LUNA,
Laboratory for Underground Nuclear Astrophysics

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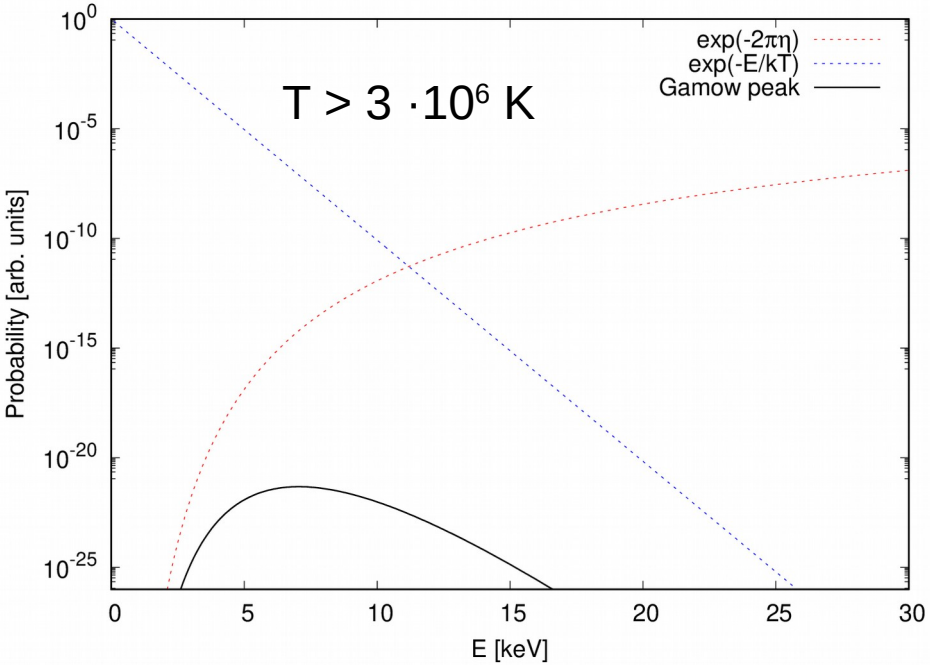
Laboratory for Underground **Nuclear Astrophysics**

- Reactions of the stellar and primordial nucleosynthesis network

- Reactions possible in a small energy window -> **Gamow Peak ~ $e^{-2\pi\eta} \cdot e^{-E/kT}$**



- Great suppression of cross-sections:
  $\sigma(E) = S(E) \cdot e^{-2\pi\eta} \cdot E^{-1} \sim$ pb
- **→ Low counting rate ~ 1 c/d**

- **Signal = a needle in a haystack of cosmic rays at the surface labs**

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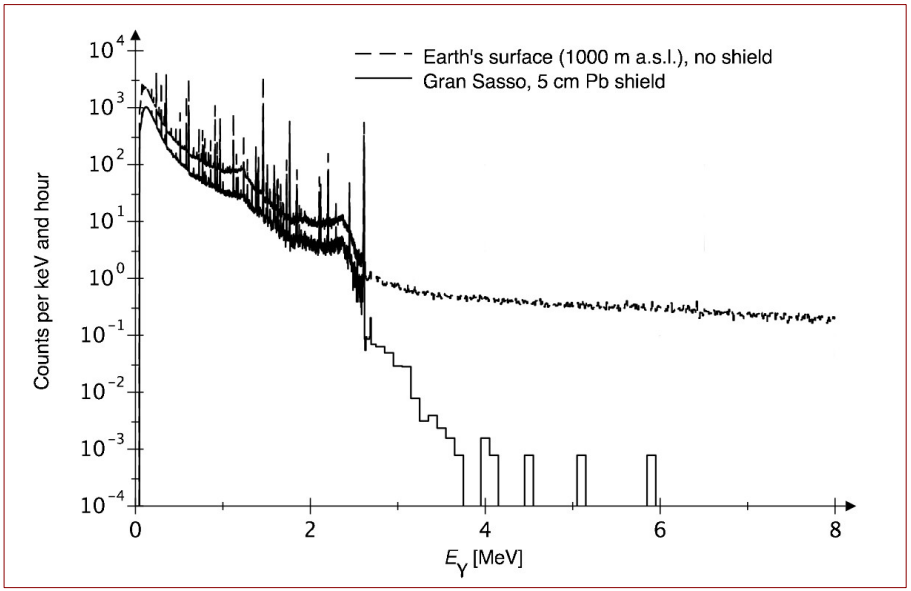
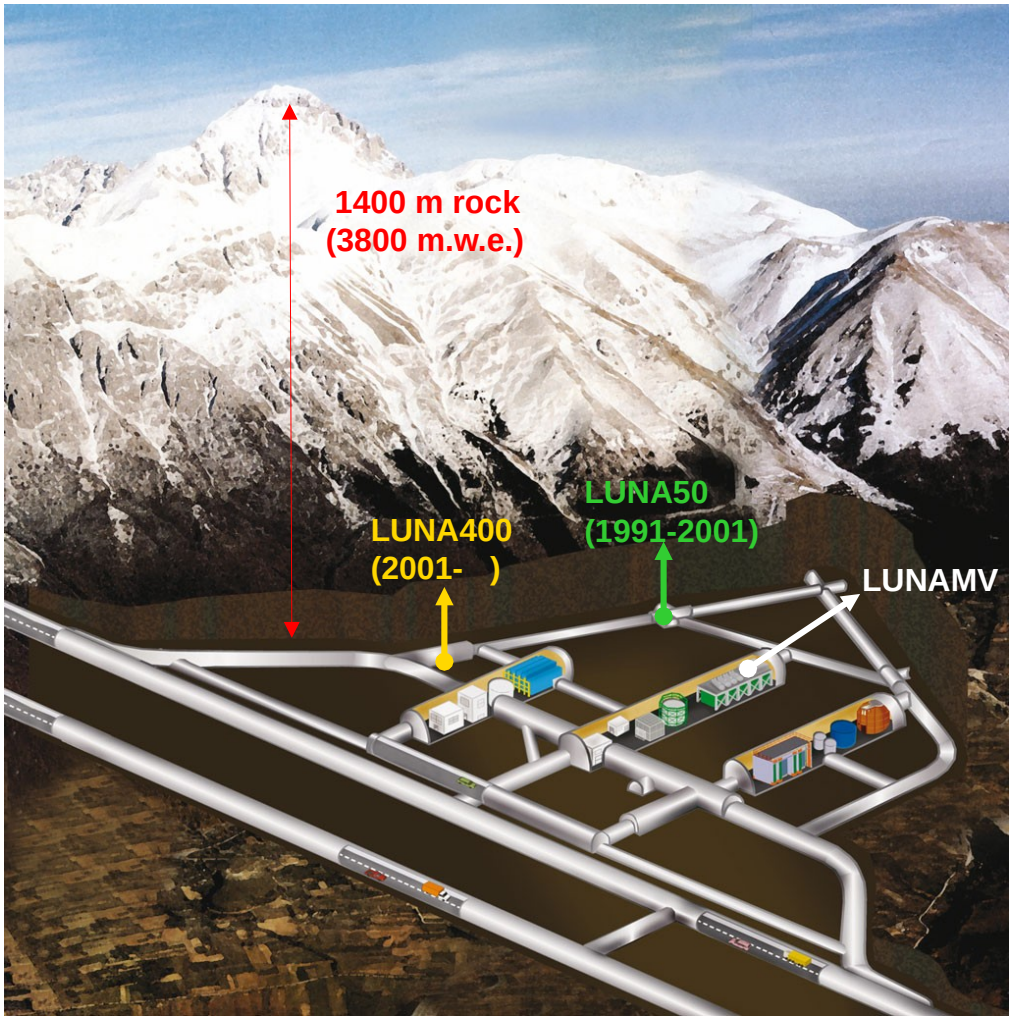


