GEANT4 simulations for a design study of a HPGe detectors array for in-plasma β-decays investigation of nuclear astrophysical interest

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Nuclear Astrophysics Goals

In the frame of the **PANDORA** (**P**lasmas for **A**strophysics, **N**uclear **D**ecays **O**bservation and **R**adiation for **A**rchaeometry) project, a new experimental approach aims at measuring, for the first time, **in-plasma β-decays lifetimes of isotopes of astrophysical interest** (s-processes, CosmoChronometers) as a function of the thermodynamical conditions of a plasma-environment partially reproducing stellar conditions. This can be done by simultaneously identifying and discriminating - through **a HPGe detectors array which will work synergically with an innovative multi-diagnostic system** - the γ-rays emitted after the isotope β-decay and the photons emitted by the plasma.

Introduction

We here focus on **GEANT4 simulations focused on the design of the array of γ-ray detectors** and the evaluation of total efficiency depending on the detector type and the optimal displacement of detectors around the trap (including collimation systems and shielding). The best compromise, due to technical constraints, is to use **14 HPGe detectors** (70% of relative efficiency with a total photopeak efficiency of ~ 0.1 - 0.2 %) surrounding the high-performance totally superconducting plasma trap. **The sensitivity of the PANDORA experiment was checked in a "virtual experiment run"**, by exploring the measurability of isotope decay rates **for the first three physical cases of PANDORA: ^{134}Cs, ^{94}Nb, ^{176}Lu.** The feasibility of the measurement in terms of the signal-to-background ratio and significance that it is possible to reach was demonstrated. The experimental run durations could take from several days to 3 months, depending on the isotope under investigation, thus shedding new light on the role of weak interactions in stellar nucleosynthesis.

