Cross section measurements of fusion reactions at astrophysically relevant energies: the LUNA experiment

INFN

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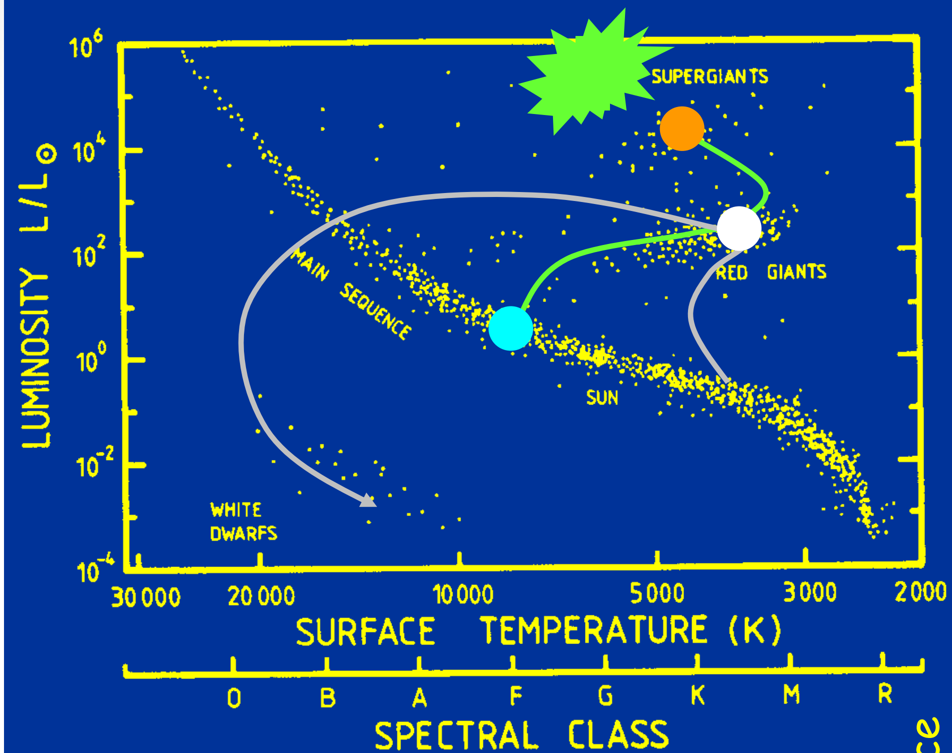
(on behalf of LUNA collaboration)

Laboratori Nazionali del Gran Sasso

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

RICAP-13 Roma International Conference on AstroParticle Physics 2013

Solar system abundances



$M < 8\ M_\odot$
star switches off
(white → black dwarf)

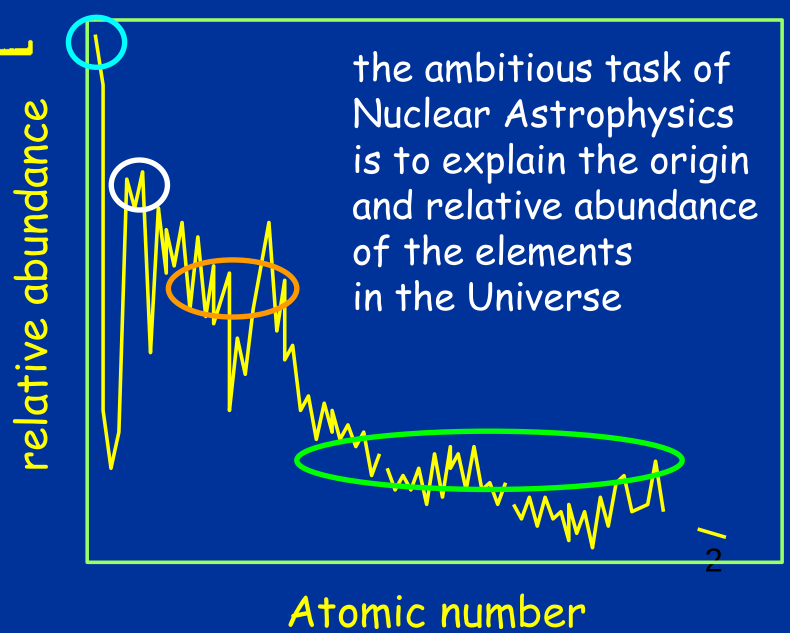
$M > 8\ M_\odot$
star explodes
(supernova)

H burning → He

He burning → C, O, Ne

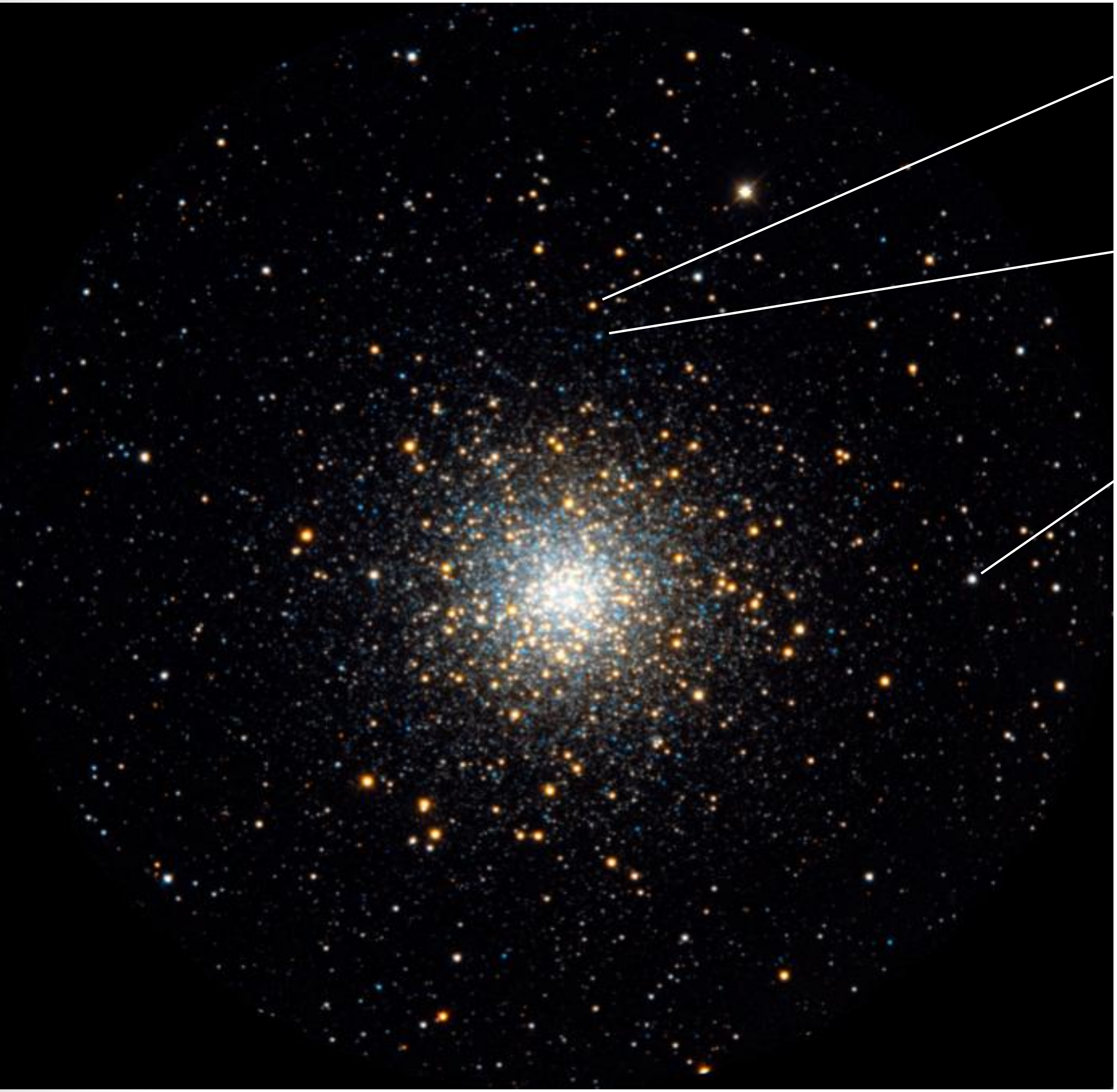
C/O … Si burning → Fe

explosive burning



the ambitious task of Nuclear Astrophysics is to explain the origin and relative abundance of the elements in the Universe

