GRAN SASSO
SCIENCE INSTITUTE

$^{14}N(p,\gamma)^{15}O$ reaction measurement for LUNA-MV project

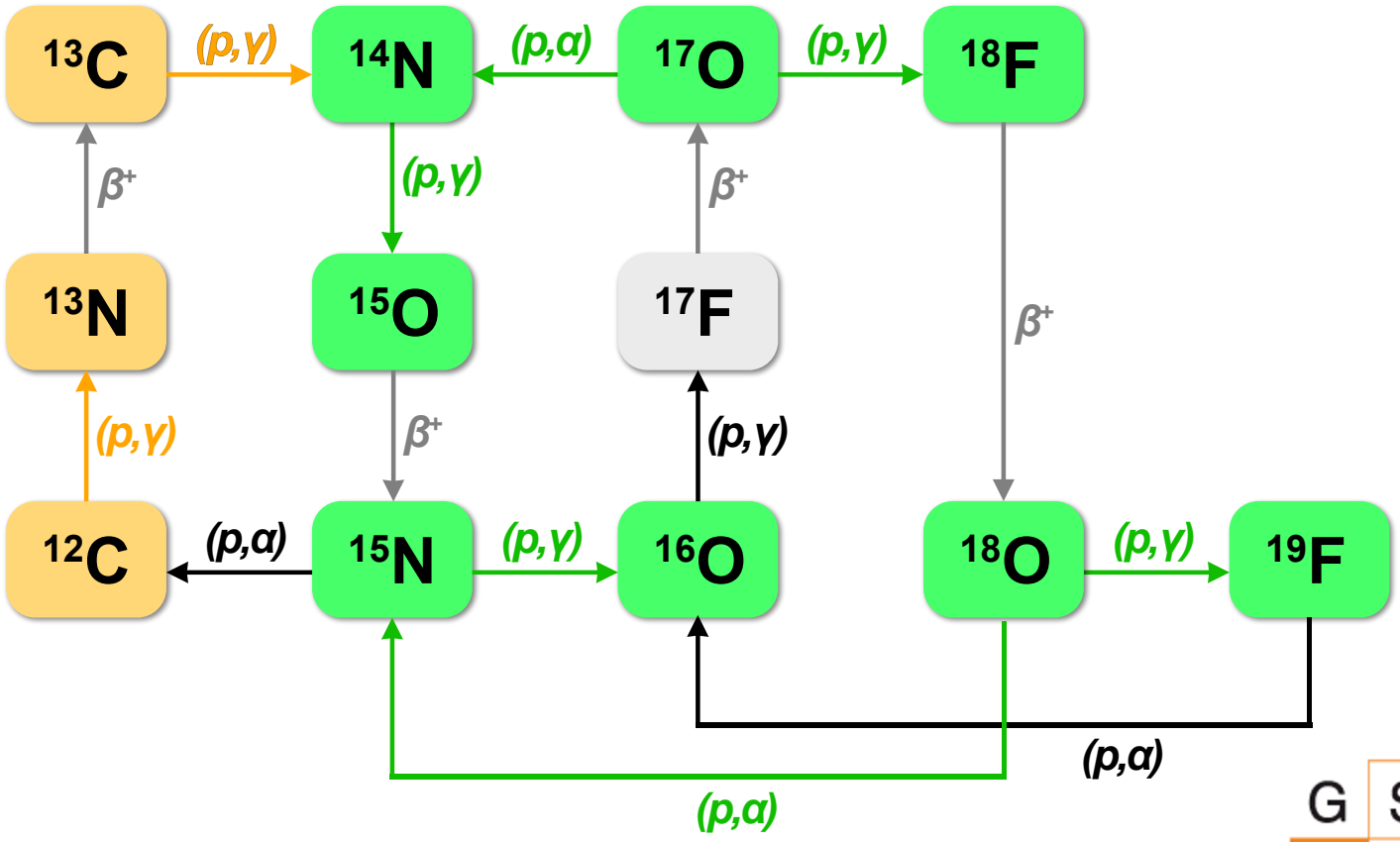
PhD project activity status

Alessandro Compagnucci

www.gssi.it

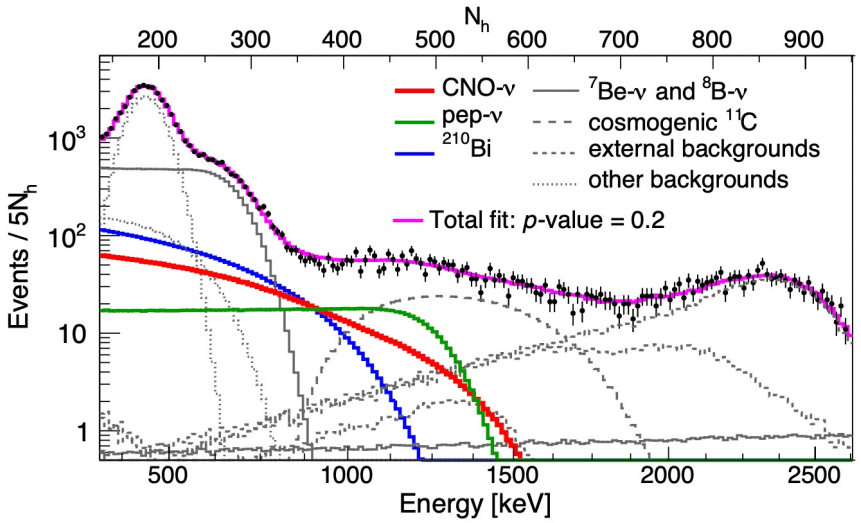
The $^{14}N(p,\gamma)^{15}O$ and the CNO cycle

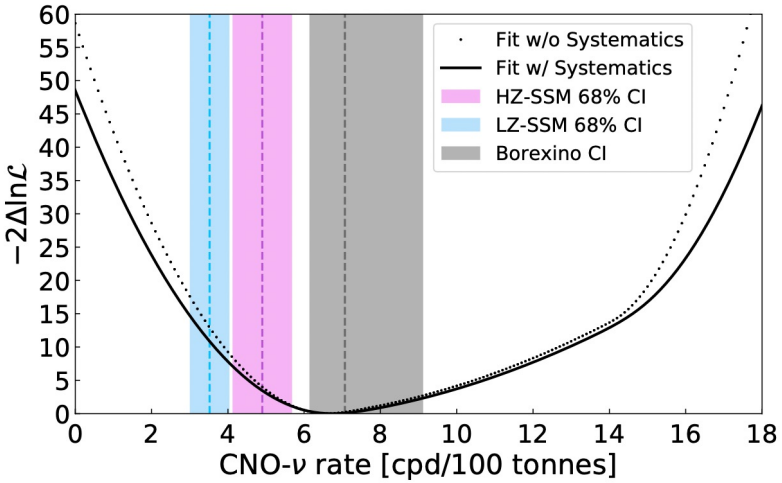
- The CNO Cycle is the main source of energy generation in massive main-sequence stars, accounts for ~1% in the Sun.
- The $^{14}N(p,\gamma)^{15}O$ is the slowest reaction of the CNO, controls its speed and energy production rate.

