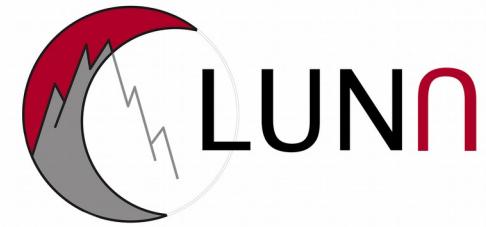




Istituto Nazionale di Fisica Nucleare



# LUNA, Laboratory for Underground Nuclear Astrophysics

D. Piatti<sup>1</sup> for LUNA collaboration

<sup>1</sup>= INFN of Padova, Italy

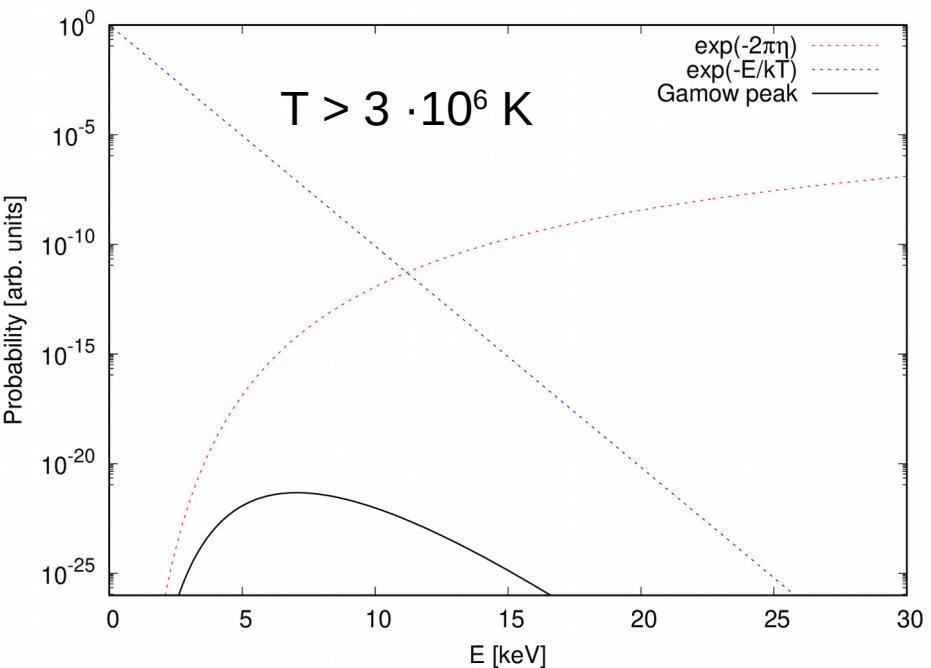
# Laboratory for Underground Nuclear Astrophysics

	122 KeV P: 100.00%	169-234 P: 100.00% E: 100.00%	167-240 P: 100.00% E: 100.00%	17-22-2 P: 100.00% E: 100.00%	STABLE 0.48%	STABLE 0.27%	STABLE 0.25%	17-24-2 P: 100.00% E: 100.00%	3-38-34 P: 100.00% E: 100.00%	46-2 MS P: 100.00% E: 100.00%	13		
	147 <sup>+</sup> P	159 <sup>+</sup> P: 100.00% E: 100.00%	149 <sup>+</sup> P: 100.00% E: 100.00%	177 <sup>+</sup> P: 100.00% E: 100.00%	159 <sup>+</sup> STABLE 100%	209 <sup>+</sup> P: 100.00% E: 100.00%	212 <sup>+</sup> P: 100.00% E: 100.00%	219 <sup>+</sup> P: 100.00% E: 100.00%	239 <sup>+</sup> P: 100.00% E: 100.00%	247 <sup>+</sup> P: 100.00% E: 100.00%	5		
	120 <sup>+</sup> P	130 <sup>+</sup> P: 100.00% E: 100.00%	140 <sup>+</sup> P: 100.00% E: 100.00%	150 <sup>+</sup> P: 100.00% E: 100.00%	160 <sup>+</sup> STABLE 99.70%	170 <sup>+</sup> STABLE 0.00%	180 <sup>+</sup> STABLE 0.20%	190 <sup>+</sup> P: 100.00% E: 100.00%	200 <sup>+</sup> P: 100.00% E: 100.00%	210 <sup>+</sup> P: 100.00% E: 100.00%	220 <sup>+</sup> P: 100.00% E: 100.00%	230 <sup>+</sup> P: 100.00% E: 100.00%	
	108 <sup>+</sup> P: 100.00%	118 <sup>+</sup> P: 100.00% E: 100.00%	138 <sup>+</sup> P: 100.00% E: 100.00%	148 <sup>+</sup> P: 100.00% E: 100.00%	158 <sup>+</sup> STABLE 0.36%	169 <sup>+</sup> P: 100.00% E: 100.00%	179 <sup>+</sup> P: 100.00% E: 100.00%	189 <sup>+</sup> P: 100.00% E: 100.00%	199 <sup>+</sup> P: 100.00% E: 100.00%	209 <sup>+</sup> P: 100.00% E: 100.00%	219 <sup>+</sup> P: 100.00% E: 100.00%	229 <sup>+</sup> P: 100.00% E: 100.00%	
	230 <sup>+</sup> P: 100.00% E: 100.00%	234 <sup>+</sup> P: 100.00% E: 100.00%	239 <sup>+</sup> P: 100.00% E: 100.00%	240 <sup>+</sup> P: 100.00% E: 100.00%	242 <sup>+</sup> STABLE 0.85%	247 <sup>+</sup> P: 100.00% E: 100.00%	250 <sup>+</sup> P: 100.00% E: 100.00%	259 <sup>+</sup> P: 100.00% E: 100.00%	269 <sup>+</sup> P: 100.00% E: 100.00%	279 <sup>+</sup> P: 100.00% E: 100.00%	289 <sup>+</sup> P: 100.00% E: 100.00%	299 <sup>+</sup> P: 100.00% E: 100.00%	
	4H <sup>+</sup> P: 100.00% E: 100.00%	7B <sup>+</sup> P: 100.00% E: 100.00%	8B <sup>+</sup> P: 100.00% E: 100.00%	10B <sup>+</sup> P: 100.00% E: 100.00%	11B <sup>+</sup> STABLE 0.2%	12B <sup>+</sup> P: 100.00% E: 100.00%	13B <sup>+</sup> P: 100.00% E: 100.00%	14B <sup>+</sup> P: 100.00% E: 100.00%	15B <sup>+</sup> P: 100.00% E: 100.00%	16B <sup>+</sup> P: 100.00% E: 100.00%	17B <sup>+</sup> P: 100.00% E: 100.00%	18B <sup>+</sup> P: 100.00% E: 100.00%	
	5B <sup>+</sup> P: 100.00% E: 100.00%	6B <sup>+</sup> P: 100.00% E: 100.00%	7B <sup>+</sup> P: 100.00% E: 100.00%	8B <sup>+</sup> P: 100.00% E: 100.00%	9B <sup>+</sup> STABLE 0.00%	10B <sup>+</sup> P: 100.00% E: 100.00%	11B <sup>+</sup> P: 100.00% E: 100.00%	12B <sup>+</sup> P: 100.00% E: 100.00%	13B <sup>+</sup> P: 100.00% E: 100.00%	14B <sup>+</sup> P: 100.00% E: 100.00%	15B <sup>+</sup> P: 100.00% E: 100.00%	16B <sup>+</sup> P: 100.00% E: 100.00%	
	2Li <sup>+</sup> P: 100.00% E: 100.00%	3Li <sup>+</sup> P: 100.00% E: 100.00%	4Li <sup>+</sup> P: 100.00% E: 100.00%	5Li <sup>+</sup> P: 100.00% E: 100.00%	6Li <sup>+</sup> STABLE 0.5%	7Li <sup>+</sup> P: 100.00% E: 100.00%	8Li <sup>+</sup> P: 100.00% E: 100.00%	9Li <sup>+</sup> P: 100.00% E: 100.00%	10Li <sup>+</sup> P: 100.00% E: 100.00%	11Li <sup>+</sup> P: 100.00% E: 100.00%	12Li <sup>+</sup> P: 100.00% E: 100.00%	13Li <sup>+</sup> P: 100.00% E: 100.00%	
	3He <sup>+</sup> P: 0.000137%	4He <sup>+</sup> P: 0.00 MeV E: 100.00%	5He <sup>+</sup> P: 0.00 MeV E: 100.00%	7He <sup>+</sup> P: 0.00 MeV E: 100.00%	8He <sup>+</sup> P: 0.00 MeV E: 100.00%	9He <sup>+</sup> P: 0.00 MeV E: 100.00%	10He <sup>+</sup> P: 0.00 MeV E: 100.00%	11He <sup>+</sup> P: 0.00 MeV E: 100.00%	12He <sup>+</sup> P: 0.00 MeV E: 100.00%	13He <sup>+</sup> P: 0.00 MeV E: 100.00%	14He <sup>+</sup> P: 0.00 MeV E: 100.00%	15He <sup>+</sup> P: 0.00 MeV E: 100.00%	
	2H <sup>+</sup> P: 100.00% E: 100.00%	3H <sup>+</sup> P: 100.00% E: 100.00%	4H <sup>+</sup> P: 100.00% E: 100.00%	5H <sup>+</sup> P: 100.00% E: 100.00%	6H <sup>+</sup> P: 100.00% E: 100.00%	7H <sup>+</sup> P: 100.00% E: 100.00%	8H <sup>+</sup> P: 100.00% E: 100.00%	9H <sup>+</sup> P: 100.00% E: 100.00%	10H <sup>+</sup> P: 100.00% E: 100.00%	11H <sup>+</sup> P: 100.00% E: 100.00%	12H <sup>+</sup> P: 100.00% E: 100.00%	13H <sup>+</sup> P: 100.00% E: 100.00%	
	1H STABLE 0.999999%	2H STABLE 0.000037%	3H STABLE 0.5%	4H STABLE 0.0000137%	5H STABLE 0.0000037%	6H STABLE 0.00000137%	7H STABLE 0.00000037%	8H STABLE 0.000000137%	9H STABLE 0.000000037%	10H STABLE 0.0000000137%	11H STABLE 0.0000000037%	12H STABLE 0.00000000137%	13H STABLE 0.00000000037%

