LUNA

Laboratory for **U**nderground **N**uclear **A**strophysics

IZABELA KOCHANEK, LNGS
for the LUNA Collaboration

Talk's Layout

- why underground
- highlights from LUNA
  - LUNA phase I (1992-2001)
  - LUNA phase II (2000-present)
  - LUNA phase III (2015-2018)
- future projects
  - LUNA MV (Europe)
  - CASPAR (US)
  - Felsenkeller (Europe)

Nuclear Astrophysics

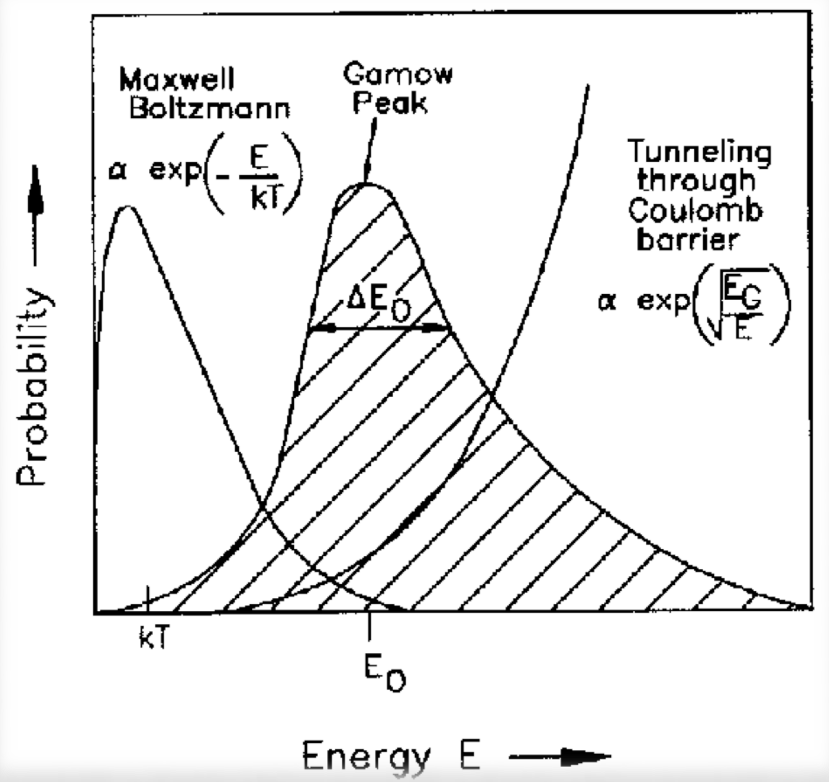
- interdisciplinary branch of physics involving nuclear physics and astrophysics

- to understand how nuclear processes generate the energy of stars over their lifetimes

- desired cross sections among the smallest measured in the nuclear laboratory
- long data-collection with attention to background

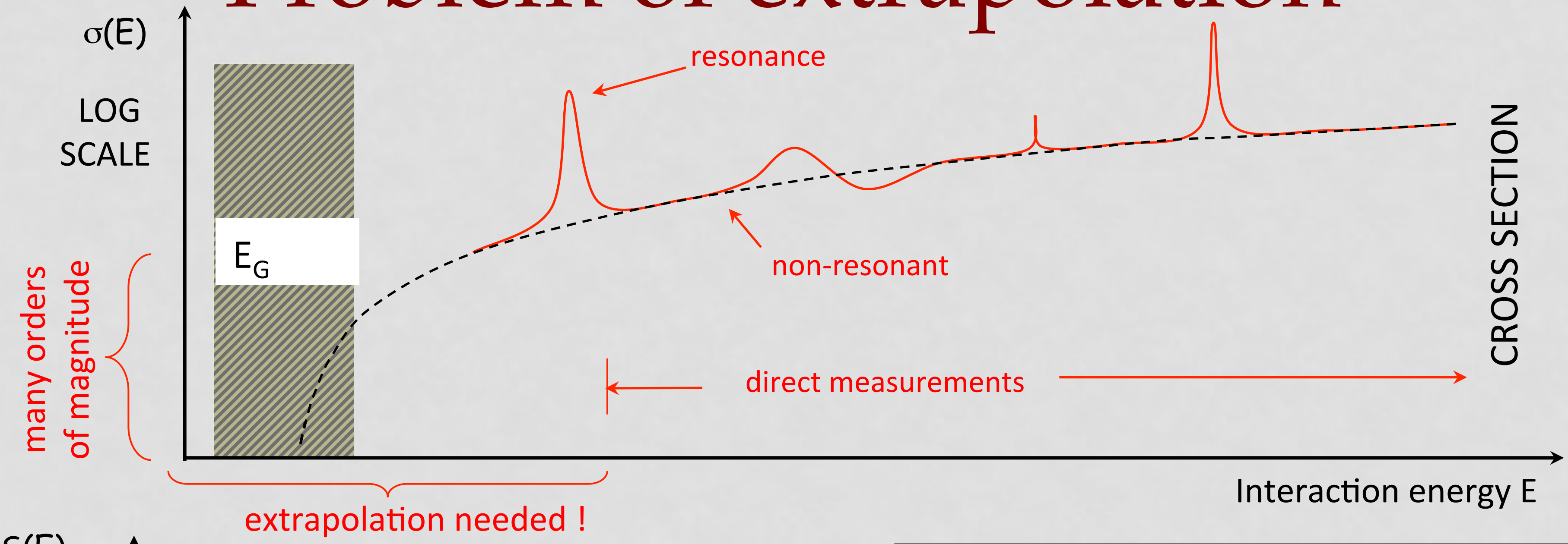
Nuclear Astrophysics

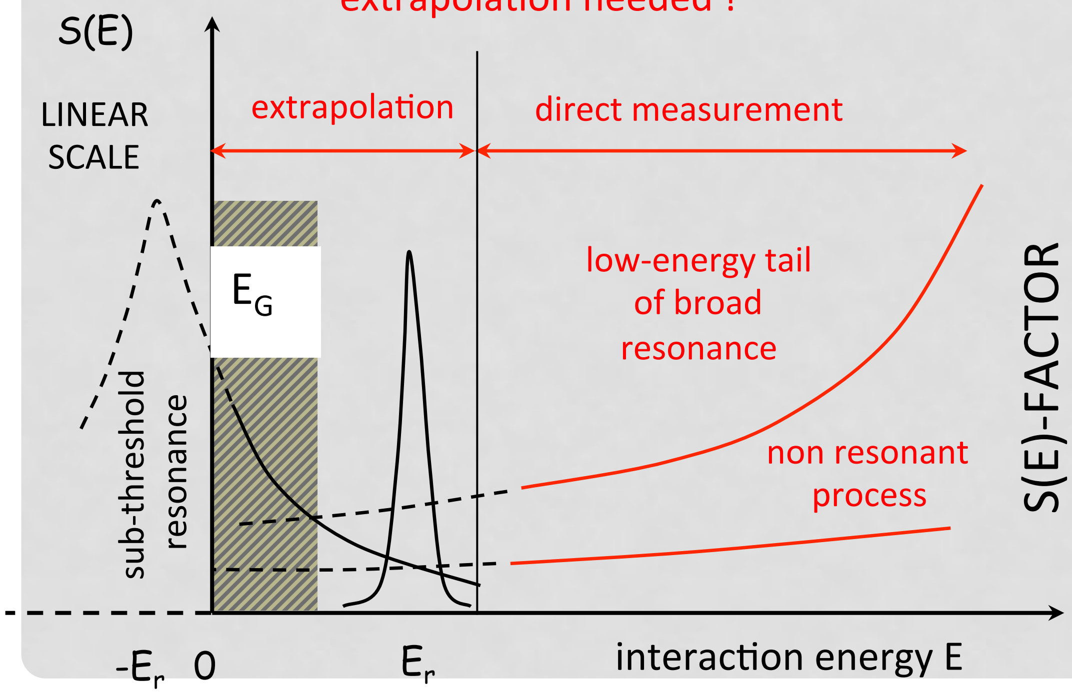
- ion energy follows the Maxwell-Boltzmann distribution
- since the fraction of nuclei having the necessary energy to overcome the Coulomb barrier is negligible, reactions between charged particles in stars occur through tunneling of the Coulomb barrier, resulting in very small interaction cross sections



