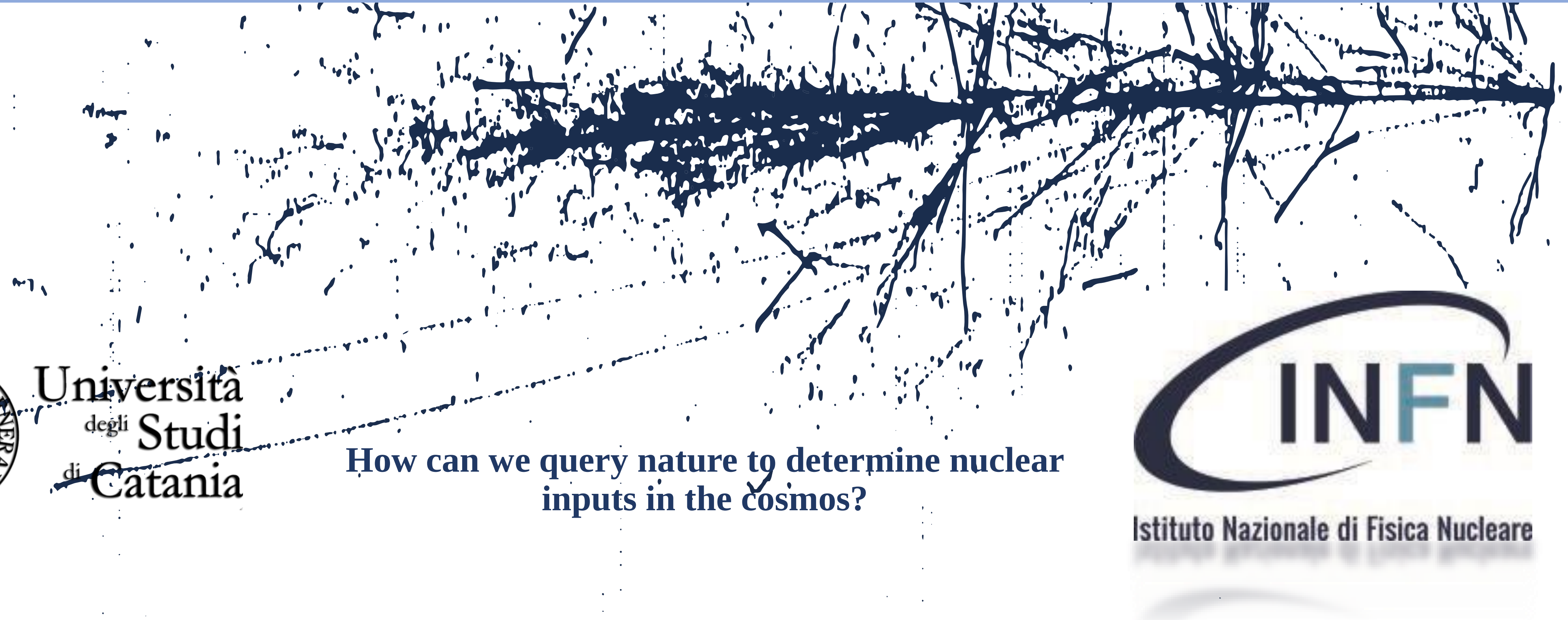
School on Nuclear Astrophysics Questions (SNAQs)

Studying ß-decay rates in stellar interiors – the PANDORA project



How can we query nature to determine nuclear inputs in the cosmos?

Bharat Mishra on behalf of the PANDORA collaboration

Dipartimento di Fisica e Astronomia "Ettore Majorana", Università degli Studi di Catania, Catania, Italy
Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali del Sud, Catania, Italy

12 May 2021
Virtual Event

What can we query nature for?

WHAT

Quantity of interest

- β-decay rates in stars
- Atomic environment affects $t_{1/2}$
- Stars are plasma, presence of CSD leads to interesting physics

WHY

Motivation

- Astrophysics models require multiple inputs
- Stellar nucleosynthesis above Fe an interplay between decay and n,p-absorption
- Uncertainties remain in σ_{abs} and $t_{1/2}$

HOW

Plasma modelling and γ-tagging

- Connecting ECR plasma properties to decay rates
- Multi-diagnostic and constant monitoring of plasma
- Measurement of ß-decay lifetime using secondary γ-rays

β-Decay Rates in Stellar Interiors: Theory

5 general types of decays

$$({}^{A}_{Z}X_{N})^{x} \rightarrow ({}_{Z+1}^{\ \ A}Y_{N-1})^{x+1} + e^{-} + \bar{\nu}_{e} \qquad \text{(continuum state } \beta^{-} \text{ decay)}$$

$$({}^{A}_{Z}X_{N})^{x} \rightarrow ({}_{Z+1}^{\ \ A}Y_{N-1})^{x} + e^{-} + \bar{\nu}_{e} \qquad \text{(bound state } \beta^{-} \text{ decay)}$$

$$({}^{A}_{Z}X_{N})^{x} \rightarrow ({}_{Z-1}^{\ \ A}Y_{N+1})^{x-1} + e^{-} + \nu_{e} \qquad \text{(continuum state } \beta^{+} \text{ decay)}$$

$$({}^{A}_{Z}X_{N})^{x} + e^{-} \rightarrow ({}_{Z-1}^{\ \ A}Y_{N+1})^{x} + \nu_{e} \qquad \text{(orbital EC)}$$

$$({}^{A}_{Z}X_{N})^{x} + e^{-} \rightarrow ({}_{Z-1}^{\ \ A}Y_{N+1})^{x-1} + \nu_{e} \qquad \text{(free electron EC)}$$

Spontaneity determined by Q-value

$$Q_0 = \begin{cases} q_0 & \text{continuum and bound state } \beta^{-} \text{ decay, orbital EC} \\ q_0 - 2m_{e^-}c^2 & \text{continuum state } \beta^{+} \text{ decay} \\ q_0 + K_e & \text{free EC} \end{cases}$$

where q_0 is

$$[m({}^{A}_{Z}X_{N}) - m({}_{Z+1}^{\ \ A}Y_{N-1})]c^2 + [E^{*}_{X} - E^{*}_{Y}] + [B_X - B_Y] - [B^{*}_{X_x} - B^{*}_{Y_{x+1}}] + [e^{*}_{X_{x,k}} - e^{*}_{Y_{x+1,k'}}]$$

Decay rate

$$\lambda = g^2 \frac{m_e^5 c^4 |M^{L}_{if}|^2}{2\pi^3 \hbar^7} f_L(Z', Q)$$

M^{l}_{if} is the nuclear matrix element

$$f_L(Z', Q) = \frac{1}{(m_e c)^5} \int_0^{p_{max}} p^2 q^2 S^L(p, q) F^{\pm}(Z', p)\,dp$$

$$f_L(Z', Q) t_{1/2} = \frac{(\ln 2) 2\pi^3 \hbar^7}{g^2 m_e^5 c^4 |M^{L}_{if}|^2}$$

