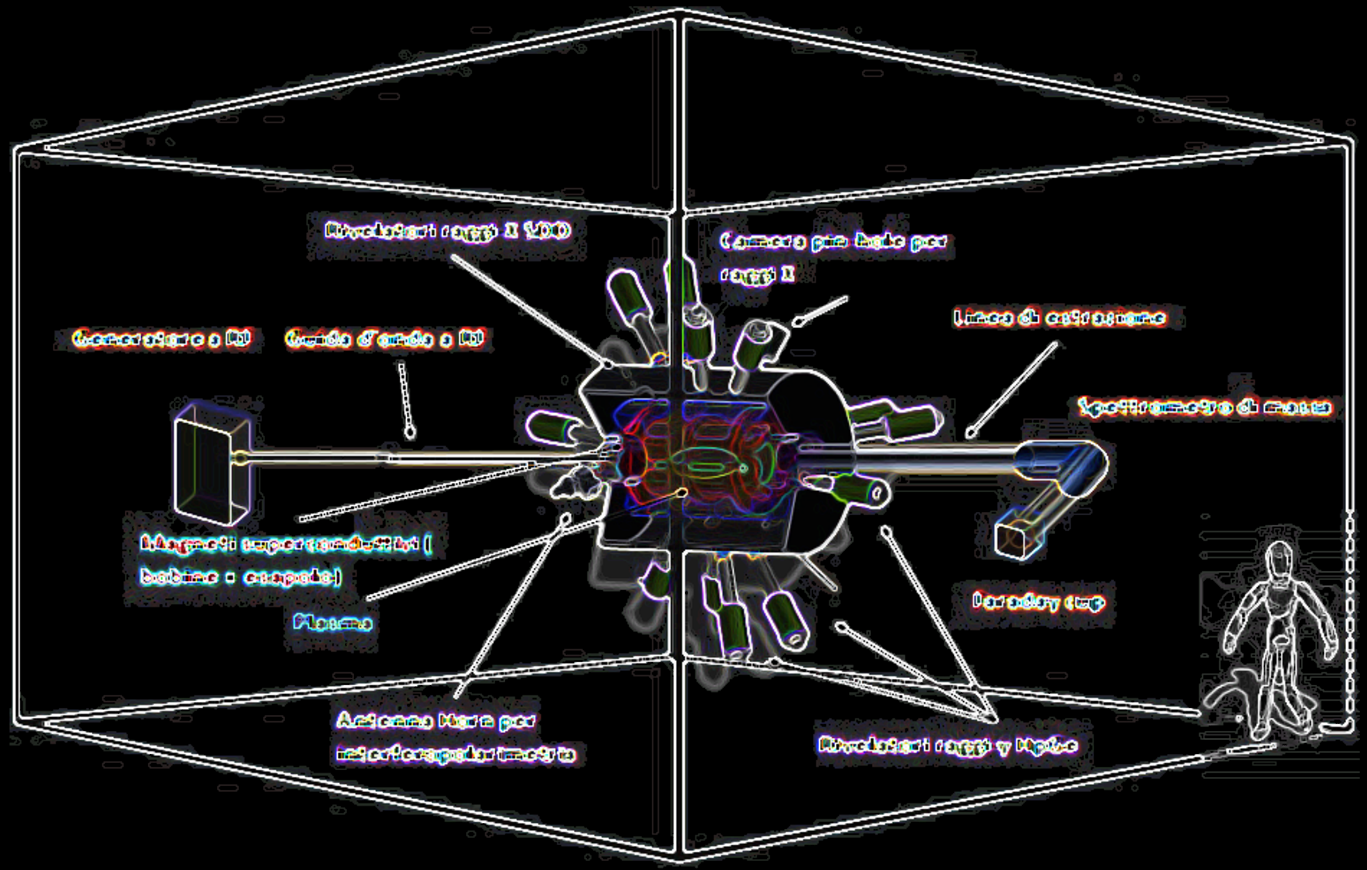

# The PANDORA Project for nuclear and astrophysical studies in laboratory plasmas: *status and perspectives*




David Mascali (INFN-LNS)
*on behalf of the PANDORA collaboration*


Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

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# β-decay investigation in matter: from early experiments to storage rings

Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

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- **Long standing question: How constant really are nuclear decay constant ?**
  - One of the paradigms of nuclear science since the very early days has been the general understanding that the decay constant is independent of extranuclear considerations

- What happens to **β-radioisotopes under extreme conditions of Temperature (2500 K), Pressure (2000 atm) or Magnetic fields (80000 G)** ? → **almost nothing… < 0,05 % decay constant variation**

*G. T. Emery, Perturbation of Nuclear Decay Rates, Annual Review of Nuclear Science 22, 1972*

*H. Mazaki et al., Effect of Pressure on the Decay Constant of $^{99m}$Tc, Phyc. Rev. C 5, 1972*

- How does the **surrounding chemical environment** (lattice structure and electron affinity) affect the host atoms decay? (e.g. $^{7}$Be →$^{7}$Li) → **A variation of E.C. lifetime of around 3,5%**

*G. T. Emery, Perturbation of Nuclear Decay Rates, Annual Review of Nuclear Science 22, 1972*

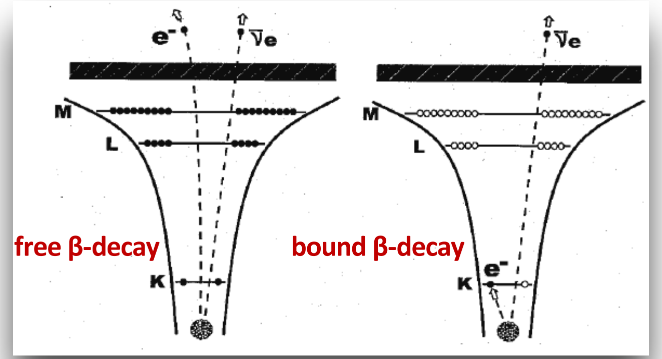
**What happens when atoms are highly ionized?** → **….the answer came from Storage Rings experiments ….**

- **Bare $^{163}$Dy$^{66+}$ nuclei, being stable as neutral atoms, become radioactive**, thus allowing the s process, **with a half-life of 33 days.**

*M. Jung at al., First observation of bound-state β⁻ decay, Phys. Rev. Lett. 69, 1992*

- **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

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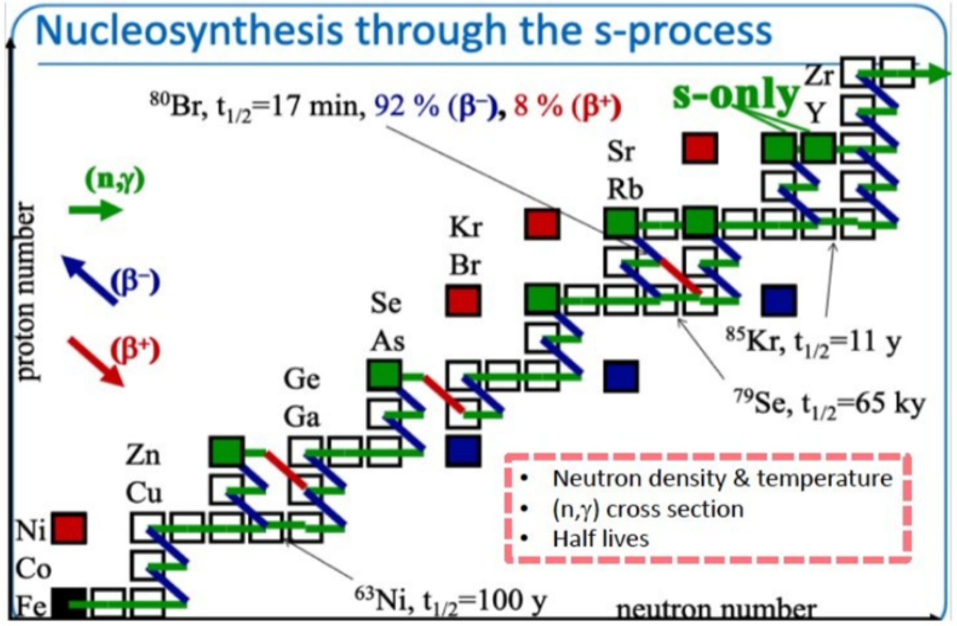
In a stellar plasma, ions are embedded in a cloud of charges, both positive and negative.

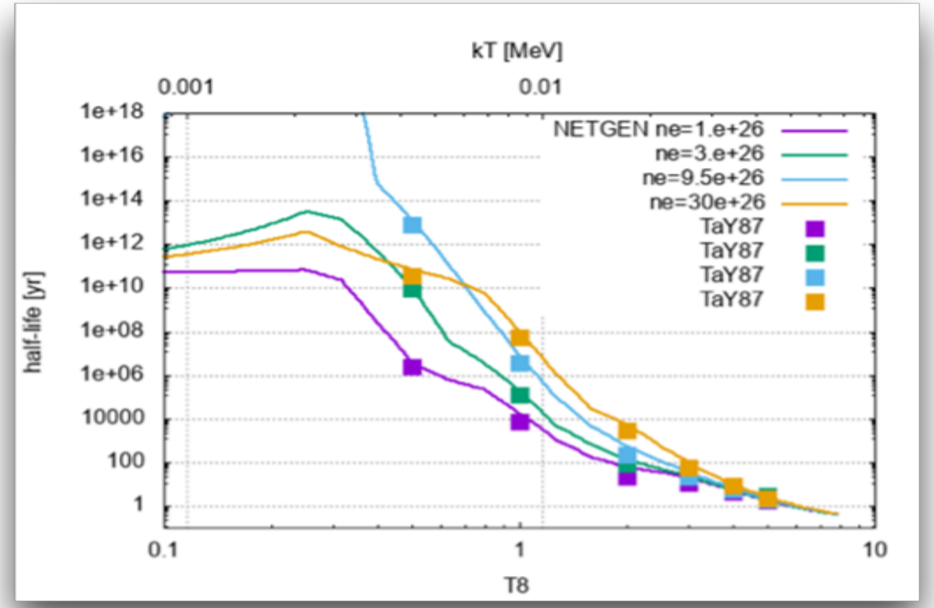
In addition to ionisation, these charges create EM fields which act as perturbation to the atomic/ionic levels, along with inelastic e-i collisions, leading to corrections of Q values which affects the decay rates.

Competition between n capture and beta decay





Busso, M., Gallino, R., Wasserburg, G.J. 1999, Ann Rev. Astron. Astrophys. 37, 239
Cristallo, S. et al. 2011, Astrophys. J. Suppl. 197, 17
Gallino, R. and Busso, M. 1986, in "From Nuclei to Stars". Proceedings of the International Fermi", Course XCI (North-Holland: Amsterdam)


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

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

Direct implication on branching points in s-process nucleosynthesys chain competition of neutron capture vs β-decay

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# Beta decay modes in stellar environment

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## The PANDORA project: a new multidisciplinary study

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

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**

→ ***Strong synergy with DTT!!***

# PANDORA concept and design

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**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*

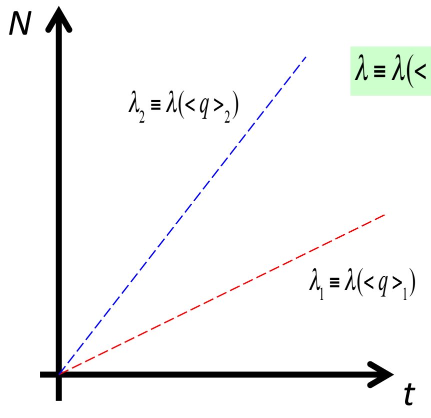
$$\frac{dN}{dt} = \lambda n_i V \rightarrow \int_0^{t_{meas.}} dN = \int_0^{t_{meas.}} \lambda n_i V\, dt \rightarrow N(T_{meas.}) = \lambda n_i V_{plasma} T_{meas.}$$

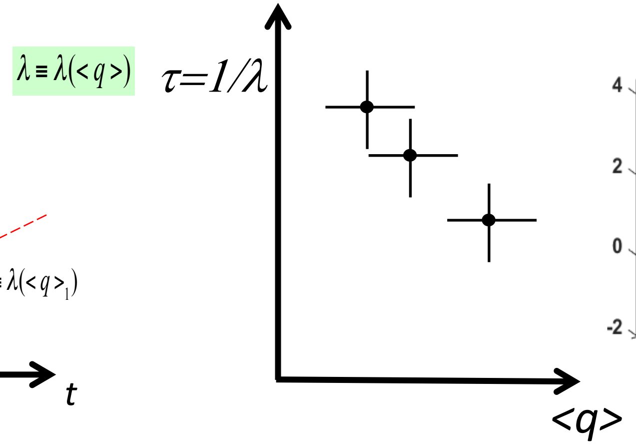
$\lambda n_i V$ is constant

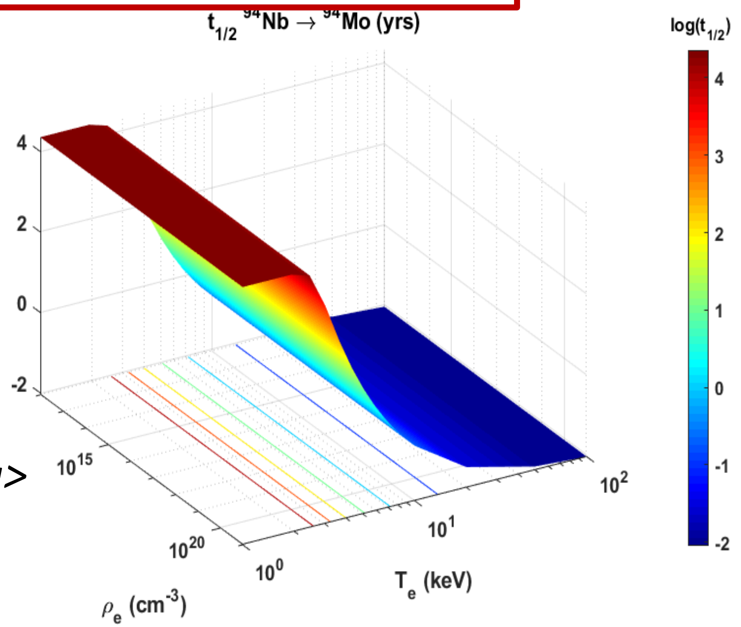
*Isotope decay constant*

*Density of the isotope in the plasma (const.)*

*Plasma volume (const.)*




Gamma-rays emitted by the daughter nuclei after the beta decay will be detected by an array of HPGE.

