d(α,γ) reaction measurement at LUNA

Nuclear Cosmology Deep Underground

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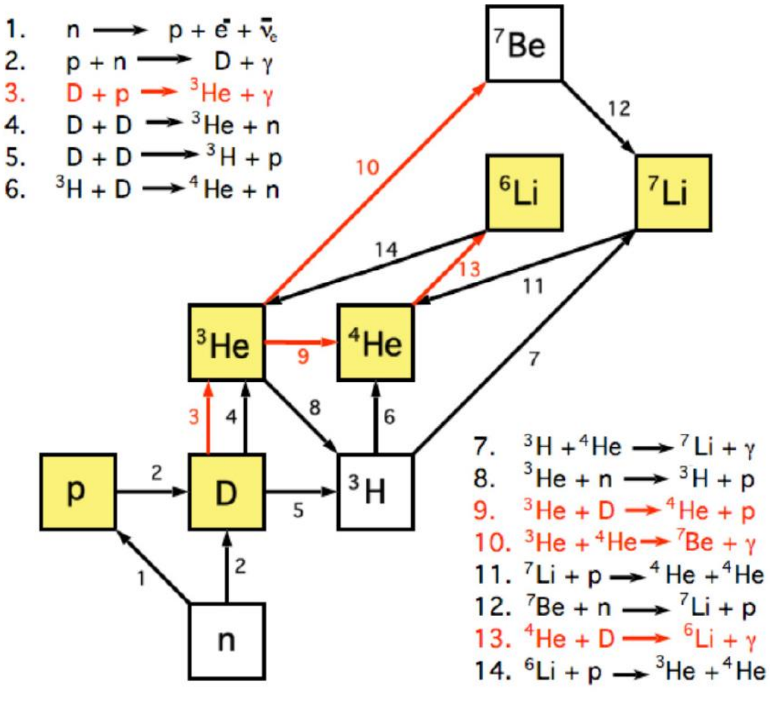
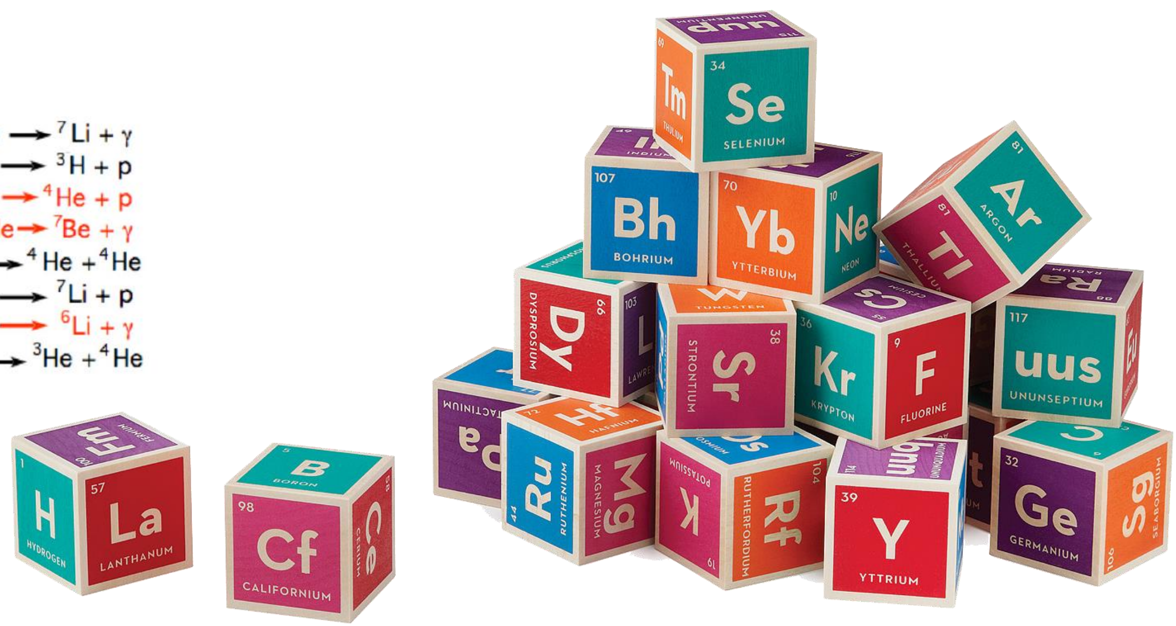
THE BIG BANG NUCLEOSYNTHESIS ERA

Only after about *three minutes and half* after the Big Bang the temperature of the Universe was lower enough to produce deuterium (deuterium bottleneck)



PRIMORDIAL NUCLEI HAD BEEN PRODUCED DURING THIS PERIOD (^{2}H,^{3}He,^{4}He,^{6}Li and ^{7}Li)



LOOKING THE PAST

- Chemical evolution of the Universe destroyed primordial abundances information
- Searching for high redshift astrophysical objects
- Up to now, *no Lithium* can be detected in extra-galactic objects

HALO STARS

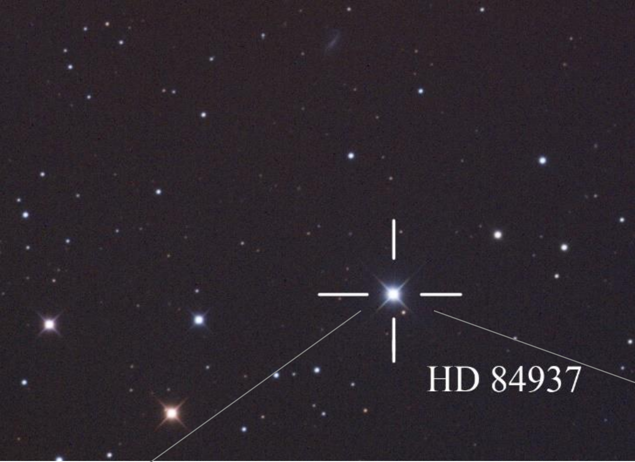
METAL POOR

↓

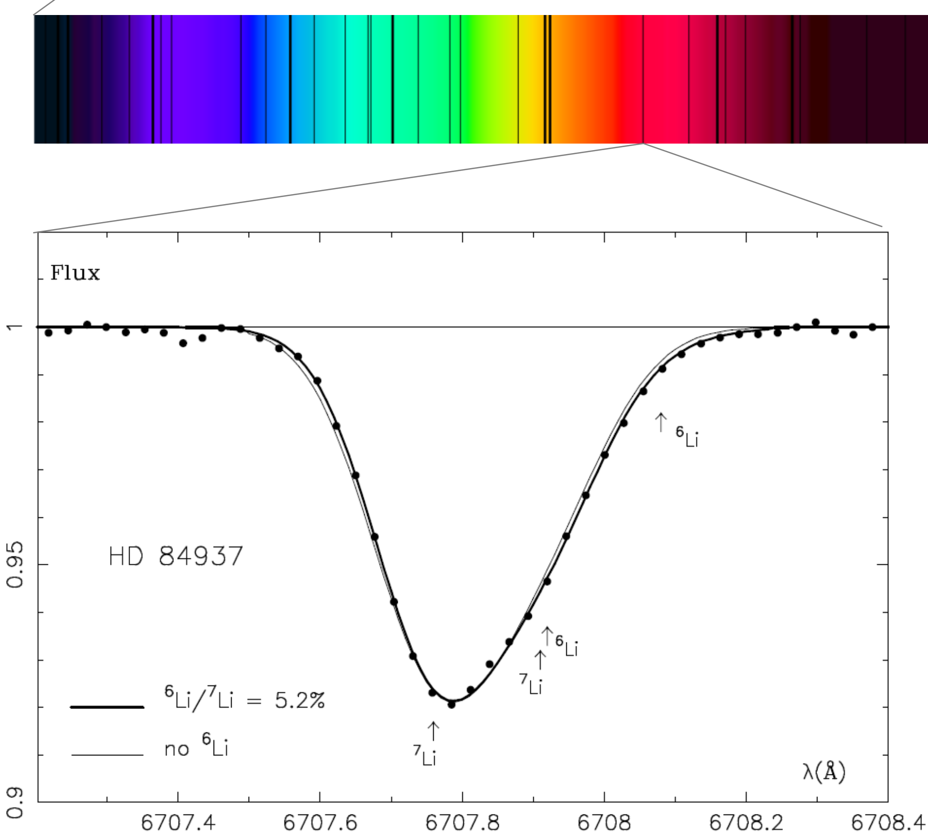
Lithium abundance in Stellar atmospheres

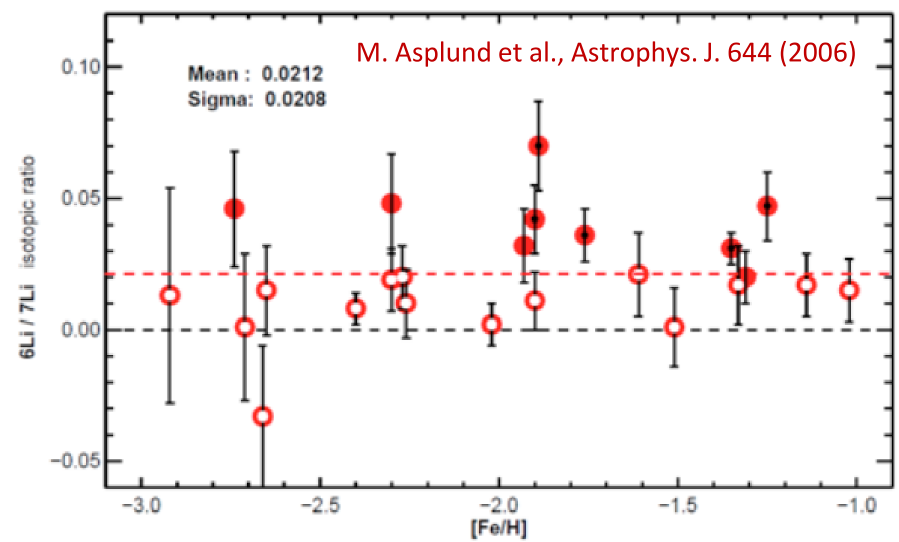
^{6}Li abundance measurement in ancient low-metallicity stars*

