LUNA

INFN BARI
Istituto Nazionale di Fisica Nucleare
Sezione di Bari

SIGILLUM UNIVERSITATIS BARENSIS MCMXX

nTOF

High precision measurements of nuclear reactions for Nuclear Astrophysics

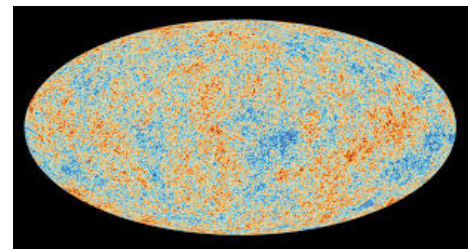
G.F. Ciani & M. Mastromarco
on behalf of LUNA and n_TOF Bari

Nuclear Astrophysics: an interdisciplinary field

Observational astronomy

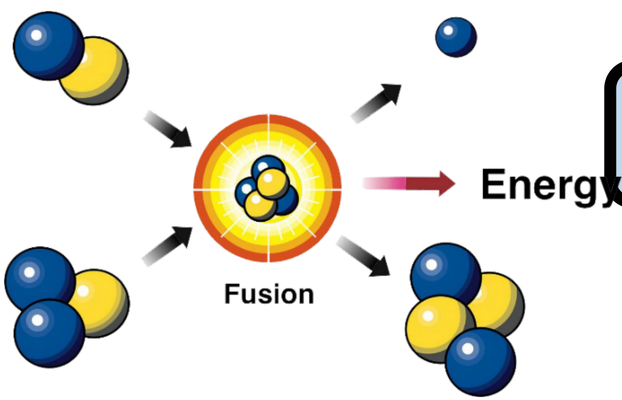
Cosmology

Nuclear astrophysics

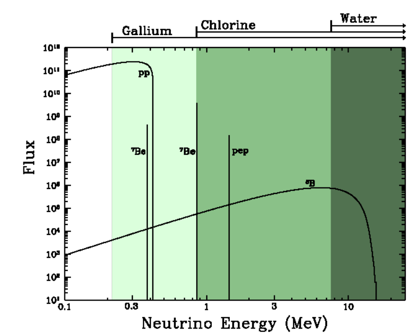


Nuclear physics

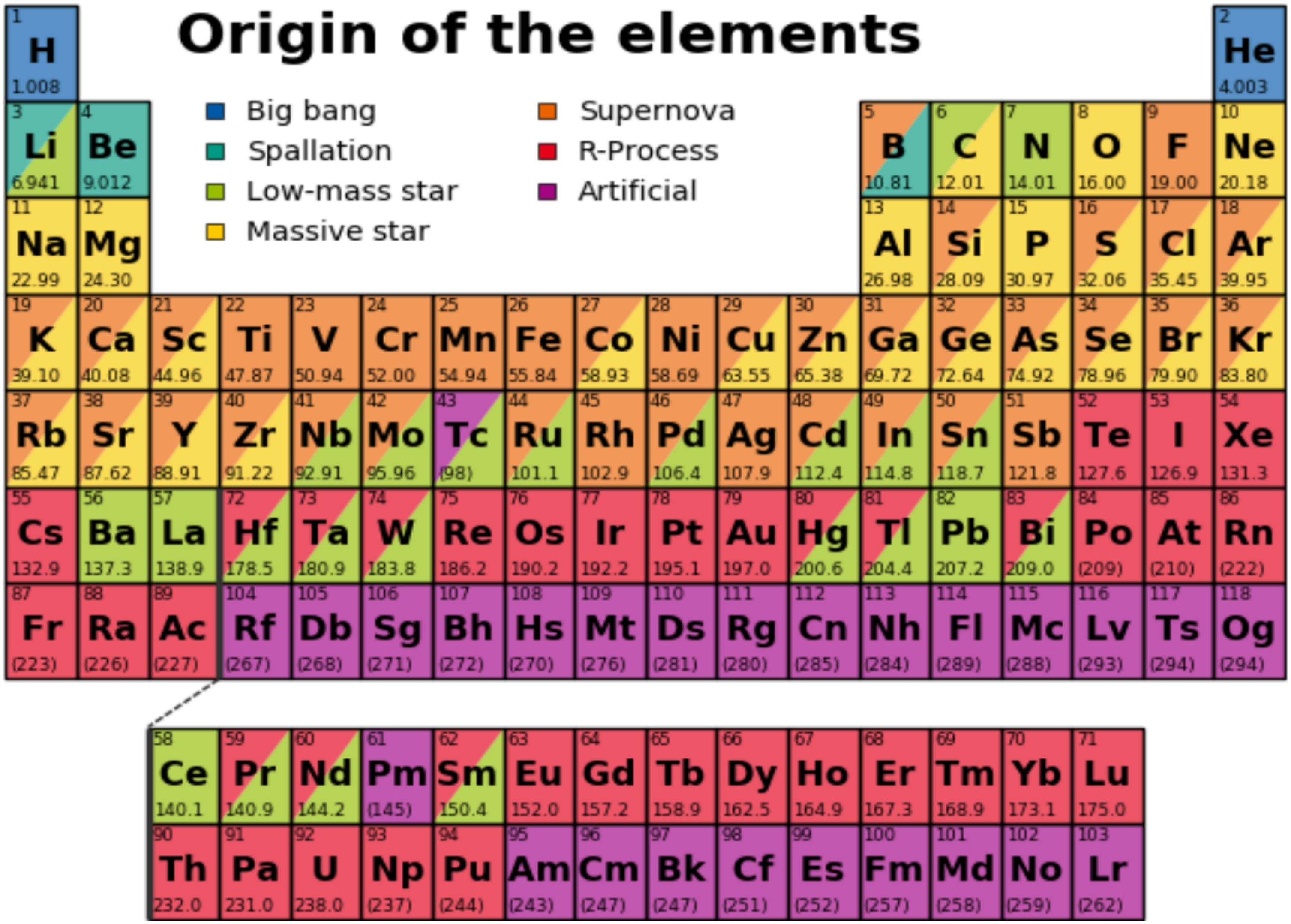
Neutrino physics



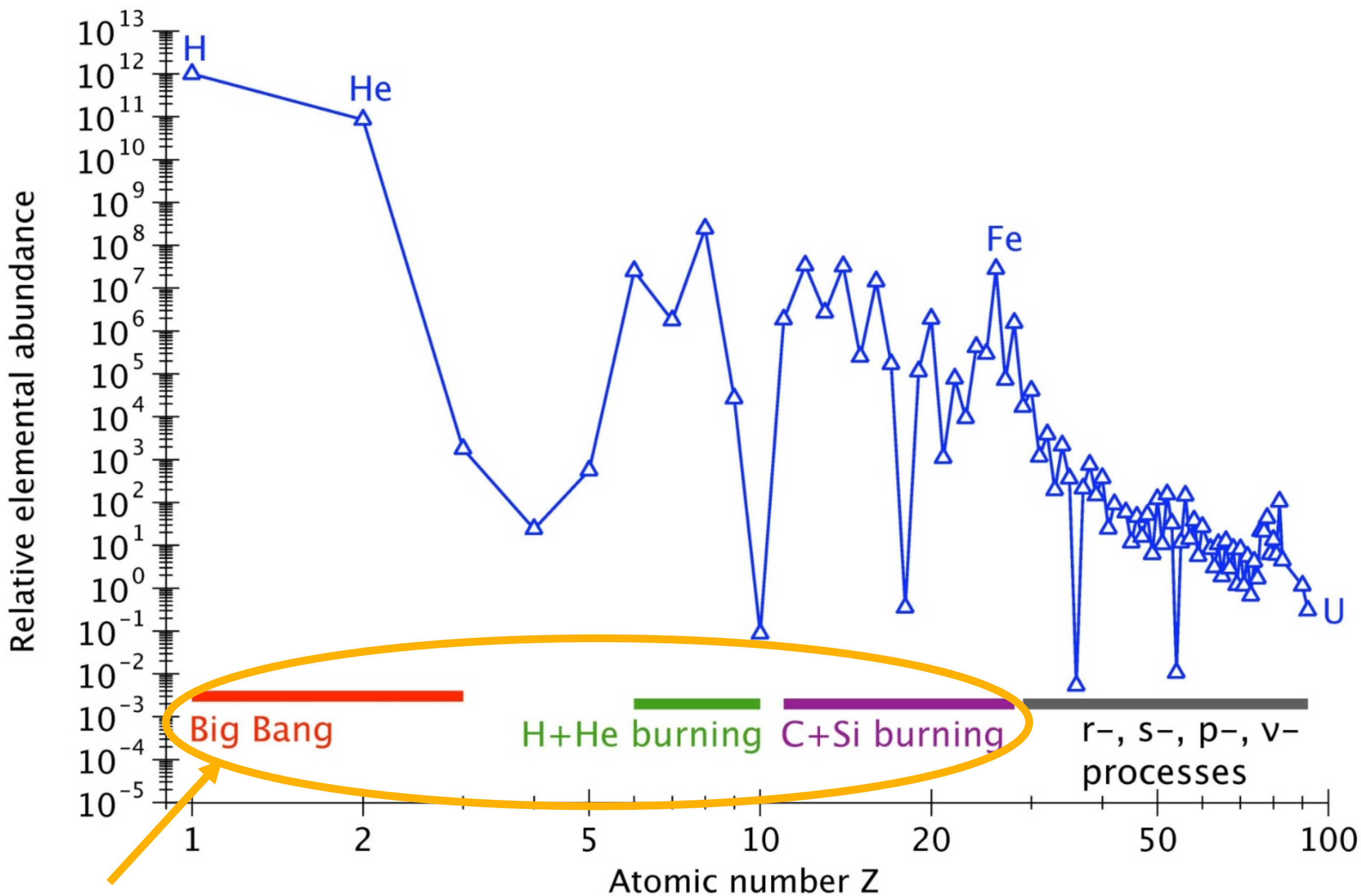
Stellar Models



The Origin of the Elements

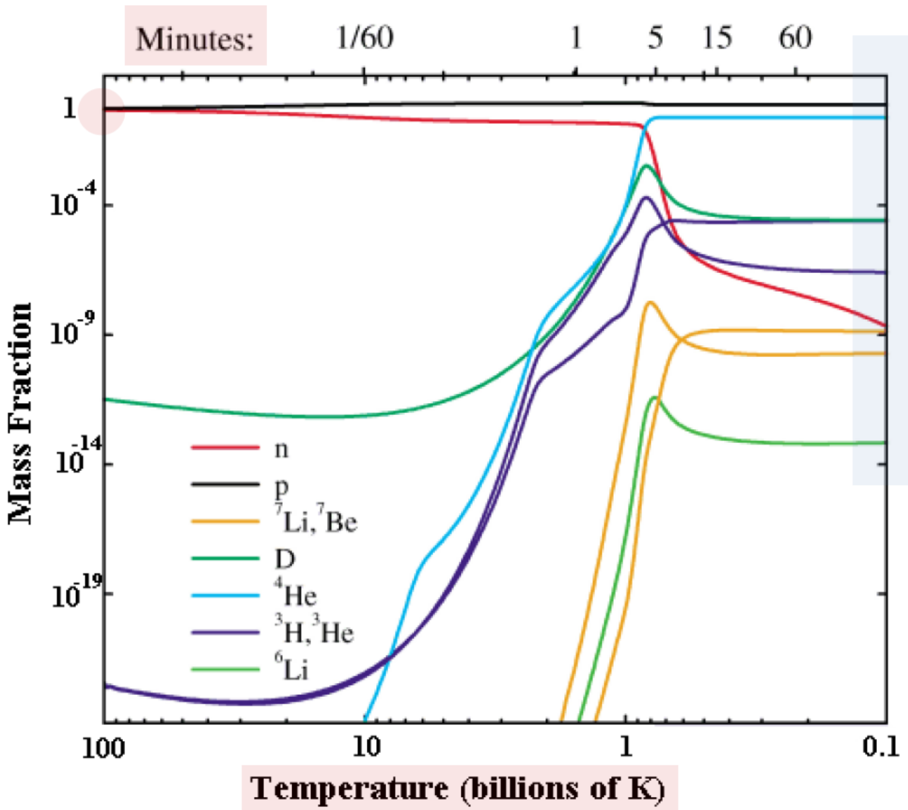


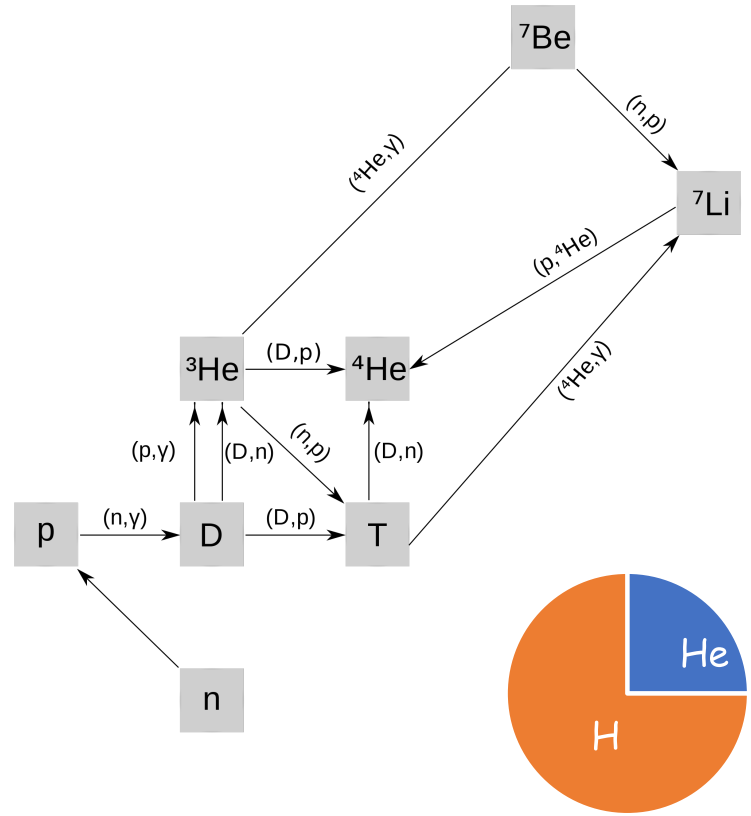
The Origin of the Elements



