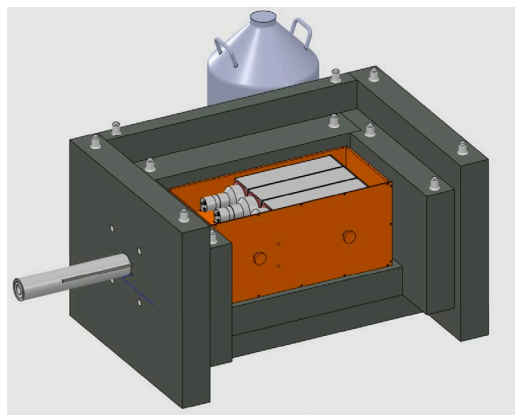
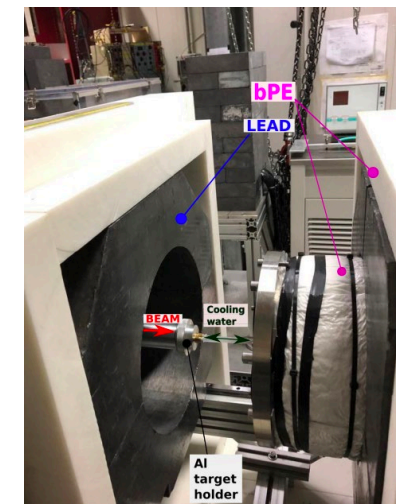




Pushing direct measurement of $^{12}\text{C}+^{12}\text{C}$ fusion reaction towards Gamow window *Edinburgh 01-06-2023*

Gianluca Imbriani



LUNA
Laboratory for Underground
Nuclear Astrophysics



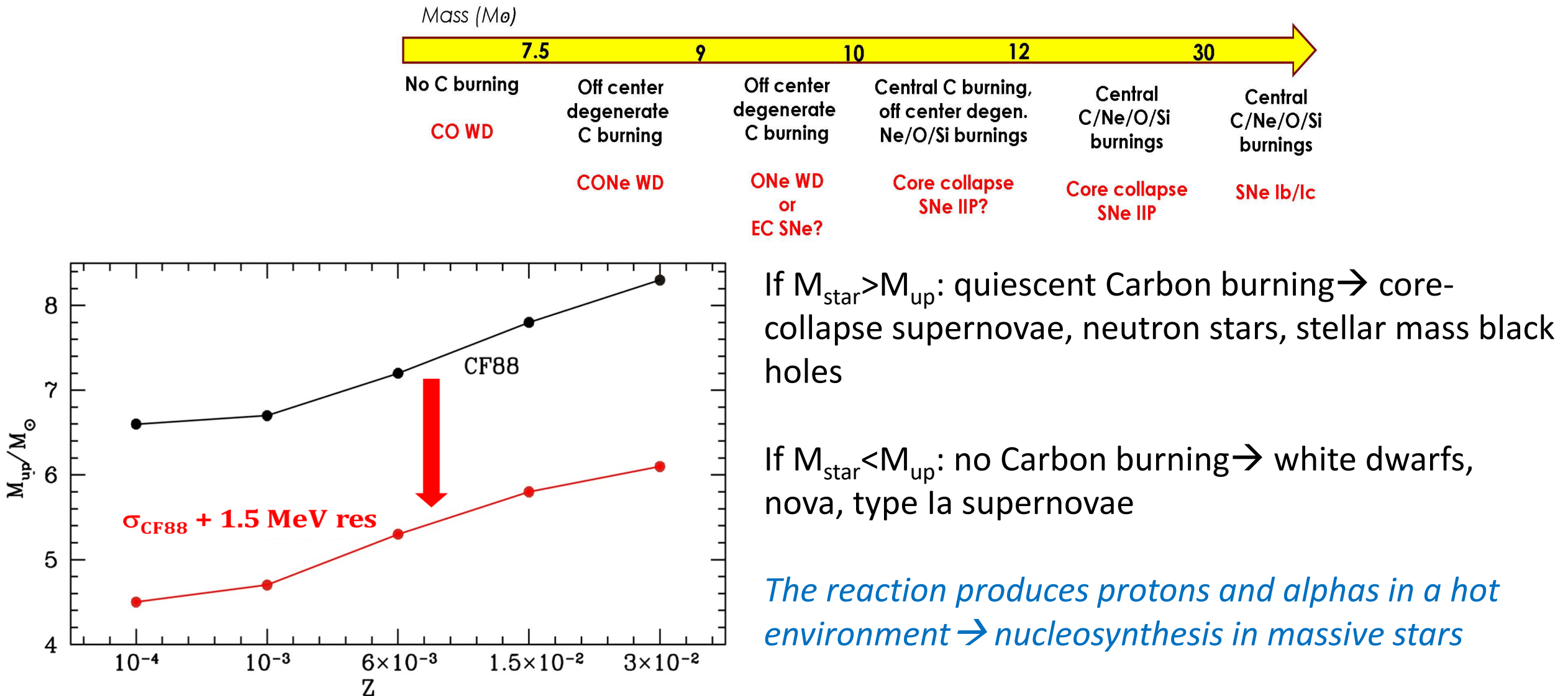
Physics Department of University of Naples Federico II,
Italian National Institute of Nuclear Physics (INFN)



UNIVERSITÀ DEGLI STUDI DI
NAPOLI FEDERICO II



$^{12}\text{C} + ^{12}\text{C}$ motivation



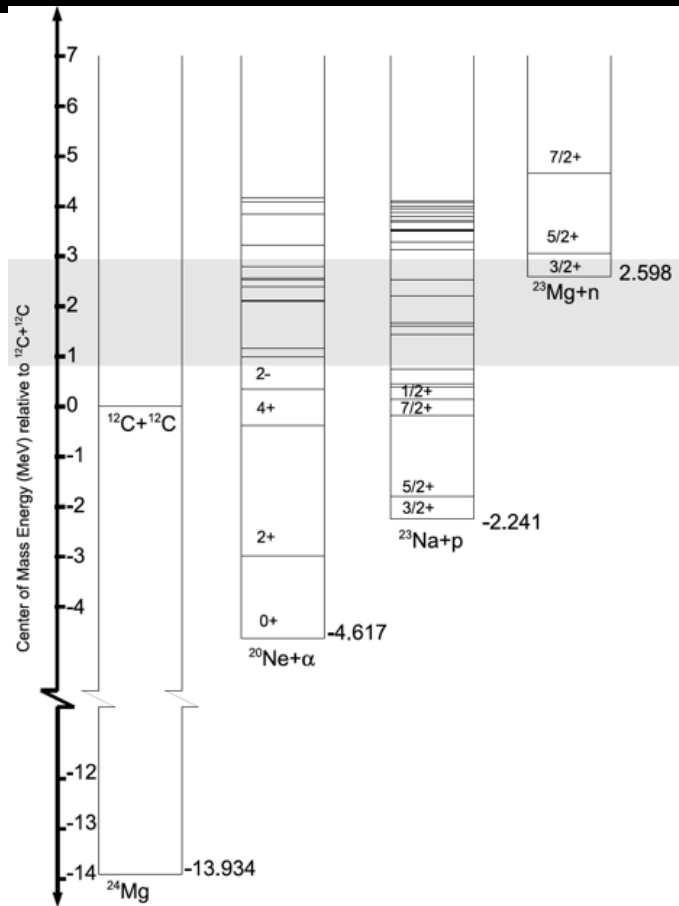
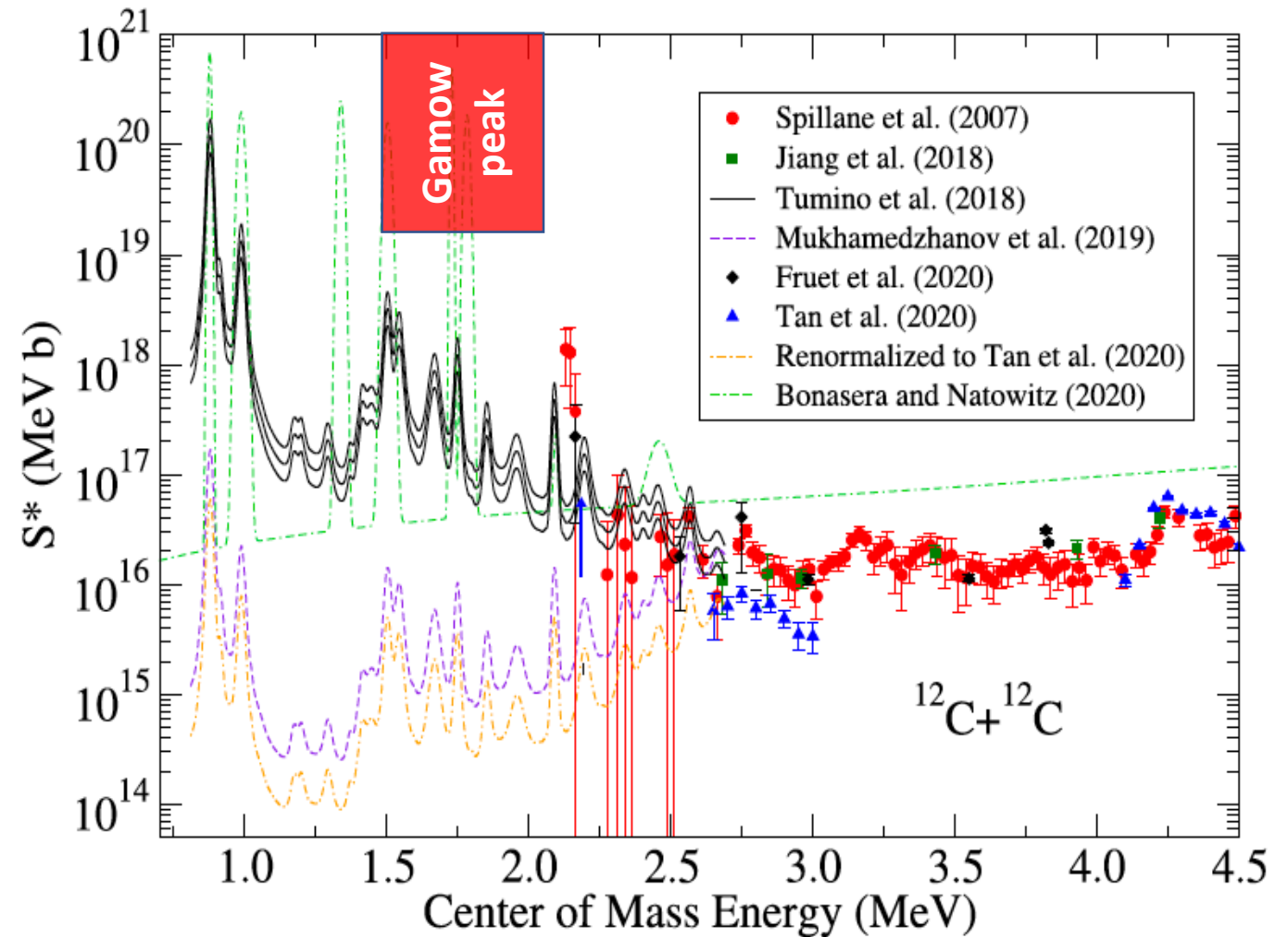
If $M_{\text{star}} > M_{\text{up}}$: quiescent Carbon burning $\rightarrow$ core-collapse supernovae, neutron stars, stellar mass black holes

If $M_{\text{star}} < M_{\text{up}}$: no Carbon burning $\rightarrow$ white dwarfs, nova, type Ia supernovae

The reaction produces protons and alphas in a hot environment $\rightarrow$ nucleosynthesis in massive stars

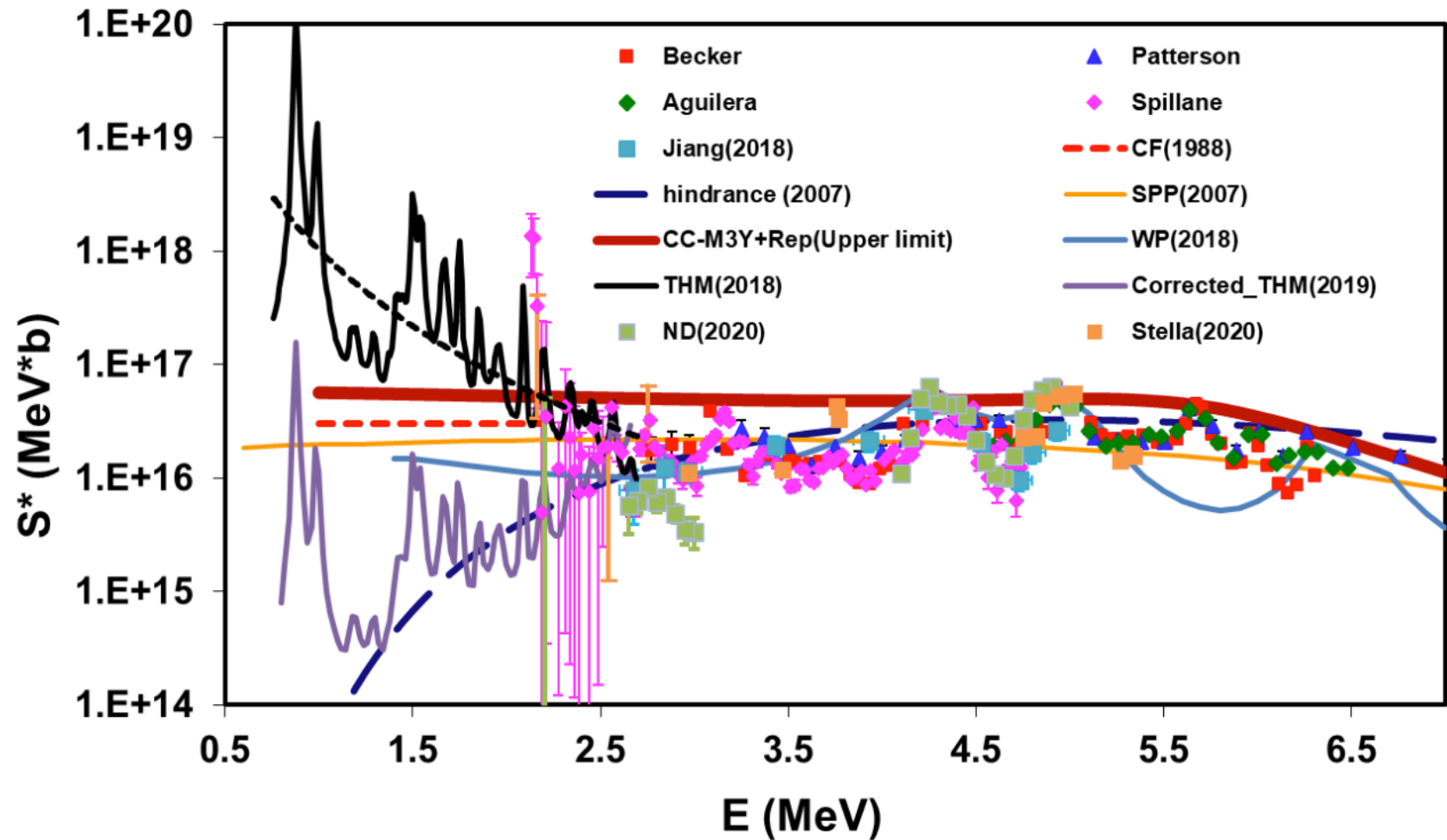
- Carbon burning can trigger Superburst events

The $^{12}\text{C}+^{12}\text{C}$ state of the art



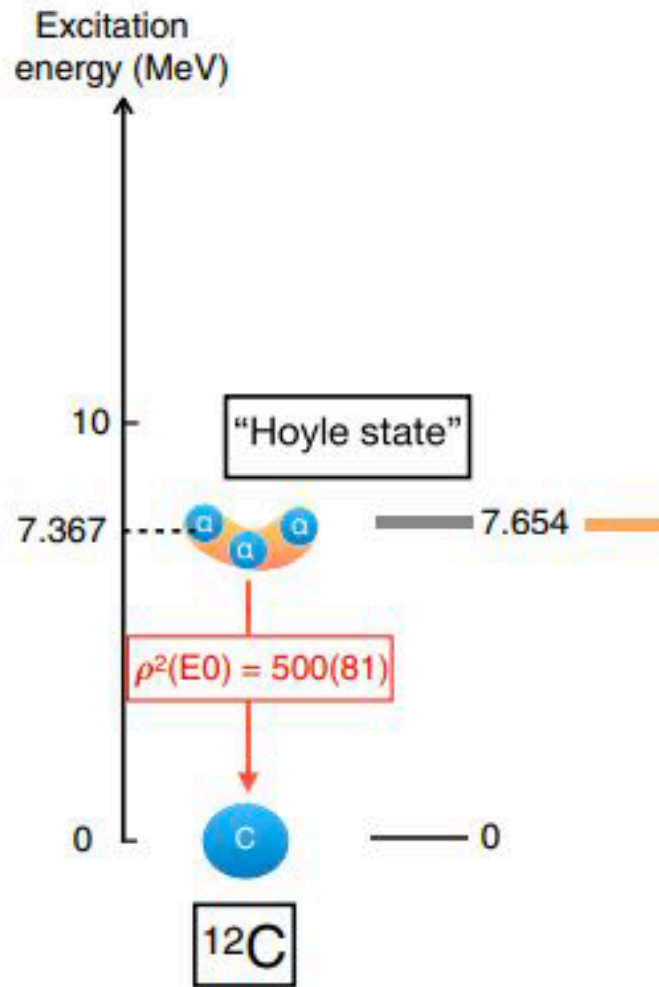
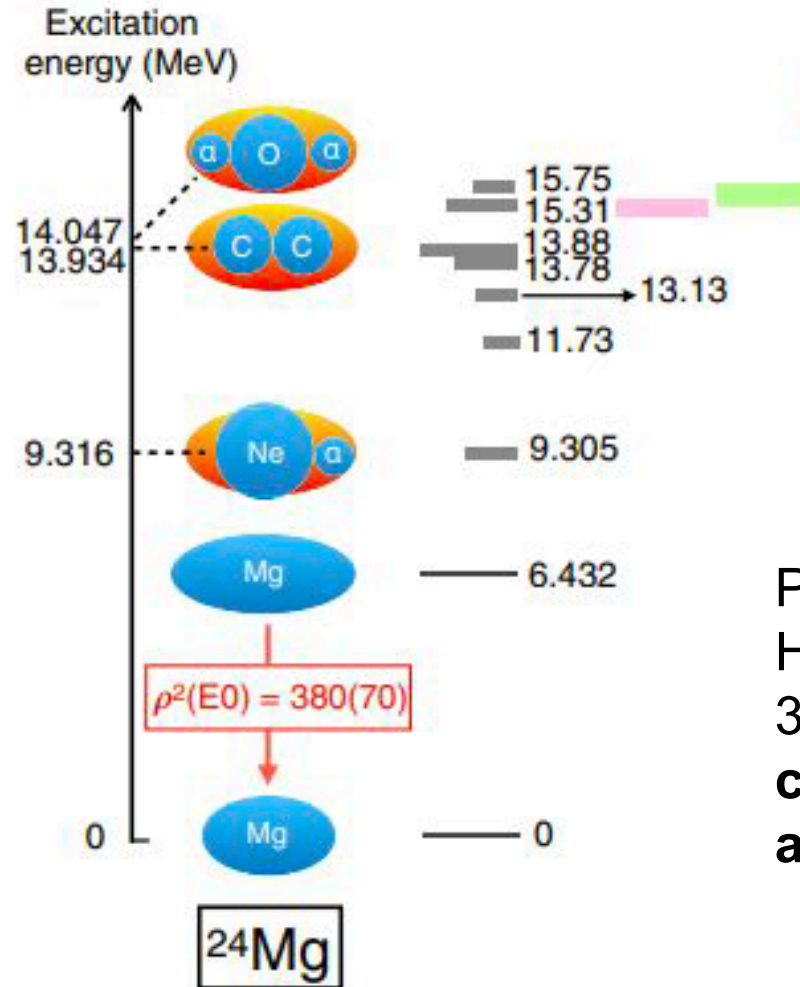
The $^{12}\text{C}+^{12}\text{C}$ state of the art

- Several datasets and models
- Direct measurements above 2.1 MeV (large scattering, large uncertainties)
- Only indirect measurements below 2.1 MeV (problems with normalization and other discrepancies)
- Very large uncertainty below 2.5 MeV
- Presence of several states at low energies



The $^{12}\text{C}+^{12}\text{C}$ possible cluster states

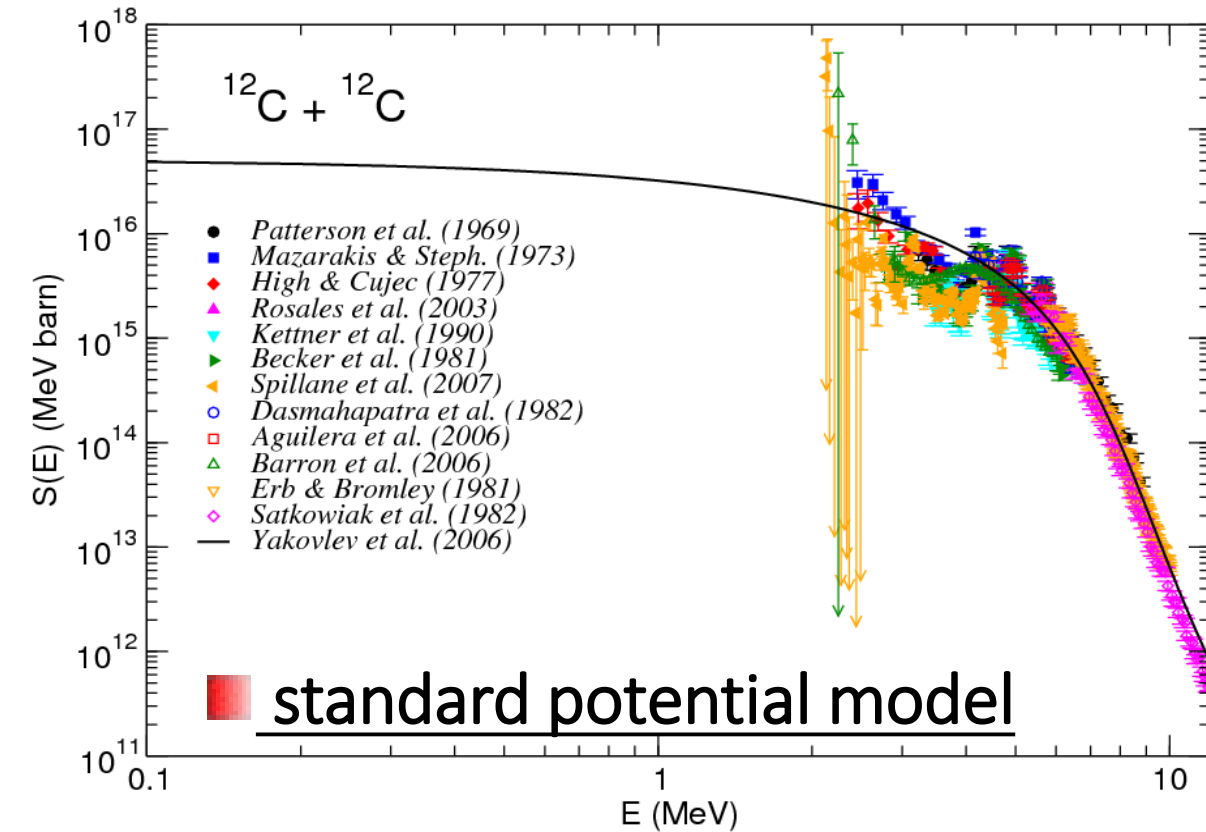
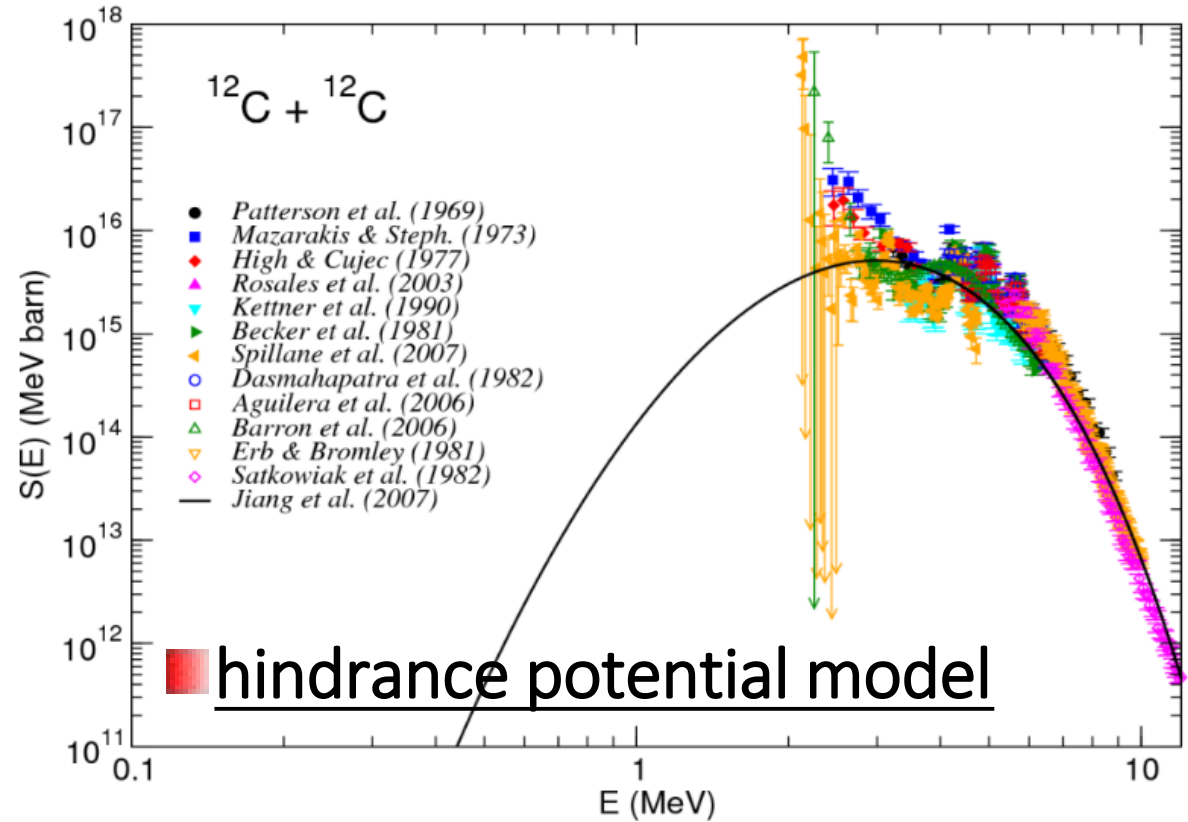
PHYSICAL REVIEW LETTERS **129**, 102701 (2022)



subset of the excited ^{24}Mg 0^+ states that are strongly populated by $^{24}\text{Mg}(\alpha, \alpha')^{24}\text{Mg}$

Possible analogy between the Hoyle state in ^{12}C as the driver of 3α fusion and **candidate cluster states in ^{24}Mg as fusion**

The $^{12}\text{C}+^{12}\text{C}$ potential model

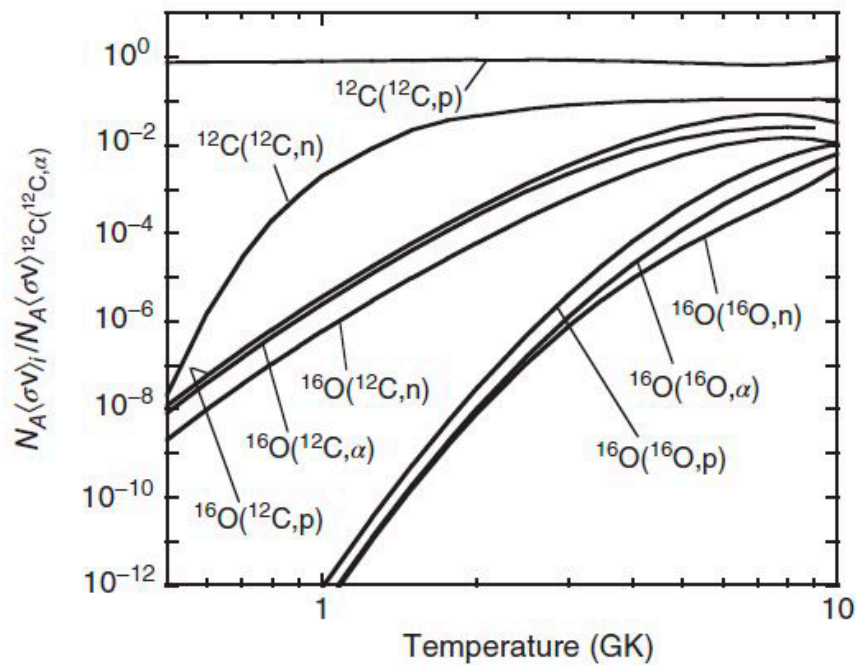
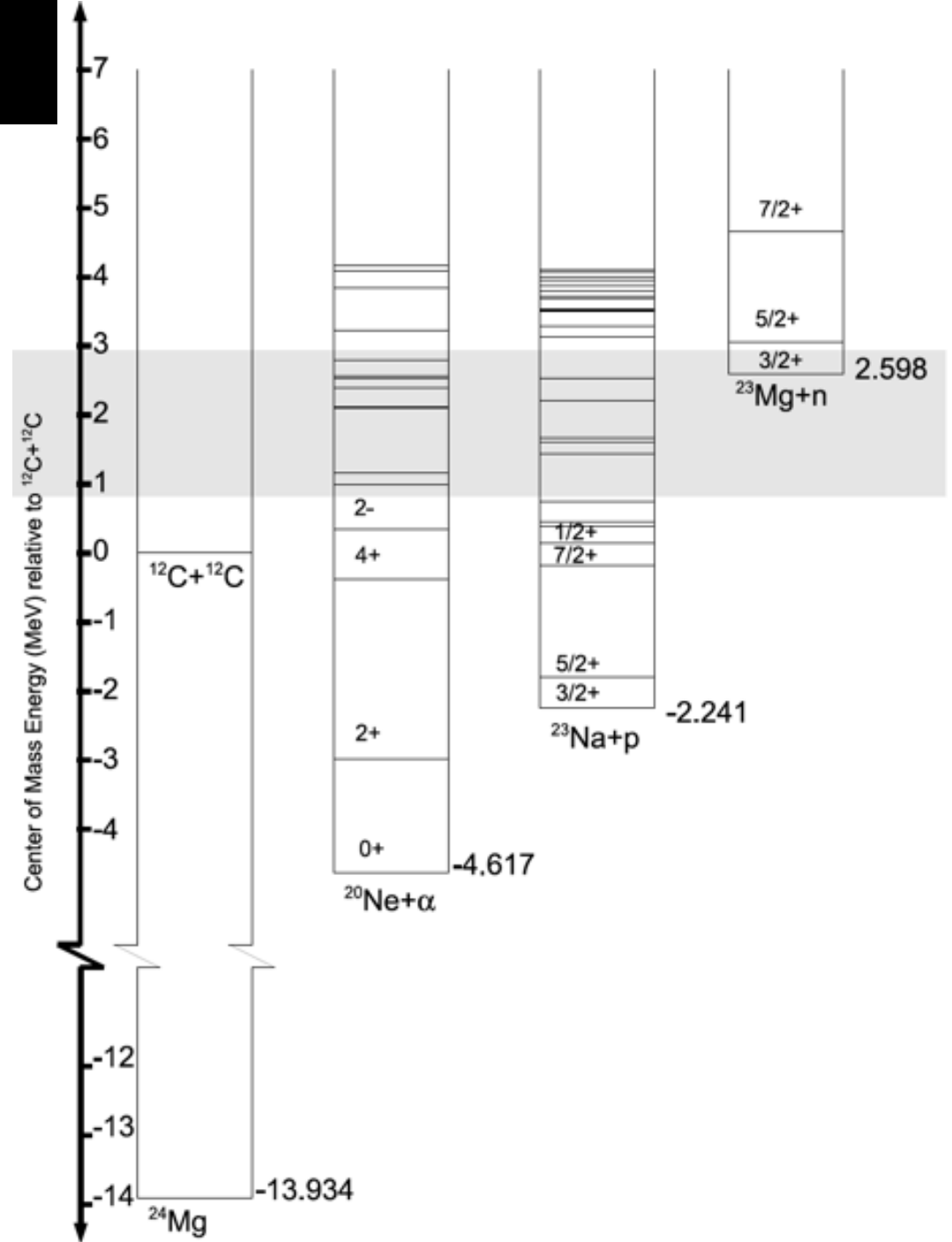


Different potential models lead to different ways to extrapolate the low energy cross section (S-factor).
The only way to distinguish is to measure below 2 MeV.

