Nuclear decay in a laser-generated plasma

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1st INFN Workshop on ‘’ High power lasers and their applications ‘’ – Catania, 11-12/01/2024

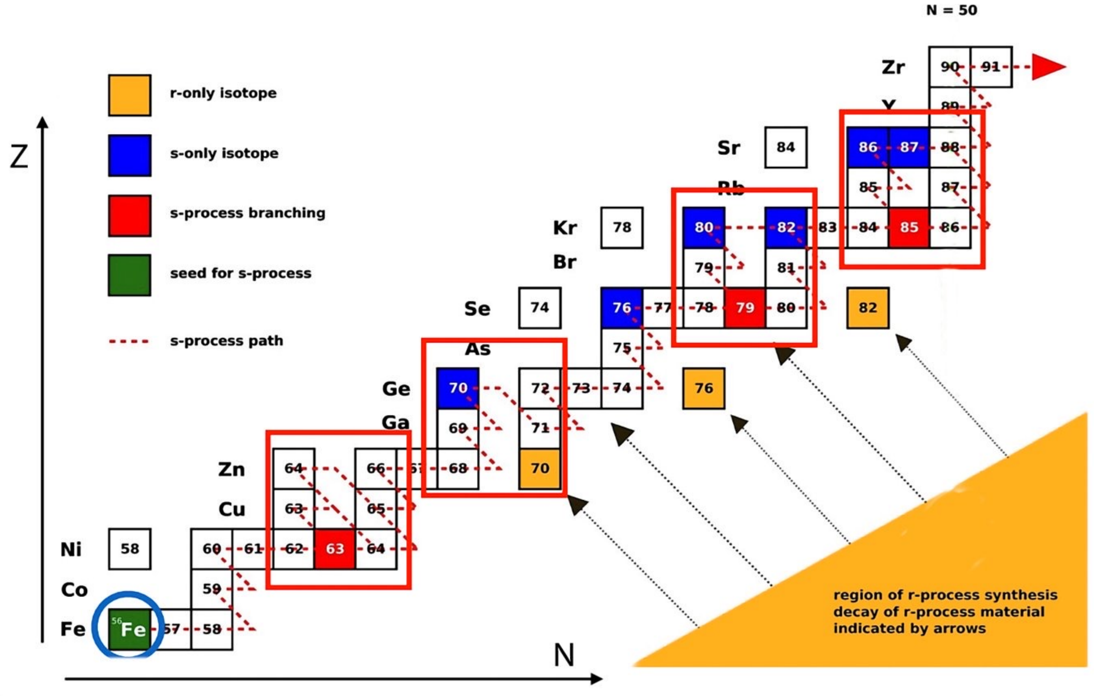
Introduction

Nucleosynthesis proceeds by nuclear fusion in massive stars until iron, where it stops because the fusion of still heavier nuclei needs energy instead of providing it.

Heavier nuclei are created by a subtle interplay between neutron capture and beta-decay.

Nuclei synthetized in the branching points of the s process strongly depends on this interplay

A major difference exists between terrestrial and stellar conditions: stellar nucleosynthesis proceeds in a hot and dense environment which affects the degree of ionization of the atoms involved in the stellar nucleosynthesis.



Theoretical models predict modifications of β-decaying radio-isotopes lifetimes in strongly ionised atoms:

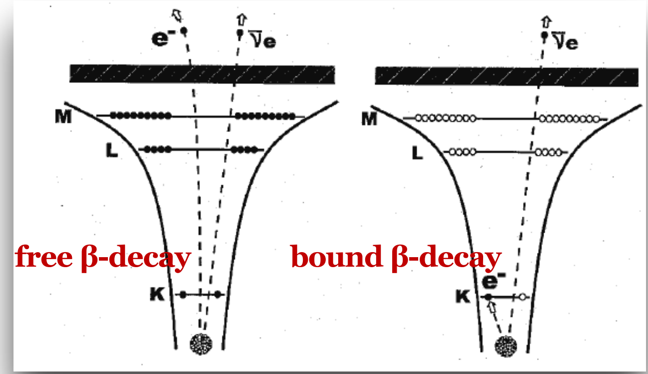
- **Evidences found in storage rings experiments: bare $^{187}Re^{75+}$ ions decay**, due to the bound-state beta decay, **becomes 9 orders of magnitude faster than neutral ^{187}Re atoms with a half-life of 42 Gyr.**

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

Beta decay in stellar environment

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

- Electron Capture becomes impossible in fully ionized atoms
- Bound state beta decay typically marginal can become important



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

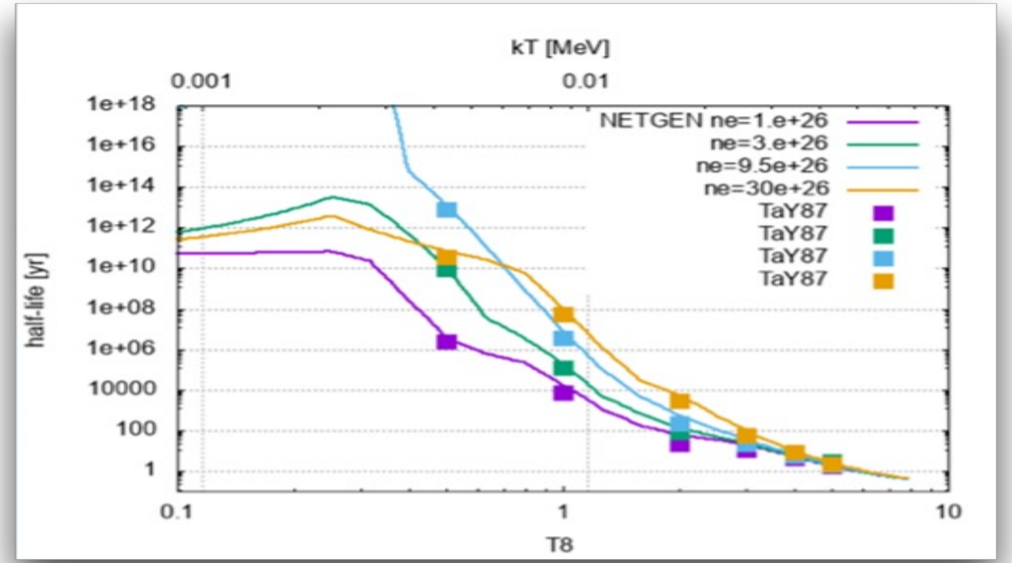
In a stellar plasma, ions are embedded in a cloud of charges, both positive and negative.

These charges create EM fields which act as perturbation to the atomic/ionic levels.

The net effect of these perturbations on the internal states of the ions leads to corrections of Q values which affects the decay rates.

Original predictions of modifications in beta decay rates in plasma due to the effect of temperature were performed by Takahashi and Yokoi

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



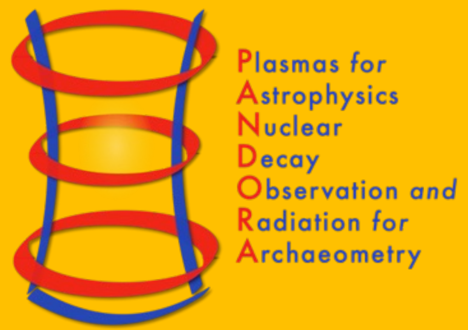
A NEW CHALLENGE: **Reproduce in laboratory some stellar-like conditions and measure the expected variations of nuclear lifetime in β–decaying nuclei**

The PANDORA project: a new multidisciplinary study

supported by the National Scientific Committee 3 (CSN3) of INFN

Laboratory-Magnetoplasmas in compact traps, historically used for ion beams production, can become **ENVIROMENT for Nuclear Physics and Nuclear Astrophysics research**

1) **for the first time, β-decay measurements** in plasmas; → **Huge impact on nuclear physics and stellar nucleosynthesis**
2) **plasma opacity measurements in conditions similar to kilonovae ejecta;** → **Heavy elements production in n-star merging**
3) **an unprecedented setup for applications**: it will be the biggest B-minimum magnetic trap with potentiality as ion source; as testbench for magnetic fusion; as radiation source for Archeometry. → **New ion and radiation sources for science and technology**



PANDORA concept

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

- Electron Density: $10^{12} – 10^{14}$ cm^{-3}
- Electron Temperature: 0.01 – 100 keV
- Ion Density: 10^{11} cm^{-3} (this density relies to the radiactive isotope concentration in plasma)
- Ion Temperature: ~ 1 eV

D. Mascali et al., EPJ web of conference 227, 2020, 01013
D. Mascali et al., EPJ-A , 53, 2017, 7

The plasma is maintained in **MHD equilibrium** for days or even weeks: **the number of decays per unit of times can be written as**:

$$\frac{dN}{dt} = \lambda n_i V \quad \Rightarrow \quad \int_0^{t_{meas.}} dN = \int_0^{t_{meas.}} \lambda n_i V \, dt \quad \Rightarrow \quad N(T_{meas.}) = \lambda n_i V_{plasma} T_{meas.}$$

$\lambda n_i V$ is constant

Plasma volume (const.)

