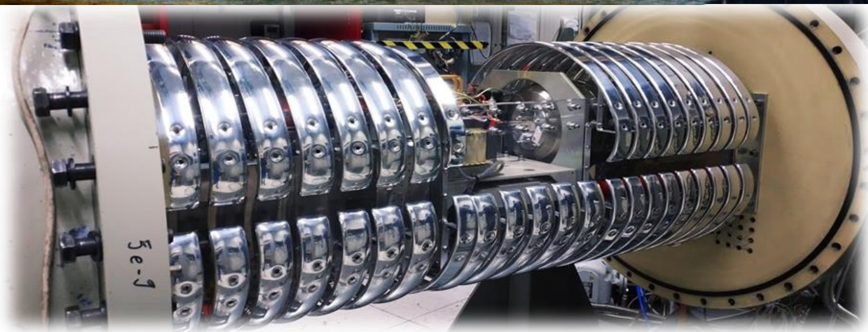


Underground nuclear astrophysics and the study of $^{22}Ne(\alpha,\gamma)\,^{26}Mg$ and $^{20}Ne(p,\gamma)\,^{21}Na$ reactions at LUNA

22 October 2020 - Phys Dept. of Warsaw University

LUNA
Laboratory for Underground Nuclear Astrophysics

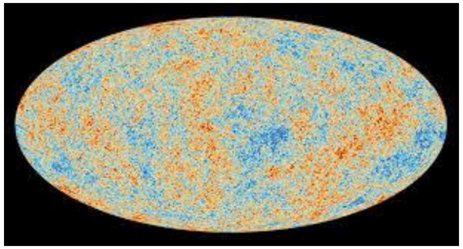
Eliana Masha
Università degli studi di Milano

INFN
Istituto Nazionale di Fisica Nucleare

Observational astronomy

Cosmology

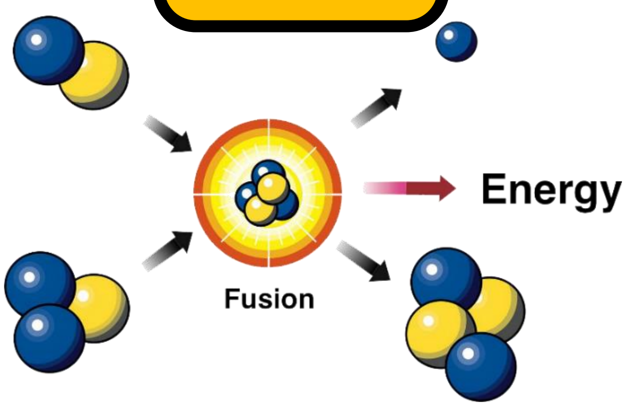
Nuclear astrophysics

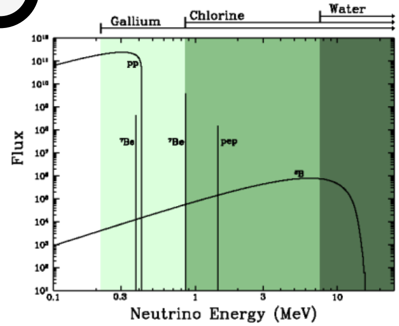


Nuclear physics

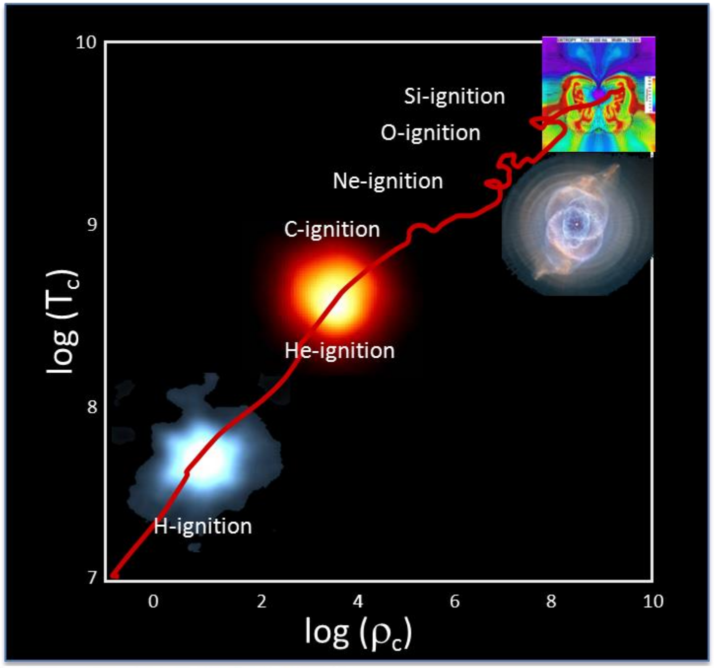
Neutrino physics

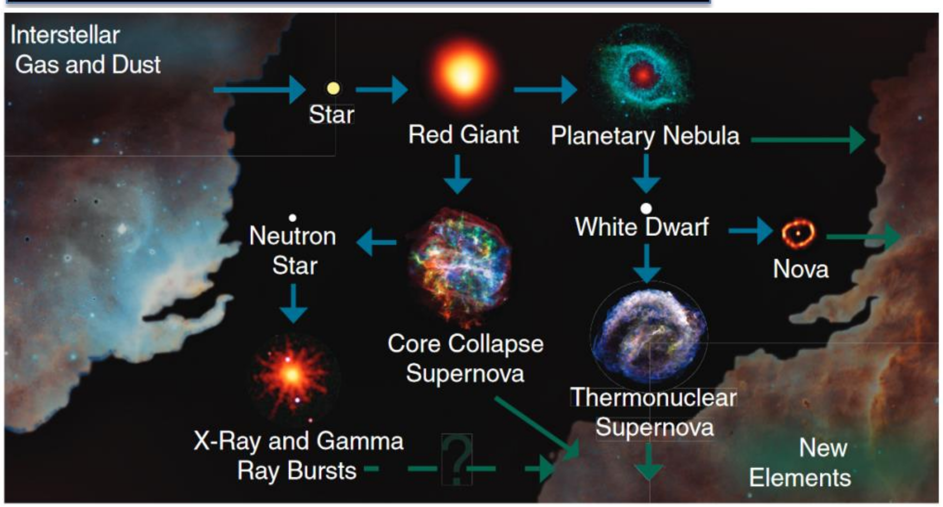
Stellar Models





Cross section and stellar models

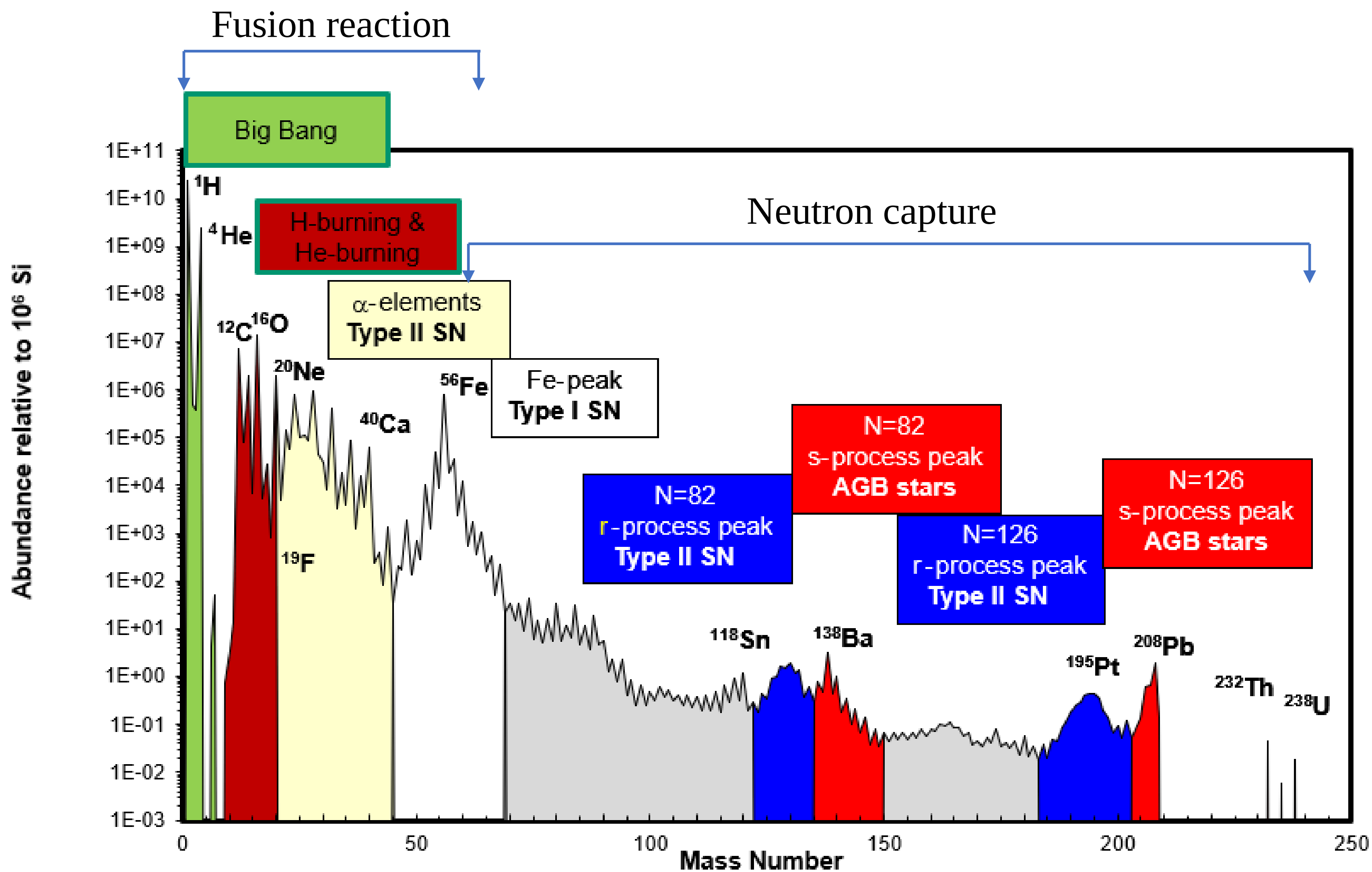




- ❖ Stars are powered by nuclear reactions
- ❖ Among the key parameters (chemical composition, opacity, ...) to model stars, reaction cross sections play an important role
- ❖ They determine the origin of the elements in the cosmos, stellar evolution and dynamic

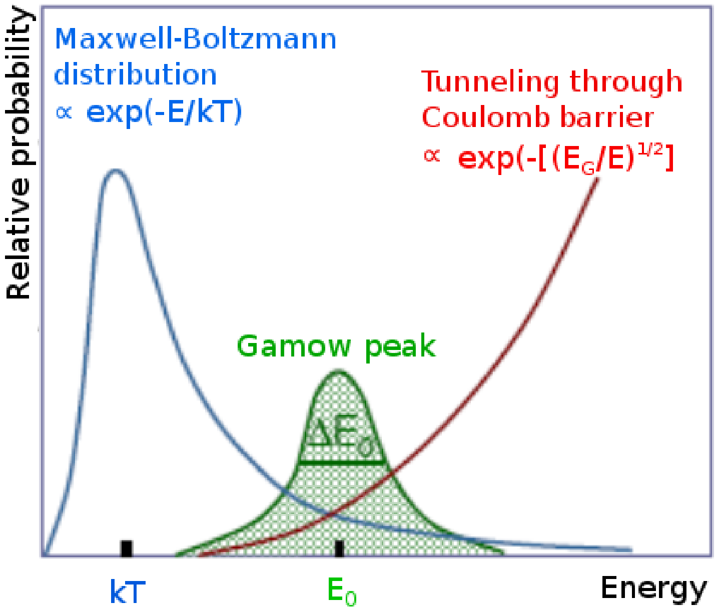
High precision data are needed!!!