Charged-particle induced reactions

Big Bang Nucleosynthesis

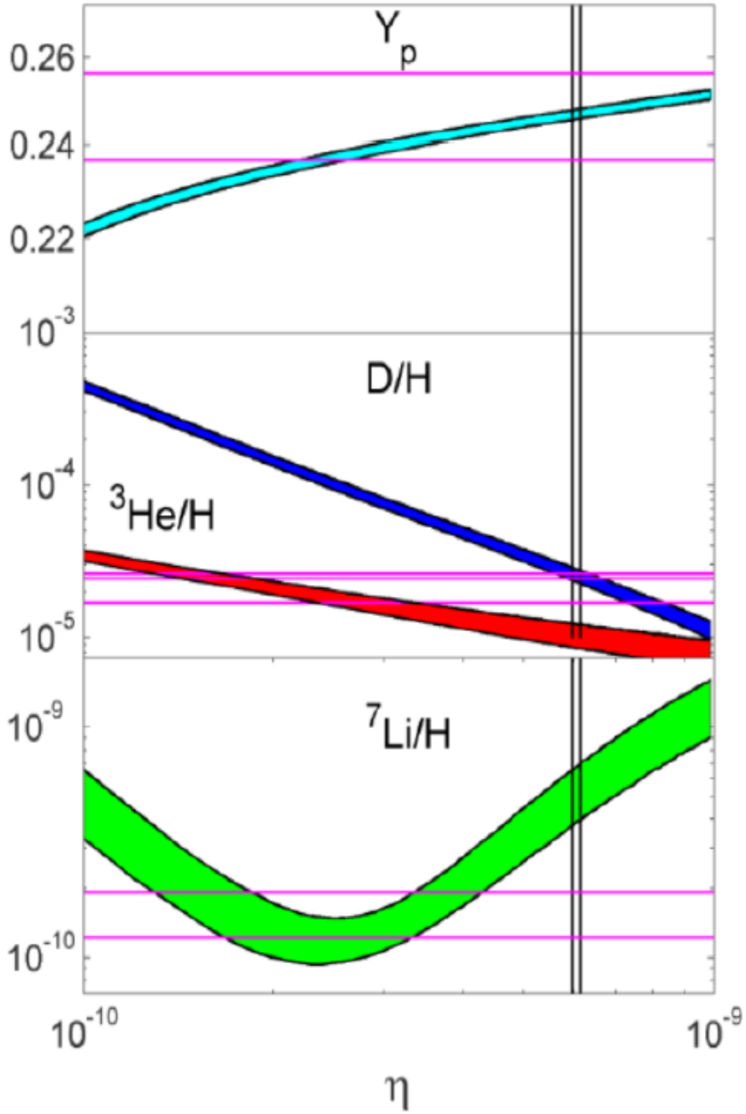




- BBN occurs 3 minutes after Big Bang

✓ After BBN we have mainly H and ^{4}He plus small amounts of D, ^{3}He, ^{6}Li and ^{7}Li

Comparison between BBN theory and observation



Agreement for most of nuclides

D/H strongly depends on the baryon to photon density.
A low uncertainty on this parameter put stronger contraints on baryon density

Discrepancy for ^7Li

Two crucial processes studied by UniBa/INFN Ba

nTOF

LUNA

PHYSICAL REVIEW LETTERS **121,** 042701 (2018)

^{7}Be(n,p)^{7}Li Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN

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(The n_TOF Collaboration [www.cern.ch/ntof])

