n + ^{7}Be cross-sections of astrophysical interest at the CERN n_TOF facility: The Cosmological ^{7}Li problem

Mario Mastromarco on behalf of the n_TOF collaboration

ISTITUTO NAZIONALE DI FISICA NUCLEARE

Big Bang Nucleosynthesis Theory: Introduction

- **Big Bang Nucleosynthesis (BBN) theory** describes the production of the lighest nuclides (D, ^{3}He, ^{4}He, ^{7}Li) between 1 s and 3 min after the Big Bang

- It rests on well understood physics of **nuclear reaction cross-sections** and **Standard Model weak** and **electromagnetic interactions**

- BBN predictions are in a broad quantitative agreement with measured primordial light-elements derived from observations of the local and high-redshift universe

Big Bang Nucleosynthesis Theory: Dynamics

- The cosmic production of light nuclides is the results of weak and nuclear interactions in the cooling-expanding universe

$$H^2 = \frac{8\pi}{3} G\rho$$

Friedman equation

- The largest contribution to the total mass-energy density ρ comes from radiation, $\rho_{rad} >> \rho_{matter}$
- Cosmic matter made of nonrelativistic particles (free nucleons)
- $\rho \sim T^4$ (adiabatic cooling) with Friedman eq. gives: $t \approx 1 \text{ sec} \left(\frac{1 \text{ MeV}}{T}\right)^2$

Big Bang Nucleosynthesis Theory: Dynamics

$$t \approx 1 \text{ sec} \left(\frac{1 \text{ MeV}}{T}\right)^2$$

- T > 1 MeV, t < 1 s, weak interactions are rapid

$$n\nu_e \leftrightarrow pe^-$$
$$p\bar{\nu}_e \leftrightarrow ne^+$$

- T ≈ 1 MeV, t ≈ 1 s, weak interactions “freezes out”

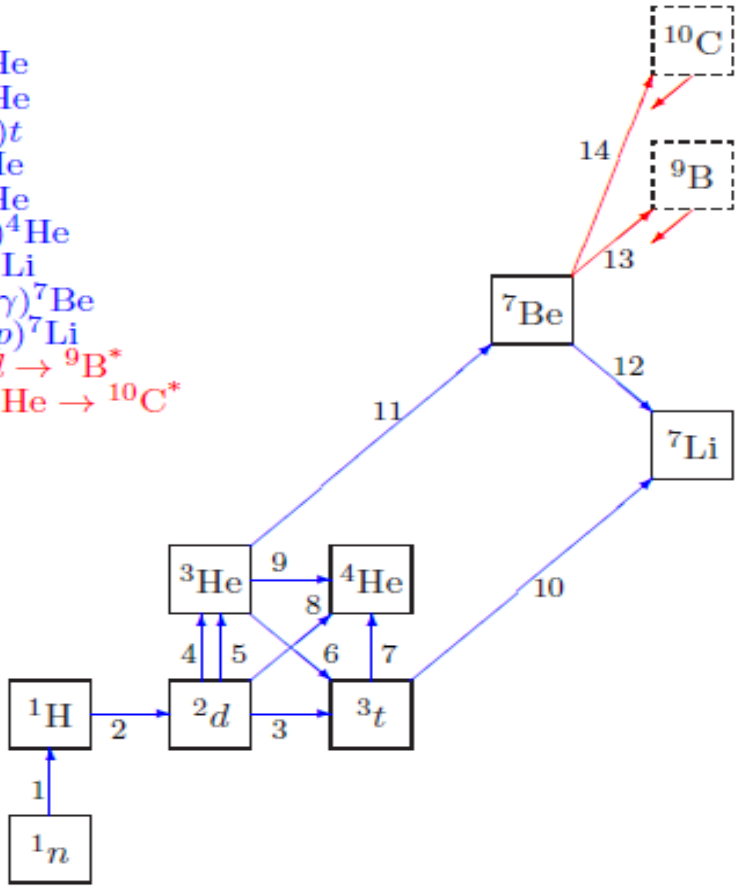
$$\frac{n}{p} = e^{-(m_n - m_p)/T} \approx 1/6$$

p(n, ɣ)D

- T ≈ 0.07 MeV, t ≈ 3-4 min, the D abundance rapidly rises starting a series of reactions in which all of the light element are built

Big Bang Nucleosynthesis Theory: key reactions

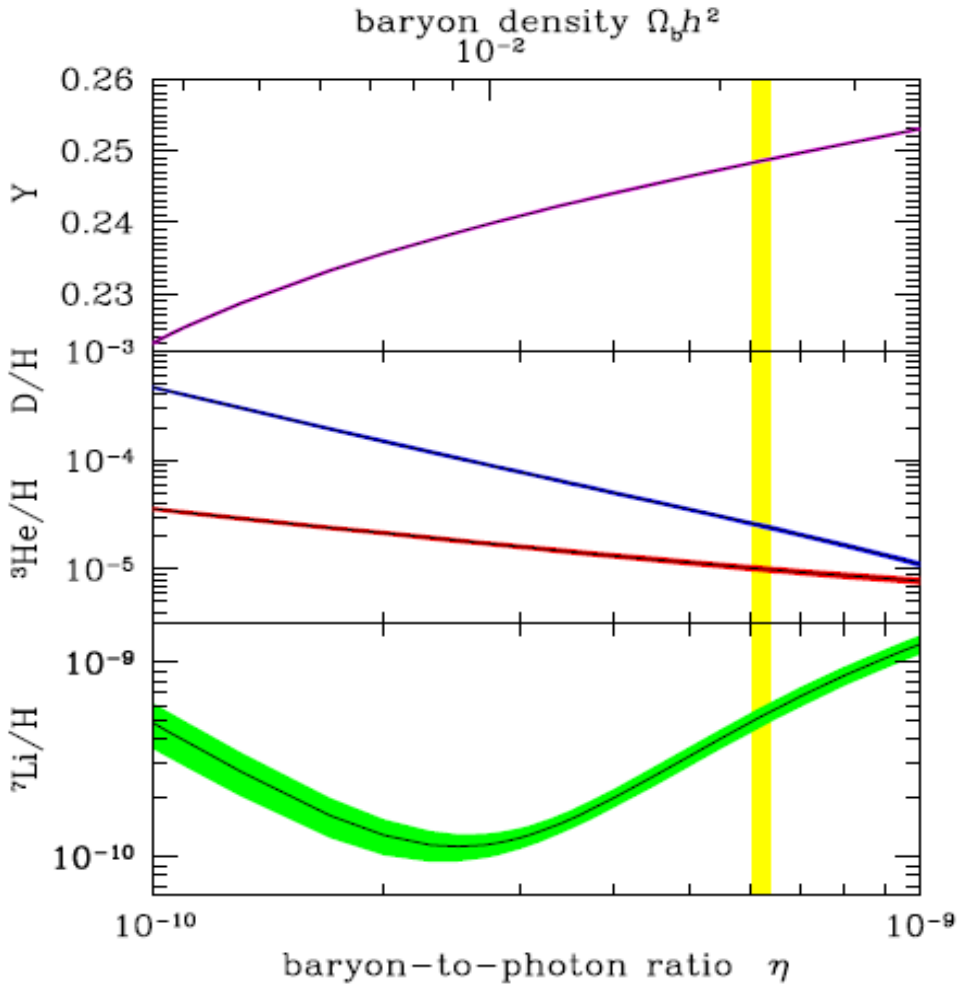
1: $n \rightarrow p\, e\, \nu$
2: $n(p,\gamma)d$
3: $d(d,p)t$
4: $d(p,\gamma)^3\mathrm{He}$
5: $d(d,n)^3\mathrm{He}$
6: $^3\mathrm{He}(n,p)t$
7: $t(d,n)^4\mathrm{He}$
8: $d(d,\gamma)^4\mathrm{He}$
9: $^3\mathrm{He}(d,p)^4\mathrm{He}$
10: $t(\alpha,\gamma)^7\mathrm{Li}$
11: $^4\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$
12: $^7\mathrm{Be}(n,p)^7\mathrm{Li}$
13: $^7\mathrm{Be} + d \rightarrow {}^9\mathrm{B}^*$
14: $^7\mathrm{Be} + {}^3\mathrm{He} \rightarrow {}^{10}\mathrm{C}^*$



Big Bang Nucleosynthesis Theory: Predictions

The free/key parameter in the BBN theory is the baryon to photon ratio

$\eta = \eta_b/\eta_\gamma = 2.74 \times 10^{-8}\, \Omega_b\, h^2$



Big Bang Nucleosynthesis Theory: Predictions (+ CMB by WMAP)

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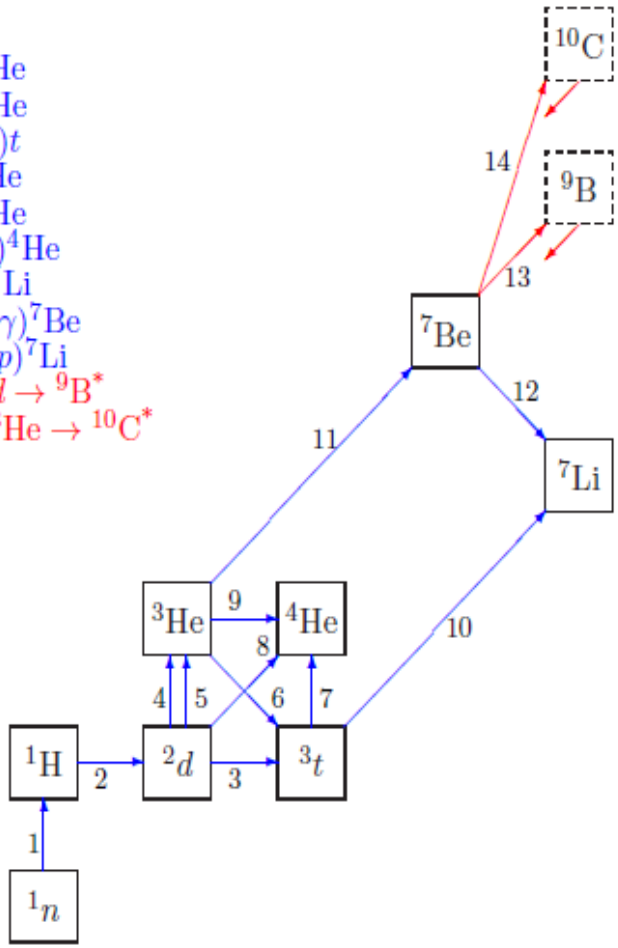

