Underground cross section measurements of stellar reactions at astrophysically relevant energies

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Laboratory Underground Nuclear Astrophysics

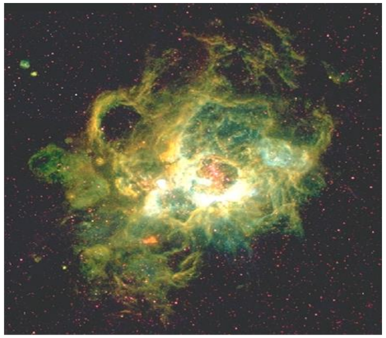
Stellar life cycle

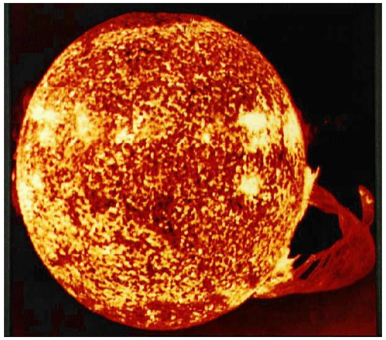
BIRTH
gravitational contraction

Interstellar gas

Stars

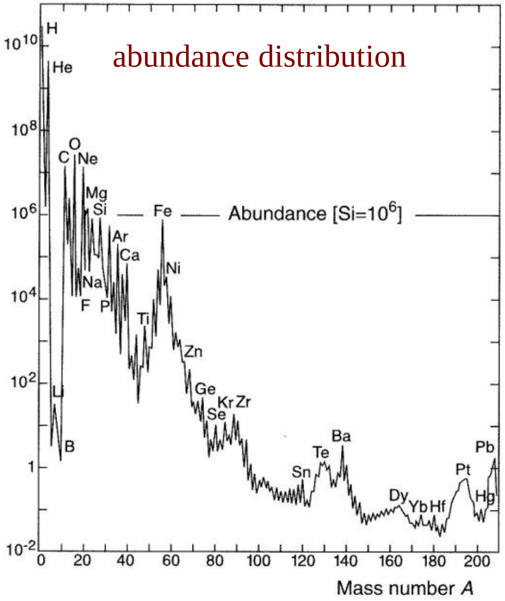
mixing of interstellar gas





thermonuclear reactions

explosion
DEATH



Accurate nuclear physics information is crucial for understanding of stars

How do other stars produce energy?
How do they evolve?

Some astrophysical motivations

✧**Solar neutrinos**:

$^{3}He(\alpha,\gamma)^{7}Be$, $^{7}Be(p,\gamma)^{8}B$ and **$^{14}N(p,\gamma)^{15}O$**

reaction	S(0) [keV b] Solar Fusion I 1998	S(0) [keV b] Solar Fusion II 2010
$p(p,e^{+}\nu_{e})d$	$(4.01 \pm 0.02)*10^{-22}$	$(4.01 \pm 0.04)*10^{-22}$
$^{3}He(^{3}He,2p)^{4}He$	$(5.4 \pm 0.4)*10^{3}$	$(5.21 \pm 0.27)*10^{3}$
$^{3}He(\alpha,\gamma)^{7}Be$	(0.53 ± 0.05)	(0.56 ± 0.03)
$^{3}He(p,e^{+}\nu_{e})^{4}He$	$2.3*10^{-20}$	$(8.6 \pm 2.6)*10^{-20}$
$^{7}Be(p,\gamma)^{8}B$	$0.019_{-0002}^{+0.004}$	$(2.08 \pm 0.16)*10^{-2}$
$^{14}N(p,\gamma)^{15}O$	$3.5_{-1.6}^{+0.4}$	1.66 ± 0.12

Neutrino fluxes of $\Phi(^{13}N)$ and $\Phi(^{15}O)$ depend almost linearly on $S_{14}(0)$

CNO neutrino flux decreases a factor ≈ 2, after LUNA $^{14}N(p,\gamma)^{15}O$ meaurements
(Peña-Garay and Serenelli arXiv:0811.2424v1)

Some astrophysical motivations

✧**Age of Globular Clusters:**

$^{14}N(p,\gamma)^{15}O$

Globular Cluster age increases of 0.7 – 1 Gyr

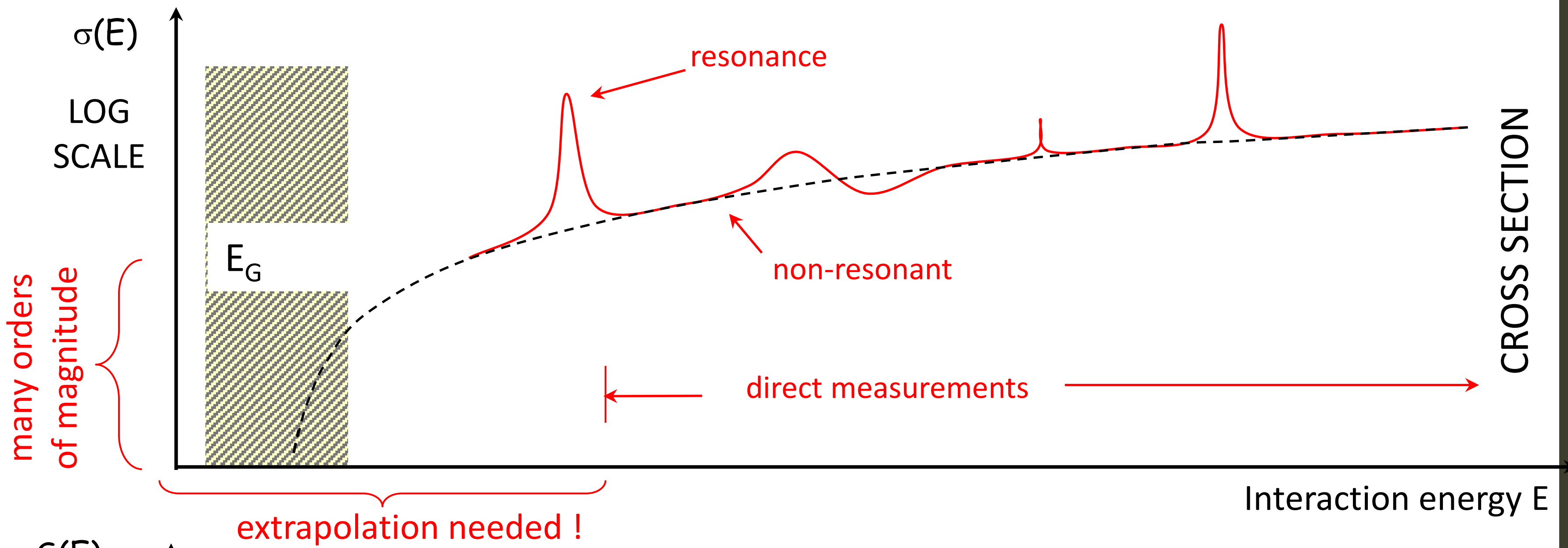
✧**AGB nucleosynthesis - $^{17}O/^{18}O$ abundaces, ^{19}F origin, ^{26}Mg excess....:**