Bemmerer et al., EPJA (2005)

~ 5 orders of magnitude lower



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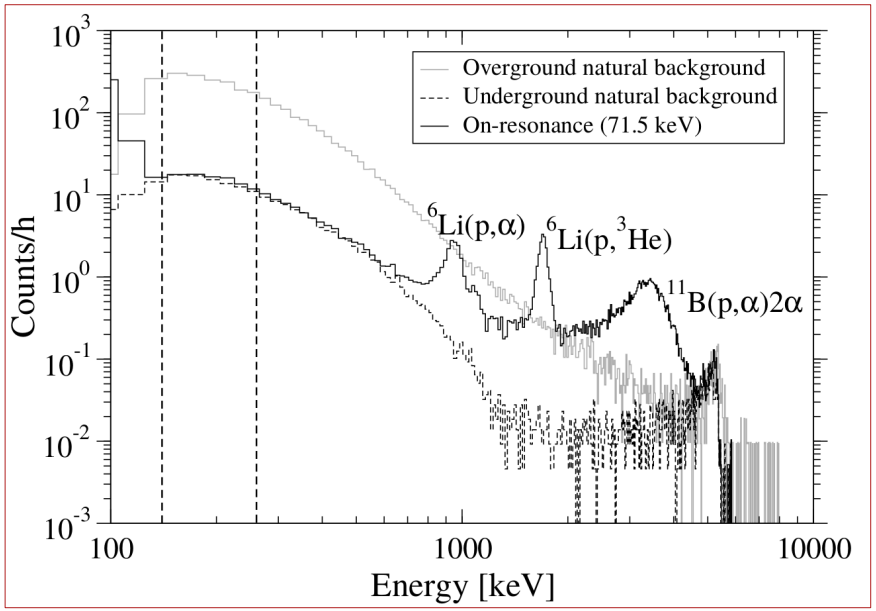
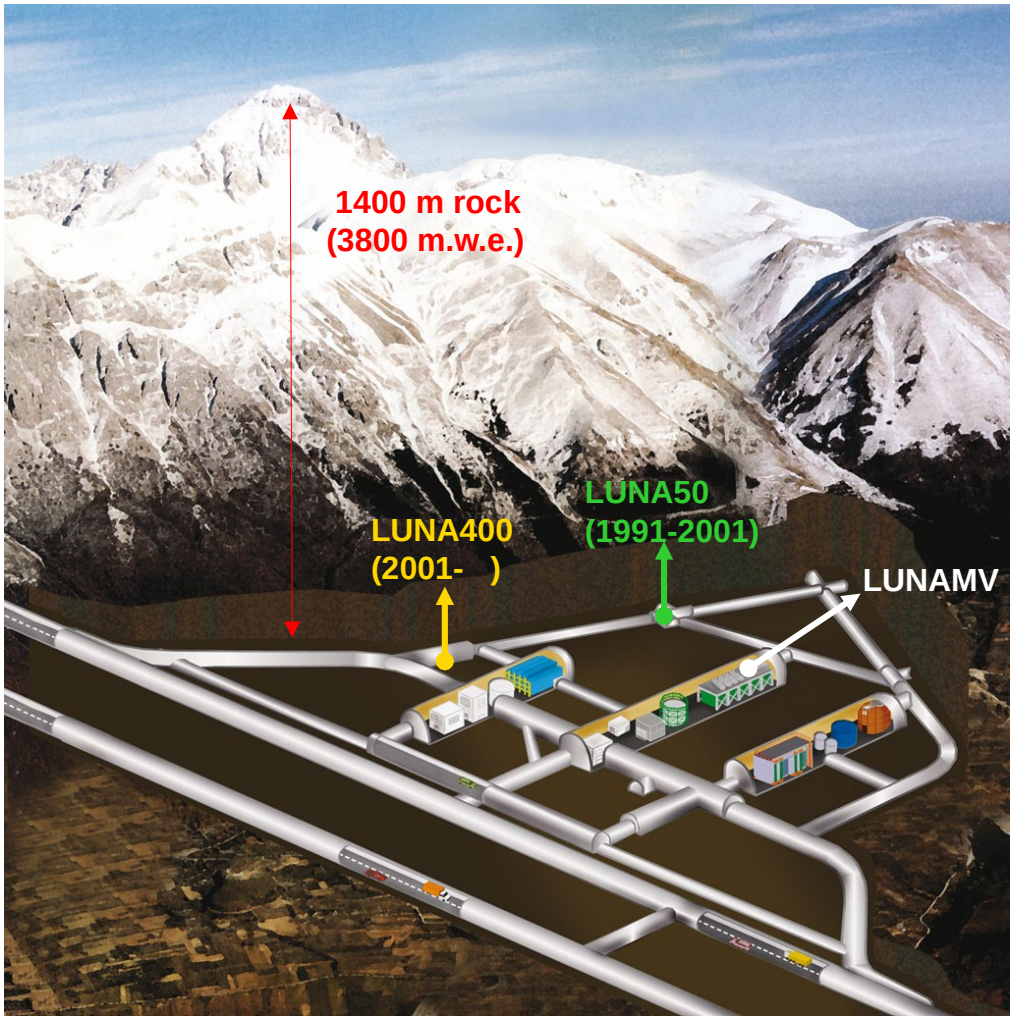
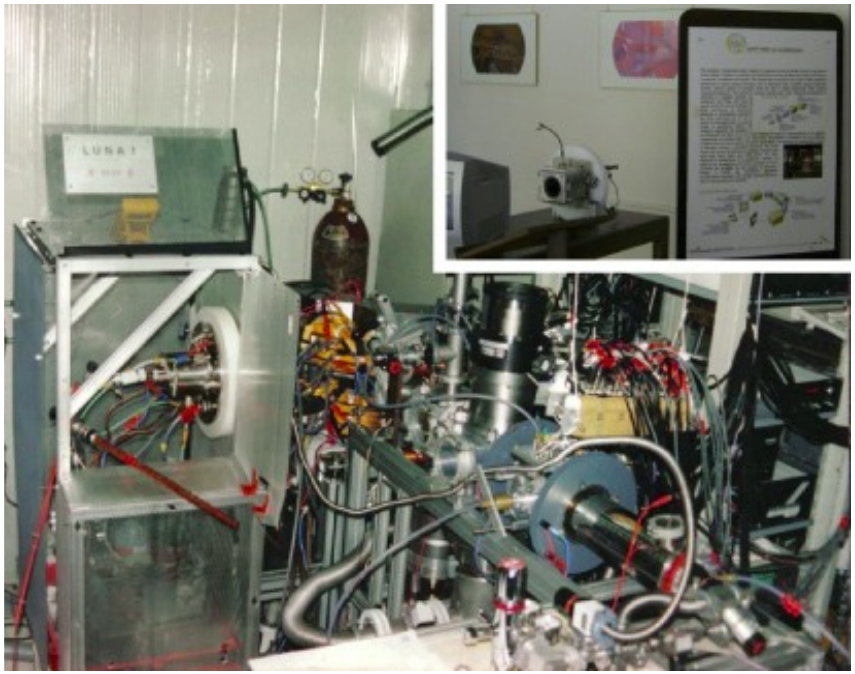


Bruno et al., PRL (2016)