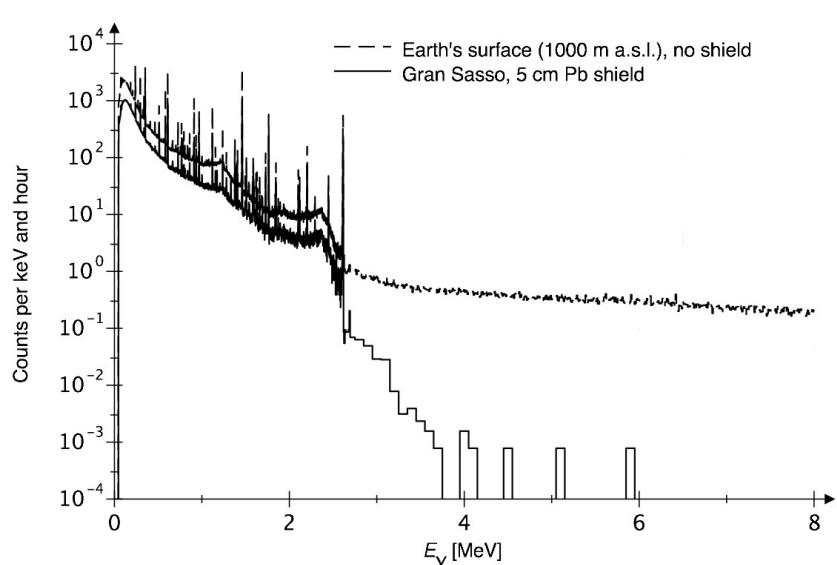
- Great suppression of cross-sections:  
 $\sigma(E) = S(E) \cdot e^{-2\pi\eta} \cdot E^{-1} \sim \text{pb}$
- Low counting rate ~ 1 c/d
- Signal = a needle in a haystack of cosmic rays at the surface labs



- Reactions of the stellar and primordial nucleosynthesis network
- Reactions possible in a small energy window → **Gamow Peak**  $\sim e^{-2\pi\eta} \cdot e^{-E/kT}$

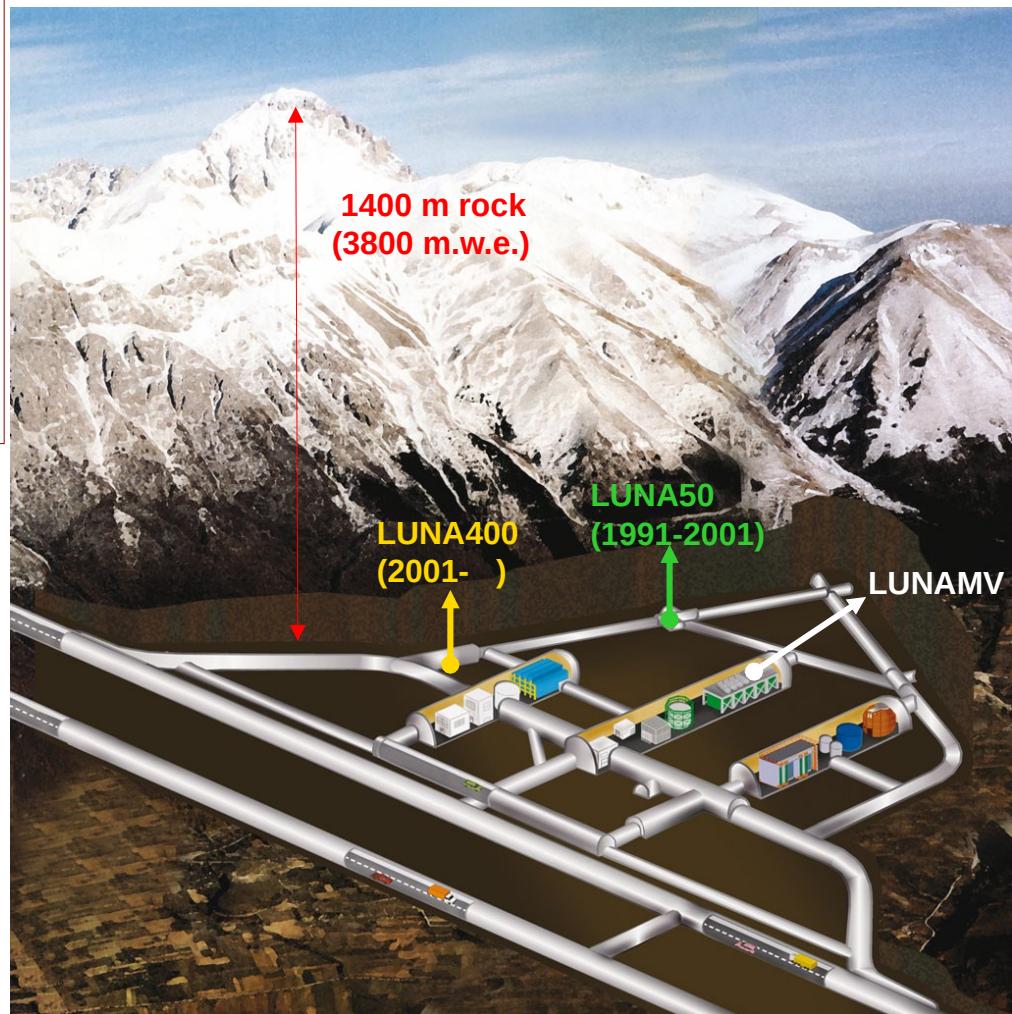


# Laboratory for Underground Nuclear Astrophysics

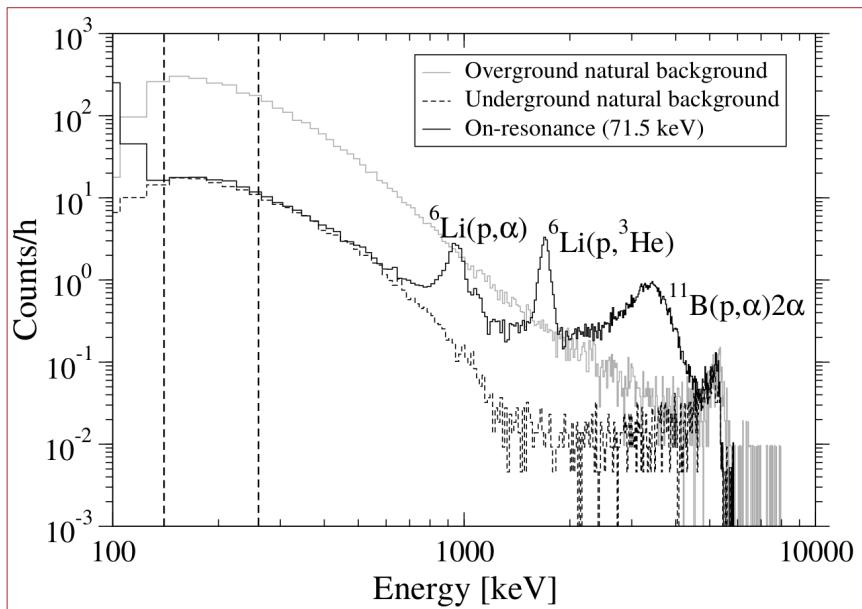


Bemmerer et al., EPJA (2005)