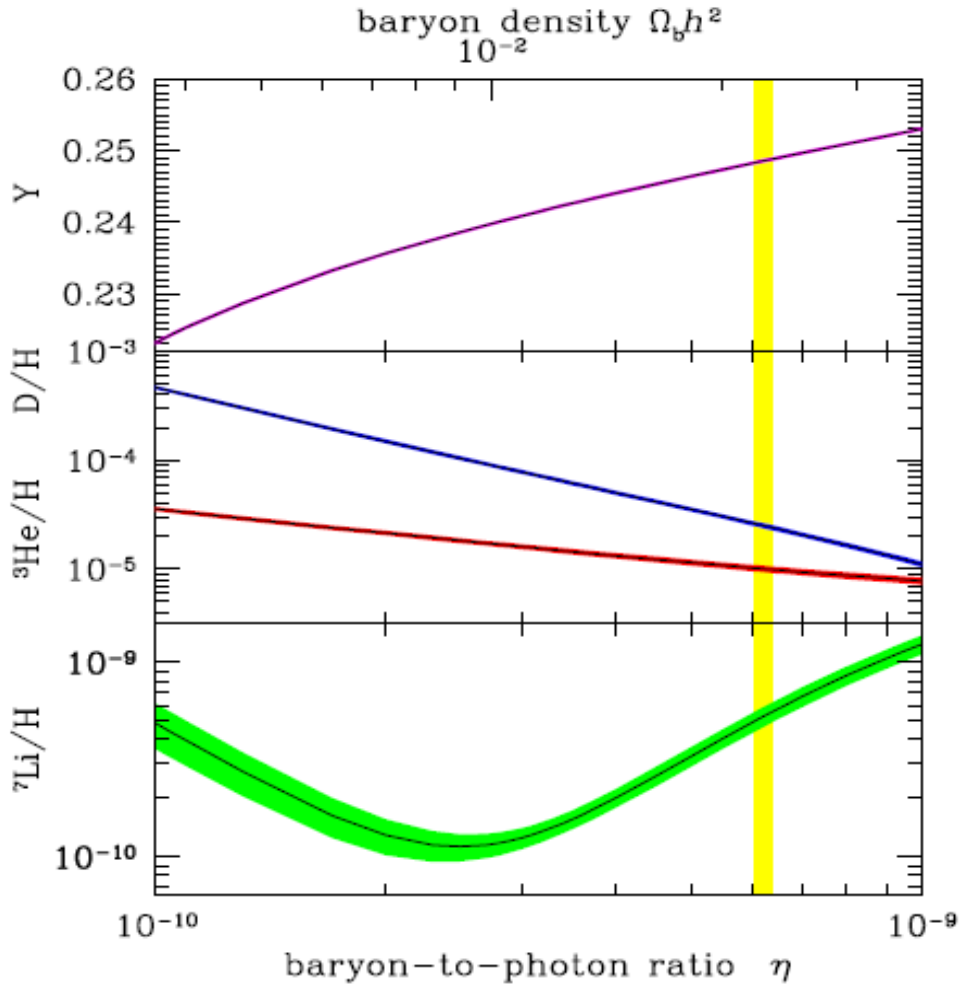

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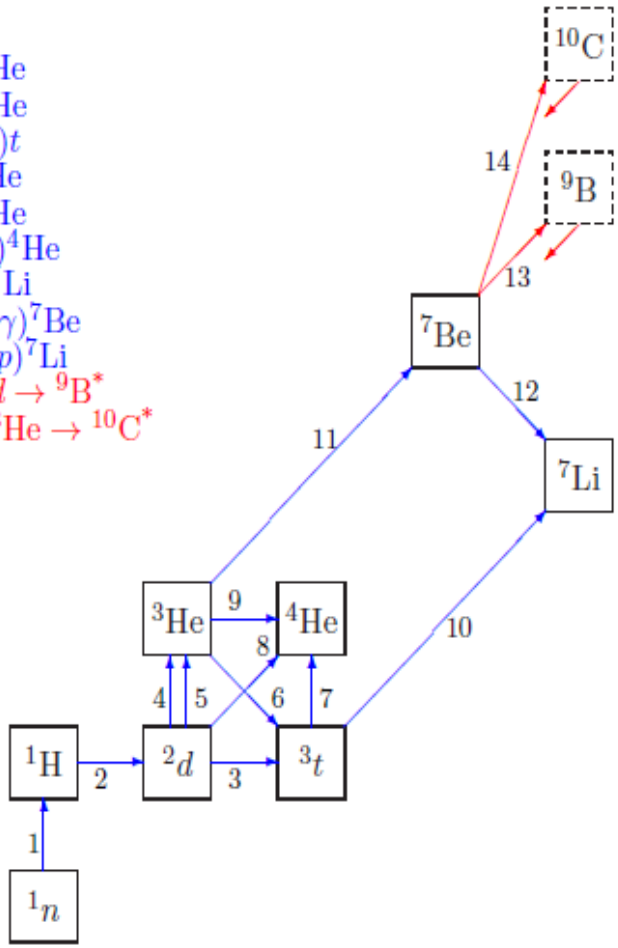
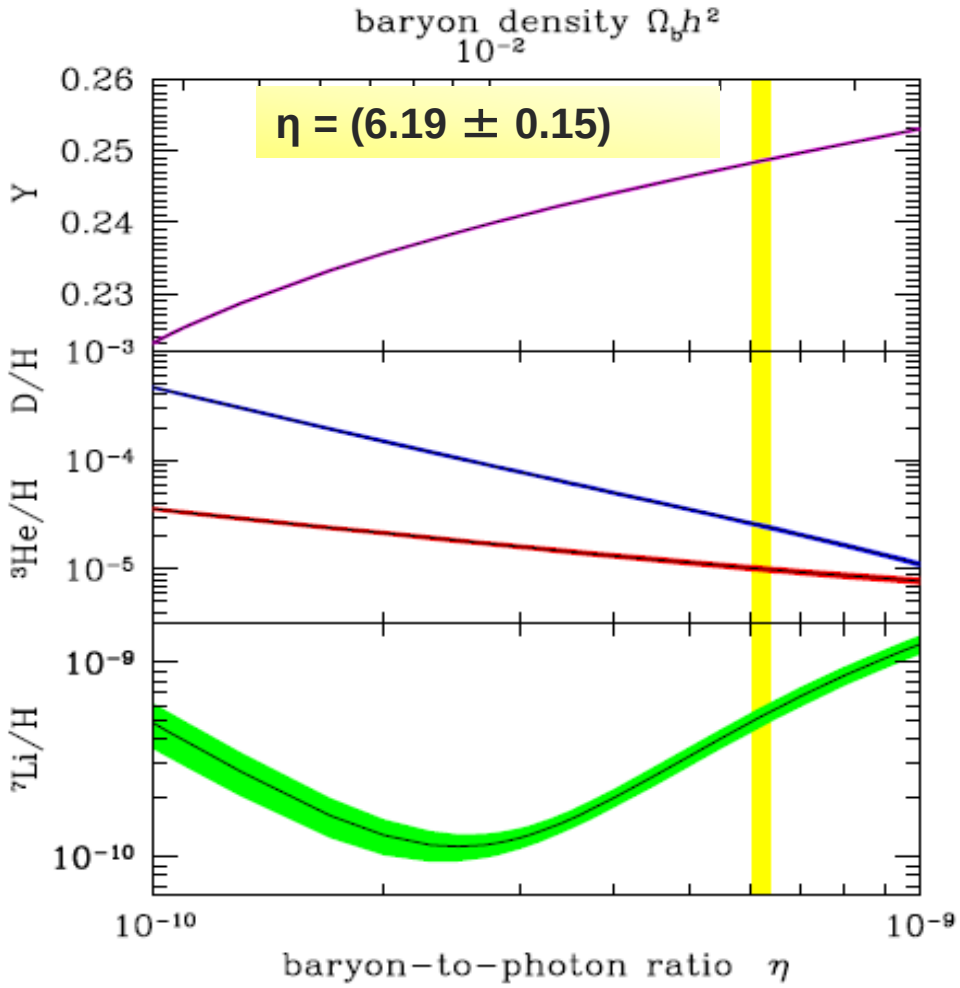
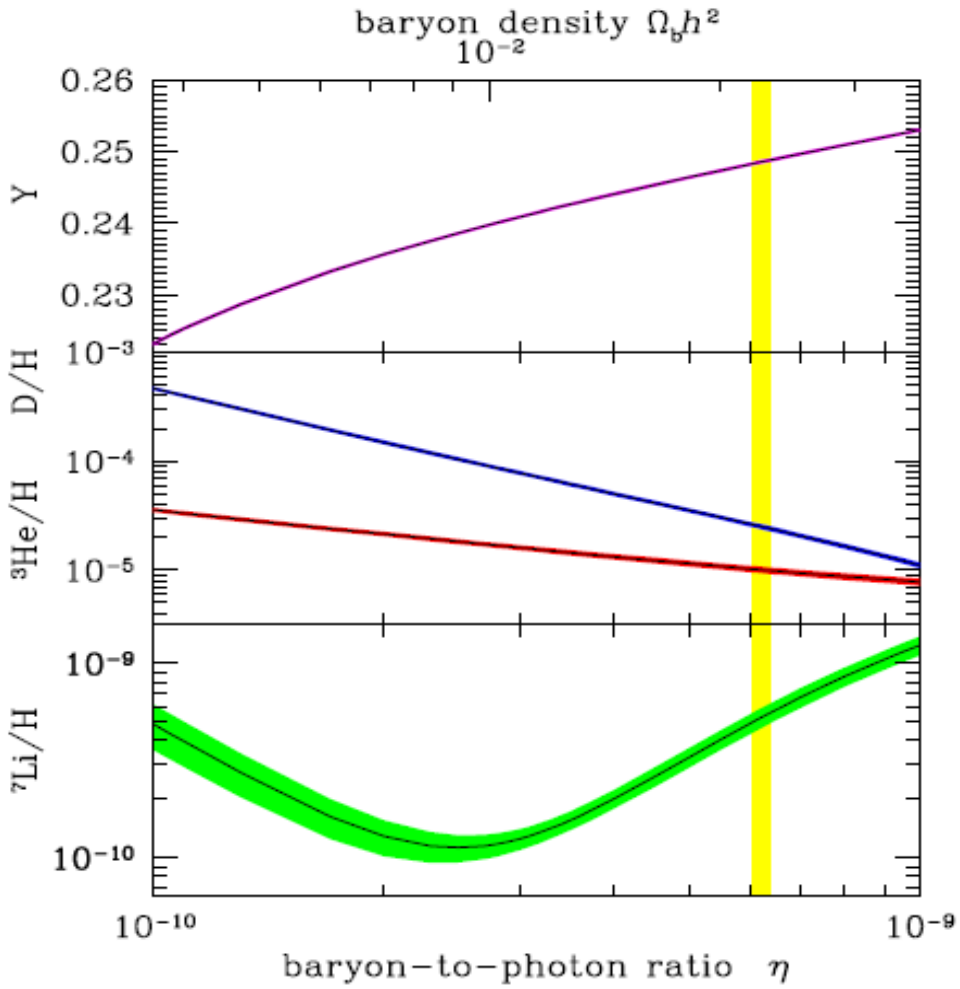




Light-Element Observations vs BBN + (CMB by WMAP)

- $(D/H)_{obb}$ = (2.82 ± 0.21) x 10^{-5}
- $(Y)_{obb}$ = ^{4}He = 0.249 ±0.009
- $(^3He)_{obb}$ not measurable at low metallicity
- $(^7Li/H)_{obb}$ = (1.58 ± 0.25) x 10^{-10}