The $^{12}\text{C}+^{12}\text{C}$ reactions



Iliadis, C., Nuclear Physics of Stars, Wiley, 2015

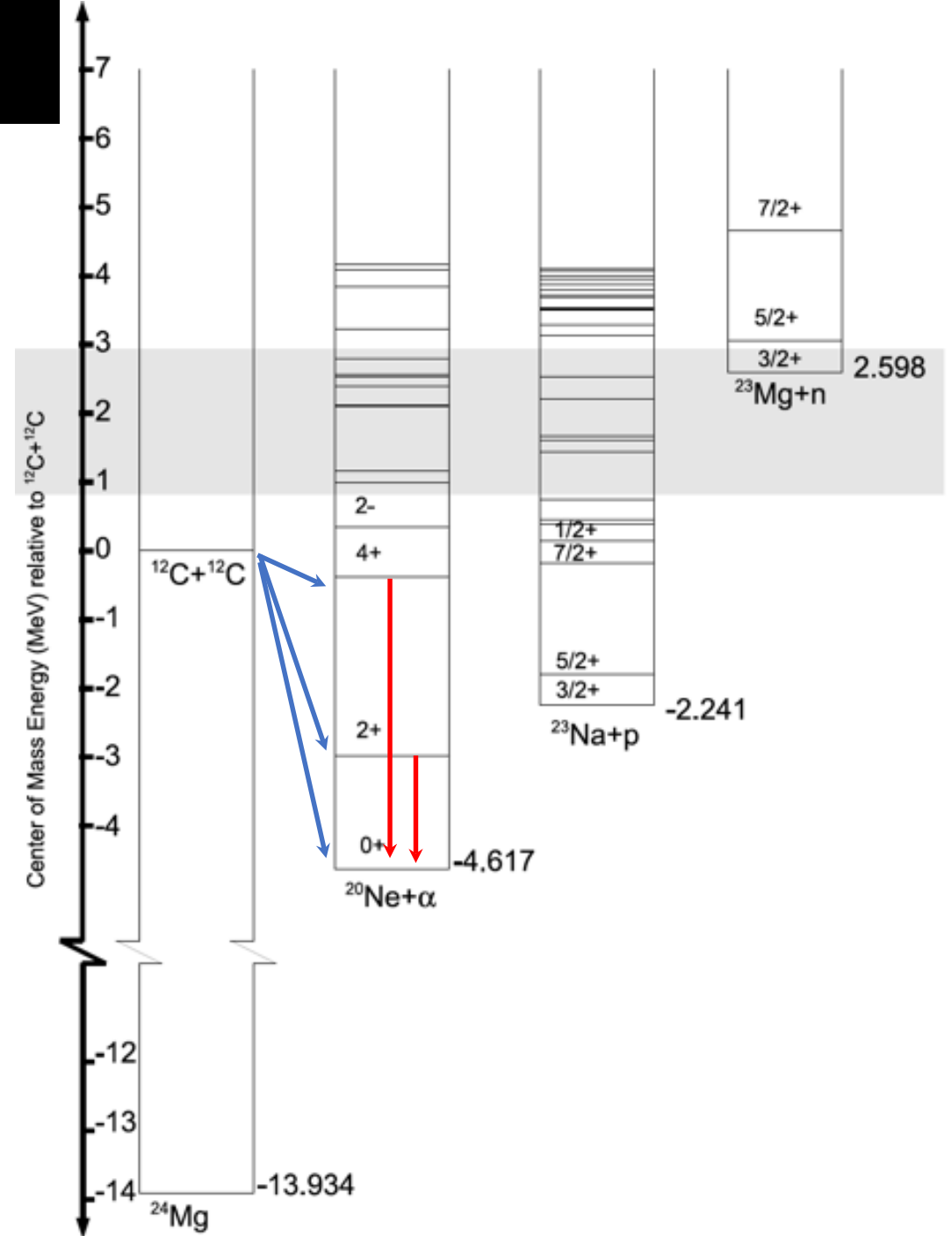


The $^{12}\text{C}+^{12}\text{C}$ reactions



γ -rays and α particles energies for excited states for
 $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ ($Q = 4.617 \text{ MeV}$)

E_x (MeV)	J^p	Main γ transitions (MeV)		ID	$E_{\alpha-\text{max}}$ (MeV) ($E_{\text{CM}} = 2 \text{ MeV}$)
0.0	0^+			α_0	8.6
1.63	2^+	$1.63 \rightarrow 0$ 1.63		α_1	6.8
4.24	4^+	$4.24 \rightarrow 1.63$ 2.61		α_2	3.9
4.96	2^-	$4.96 \rightarrow 1.63$ 3.33		α_3	3.1
5.62	3^-	$5.62 \rightarrow 1.63$ 3.98		α_4	2.2
5.78	1^-	$5.78 \rightarrow 1.63$ 4.15	$5.78 \rightarrow 0$ 5.78	α_5	2.0

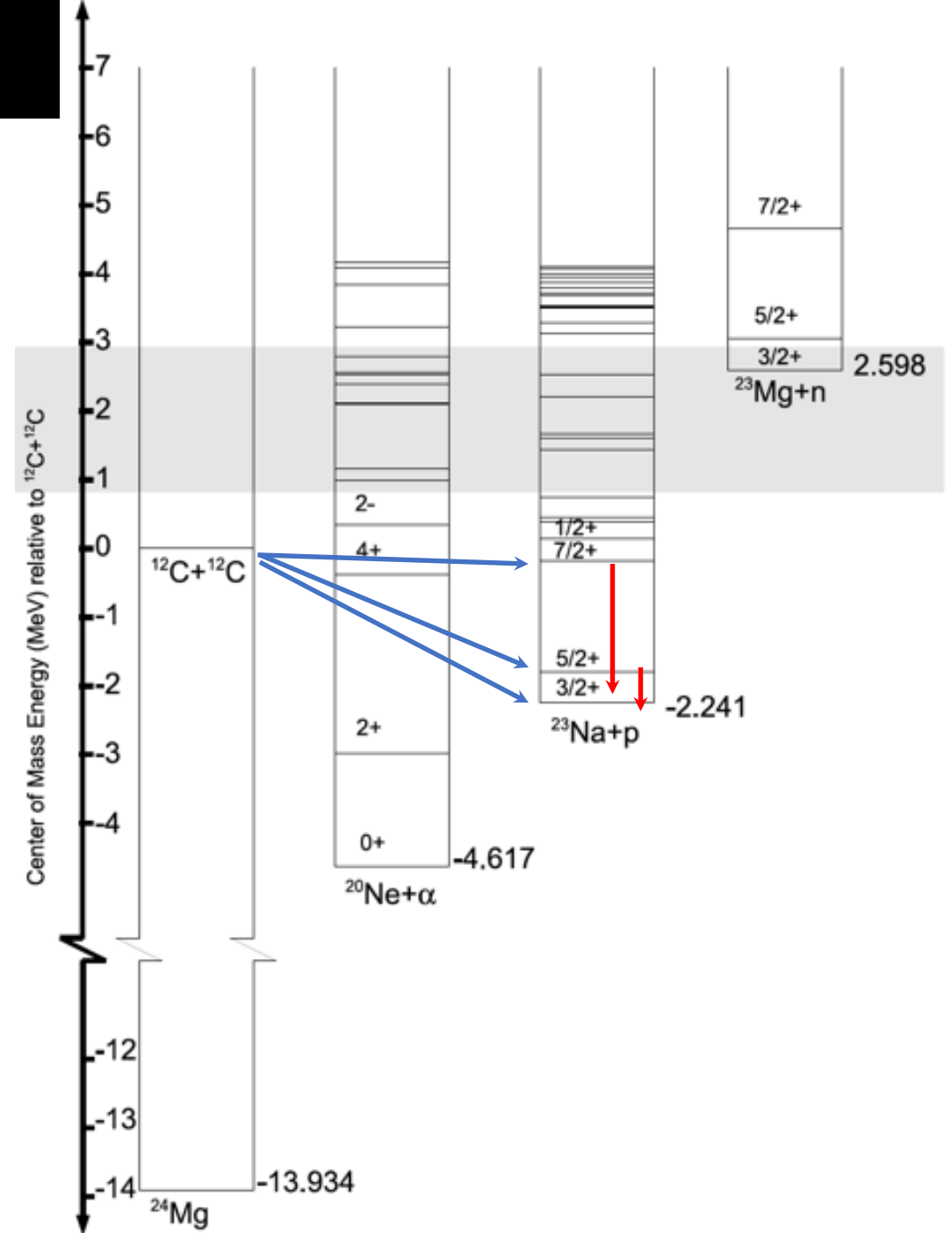


The $^{12}\text{C}+^{12}\text{C}$ reactions



γ -rays and p particles energies for excited states for
 $^{12}\text{C}(^{12}\text{C}, \text{p})^{23}\text{Na}$ ($Q = 2.241 \text{ MeV}$)

E_x (MeV)	J^p	Main γ transitions (MeV)		ID	$E_{\text{p-max}}$ (MeV) ($E^{\text{CM}} = 2 \text{ MeV}$)
0.0	$3/2^+$			p_0	5.3
0.44	$5/2^+$	$0.44 \rightarrow 0$ 0.44		p_1	4.8
2.07	$7/2^+$	$2.07 \rightarrow 0.44$ 1.63		p_2	3
2.39	$1/2^+$	$2.39 \rightarrow 0.44$ 1.95	$2.39 \rightarrow 0$ 2.39	p_3	2.6
2.64	$1/2^-$	$2.64 \rightarrow 0$ 2.64		p_4	2.3
2.70	$9/2^+$	$2.70 \rightarrow 2.07$ 0.62	$2.70 \rightarrow 0.44$ 2.26	p_5	2.3
2.98	$3/2^+$	$2.98 \rightarrow 0.44$ 2.54	$2.98 \rightarrow 0$ 2.98	p_6	1.9



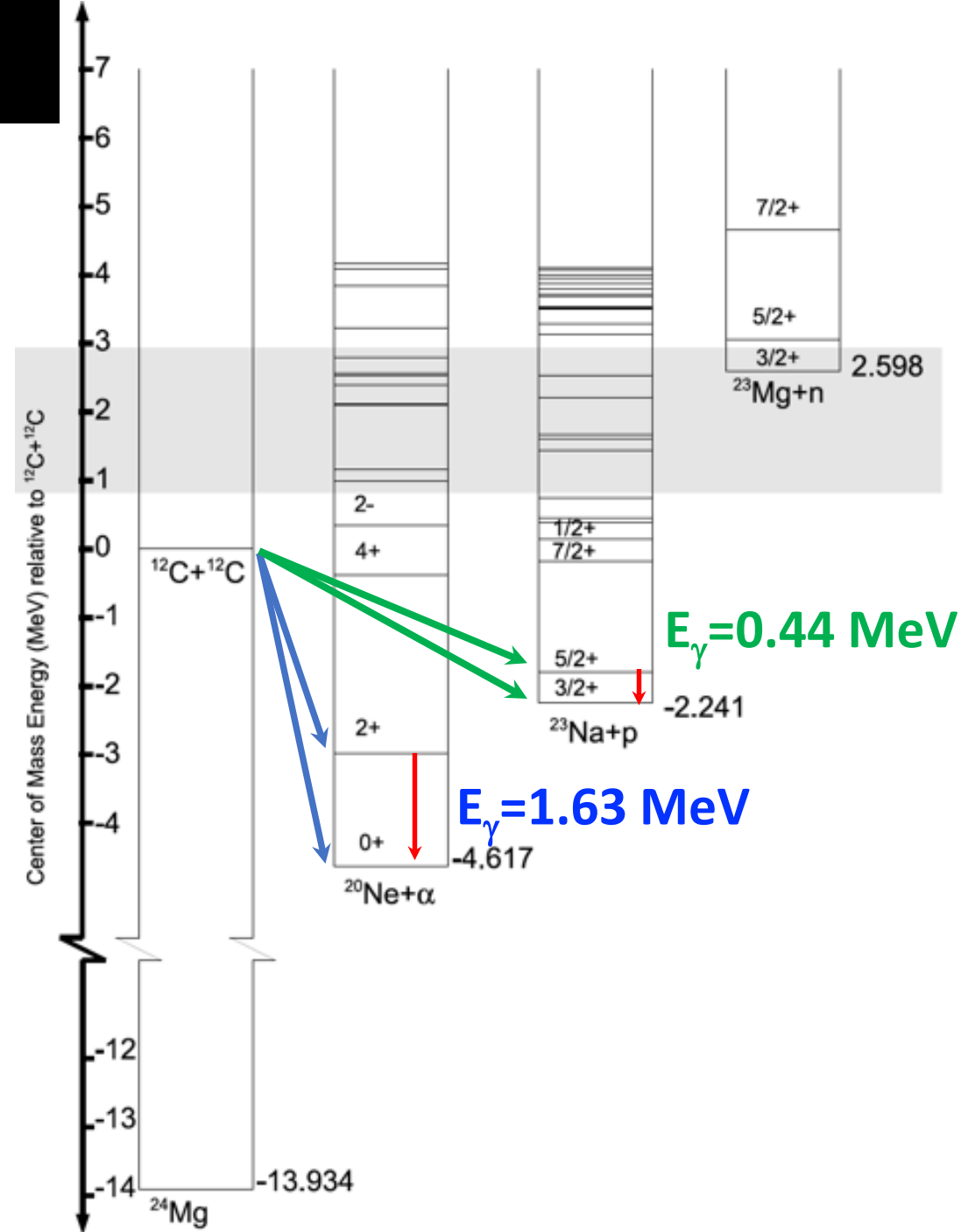
The $^{12}\text{C}+^{12}\text{C}$ study via γ detection



γ -rays and α particles energies for excited states for $^{12}\text{C}(^{12}\text{C}, \alpha)^{20}\text{Ne}$ ($Q = 4.617 \text{ MeV}$)					
E_x (MeV)	J^p	Main γ transitions (MeV)		ID	$E_{\alpha-\text{max}}$ (MeV) ($E^{\text{CM}} = 2 \text{ MeV}$)
0.0	0^+			α_0	8.6
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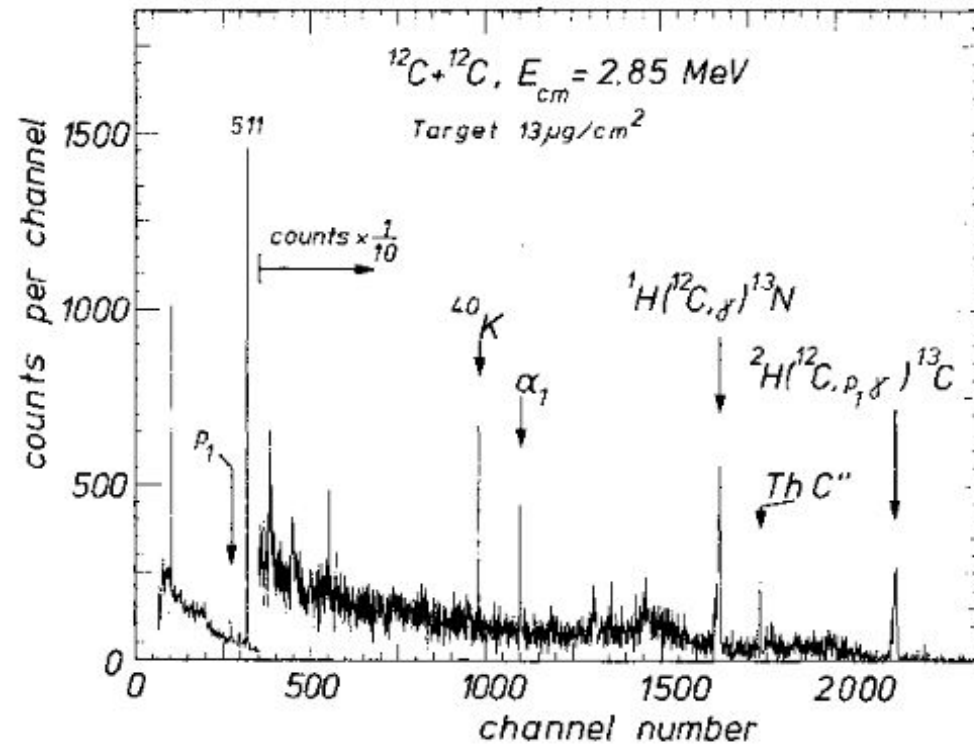


γ -rays and p particles energies for excited states for $^{12}\text{C}(^{12}\text{C}, p)^{23}\text{Na}$ ($Q = 2.241 \text{ MeV}$)					
E_x (MeV)	J^p	Main γ transitions (MeV)		ID	$E_{p-\text{max}}$ (MeV) ($E^{\text{CM}} = 2 \text{ MeV}$)
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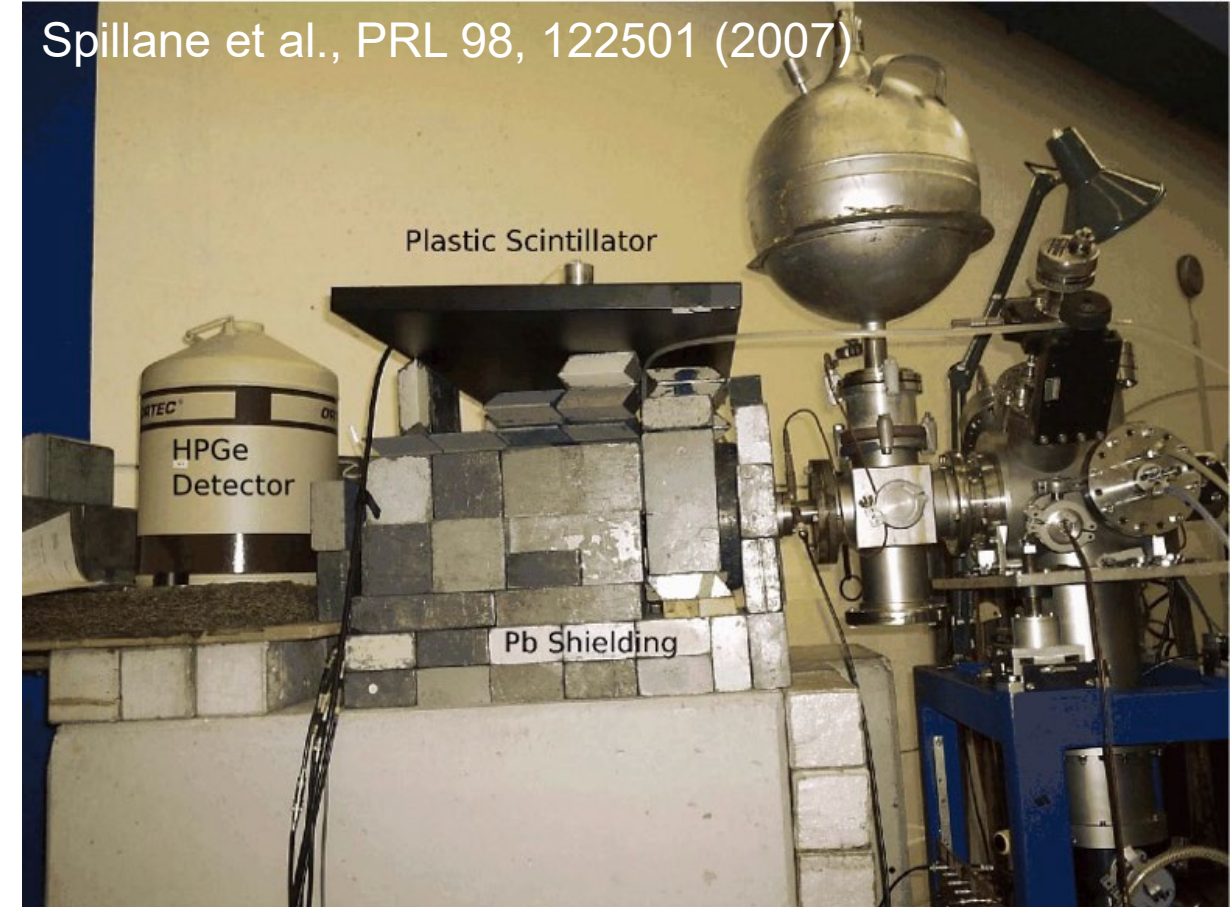


Measuring $^{12}\text{C}+^{12}\text{C}$ in laboratory: γ -rays detection

Kettner



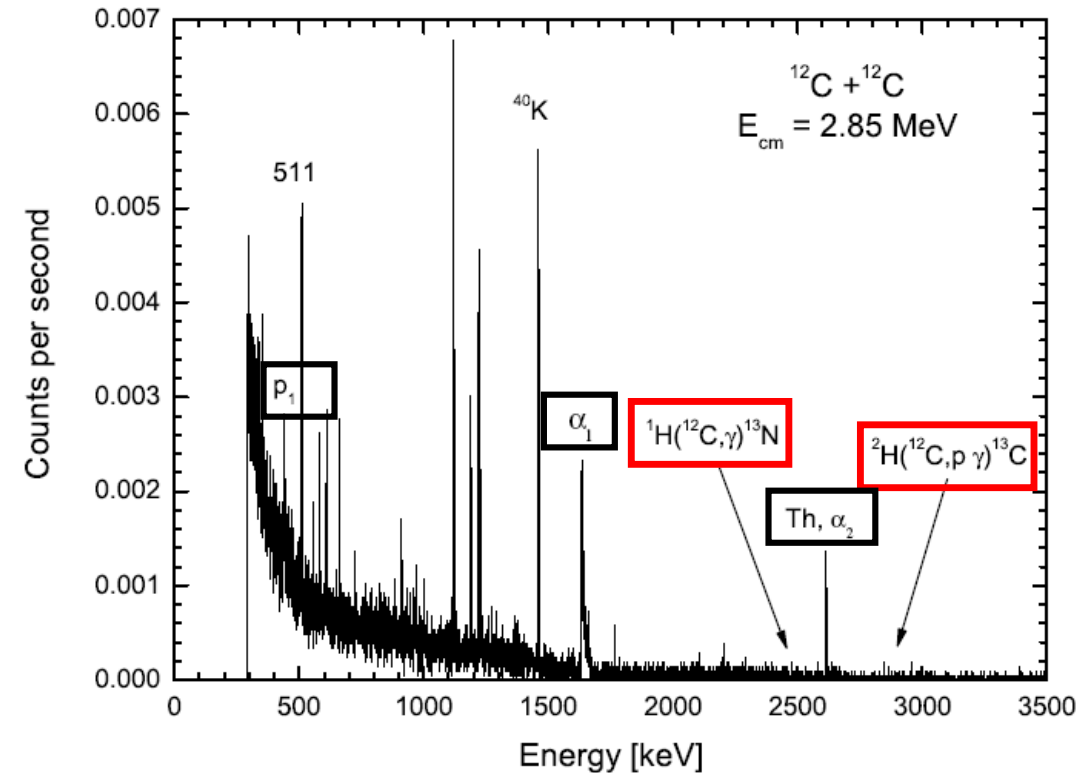
Spillane et al., PRL 98, 122501 (2007)



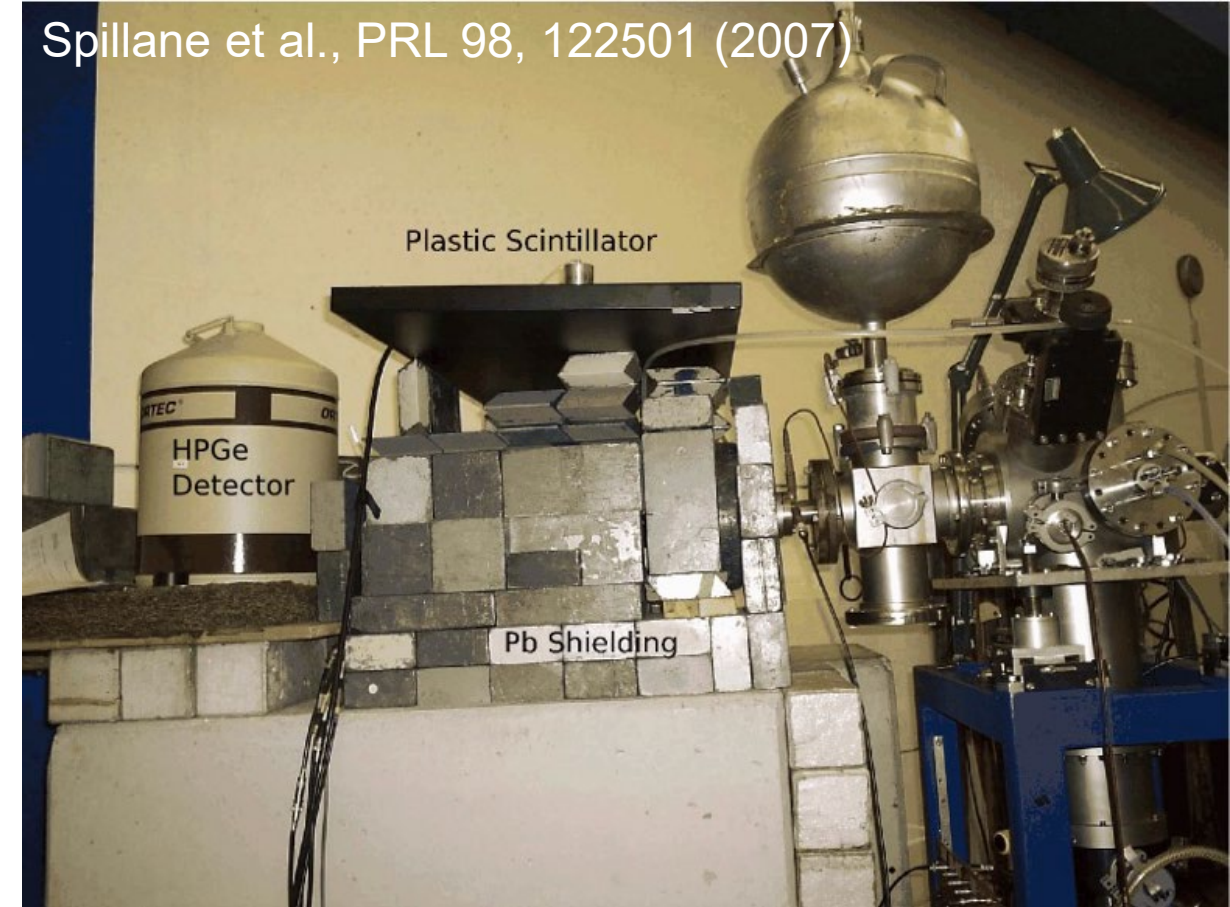
initial heating of the target by means of the beam itself: desorption of H and ^2H is sufficient for the measurement based on photon detection

Measuring $^{12}\text{C}+^{12}\text{C}$ in laboratory: γ -rays detection

Figures from Spillane's PhD thesis Spillane

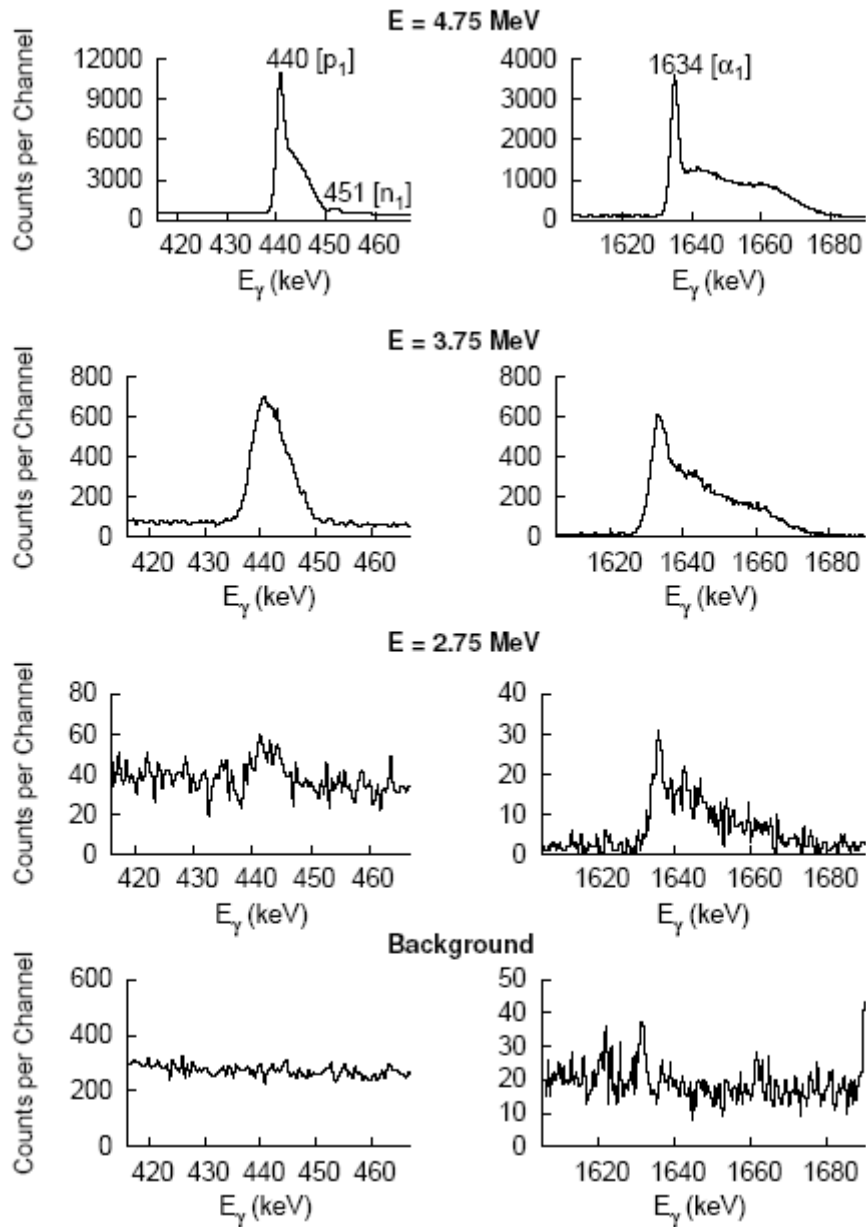


Spillane et al., PRL 98, 122501 (2007)

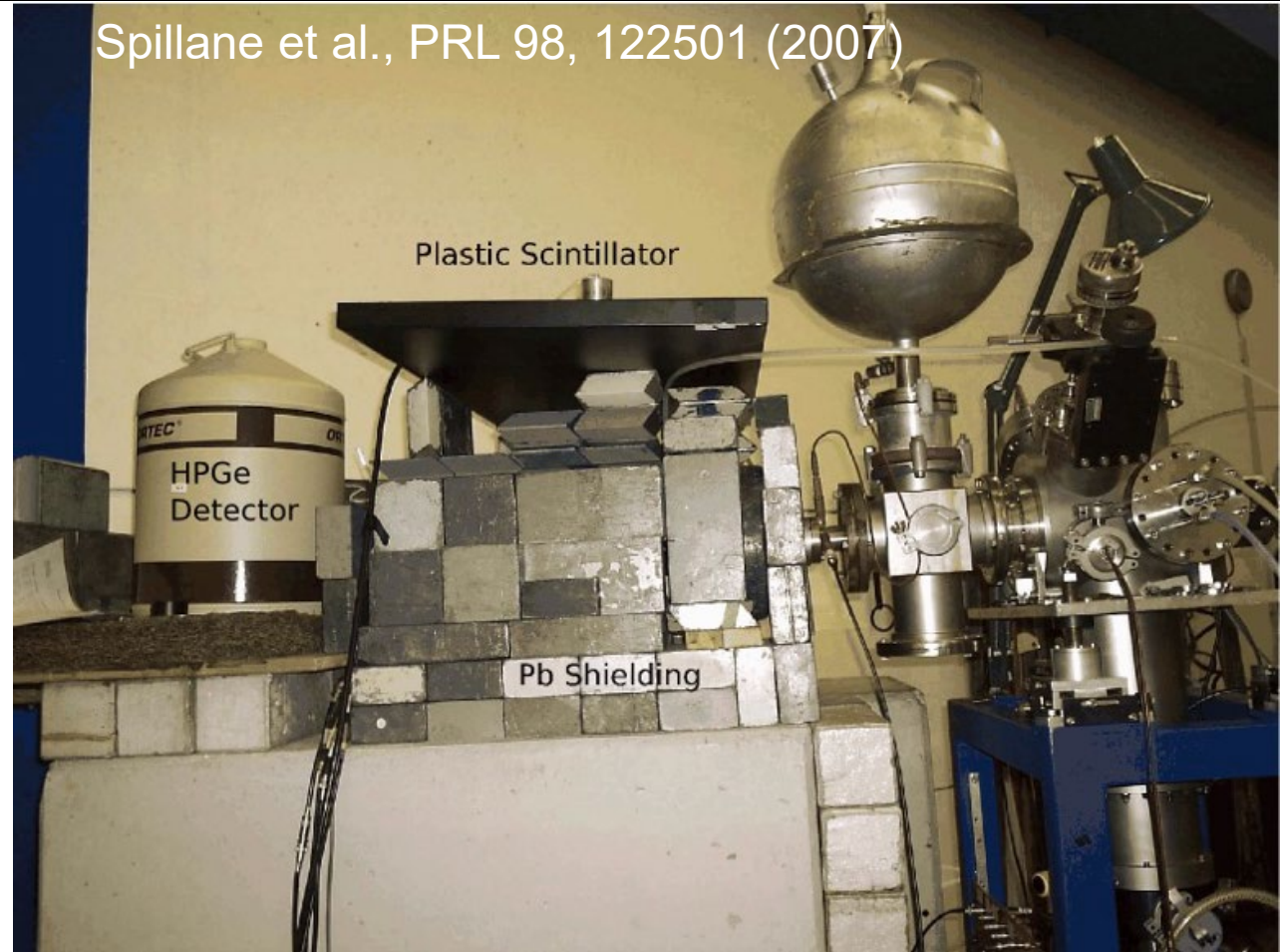


initial heating of the target by means of the beam itself: desorption of H and ^2H is sufficient for the measurement based on photon detection

