Nuclear physics measurements with a laser-induced plasma: potential experimental issues and open questions

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[*] *INFN Laboratori Nazionali di Frascati*

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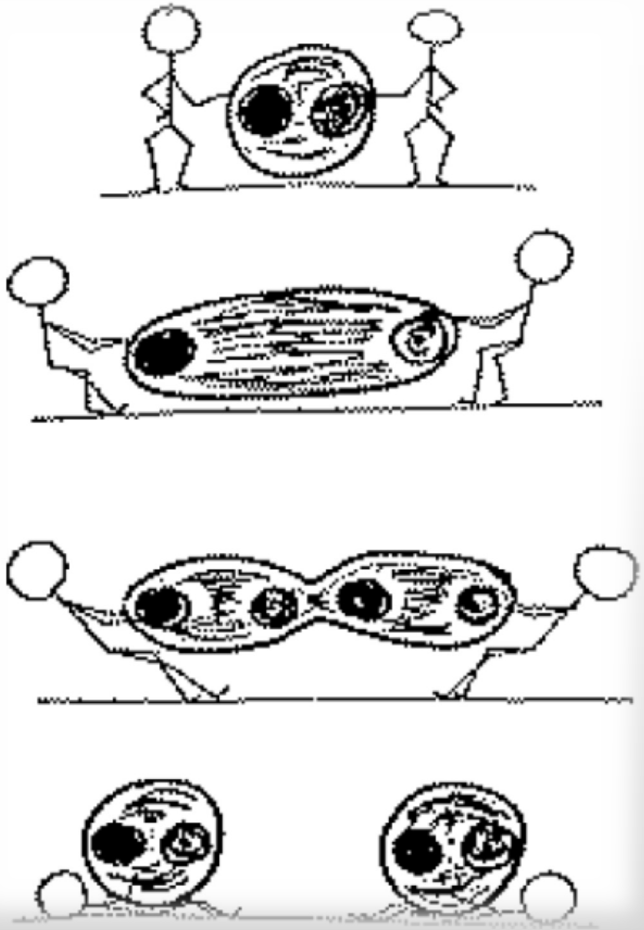

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Nuclear physics measurements with a laser-induced plasma potential experimental issues and open questions

How do we measure them?

Klaus Spohr - Monday, July 1°

Nuclear physics measurements with a laser-induced plasma: potential, experimental issues and open questions

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What are the sistematics?

Harald Griesshammer - Tuesday, July 2°

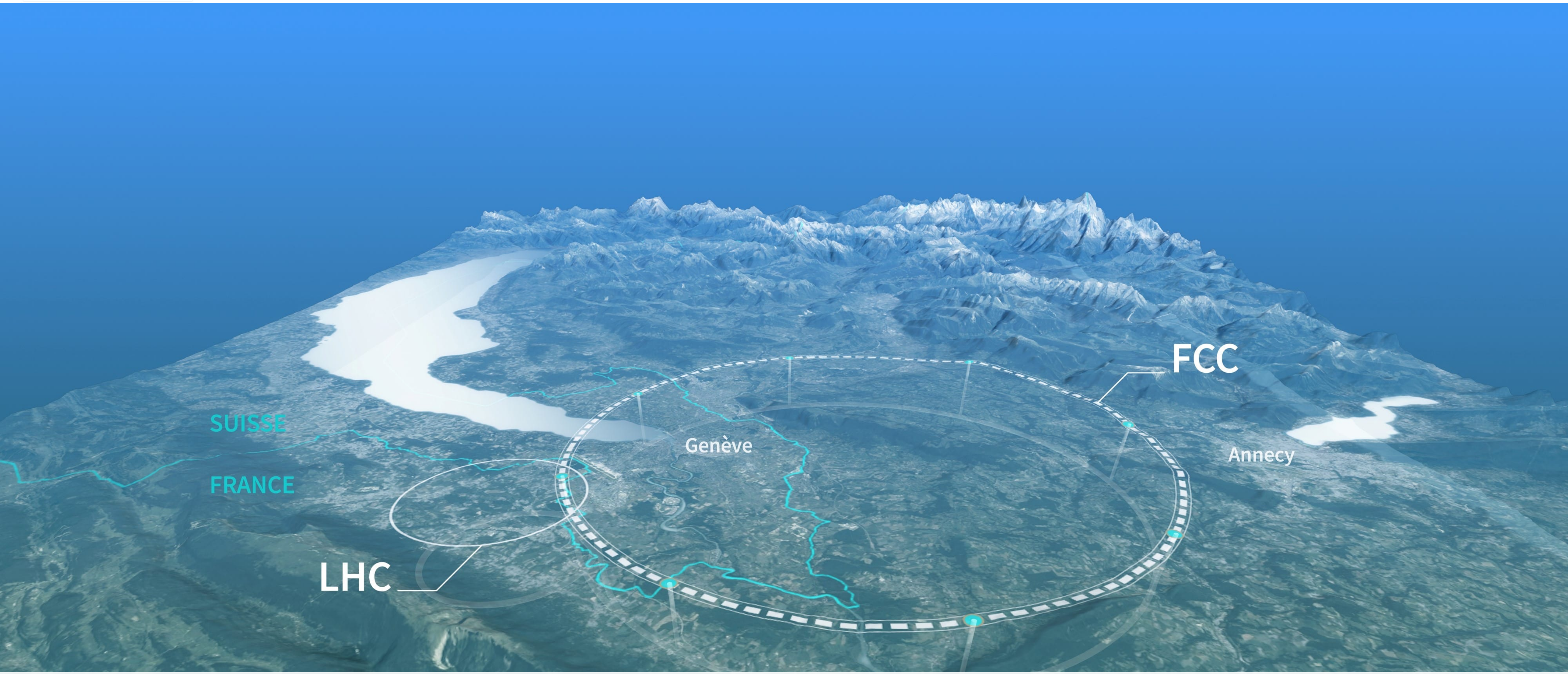
EuPRAXIA

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

HOME EUPRAXIA FOR BEGINNERS EVENTS CONTACT US INTRANET

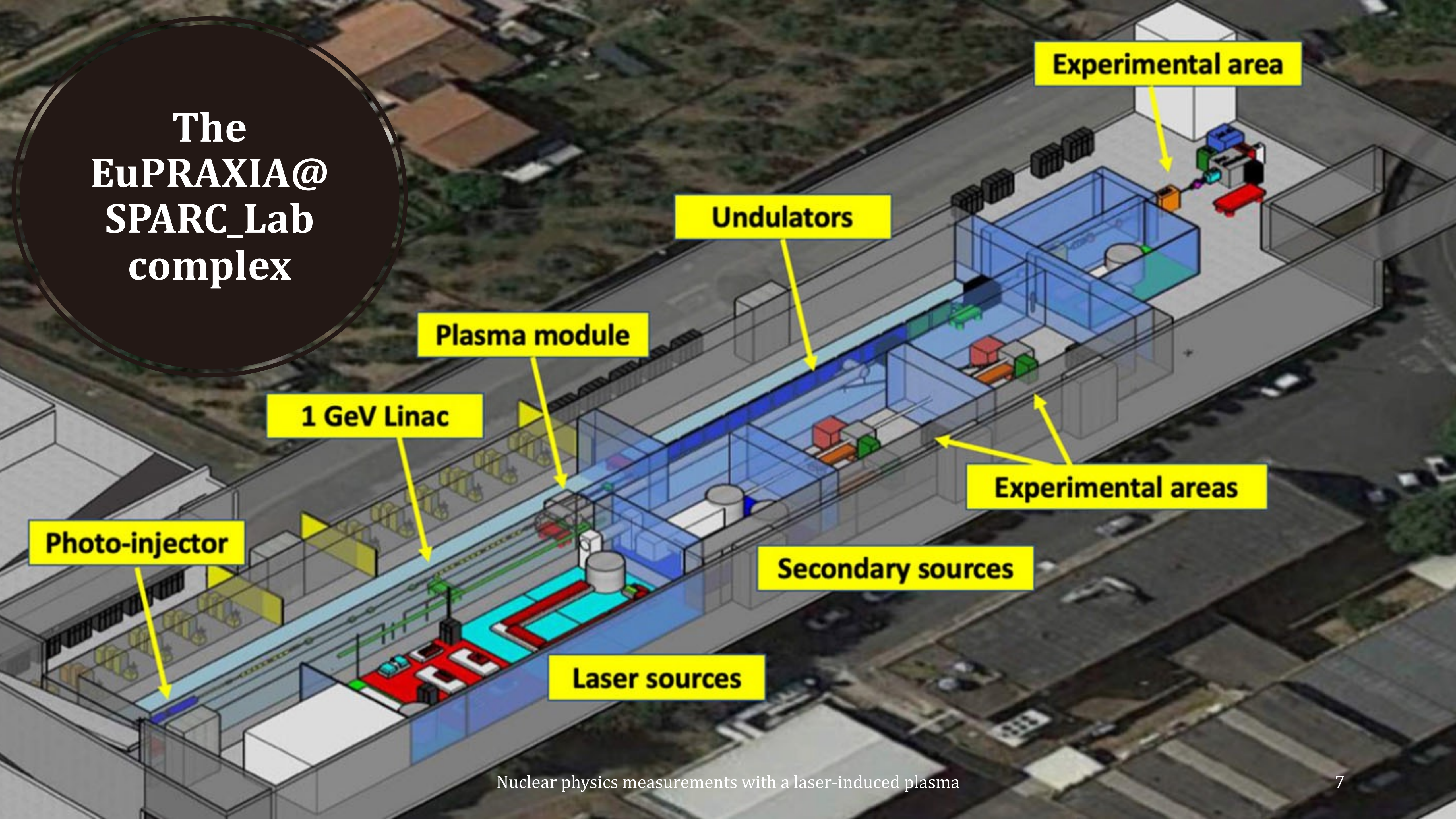
EUPRAXIA TARGETS THE REALIZATION OF A "EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS"

Novel and small plasma accelerator compared to the FLASH accelerator at DESY. Credit: Heiner Müller-Elsner/DESY



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

The EuPRAXIA@SPARC_Lab complex



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EuPRAXIA sources

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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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At the moment **FLAME** is operational:

- Titanium–Sapphire laser based on the Chirped Pulse Amplification (CPA) scheme
- maximum energy of 7 J
- temporally compressed down to 25 fs
- peak power of 200 TW
- 10 Hz repetition rate

https://sparclab.lnf.infn.it/sparc_lab-home/flame-laser/laser-source/

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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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The periodic table of elements

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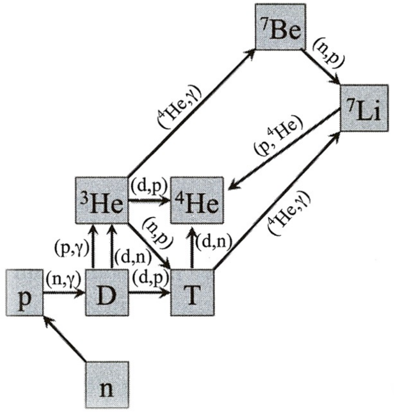
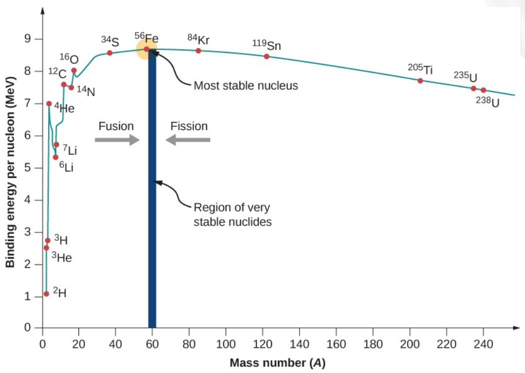
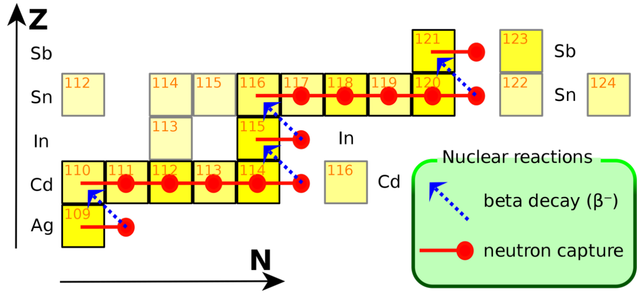


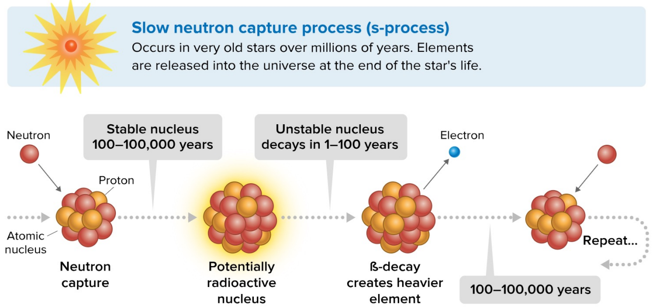


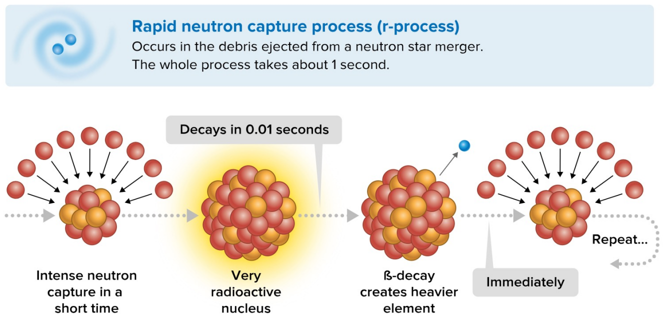
- Alkali metals
- Alkaline-earth metals
- Transition metals
- Other metals
- Other nonmetals
- Halogens
- Noble gases
- Rare-earth elements (21, 39, 57–71) and lanthanoid elements (57–71 only)
- Actinoid elements

period \ group	1*	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og

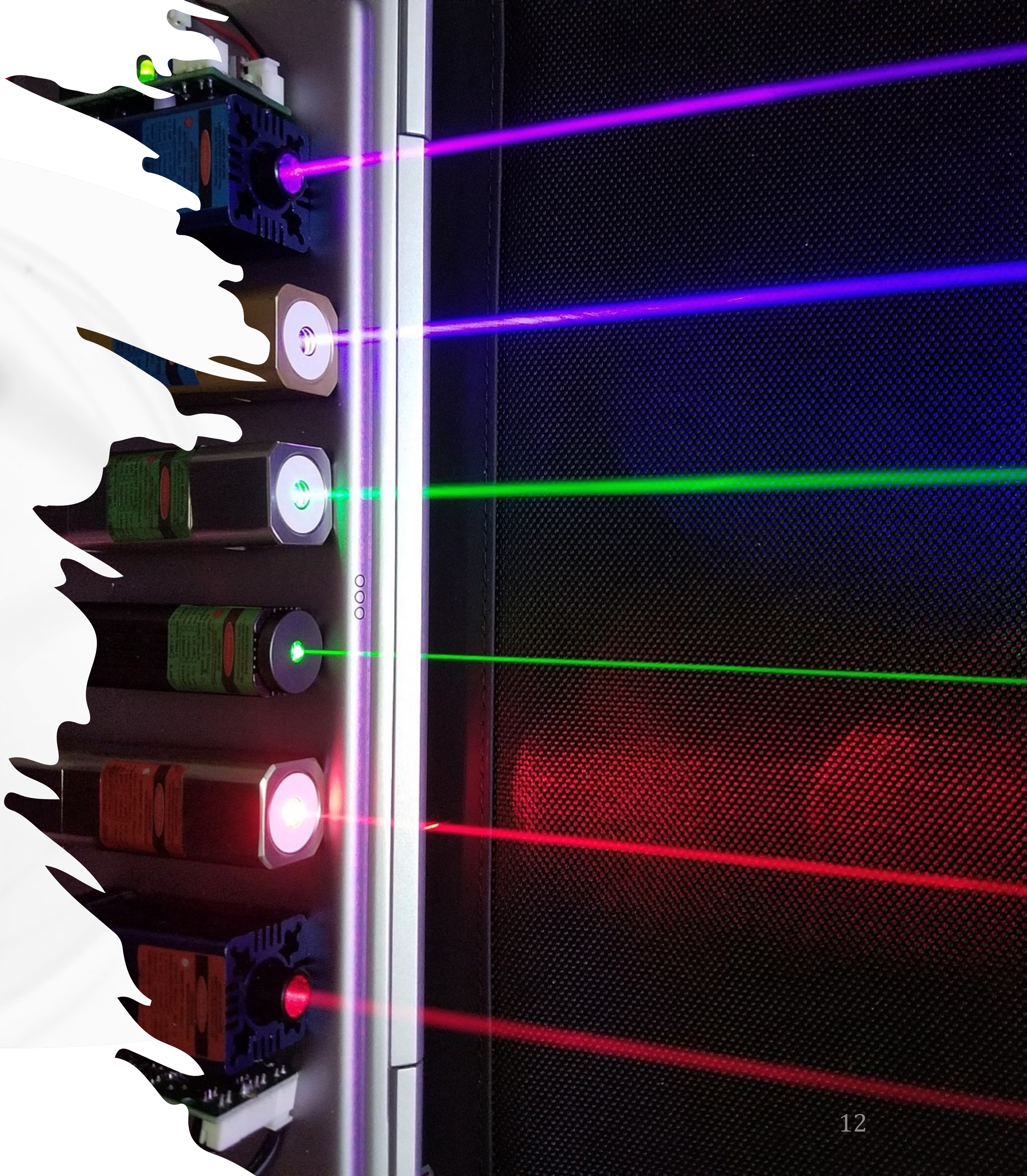
lanthanoid series 6	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
actinoid series 7	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr







Why laser



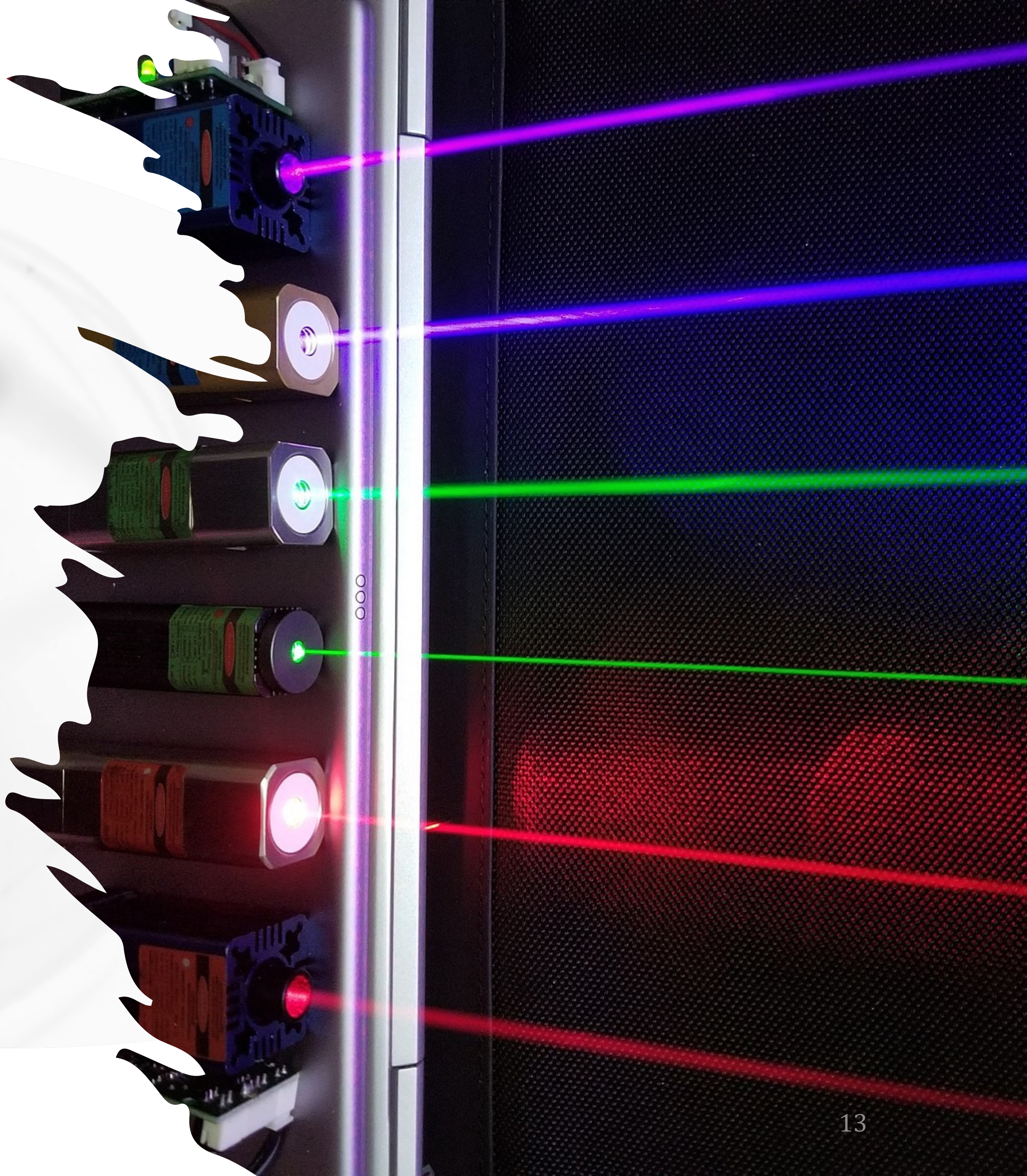
When a high intensity laser pulse (above 10^{18} W/cm^2) is focused in a spot of the order of a few microns on a target placed in vacuum, a plasma consisting of electrons and ions is created almost instantaneously.