- the convolution of the above mentioned functions determines a relatively narrow energy window, the "**Gamow window**"
- represents the effective energy window in which most charged particle induced nonresonant thermonuclear reactions occur

Problem of extrapolation





$R_{lab} = \boldsymbol{\sigma} \cdot \varepsilon \cdot I_p \cdot \rho \cdot N_{av}/A$

$\varepsilon \sim 10\ \%$

pb < σ < nb $\quad I_P \sim mA$

$\rho \sim \mu g/cm^2$

event/month < R_{lab} < event/day

$\sigma(E) = \mathbf{S(E)}/E \exp(-2\eta\pi)$

Thermonuclear Reactions in Lab

low cross sections → low yields → poor signal-to-noise ratio

Yield = N_p x N_t x cross section x detection efficiency

10^{14} pps (~100 μA q=1+) typical stable beam intensities

10^{19} atoms/cm^2 typical solid state targets

10^{-15} barn (often even smaller)

100% for charged particles
~1% for gamma rays

Y = 0.3-30 counts/year

- improving signal (beam currents, target densities, efficiency)
- reducing noise (i.e. background)
- a combination of both

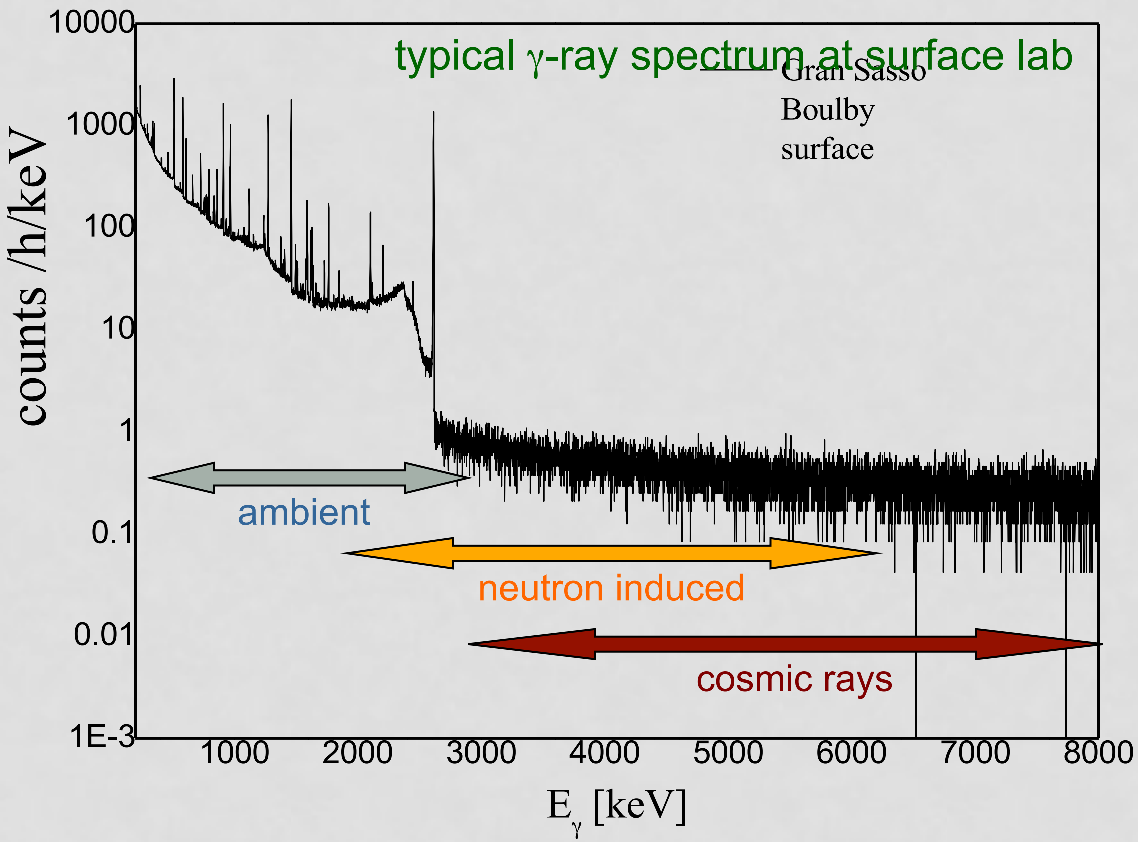
Experimental Challenges & Key Requirements

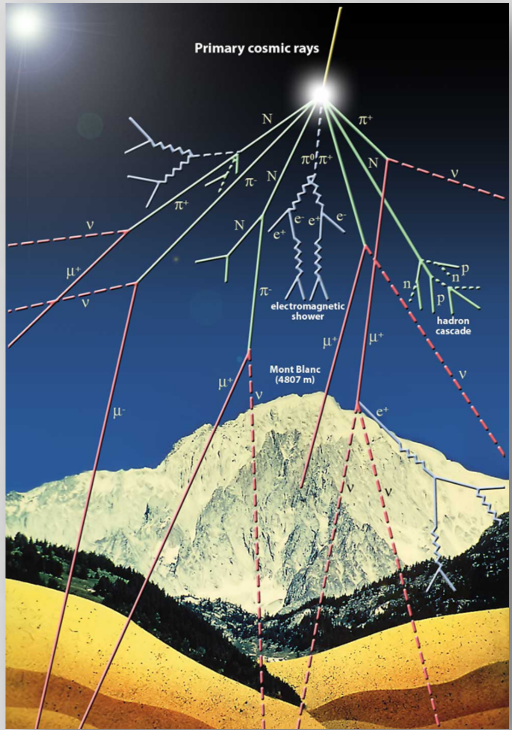
- long term stability & high energy-accuracy
- ultra pure targets & known stoichiometry
- high detection efficiency
- wide energy ranges for reliable extrapolations
- concurrent measurements with different techniques to minimize systematic dependencies

DEDICATED (UNDERGROUND) FACILITY

Sources of γ-ray Background

- natural radioactivity (from U and Th chains and from Rn)
- cosmic rays (muons, $^{1,3}H$, ^{7}Be, ^{14}C, …)
- neutrons from (α,n) reactions and fission