~ 5 orders of magnitude lower

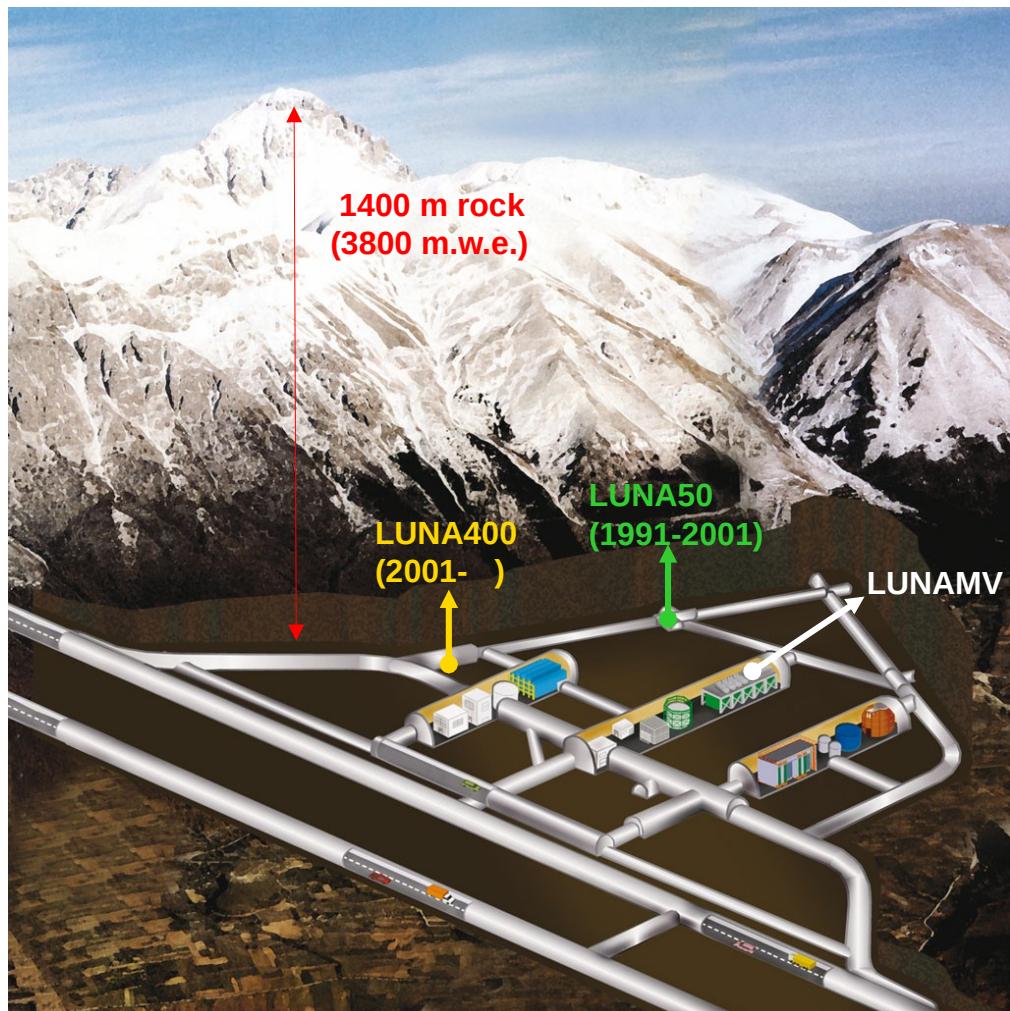


# Laboratory for Underground Nuclear Astrophysics



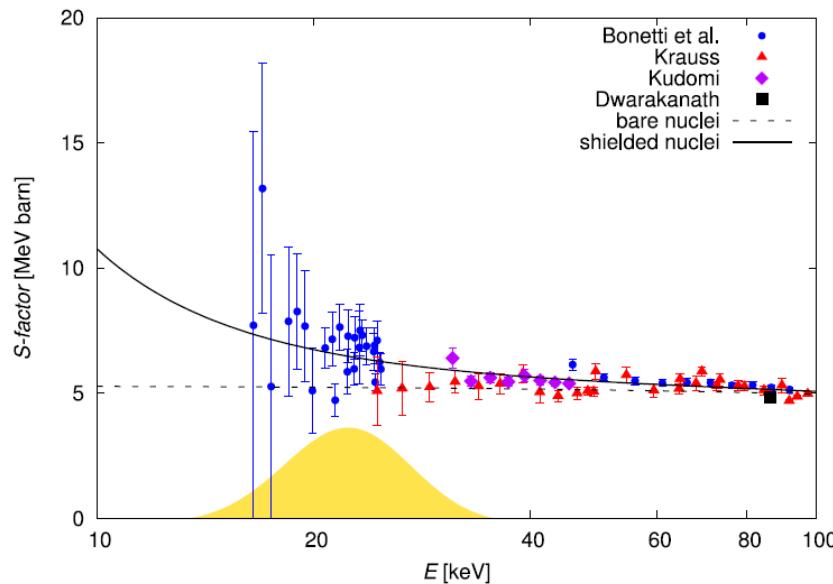
Bruno et al., PRL (2016)

Background reduced by factor 15

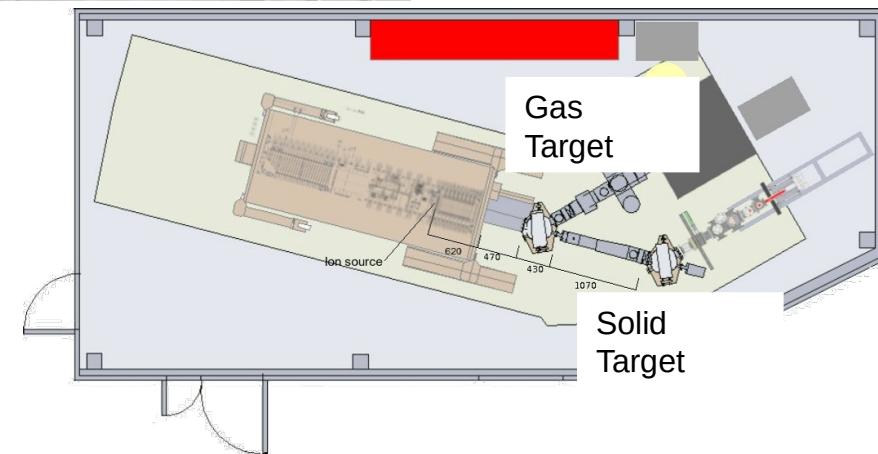
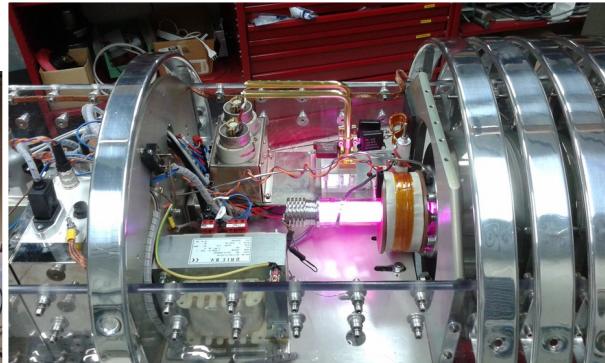


