Reaction rate measurements in underground laboratories


Laboratory
Underground
Nuclear
Astrophysics

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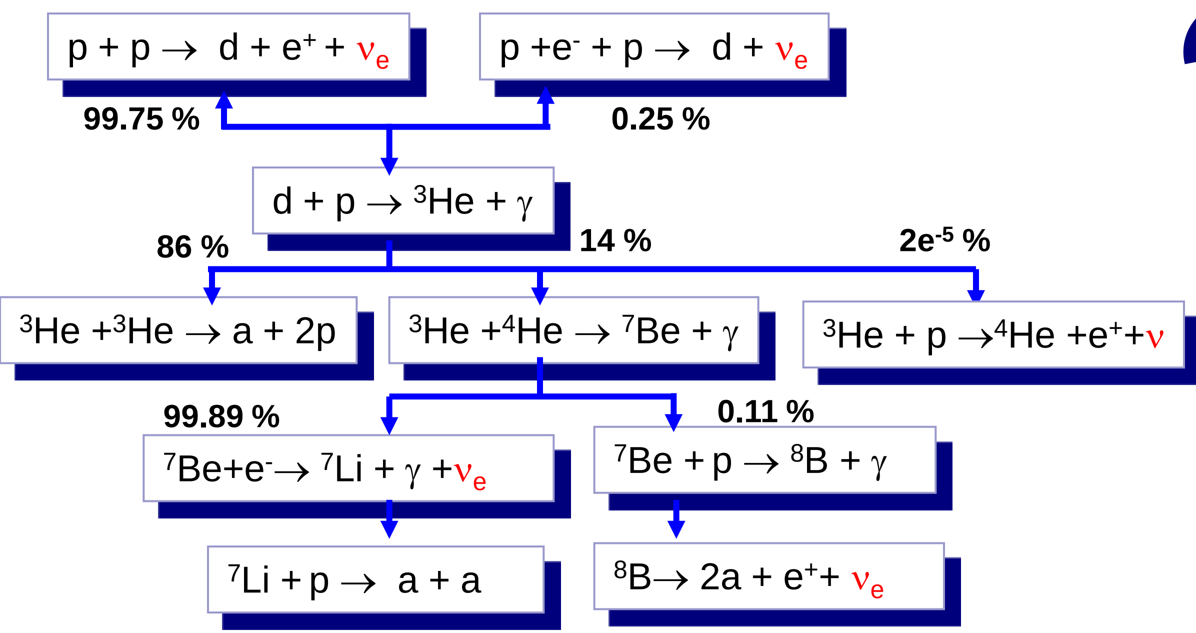
Outline

- Nuclear fusion reactions in Stars: H-burning
- Why going underground ?
- The LUNA experiment:
  - Main nuclear reactions studied
  - Experimental techniques and challenges
- Perspectives in underground nuclear astrophysics

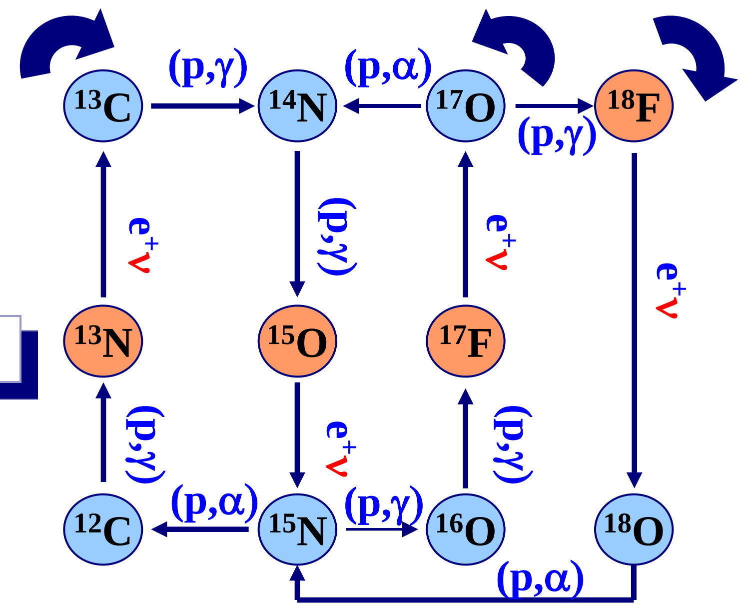
H-burning

produces energy for most of the life of the stars

pp chain

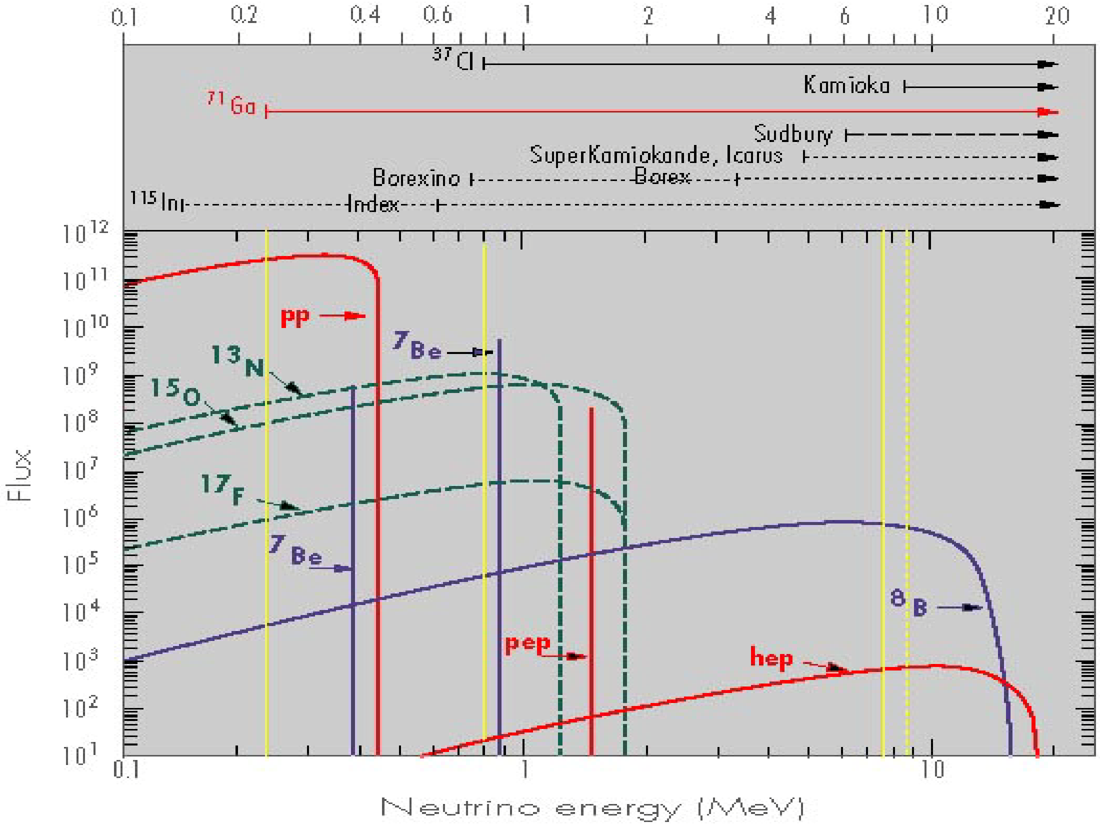


CNO cycle



$$4p \rightarrow {}^{4}He + 2e^{+} + 2\nu_e + 26.73\ MeV$$

Solar ν fluxes



SNO+SK

$$\frac{\Delta\phi(^8B)}{\phi(^8B)} = 3\%$$

Borexino

$$\frac{\Delta\phi(^7Be)}{\phi(^7Be)} = 10\%$$

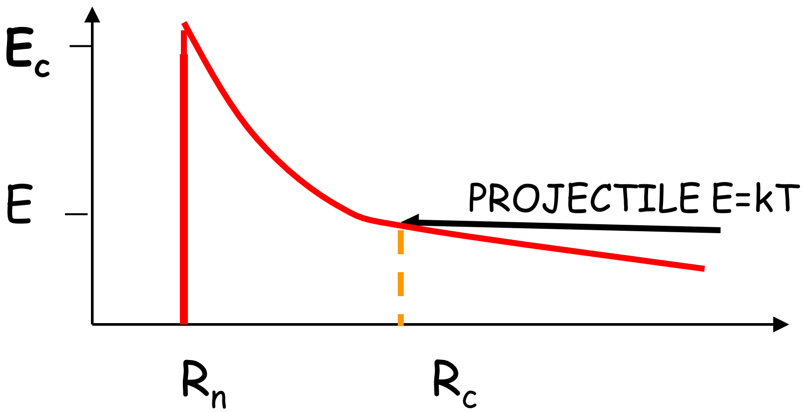
$\Phi_B = \Phi_B$ (SSM) · $S_{33}^{-0.43}\ S_{34}^{0.84}\ S_{17}^{1}\ S_{e7}^{-1}\ S_{pp}^{-2.7} com^{1.4}\ opa^{2.6}\ dif^{0.34}\ lum^{7.2}$