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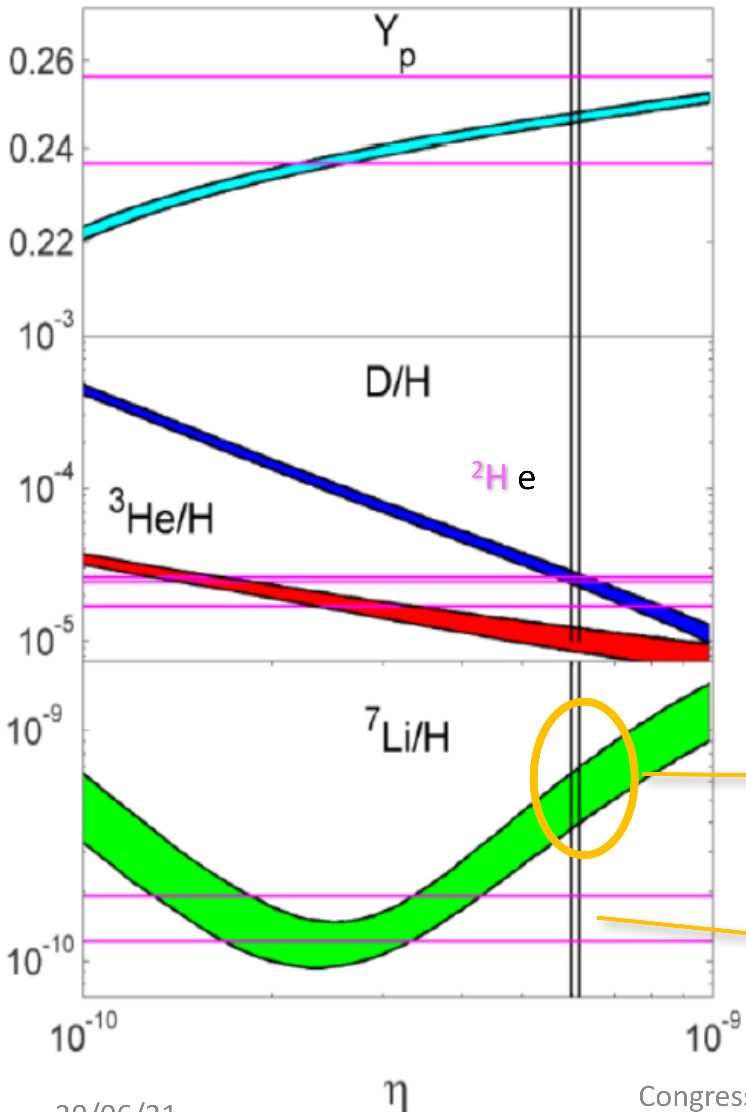
The baryon density of the Universe from an improved rate of deuterium burning

V. Mossa, K. Stöckel, F. Cavanna, F. Ferraro, M. Aliotta, F. Barile, D. Bemmerer, A. Best, A. Boeltzig, C. Broggini, C. G. Bruno, A. Caciolli, T. Chillery, G. F. Ciani, P. Corvisiero, L. Csedreki, T. Davinson, R. Depalo, A. Di Leva, Z. Elekes, E. M. Fiore, A. Formicola, Zs. Fülöp, G. Gervino, A. Guglielmetti, C. Gustavino, G. Gyürky, G. Imbriani, M. Junker, A. Kievsky, I. Kochanek, M. Lugaro, L. E. Marcucci, G. Mangano, P. Marigo, E. Masha, R. Menegazzo, F. R. Pantaleo, V. Paticchio, R. Perrino, D. Piatti, O. Pisanti, P. Prati, L. Schiavulli, O. Straniero, T. Szücs, M. P. Takács, D. Trezzi, M. Viviani & S. Zavatarelli -Show fewer authors

Nature **587**, 210–213(2020) | Cite this article

n_TOF and the cosmological lithium problem



BBN calculation

Observed ^{7}Li

Cosmological lithium problem (CLP): discrepancy by a factor 3 between primordial abundance of ^{7}Li from the astronomical observation and predicted by Big Bang Nucleosynthesis (BBN) calculation.

Possible solution for the CLP

ONE POSSIBILITY IS THE SO CALLED NUCLEAR SOLUTION

95% of primordial ^{7}Li is produced from ^{7}Be dacay (electron capture)

$$^{7}\mathbf{Be} + \mathbf{e}^{-} \rightarrow \ ^{7}\mathbf{Li} + \boldsymbol{\nu}_{e}$$

Reducing ^{7}Be quantity produced during BBN would reduce also primordial ^{7}Li abundance

For example is there a ^{7}Be rate destruction underestimation ?

Two possible n-induced reactions involved

^{7}Be(n,p)7Li

97% contribution in the ^{7}Be destruction by n capture →

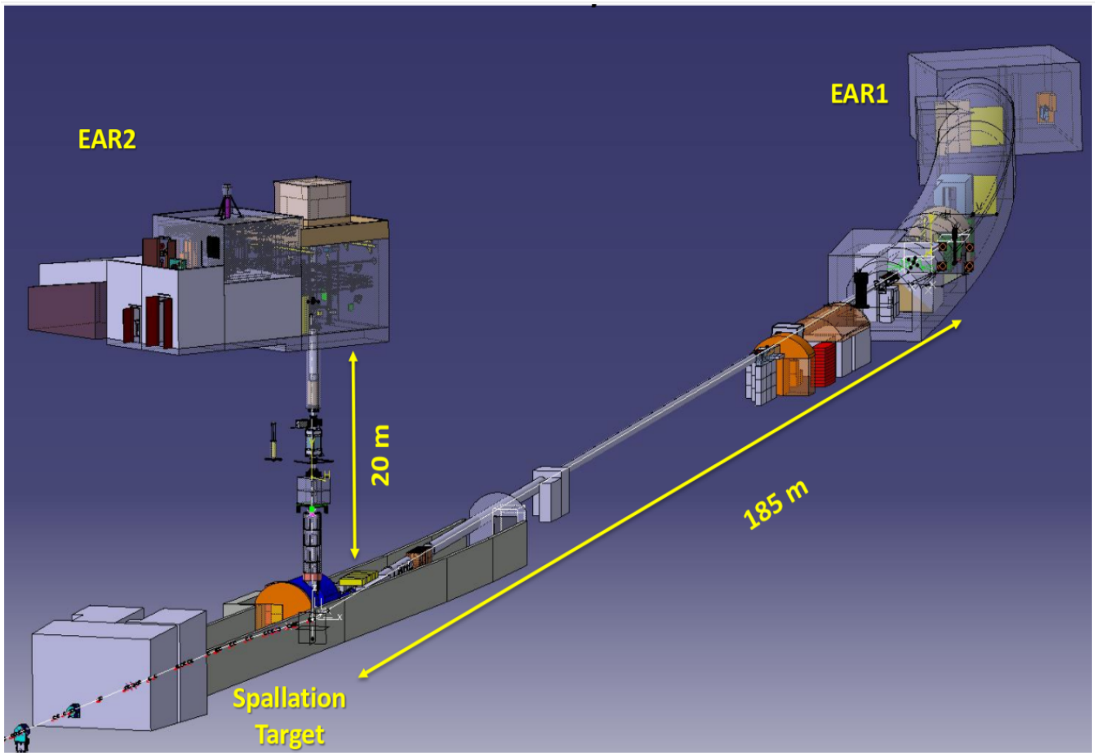
^{7}Be(n,α)^{4}He

2.5% contribution in the ^{7}Be destruction by n capture

n_TOF BA contributions

- **Measurement proposed by n_TOF BA group**
- **responsible for target implantation (ISOLDE)**
- **Data Analysis mainly by L. Damone (PhD in Bari, CSN III Villi Prize 2020)**

Facility 'NEUTRON TIME OF FLIGHT' N_tof @ CERN



^{7}Be target used for the measurement has short half life (52 d) implanted with a radioactive beam at ISOLDE (CERN).

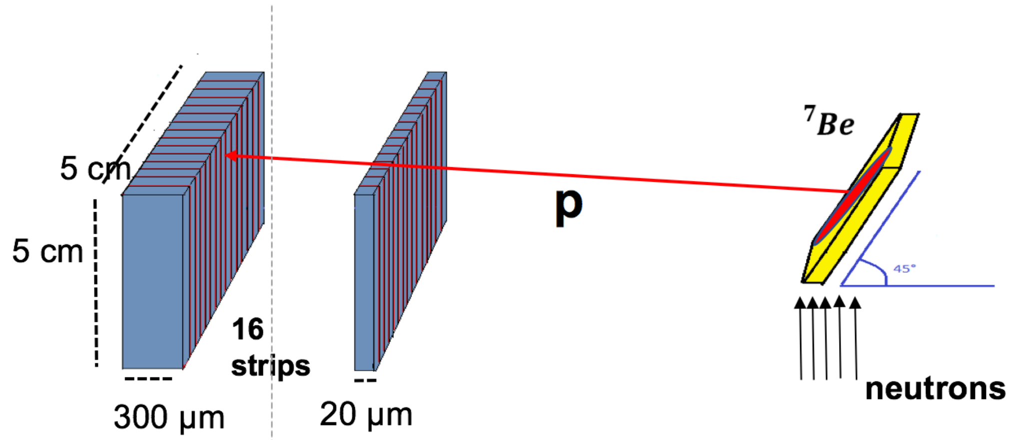
This is an excellent example of sinergy generating an unique case in the world where it is possible to perform an experiment with neutron beam and a short life radioactive target.