Accelerated charges produce Bremsstrahlung radiation → photon bath (X-rays) that can in principle populate excited states

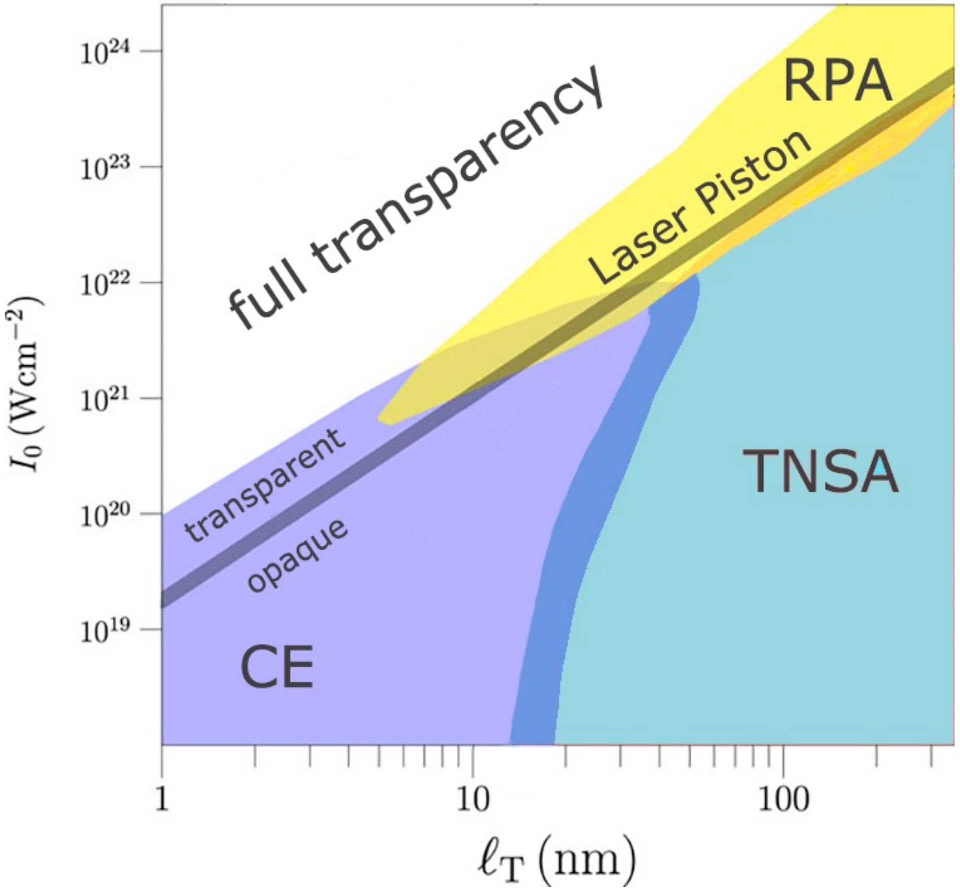
What is the spectrum of such a radiation?

Up to what extent it reproduces stellar conditions?

Why laser



Laser-matter interaction



- **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

Plot from Tanaka *et al.*, «*Current status and highlights of the ELI-NP research program*», https://doi.org/10.1063/1.5093535

Laser-matter interaction

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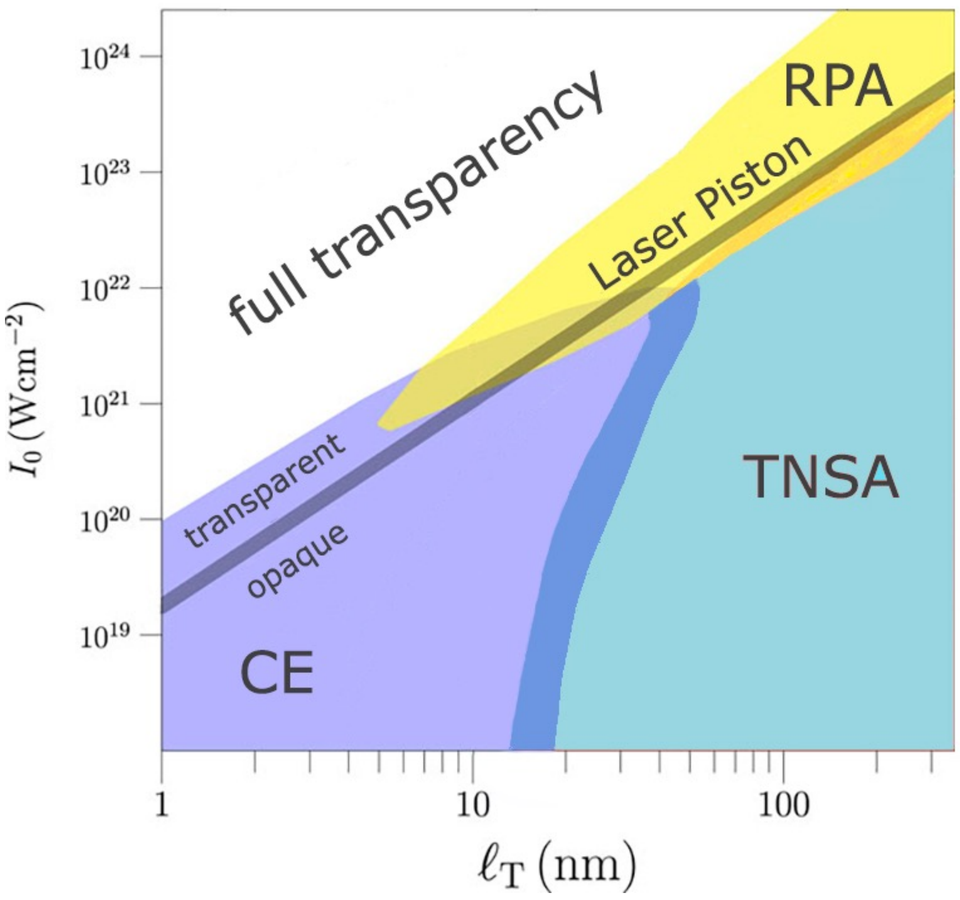


A precise control of the experimental conditions is challenging with high-power lasers → variations observed between experiments performed with equivalent setups

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 ongoing investigations.

Looking for scaling laws as $Y_n \propto I^4$, presented by Akifumi (*https://indico.ectstar.eu/event/210/contributions/4880/attachments/3174/4475/ECT20240701.pdf*)

What is the extent of systematic uncertainties coming from the laser?

Plot from Tanaka *et al.*, «*Current status and highlights of the ELI-NP research program*», https://doi.org/10.1063/1.5093535

Why plasma

Why plasma

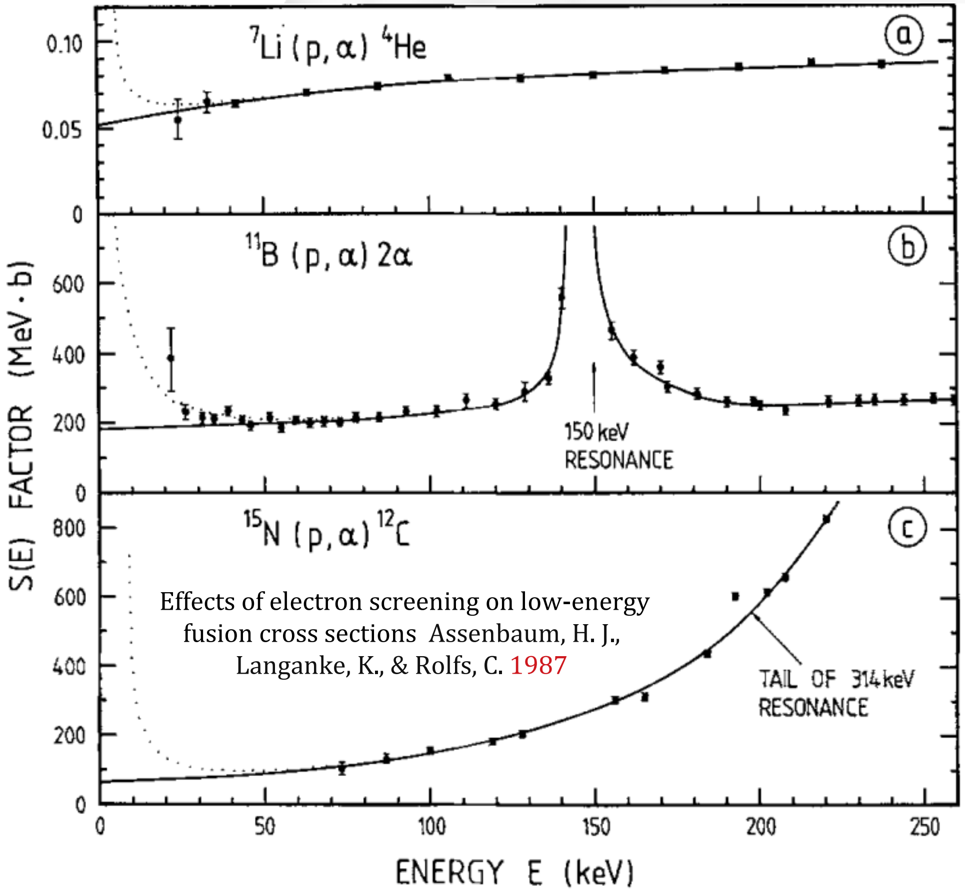
Stars are hot!

In stellar cores, the relevant nuclear processes occur in fully ionized isotopes → how do half-lives depend on the ionization degree?

What is the impact of electron screening?

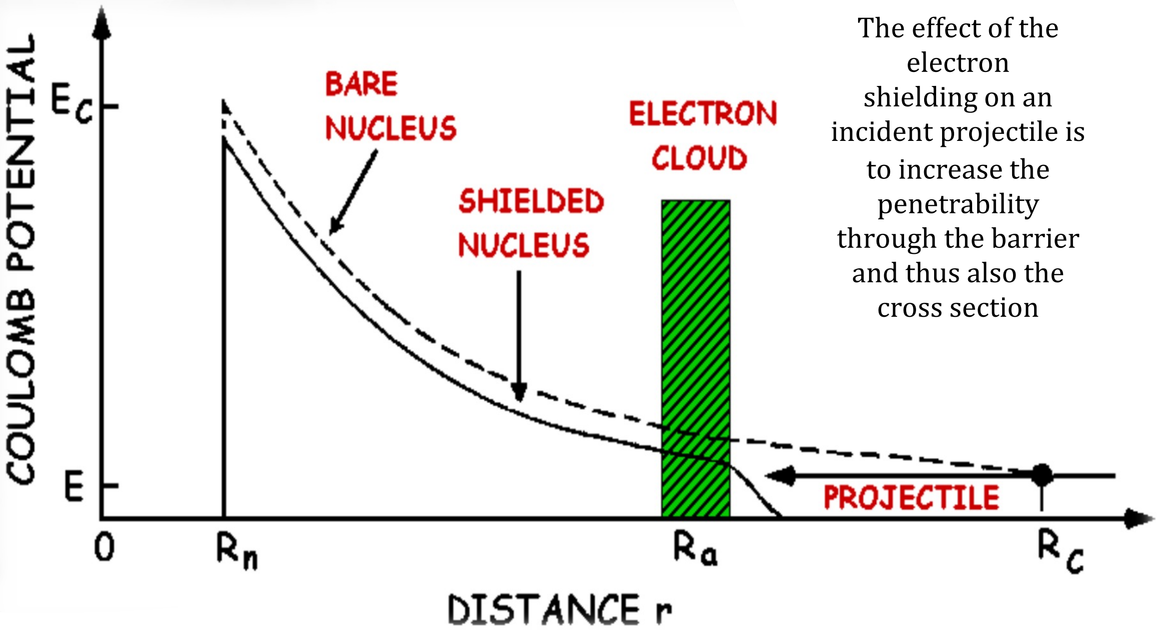
Why plasma: fusion processes

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

Why plasma: β-decays

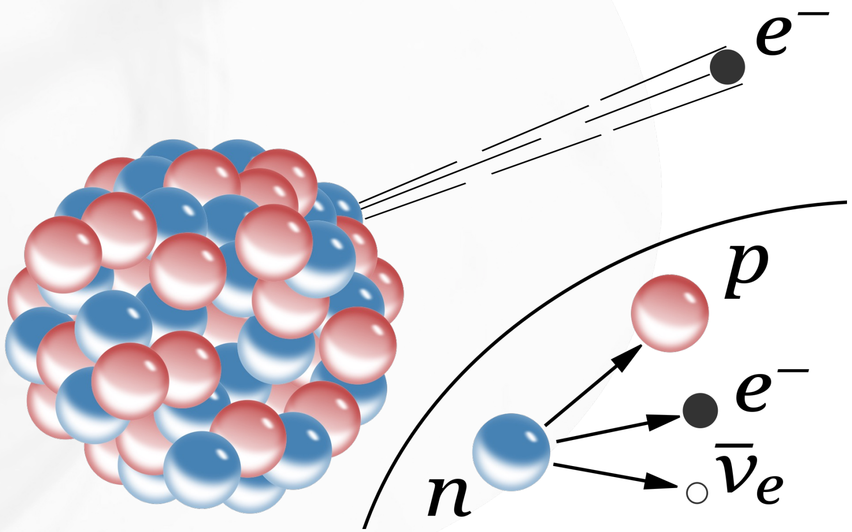
See talk by B. Mishra

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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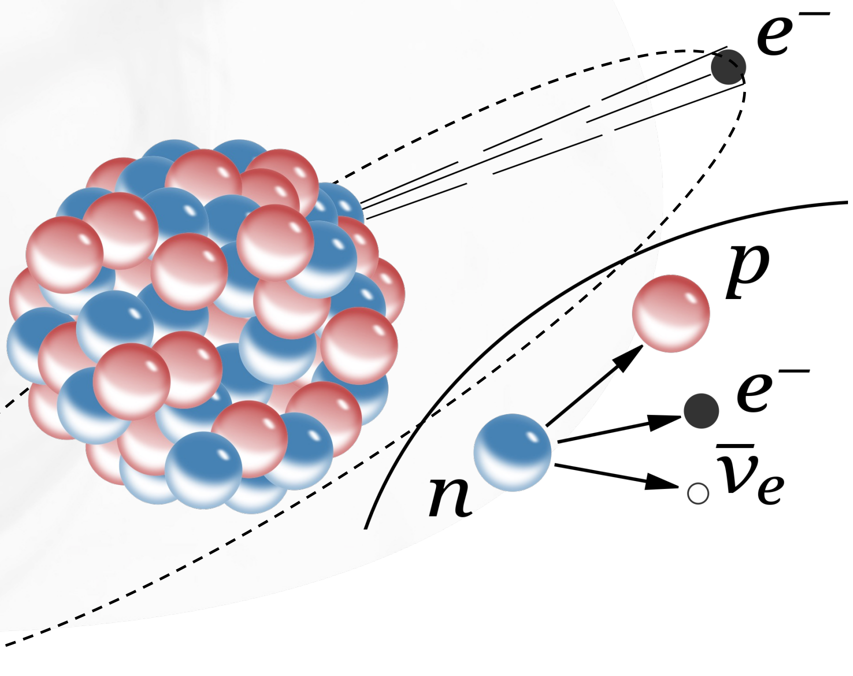

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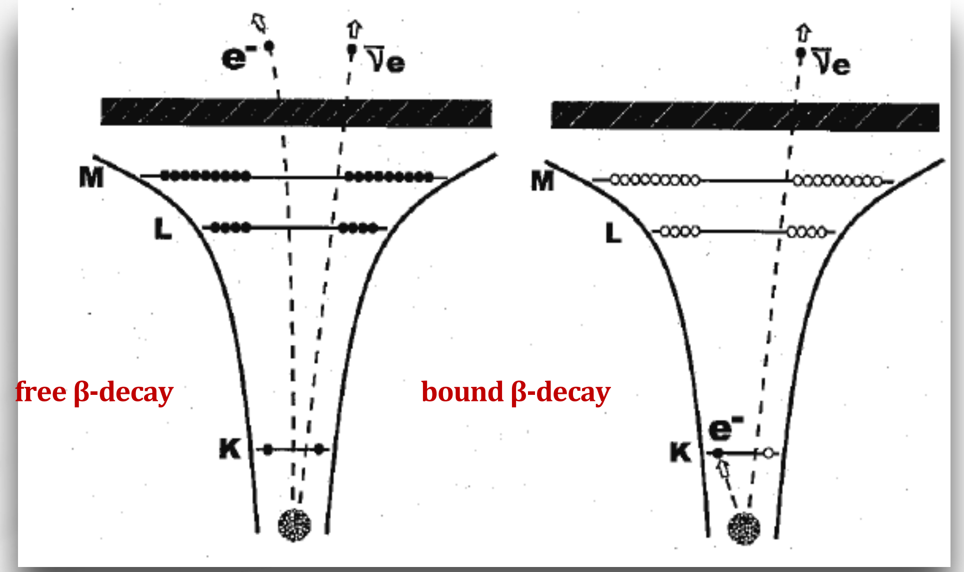
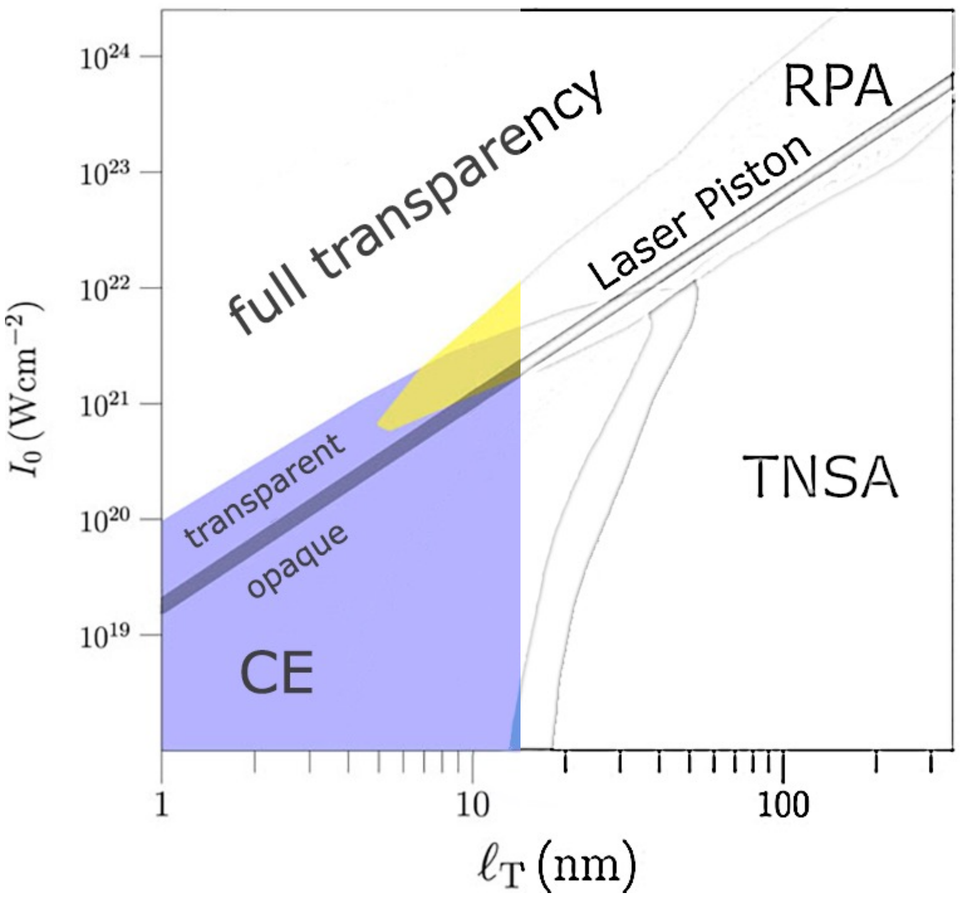