Density of the isotope in the plasma (const.)

Isotope decay constant

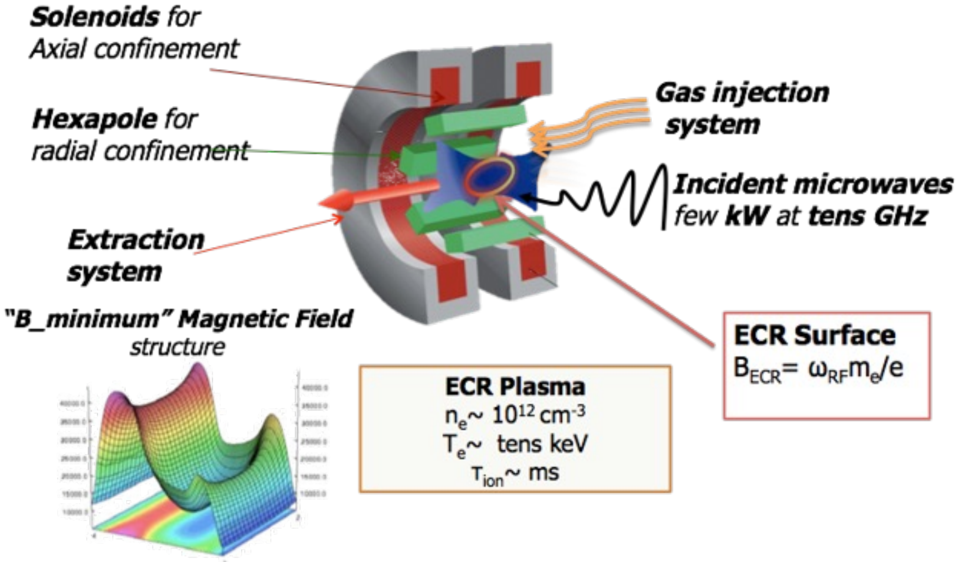
While the isotopes decay, the confined **daughter nuclei emit γ-rays of hundreds of keV, which are detected by a HPGe detector array**

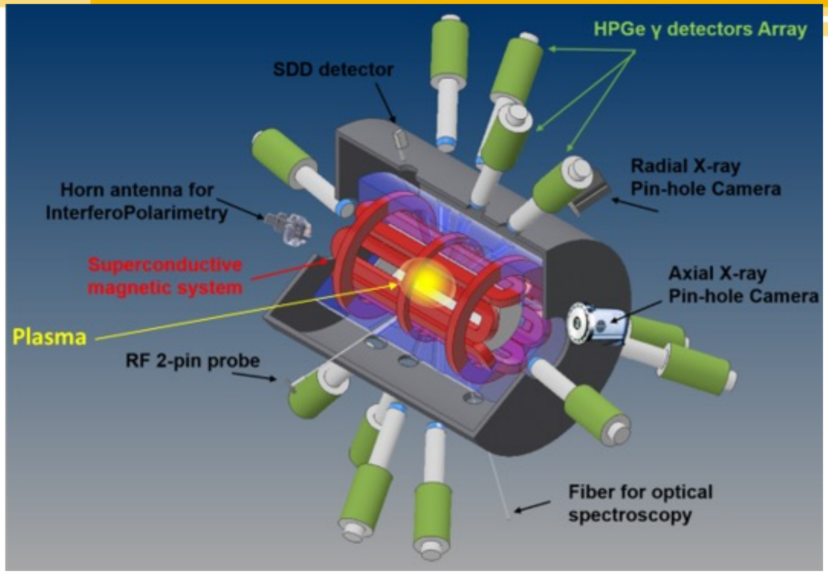
In-plasma radioactivity can be correlated to plasma parameters monitored by an **innovative non-invasive multi-diagnostics setup**

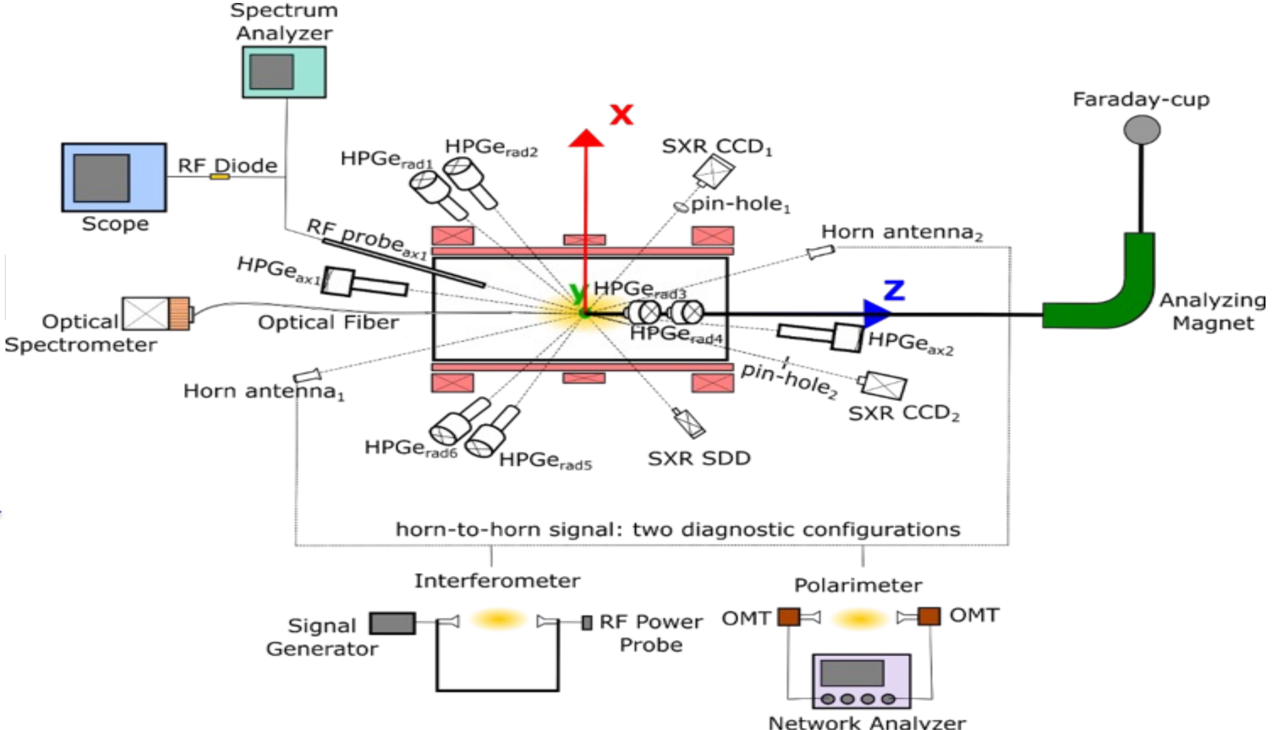
PANDORA design

PANDORA Experimental Setup:

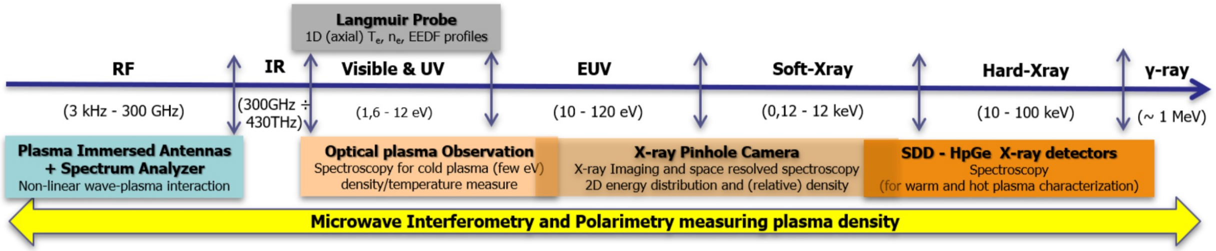
- **Trap**
- **Detector array**
- **Plasma Diagnostics**







Plasma Emitted Radiation



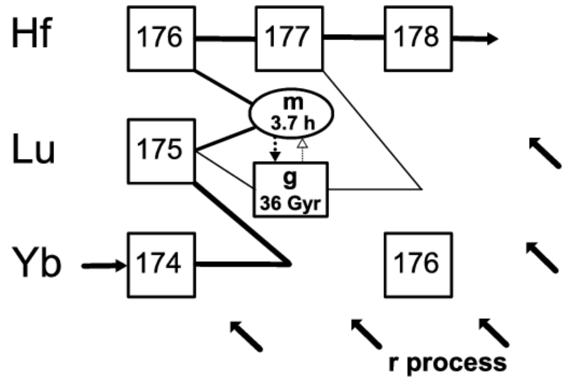
Physics cases

Three cases were selected for the first campaign of measurement

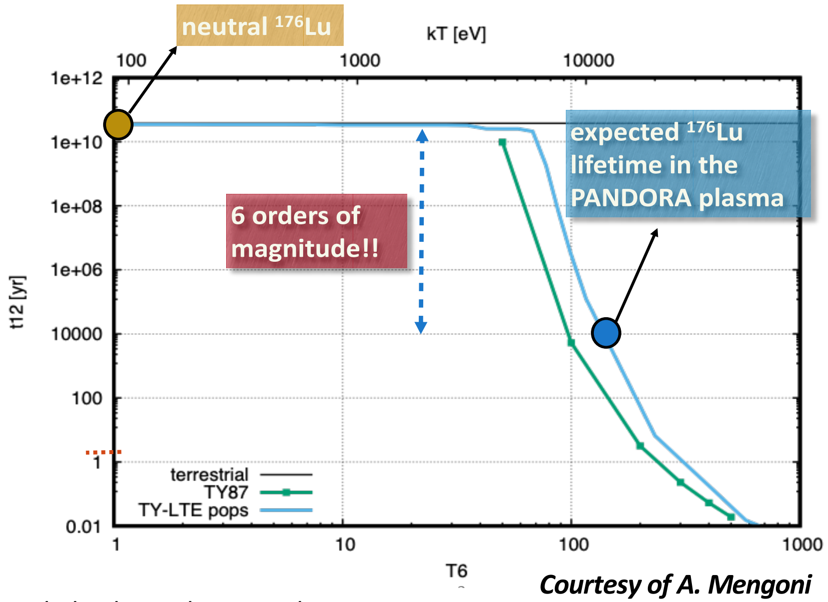
Isotope	$T_{1/2}$ [yr]	E_γ [keV]
^{176}Lu	$3.78 \cdot 10^{10}$	202.88 & 306.78
^{134}Cs	2.06	795.86
^{94}Nb	$2.03 \cdot 10^{4}$	871.09

- **^{176}Lu:** This nucleus is 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 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 121 keV with a very short lifetime



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



Courtesy of A. Mengoni

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

"Measurability" of ^{176}Lu lifetime was evaluated using GEANT4 simulations:

- 3 sigma confidence level can be reached in a measurement time from 15 day to 3 months depending on the half-life variation

One limitation of this approach allows to measure only the g.s. of ^{176}Lu
The T of the system is too low to populate the isomeric state (E_{ex} = 121 keV)

E. Naselli et al., EPJ web of conferences 227, 2020, 02006
D. Mascali et al., EPJ web of conferences 227, 2020, 01013

Comparison with theory

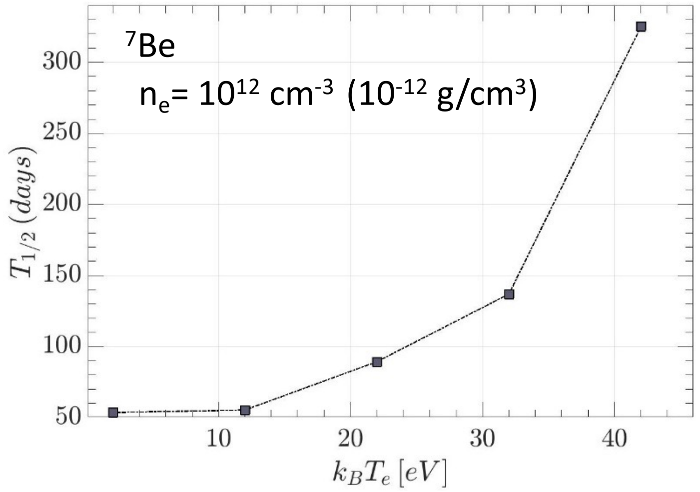
Once measured the variation, it can be compared to Takahashi-Yokoi theory (without LTE hypothesis)

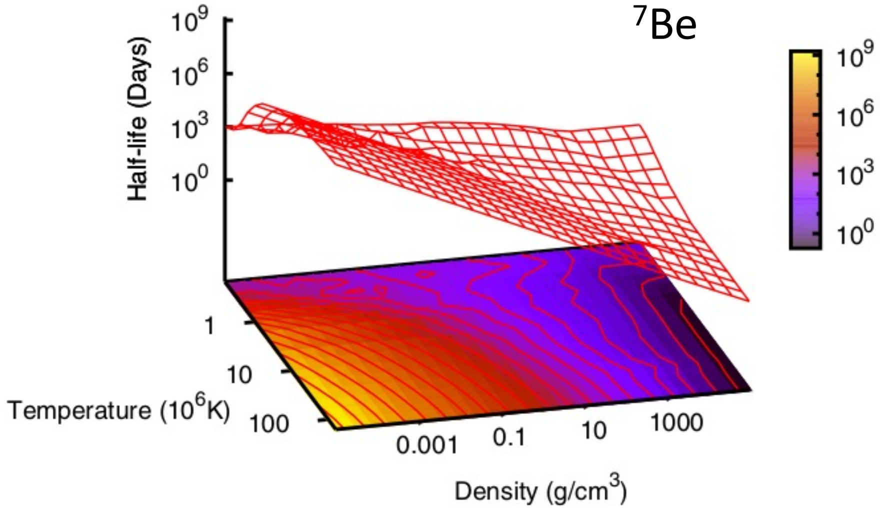
To make the comparison we need to extend Takahashi-Yokoi theory to n-LTE conditions

Once benchmarked theory can be applied to stellar environment assuming n_e and T_e leading to ions in LTE population

Ex. of this approach done in ^{7}Be

$T_{1/2}$ calculation using Takahashi-Yokoi theory in n-LTE conditions





Different important concepts came into play in this comparison

Which are the main differences between LTE and n-LTE conditions ?