Measuring $^{12}\text{C}+^{12}\text{C}$ in laboratory: γ -rays detection

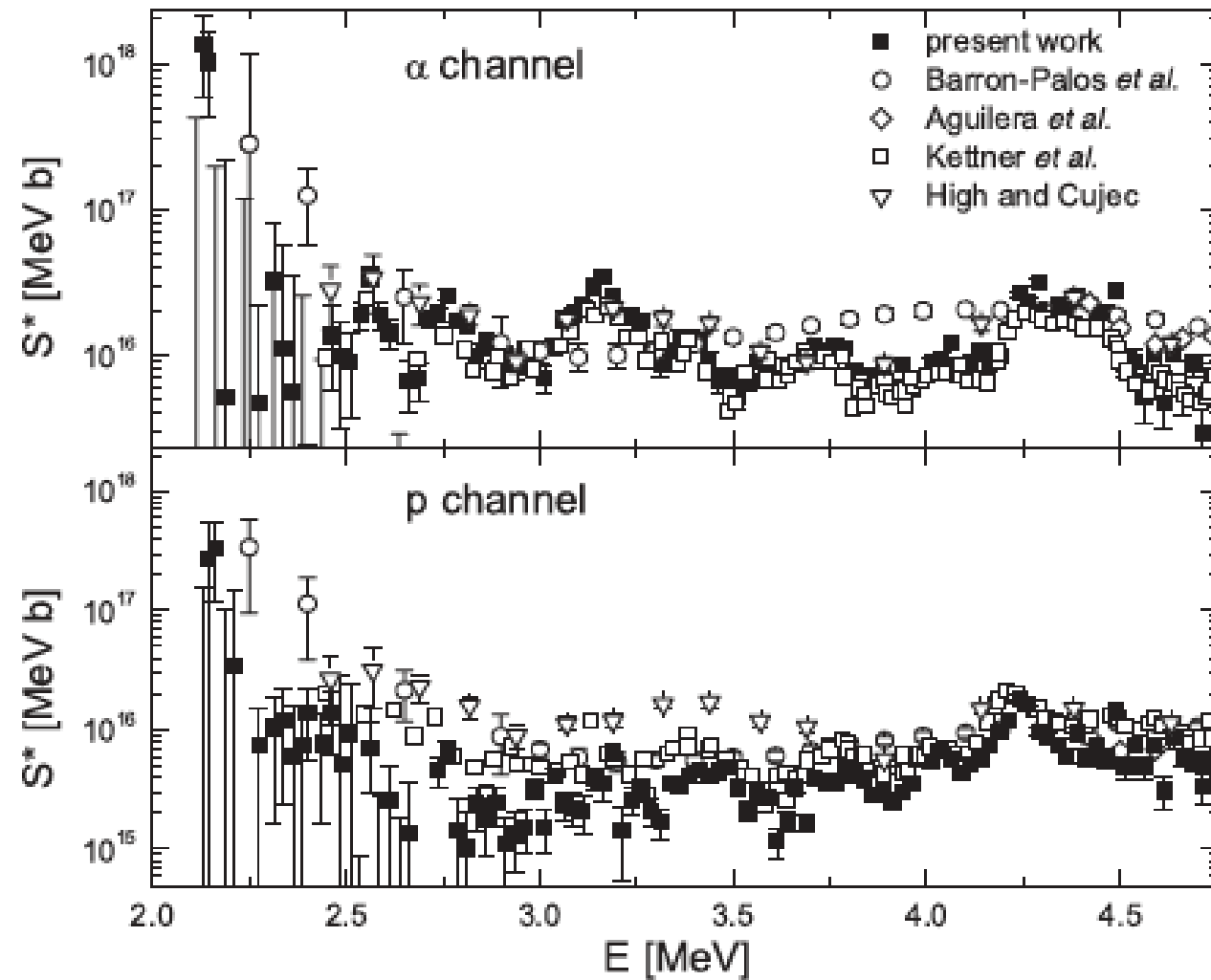
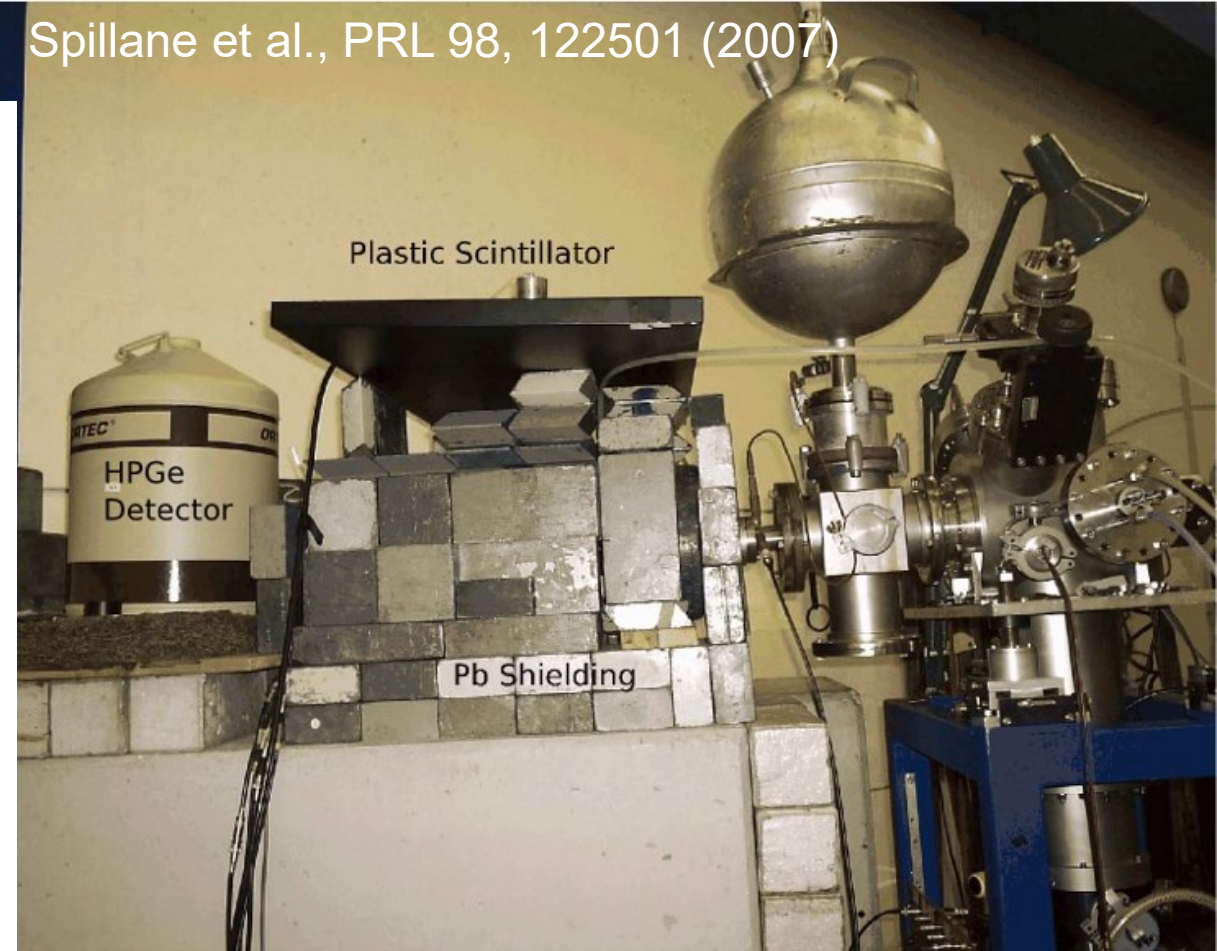


Spillane et al., PRL 98, 122501 (2007)

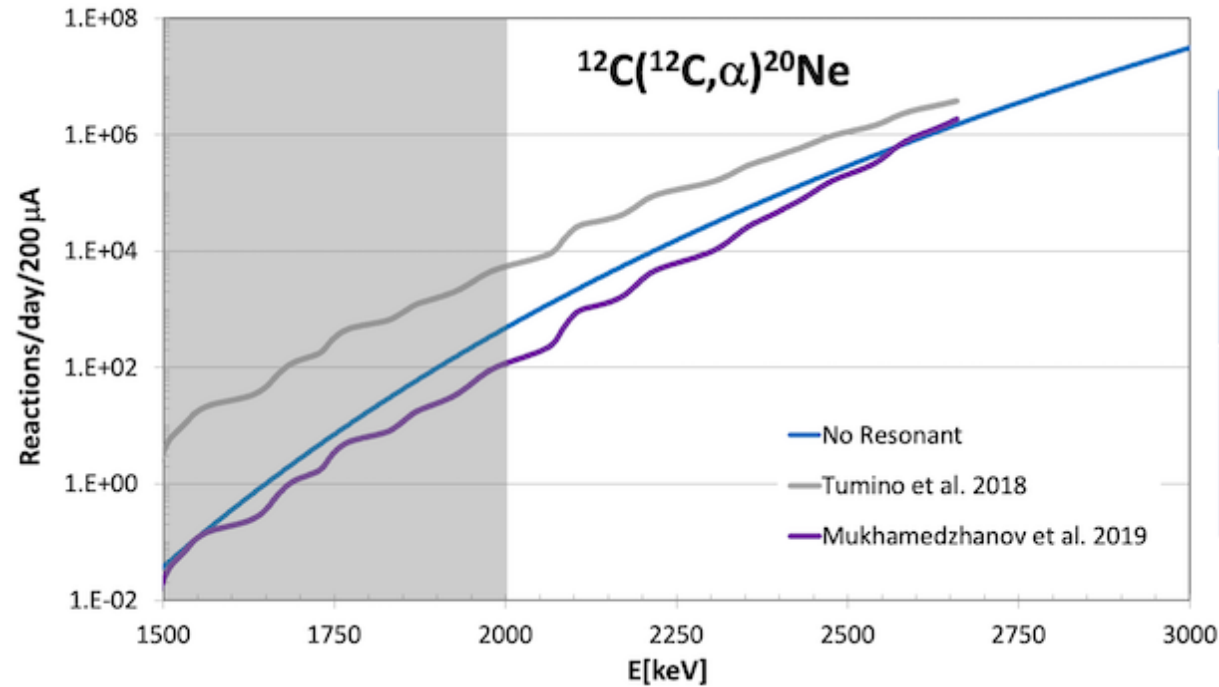


Measuring $^{12}\text{C}+^{12}\text{C}$ in laboratory: γ -rays detection

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

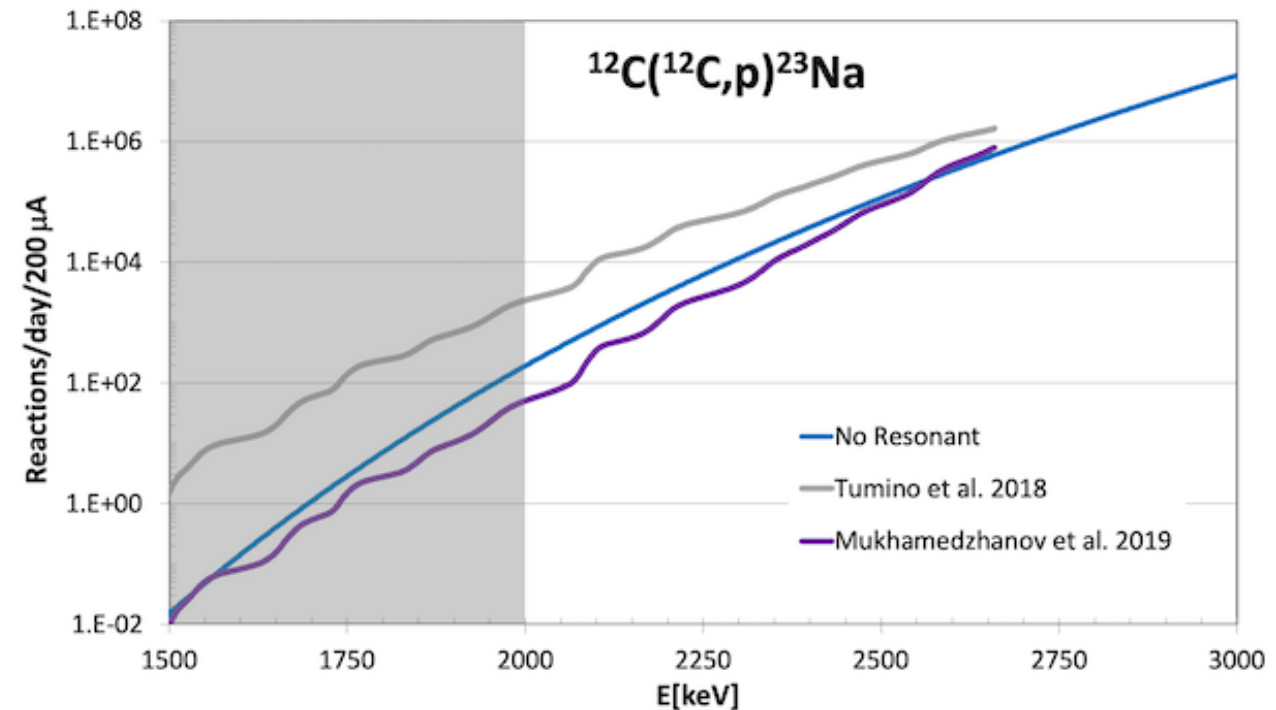


The $^{12}\text{C}+^{12}\text{C}$ expected count rate



Reaction per day with 200 μA

		1500 keV	1750 keV	2000 keV
α_1 (1640 keV)	Tumino 2018	3.5	350	5500
	No Resonant	0.038	7.5	525
	Mukhamedzhanov 2019	0.025	3.5	125
p_1 (440 keV)	Tumino 2018	1.5	150	2500
	No Resonant	0.02	3	200
	Mukhamedzhanov 2019	0.01	1.5	50

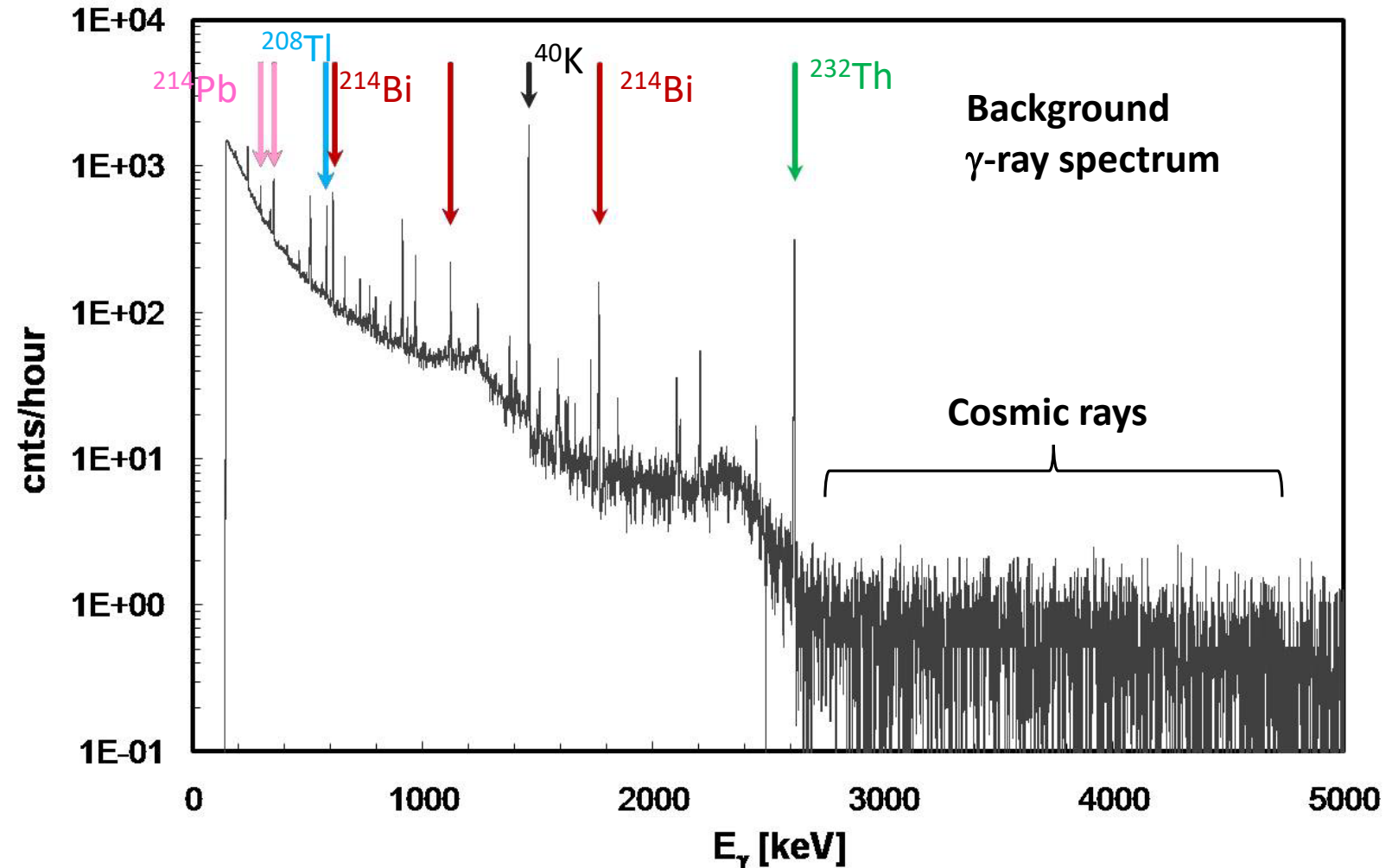


γ -ray natural background

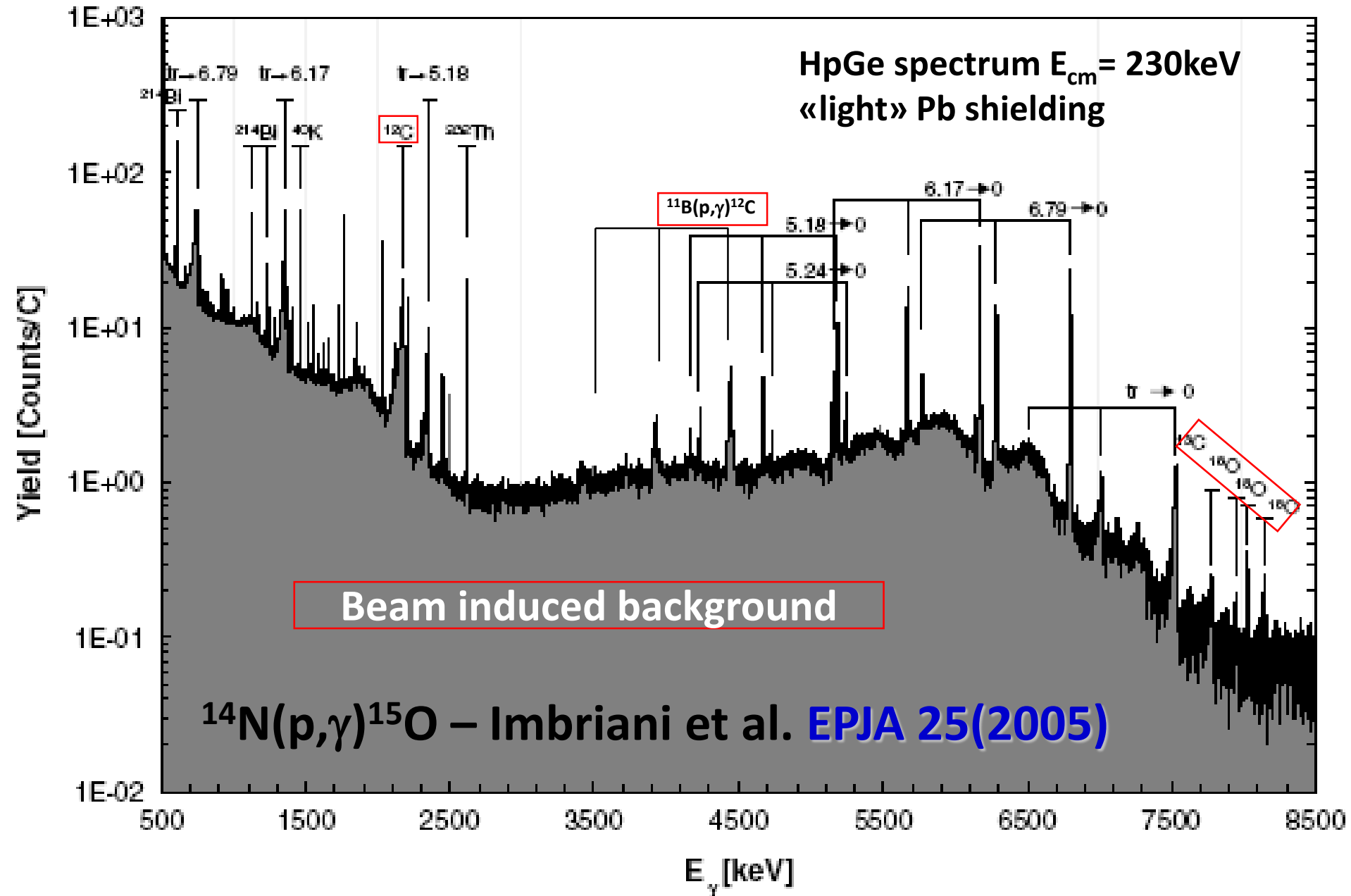
1. Environmental radioactivity (γ -rays of low energy):

- a) natural radioactive series ^{226}Ra , ^{214}Bi , ^{214}Pb (from ^{238}U) and ^{224}Ra , ^{208}Tl , ^{212}Pb (from ^{232}Th);
- b) radon (^{222}Rn - ^{220}Rn) a short-lived radioactive gas (from ^{238}U and ^{232}Th respectively);
- c) long-lived natural radionuclides such as ^{40}K , ^{87}Rb , ^{115}In , ^{133}La , ^{142}Ce , etc.

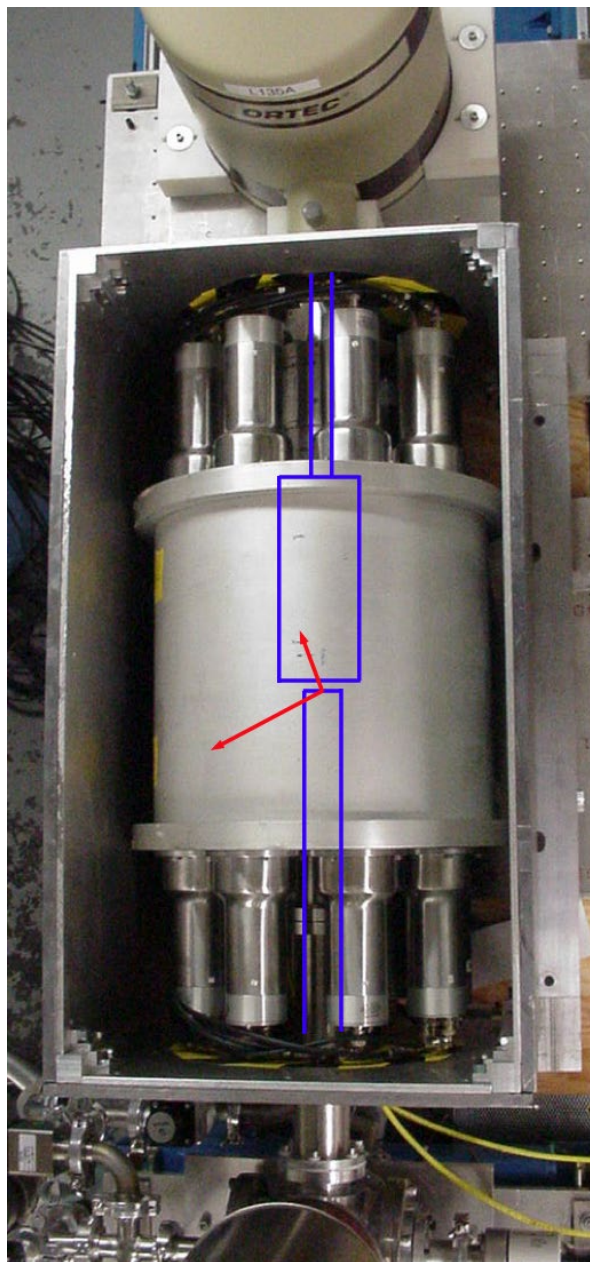
2. Cosmic rays (γ -rays of high energy).



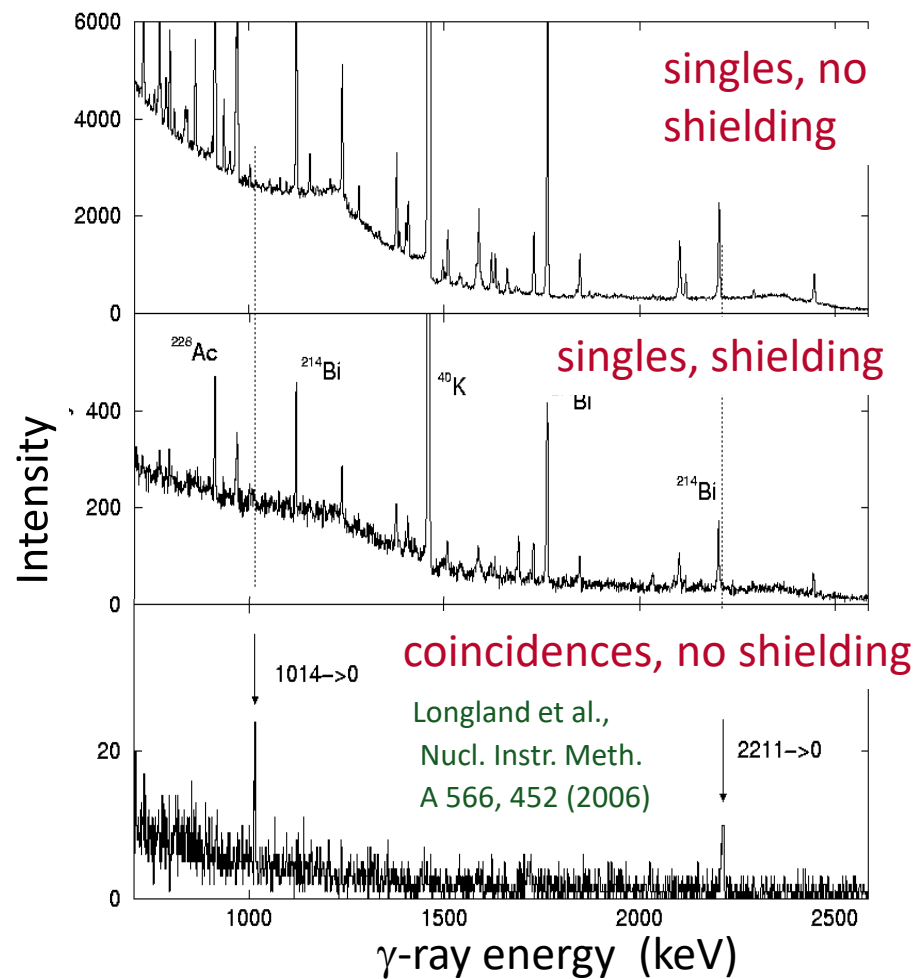
Beam induced background



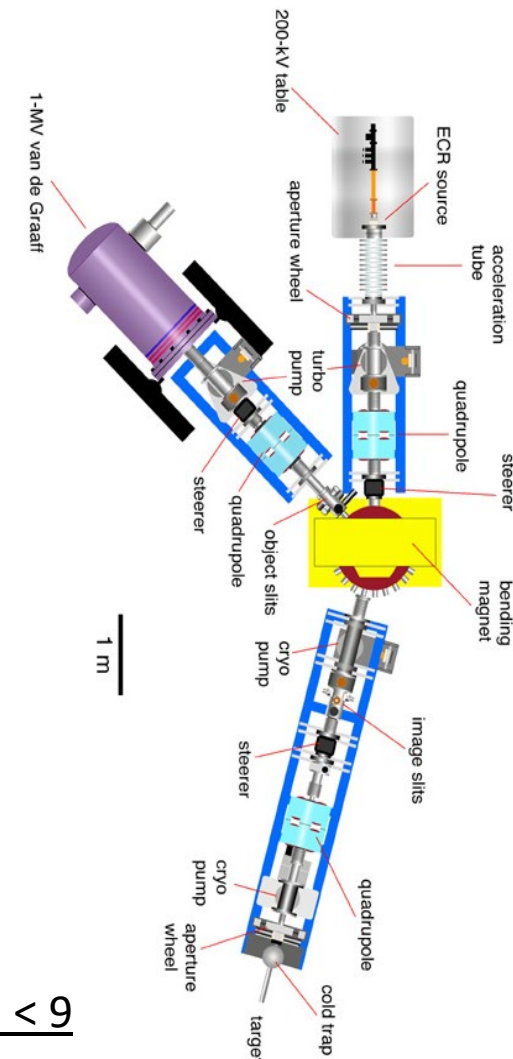
Coincidence $\gamma\gamma$ + passive shielding



resonance at 227 keV in $^{26}\text{Mg}(p,\gamma)^{27}\text{Al}$, $1\mu\text{A}$



LENA - experiment

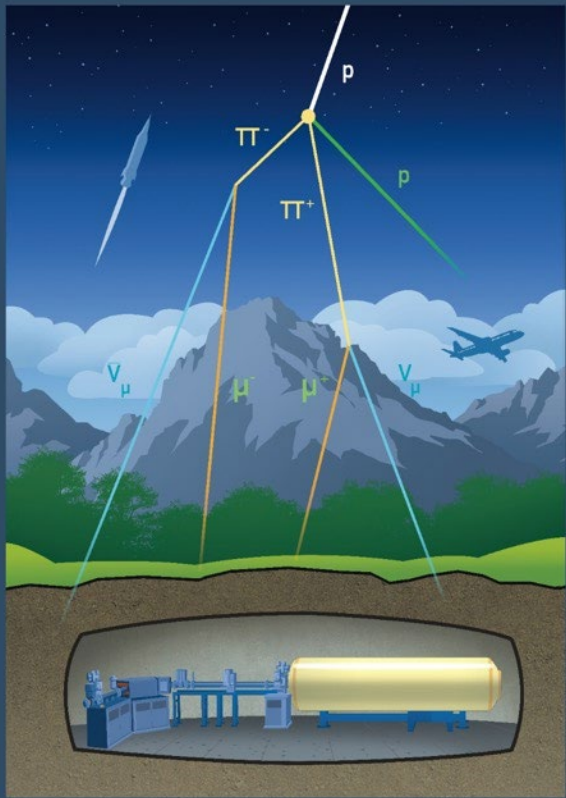
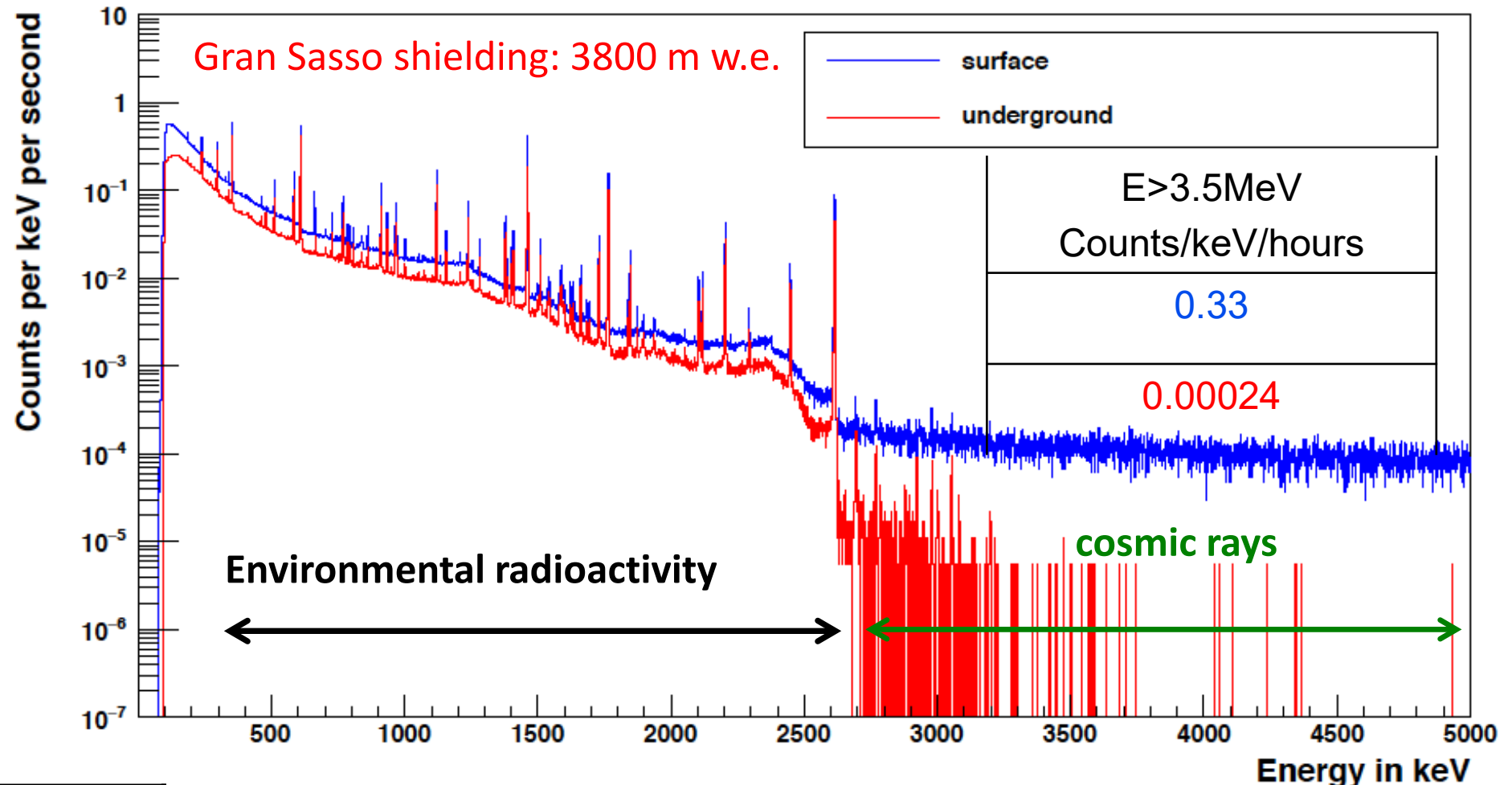


Background reduction:

up to 3000 for $0.6 < E_\gamma (\text{MeV}) < 3$ and 20 for $3 < E_\gamma (\text{MeV}) < 9$

Strong reduction of the efficiency!!