Y. Litvinov and F. Bosh: Rep. Prog. Phys. 74, 016301 (2011)

Experiments at the 10^2 TW regime

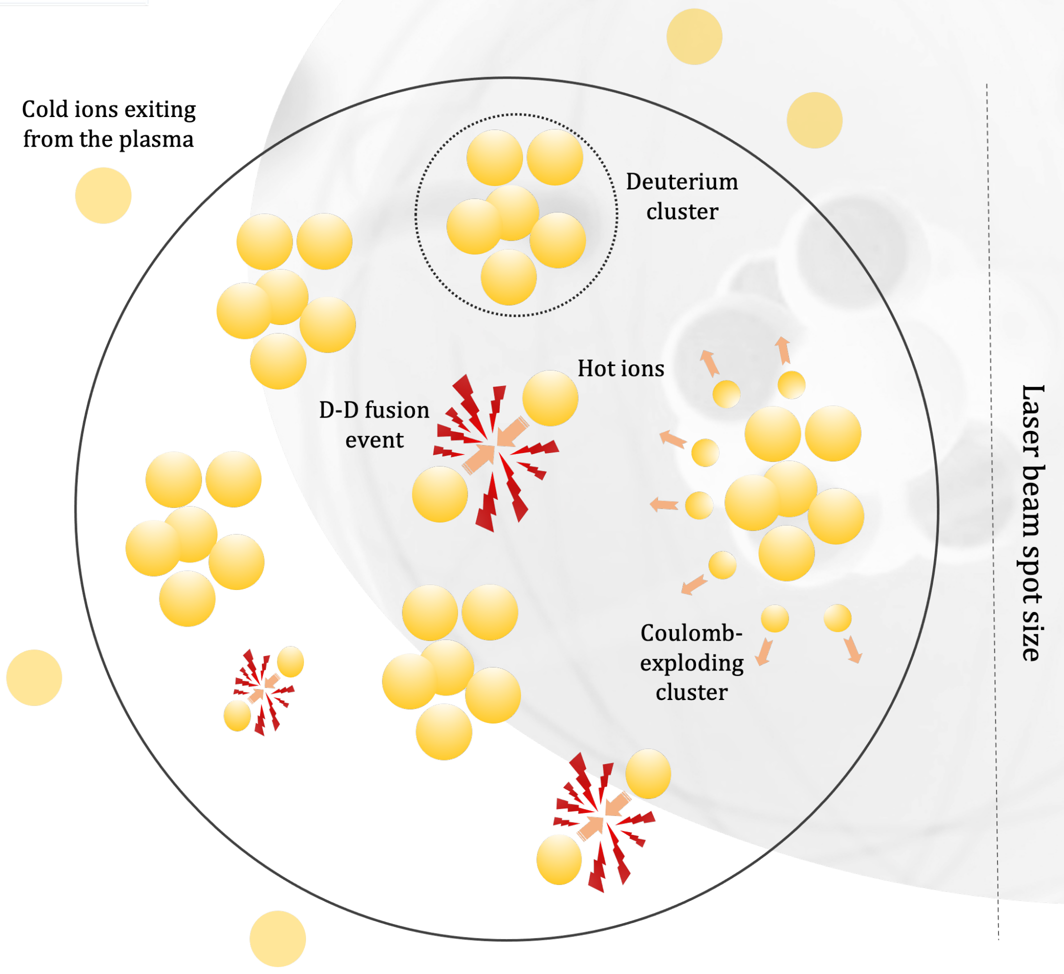


Low-density target → one of the most effective way for transferring energy from lasers to a gas target occurs **when the molecules in the gas are organized in clusters**

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

Plot from Tanaka *et al.*, «*Current status and highlights of the ELI-NP research program*», https://doi.org/10.1063/1.5093535

Deuterium fusion process in plasma



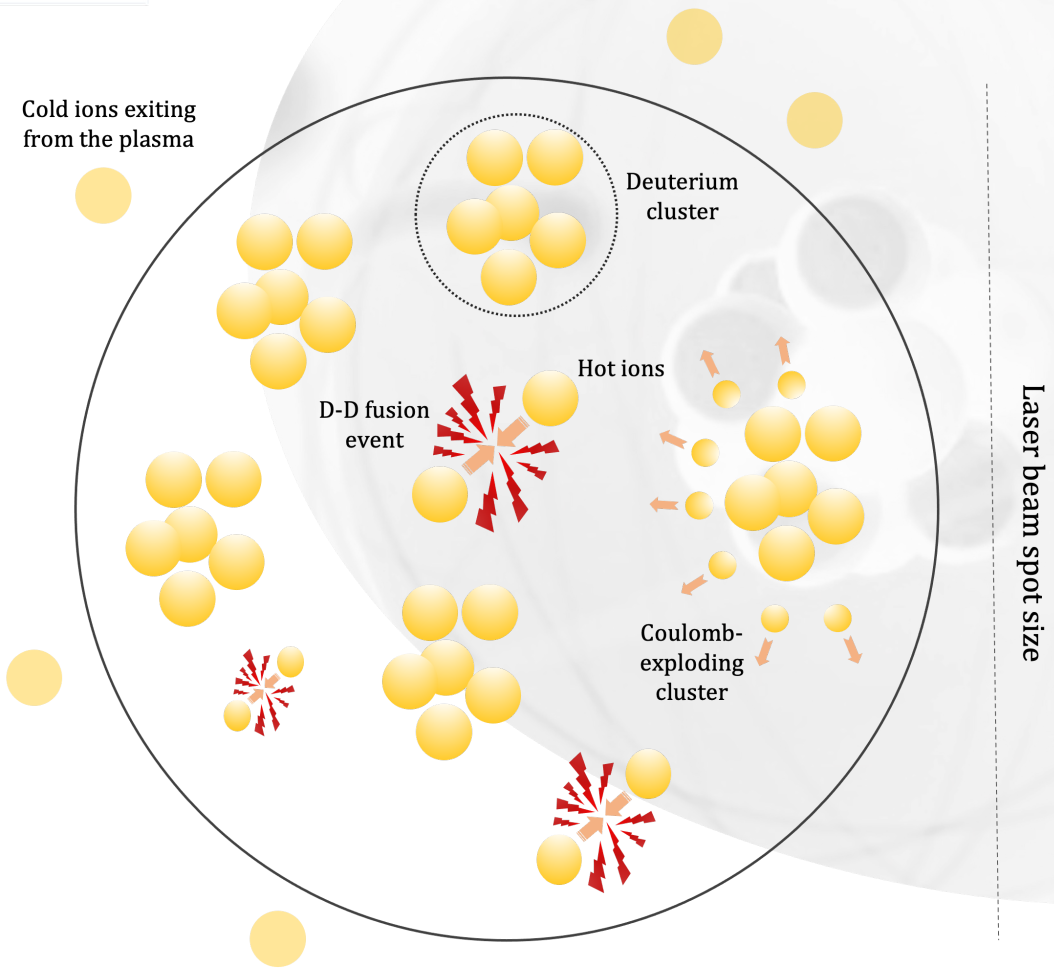
$$d + d \rightarrow\ ^{3}He + \mathrm{n}\ (2.45\ \mathrm{MeV})$$

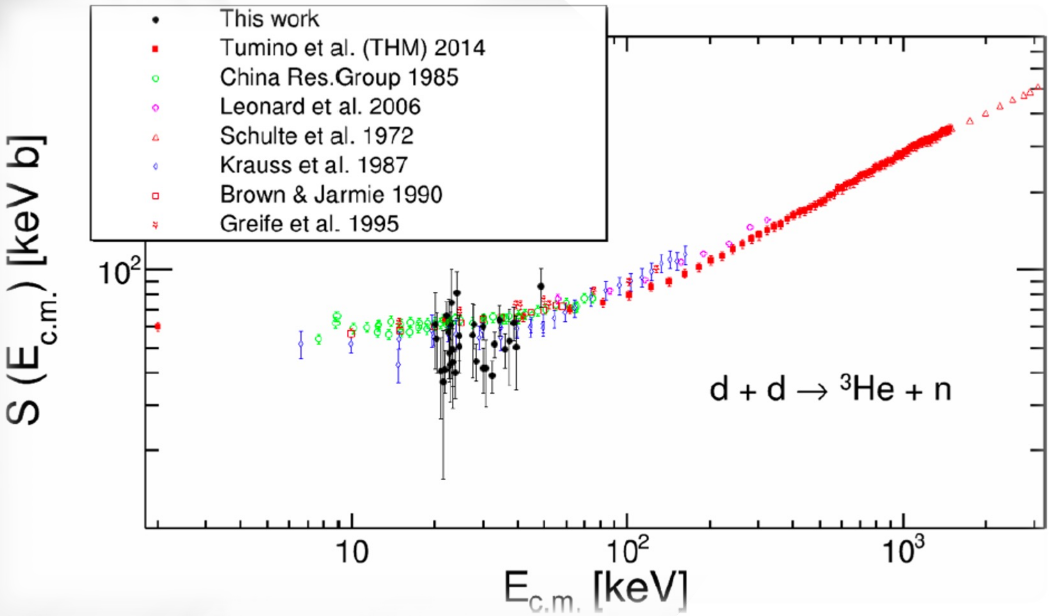
It is a nuclear fusion reaction crucial for understanding early phases of **Nucleosynthesis**

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

Deuterium fusion process in plasma

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

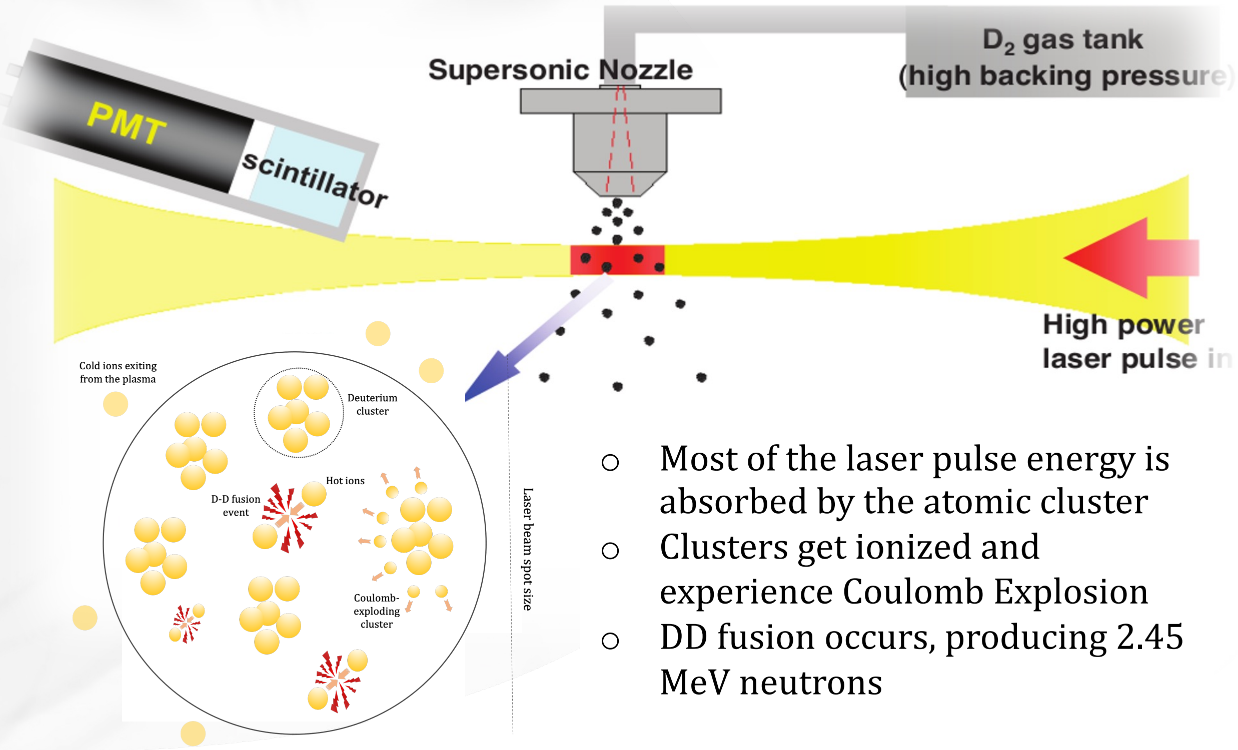
1. The deuterium gas is kept at a low temperature, close to the critical temperature **where gas and liquid phase coexist.**

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

Deuterium fusion process in plasma

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

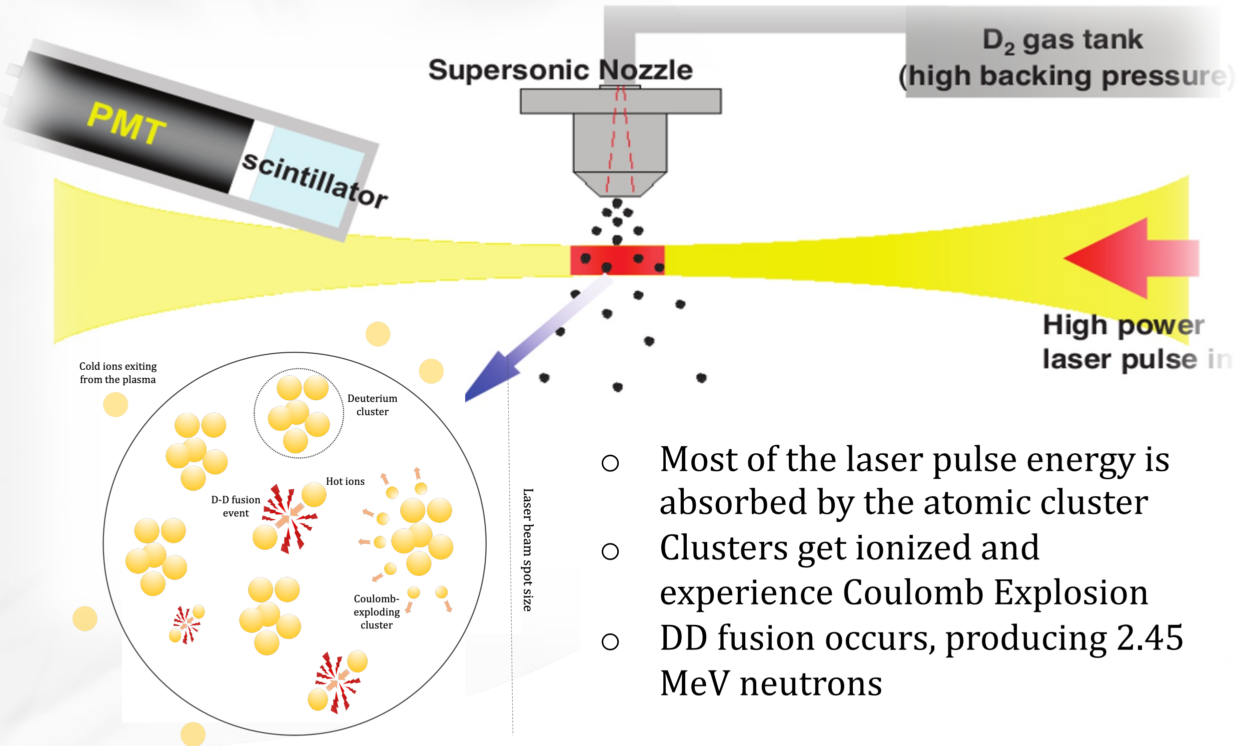
How to be *quantitative*?

1. In order to estimate a cross-section, absolute normalization must be obtained

2. It implies correction for acceptance and efficiency of the experimental setup, and estimation of the initial number of nuclei N_0

3. Toward this estimation, a measurement campaign for characterizing the target system and the ionized volume is being programmed → *Rayleigh scattering, interferometry for measuring the gas density and isotropy*

The open question is: *what are the systematic uncertainties on this quantities?*



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^{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].

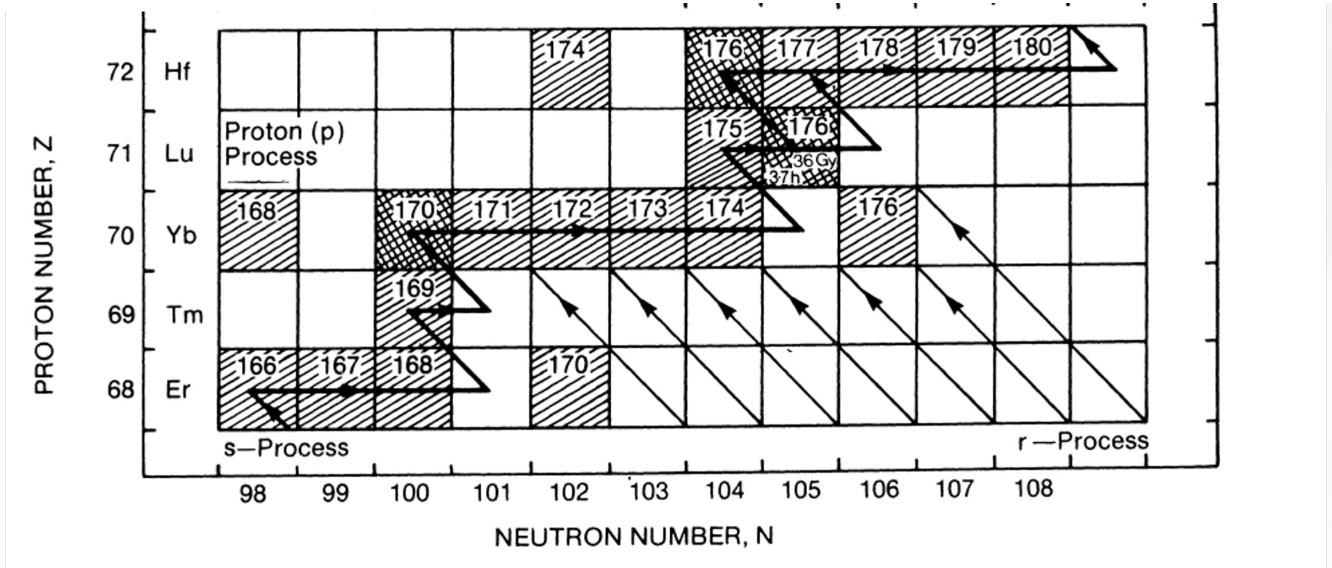
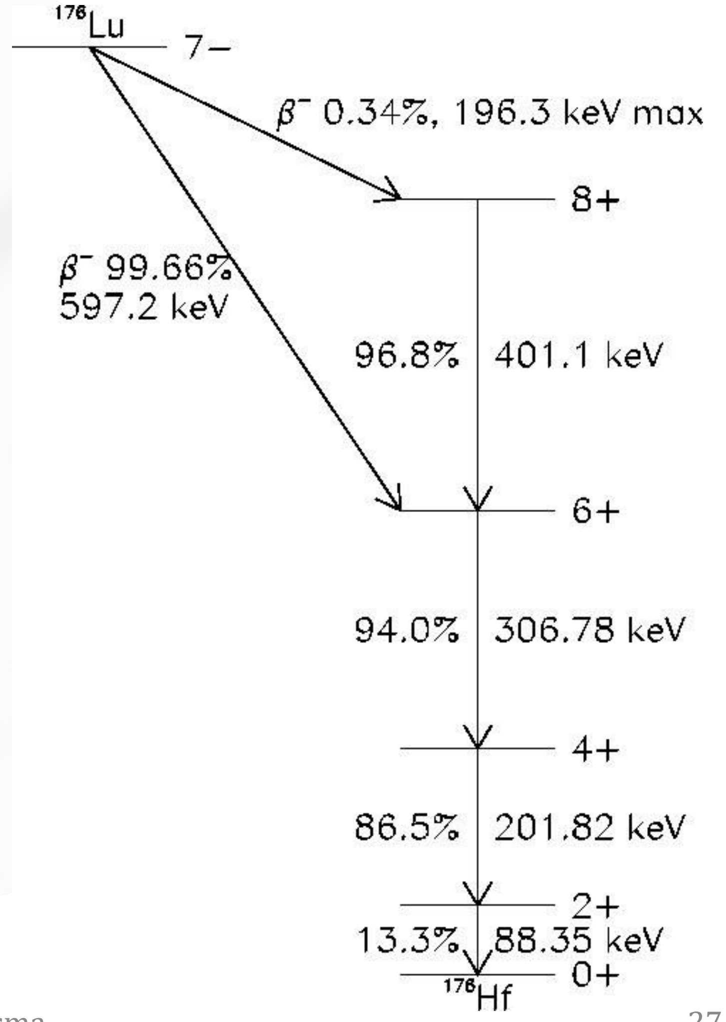


Figure 1. *s*-process path in the rare earth element mass region. *s*-only process nuclides ^{170}Yb, ^{176}Lu and ^{176}Hf are shielded from *r*-process contributions by ^{170}Er and ^{176}Yb respectively. The *s*-process branches at ^{176}Lu if a significant population of the 3.68 h isomeric state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