***located in our galaxy halo**

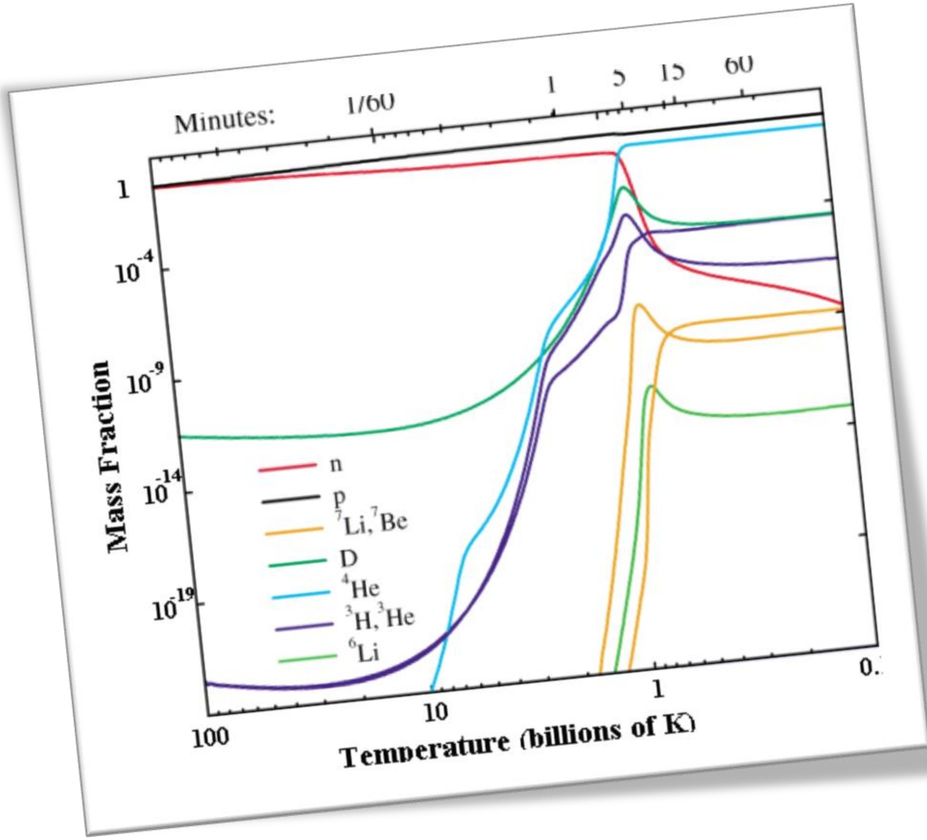


- Search for metal poor stars*
- Obtain an high resolution absorption spectrum
- Fit the Lithium (^{6}Li+^{7}Li) absorption line in order to obtain the ^{6}Li (stellar atmospheric) abundance
- Use a detailed model of stellar atmospheres and calculate the ^{6}Li primordial abundance. → $^6Li/H \cong 10^{-11}$





BIG BANG NUCLEOSYNTHESIS



The abundance of primordial light nuclei at the beginning of the Universe, during the Big Bang Nucleosynthesis era, can be estimated by means of:

COSMOLOGY

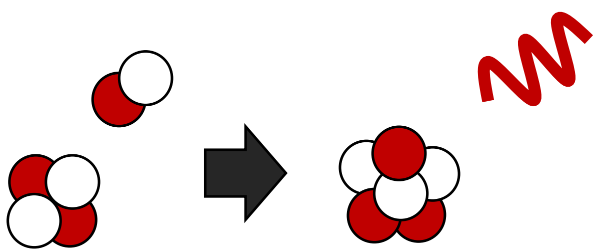
PARTICLE PHYSICS

NUCLEAR PHYSICS

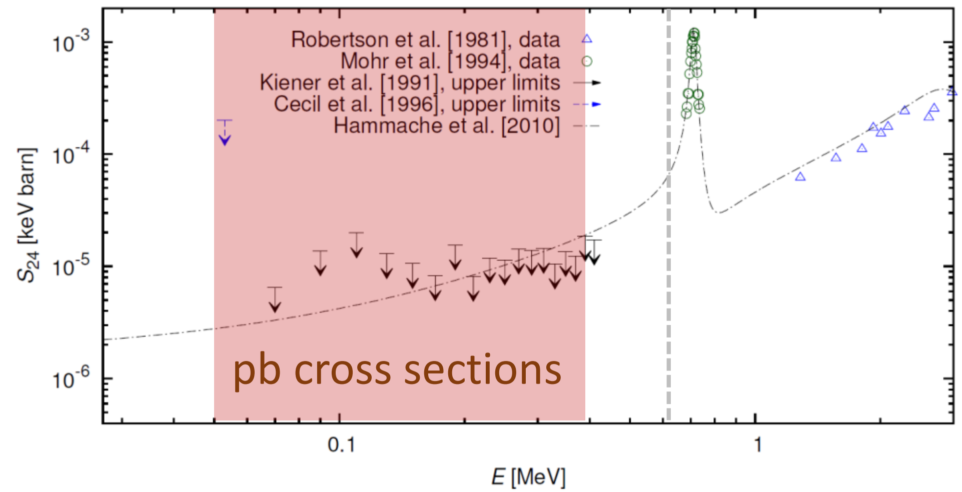
- **Cosmological Model (ΛCDM)**
  - Measurement of the cosmological parameters → CMB
- **Particle Physics**
  - Measurement of the involved cross sections → HEP
- **Nuclear Physics**
  - Measurement of the involved cross sections → Nuclear **Under**/Over ground labs

PRIMORDIAL LITHIUM-6 ABUNDANCE

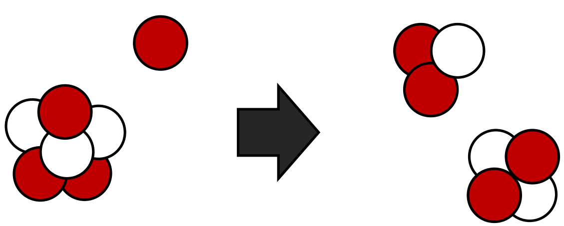
LITHIUM-6 PRODUCTION



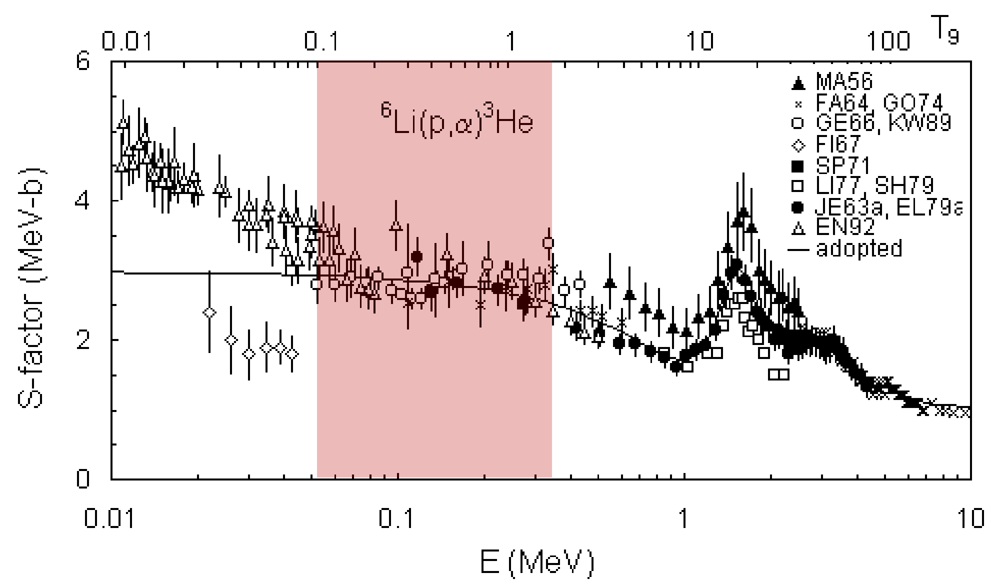
$$^{4}He + {}^{2}H \rightarrow {}^{6}Li + \gamma$$



LITHIUM-6 DESTRUCTION



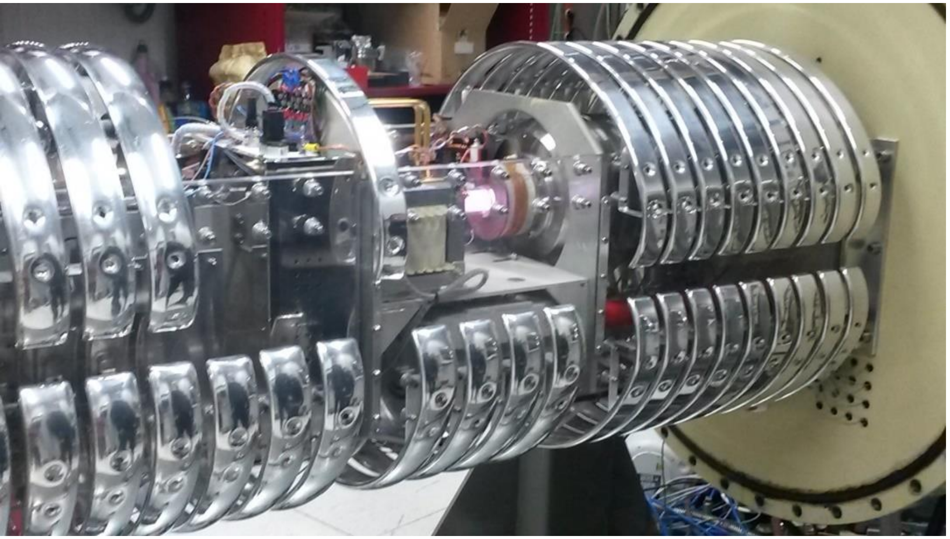
$$^{6}Li + {}^{1}H \rightarrow {}^{3}He + {}^{4}He$$



The main source of uncertainty is coming from the ^{2}H(α,γ)^{6}Li reaction

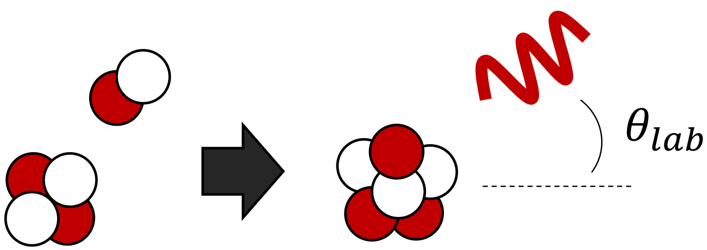
THE $^{2}H(\alpha,\gamma)^{6}Li$ MEASUREMENT AT LUNA*

*Laboratory for Underground Nuclear Astrophysics



The LUNA 400 kV accelerator features requested for the $^{2}H(\alpha,\gamma)^{6}Li$:

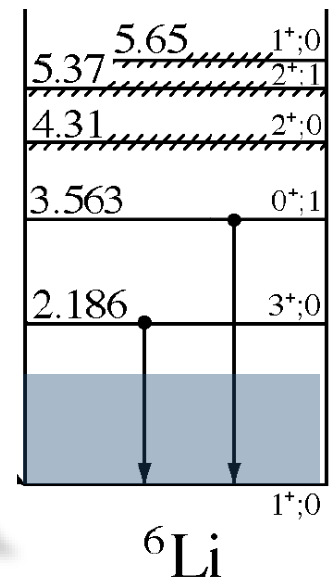
- The beam energy is within the BBN energy range 40-400 keV (absolute value $\pm 0.3\ keV$, spread $< \ 0.1\ keV$)
- High α current for low cross section measurements (< 500 μA)
- Long term stability in order to have long runs (5 eV/h)