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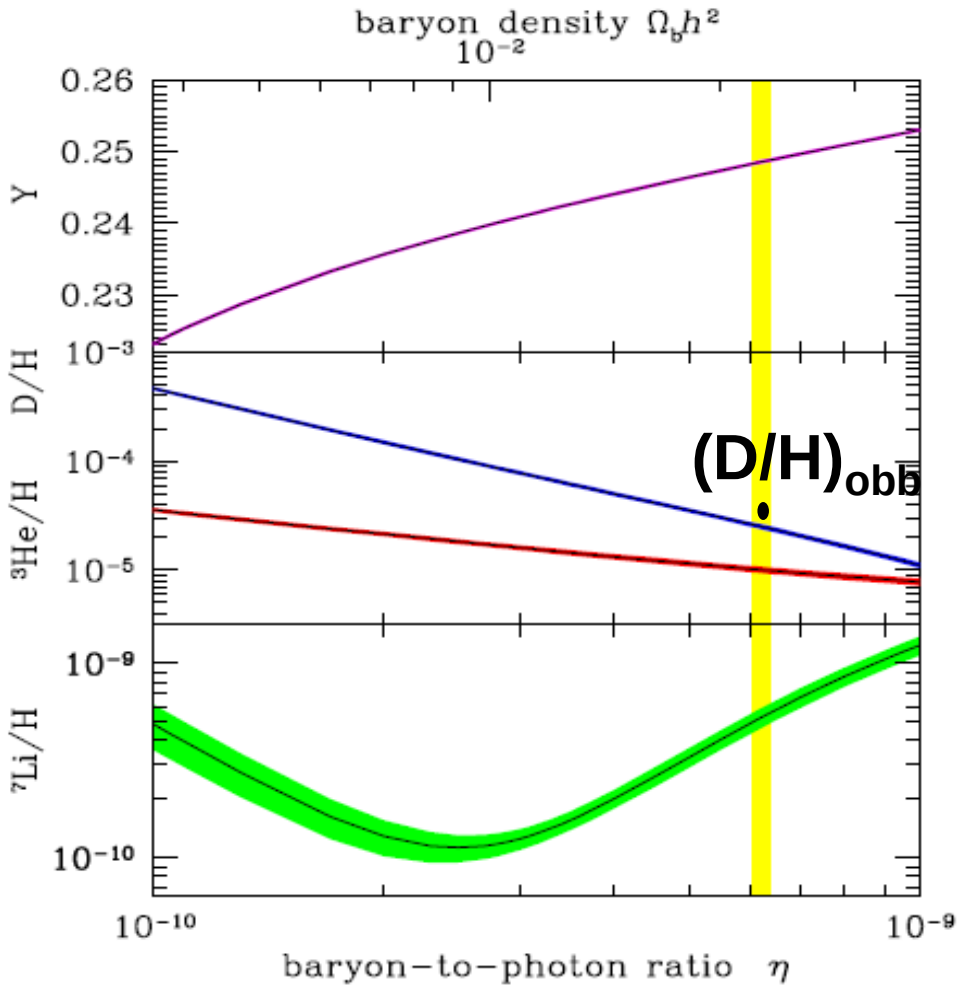

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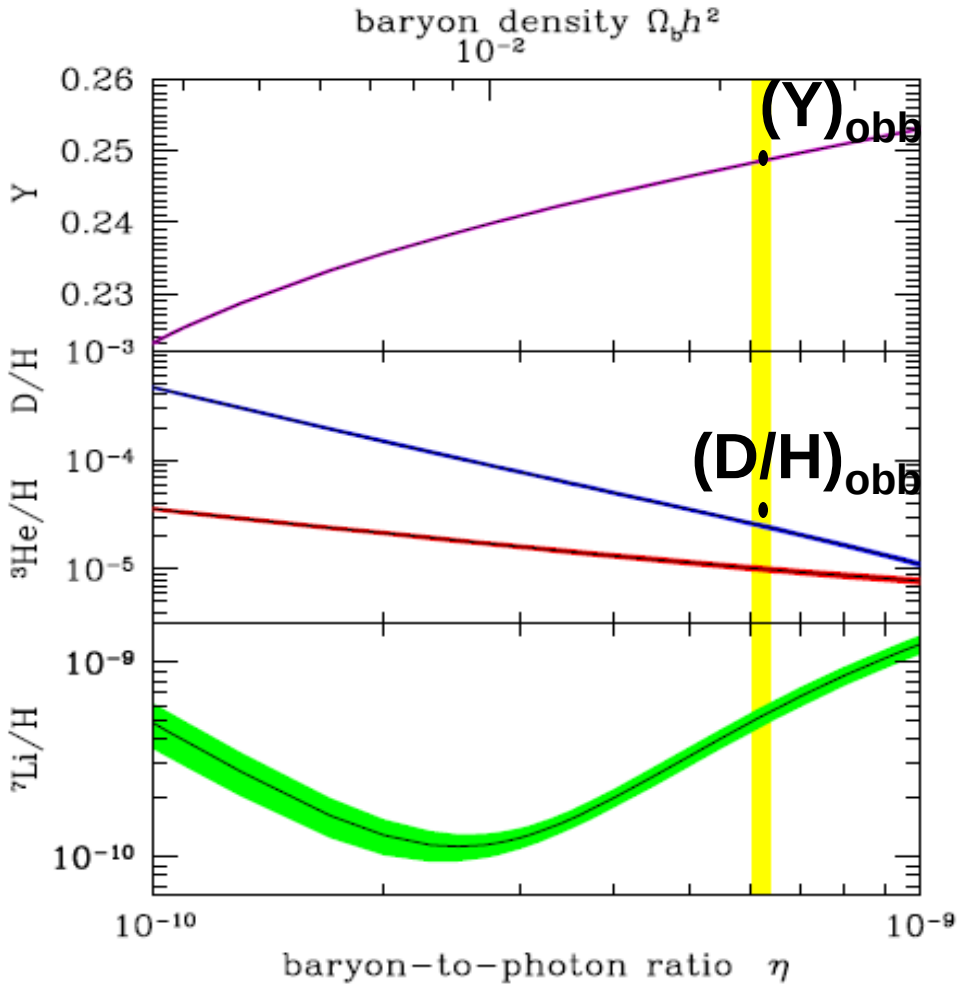

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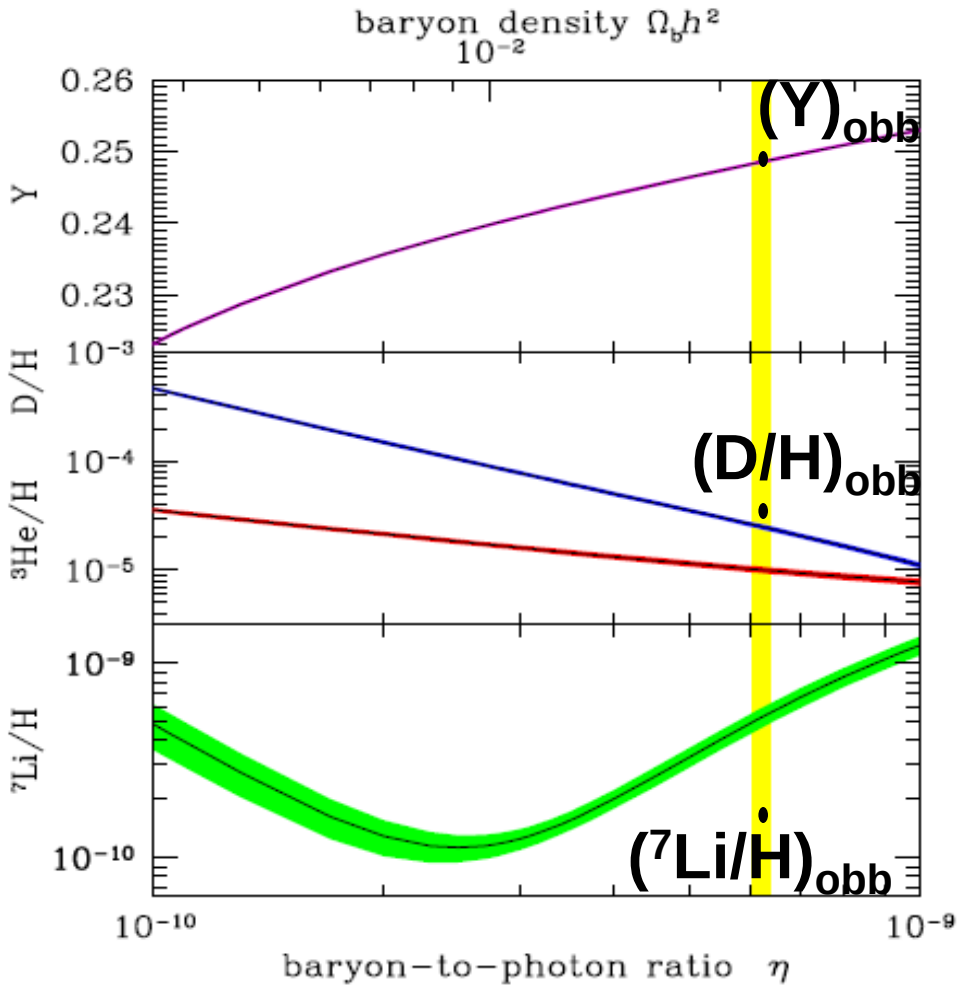


The Cosmological Lithium Problem: possible solutions

- Astrophysical
- Nuclear Physics
- Beyond the Standard Model

Nuclear Physics Solution

95% of primordial ^{7}Li comes from the **electron capture decay** of ^{7}Be:

^{7}Be + e^{-} -> ^{7}Li + ν_e ($t_{1/2}$ = 53 days)

Therefore the production and the destruction of ^{7}Be is the key to understand the ^{7}Li abundance resulting from the BBN.

