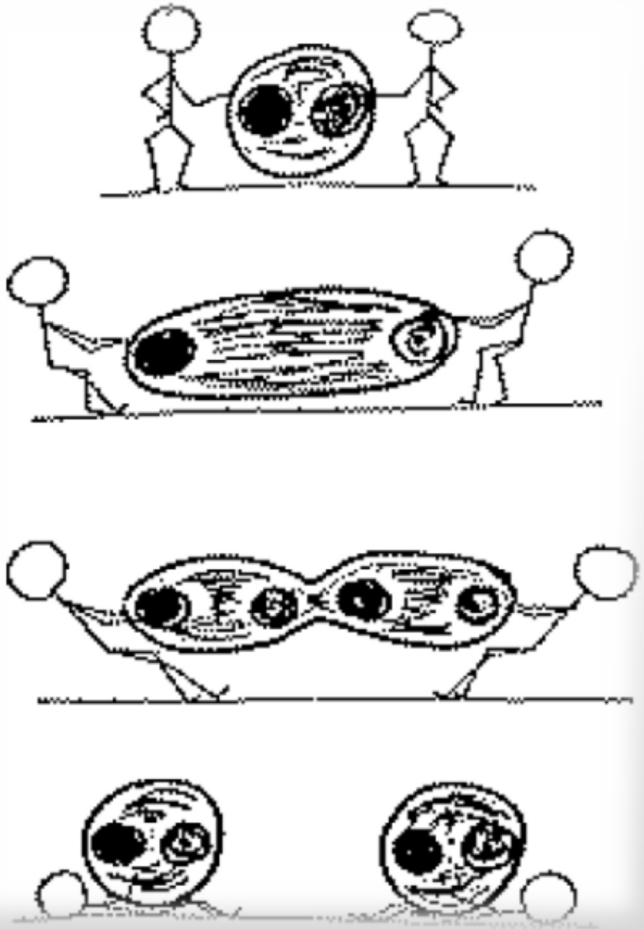
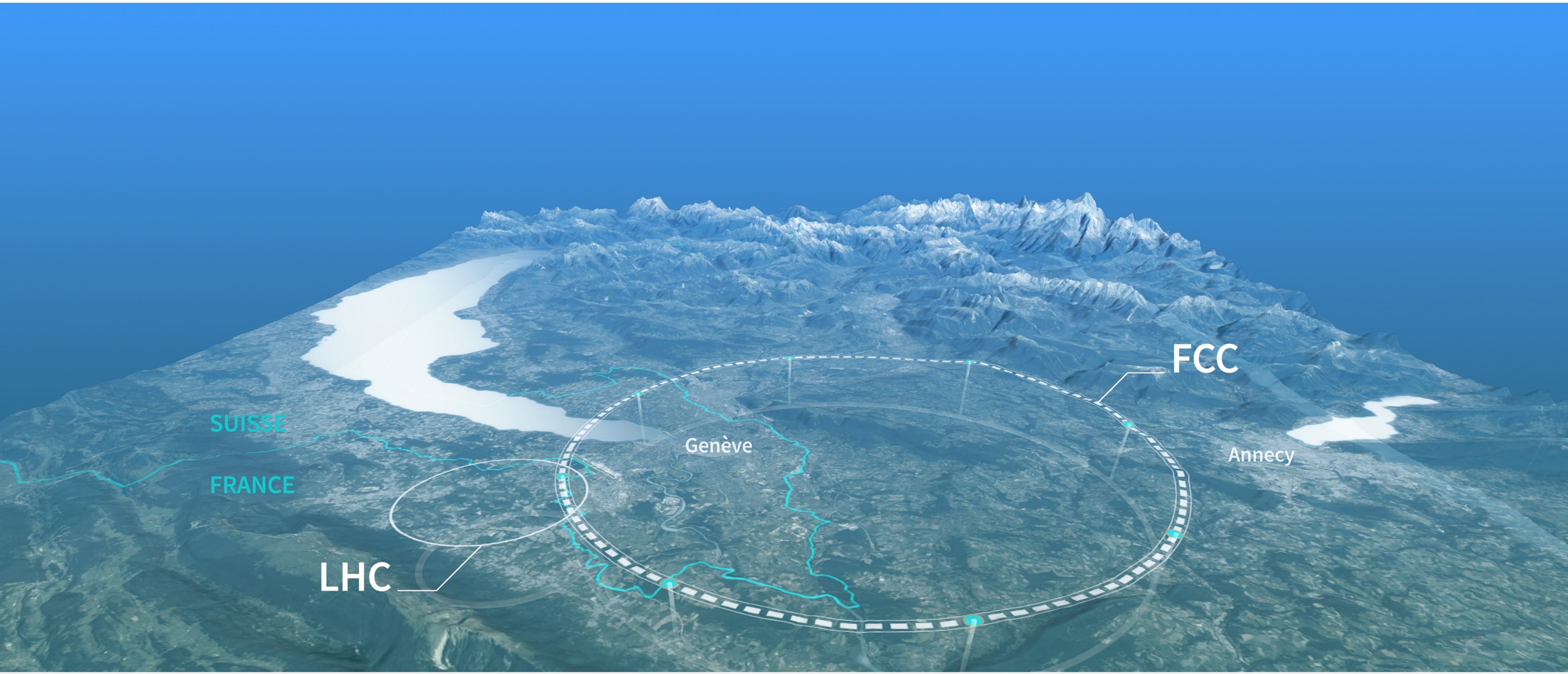
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Fundamental research and applications with the EuPRAXIA facility at LNF



Silvia Pisano

Centro Ricerche «Enrico Fermi»
Laboratori Nazionali di Frascati - INFN

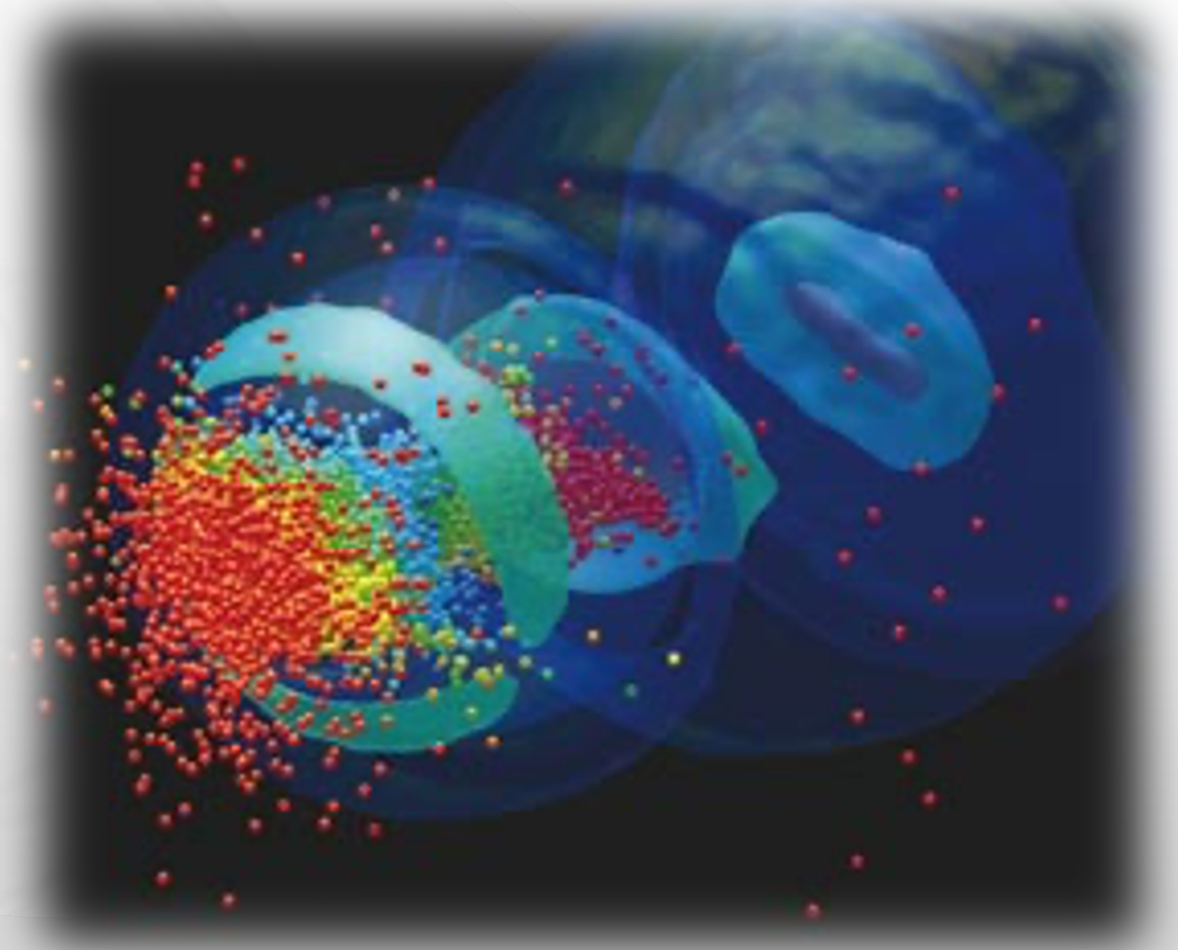


Large Hadron (LHC) and Future Circular (FCC) colliders

Plasma acceleration

While globally plasma is electrically neutral, if an external electromagnetic field strong enough is applied, the plasma electrons will separate spatially from the massive ions creating a charge imbalance in the perturbed region → charge separation field that can accelerate an injected particle beam

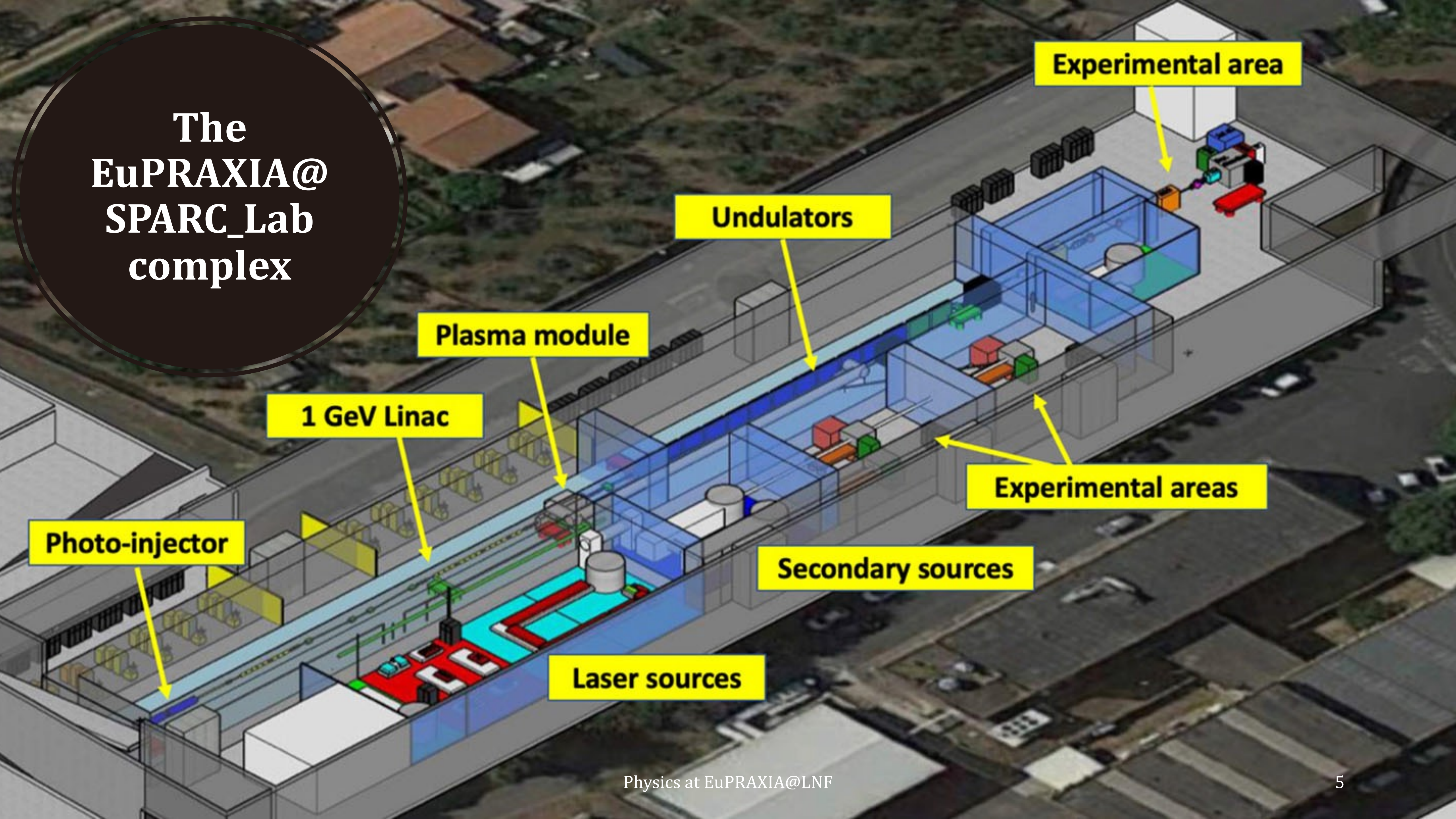
One can then perturbe this field to resonantly excites a plasma wake, which accelerates a trailing witness bunch injected at the accelerating phase at a few **GeV/m**.

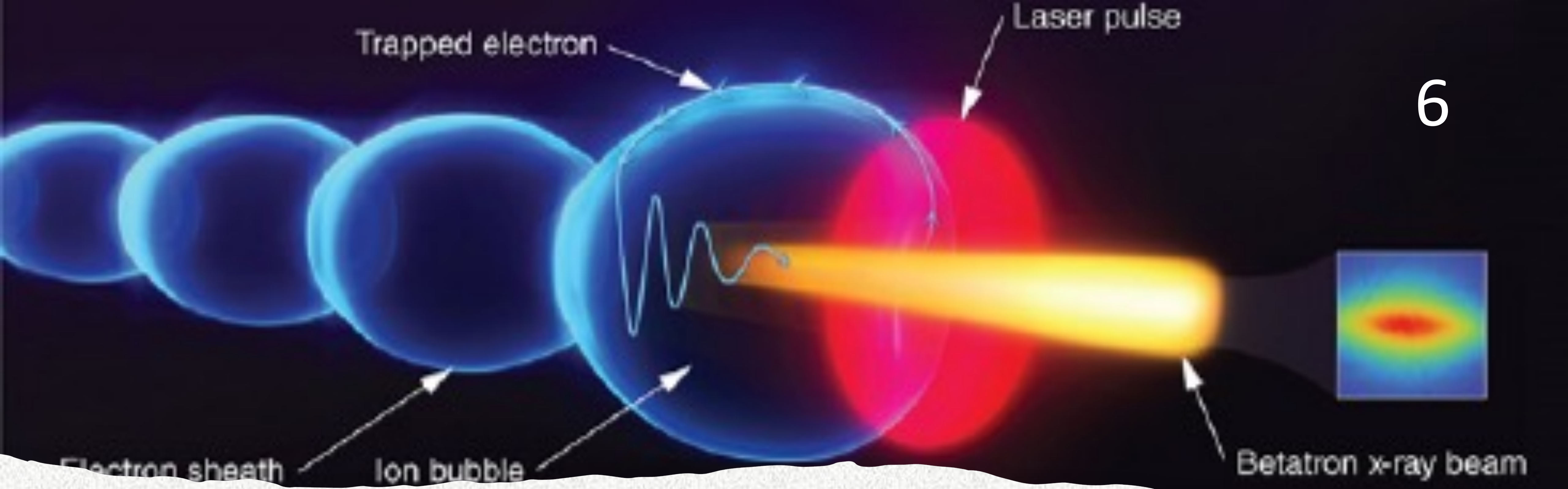


EuPRAXIA

https://www.eupraxia-project.eu/accelerator-technology.html

The EuPRAXIA@ SPARC_Lab complex





EuPRAXIA Advanced Photon Sources "EuAPS"

"Advanced Photon Sources act here as drivers for plasma waves in ultra-high-gradient accelerators or as plasma-based sources of ultra-short pulses of high intensity x-rays. The proposed work will enable the production of unique ultra-short particle and photon beams with applications in ultra-fast science, amongst others highly accurate medical imaging, material characterization and medical treatment. "

EuPRAXIA sources

EuPRAXIA is a leading European project aimed at the **development of a dedicated, groundbreaking, ultra-compact accelerator research infrastructure based on novel plasma acceleration concepts and laser technology.**

LNF will be equipped with a unique combination of:

- an **X-band RF LINAC** generating high-brightness GeV-range electron beams
- a **0.5 PW class laser system**
- the **first fifth-generation free electron laser (FEL) source driven by a plasma-based accelerator (EuPRAXIA)**
- **Betatron radiation (EuAPS)**: Wiggler-like radiation emitted by electrons accelerated in plasma wakefields → it will gives rise to brilliant, ultra-short X-ray pulses

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The laser can be used to produce plasma and will allow to perform measurements as

1. *Fusion processes of astrophysical interest in plasma*
2. *Nuclear decays in plasma*

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EuPRAXIA sources

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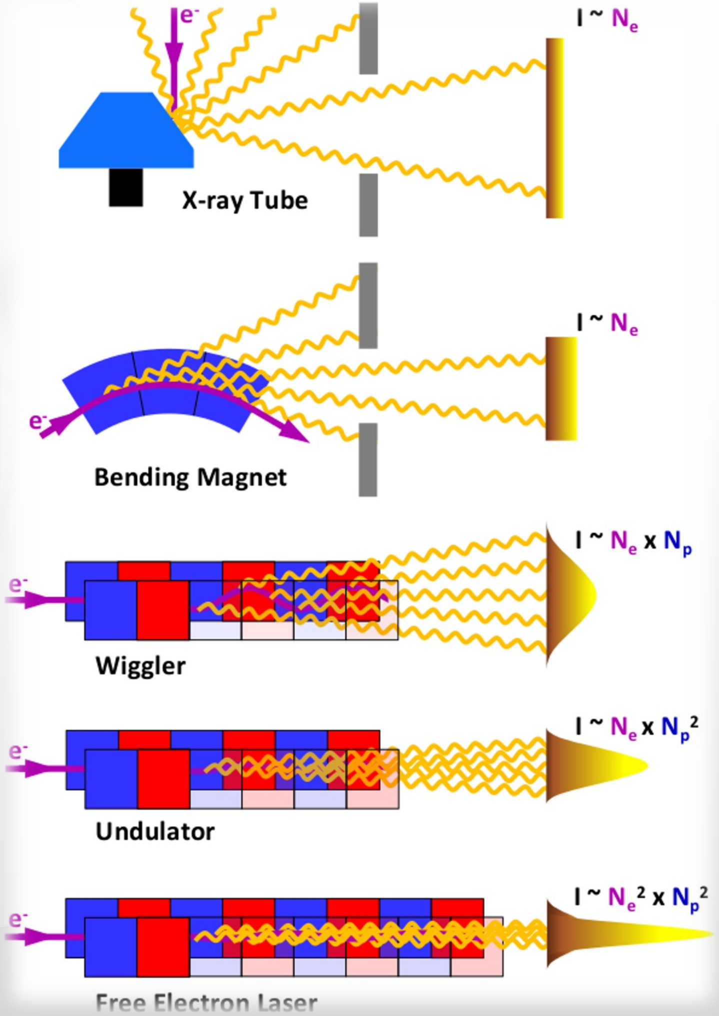

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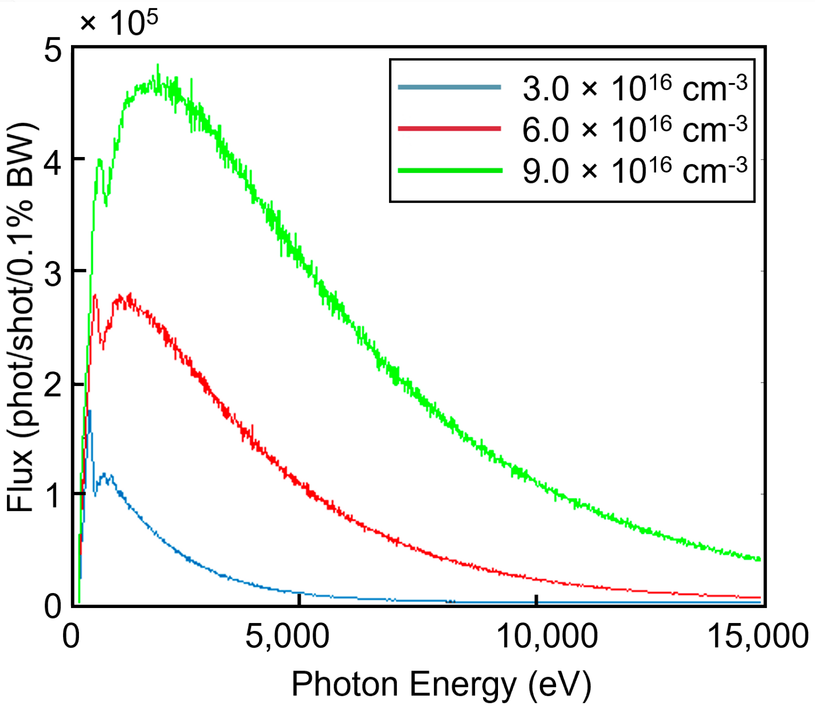

Parameter [Units]	Value
Beam energy [MeV]	600–950
Plasma density [cm^{-3}]	3.0×10^{16}
RMS transverse beam size [μm]	3.0
Charge [pC]	45
Capillary (plasma) length [m]	0.6
Pulse duration [fs]	10

https://www.mdpi.com/2410-3896/7/1/23

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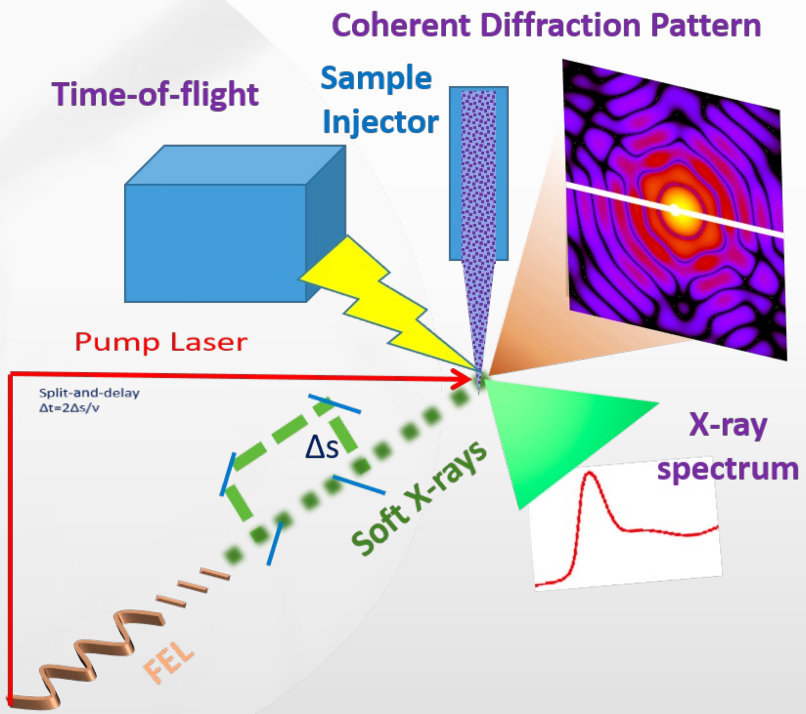

Biology and material science

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Betatron and FEL applications

Free-electron laser at EuPRAXIA:

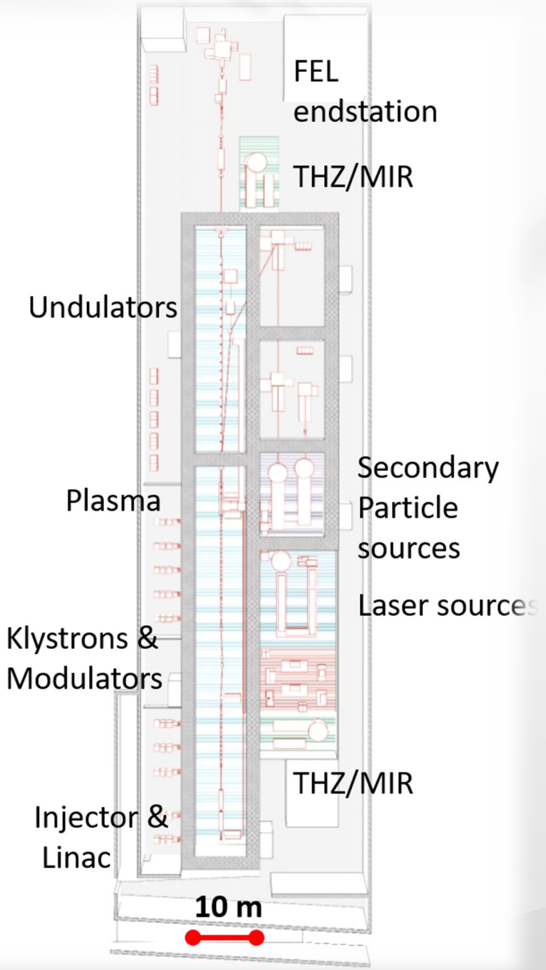
- Photon pulses with high intensity: 10^{12} photons/pulse
- $\lambda \rightarrow 4$ nm: water window
- Spectra in the *soft X-ray region*
- Pulse energy up to 180 μJ
- Bandwidth will range between 0.4% and 0.9%, according to the machine operation scheme

Betatron at EuAPS:

- Spectra in the *hard X-ray region*
- Peak at few keV

Both:

- pulse duration of tens of fs



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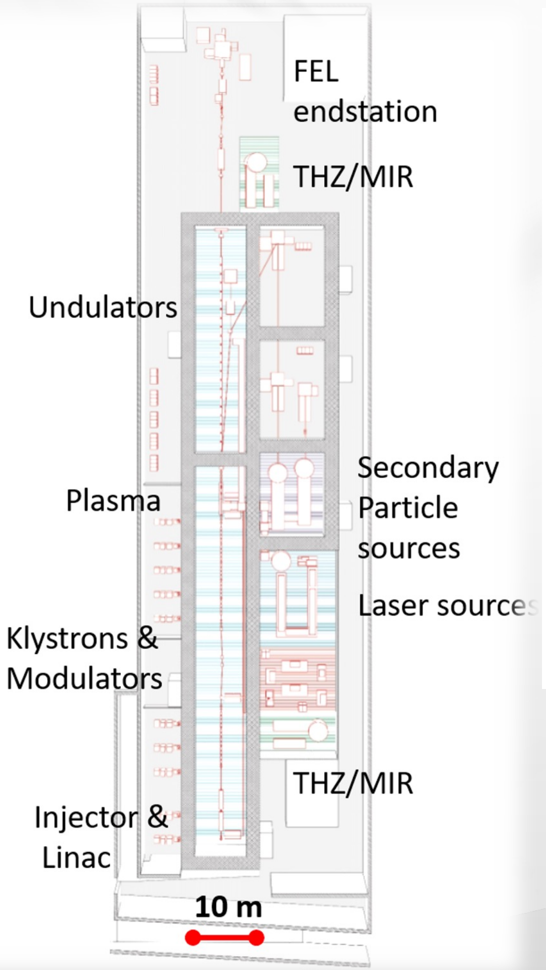

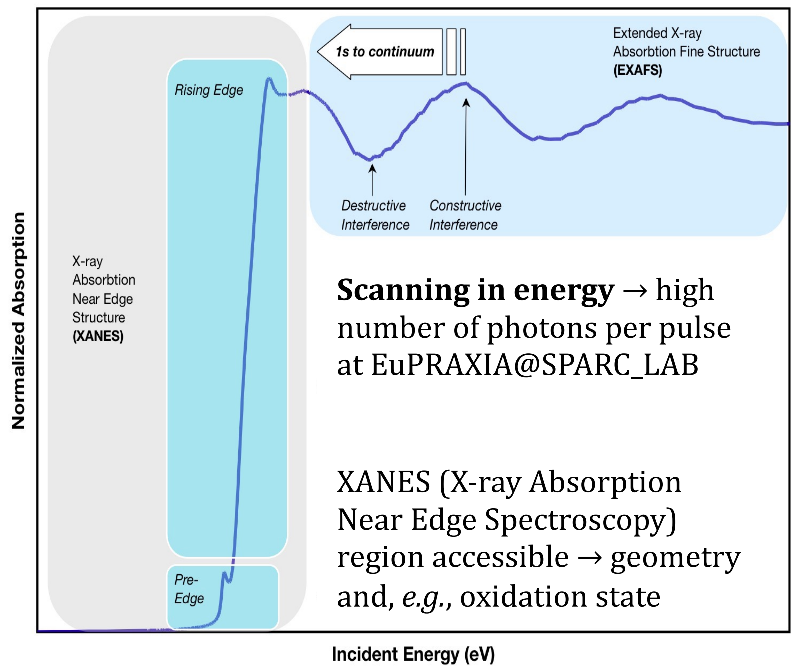

Scanning in energy → high number of photons per pulse at EuPRAXIA@SPARC_LAB

XANES (X-ray Absorption Near Edge Spectroscopy) region accessible → geometry and, *e.g.*, oxidation state

$\sigma(\lambda)$ → Some processes are activated by soft X-rays, and also need a high intensity as with FEL. However, some excitation will be beyond the reach of the FEL spectra (as Al)

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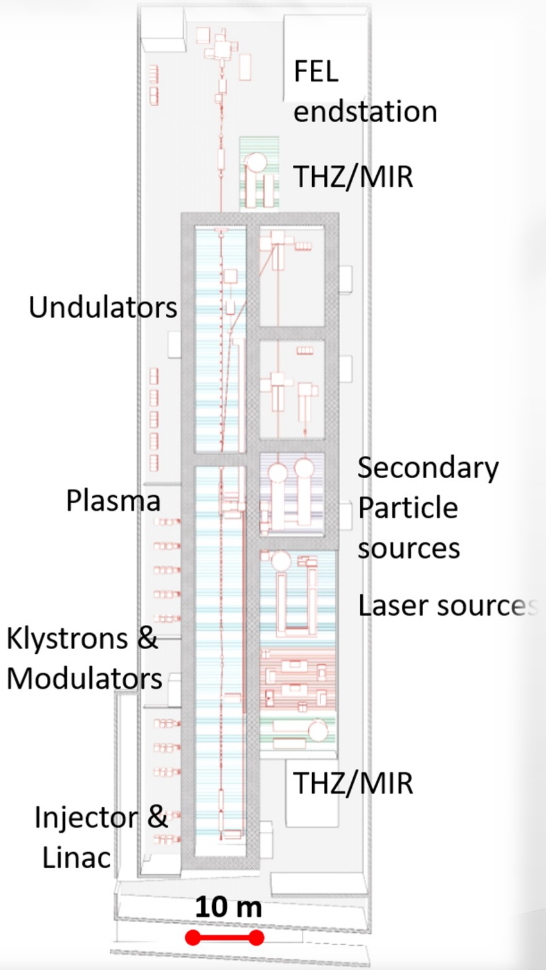

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Betatron and FEL applications

Biology aims at single particle imaging!

However, at the moment no atomic resolution structural information from single biological macromolecules is feasible due to FEL intensity, the available detectors, and techniques to introduce the sample into the focused X-ray sampling position

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Water window → region of the electromagnetic spectrum in which water is transparent to soft x-rays: it goes from the K-absorption edge of carbon at 282 eV - 68 PHz, 4.40 nm wavelength - to the K-edge of oxygen at 533 eV - 129 PHz, 2.33 nm wavelength.

Water is transparent to these X-rays, while carbon and its organic compounds are absorbing → **the absorption contrast between the carbon of organelles and the water of both cytoplasm and the liquid surrounding the cell is maximal**!