New precise determination of Solar ν fluxes

↓

Nuclear cross sections have to be known with comparable precision

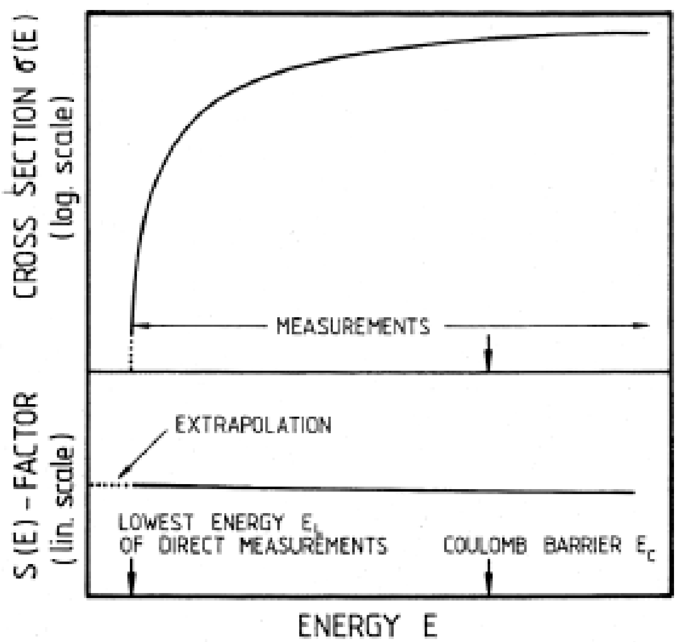
Reaction rate for charged particles



Gamow energy

$^{3}He(^{3}He,2p)^{4}He$	22 keV
$d(p,\gamma)^{3}He$	7 keV
$^{14}N(p,\gamma)^{15}O$	27 keV
$^{12}C(\alpha,\gamma)^{16}O$	300 keV

$$\sigma(E) = \frac{S(E)}{E} e^{-31.29 Z_p Z_t \sqrt{\frac{\mu}{E}}}$$



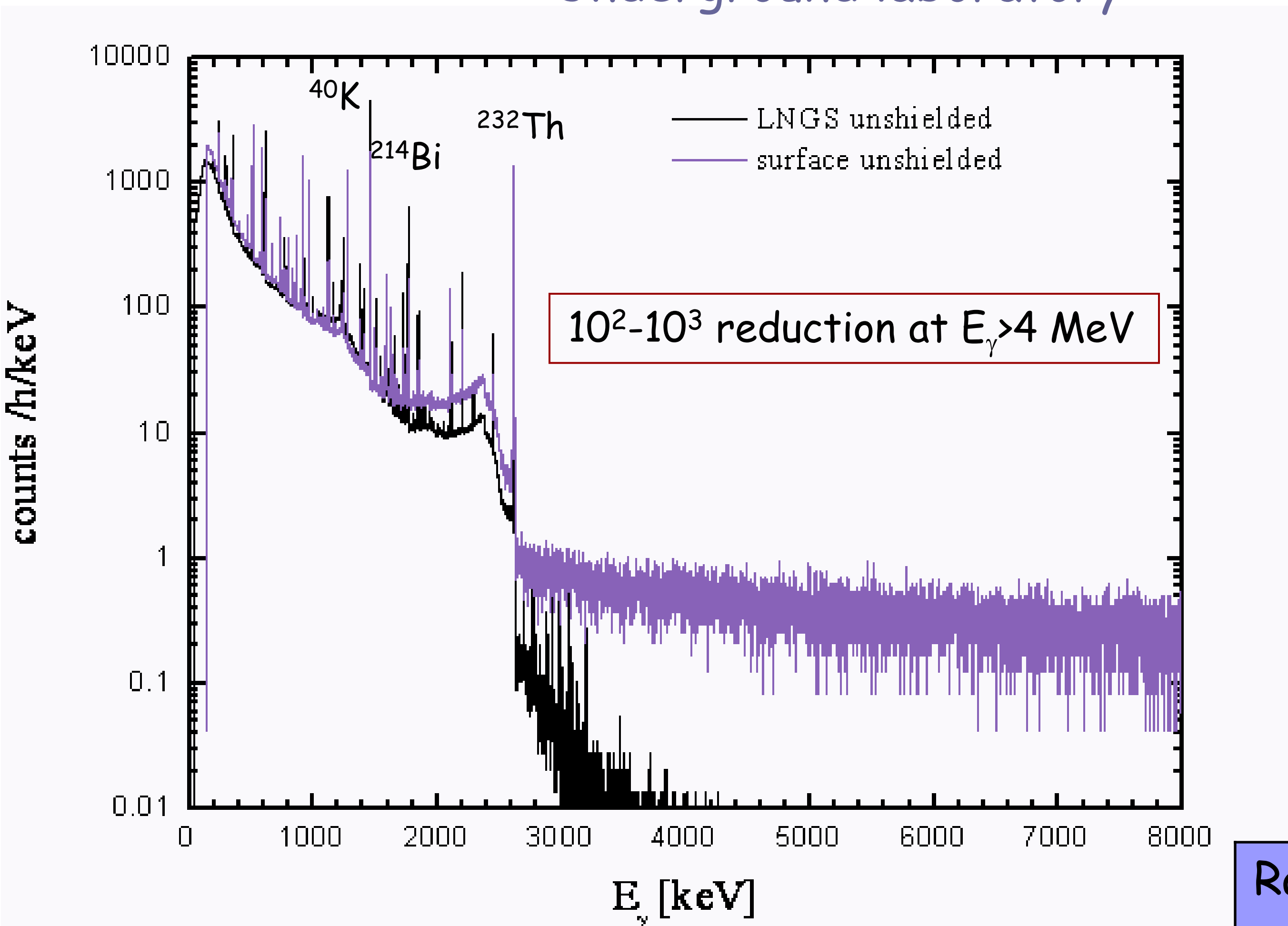
pb < σ < nb

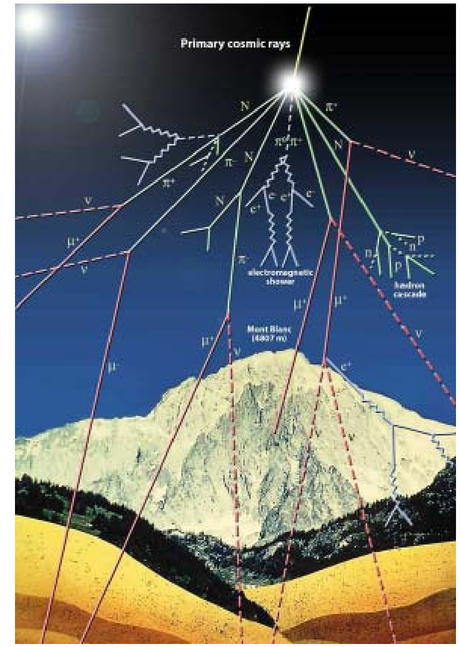
event/month < R_{lab} < event/day

Extrapolation is needed !!

Cosmic ray induced background

Underground laboratory





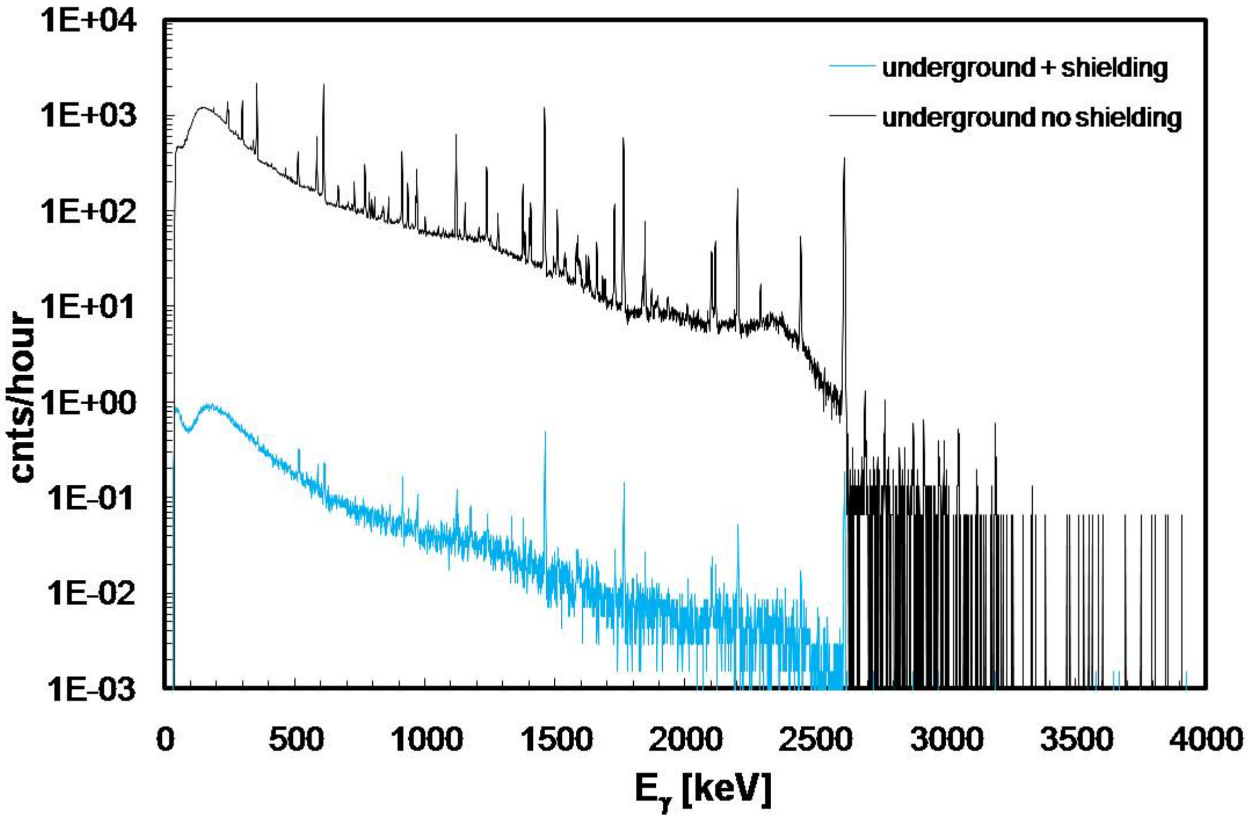
Advantage of underground measurements for reaction with high Q-values:

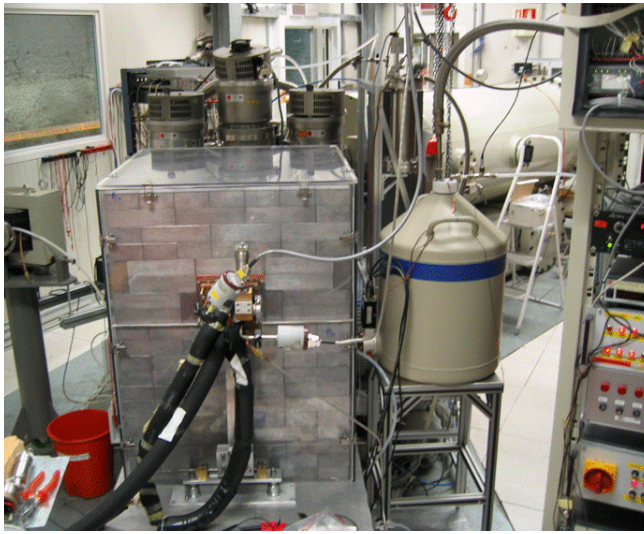
$d(p,\gamma)^3He$, $^{14}N(p,\gamma)^{15}O$, $^{15}N(p,\gamma)^{16}O$, $^{25}Mg(p,\gamma)^{26}Al$

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

Natural radioactivity background

Underground Lead shield + Radon box





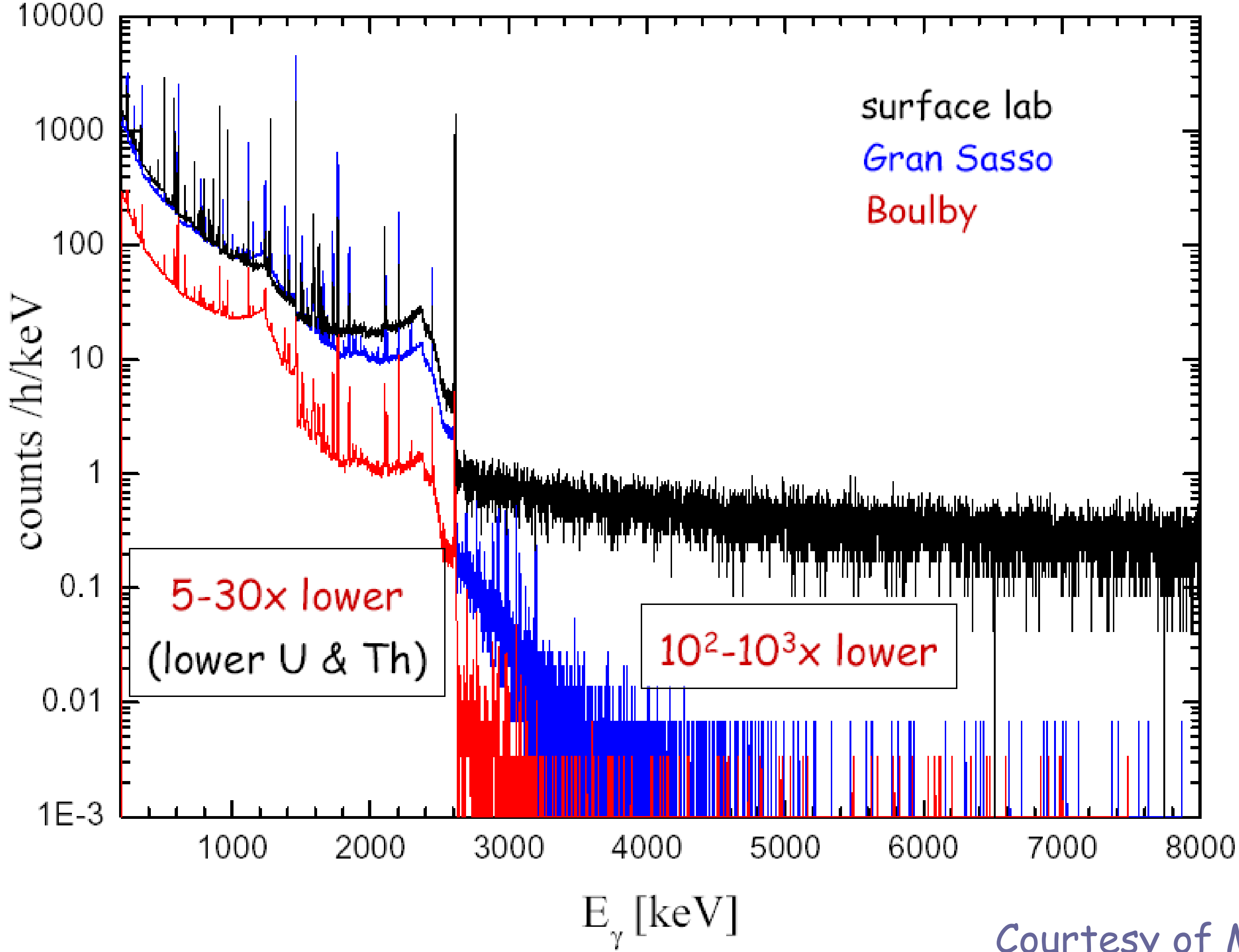
Passive shielding is more effective underground since the μ flux, that create secondary γs in the shield, is suppressed.

Advatnage for underground measurements also for low Q-value reactions:

$^3He(\alpha,\gamma)^7Be$, $D(\alpha,\gamma)^6Li$

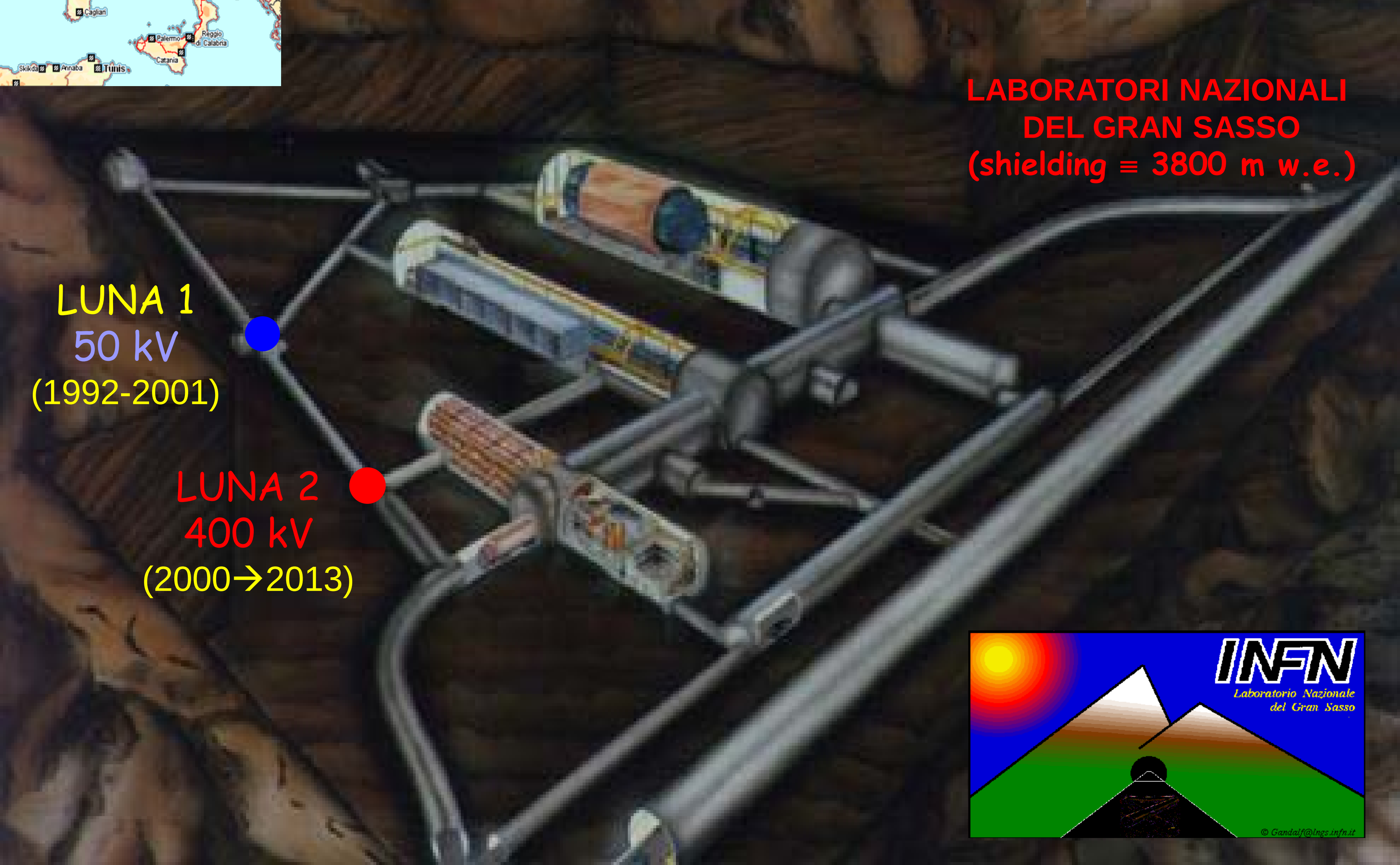
Natural radioactivity background

Underground salt mine



Courtesy of M. Aliotta

Laboratory for Underground Nuclear Astrophysics



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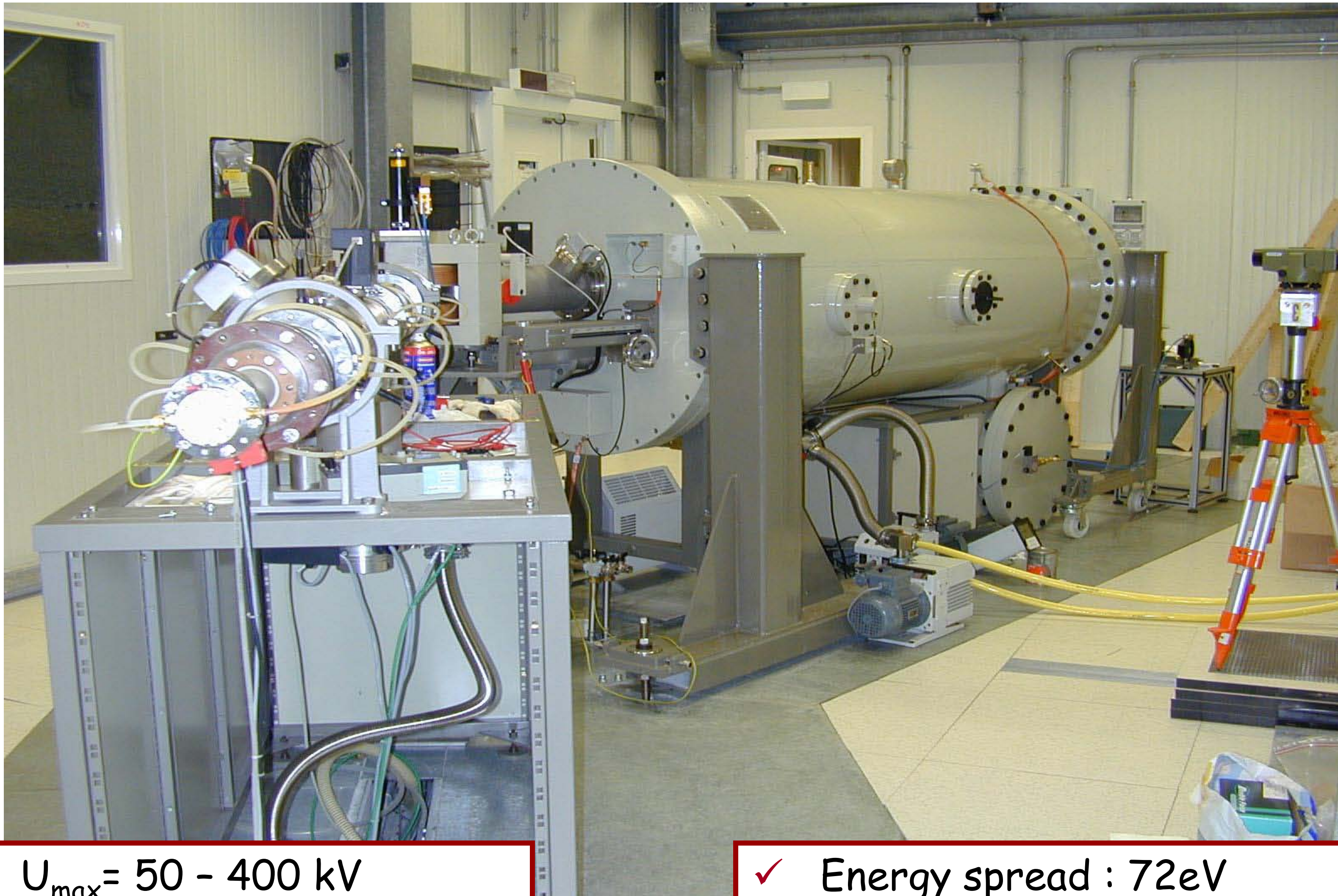
400 kV: LUNAII



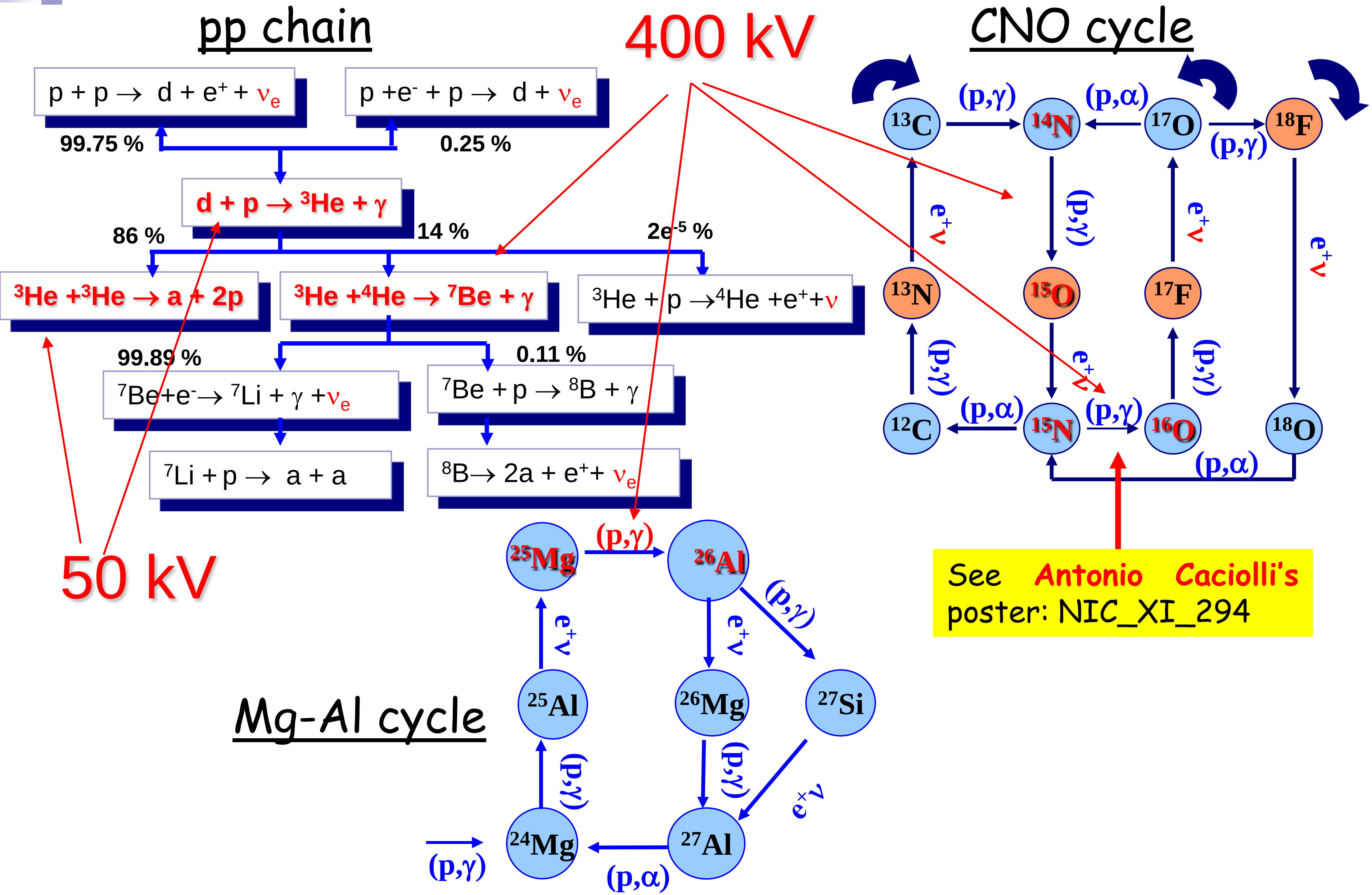
- ✓ U_{max}= 50 – 400 kV
- ✓ I ~ 500 μA for protons