- Proton beamline (20 GeV)
- a spallation target (lead)
- two neutron beamlines
- two experimental areas (EAR1 e EAR2)

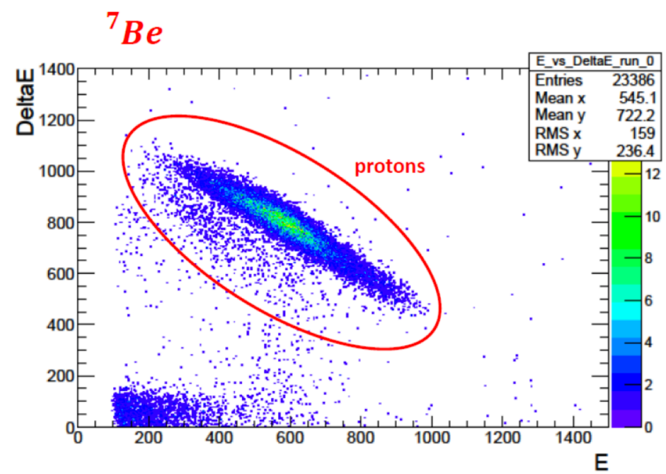
Experimental setup (n, p)^{7}Li

Q = 1.64 MeV, low energy protons: High purity ^{7}Be sample was neccessary

•^{7}**Be beam at ISOLDE separated** by means of a magnetic dipole, and implanted on a **20 m thick Al backing**



Protons detected by a dE-E telescope silicon detector



Results and astrophysical implications

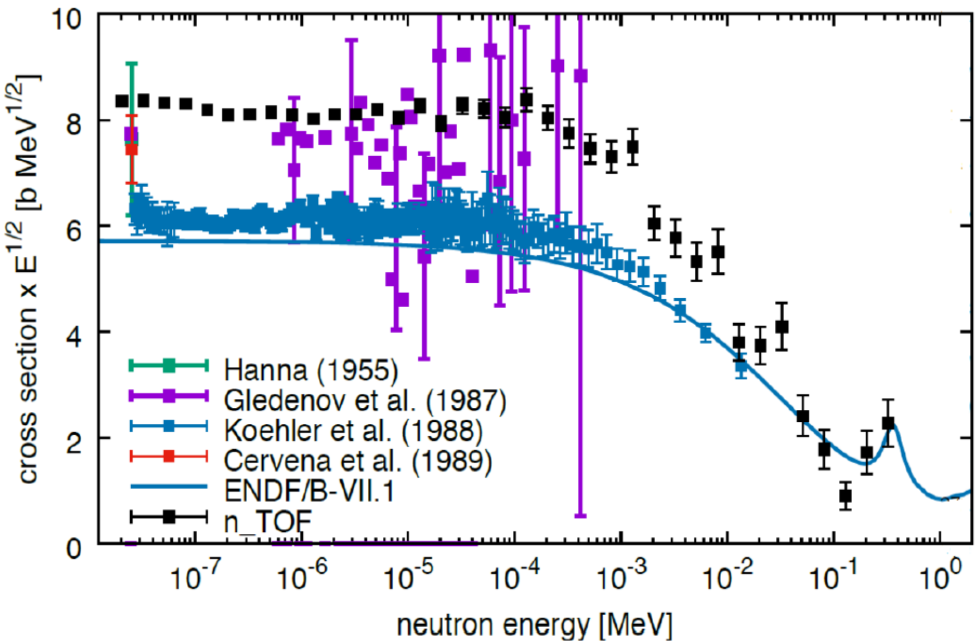


Figure from Damone et al. PHYSICAL REVIEW LETTERS 121, 042701 (2018)

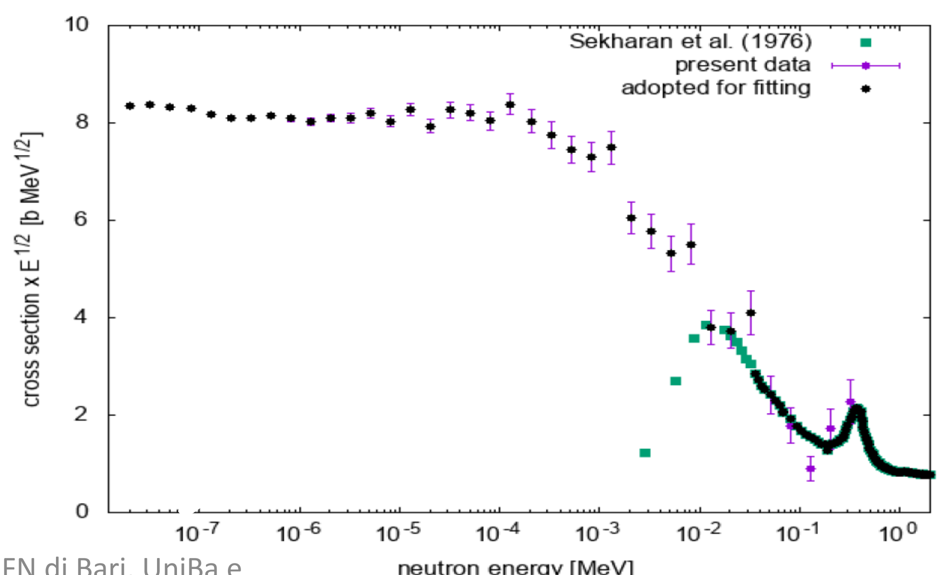
thermal E:
- 52.3 ± 5.2 kb
- n_TOF data about 35% -40% larger than literature

From 1 keV convergence of data with indirect one (time reversal reaction)

325 keV: Upper limit due to background

Cross section fit performed in the region of interest of BBN (> 10^{-2} MeV)

n-TOF data in agreement with the **time-reversal reaction** ^{7}Li(p,n)^{7}Be (Sekharan et al.) da 35 keV a 2 MeV



Conseguences on BBN

code AlterBBN: calculation of abundances of isotopes as a function of the time having as input the reaction rates of 12 most important reaction in the BBN network

Mishra and Basu (2012) [112]	5.02
Coc et al. (2014)[113]	$4.94^{+0.40}_{-0.38}$
Coc et al. (2015) [114]	5.61 ± 0.26
Singh et al. (2017) [115]	4.45 ± 0.07
This work with standard rates	5.46
This work with present rate ($\eta_{10} = 6.09 \pm 0.06$)	5.26 ± 0.40
This work with present rate ($5.8 \leq \eta_{10} \leq 6.6$)	4.73-6.23
Observations [2]	1.6 ± 0.3

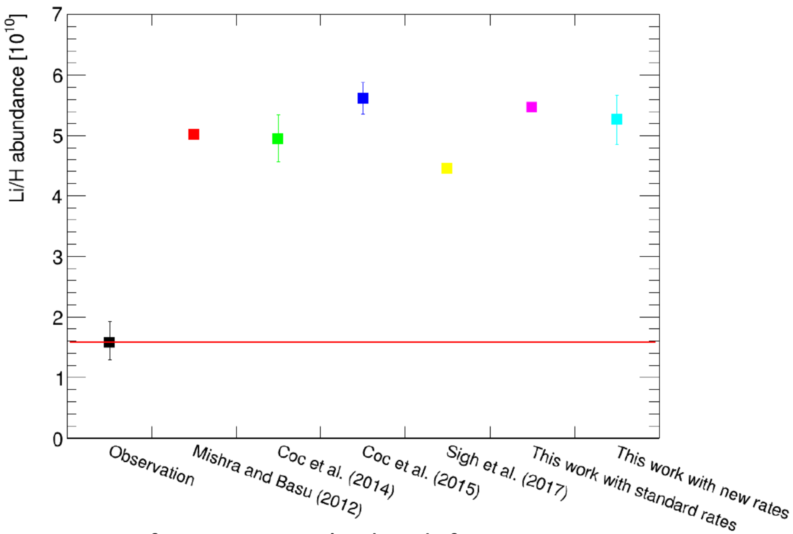


Figure from Damone's PhD defense

New obtained results after this work, the 7Li production is reduced by 10% with respect other data in literature (Coc et al. 2015).
This variation does not improve the Lithium problem, but it excludes a nuclear solution for the problem .