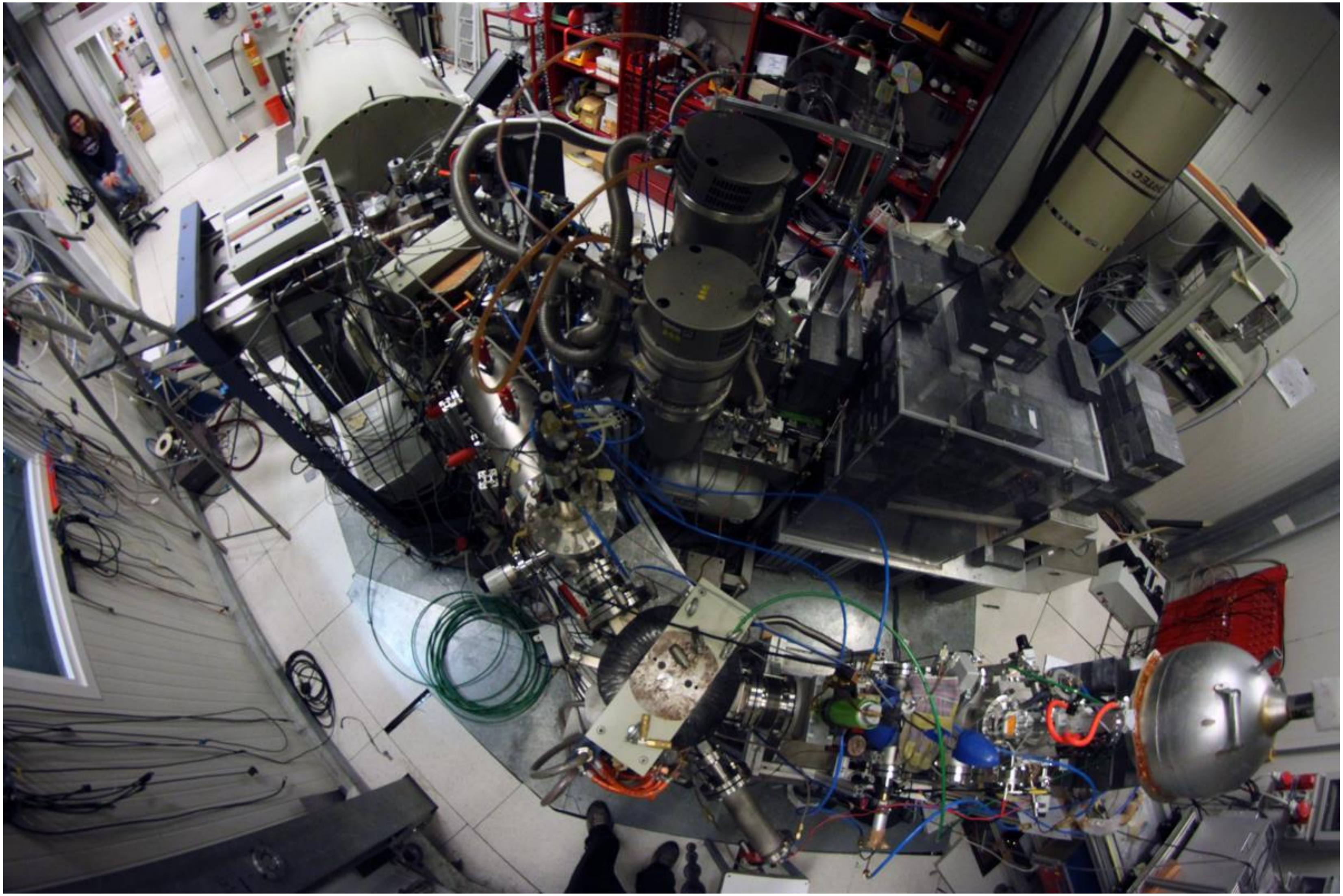
$$^{4}He + {}^{2}H \rightarrow {}^{6}Li + \gamma$$

$$E_\gamma = \frac{m_\alpha^2 + m_d^2 - m_{Li}^2 + 2m_d(E_\alpha + m_\alpha)}{2[E_\alpha + m_\alpha + m_d - p_\alpha \cos(\theta_{lab})}$$

The $^{2}H(\alpha\gamma)^{6}Li$ in the BBN energy range "is" a direct capture reaction → **unknown resonances?**



THE $^2H(\alpha,\gamma)^6Li$ EXPERIMENTAL SETUP



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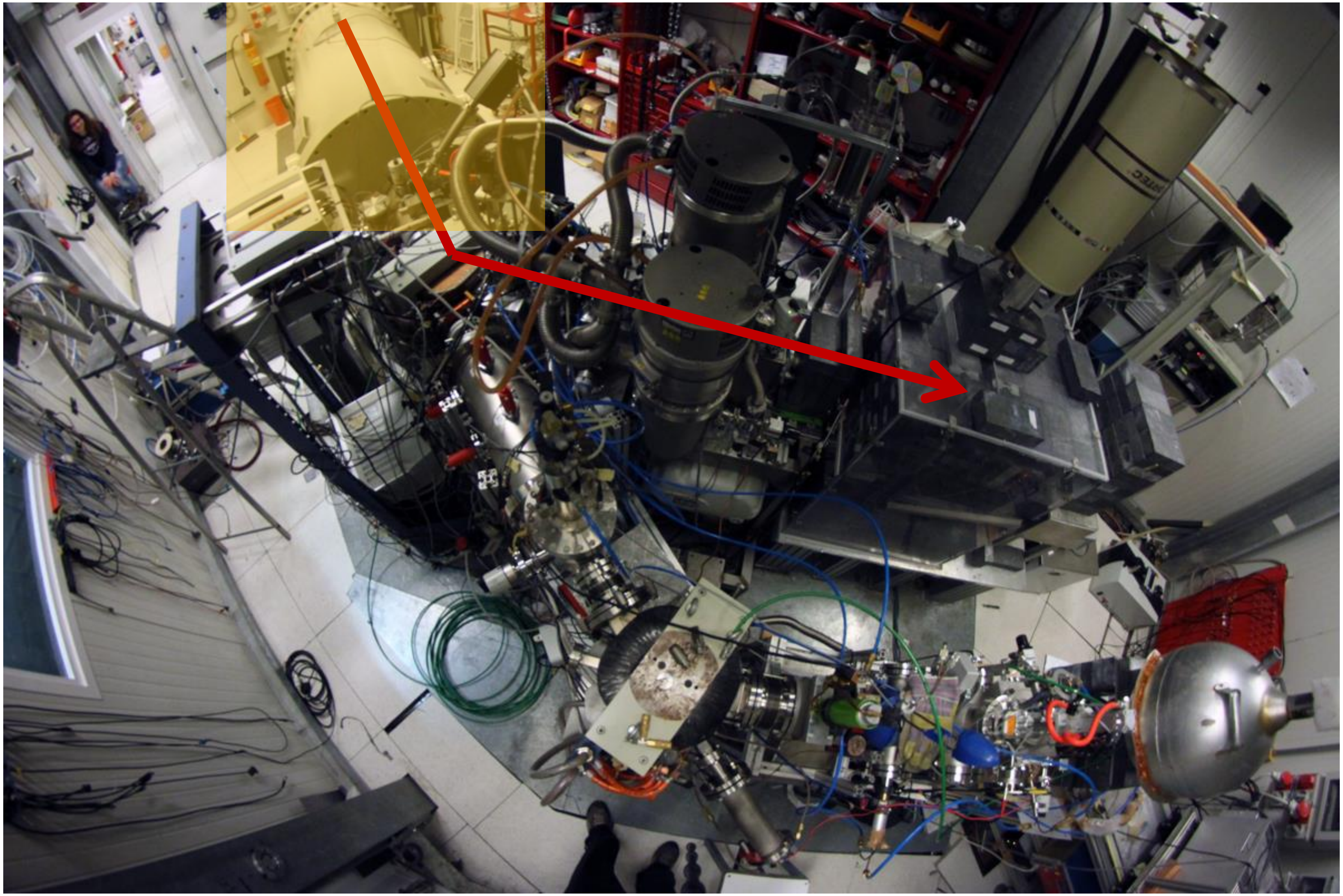