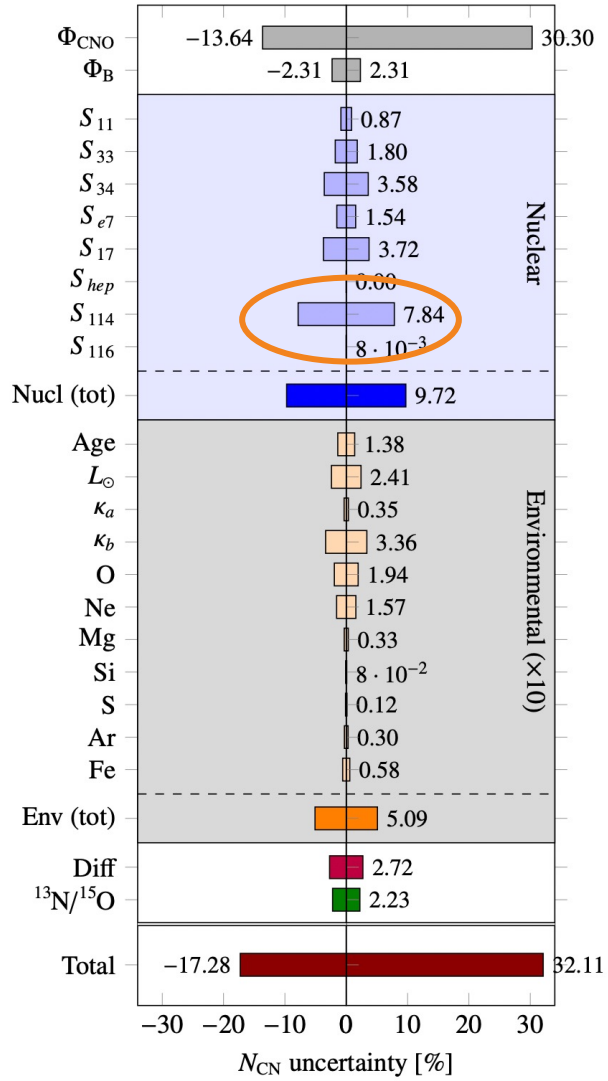


The $^{14}N(p,\gamma)^{15}O$ and the CNO cycle

- Solar CNO neutrino flux recently detected for the first time by Borexino (2020). → Solar metallicity probe.
- The result of Borexino disfavours "low metallicity" SSM prediction, but large uncertainties still remains. After CNO Flux itself, biggest contribution to the uncertainty budget from $^{14}N(p,\gamma)^{15}O$ cross section.

