Latest results from LUNA experiment

Francesca Cavanna, INFN Genova

NAVI physics days

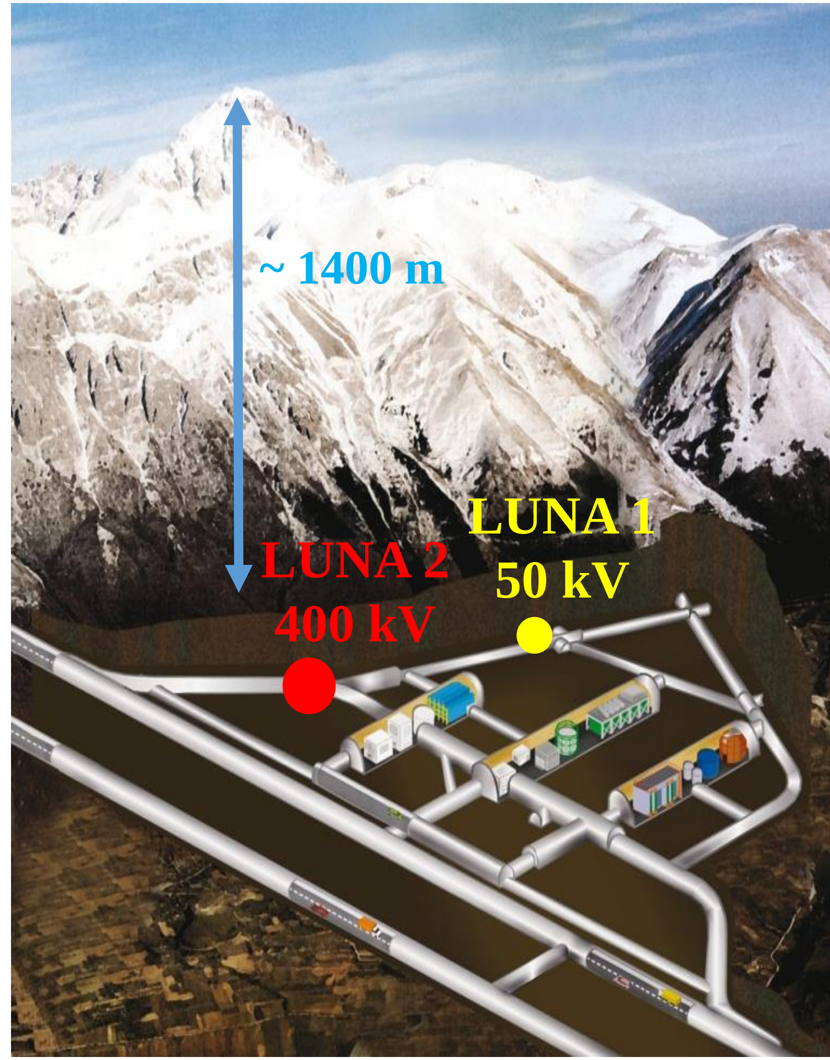
GSI, Darmstadt

Laboratory for Underground Nuclear Astrophysics

Sources of gamma background

- Environmental radioactivity:
  - ^{238}U and ^{232}Th chains and ^{40}K
- Cosmic rays:
  - Mainly muons at sea level

Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}



LNGS (1400 m rock shielding ≡ 4000 m w.e.)

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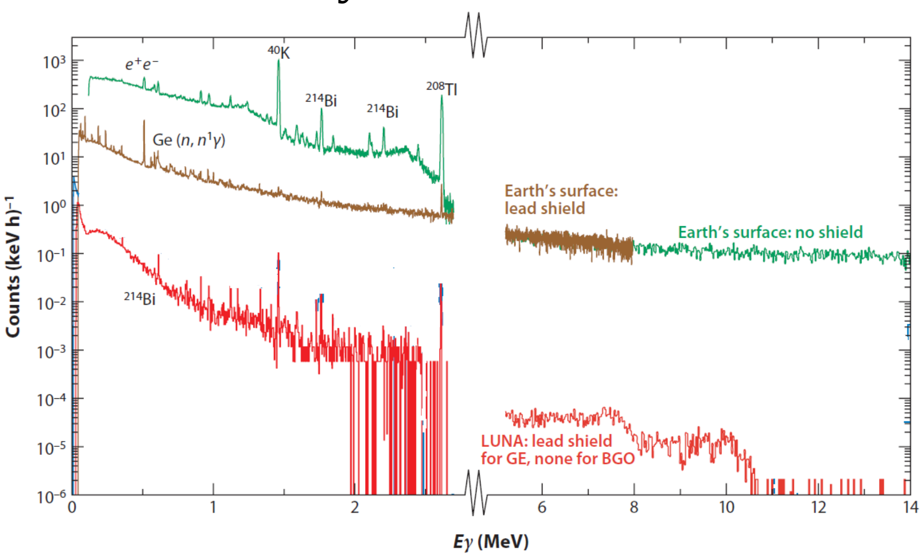

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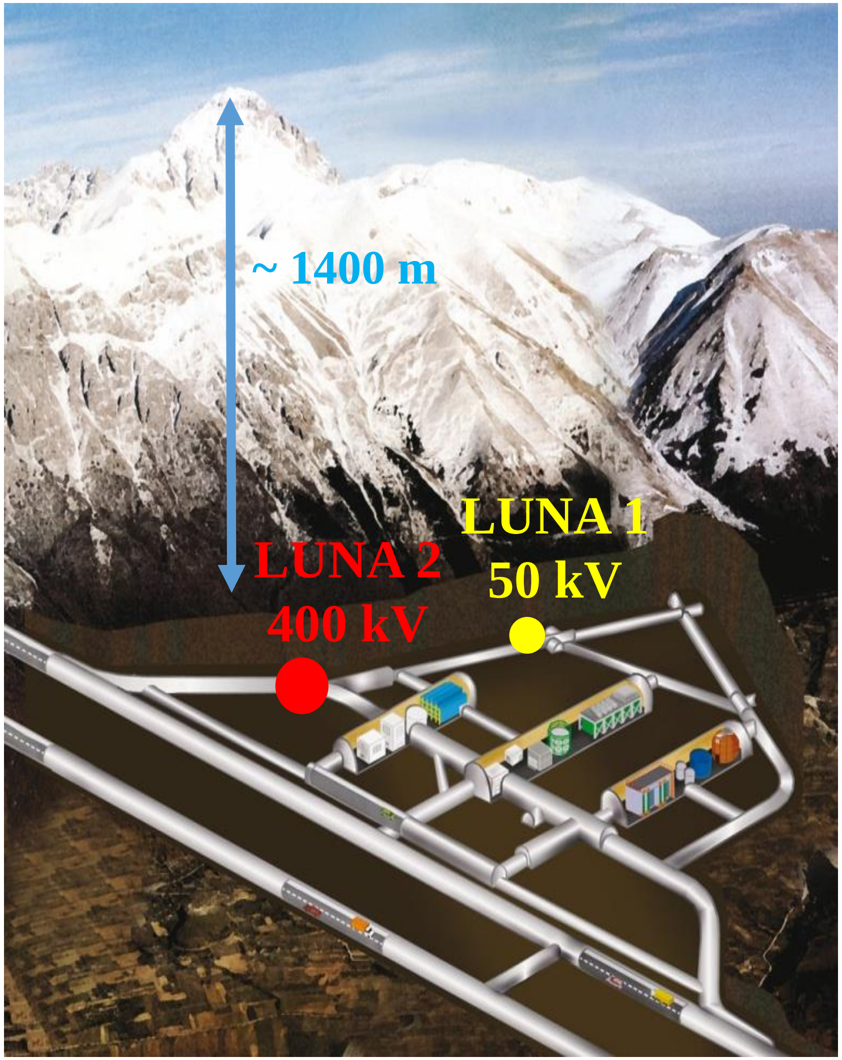
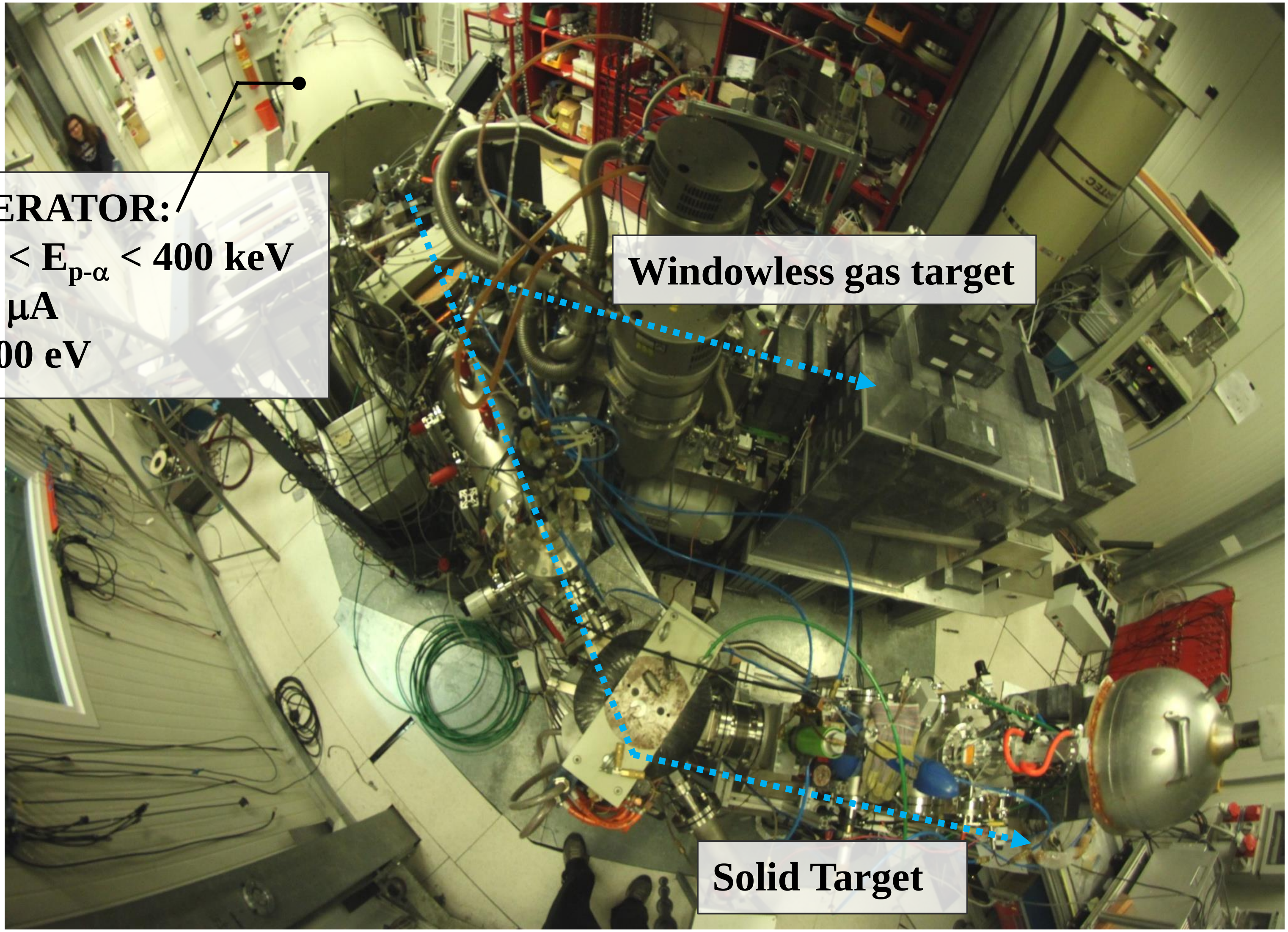
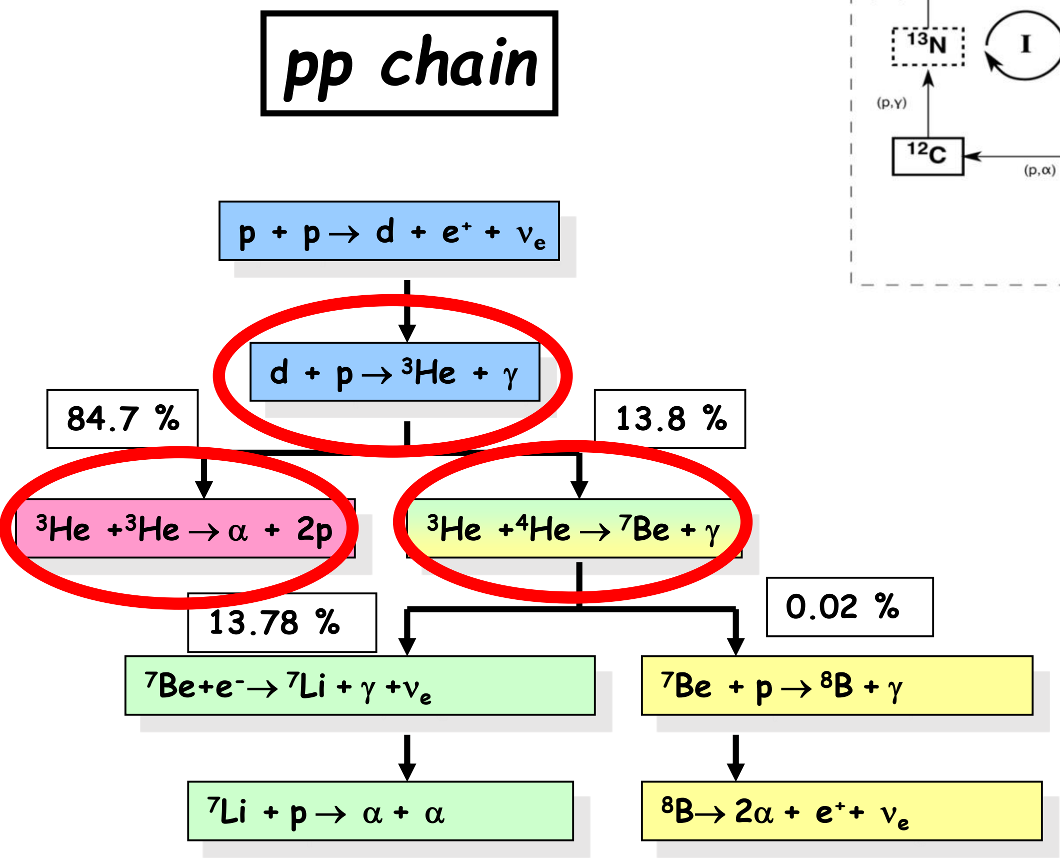


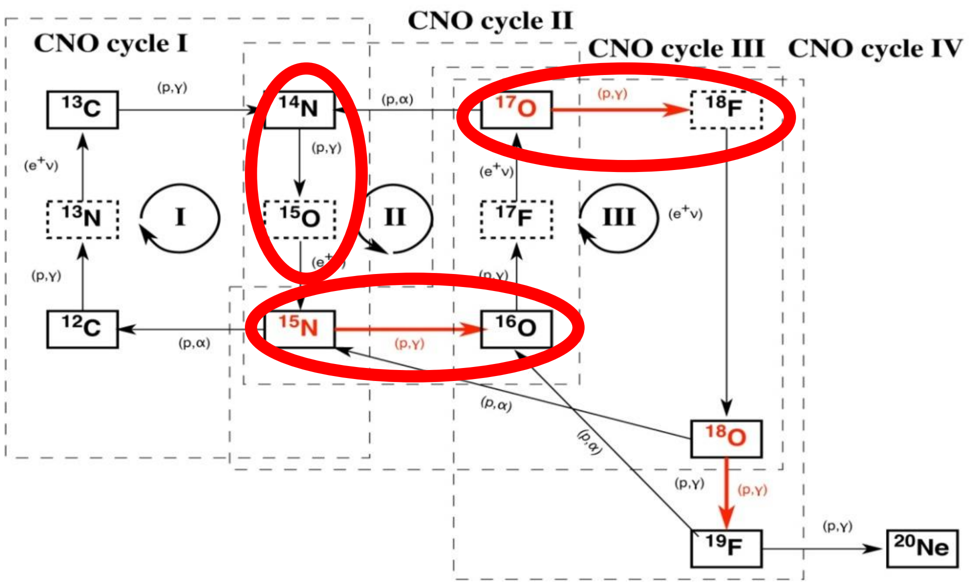
LNGS (1400 m rock shielding ≡ 4000 m w.e.)