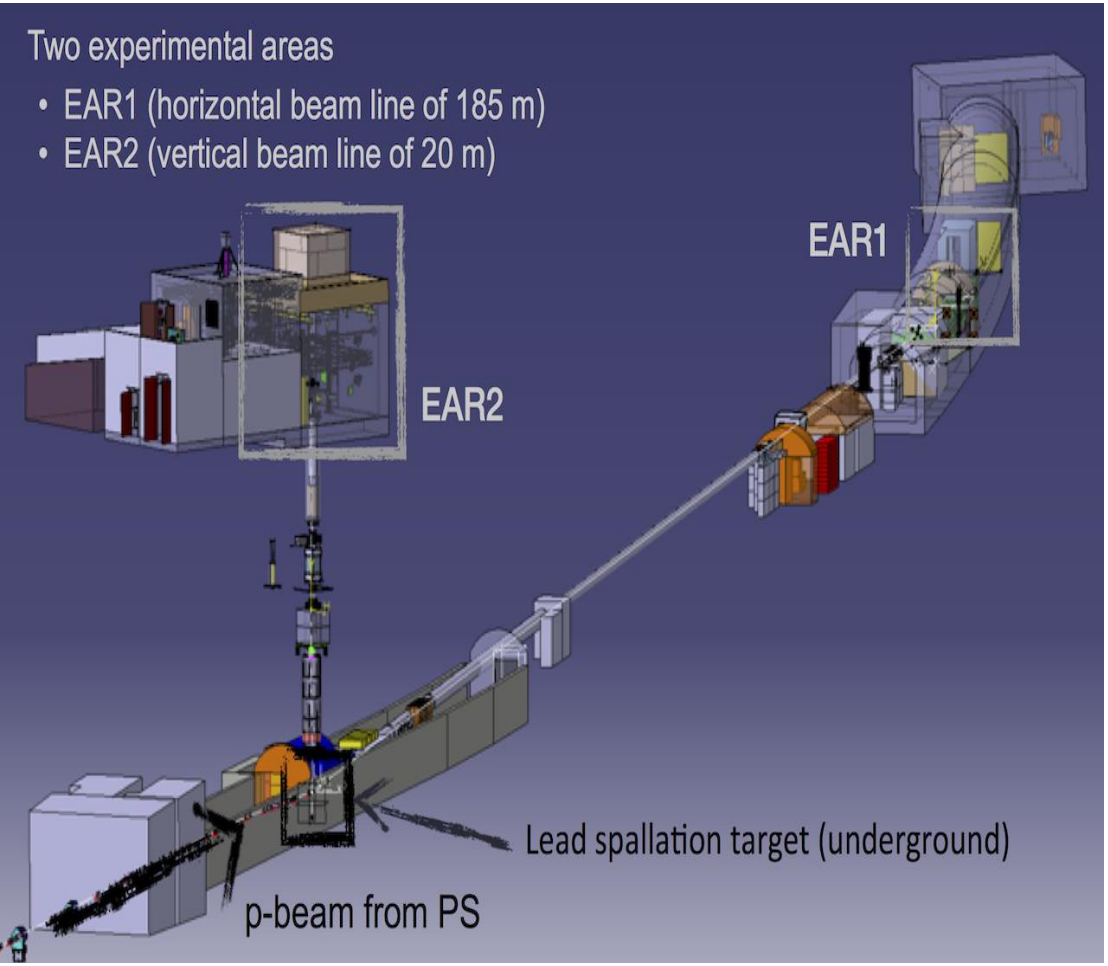
^{7}Be(n, α)^{4}He, 2.5%

Possible ^{7}Be destruction channel:

^{7}Be(n, p)^{7}Li, 97%

Lack of experimental data due to intrinsic difficulty of the measurement: **Specific activity 13GBq/μg**, **$t_{1/2}$ = 53 days**

Features of EAR2 @ n_TOF



The high instantaneous neutron flux of **10^7/pulse** and the white energy range from **2 meV to 100 MeV** in **EAR2** allows:

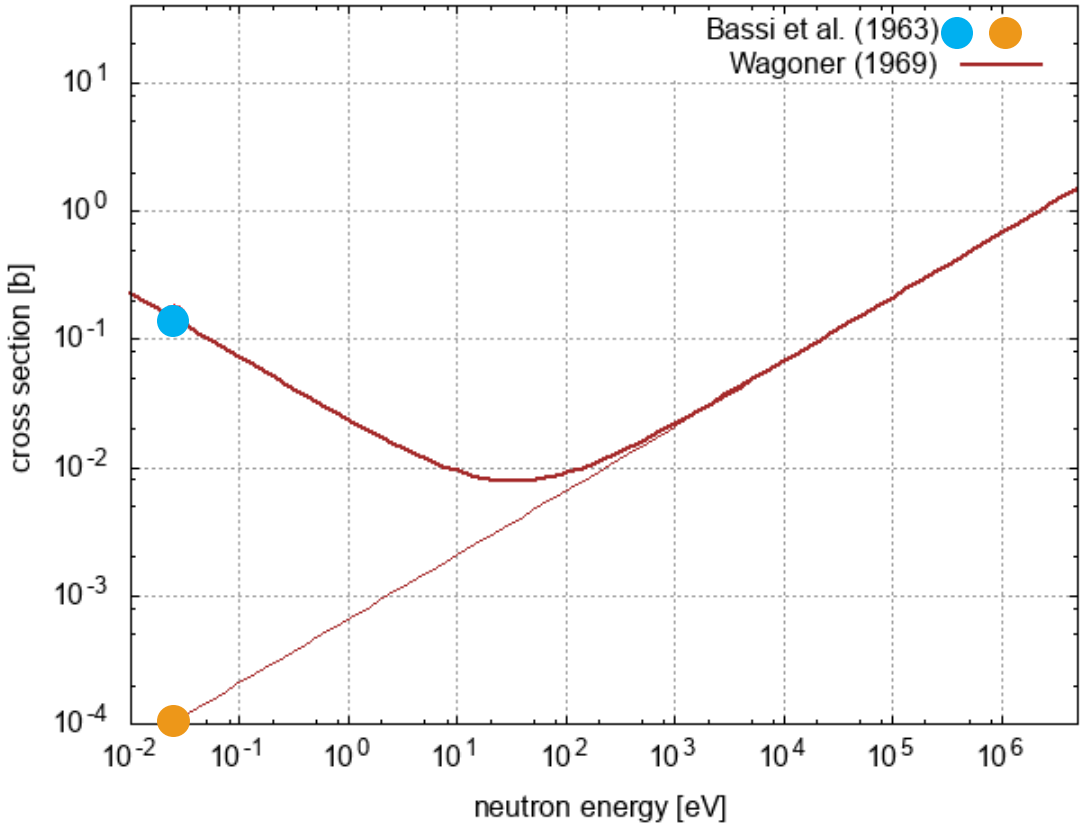
- **measure very small sample (<< 1mg)**
- **measure short lived radioisotopes**
- **collect data on a more shorter time**
- **measure (n, cp) reactions with thin sample**

Available data for (n, α)

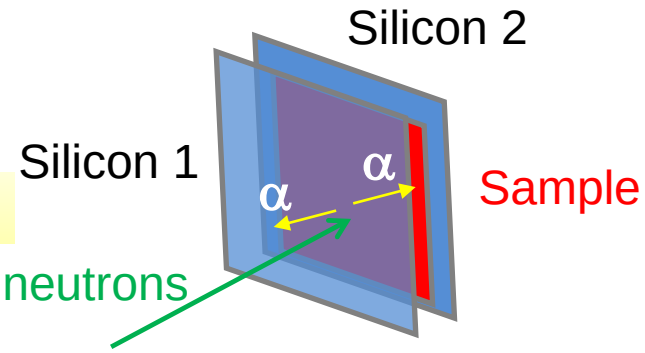
Only one measurement at thermal by Bassi et al.

Cross-section by Wagoner (1969):

- **s-wave component: 1/v normalized at thermal**
- **p-wave component: ~ $E^{1/2}$**



Experimental setup for (n, α)α



Q = 19 MeV, α coincidence back to back of 8.5 MeV each one

4
3

Electrodeposition on a 5-μm-thick Al foil

2
1

Droplet deposition on a 0.6-μm-thick polyethylene foil

Experimental setup for (n, α)α

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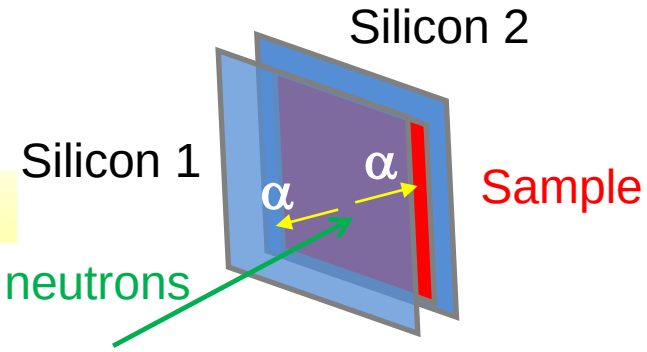

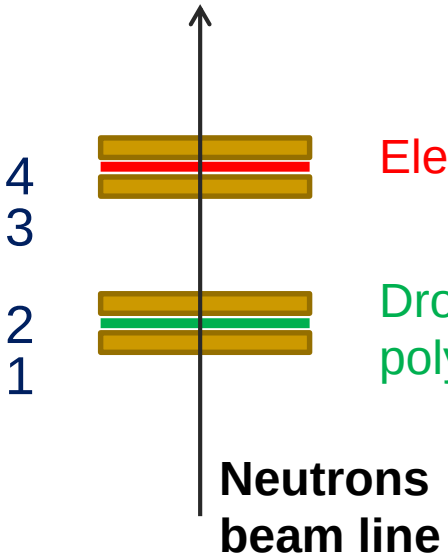

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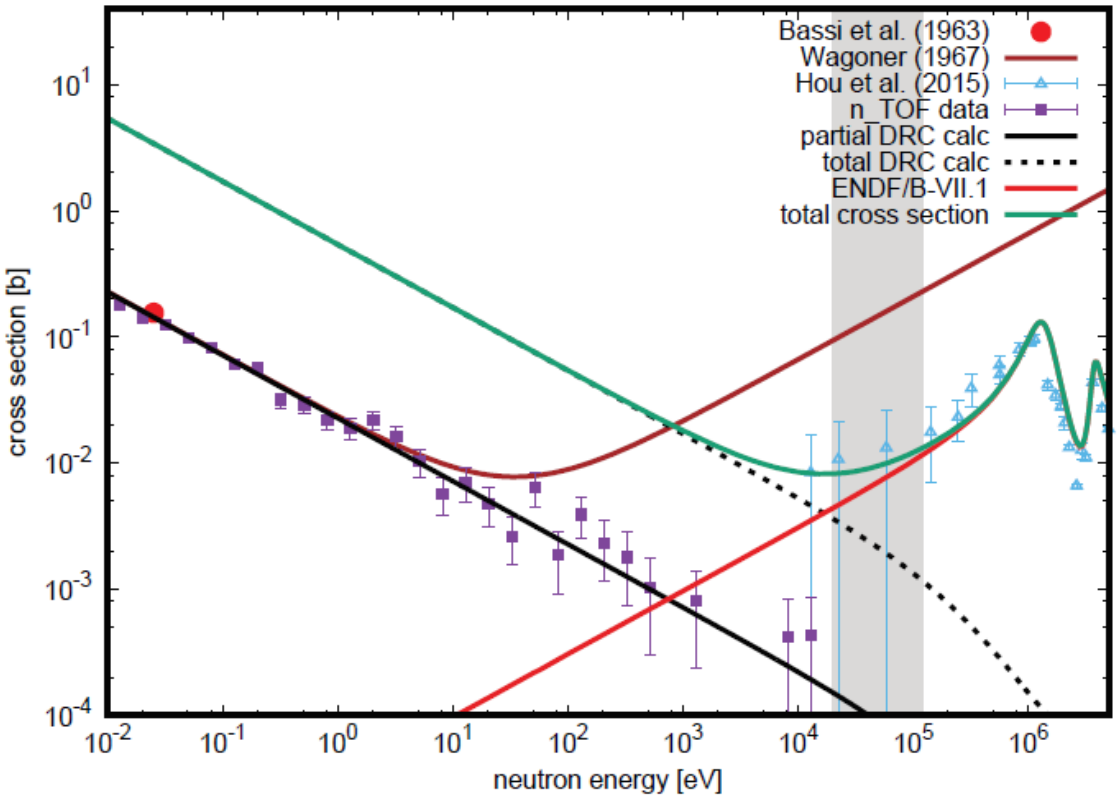
Results and pubblications



