Direct measurement of the $^{22}Ne(p,\gamma)^{23}Na$ reaction cross section at LUNA

Nuclear Astrophysics at the Canfranc Underground Laboratory

2nd CUNA Workshop

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Laboratory Underground Nuclear Astrophysics

Overview

Astrophysical motivation

- The NeNa cycle
- The ^{22}Ne(p,γ)^{23}Na reaction

The experimental apparatus

- LUNA - gas target (D. Bemmerer)
- HPGe setup
- BGO setup
- Experimental methods

Measurements

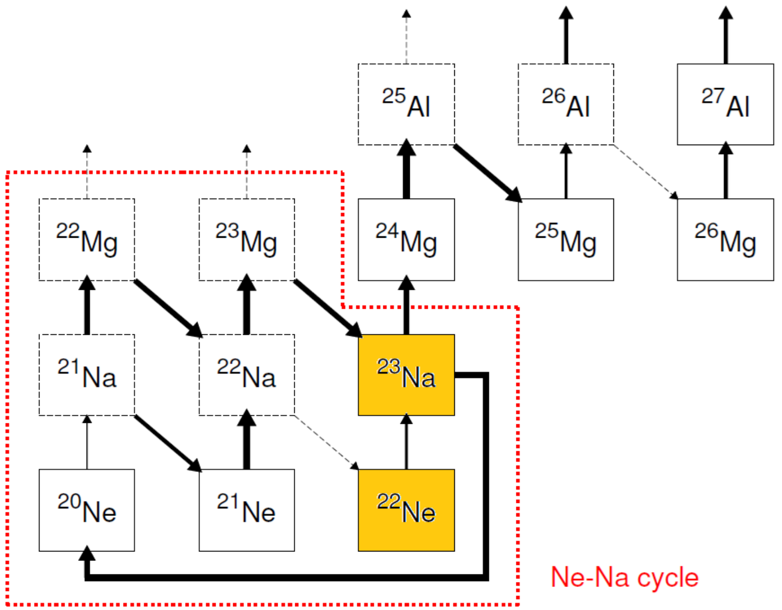
- New resonances
- New upper limits

Very quickly (Astrophysical motivation; LUNA - gas target; HPGe setup)

Some detailed information (BGO setup; Experimental methods)

Very preliminary results (Measurements)

The NeNa cycle

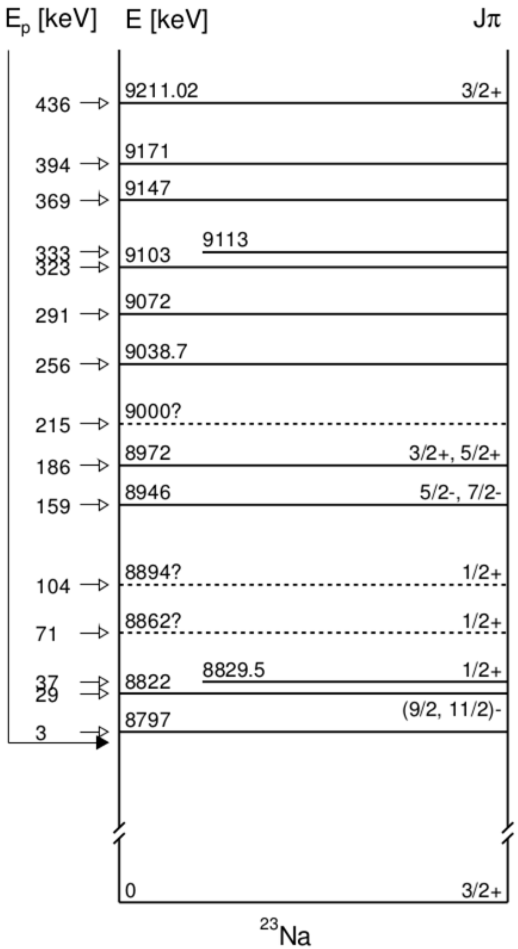


- H burning cycle
- It affects the nucleosynthesis of the elements between ^{20}Ne and ^{26}Al (link with the MgAl cycle)
- Active in RGB stars, AGB stars (HBB), CN and SN Ia

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)

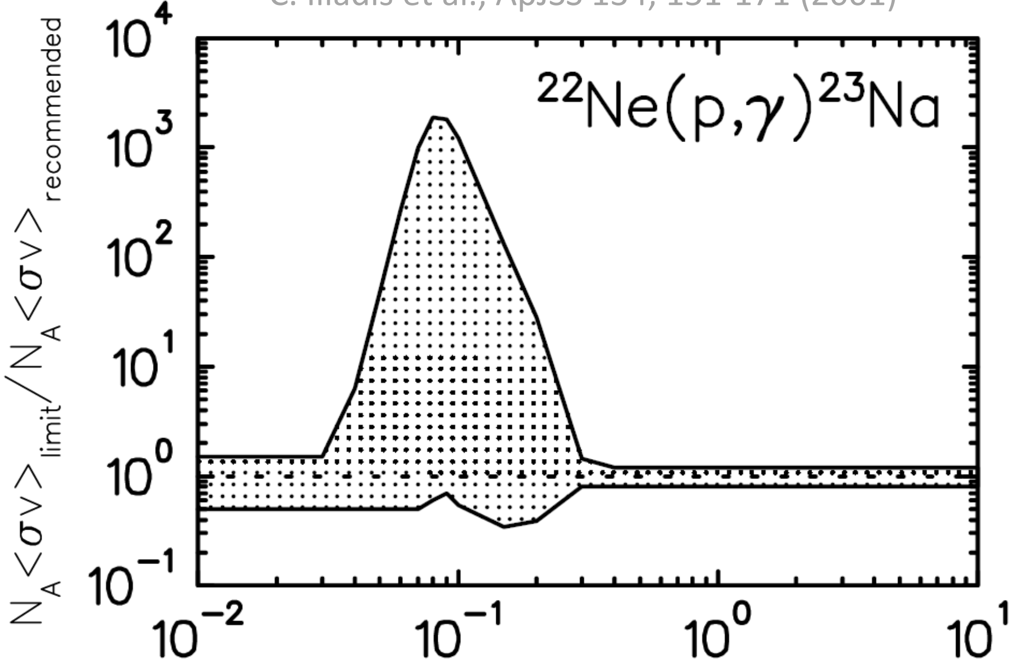
The $^{22}Ne(p,\gamma)^{23}Na$ reaction

2001



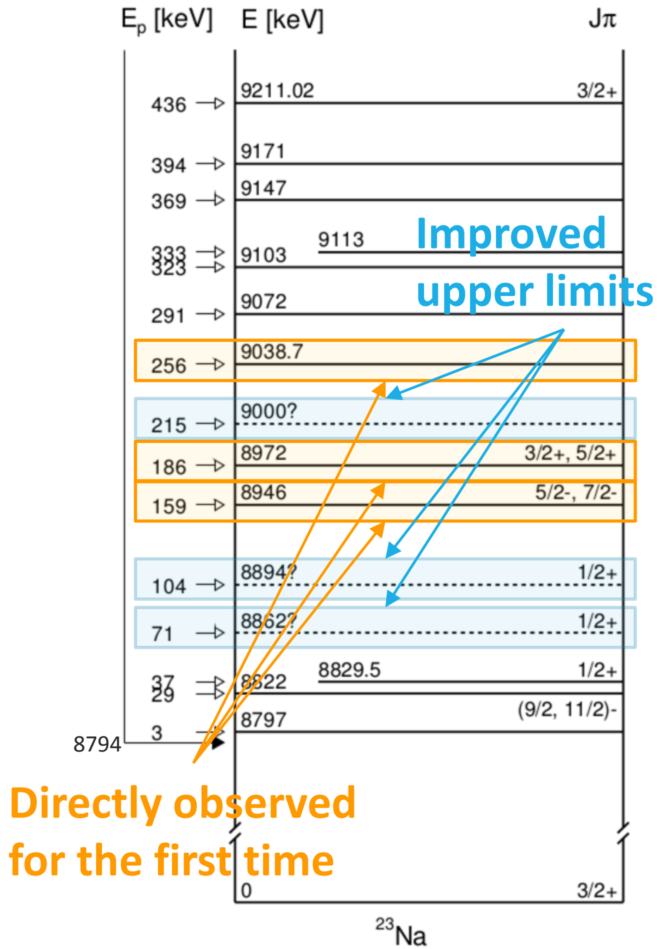
- Several excited states
- Some of them have never been directly observed

C. Iliadis et al., ApJSS 134, 151-171 (2001)

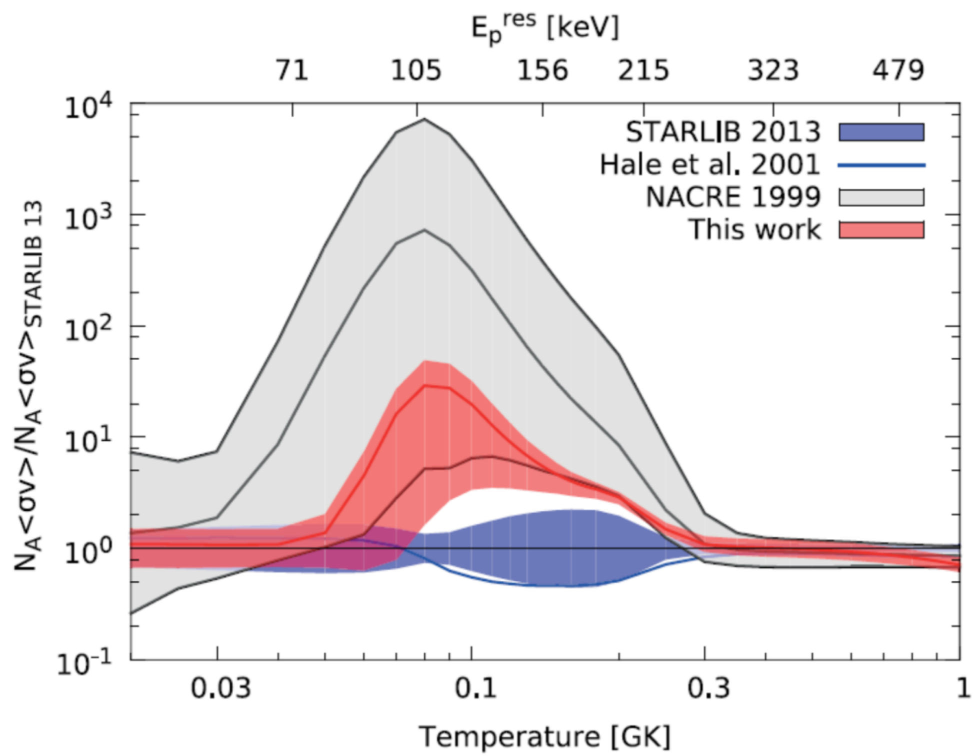


The $^{22}Ne(p,\gamma)^{23}Na$ reaction

2015



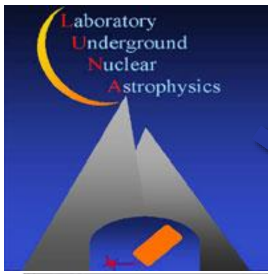
- Newly measured resonance strengths
- Still room for some improvements



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

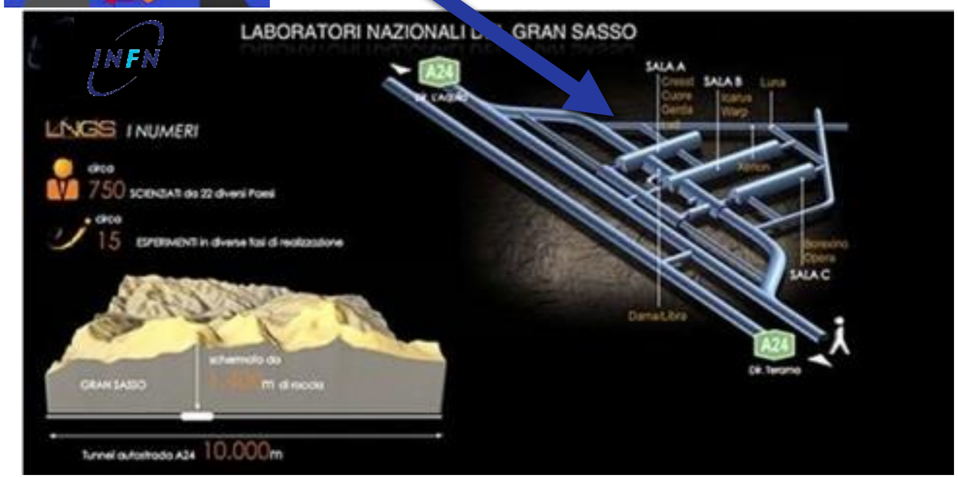
LUNA - location

[^{22}Ne ROI]