LUNA and the primordial deuterium abundance

Deuterium abundance strongly dependent by the baryon density

- Observed abundance

Direct astronomical observations

$[D/H]_{OBS} = (2.527 \pm 0.030) \times 10^{-5}$

Cooke et al, APJ 855 (2018) 102

- Predicted abundance (BBN theory):

From BBN theory, knowing the cosmological parameters and the cross sections of the processes responsible for D creation and destruction $[D/H]_{BBN}$

$[D/H]_{BBN} = (2.439 \pm 0.052) \times 10^{-5}$

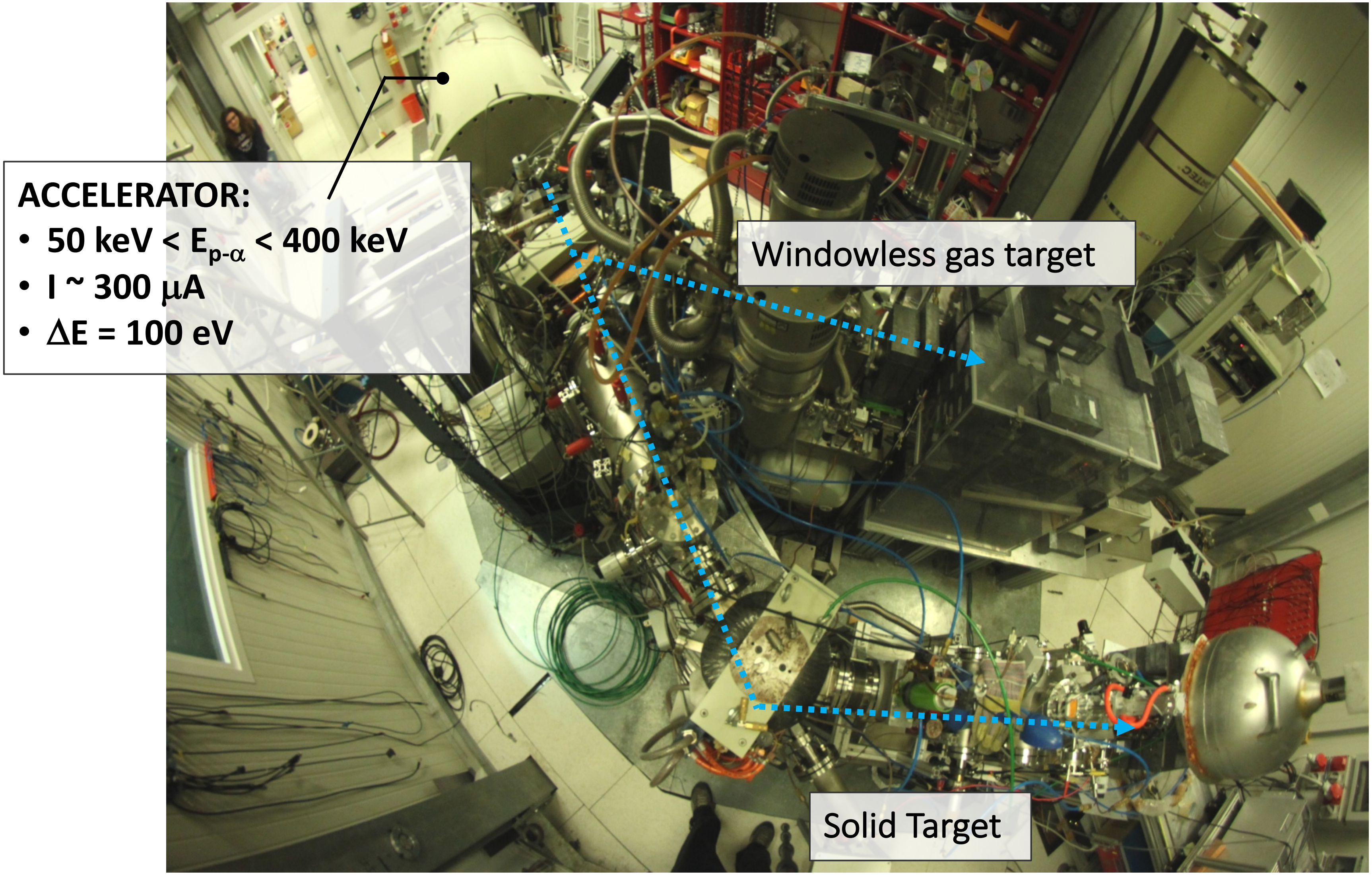
Planck, A&A 641 (2018) A6

✓ By comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$ → more stringent constraints to the universal barion density Ω_B and/or N_{eff}

One of the cross section with highest uncertainties was the $p(D,\gamma)^3He$ (Q= 5.493 MeV).

In order to improve the theory, 3% overall uncertainty on the cross section was required. LUNA “accepted” this challenge!

LUNA experimental setup



Experimental challenges of direct measurement

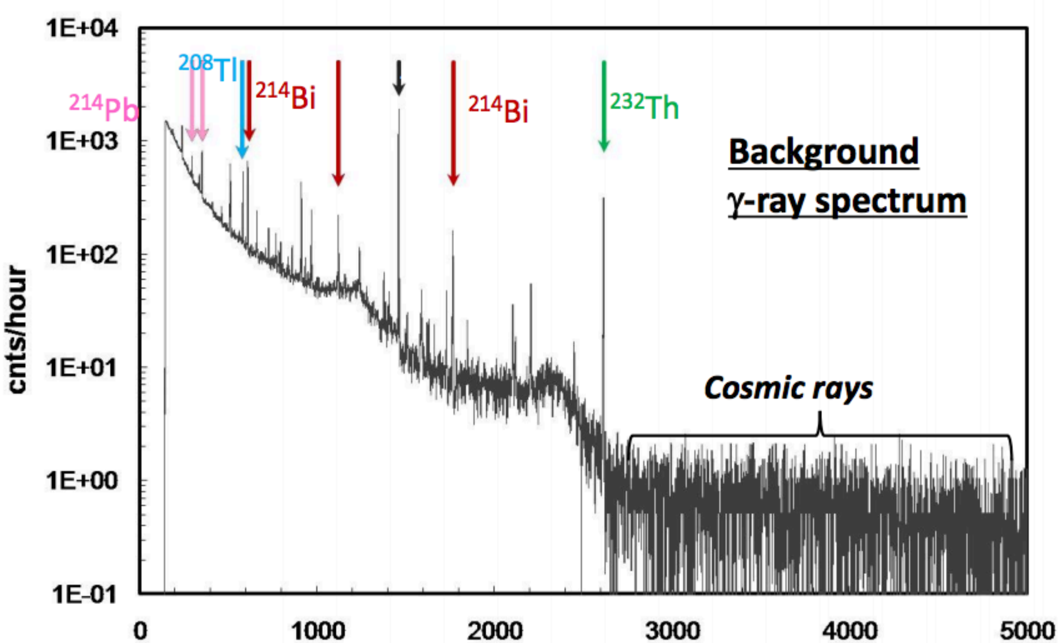
Counting Rate = N_p x N_t x cross section x detection efficiency

10^{14} pps (~ 50 µA q=1+)

