

Misura diretta di sezioni d'urto di interesse astrofisico a LUNA: la reazione $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

IFAE 2016

Federico Ferraro (per la collaborazione LUNA)



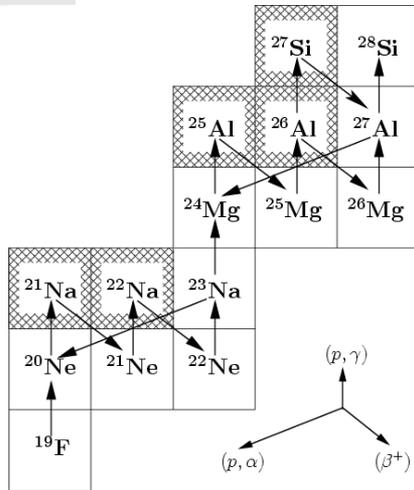
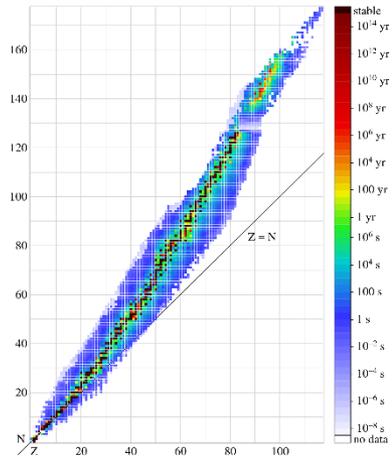
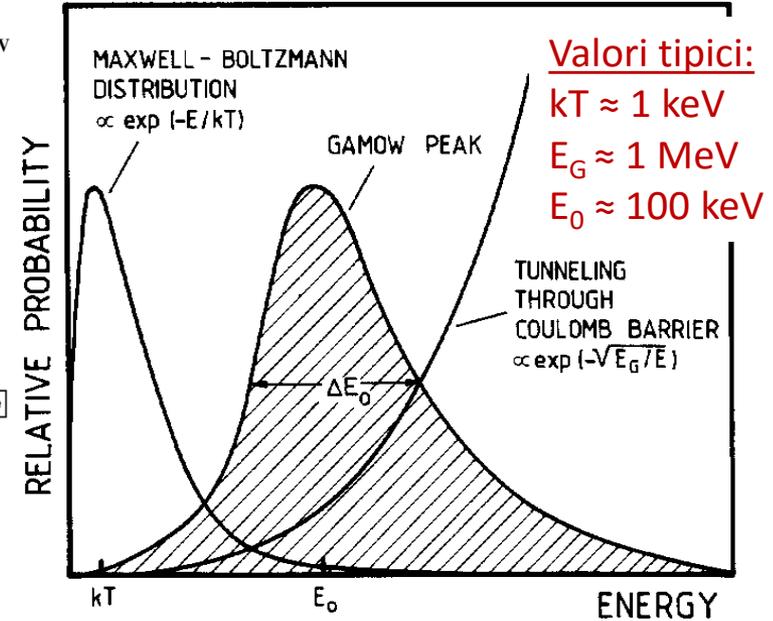
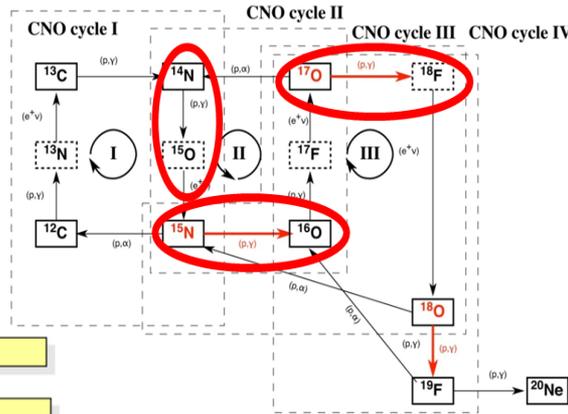
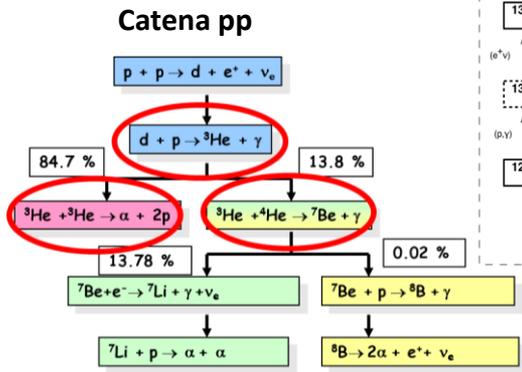
Università degli studi di Genova



INFN-Sezione di Genova



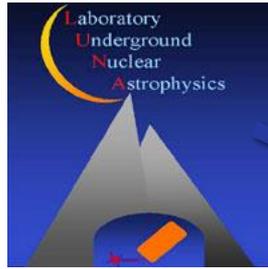
LUNA



Debolmente variabile

$$\sigma(E) = \frac{1}{E} \exp(-31.29 Z_1 Z_2 \sqrt{\mu/E}) S(E)$$

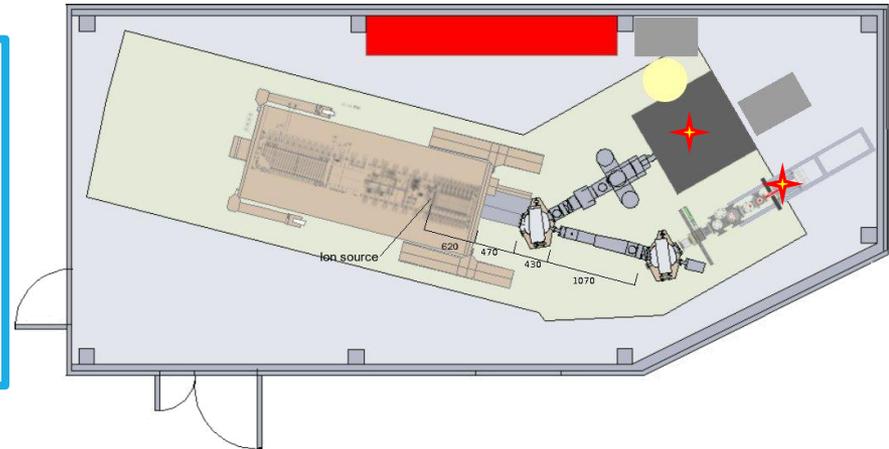
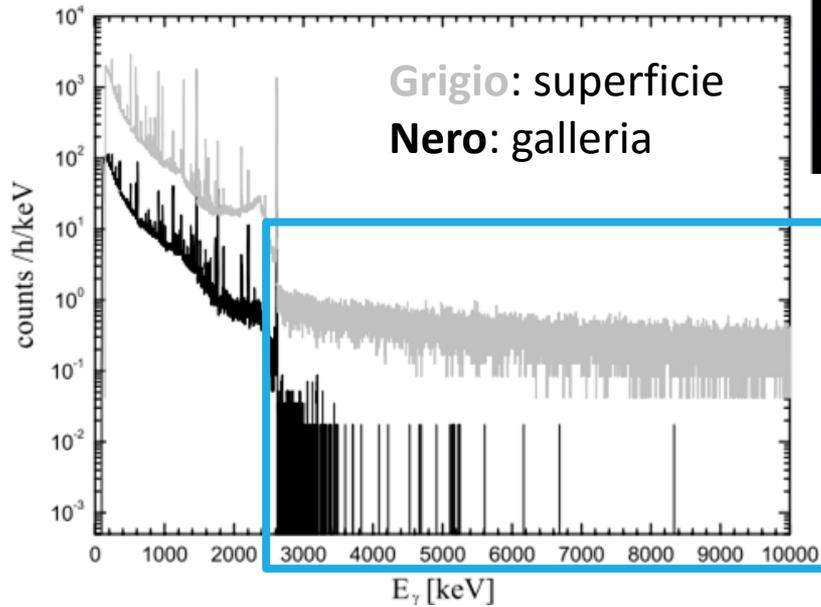
Fortemente variabile



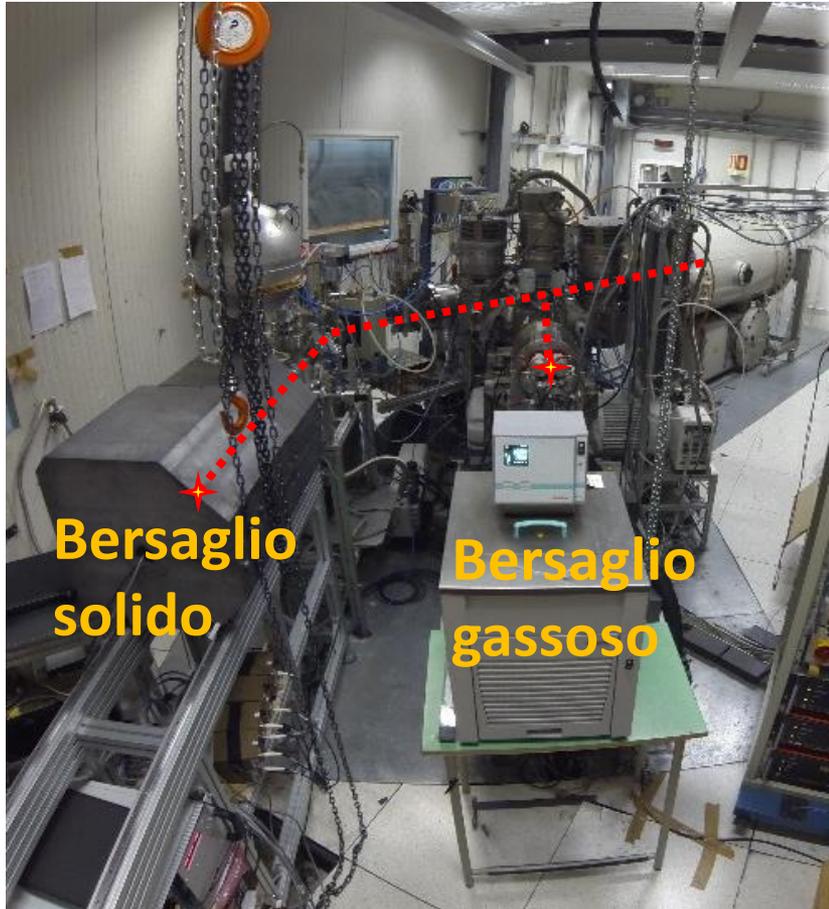
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- Soppressione dei muoni: 10^6
- Soppressione dei neutroni: 10^3