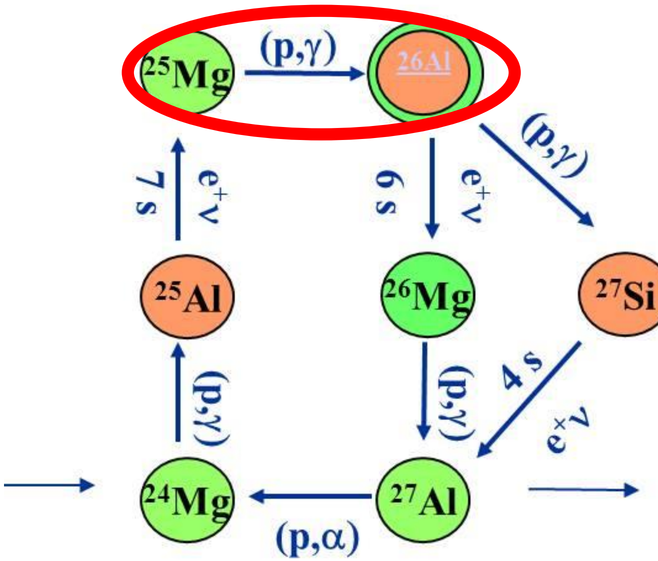
LUNA experimental setup



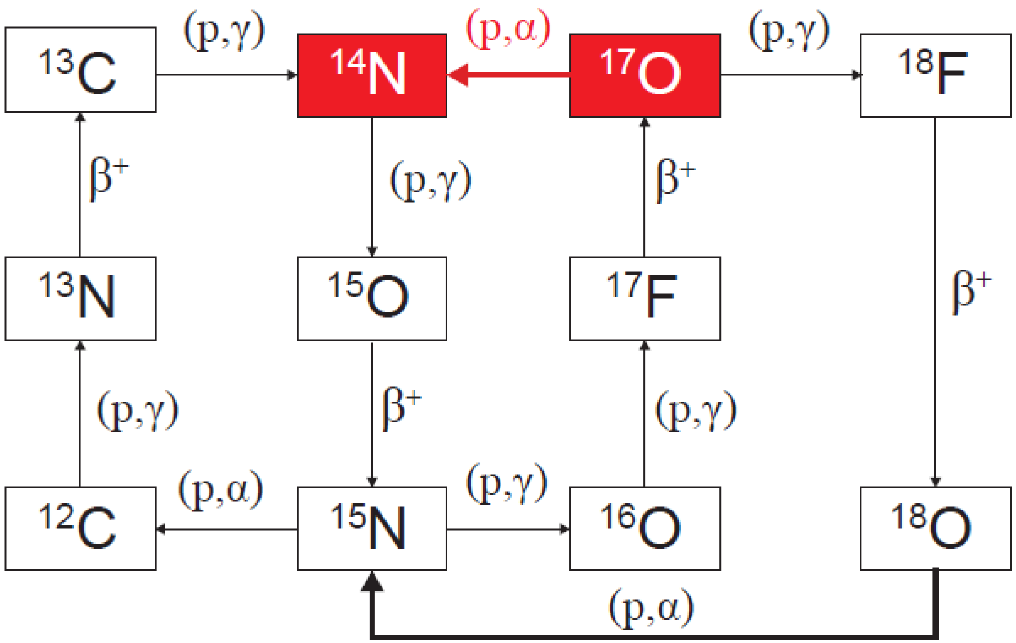
Completed measurements

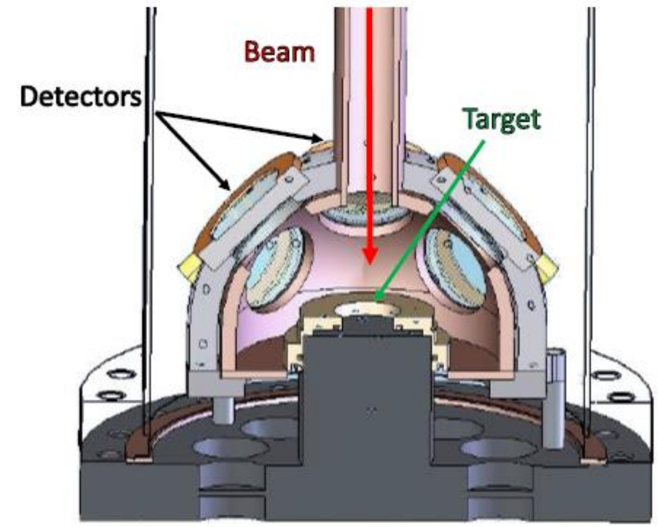






Concluded measurements: $^{17}O(p,\alpha)^{14}N$



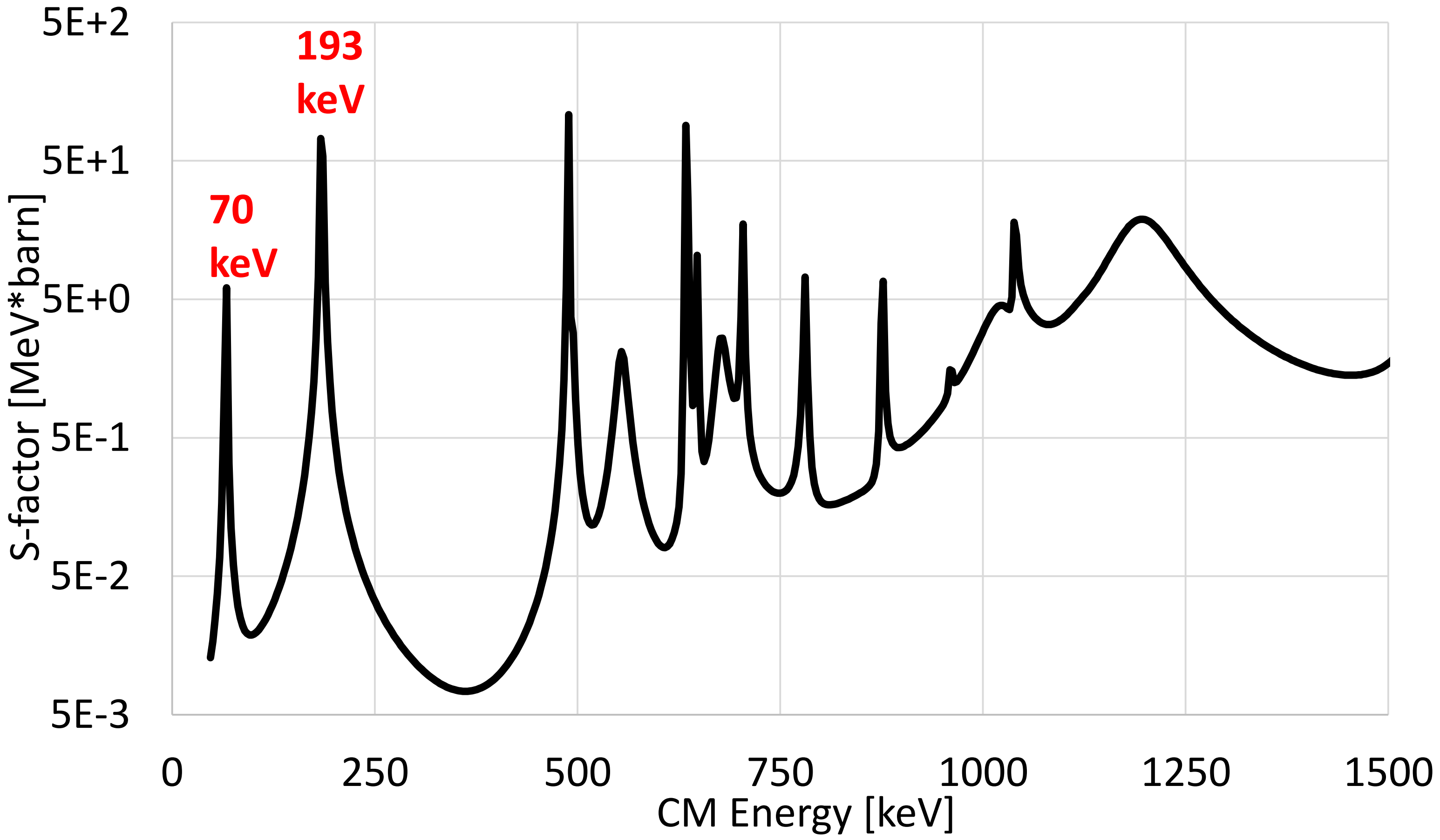


- At branching point between CNO-II and CNO-III
- In completion with gamma channel
- Critical for ^{17}O and ^{18}F abundances
- Important in a variety of scenarios (AGB, Classical Novae..)

C.G. Bruno et al., Eur. Phys. J. **A51**, 94 (2015)

Concluded measurements: $^{17}O(p,\alpha)^{14}N$

- Q-value = 1.2 MeV. Expected alpha energy = 1 MeV
- Two narrow resonances at **70** and **193** keV (Lab. frame)
- Resonances dominant at astrophysical temperatures



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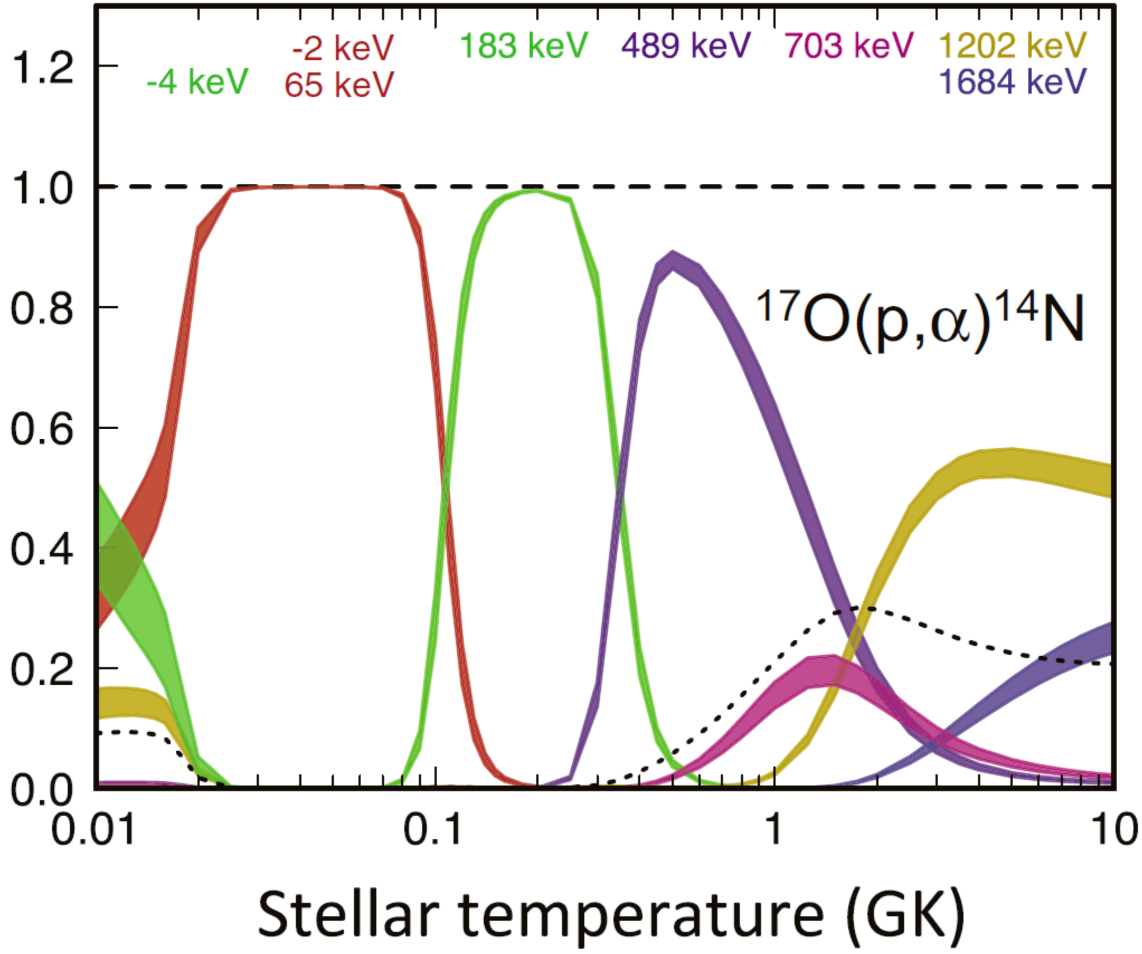
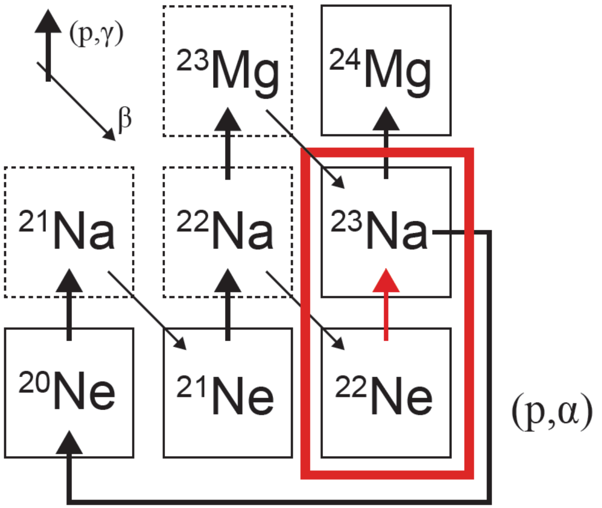


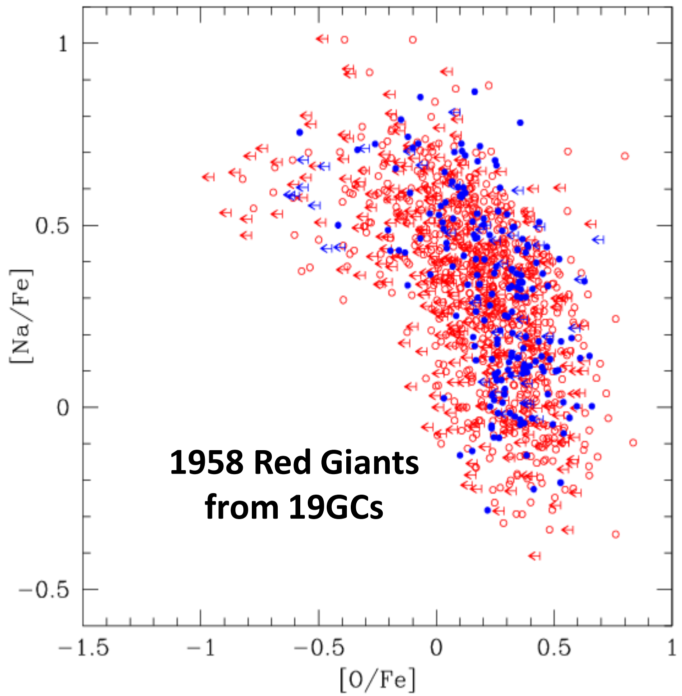
Buckner et al., PRC **91** (2015)

Concluded measurements: $^{22}Ne(p,\gamma)^{23}Na$ – HpGe

The Neon - Sodium cycle strongly influences the abundance of Ne, Na, Mg and Al isotopes in:

- Hydrostatic hydrogen burning in massive stars
- Shell hydrogen burning in Red Giant Branch and Asymptotic Giant Branch stars (Na-O anticorrelation problem)





Carretta A&A 505 (2009)

$^{22}Ne(p,\gamma)^{23}Na$ is the most uncertain reaction in the NeNa cycle

Concluded measurements: ^{22}Ne(p,γ)^{23}Na – HpGe

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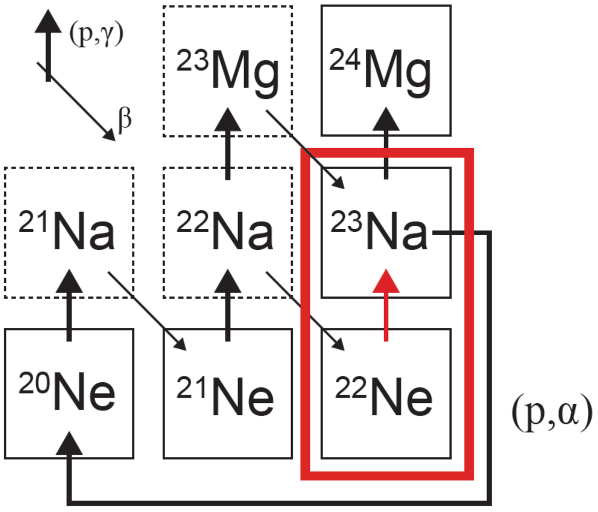