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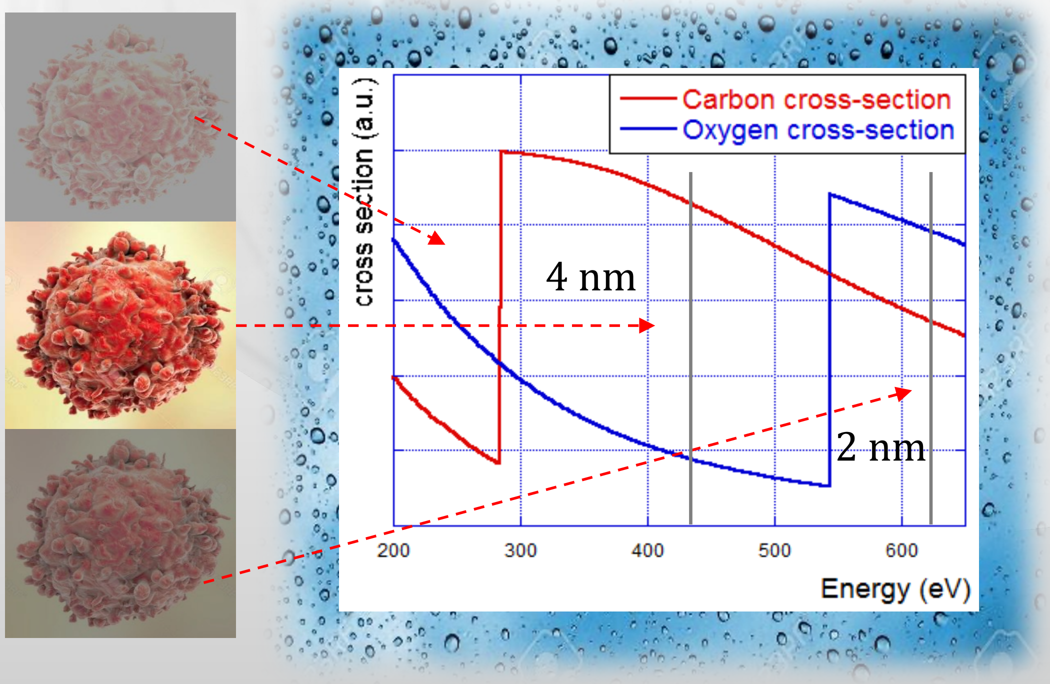

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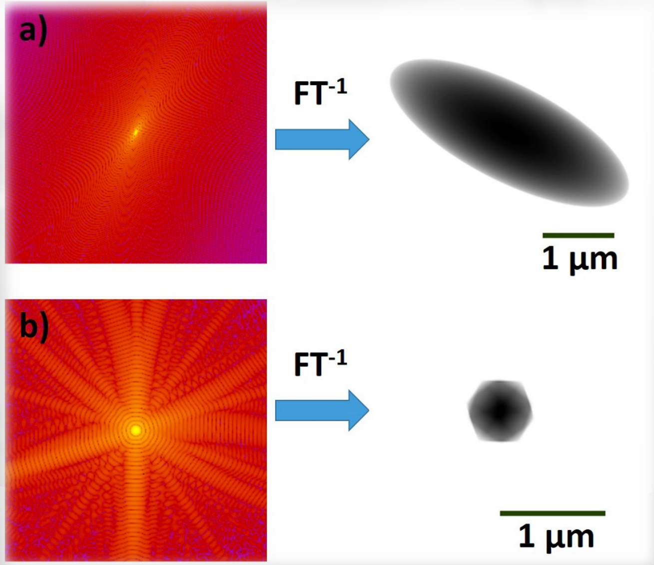
- Water window and room temperature
- High degree of transverse coherence (between 80% and 100%) → 2D images of a variety of biological samples, including bacteria, viruses, cells
- Combining diffractive patterns on identical objects may allow 3D reconstruction



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Betatron and FEL applications

Warm dense matter

Article Talk

From Wikipedia, the free encyclopedia

Warm dense matter, abbreviated **WDM**, can refer to either equilibrium or non-equilibrium states of matter in a (loosely defined) regime of temperature and density between condensed matter and hot plasma. It can be defined as the state that is too dense to be described by weakly coupled plasma physics yet too hot to be described by condensed matter physics. In this state, the potential energy of the Coulomb interaction between electrons and ions is on the same order of magnitude (or even significantly exceeds) their thermal energy, while the latter is comparable to the Fermi energy.[1] Typically, WDM has a density somewhere between 0.01 and 100 g/cm^3 and a temperature on the order of several thousand kelvins (somewhere between 1 and 100 eV, in the units favored by practitioners).

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Betatron and FEL applications

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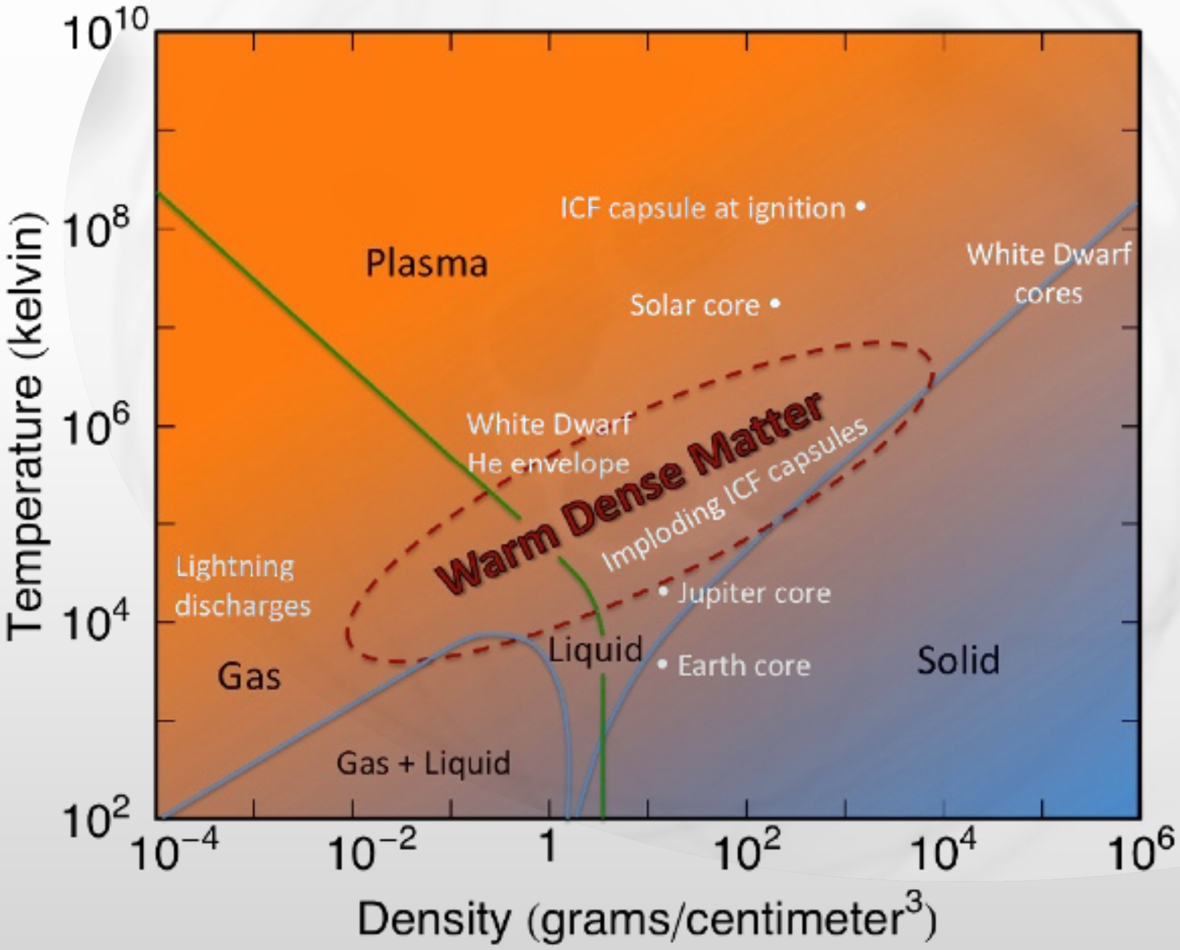

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- $V_{\text{Coulomb}} \geq E_{\text{Thermal}}$
- Typical densities are between 0.01 and 100 g/cm^3, typical temperatures between 1 and 100 eV
- *Femtosecond lasers can rapidly heat matter, leading to ultrafast solid-liquid-WDM transitions*

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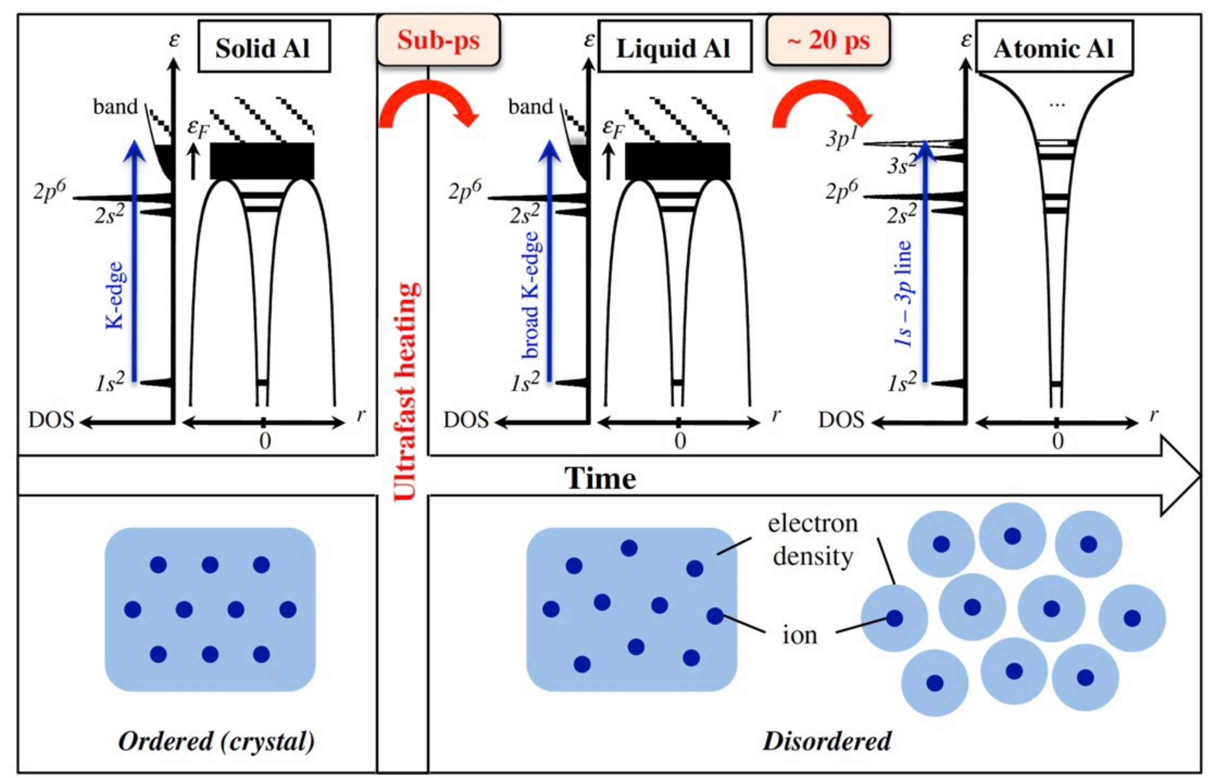
Betatron and FEL applications



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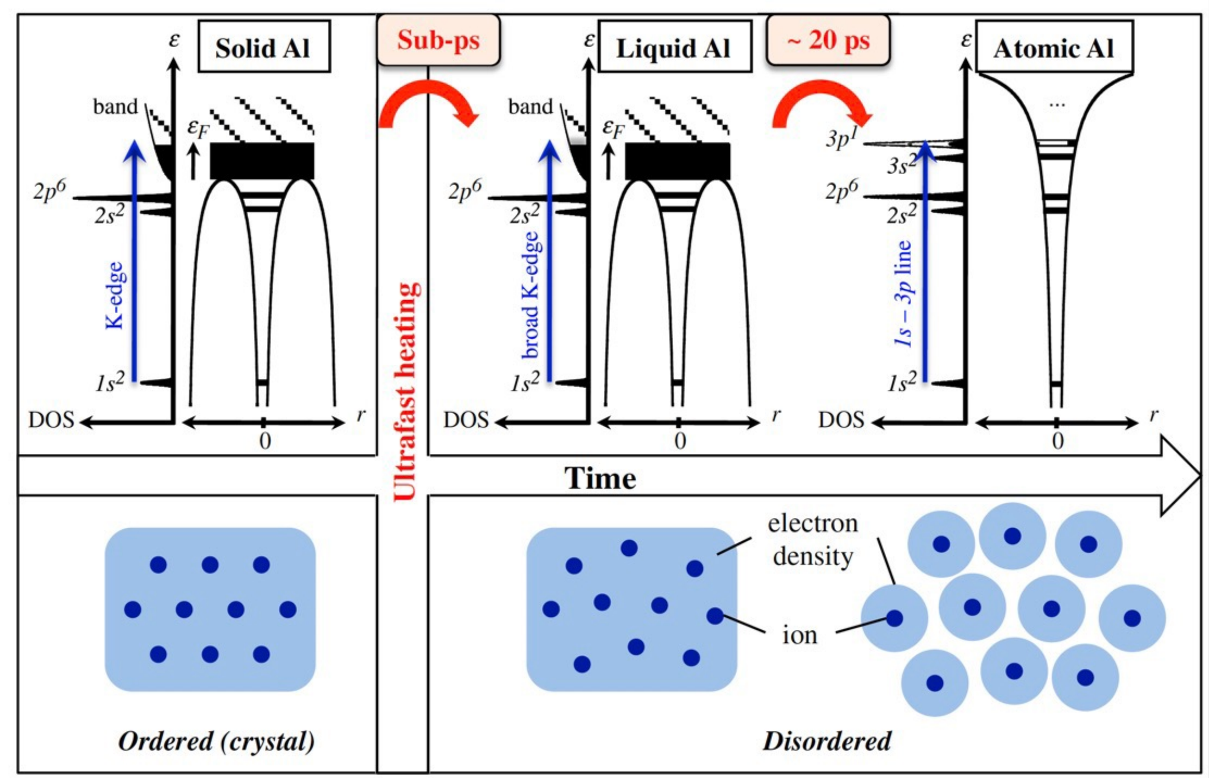

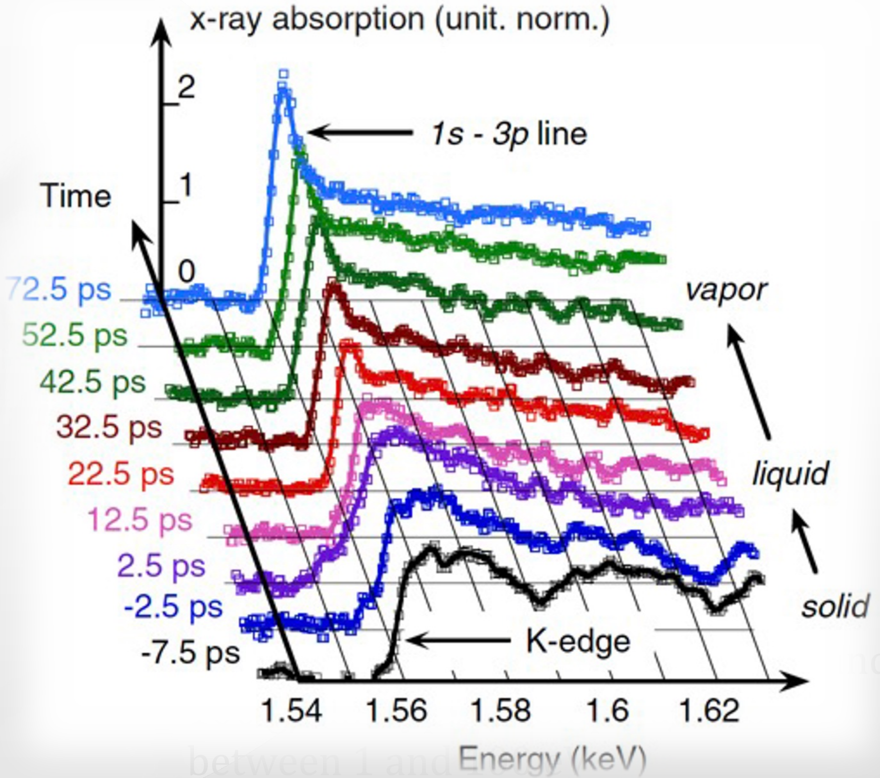

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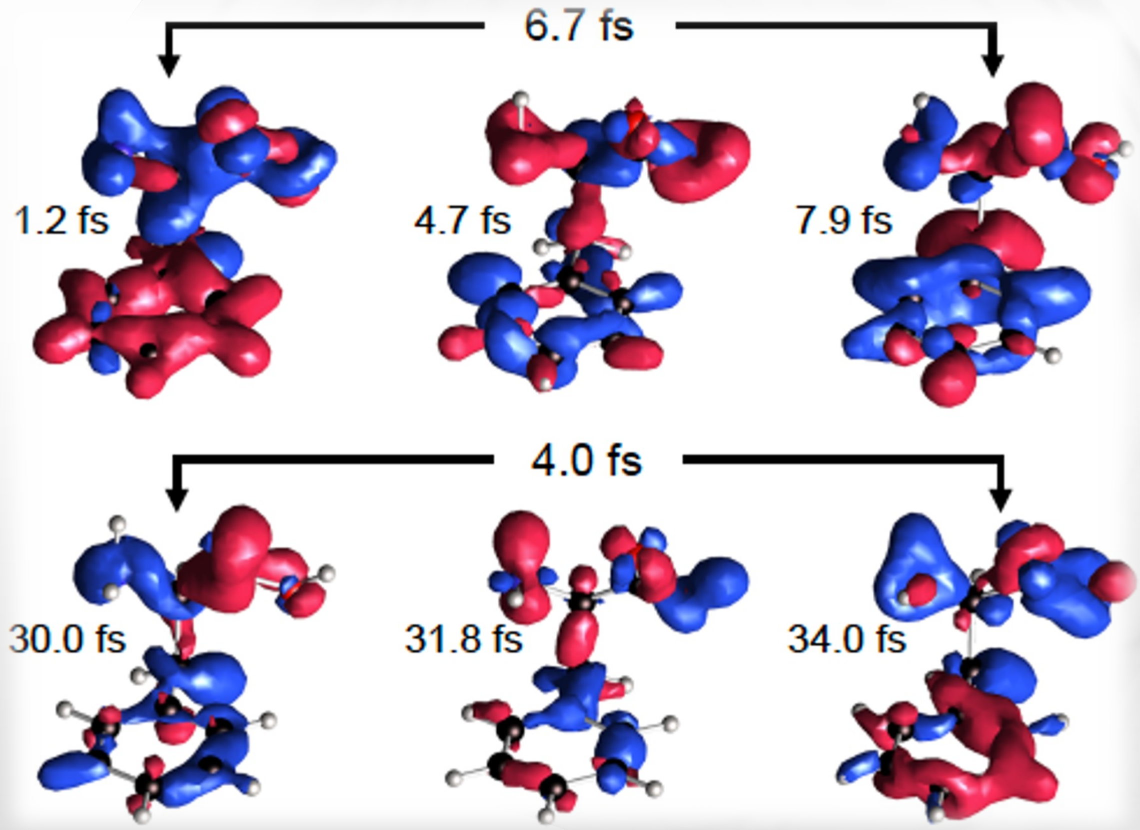

Real-space distribution of the molecular charge at six representative times of the phenylalanine aminoacid after illumination with an ionizing XUV 300-as pulse

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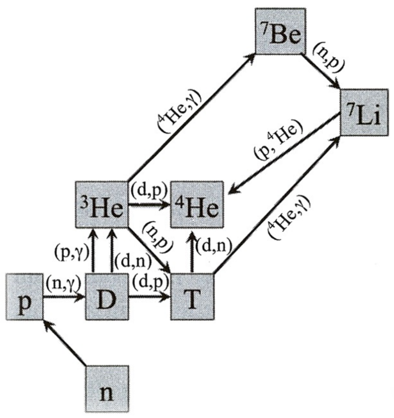
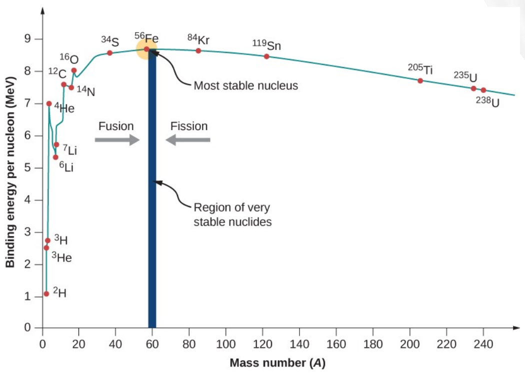
How organic and biological molecules redistribute the energy of absorbed light?

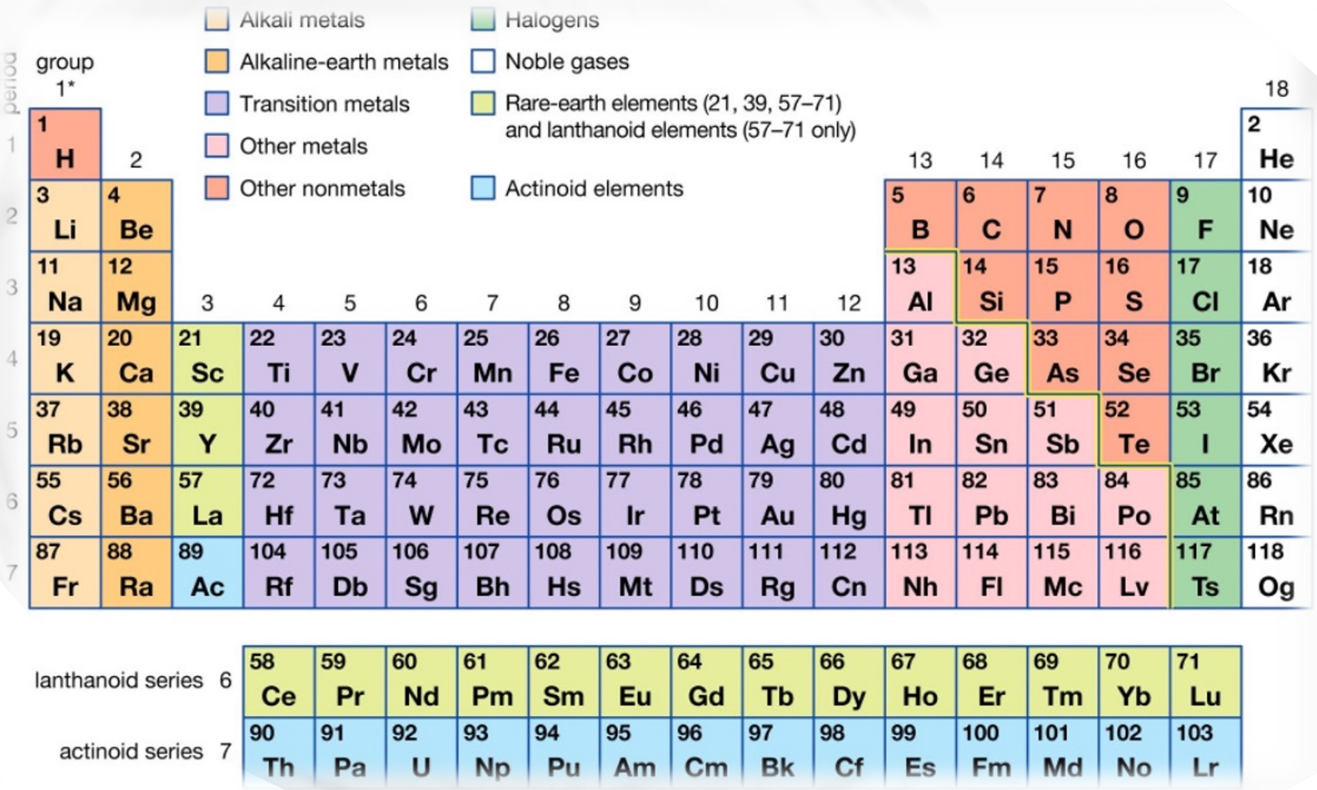
→ *It will help understanding the basic mechanisms of photo protection/damage of amino acids, proteins and DNA/RNA*

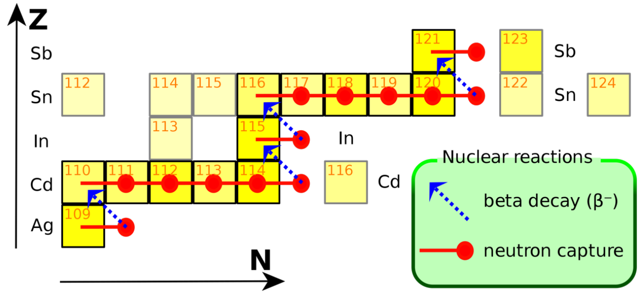
Nuclear physics

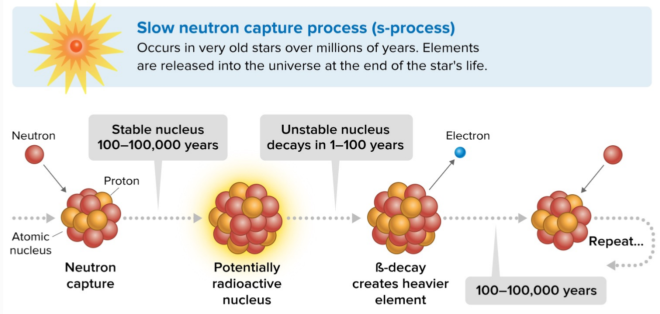
The periodic table of elements

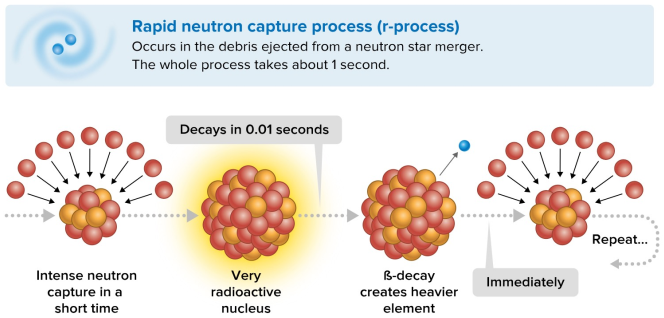










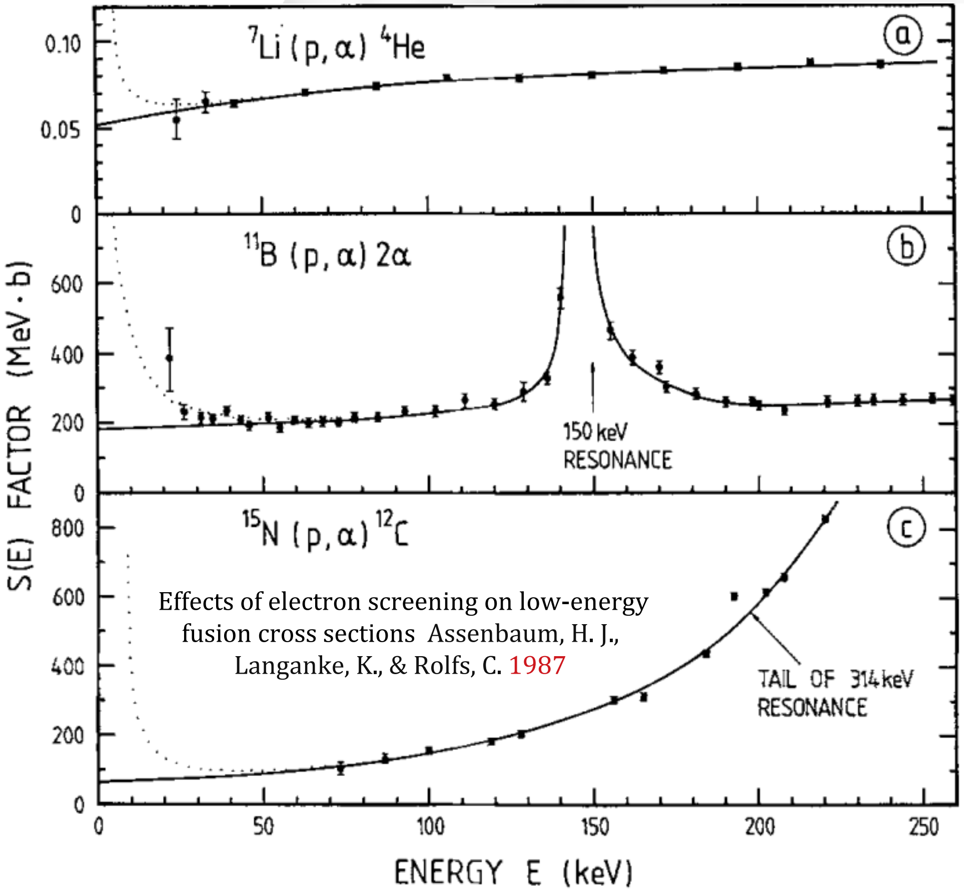


See talk by F. Villante

Why plasma

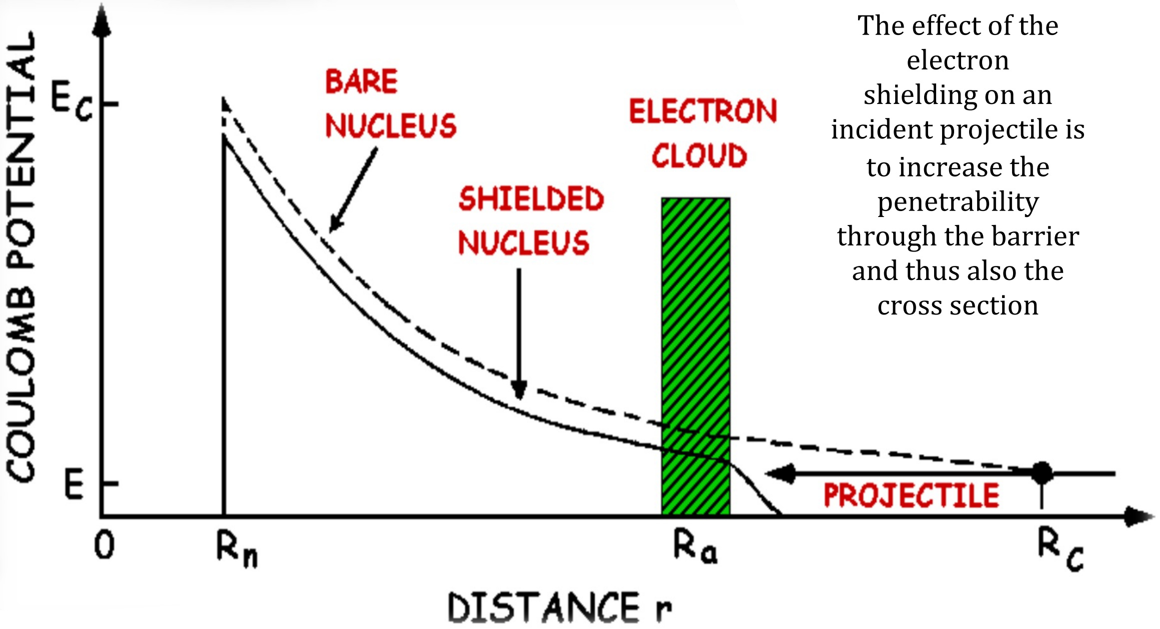
Why plasma: fusion processes

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

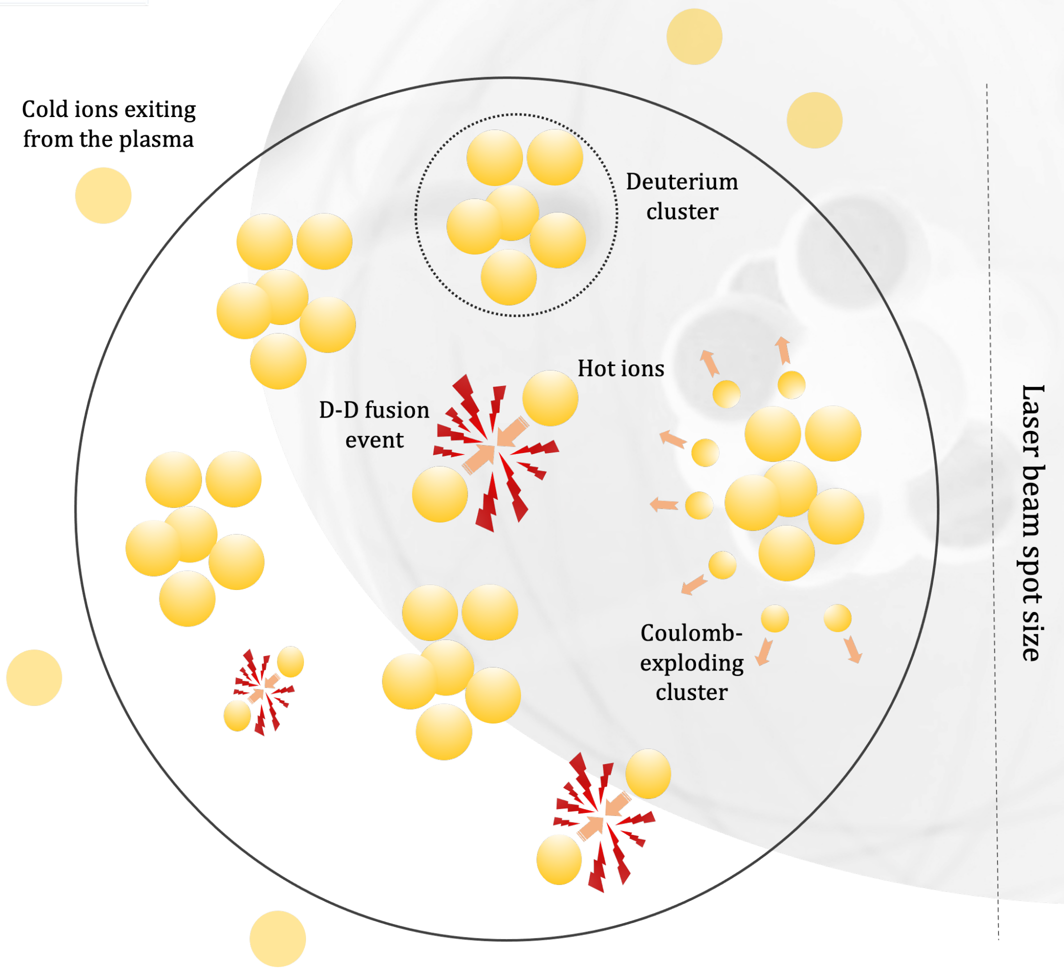
Relatively small enhancements due to electron screening could cause significant errors in the extrapolation to lower energies, if the cross-section curve is forced to follow the trend of the enhanced cross sections without correcting for screening.