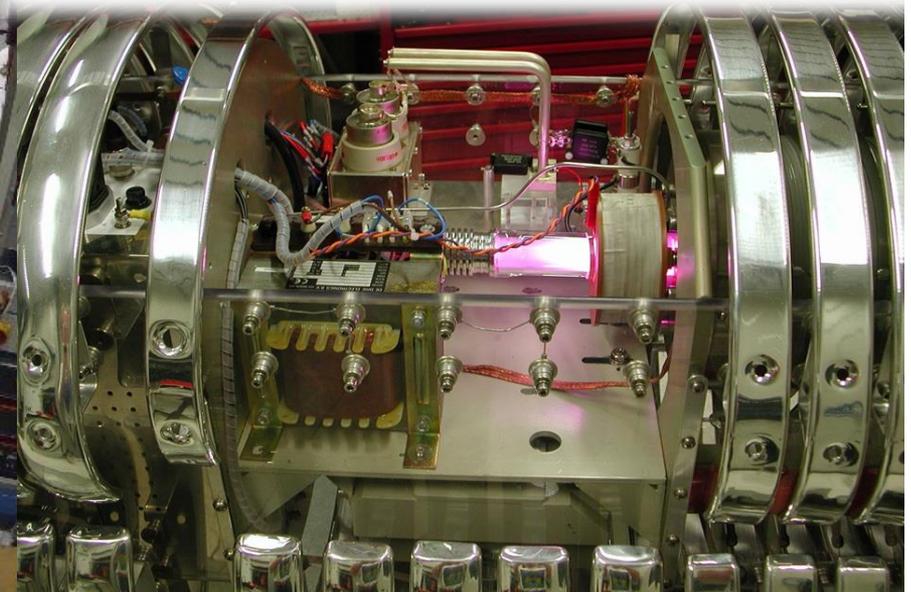
Rep. Prog. Phys. **72** (2009) 086301



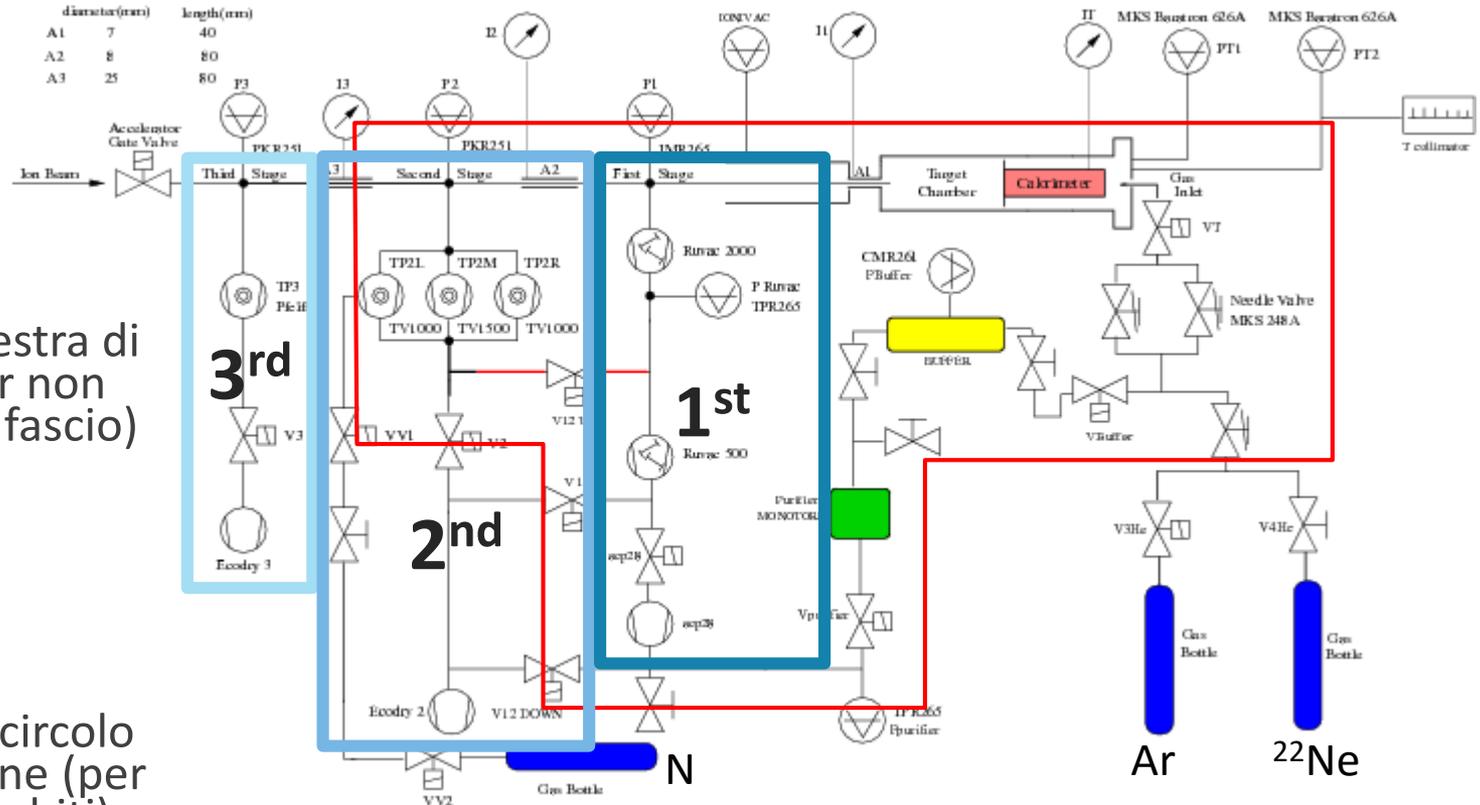
LUNA



Energia di fascio: 50-400 keV
Corrente di fascio: 10-500 μA
Incertezza sull'energia: 100 eV
Stabilità dell'energia di fascio: 5 eV/h

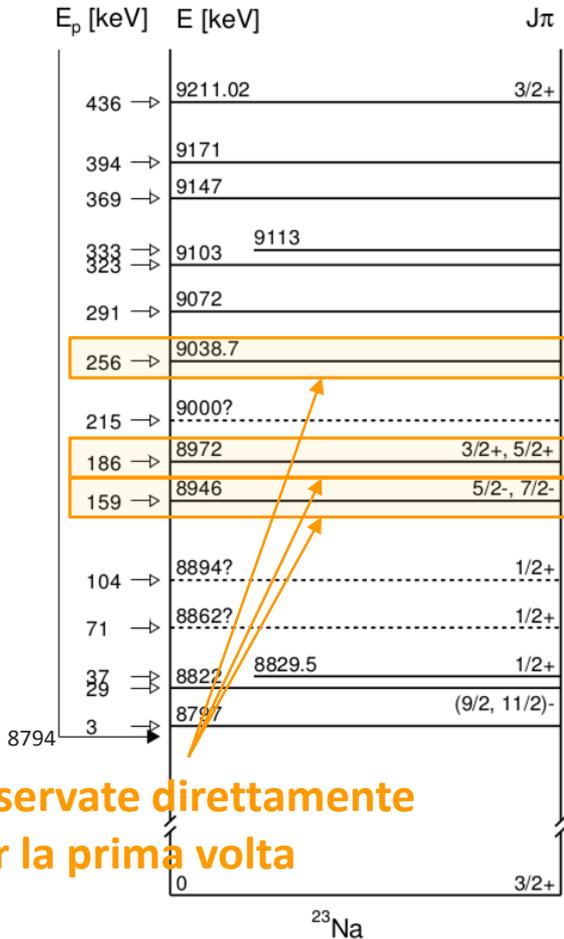


Bersaglio gassoso



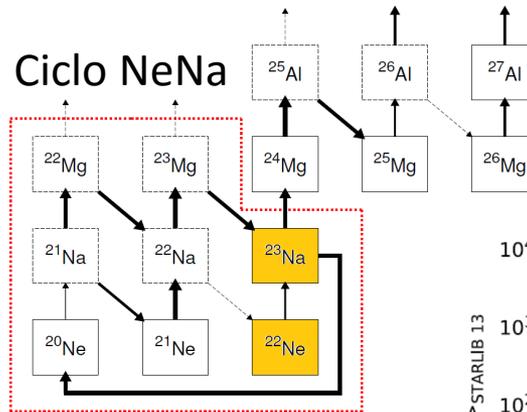
- Nessuna finestra di ingresso (per non degradare il fascio)
- 3 stadi di pompaggio differenziale
- Sistema di ricircolo e purificazione (per gas rari/arricchiti)

La reazione $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

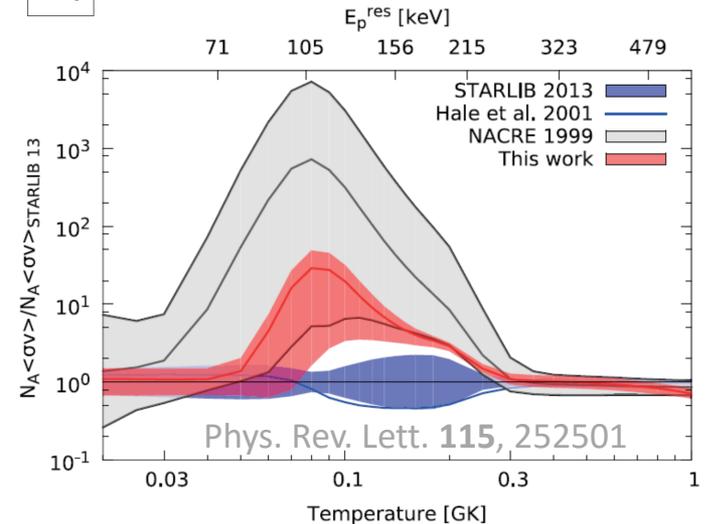


Osservate direttamente per la prima volta

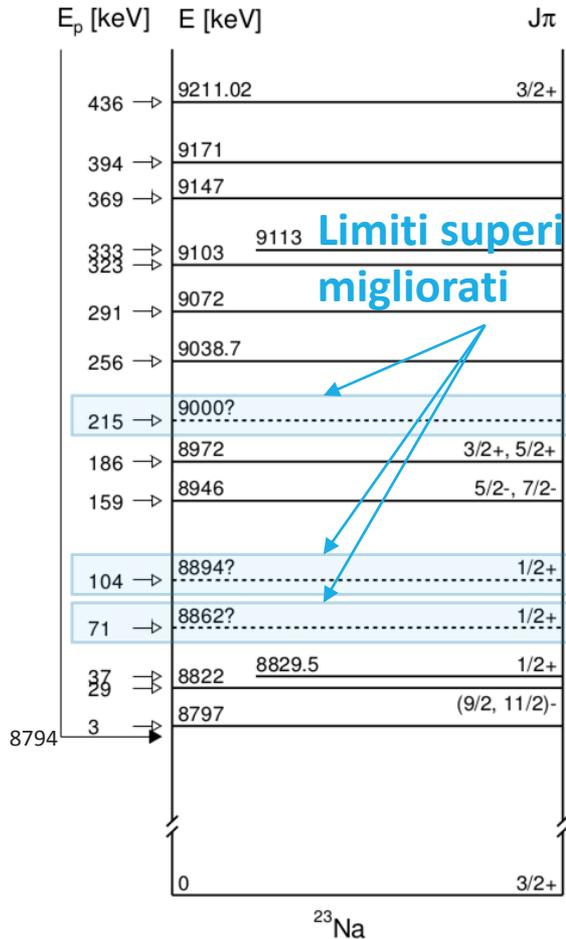
- osservate direttamente per la prima volta 3 risonanze (durante la fase HPGe)



Diverse valutazioni del tasso di reazione!
Cruciali le risonanze a bassa energia!

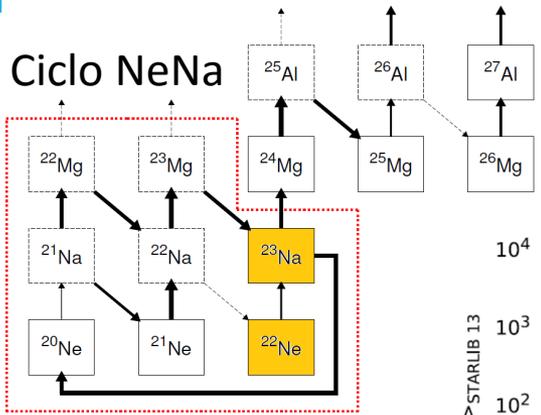


La reazione $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

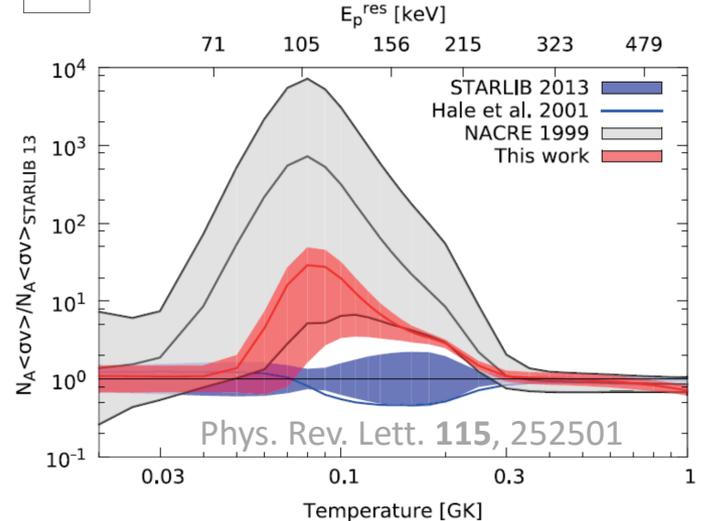


Limiti superiori migliorati

- Necessità di investigare in modo approfondito la regione a bassa energia (la sezione d'urto minore richiede un rivelatore più efficiente)



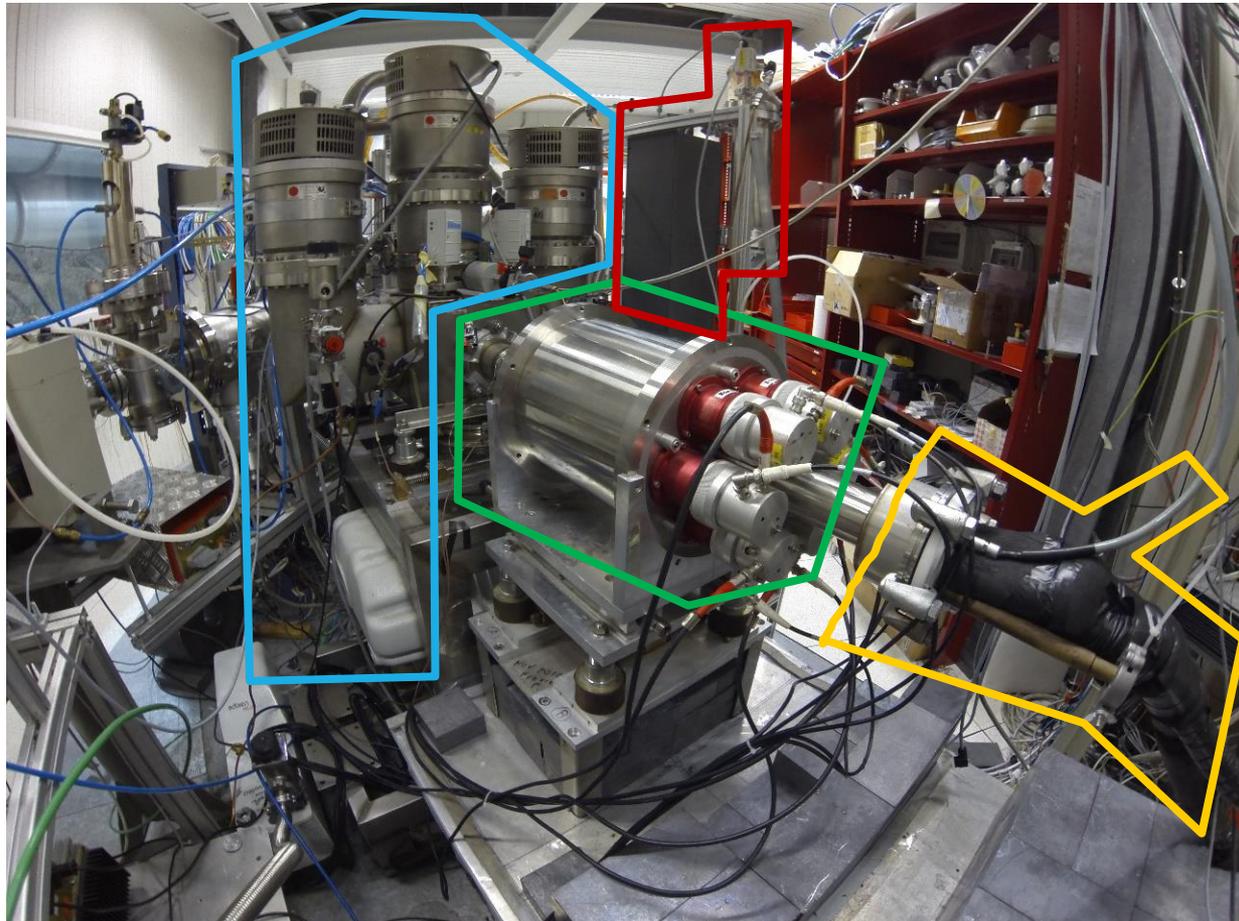
Diverse valutazioni del tasso di reazione!
Cruciali le risonanze a bassa energia!