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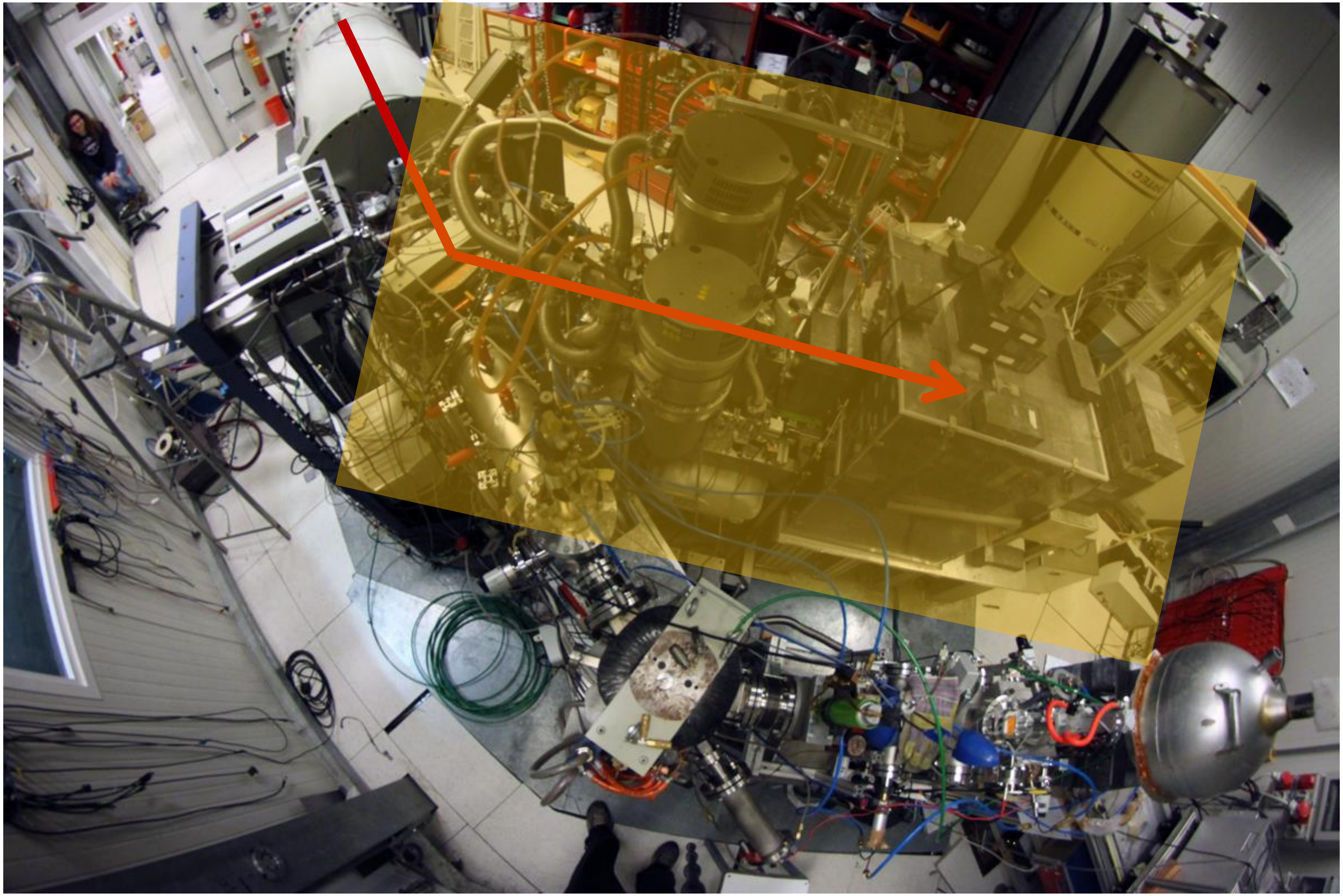
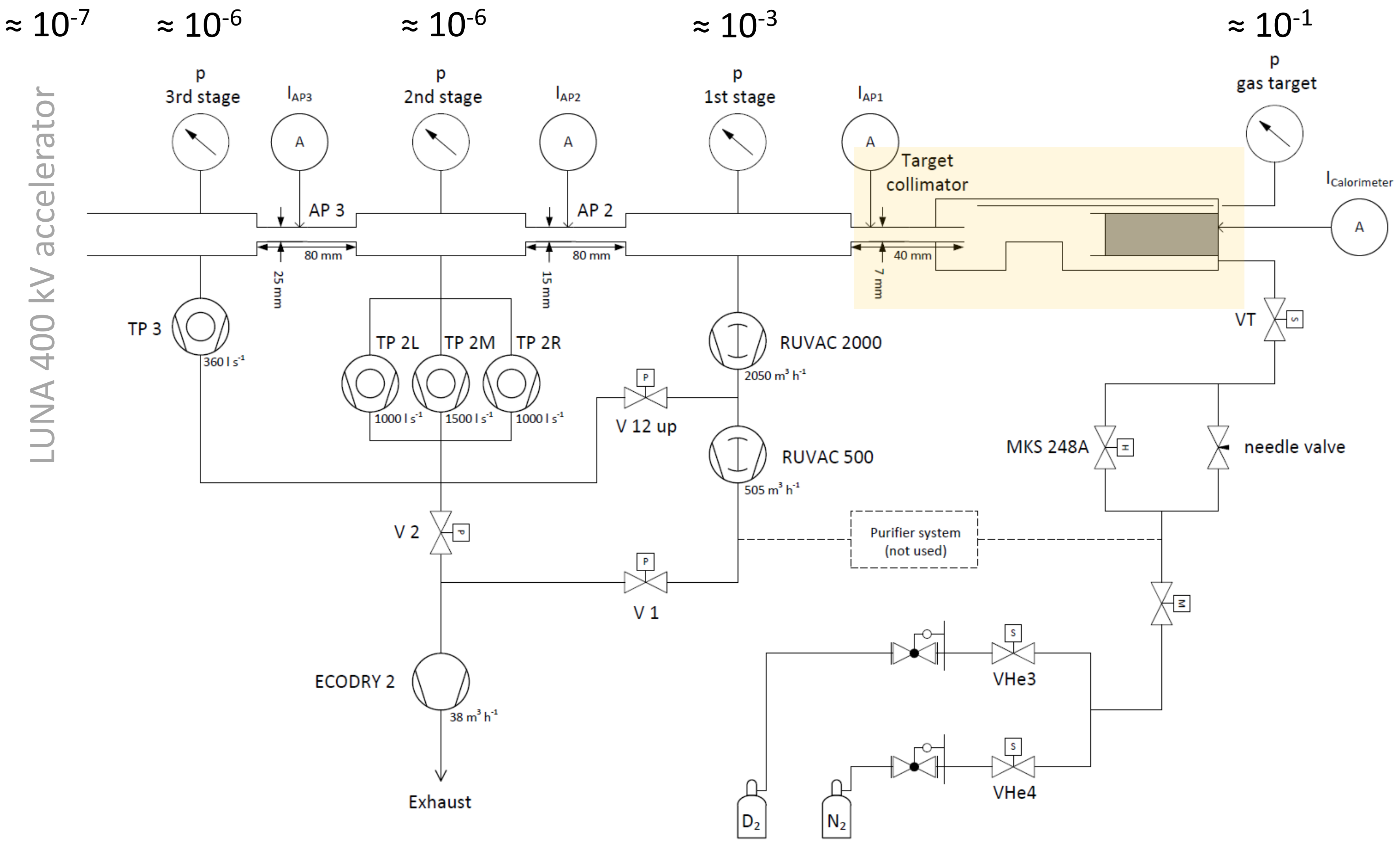
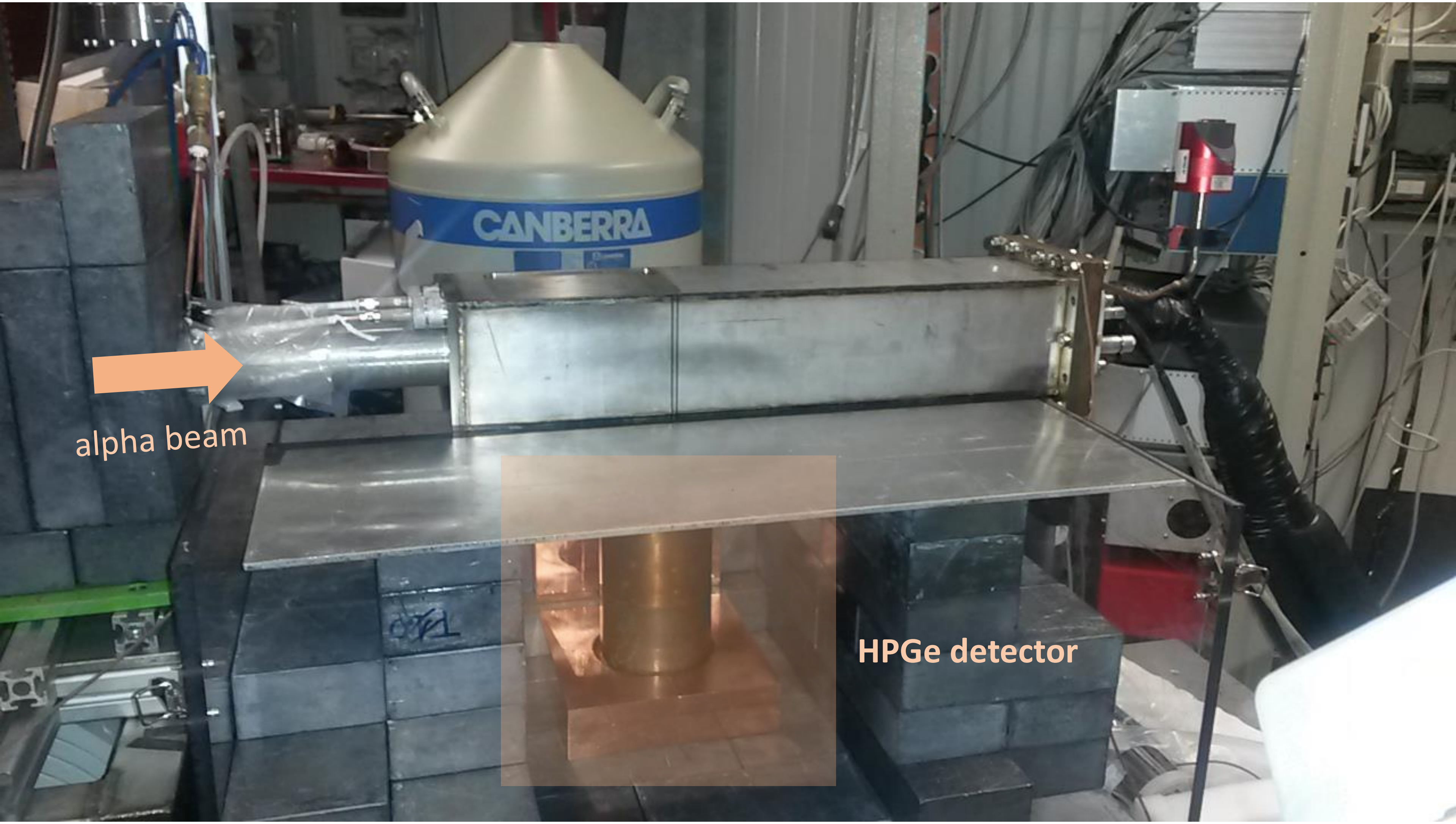


THE LUNA GAS TARGET



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

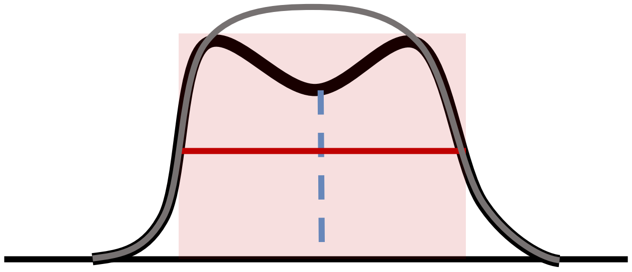
THE $^2H(\alpha,\gamma)^6Li$ GAS CHAMBER



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

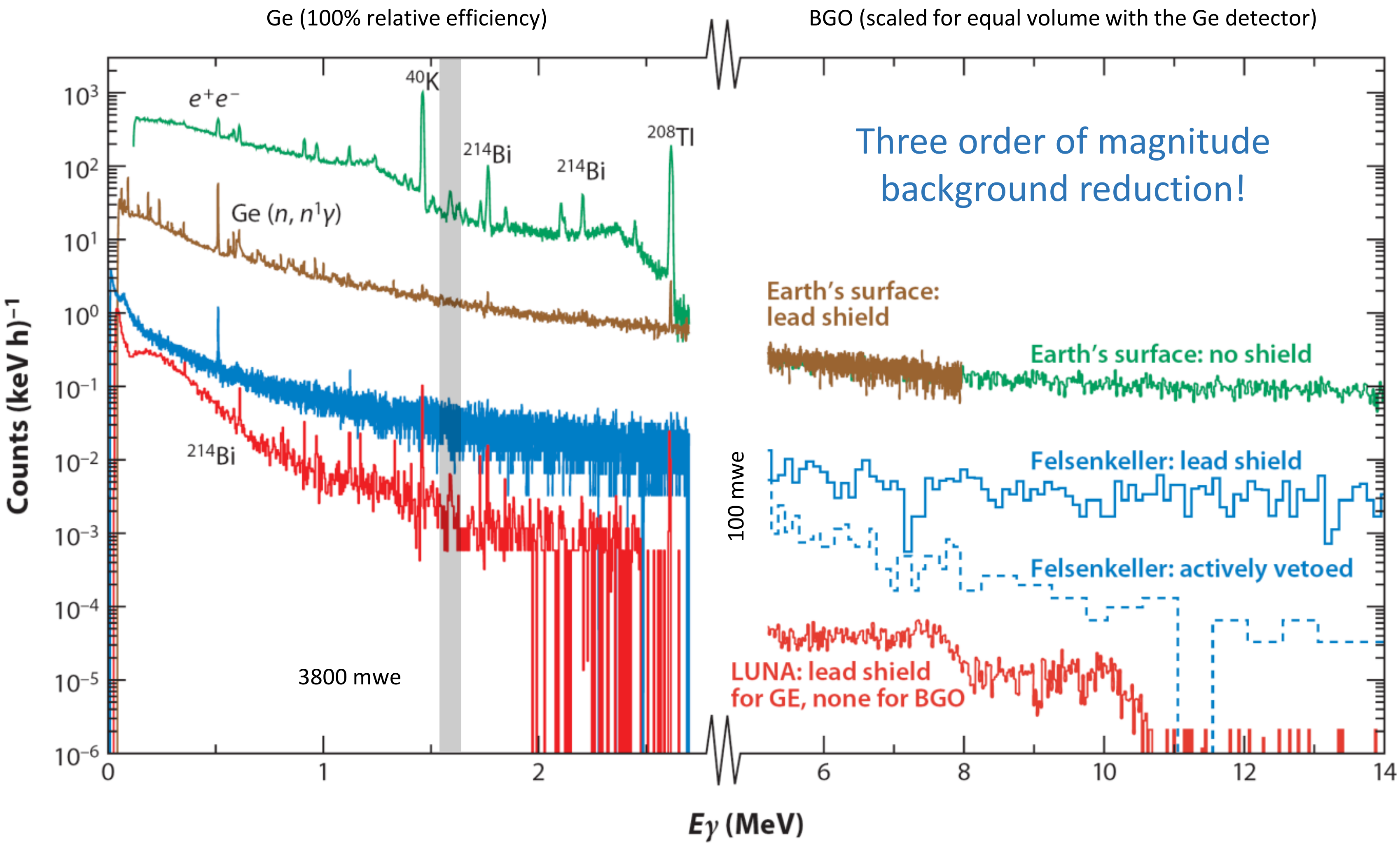
- 137% efficiency High Purity Germanium Detector.
- Close geometry in order to increase the geometrical efficiency.
- Doppler effect: peak shape analysis.

