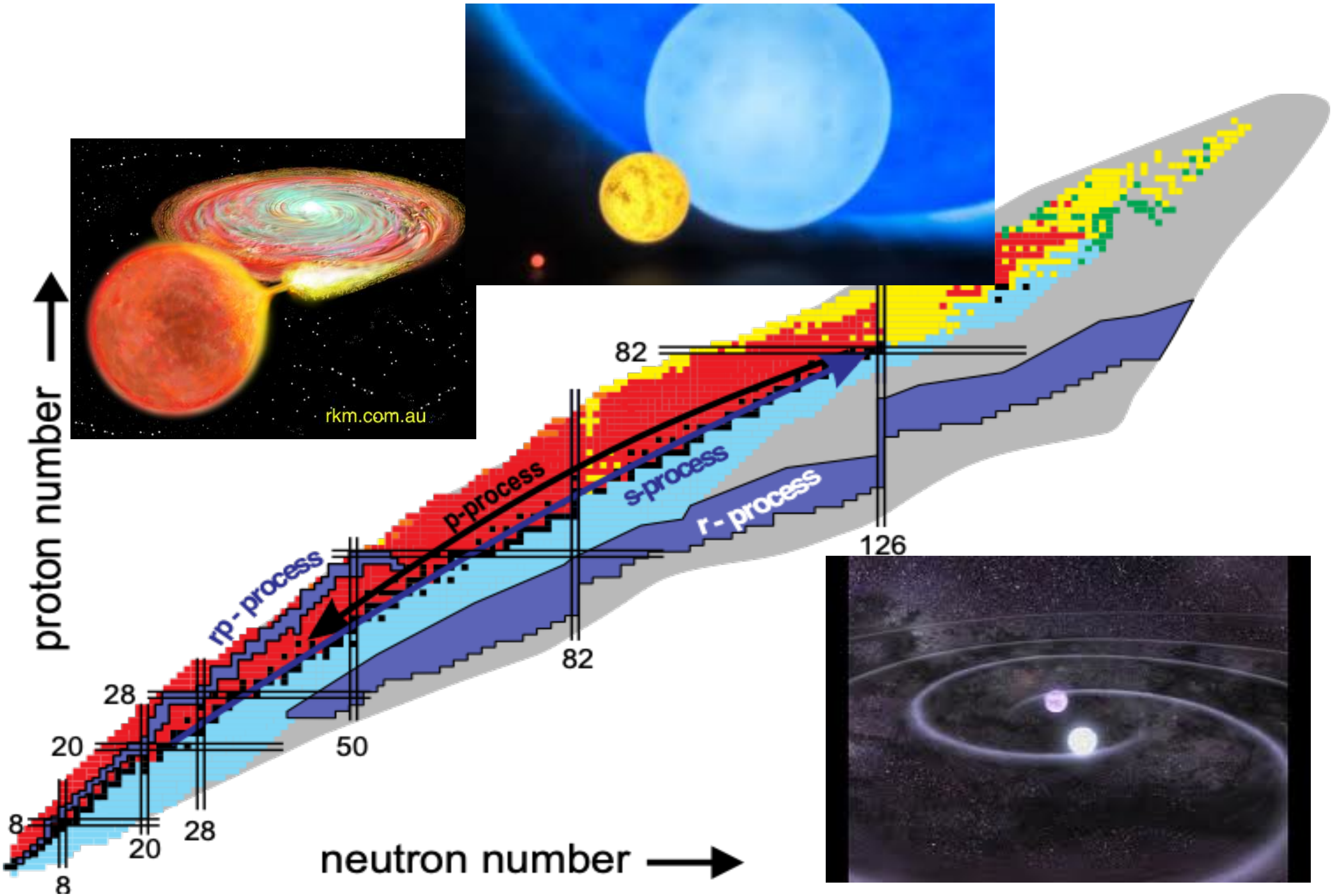
HEAVY ELEMENT PRODUCTION,

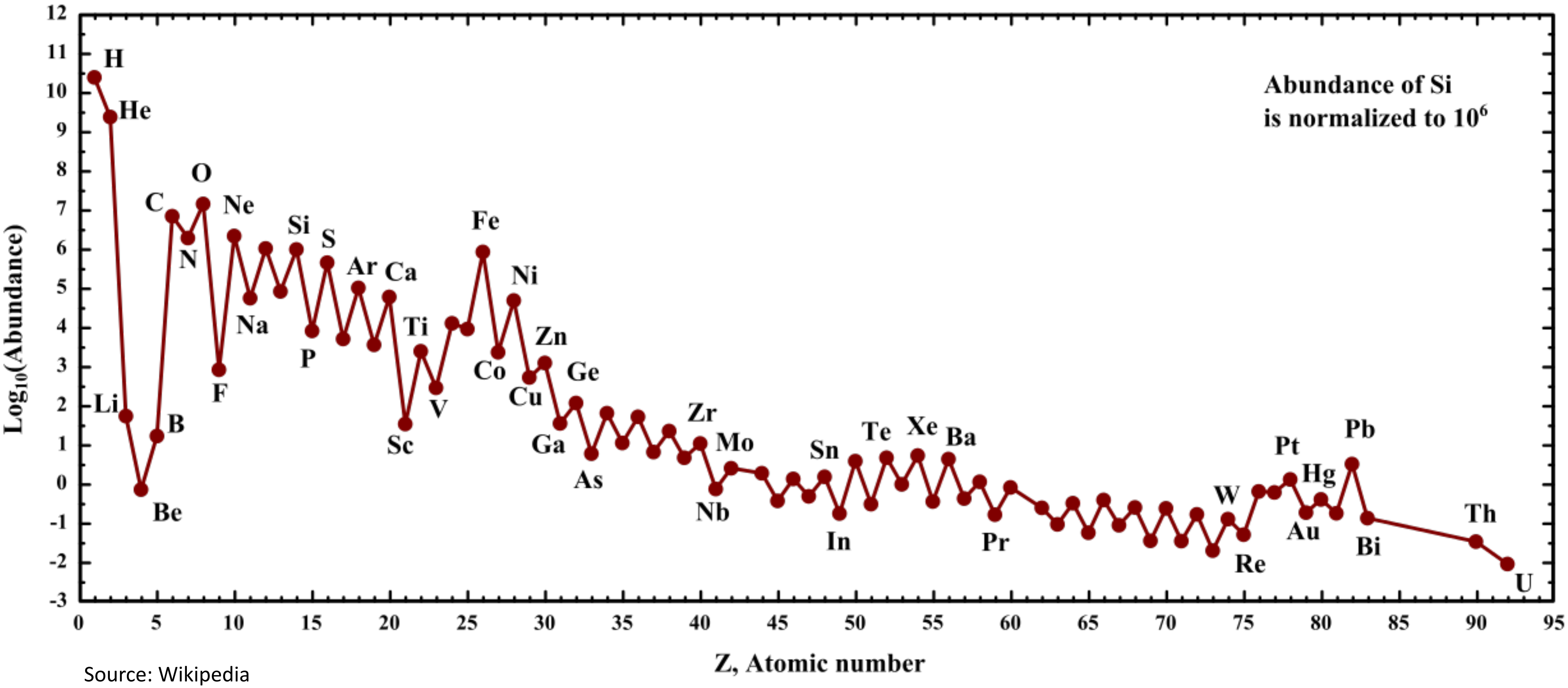
THE R AND S PROCESS

Kai Schweda

Where and how was gold cooked?



SOLAR ABUNDANCES - KEY FACTS



Source: Wikipedia

Decrease in abundance with atomic number:

- Large negative anomaly at Be, B, Li
- Moderate positive anomaly around Fe
- Sawtooth pattern from odd-even effect

THE S-PROCESS

Elements beyond the iron group:

- not produced by charged-particle reactions (Coulomb barrier)
- possibility: neutron captures
- are free neutrons available in stars

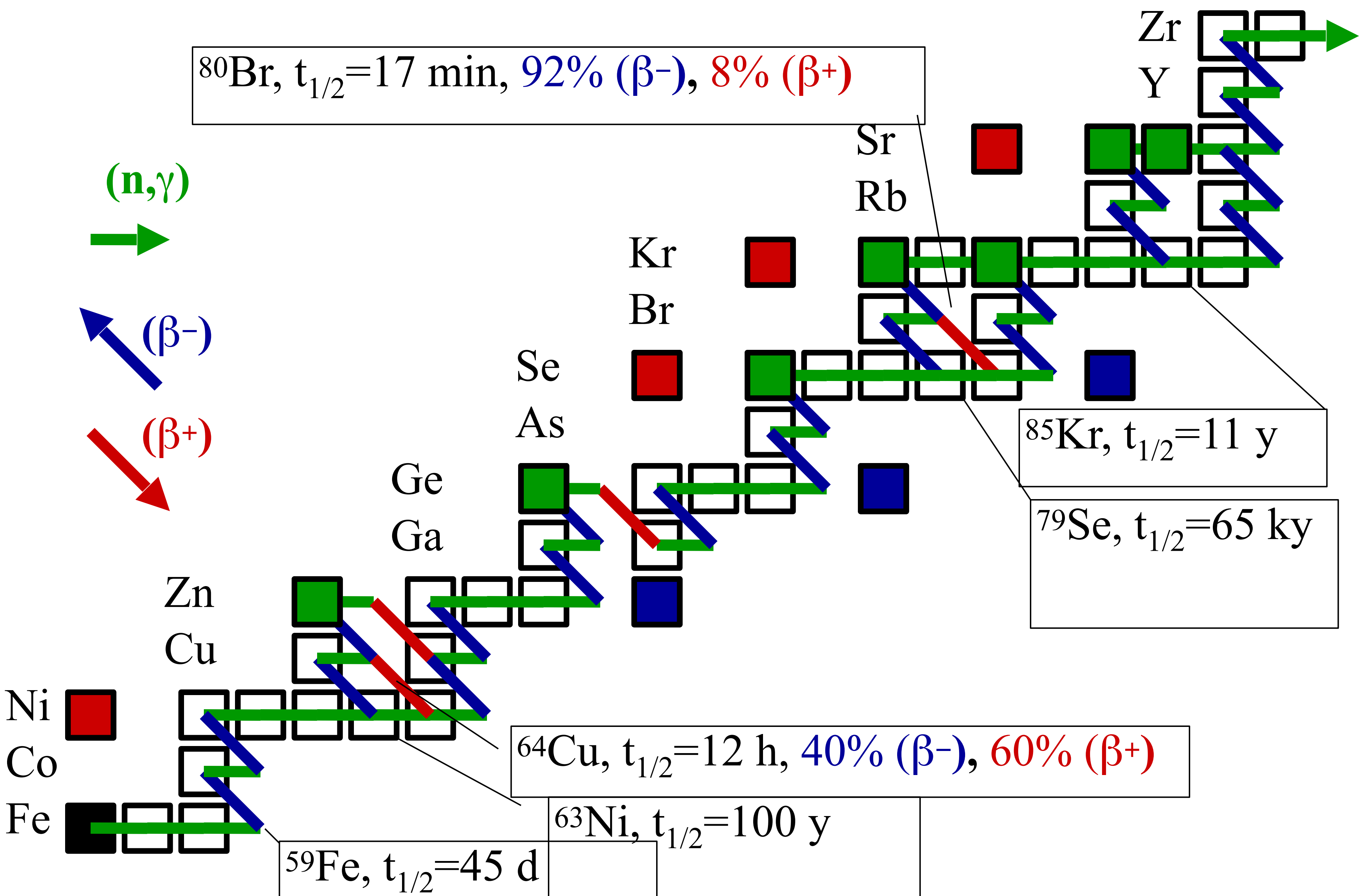
$^{22}\text{Ne}(\alpha, n) \rightarrow^{25} \text{Mg}$

$^{13}\text{C}(\alpha, n) \rightarrow^{16} \text{O}$

β-decay times close to valley of stability ~h,d,y
small compared to stellar evolution time

