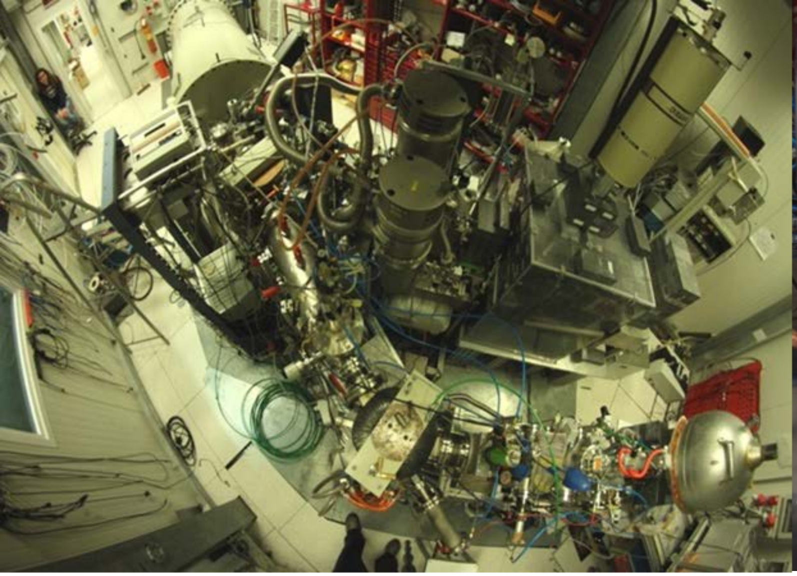
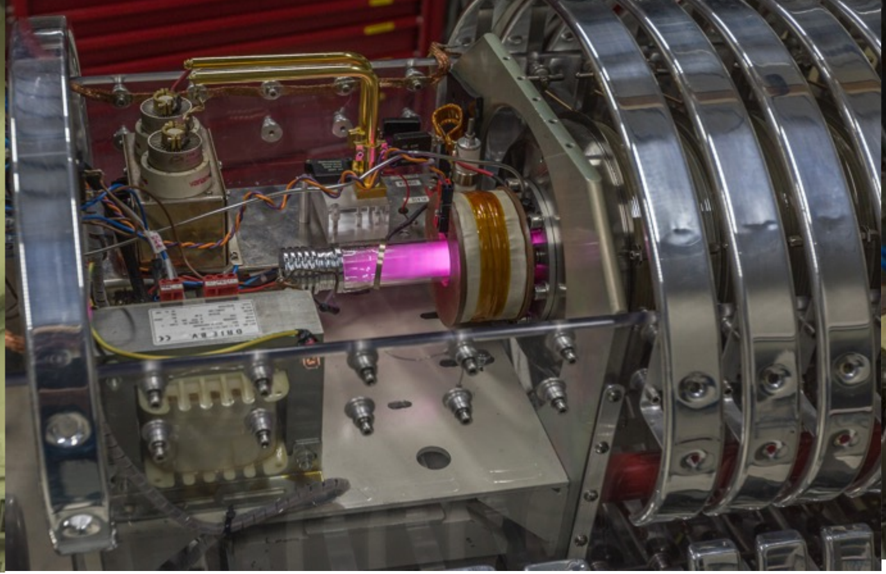
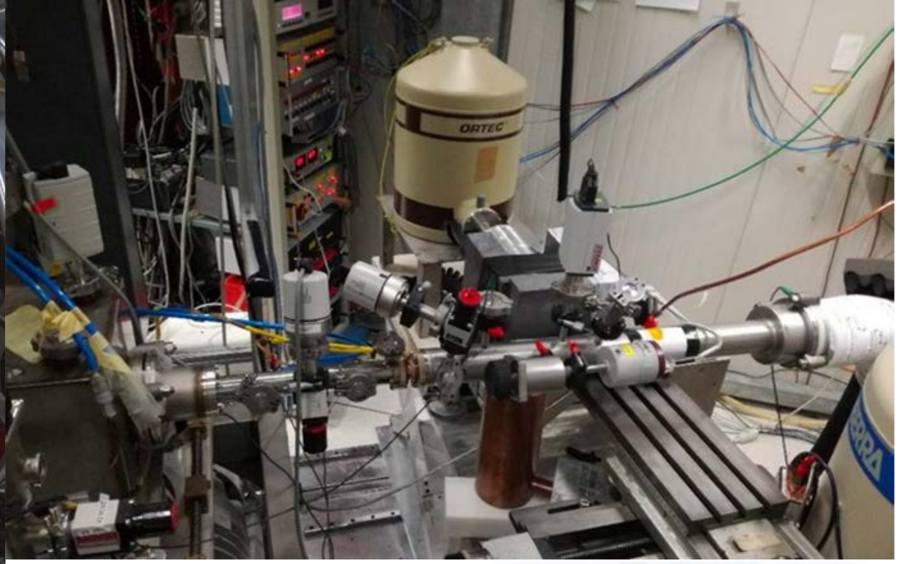

The baryon density of the Universe from an improved measurement of D(p,γ)^{3}He cross section at LUNA

Gianluca Imbriani & Gianpiero Mangano

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

LUNA
Laboratory for Underground Nuclear Astrophysics

INFN Sezione di Napoli

UNIVERSITA' DEGLI STUDI DI NAPOLI FEDERICO II

LUNA collaboration

Laboratori Nazionali del Gran Sasso, INFN, ASSERGI, Italy/*GSSI, L'AQUILA, Italy
A. Boeltzig, A. Compagnucci and M. Junker
Università degli Studi di Bari and INFN, BARI, Italy
V. Paticchio, L. Schiavulli
Università degli Studi della Campania and INFN, NAPOLI, Italy
G.F. Ciani
Università degli Studi di Genova and INFN, GENOVA, Italy
P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli
INFN Lecce, LECCE, Italy
R. Perrino
Università degli Studi di Milano and INFN, MILANO, Italy
A. Guglielmetti, E. Masha
Università degli Studi di Napoli "Federico II" and INFN, NAPOLI, Italy
A. Best, A. Di Leva, G. Imbriani, D. Rapagnani
Università degli Studi di Padova and INFN, PADOVA, Italy
C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti and J. Skowronski
INFN Roma, ROMA, Italy
C. Gustavino, A. Formicola
Osservatorio Astronomico di Collurania, TERAMO and INFN LNGS, Italy
O. Straniero
Università di Torino and INFN, TORINO, Italy
F. Cavanna, G. Gervino, P. Colombetti
Konkoly Observatory, Hungarian Academy of Sciences, BUDAPEST, Hungary
M. Lugaro
Institute of Nuclear Research (ATOMKI), DEBRECEN, Hungary
L. Csedreki, Z. Elekes, Zs. Fülöp, Gy. Gyürky, T. Szücs
Helmholtz-Zentrum Dresden-Rossendorf, DRESDEN, Germany
D. Bemmerer, K. Stöckel, M. Takács
University of Edinburgh, EDINBURGH, United Kingdom
M. Aliotta, C.G. Bruno, T. Chillery, T. Davinson

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p+D Working Group
Francesca Cavanna (WG leader)
Daniel Bemmerer
Antonio Caciolli
Piero Corvisiero
Federico Ferraro
Carlo Gustavino
Viviana Mossa
Vincenzo Paticchio
Klaus Stöckel
Sandra Zavatarelli

garian Academy of Sciences,
ch (ATOMKI), DEBRECEN,
löp, Gy. Gyürky, T. Szücs
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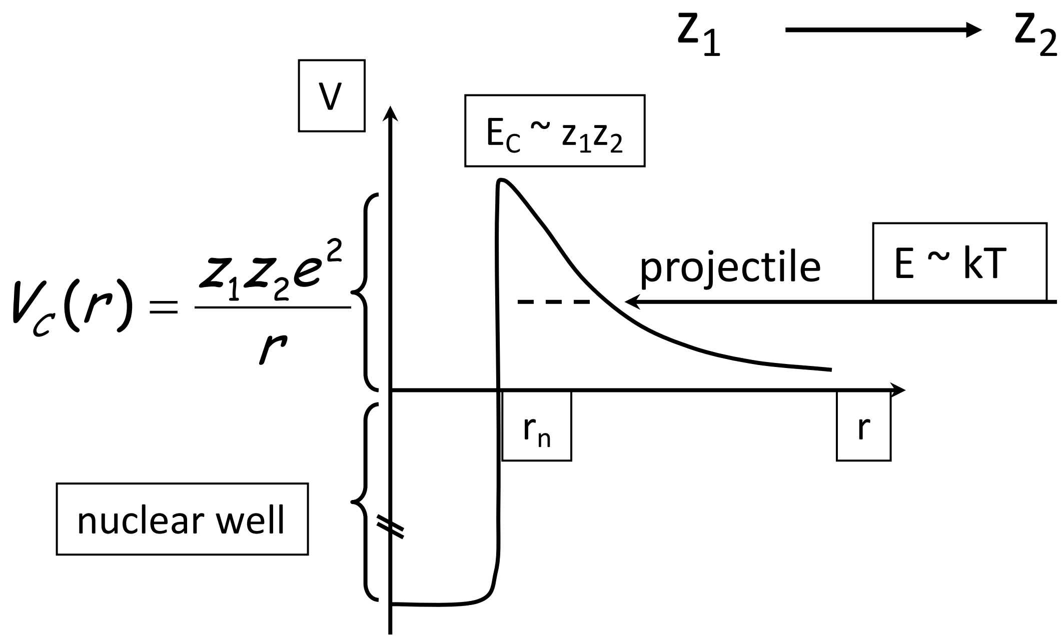
Napoli January 2020

Charged particle reactions in the cosmos and stars

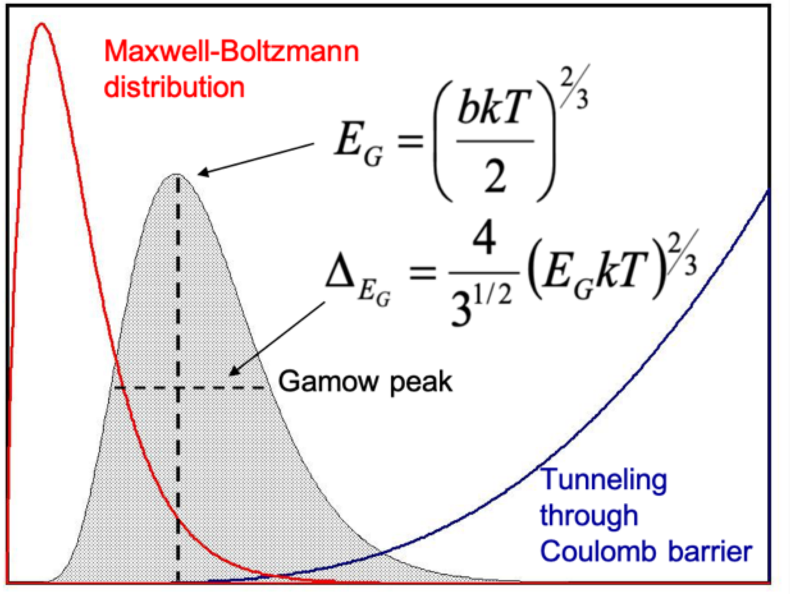


$$\sigma(E) = \frac{S(E)}{E} \exp(-2\pi\eta) \qquad \eta = \frac{Z_1 Z_2 e^2}{\hbar v}$$

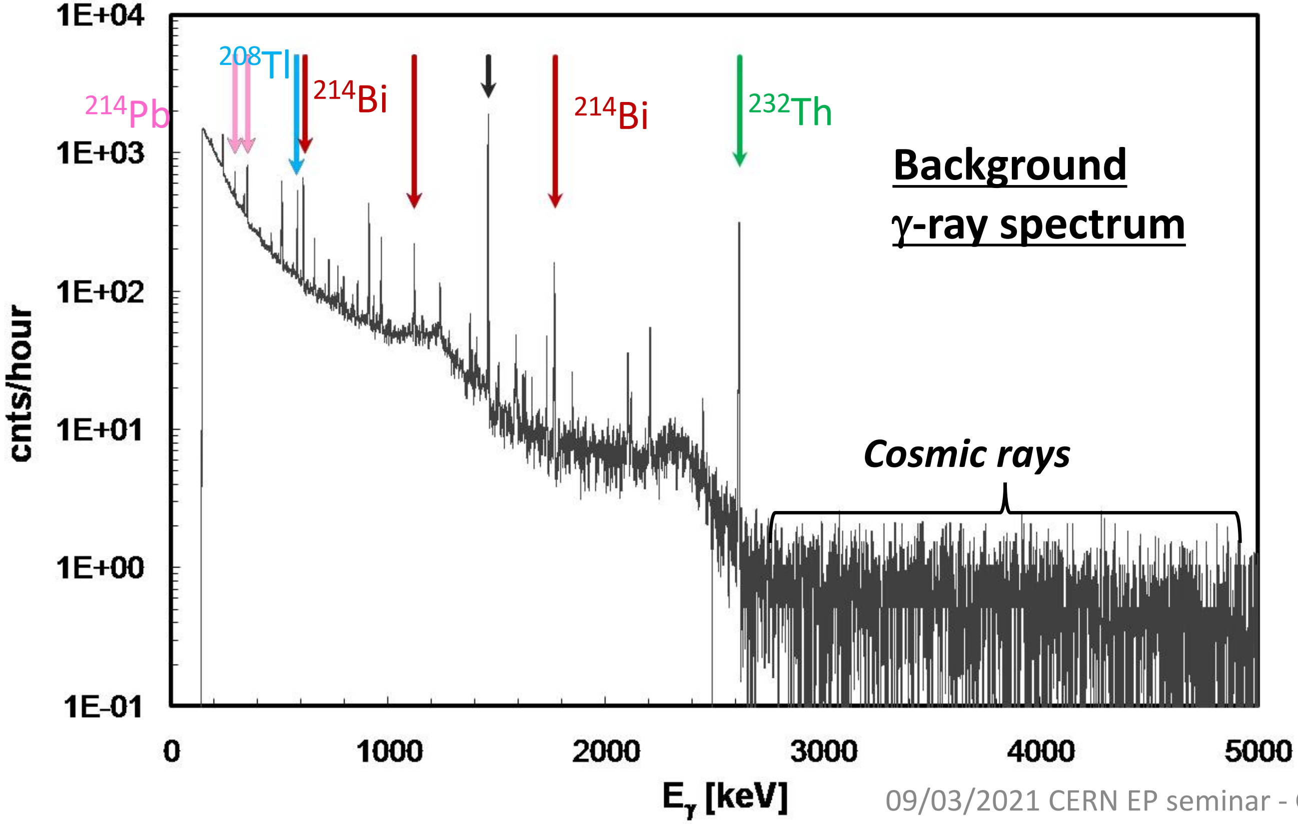
S(E) = Astrophysical Factor

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

	T [T9]	E_G (keV)
p+D	5	300
	1	100
	0.1	23



Experimental Challenges of Direct Measurement



Counting Rate = N_p x N_t x cross section x detection efficiency

10^{14} pps (~ 50 μA q=1+)