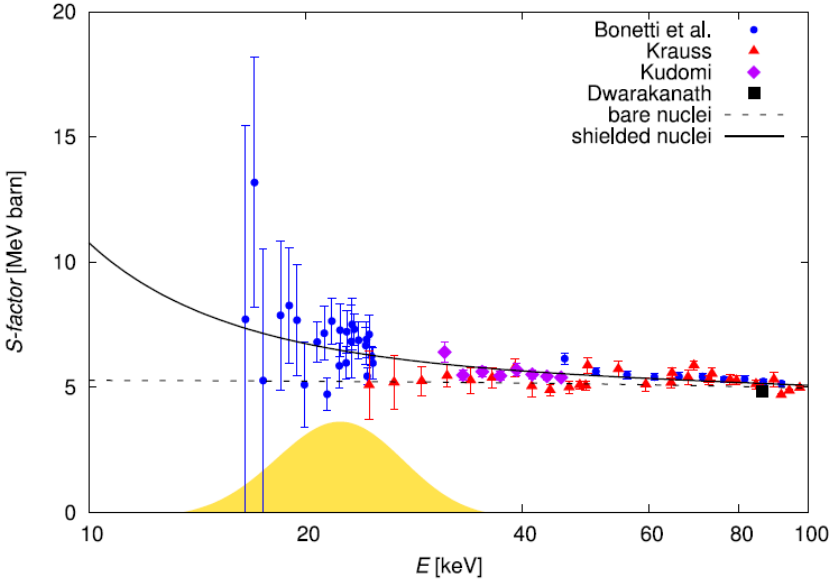
Background reduced by factor 15



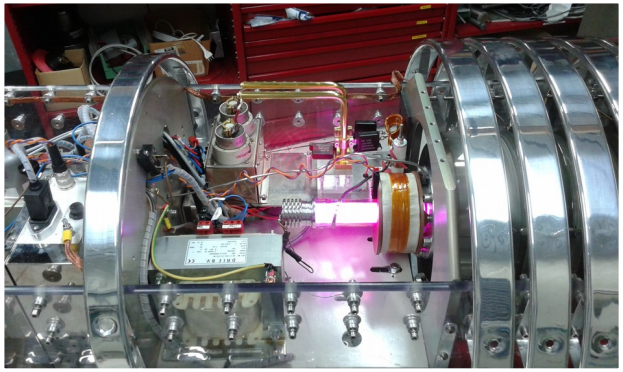
LUNA50kV: Yesterday

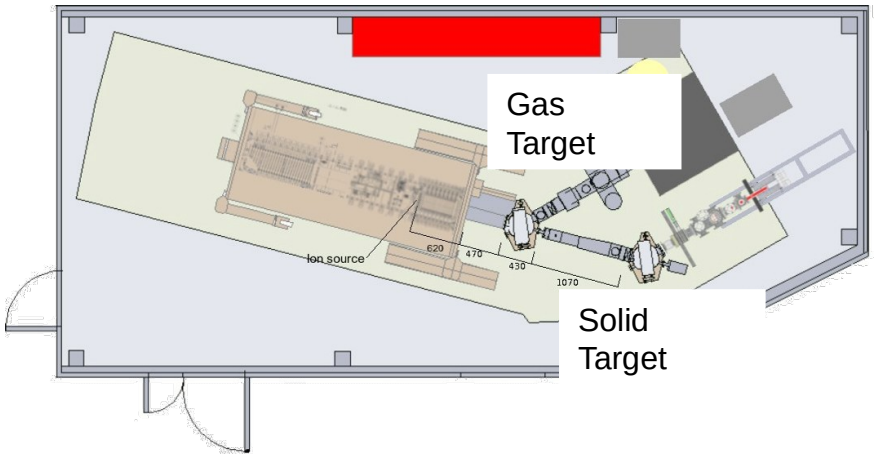


- Activity 1991 – 2001
- Home-made accelerator
- H^+ and He^+ beams
- pp-chain:
  - $^2H(p,\gamma)^3He$
  - $^3He(^3He,2p)^4He$

