A new approach to β-decays studies impacting nuclear physics and astrophysics: the PANDORA setup

Nuclear Physics in Astrophysics – X – CERN, 8/09/2022

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.

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.

This raises the question whether or not the high degree of ionization could induce any significant differences of the beta-decay properties with respect to neutral atoms.

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

- **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

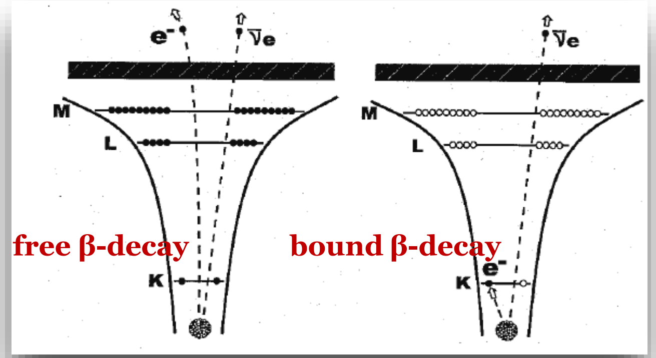
What happens when atoms are highly ionized? → **….the answer came from Storage Rings experiments ….**

- **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



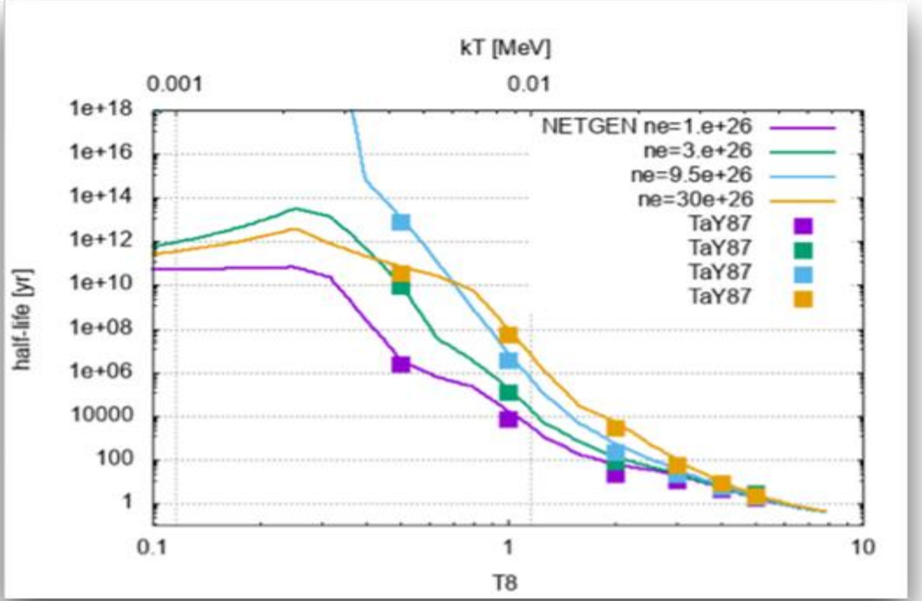
Beta decay in stellar environment

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

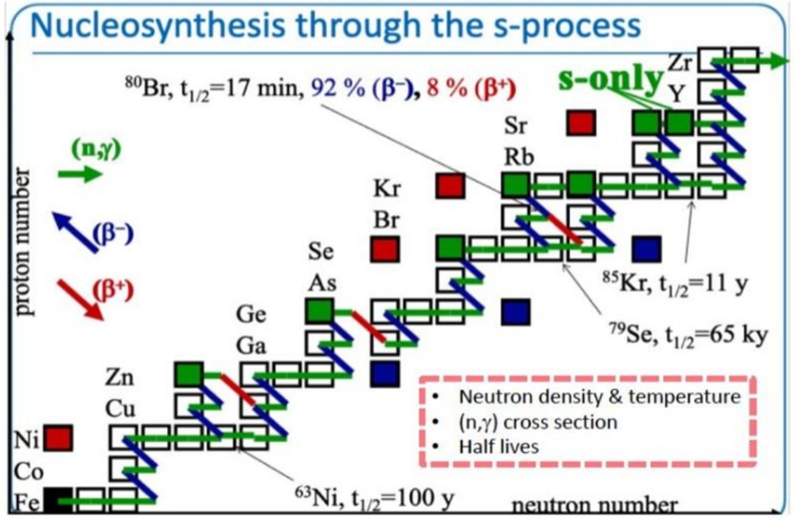
These charges create EM fields which act as perturbation to the atomic/ionic levels leading to corrections of Q values which affects the decay rates.

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

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



Competition between n capture and beta decay



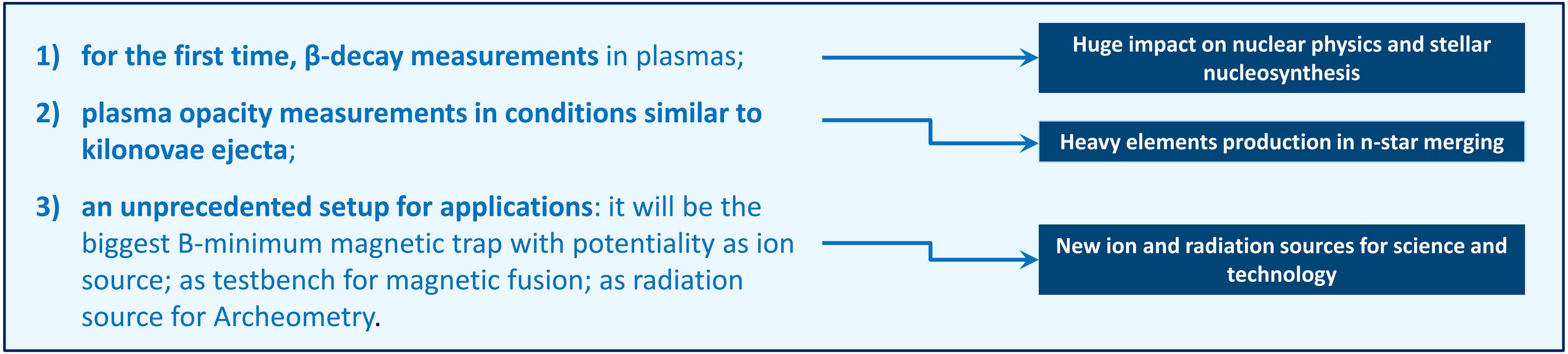
Busso, M., Gallino, R., Wasserburg, G.J. 1999, Ann Rev. Astron. Astrophys. 37, 239
Cristallo, S. et al. 2011, Astrophys. J. Suppl. 197, 17
Gallino, R. and Busso, M. 1986, in "From Nuclei to Stars". Proceedings of the International Fermi", Course XCI (North-Holland: Amsterdam)