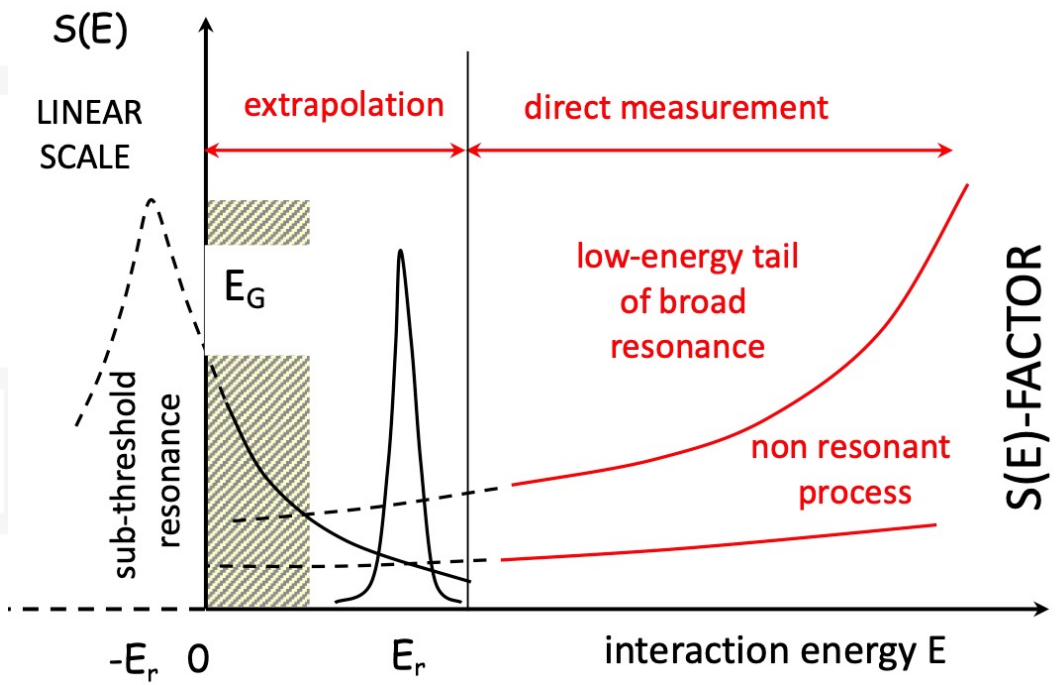


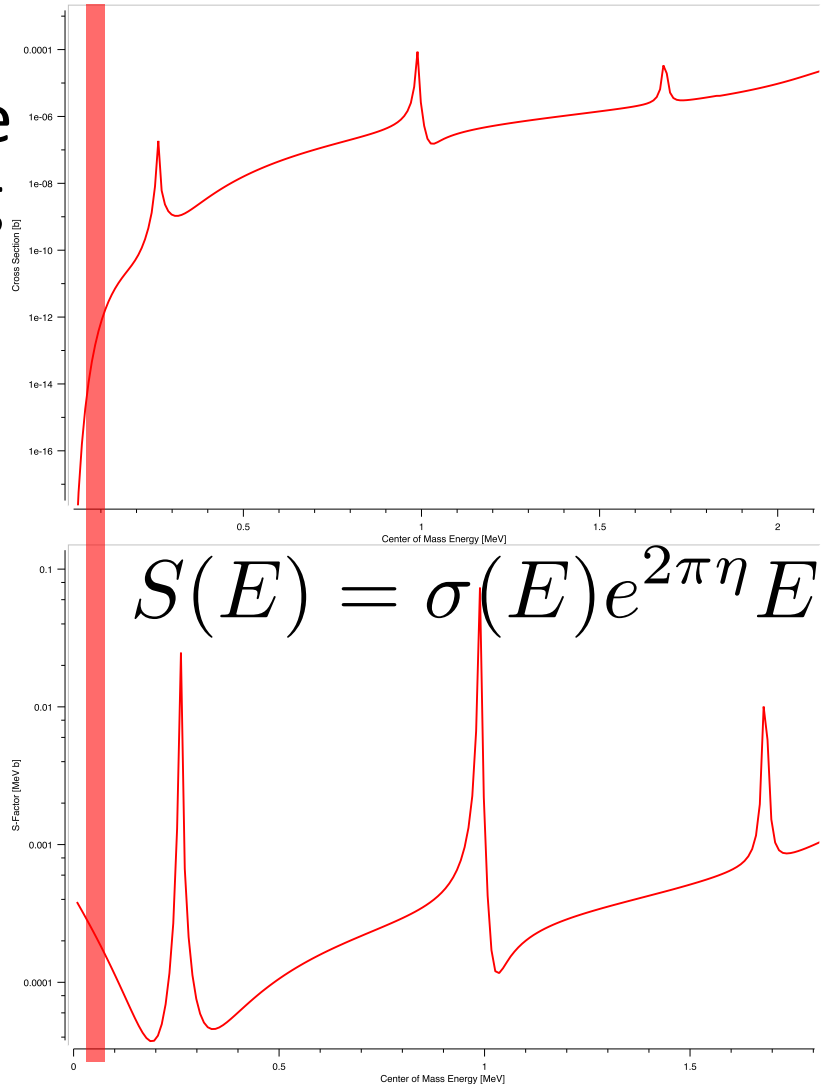




Uncertainties in $^{14}N(p,\gamma)^{15}O$ cross section determination

- The precise measurement charged-particle induced cross sections near stellar burning energy is challenging.

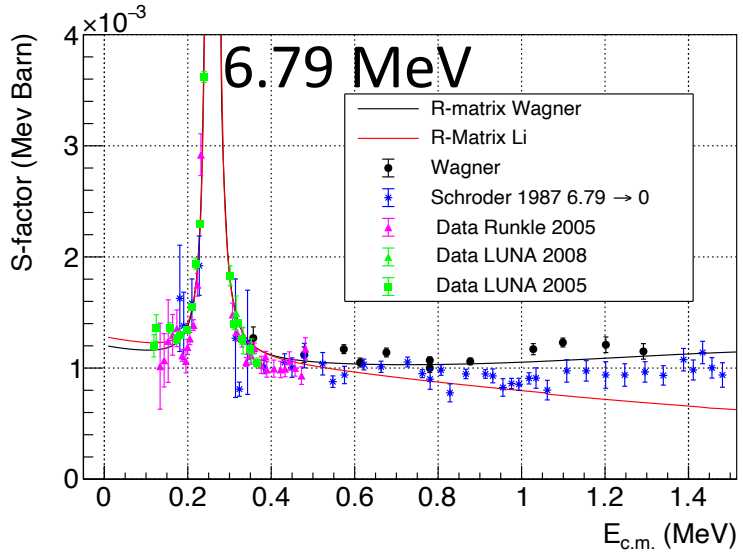


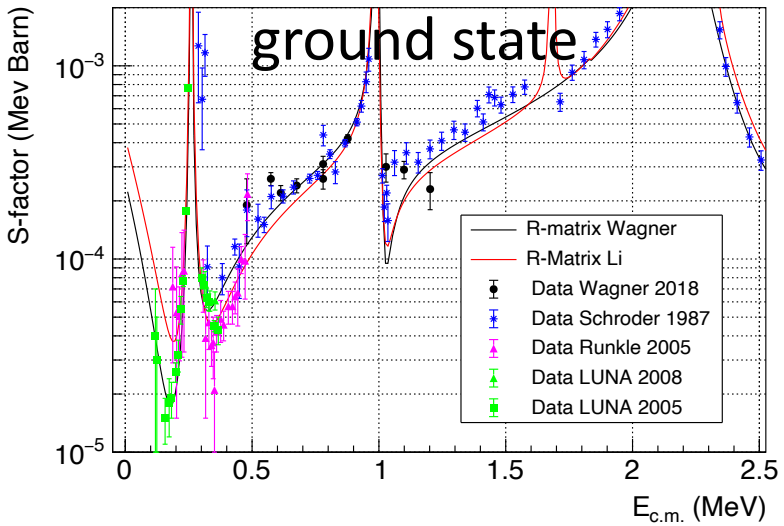


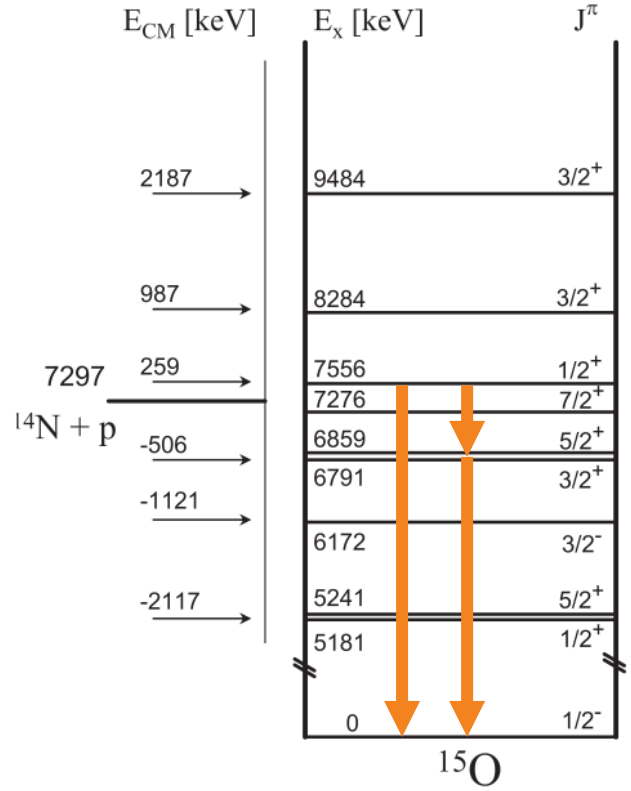
$$S(E) = \sigma(E)e^{2\pi\eta}E$$

Uncertainties in $^{14}N(p,\gamma)^{15}O$ cross section determination: The role of nuclear structure

- Most important transitions contributing to the total capture: 6.79 MeV excited state, g.s of ^{15}O
- Secondary transitions: 6.17, 5.24, 7.28, 6.86, 5.18 MeV
- R-matrix analysis fails to provide a consistent view of both high and low energy data, why?