The origin of the elements



Nuclear Astrophysics ambitious task is to explain the origin and relative abundance of the elements in the Universe

Gamow peak



Sun:

kT = 1 keV

$E_C \approx 0.5\text{-}2$ MeV

$E_0 \approx 5\text{-}30$ keV

for reactions of H burning

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

Astrophysical S-factor

Reaction Rate = N_p x N_t x cross section x efficiency

10^{14} pps

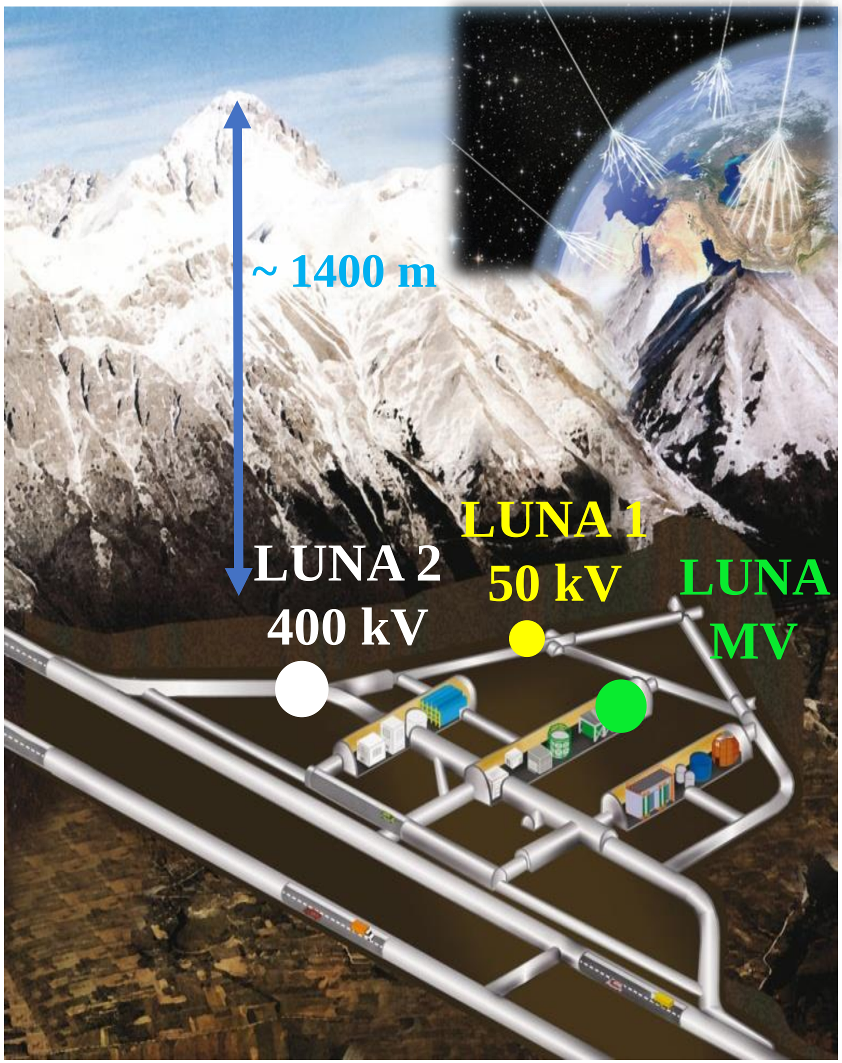
10^{19} atoms/cm^2

10^{-12} barn

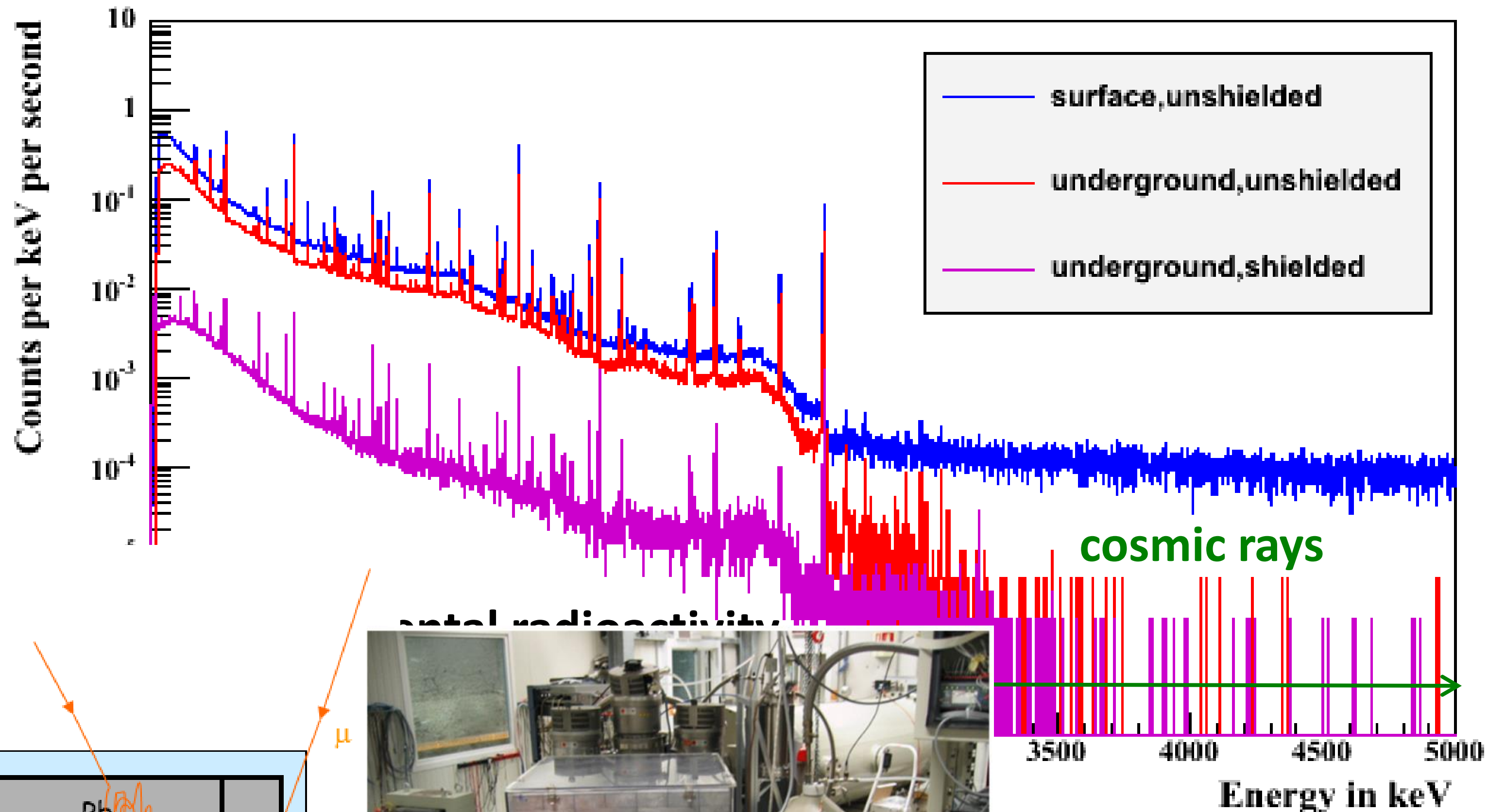
~1-10%

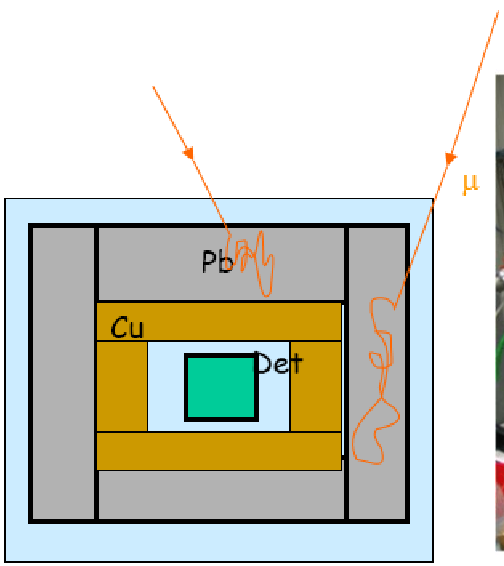
R_{lab} = 1-10 counts/day

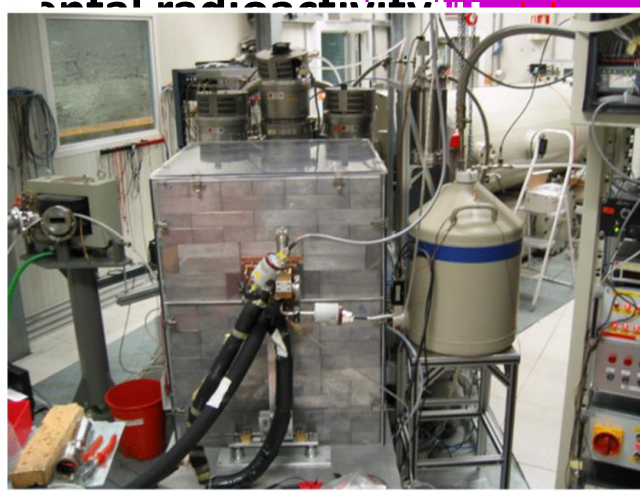
Laboratory for Underground Nuclear Astrophysics - LUNA



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



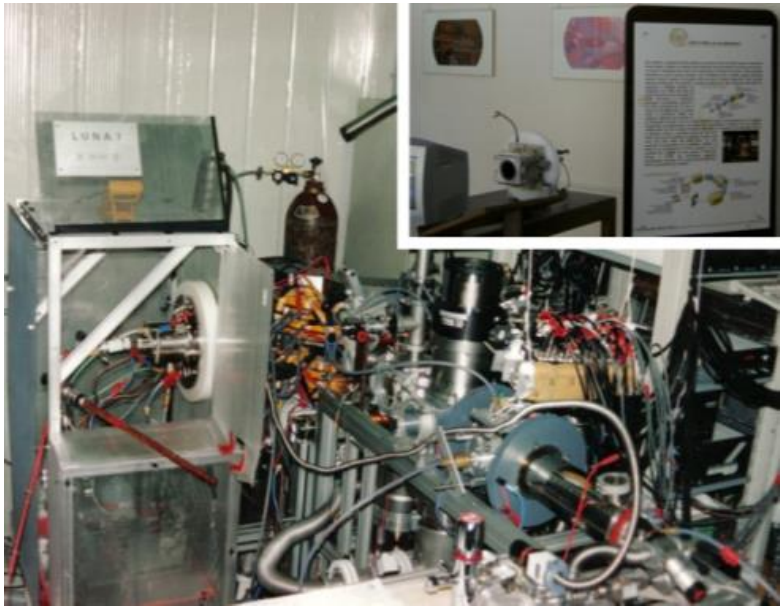




Radiation	LNGS/surface
Muons	10^{-6}
Neutrons	10^{-3}

LUNA 50kV - Past

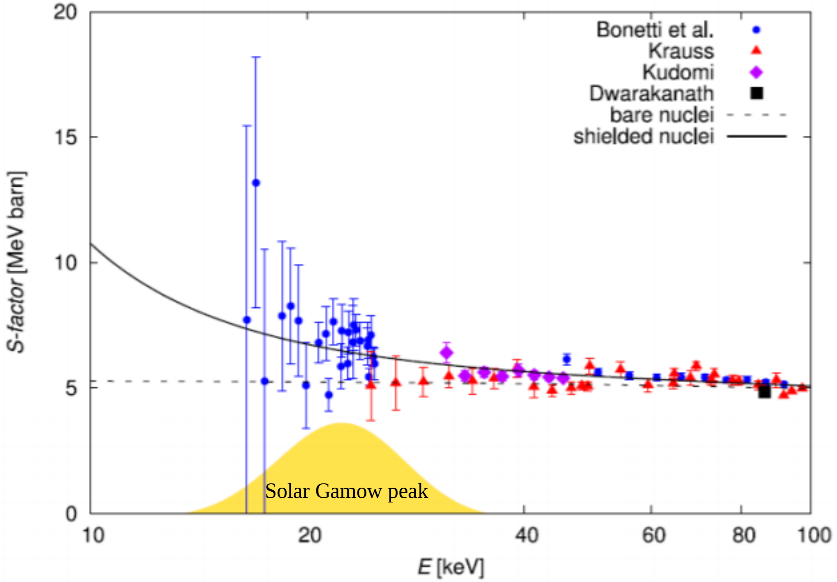
- Activity: 1991 – 2001
- Home-made accelerator
- H^+ and He^+ beams



pp-chain:

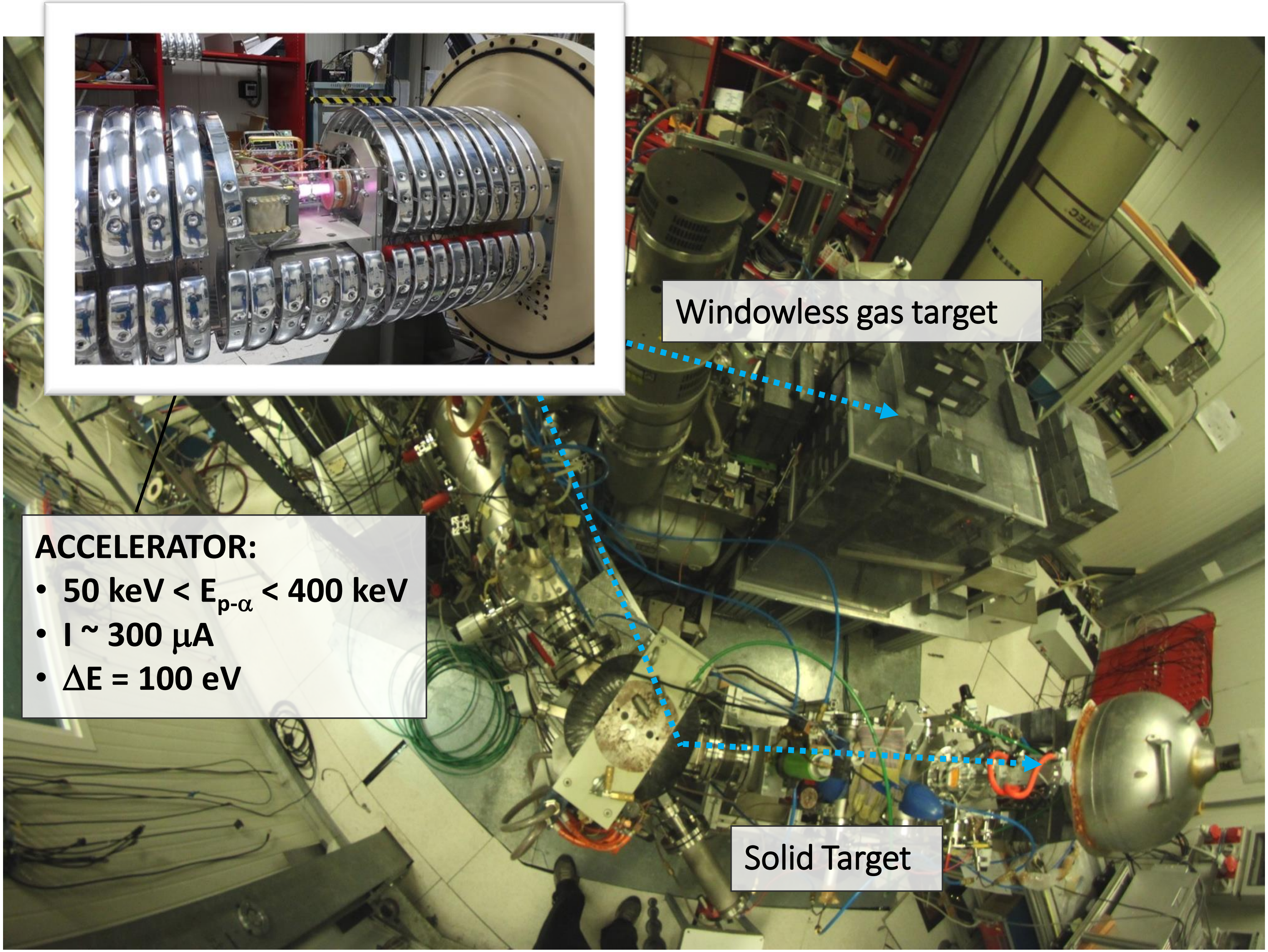
- $^{2}H(p,\gamma)^{3}He$
- $^{3}He(^{3}He,2p)^{4}He$

