Measurement of the $^{7}Be(n,p)\,^{7}Li$ cross section in EAR2@n_TOF for the Cosmological Lithium Problem

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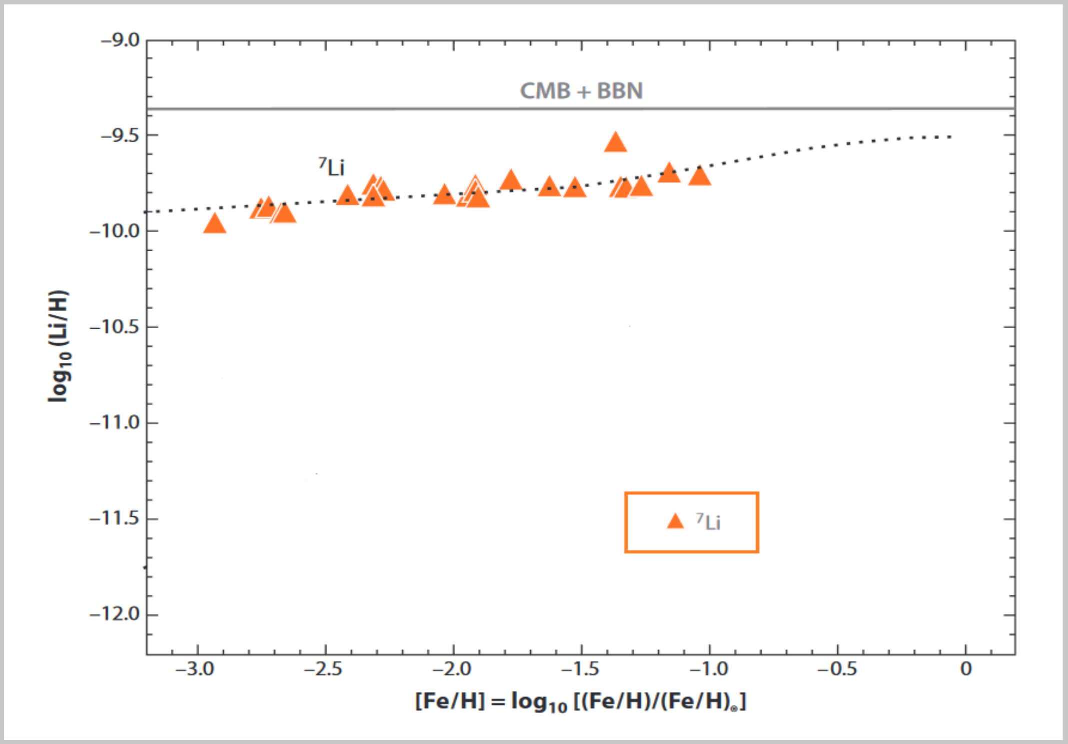
Outlook

- The Cosmological Lithium Problem
- Results for the $^{7}\mathrm{Be}(\mathrm{n},\alpha)$ cross-section
- Experimental Set-up for the $^{7}\mathrm{Be}(\mathrm{n},\mathrm{p})$ cross-section
- Results for the $^{7}\mathrm{Be}(\mathrm{n},\mathrm{p})$ measurement
- Conclusions

The Cosmological Lithium Problem

Observations



Discrepancy of a factor 3 between observations and BBN modeling!

Theoretical predictions

WMAP

$$\eta \equiv \frac{N_b}{N_\gamma} = 2.74 \times 10^{-8}\Omega_b h^2$$

$$\left(\frac{Li}{H}\right)_{BBN} \cong (5.14^{+0.71}_{-0.62}) \times 10^{-10}$$

$$\left(\frac{Li}{H}\right)_{obs} \cong (1.58^{+0.06}_{-0.44}) \times 10^{-10}$$

The Cosmological Lithium Problem

Nuclear solutions

95% of the primordial ^{7}Li comes from electron capture decay of the ^{7}Be. Therfore the production and distruction of ^{7}Be is the key to understand the ^{7}Li abundance resulting from the Big Bang Nucleosinthesis.

Possible ^{7}Be destruction channels

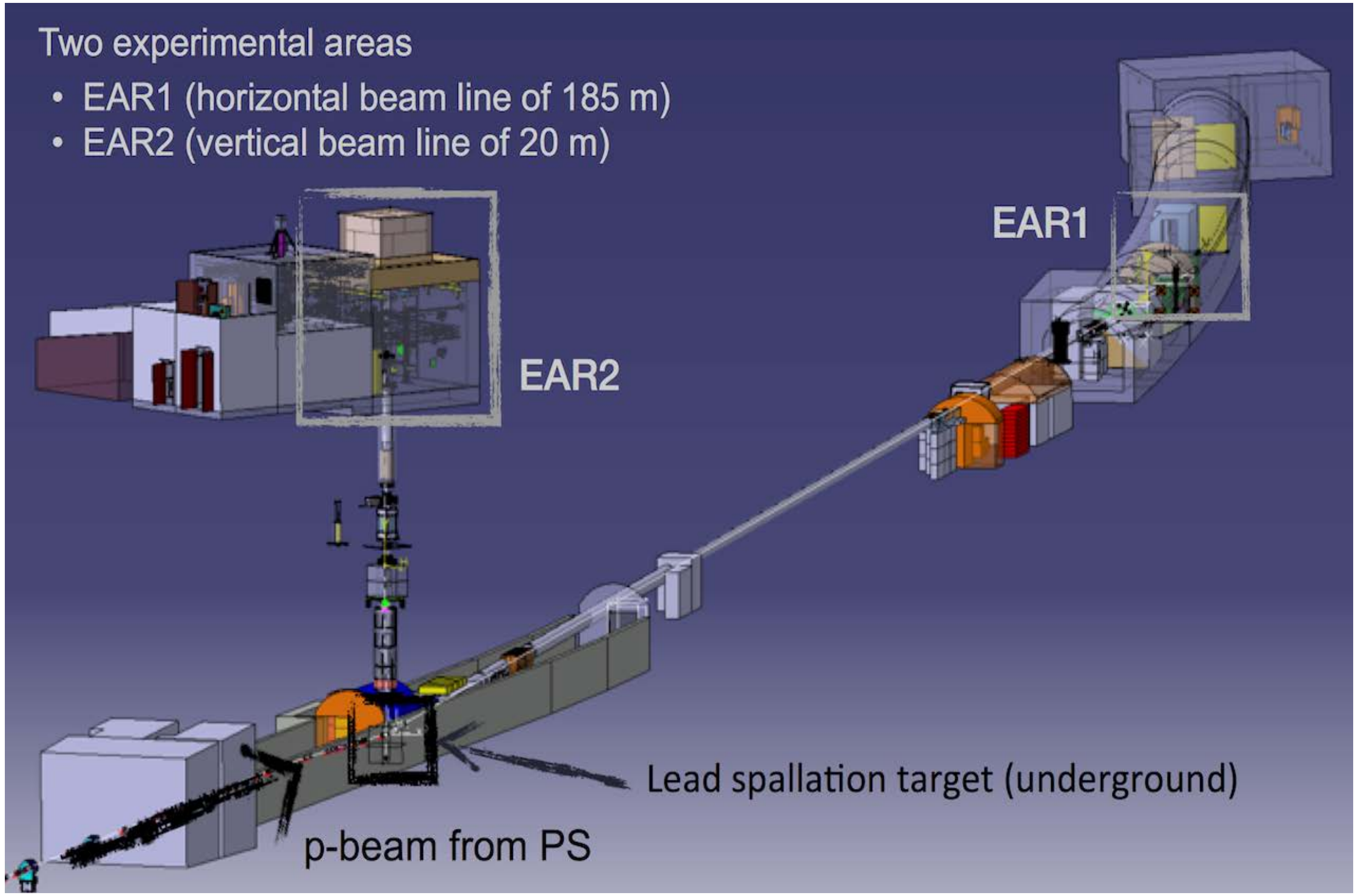
$^{7}Be\,(n,p)\,^{7}Li$	**97% of the total destruction rate of ^{7}Be**
$^{7}Be\,(n,\alpha)\,^{4}He$	**2.5% of the total destruction rate of ^{7}Be**

<u>Lack of experimental data due to the intrinsic difficulty of the measurement:</u>

- Short half life of **^{7}Be** (53 days) with a specific activity of 13 GBq/μg

} **High flux neutron beam is required**

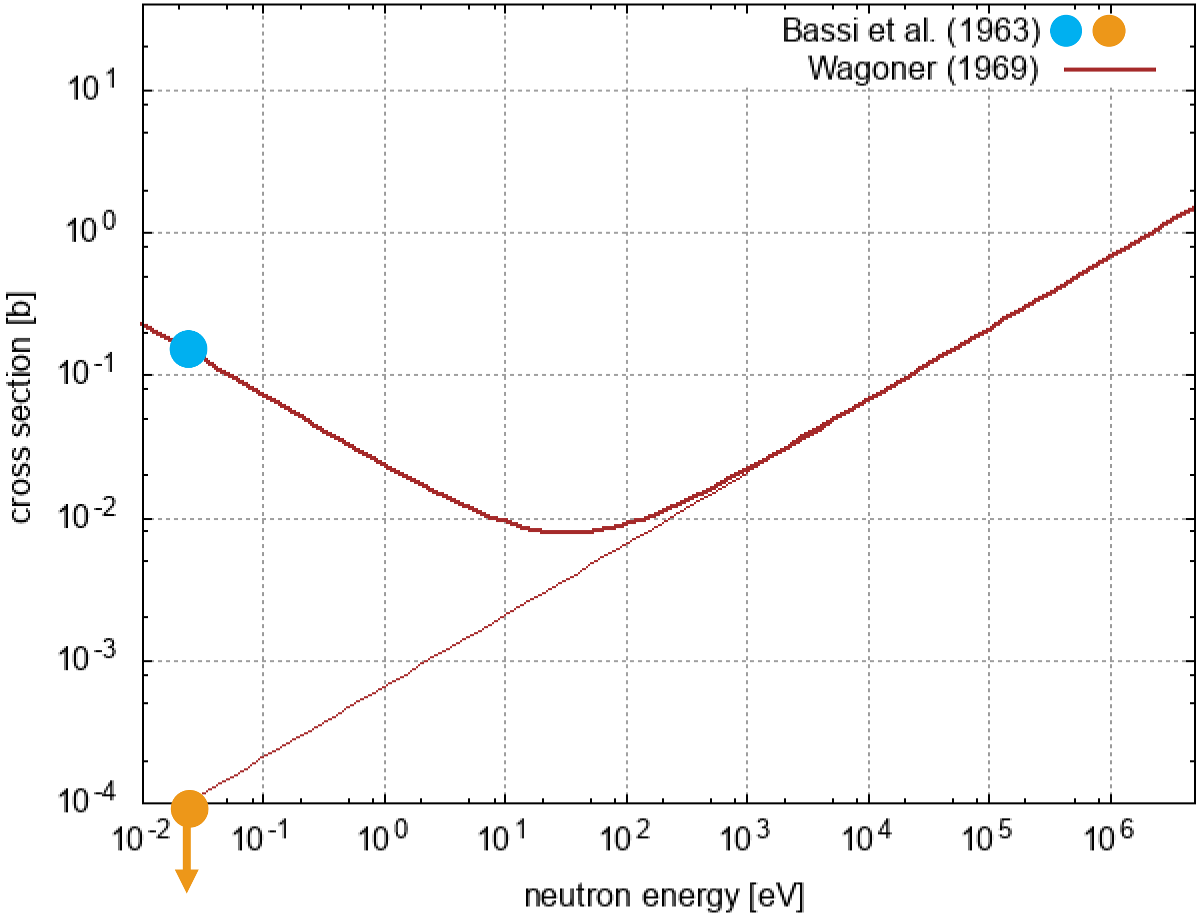
Features of EAR2@n_TOF



The **high flux** and the wide energy range (2 meV < En < 100 MeV) in EAR2 allows to:

- measure samples of **very small mass (<<1 mg)**
- measure **short-lived radioisotopes** (down to a few weeks)
- collect data on a much **shorter time**
- **measure (n,charged particle)** reactions with **thin samples**

Avaliable data for $^{7}\mathrm{Be}(n,\alpha)\alpha$



^{7}**Be(n,α) only one** measurements:

