Nuclear Physics at EuPRAXIA

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[*] INFN Laboratori Nazionali di Frascati

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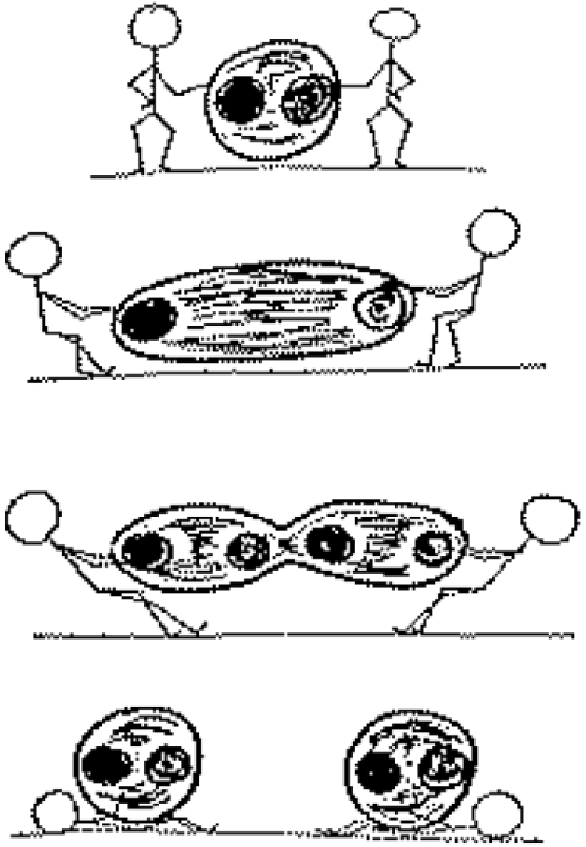

CSN3 Fisica Nucleare

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1. QUARKS AND HADRON DYNAMICS

KAONNIS, JLAB12, MAMBO, ULYSSES, EIC

2. PHASE TRANSITION IN HADRONIC MATTER

ALICE, NA60+

3. NUCLEAR STRUCTURE AND REACTION MECHANISMS

FORTE, GAMMA, CHIRONE, NUCL-EX, NUMEN, PRISMA_FIDES

4. NUCLEAR ASTROPHYSICS

ASFIN, ERNA, LUNA, n_TOF, PANDORA, Future Experiments

5. FUNDAMENTAL INTERACTIONS

LEA, ALPHA, JEDI, VIP, FAMU

6. APPLICATIONS AND SOCIETAL BENEFITS

FOOT

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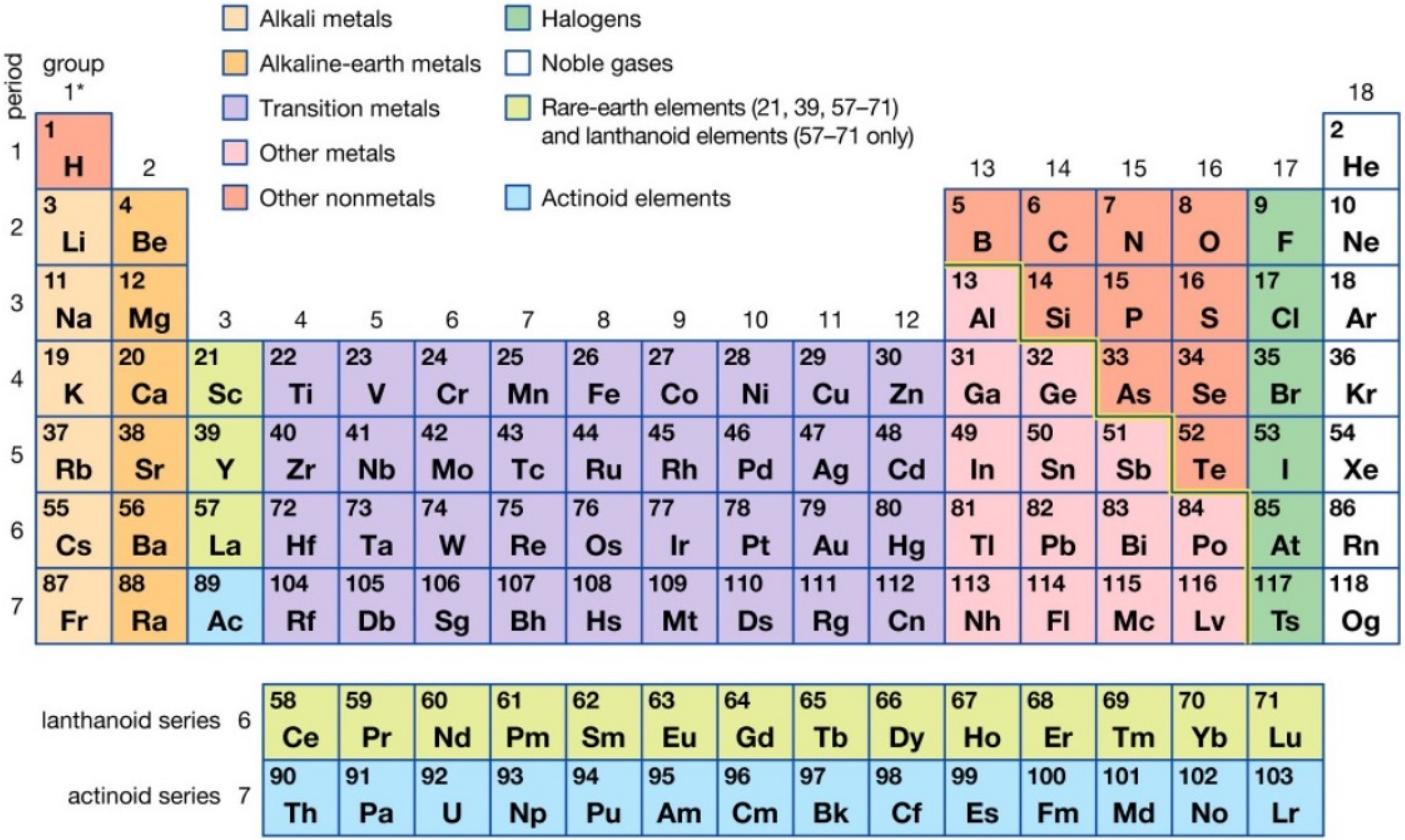
The periodic table of elements



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Big-Bang Nucleosynthesis

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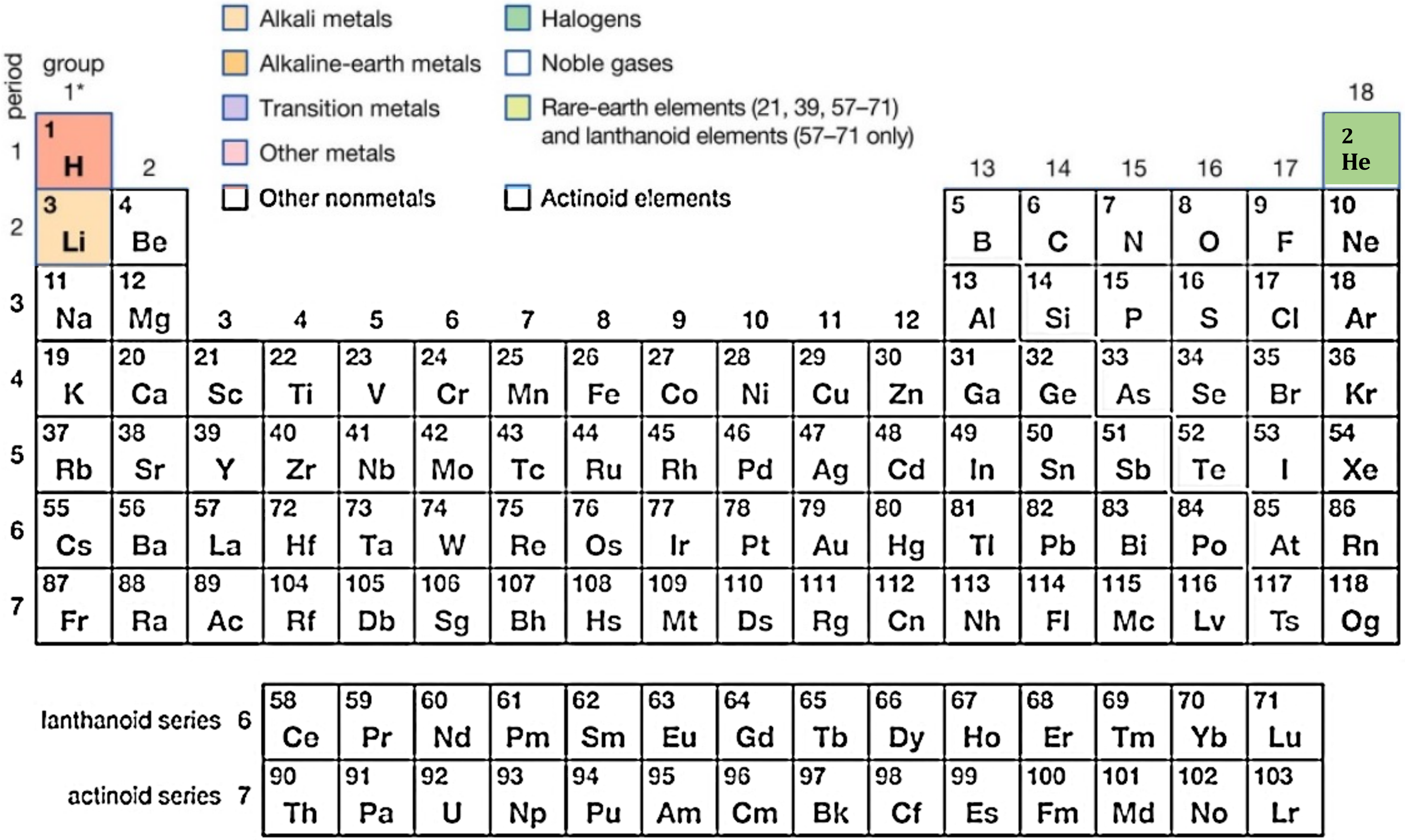

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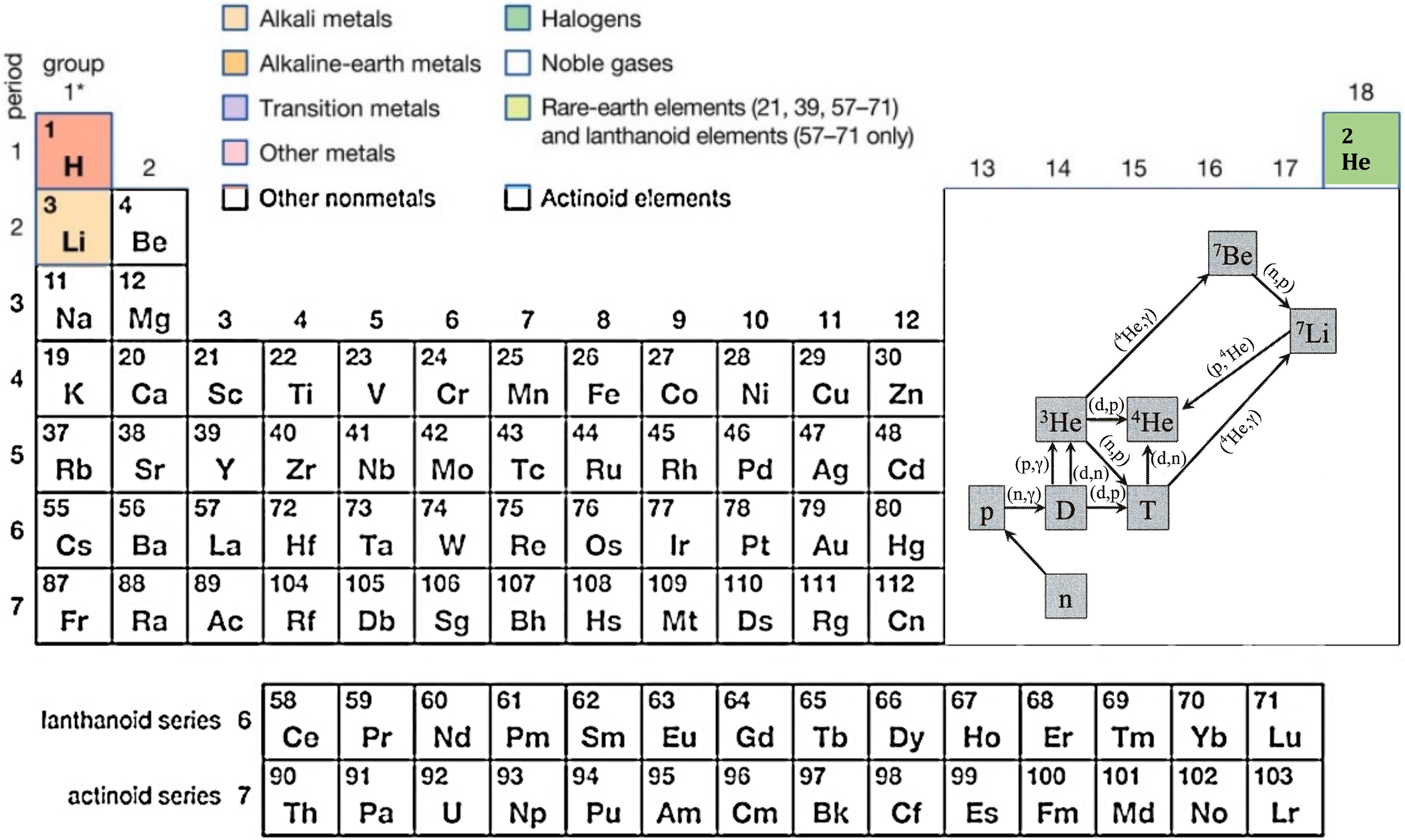
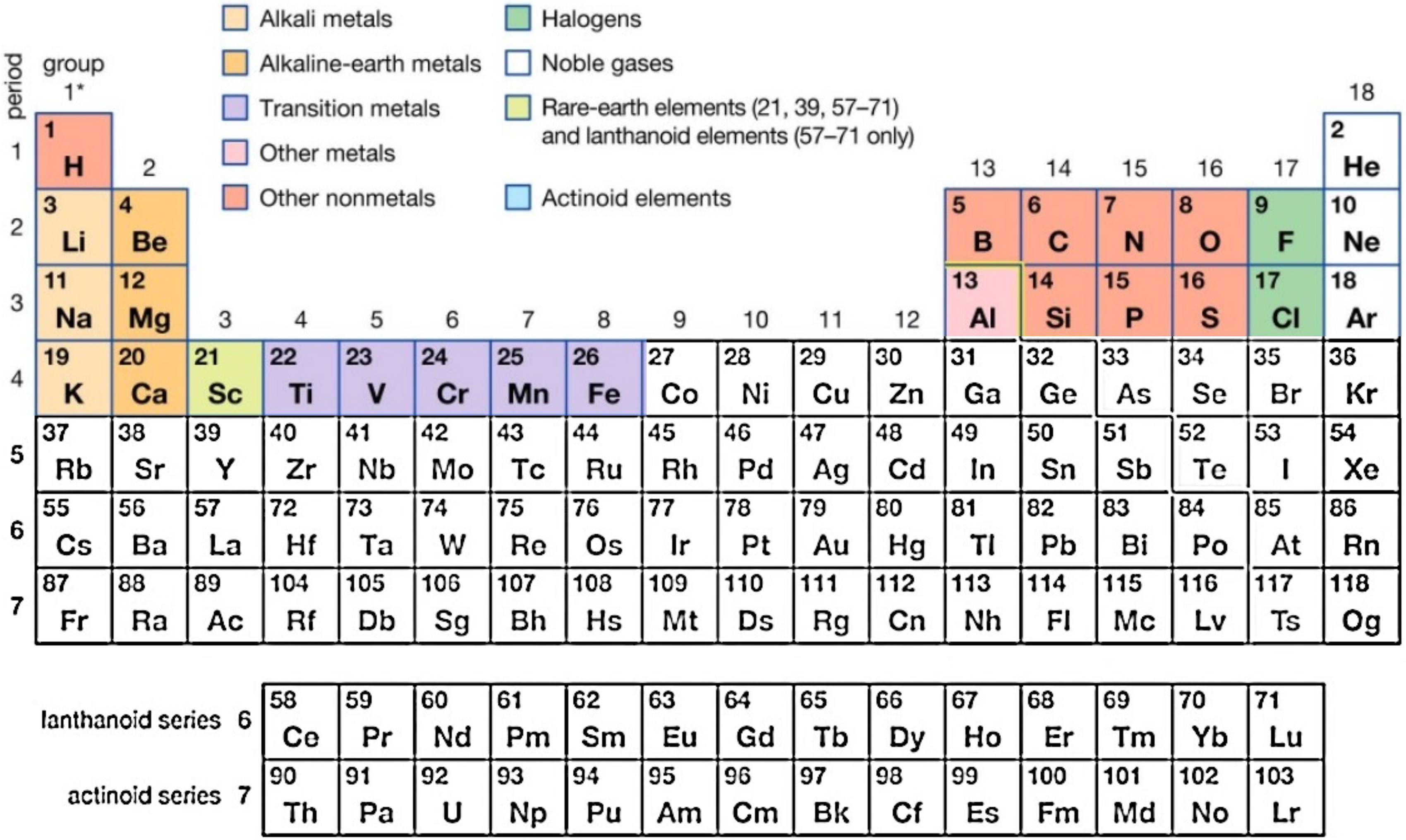


Stellar Nucleosynthesis



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Stellar Nucleosynthesis

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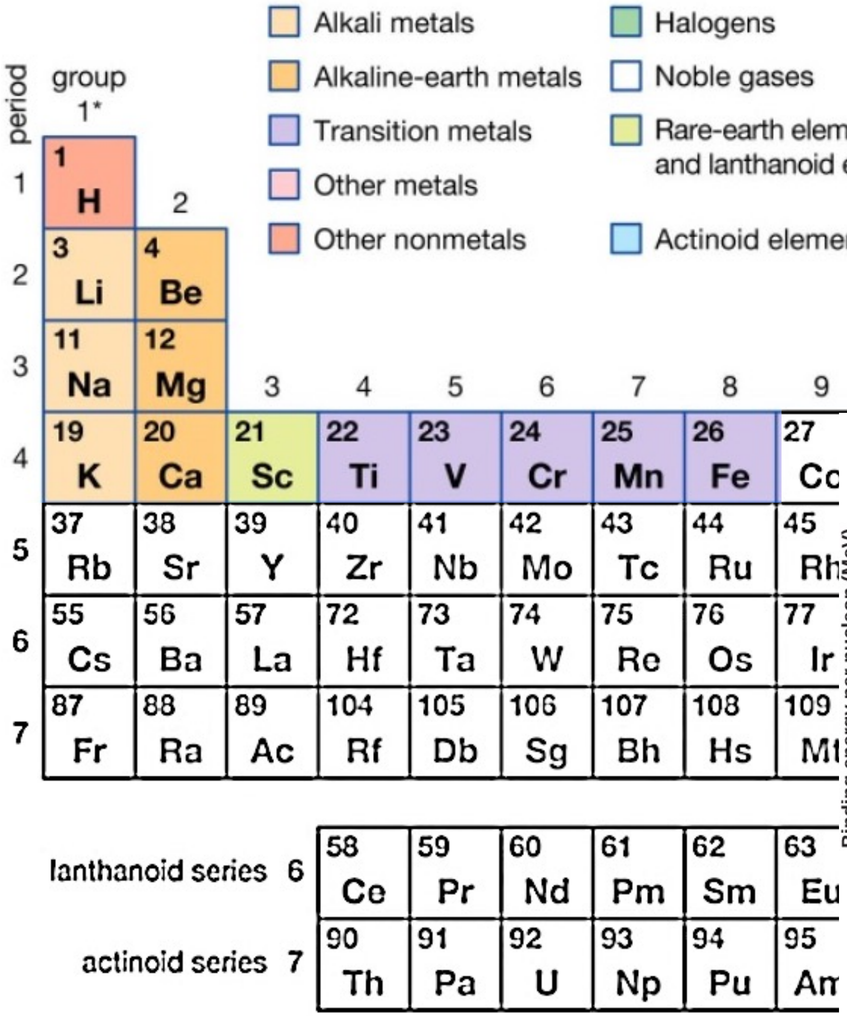
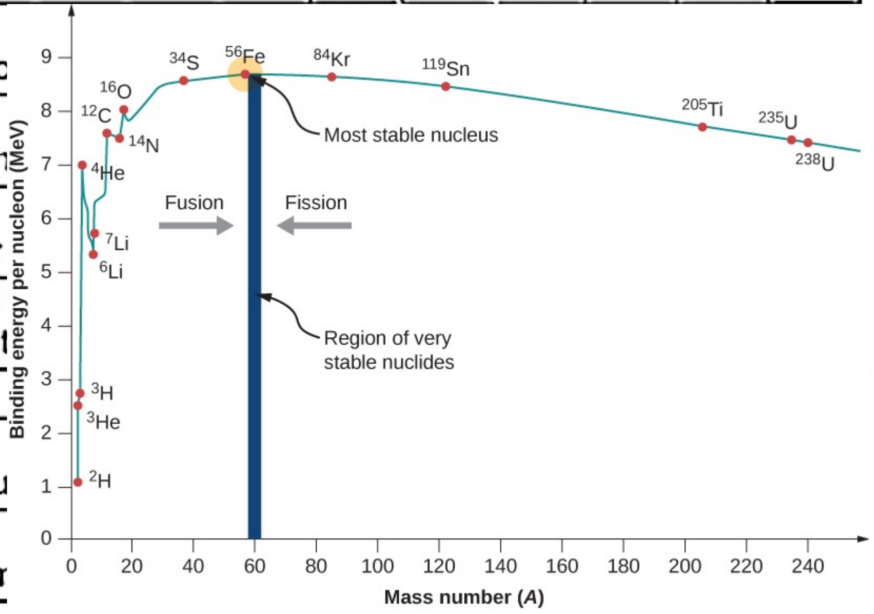
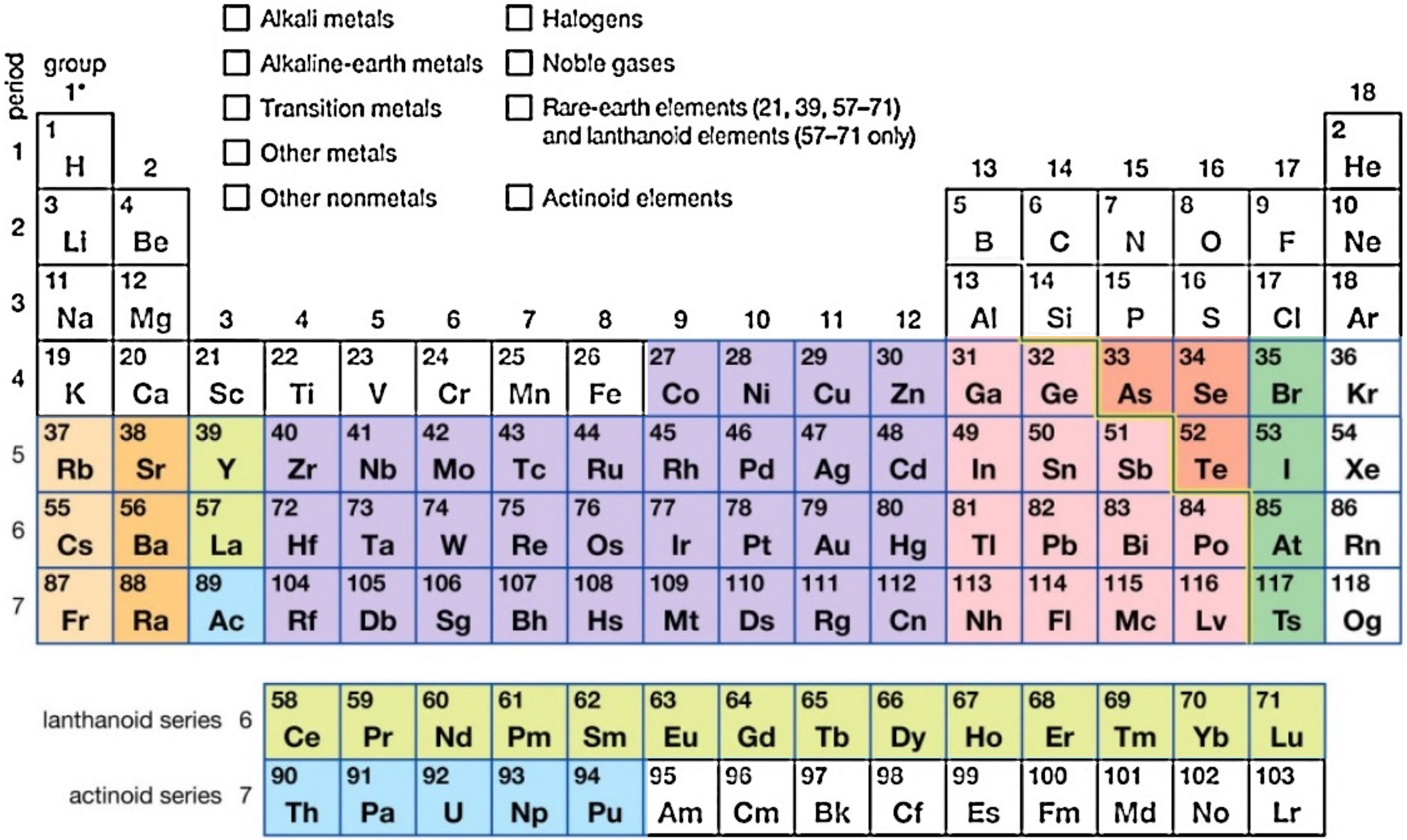




S- and *r*-process Nucleosynthesis



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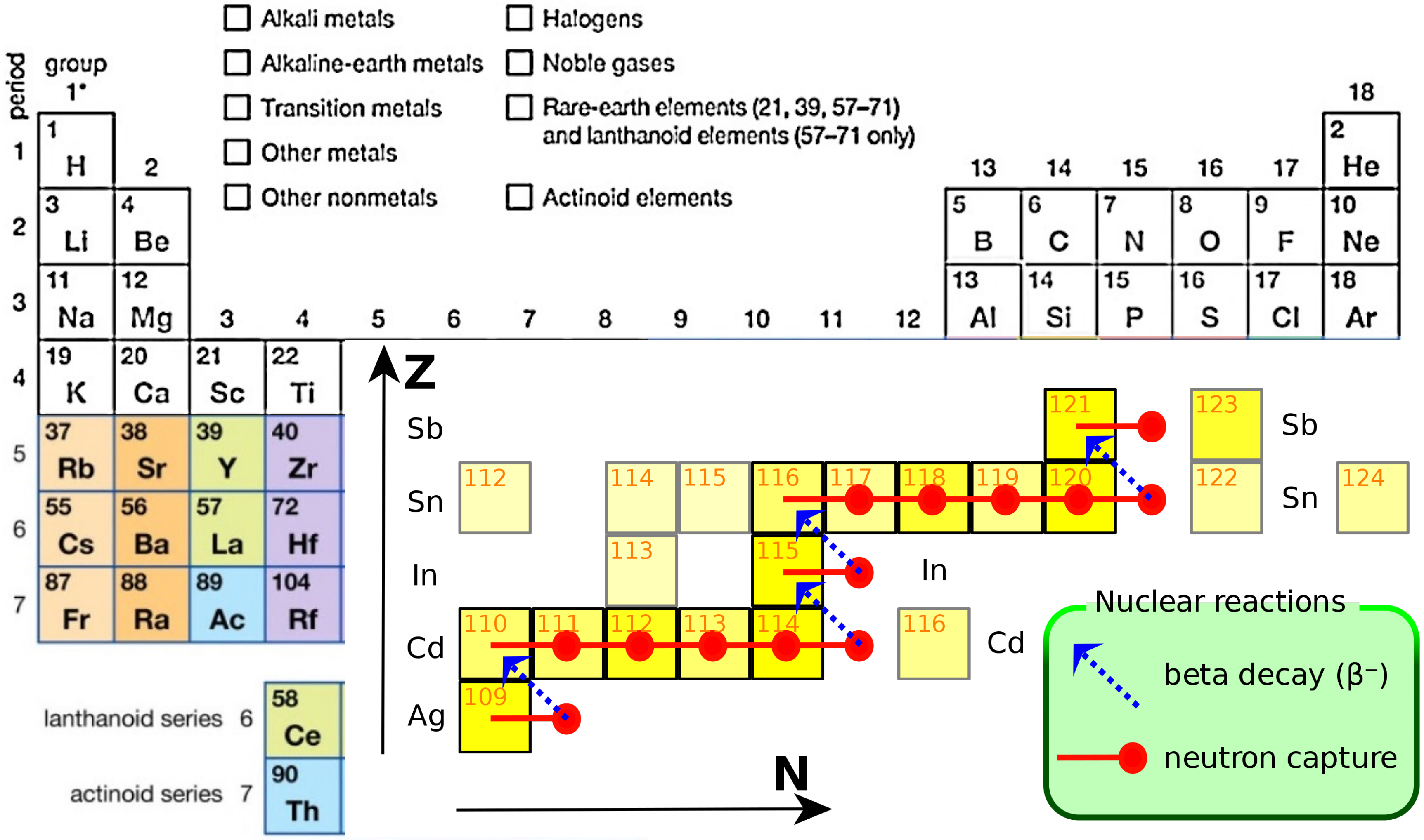