~ 10^{17} atoms/cm^2 gas target density

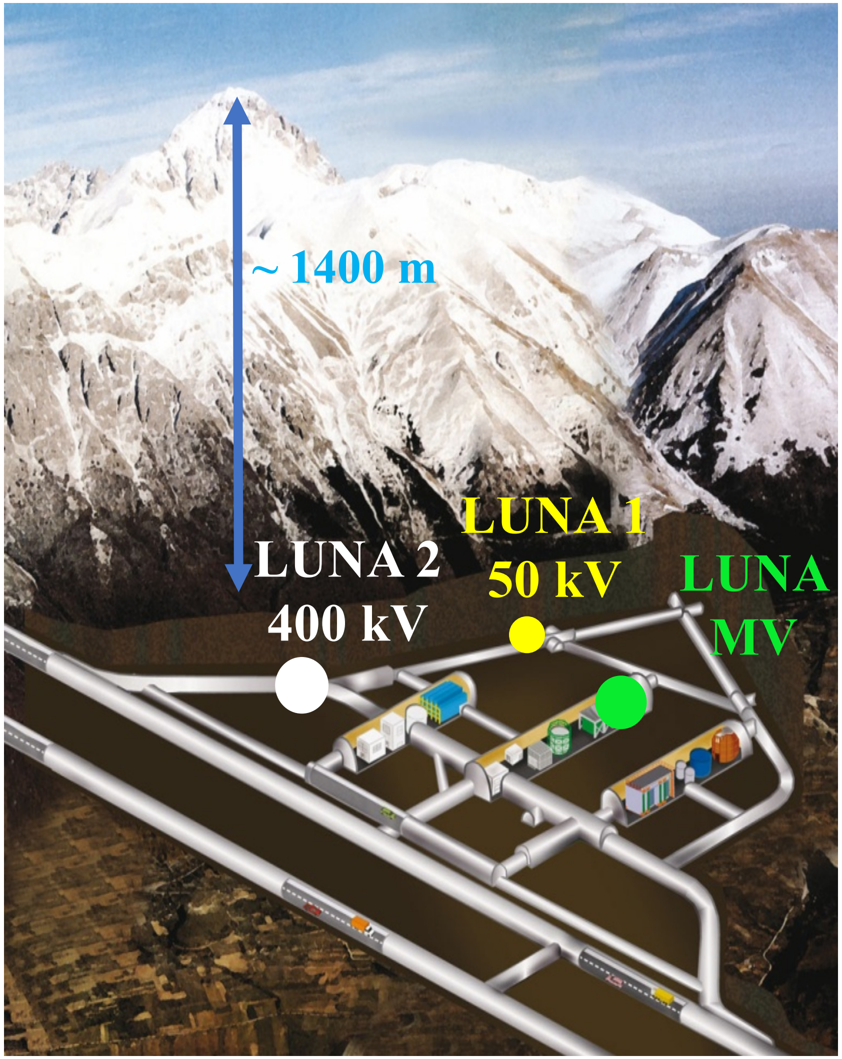
~ 10^{-32} cm^2

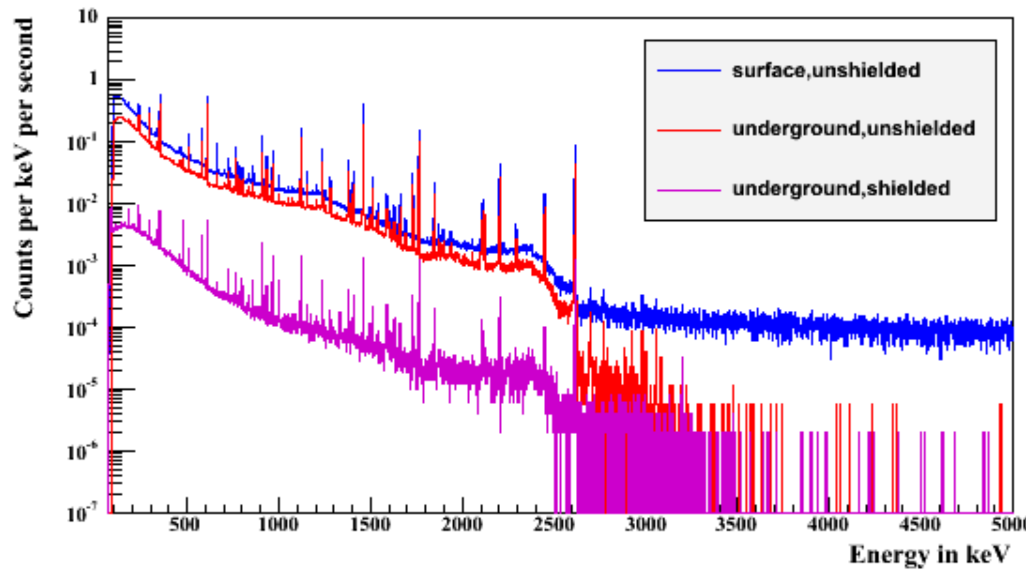
~ 0.1 % for high energy γ rays (HPGe detectors)



C ~ 0.3 counts/hour

LUNA: Laboratory for Underground Nuclear Astrophysics





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

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

$D(p,\gamma)^3He$: experimental setup

Measurement goal:

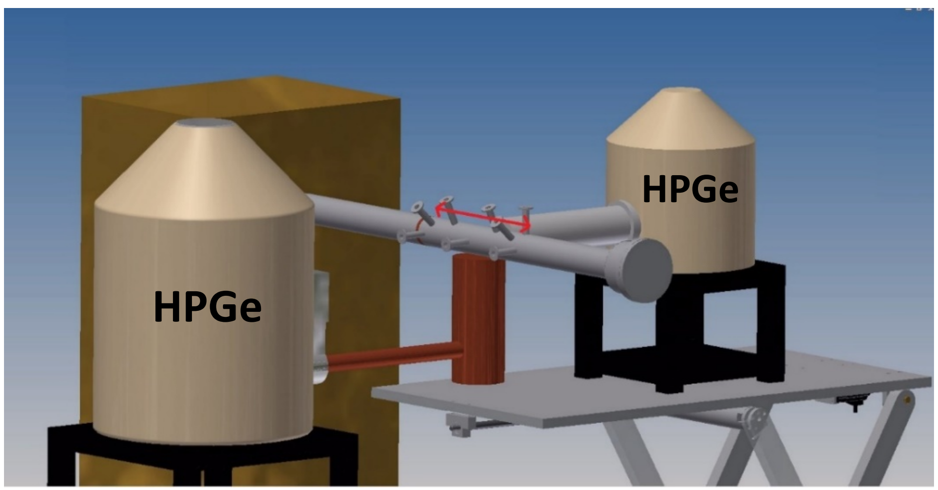
- ✓ Cross section measurement with ~3% accuracy
- ✓ E_{cm}= 30-300 keV

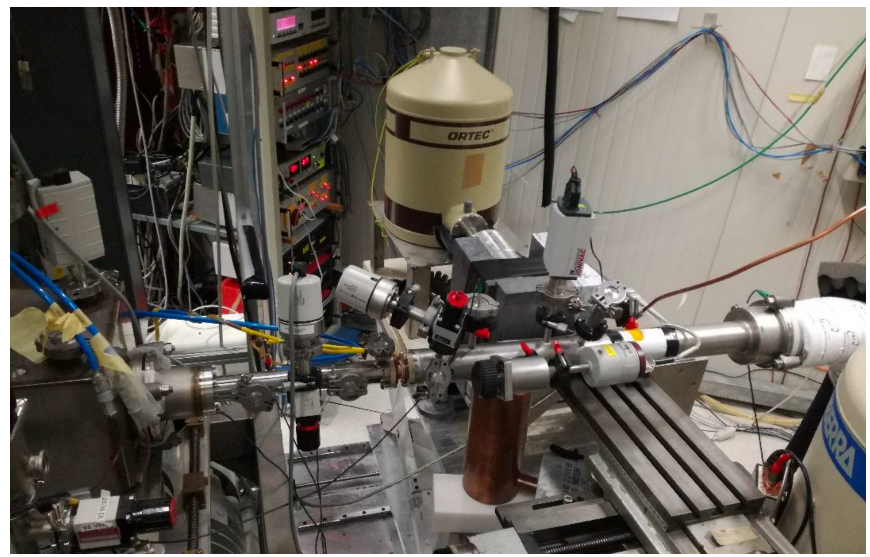
Experimental setup:

- ✓ **Proton beam**
- ✓ **D_2 windowless gas target (P=0.3 mbar)**
- ✓ **HPGe detectors for γ-rays**

LUNA BA contributions

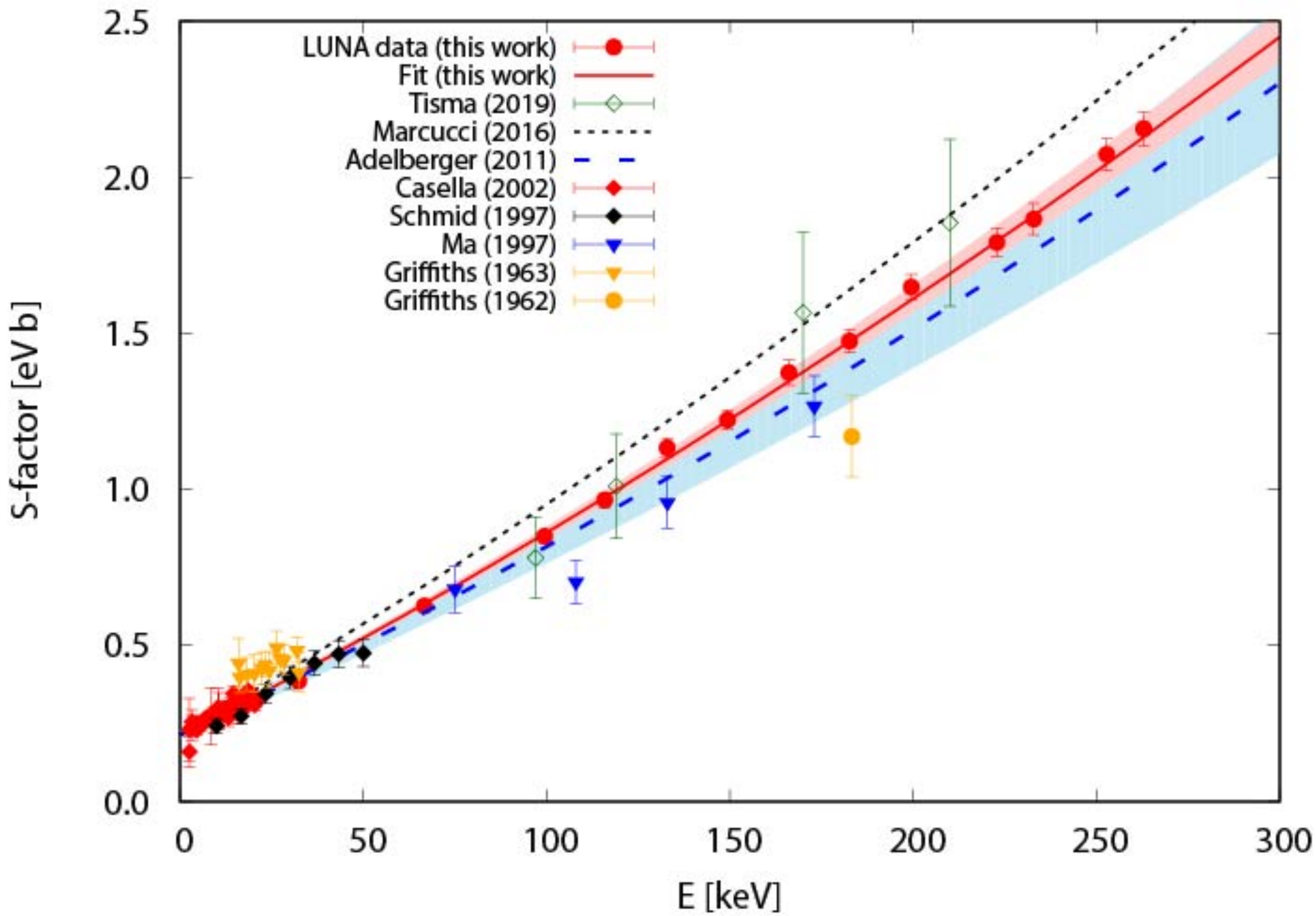
- Setup designed, builted and mounted by UniBa & INFN mechanical workshops
- Development of experimental techiniques
- DAQ development
- Data taking and analysis (V. Mossa PhD in Bari)