- **Bassi at al.**, 1963, **Thermal neutron energy**

reaction rate by Wagoner (1969):

s-wave component:
1/v normalized at thermal

p-wave component:
~ $E^{1/2}$

Set-up for $^{7}\mathrm{Be}(n,\alpha)\alpha$

☺

- Q= 19 MeV
- 2 α coincidence

Silicon Sandwich: high sensitivity

Chemical purification is sufficient

☹

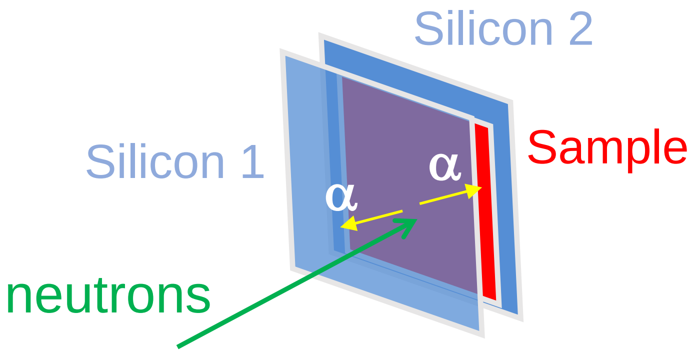
- Low cross section

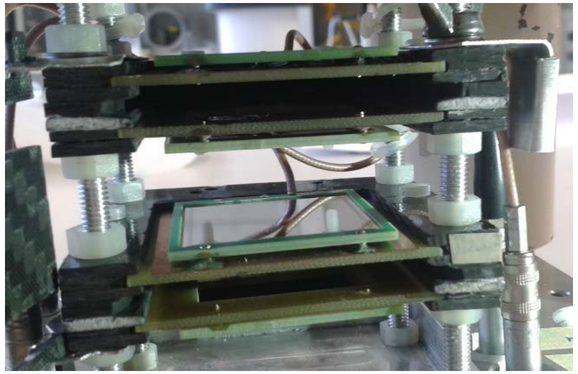
High efficiency needed

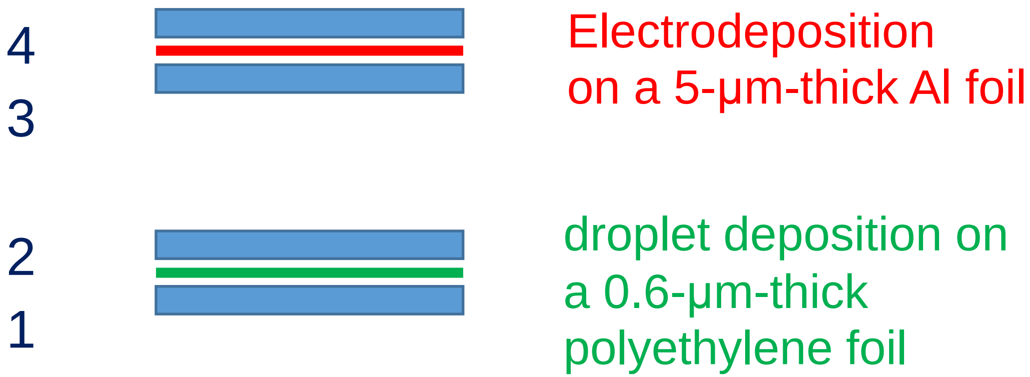
Large mass (μg)

Silicon Sandwich in beam

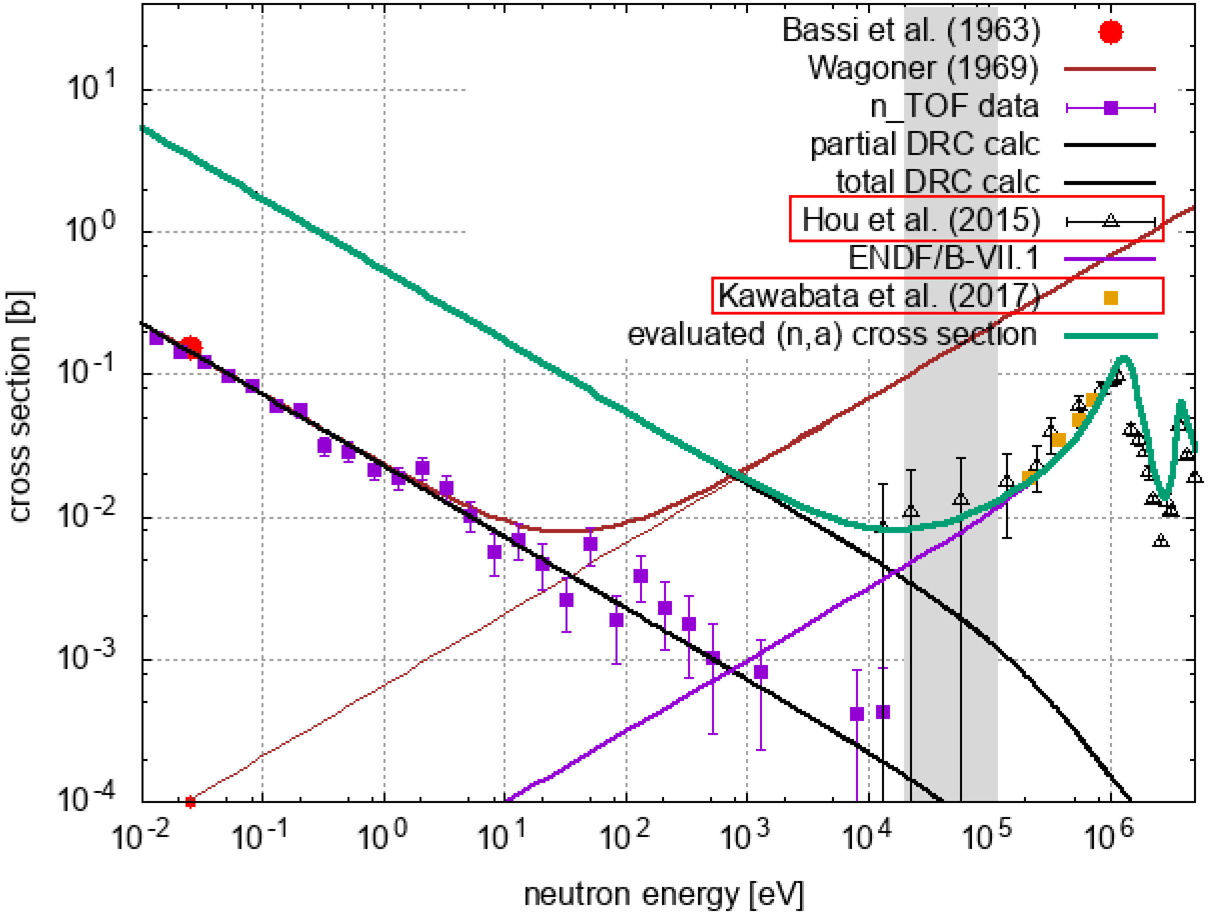
No isotopic separation







$^{7}Be(n,\alpha)\alpha$ results and publication



$^{7}Be\ (n,\alpha)\ ^{4}He$

PRL **117**, 152701 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

$^{7}Be(n,\alpha)^{4}He$ 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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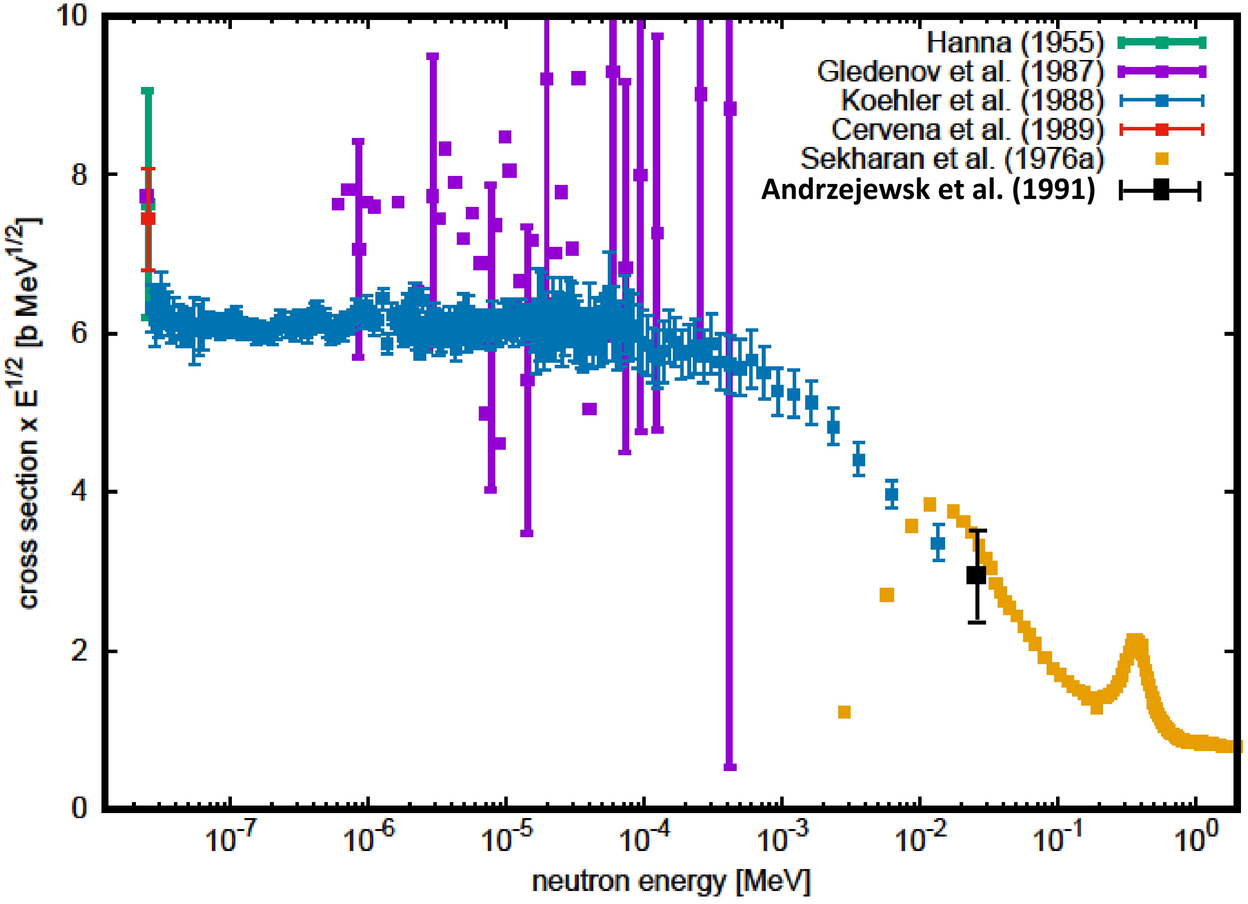
Avaliable data for ^{7}Be(n,p)



^{7}Be(n,p) three measurements:

- **Koehler at al., 1988, 0.025 eV- 13.5 keV**
- **Gledenov et al., 1987, 0.025 eV- ~500 eV**
- **Andrzejewsk et al., 1991, ~25 keV**

$^{7}Be(n,p)\,^{7}Li$ Experimental set-up

☺

- High cross section

High efficiency not needed

Low mass (ng)