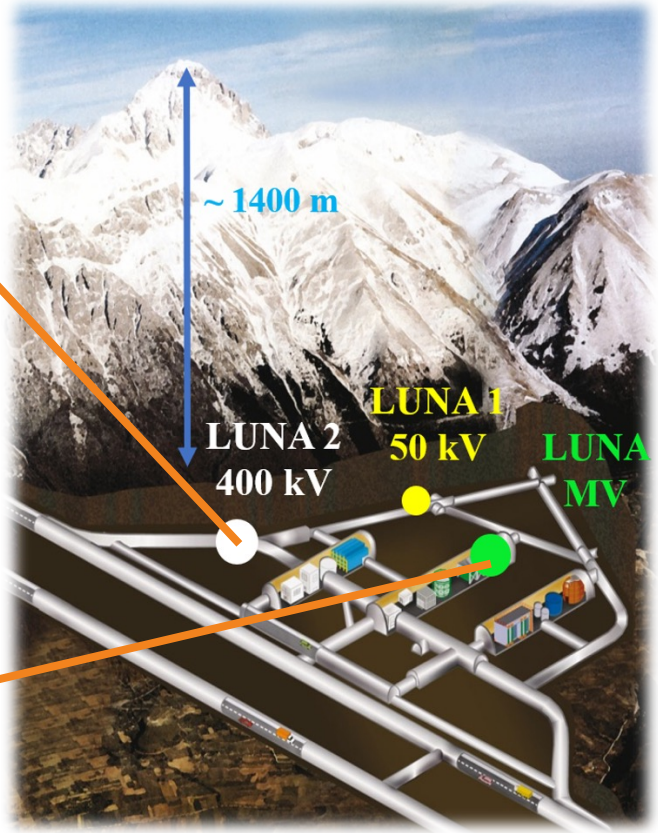


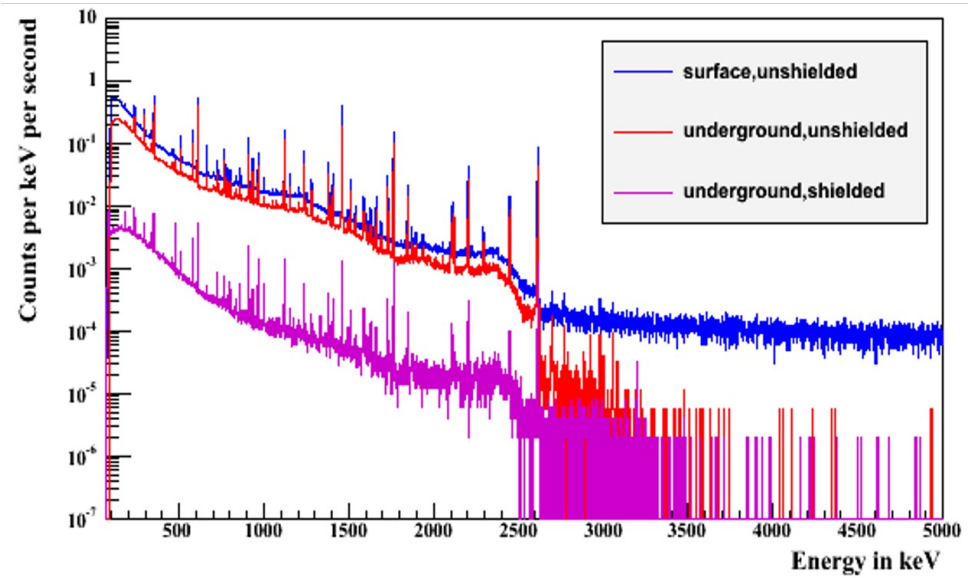


Underground Nuclear Astrophysics at LUNA

Open tank of the LUNA 400 kV accelerator

The new 3.5 MV accelerator facility





LUNA

GSSI

The accelerator system for the LUNA-MV project

- Energy range 0.3-3.5 MeV
- H^+,He^+,$^{12}C^+$,$^{12}C^{++}$
- High current, energy stability below 10^{-5}, uninterrupted operation time >24h
- Scientific program:
  - $^{14}N(p,\gamma)^{15}O$
  - $^{12}C+^{12}C$, $^{22}Ne(\alpha,n)^{25}Mg$, $^{13}C(\alpha,n)^{16}O$ …

Ion specie	Beam Intensity (eμA)	
	TV range 0.3 MV–0.5 MV	TV range 0.5–3.5MV
$^1H^+$	500	1000
$^4He^+$	300	500
$^{12}C^+$	100	150
$^{12}C^{+2}$	60	100

Beam intensity on target at different terminal voltage.

Sen, A. *et al.* (2019) 'A high intensity, high stability 3.5 MV Singletron™ accelerator', *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms*, 450, pp. 390–395. doi:10.1016/j.nimb.2018.09.016.

Towards $^{14}N(p,\gamma)^{15}O$ measurement @ LUNA-MV

- Low background measurement over a wide-energy range, in order to address the existing issues in the extrapolations
- Angular distribution
- Measuring weaker transitions
- Pilot LUNA-MV project

  → Verifing the performance of the accelerator

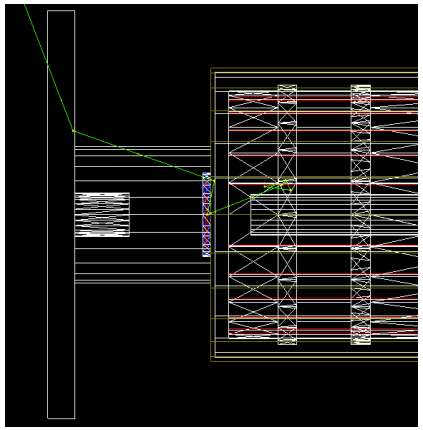
My PhD project: $^{14}N(p,\gamma)^{15}O$ measurement @ LUNA-MV

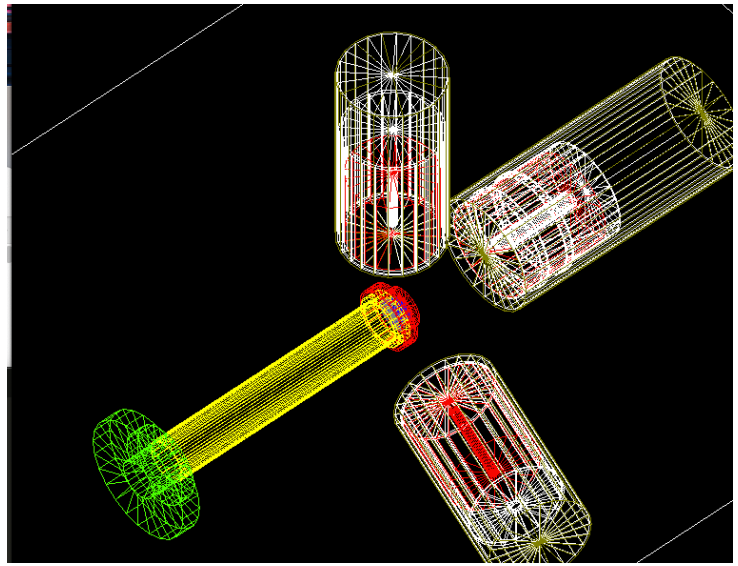
- Simulations and measurement planning
- Target production
- Target characterization
  - Atomki Tandetron
  - Luna-400
- Setup design and costruction
- Accelerator commissioning

