Experimental challenges in Underground Nuclear Astrophysics Laboratory

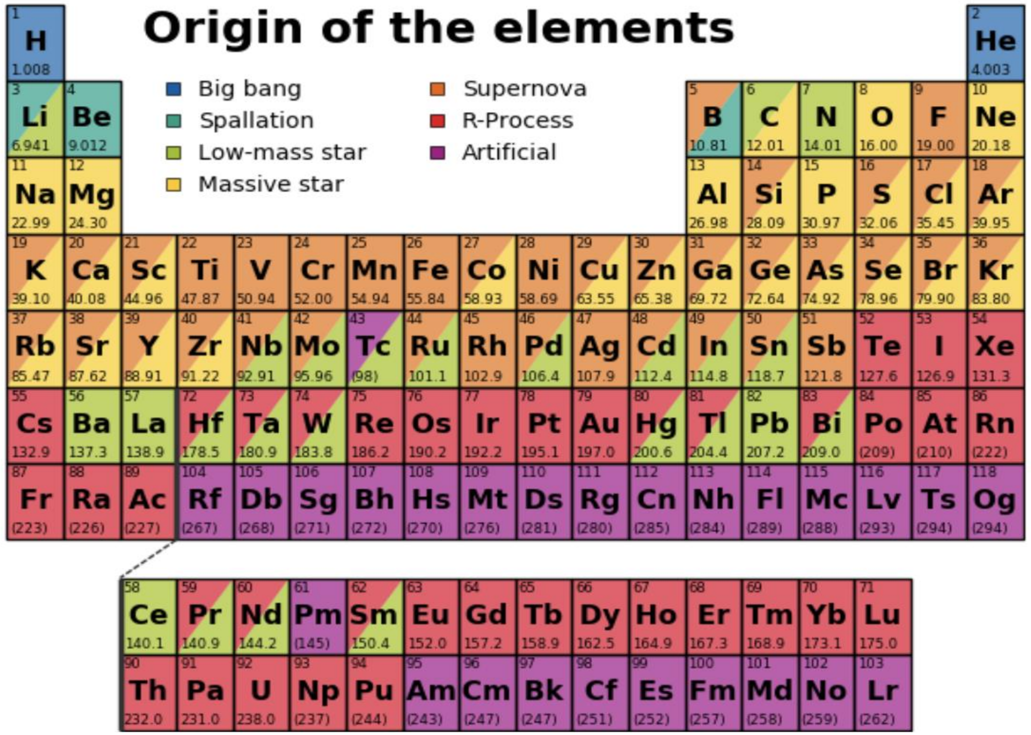
Alba Formicola
INFN Roma
On behalf of the LUNA collaboration

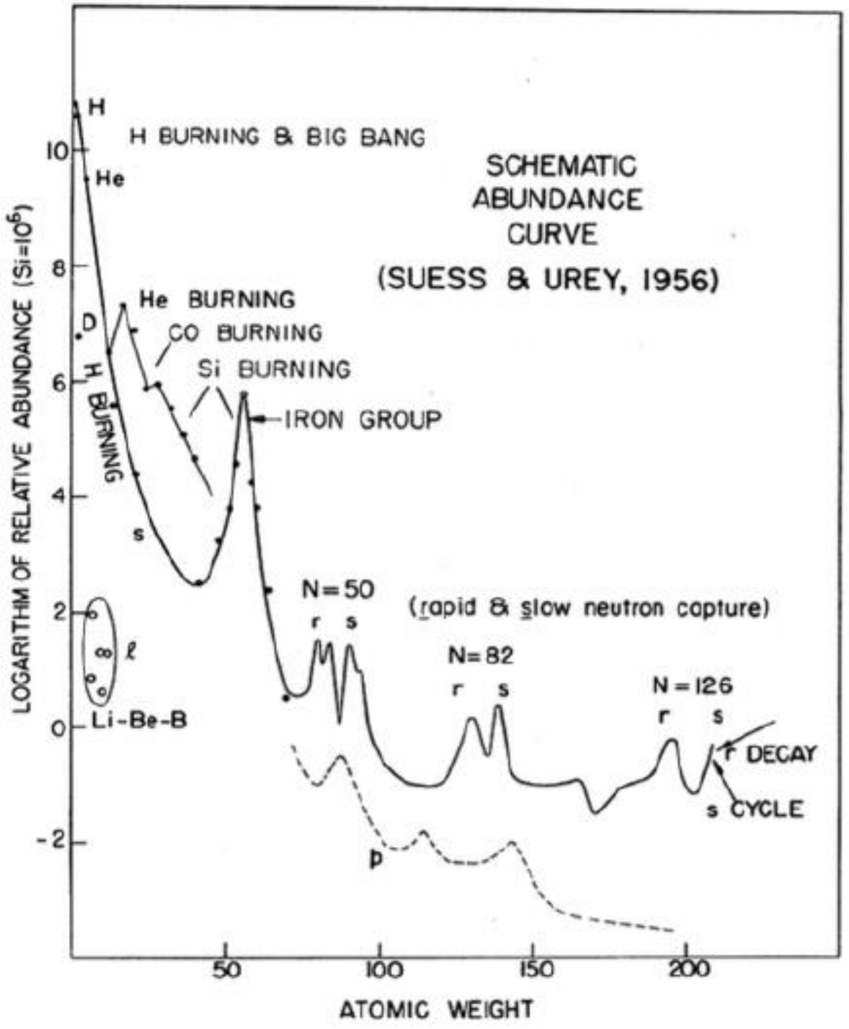
https://luna.lngs.infn.it

Layout

- Astrophysical motivations
- Introduction on direct measurements of cross section of astrophysical interest
- Why going underground
- Highlights from LUNA: - $^{14}N(p,\gamma)^{15}O$ -
- Next Scientific Projects at Luna 400kV &Bellotti Ion Beam Facility

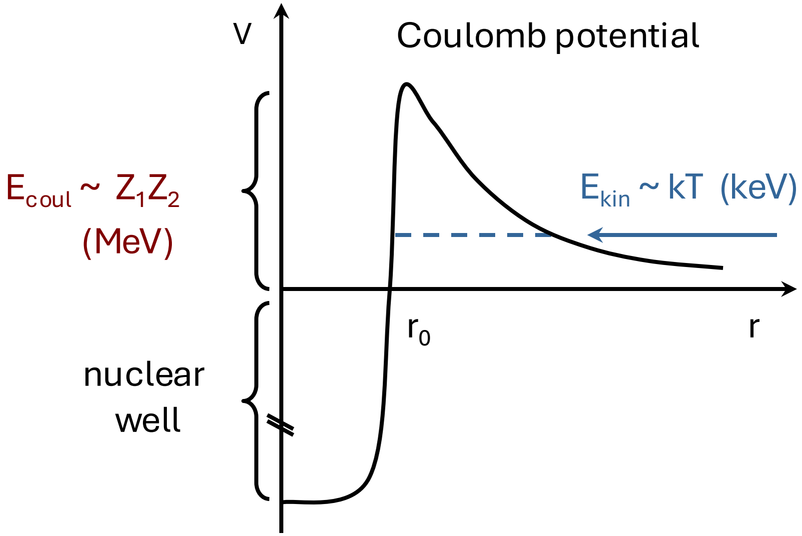
Origin and the relative abundances of the elements in the Universe





Nuclear reactions between charged particles

charged particles ➡ Coulomb barrier   energy available: from thermal motion

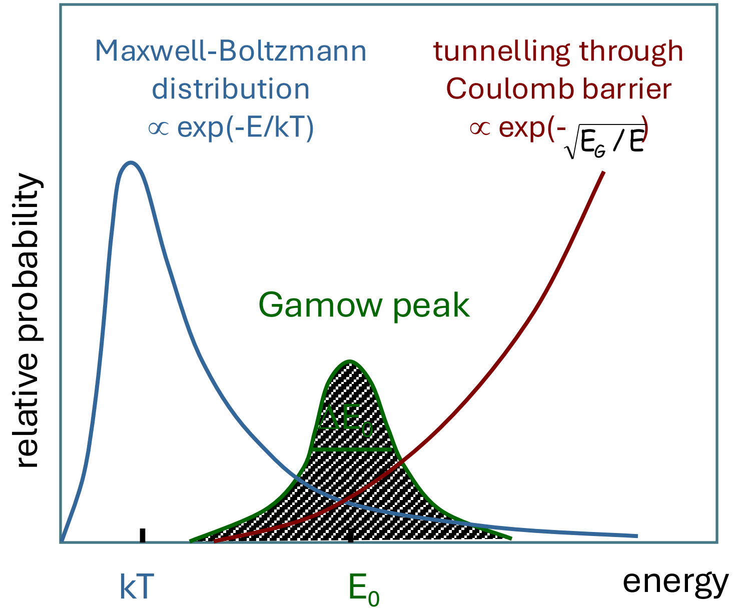


during <u>static burning</u>: $kT \ll E_{coul}$

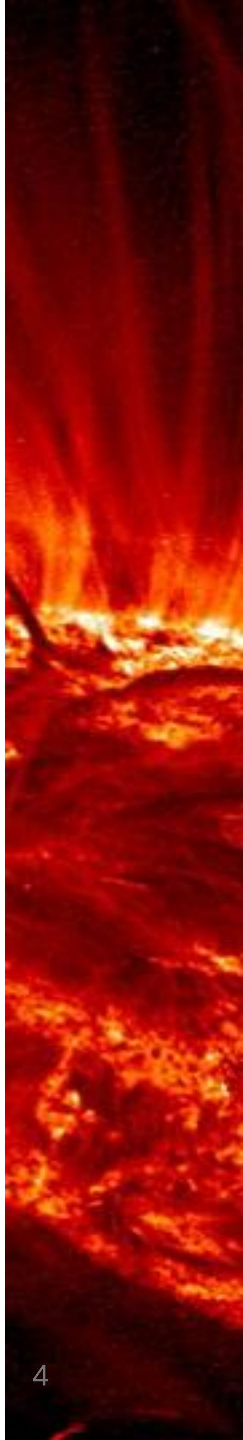
$T \sim 15\text{x}10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

reactions occur through <u>TUNNEL EFFECT</u>

tunneling probability $P \propto \exp(-2\pi\eta)$



Reaction	E_0 [keV]
p+p	6
^{3}He+^{3}He	22
^{3}He+^{4}He	23
^{7}Be+p	18
^{14}N+p	27

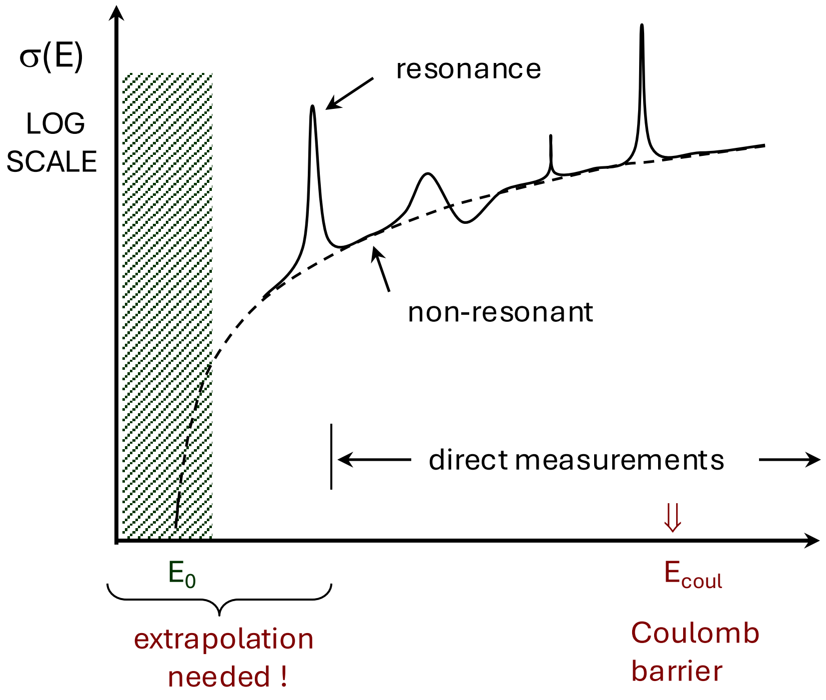


Experimental approach

measure σ(E) over as wide a range as possible, then <u>extrapolate</u> down to E_0!

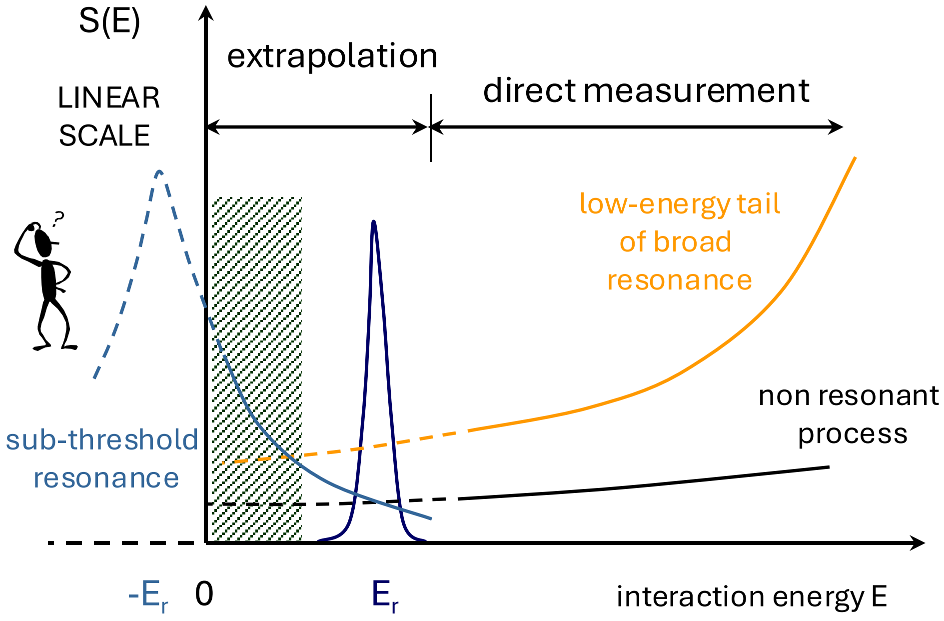
CROSS SECTION

$$\sigma(E) = \frac{1}{E}\exp(-2\pi\eta)\,S(E)$$



S-FACTOR

$$S(E) = E\sigma(E)\exp(2\pi\eta)$$



<u>DANGER OF EXTRAPOLATION !</u>

Nuclear astrophysics experiments: direct measurements

Quiescient burning (essentiallly p and α radiative capture) $E_0 \ll CB$; $s < pb$

i. direct measurments at $E=E_0$

ii. extrapolation from high energy measurements

iii. indirect methods (Coul. break-up, delayed activity transfer reactions, "trojan horses")

Imply very low background (underground lab)

Imply use of efficient and selective detection apparata

Imply comparison with direct methods and model tuning

Experimental approach

Yield = $N_{projectiles}$ x N_{target} x cross section x detection efficiency

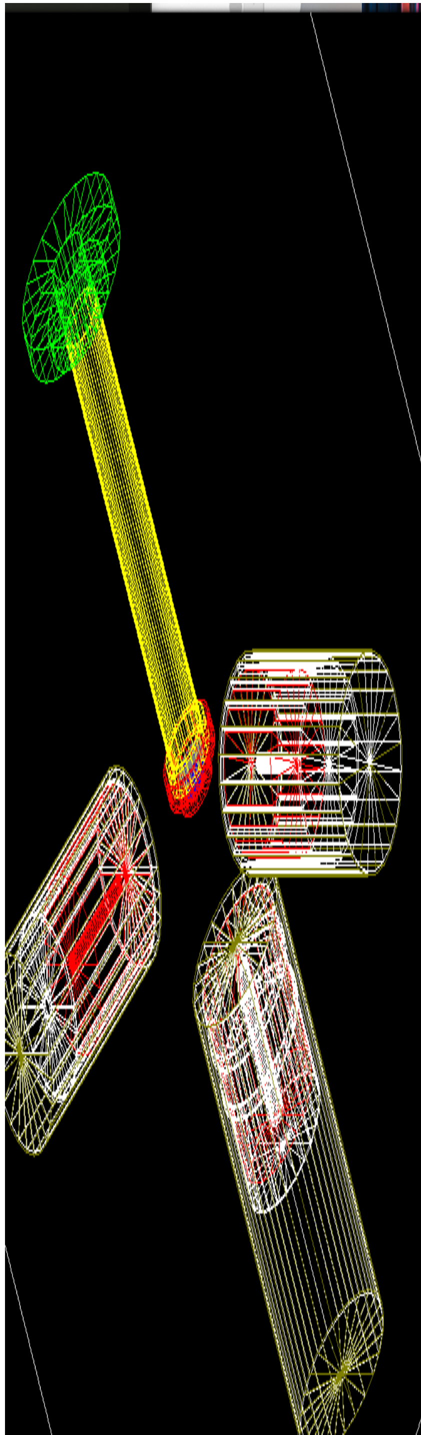
maximising the yield requires:

- improving “signal” (e.g. high beam currents, high target density, high efficiency)
- reducing “noise” (i.e. background)
- combination of both

Concurrent measurements with different techniques to minimize systematic dependencies

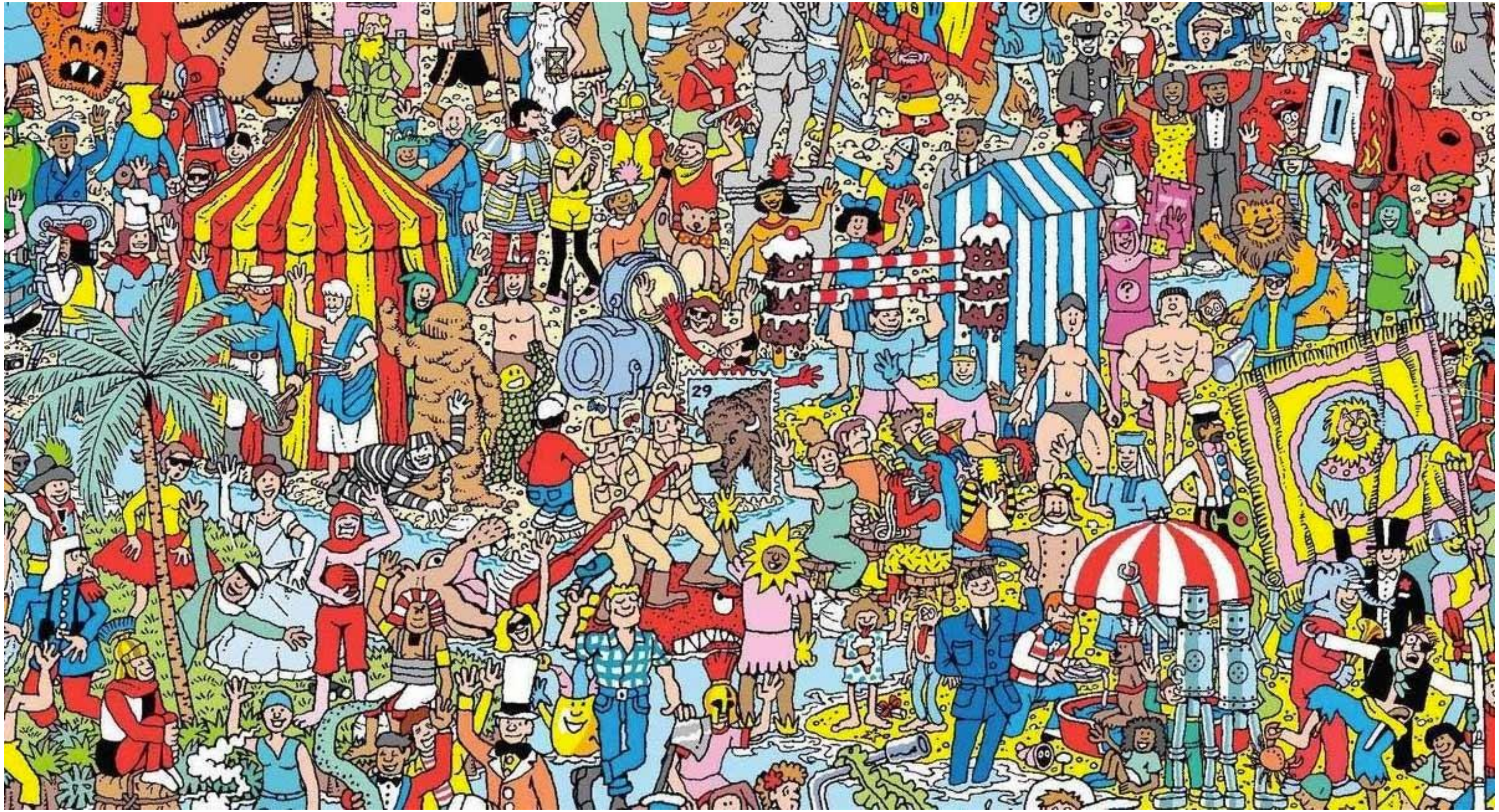
DEDICATED (UNDERGROUND) FACILITY

Counting Rate = 30-3000 counts/year= 0.1- 10 counts/day



He is Waldo…
our rare
event

WHERE IS WALDO?

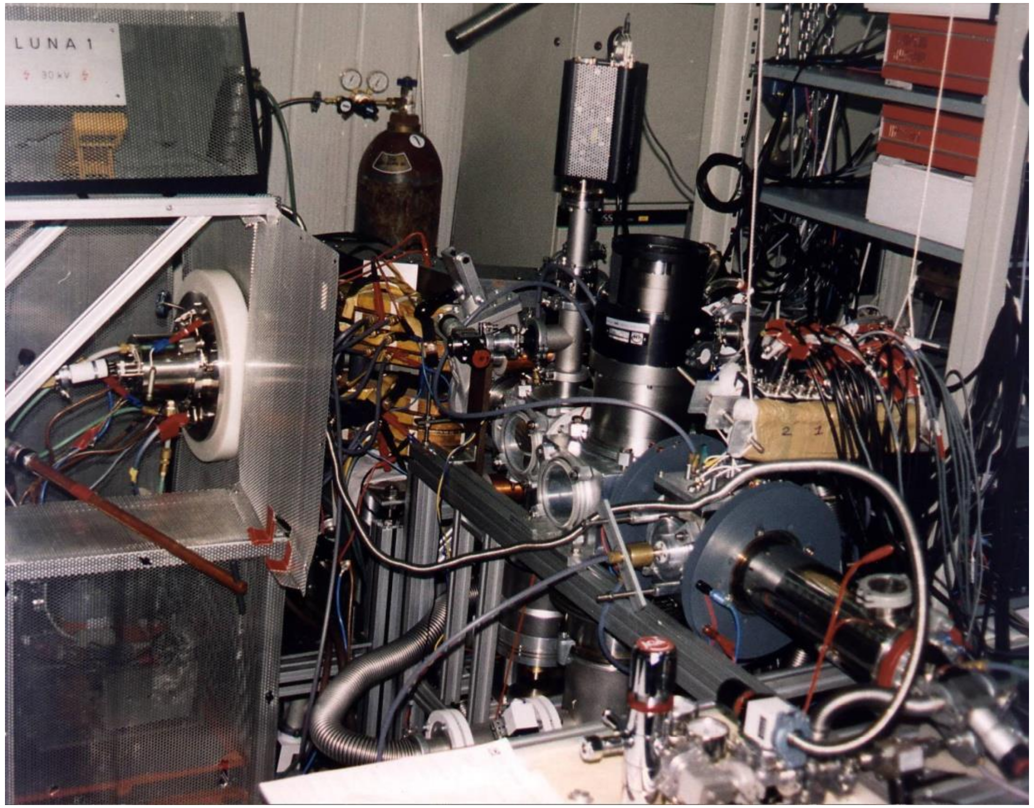


Nuclei in the Cosmos I, 1990, Baden/Vienna, Austria

Gianni Fiorentini & Claus Rolfs

Solar neutrino problem…. LUNA 50 kV

1991: Birth of Underground Nuclear Astrophysics.
Thanks to E. Bellotti, C. Rolfs and G. Fiorentini



$E_{beam} \approx 1 – 50$ keV
$I_{max} \approx 500\ \mu A$ protons, ^3He

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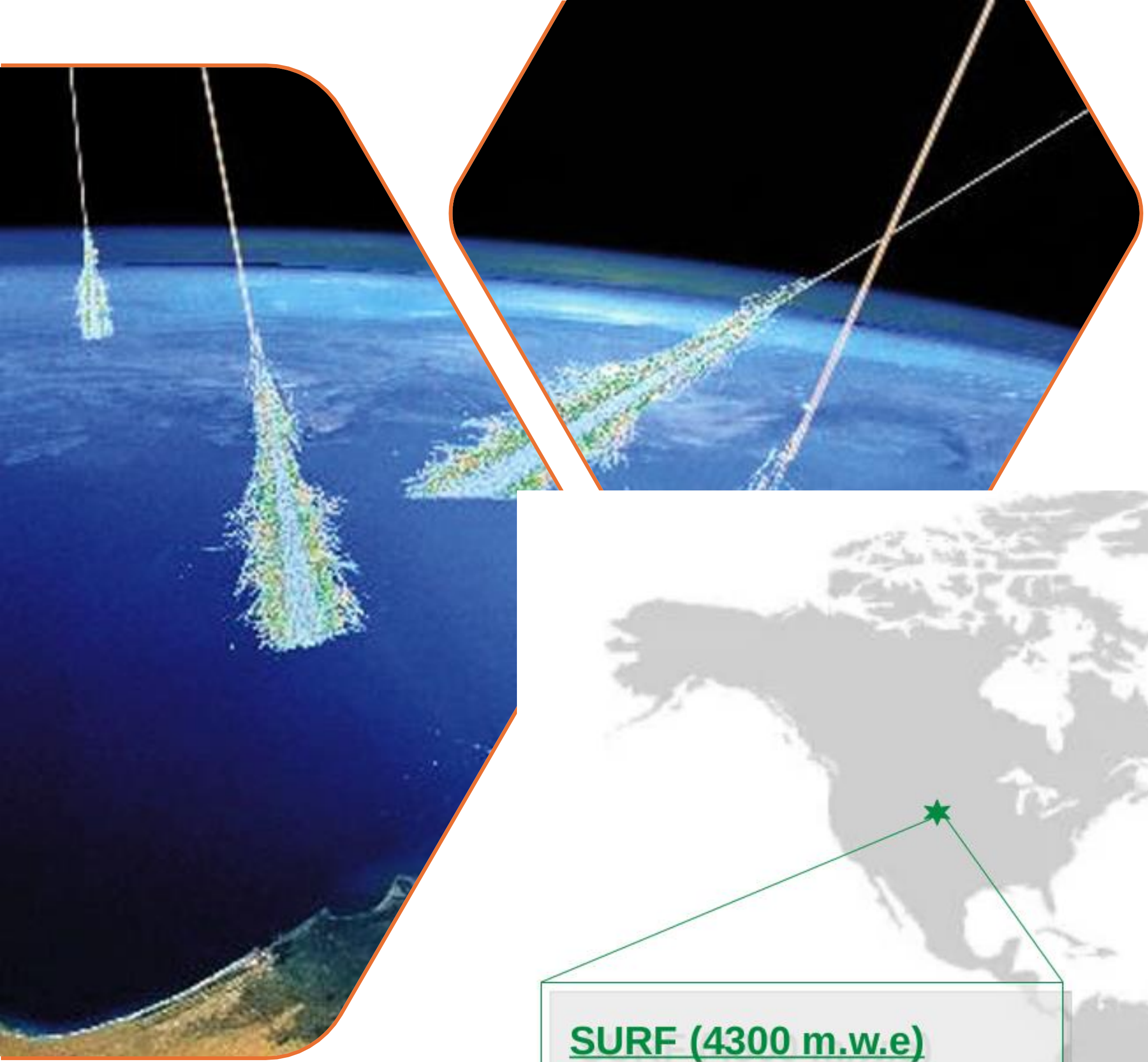
SCHOOL OF NATURAL SCIENCES   JOHN N. BAHCALL

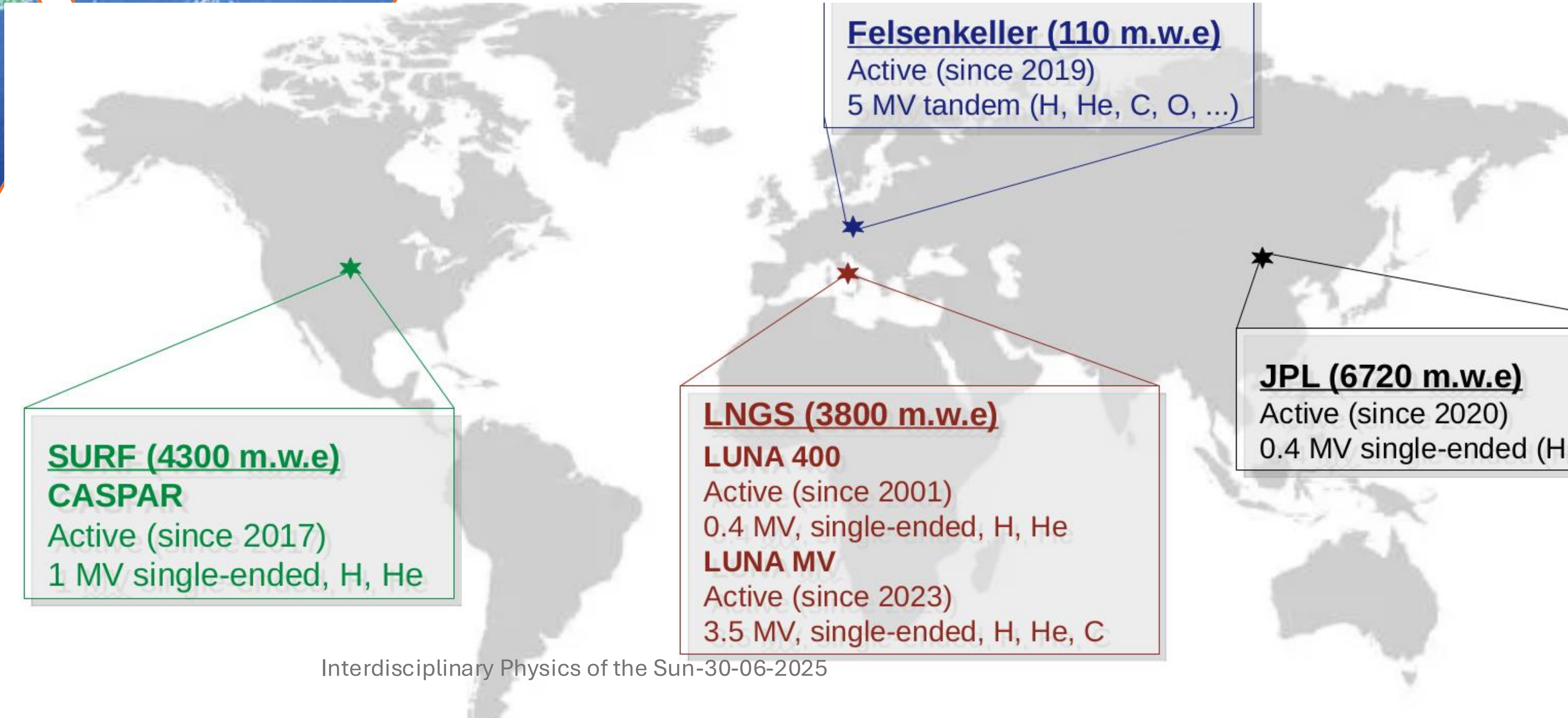
28 May 1997

Professor P. Corvisiero
Professor C. Rolfs
Spokesmen for the LUNA-Collaboration

Dear Professors Corvisiero and Rolfs:

I am writing to you about a historic opportunity of which I first became aware at the recent meeting on Solar Fusion Reactions at the Institute of Nuclear Theory, Washington University. At this meeting, I had the opportunity to see for the first time the results of the LUNA measurements of the important $3He - 3He$ reaction in a region that covers a significant part of the Gamow energy peak for solar fusion. This was a thrill that I had never believed possible. These measurements signal the most important advance in nuclear astrophysics in three decades.

