Accelerator for stellar reactions

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LUNA
Laboratory for Underground Nuclear Astrophysics

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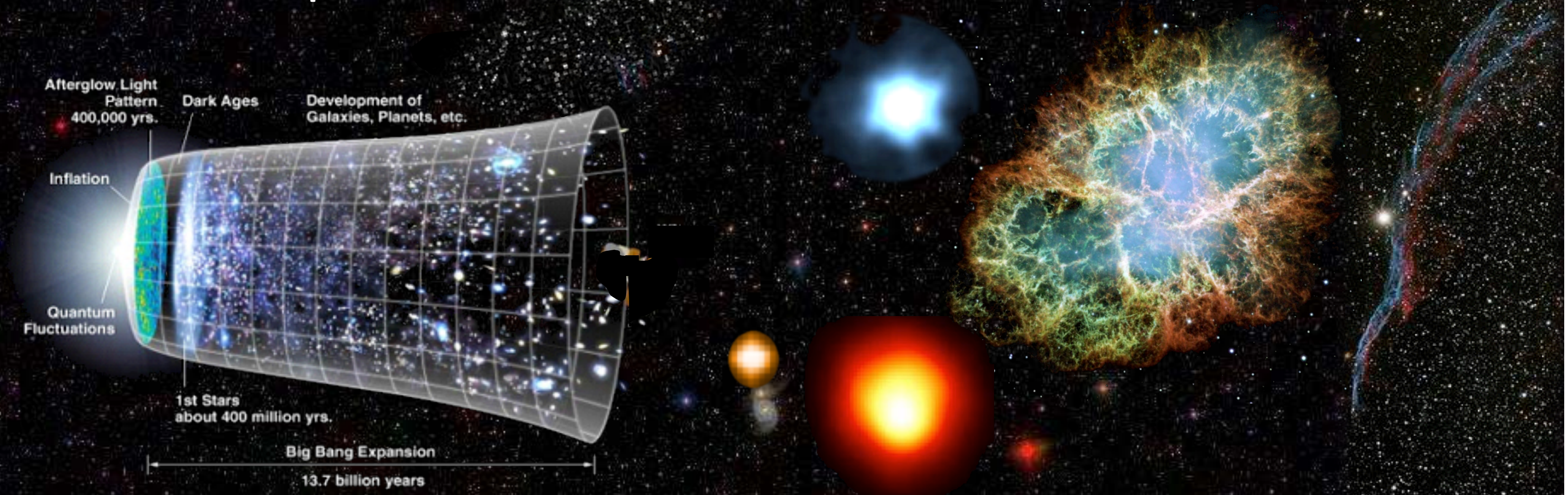
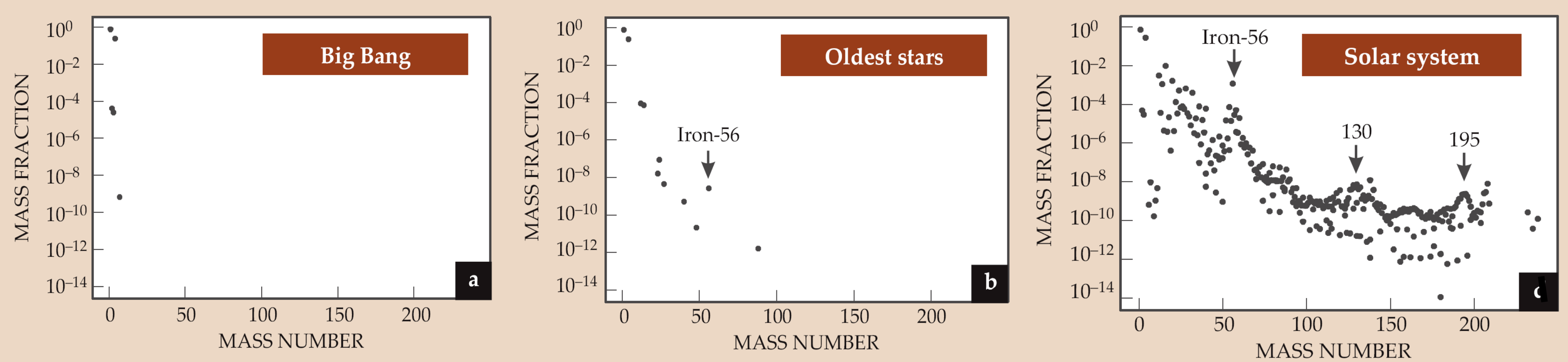
Galactic chemical evolution

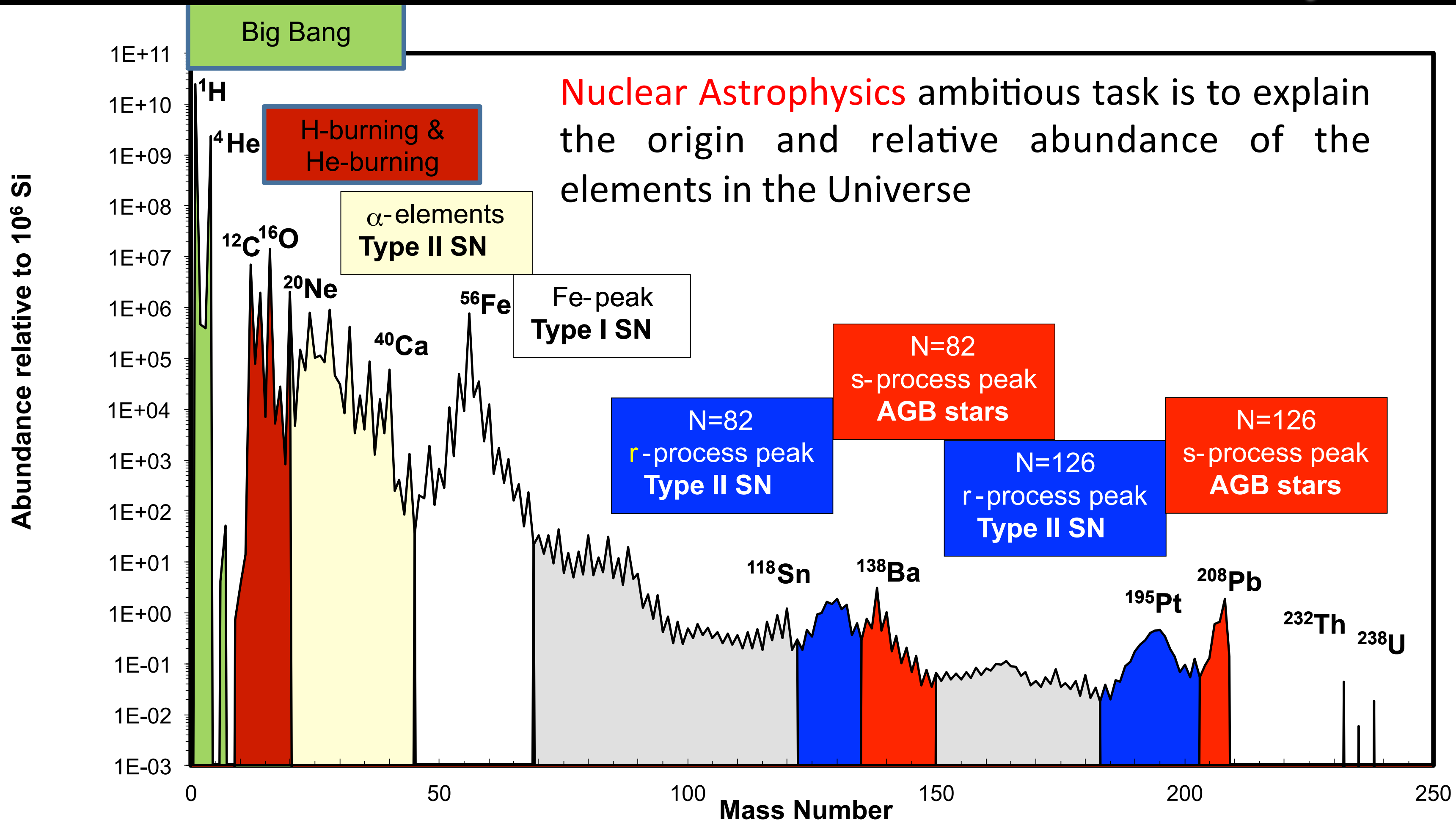
Almost all important events in the Universe have left behind them nuclear clues



Subject of N.A. is the understanding of nuclear processes taking place in astrophysical environments



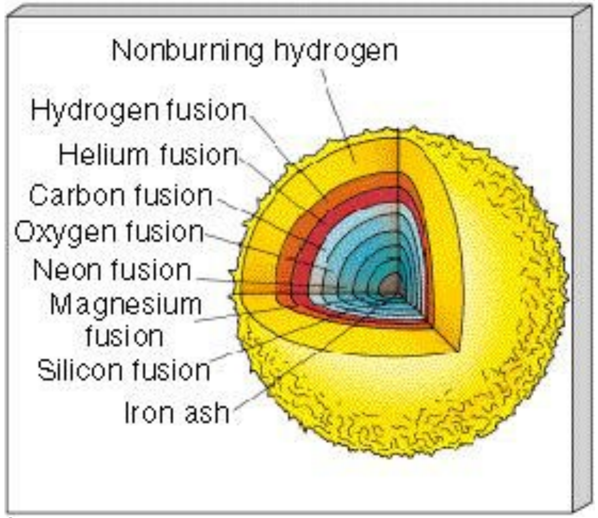
Element abundances in the solar system



Modern nucleosynthesis calculations incorporate thousands of nuclei, following all possible reaction channels. A number of reactions play a key role, either by controlling both the timescale and associated energy production or by regulating the reaction flow.

Stellar evolution during thermal equilibrium

$$\frac{dP}{dM_r} = -\frac{GM_r}{4\pi r^4}$$ hydrostatic equilibrium



$$\frac{dT}{dM_r} = \nabla \frac{GM_r T}{4\pi r^2 P}$$ heat transport

$$\frac{dr}{dM_r} = -\frac{1}{4\pi r^2 \rho}$$ mass contuinity

$$\frac{dL_r}{dM_r} = \varepsilon_g + \varepsilon_\upsilon + \varepsilon_n$$ energy conservation

$$\varepsilon_n = \varepsilon_{12} + \varepsilon_{34} = (r_{12} - r_{34})\frac{Q}{\rho}$$

$$r_{12} = N_1 N_2 \langle \sigma v \rangle$$

$$\frac{dY_i}{dt} = \sum_j c_j(j)\lambda_j Y_j + \sum_{j,k} c_i(j,k)\rho N_A \langle \sigma v \rangle_{j,k} Y_j Y_k + \ldots\ldots$$

chemical evolution

Some examples

- **BBN and H-burning in the Sun and solar neutrinos**:

$p+p \rightarrow d+e^{+}+\nu$, $p(d,\gamma)^{3}He$, $d(\alpha,\gamma)^{6}Li$, $^{3}He(^{3}He, 2p)^{4}He$, $^{3}He(\alpha,\gamma)^{7}Be$, $^{7}Be(p,\gamma)^{8}B$ and $^{14}N(p,\gamma)^{15}O$

- **Age of Globular Clusters and C production in AGB:**

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

- **AGB nucleosynthesis – light nuclei abundances:**

$^{14}N(p,\gamma)^{15}O$, $^{15}N(\alpha,\gamma)^{19}F$, $^{15}N(p,\gamma)^{16}O$, $^{15}N(p,\alpha)^{12}C$, $^{17}O(p,\gamma)^{18}F$, $^{17}O(p,\alpha)^{14}N$, $^{18}O(p,\gamma)^{19}F$, $^{18}O(p,\alpha)^{15}N$, $^{18}O(\alpha,\gamma)^{22}Ne$, $^{18}F(\alpha,p)^{21}Ne$, $^{19}F(\alpha,p)^{22}Ne$, $^{22}Ne(p,\gamma)^{23}Na$, $^{23}Na(p,\gamma)^{24}Mg$, $^{24}Mg(p,\gamma)^{25}Al$, $^{25}Mg(p,\gamma)^{26}Al(\beta^{+})^{26}Mg$, $^{26}Mg(p,\gamma)^{27}Al$

- **Main neutron sources:**

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

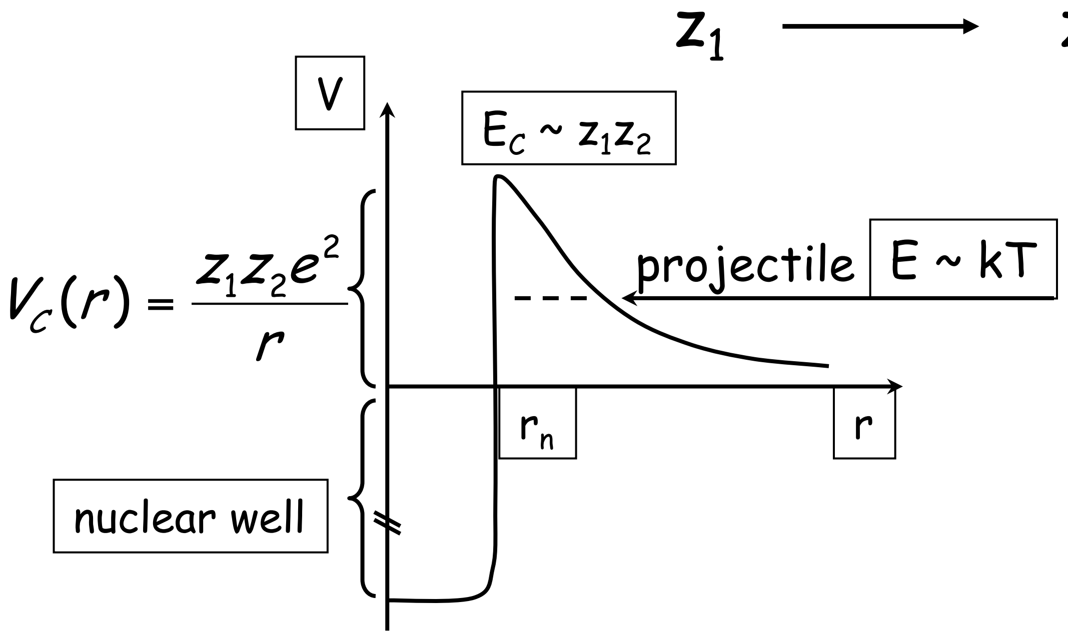
- **Explovive CNO burning:**

$^{15}O(\alpha,\gamma)^{19}Ne$, $^{14}O(\alpha,\gamma)^{18}Ne$, $^{18}Ne(\alpha,p)^{21}Na$

- **He and advanced burnings:**

$^{12}C(\alpha,\gamma)^{16}O$, $^{12}C(^{12}C, p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$, $^{16}O(\alpha,\gamma)^{20}Ne$

Charged particle reactions in stars



Example

z_1=p and z_2=p (e.g. in the Sun)

$T \sim 15 \times 10^6$ K $\Rightarrow E = kT \sim 1$ keV

$E_C = 550$ keV

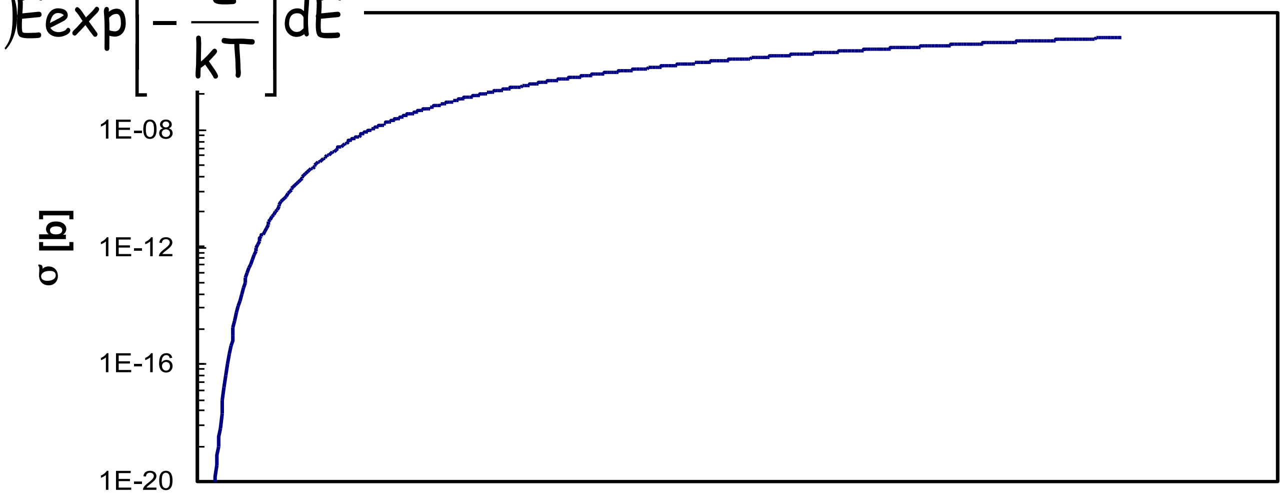
during quiescent burnings:

$kT \ll E_c$

reactions occur through

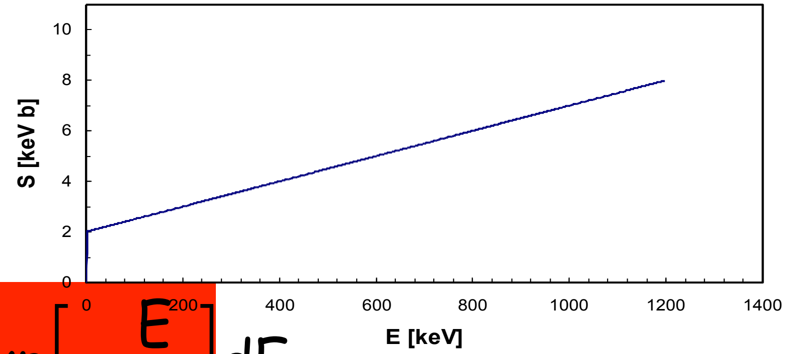
TUNNEL EFFECT

$$< \sigma v > = \left(\frac{8}{\pi \mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \sigma(E) E \exp\left[-\frac{E}{kT}\right] dE$$



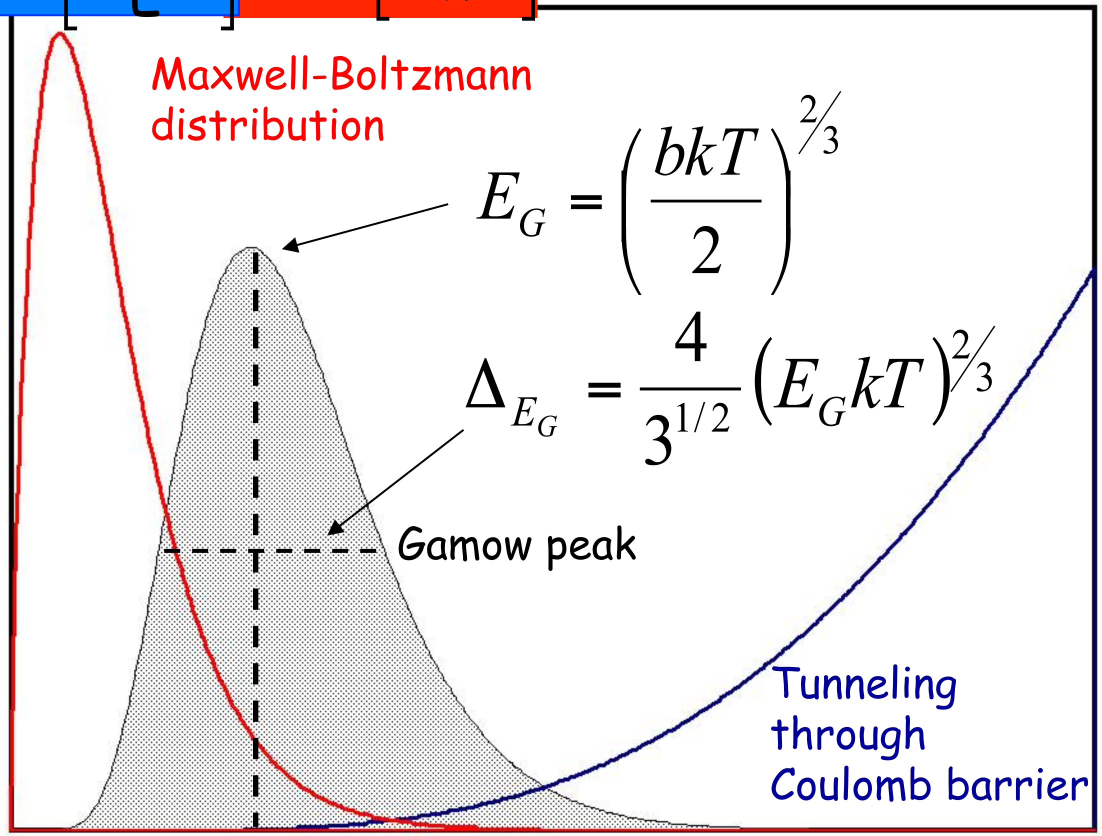
Astrophysical factor and Gamow peak

$$\sigma(E) = \frac{S(E)}{E}\exp(-2\pi\eta) \qquad \eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

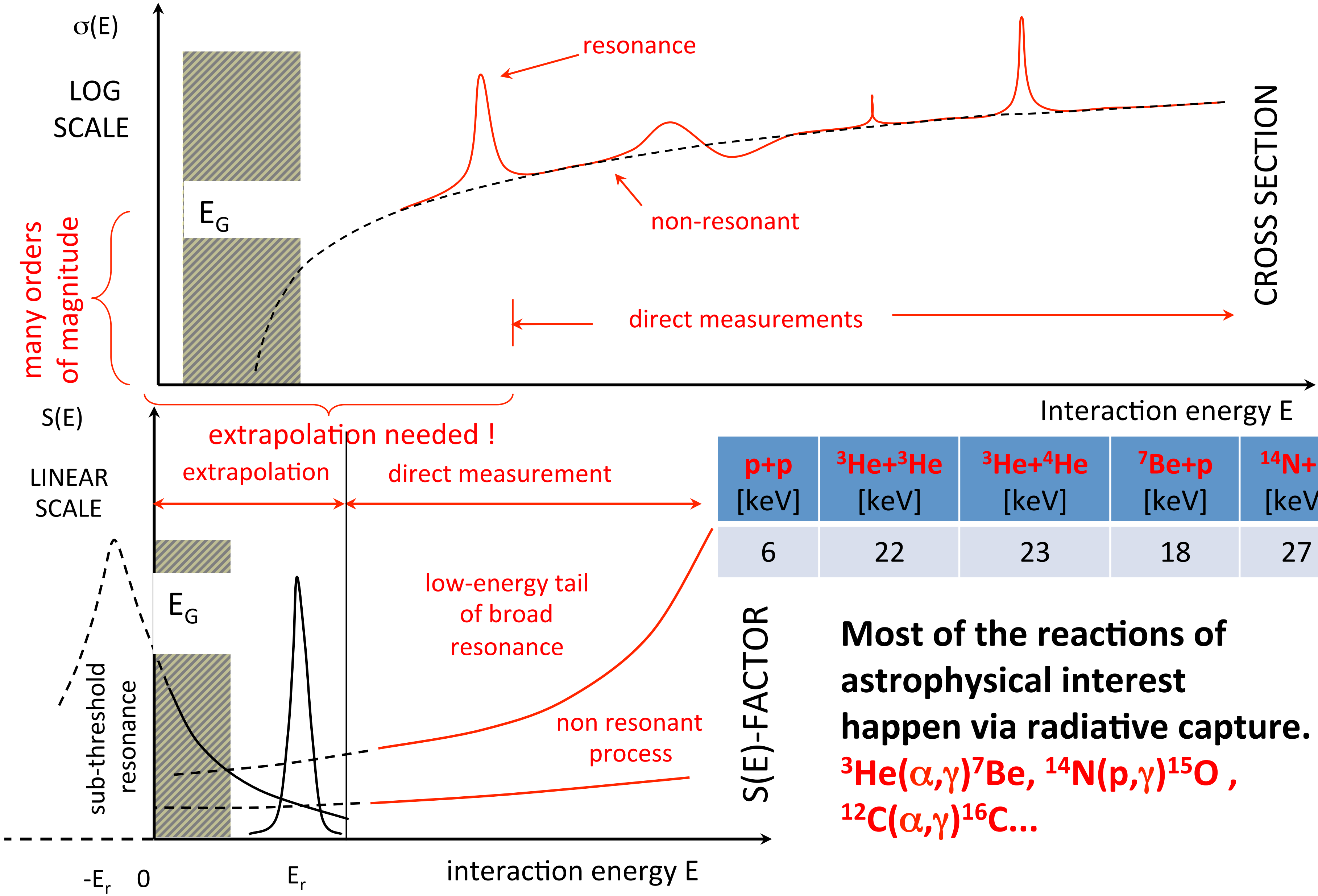


$$<\sigma v> = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{1}{(kT)^{3/2}} \int_0^\infty \frac{S(E)}{E}\exp\left[-\frac{b}{E^{1/2}}\right] E\exp\left[-\frac{E}{kT}\right] dE$$

reaction	Coulomb barrier (keV)	E_G (keV)
p + p	550	5.9
α + ^{12}C	3430	56-200
^{16}O + ^{16}O	14070	200-500



Problem of extrapolation

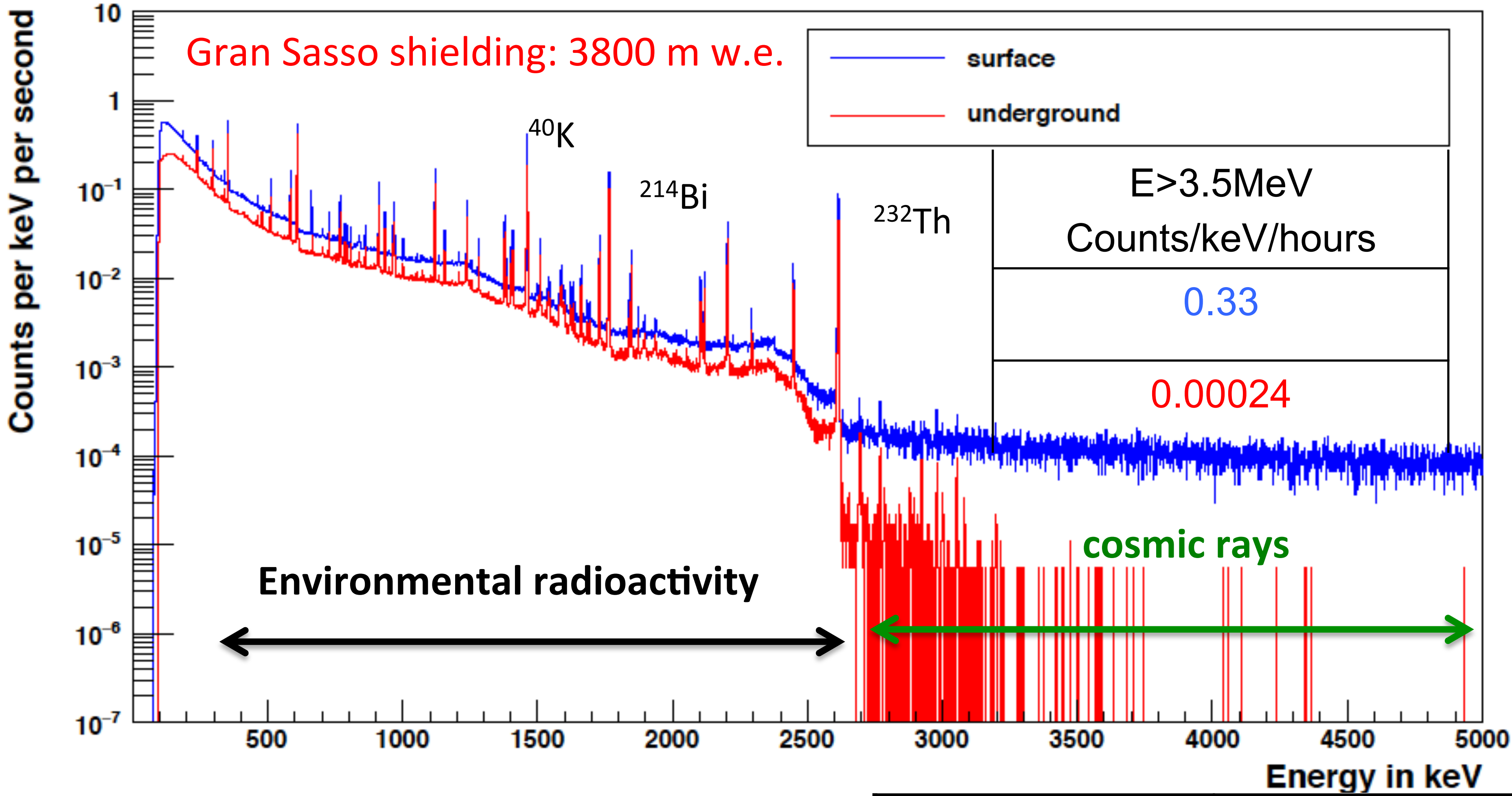


p+p [keV]	$^3He+^3He$ [keV]	$^3He+^4He$ [keV]	^7Be+p [keV]	$^{14}N+p$ [keV]
6	22	23	18	27

Most of the reactions of astrophysical interest happen via radiative capture.

$^3He(\alpha,\gamma)^7Be$, $^{14}N(p,\gamma)^{15}O$, $^{12}C(\alpha,\gamma)^{16}C$...

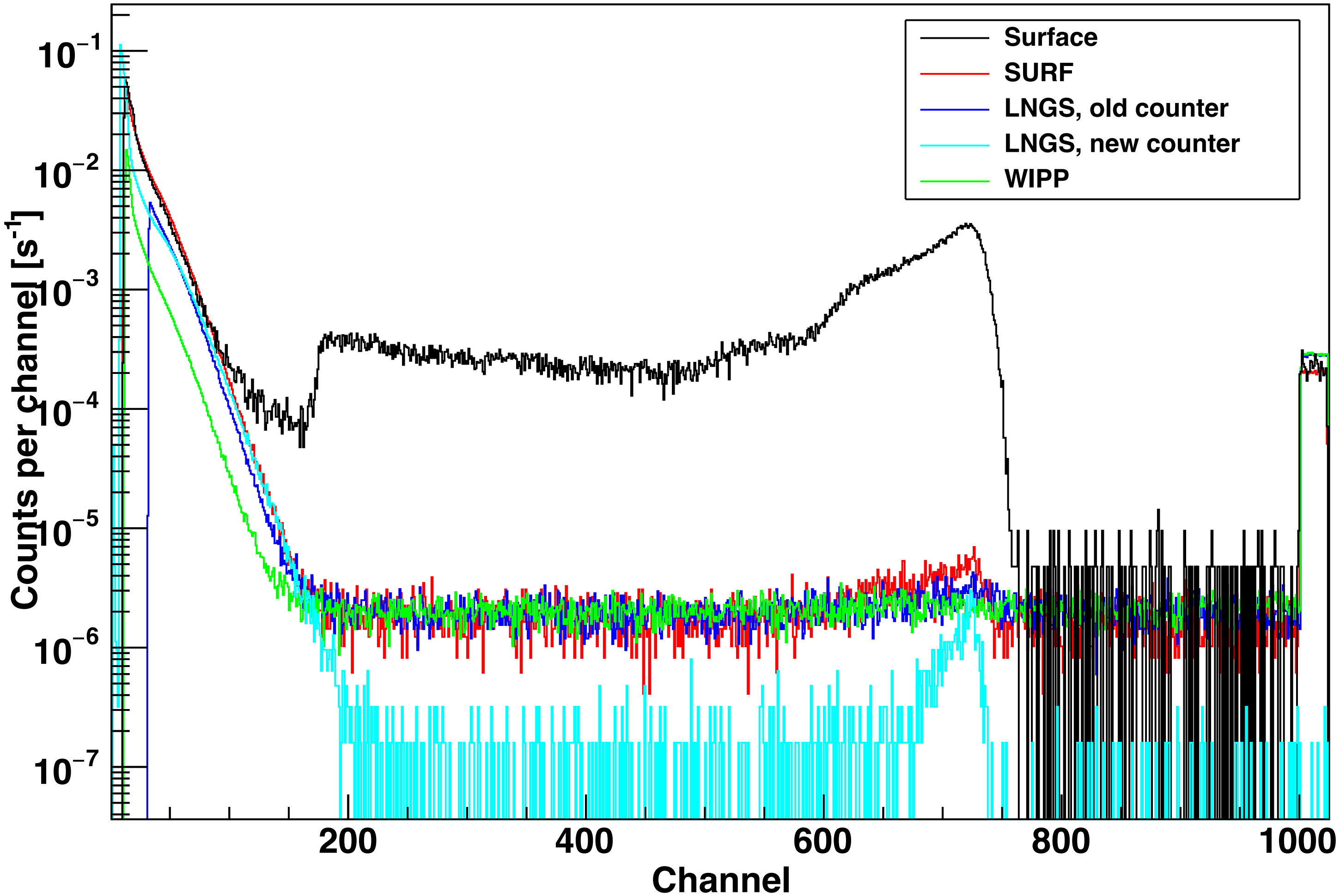
Why going underground γ-background



Therefore, the advantage of an underground environment is evident for high Q-value reactions such as **$^{14}N(p,\gamma)^{15}O$, $^{15}N(p,\gamma)^{16}O$, $^{17}O(p,\gamma)^{18}F$, $^{25}Mg(p,\gamma)^{26}Al$**......

