Stellar helium burning studied at LUNA-MV

$^{14}N(\alpha,\gamma)^{18}F$
$^{15}N(\alpha,\gamma)^{19}F$
$^{16}O(\alpha,\gamma)^{20}Ne$
$^{18}O(\alpha,\gamma)^{22}Ne$

LUNA-MV round table, Assergi 10.-11.02.2011

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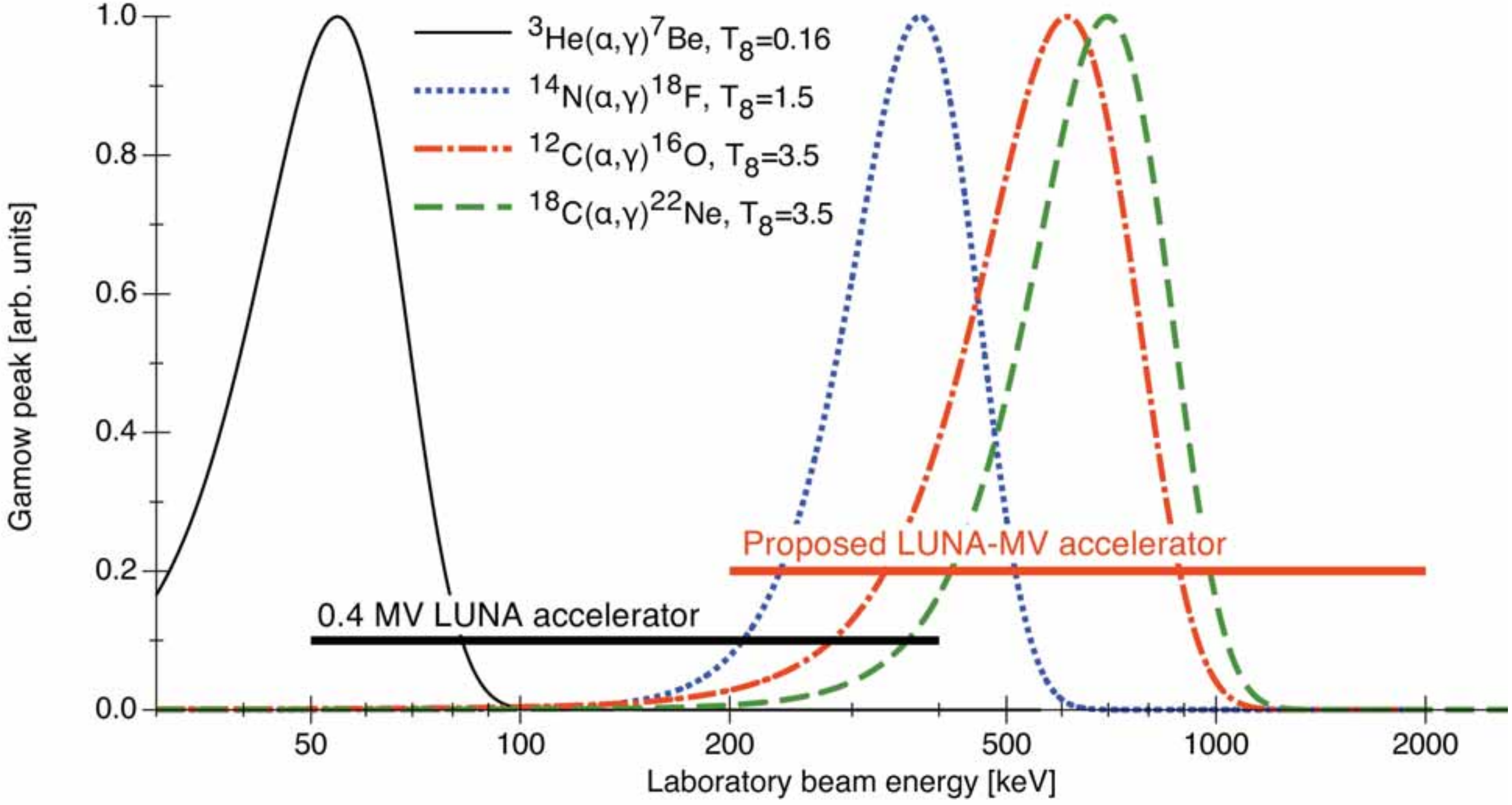
Stellar helium burning studied at LUNA-MV

- Science case, stellar helium burning
- Example of a completed (α,γ) study: $^{3}He(\alpha,\gamma)^{7}Be$ at LUNA-0.4 MV
- Exciting adventures besides the Holy Grail
  - $^{14}N(\alpha,\gamma)^{18}F$
  - $^{15}N(\alpha,\gamma)^{19}F$
  - $^{16}O(\alpha,\gamma)^{20}Ne$
  - $^{18}O(\alpha,\gamma)^{22}Ne$