Silicon Telescope out of the beam

Isotopic separation possible

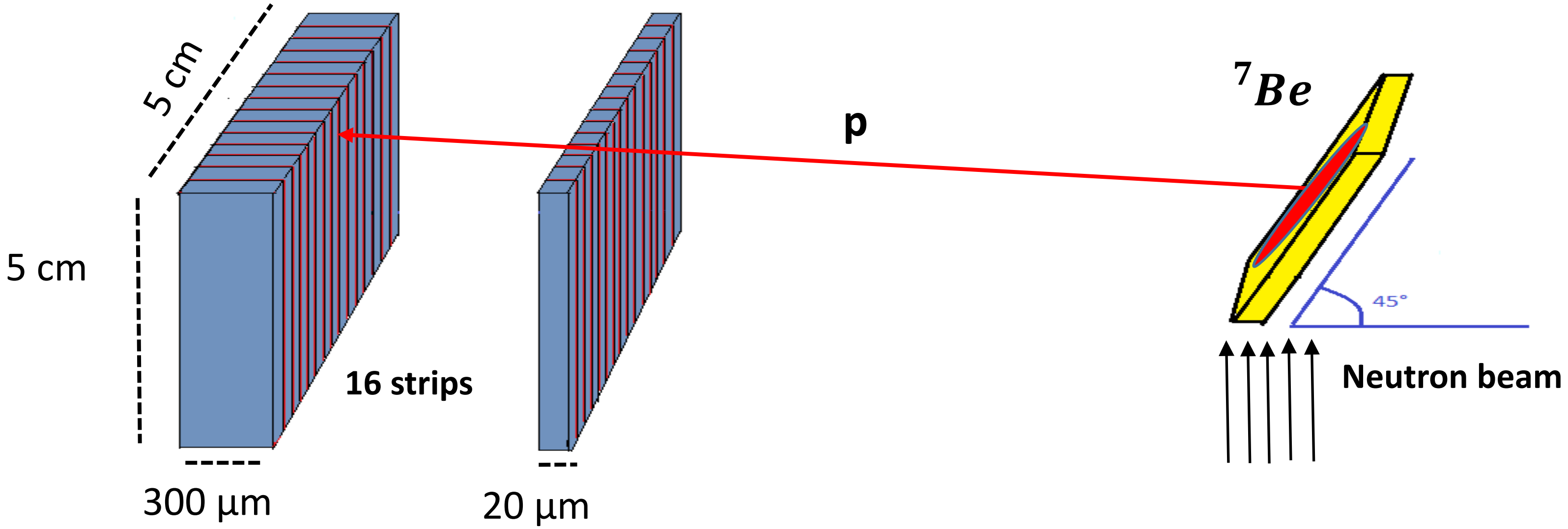
☹

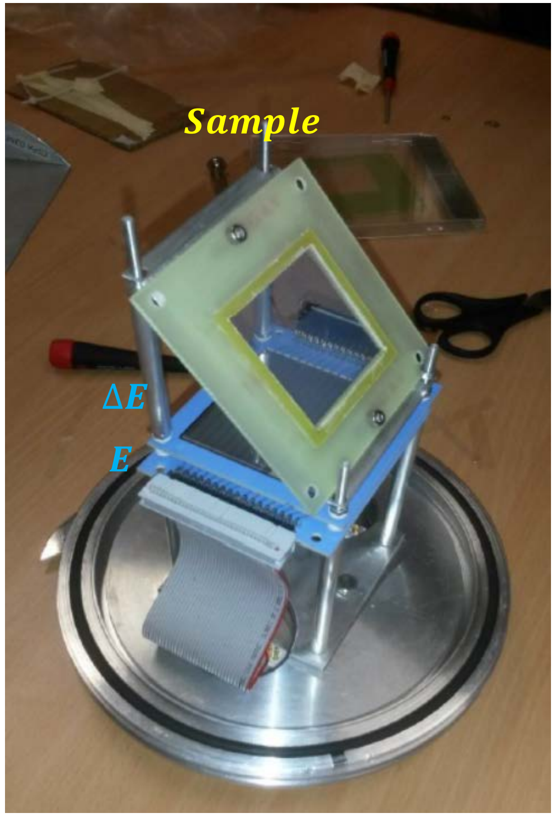
- Q= 1.644 MeV
- Only 1 proton

Silicon Telescope

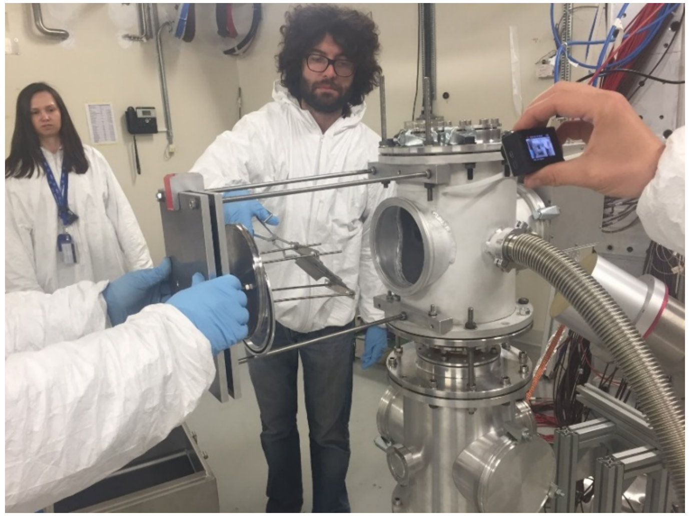
Pure ^{7}Be target mandatory

Reference reaction: $^{6}Li(n,t)\,^{4}He$

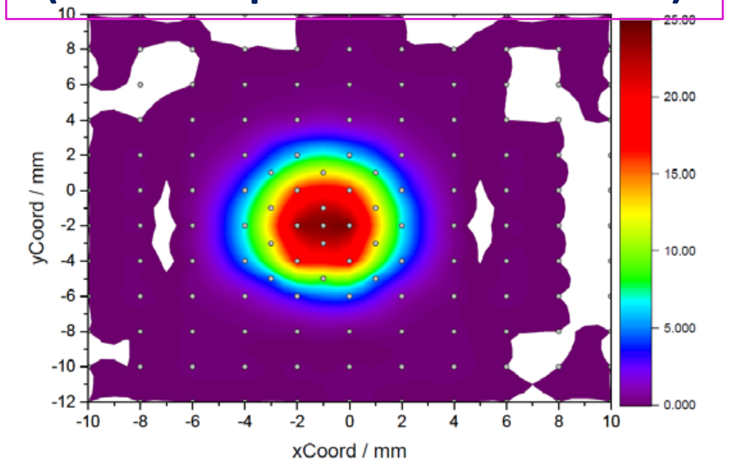




^{7}Be(n, p) ^{7}Li: Sample preparation @PSI/ISOLDE



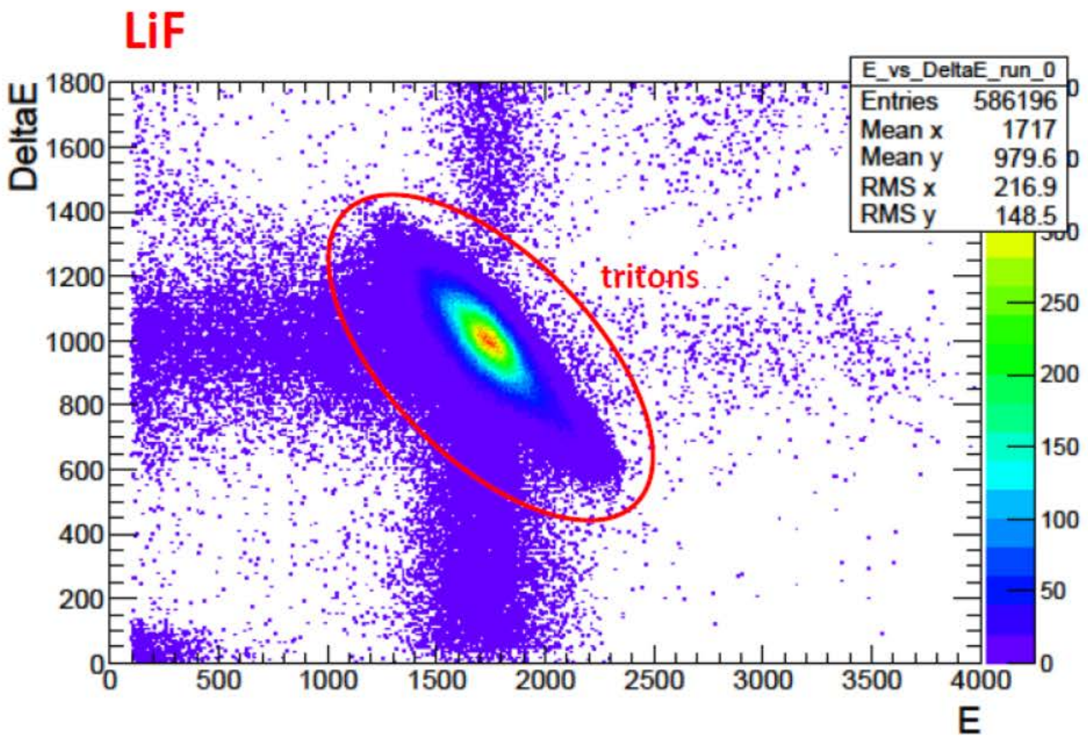
Sample characterization @PSI (Gaussian profile 0.5 cm FHWM)

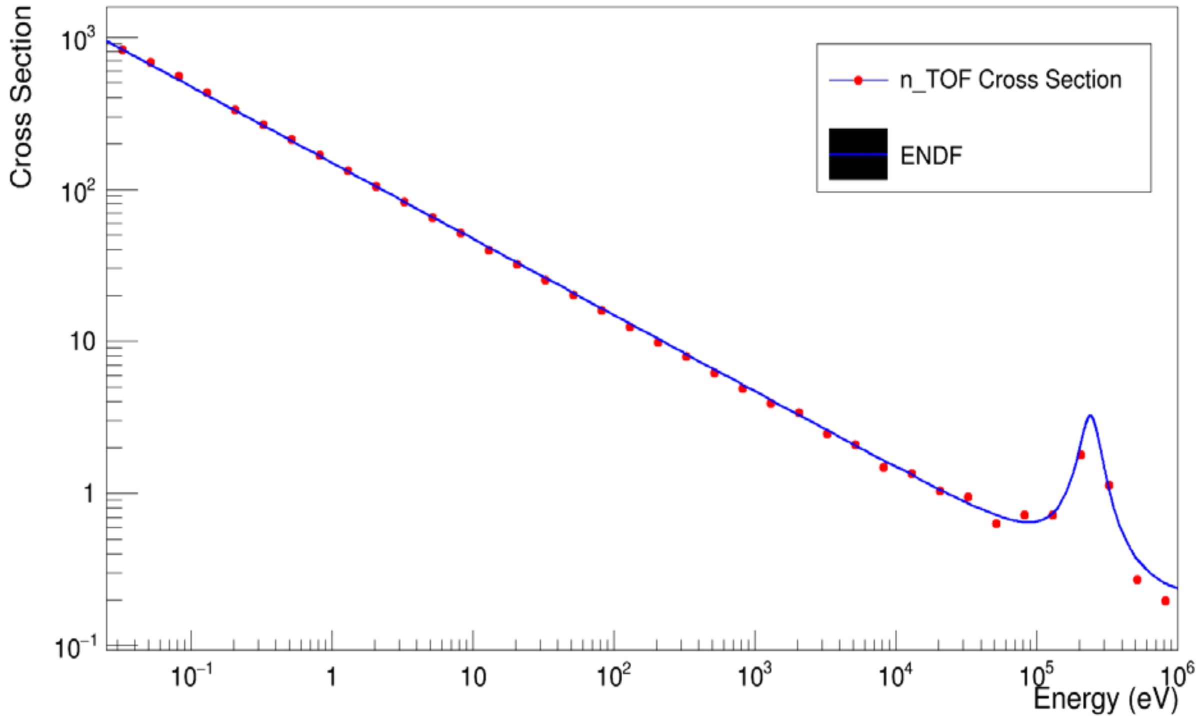


- 200 GBq of ^{7}Be extracted from the cooling water of the SINQ spallation source at PSI
- Transported to ISOLDE at CERN and installed in the ion source to produce 30 keV ion beam.
- ^{7}Be beam separated by means of a magnetic dipole, and implanted on a 20 m thick aluminum backing.
- Sample of ***1 GBq*** ^{7}Be (~80 ng) transported to EAR2@n_TOF and placed in the neutron beam.