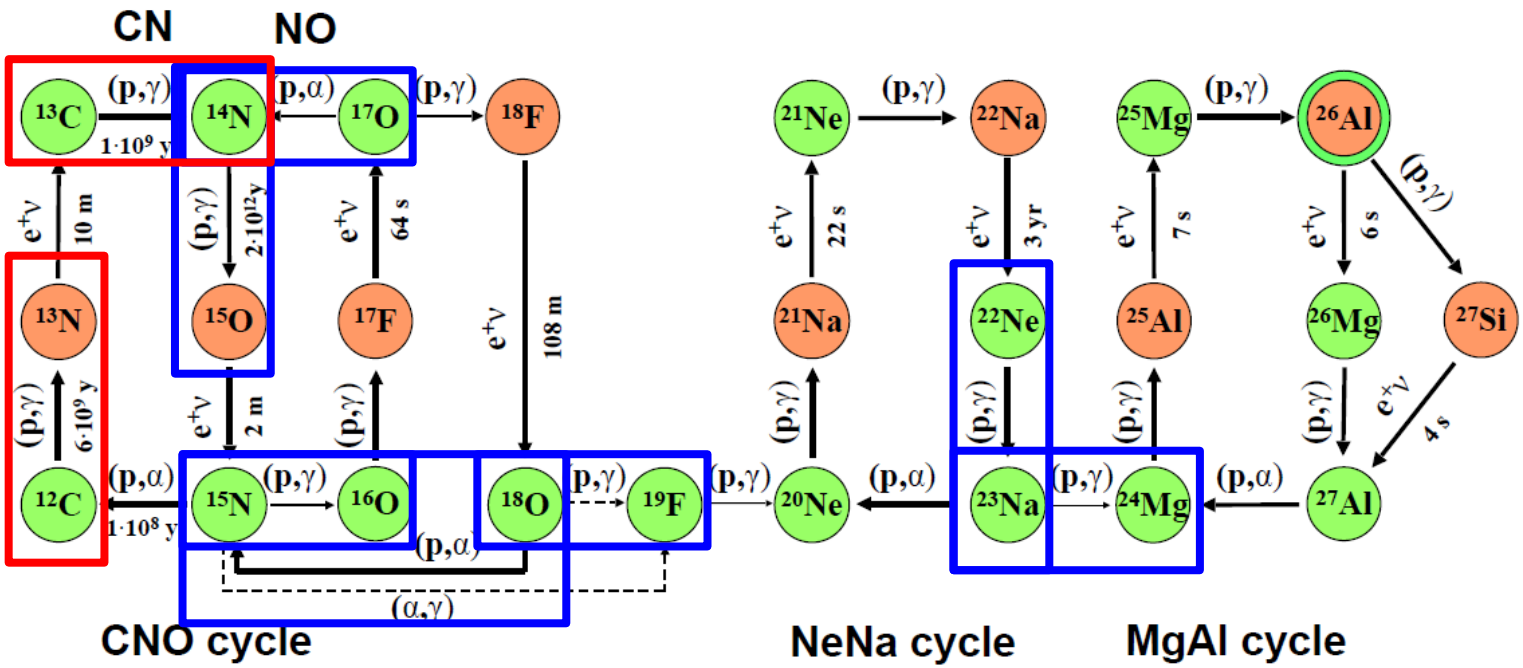


LUNA400kV: Today





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



- $^{22}Ne(\alpha,\gamma)^{26}Mg$
- $^{13}C(\alpha,n)^{16}O$

} s-process in AGB stars and in massive stars

- p+D

} High precision measurement → High accuracy D abundance

- $^{6}Li(p,\gamma)^{7}Be$

} He et al. 2013 → resonance at E_{cm} = 195 keV

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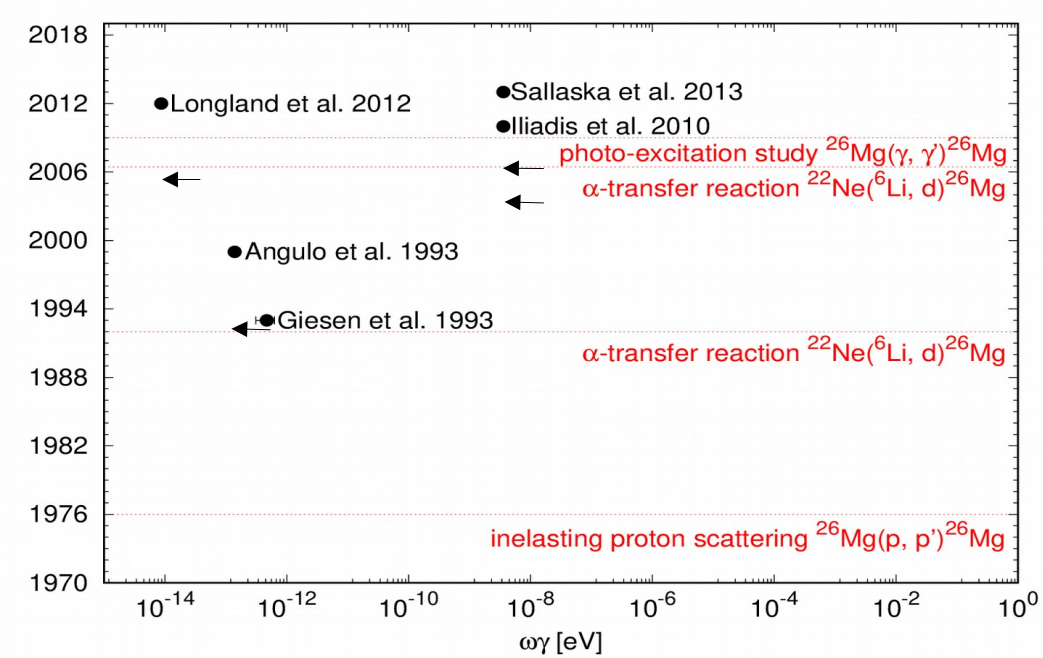
$^{22}Ne(\alpha,\gamma)^{26}Mg$ – Astrophysical Motivation

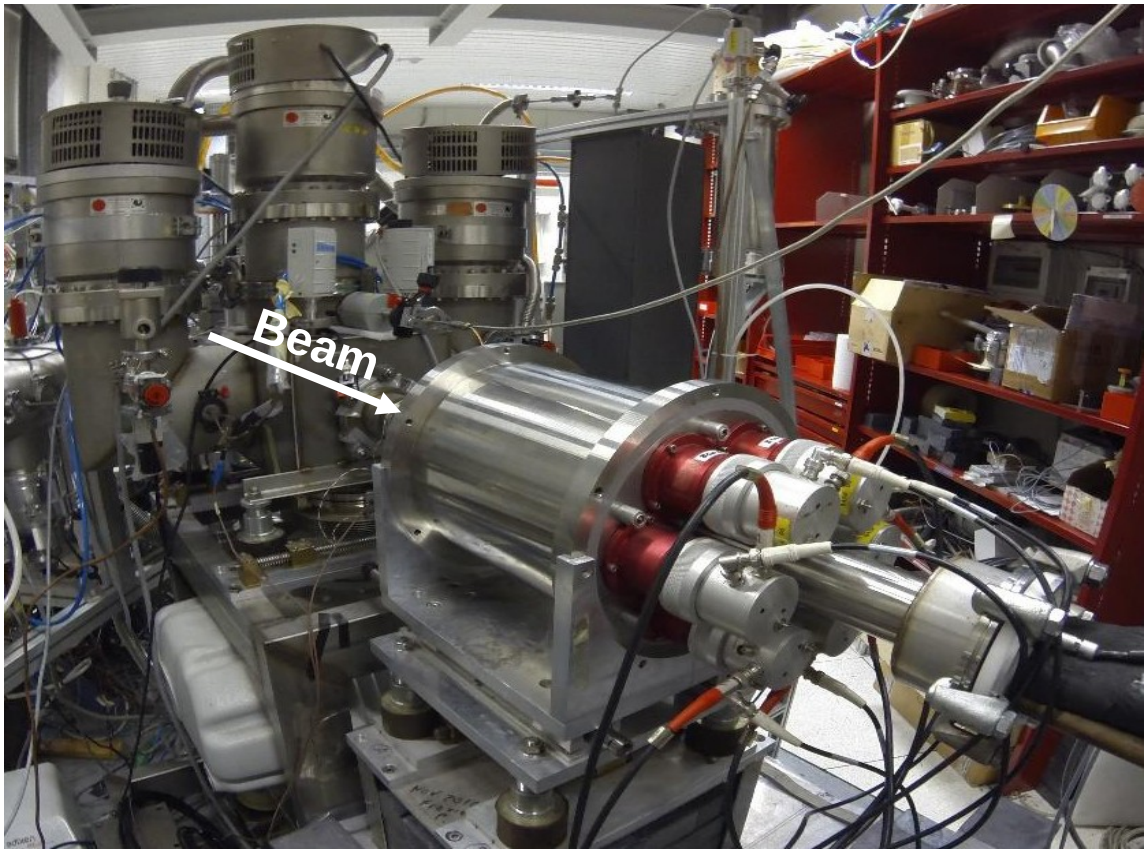
- $^{22}Ne(\alpha,\gamma)^{26}Mg$ (Q = 10.6 MeV) competes with **$^{22}Ne(\alpha,n)^{25}Mg$** (Q = - 478 keV)
- $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction rate **high uncertainty** affects isotopes production up to ^{31}P in AGB stars [Karakas et al. 2006]