Why going underground: γ -background



Radiation

LNGS/out

muons

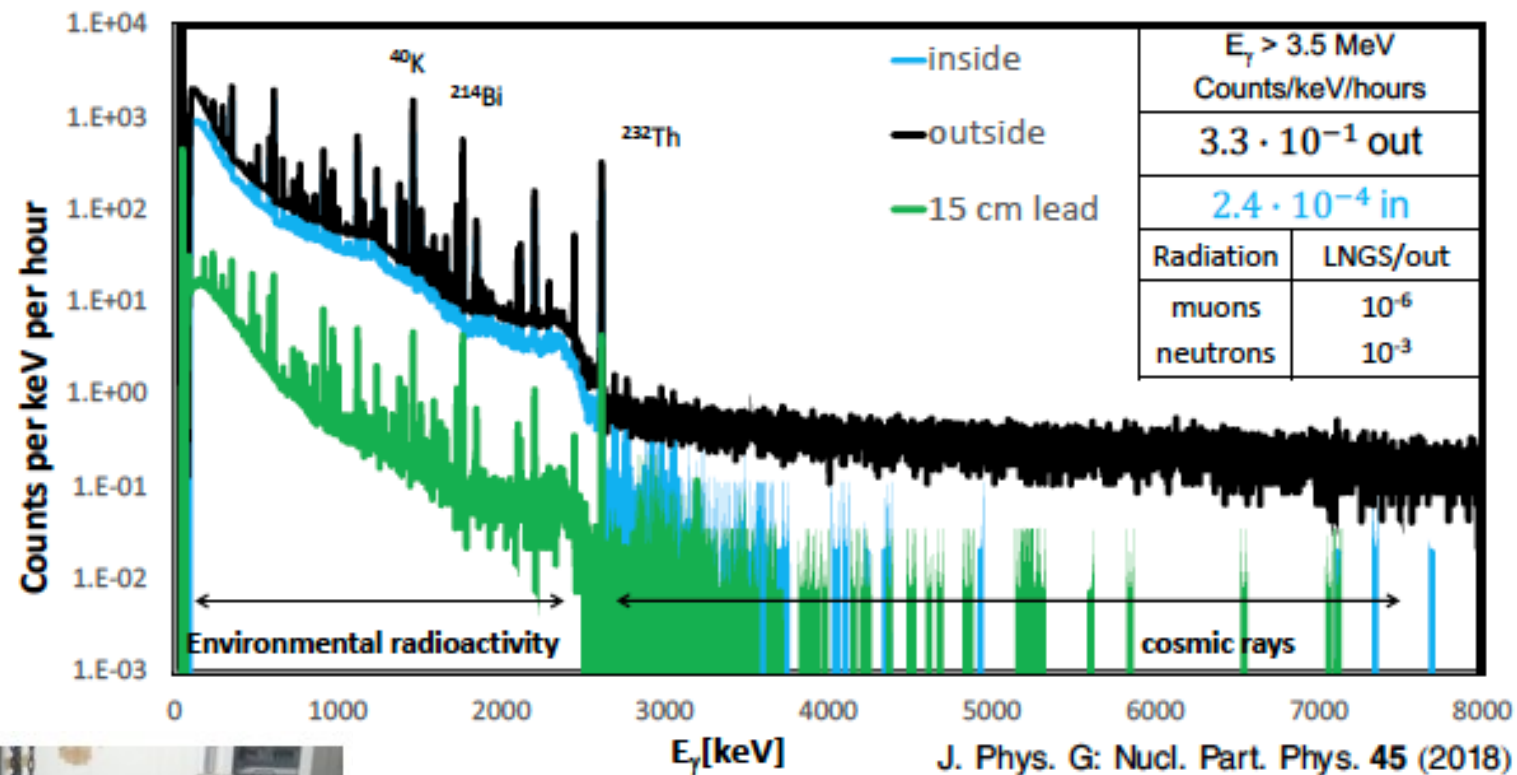
10^{-6}

neutrons

10^{-3}

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

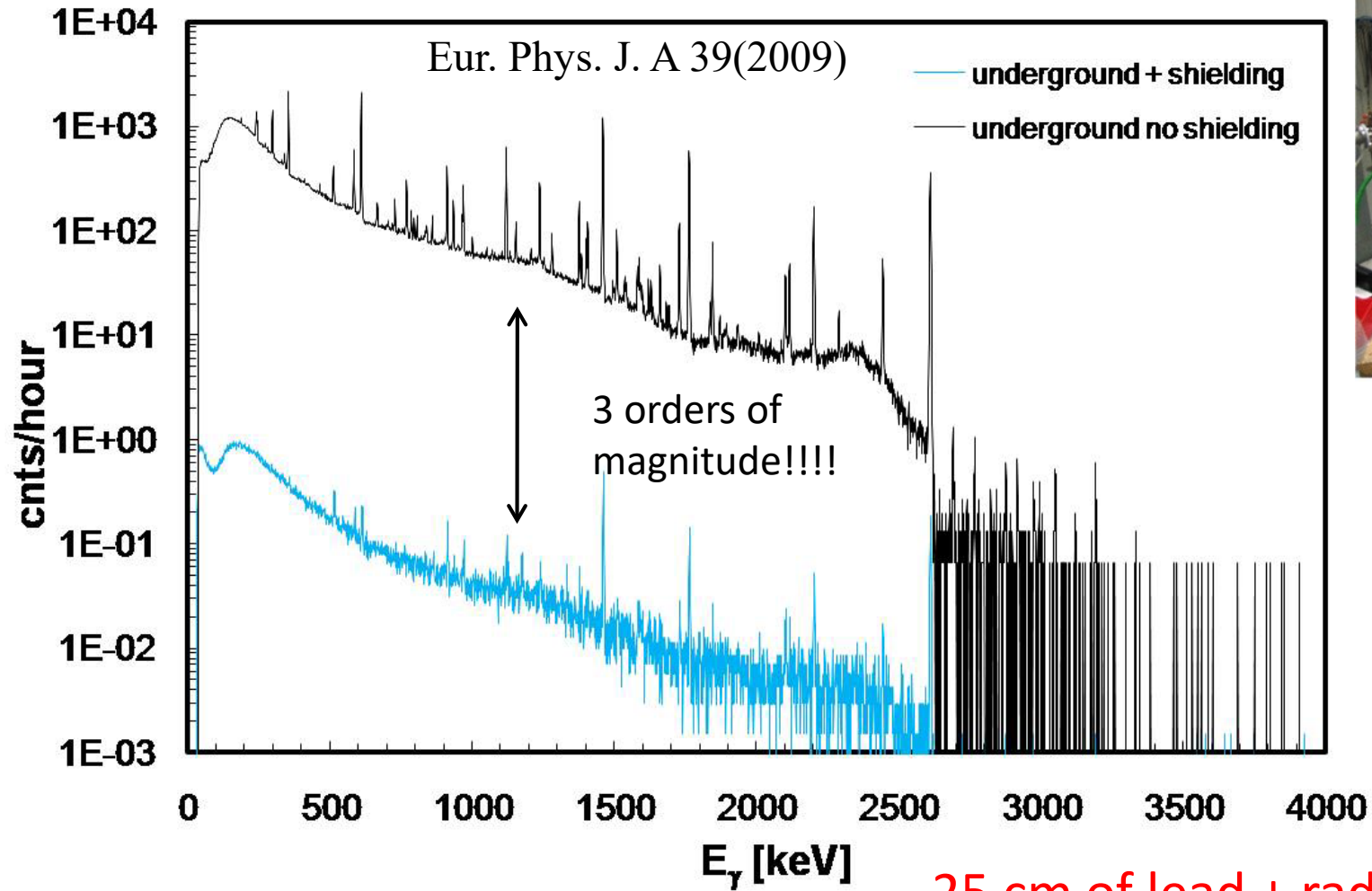
Why going underground: γ -background



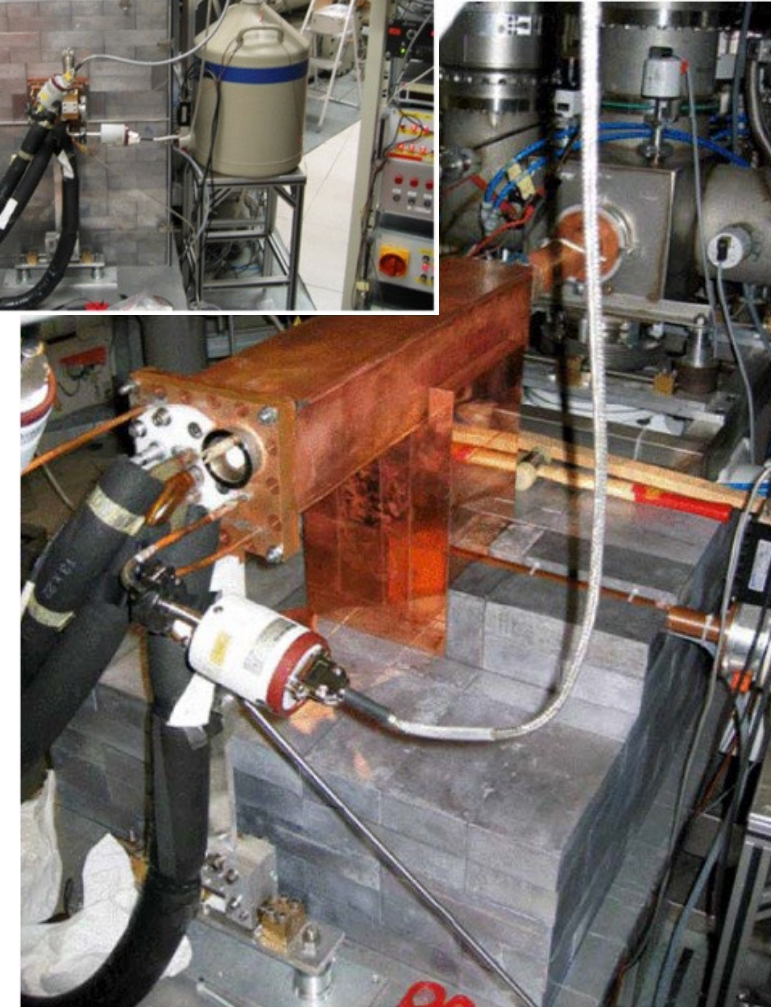
			Surface		Underground		
			unshielded		unshielded	shielded (this setup)	
^{40}K	primordial	1460 keV	*		2244	15	counts / hour
^{214}Bi	^{238}U chain	1764 keV	*		1271	13	counts / hour
^{208}Tl	^{232}Th chain	2614 keV	*		679	15	counts / hour
region 3300 – 6000 keV			$3.30(2) \cdot 10^{-1}$		$2.4(4) \cdot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

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

Why going underground: γ -background

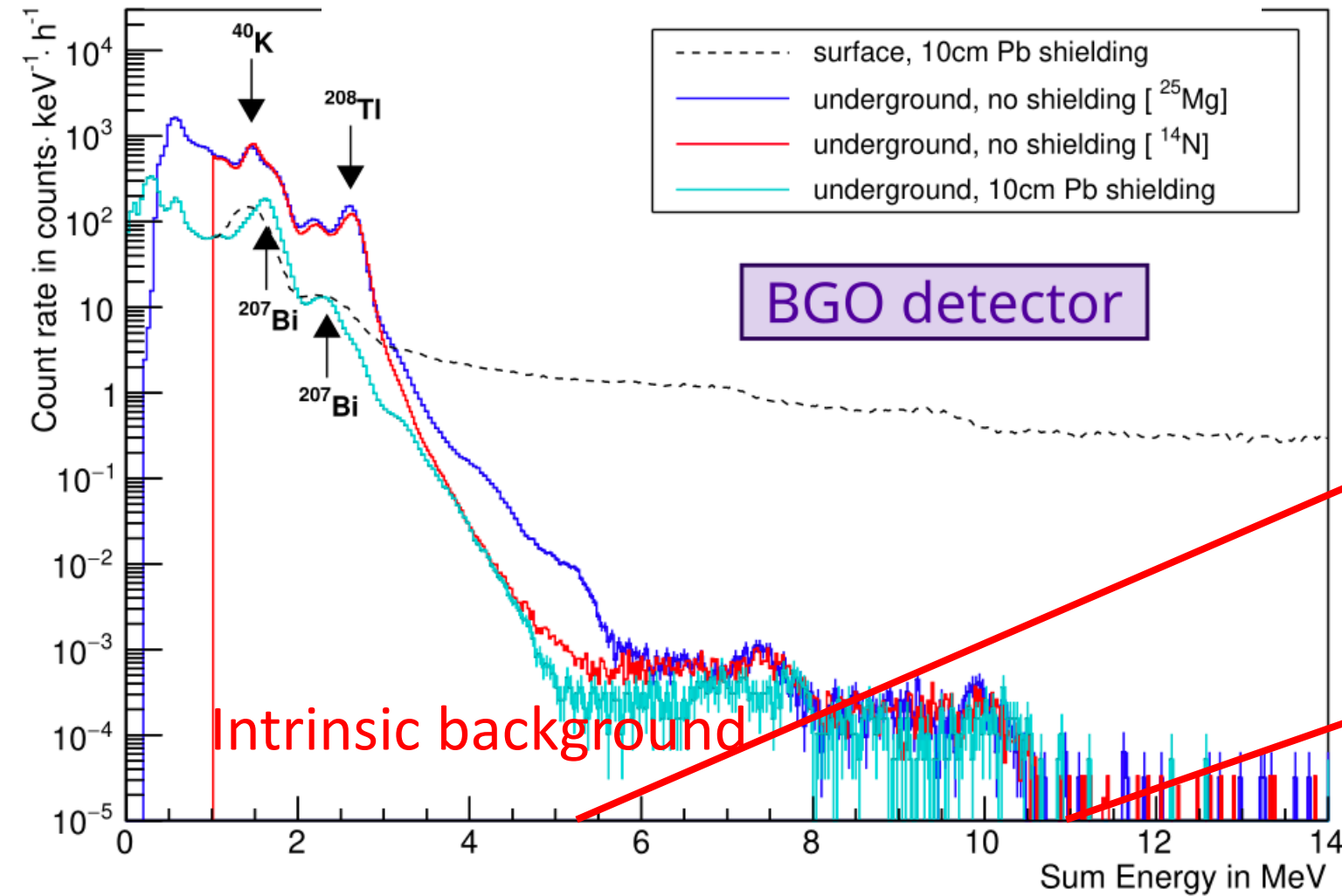
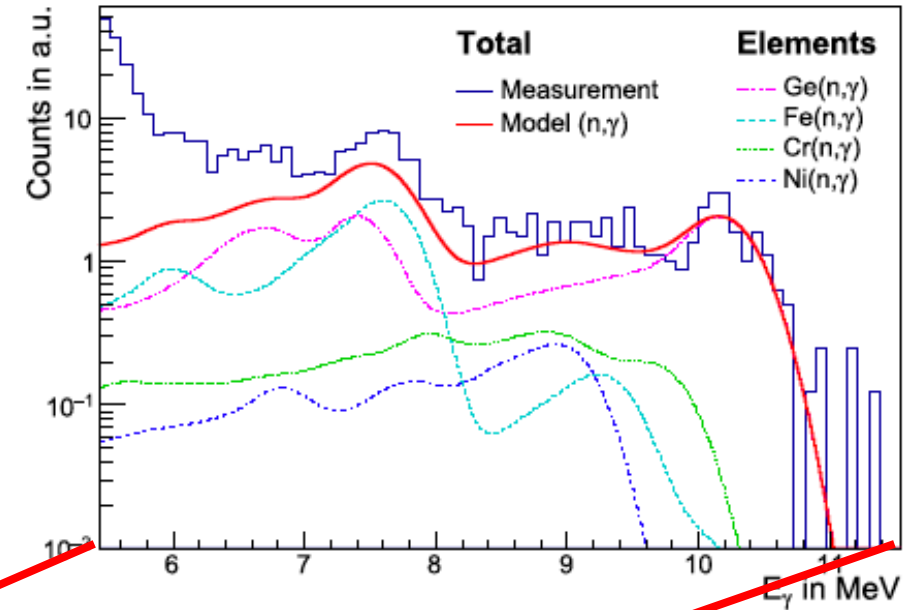
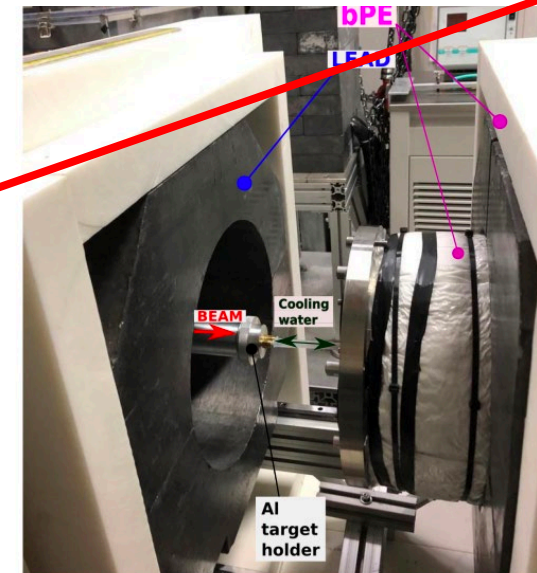


25 cm of lead + radon box



γ -detection: high efficiency for low counting

J. Phys. G: Nucl. Part. Phys. 45 (2018) 025203 (18pp)



γ -detection: high efficiency for low counting

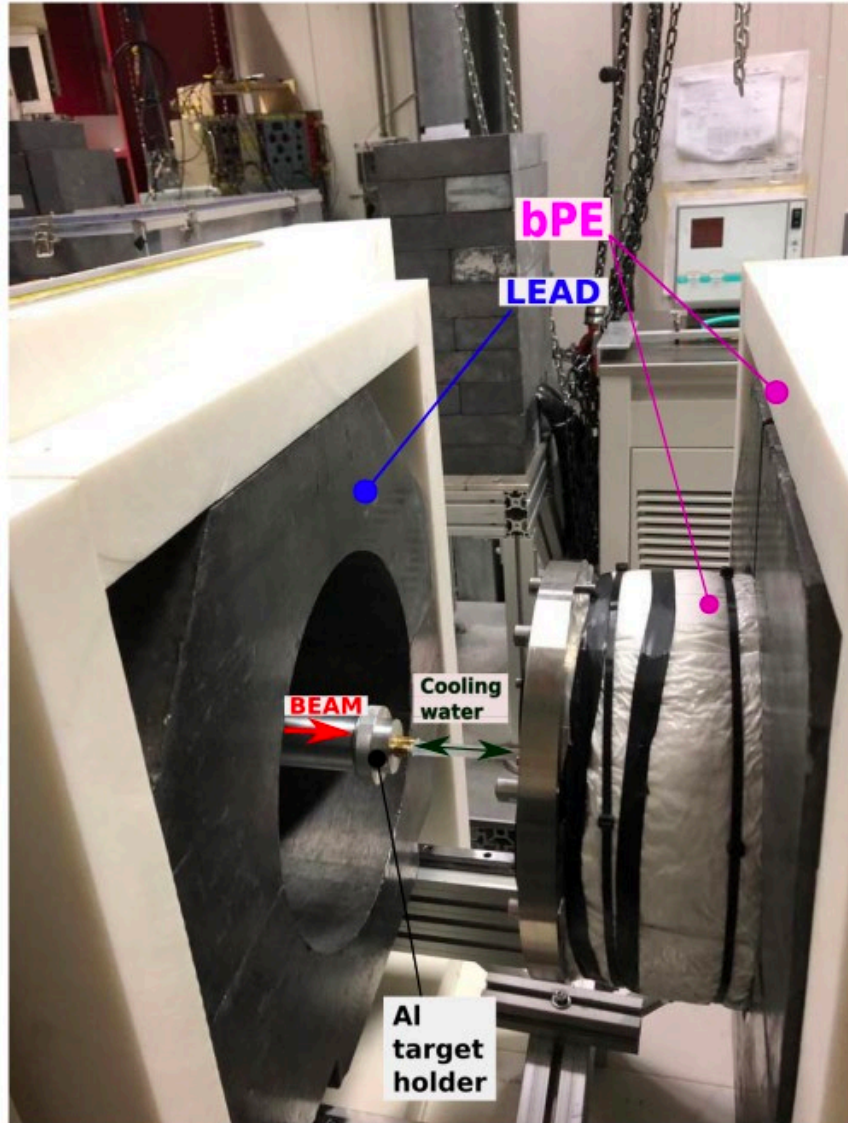
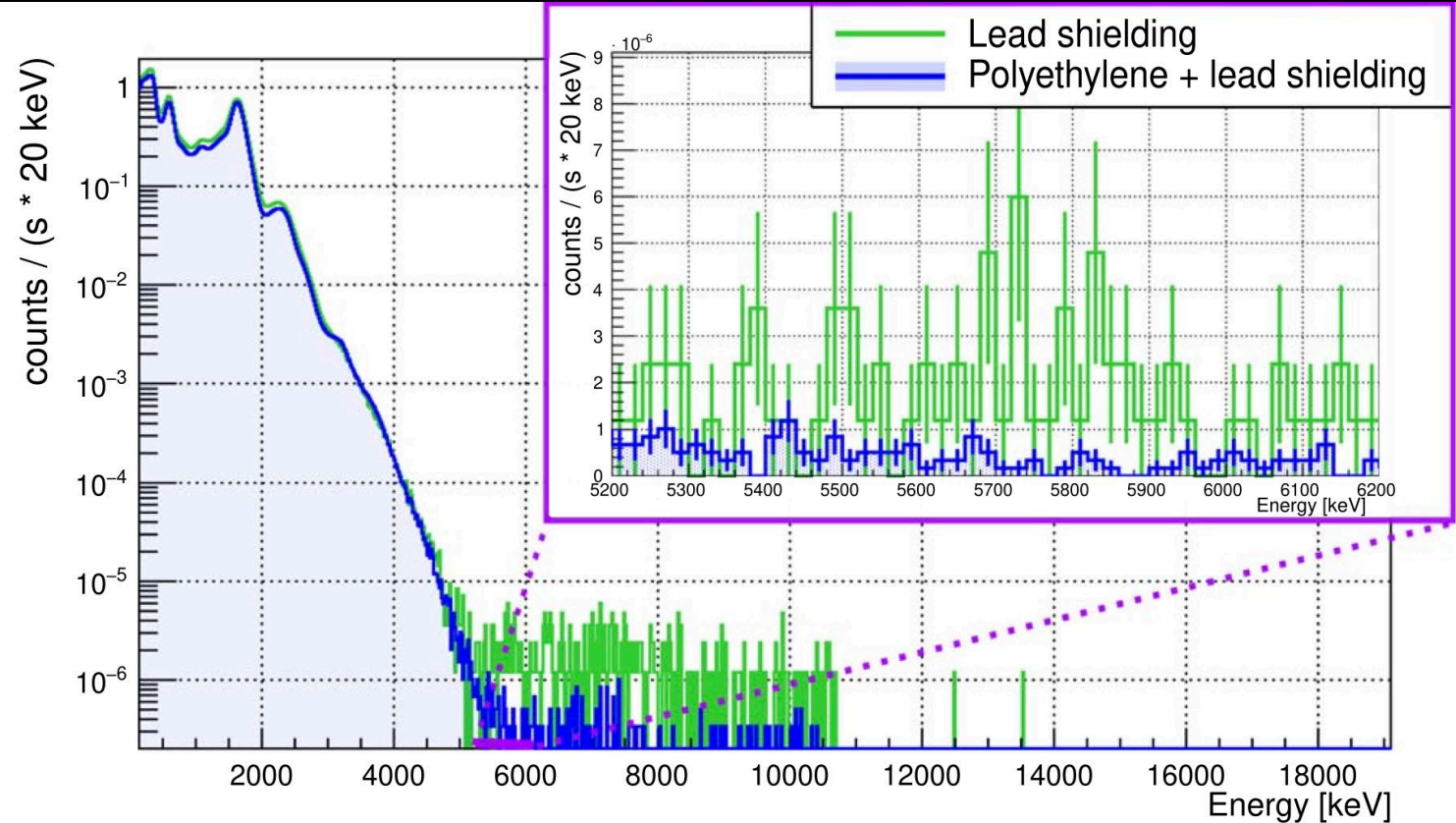


Figure 5. Measured background with Setup B (black) and C (blue). The inset shows the region of interest for the $E_{c.m.}^{res.} = 65$ keV resonance of the $^{17}\text{O}(p, \gamma)^{18}\text{F}$ reaction.

~ a factor of 5 of reduction between 5 and 10 MeV.

OPEN ACCESS

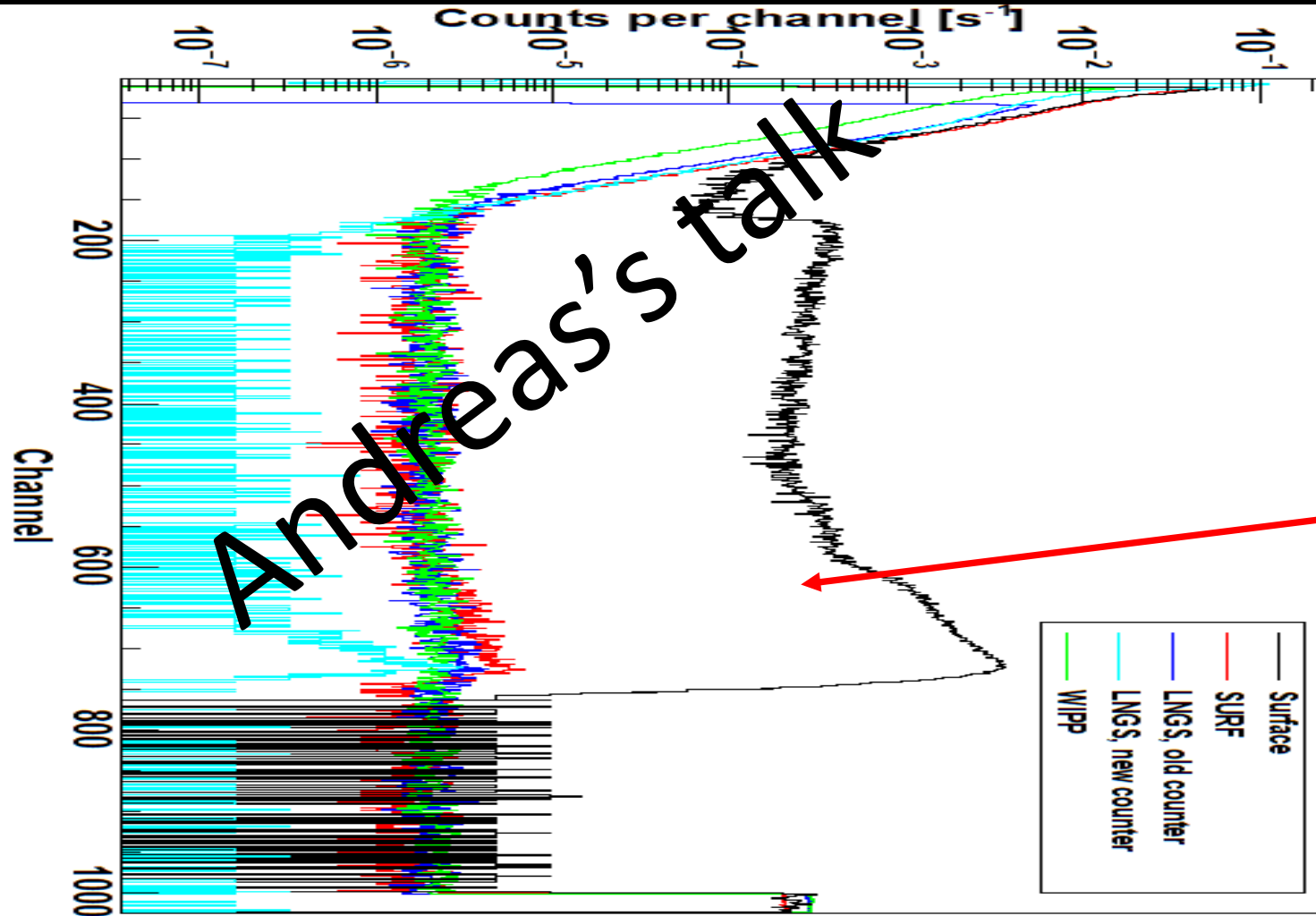
IOP Publishing

Journal of Physics G: Nuclear and Particle Physics

J. Phys. G: Nucl. Part. Phys. **50** (2023) 045201 (20pp)

<https://doi.org/10.1088/1361-6471/acb961>

Why going underground: n-background



INTRINSIC: α particles source of intrinsic background from U and Th impurities in the counters' case

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

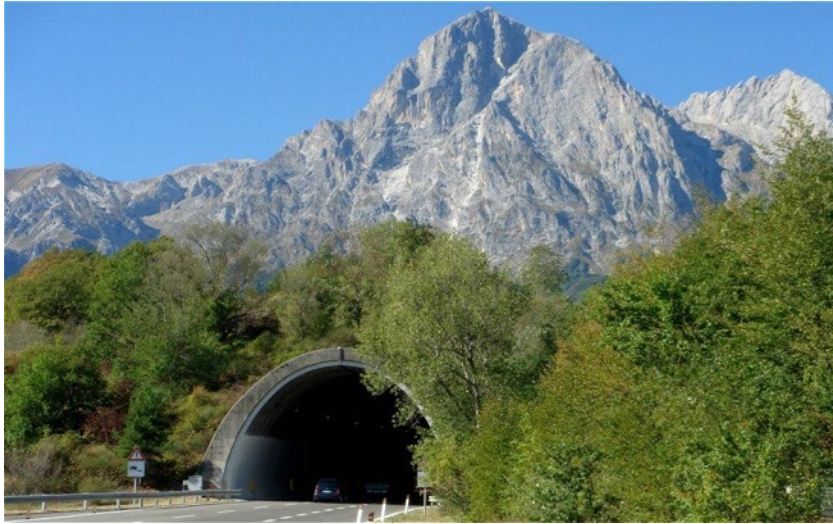
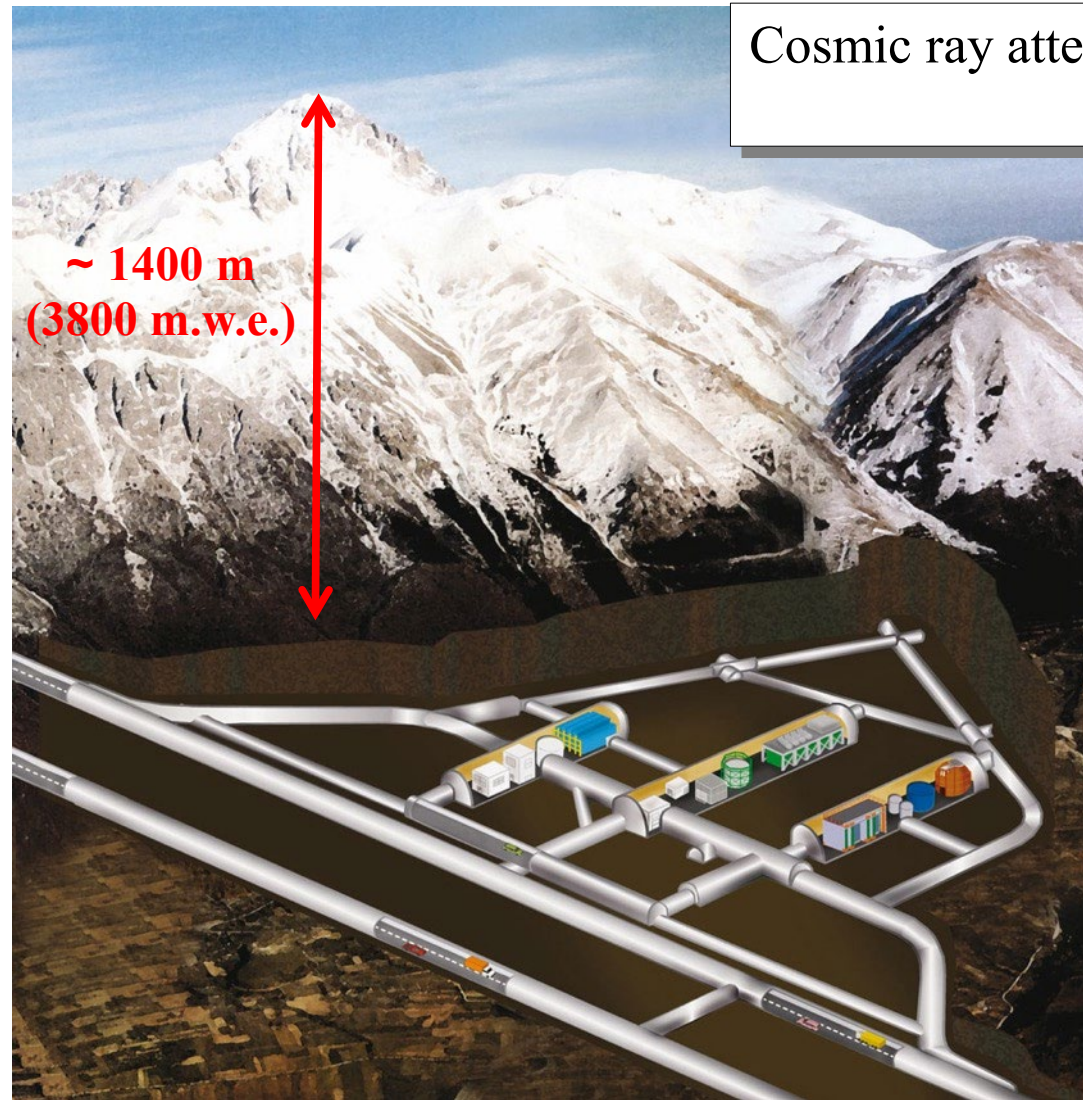
Radiation	LNGS/out
muons	10^{-6}
neutrons	10^{-3}

LNGS laboratory

Laboratori Nazionali del Gran Sasso



LNGS laboratory



Cosmic ray attenuation: $\mu \rightarrow 10^{-6}$

$n \rightarrow 10^{-3}$

LUNA: a long story of discoveries

LNGS - 91/18
December 1991

Nuclear Astrophysics at the Gran Sasso Laboratory
(Proposal of a pilot project with a 30 kV accelerator)

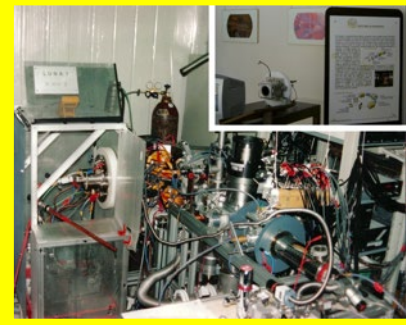
C Arpesella, C Barnes, E Bellotti, C Brogгинi, P Corvisiero,
N Ferrari, G Fiorentini, S Fubini, G Gervino, U Greife,
R Kavanagh, G Mezzorani, P Prati, P Quarati, C Rolfs, H Schulte and H P
Trautvetter



INFN - Laboratori Nazionali del Gran Sasso

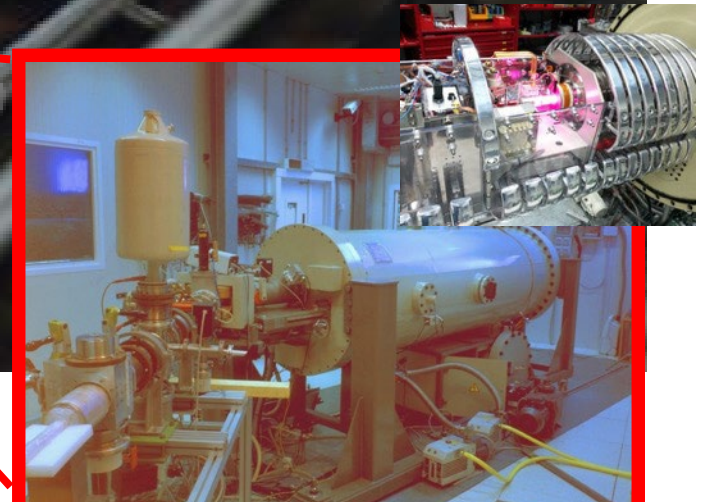
LNGS

LUNA-MV – 2022/



LUNA-50 kV
– 1992/00

LUNA-400 kV
– 2000/



LUNA: a long story of discoveries

LNGS - 91/18
December 1991

Main topics:

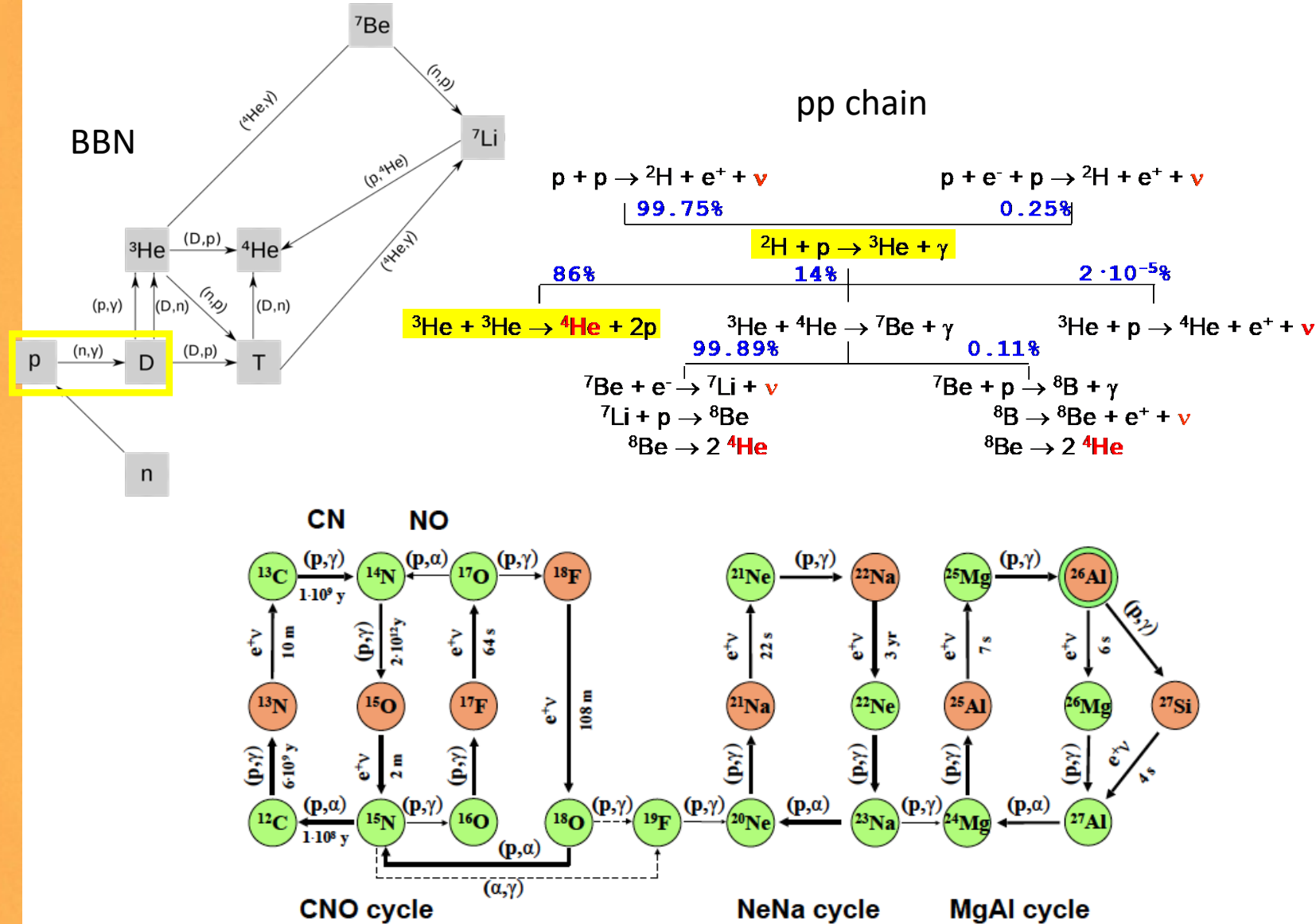
- Big Bang Nucleosynthesis;
- Hydrogen stellar burning;
- Solar neutrino;
- Age of globular clusters.