General theory

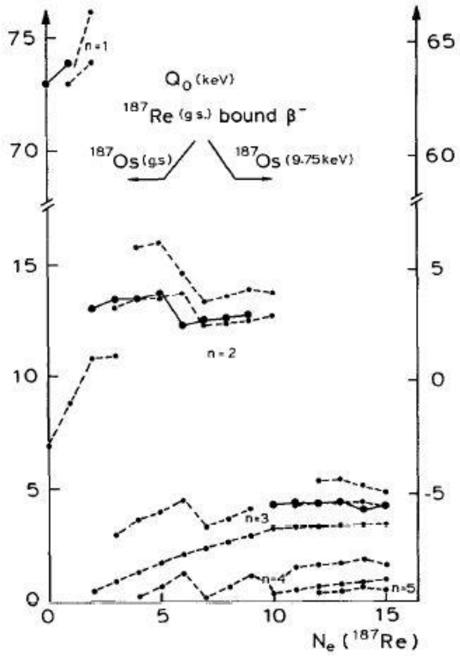
In stars/plasma

Q-value associated with decay channels changes

$$\boxed{Q \approx Q_0 + \sum_{x=x_X}^{Z_X - 1} \Delta_x - \sum_{x=x_Y}^{Z_Y - 1} \Delta_x}$$

Multiple decay modes

$$\lambda = \sum_{l} \sum_{L} g^2 \frac{m_e^5 c^4 |M^{Ll}_{if}|^2}{2\pi^3 \hbar^7} f_L(Z', Q^l)$$



Q-value of bound state ^{187}Re→^{187}Os transitions as a function of degree of ionization [1]

CSD and level population of plasma ions

EEDF of plasma electrons

Each decay mode has associated lepton phase volume

$$f^{*}_{IF(m)} = \int_1^{E_{max}} (E^2 - 1)^{1/2} E q^2 F_0 S_{(m)} f_d \, dE \qquad \text{(continuum decay)}$$

$$f^{*}_{IF(m)} = \sum_{y} \sigma_y(\pi/2)[g_x \text{ or } f_x]^2 q^2 S_{(m)x} \qquad \text{(bound state decays/captures)}$$

[1] K. Takahashi and K. Yokoi, Nucl. Phys. A, (1983).

Why should we query nature to determine ß-decay rates?

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Nuclear Astrophysics Cases

Astrophysical models involve competition between one or more processes

Model usability limited by uncertainty in inputs – $t_{1/2}$, σ_{abs}, $k_B T$, ρ

Solar nucleosynthesis and neutrino flux [2]:

^{7}Be decay and ^{7}Be*(p,γ)*^{8}B are competing processes, the former produces neutrino flux

Cosmological lithium problem [2]:

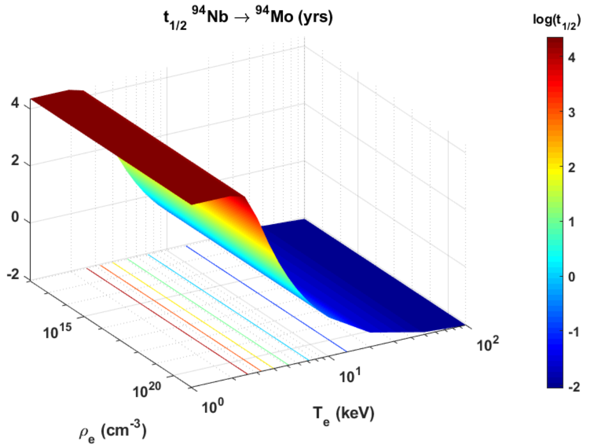
^{7}Be decay also determines ^{7}Li abundance, overestimated

S-process branching:

Competition between s-process and decay leads to branching

Cosmochronometers/ Cosmotherometers:

Modification of decay rates can alter use of radionuclides



Modification of half-life as a function of plasma parameters – effect of ion CSD

Nucleosynthesis of ^{134}Ba and ^{136}Ba from ^{134}Cs [3]

Uncertainty in *n* σ_{abs} and ^{134}Cs $t_{1/2}$

Abundance of ^{94}Nb and ^{94}Mo in presolar SiC grains [3]

Complex model, large uncertainties surrounding s-process in binary AGB star systems

^{176}Lu as cosmochronometer or cosmothermometer [3]

Uncertainties in $t_{1/2}$ as calculated in LTE approach

Temperature effects stronger than density – scalability to astrophysical plasmas

[2] D. Mascali, A. Musumarra, F. Leone, F.P. Romano, A. Galatá, S. Gammino and C. Massimi, Eur. Phys. J. A 53, 145 (2017).
[3] D. Mascali *et al*, EPJ Web of Conferences 227, 01013 (2020).

How we query nature to determine ß-decay rates in the cosmos?

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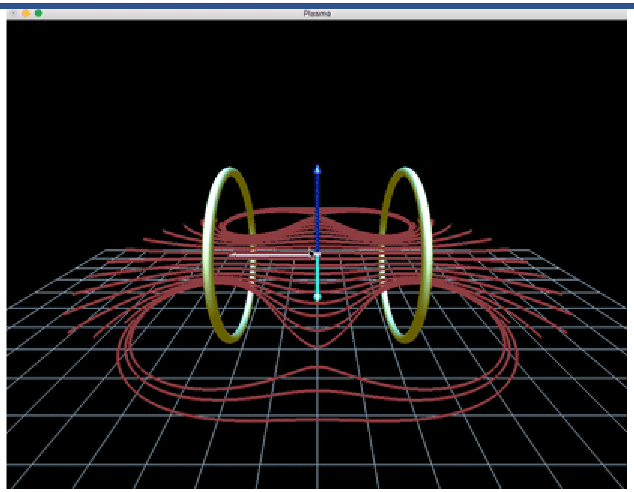
Electron Cyclotron Resonance Plasmas in Compact Magnetic Traps

- **Stellar interiors are high density and high temperature plasmas**
- **Experimental validation/correction of theory**
- **Extrapolation to astrophysical environment**

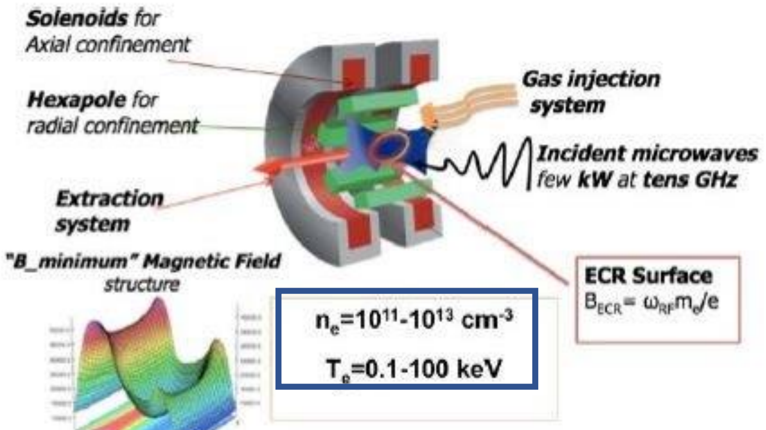
Magnetic field B applied longitudinally causing electrons to gyrate at frequency $\omega_c = \frac{eB}{m_e}$