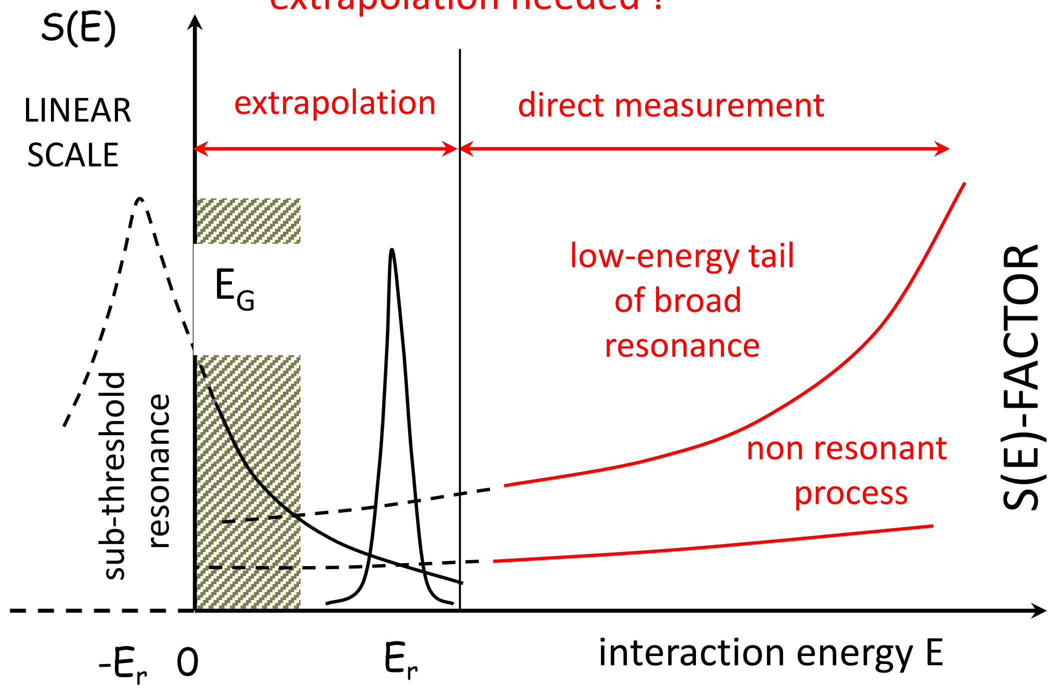
$^{13}C(\alpha,n)^{16}O$, $^{22}Ne(\alpha,n)^{25}Mg$ $^{14}C(\alpha,\gamma)^{18}O$, $^{14}N(\alpha,\gamma)^{18}F$, $^{15}N(\alpha,\gamma)^{19}F$, **$^{15}N(p,\gamma)^{16}O$**, $^{15}N(p,\alpha)^{12}C$, **$^{17}O(p,\gamma)^{18}F(\beta^{+})^{18}O$**, $^{18}O(\alpha,\gamma)^{22}Ne$, $^{18}O(p,\alpha)^{15}N$, $^{18}F(\alpha,p)^{21}Ne$, $^{19}F(\alpha,p)^{22}Ne$, $^{24}Mg(p,\gamma)^{25}Al(\beta^{+})^{25}Mg$, **$^{25}Mg(p,\gamma)^{26}Al(\beta^{+})^{26}Mg$**, $^{26}Mg(p,\gamma)^{27}Al$...

✧**He and advaced burnings (see M.Junker 's talk):**

$^{12}C(\alpha,\gamma)^{16}C$, $^{12}C(^{12}C, p)^{23}Na$, $^{12}C(^{12}C,\alpha)^{20}Ne$

Problem of extrapolation





$$R_{lab} = \boldsymbol{\sigma} \cdot \varepsilon \cdot I_p \cdot \rho \cdot N_{av} / A$$

$pb < \sigma < nb$

$\varepsilon \sim 10\ \%$

$I_P \sim mA$

$\rho \sim \mu g/cm^2$

$$\text{event/month} < R_{lab} < \text{event/day}$$

$$\sigma(E) = \mathbf{S(E)}/E \exp(-2\eta\pi)$$

Experimental approach:

Quiescent burning stages of stellar evolution

<u>FEATURES</u> $T \sim 10^6 - 10^8$ K $\Rightarrow$ $E_0 \sim 100$ keV $<<$ E_{coul} $\Rightarrow$ tunnel effect

$\Rightarrow$ 10^{-18} barn $< \boldsymbol{\sigma} < 10^{-9}$ barn

$\Rightarrow$ average interaction time $\tau \sim <\sigma v>^{-1} \sim 10^9$ y

unstable species <u>DO NOT</u> play significant role

<u>PROBLEMS</u> 10^{-18} b $< \boldsymbol{\sigma} < 10^{-9}$ b $\Rightarrow$ poor signal-to-noise ratio

$\Rightarrow$ major experimental challenge

$\Rightarrow$ extrapolation procedure required

<u>REQUIREMENTS</u> poor signal-to-noise ratio $\Rightarrow$ long measurements

$\Rightarrow$ ultra pure targets

$\Rightarrow$ high beam intensities

$\Rightarrow$ high detection efficiency

Background signals

The main problem of direct measurements is determined by the background signals, which, together with the low cross sections, set a limit to the energy range that can be investigated.

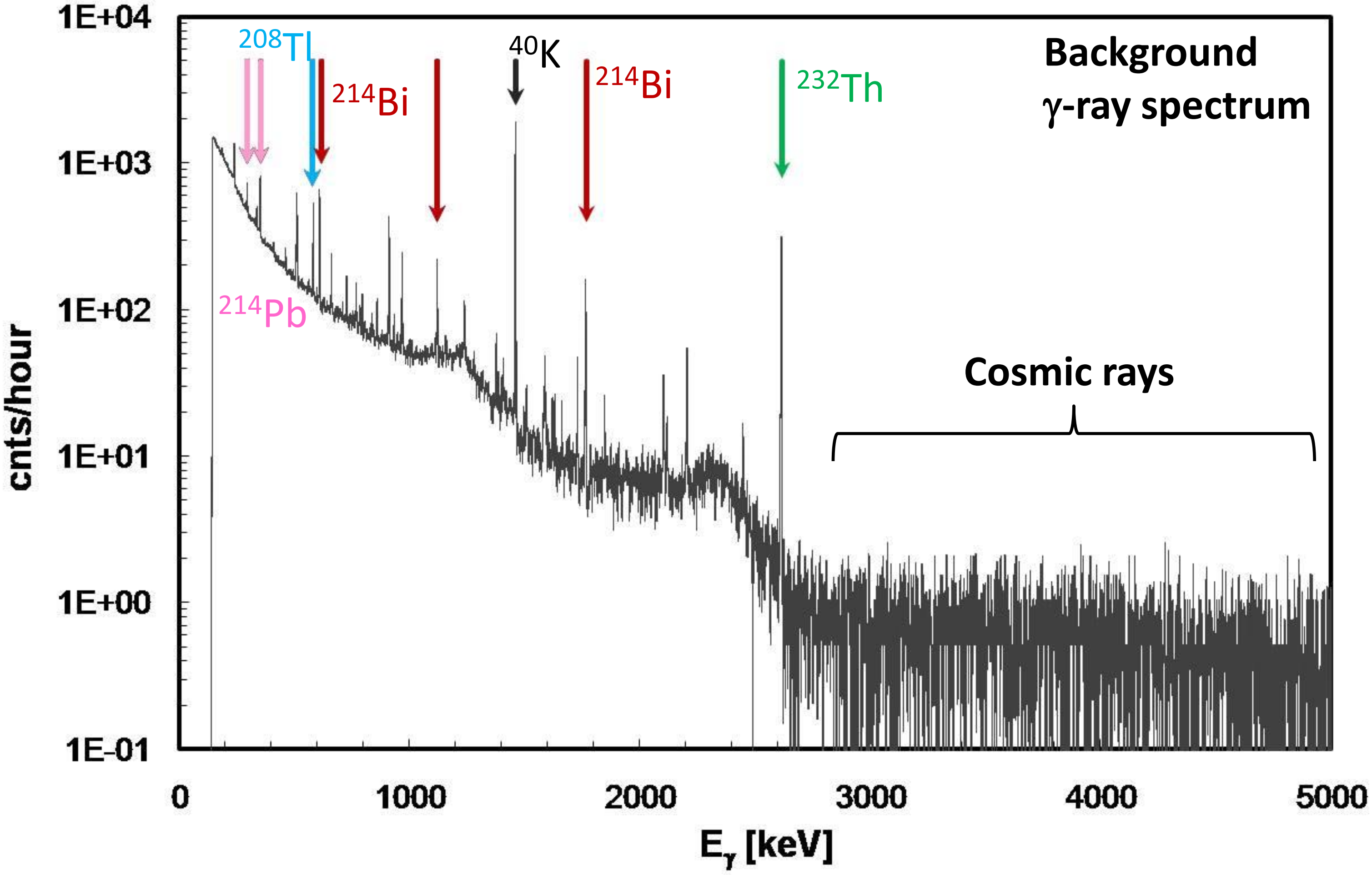
Three are the main sources of background:

environmental radioactivity
cosmic rays
beam-target induced nuclear reactions

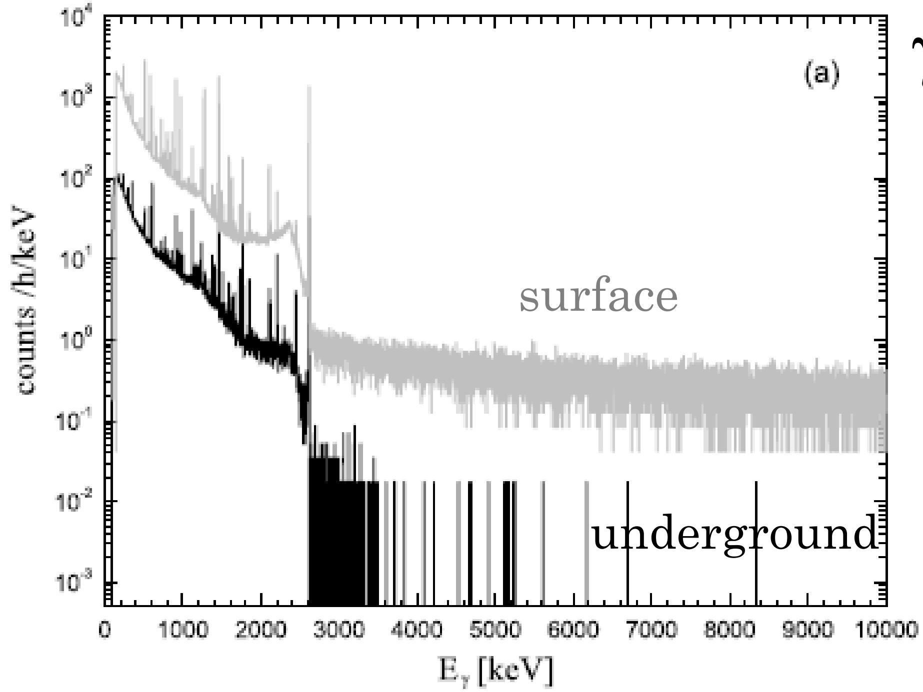
Each of these sources produces background of different nature and energy, so that each reaction to be studied deserves a special care in suppressing the relevant background component.

γ-ray Background

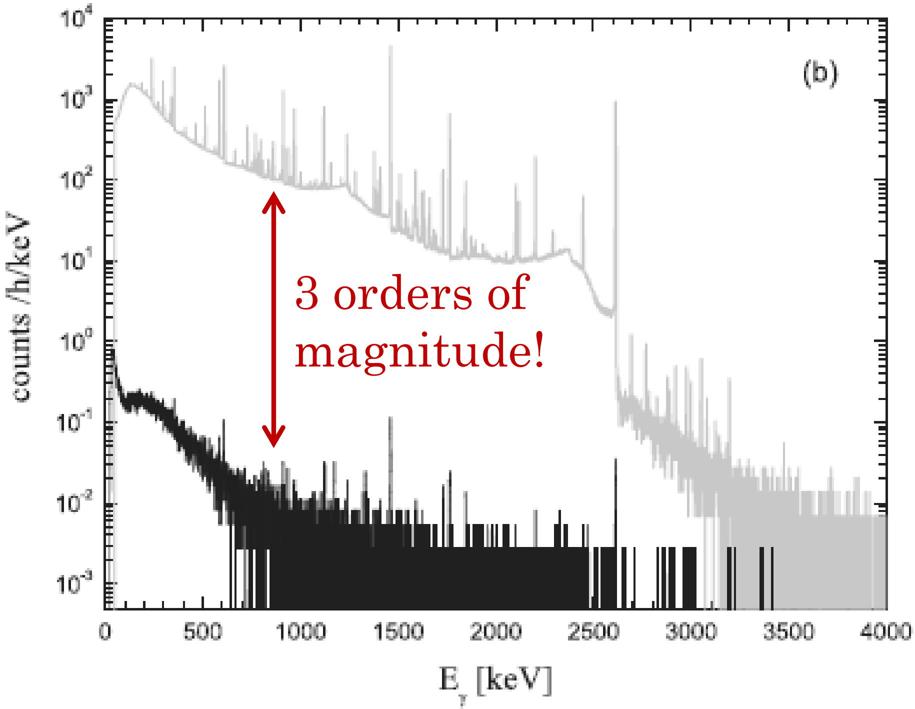
1. **Environmental radioactivity (γ-rays of low energy)**:
   a) natural radioactive series ^{226}**Ra**, ^{214}**Bi**, ^{214}**Pb** (from ^{238}**U**) and ^{224}**Ra**, ^{208}**Tl**, ^{212}**Pb** (from ^{232}**Th**);
   b) radon (^{222}**Rn** - ^{220}**Rn**) a short-lived gas (from ^{238}**U** and ^{232}**Th** respectively);
   c) long-lived natural radionuclides such as ^{40}**K**, ^{87}**Rb**, ^{115}**In**, ^{133}**La**, ^{142}**Ce**, etc.
2. **Cosmic rays (γ-rays of high energy).**



γ-ray Natural Background



between E_g =7 and 12MeV the bck suppression factor is 100 times



underground passive shielding is more effective since μ flux, that create secondary γ's in the shield, is suppressed