# PANDORA concept and design

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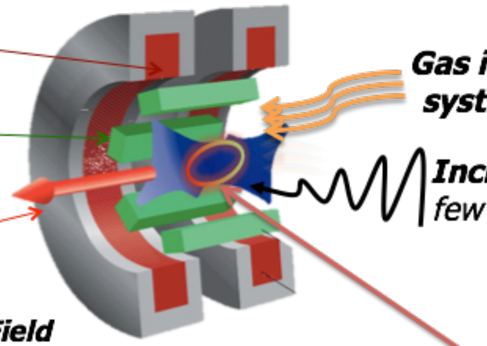
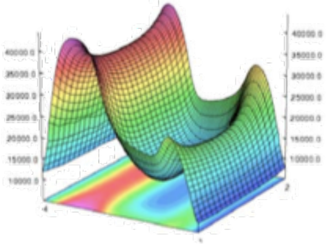
**PANDORA Experimental Setup:**
- Trap
- Detector array
- Plasma Diagnostics

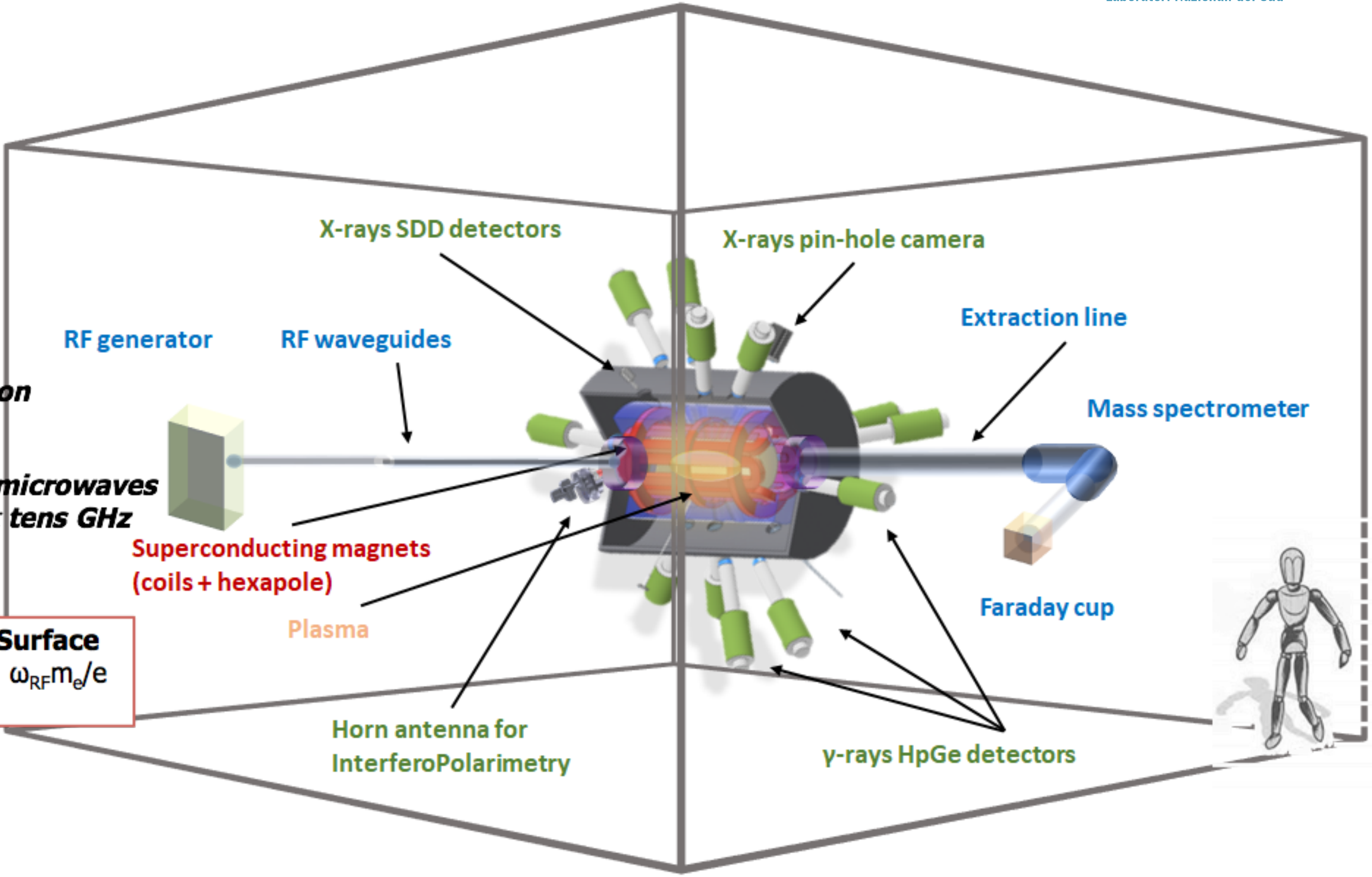



***"B_minimum" Magnetic Field*** *structure*



**ECR Plasma**
$n_e \sim 10^{12}\ cm^{-3}$
$T_e \sim$ tens keV
$\tau_{ion} \sim$ ms

**ECR Surface**
$B_{ECR} = \omega_{RF} m_e / e$




D. Mascali et al., *Universe* **2022**, 8(2)

Plasmas for Astrophysics

| Isotope | Lab $t_{1/2}$ (yr) | Jπ | Z | $E_\gamma$ (keV) | Type of decay | Bound state decay [16] |
|---|---|---|---|---|---|---|
| | | | | | | |
| $^{63}$Ni | 100.1 | 1/2- | 28 | No | β- | Y (X-rays from $^{63}$Cu?) |
| $^{79}$Se | 1.13x10$^{5}$ | 7/2+ | 34 | No | β- | |
| ($^{79m}$Se | 3.9m | 1/2- | 34 | 95.7 | IT, β-) | |
| $^{81}$Kr | 2.29x10$^{5}$ | 7/2+ | 36 | 276 | ε | |
| ($^{81m}$Kr | 13.1s | 1/2- | 36 | 190.62 | IT, ε) | |
| $^{85}$Kr | 10.756 | 9/2+ | 36 | 130-514 | β- | |
| ($^{85m}$Kr | 4.48h | 1/2- | 36 | 129-731 | IT, β-) | |
| $^{93}$Zr | 1.5x10$^{6}$ | 5/2+ | 40 | 30.7 | β- | |
| $^{95}$Zr | 64d | 5/2+ | 40 | 235-756 | β- | |
| $^{99}$Tc | 2.1x10$^{5}$ | 9/2+ | 43 | 89.6 | β- | |
| $^{106}$Ru(?) | 373.5d | 0+ | 44 | Many ($^{106}$Rh) | β- | Y (X-rays from $^{106}$Rh?) |
| $^{134}$Cs | 2.065 | 4+ | 55 | >600 | β-, ε | |
| ($^{134m}$Cs | 2.903h | 8- | 55 | 138.744 | IT | |
| $^{135}$Cs | 2.3x10$^{6}$ | 7/2+ | 55 | 786,846 | β- | |
| $^{137}$Cs | 30.07y | 7/2+ | 55 | 238-661 | β- | |
| $^{147}$Pm | 2.6 | 7/2+ | 61 | 76-197 | β- | |
| $^{151}$Sm | 90 | 5/2- | 62 | No | β- | Y (X-rays from $^{151}$Eu?) |
| $^{155}$Eu | 4.7 | 5/2- | 63 | 10-146 | β- | Y (X-rays from $^{155}$Gd?) |
| $^{171}$Tm | 1.92d | 1/2+ | 69 | 66.7 | β- | |
| $^{176}$Lu | 3.78x10$^{10}$ | 7- | 71 | 88-400 | β- | |
| ($^{176m}$Lu | 3.635h | 1- | 71 | 82-1237 | β-, ε) | |
| $^{204}$Tl | 5.45 | 2- | 81 | 511 e+e- | β- ε+ β- | |
| $^{94}$Nb | 2.03x10$^{4}$ | 6+ | 41 | 702-871 | β- | |
| $^{93}$Mo | 4.0x10$^{3}$ | 5/2- | 42 | 30.7 | ε | |
| $^{129}$I | 1.57x10$^{7}$ | 7/2+ | 53 | 40 | β- | |
| $^{205}$Tl | stable | 1/2+ | 81 | No | if ion. β- | Y (X-rays from $^{205}$Pb?) |

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**More than 120 isotopes of astrophysical and nuclear physics interest!! PANDORA can become, in perspective, a big facility!**

## Physics Cases

- Scientific relevance
- Expected Effects on the lifetime from charge states or ion temperature
- Trap size
- Type of element (gas, metal, rare isotope, commercial or not, etc.)

*Trap properties fix charge state distribution!*

| Isotope | $T_{1/2}$ (yr) | Eγ (keV) |
|---|---|---|
| $^{176}$Lu | 3.78x10$^{10}$ | 88-400 |
| $^{134}$Cs | 2.06 | >600 |
| $^{94}$Nb | 2.03x10$^{4}$ | >700 |

Short-list for PANDORA-Phase 1

*D. Mascali et al., EPJ web of conference 227, 2020, 01013*

# MAIN SUBSYSTEMS: STATUS & UPDATES
# → Models and Theory

Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

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## ….but also improved stellar physics help in describing the overall scenario

## Role played by magnetic fields in AGB stars:

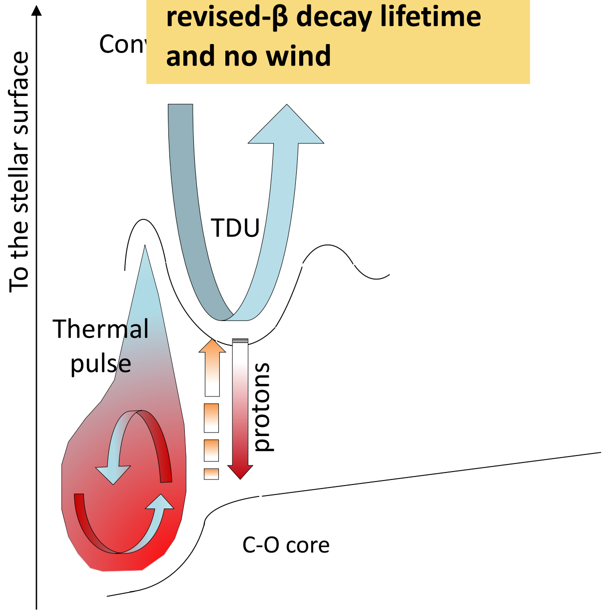
important not only for c

**TY-β decay lifetime and no wind**

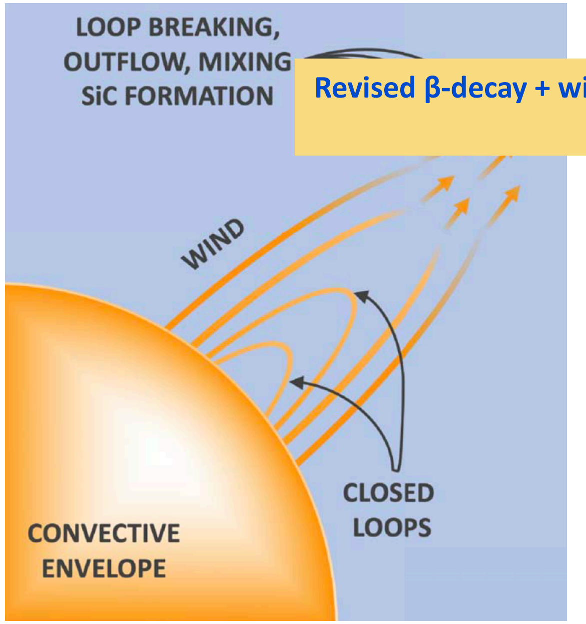
capture processes, but also for mixing their products into the circumstellar envelopes

A scenario emerges where the present knowledge of s-process nucleosynthesis can be improved through advanced stellar model coupled to better data on weak interactions in stellar like conditions.

**revised-β decay lifetime and no wind**




**Revised β-decay + wind**




*S Palmerini, et al., The Astrophysical Journal 921 (1), 7*

# MAIN SUBSYSTEMS: STATUS & UPDATES
# → Models and Theory

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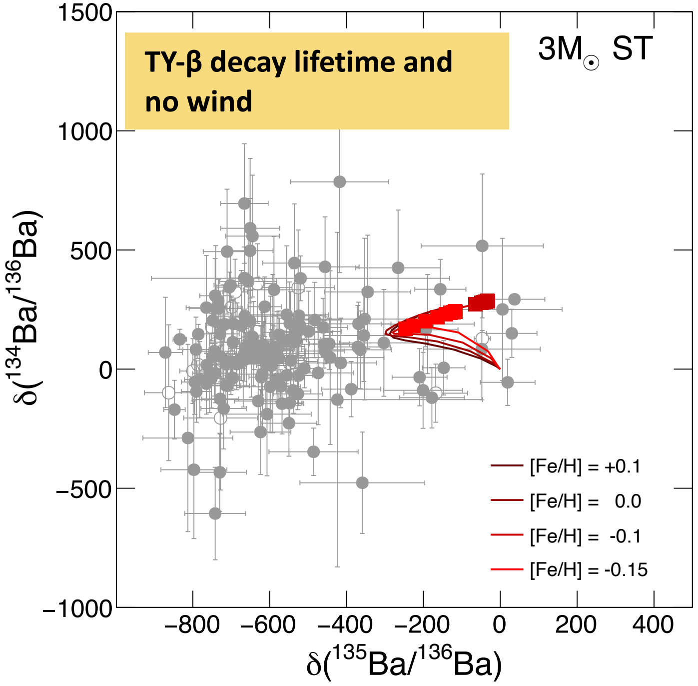
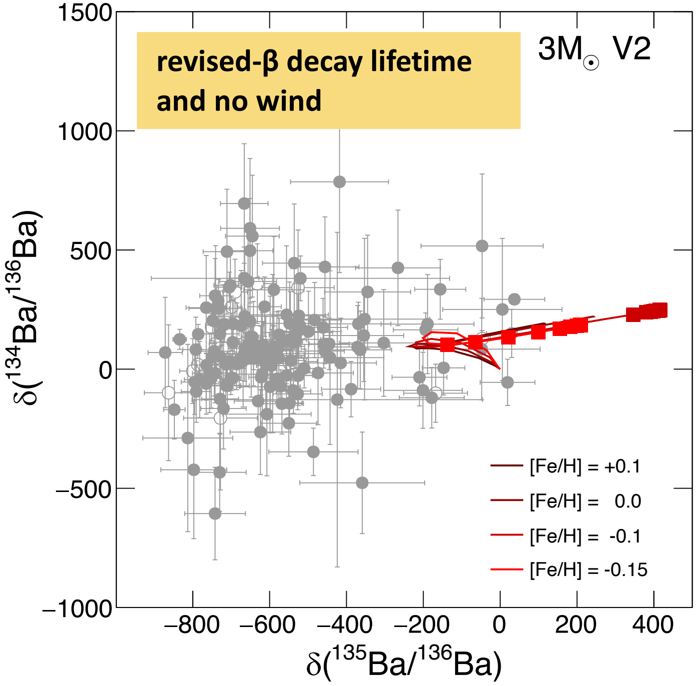
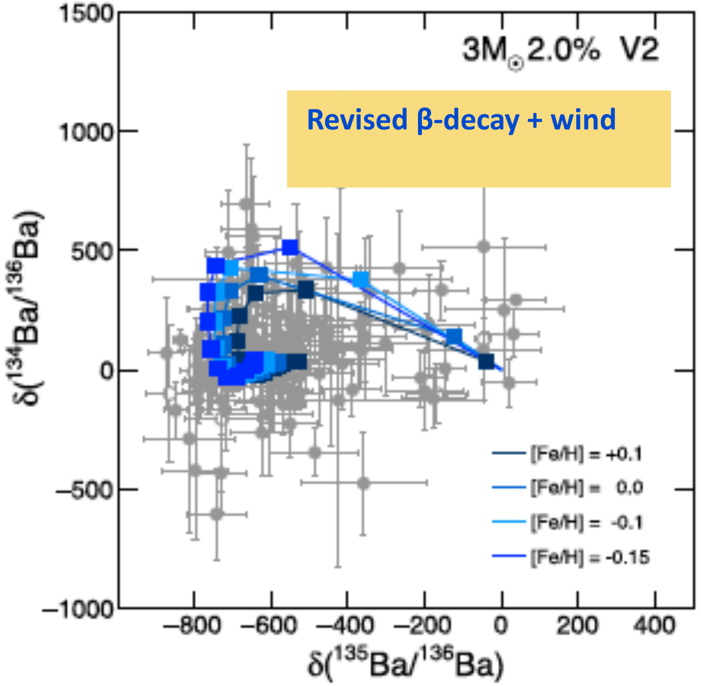