Slow s-process: τ(n-capture) $\gg$ $\tau(\beta$-decay$)$, read giant phase
Rapid r-process: τ(n-capture) $\ll$ $\tau(\beta$-decay$)$, later, maybe supernova

S-Process: slow neutron capture and beta-decays along the stability valley



^{80}Br, $t_{1/2}$=17 min, 92% (β−), 8% (β+)

^{85}Kr, $t_{1/2}$=11 y

^{79}Se, $t_{1/2}$=65 ky

^{64}Cu, $t_{1/2}$=12 h, 40% (β−), 60% (β+)

^{63}Ni, $t_{1/2}$=100 y

^{59}Fe, $t_{1/2}$=45 d

NEUTRON CAPTURE CROSS SECTION

no Coulomb barrier

for thermal energies: often $\sigma(v) \sim \frac{1}{v}$

cross section increases for low energy

$\langle \sigma v \rangle = \int_0^{\mathrm{inf}} \sigma v \Phi(v) dv \sim C \cdot \int_0^{\mathrm{inf}} \Phi(v) dv =$ constant

weak energy dependence of $\langle \sigma v \rangle$

define $\langle \sigma \rangle := \frac{\langle \sigma v \rangle}{v_T}$, with $v_T = = \left(\frac{2kT}{\mu_n} \right)^{\frac{1}{2}}, \; \mu_n = \frac{m_n m_A}{mN + m_A}$

often: $\langle \sigma \rangle \approx \sigma(v_T)$

exceptions: close to magic numbers $\sigma \downarrow$

light elements, more complicated

TIME SCALE

$T = 1 - 2 \cdot 10^8\text{K}$

$k_B T \approx 20\text{keV}, v = 2 \cdot 10^6\text{m/s}$

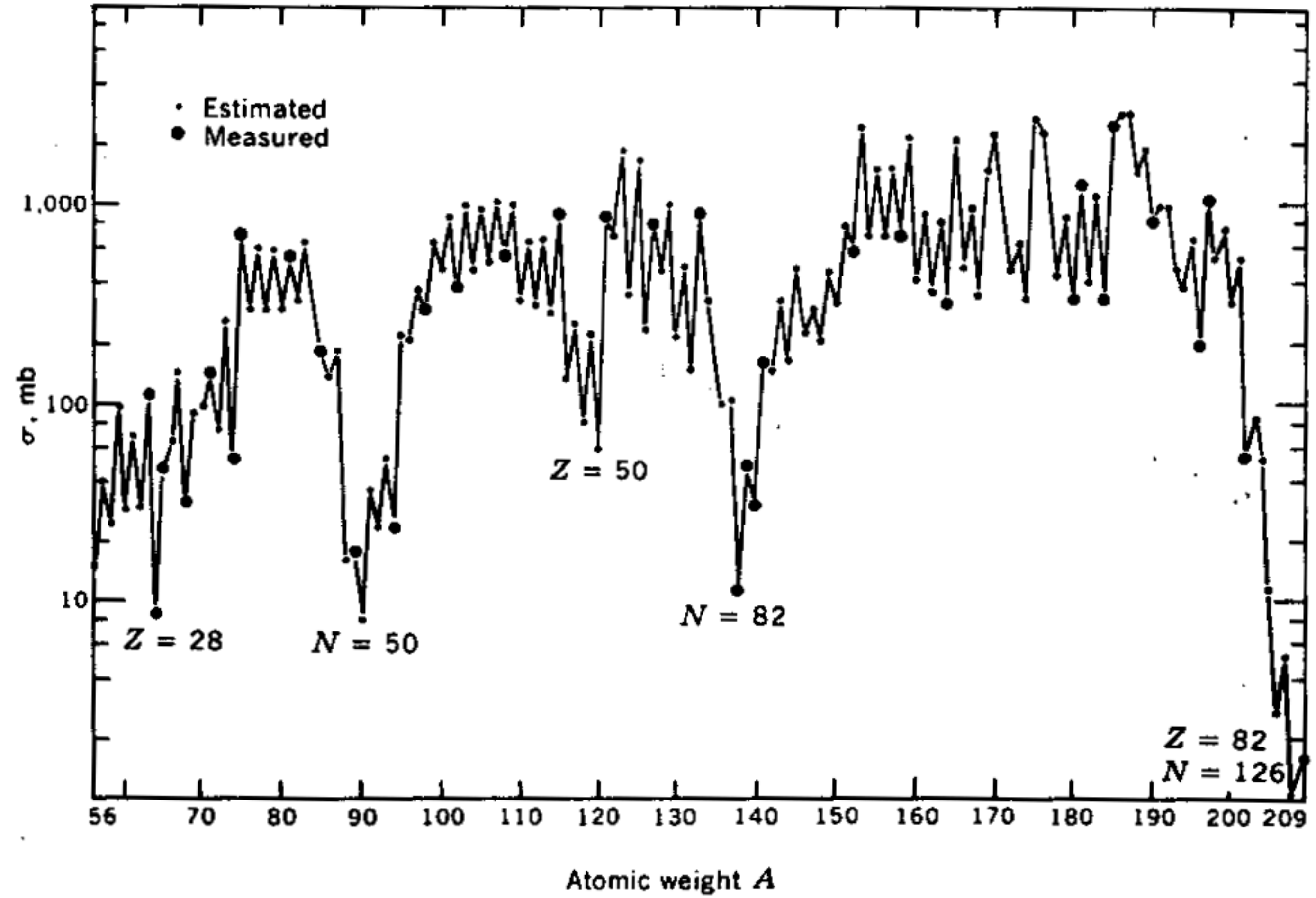
$n_n = 10^{14}/\text{m}^3$

rate $\approx n_n \langle \sigma v \rangle, \sigma \approx 0.1b = 10^{-29}\text{m}^2$

rate $\approx 10^{14}\text{m}^{-3} \cdot\ 2 \cdot 10^6\text{m/s} \cdot 10^{-29}\ \text{m}^2 = 2 \cdot 10^{-9}\text{s}^{-1}$

1 neutron capture in 20 years : slow (!)

CROSS SECTION TO NEUTRON CAPTURE



Drop by factor of 100 - 1000 around closed shells

NEUTRON CROSS SECTION X SOLAR ABUNDANCE

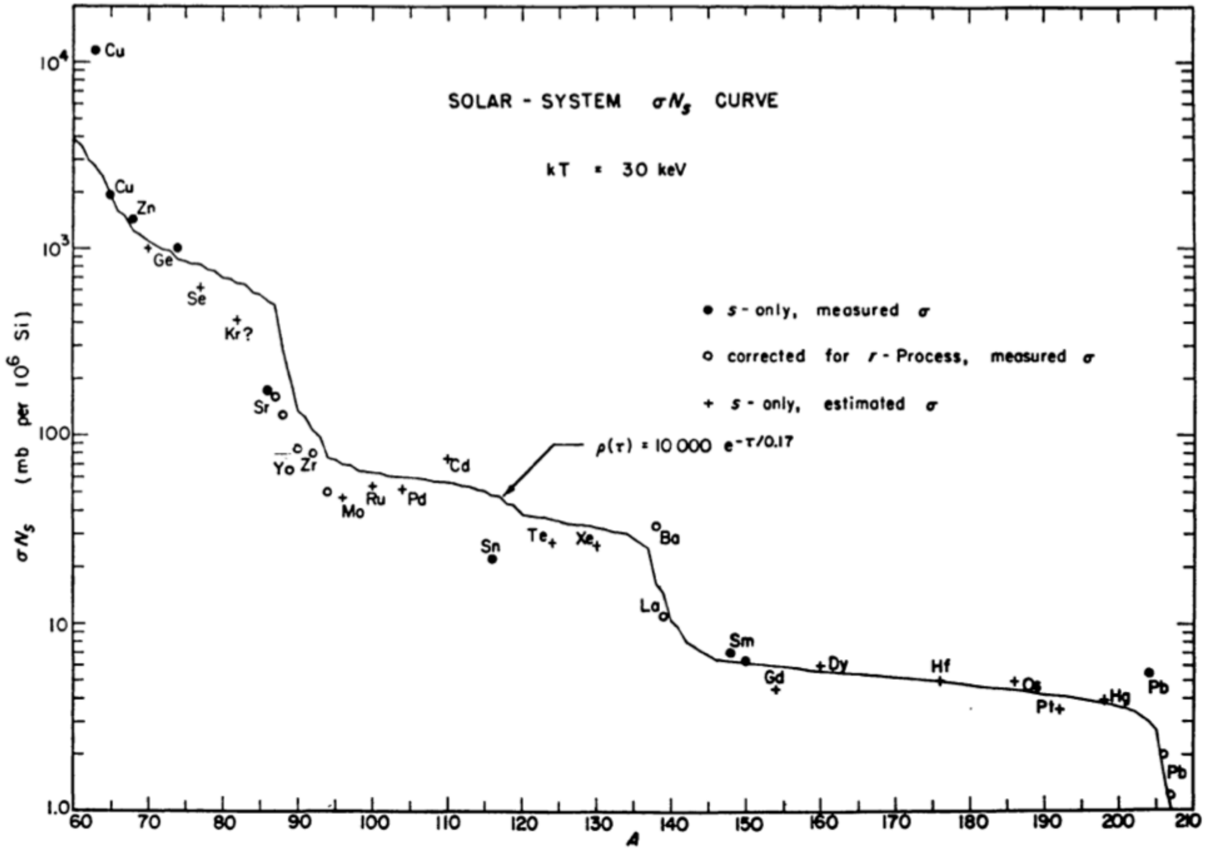
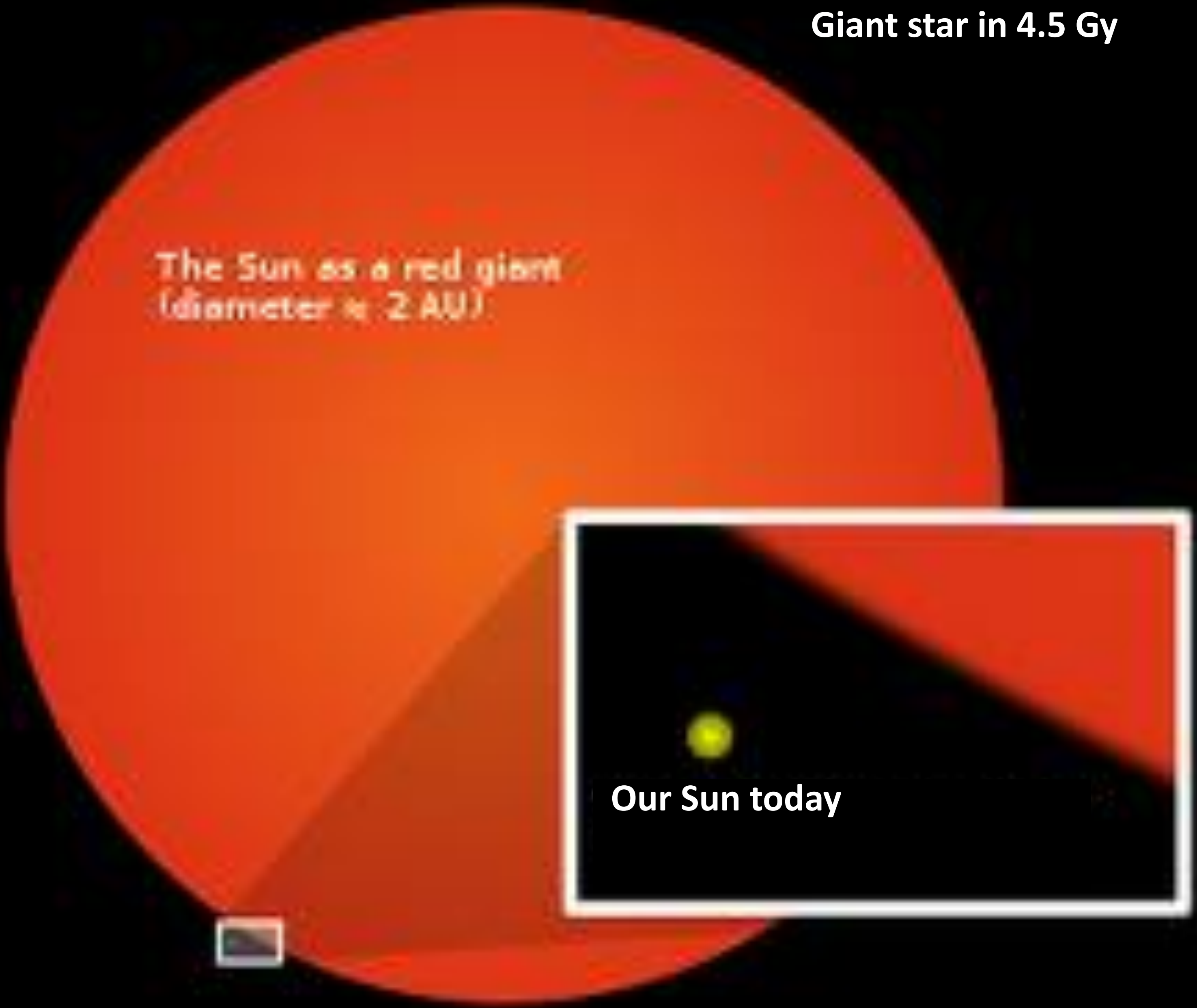


FIG. 1.—Solar-system σN_s-curve. The product of the neutron-capture cross-section at $kT = 30$ keV (in mb) times isotopic abundance (Si = 10^6) is plotted versus atomic mass number A. The solid line is a calculated curve corresponding to an exponential distribution of integrated neutron flux.

