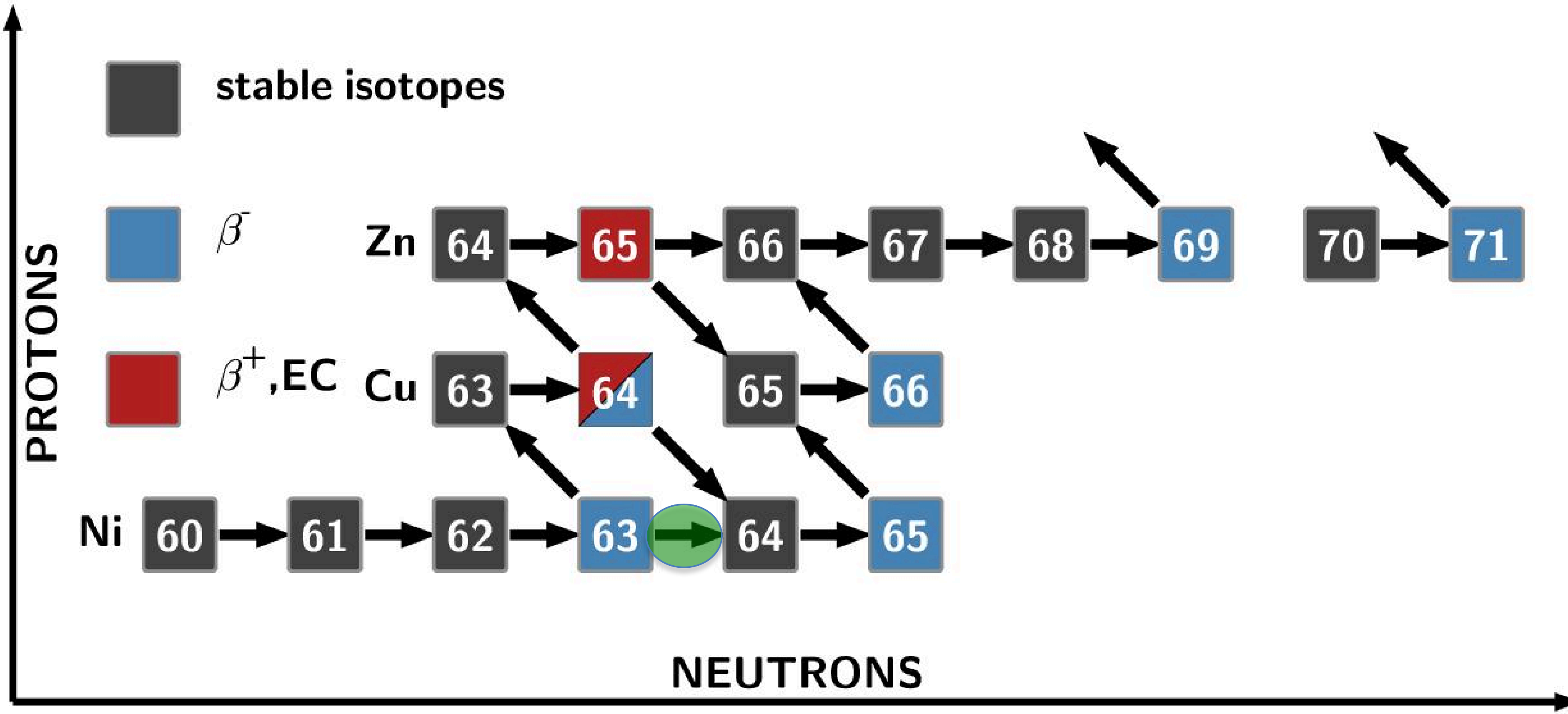


Abbondanno et al, PRL, 93 (2004) 161103