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

See talk by L. Guardo

Deuterium fusion process in plasma



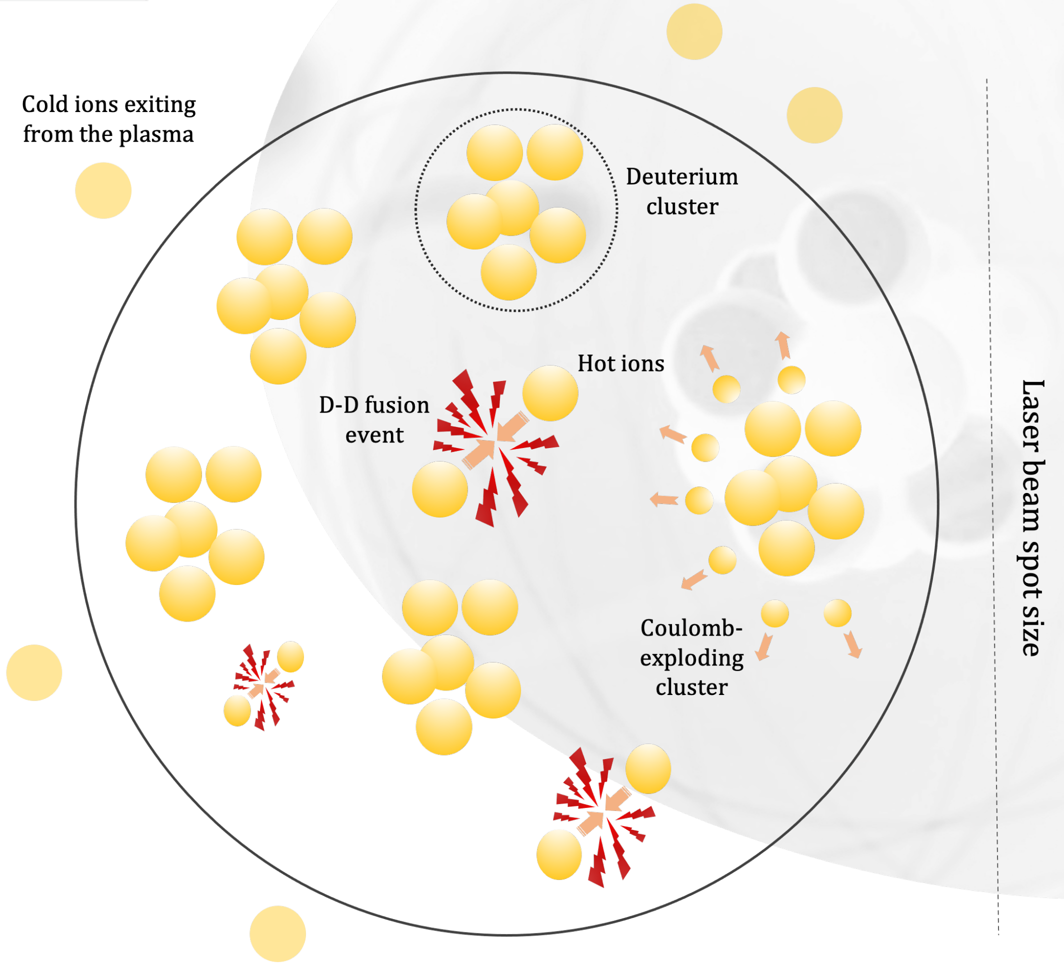
$$d + d \rightarrow \ ^3He + \text{n (2.45 MeV)}$$

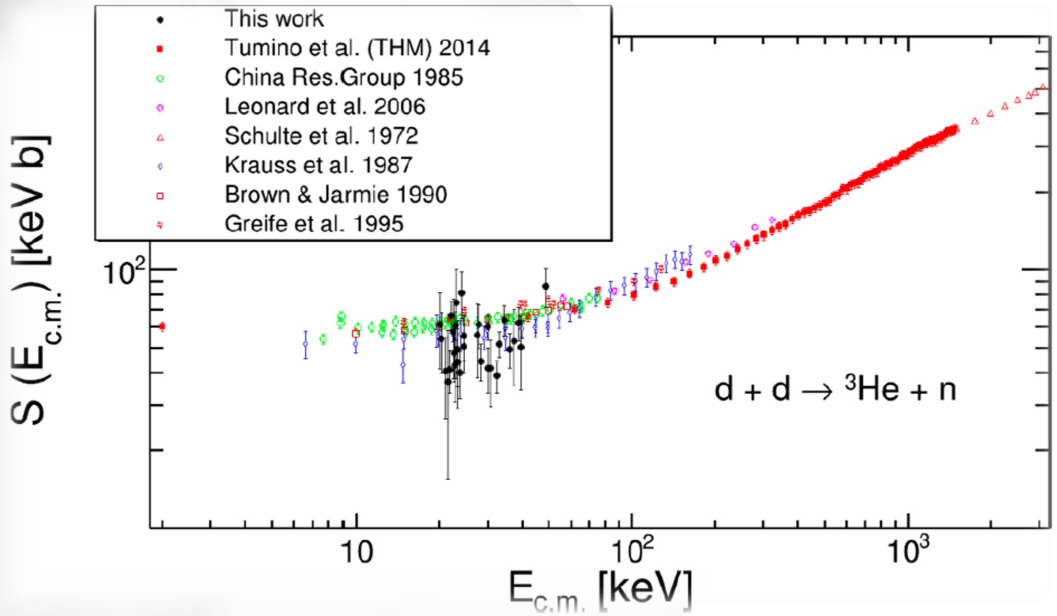
It is a nuclear fusion reaction crucial for understanding early phases of **Nucleosynthesis**

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.**

Deuterium fusion process in plasma





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

See talk by L. Guardo

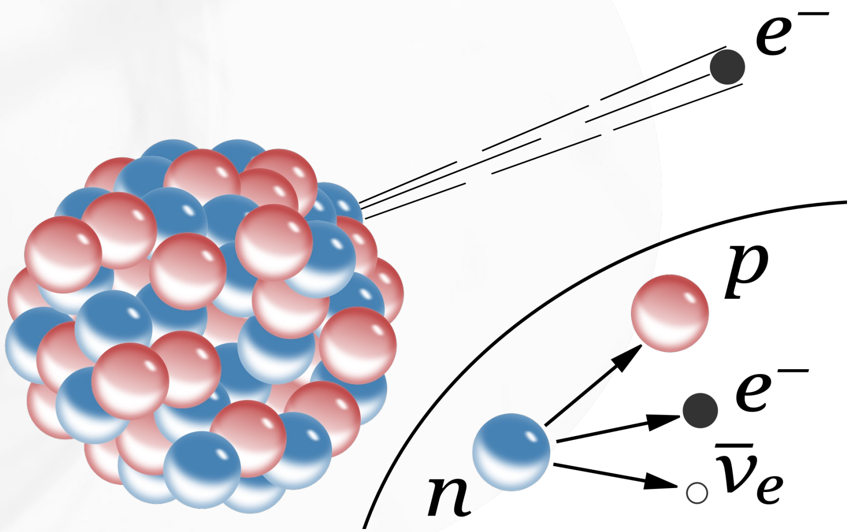
Why plasma: β-decays

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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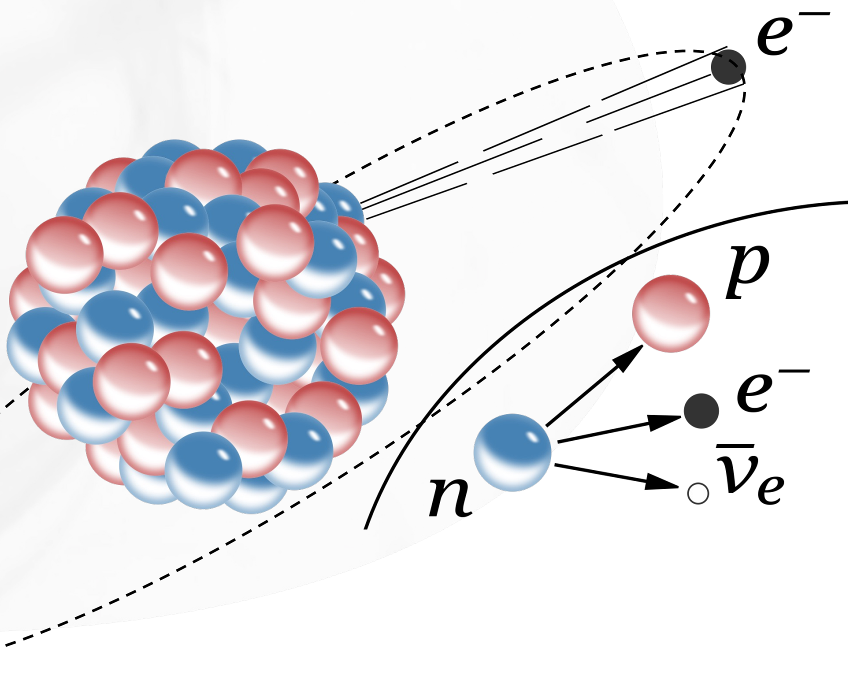
2. Bound state β-decay typically marginal can become important.

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.



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?

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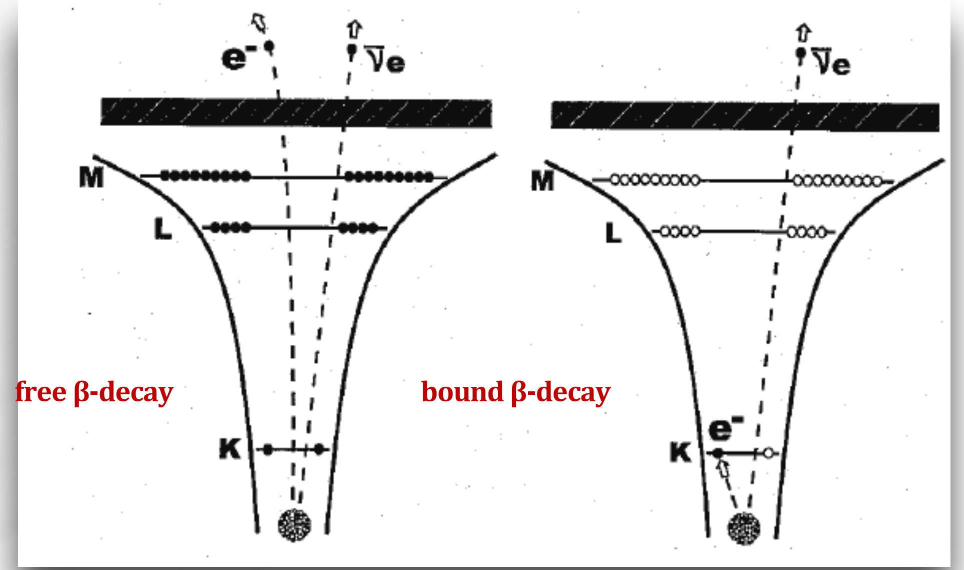

Y. Litvinov and F. Bosh: Rep. Prog. Phys. 74, 016301 (2011)

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Why plasma: β-decays

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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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.**

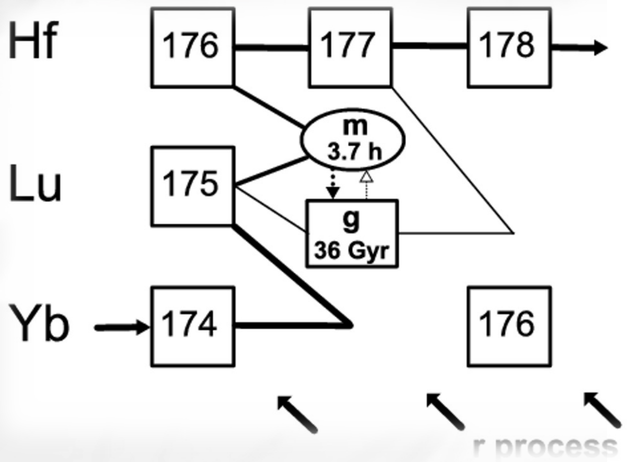
Q-value modifications: *in a stellar plasma, ions are embedded in a cloud of charges, both positive and negative. These charges create EM fields which act as perturbation to the atomic/ionic levels leading to corrections of Q-values which affects the decay rates.*

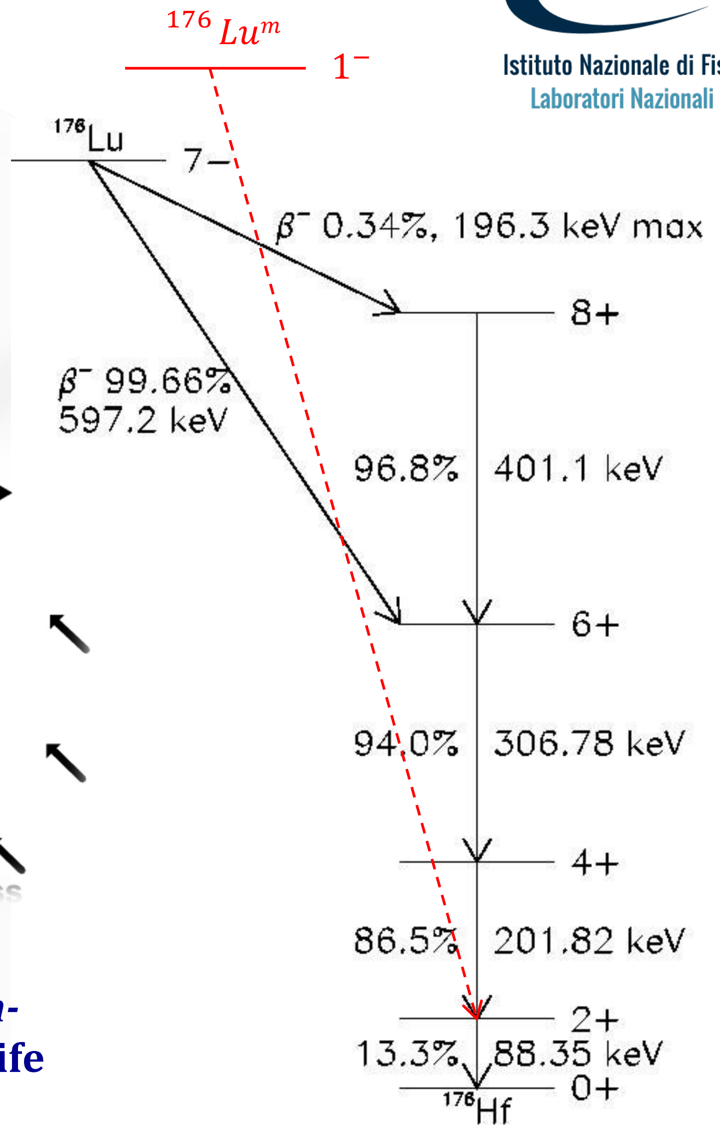
F. Bosch at al., Observation of Bound-State β⁻ Decay of Fully Ionized ^{187}Re: ^{187}Re–^{187}Os Cosmochronometry, Phys. Rev. Lett. 77, 1996

^{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

See talk and poster by B. Mishra

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**
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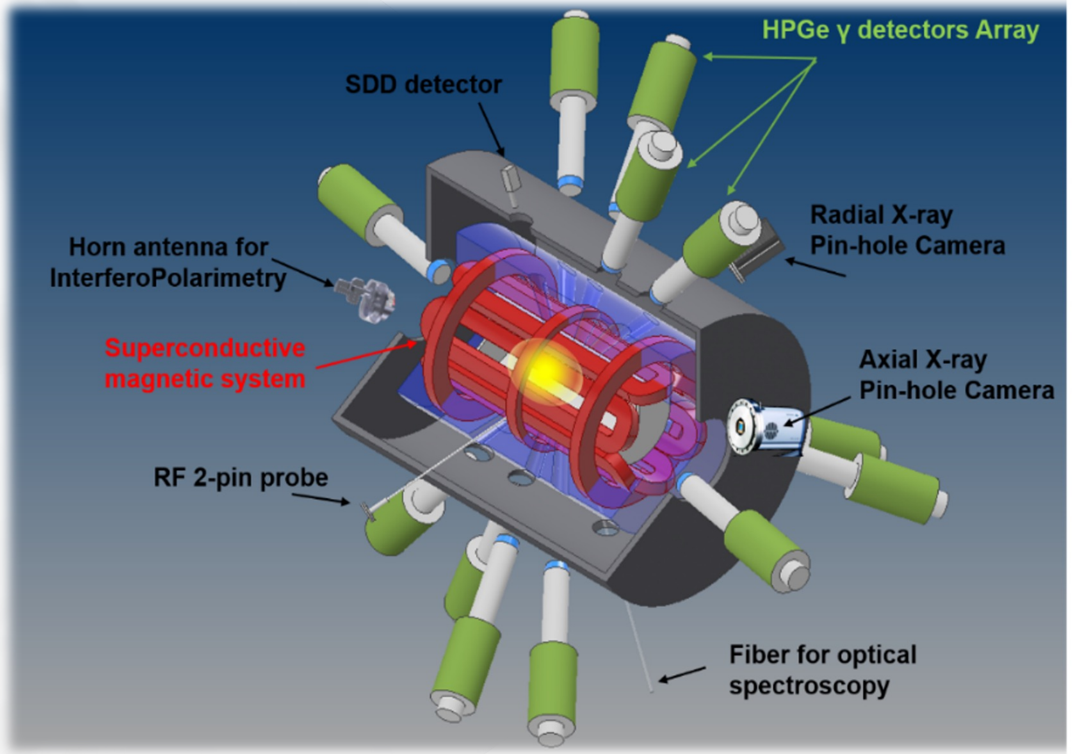

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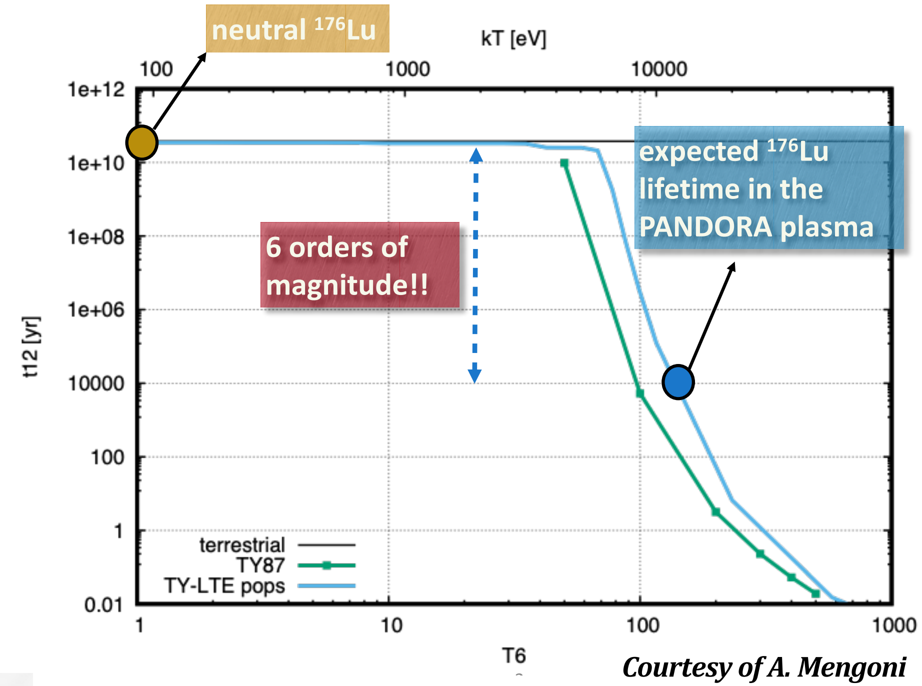
^{176}Lu: lifetime vs. T – theoretical predictions



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

See talk and poster by B. Mishra

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Why to use laser-induced plasma

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Laboratori Nazionali di Frascati

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Using a laser-plasma as a source of polychromatic high energy X-ray photon flux one could simultaneously investigate isomeric photoactivation as well as in-plasma decay rate modification of ground and isomer levels

Thermalization between the ground and isomer levels may occur

See poster by B. Mishra

***The laser-plasma can be expected to produce X-ray spectra similar to the stellar interior, which can answer the question of equilibration more accurately than previous experiments on this topic*!**

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Why to use laser-induced plasma

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Magnetic confinement

PRO:

- **Long-living plasma** (order of weeks)
- Steady state dynamical equilibrium for density and temperature (by compensating ion losses)
- Hence, over days/weeks constant values for charge state distribution of in-plasma ions
- Online monitoring of plasma density, temperature, volume, at any energy domain in nLTE conditions

CONS:

- Low density/high temperature plasma: **nLTE conditions**
- Difficult "plasmization" of solid/metallic isotopes
- **No access to nuclear excited state studies** (too low T)

Laser-induced plasma

PRO:

- **High density plasma, reaching LTE**
- Fully thermodynamical equilibrium allows, in principle, to **estimate the population of nuclear excited states**

CONS:

- **Difficult to implement diagnostics** following on-time the fast time-variation of plasma parameters
- **Short living plasma**, with duration much shorter than typical lifetimes of isotopes involved in stellar nucleosynthesis

Biophysics:

- Francesco Stellato[§]
- Antonella Balerna[*]

Nuclear physics:

- Giorgio Finocchiaro[°]
- Paola Gianotti[*]
- Dario Lattuada[+°]
- David Mascali[°]
- Alberto Mengoni[^]
- Bharat Mishra[°]
- Eugenia Naselli[°]
- Angelo Pidatella[°]
- Silvia Pisano[*]
- Domenico Santonocito[°]

The environment matters!

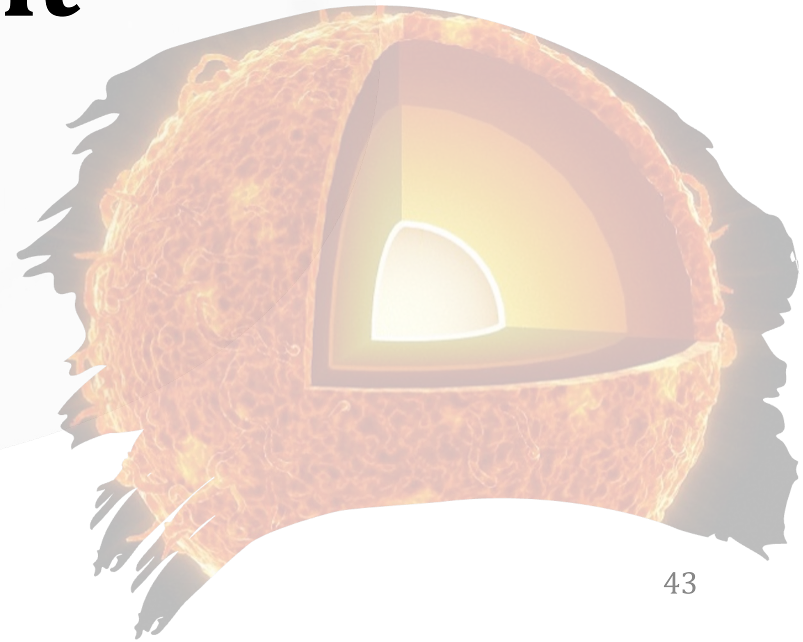
[§] Università di Roma «Tor Vergata»

[+] Università degli studi di Enna "Kore"

[°] INFN Laboratori Nazionali del Sud

[^] INFN & ENEA Bologna

[*] INFN Laboratori Nazionali di Frascati



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Biology and applications

EuPRAXIA@SPARC_LAB

Betatron and FEL applications

Applications:

1. *Coherent Imaging of Biological Samples*
2. *Time-Resolved X-ray Absorption Spectroscopy in the Water Window*
3. *Time-Resolved Coherent Raman Experiments with X-ray Pulses*
4. *Photo-Fragmentation of Molecules*
5. *Resonant Inelastic X-ray Scattering*
6. *THz/MIR Sources*

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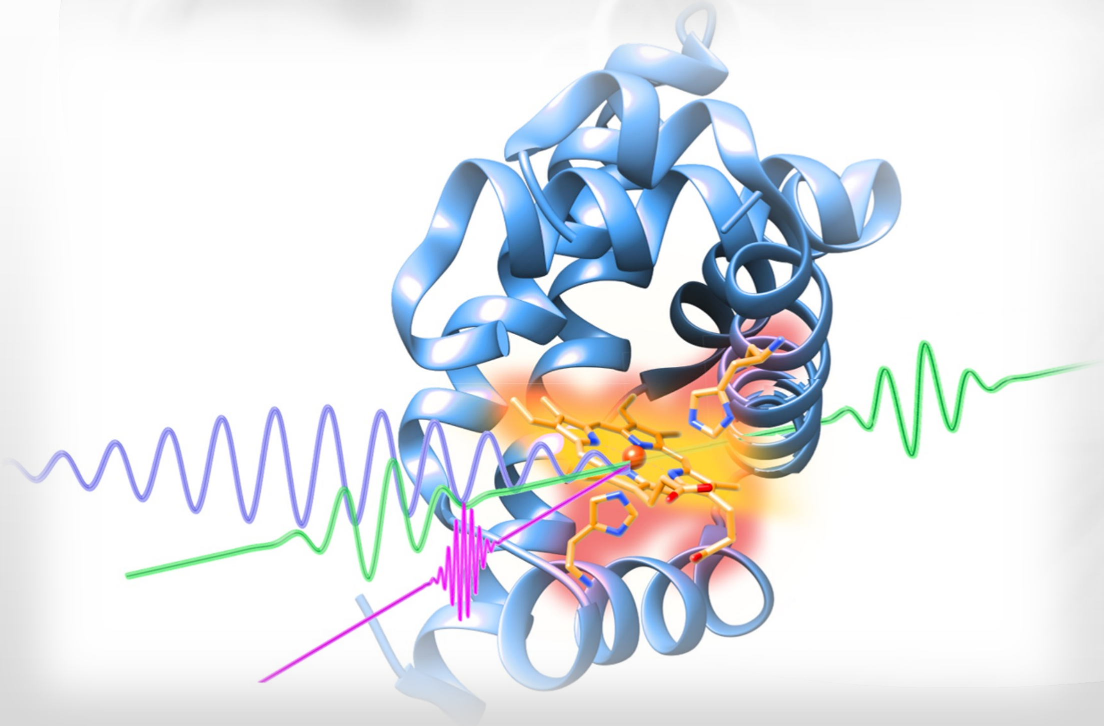
Betatron and FEL applications

X-ray pulses can be exploited as pump pulse for stimulating chemical reactions or for generating coherent excitations, and, on the other hand, they can be used as selective probe to monitor the evolution from reactant to photoproduct



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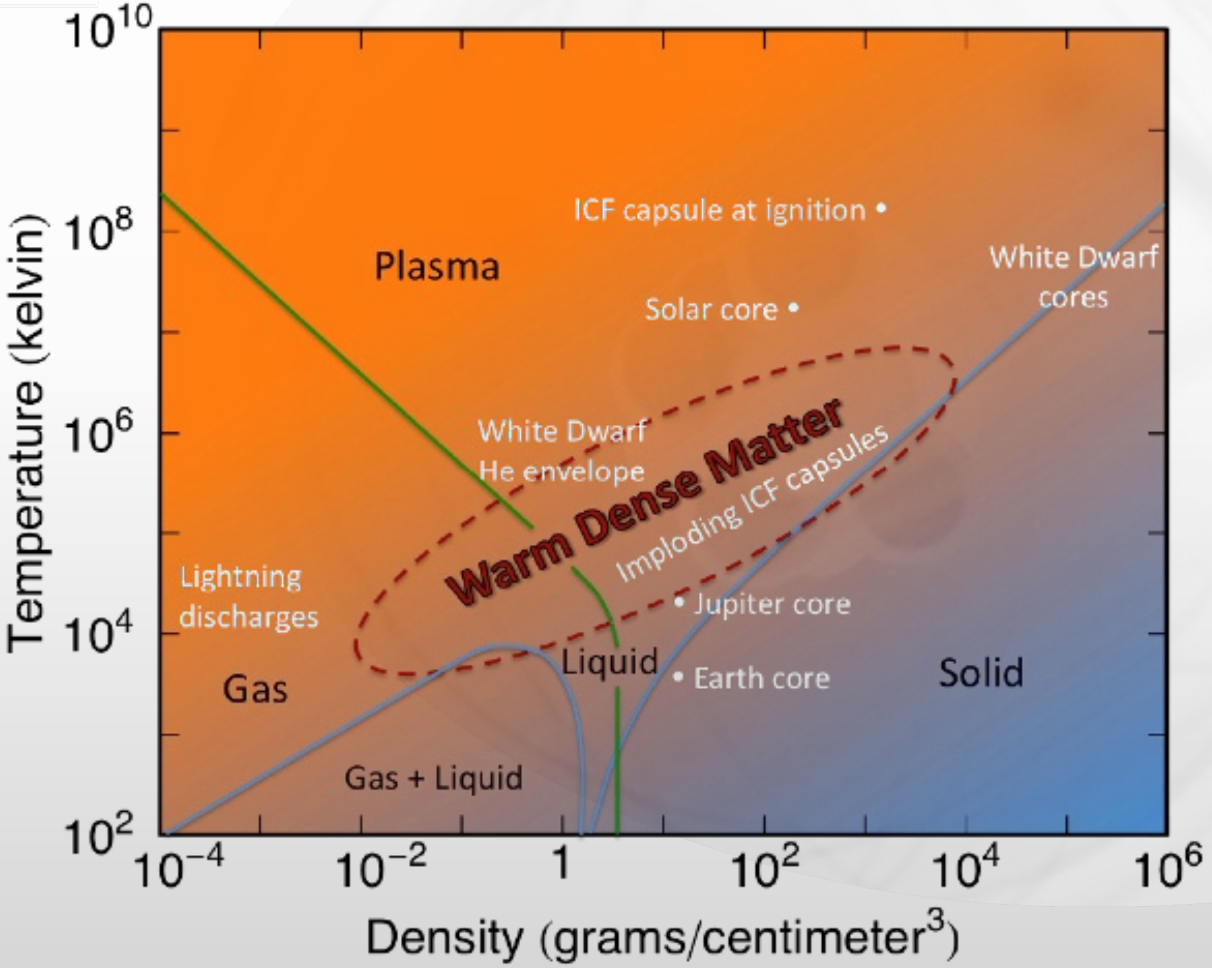
Monitoring transient atomic motions that govern physical, chemical and biological phenomena, measuring structural molecular changes of reacting species over few Ångstrom lengths on sub-picosecond timescales
→ **pump–probe scheme**

EuPRAXIA@SPARC_LAB Betatron: Warm Dense Matter



1. Cores of large planets
2. Systems initially solid and evolving in a plasma
3. X-ray driven inertial fusion implosion (aspects of indirect-drive inertial fusion)

Femtosecond lasers can rapidly heat matter, leading to ultrafast solidliquid-WDM transitions, followed by a more complex multiphase expansion at a picosecond time scale. Highly nonequilibrium states of matter are expected, due to the finite rate of energy transfer from the excited electrons to the lattice.

As the atomic structure modification is supposed to be driven by the photoexcited electrons, it is of primary importance to determine the respective time scales of the evolution of both electron and atomic structures.