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

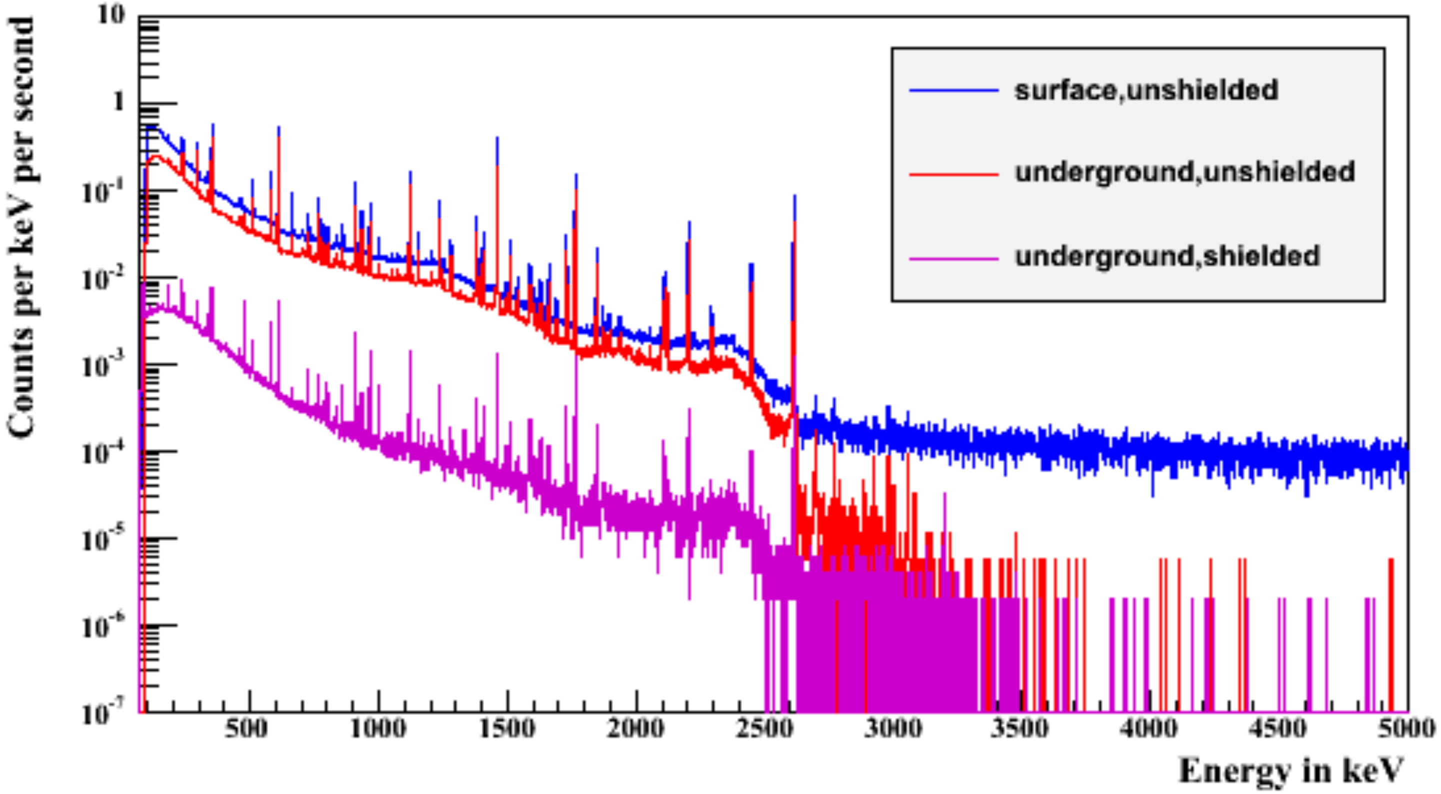
Why going underground n-background



Therefore, the advantage of an underground environment is evident for n-source reaction as **$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$**

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

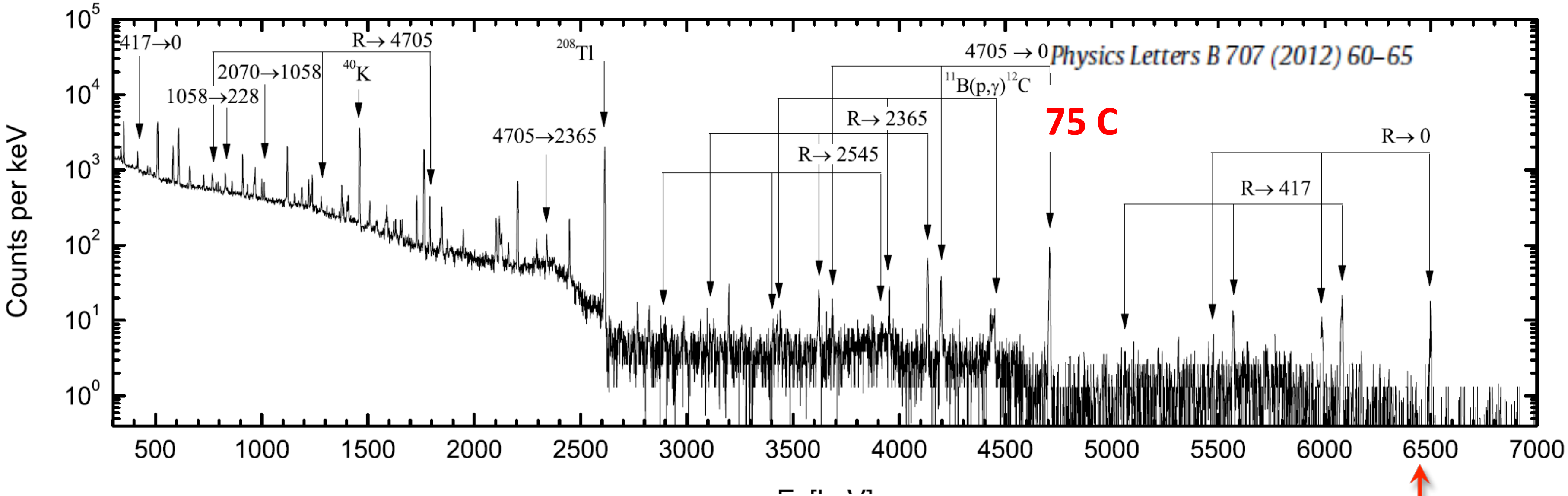
Underground Pb-shielding

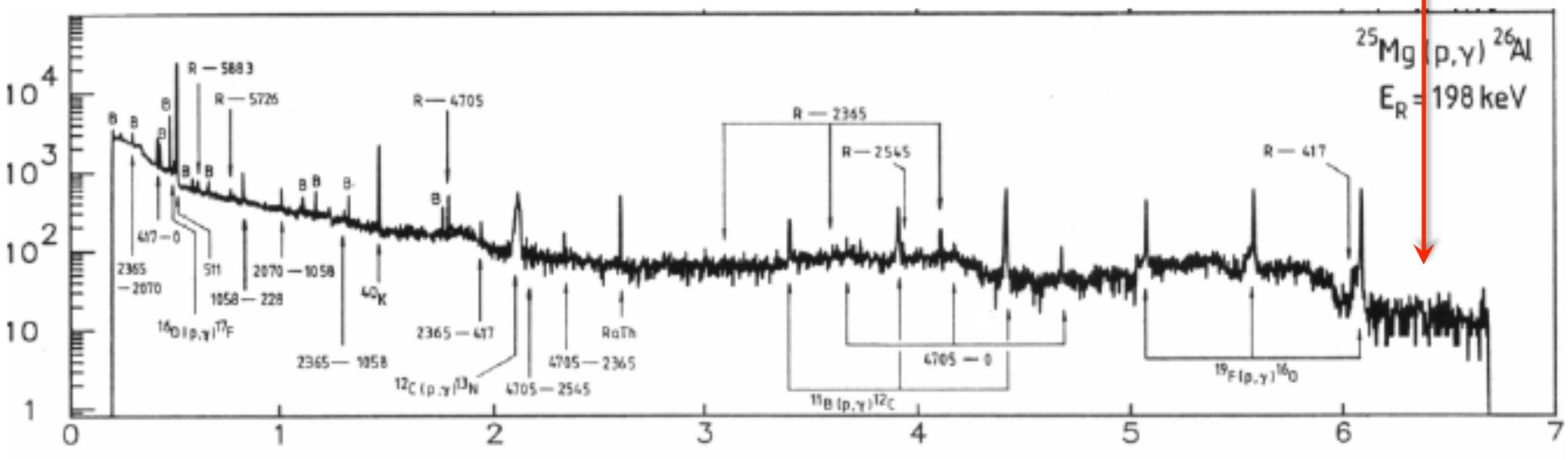


			Surface	Underground		
			unshielded	unshielded	shielded (this setup)	
^{40}K	primordial	1460 keV	*	2244	15	counts / hour
^{214}Bi	^{238}U chain	1764 keV	*	1271	13	counts / hour
^{208}Tl	^{232}Th chain	2614 keV	*	679	15	counts / hour
region 3300 – 6000 keV			$3.30(2) \cdot 10^{-1}$	$2.4(4) \cdot 10^{-4}$	$1.9(2) \cdot 10^{-4}$	counts / keV / hour

HPGe fully sorrounded (55°) with 15 cm of Pb

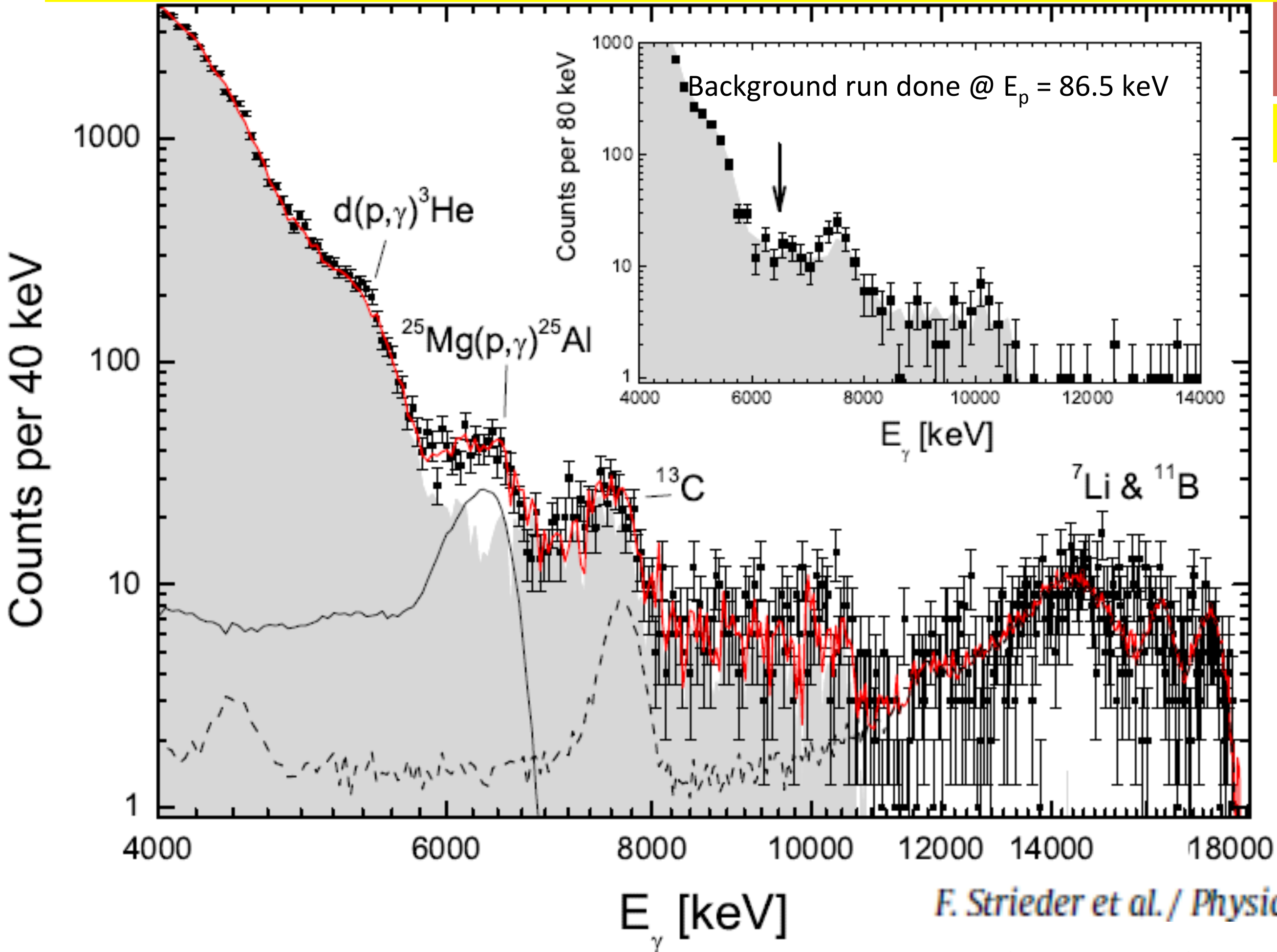
$^{25}Mg(p,\gamma)^{26}Al$ - HPGe spectra E_R = 190 keV





$^{25}Mg(p,\gamma)^{26}Al$ - BGO spectra E_R = 90 keV

the weakest ever directly measured resonance strength



$\omega\gamma$ [10^{-10} eV] LUNA	$\omega\gamma$ [10^{-10} eV] NACRE ind.
2.9 ± 0.6	$1.16^{+1.16}_{-0.39}$

BR→0 = (60^{+20}_{-10}) %

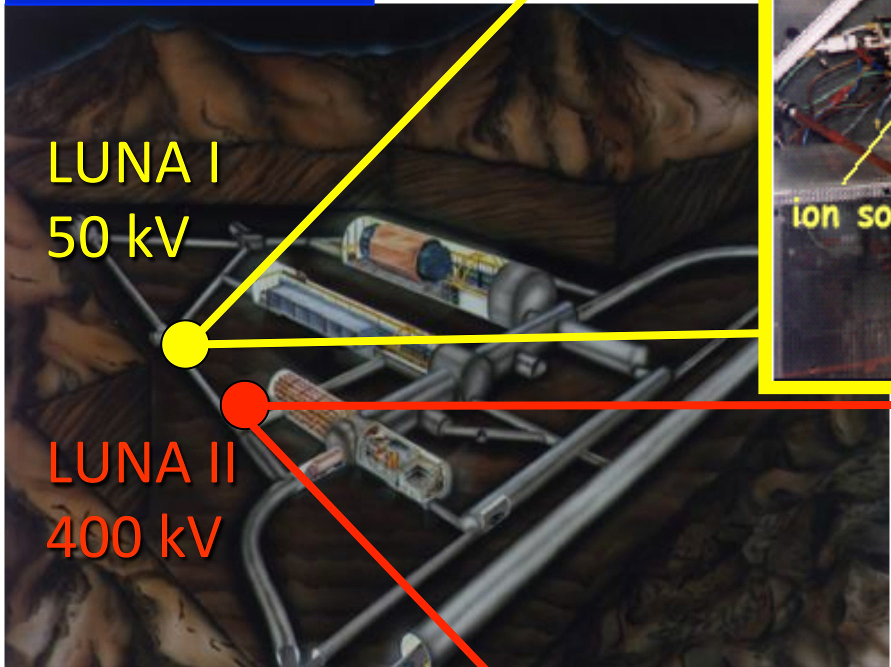
F. Strieder et al. / Physics Letters B 707 (2012) 60–65

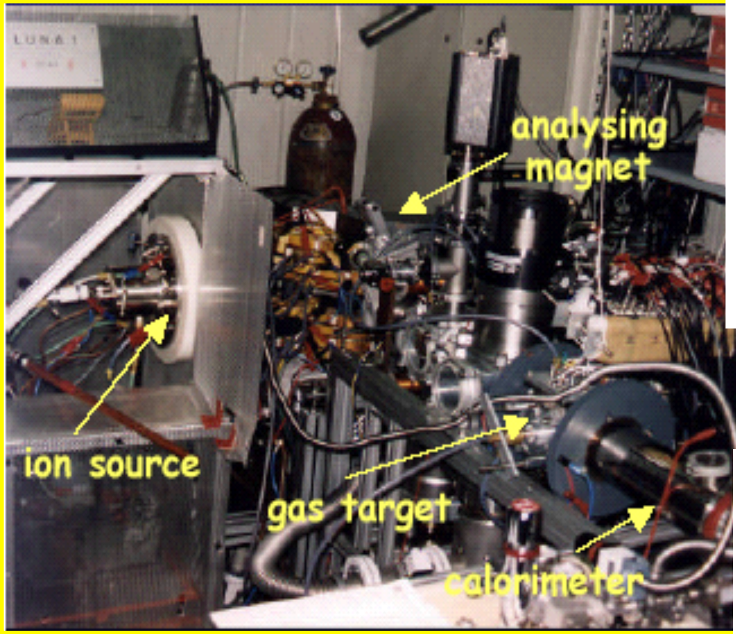
The BGO γ-ray total sum spectrum on the 92 keV $^{25}Mg(p,\gamma)^{26}Al$ resonance (E_p = 100 keV).