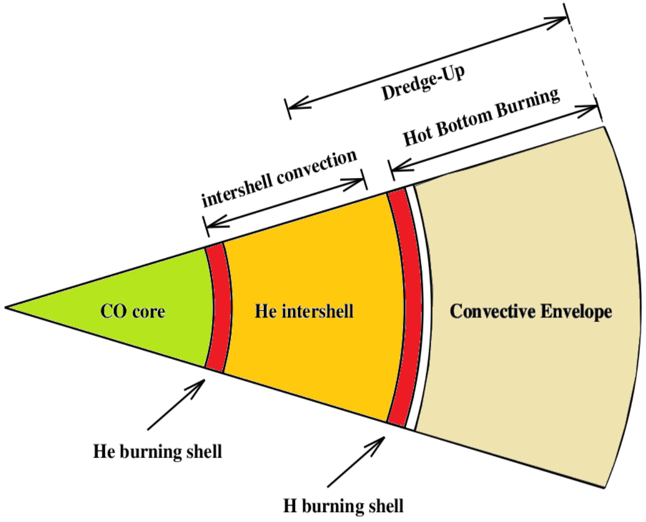

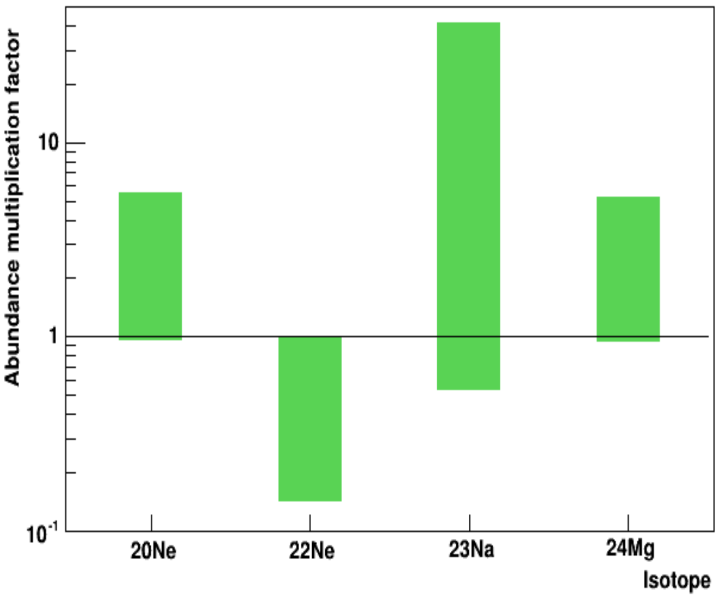

- Explosive H burning in classical novae and supernovae IA explosion

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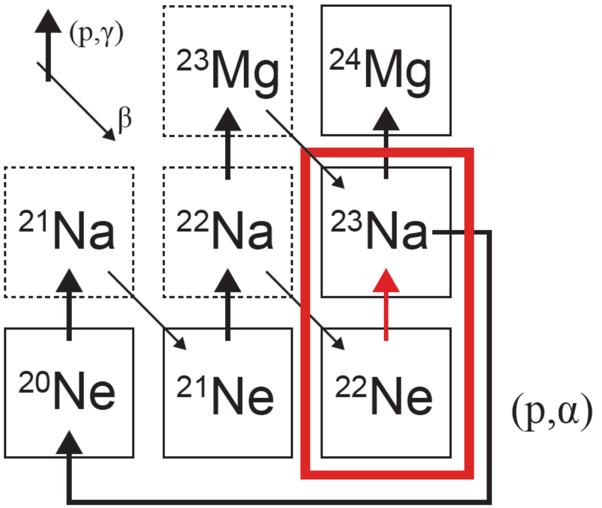

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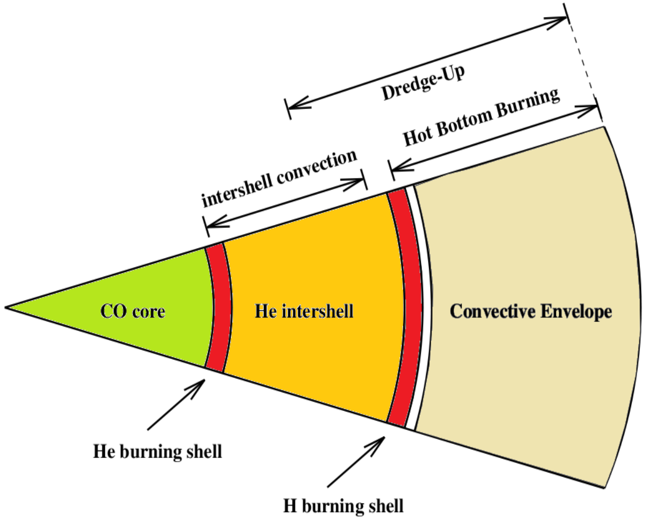

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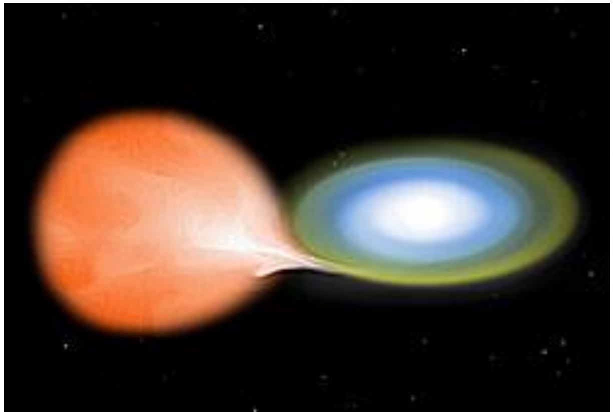

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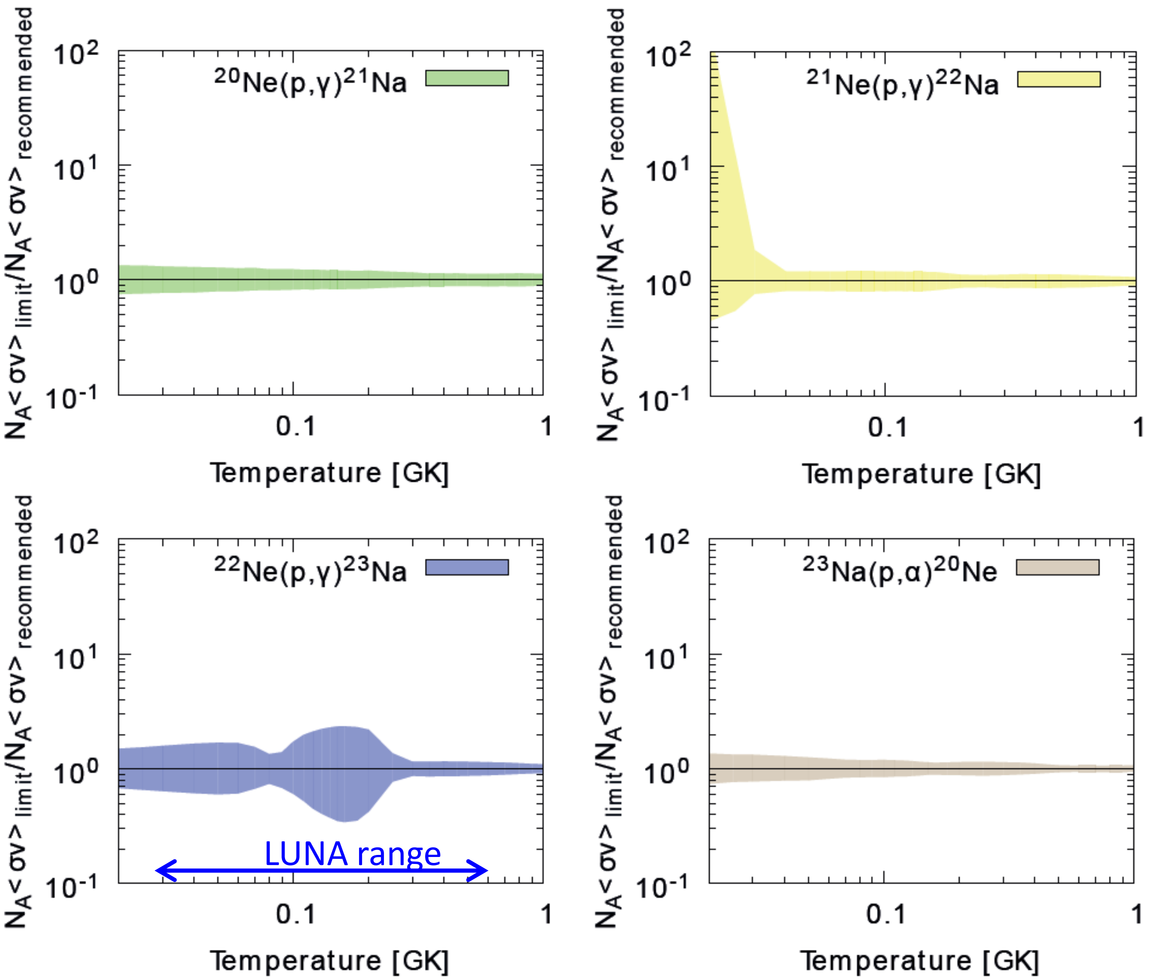
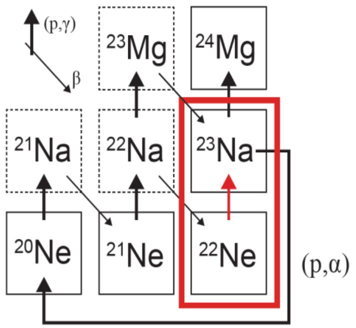
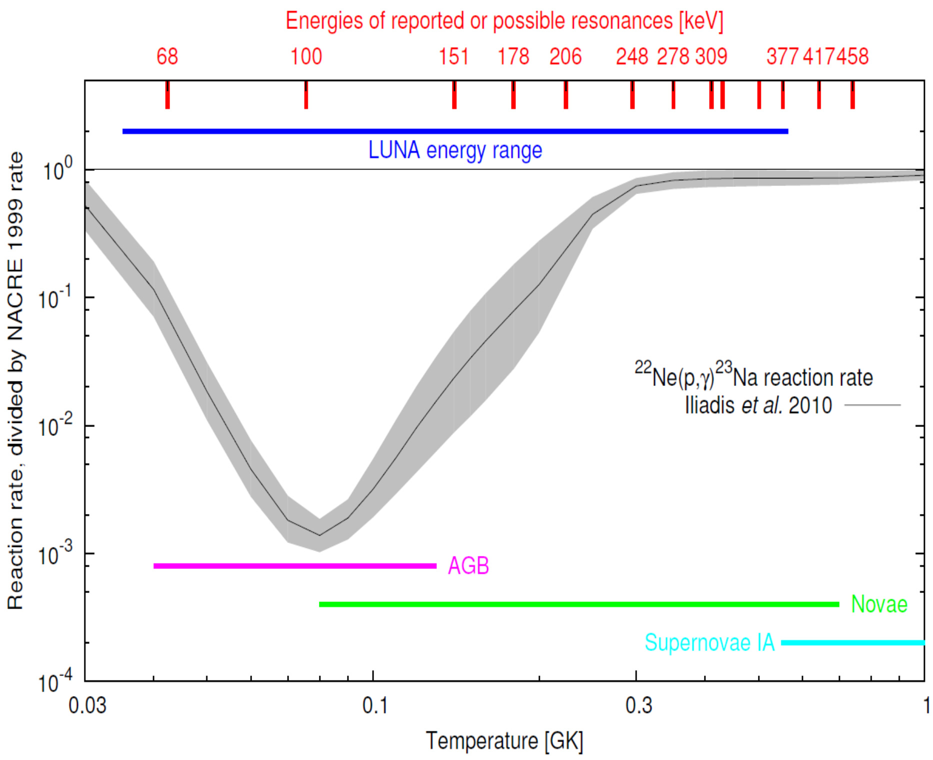


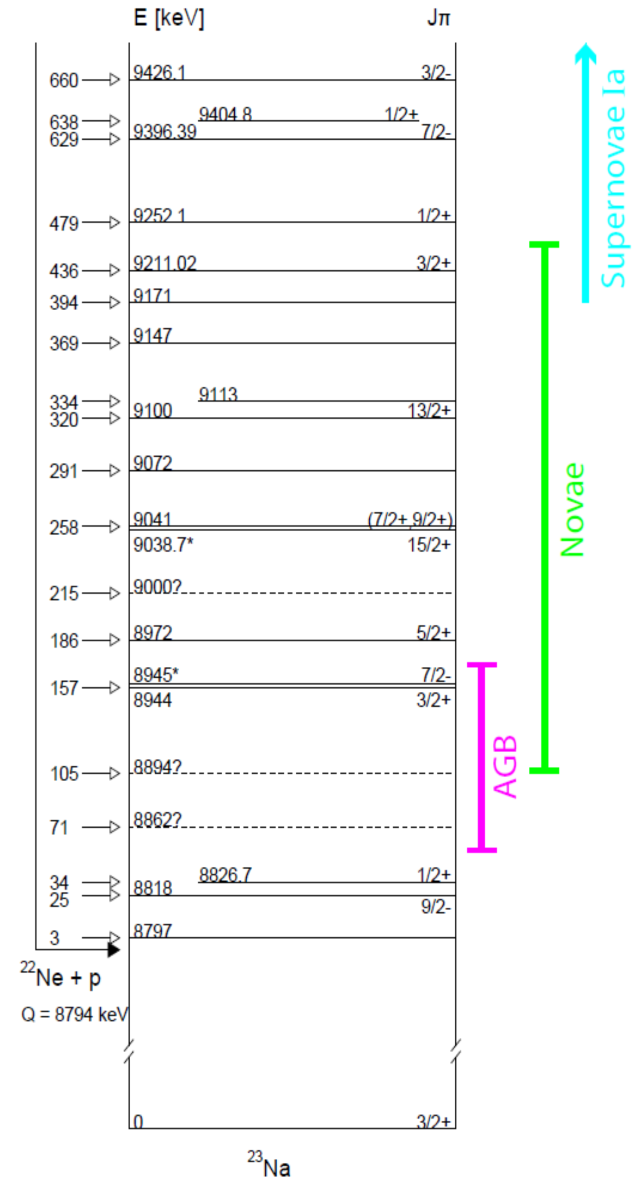


Reaction rate from Iliadis et al. 2010

Concluded measurements: $^{22}Ne(p,\gamma)^{23}Na$ – HpGe

- NACRE reaction rate compilation 1999
- Iliadis et al. compilation 2010
- Strong differences





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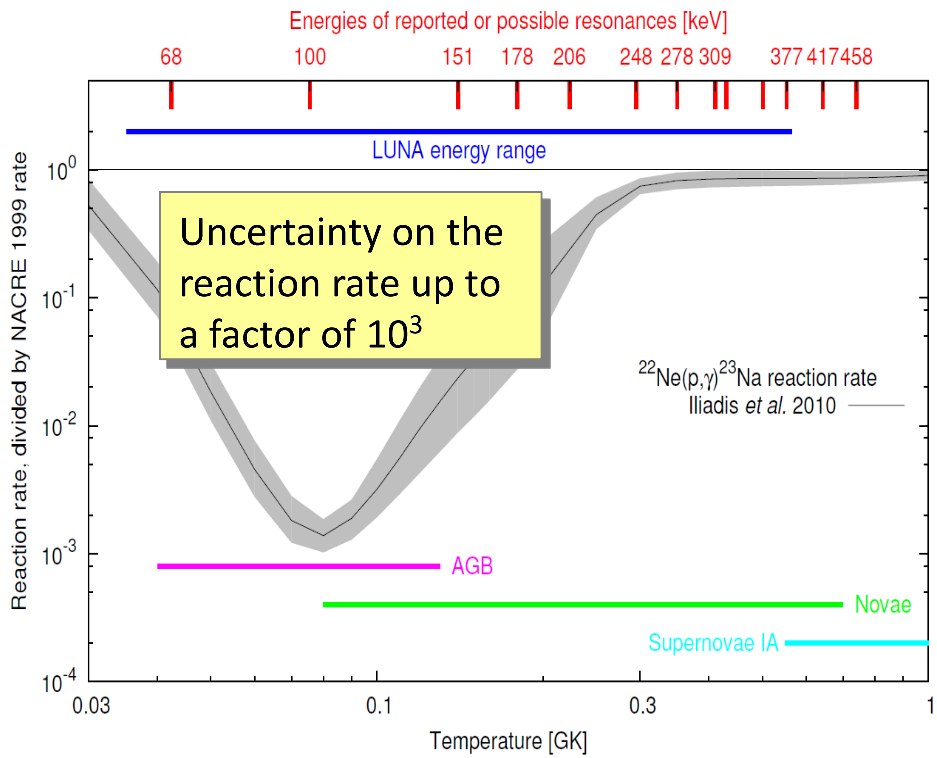