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^{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

M. Barbagallo,[1] A. Musumarra,[2,3] L. Cosentino,[3] E. Maugeri,[4] S. Heinitz,[4] A. Mengoni,[5] R. Dressler,[4] D. Schumann,[4] F. Käppeler,[6] N. Colonna,[1,*] P. Finocchiaro,[3] M. Ayranov,[7] L. Damone,[1] N. Kivel,[4] O. Aberle,[8] S. Altstadt,[9] J. Andrzejewski,[10] L. Audouin,[11] M. Bacak,[12] J. Balibrea-Correa,[13] S. Barros,[14] V. Bécares,[13] F. Bečvář,[15] C. Beinrucker,[9] E. Berthoumieux,[16] J. Billowes,[17] D. Bosnar,[18] M. Brugger,[8] M. Caamaño,[19] M. Calviani,[8] F. Calviño,[20] D. Cano-Ott,[13] R. Cardella,[3,8] A. Casanovas,[20] D. M. Castelluccio,[5] F. Cerutti,[8] Y. H. Chen,[11] E. Chiaveri,[8] G. Cortés,[20] M. A. Cortés-Giraldo,[21] S. Cristallo,[22] M. Diakaki,[23] C. Domingo-Pardo,[24] E. Dupont,[16] I. Duran,[19] B. Fernandez-Dominguez,[19] A. Ferrari,[8] P. Ferreira,[14] W. Furman,[25] S. Ganesan,[26] A. García-Rios,[13] A. Gawlik,[10] T. Glodariu,[27] K. Göbel,[9] I. F. Gonçalves,[14] E. González-Romero,[13] E. Griesmayer,[12] C. Guerrero,[21] F. Gunsing,[16] H. Harada,[28] T. Heftrich,[9] J. Heyse,[29] D. G. Jenkins,[30] E. Jericha,[12] T. Katabuchi,[31] P. Kavrigin,[12] A. Kimura,[28] M. Kokkoris,[23] M. Krtička,[15] E. Leal-Cidoncha,[19] J. Lerendegui,[21] C. Lederer,[32] H. Leeb,[33] S. Lo Meo,[5,34] S. J. Lonsdale,[32] R. Losito,[8] D. Macina,[8] J. Marganiec,[10] T. Martínez,[13] C. Massimi,[35,34] P. Mastinu,[36] M. Mastromarco,[1] A. Mazzone,[37,1] E. Mendoza,[13] P. M. Milazzo,[38] F. Mingrone,[35,34] M. Mirea,[27] S. Montesano,[8] R. Nolte,[39] A. Oprea,[27] A. Pappalardo,[3] N. Patronis,[40] A. Pavlik,[41] J. Perkowski,[10] M. Piscopo,[3] A. Plompen,[29] I. Porras,[42] J. Praena,[21,42] J. Quesada,[21] K. Rajeev,[26] T. Rauscher,[43,44] R. Reifarth,[9] A. Riego-Perez,[20] P. Rout,[26] C. Rubbia,[8] J. Ryan,[17] M. Sabate-Gilarte,[8] A. Saxena,[26] P. Schillebeeckx,[29] S. Schmidt,[9] P. Sedyshev,[25] A. G. Smith,[17] A. Stamatopoulos,[23] G. Tagliente,[1] J. L. Tain,[24] A. Tarifeño-Saldivia,[24] L. Tassan-Got,[11] A. Tsinganis,[8] S. Valenta,[15] G. Vannini,[35,34] V. Variale,[1] P. Vaz,[14] A. Ventura,[34] V. Vlachoudis,[8] R. Vlastou,[23] J. Vollaire,[8] A. Wallner,[45,41] S. Warren,[17] M. Weigand,[9] C. Weiß,[8] C. Wolf,[9] P. J. Woods,[32] T. Wright,[17] and P. Žugec[18]

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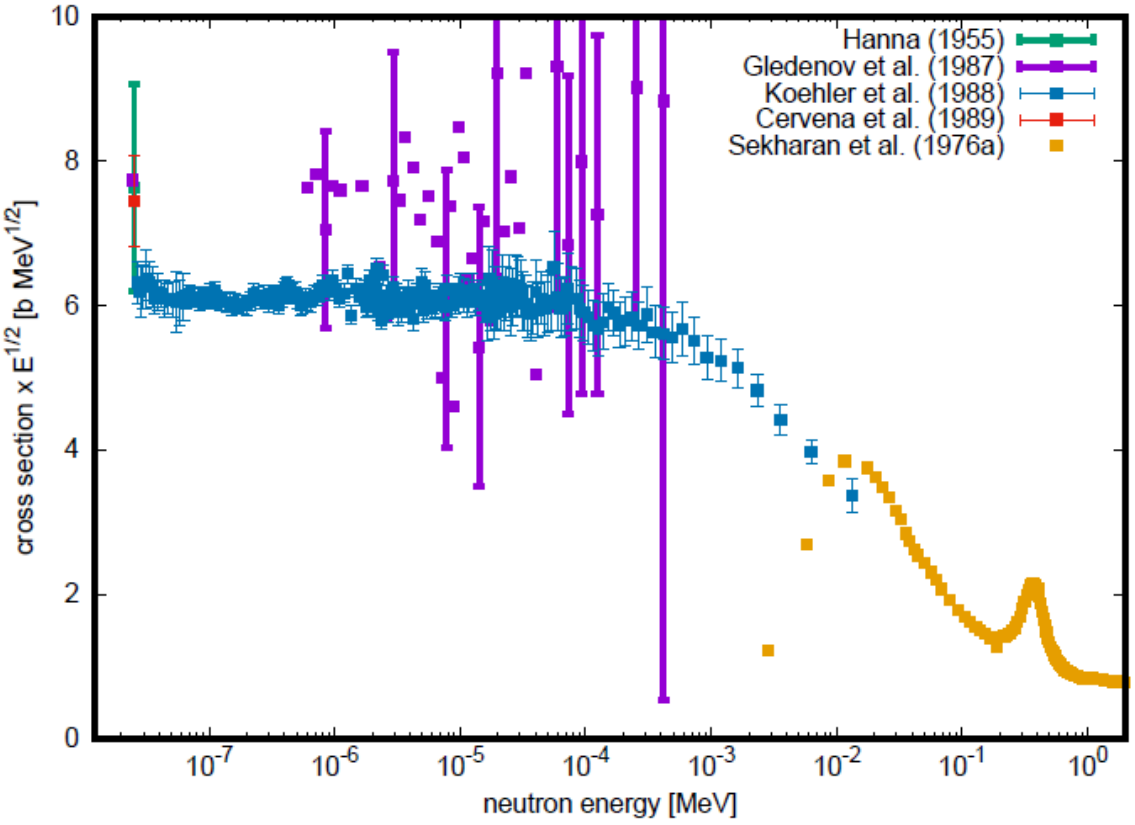
Available data for (n, p)^{7}Li



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- **Koeheler et al. from thermal to 13 KeV**

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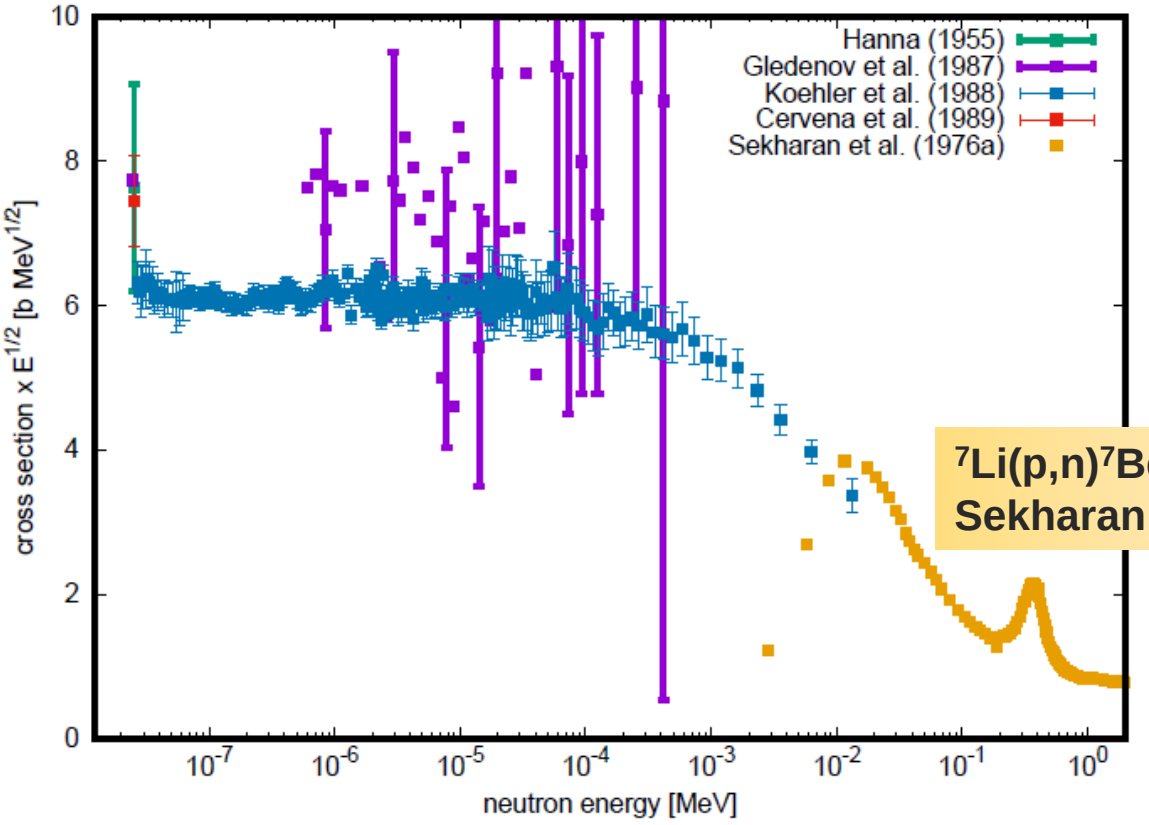

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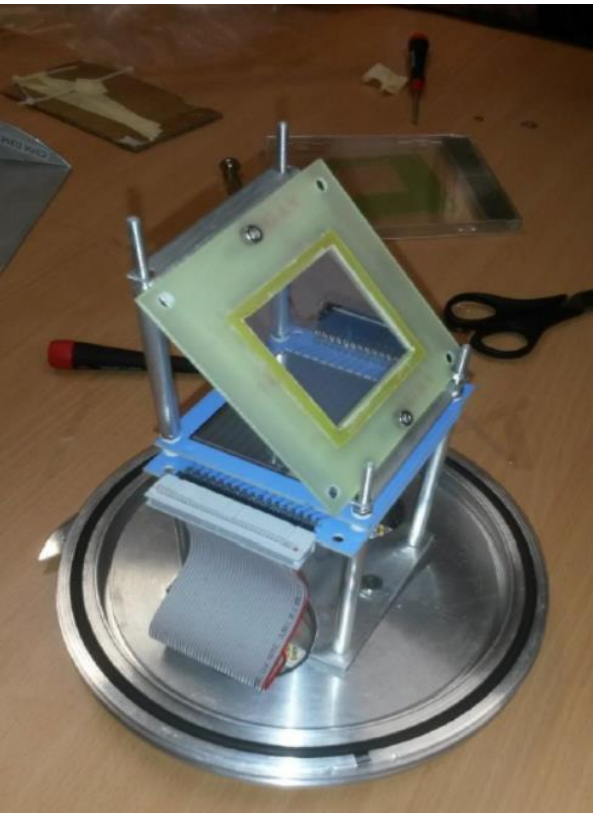
- **Koeheler et al. from thermal to 13 KeV**