Simonucci et al. – Astrophys. J. 764:118 (2013)

Thermodynamic Equilibrium (TE)

- Electrons follow Maxwell distribution function

$$f(E) = \frac{2}{\sqrt{\pi}}\sqrt{\frac{E}{k_B T_e^3}}\, e^{-\frac{E}{k_B T_e}}$$

- Ionisation stages obey Saha equation

$$\frac{n_{i+1} n_e}{n_i} = 2\left[\frac{2\pi m_e k_B T_i}{h^2}\right]^{3/2} e^{-E_{Iz}/k_B T_i}$$

- Excited levels within an ionisation stage obey Boltzmann equation

$$n_{ij} = n_i \frac{g_{ij} e^{-Eij/k_B T_i}}{\sum_j g_{ij} e^{-Eij/k_B T_i}}$$

- Radiation field obeys Planck distribution

$$B_\nu(T_r) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/k_B T_r} - 1}$$

All 4 distributions defined by same temperature T (= T_e = T_i = T_r)

Local Thermodynamic Equilibrium (LTE)

- Electrons follow Maxwell distribution function

$$f(E) = \frac{2}{\sqrt{\pi}}\sqrt{\frac{E}{k_B T_e^3}}\,e^{-\frac{E}{k_B T_e}}$$

- Ionisation stages obey Saha equation

$$\frac{n_{i+1}n_e}{n_i} = 2\left[\frac{2\pi m_e k_B T_i}{h^2}\right]^{3/2} e^{-E_{Iz}/k_B T_i}$$

- Excited levels within an ionisation stage obey Boltzmann equation

$$n_{ij} = n_i \frac{g_{ij} e^{-Eij/k_B T_i}}{\sum_j g_{ij} e^{-Eij/k_B T_i}}$$

- Radiation field **doesn't follow** Planck distribution - **radiation transport code needed**

All distributions except radiation field defined by same temperature T (= T_e = T_i)

Non - Local Thermodynamic Equilibrium (n-LTE)

- Electrons are (generally) **non-Maxwellian**
- Ionisation stages **are not modelled** according to Saha equations
- Excited states **do not obey** Boltzmann equation

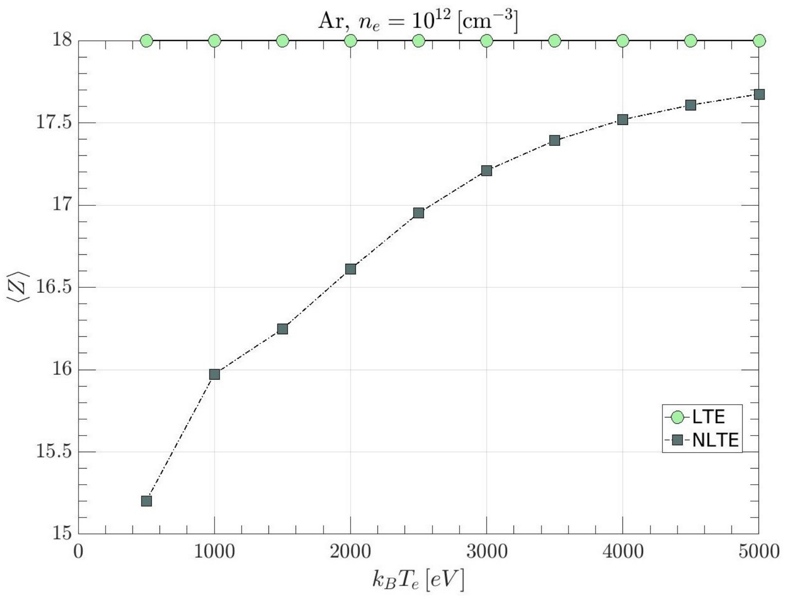
- Radiation modelling requires transport code. **No concept of unique temperature because no distributions exist**

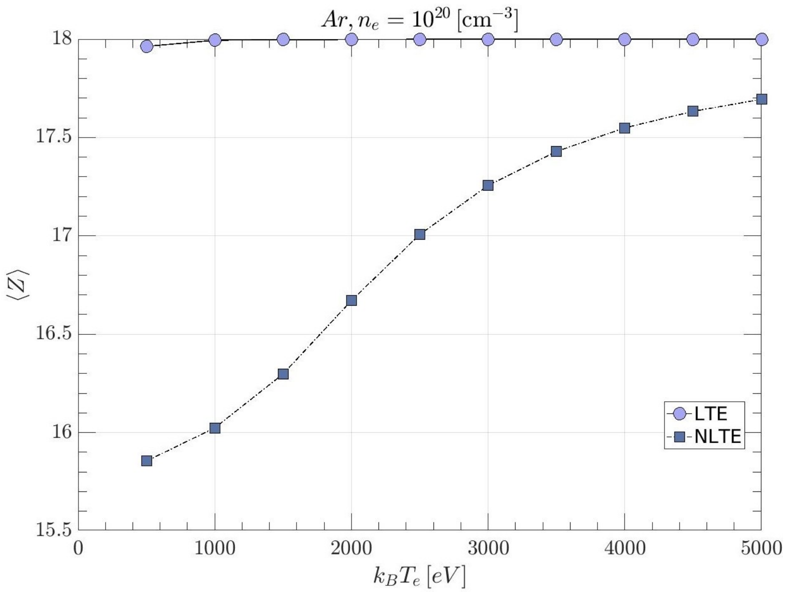
- A comprehensive rate equations matrix is constructed based on collisional and radiative processes - CR Model – and iteratively solved till steady-state is reached

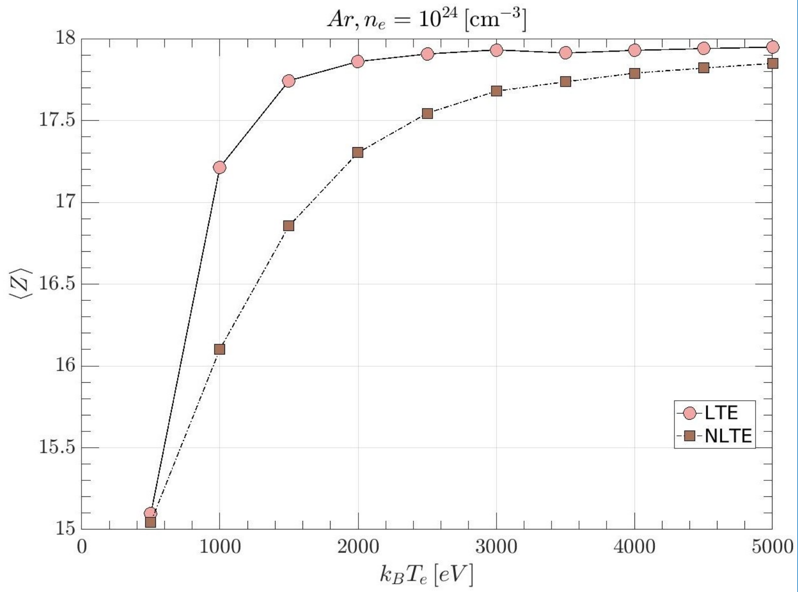
Laboratory Plasmas

Laboratory plasmas (magnetic confinement) are low density and high temperature systems (n-LTE)
Thermodinamic conditions affect the CSD of the ions in the plasma.
CSD is one of the main ingredients in Takahashi-Yokoi theory

Plasma average charge state as affected by LTE vs. NLTE regime, as function of plasma density and energy







In the limit of high density and high temperature, laboratory plasmas are effectively LTE, which simplifies analysis

Pro and Cons between magnetic confinement vs laser produced plasma

Magnetic confinement

PRO:

- Long-living plasma (order of weeks)
- steady state dynamical equilibrium for density and temperature,
- →hence, over days/weeks constant values for charge state distribution of in-plasma ions
- Online monitoring of plasma density, temperature, volume, eventual kinetic turbulence, 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)

Scenario can be different using plasma produced by HP lasers

PRO:

- High density plasma, reaching LTE
- Online production of RIBs is in principle possible
- **Fully thermodynamical equilibrium allows, in principle, nuclear excitation**