Solar system abundances

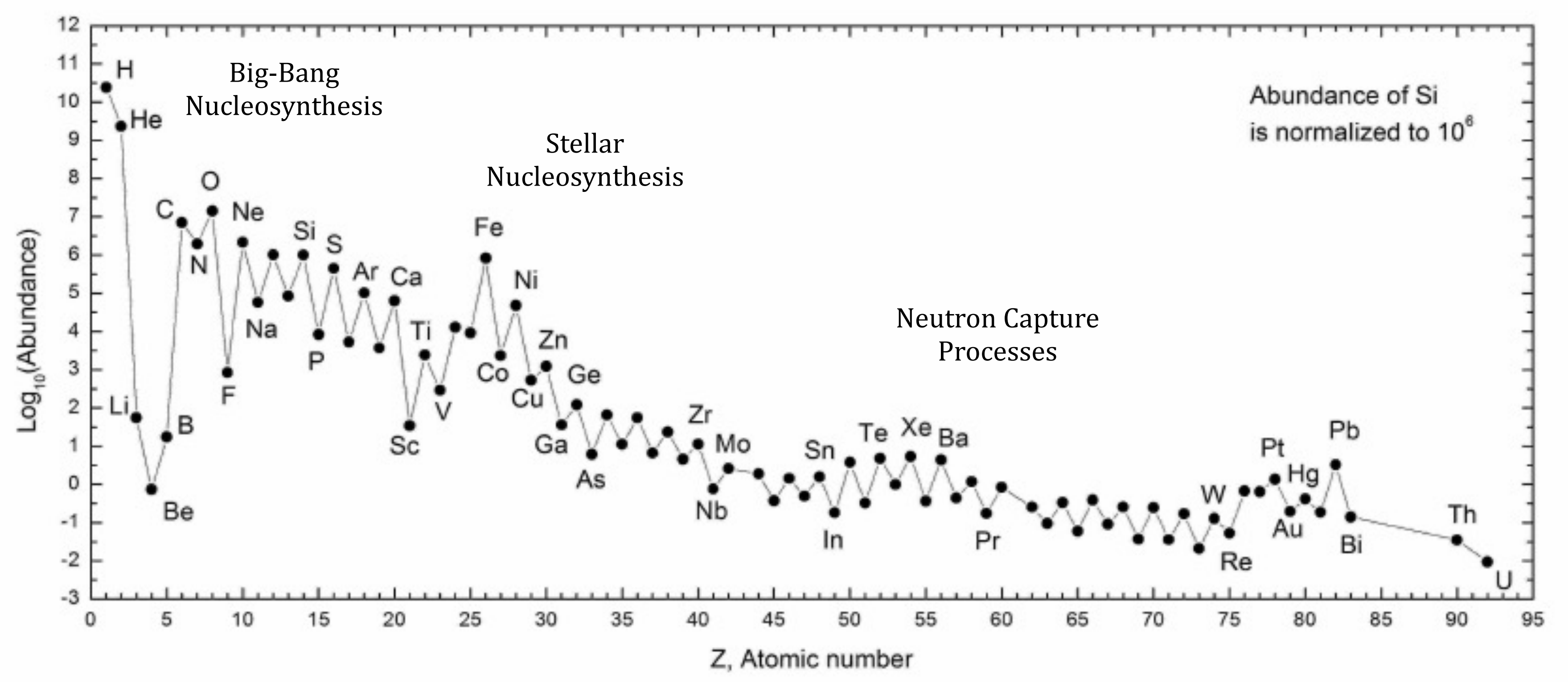
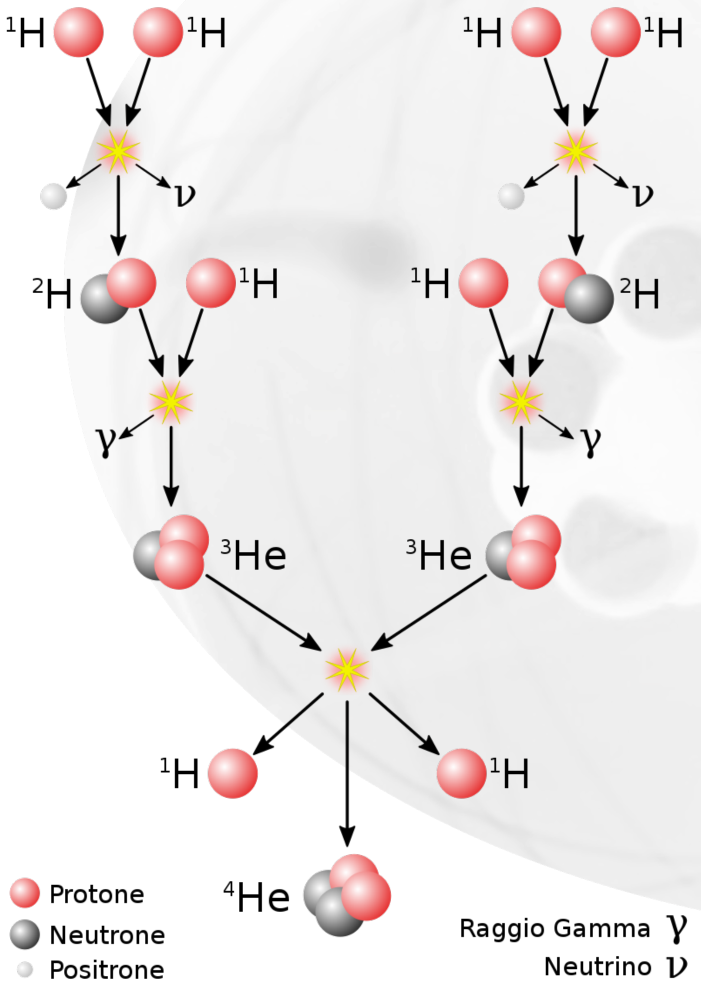
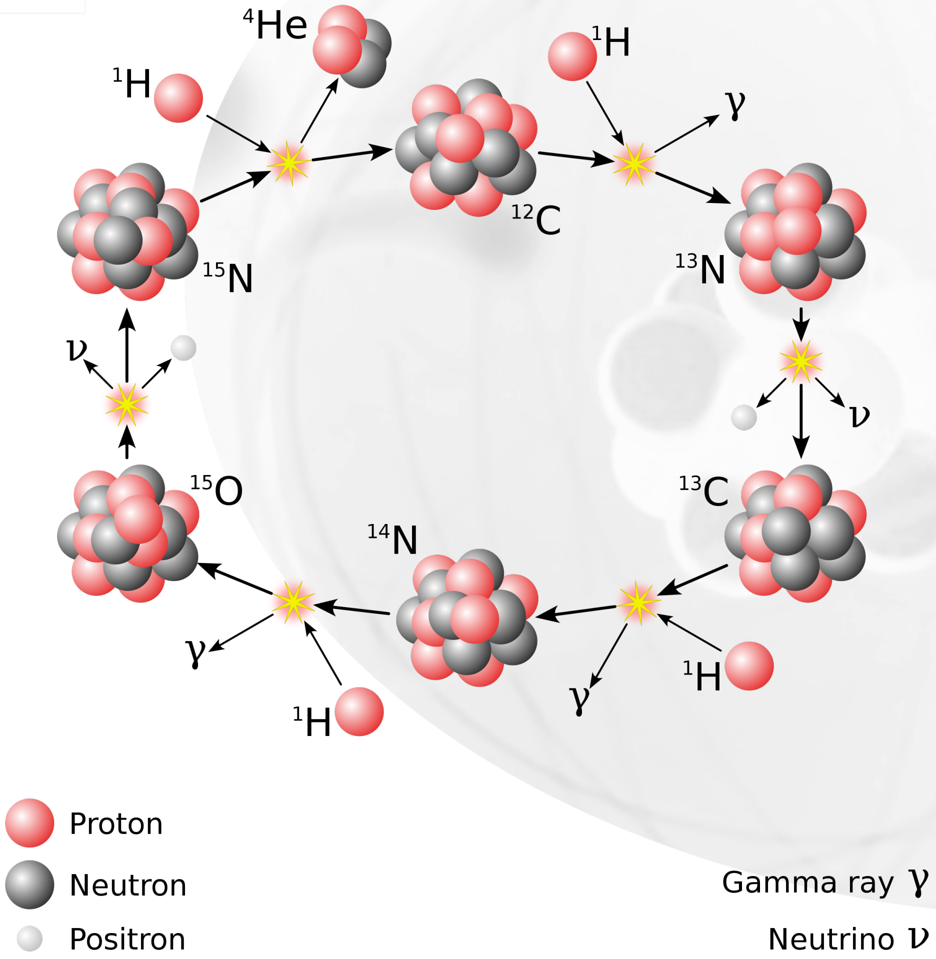


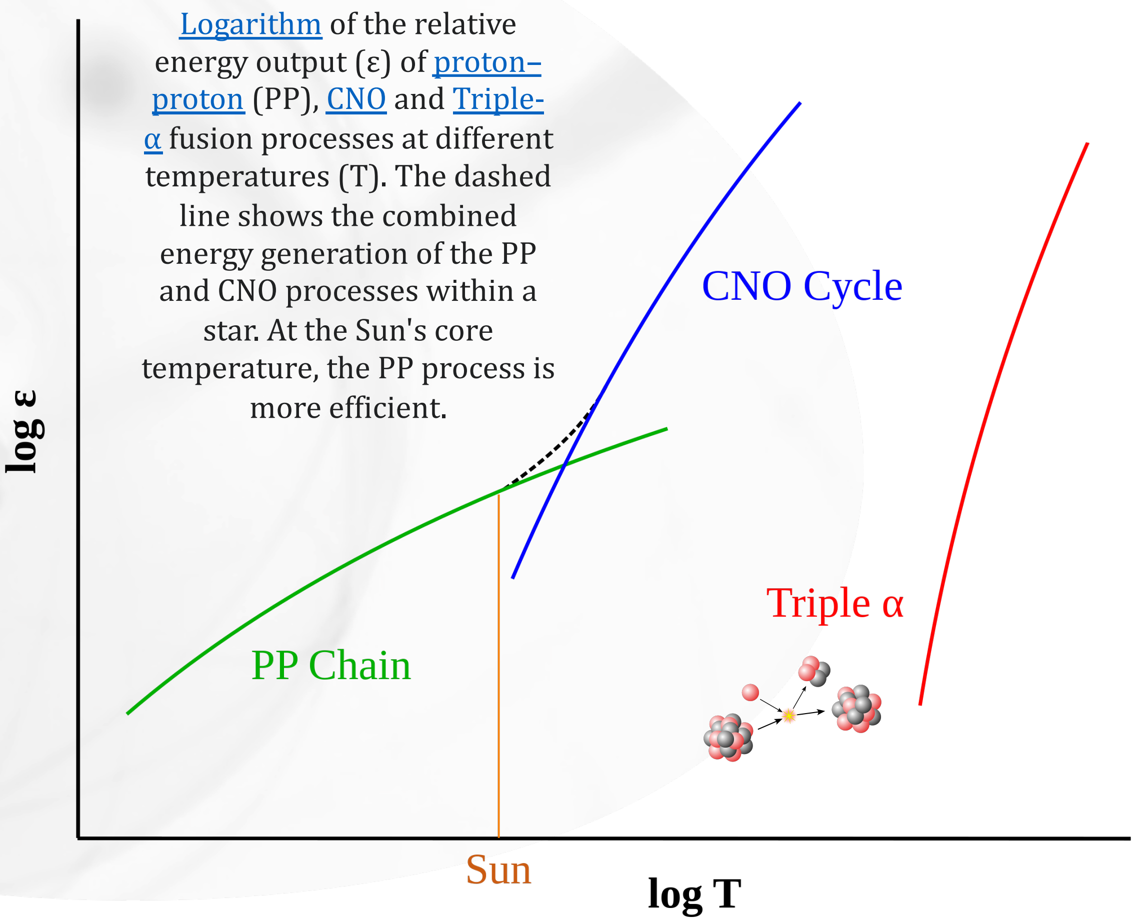
Figure 1.1: Solar abundance distribution normalised to Silicon at 10^6, adapted from Lodders 2003. The peaks in the distribution show the signatures of the different processes. The first peak around helium results from the primordial nucleosynthesis. The second peak around iron originates from nuclear statistical equilibrium and the following double peak structures from neutron capture processes.

Fusion processes: light elements



Fusion processes: elements up to Fe





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Fusion processes: heavy elements

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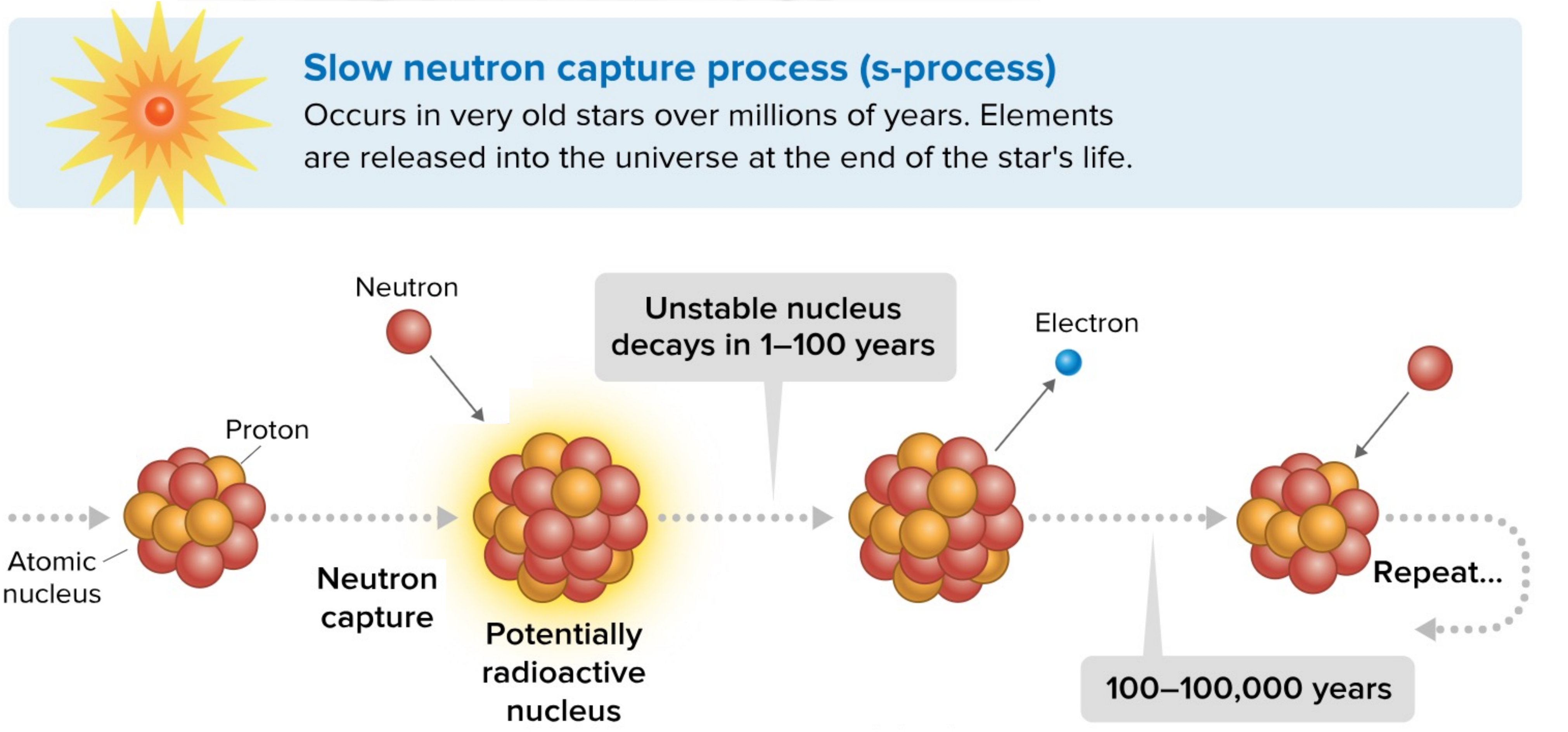
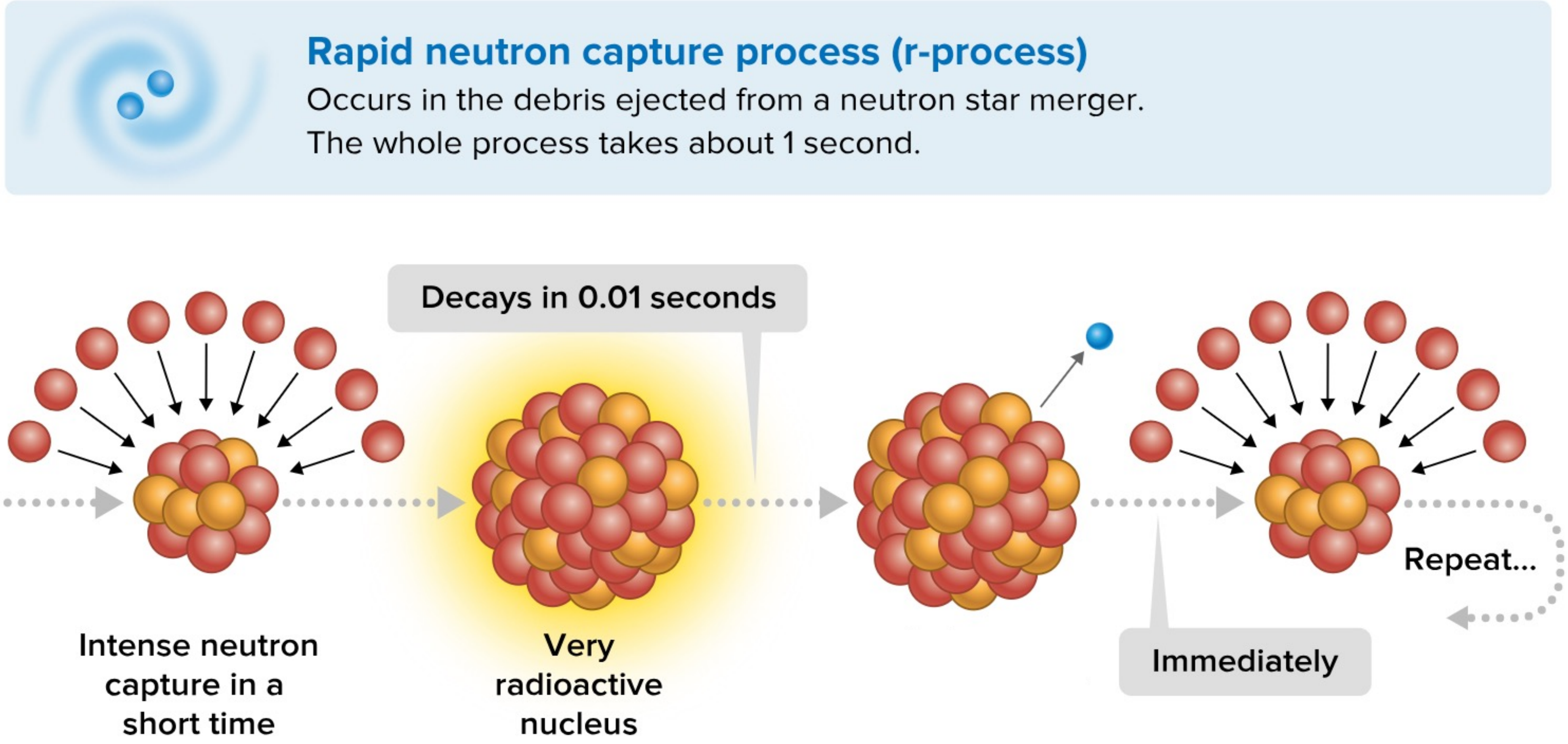


Picture from *https://knowablemagazine.org/article/physical-world/2018/crash-stars-reveals-origins-heavy-elements*

Fusion processes: heavy elements



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Why plasma

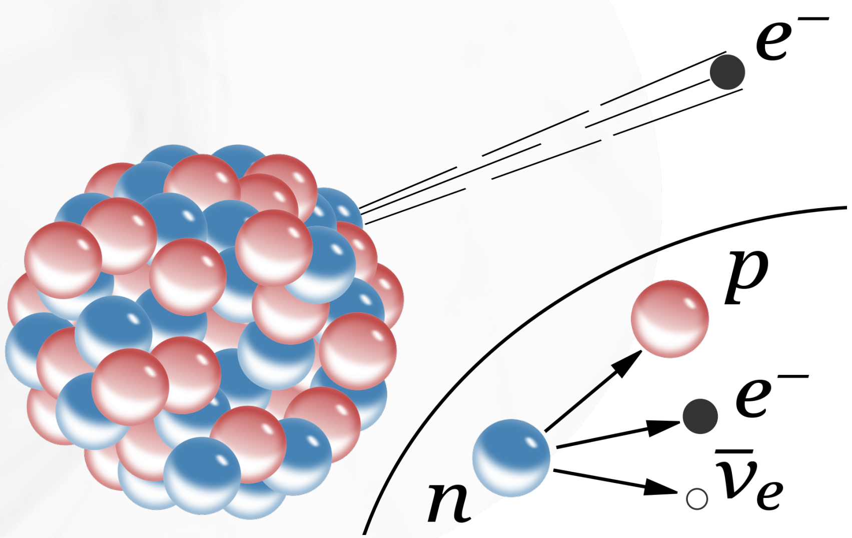
Why plasma: β-decays

Stellar nucleosynthesis proceeds in a hot and dense environment which affects the degree of ionization of the atoms involved in the stellar nucleosynthesis.

What happens when atoms are highly ionized?

The beta decay in highly ionized atoms shows important variations compared to neutral species

1. Electron Capture becomes impossible in fully ionized atoms.
2. Bound state β-decay typically marginal can become important.



https://www.frontiersin.org/research-topics/25146/nuclear-physics-and-astrophysics-in-plasma-traps

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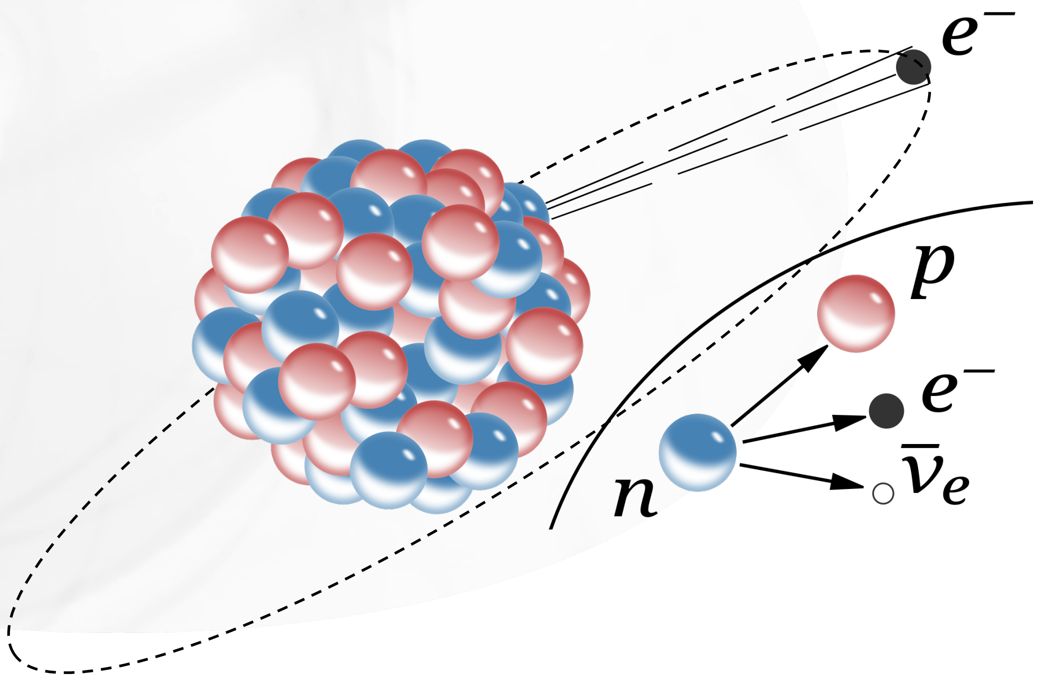
Bound-state β-decay is a nuclear β- decay process in which an electron is created in a previously unoccupied atomic orbital rather than in the continuum.