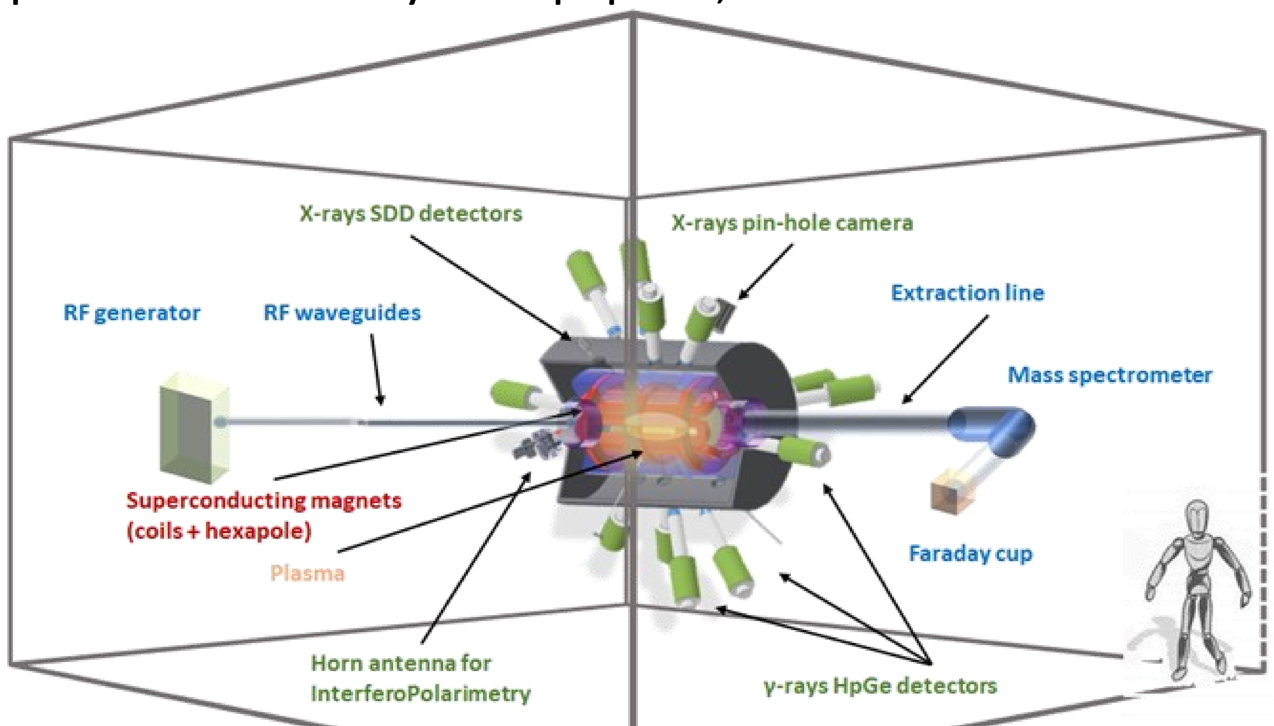
The PANDORA Setup

PANDORA Setup includes three main pillars:

1) **A totally superconductive magnetic plasma trap made of three coils and a hexapole to confine the plasma;**
2) **An array of 14 γ-ray detectors to tag the β-decay by detecting the γ-ray emitted by daughter nuclei;**
3) **An innovative multidiagnostic system (i.e., optical, X-ray, interfero-polarimetry, RF probe and pin-hole camera, etc.) to monitor and measure online all plasma parameters and thermodynamical properties;**