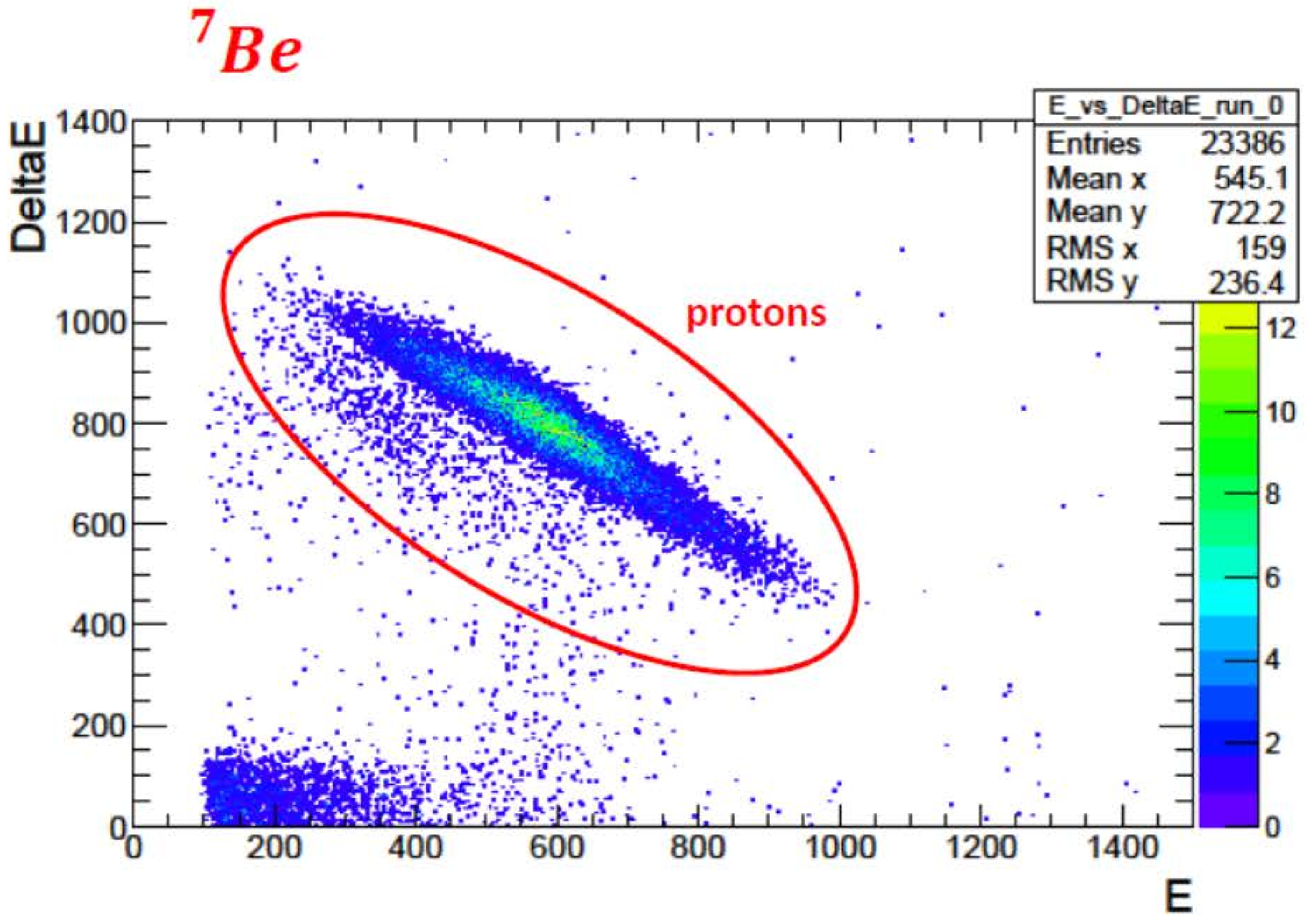
First time a neutron measurement performed with a sample produced at a Radioactive Beam Facility (ISOLDE)

Reference reaction: $^{6}Li(n,t)\,^{4}He$





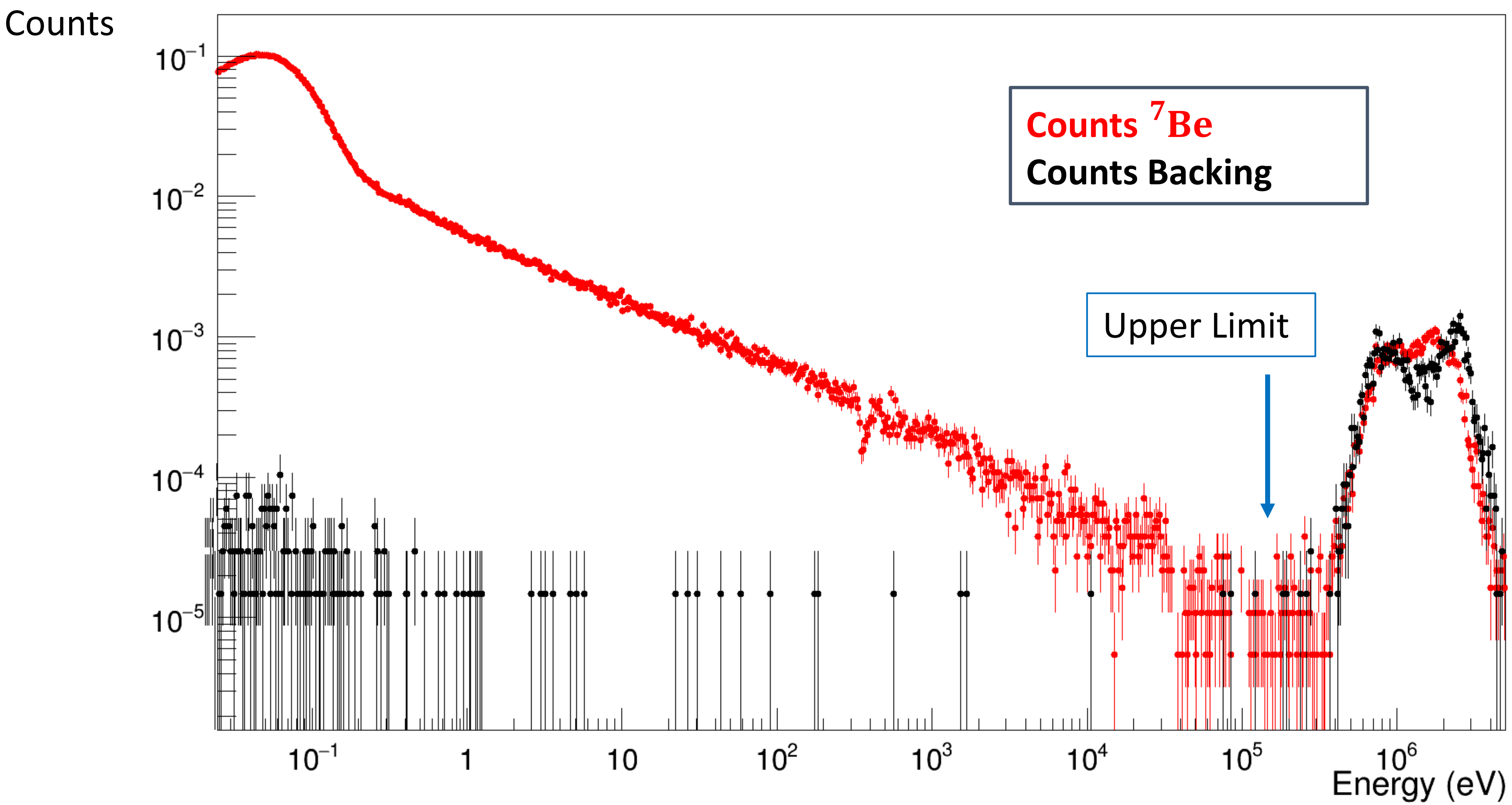
^{7}Be coincidences



$$n + {}^{7}Be \rightarrow p + {}^{7}Li$$

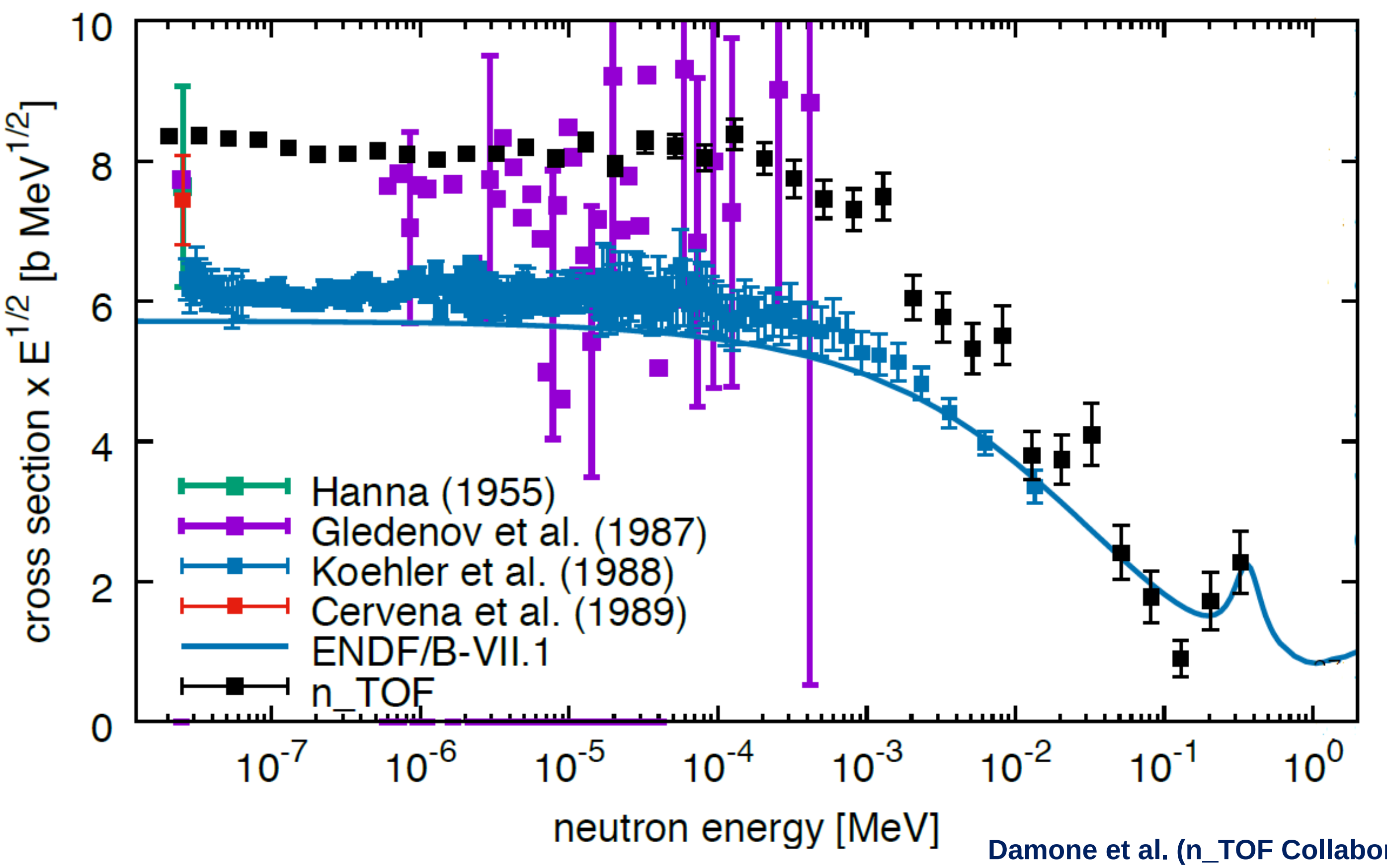
Q = 1.644 MeV

Background check



Results and implications

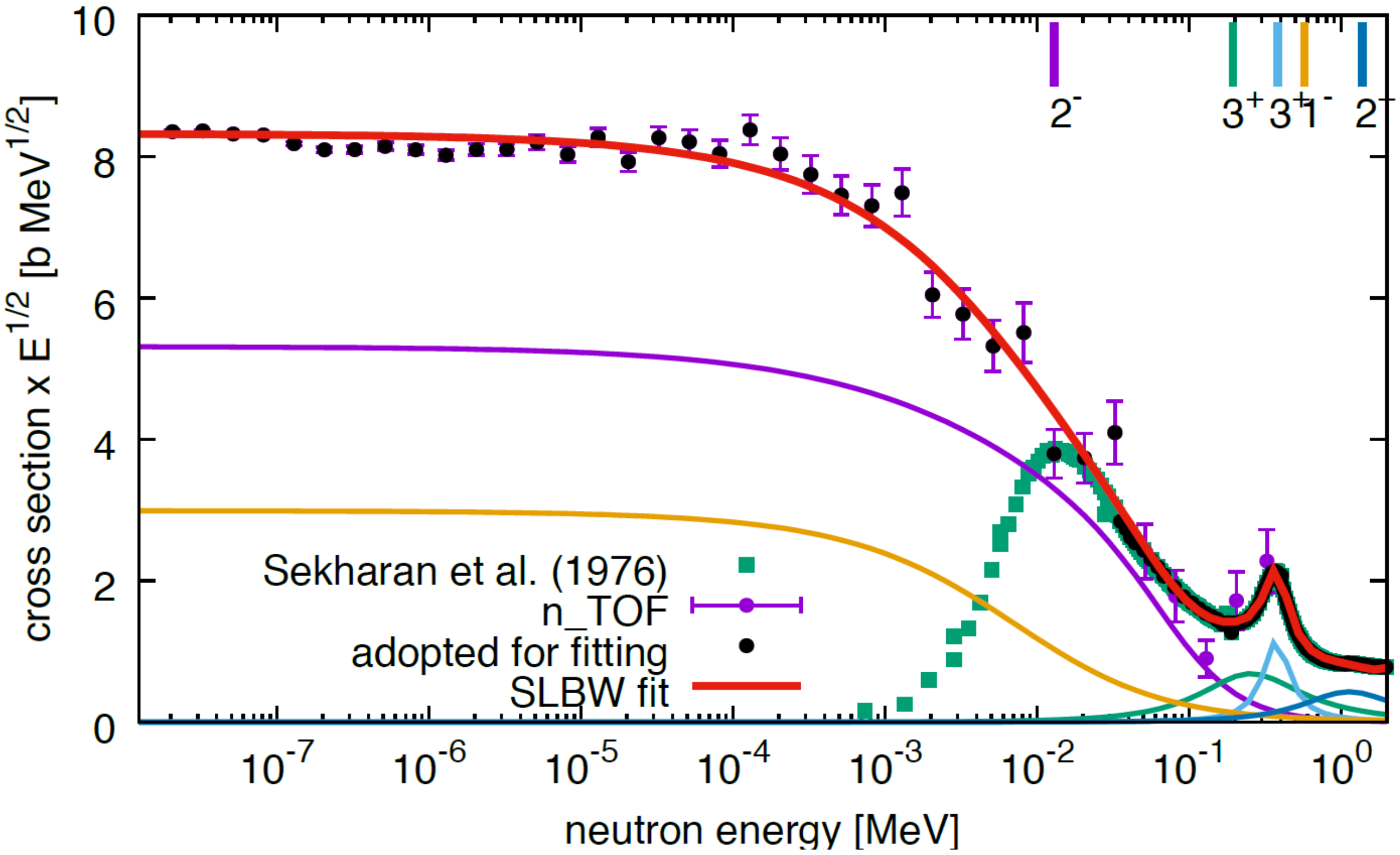
The $^7Be(n,p)\,^7Li$ reduced cross section measured at n TOF compared with the results of previous measurements and with the ENDF/B-VII.1 library