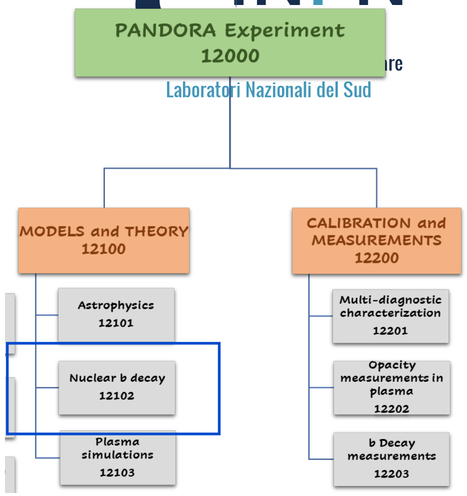




*S Palmerini, et al., The Astrophysical Journal 921 (1), 7*

# MAIN SUBSYSTEMS: STATUS & UPDATES

# → Models and Theory

TIFPA/Univ. Camerino groups



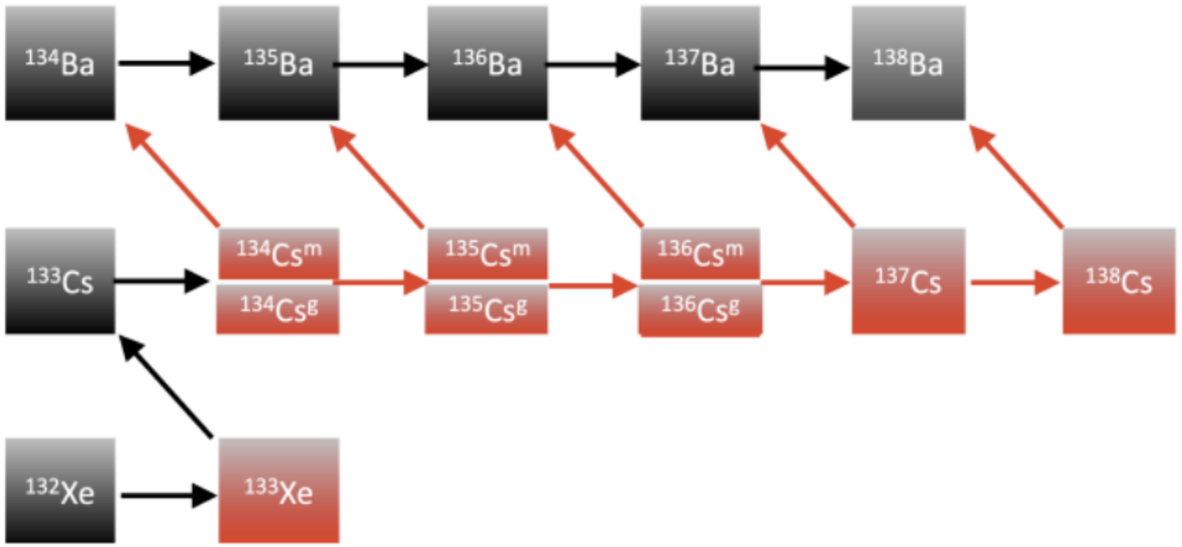

**New fully quantum-mechanical models have been developed** to better take into account the nuclear structure effect (electronic and nuclear DOF) in beta decay theory ( treatment of forbidden non-unique transitions) **and applied to $^{134}$Cs and $^{135}$Cs**.

The abundance of Ba in AGB stars depends solely on slow (s) n-captures

The s-process contribution to the element Ba starts from neutron captures on the stable isotope $^{133}$Cs

Branching point at $^{134}$Cs, where n-captures compete mainly with β−decay (lab. half-life = 2 yr) to excited states of $^{134}$Ba and, less effectively, with electron captures to $^{134}$Xe (half-life = 6.8·10$^{5}$ yr)

From $^{134}$Cs, n-captures feed the $^{135}$Cs, then $^{136}$Cs (half-life =13.16 d) and 137 Cs (half-life = 30.07 y), which are sites of branching points for the s-process path




*S. Taioli et al. The Astrophysical Journal 933(2):158, July 2022*

*by S. Simonucci, S. Taioli, et al.*

# MAIN SUBSYSTEMS: STATUS & UPDATES
# → Models and Theory

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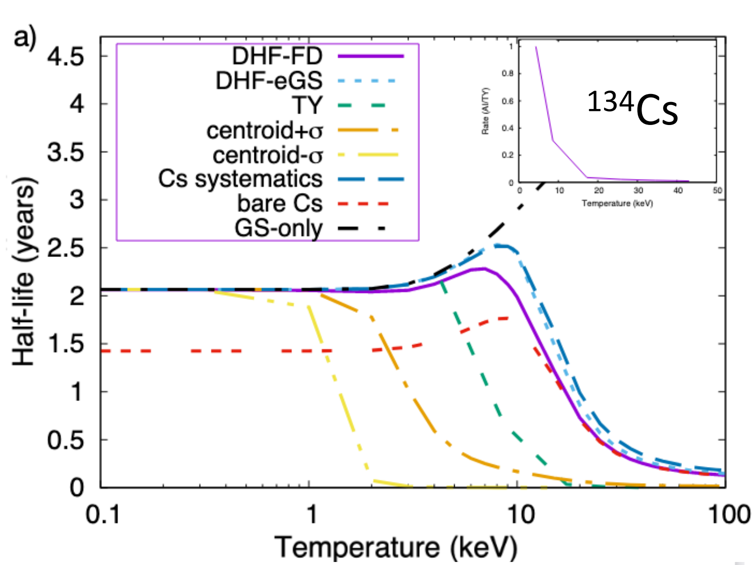
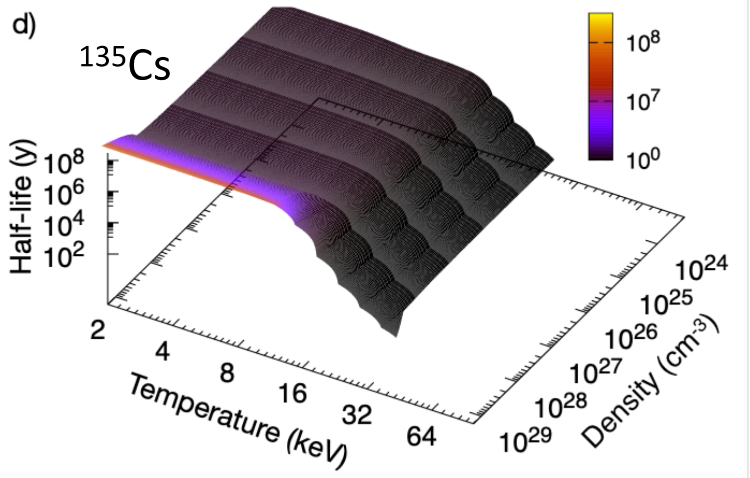
**The calculations of decay rate have been carried out by solving the Dirac-Hartree-Fock (DHF) equations**




The beta decay rate of Cs is affected concurrently by two major factors:

- the presence of 3 nuclear excited states of Cs
- the electronic excitation, also up to a complete ionization

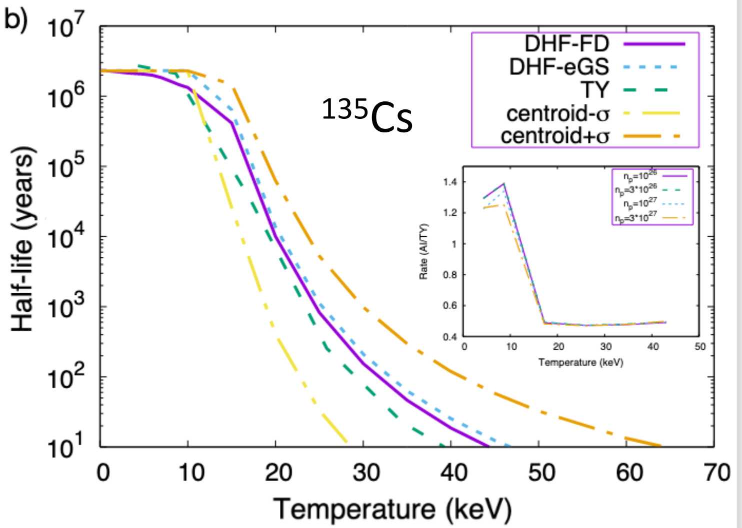



Table I. Comparison between $^{134}$Cs rates obtained using our model and by TY [2] (units in $s^{-1} \times 10^{-8}$).

| $T_8$ [a] | TY [b] | This work [b] |
|---|---|---|
| 0.5 (4.31) | 1.02 | 1.02 |
| 1 (8.62) | 3.28 | 1.01 |
| 2 (17.23) | 63.1 | 2.28 |
| 3 (25.85) | 211.0 | 4.73 |
| 4 (34.47) | 481.0 | 7.22 |
| 5 (43.09) | 889.0 | 9.36 |

**PANDORA domain** (rows 0.5–2)

[a] $T_8 = 10^8$ K (corresponding values in keV in parentheses).
[b] $n_p = 10^{26}$ cm$^{-3}$