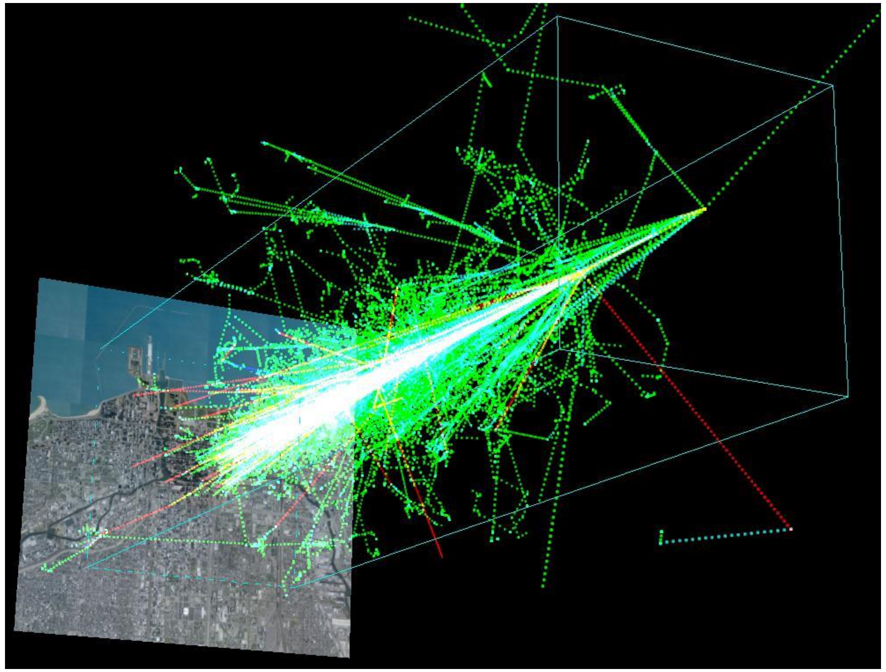




Felsenkeller (110 m.w.e)
Active (since 2019)
5 MV tandem (H, He, C, O, ...)
SURF (4300 m.w.e)
CASPAR
Active (since 2017)
1 MV single-ended, H, He
LNGS (3800 m.w.e)
LUNA 400
Active (since 2001)
0.4 MV, single-ended, H, He
LUNA MV
Active (since 2023)
3.5 MV, single-ended, H, He, C
JPL (6720 m.w.e)
Active (since 2020)
0.4 MV single-ended (H

Background sources

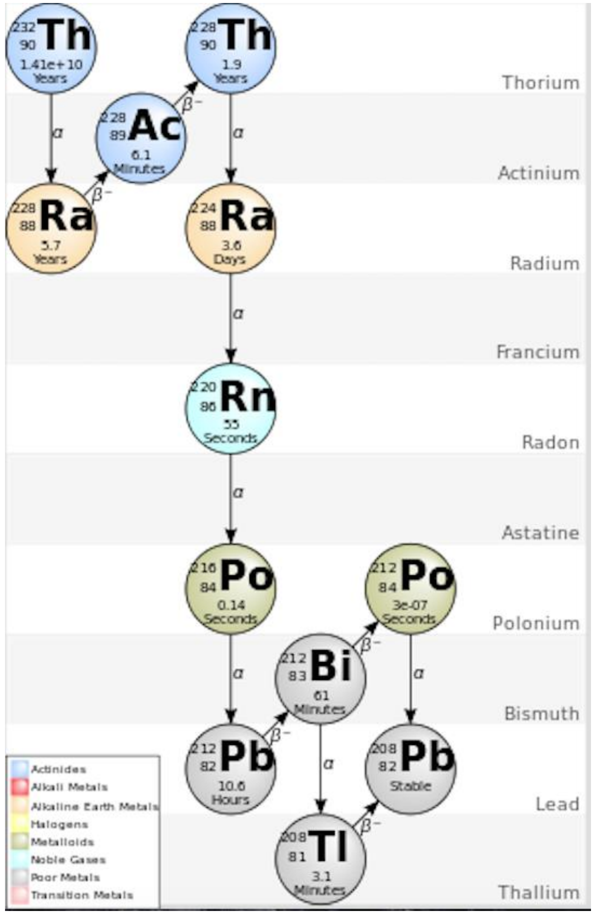
Cosmic rays



http://astro.uchicago.edu/cosmus/projects/aires/

Primary cosmic rays: mostly protons
Create showers of secondary particles
in atmosphere
in the end muons and neutrons reach surface

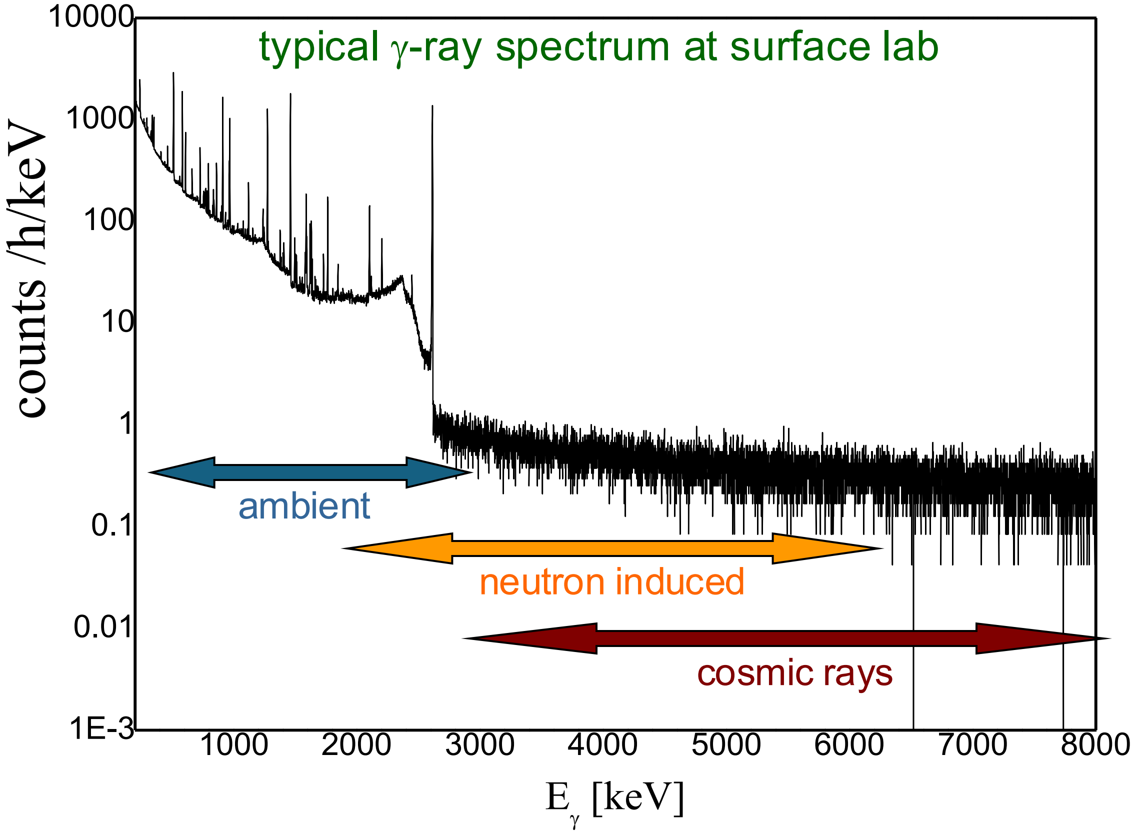
Natural radioactivity

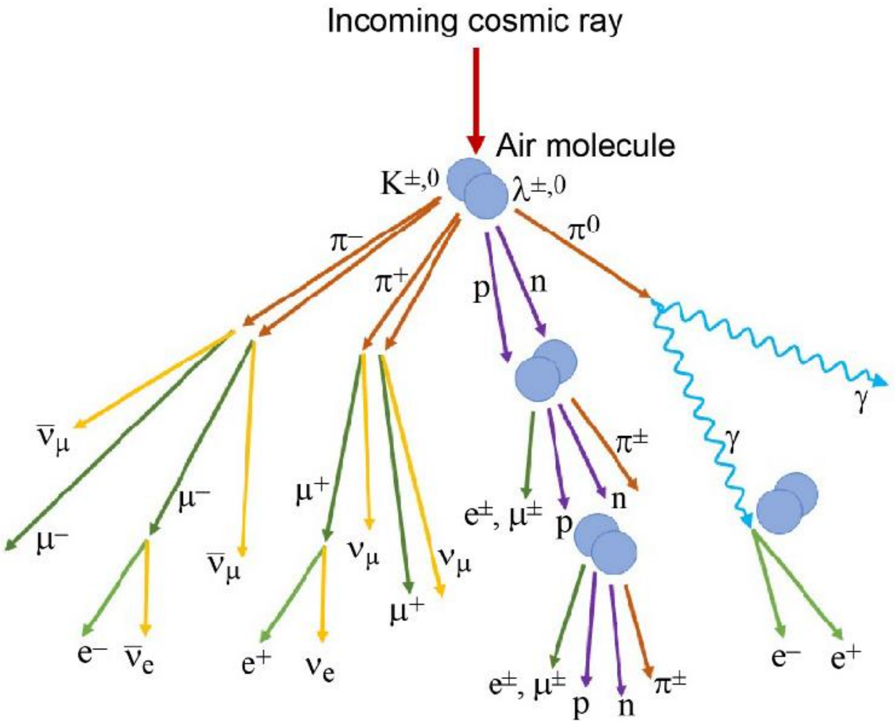


Natural decay chains: Thorium, Uranium series
Potassium-40
Radon (from decay chains): gaseous
Impact mostly gamma-ray measurements

Main Sources of Background

- natural radioactivity (from U and Th chains ar
- cosmic rays
- neutrons from (a,n) reactions and fission

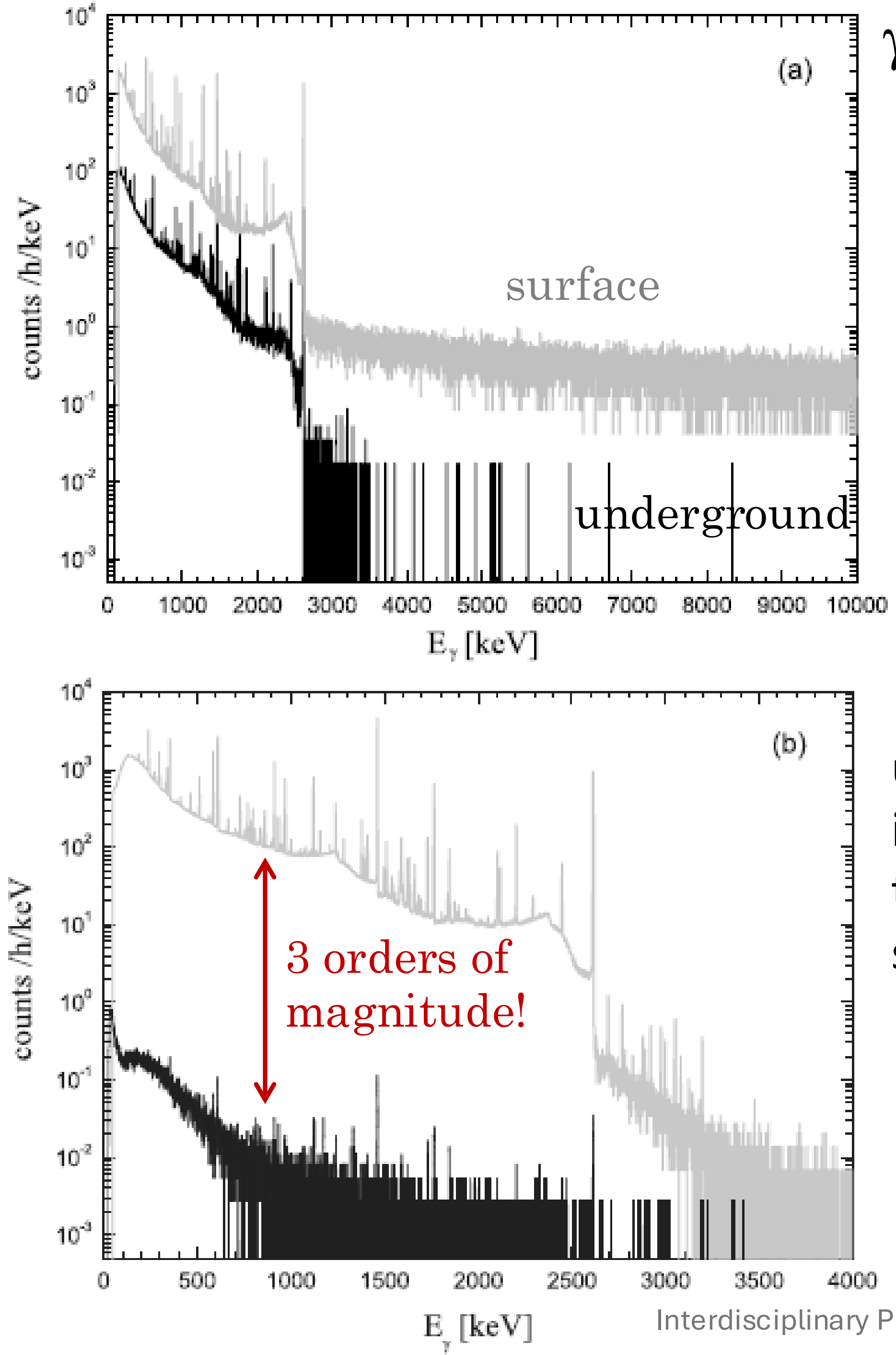




Background reduction by:

- 6 orders of magnitude for muons
- 3 orders of magnitude for neutrons

γ-ray natural background

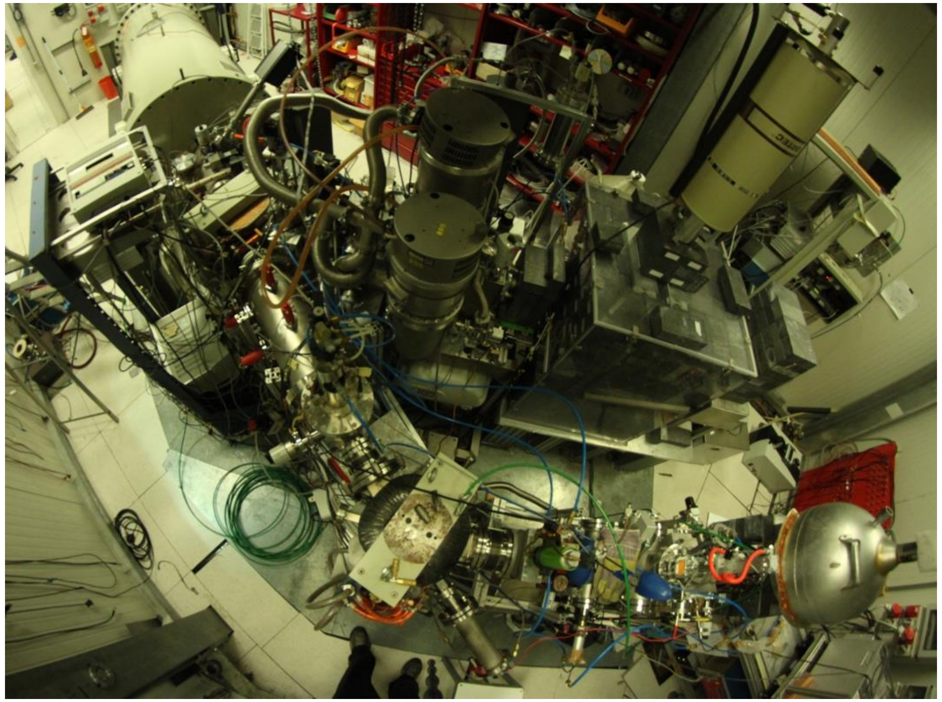


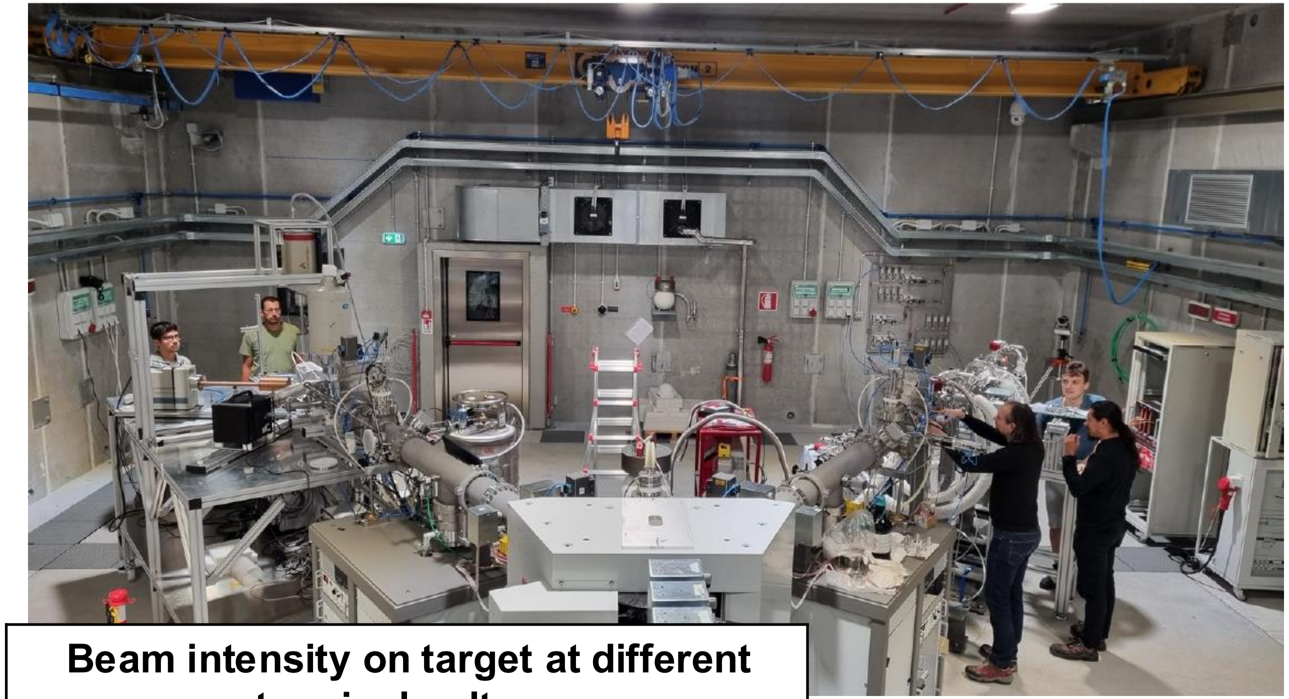
between E_g =7 and 12MeV the bck suppression factor is 100 times better than was achieved in laboratories using active shielding