R-wave launched into the plasma at same frequency, leading to resonance heating

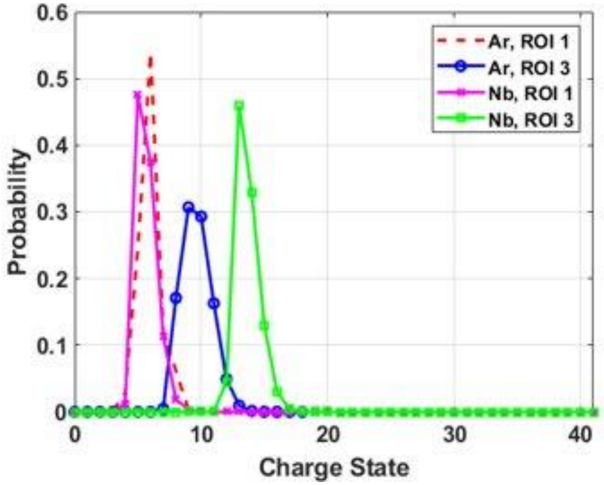


Electron confinement in ECRIS

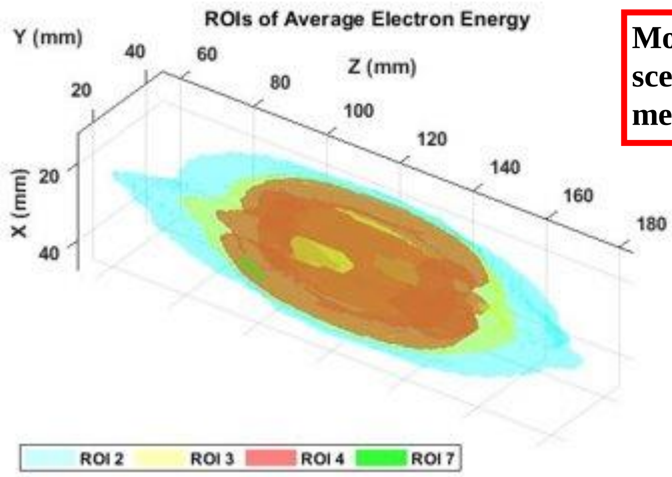
Important properties



Schematic of ECRIS operation and global electron properties [2]



Example of anisotropic ion CSD in ECR plasmas (preliminary model) [5]



Isosurfaces of constant <E> [4]

Model scalable to astrophysical scenarios because T_e dependence measurable (n_e effect negligible!)

ROI	N_e (cm^{-3})	N_1	kT_1 (eV)	N_2	kT_2 (keV)
1	0	0	–	0	–
2	$1.0171E+15$	0.9998	19.0	0.0002	4.2142
3	$6.1180E+14$	0.9945	109.9	0.0055	3.0010
4	$1.1620E+15$	0.9849	164.7	0.0151	3.1882
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[4] B. Mishra *et al*, to be submitted to EPJ D
[5] B. Mishra, A. Pidatella, S. Biri, A. Galatà, A. Mengoni, E. Naselli, R. Rácz, G. Torrisi and D. Mascali, accepted Nuovo Cimento C, 2021

Measurement of $t_{1/2}$: γ-Tagging

ECR magnetoplasma can be maintained in MHD equilibrium for days or even weeks

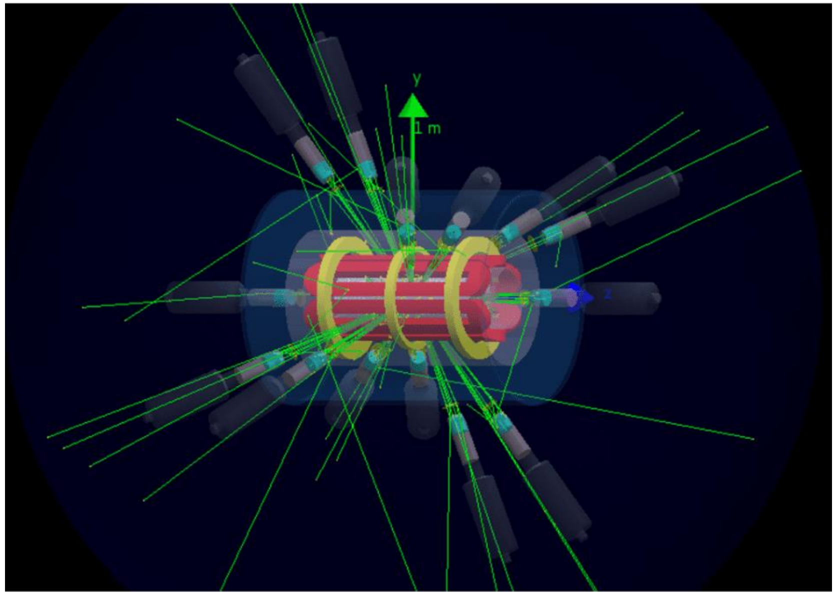
$$\frac{dN}{dt} = \lambda n_i V \quad \Rightarrow \quad N(T_{meas}) = \lambda n_i V_{plasma} T_{meas}$$

$\lambda n_i V$ is constant

Isotope activity **$\lambda \equiv \lambda(T, n)$**

Density of the isotope in the plasma (const.)

Plasma volume (const.)



Numerical simulations to determine detection efficiency according to chosen plasma model - 14 HpGe detectors (preliminary model)

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

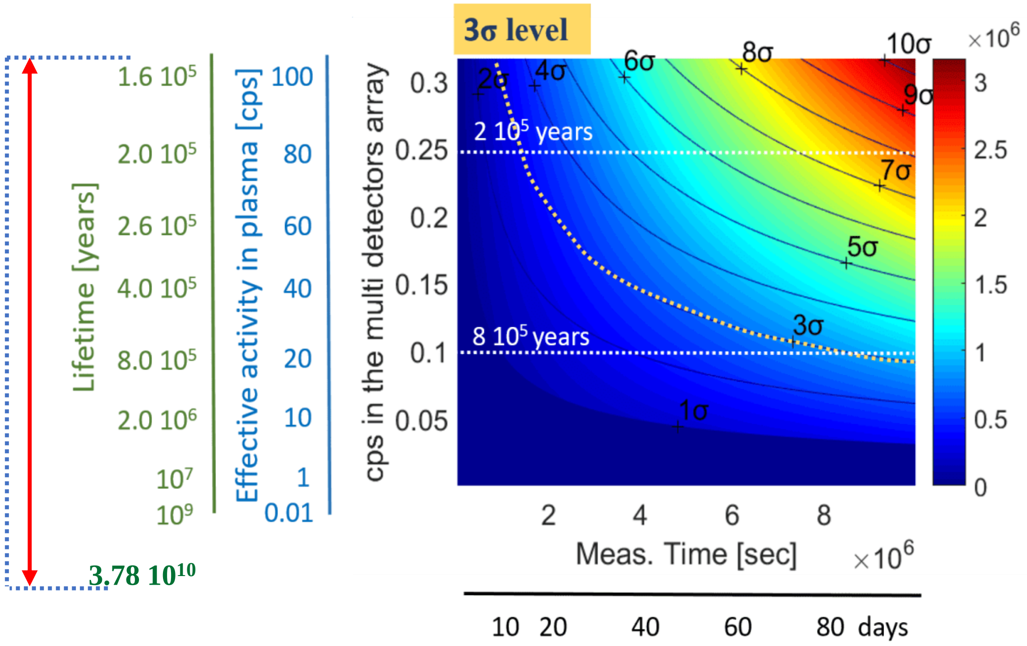
Current models predict measurements lasting from tens of days to a couple of months to obtain a 3σ level of confidence (can be extended to 5σ as well)