Seagar, Fowler, and Clayton 1965

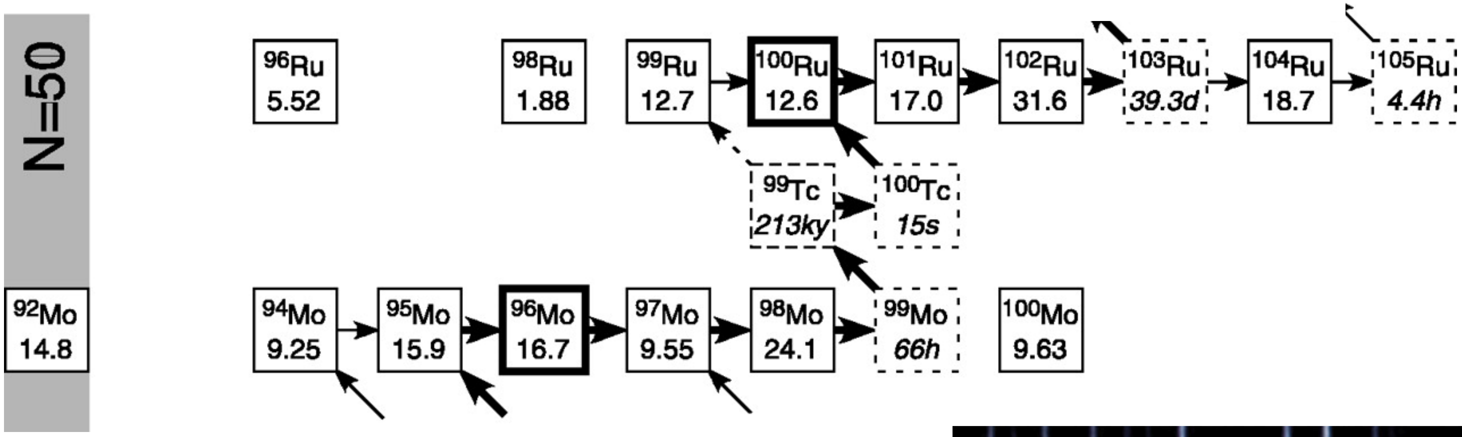
steady state: $$\frac{dN_A}{d\tau} = -\,n_A\sigma_A + n_{A-1}\sigma_{A-1} = 0$$

Our sun as a Red Giant star in 4.5 Gy



Our Sun today

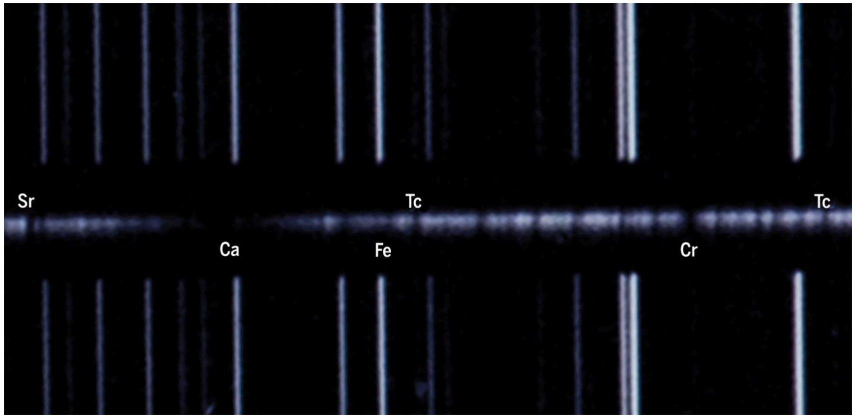
Z=43 TECHNETIUM



^{97}Tc, $T_{1/2}$ = 4.2 My

^{99}Tc, $T_{1/2}$ = 0.2 My

Asymptotic Giant Branch stars (>1Gy) must be produced in s-process



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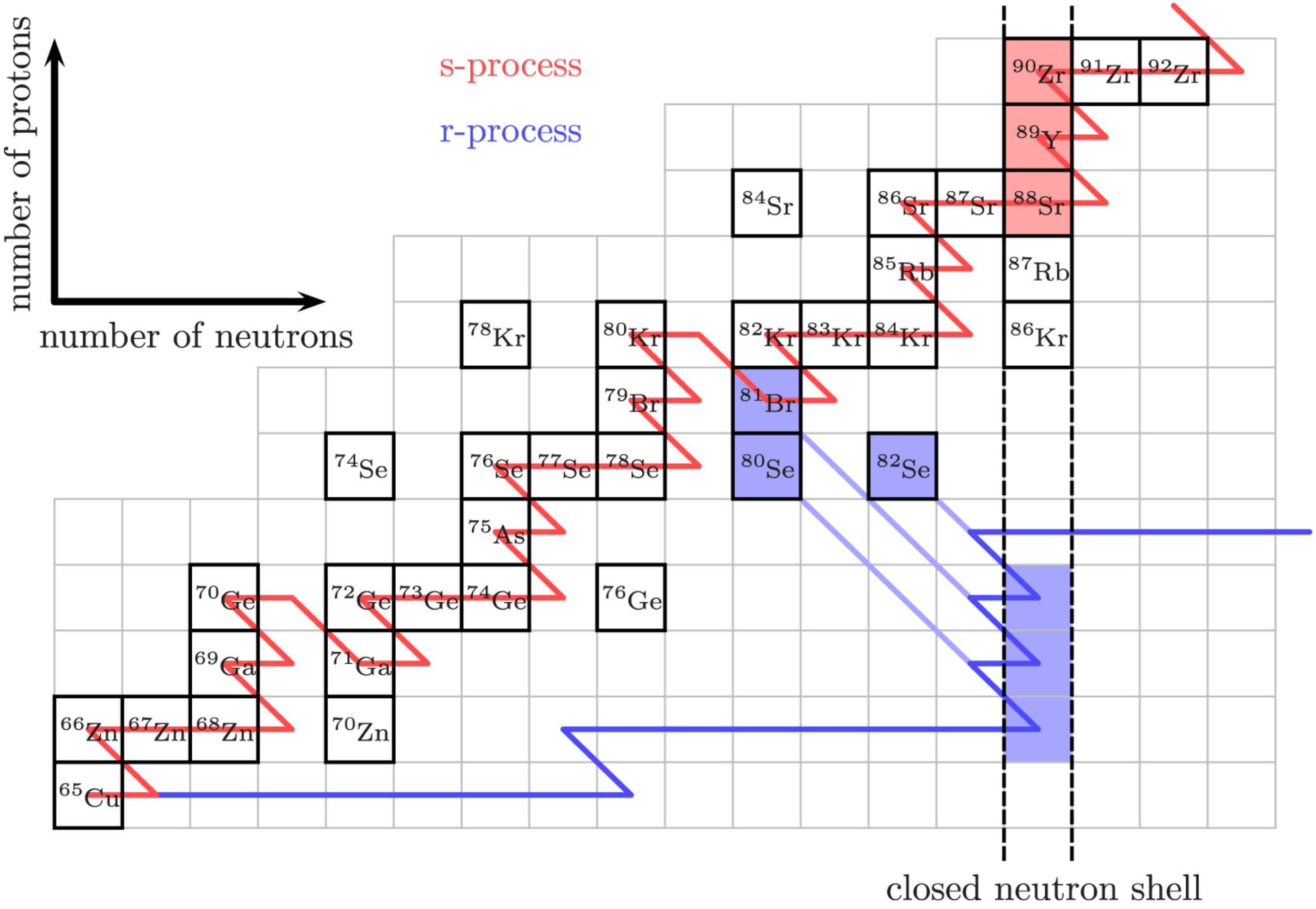
R-PROCESS CONSIDERATIONS

- if neutrons are to produce the r-process nuclei then β-decay must be responsible for the increase in proton number along the r-process path
- protons would combine with neutrons and end up in helium.
- neutron density must be high because the abundances themselves indicate a path that is very neutron-rich and because only very neutron-rich nuclei have sufficiently short β-decay lifetimes to decay and reach, e.g., Uranium
- beta decay lifetimes of neutron- ich nuclei become increasingly short due to
  large Q-value for decay
  the lifetime goes roughly as the available energy to the fifth power
- typical time for the total r-process is just a few seconds
- Neutron rich nuclei have smaller neutron capture cross sections because Qn decreases, eventually approaching zero

R-PROCESS AND S-PROCESS



The r-process elements are created when the neutron rich elements undergo beta decay.

HOW IT WORKS

The r-process proceeds by rapidly capturing neutrons while keeping Z constant, until a”waiting point” is reached.

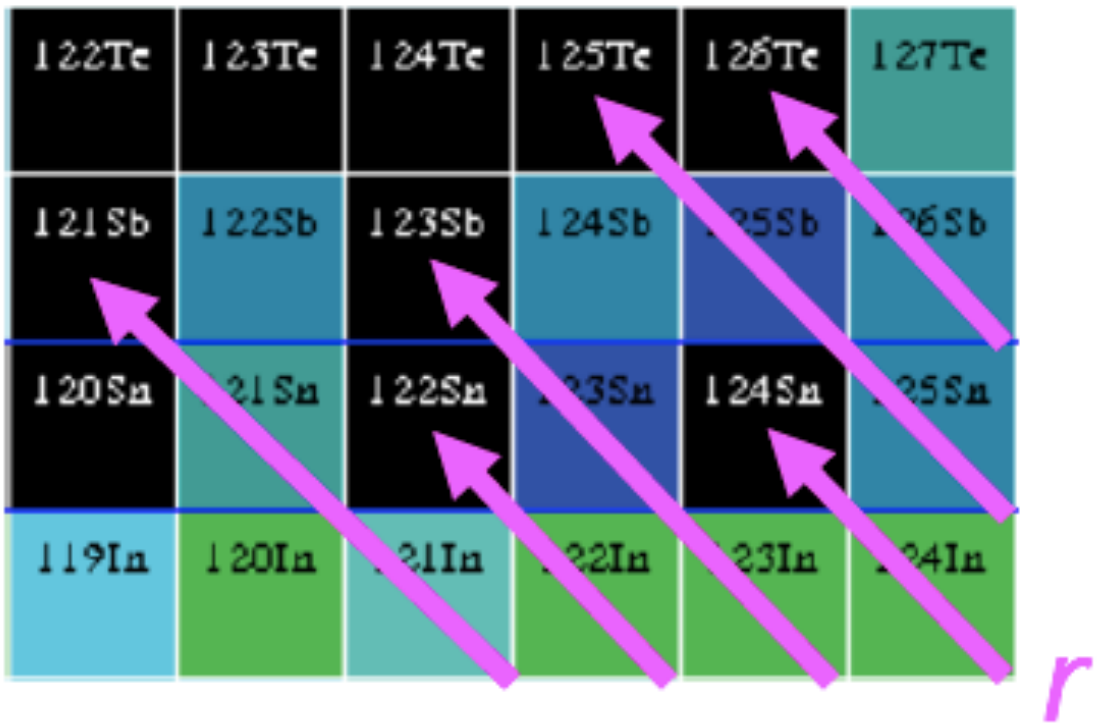
At the waiting point(s), photo-neutron ejection (photo-disintegration) balances neutron capture.