underground passive shielding is more effective since μ flux, that create secondary γ's in the shield, is suppressed

0.3 m^3 Pb-Cu shield suppression three orders of magnitude below 2MeV

LUNA-400 and Ion Bellotti Facility at LNGS





Courtesy M.Junker

Ion species	Terminal Voltage (keV)	Beam Intensity (μA)
$^{1}H^{+}$	50-400	250
$^{4}He^{+}$	50-400	250

Beam intensity on target at different terminal voltage		
Ion specie	Terminal Voltage	
	0.3 MV – 0.5 MV	0.5 MV - 3.5 MV
$^{1}H^{+}$	500 μA	1000 μA
$^{4}He^{+}$	300 μA	500 μA
$^{12}C^{+}$	100 μA	150 μA
$^{12}C^{+2}$	60 μA	100 μA
Number of beam lines		2
Terminal Voltage range		0.3 – 3.5 MV

Activities at LUNA 400kV accelerator

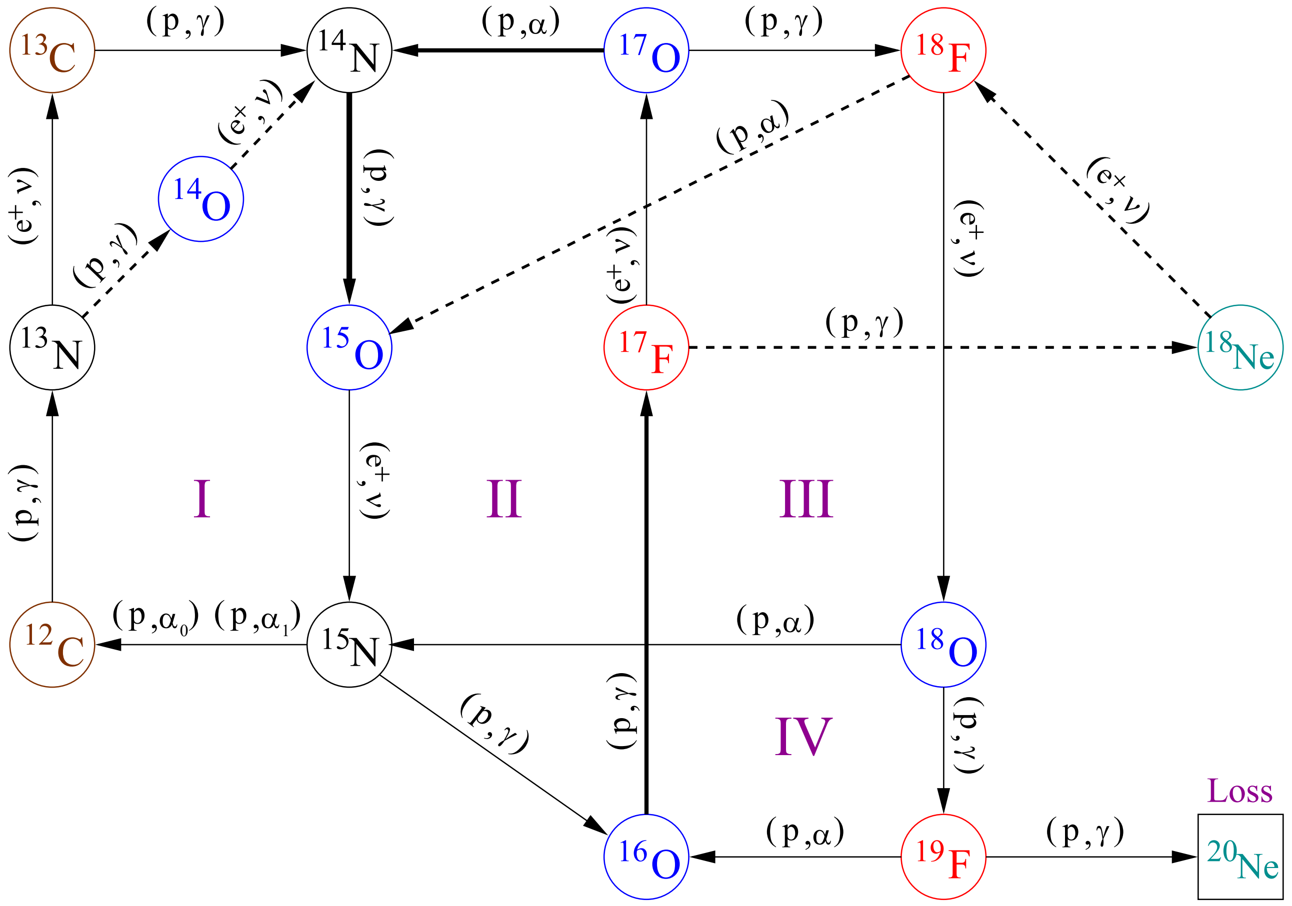
Reaction	Data acquisition	Target and Detectors
$^{16}O(p,\gamma)^{17}F$	Completed 03/2023	Solid target, BGO, HPGe + 2 CeBr
$^{21}Ne(p,\gamma)^{22}Na$	Completed 10/2023	Gas Target and 2 HPGe
$^{14}N(p,\gamma)^{15}O$	Completed 02/2025	Solid Target and BGO
$^{23}Na(p,\alpha)^{20}Ne$	Started 10/2023	Solid Target and 6 Silicons
$^{19}F(p,\gamma)^{20}Ne$	Started 02/2025	Solid target and BGO detector
$^{24}Mg(p,\gamma)^{25}Al$	Started 02/2025	Solid target and BGO detector

see Eliana Masha's talk for further details 01/07

see Gianluca Imbriani 's talk for further details 01/07

Hydrostatic Hydrogen Burning

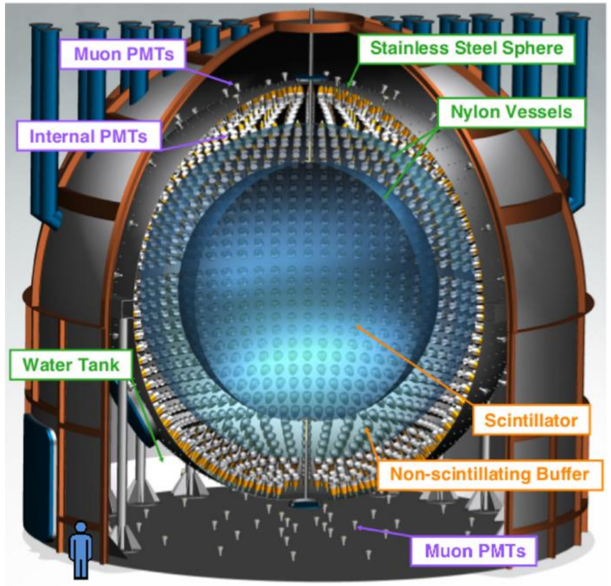
Sun (T=15.6 MK), stellar core (T=8-55 MK),
shell of AGB stars (T=45-100 MK)



- 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,γ)^{15}O is the **slowest reaction of the CNO**, controls its speed and energy production rate.

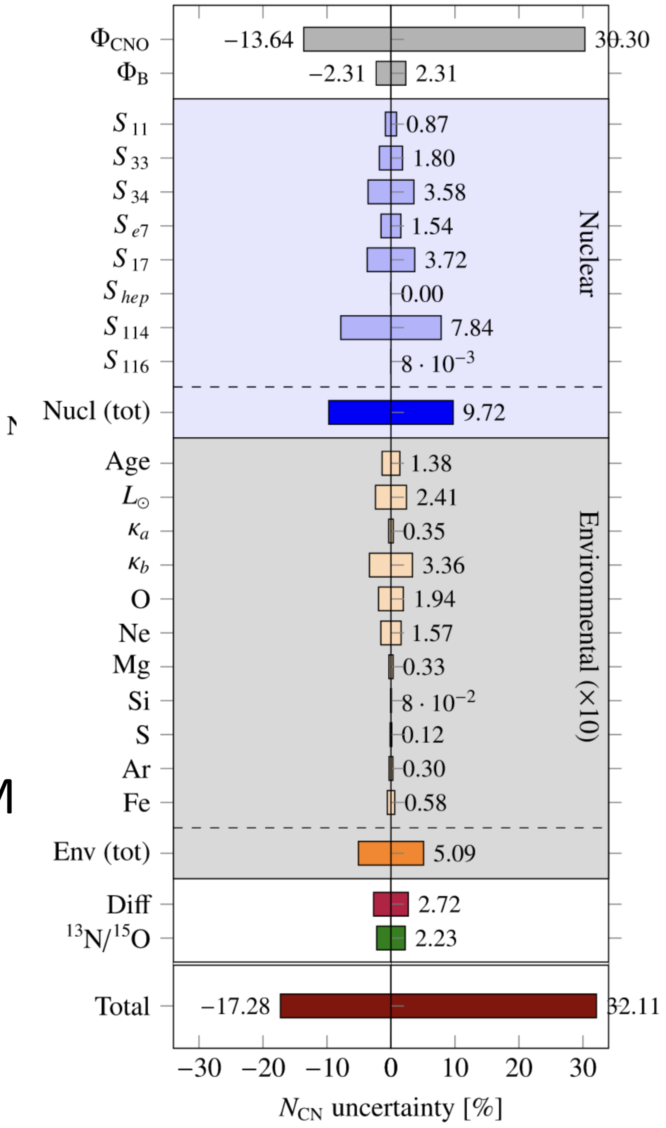
To Solve Solar Neutrino puzzle...S_{14}(E) Factor



Basilico et al. PRD (2023)

Solar CNO neutrino flux recently detected for the first time by Borexino (2020). → **Solar metallicity probe.**

The result of Borexino, using the information of directional Cherenkov light in large-scale liquid scintillator detectors disfavours "low metallicity" SSM prediction, **but large uncertainties** remains.



Appel, S. et al. (2022) PRL

$$\phi(^{13}N) \propto S_{11}^{-2.53}\ S_{33}^{0.02}\ S_{34}^{-0.05}\ S_{1,14}^{0.85}\ L_\odot^{5.16}\ R_\odot^{0.28}\ (Z/X)^{1.86}\ (age)^{1.01}$$

$$\phi(^{15}O) \propto S_{11}^{-2.93}\ S_{33}^{0.02}\ S_{34}^{-0.05}\ S_{1,14}^{1,00}\ L_\odot^{5.94}\ R_\odot^{0.49}\ (Z/X)^{2.03}\ (age)^{1.27}$$

The $^{14}N(p,\gamma)^{15}O$ reaction: Bottleneck of the CNO cycle

Cross section never measured directly at solar energies (~15 keV).