Gamow peaks for helium burning reactions



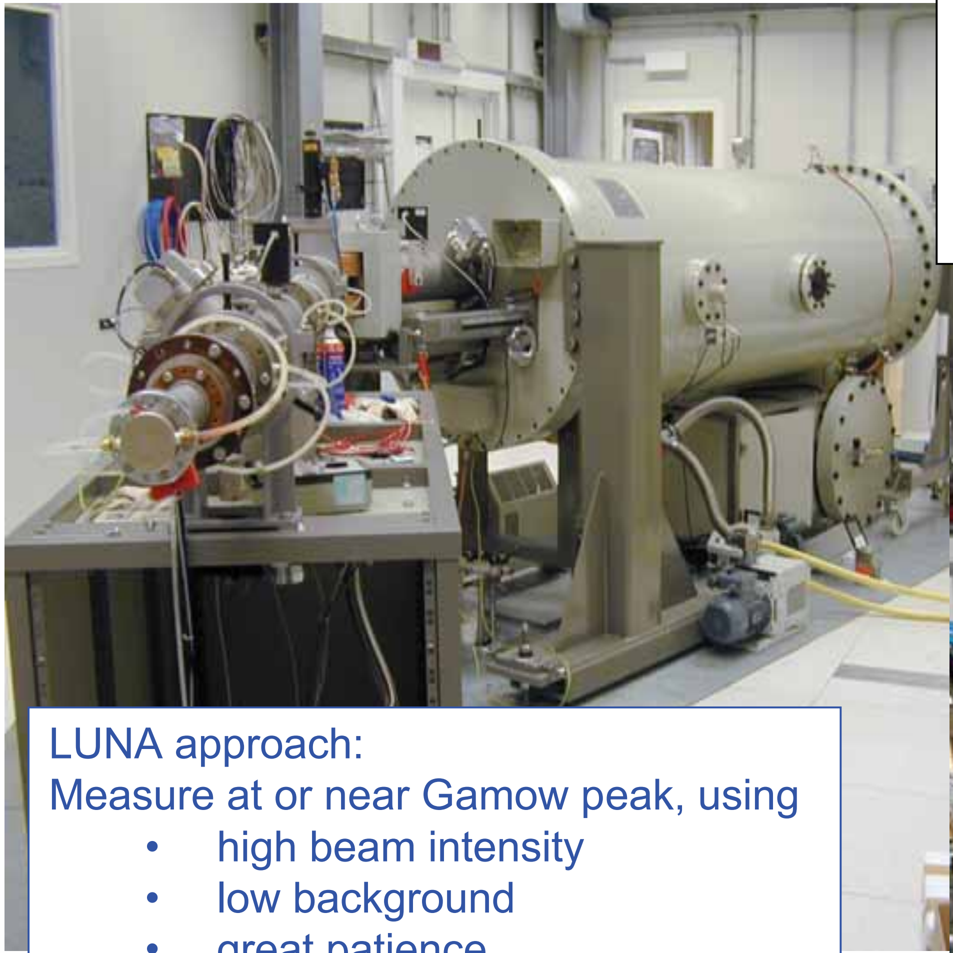
Gas target setup at the LUNA 0.4 MV accelerator

Windowless gas target, 3 pumping stages:

1. Two Roots pumps
2. Three 1500 l/s turbomolecular pumps
3. One 350 l/s turbomolecular pump

Two options for γ-ray detection:

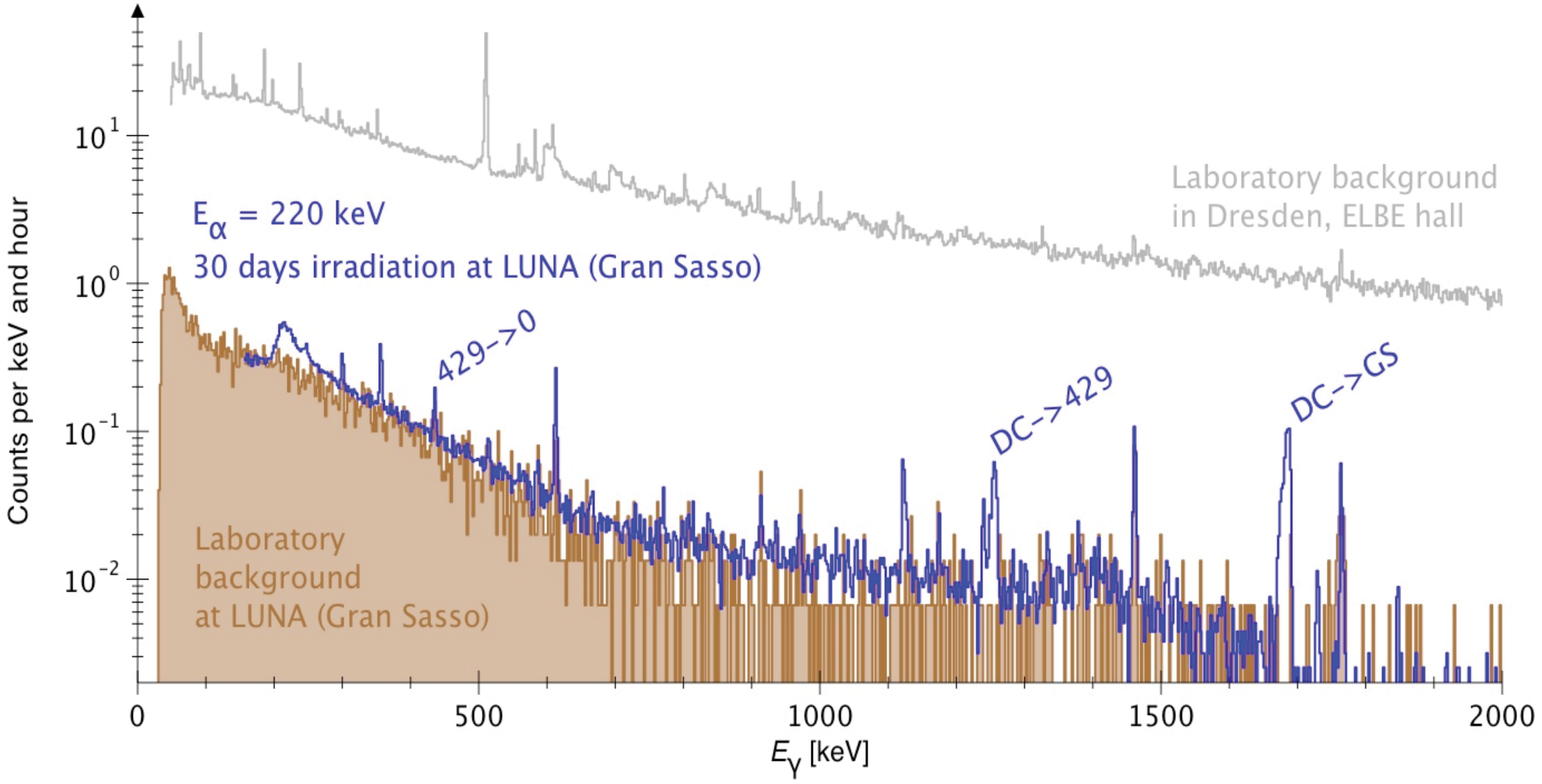
a. HPGe detector, lead + copper shielding
b. BGO borehole detector, ~70% efficiency



