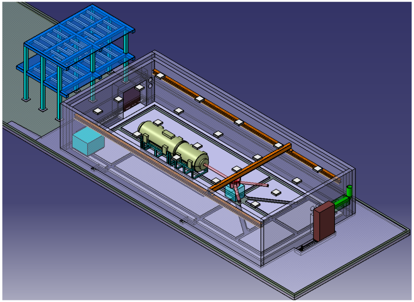
Underground nuclear astrophysics at LUNA and the Bellotti Ion Beam facility of INFN-LNGS



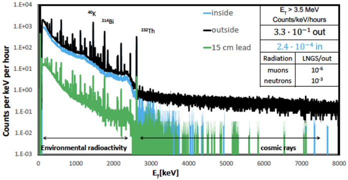
Andreas Best (andreas.best@unina.it)
University of Naples, INFN Naples

CGS-17
Grenoble, France

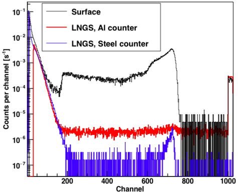
LNGS

- 4300 m.w.e. underneath Gran Sasso mountains 1 h east of Rome
- 30 years of nuclear astrophysics experiments
- Electrical, chemical, mechanical workshops on site
- Convenient access through freeway tunnel
- Two running accelerators

Why go underground? (it's cold, dark, wet. . .)



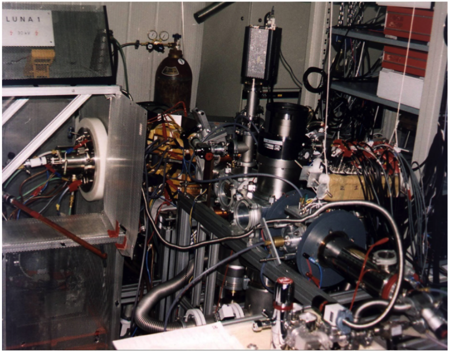
J. Phys. G: Nucl. Part. Phys. **45** (2018) 025203



- Muons major high-energy (> 3 MeV) background in γ-detection
- Cosmic muons absorbed by rock
- "Automatic" suppression by 3 o.o.m
- Below 3 MeV bg comes from rocks etc, but can build very massive shield
- 3 o.o.m. reduction achieved with lead, copper, radon box

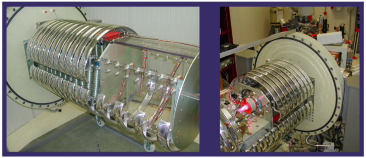
- Atmospheric neutrons removed
- Remainder (10^{-3}) comes from decays in environment
- Material choice now makes a difference
- Add PSD and passive shielding
- Example: ^{13}C$(\alpha$,n$)^{16}$O 1 bg count/hour with 18 ^{3}He counters

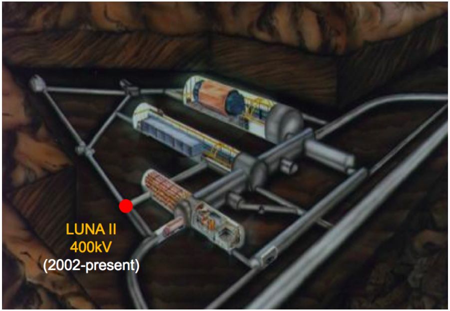
LUNA 1

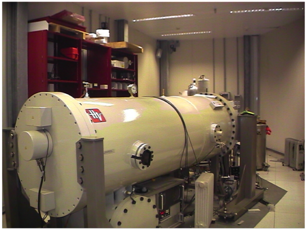


- Setup to measure p-p chain reactions
- 50 kV platform built by students
- $^3He(^3He, 2p)^4He$ - solar neutrino problem (Bonetti et al. Phys. Rev. Lett. 82 (1999) 5205)