Grey: surface
Black: underground

Grey: underground with no shielding
Black: underground with lead shield



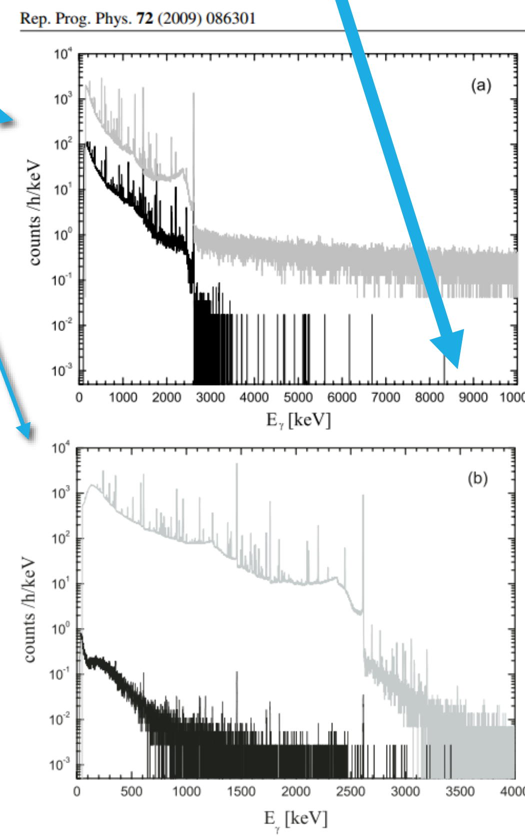
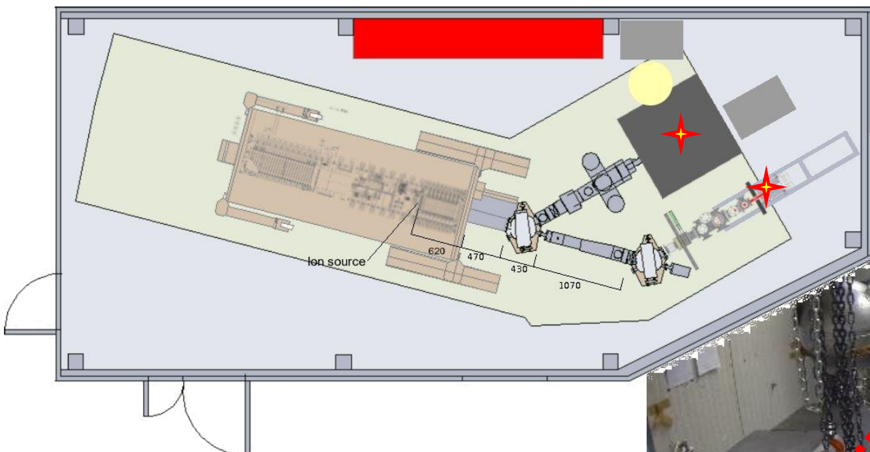


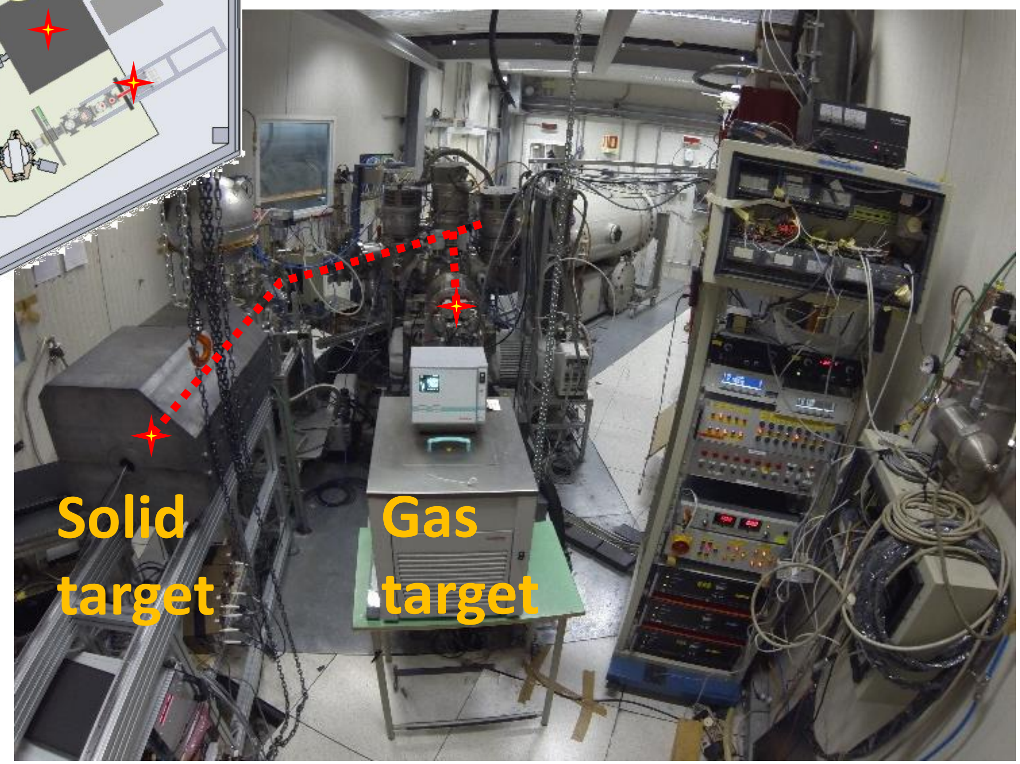
Figure 4. The upper panel illustrates spectra of γ-ray background as observed with a Ge detector placed outside (grey line) and inside (black line) of LNGS. The lower panel shows a comparison of low-energy spectra inside LNGS without lead shielding (grey line) and including a heavy lead shield (black line).

- Muon flux suppression: **10^6**
- Neutron flux suppression: **10^3**

LUNA - features

- Proton beam energy: 50-400 keV
- Beam current: up to 500 μA

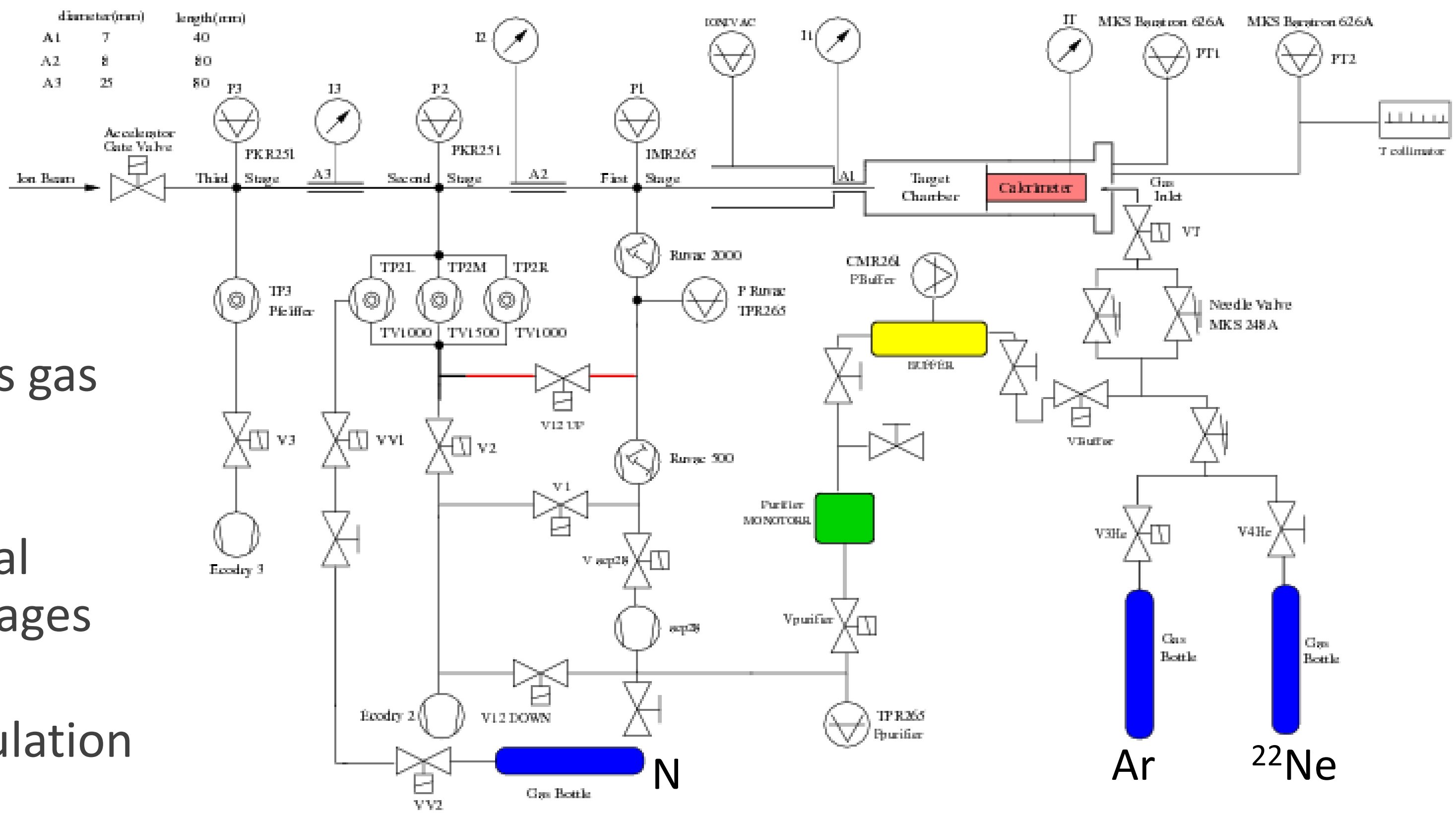




- Energy spread: 100 eV
- Long term stability: 5 eV/h

The gas target

- Windowless gas target
- 3 differential pumping stages
- Gas re-circulation system



The gas target

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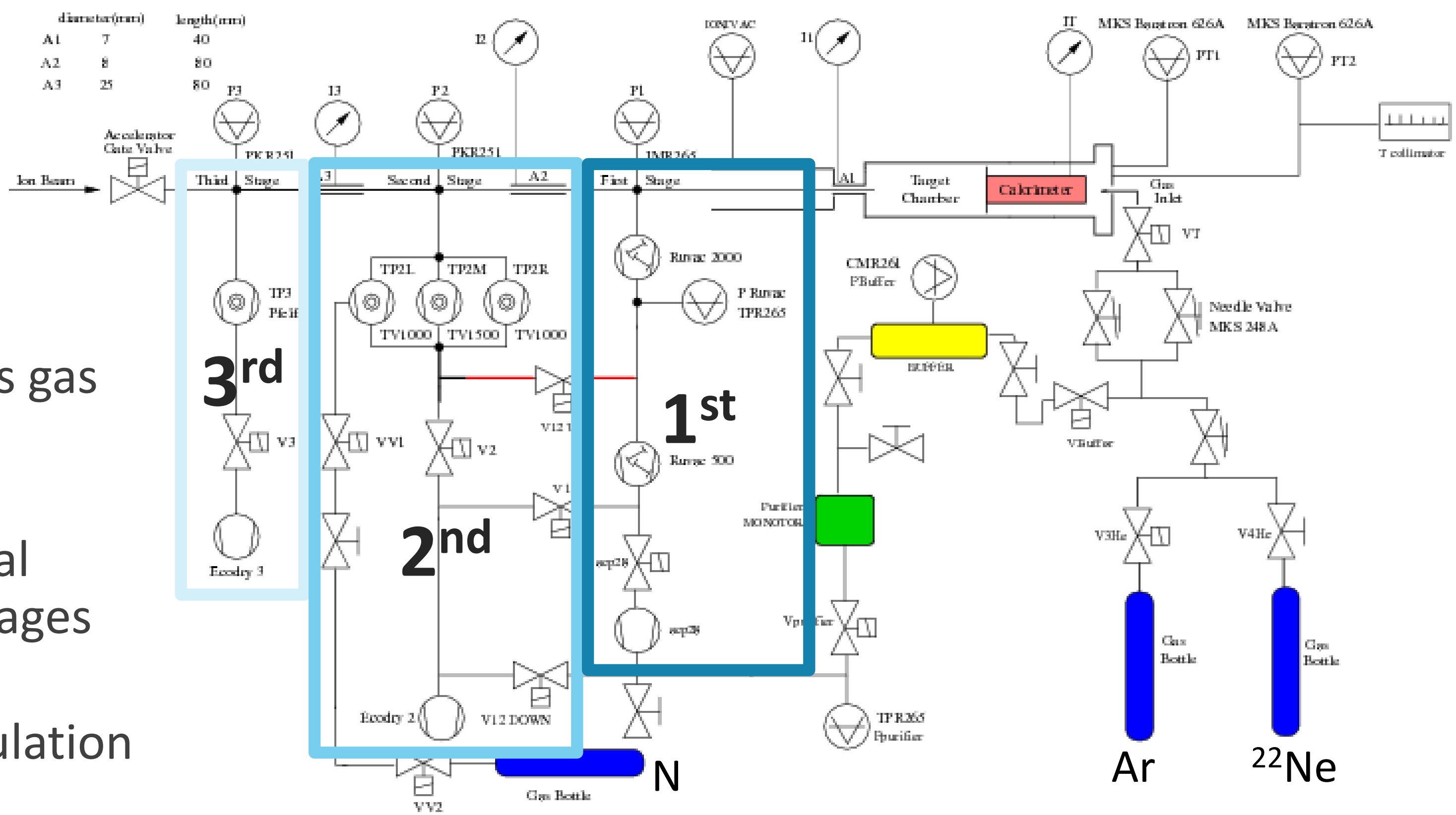