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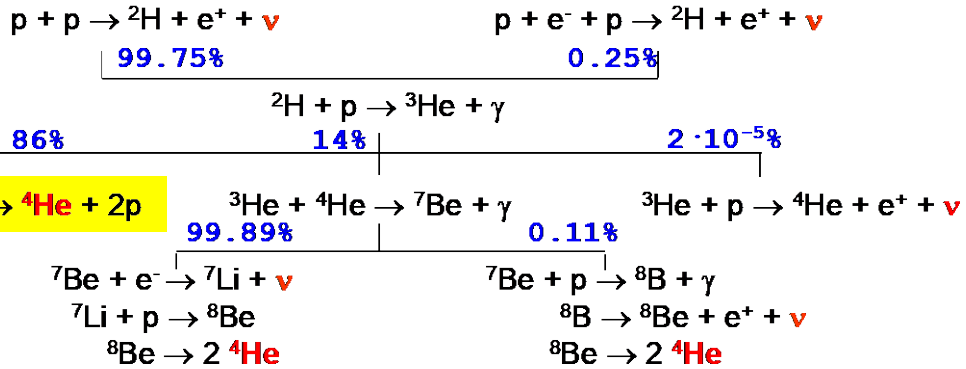
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INFN - Laboratori Nazionali del Gran Sasso



LUNA 50 kV: the dream of W. Fowler



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 $3\text{He} - 3\text{He}$ 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. Bachall

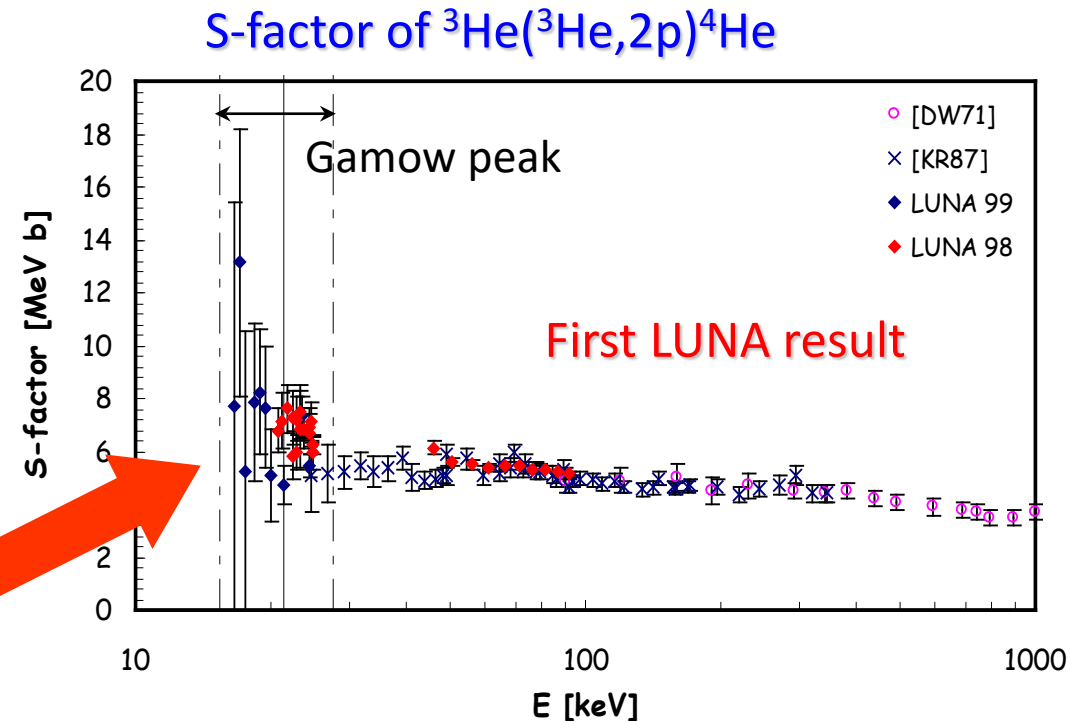
VOLUME 82, NUMBER 26

PHYSICAL REVIEW LETTERS

28 JUNE 1999

First Measurement of the ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$ Cross Section down to the Lower Edge of the Solar Gamow Peak

R. Bonetti,¹ C. Brogгинi,^{2,*} L. Campajola,³ P. Corvisiero,⁴ A. D'Alessandro,⁵ M. Dessalvi,⁴ A. D'Onofrio,⁶ A. Fubini,⁷ G. Gervino,⁸ L. Gialanella,⁹ U. Greife,⁹ A. Guglielmetti,¹ C. Gustavino,⁵ G. Imbriani,³ M. Junker,⁵ P. Prati,⁴ V. Roca,³ C. Rolf,⁹ M. Romano,³ F. Schuermann,⁹ F. Strieder,⁹ F. Terrasi,³ H.P. Trautvetter,⁹ and S. Zavatarelli⁴
(LUNA Collaboration)

 $\sigma_{\min} = 0.02 \text{ pb}$

2 events/month !

LUNA 50 kV: stopping power

Energy loss of deuterons in ^3He gas: a threshold effect

A. Formicola *et al.*: Energy loss of deuterons in ^3He gas: a threshold effect

445

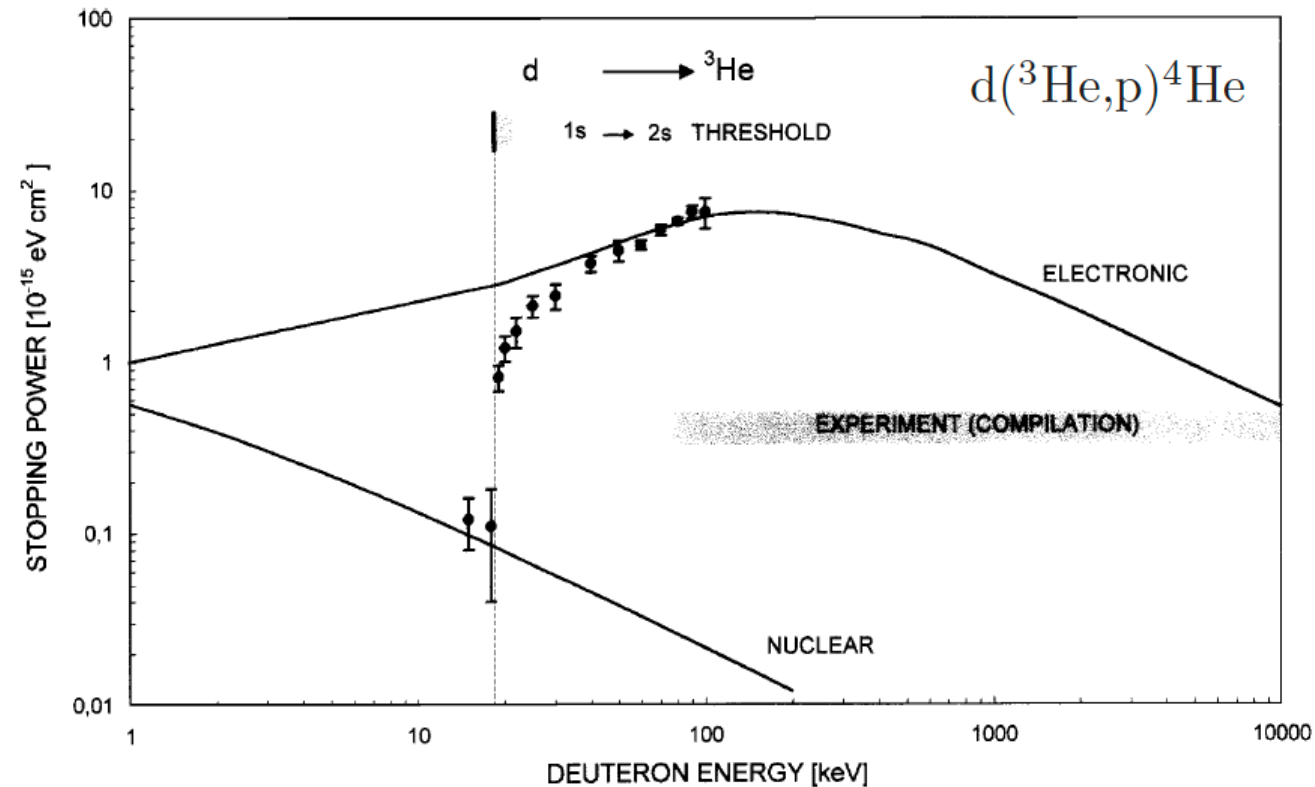


Fig. 2. Energy loss of deuterons in ^3He gas as function of deuteron energy. The “electronic” curve represents the electronic stopping power from the compilation [3] based on data above 80 keV (shadowed box) and the “nuclear” curve is the expected nuclear stopping power [3]. The present data show a threshold effect in the electronic stopping power at $E_d = 18$ keV.

LUNA: a long story of discoveries

LNGS - 91/18
December 1991

Main topics:

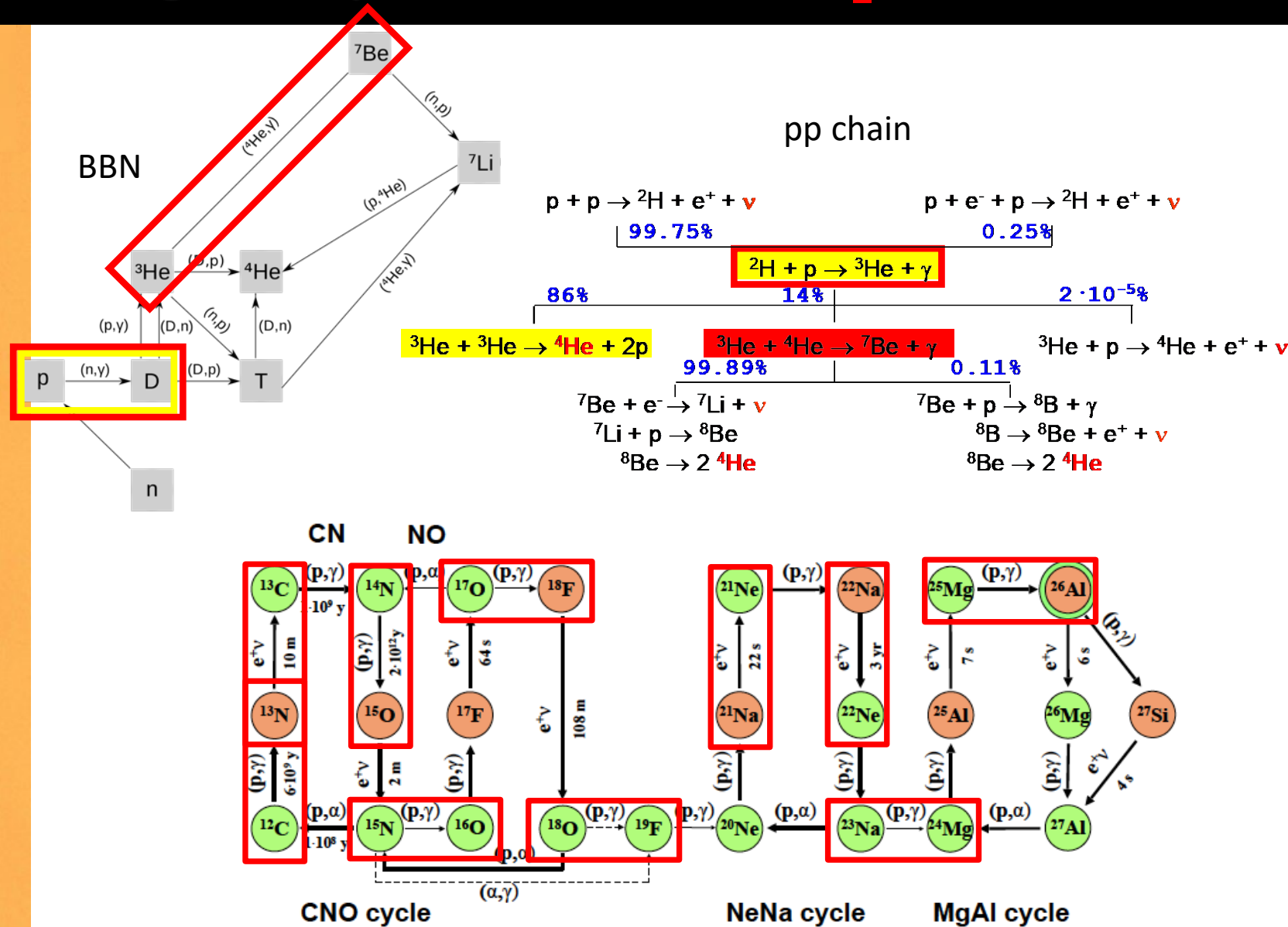
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R Kavanagh, G Mezzorani, P Prati, P Quarati, C Rolfs, H Schulte and H P
Trautvetter

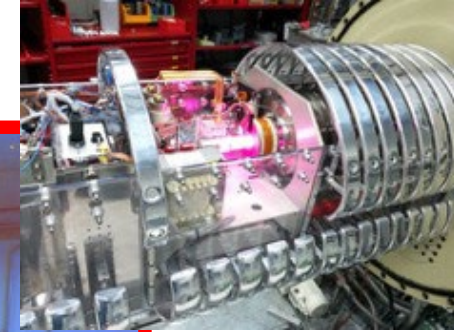
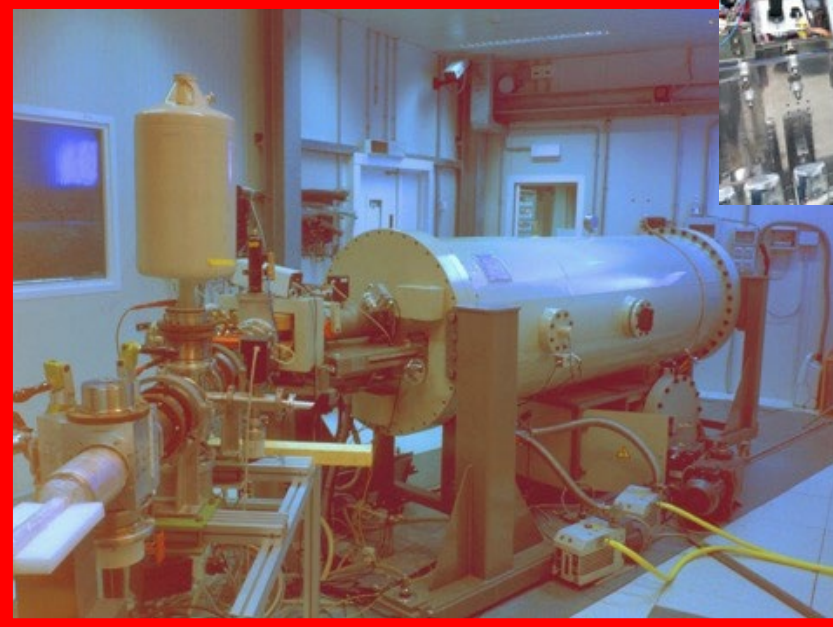


INFN - Laboratori Nazionali del Gran Sasso



LUNA – available experimental set-ups

LNGS



LUNA-400 kV
– 2000/

Voltage Range :
50 - 400 kV

Output Current:
500 μ A

Beam energy spread:
70 eV

LUNA 400 kV: $^{14}\text{N}(p,\gamma)^{15}\text{O}$



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Physics Letters B 591 (2004) 61–68

PHYSICS LETTERS B

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Eur. Phys. J. A **25**, 455–466 (2005)

DOI 10.1140/epja/i2005-10138-7

THE EUROPEAN
PHYSICAL JOURNAL A

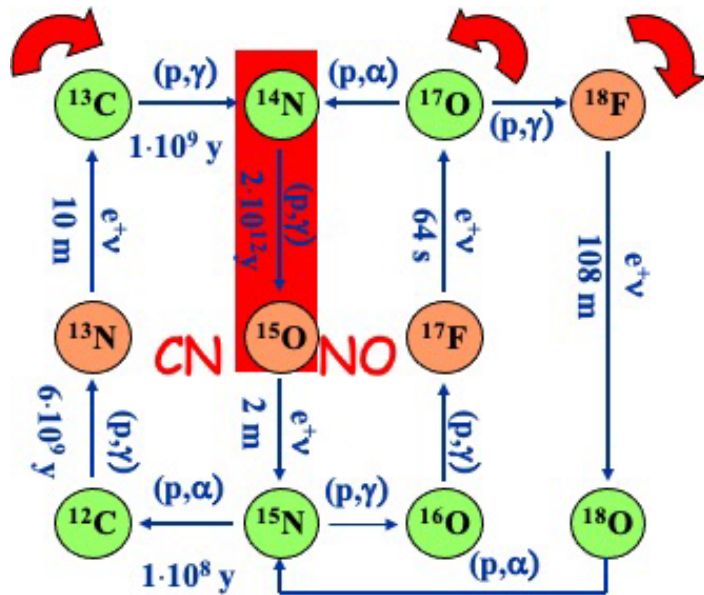
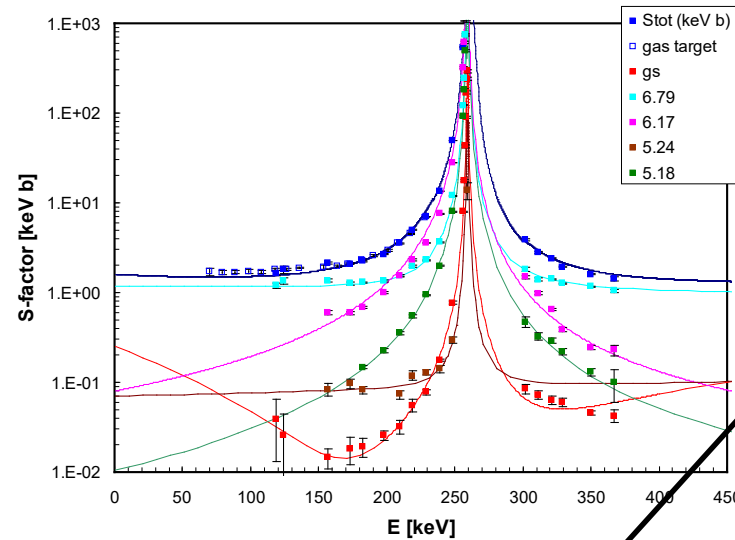
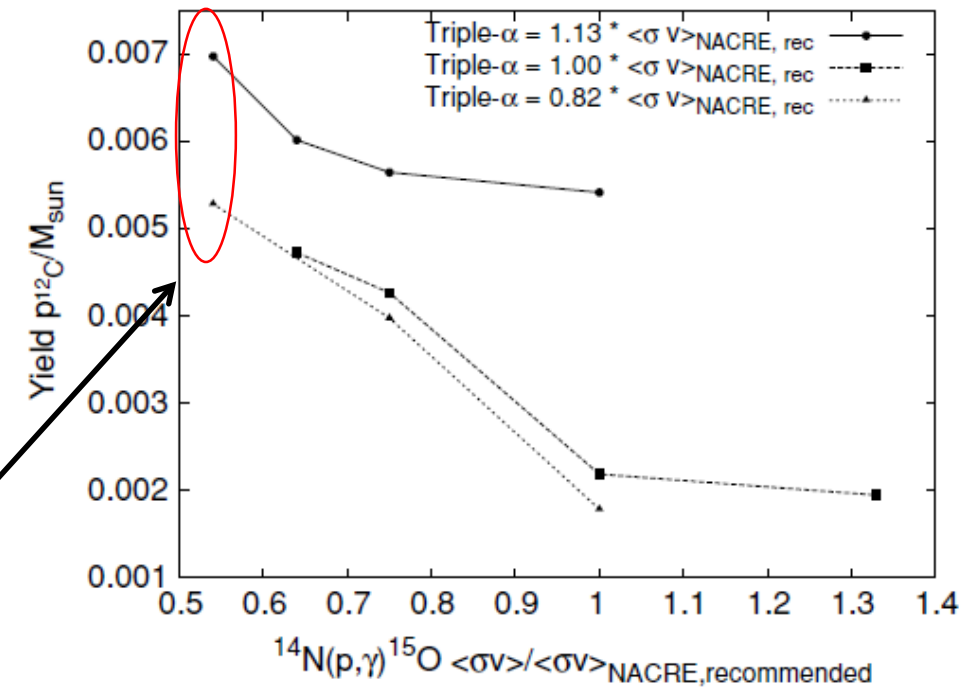
S-factor of $^{14}\text{N}(p,\gamma)^{15}\text{O}$ at astrophysical energies*

Astrophysical S-factor of $^{14}\text{N}(p,\gamma)^{15}\text{O}$ *

A. Formicola^a, G. Imbriani^b, H. Costantini^c, C. Angulo^d, D. Bemmerer^e, R. Bonetti^f, C. Broggini^g, P. Corvisiero^h, J. Cruz^h, P. Descouvemontⁱ, Z. Fülöp^j, G. Gervino^k, A. Guglielmetti^l, C. Gustavino¹, G. Gyürky^j, A.P. Jesus^h, M. Junker¹, A. Lemut^e, R. Menegazzo^g, P. Prati^c, V. Roca^m, C. Rolfs^a, M. Romano^m, C. Rossi Alvarez^g, F. Schümann^a, E. Somorjai^j, O. Straniero^b, F. Strieder^a, F. Terrasi^a, H.P. Trautvetter^a, A. Vomiero^o, S. Zavatarelli^c

G. Imbriani^{1,a}, H. Costantini², A. Formicola³, A. Vomiero⁴, C. Angulo⁵, D. Bemmerer⁶, R. Bonetti⁷, C. Broggini⁶, F. Confortola², P. Corvisiero², J. Cruz⁸, P. Descouvemont⁹, Z. Fülöp¹⁰, G. Gervino¹¹, A. Guglielmetti⁷, C. Gustavino³, Gy. Gyürky¹⁰, A.P. Jesus⁸, M. Junker³, J.N. Klug¹², A. Lemut², R. Menegazzo⁶, P. Prati⁴, V. Roca¹, C. Rolfs¹², M. Romano¹, C. Rossi-Alvarez⁶, F. Schümann¹², D. Schürmann¹², E. Somorjai¹⁰, O. Straniero^{13,14}, F. Strieder¹², F. Terrasi^{15,14}, and H.P. Trautvetter¹²

FALK HERWIG, SAM M. AUSTIN, AND JOHN C. LATTANZIO



With $^{14}\text{N}(p,\gamma)^{15}\text{O}$ rate = $\frac{1}{2}$ of NACRE agreement between observation and calculation.

LUNA 400 kV: $^{14}\text{N}(p,\gamma)^{15}\text{O}$



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Physics Letters B 591 (2004) 61–68

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A&A 420, 625–629 (2004)
DOI: 10.1051/0004-6361:20040981
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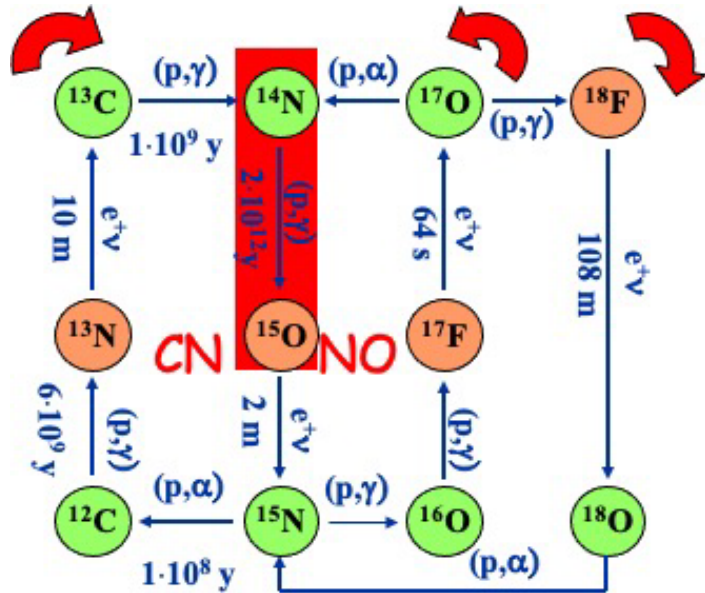
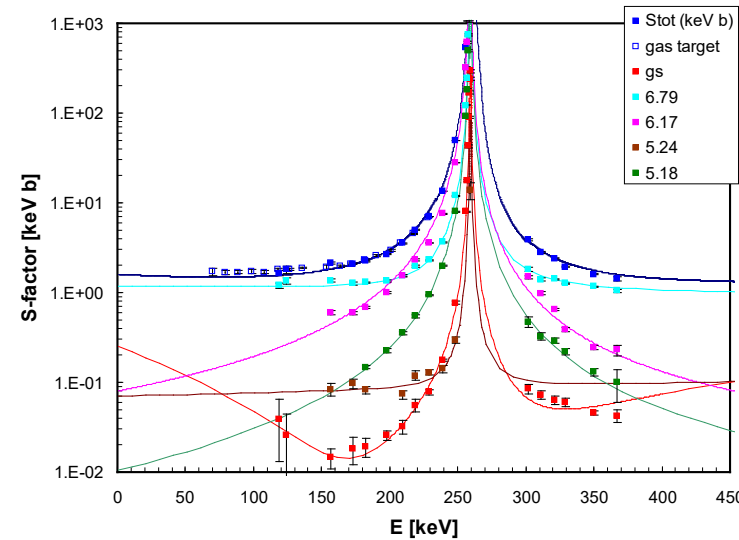
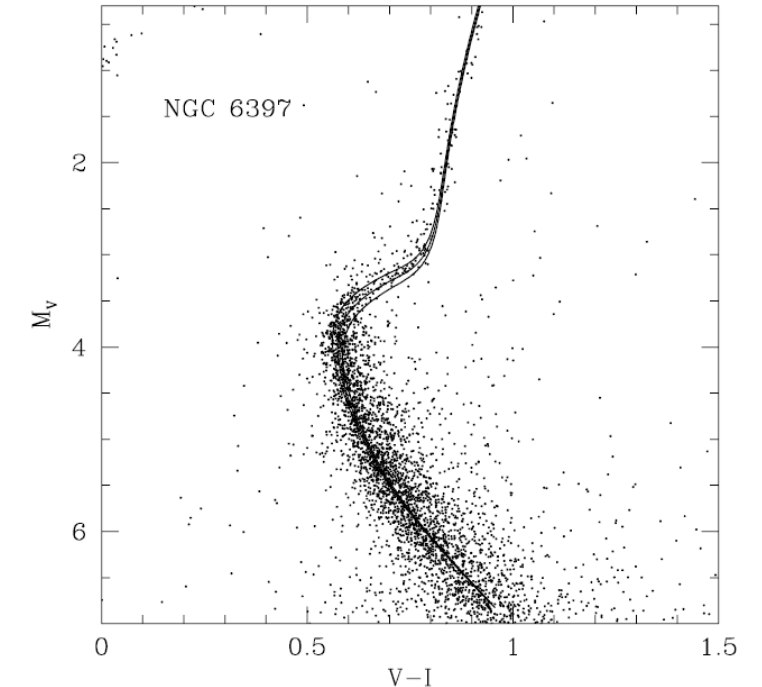
**Astronomy
&
Astrophysics**

Astrophysical S -factor of $^{14}\text{N}(p,\gamma)^{15}\text{O}$ *

A. Formicola^a, G. Imbriani^b, H. Costantini^c, C. Angulo^d, D. Bemmerer^e, R. Bonetti^f,
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A. Vomiero^o, S. Zavatarelli^c

The bottleneck of CNO burning and the age of Globular Clusters

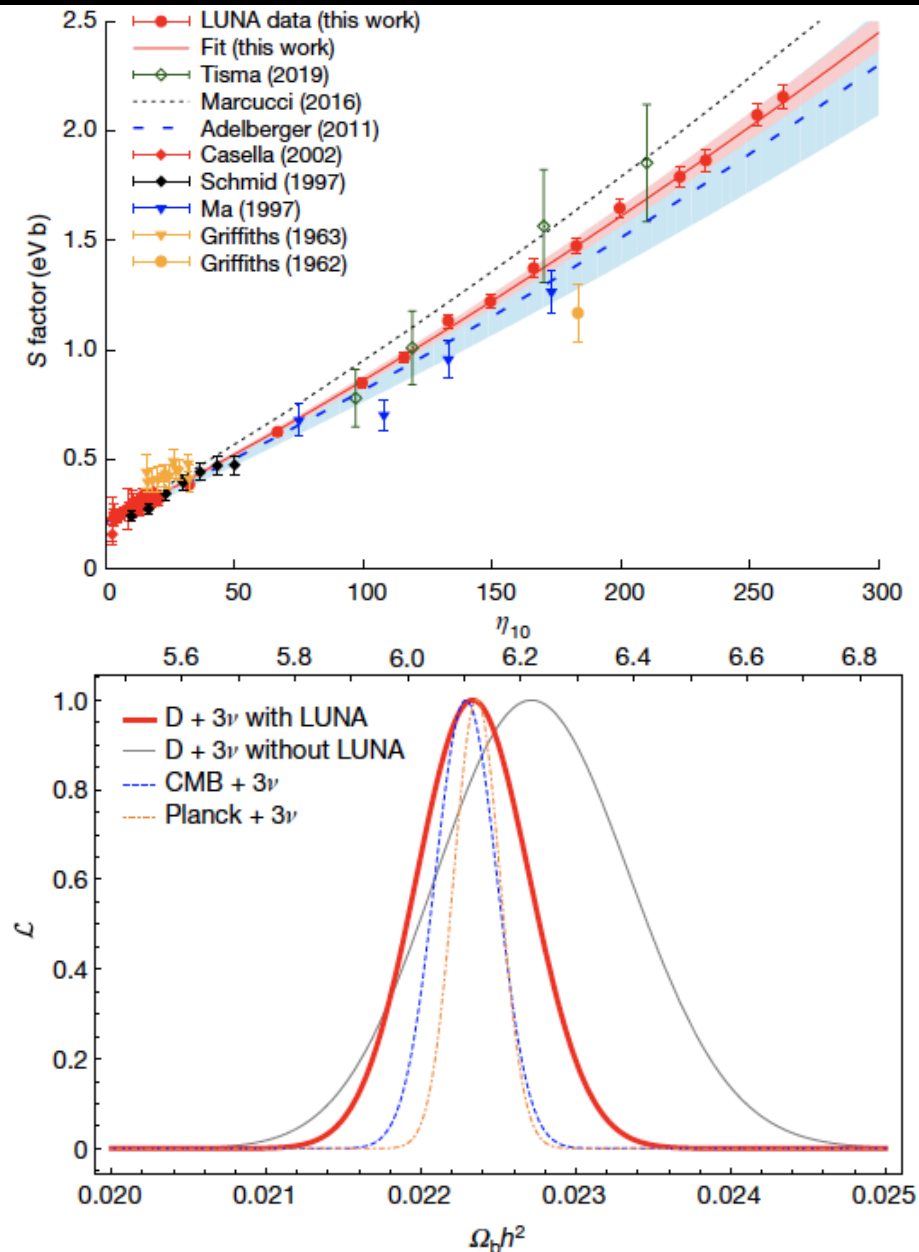
G. Imbriani^{1,2,3}, H. Costantini⁴, A. Formicola^{5,6}, D. Bemmerer⁷, R. Bonetti⁸, C. Broggini⁹, P. Corvisiero⁴, J. Cruz¹⁰,
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R. Menegazzo⁹, P. Prati⁴, V. Roca^{2,3}, C. Rolfs⁵, M. Romano^{2,3}, C. Rossi Alvarez⁹, F. Schümann⁵, E. Somorjai¹¹,
O. Straniero^{1,2}, F. Strieder⁵, F. Terrasi^{2,13}, H. P. Trautvetter⁵, A. Vomiero¹⁴, and S. Zavatarelli⁴



The age of the oldest Globular Clusters should be increased by about 0.7-1 Gyr.