Fase BGO

Sistema di pompaggio differenziale

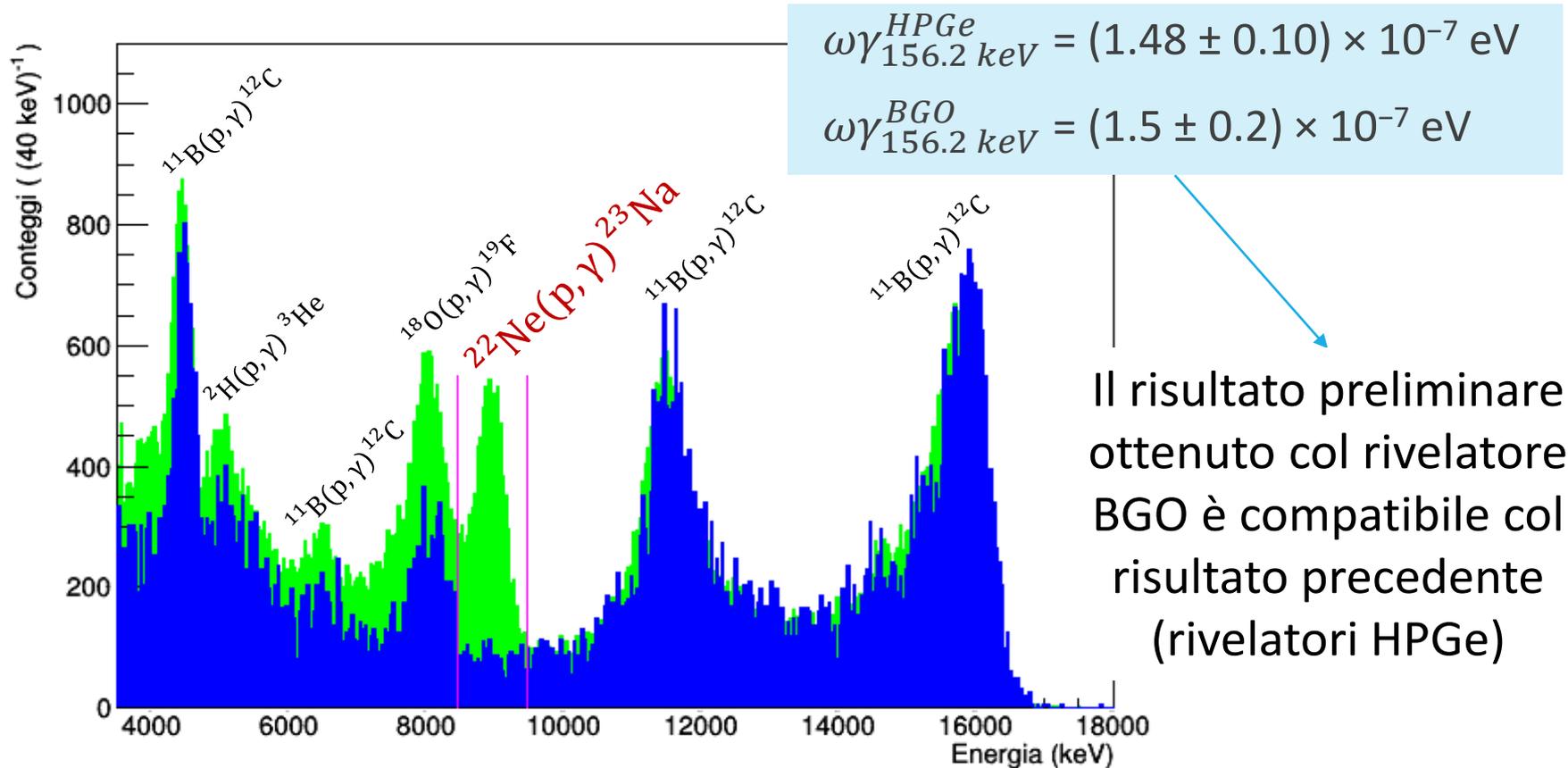
Rivelatore BGO (attorno alla camera)