*S. Taioli et al. ApJ 933(2):158, July 2022*

# MAIN SUBSYSTEMS: STATUS & UPDATES

# → Models and Theory

Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

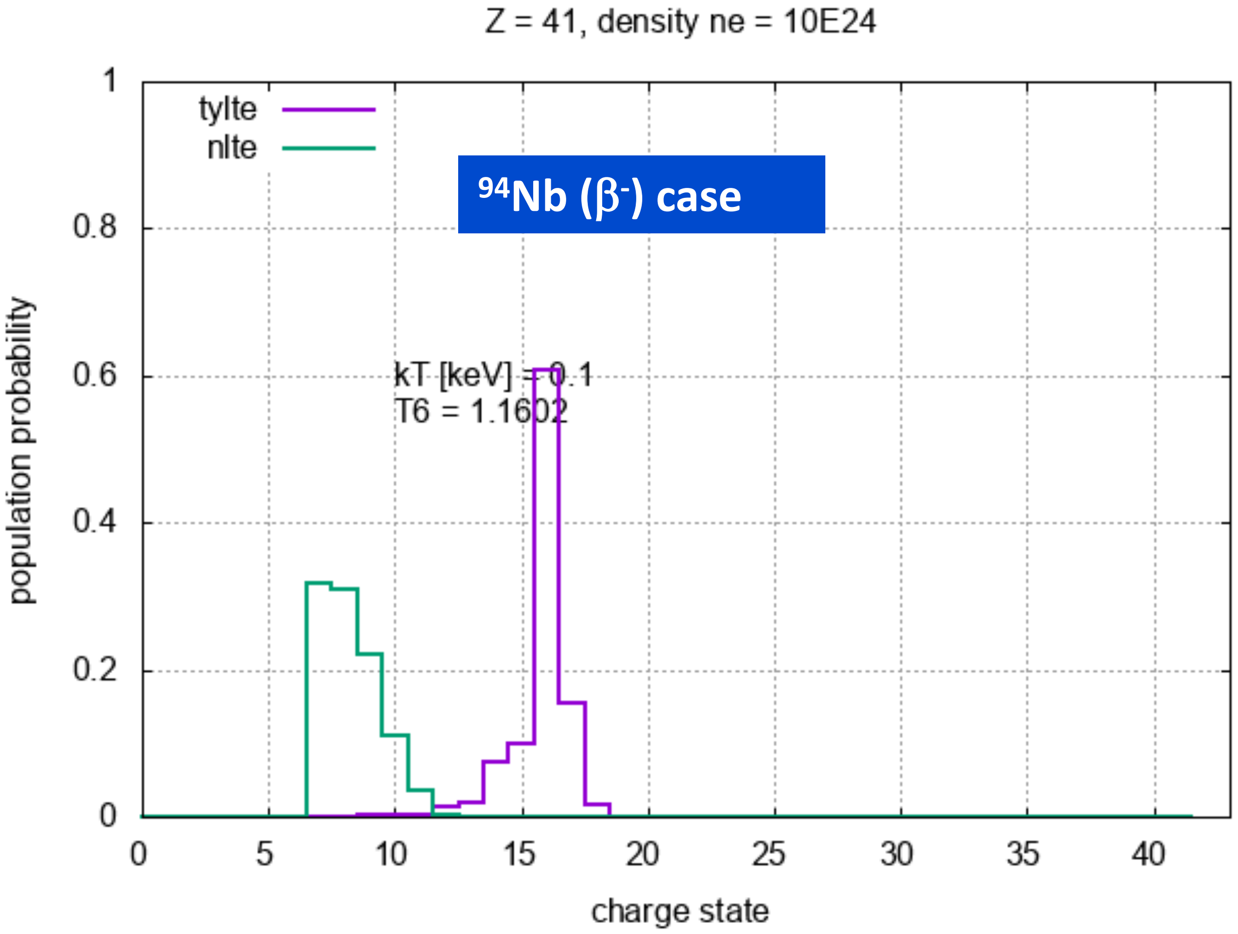
INFN - Bologna

## LTE

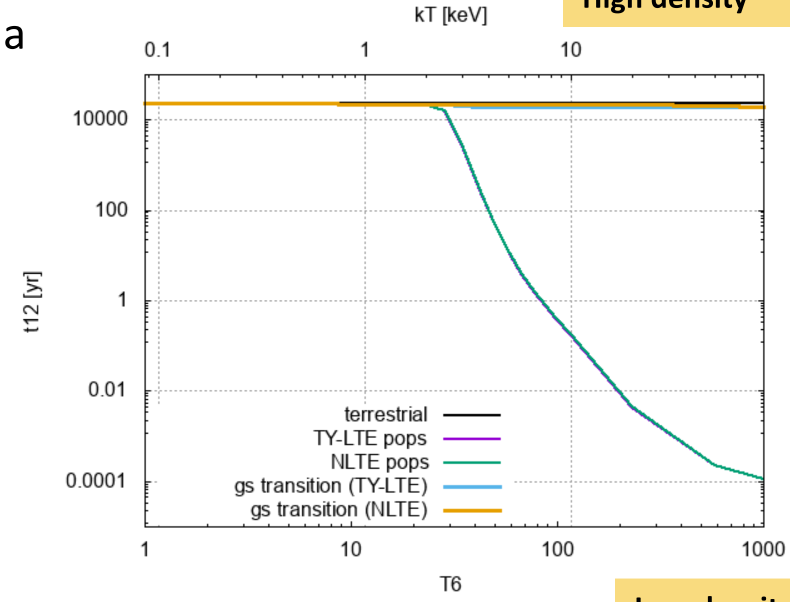
high densities & low temperatures

## NLTE

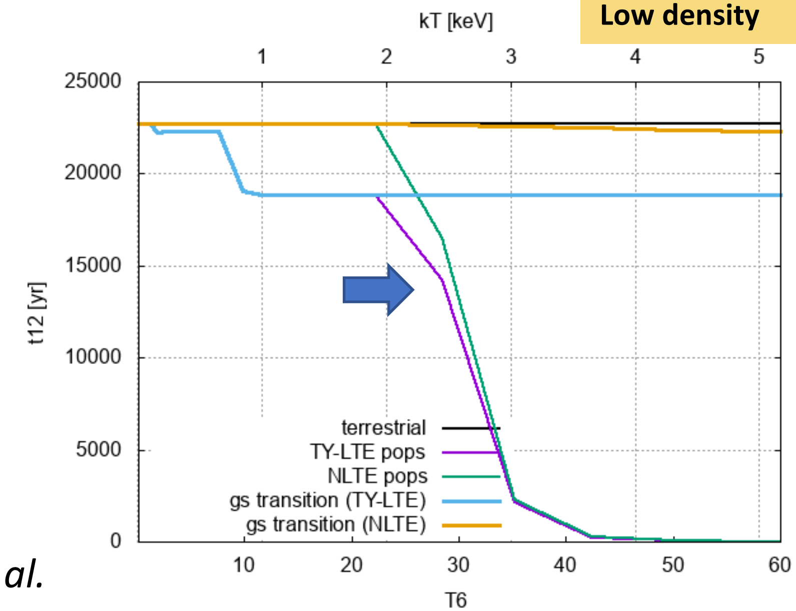
low densities & high temperatures




High density




Low density



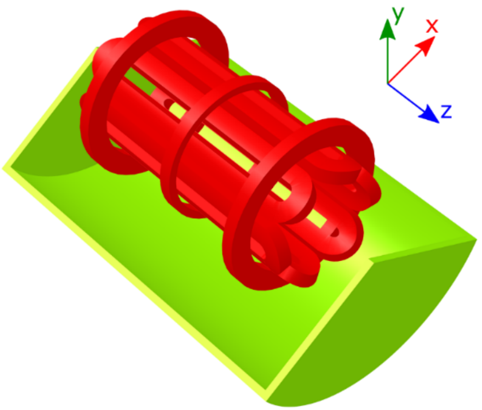

*by A. Mengoni et al.*

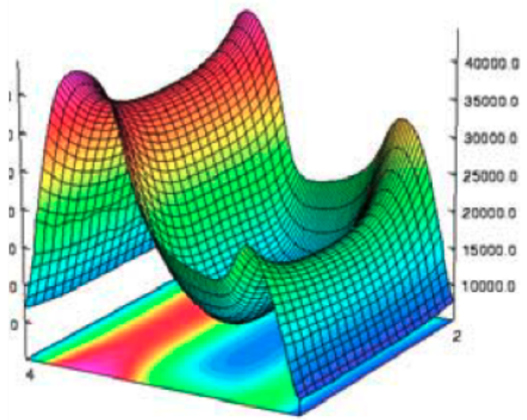
# PANDORA design: the magnetic trap

**The magnetic trap is made of:**

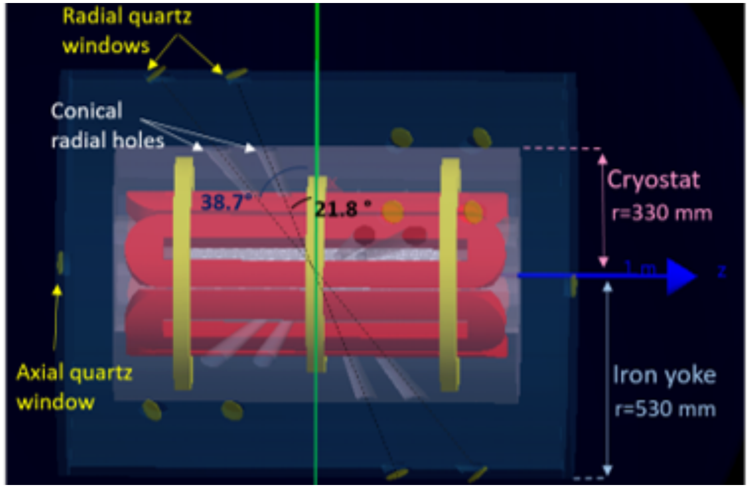
- 3 superconducting coils for axial confinement
- a superconducting exapole for radial confinement

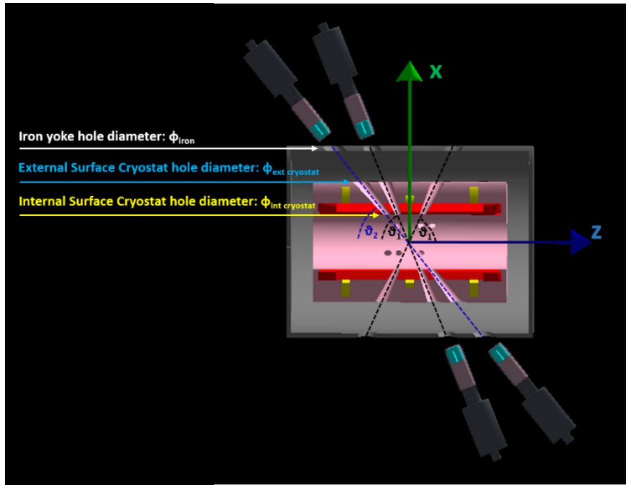
*GS Mauro et al, Frontiers in Physics, 621(2022)*



**$B_{minimum}$ Magnetic Field**




**High charge state ions production**: ➡ ions must remain in the plasma long enough (tens of ms) to reach high charge states ( $n_e \times \tau_i$ )

➡ since $n_e \propto (\omega_{RF})^2$ high operating frequencies are needed

**PANDORA trap has been designed to operate at 18-21 GHz in MHD-stable configuration using Double or Triple frequency heating** to improve plasma stability and sources performances

# PANDORA design: the HPGE array

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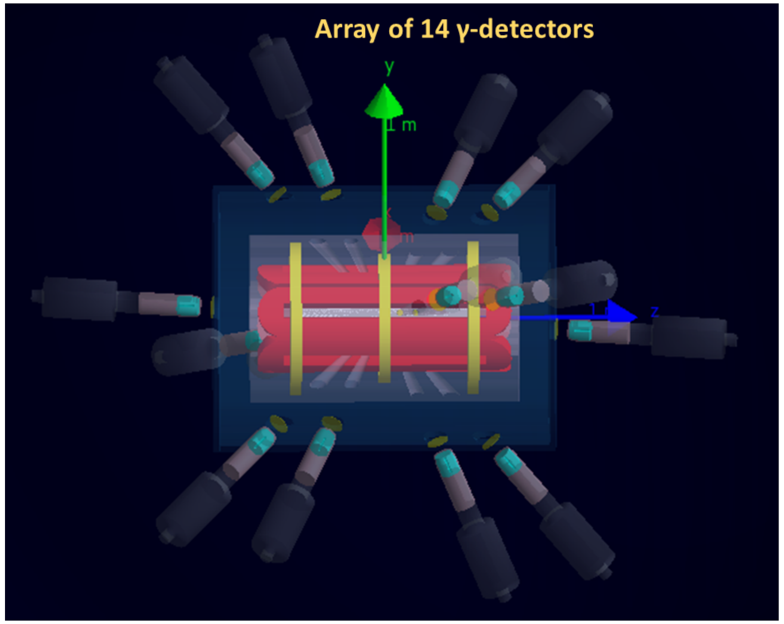
## Main issues carefully evaluated:

- Photopeak detection efficiency (interplay between detector number and mechanical constraint)
- Signal to noise ratio (high background self-generated inside the trap)

Harsh experimental conditions (sufficiently fast response from detectors)

- Magnetic field effects on HPGe charge collection

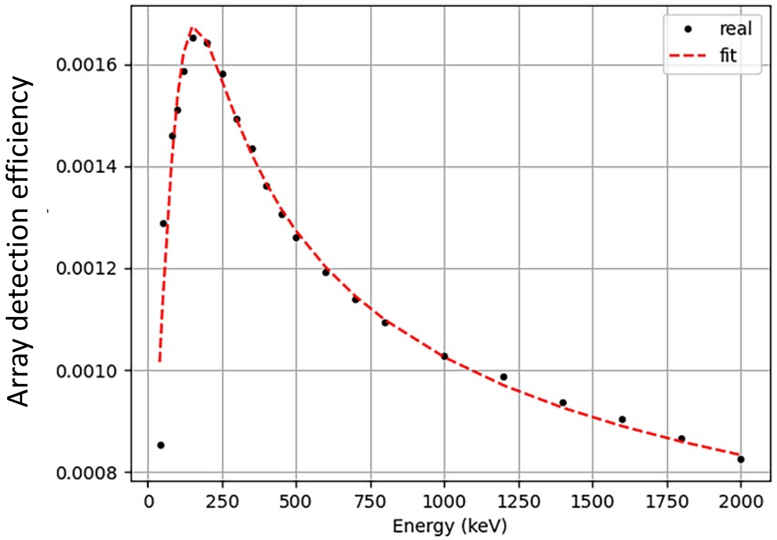



**Array of 14 HPGe detectors placed around the trap**

**Normal Working conditions willl require:**

E Naselli et al, *Frontiers in Physics, 692 (2022)*
D Santonocito et al, *Frontiers in Physics, 2022*

- Cooling system for HPGe array is under study
- A new lab to store, repair and perform the maintenance of detectors (its placement has been identified)




**Formalized a Collaboration Agreement with GAMMA to use 16 HPGe detectors of GALILEO**

- Interest of GAMMA in the physics case
- Ideal plan to move detectors to LNS in the second half of 2023
- Detectors could be used in PANDORA till the end of 2025 (then move back to LNL for experiments)

# PANDORA design: multi-diagnostics setup

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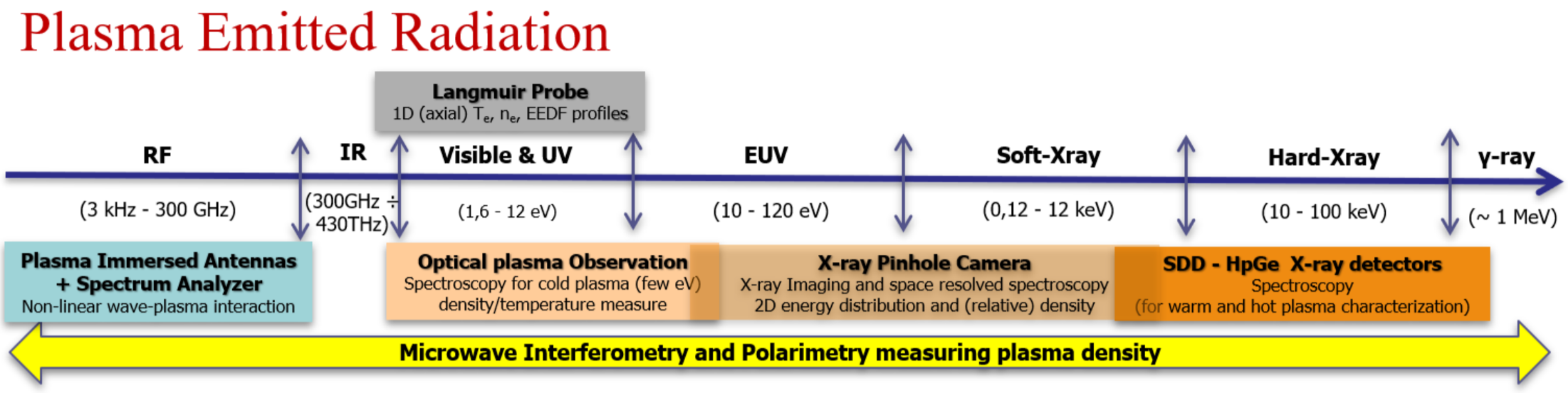
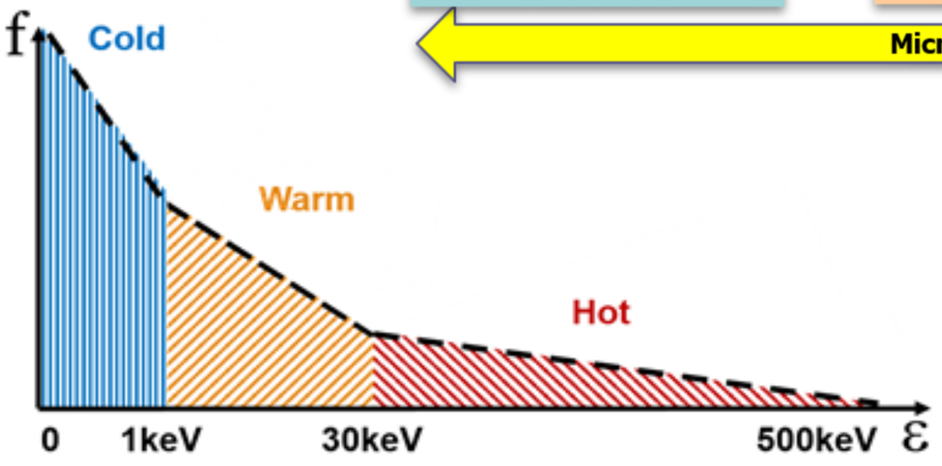
**Since the ionization states and charge state distributions are determined by the plasma temperature, at a given density and assuming a certain confinement time, plasma diagnostics plays a relevant role in order to relate the plasma environment properties to the measured lifetimes**



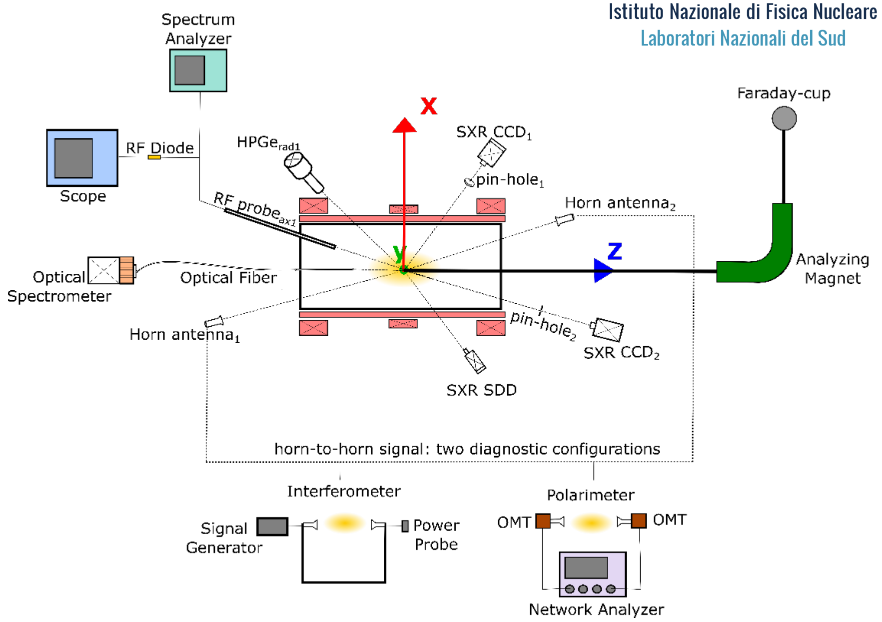




- on-line monitoring of all plasma parameters (ρ, T, CSD)
- investigation of the plasma properties in all energetic domains
- performing high-resolution spatial and time resolved analysis