The lower limit to the Age of the Universe is 14 ± 1 Gyr. In good agreement with the precise determination of WMAP.

$D(p,\gamma)^3\text{He}$: baryon density of the Universe



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Article | Published: 11 November 2020

The baryon density of the Universe from an improved rate of deuterium burning

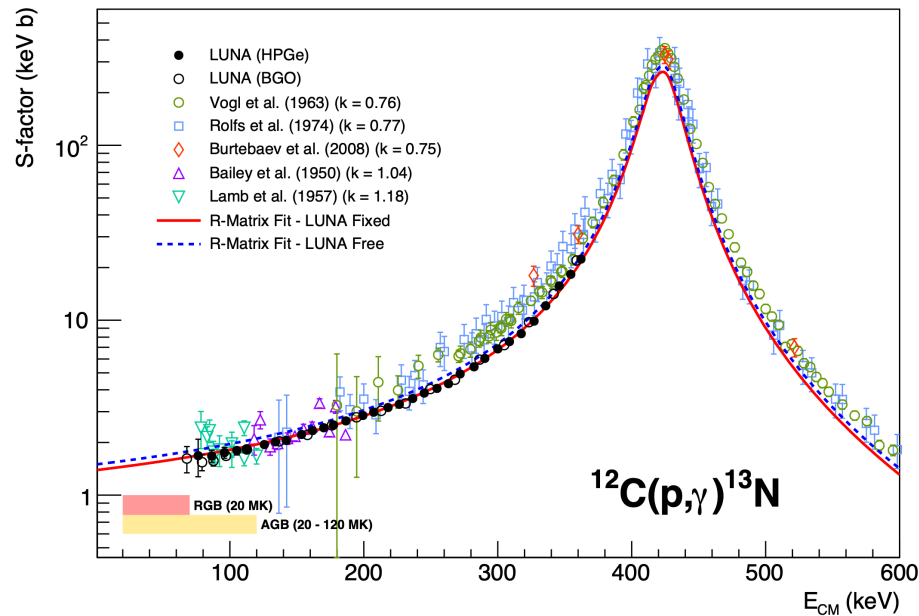
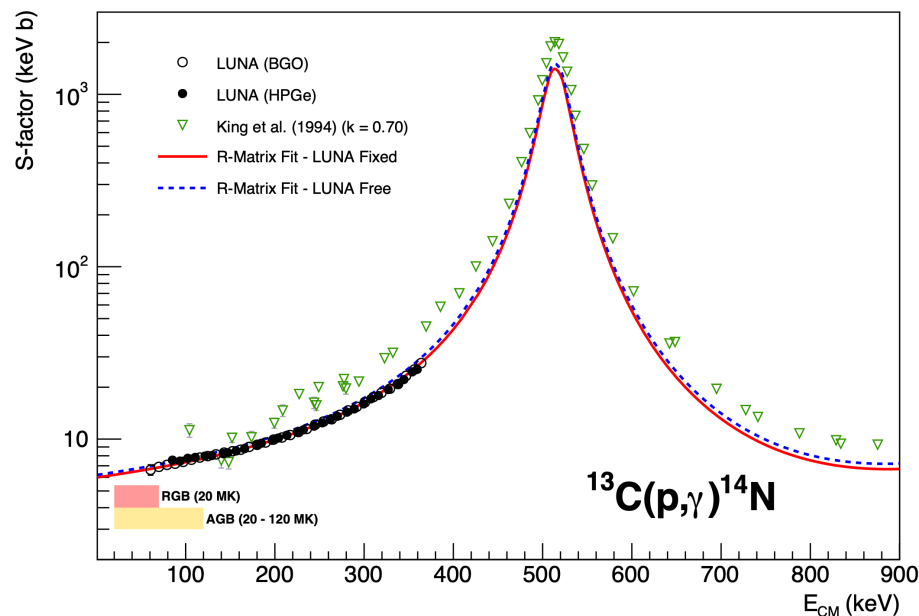
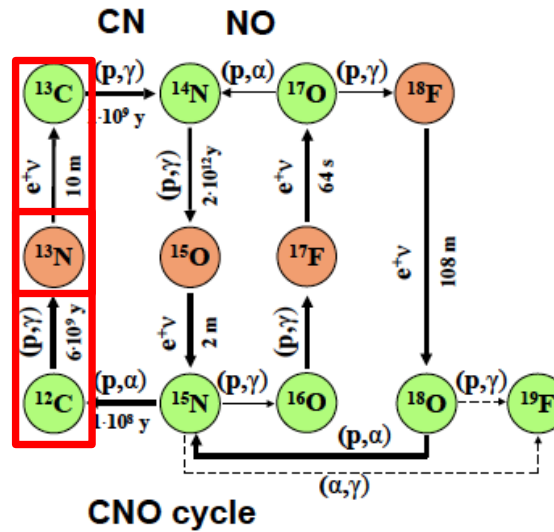
V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Cacioli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino , G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Patricchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szűcs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli  -Show fewer authors

Nature 587, 210–213(2020) | Cite this article

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Likelihood distribution of the baryon density and the baryon-to-photon ratio.

$^{12,13}\text{C}(p,\gamma)^{13,14}\text{N}$: CNO H-burning



1. HPGe Campaign

- $E_p = 80 - 400$ keV
- **Gamma (Peak) Shape Analysis**

2. BGO Campaign

- $E_p = 65 - 400$ keV
- $^{13}\text{C}(p,\gamma)^{14}\text{N}$: **Sum Peak Method**
- $^{12}\text{C}(p,\gamma)^{13}\text{N}$: **Activation Method**

Results

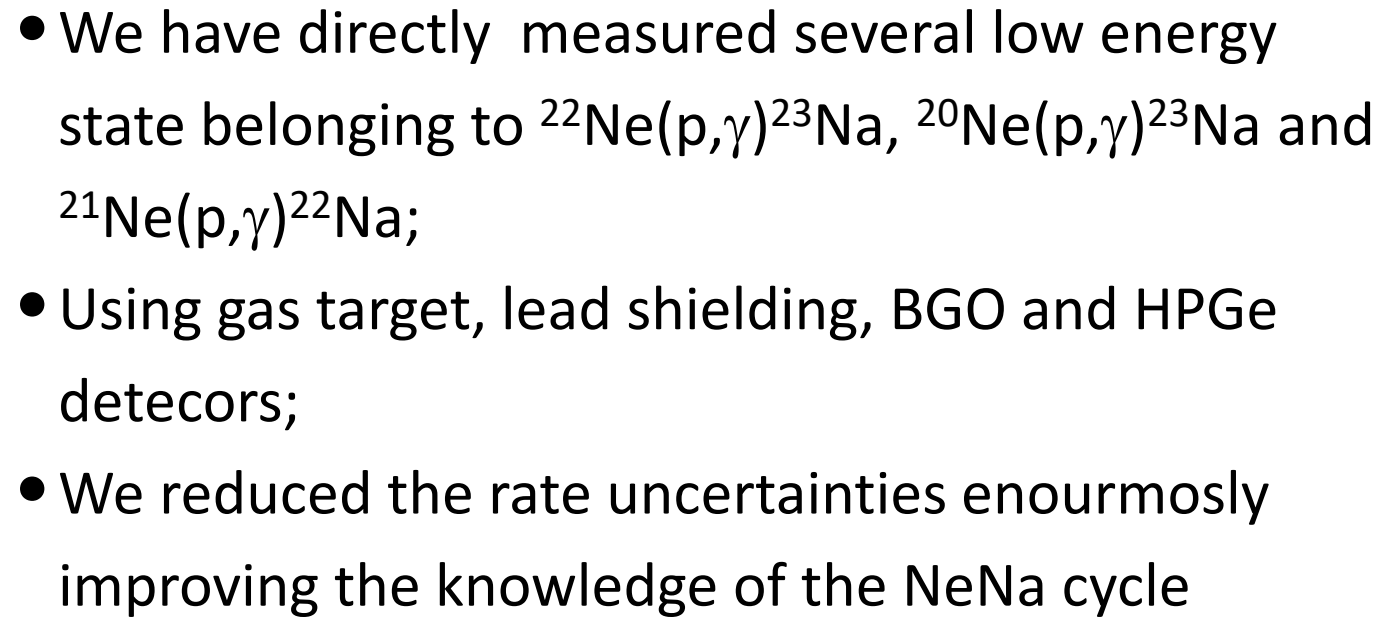
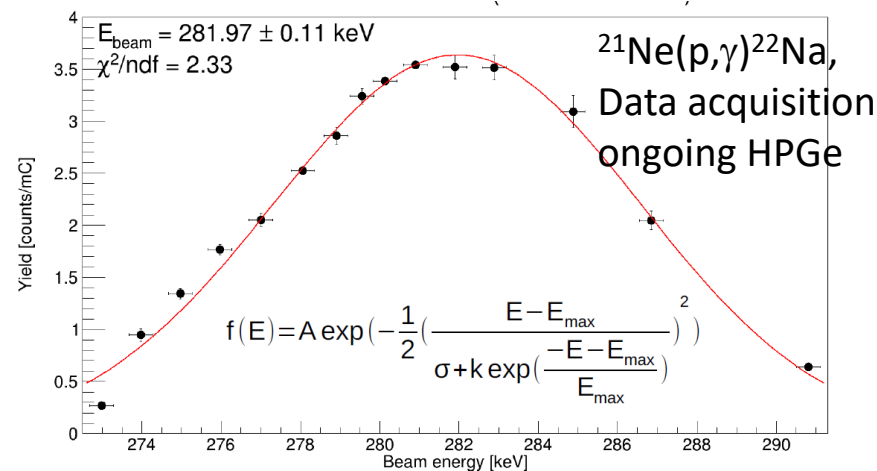
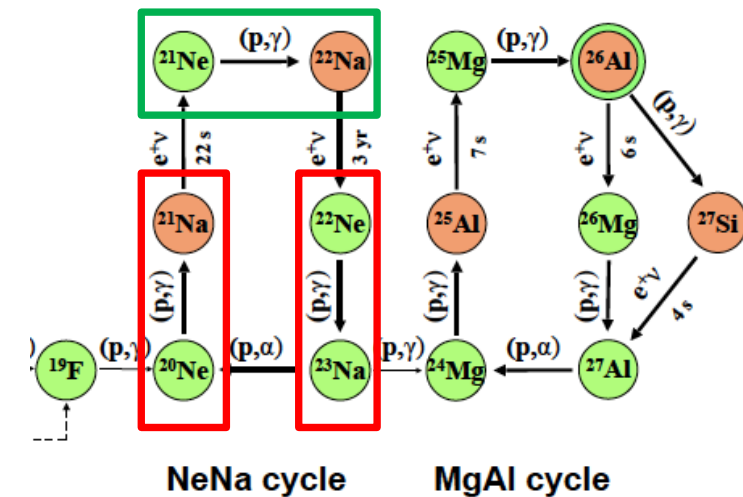
$^{12}\text{C}(p,\gamma)^{13}\text{N}$: $\sim 25\%$ lower than literature.

$^{13}\text{C}(p,\gamma)^{14}\text{N}$: $\sim 35\%$ lower than literature.

Papers:

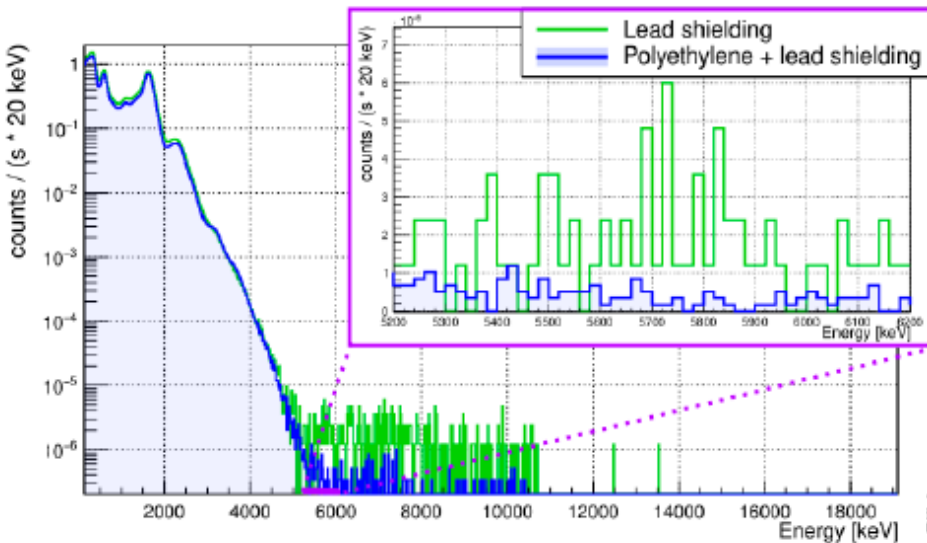
- **JPhysG 2023**: technical paper about background
- **PRL**: letter about the results, referee report just received

1



$^{17}\text{O}(p,\gamma)^{18}\text{F}$: CNO H-burning

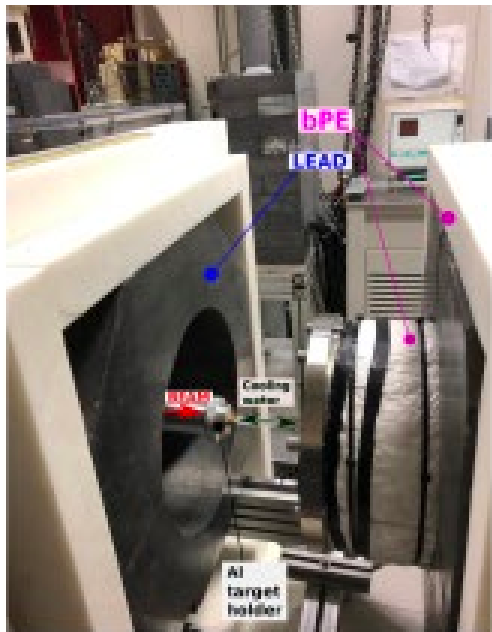
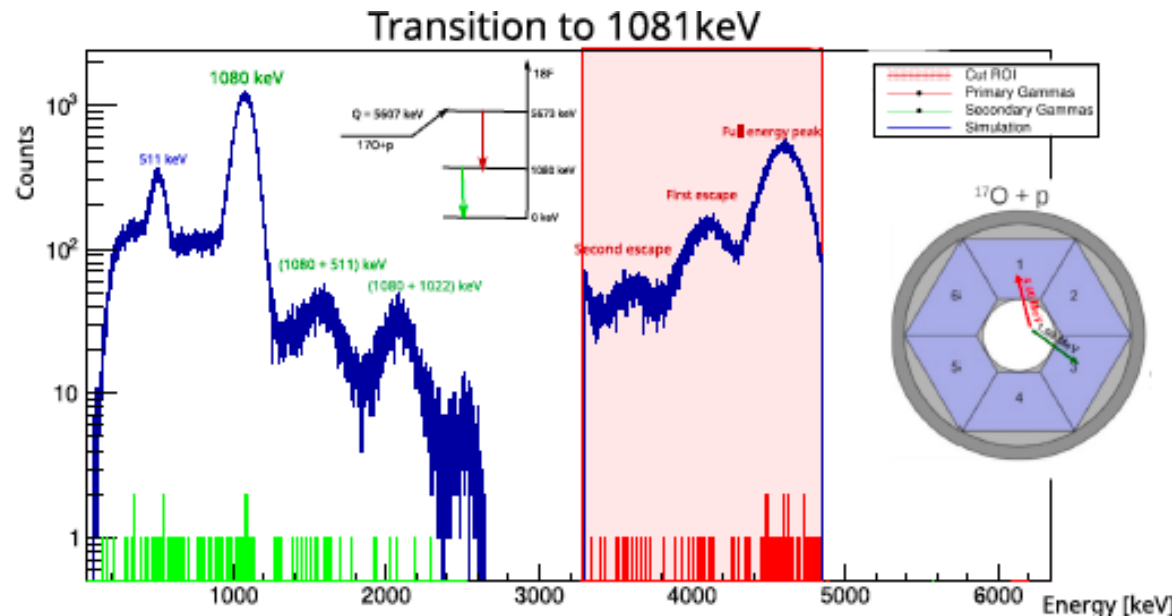
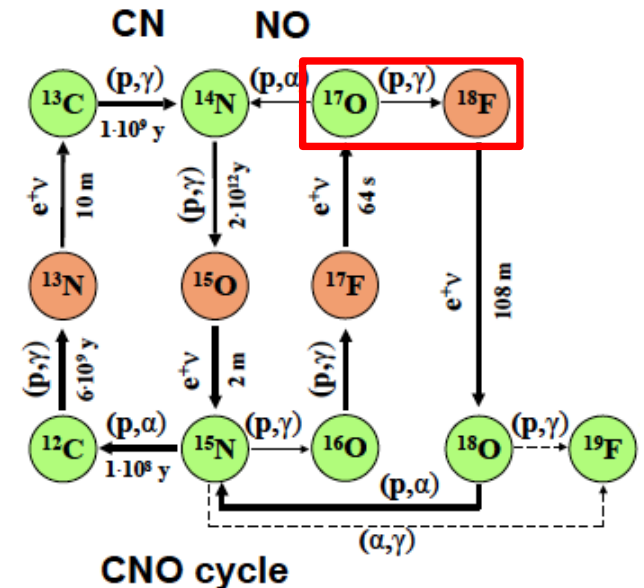
Factor 4 background reduction



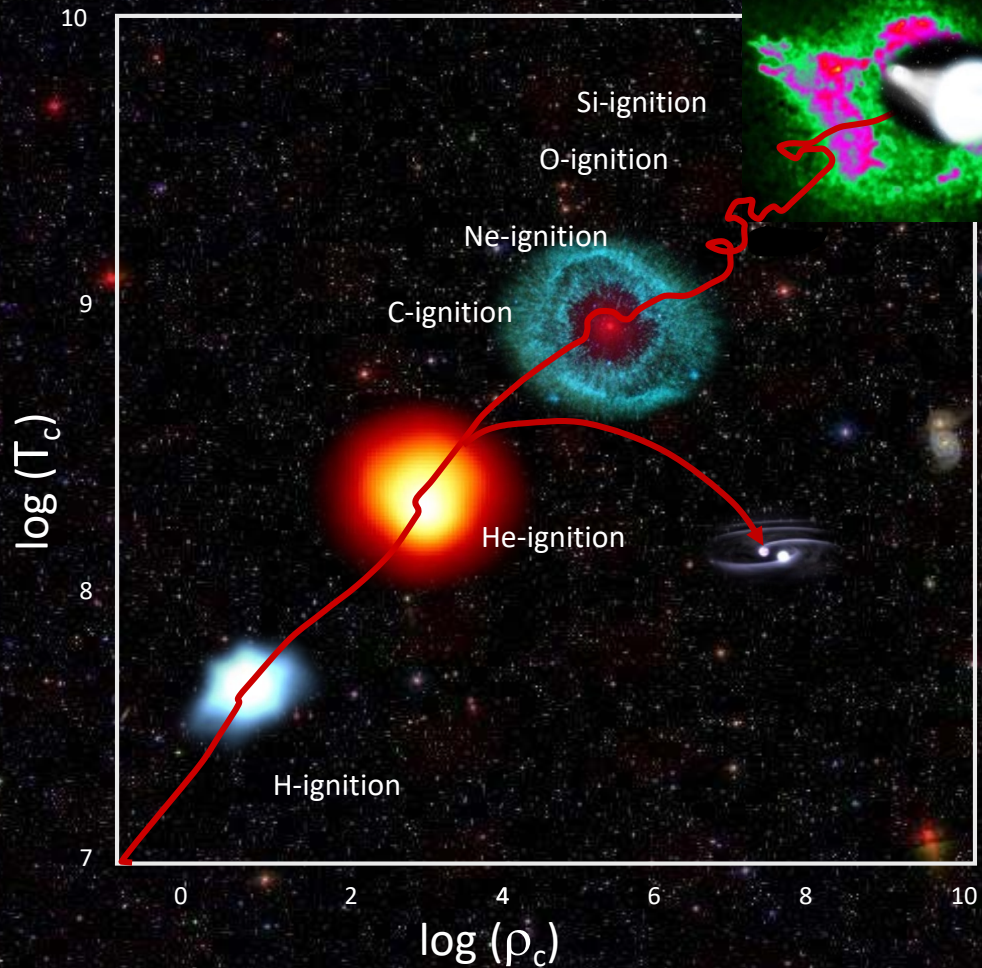
- Footprint of AGB nucleosynthesis and link to other cycles;
- 65 keV resonance direct measurement;
- Expected counting: 0.1 Counts/hour;
- Improved passive and active shielding to reduce background at about 5.6 MeV (10 cm of lead + 4 cm of B.P.) and coincidence technique;
- BGO detector;
- 400 C (1 month of continuous beam operation) and about 100 counts.

Weakest resonance ever directly measured

$$\omega\gamma = (25.5 \pm 4.2) \text{ peV}$$



Nuclear Burning in Stars



• $\Rightarrow {}^{56}\text{Fe}$ Neon, Oxygen, Silicon Burning

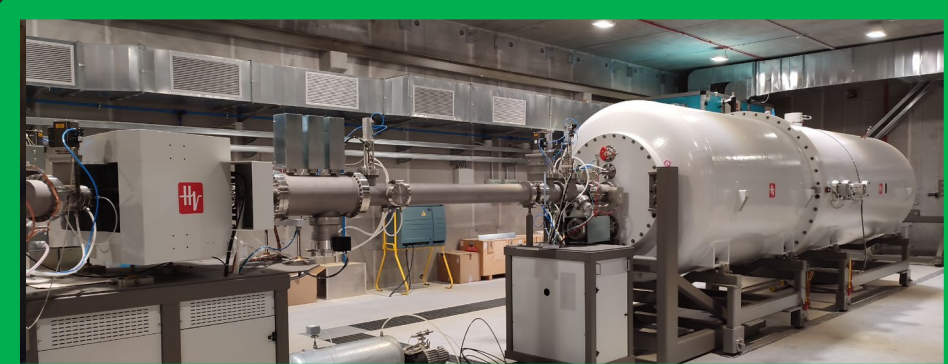
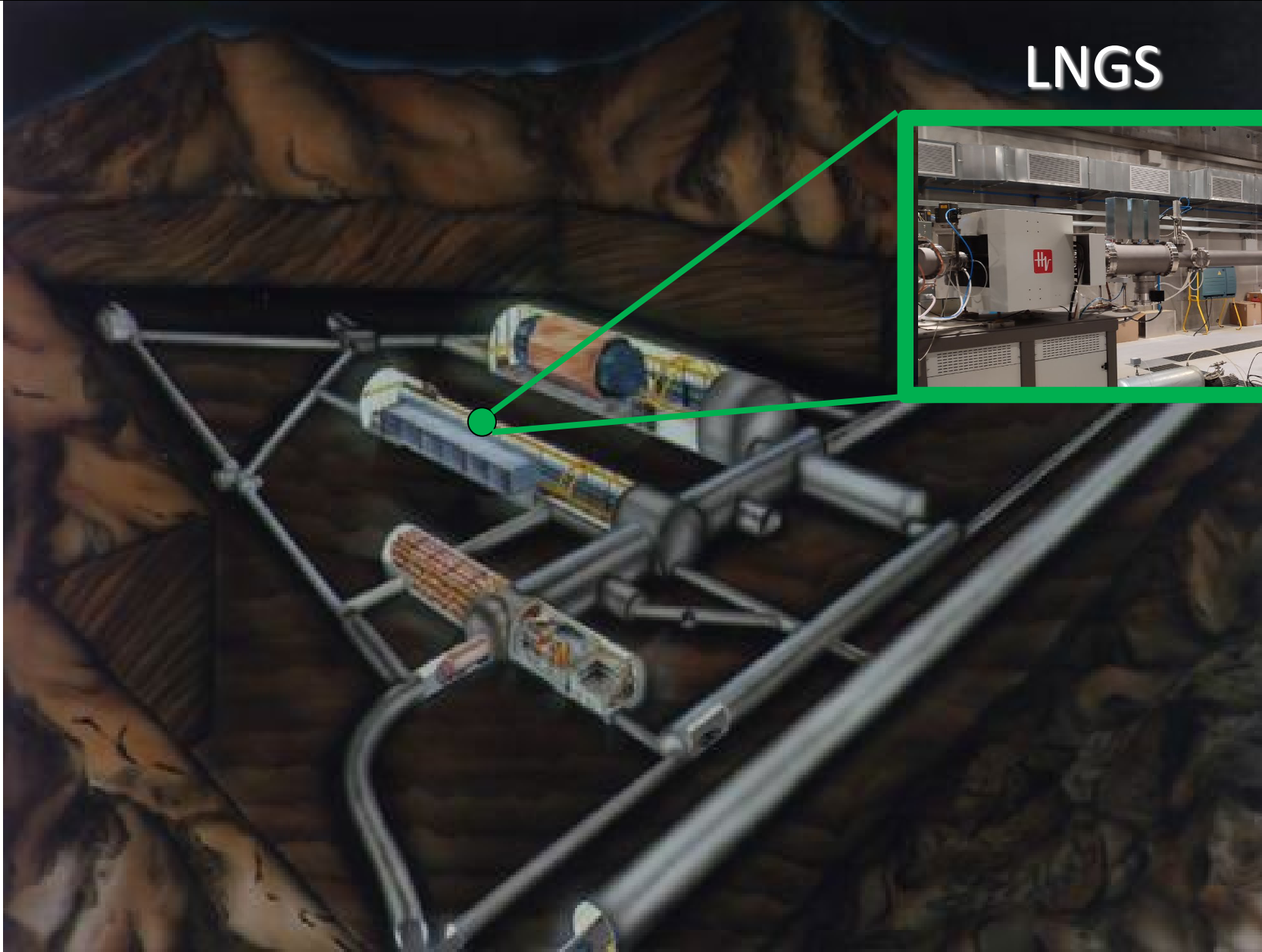
• $2 {}^{12}\text{C} \Rightarrow {}^{24}\text{Mg}$ Carbon Burning

• $3 {}^4\text{He} \Rightarrow {}^{12}\text{C} + 8\text{MeV}$ Helium Burning

• $4 {}^1\text{H} \Rightarrow {}^4\text{He} + 26\text{MeV}$ Hydrogen Burning

Status of LUNAMV project

LNGS



Status of LUNAMV project



The 3.5 MV machine

Requested beam intensities



HIGH VOLTAGE ENGINEERING EUROPA B.V.

Amsterdamseweg 63, 3812 RR Amersfoort, P.O. Box 99, 3800 AB Amersfoort, The Netherlands
Phone: +31-33-4619741. Fax +31-33-4615291. Trade register Amersfoort nr. 31014544
E-mail: info@highvolteng.com – Web: www.highvolteng.com

LNGS del INFN
G.E. n. 10674/2015

01497/A29897-05
August 26, 2015

Specifications

- Servicing interval : > 700 hrs (at max beam intensity (1000 uA))
- Annual operation capability : > 7400 hrs (at max beam intensity)
- Beam currents****
 - $^1\text{H}^+$ (TV: 0,3 – 0,5 MV) : 500 eμA (700 uA)
 - $^1\text{H}^+$ (TV: 0,5 – 3,5 MV) : 1000 eμA (1200 uA)
 - $^4\text{He}^+$ (TV: 0,3 – 0,5 MV) : 300 eμA (400 uA)
 - $^4\text{He}^+$ (TV: 0,5 – 3,5 MV) : 500 eμA (700 uA)
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 - $^{12}\text{C}^+$ (TV: 0,5 – 3,5 MV) : 150 eμA (200 uA)
 - $^{12}\text{C}^{2+}$ (TV: 0,5 – 3,5 MV) : 100 eμA (100 uA)
- X-ray radiation level***** : < 0,5 μSv/h

Acceptance tests

Test di verifica		Punteggio massimo	Punteggio raggiunto	Percentuale gruppo	Percentuale raggiunta
prestazioni di sistema e correnti di fascio	Beam currents			50%	47.1%
	Terminal voltage @ 3.5 MV, 4 h	10	10		
	12C+, 0.3 MV, 30 min	10	10		
	12C+, 1.0 MV, 30 min	10	10		
	12C+, 2.0 MV, 30 min	10	10		
	12C+, 3.5 MV, 4 h	10	6.9		
	12C++, 1.0 MV, 30 min	10	10		
	12C++, 2.0 MV, 30 min	10	10		
	12C++, 3.5 MV, 4h	10	10		
	4He+, 0.3 MV, 30 min	10	10		
	4He+, 1.0 MV, 30 min	10	10		
	4He+, 2.0 MV, 30 min	10	10		
	4He+, 3.5 MV, 4 h	10	7.9		
	1H+, 0.3 MV, 30 min	10	9.7		
	1H+, 1.0 MV, 30 min	10	10		
	1H+, 2.0 MV, 30 min	10	10		
	1H+, 3.5 MV, 4 h	10	3.8		
	System performance				
	Source ion switchover time	10	10		
	Intervention time after maximum operating time	10	10		
	Maximum operating time without tank opening	10	10		
	Yearly maximum operating time	10	10		

The 3.5 MV machine

Requested beam intensities



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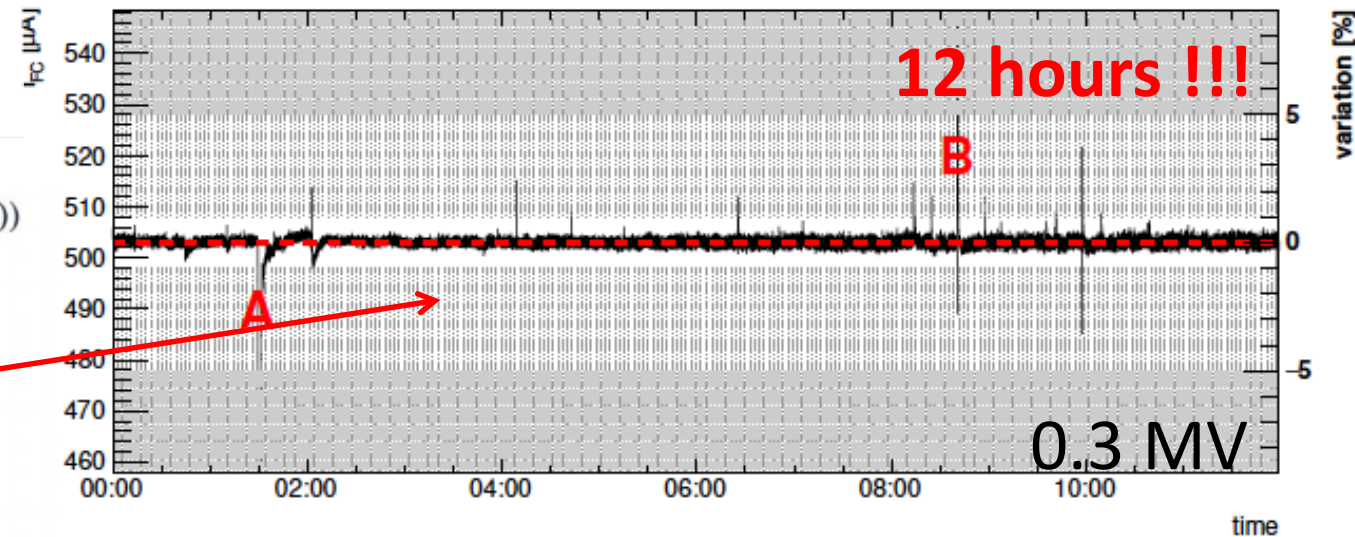
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August 26, 2015

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$^{12}\text{C}^{2+}$ (TV: 0,5 – 3,5 MV)	: 100 eμA (100 uA)
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Acceptance tests