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

Beta decay modes in stellar environment

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;
2) **plasma opacity measurements in conditions similar to kilonovae ejecta**;
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.

Huge impact on nuclear physics and stellar nucleosynthesis

Heavy elements production in n-star merging

New ion and radiation sources for science and technology

PANDORA concept and design

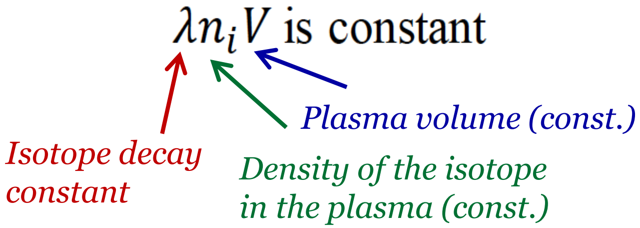
Build a plasma trap where ion species are confined in a magnetic field and a plasma is created with:

- 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, 01
D. Mascali et al., EPJ-A , 53, 2017, 7

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

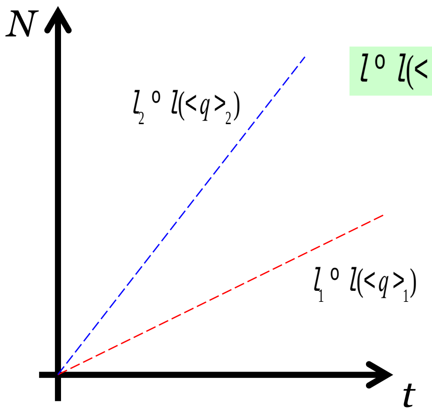
$$\boxed{\frac{dN}{dt} = \lambda n_i V} \rightarrow \int_0^{t_{meas.}} dN = \int_0^{t_{meas.}} \lambda n_i V dt \rightarrow \boxed{N(T_{meas.}) = \lambda n_i V_{plasma} T_{meas.}}$$


$\lambda n_i V$ is constant

Isotope decay constant

Density of the isotope in the plasma (const.)

Plasma volume (const.)



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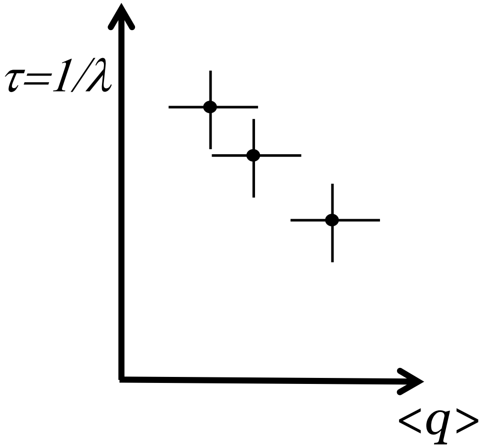
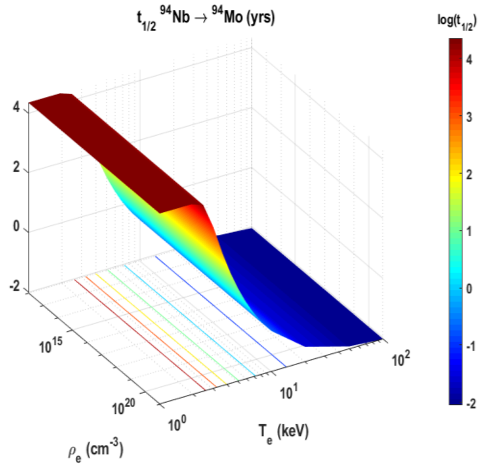
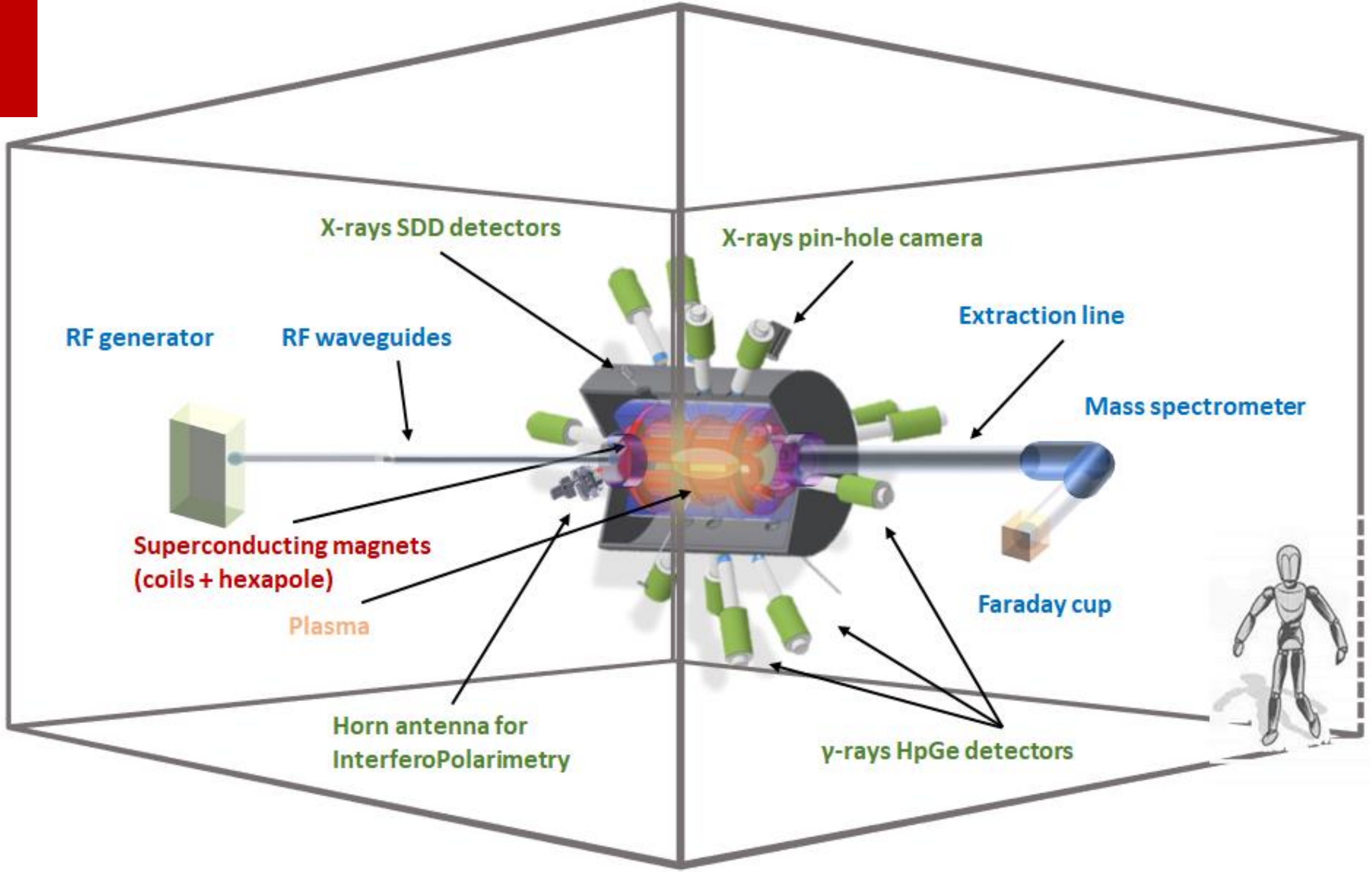