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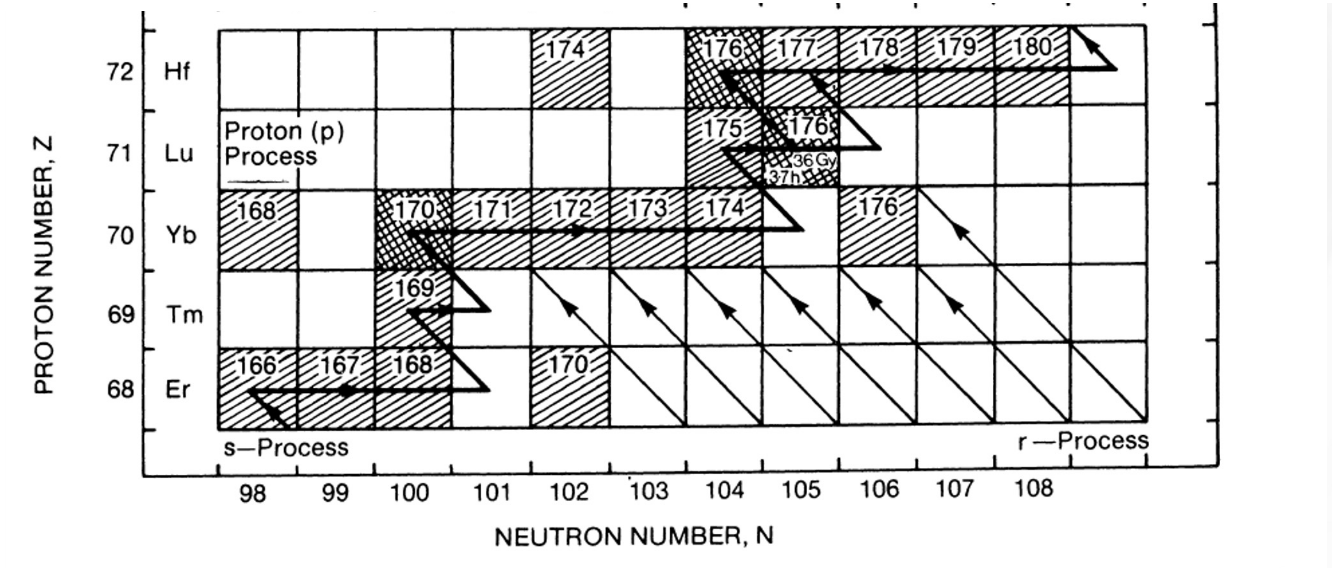

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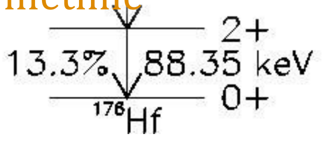
- **the s-process branching point at ^{176}Lu is among the most important ones** for the understanding of slow neutron captures in the Asymptotic Giant Branch (AGB) phases of low and intermediate mass stars;
- **it determines the abundance of ^{176}Hf, an "s-only" nucleus**
- Scenario is complex due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



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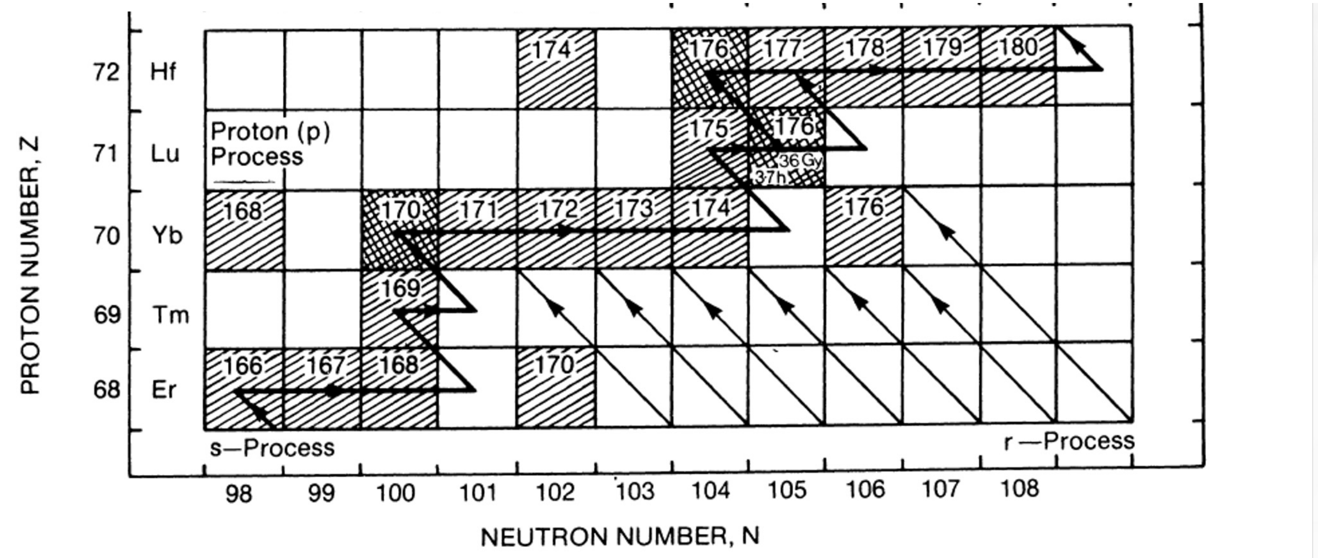

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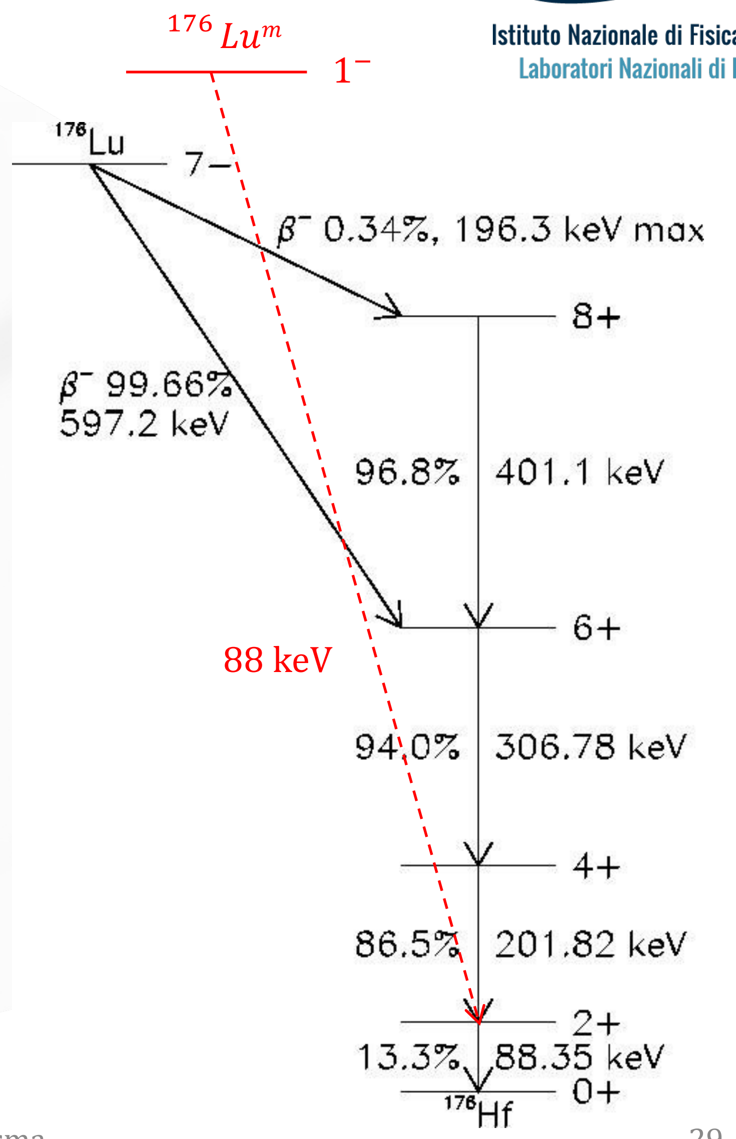

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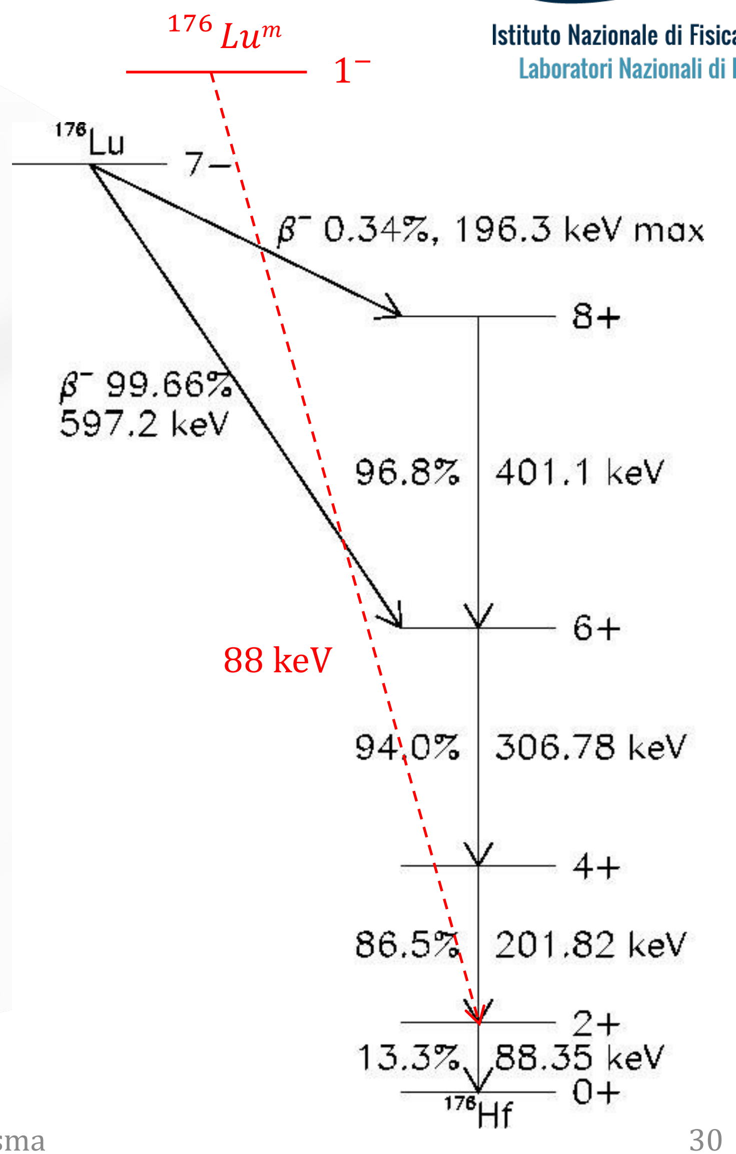
PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

^{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.



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Cosmo-chronometer or stellar thermometer?

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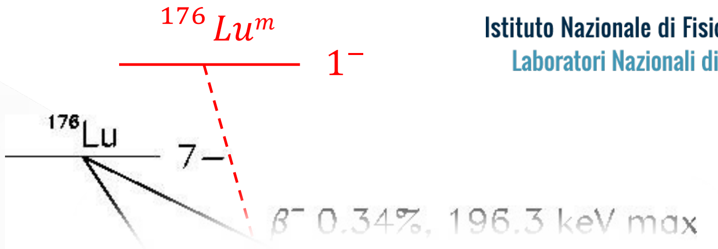

PHYSICAL REVIEW C VOLUME 44, NUMBER 6 DECEMBER 1991

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

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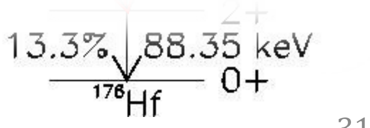
(Received 17 October 1990)

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 $T \geq 3\times10^8$ 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.

The intermixing between nuclear levels in ^{176}Lu has been an open topic in nuclear astrophysics for years because it has a direct impact on its treatment as a **cosmochronometer**.

The contribution of the isomer level will drastically modify the half-life (from years to a couple of hours) and switch its use to a **cosmothermometer** instead.



^{176}Lu decay rates in stellar-like high density and energetic plasma

How can we populate the 1^- 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 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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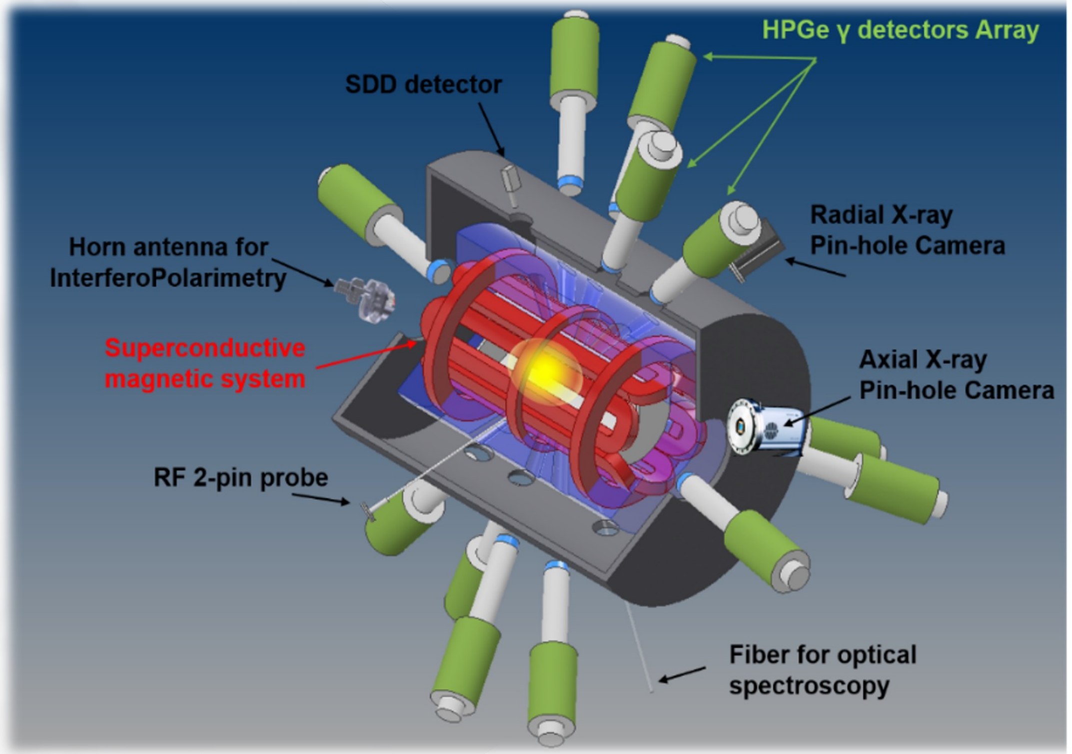
How to measure ^{176}Lu $t_{1/2}$ in plasma?

See talk by B. Mishra

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 eV → Ions are cold: no access to the excited states**



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Why to use laser-induced plasma

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, maybe 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

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Why to use laser-induced plasma

Theoretical questions

X-ray spectrum produced in the plasma

How similar it is to the one in the stellar environment?

How do we measure them (astrophysical observables etc.)? And with what precision?

If there is no thermalization, having a direct measurement of the spectrum can be enough to estimate a possible population of the isomer?

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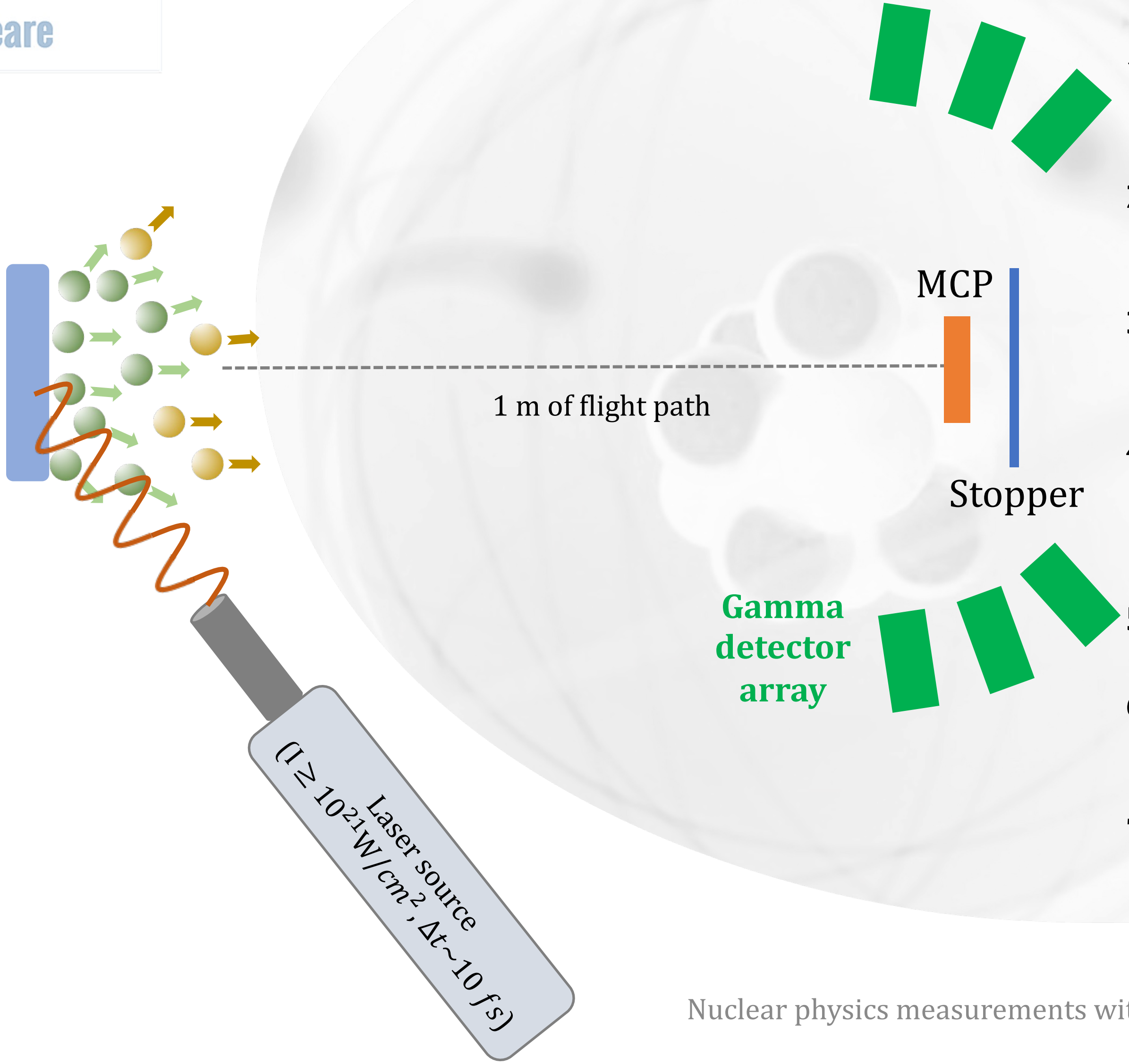
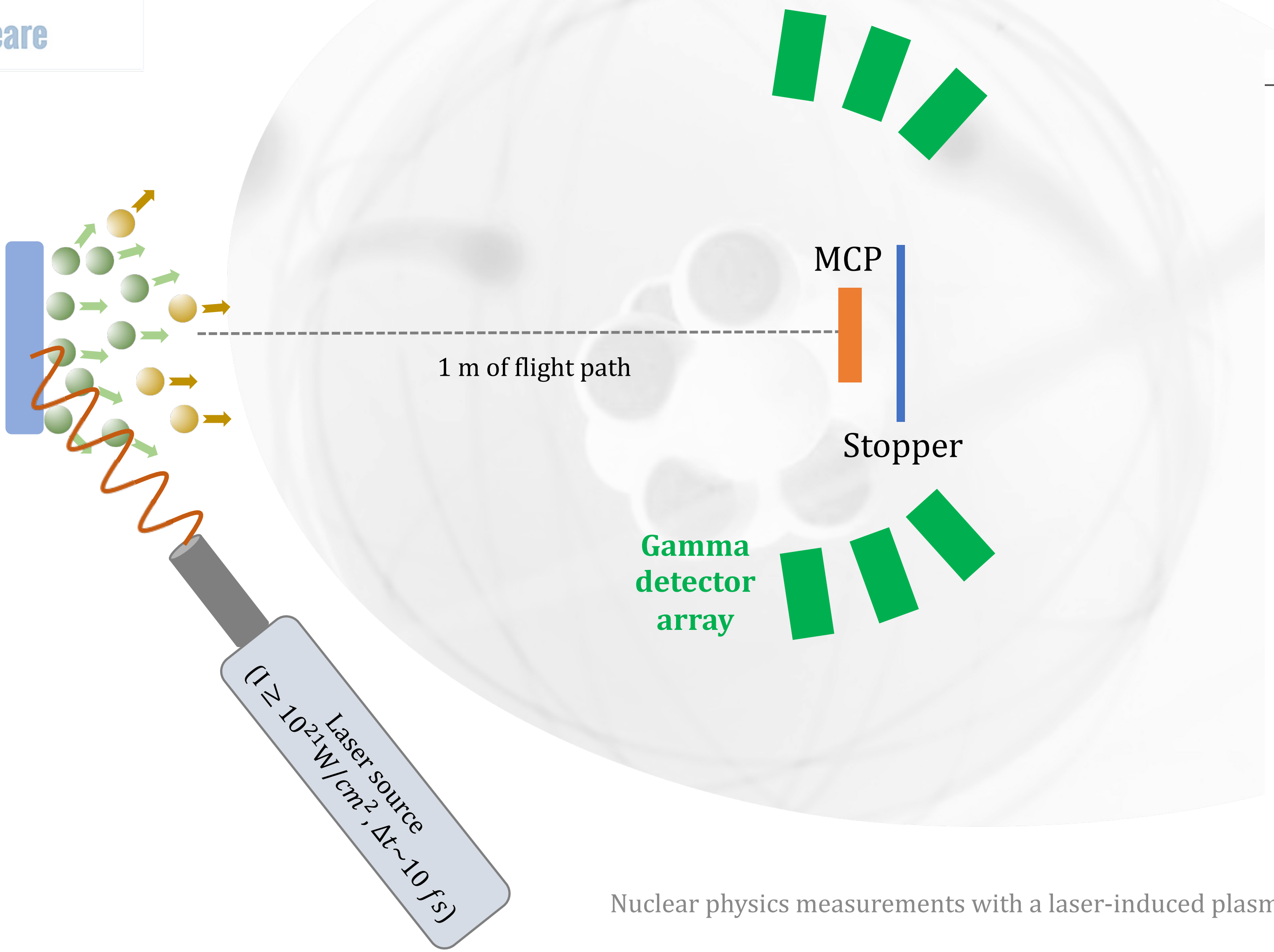
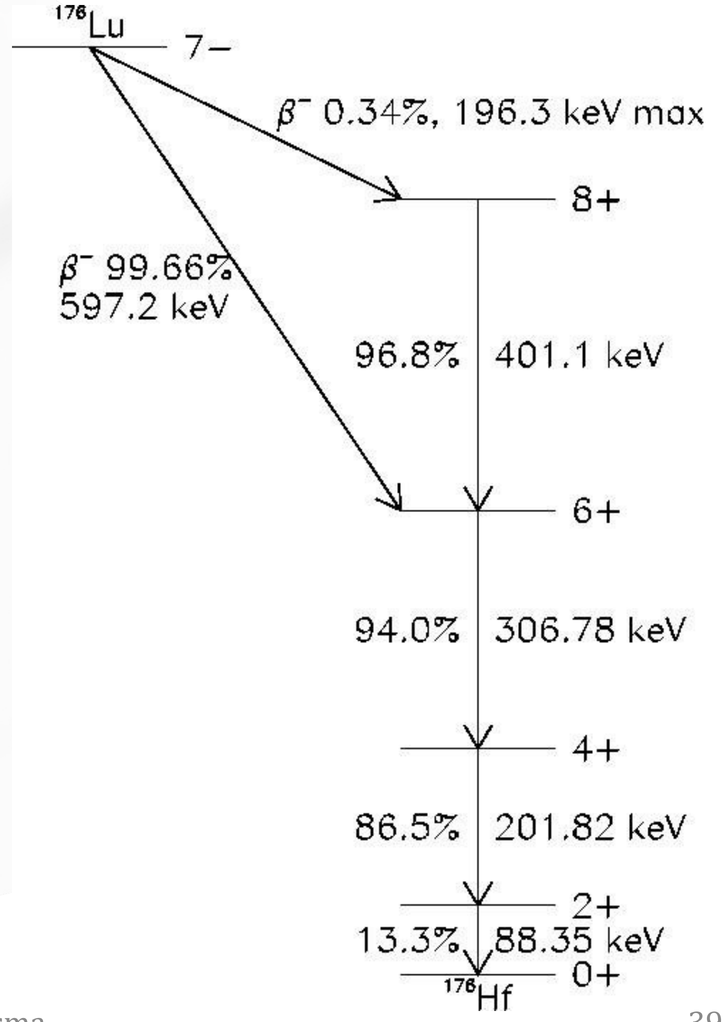
Possible experimental setup for β-decay