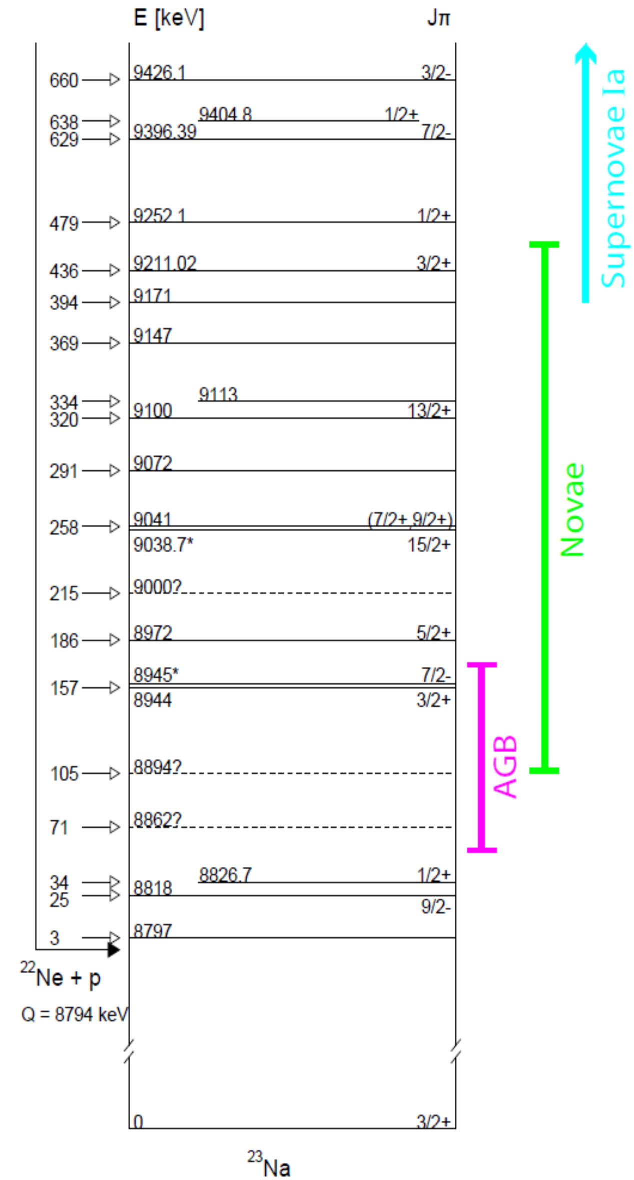

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R. Depalo et al., PRC **92**, 4 (2015)

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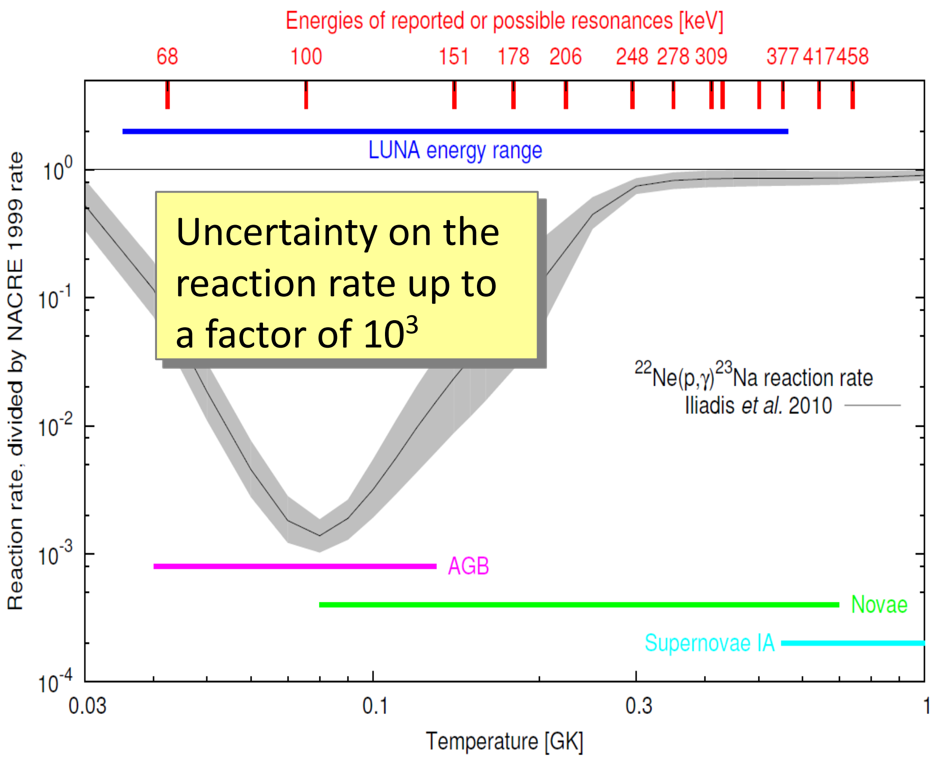

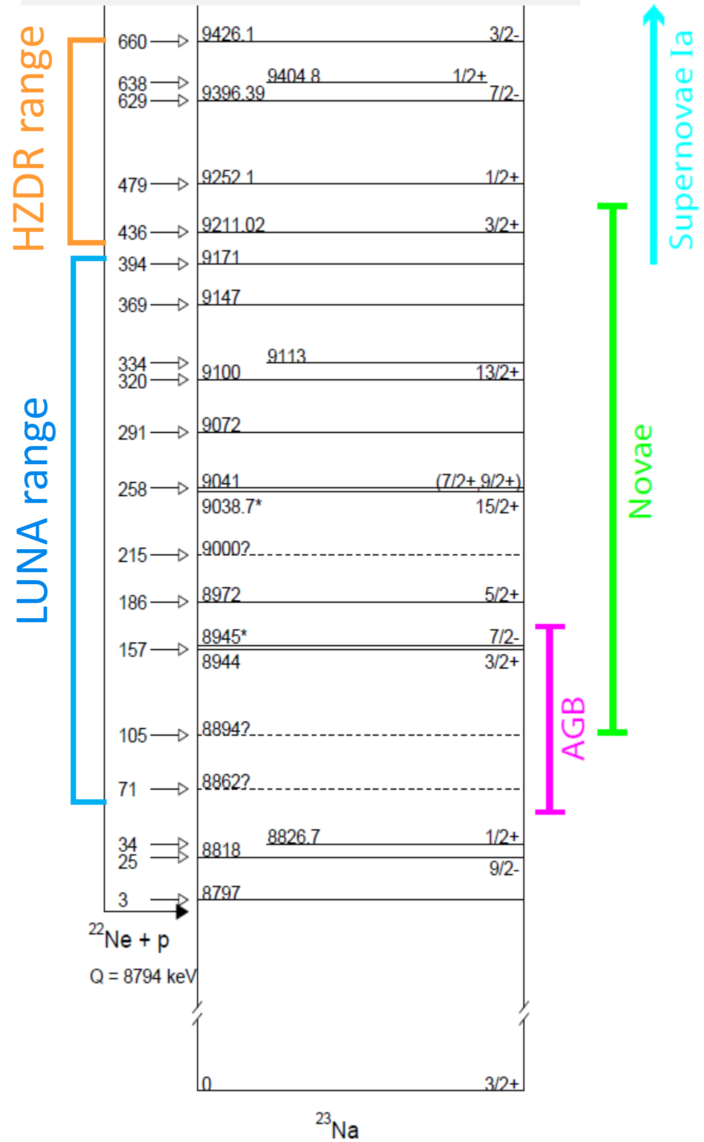

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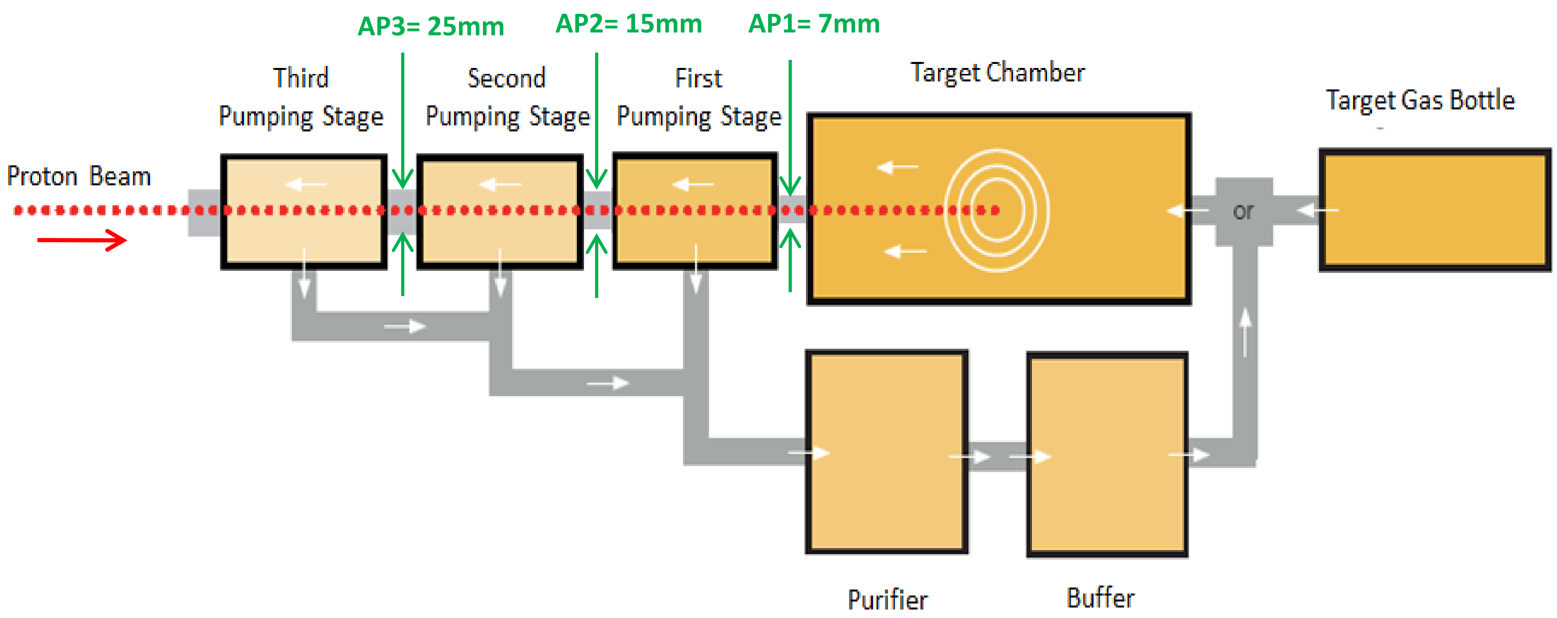
Windowless gas target:
- **3 differential pumping stages**
- **Gas recirculation and purification system**



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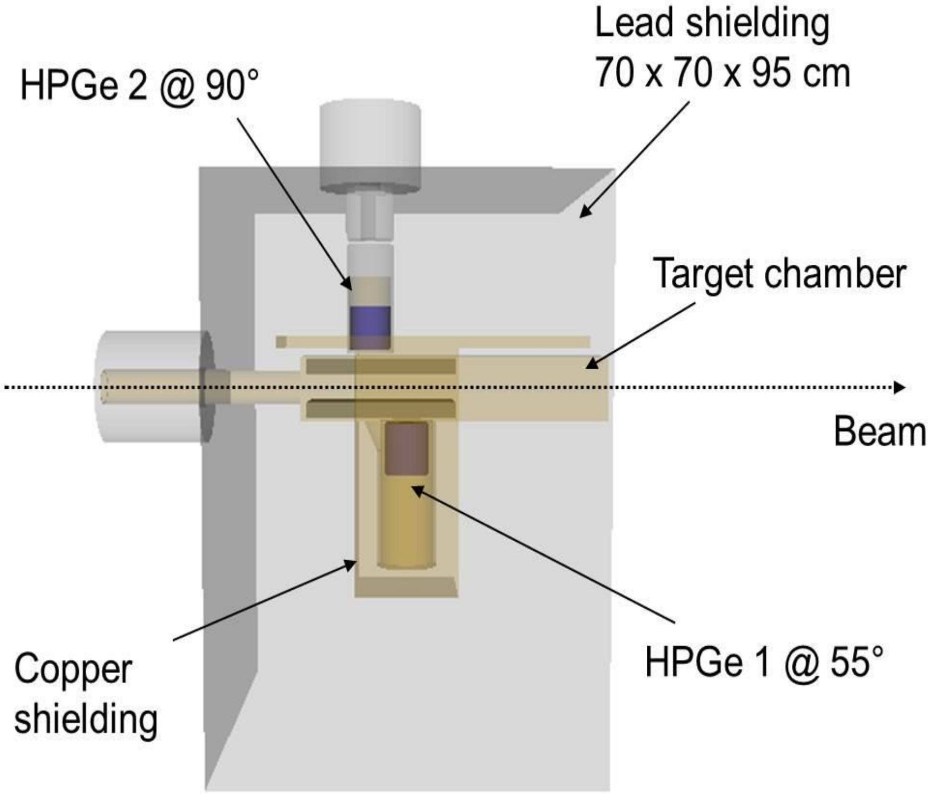
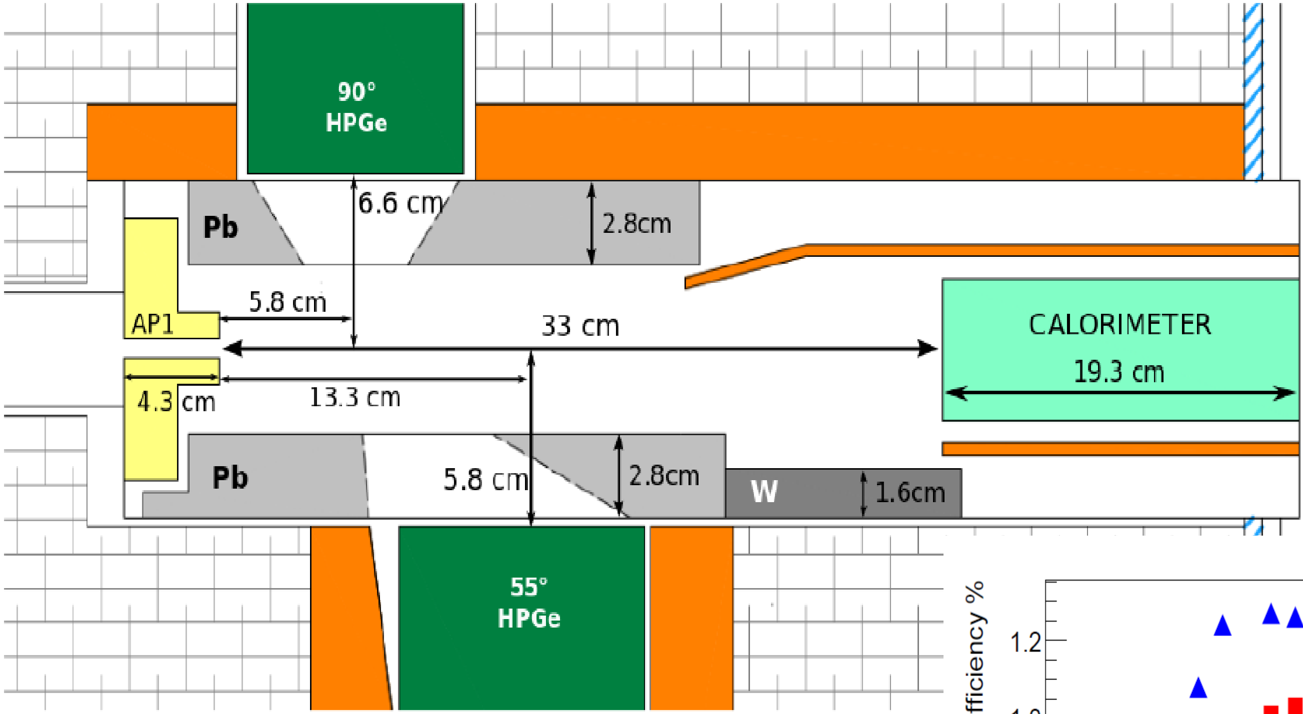