PANDORA concept and design

PANDORA Experimental Setup:

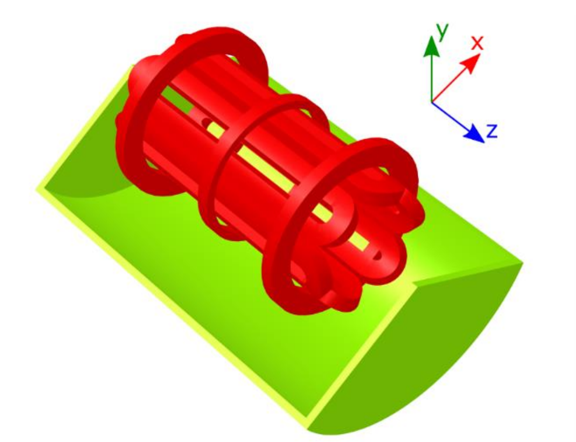
- **Trap**
- **Detector array**
- **Plasma Diagnostics**

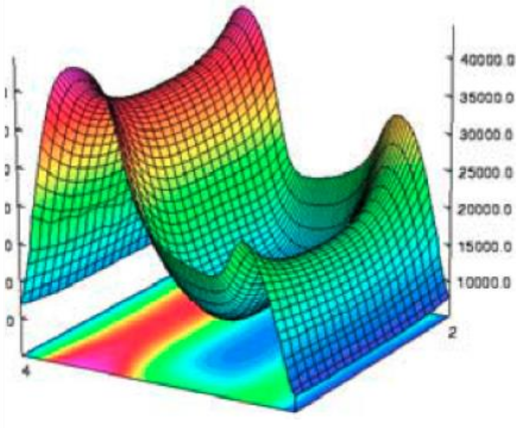


PANDORA design: the magnetic trap

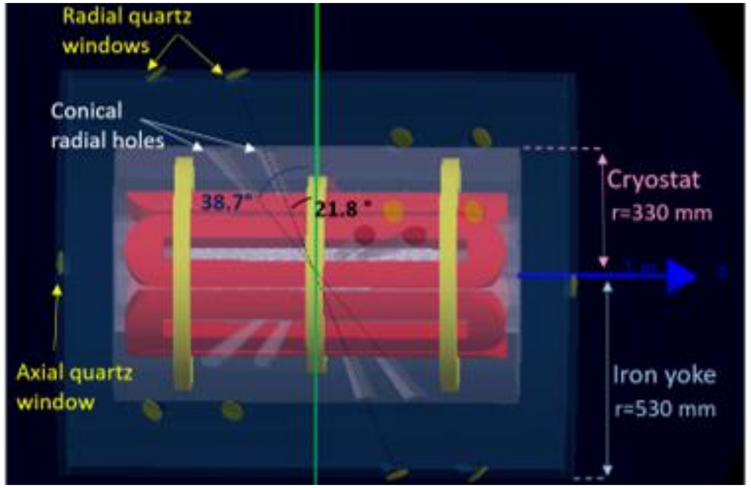
The magnetic trap is composed by:

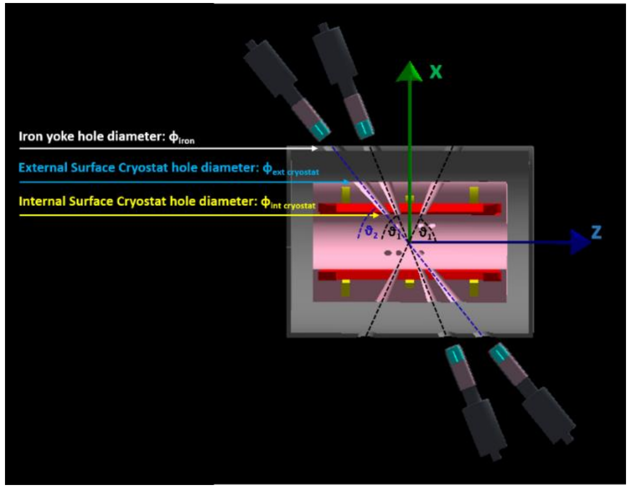
- 3 superconducting coils for axial confinement
- a superconducting exapole for radial confinement





$B_{minimum}$ 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

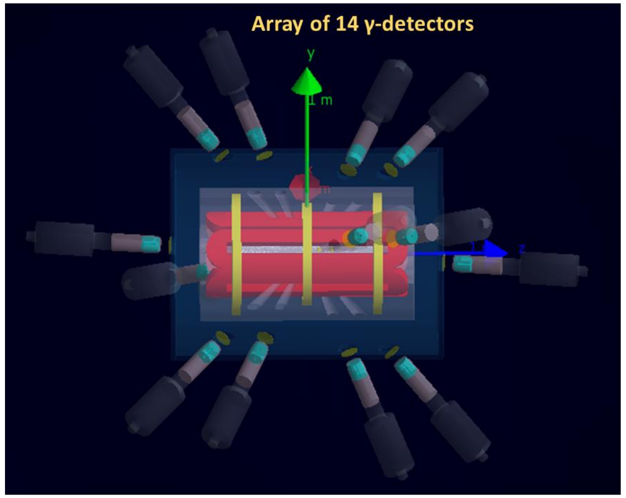
PANDORA design: the HPGE array

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)**

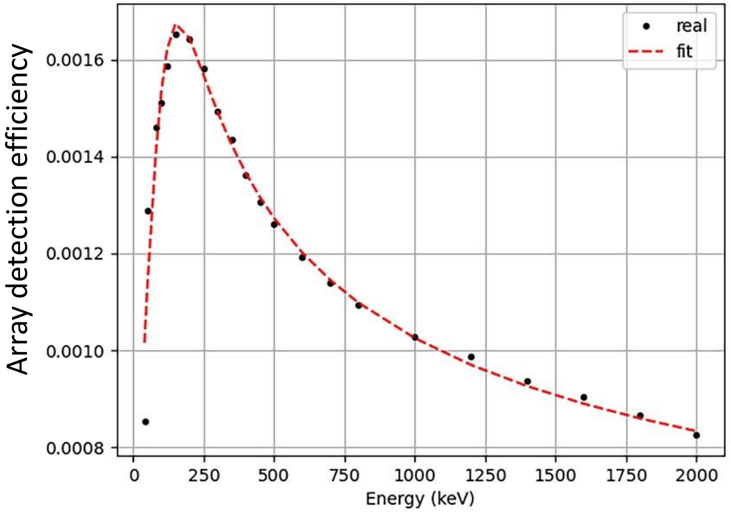
→ Harsh experimental conditions (sufficiently fast response from detectors)

- **Magnetic field effects on HPGe charge collection**



Array of 14 HPGe detectors placed around the trap
Normal Working conditions willl require:

- 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)

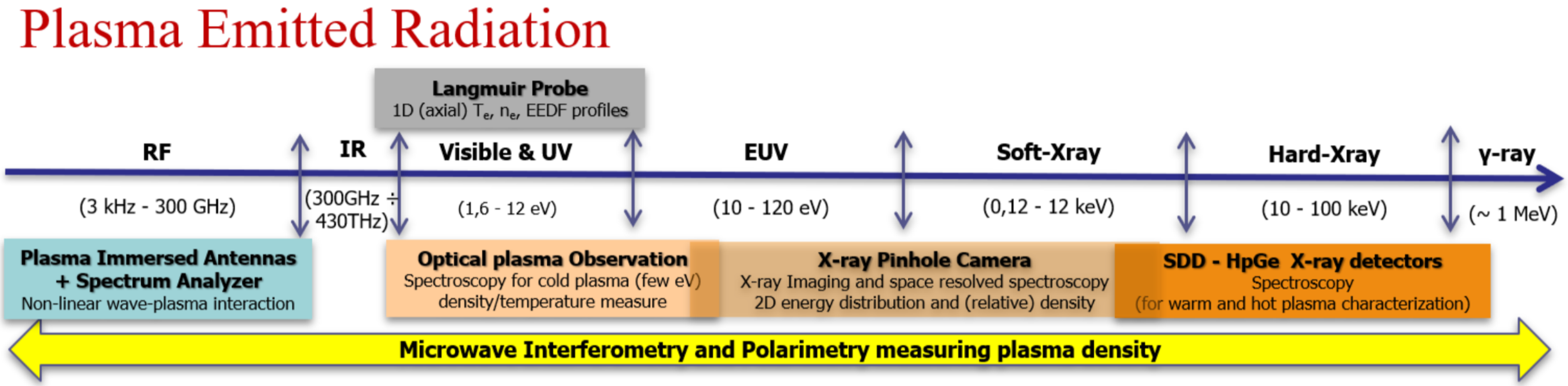


Formalized a Collaboration Agreement with GAMMA to use 16 HPGe detectors of GALILEO

- 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

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



Plasma Emitted Radiation

Langmuir Probe
1D (axial) T_e, n_e, EEDF profiles

RF (3 kHz - 300 GHz)
IR (300GHz ÷ 430THz)
Visible & UV (1,6 - 12 eV)
EUV (10 - 120 eV)
Soft-Xray (0,12 - 12 keV)
Hard-Xray (10 - 100 keV)
γ-ray (~ 1 MeV)