At zero temperature, the waiting point would be the neutron drip line (Sn≤0), but the r-process actually happens at high temperature (a necessary condition to obtain the high neutron density)

At the waiting point (or points), beta decay eventually happens creating Z+1.

Neutron capture continues for that new element until a new waiting point is found.

STEADY-FLOW APPROXIMATION

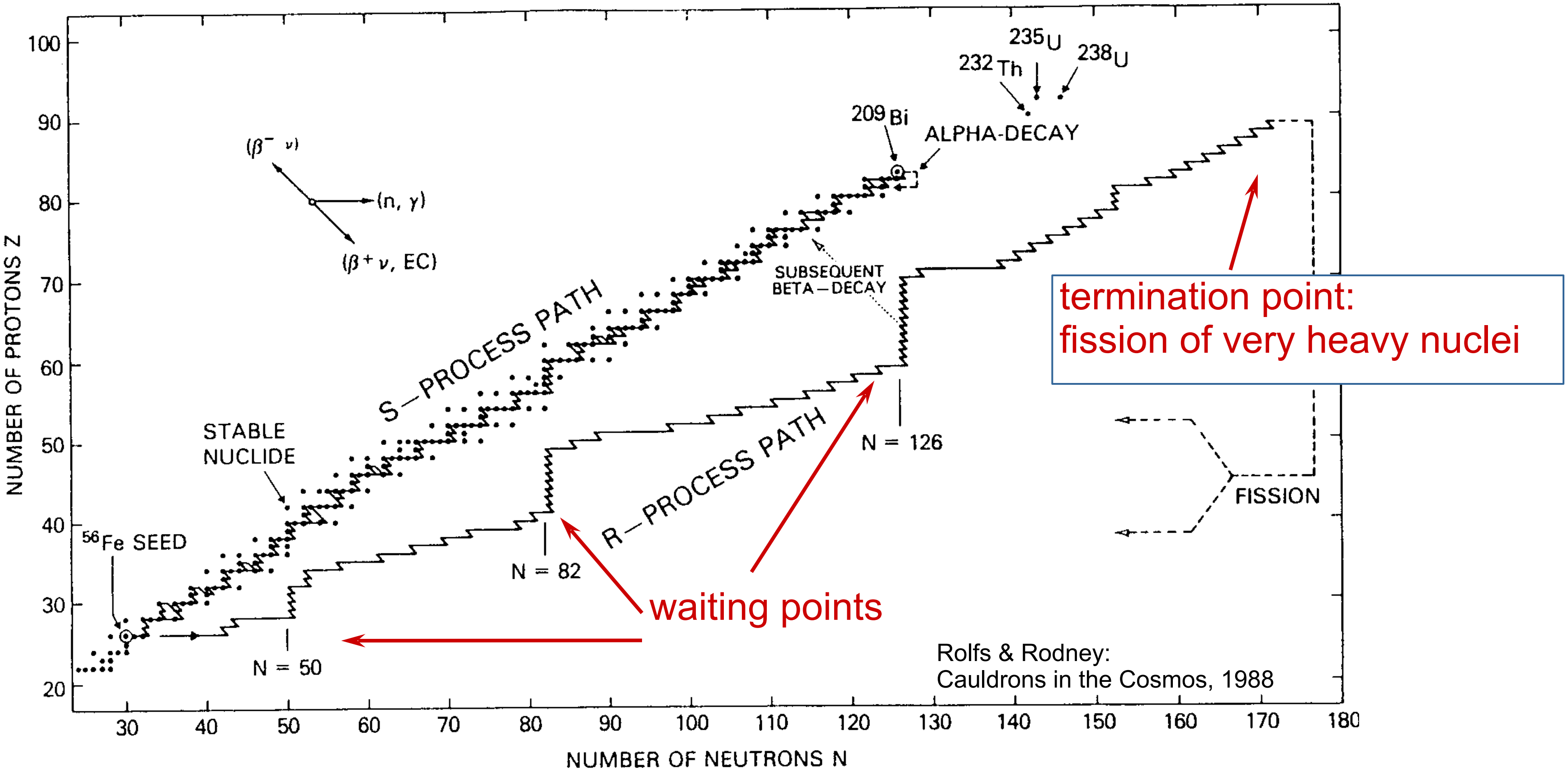


^{122,124}Sn: shielded from s-process, only produced in r-process, ~5% rel. abund.

^{120}Sb: produced in r and s process, 32% rel. abund.

^{122,123,124}Te: shielded from r-process, only produced in s-process

The r (rapid neutron capture) - process



termination point:
fission of very heavy nuclei

waiting points

Rolfs & Rodney:
Cauldrons in the Cosmos, 1988

typical lifetimes for unstable nuclei far from the valley of β stability: $10^{-4} – 10^{-2}$ s

Requiring n capture time: $\tau_n \sim 10^{-4}$ s ⇔ $\boxed{N_n \sim 10^{20}\ n/cm^3}$

explosive scenarios needed to account for such high neutron fluxes

HOW IT WORKS

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At the waiting point(s), photo-neutron ejection (photo-disintegration) balances neutron capture.

At zero temperature, the waiting point would be the neutron drip line ($S_n \leq 0$), but the r-process actually happens at high temperature (a necessary condition to obtain the high neutron density)

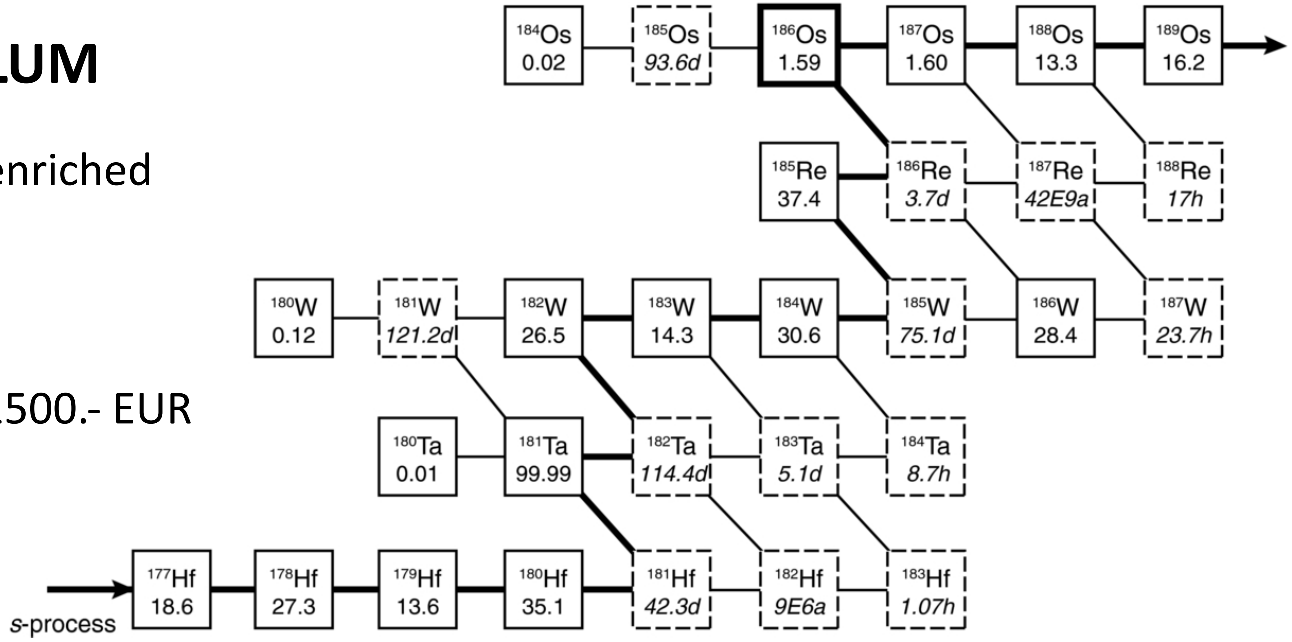
At the waiting point (or points), beta decay eventually happens creating Z+1.

Neutron capture continues for that new element until a new waiting point is found.