2 events/month



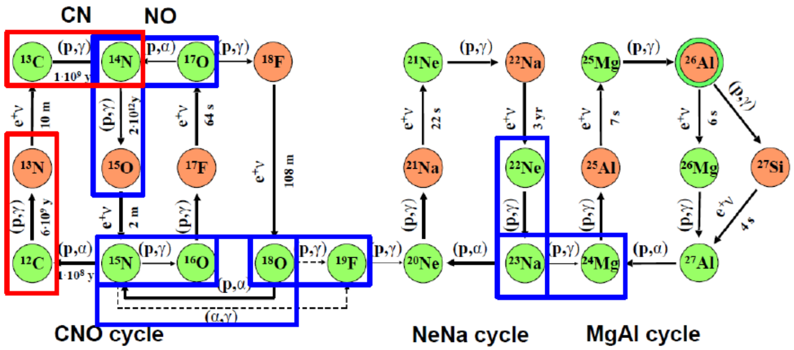
R. Bonetti et al., Phys. Rev. Lett. 82, (1999) 2700

LUNA 400kV - Present



ACCELERATOR:

- 50 keV < $E_{p\text{-}\alpha}$ < 400 keV
- I ~ 300 μA
- ΔE = 100 eV



Activity: 2001 –

- **Big Bang nucleosynthesis:** ^{2}H(α, γ)^{6}Li ^{2}H(p, γ)^{3}He ^{6}Li(p, γ)^{7}Be

- **Hydrogen burning in the Sun:** ^{14}N(p,g)^{15}O

- **Hydrogen burning in massive stars:** ^{15}N(p, γ)^{16}O ^{22}Ne(p, γ)^{23}Na

^{23}Na(p, γ)^{24}Mg ^{25}Mg(p, γ)^{26}Al ^{17}O(p, γ)^{18}F ^{17}O(p, α)^{14}N ^{18}O(p, γ)^{19}F ^{18}O(p,a)^{15}N

- **Helium burning:** ^{13}C(α,n)^{16}O **^{22}Ne(α,γ)^{26}Mg**

- **Ongoing:** ^{12}C/^{13}C(p, γ)^{13}N/^{14}N **^{20}Ne(p,γ)^{21}Na**

Study of the $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction at LUNA

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

^{22}Ne produced via $^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne$

- The **$^{22}Ne(\alpha,\gamma)^{26}Mg$** ($Q_{val}$ = 10.6 MeV) competes with $^{22}Ne(\alpha,n)^{25}Mg$ (Q_{val} = -478 keV)

Source of neutrons for s-process in:

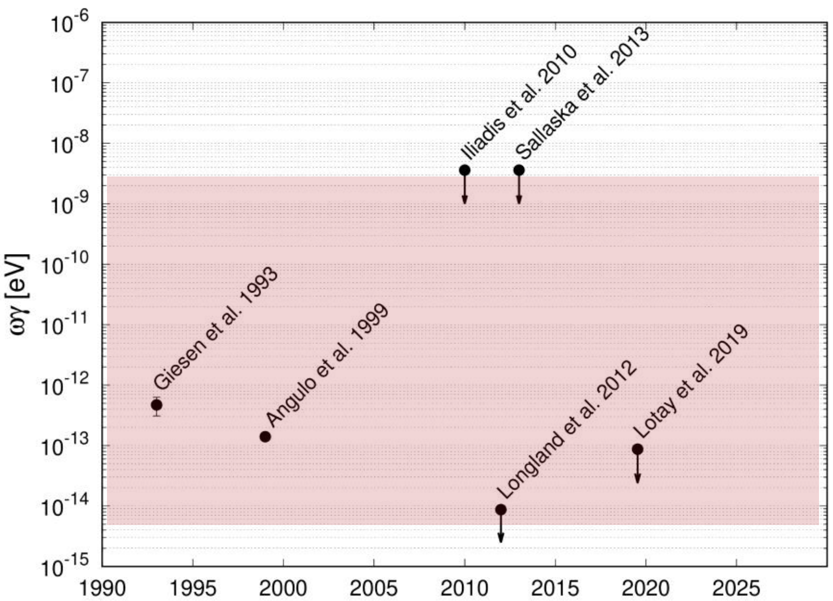
- **Intermediate AGB stars ($T \geq 2.5 \cdot 10^{8}$ K → Unstable intershell He-burning)**
- **massive stars ($T \geq 3 \cdot 10^{8}$ K and $T \sim 10^{9}$ K → Core He and C burning)**

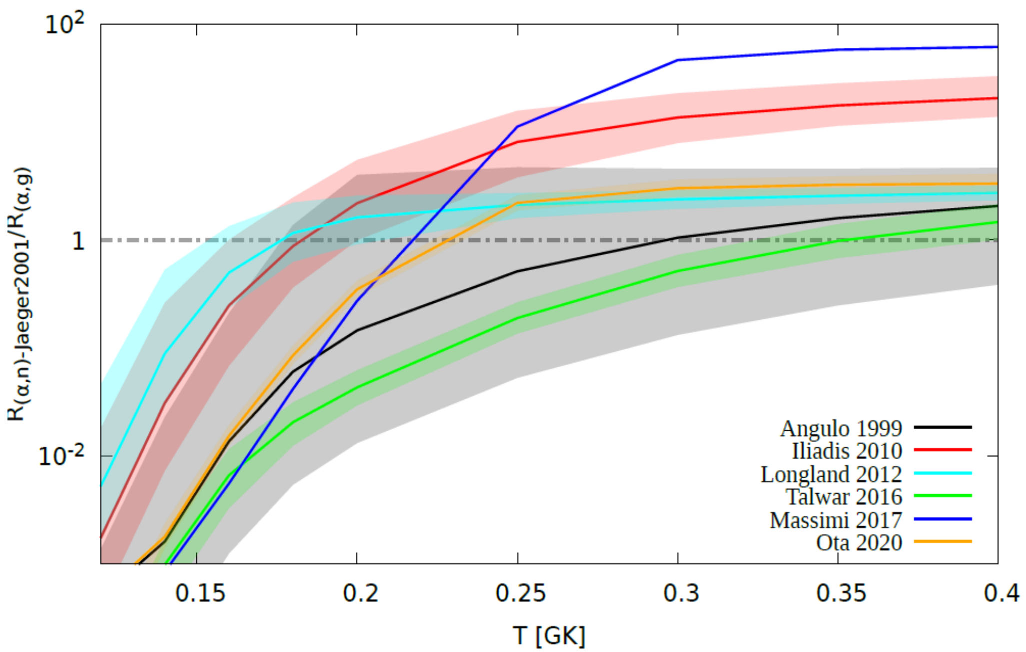
- $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction affects the production of isotopes ^{25}Mg – ^{31}P in intermediate mass AGB stars (Karakas et al. 2006).

$^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction – State of the art

In the energy range (temperature) when the ^{22}Ne becomes efficient the thermonuclear reaction rate dominated is dominated by the **395keV resonance**.

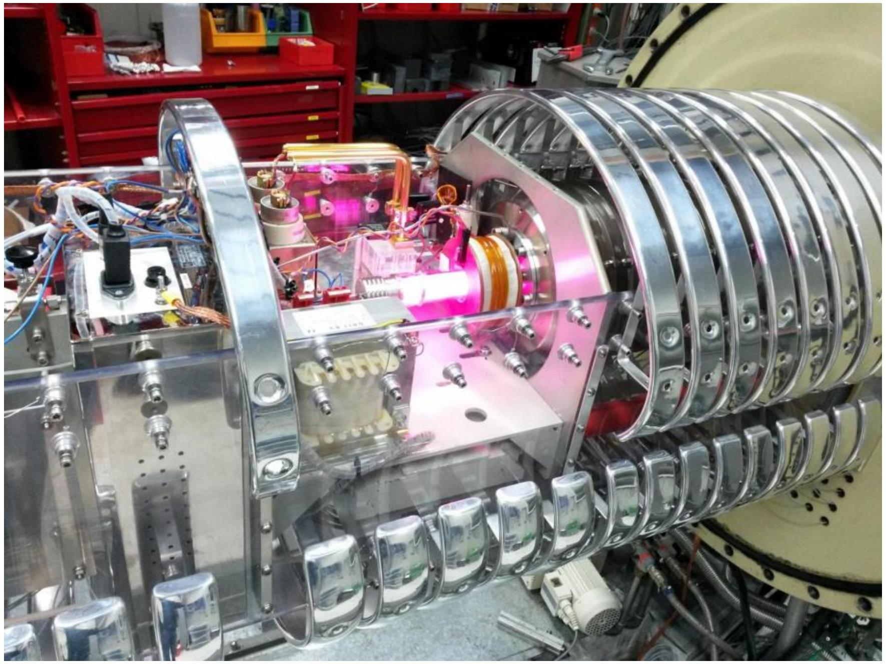
NO DIRECT MEASUREMENTS!

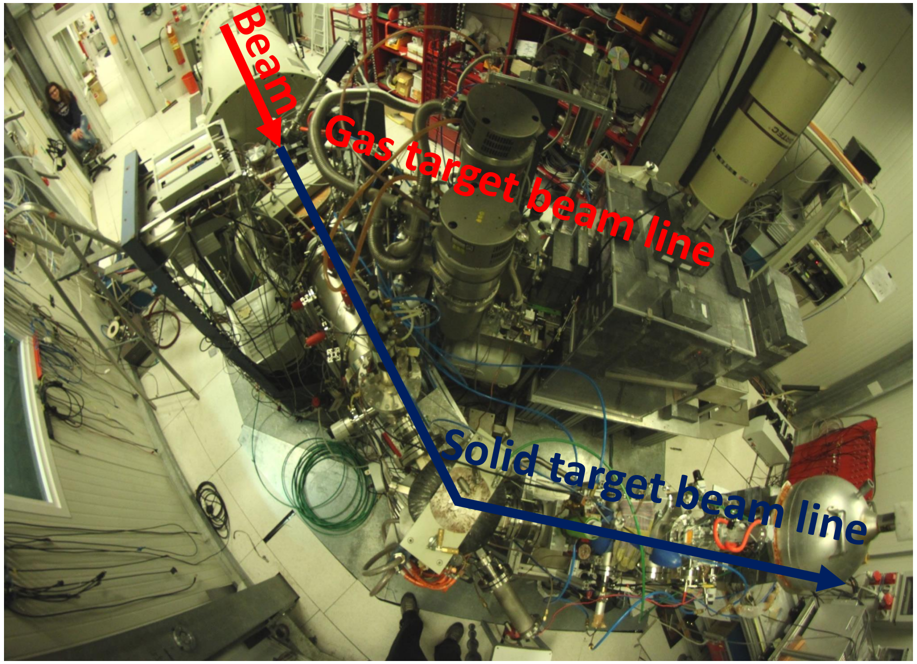




6 ORDERS OF MAGNITUDE!!!

$^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction – Experimental setup





$E_{beam} \approx 50 – 400$ keV

$I_{max} \approx 250\ \mu A$ alphas

Long term stability ≈ 5eV/h

Differentially pumped windowless gas target

99.9% enriched ^{22}Ne gas at 1 mbar

Two different campaigns:

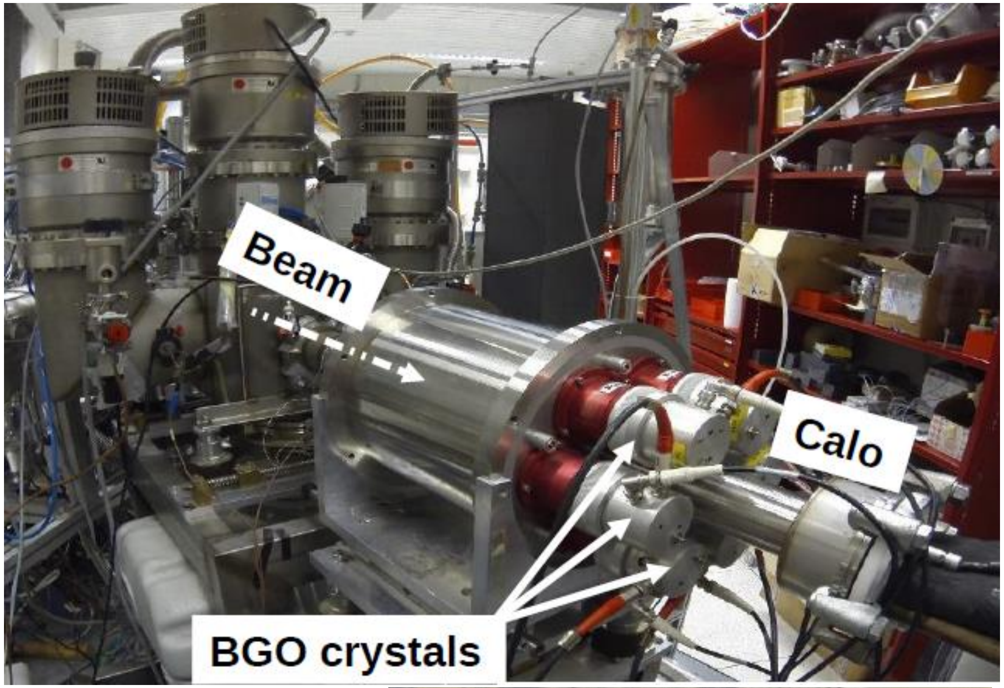
- Phase I - Summer 2016
- Phase II - May - August 2019

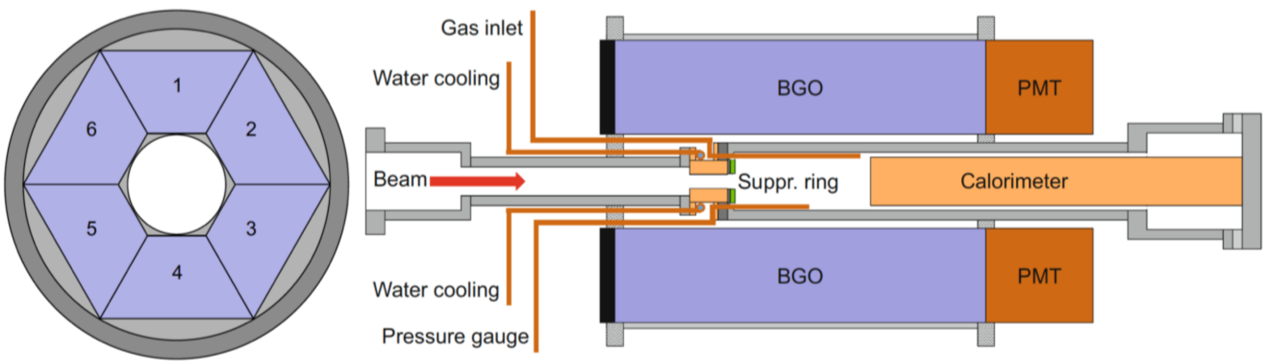
$^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction – Experimental setup (Phase I)

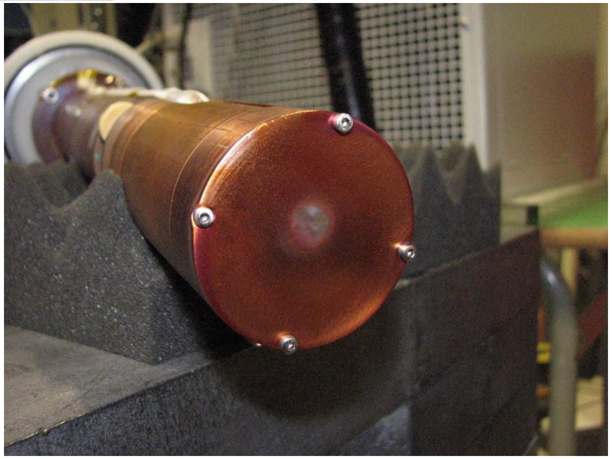
- Calorimetric measurement of the beam intensity, I_{beam}:

$$I_{beam} = \frac{W_0 - W_{run}}{E_{beam} - \Delta E}$$

- High efficiency detector
  - 6 BGO crystals, Ω~4π
  - Optically independent
  - Addback spectrum offline
  - ~40% efficiency

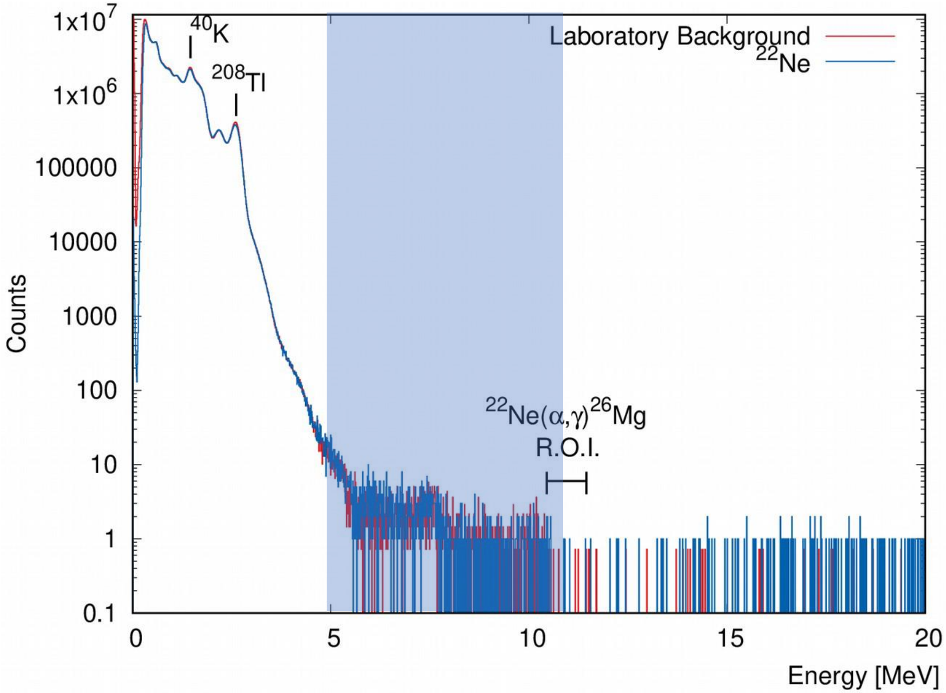






Ferraro et al., EPJA, 2018

$^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction – Experimental setup



Low signal in the ROI

Precise knowledge of:

- ✓ Laboratory background
- ✓ Beam induced background

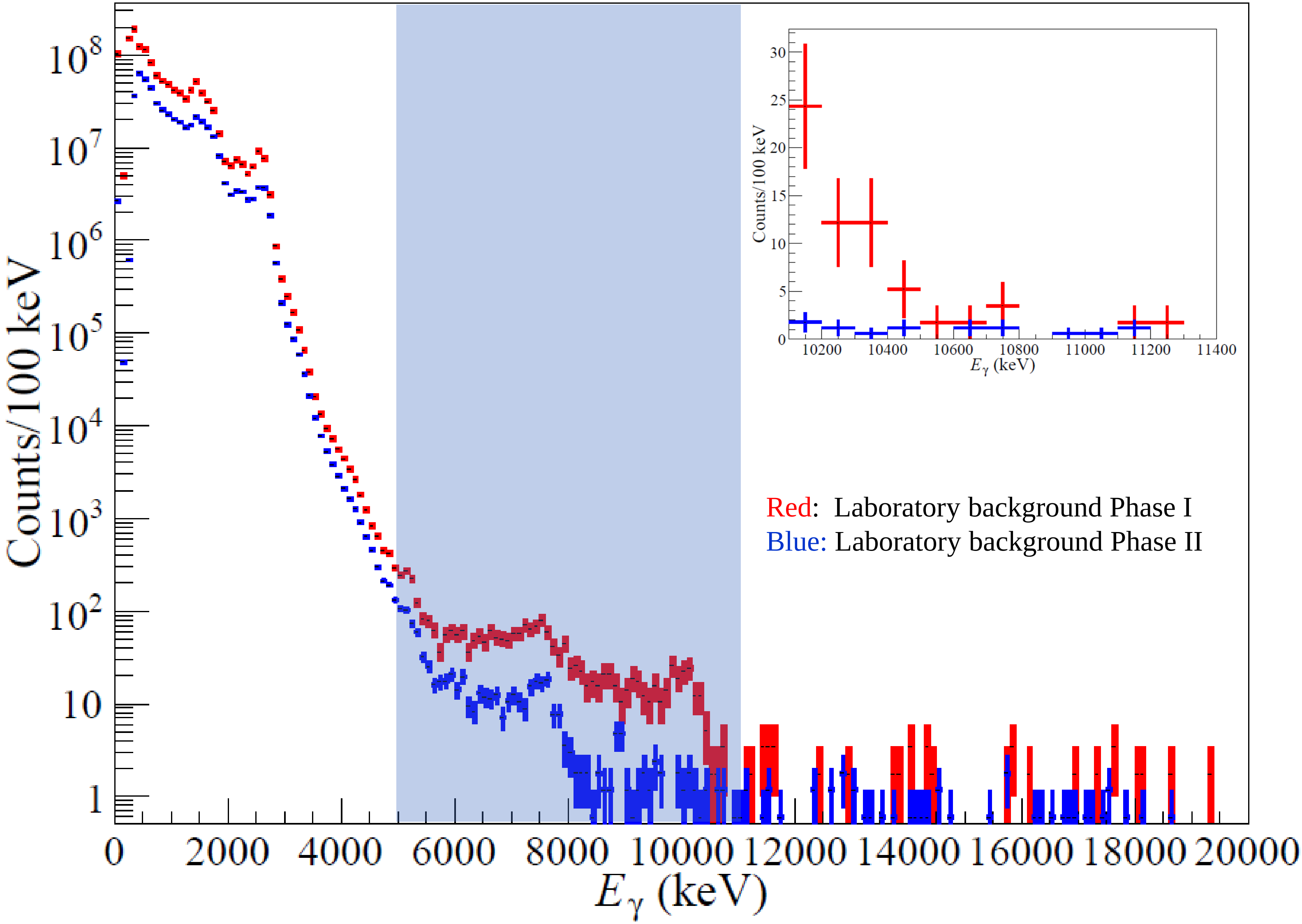
- Improved setup (Phase II)
- 10 cm thick shield of borated polyethylene→ reduce **neutron background**
- Increase BIB statistics

↓

395 keV α-beam on Argon gas at 0.468 mbar

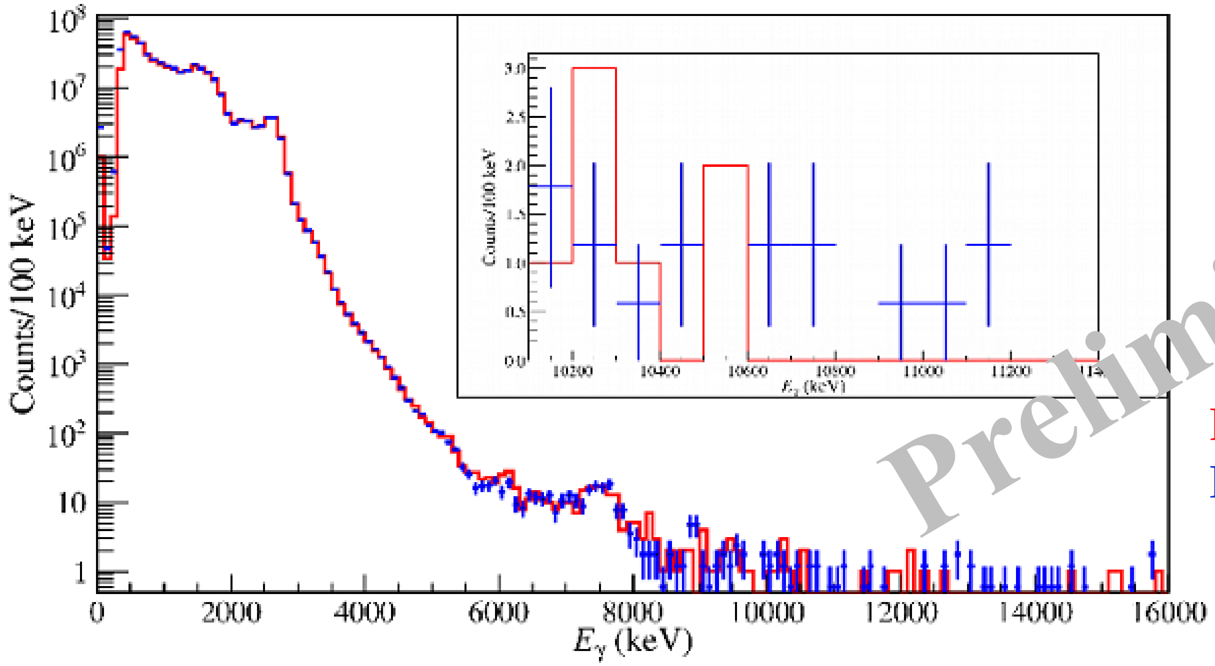
E. Masha

$^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction – Experimental setup



Neutron induced background region reduced by a factor of 2-3!