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



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

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



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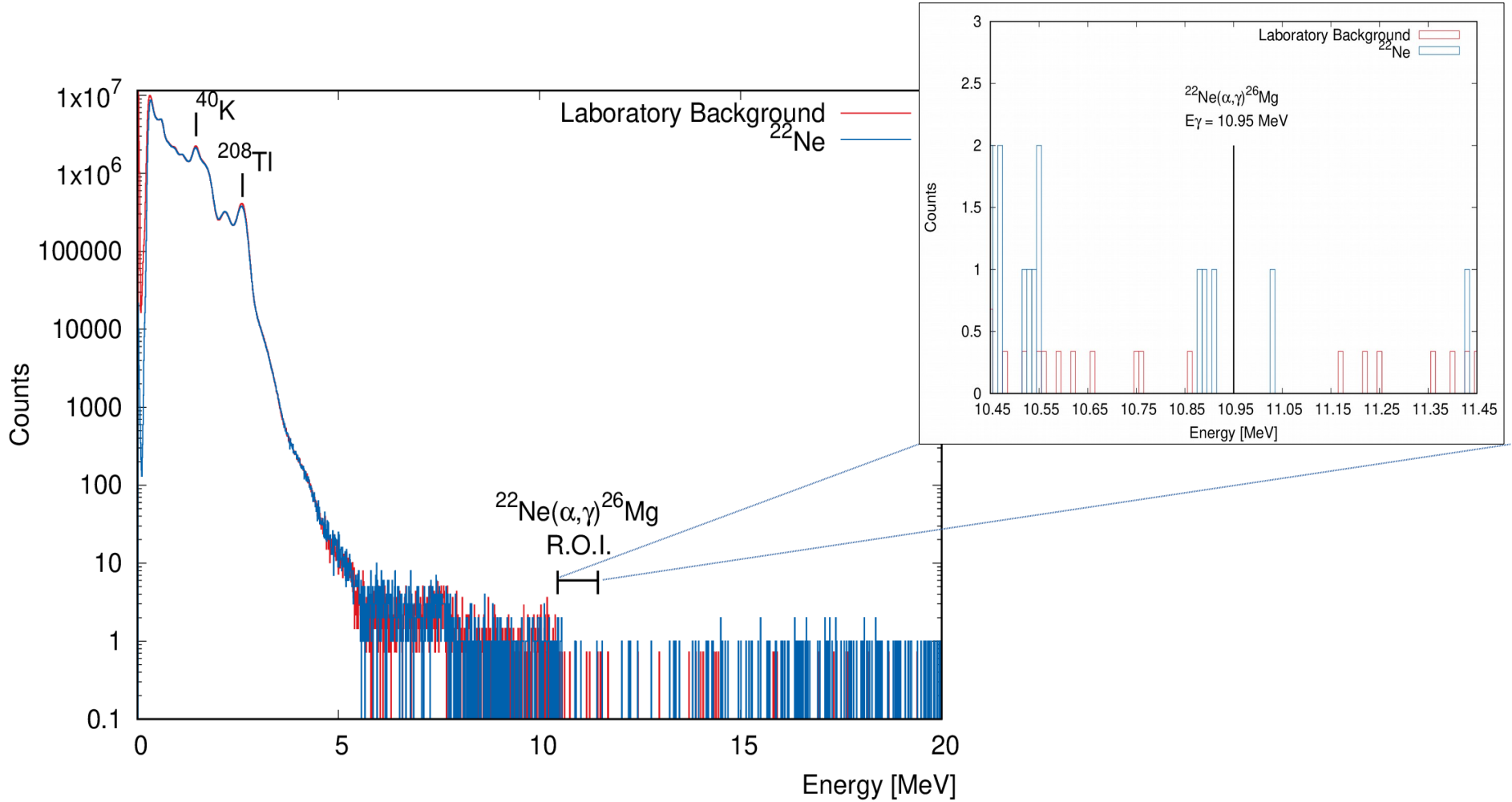
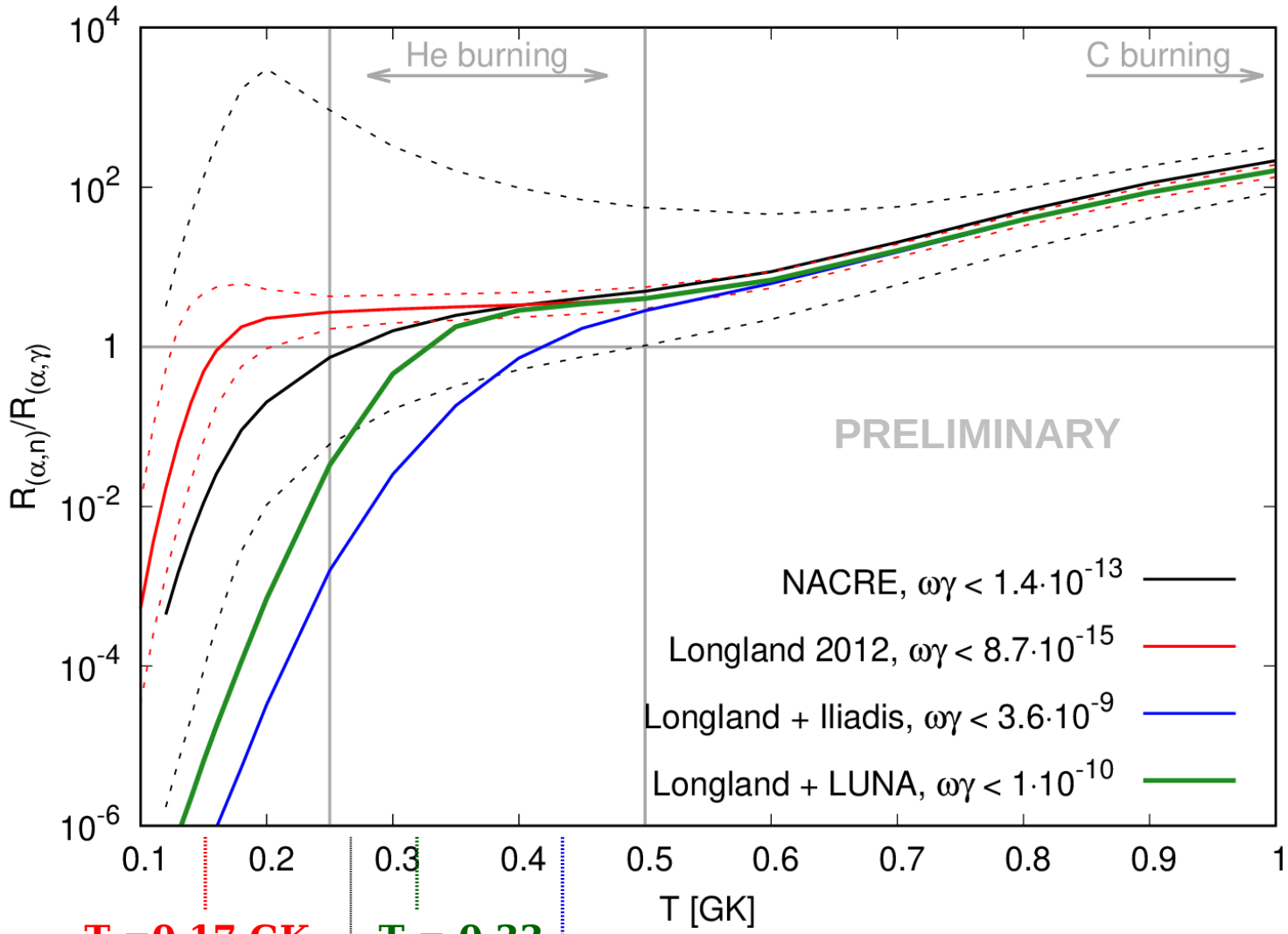
	t_m [d]	Charge [C]	Target Gas	P_{target} [mbar]	Eα [keV]	ΔEα [keV]
Laboratory Background	49	-	-	vacuum	-	-
Beam Induced Background	0.5	13.5	Ar	0.468	399.9	10.8
On Resonance	21.2	430	^{22}Ne	1	399.9	10.8

- 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 → **N < L_c (95% confidence level)**