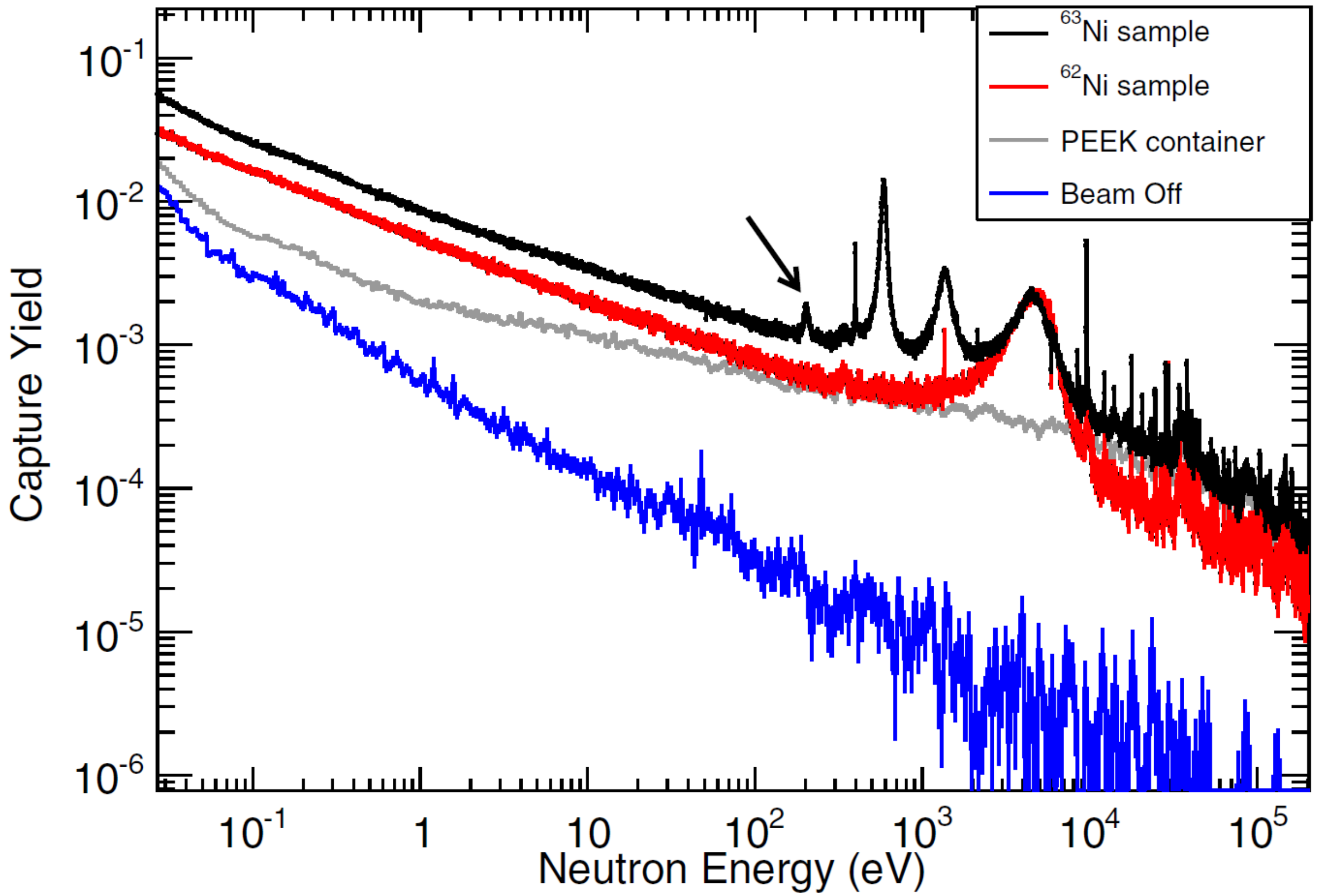
Maxwellian Averaged Cross Section



^{63}Ni – a s-process branch point