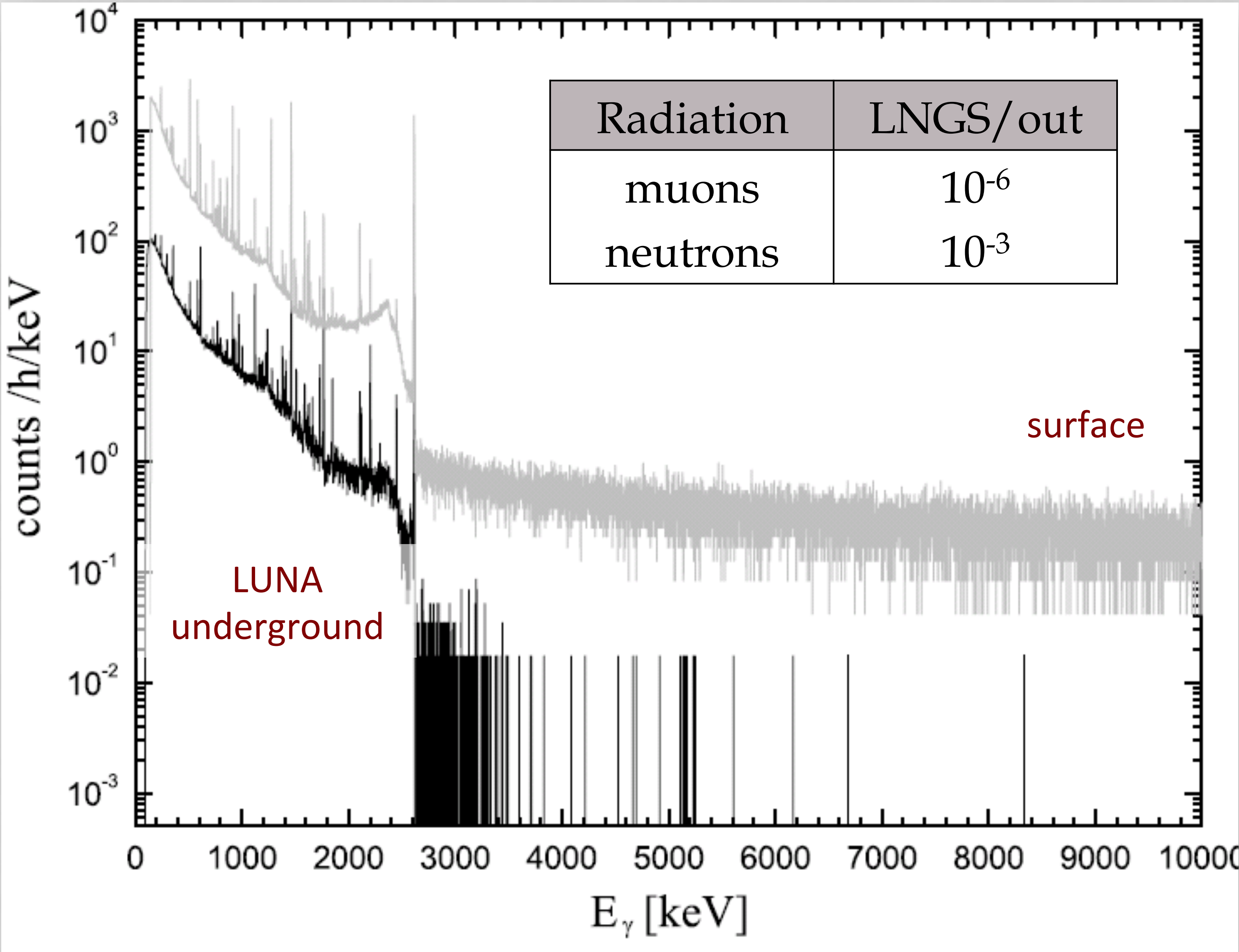
LUNA

Laboratori Nazionali
del Gran Sasso

1.4km rock overburden
million-fold reduction
in cosmic background

first (and so far only) underground accelerator in the world

γ-ray Background at LUNA



Radiation	LNGS/out
muons	10^{-6}
neutrons	10^{-3}

Costantini et al. Rep. Prog. Phys. 72 (2009) 086301

Which reactions can (should) be studied underground?

- high Q-value radiative capture reactions
- reactions producing neutrons
- some reactions producing charged particles
- reactions not limited by beam-induced background