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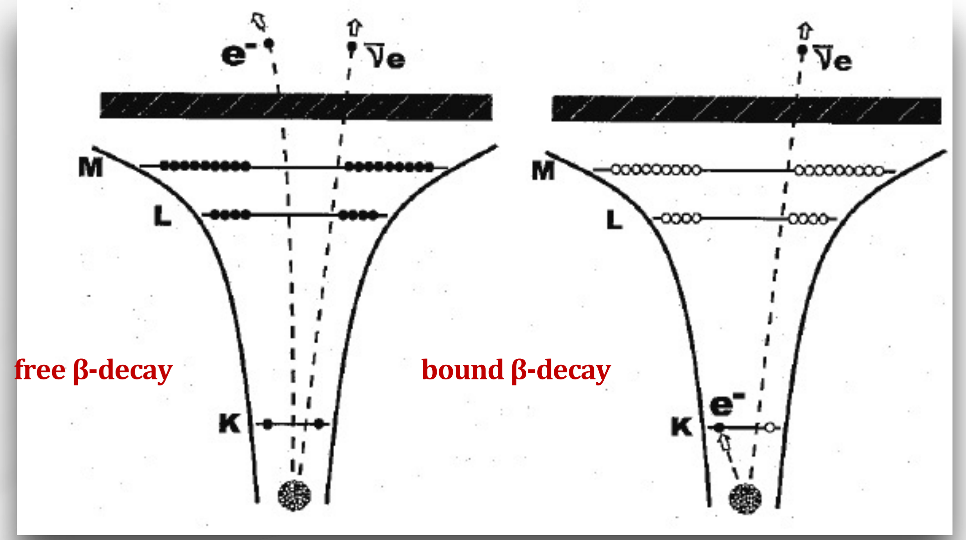

Y. Litvinov and F. Bosh: Rep. Prog. Phys. 74, 016301 (2011)

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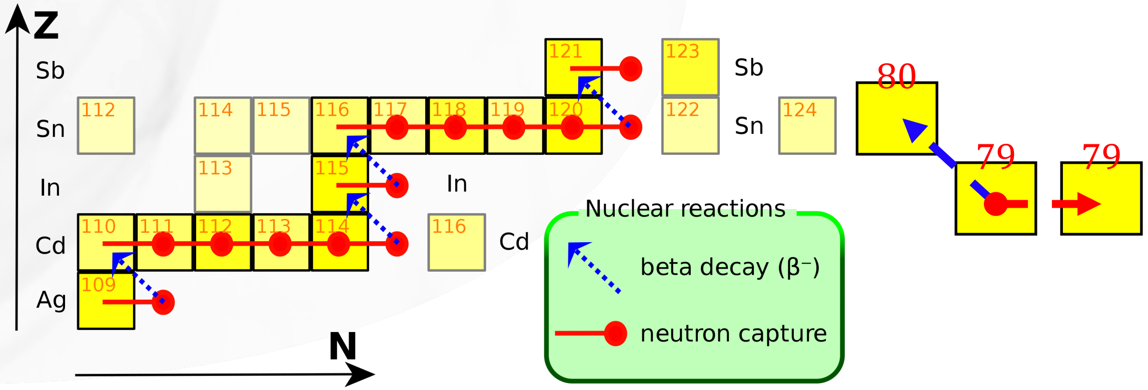
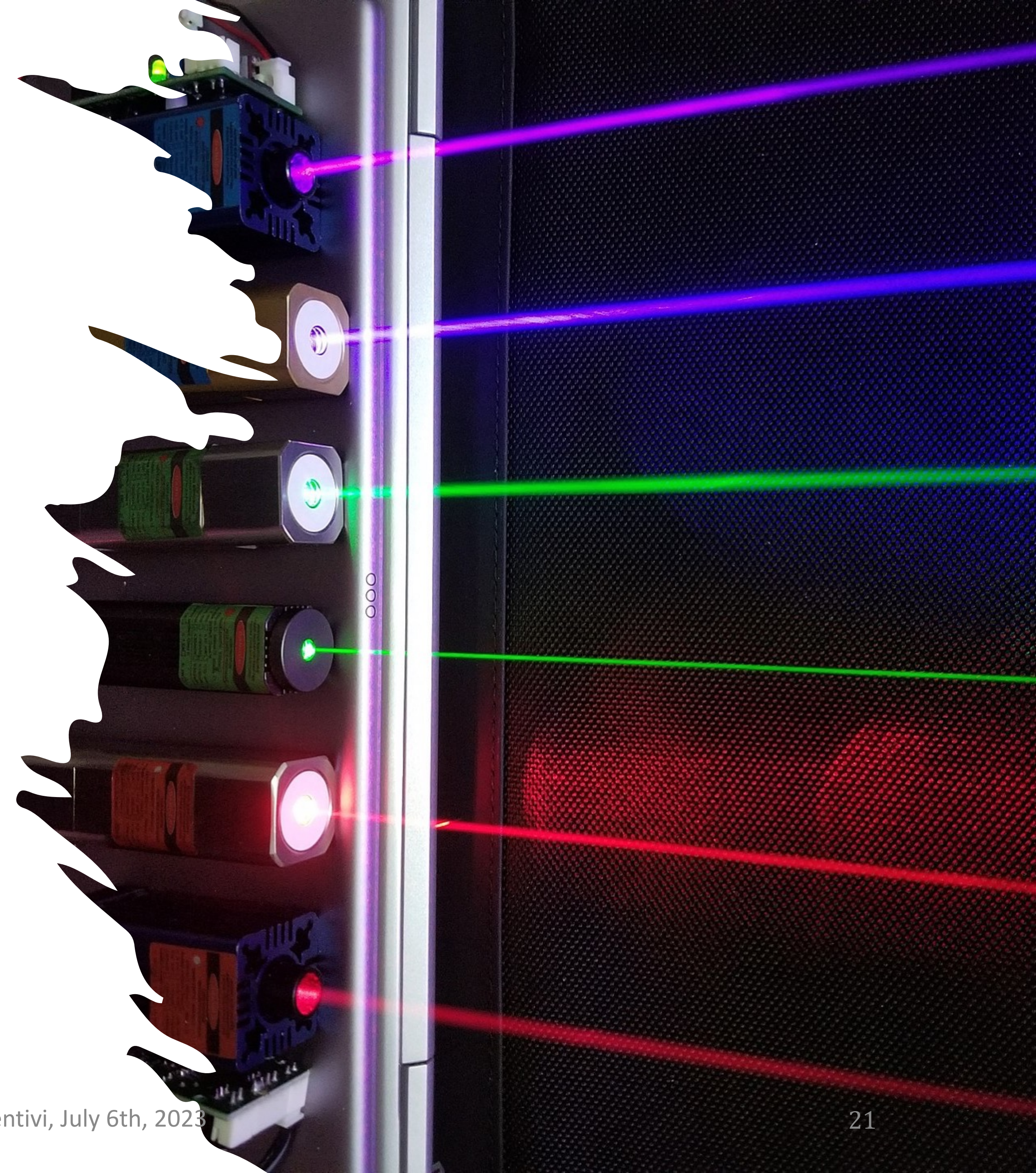
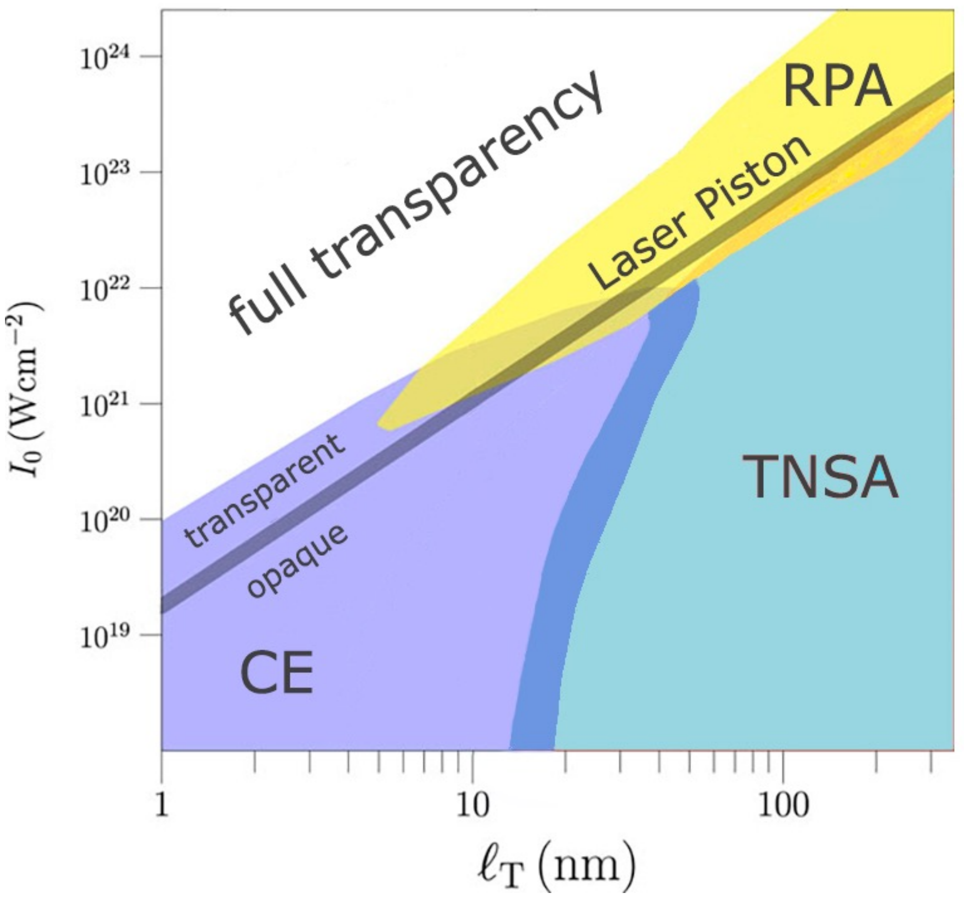
Example: Bare $^{187}Re^{75+}$ ions decay, due to the bound-state beta decay, **becomes 9 orders of magnitude faster than neutral ^{187}Re atoms with a half-life of 42 Gyr.**



Why laser



Laser-matter interaction

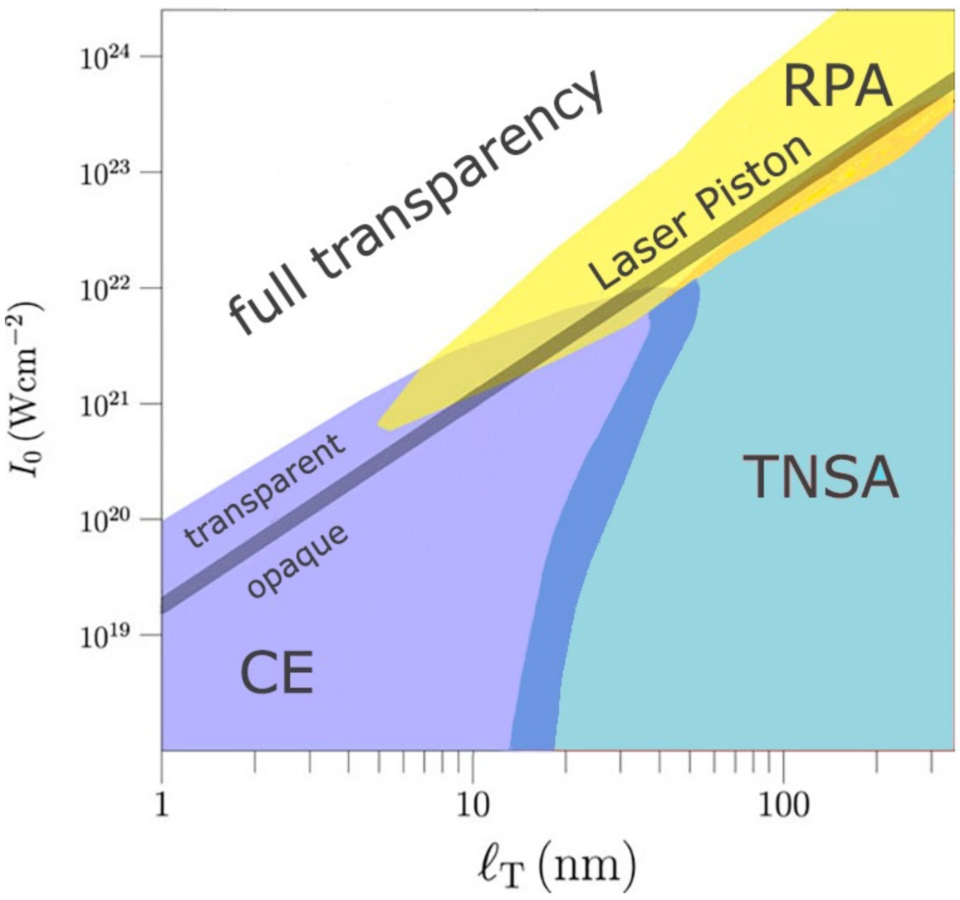


When a high intensity laser pulse (above 10^{18} W/cm^2) is focused in a spot of the order of a few microns on a target placed in vacuum, a plasma consisting of electrons and ions is created almost instantaneously.

- **Target Normal Sheath Acceleration (TNSA):** effective in accelerating protons and light ions → a short laser pulse interacting with the target front surface produces a plasma made of ions and fast electrons.

- **Coulomb Explosion (CE):** optimized for clustered gaseous targets, intensities in the range $10^{18} \div 10^{20}$ W/cm^2 and $\tau < 200$ fs → an explosion may occur due to the intense laser field that, extricating several electrons from the molecule cluster, induces a high level of ionization. Possible also for thin (1-10 nm), solid targets or nano-structured targets

Laser-matter interaction



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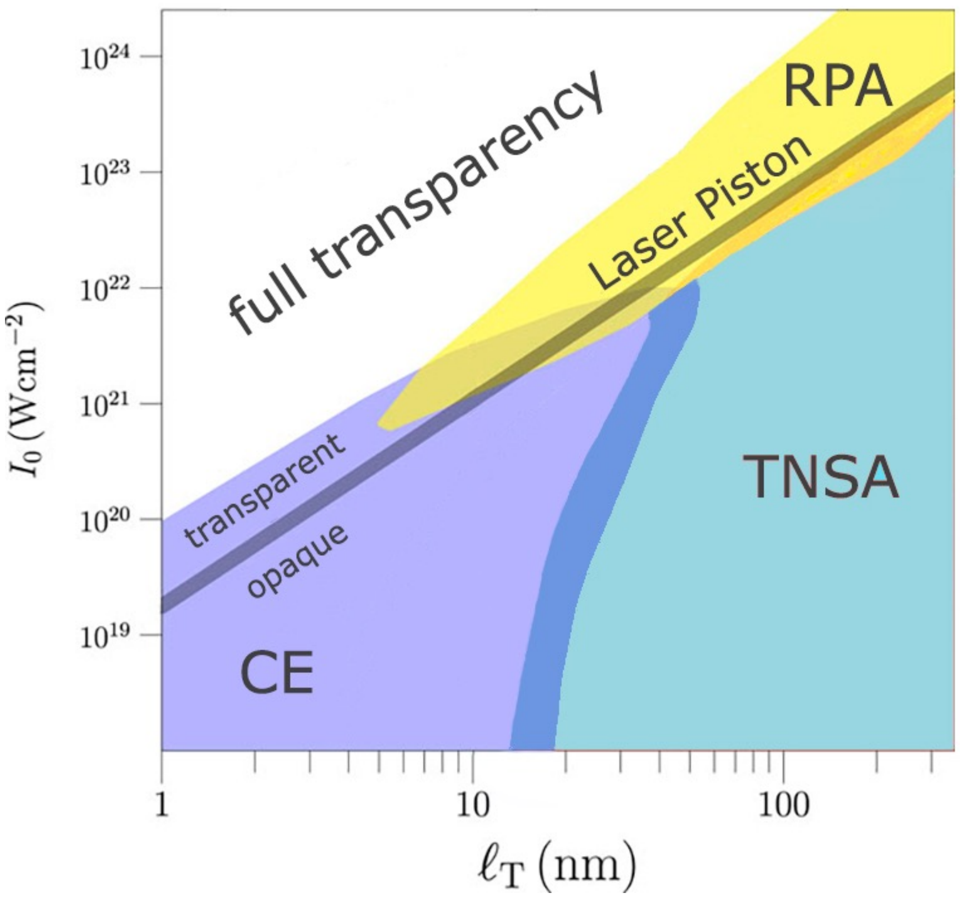
- **Radiation Pressure Acceleration (RPA), or Laser Piston regime:** based on the action of the radiation pressure induced in the interaction of a short laser pulse, of extremely high intensity (above $10^{20} \div 10^{21}$ W/cm^2), with a thin and dense pre-plasma layer created, in front of a target, by the laser-pulse leading edge. The plasma electrons are locally separated from the plasma ions creating a strong accelerating field which efficiently accelerates the ions in the irradiated target area.

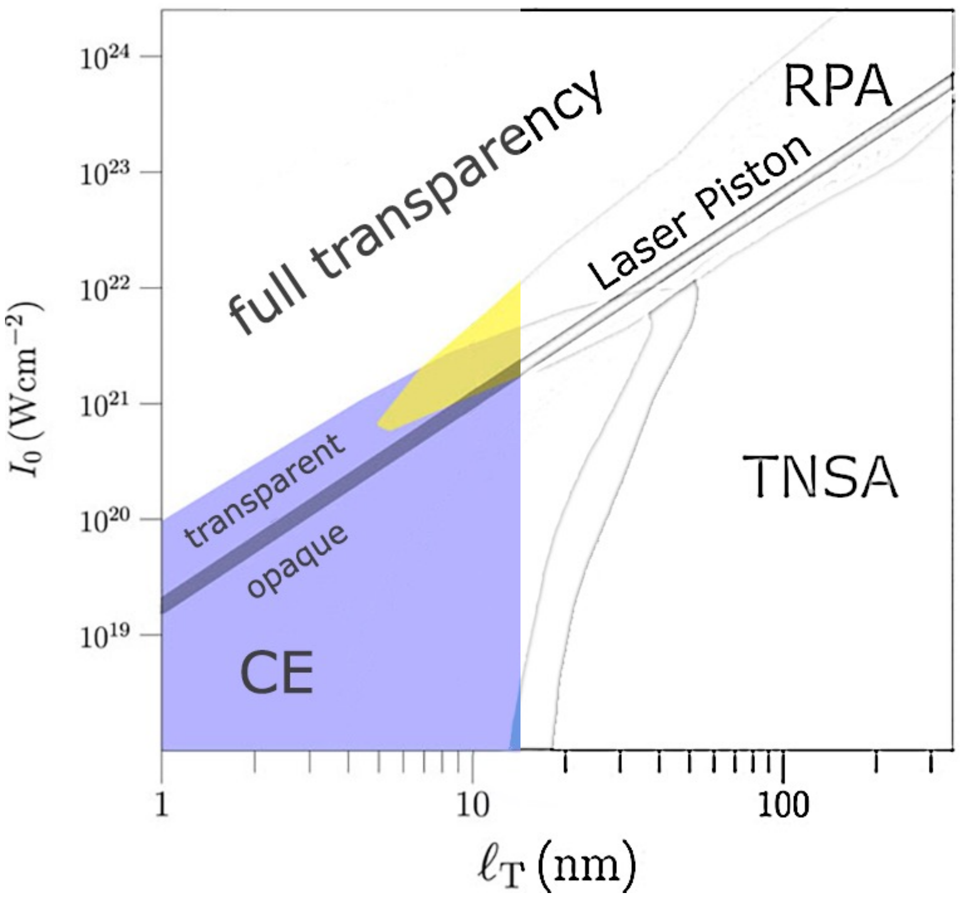
Laser-matter interaction



A precise control of the experimental conditions is challenging with high-power lasers → variations observed between experiments performed in conditions which would seem similar at a first glance.

The scaling of the most important characteristics (such as the energy per particle) with laser and target parameters is still unclear to a large extent, despite the large number of investigations performed.

Experiments at the 10^2 TW regime

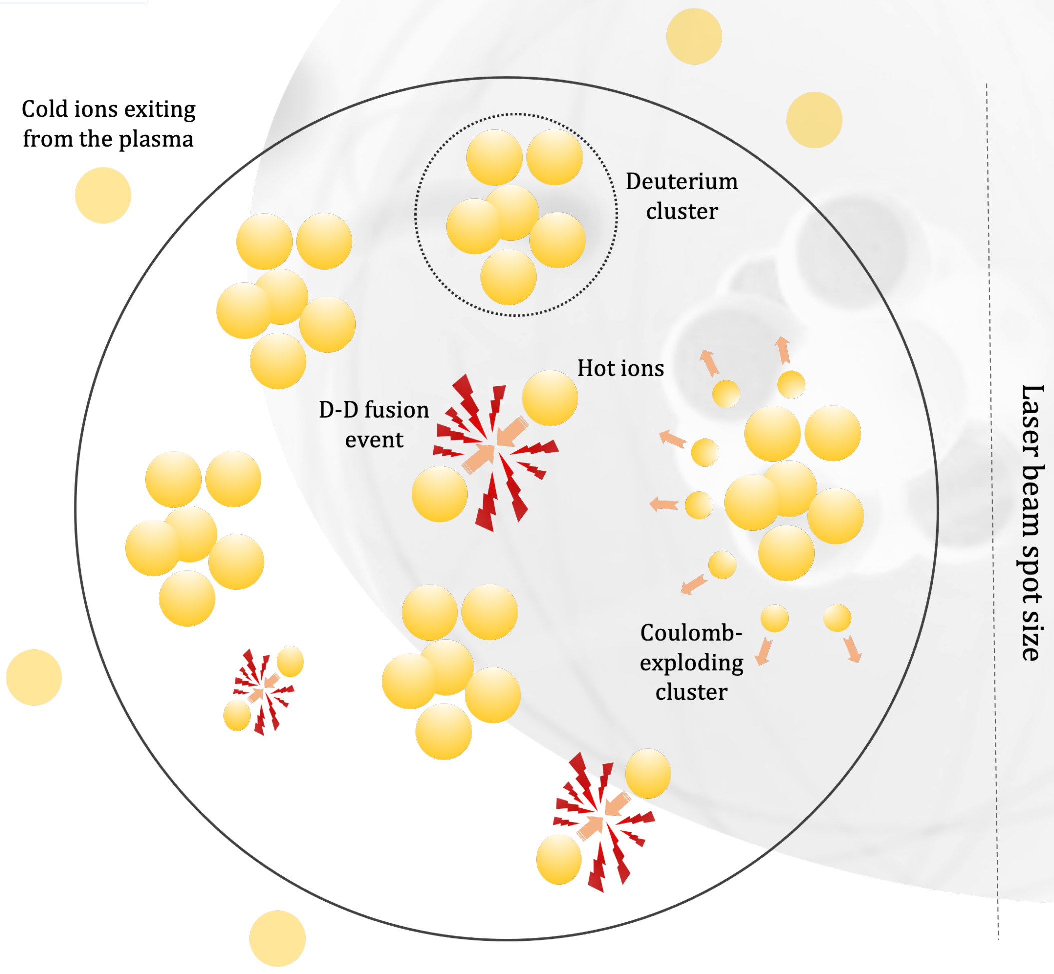


Low-density target → one of the most effective way for transferring energy from lasers to a gas target occurs **when the molecules in the gas are organized in clusters**

If the electromagnetic field is strong enough the cluster atoms are ionized, and a Coulomb Explosion can take place.

Deuterium fusion process in plasma

$d + d \rightarrow {}^{3}He + \mathrm{n}\ (2.45\ \mathrm{MeV})$



It is a nuclear fusion reaction occurred **in the Big-Bang Nuclosynthesis** → a *deuterium nucleus formed from a proton and a neutron fuses with another proton to form a helium-3 nucleus.*

It took place right after the hadronization step was over, when there were free p and n that eventually combine to form deuterium.

Indirect measurements of the deuterium burning available (1.5 MeV ÷ 2 keV), also exploiting the so-called Trojan-Horse Method. **However, a full comprehension of possible electron screening effects is crucial.**

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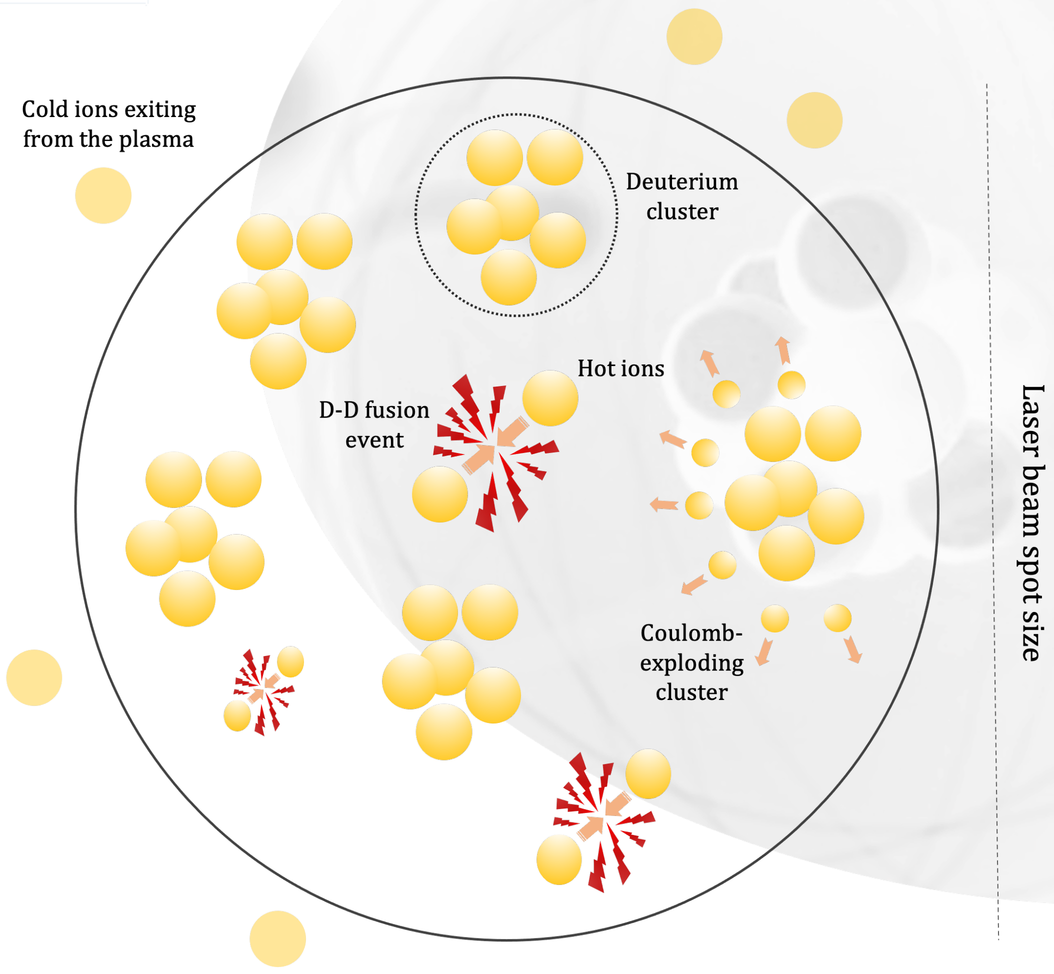
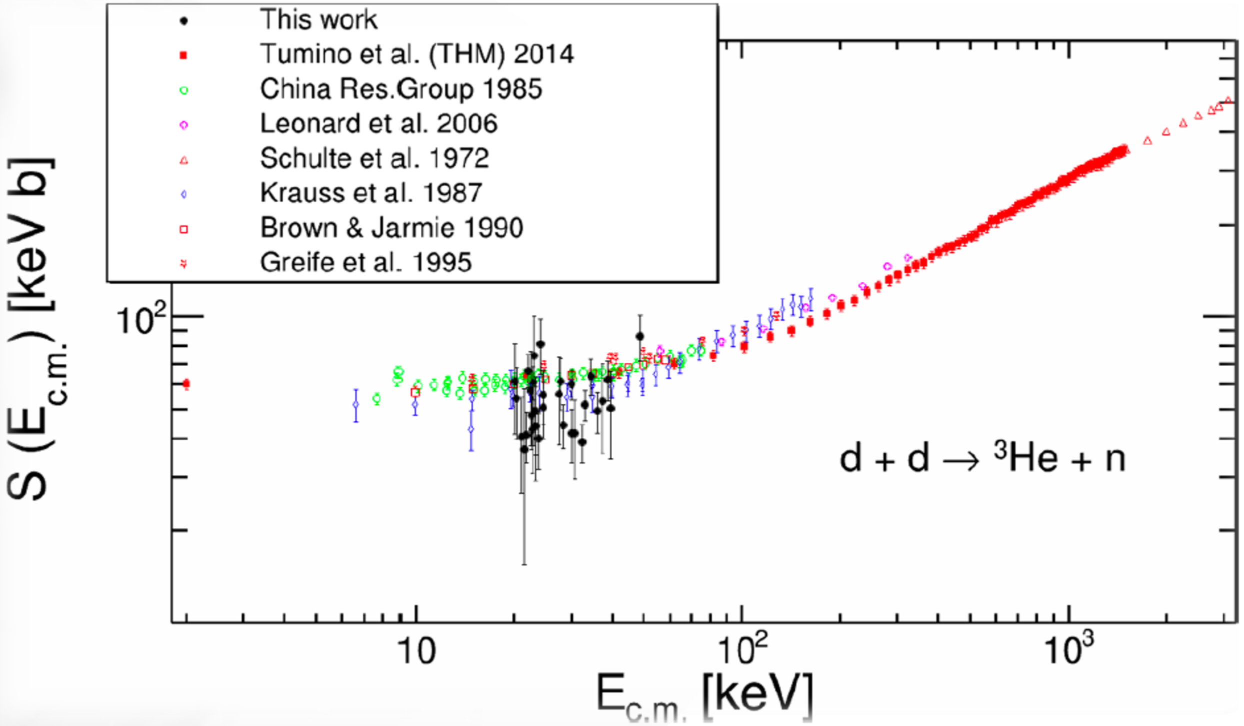


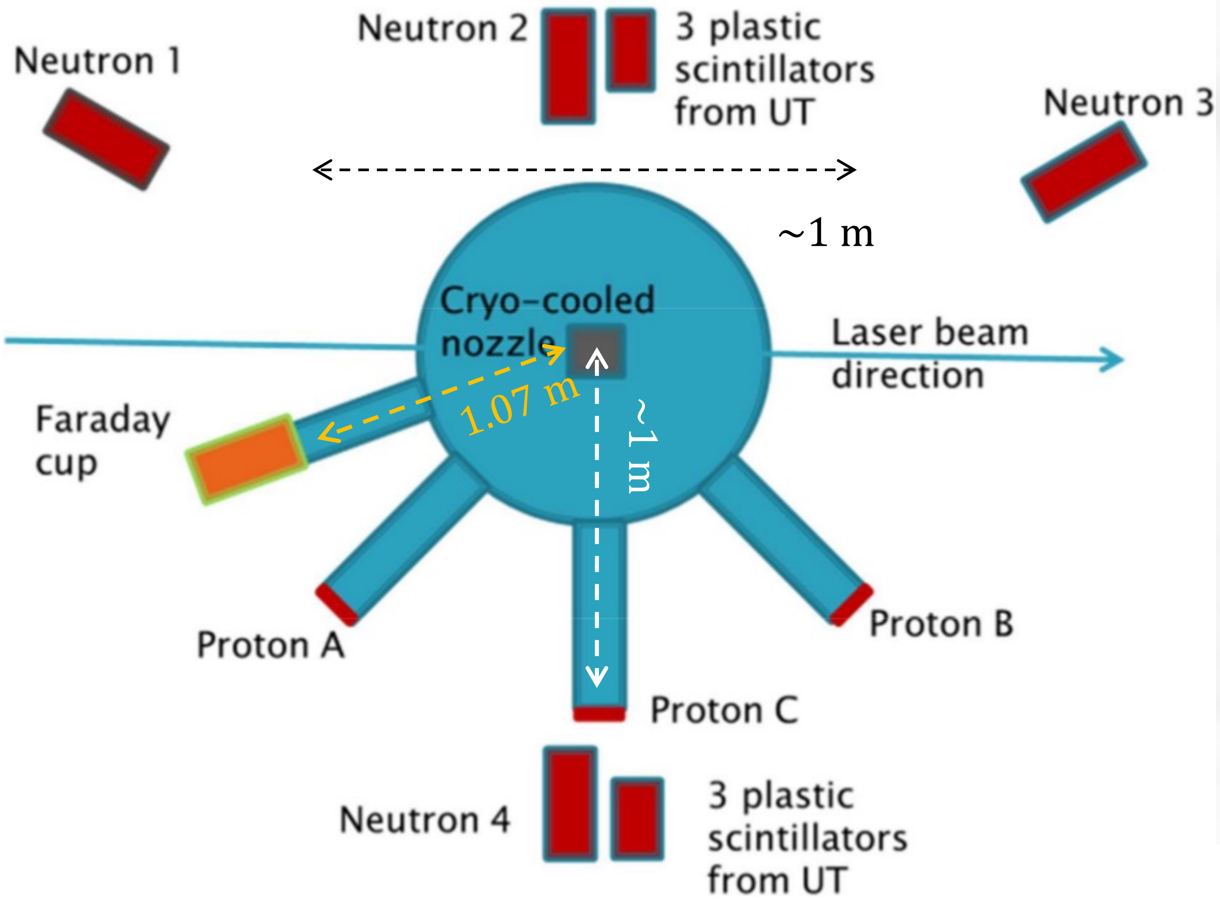


Model-independent determination of the astrophysical S factor in laser-induced fusion plasmas