$$E_{\gamma} = \frac{m_{\alpha}^{2} + m_{d}^{2} - m_{Li}^{2} + 2m_{d}(E_{\alpha} + m_{\alpha})}{2[E_{\alpha} + m_{\alpha} + m_{d} - p_{\alpha}\cos(\theta_{lab})}$$



RoI position and width depend on the beam energy: 1.5-1.6 MeV

THE $^2H(\alpha,\gamma)^6Li$ HPGe Detector

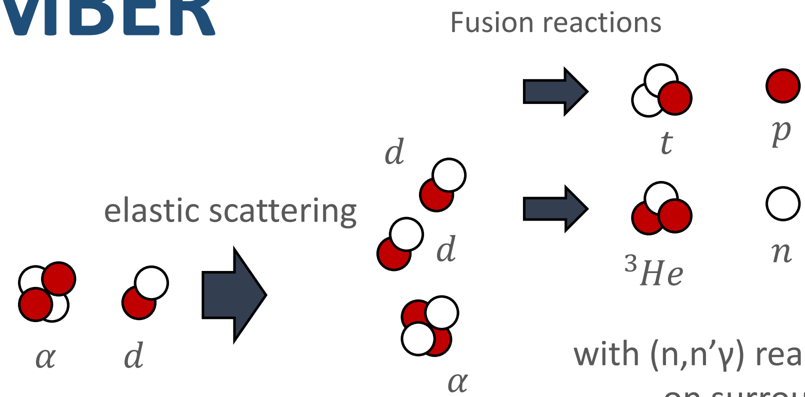


Deep Underground Laboratory is mandatory → Laboratori Nazionali del Gran Sasso (LNGS)

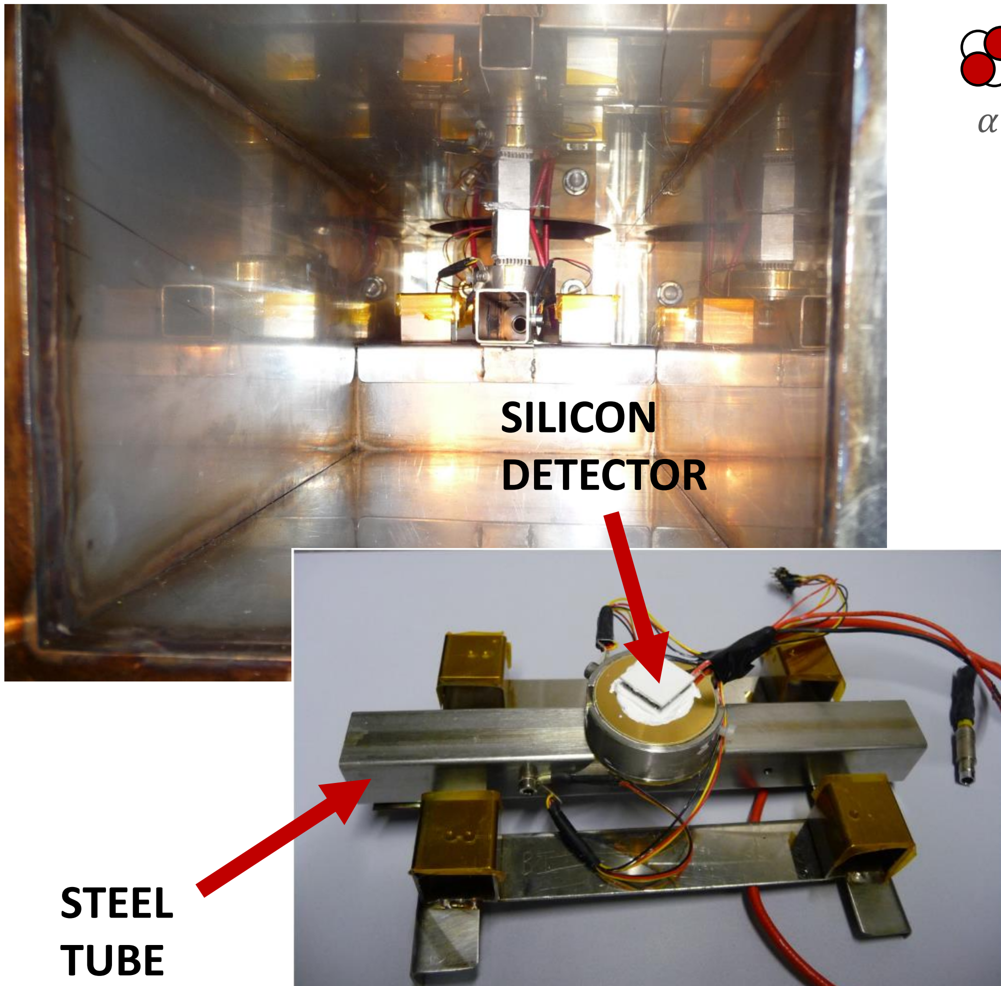
THE $^{2}H(\alpha,\gamma)^{6}Li$ GAS CHAMBER

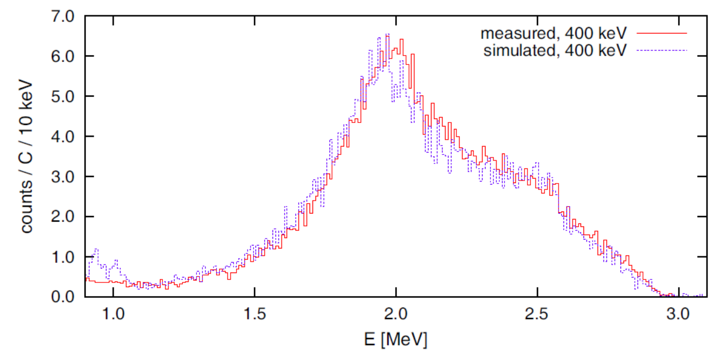
THE $^{2}H(\alpha,\gamma)^{6}Li$ GAS CHAMBER

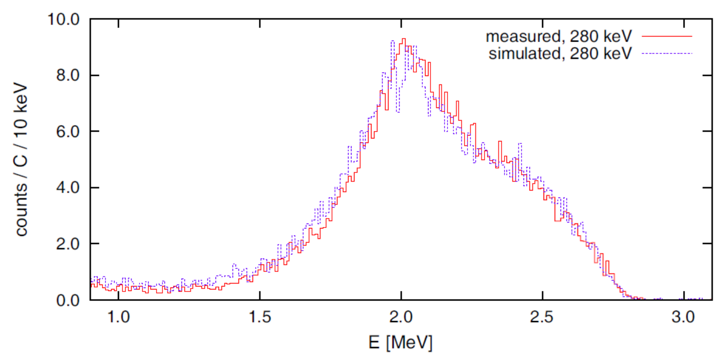
This reaction exhibits a huge **beam induced background** (BIB):



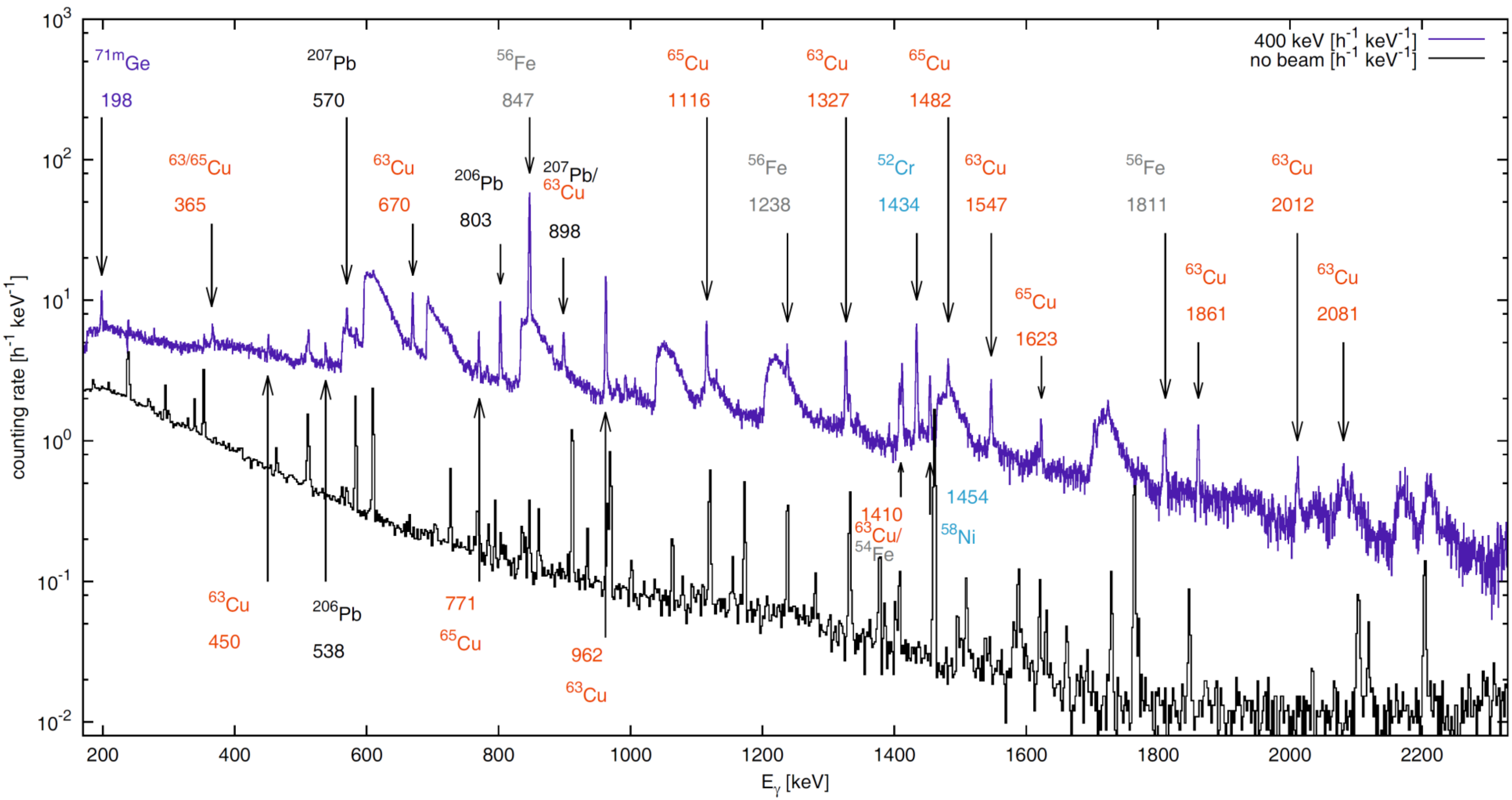
with (n,n'γ) reactions on surrounding materials