First Physics Cases

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



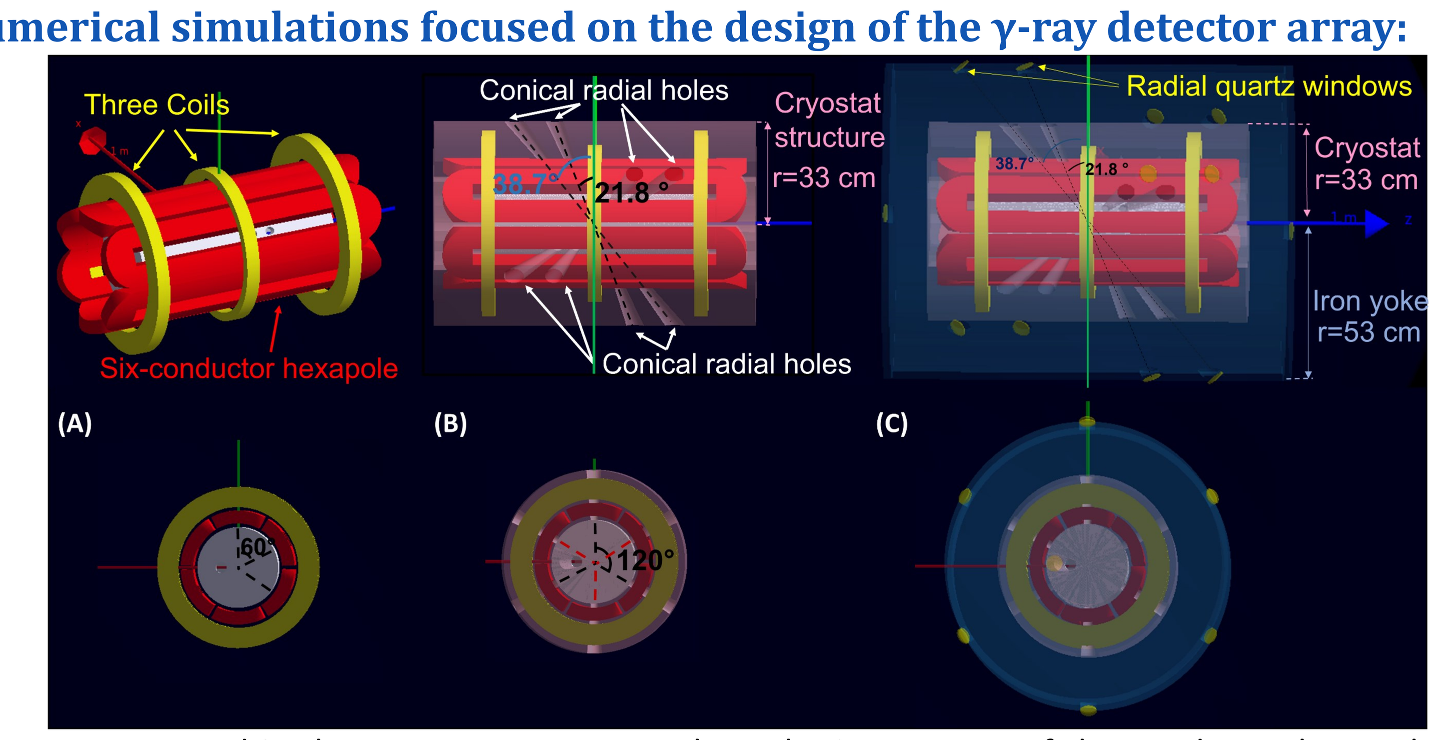
The Experimental Approach

PANDORA proposes a totally innovative experimental approach which includes 5 steps:

1) A buffer plasma is created from He, O or Ar up to density of 10^{13} cm^{-3} by **ECR** and confined by **magnetic field**;
2) The **isotope is vaporized by proper ovens** into the chamber **to be transformed into plasma-state;**
3) The plasma is maintained in **MHD equilibrium** for even weeks: $\frac{dN}{dt} = \lambda n_i V$ ⟶ $N(T_{meas_i}) = \lambda n_i V_{plasma} T_{meas_i}$
4) While the isotopes decay, the confined **daughter nuclei emit γ-rays of hundreds of keV, detected by a HPGe detector array**;
5) In-plasma radioactivity can be correlated to plasma parameters by an **innovative non-invasive multi-diagnostics setup**;

Design of the PANDORA setup in GEANT4

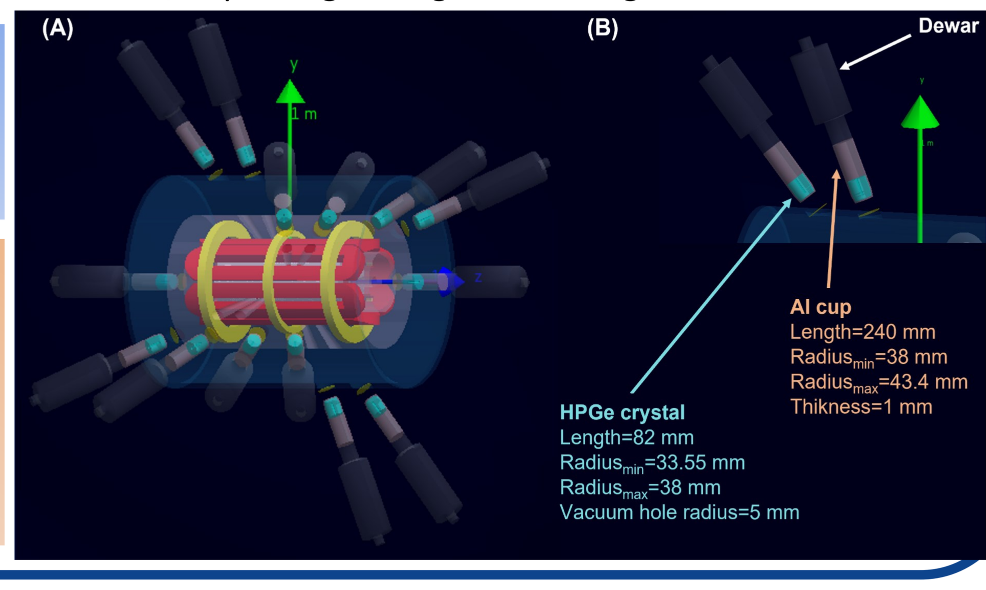
Numerical simulations focused on the design of the γ-ray detector array:



Holes were created in the cryostat structure—along the interspaces of the conductor hexapole—in order to use it as a multicollimator and to suppress as much as possible the photon flux coming from the walls and not directly from the plasma core, improving the signal-to-background ratio.