LUNA approach:
Measure at or near Gamow peak, using

- high beam intensity
- low background
- great patience

^{3}He(α,γ)^{7}Be experiment at LUNA-0.4 MV, prompt-γ spectrum



Stellar helium burning

- Core helium burning, and shell hydrogen burning
- Not only ^{12}C, but also ^{14,15}N are found and can be burnt by α-capture processes
- Besides the “holy grail” reaction, also some other interesting reactions are found:
    - $^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F}$
    - $^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$
    - $^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$
    - $^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne}$
- Consequences for the production of neutrons, via

$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F} \rightarrow {}^{18}\mathrm{O}(\alpha,\gamma)^{22}\mathrm{Ne} \rightarrow {}^{22}\mathrm{Ne}(\alpha,n)^{25}\mathrm{Mg}$

- Consequences for the production of fluorine, via

$^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$

$^{14}\mathrm{N}(\alpha,\gamma)^{18}\mathrm{F} \rightarrow {}^{18}\mathrm{O}(p,\alpha)^{15}\mathrm{N} \rightarrow {}^{15}\mathrm{N}(\alpha,\gamma)^{19}\mathrm{F}$

- Consequences for escape from main helium burning, via

$^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$

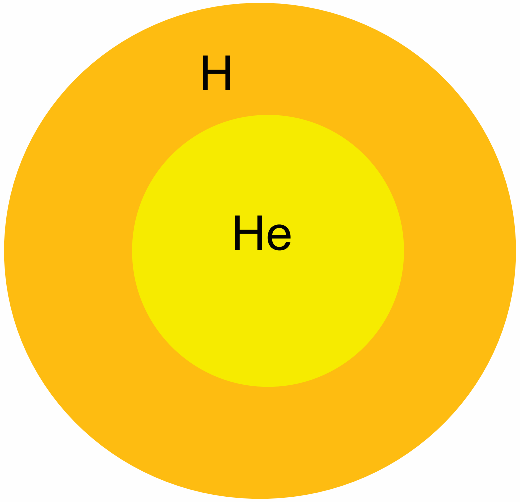
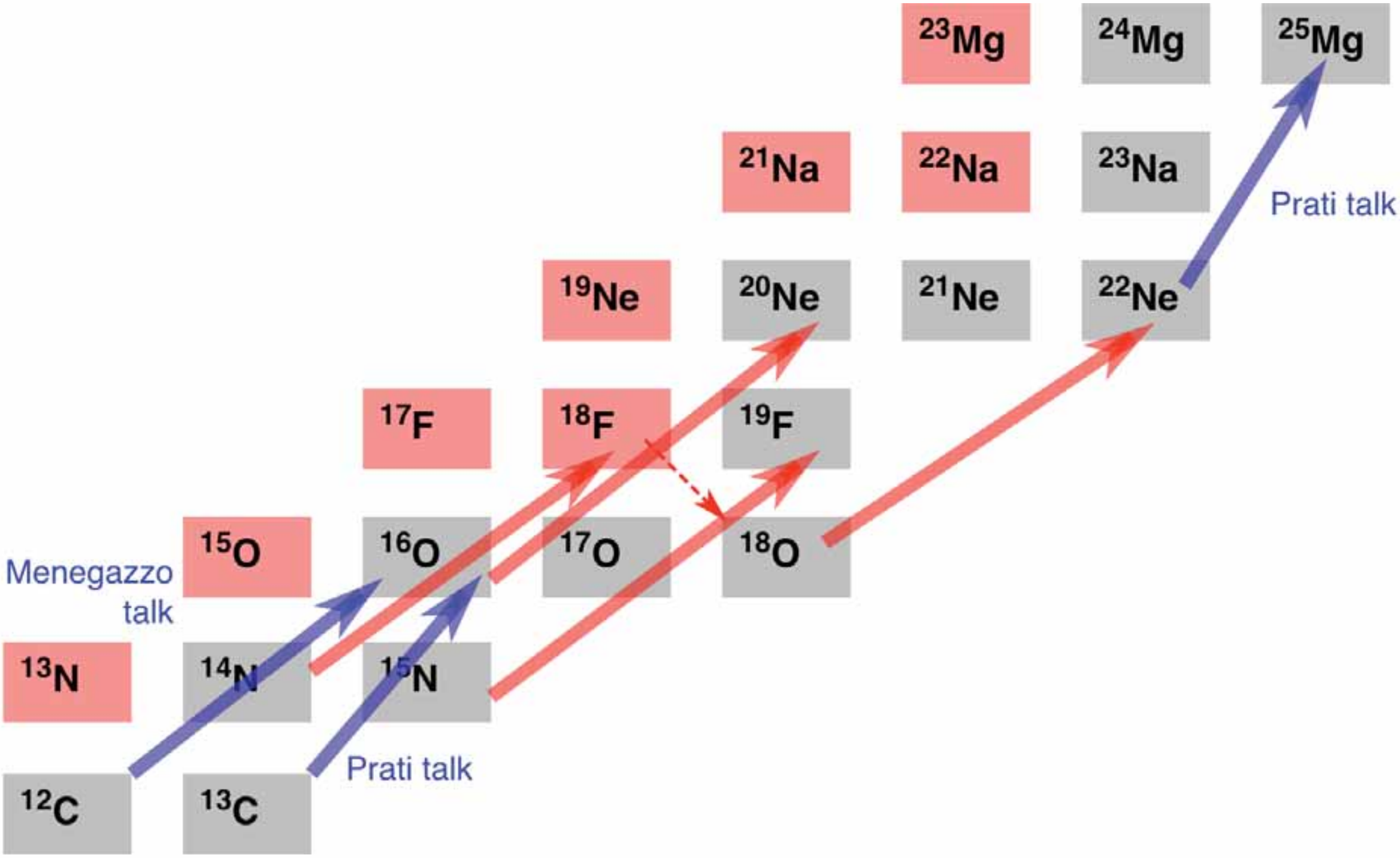