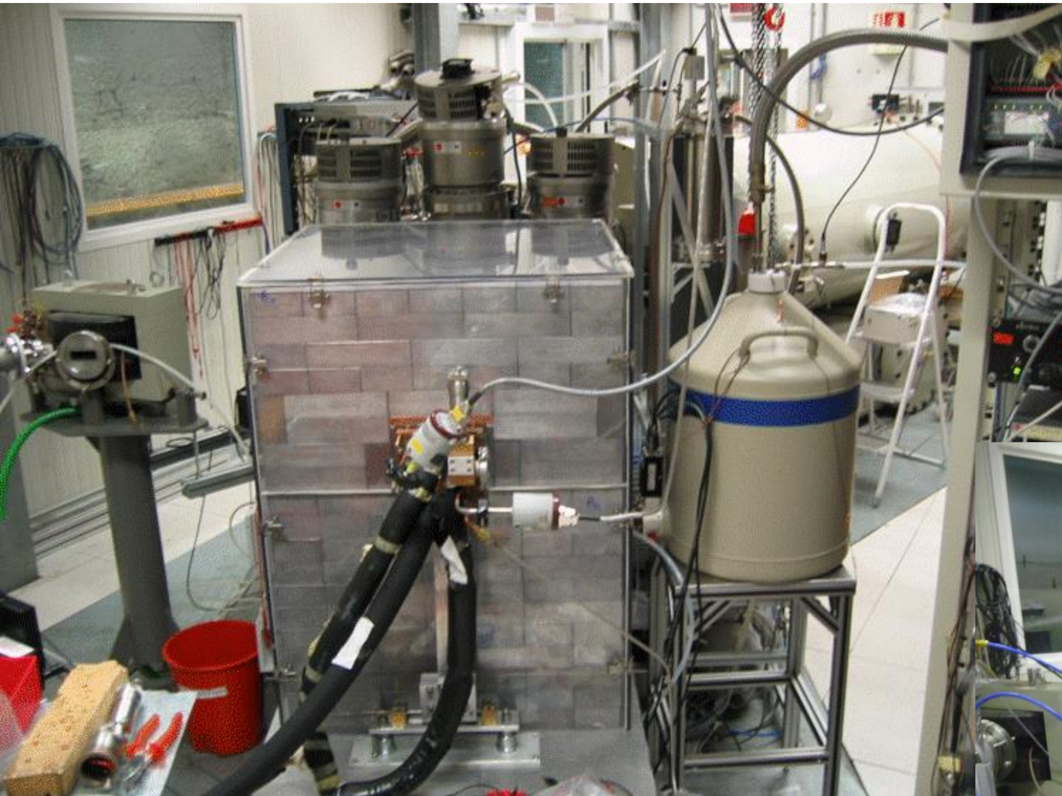


THE $^2H(\alpha,\gamma)^6Li$ GAS CHAMBER



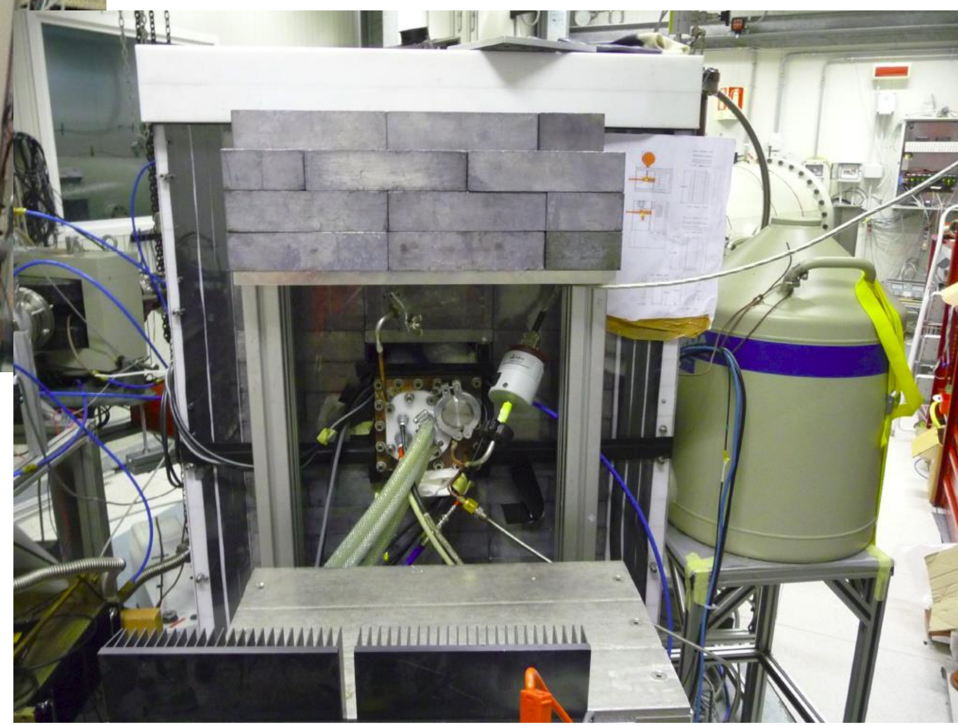
M. Anders et al., *Eur. Phys. J. A* **49** (2013) 28

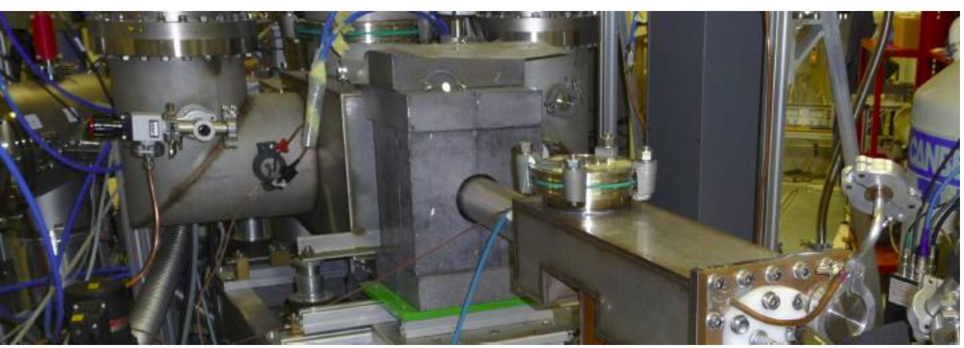
$^{2}H(\alpha,\gamma)^{6}Li$ GAS TARGET SHIELDING



In order to minimize the natural background and to prevent any possible increasing of the LNGS neutron background the follow passive shields have been implemented:

- Lead castle
- Anti-Radon box
- Borated HDPE

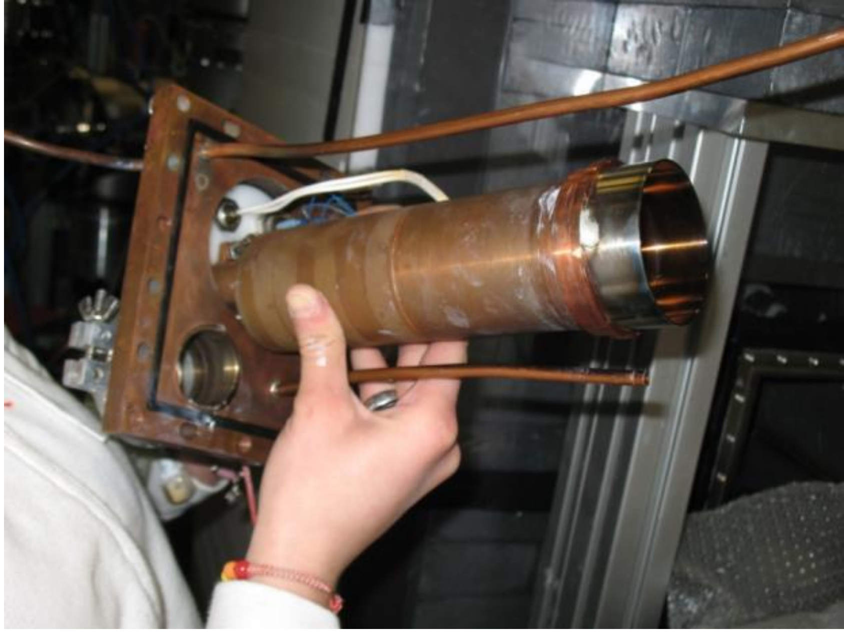




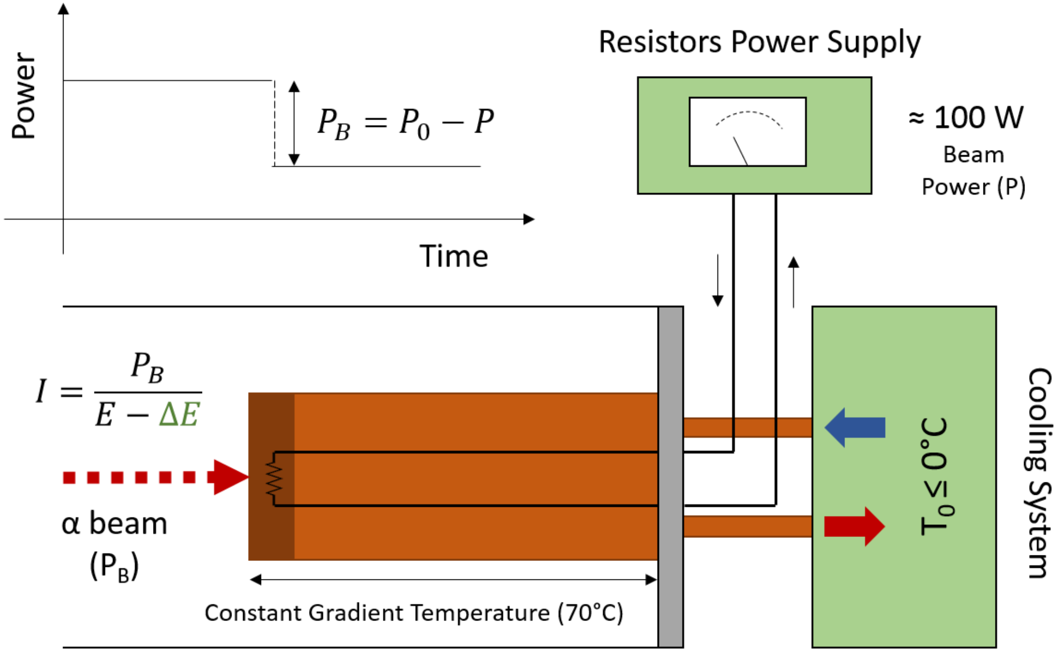
THE $^{2}H(\alpha,\gamma)^{6}Li$ CALORIMETER

THE LUNA CALORIMETER

In order to measure the beam current a constant temperature gradient calorimeter has been used.