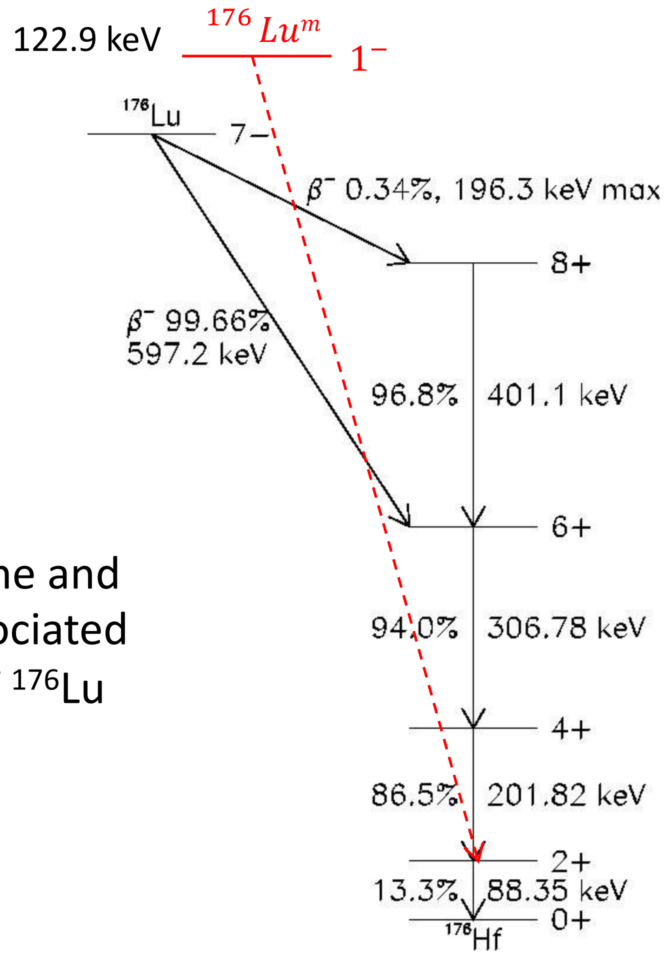
CONS:

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

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

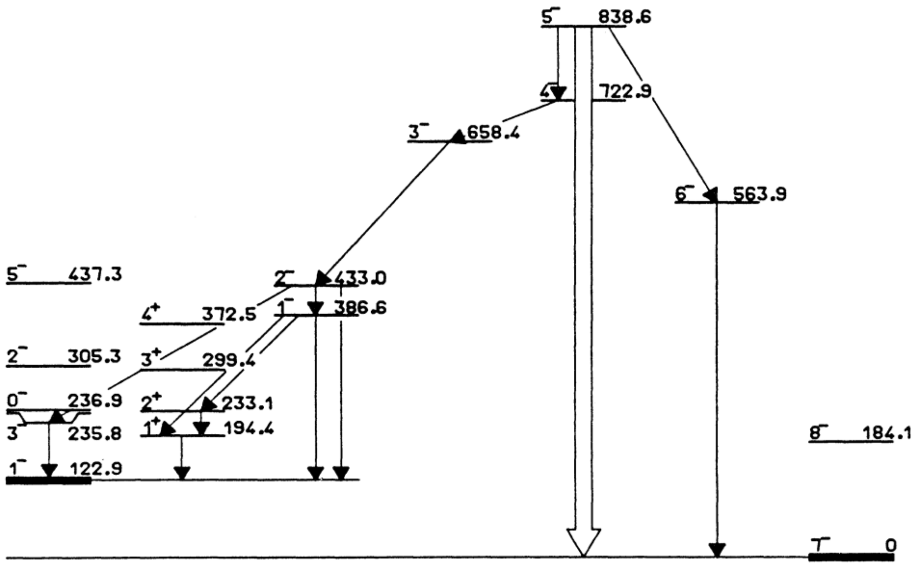
The intermixing between nuclear levels in ^{176}Lu has been an open topic in nuclear astrophysics for years because it has a direct impact on its treatment as a cosmochronometer.

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.



β⁻ decay scheme and γ energies associated with 7⁻ level of ^{176}Lu

assumed level scheme of ^{176}Lu



To populate 1⁻ level it is needed to populate a level at about 800 keV !

^{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 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

Thermalisation between the ground and isomer levels occurs when:

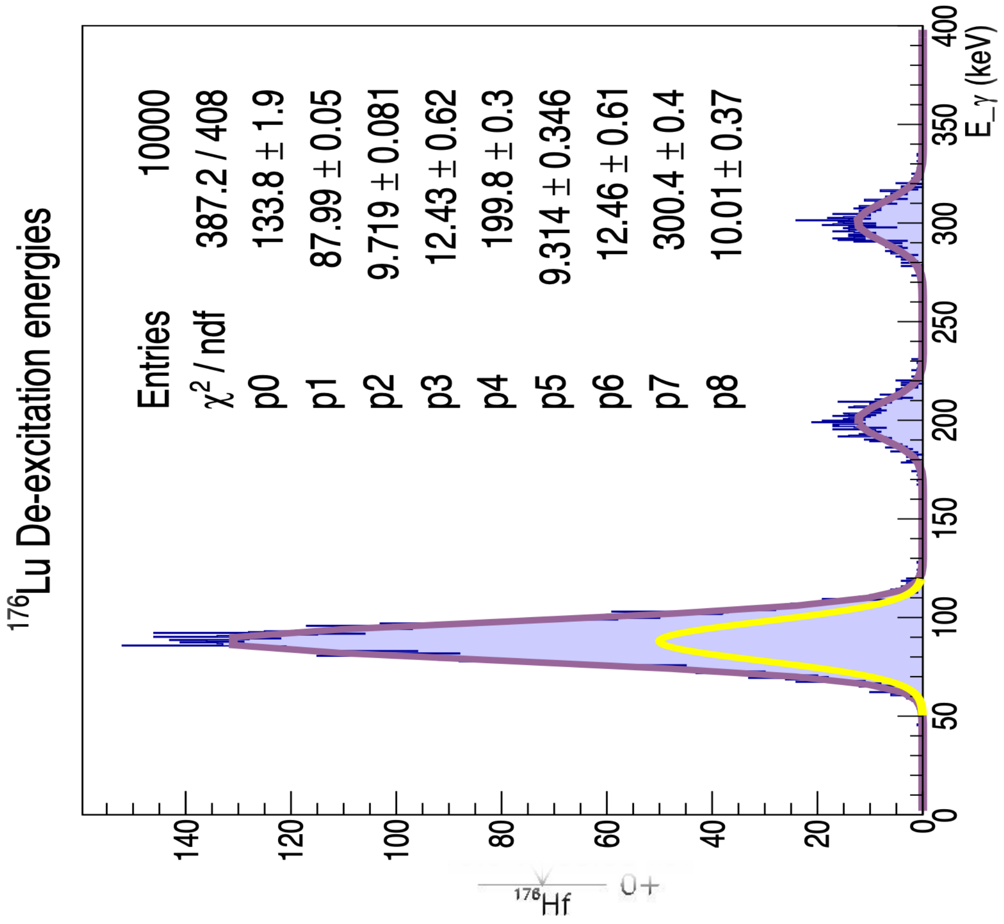
$\lambda^c(n_e, n_i, T, s) >= \lambda_m^d\,(n_e, n_i, T, s)$ → the onset of equilibrium between the levels

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.

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

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.