The 3.5 MV machine

Requested beam intensities



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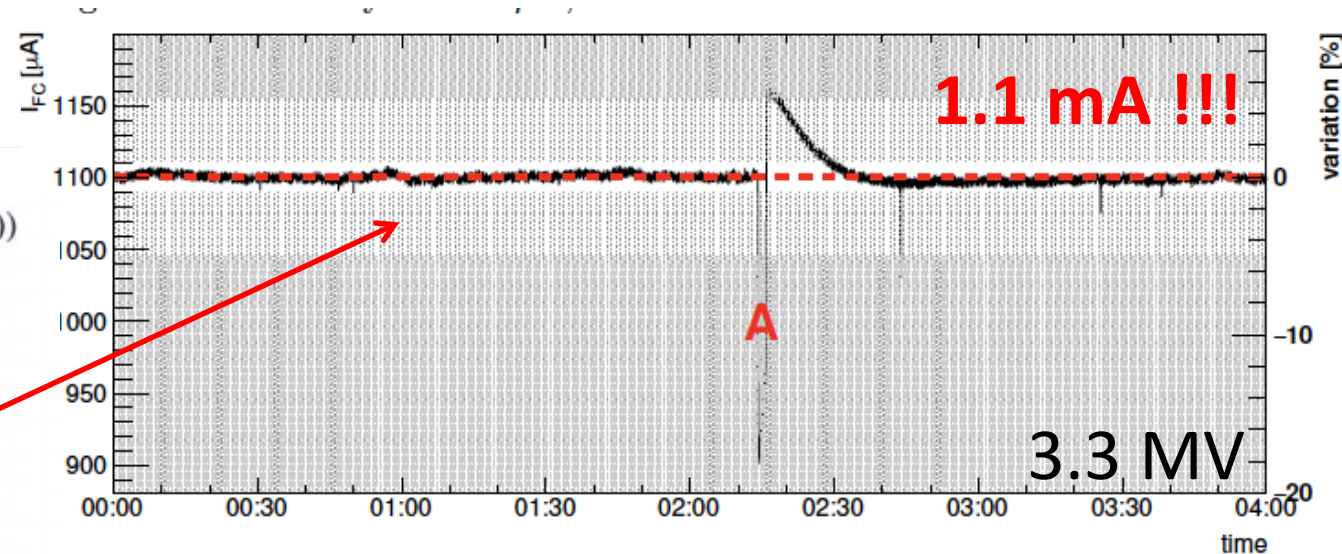
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The 3.5 MV machine

Requested beam intensities



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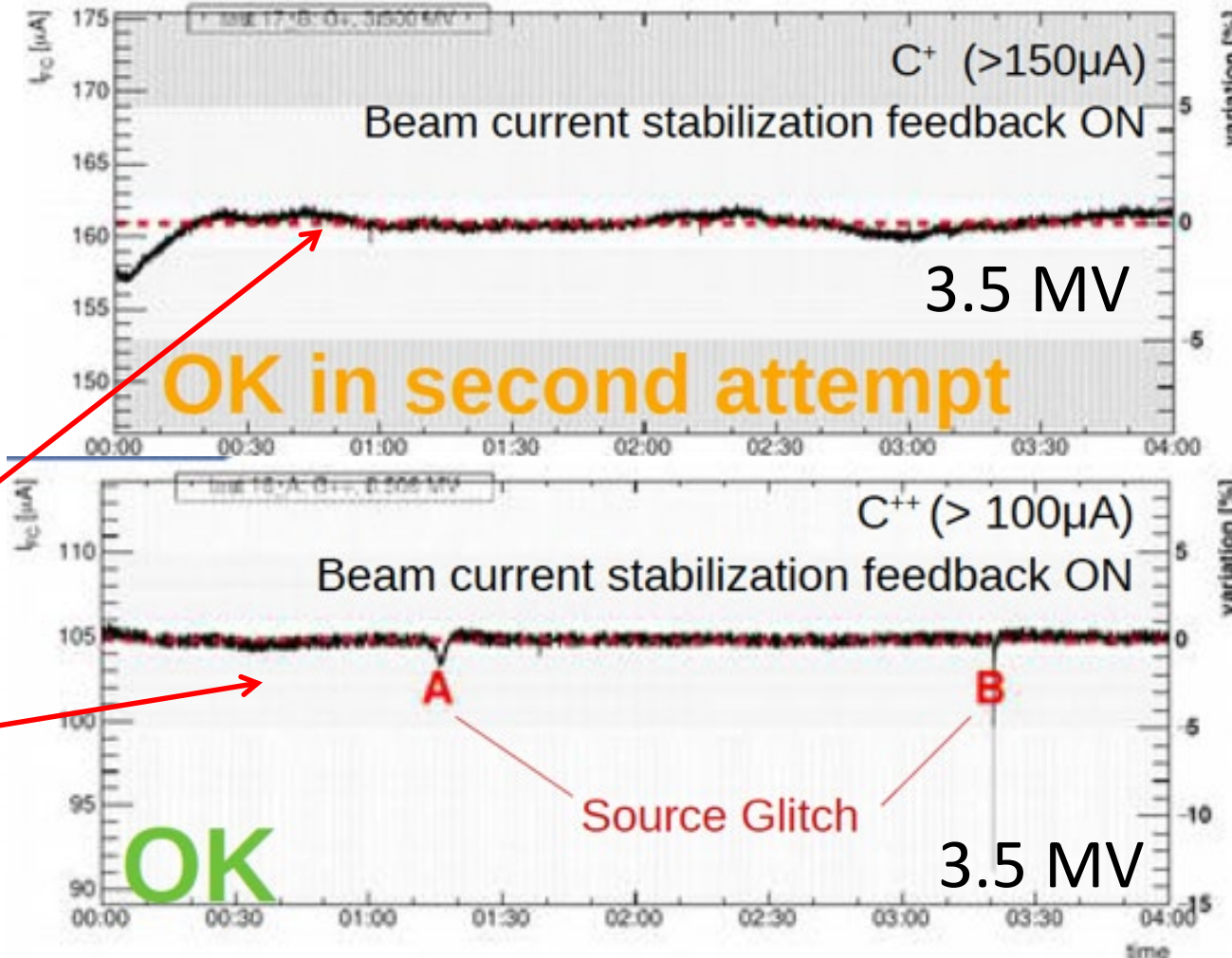
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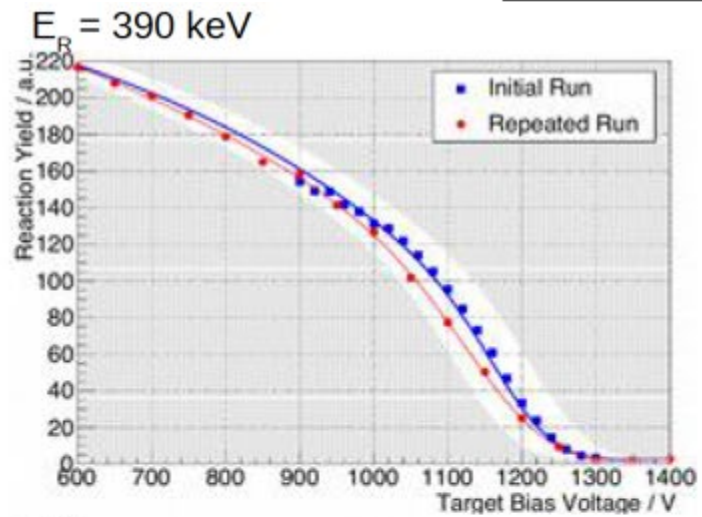
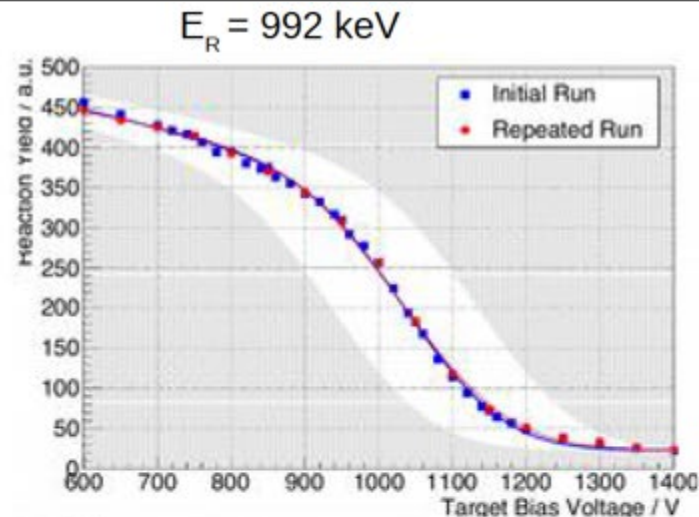
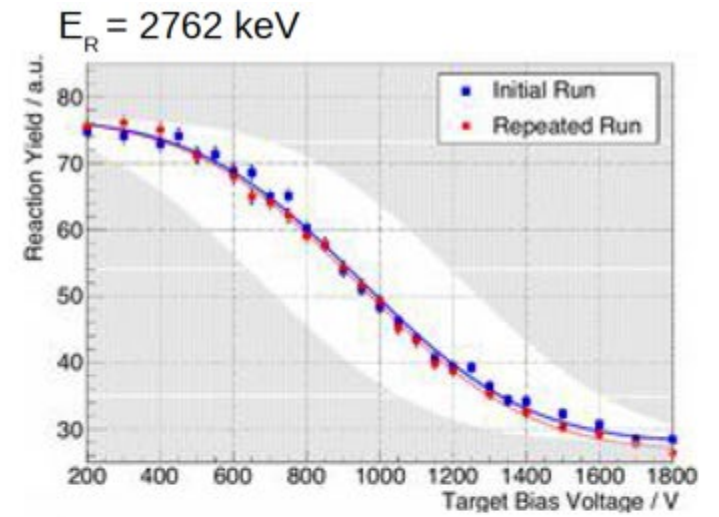
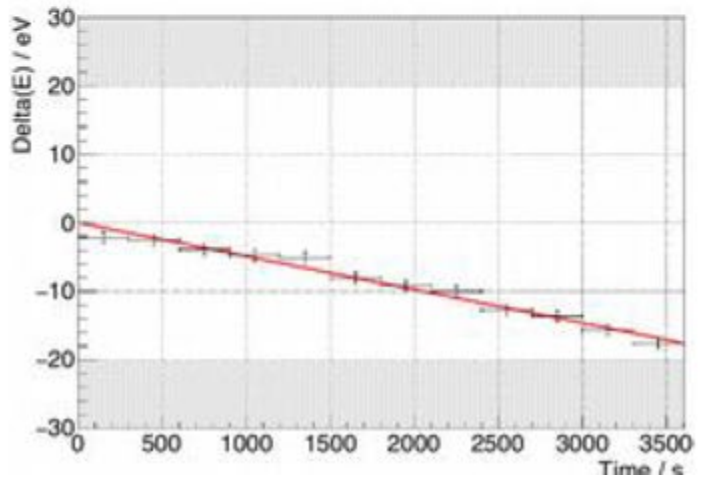
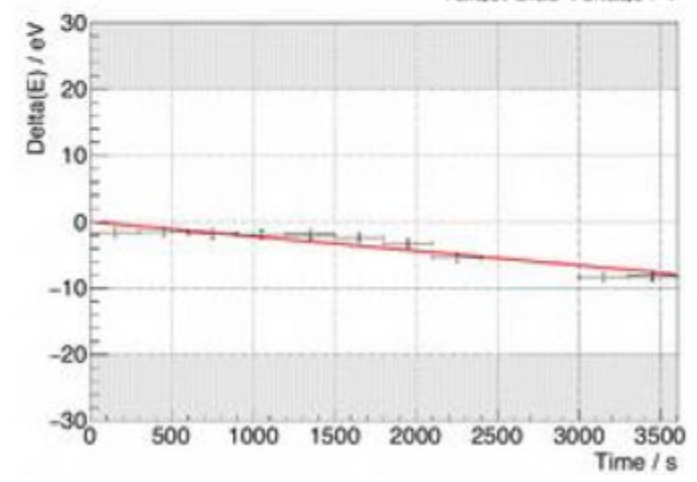
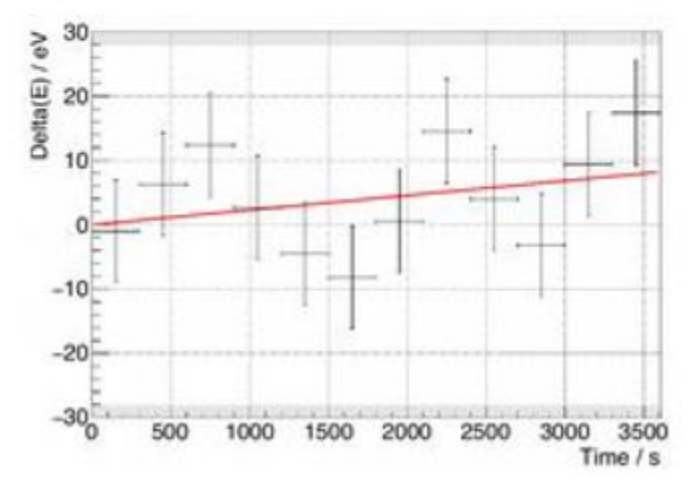
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Acceptance tests

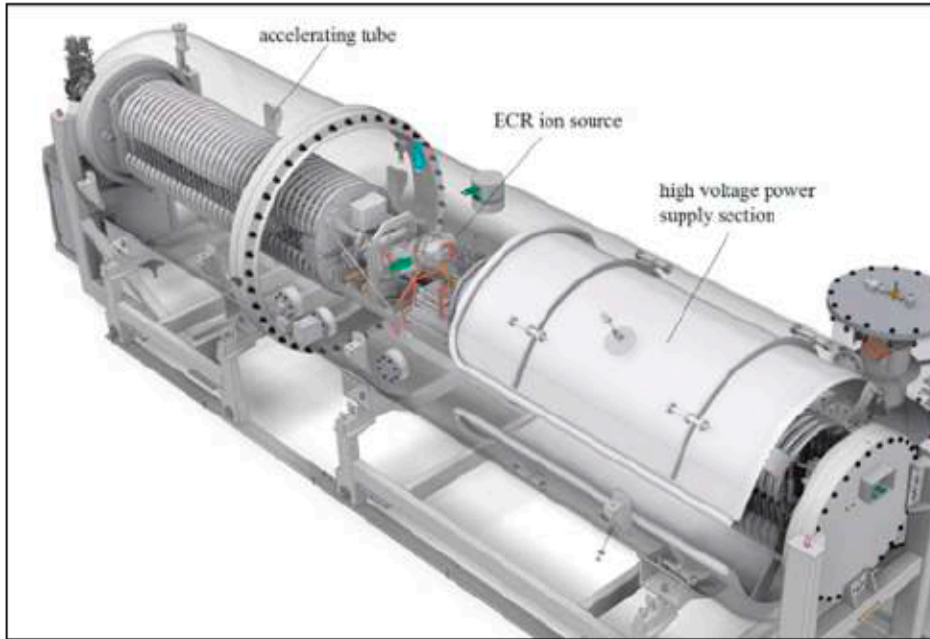


Test during FAT energy stability and spread via (p, γ) resonances

Energy [keV]	Reaction	Passing criteria [eV]/[eV/hour]
390	$^{25}\text{Mg}(p, \gamma)^{26}\text{Al}$	50 / 20
992	$^{27}\text{Al}(p, \gamma)^{28}\text{Si}$	99 / 20
2762	$^{26}\text{Mg}(p, \gamma)^{27}\text{Al}$	276 / 28



The LNGS-MV accelerator

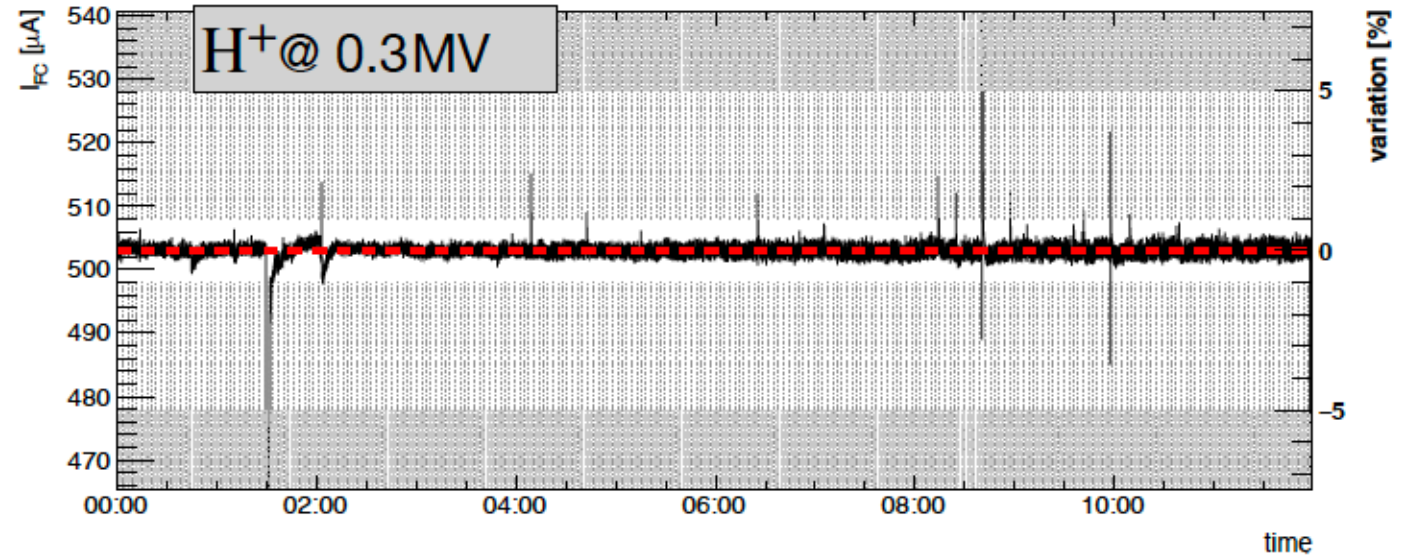
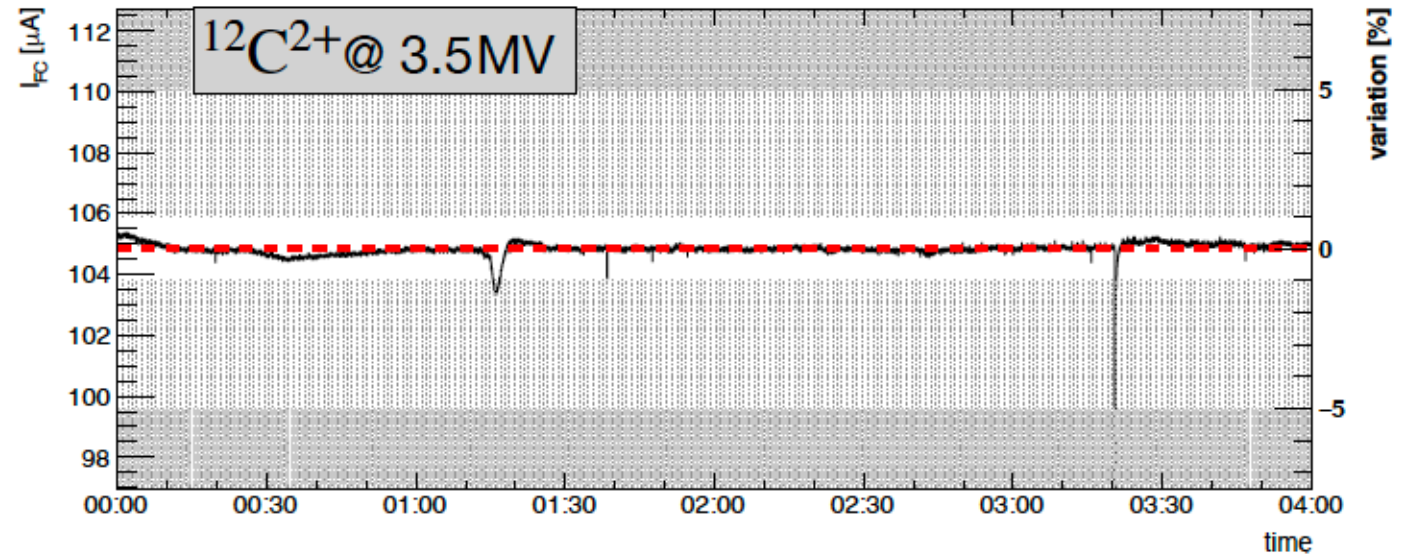


Available beams:

H, He, C⁺ and C⁺⁺

Competitors:

- JUNA, China -> 400 kV machine, available beams: H, He⁺ and He⁺⁺;
- CASPAR, USA -> 1 MV machine, available beams: H and He⁺



LNGS is still the unique place where to find an underground carbon beam!

LUNA MV first years scientific proposal

- CNO Hydrogen burning, Age of Globular Clusters and C production in AGB:

$^{14}\text{N}(p,\gamma)^{15}\text{O}$ *also for final scientific commissioning the MV accelerator*

First experiment, ready to start

- C burning:

$^{12}\text{C}+^{12}\text{C}$ fusion

Pillar processes

detections of both particles and γ -rays

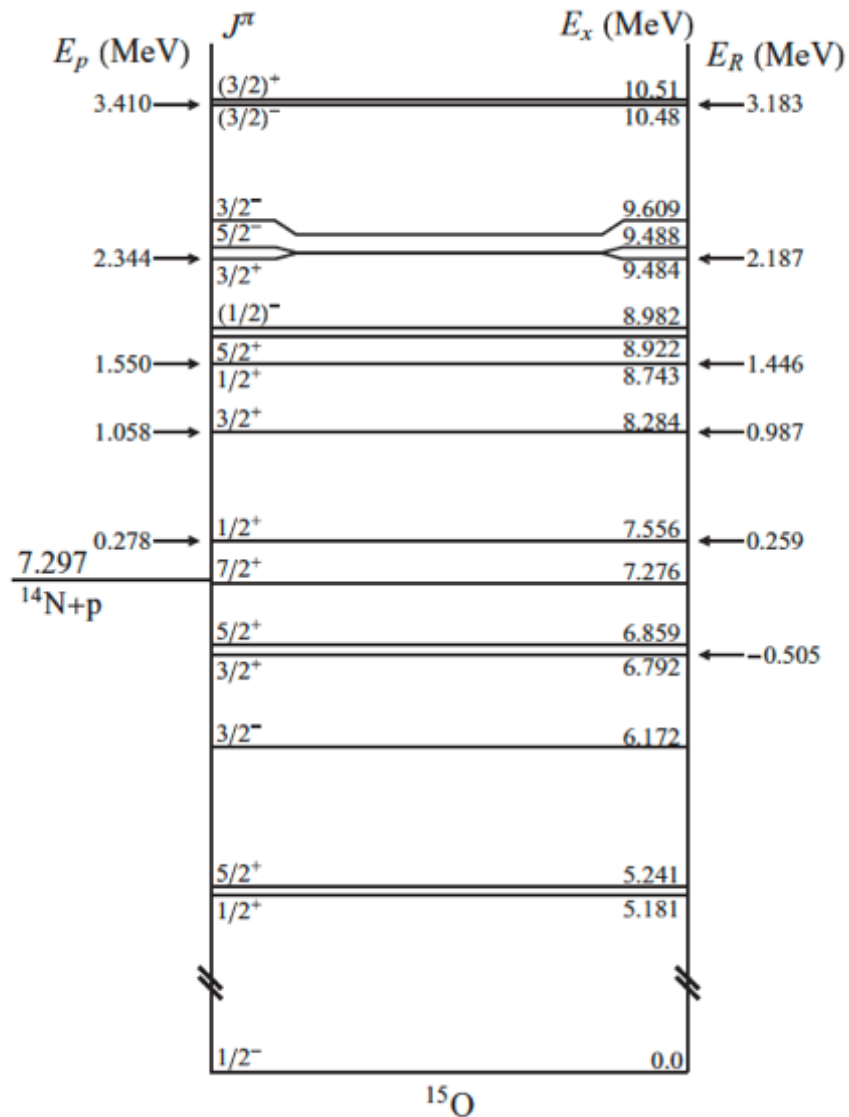
γ -experiment ready to start by spring of 2024

- Main neutron source:

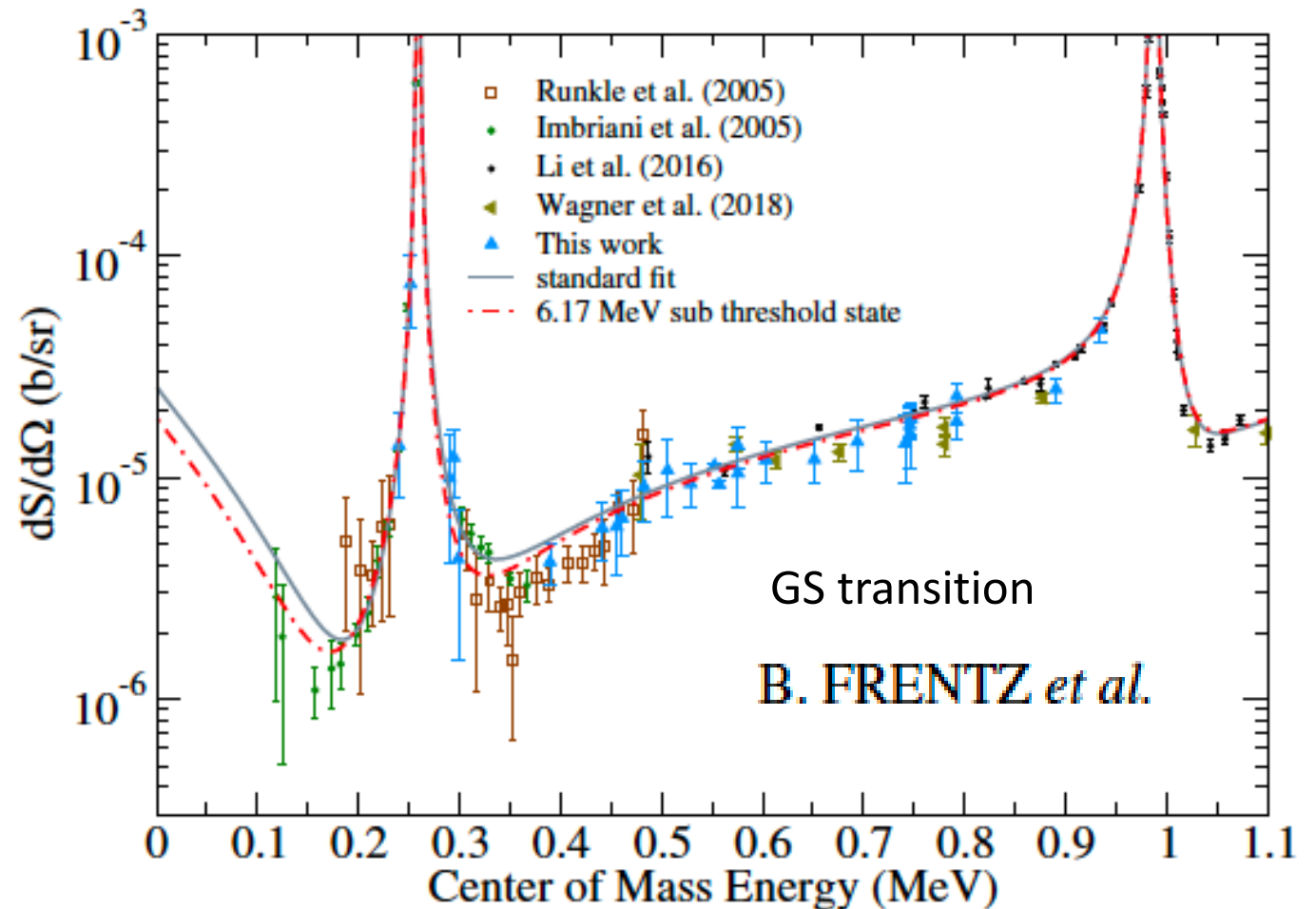
$^{22}\text{Ne}(\alpha,n)^{25}\text{Mg}$

Data taking ready to start by second half of 2023

$^{14}\text{N}(p,\gamma)^{15}\text{O}$: open issues



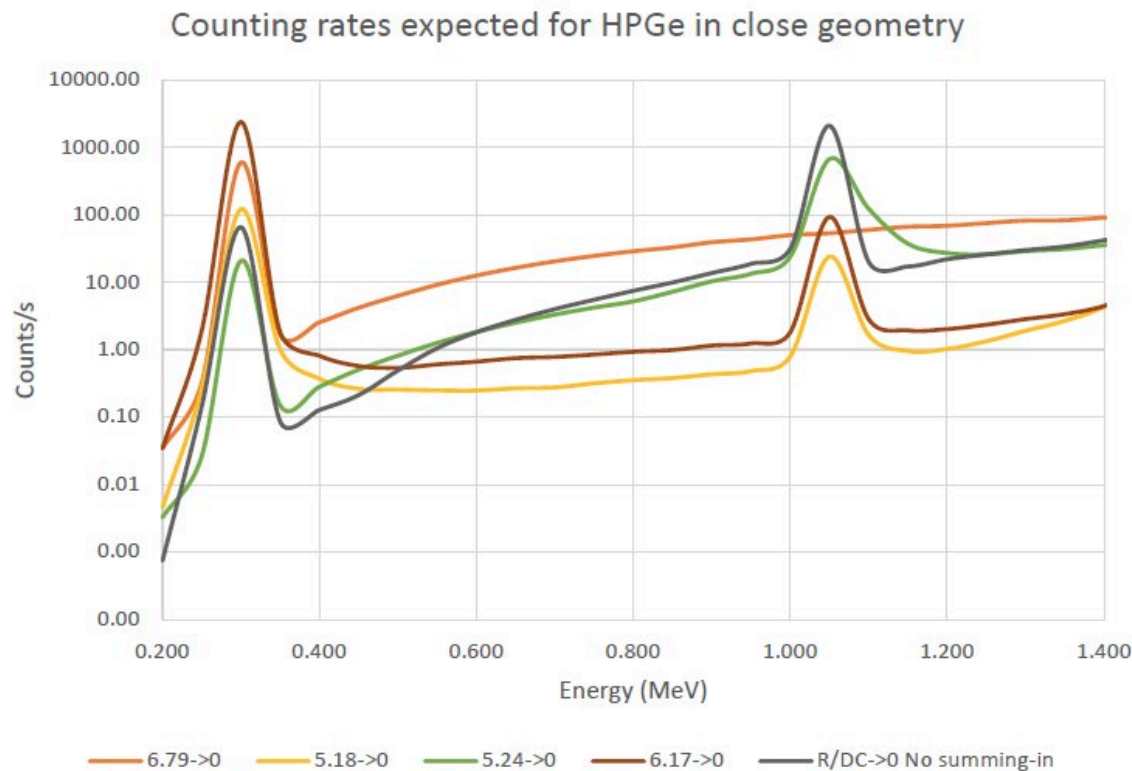
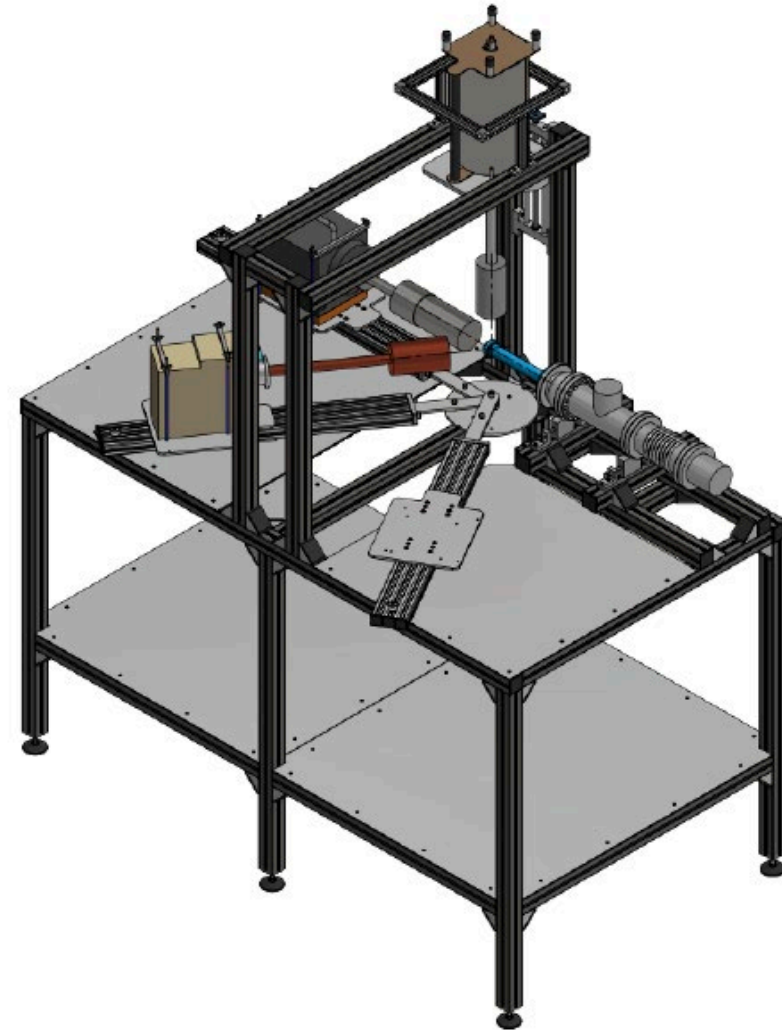
PHYSICAL REVIEW C 106, 065803 (2022)



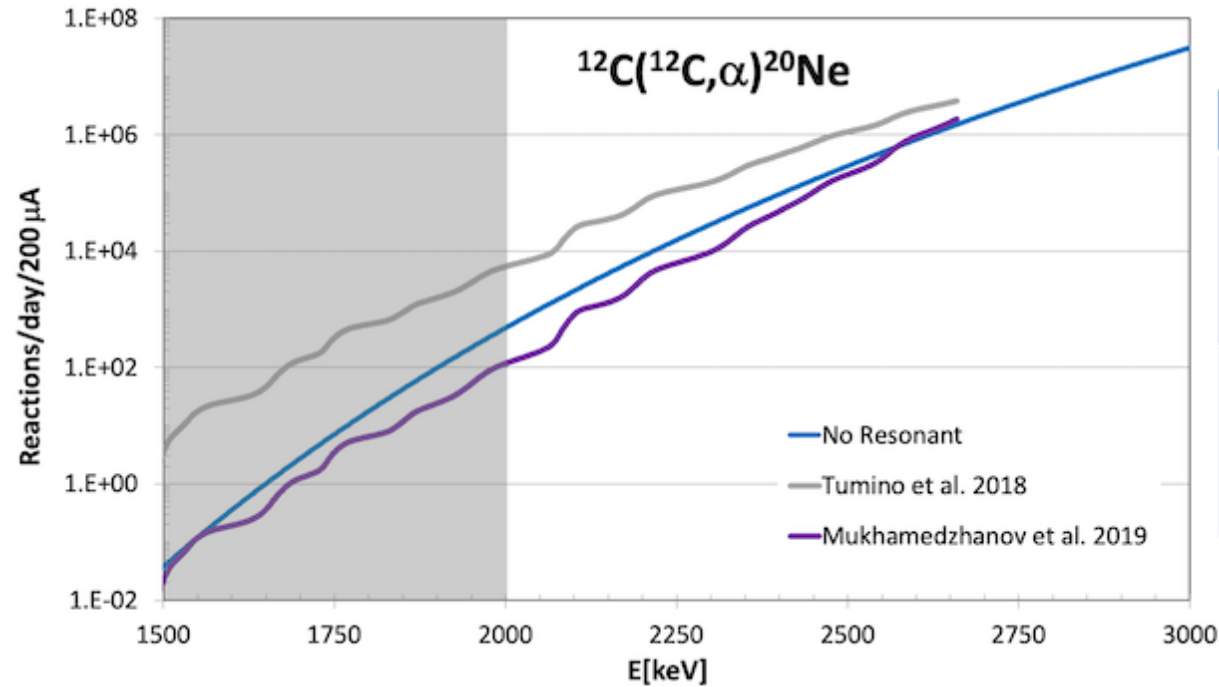
$^{14}\text{N}(p,\gamma)^{15}\text{O}$ @ LUNAMV

There is the need to cover the energy window between about 1.5 MeV down to 250 keV using the same detection setup

- 3 HPGe detectors for angular distribution measurement.