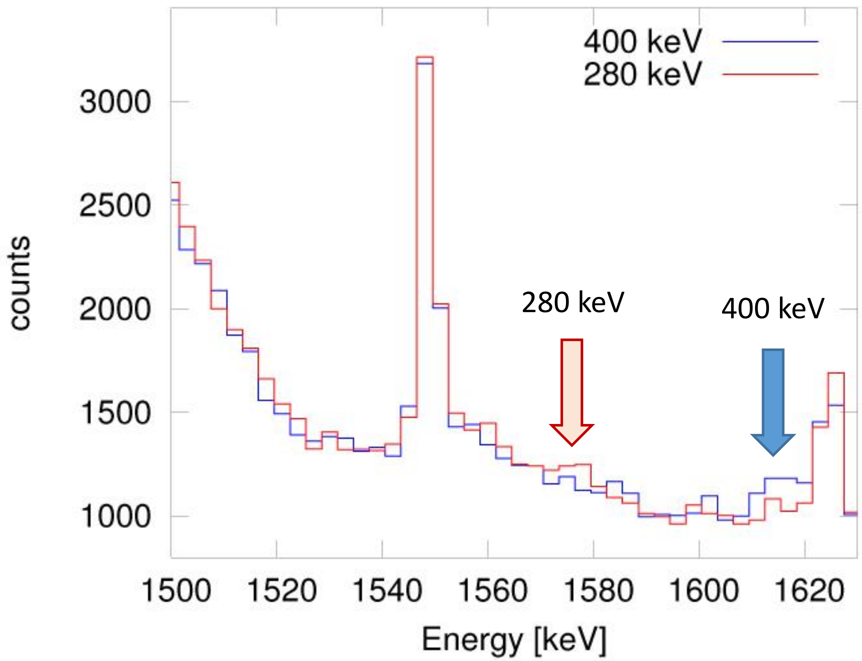


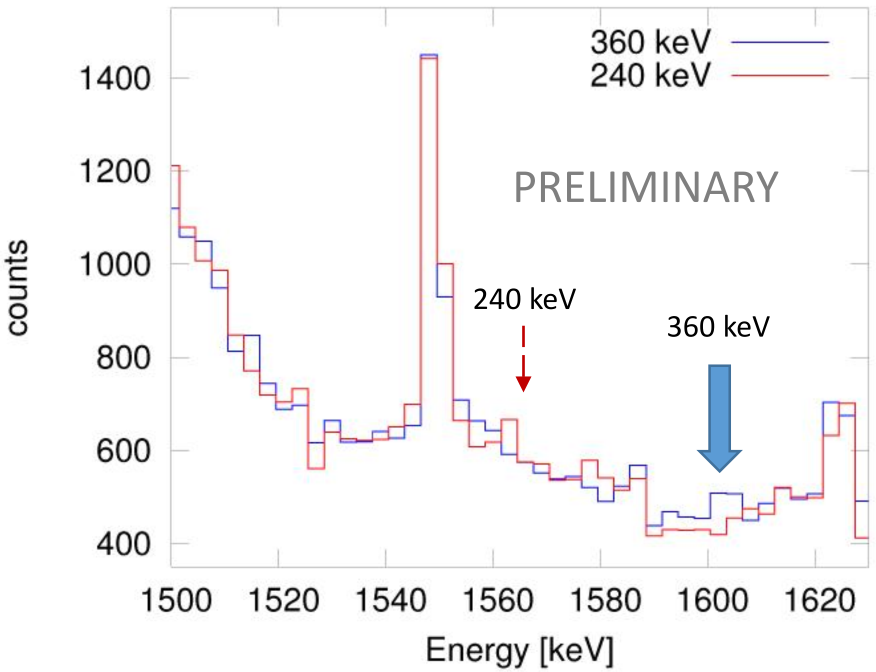
Source	Systematic uncertainties
Angular distribution	9%
Detector efficiency	8%
Beam current	3%
Temperature	3%
Pressure	1%
Target length	1%
Gas purity	1%
Beam energy	< 1%
total	**13%**



THE $^2H(\alpha,\gamma)^6Li$ MEASUREMENT AT LUNA

Four different beam energies have been investigated (240, 280, 360 and 400 keV).
Seven (4 in lab) years has been spent in order to take and analyze the data.





$$E_\gamma = \frac{m_\alpha^2 + m_d^2 - m_{Li}^2 + 2m_d(E_\alpha + m_\alpha)}{2[E_\alpha + m_\alpha + m_d - p_\alpha \cos(\theta_{lab})}$$

E [keV]	E_α [keV]	P [mbar]	Q [C]	t [h]
80	240	0.306	211.5	217.7
93	280	0.308	538.9	490.9
120	360	0.306	252.7	205.2
133	400	0.306	514.3	437.7

PEAK SHAPE ANALYSIS HAS ALSO BEEN PERFORMED

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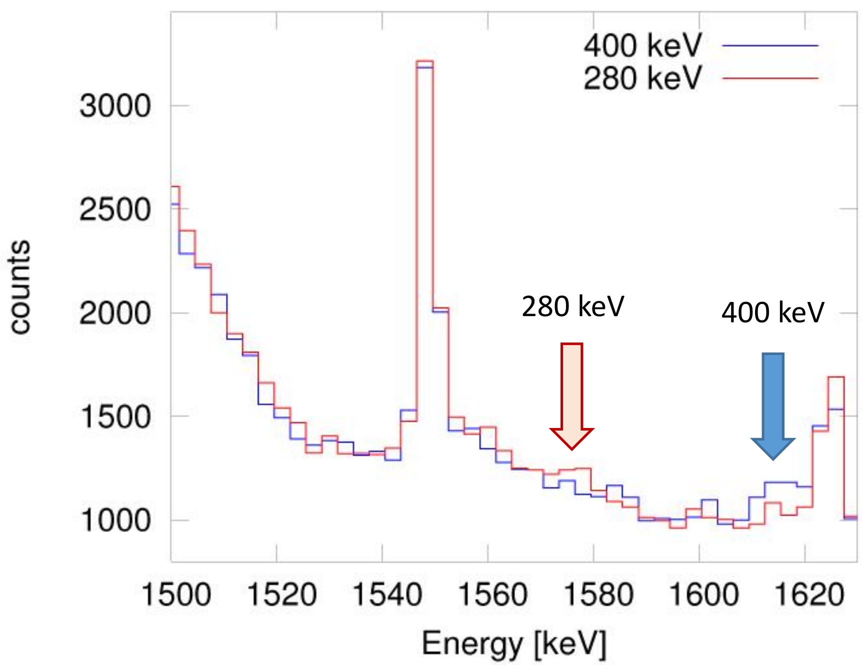
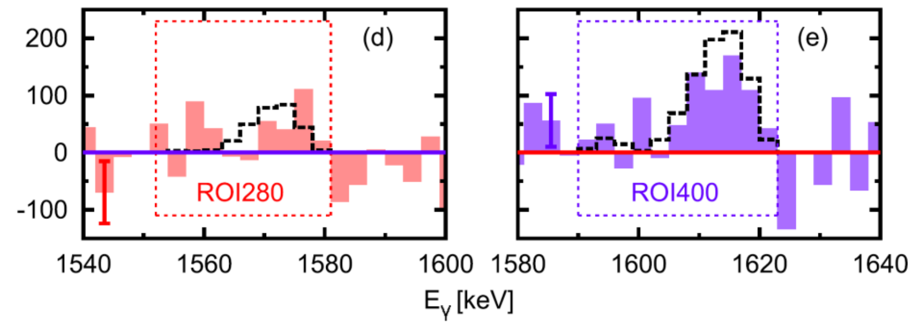
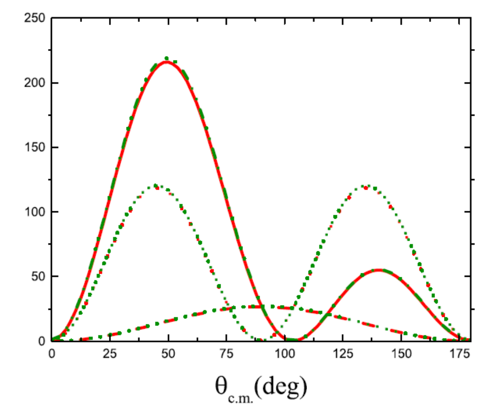




A. M. Mukhamedzhanov et al., arXiv: 1602.07395 (25 Feb. 2016)



$$E_{\gamma} = \frac{m_{\alpha}^{2} + m_{d}^{2} - m_{Li}^{2} + 2m_{d}(E_{\alpha} + m_{\alpha})}{2[E_{\alpha} + m_{\alpha} + m_{d} - p_{\alpha}\cos(\theta_{lab})}$$