EuPRAXIA@SPARC_LAB Betatron: Warm Dense Matter

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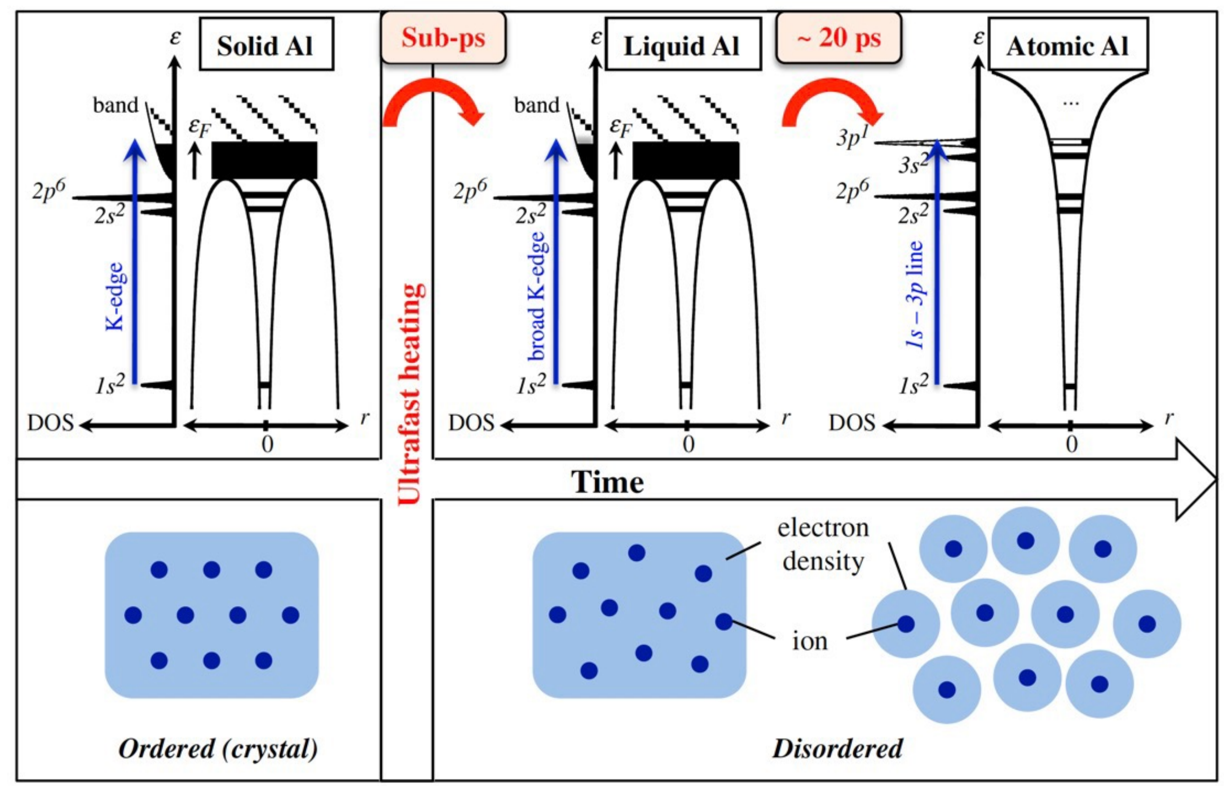
Schematic of the aluminum solid-liquid-vapor transition dynamics at the atomic level

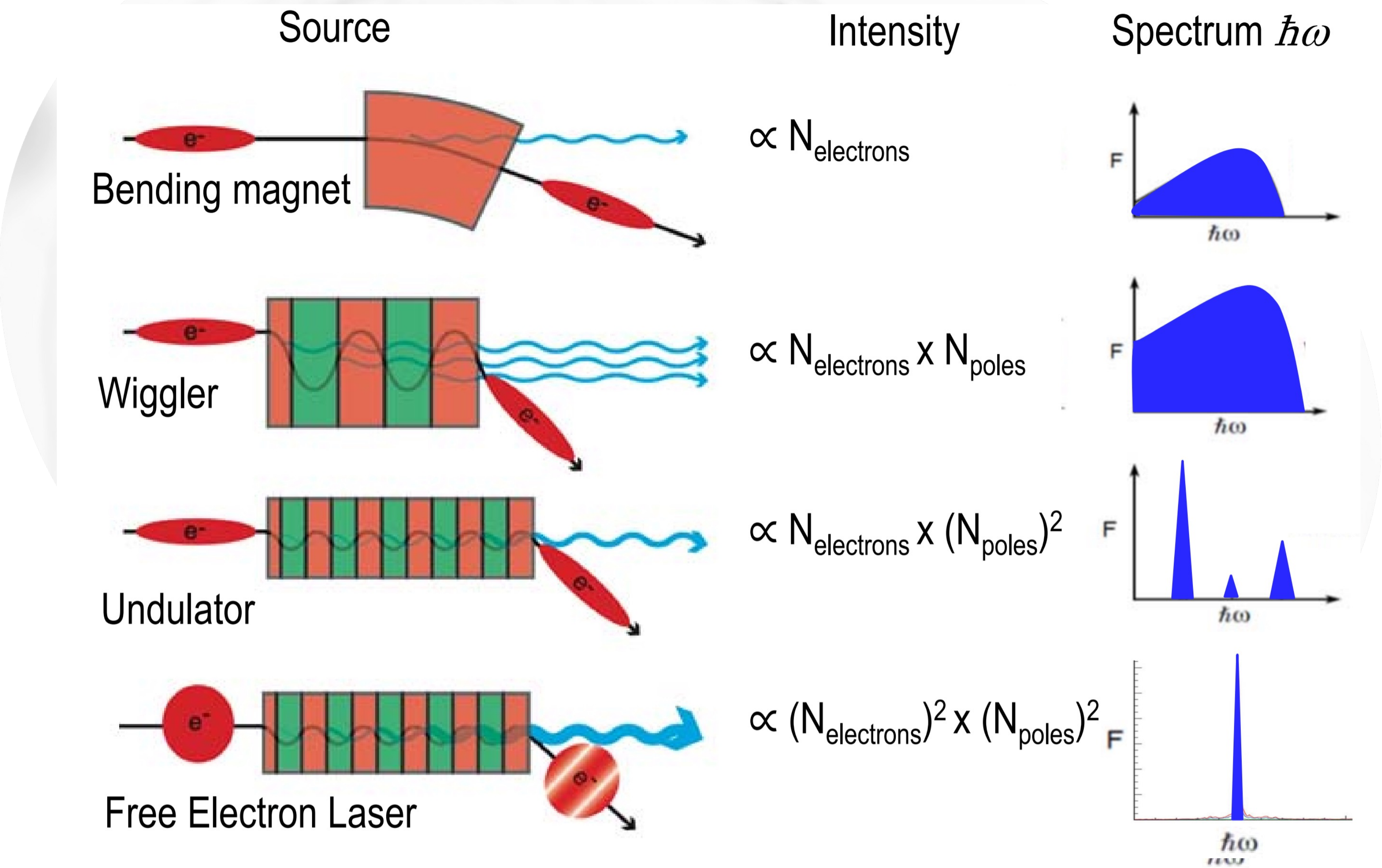


Solid Al: in the solid case, the conduction band is partially occupied by valence electrons up to the Fermi energy EF, leading to a sharp x-ray absorption K edge.

Liquid Al: the laser deposits energy in the valence electrons and induces a thermal broadening of the band occupation, leading to the K-edge broadening. The energy is transferred from electrons to the lattice, breaking the crystalline order

Atomic Al: due to high thermal pressure, hydrodynamic expansion occurs driving the transition to atomic vapor. In isolated atoms, the electrons are localized on the atomic orbitals. As the 3p orbital is partially unoccupied, the 1s-3p line can be observed in the x-ray absorption spectrum.

Differences among radiation sources



Coherent Imaging of Biological Samples

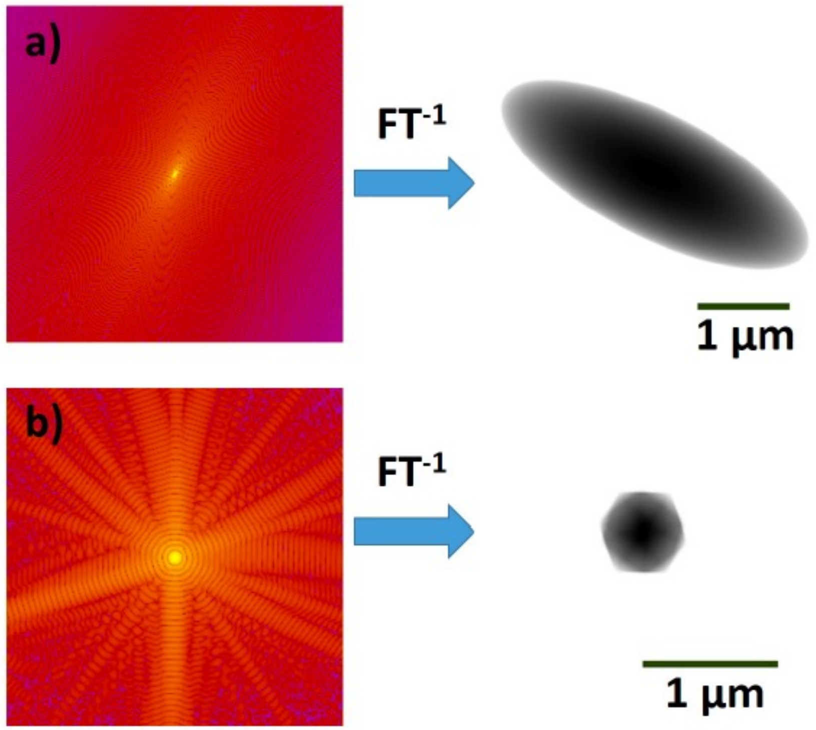


Figure 3. Simulated data for coherent imaging experiments at the EuPRAXIA@SPARC_LAB FEL. (**a**) A simulated diffraction pattern and the reconstruction of the electron density of a 2 µm long spheroid, with a shape similar to that of an elongated bacterium. (**b**) A simulated diffraction pattern from a 600 nm diameter icosahedral virus. Simulations were performed using the software Condor [24] assuming a Gaussian-shaped beam with a diameter of 3 µm, a wavelength of 2.87 nm and a pulse intensity of 100 µJ, which is, according to simulations, the expected pulse energy delivered on the sample by an EuPRAXIA@SPARC_LAB pulse.

Nuclear physics: fusion processes

Deuterium fusion process in plasma

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1. The deuterium gas is kept at a low temperature, close to the critical temperature **where gas and liquid phase coexist**.

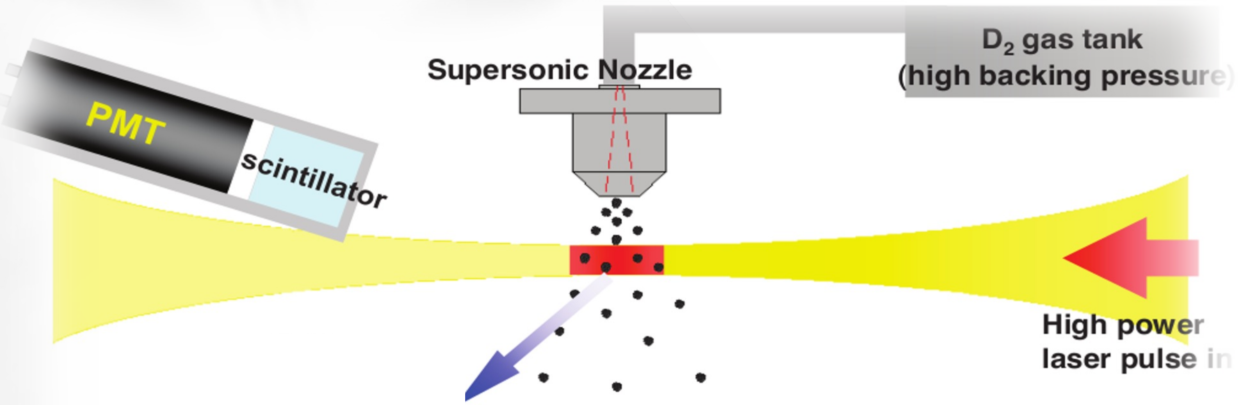
2. The adiabatic expansion through a supersonic nozzle in the reaction chamber induces the clusterization of the D molecules, which are then irradiated by a laser pulse.

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

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



- 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

Nuclear physics: beta decays in plasma

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

Scaling results to stellar environment

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

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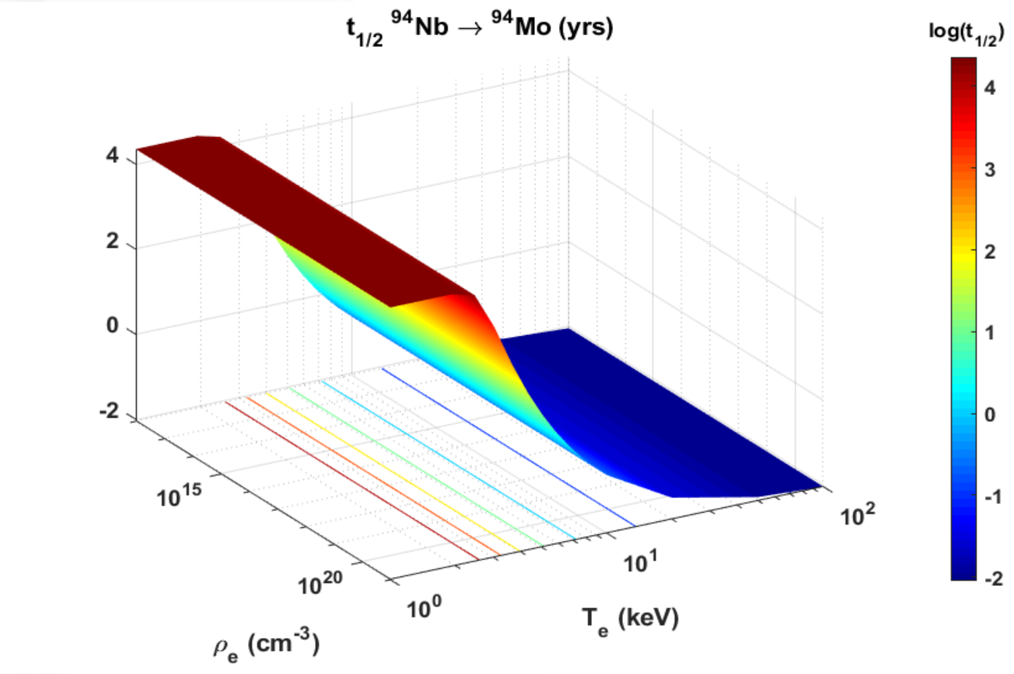
- **Ion temperature: ~ 1 e → Ions are cold: no access to the excited states**

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

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

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



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

How can we populate the 1^- isomeric level?

The intermixing depends on photoactivation rate λ^c of the nucleus through a bath of high energy X-ray photons obeying a Planck distribution in the thermal equilibrium stellar plasma.

Using a laser-plasma as a source of polychromatic high energy X-ray photon flux one could simultaneously investigate isomeric photoactivation as well as in-plasma decay rate modification of ground and isomer levels

The experimental methodology revolves around the measurement of two quantities:

- *photoactivation rate* λ^c (n_e, n_i, T, s)
- *decay rates* λ^d (n_e, n_i, T, s) *from g.s. and isomeric states*

Thermalization between the ground and isomer levels occurs when:

$\lambda^c(n_e, n_i, T, s) >= \lambda_m^d (n_e, n_i, T, s)$
(*onset of equilibrium between the levels*)

See poster by B. Mishra

***The laser-plasma can be expected to produce X-ray spectra similar to the stellar interior, which can answer the question of equilibration more accurately than previous experiments on this topic*!**

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Why to use laser-induced plasma

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

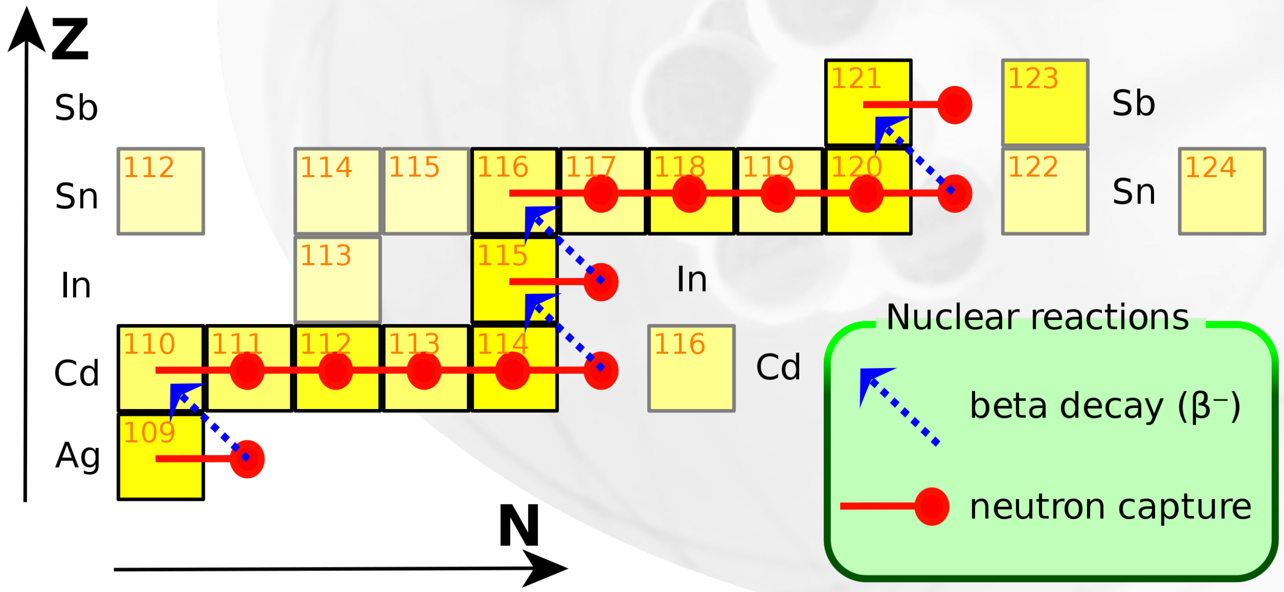
Simulations by B. Mishra et al.

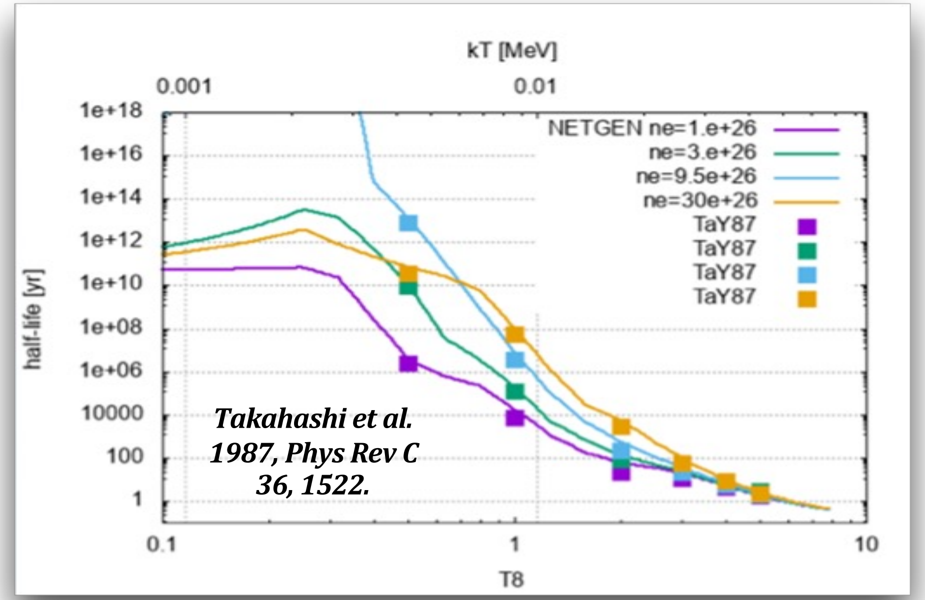
Exploring the onset of a (Full) Local Thermal Equilibrium:

- 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.**

Why plasma: β-decays

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*.





https://doi-org.ezproxy.cern.ch/10.1103/PhysRevC.36.1522

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

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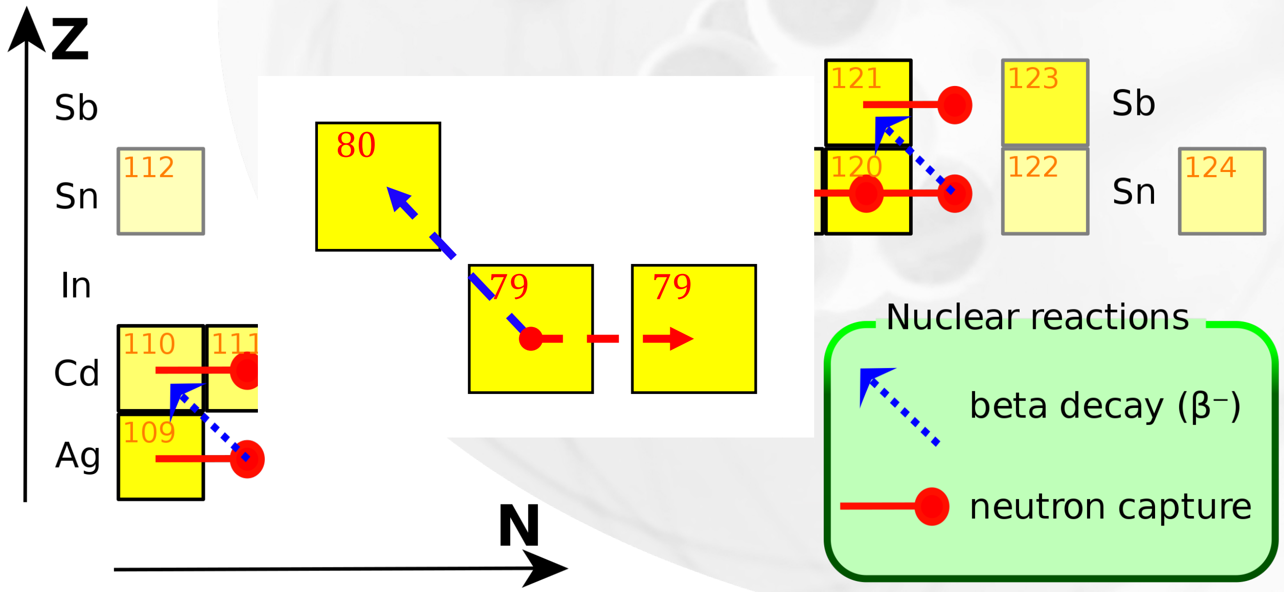

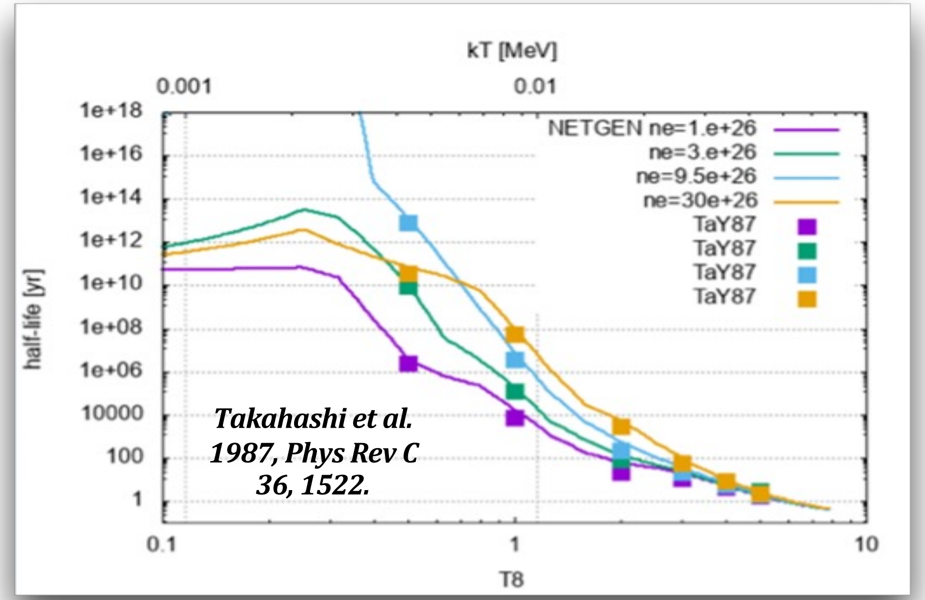

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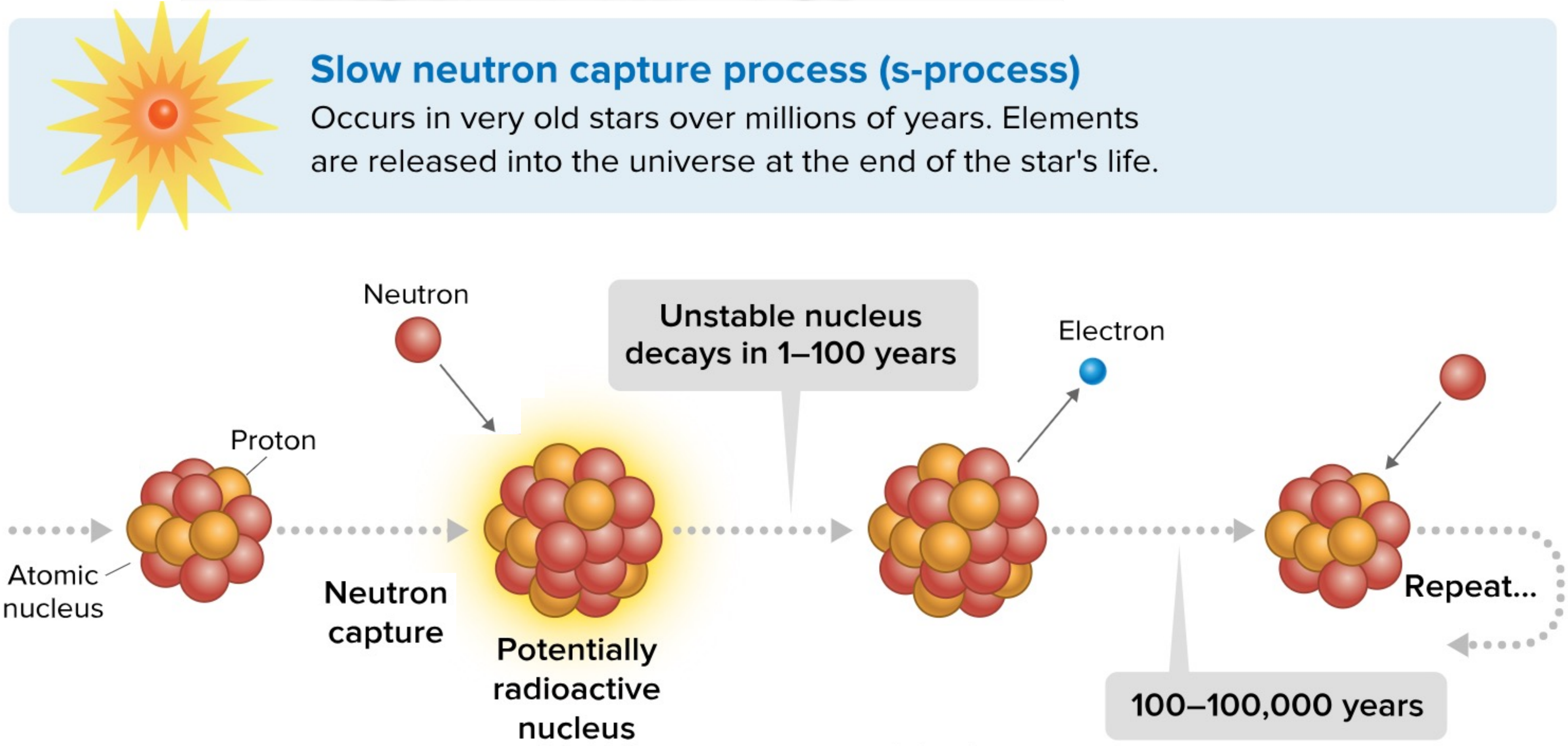
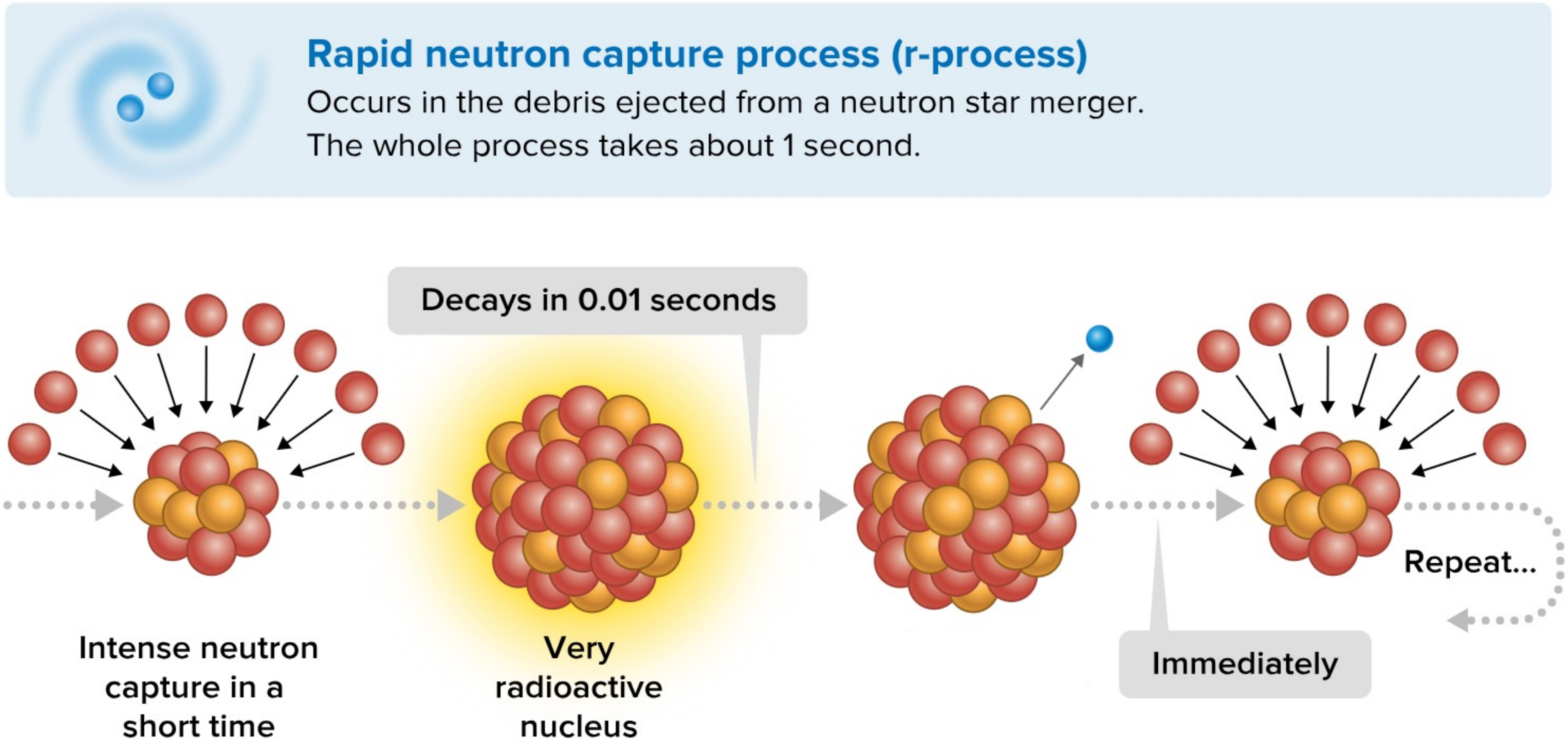
Original predictions of modifications in β-decay rates in plasma by Takahashi and Yokoi

Fusion processes: heavy elements



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

Fusion processes: heavy elements



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

s-process endpoint

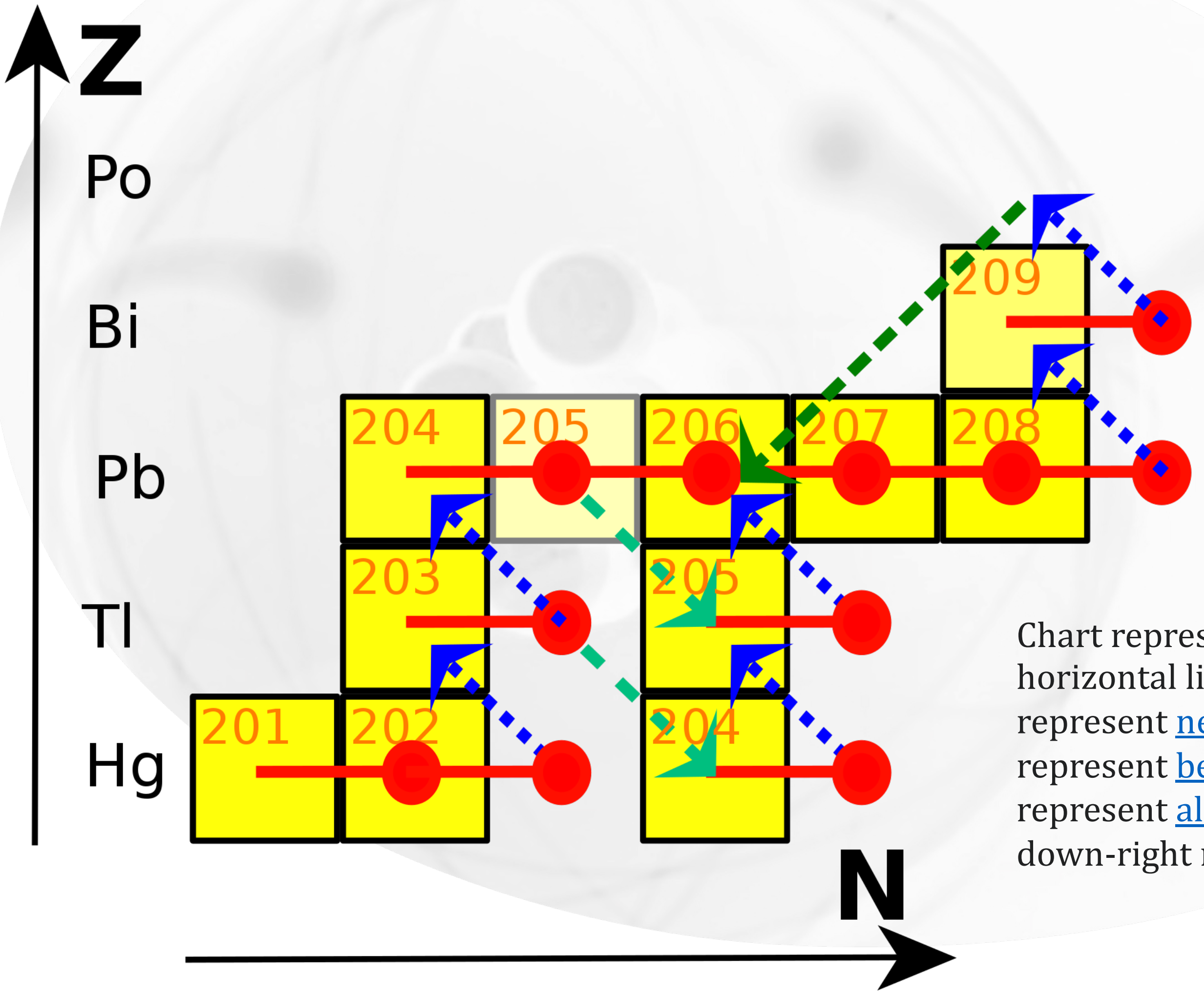
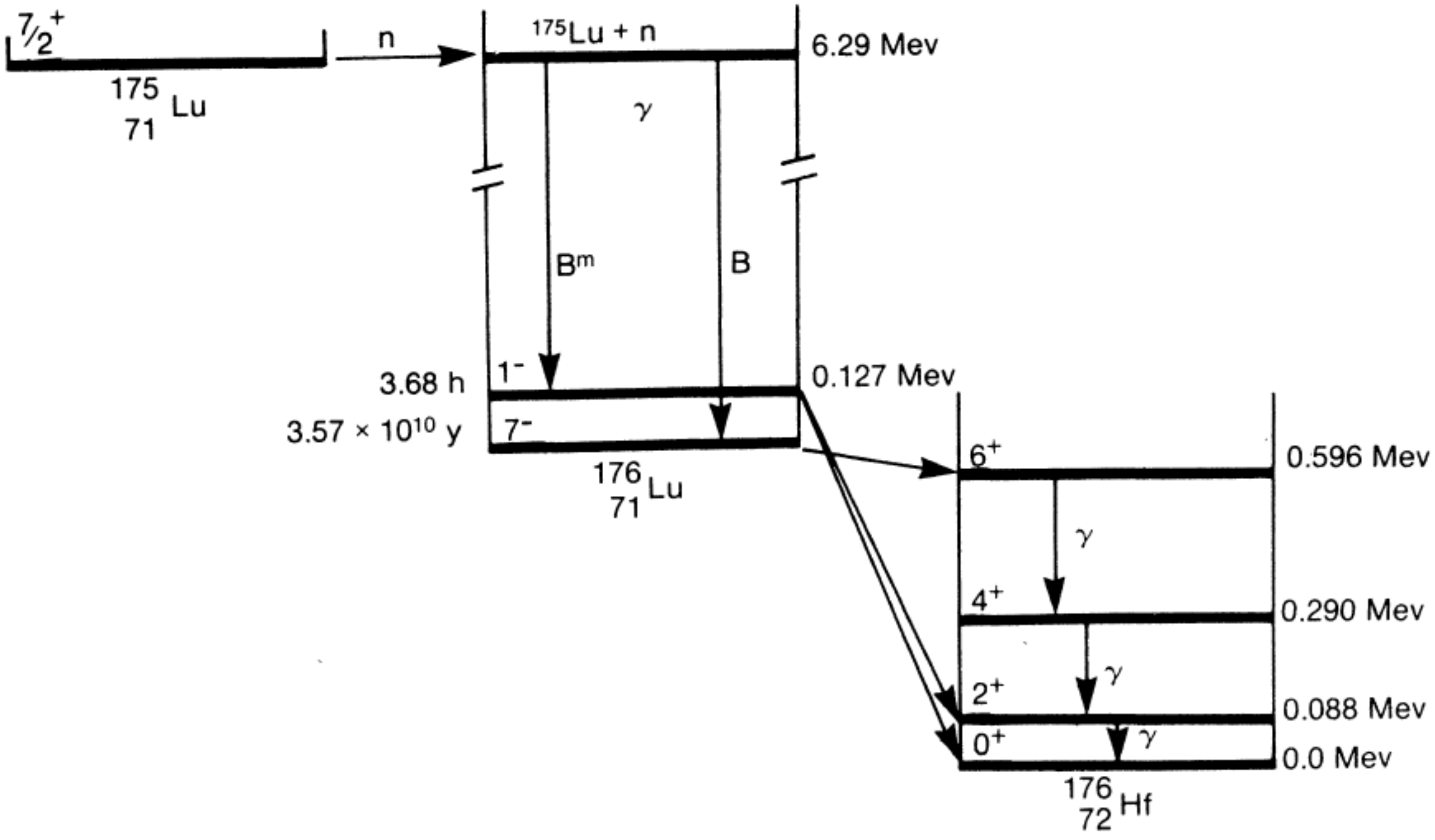