Array of 14 γ-ray detectors (two placed axially and 12 radially). Each detector was placed collinearly at each collimator.

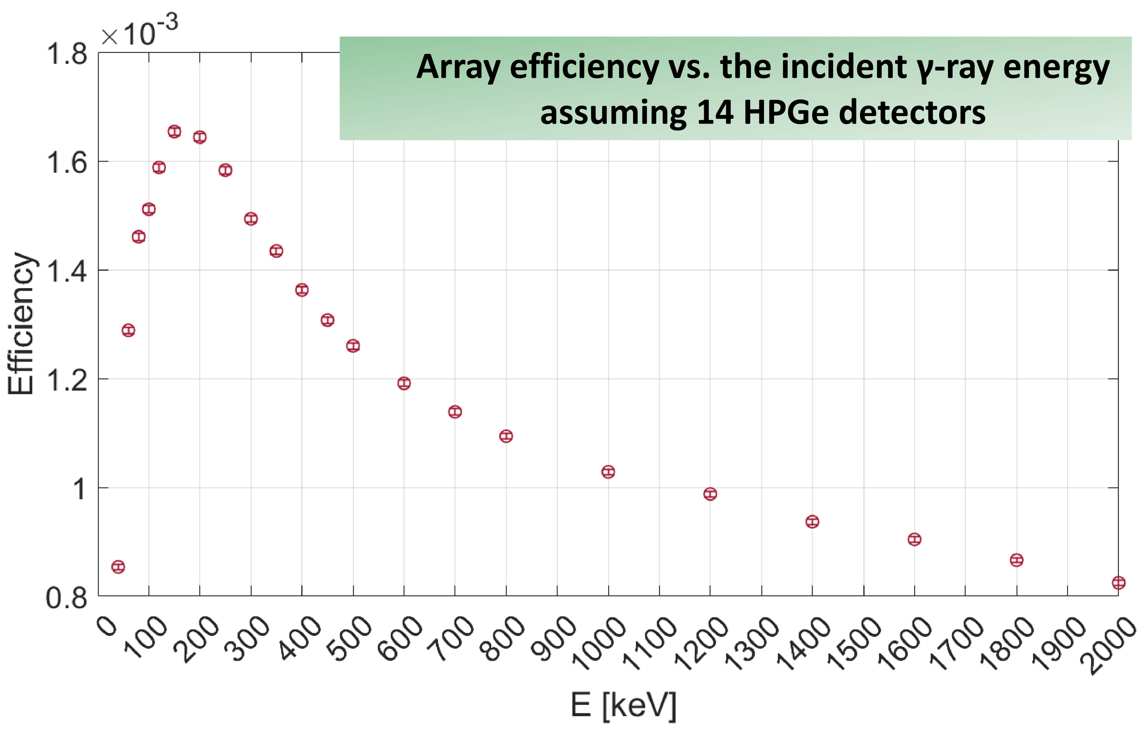
The HPGe detectors were chosen for their excellent energy resolution (0.2% @ 1 MeV), since the harsh environment (the background is represented by the intense plasma self-emission) strongly affects the signal-to-background ratio.