Globular cluster M 10



Red giant stars:
H→He via CNO cycles in
H shell surrounding He core

Horizontal branch stars:
He→C, O in core
H→He in shell

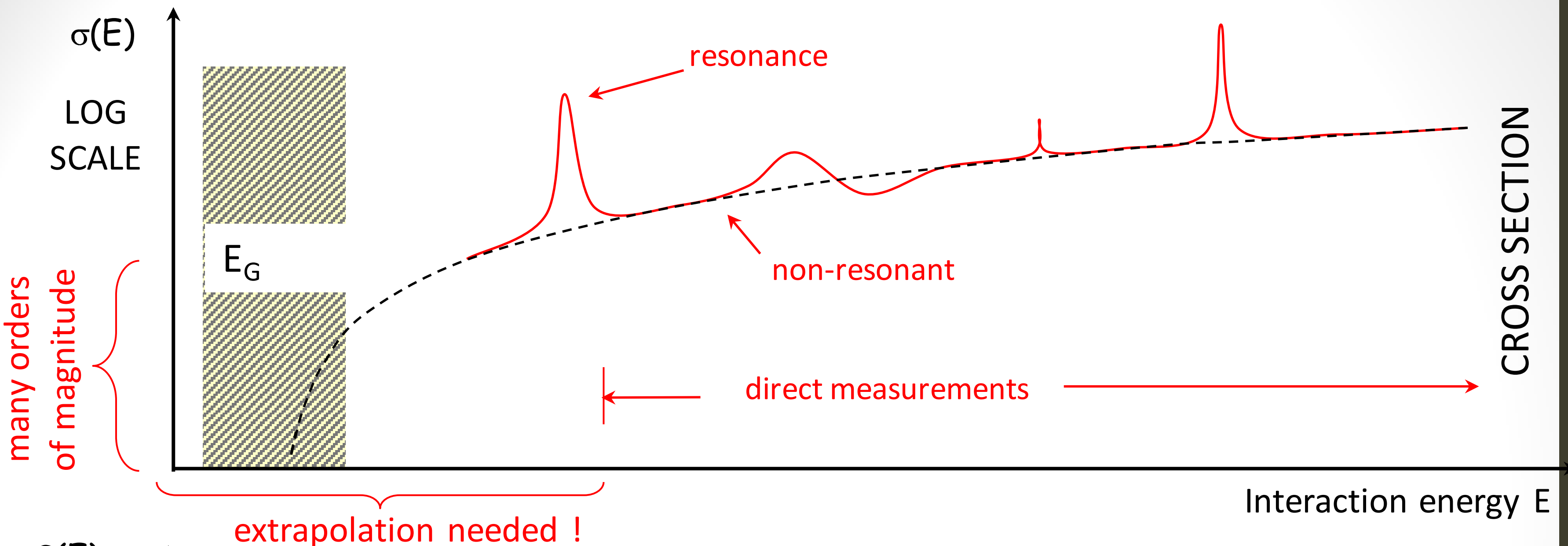
Main sequence stars:
H→He via pp chains in core

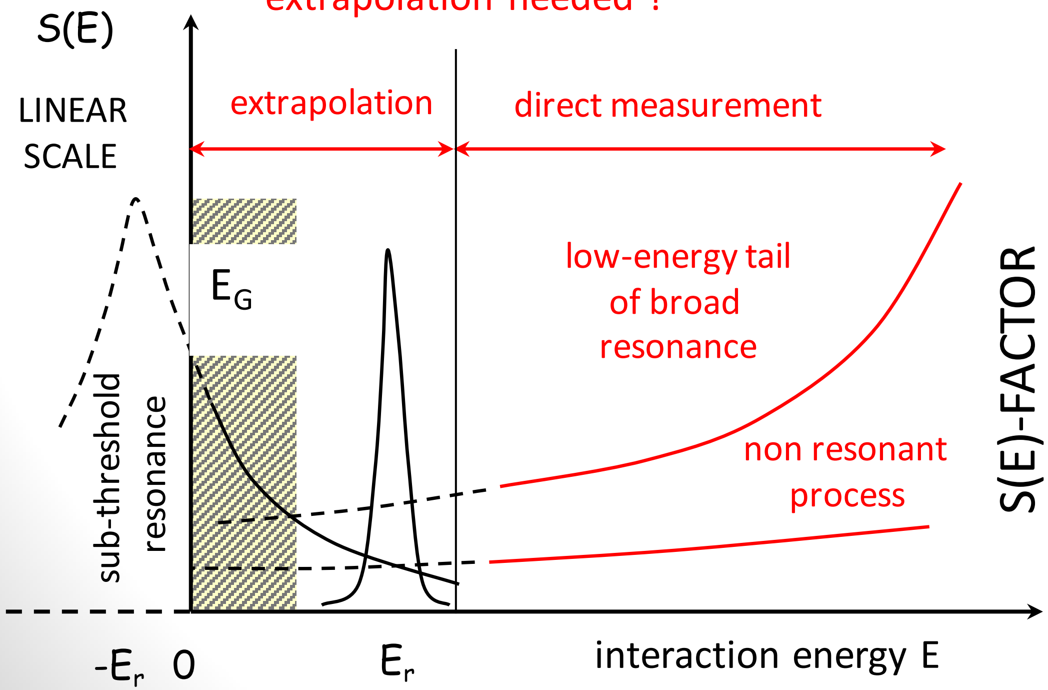
Accurate nuclear physics information is crucial for understanding of stars

How do other stars produce energy?
How do they evolve?