# LUNA50kV: Yesterday

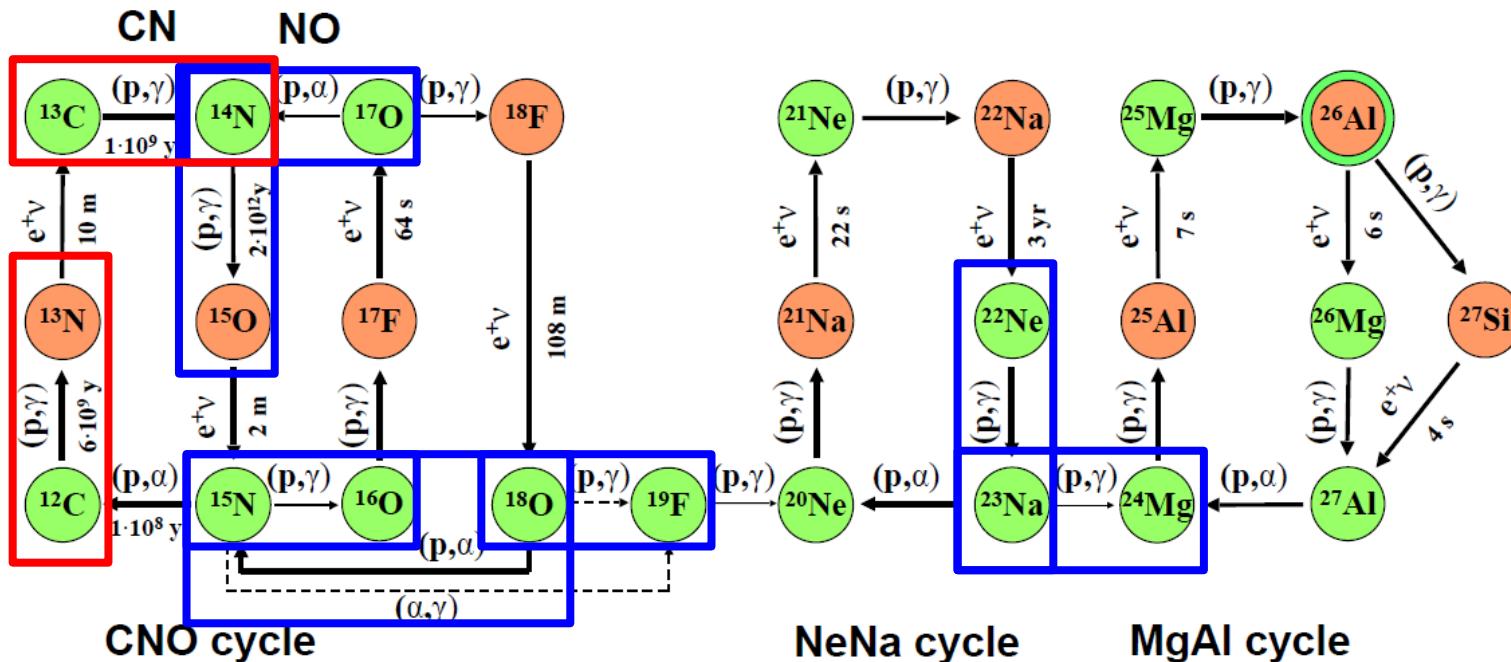
- Activity 1991 – 2001
- Home-made accelerator
- H<sup>+</sup> and He<sup>+</sup> beams
- pp-chain:
  - $^2\text{H}(\text{p},\gamma)^3\text{He}$
  - $^3\text{He}(^3\text{He},2\text{p})^4\text{He}$



# LUNA400kV: Today



- 2001 - ...
- LUNA400 kV → High intensity and high stability H<sup>+</sup> and He<sup>+</sup> beam
- Delivered to the Solid Target or Gas Target
- CNO cycle and “relatives” + primordial nucleosynthesis:



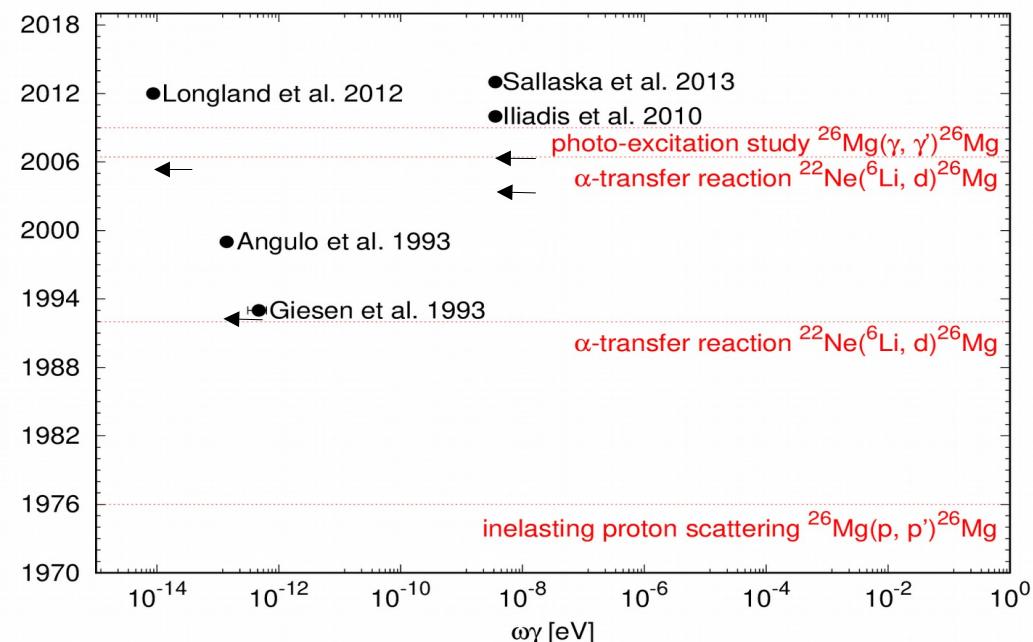
- $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$
  - $^{13}\text{C}(\alpha, n)^{16}\text{O}$
  - p+D
  - $^6\text{Li}(p, \gamma)^7\text{Be}$
- } s-process in AGB stars and in massive stars
- } High precision measurement → High accuracy D abundance
- } He et al. 2013 → resonance at  $E_{cm} = 195$  keV

# $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ – Astrophysical Motivation

- $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$  ( $Q = 10.6$  MeV) competes with  $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$  ( $Q = -478$  keV)
- $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$  reaction rate **high uncertainty** affects isotopes production up to  $^{31}\text{P}$  in AGB stars [Karakas et al. 2006]

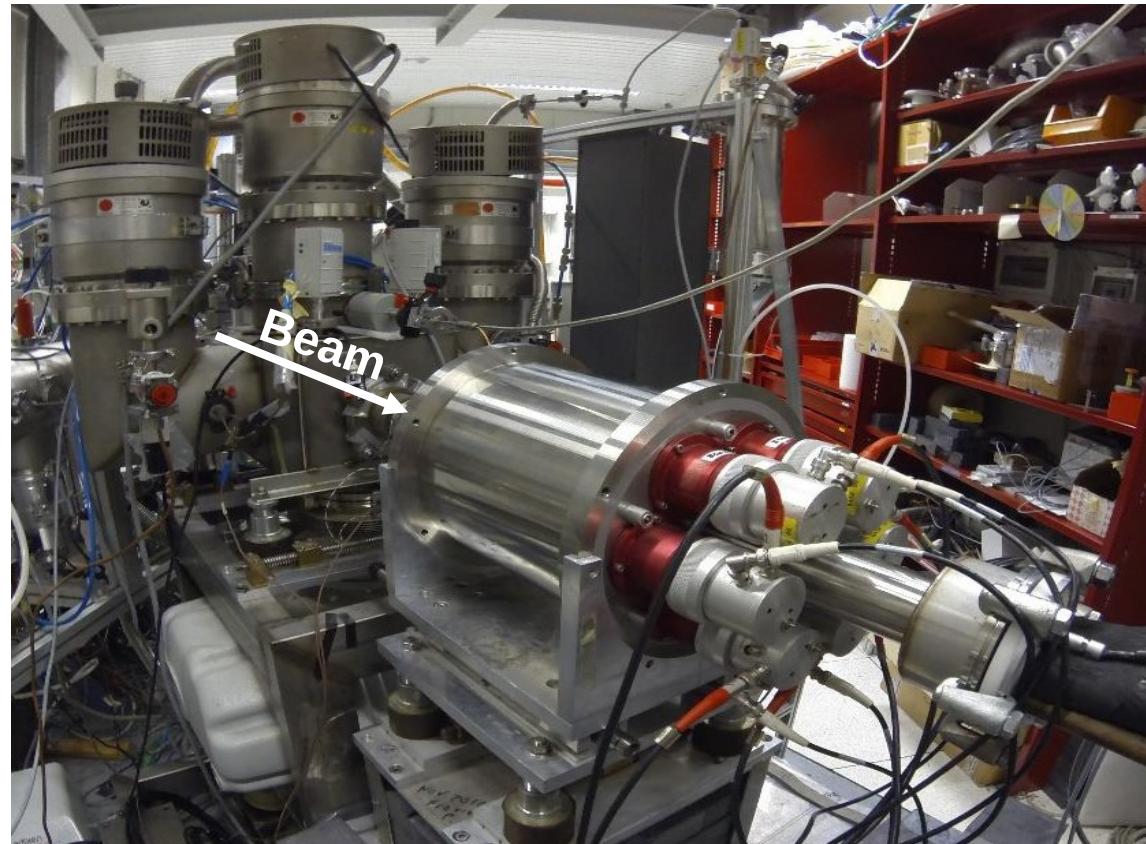


- Poorly constrained strength
- of 395 keV resonance:
- No direct measurements
- Only Upper Limits reported
- **6 orders of magnitude range**