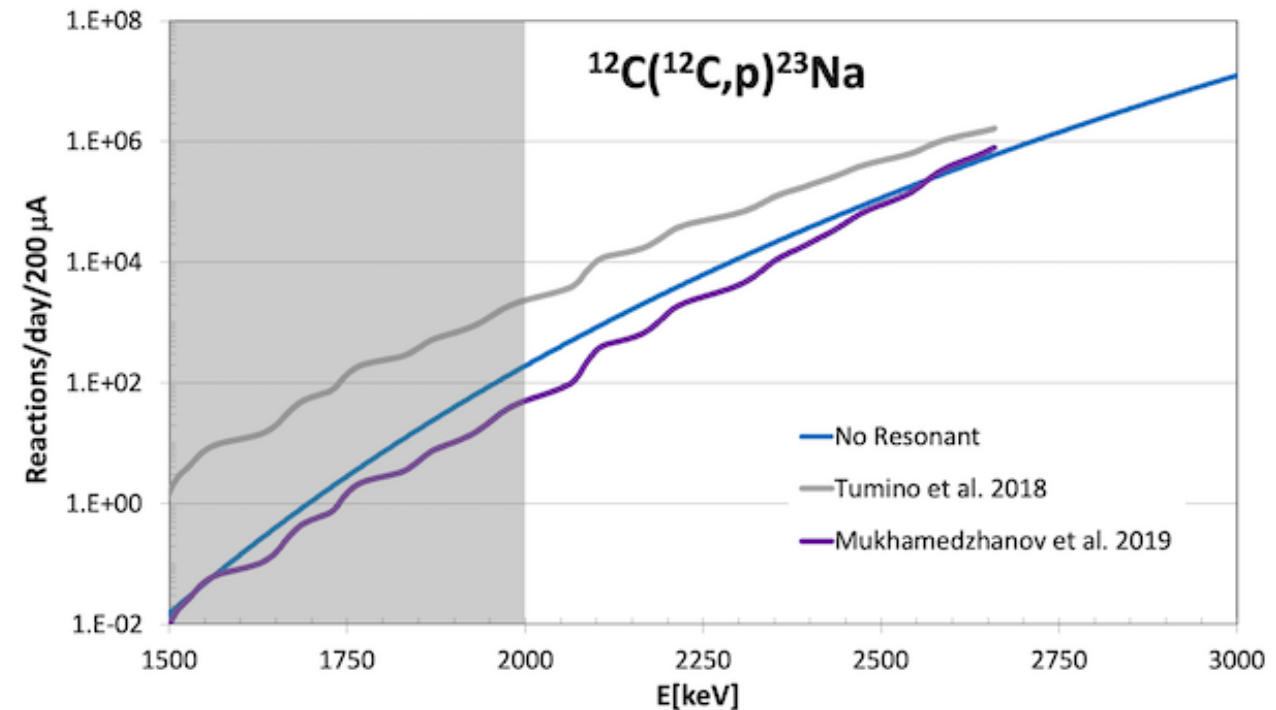


The $^{12}\text{C}+^{12}\text{C}$ expected count rate

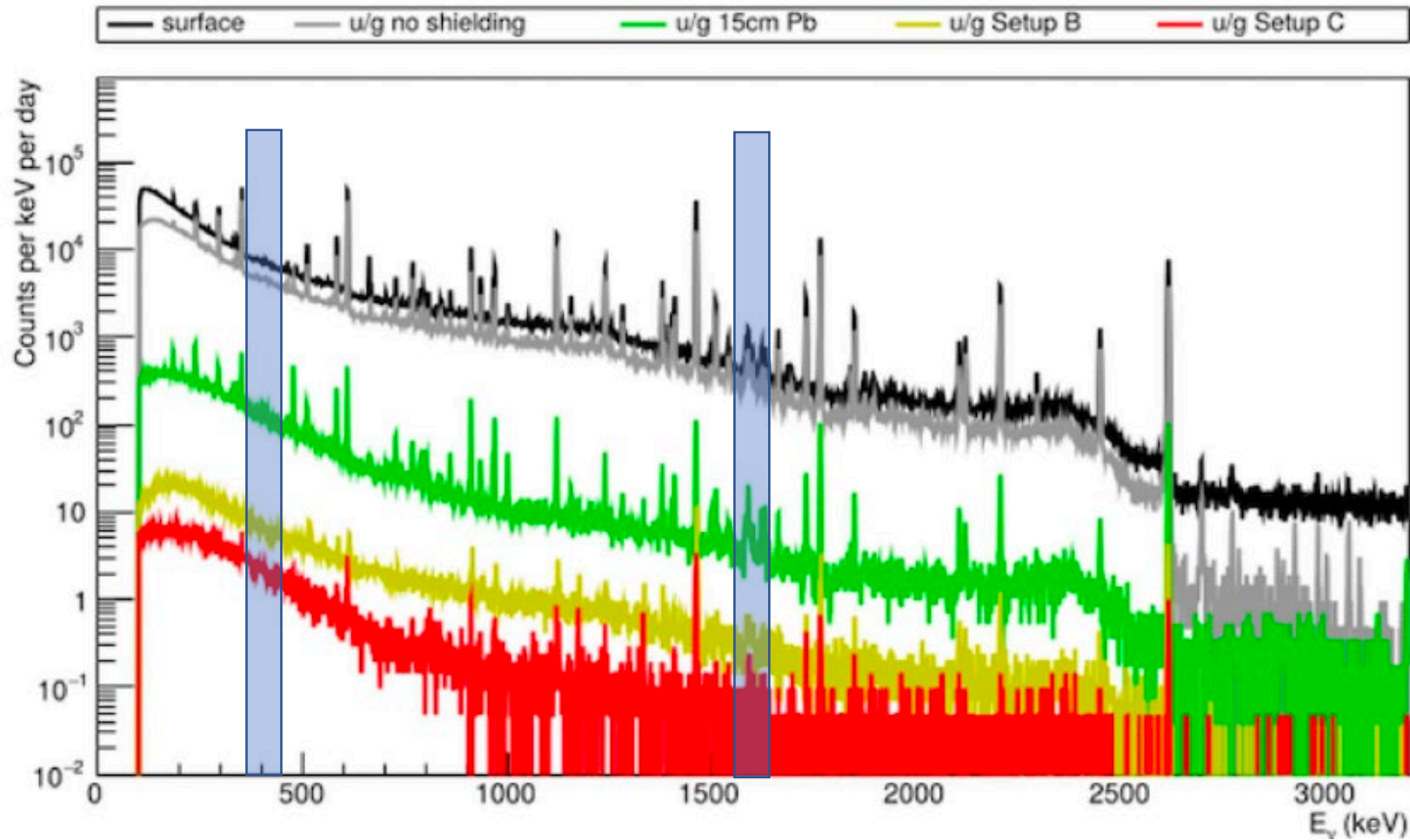


Reaction per day with 200 μA

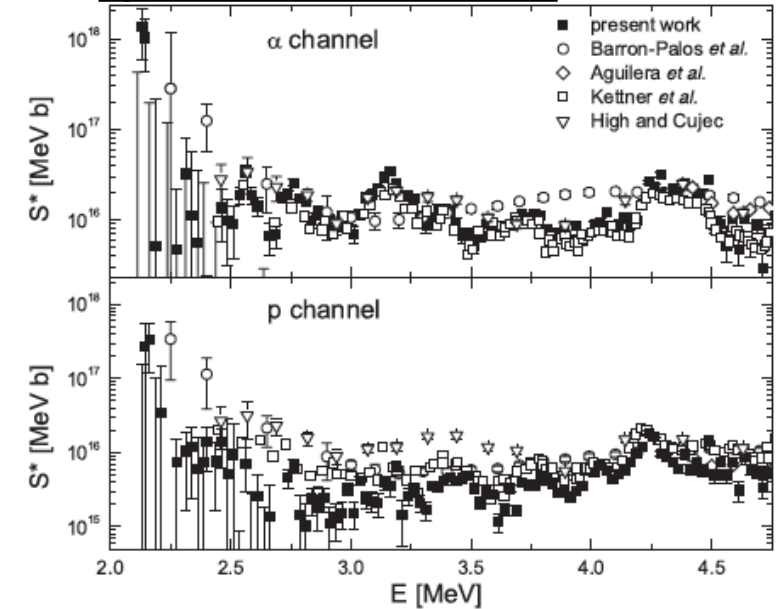
		1500 keV	1750 keV	2000 keV
α_1 (1640 keV)	Tumino 2018	3.5	350	5500
	No Resonant	0.038	7.5	525
	Mukhamedzhanov 2019	0.025	3.5	125
p_1 (440 keV)	Tumino 2018	1.5	150	2500
	No Resonant	0.02	3	200
	Mukhamedzhanov 2019	0.01	1.5	50



Underground shielding



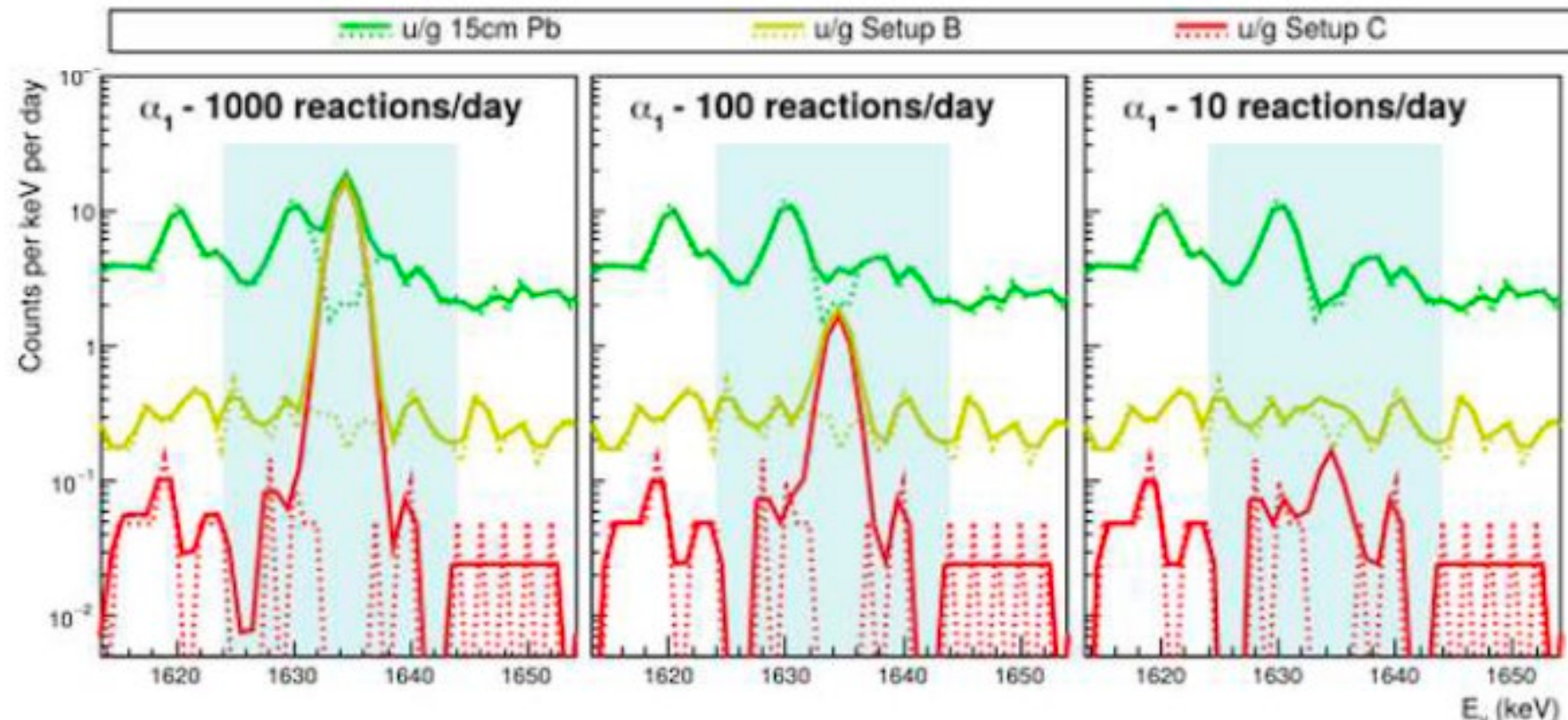
Spillane et al. PRL 2009



More than 4 OoM less background compared with Spillane et al.

Massive shielding very effective underground:
we will detect the structures below $E_{cm} = 2.5$ MeV and presence of hindrance !!!!

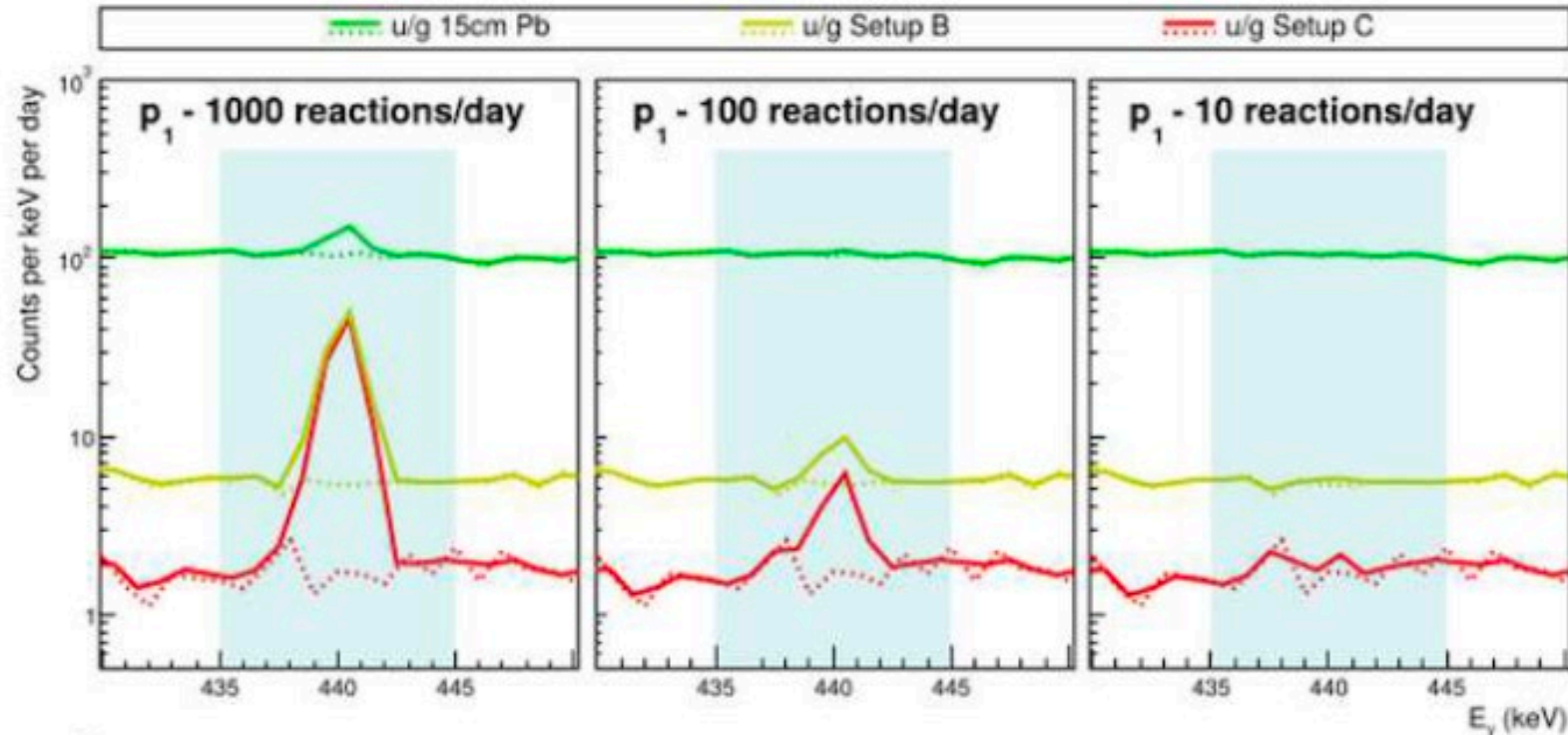
Measuring $^{12}\text{C}+^{12}\text{C}$ in laboratory: γ -rays detection @LNGS



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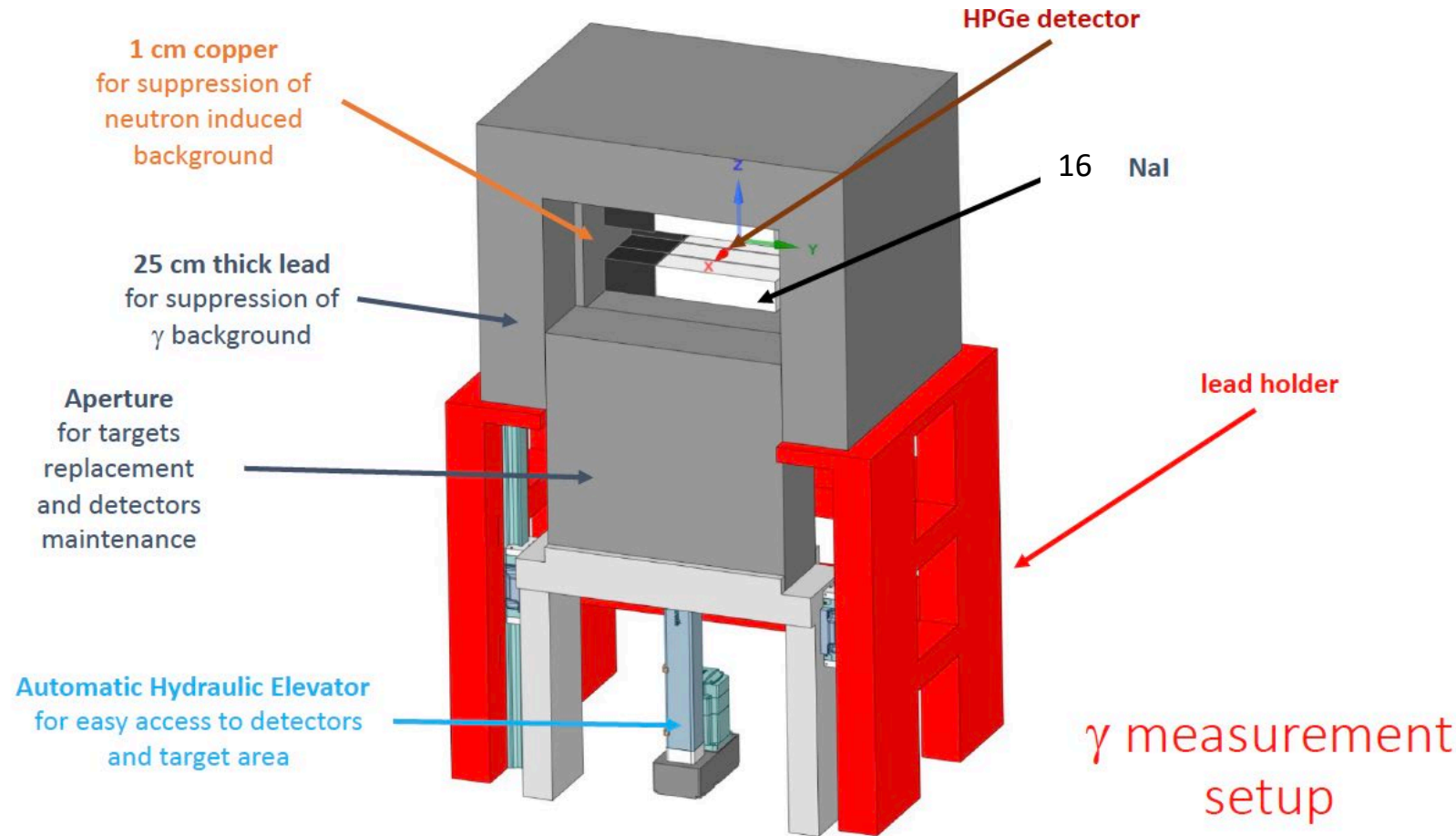


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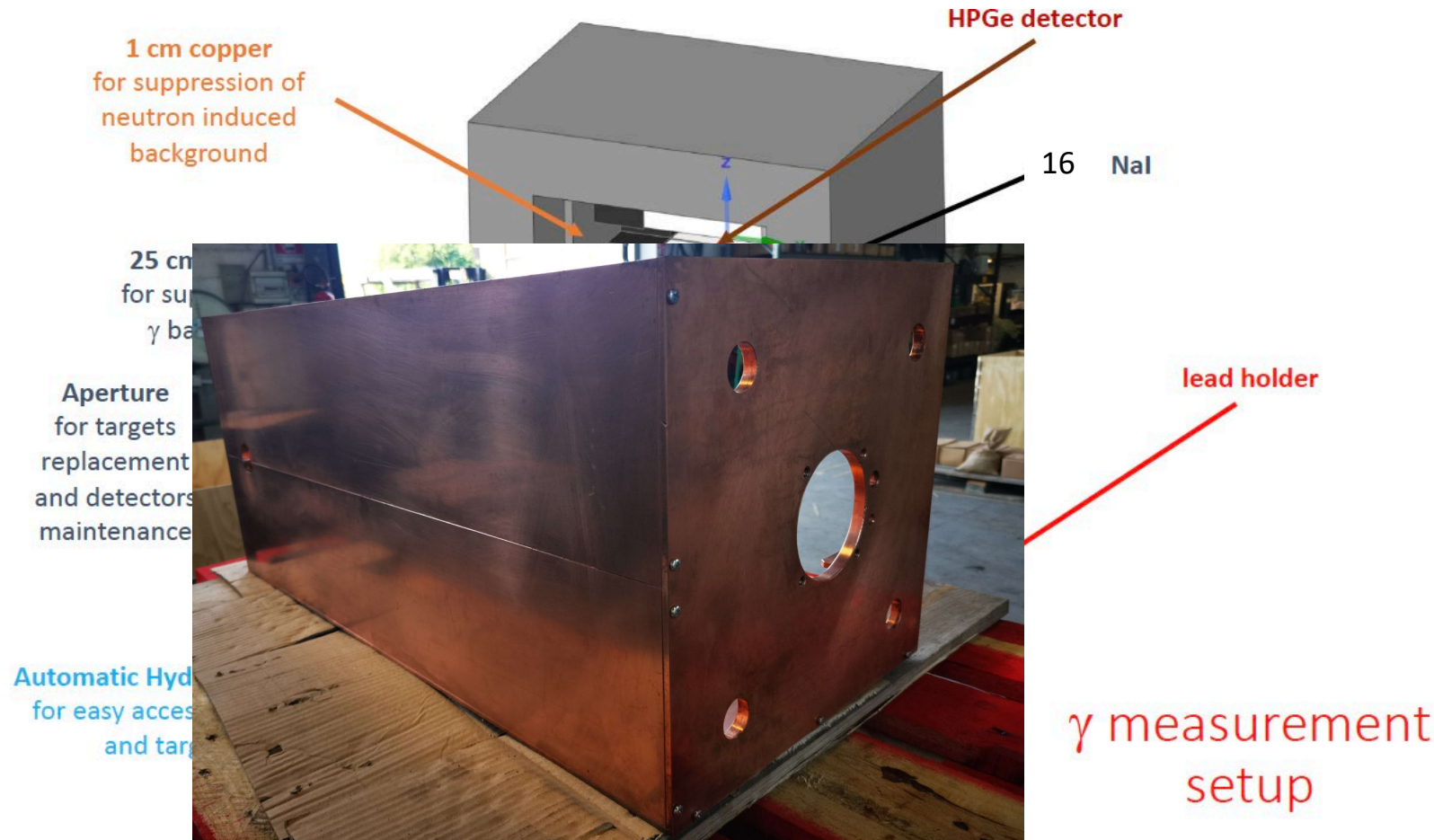
The $^{12}\text{C}+^{12}\text{C}$ setup at LUNA-MV

- 25 cm thick lead shielding, under production;
- An 150% HPGe;
- 16 NaI detector as further active shielding/anti-Compton;
- Work ongoing on targets characterization in collaboration with LNL

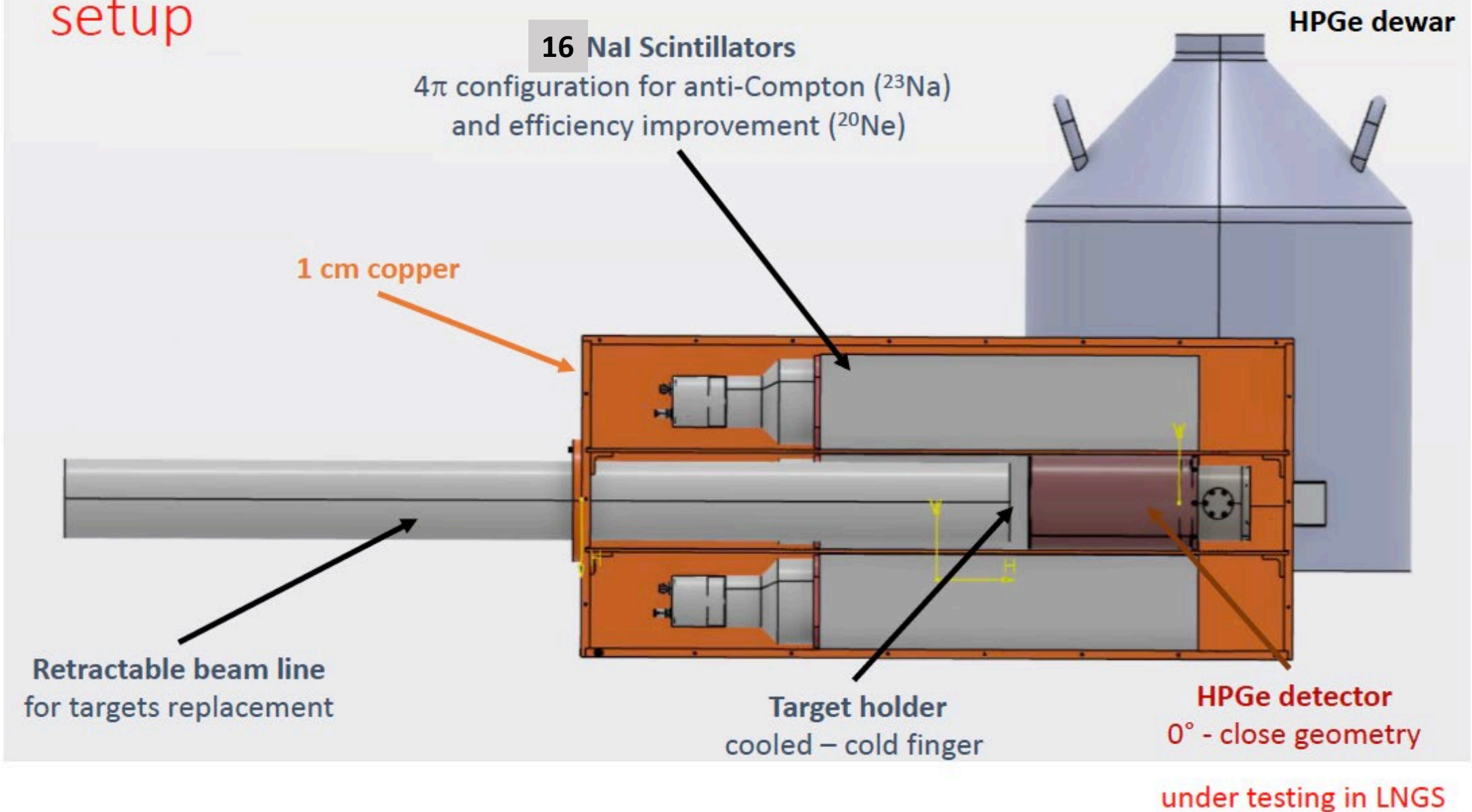


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γ measurement setup



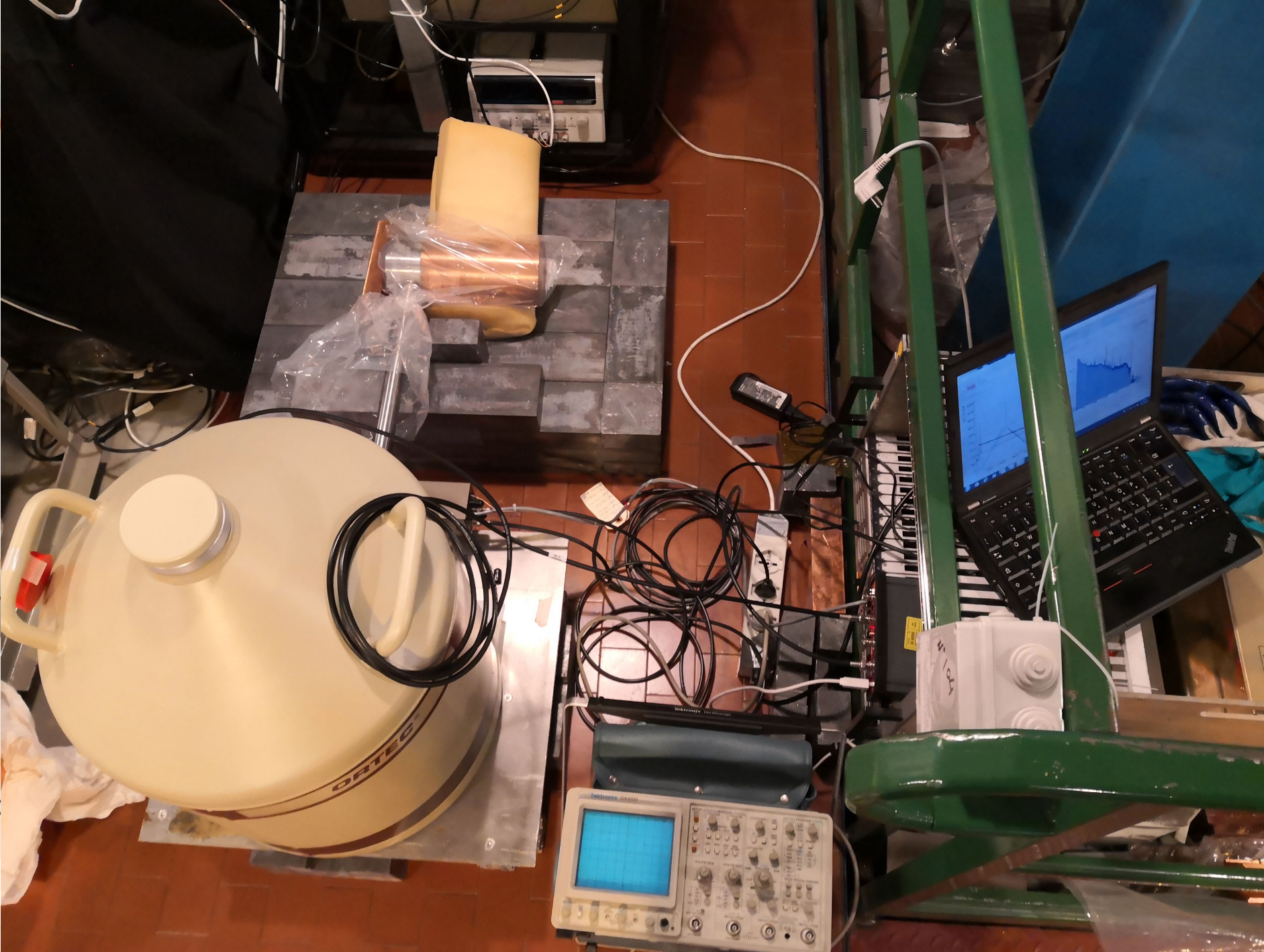
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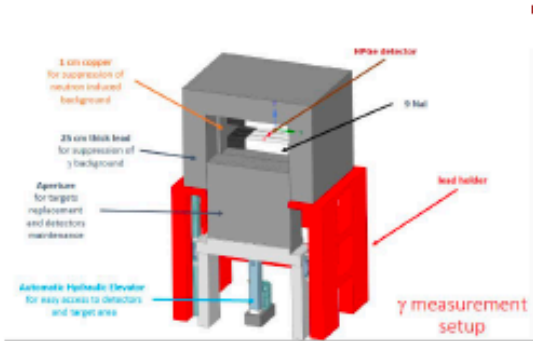
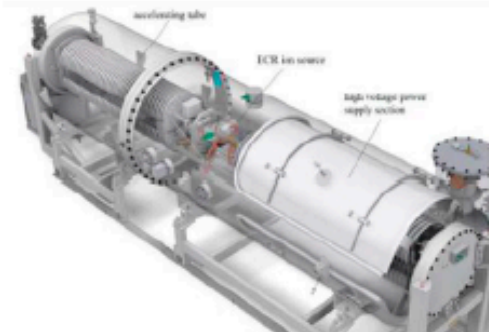
Ret
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LNGS



Expected setup efficiency and sensitivity



Minimum daily reaction rate to reach 50% statistical uncertainty, considering detection efficiency, beam current (200 pμA) and data taking time (60 days). Units: reactions/day

	$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{20}\text{Ne} + \alpha$ $E_\gamma = 1634 \text{ keV}$	$^{12}\text{C} + ^{12}\text{C} \rightarrow ^{23}\text{Na} + p$ $E_\gamma = 440 \text{ keV}$
HPGe	5	13
HPGe + anti-Compton (depending on funding)	3	10

Thank you for your attention



Few months ago...
my last visit in Edinburgh