Credner & Kohle, Sternwarte Bonn

Problem of extrapolation





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

$pb < \sigma < nb$

$\varepsilon \sim 10\ \%$

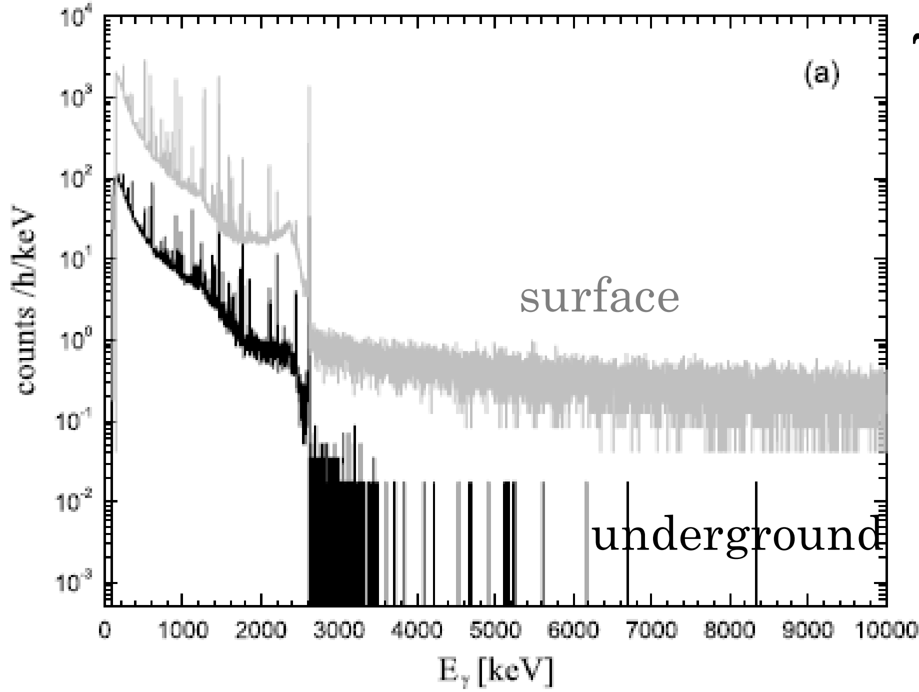
$I_P \sim mA$

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

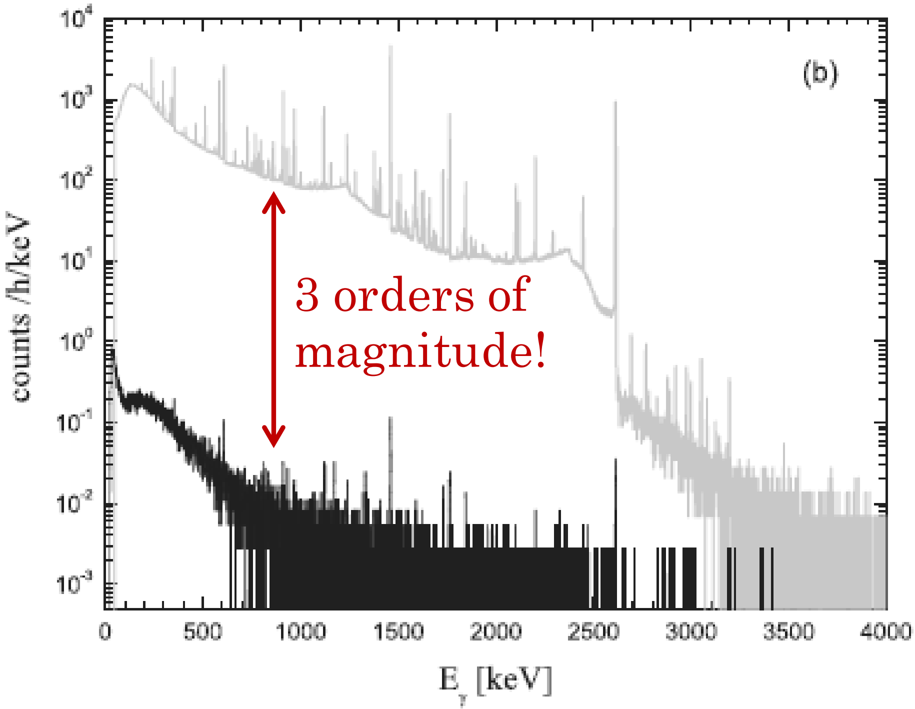
$\text{event/month} < R_{lab} < \text{event/day}$

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

γ-ray natural background



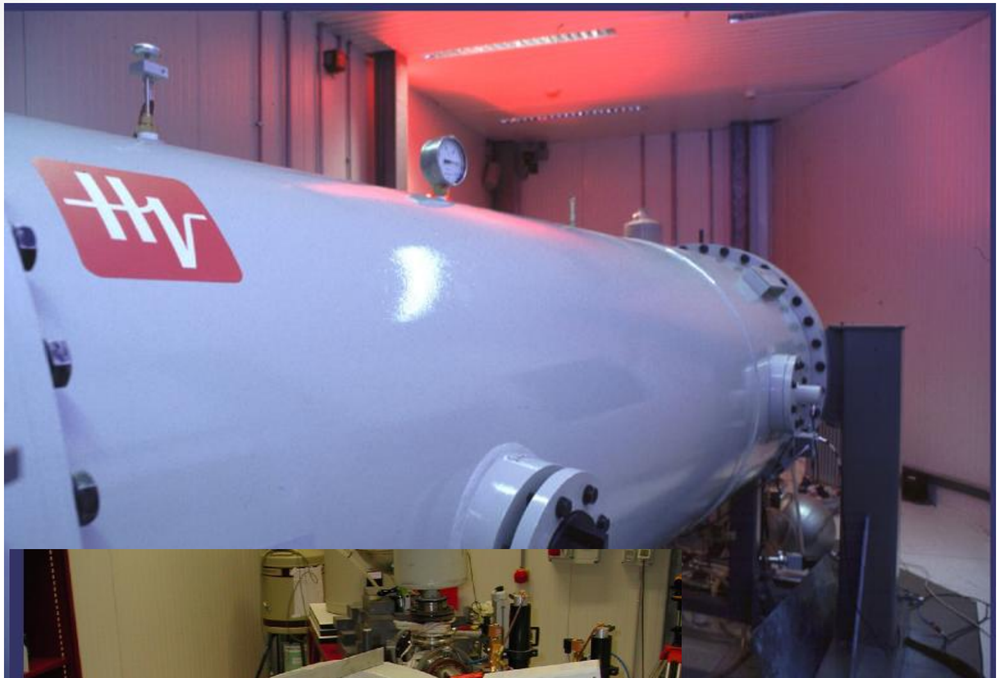
between E_g =7 and 12MeV the bck suppression factor is 100 times

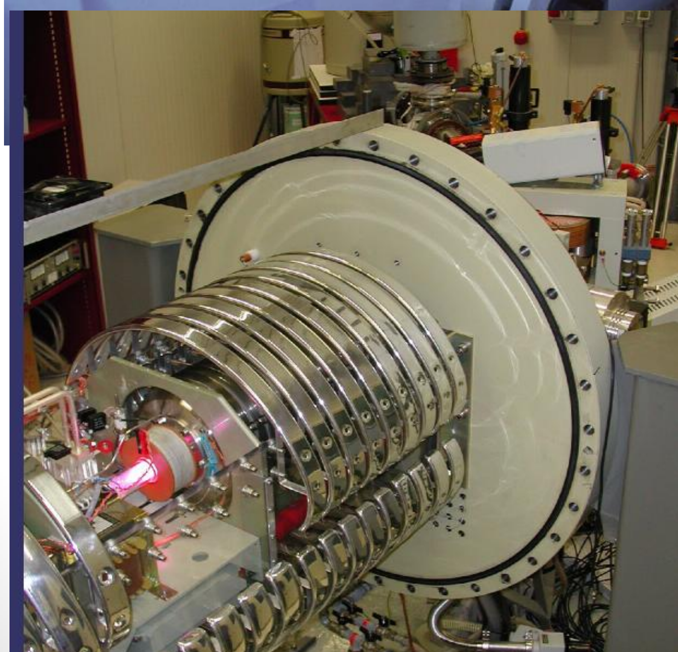


underground passive shielding is more effective since μ flux, that create secondary γ's in the shield, is suppressed

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

LUNA II 400kV accelerator



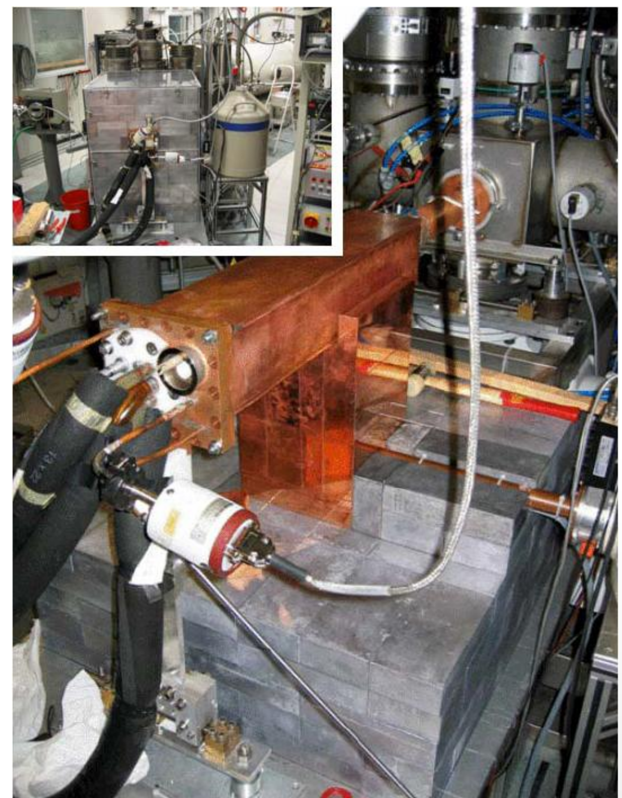


$U_{terminal}$ = 50 – 400kV

I_{max} = 500μA (on target)