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

until 6 order of magnitudes

Expected ^{176}Lu lifetime in the PANDORA plasma

Neutral ^{176}Lu



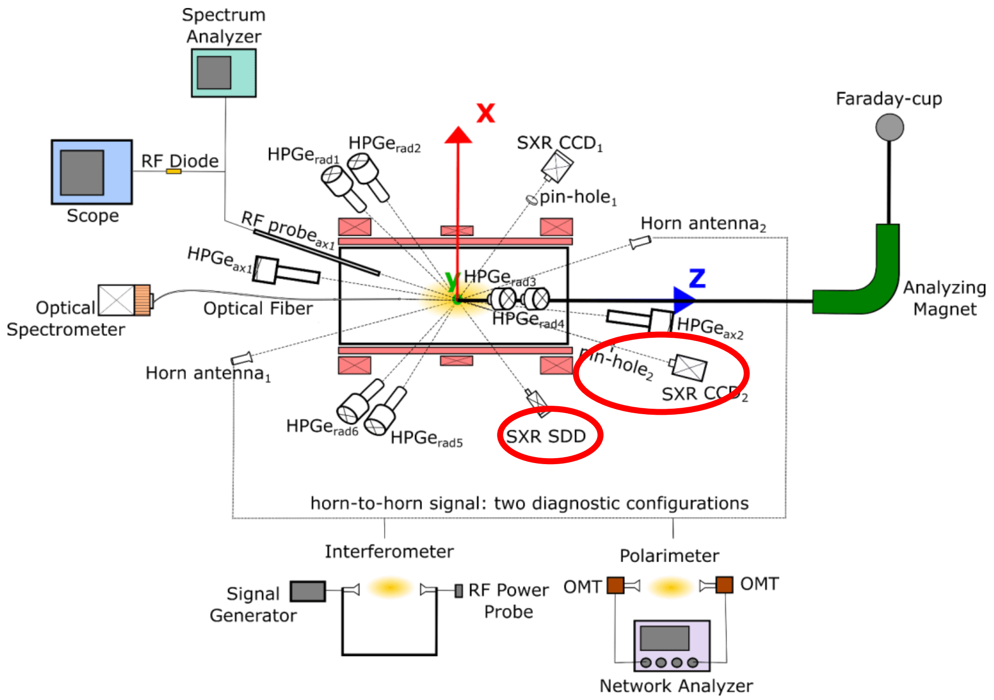
E. Naselli, EPJ web of conferences, 2019

E. Naselli, Oral – 1st Workshop on PANDORA: Measuring β-decays in plasmas, 2019

E. Naselli, Oral - European Summer School on Experimental Nuclear Astrophysics, 2019

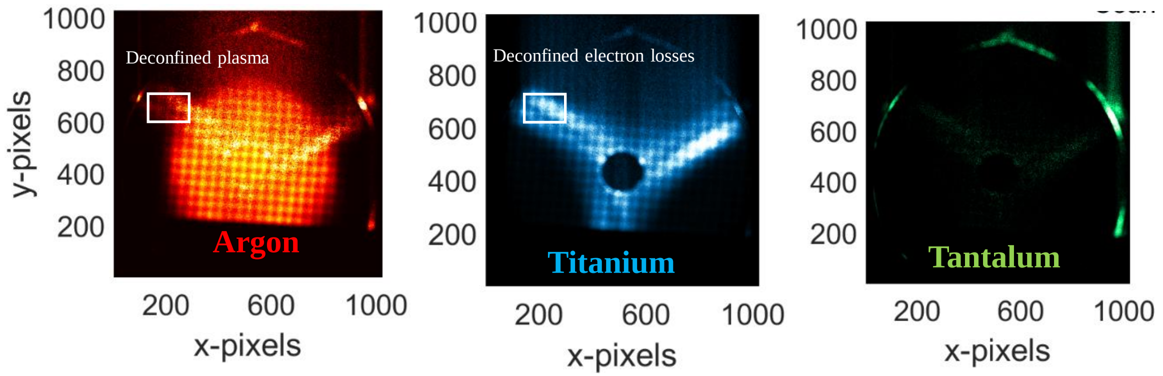
Plasma Monitoring: Multi-Diagnostic Setup

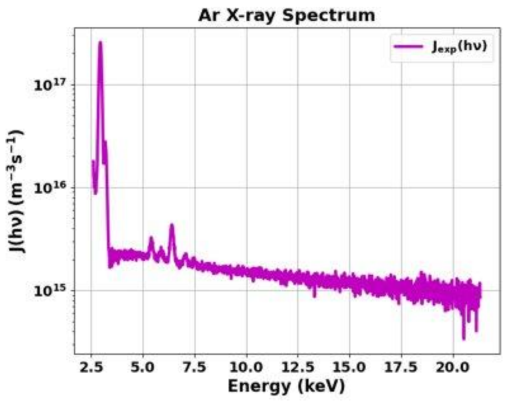
Constant monitoring of plasma density and temperature during acquisition time of paramount importance



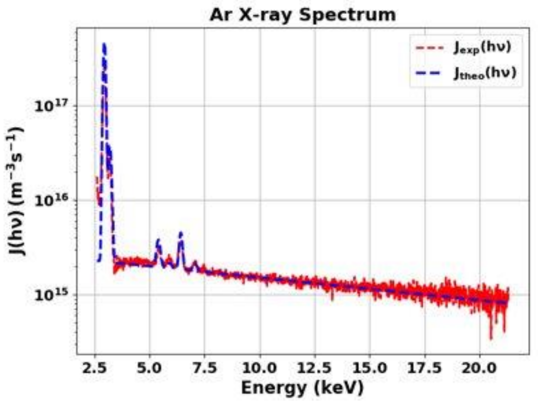
Multidiagnostic setup at LNS [6]

Plasma structure inspection **Axial losses inspection** **Radial losses inspection**





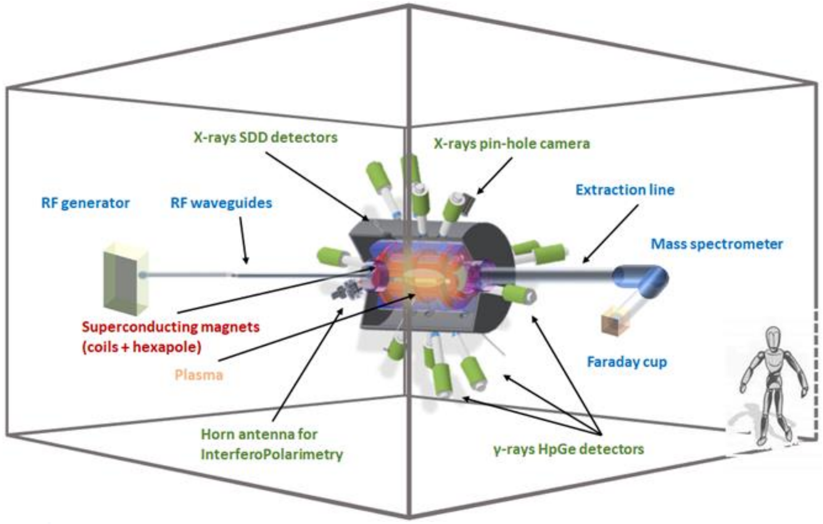
$$J_{theo}(h\nu) = J_{theo,brem}(h\nu) + J_{theo,line}(h\nu)$$