Total second campaign statistics on resonance



Red line: on resonance
Blue line: no beam background

There is no evidence of signal in the ROI → **N < LC (95% confidence level)**

Upper limit calculation

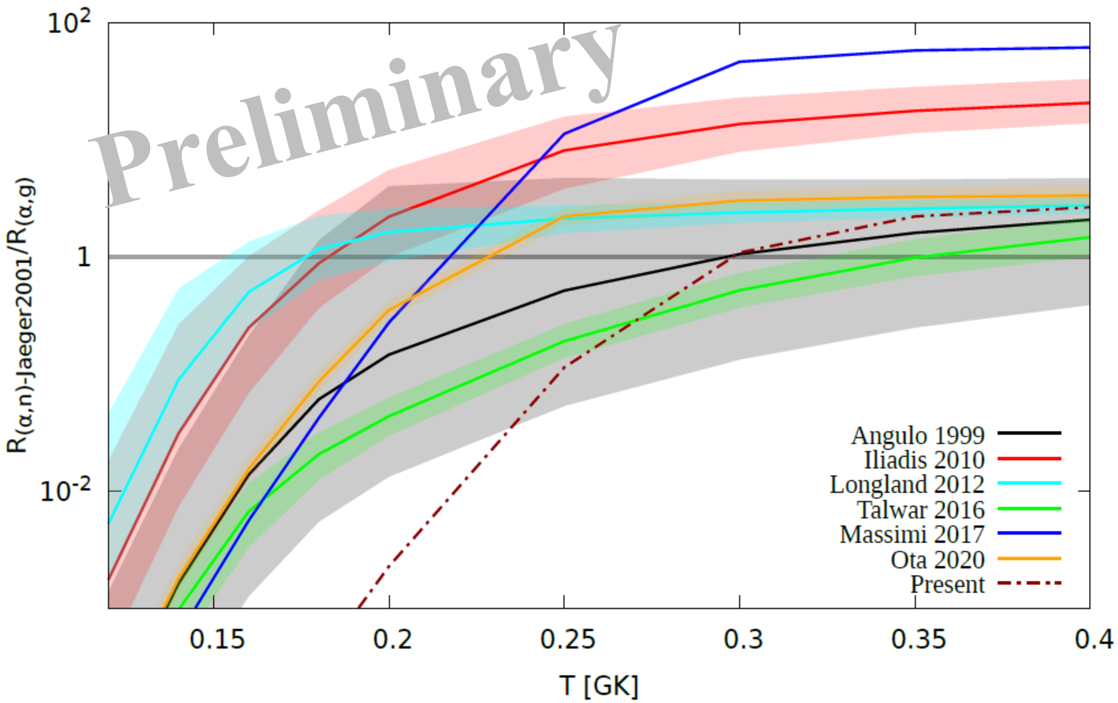
Phase I
$\omega\gamma < 1.43 \cdot 10^{-10}$ **eV**

→

Phase II
$\omega\gamma < 3.7 \cdot 10^{-11}$ **eV**

^{22}Ne(α,γ)^{26}Mg reaction – Experimental setup

^{22}Ne(α,γ)/^{22}Ne(α,n) reaction rate ratio



Present ^{22}Ne(α,γ)^{26}Mg reaction rate based on results of Phase II

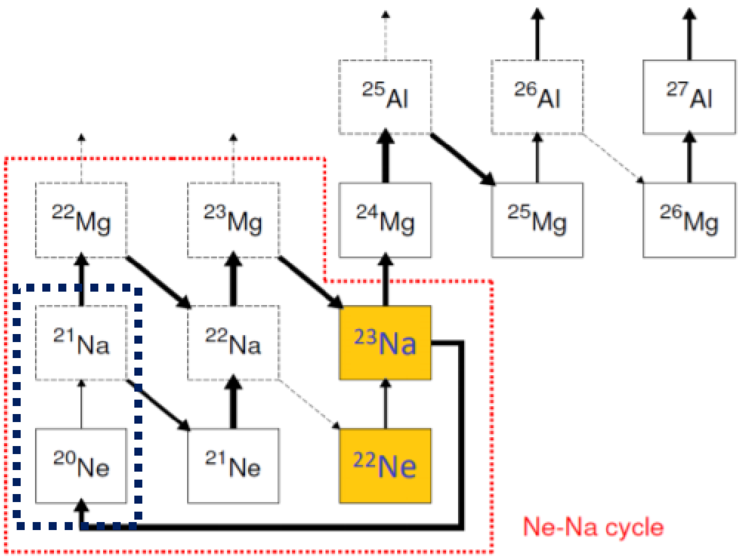
Astrophysical impact

Investigation of the astrophysical impact on the production of ^{25}Mg and ^{26}Mg ongoing!
Calculation of the temperature and abundance evolution of TP-AGBs using PARSEC-COLIBRI code (P. Marigo et al. 2013)
$M_i = 5M_\odot$
Solar-like metallicity Z = 0.014

Study of the $^{20}Ne(p,\gamma)^{21}Mg$ reaction at LUNA

^{20}Ne(p,γ)^{21}Na reaction – Astrophysical motivation

^{20}Ne(p,γ)^{21}Na (Q = 2431.6 keV) is the slowest reaction of the NeNa cycle and governs the velocity of the entire cycle. It affects the production of all neon isotopes.



NeNa cycle

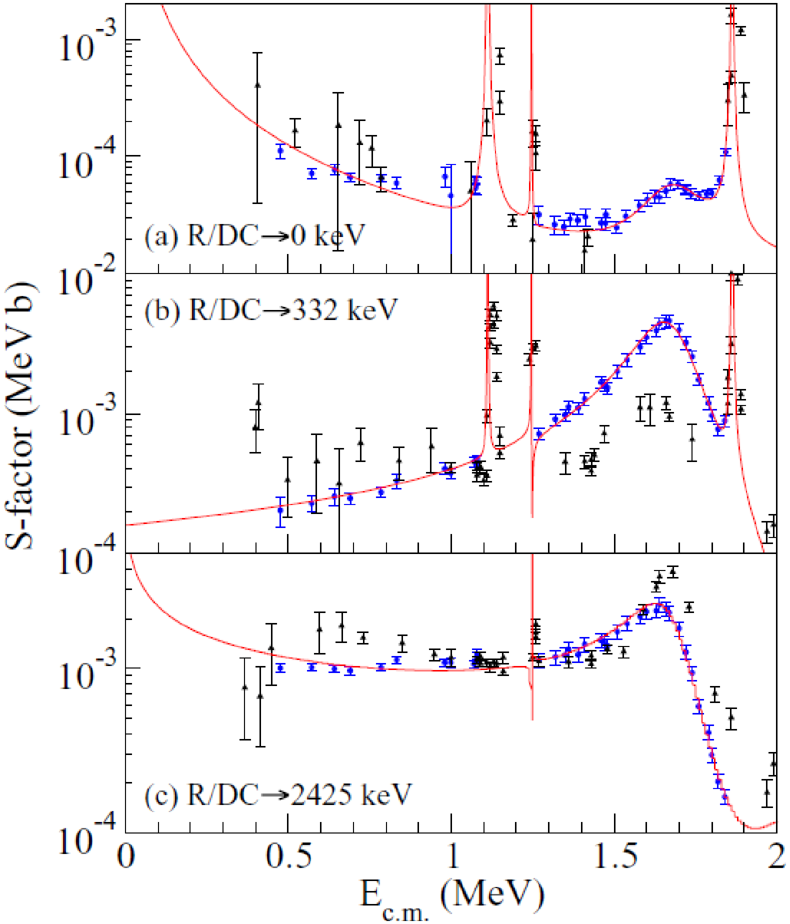
- Advanced H-burning cycle
- Not important for energy production
- Cruciar role for production of isotopes Ne - Al

^{22}Ne(p,γ)^{23}Na reaction already studied at LUNA

Astrophysical scenarios:

- Red Giant Branch stars
- Asymptotic Giant Branch stars
- Novae
- Massive stars

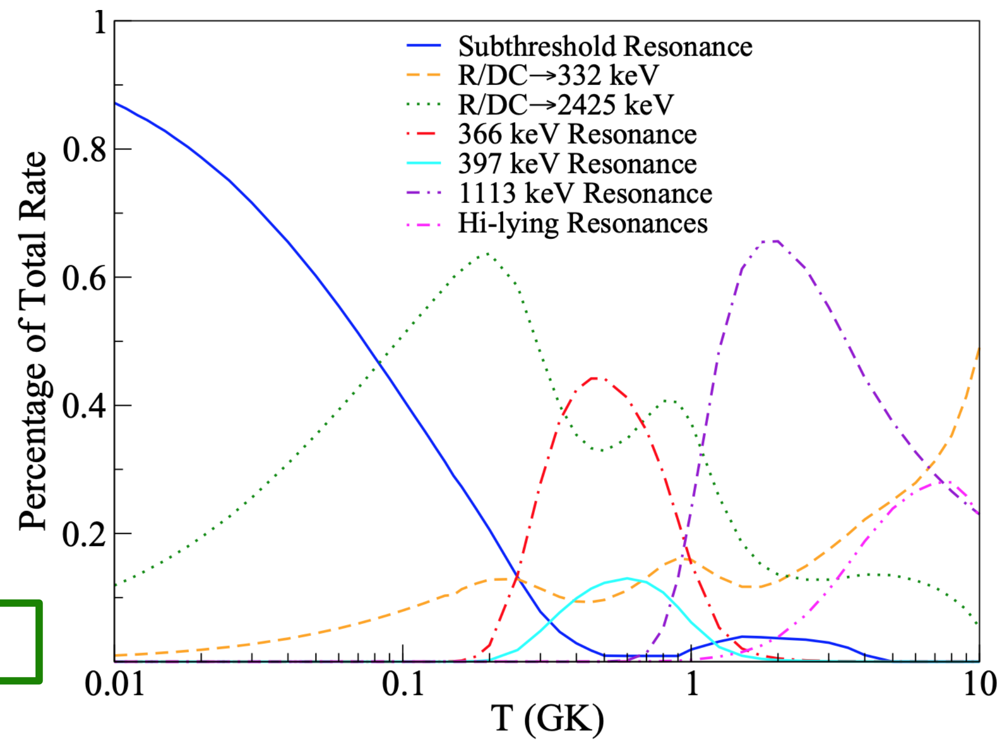
$^{20}Ne(p,\gamma)^{21}Na$ reaction – State of the art



Lyon et al., PRC 2018

- Resonance at E = 366 keV (E_x = 2797.5 keV)
- Direct capture component for E < 400 keV

Contributions to the total reaction rate



No experimental data below 400keV!

$^{20}Ne(p,\gamma)^{21}Na$ reaction – 366 keV resonance

Measurement plan:

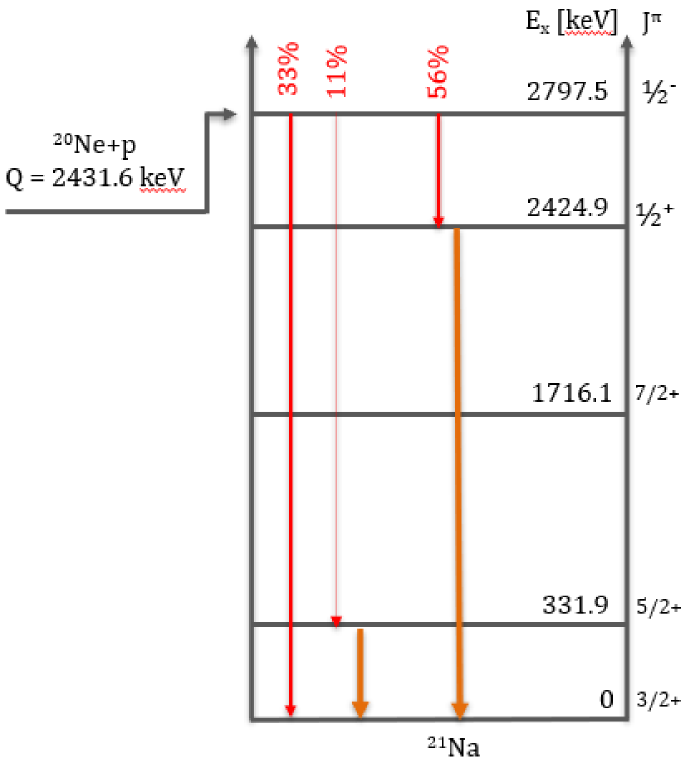
- First campaign: study of the 366 keV resonance (Ongoing)
- Second campaign: direct capture cross section E < 400 keV

$E_X = 2797.9 \pm 0.5$ keV
$E_{CM\_res} = 366.2 \pm 0.5$ keV
FWHM = 0.035 eV ($T_{1/2}$ = 13 fs)

Branchings		
Transition [keV]	Rolfs et al., 1975	Cooper (PhD thesis, 2019)
R-> 2425	56 ± 4	61.5 ± 7.3
R-> 332	11 ± 4	1.6 ± 1.1
R -> 0	33 ± 4	35.9 ± 5.3