  I ~ 250 μA for alphas

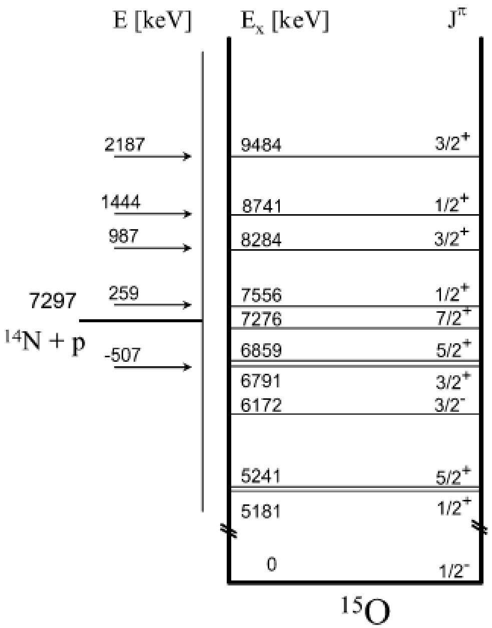
- ✓ Energy spread : 72eV
- ✓ Total uncertainty is ±300 eV

  between Ep = 100 ÷ 400keV

H-burning measurements at LUNA

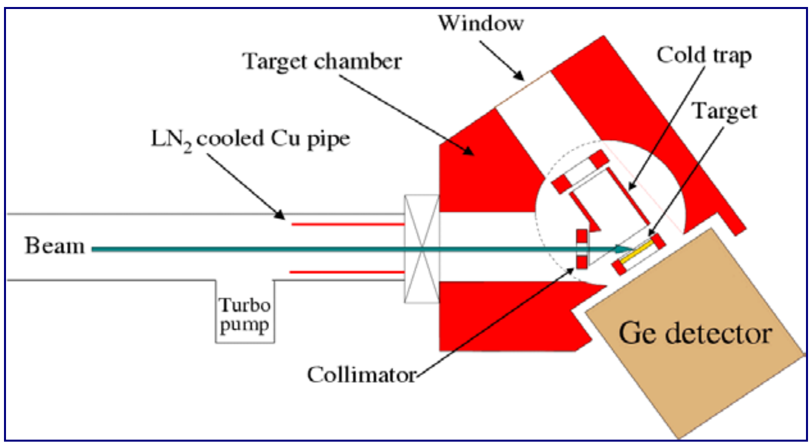


$^{14}N(p,\gamma)^{15}O$

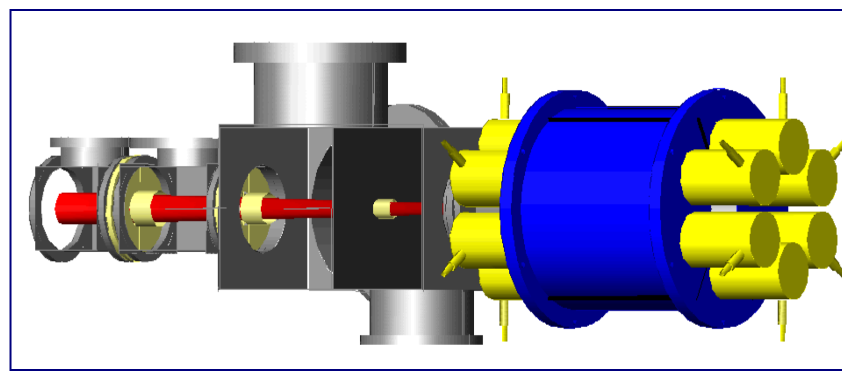


- Slowest reaction of CNO cycle
- Determines rate of CNO neutrinos from the Sun
- Determines the age of the Globular Clusters

2 experimental approaches

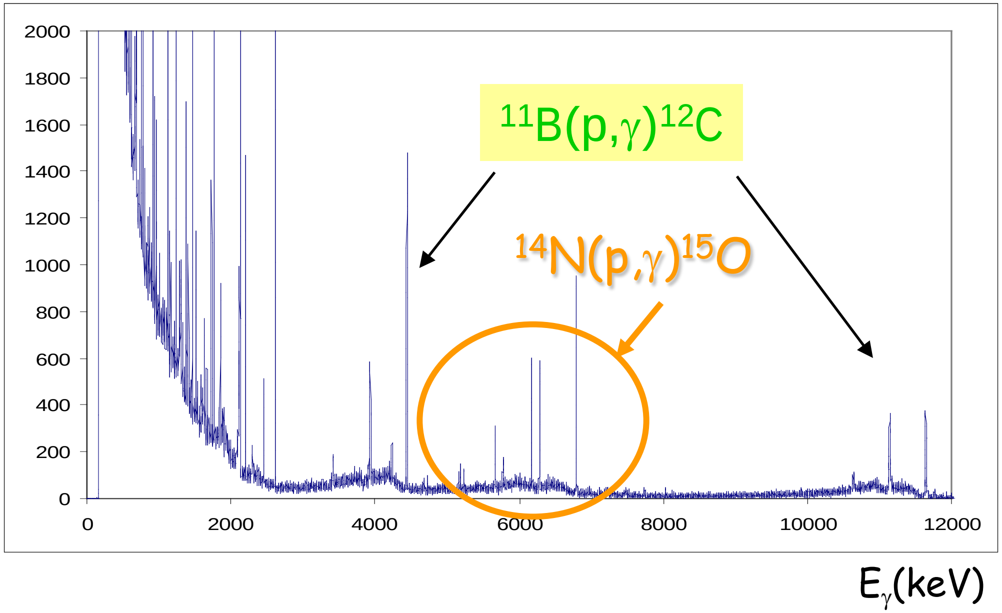


HpGe +solid target (E_{min}=120 keV)



BGO crystal + gas target (E_{min}=70 keV)