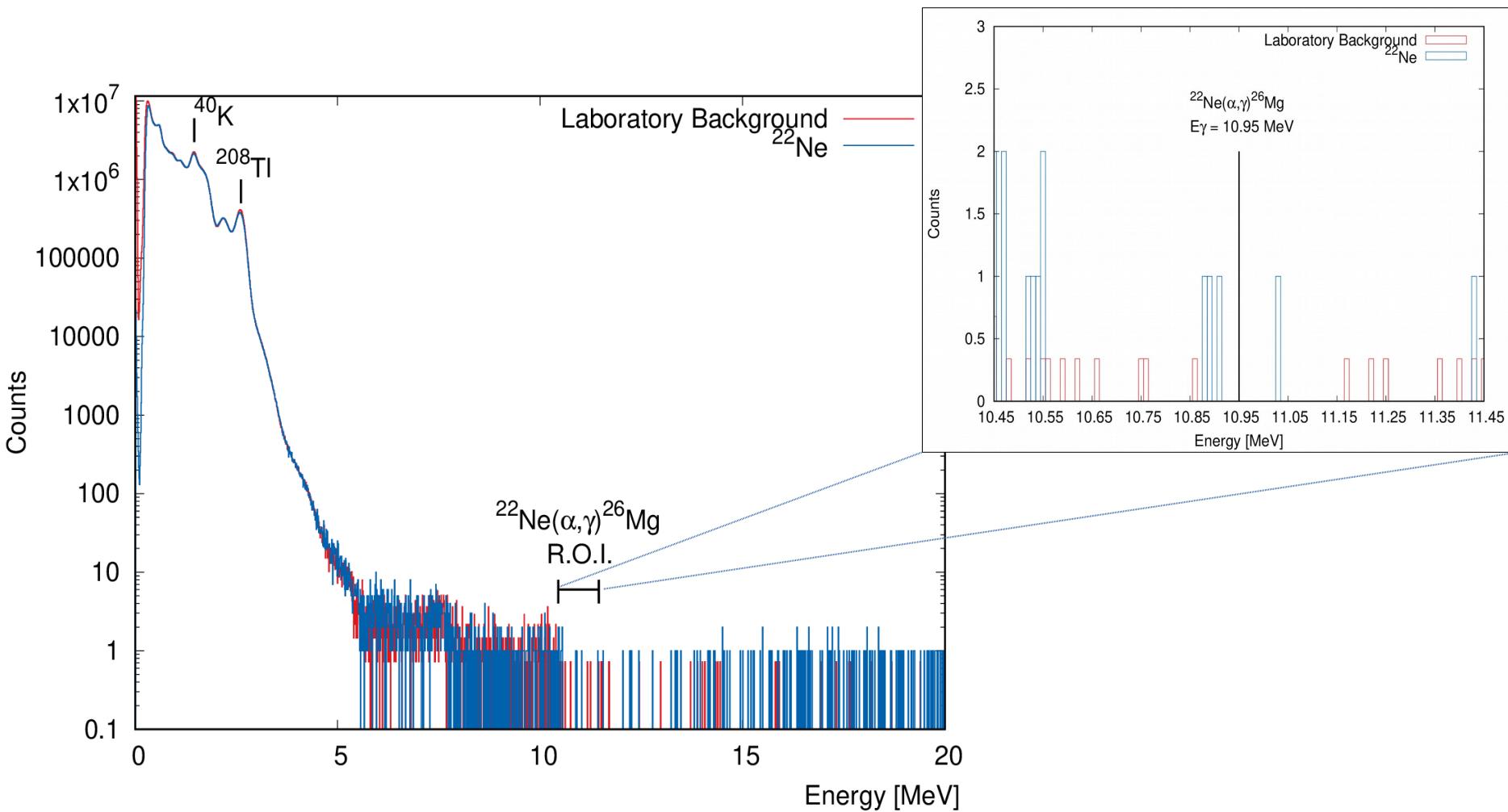
# $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ – phase I

- 99.9% enriched and pure  $^{22}\text{Ne}$  gas
- 399.9 keV  $^+H$  beam,  $I \sim 250 \mu\text{A}$
- Differential pumped windowless gas target system → three pumping stages
- $P_{\text{line}} = 10^{-7} \rightarrow 10^{-3} \text{ mbar}$ ,  
 $P_{\text{chamber}} = 1 \text{ mbar}$
- Recirculation mode
- Calorimetric measurement of the beam intensity
- High efficiency detector



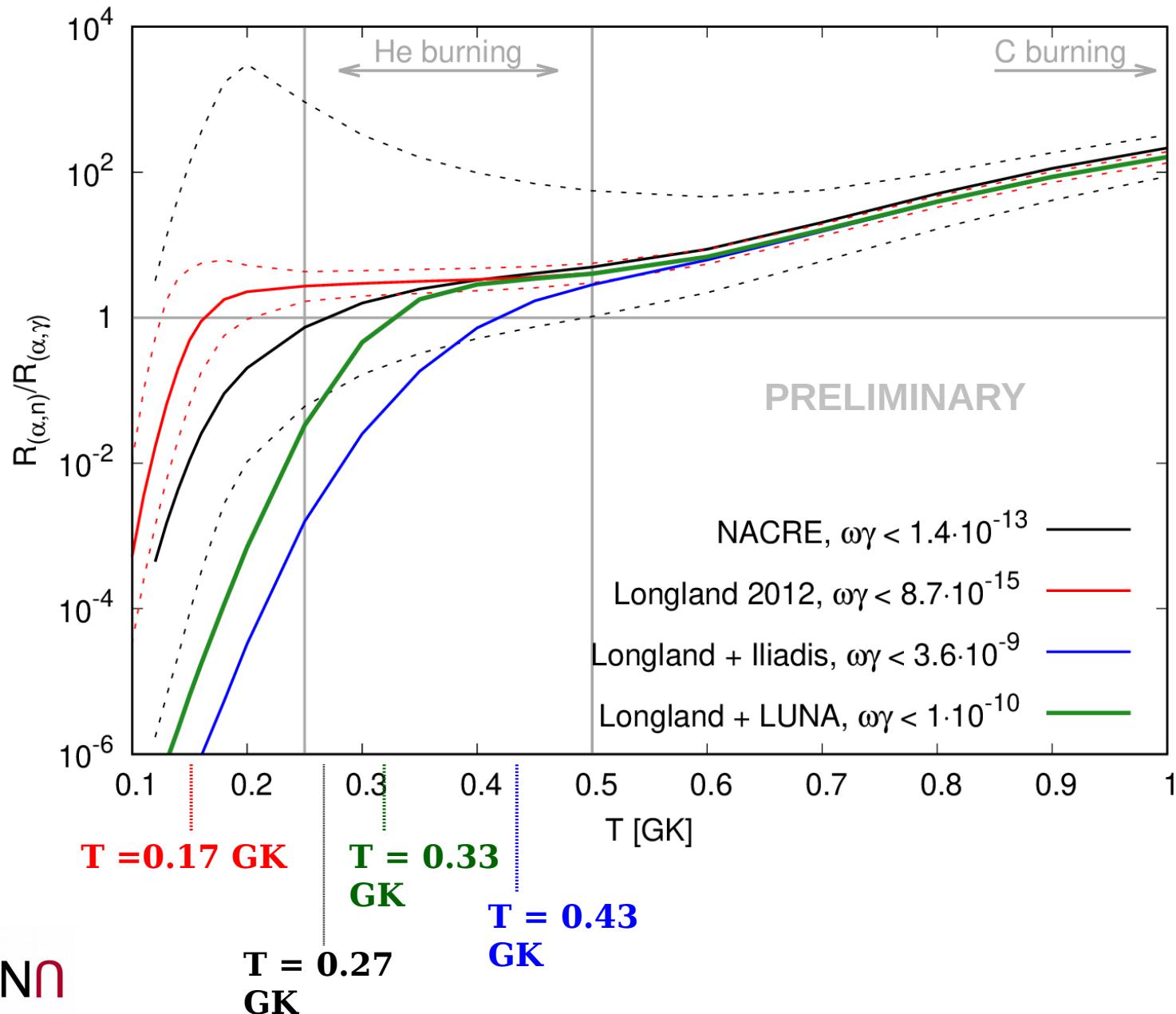
	$t_m$ [d]	Charge [C]	Target Gas	$P_{target}$ [mbar]	$E_\alpha$ [keV]	$\Delta E_\alpha$ [keV]
<b>Laboratory Background</b>	49	-	-	vacuum	-	-
<b>Beam Induced Background</b>	0.5	13.5	Ar	0.468	399.9	10.8
<b>On Resonance</b>	21.2	430	$^{22}\text{Ne}$	1	399.9	10.8