The gas target

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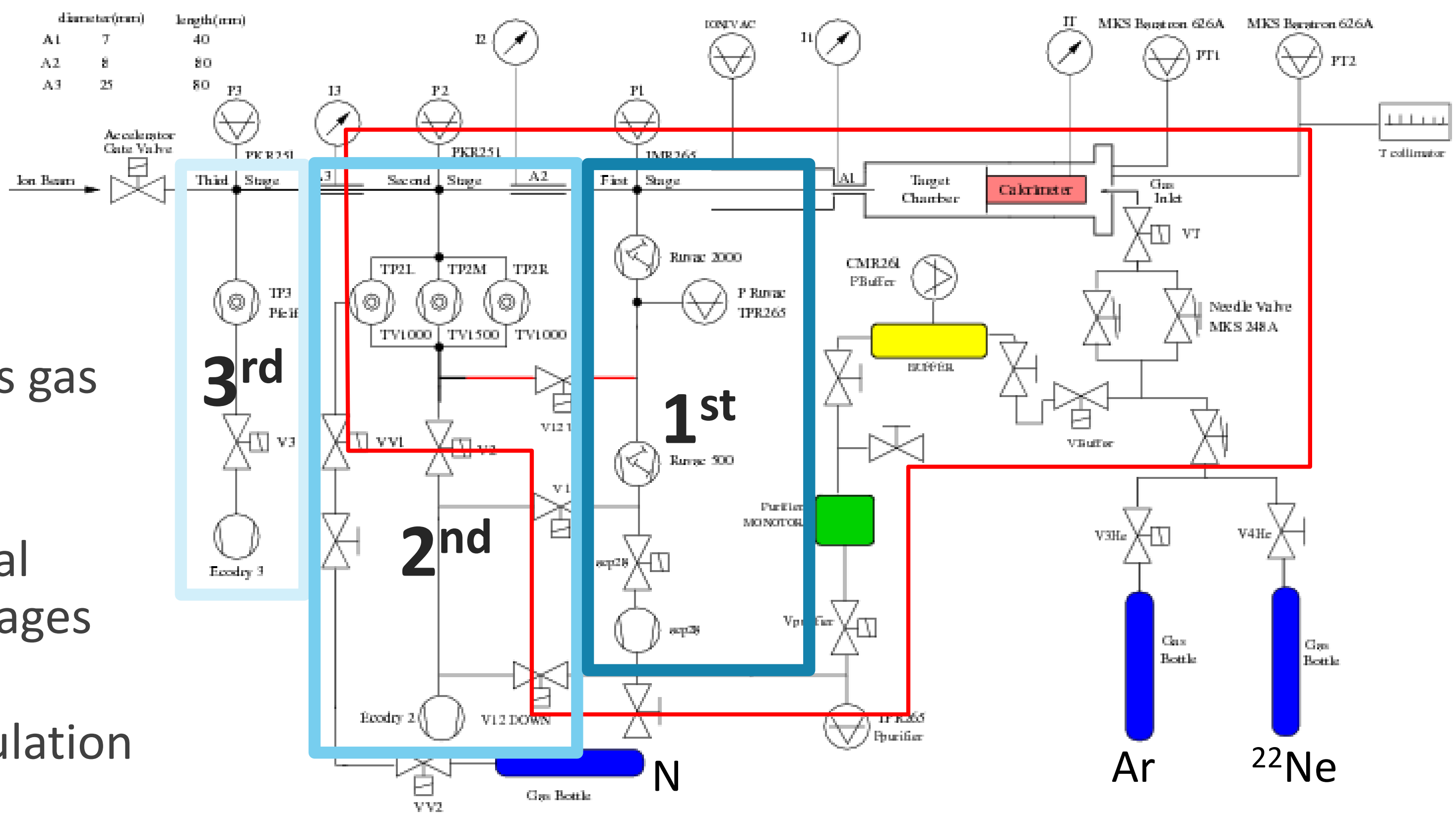
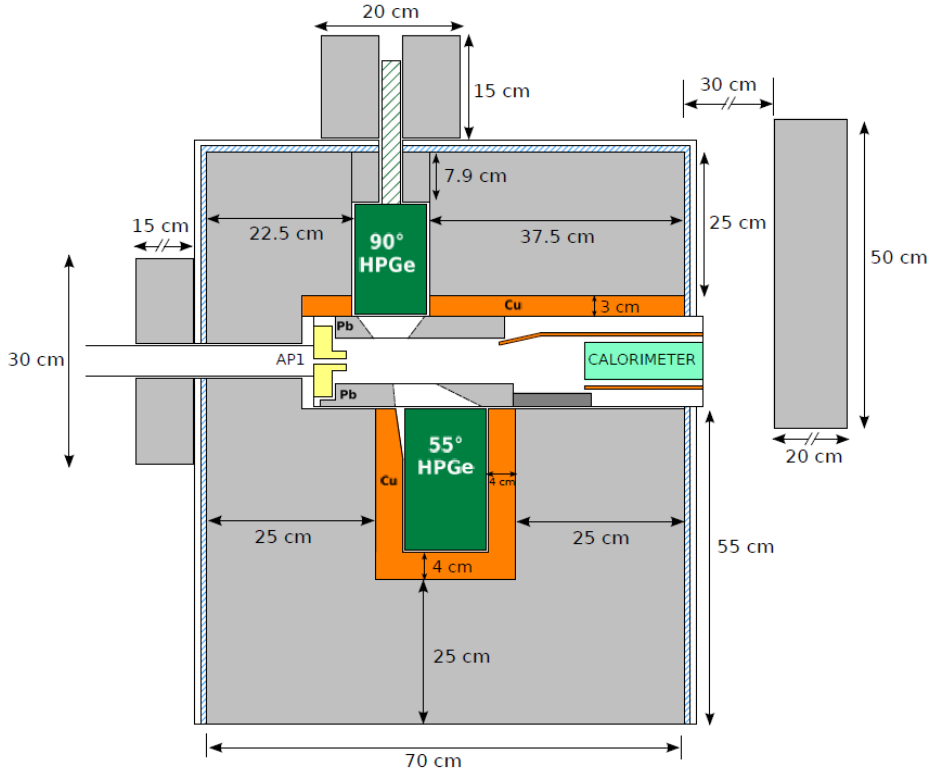


HPGe phase



- HPGe @ 90° (90% rel. eff.)
- HPGe @ 55° (137% rel. eff.)
- 22-25 cm Pb shield
- Radon box
- 4 cm Cu liner for the HPGe @ 55°
- Pb shields inside the chamber
- W brick inside the chamber
- Pb wall on the back

HPGe phase

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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 $^{22}Ne(p,\gamma)^{23}Na$ 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.

INFN

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

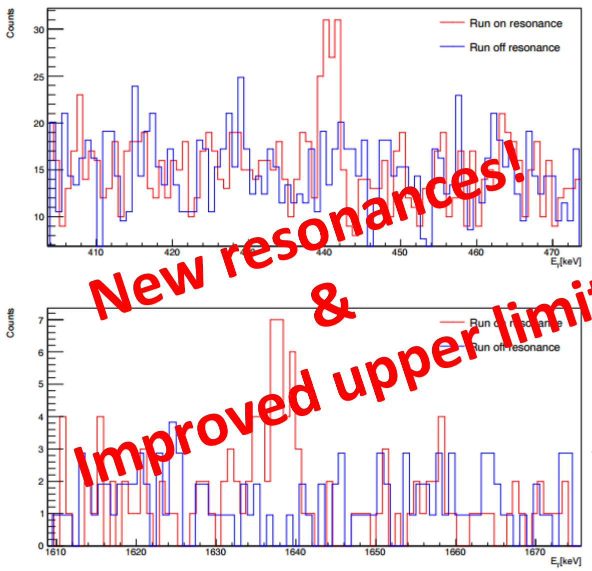
HPGe phase

- First direct observation of the 189.5 keV resonance:

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

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

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



close to the previous upper limit of 2.6 × 10^{-6} eV

J. Görres, C. Rolfs, P. Schmalbrock, H.P. Trautvetter, J. Keinonen, Nucl. Phys. A 385, 57 (1982).

Fig. 3. Observed γ-ray spectra near 440 (top panel) and 1636 keV (bottom panel), for the E_p = 186 keV resonance in $^{22}Ne(p,\gamma)^{23}Na$. The off-resonance spectrum is overplotted, scaled by a factor of 0.96 for the same charge.

- Precise measurement of $\omega\gamma_{189.5\ keV}$:

  $\omega\gamma_{189.5\ keV}$ = (1.87 ± 0.06) × 10^{-6} eV

- 2 newly observed resonances at 259.7 keV and 156.2 keV with their strength:

  $\omega\gamma_{259.7\ keV}$ = (6.89 ± 0.16) × 10^{-6} eV

  $\omega\gamma_{156.2\ keV}$ = (1.48 ± 0.06) × 10^{-7} eV

- Upper limits on the strengths of the resonances at 215 keV, 105 keV and 71 keV:

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

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

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

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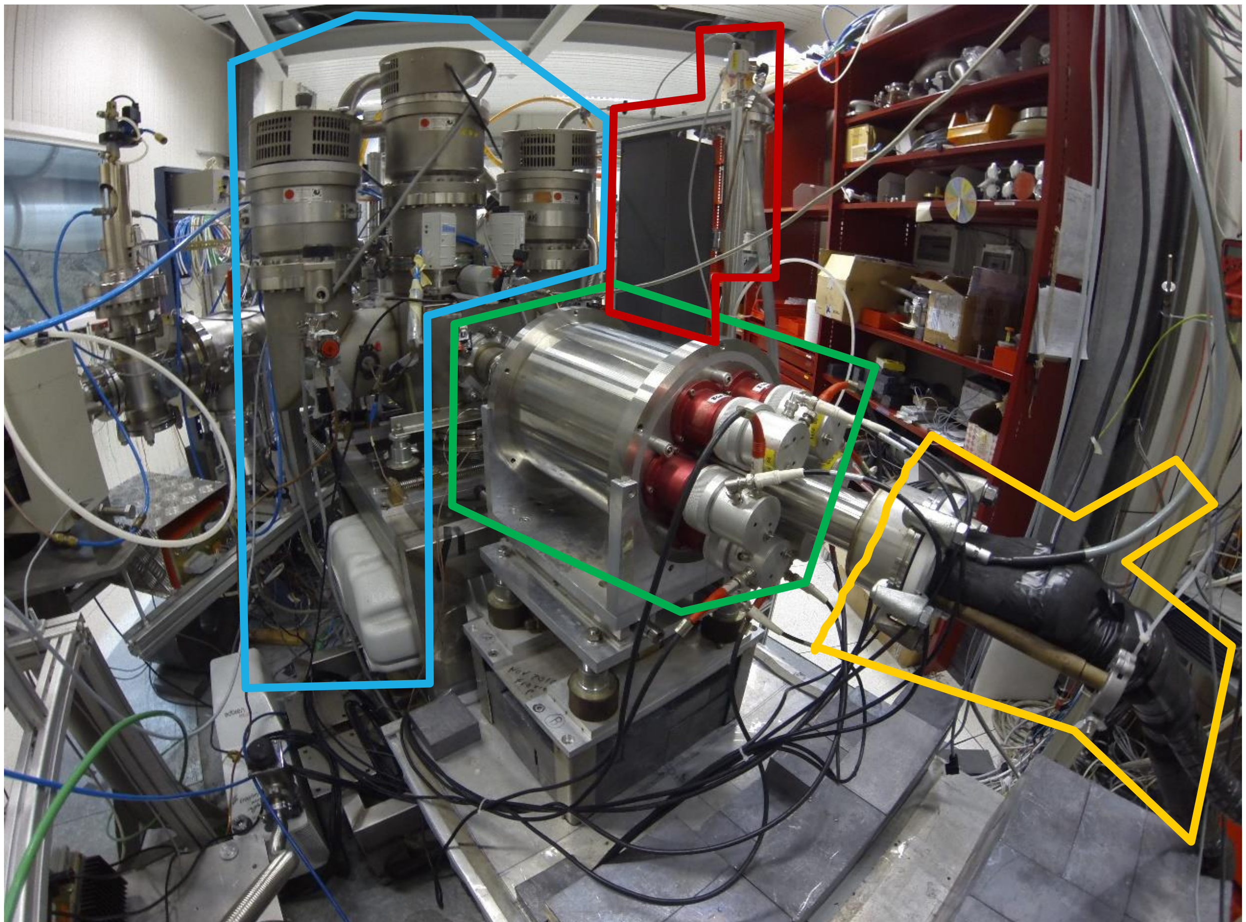
BGO phase