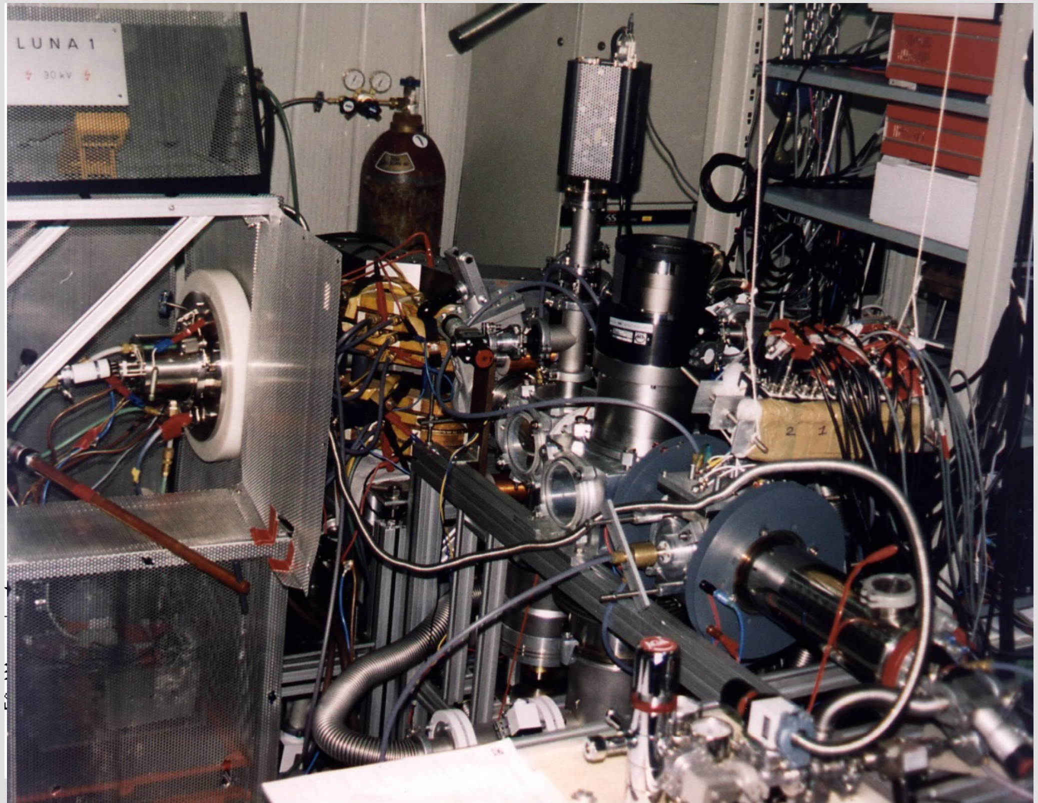
Gran Sasso National Laboratory

LUNA Phase I (1992-2001): 50 kV accelerator

investigate reactions in solar pp chain

90° analysing magnet

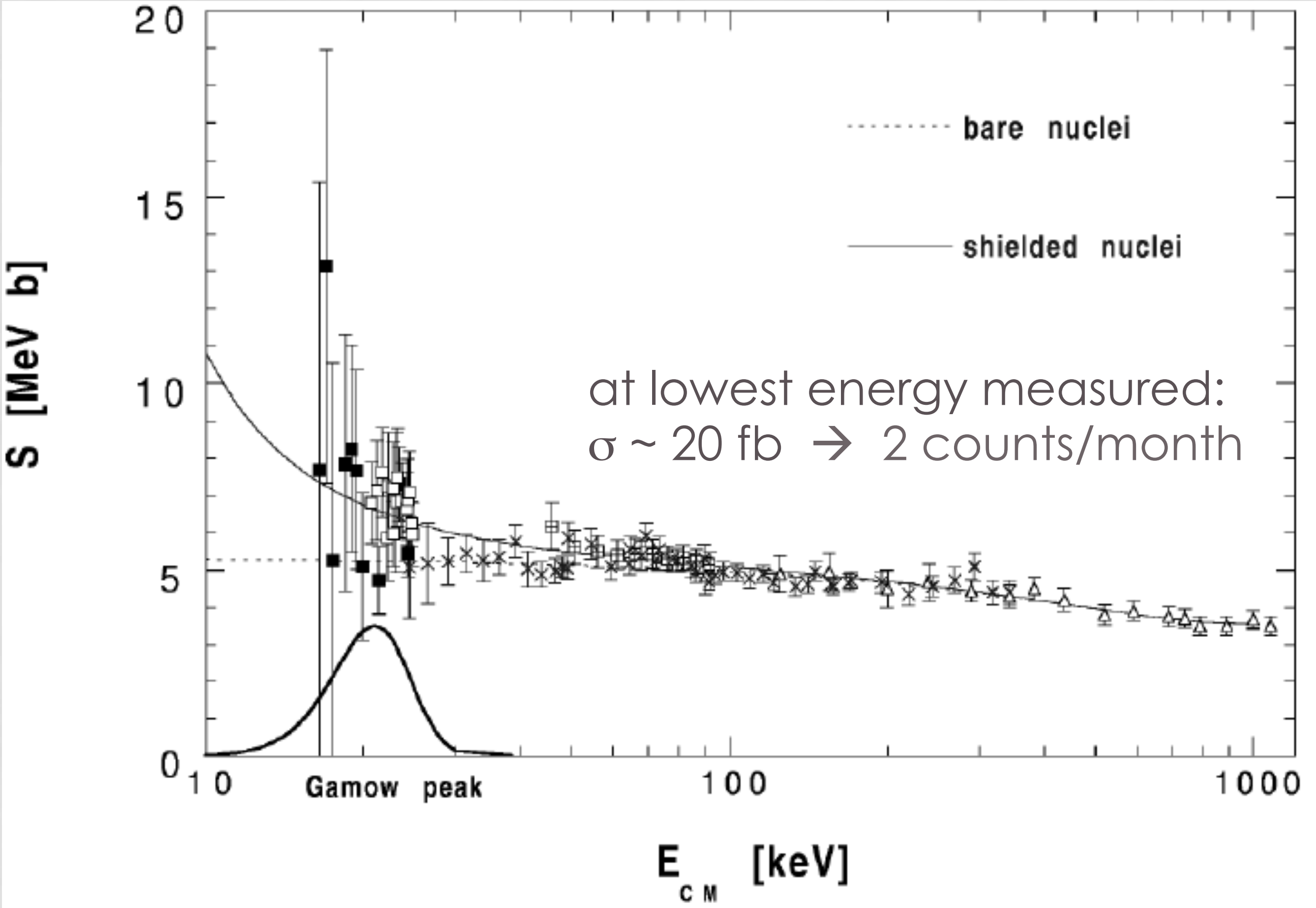
duoplasmatron ion source on 50kV platform



chamber

entirely built by students!

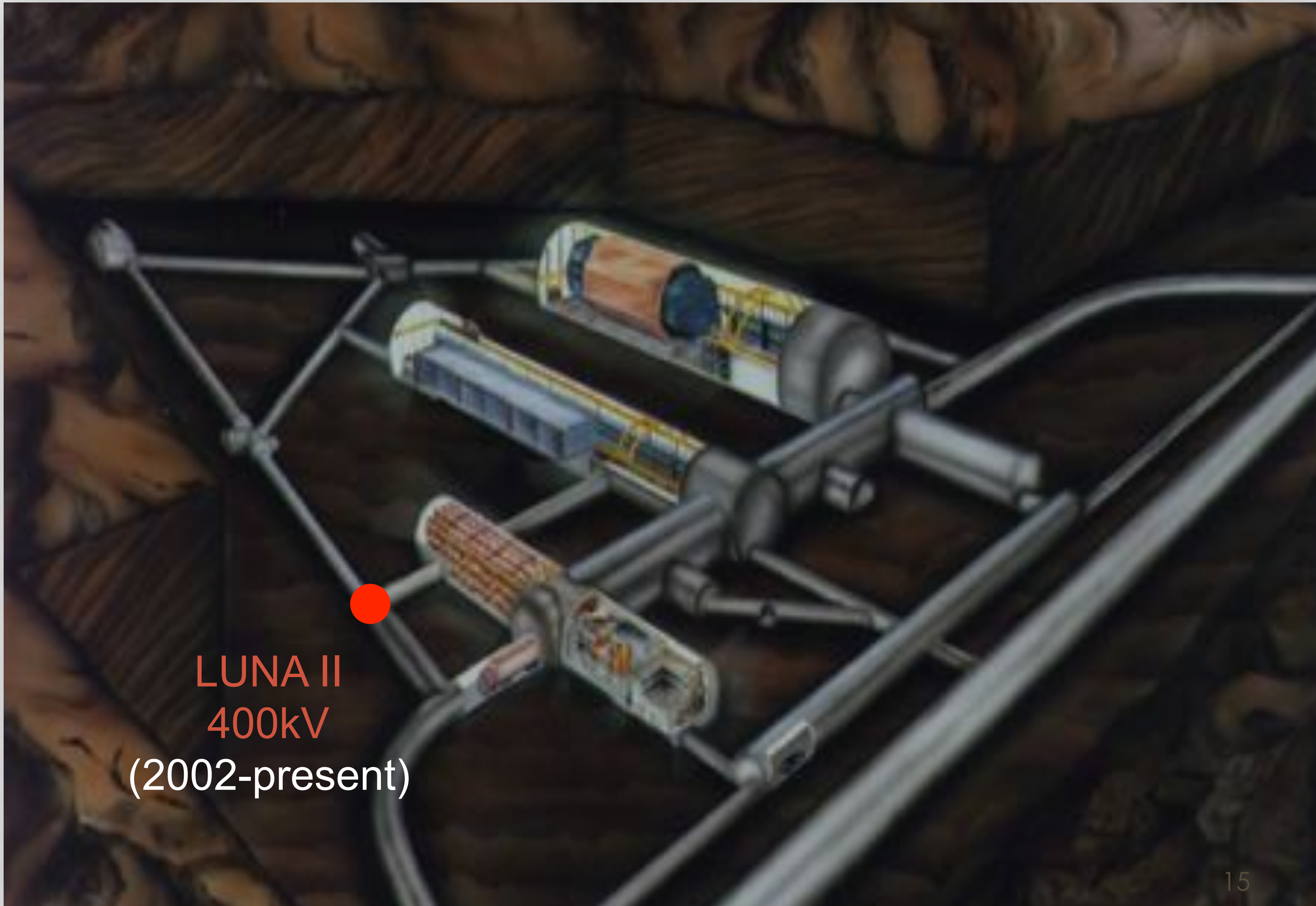
The $^3He(^3He, 2p)^4He$ Reaction and the Solar Neutrino Puzzle



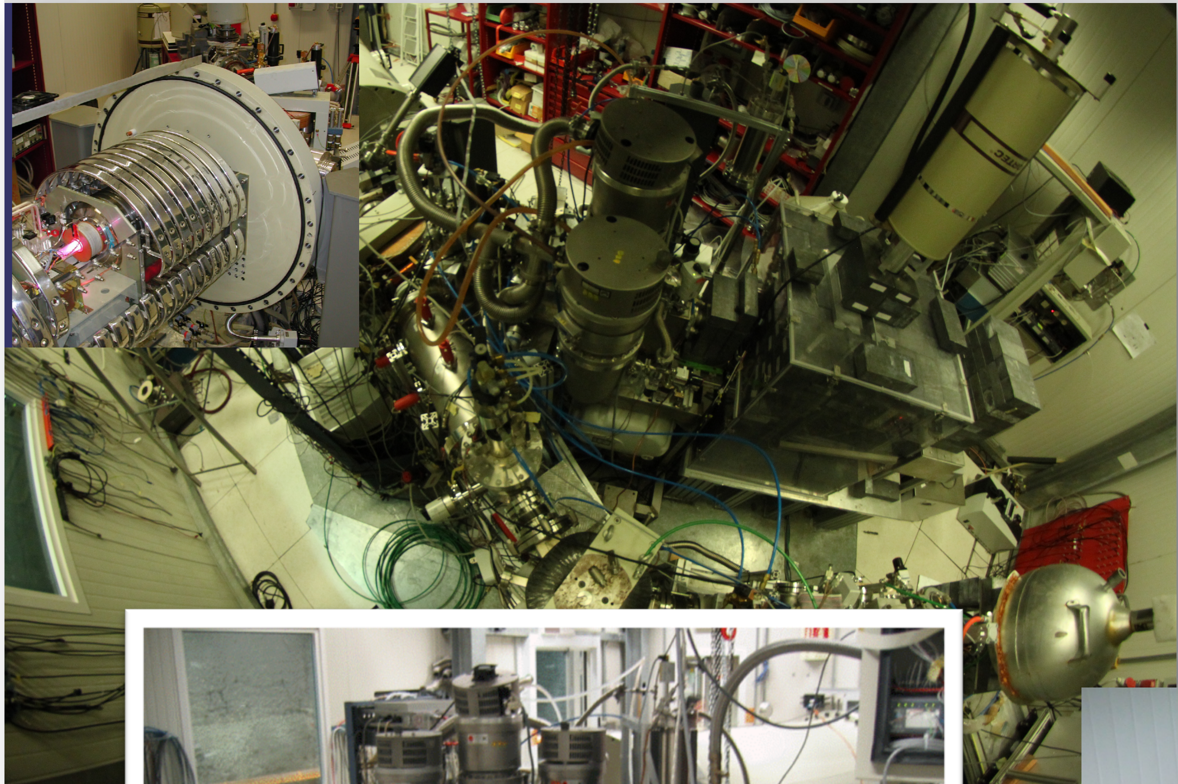
Bonetti *et al*. Phys. Rev. Lett. 82 (1999) 5205