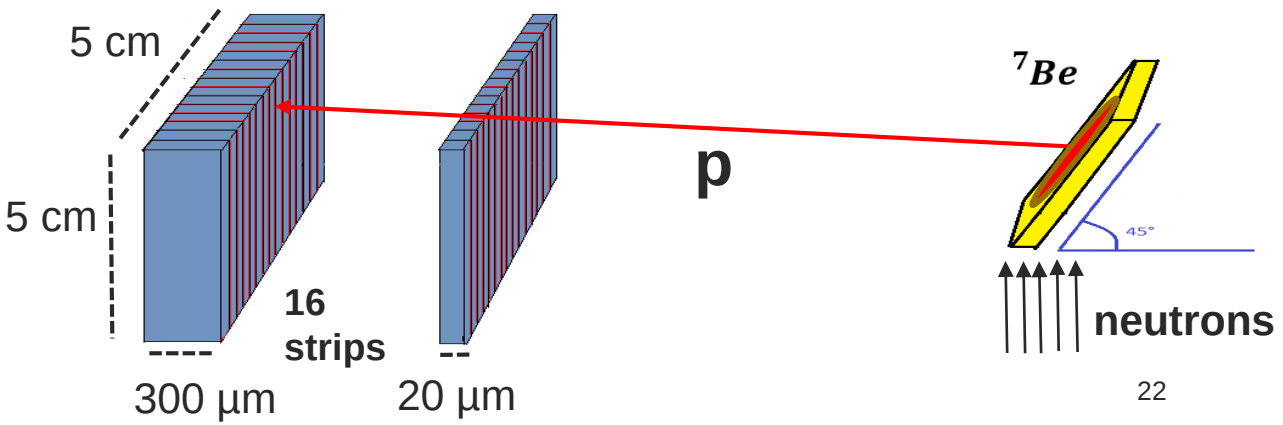
^{7}Li(p,n)^{7}Be reaction by Sekharan et al.

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

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

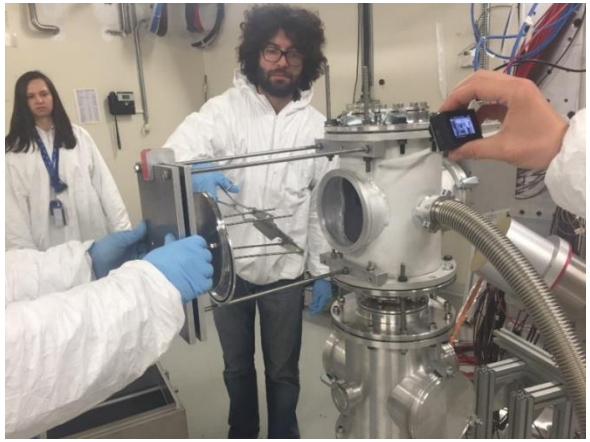


High Cross-section: Lower mass, detector out of the Beam

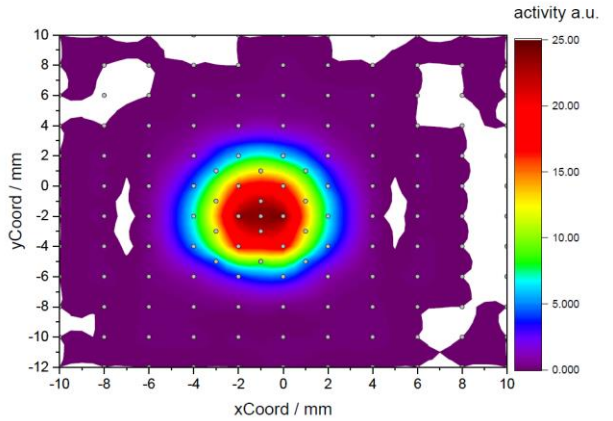


Sample preparation

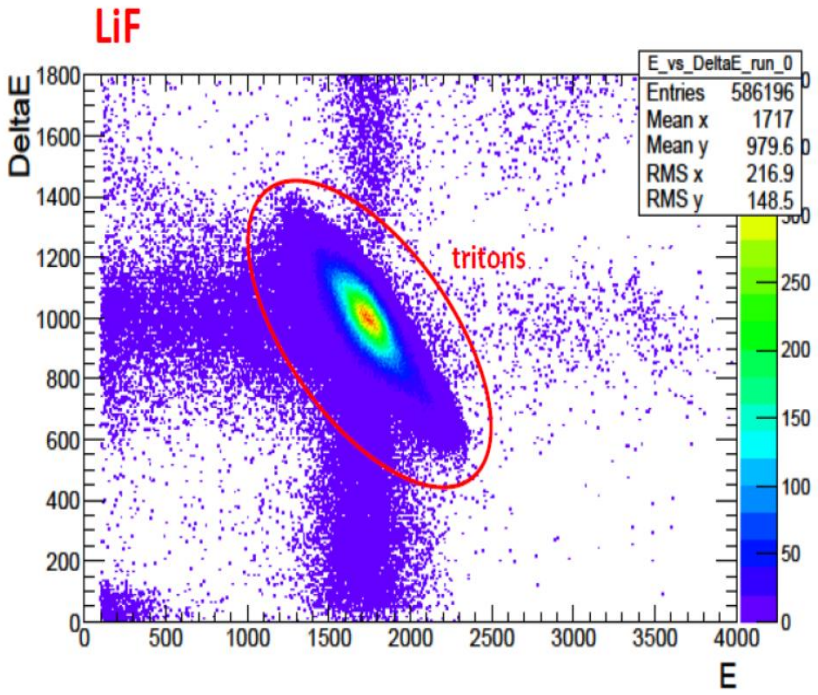
- **200 GBq of ^{7}Be** extracted from the cooling water of the SINQ spallation source at PSI
- Transported to **ISOLDE at CERN** and installed in the ion source to produce 30 keV ion beam
- **^{7}Be separated** by means of a magnetic dipole, and implanted on a **20 m thick Al backing**
- Sample of **1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



Sample characterization @ PSI (Gaussian profile 0.5 cm FHWM)



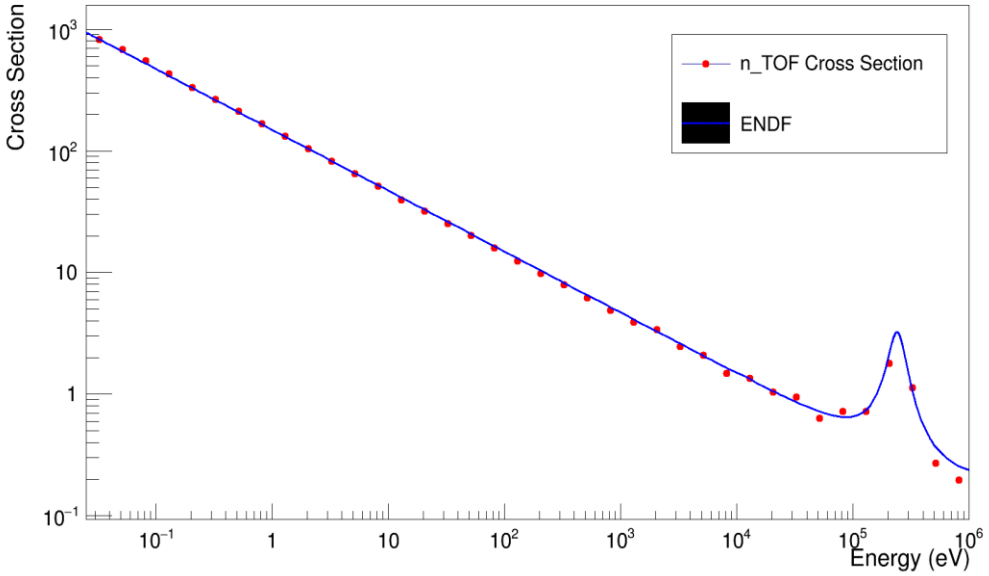
Reference reaction: LiF sample



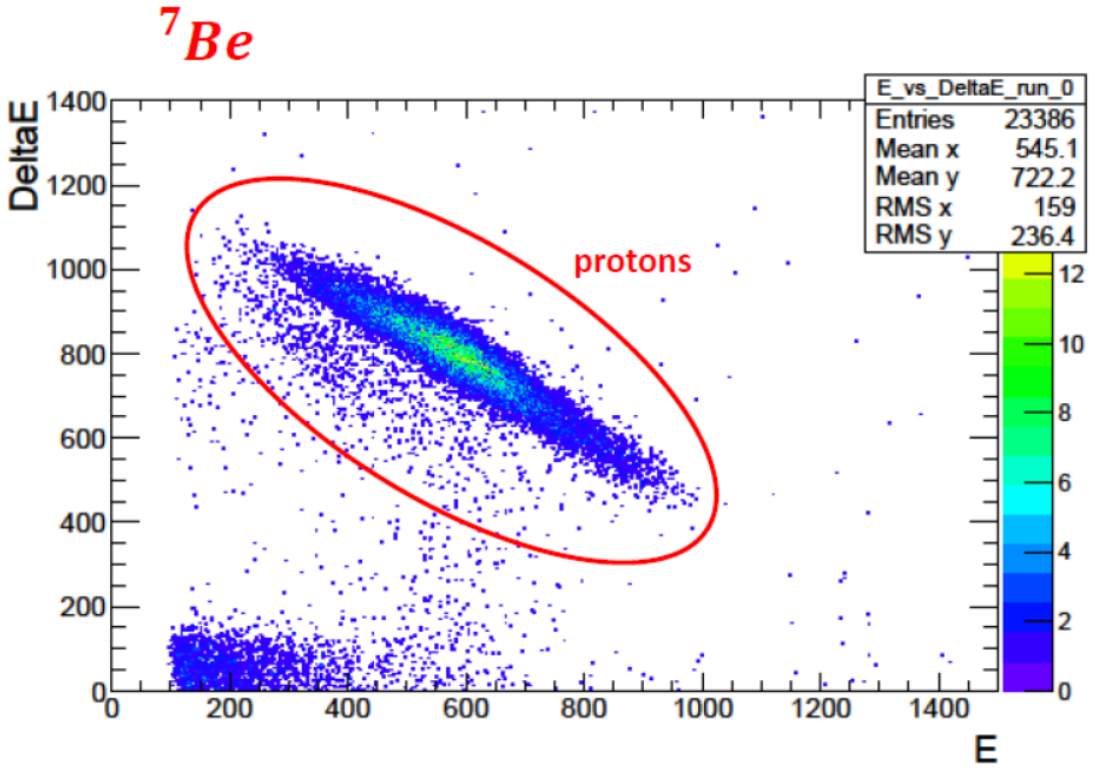
$$n + {}^{6}\mathrm{Li} \rightarrow \alpha + t$$