Differential pumping system

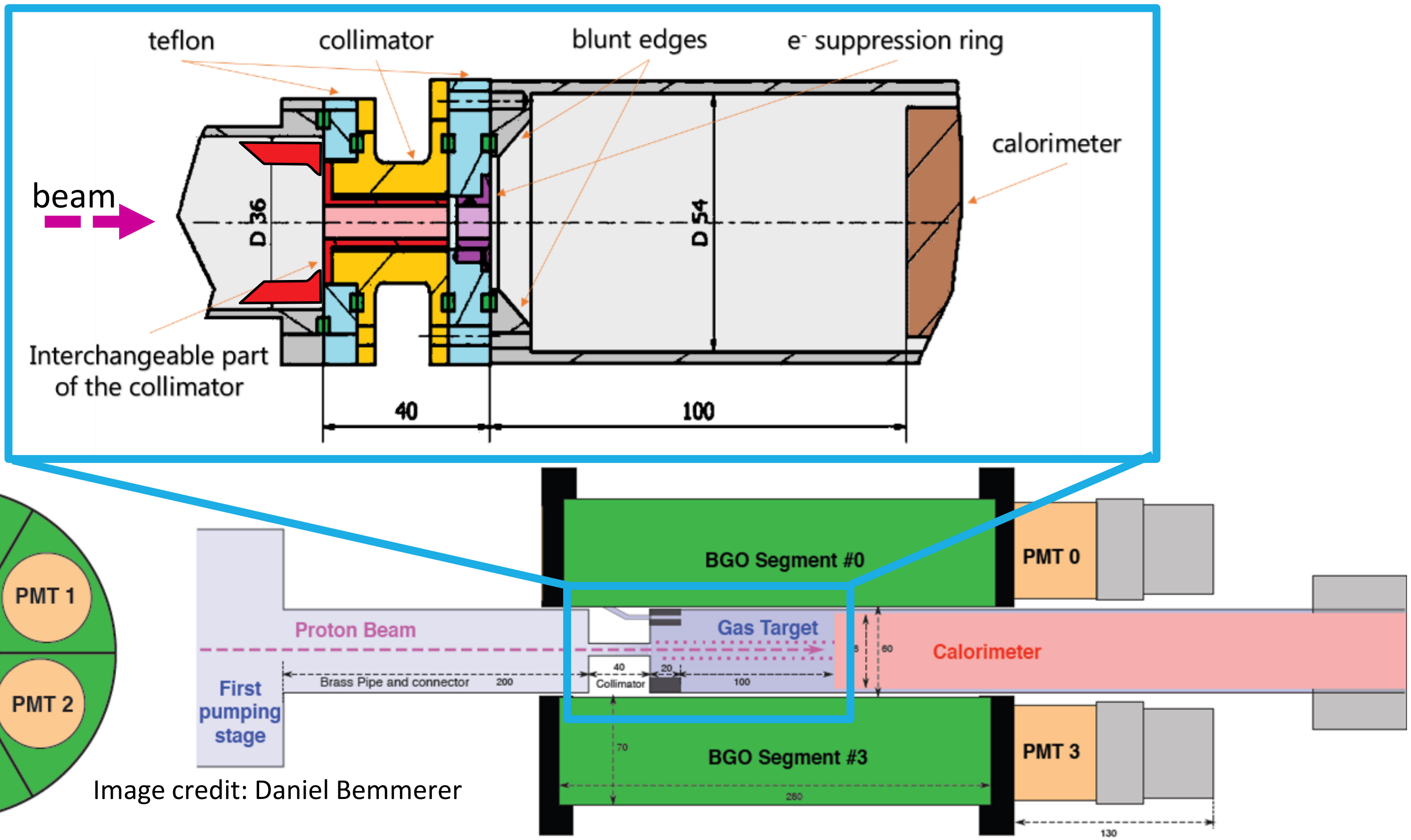
Gas purifier



BGO detector (around the target chamber)

Connections to the calorimeter control system

BGO setup



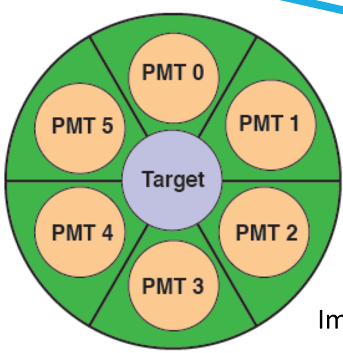
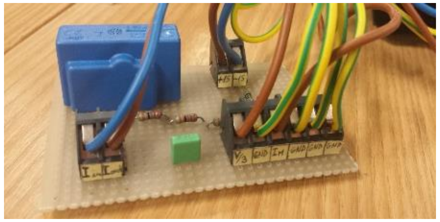


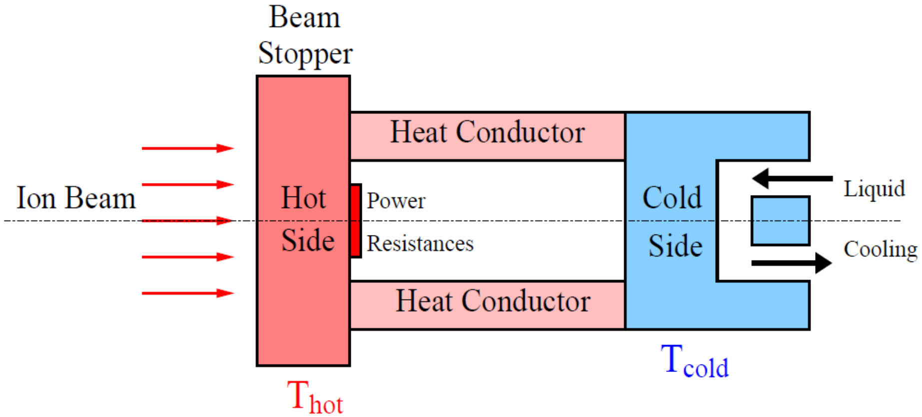
Image credit: Daniel Bemmerer

Resolution: ≈ 400 keV in the ROI
Efficiency: ≈ 64% in the ROI

Calorimeter

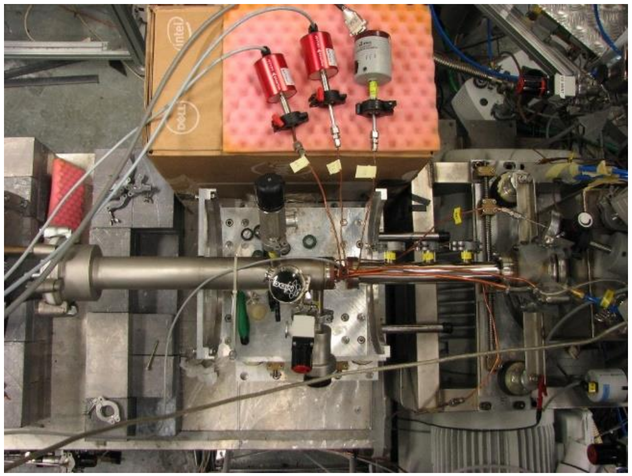


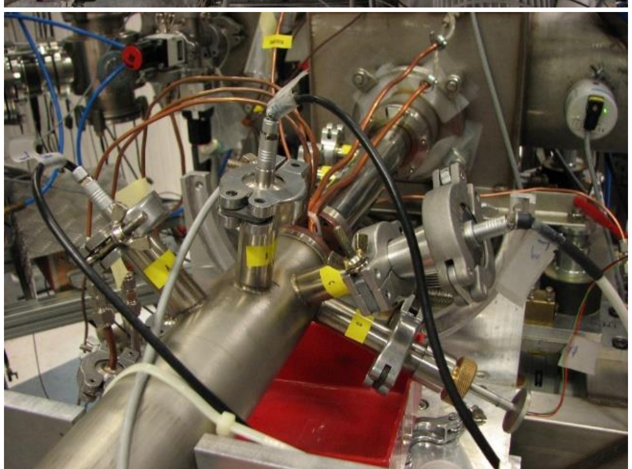
$$
\begin{aligned}
W_{\text{beam}} &= W_0 - W_{\text{run}} \\
I_{\text{target}} &= \frac{W_{\text{beam}}}{E_{\text{cal}}} \cdot q_e \\
&= \frac{W_0 - W_{\text{run}}}{E_p - \Delta E_{\text{target}}} \cdot q_e
\end{aligned}
$$

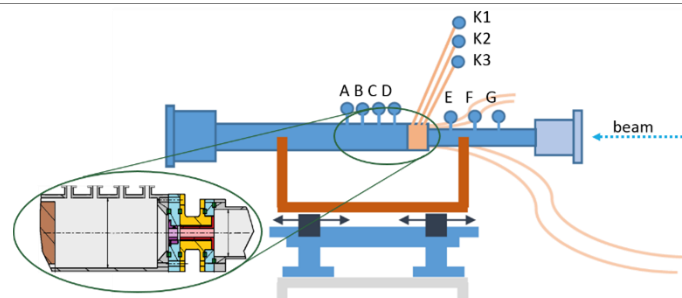


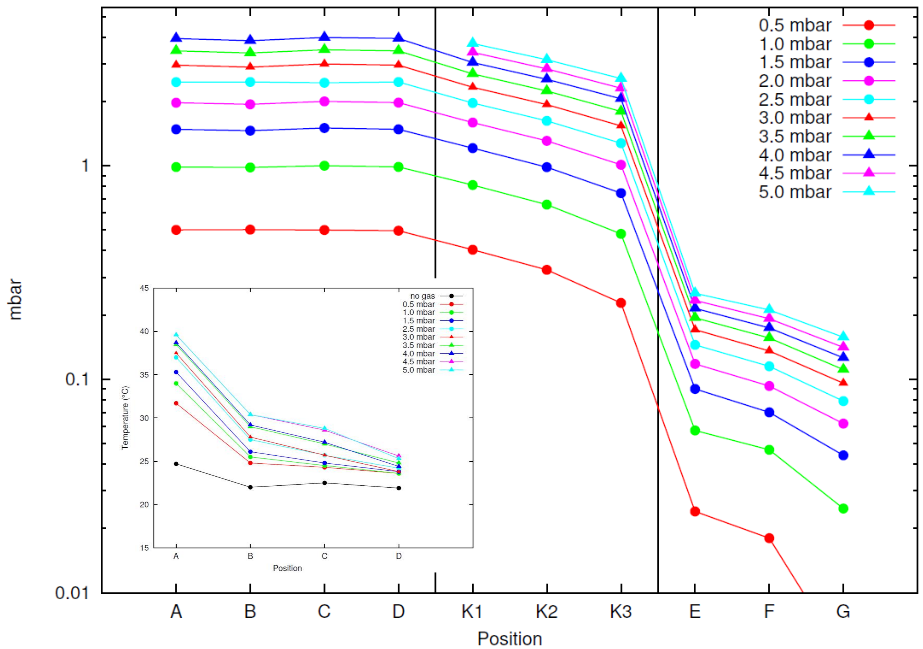
- NI-cRIO modules
- LV programmed Integrated controller
- 4 RTDs (3 on the h.s., 1 on the c.s.)
- Hot side temperature active control: 8 power resistors
- Cold side liquid-cooling
- Operating power: ~ 120 W
- Beam power: ~ 80 W