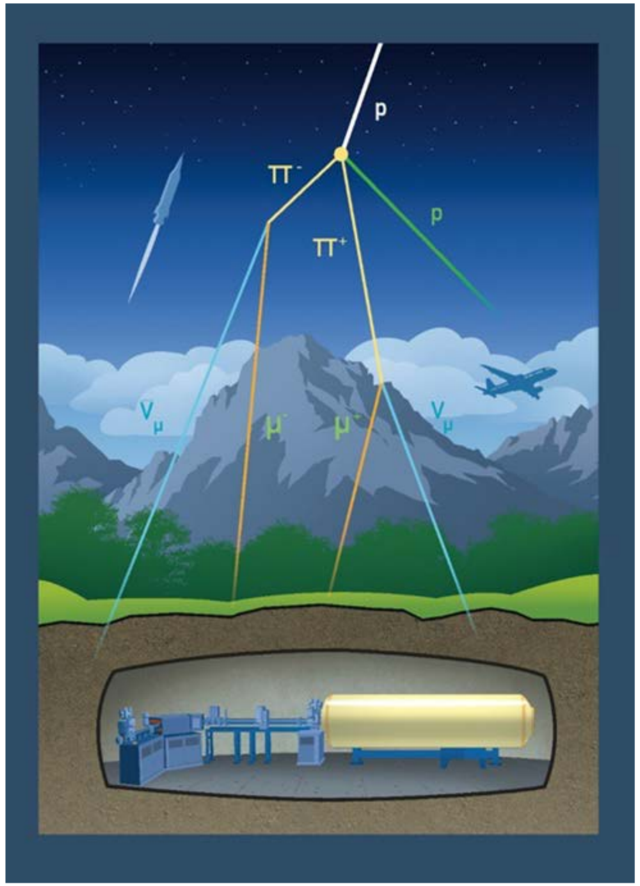
~ 10^{17} atoms/cm^2 gas target density

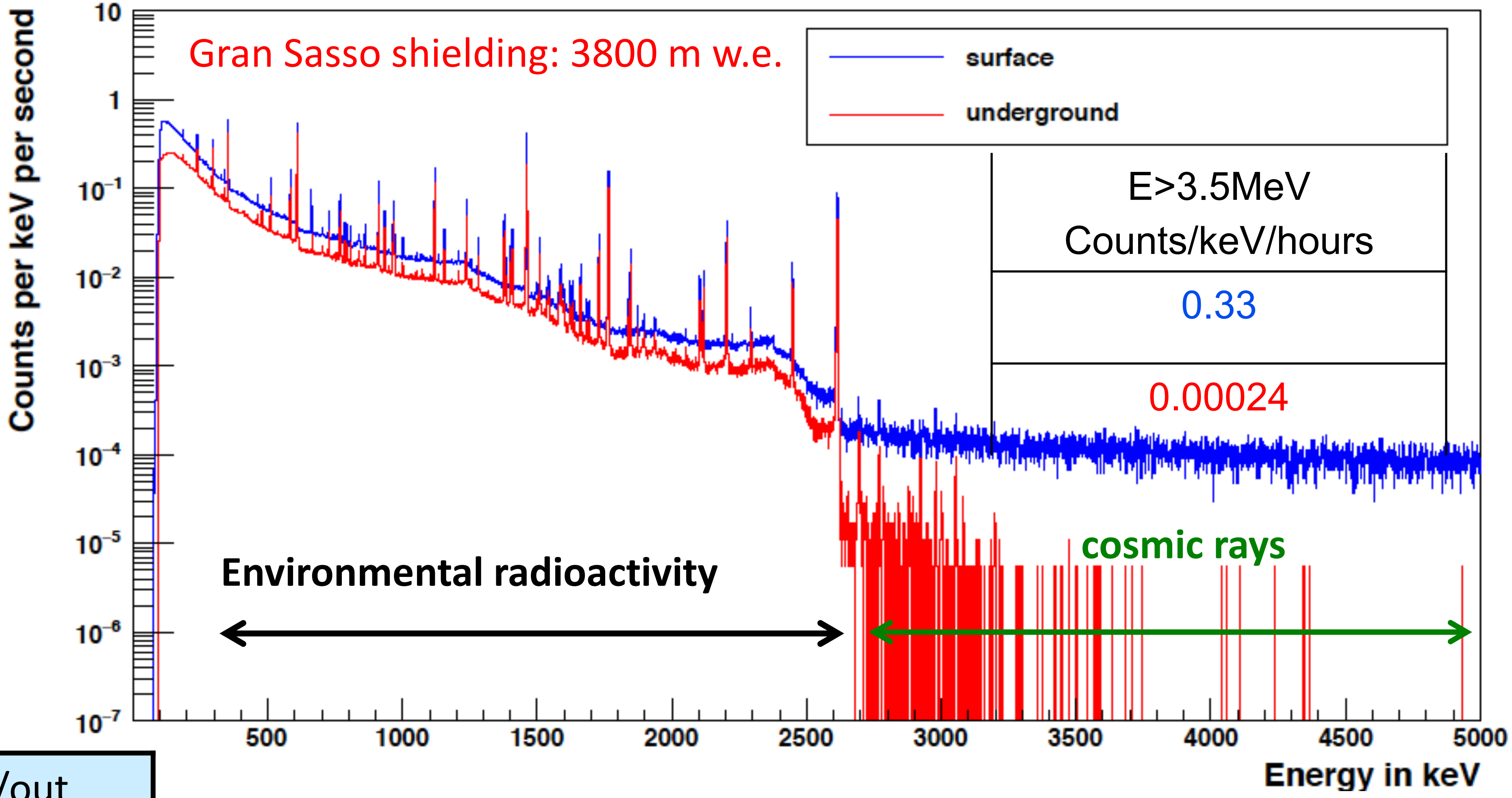
~ 10^{-32} cm^2

~ 0.1 % for high energy γ rays (HPGe detectors)