1. The shaded area → envinromental background
2. Thin solid line → $^{25}Mg(p,\gamma)^{26}Al$ simulation varying the primaries branchings .
3. Solid red line → total yield fit including background and simulation.

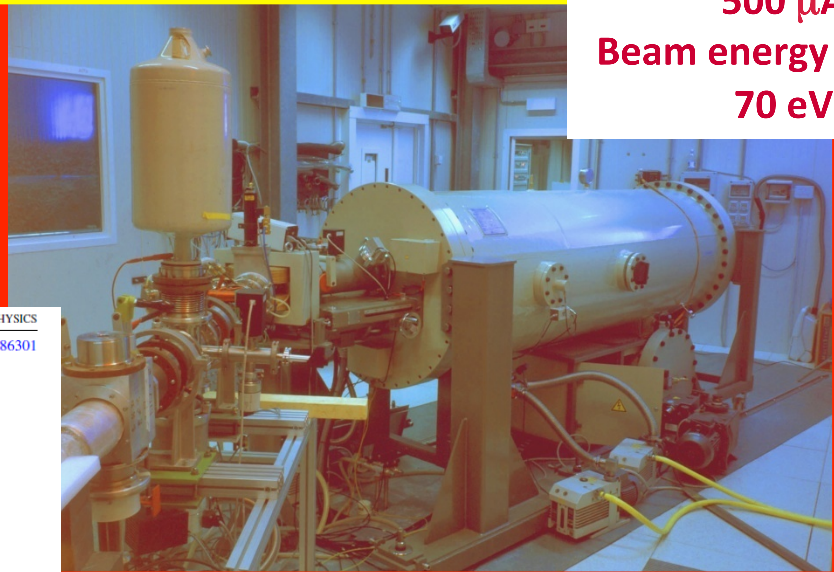
LUNA - experimental set-ups

LNGS Lab





Voltage Range :
1 - 50 kV
Output Current:
1 mA
Beam energy spread:
20 eV



Voltage Range :
50 - 400 kV
Output Current:
500 μA
Beam energy spread:
70 eV

IOP Publishing — Reports on Progress in Physics
Rep. Prog. Phys. 72 (2009) 086301 (25pp) doi:10.1088/0034-4885/72/8/086301

LUNA: a laboratory for underground nuclear astrophysics

H Costantini[1], A Formicola[2], G Imbriani[3,4], M Junker[2], C Rolfs[5] and F Strieder[5]

H-burning @ LUNA – three important results

- **BBN and H-burning in the Sun and solar neutrinos**:

p+p->d+e^++ν, p(d,γ)^{3}He, d(α,γ)^{6}Li, ^{3}He(^{3}He, 2p)^{4}He, ^{3}He(α,γ)^{7}Be, ^{7}Be(p,γ)^{8}B and ^{14}N(p,γ)^{15}O

- **Age of Globular Clusters and C production in AGB:**

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- **AGB nucleosynthesis − light nuclei abundances:**

^{14}N(p,γ)^{15}O, ^{15}N(α,γ)^{19}F, ^{15}N(p,γ)^{16}O, ^{15}N(p,α)^{12}C, ^{17}O(p,γ)^{18}F, ^{17}O(p,α)^{14}N, ^{18}O(p,γ)^{19}F, ^{18}O(p,α)^{15}N, ^{18}O(α,γ)^{22}Ne, ^{18}F(α,p)^{21}Ne, ^{19}F(α,p)^{22}Ne, ^{22}Ne(p,γ)^{23}Na, ^{23}Na(p,γ)^{24}Mg, ^{24}Mg(p,γ)^{25}Al, ^{25}Mg(p,γ)^{26}Al(β^+)^{26}Mg, ^{26}Mg(p,γ)^{27}Al

- **Main neutron sources:**

^{13}C(α,n)^{16}O, ^{22}Ne(α,n)^{25}Mg

- **Explovive CNO burning:**

^{15}O(α,γ)^{19}Ne, ^{14}O(α,γ)^{18}Ne, ^{18}Ne(α,p)^{21}Na

- **He and advaced burnings:**

^{12}C(α,γ)^{16}O, ^{12}C(^{12}C, p)^{23}Na, ^{12}C(^{12}C,α)^{20}Ne, ^{16}O(α,γ)^{20}Ne

Possible nuclear solution of the Solar neutrino problem (before SNO and Borexino)

$p + p \rightarrow {}^2H + e^+ + \nu$ [0.27 MeV] $p + e^- + p \rightarrow {}^2H + \nu$ [1.44 MeV]

99.75% 0.25%

${}^2H + p \rightarrow {}^3He + \gamma$

86% 14% $2 \cdot 10^{-5}$%

${}^3He + {}^3He \rightarrow {}^4He + 2p$ ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$ ${}^3He + p \rightarrow {}^4He + e^+ + \nu$

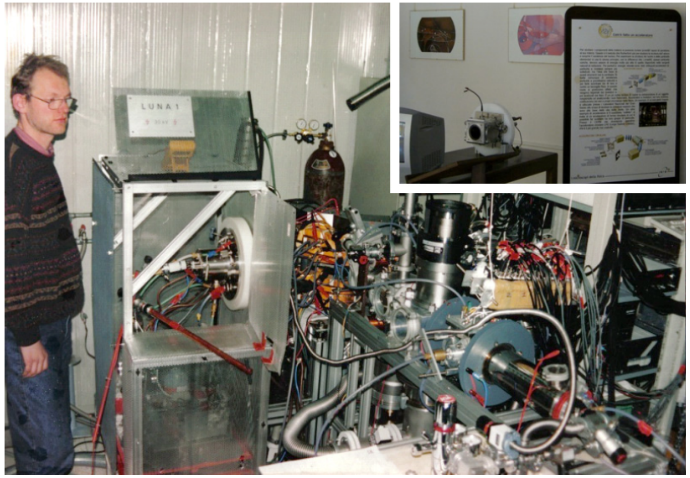
99.89% 0.11%

${}^7Be + e^- \rightarrow {}^7Li + \nu$ [0.81 MeV] ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^7Li + p \rightarrow {}^8Be$ ${}^8B \rightarrow {}^8Be + e^+ + \nu$ [6.80 MeV]

${}^8Be \rightarrow 2\ {}^4He$ ${}^8Be \rightarrow 2\ {}^4He$

${}^3He({}^3He,p){}^4He$ measurement @ LUNA 50 kV 2001



The dream of W. Fowler

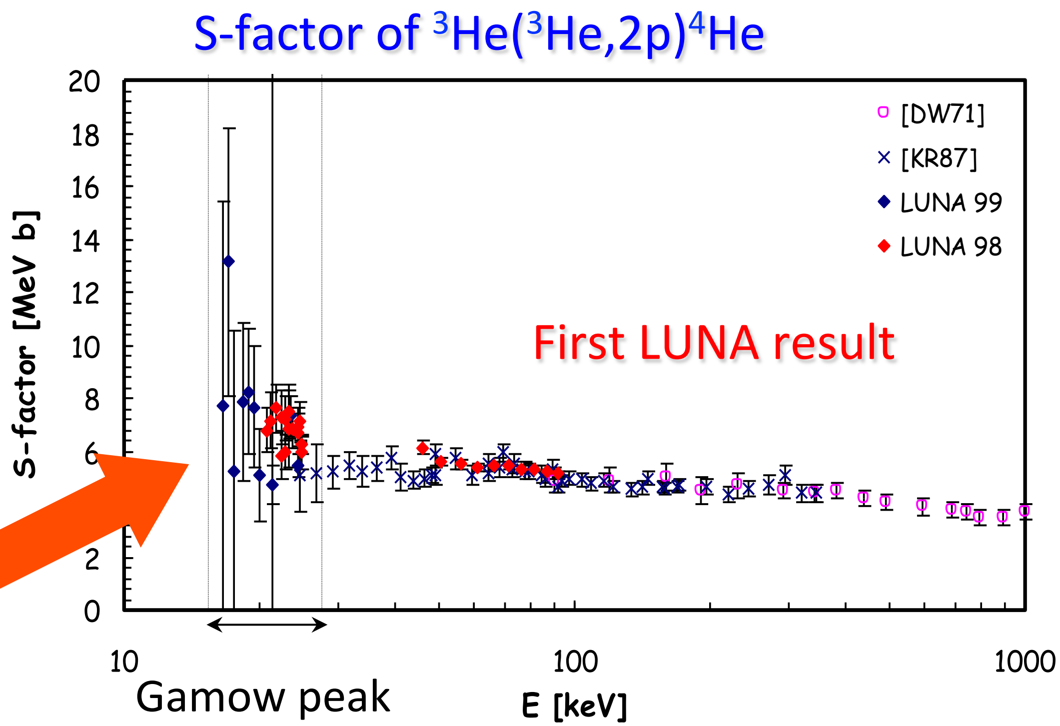
Cross section of $^3He(^3He,2p)^4He$ measured at solar energies
Phys. Rev. C 57(1998)2700

First measurement of the $^3He(^3He,2p)^4He$ cross section down to the lower edge of the solar Gamow peak Phys. Rev. Lett. 82(1999)5205

S(0)=5.3 ± 0.3 MeVb 6%

$\sigma_{min=}$ 0.02 pb

2 events/month !



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.

J. Bahcall

The measurement of $^{3}He(^{4}He,g)^{7}Be$ @ LUNA

$p + p \rightarrow {}^{2}H + e^{+} + \nu$ [0.27 MeV] $\quad$ $p + e^{-} + p \rightarrow {}^{2}H + \nu$ [1.44 MeV]

99.75% $\quad$ 0.25%

$^{2}H + p \rightarrow {}^{3}He + \gamma$

86% $\quad$ 14% $\quad$ $2 \cdot 10^{-5}$%

$^{3}He + {}^{3}He \rightarrow {}^{4}He + 2p$ $\quad$ $^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$ $\quad$ $^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu$

99.89% $\quad$ 0.11%

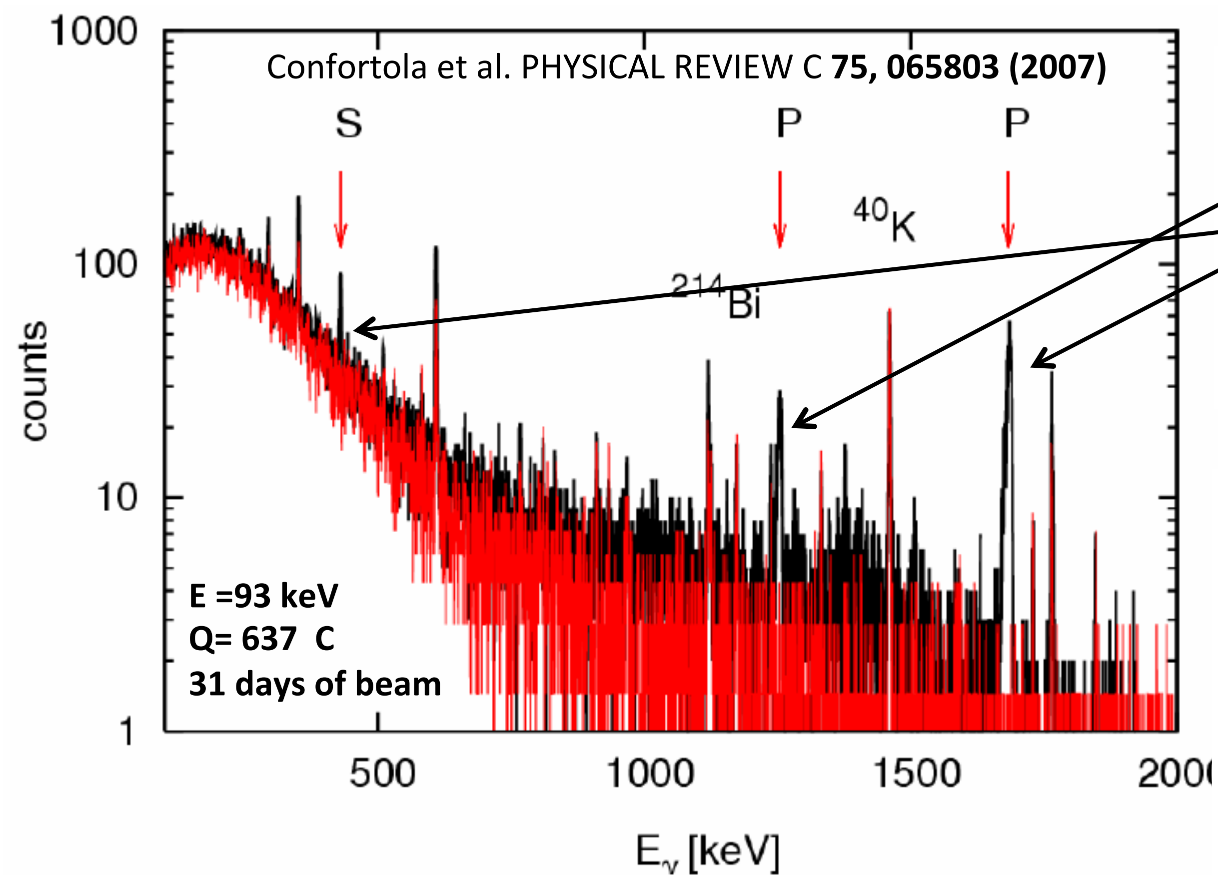
$^{7}Be + e^{-} \rightarrow {}^{7}Li + \nu$ [0.81 MeV] $\quad$ $^{7}Be + p \rightarrow {}^{8}B + \gamma$

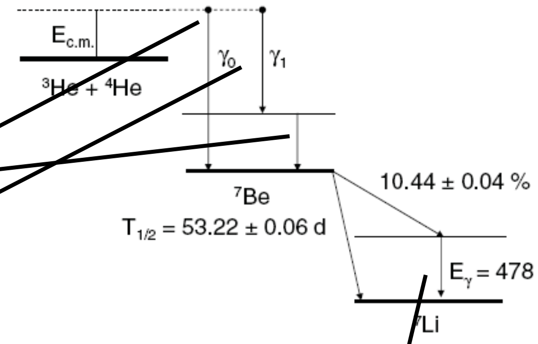
$^{7}Li + p \rightarrow {}^{8}Be$ $\quad$ $^{8}B \rightarrow {}^{8}Be + e^{+} + \nu$ [6.80 MeV]

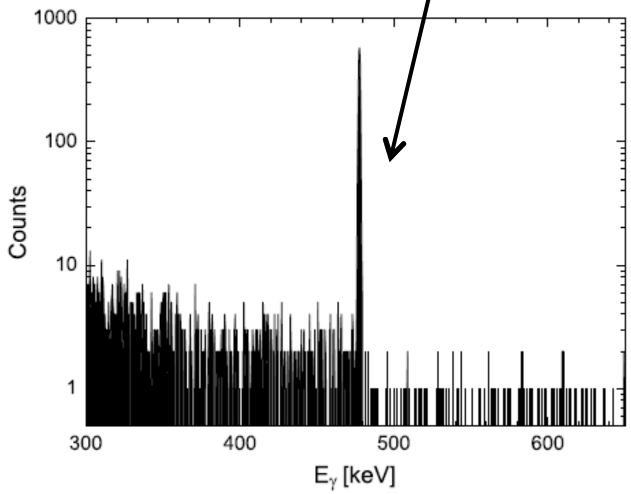
$^{8}Be \rightarrow 2\,{}^{4}He$ $\quad$ $^{8}Be \rightarrow 2\,{}^{4}He$