$\omega\gamma_{Rolfs} = (0.11 \pm 0.02)$ meV

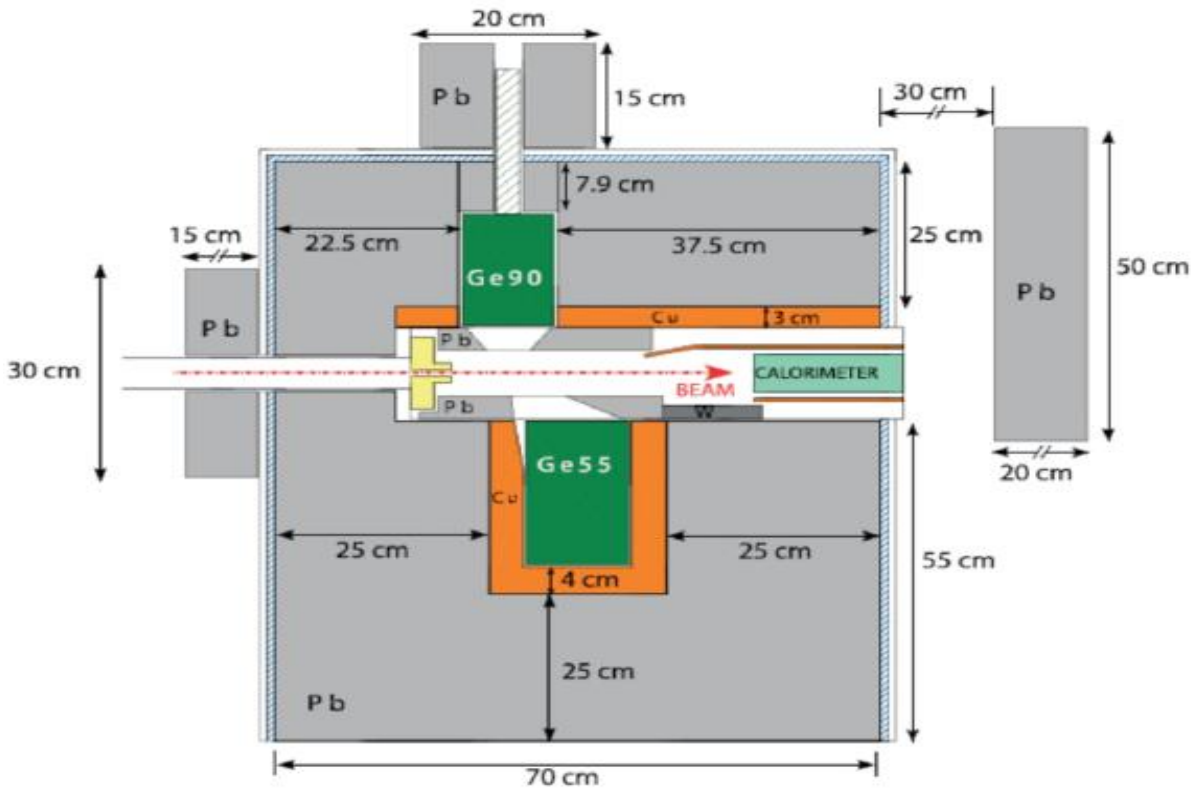
$\omega\gamma_{Cooper} = (0.072 \pm 0.0068)$ meV

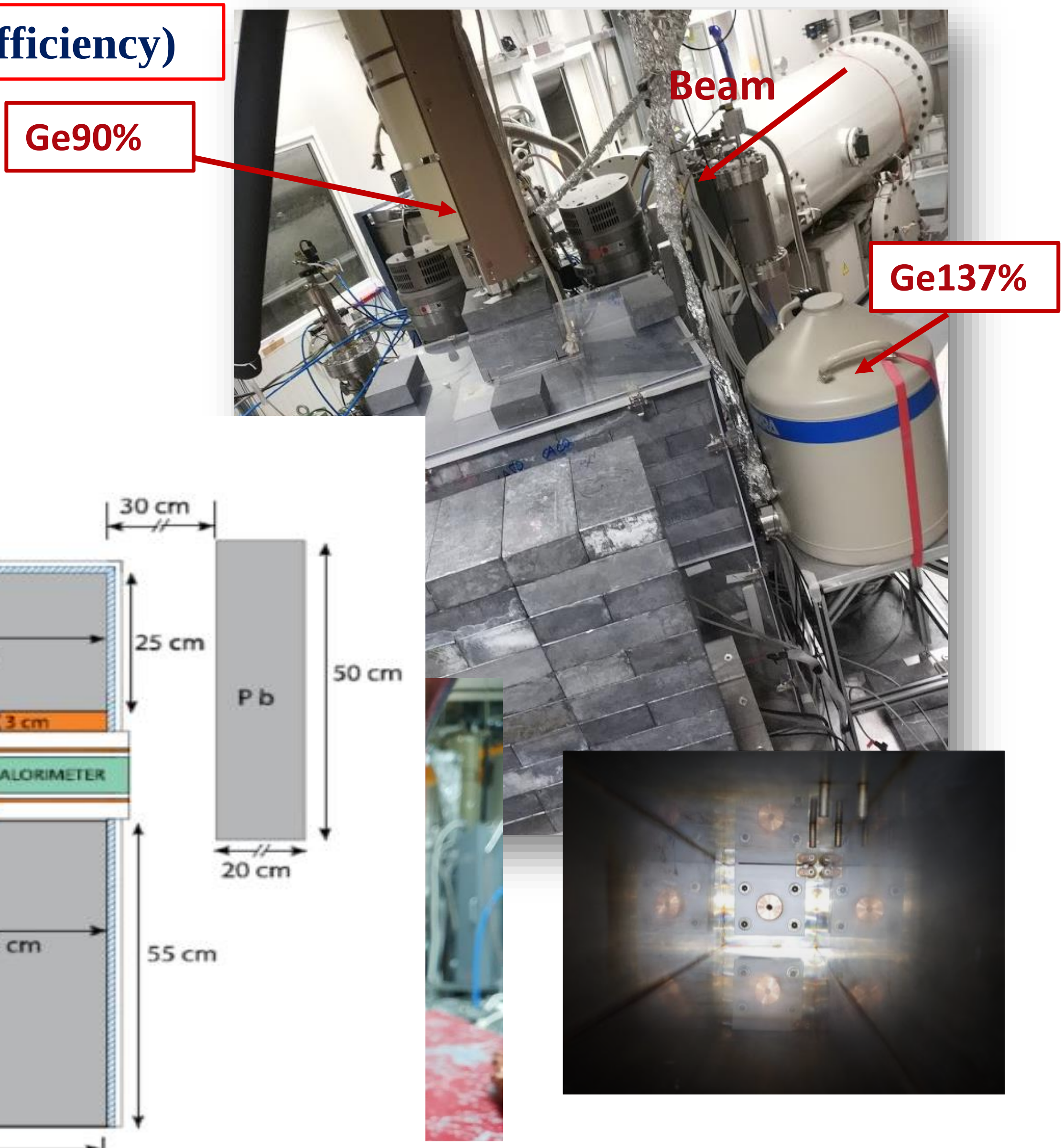


^{20}Ne(p,γ)^{21}Na reaction – Experimental setup

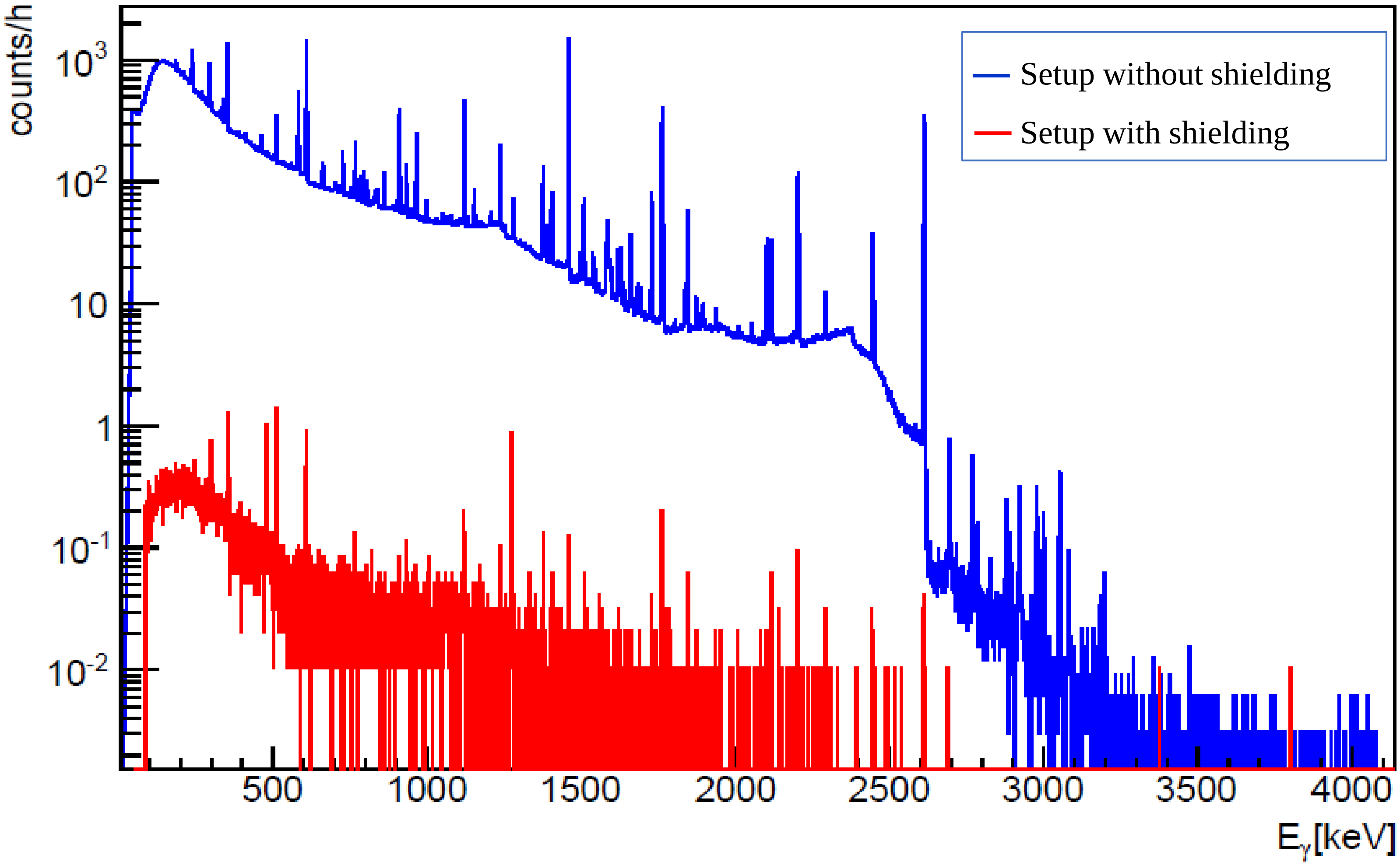
HPGe setup (High resolution, Low efficiency)

- Collimated HPGe detector:
  - 137%detector @ 55°
  - 90% detector @ 90°



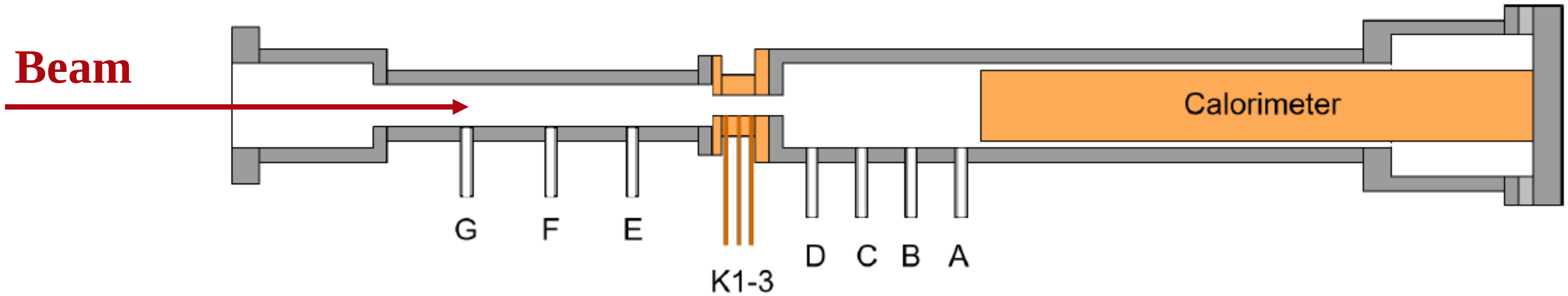


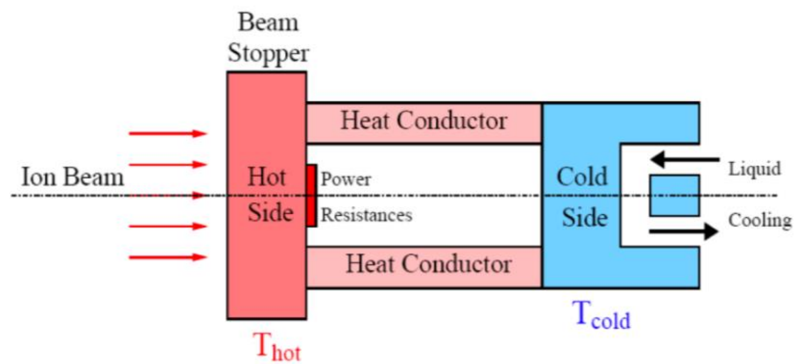
Laboratory Background with and without lead shielding