Chart of nuclides, view of helium burning reactions

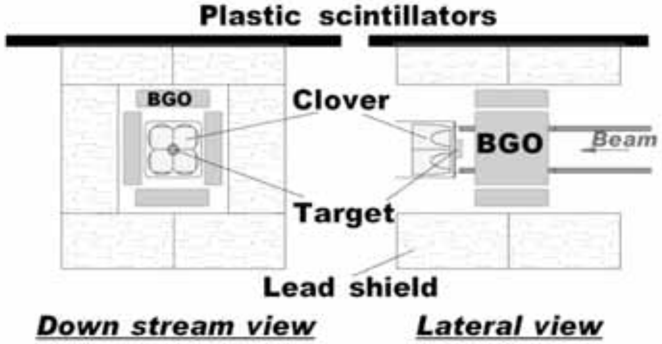


The $^{18}O(\alpha,\gamma)^{22}Ne$ reaction (1)

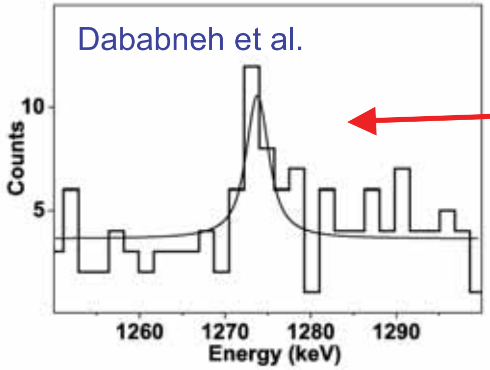
- Q-value = 9.668 MeV; neutron threshold at $E_\alpha = 0.851$ MeV

- Best previous experiment in Karlsruhe:
  S. Dababneh et al., Phys. Rev. C 68, 025801 (2003)
- 70 µA α-beam intensity, $Al_2{}^{18}O_3$ targets
- Setup with passive and active shielding
- Study of resonance strengths

- Lowest resonance seen only in decay of first excited state in ^{22}Ne, assumed 50% branching



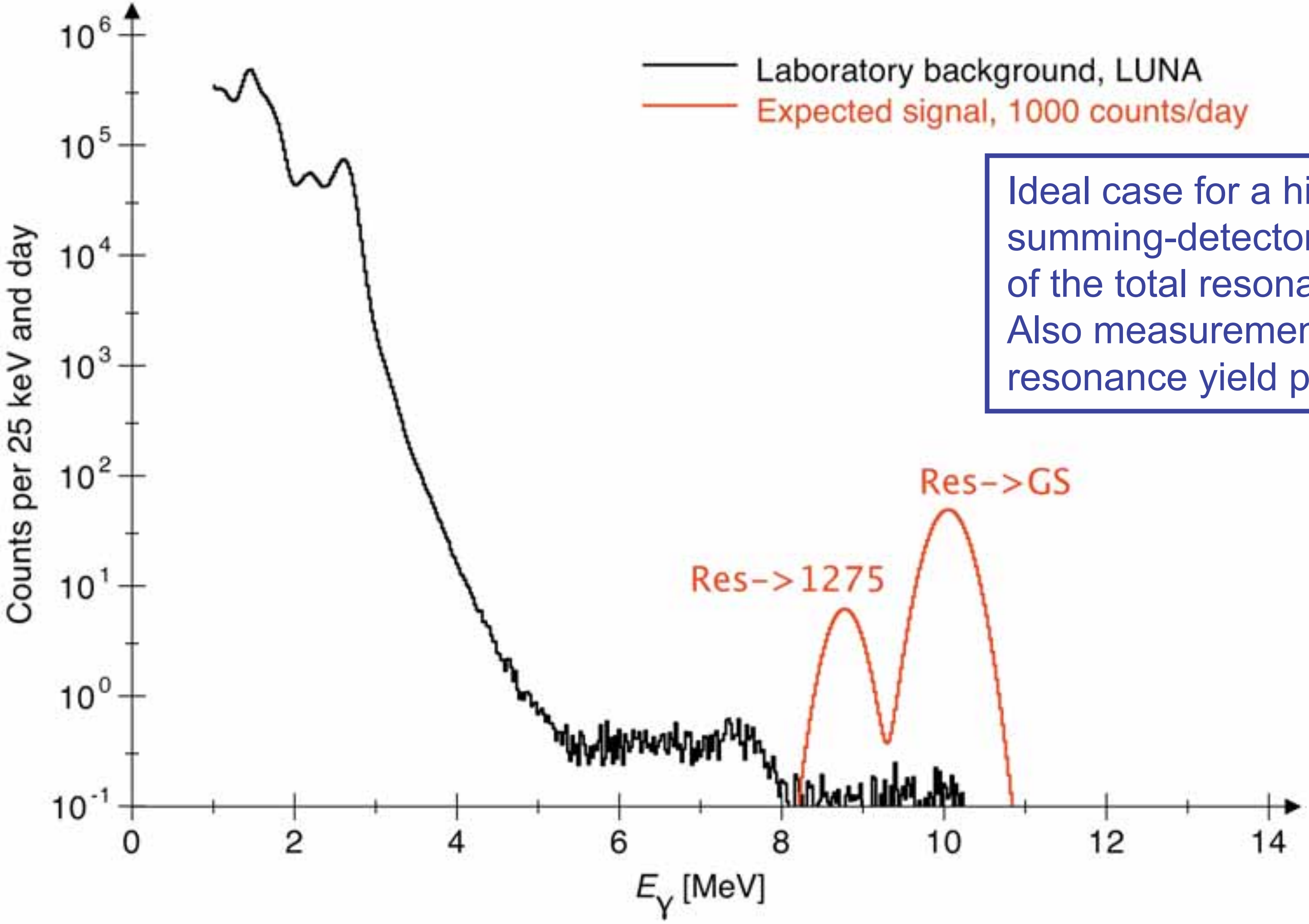
Dababneh et al.