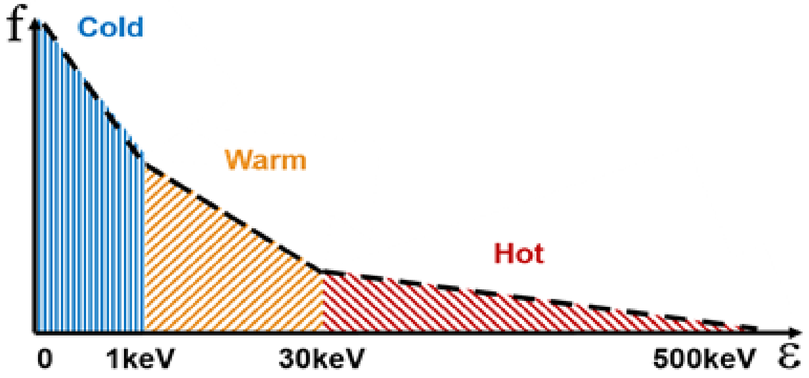
Plasma Immersed Antennas + Spectrum Analyzer
Non-linear wave-plasma interaction

Optical plasma Observation
Spectroscopy for cold plasma (few eV)
density/temperature measure

X-ray Pinhole Camera
X-ray Imaging and space resolved spectroscopy
2D energy distribution and (relative) density

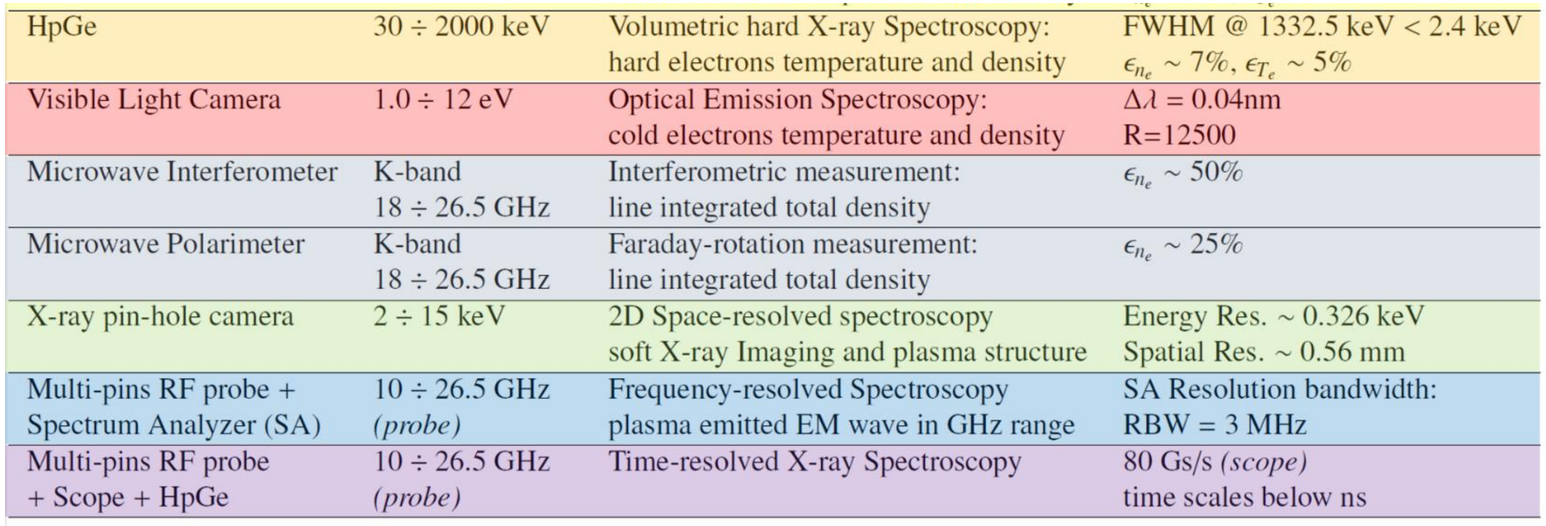
SDD - HpGe X-ray detectors
Spectroscopy
(for warm and hot plasma characterization)

Microwave Interferometry and Polarimetry measuring plasma density

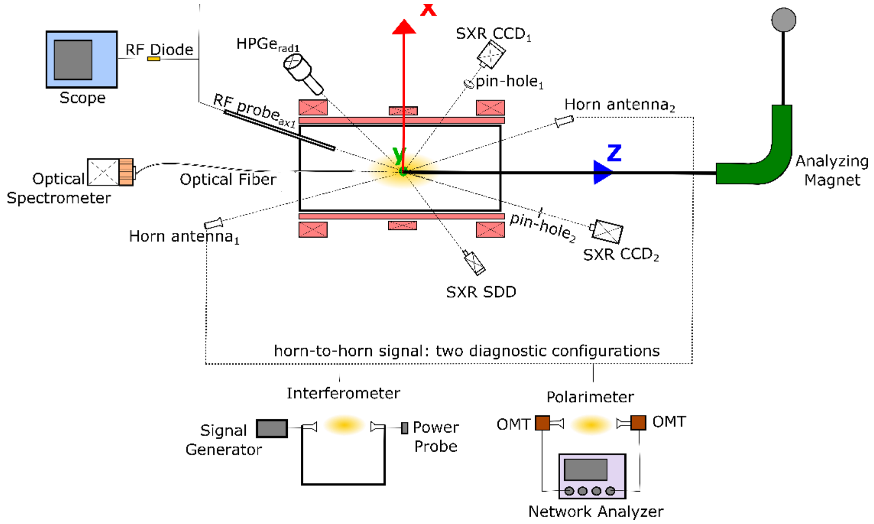


- on-line monitoring of all plasma parameters (ρ, T, CSD)
- investigation of the plasma properties in all energetic domains
- performing high-resolution spatial and time resolved analysis