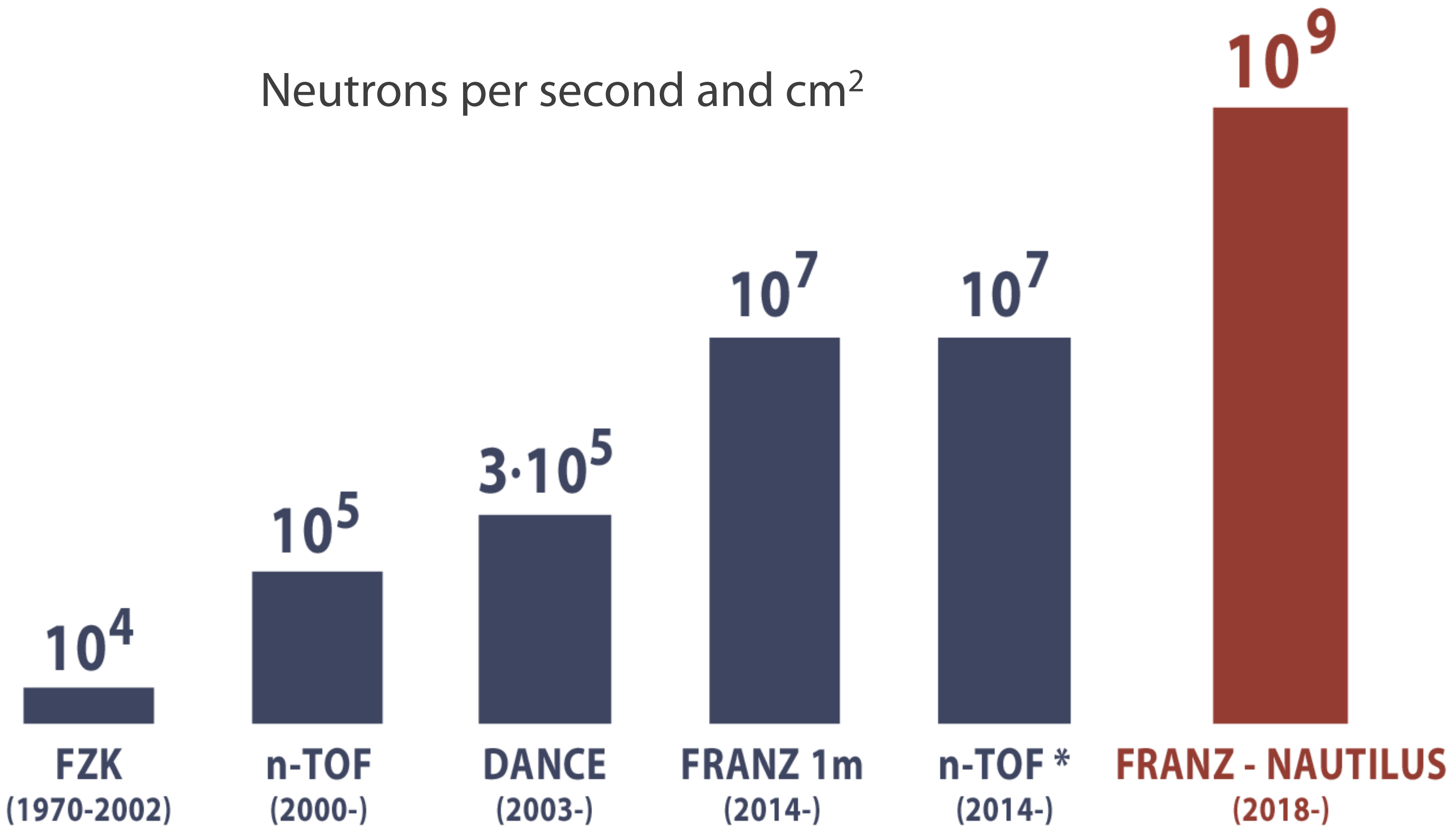


^{63}Ni – measured at nTOF



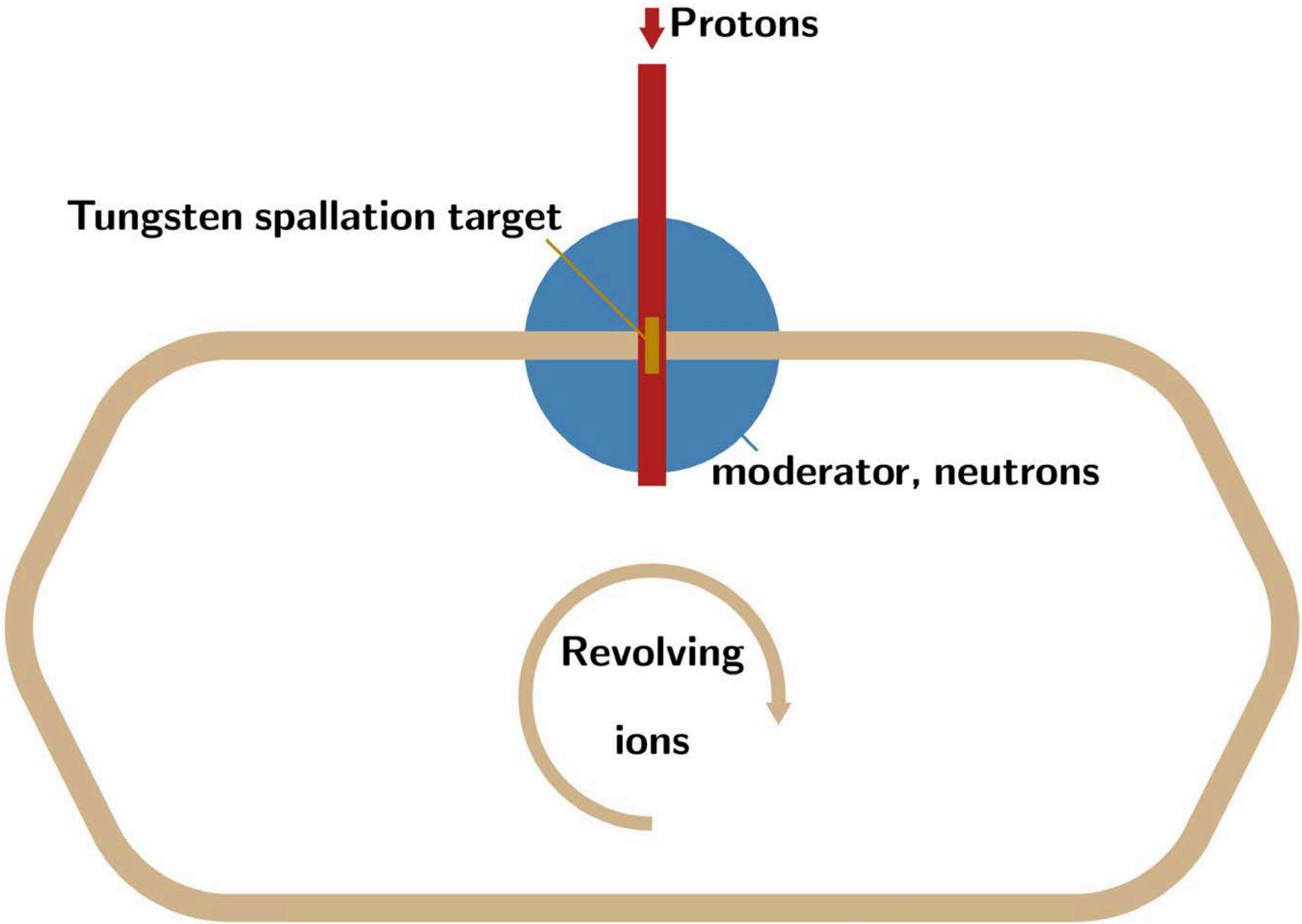