LUNA 2

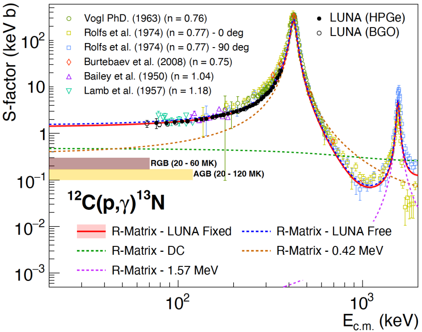


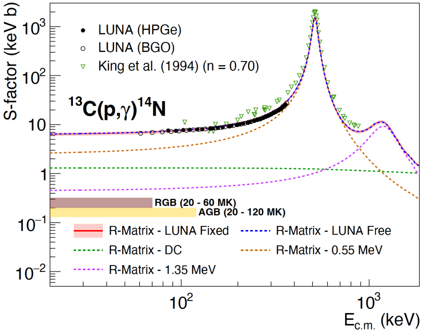




- Moved down the corridor a few meters
- In operation since 2002
- 50 - 400 kV accelerator, $I \approx 500\mu$A
- $^{14}N(p,\gamma)^{15}O$ - CNO neutrinos / age of the Universe
- p+d: Big-bang nucleosynthesis (Mossa et al. Nature 2020)

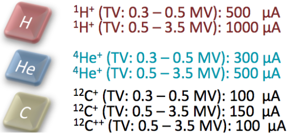
Most recent

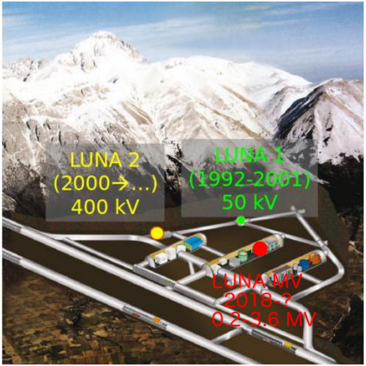




- New study of $^{12,13}C(p,\gamma)^{13,14}N$
- BGO (high eff.) and HPGe (partial c.s.), massive lead+PE shield
- Skrowonski et al. accepted in PRL

LUNA MV

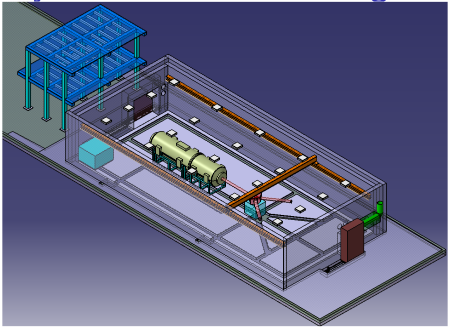


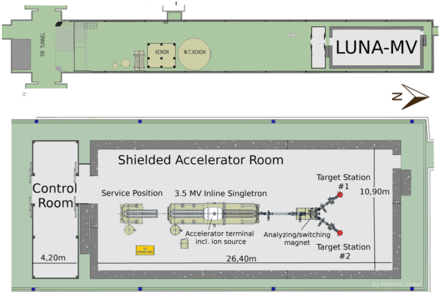


- Progetto Premiale MIUR - 2 grants total 5.3 MEuro
- 0.3 - 3.5 MV single-ended Cockcroft-Walton [1]
- High-intensity H, He, C beams
- Designed for energy & current stability
- Two beamlines ready to go
- Program: carbon burning, neutron sources

[1] Sen, A. et al. NIM B 450 (2019), 390

Layout, neutron shielding



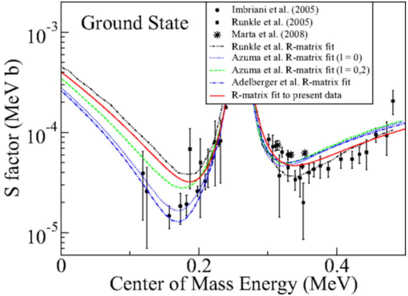


- 80 cm concrete walls to reduce any produced neutron flux below bg level outside
- Beam intensity limited as function of species, energy
- Neutron monitors provide interlock

MCNP: $\Phi_n = 1.38\ 10^{-7}$ n/(cm^2 s)
GEANT4: $\Phi_n = 3.40\ 10^{-7}$ n/(cm^2 s)

Φ_n(LNGS) = 3 10^{-6} n/(cm^2 s)

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



- **Notre Dame:**

$S_{6.79}(0) = 1.29 \pm 0.04(\text{stat}) \pm 0.09(\text{syst})$ keV b

$S_{g.s.}(0) = 0.42 \pm 0.04(\text{stat})^{+0.09}_{-0.19}(\text{syst})$ keVb,

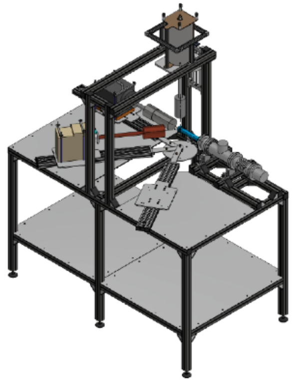
- **Dresden:**

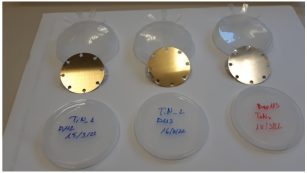
$S_{6.79}(0) = 1.24 \pm 0.11$ keV b

$S_{GS}(0) = 0.19 \pm 0.05$ keV b.