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)

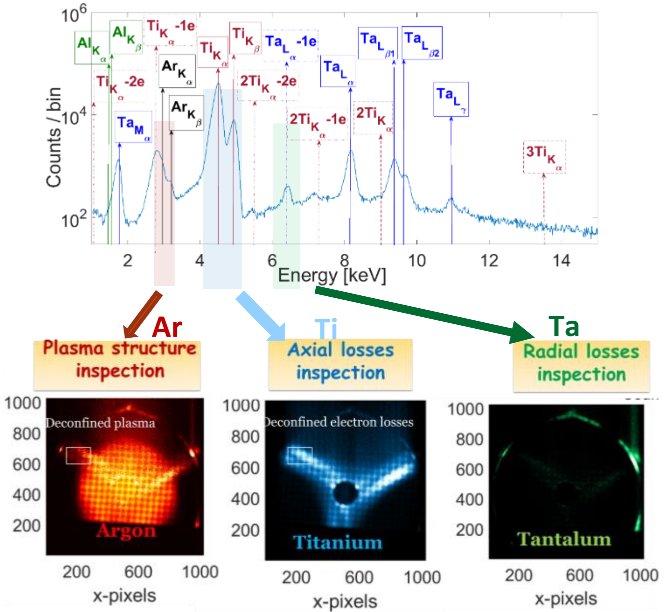
HPGe for "hot electrons": probing volumetric hard X-radiation (30 - 2000 keV)

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

Physics cases

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

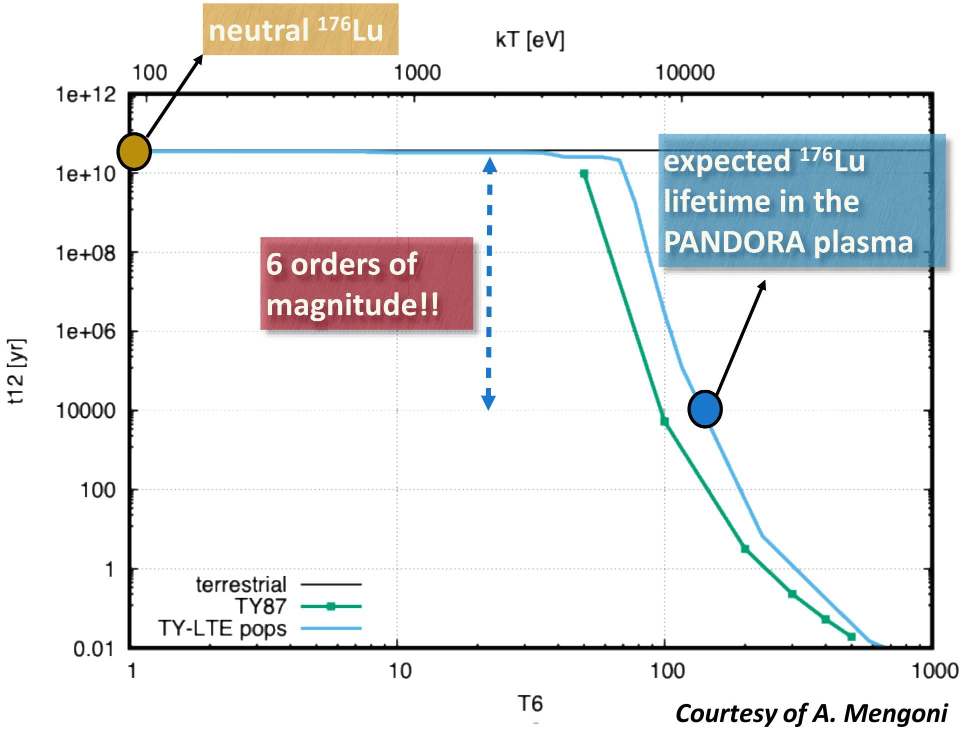
Three cases were selected for the first campaign of measurement

first run foreseen in 2024

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

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



neutral ^{176}Lu

6 orders of magnitude!!