$^{3}He(^{4}He,\gamma)^{7}Be$ measurement @ LUNA 400kV

γ-spectrum of $^3He(^4He,\gamma)^7Be$ @ LUNA







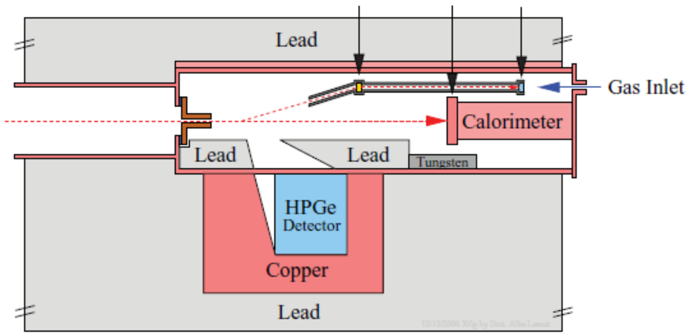
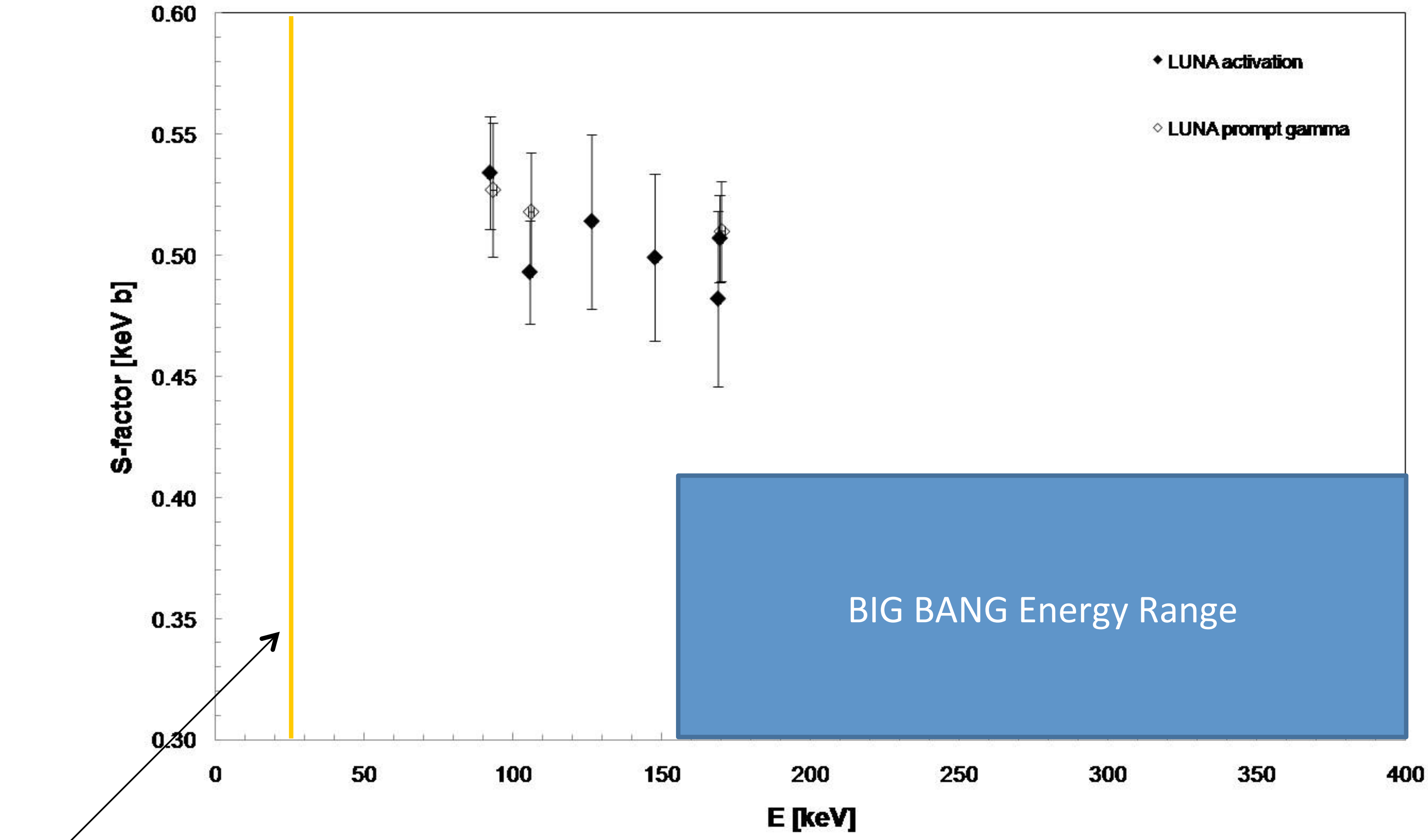


Figure 14. Gamma-ray spectrum of the ^7Be activity for a sample irradiated at $E = 148$ keV. The spectrum was obtained with a HPGe detector of the LNGS low-level laboratory. The total running time was 6 days and the measured activity about 480 mBq.

$^{3}He(^{4}He,\gamma)^{7}Be$ results

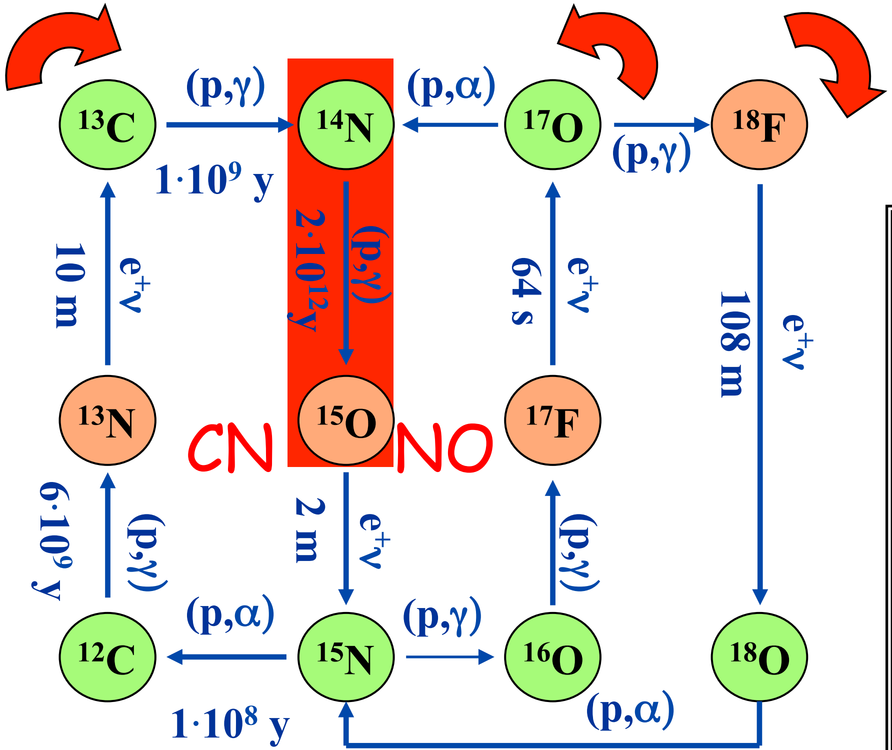


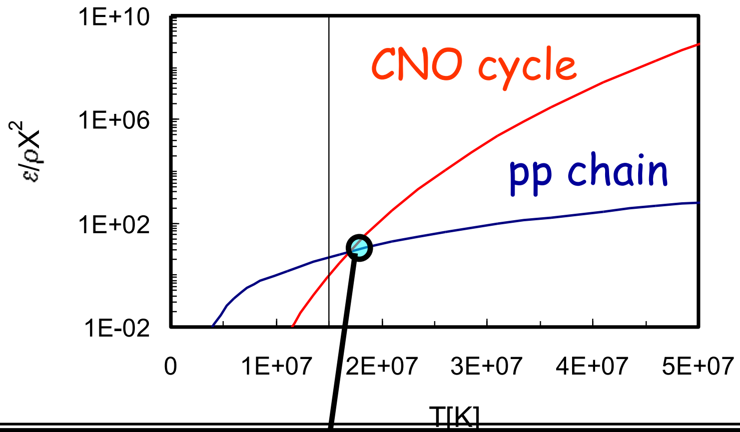
Solar Gamow Energy

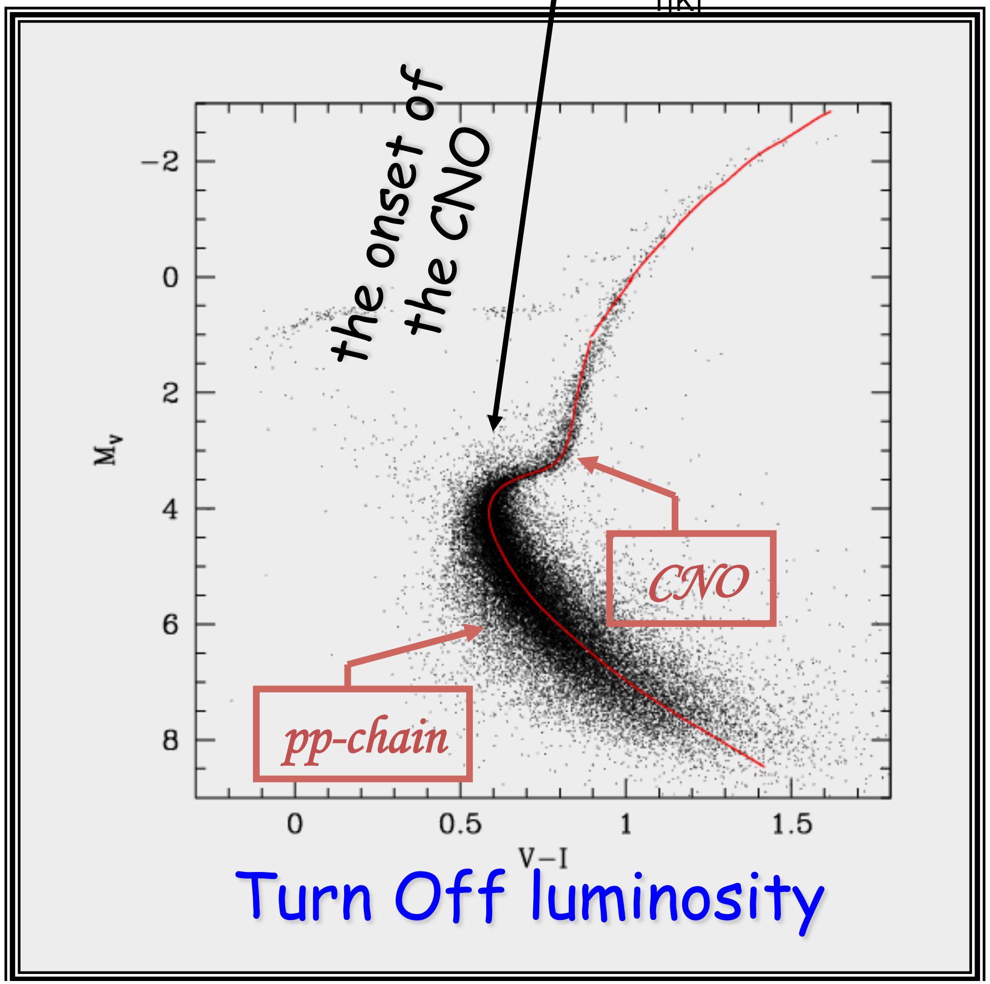
Uncertainty about 5%

$$S(0) = 0.542 \pm 0.011(\text{MC fit}) \pm 0.006(\text{model})^{+0.019}_{-0.011}(\text{phase shifts})\ \text{keV b}.$$

$^{14}N(p,\gamma)^{15}O$: Age of Globular Clusters



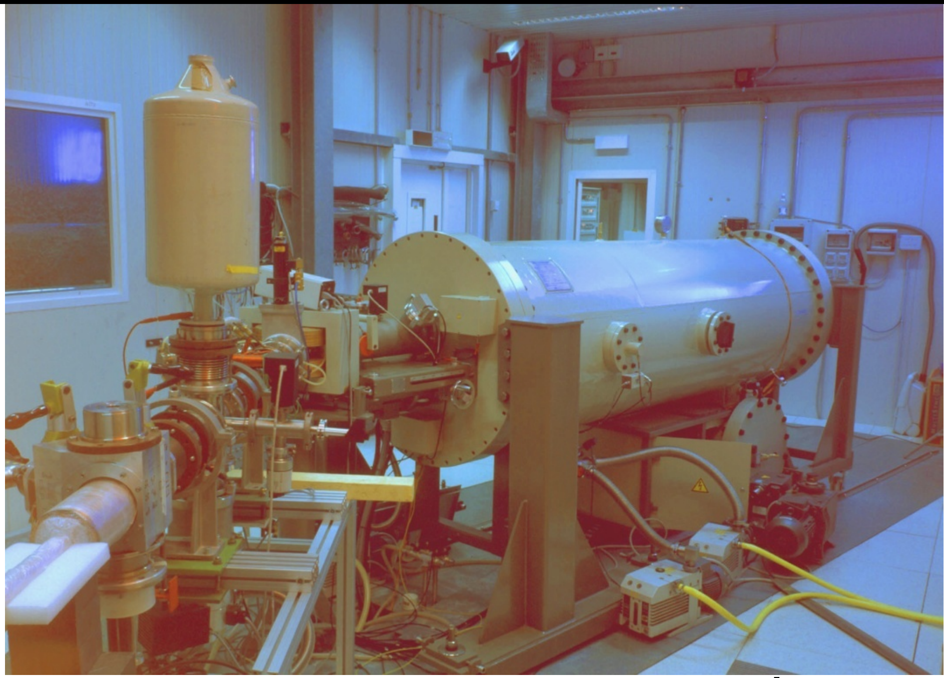




CN	NO
Q_{eff} = 26.02 MeV	Q_{eff} = 25.73 MeV

$^{14}N(p,\gamma)^{15}O$ is the bottleneck of the cycle, therefore the initial abundance of C, N, O is, mostly, converted in ^{14}N!!

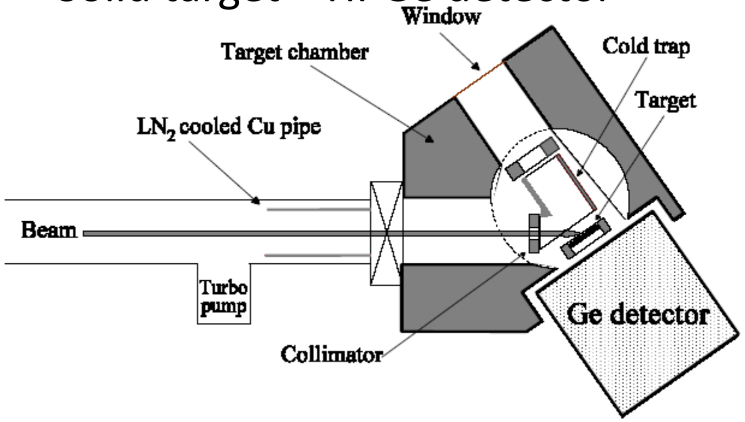
$^{14}N(p,\gamma)^{15}O$ @ LUNA400kV



Accelerator Specifications

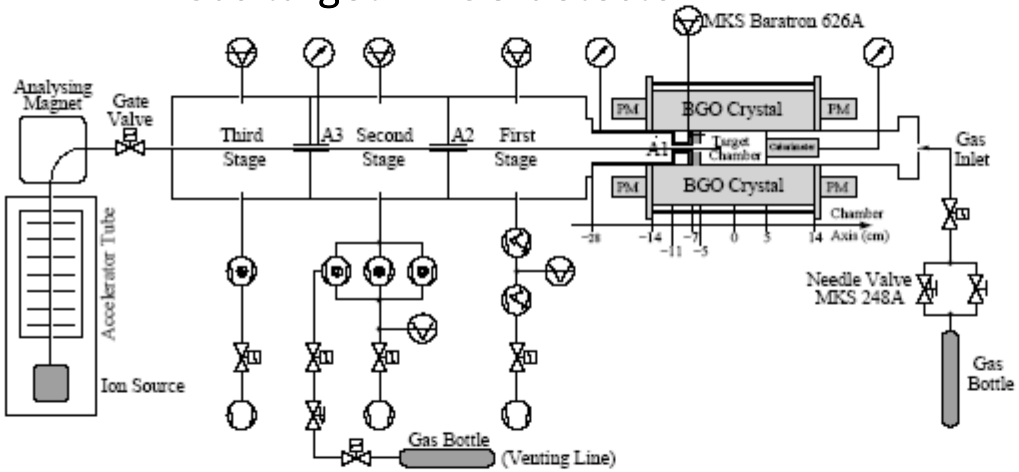
- ✓ U = 50 – 400 kV
- ✓ I ~ 300 μA *for proton*
- ✓ ΔE_{max}= 0.07 keV
- ✓ Energy spread : 72eV
- ✓ Total uncertainty is ± 300 eV for E_p=100 ÷ 400keV