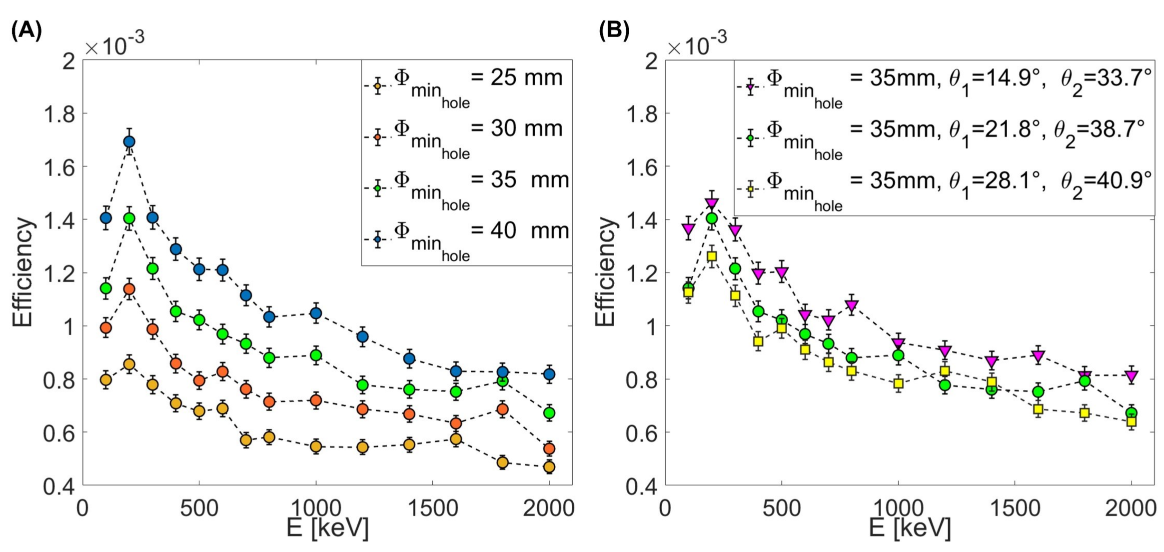
Results by Numerical Simulations

Evaluation of the array efficiency

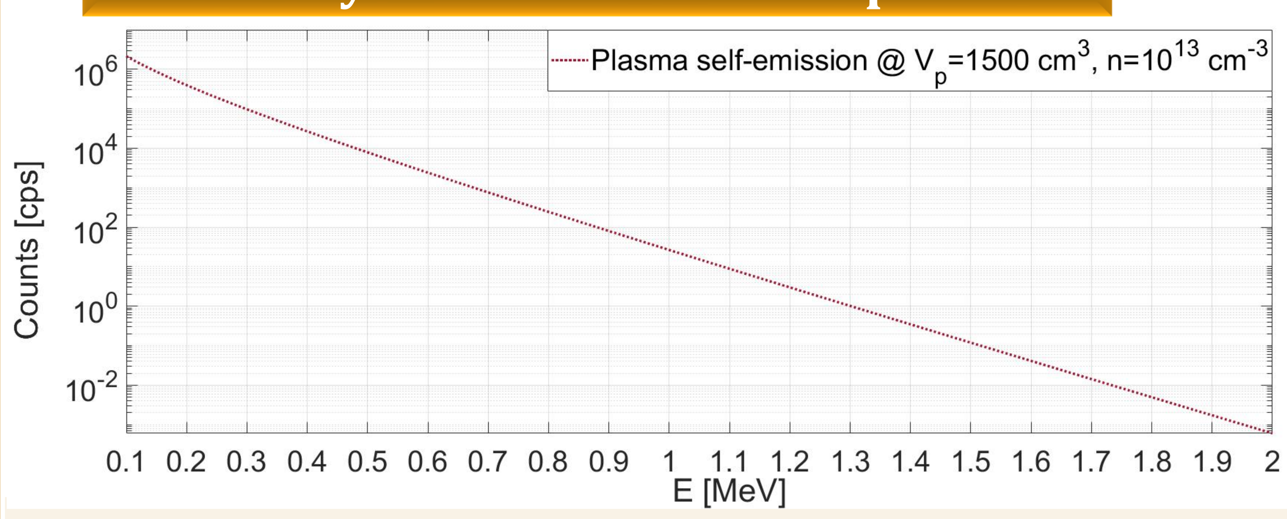
Simulations were performed considering an **isotropic ellipsoidal source** placed in the center of the plasma chamber, having semi-axis lengths of 79x79x56 mm^3 (corresponding to the plasma volume in the PANDORA plasma trap). **The γ-ray energy range explored extends from 40 keV to 2 MeV**. For the evaluation of the background due to plasma self-emission, we considered a **density of n = 10^{13} cm^{-3}, and a volume of 1500 cm^3**.