Z=73 TANTALUM

1mg $^{180}\text{Ta}^{m}$, 5% enriched
= 1500.- EUR

1 ounce of gold:
28350mg Au ≈ 1500.- EUR



^{181}Ta: stable

rarest element on earth

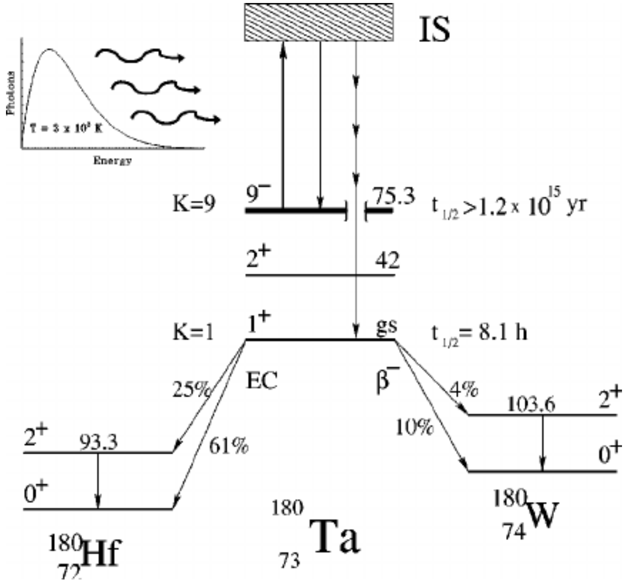
^{180}Ta ground state: decays in 8h

$^{180}\text{Ta}^{m}$: $T_{1/2} > 10^{15}$ y, metastable

shielded from s process

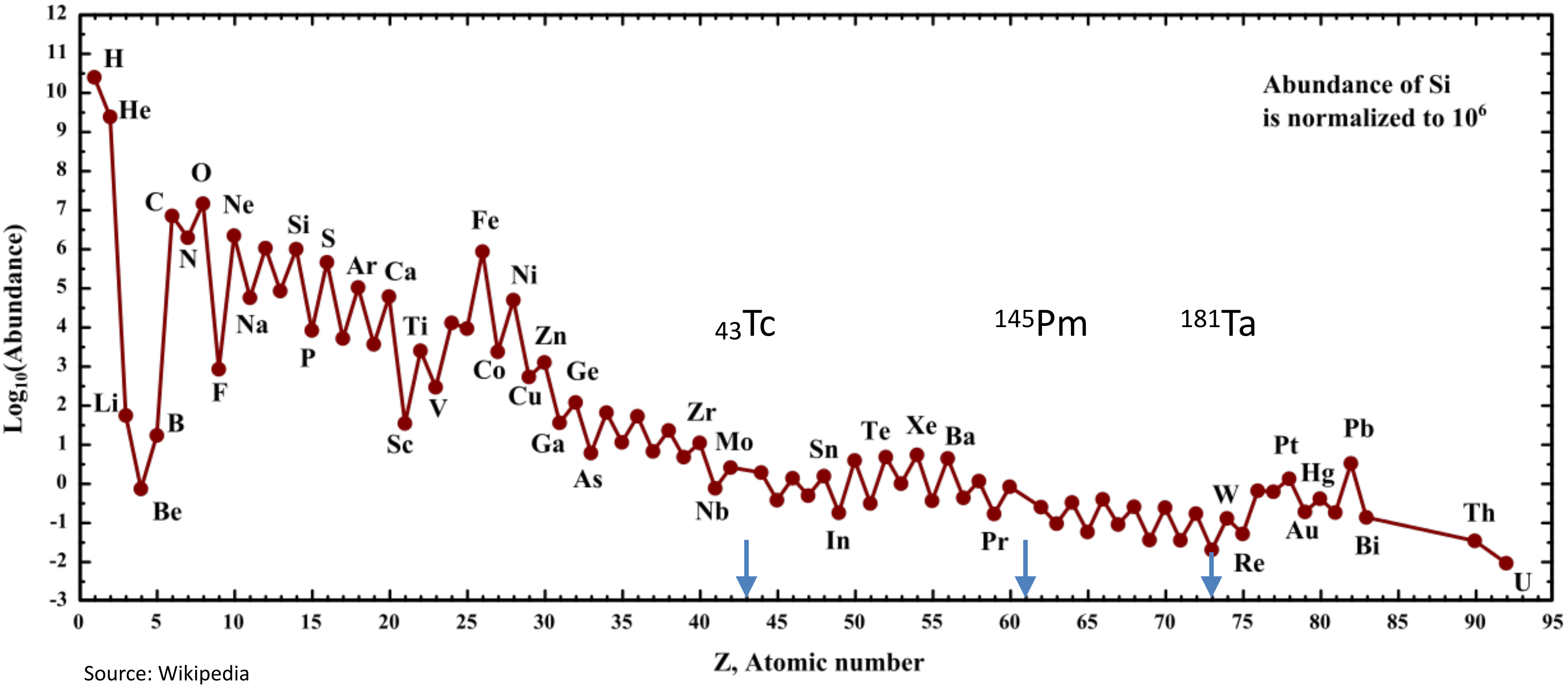
shielded from r process

0.01% of ^{181}Ta



P. v. Neumann-Cosel Nuclear Physics A719 (2003) 21c-28c,
Sharon Weinberger, Imaginary Weapons.

SOLAR ABUNDANCES - KEY FACTS



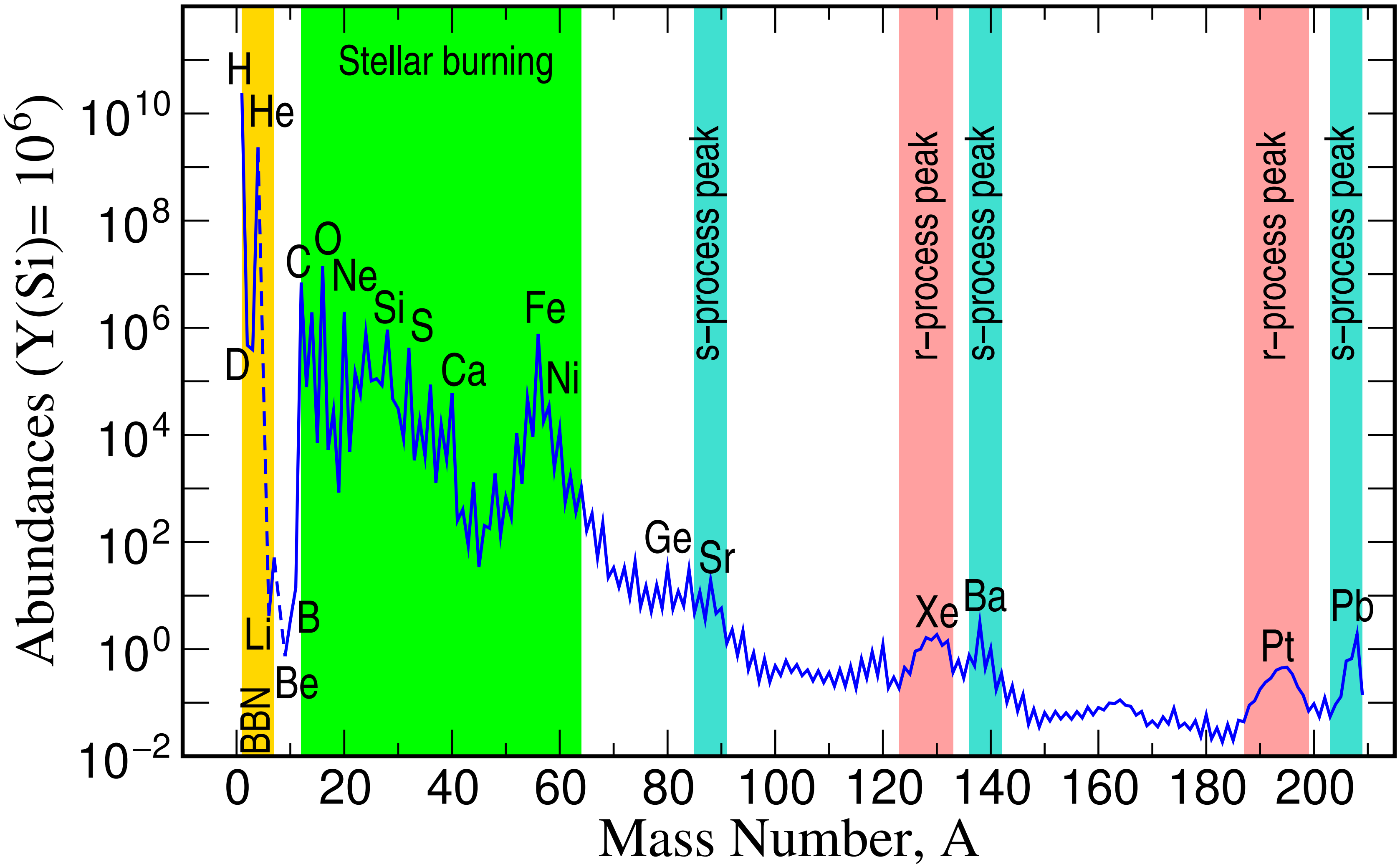
Source: Wikipedia

^{98}Tc: life time 4.2 My

^{145}Pm: life time 17.7a

^{181,180}Ta: (meta)stable

NUCLEOSYNTHESIS - DOMINANT PROCESSES



arXiv:1901.01410, submitted to Rev. Mod. Phys.

SUPERNOVA SN1987A

Source: ESO Schmidt Telescope

Feb. 23, 1987
type II supernova
Large Magellanic Cloud
168 000 light years

25 neutrinos detected within 13 seconds
Kamiokande II: 12 (anti)-neutrinos
IMB: 8 (anti)-neutrinos
Baksan: 5 (anti)-neutrinos

from time-of-flight of neutrinos:
ν-mass < 16 eV

neutrinos are stable !

10^{58} neutrinos from β-decay

NUCLEOSYNTHESIS SOURCES OF THE ELEMENTS

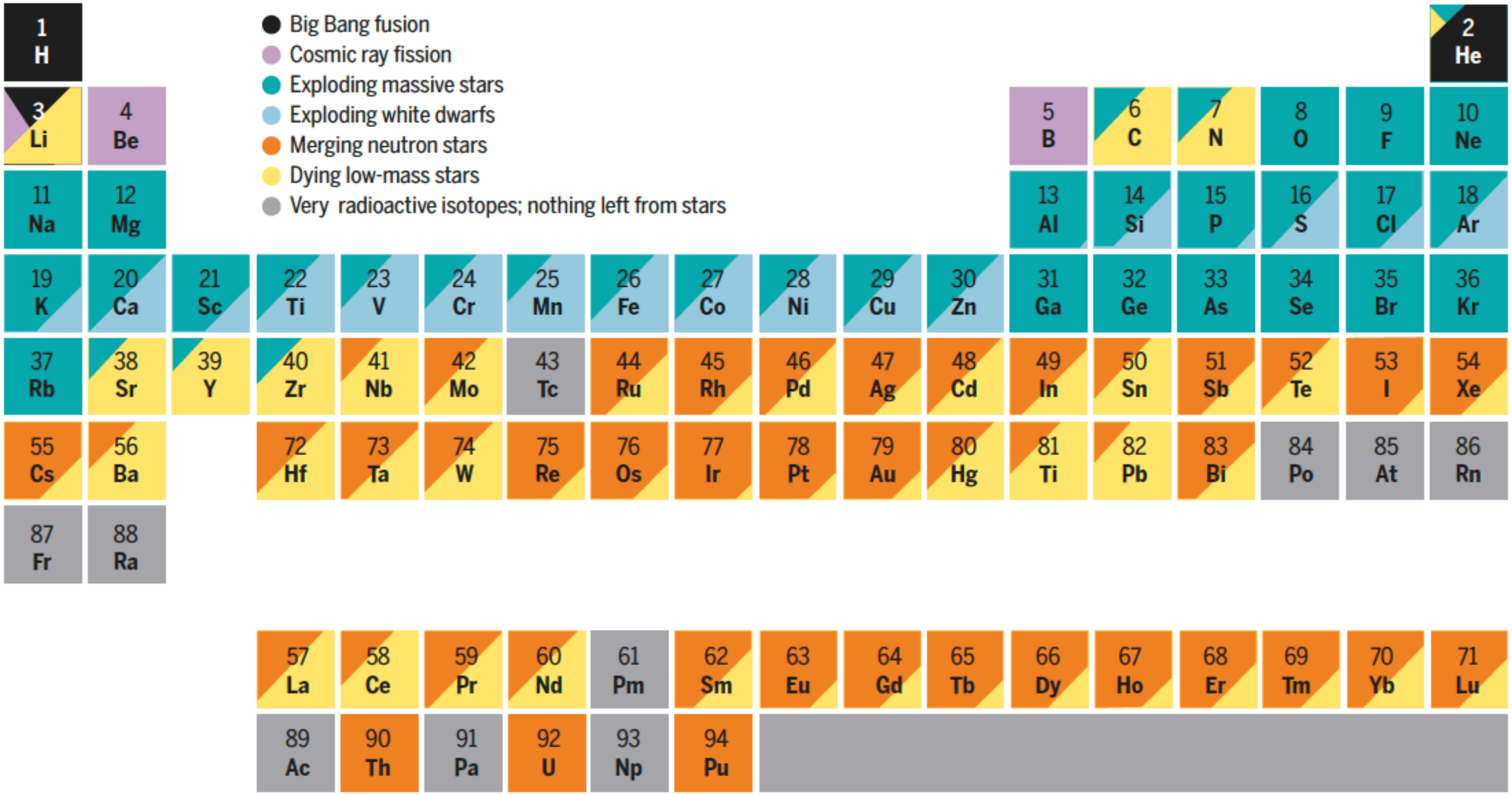


Fig. 1. Nucleosynthetic sources of elements in the Solar System. Each element in this periodic table is color-coded by the relative contribution of nucleosynthesis sources, scaled to the time of Solar System formation. Only elements that occur naturally in the Solar System are shown; artificially made elements and elements produced only through radioactive decay of long-lived nuclei are shown in gray. The data plotted in this figure are available in table S1.