Lederer et al, PRL, 110 (2013) 022501

Neutron flux in astrophysical region



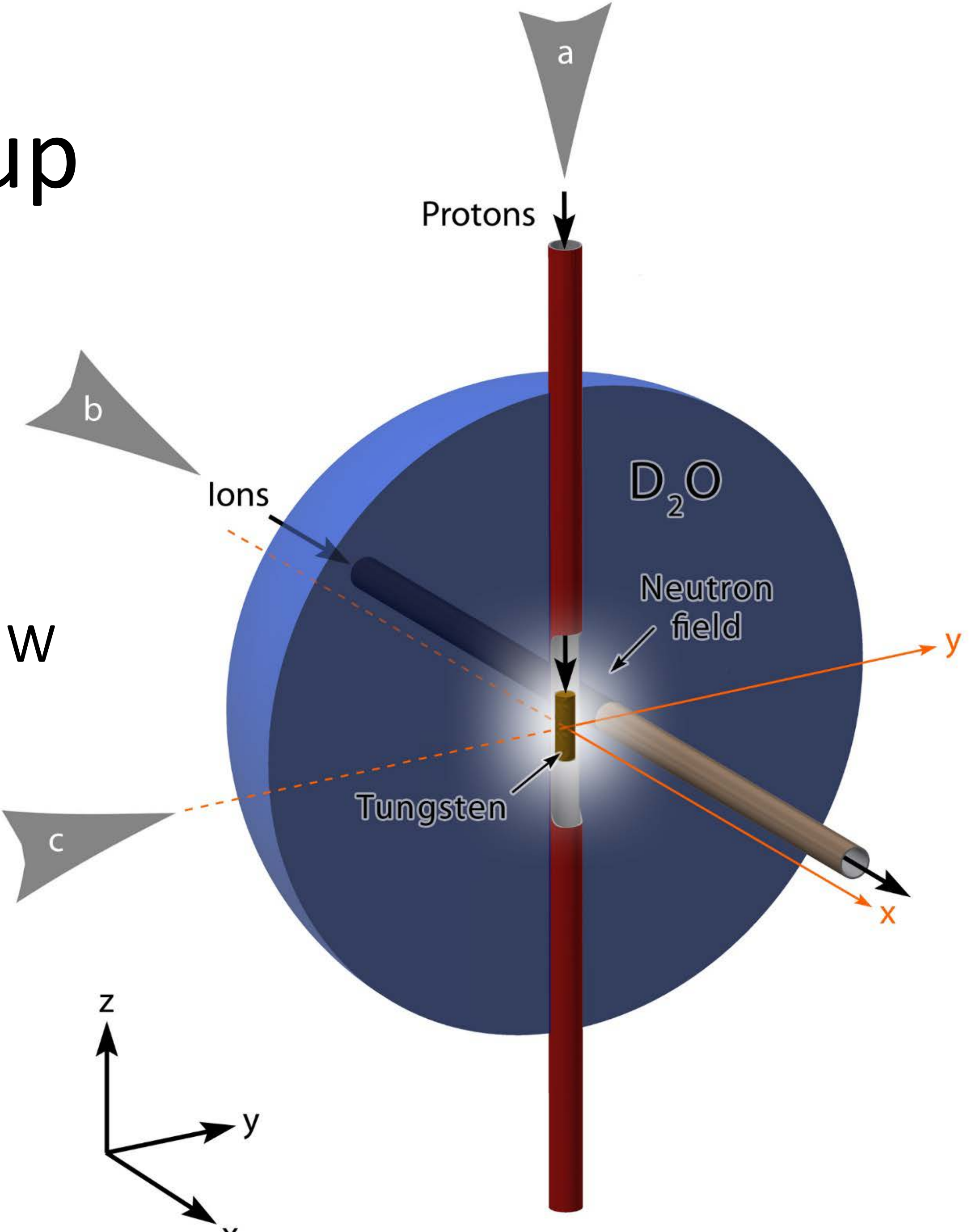
(n,γ) experiments with unstable isotopes and fundamental stellar physics evaluations