1. A high-power 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.
7. Fast detectors are needed → they must be operational despite the gamma flash

Possible experimental setup for β-decay





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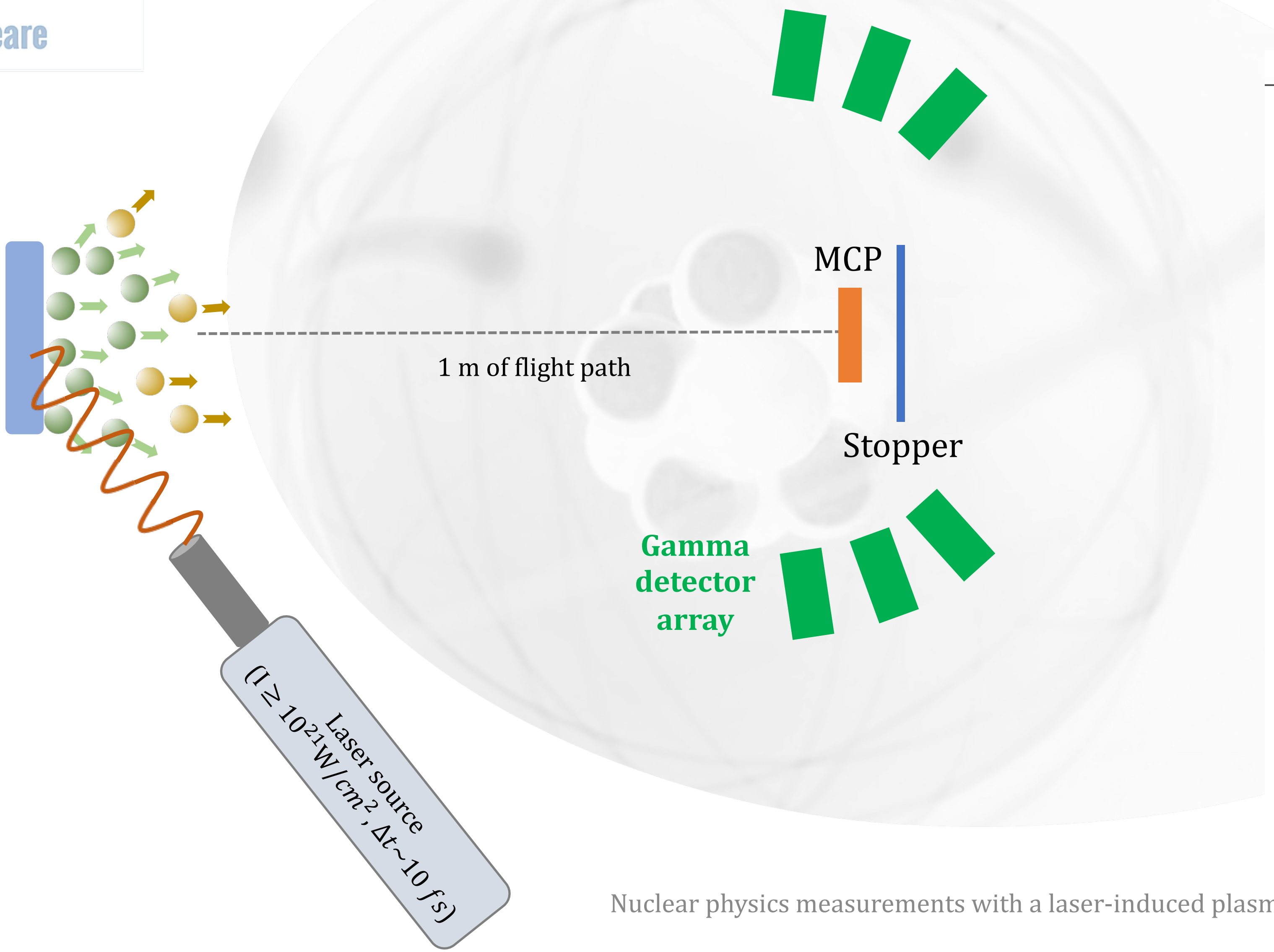

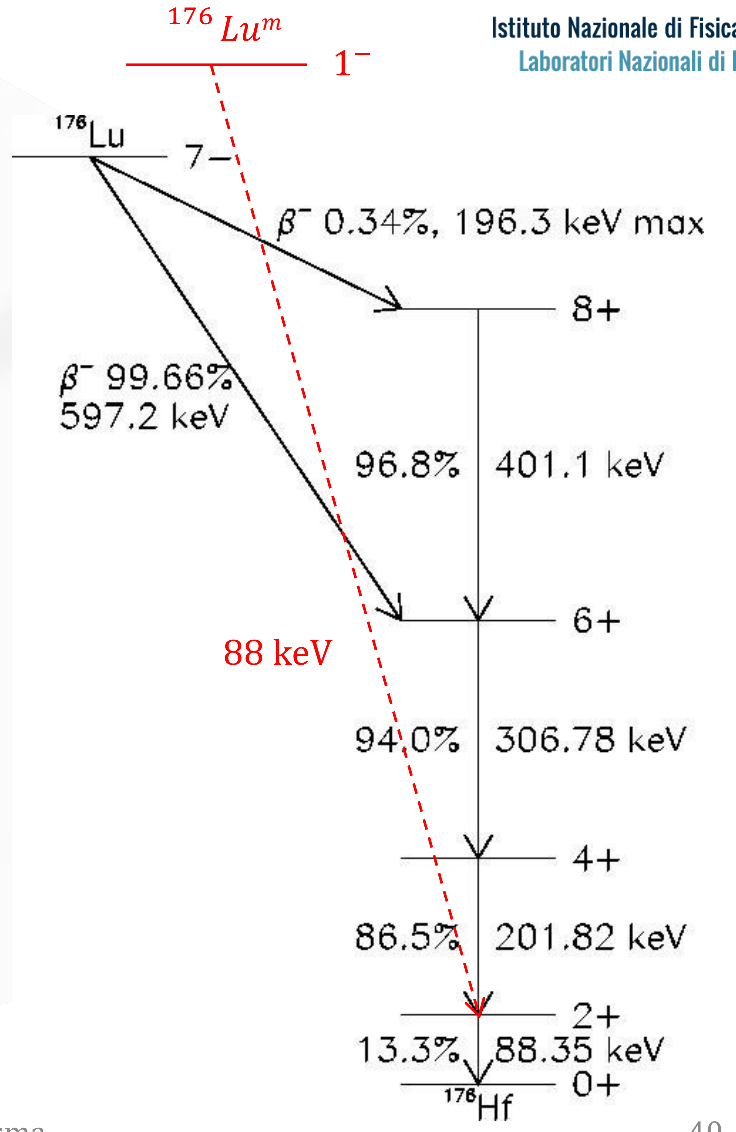

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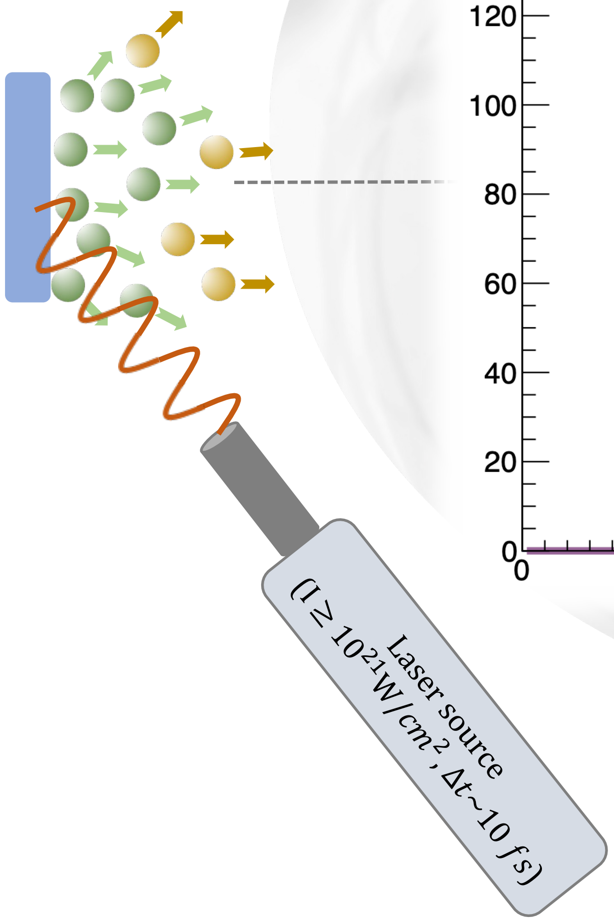

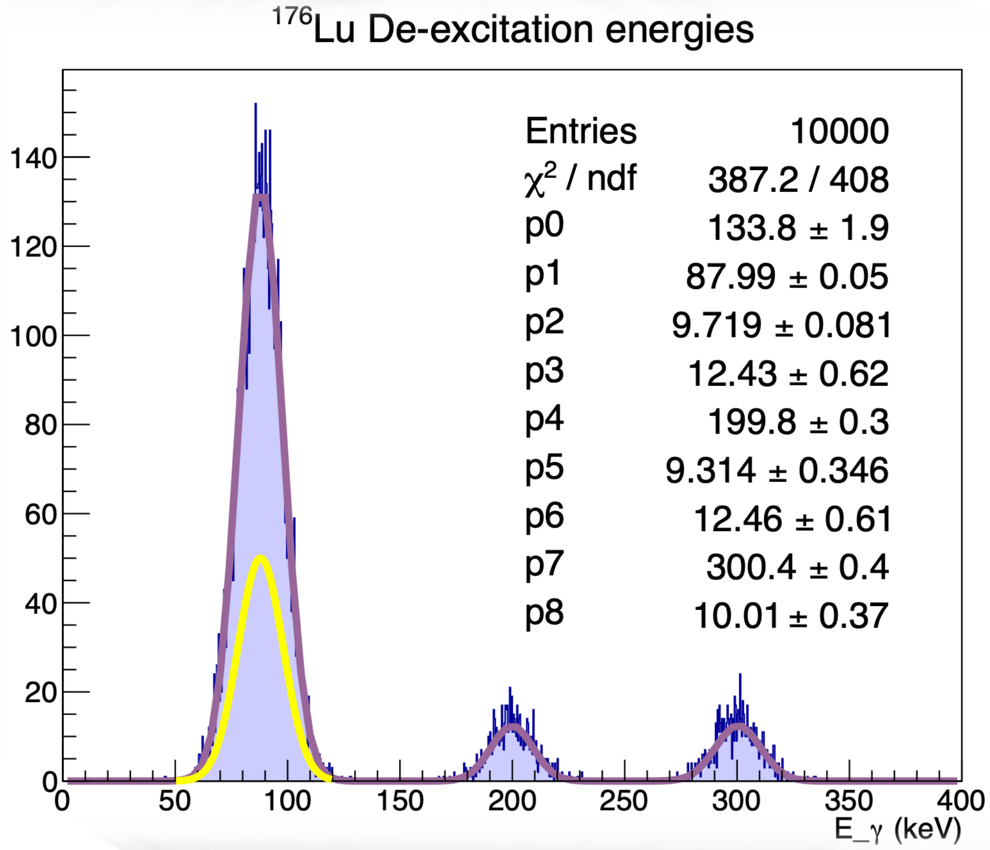

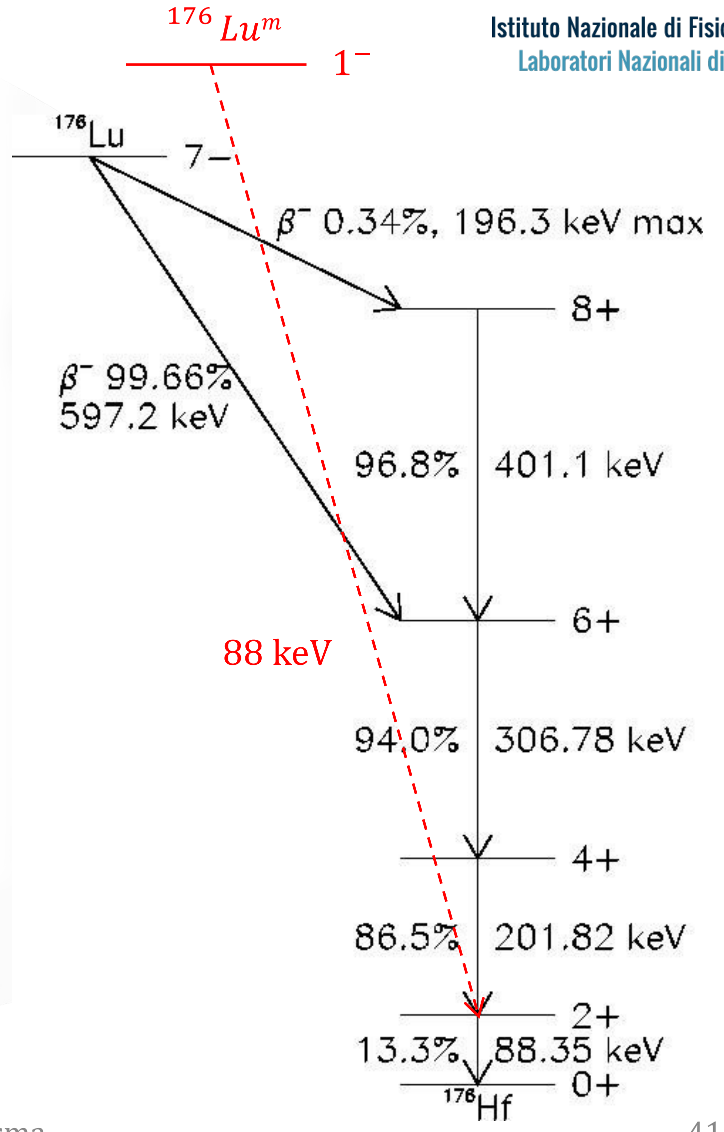

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^{176}Lu decay rates in stellar-like high density and energetic plasma

How can we populate the 1^- level? → *through a proper tuning of laser intensity and target density. But is the spectrum occurring in the plasma reproducible form one measurement to the other?*

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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

Preliminary work is needed before such an approach could be used:

- Better knowledge of ^{176}Lu level scheme
- Accurate measurement of plasma T (if any)
- Scaling with laser pulse duration and intensity

^{176}Lu decay rates in stellar-like high density and energetic plasma

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Is it possible to disentangle the different contributions to the population of $^{176}Lu^{m}$?

- NECC → contribution always present in plasma: how can it be disentangled from the photo-excitation channel? Photon and electron spectra must be under control → a proper diagnostic system is needed
- Access through neutrons: what is the dependence of this contribution on E_n (see talk by Akifumi and Hayakawa)? Is it possible to estimate it by changing the target composition?
- Are all these contrbutions present in stars? What is the relative weight of the different mechanisms?

^{176}Lu decay rates in stellar-like high density and energetic plasma

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Nuclear physics measurements with a laser-induced plasma: experimental issues and open questions

How do we measure them?

- Detectors and electronics must be compatible with EMP, and their response fast enough
- Accessible isotopes can be limited by experimental conditions

What are the sistematics?

- How stable is the laser system (position, spot size) and to what extent measurement setup is reproducible?
- Target characterization is essential to normalize «countings»

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Nuclear physics measurements with a laser-induced plasma potential experimental issues and open questions

How well we do know the stellar environment?

- In order to properly use plasma measurements to mimick stellar conditions, the latter must be well determined → *what are the astrophysical observables used to determine them?*
- *With what precisions are they known?*
- To what extent are the spectra of the different radiations present in stellar cores known?