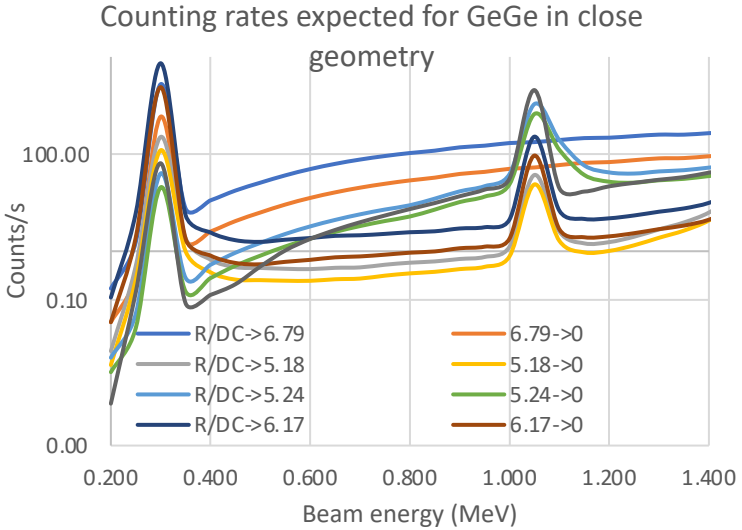
Simulations and measurement planning

- Angular distribution setup + Excitation function in close geometry simulated with Geant4.
- 3 HPGe detectors with ~120% relative efficiency
- Detectors at 10 cm from target, angles covered: 0°,45°,90°,135°...

HPGe characterization with sources at STELLA (LNGS)







Beam time (h) to 3%, down to 250 keV, primary trans.

Transition	0 deg	90 deg
6.79	6.2	0.7
5.18	27.1	25.0
g.s (+ summing-in)	37.6	33. 6

My PhD project: $^{14}N(p,\gamma)^{15}O$ measurement @ LUNA-MV

- Simulations and measurement planning
- Target production
- Target characterization
  - Atomki Tandetron
  - Luna-400
- Setup design and costruction
- Accelerator commissioning

Solid Targets production

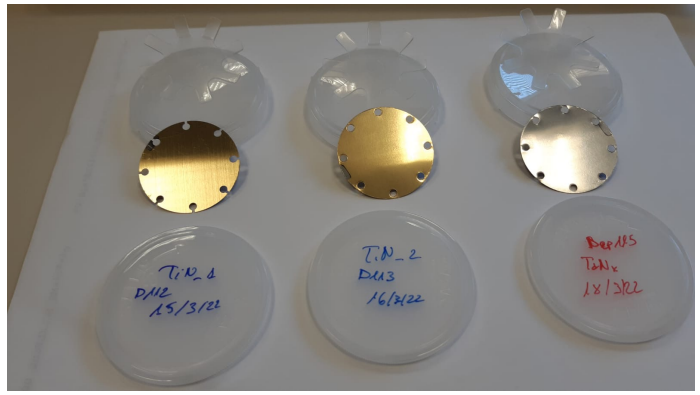
Sputtered targets

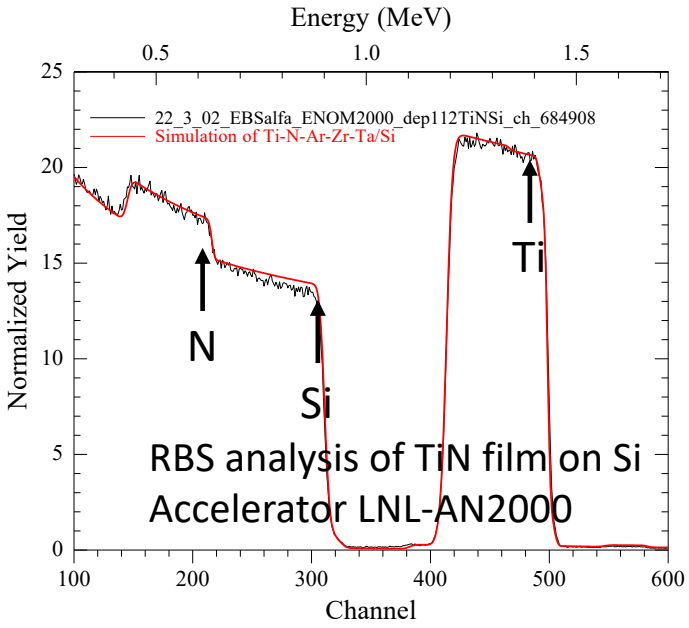
(Matteo campostrini, Valentino Rigato @ **LNL, Italy**):

- Thin films on Ta backing produced using Reactive Magnetron Sputtering
- TiN or Me_xN_y , with Me= Ta, Nb, Zr on Ta backing.
- Sputtered TiN targets already proved to be durable and withstand well irradiation with high beam intensities.
- Higher Z metals promise reduction of the beam induced background.
  → Issues at higher energies with Ti(p,γ), Ti(p,n)

- 4 targets produced

Characterization → RBS, NRRA



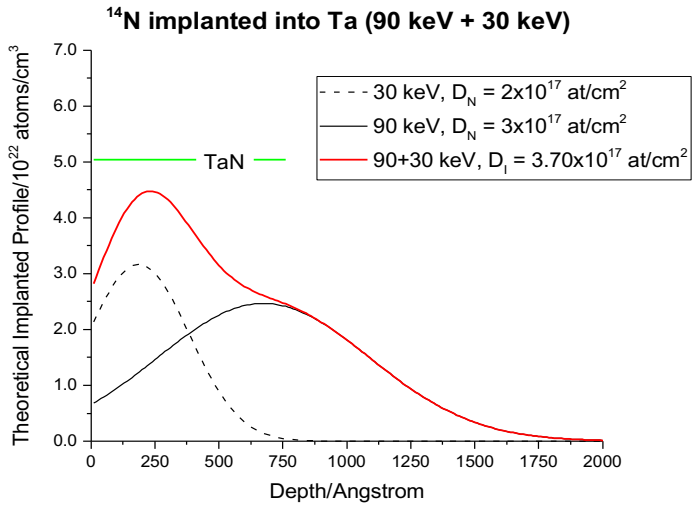


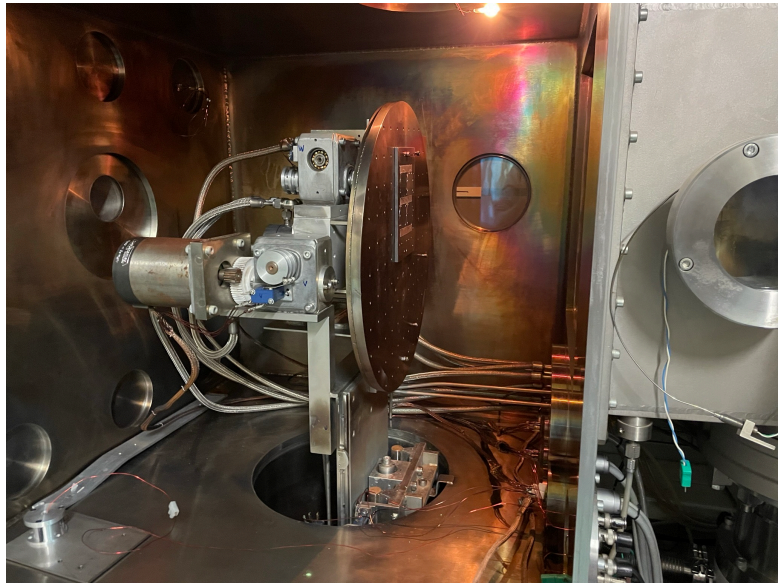
Solid Targets production

Implanted targets

(João Cruz @ **IST, Lisbon** - Under **RADIATE Transnational Access**):

- ^{14}N on Tantalum
- Isotopically pure
- Ta_xN_y → Higher beam energy reachable, lower Beam Induced Background ($^{15}N(p,\alpha\gamma)$ an issue at higher energies..)