Resonance energy (keV)	$\omega\gamma_{partial}$ (μeV) Dababneh 2003	$\omega\gamma$ (μeV) Dababneh 2003	$\omega\gamma$ (μeV) NACRE [24]
470	0.24±0.08	0.48±0.16	0.6
566	0.63±0.09	0.71±0.17	0.01
660		229±19	239±23
750		490±40	530±50

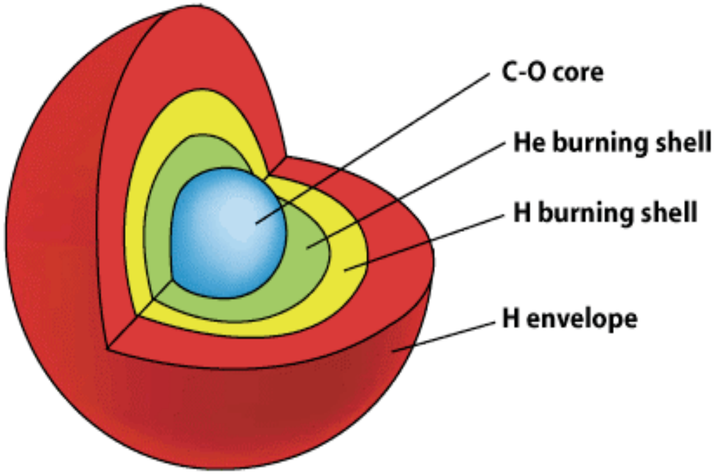
The $^{18}O(\alpha,\gamma)^{22}Ne$ reaction (2)

- *Q*-value = 9.668 MeV; (α,n) threshold at E_α = 0.851 MeV
- 24 hours at 250 µA beam, existing LUNA BGO detector, E_α=470 keV, $Al_2{}^{18}O_3$ targets:



Ideal case for a high-precision summing-detector measurement of the total resonance strength! Also measurement / limit of off-resonance yield possible.