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Fundamental research and applications with the EuPRAXIA facility at LNF

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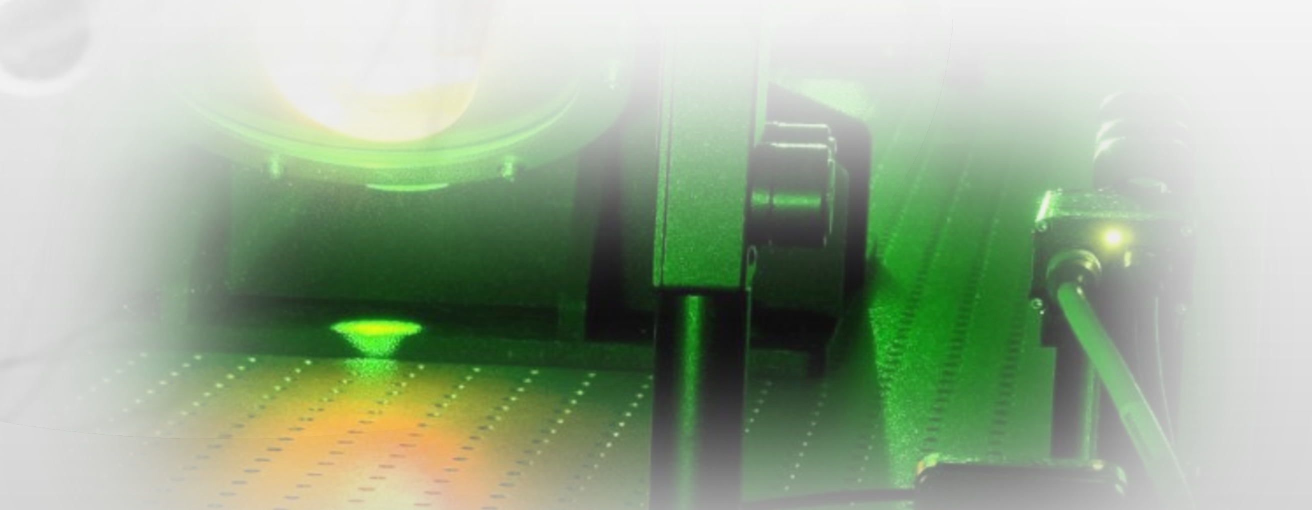

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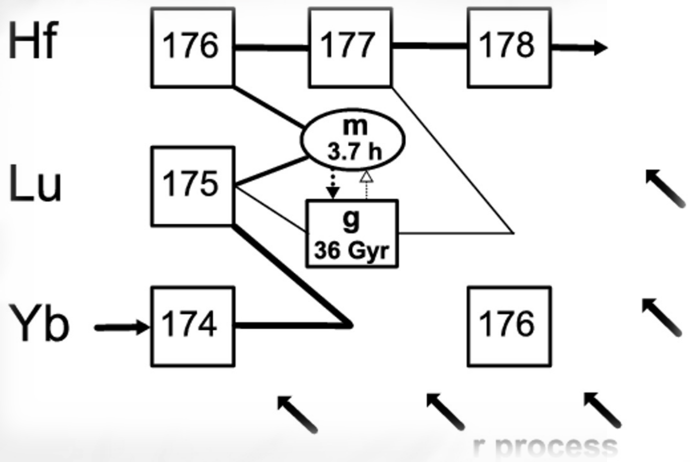
The naïve idea of the experiment is:

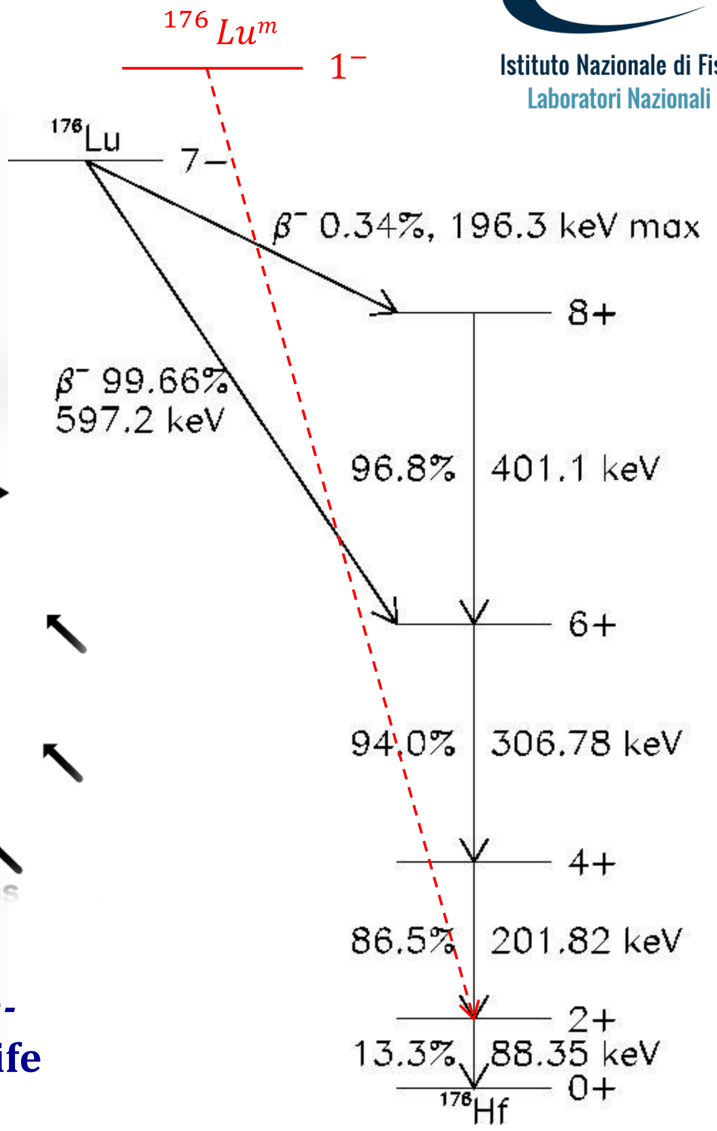
- ps lasers are directed toward a solid target composed of ^{176}Lu
- laser-generated plasma emits high energy X-ray bremsstrahlung produced from reactions between energetic electrons and buffer/^{176}Lu ions
- These X-rays are absorbed by the ^{176}Lu nuclei which get photoactivated to the 1^- isomer level according to a cross section σ(E) photoactivation rate $\lambda^c(n_e, n_i, T, s)$
- ^{176}Lu nuclei undergo β^- decay to ^{176}Hf from both the 7^- and 1^- levels
- Daughter nuclei will decay emitting specific gamma-rays
- Assuming the plasma remains active and stable LTE for a time T, the total number of specific γ-photons recorded can be correlated to the aforementioned rates
- The yield of 88.25 keV photons can be correlated to $\lambda_m^d(n_e, n_i, k_B T, s)$ if the photoactivation rate $\lambda^c(n_e, n_i, k_B T, s)$ is known
- Same considerations works for decay from g.s.

^{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

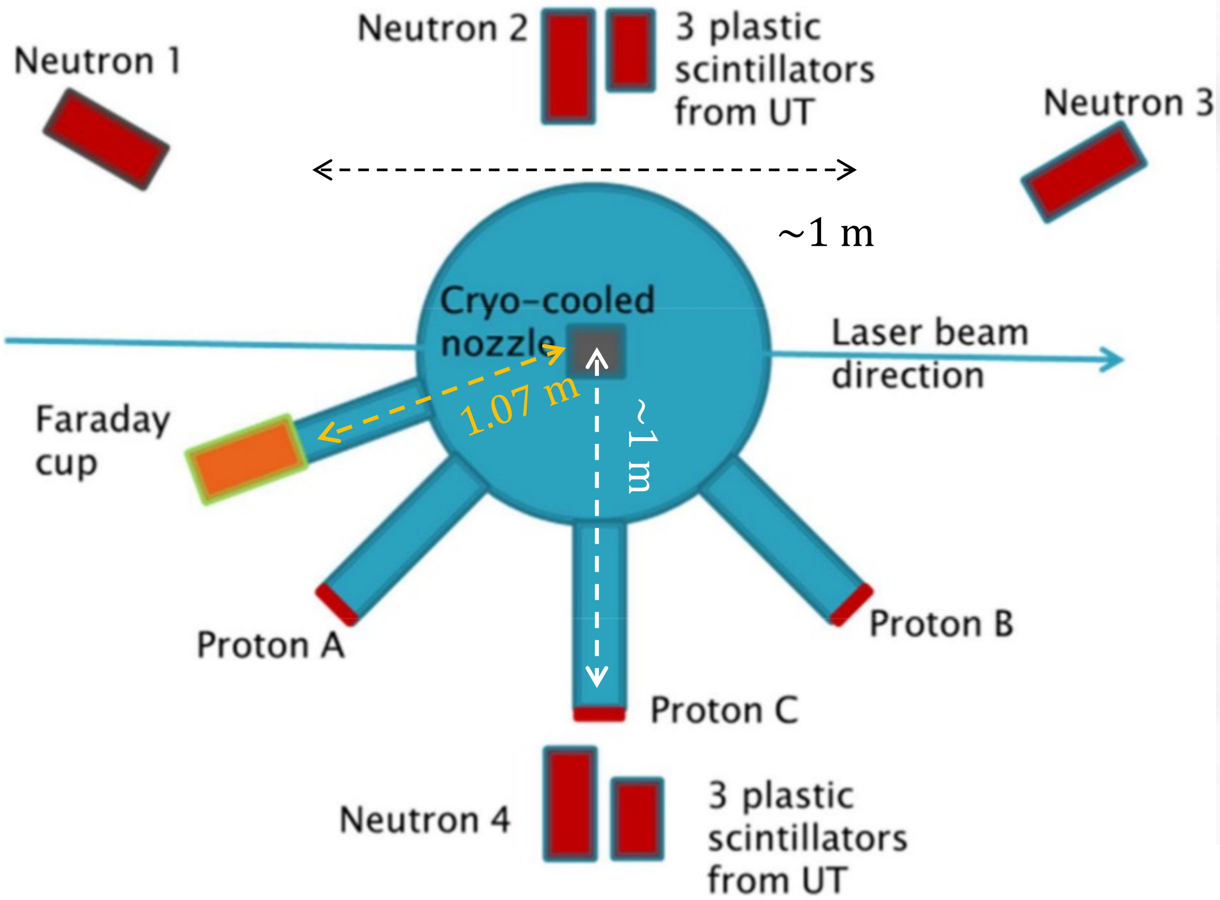




Important to investigate the *in-plasma* variations of the half-life

See talk and poster by B. Mishra

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

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

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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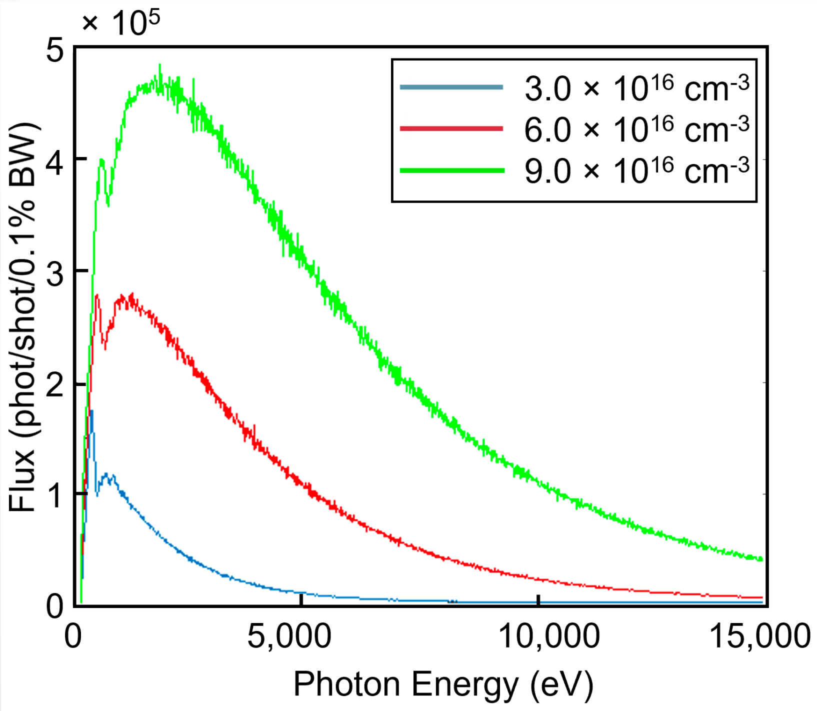

Parameter [Units]	Value
Beam energy [MeV]	600–950
Plasma density [cm^{-3}]	3.0×10^{16}
RMS transverse beam size [μm]	3.0
Charge [pC]	45
Capillary (plasma) length [m]	0.6
Pulse duration [fs]	10

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

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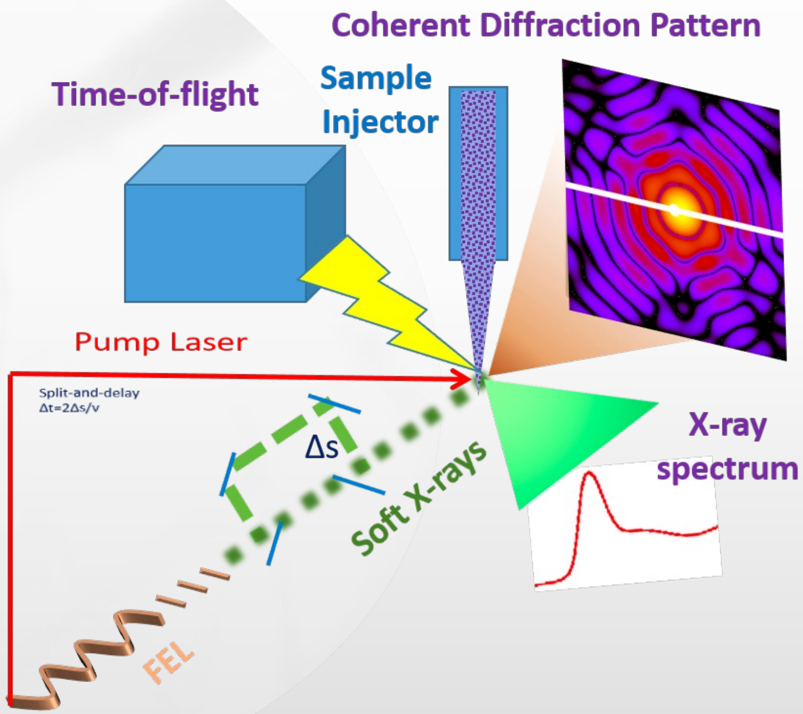
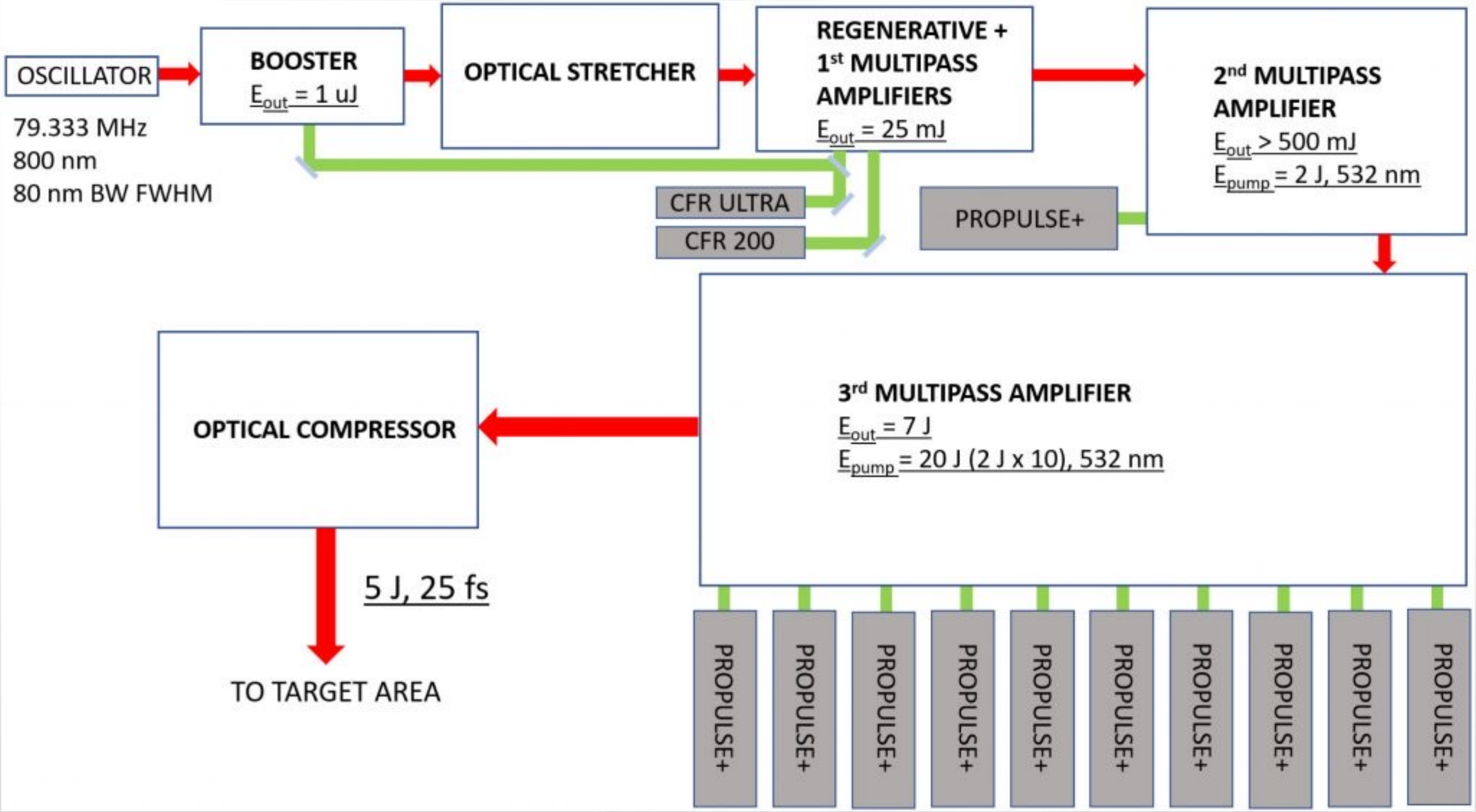
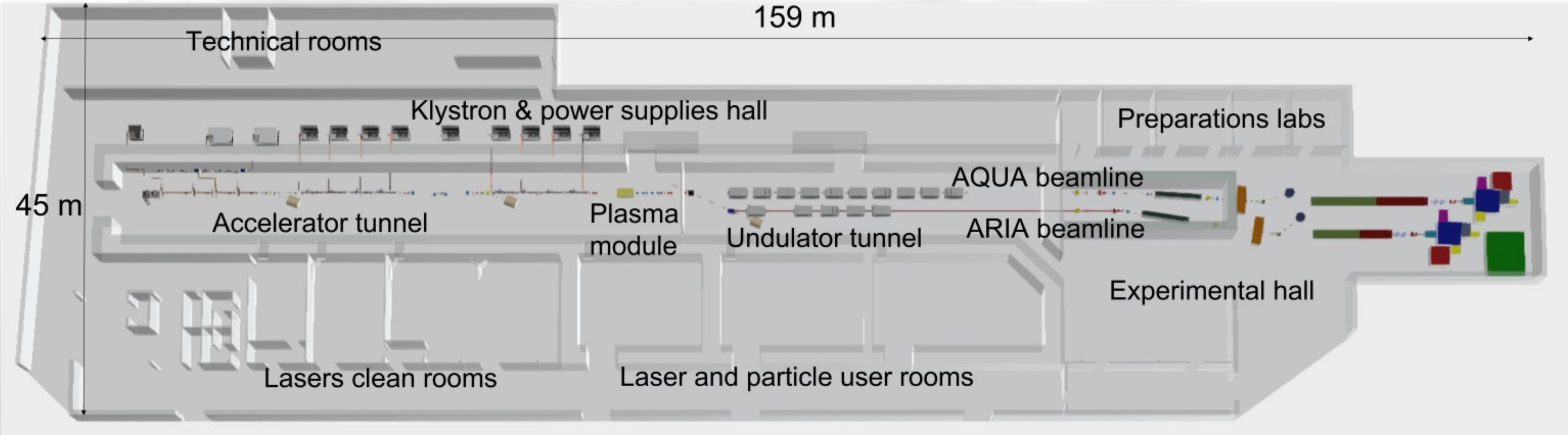