Damone et al. (n_TOF Collaboration) Phys. Rev. Lett. (2018) accepted

Results and implications

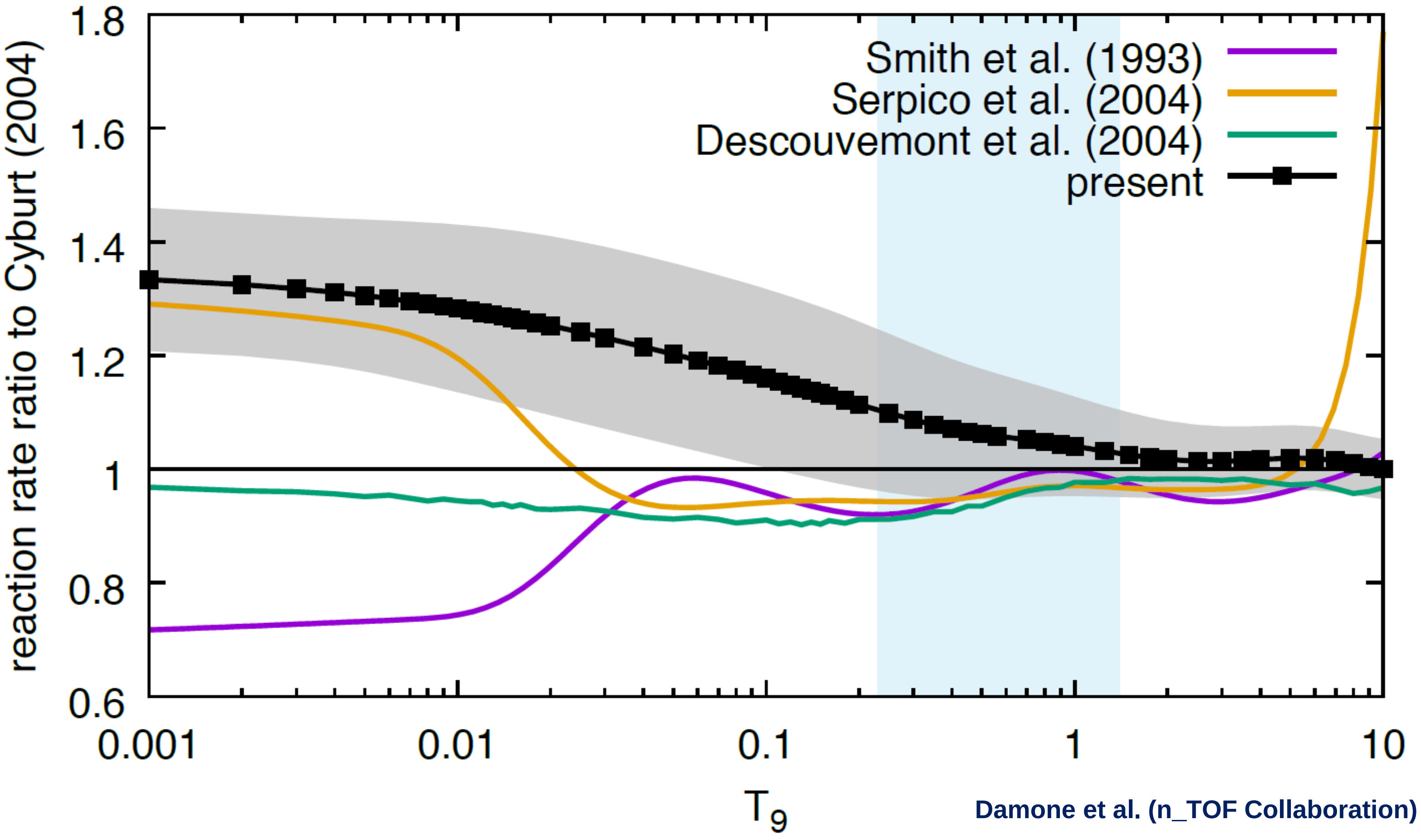
Resonance fit



Damone et al. (n_TOF Collaboration) Phys. Rev. Lett. (2018) accepted

Results and implications

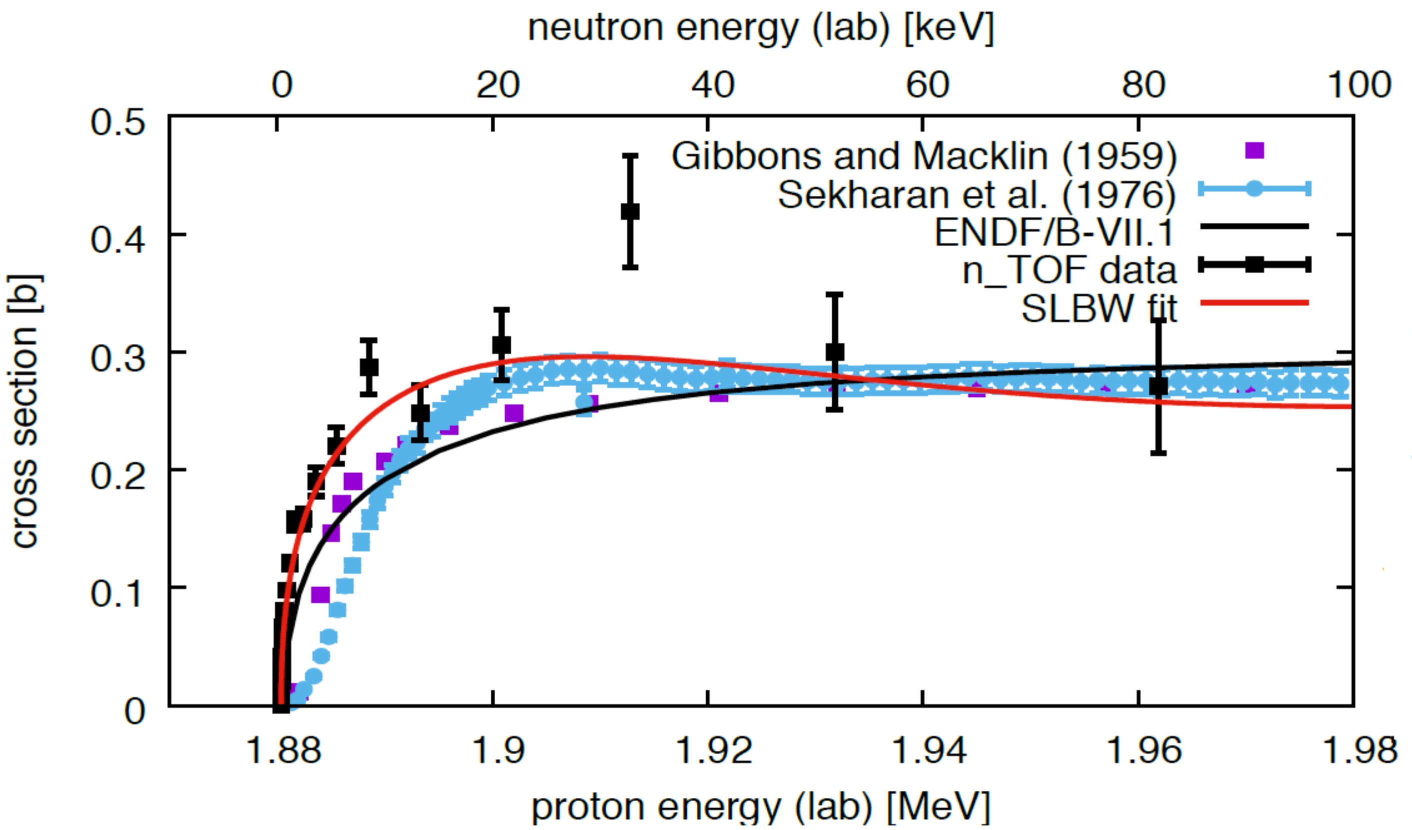
Comparison of the reaction rates for the $^7Be(n,p)\,^7Li$ reaction



Damone et al. (n_TOF Collaboration) Phys. Rev. Lett. (2018) accepted

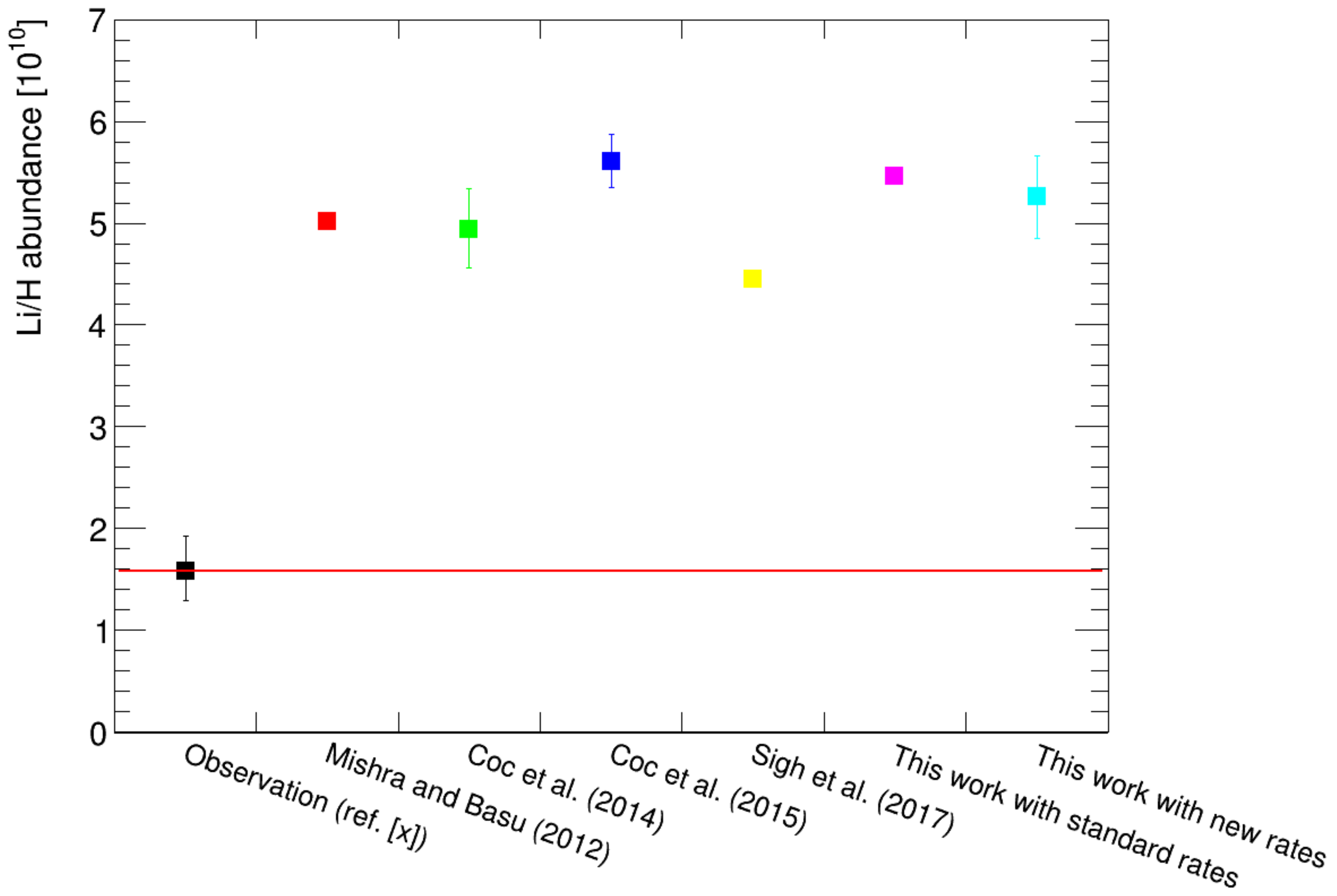
Results and implications

The cross section of the $^{7}\mathrm{Li(p,n)}\,^{7}\mathrm{Be}$ obtained by time-reversing the n TOF data of the $^{7}\mathrm{Be(n,p)}\,^{7}\mathrm{Li}$ reaction.