Model fit to emissivity density of Ar Plasma [4]

[4] B. Mishra *et al*, to be submitted to EPJ D
[6] E. Naselli *et al*, Journal of Instrumentation (JINST), 2019
E. Naselli - Invited talk, 3rd European Conference of Plasma Diagnostic, Lisbon (Portugal), 2019
E. Naselli et al., accepted to be published IL NUOVO CIMENTO C, 2021
E. Naselli, Oral - 24th International Workshop on ECR Ion Source (ECRIS), 2020
E. Naselli, Oral – 106th National Congress Italian Physical Society (SIF), 2020

Current Status



Superconducting coils for trap

Klystron amplifiers for microwaves

CCD camera for soft X-ray detection

HpGe detector array for γ-tagging

UNDER PROCUREMENT

IN COLLABORATION WITH GAMMA/GALILEO

Conclusion and Future Perspectives

β-decay rates one of the most important quantities for astrophysics models

Plasmas in stellar environments influence $t_{1/2}$ – models to predict modification due to CSD exist but need to be verified [1]

Plasmas with relevant properties can be generated through ECR with magnetic confinement

ESTABLISHED

$t_{1/2}$ can be measured in such plasmas, and once theory is verified/improved, can be extrapolated to real astrophysical scenarios – reduce uncertainty

Robust model connecting plasma dynamics with CSD and activity λ of radionuclides

Using MHD-stable plasmas to measure λ using secondary γ-tagging

Multi-diagnostic monitoring to verify system stability for entire duration of experimentation

ONGOING

Sandor Biri
Richard Rácz

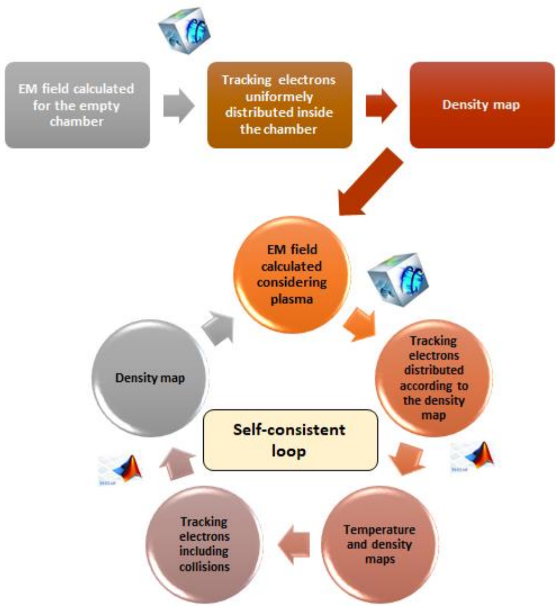
David Mascali
Domenico Santonocito
Angelo Pidatella
Eugenia Naselli
Giuseppe Torrisi

Alessio Galatà

Alberto Mengoni

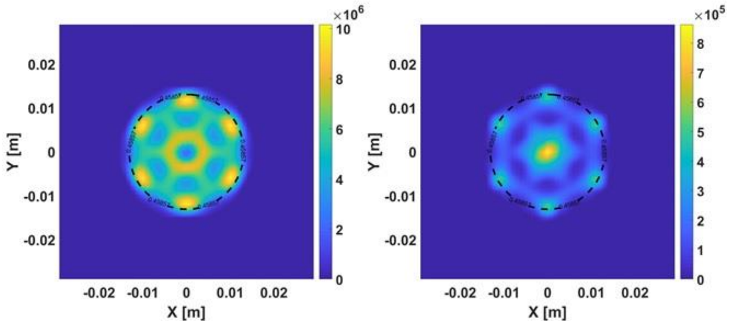
THANK YOU FOR YOUR ATTENTION!

Additional Content 1 - ECR Plasma Electron Dynamics

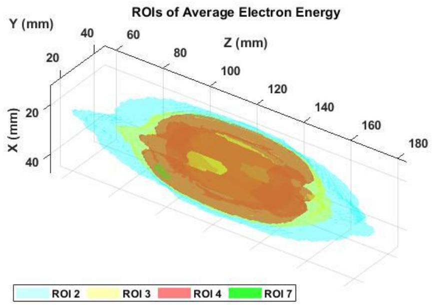


Schematic of COMSOL Multiphysics© + MATLAB© self-consistent numerical modelling for electrons [7]

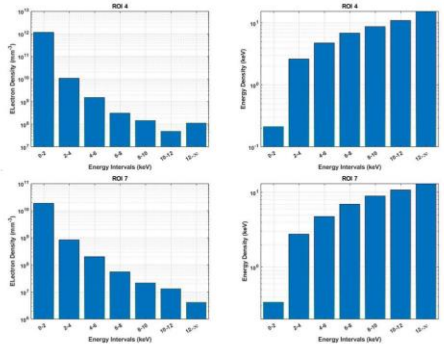
Electron energy and occupation maps intrinsically space-dependent because EM fields involved are anisotropic



XY-projections of occupation maps in [2,4] keV (left) and [6,8] keV (right) [4]



Isosurfaces of constant <E>



Collective density (left) and energy density (right) in ROI 4 (top) and ROI 7 (bottom)

4 choices of EEDF – mix of Maxwell and Druyvesteyn distribution functions

Ref. case name	Type
EEDF1	Low-E f_M + High-E f_M
EEDF2	Low-E f_M + High-E f_D
EEDF3	Low-E f_M + Medium-E f_M + High-E f_M
EEDF4	Low-E f_M + Medium-E f_D + High-E f_M

$$f_D(E; k_B T_e) = 1.04 \frac{\sqrt{E}}{(\sqrt{k_B T_e})^3} e^{-0.55 E^2/(k_B T_e)^2}.$$

Each EEDF tested in each ROI – better and more physical analysis

MSE and r^2 calculated for each cell of the ROI, then mean and SD of both quantities evaluated

$$\langle MSE \rangle_j = \frac{1}{N(j)} \sum_{k(j)=1}^{N(j)} MSE_{k(j)}, \qquad \langle r^2 \rangle_j = \frac{1}{N(j)} \sum_{k(j)=1}^{N(j)} (r^2)_{k(j)},$$

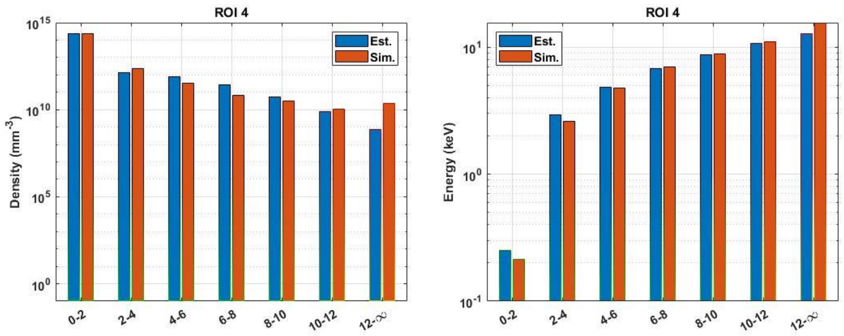
$$\sigma_{\langle MSE \rangle_j} = \frac{1}{\sqrt{N(j)-1}} \sqrt{\sum_{k(j)=1}^{N(j)} (MSE_{k(j)} - \langle MSE \rangle_j)^2} \qquad \sigma_{\langle r^2 \rangle_j} = \frac{1}{\sqrt{N(j)-1}} \sqrt{\sum_{k(j)=1}^{N(j)} ((r^2)_{k(j)} - \langle r^2 \rangle_j)^2}$$