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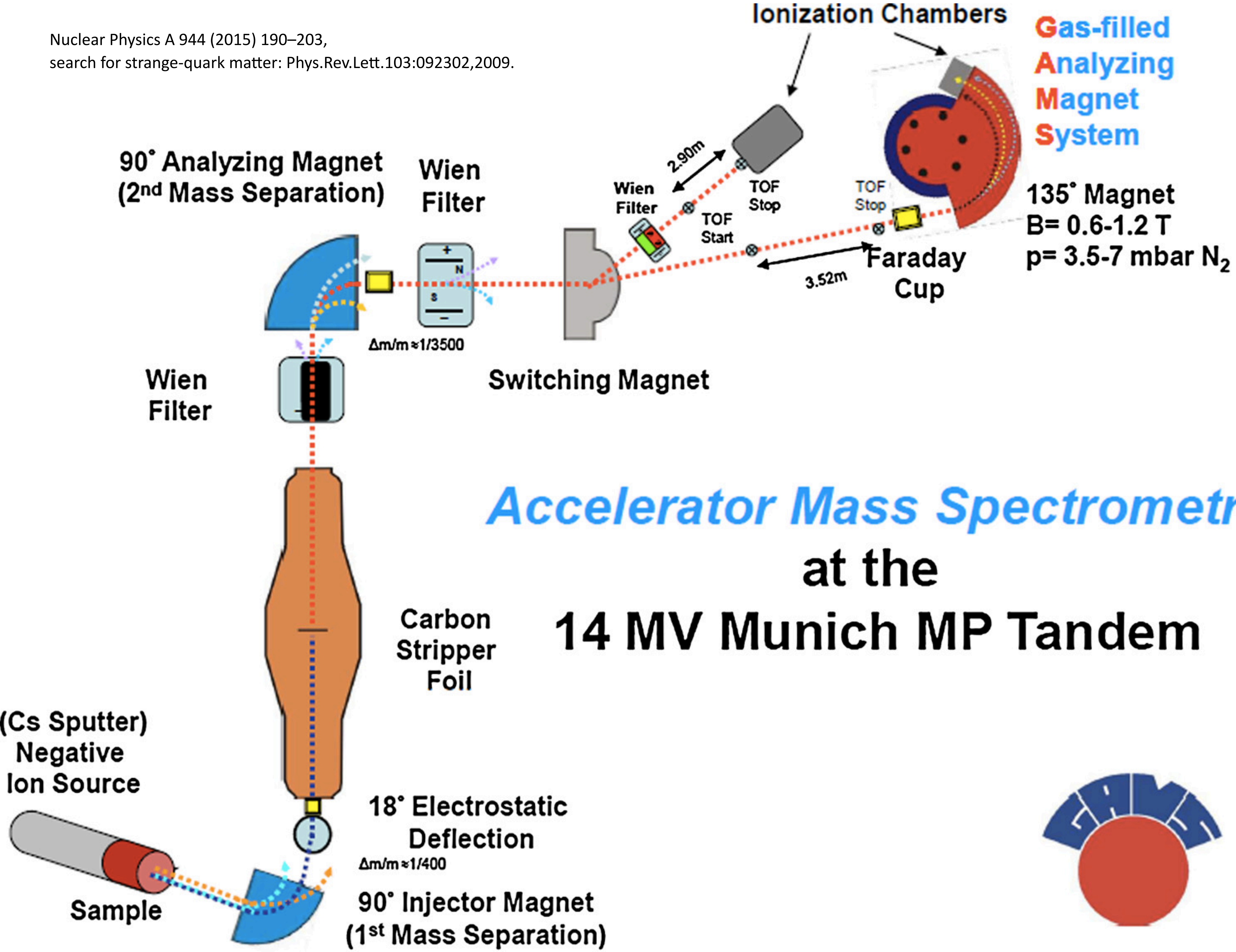
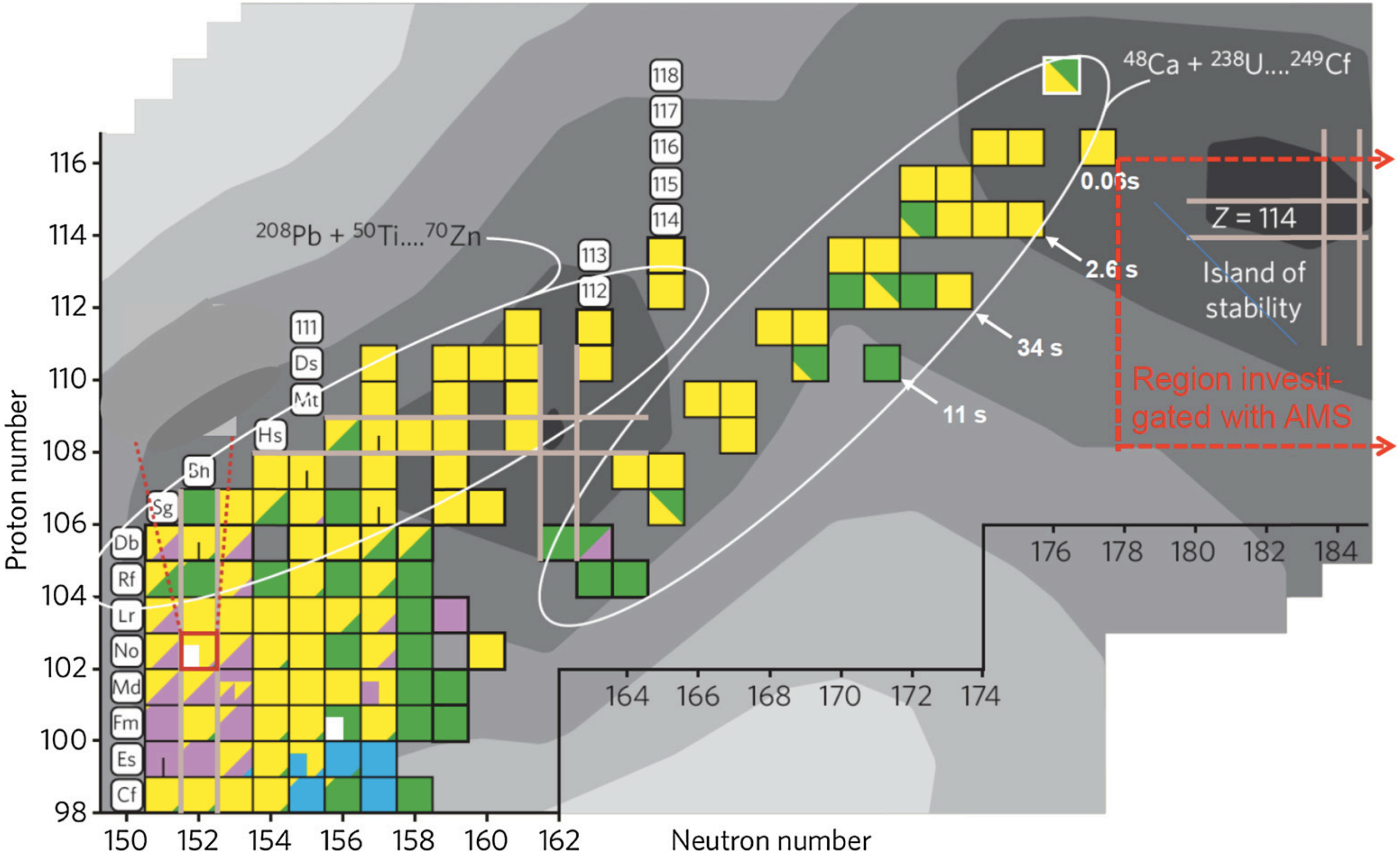
Nuclear Physics A 944 (2015) 190–203,
search for strange-quark matter: Phys.Rev.Lett.103:092302,2009.



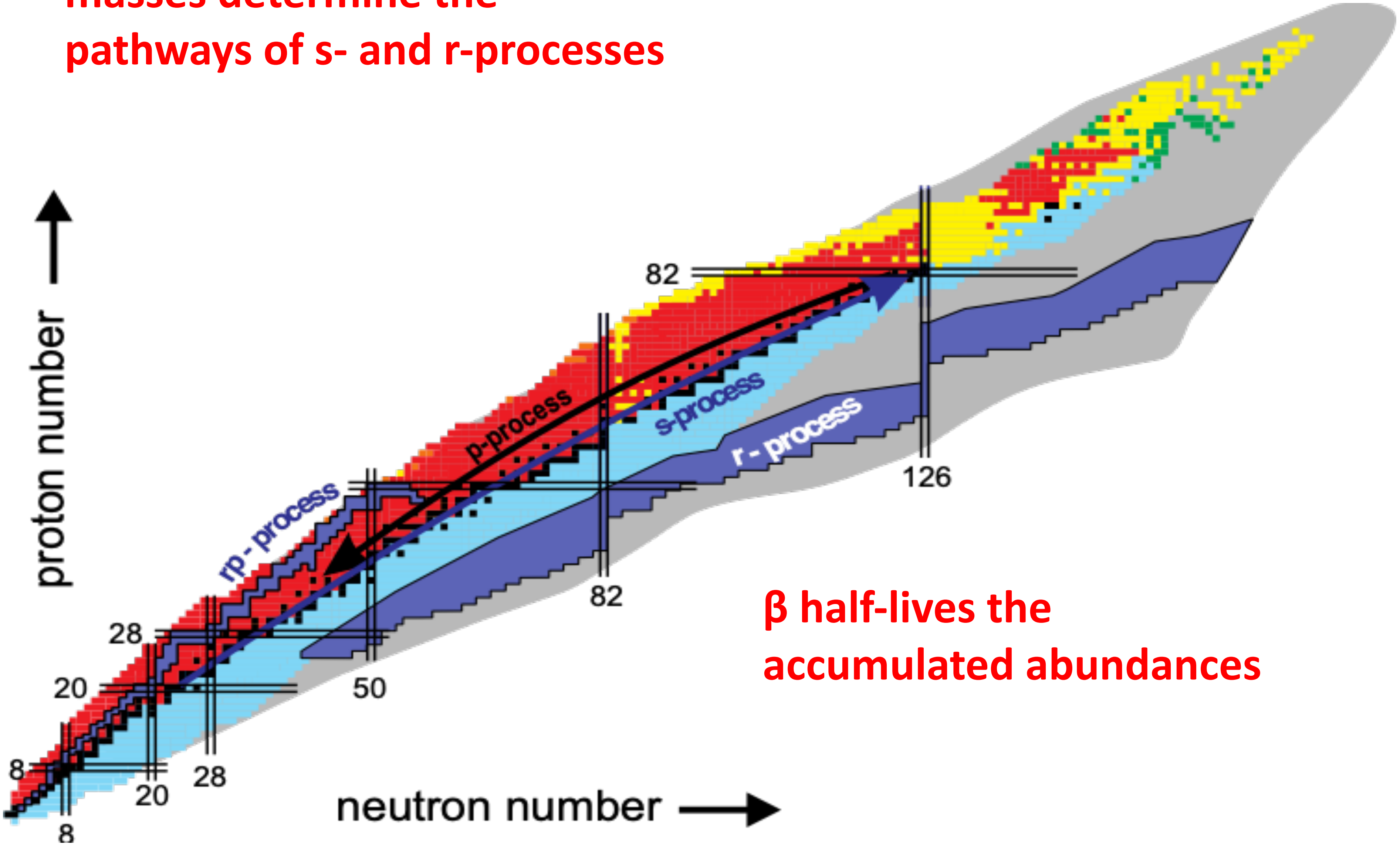
Accelerator Mass Spectrometry at the 14 MV Munich MP Tandem