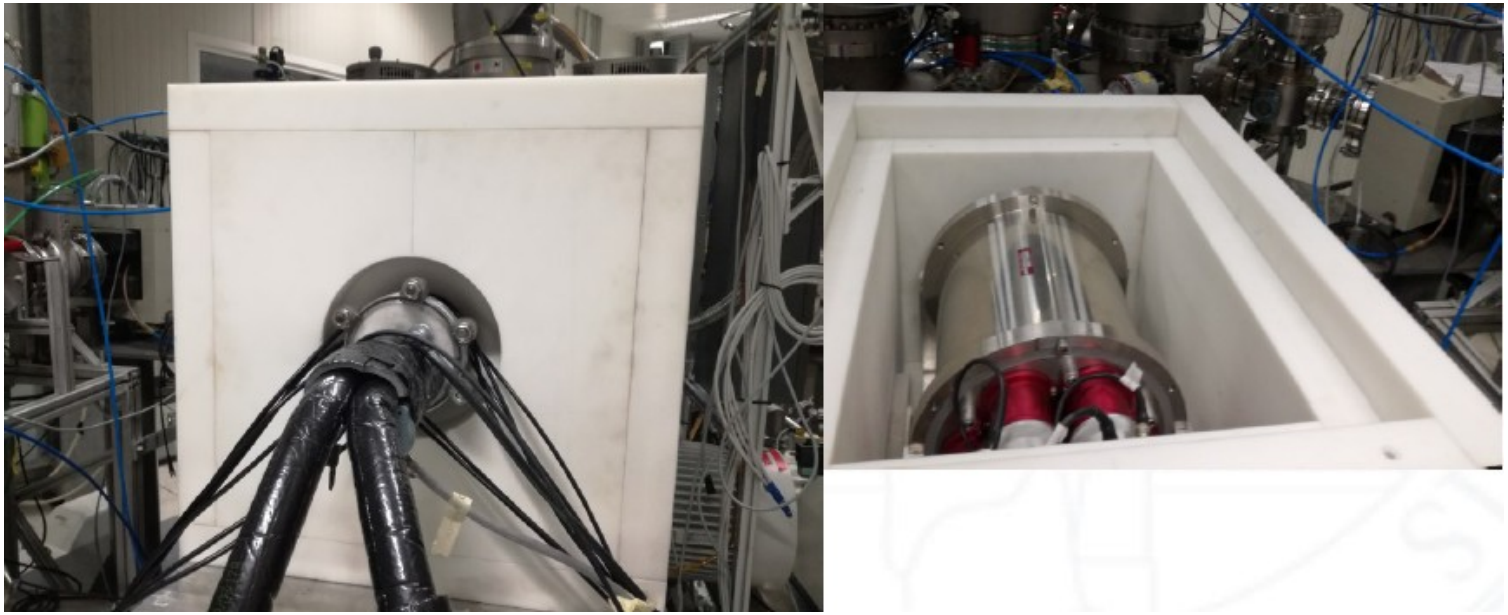
T =0.17 GK

T = 0.33 GK

T = 0.43 GK

T = 0.27 GK

$^{22}Ne(\alpha,\gamma)^{26}Mg$ – 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

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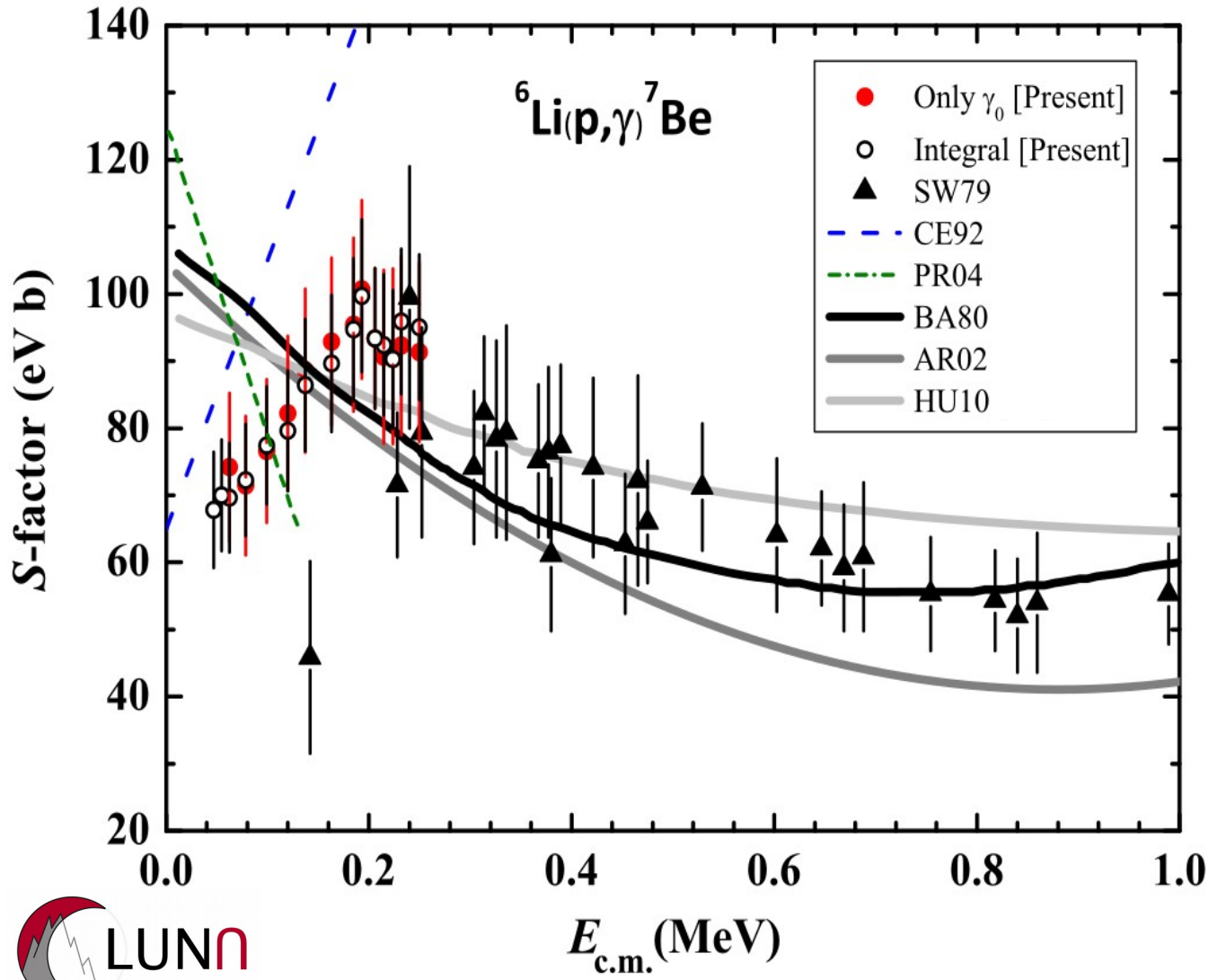
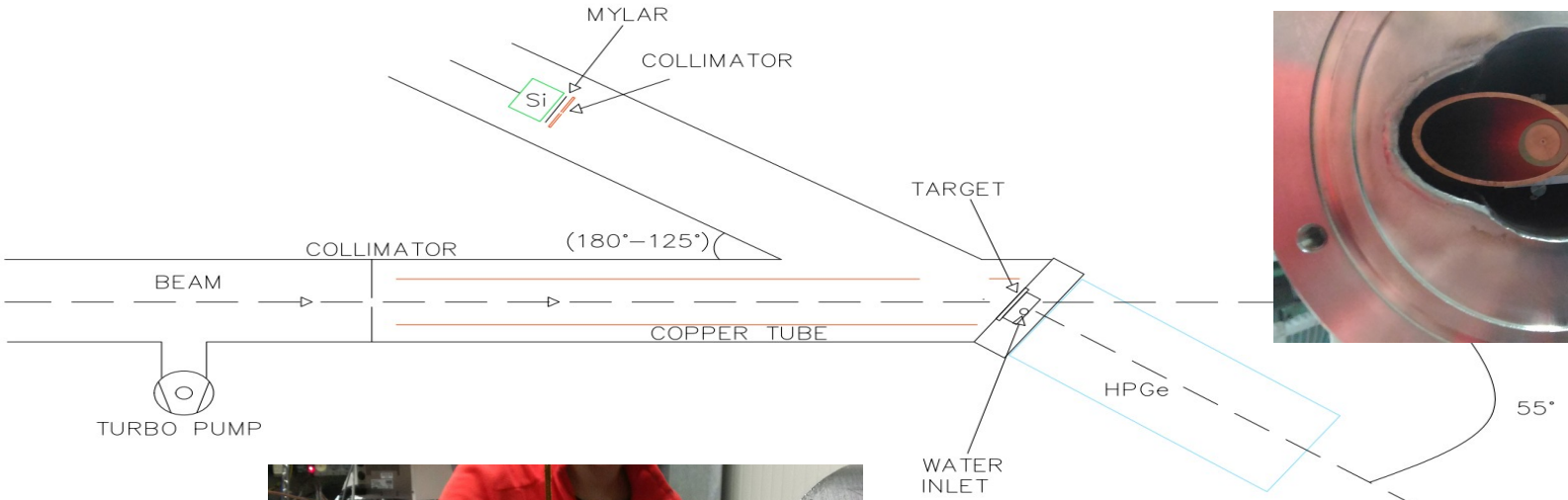
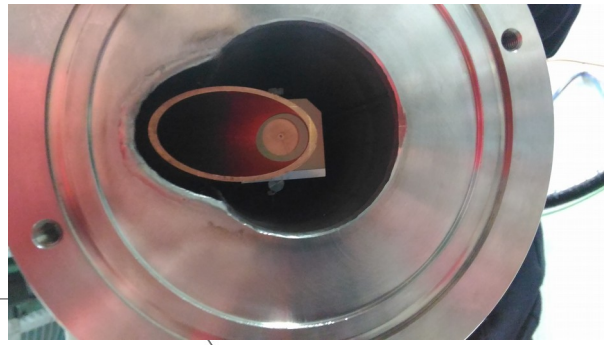
$^{6}Li(p,\gamma)^{7}Be$ – Astrophysical Motivation