C ~ 0.3 counts/hour

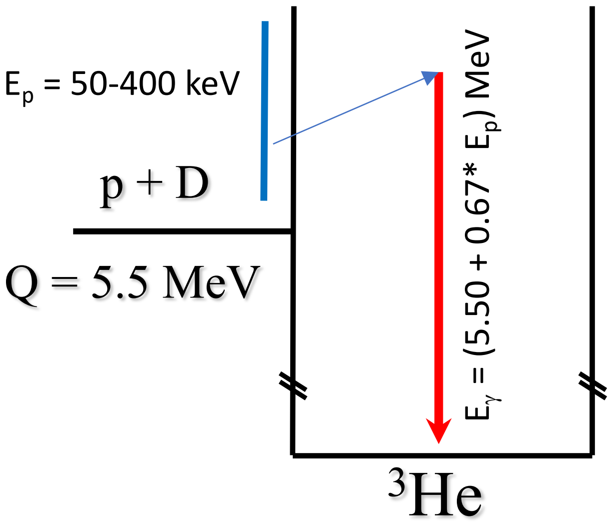
Why going underground: γ-background



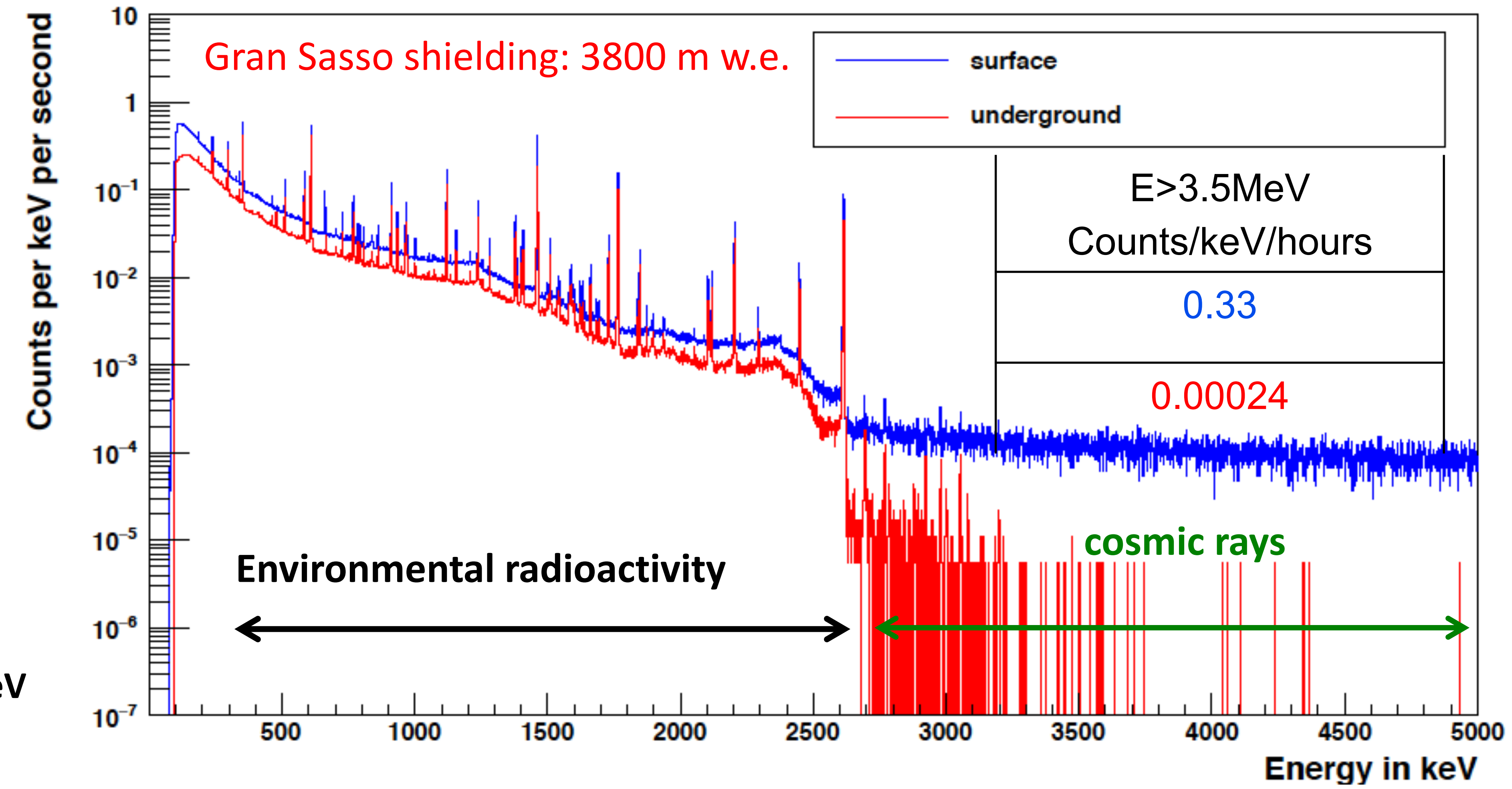


Radiation	LNGS/out
muons	10^{-6}
neutrons	10^{-3}

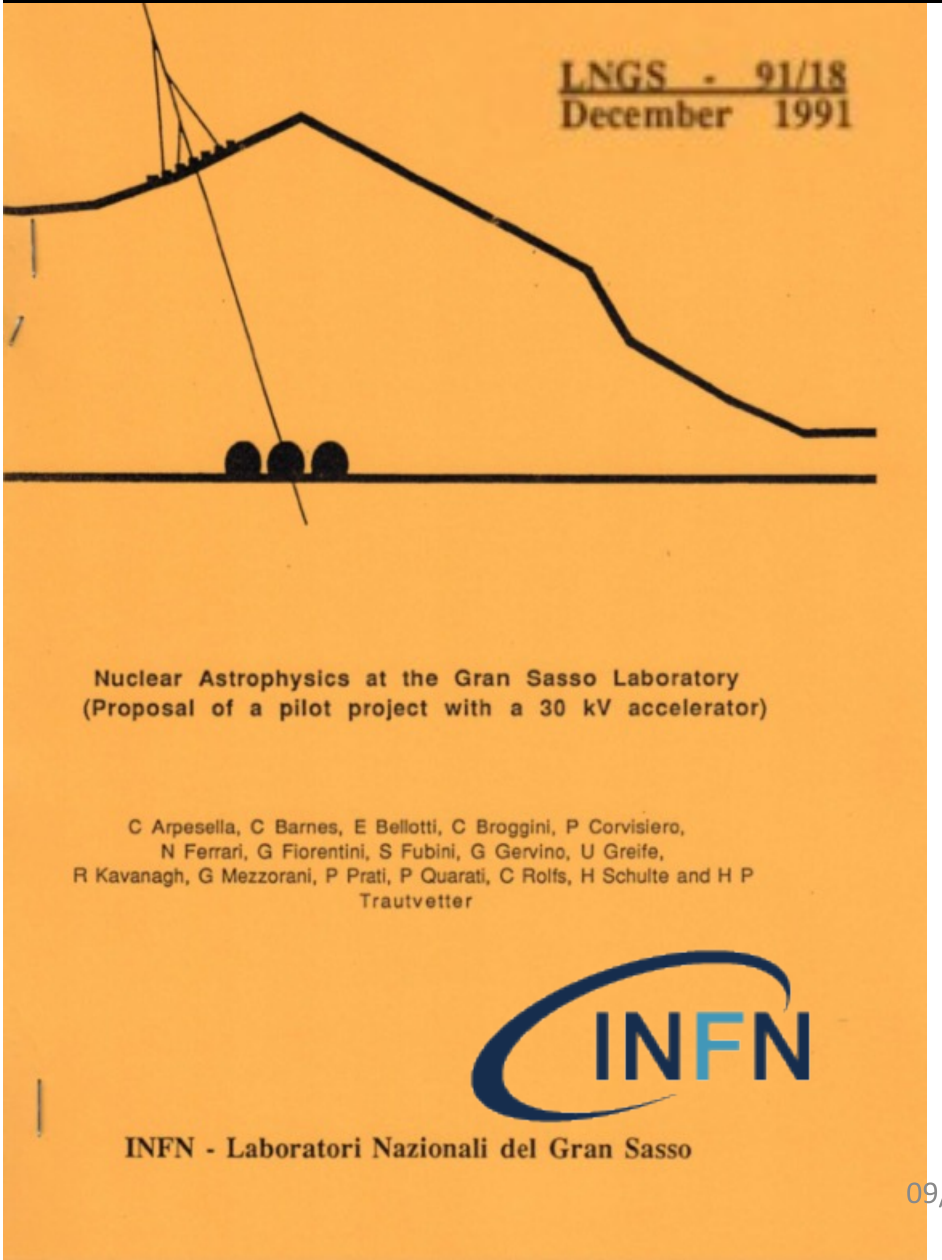
Why going underground: γ-background



$p(D,\gamma)^3He$ -> $E_\gamma > 5$ MeV



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 Broggini, P Corvisiero,
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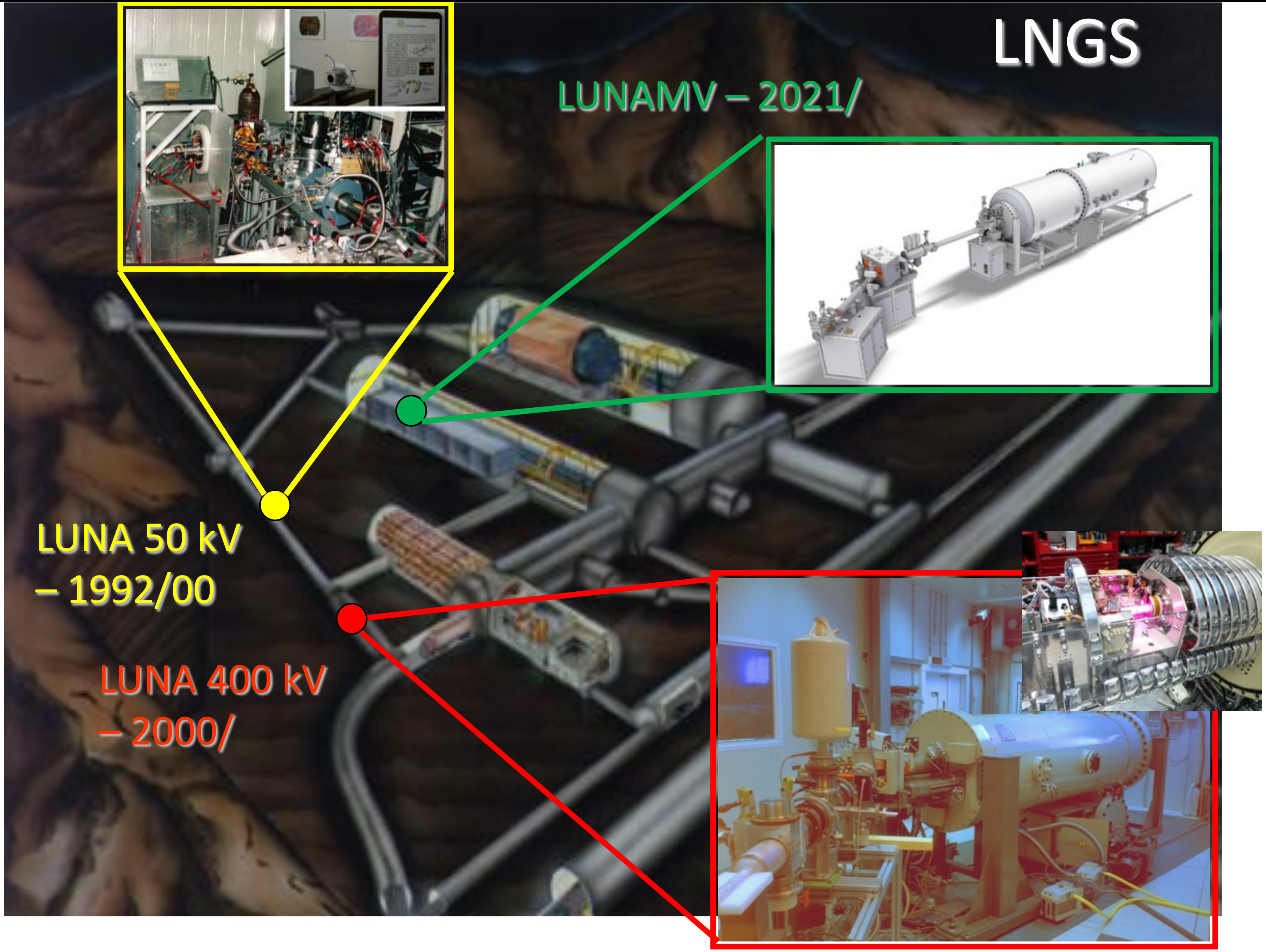
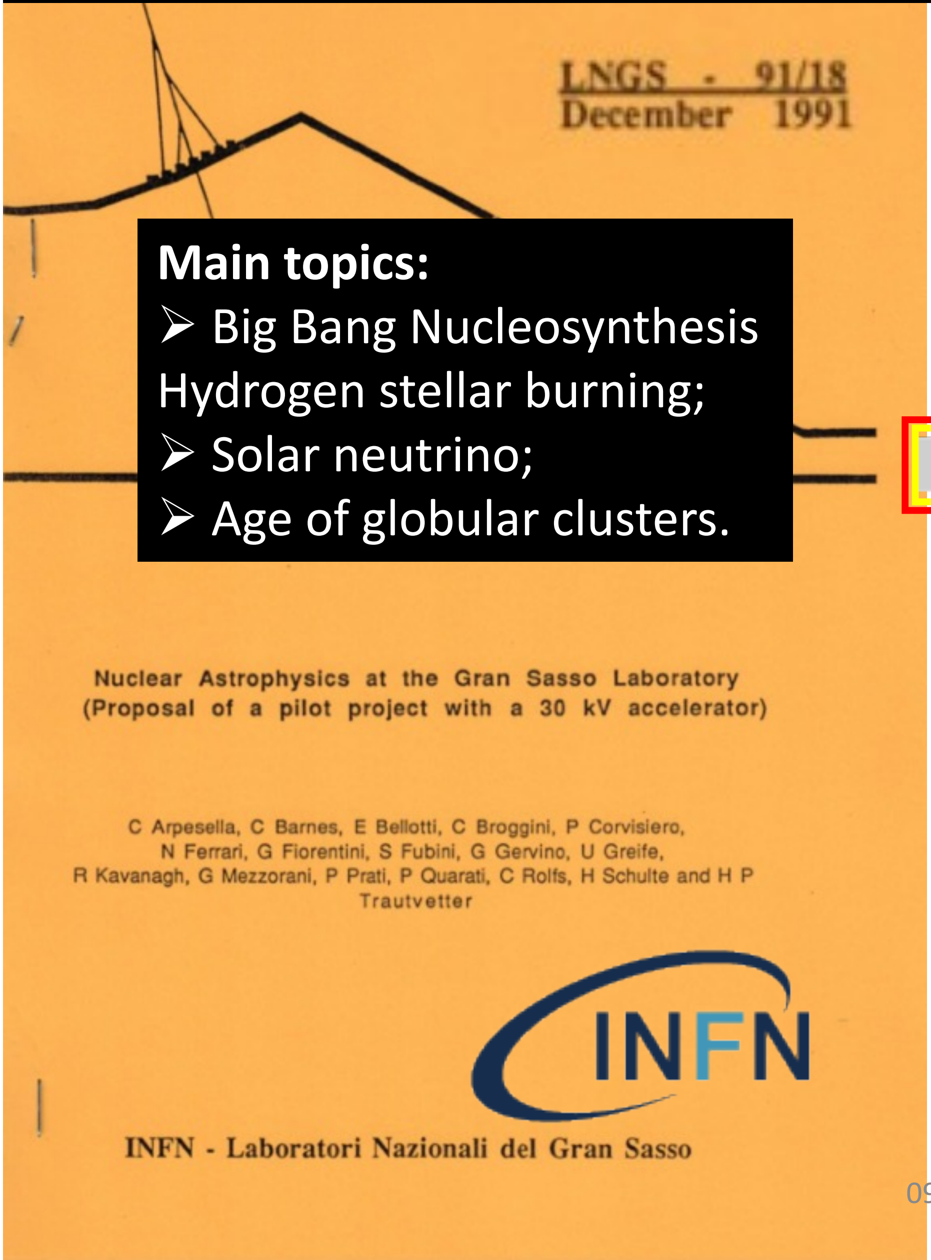


LUNA: a long story of discoveries

Main topics:
- Big Bang Nucleosynthesis
Hydrogen stellar burning;
- Solar neutrino;
- Age of globular clusters.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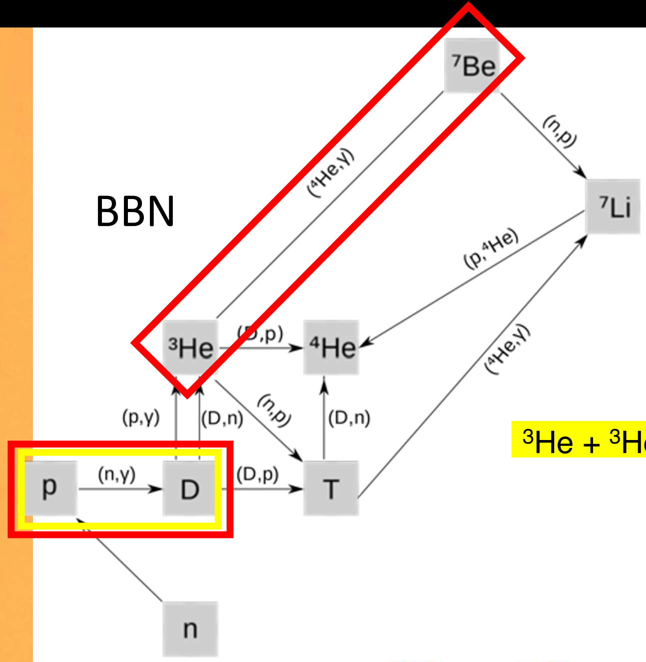
BBN



pp chain

$p + p \to {}^2H + e^+ + \nu$ — 99.75%

$p + e^- + p \to {}^2H + e^+ + \nu$ — 0.25%

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

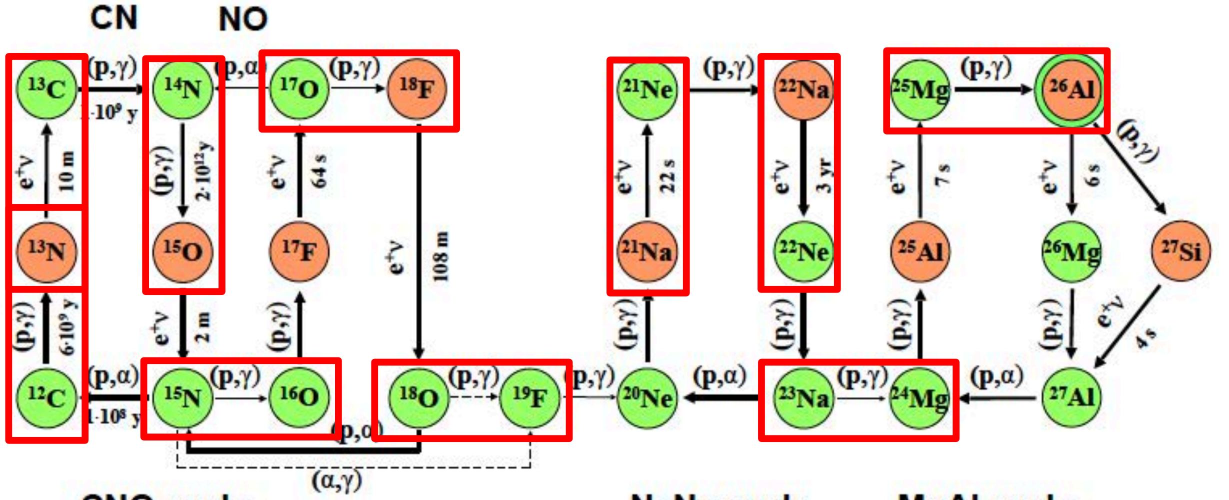
86%: ${}^3He + {}^3He \to {}^4He + 2p$

14%: ${}^3He + {}^4He \to {}^7Be + \gamma$

$2\cdot10^{-5}$%: ${}^3He + p \to {}^4He + e^+ + \nu$

99.89%:
${}^7Be + e^- \to {}^7Li + \nu$
${}^7Li + p \to {}^8Be$
${}^8Be \to 2\,{}^4He$