E Naselli et al, *Journal of Instrumentation 14 (10), C10008 - 2019*

# PANDORA design: multi-diagnostics setup

| 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 $\epsilon_{n_e} \sim 7\%$, $\epsilon_{T_e} \sim 5\%$ |
| 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)**

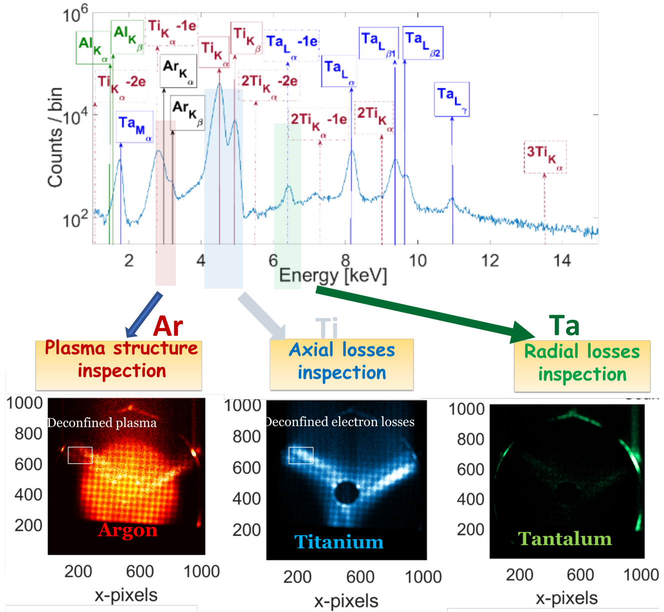
**HPGe for "hot electrons": probing volumetric hard X-radiation (30 - 2000 keV)**

**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**



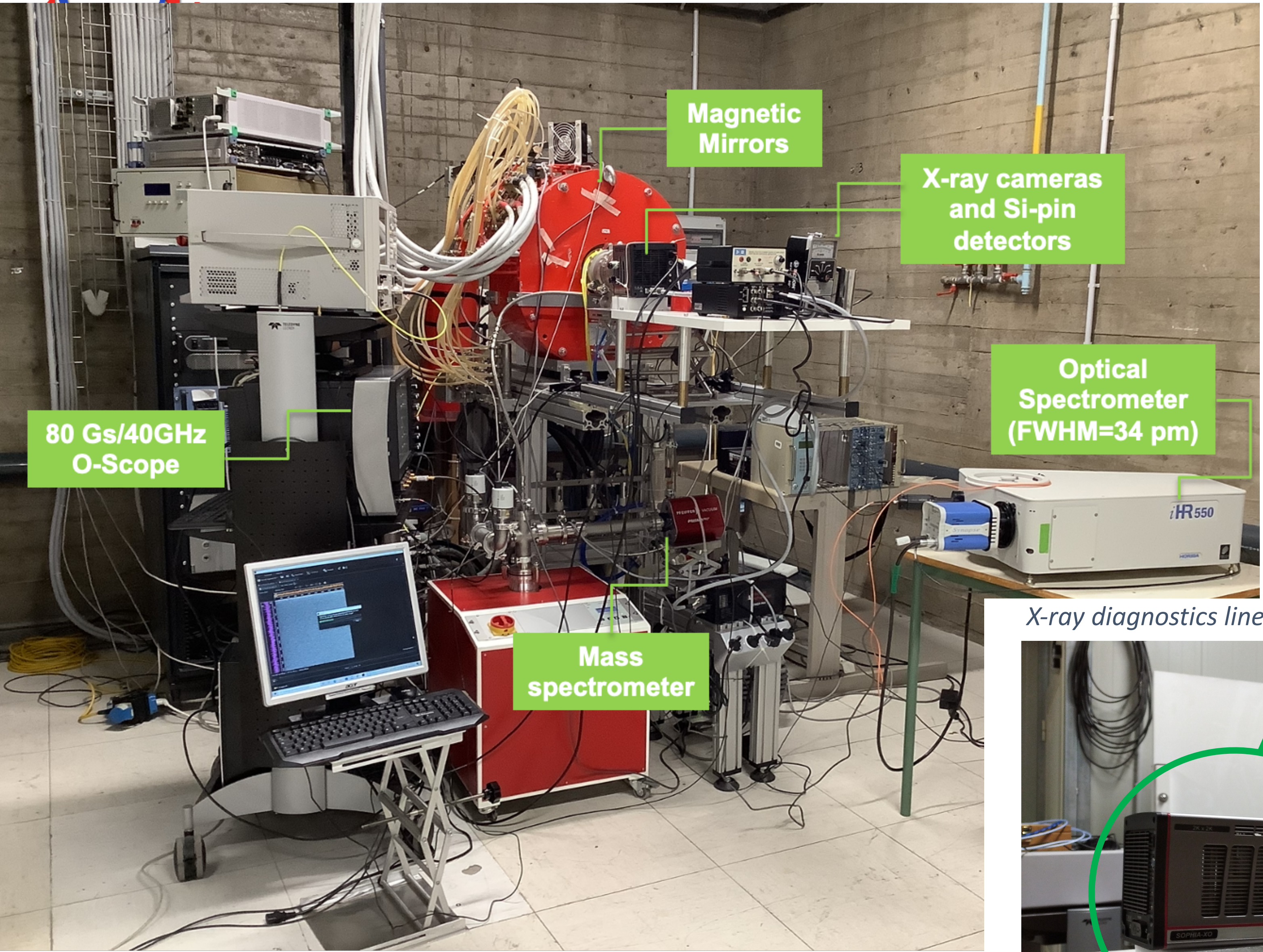

***See talk by E. Naselli!!***


*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*

**Dic 2021-Feb. 2022**

## Experimental tests on the Flexible Plasma Trap @ LNS

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

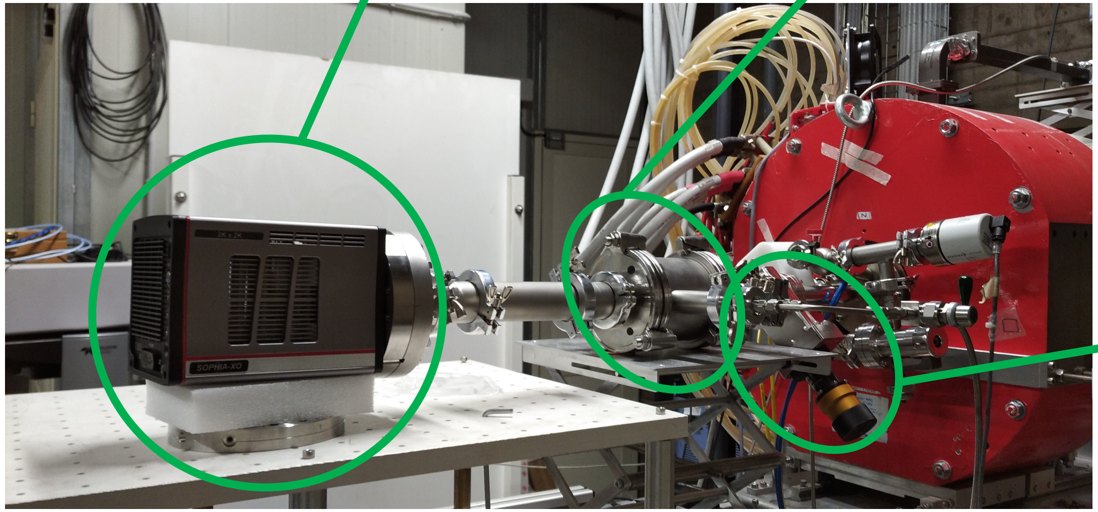




SOPHIA CCD camera

X-ray focal system

*X-ray diagnostics line*



Valve

# Virtual Experiments on the main Physics cases

Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

INFN LNS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud

**The collaboration with theoreticians** allowed to **identify of a long list of isotopes** (more than 100) **of potential interest for stellar nucleosynthesis**

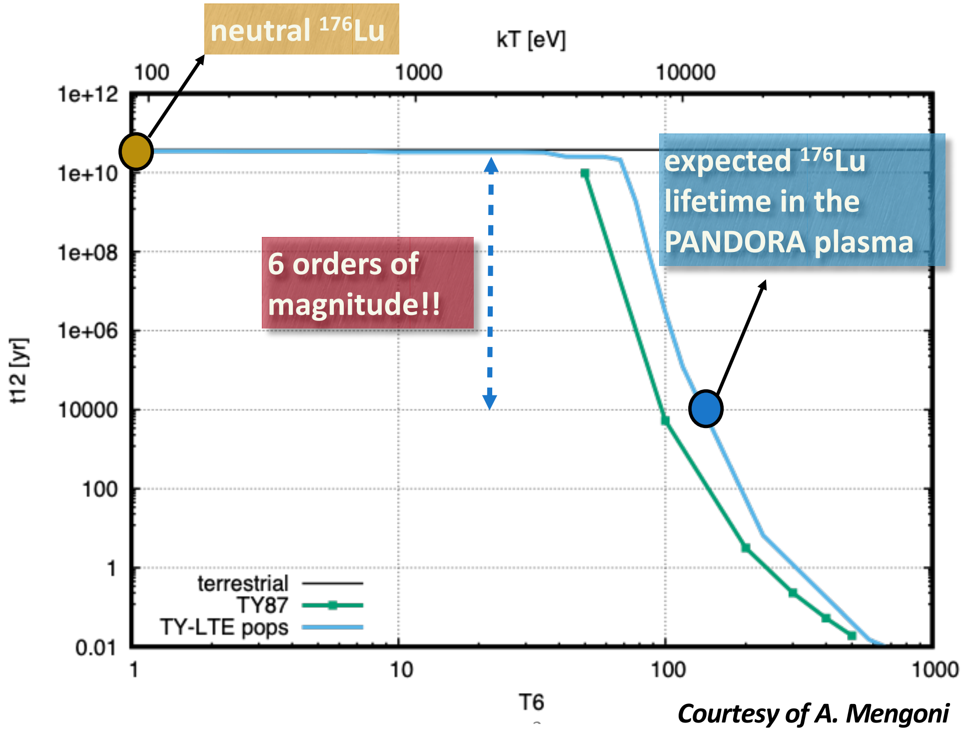
**Three cases were selected for the first campaign of measurement**

first run foreseen in 2024

| Isotope | $T_{1/2}$ [ yr ] | $E_\gamma$ [ 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**;