Astrophysicists rely on extrapolations that are still highly uncertain

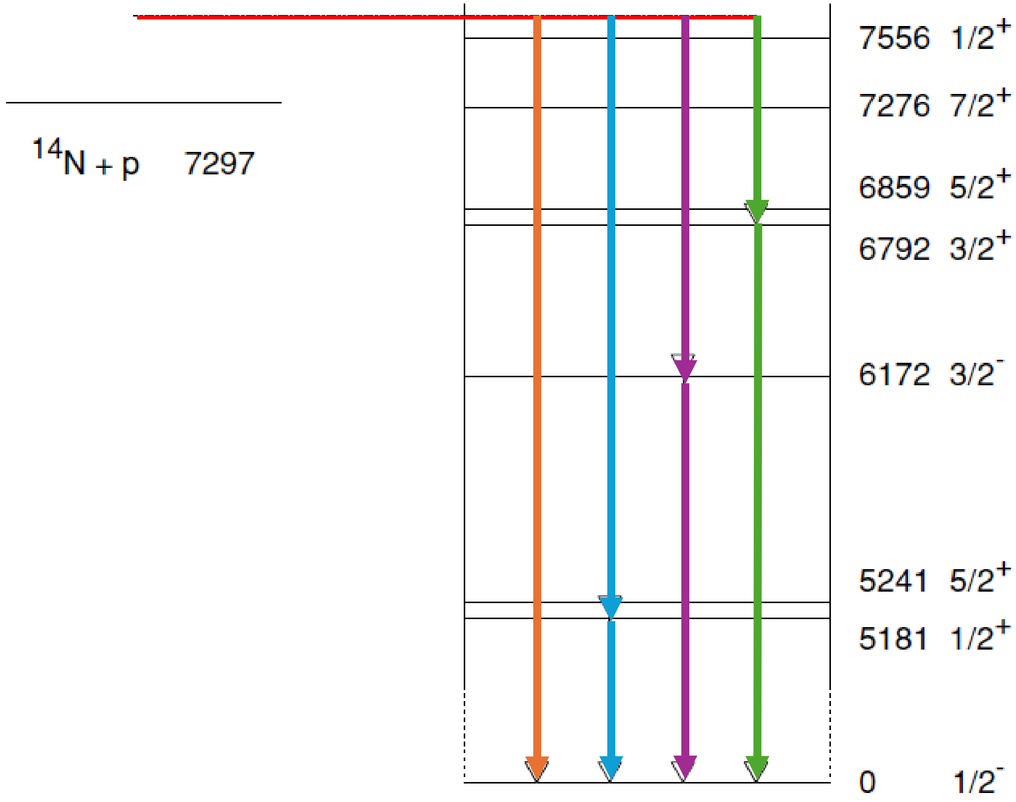


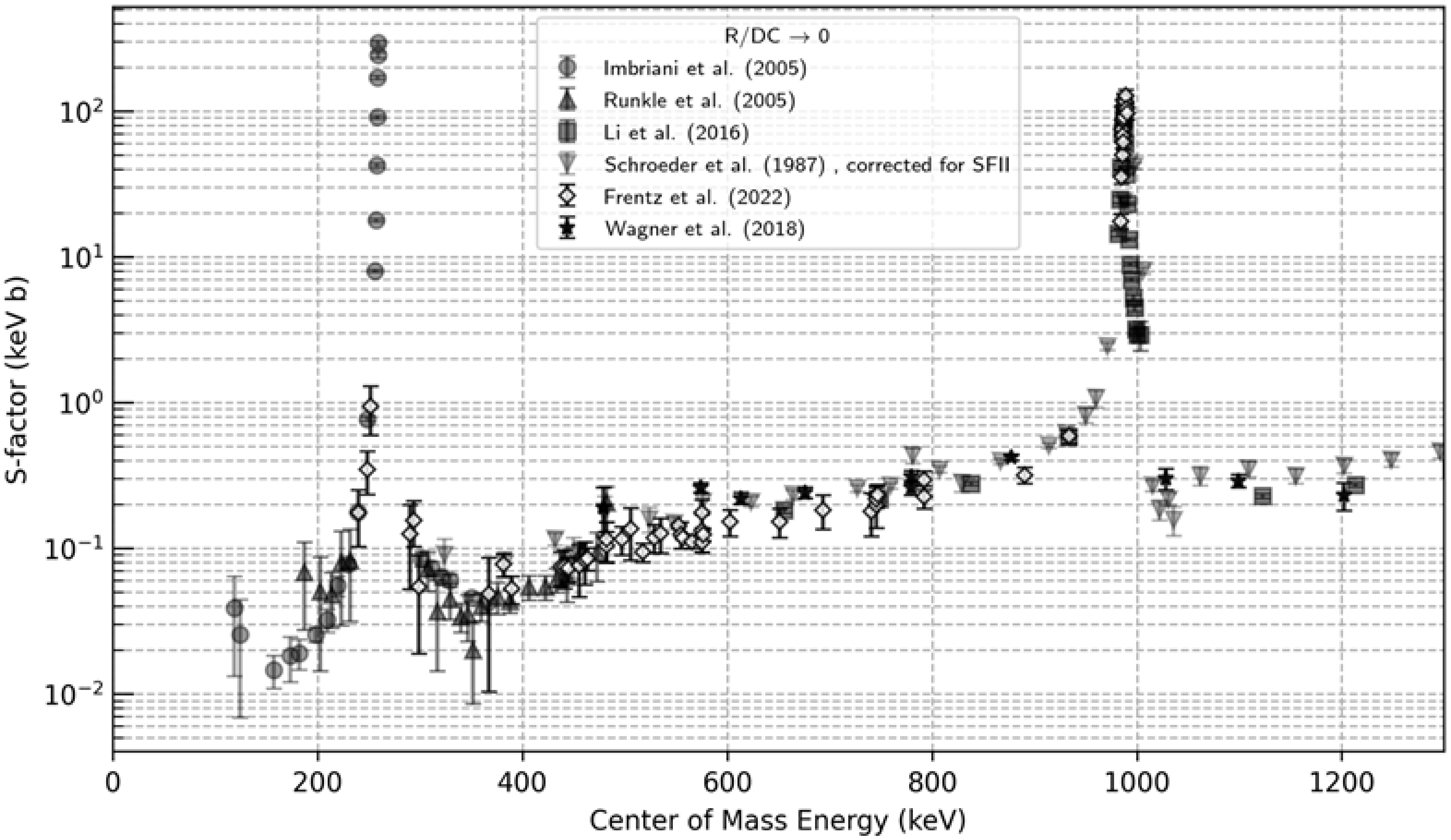
TABLE IX $S_{1\,14}(0)$ as the sum of the different transitions.

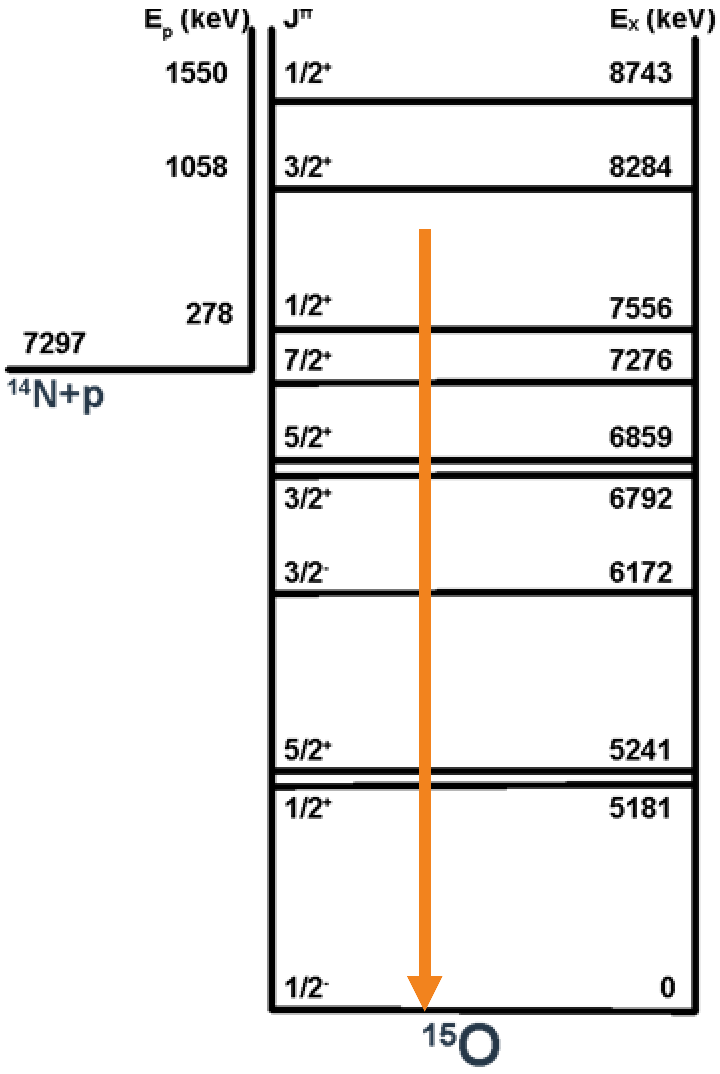
Transition	$S_{1\,14}(0)$ (keV b)	$\Delta S_{114}(0)$	Reference
tr $\to$ 0	0.30 ± 0.11	37%	Present
tr $\to$ 6.79	1.17 ± 0.03	2.9%	Present
tr $\to$ 6.17	0.13 ± 0.05	38%	SF II
tr $\to$ 5.18	0.010 ± 0.003	30%	SF II
tr(5.24) $\to$ 0	0.068 ± 0.020	30%	SF II
R-matrix sum	1.68 ± 0.13	7.6%	
Additional syst. uncert.		3.5%	
Total	1.68 ± 0.14	8.4%	

Taken from Solar Fusion III arXiv:2405.06470v1 (2024)

see Alessandra Gugliemetti's talk for further details 02/07

Open issues with $^{14}N(p,\gamma)^{15}O$



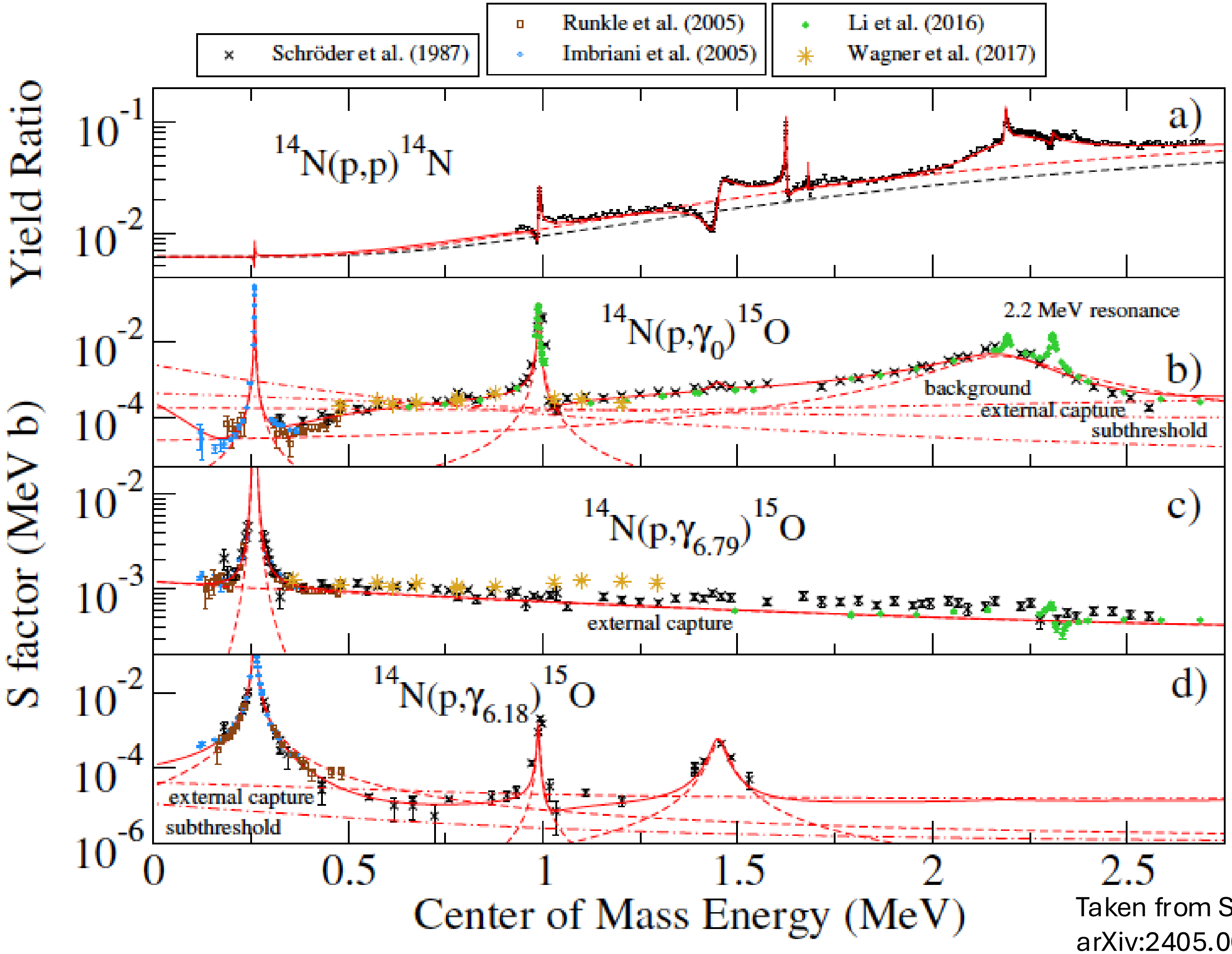


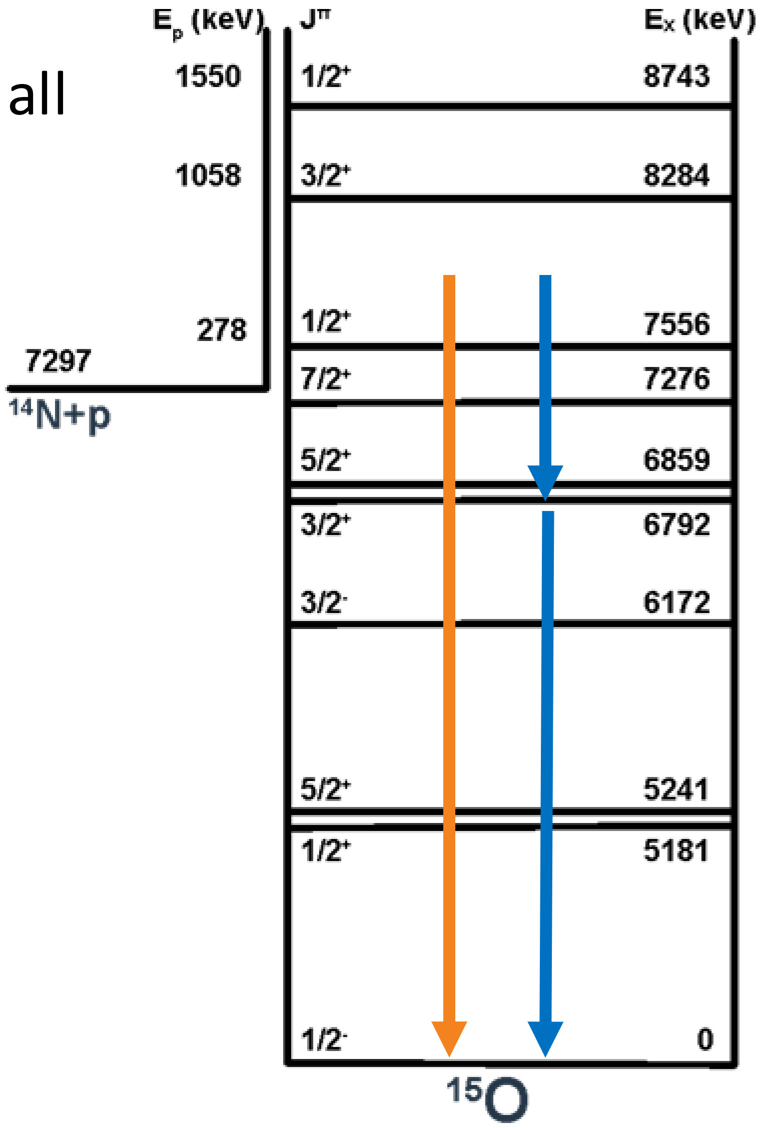
Level scheme for ^{15}O

Transition to the **ground state** of ^{15}O: Very difficult to reconcile all the measurements in a consistent picture.

Open Issues with the $^{14}N(p,\gamma)^{15}O$ reaction

Transition to the ground state of ^{15}O: very difficult to reconcile all the measurements in a consistent picture





Level scheme for ^{15}O

Taken from Solar Fusion III
arXiv:2405.06470v2 [astro-ph.SR] 27 Nov 2024

Open issues with $^{14}N(p,\gamma)^{15}O$

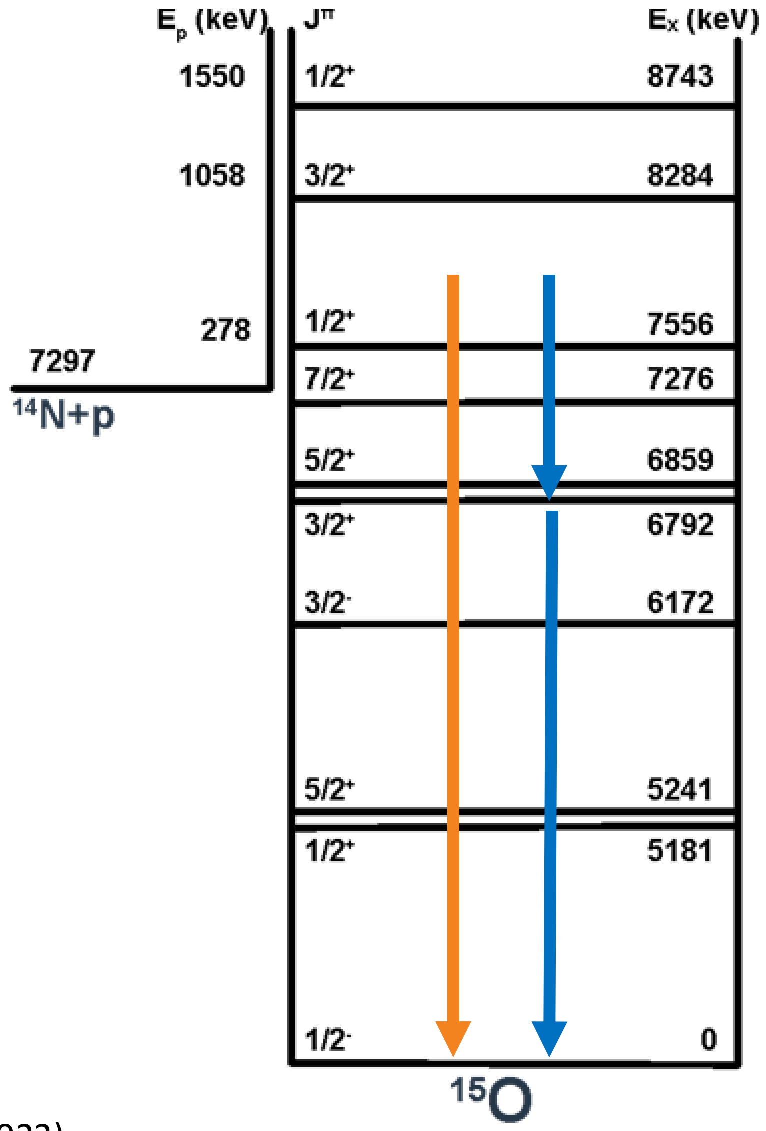
The transition to the **6.79 MeV** excited state of ^{15}O and to the **ground state** are fairly well know but effected to problems with their extrapolations at low energies

TABLE I. A summary of zero energy S factors for the $^{14}N(p,\gamma)^{15}O$ reaction.