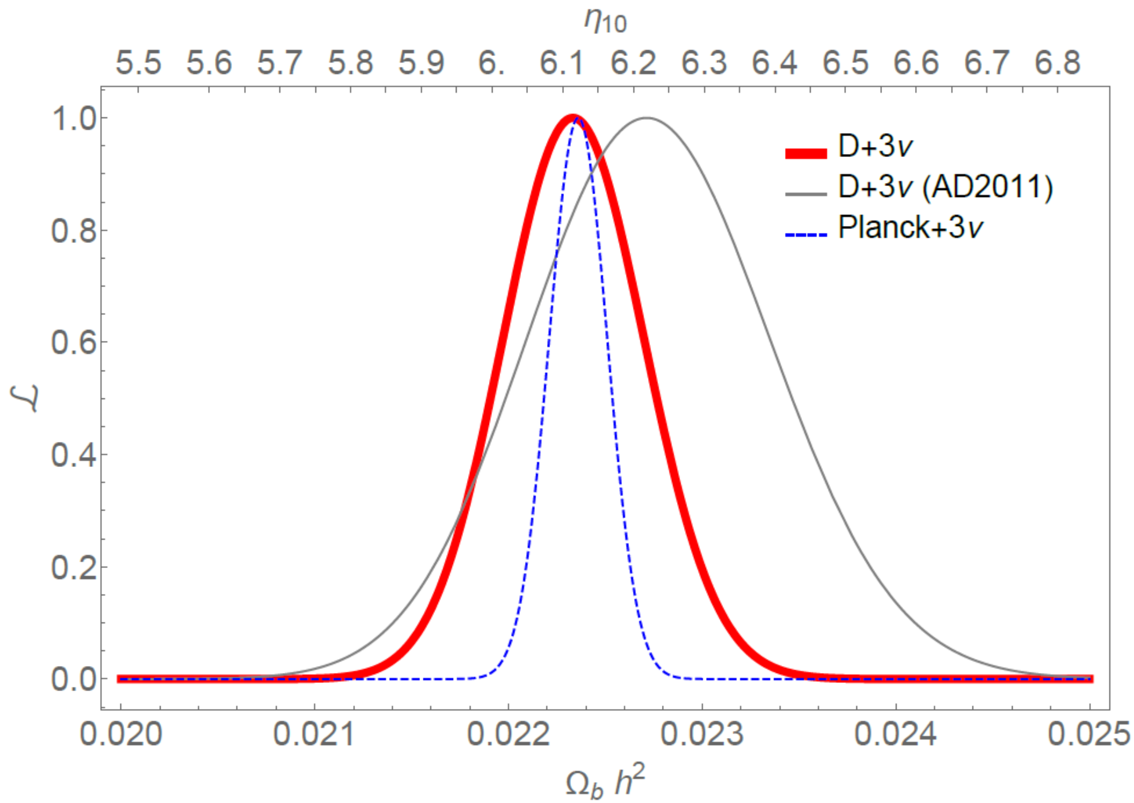
$D(p,\gamma)^3He$: S-factor results

$$S(E) = \sigma(E) E e^{-2\pi\eta}$$



The baryon density of the Universe

- Baryon density obtained with PARTHENOPE code by comparing $[D/H]_{OBS}$ and $[D/H]_{BBN}$
- N_{eff} = 3.045, fixed
- Comparison with Planck results



Analysis performed by Ofelia Pisanti and Gianpiero Mangano

References

- V. Mossa et al. Eur. Phys. J. A (2020) 56:144 "**Setup commissioning for an improved measurement of the D(p,γ)3He cross section at Big Bang Nucleosynthesis energies** "

- V. Mossa et al. **210** Nature Vol587 "**The baryon density of the Universe from an improved rate of deuterium burning** "

- L. Damone PRL 121, 042701 (2018) **"^{7}Be(n,p)^{7}Li Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN"**

- M. Barbagallo et al. ,PRL 117, 152701 (2016) **"^{7}Be(n,a)^{4}He Reaction and the Cosmological Lithium Problem: Measurement of the Cross Section in a Wide Energy Range at n_TOF at CERN"**

The local groups

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- N. Colonna,D. Diacono, M. Mastromarco, A.Mazzone ,G. Tagliente, V. Variale | Università di Bari and INFN Bari

THANK YOU

"The nitrogen in our DNA, the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interiors of collapsing stars. We are made of starstuff."

Carl Segan, COSMOS

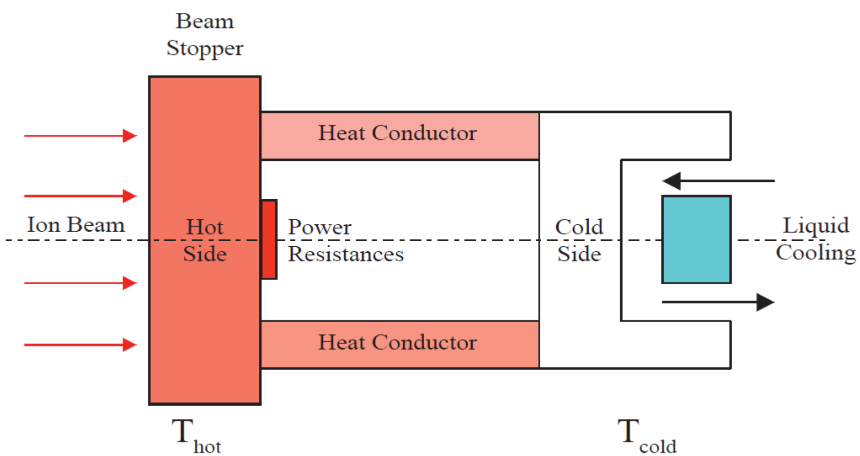
D(p,γ)^{3}He: study of systematic uncertainties

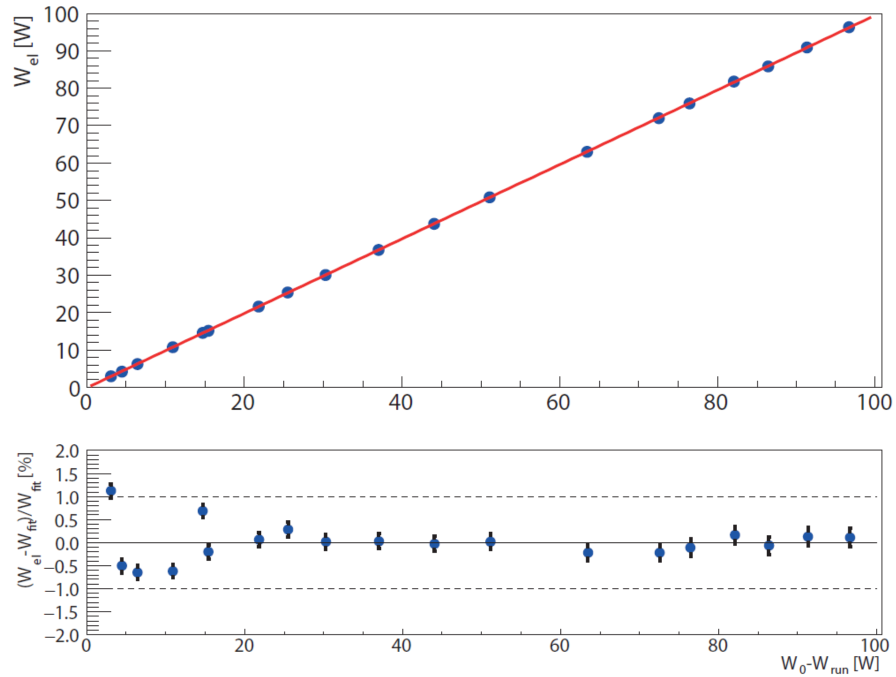
$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z, E_\gamma) W(z) dz}$$