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



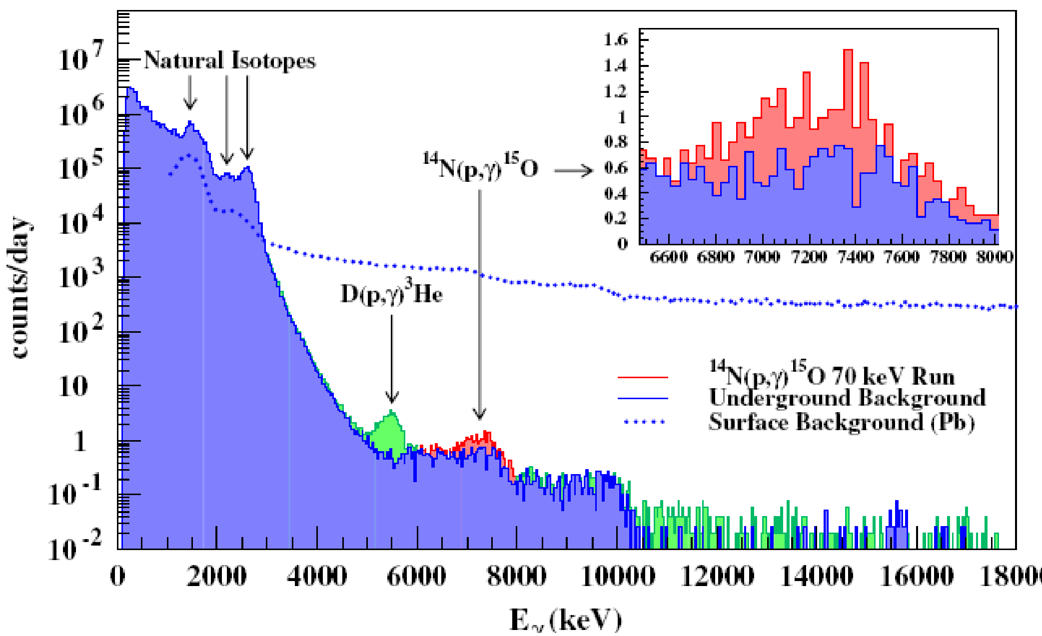
HPGe phase

Spectrum at E_b=200 keV

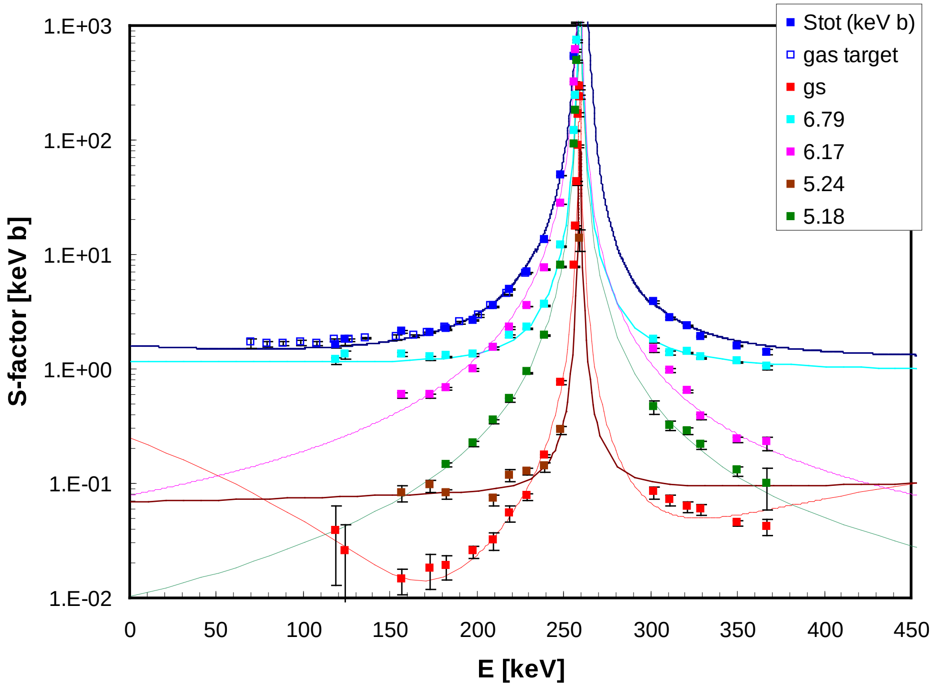
BGO phase

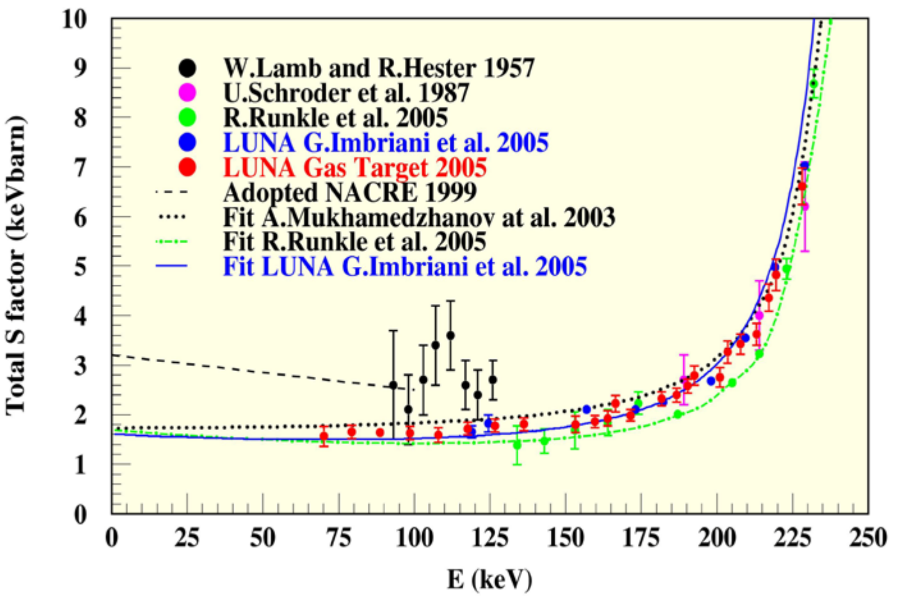
Spectrum at E_b=80 keV

Reaction Rate = 10.95 ± 0.83 counts/day
Background rate = 21.14 ± 0.75 counts/day



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





Both results confirm the low reaction rate

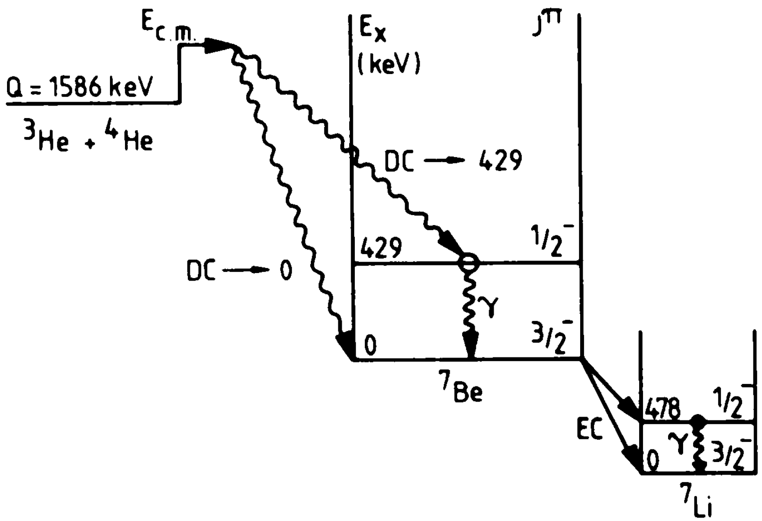
- GC age increases of 0.7-1 Gyr
- CNO neutrino flux decreases a factor ≈ 2
- more efficient dredge up in AGB stars

For a precise S-factor extrapolation, new high energy data are needed

M.Marta: NIC_XI_279

P.Bertone: NIC_XI_206

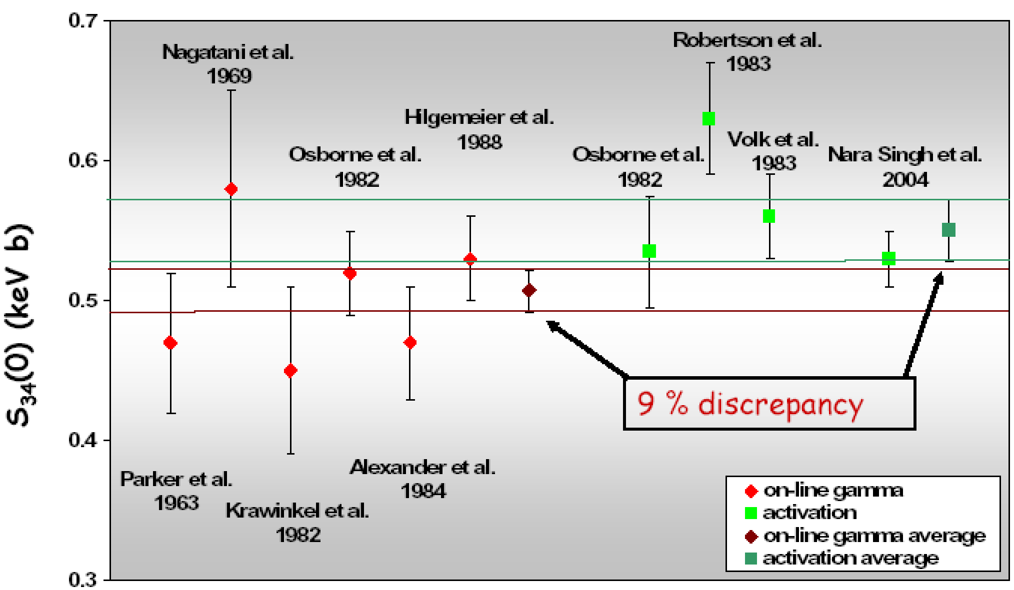
$^3He(\alpha,\gamma)^7Be$



- Major nuclear source of uncertainty for ^8B neutrino flux determination

	$\frac{\Delta\Phi_B}{\Delta\sigma}$	$\frac{\Delta\Phi_B}{\Phi_B}$
$^3He(^3He,2p)^4He$	-0.43	2.1%
$^4He(\alpha,\gamma)^7Be$	0.84	7.5%
$^7Be(p,\gamma)^8B$	1.00	3.8%

δ

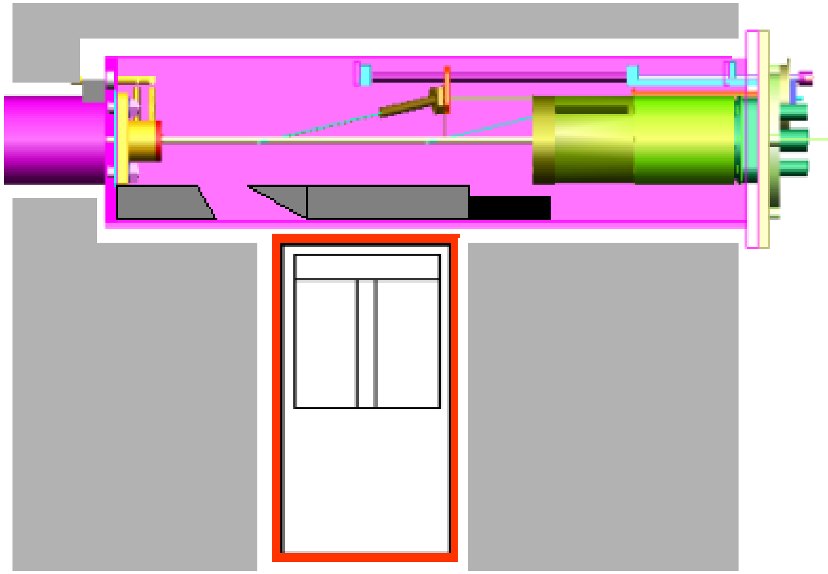


- Large uncertainty derived from discrepancy between results obtained with prompt gamma detection and activation techniques

Main goal: high precision measurement

$^3He(\alpha,\gamma)^7Be$: prompt γ and activation

- ^{3}He recirculating gas target
- HpGe detector in close geometry for online γ detection
- Removable calorimeter cap for offline ^{7}Be counting (with separated HPGe Detector)
- Si-monitor for target density measurements (beam heating effect)
- 0.3 m^3 Pb-Cu shield around detector
- chamber in OFC to reduce background on the detector