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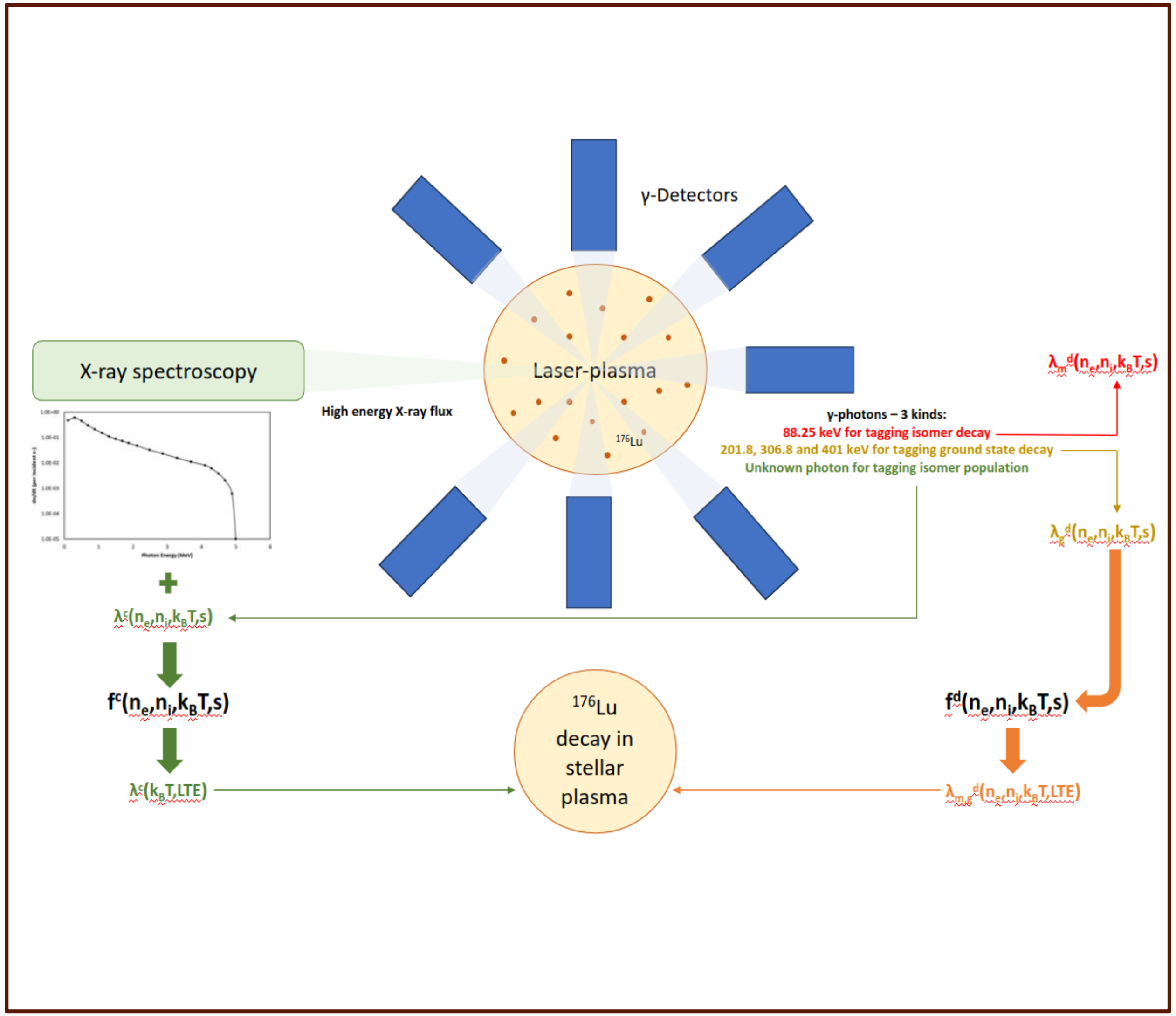
- Same considerations works for decay from g.s.
- The in-plasma photoactivation rate is the common factor in both the above cases.
- One of the photons in the cascade of 176Lu can serve as a fingerprint of the isomer population and hence $\lambda^c(n_e,n_i,T,s)$.

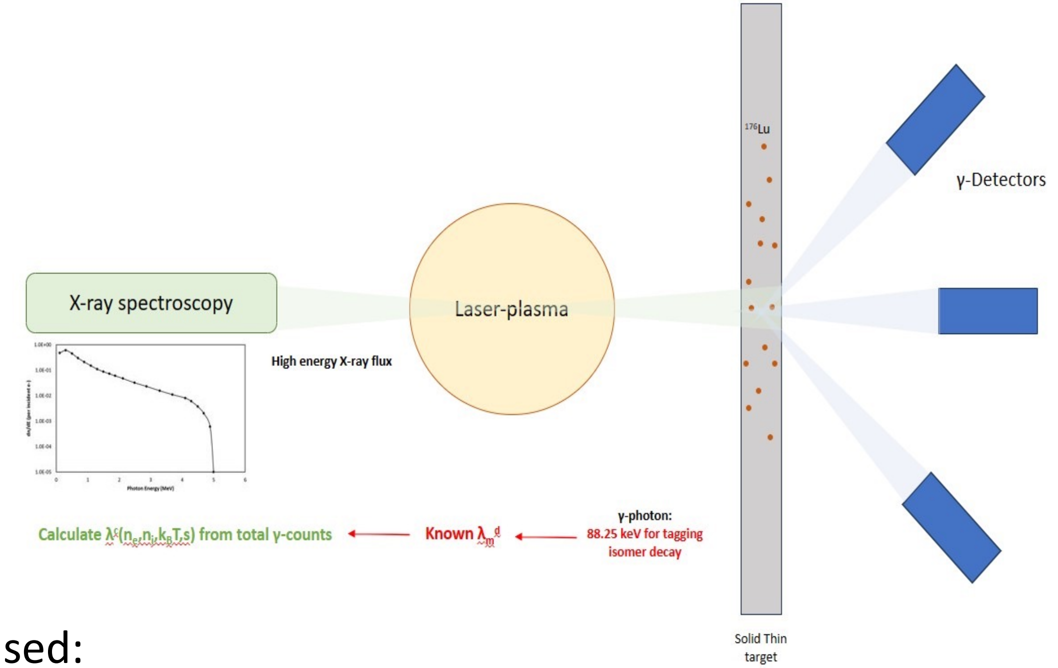


^{176}Lu decay rates in stellar-like high density and energetic plasma

The previous idea relies on the possibility to identify a tagging transition in the decay of ^{176}Lu that can be used to as fingerprint of the isomeric state population.

If $\lambda^c(n_e, n_i, k_B T, s)$ cannot be directly measured in-plasma it needs to be extracted in other way.

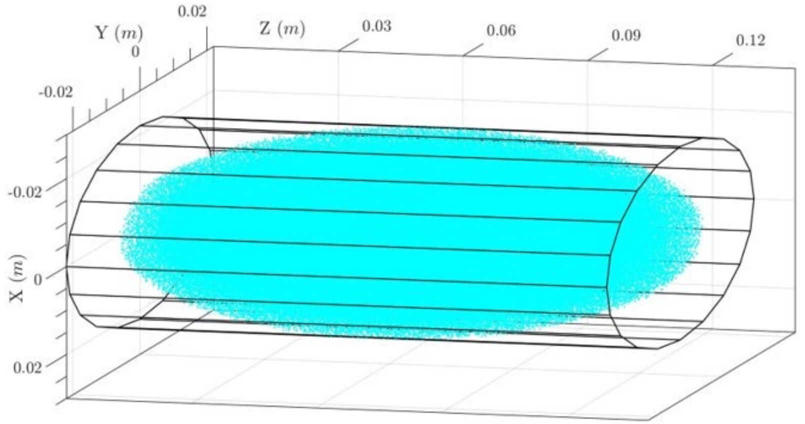
- A laser-generated plasma acts as a source of X-ray spectrum which illuminates a target of ^{176}Lu nuclei and causes isomer activation.
- The isomer decays with a known lifetime of 3.7 hours.
- measuring the total number of 88.25 keV photons collected in time *T*, the photoactivity can be reconstructed and associated with the conditions of the illuminating plasma.
- This value can be used to calculate the plasma-induced decay rates and comment on the thermalisation.