- Commissioning & science measurement
- Recent measurements at Notre Dame, Dresden, Debrecen
- Improvements required for astro input
- Connect high-energy to low-E region covered by LUNA 400
- Angular resolution measurements
- Increased sensitivity

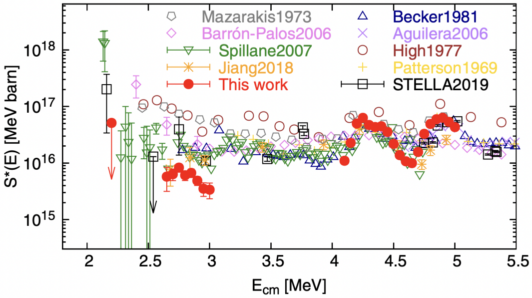
Setup





- Sputtered/implanted targets
- Phase 1: 1 HPGE close geometry
- Phase 2: angular distributions, 3 HPGe
- Target characterisation at LUNA400 and external facilities
- First beamtime completed

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



Tan et al. PRL 124 (2020) 192702

- Determines fate of massive stars
- $^{12}C(^{12}C, p, \alpha)^{23,20}\{Na,Ne\}$
- proton, alpha (and neutron) channels
- p_i, α_i channels $\rightarrow$ secondary γ-rays
- $^{12}C(^{12}C, p_1)^{23}Na$: Q = 2.241 MeV, 440 keV γ
- $^{12}C(^{12}C, \alpha_1)^{20}Ne$: Q = 4.617 MeV MeV, 1634 keV γ

$^{12}C+^{12}C$ - γ measurements

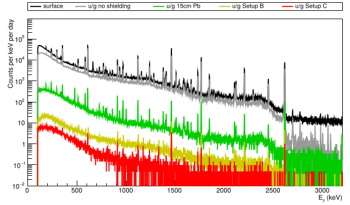


Figure 9a: *Environmental background in HPGe detectors in different shielding configurations.*

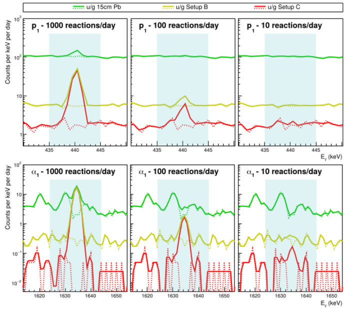
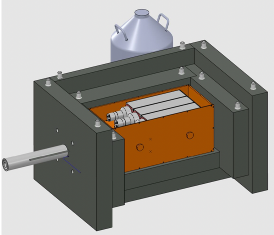
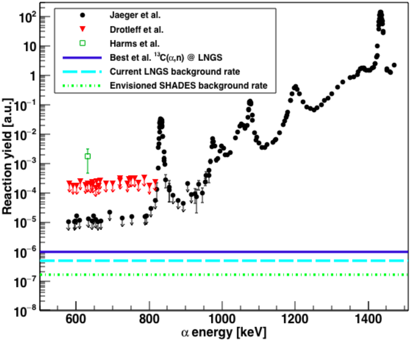


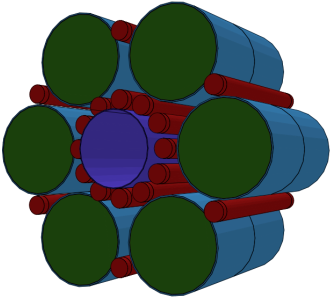
Figure 9b: *Visualization of a hypothetical reaction yield (solid) on top of the background levels of shielded setups from Fig. 9a (dotted).*



- Massive lead shield and radon flushing → push sensitivity to better than 100 reactions/day
- Particle measurement also foreseen, detector design under investigation