Chart representing the final part of the *s*-process. Red horizontal lines with a circle in their right ends represent neutron captures; blue arrows pointing up-left represent beta decays; green arrows pointing down-left represent alpha decays; cyan/light-green arrows pointing down-right represent electron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

Decay scheme for lutetium



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Big-Bang Nucleosynthesis

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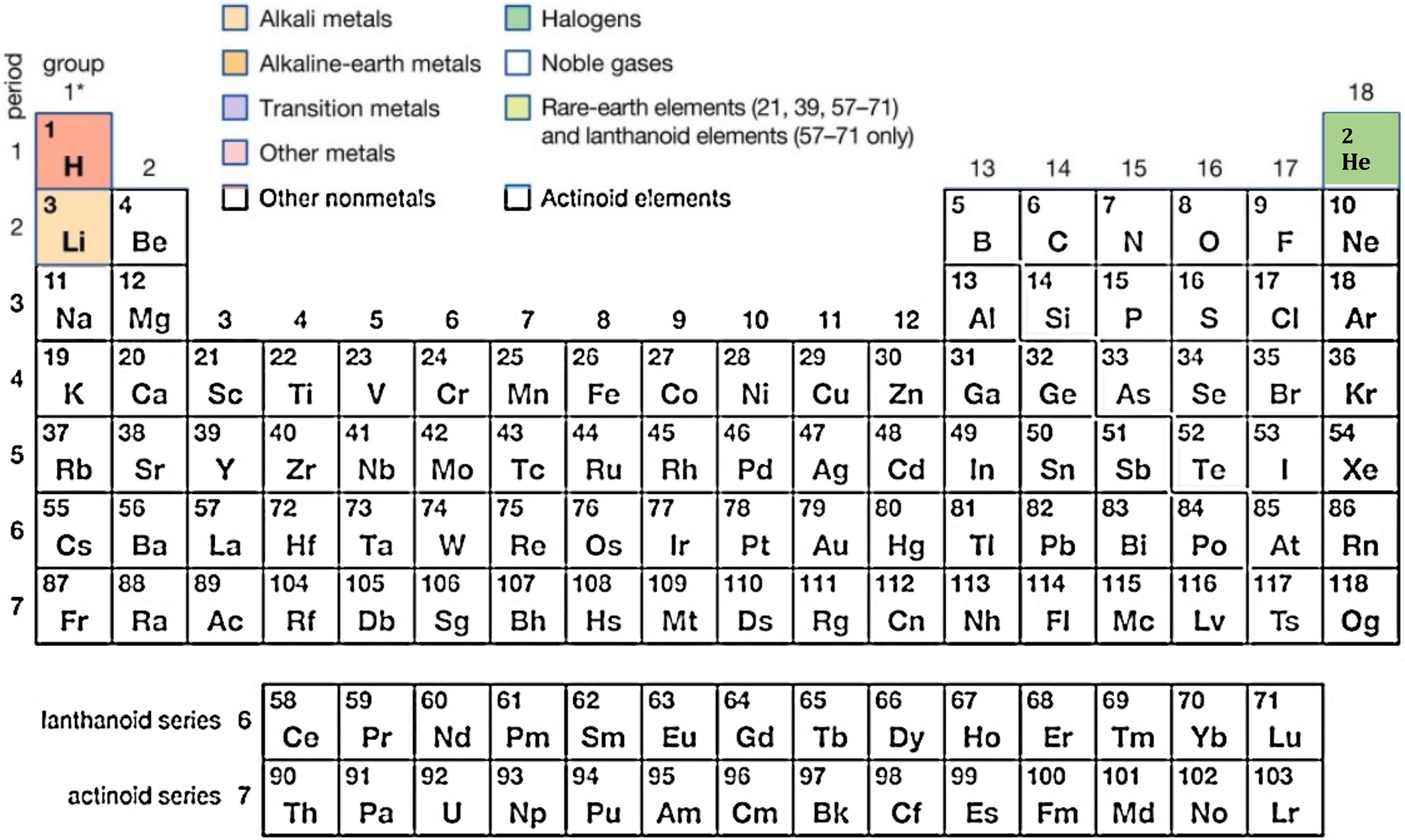

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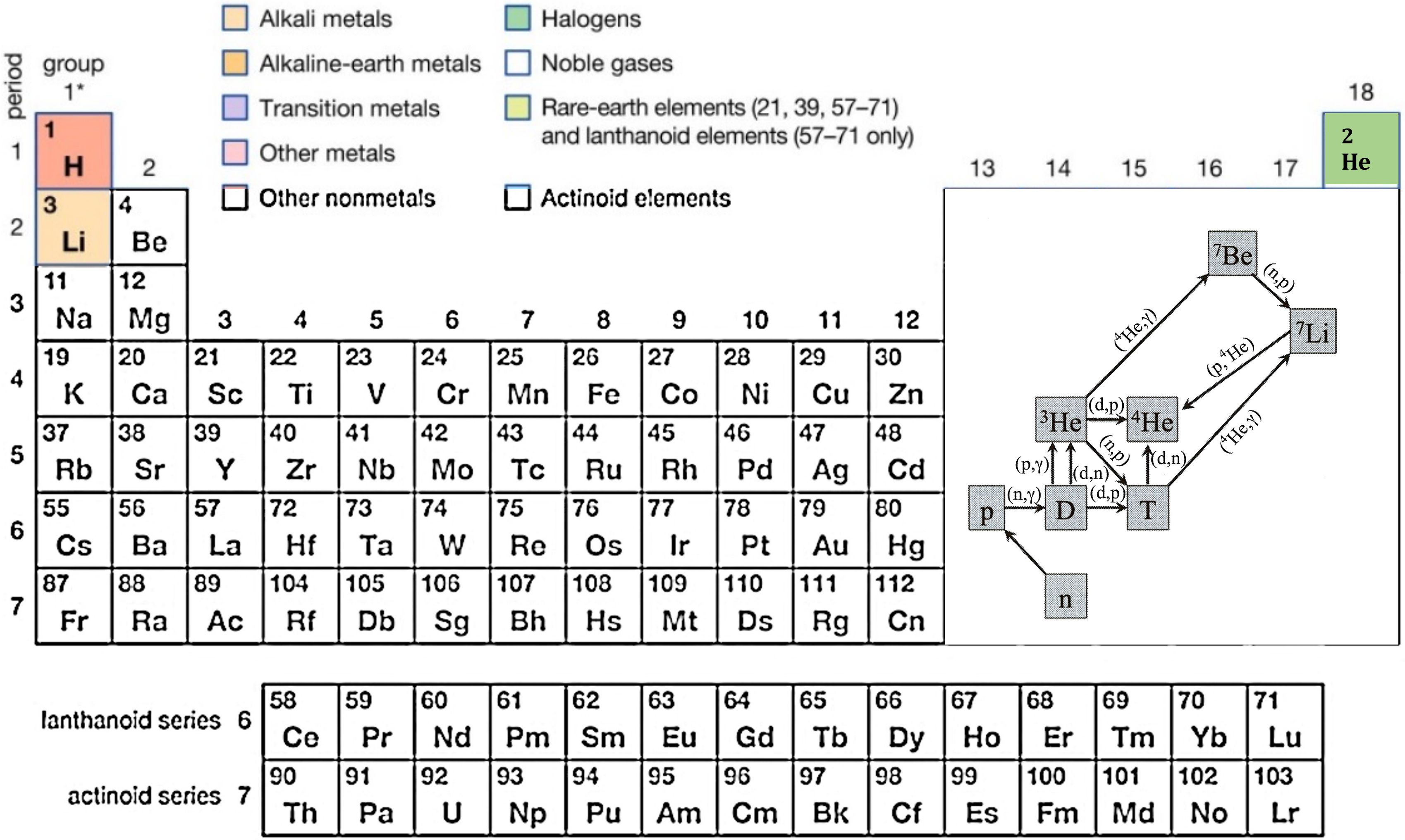

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Stellar Nucleosynthesis

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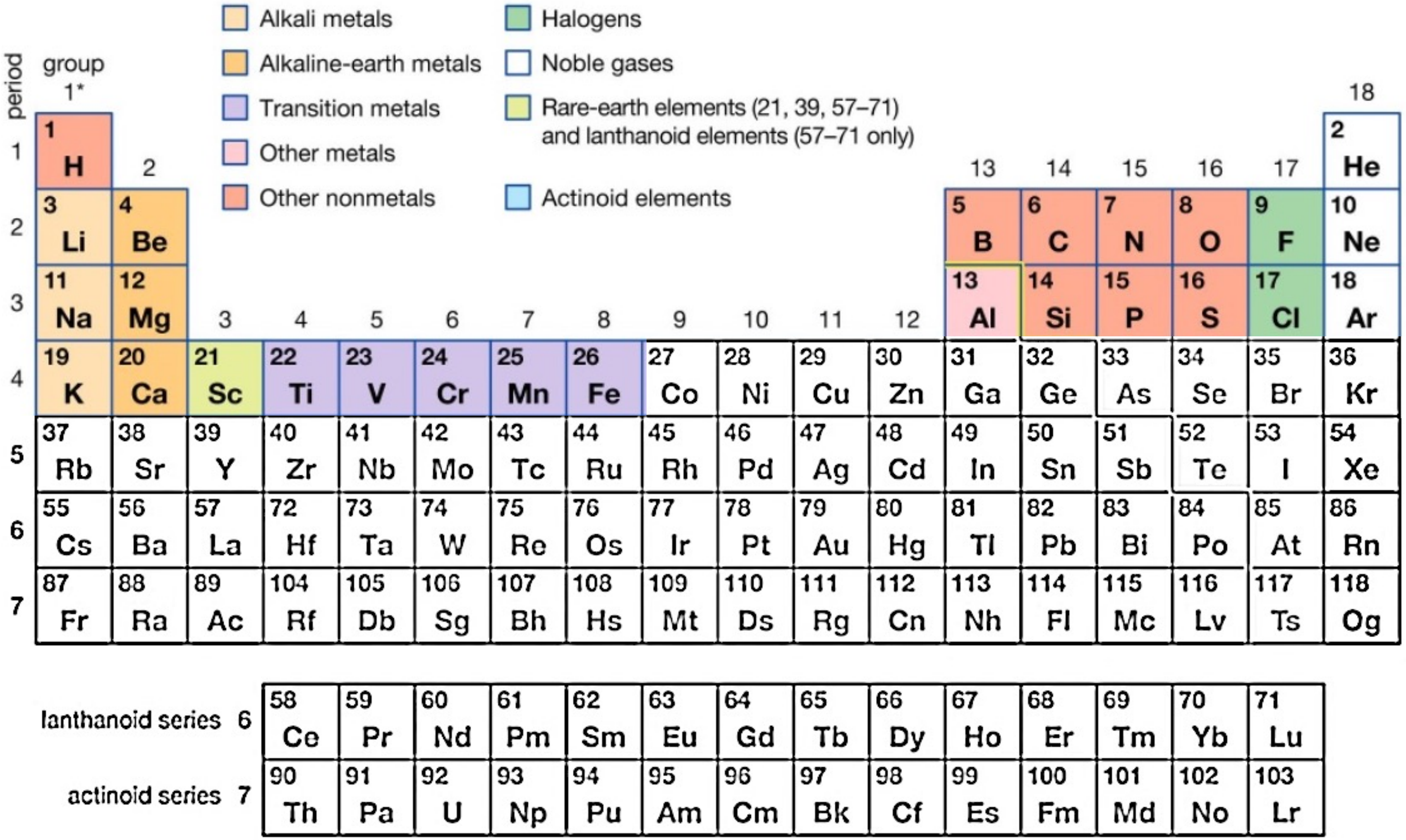

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Stellar Nucleosynthesis

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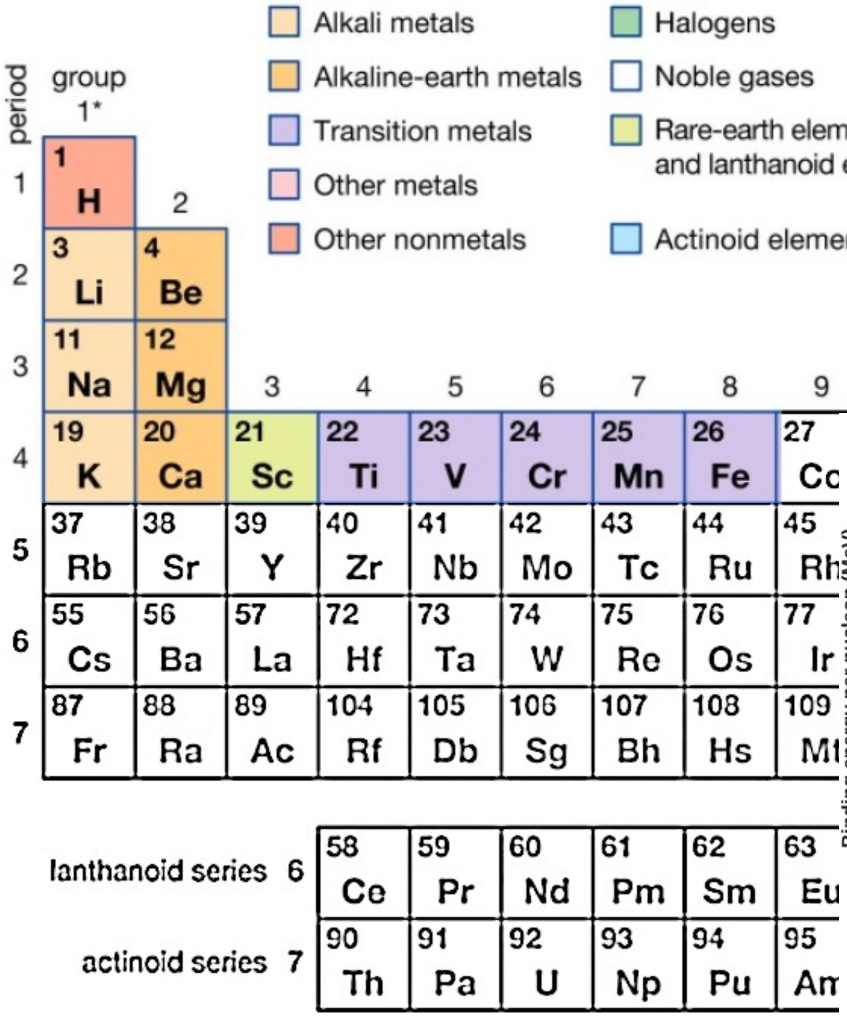
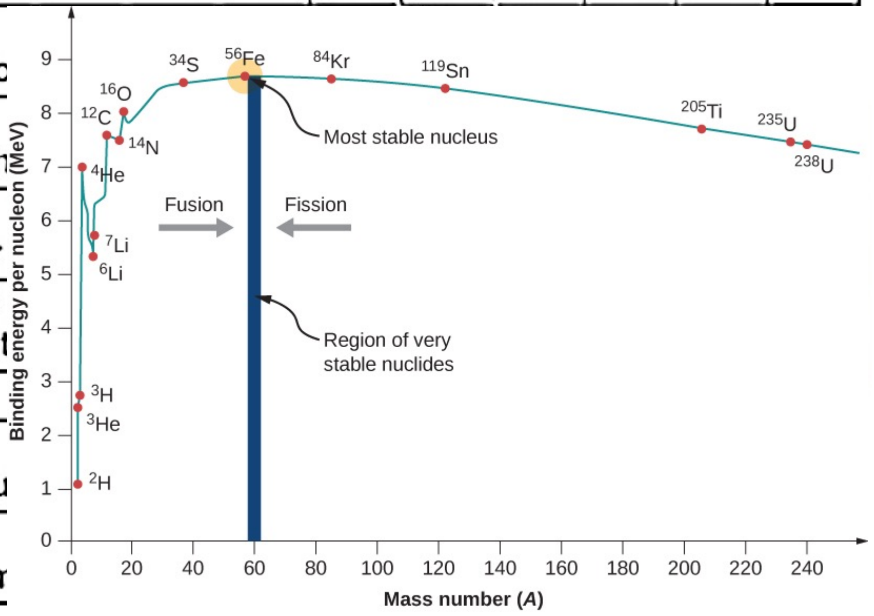
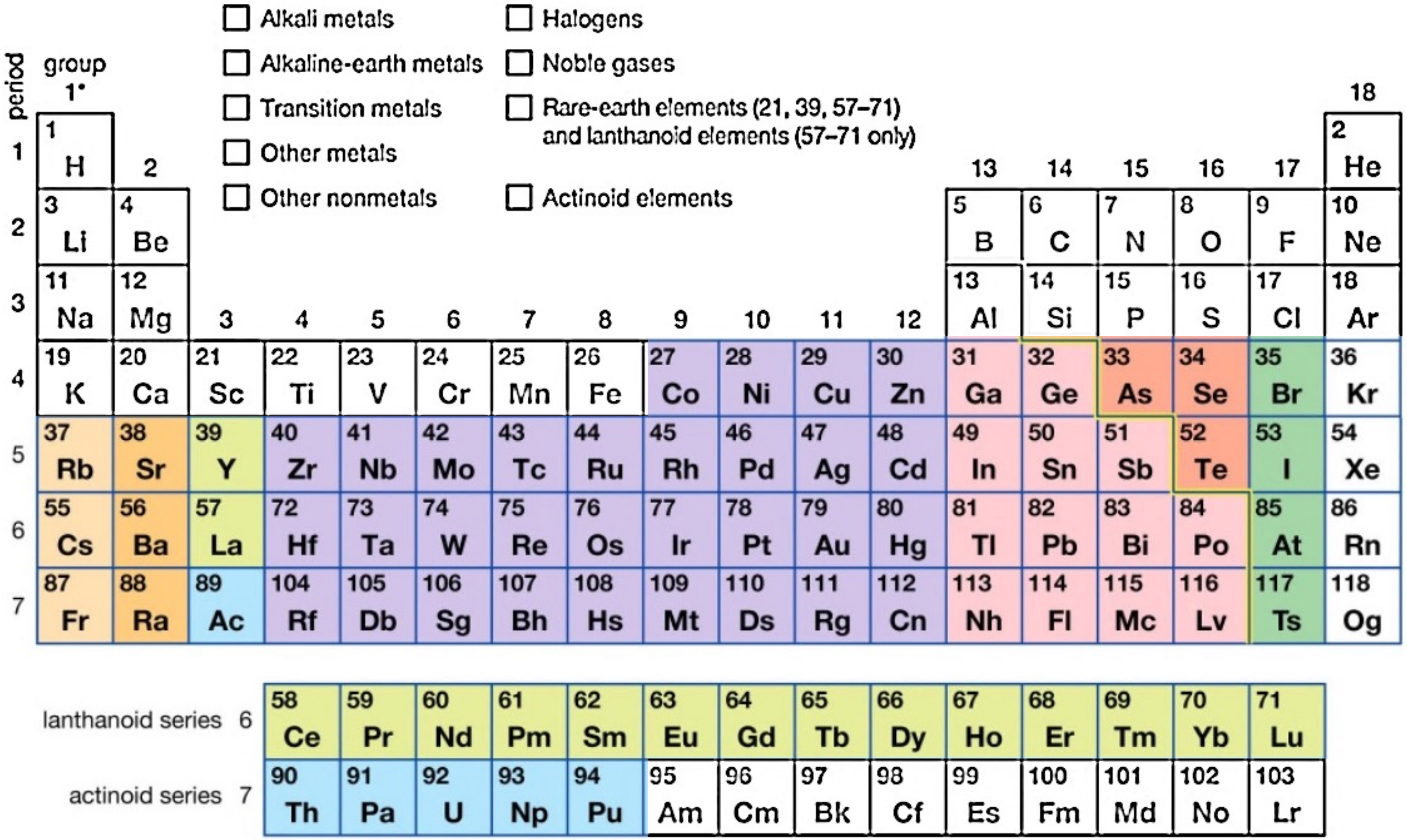




S- and *r-*process Nucleosynthesis



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^{176}Lu physics case

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Cosmo-chronometer or stellar thermometer?

^{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].

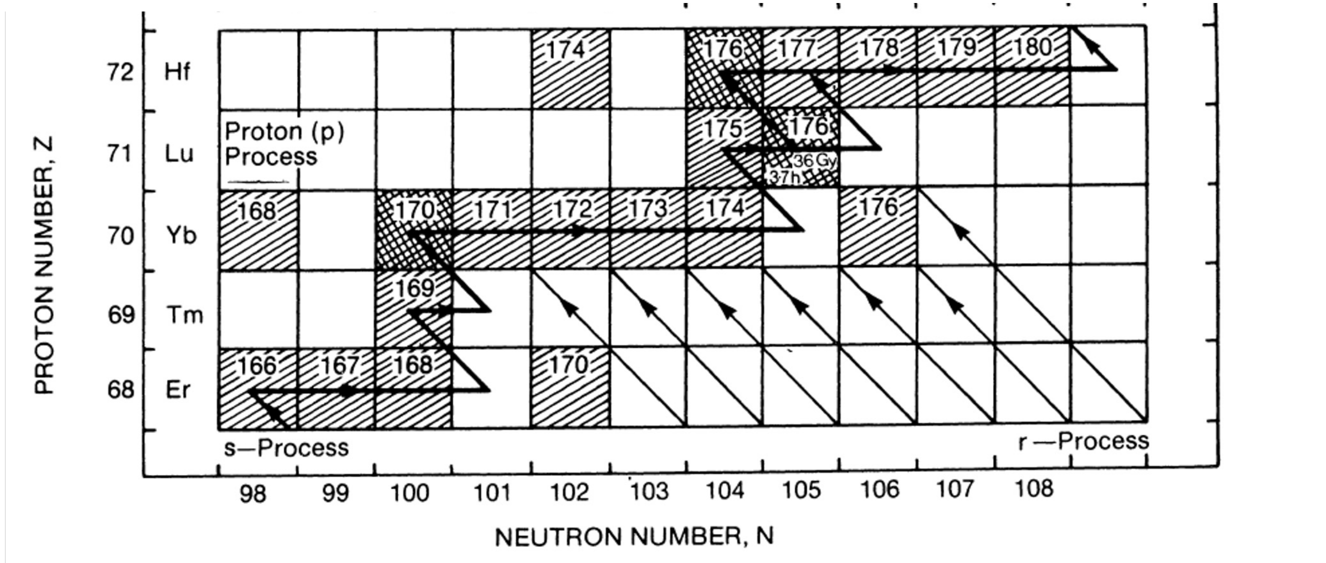
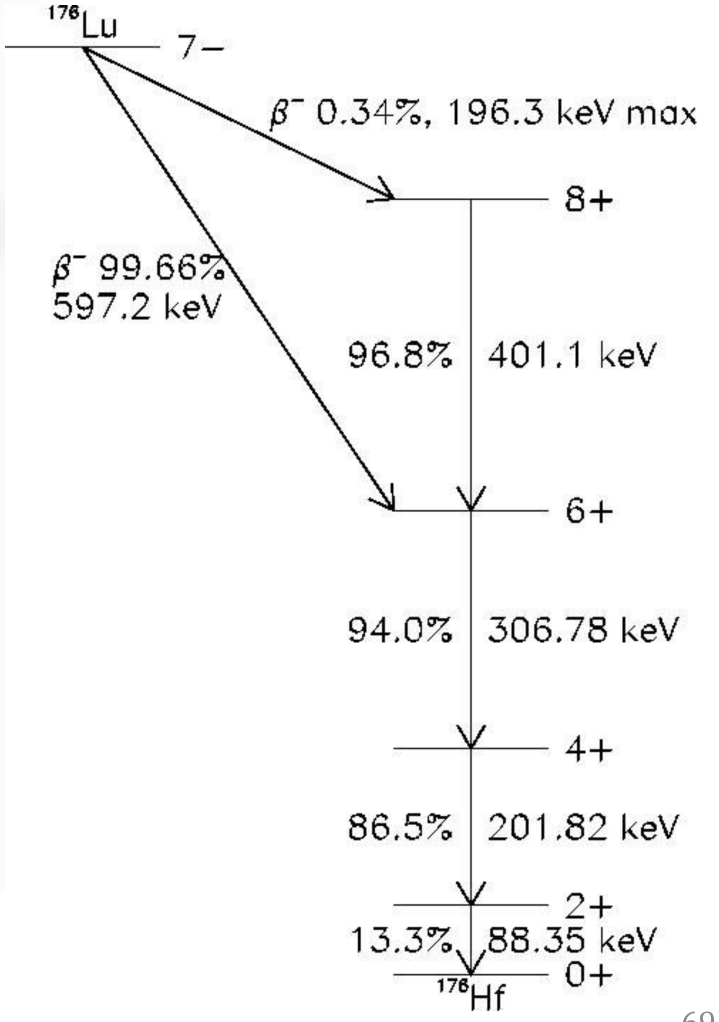


Figure 1. *s*-process path in the rare earth element mass region. *s*-only process nuclides ^{170}Yb, ^{176}Lu and ^{176}Hf are shielded from *r*-process contributions by ^{170}Er and ^{176}Yb respectively. The *s*-process branches at ^{176}Lu if a significant population of the 3.68 h isomeric state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



^{176}Lu physics case

Cosmo-chronometer or stellar thermometer?

^{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].

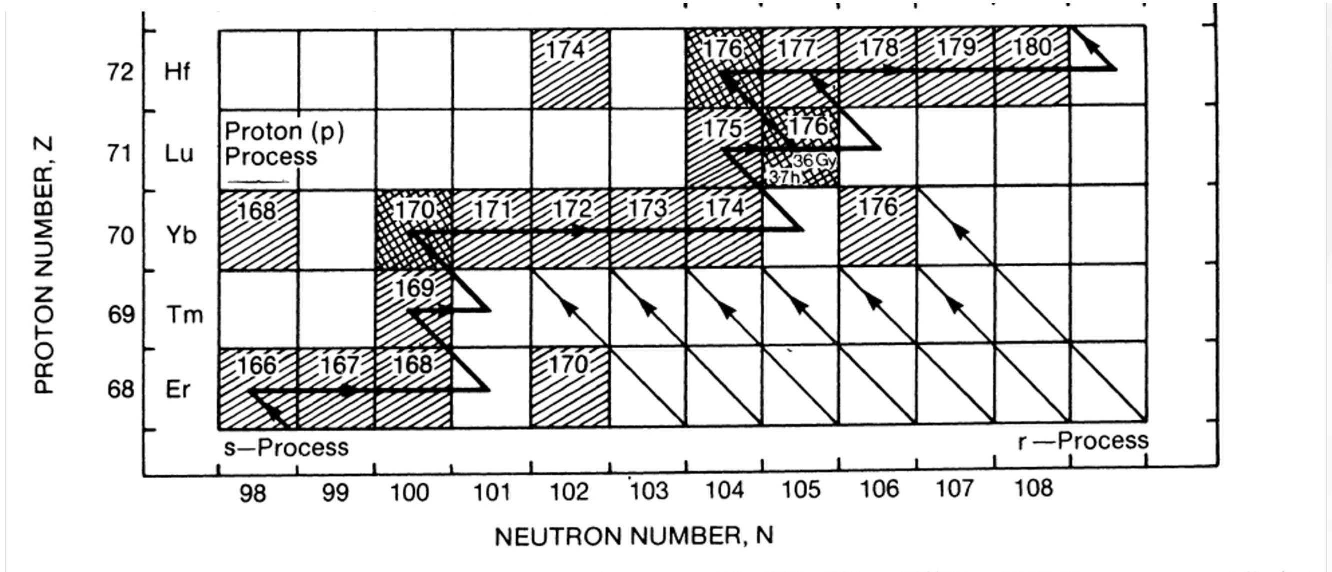
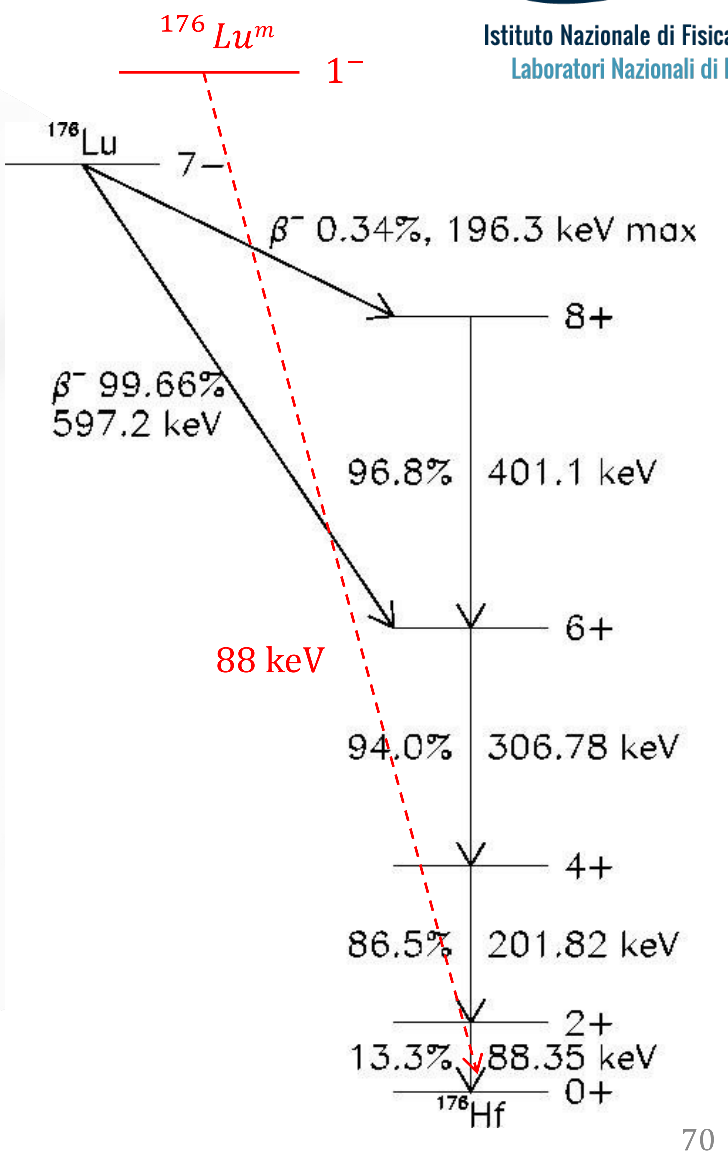


Figure 1. *s*-process path in the rare earth element mass region. *s*-only process nuclides ^{170}Yb, ^{176}Lu and ^{176}Hf are shielded from *r*-process contributions by ^{170}Er and ^{176}Yb respectively. The *s*-process branches at ^{176}Lu if a significant population of the 3.68 h isomeric state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