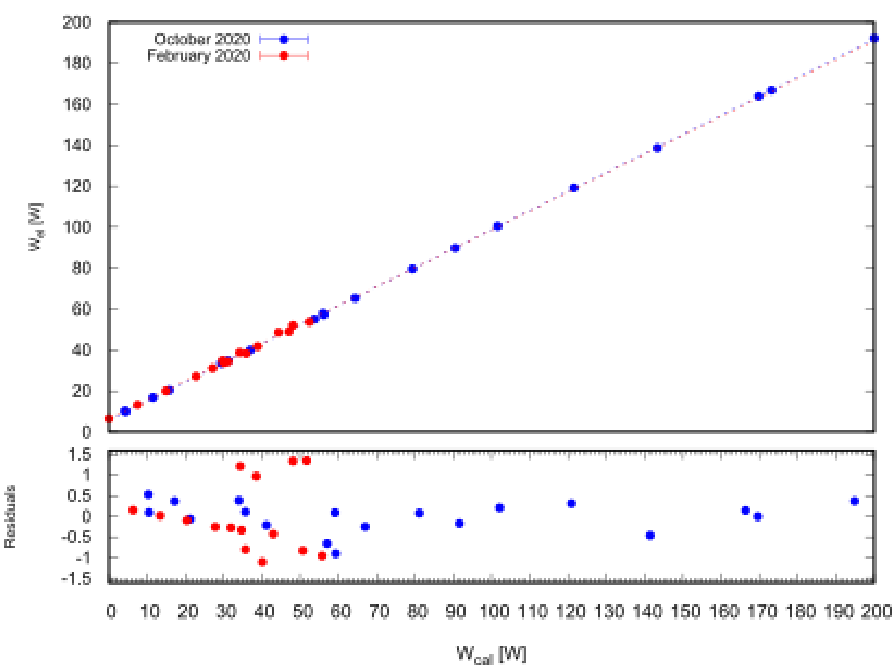
^{20}Ne(p,γ)^{21}Na reaction – 366 keV resonance

Calorimeter calibration





Cold side: -5° C
Hot site: 70° C

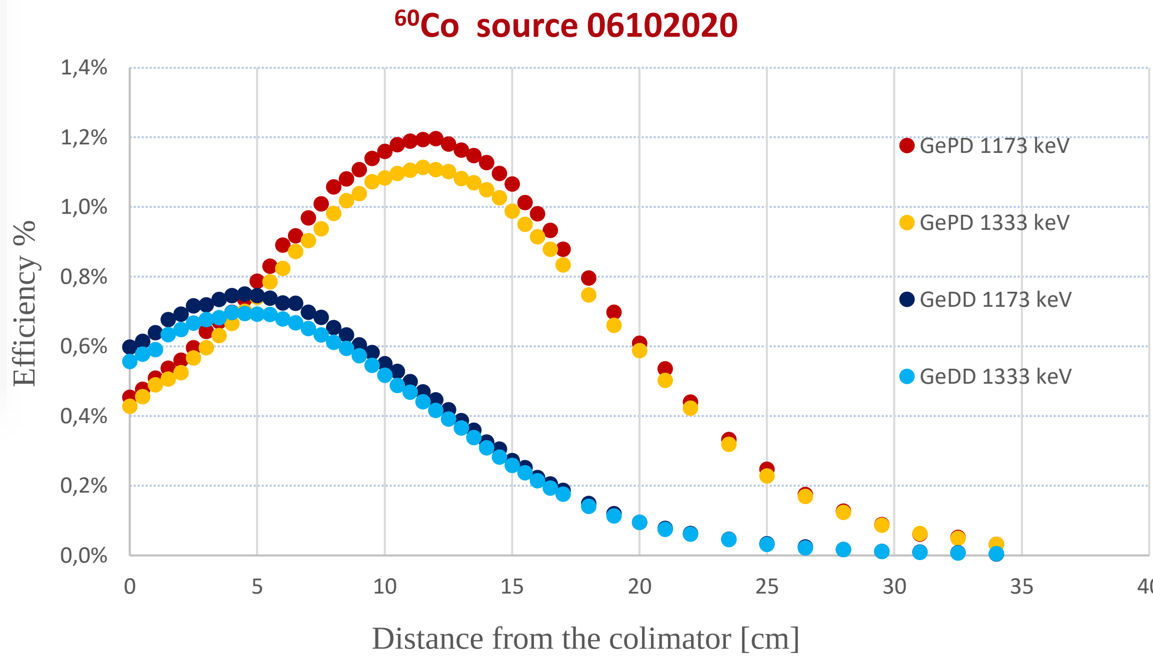


The calorimeter has been calibrated evacuating the target chamber and using the calorimeter as a Faraday cup

$^{20}Ne(p,\gamma)^{21}Na$ reaction – 366 keV resonance

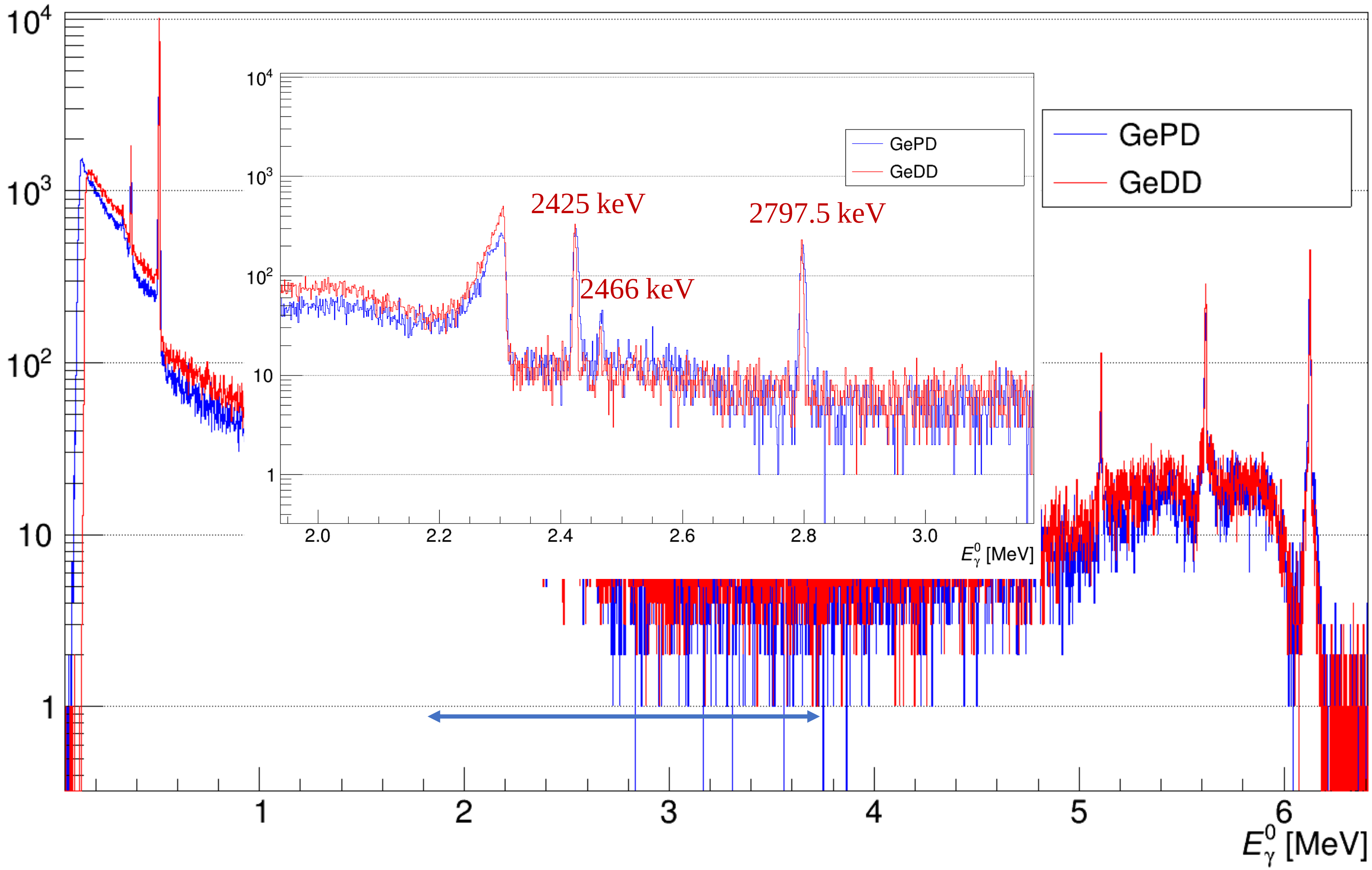
Efficiency

Calibrated radioactive sources: ^{60}Co, ^{137}Cs and the 278 keV resonance of the $^{14}N(p,\gamma)^{15}O$ reaction to determine γ- detection efficiency.



$^{20}Ne(p,\gamma)^{21}Na$ reaction – 366 keV resonance

First measurement at E_p=395 keV in 2mbar natural neon gas.

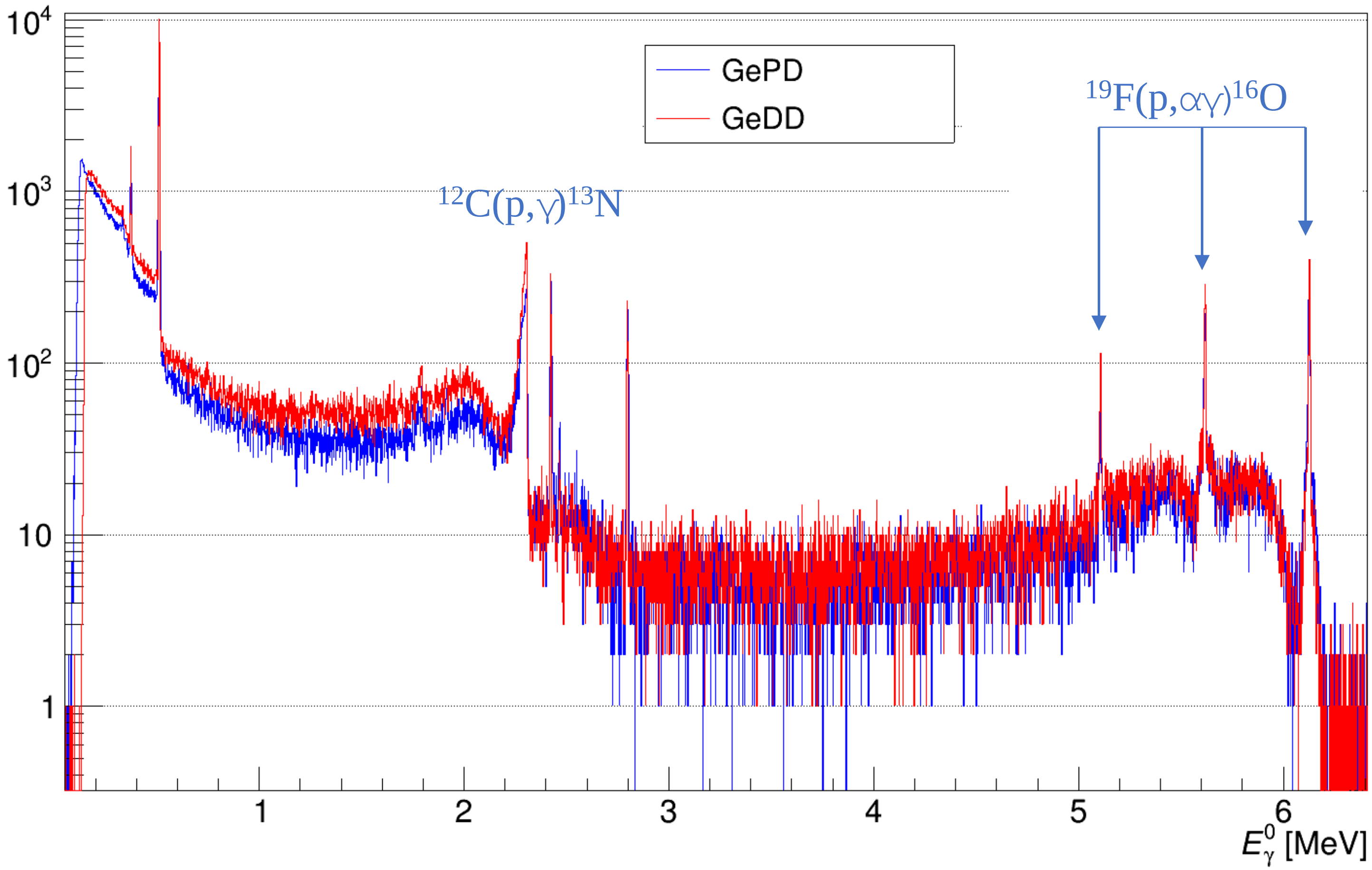


$^{20}Ne(p,\gamma)^{21}Na$ reaction – 366 keV resonance

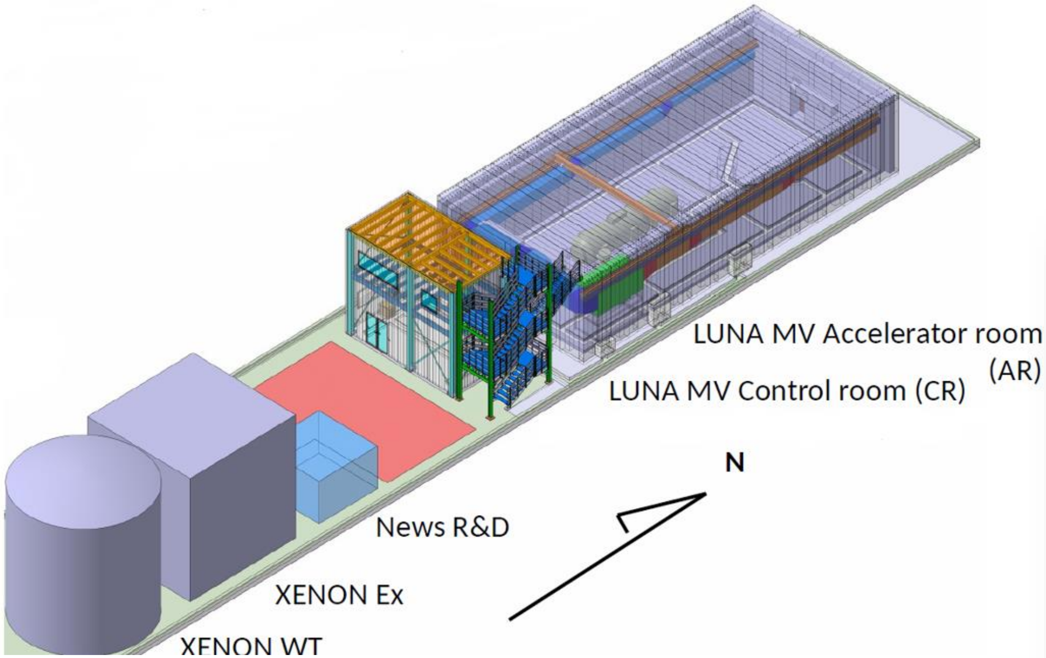
Resonance is running right now

Possible problems?