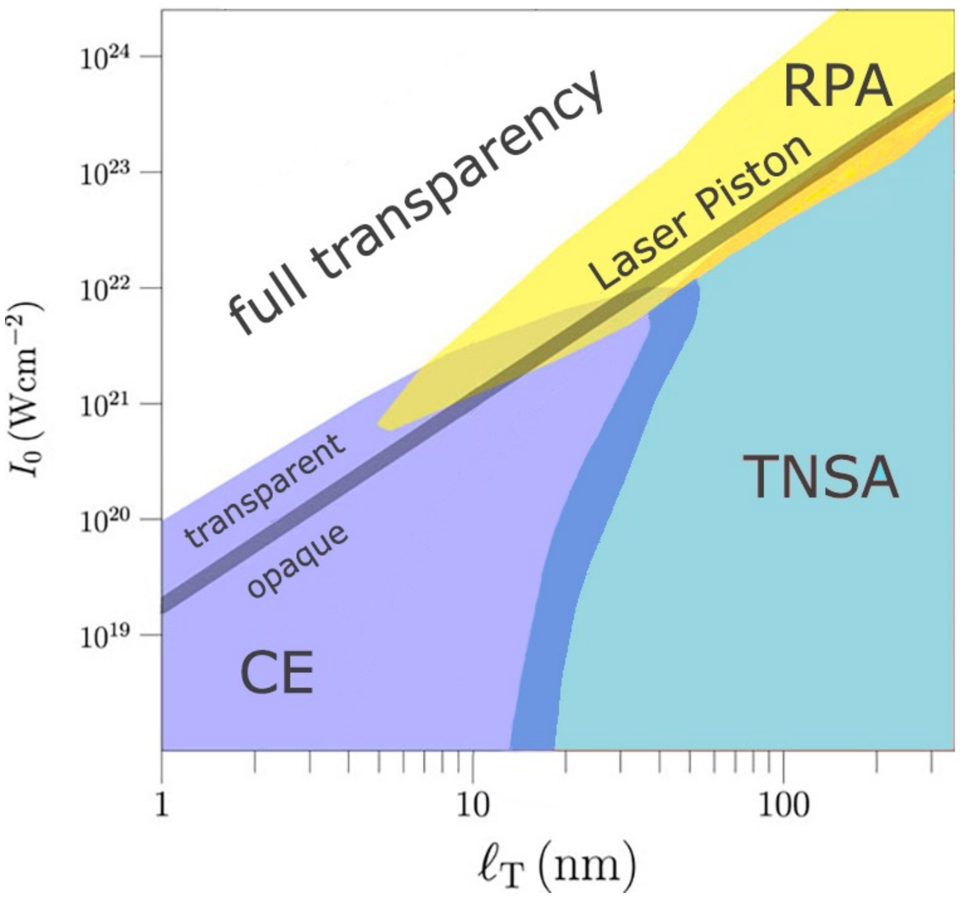
EuPRAXIA sources: laser



EuPRAXIA sources



Laser-matter interaction

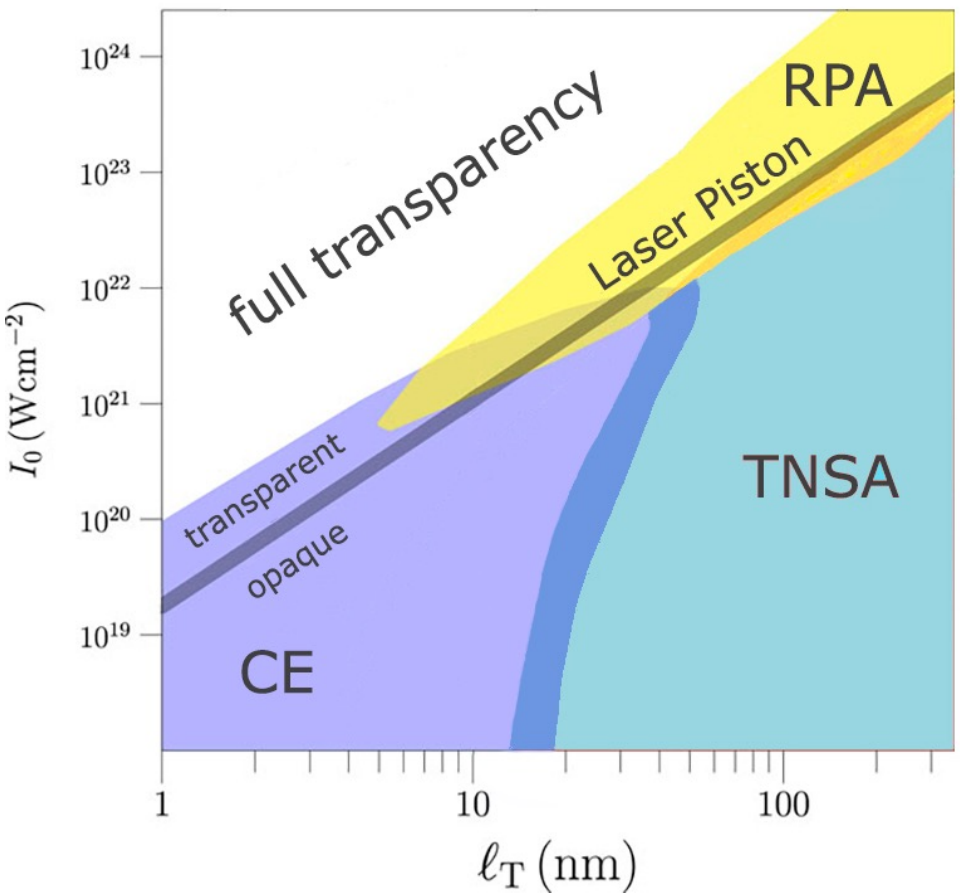


When a high intensity laser pulse (above 10^{18} W/cm^2) is focused in a spot of the order of a few microns on a target placed in vacuum, a plasma consisting of electrons and ions is created almost instantaneously.

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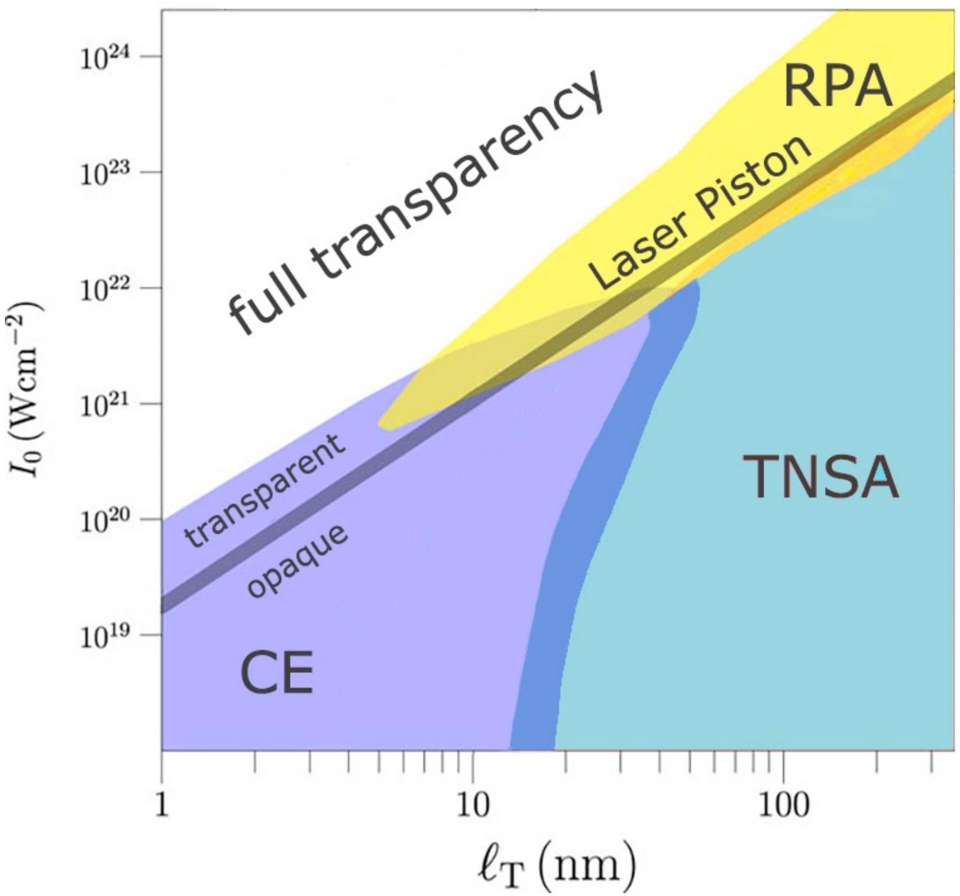
- **Radiation Pressure Acceleration (RPA), or Laser Piston regime:** based on the action of the radiation pressure induced in the interaction of a short laser pulse, of extremely high intensity (above $10^{20} \div 10^{21}$ W/cm^2), with a thin and dense pre-plasma layer created, in front of a target,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

Nuclear physics: fusion processes

Nuclear physics: beta decays in plasma

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

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Scaling results to stellar environment

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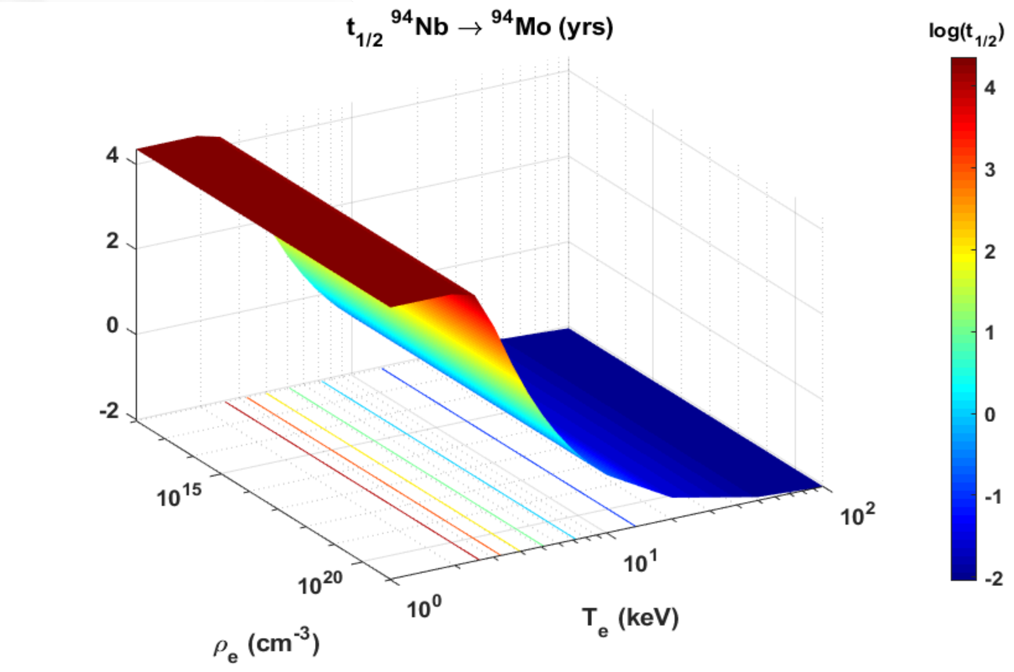
$$\frac{dN}{dt} = \lambda n_i V \rightarrow \int_0^{T_{meas}} dN = \int_0^{T_{meas}} \lambda n_i V\ dN$$

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

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



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* $\lambda^c (n_e, n_i, T, s)$
- *decay rates* $\lambda^d (n_e, n_i, T, s)$ *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*)

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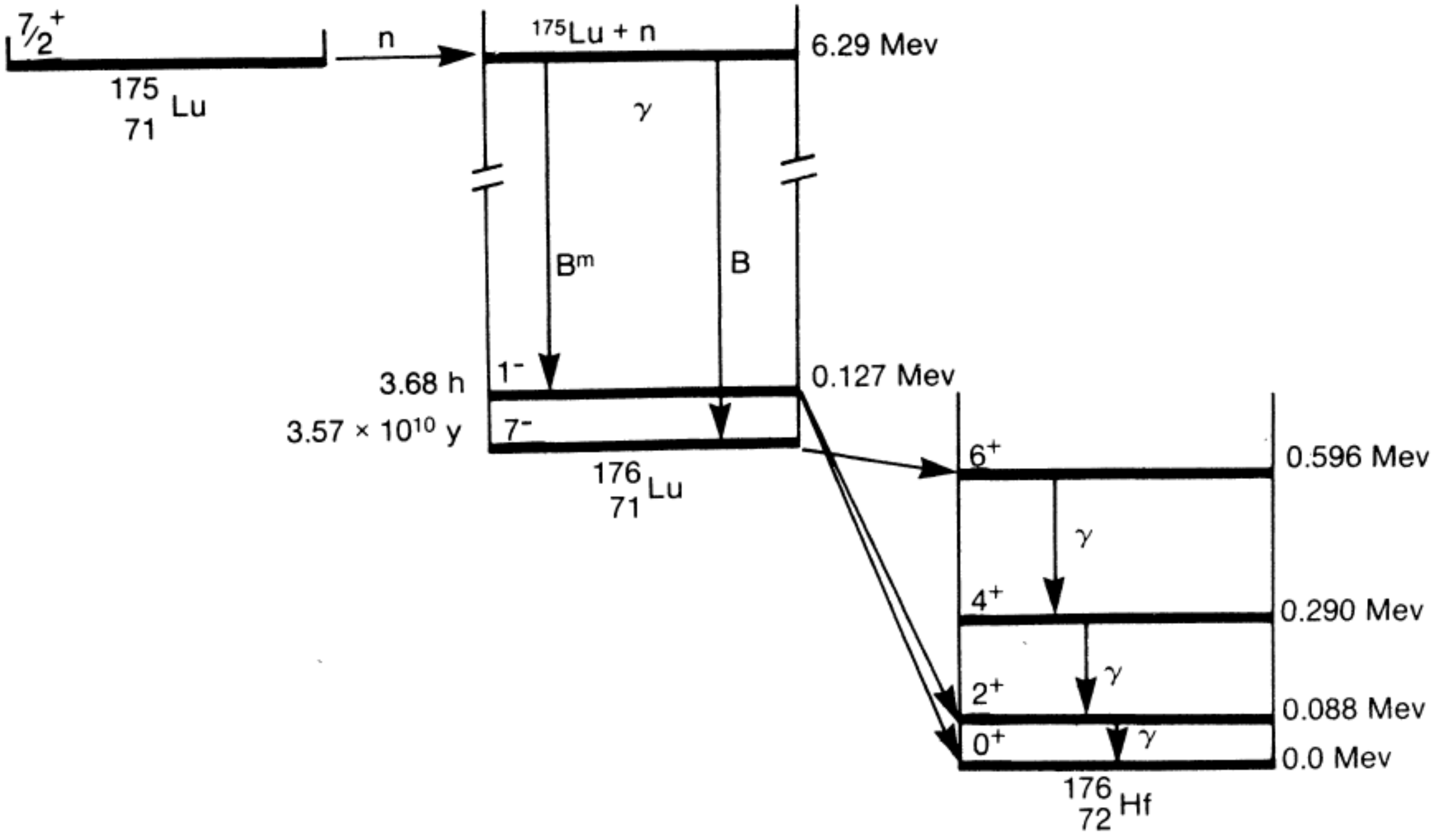
$$N(T_{meas}) = \lambda n_i V T_{meas}$$

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.

Decay scheme for lutetium



^{176}Lu physics case

Cosmo-chronometer or stellar thermometer?

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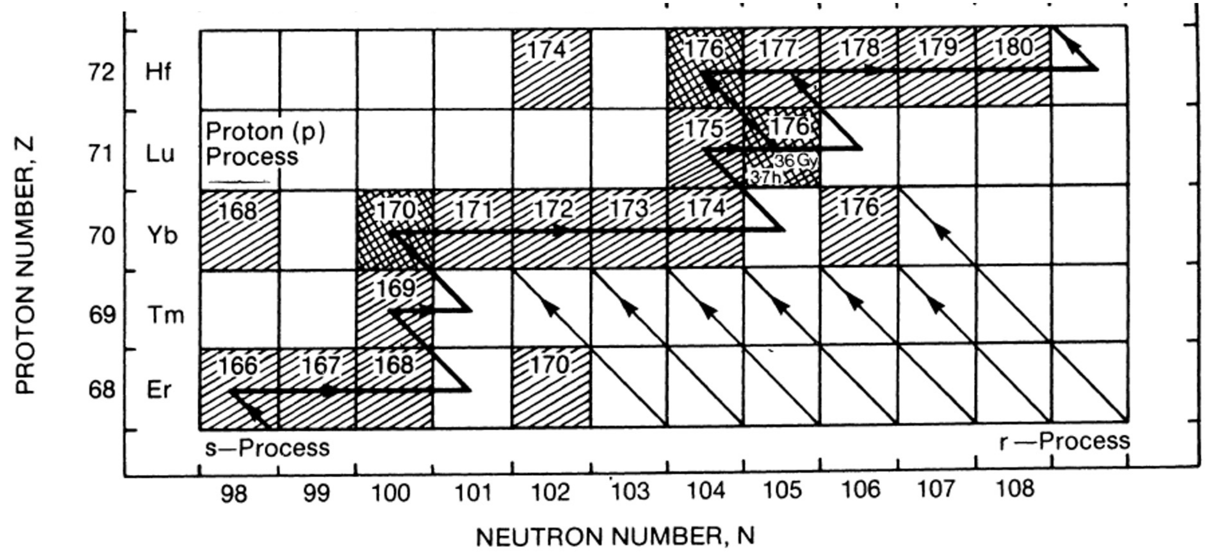
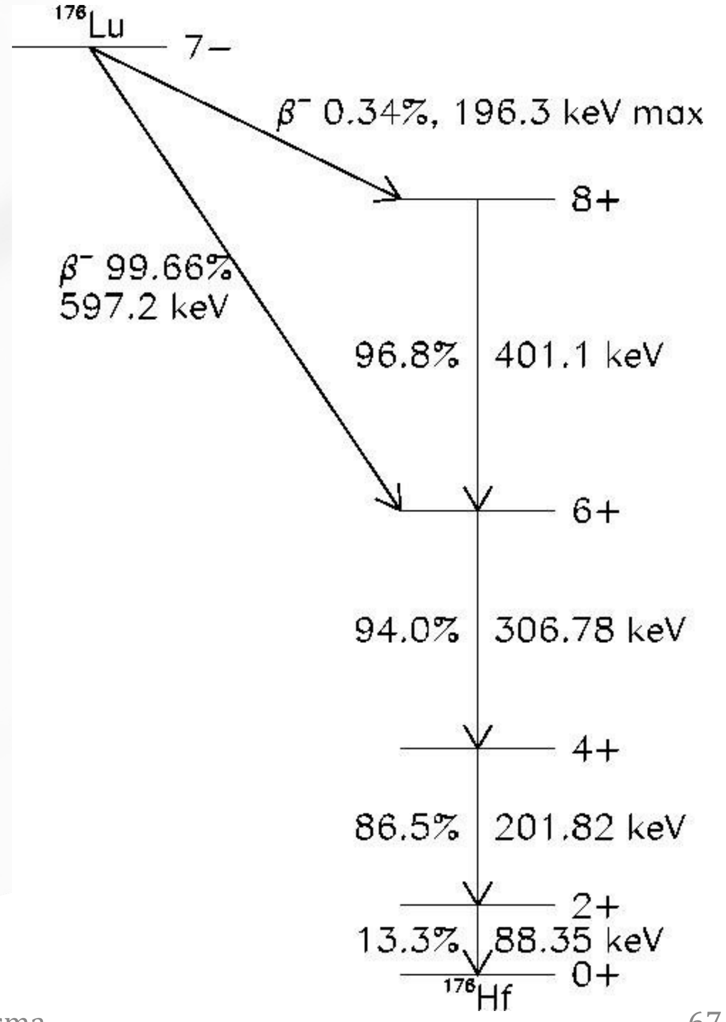


Figure 1. *s*-process path in the rare earth element mass region. *s*-only process nuclides ^{170}Yb, ^{176}Lu and ^{176}Hf are shielded from *r*-process contributions by ^{170}Er and ^{176}Yb respectively. The *s*-process branches at ^{176}Lu if a significant population of the 3.68 h isomeric state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



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

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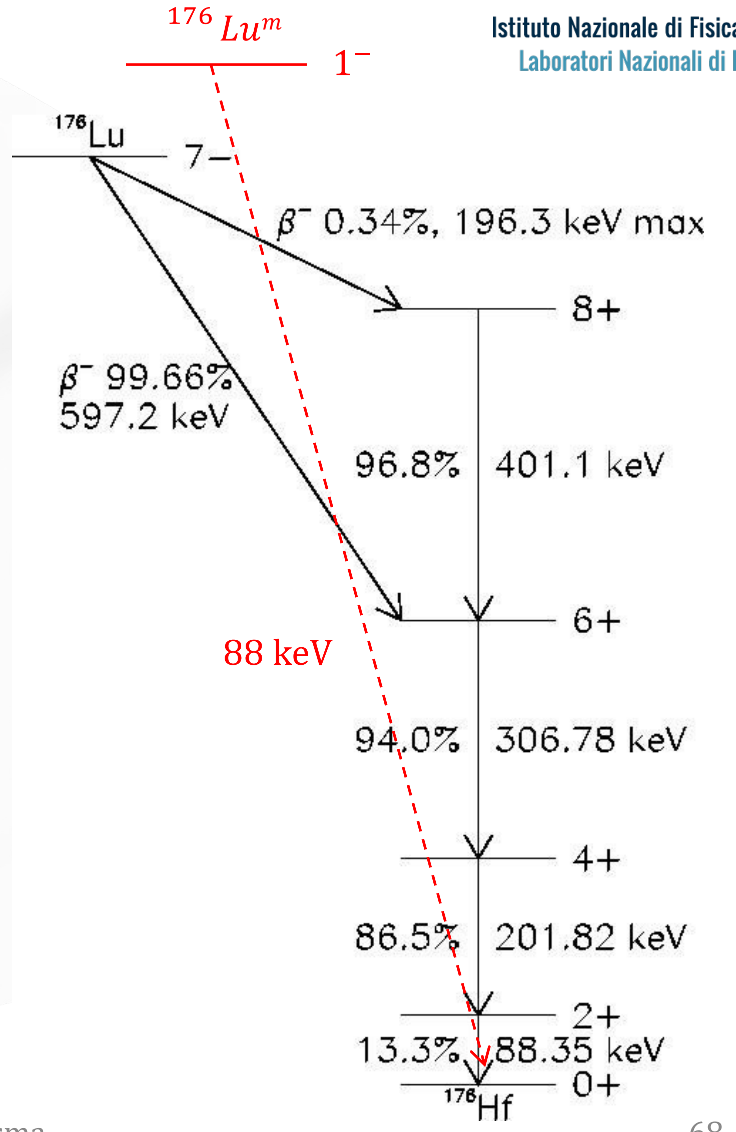
A level scheme of ^{176}Lu up to ~1400 keV excitation energy is deduced from a γ-γ coincidence experiment and previously published particle transfer data. 170 γ-ray transitions are placed between 85 levels. We identify 27 previously unknown levels and 131 previously unknown transitions in ^{176}Lu. With 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.