Branch Isotope	Half-Life	Facility	Observable	Stellar Physics	Comment
^{151}Sm	93 yr	FZK, n_TOF, DANCE	^{152}Gd in solar distribution ^{151}Eu/^{153}Eu ratio hyperfine line split	**Timescale of hot Helium-shell flash** **s-process in very old stars**	done
^{134}Cs	2 yr	DANCE, FRANZ	Ba isotope ratios from presolar grains	**Sets ^{12}C abundance of He-shell flash**	current uncertainty: ± 30%
^{135}Cs	2 Myr	everywhere	Ba isotope ratios	**Amount of rotation**	± 10%
^{95}Zr	64 d	?inverse?	^{96}/Zr/^{94}Zr ratio presolar grains	**Temperature at bottom of He-shell flash region**	Current uncertainty: 20 - 80 mb


Protons
Tungsten spallation target
moderator, neutrons
Revolving
ions

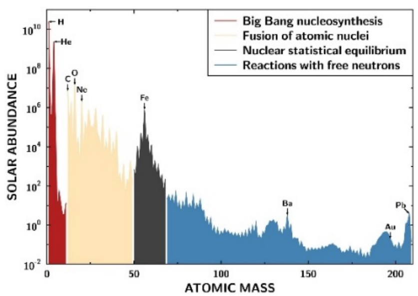
Proposed setup

- Moderator: 0.5-2m D_2O
- Spallation target: 10-50 cm W
- Protons: 0.5 – 50 GeV

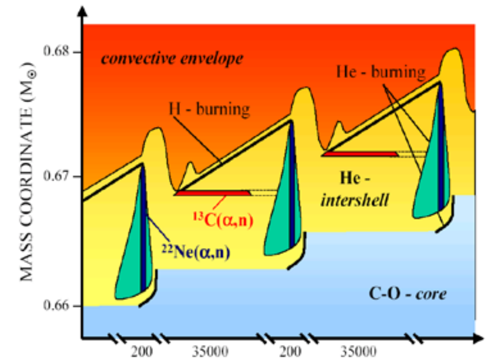


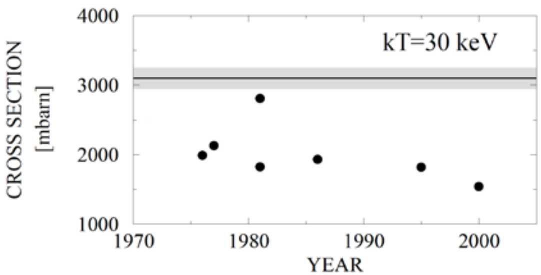
Reifarth et al, Phys. Rev ST Accelerator and Beams, 20, 044701 (2017)

Summary

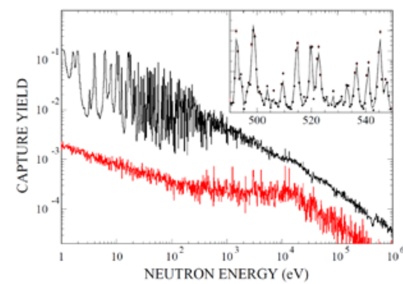


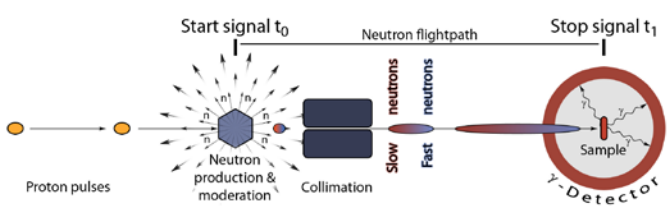
Why?





What?





How?