D. Lattuada, M. Barbarino, A. Bonasera, W. Bang, H. J. Quevedo, M. Warren, F. Consoli, R. De Angelis, P. Andreoli, S. Kimura, G. Dyer, A. C. Bernstein, K. Hagel, M. Barbui, K. Schmidt, E. Gaul, M. E. Donovan, J. B. Natowitz, and T. Ditmire

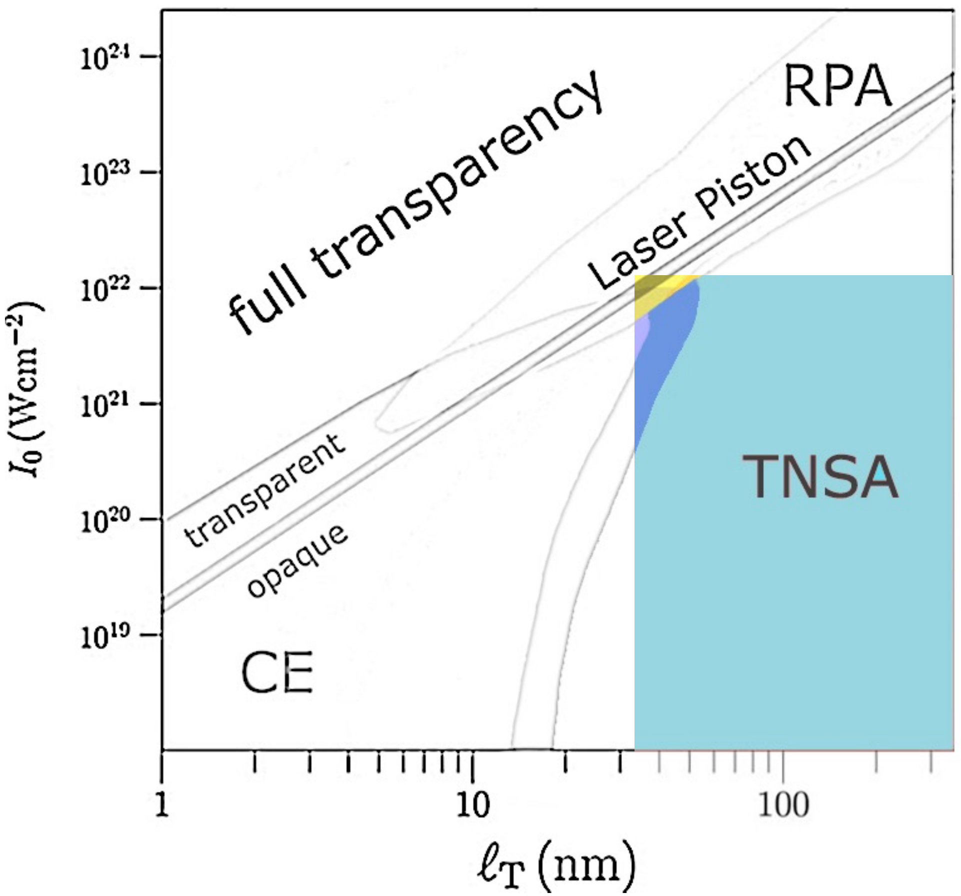
Phys. Rev. C **93**, 045808 – Published 19 April 2016

Experimental area: an example



- Proper *time-of-flight paths* must be foreseen for a reliable particle identification
- Neutron detectors must be kept displaced enough from the walls
- Cablings, signal transportation

Experiments at the PW regime



High-density target → solid, Lu target

Target choice to be optimized in view of the thermalization goal.

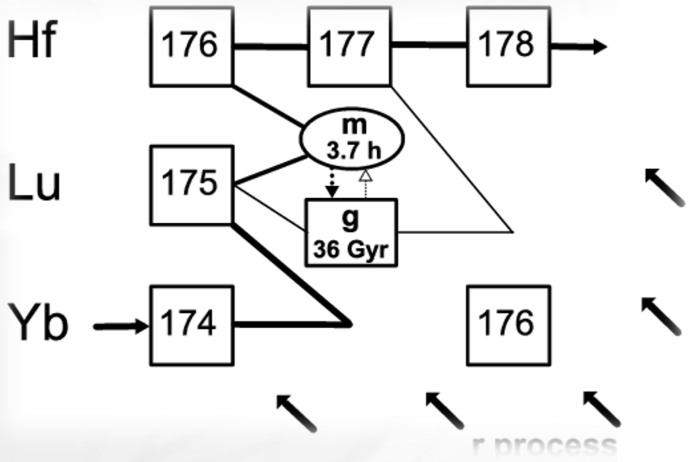
https://www.frontiersin.org/articles/10.3389/fphy.2022.727718/full

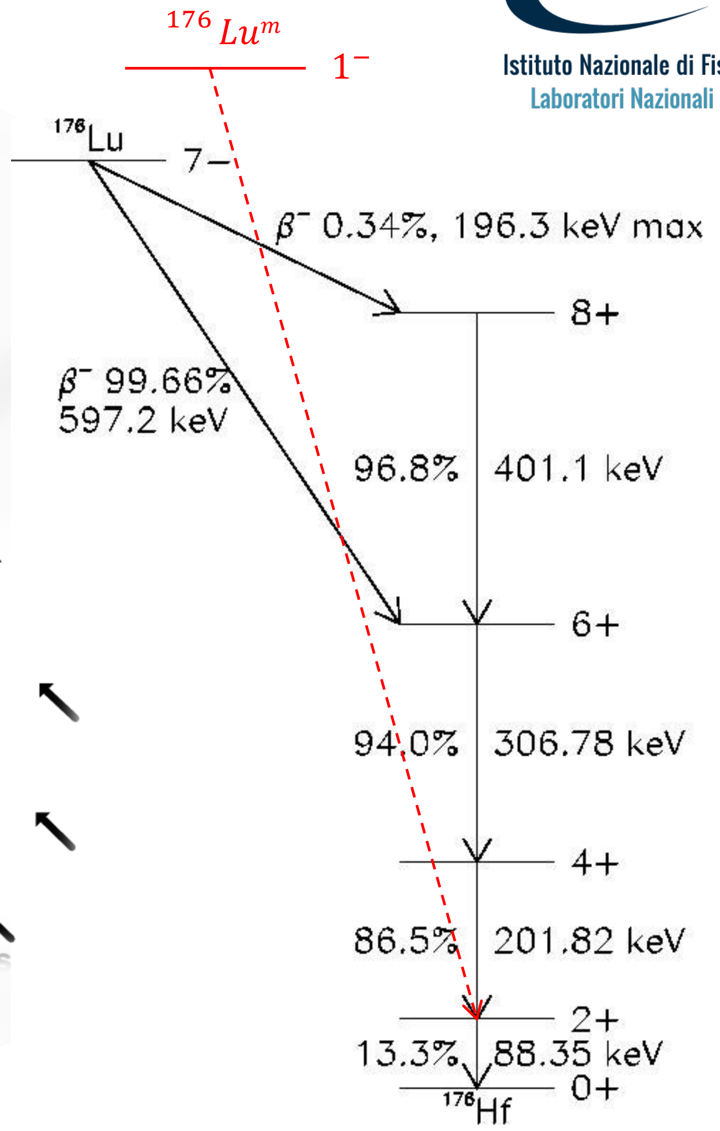
^{176}Lu physics case

^{176}Lu physics case

^{176}Lu: is a very long-lived in laboratory conditions and **in principle might act as a cosmo-chronometer**

- **the s-process branching point at ^{176}Lu is among the most important ones** for the understanding of slow neutron captures in the Asymptotic Giant Branch (AGB) phases of low and intermediate mass stars;
- **it determines the abundance of ^{176}Hf, an "s-only" nucleus**
- Scenario is complex due to the presence of an isomeric state placed at 122.45 keV with a very short lifetime





Important to investigate the *in-plasma* variations of the half-life

Measurement strategy

1. Once the solid ^{176}Lu target is hit by a laser pulse with an intensity as high as $10^{21}\ W/cm^2$, the ionization and the subsequent ion emission takes place

2. Lu ions travelling at a velocity of the order of hundreds of keV

3. Given the high energy administered by the laser in a short time interval, a local thermal equilibrium can be reached not only by the electrons, but also by the ion clouds, that can reach temperature as high as 10^8K

4. At this temperature, the nuclei may be excited, and the Lu isomeric state $^{176,m}Lu$ can be populated

5. ^{176}Lu decays to the Hf 6^+ excited states, whose de-excitation proceeds through three different steps, leading to the subsequent emission of photons with energies equal to E_γ = 307, 202 and 88 keV. $^{176,m}Lu$, on the other hand, directly decays to the first Hf excited state → only the emission of a photon with E_γ = 88 keV is observed

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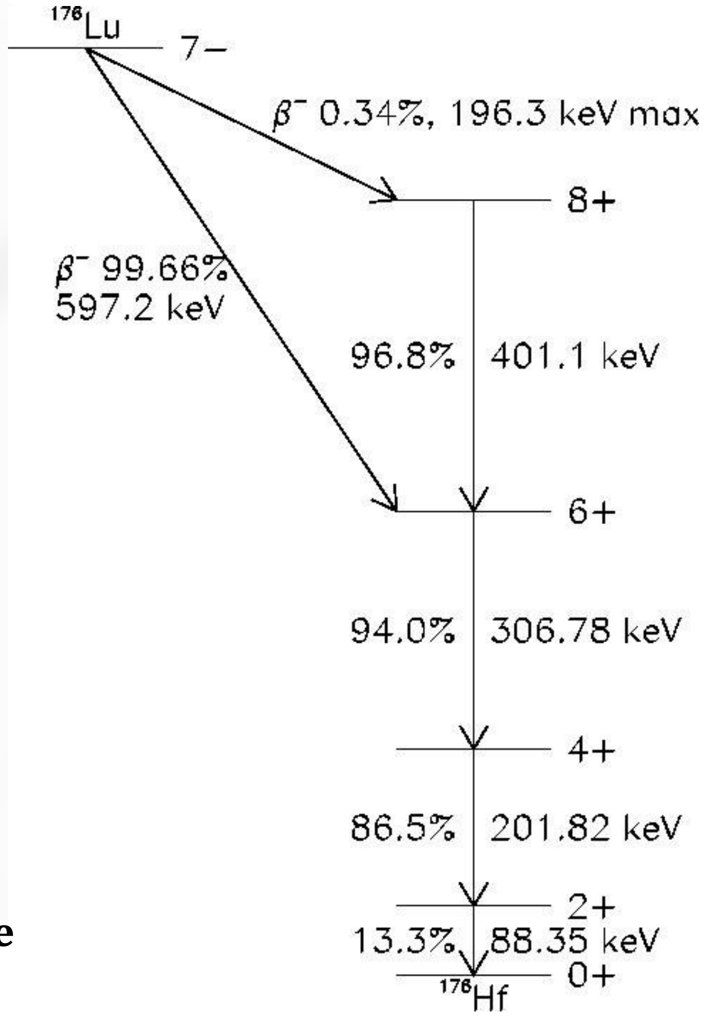

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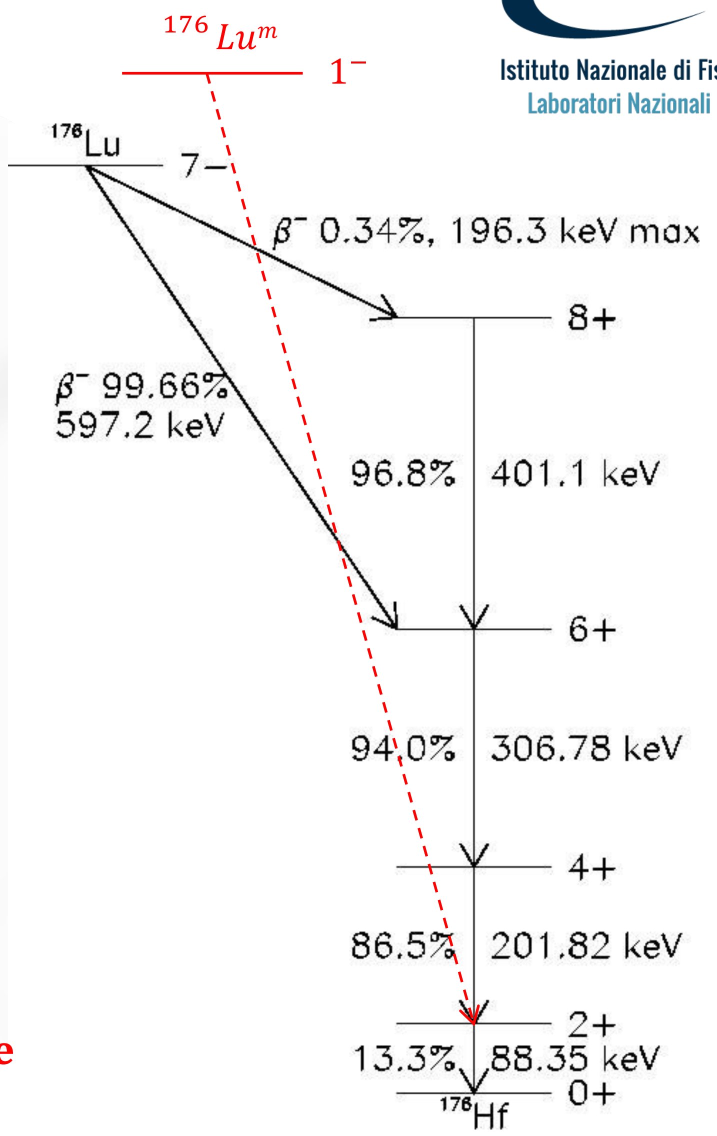

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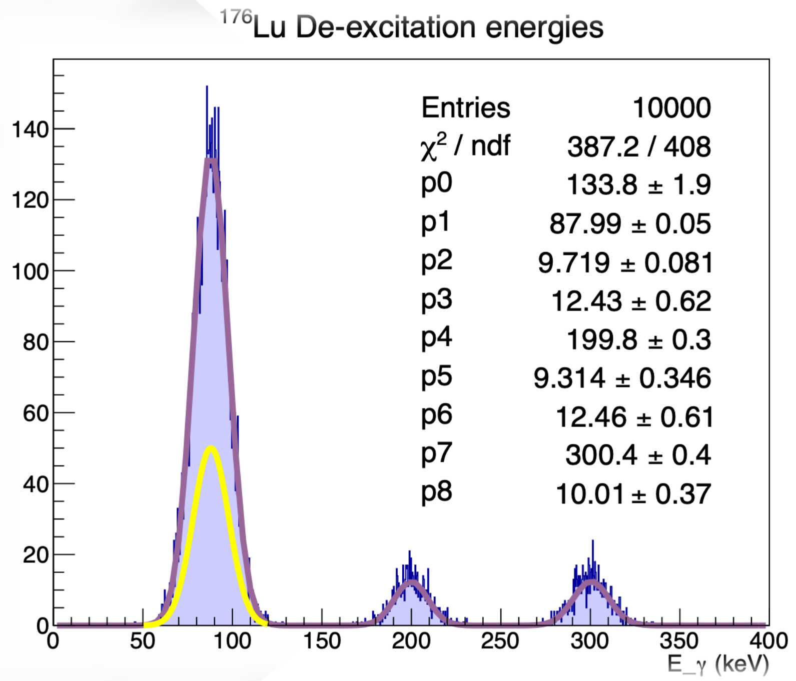
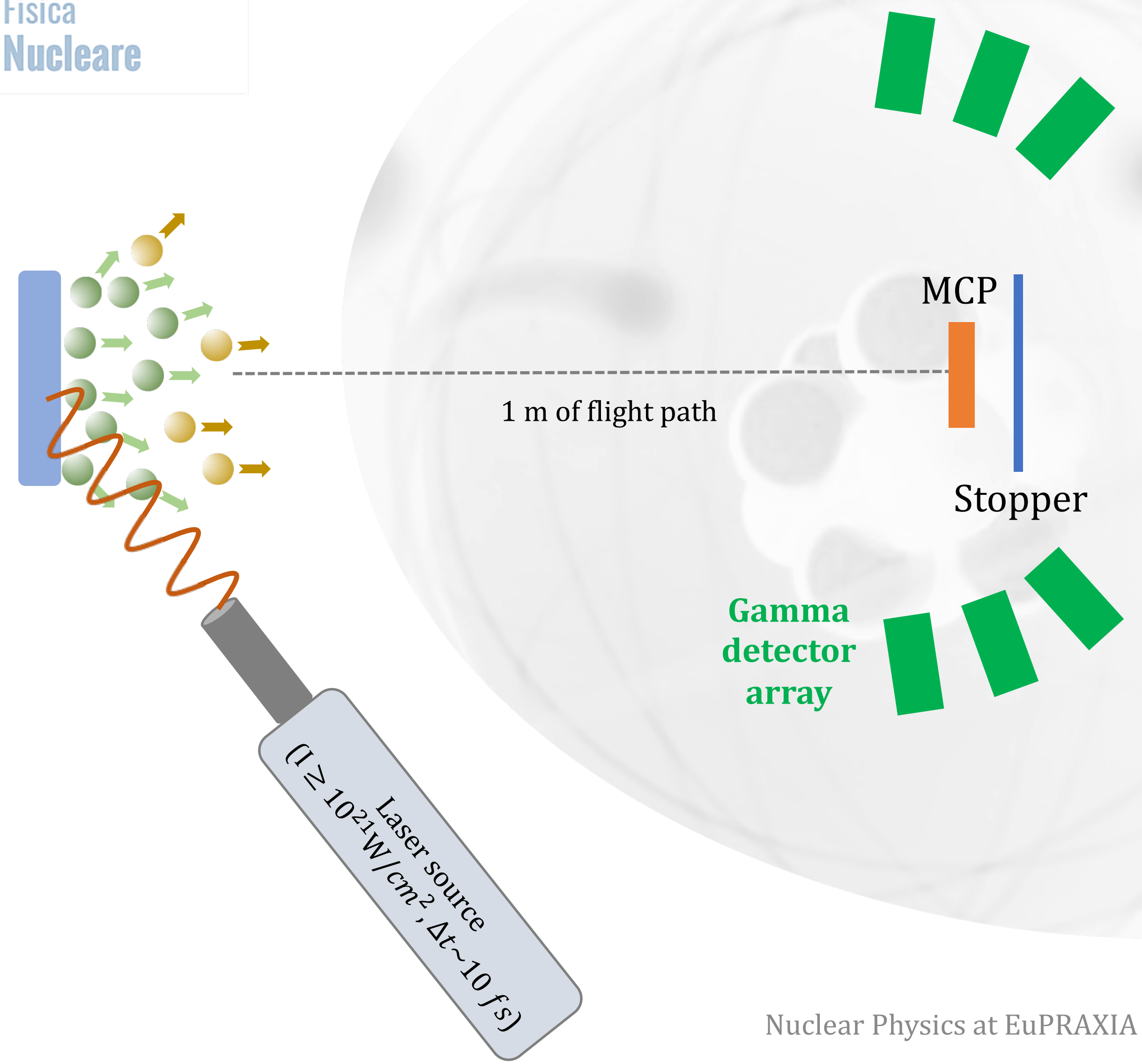
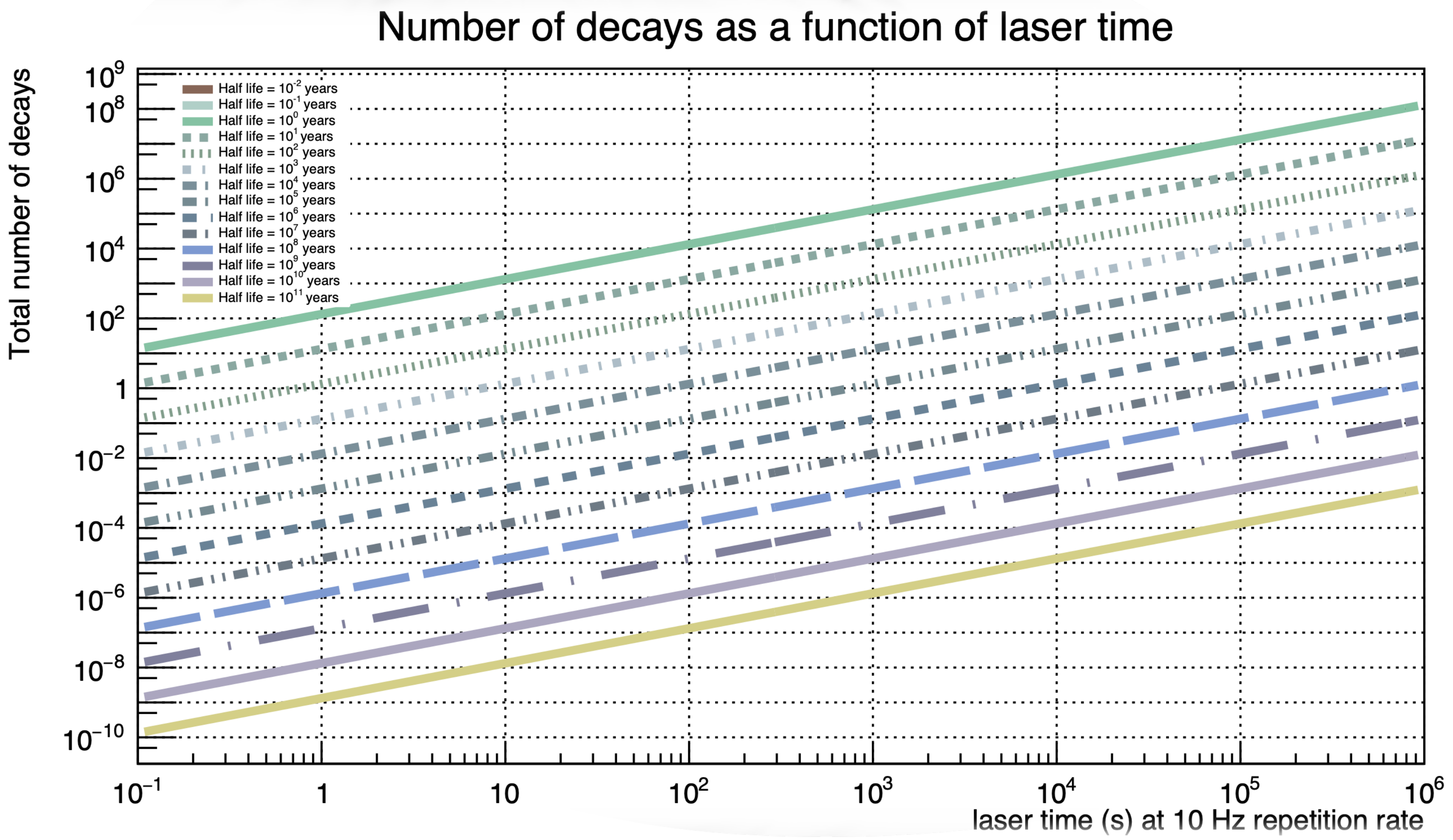


Possible experimental setup for $\boldsymbol{\beta}$-decay



1. A PW laser pulse is sent to a solid target containing the radio-isotope under investigation.
2. The plasma is created and a forward emission of the thermalized excited nuclei takes place.
3. The nuclei travel and eventually decay in flight, populating daughter nuclei in excited states.
4. The flight path, and then the distance between the target and a suitable stopper, must be optimized in order to guarantee a proper time window for the decay measurement ($\sim 1\mu s$).
5. This poses limits on the half-life range that can be explored.
6. The gamma emitted in the decay process may be detected through a dedicated detection system.

Projections for a 10 Hz repetition rate



Conclusions

1. **Possible physics program with hundreds of TW lasers**: study of fusion processes in plasma, only barely explored at the moment in stellar-like conditions → few seminal measurements available (*e.g.*, *Lattuada et al.*), to be confirmed with higher statistics.