Production of the chemical element fluorine



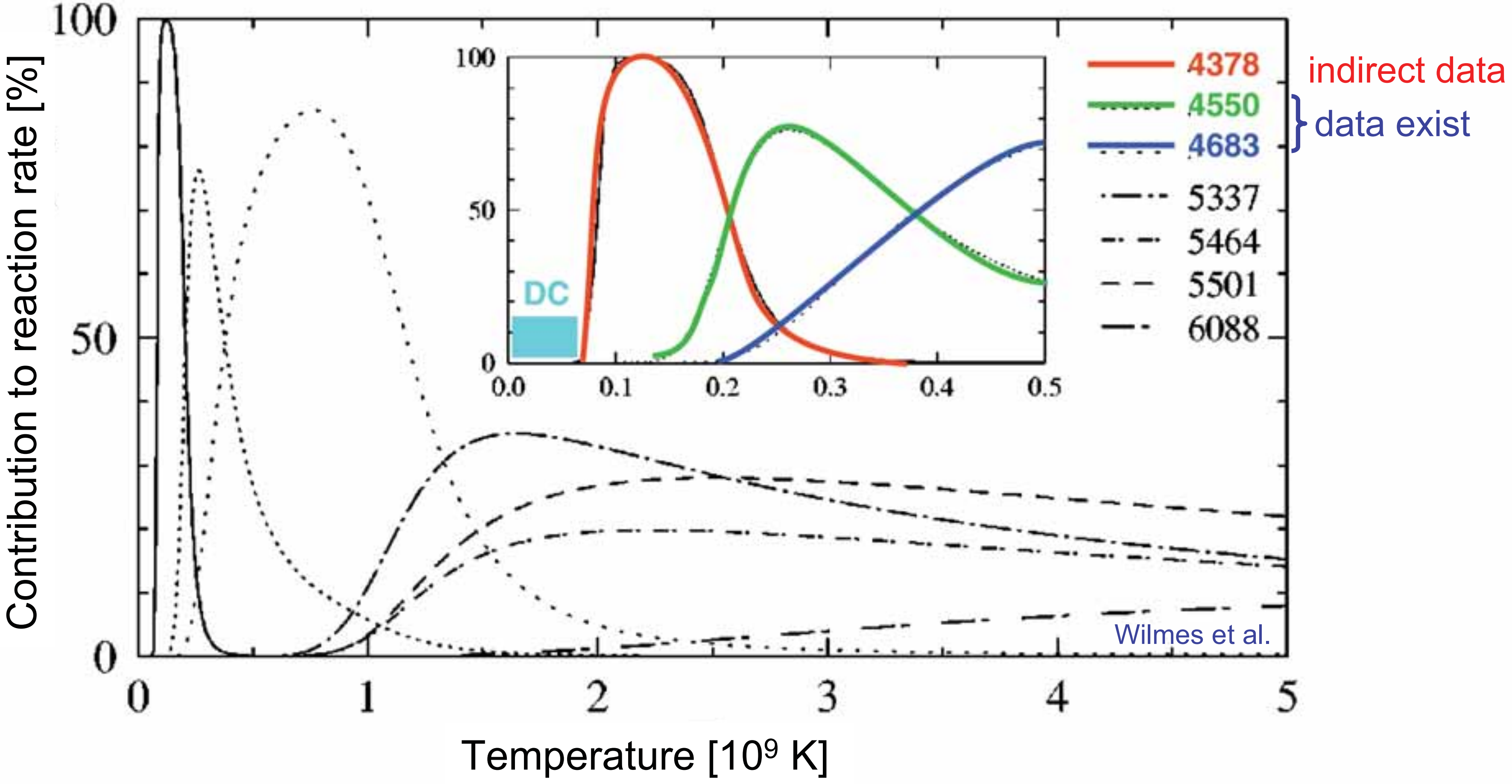
Production of ^{19}F

- Supernovae
- Wolf-Rayet stars
- Asymptotic Giant Branch (AGB) stars

Solar system	A(^{19}F) = $4 * 10^4$	Asplund, Grevesse & Sauval 2005
AGB stars	A(^{19}F) = $9 * 10^7$	Werner, Rauch & Kruk 2005 recently much lower values: Abia et al. 2010
Primitive star, [Fe/H]= -2.5	A(^{19}F) = $9 * 10^4$	Schuler et al. 2007

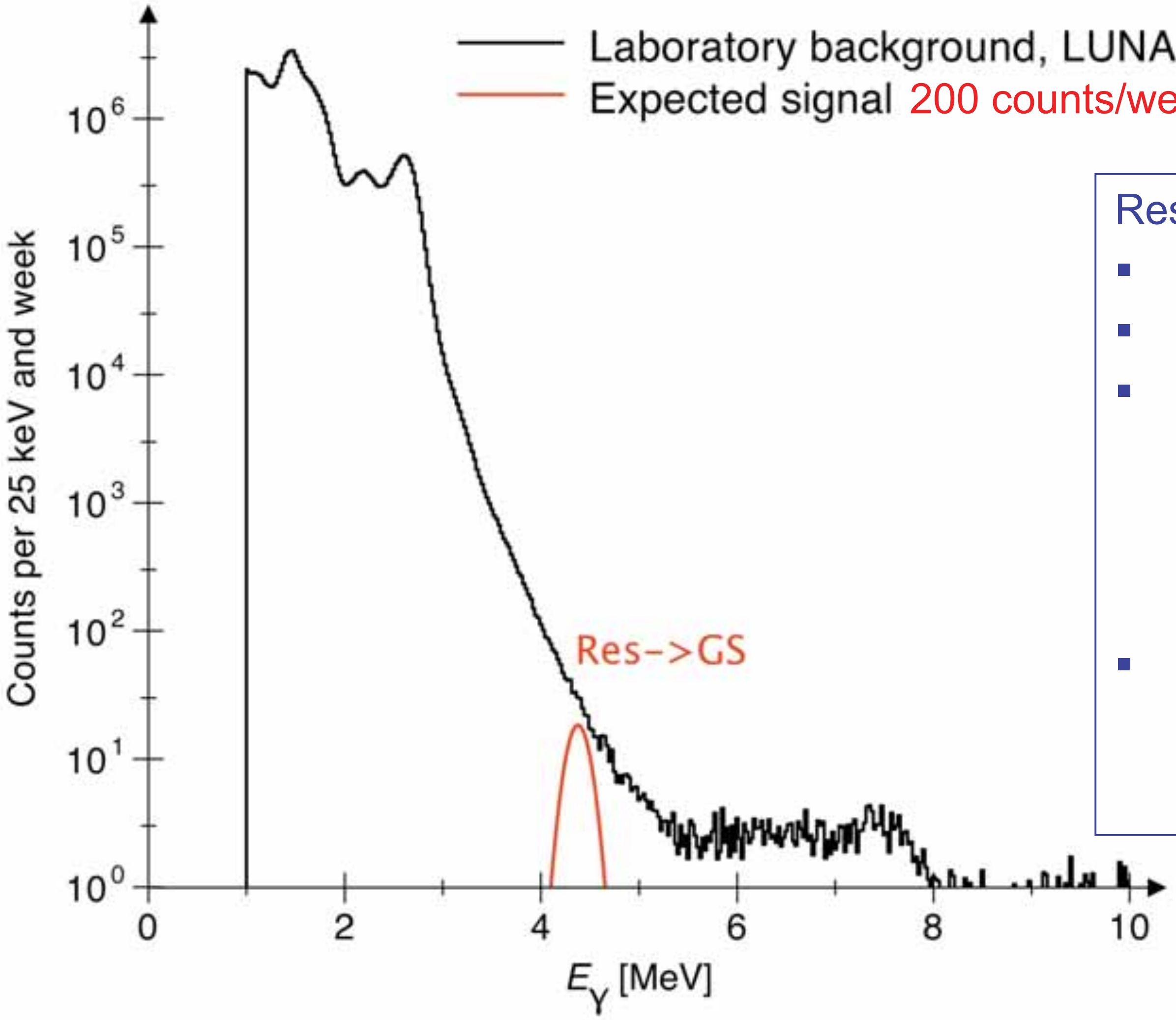
The $^{15}N(\alpha,\gamma)^{19}F$ reaction (1), important for ^{19}F nucleosynthesis