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PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

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

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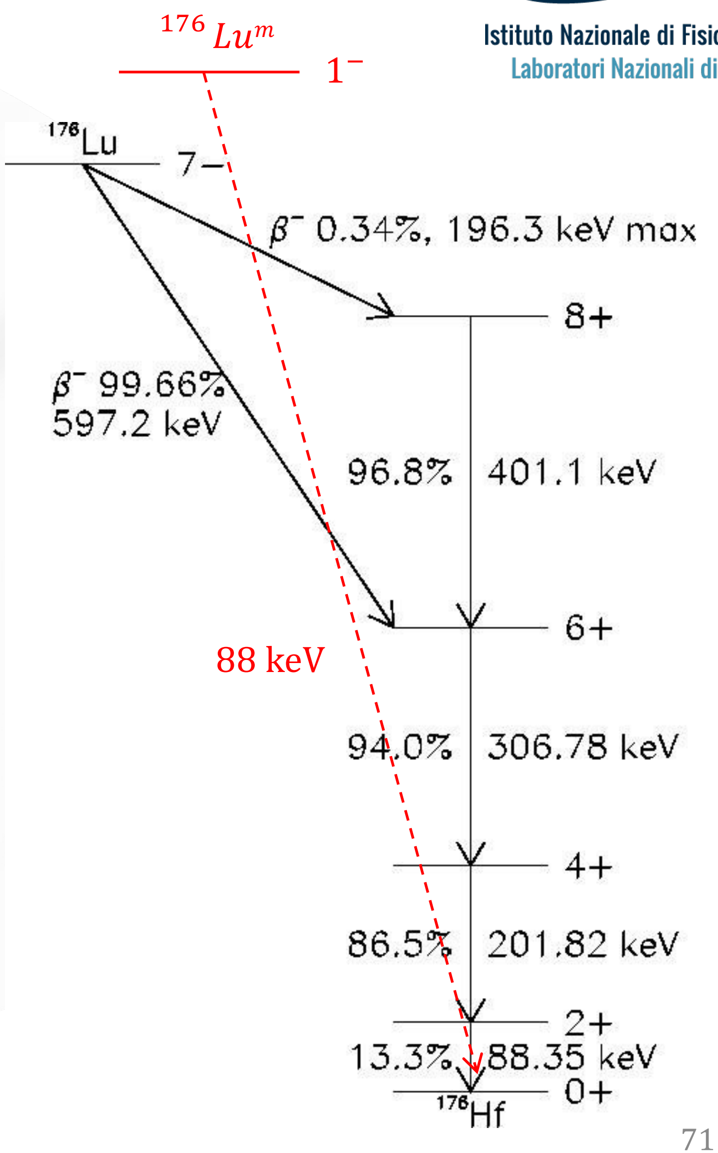
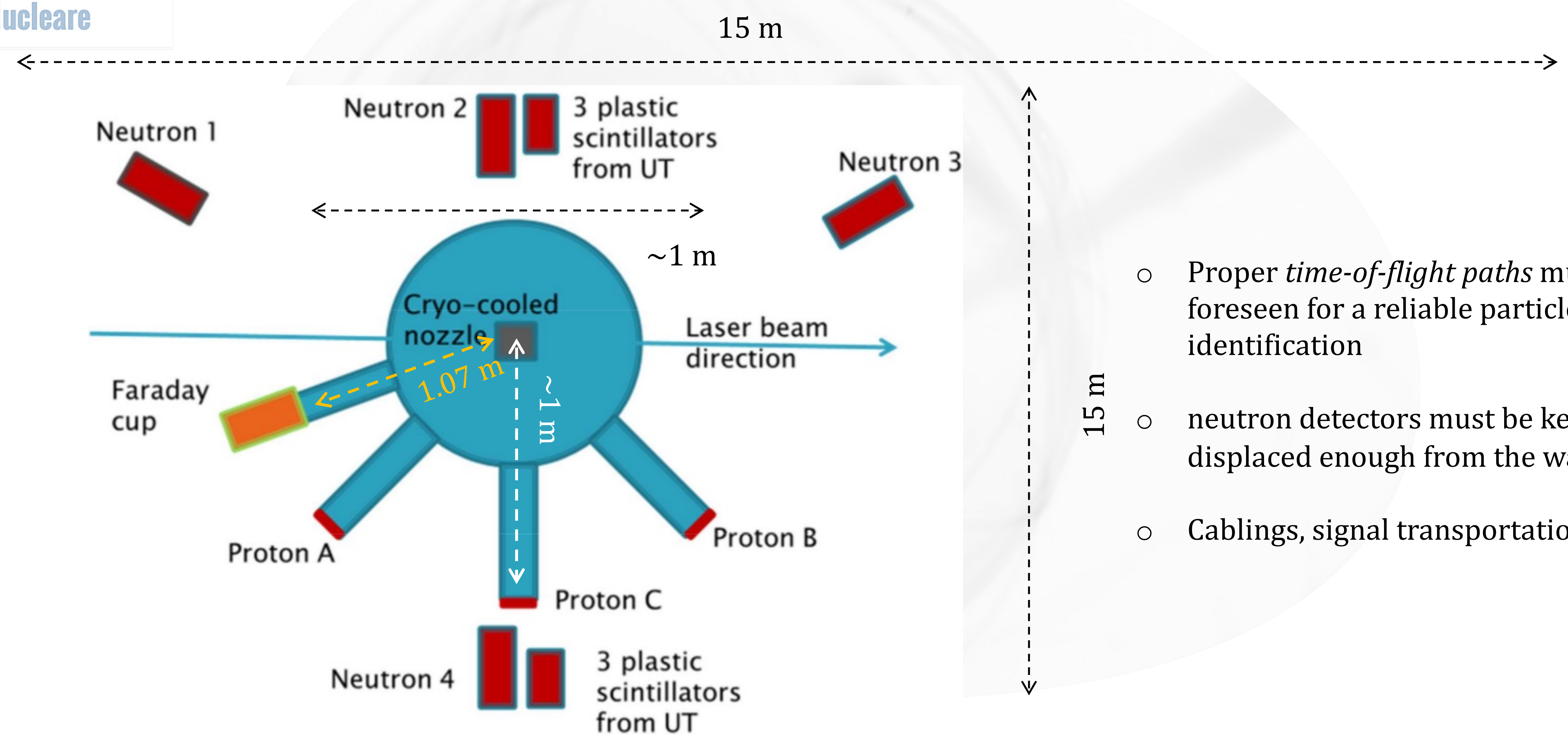
Nuclear Science Division, Lawrence Berkeley Laboratory, 1 Cyclotron Road, Berkeley, California 94720 and Center for Particle Astrophysics, University of California, Berkeley, California 94720

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.



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

Measurement strategy

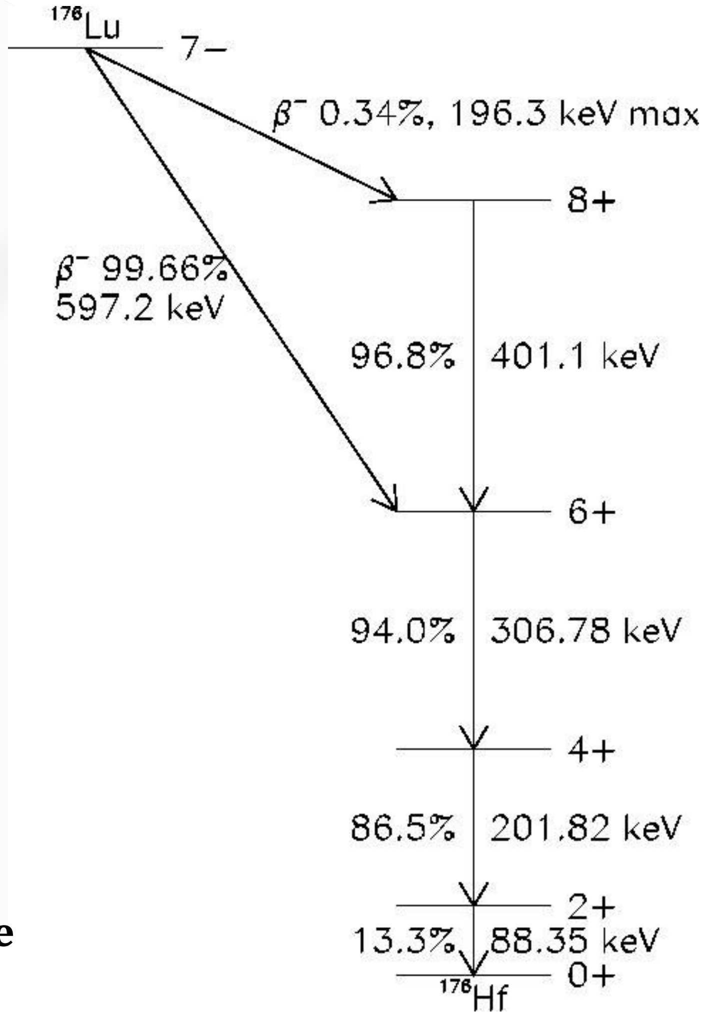
1. Once the solid ^{176}Lu target is hit by a laser pulse with an intensity as high as $10^{21}\ W/cm^2$, the ionization and the subsequent ion emission takes place

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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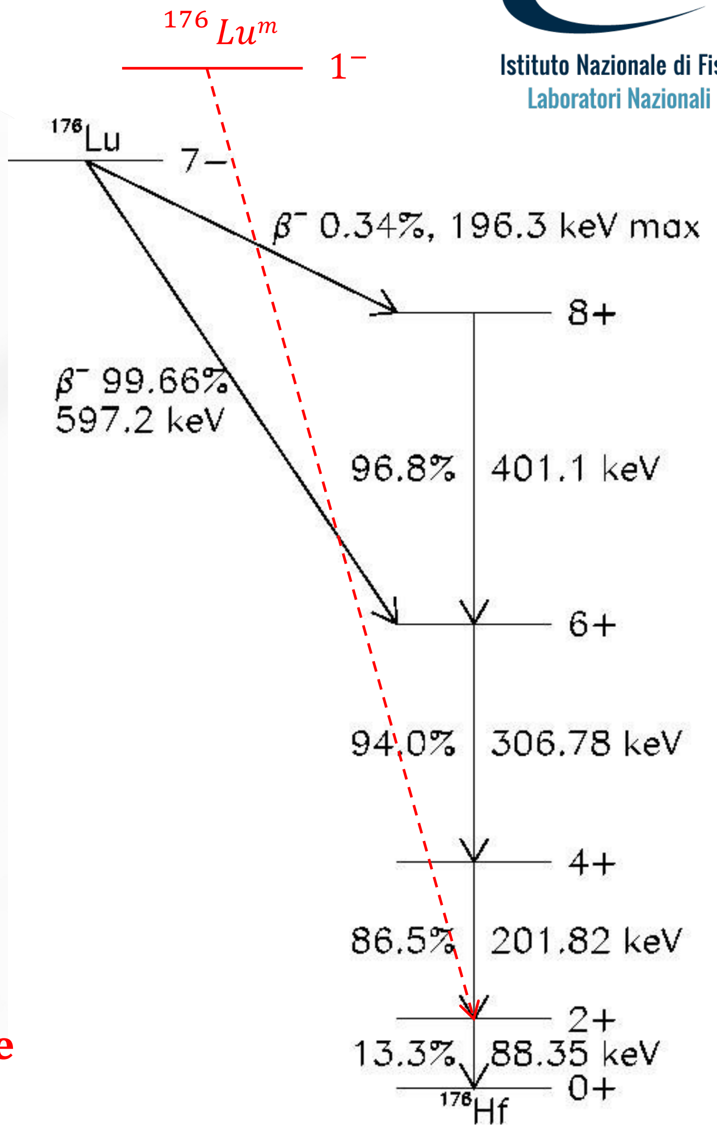

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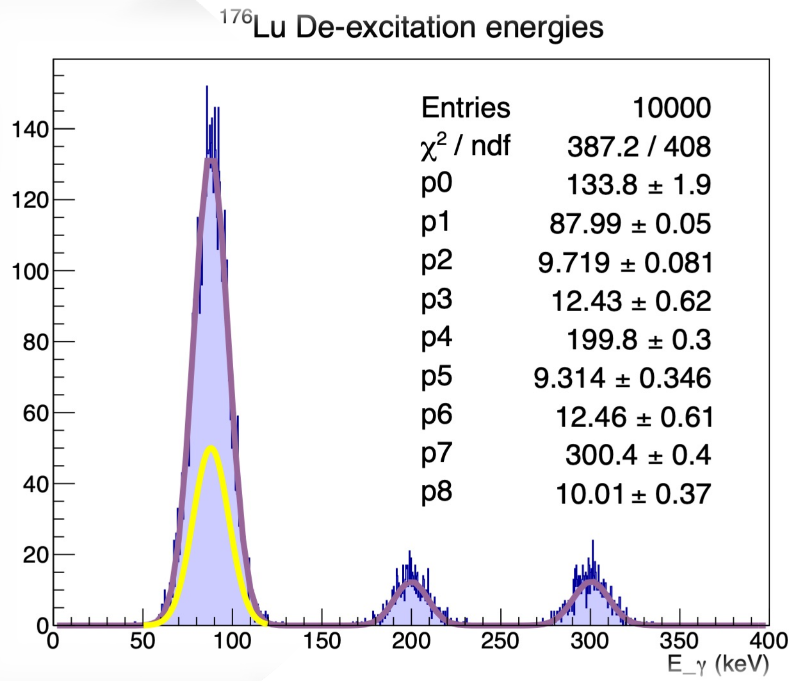
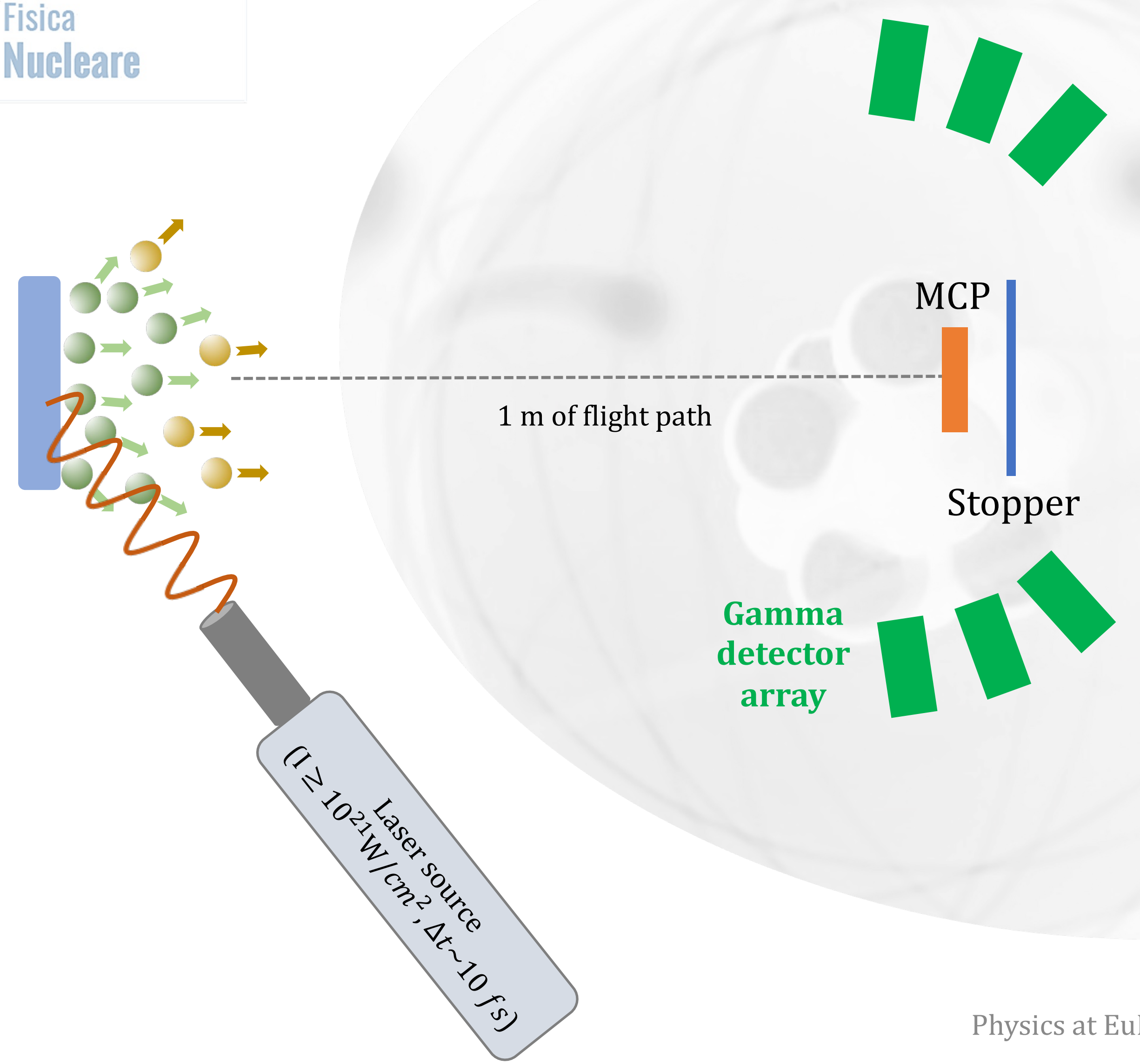
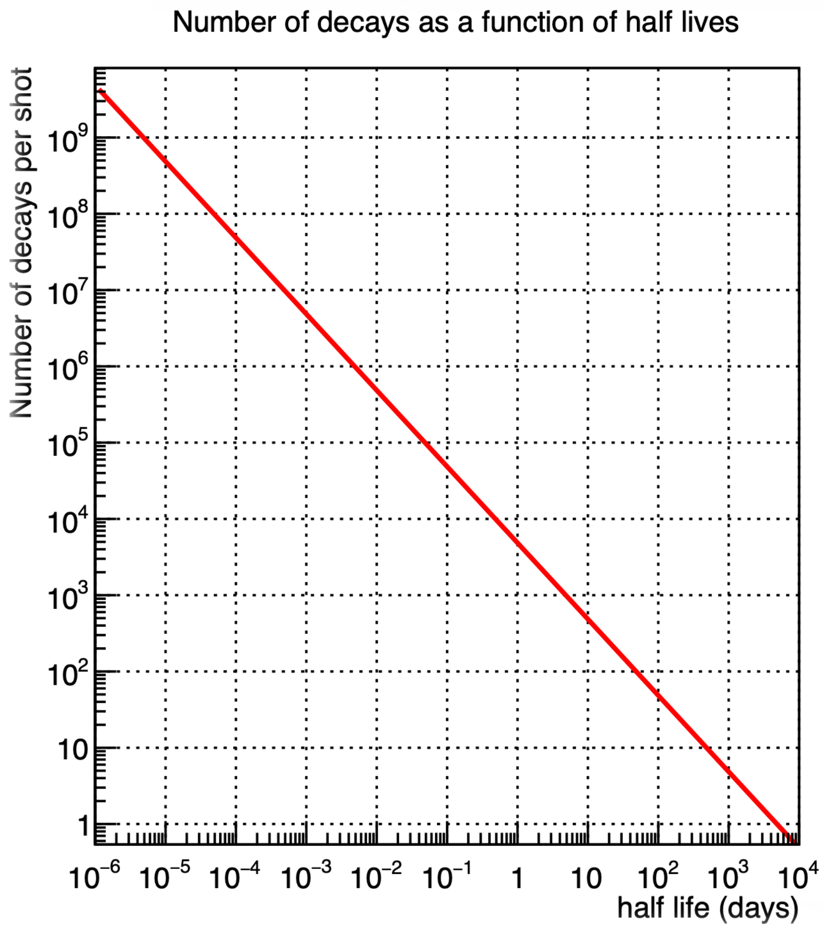


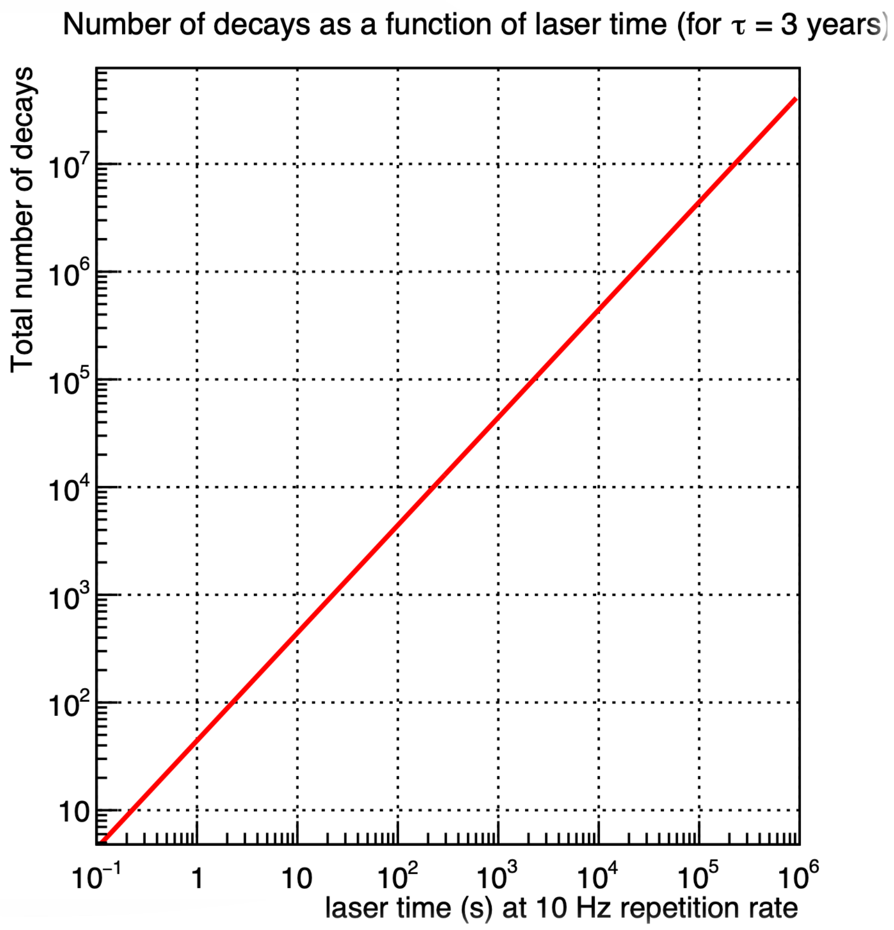
Possible experimental setup for β-decay



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





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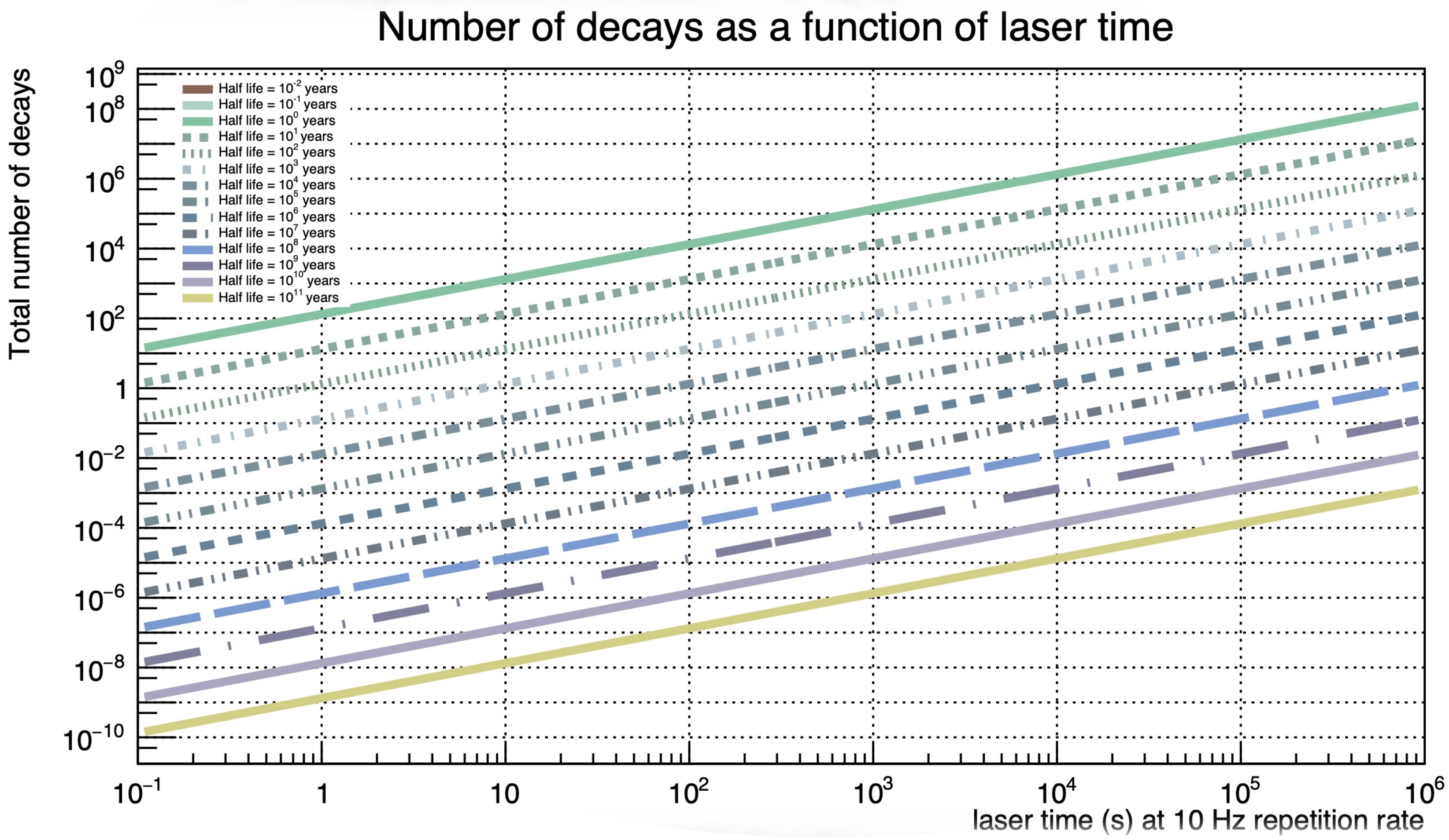

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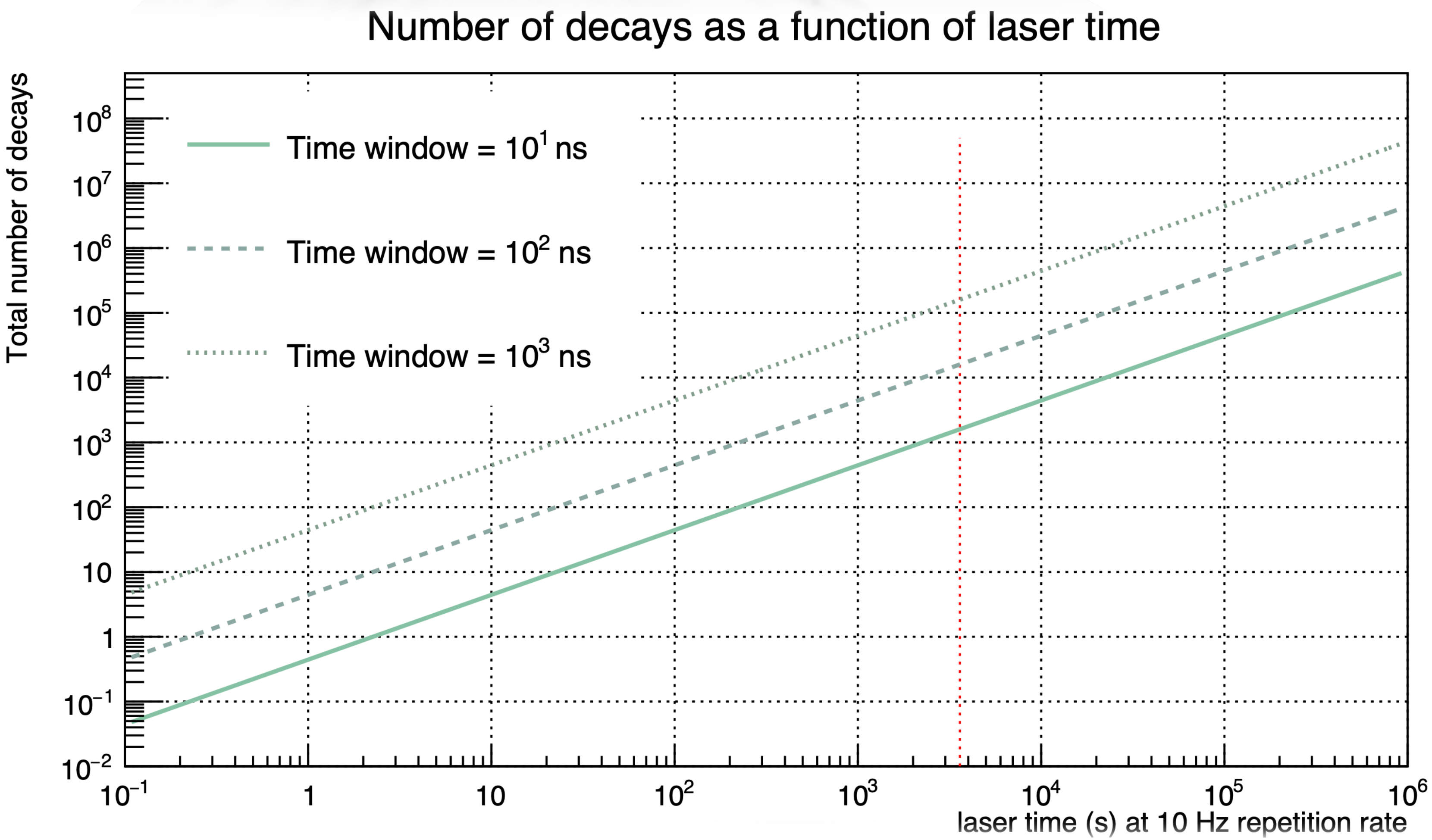

Nuclear physics: general information

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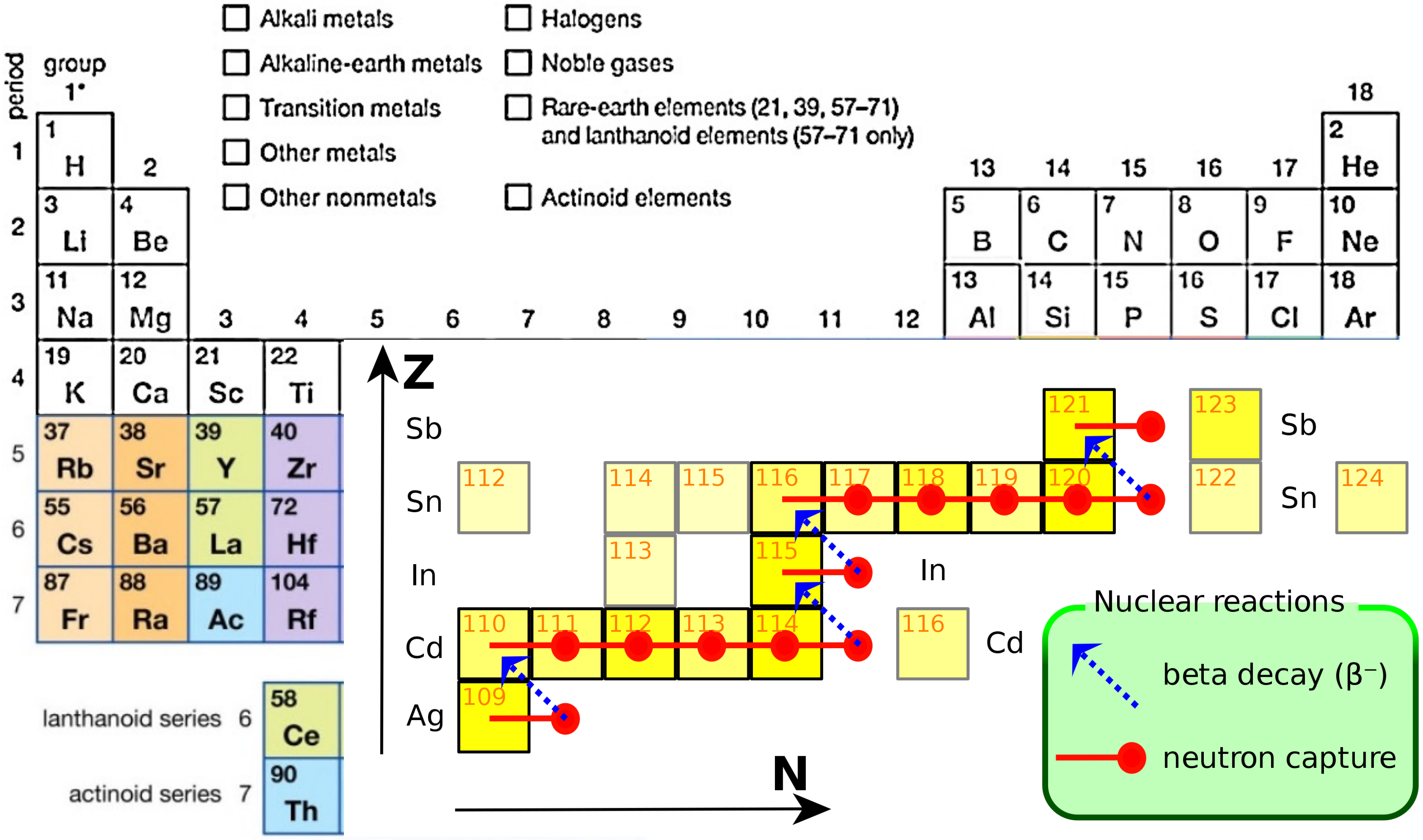
S- and *r*-process Nucleosynthesis