P and T profiles







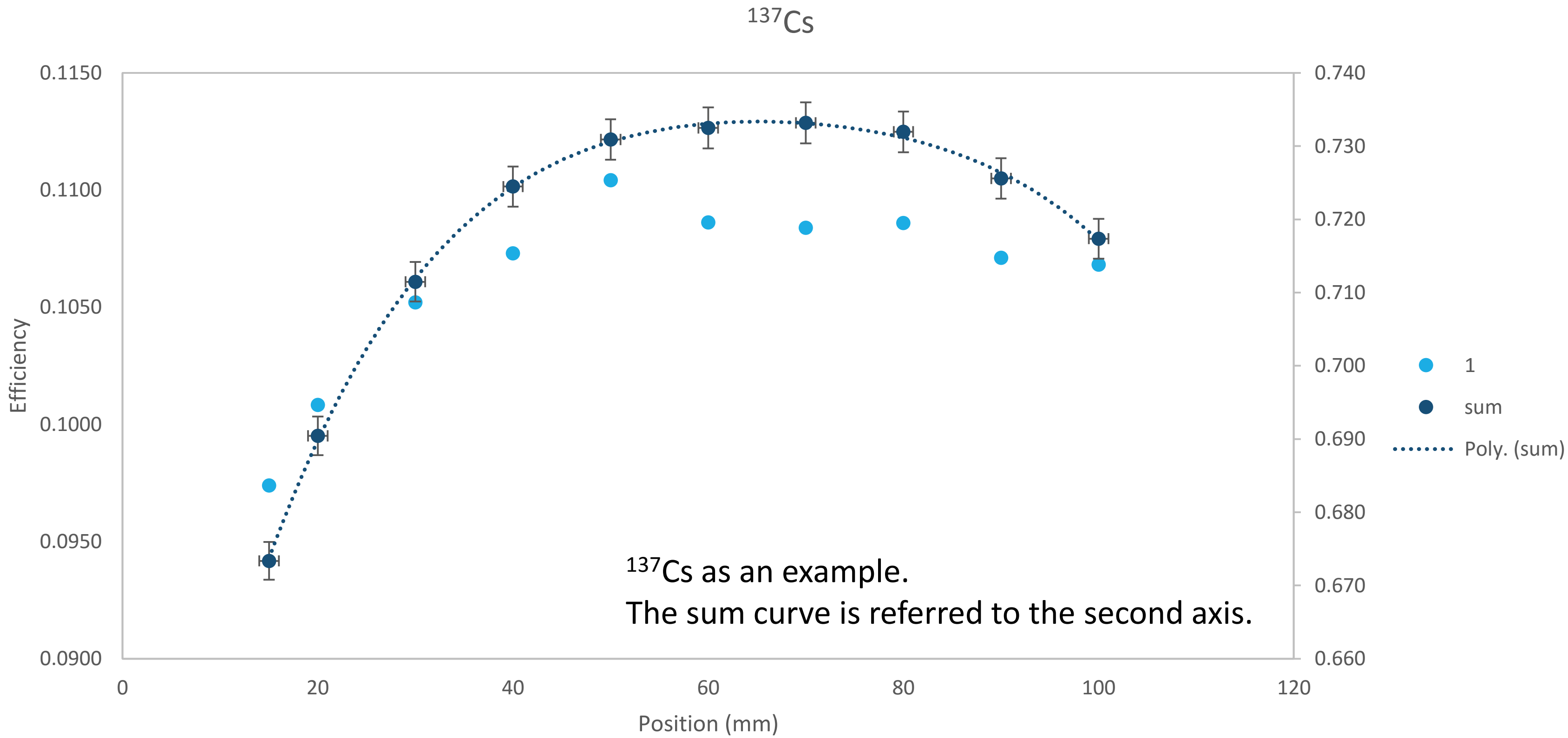


Efficiency

- Measured along the beam axis
- 10 different positions
- ^{137}Cs, ^{7}Be, ^{88}Y, ^{60}Co, $^{14}N(p,\gamma)^{15}O$
- Very light source holder
- MC simulations

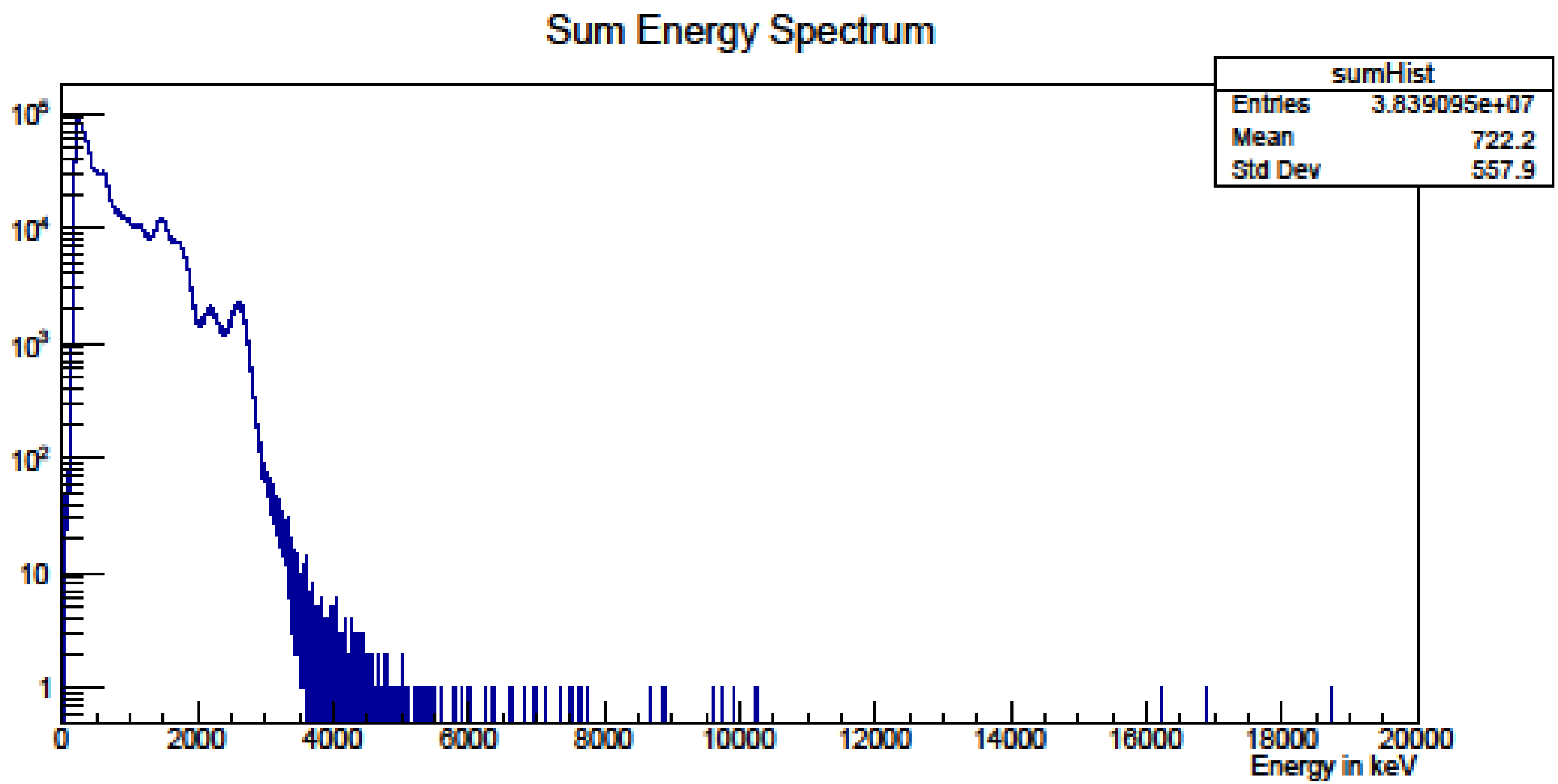
Source holder

Efficiency

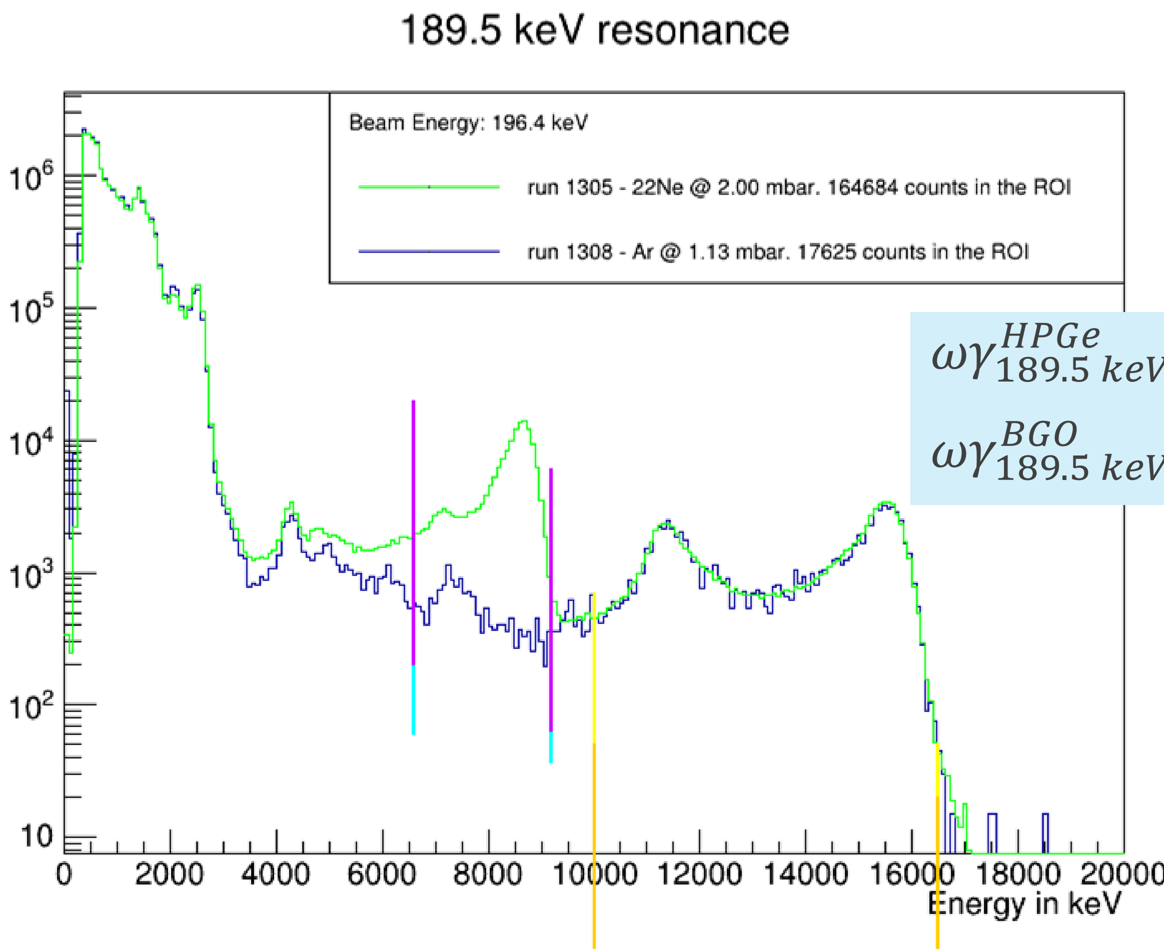


MC fine tuning ongoing
(to reproduce the measured efficiency and the features in the spectra)