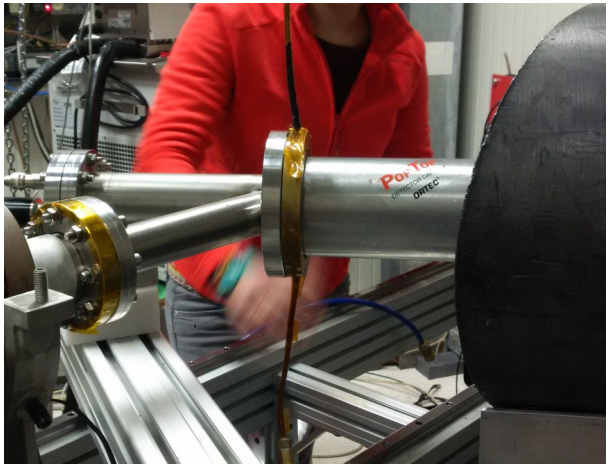


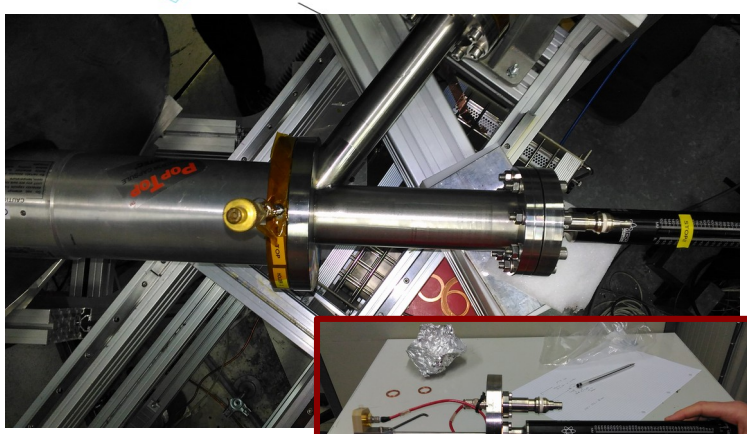
- **High uncertainty** of the experimental data
- **Poor overlap** between the data sets
- **No agreement on the slope of the S-factor at low E_p**

He et al., Phys. Rev. Lett. B (2013)





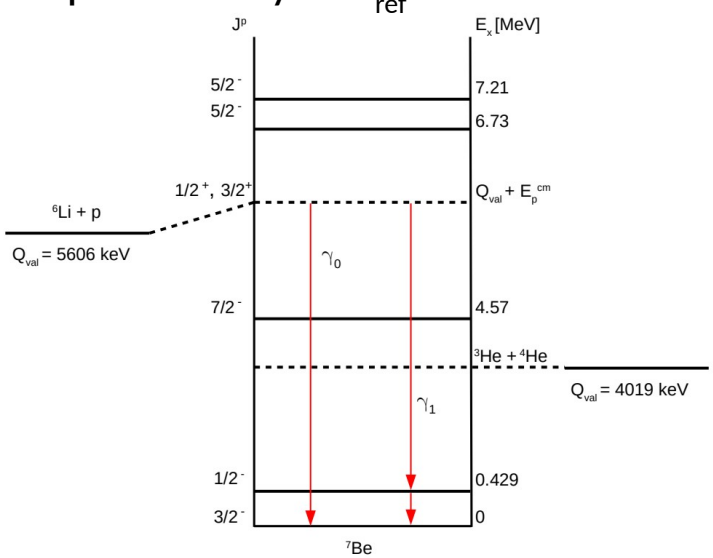


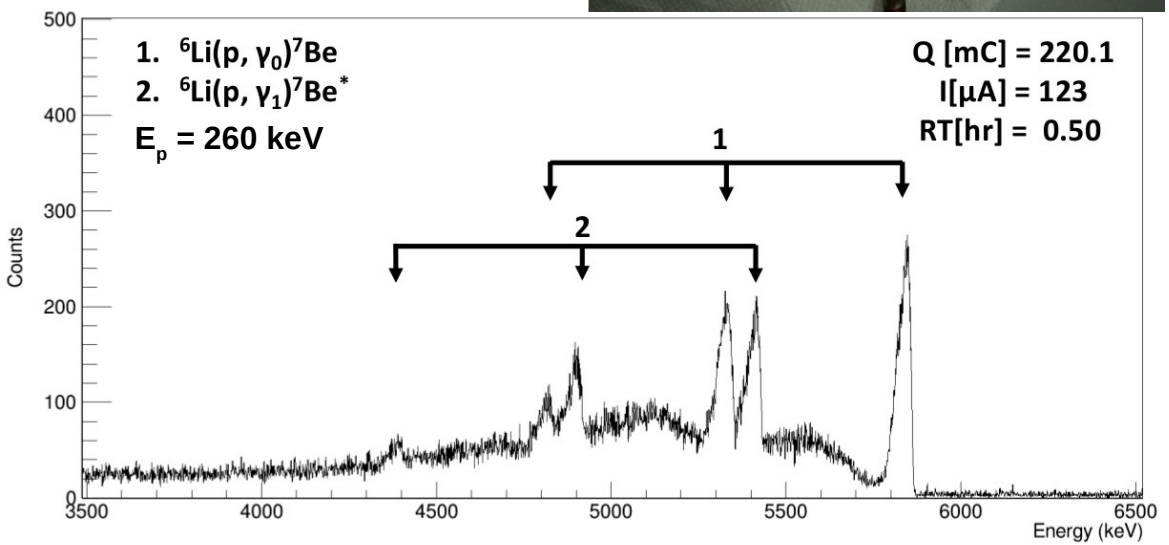


- Cold Finger + secondary e^- suppression
- Water cooled target
- HPGe at -55° and Si at +125° w.r.t. beam direction
- HPGe at 1.7 cm and Si at 10 cm w.r.t. target