- *Q*-value = 4.014 MeV
- Best previous experiment in Stuttgart: S. Wilmes et al., Phys. Rev. C 66, 065802 (2002)
- 120 μA α-beam intensity, Rhinoceros gas target, study of resonance strengths
- Lowest resonance strength only deduced indirectly: Level at E_x=4378 keV



The $^{15}N(\alpha,\gamma)^{19}F$ reaction (2)

- *Q*-value = 4.014 MeV
- 6 neV strength of the E_α=461 keV resonance, from indirect studies, ^{15}N gas target
- 250 µA α-beam intensity, existing LUNA BGO summing detector



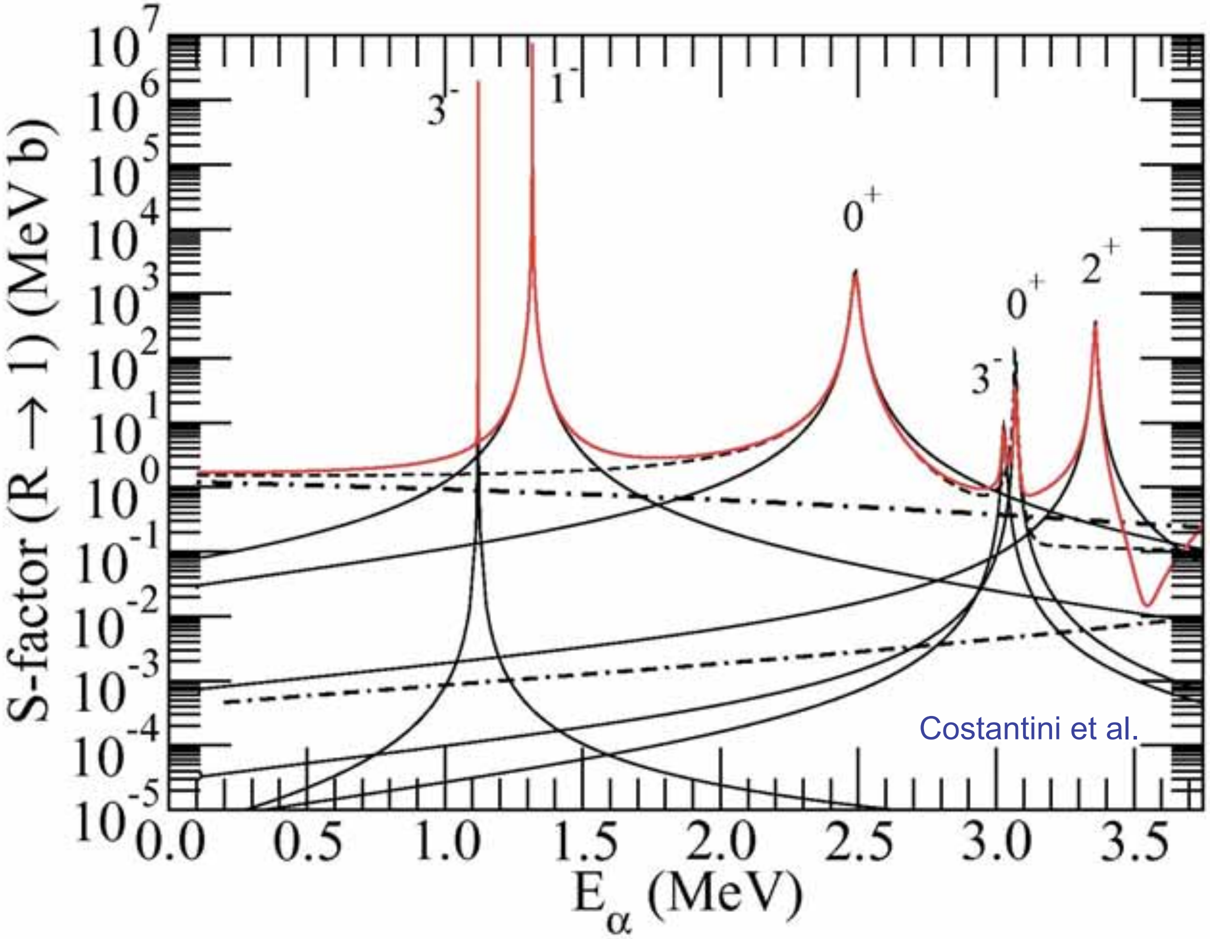
Research & development needed:

- Reduction of pile-up
- Lead shielding of detector
- Purity of gas in beam drift tubes, in order to limit H^+ in He^+ beam to 10^{-8}, to avoid $^{15}N(p,\alpha\gamma)^{12}C$ contaminant

- If successful, precisely understand this way of ^{19}F production by experiment

The $^{16}O(\alpha,\gamma)^{20}Ne$ reaction (1) *...not included in 2007 LUNA-MV LOI*