2. **Possible physics program with hundreds of TW lasers**: also other fusion processes can be explored (*e.g.*, ^{12}C burning, crucial for the field of nuclear astrophysics)

3. **Possible physics program with PW lasers:** first-time *in-plasma* measurement of the ^{176}Lu $t_{1/2}$ → implications for the understanding of the heavy-element production through *s*-processes

4. Natural evolution of PANDORA@CSN3 physics program

5. Possible dedicated detector R&D program (*e.g.*, for timing)

backup

Projections for a 10 Hz repetition rate

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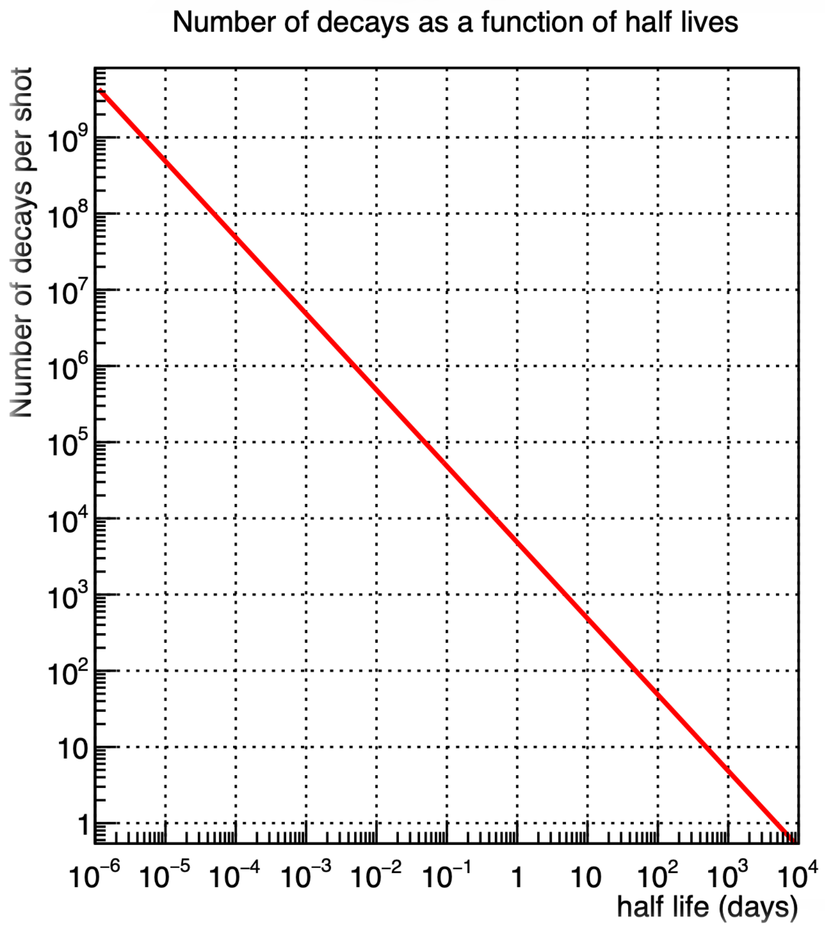
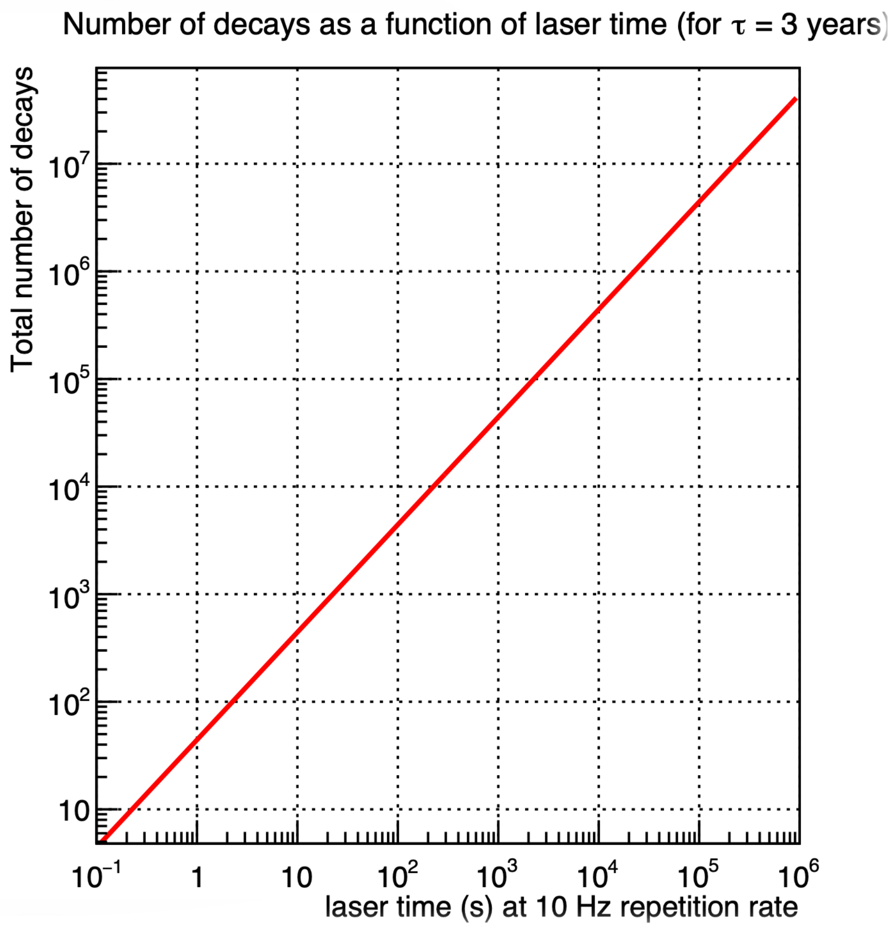
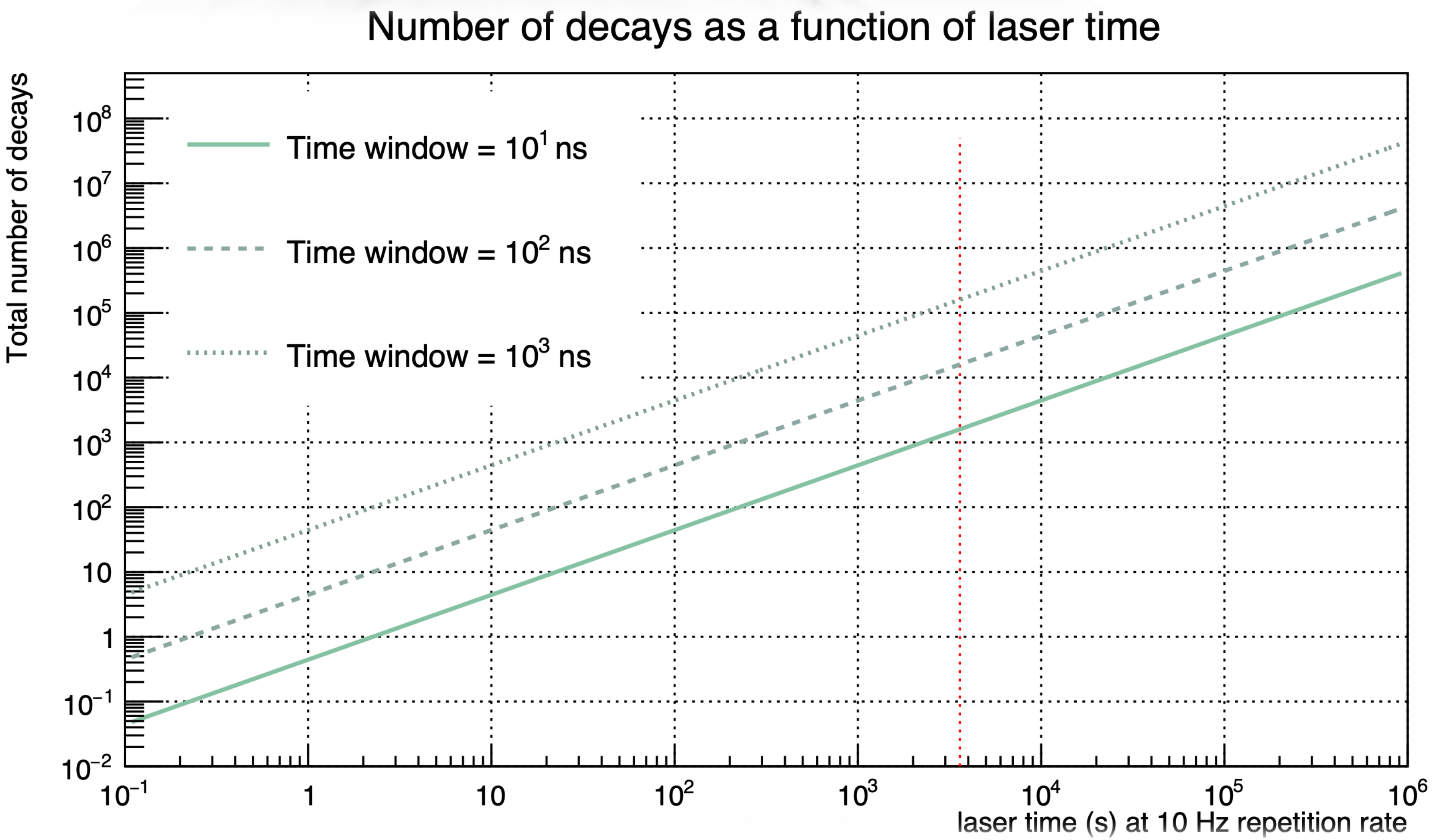




Projections for a 10 Hz repetition rate

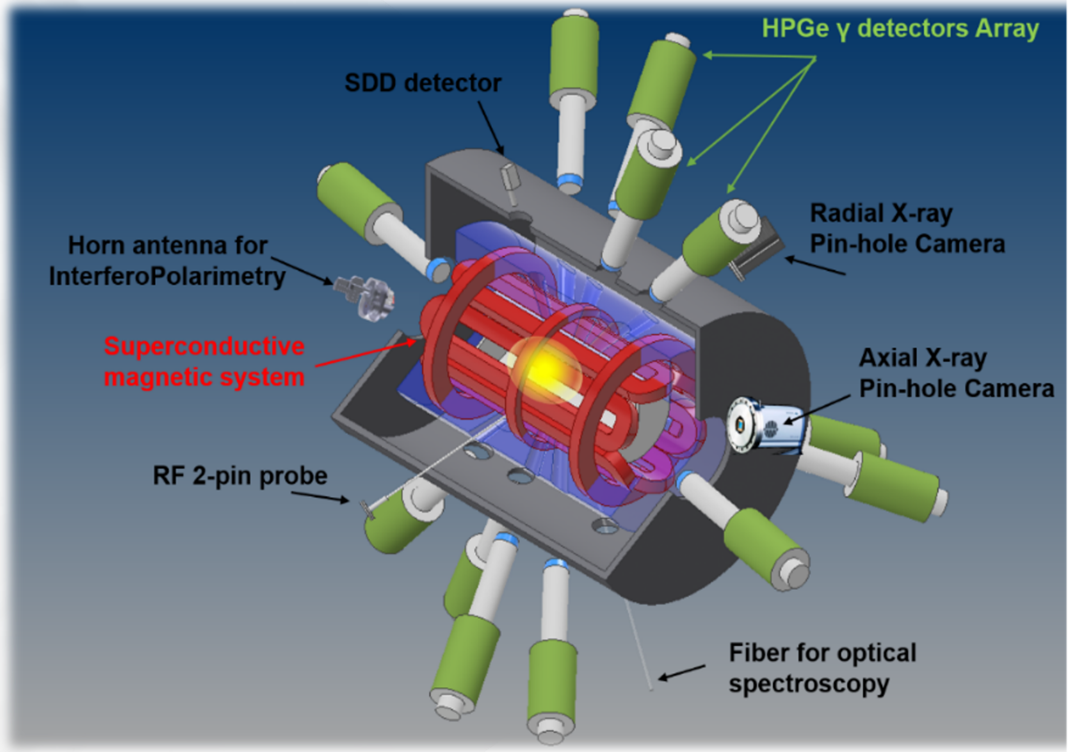


How to measure ^{176}Lu $t_{1/2}$ in plasma?

The PANDORA experiment

Build a plasma trap where ion species are confined in a magnetic field and a plasma is created with:

- **Electron density: $10^{12} \div 10^{14}\ cm^{-3}$**
- **Electron temperature: 0.1 ÷ 100 keV**
- **Ion density: $10^{11}\ cm^{-3}$ → relies on the radiactive isotope concentration in plasma**
- **Ion temperature: ~ 1 e → Ions are cold: no access to the excited states**



$$\frac{dN}{dt} = \lambda n_i V \rightarrow \int_0^{T_{meas}} dN = \int_0^{T_{meas}} \lambda n_i V\ dN$$

$$\mathrm{N}(T_{meas}) = \lambda n_i V T_{meas}$$

$n_i V$: density and plasma volume, constant → to be measured using multiple diagnostic tools

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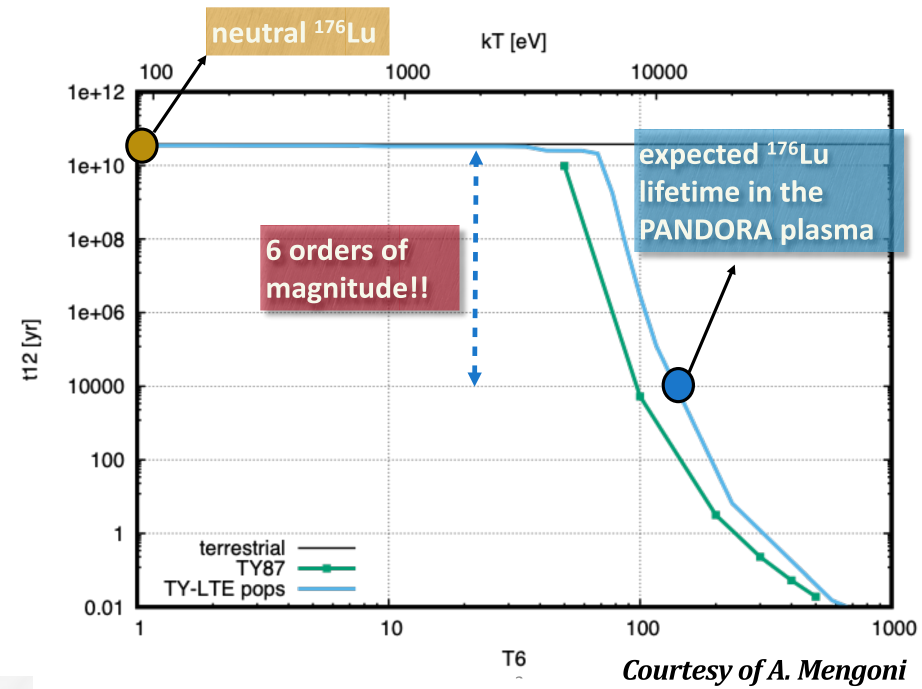
^{176}Lu: lifetime vs. T – theoretical predictions



Courtesy of A. Mengoni

Takahashi et al. 1987, Phys Rev C 36, 1522

PANDORA: only ground state will be studied → T too low to investigate variation on the isomeric state

How to measure ^{176}Lu $t_{1/2}$ in plasma?

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Scaling results to stellar environment

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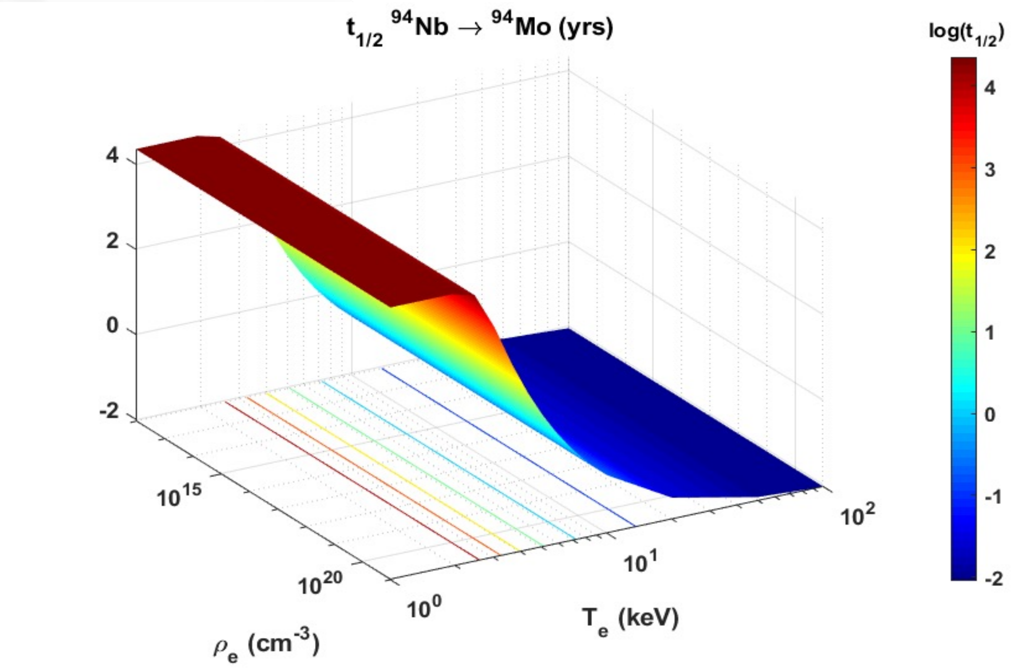

T_e = 0.1-100 keV in a lab. Magnetoplasma

Variation with T_e stronger than with ρ_e → "stellar effect" can be modelled by ECR (*Electron Cyclotron Resonance*) plasma

Why to use laser-induced plasma

Build a plasma trap where ion species are confined in a magnetic field and a plasma is created with:

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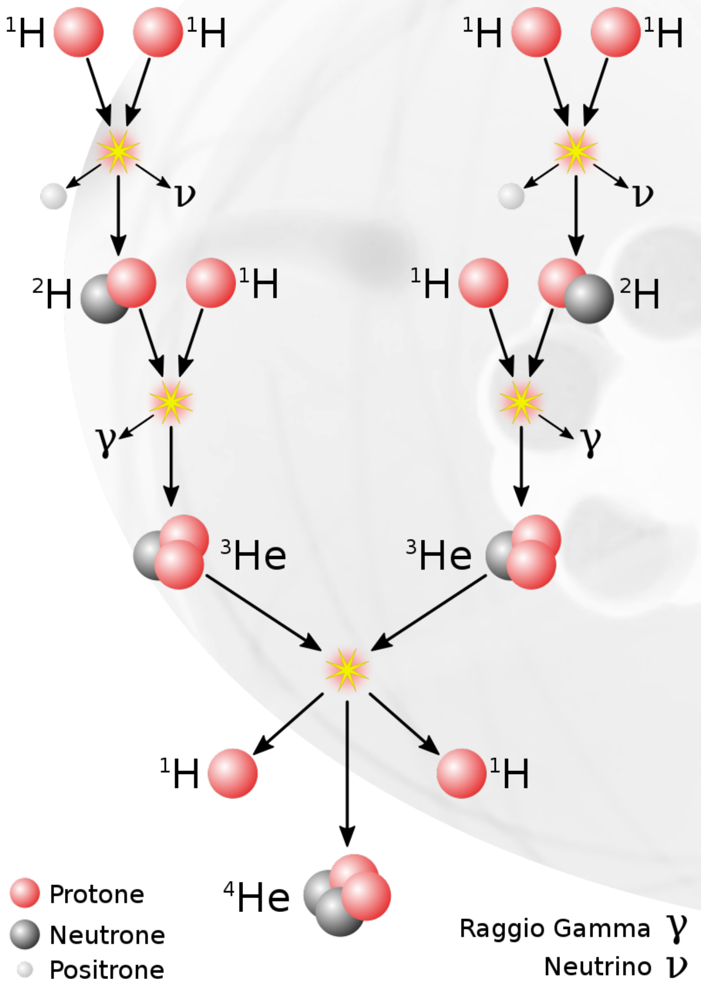
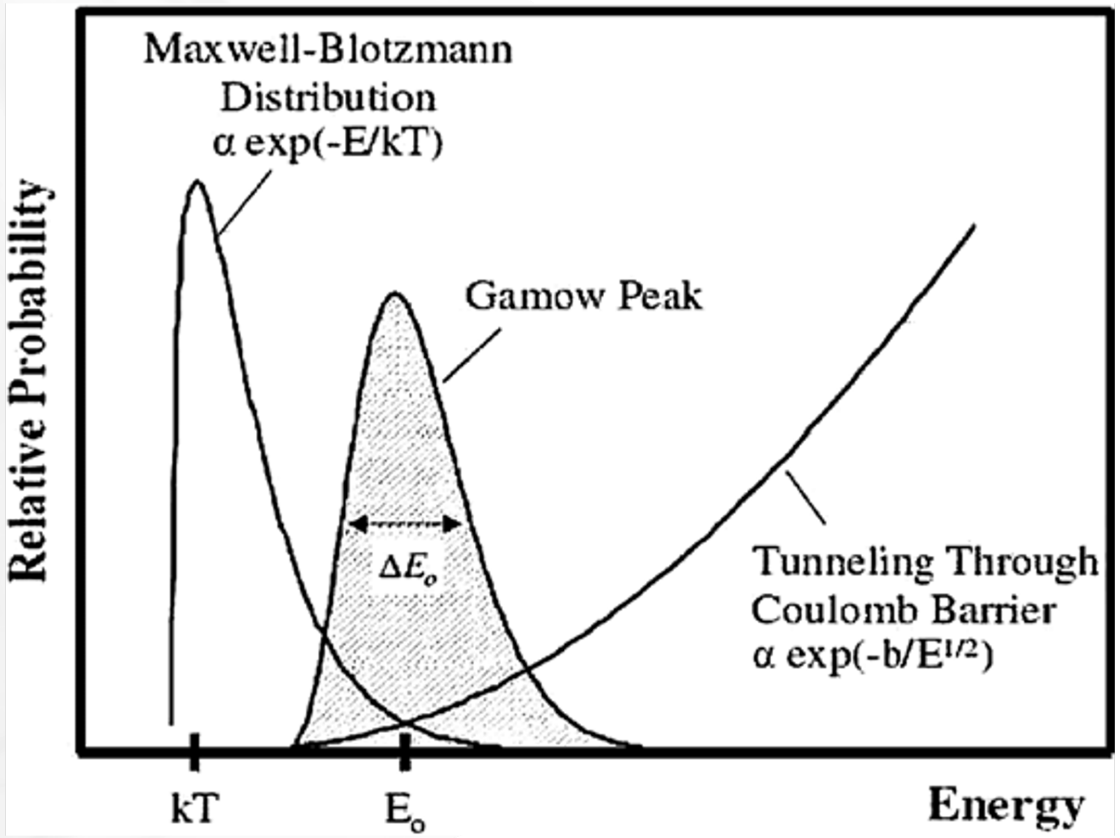
Exploring the onset of a (Full) Local Thermal Equilibrium:

- Typical lifetime of nuclear excited states ~ 10^{-15} s
- Assuming an excited state for, *e.g.*, ^{176}Lu*, around 122.45 keV
- Considering n_e=<q>n_i= $10^{27}\ m^{-3}$ (a typical stars interior density), at T_e=T_i=6.68 keV, the excited level lifetime is already exactly the same of the excitation rate, meaning **that this level can be populated and it is in thermal equilibrium in the assumed laser-induced plasma lifetime** (order of ps or tens of ps)
- Calculation also rescaled to a more realistic expected density of a real laser-induced plasma scenario (n=e=n_i= $10^{25}\ m^{-3}$) → the required plasma temperature to get the thermal equilibrium goes to around 37.5 keV. **This value seems to be however absolutely achievable in the foreseen laboratory scenario, confirming that the decay from excited states is in principle feasible.**

Simulations by B. Mishra et al.: thanks, Bharat!

Fusion processes: light elements





s-process endpoint

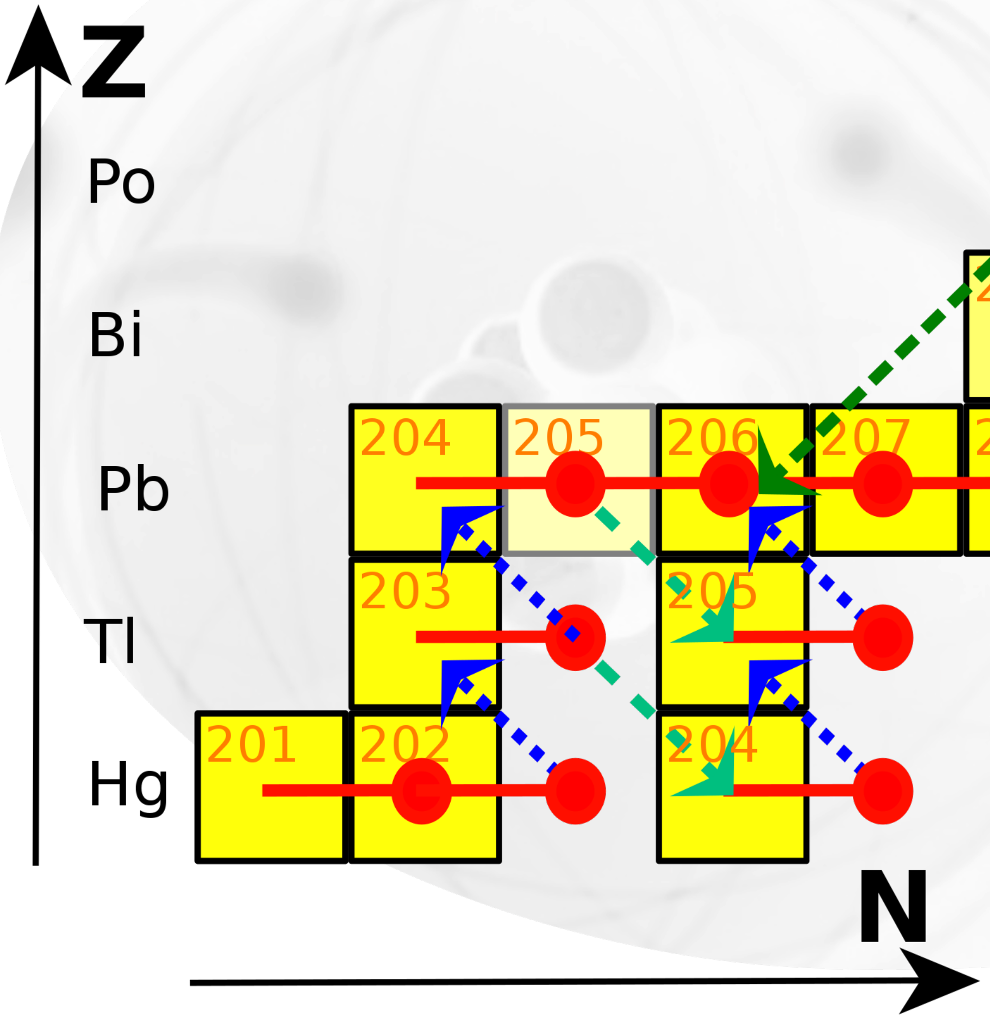
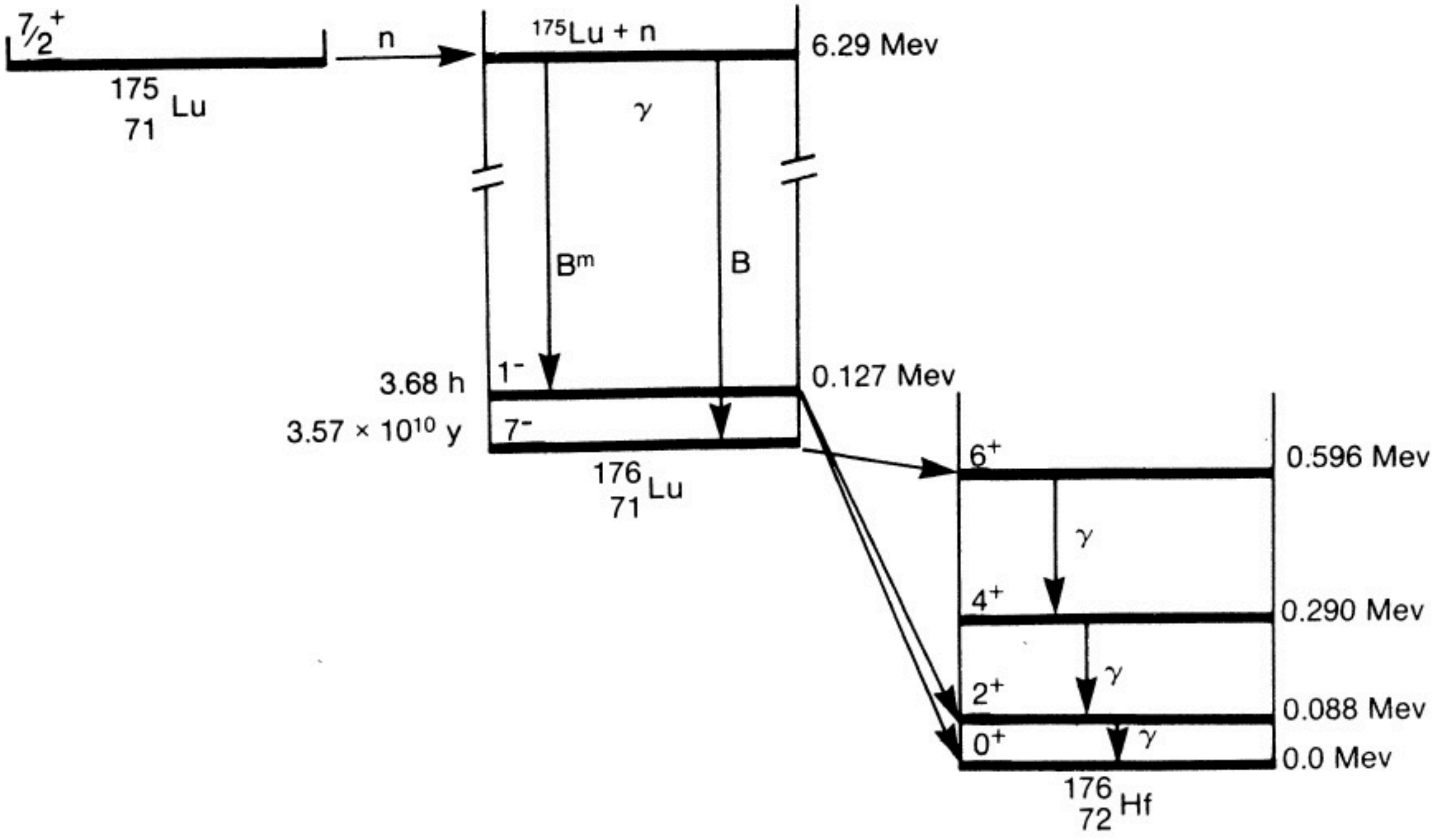


Chart representing the final part of the *s*-process. Red horizontal lines with a circle in their right ends represent neutron captures; blue arrows pointing up-left represent beta decays; green arrows pointing down-left represent alpha decays; cyan/light-green arrows pointing down-right represent electron captures.