0.11%:
${}^7Be + p \to {}^8B + \gamma$
${}^8B \to {}^8Be + e^+ + \nu$
${}^8Be \to 2\,{}^4He$



LABORATORY FOR UNDERGROUND NUCLEAR ASTROPHYSICS: MV

LNGS will remain world reference for this field

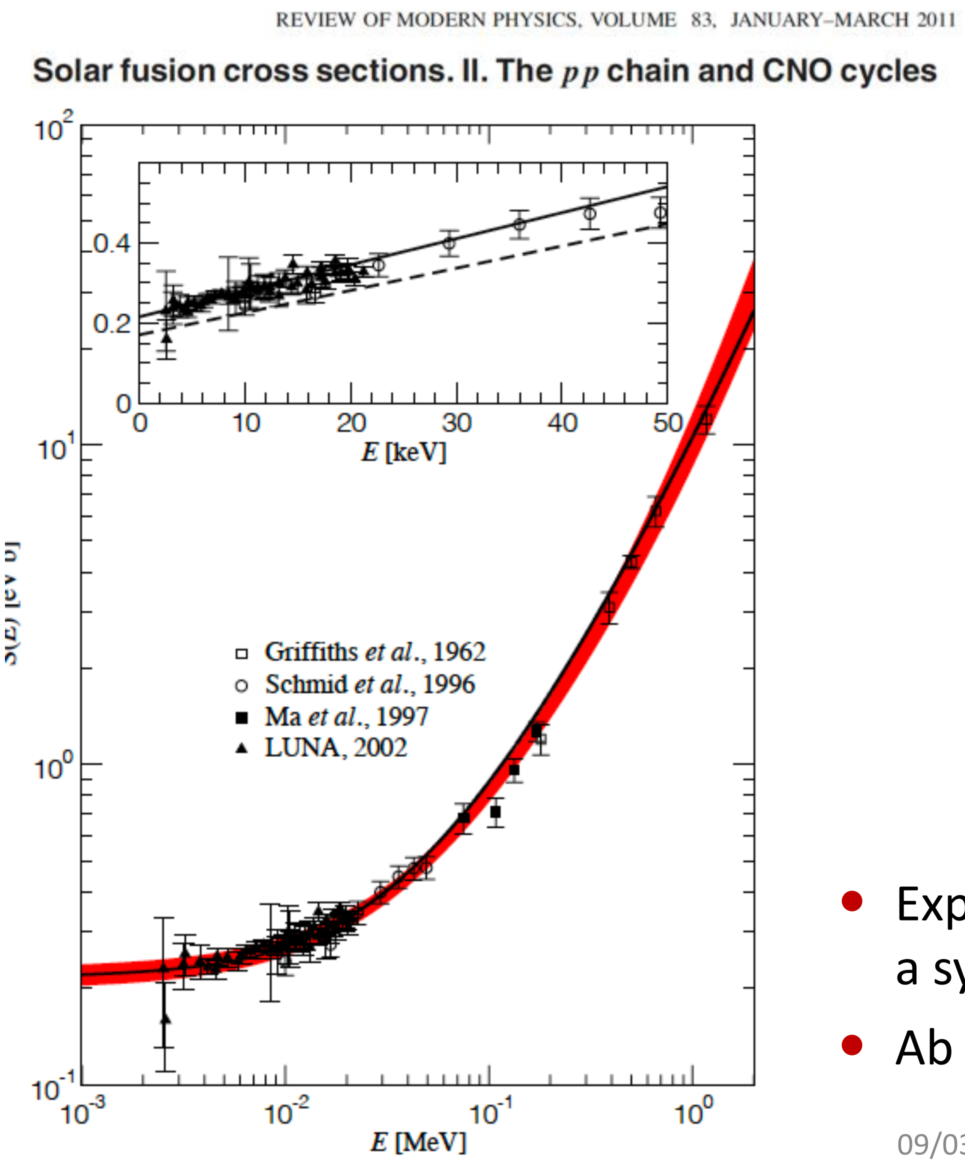
Age of Globular Clusters and C production in AGB: $^{14}N(p,\gamma)^{15}O$

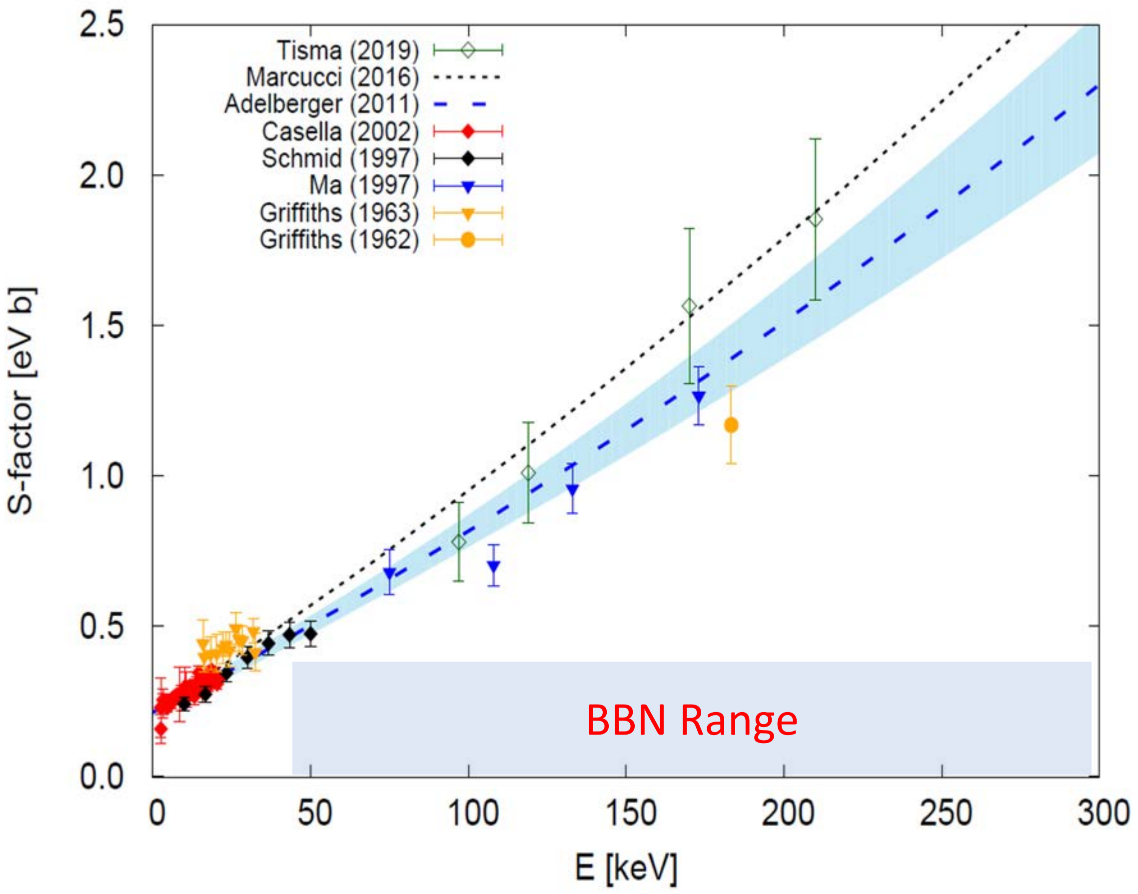
Main neutron sources: $^{13}C(\alpha,n)^{16}O$

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

He and advaced burnings: $^{12}C(^{12}C, p)^{23}Na$ & $^{12}C(^{12}C,\alpha)^{20}Ne$

$D(p,\gamma)^3He$: State of the art





- Experimental data: two datasets available in the BBN energy range with a systematic error of 9-15%
- Ab initio calculations disagree with experimental data

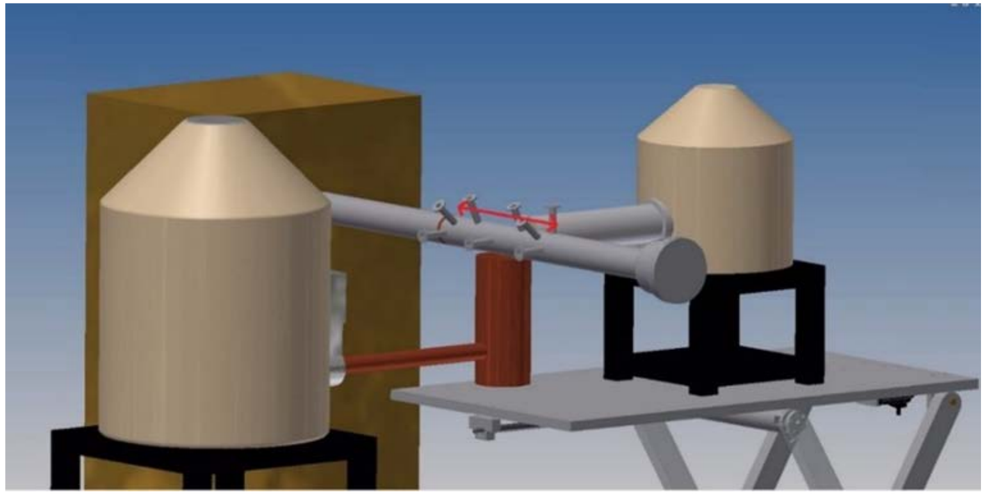
D(p,γ)^{3}He: experimental setup

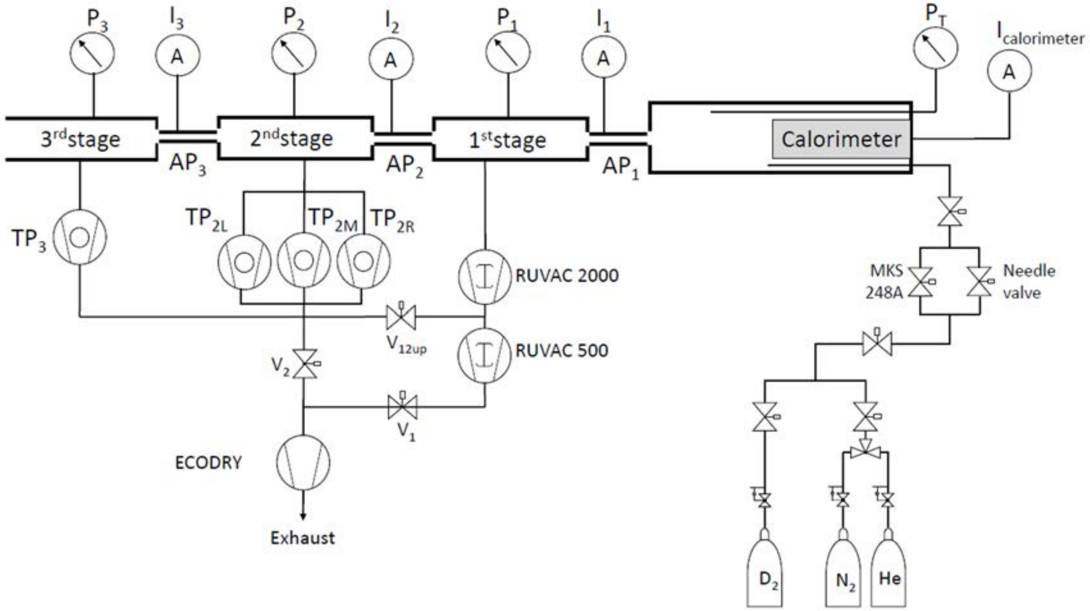
Measurement goal:

- Cross section measurement with ~3% accuracy
- E_{cm}= 30-300 keV

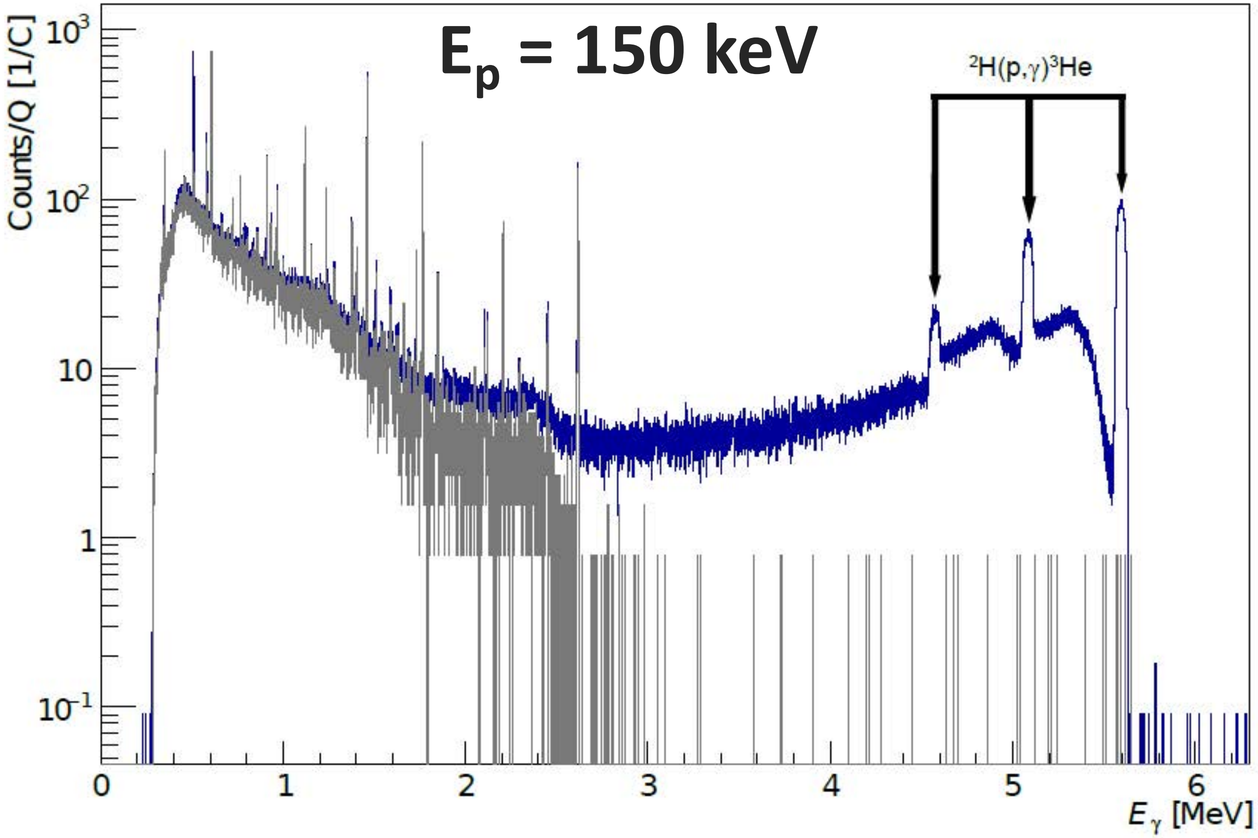
Experimental setup:

- Proton beam
- D_2 windowless gas target (P=0.3 mbar)
- HPGe detectors for γ-rays





$D(p,\gamma)^3He$: data analysis



$$N_\gamma(E) = N_p N_D \sigma(\mathrm{E}) \mathcal{E}(E)$$

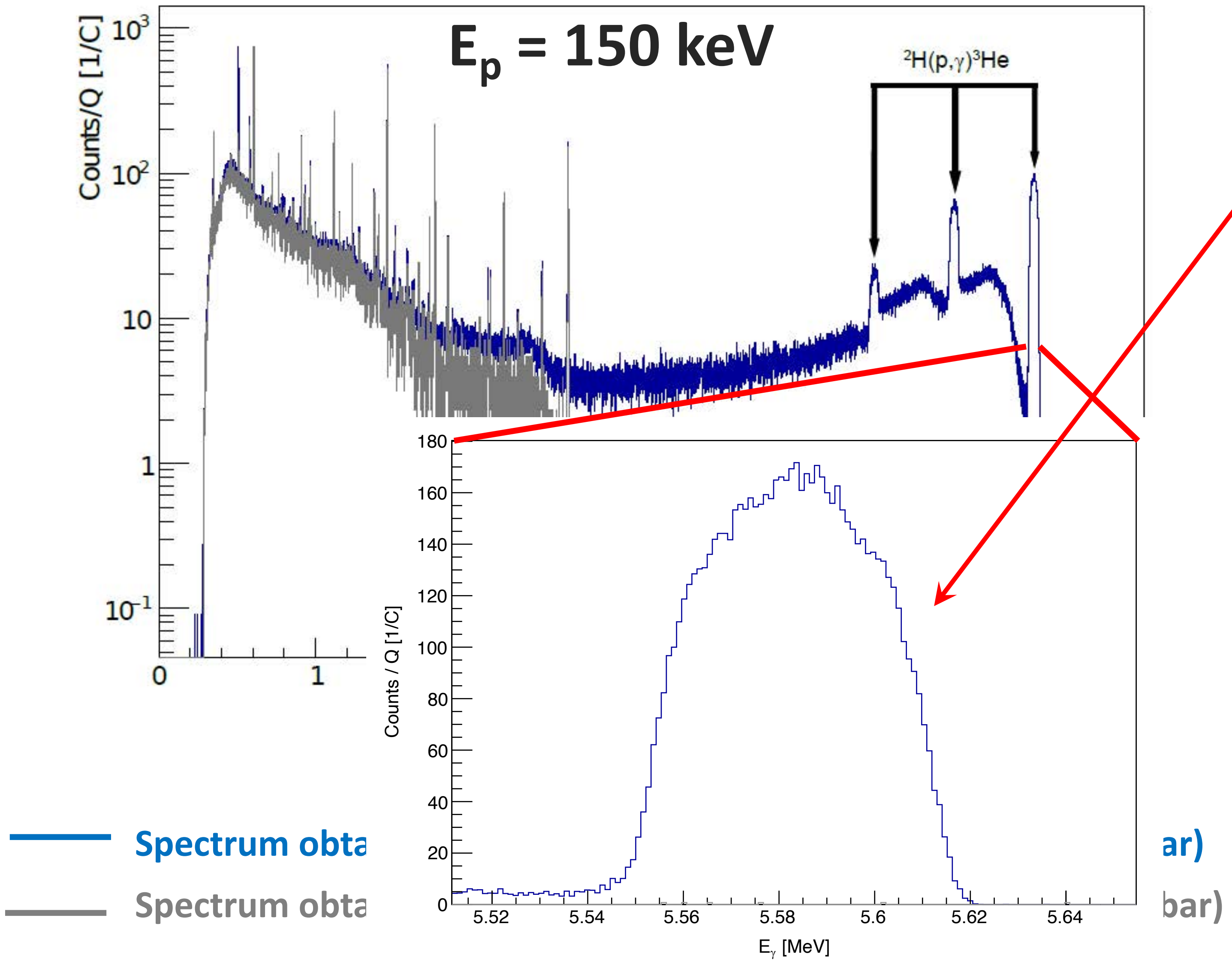
$$N_D = \int_0^L \rho(z)\, \mathcal{E}(z,E) W(z) dz$$

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z) \varepsilon(z, E_\gamma) W(z) dz}$$

Spectrum obtained @ E_p = 150 keV with D_2 gas target (P=0.3 mbar)

Spectrum obtained @ E_p = 150 keV with ^4He gas target (P=0.3 mbar)

D(p,γ)^{3}He: data analysis



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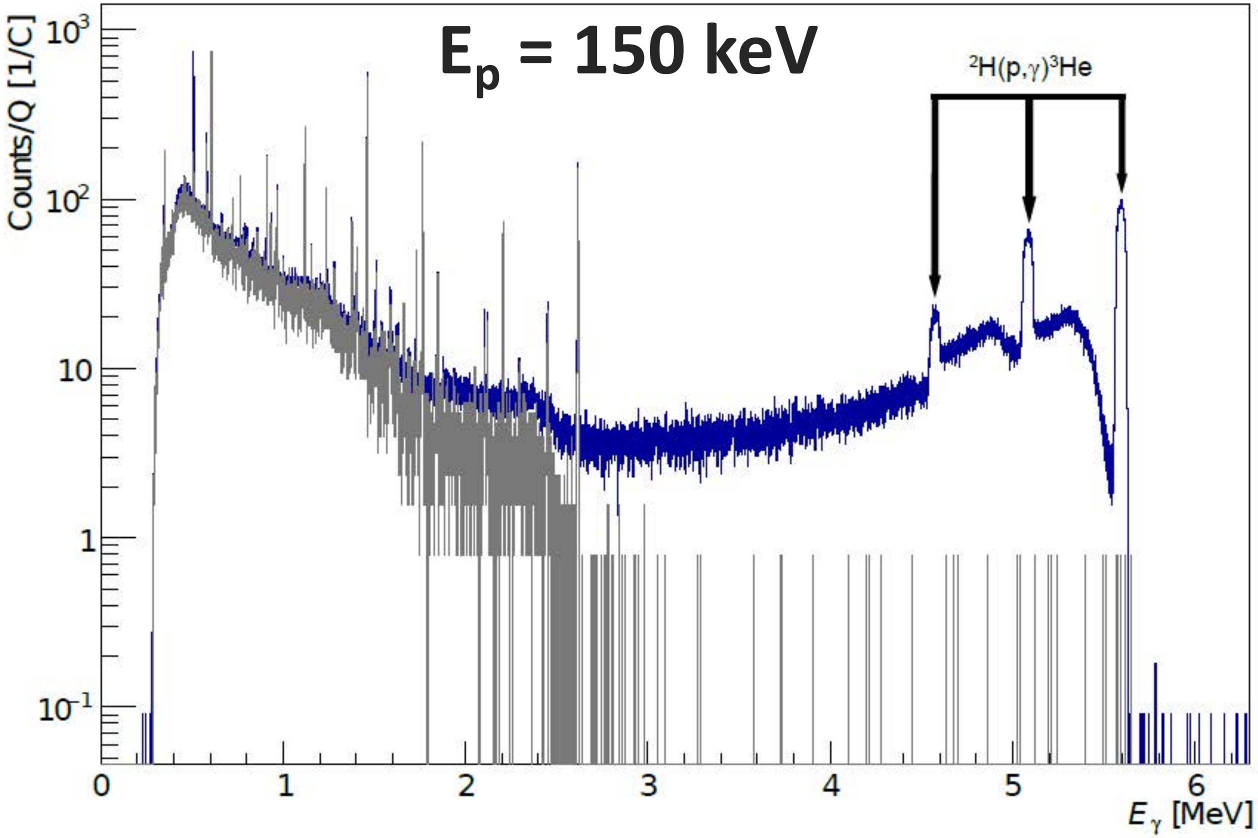

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z, E_\gamma) W(z) dz}$$

Source	Method	ΔS/S (%)
Beam energy	Direct measurement	0.2
Energy loss	Low gas pressure	0.04
T and P profiles	Direct measurement	1.0
Beam heating	Direct measurement	0.5
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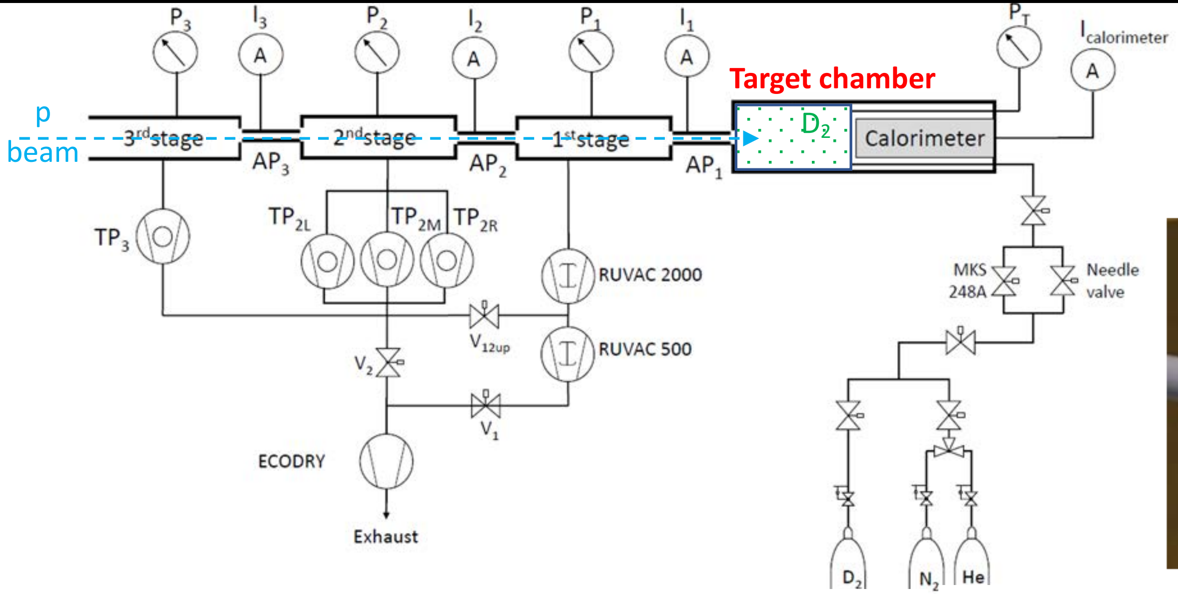
$D(p,\gamma)^3He$: systematic uncertainties



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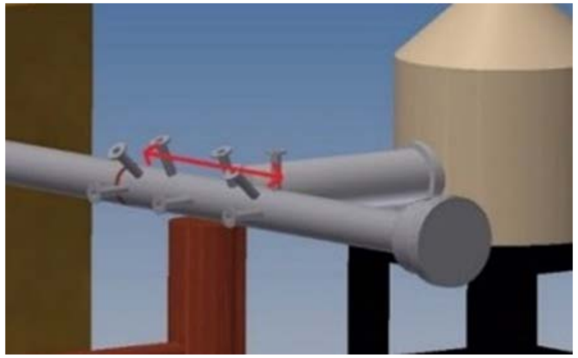