- Beam Induced Background



LUNA MV - Future



H $^{1}H^{+}$ (TV: 0.3 – 3.5 MV): 500-1000 μA

He $^{4}He^{+}$ (TV: 0.3 – 3.5 MV): 300-500 μA

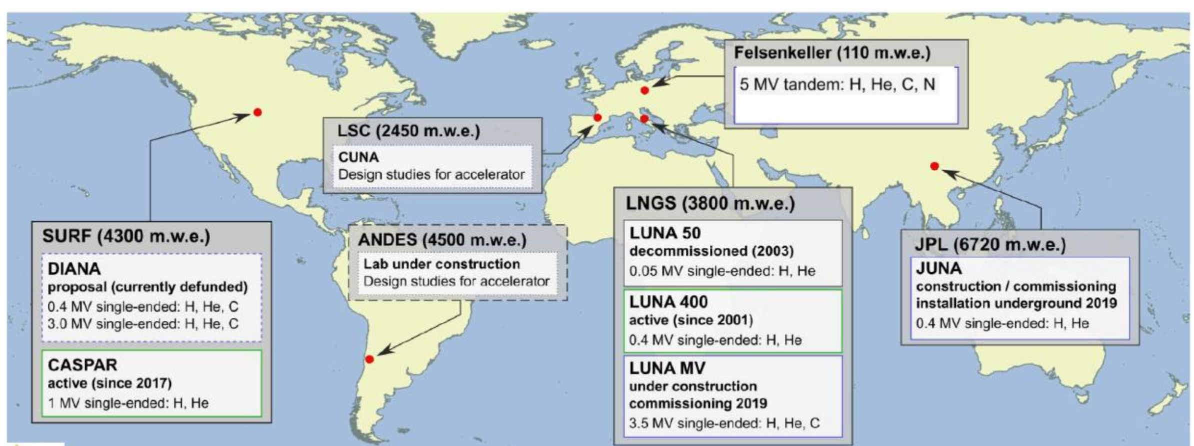
C $^{12}C^{+}$ (TV: 0.3 – 3.5 MV): 150 μA

$^{12}C^{++}$ (TV: 0.5 – 3.5 MV): 100 μA

LUNA MV - Future

- Two beamlines
- Study of helium and carbon burning
  - ❑ $^{14}N(p,\gamma)^{15}O$ → CNO bottle-neck
  - ❑ $^{12}C + ^{12}C$ → **Fate of massive stars**
  - ❑ $^{22}Ne(\alpha,n)^{25}Mg$ and $^{13}C(\alpha,n)^{16}O$ → **s-process in AGB and massive stars**

Nuclear Astrophysics Underground Laboratories



courtesy: A. Boeltzig

- Underground nuclear astrophysics at LUNA: Yestarday, today and tomorrow
- First direct measurement of the 395 keV resonance of $^{22}Ne(\alpha,\gamma)^{26}Mg$ reaction
- Study of the $^{20}Ne(p,\gamma)^{21}Na$ reaction below 400keV
- We are not alone anymore

Questions?

The LUNA collaboration

INFN Roma1, Italy: C. Gustavino, A. Formicola
HZDR Dresden, Germany: D. Bemmerer, K. Stöckel,
INFN and Università di Padova, Italy: C. Broggini, A. Caciolli, R. Depalo, P. Marigo, R. Menegazzo, D. Piatti
INFN LNGS /GSSI, Italy: A. Boeltzig, L. Csedreki, L. Di Paolo, M. Junker
MTA-ATOMKI Debrecen, Hungary: Z. Elekes, Zs. Fülöp, Gy. Gyürky, M. Takács
Konkoly Observatory, Hungarian Academy of Sciences, Hungary: M. Lugaro
INAF Teramo, Italy: O. Straniero
Università di Genova and INFN Genova, Italy: P. Corvisiero, F. Ferraro, P. Prati, S. Zavatarelli
Università di Milano and INFN Milano, Italy: A. Guglielmetti, E. Masha
Università di Napoli and INFN Napoli, Italy: A. Best, G.F. Ciani, A. Di Leva, G. Imbriani
Università di Torino and INFN Torino, Italy: F. Cavanna, G. Gervino, P. Colombetti
University of Edinburgh, United Kingdom: M. Aliotta, C.G. Bruno, T. Chillery, T. Davinson
Università di Bari and INFN Bari, Italy: F. Barile, V. Paticchio, L. Schiavulli, R. Perrino

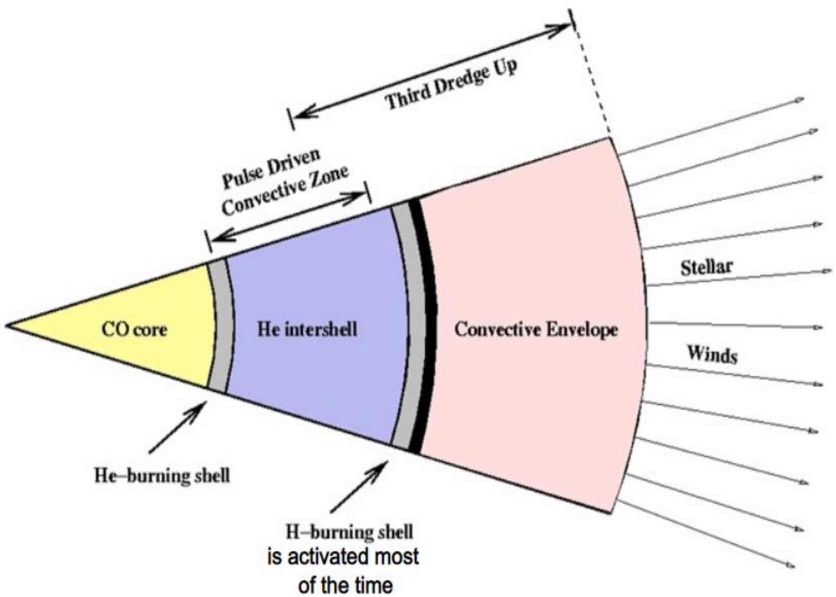
"Some people are so crazy that they actually venture into deep mines to observe the stars in the sky"
Naturalis Historia – Pliny, 44 A.D

Thank you!

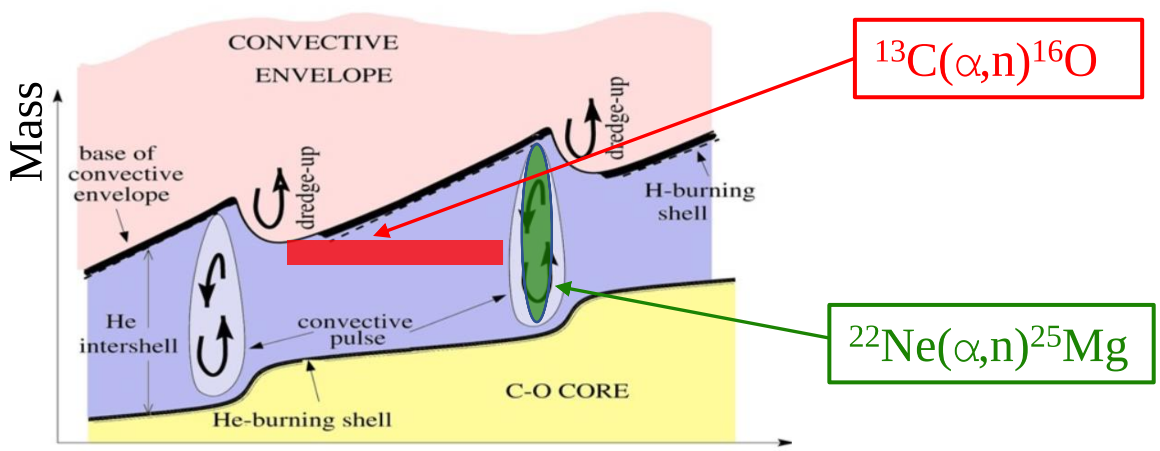
Info: eliana.masha@unimi.it
alessandra.guglielmetti@mi.infn.it

Extra Slide

AGB stars and the slow neutron capture process



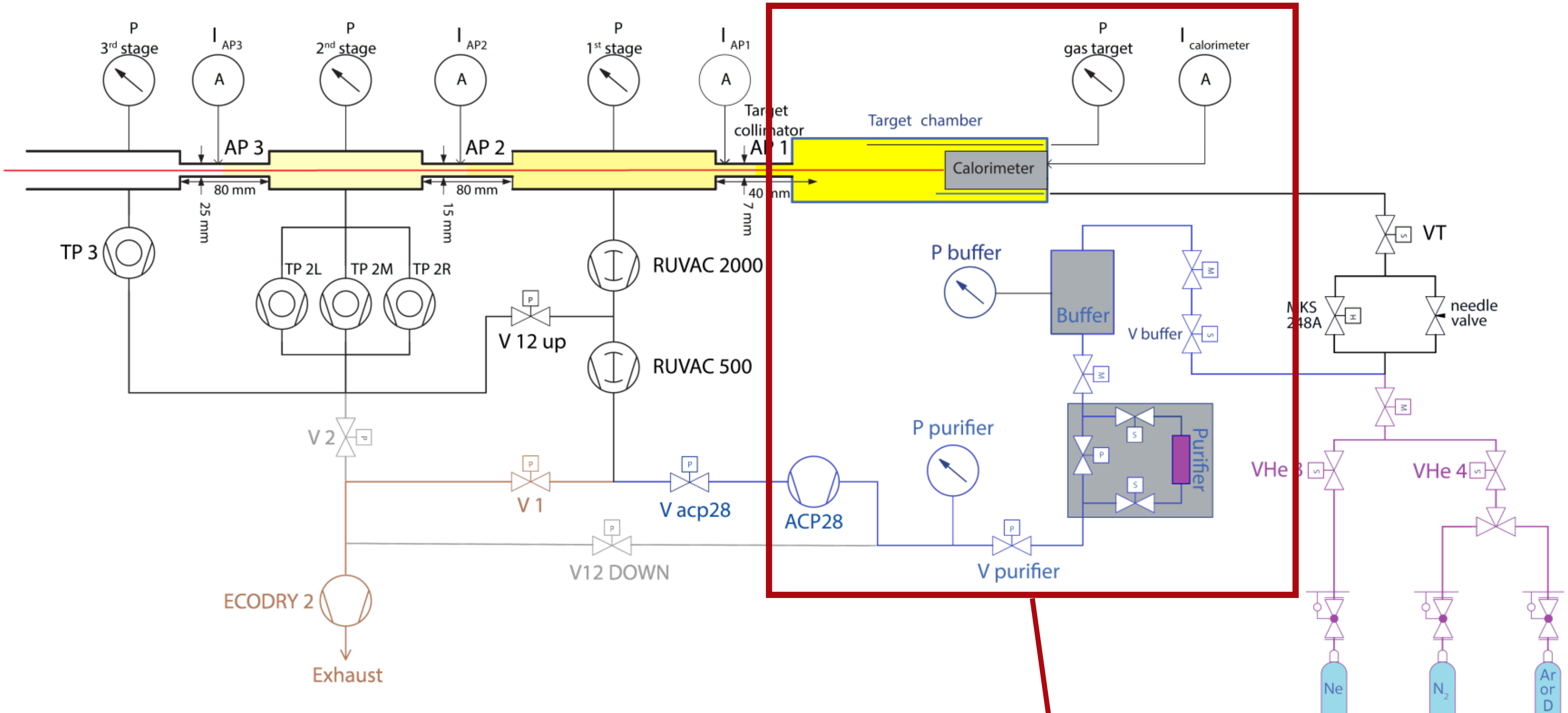
- Thermally pulsing stage (TP)
- Temperatures in the base of the convective zone sufficiently high to ignite the $^{22}Ne(\alpha,n)^{25}Mg$ reaction
- ^{22}Ne produced via $^{14}N(\alpha,\gamma)^{18}F(\beta^{+}\nu)^{18}O(\alpha,\gamma)^{22}Ne$



Low mass AGB stars (~4M$_\odot$)
Lower temperature
In between pulses

Intermediate mass AGB stars
Higher temperature
During thermal pulses

Windowless gas target used at LUNA



Recirculation if needed