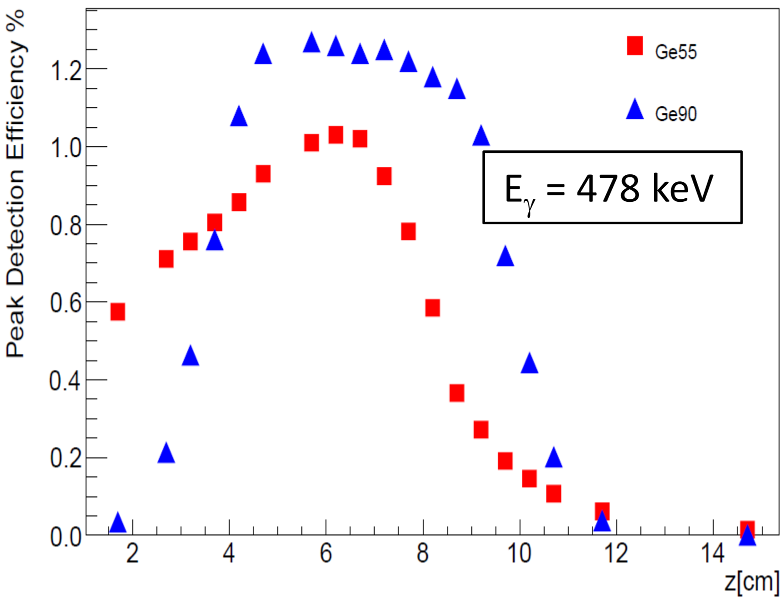
Calorimeter

- Two large HPGe detectors (135% and 90% relative efficiency)
- 15-20 cm thick lead shielding
- 5 cm additional copper shield for 55° detector

Concluded measurements: $^{22}Ne(p,\gamma)^{23}Na$ – HpGe



F. Cavanna et al. EPJ A 50, 179 (2014)



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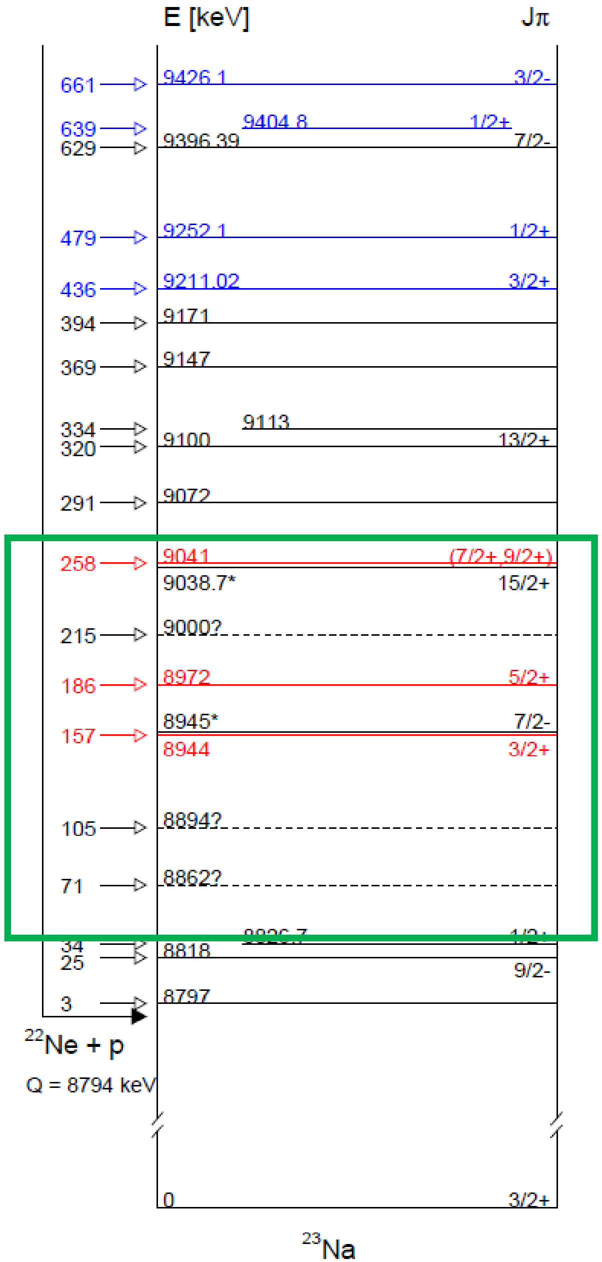


- The experiment has been carried out within the "green" box
- The "red" resonances have been directly observed for the first time
- For the resonances at 71, 105 and 215 keV in "black" quoted an upper limit

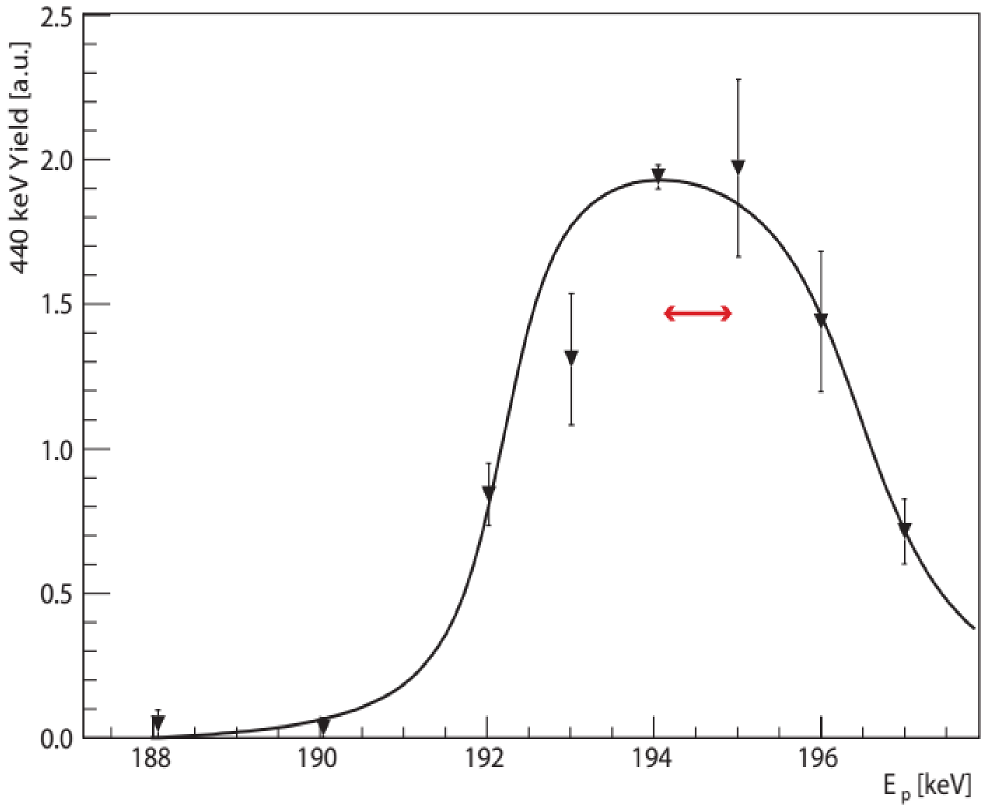
Concluded measurements: $^{22}Ne(p,\gamma)^{23}Na$ – HpGe

Reaction	$E_{R,lab}$ LUNA [keV]	$E_{R,lab}$ literature [keV]
$^{21}Ne(p,\gamma)^{22}Na$	271.5 ± 1.0	271.56 ± 0.04 [Becker 92]
$^{20}Ne(p,\gamma)^{21}Na$	385.6 ± 0.6	384.5 ± 0.5 [Firestone04]

With this experiment we were able to reproduce the resonance energies of the literature:

- Determination of the proton energy loss in neon gas under control
- Energy calibration of the accelerator under control

Concluded measurements: $^{22}Ne(p,\gamma)^{23}Na$ – HpGe



$$E_{R,lab} = E_p - (x + x_{coll}) \frac{dE}{dx} - \Delta E_{pipe}$$

Concluded measurements: $^{22}Ne(p,\gamma)^{23}Na$ – HpGe

$E_{R,lab}$ LUNA [keV]	$E_{R,lab}$ Iliadis10 [keV]	$E_{R,lab}$ Jenkins13 [keV]	% change of TRR (T=0.1 GK)
156.2 ± 0.7	158 ± 2	157 ± 1	10%
189.5 ± 0.7	186 ± 2	186 ± 1	-30%
259.7 ± 0.6	259.2 ± 1.0	258 ± 1	-20%

$$\langle \sigma v \rangle = \left(\frac{2\pi}{\mu k T} \right)^{3/2} \hbar^2 (\omega\gamma) e^{-E_R/(kT)}$$

Concluded measurements: ^{22}Ne(p,γ)^{23}Na – HpGe

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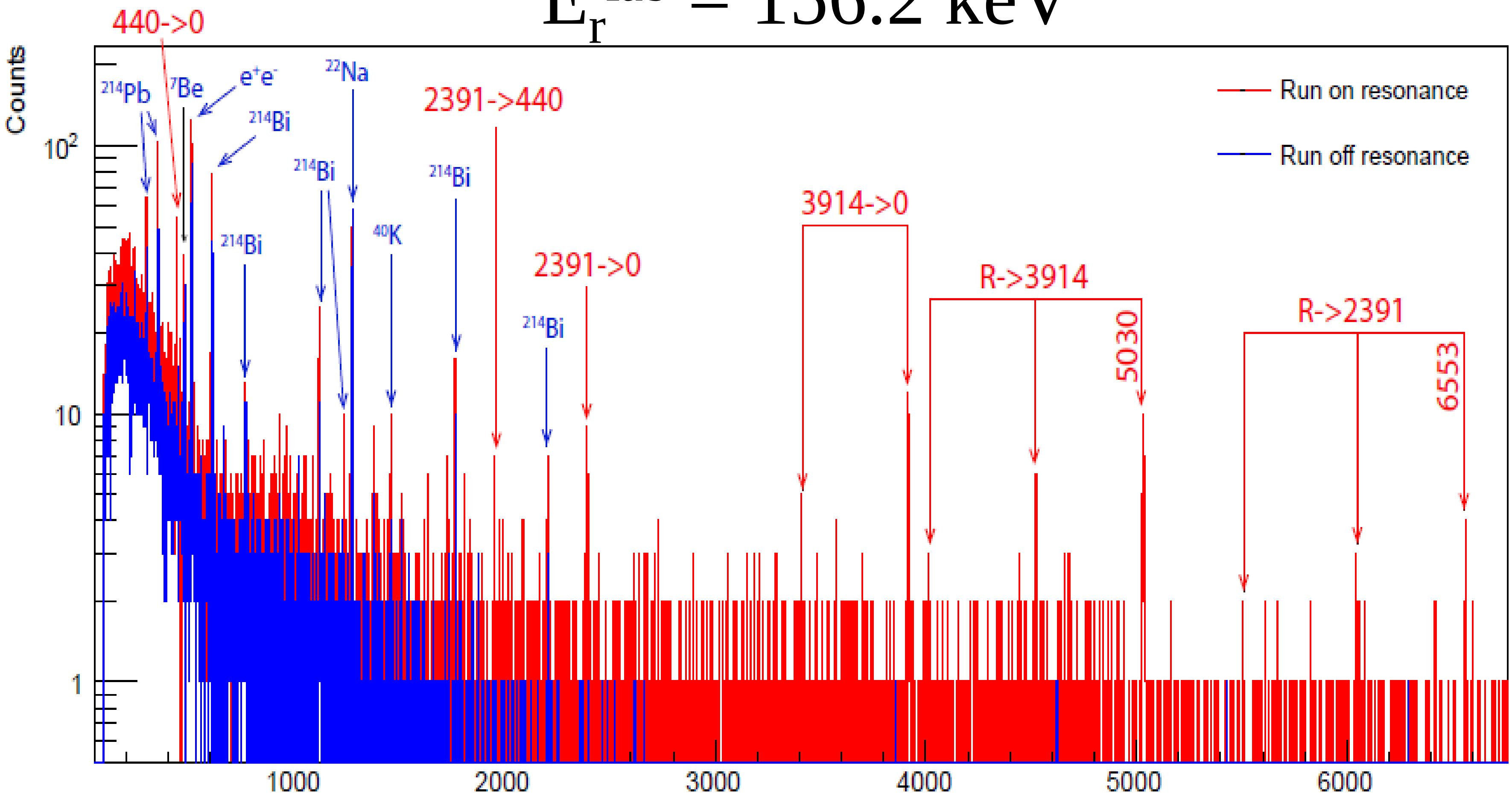
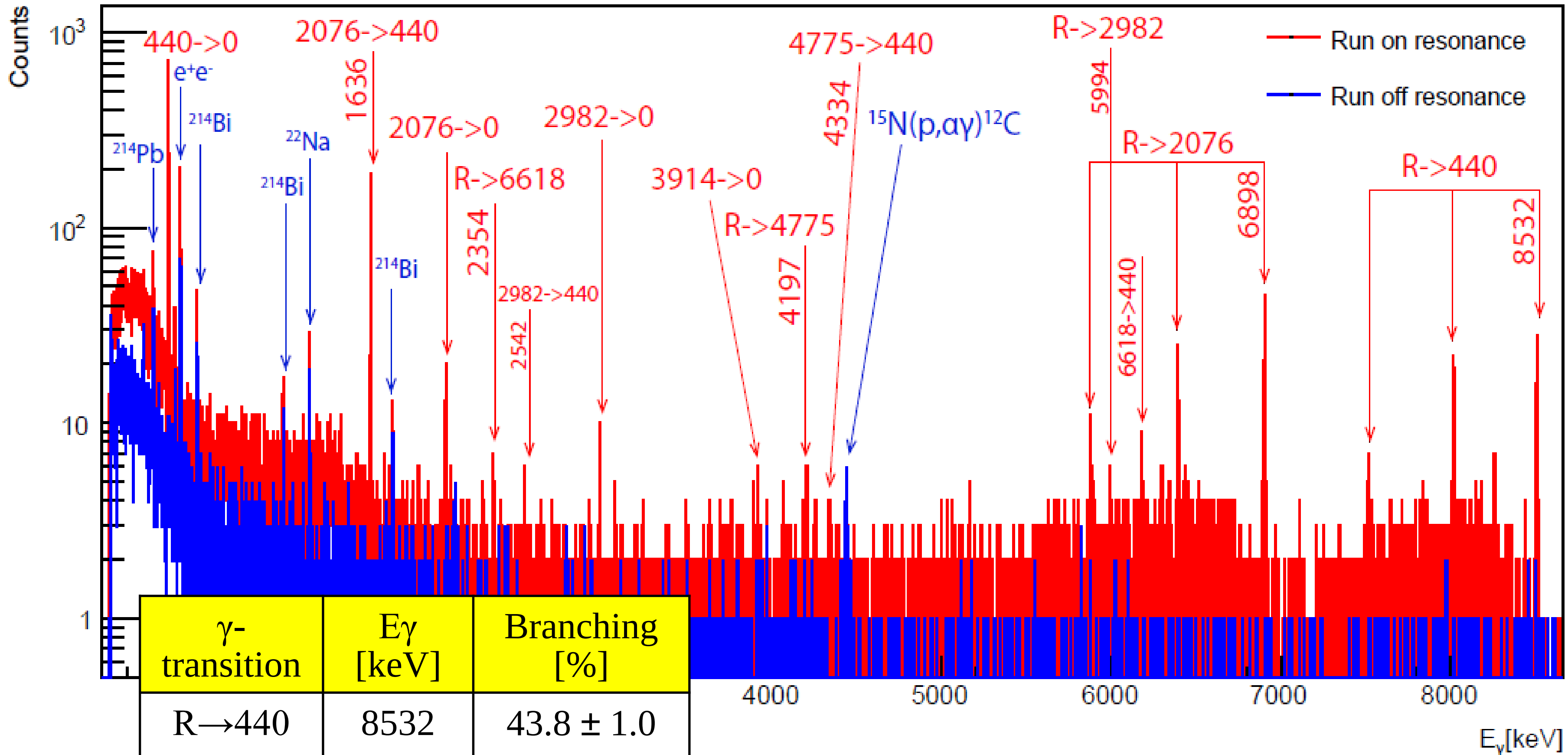
$E_r^{lab} = 156.2$ keV