Mean – average value of the statistic in the ROI

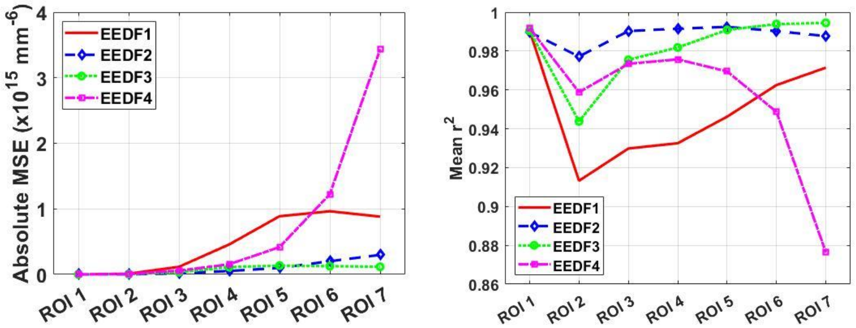
SD – variation of actual value from the mean *within* the ROI

Thus, low mean MSE, high mean r^2, and low SD for both implies best performance

[4] B. Mishra *et al*, to be submitted to EPJ D
[7] A. Galatà, C. S. Gallo, D. Mascali, and G. Torrisi, e-print arXiv:1912.01988



Simulated density (left) and energy density (right) vs EEDF2 estimate in ROI 3



ROI averaged MSE (left) and r^2 (right) of EEDF2 estimate [4]

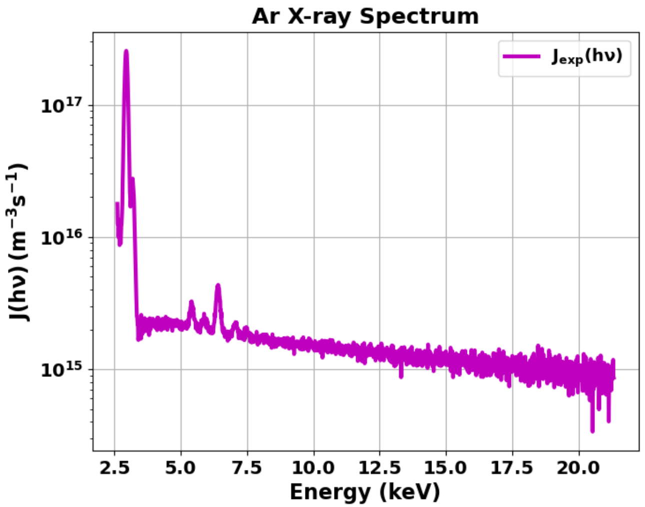
New improved simulations of 3D electron maps at higher energy ranges (3-100 keV)

$$J_{theo}(h\nu) = J_{theo,brem}(h\nu) + J_{theo,line}(h\nu)$$

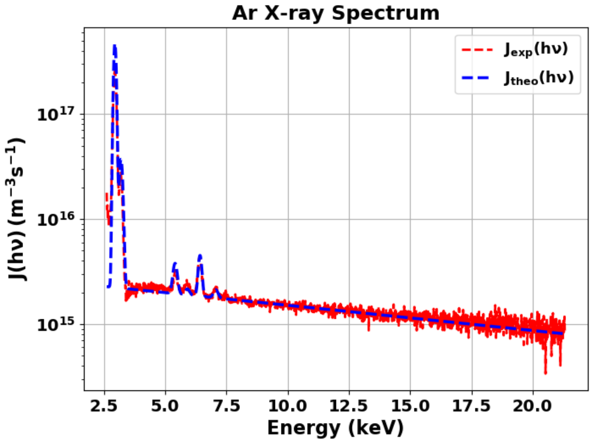
$$J_{theo,K\alpha} = h\nu_{K\alpha}\frac{\rho_e\rho_i\omega_{K\alpha}}{\Delta E}\int_I^\infty \sigma_{K,ion}v_e f(E)\mathrm{d}E$$

$$J_{theo,K\beta} = h\nu_{K\beta}\frac{\rho_e\rho_i\omega_{K\beta}}{\Delta E}\int_I^\infty \sigma_{K,ion}v_e f(E)\mathrm{d}E$$

$$J_{theo,brem}(h\nu) = \rho_e\rho_i(Z\hbar)^2\left(\frac{4\alpha}{\sqrt{6m_e}}\right)^3\left(\frac{\pi}{kT}\right)^{1/2}\mathrm{e}^{(-h\nu/kT)}$$



Emissivity density of Ar Plasma [4]

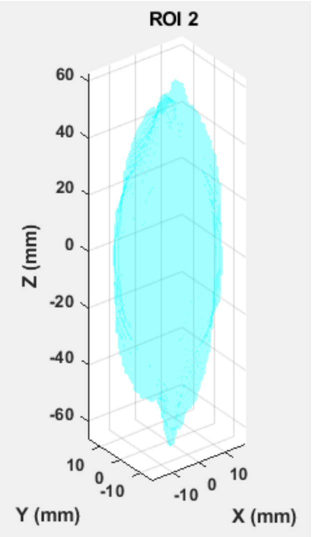


Model fit to emissivity density of Ar Plasma [4]

[4] B. Mishra *et al*, to be submitted to EPJ D

Additional Content 2 - ECR Plasma Ion Dynamics

Each ROI as a single *grand* cell → **Collective electron density and EEDF** → **FLYCHK** → **Ion density / Ion CSD / Ion level population**