- Laboratory Background spectra acquired before and during the measurement
- Experimental Problems → insufficient statistics for the B.I.B. estimation
- Contamination in the target gas was monitored using a mass spectrometer and the Buffer pressure as reference



- There is no evidence of signal in the ROI  $\rightarrow N < L_c$  (**95% confidence level**)





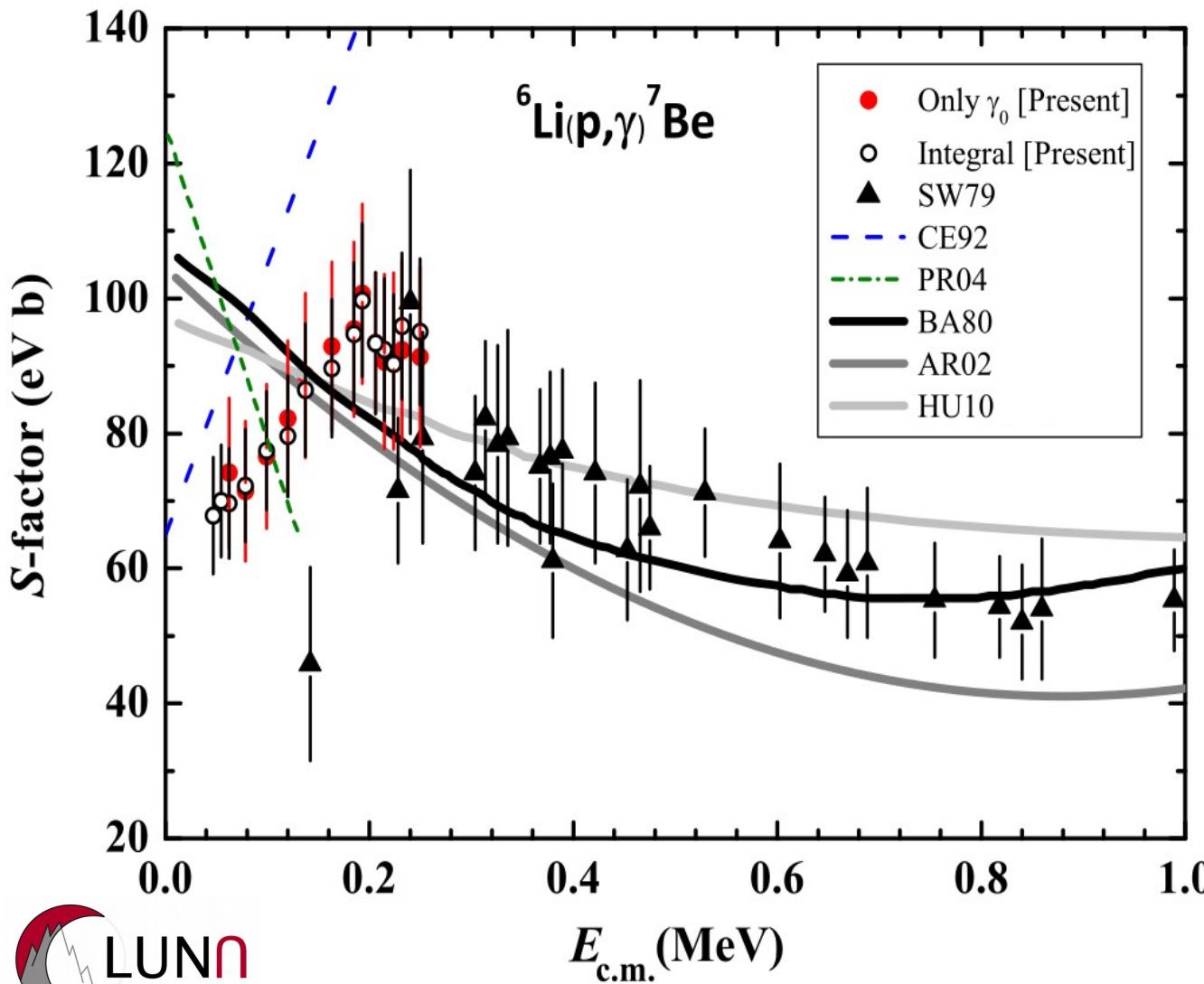
# $^{22}\text{Ne}(\alpha, \gamma)^{26}\text{Mg}$ – phase II



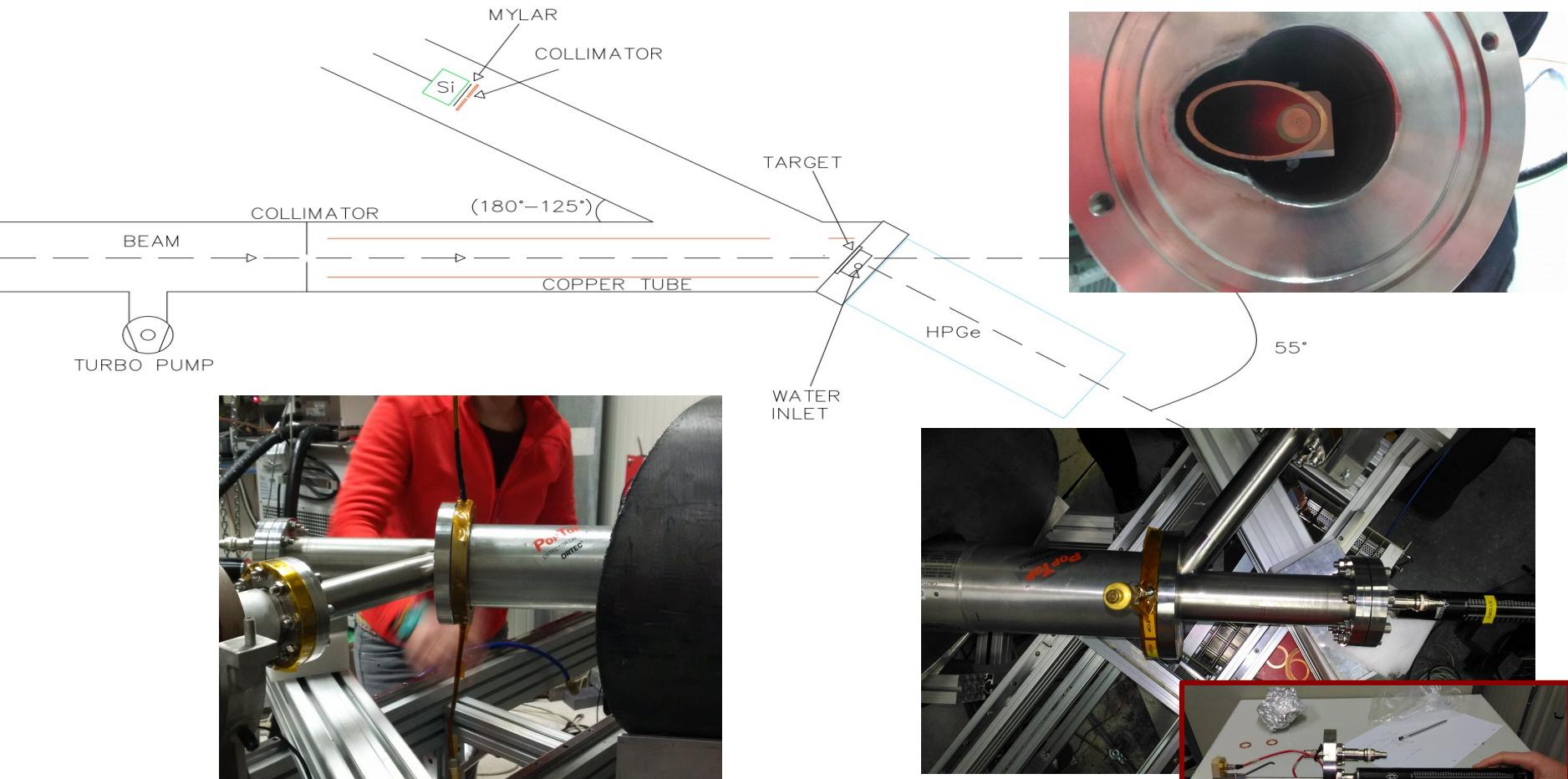
- 10 cm thick shield of borated polyethylene
- Setup improved
- B.I.B. to be measured at the same statistic