Laboratory background



A quick crosscheck

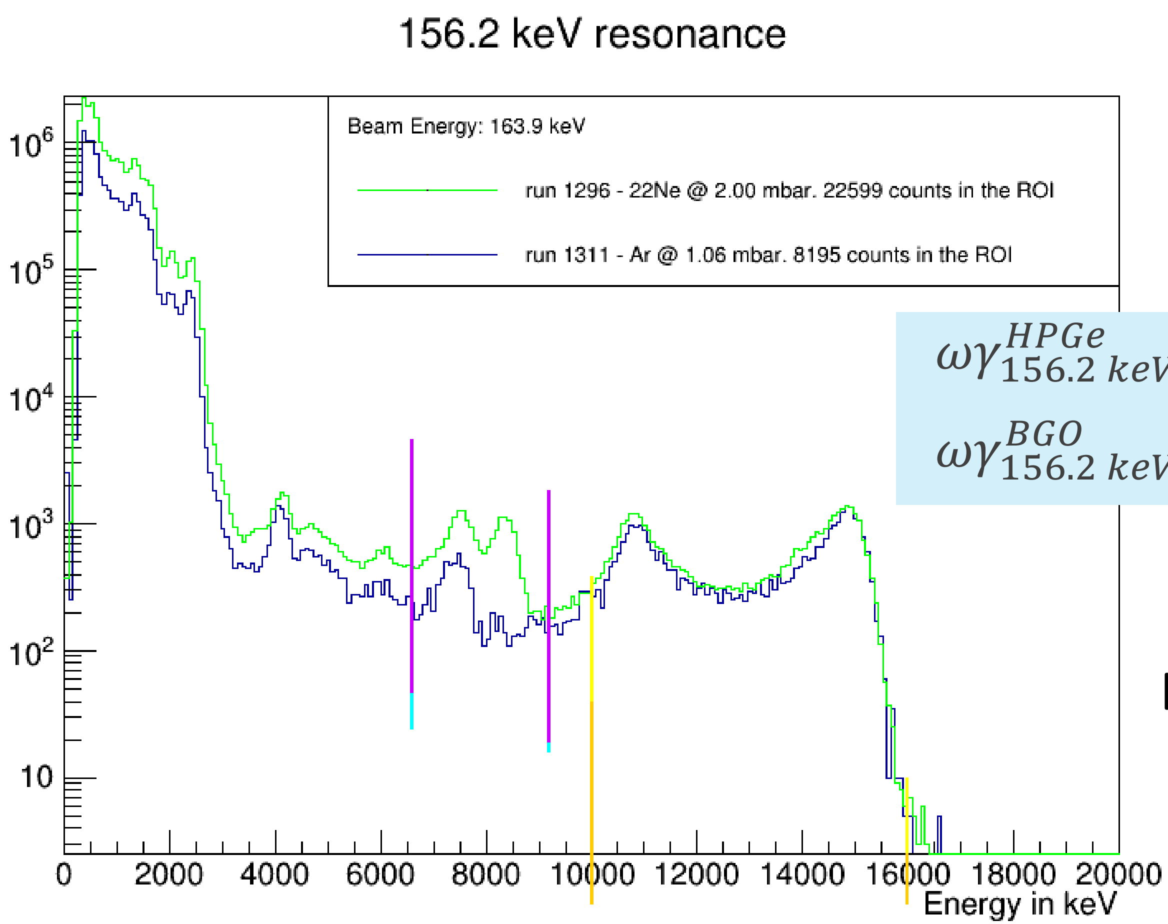


$$\omega\gamma_{189.5\ keV}^{HPGe} = (1.87 \pm 0.06) \times 10^{-6}\ \text{eV}$$

$$\omega\gamma_{189.5\ keV}^{BGO} = (1.9 \pm 0.2) \times 10^{-6}\ \text{eV}$$

BGO (very preliminary) result is consistent with HPGe result

A quick crosscheck

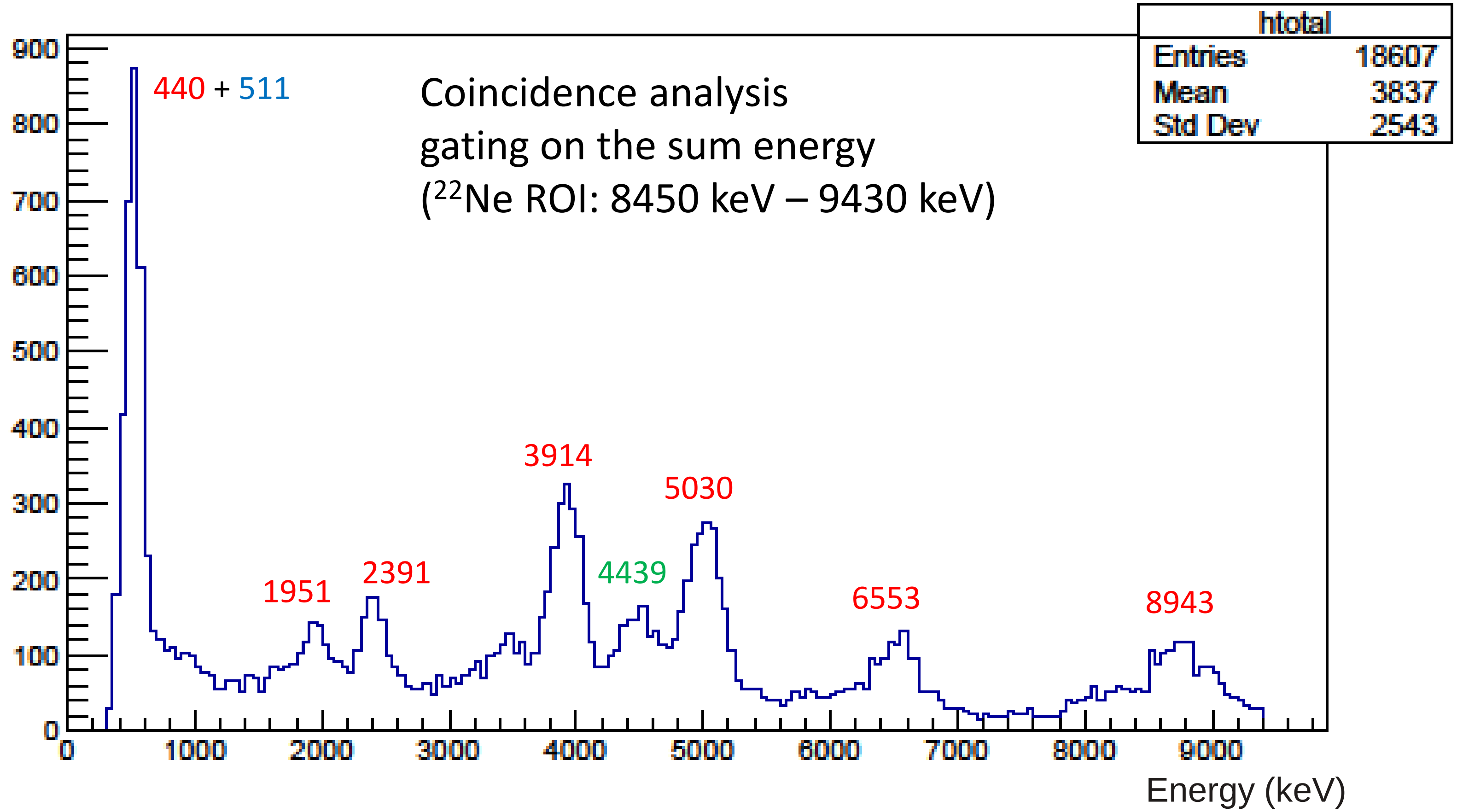


$$\omega\gamma^{HPGe}_{156.2\ keV} = (1.48 \pm 0.10) \times 10^{-7}\ \text{eV}$$

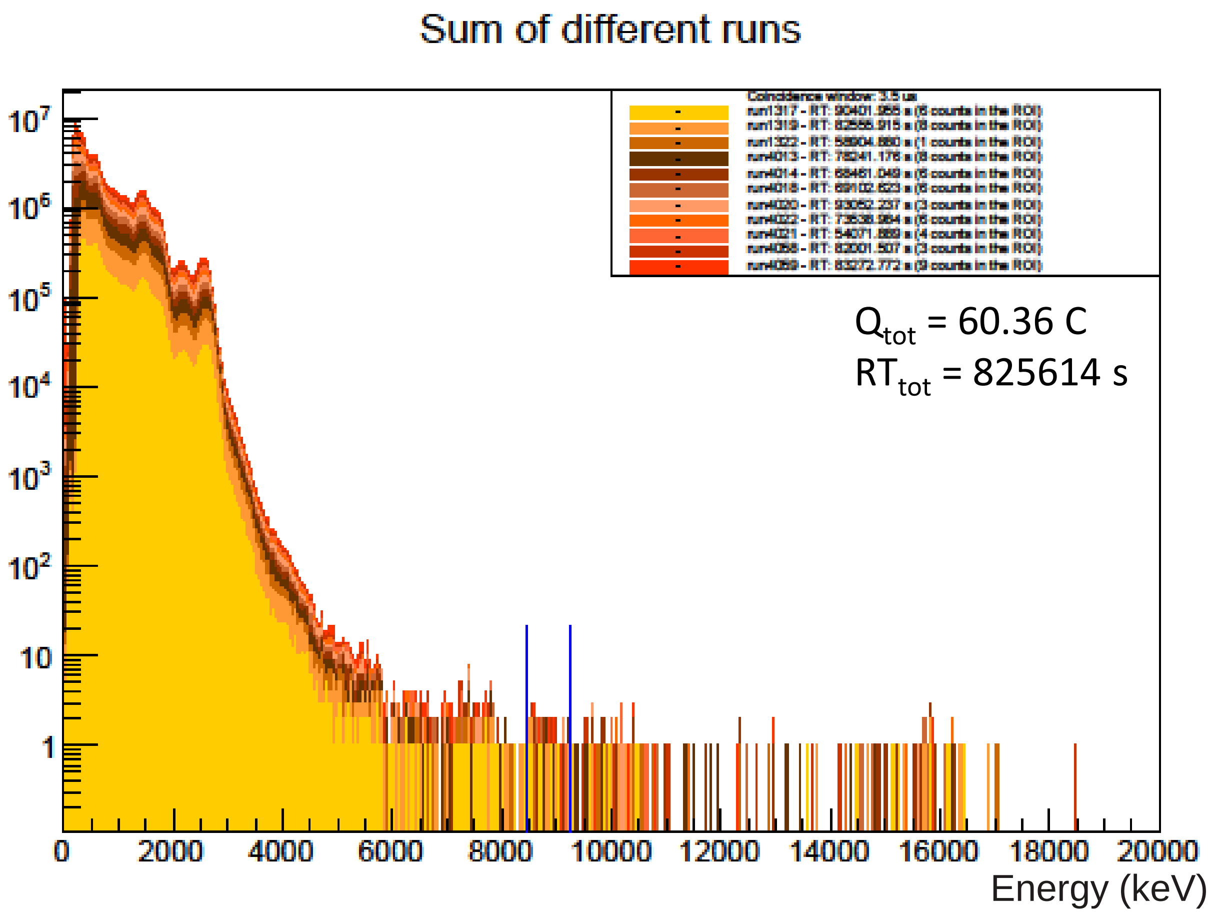
$$\omega\gamma^{BGO}_{156.2\ keV} = (1.5 \pm 0.2) \times 10^{-7}\ \text{eV}$$

BGO (very preliminary) result is consistent with HPGe result

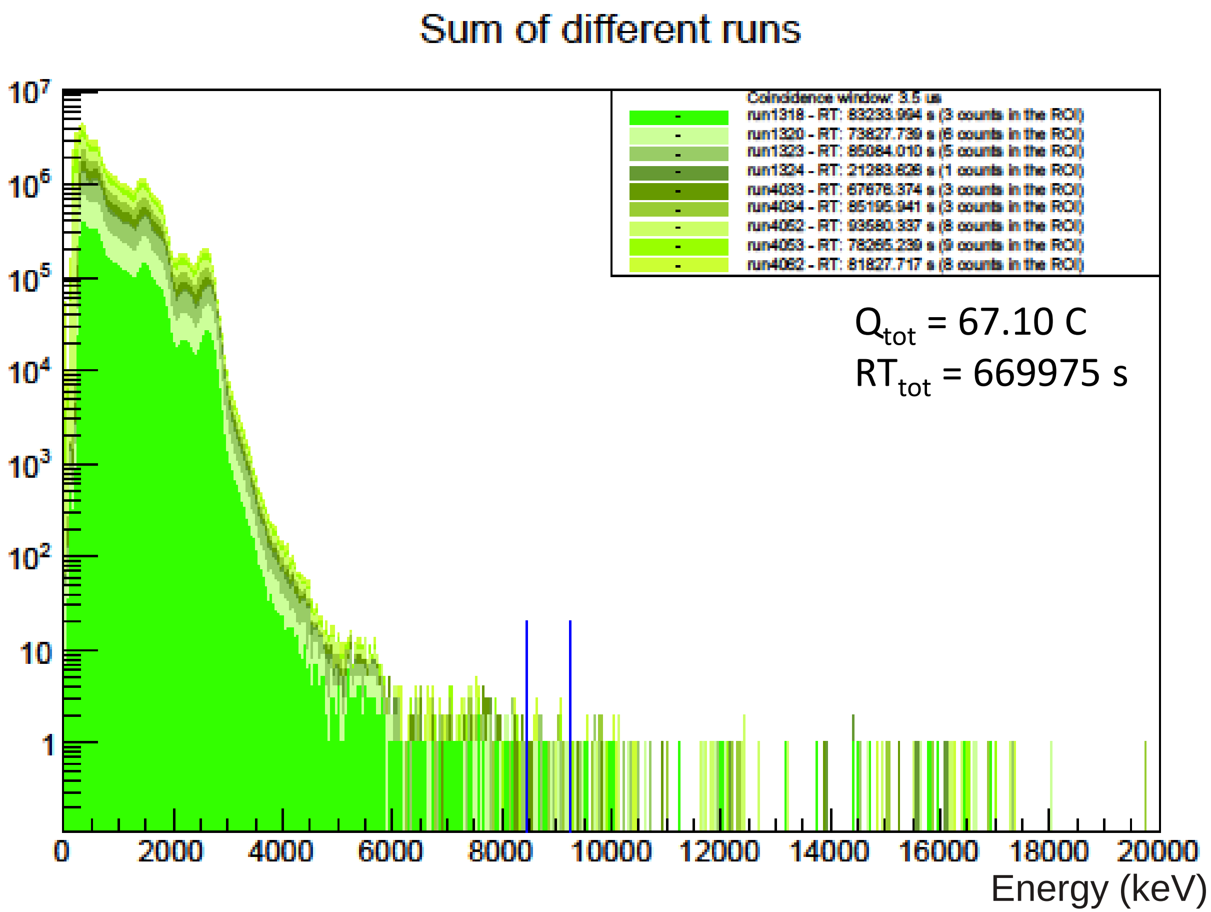
Decay from 8943.5 keV excited state (156.2 keV resonance)