SEARCH FOR THE ISLAND OF STABILITY



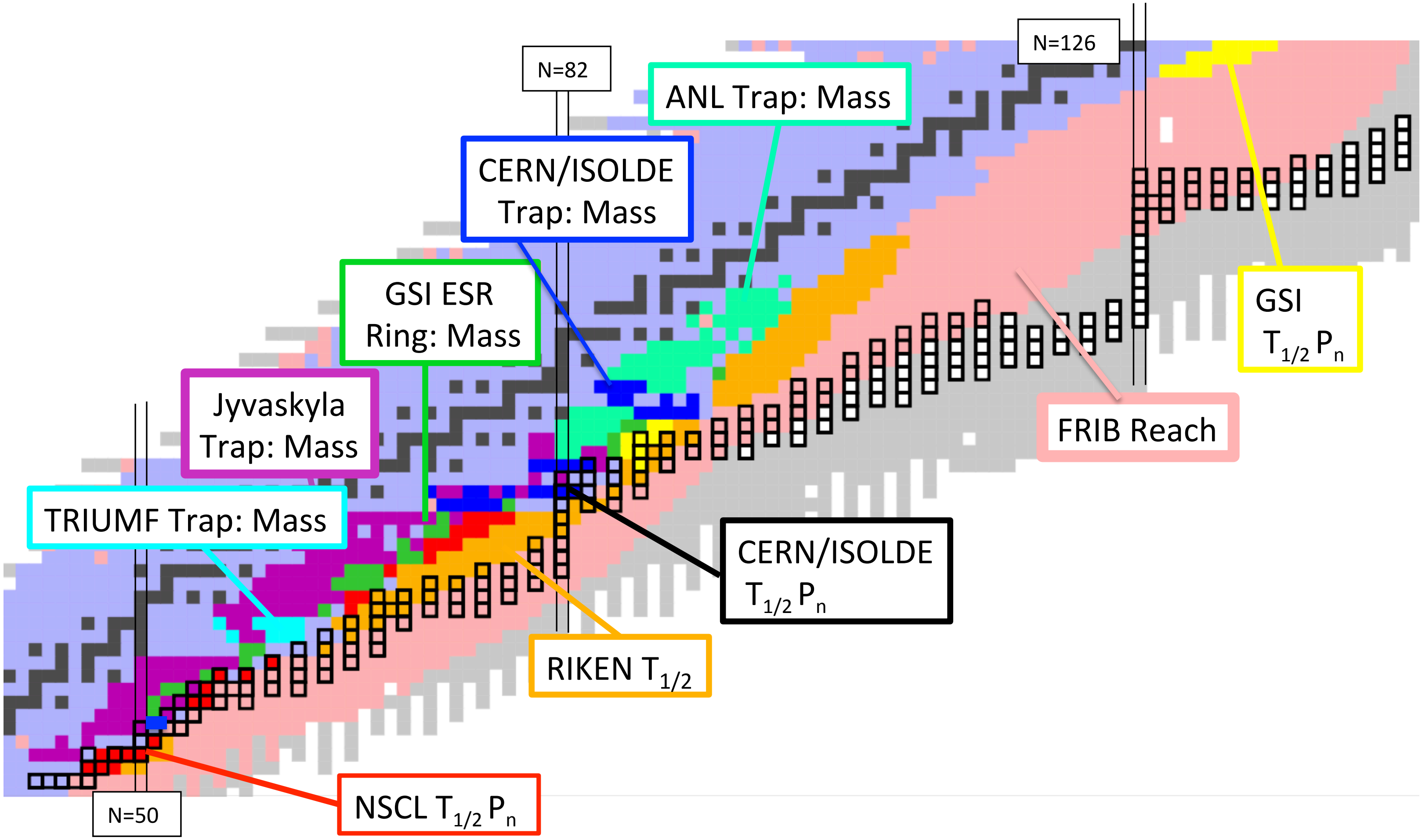
Where and how was gold cooked?

masses determine the pathways of s- and r-processes



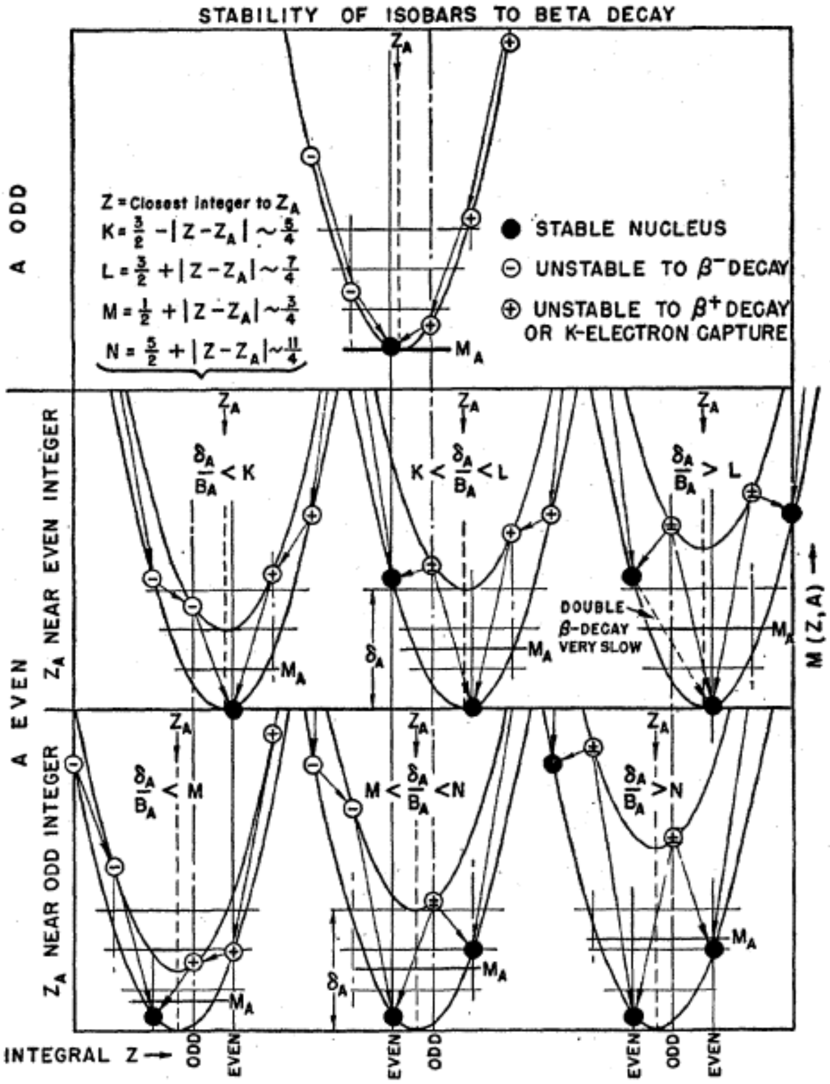
β half-lives the accumulated abundances

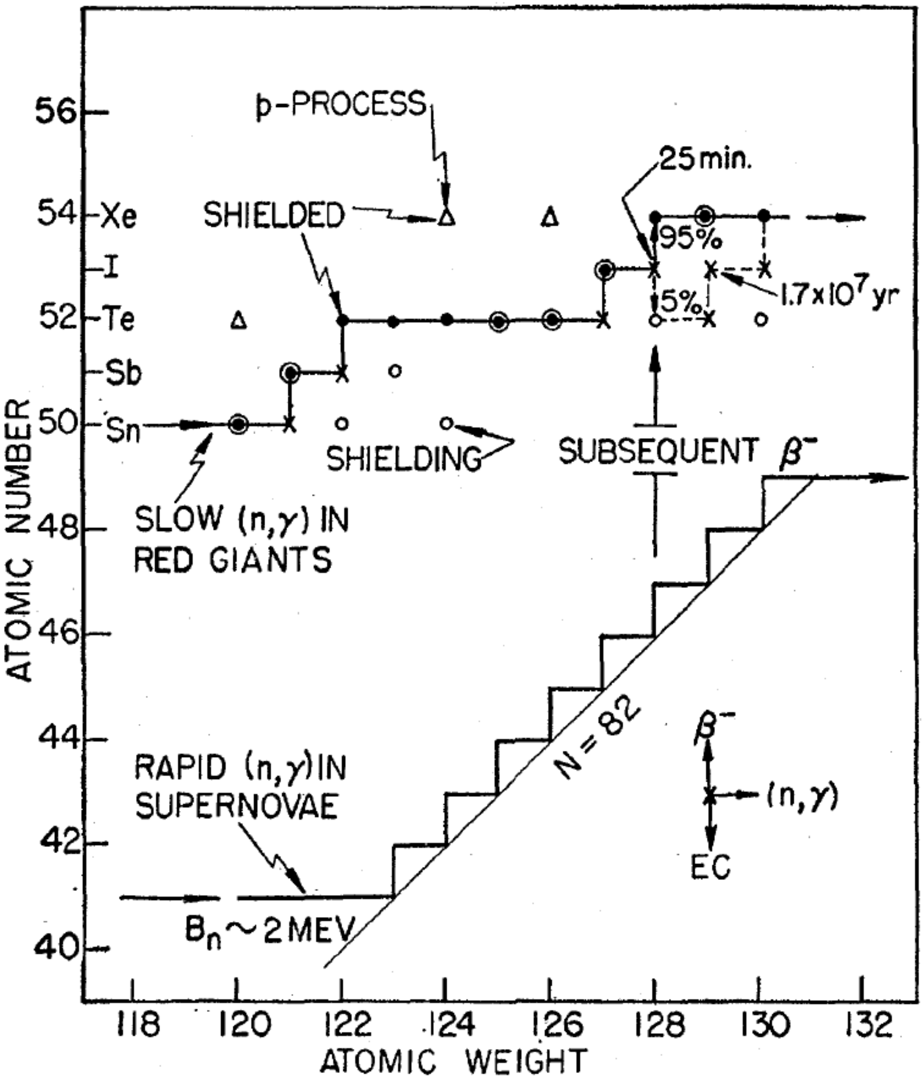
EXISTING AND FUTURE FACILITIES



BACKUP

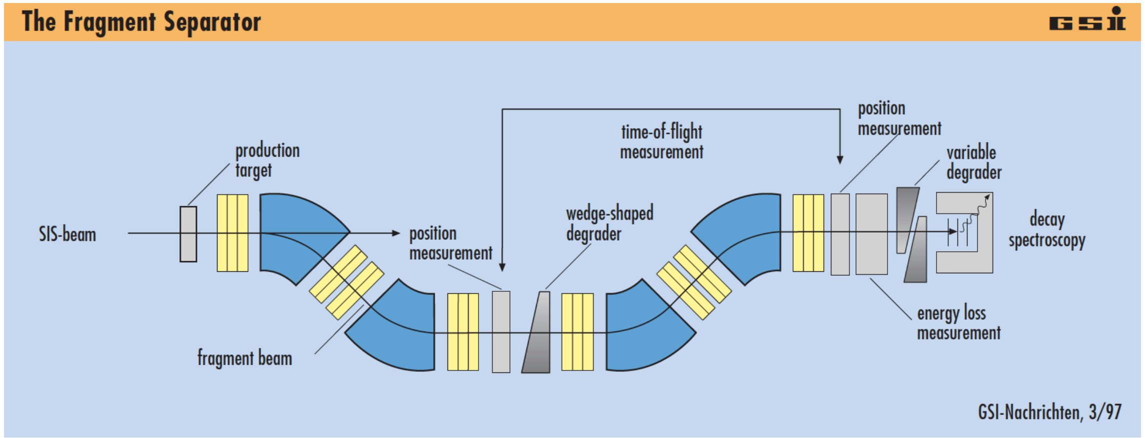
SHIELDING



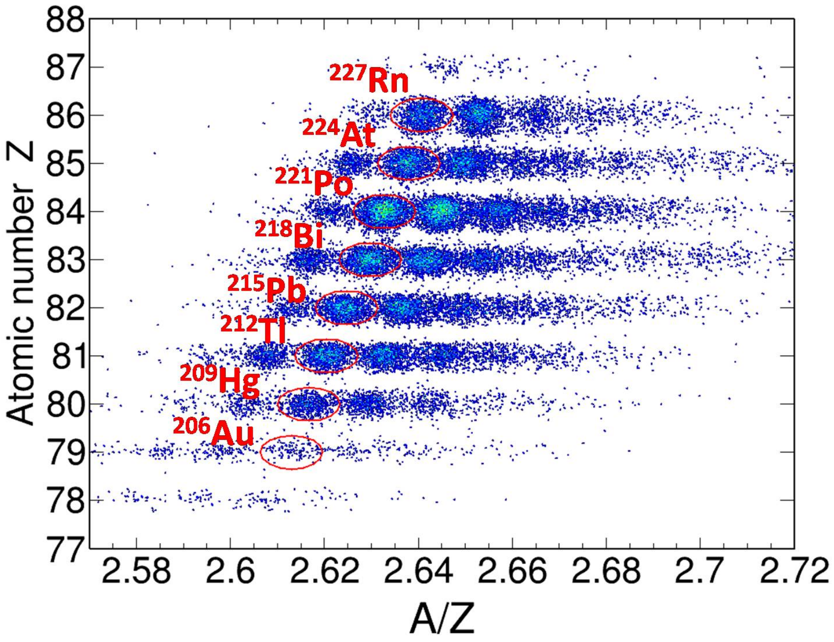


Burbidge, Burbidge, Fowler, Hoyle: Rev. Mod. Phys. 29 (1957) 547.