first measurement within solar Gamow energy!
no extrapolation needed; no new resonance found

LUNA 400kV site



The LUNA 400KV Underground Laboratory



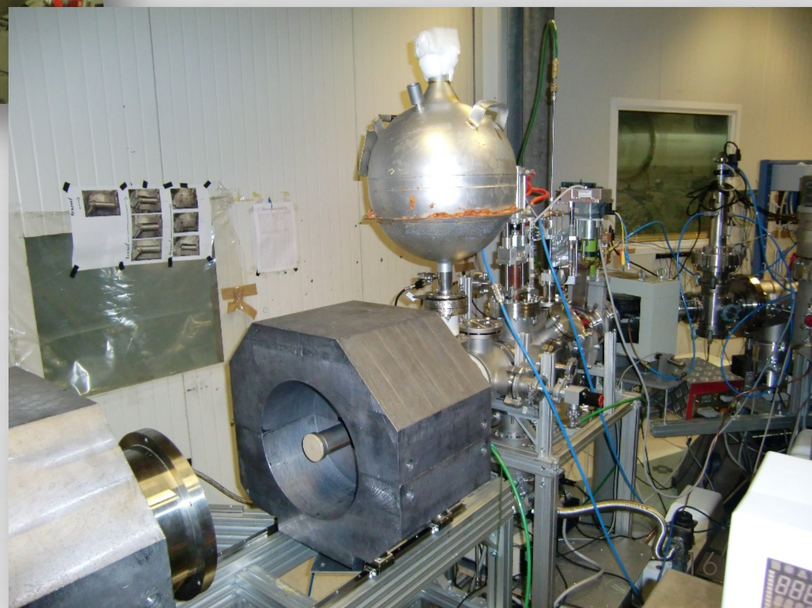
$U_{terminal}$ = 50 – 400 kV

I_{max} = 500 μA (on target)

ΔE = 0.07 keV

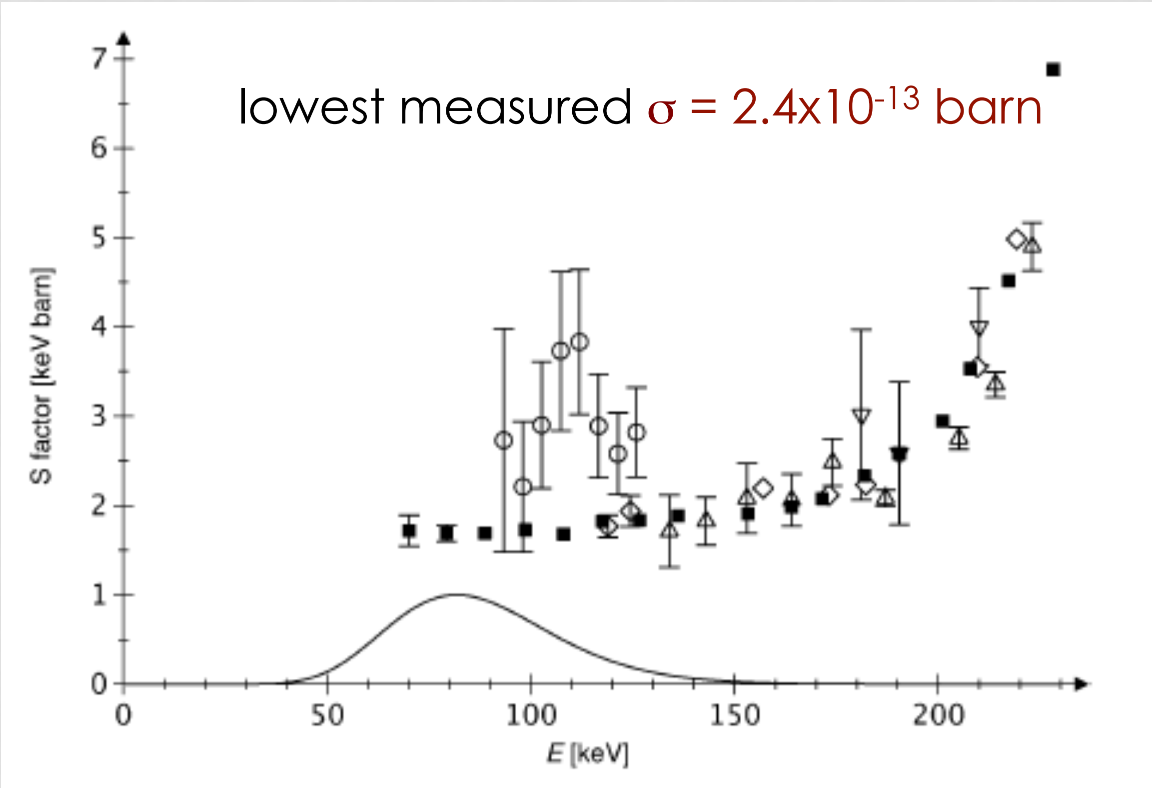
Allowed beams:

H^+, ^4He, (^3He)



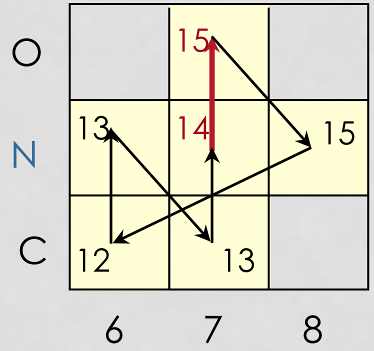
The $^{14}N(p,\gamma)^{15}O$ reaction

slowest reaction in CNO cycle



A. Lemut et al Phys Lett B634 (2006) 483
A. Formicola et al. PL B591 (2004) 61-68
G. Imbriani et al. A&A 420 (2004) 625

CNO cycle

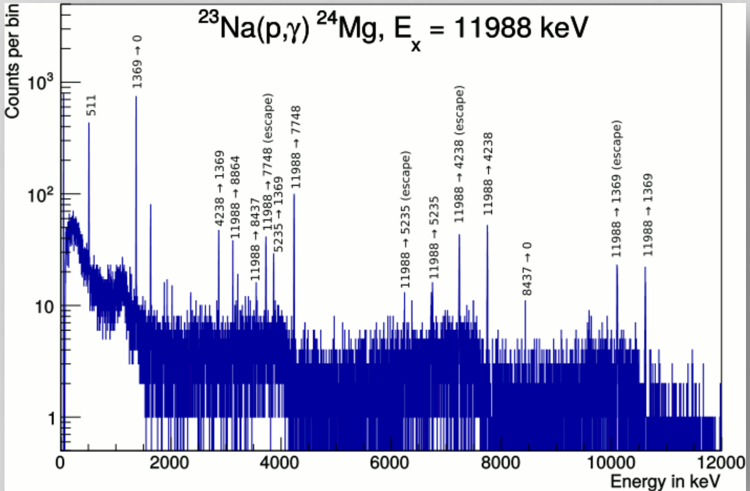


- solar neutrino flux from CNO reduced by factor 2
- age of globular cluster increased by 1Gy !!