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

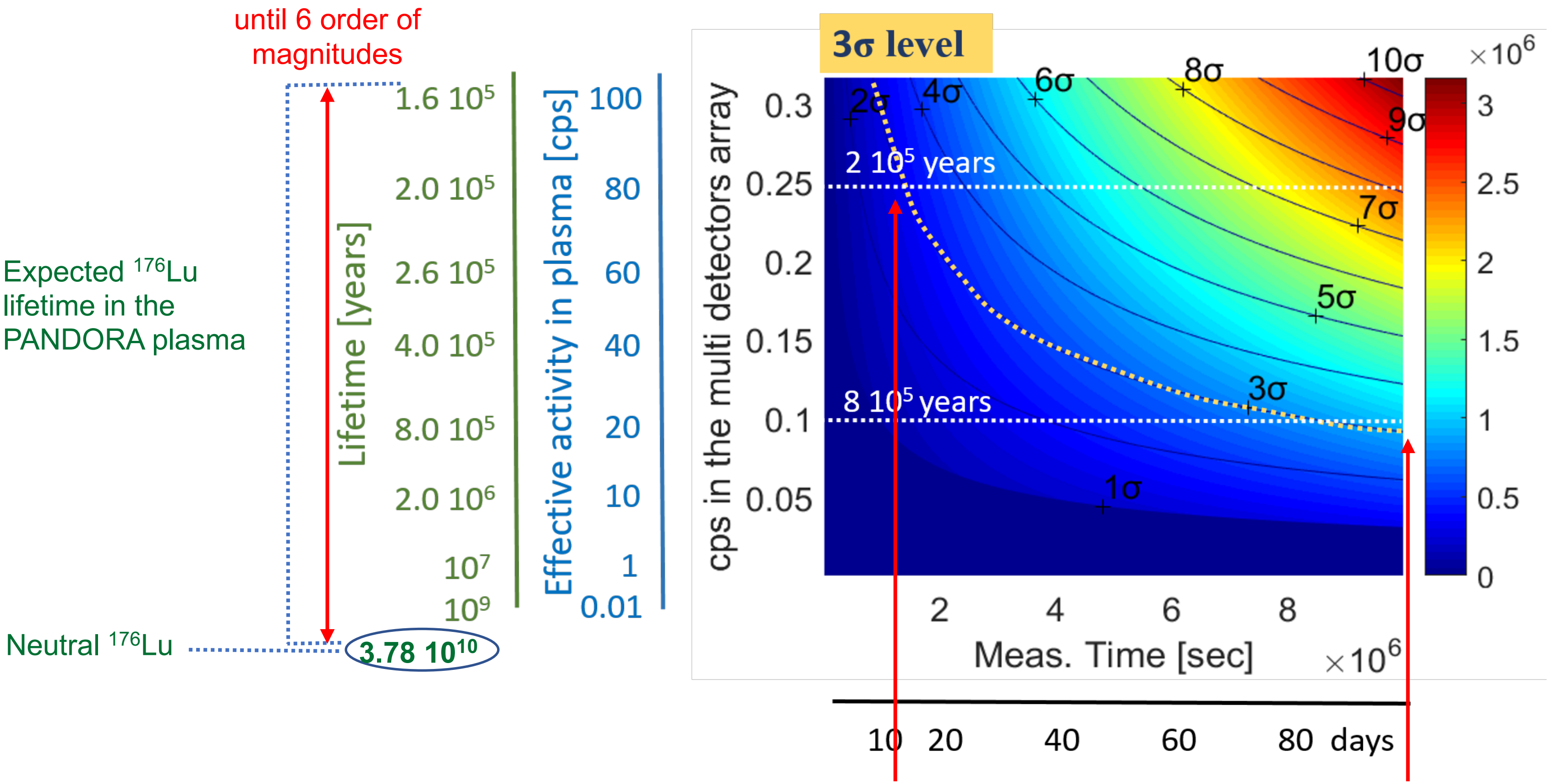



*Courtesy of A. Mengoni*

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

# 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 ] | $E_\gamma$ [ keV ] |
|---|---|---|
| $^{176}$Lu | $3.78 \cdot 10^{10}$ | 202.88 & 306.78 |
| $^{134}$Cs | 2.06 | 795.86 |
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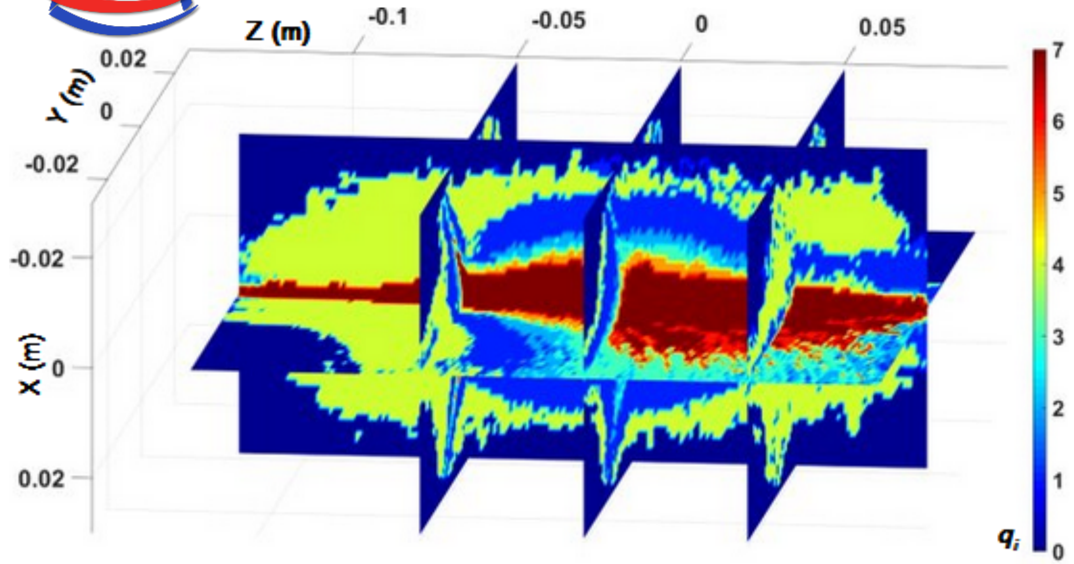
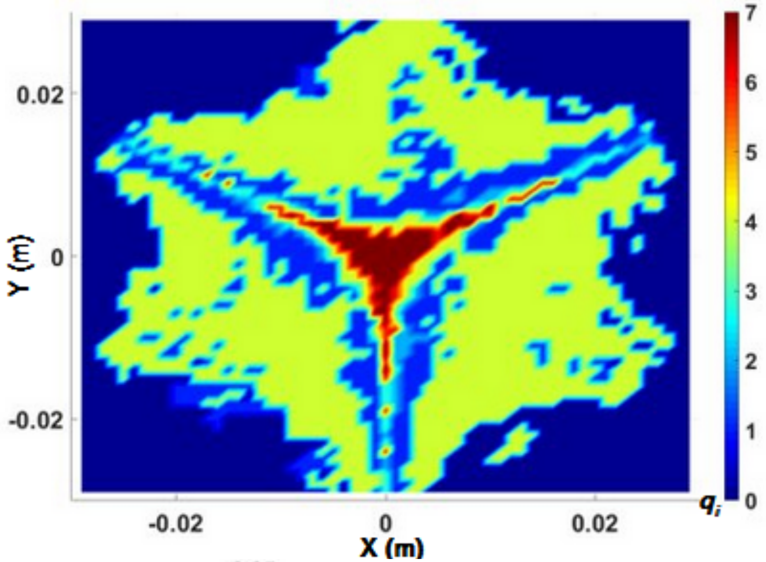
*E. Naselli et al., EPJ web of conferences 227, 2020, 02006*
*D. Mascali et al., EPJ web of conferences 227, 2020, 01013*

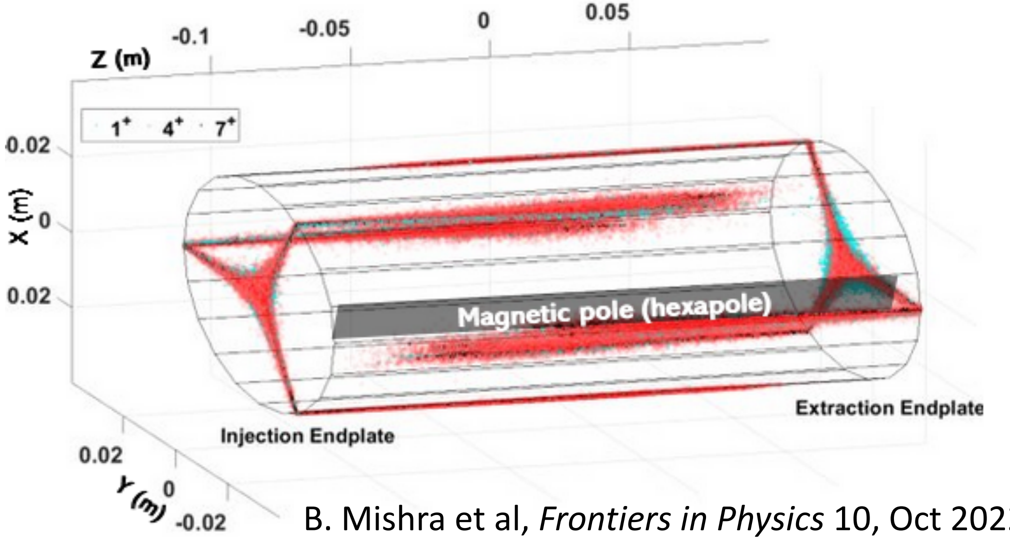
# (Very) Preliminary Results: Space-Resolved CSD (Ar buffer)

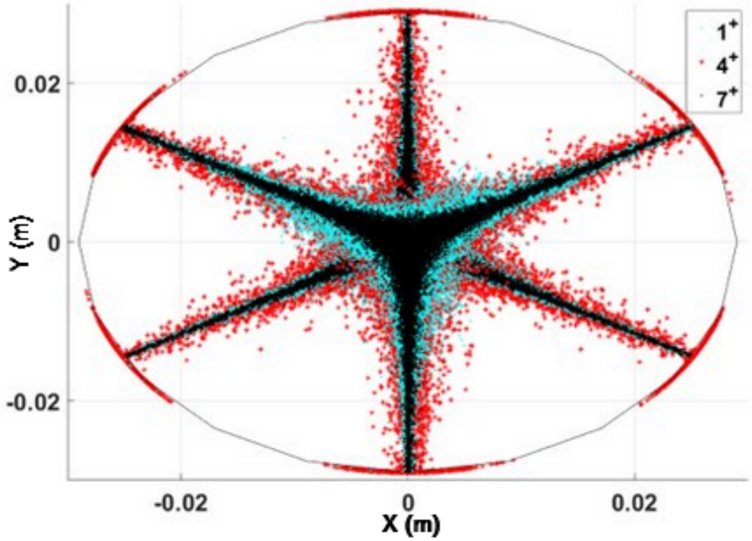



**Region of peak occupation of various charge states - evidence of space-resolved CSD**

**Scatter plots of macroparticles of various charge states lost from the simulation domain – resemblance with occupancy map inside simulation domain**




***See talk by B. Mishra!!***

B. Mishra et al, *Frontiers in Physics* 10, Oct 2022

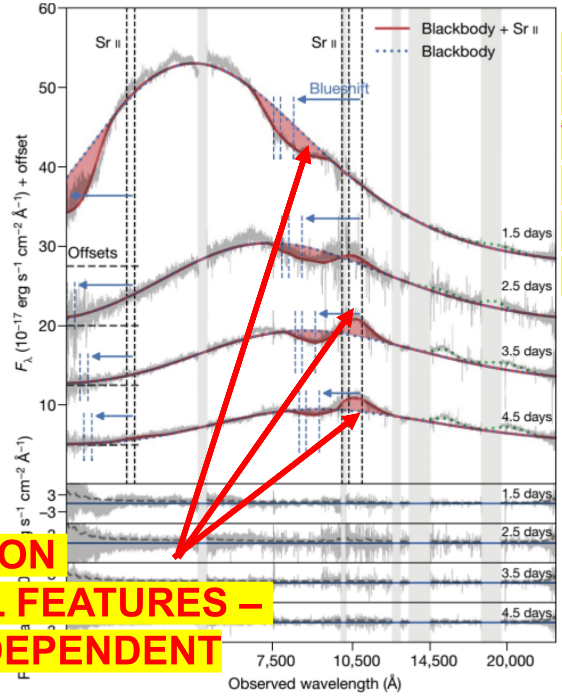
Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

# State-of-the-art on *r*-process and KN

- **Merger** of **binary neutron stars**: ejection of **n-rich matter**, rapid neutron capture (***r*-process**) nucleosynthesis
- **Radioactive decay** of synthesized r-process nuclei **power** electromagnetic transient: ***kilonovae* (KN)**
- **Gravitational wave events** (e.g., GW170817) from such merging detected along with KN counterpart AT2017gfo
- Detection of AT2017gfo spectrum: first direct evidence that these sites are among the major producer of nuclei heavier than iron via *r*-process
- **Plasma opacity** greatly **impacts** on energy **transport and spectroscopic observations** in many astrophysical environments
- Role played by the **opacity on KN emission,** as it delivers information on the post-merging plasma **ejecta composition** (*r*-process multi-components)
- **Large theoretical uncertainty** factor from an almost total ignorance on ejecta opacity at the typical conditions of a KN event

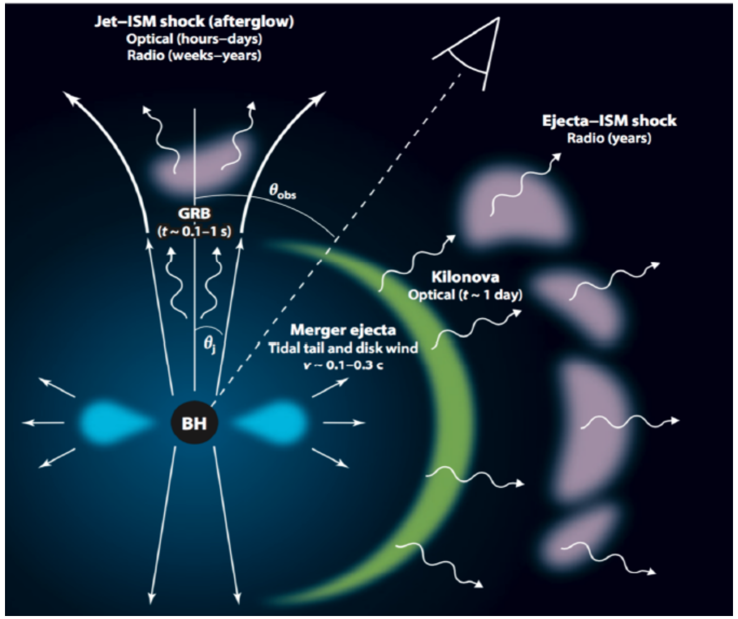
**GOAL**

- Trapped magneto-plasmas conceived in **PANDORA** may open the route to **experimental in-laboratory measurements of opacities** at $n_e$ and $T_e$ resembling ejecta plasma conditions: **shed light on r-process** generated metallic species at **specific time-stages of KN diffusion**




**BLACKBODY SPECTRUM VS. OBSERVED KN SPECTRUM**

**ABSORPTION SPECTRAL FEATURES – OPACITY DEPENDENT**

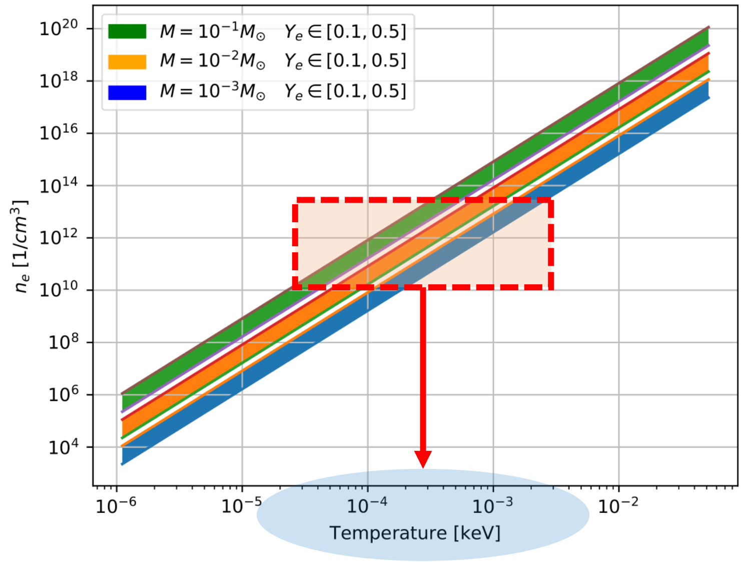


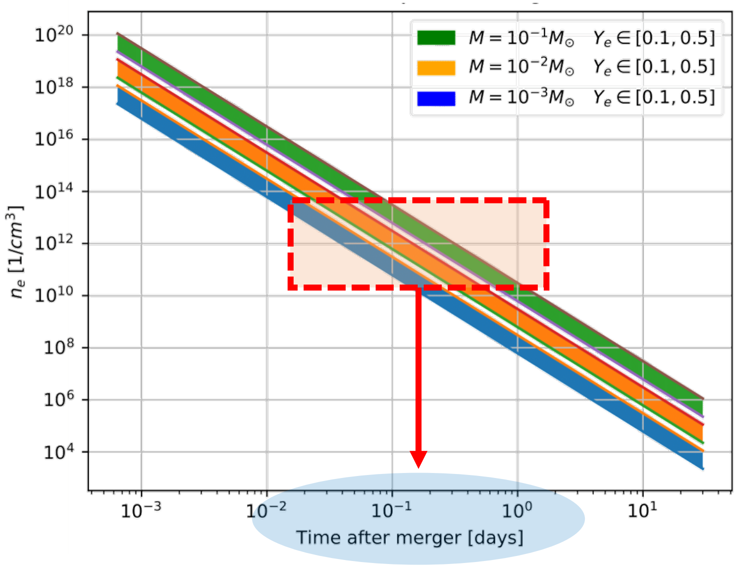

Metzger B.D., Kilonovae. Living Rev Relativ 23, 1 (2020)
Watson, D., et al. Nature 574497-500, (2019)

# What can be studied in PANDORA plasmas?

Plasmas for Astrophysics Nuclear Decay Observation and

INFN LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

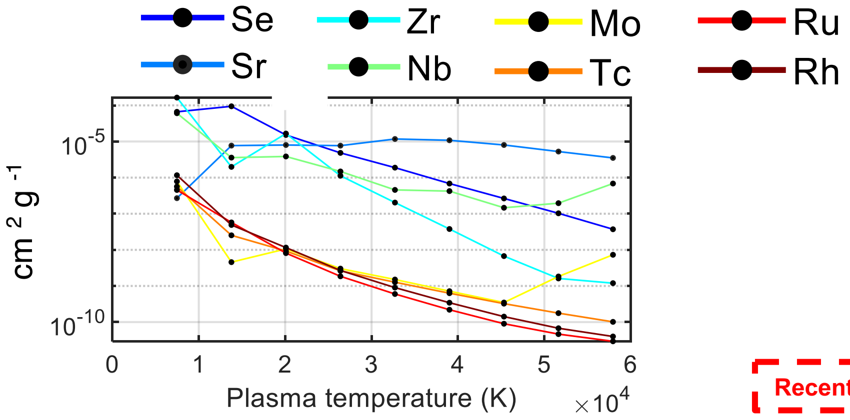


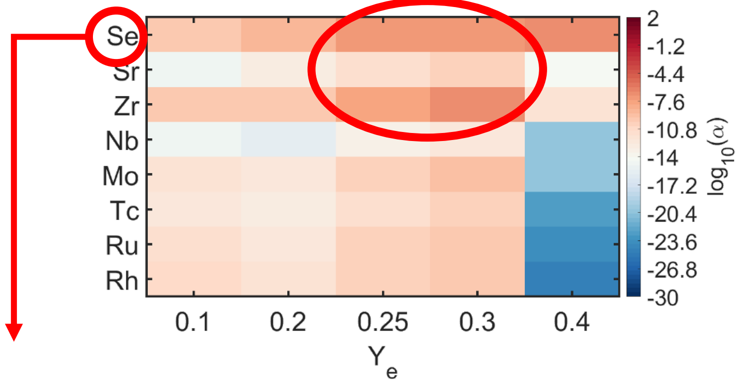

- **MODEL**: time-evolving ejecta through homologous expansion of a fluid element under adiabatic conditions (vs. mass M, temperature T, velocity v, and electron fraction $Y_e$)
- **Plasma density** in PANDORA: **$10^{10-13}$ cm$^{-3}$**
- **Plasma temperature** in PANDORA: **few eV**
- **Time after merger: from $10^{-2}$ up to 1 days → blue-KN stage**