MEASUREMENT OF BETA DECAY HALF LIVES BEYOND N=126



GSI-Nachrichten, 3/97



BELEN @ GSI, PRL 117, 012501 (2016)

dipole:

$$\frac{mv^2}{r} = q \cdot (\vec{v} \times \vec{B}) \rightarrow \frac{m \cdot v}{Z \cdot e} = B \cdot r$$

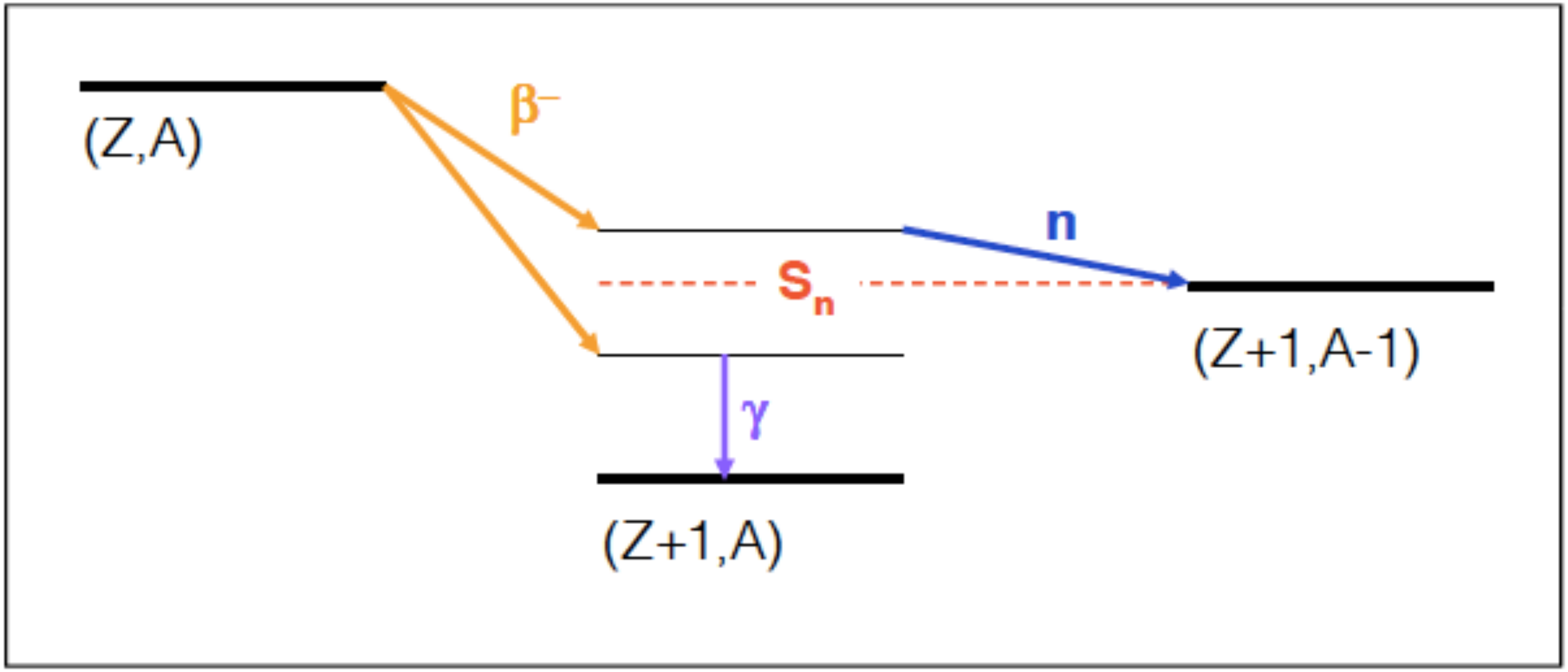
energy loss, Bethe equation:

$$-\frac{\mathrm{d}E}{\mathrm{d}x} \sim \frac{4\pi n z^2}{m_e v^2}$$

time-of-flight: v

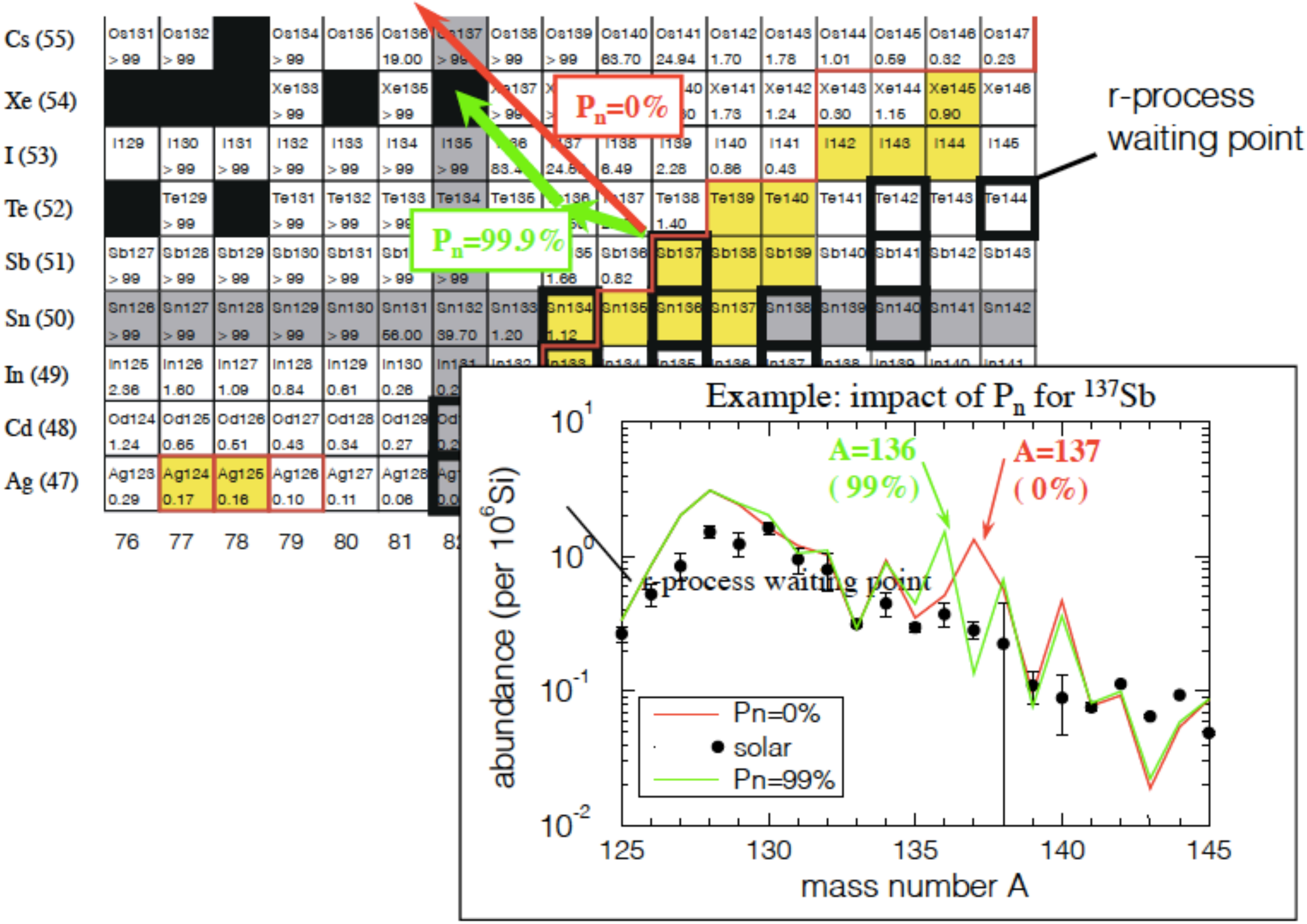
ROLE OF BETA DELAYED NEUTRON EMISSION

neutron rich nuclei can emit one or more neutrons if $S_n < Q_\beta$

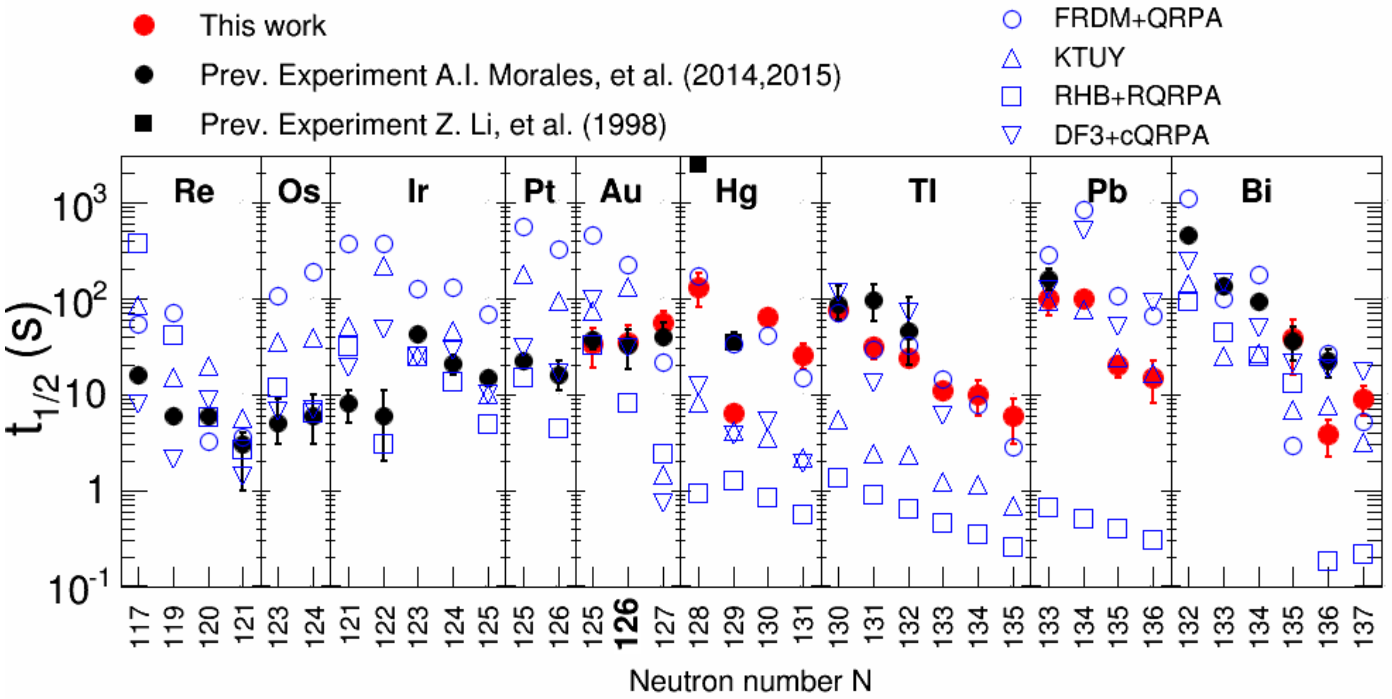


if some fraction of of β-decays end up in daughter nucleus being excited above neutron threshold S_n, then some fraction P_n of the decays will emit a neutron.

ROLE OF BETA DELAYED NEUTRON EMISSION



MEASUREMENT OF BETA DECAY HALF LIVES BEYOND N=126



β-delayed neutrons in ^{3}He counters

heaviest species where neutron emission has been observed so far.

challenge to microscopic and phenomenological models

BELEN @ GSI, PRL 117, 012501 (2016)