Solar system abundances

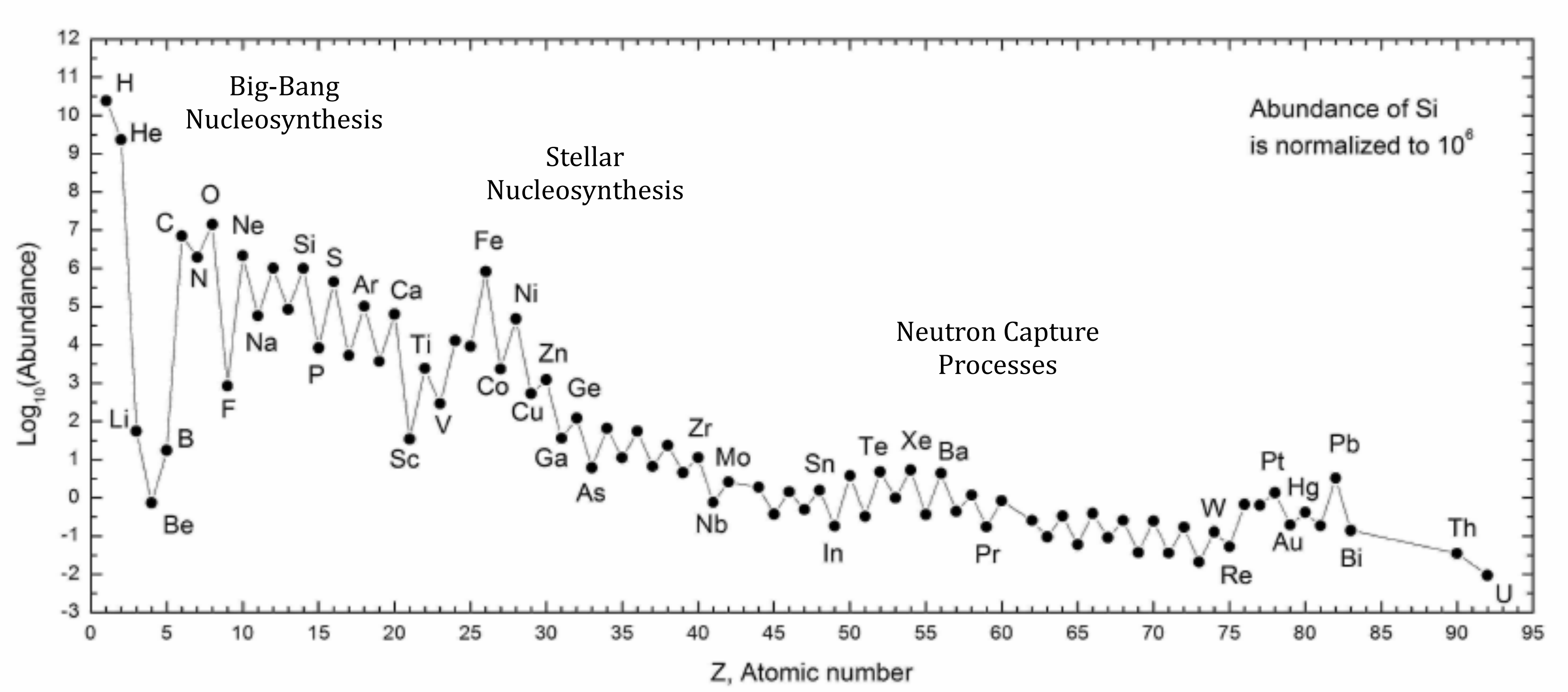
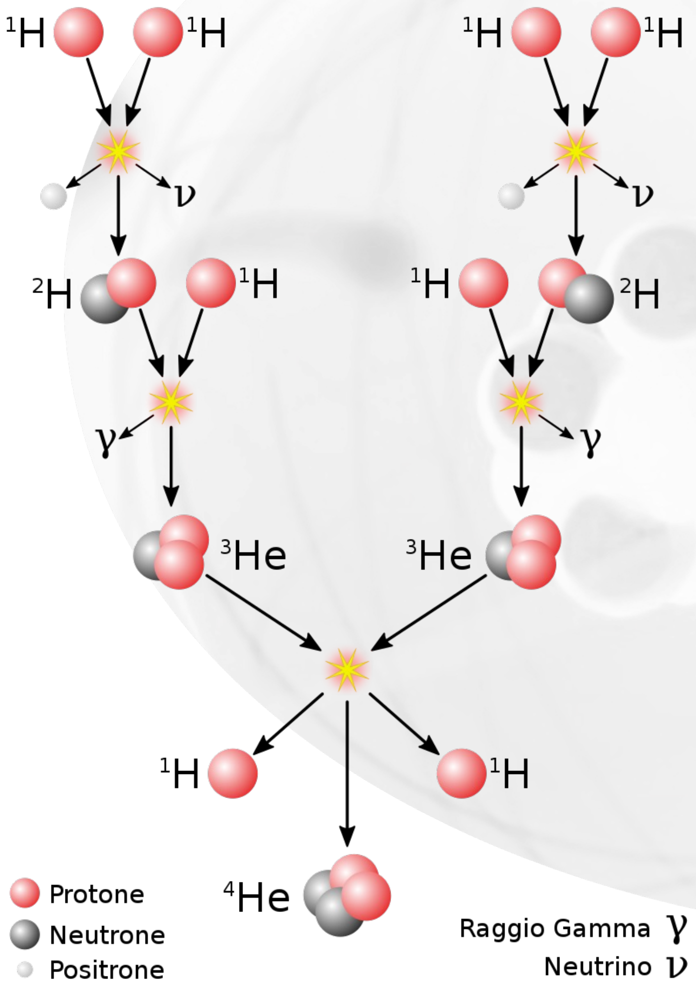
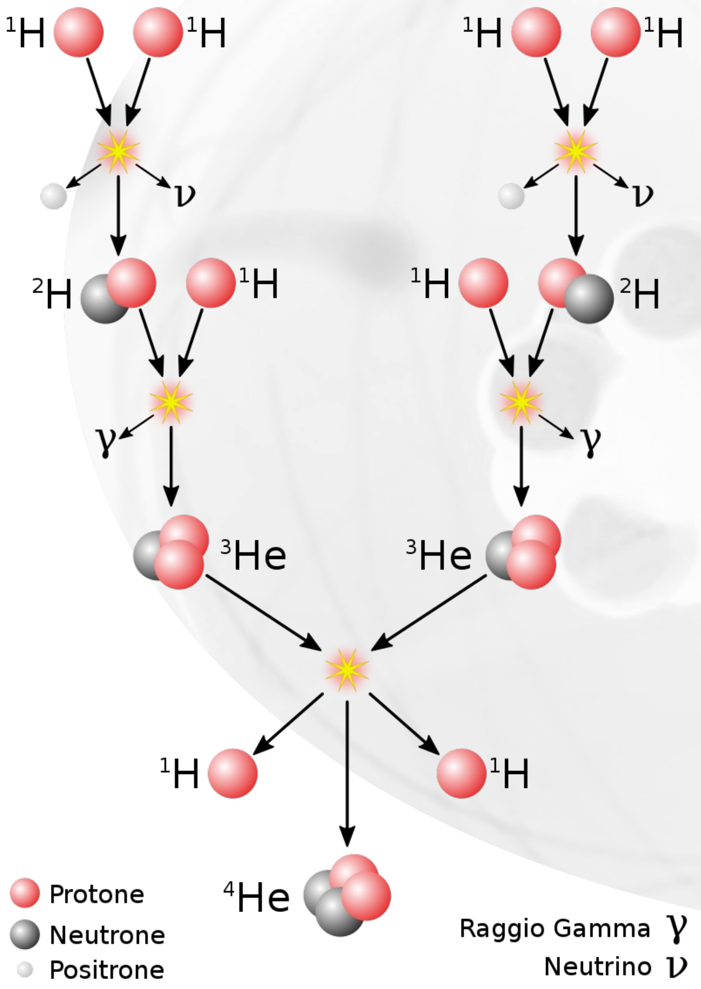


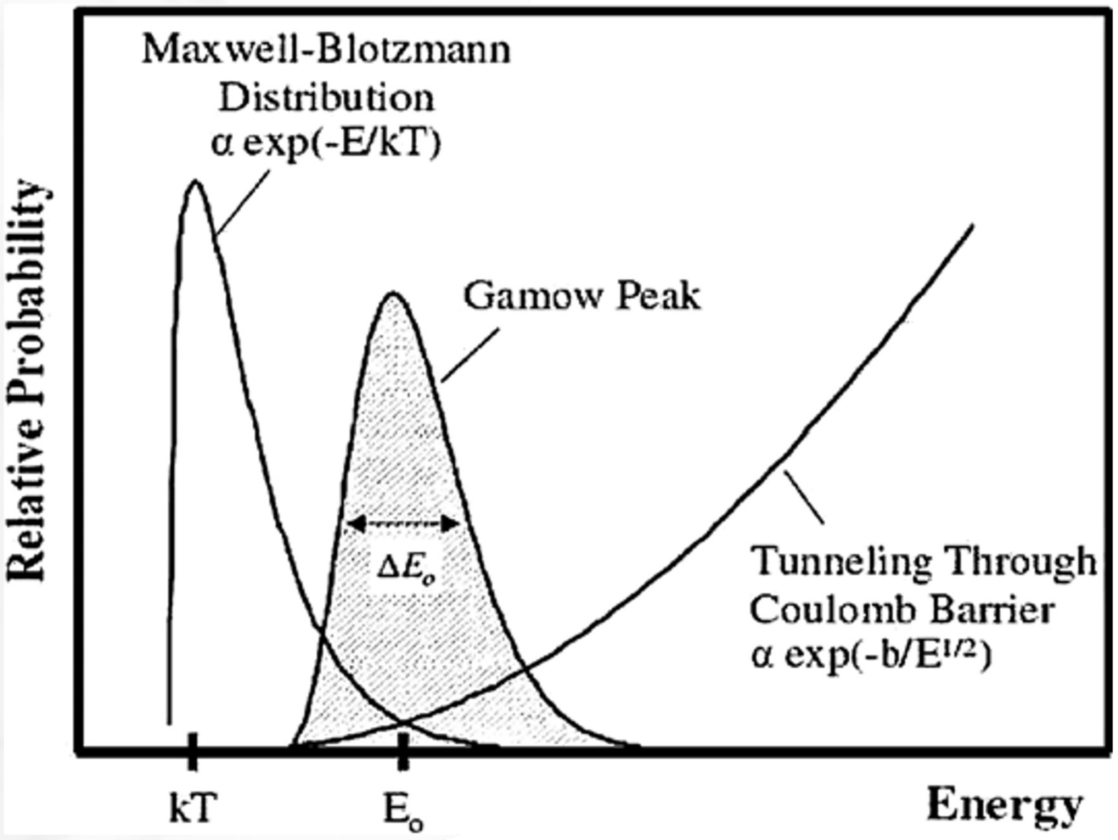
Figure 1.1: Solar abundance distribution normalised to Silicon at 10^6, adapted from Lodders 2003. The peaks in the distribution show the signatures of the different processes. The first peak around helium results from the primordial nucleosynthesis. The second peak around iron originates from nuclear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

Fusion processes: light elements

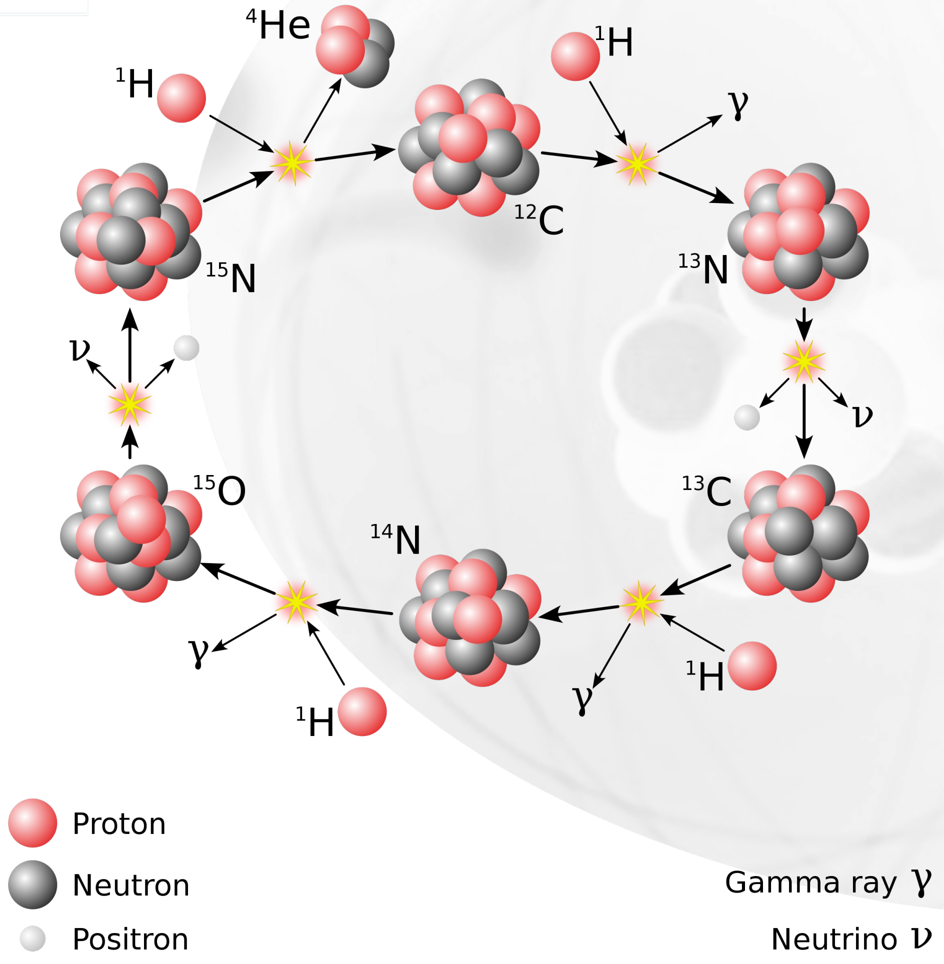


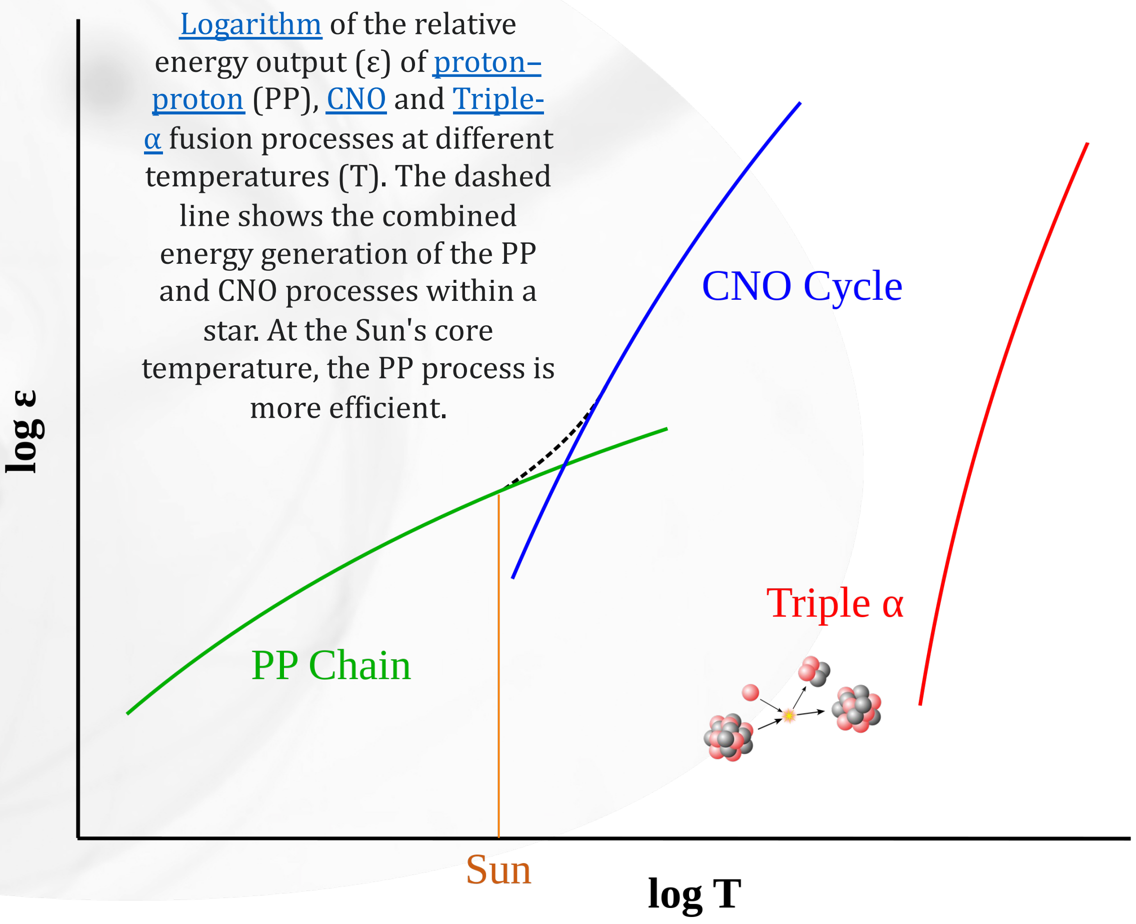
Fusion processes: light elements



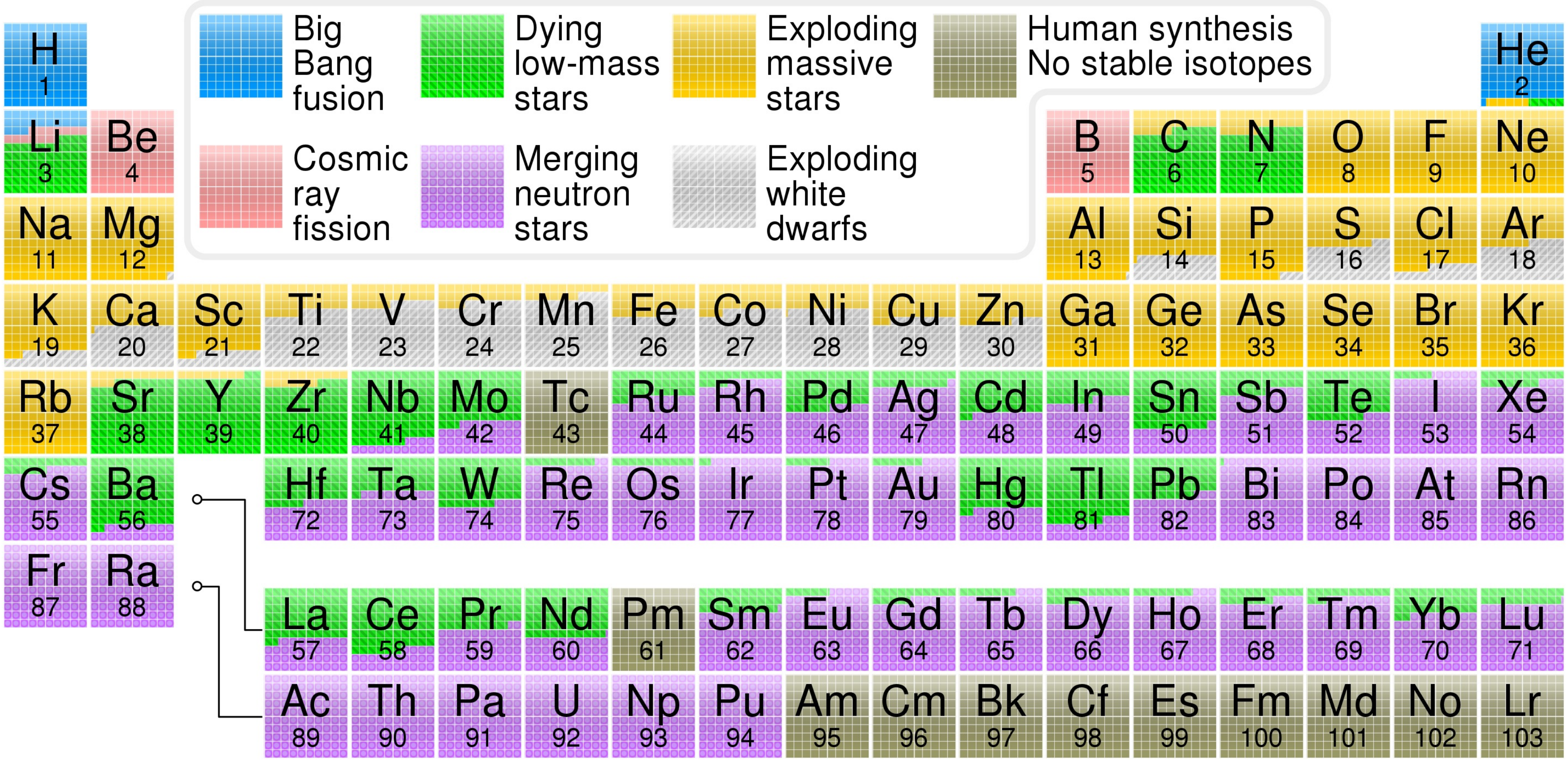


Fusion processes: elements up to Fe





Cosmogenic origin of elements



Main nucleosynthesis path

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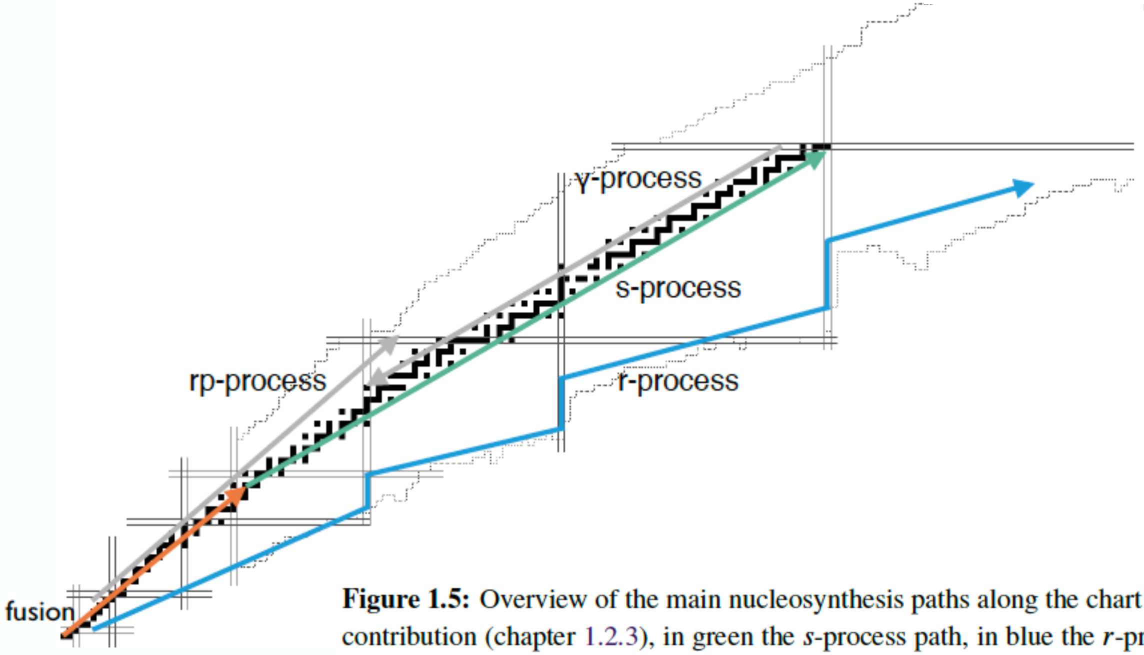
Figure 1.6: The *s*-process path. If a beta unstable isotope is reached, it decays back to the next stable isotope. Stable isotopes are marked grey, and unstable isotopes white.



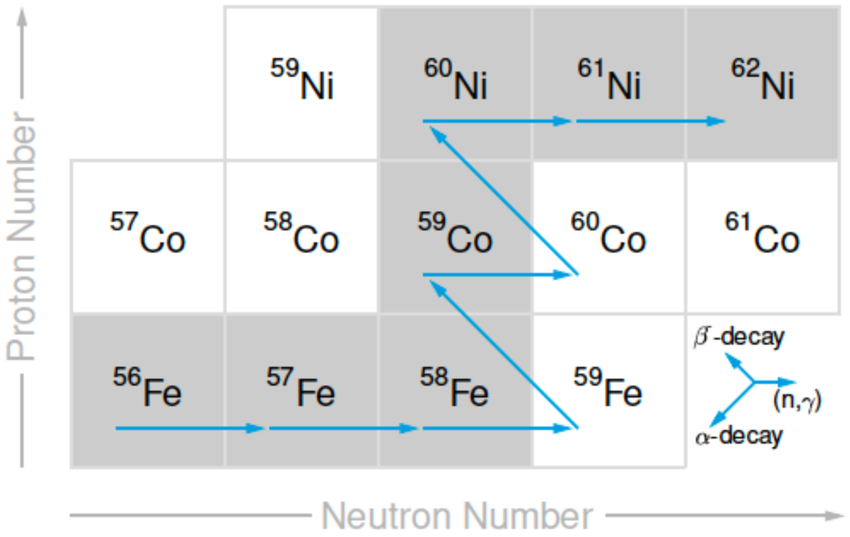


Figure 1.5: Overview of the main nucleosynthesis paths along the chart of nuclides. In orange the fusion contribution (chapter 1.2.3), in green the *s*-process path, in blue the *r*-process path (page 24) and in grey the *rp*- and γ processes (page 24). The *s* process and the γ process are secondary 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).

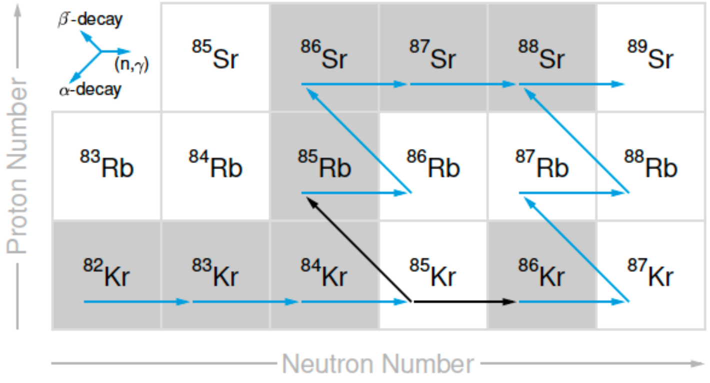
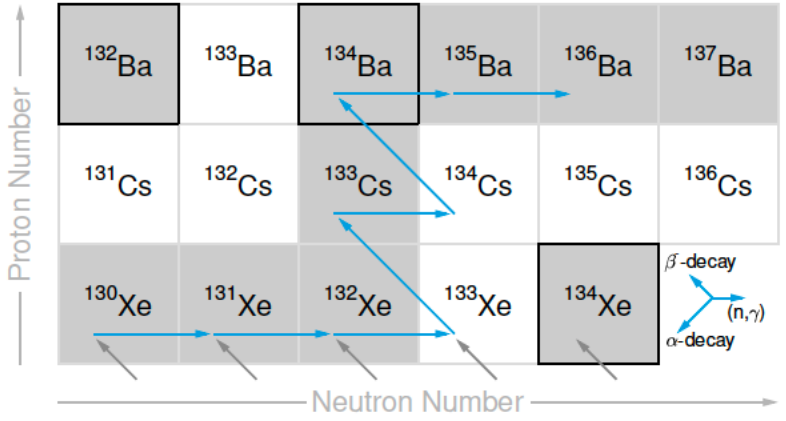


Figure 1.10: Branching point ^{85}Kr along the *s*-process path. ^{85}Kr has a half-life of about 10 years, which would make it an excellent probe for *s*-process conditions, if all reaction channels would be known to good precision. Stable isotopes are marked grey, and unstable isotopes white.

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

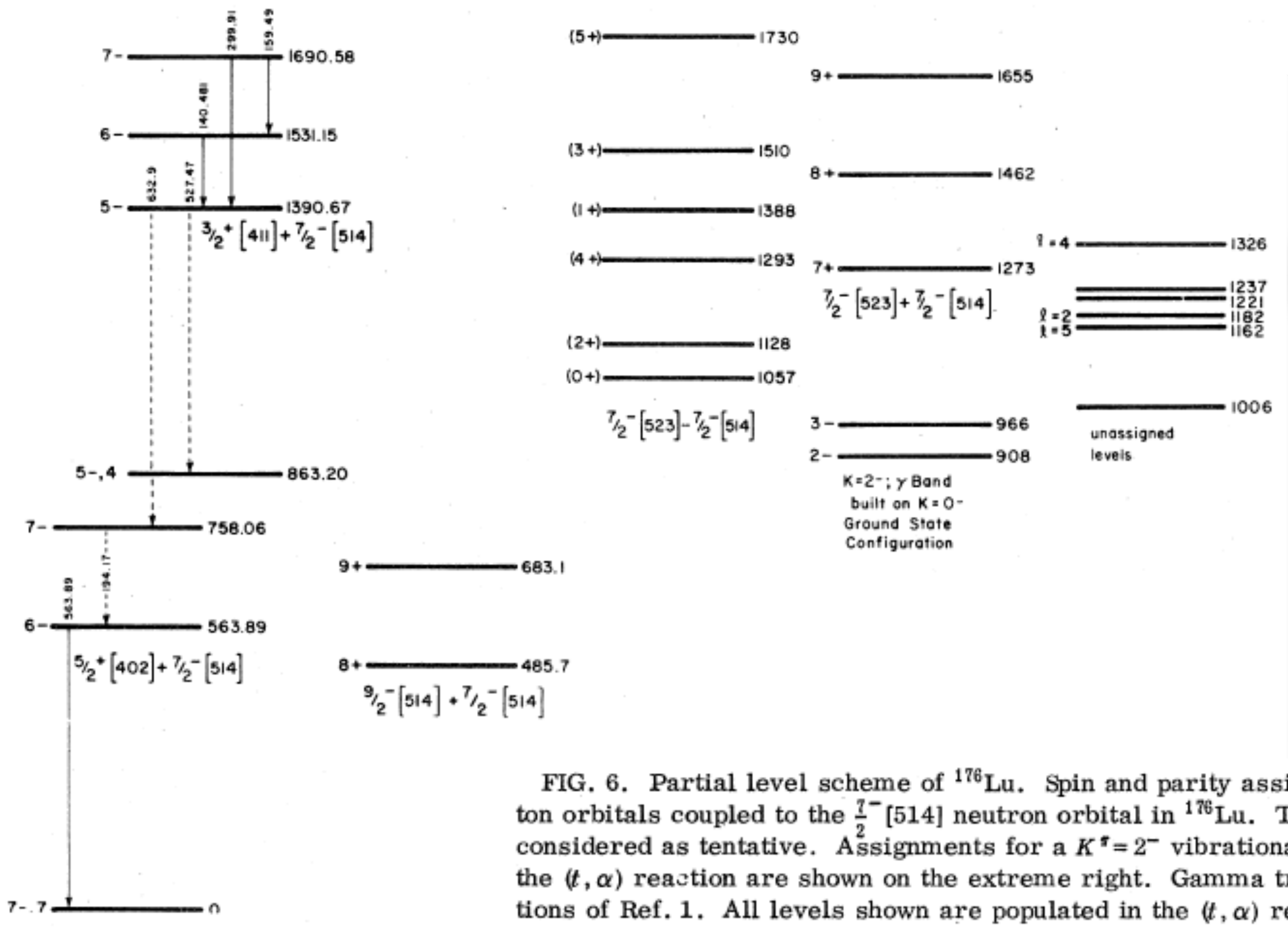


FIG. 6. Partial level scheme of ^{176}Lu. Spin and parity assignments of the $\frac{3}{2}^+$[411], $\frac{7}{2}^-$[523], $\frac{5}{2}^+$[402], and $\frac{9}{2}^-$[514] proton orbitals coupled to the $\frac{7}{2}^-$[514] neutron orbital in ^{176}Lu. The assignments for the $K^\pi = 0^+$ $\frac{7}{2}^-$[523] − $\frac{7}{2}^-$[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.

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^{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.