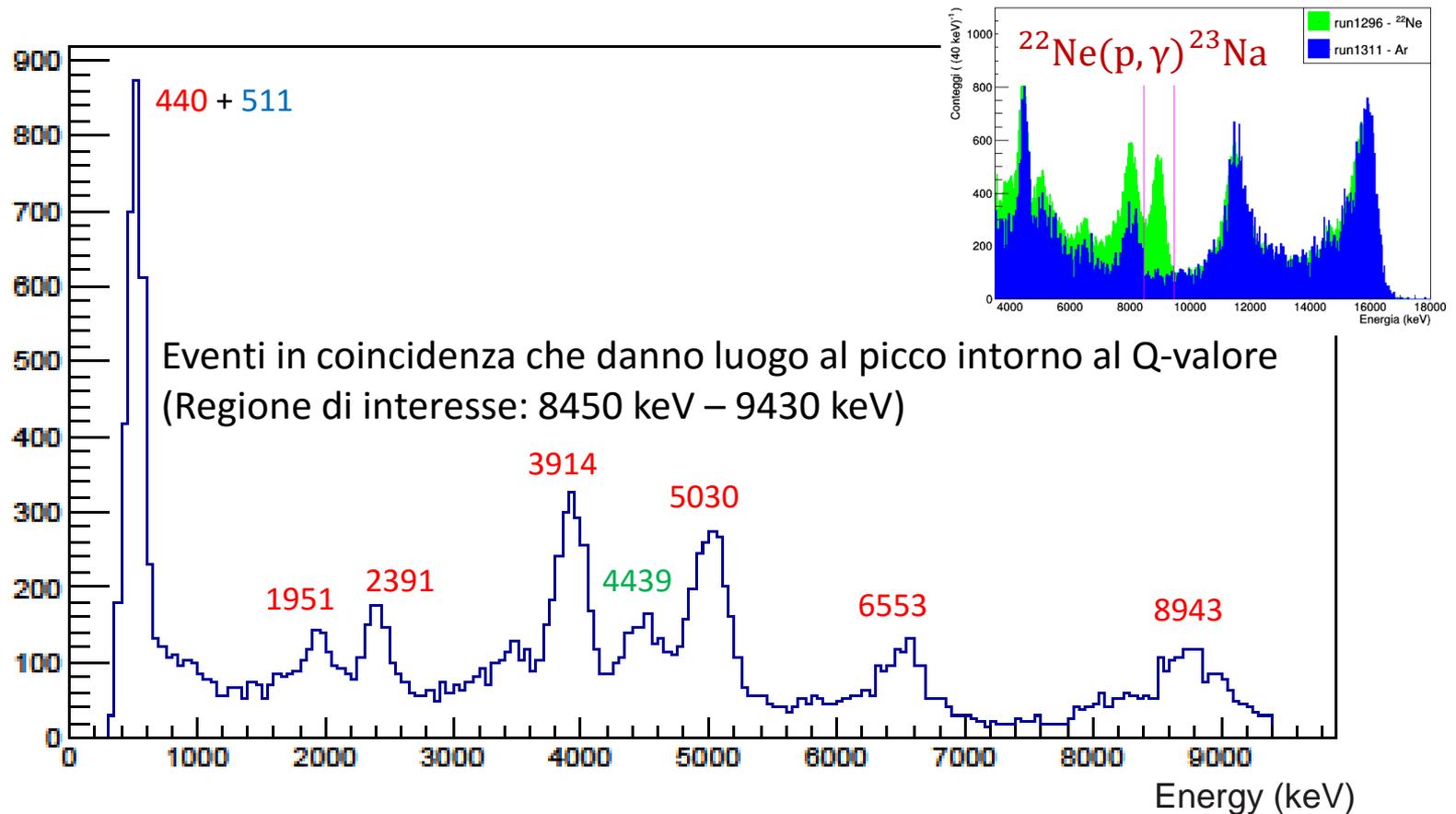
Purificatore

Connessioni del sistema di controllo del calorimetro

Risonanza a 156.2 keV

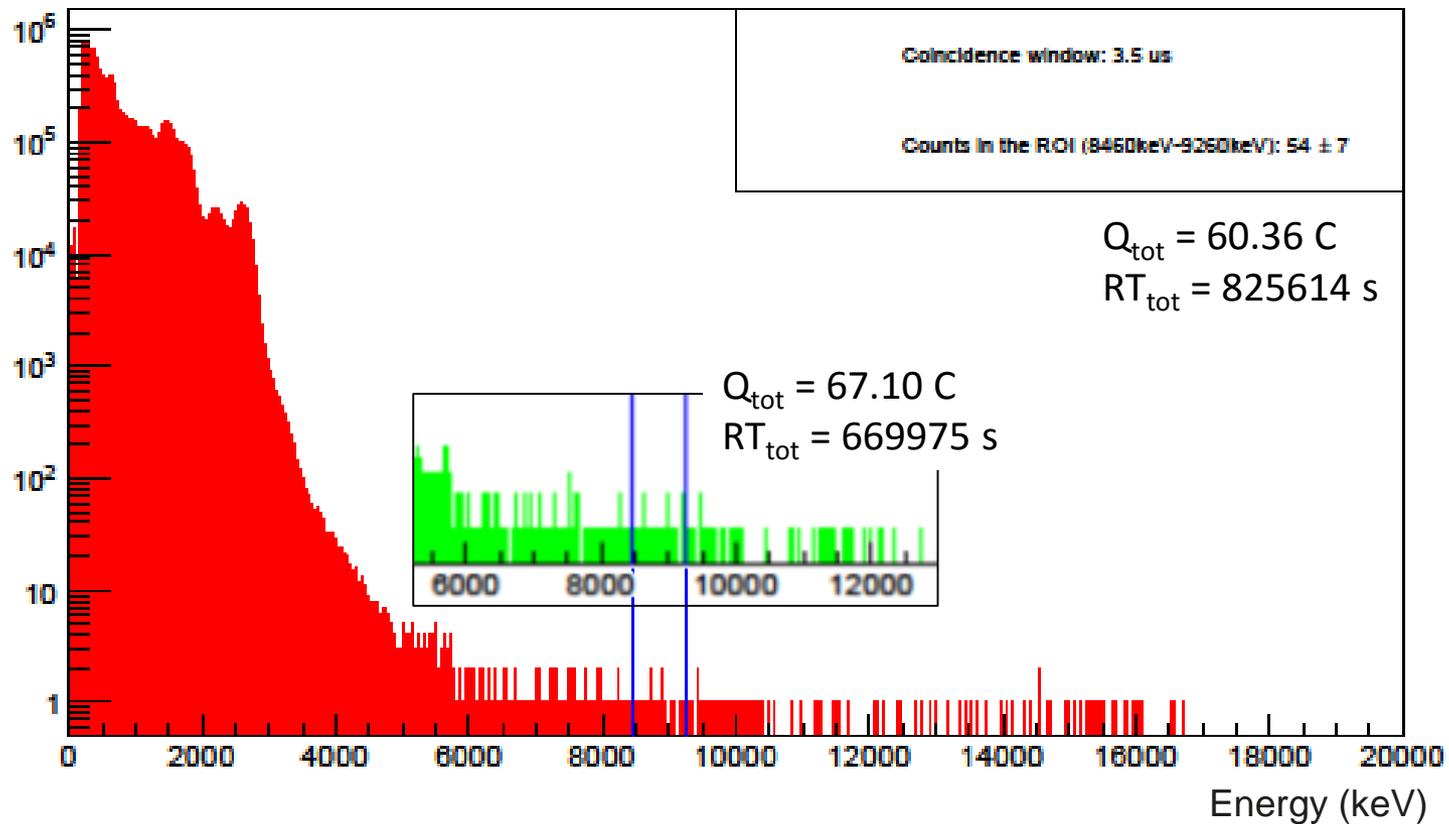


Decadimento dallo stato eccitato a 8943.5 keV del ^{23}Na

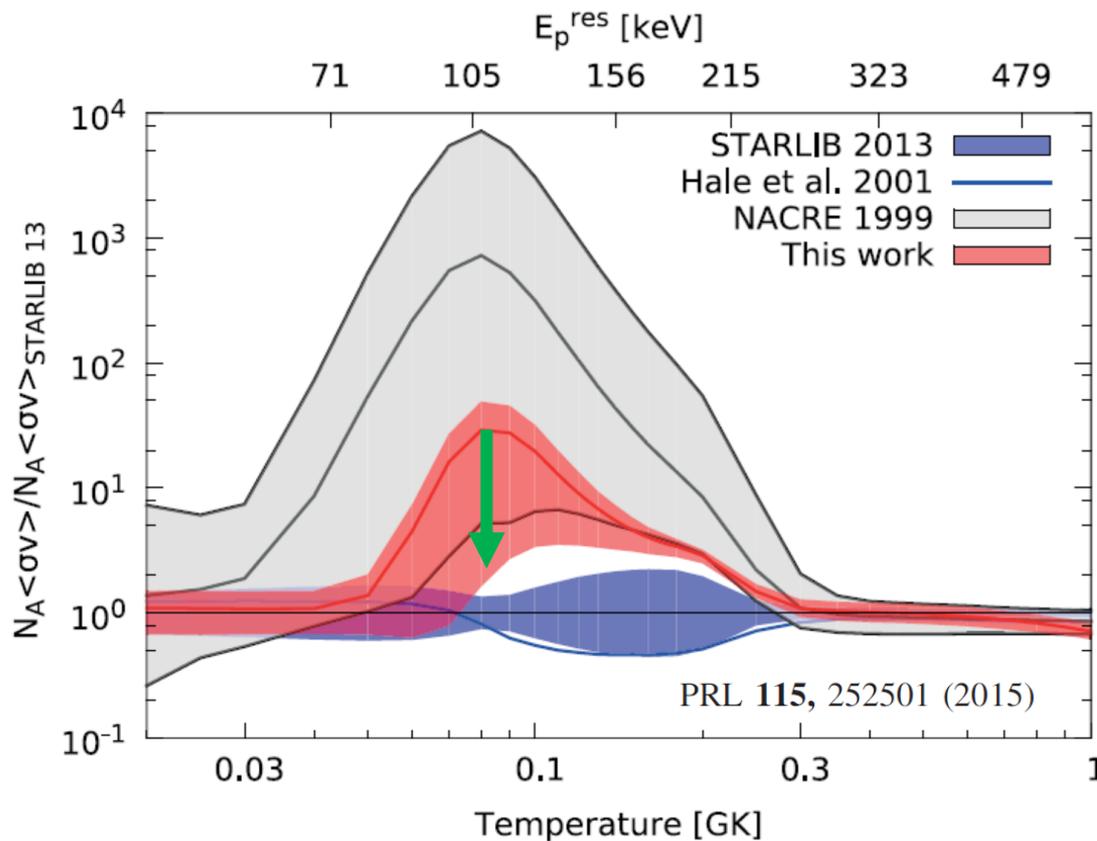


$E_p = 71 \text{ keV}$ (energia in prossimità del centro della camera)

Spettro somma



Risonanze a bassa energia risultati preliminari



$$\omega_{105 \text{ keV}}^{HPGe} \leq 7.6 \times 10^{-9} \text{ eV}$$

$$\omega_{71 \text{ keV}}^{HPGe} \leq 1.5 \times 10^{-9} \text{ eV}$$

HPGe



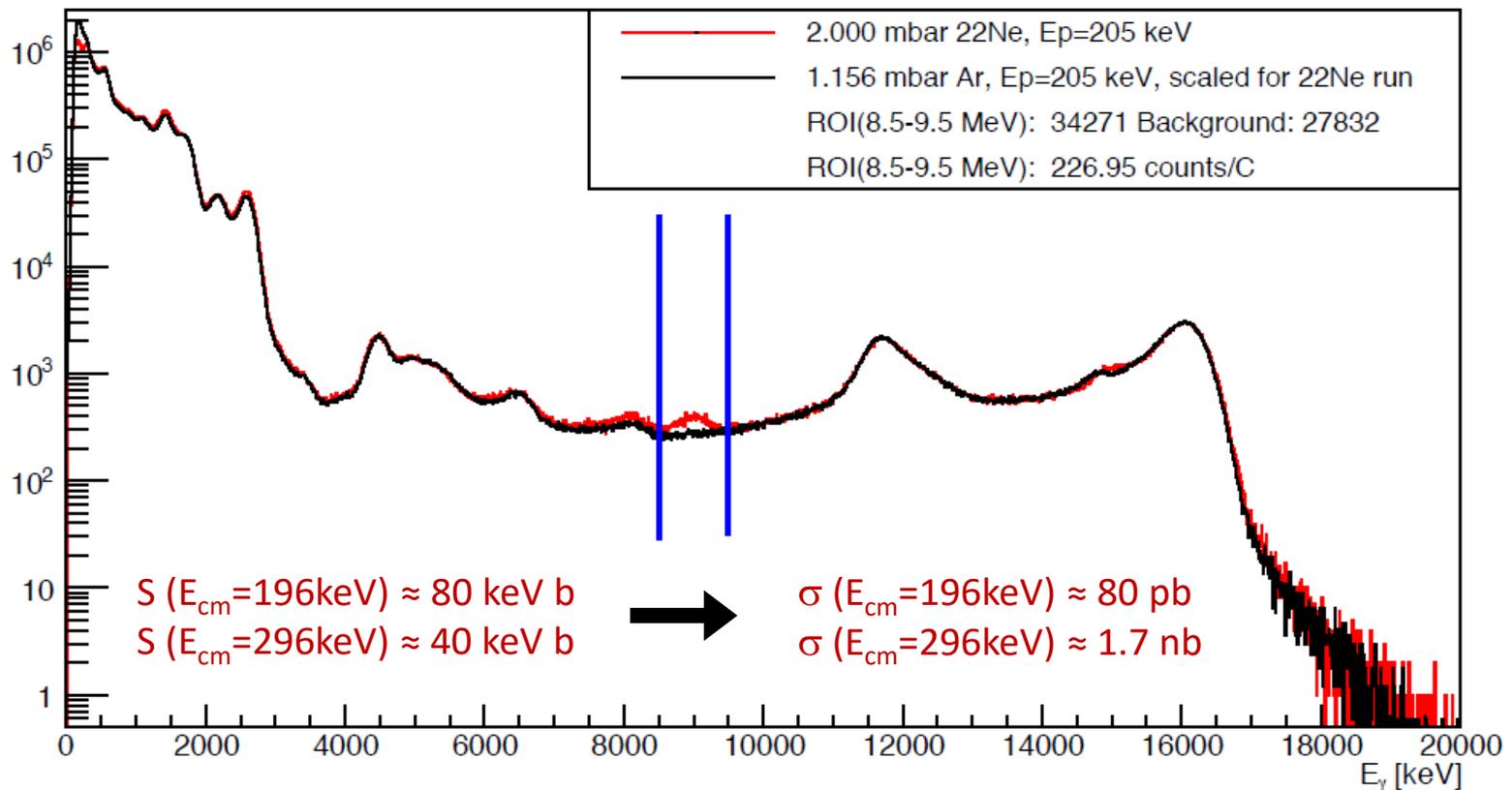
$$\omega_{105 \text{ keV}}^{BGO} \leq 5.3 \times 10^{-11} \text{ eV}$$

$$\omega_{71 \text{ keV}}^{BGO} \leq 2.1 \times 10^{-11} \text{ eV}$$

BGO

Cattura diretta risultati preliminari

2.000 mbar ^{22}Ne , $E_p=205$ keV



Conclusioni

COSA ABBIAMO FATTO NEGLI ULTIMI TEMPI...

- Abbiamo **osservato direttamente per la prima volta 3 risonanze** (fase HPGe della misura)
- Sono stati **posti limiti superiori molto più stringenti** di quelli presenti in letteratura, risolvendo un problema nella determinazione del tasso di reazione stellare
- É stato **misurato il contributo non risonante** alla sezione d'urto a 205 keV e 310 keV

COSA ABBIAMO IN MENTE PER IL FUTURO?

- Dobbiamo misurare il contributo non risonante alla sezione d'urto in altri due punti, così da poter compiere un'**estrapolazione a bassa energia**
- Misureremo entro fine anno la sezione d'urto della reazione $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ utilizzando lo stesso *setup*
- Molte altre reazioni da studiare
- LUNA-MV...

Grazie per l'attenzione

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Riserva

Sezione d'urto

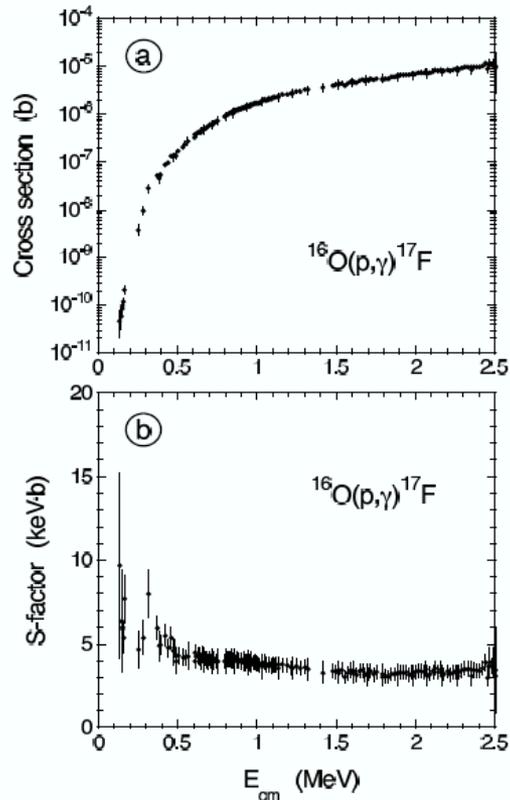


Fig. 3.10 (a) Experimental cross section and (b) astrophysical S-factor of the $^{16}\text{O}(p,\gamma)^{17}\text{F}$ reaction. Note the strongly varying cross section on a logarithmic scale in part (a) and the smooth behavior of the S-factor on a linear scale in part (b). Data from Angulo et al. (1999).

$$\sigma(E) = \underbrace{\frac{1}{E} \exp(-31.29 Z_1 Z_2 \sqrt{\mu/E})}_{\text{Fortemente variabile}} \underbrace{S(E)}_{\text{Debolmente variabile}}$$

Tasso di reazione risonante

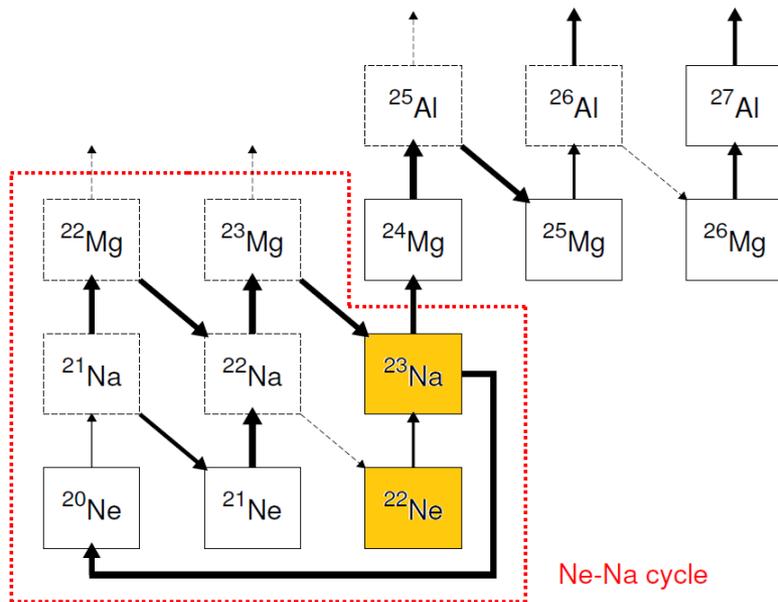
$$\sigma_{\text{BW}}(E) = \frac{\lambda^2}{4\pi} \frac{(2J+1)(1+\delta_{01})}{(2j_0+1)(2j_1+1)} \frac{\Gamma_a \Gamma_b}{(E_r - E)^2 + \Gamma^2/4}$$

$$\omega \equiv (2J+1)(1+\delta_{01})/[(2j_0+1)(2j_1+1)]$$

$$\begin{aligned} N_A \langle \sigma v \rangle &= \left(\frac{8}{\pi m_{01}} \right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty E \sigma_{\text{BW}}(E) e^{-E/kT} dE \\ &= N_A \frac{\sqrt{2\pi} \hbar^2}{(m_{01} kT)^{3/2}} \omega \int_0^\infty \frac{\Gamma_a \Gamma_b}{(E_r - E)^2 + \Gamma^2/4} e^{-E/kT} dE \end{aligned}$$

$$\begin{aligned} N_A \langle \sigma v \rangle &= N_A \frac{\sqrt{2\pi} \hbar^2}{(m_{01} kT)^{3/2}} e^{-E_r/kT} \omega \frac{\Gamma_a \Gamma_b}{\Gamma} 2 \int_0^\infty \frac{\Gamma/2}{(E_r - E)^2 + \Gamma^2/4} dE \\ &= N_A \frac{\sqrt{2\pi} \hbar^2}{(m_{01} kT)^{3/2}} e^{-E_r/kT} \omega \frac{\Gamma_a \Gamma_b}{\Gamma} 2\pi \\ &= N_A \left(\frac{2\pi}{m_{01} kT} \right)^{3/2} \hbar^2 e^{-E_r/kT} \omega \gamma \end{aligned}$$