Uncertainties

Prompt- γ

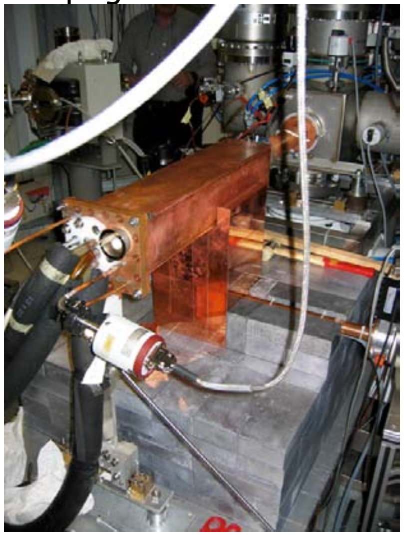
Beam current	1.5%
Target density	1.5%
Detection efficiency	1.5%
Angular distribution	2.5%
^{3}He purity	0.1%

Activation

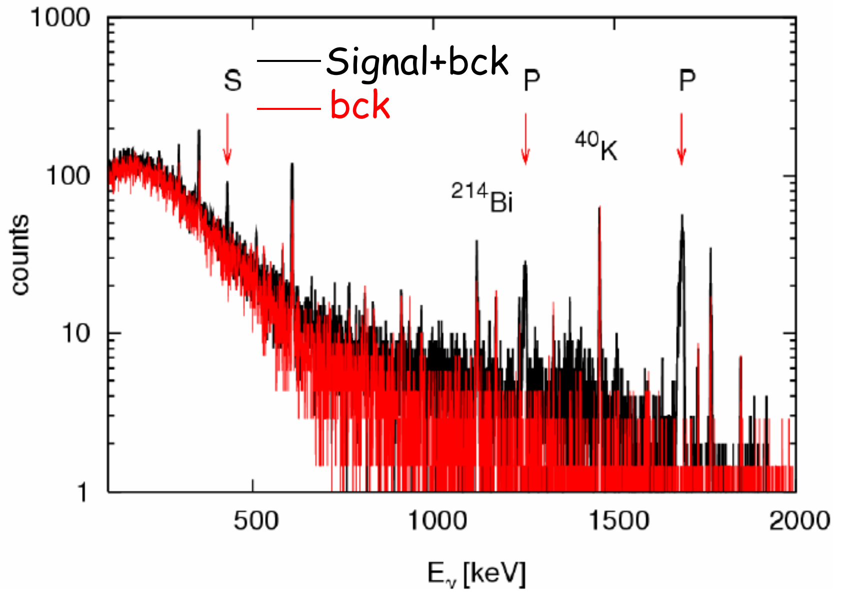
^{7}Be detection efficiency	1.8%
Beam current	1.5%
Target density	1.5%
^{7}Be backscattering	0.5%
^{7}Be collection efficiency	0.4%
^{7}Be distribution effects	0.4%
478 keV branching	0.4%
^{7}Be life time	0.1%
^{3}He purity	0.1%

$^3He(\alpha,\gamma)^7Be$: prompt γ and activation

Prompt gamma measurements

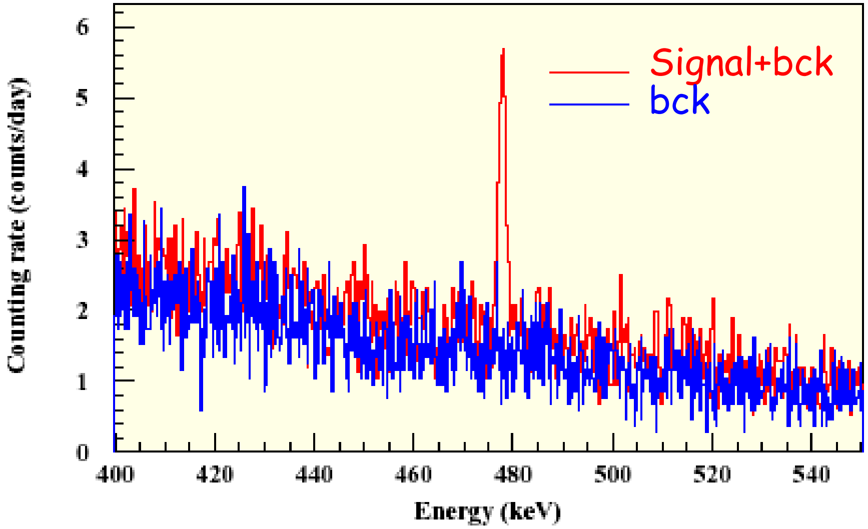


E=93 keV T=31,2 days

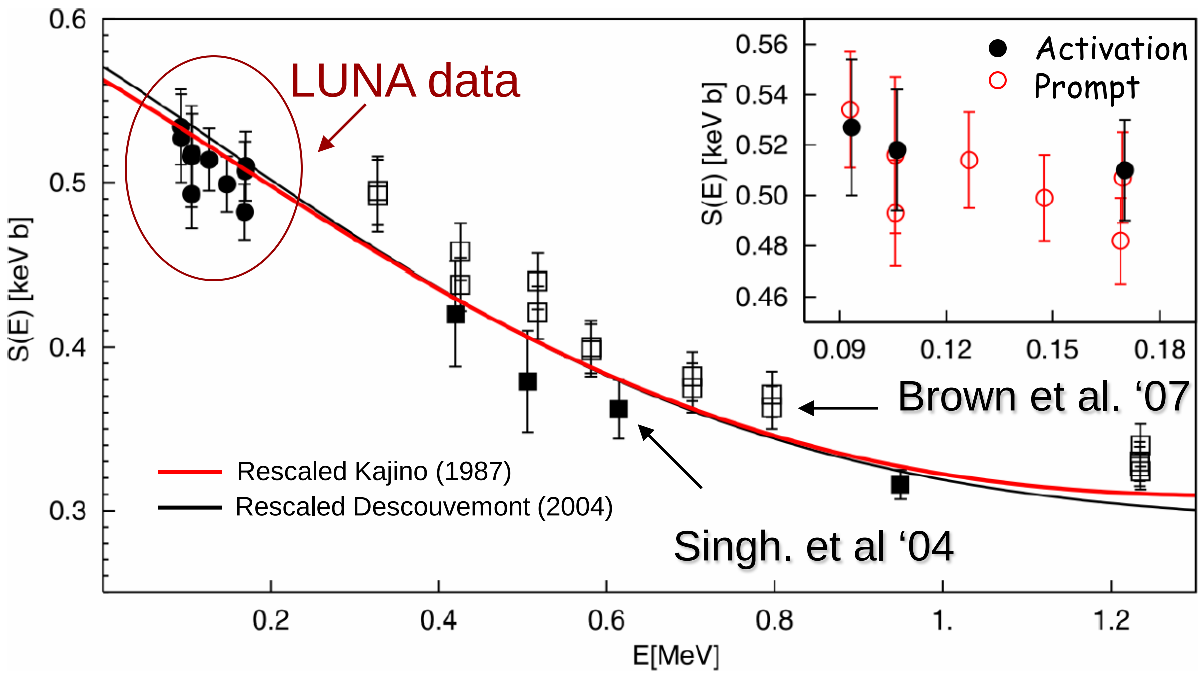


Activation measurements

E=93 keV T=11,6 days



$^3He(\alpha,\gamma)^7Be$



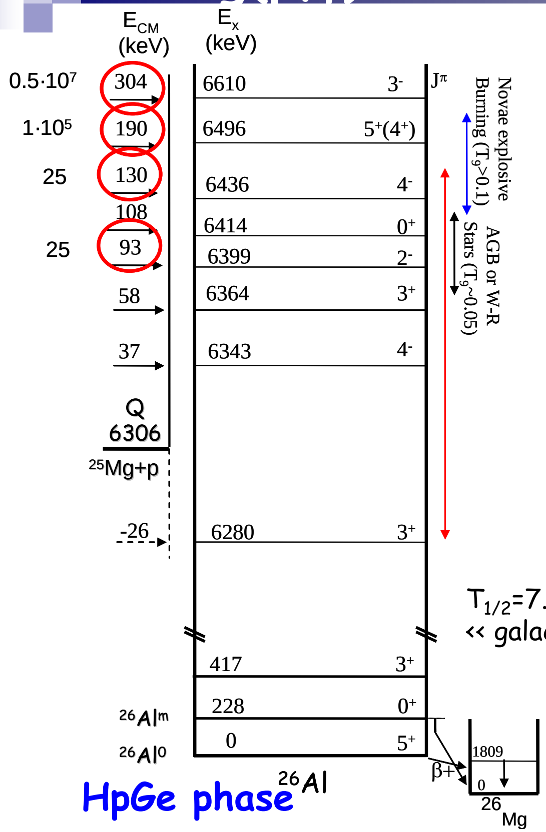
- no discrepancy between prompt and activation methods
- decrease of uncertainty on ^8B neutrino flux. From LUNA results: $$\frac{\Delta\Phi_B}{\Phi_B} = 8\% \rightarrow 3\%$$

- There is a new measurement in energy region 0.65 < E < 2.5 MeV with recoil separator (ERNA)

See next talk by A. di Leva

S-factor extrapolation would benefit from full-energy range experiment (0.1-2 MeV) to determine S-factor energy dependence at low energies

$^{25}Mg(p,\gamma)^{26}Al$



$T_{1/2}$=7.2 10^5 y
« galactic time scale

• Radioactive ^{26}Al in the galaxy → evidence that ^{26}Al nucleosynthesis is still active (SN and NOVAE)

•^{26}Mg excess in meteorites→ Signature of ^{26}Mg production during Hydrogen burning (AGB)