Solid target + HPGe detector

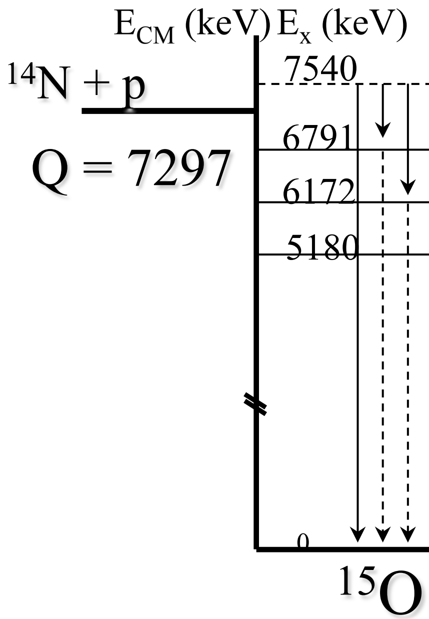


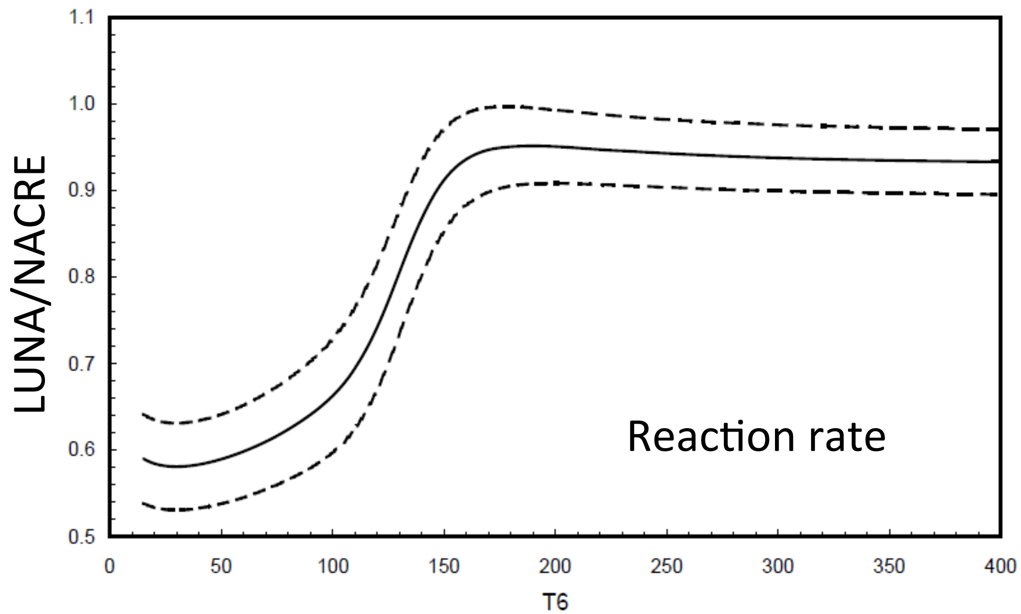
TiN (1/(1.08 ± 0.05)) targets

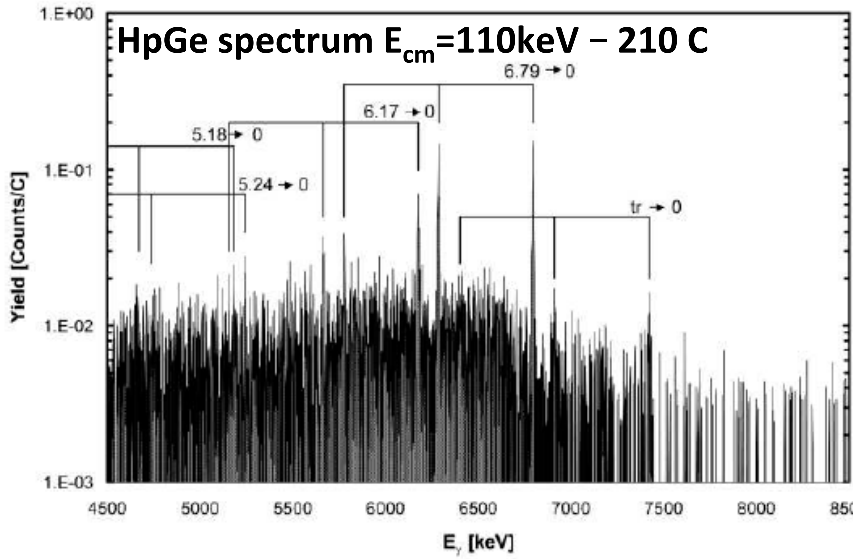
Gas target + BGO detector

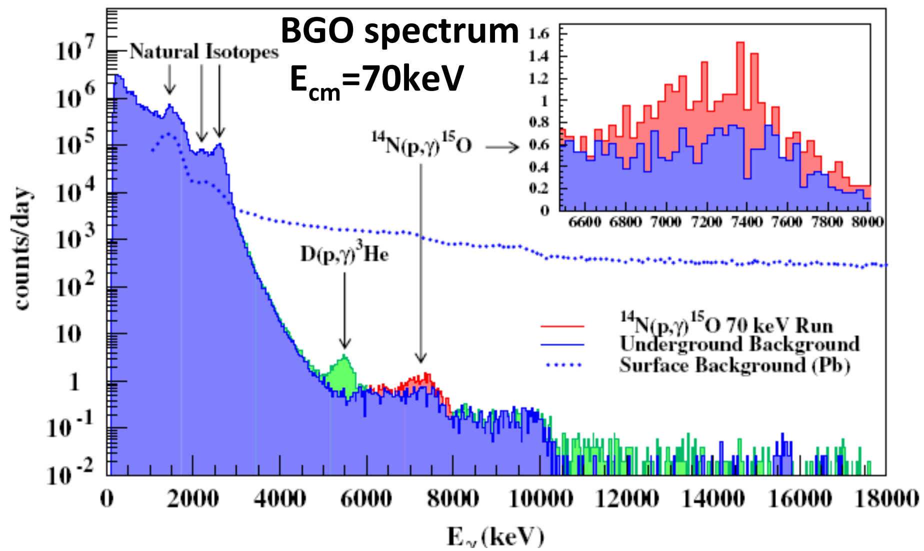


$^{14}N(p,\gamma)^{15}O$: LUNA results



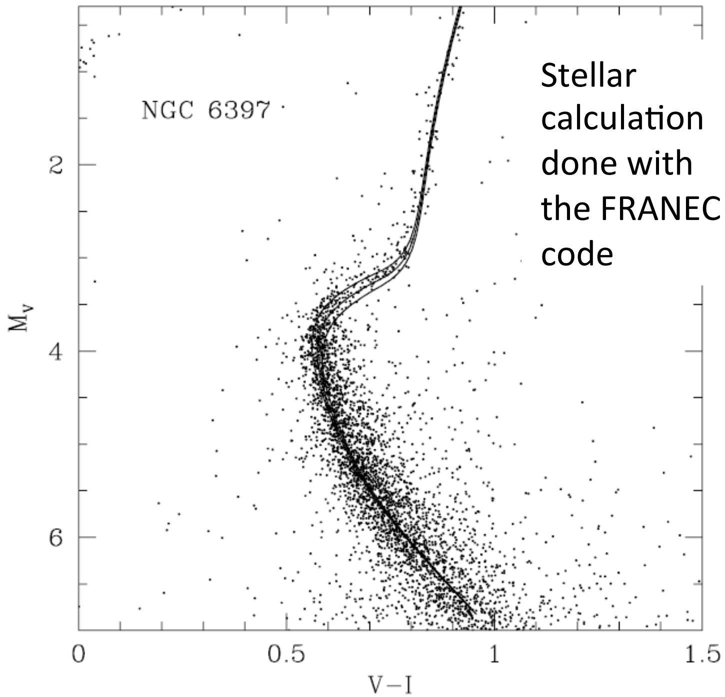






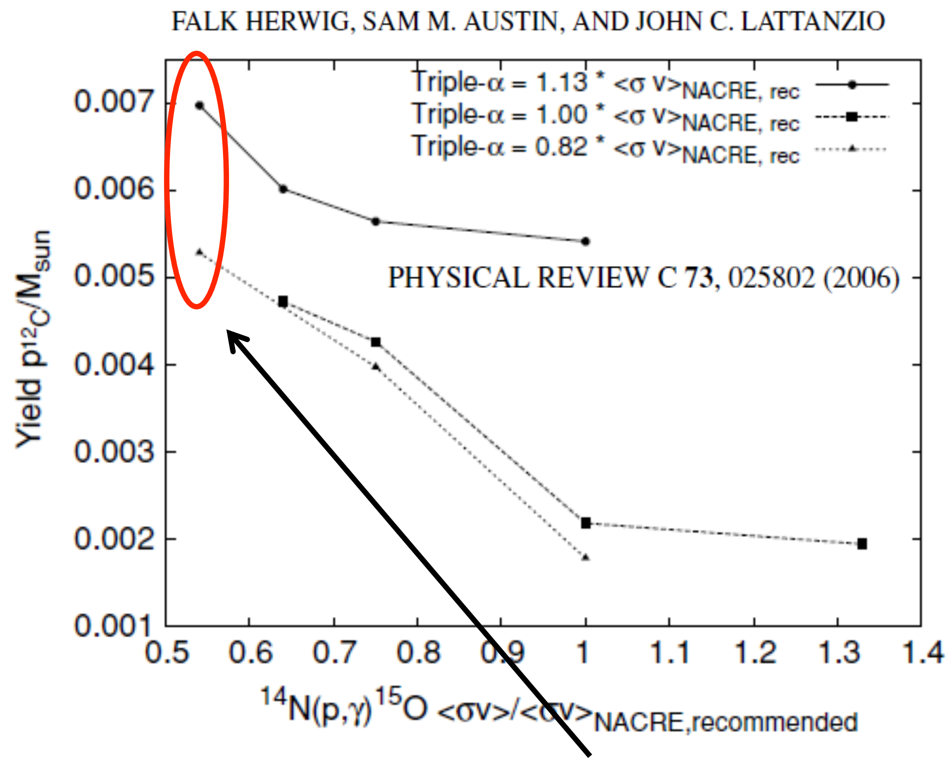
$^{14}N(p,\gamma)^{15}O$: astrophysical consequences

G. Imbriani, et al., A&A 420(2004)



The age of the oldest Globular Clusters should be <u>increased by about 0.7-1 Gyr</u>. The lower limit to the Age of the Universe is <u>14 ± 1 Gyr</u>.

In good agreement with the precise determination of WMAP.



With **$^{14}N(p,\gamma)^{15}O$** rate = ½ of NACRE agreement between observation and calculation.

<u>CNO ν-flux reduced by a factor 2</u>

LUNA measurements 1991-2017

- **BBN and H-burning in the Sun and solar neutrinos**:

$p+p \rightarrow d+e^{+}+\nu$, $p(d,\gamma)^{3}He$, $d(\alpha,\gamma)^{6}Li$, $^{3}He(^{3}He, 2p)^{4}He$, $^{3}He(\alpha,\gamma)^{7}Be$, $^{7}Be(p,\gamma)^{8}B$ and $^{14}N(p,\gamma)^{15}O$

- **Age of Globular Clusters and C production in AGB:**

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

- **AGB nucleosynthesis – light nuclei abundances:**

$^{14}N(p,\gamma)^{15}O$, $^{15}N(\alpha,\gamma)^{19}F$, $^{15}N(p,\gamma)^{16}O$, $^{15}N(p,\alpha)^{12}C$, $^{17}O(p,\gamma)^{18}F$, $^{17}O(p,\alpha)^{14}N$, $^{18}O(p,\gamma)^{19}F$, $^{18}O(p,\alpha)^{15}N$, $^{18}O(\alpha,\gamma)^{22}Ne$, $^{18}F(\alpha,p)^{21}Ne$, $^{19}F(\alpha,p)^{22}Ne$, $^{22}Ne(p,\gamma)^{23}Na$, $^{23}Na(p,\gamma)^{24}Mg$, $^{24}Mg(p,\gamma)^{25}Al$, $^{25}Mg(p,\gamma)^{26}Al$, $^{26}Mg(p,\gamma)^{27}Al$

- **Main neutron sources:**

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

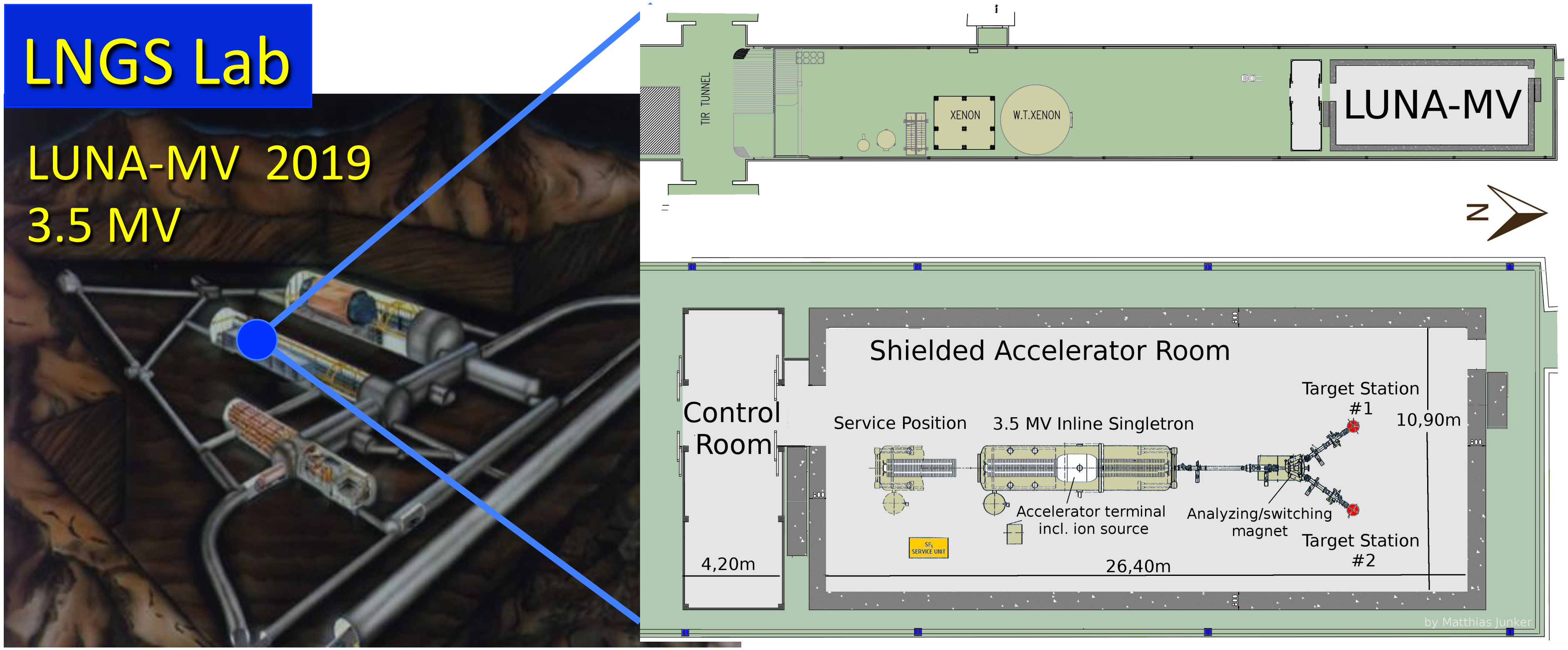
- **Explovive CNO burning:**

$^{15}O(\alpha,\gamma)^{19}Ne$, $^{14}O(\alpha,\gamma)^{18}Ne$, $^{18}Ne(\alpha,p)^{21}Na$

- **He and advaced burnings:**

$^{12}C(\alpha,\gamma)^{16}O$, $^{12}C(^{12}C, p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$, $^{16}O(\alpha,\gamma)^{20}Ne$

LUNA MV – future setup



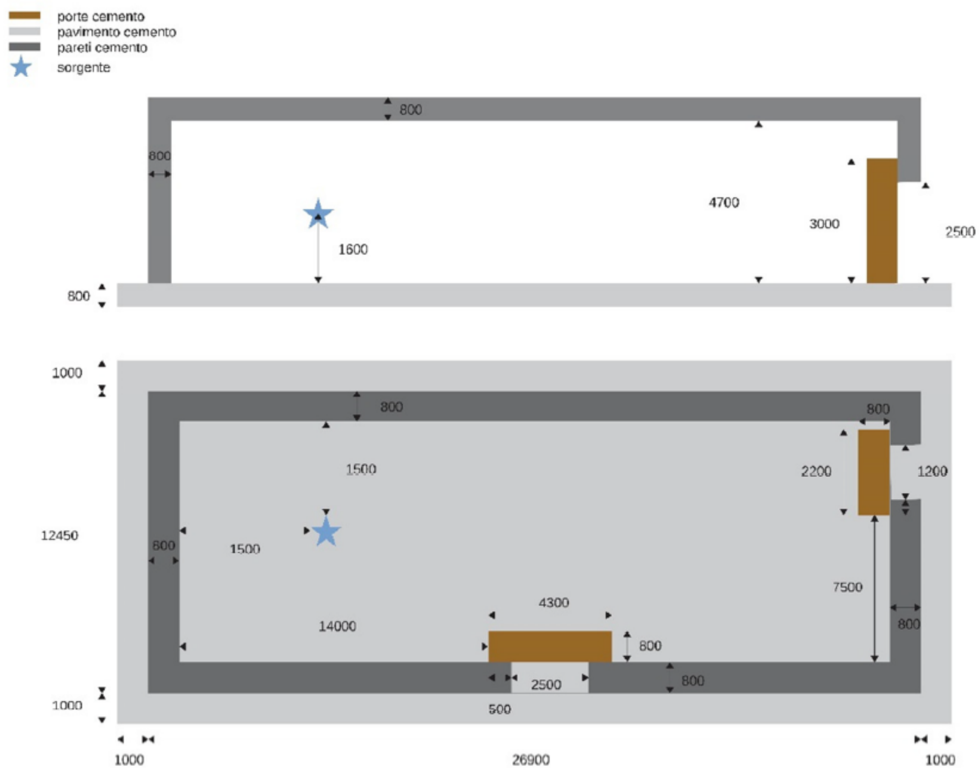
The accelerator and the neutron shielding