0.3 m^3 Pb-Cu shield suppression three orders of magnitude below 2MeV

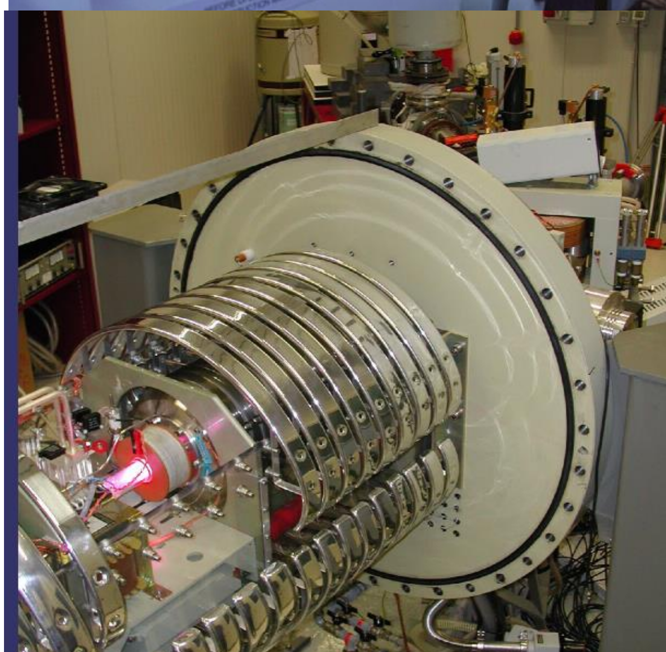
LUNA II 400kV accelerator

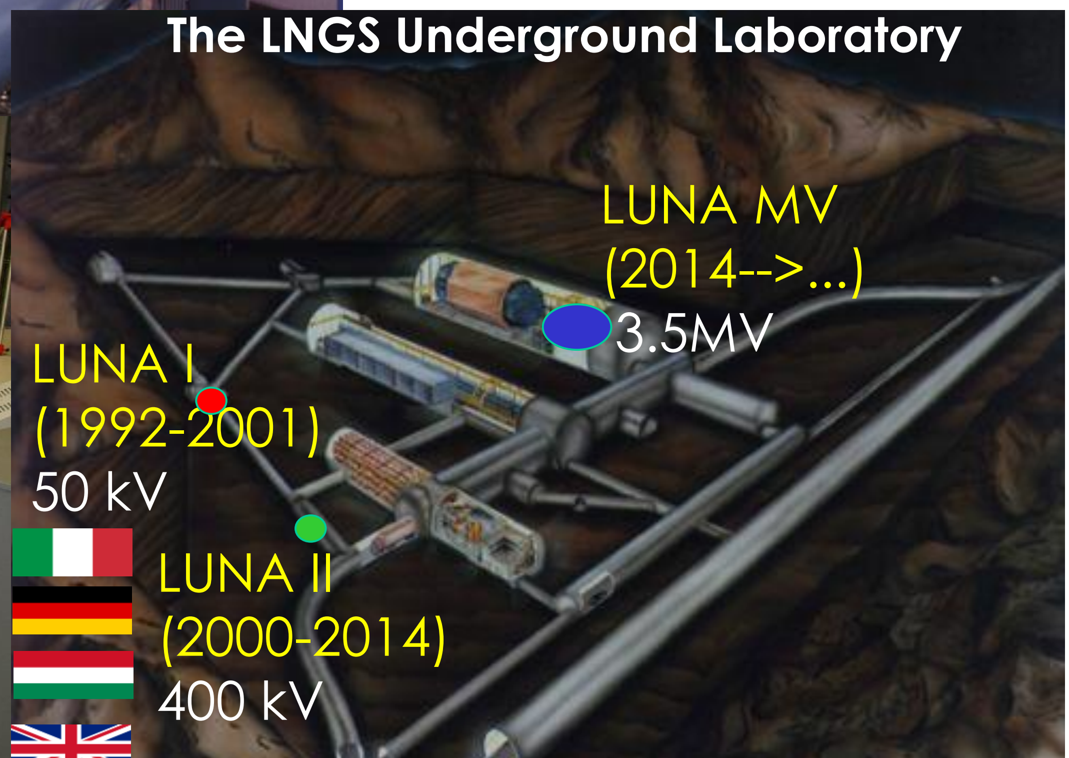
$U_{terminal}$ = 50 – 400kV

I_{max} = 500μA (on target)

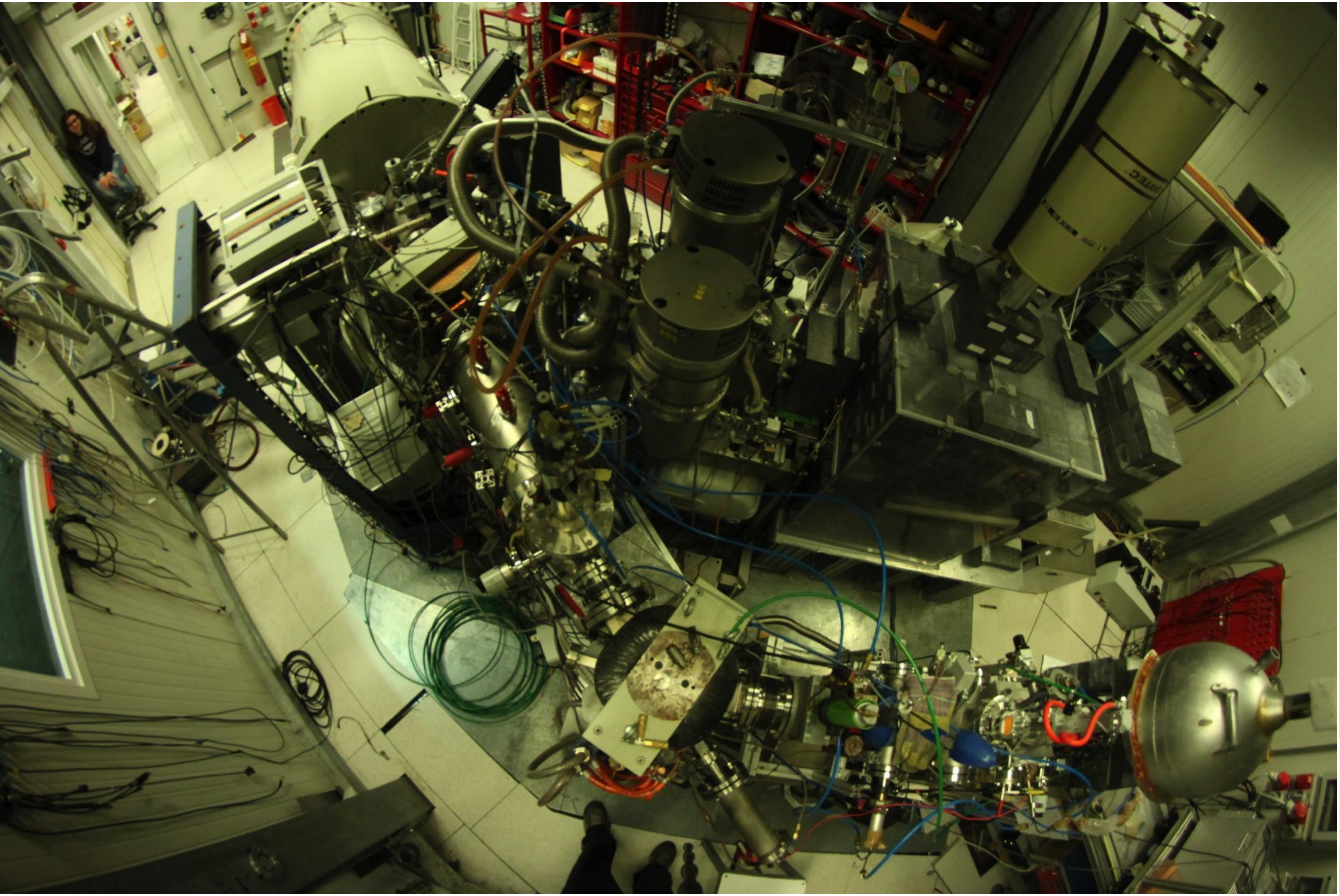
ΔE = 0.07keV

Allowed beams: H^+, ^4He, (^3He)