Year	Reference	Astrophysical S factor $S(0)$ (keV b) R/DC → 0.00	R/DC → 6.792	R/DC → 6.172	Others[d]	Total
1987	Schröder *et al.* [9]	1.55 ± 0.34	1.41 ± 0.02	0.14 ± 0.05	0.1	3.20 ± 0.54
2001	Angulo *et al.*[a] [10]	$0.08^{+0.13}_{-0.06}$	1.63 ± 0.17	$0.06^{+0.01}_{-0.02}$	−−	1.77 ± 0.20
2003	Mukhamedzhanov *et al.* [16]	0.15 ± 0.07	1.40 ± 0.20	0.133 ± 0.02	0.02	1.70 ± 0.22
2004	Formicola *et al.* [17]	0.25 ± 0.06	1.35 ± 0.05 (stat) ± 0.08 (sys)	$0.06^{+0.01}_{-0.02}$[b]	0.04	1.7 ± 0.1 (stat) ± 0.02 (sys)
2005	Imbriani *et al.* [11]	0.25 ± 0.06	1.21 ± 0.05	0.08 ± 0.03	0.07	1.61 ± 0.08
2005	Runkle *et al.* [15]	0.49 ± 0.08	1.15 ± 0.05	0.04 ± 0.01	−−	1.68 ± 0.09
2005	Angulo *et al.* [18]	0.25 ± 0.08	1.35 ± 0.04	0.06 ± 0.02	0.04	1.70 ± 0.07 (stat) ± 0.10 (sys)
2006	Bemmerer *et al.* [13]	−−	−−	−−	−−	1.74 ± 0.14 (stat) ± 0.14 (sys)[c]
2008	Marta *et al.* [14]	0.20 ± 0.05	−−	0.09 ± 0.07	−−	1.57 ± 0.13
2010	Azuma *et al.* [19]	0.28	1.3	0.12	0.11	1.81
2011	Adelberger *et al.* [3]	0.27 ± 0.05	1.18 ± 0.05	0.13 ± 0.06	0.08	1.66 ± 0.08
2016	Li *et al.* [20]	0.42 ± 0.04 (stat) $^{+0.09}_{-0.19}$ (sys)	1.29 ± 0.06 (stat) ± 0.06 (sys)	−−	−−	−−
2018	Wagner *et al.* [21]	0.19 ± 0.01 (stat) ± 0.05 (sys)	1.24 ± 0.02 (stat) ± 0.11 (sys)	−−	−−	−−
2022	This work	$0.33^{+0.16}_{-0.08}$	1.24 ± 0.09	0.12 ± 0.04	−−	1.69 ± 0.13

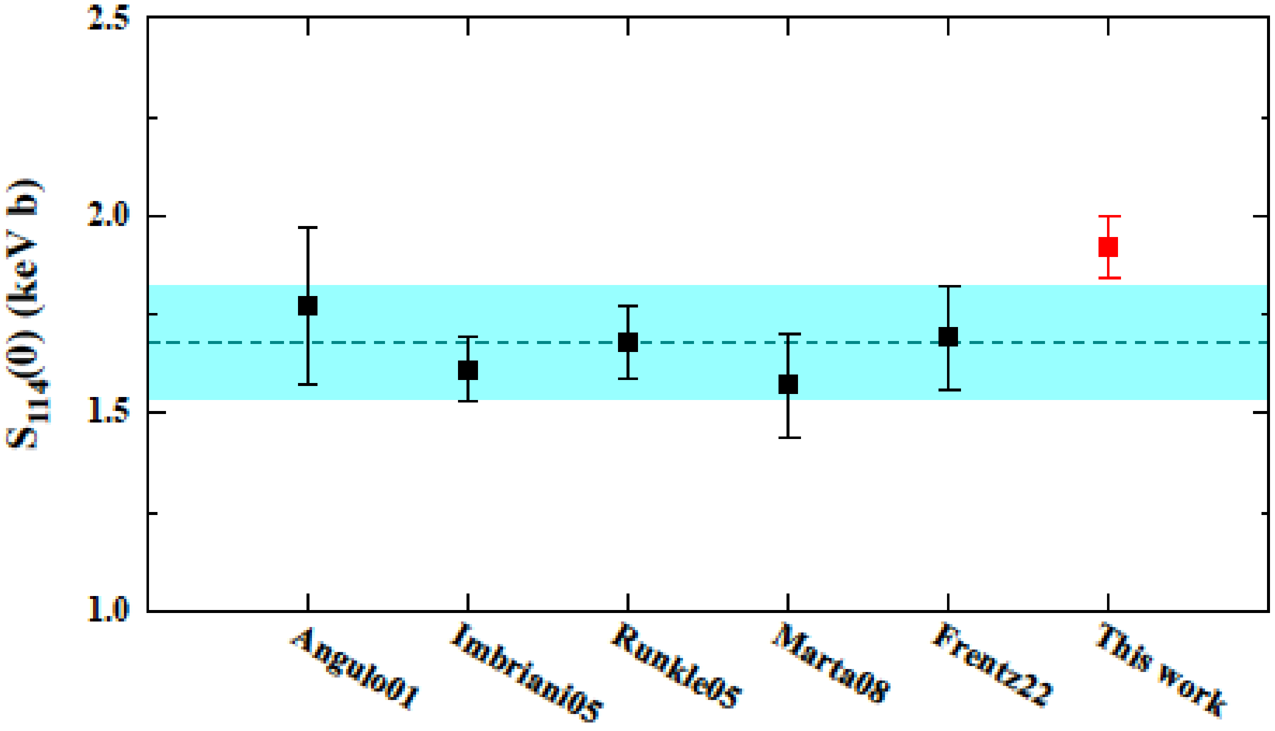
[a] R-matrix analysis on available data, not a measurement.
[b] Adopted from Angulo and Descouvemont [10].
[c] Measured S factor at 70 keV.

Taken from Frentz et al (2022)



Level scheme for ^{15}O

Open issues with $^{14}N(p,\gamma)^{15}O$



The cyan shaded area denotes the range of the value recommended in SF-III at 1 σ C.L.

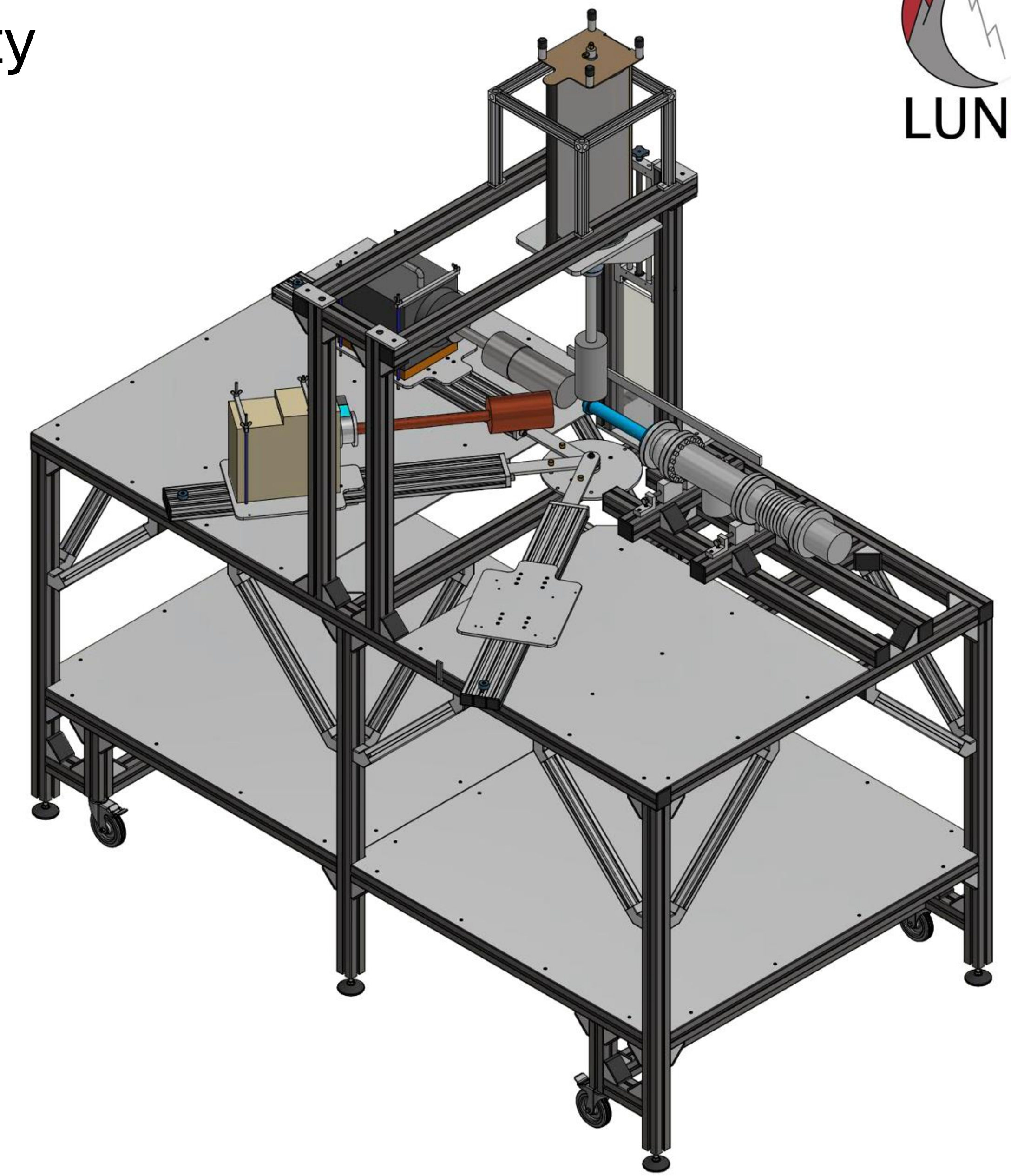
adopted by Chen et al. 2024

https://doi.org/10.48550/arXiv.2410.16086

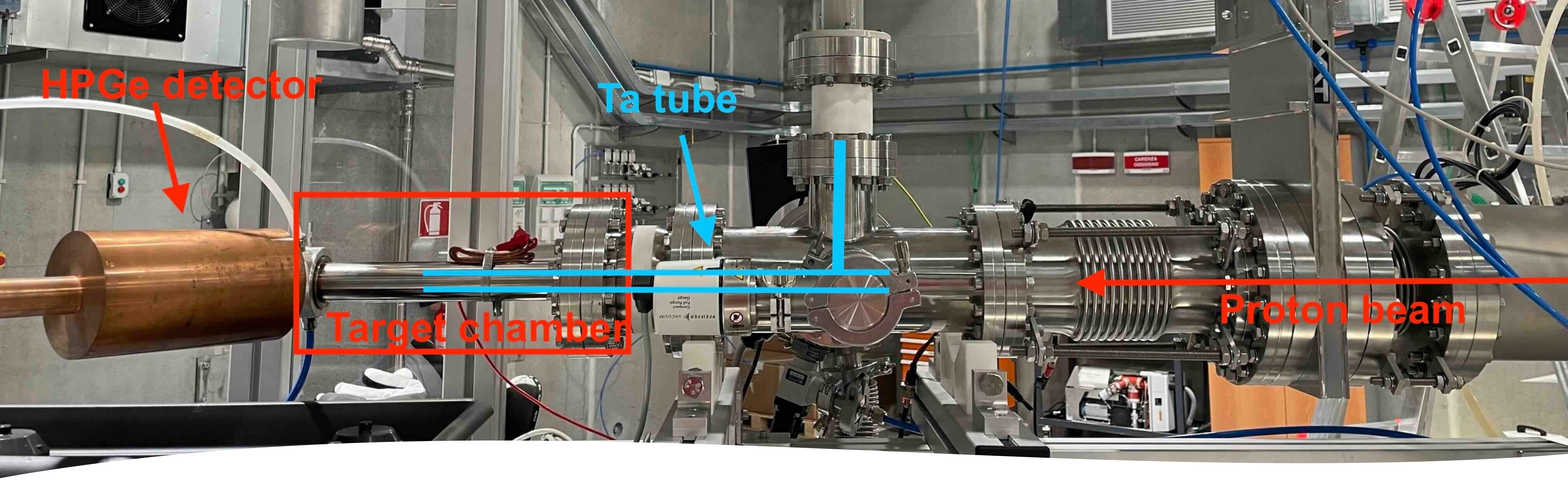
$^{14}N(p,\gamma)^{15}O$ at the Bellotti Ion Beam Facility

PhD-GSSI Thesis Alessandro Compagnucci

- Single HPGe at 55° in close geometry, excitation function.
- Three HPGe detectors for angular distribution: 55°-135°-90° + 0°-120°-90°



Credit of Project and Mechanical serivce INFN Bari



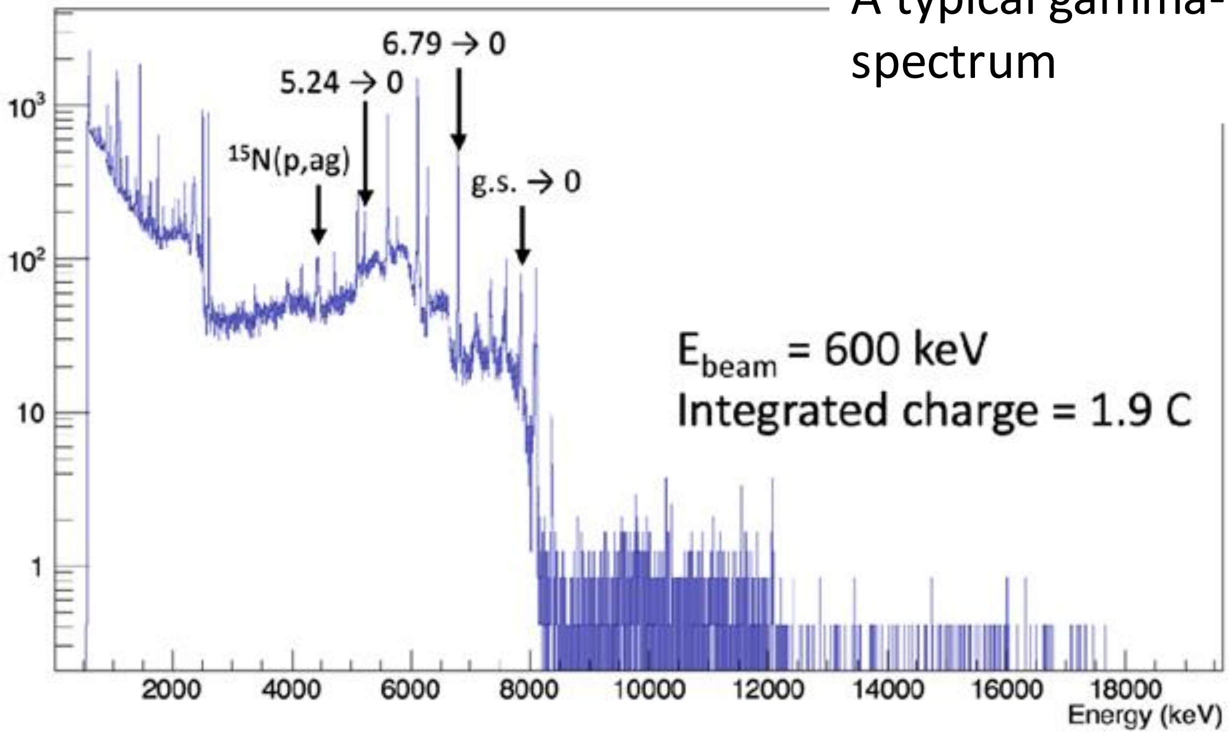
Beamline setup at Bellotti Ion Beam Facility