Decay scheme for lutetium



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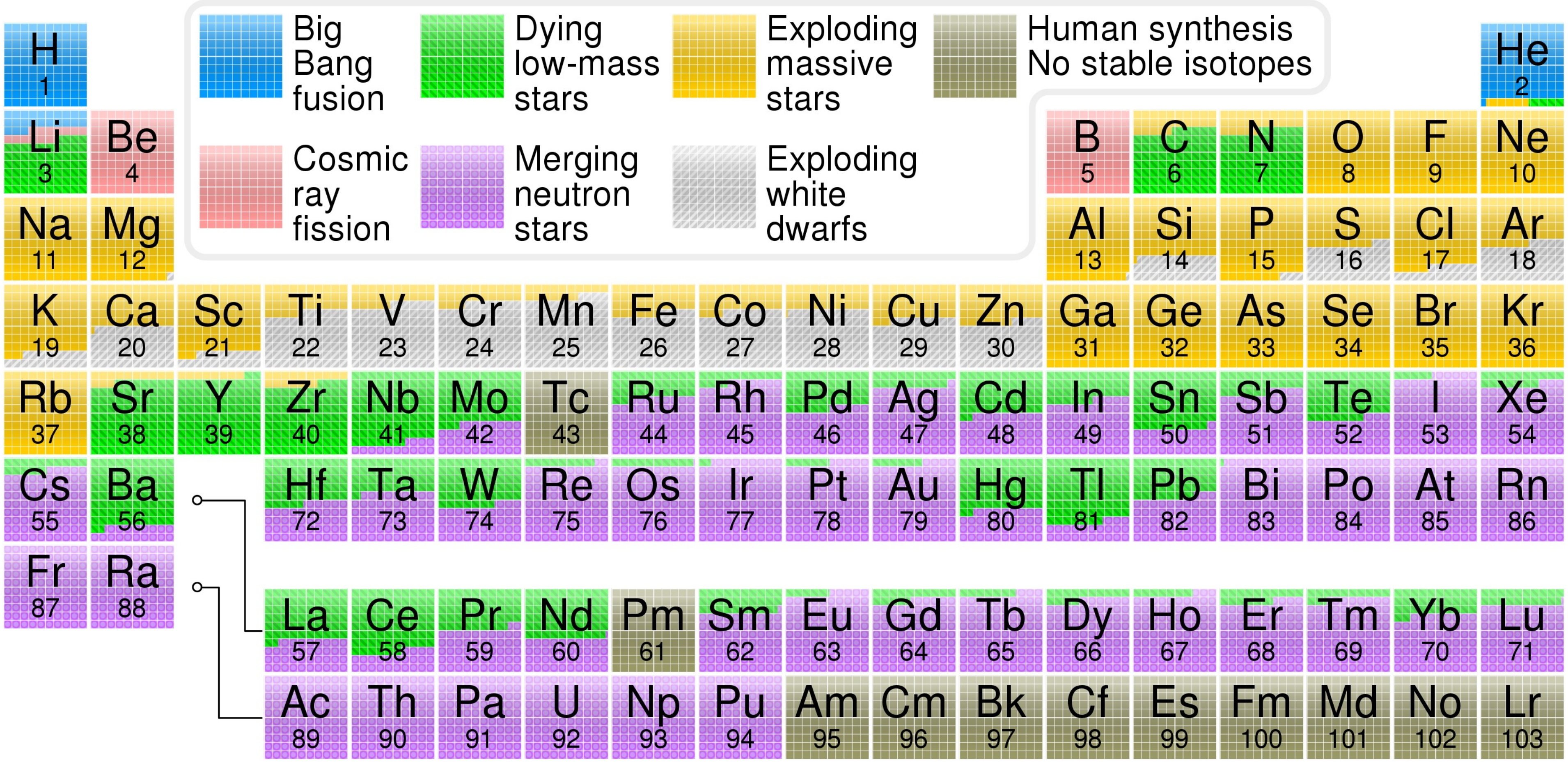
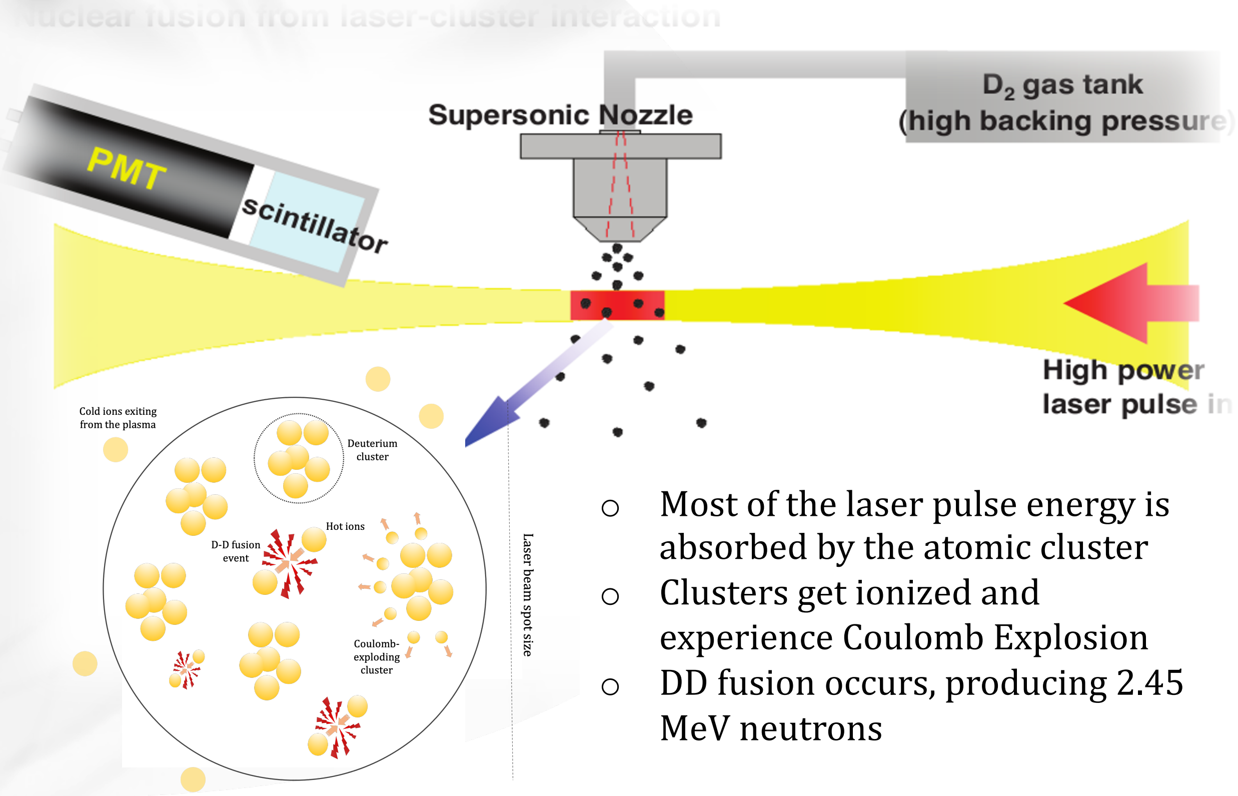
Cosmogenic origin of elements



Deuterium fusion process in plasma

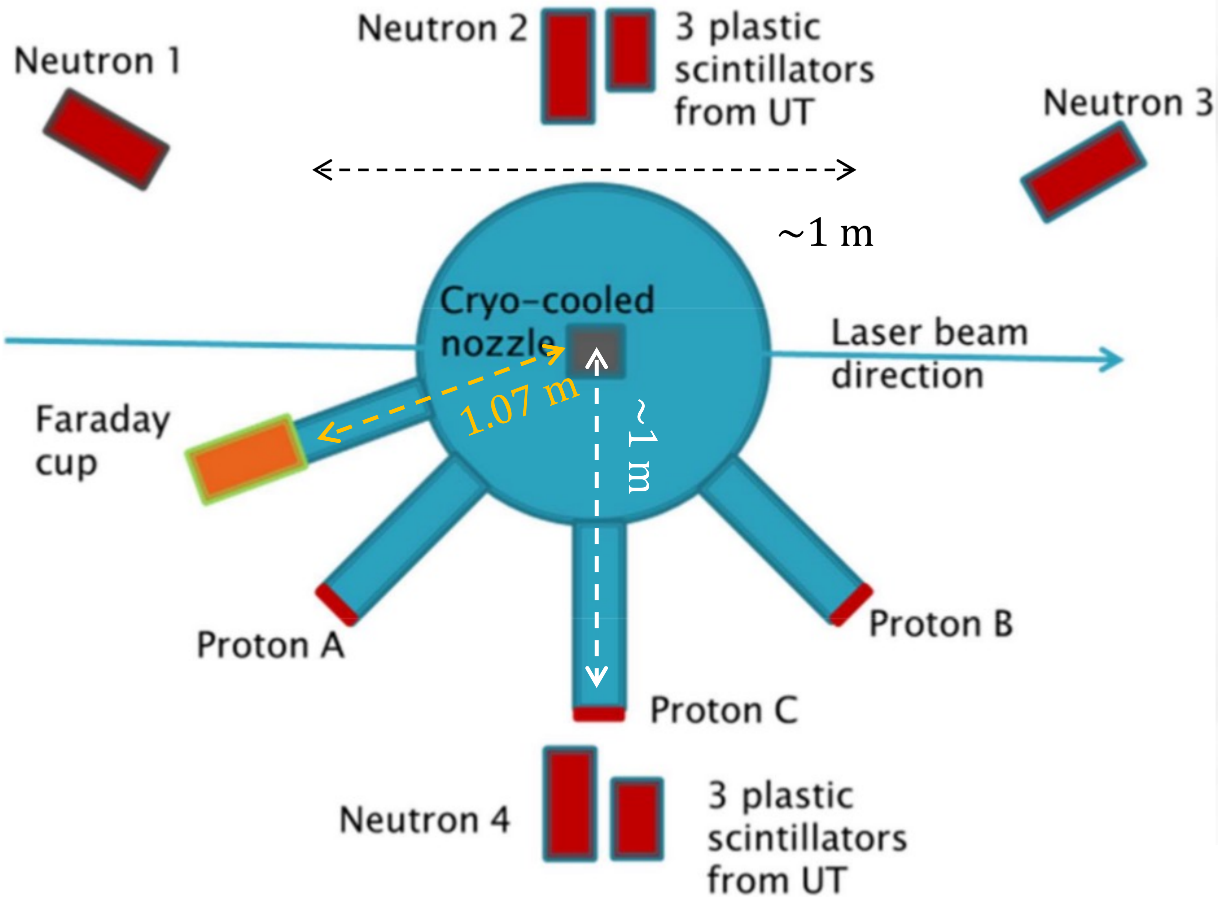
$d + d \rightarrow {}^{3}He + \mathrm{n}$ (2.45 MeV)

1. The deuterium gas is kept at a low temperature, close to the critical temperature **where gas and liquid phase coexist**.
2. The adiabatic expansion through a supersonic nozzle in the reaction chamber induces the clusterization of the D molecules, which are then irradiated by a laser pulse.
3. Most of the pulse energy is absorbed by the clusters, causing the escape of the electrons and the formation of a plasma.
4. The high level of electrostatic fields reached in it produces the so-called Coulomb Explosion → **emission of hot deuterium ions** (with kinetic energy in the range tens-hundreds keV) that can fuse with ions coming from the explosion of other clusters.
5. **High laser repetition rate and coarse granularity for the PID arrays** to identify the fusion reaction products



- Most of the laser pulse energy is absorbed by the atomic cluster
- Clusters get ionized and experience Coulomb Explosion
- DD fusion occurs, producing 2.45 MeV neutrons

Experimental area: an example



- Proper *time-of-flight paths* must be foreseen for a reliable particle identification
- Neutron detectors must be kept displaced enough from the walls
- Cablings, signal transportation

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Why plasma: fusion processes

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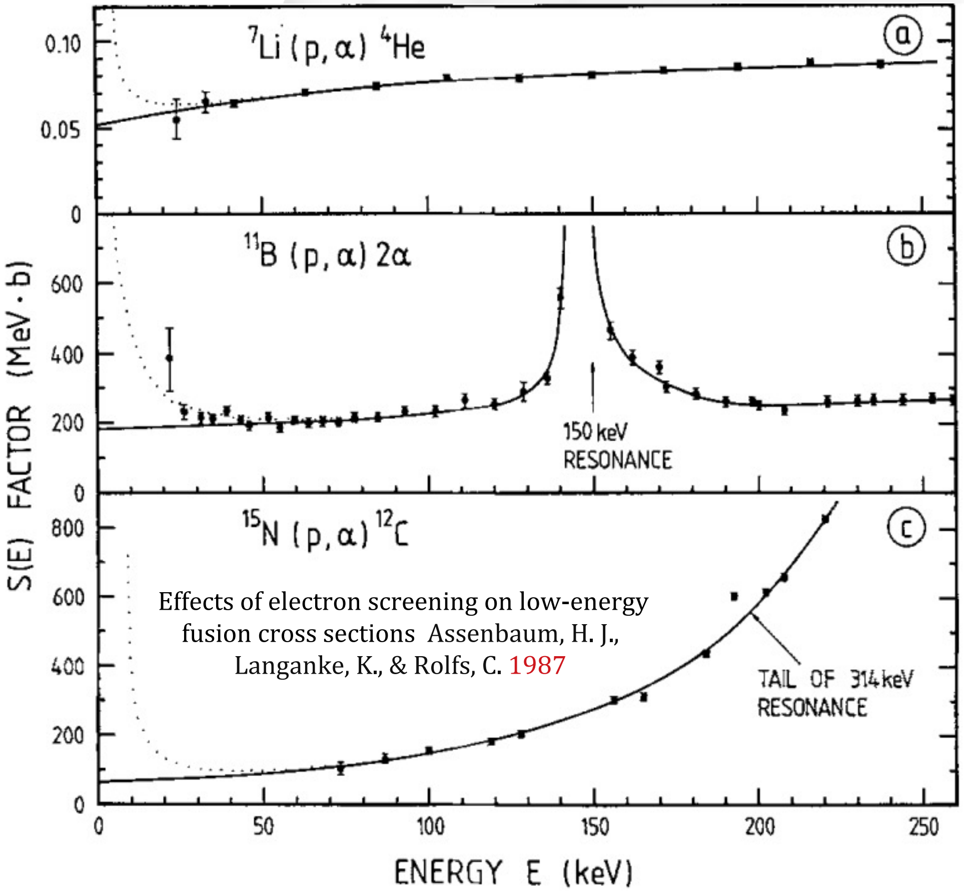
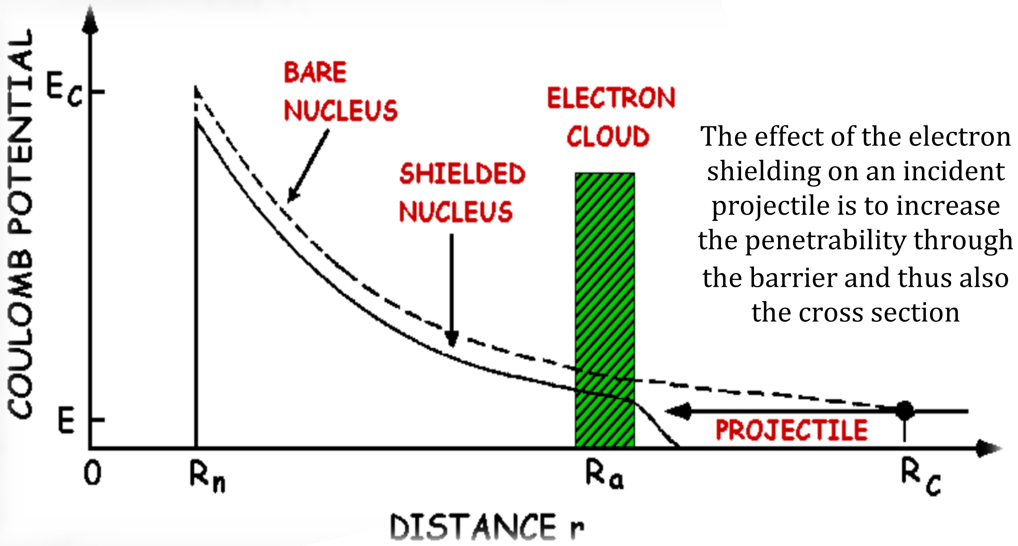
ELECTRON SCREENING AND THERMONUCLEAR REACTIONS E. E. SALPETER 1954



Effects of electron screening on low-energy fusion cross sections Assenbaum, H. J., Langanke, K., & Rolfs, C. 1987

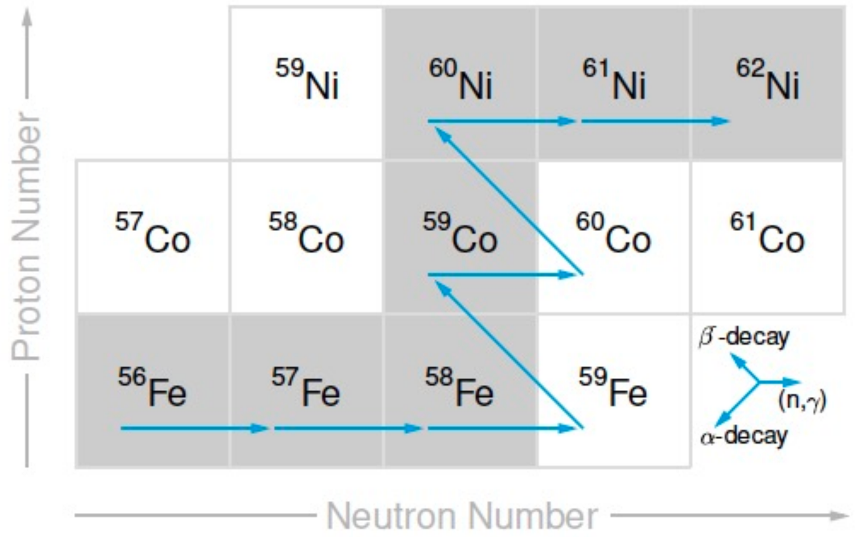
Relatively small enhancements due to electron screening could cause significant errors in the extrapolation to lower energies, if the cross-section curve is forced to follow the trend of the enhanced cross sections without correcting for screening.



The effect of the electron shielding on an incident projectile is to increase the penetrability through the barrier and thus also the cross section

Main nucleosynthesis path

Figure 1.6: The *s*-process path. If a beta unstable isotope is reached, it decays back to the next stable isotope. Stable isotopes are marked grey, and unstable isotopes white.



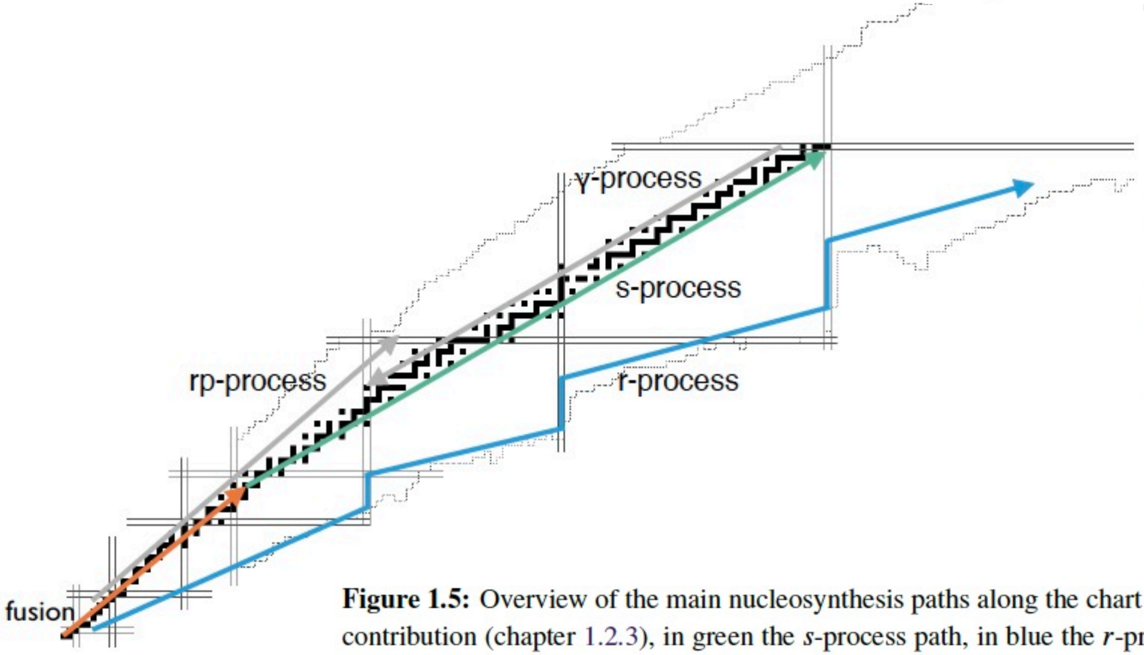


Figure 1.5: Overview of the main nucleosynthesis paths along the chart of nuclides. In orange the fusion contribution (chapter 1.2.3), in green the *s*-process path, in blue the *r*-process path (page 24) and in grey the *rp*- and γ processes (page 24). The *s* process and the γ process are secondary processes, which depend on certain seed isotopes, whereas fusion, the *r* process and the *rp* process are primary processes, which are not dependent on prior nucleosynthesis. Adapted from Glorius 2013.

Branching points and s-only isotopes

Branching points

Branching points are isotopes or isomers on the *s*-process path, which undergo a β-decay on the same timescale as a neutron capture. This leads to a branching in the *s*-process path where some of the mass flow follows the β-decay branch and the rest of the mass flow the neutron capture path (figure 1.10).

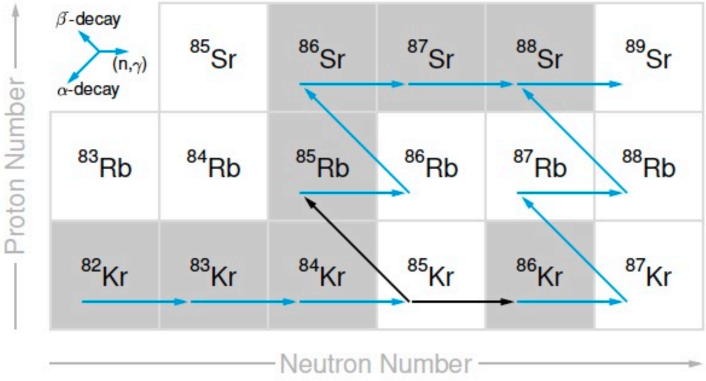
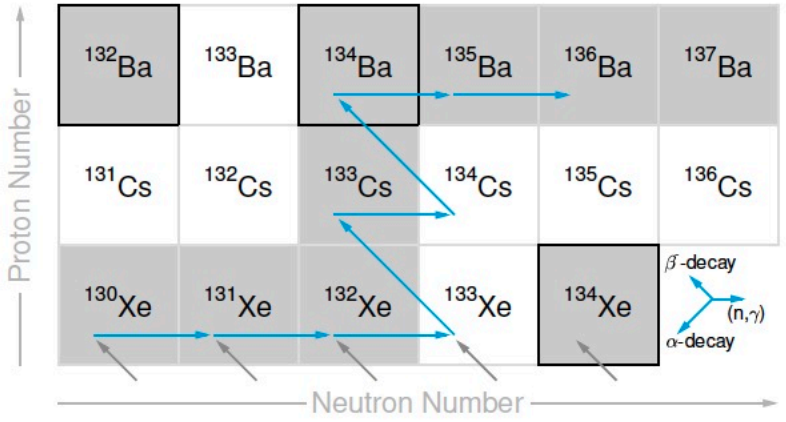


Figure 1.10: Branching point ^{85}Kr along the *s*-process path. ^{85}Kr has a half-life of about 10 years, which would make it an excellent probe for *s*-process conditions, if all reaction channels would be known to good precision. Stable isotopes are marked grey, and unstable isotopes white.

The *s*-only isotopes

The *s*-only isotopes are isotopes, which are created almost solely by the *s* process and are shielded from other processes. These isotopes are often considered when comparing observations to simulations (figure 1.11).



^{176}Lu level scheme

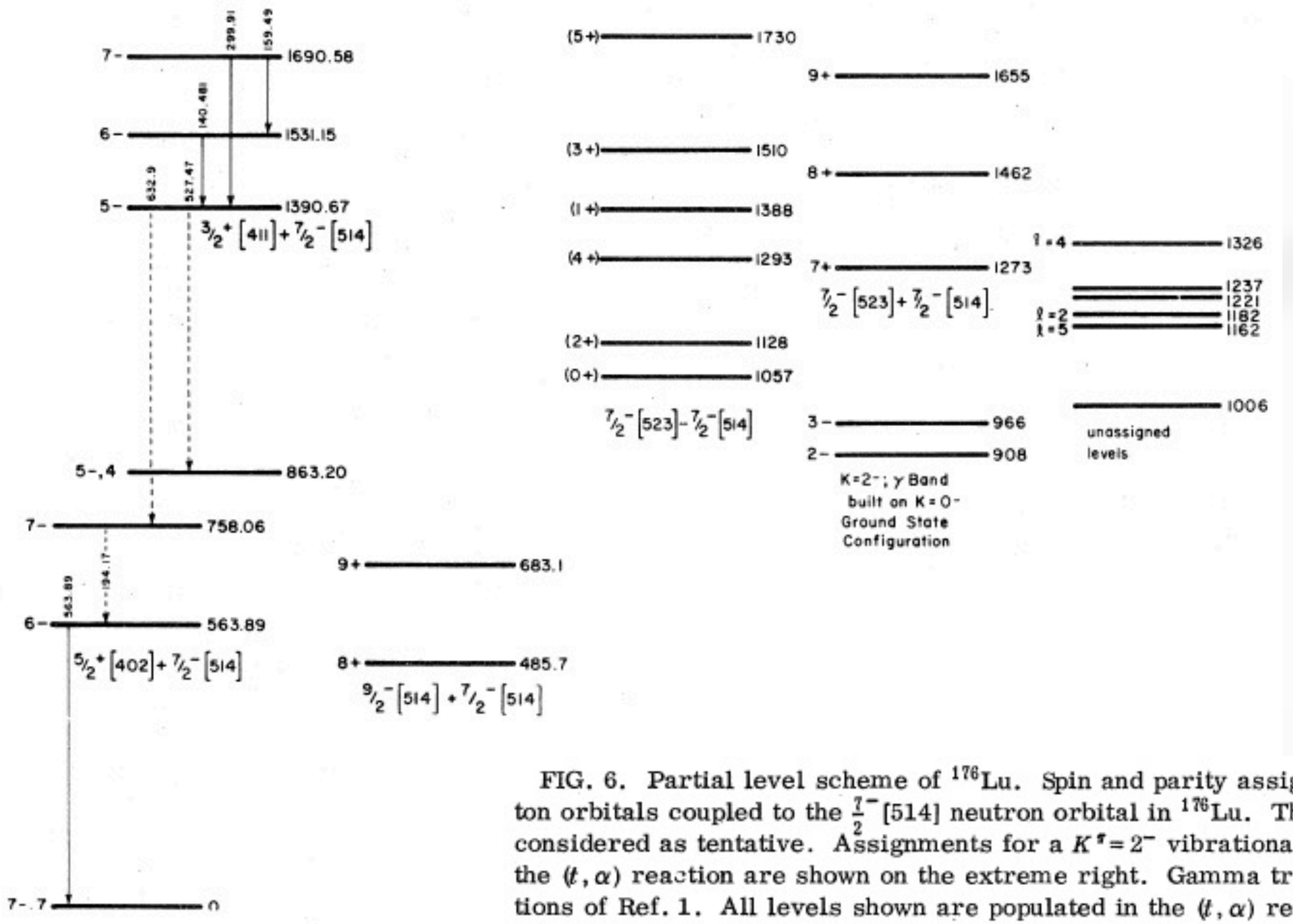


FIG. 6. Partial level scheme of ^{176}Lu. Spin and parity assignments of the $\frac{3}{2}^+$[411], $\frac{7}{2}^-$[523], $\frac{5}{2}^+$[402], and $\frac{9}{2}^-$[514] proton orbitals coupled to the $\frac{7}{2}^-$[514] neutron orbital in ^{176}Lu. The assignments for the $K^\pi = 0^+$ $\frac{7}{2}^-$[523] $-$ $\frac{7}{2}^-$[514] band are considered as tentative. Assignments for a $K^\pi = 2^-$ vibrational band are included and the unassigned levels populated in the (t, α) reaction are shown on the extreme right. Gamma transitions assigned were taken from unassigned transitions of Ref. 1. All levels shown are populated in the (t, α) reaction.

^{176}Lu physics case

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The Decay Scheme of Natural Lutetium 176

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(Received February 26, 1953)

THE nuclide lutetium 176 is of particular interest for two related reasons; first, that it is the central member of one of the four known triads of naturally occurring adjacent isobars, and second, that its spin of at least 7 units[1] is the highest known. Flammersfeld has reported a decay scheme for this nuclide,[2] in which both *K* capture and β-decay appear, the ratio of the branches being $K/\beta^-=2$. The observed gamma-ray was placed in the *K* branch, and its energy fixed at 0.260 Mev.