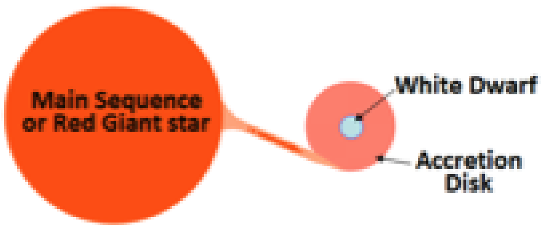


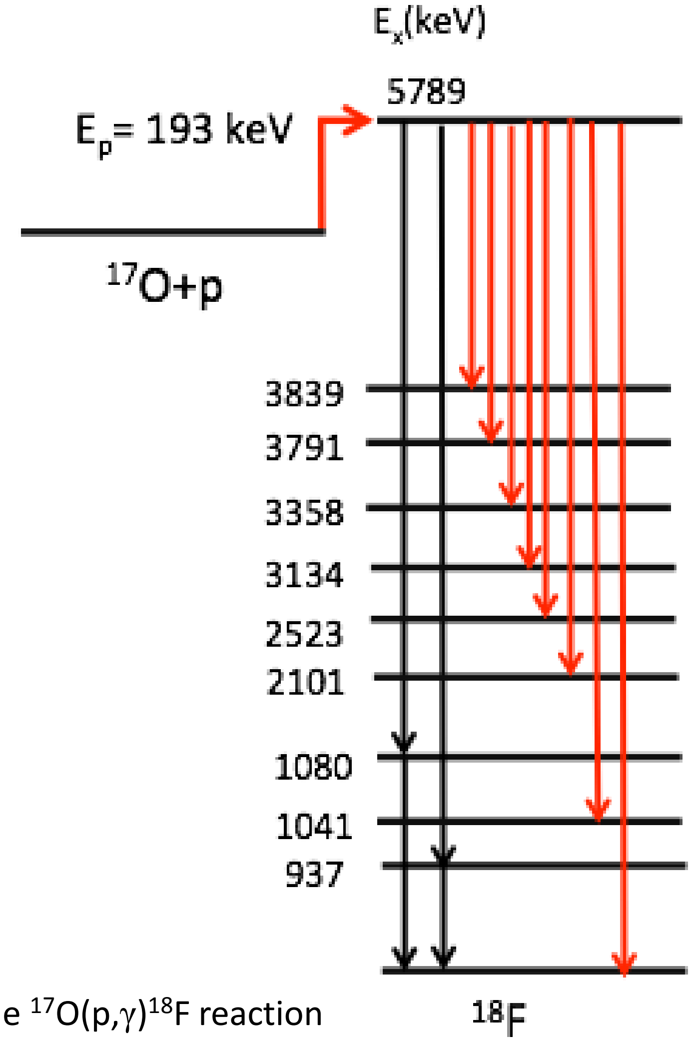
LUNA II 400kV accelerator



$^{17}O(p,\gamma)^{18}F$ reaction at Nova energy

Relevant for nucleosynthesis in:
RGB and AGB stars (H shell burning),
massive stars (H core burning),
classical novae (H explosive burning)



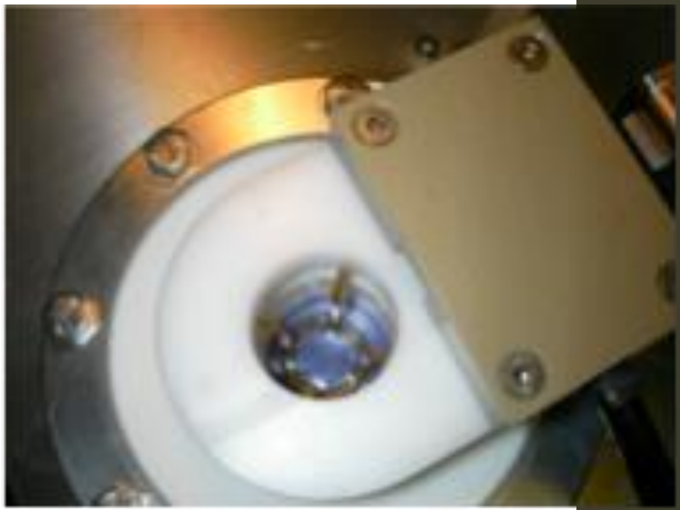


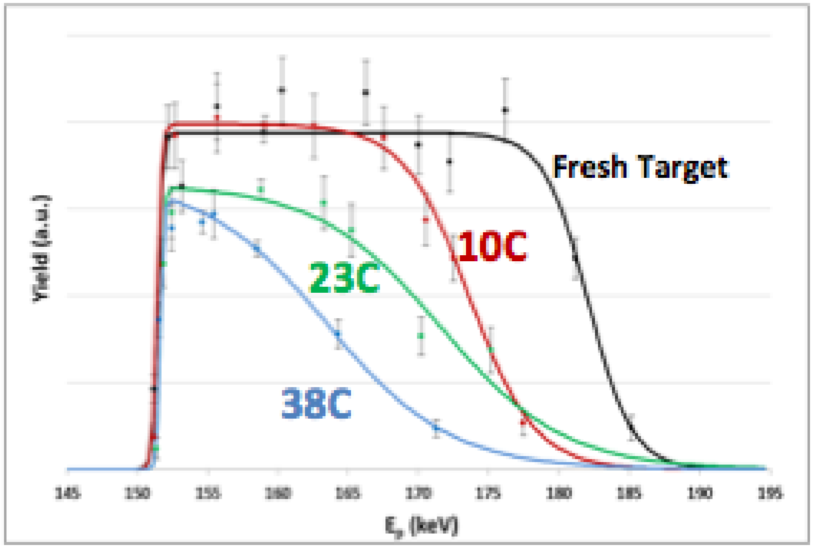
Determines the abundances of O isotopes (astronomical observations and pre-solar grains) and ^{18}F (nova explosions)

Rolfs *et al.* Nuc. Phys. A217 29-70 (**1973**) – 1st investigation of the $^{17}O(p,\gamma)^{18}F$ reaction
Fox *et al.* Phys. Rev. C 71, 055801 (**2005**) – 1st 193 keV res. meas. : **$\omega\gamma_{193}$= (1.2±0.2) μeV**
Chafa *et al.* Phys. Rev. C 75, 033810 (**2007**) – Activation meas. : **$\omega\gamma_{193}$= (2.2±0.4) μeV**
Newton *et al.* Phys. Rev. C 81, 045801 (**2010**): cross section measurements
Hager *et al.* Phys Rev. C 85,035803 **(2012)**: cross section measurements

Ta_2O_5 targets

Ta_2O_5 targets prepared by anodization with enriched water ^{17}O up to 69% (with 5% ^{18}O)
Special efforts to minimize F contaminations
Stoichiometry and isotopic composition checked by RBS and SIMS techniques



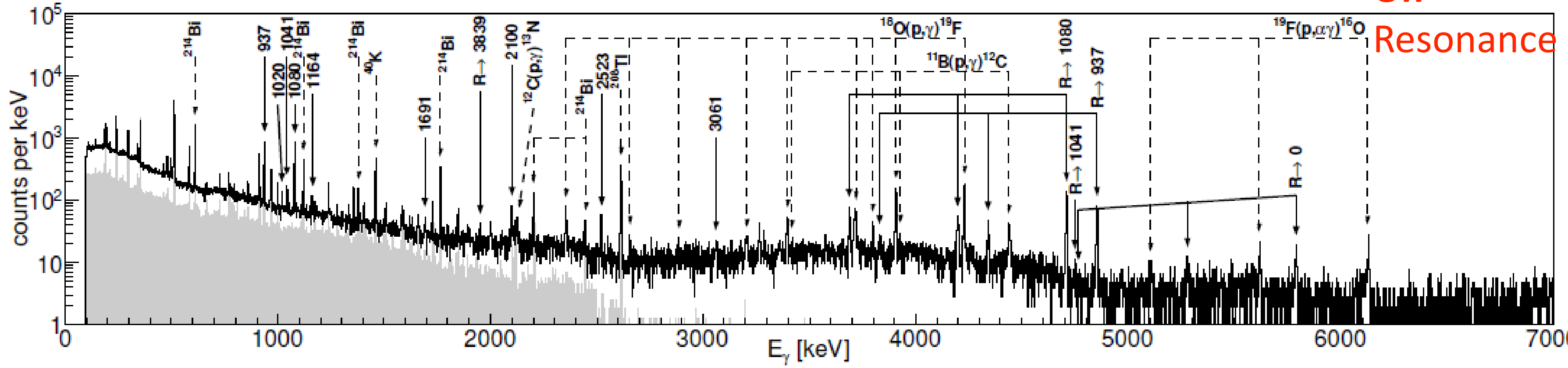


151 keV $^{18}O(p,\gamma)^{19}F$ resonance scans performed before each long measurement to monitor target degradation