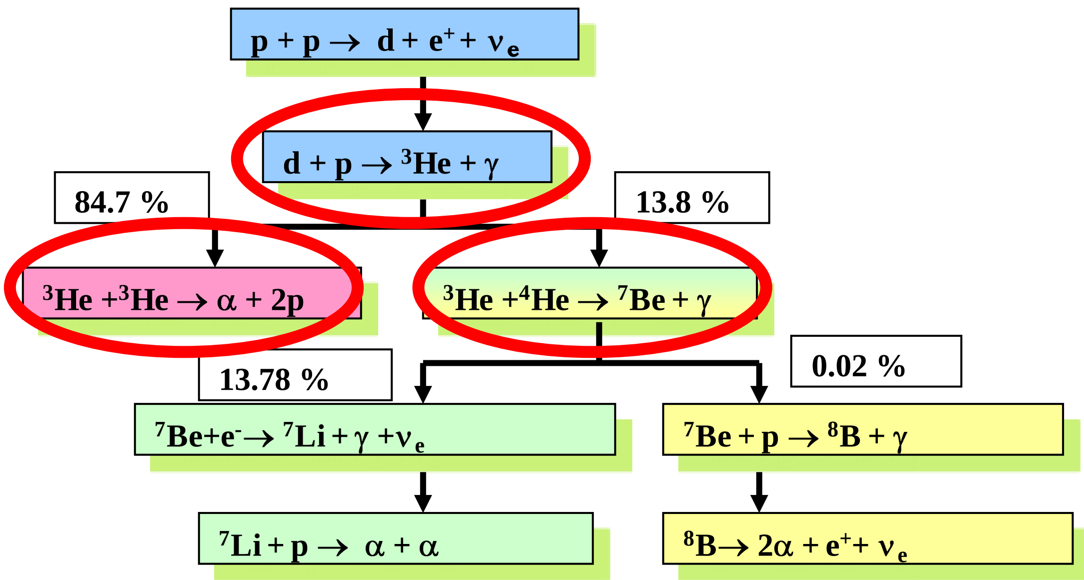
ΔE = 0.07keV

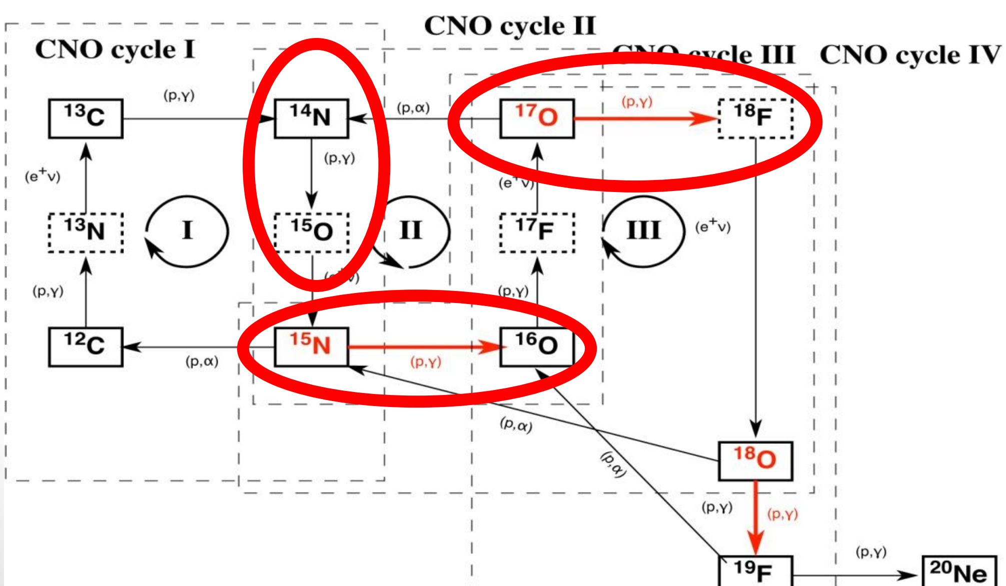
Allowed beams: H^+, ^4He, (^3He)

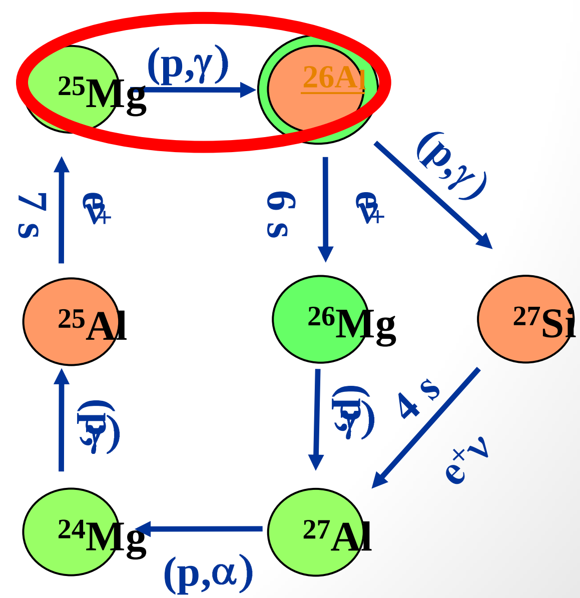


Key reactions measured at LUNA 50kV-400kV

pp chain







Importance of experimental reaction rates for understanding of nucleosynthesis, energy production in stars, solar neutrino problem, theories of stellar evolution

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

The rate of the energy production in the CNO cycle ($T>10^7$K and $M>1.1M_{\odot}$) is governed by the $^{14}N(p,\gamma)^{15}O$ slowest reaction, a variation of its rate can influence:

- ❑ Neutrino fluxes of $\Phi(^{13}N)$ and $\Phi(^{15}O)$ depend almost linearly on $S_{14}(0)$
- ❑ Age of Globular Cluster

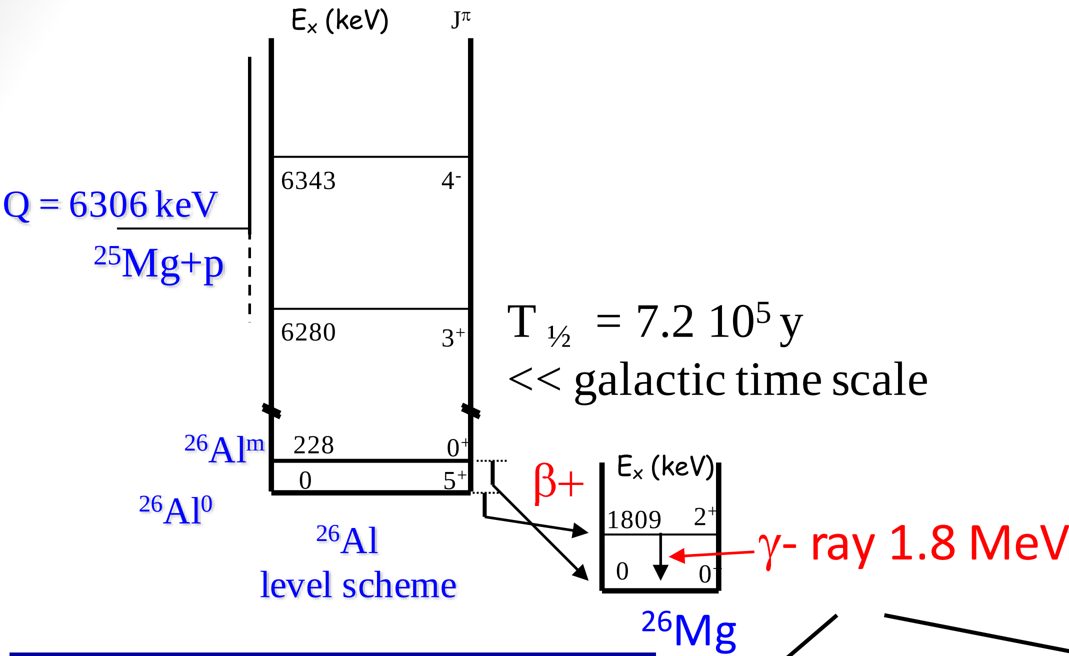
After LUNA measurments

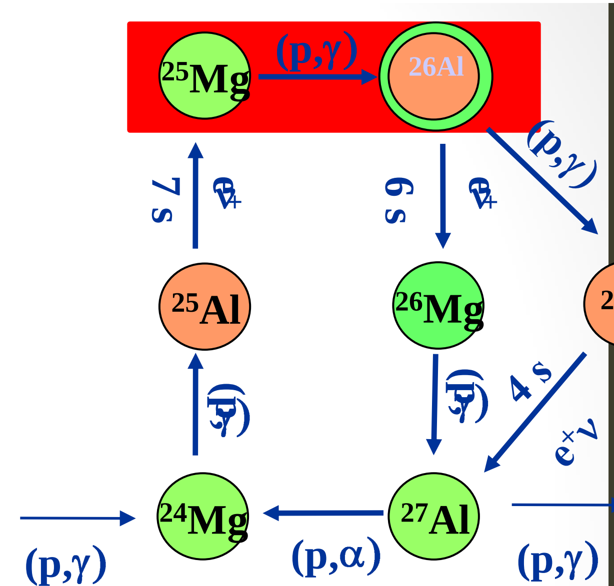
- ❖ CNO neutrino flux decreases a factor ≈ 2
- ❖ Globular Cluster age increases of 0.7 – 1 Gyr