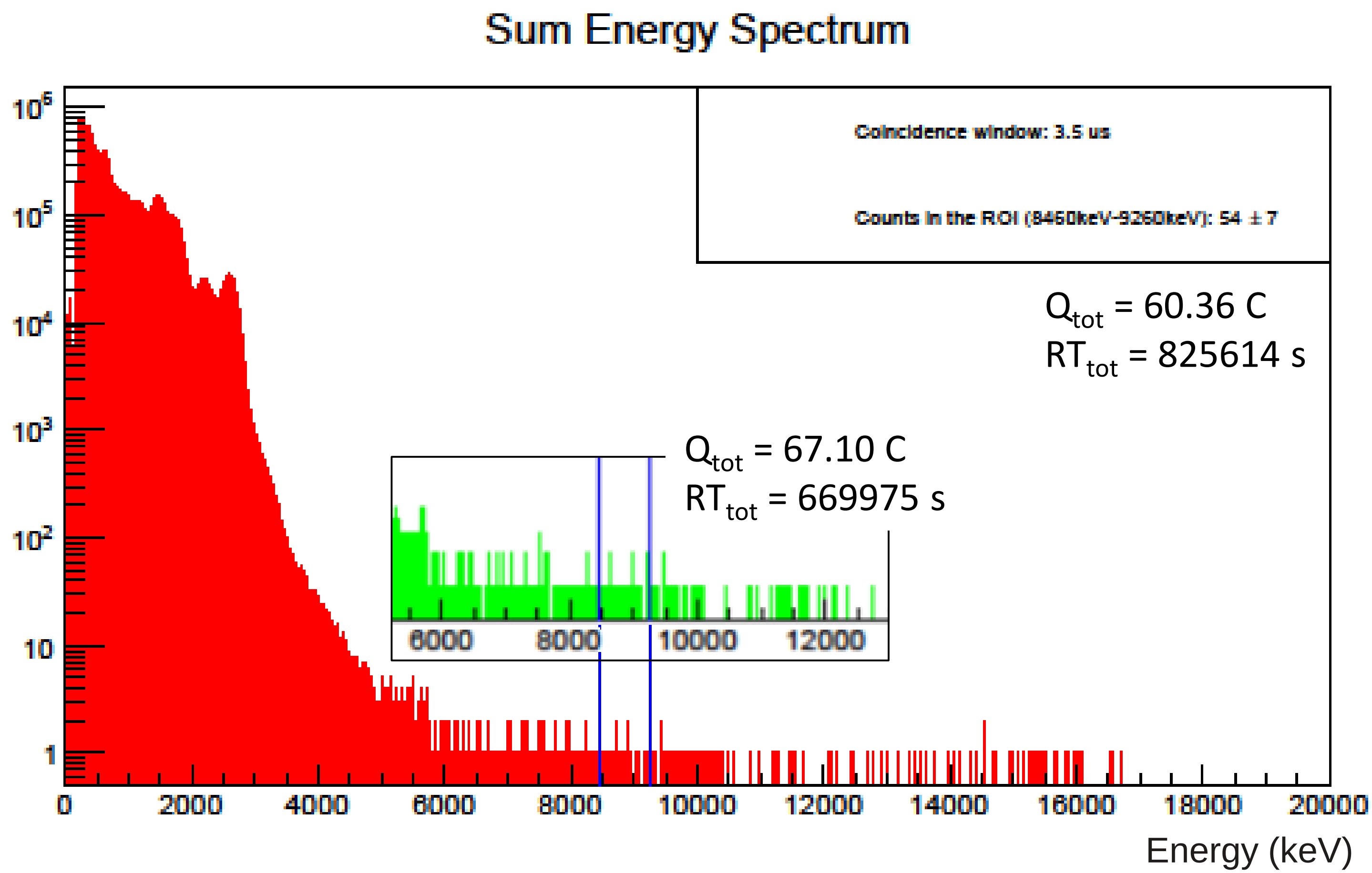
^{22}Ne @ E_p=71 keV (target chamber center)



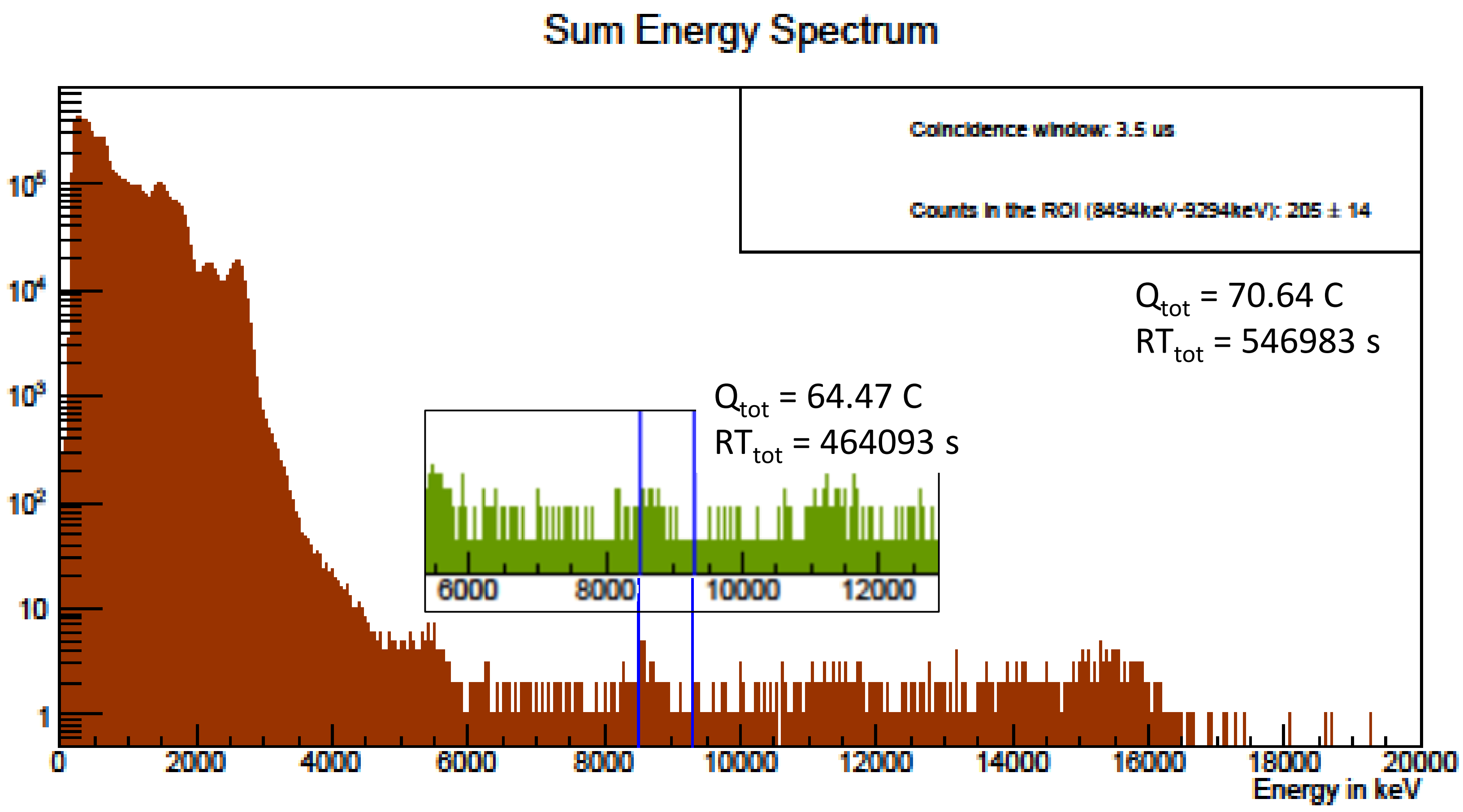
Ar @ E_p=71 keV (target chamber center)



E_p=71 keV (target chamber center)



E_p=105 keV



Sum Energy Spectrum
Coincidence window: 3.5 us
Counts in the ROI (8494keV-9294keV): 205 ± 14
Q_{tot} = 70.64 C
RT_{tot} = 546983 s
Q_{tot} = 64.47 C
RT_{tot} = 464093 s
6000
8000
10000
12000
10^5
10^4
10^3
10^2
10
1
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
20000
Energy in keV

Low energy resonances preliminary results

HPGe

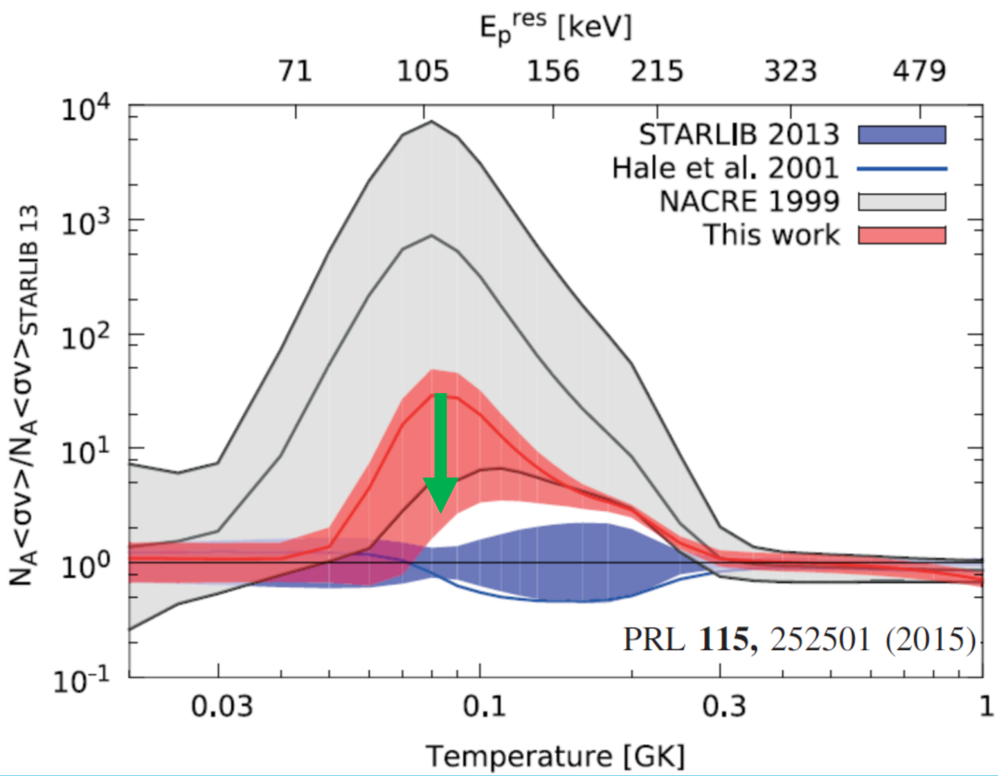
$\omega\gamma^{HPGe}_{105\ keV}$ **≤ 7.6 × 10⁻⁹ eV**