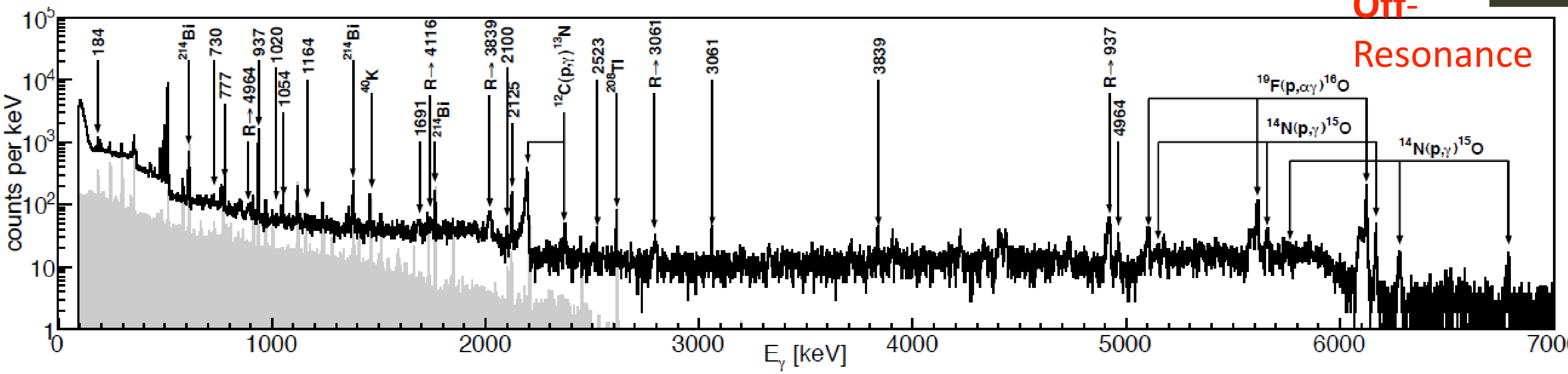
A. Caciolli et al., Eur. Phys. J. A, 48, 144 (2012)

$^{17}O(p,\gamma)^{18}F$ - prompt γ-ray spectroscopy

On-Resonance

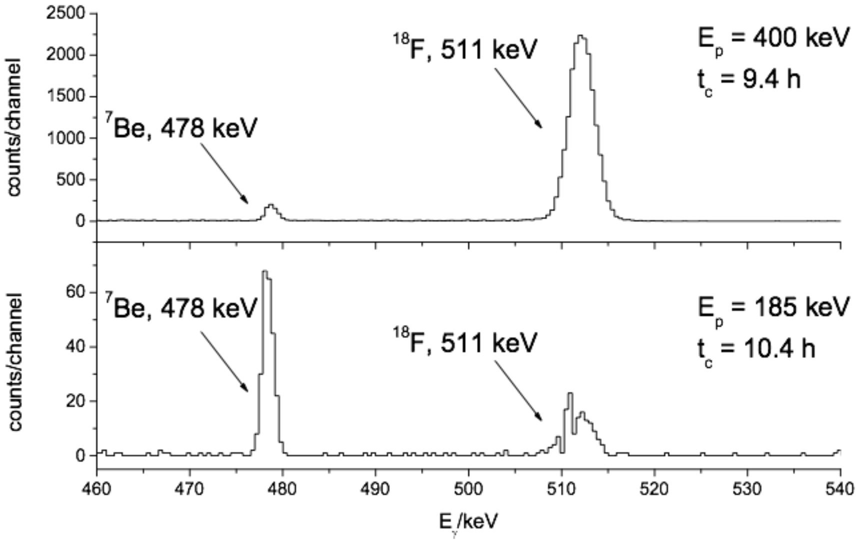


Off-Resonance

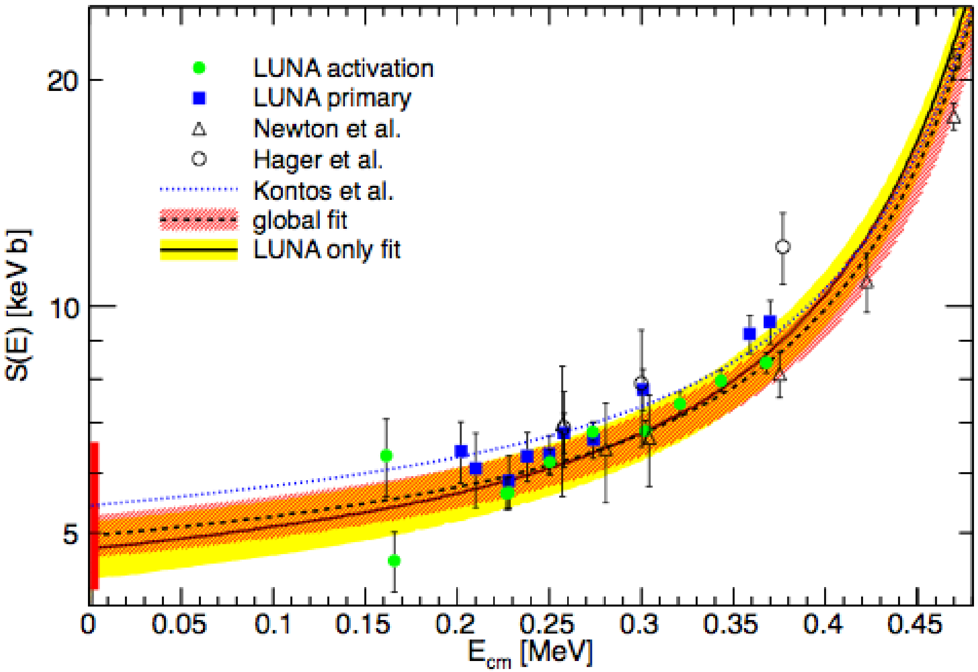


$^{17}O(p,\gamma)^{18}F$ - activation measurements

^{18}F decays β^+ with $T_{1/2}$ = 110 min
activity measured at the STELLA Laboratory at LNGS
5% efficiency for 511 keV γ-rays, background ~0.5 counts/h
6 h irradiation and 6 h counting performed on every run
resonance strength measured by using 6 runs on 3 different targets



$^{17}O(p,\gamma)^{18}F$ - Off resonance S-factor



$\omega\gamma_{193}$ = (1.67 ± 0.12) μeV

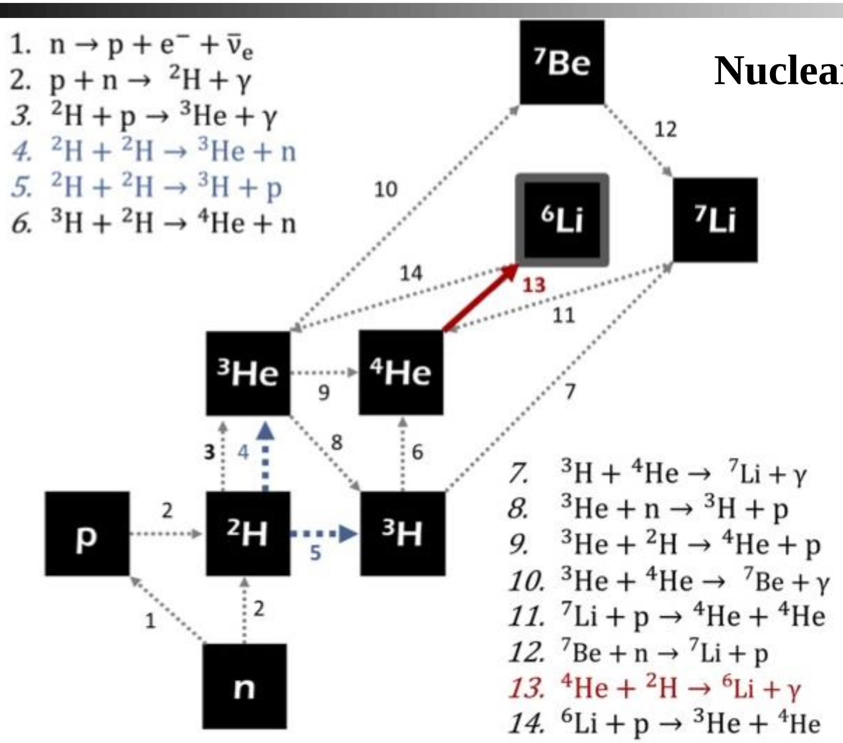
Global fit to available data
high energy resonance parameters
 fom Kontos et al.
PRC 86, 55801 (2012)

Novae models computed with the SHIVA code: maximum variations of ^{18}O and ^{18}F of the order of 10%.