γ-transition	E_γ [keV]	Branching [%]
R→2391	6553	23 ±4
R→3914	5030	77 ±4

	ωγ [eV]
Ge55	[1.45 ± 0.12 (stat) ± 0.03 (syst)] 10^{-7}
Ge90	[1.52 ± 0.17 (stat) ± 0.03 (syst)] 10^{-7}
Average	[1.48 ± 0.10 (stat) ± 0.03 (syst)] 10^{-7}

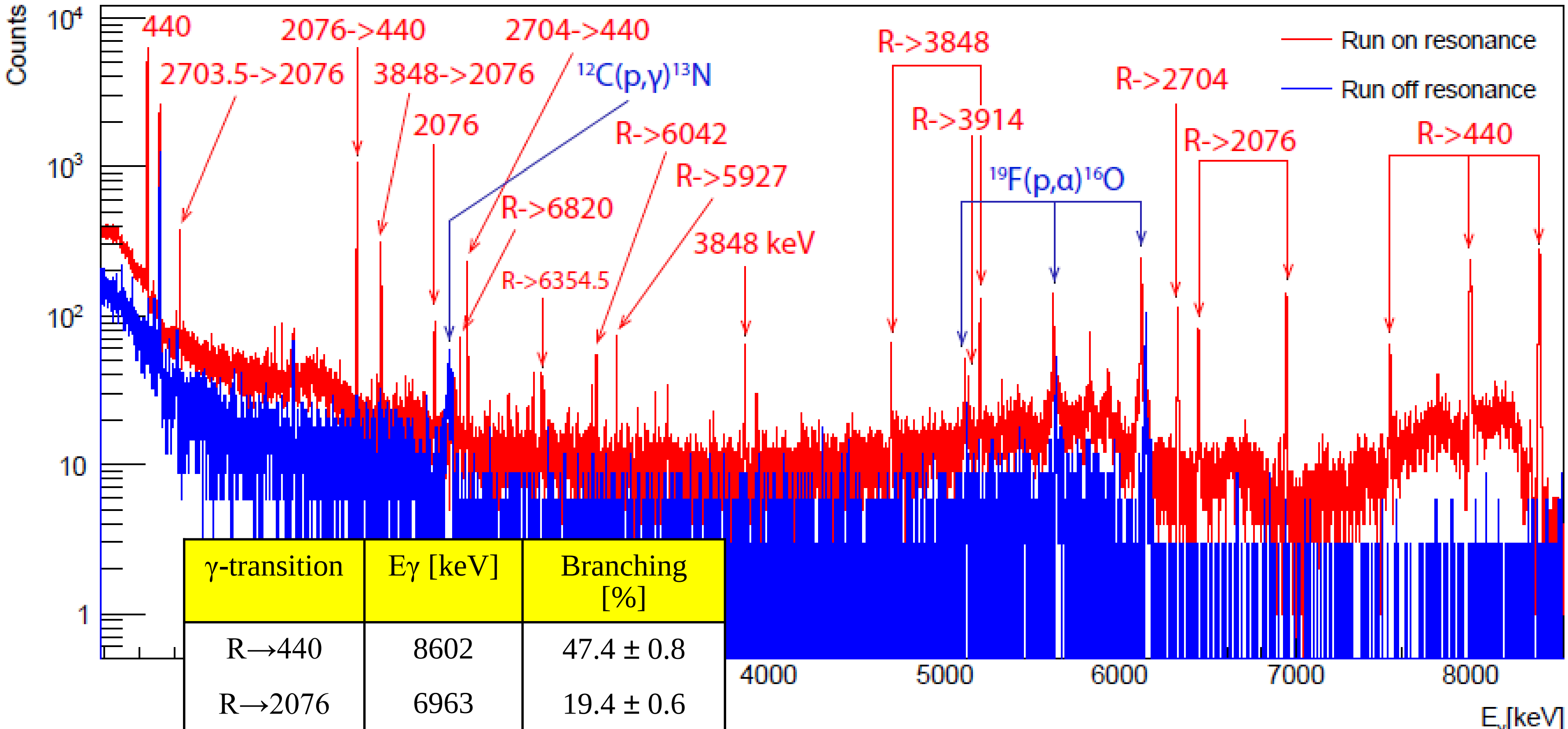
$E_r^{lab} = 189.5$ keV



γ-transition	Eγ [keV]	Branching [%]
R→440	8532	43.8 ± 1.0
R→2076	6896	47.7 ± 0.9
R→2982	5990	3.8 ± 0.5
R→3914	5058	1.0 ± 0.2
R→4775	4197	1.9 ± 0.3
R→6618	2354	2.8 ± 0.2

	ωγ [eV]
Ge55	[1.85 ± 0.04 (stat) ± 0.04 (syst)] 10^{-6}
Ge90	[1.88 ± 0.04 (stat) ± 0.04 (syst)] 10^{-6}
Average	[1.87 ± 0.03 (stat) ± 0.05 (syst)] 10^{-6}

$E_r^{lab} = 259.7$ keV



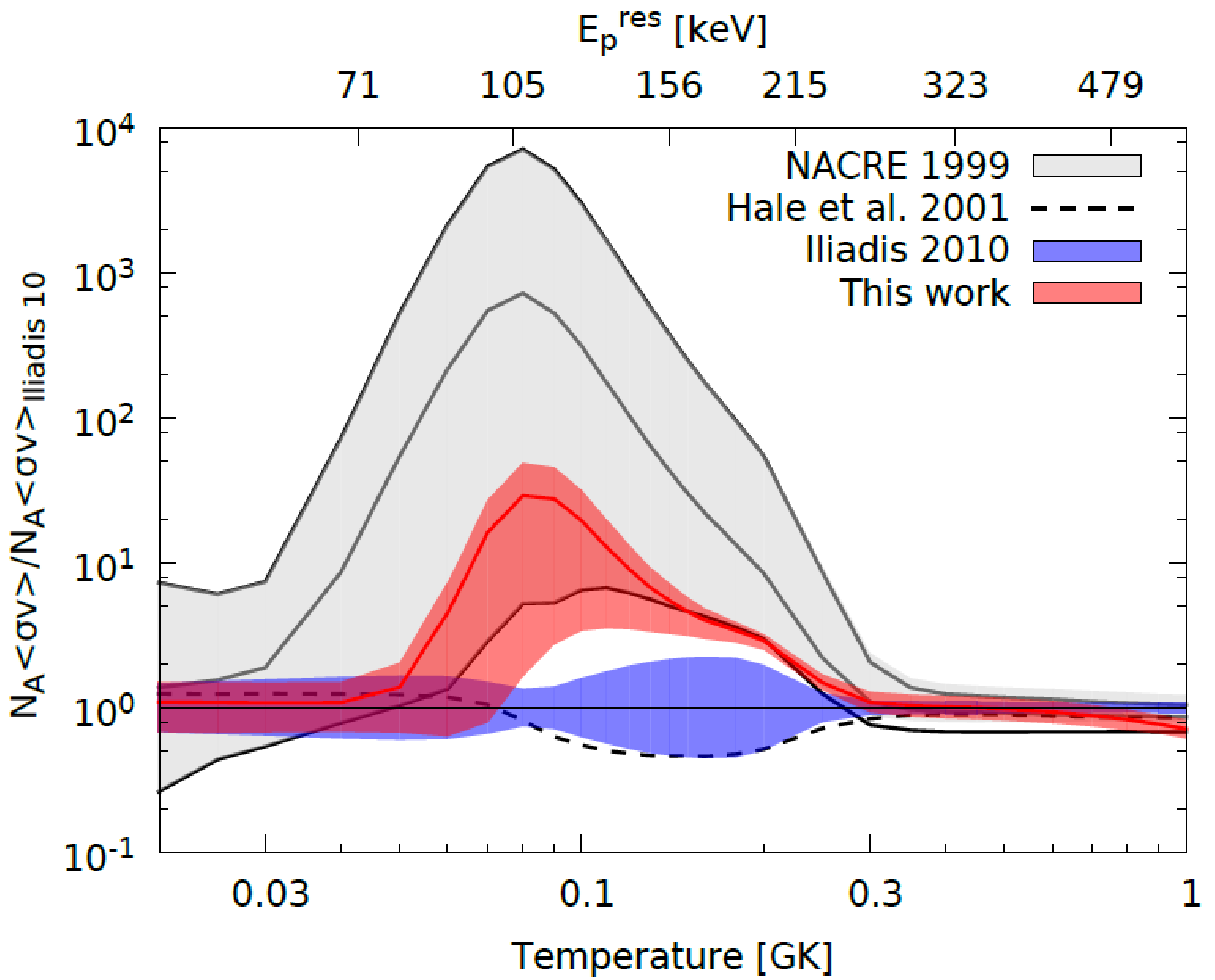
γ-transition	Eγ [keV]	Branching [%]
R→440	8602	47.4 ± 0.8
R→2076	6963	19.4 ± 0.6
R→2704	6335	11.4 ± 0.5
R→3848	5193	13.9 ± 0.6
R→3914	5127	1.5 ± 0.3
R→5927	3115	3.9 ± 0.2
R→6042	3000	2.6 ± 0.2
R→6354.5	2686.5	1.5 ± 0.2
R→6820	2221	2.2 ± 0.2

	ωγ [eV]
Ge55	[6.91 ± 0.11 (stat) ± 0.14 (syst)] 10^{-6}
Ge90	[6.87 ± 0.13 (stat) ± 0.14 (syst)] 10^{-6}
Average	[6.89 ± 0.08 (stat) ± 0.14 (syst)] 10^{-6}

Concluded measurements: $^{22}Ne(p,\gamma)^{23}Na$ – HpGe

$E_{R,lab}$ [keV]	$\omega\gamma$ [eV]			
	This work	Direct experiment [Görres82]	Indirect experiment [Hale01]	Iliadis et al. [2010]
71	$\leq 1.5\ 10^{-9}$	$\leq 3.2\ 10^{-6}$	$\leq 1.9\ 10^{-10}$	-
105	$\leq 7.6\ 10^{-9}$	$\leq 0.6\ 10^{-6}$	$\leq 1.4\ 10^{-7}$	-
156.2	$[1.48 \pm 0.10]\ 10^{-7}$	$\leq 1.0\ 10^{-6}$	$\leq 9.2\ 10^{-9}$	$(9.2\pm3.7)10^{-9}$
189.5	$[1.87 \pm 0.06]\ 10^{-6}$	$\leq 2.6\ 10^{-6}$	$\leq 2.6\ 10^{-6}$	$\leq 2.6\ 10^{-6}$
215	$\leq 2.8\ 10^{-8}$	$\leq 1.4\ 10^{-6}$	$\leq 1.4\ 10^{-6}$	-
259.7	$[6.89 \pm 0.16]\ 10^{-6}$	$\leq 2.6\ 10^{-6}$	$\leq 1.3\ 10^{-7}$	$\leq 1.3\ 10^{-7}$

Concluded measurements: $^{22}Ne(p,\gamma)^{23}Na$ – HpGe



F. Cavanna *et al.*, Physical Review Letters **115**, 252501 (2015)

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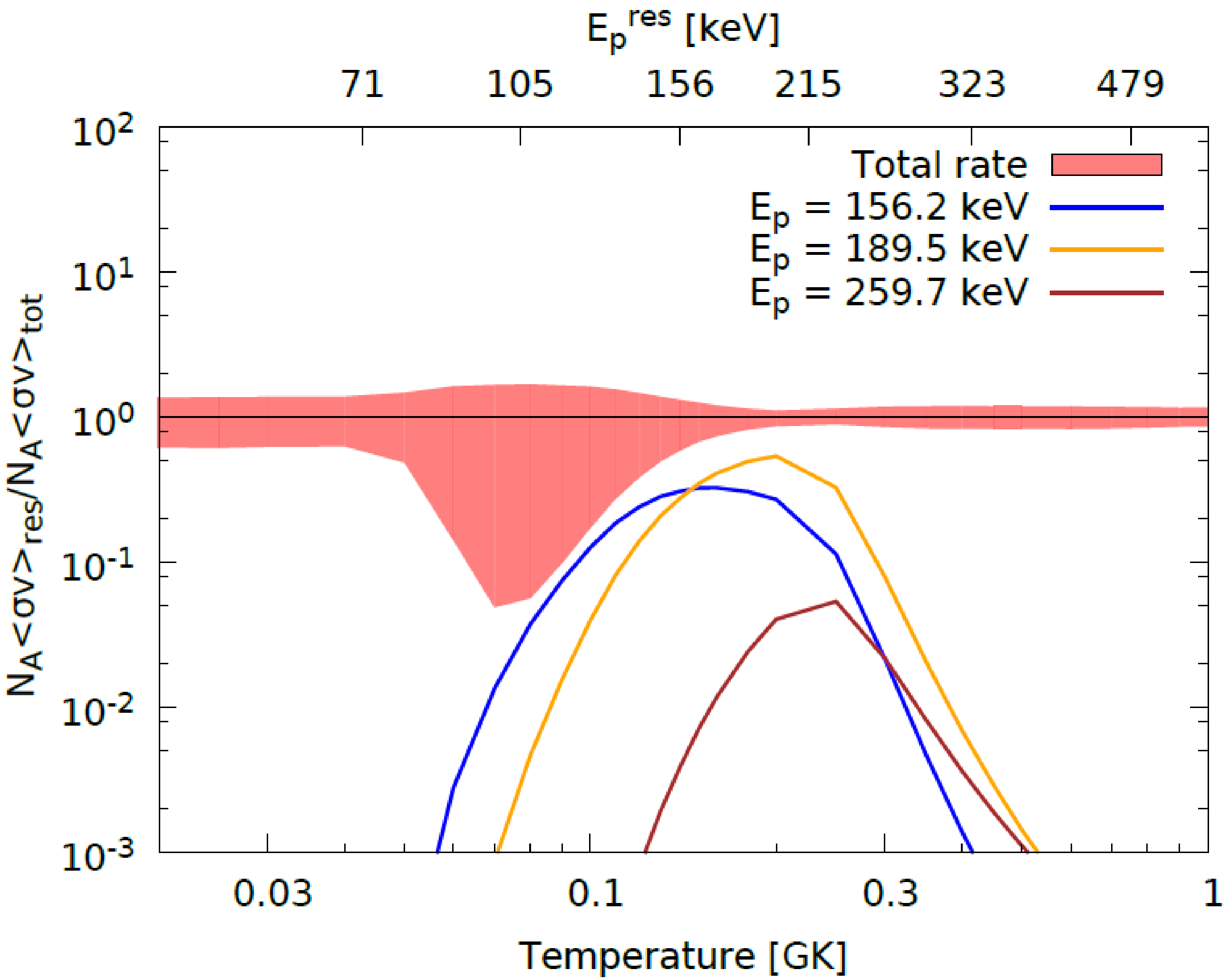
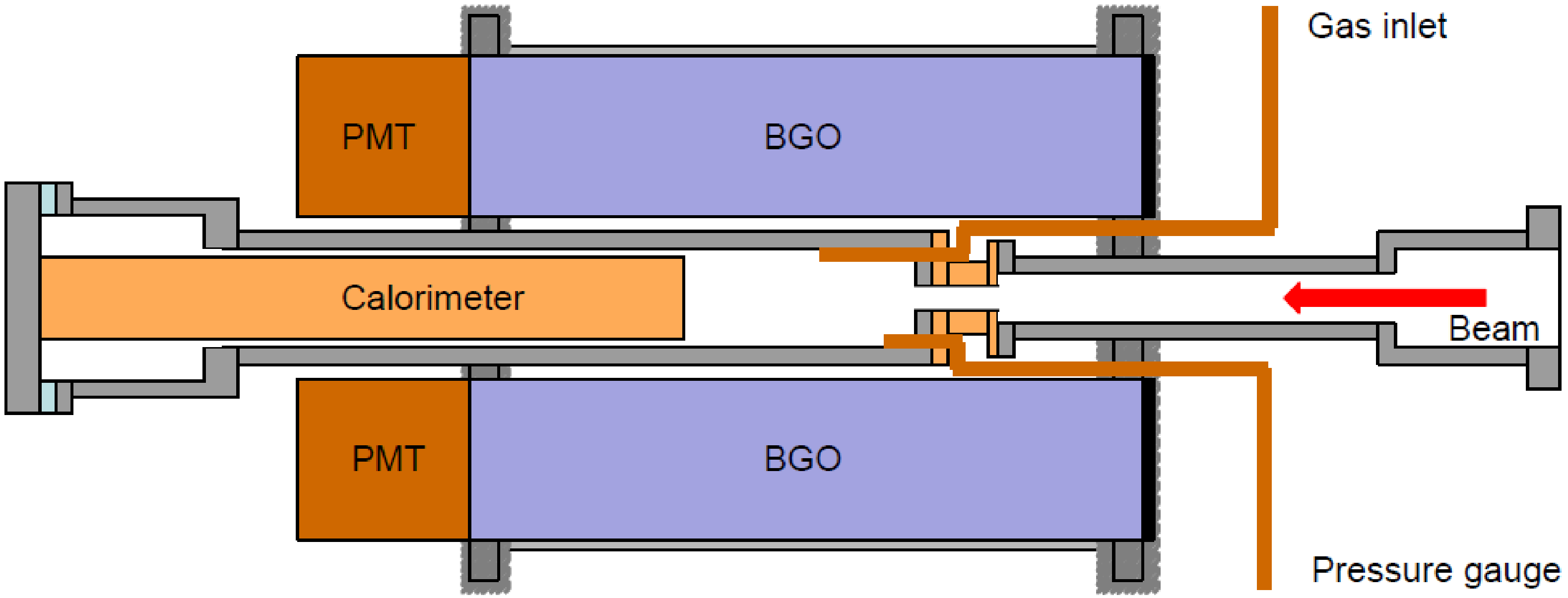