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

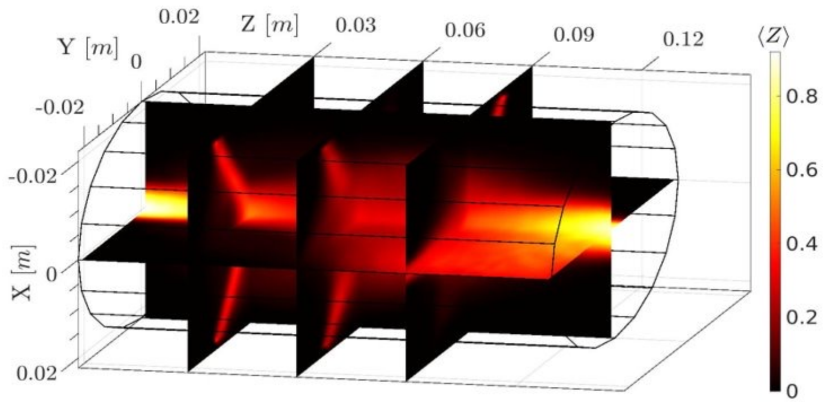
- Better knowledge of 176Lu level scheme
- Accurate measurement of plasma T
- Scaling with laser pulse duration and intensity

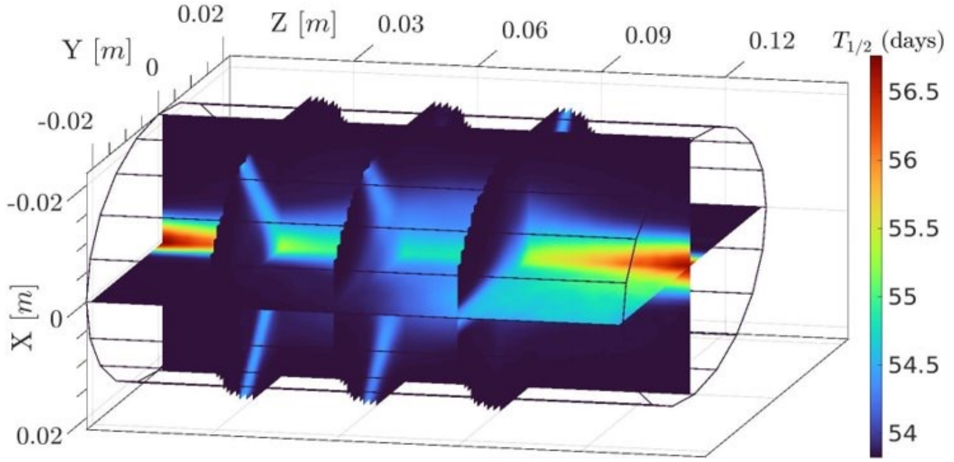
Spatial distribution of β-decay rates in ECR magnetoplasmas depend on plasma properties, but also on isotope injection system



Diffused injection of neutral isotopes at high temperature leads to faster deconfinment and lower degree of ionisation

Laser-plasmas can act as efficient RIB facilities to generate mono-charged beams that can be injected into the plasma trap for optimised "plasmisation" of isotopes

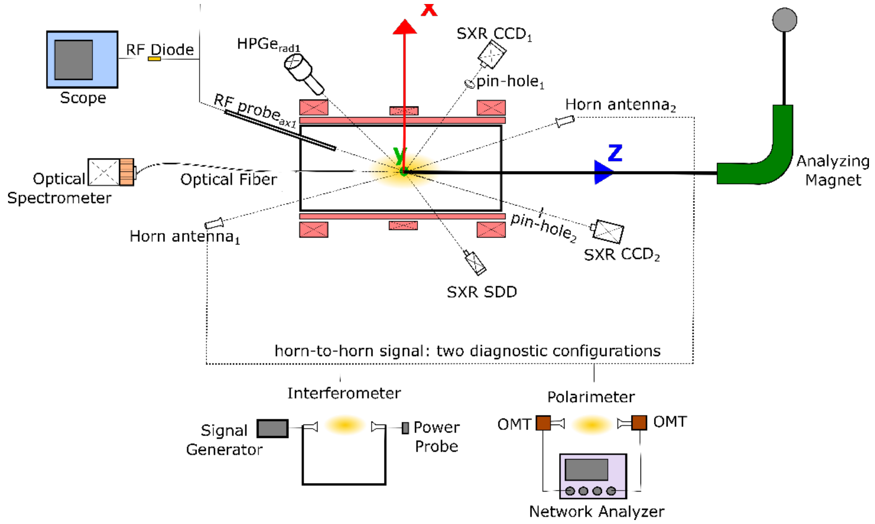




Thanks for your attention

PANDORA design: multi-diagnostics setup

HpGe	30 ÷ 2000 keV	Volumetric hard X-ray Spectroscopy: hard electrons temperature and density	FWHM @ 1332.5 keV < 2.4 keV $\epsilon_{n_e} \sim 7\%$, $\epsilon_{T_e} \sim 5\%$
Visible Light Camera	1.0 ÷ 12 eV	Optical Emission Spectroscopy: cold electrons temperature and density	$\Delta\lambda = 0.04$nm R=12500
Microwave Interferometer	K-band 18 ÷ 26.5 GHz	Interferometric measurement: line integrated total density	$\epsilon_{n_e} \sim 50\%$
Microwave Polarimeter	K-band 18 ÷ 26.5 GHz	Faraday-rotation measurement: line integrated total density	$\epsilon_{n_e} \sim 25\%$
X-ray pin-hole camera	2 ÷ 15 keV	2D Space-resolved spectroscopy soft X-ray Imaging and plasma structure	Energy Res. ~ 0.326 keV Spatial Res. ~ 0.56 mm
Multi-pins RF probe + Spectrum Analyzer (SA)	10 ÷ 26.5 GHz *(probe)*	Frequency-resolved Spectroscopy plasma emitted EM wave in GHz range	SA Resolution bandwidth: RBW = 3 MHz
Multi-pins RF probe + Scope + HpGe	10 ÷ 26.5 GHz *(probe)*	Time-resolved X-ray Spectroscopy	80 Gs/s *(scope)* time scales below ns



SDD for "warm electrons": probing volumetric soft X-radiation (2 – 20 keV)

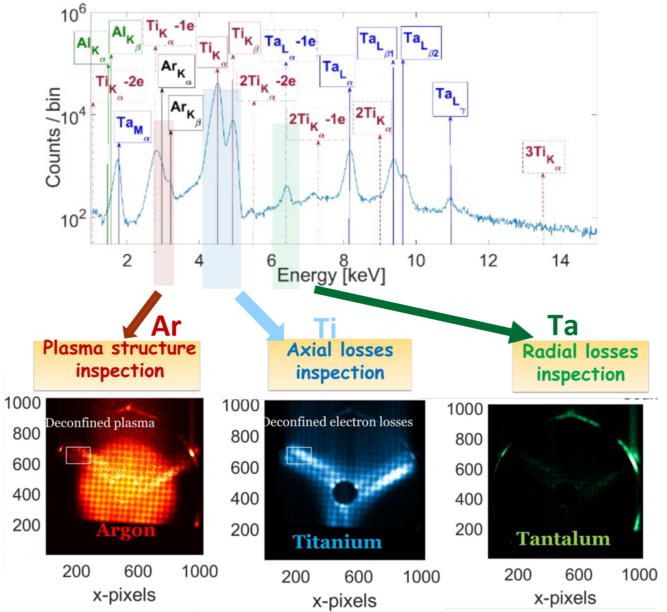
HPGe for "hot electrons": probing volumetric hard X-radiation (30 - 2000 keV)

OES for "cold electrons": probing volumetric optical radiation (1 – 12 eV)

Microwave Interferometry and Polarimetry to measure the line-integrated total density

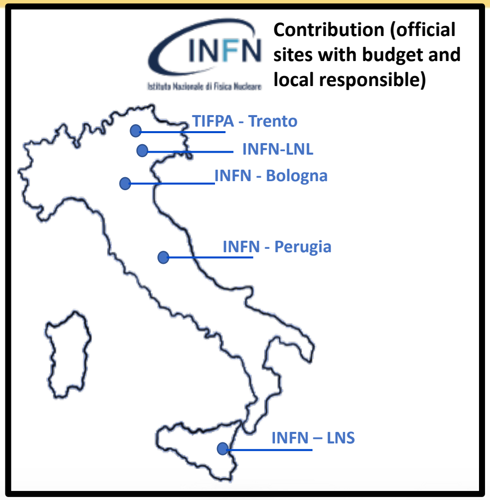
Pinhole camera for high resolution spatially-resolved soft X-ray spectroscopy to investigate plasma structure and confinement dynamics in the range 2 - 20 keV