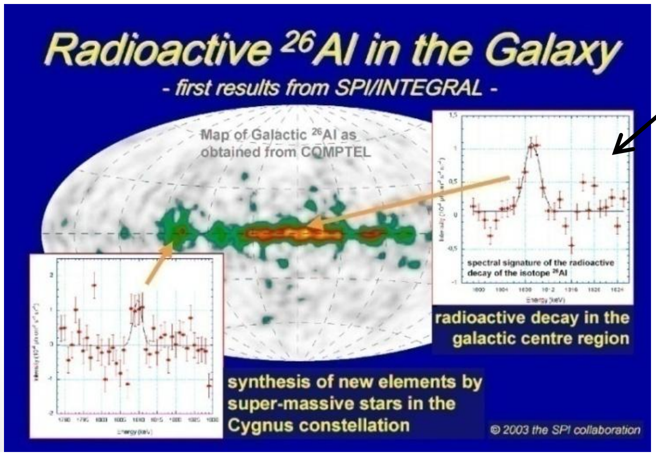
Formicola et al. Phys.Lett.B 591 (2004) 61
G.Imbriani et al. (2005)
Marta et al. PRC 78 (2008) 022802

A close look on last LUNA works mainly: **$^{25}Mg(p,\gamma)^{26}Al$, D $(\alpha,\gamma)^6Li$, $^{17}O(p,\gamma)^{18}F$**

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





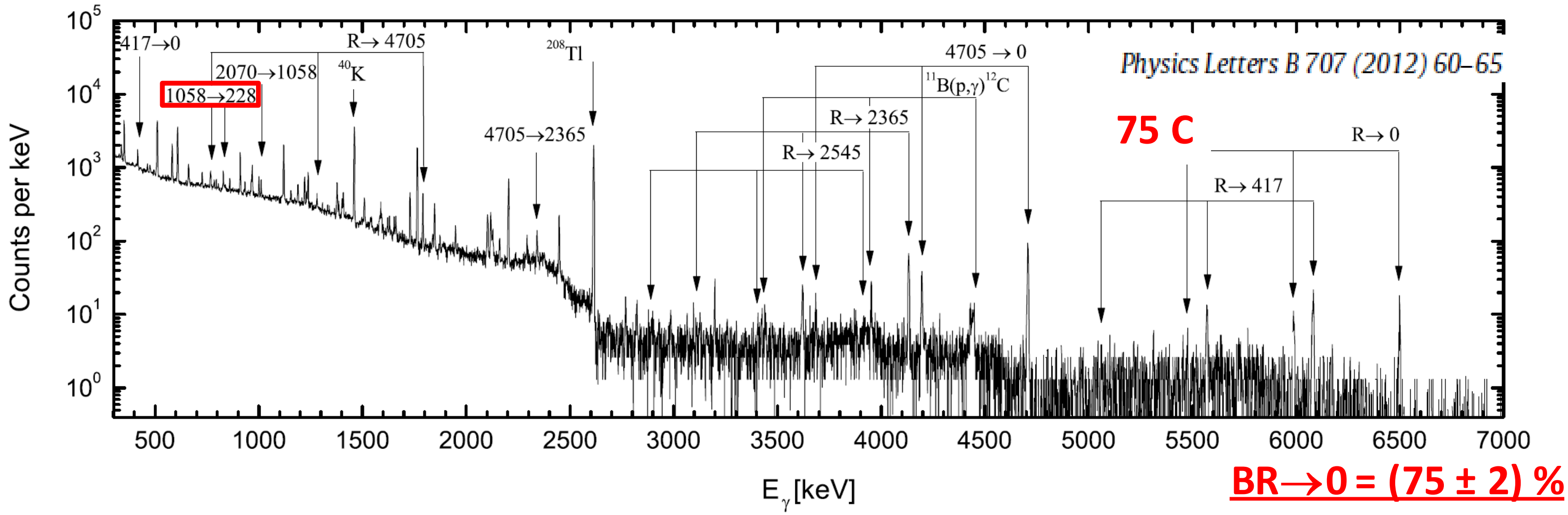


^{26}Mg excess in meteorites

Evidence that ^{26}Al nucleosynthesis is still active (WR stars, SN and NOVAE)

Signature of ^{26}Mg production during the Hydrogen burning (RGB, AGB)

$^{25}Mg(p,\gamma)^{26}Al$ - HPGe spectra E_R = 190 keV



LUNA results fully cover the temperature range of core massive main sequence stars (Wolf-Rayet) as well as the H-burning shell of RGB and AGB stars.

Astrophysical consequence i.e. WR stars:

→ the expected production of $^{26}Al_{gs}$ in stellar H-burning zones is lower than previously estimated.

This implies a reduction of the estimated contribution of WR stars to the galactic production of ^{26}Al.(O.Straniero et al. ApJ 763 (2013))

D(^{4}He,γ)^{6}Li cross section

The claimed ^{6}Li abundance in metal-poor stars is very large (Asplund et al. 2006) compared to BBN predictions (NACRE compilation). Possible reasons are:

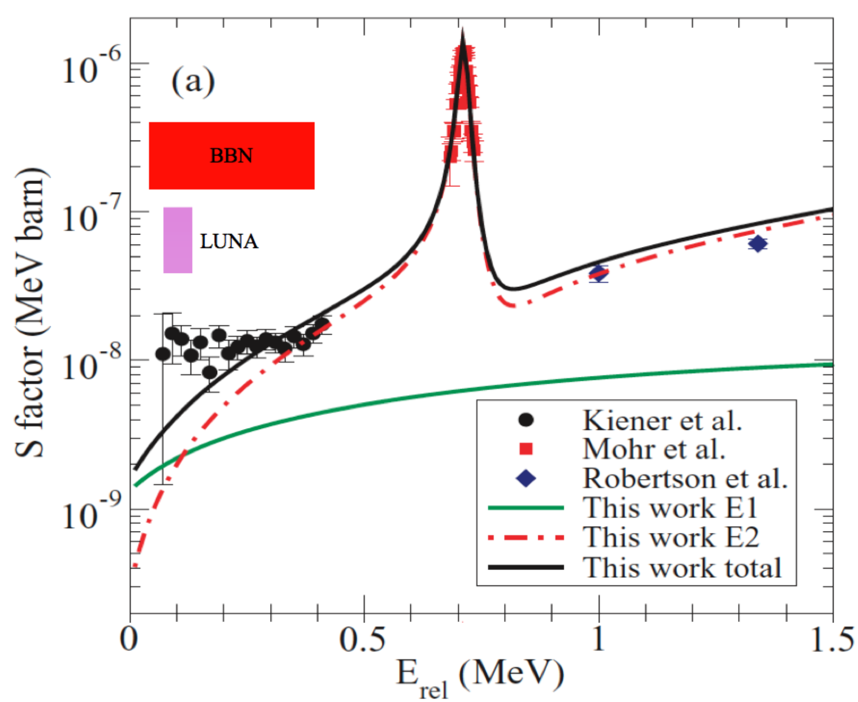
- Systematics in the ^{6}Li observation in the metal-poor stars
- Unknown ^{6}Li sources older than the birth of the galaxy
- …Lack of the knowledge of the D(^{4}He,γ)^{6}Li reaction.