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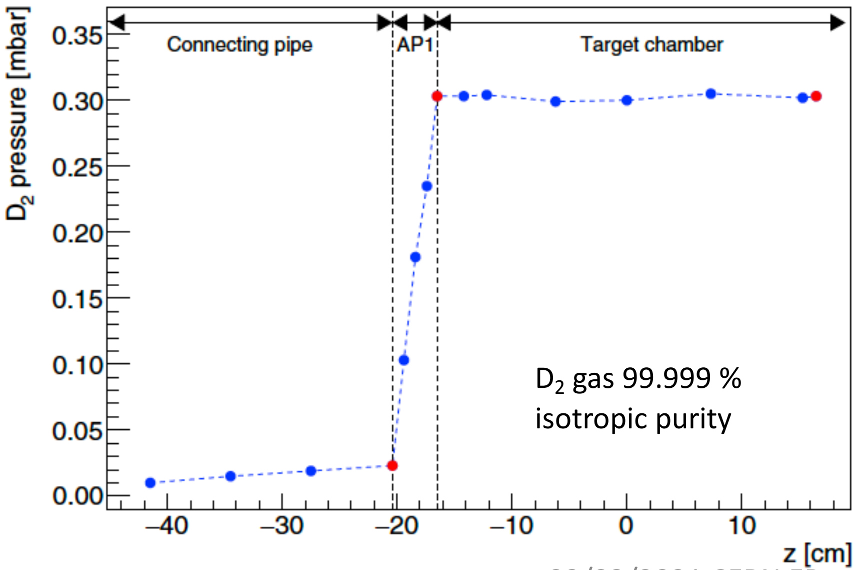

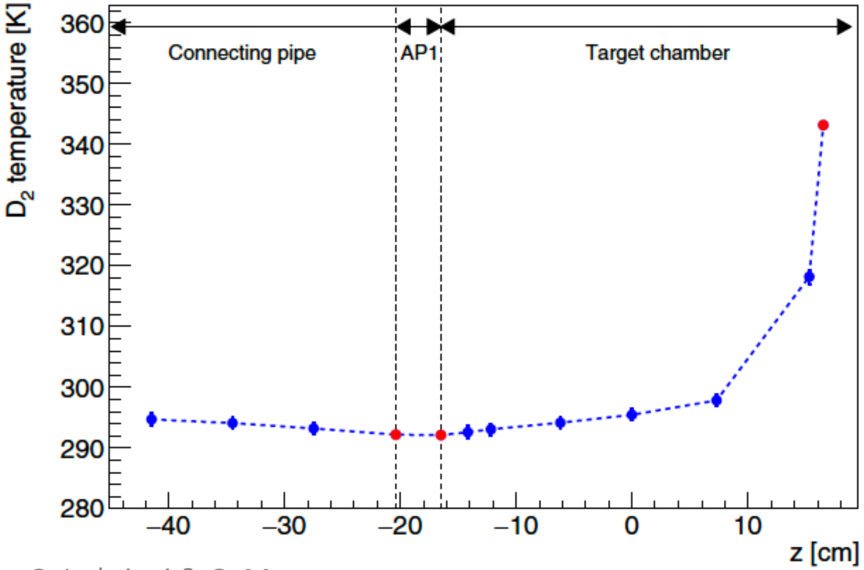

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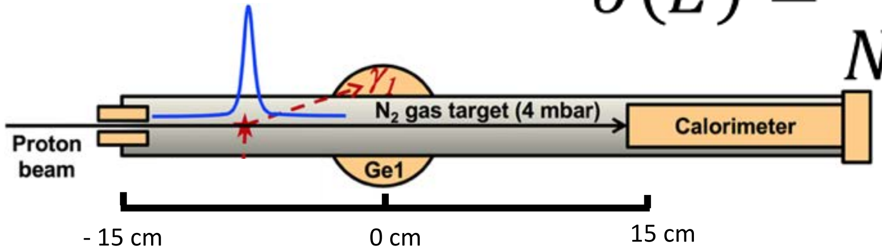

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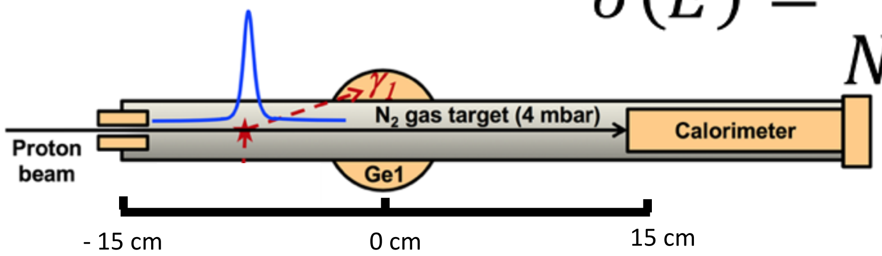
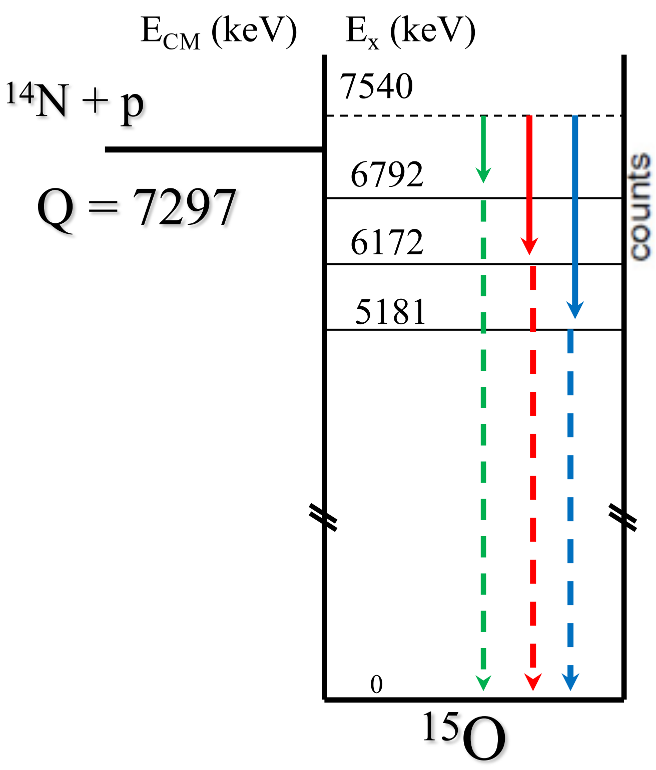
Eur. Phys. J. A (2020) 56:144
https://doi.org/10.1140/epja/s10050-020-00149-1

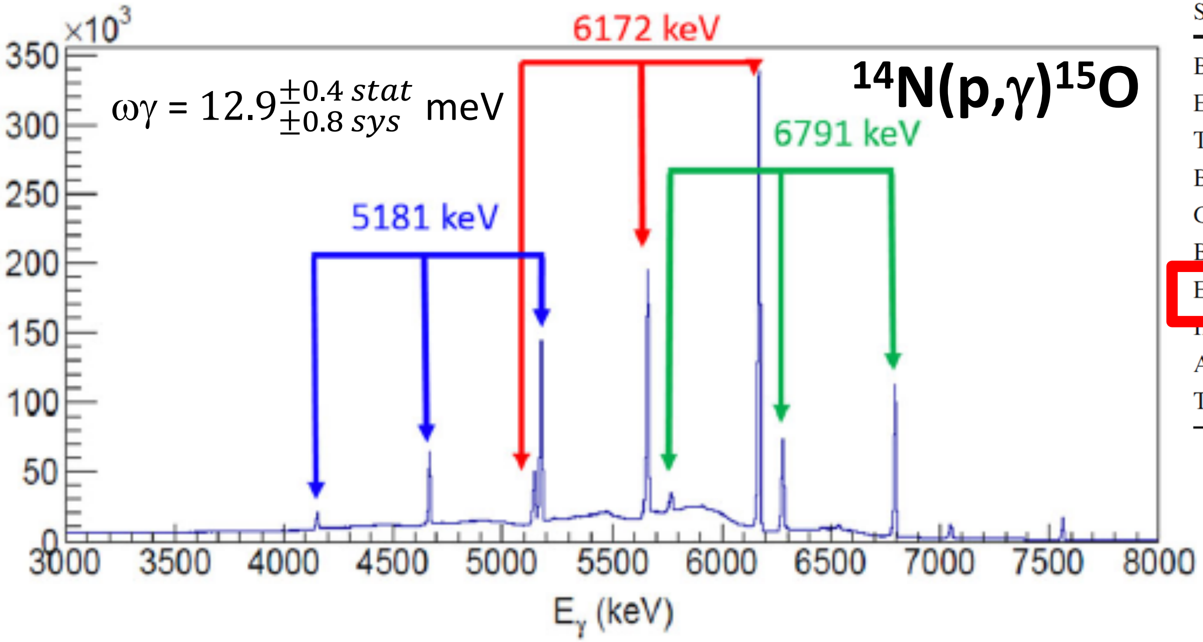
$D(p,\gamma)^3He$: systematic uncertainties

E_x[keV]	BR [%]
6792	23.0 ± 0.3
6172	58.3 ± 0.3
5181	16.9 ± 0.2

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\,\varepsilon(z, E_\gamma)\,W(z)\,dz}$$







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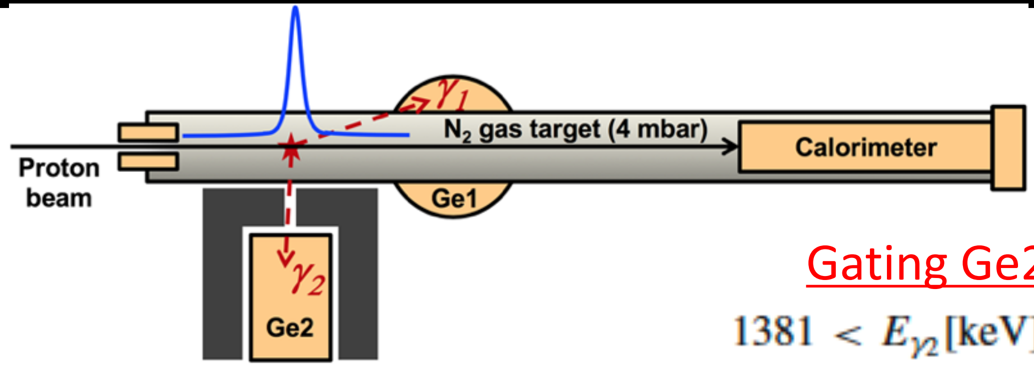

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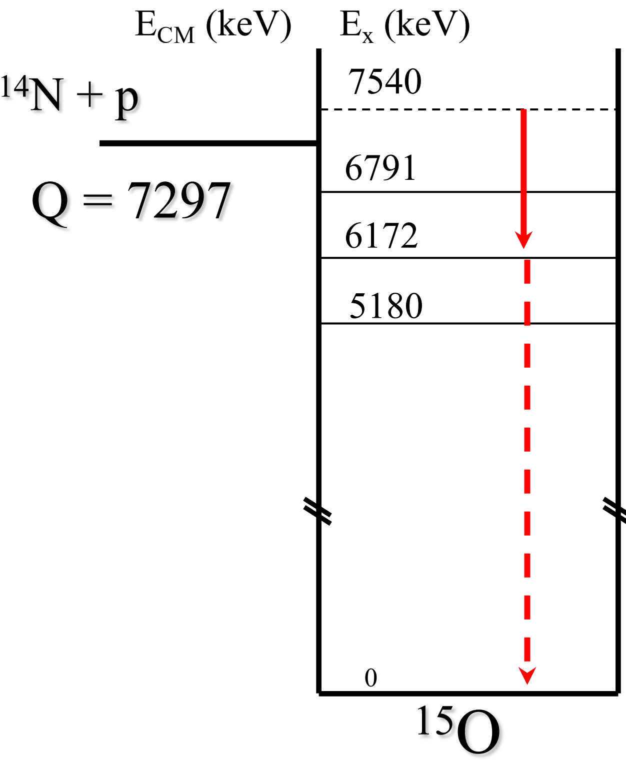
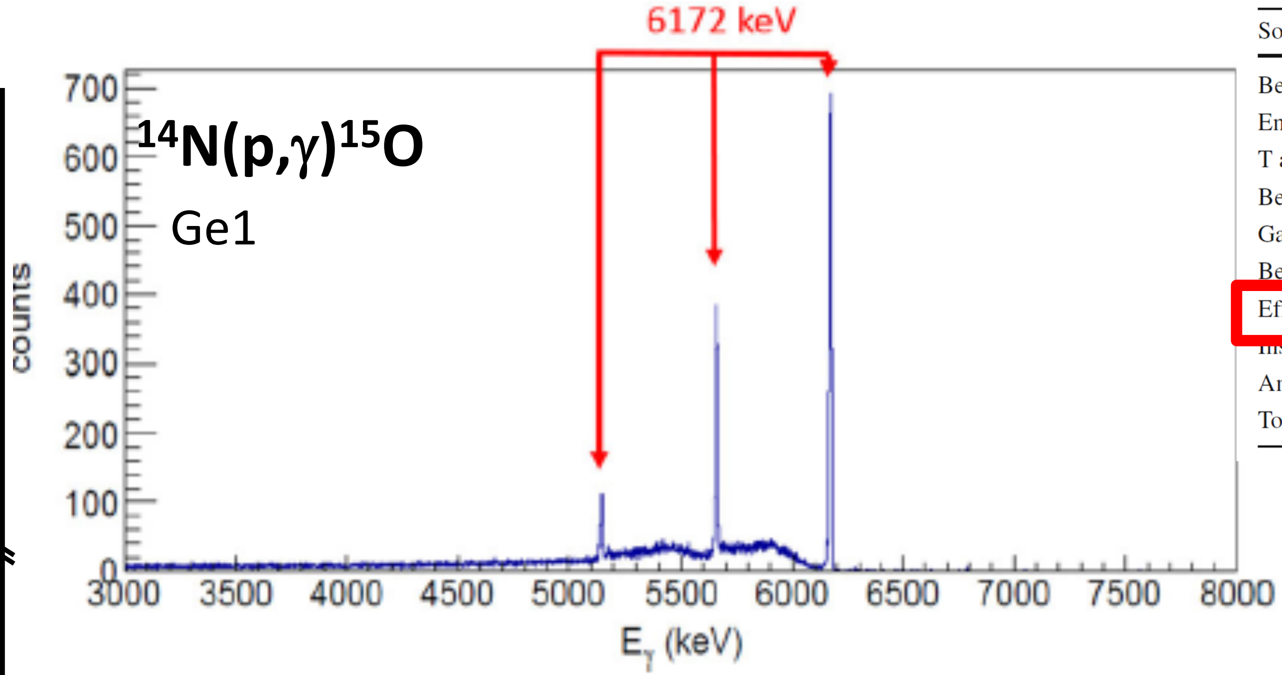
Gating Ge2