- 4 targets produced

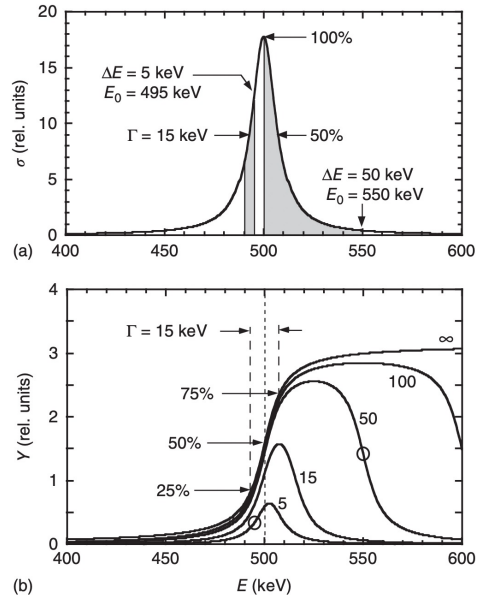
Characterization → RBS, NRRA

My PhD project: $^{14}N(p,\gamma)^{15}O$ measurement @ LUNA-MV

- Simulations and measurement planning
- Target production
- Target characterization
  - Atomki Tandetron
  - Luna-400
- Setup design and costruction
- Accelerator commissioning

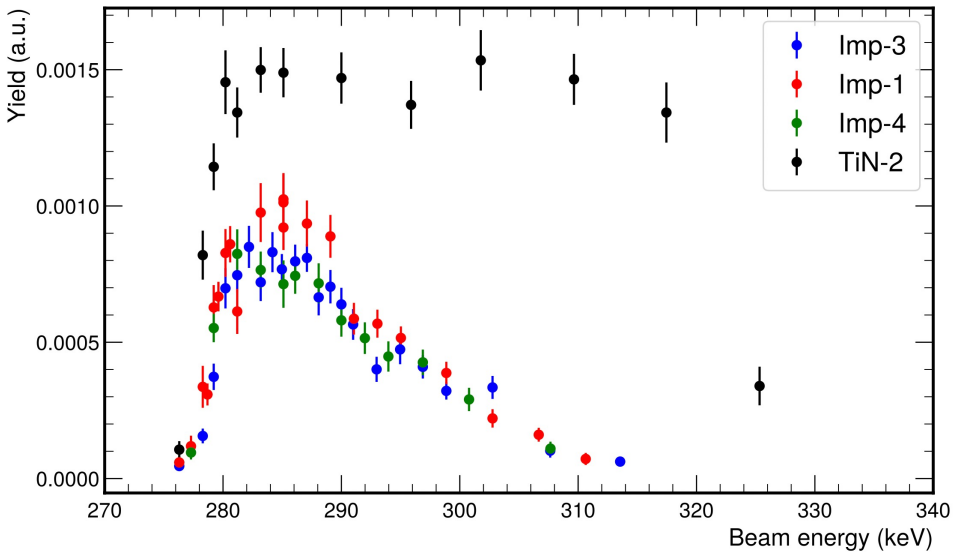
Solid Targets characterization

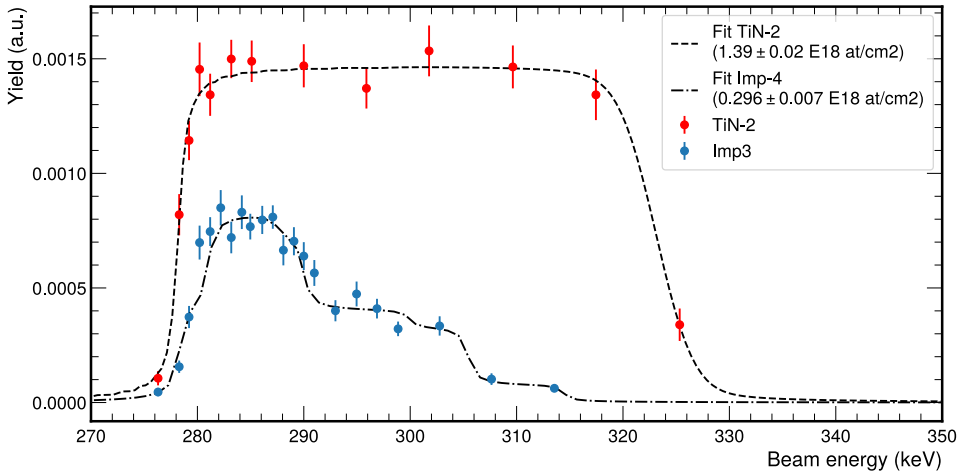
- Characterization campaigns performed to study target thickness, stability and beam-induced background.
- Atomki Tandetron, Hungary:
  - **278 keV ^{14}N** resonance scan
  - **429 keV ^{15}N** resonance scan



From Iliadis C. "*Nuclear physics of the stars*"

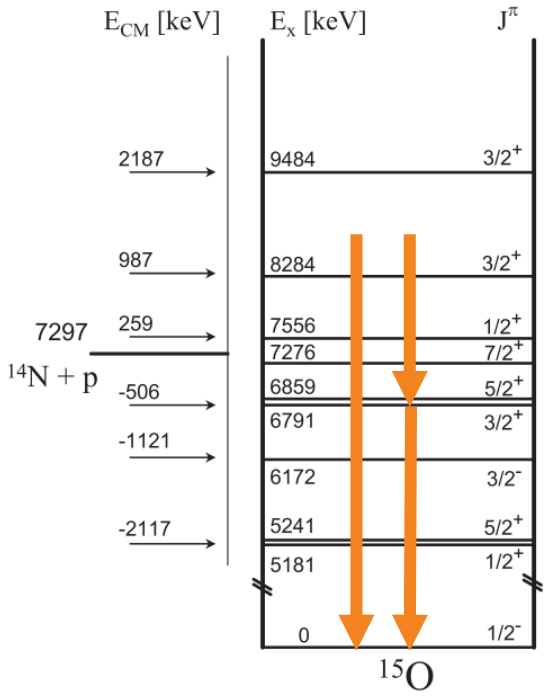
$$Y(E_0) = \int_{E_0-\Delta E}^{E_0} \sigma(E)dE \propto \arctan\left(\frac{E_0 - E_R}{\Gamma/2}\right) - \arctan\left(\frac{E_0 - E_R - \Delta E}{\Gamma/2}\right)$$