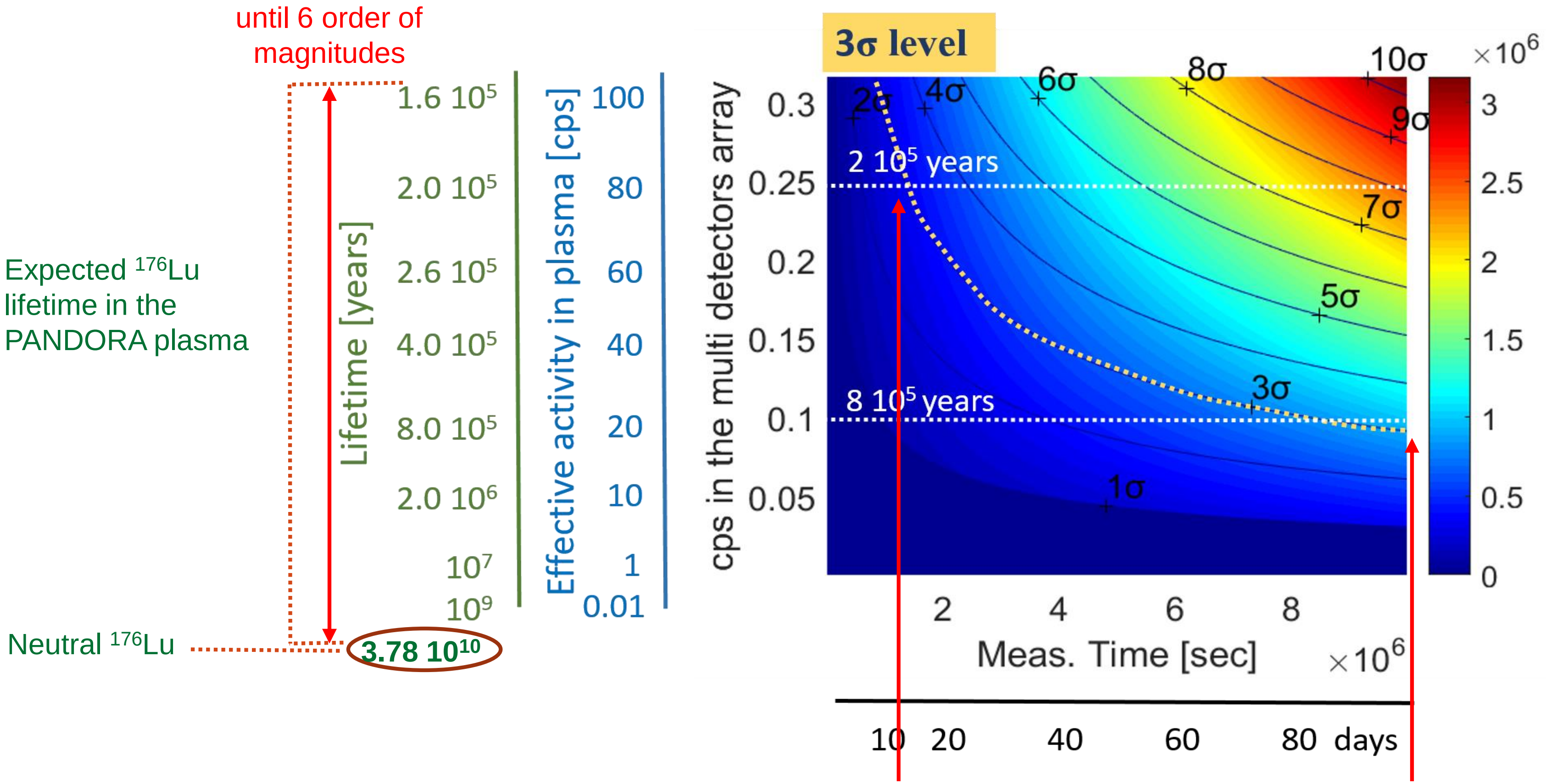
expected ^{176}Lu lifetime in the PANDORA plasma

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

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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

Measurement of Plasma opacity relevant for Kilonovae light-curve

Recreate an environment resembling thermodynamical conditions similar to CB ejecta at specific stages of their evolution

Improve knowledge on the physics of Kilonovae → relevant for origin of heavy nuclei produced via r – process nucleosynthesis.

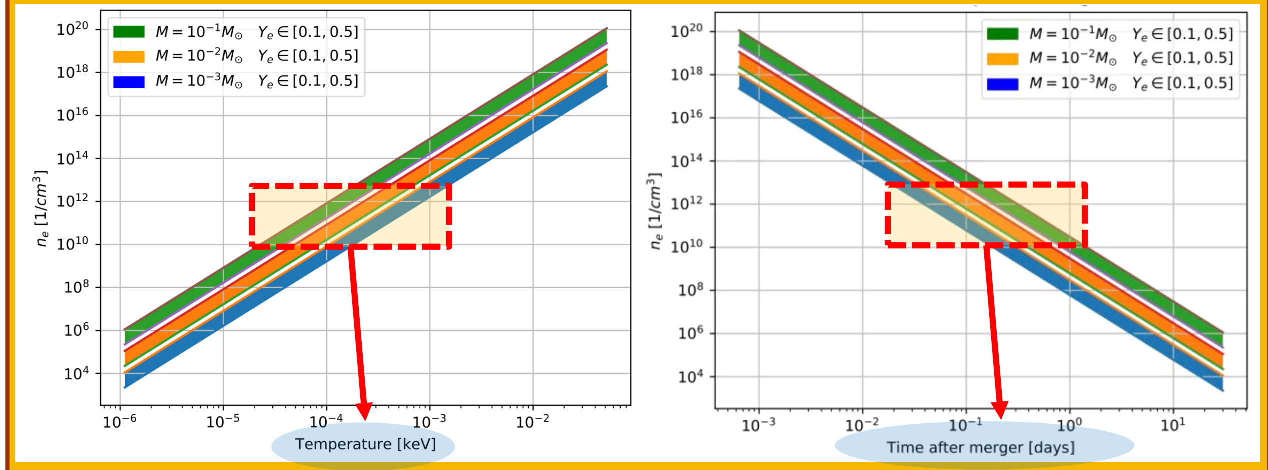
As a result of the merging dynamics and depending on the ejecta neutron richness, both heavy and light nuclei are synthesized via the r -process.

The presence of both r -process elements can be disentangled by analyzing the KN light curve.

- KN light-curve is affected by ejecta atomic **opacity**, and it delivers information on the post-merging plasma ejecta composition– spectra are a convolution of plasma emissivity and opacity.
- **Opacity from theoretical models presents large uncertainty factors**

→ experimental data are needed !