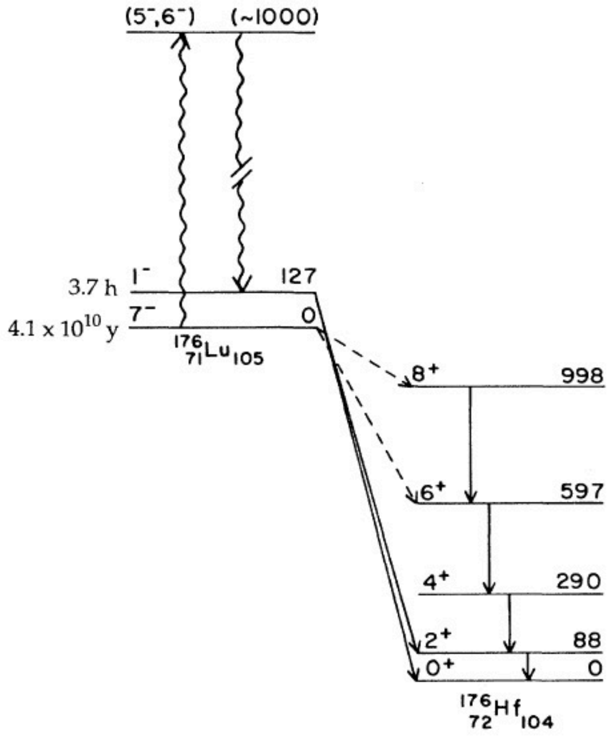
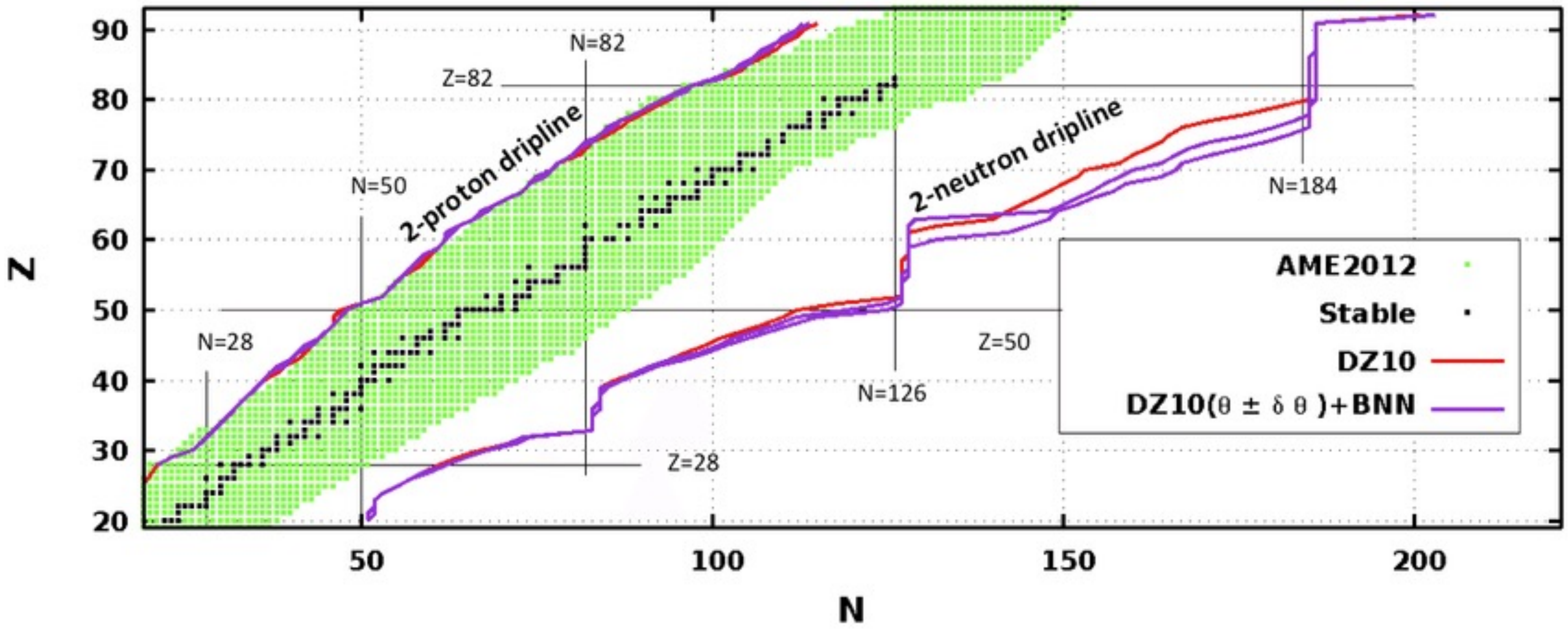


FIG. 3. A partial level scheme of ^{176}Lu, showing the positions and decays of the ground state and isomer at 122.9 keV. The equilibration of these two levels could be achieved by way of a level of intermediate spin, as illustrated in the figure.

Drip lines



90
80
70
60
50
40
30
20
Z
50
100
150
200
N
N=82
Z=82
2-proton dripline
N=50
2-neutron dripline
N=184
N=28
Z=50
N=126
Z=28
AME2012
Stable
DZ10
DZ10(θ ± δ θ)+BNN

^{176}Lu physics case

PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

^{176}Lu: An unreliable *s*-process chronometer

K. T. Lesko, E. B. Norman, R-M. Larimer, and B. Sur
Nuclear Science Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720 and Center for Particle Astrophysics, University of California, Berkeley, California 94720

C. B. Beausang*
Nuclear Science Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720

(Received 17 October 1990)

A level scheme of ^{176}Lu up to ~1400 keV excitation energy is deduced from a γ-γ coincidence experiment and previously published particle transfer data. 170 γ-ray transitions are placed between 85 levels. We identify 27 previously unknown levels and 131 previously unknown transitions in ^{176}Lu. With this γ-ray data we place the energy of the isomer at 122.9 keV. A level at 838.5 keV ($J^{\pi}=5^{-}$, $t_{1/2}<10$ ns) is found to decay with substantial strength to both the ground state (7^{-}, 4.08×10^{10} yr) and the 122.9 keV isomer (1^{-}, 3.7 hr). The presence of this level guarantees the thermal equilibrium of ^{176}Lu^{g,m} for $T\geq3\times10^{8}$ K and therefore during *s*-process nucleosynthesis. The resulting temperature sensitivity of its effective half-life rules out the use of ^{176}Lu as an *s*-process chronometer. The use of ^{176}Lu to determine *s*-process temperatures is discussed.

^{176}Lu physics case

^{176}Lu is one of the few naturally occurring radio nuclides that have survived from the era of nucleosynthesis. Its present isotopic abundance [1] is 2.6% and its half-life is 4.08×10^{10} yr [2].

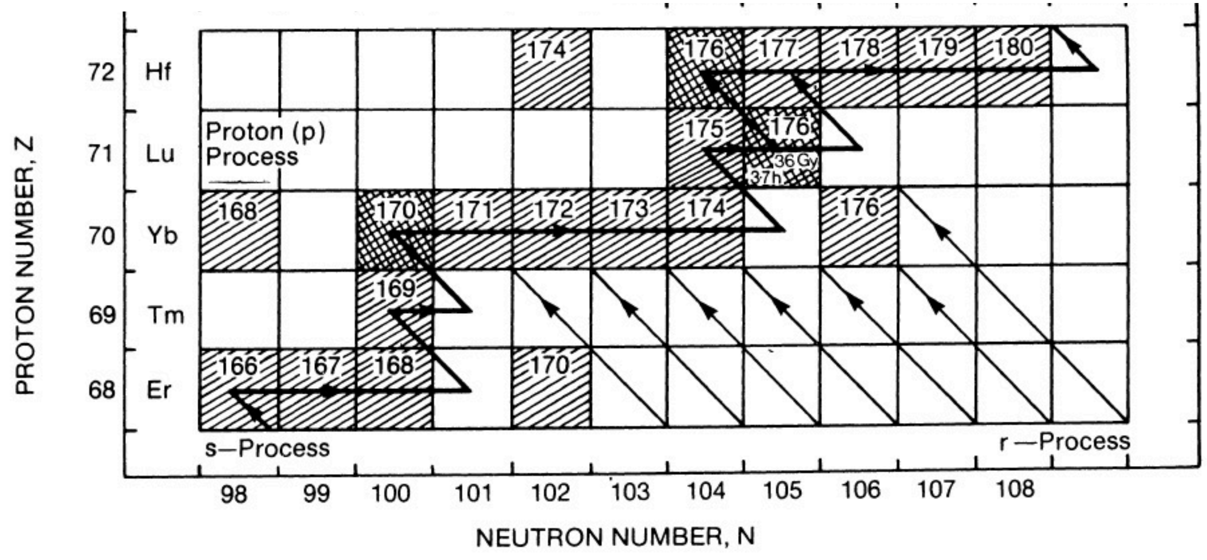
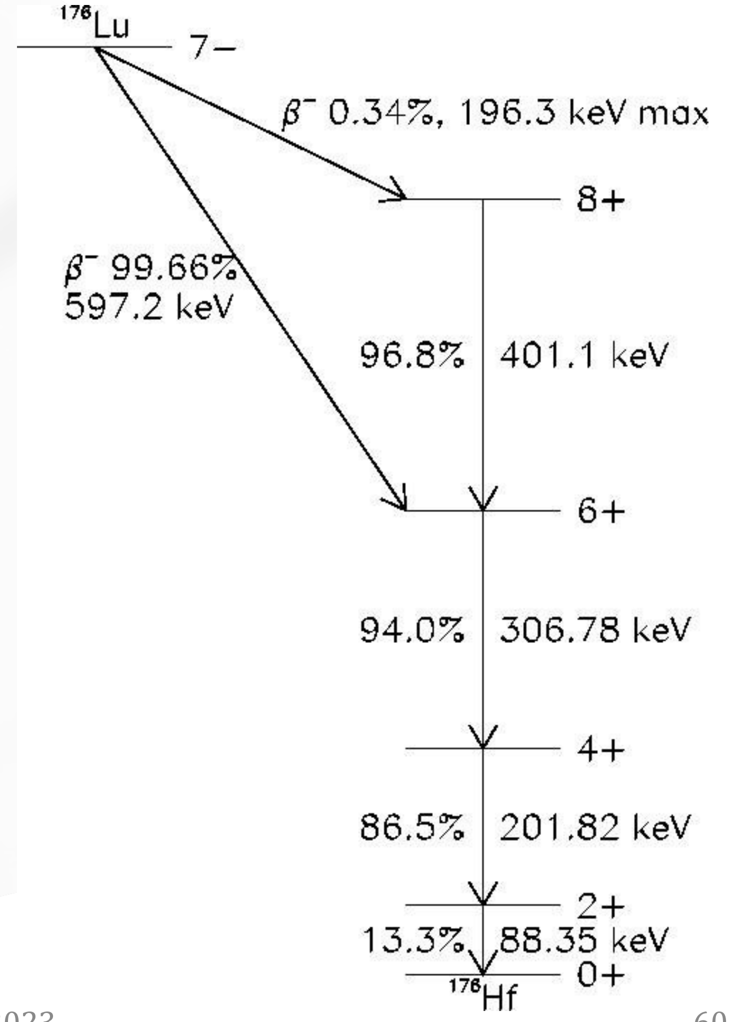
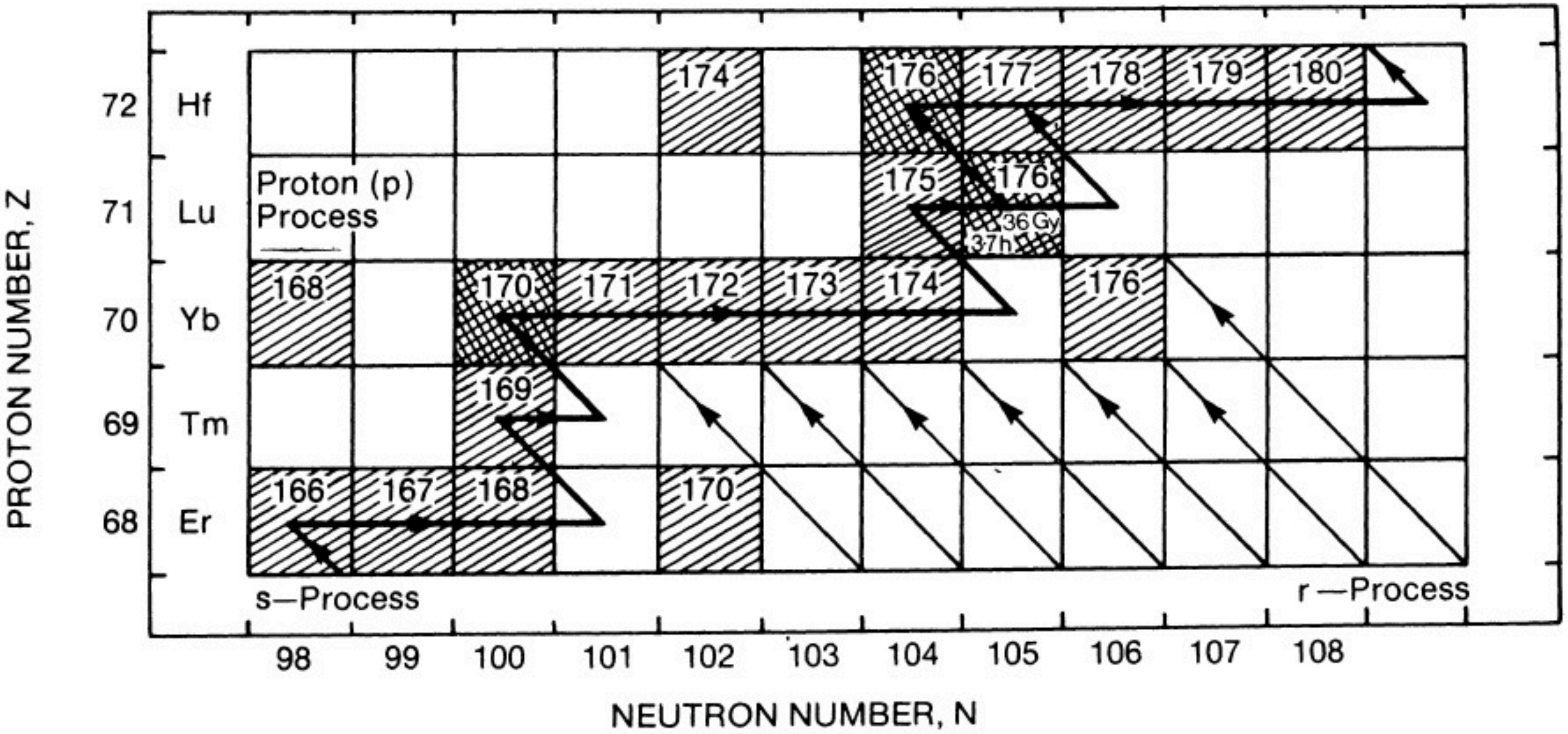


Figure 1. *s*-process path in the rare earth element mass region. *s*-only process nuclides ^{170}Yb, ^{176}Lu and ^{176}Hf are shielded from *r*-process contributions by ^{170}Er and ^{176}Yb respectively. The *s*-process branches at ^{176}Lu if a significant population of the 3.68 h isomeric state occurs.



^{176}Lu branch in the s-process



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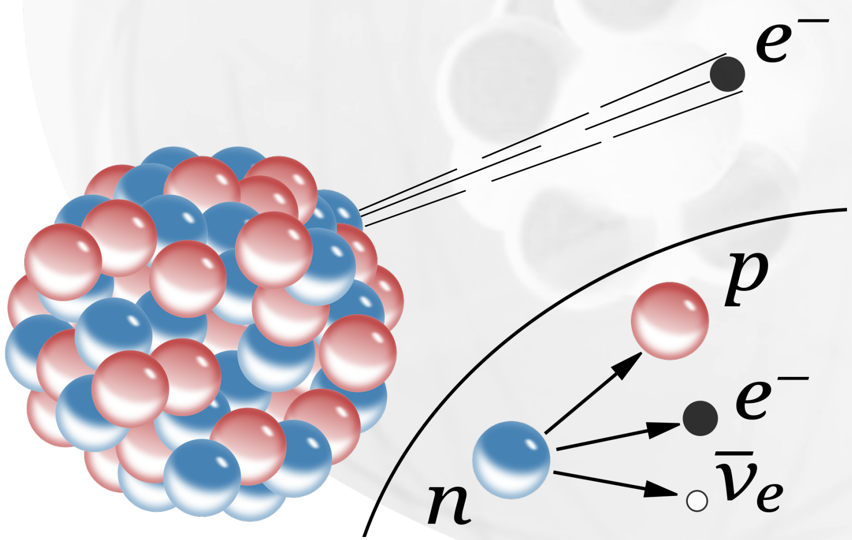
Why plasma: β-decays

β-decay in stellar environment: in a stellar plasma, ions are embedded in a cloud of charges, both positive and negative. These charges create EM fields which act as perturbation to the atomic/ionic levels leading to corrections of Q values which affects the decay rates.



Bound-state β-decay is a nuclear β- decay process in which an electron is created in a previously unoccupied atomic orbital rather than in the continuum.

For fully ionized atoms (bare nuclei), it is possible for electrons to fail to escape the atom, and to be emitted from the nucleus into low-lying atomic bound states (orbitals). This cannot occur for neutral atoms with low-lying bound states which are already filled by electrons.

https://www.frontiersin.org/research-topics/25146/nuclear-physics-and-astrophysics-in-plasma-traps

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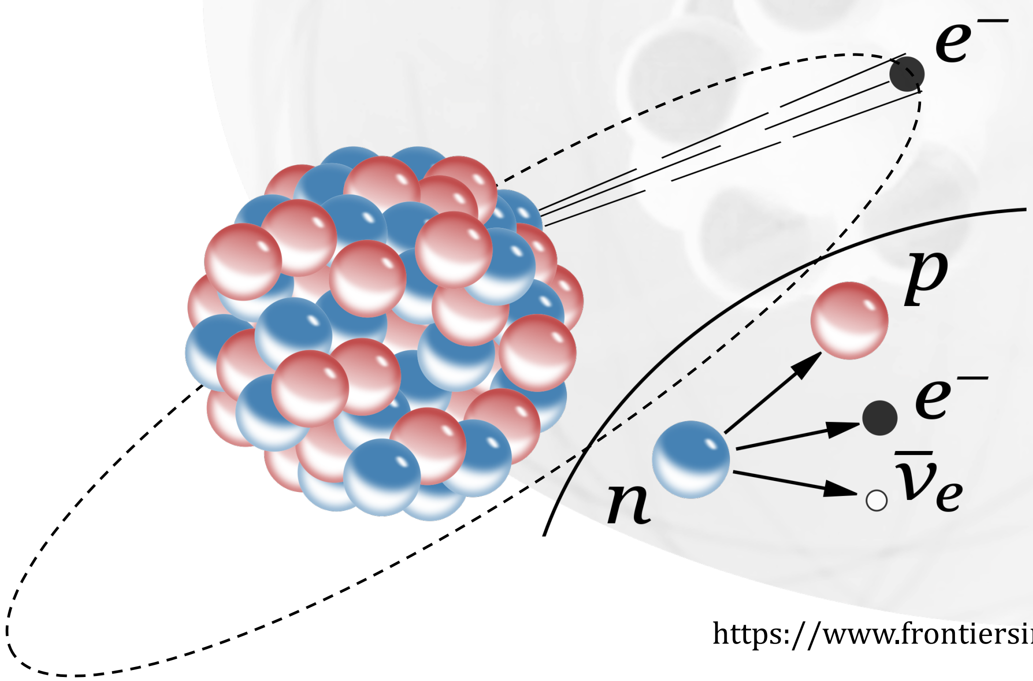

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^{176}Lu physics case

Cosmo-chronometer or stellar thermometer?

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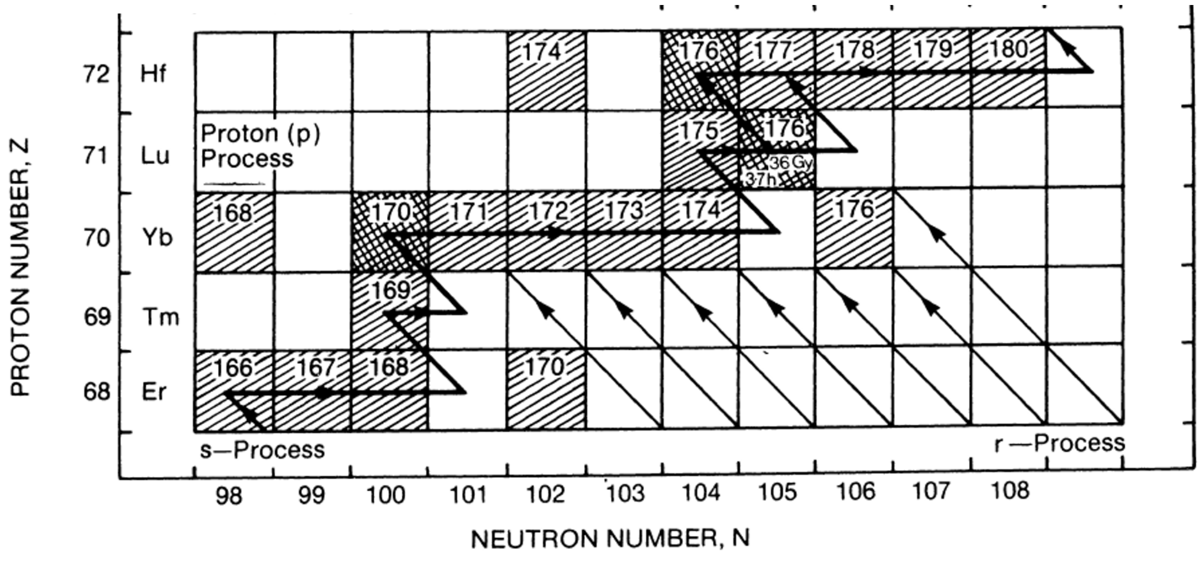

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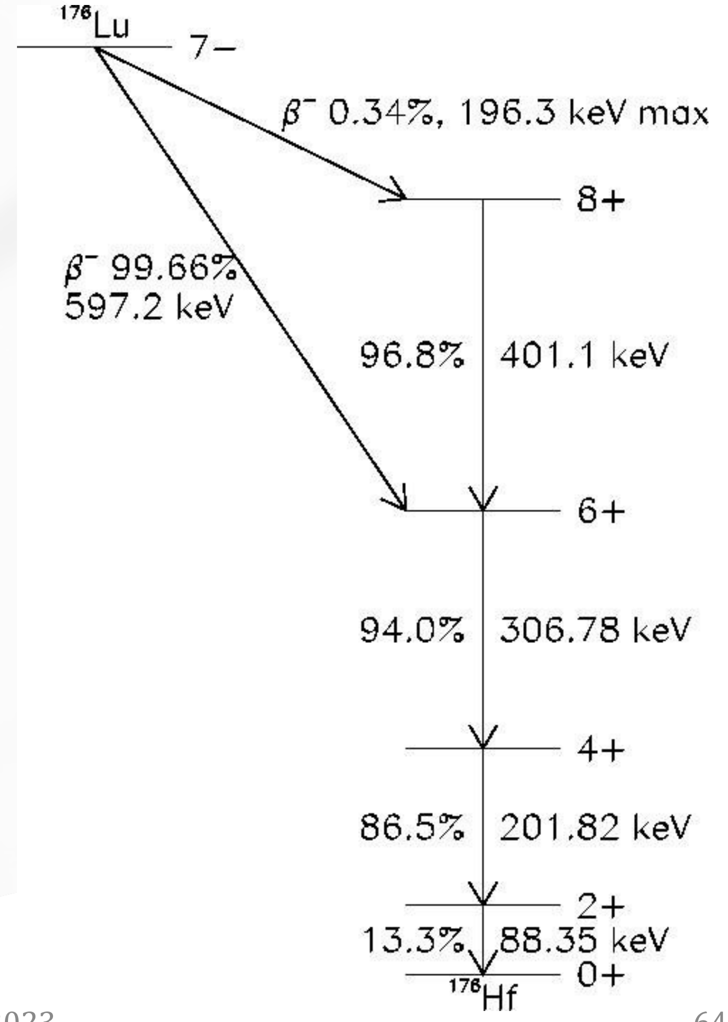

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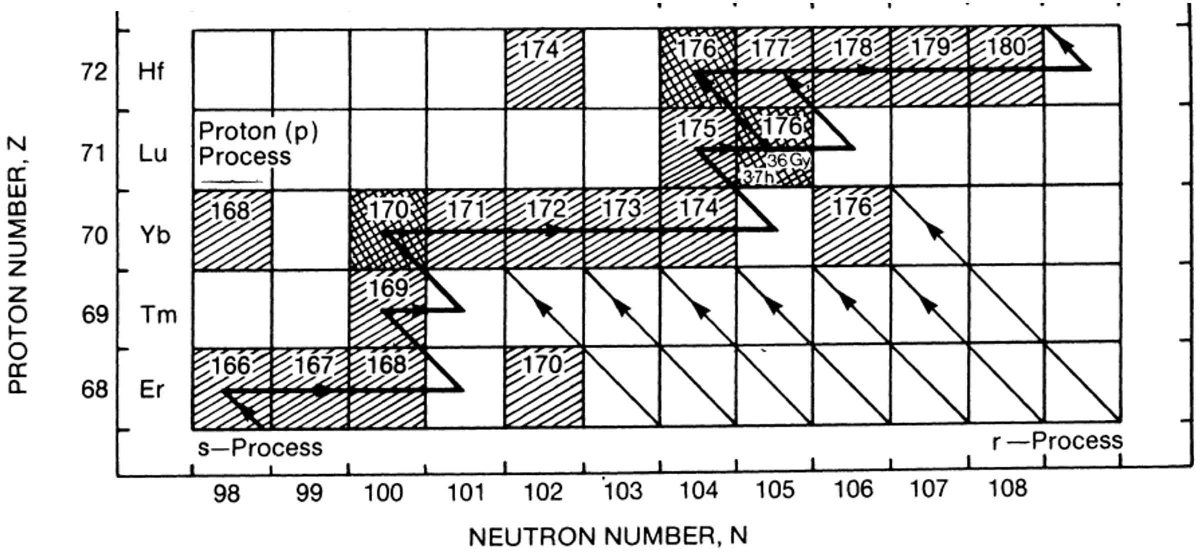

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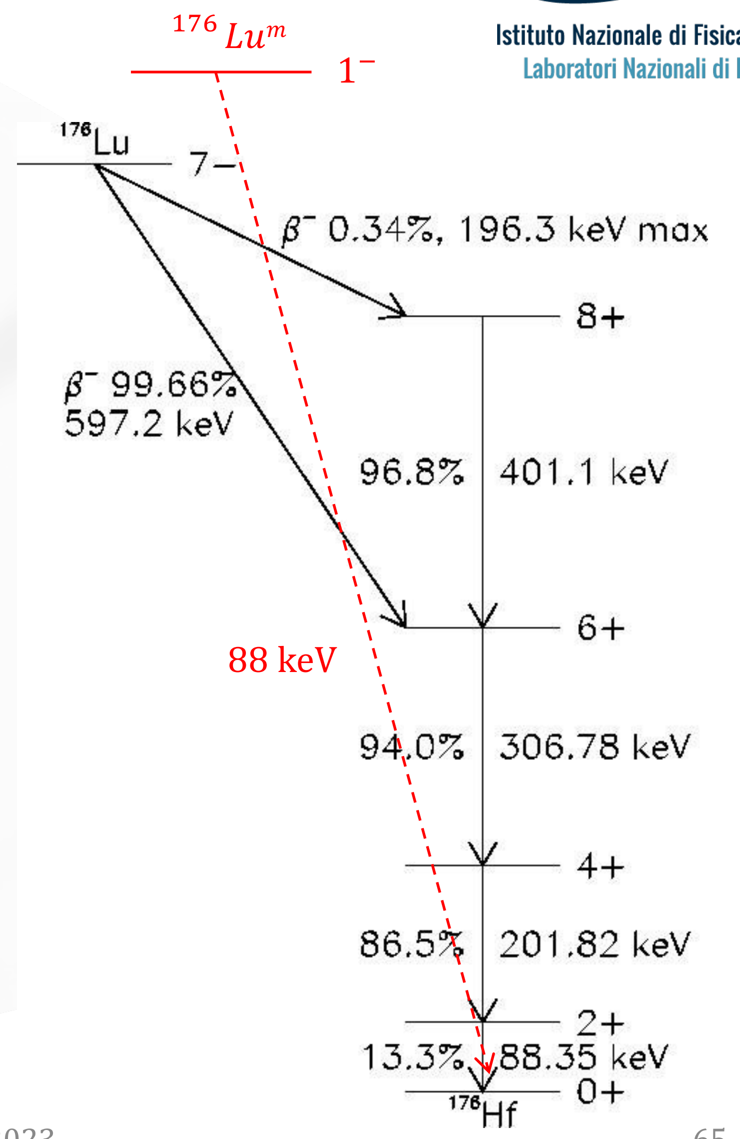

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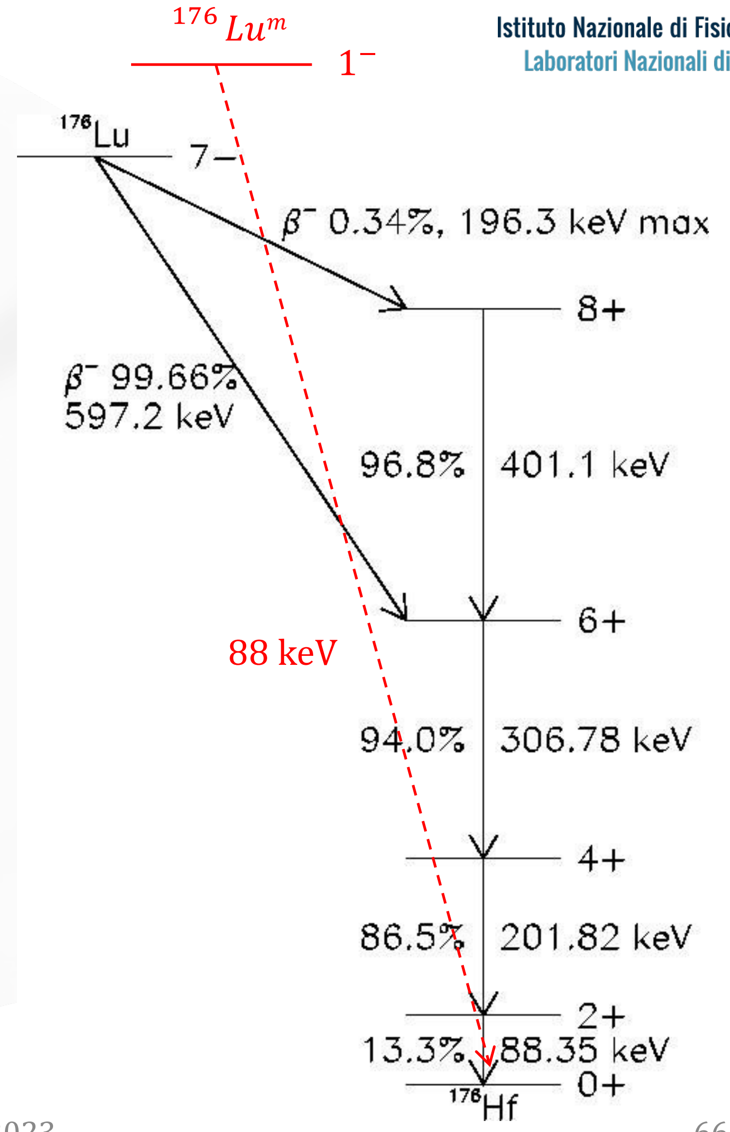
Nuclear Science Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720
(Received 17 October 1990)

A level scheme of ^{176}Lu up to $\sim$1400 keV excitation energy is deduced from a γ-γ coincidence experiment and previously published particle transfer data. 170 γ-ray transitions are placed between 85 levels. We identify 27 previously unknown levels and 131 previously unknown transitions in ^{176}Lu. With this γ-ray data we place the energy of the isomer at 122.9 keV. A level at 838.5 keV ($J^\pi = 5^-$, $t_{1/2} < 10$ ns) is found to decay with substantial strength to both the ground state (7^-, 4.08×10^{10} yr) and the 122.9 keV isomer (1^-, 3.7 hr). The presence of this level guarantees the thermal equilibrium of ^{176}Lu^{g,m} for $T \geq 3 \times 10^8$ K and therefore during *s*-process nucleosynthesis. The resulting temperature sensitivity of its effective half-life rules out the use of ^{176}Lu as an *s*-process chronometer. The use of ^{176}Lu to determine *s*-process temperatures is discussed.