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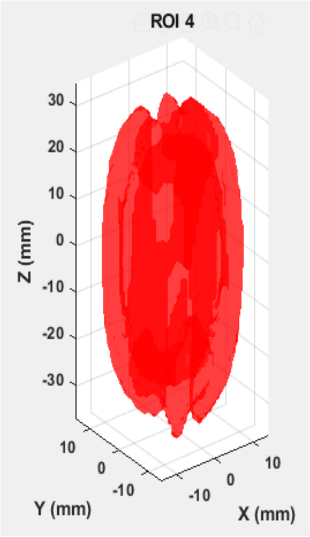
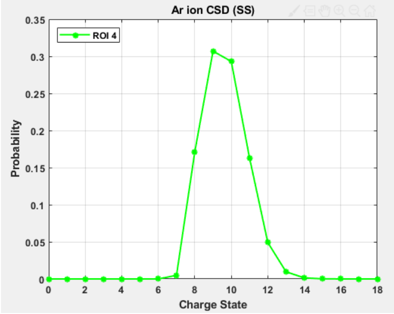
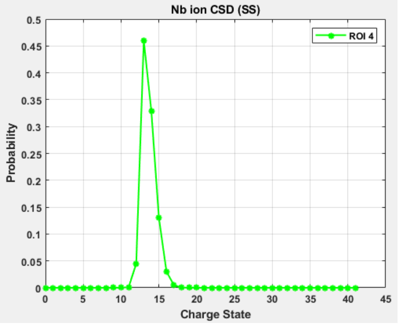
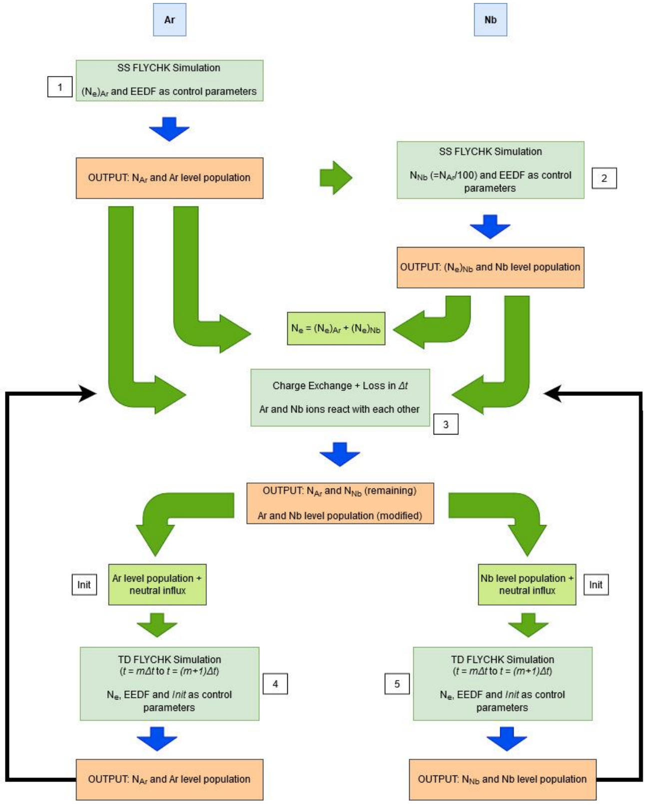
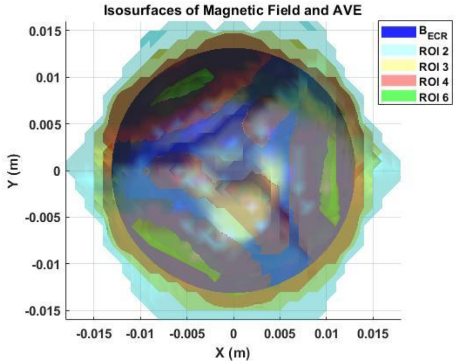








Flow chart showing steps of TD simulation



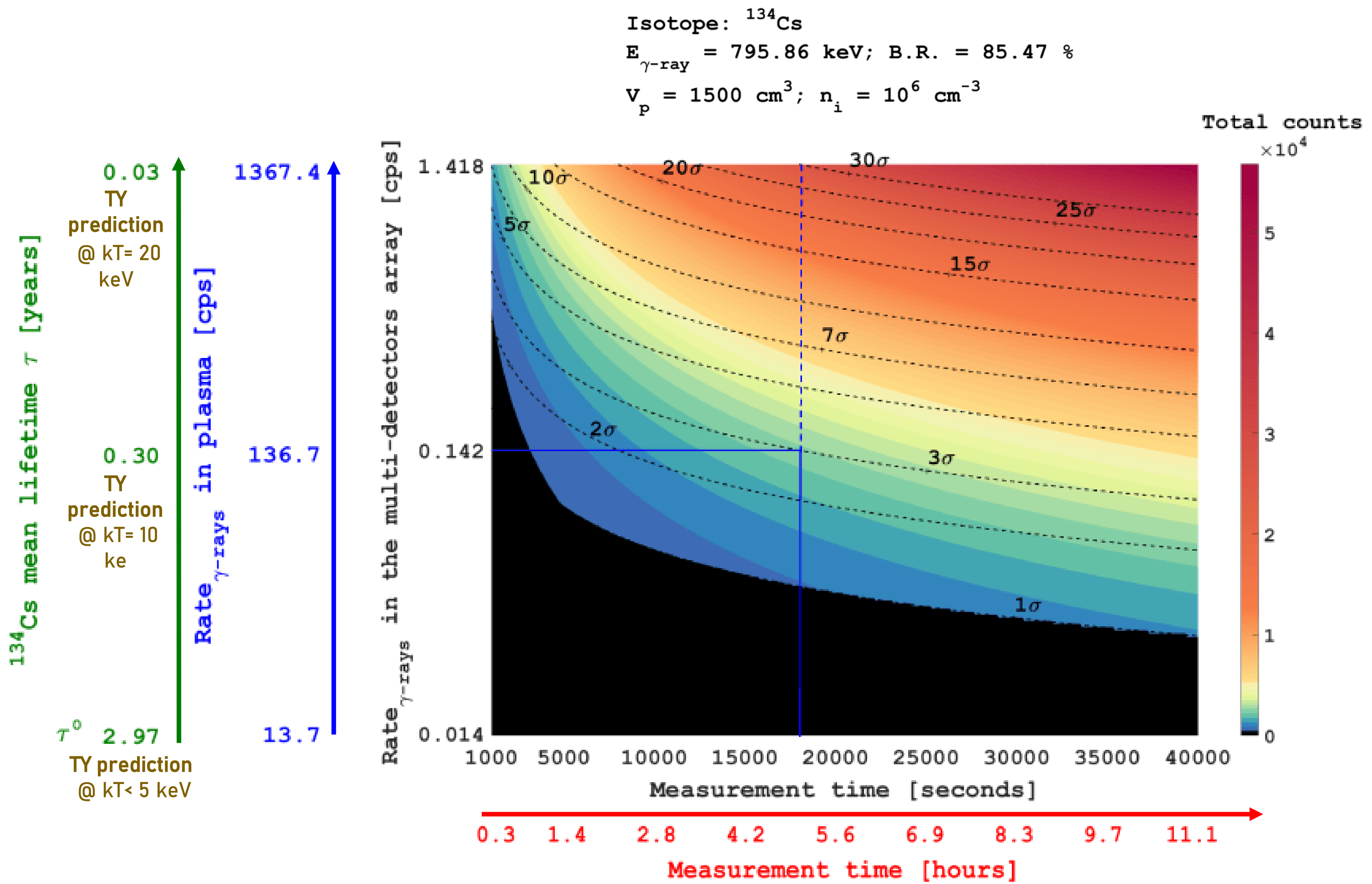
Outside ECR: ROI 1, 2, 3 (τ_{halo})
Inside ECR: ROI 4, 5, 6, 7, 8 ($\tau_{plasmoid}$)

$$\tau_i^q = 7.1 \times 10^{-20} (\frac{l}{2})^2 \ln \Lambda_{ij} \frac{q^2}{T_i^{5/2}} n_e \sum_j \sqrt{A_j} \langle q \rangle_j$$