$Q = 4.78$ MeV

Coincidence window = 100 ns

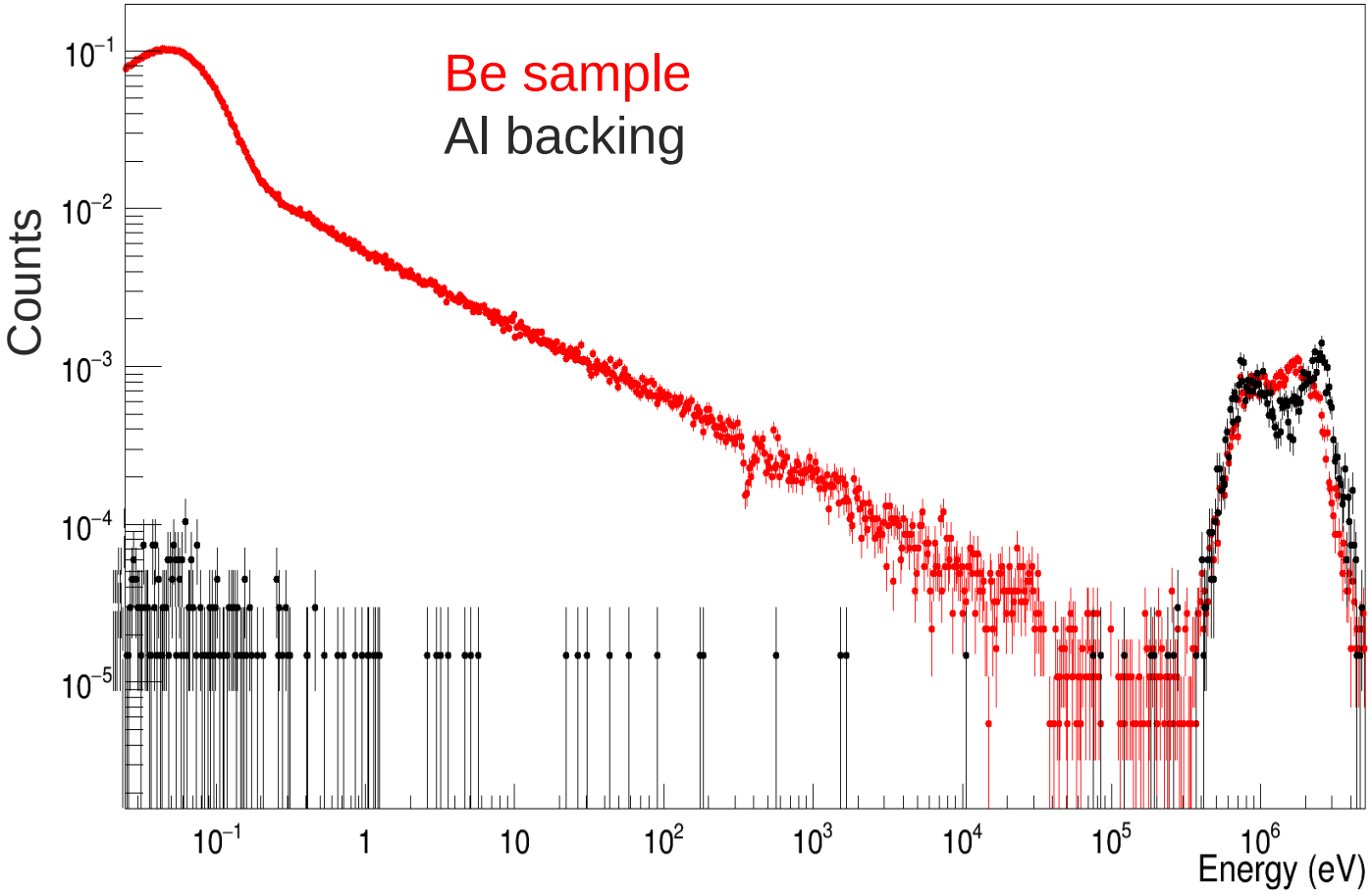


^{7}Be coincidence



n + ^{7}Be -> p + ^{7}Li
Q = 1.64 MeV

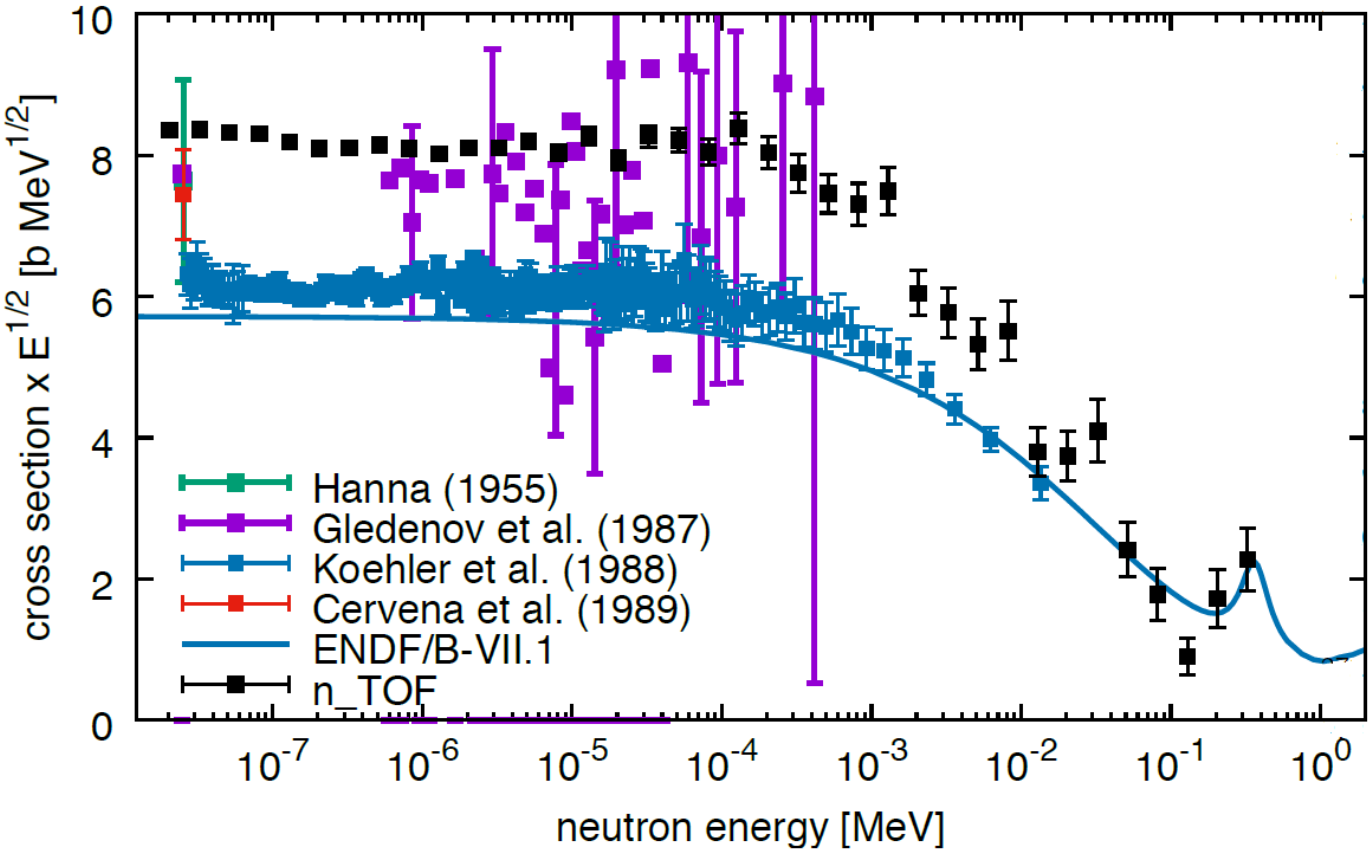
Background check



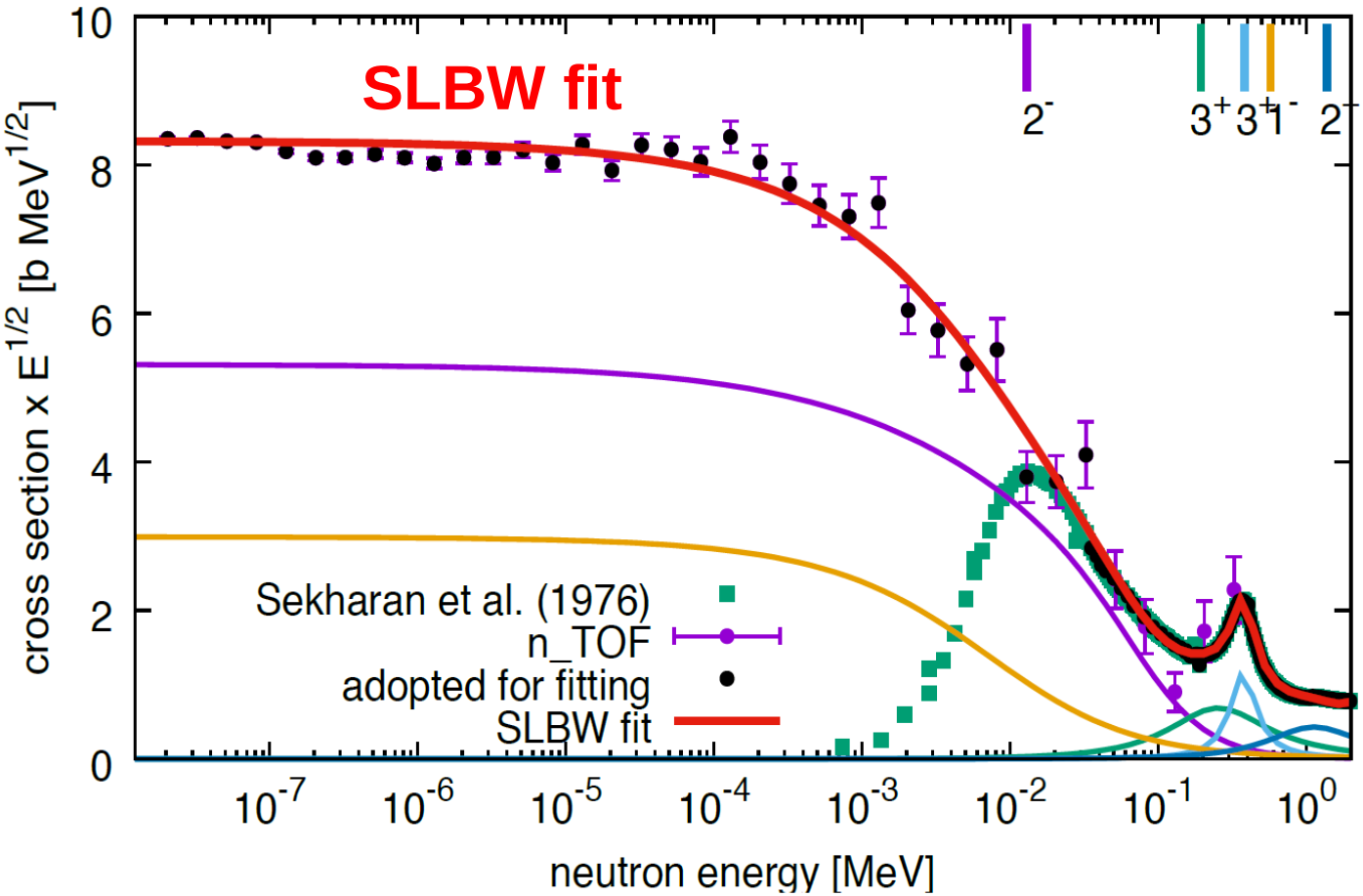
N present in the Al backing foil: **upper limit at 320 KeV neutron energy**