$\omega\gamma^{HPGe}_{71\ keV}$ **≤ 1.5 × 10⁻⁹ eV**

$\omega^{BGO}_{105\ keV}$ **≤ 5.6 × 10⁻¹¹ eV**

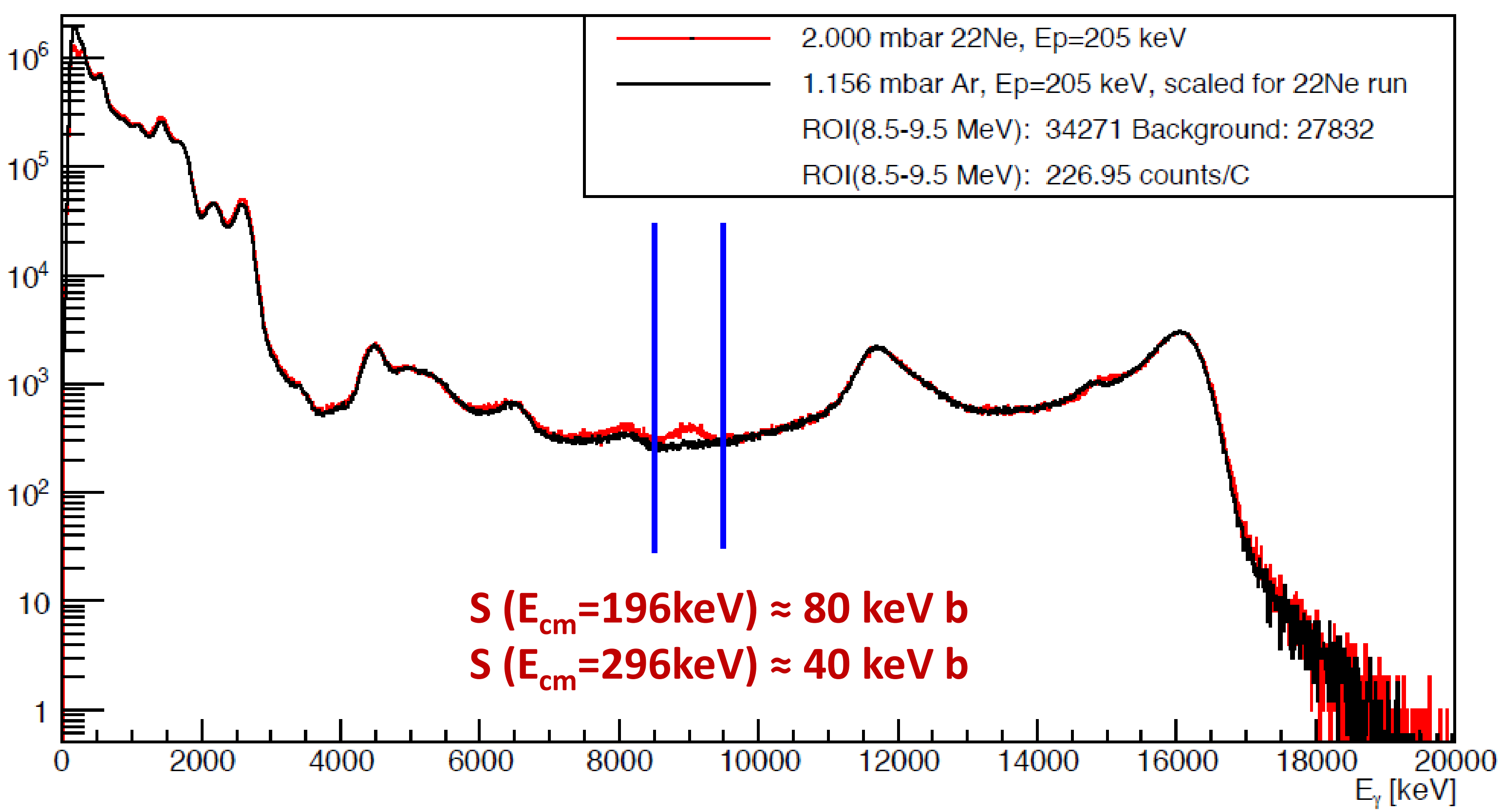
$\omega\gamma^{BGO}_{71\ keV}$ **≤ 2.3 × 10⁻¹¹ eV**

BGO



Direct capture preliminary results

2.000 mbar 22Ne, Ep=205 keV



Conclusions

WHAT WE DID SO FAR…

- 3 new low-energy resonances have been directly observed for the first time during the HPGe phase
- Improved upper limits have been determined for the tentative resonances both during the HPGe phase and the BGO phase
- DC contribution measured @ 205 keV and 310 keV

WHAT TO DO NOW?

- We still have to measure the DC cross section in other 2 points and determine its contribution to the reaction rate
- Measure the $^{22}Ne(\alpha, \gamma)^{24}Mg$ cross section (using the same setup)

The LUNA collaboration

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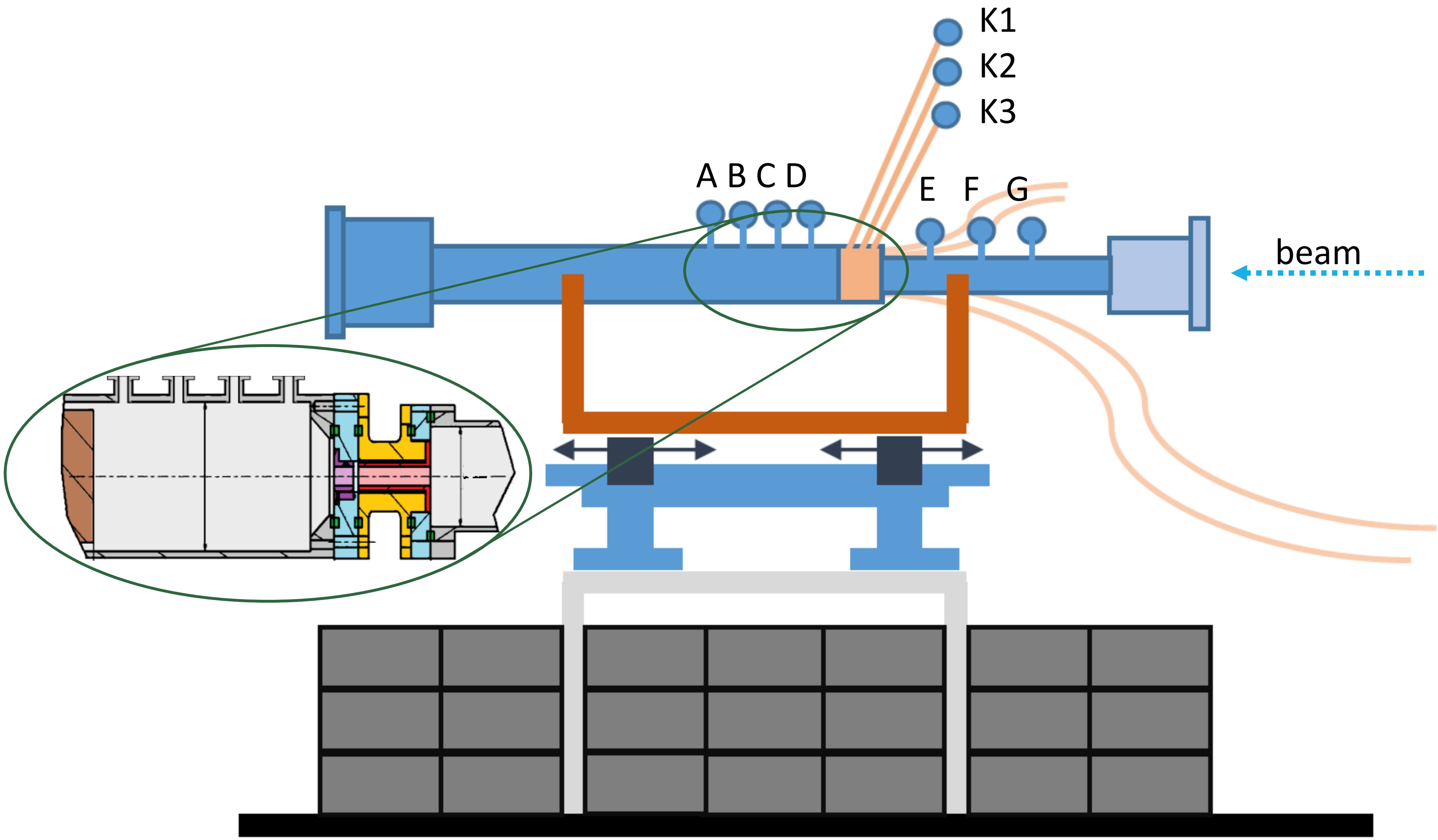
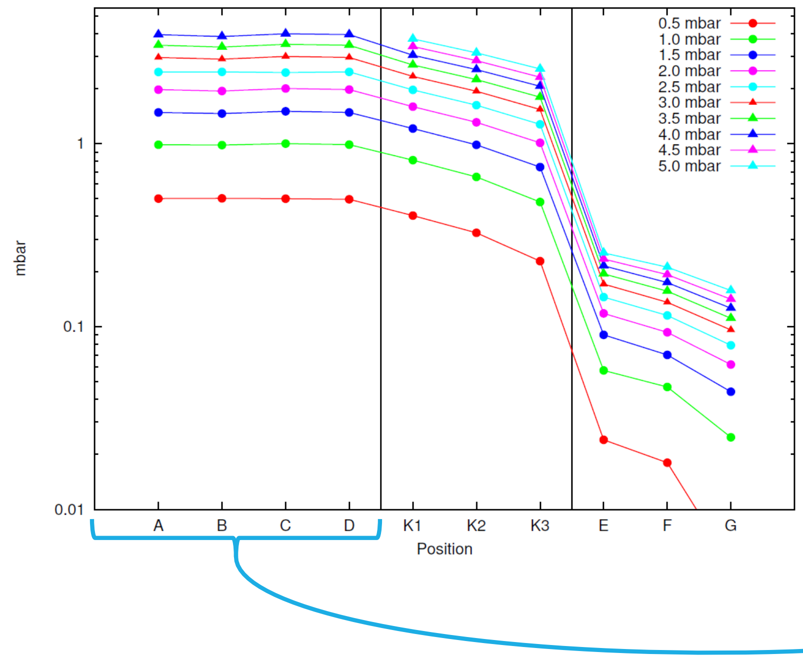
Other stuff

P and T profiles

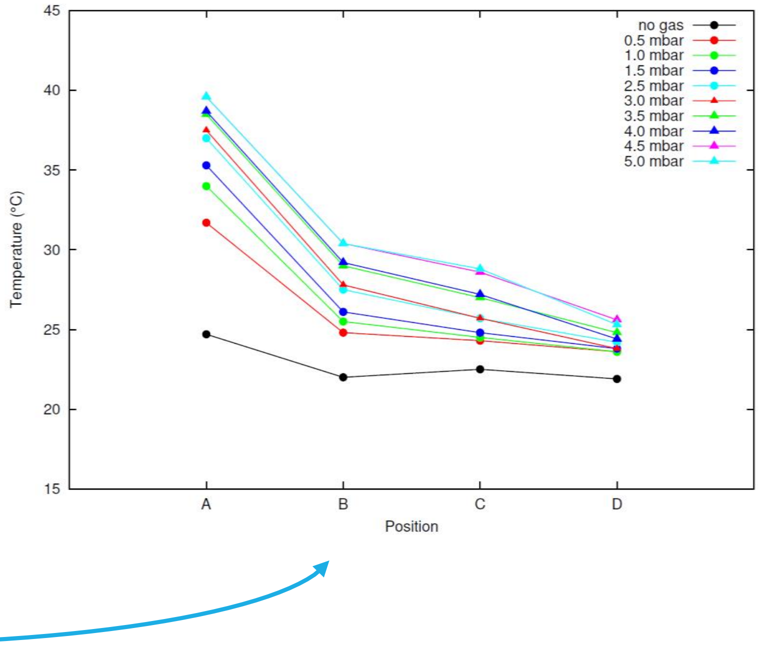


P and T profiles

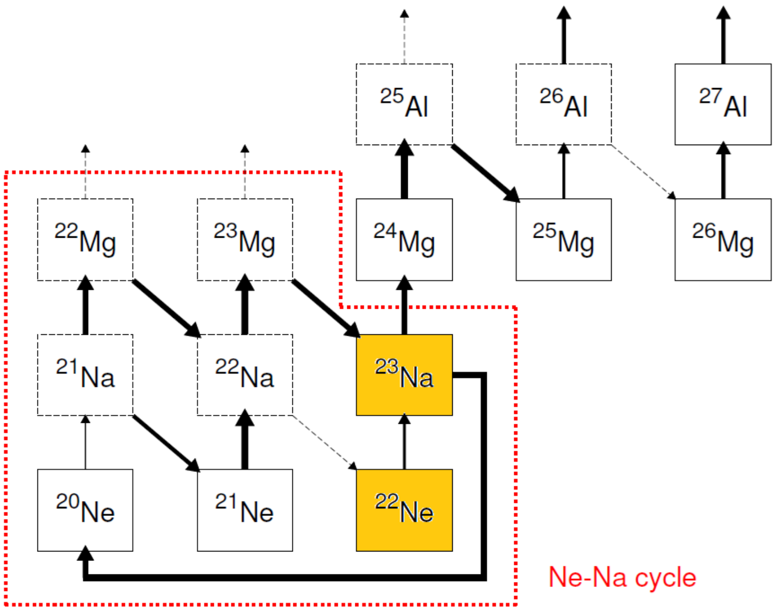
PRESSURE PROFILE



TEMPERATURE PROFILE



The NeNa cycle



- ^{22}Ne provides neutrons for neutron-capture driven nucleosynthesis.
- In a hydrogen-rich scenario, ^{22}Ne is mainly destroyed by the $^{22}Ne(p,\gamma)^{23}Na$ reaction.