→ Goal: 1 order of magnitude down

# ${}^6\text{Li}(\text{p},\gamma){}^7\text{Be}$ – Astrophysical Motivation



- **High uncertainty** of the experimental data
- **Poor overlap** between the data sets
- **No agreement** on the slope of the S-factor at low  $E_{\text{p}}$

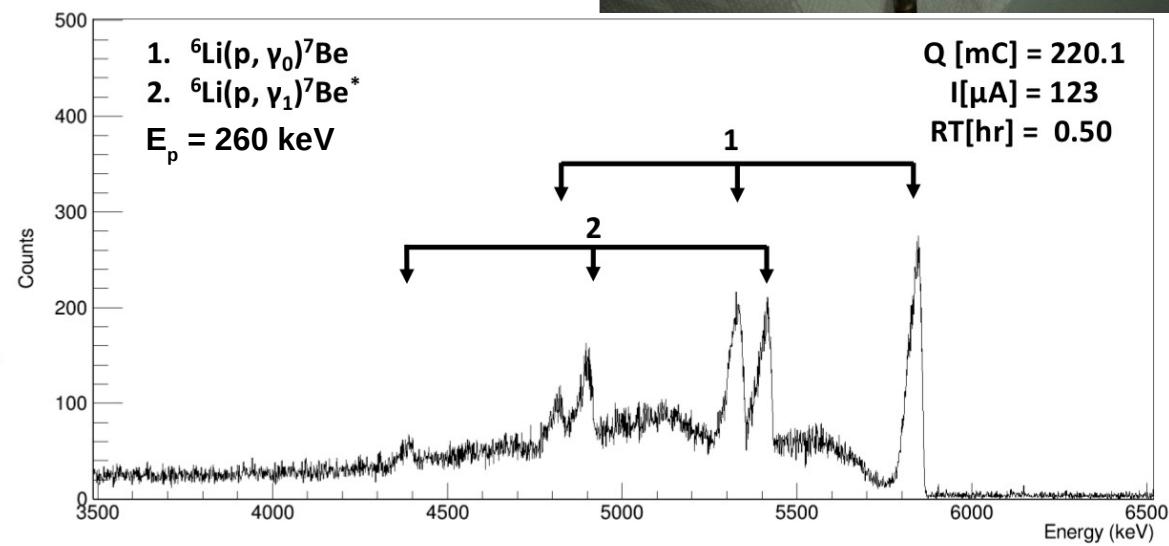
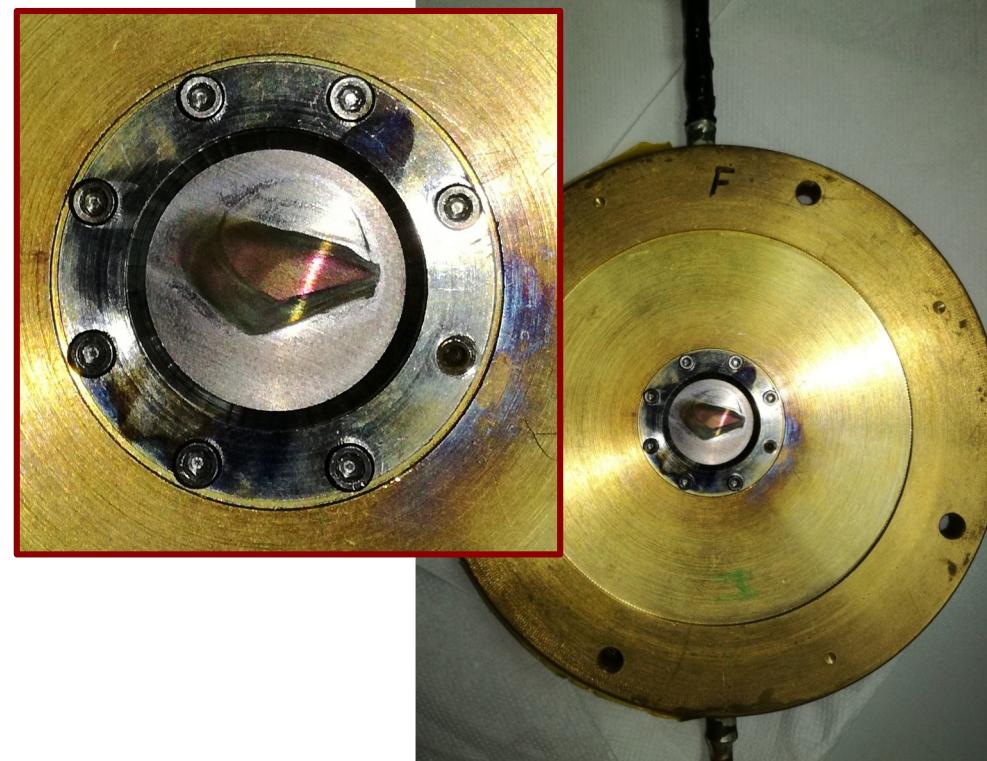
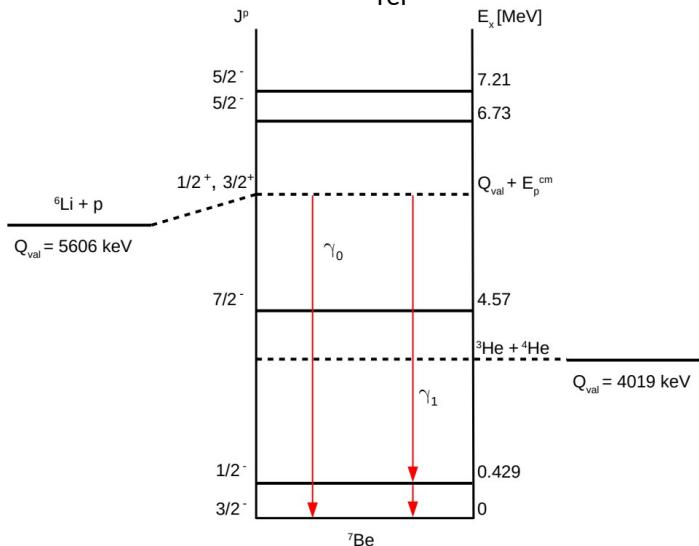


- Cold Finger + secondary  $e^-$  suppression
- Water cooled target
- HPGe at  $-55^\circ$  and Si at  $+125^\circ$  w.r.t. beam direction
- HPGe at 1.7 cm and Si at 10 cm w.r.t. target

Target Type	Nominal Thickness
${}^6\text{Li}_2\text{O}$	<ul style="list-style-type: none"> <li>• 40 <math>\mu\text{g}/\text{cm}^2</math></li> <li>• 20 <math>\mu\text{g}/\text{cm}^2</math></li> </ul>
${}^6\text{Li}_2\text{WO}_4$	<ul style="list-style-type: none"> <li>• 100 <math>\mu\text{g}/\text{cm}^2</math></li> <li>• 130 <math>\mu\text{g}/\text{cm}^2</math></li> </ul>
${}^6\text{LiCl}$	<ul style="list-style-type: none"> <li>• Infinite</li> </ul>