Il ciclo NeNa



- Ciclo di combustione dell'idrogeno
- Influenza la nucleosintesi degli elementi tra ^{20}Ne e ^{26}Al (collegamento al ciclo MgAl)
- Attivo nelle stelle RGB, AGB (HBB) e nelle esplosioni di CN e SN Ia

J. Marion and W. Fowler, ApJ 125 221-32 (1957)
C. Iliadis et al., ApJSS 142, 105-137 (2002)
N. Prantzos et al., A&A 470, 179190 (2007)
R. G. Izzard et al., A&A 466, 641 (2007)
E. Carretta et al., A&A 505, 117 (2009)
A. Parikh et al., A&A 557, A3 (2013)

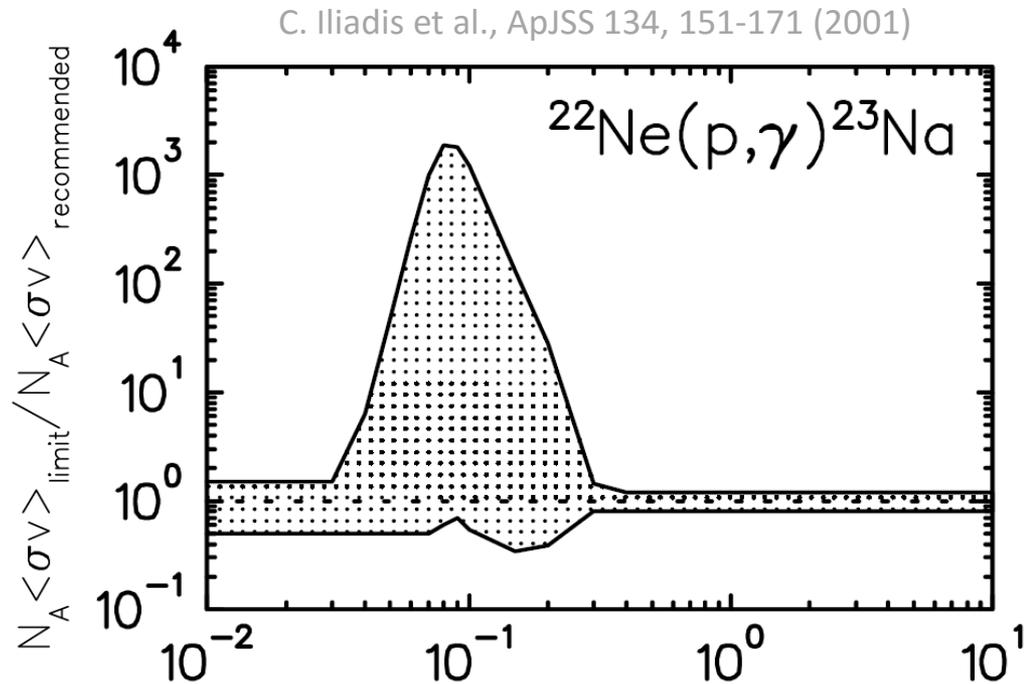
2007

La reazione $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

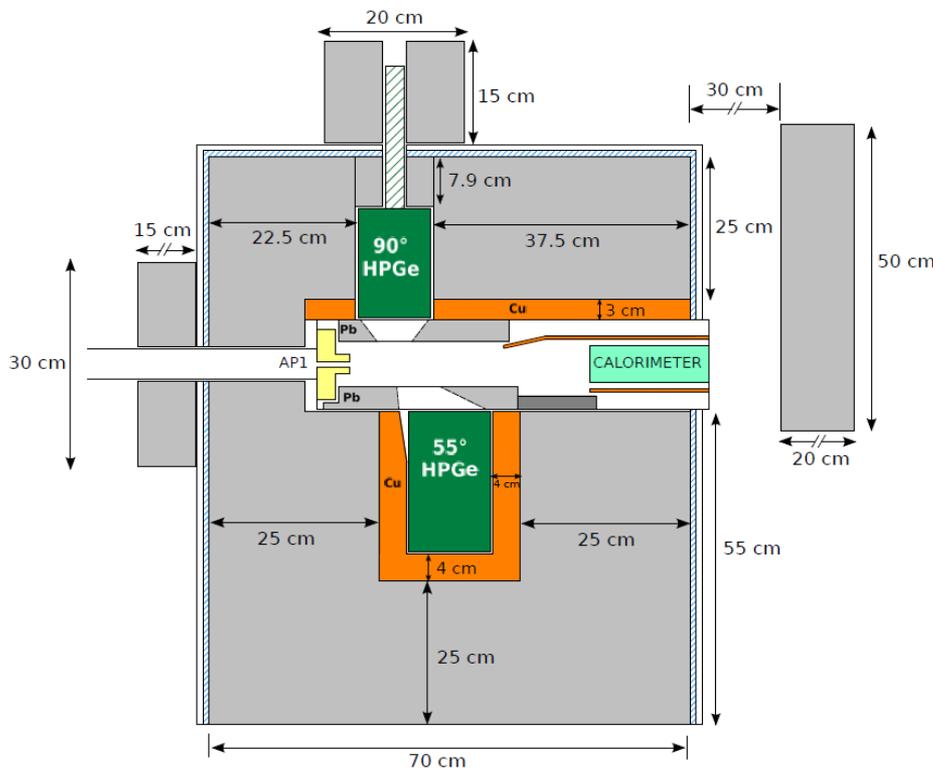
E_p [keV]	E [keV]	$J\pi$
436 →	9211.02	3/2+
394 →	9171	
369 →	9147	
333 →	9103	9113
323 →		
291 →	9072	
256 →	9038.7	
215 →	9000?	
186 →	8972	3/2+, 5/2+
159 →	8946	5/2-, 7/2-
104 →	8894?	1/2+
71 →	8862?	1/2+
37 →	8822	8829.5
29 →		
3 →	8797	(9/2, 11/2)-
	0	3/2+

^{23}Na

- Molti stati eccitati
- Alcuni di essi non sono mai stati osservati direttamente



Fase HPGe



- HPGe @ 90° (90% rel. eff.)
- HPGe @ 55° (137% rel. eff.)
- 22-25 cm Pb
- Contenitore anti-radon
- sostegno da 4 cm di Cu per HPGe @ 55°
- Schermatura di Pb dentro alla camera
- Schermatura di W in prossimità del calorimetro
- Schermatura di Pb sul retro

UNDERGROUND LABORATORIES

LUNA observes a rare nuclear reaction that occurs in giant red stars

In December, the Laboratory for Underground Nuclear Astrophysics (LUNA) experiment (*CERN Courier* October 2004 p31) reported the first direct observation of sodium production in giant red stars, one of the nuclear reactions that are fundamental to the formation of the elements that make up the universe.

LUNA is a compact linear accelerator for light ions (maximum energy 400 keV). A unique facility, it is installed in a deep-underground laboratory and shielded from cosmic rays. The experiment aims to study the nuclear reactions that take place inside stars, where elements that make up matter are formed and then driven out by gigantic explosions and scattered as cosmic dust.

For the first time, LUNA has observed three low-energy resonances in the neon-sodium cycle, the $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$ reaction, responsible for sodium production in red giants and energy generation. LUNA recreates the energy ranges of nuclear

reactions and, with its accelerator, goes back in time to one hundred million years after the Big Bang, when the first stars formed and the processes that gave rise to the huge variety of elements in the universe started.

This result is an important piece in the puzzle of the origin of the elements in the universe, which LUNA has been studying for 25 years. Stars assemble atoms through a complex system of nuclear reactions. A very small fraction of these reactions have been studied at the energies existing inside of the stars, and a large part of those few cases have been observed using LUNA.

A high-purity germanium detector with relative efficiency up to 130% was used for this particular experiment, together with a windowless gas target filled with enriched gas. The rock surrounding the underground facility at the Gran Sasso National Laboratory and additional passive shielding protected the experiment from cosmic rays and ambient radiation, making the direct observation of such a rare process possible.



Members of the LUNA collaboration pictured next to the facility.

● Further reading

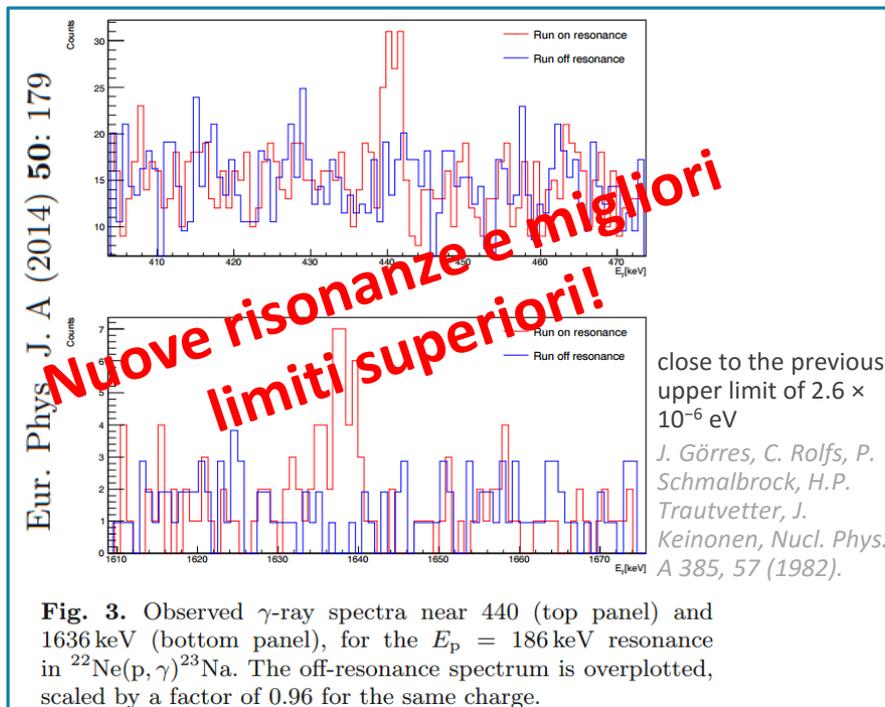
F Cavanna *et al.* (The LUNA Collaboration) 2015 *Phys. Rev. Lett.* 115 252501

Fase HPGe

- Prima misura diretta della risonanza a 189.5 keV:

$$\omega\gamma_{189.5 \text{ keV}} \geq 0.12 \times 10^{-6} \text{ eV (90\% C.L.)}$$

Eur. Phys J. A (2014) **50**: 179



- Misura precisa di $\omega\gamma_{189.5 \text{ keV}}$:

$$\omega\gamma_{189.5 \text{ keV}} = (1.87 \pm 0.06) \times 10^{-6} \text{ eV}$$

- 2 risonanze osservate direttamente per la prima volta a 259.7 keV e 156.2 keV e misura della loro forza:

$$\omega\gamma_{259.7 \text{ keV}} = (6.89 \pm 0.16) \times 10^{-6} \text{ eV}$$

$$\omega\gamma_{156.2 \text{ keV}} = (1.48 \pm 0.06) \times 10^{-7} \text{ eV}$$

- Limiti superiori sulla forza delle risonanze a 215 keV, 105 keV e 71 keV:

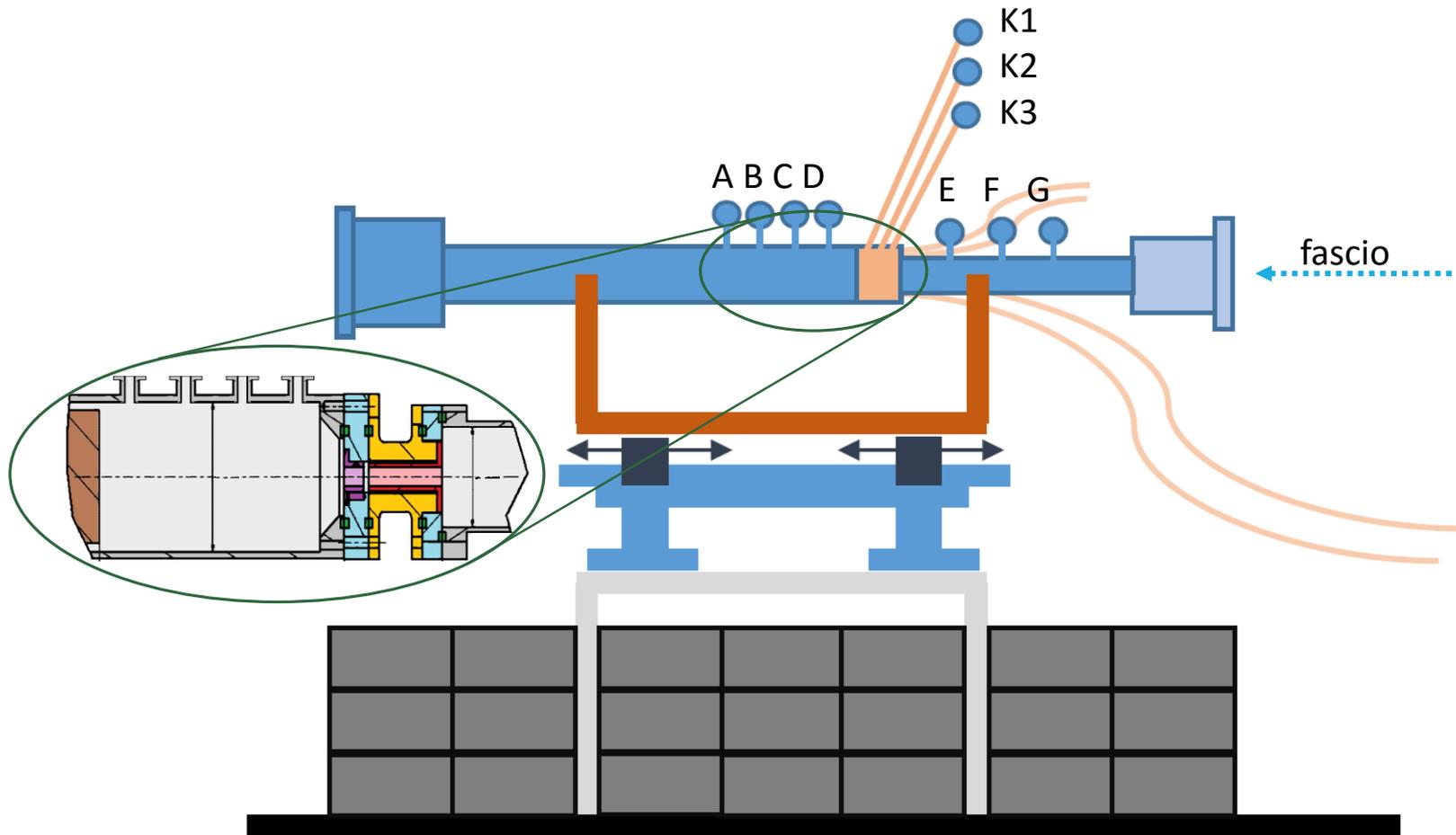
$$\omega\gamma_{215 \text{ keV}} \leq 2.8 \times 10^{-8} \text{ eV}$$

$$\omega\gamma_{105 \text{ keV}} \leq 7.6 \times 10^{-9} \text{ eV}$$

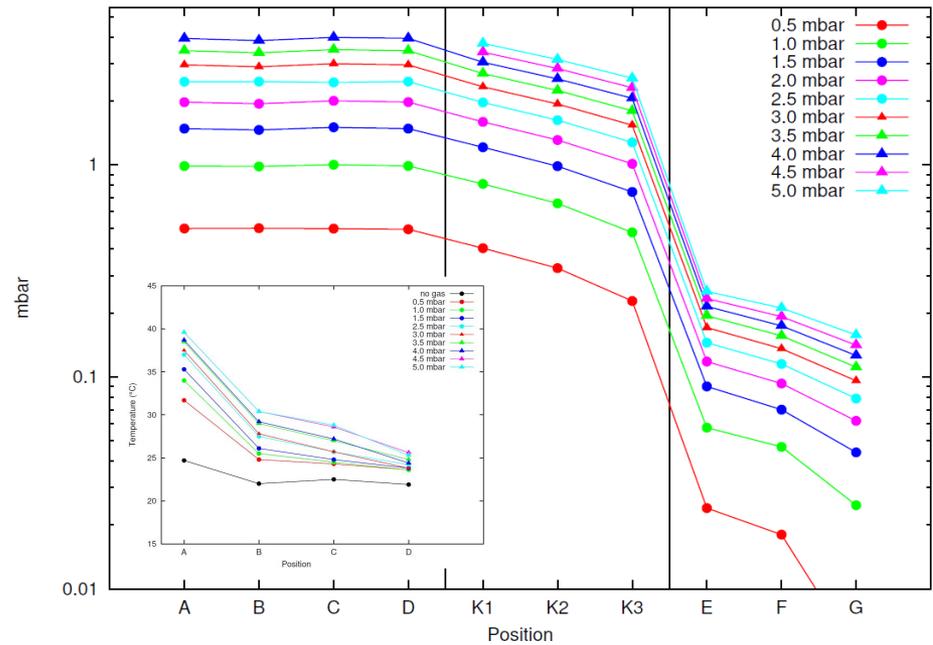
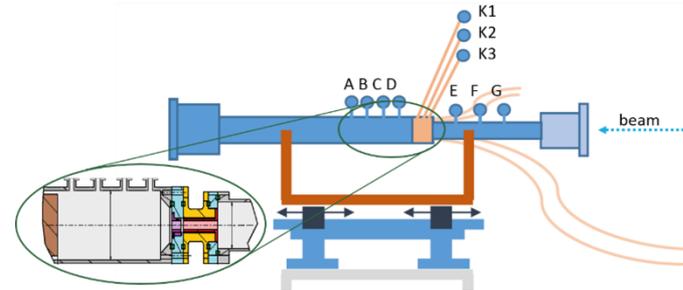
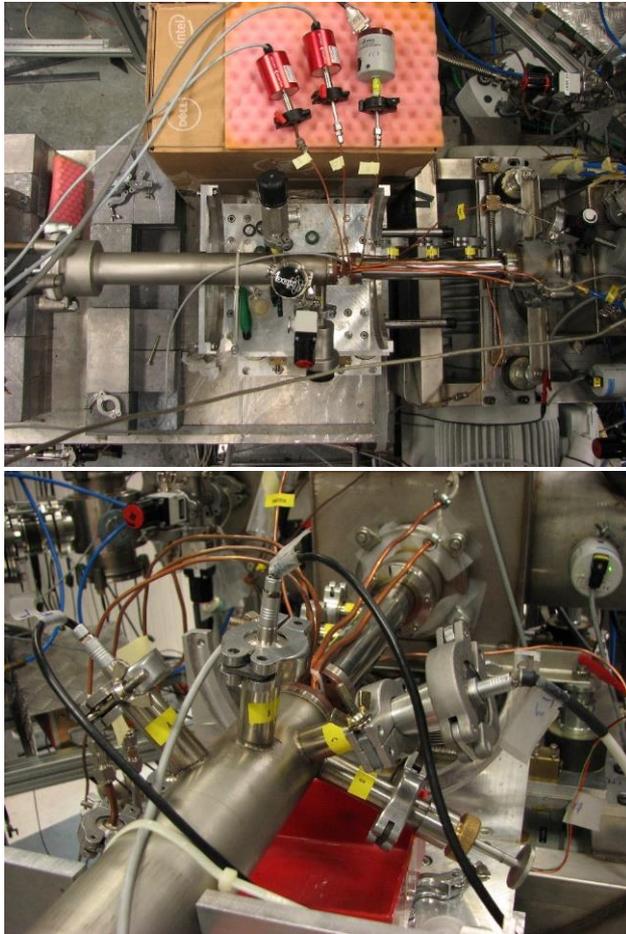
$$\omega\gamma_{71 \text{ keV}} \leq 1.5 \times 10^{-9} \text{ eV}$$

Phys. Rev. Lett. **115**, 252501

Profili di P e T

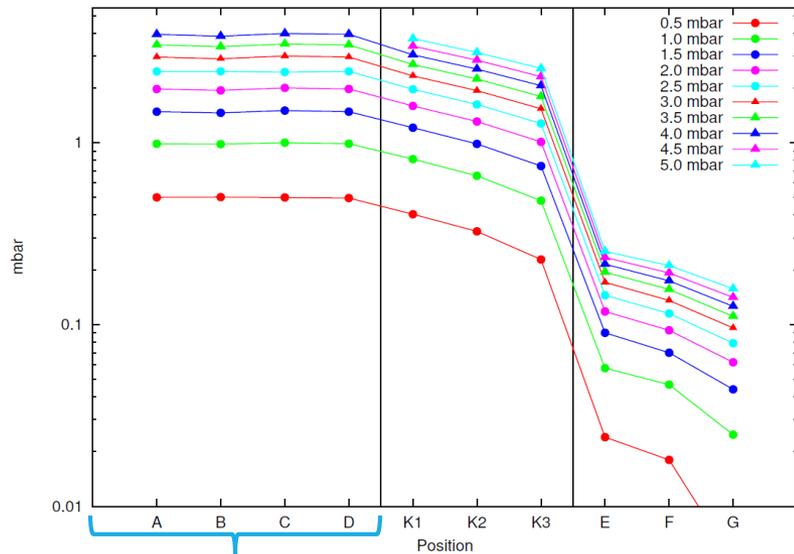


Profili di P e T

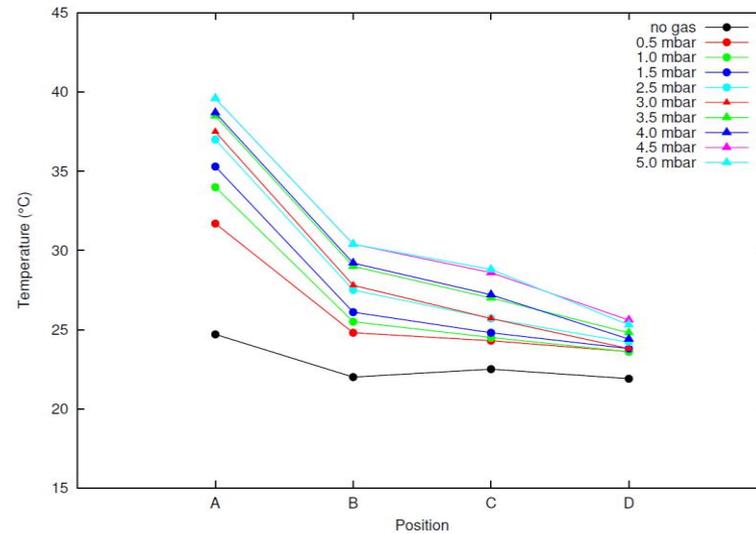


Profili di P e T

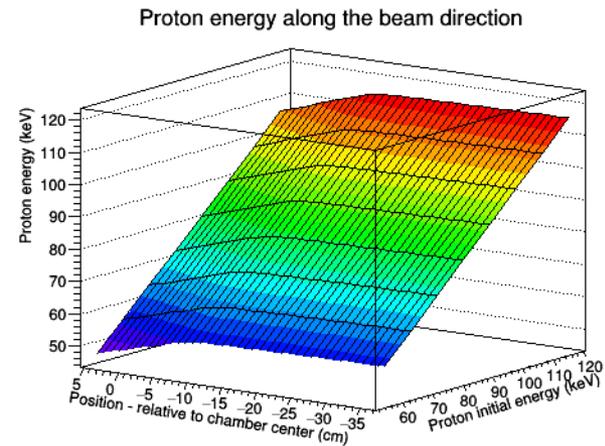
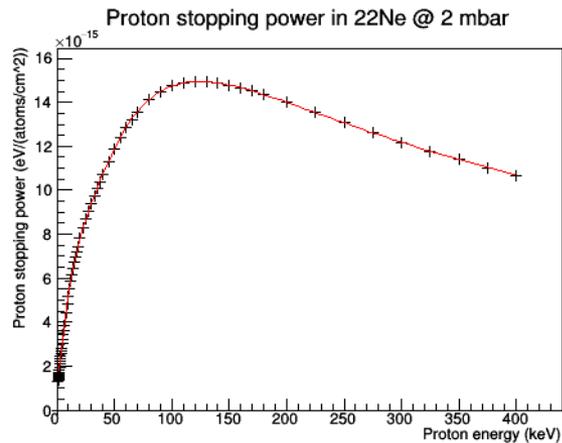
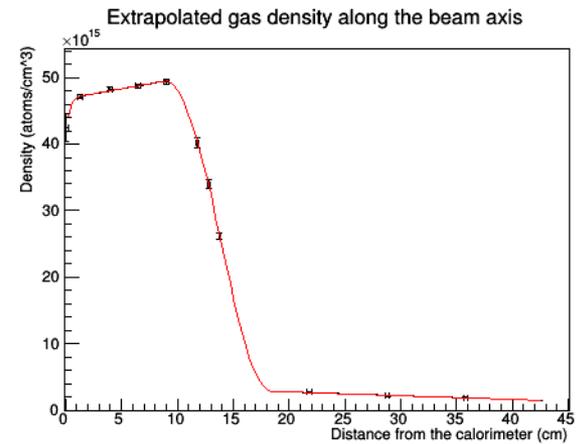
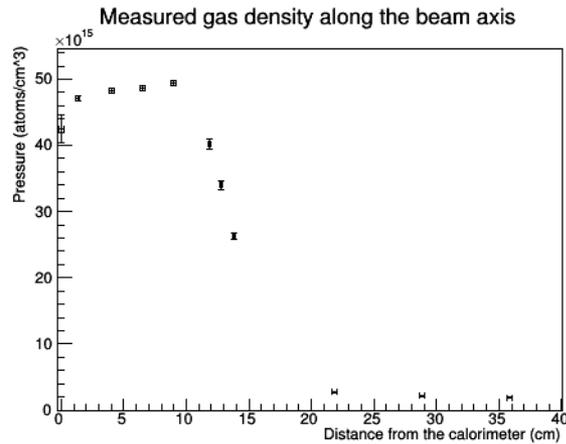
PROFILO DI PRESSIONE