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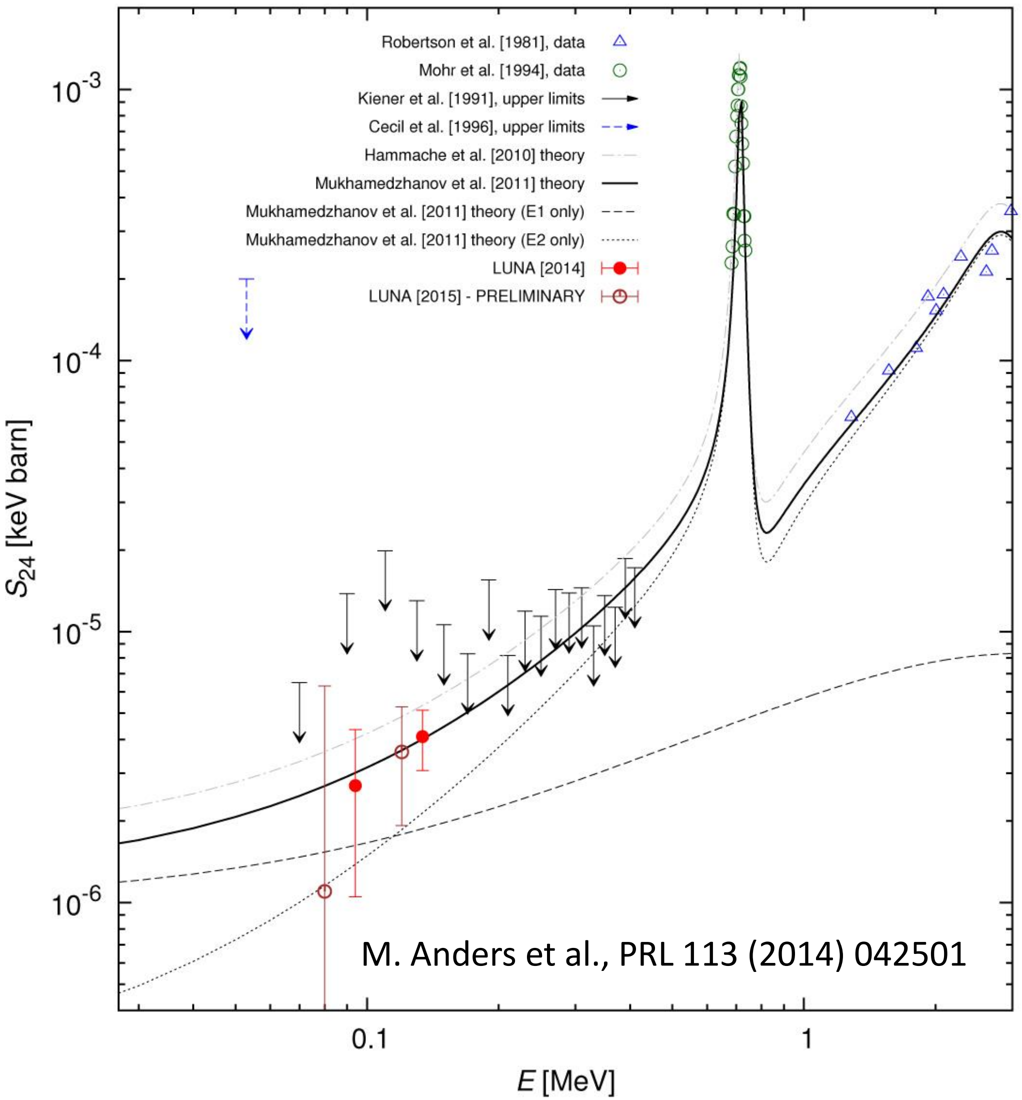
THE $^{2}H(\alpha,\gamma)^{6}Li$ MEASUREMENT AT LUNA



The S-factor of the $^{2}H(\alpha,\gamma)^{6}Li$ nuclear reaction has been measured, providing the firs data points at BBN energies. Using the new $^{2}H(\alpha,\gamma)^{6}Li$ cross section a relative BBN lithium-6 abundance:

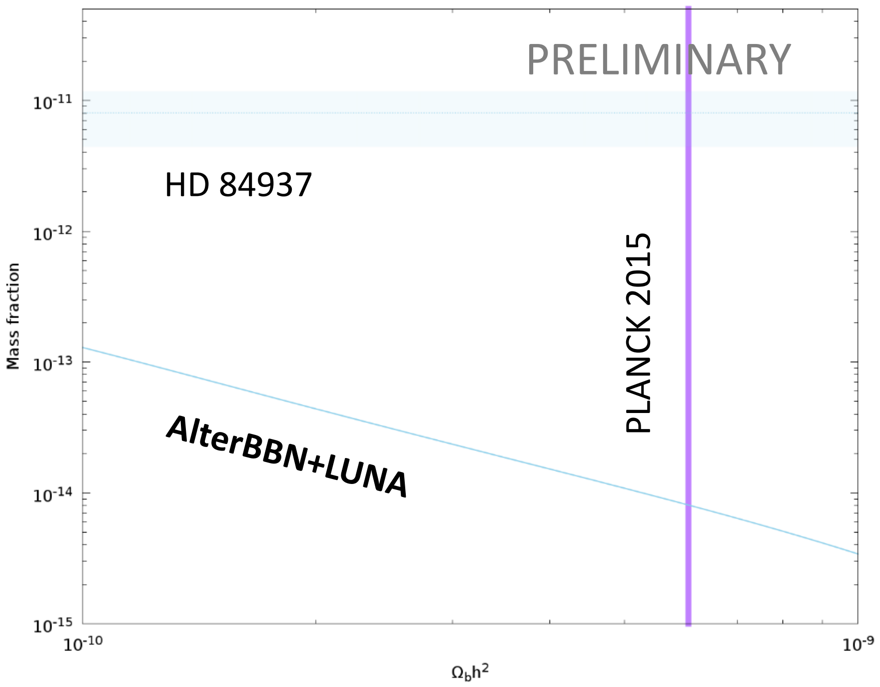
$$^{6}Li/H = (0.80 \pm 0.18) \times 10^{-14}$$

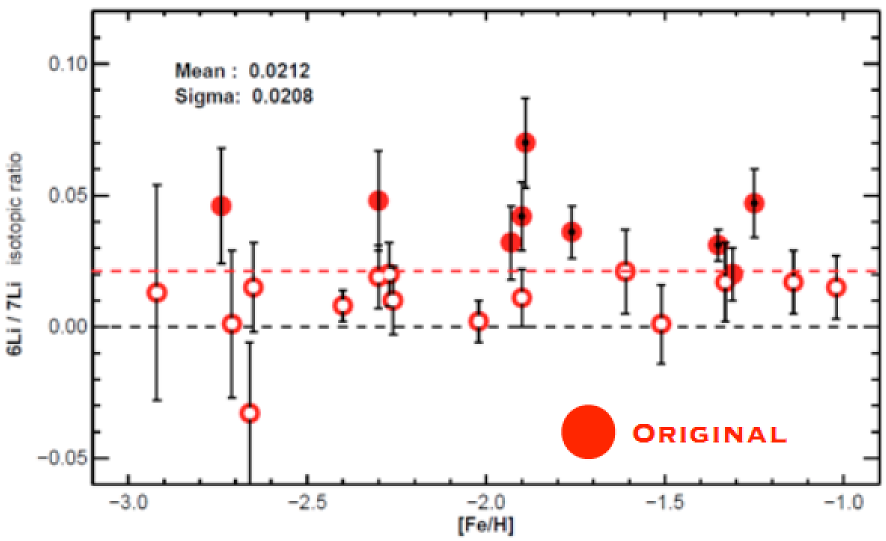
is obtained. It is 27% lower than the value obtained when using the CF88 rate for $^{2}H(\alpha,\gamma)^{6}Li$

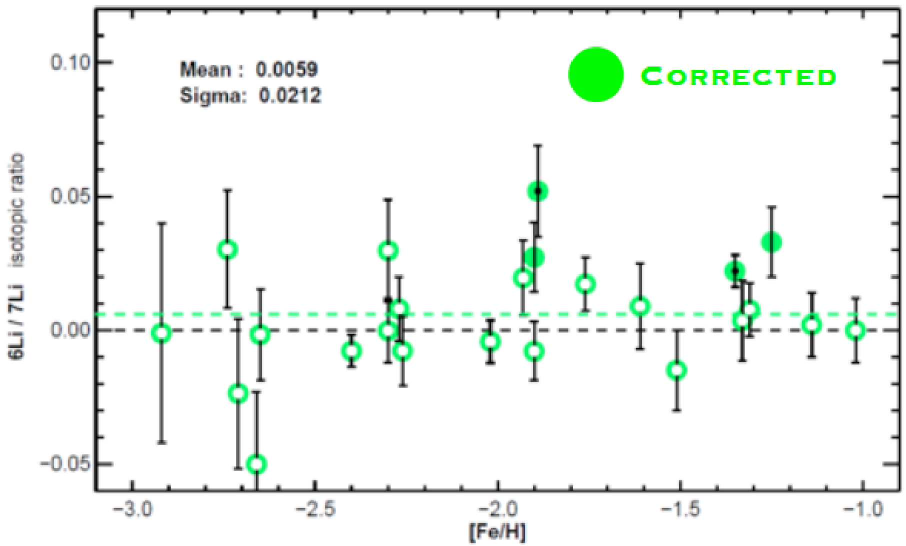
$$S_{24}(134\,\text{keV}) = (4.0^{+0.8\,(\text{stat})}_{-0.9} \pm 0.5^{(\text{syst})}) \times 10^{-6}\ \text{keV}\,b,$$

$$S_{24}(94\ \text{keV}) = (2.7^{+1.5\,(\text{stat})}_{-1.6} \pm 0.3^{(\text{syst})}) \times 10^{-6}\ \text{keV}\,b.$$

THE SECOND LITHIUM PROBLEM IN 2016



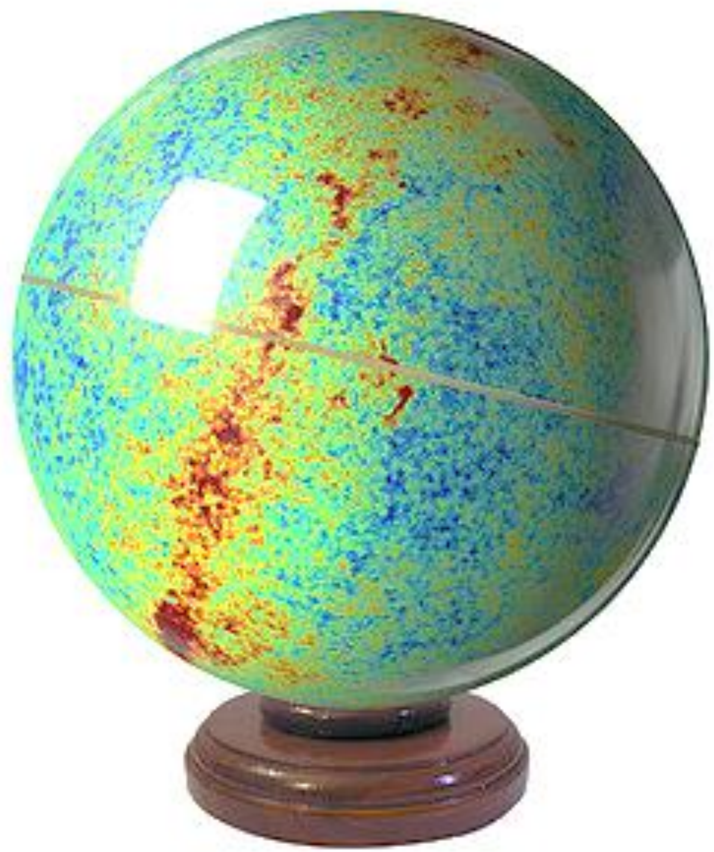




- Using AlterBBN code + LUNA all data we obtain a three order of magnitude difference between observed and calculated ^{6}Li primordial abundance → **Second Lithium Problem**
- Using different stellar atmosphere models, in one (1D) or three (3D) dimensions and with or without Local Thermodynamic Equilibrium (LTE/NLTE) different results have been obtained

M. Steffen et al., Light elements in the Universe (2010)

CONCLUSIONS: THE SECOND LITHIUM PROBLEM



- **LUNA data firmly ruling out standard BBN production as a possible explanation for the reported ^{6}Li detections**.
- As a result, possible remaining scenarios explaining the observed ^{6}Li abundance may be, under very special conditions, a stellar flare in situ production of ^{6}Li or *nonstandard* physics solutions.

Cosmic lithium-6 is clearly a high interesting probe of physics beyond the **Standard Model**

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