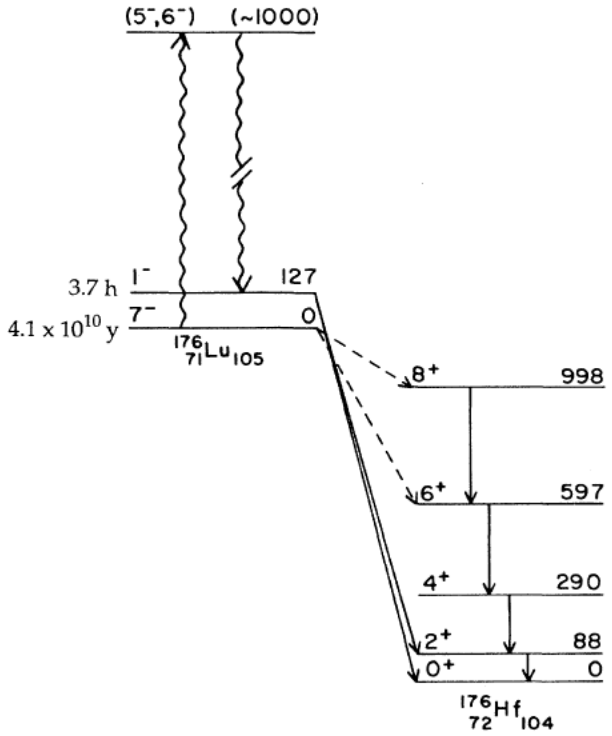
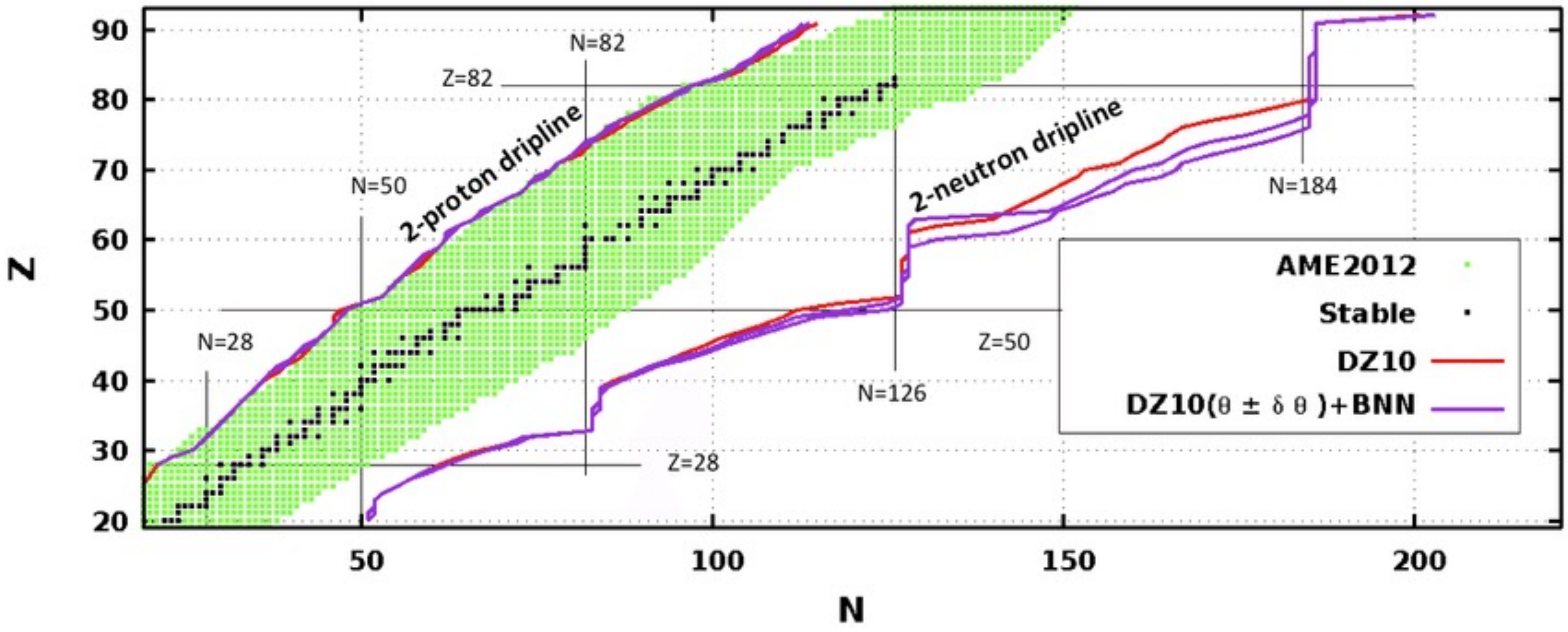


FIG. 3. A partial level scheme of ^{176}Lu, showing the positions and decays of the ground state and isomer at 122.9 keV. The equilibration of these two levels could be achieved by way of a level of intermediate spin, as illustrated in the figure.

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
N=28
2-neutron dripline
N=184
Z=50
N=126
Z=28
AME2012
Stable
DZ10
DZ10(θ ± δ θ)+BNN

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^{176}Lu physics case

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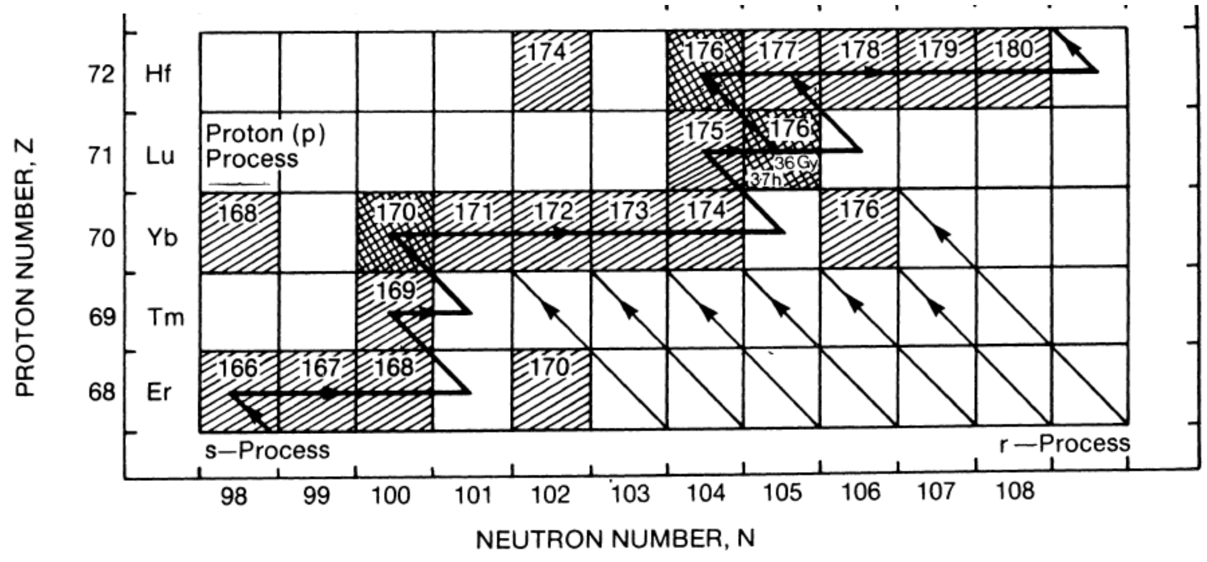

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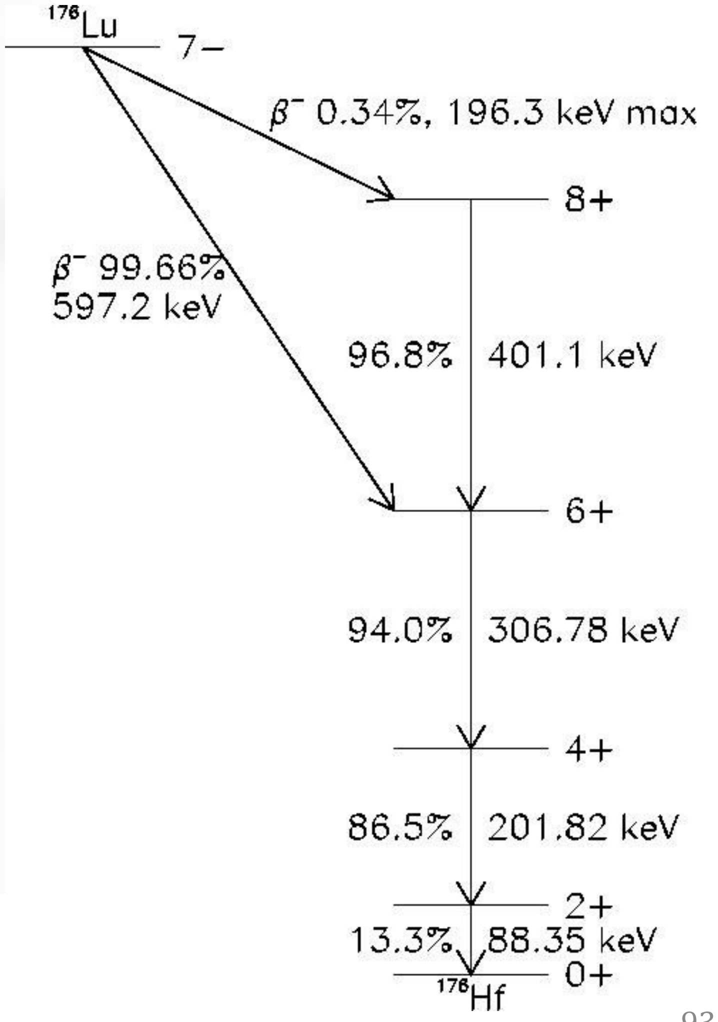
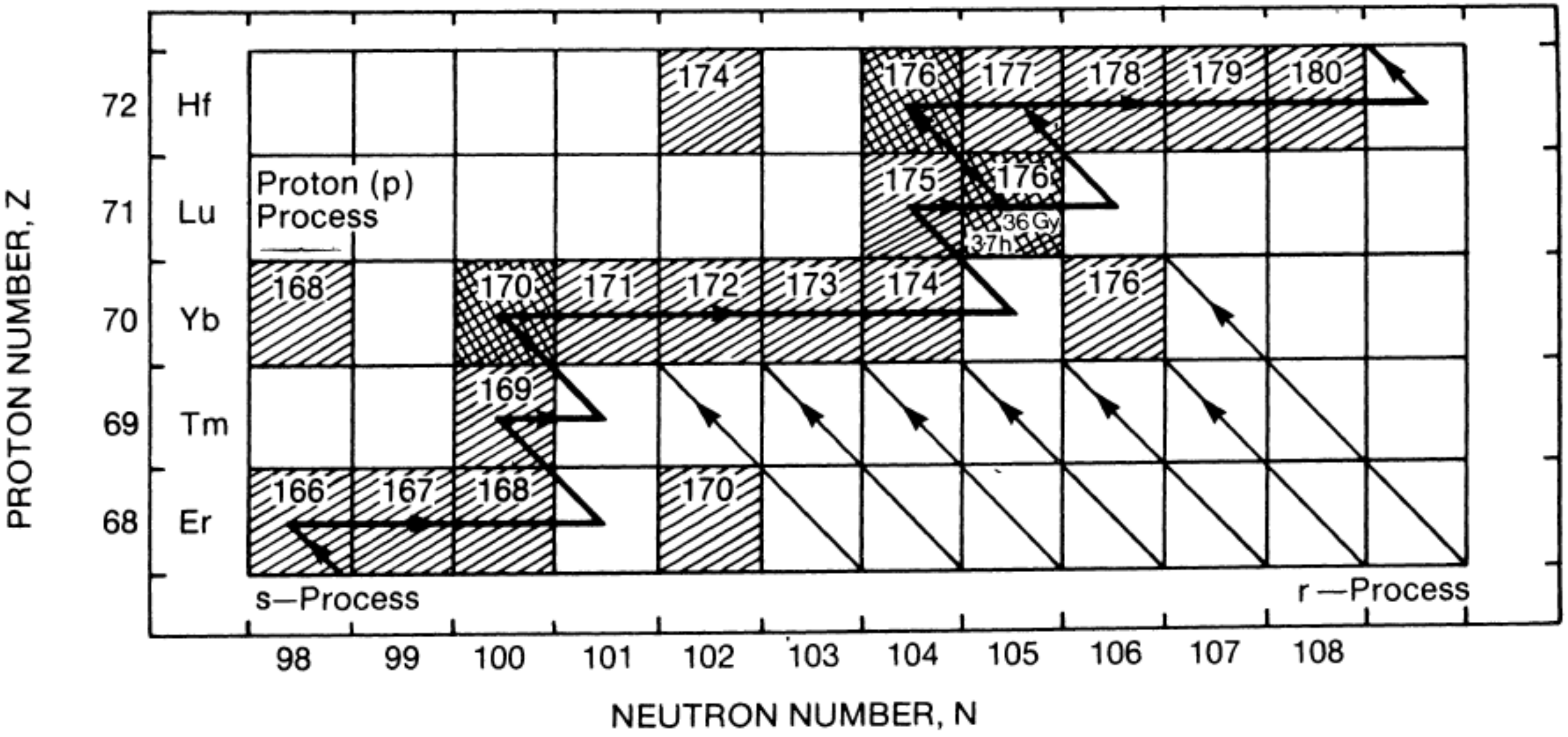


^{176}Lu branch in the s-process



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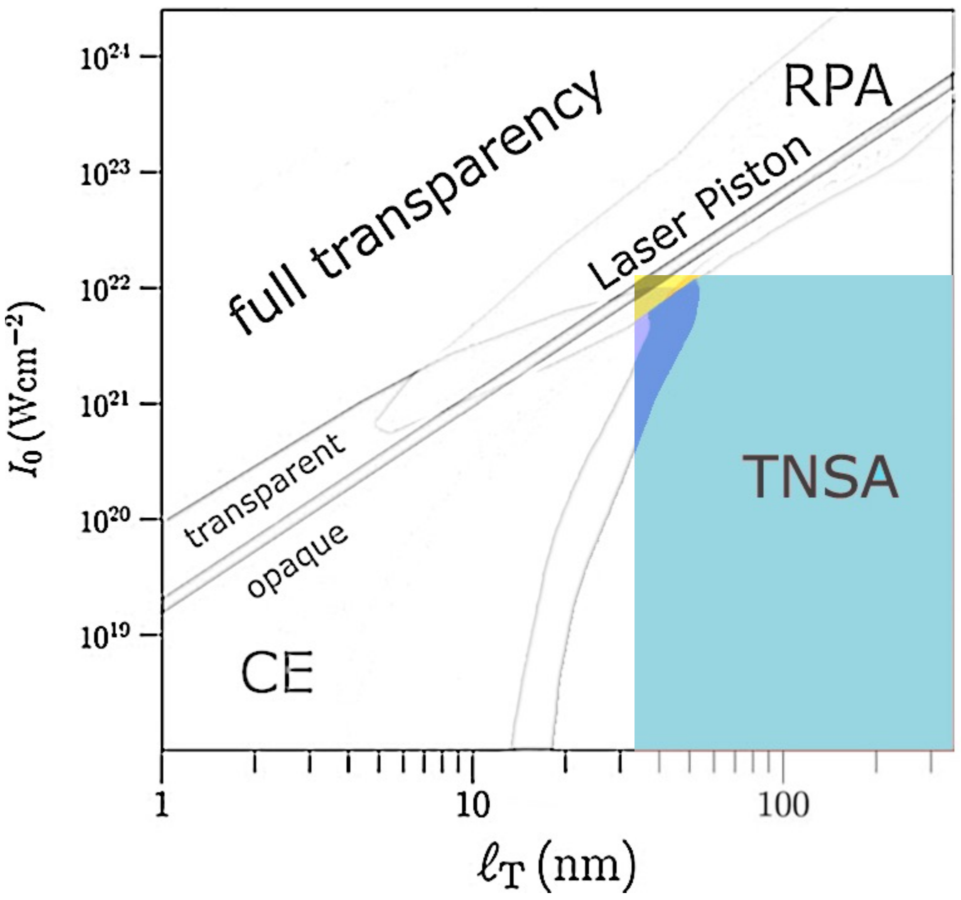
Experiments at the PW regime



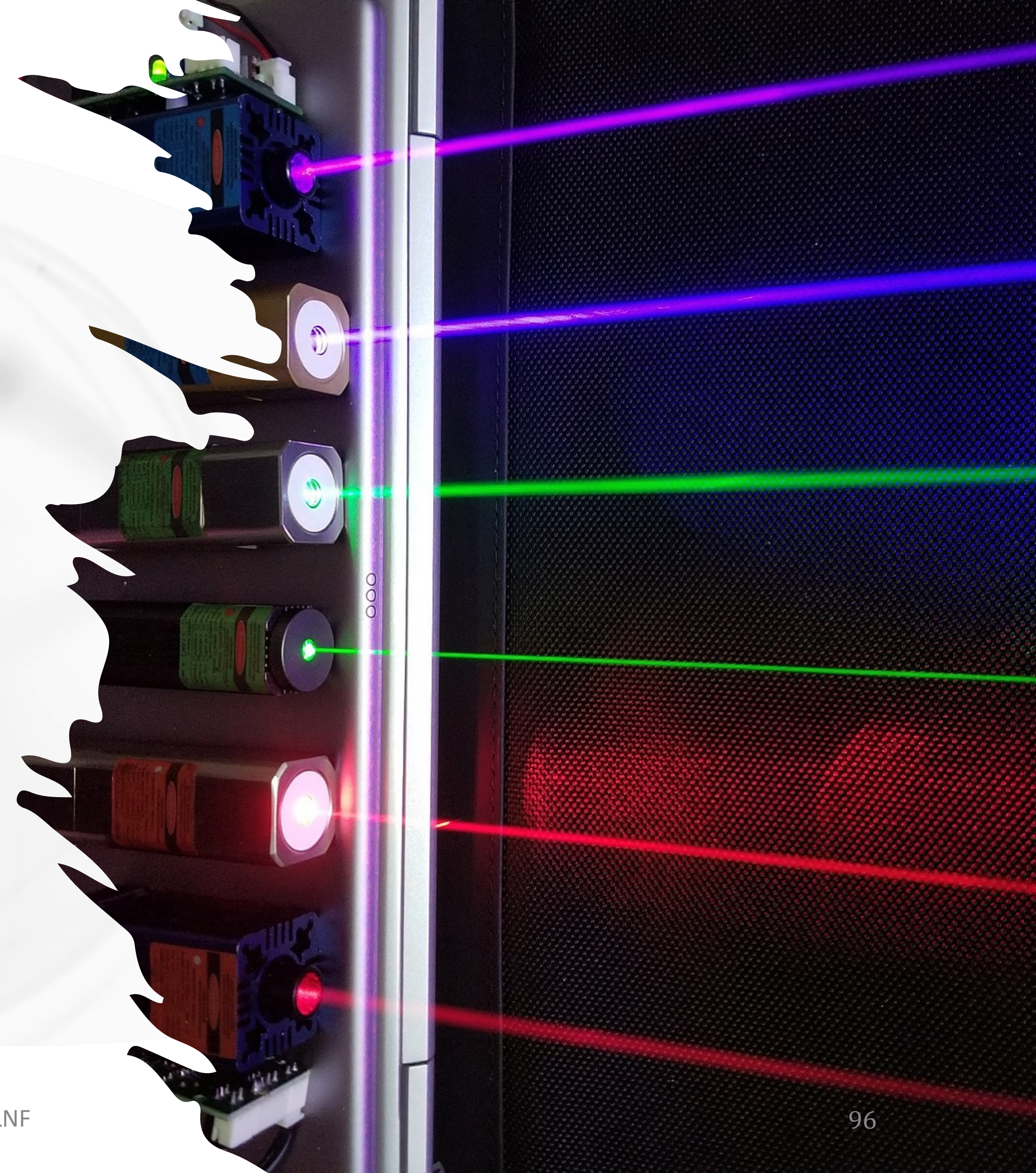
High-density target → solid, Lu target

Target choice to be optimized in view of the thermalization goal

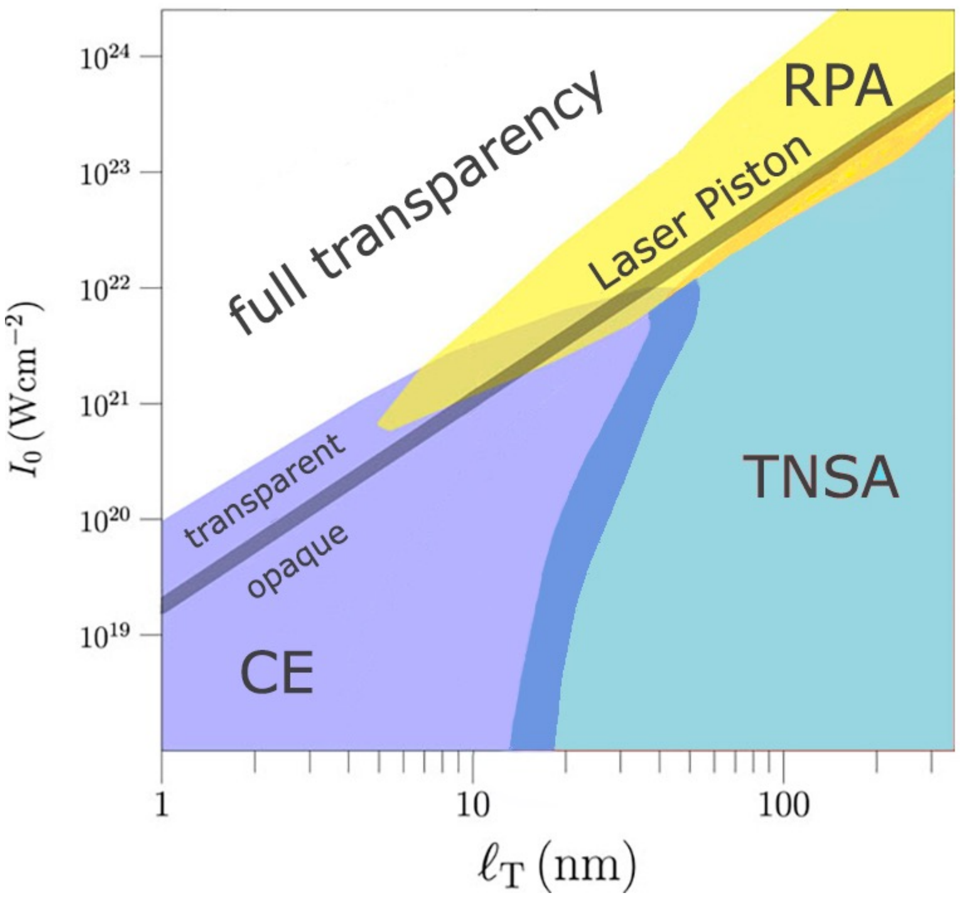
Possible choice: non-isotopic cuboids of metallic bulk material (*e.g.*, natural Lu) coated with a layer of at least 200-300 μm of isotopic enriched material

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

Why laser



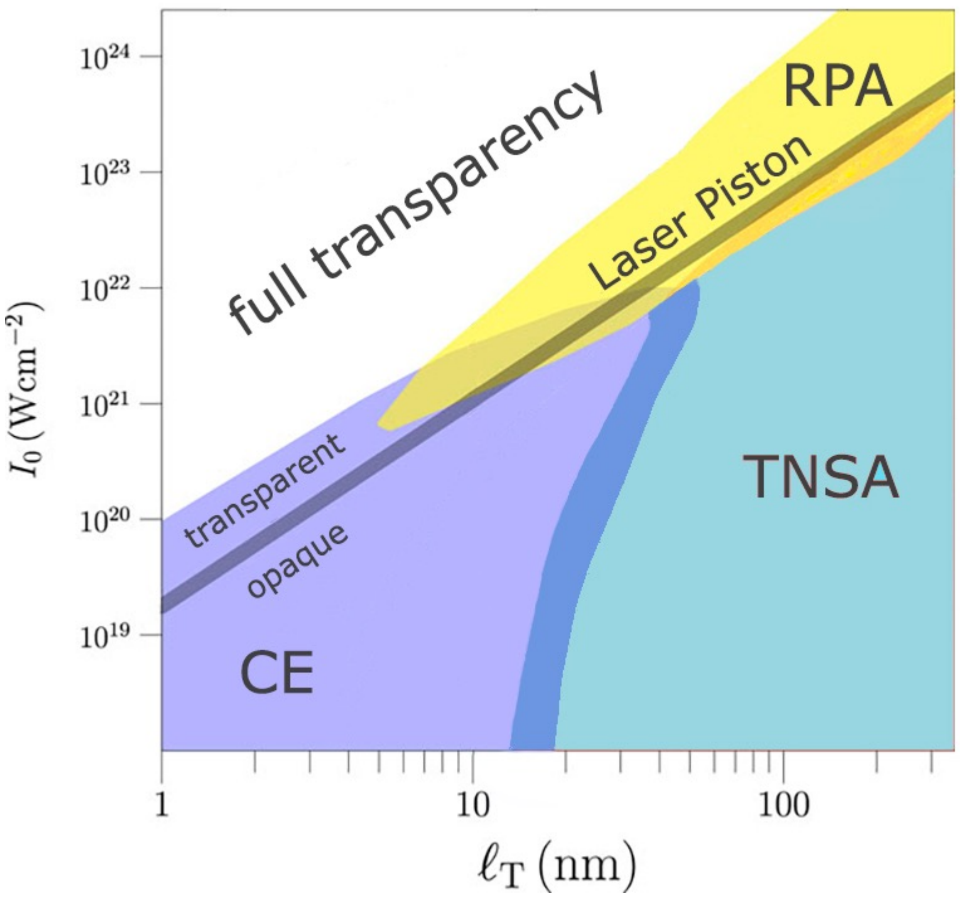
Laser-matter interaction



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 τ < 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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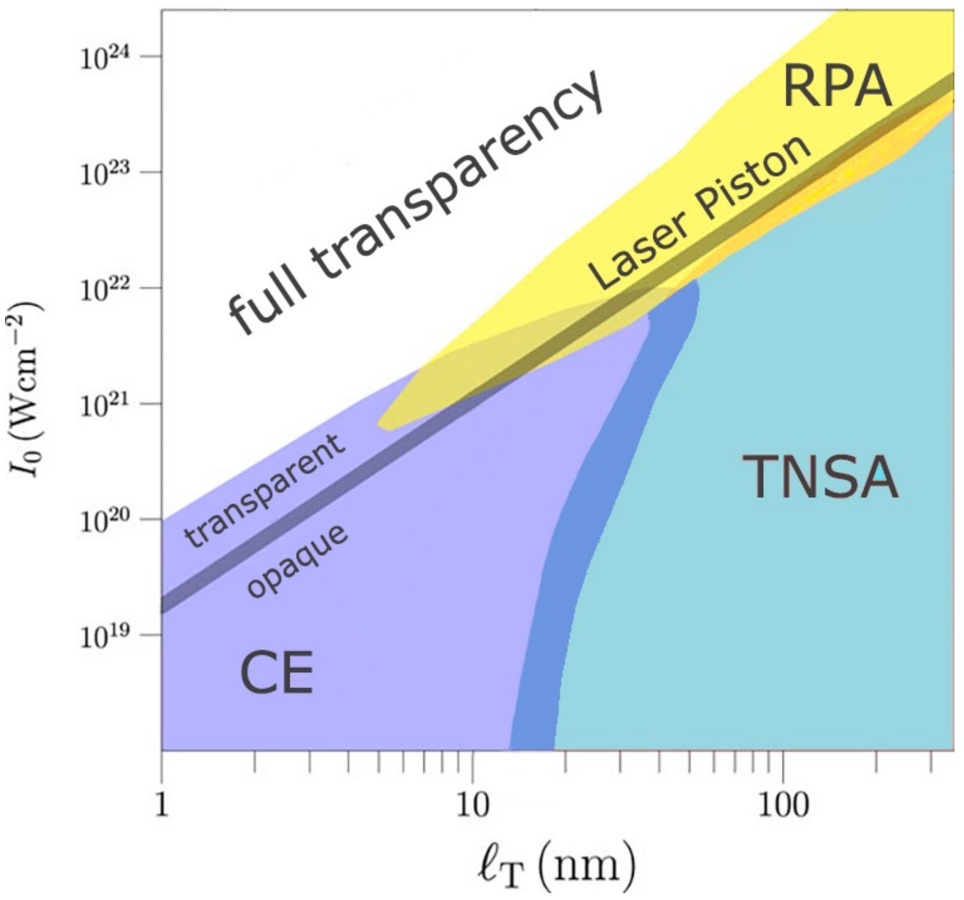
- **Radiation Pressure Acceleration (RPA), or Laser Piston regime:** based on the action of the radiation pressure induced in the interaction of a short laser pulse, of extremely high intensity (above $10^{20} \div 10^{21}$ W/cm^2), with a thin and dense pre-plasma layer created, in front of a target, 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.

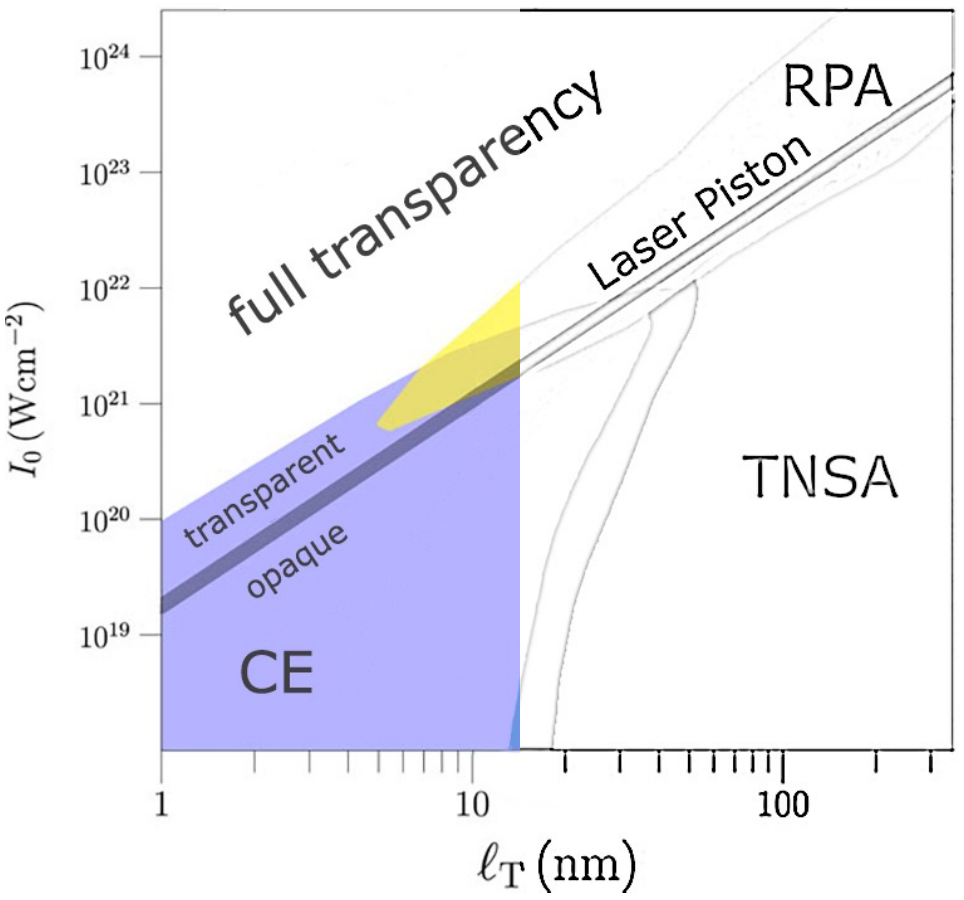
Laser-matter interaction



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.

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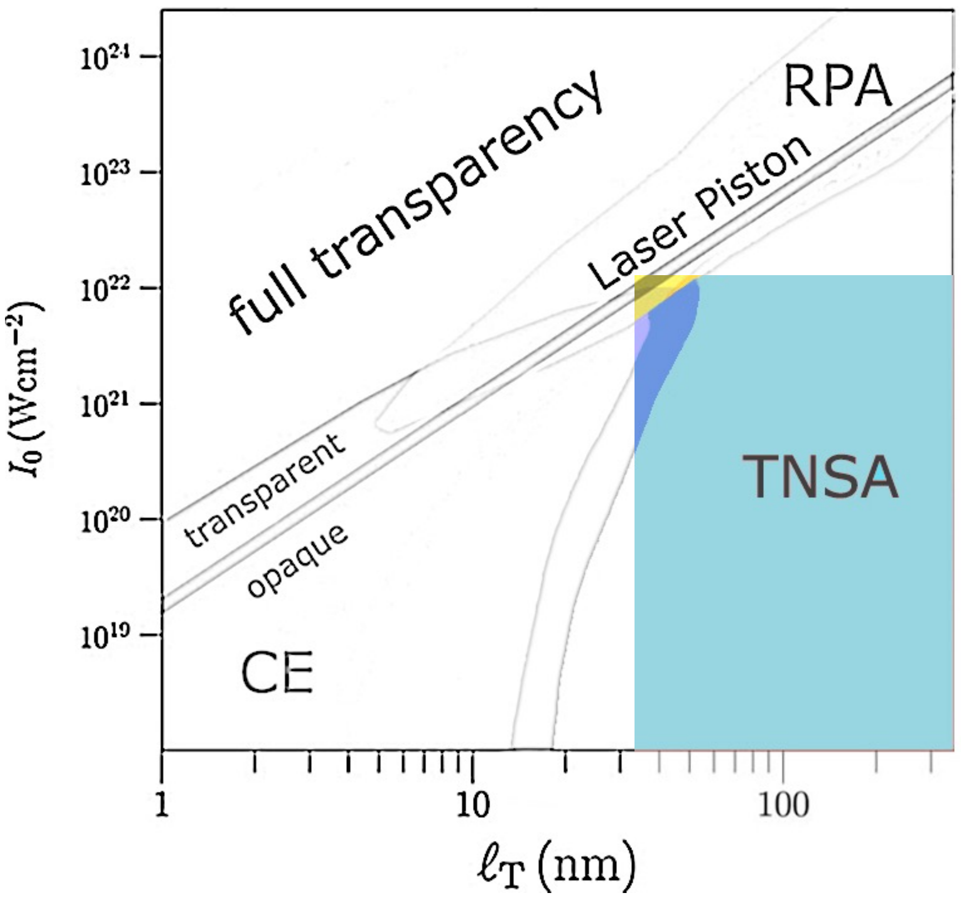
5. ^{176}Lu decays to the Hf 6^+ excited states, whose de-excitation proceeds through three different steps, leading to the subsequent emission of photons with energies equal to E_γ = 307, 202 and 88 keV. $^{176,m}Lu$, on the other hand, directly decays to the first Hf excited state → only the emission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

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