PROFILO DI TEMPERATURA



Profilo di densità



Il setup del rivelatore BGO

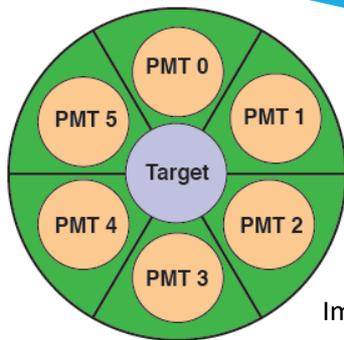
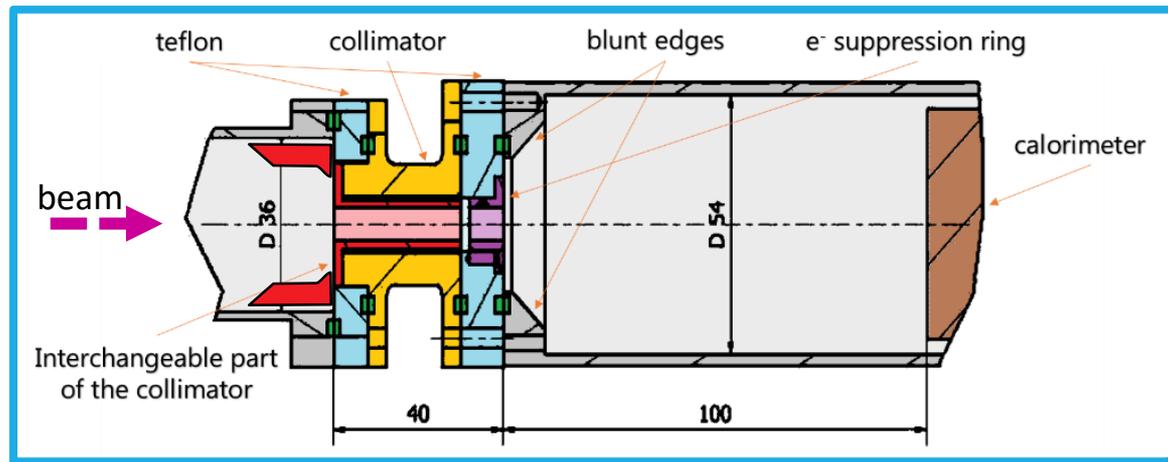
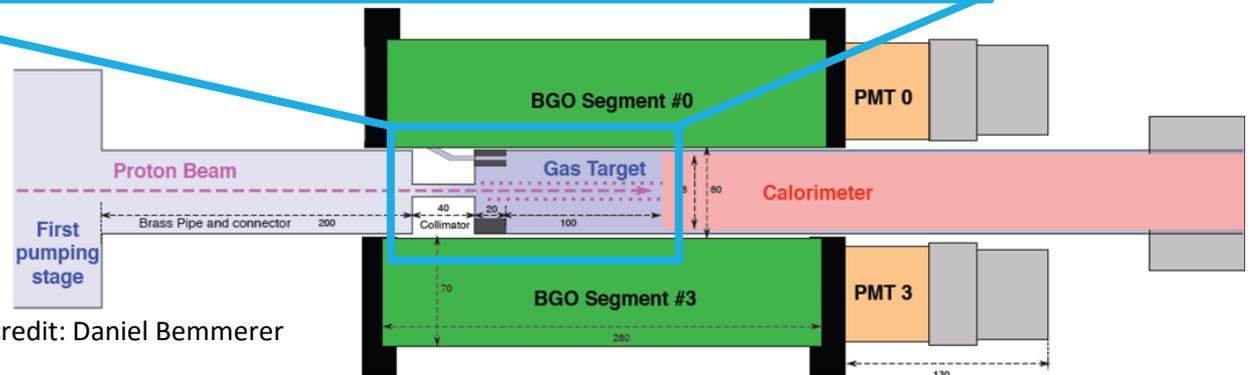
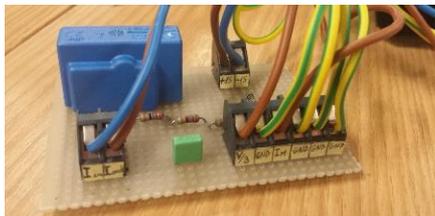


Image credit: Daniel Bemmerer



Risoluzione: ≈ 400 keV nella RdI
 Efficienza: $\approx 64\%$ nella RdI

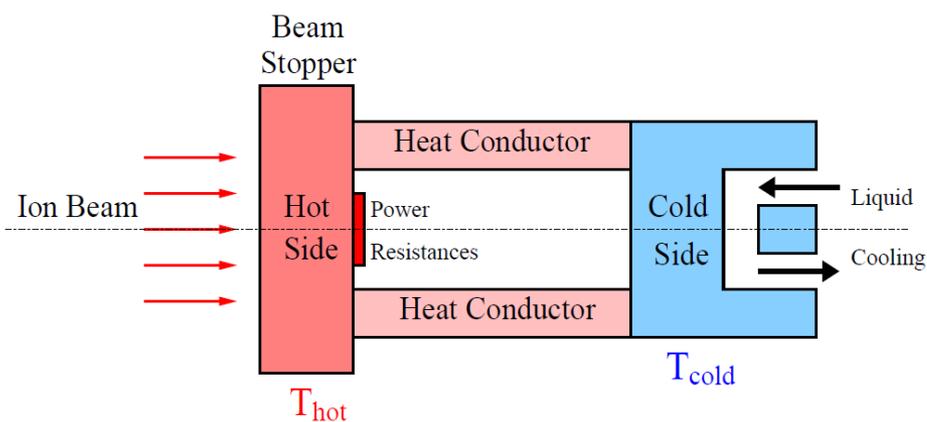
Calorimetro



$$W_{\text{beam}} = W_0 - W_{\text{run}}$$

$$I_{\text{target}} = \frac{W_{\text{beam}}}{E_{\text{cal}}} \cdot q_e$$

$$= \frac{W_0 - W_{\text{run}}}{E_p - \Delta E_{\text{target}}} \cdot q_e$$

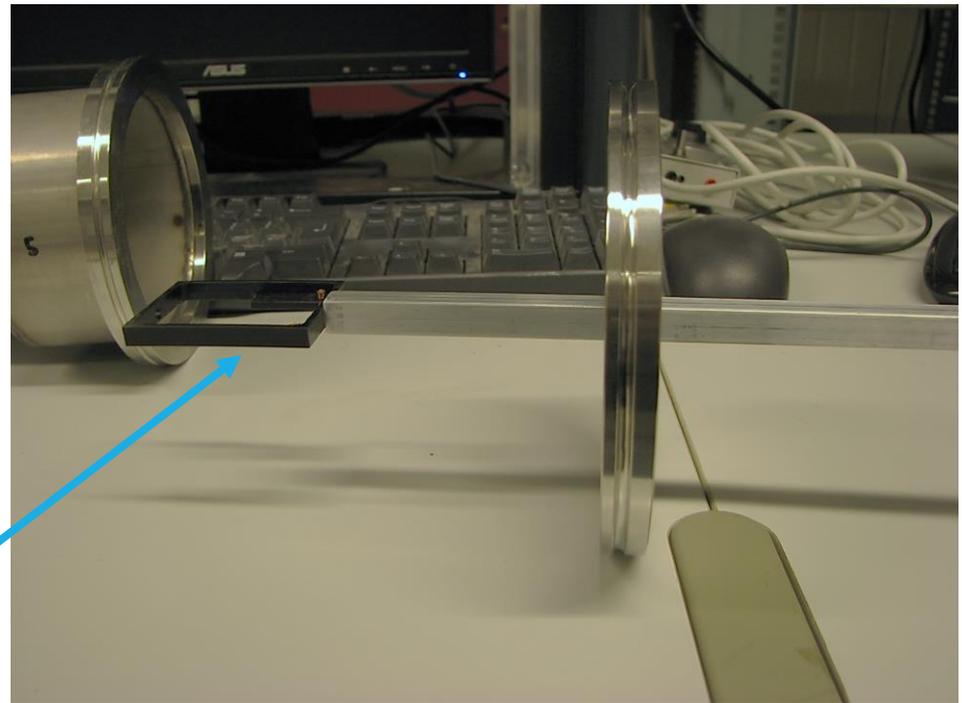


- Moduli NI-cRIO
- Controllore integrato programmato in LabVIEW
- 4 RTDs (3 lato caldo, 1 lato freddo)
- Controllo attivo della temperatura: 8 resistori di potenza
- Raffreddamento a liquido del lato freddo
- Potenza senza fascio: ~ 120 W
- Potenza con fascio: ~ 80 W

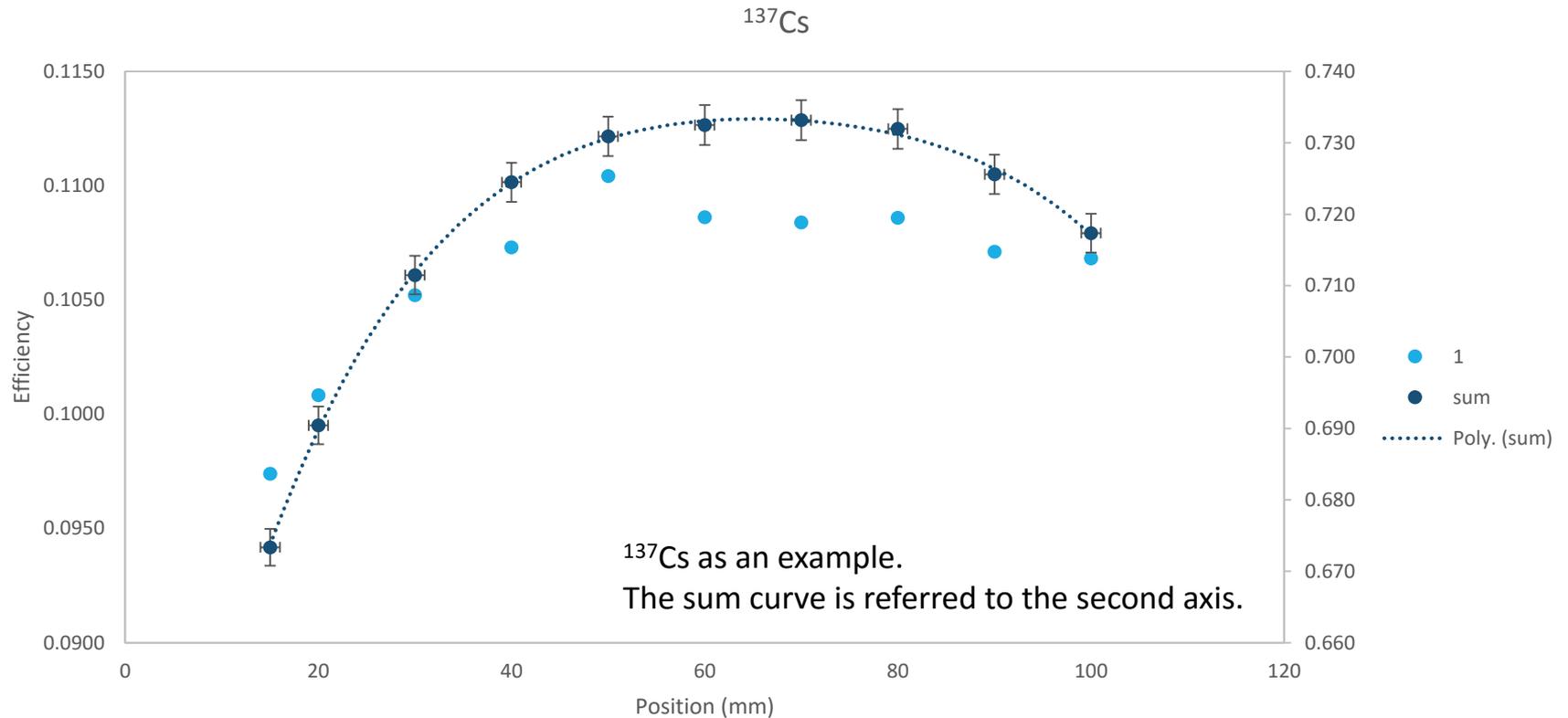
Efficienza

- Misurata lungo l'asse
- 10 posizioni (camera di 10,8 cm)
- ^{137}Cs , ^7Be , ^{88}Y , ^{60}Co , $^{14}\text{N}(p,\gamma)^{15}\text{O}$
- Sostegno in materiale leggero
- Simulazioni MC