Istituto Nazionale di Fisica Nucleare
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The onset of the LTE (Local Thermal Equilibrium)

- È necessario dissipare l'energia per avere termalizzazione

- *We are assuming a typical lifetime of nuclear excited states to be in the order of fs (a few 10^-15 sec). We are using a typical reaction rate estimate according to the well-known formula R=I_XNtσ, where I_X is the in-plasma total photon flux in s^-1, N_t is a surface "target" density term, that in a plasma represents the radius averaged density in an assumed spherical plasma plume, and σ is the interaction cross-section. Assuming an excited state for, e.g., 176Lu*, around 122.45 keV, and considering n_e=<q>n_i=10^27 m-3 (a typical stars interior density), at T_e=T_i=6.68 keV the excited level lifetime is already exactly the same of the excitation rate, meaning that this level can be populated and it is in thermal equilibrium in the assumed laser-induced plasma lifetime (order of ps or tens of ps).*
  This calculation has been also rescaled to a more realistic expected density of a real laser-induced plasma scenario, assuming n=e=n_i=10^25 m-3. In this case, the required plasma temperature to get the thermal equilibrium goes to around 37.5 keV. This value seems to be however absolutely achievable in the foreseen laboratory scenario, confirming that the decay from excited states is in principle feasible.

Why plasma: β-decays

Stellar nucleosynthesis proceeds in a hot and dense environment which affects the degree of ionization of the atoms involved in the stellar nucleosynthesis.

What happens when atoms are highly ionized?

The beta decay in highly ionized atoms shows important variations compared to neutral species

1. Electron Capture becomes impossible in fully ionized atoms.
2. Bound state β-decay typically marginal can become important.

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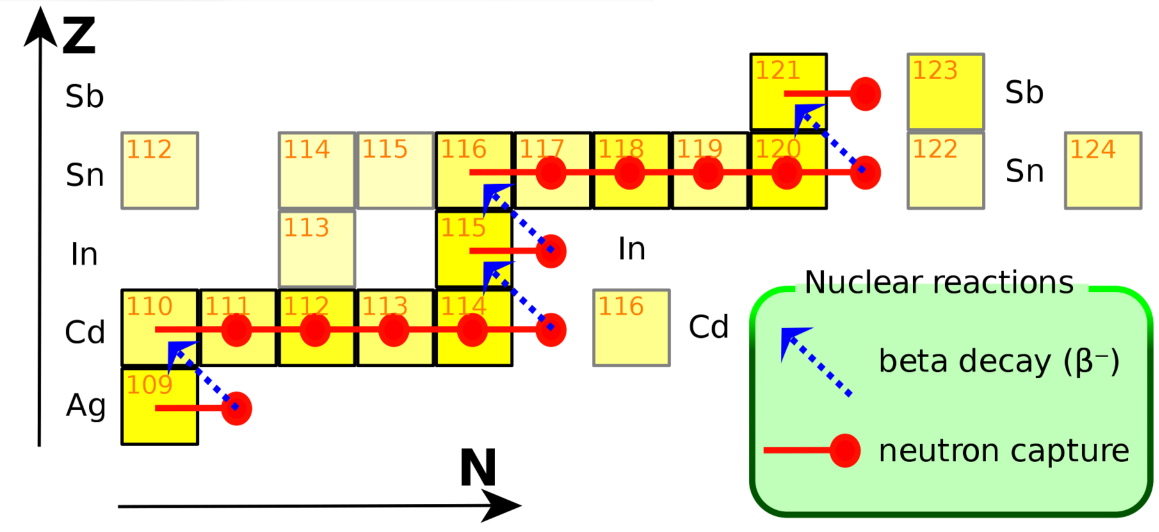
Bound-state β-decay is a nuclear β- decay process in which an electron is created in a previously unoccupied atomic orbital rather than in the continuum.



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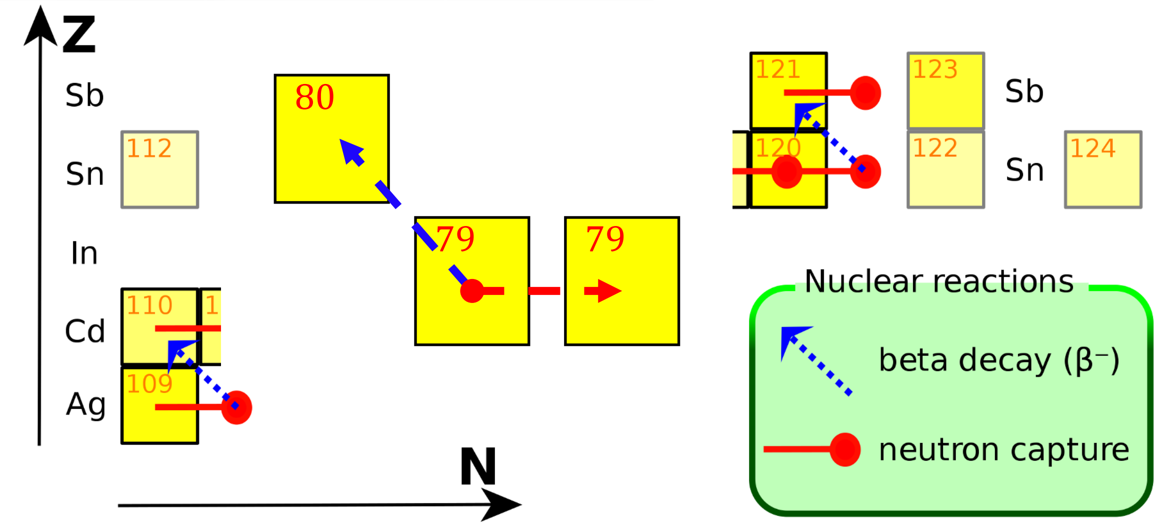

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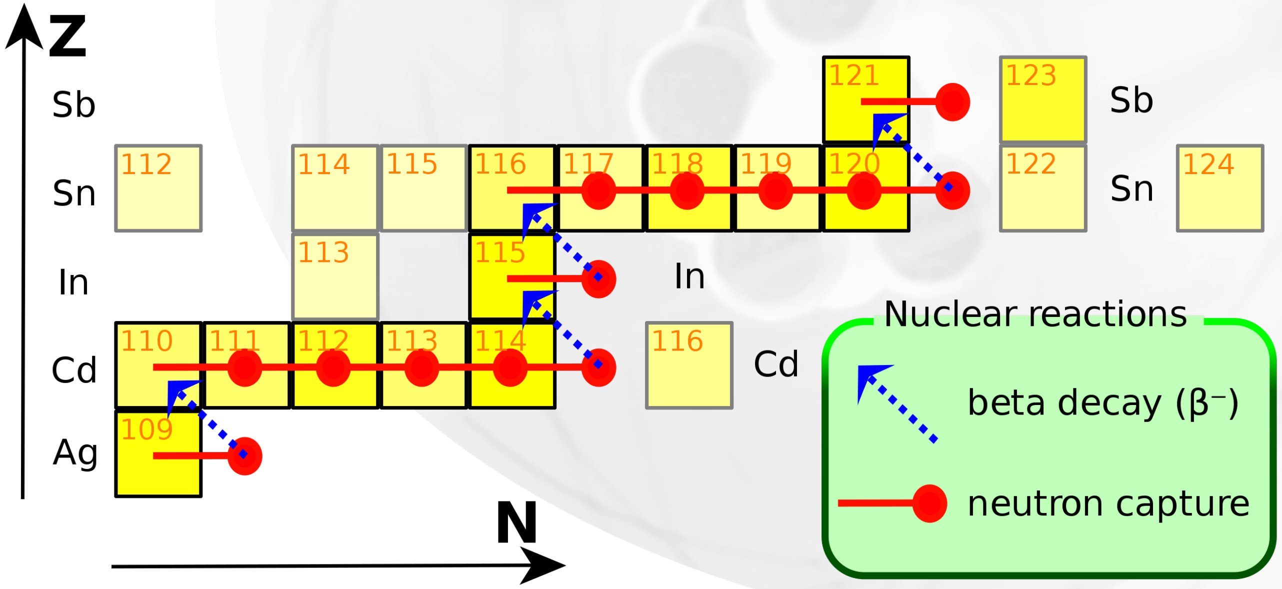
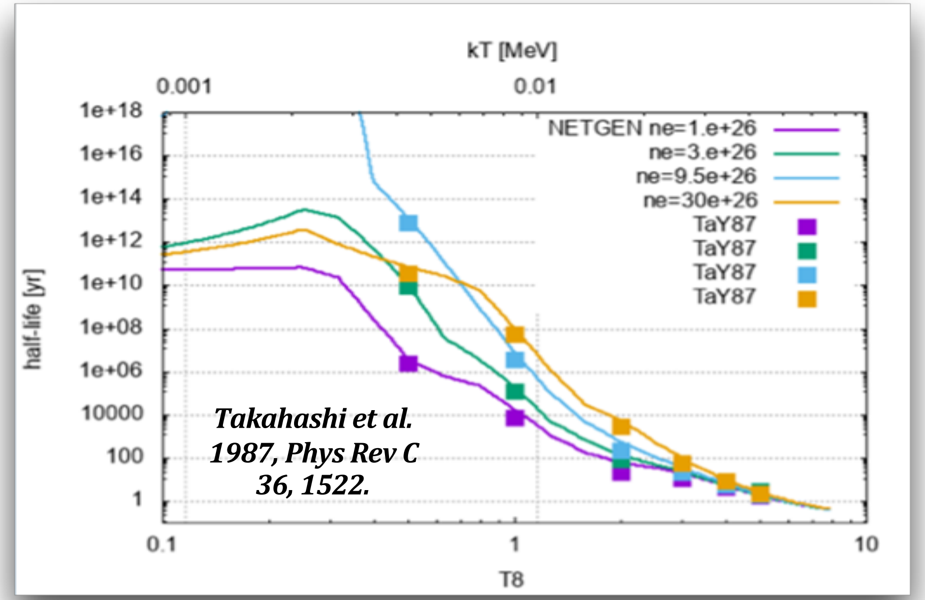
Stellar plasma environment (ρ, T) can play a major role in modifying the rates at the branching point in s-process nucleosynthesis. *Temperature dependent variations evaluated in the seminal work of Takahashi and Yokoi*.





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Original predictions of modifications in β-decay rates in plasma by Takahashi and Yokoi

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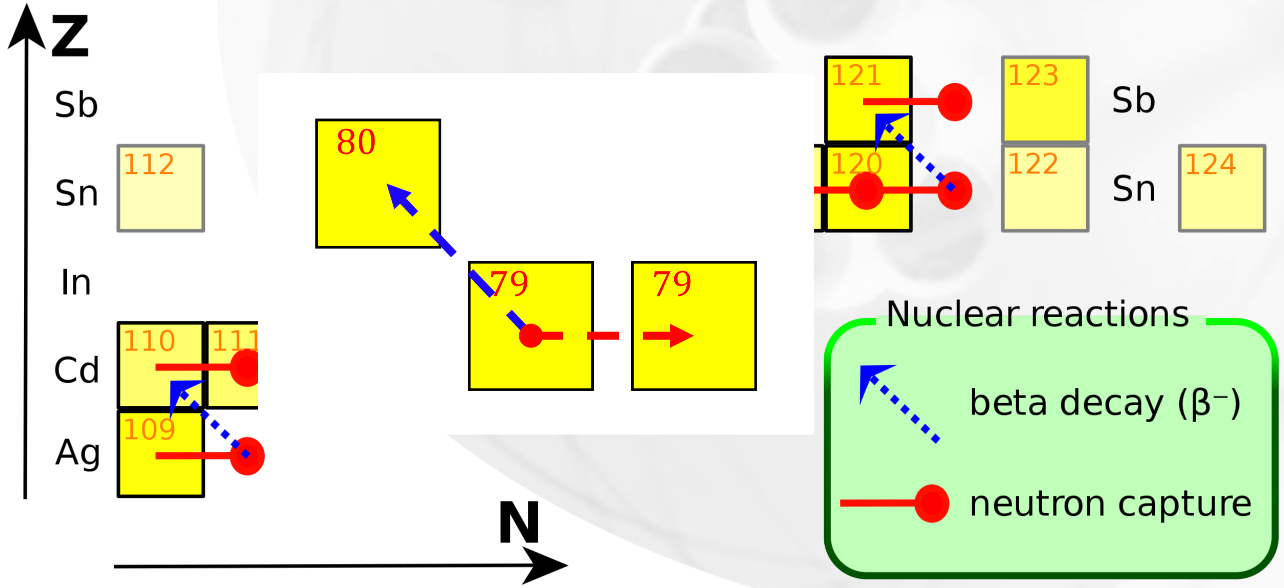

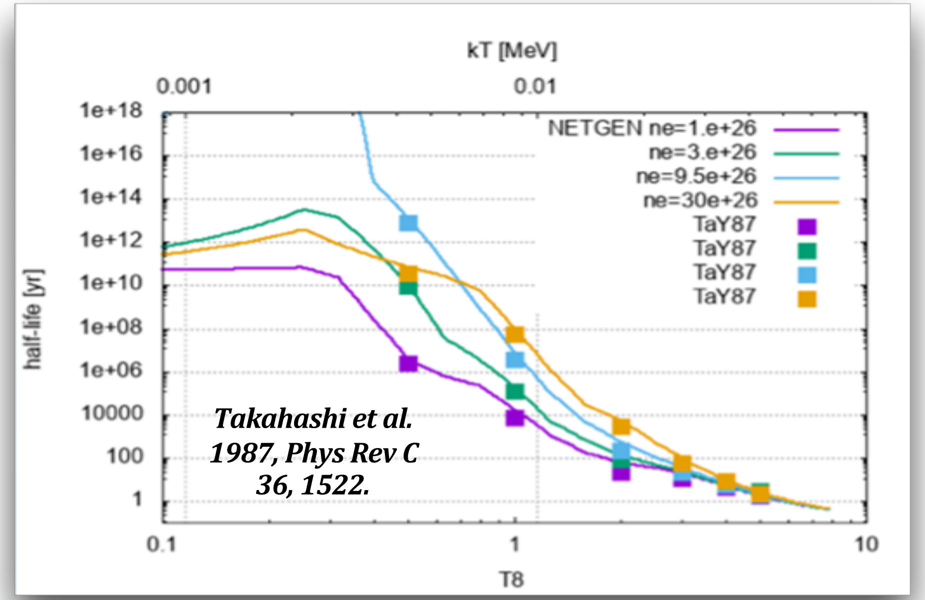

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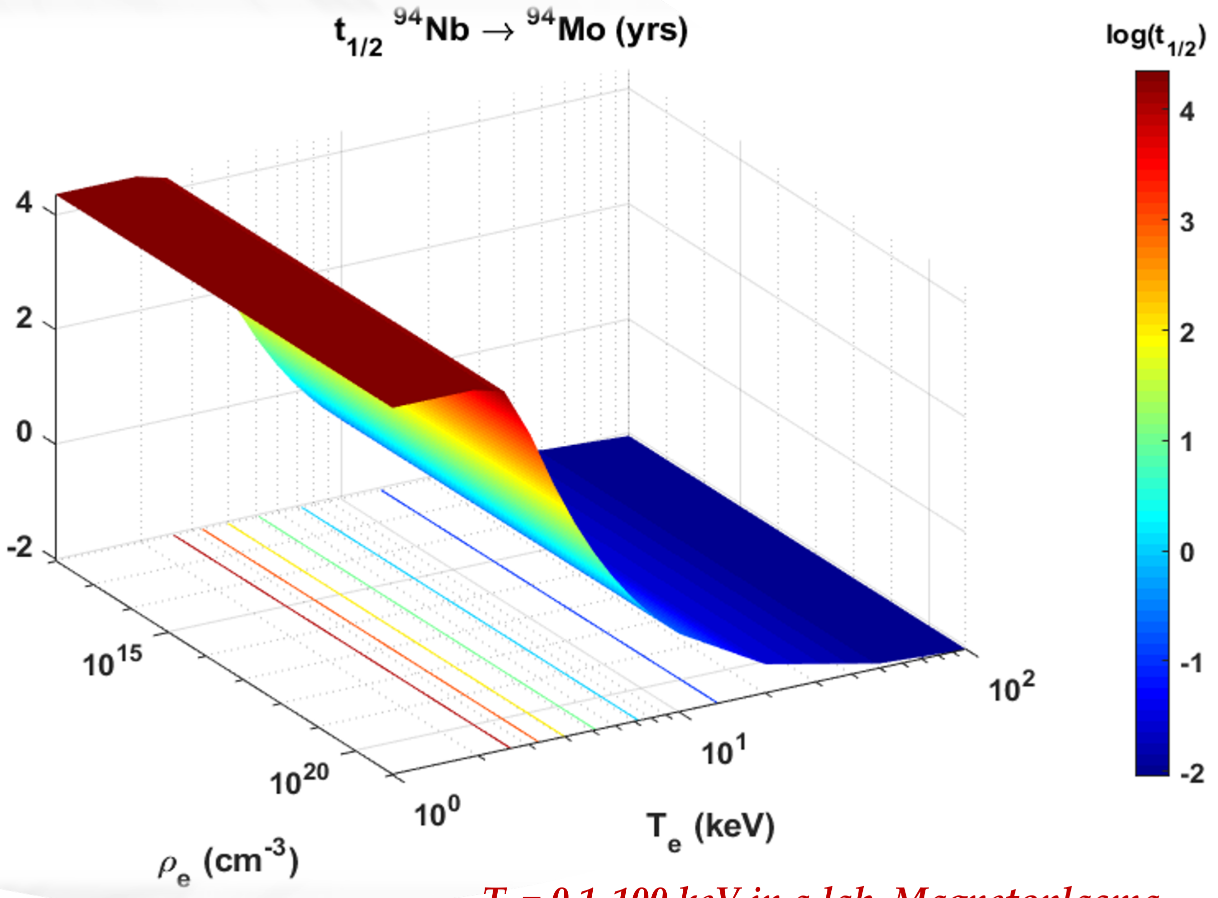
Scaling results to stellar environment

Once measured the variation, it can be compared to Takahashi-Yokoi theory (without LTE hypothesis)

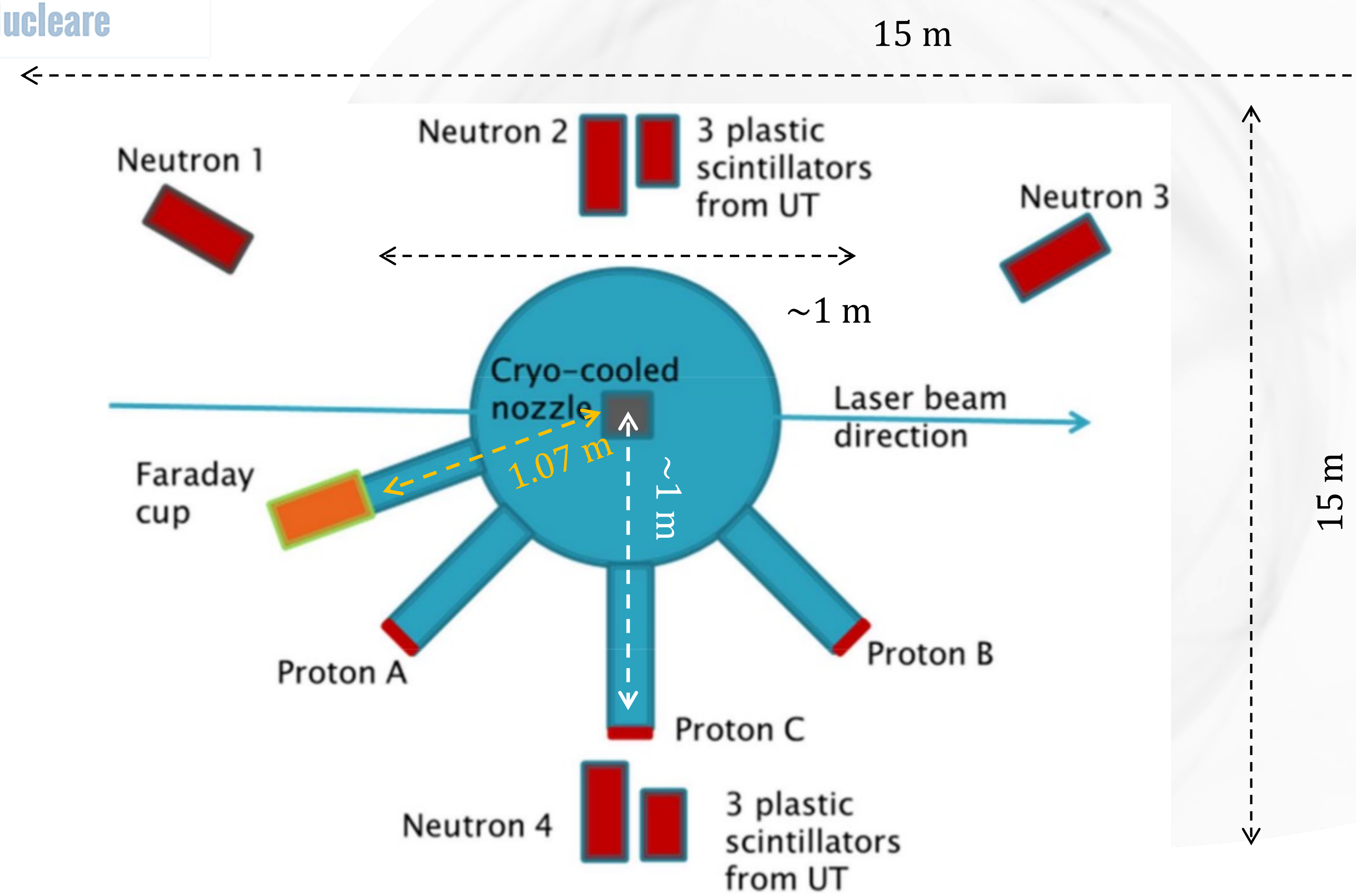
Adapt to stellar atmosphere assuming $\boldsymbol{n_e}$ and $\boldsymbol{T_e}$ leading to ions in LTE population

Variation with T_e stronger than with ρ_e so "stellar effect" can be modelled in ECR plasmas



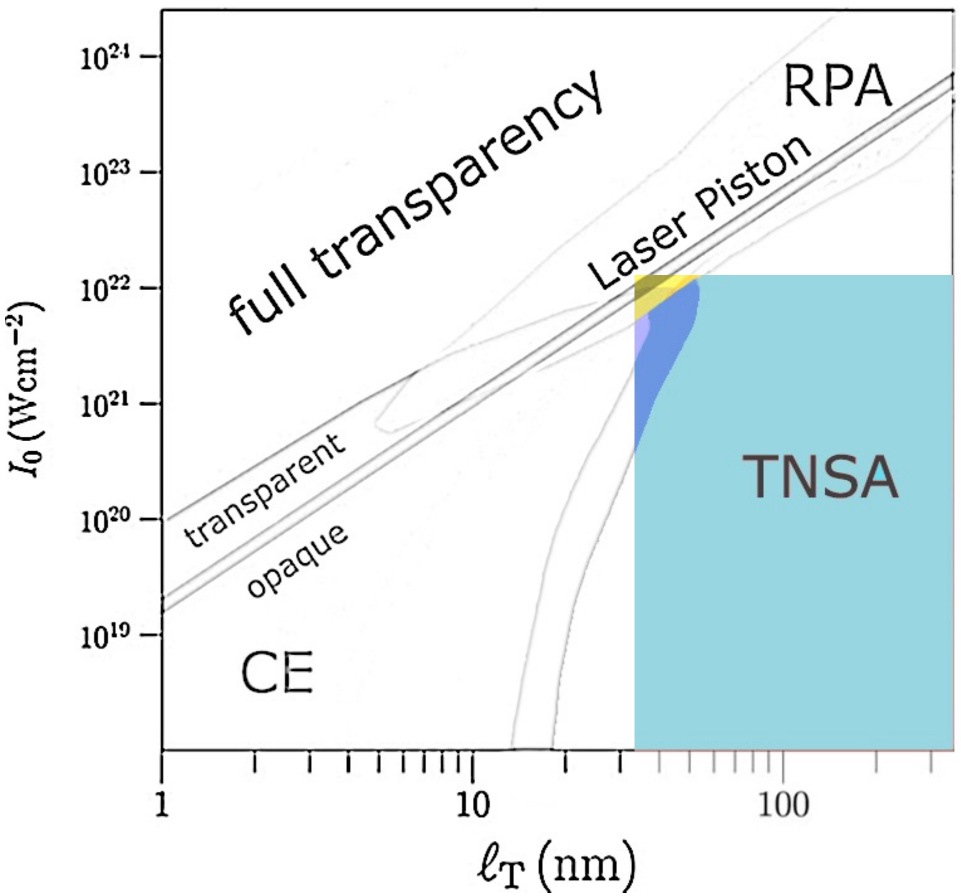
T_e = 0.1-100 keV in a lab. Magnetoplasma

Experimental area: an example



- Proper *time-of-flight paths* must be foreseen for a reliable particle identification
- neutron detectors must be kept displaced enough from the walls
- Cablings, signal transportation

Experiments at the PW regime



High-density target → solid, Lu target

Target choice to be optimized in view of the thermalization goal

Possible choice: non-isotopic cuboids of metallic bulk material (*e.g.*, natural Lu) coated with a layer of at least 200-300 μm of isotopic enriched material

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