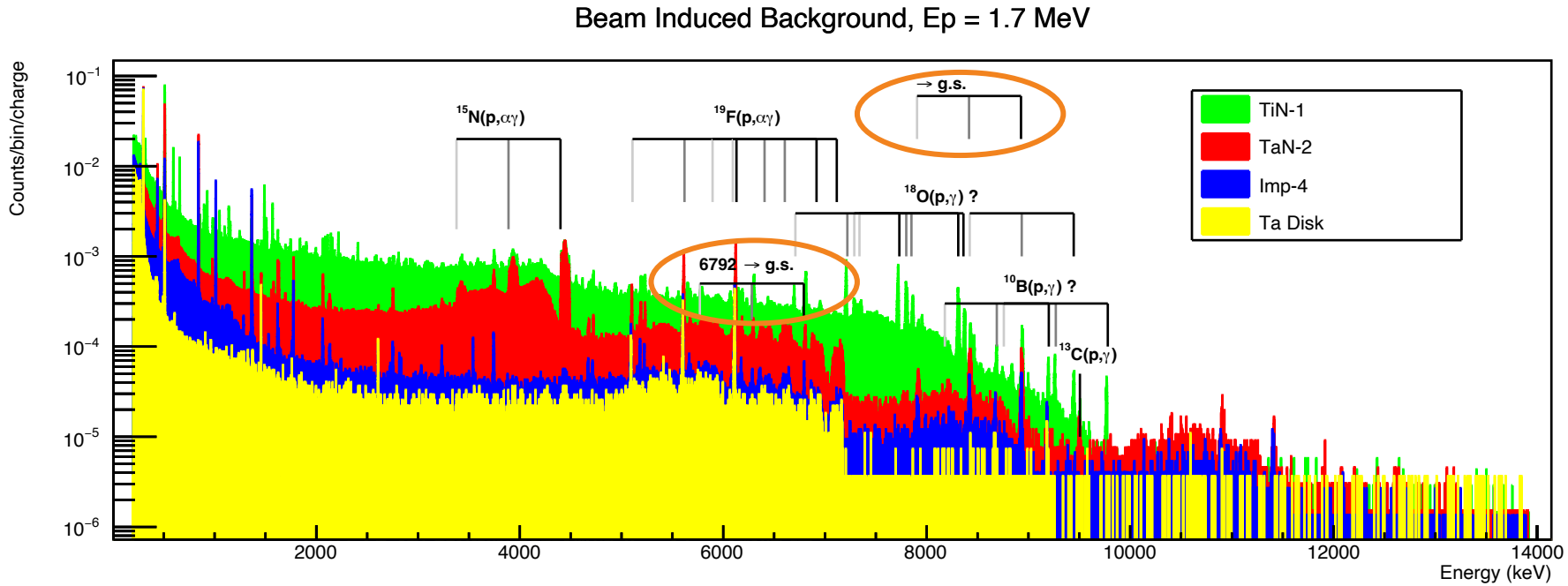




Solid Targets characterization

- Characterization campaigns performed to study target thickness, stability and beam-induced background.
- Atomki Tandetron, Hungary:
  - **Beam induced background runs at 1.7 MeV**: Implanted and sputtered targets vs. Ta Backing

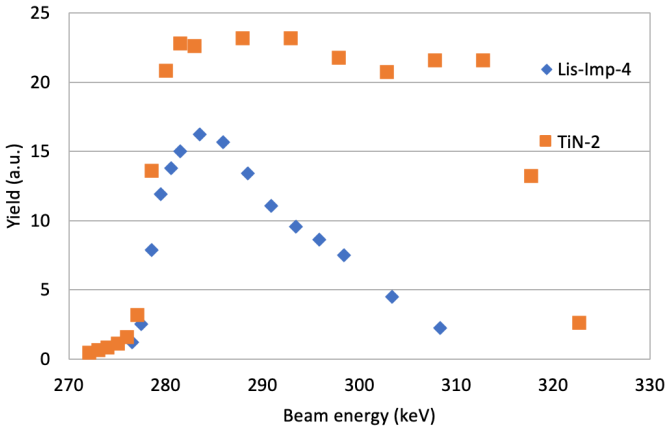




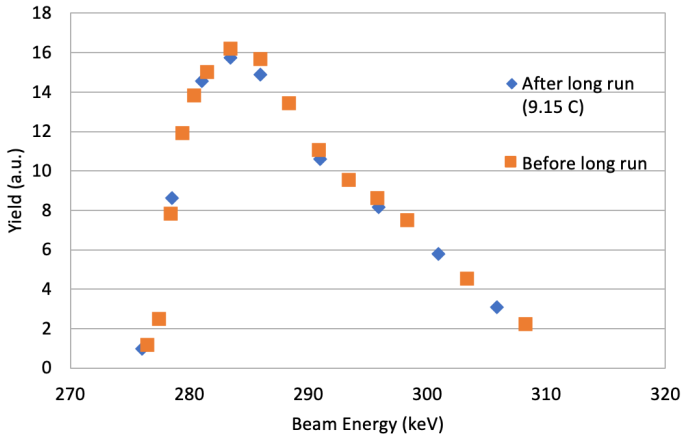
Solid Targets characterization

- Characterization campaigns performed to study target thickness, stability and beam-induced background.
- LUNA-400, LNGS, BGO Setup:
  - **278 keV ^{14}N** resonance scan
  - **340 keV ^{19}F** resonance
  - **Long Run** to test target stability