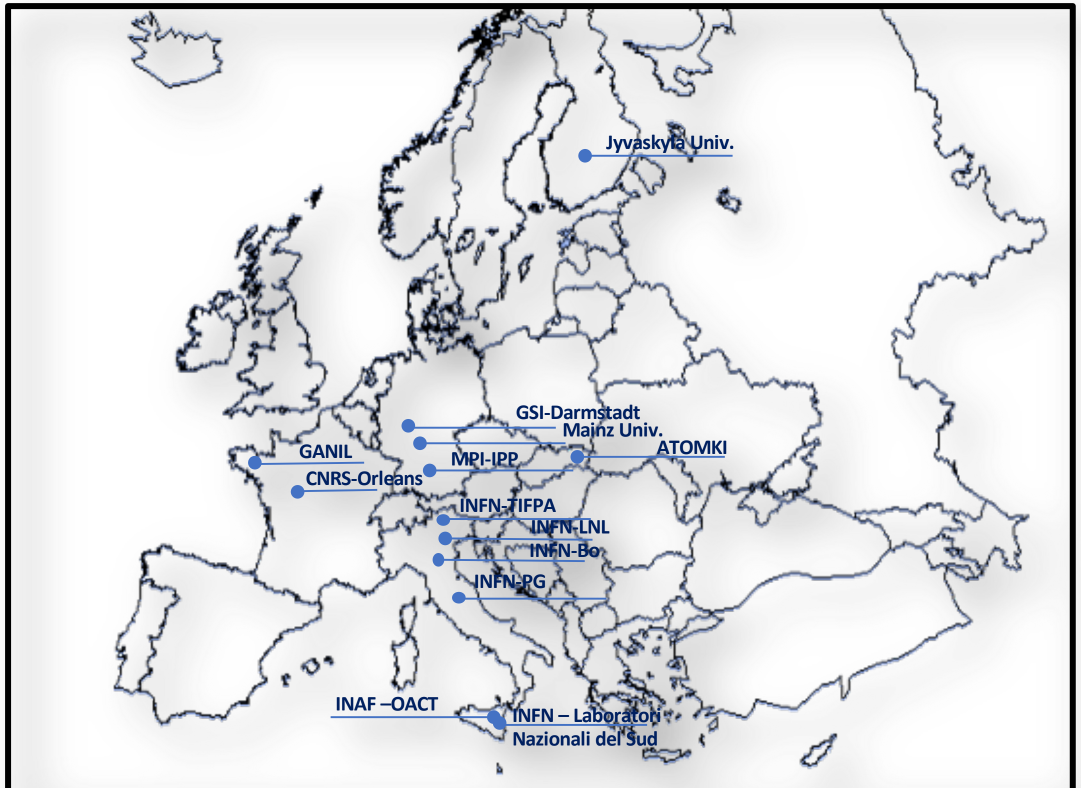
RF probe + Spectrum Analyzer and/or Scope for time-resolved Spectroscopy



E. Naselli et al., Il Nuovo Cimento 44 C, 2021, 64
S. Biri et al., JINST 16, 2021, P03003
R. Racz et al., Plasma Sources Science and Technology 26, 2017, 7
D. Mascali et al., Review of Scientific Instruments 87, 2016, 02A510

PANDORA collaboration





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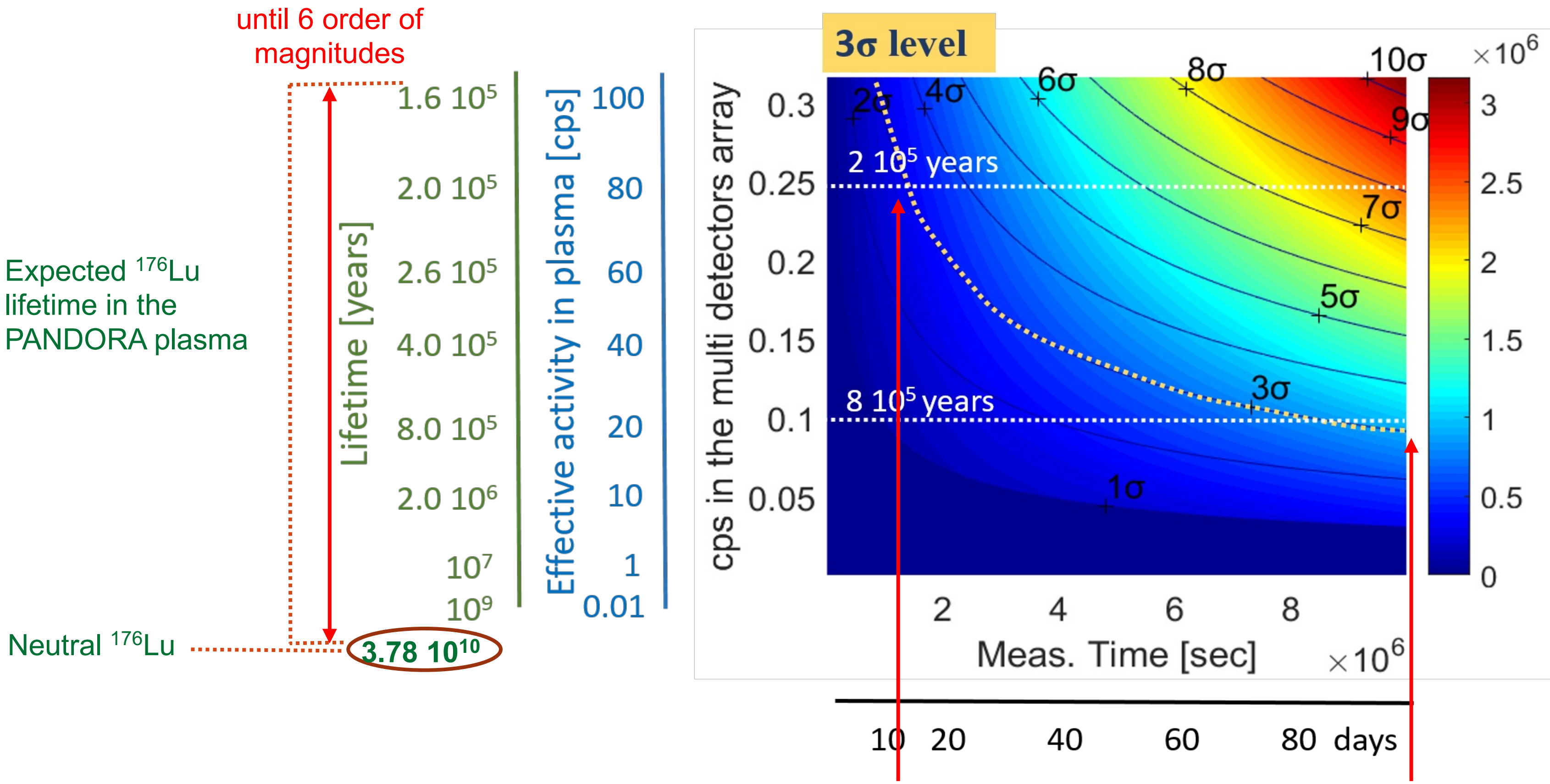
Evaluation of ^{176}Lu lifetime measurability

"Measurability" of ^{176}Lu lifetime was evaluated using GEANT4 simulations assuming an array of 14 HPGe-detectors



1% Lu of 10^{13} cm^{-3} (Vp=1500 cm^3)

Physics Cases

Isotope	$T_{1/2}$ [yr]	E_γ [keV]
^{176}Lu	$3.78 \cdot 10^{10}$	202.88 & 306.78
^{134}Cs	2.06	795.86
^{94}Nb	$2.03 \cdot 10^{4}$	871.09

E. Naselli et al., EPJ web of conferences 227, 2020, 02006
D. Mascali et al., EPJ web of conferences 227, 2020, 01013