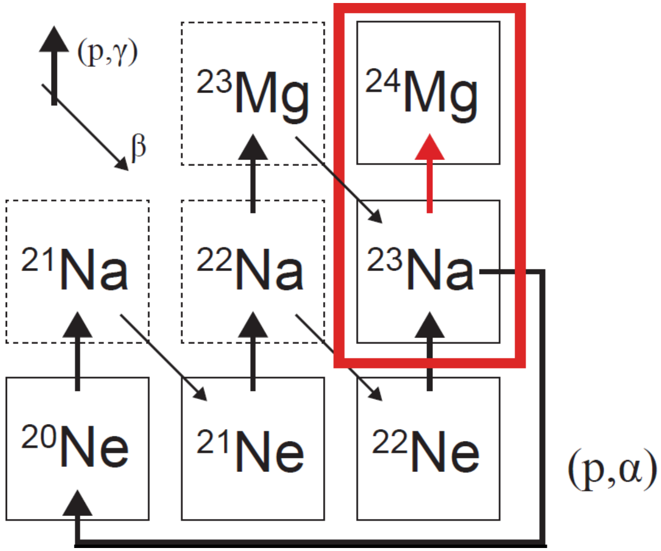
F. Cavanna *et al.*, Physical Review Letters **115**, 252501 (2015)

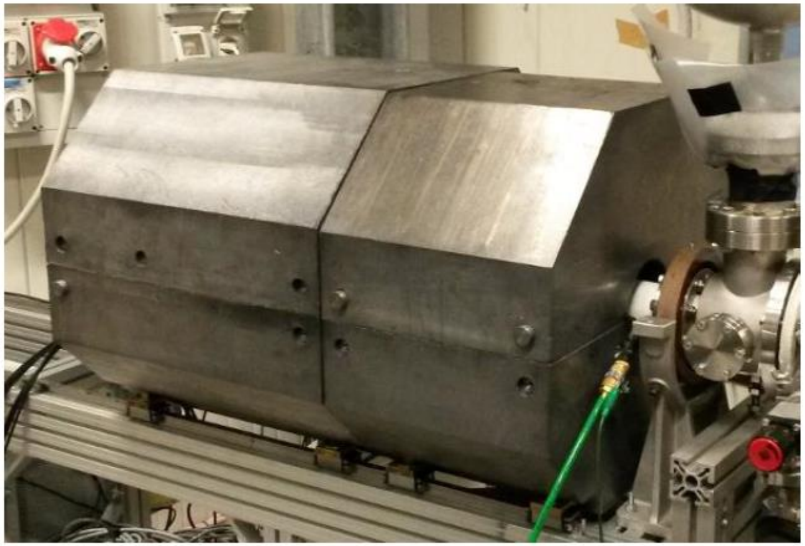
Ongoing measurements: ^{22}Ne(p,γ)^{23}Na – BGO



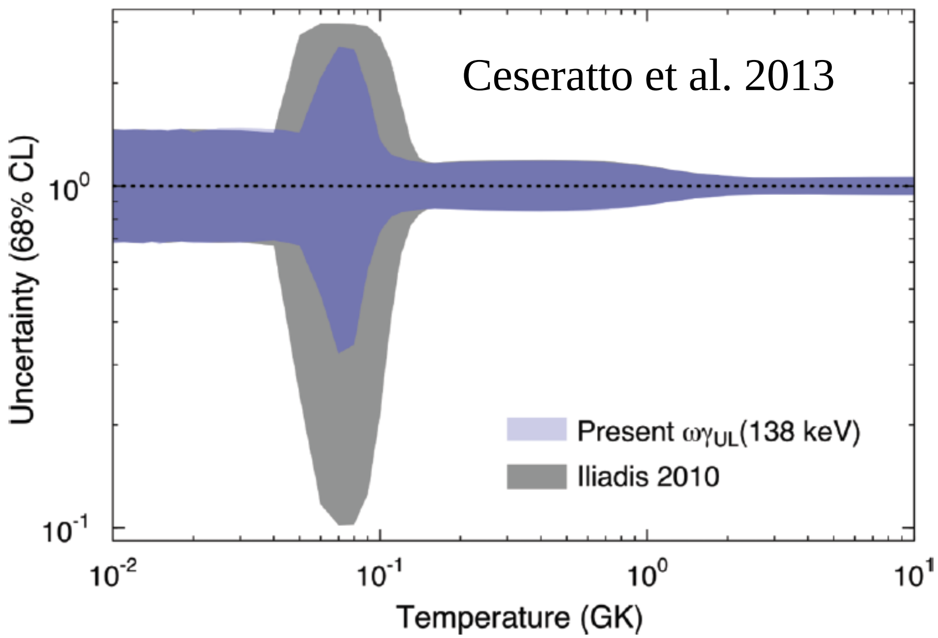
- Goals of the BGO phase:
  - **Further investigate the resonances at 71 and 105 keV**
  - Measure the direct capture
- Gas characterization concluded
- Data taking concluded
- Data analysis in progress

Ongoing measurements: $^{23}Na(p,\gamma)^{24}Mg$

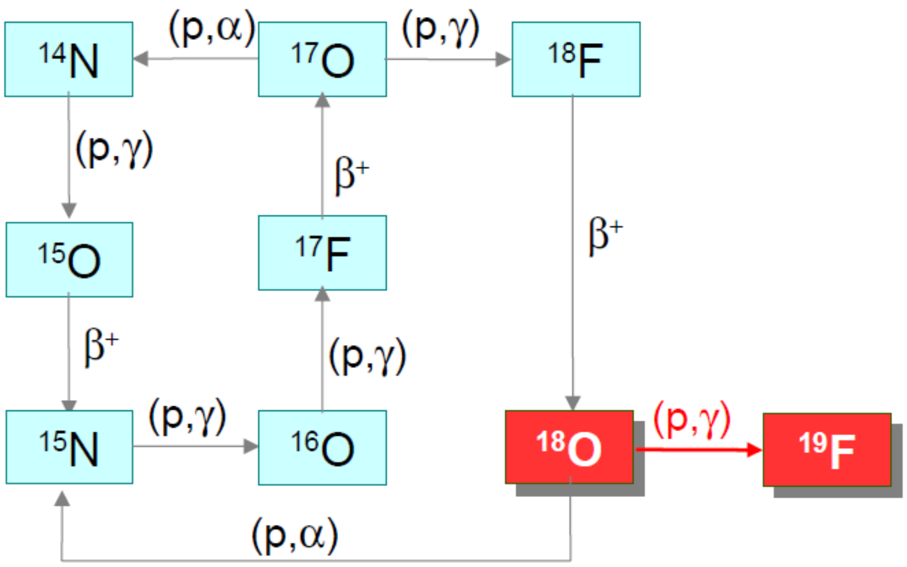


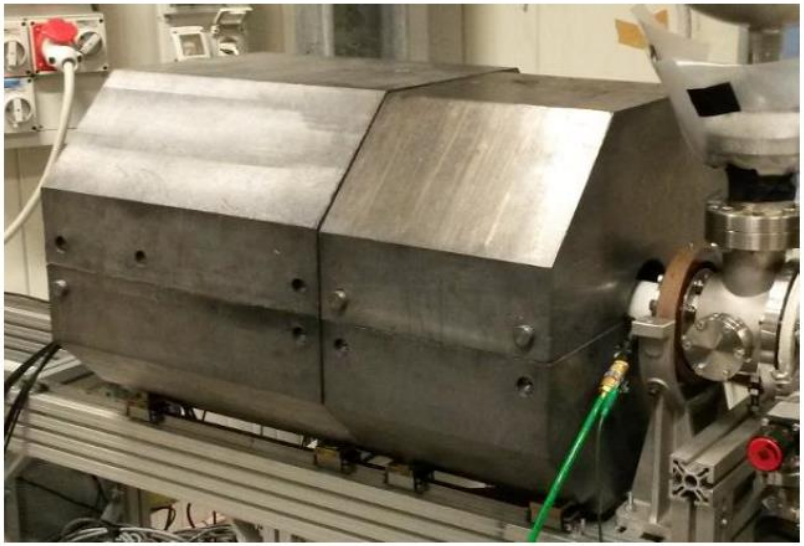


- In the Gamow window of AGB – HBB, the uncertainty is dominated by 138 keV resonance ($\omega\gamma \leq 5.2$ neV)
- Aim of the $^{23}Na(p,\gamma)^{24}Mg$ is to measure the strength of the 138 keV resonance
- Solid target + BGO detector



Ongoing measurements: $^{18}O(p,\gamma)^{19}F$



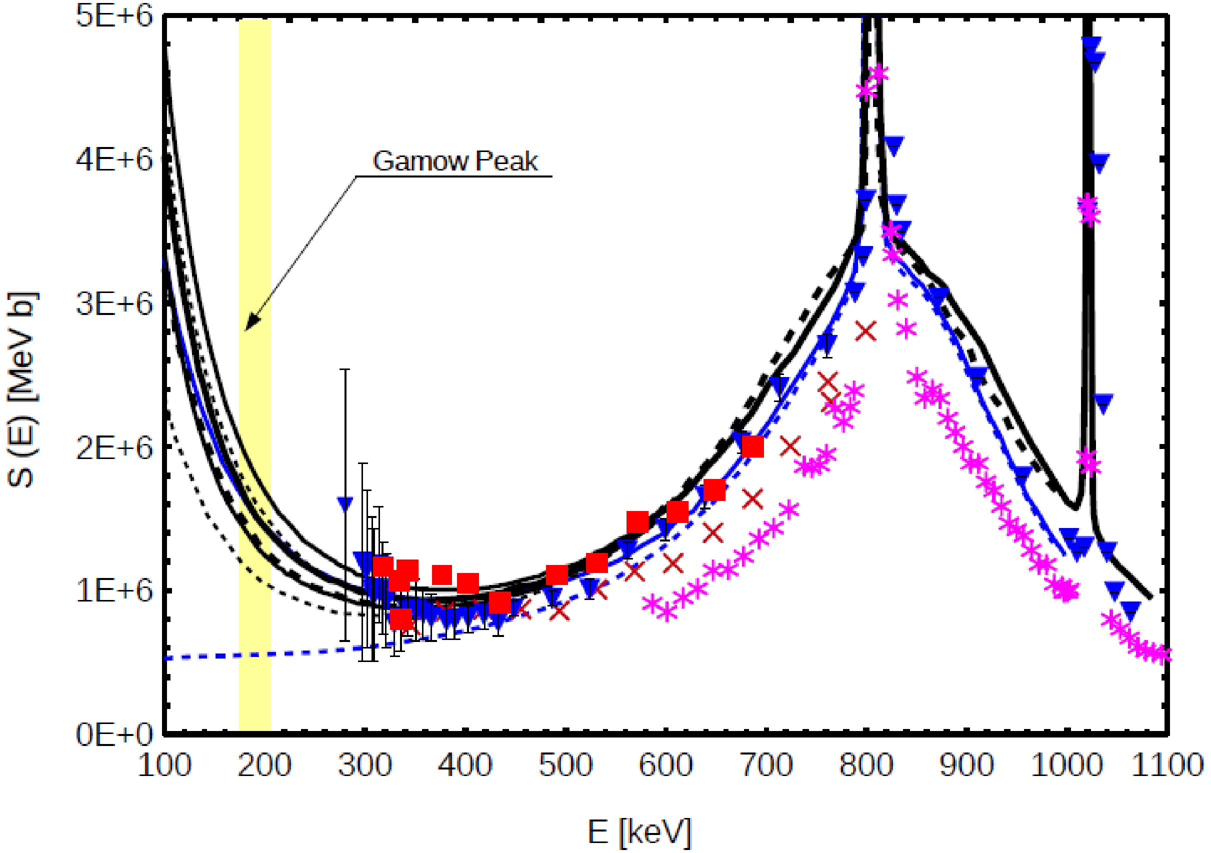


- Aim of the measurement: 95 keV resonance and DC component

✓Buckner et al. 2015: 95 keV resonance negligible ($\omega\gamma \leq 7.8$ neV)

✓Fortune et al. 2013: 95 keV dominant ($\omega\gamma \leq 0.7$ µeV)

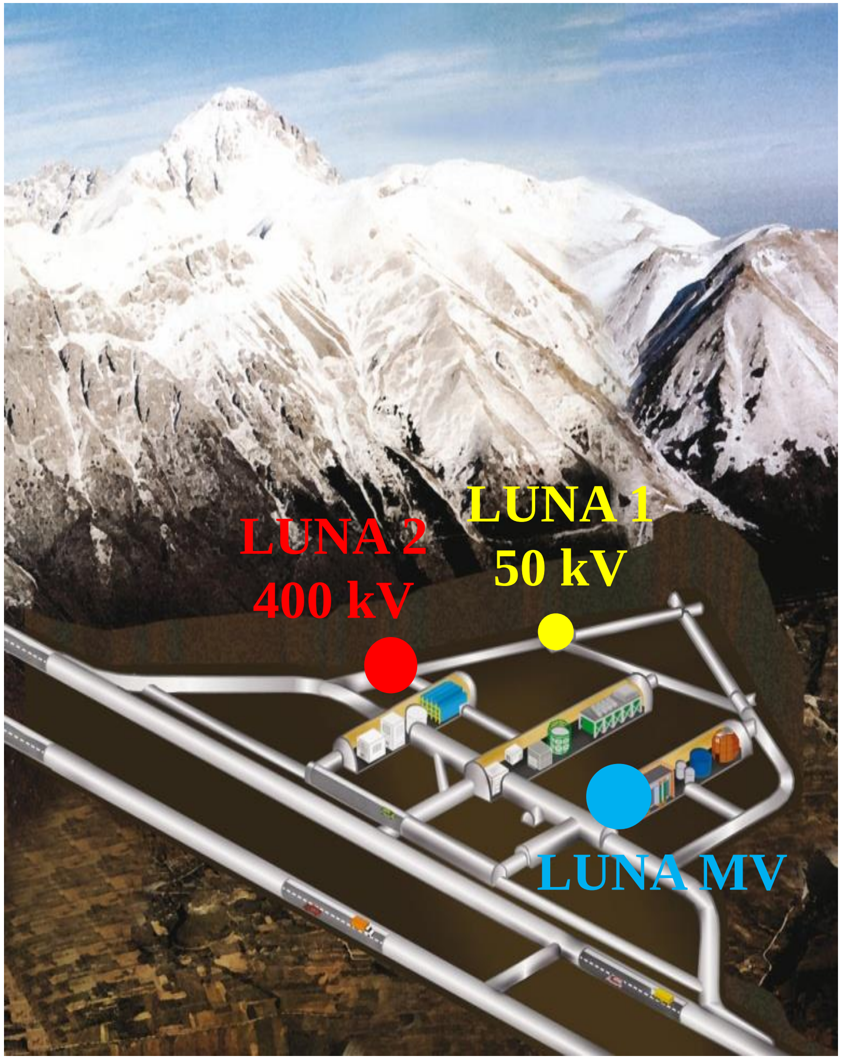
Planned measurements: $^{13}C(\alpha,n)^{16}O$