- *Q*-value = 4.734 MeV
- Cross section is so low that it terminates main helium burning
- Best previous experiment in Stuttgart and Notre Dame, plus R-matrix fit:
  H. Costantini et al., Phys. Rev. C 82, 035802 (2010)
- Notre Dame: 150 μA α-beam intensity, anodized Ta_2O_5 targets

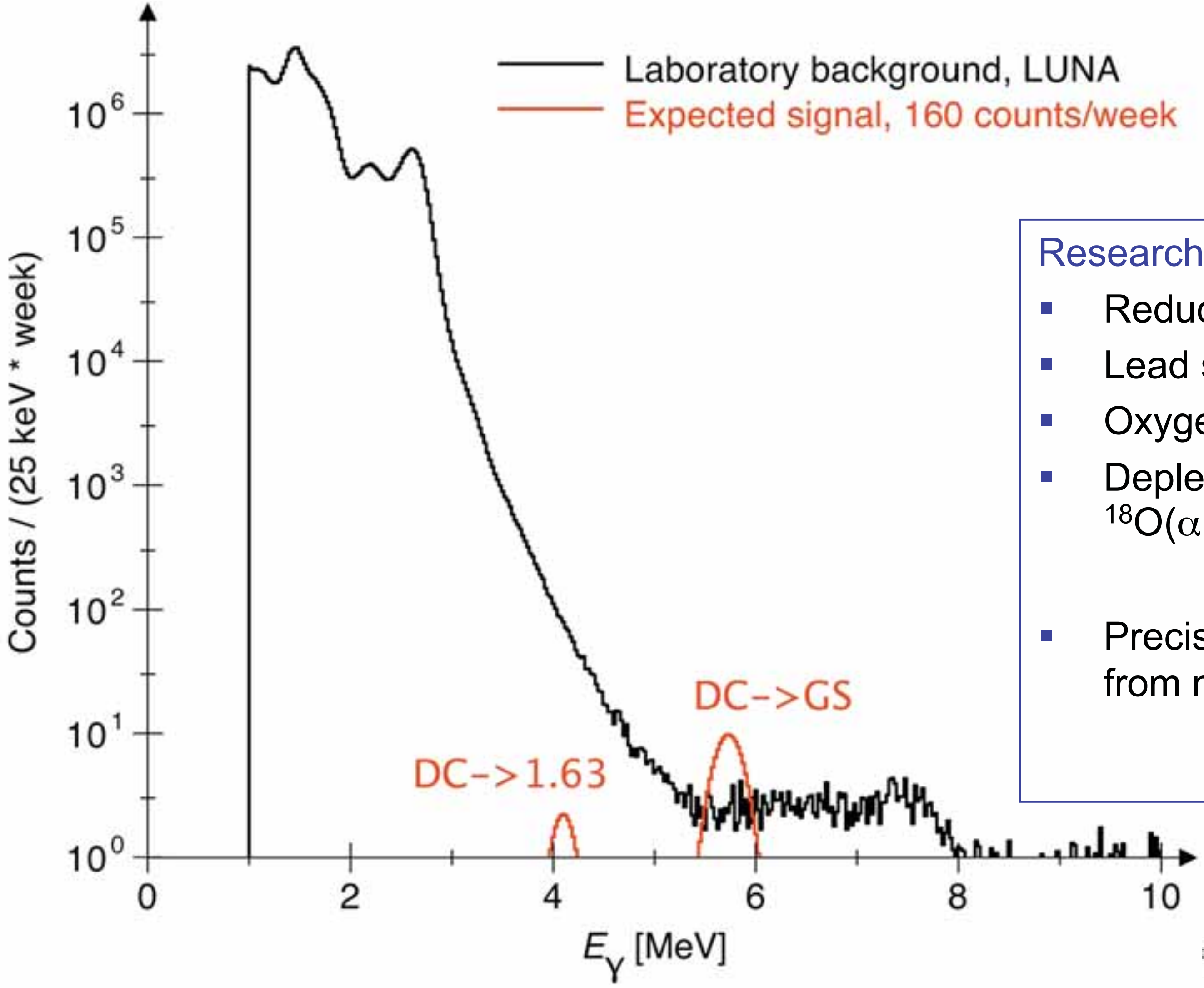


Costantini et al.

- Complicated fit including many nodes
- Gamow peak below 1 MeV α-energy

The $^{16}O(\alpha,\gamma)^{20}Ne$ reaction (2)

- One off-resonance data point at E_α=1 MeV, just below the lowest resonance
- assume 250 µA α-beam intensity, ^{16}O gas target of 6 ·10^{17} atoms/cm^2



Research & development needed:

- Reduction of pile-up
- Lead shielding of detector
- Oxygen gas target
- Depletion in ^{18}O, to avoid $^{18}O(\alpha,n)$ for E_α>0.86 MeV

- Precisely calibrate breakout from main helium burning.

Summary, helium burning reactions for LUNA-MV

- Helium-burning reactions play an important role in setting the stage for the astrophysical s-process, and for the synthesis of ^{19}F

- Ample experience with α-capture reactions at the existing LUNA accelerator

- Experiments on the ^{14}N(α,γ)^{18}F, ^{15}N(α,γ)^{19}F, ^{16}O(α,γ)^{20}Ne, and ^{18}O(α,γ)^{22}Ne reactions
would be feasible at a LUNA-MV accelerator,
and would provide visible benefit to the astrophysical community

- Like the knights of King Arthur's Round Table
searching for the Holy Grail,

  the knights of the LUNA-MV Round Table
searching for ^{12}C(α,γ)^{16}O....

  ...may find also other interesting challenges on the way there!