IN FACT:

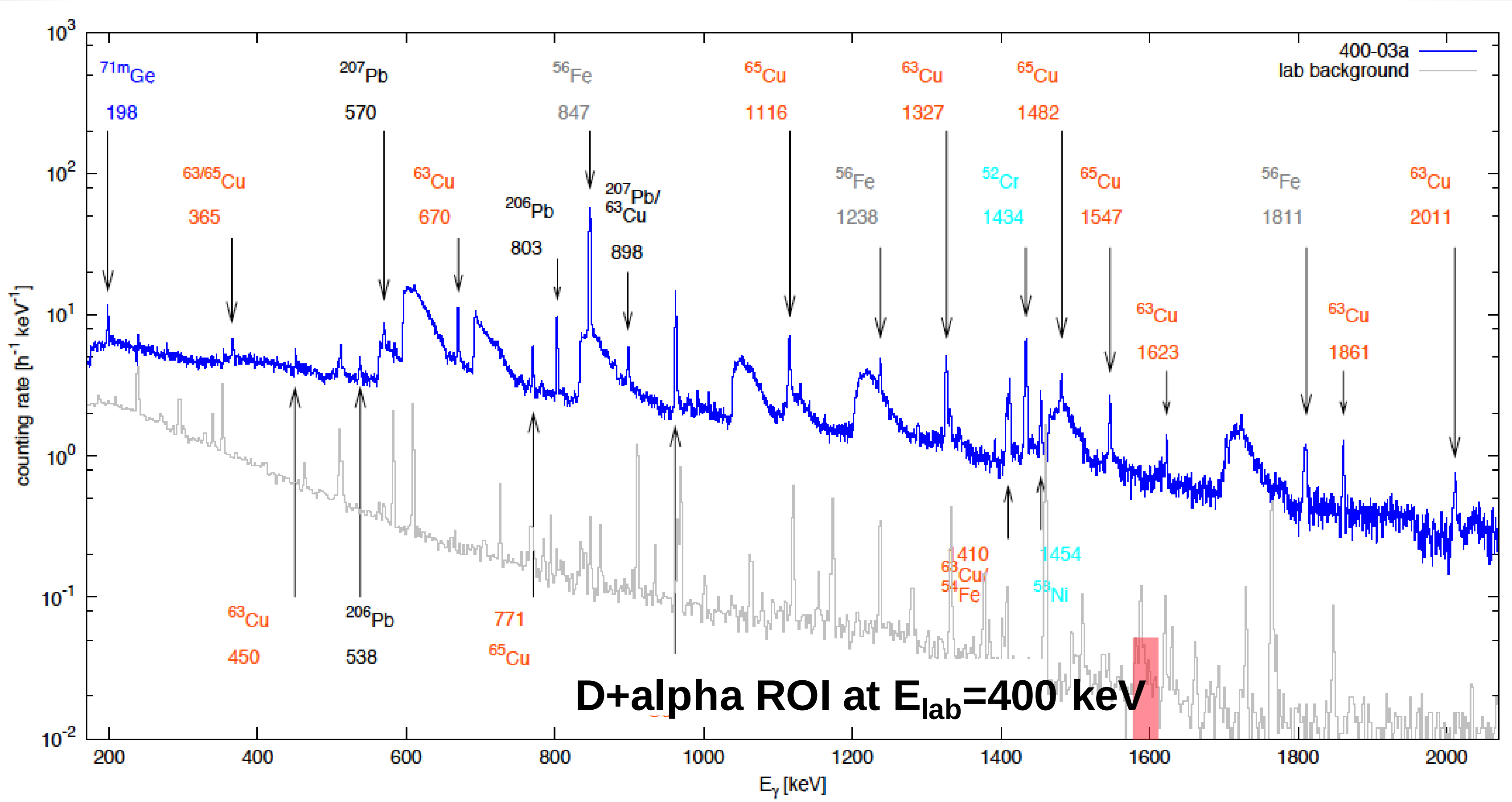
NO DIRECT MEASUREMENTS in the BBN energy region in literature (large uncertainty due to extrapolation)

INDIRECT coulomb dissociation measurements strongly depends on the theoretical assumptions, because the nuclear part is dominant.