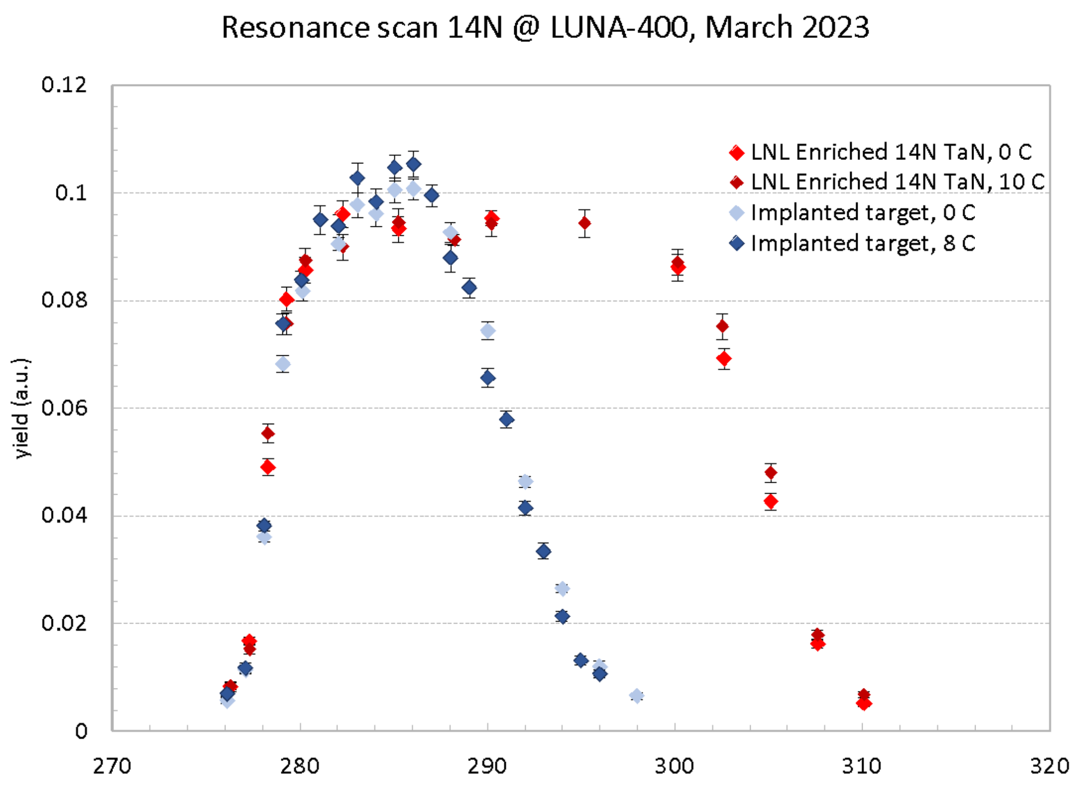
- Upstream:
  - Faraday cup
  - BPM
  - Steerer/Wobbler
  - Switching Magnet
  - …

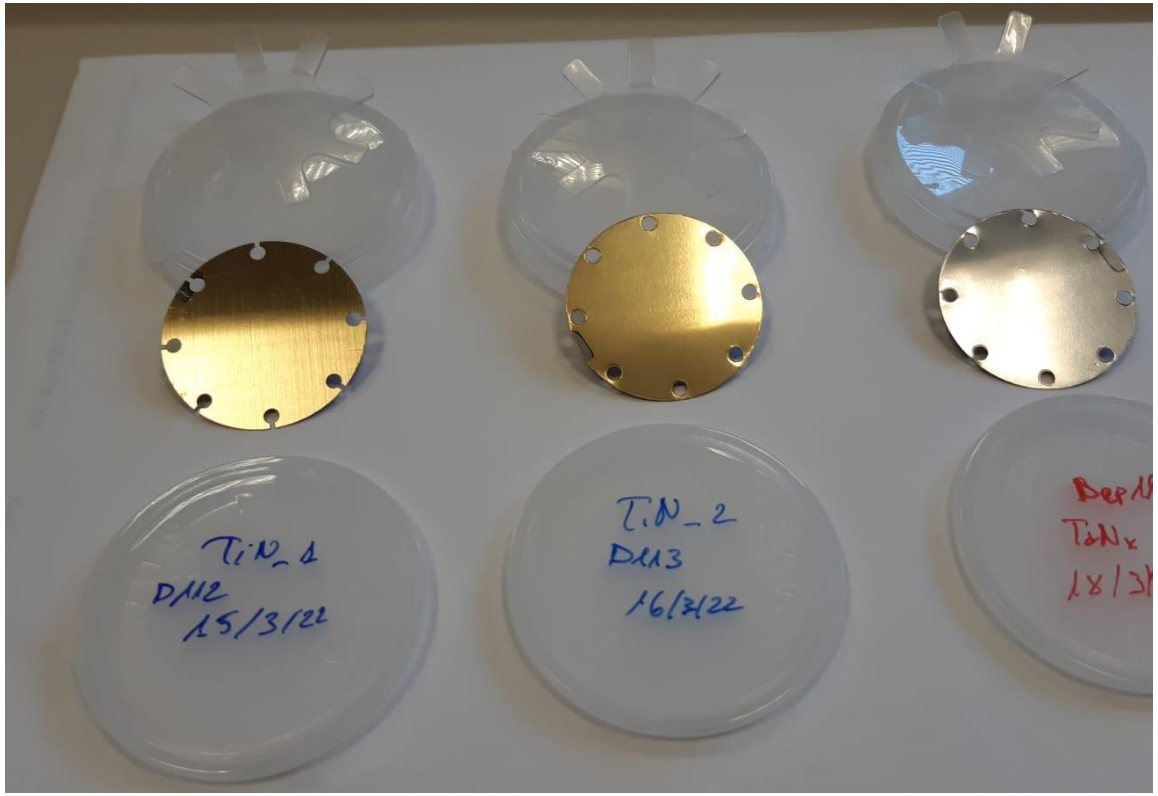
$^{14}N(p,\gamma)^{15}O$ measurement at the Bellotti IBF

- Excitation function measurement **(June 2023)**:
  - **0.25-1.3 MeV** in 50 keV steps,
  - 55° HPGe at 5 cm from target,
  - Total charge collected: **38 C** (up to 300 μA).
- Angular distribution measurement **(October 2023 - February 2024)**
  - **0.4 - 1.1 MeV** in 100 keV steps
  - 3 HPGe detectors 15 cm from target
  - Total charge collected: **150 C**

A typical gamma-ray spectrum





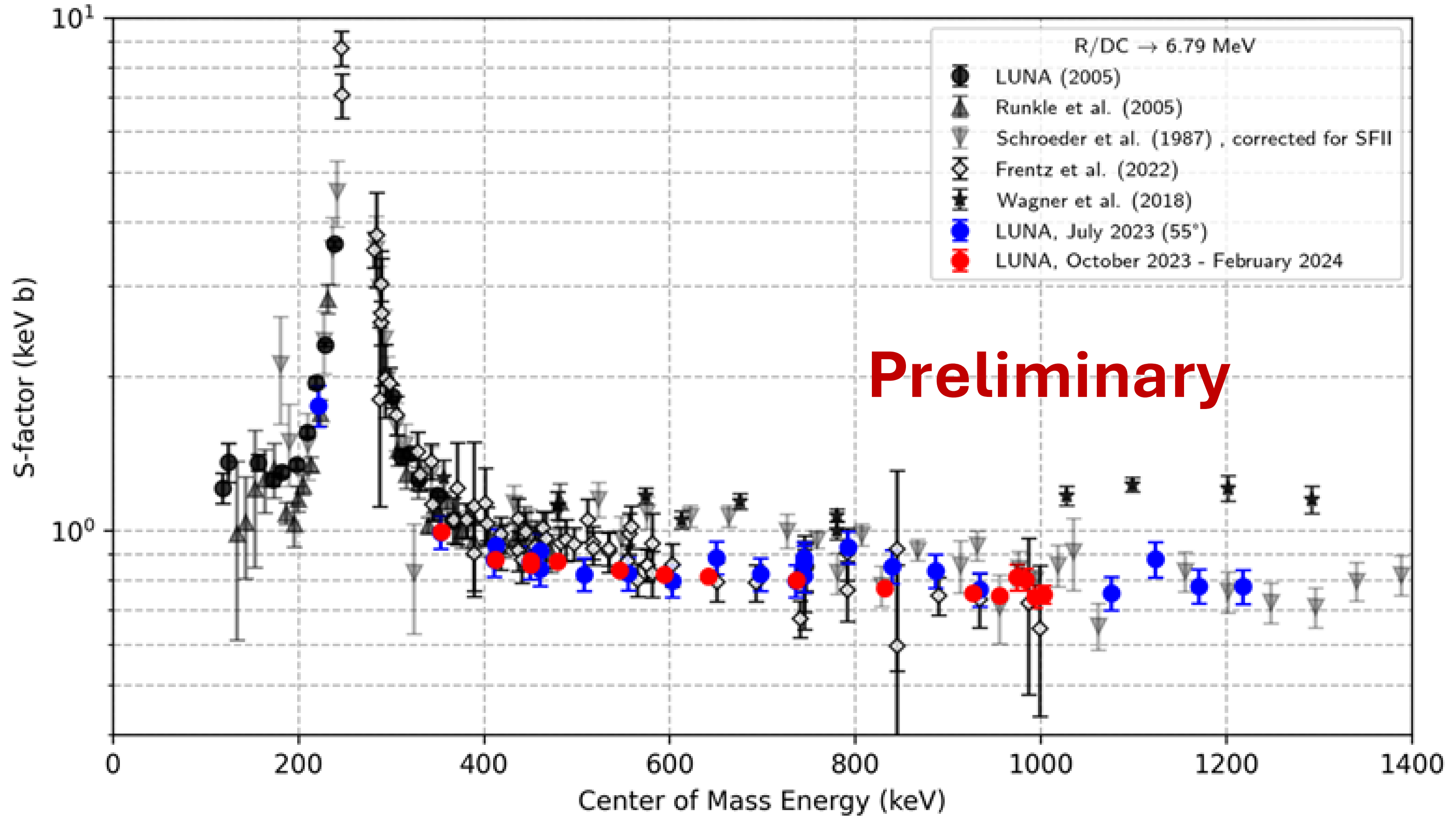


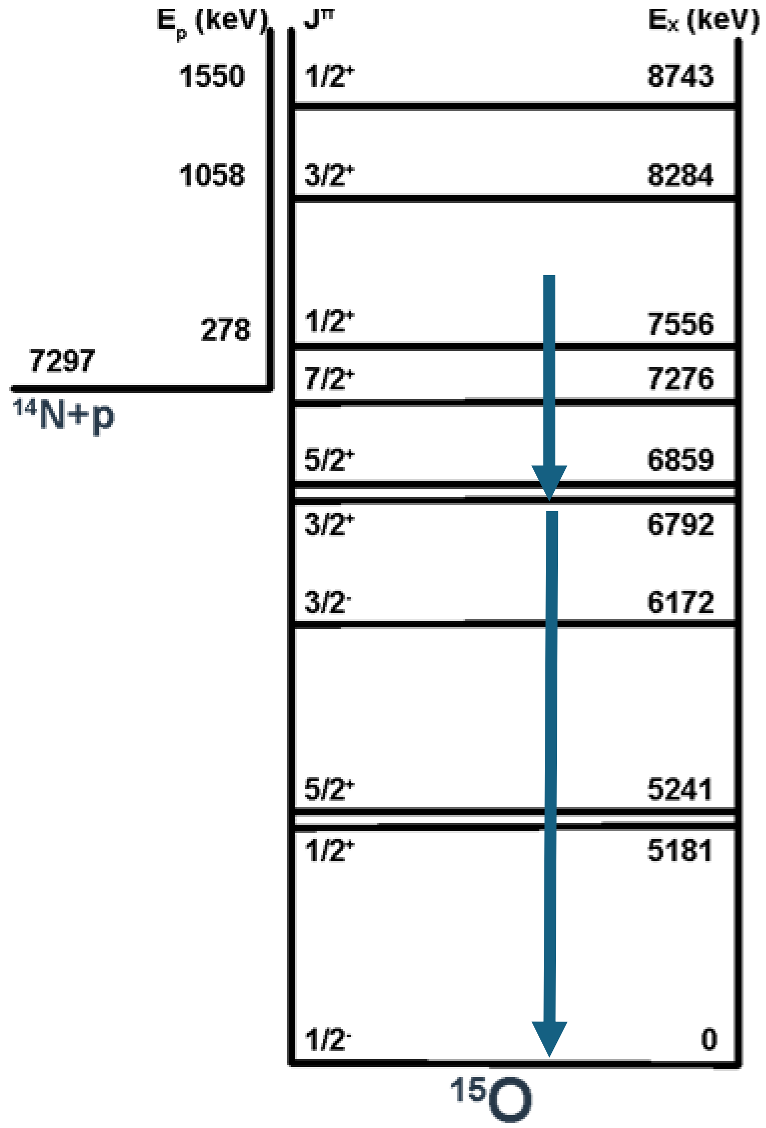
Solid Targets

Sputtered TaN targets: Produced at LNL-INFN Enriched (99.95%) nitrogen gas. Tested for stability up to 40 C.

Implanted targets: Produced at IST, Lisbon. Tested for stability up to 15 C.