Damone et al. (n_TOF Collaboration) Phys. Rev. Lett. (2018) accepted

Results and implications



Conclusions

- The $^{7}Be(n,p)^{7}Li$ cross-section measurement has been performed at n_TOF-EAR2, using a 1.1 GBq and 20MBq pure samples implanted at GLM beam line of ISOLDE, starting from a 200 GBq ^{7}Be solution collected at PSI.
- At n_TOF the $^{7}Be(n,p)^{7}Li$ cross-section has been measured for the first time in the energetic range of interest for the problem.
- The reaction rate of the the $^{7}Be(n,p)^{7}Li$ performed @n_TOF cause a decrease of 10% of the abundance predicted for the primordial ^{7}Li.
- Our results exclude the channels (n,a) and (n,p) as a solution for the problem that could be reduced in the hypothesis in which mixing mechanisms such as gravitational settling or atomic diffusion are able to lower the superficial abundance of lithium in the stars of low metallicity.

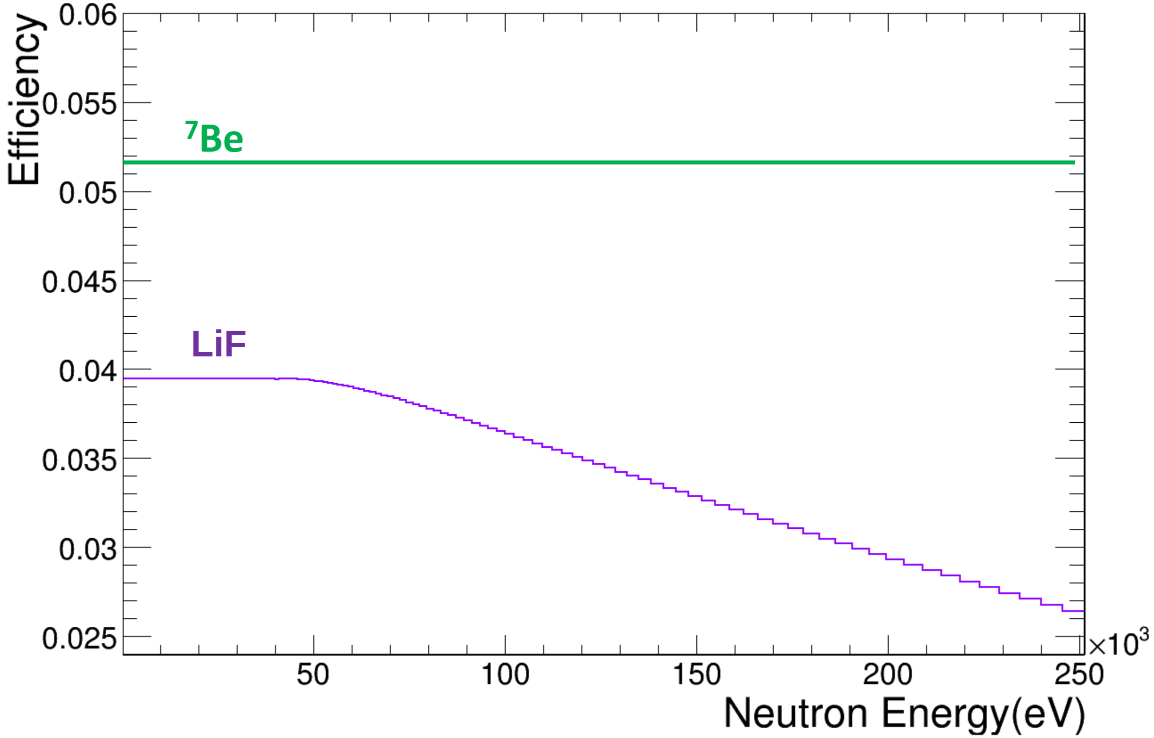
The bare truth is
beyond this wall...
we just need to find
the proper tool to
climb it over!

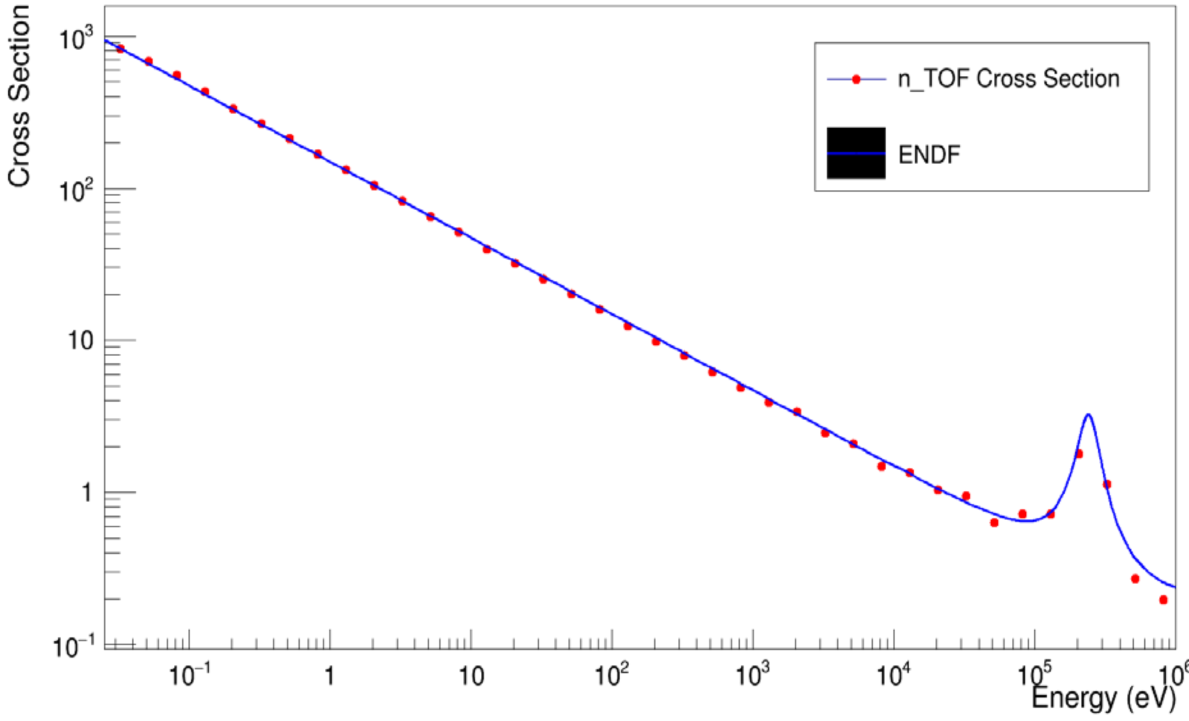
Backup slides

Data Analysis

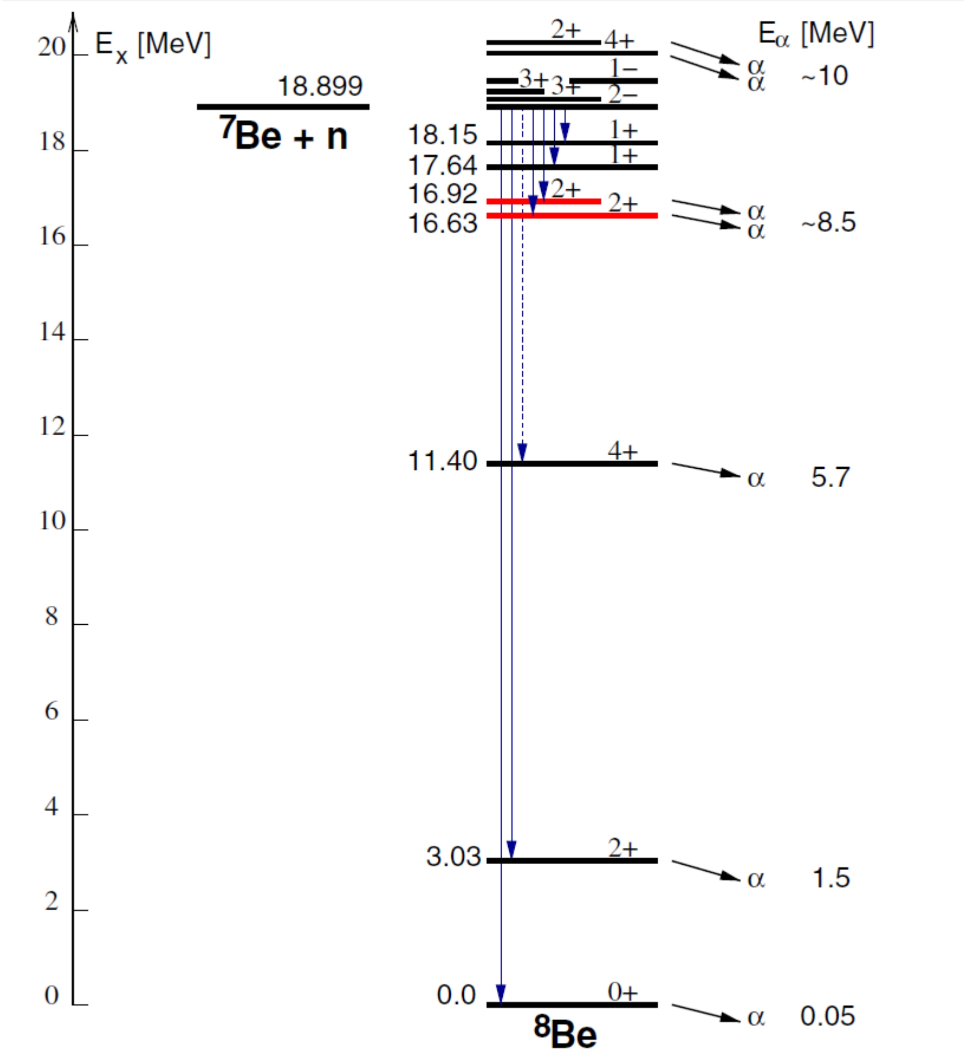
$$\sigma_{Be} = \frac{C_{Be}(E_n)}{C_{Li}(E_n)} \cdot \frac{\varepsilon_{Li}}{\varepsilon_{Be}} \cdot \frac{f_{c_{Li}}}{f_{c_{Be}}} \cdot \sigma_{Li}(E_n) \cdot \frac{1}{N_S}$$

f_C : Convolution of the normalized neutron beam spatial profile and target nuclei distribution (b^{-1}).