Source	Method	ΔS/S (%)
Beam energy	Direct measurement	0.2
Energy loss	Low gas pressure	0.04
T and P profiles	Direct measurement	1.0
Beam heating	Direct measurement	0.5
Gas purity	Data sheet	0.1
Beam current	Calorimeter calibration	1.0
Efficiency	Direct measurement	2.0
Instrumental effects	Pulser method	0.2
Angular distribution	Simulations	0.5
Total		2.6

D(p,γ)^{3}He: study of systematic uncertainties

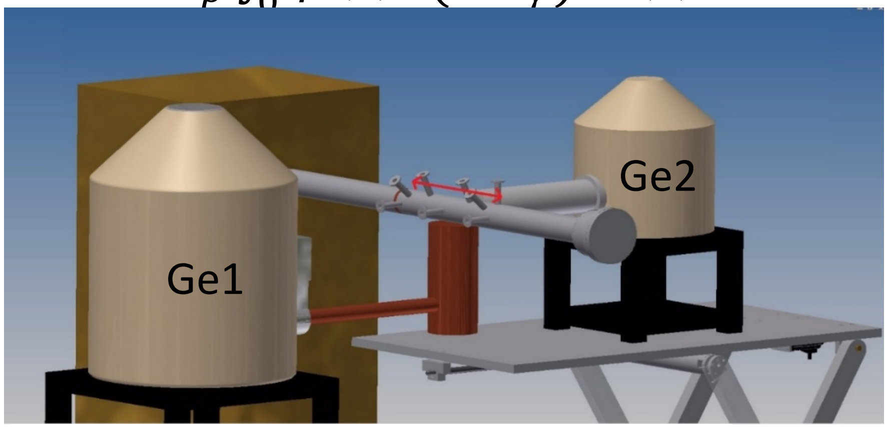
- Goal: 3% accuracy on the D(p,γ)^{3}He cross section (Q= 5.5 MeV)
- $\sigma(E) = \dfrac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z,E_\gamma)W(z)dz}$

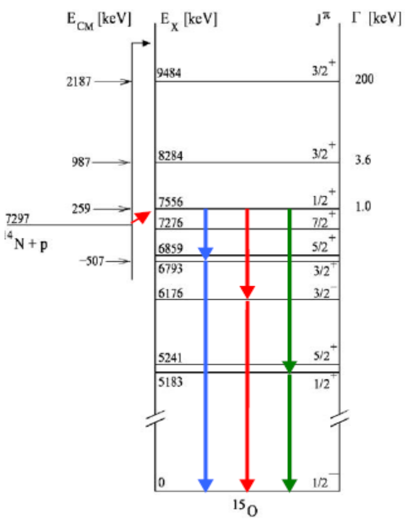




D(p,γ)^{3}He: study of systematic uncertainties

$$\sigma(E) = \frac{N_\gamma(E)}{N_p \int_0^L \rho(z)\varepsilon(z,E_\gamma)W(z)dz}$$





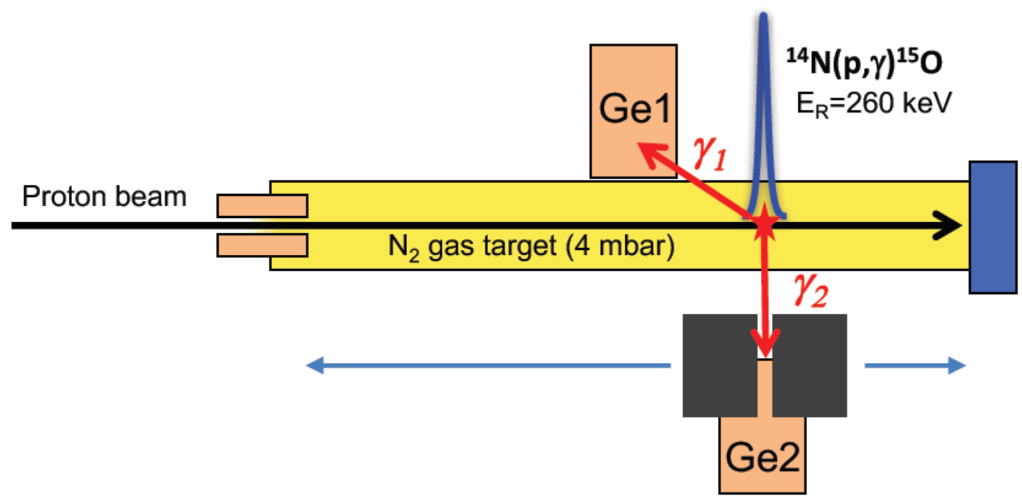
Eγ (keV)	BR (%)
765+6791	22.9
1384+6172	57.8
2375+5181	17.1

E_γ= 5.5-5.8 MeV → efficiency calibration:

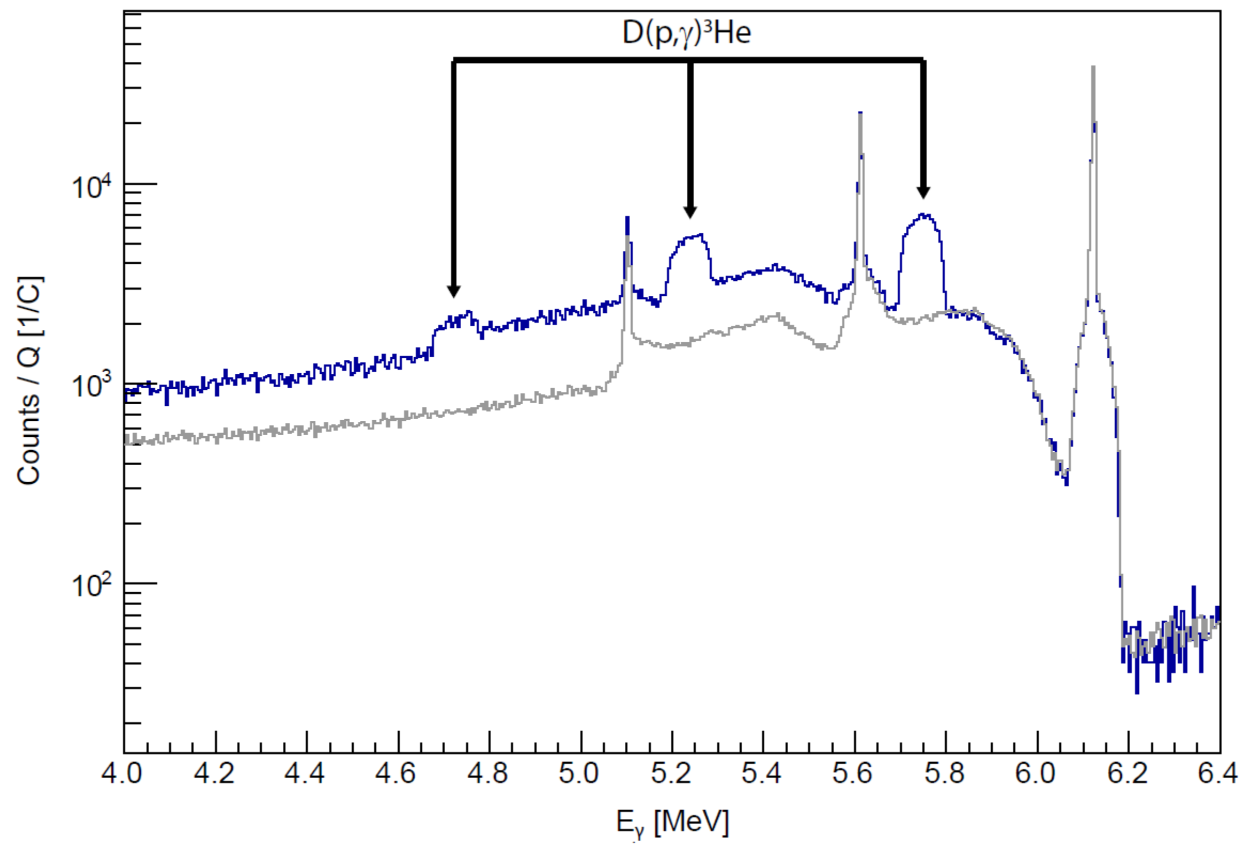
- ✓ radioactive sources
- ✓ E_R = 260 keV resonance of ^{14}N(p,γ)^{15}O

Calibration exploiting the reaction:

$^{14}N + p \rightarrow {}^{15}O + \gamma_1 + \gamma_2$



D(p,γ)^{3}He: spectra



- ✓ Spectrum obtained @ E_p = 395 keV with D_2 gas target (P=0.3 mbar)
- ✓ Spectrum obtained @ E_p = 395 keV with ^{4}He gas target (P=0.3 mbar)