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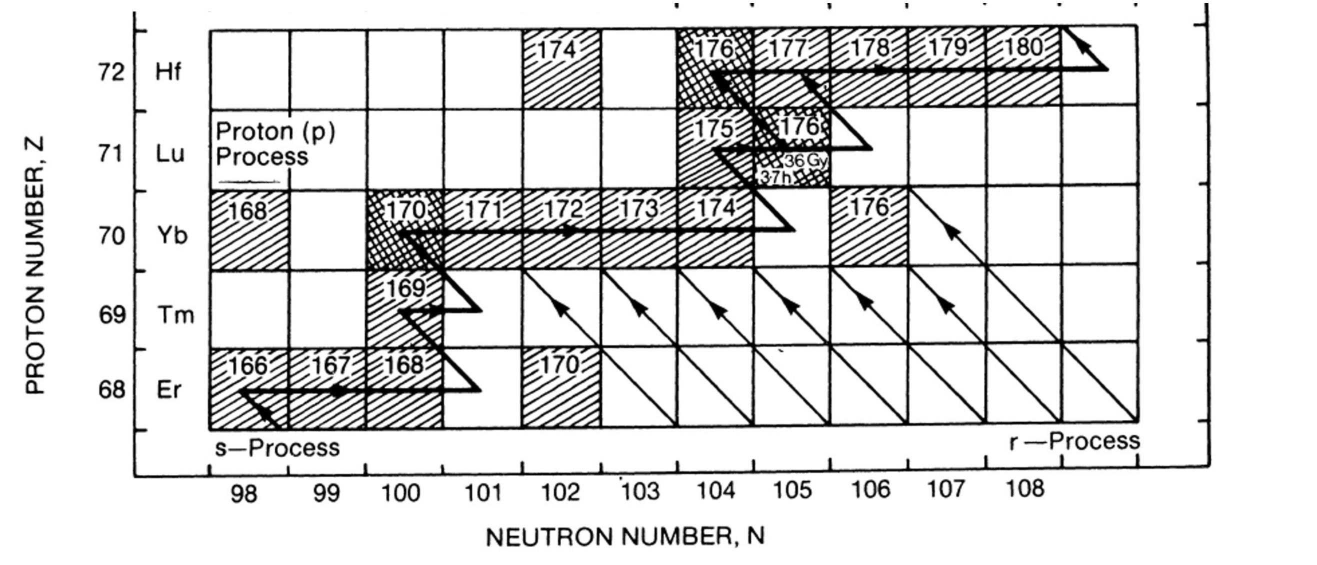

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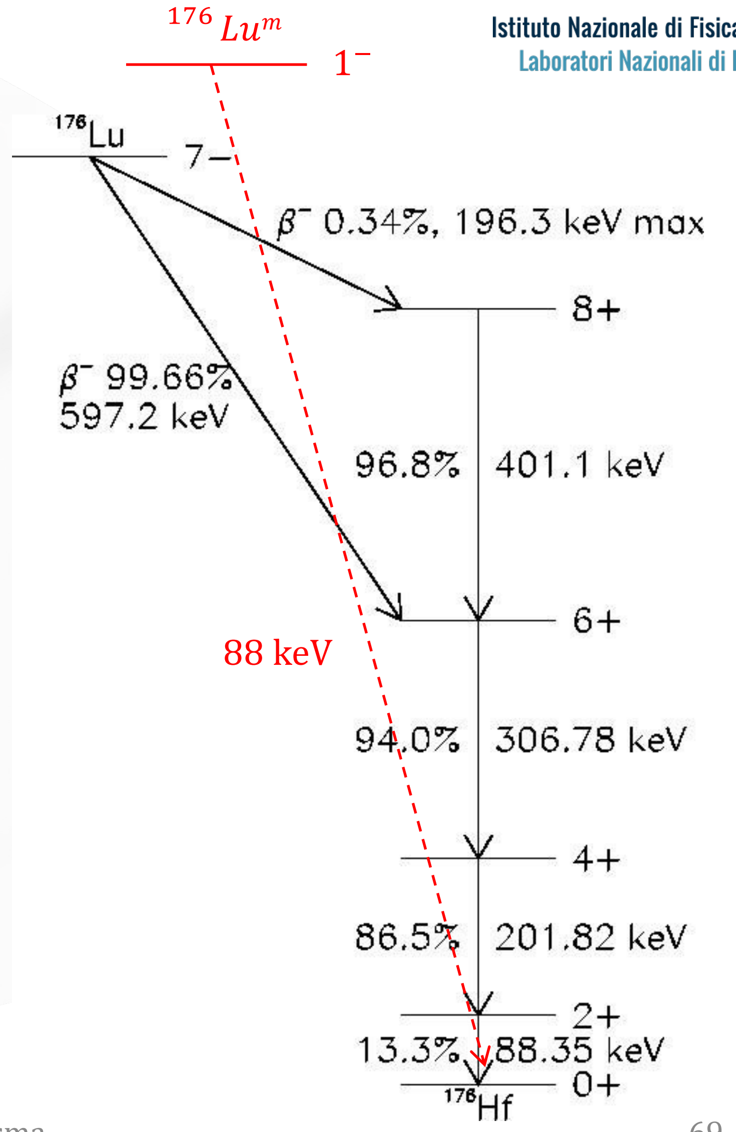

CSN3 Fisica Nucleare

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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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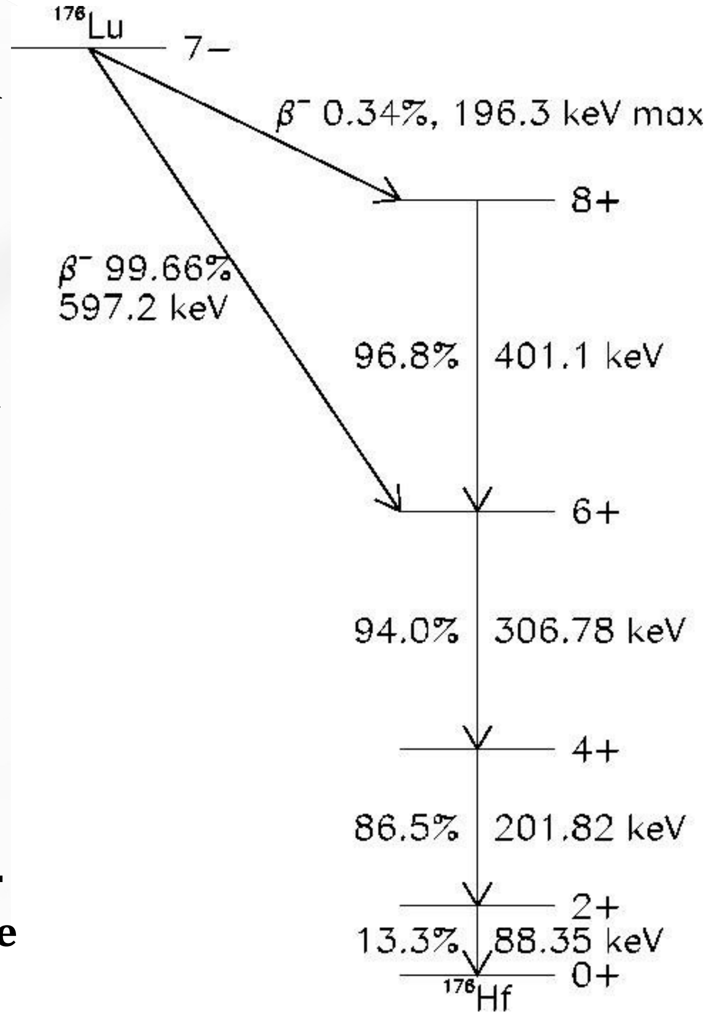

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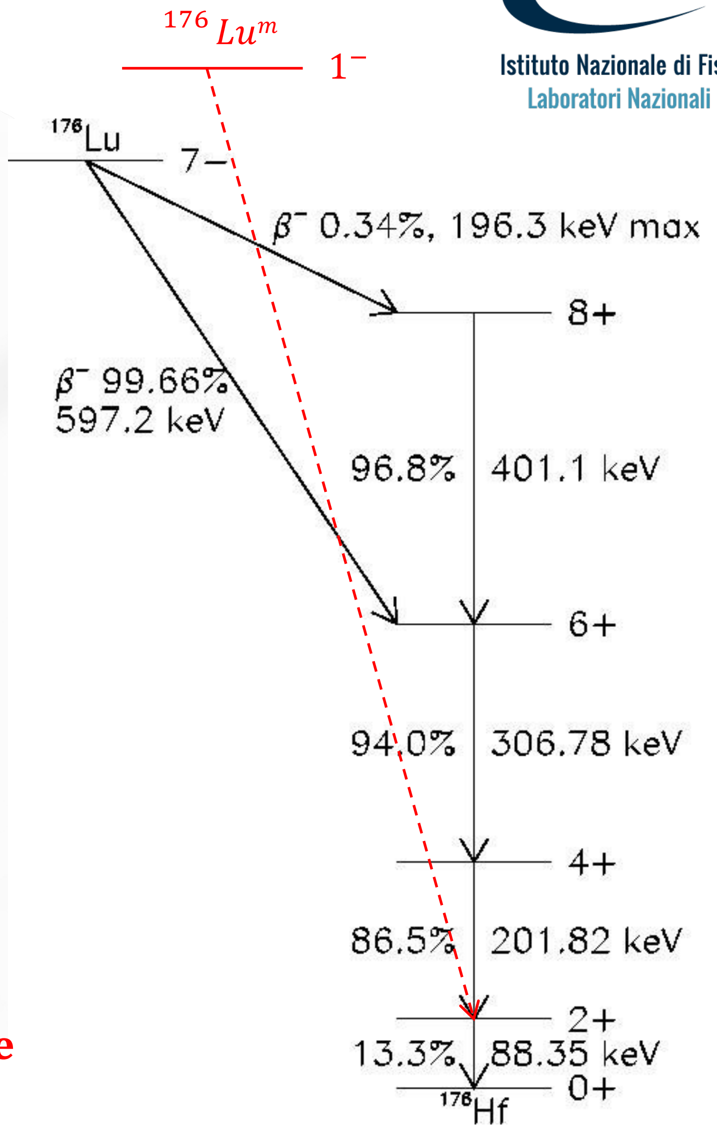

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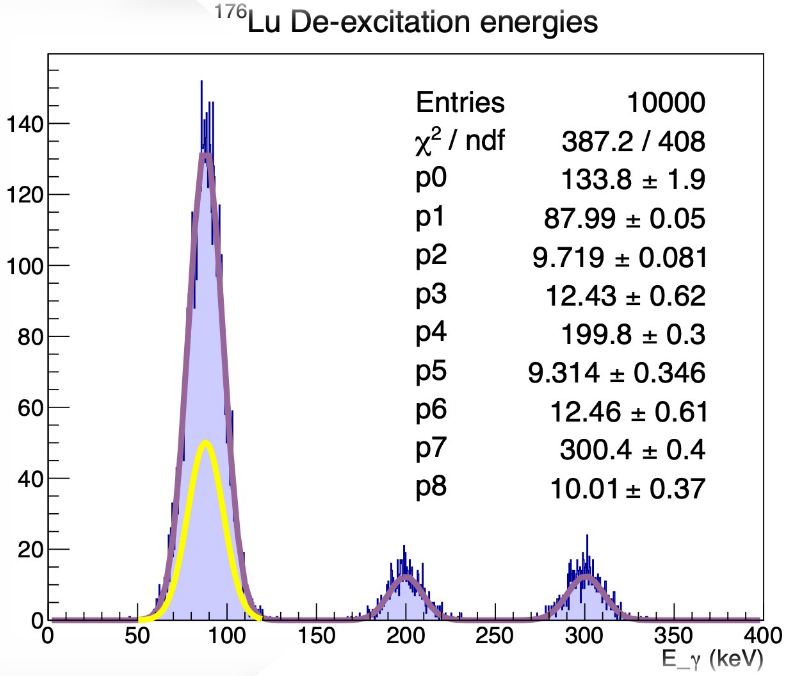
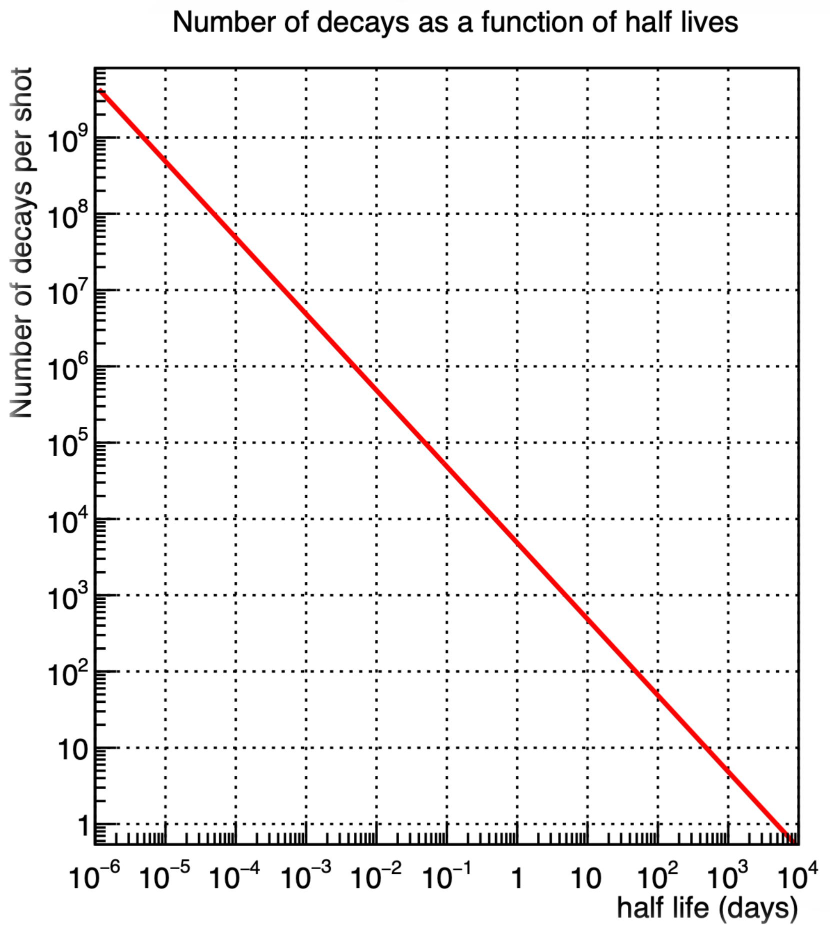
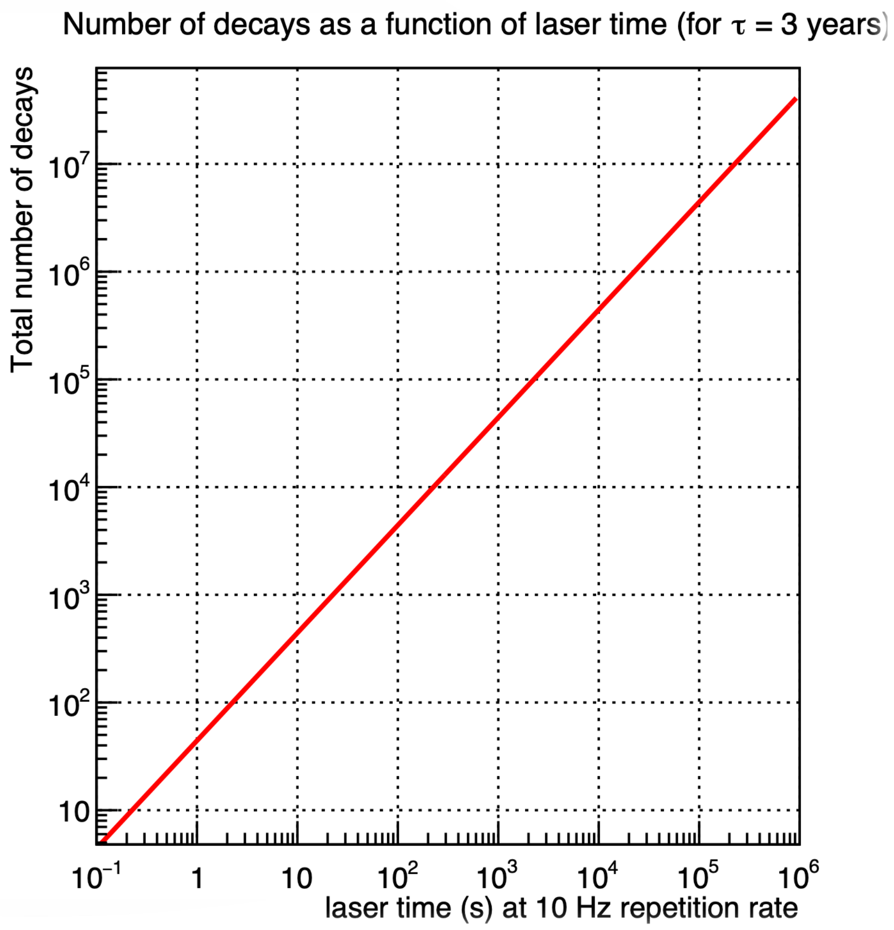


Projections for a 10 Hz repetition rate





CSN3 Fisica Nucleare

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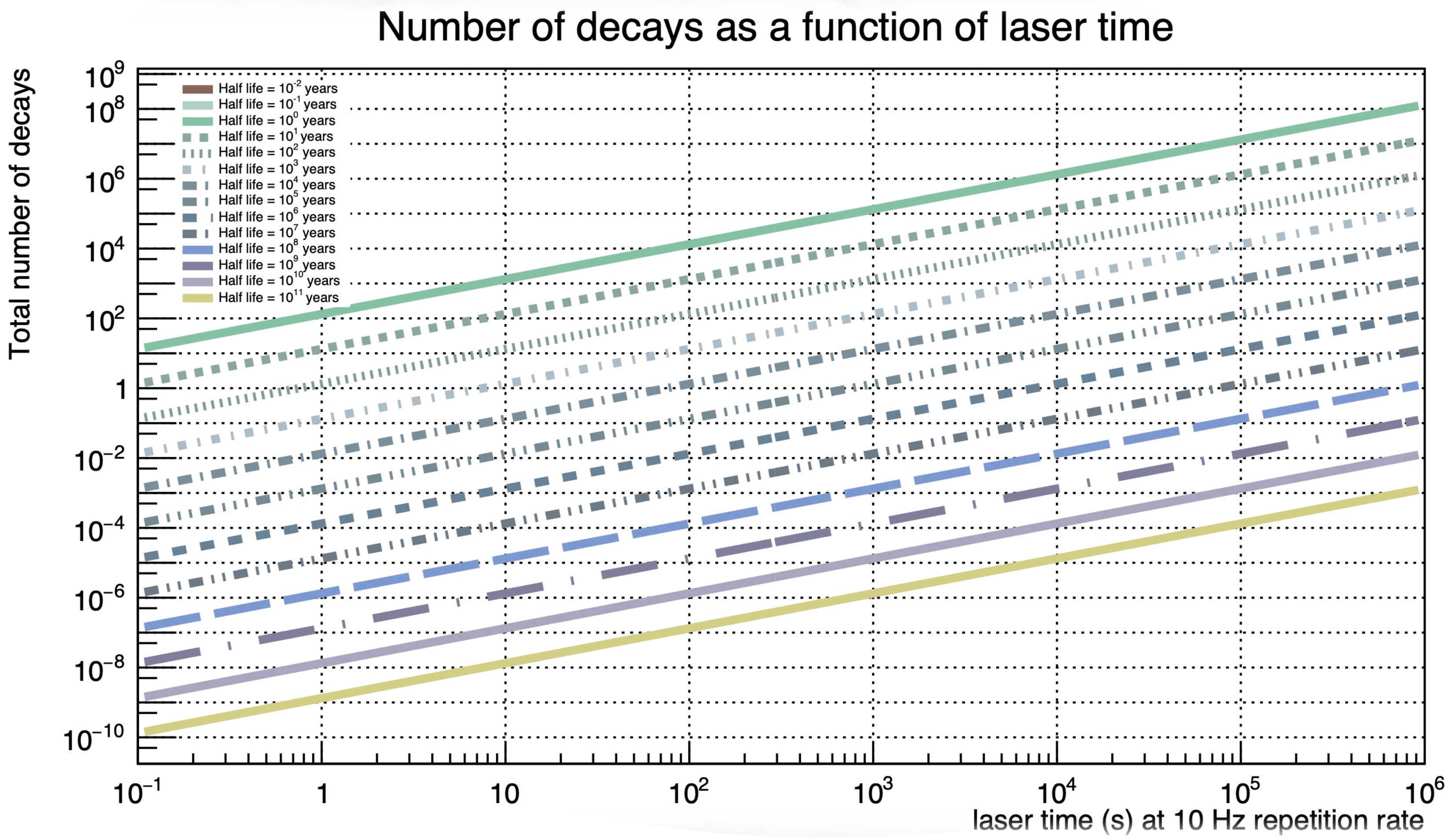

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