Pidatella, A., et al. Nuovo Cimento 44 C (2021) 65

O. Korobkin *et al.*, Mon. Not. R. Astron. Soc., **426** (2012) 3-1940:1949
D. Radice *et al.*, Astrophys. J., **869** (2018) 2-130
J. Lippuner et al., Astrophys. J. Supplements, **233** (2017) 18
Chung H.-K. et al., High Energy Density Phys., 1 (2005) 3




**Opacity weighted on abundances from SKYNET**




**IDENTIFICATION OF PHYSICS CASES**

- **Time-dependent r-process elements abundances from SKYNET**, with distribution of ejecta properties from astrophysical simulations → **LIGHT R-PROCESS ELEMENTS, LOW NEUTRON RICHNESS**
- **MEAN OPACITY vs. T**, weighted with abundances from SKYNET: **synthetic spectra** of opacity from **FLYCHK**

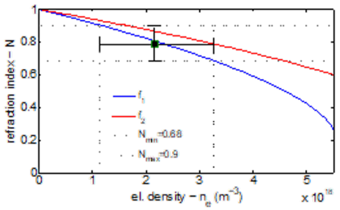
**Recent supporting work on Se relevance** : K., Hotokezaka, M. Tanaka, et al., MNRAS **515**, L89–L93 (2022)

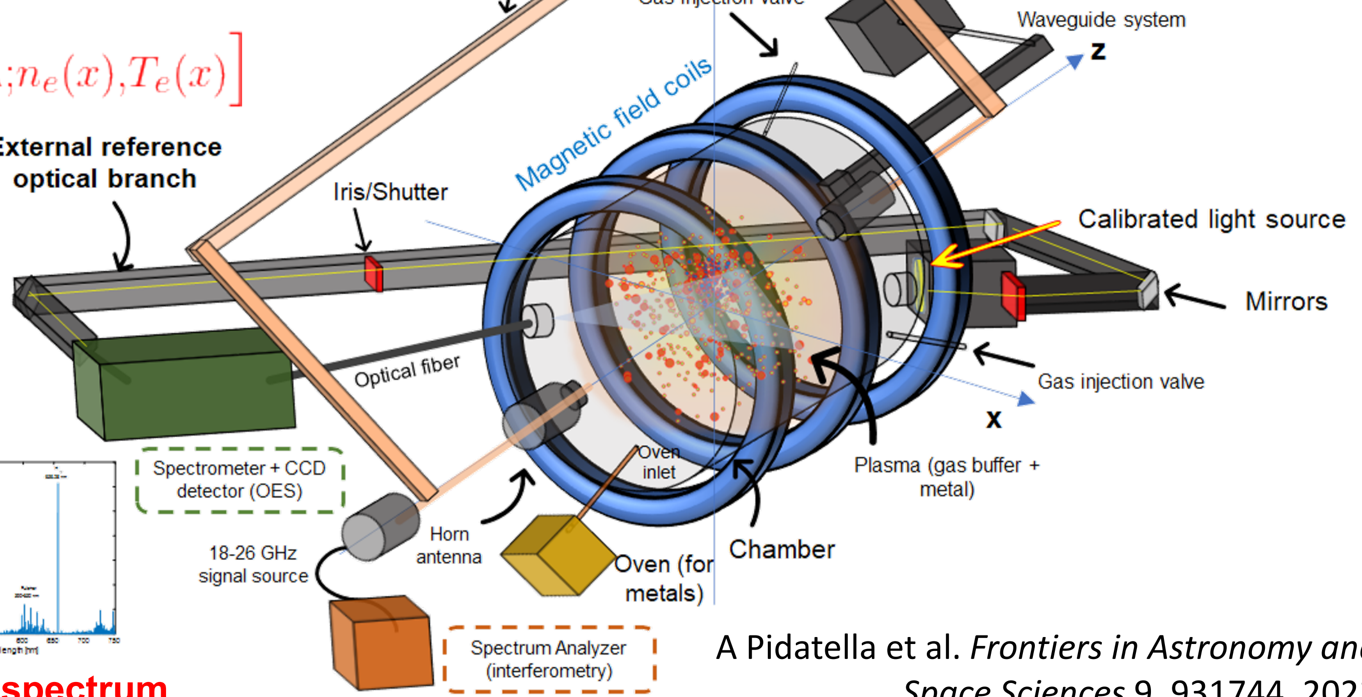
# FPT: plasma characterization and experimental design

Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

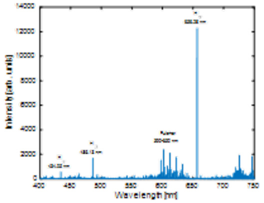
INFN LNS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud

$$T(\lambda) = \frac{I_a(\lambda)}{I_b(\lambda))} = e^{-\tau^{el}(\lambda)} = e^{-\int_0^L dx \rho(x) \kappa \left[\lambda; n_e(x), T_e(x)\right]}$$




- TO BE DONE – **TRANSMISSION MEASUREMENTS TO RETRIEVE PLASMA OPACITY:** : **absolute calibration**, light-r process elements **plasmas (Se, Sr, Zr) opacity measurements via OES**.



A Pidatella et al. *Frontiers in Astronomy and Space Sciences* 9, 931744, 2022

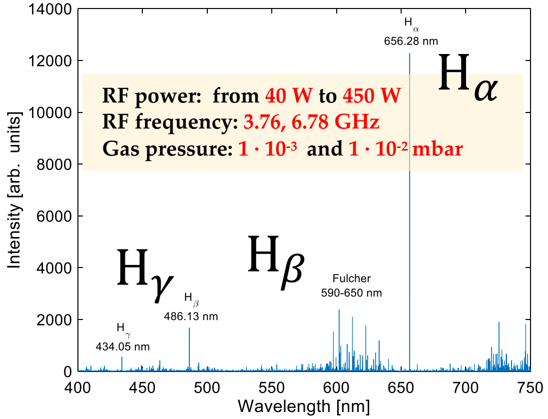
- COMPLETED - **Experimental $H_2$/Ar plasma characterization** performed on FPT: commissioning with **radial injection** and **high-power**

The comparison between the theoretical and experimental **line ratios** allows to evaluate the **plasma parameters (electron density and temperature)**

| $H_\beta/H_\gamma$, $H_\alpha/H_\beta$ | $n_e$, $T_e$ |
|---|---|

$$\frac{I_\alpha}{I_\beta} = \frac{\eta_\alpha}{\eta_\beta} \frac{\chi_\alpha(\rho,T)}{\chi_\beta(\rho,T)} \to \langle\rho\rangle, \langle T\rangle$$

**Hydrogen spectrum**




Pidatella, A., Presented at the conference *Probing the Universe with Multimessenger Astronomy (PUMA) 2022*

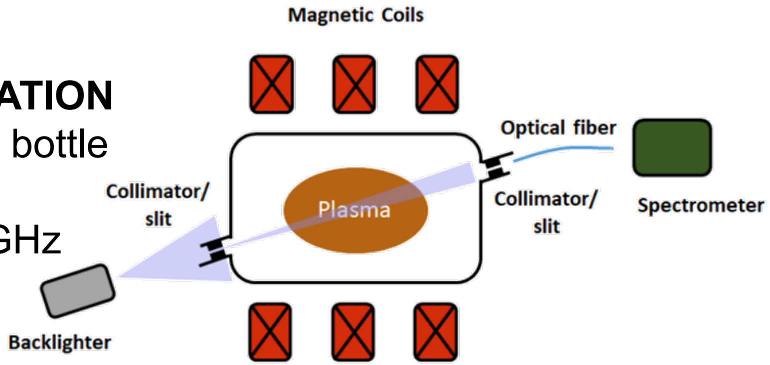
- **Concept design of the experimental setup on the Flexible Plasma Trap (FPT)**
  - Independent multi-diagnostic system: (1) OES for transmission measurements, (2) secondary diagnostic for plasma conditions

# First test to reproce KN conditions with Flexible Plasma Trap

First test of measurements to reproduce KN conditions were performed using the Flexible Plasma Trap to produce and confine the plasma.

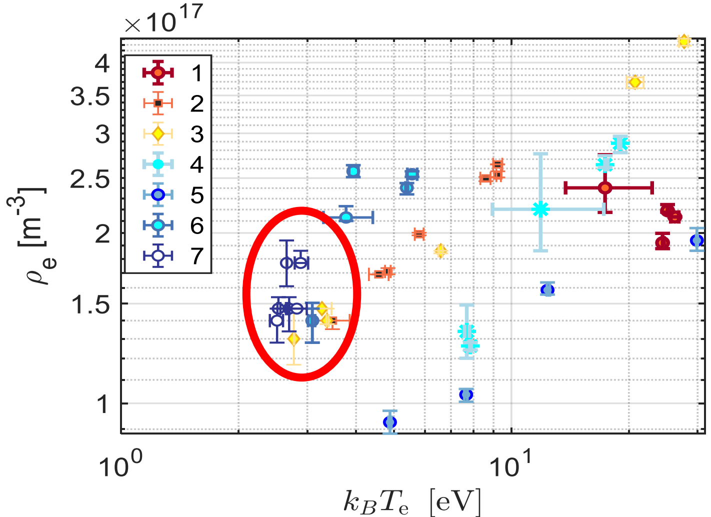
- Plasma parameters and stability were monitored online using non-invasive diagnostics developed for PANDORA
- Optical emission spectroscopy (OES) was used to probe plasma emission in the blue-KN stage

- **FTP PLASMA TRAP CONFIGURATION**
  - Simple mirror field, magnetic bottle
  - RF power : 50÷450 W
  - Heating RF frequency: 3÷4 GHz

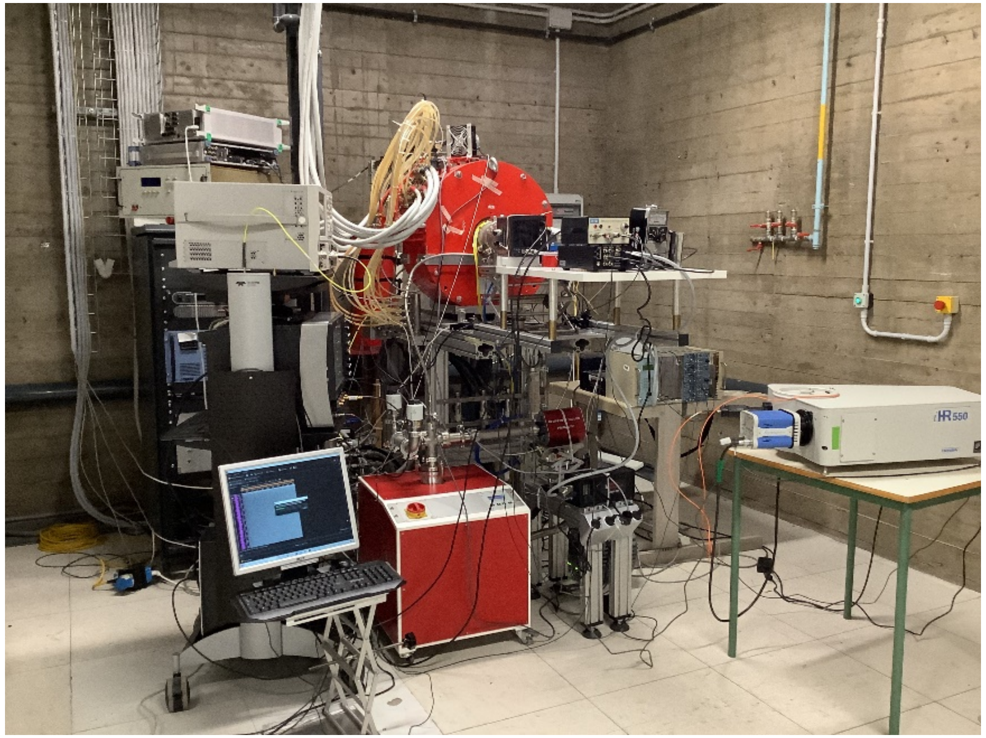



**Experimental $H_2$/Ar plasma characterization** performed on FPT:

The comparison between the theoretical and experimental **line ratios** allows to evaluate the **plasma parameters (average electron density and temperature) through YACORA CR model line ratios**

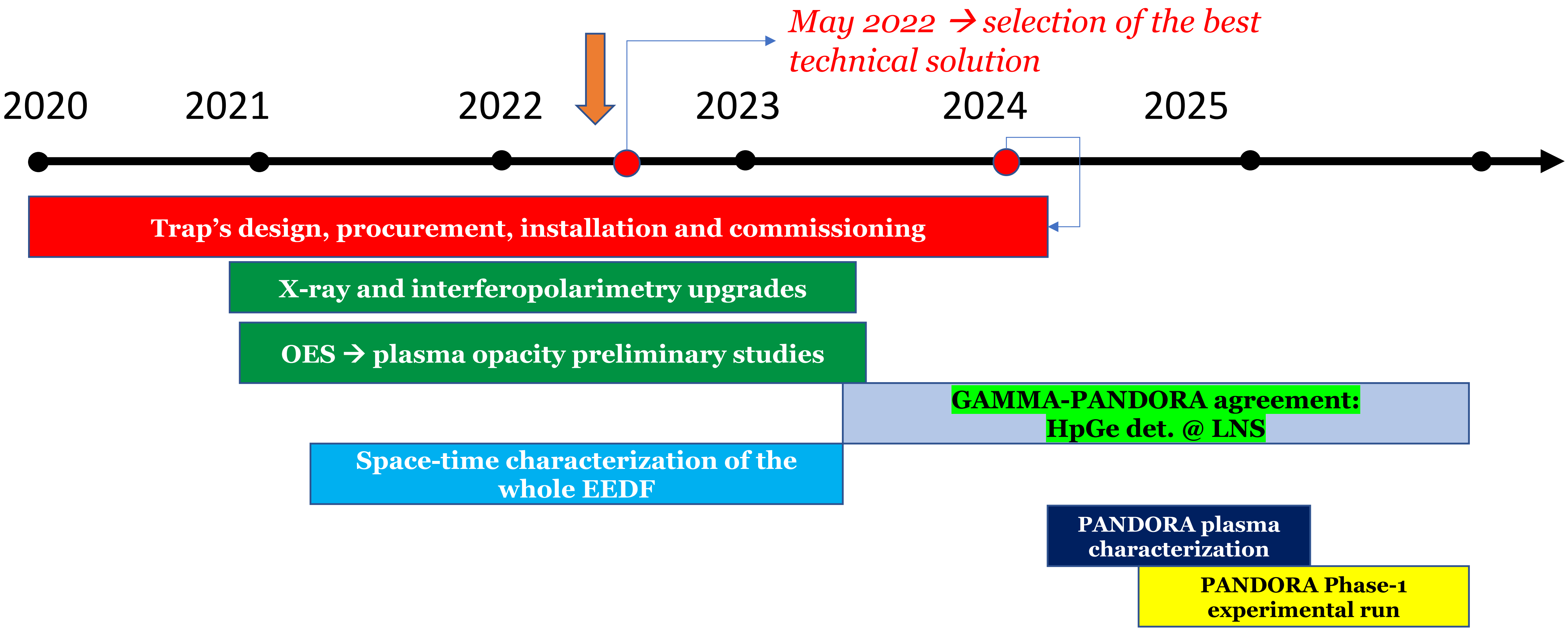


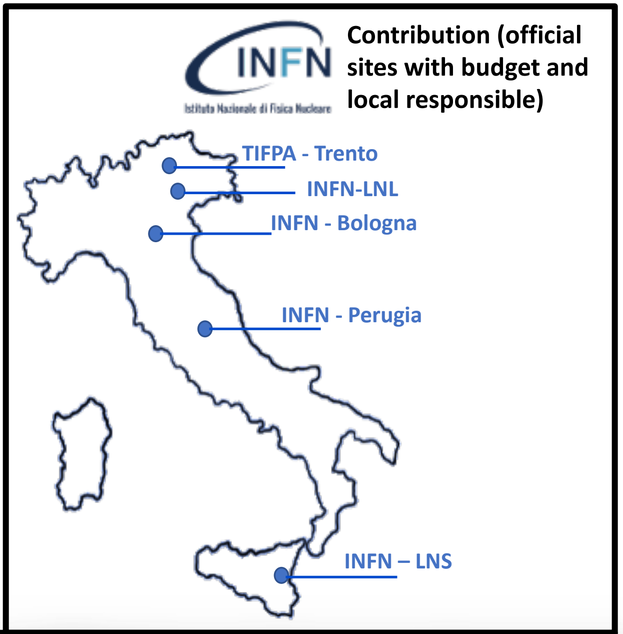

Flexible Plasma Trap @ LNS (setup Feb 2022)