Target Type	Nominal Thickness
$^{6}Li_2O$	• 40 μg/cm² • 20 μg/cm²
$^{6}Li_2WO_4$	• 100 μg/cm² • 130 μg/cm²
$^{6}LiCl$	• Infinite

- E_p: 80 → 390 keV
- Stability of the target checked periodically at E_{ref}

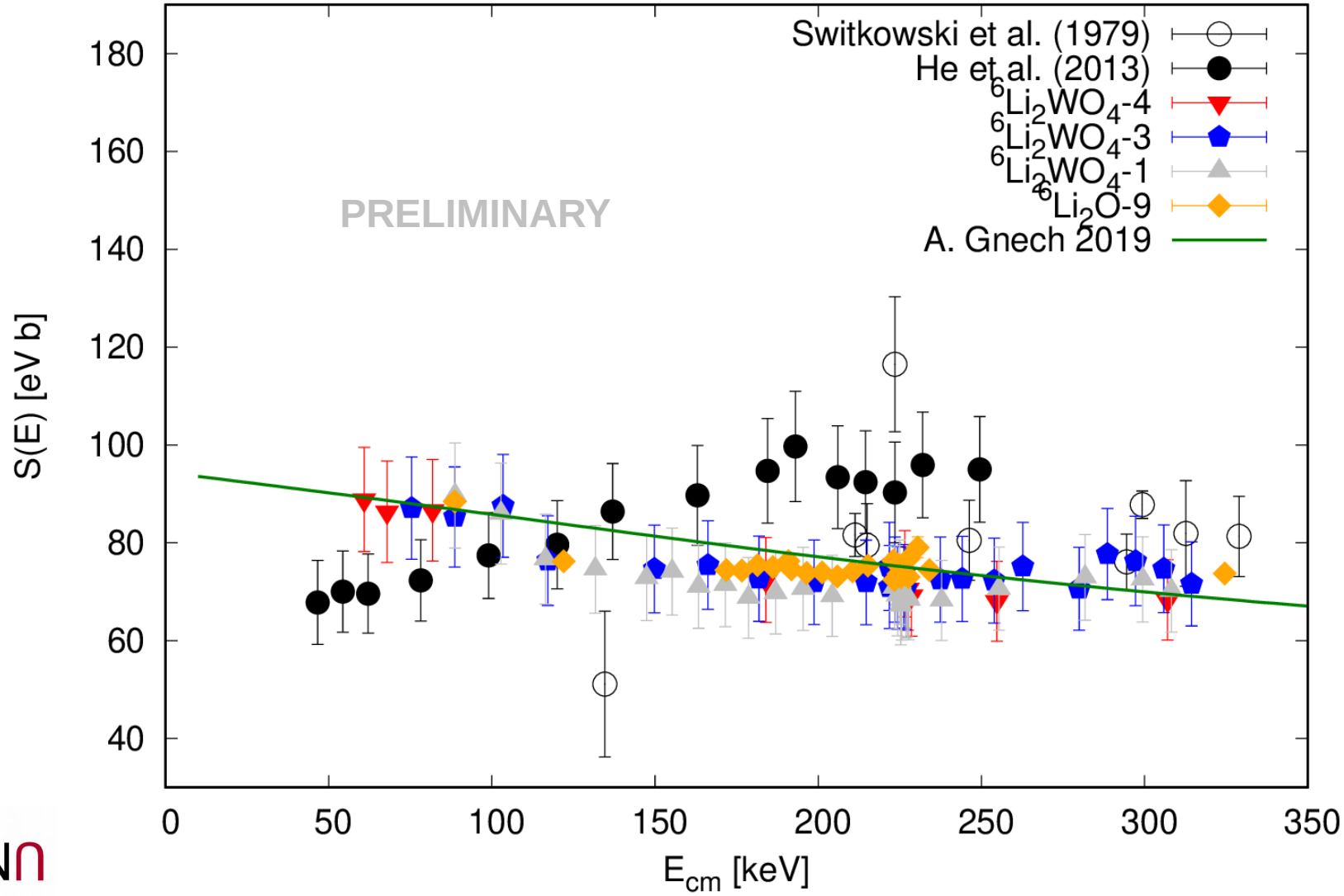




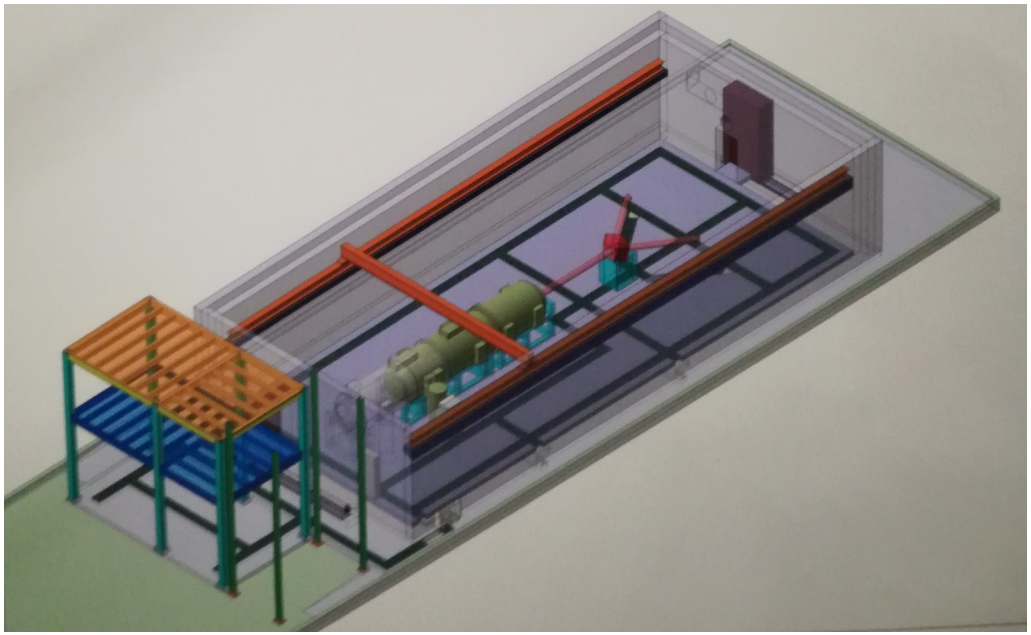
- Measurement performed at Helmholtz- Zentrum Dresden-Rossendorf Laboratories
- After the experiment at LUNA
- Two techniques:
- **<u>NRA</u>:** exploiting the resonance at 1175 keV $^{6}Li(\alpha,\gamma)^{10}B$ ($\omega\gamma$ = 0.366 ± 0.038 eV, Γ = 1.7 eV) [Gyürky et al., EPJA (2004)]
- **→ Distribution of ^{6}Li with target depth**

- **<u>ERDA</u>**: incident ion $^{35}Cl^{7+}$, incident angle 70°, scattering angles 31° and 41°
- **→ Composition of the target**

Results


Switkowski et al. (1979)
He et al. (2013)
$^6Li_2WO_4$-4
$^6Li_2WO_4$-3
$^6Li_2WO_4$-1
$^6Li_2O$-9
A. Gnech 2019
PRELIMINARY
S(E) [eV b]
E_{cm} [keV]
180
160
140
120
100
80
60
40
0
50
100
150
200
250
300
350

LUNAMV: Tomorrow



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

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LUNAMV: Tomorrow

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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)

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LUNA Collaboration

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Thank You