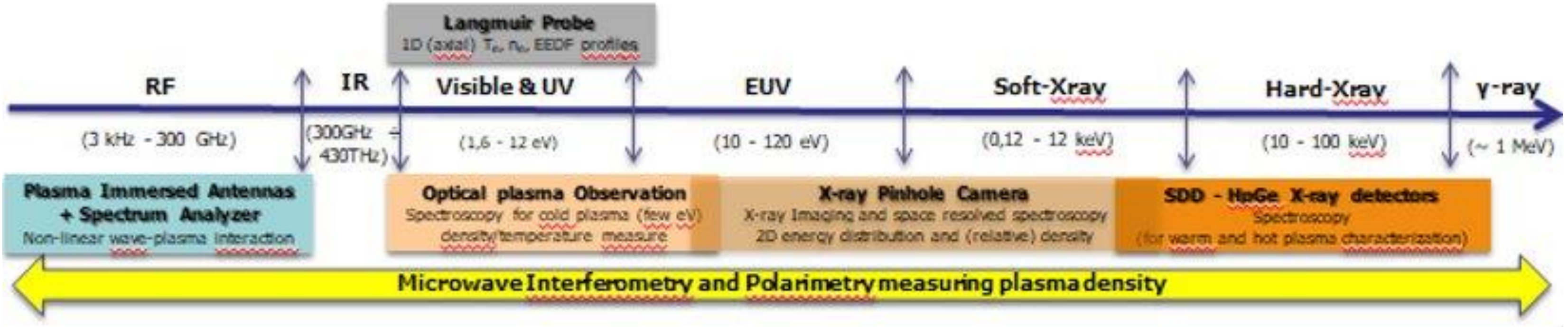
$$\tau_{ES}^q = \tau_i^q e^{\frac{qe\Delta\phi}{k_B T_i}} \qquad \frac{1}{\tau_{plasmoid}} = \frac{1}{\tau_i^q} + \frac{1}{\tau_{ES}^q}$$

$$\tau_M = Rl_h / v_{T_i} \qquad \tau_{halo} = \tau_M$$

Additional Content 3 – Confidence Plots for ^{134}Cs



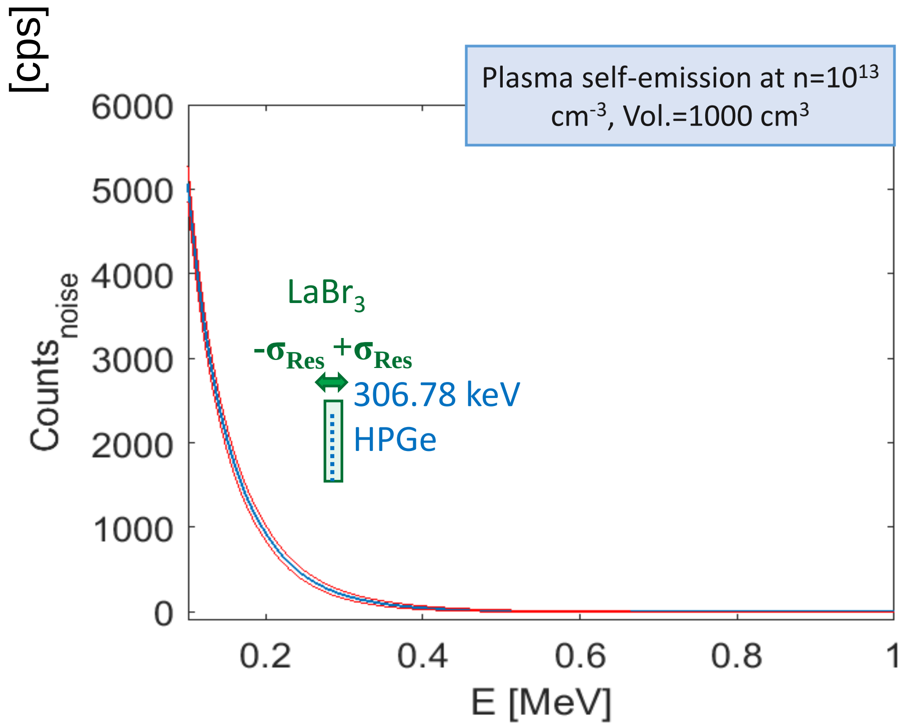
Additional Content 4 – Plasma Diagnostics



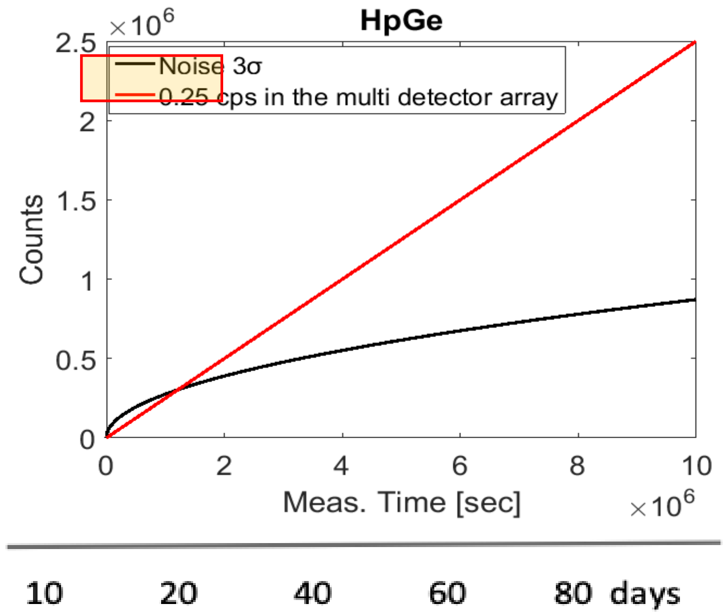
Diagnostic tool	Sensitive Range	Measurement	Resolution & Meas. Error
SDD	1.0 ÷ 30 keV	Volumetric soft X-ray Spectroscopy: warm electrons temperature and density	Res. ~ 120 eV ϵ_{n_e} ~ 7%, ϵ_{T_e} ~ 5%
HpGe	30 ÷ 400 keV	Volumetric hard X-ray Spectroscopy: hard electrons temperature and density	Res. ~ 200 eV ϵ_{n_e} ~ 7%, ϵ_{T_e} ~ 5%
Visible Light Camera	1.0 ÷ 12 eV	Optical Emission Spectroscopy: cold electrons temperature and density	$\Delta\lambda$ = 0.04nm R=12500
Microwave Interferometer	K-band 18 ÷ 26.5 GHz	Interferometric measurement: line integrated total density	ϵ_{n_e} ~ 50%
Microwave Polarimeter	K-band 18 ÷ 26.5 GHz	Faraday-rotation measurement: line integrated total density	ϵ_{n_e} ~ 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

Additional Content 5 – Calculating Acquisition Time

The noise (consisting, especially, in the plasma self emission) affects the detection of the signal



The noise spectrum was used to evaluate the time needed to have a significant 3 level signal



The intersection from the two lines shows the point where the signal over comes the 3 noise level, and the correspondent abscissa is the measurement time needed to have a 3 level of confidence

Trend of the **signal counts** (in red) compared to the **3 times the noise** (in black)

$$\boxed{\text{Noise}_{3\sigma} = 3\sqrt{Noise_{cps} \cdot Tmeas}}$$

$$\boxed{N(T_{meas}) = \lambda n_i V_{plasma} T_{meas}}$$