FOR THE FIRST TIME, the D(^{4}He,γ)^{6}Li reaction has directly been studied

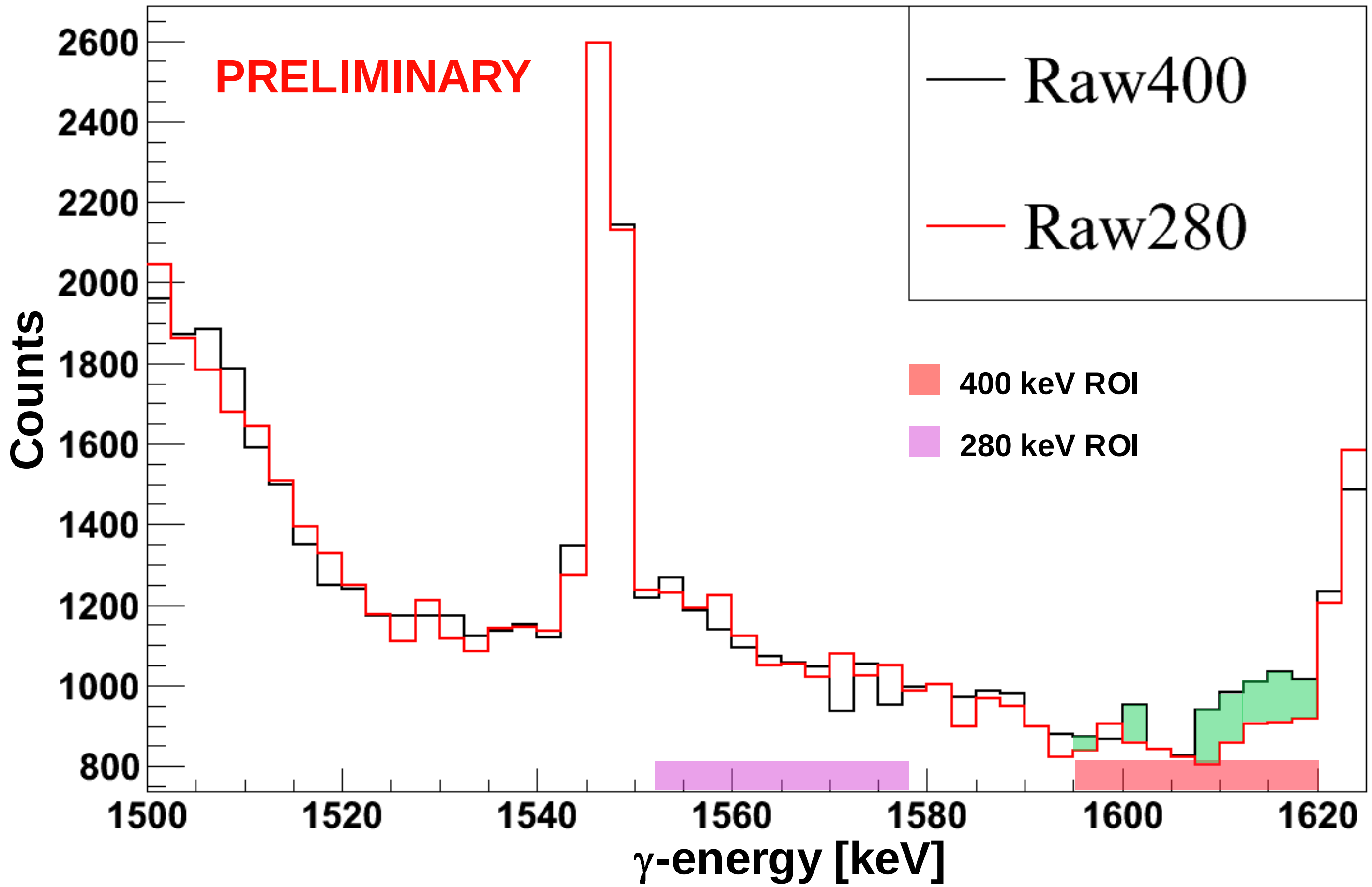


Beam Induced Background and Natural Background



M.Anders et al. Eur. Phys. J. A 49 (2013) 28

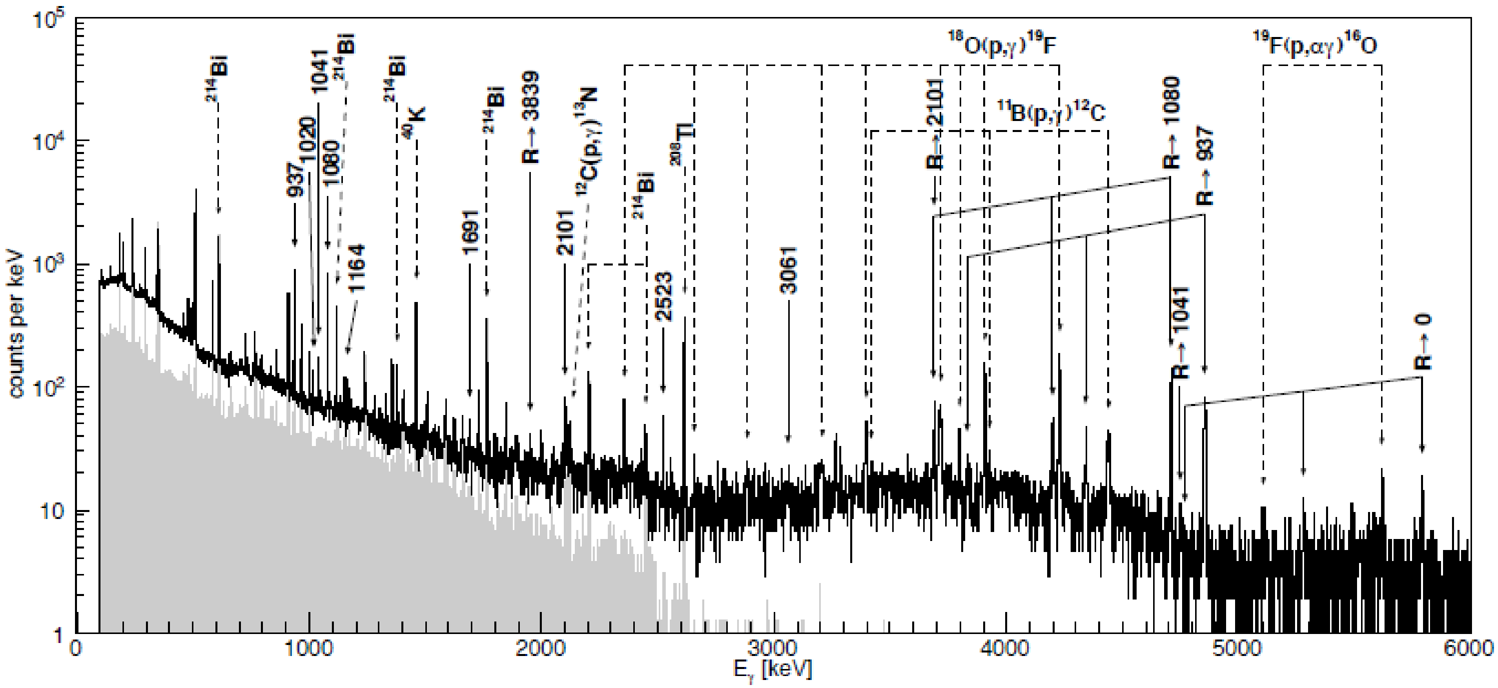
Preliminary results (E_{lab}=400/280 keV)



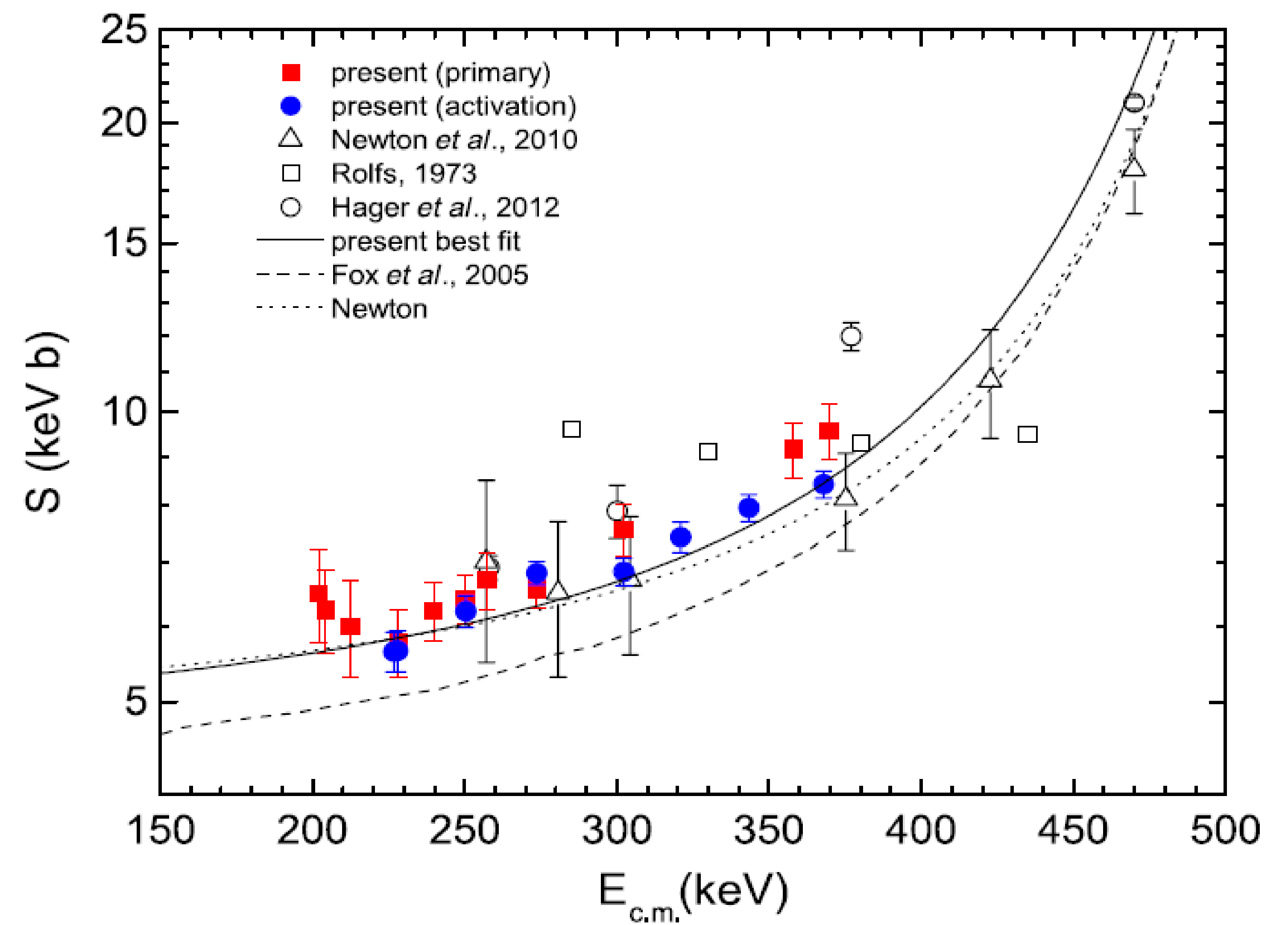
400 keV: T=18,2 days; <P>=0,306 mbar; Q=514 C
280 keV: T=20,5 days; <P>=0,308 mbar; Q=539 C
Counting excess observed in the E_{lab}=400 keV RoI