↓

Any astrophysical scenario for ^{26}Al nucleosynthesis must be concordant with both observations

HpGe phase

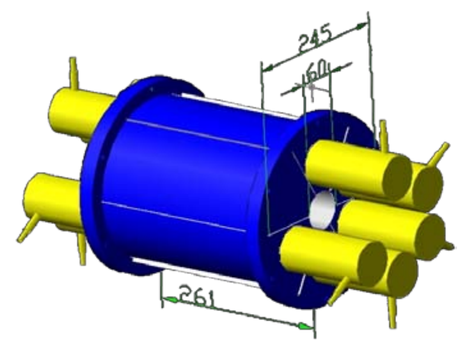
E_R=304, 190 keV

AMS technique

CIRCE lab. Caserta, Italy

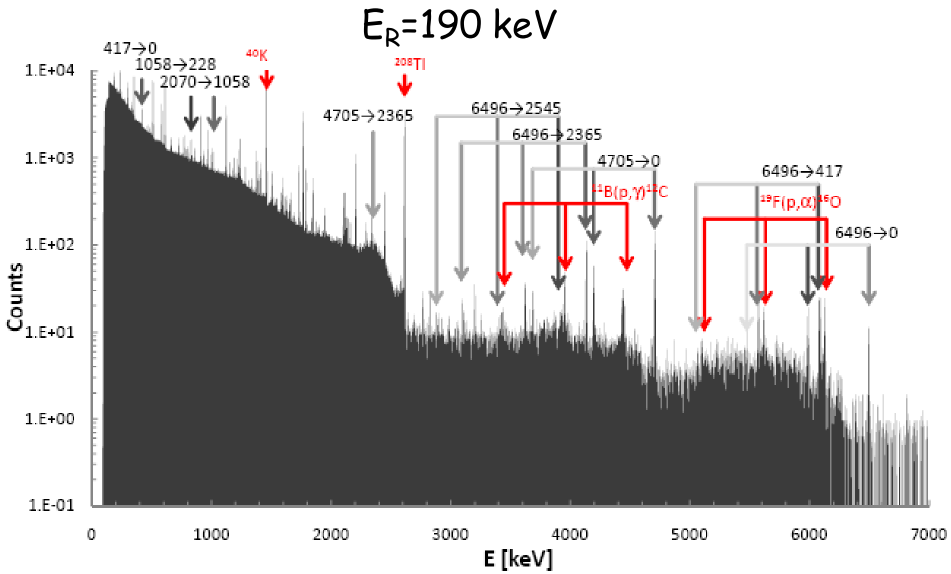
E_R=304 keV

BGO phase

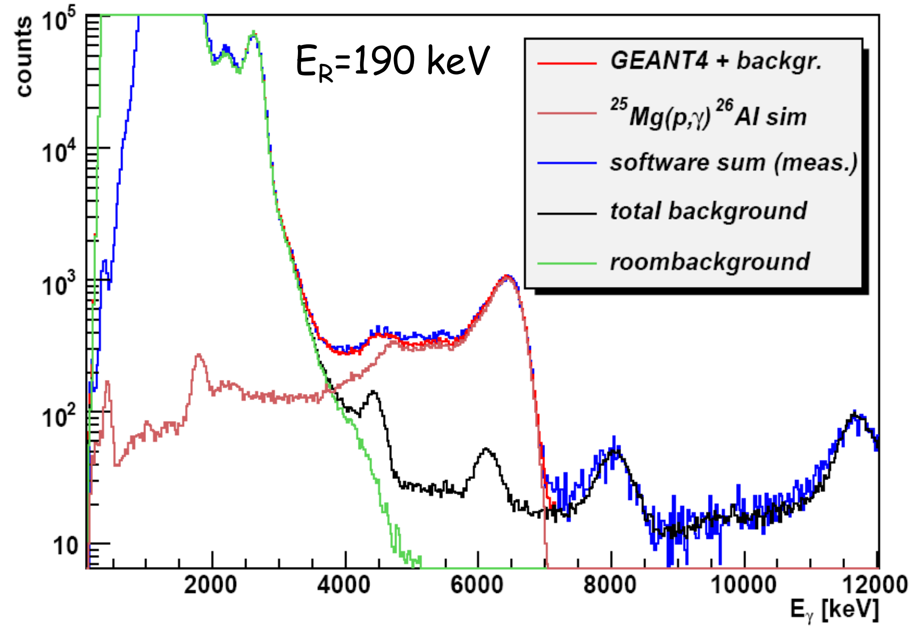


E_R=304, 190, 130, 93 keV

$^{25}Mg(p,\gamma)^{26}Al$



HpGe phase



BGO phase

E_R[keV]	ωγ [meV] LUNA HPGe	ωγ [meV] LUNA BGO	$\omega\gamma_{AMS}/\omega\gamma_{BGO}$ LUNA AMS	ωγ [meV] Iliadis et al. 1990	ωγ [meV] Arazi et al.2006	ωγ [meV] NACRE
304	**31.2 ± 0.9**	**30.6 ± 0.8**	**1.01 ± 0.06**	**29 ± 2**	**24 ± 2**	**31 ± 2**
190	**(8.6 ± 0.8)×10^{-4}**	**(9.2 ± 0.7)×10^{-4}**	–	**(7.1 ± 1.0) ×10^{-4}**	**(1.5 ± 0.3) × 10^{-4}**	**(7.1 ± 0.9) × 10^{-4}**

Present and future measurements at LUNA

- $^{15}N(p,\gamma)^{16}O$: solid target with HpGe (0.12 < E < 2.5 MeV) in collaboration with ND

  solid target with BGO E_{min}=70 keV

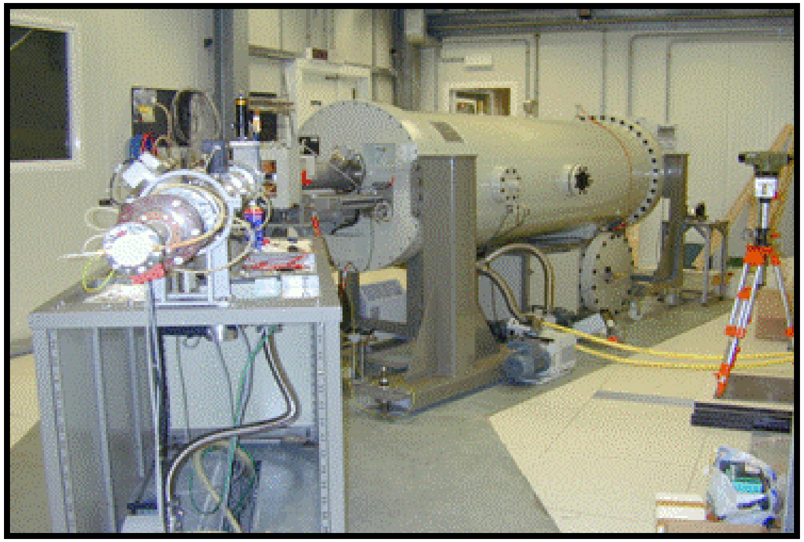
See **Antonio Caciolli's** poster: NIC_XI_294

- $D(\alpha,\gamma)^{6}Li$: gas target with HpGe IN PROGRESS

See **Martin Erhard's** talk this morning at **BBN session**

- $^{17}O(p,\gamma)^{18}F$: IN PREPARATION
- $^{22}Ne(p,\gamma)^{23}Na$
- $^{18}O(p,\gamma)^{19}F$
- $^{23}Na(p,\gamma)^{24}Mg$

...



Perspectives

Relevant questions remain about:
energy production, time scale and nucleosynthesis

Which other reactions could benefit from an underground measurement?

He-burning reactions:
$^{12}C(\alpha,\gamma)^{16}O$ $^{14}N(\alpha,\gamma)^{18}F$ $^{15}N(\alpha,\gamma)^{19}F$ $^{18}O(\alpha,\gamma)^{22}Ne$ ...

Neutron sources:
$^{13}C(\alpha,n)^{16}O$ $^{22}Ne(\alpha,n)^{25}Mg$

Heavy Ion burning:
$^{12}C + ^{12}C$, $^{16}O+^{12}C$

→ Need higher energies than the one delivered by LUNA 400 kV

→ New future facilities are proposed for underground nuclear astrophysics

Proposed projects

- LUNA-Upgrade, Laboratori Nazionali del Gran Sasso, Italy
- DIANA, Homestake Mine, SD USA

A.Lemut: NIC_XI_254

- ELENA, Boulby Mine, UK
- CUNA, Canfranc Laboratorio Subterraneo de Canfranc, Spain

L.Fraile: NIC_XI_093

- Felsenkeller shallow underground laboratory, Dresden, Germany

D. Bemmerer: NIC_XI_237

See **M. Wiescher's** talk on Friday!!

Conclusions

- LUNA has proved that for many nuclear reactions of astrophysical importance, there is a great advantage of an underground study

- Extremely low reaction rate measurements need special effort to achieve background reduction, target stability, beam stability and intensity

- New underground facilities are foreseen in the future around the world $\rightarrow$ new challenges to improve accelerator, target and detector technologies should be faced

The LUNA Collaboration

Laboratory Underground Nuclear Astrophysics

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