Sources of background



Background

- Pile up of γ rays from the ^{7}Be decay
- Pile up of protons from the competing $^{7}\mathrm{Be(n,p)}\ ^{7}\mathrm{Li}$ reaction
- Production of $^{8}\mathrm{Li}$ via neutron capture on $^{7}\mathrm{Li}$, which undergoes β decay into $^{8}\mathrm{Be}$
- $^{9}\mathrm{Be(n,2n)}$, $^{7}\mathrm{Li(p,\gamma)}$, $^{7}\mathrm{Be(p,\gamma)}$

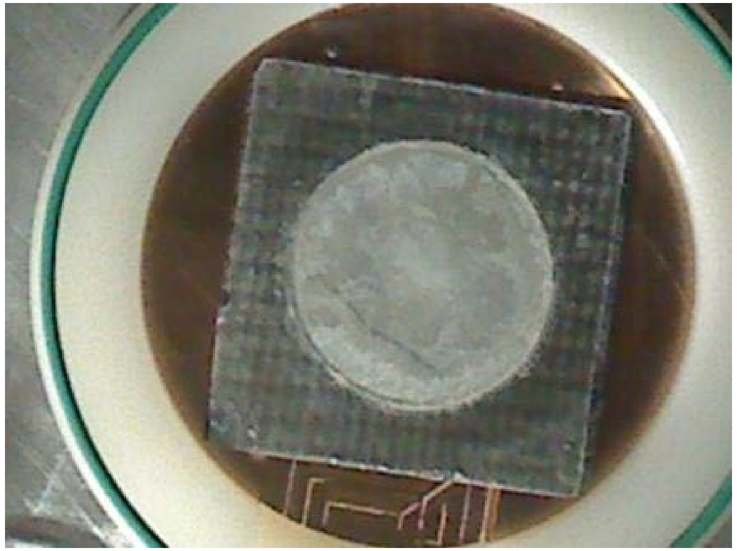
Solutions

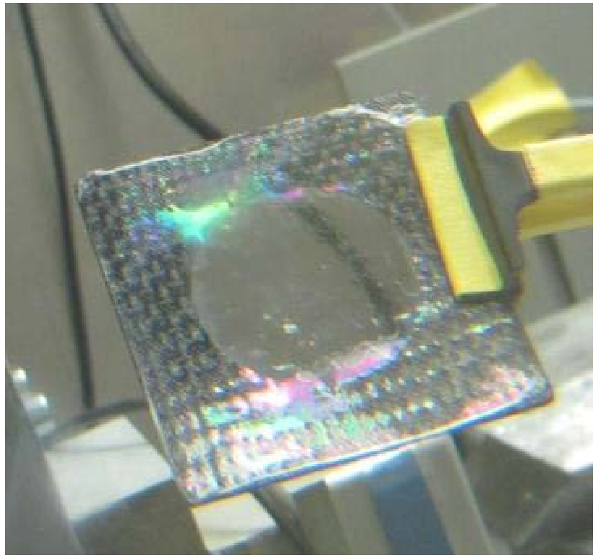
- 2 MeV threshold on the signal amplitude
- Coincident signals of uncorrelated Si detectors
- only the 3.03 MeV state of $^{8}\mathrm{Be}$ populated by $^{8}\mathrm{Li}$ decay, α emitted with an energy of 1.5 MeV
- corresponding signals at a much shorter neutron time of flight

Samples

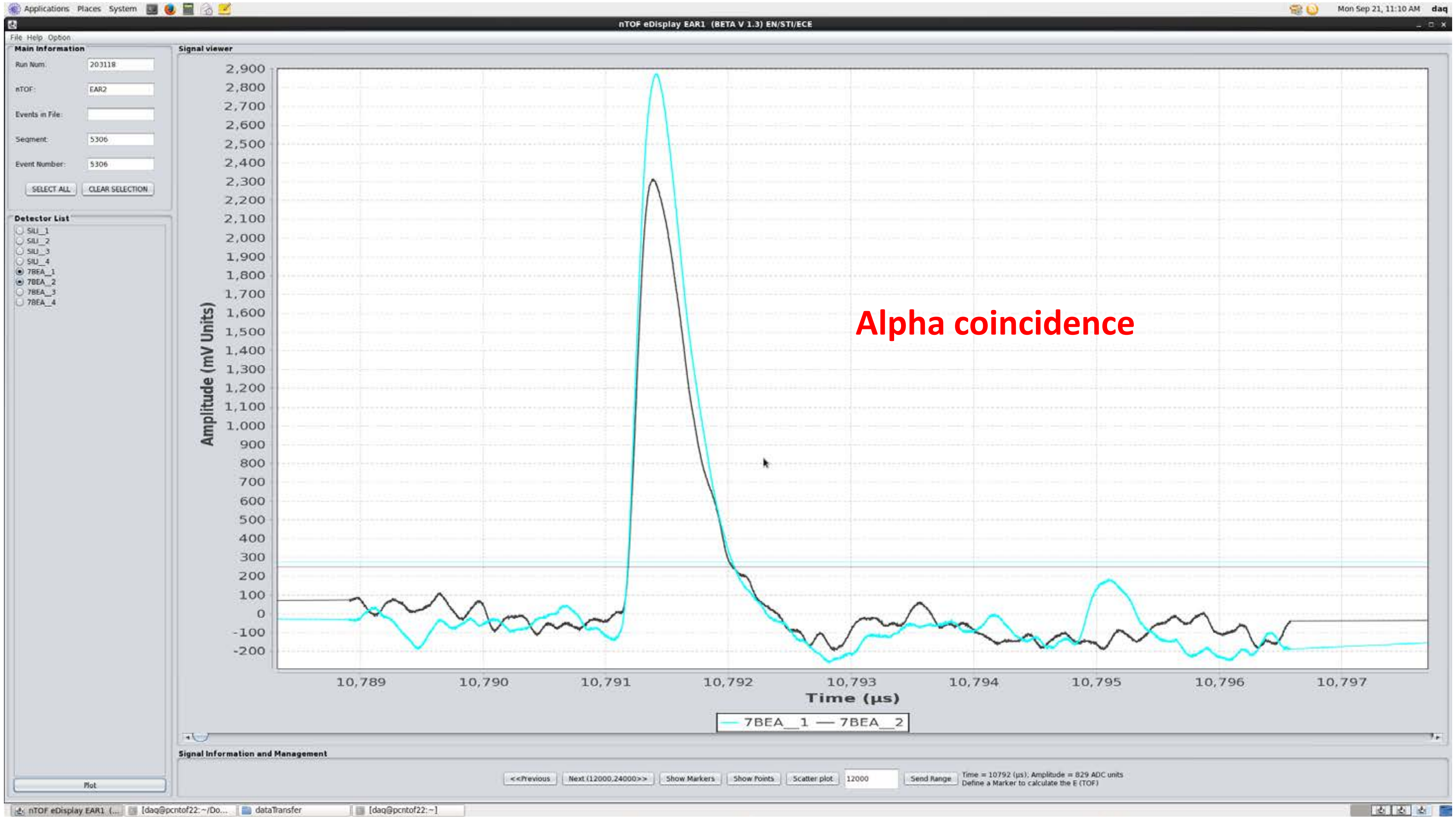
	Vaporization	Molecular Plating
Backing	Stretched PE (0.6 μm)	Aluminum (5 μm)
Activity	20 GBq	19 GBq
Diameter	30 mm	31.6 mm

2 different samples: Molecular plating
(3.5 μg total mass) Vaporization of droplets