$^{22}Ne(\alpha, n)^{25}Mg$

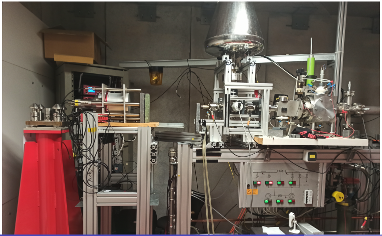




- Weak s process neutrons
- Threshold 565 keV: perfect for LUNA MV
- Jaeger et al. only stopped by neutron bg flux
- LNGS automatic reduction by 3-4 o.o.m.
- Beam-induced reaction can be showstopper
- "SHADES" ERC project
- Installation underway

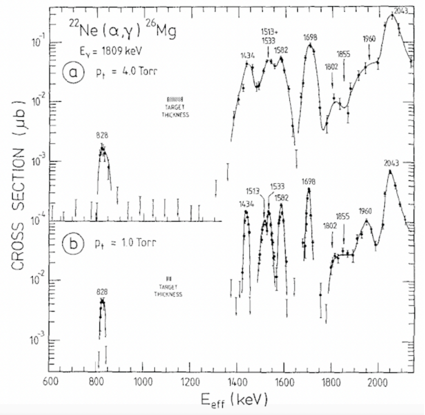
European Research Council
Established by the European Commission

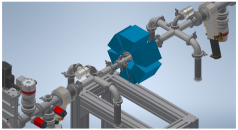
SHADES - Setup

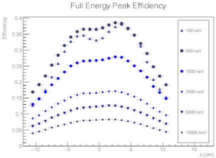


- Require some sort of energy sensitivity
- Hybrid detector array: ^{3}He counters & liquid scintillator
- High efficiency + energy sensitive
- Recirculating gas target

$^{22}Ne(\alpha,\gamma)^{26}Mg$







- Competiton for n-channel & Mg isotopic ratio
- Direct data Wolke et al. 1989 (!)
- Some remeasurements of 830 keV res (TUNL)
- CASPAR + LUNA few new upper limits
- Vast terra incognita to explore
- Synergize with ERC setup
- Project EASγ funded by MUR

Summary

- Will investigate some of the most important reactions for astrophysics
- Factory acceptance test passed in late 2019
- Installation completed
- On-site acceptance tests finished December 2022
- First proton beam on ^{14}N this June
- LUNA 400 to be installed near MV
- Both accelerators will be INFN "Bellotti Ion beam facility"
- LNGS accelerator service established + PAC formed
- **Contact me for postdoc postions**

LUNA collaboration

Laboratori Nazionali del Gran Sasso, INFN, ASSERGI, Italy/GSSI, L'AQUILA, Italy
A. Compagnucci, R. Gesué F. Ferraro, M. Junker
Università degli Studi di Bari and INFN, BARI, Italy
F. Barile, G.F. Ciani, V. Paticchio, L. Schiavulli
Konkoly Observatory, Hungarian Academy of Sciences, BUDAPEST, Hungary M. Lugaro
Institute of Nuclear Research (ATOMKI), DEBRECEN, Hungary
L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyürky, T. Szücs
Helmholtz-Zentrum Dresden-Rossendorf, DRESDEN, Germany
D. Bemmerer, A. Boeltzig, E. Masha
University of Edinburgh, EDINBURGH, United Kingdom
M. Aliotta, L. Barbieri, C.G. Bruno, T. Davinson, J. Marsh, D. Robb, R. Sidhu
Università degli Studi di Genova and INFN, GENOVA, Italy
P. Prati, S. Zavatarelli
INFN Lecce, LECCE, Italy
R. Perrino
Università degli Studi di Milano and INFN, MILANO, Italy
R. Depalo, A. Guglielmetti
Università degli Studi di Napoli "Federico II" and INFN, NAPOLI, Italy
C. Ananna, A. Best, D. Dell'Aquila, A. Di Leva, G. Imbriani, D. Mercogliano
Università degli Studi di Padova and INFN, PADOVA, Italy
C. Broggini, A. Caciolli, P. Marigo, R. Menegazzo, D. Piatti, J. Skowronski
INFN-LNL, Legnaro, Italy
M. Campostrini, V. Rigato
INFN Roma, ROMA, Italy
A. Formicola , C. Gustavino
Osservatorio Astronomico di Collurania, TERAMO and INFN LNGS, Italy
O. Straniero
Università di Torino and INFN, TORINO, Italy
F. Cavanna, G. Gervino, P. Colombetti