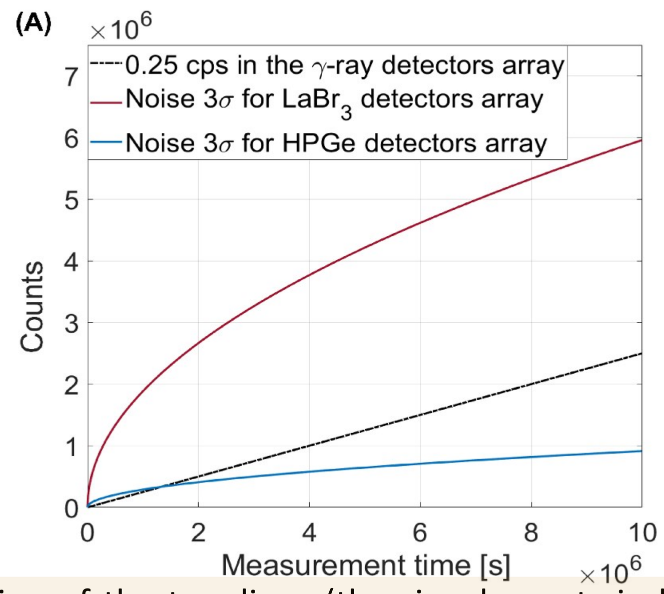
Further simulations were performed to investigate the effect due to the position and size of the collimator holes, in order to define a tolerance range for each parameter, considering the technical constraints that can arise in the design of the magnetic trap.



Sensitivity of the PANDORA Experiment



Considering the typical background spectrum due to plasma self-emission and the total efficiency of the system, the background rate that would be measured by the PANDORA setup was evaluated. Such a rate was compared to the rate of the γ-rays emitted from the daughter nuclei after the β-decay and detected in the array.