$^{1}H^{+}$ (TV: 0.3 – 0.5 MV): 500 µA
$^{1}H^{+}$ (TV: 0.5 – 3.5 MV): 1000 µA

$^{4}He^{+}$ (TV: 0.3 – 0.5 MV): 300 µA
$^{4}He^{+}$ (TV: 0.5 – 3.5 MV): 500 µA

$^{12}C^{+}$ (TV: 0.3 – 0.5 MV): 100 µA
$^{12}C^{+}$ (TV: 0.5 – 3.5 MV): 150 µA
$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 µA

- inline Cockcroft Walton accelerator
- **TERMINAL VOLTAGE: 0.2 – 3.5 MV**
- Precision of terminal voltage reading: 350 V
- Beam energy reproducibility: 0.01% TV
- Beam energy stability: 0.001% TV / h
- Beam current stability: < 5% / h



- 80 cm thick concrete shielding calculated by GEANT4 & MCNP
- E_n = 5.6 MeV, 2 10^3 n/s, isotropic

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)

LUNA-MV basic schedule

Action	Date
Approval of the first HVEE technical design	October 2016
Opening of the tendering procedure for LUNA-MV plants	November 2016
Submission of the Authorization request to «Prefettura dell'Aquila»	December 2016
Beginning of the clearing works in Hall B	February 2017
End of the tendering procedure for the new LUNA-MV building	June 2017
Beginning of the construction works in Hall B	September 2017
End of the tendering procedure for LUNA-MV plants	October 2017
Beginning of the construction of the plants in the LUNA-MV building	December 2017
Completion of the new LUNA-MV building and plants	April 2018
In-house acceptance test for the new LUNA-MV accelerator	May 2018
LUNA-MV accelerator delivering at LNGS	July 2018
Conclusion of the commissioning phase	December 2018
Beginning First Experiment	January 2019

LUNA future measurements

- **BBN and H-burning in the Sun and solar neutrinos**:

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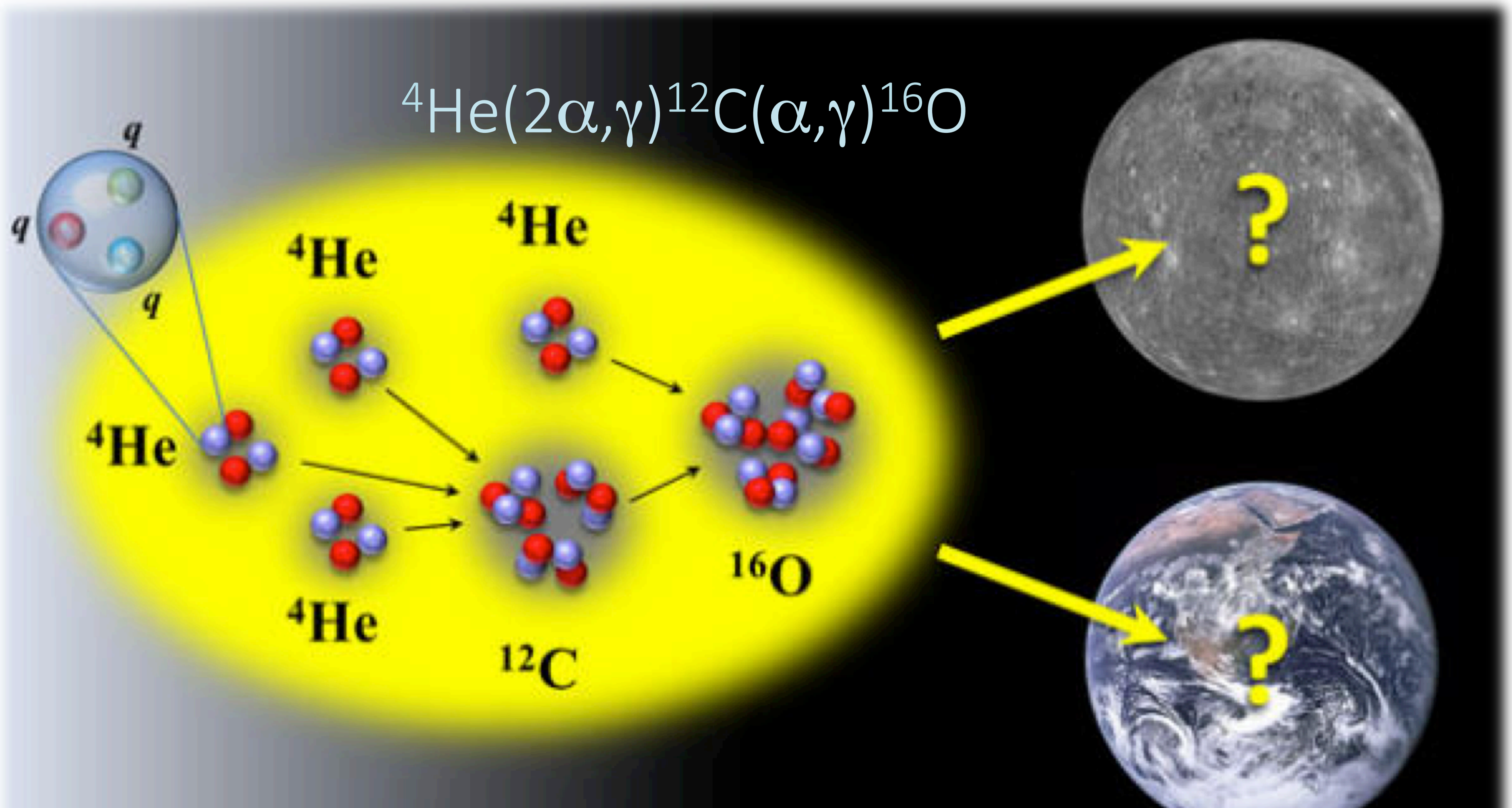
Helium Burning: The Cosmo-Chemistry of Carbon and Oxygen



$^{12}C(^{12}C,p)^{23}Na(p,\alpha)^{20}Ne$

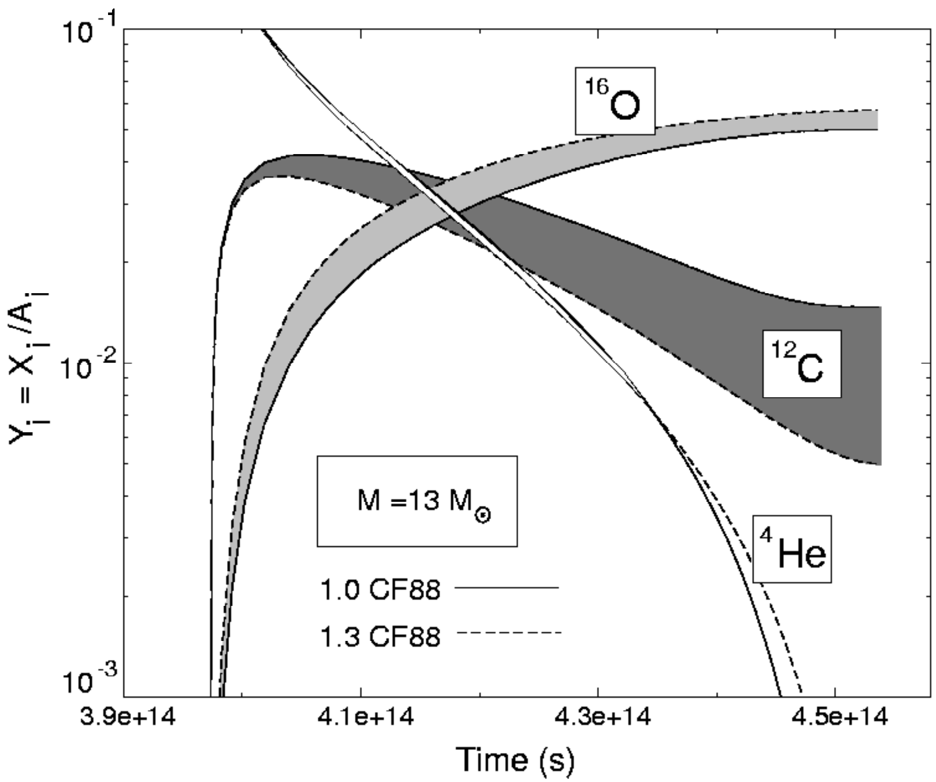
$^{12}C(^{12}C,\alpha)^{20}Ne$

$^{12}C(^{16}O,p)^{27}Al(p,\alpha)^{24}Mg$

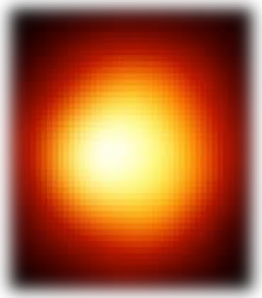
$^{12}C(^{16}O,\alpha)^{24}Mg$

The “holy Grail”

The step after carbon is being formed in a high temperature density environment:
$^{12}C(\alpha,\gamma)^{16}O$ determining the early $^{12}C/^{16}O$ ratio

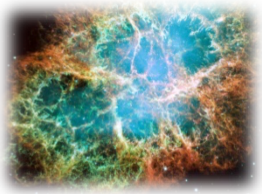


- Late Stellar Evolution
  determines Carbon and/or Oxygen phase

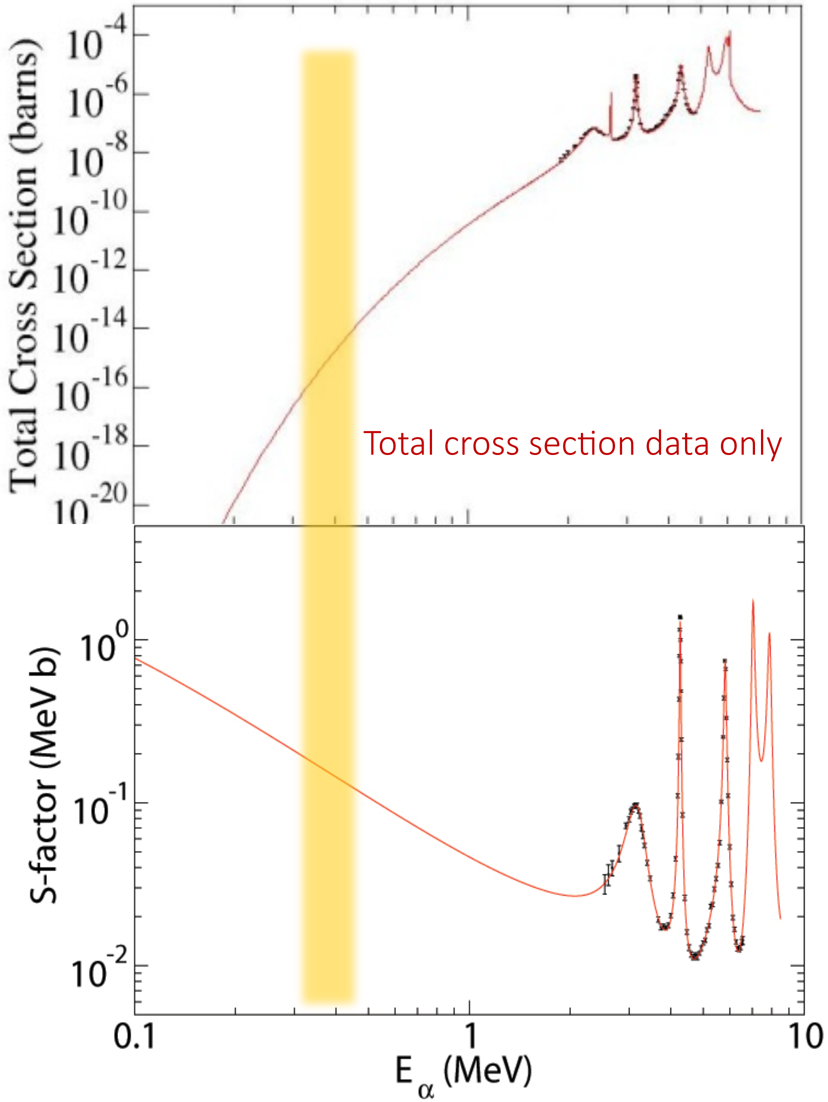


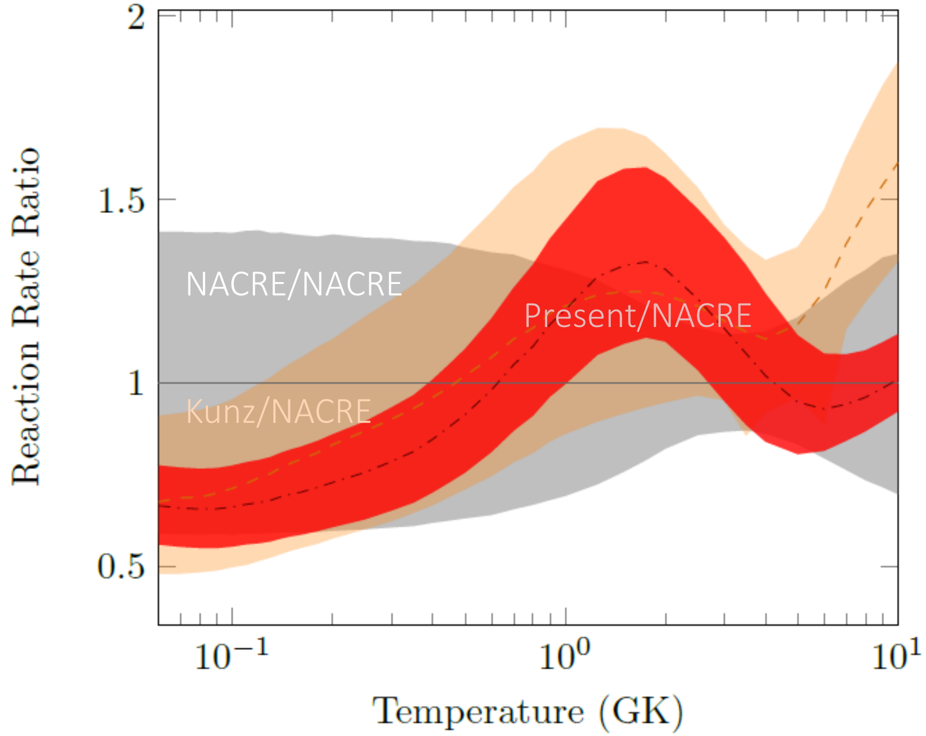
- Type Ia Supernova
  central carbon burning of C/O white dwarf

- Type II Supernova
  shock-front nucleosynthesis in C and He shells of pre-supernova star



R-Matrix Analysis
phenomenology, but …





R-matrix (AZURE) based cross section extrapolation on the basis of all existing reaction data through ^{16}O compound nucleus give 15%-20% uncertainty in reaction rate extrapolation.