Results and implications

The n_TOF ^{7}Be(n, p)^{7}Li Weighted cross-section compared with previous measurements and with ENDF/B-VII.1 evaluations

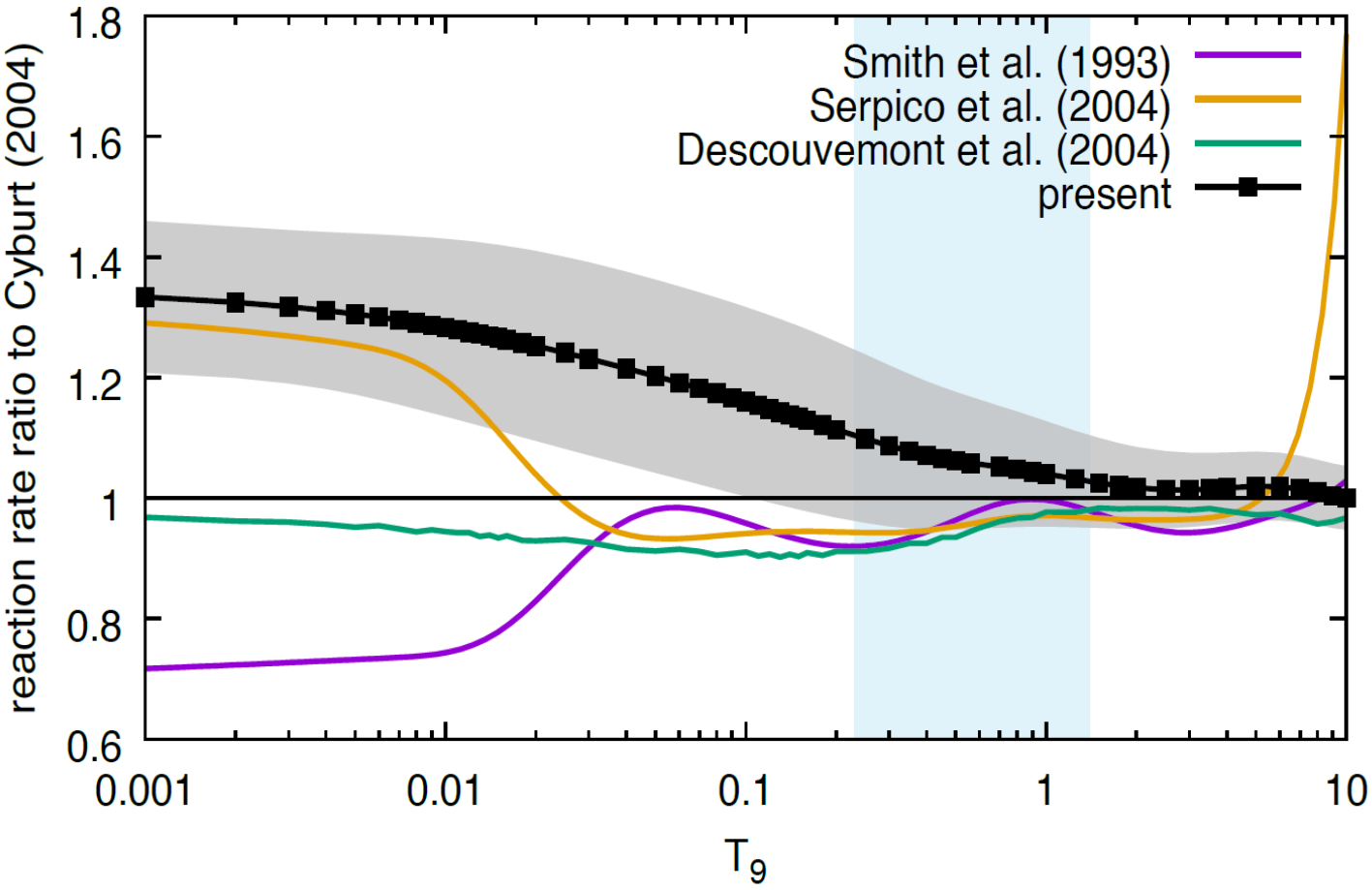


Results and implications



Results and implications

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



Conclusions

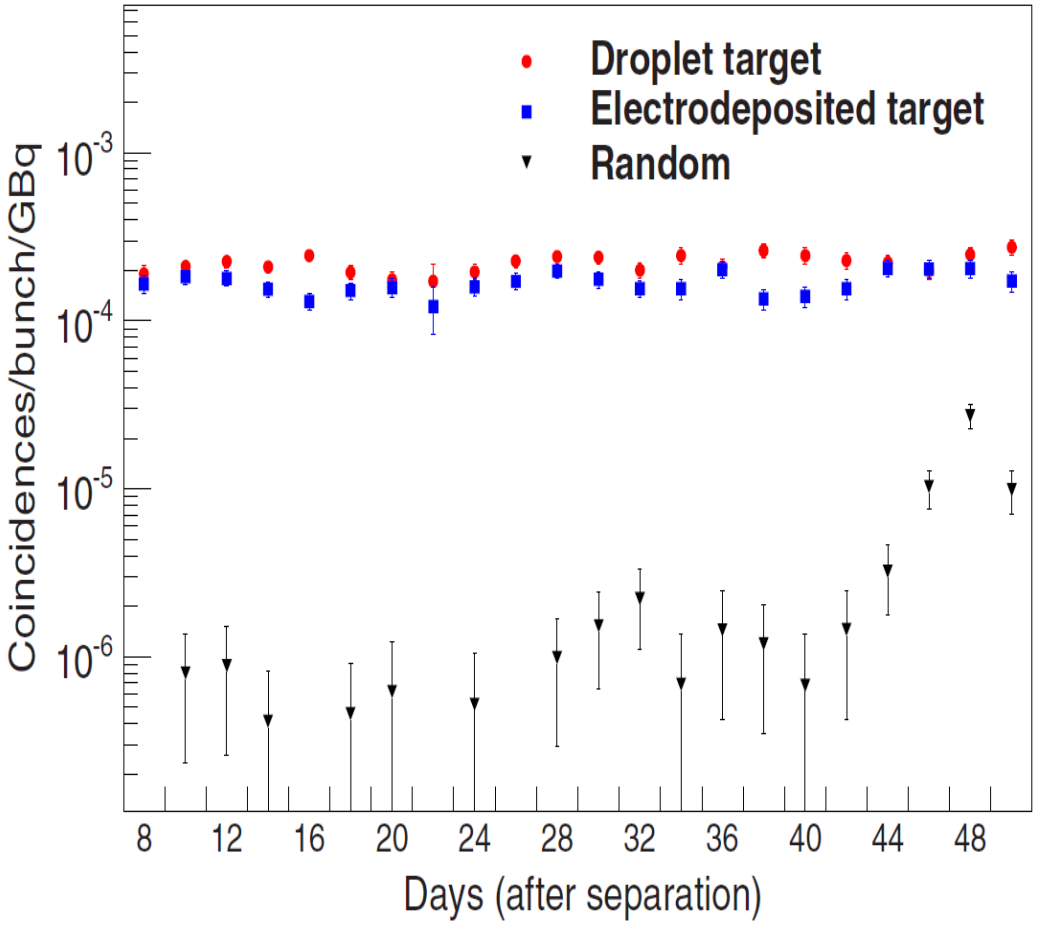
- **At n_TOF the ^{7}Be(n, γα)α and the ^{7}Be(n, p)^{7}Li cross-section have been measured for the first time in the energetic range of interest for the problem**

- The ^{7}Be(n, γα)α relative large change in the reaction rate has a minor effect on the lithium and beryllium production during the BBN (≈ 2%)

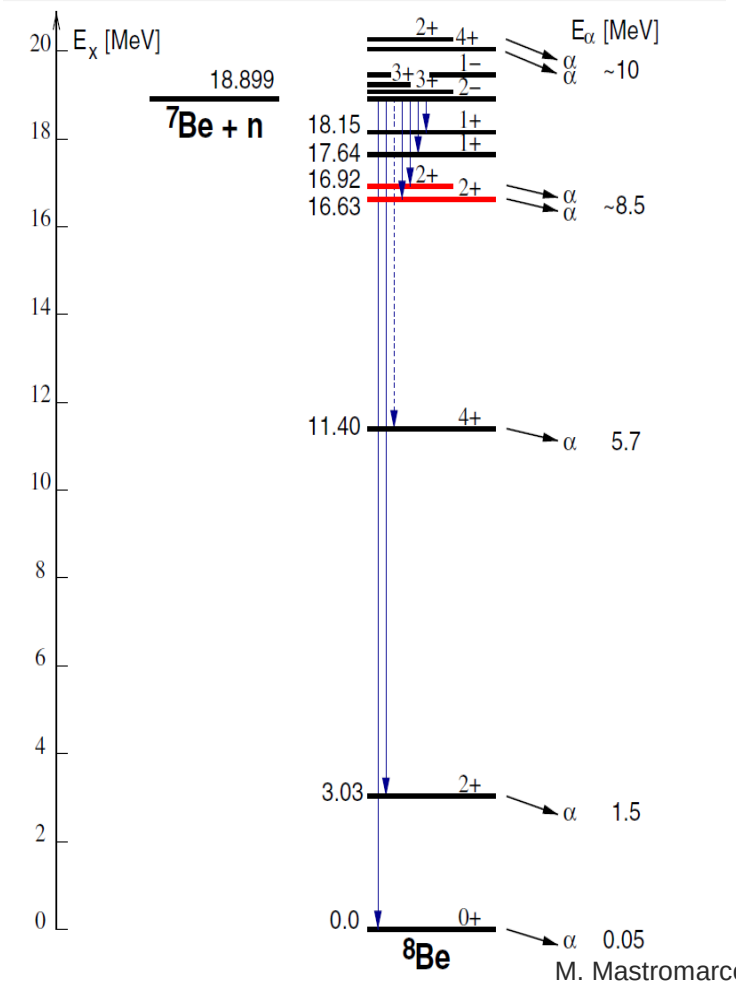
- **The reaction rate of the the ^{7}Be(n,p)^{7}Li performed at n_TOF cause a decrease of 10% of the abundance predicted for the primordial ^{7}Li**

- We have not solved the problem, but at least now we are sure that the solution is not linked to the neutron channel reaction.

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



Sources of background



Background

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

Solutions

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

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}).