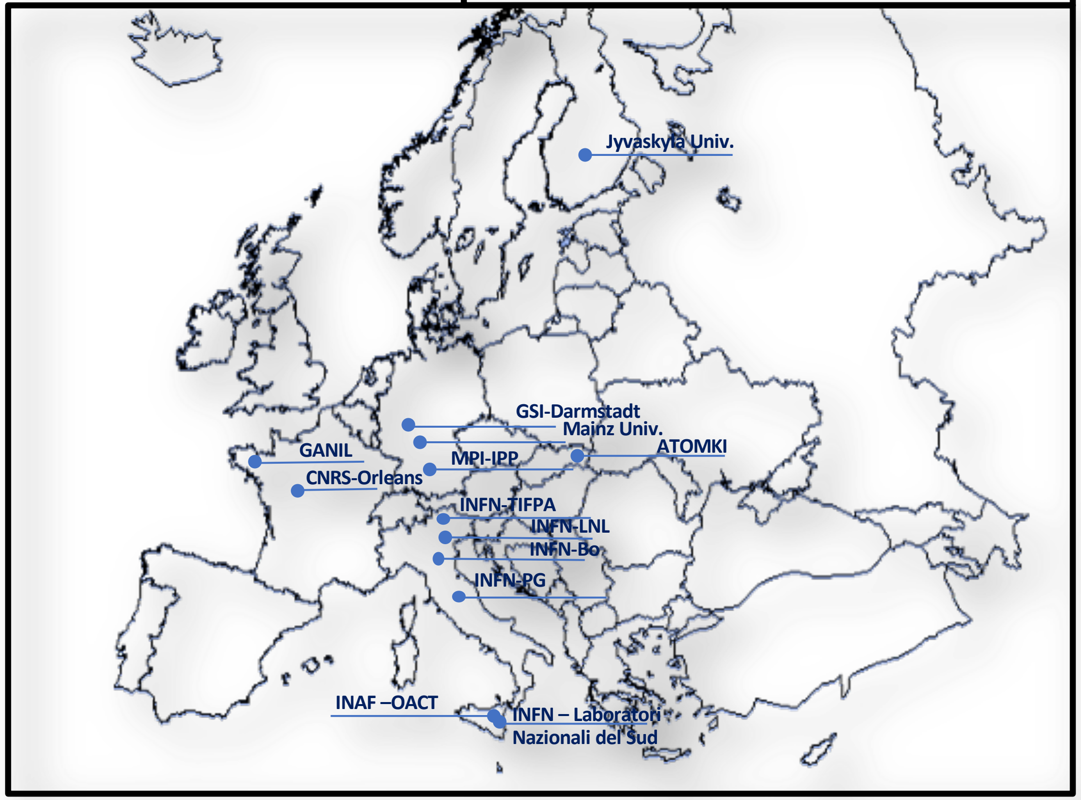


*Pidatella, A.,et al. Frontiers in Astronomy and Space Sciences 10.3389/fspas.2022.931744 (2022)*

# PANDORA Timescale – GANTT "master"






# PANDORA collaboration

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[3] INFN – Sez. di Bologna, I-40127 Bologna, Italy
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[31] Università degli Studi di Modena e Reggio Emilia Dipartimento di Ingegneria Enzo Ferrari: Modena, IT

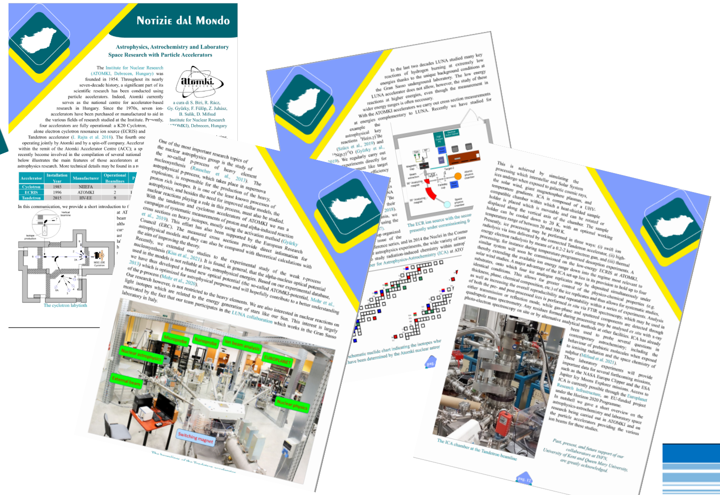
# PANDORA joins to GIANTS (*Italian Groups of Theoretical and Experimental Nuclear Astrophysics*)



*Sep 2020*
*Focus on*
*PANDORA*

GIANTS is involved in **dissemination of nuclear astrophysics activities in a quarterly newsletter**, in several outreach activities and workshops.

It includes 5 INFN nuclear astrophysical groups:
**ASFIN**, **ERNA**, **LUNA**, **n_TOF**
and now also **PANDORA**!




*July 2021*
*World News on*
*ATOMKI Lab*

INFN LNS

Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

# Thanks for your attention

**TDR available at the following link:**
https://pandora.infn.it/public/pandora-tdr

and also from INFN-LNS website:
https://www.lns.infn.it/it/apparati/pandora.html

A special topic on Frontiers dedicated to PANDORA physics and technology (11 papers)

Plasmas for Astrophysics Nuclear Decay Observation and Radiation for Archaeometry

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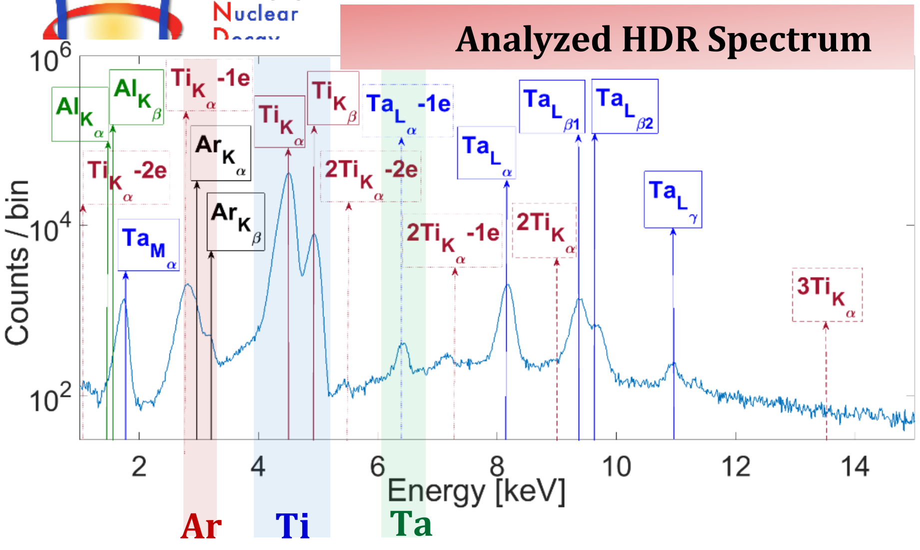
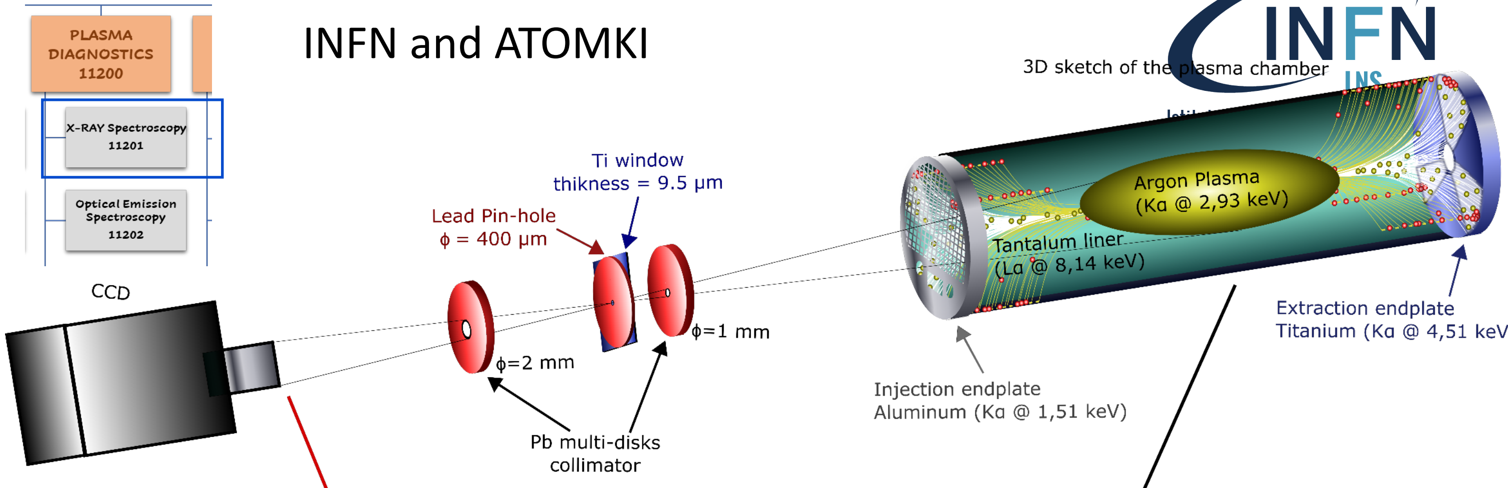
Nuclear Physics and Astrophysics in Plasma Traps

INFN LNS
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

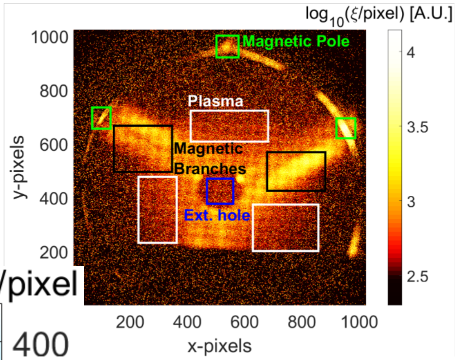
# X-ray imaging and space resolved spectroscopy: *The Experimental Setup – Lead multi-disks collimator*



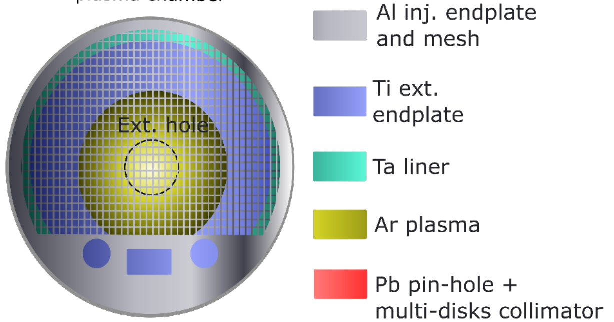

## INFN and ATOMKI




Typical X-ray image acquired by the CCD

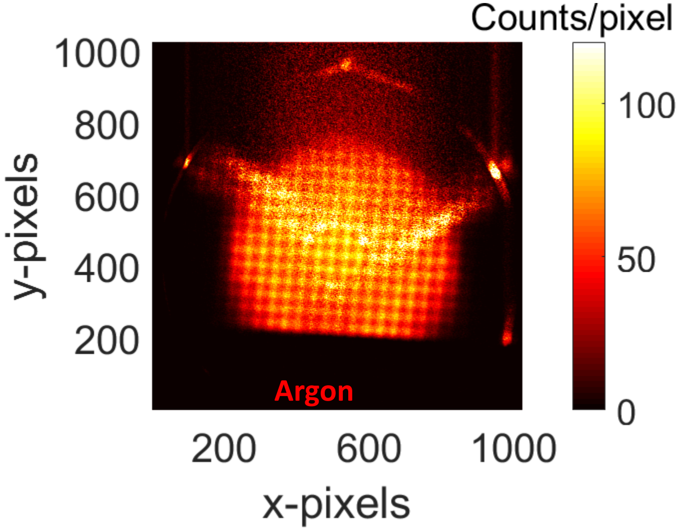



Prespective front view of the plasma chamber

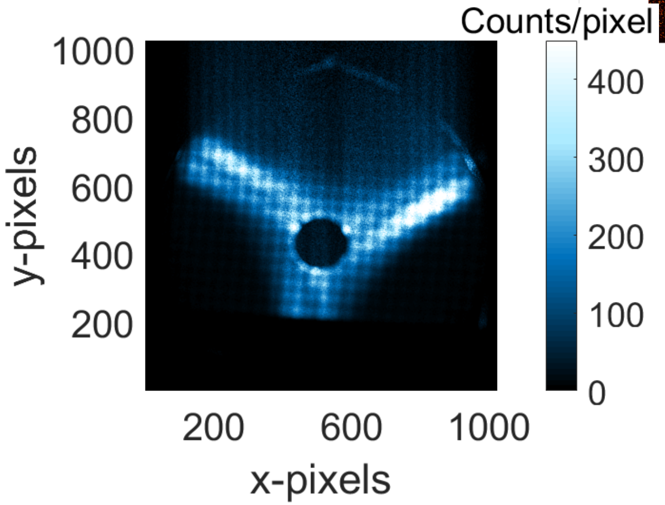



*E. Naselli et al., Condensed Matter 7(1):5, Dec. 2021*

**HDR Imaging**
**Plasma structure inspection**




**HDR Imaging**
**Axial losses (on Ti plate) inspection**




Algorithm for PhC analysis of X-ray pin-hole camera systems has been now completed, providing exceptionally high Signal-Over-Noise ratios (including read-out noise removal) and the possibility to get HDR X-ray plasma images including spectroscopical information

*by E. Naselli, R. Racz, et al.*