Sostegno della
sorgente

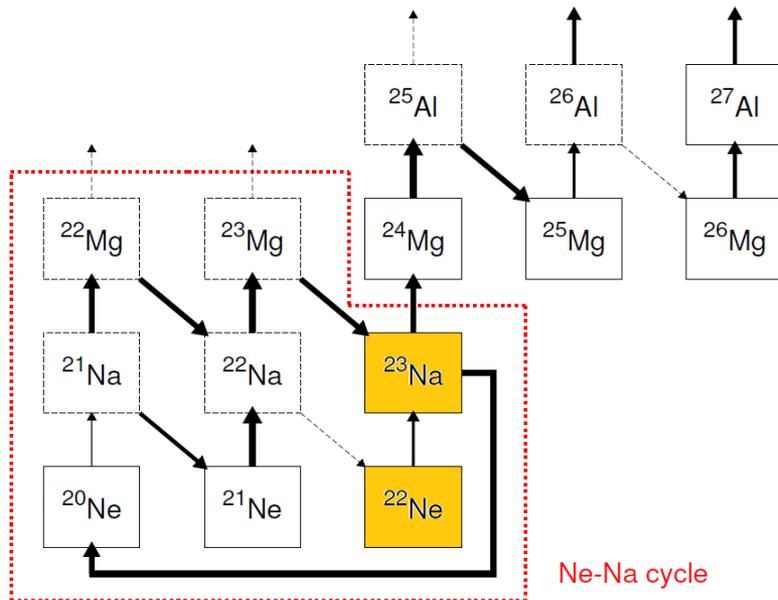


Efficienza



In corso una regolazione fine del MC
(per riprodurre i dati delle sorgenti e gli spettri in azoto)

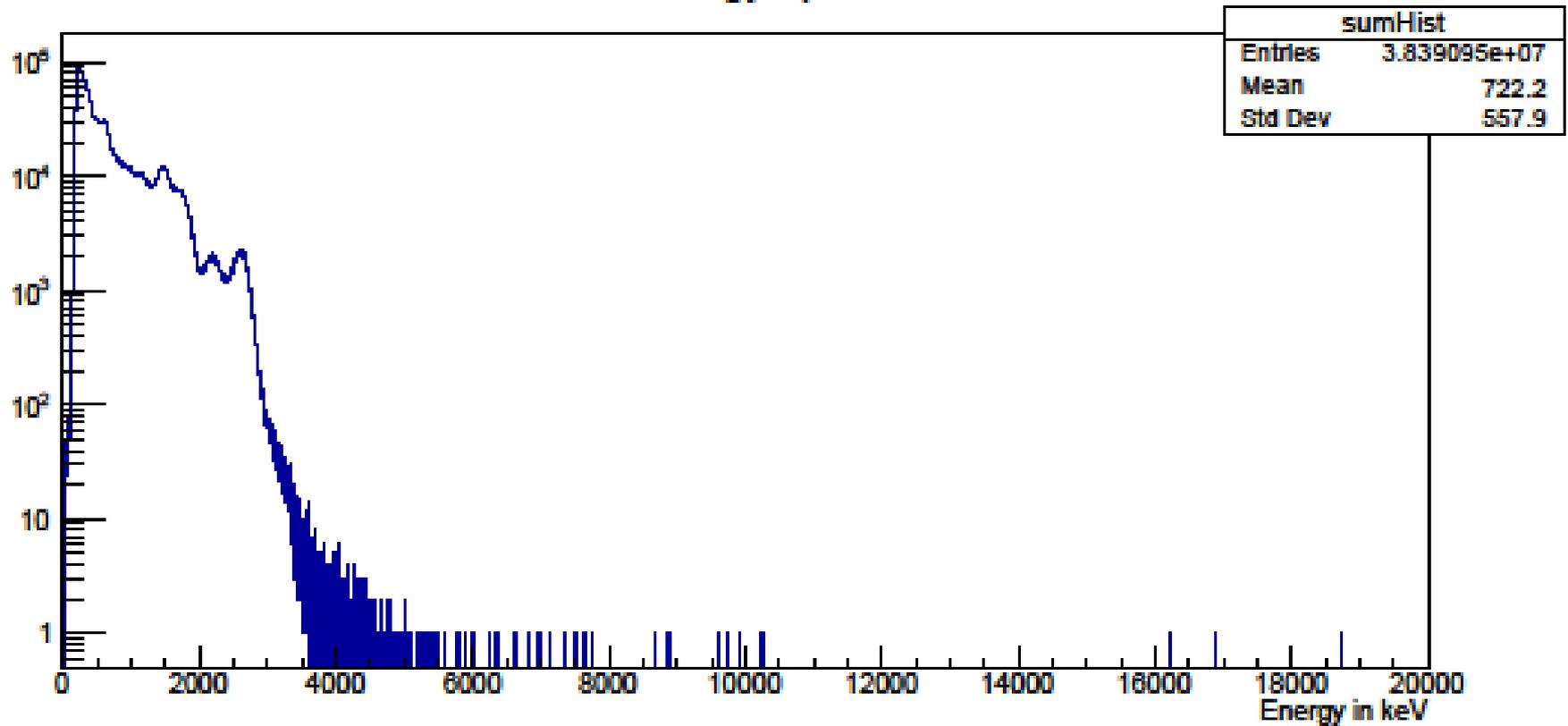
Il ciclo NeNa



- ^{22}Ne fornisce neutron per la nucleosintesi guidata dalla cattura neutronica (tramite reazione competitiva alla $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$)
- In uno scenario ricco di idrogeno, il ^{22}Ne viene distrutto prevalentemente tramite la reazione $^{22}\text{Ne}(p,\gamma)^{23}\text{Na}$

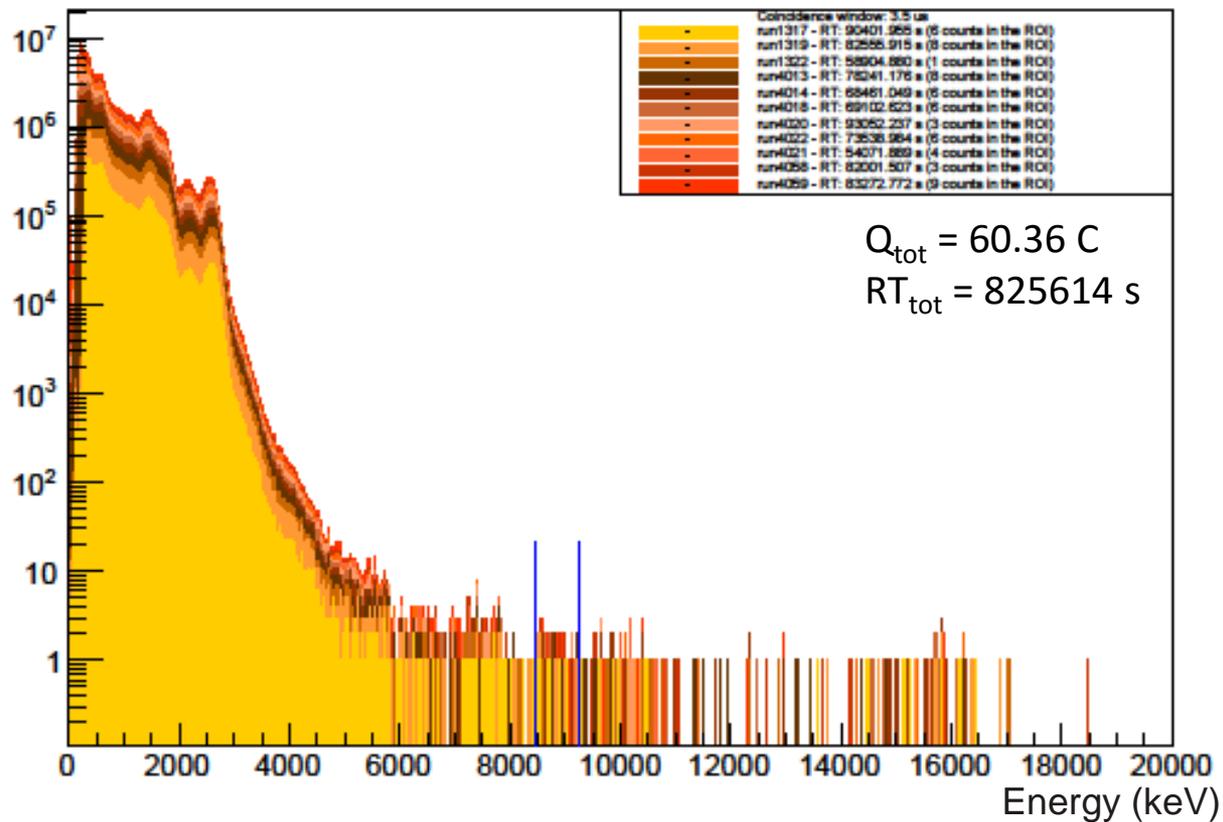
Fondo in assenza di fascio

Sum Energy Spectrum



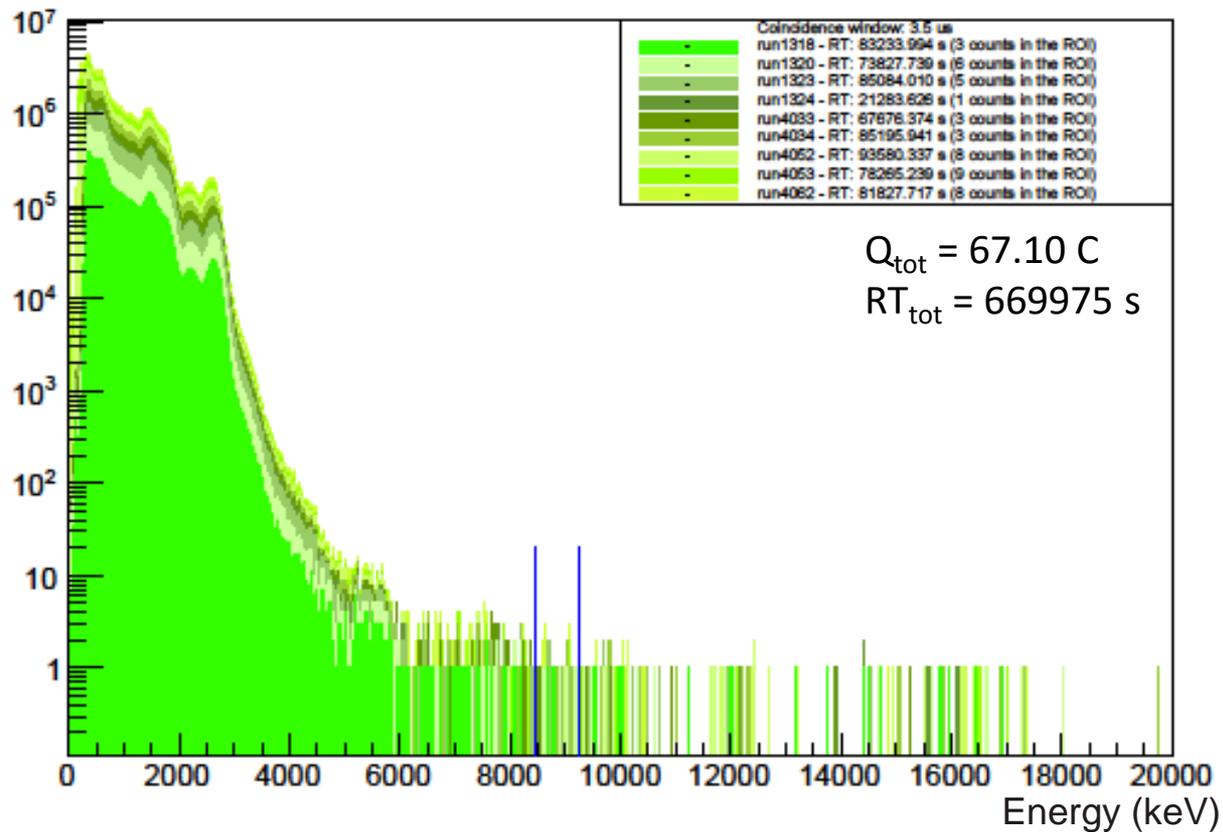
^{22}Ne @ $E_p = 71 \text{ keV}$ (al centro della camera di interazione)

Sum of different runs



Ar @ $E_p = 71$ keV (al centro della camera di interazione)

Sum of different runs



$$E_p = 105 \text{ keV}$$

Sum Energy Spectrum