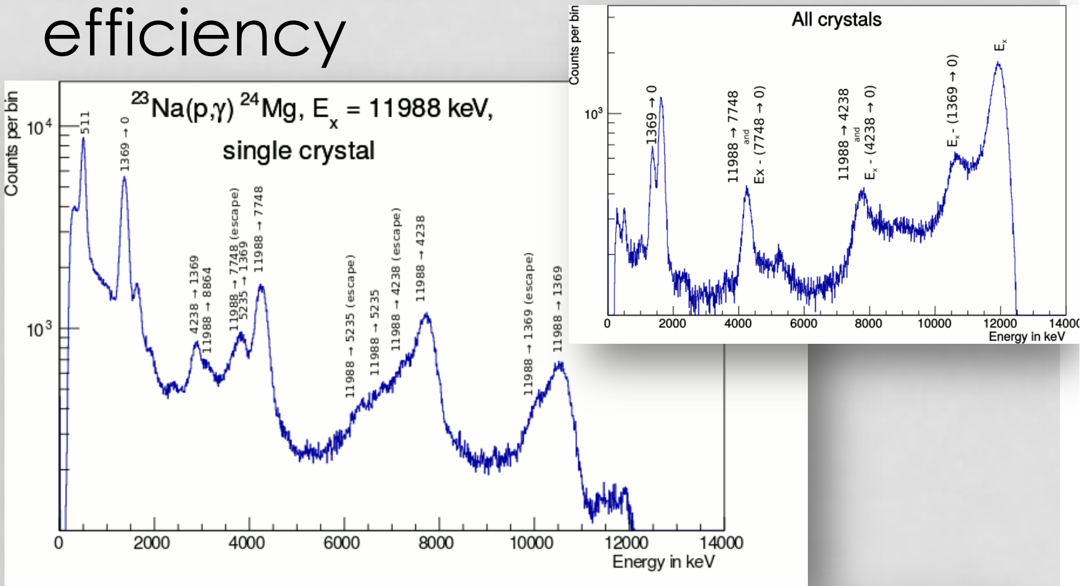
$^{23}Na(p,\gamma)^{24}Mg$ at LUNA

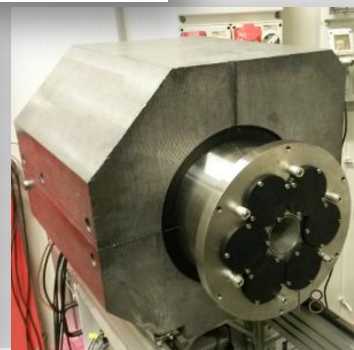
Direct measurements underground at LNGS:
solid target, two shielded detector setups.
Data taking of both phases concluded. Analysis ongoing.

HPGe for high resolution



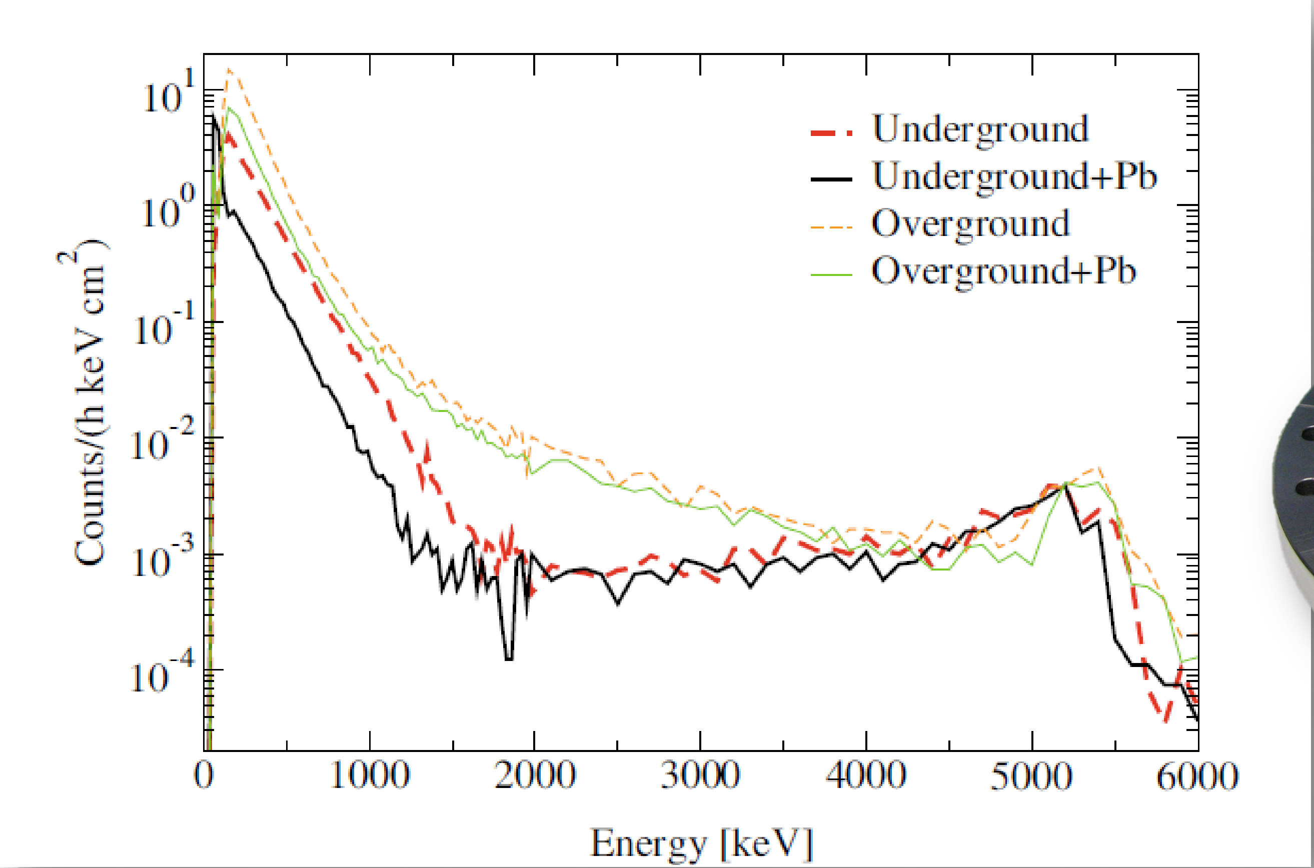
segmented 4π BGO for high efficiency

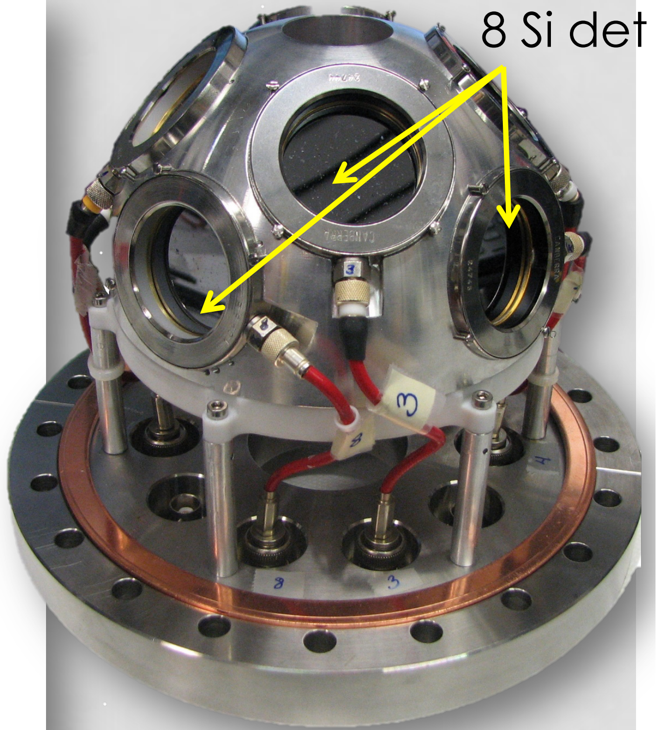




Alpha background and low resonance study of the $^{17}O(p,\alpha)^{14}N$ reaction