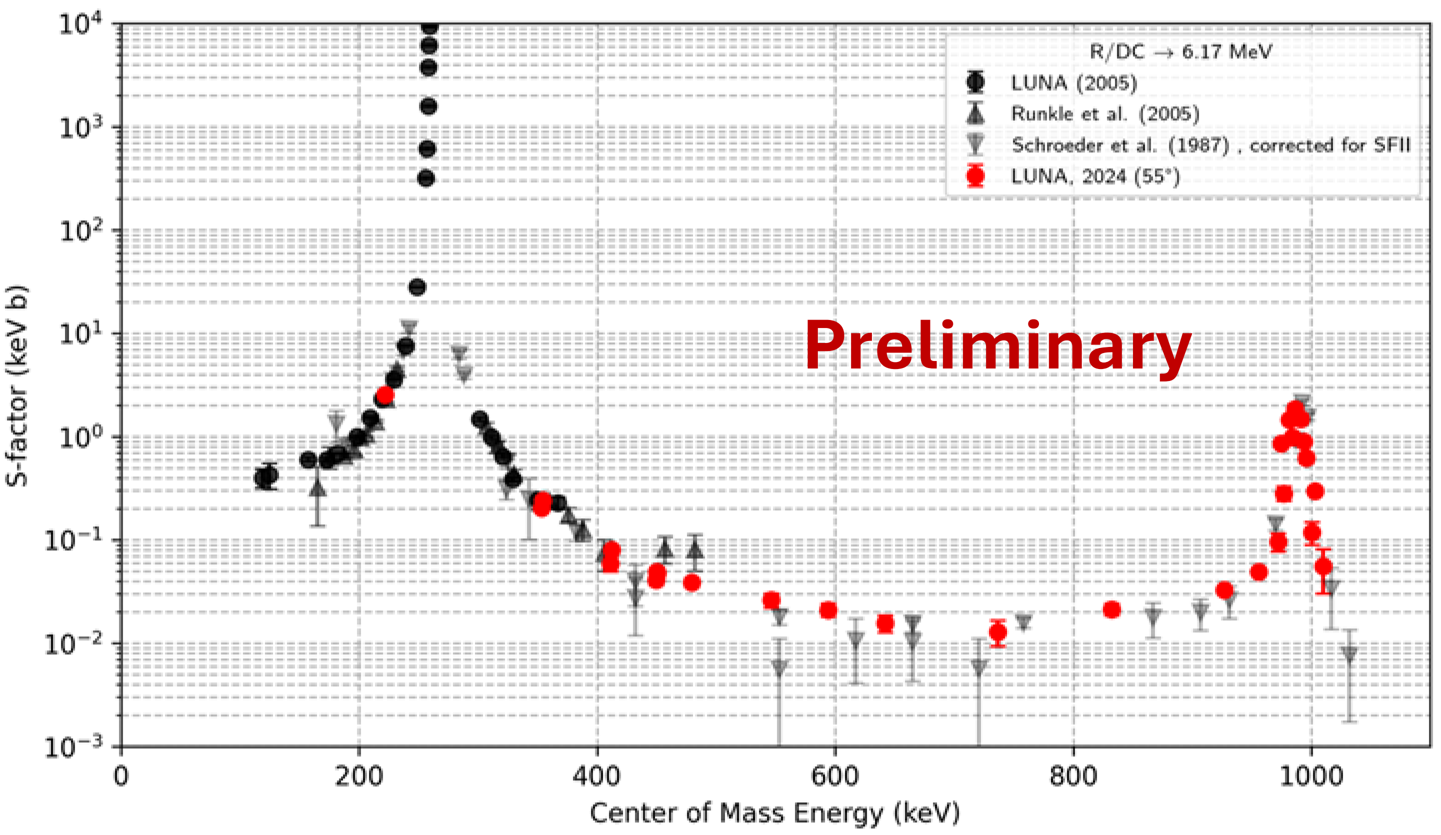
S(E)-factor: R/DC → 6.79 MeV

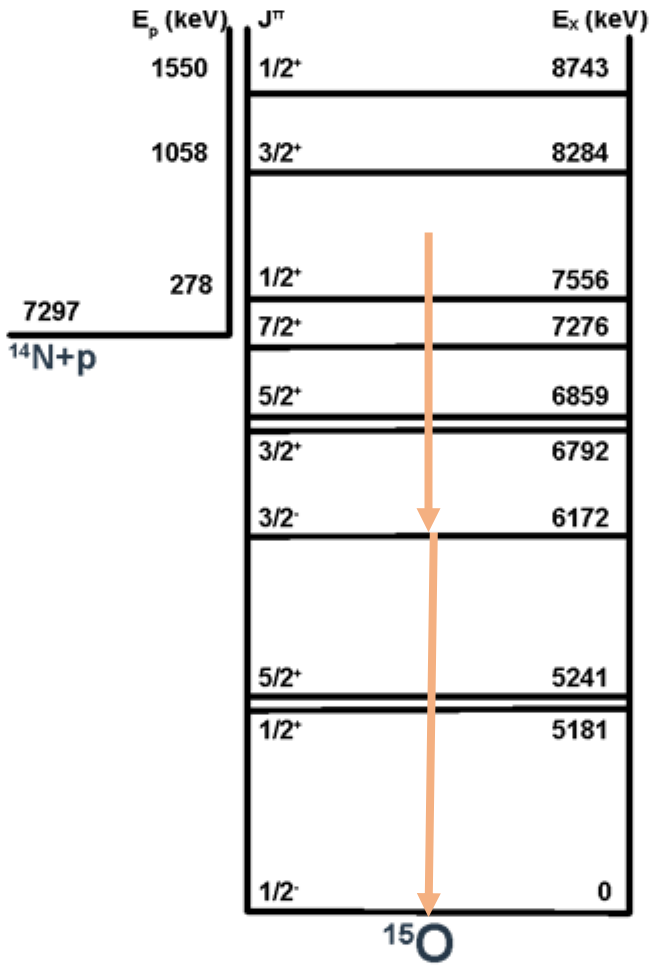




Level scheme for ^{15}O

S(E)-factor: R/DC → 6.17 MeV

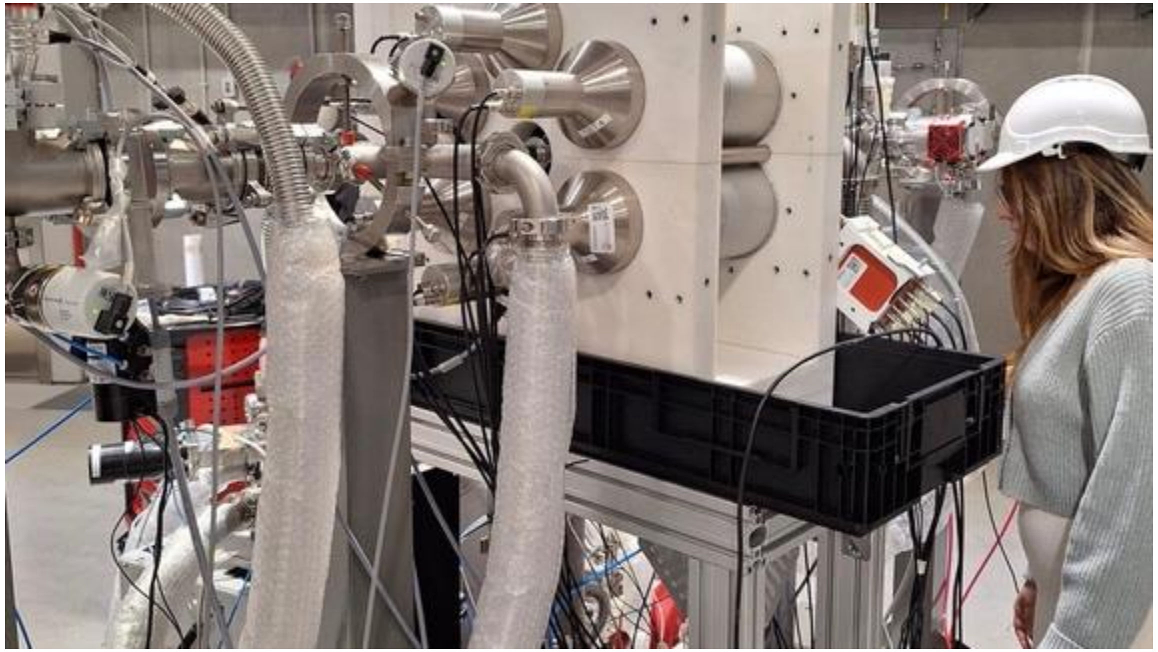


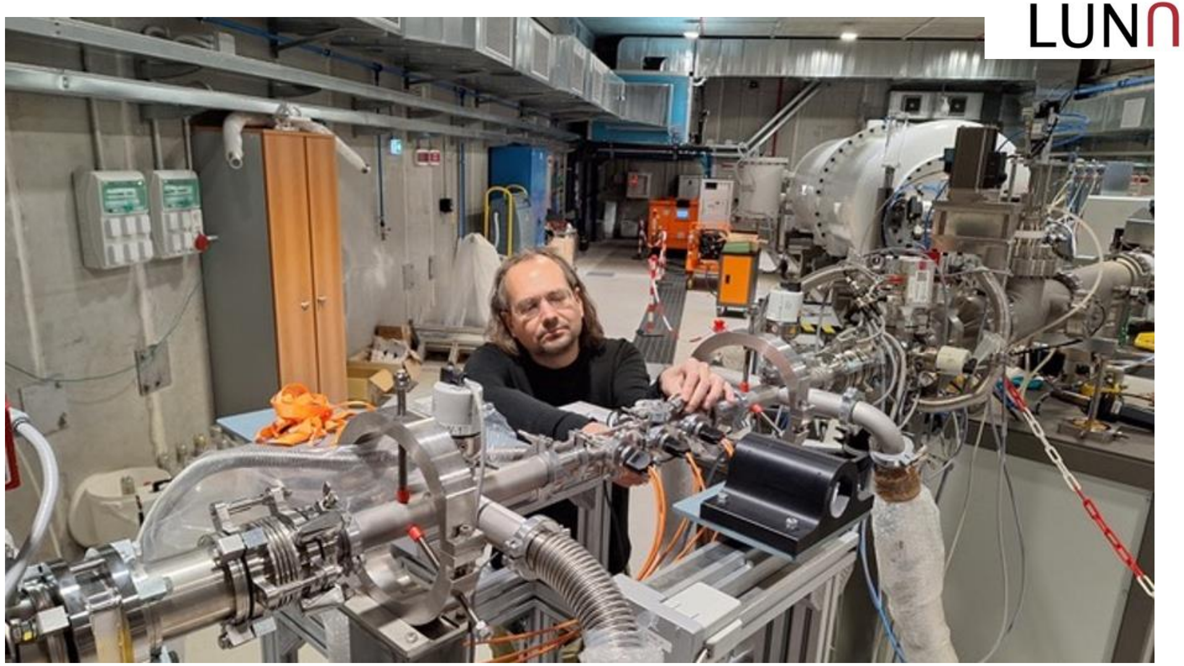


Level scheme for ^{15}O

First new measurement since Schroeder et al (1987) in this energy range!

SHADES Project $^{22}Ne(\alpha, n)^{25}Mg$ at Bellotti IBF

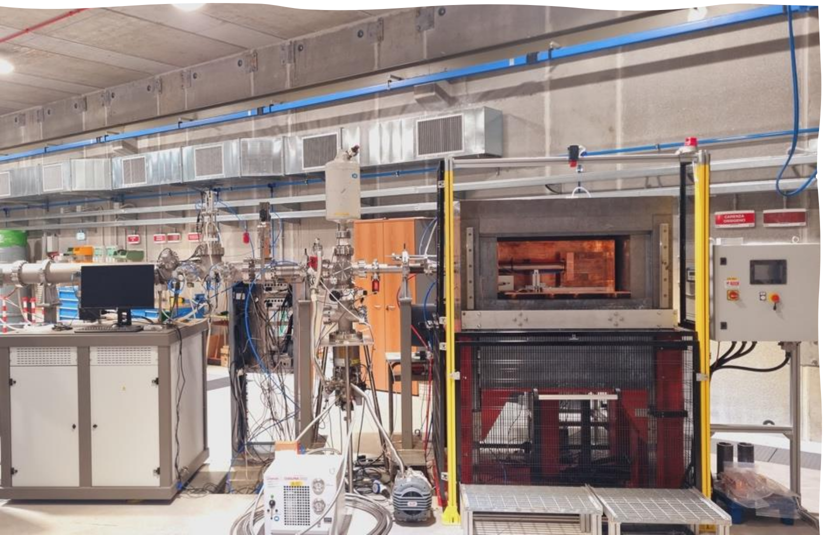


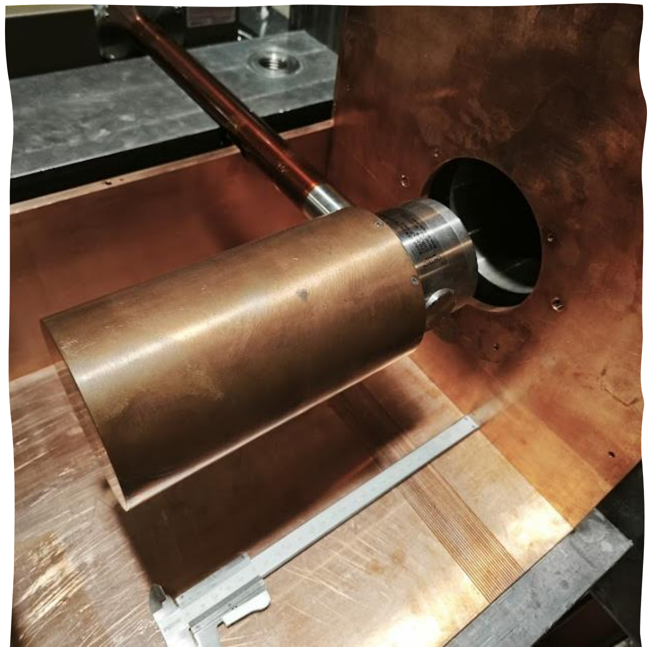


- Hybrid detector array: 3He counters & liquid scintillator
- Provides good efficiency with certain energy sensitivity
- Coated apertures against BIB
- Gas target (recirculating) for long, uninterrupted runs

ERC-StG SHADES, no. 852016 (PI: A.Best)

European Research Council
Established by the European Commission





$^{12}C+^{12}C$ status

- Pb shielding completed
- Cu shielding installed
- beamline installed and tested
- detector installed and tested
- **Data taking started**

Next Scientific Programme 2026 Bellotti IBF

- Complete data taking of $^{22}Ne(\alpha, n)^{25}Mg$
- Continue data taking of 12C+12C γ-detection
- Start commissioning setup $^{22}Ne(\alpha, g)^{26}Mg$
- Start new feasibility study on 12C+12C α-detection

LUNA 400kV

DocID	Rev.	Validità
INFN-CSN3-QA-LUNA-100-00	0	Bozza

Reaction	Energy range E_{cm}[keV]	Required time	Comments	Group
$^{27}Al(p,\alpha)^{24}Mg$	73-392	2 month	setup available	I
$^{10}B(\alpha,p)^{13}C$	165-285	1 month	setup available	I
$^{10}B(\alpha,d)^{12}C$	165-285	7 days	setup available	I
$^{10}B(\alpha,n)^{13}N$	214-286	2 month	activation + BGO setup available	II
$^{19}F(p,\gamma)^{20}Ne$	190-380	1 month	BGO setup available upgrade may be needed	II,III
$^{24}Mg(p,\gamma)^{25}Al$	250-400	1 month	BGO setup available	I
$^{19}F(p,\gamma)^{20}Ne$	156-190	3 month	activation + BGO upgrade ideal	III
$^{6}Li(\alpha,\gamma)^{10}B$	390-480	2 month	setup available-but $^{4}He^{++}$ needed	III
$^{7}Li(\alpha,\gamma_0)^{11}B$	190-255	1 month	setup available	II
$^{7}Li(\alpha,\gamma_3)^{11}B$	210-255	1 month	setup available	I
$^{7}Li(\alpha,\gamma_0)^{11}B$	190-510	2 month	setup available-but $^{4}He^{++}$ needed	III
$^{19}F(p,\alpha_0)^{16}O$	95-380	1 week	setup	I
$^{19}F(p,\alpha_\pi)^{16}O$	143-380	2 months	BGO,setup available +upgrade	II
$^{14}N(p,\gamma)^{15}O$	250-350	3 months	angular distribution: HPGe available	III
$^{14}N(p,\gamma)^{15}O$	60-100	7 months	total cross section: BGO	III

Table 1: Table. Overview of proposed reaction studies at the LUNA 400kV accelerator, data-taking times required for a statistical precision of at least 5%, and associated group assignment (note: the time indicated does not include setting up and/or contingency). Reactions for which required resources (setup, detectors, electronics, DAQ, etc) are already available, have been assigned to group I and could potentially be studied at the LUNA 400kV accelerator in its existing location/configuration. Reactions in groups II or III require either longer beam-times ($\geq$ 1 month data taking), new developments (detectors and/or ion source), or both.

ESFRI Landscape Analysis 2024

The Gran Sasso National Laboratory (LNGS), the largest underground laboratory in the world devoted to neutrino and astroparticle physics, is also of particular importance for nuclear astrophysics. It offers the most advanced underground infrastructure in terms of dimensions, complexity and completeness. For the last 30 years, research in nuclear astrophysics has been carried out by the LUNA Collaboration at LNGS. The collaboration plans to install a new LUNA 400-kV accelerator at LNGS.

LUNA collaboration is participating to the most important international network activities in NA field,
ChETEC-INFRA (Chemical Elements as Tracers of the Evolution of the Cosmos – Infrastructures for Nuclear Astrophysics https://www.chetec-infra.eu)
IReNA (International Research Network for Nuclear Astrophysics https://www.irenaweb.org).

Perspectives at the Bellotti IBF

Workshop on Nuclear Physics, Astrophysics and Applications in Underground Laboratories

OCTOBER 8-10, 2025
Laboratori Nazionali del Gran Sasso
Assergi, L'Aquila, Italy

The workshop aims to bring together scientists interested in research at the deep underground Bellotti Ion Beam Facility (IBF) at INFN's Laboratori Nazionali del Gran Sasso (LNGS), to explore opportunities and challenges in an international context and to stimulate networking.

Topics

- Bellotti IBF in the international context of underground nuclear astrophysics
- Bellotti IBF for Physics beyond the standard model
- Perspectives in Applied Physics research at Bellotti IBF

Scientific advisory committeee

- Sandrin M. Courtin,University of Strasbourg, France
- Federico Ferraro, INFN-LNGS, Italy
- Alba Formicola, INFN-Roma 1, Italy
- Jordì Josè, UPC Barcelona/IEEC, Spain
- Matthias Junker, INFN-LNGS, Italy
- Matthias Laubenstein, INFN-LNGS, Italy
- Marcello Messina, INFN-LNGS, Italy
- Valentino Rigato, INFN-LNL, Italy
- Daniel Robertson, University of Notre Dame, Indiana, USA

Local organizing committeee

- Chair: Federico Ferraro, INFN-LNGS, Italy
- Riccardo Maria Gesuè, GSSI & INFN-LNGS, Italy
- Thomas Chillery, INFN-LNGS, Italy
- Dipali Basak, INFN-LNGS, Italy

Scientific secretary

- Fausto Chiarizia, INFN-LNGS, Italy

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