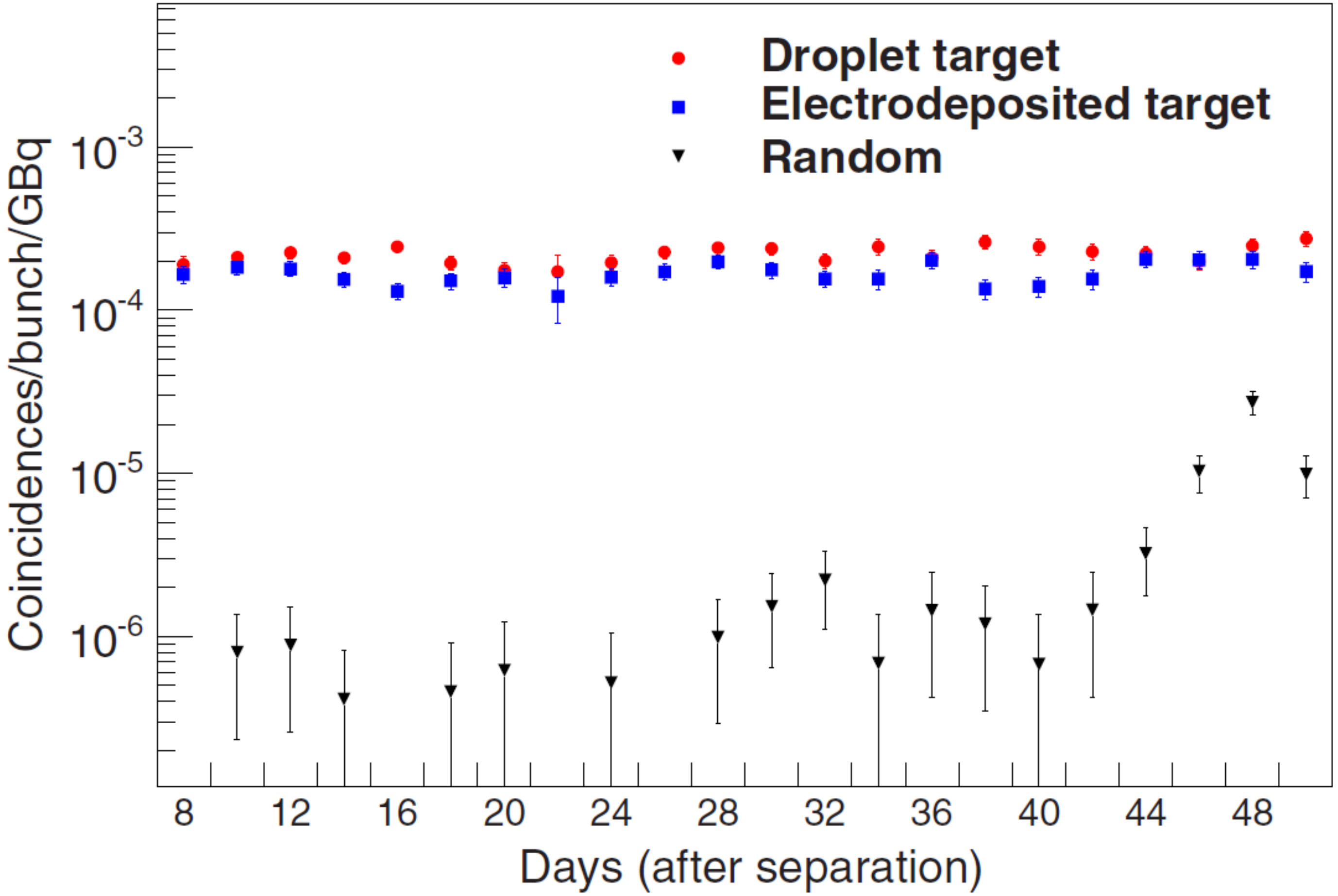




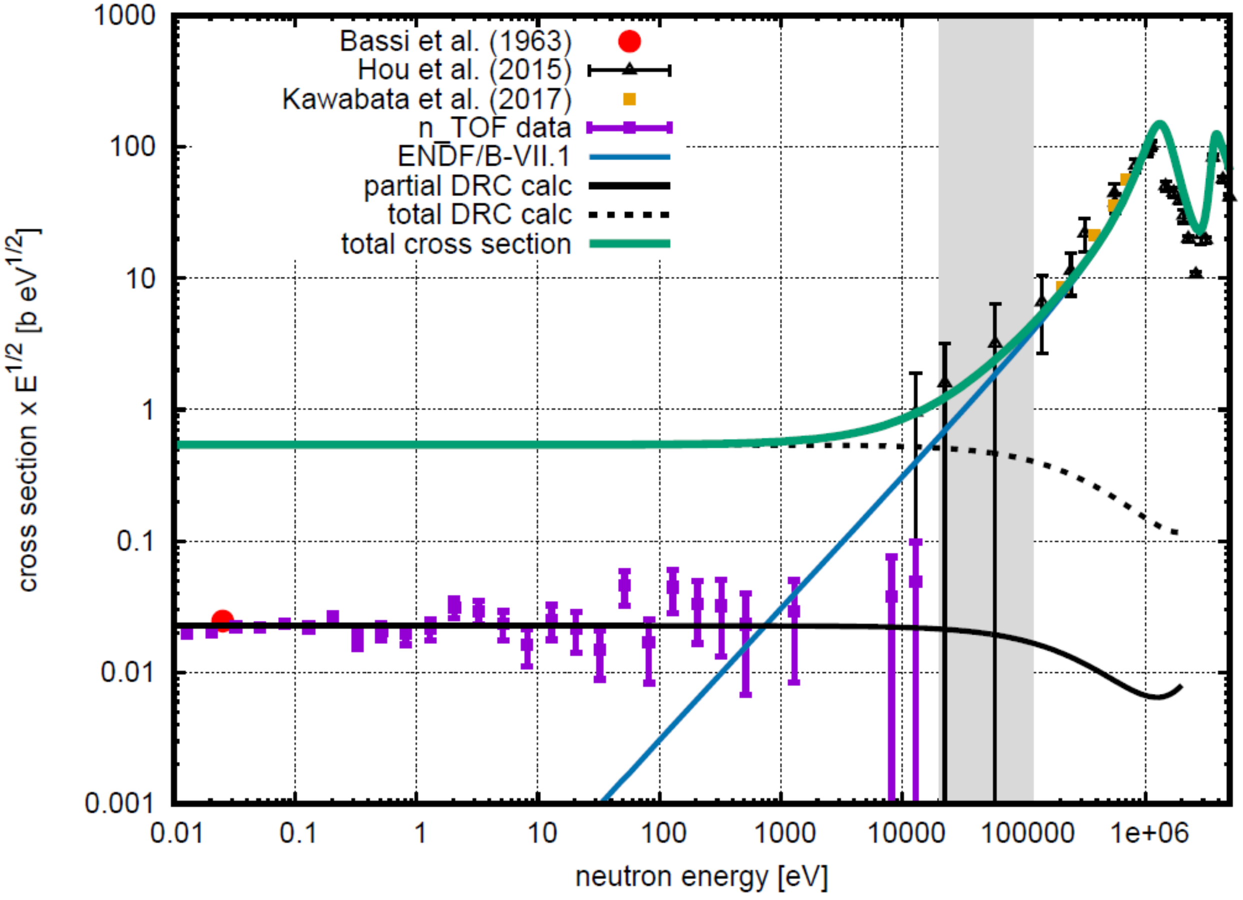
First signal



$^{7}Be(n,\alpha)\,^{4}He$ reaction

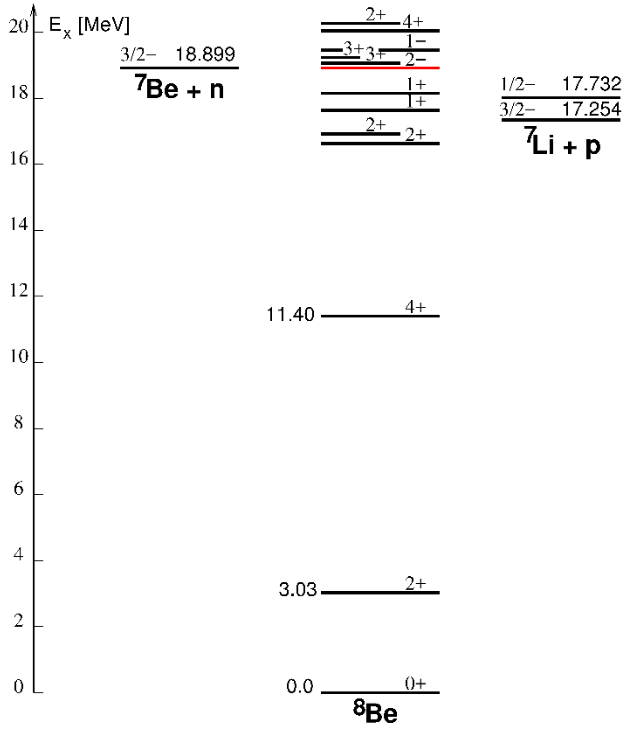


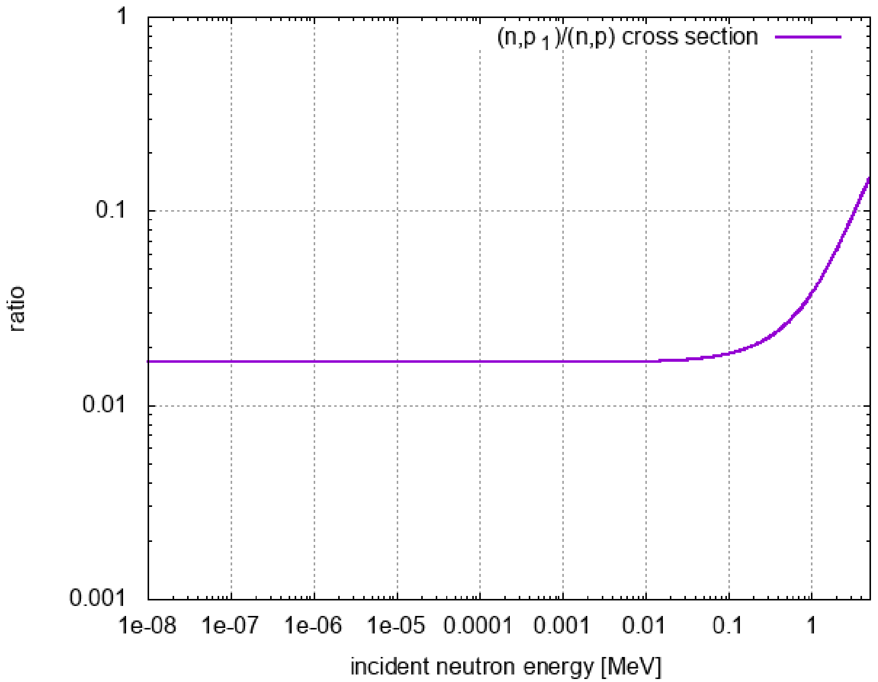
$^{7}Be(n,\alpha)\,^{4}He$ reaction



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

The first exited state in ^{7}Li at 478 keV has a spin and parity $J^\pi = 1/2^-$. Therefore, if a $J^\pi = 2^-$ is formed by s-wave neutron on ^{7}Be, the state cannot decay into ^{7}Li(1st) by emitting *l=0* (no sufficient angular momentum), nor *l=1* (no parity conservation) protons. Because the 2^- state just above threshold in ^{8}Be dominates the reaction mechanisms in a wide energy range, it is possible to estimate the (n,p_1) contribution to the ^{7}Be(n,p)^{7}Li cross section by calculating the ration of penetrabilities of *l=2* to *l=0* protons in the p + ^{7}Li(1s) exit channel. The result of this estimate is shown in the figure below.





$^7\mathrm{Be}(n,p)\,^7\mathrm{Li}$ reaction

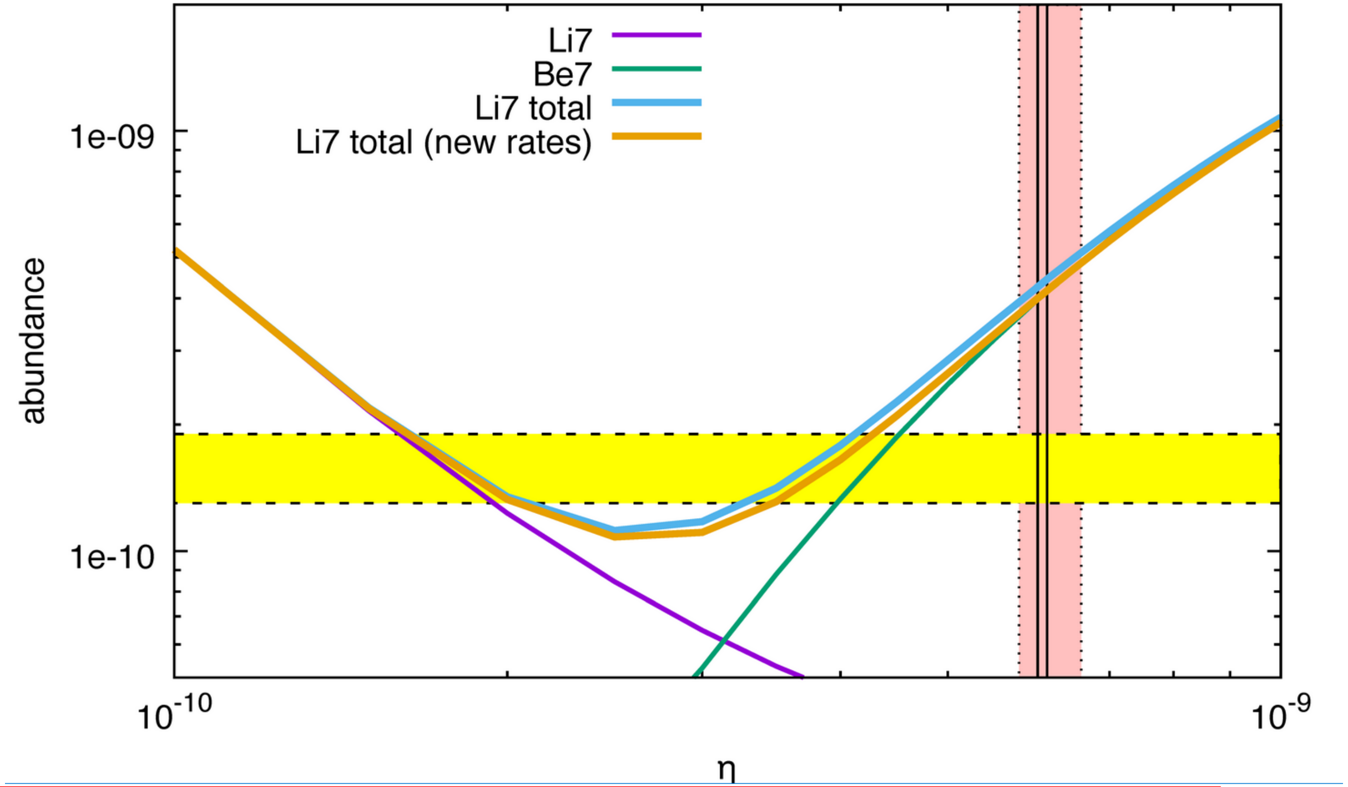
List of the 12th most important reactions in the BBN network

	code index	reaction	adopted	options
1	12	$^1H(n,\gamma)D$	ando	ando skm
2	16	$^3He(n,p)T$	stlb	stlb de04 skm
3	17	$^7Be(n,p)^7Li$	ntof	ntof cy04 skm
4	19	$^7Be(n,\alpha)^4He$	ntof	wag ntof
5	20	$D(p,\gamma)^3He$	il16	il16 skm
6	24	$^7Li(p,\alpha)^4He$	stlb	stlb cf88 de04 skm
7	26	$T(\alpha,\gamma)^7Li$	stlb	stlb skm
8	27	$^3He(\alpha,\gamma)^7Be$	il16	il16 ncr2 skm cd08
9	28	$D(d,n)^3He$	stlb	stlb skm
10	29	$D(d,p)T$	stlb	stlb skm
11	30	$T(d,n)^4He$	stlb	stlb de04 cf88 skm
12	31	$^3He(d,p)^4He$	stlb	stlb de04 skm

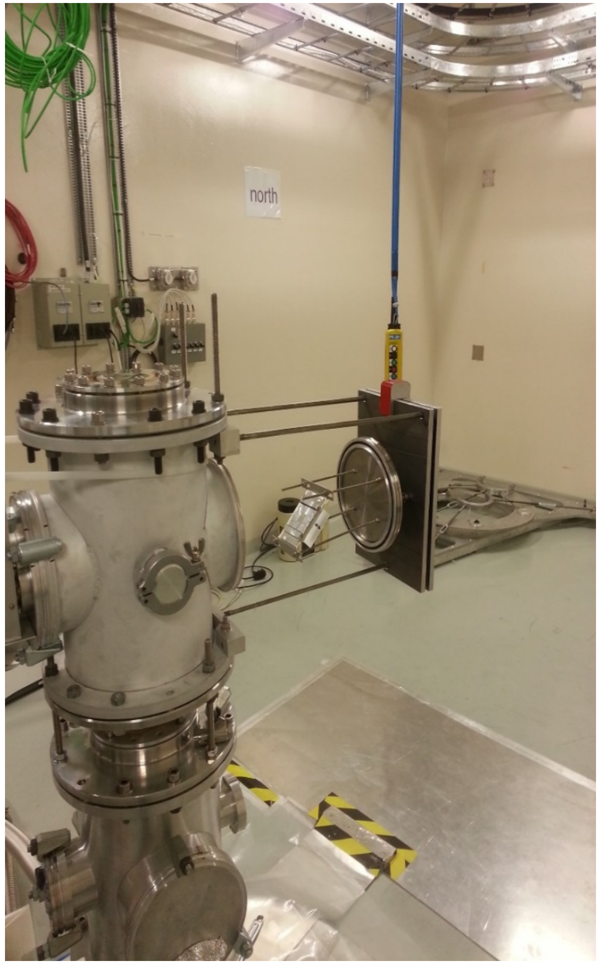
```
#wag  : Wagoner, R.V., ApJS, 18, 247 (1969)
#cf88 : Caughlan and Fowler, ADNDT 40, 283 (1988)
#skm  : Smith, Kawano and Malaney, ApjS 85, 2019 (1993)
#de04 : Descouvemont et al. ADNDT 88, 203 (2004)
#cy04 : Cyburt, PRD 70, 023505 (2004)
#ando : Ando et al. Phys. Rev. C 74, 025809 (2006)
#il16 : Iliadis et al., ApJ 831, 107 (2016)
#ncr2 : fit to ncare2 library
#stlb : fit to starlib table
#ntof : rate from n_TOF experiments
```

$^{7}Be(n,p)\ ^{7}Li$ reaction

	Y_p	D/H [10^{-5}]	^{3}He/H [10^{-5}]	^{7}Li/H [10^{-10}]
present with standard rates	0.246	2.43	1.08	5.46
present with new rate (η_{10} = 6.09)	0.246	2.43	1.08	5.26 ± 0.40
present with new rate ($5.8 \leq \eta_{10} \leq 6.6$)	0.246	2.43	1.08	4.73 - 6.23
observations	0.245 ± 0.003	2.569 ± 0.027	-	1.6 ± 0.3



$^{7}Be(n,p)\ ^{7}Li$ Experimental set-up



^{7}Be High Purity Sample

Activity	**1.1 GBq**
Radius	2.5 mm

LiF Sample

xy	$5 \times 5\ cm^2$
z	1.66 µm