Carbon burning in stars

Conversion of ^{4}He into ^{12}C and ^{16}O
depending on the $^{12}C(\alpha,\gamma)^{16}O$ reaction

$$^{12}C(^{12}C,p)^{23}Na \quad Q = 2.240\,MeV$$

$$^{12}C(^{12}C,\alpha)^{20}Ne \quad Q = 4.617\,MeV$$

$$^{12}C(^{12}C,p)^{23}Na \quad Q = -2.598\,MeV$$

$$^{16}O(^{16}O,p)^{31}P \quad Q = 7.628\,MeV$$

$$^{16}O(^{16}O,\alpha)^{28}Si \quad Q = 9.594\,MeV$$

$$^{16}O(^{16}O,n)^{31}S \quad Q = 1.499\,MeV$$

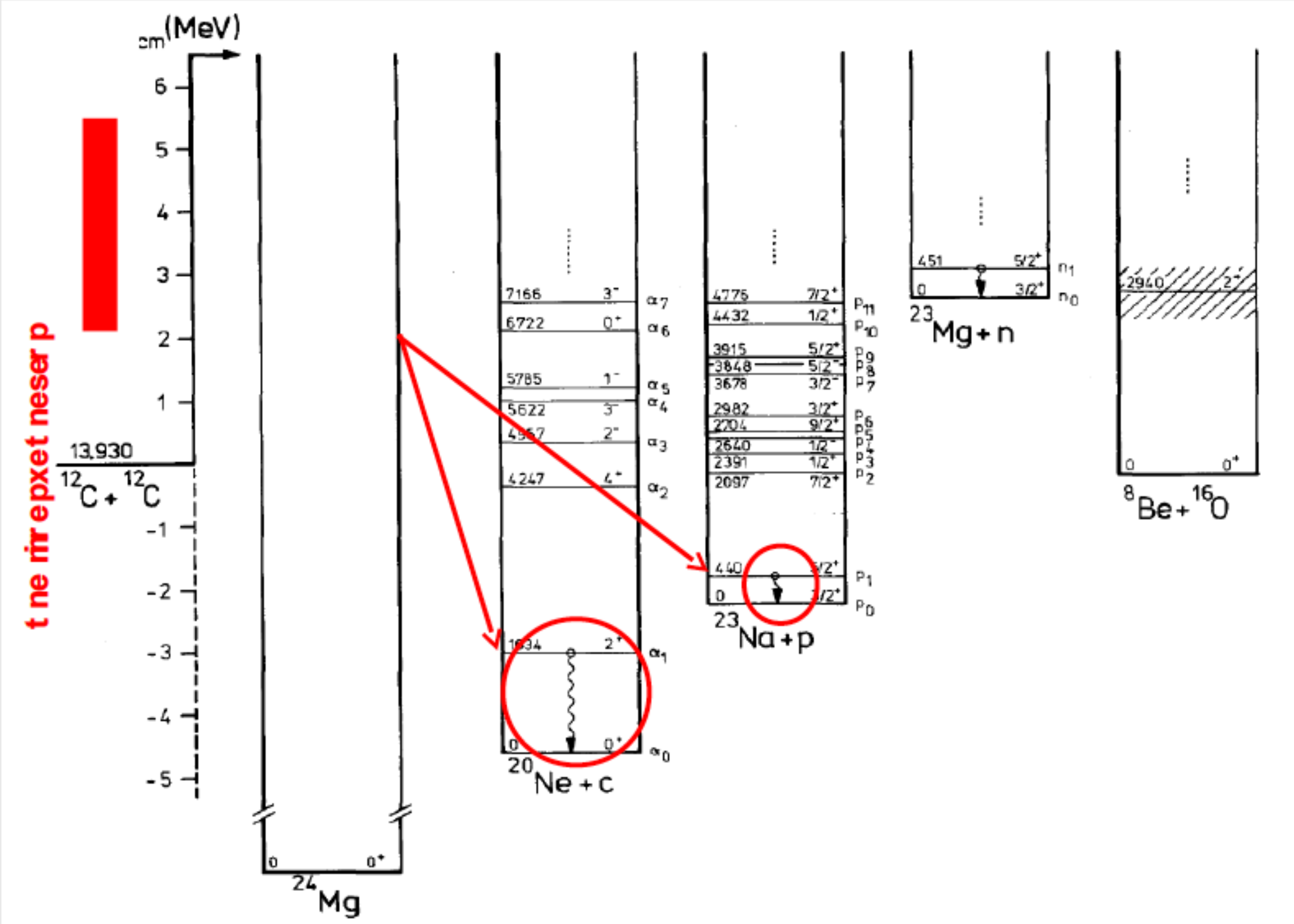
$$^{16}O(^{12}C,p)^{27}Al \quad Q = 7.170\,MeV$$

$$^{16}O(^{12}C,\alpha)^{24}Mg \quad Q = 6.771\,MeV$$

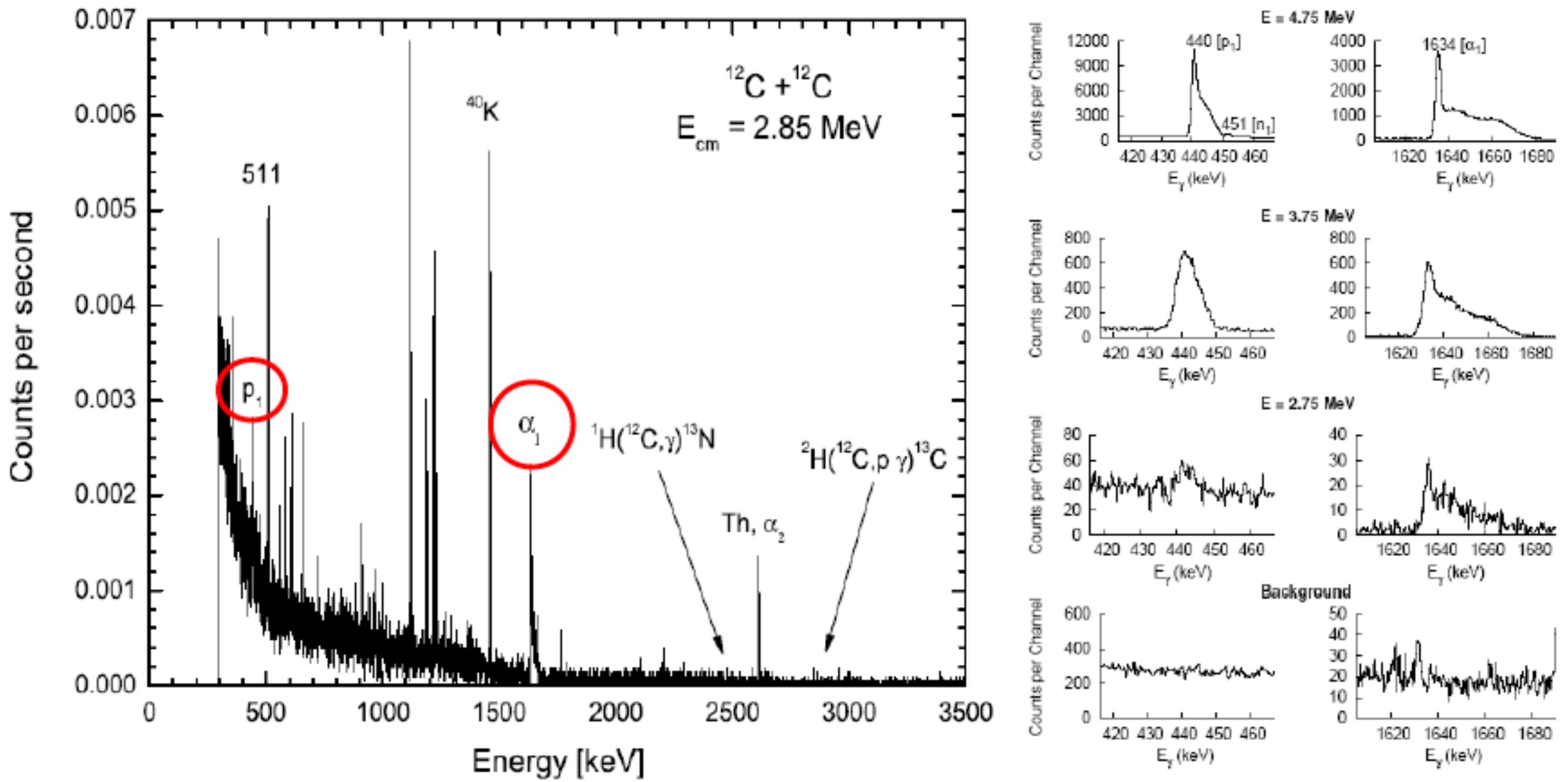
$$^{16}O(^{12}C,n)^{27}Si \quad Q = -0.424\,MeV$$

Wide range of possible
heavy ion
reactions at low energies

Carbon burning in stars

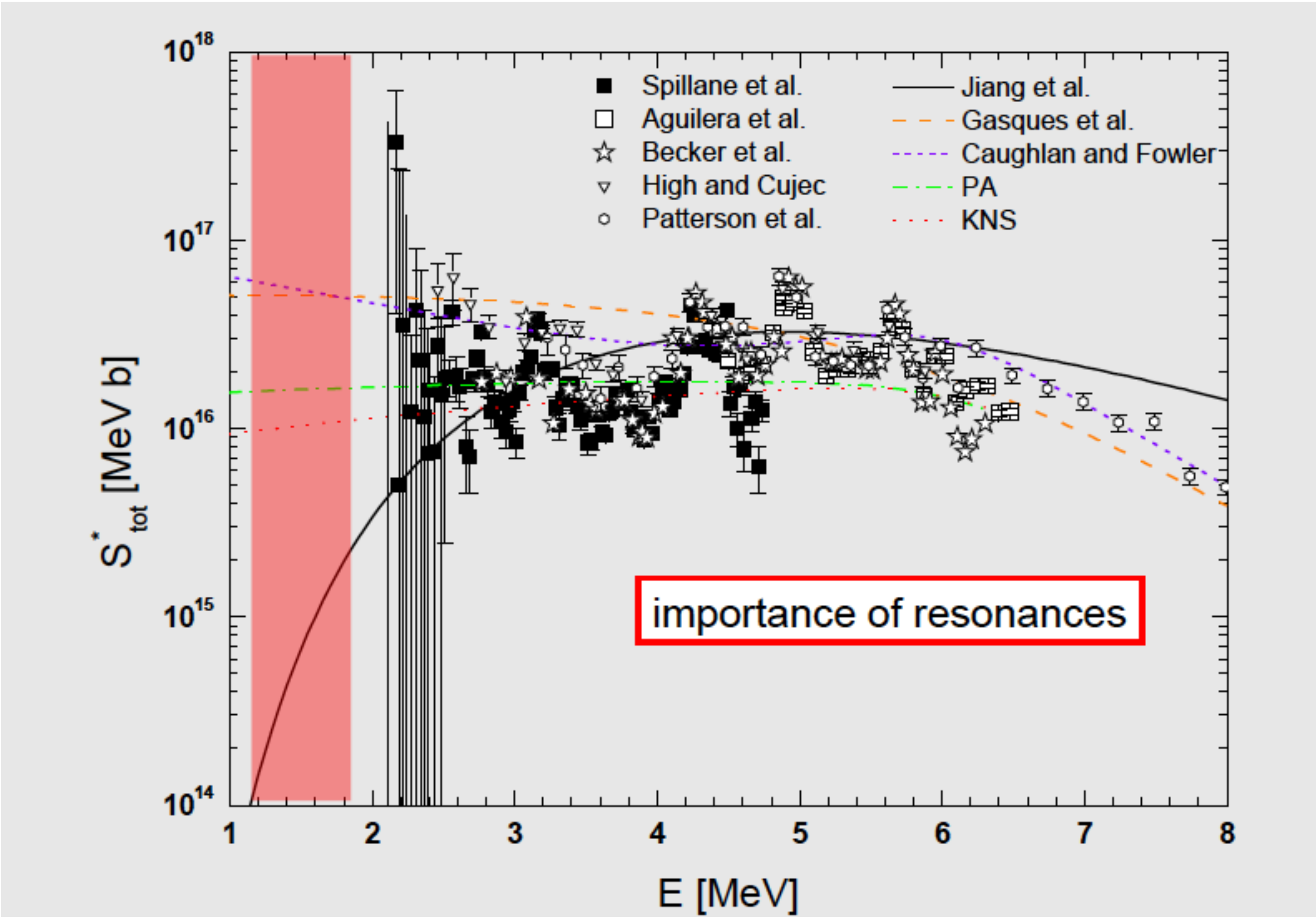


Experimental results in γ-ray spectrometry



Spillane et al., PRL 98, 122501 (2007)

Total S-factor



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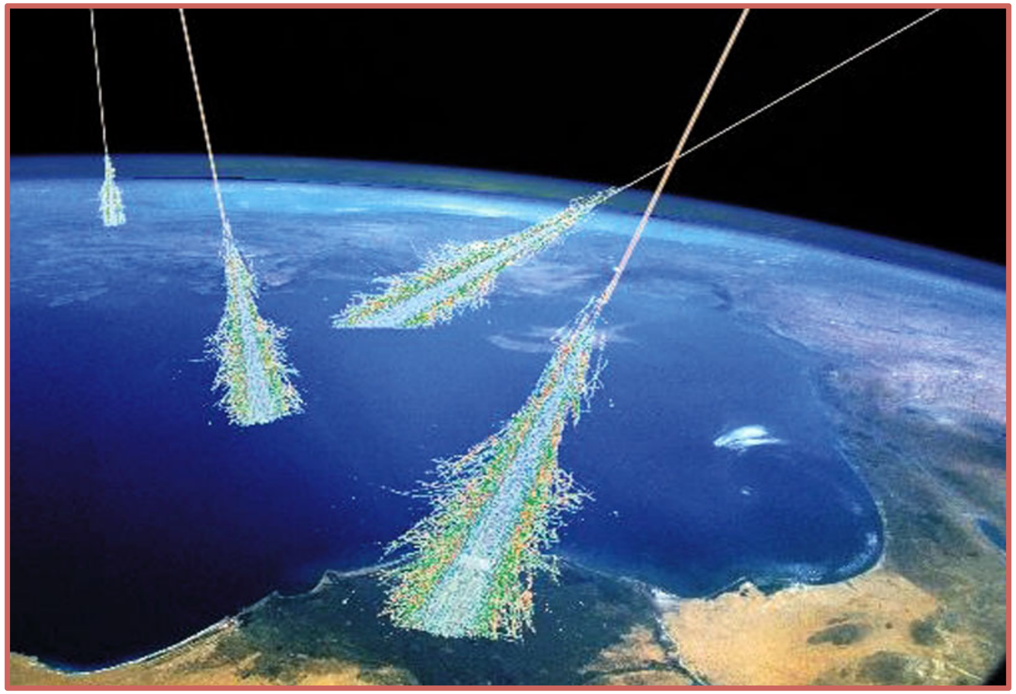

open questions

&

future projects

JUNA CJPL (China Jinping Underground Laboratory)

CASPAR SURF (Sanford Underground Research Facility)

Compact **A**ccelerator **S**ystem for **P**erforming **A**strophysical **R**esearch

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Joe VanDriel
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Dan Robertson (TC)
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Michael Wiescher
Rory Hamilton
Zach Meisel
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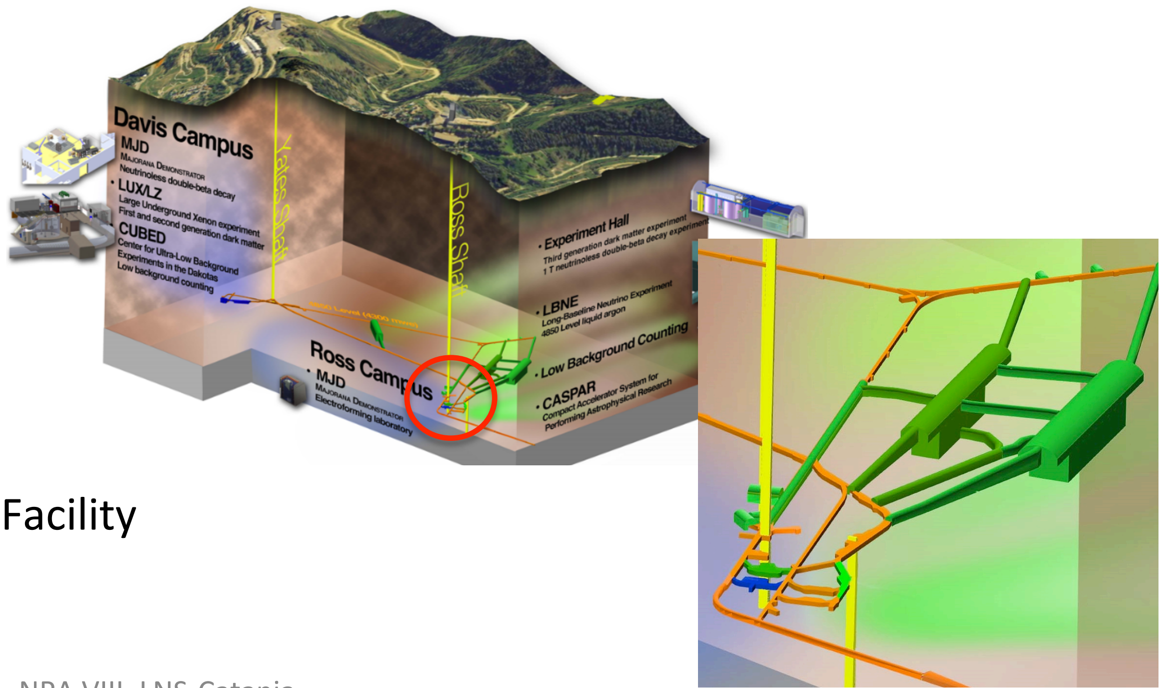

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