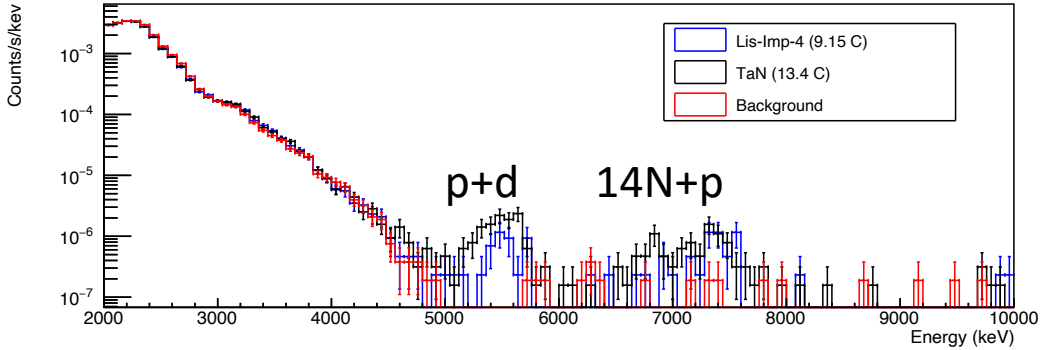
TiN and Implanted profile comparison



Implanted profile before and after irradiation



4π BGO Sum Spectrum, E_p=100 keV

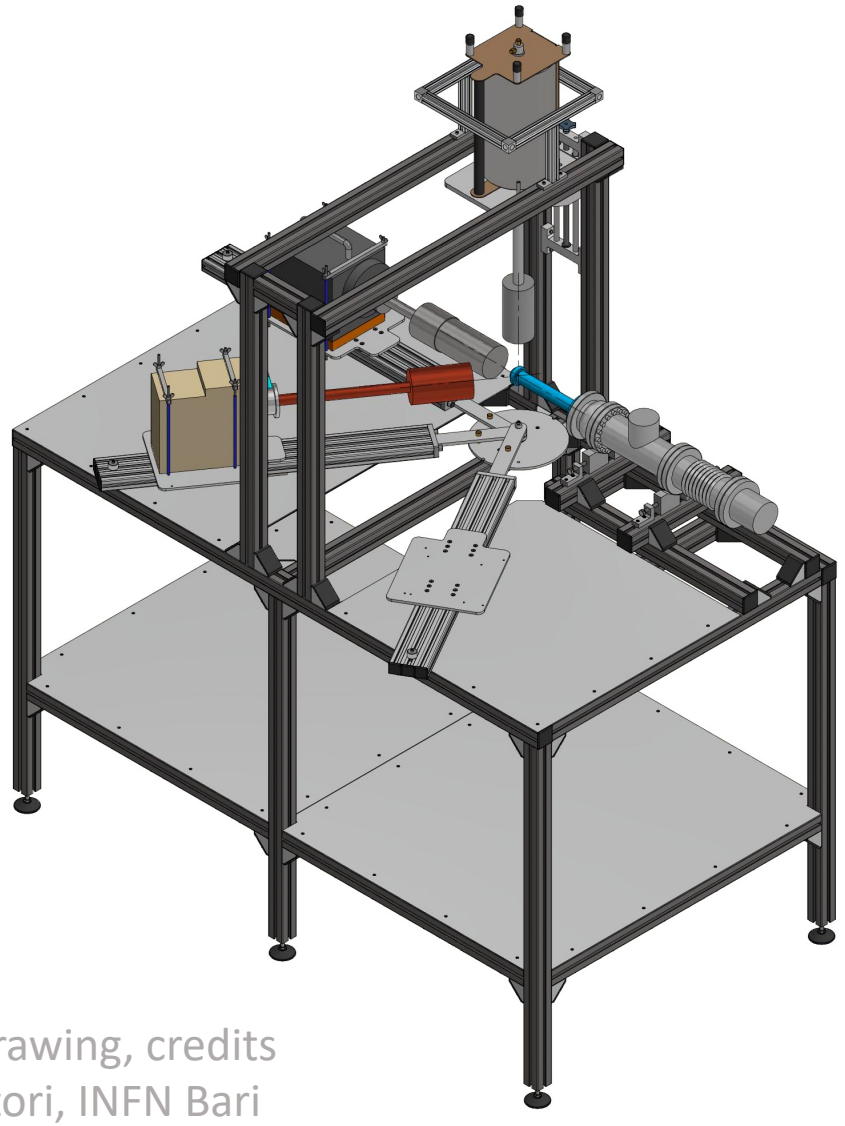


My PhD project: $^{14}N(p,\gamma)^{15}O$ measurement @ LUNA-MV

- Simulations and measurement planning
- Target production
- Target characterization
  - Atomki Tandetron
  - Luna-400
- Setup design and costruction
- Accelerator commissioning

Setup design

- The support structure for the beamline and the detectors will be designed and constructed in collaboration with Bari LNGS Mechanical Workshop



preliminary CAD drawing, credits
M.Mongelli, C.Pastori, INFN Bari

My PhD project: $^{14}N(p,\gamma)^{15}O$ measurement @ LUNA-MV

- Simulations and measurement planning
- Target production
- Target characterization
  - Atomki Tandetron
  - Luna-400
- Setup design and costruction
- Accelerator commissioning

LNGS 3.5 MV Accelerator facility: Commissioning activities

- Partecipation in the installation and characterization of the Neutron monitoring system.

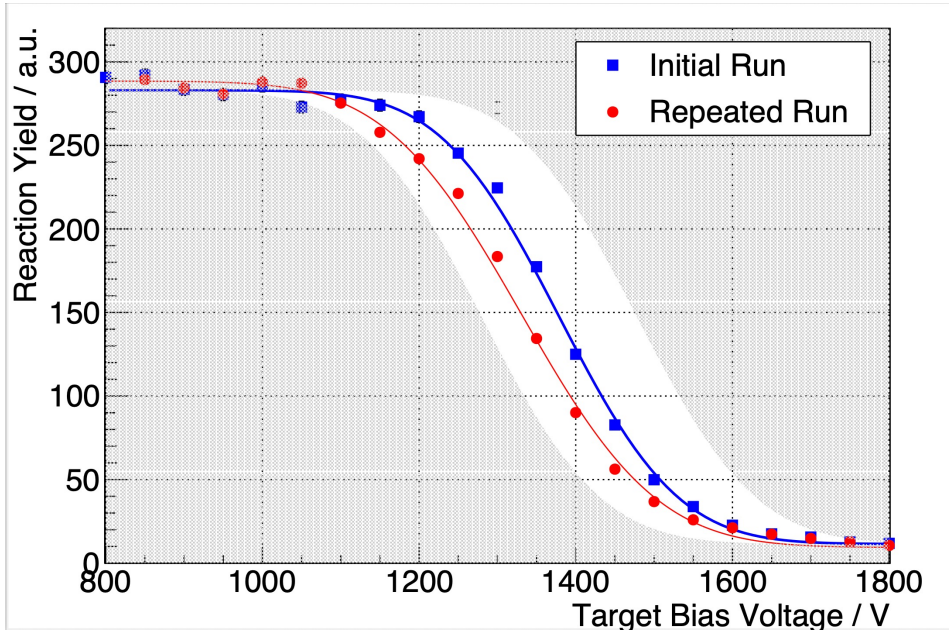
The ELSE
LUPIN
HE3-NP
GS

- Installation of HPGe detector to monitor *"hot spot"* of gamma ray production during beam tests.

- Beam line alignment.

LNGS 3.5 MV Accelerator facility: First beam tests

- Series of tests assessing system performance, beam currents, energy stability and reproducibility.
- $^{25}Mg(p,y)^{26}Al$ 390 keV resonance scan



Outlook

- With the installation phase near conclusion, the accelerator facility is expected to achieve operational readiness by early 2023, scientific commissioning and data taking will follow.
- A renewed measurement of the $^{14}N(p,\gamma)^{15}O$ will provide high-quality data over a wide energy range to address the existing issues between low energy data and higher-energy extrapolation.