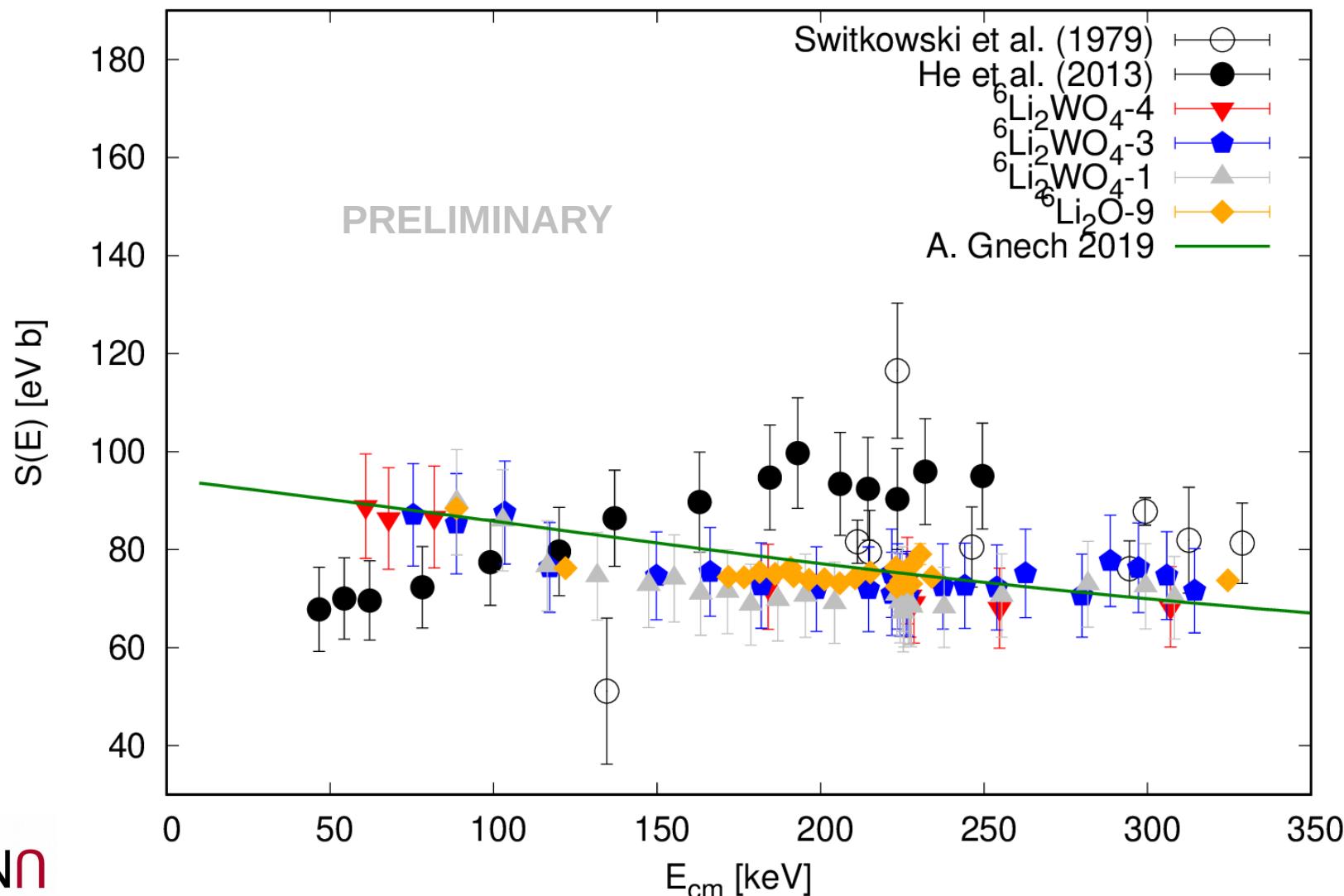
- $E_p$ : 80 → 390 keV
- Stability of the target checked

periodically at  $E_{\text{ref}}$



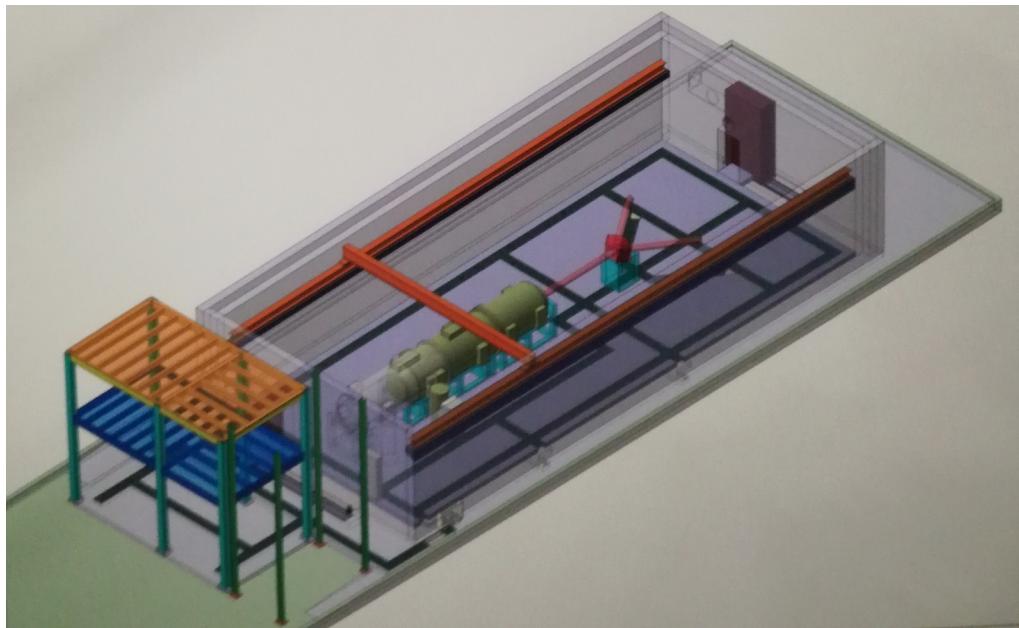
- Measurement performed at Helmholtz- Zentrum Dresden-Rossendorf Laboratories
- After the experiment at LUNA
- Two techniques:
- **NRA**: exploiting the resonance at 1175 keV  ${}^6\text{Li}(\alpha,\gamma){}^{10}\text{B}$  ( $\omega\gamma = 0.366 \pm 0.038$  eV,  $\Gamma = 1.7$  eV) [Gyürky et al., EPJA (2004)]
- → **Distribution of  ${}^6\text{Li}$  with target depth**
- **ERDA**: incident ion  ${}^{35}\text{Cl}^{7+}$ , incident angle  $70^\circ$ , scattering angles  $31^\circ$  and  $41^\circ$
- → **Composition of the target**

# Results



# LUNAMV: Tomorrow

- High performance 3.5MVaccelerator by HV → now under test
- H<sup>+</sup>, He<sup>+</sup>, <sup>12</sup>C<sup>+</sup> and <sup>12</sup>C<sup>2+</sup> beams
- Two beamlines
- Study of helium and carbon buning
  - <sup>14</sup>N(p, $\gamma$ )<sup>15</sup>O → CNO bottle-neck
  - <sup>12</sup>C + <sup>12</sup>C → “Holy Grail”
  - <sup>22</sup>Ne( $\alpha$ ,n)<sup>25</sup>Mg and <sup>13</sup>C( $\alpha$ ,n)<sup>16</sup>O  
→ s-process in AGB and massive stars



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# Conclusion

- The extremely low laboratory background of LNGS has allowed for the **first time** the realization of nuclear physics experiments with very small count rates, down to a couple of events per month
- **Several hydrogen burning and BBN fusion reactions** have been studied in the last 25 years
- **A new phase** devoted to helium and carbon burning **is** starting with **LUNA-MV**
- **LUNA will be not anymore alone:** JUNA (China), Felsenkeller (Germany), Caspar (United States)



# LUNA Collaboration

- A. Boeltzig, L. Csedreki, A. Formicola, M. Junker, D. Ciccotti | **INFN LNGS**  
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R. Perrino | **INFN Lecce, Italy**

Thank You