$1381 < E_{\gamma 2}[\mathrm{keV}] < 1389$





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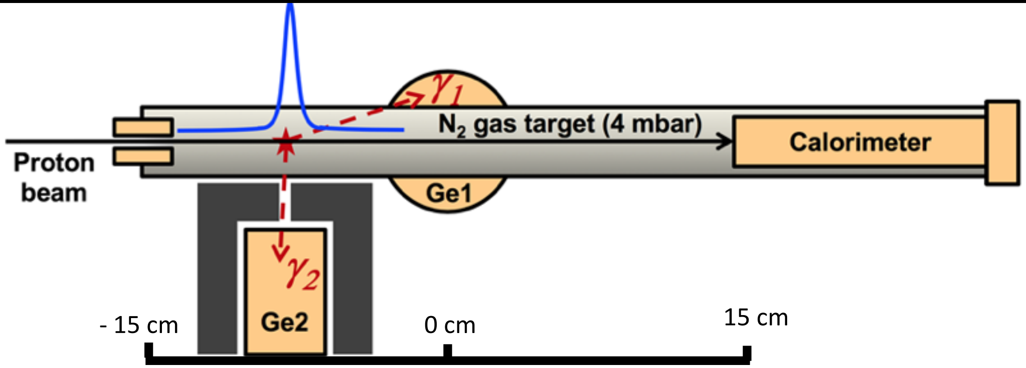

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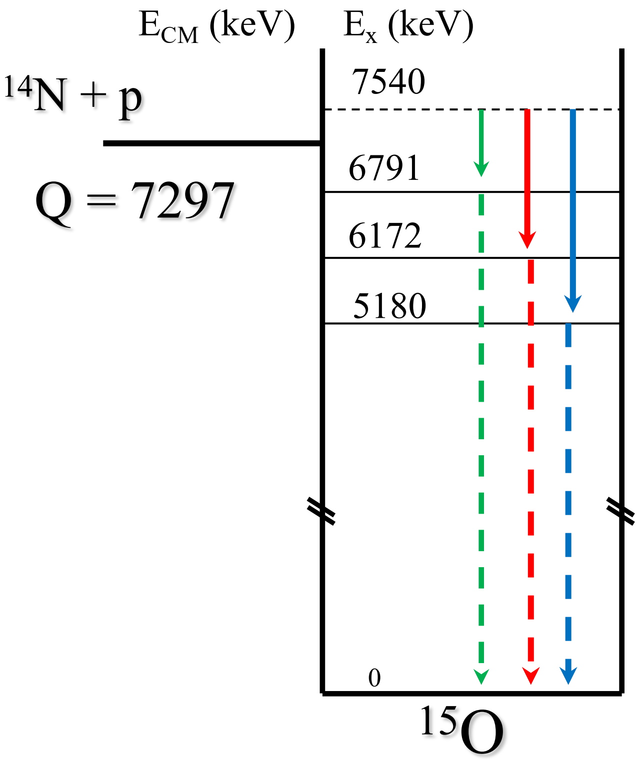

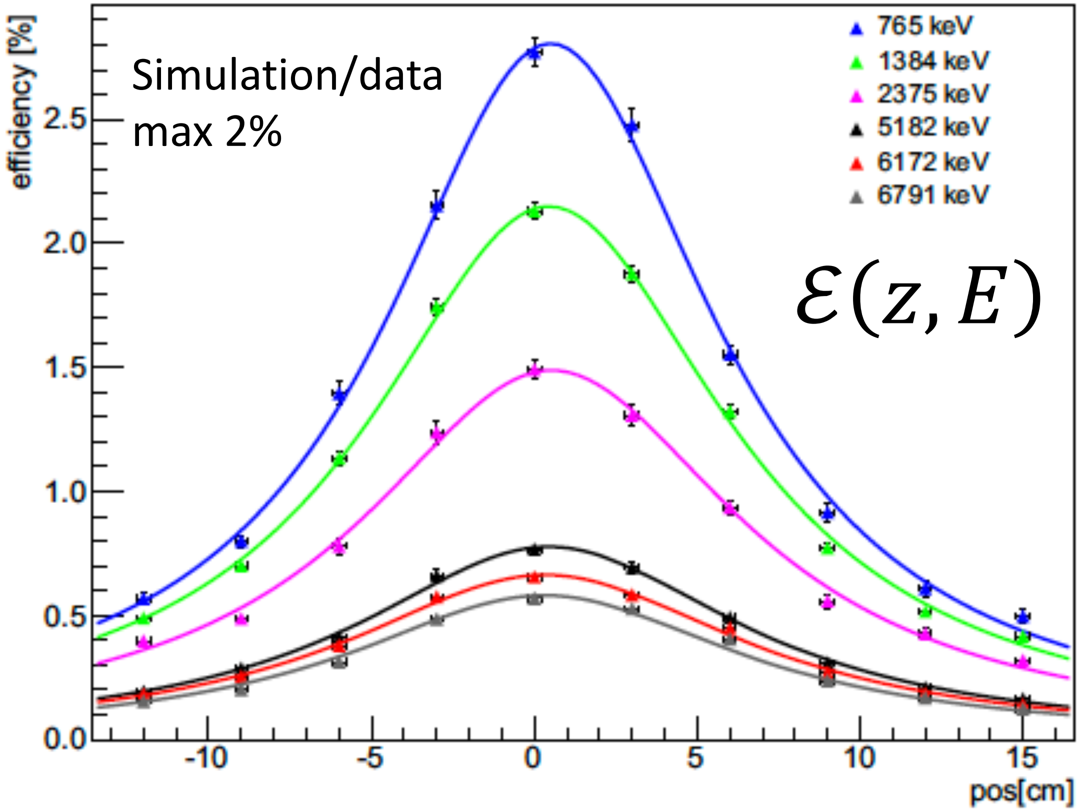

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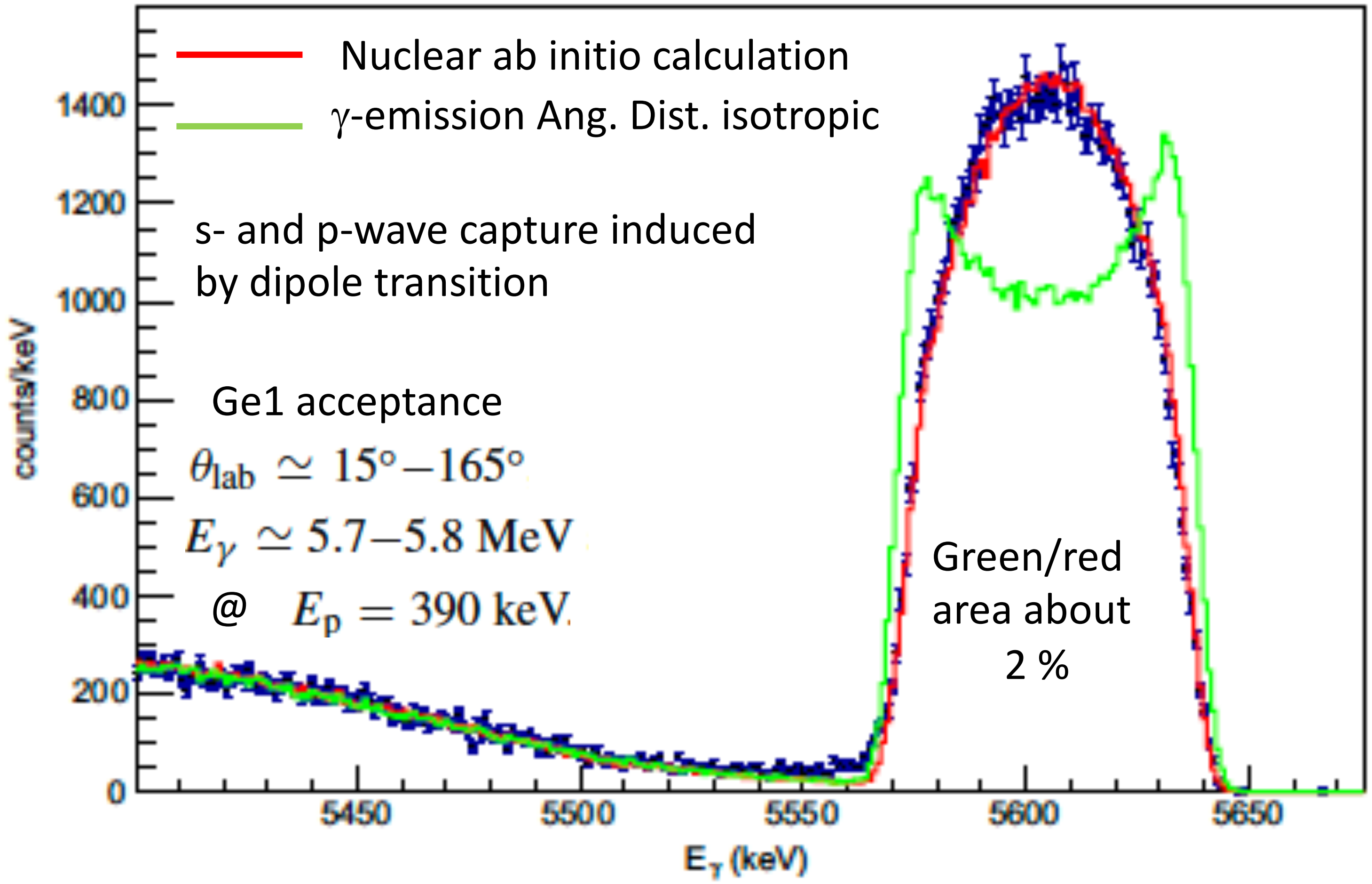

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Efficiency	Direct measurement	2.0
Instrumental effects	Pulser method	0.2
Angular distribution	Simulations	0.5
Total		2.6