Courtesy by C.Gustavino

γ-spectrum at resonance energy of the $^{17}O(p,\gamma)^{18}F$ reaction

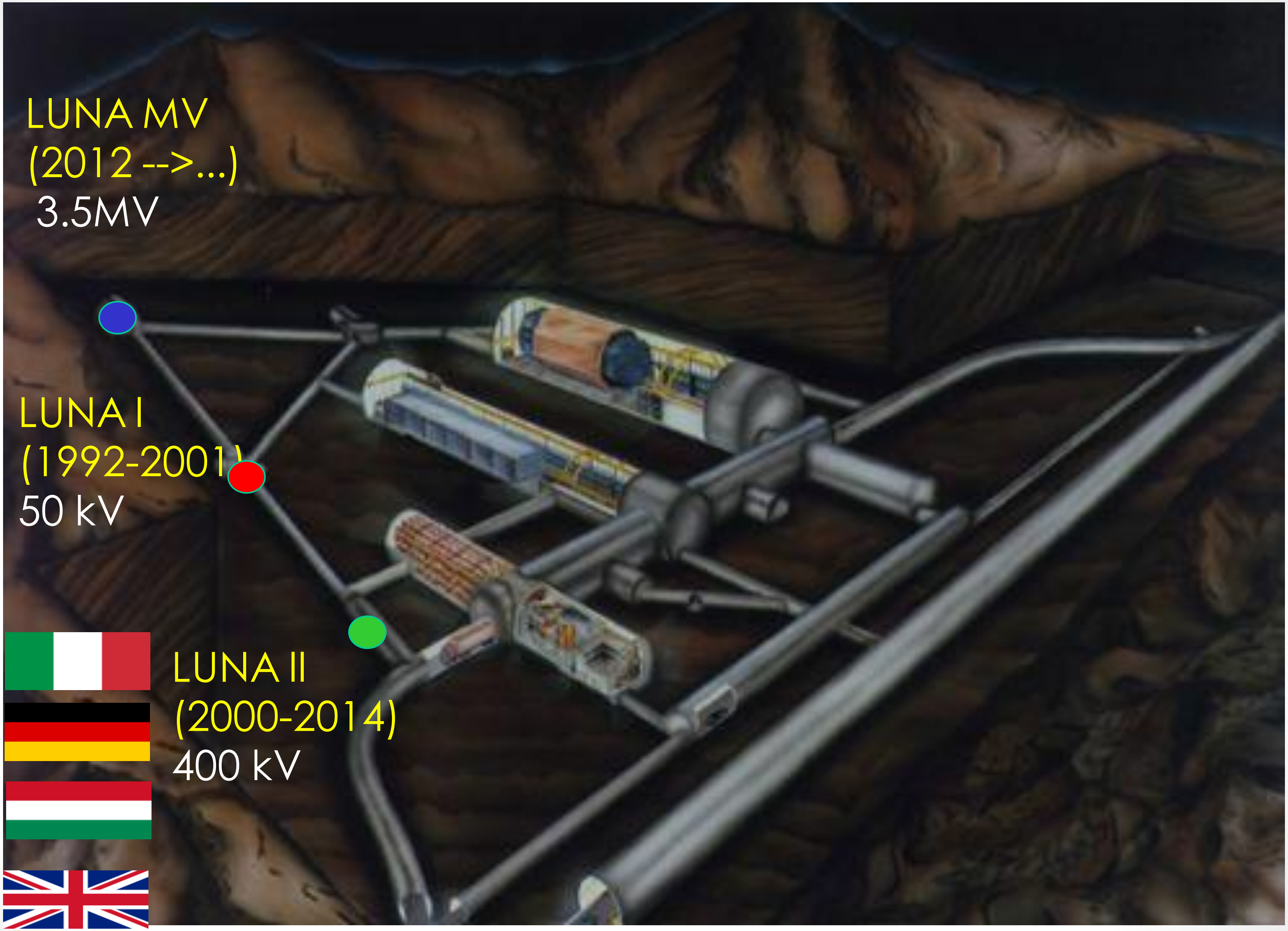


Total $^{17}O(p,\gamma)^{18}F$ reaction cross section measured between $E_{cm} \approx 200 - 370$ keV leading to a four-fold reduction in reaction rate uncertainty in novae region.



A.Caciolli et al. Eur.Phys.J A48(2012)144
D. Scott et al. Phys.Rev.Lett. 109,202501, 2012
A.Di Leva et . in preparation

The LNGS Underground Laboratory



The LUNA MV project (Progetto Premiale , P.I. A.Guglielmetti)
financial support for the first year 2.8ME

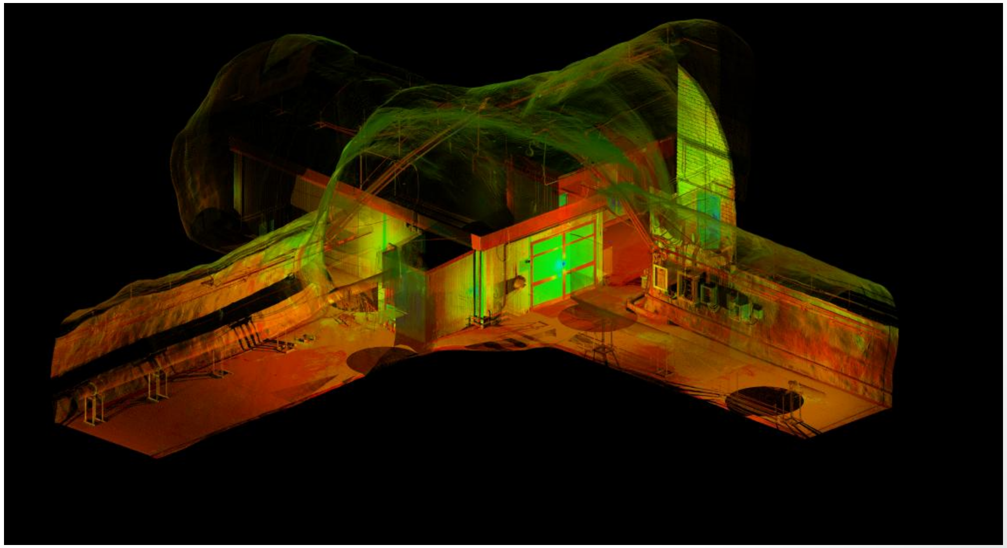
April 2007: a Letter of Intent (LoI) was presented to the LNGS Scientific Committee (SC) containing key reactions of the He burning and neutron sources for the s-process:

$^{12}C(\alpha,\gamma)^{16}O$
$^{13}C(\alpha,n)^{16}O$
$^{22}Ne(\alpha,n)^{25}Mg$
(α,γ) reactions on $^{14,15}N$ and ^{18}O

These reactions are relevant at higher temperatures (larger energies) than reactions belonging to the hydrogen-burning studied so far at LUNA

↓

Higher energy machine→
3.5 MV single ended positive ion accelerator



Summary

- Optimization of peak to background is crucial.
  High intensity beams, underground passive shielding

- Low energy measurements necessary to remove
  or reduce cross section extrapolation uncertainties

- $^{17}O(p,\alpha)^{14}N$ and $^{22}Ne(p,\gamma)$ ^{23}Na cross section measurments
  are in progress

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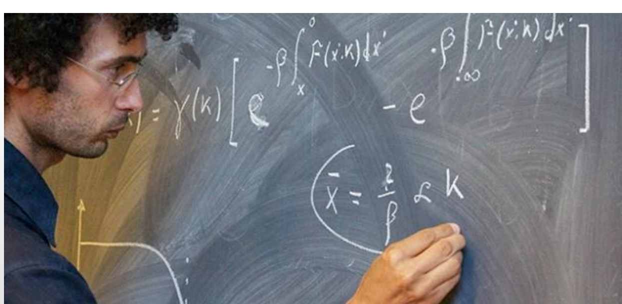

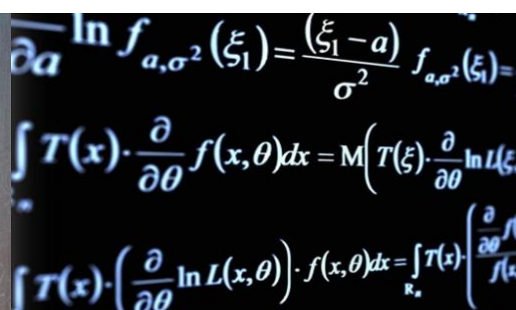

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