- Big uncertainties in R-matrix extrapolation
- Planned measurement below 300 keV
- Solid or gas target, both options under investigation

The future: LUNA MV Project

- 3.5 MV accelerator
- New experimental hall: Hall C of LNGS
- Intense H^+, $^4He^+$, $^{12}C^+$
- Scientific program:
  - $^{13}C(\alpha,n)^{16}O$
  - $^{22}Ne(\alpha,n)^{25}Mg$
  - $^{12}C(\alpha,\gamma)^{16}O$
  - $^{12}C+^{12}C$



The future: LUNA MV Project

Laboratory for Underground Nuclear Astrophysics

LUNA MV

Time schedule

- Tender for the accelerator now completed and contract signed with High Voltage Engineering Europe
- The neutron shielding is now being finalized
  - the neutron flux at LNGS will not be increased
- Building and infrastructure construction planned for 2017
  - OPERA decommissioning started in January 2015. Will finish by October 2016
- Commissioning planned for 2018

The LUNA collaboration

Laboratory
Underground
Nuclear
Astrophysics

- A. Best, A. Boeltzig*, A. Formicola, S. Gazzana, I. Kochanek, M. Junker, L. Leonzi | INFN LNGS /*GSSI, Italy
- D. Bemmerer, F. Cavanna, M. Takacs, T. Szucs | **HZDR Dresden, Germany**
- C. Broggini, A. Caciolli, R. Depalo, R. Menegazzo, D. Piatti | Università di Padova and INFN Padova, Italy
- C. Gustavino | INFN Roma1, Italy
- Z. Elekes, Zs. Fülöp, Gy. Gyurky| **MTA-ATOMKI Debrecen, Hungary**
- O. Straniero | INAF Osservatorio Astronomico di Collurania, Teramo, Italy
- F. Cavanna, P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli | Università di Genova and INFN Genova, Italy
- A. Guglielmetti, D. Trezzi | Università di Milano and INFN Milano, Italy
- A. Di Leva, G. Imbriani, | Università di Napoli and INFN Napoli, Italy
- G. Gervino | Università di Torino and INFN Torino, Italy
- M. Aliotta, C. Bruno, T. Davinson | **University of Edinburgh, United Kingdom**
- G.F. Ciani, G. D'Erasmo, E.M. Fiore, V. Mossa, F. Pantaleo, V. Paticchio, R. Perrino, L. Schiavulli, A. Valentini| Università di Bari and INFN Bari, Italy

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- C. Gu
- Z. Ele
- O. Straniero | INAF Osservatorio Astronomico di Collurania, Teramo, Italy
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Thanks for your attention!

Detection efficiency

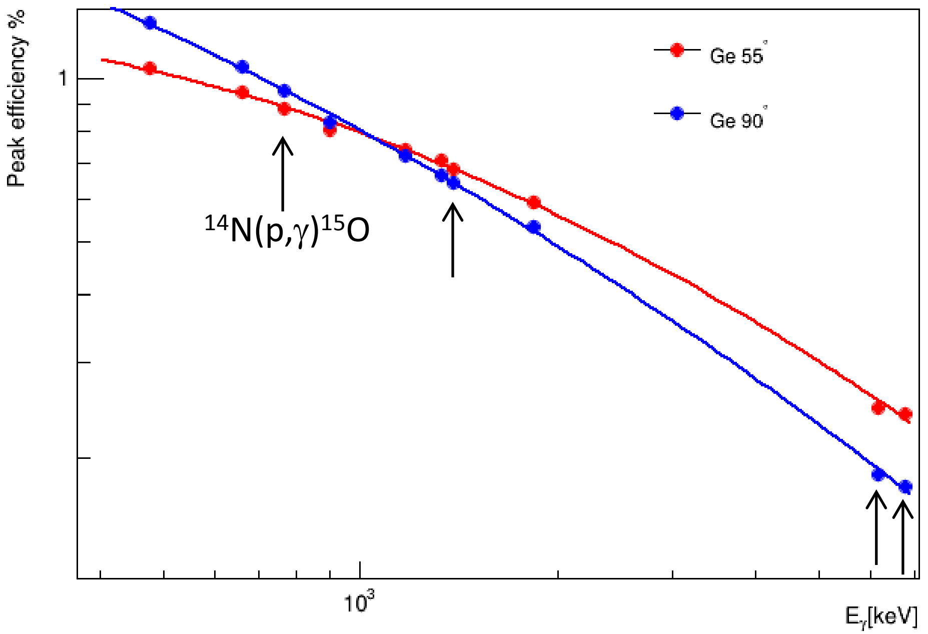
Low energies (478 keV – 1863 keV)

Efficiency measured with 4 point-like sources:

Source	E_γ [keV]
^{7}Be	477.60
^{137}Cs	661.66
^{60}Co	1173.23 1332.49
^{88}Y	898.04 1836.06

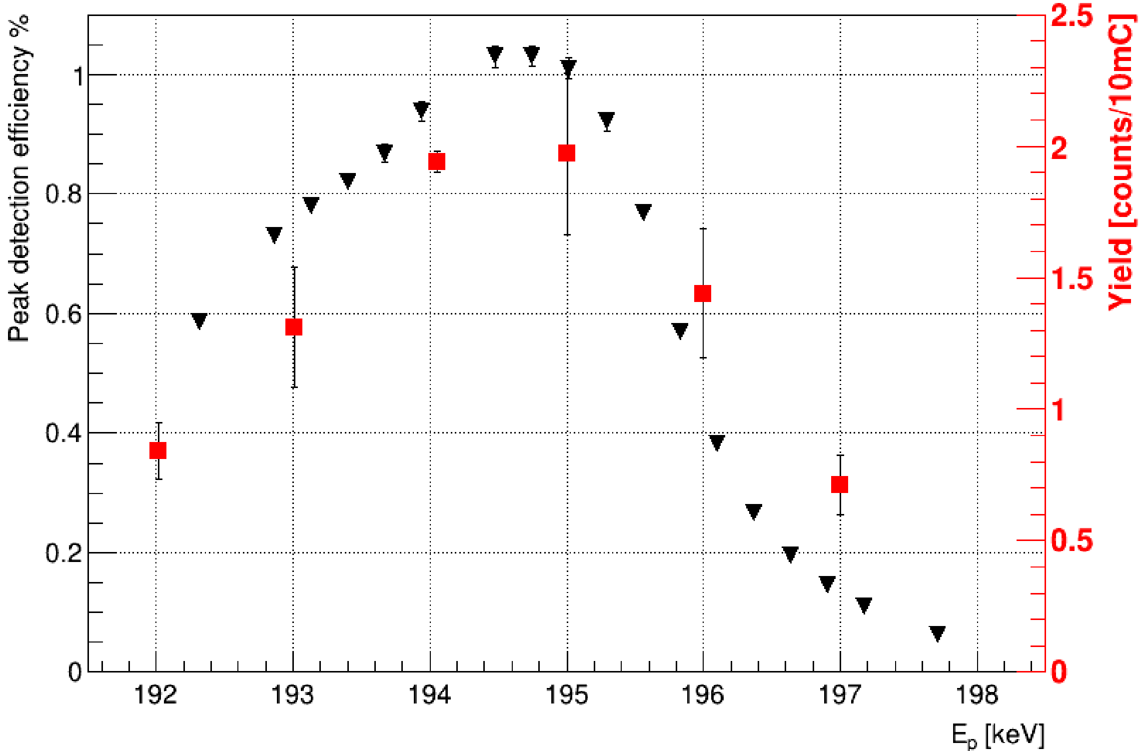
"High" energies (763 keV – 6791 keV)

Efficiency curve extended up to 6791 keV with the $^{14}N(p,\gamma)^{15}O$ resonance at E_{Lab} = 278 keV



Determination of the resonance energy

^{7}Be source
E_γ = 478 keV



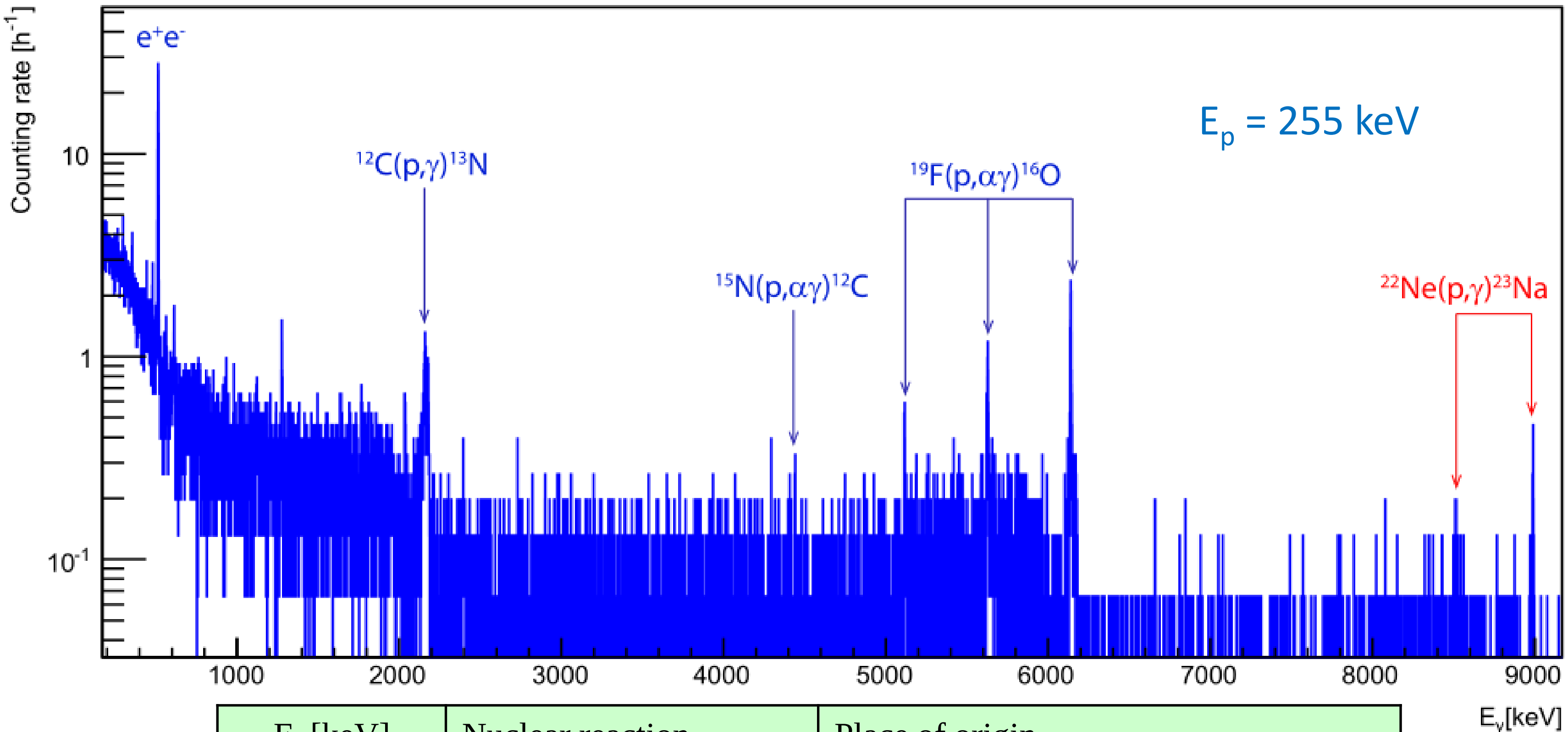
Yield profile of the resonance obtained with the 440 keV gamma

$$E_{R,lab} = E_p - (x + x_{coll})\,\frac{dE}{dx} - \Delta E_{pipe}$$

- E_p proton energy corresponding to the maximum in the yield profile
- x distance between the source and the beam collimator
- x_{coll} effective collimator length
- $\frac{dE}{dx}$ proton energy loss per unit length in neon gas
- ΔE_{pipe} corrective term (0.4-0.6 keV)

$E_{R,lab}$ LUNA [keV]	$E_{R,lab}$ Iliadis10 [keV]
189.5 ± 0.7	186 ± 2

Beam induced background



E_γ [keV]	Nuclear reaction	Place of origin
2178	$^{12}C(p,\gamma)^{13}N$ DC → 0	Collimator - Calorimeter
4439	$^{15}N(p,\alpha\gamma)^{12}C$	Implanted nitrogen
6130	$^{19}F(p,\alpha\gamma)^{16}O$	Calorimeter
5619	$^{19}F(p,\alpha\gamma)^{16}O$ SE	Calorimeter
5108	$^{19}F(p,\alpha\gamma)^{16}O$ DE	Calorimeter

Summary of resonance strength

Energy [keV]		Strength $\omega\gamma$ [eV]					
E_p^{res}	E_x	Previous direct	Previous indirect	NACRE [31] adopted	Iliadis et al. [35] adopted	Present work direct	Present work adopted
29	8822	-	$\leq 2.6\,10^{-25}$ [35]	-	$\leq 2.6\,10^{-25}$	-	$\leq 2.6\,10^{-25}$
37	8829	-	$(3.1 \pm 1.2)\,10^{-15}$ [35]	$(6.8 \pm 1.0)\,10^{-15}$	$(3.1 \pm 1.2)\,10^{-15}$	-	$(3.1 \pm 1.2)\,10^{-15}$
71	8862	$\leq 3.2\,10^{-6}$ [27]	$\leq 1.9\,10^{-10}$ [29]	$\leq 4.2\,10^{-9}$	-	$\leq 1.5\,10^{-9}$	$\leq 1.5\,10^{-9}$
105	8895	$\leq 0.6\,10^{-6}$ [27]	$\leq 1.4\,10^{-7}$ [29]	$\leq 6.0\,10^{-7}$	-	$\leq 7.6\,10^{-9}$	$\leq 7.6\,10^{-9}$
156.2 ± 0.7	8943.5 ± 0.7	$\leq 1.0\,10^{-6}$ [27]	$(9.2 \pm 3.7)\,10^{-9}$ [35]	$(6.5 \pm 1.9)\,10^{-7}$	$(9.2 \pm 3.7)\,10^{-9}$	$[1.48 \pm 0.10]\,10^{-7}$	$[1.48 \pm 0.10]\,10^{-7}$
189.5 ± 0.7	8975.3 ± 0.7	$\leq 2.6\,10^{-6}$ [27]	$\leq 2.6\,10^{-6}$ [29]	$\leq 2.6\,10^{-6}$	$\leq 2.6\,10^{-6}$	$[1.87 \pm 0.06]\,10^{-6}$	$[1.87 \pm 0.06]\,10^{-6}$
215	9000	$\leq 1.4\,10^{-6}$ [27]	-	$\leq 1.4\,10^{-6}$	-	$\leq 2.8\,10^{-8}$	$\leq 2.8\,10^{-8}$
259.7 ± 0.6	9042.4 ± 0.6	$\leq 2.6\,10^{-6}$ [27]	$\leq 1.3\,10^{-7}$ [29]	$\leq 2.6\,10^{-6}$	$\leq 1.3\,10^{-7}$	$[6.89 \pm 0.16]\,10^{-6}$	$[6.89 \pm 0.16]\,10^{-6}$
291	9072	$\leq 2.2\,10^{-6}$ [27]	-	$\leq 2.2\,10^{-6}$	$\leq 2.2\,10^{-6}$	-	$\leq 2.2\,10^{-6}$
323	9103	$\leq 2.2\,10^{-6}$ [27]	-	$\leq 2.2\,10^{-6}$	$\leq 2.2\,10^{-6}$	-	$\leq 2.2\,10^{-6}$
334	9113	$\leq 3.0\,10^{-6}$ [27]	-	$\leq 3.0\,10^{-6}$	$\leq 3.0\,10^{-6}$	-	$\leq 3.0\,10^{-6}$
369	9147	-	$\leq 6.0\,10^{-4}$ [29]	-	$\leq 6.0\,10^{-4}$	-	$\leq 6.0\,10^{-4}$
394	9171	-	$\leq 6.0\,10^{-4}$ [29]	-	$\leq 6.0\,10^{-4}$	-	$\leq 6.0\,10^{-4}$

Calorimeter