Feasibility study: astrophysical modelling BNS ejecta, nuclear network for nucleosynthesis yields, and population kinetics code for synthetic spectra



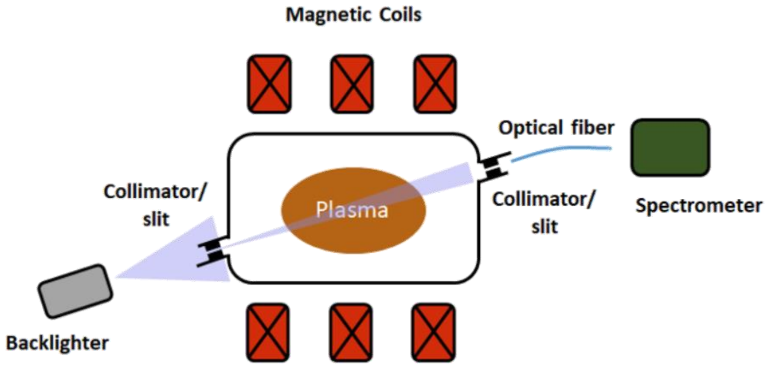
Pidatella, A., et al. Nuovo Cimento 44 C (2021) 65

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

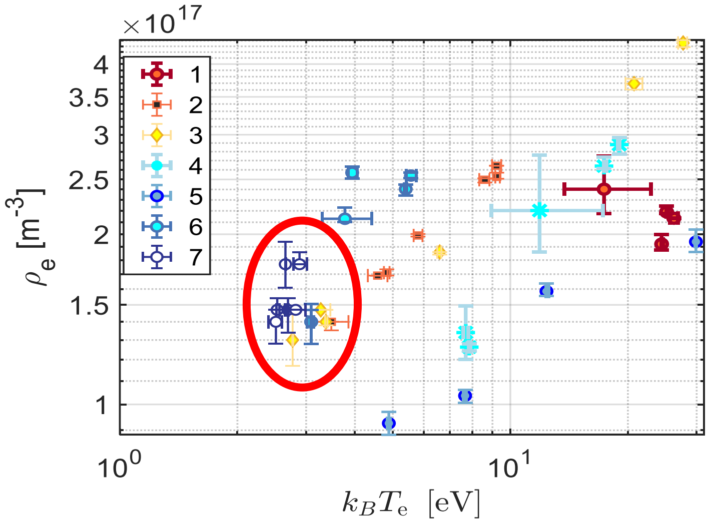


Flexible Plasma Trap @ LNS (setup Feb 2022)

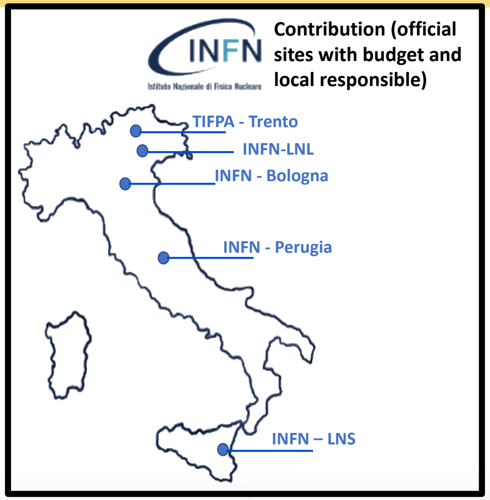
Pidatella, A.,et al. Frontiers in Astronomy and Space Sciences 10.3389/fspas.2022.931744 (2022)

Experimental H_2/Ar plasma characterization performed on FPT:

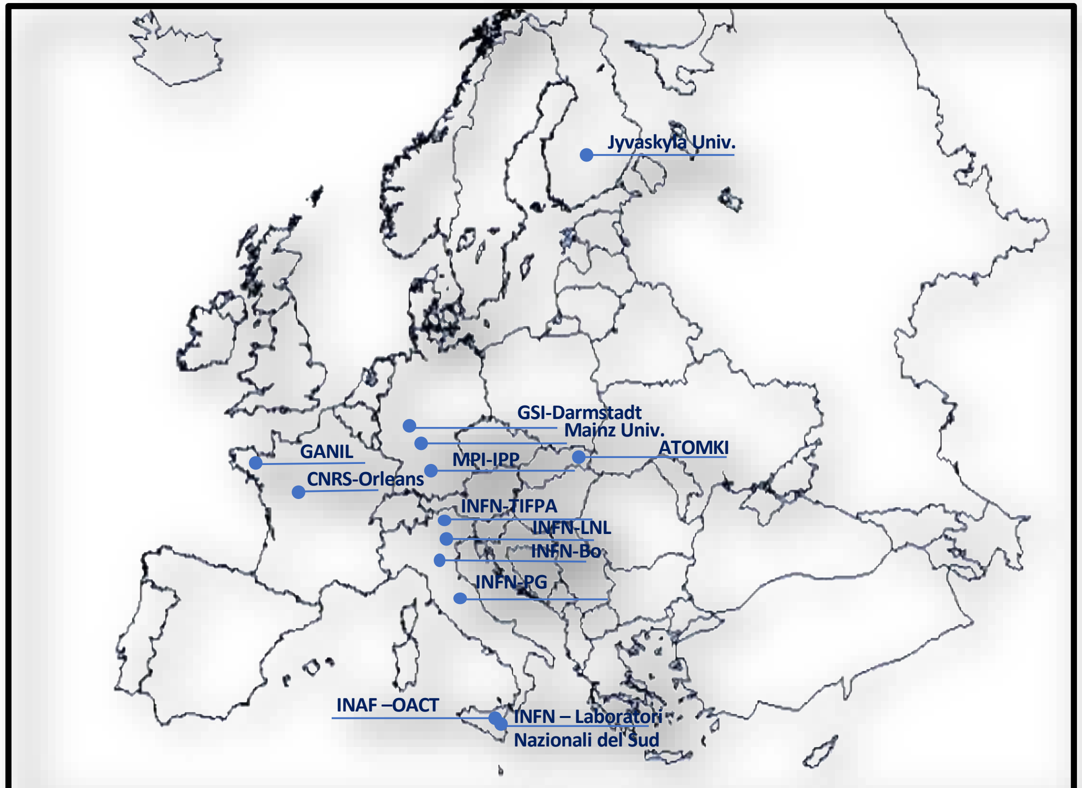
The comparison between the theoretical and experimental **line ratios** allows to evaluate the **plasma parameters (average electron density and temperature) through YACORA CR model line ratios**



PANDORA collaboration



Contribution (official sites with budget and local responsible)



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Thanks for your attention