Underground+Pb vs. Overground
factor ~10-15 reduction in the range 200 keV - 2.5 MeV



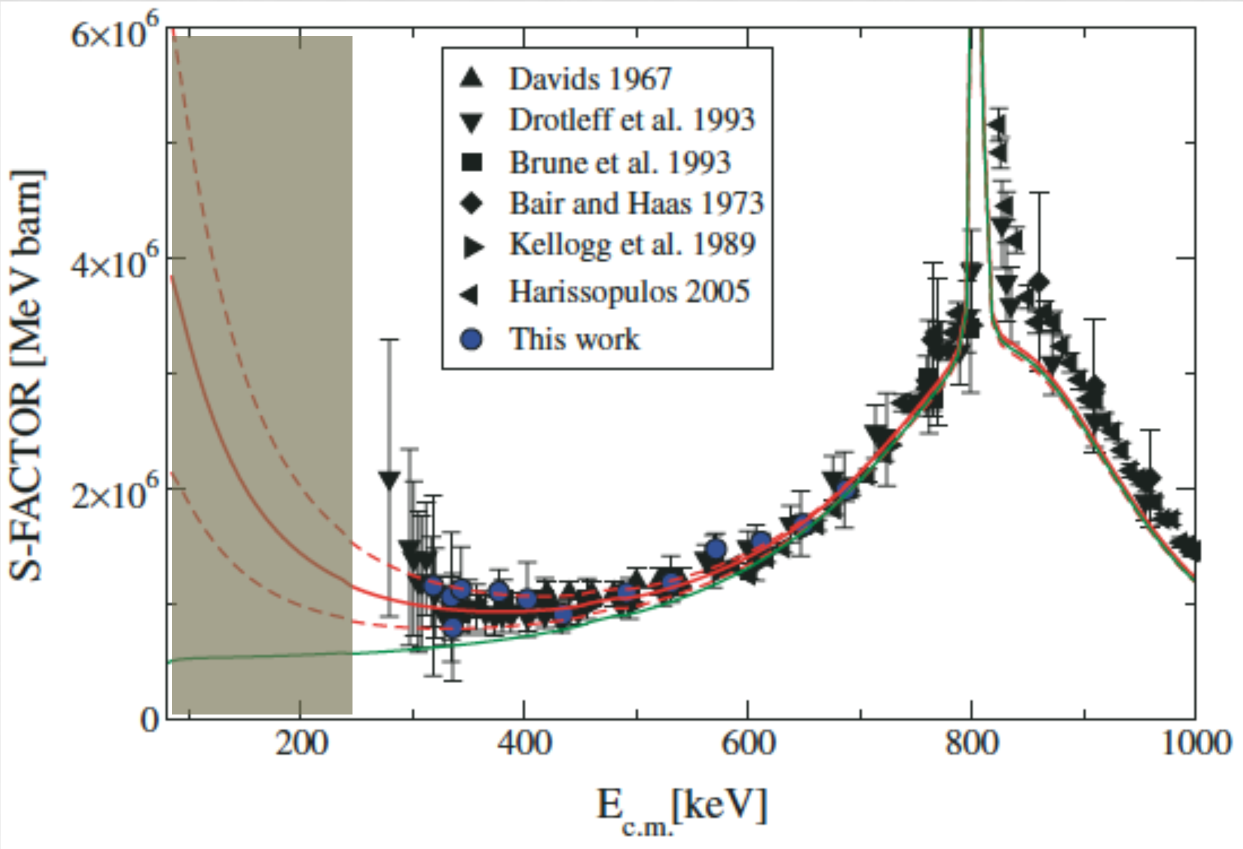


- $^{17}O(p,\alpha)^{14}N$ Expected alpha energy about 1 MeV
- Two narrow resonances at 70 and 193 keV dominant at astrophysical temperatures

PRL in print

The $^{13}C(\alpha, n)^{16}O$ reaction

importance: s-process in AGB stars
Gamow region: 130 - 250 keV
min. measured E: 270 keV



mainly hampered by cosmic background

LUNA's Achievements to Date

- electron screening & stopping power

  $d(^3He,p)^4He$ and $^3He(d,p)^4He$

- solar fusion reactions

  $^3He(^3He,2p)^4He$, $^2H(p,\gamma)^3He$, $^3He(\alpha,\gamma)^7Be$

- CNO and Mg-Al cycles

  $^{14}N(p,\gamma)^{15}O$, $^{15}N(p,\gamma)^{16}O$, $^{25}Mg(p,\gamma)^{26}Al$

- explosive hydrogen burning in novae and AGB stars

  $^{17}O(p,\gamma)^{18}F$, $^{17}O(p,\alpha)^{14}N$

- BBN and the lithium problem

  $^2H(\alpha,\gamma)^6Li$

- NeNa cycle

over 50 publications (including 13 Letters, 2 Reviews) and numerous Master and PhD Theses

Training Opportunities

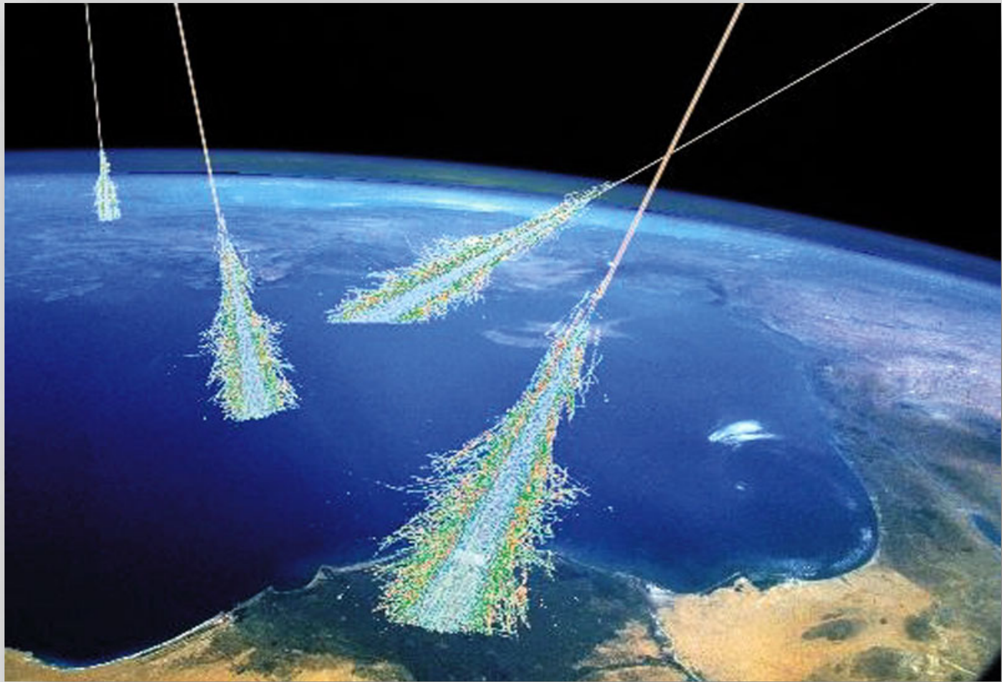
hands-on experience on:

- ion source and accelerator systems
- beam transport and optimization
- vacuum systems
- target preparation and characterization
- detection systems and electronics
- data acquisition techniques and data analysis
- small-sized international collaboration

thesis availabilities: iza.kochanek@lngs.infn.it

Current Limitations

- strong limitation on neutron production
- limited beam species (p, α, ^3He)
- limited energy range

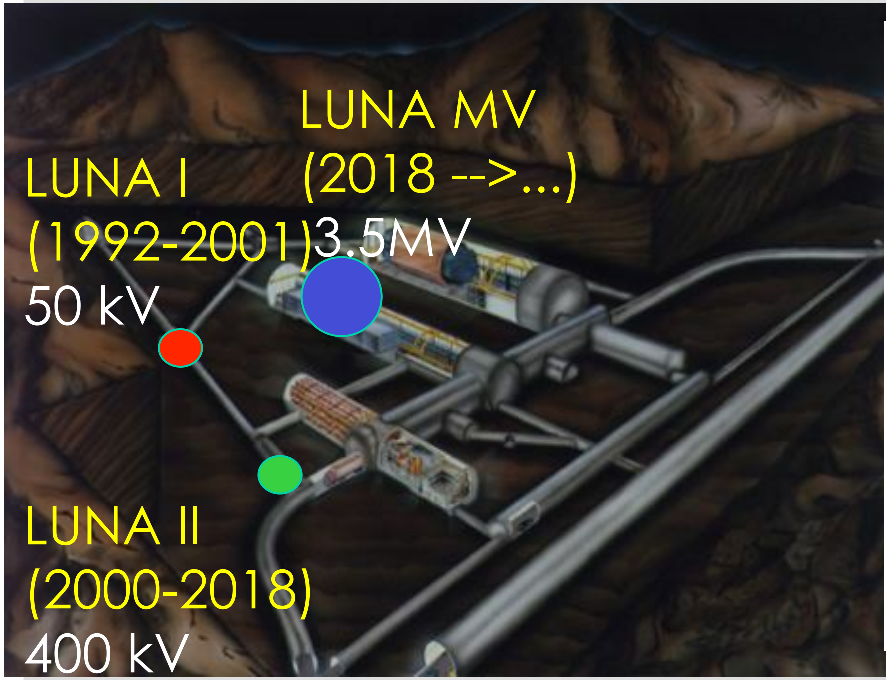


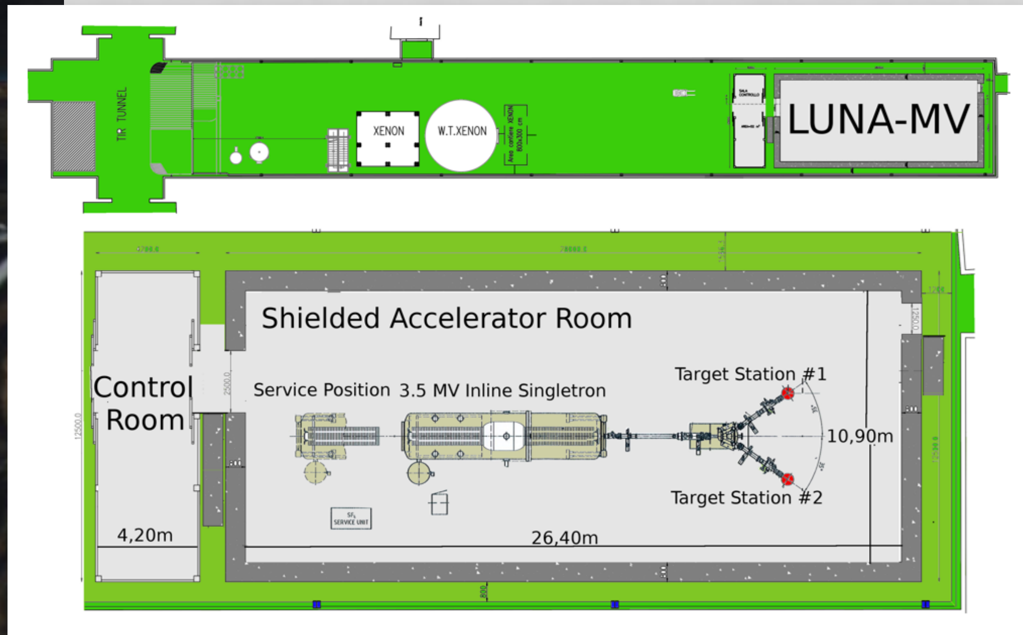
future projects

✓ CUNA	LSC	Laboratorio Subterráneo de Canfranc
✓ JUNA	CJPL	China Jinping Underground Laboratory
✓ CASPAR	SURF	Sanford Underground Research Facility
✓ LUNA MV	LNGS	Gran Sasso National Laboratory

LUNA MV project

LUNA MV will be installed in the North part of Hall B of LNGS





Funded by the Italian Research Ministry as a "premium project" with 5.3 Meuro.
HVEE has been selected through a public tender as provider of the new accelerator (0.3<TV<3.5 MV) able to deliver intense H, He and C beams

Expected installation at LNGS in 2018. First experiment in 2019

LUNA MV- scientific program (2019 ....)

- **$^{13}C(\alpha,n)^{16}O$**: enriched ^{13}C solid or gas target. Neutron detector Data taking at LUNA 400 kV in 2017-2018.
- **$^{22}Ne(\alpha,n)^{25}Mg$**: enriched ^{22}Ne gas target. Neutron detector.
- **$^{12}C(\alpha,\gamma)^{16}O$**: ^{12}C solid target depleted in ^{13}C and alpha beam or a jet gas target and ^{12}C beam.
- **$^{12}C+^{12}C$**: solid state target. Gamma and particle detectors
- Commissioning measurement: **$^{14}N(p,\gamma)^{15}O$**. High scientific interest for revised data covering a wide energy range (400 keV- 3.5 MeV).

LUNA MV is open to new collaborations on the whole program or even on single experiments (please refer for any information SP: prati@ge.infn.it)

On December 1st, 2016 a workshop will be organized at LNGS both to celebrate the first 25-year period of LUNA activities ("*Silver Moon*") and to present the perspectives for the next decades :http://silvermoon.lngs.infn.it/

Summary and Outlook

Underground measurements have revolutionized experimental nuclear astrophysics and our understanding of stellar energy generation, nucleosynthesis, and neutrino physics

New underground facilities will open up exiting new opportunities for further major breakthrough in the field

The LUNA COLLABORATION (as of May 2016)

- A. Boeltzig*, G.F. Ciani*, L. Di Paolo, A. Formicola, I. Kochanek, M. Junker, | INFN LNGS / *GSSI, Italy
- D. Bemmerer, M. Takacs, T. Szucs | HZDR Dresden, Germany
- C. Broggini, A. Caciolli, R. Depalo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy
- Z. Elekes, Zs. Fülöp, Gy. Gyurky | MTA-ATOMKI Debrecen, Hungary
- O. Straniero | INAF Osservatorio Astronomico di Collurania, Teramo, Italy
- F. Cavanna, P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | Università di Genova and INFN Genova, Italy
- A. Guglielmetti, D. Trezzi | Università di Milano and INFN Milano, Italy
- A. Best, A. Di Leva, G. Imbriani, | Università di Napoli and INFN Napoli, Italy
- G. Gervino | Università di Torino and INFN -Torino, Italy
- M. Aliotta, C. Bruno, T. Davinson | University of Edinburgh, United Kingdom
- G. D'Erasmo, E.M. Fiore, V. Mossa, F. Pantaleo, V. Paticchio, R. Perrino, L. Schiavulli, A. Valentini | Università di Bari and INFN Bari, Italy