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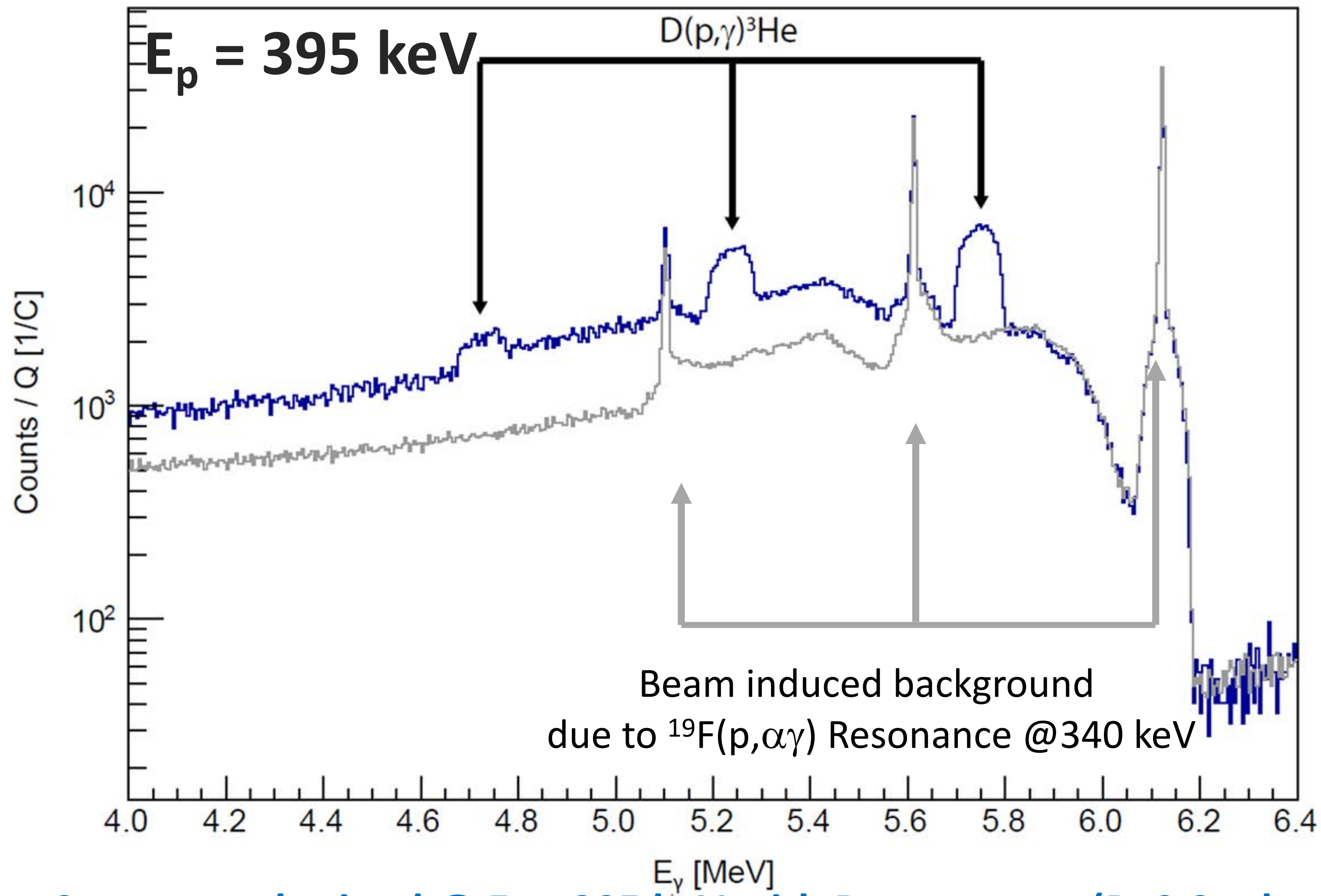
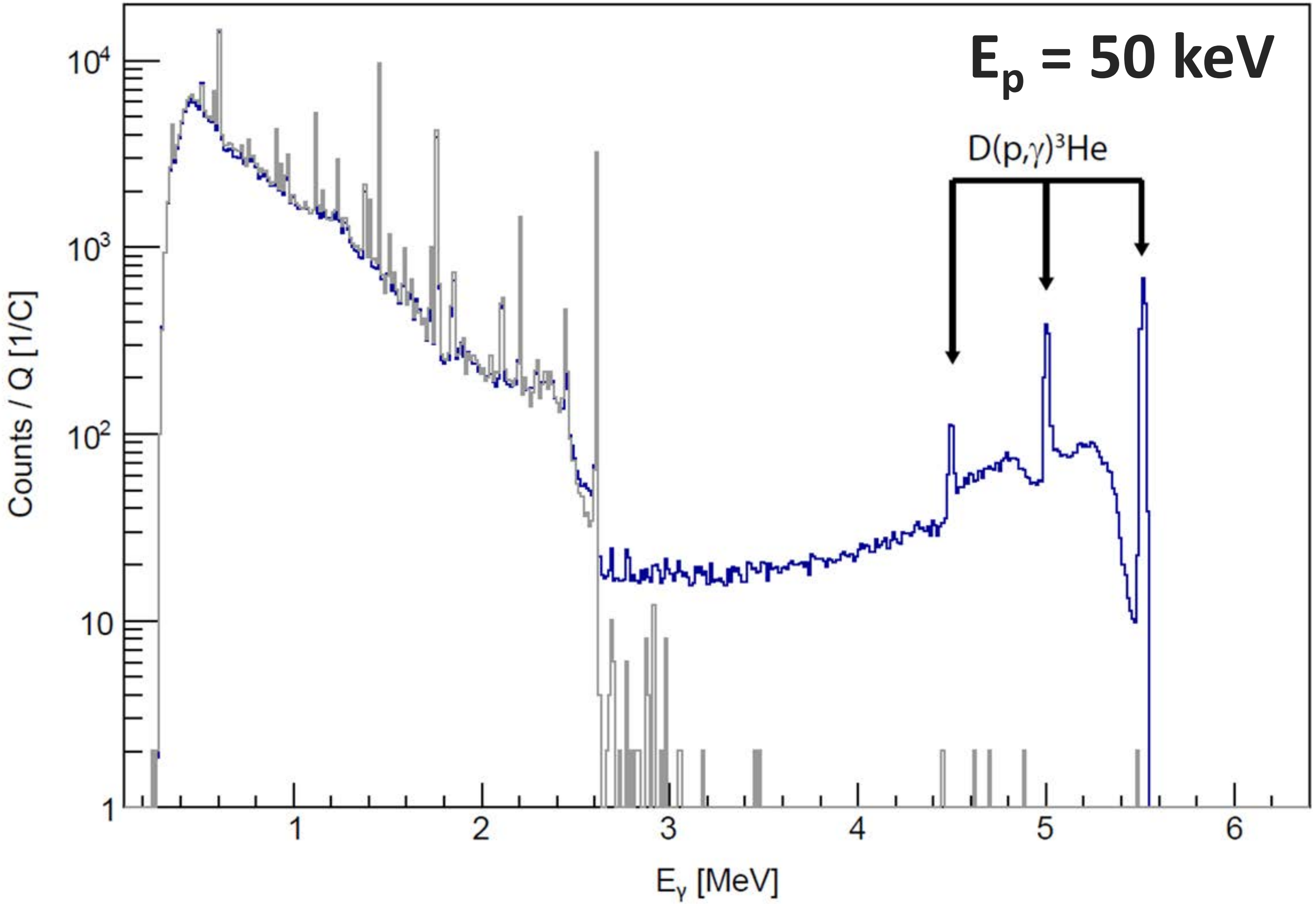
D(p,γ)^{3}He: beam induced background



Spectrum obtained @ E_p = 395 keV with D_2 gas target (P=0.3 mbar)

Spectrum obtained @ E_p = 395 keV with ^4He gas target (P=0.3 mbar)

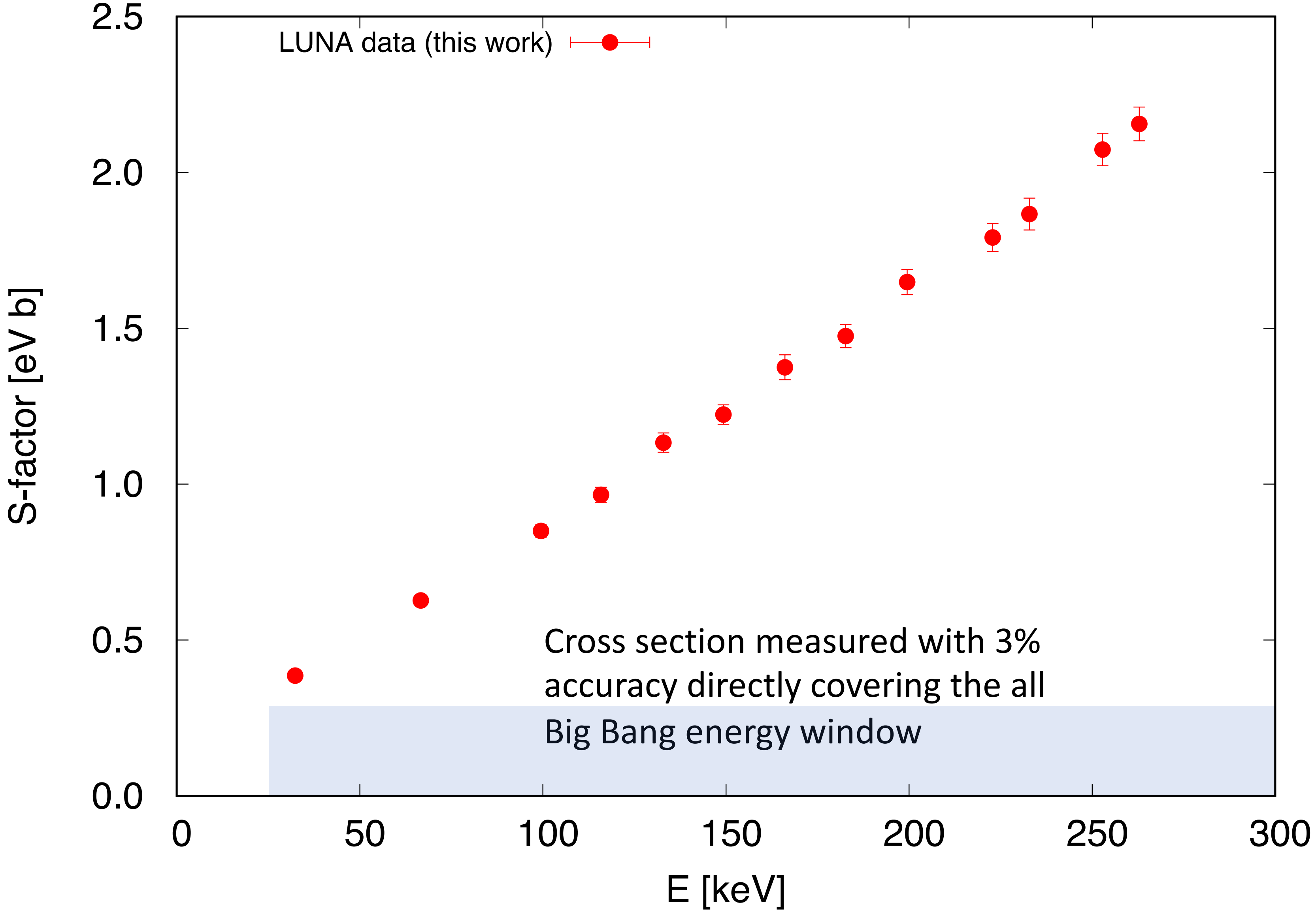
D(p,γ)^{3}He: lowest energy spectrum



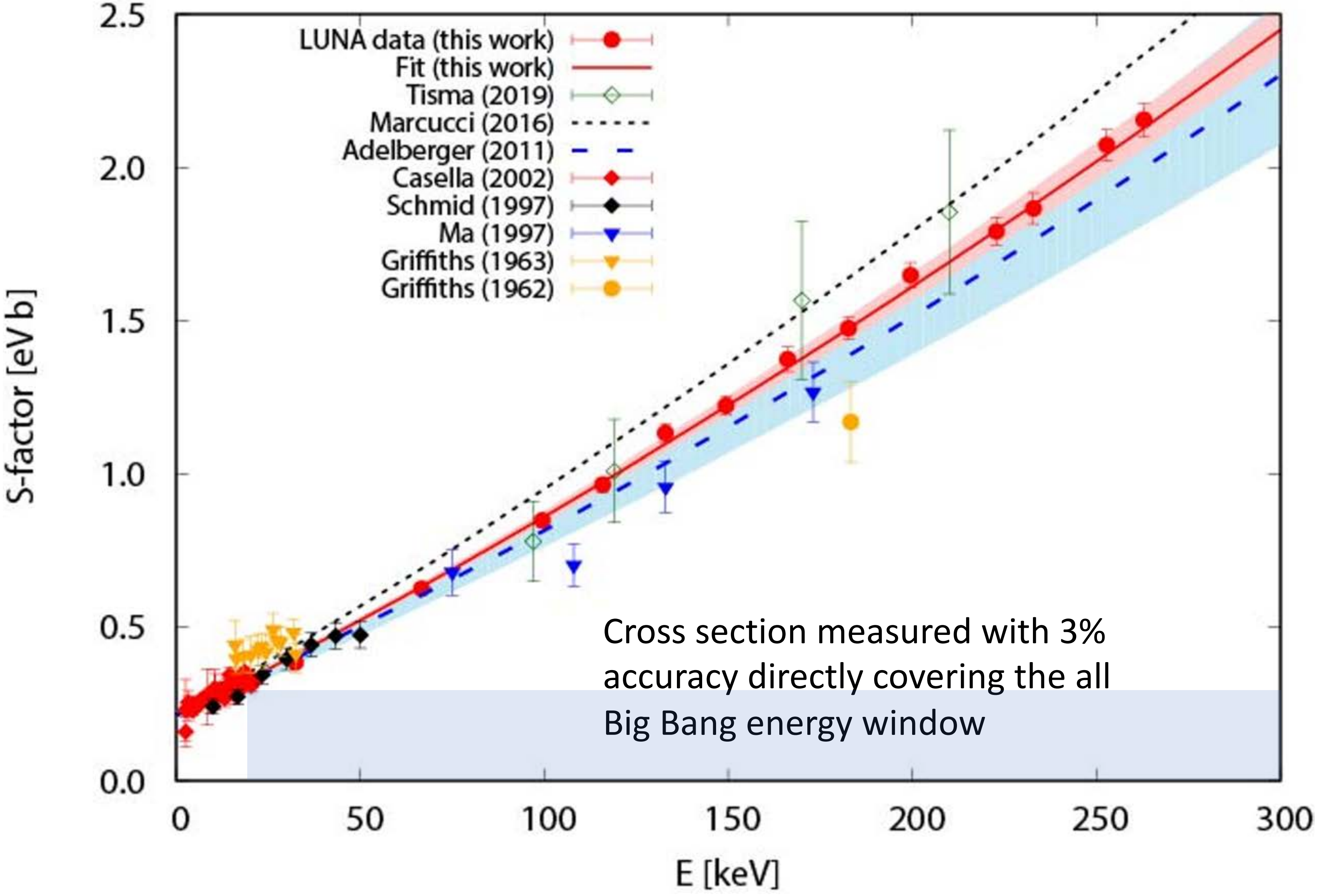
Spectrum obtained @ E_p = 50 keV with D_2 gas target (P=0.3 mbar)

Spectrum obtained @ E_p = 50 keV with ^{4}He gas target (P=0.4 mbar)

$D(p,\gamma)^3He$: S-factor results



$D(p,\gamma)^3He$: S-factor results



Cross section measured with 3% accuracy directly covering the all Big Bang energy window

D(p,γ)^{3}He: S-factor results

Article

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

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V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, 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. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli

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