D. A. Scott et al., Phys. Rev. Lett. 109, 202501 (2012)
A. Di Leva et al., Phys. Rev. C 89, 015803 (2013)

$^{2}H(\alpha,\gamma)^{6}Li$ motivation

Nuclear reactions involved during the BBN era



The amount of ^{6}Li predicted by the BBN is about 3 orders of magnitude lower than the observed as absorption lines in metal-poor stars' electromagnetic spectra.

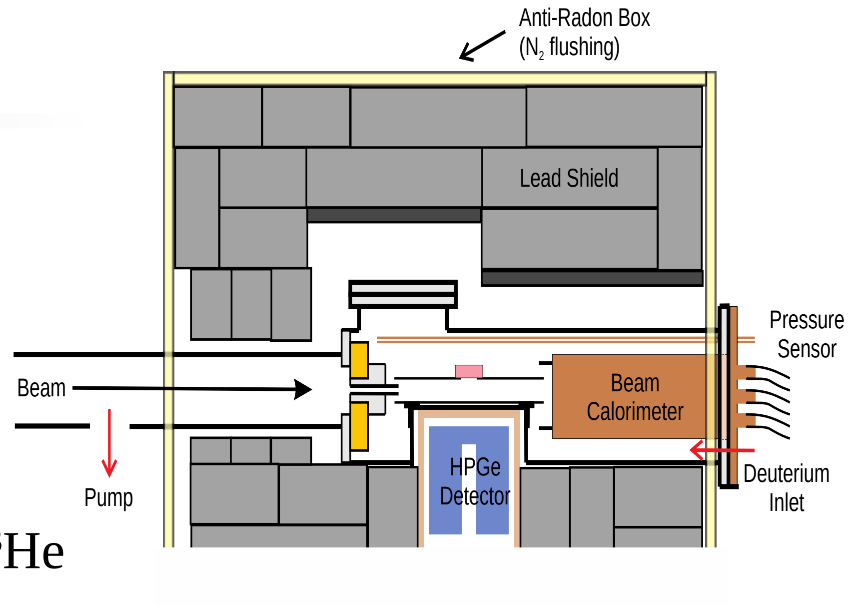
The difference between observed and calculated ^{6} Li/^{7} Li ratios may reflect unknown post-primordial processes or physics beyond the Standard Model .

$^{2}H(\alpha,\gamma)^{6}Li$

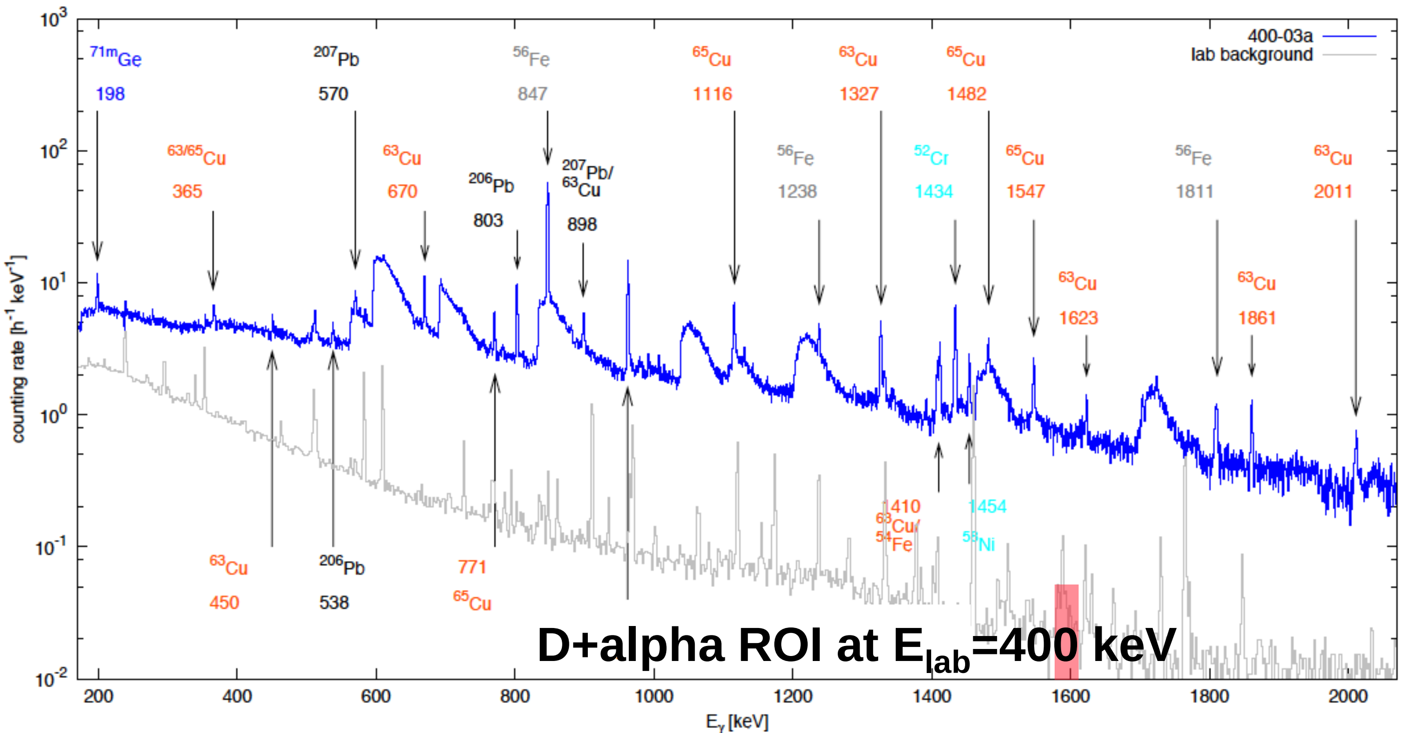
Experimental setup:

windowless D gas target 0.3mbar

HPGe detector at 90^{0} –in close geometry

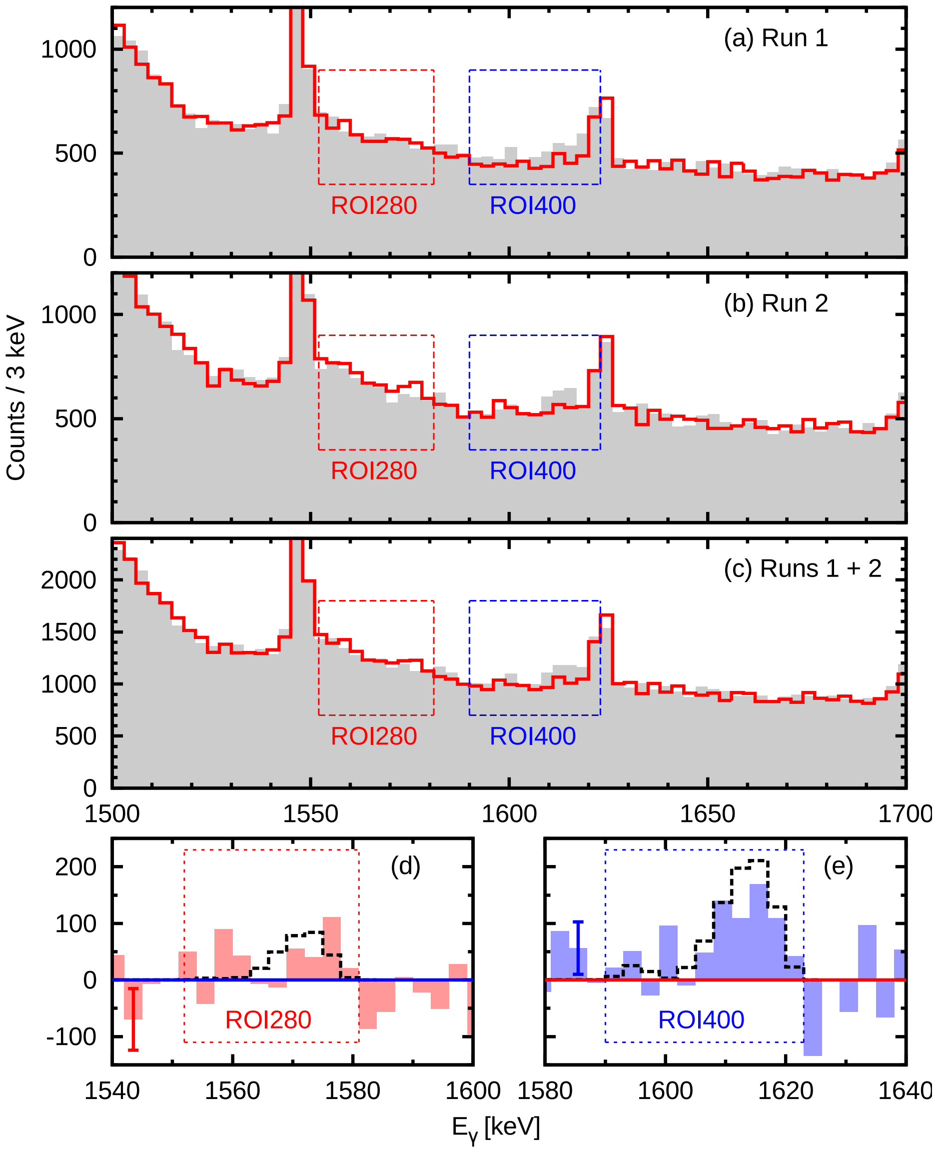


Beam Induced Background : $^{2}H(d,n)^{3}He$



M.Anders et al.Eur. Phys. J. A 49 (2013) 28

$^{2}H(\alpha,\gamma)^{6}Li$ reaction- prompt γ-ray spectroscopy



$E_\gamma = Q + E_{\alpha cm} + \Delta E_{doppler} + E_{recoil}$

Q=1473.48keV

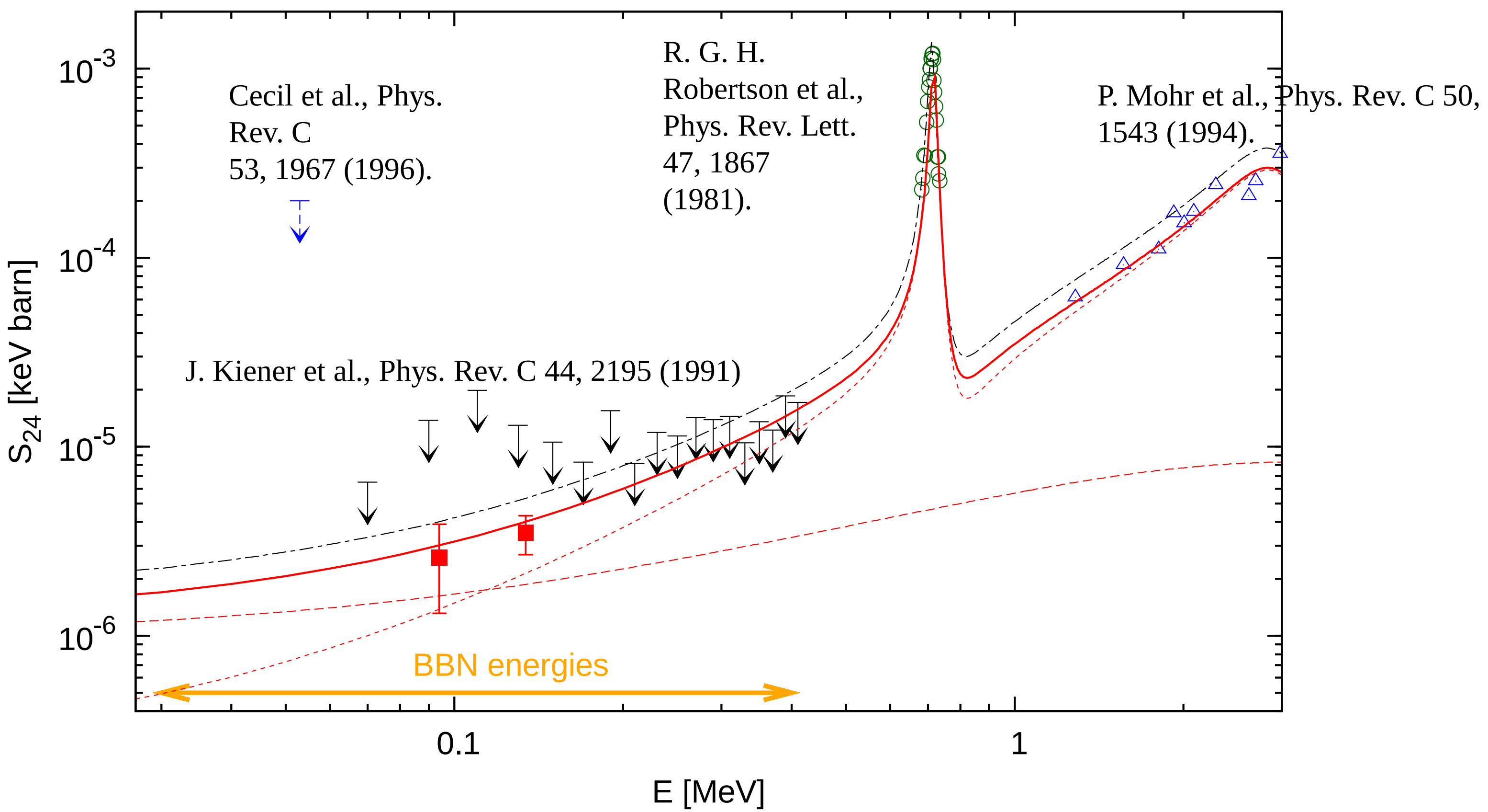
Eα=400keV filled grey histograms
Eα=280keV empty red histograms

Run 1 and Run 2 are two subsamples acquired in two different periods

The collected charge is at each energy, i.e. about 550 C.

The dashed line represents the expected γ-ray line shape based on the Mukhamedzhanov theoretical description of the angular distribution for the D(α,γ)6Li reaction

Astrophysical S-factor of the $^{2}H(\alpha,\gamma)^{6}Li$ reaction



Using the new cross section and the previous LUNA data a BBN lithium abundance ratio of $^{6}Li/^{7}Li = (1.5\pm0.3)\times10^{-5}$ is obtained, firmly ruling out standard BBN production as a possible explanation for the reported ^{6}Li detections

M.Anders et al. Phys.Rev.Lett.113, 042501 (2014)

Summary & Outlook

- Optimization of peak to background is crucial. High intensity beams, underground passive shielding
- Low energy measurements are necessary to remove or reduce cross section extrapolation uncertainties
- $^{18}O(p,\alpha)\,^{19}F$ data taking in conclusion-
  $^{22}Ne(p,\gamma)\,^{23}Na$ BGO phase in progress
  $^{23}Na(p,\gamma)\,^{24}Mg$ in progress
- $^{22}Ne(p,\gamma)\,^{23}Na$ cross section measurements (see F.Cavanna's talk)
- Perspectives LUNA 400kV- LUNA MV in LNGS (see M.Junker's talk)

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