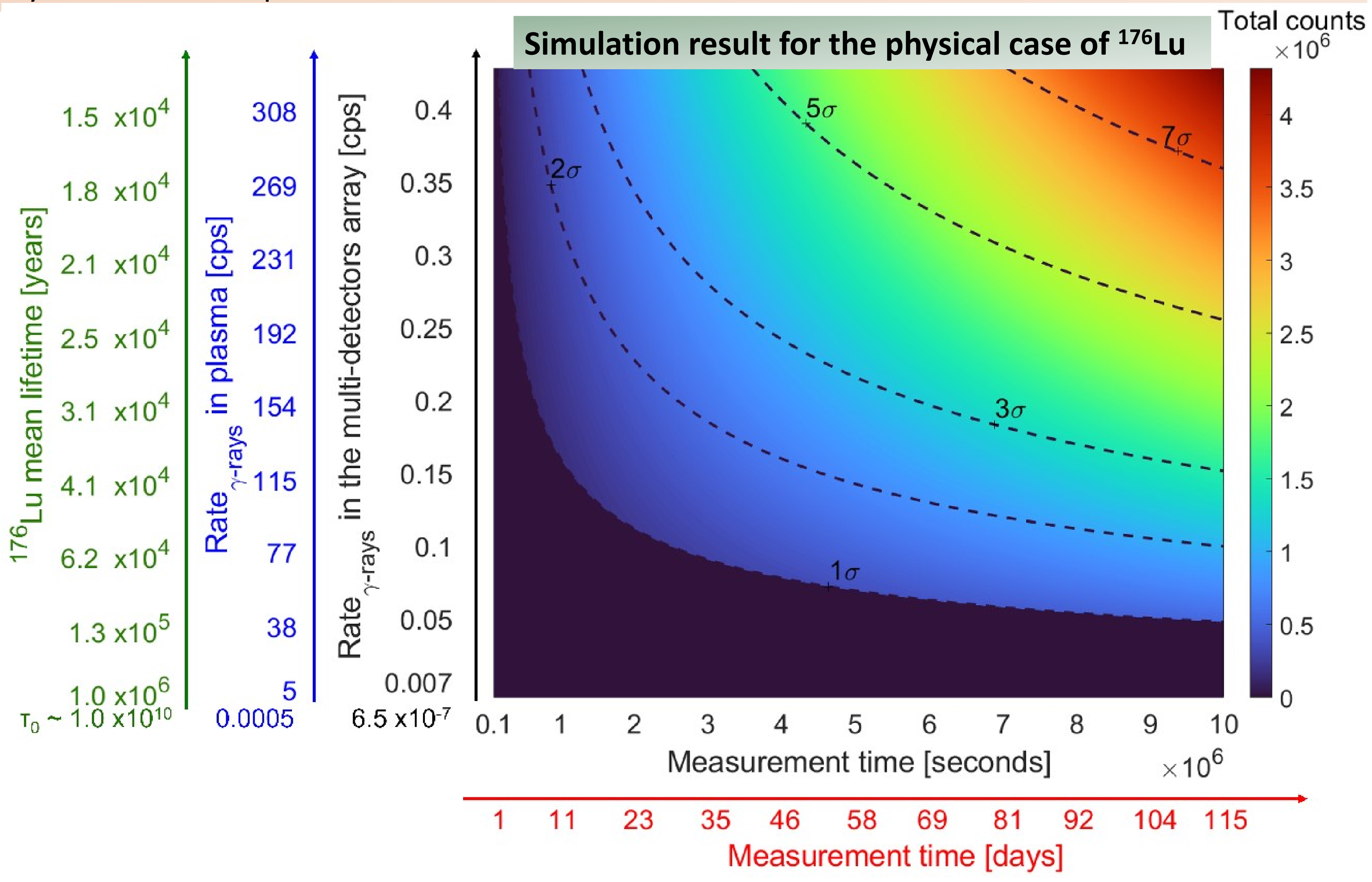


The intersection of the two lines (the signal counts in black and the three times the background level in blue, for HPGe) is the point where the signal exceeds the 3σ background level and the corresponding abscissa is the measurement time needed to have a 3σ significance.

Virtual experimental run

The sensitivity of the PANDORA experiment was checked in a ***"virtual experimental run"***: to estimate the measurement time needed to reach the 3σ significance considering different lifetimes, that is, different rates in the detector array, dedicated plots showing the total counts and the expected significance vs. the measurement time for the first three physics cases were performed.

- The **green vertical axis reports a decreasing lifetime**, starting from the lifetime of the neutral isotope (5,45·10^{10} years) to the values predicted by the theory and reachable in the PANDORA trap (**the expected collapse of the lifetime is six order of magnitude for ^{176}Lu** at a plasma temperature of ~10 keV).
- The **effective activity in plasma**—assuming a plasma of 1,500 cm^3 in volume with a relative concentration of 1% of Lu with respect to the buffer density (10^{13} ions/cm^3)—was estimated (**blue vertical axis**).
- Including the efficiency of the HPGe detector array estimated by GEANT4 simulations, **the counting rate of the detector array was evaluated (black vertical axis)**.
- **The x-axis indicates the measurement time.**
- **Pseudocolors give the total number of counts at the peak of interest** (i.e., the number of γ-rays emitted by Hf at Eγ=306.78 keV). The condition that the signal overcomes the 3σ background level defines the measurement time needed to have a 3σ significance.
- **Black dashed lines shown in the plot represent *isosignificance* contours at each given combination of expected activity and measurement time.**



The feasibility of the measurement, depending on the relevance of lifetime decrease and on the isotope under investigation, is deemed to last from a day (i.e., in the case of six orders of magnitude collapse for ^{176}Lu) up to 3 months. The specific sensitivity for discriminating among the set of theoretical predictions was investigated as well as eventually fit the nucleosynthesis data which disagree from the current decay rate predictions.

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