Light element LiBeB depletion in astrophysics and related (p,α) cross section measurements via the THM

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Outlook

Some astrophysics……

- Introduction to the problem of the "relatively low" abundances of lithium, beryllium and boron (LiBeB);
- Abundances.vs.Metallicity: key formulas and the observational status;
- Lithium and primordial nucleosynthesis (BBN): stellar observations.vs.WMAP;
- LiBeB as probes for stellar structure: observational status and proposed theoretical models.

Some nuclear physics…..

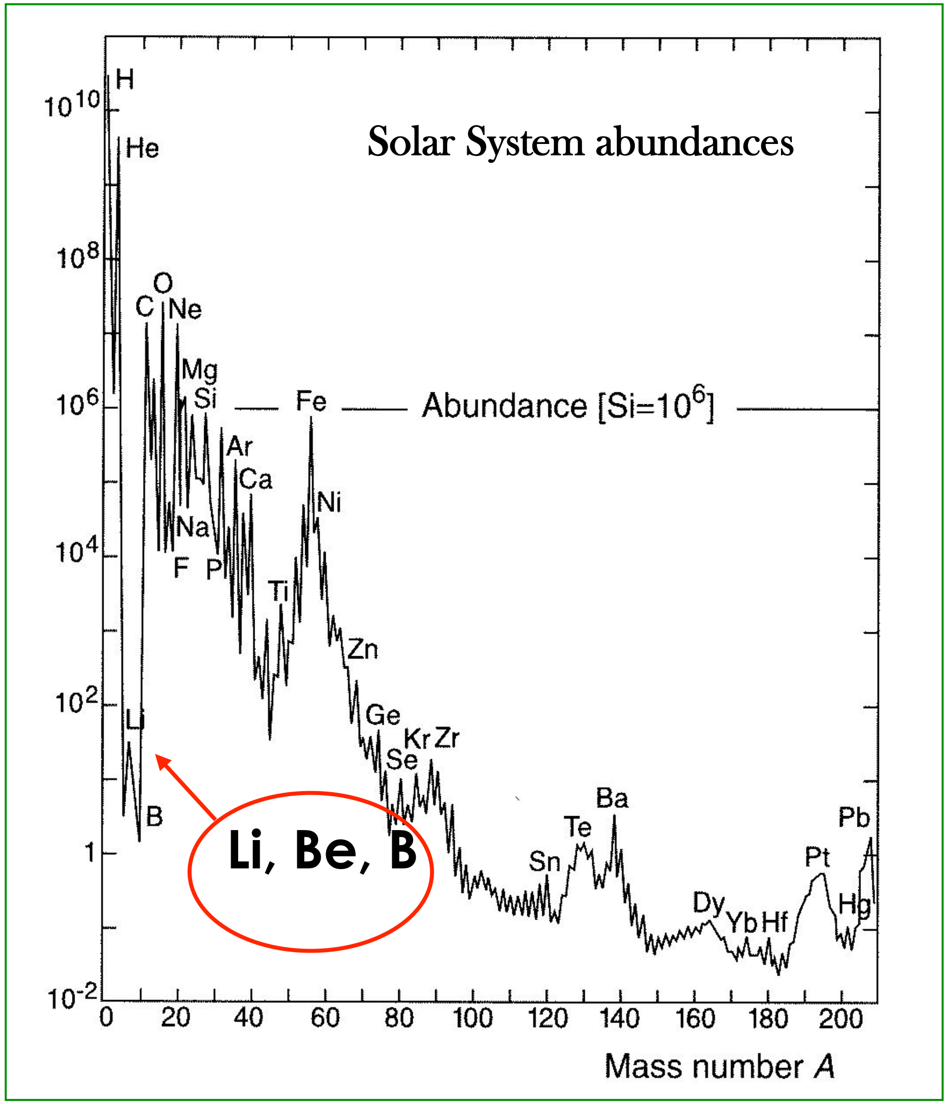
- Cross section measurements at the Gamow peak and related difficulties;
- The Trojan Horse Method as a tool for nuclear astrophysics;
- The $^{11}B(p,\alpha)^{8}Be$ reaction via the THM: a step-by-step analysis;
- The $^{7}Li(p,\alpha)^{4}He$ reaction via the THM: recent results and applications to RGB;
- The $^{6}Li(p,\alpha)^{3}He$ reaction via the THM: recent results and applications to PMS.

Why studying Lithium, Beryllium and Boron (LiBeB)?

- First, their relative abundance are very low if compared to their neighbors of the periodic table (H, He, C etc.) and a specific process for their production is needed;
- second, it's important to study their role in the framework of primordial nucleosynthesis;
- third, by studying the simultaneous abundances of lithium, beryllium and boron, it's possible to determine details for a deeper understanding of the internal stellar structure and evolution.

Lithium, Beryllium and Boron (LiBeB) in astrophysics: introduction (I)

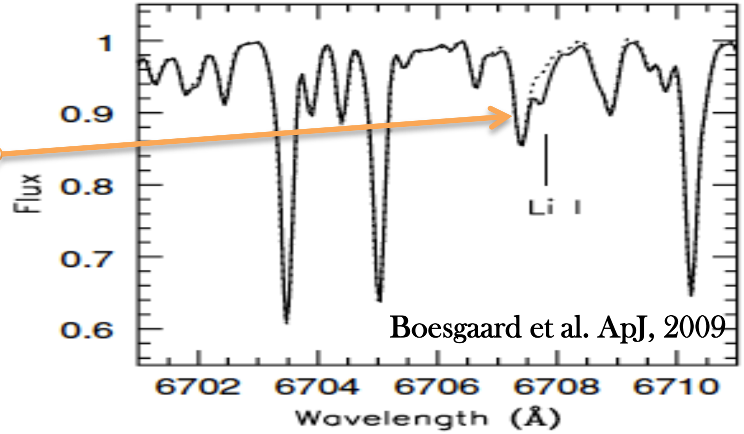
- Galactic cosmic rays (GRR) and solar system (SS) show very low relative abundances of Li, Be and B with respect the other elements (H,He,C,N….);
- **Main Production Sites**: Spallation processes on ISM; BBN (mainly for lithium and "probably" beryllium); further scenerios (induced neutrino nucleosynthesis, nova outburst…..)
- **Main Destruction Sites**: Stellar interior in the temperature range of 2<T(MK)<5
- LiBeB can be used to better understand primordial nucleosynthesis (lithium) and mixing mechanisms acting in stellar interior.



Lithium, Beryllium and Boron (LiBeB): abundances.vs.metallicity

Stellar abundances determination can be performed by means of the spectral analysis of stellar atmosphere, by studying characteristic absorption lines. For LiBeB we have to study the lines:

element	λ observation (Å)
Lithyum	6707.76;6707.91 (V)
Beryllium	3130.41;3131.06 (NUV)
Boron	2496.77;2497.72 (UV)



The deepth of the absorption line gives information about the number of atoms of a given element in that atmosphere, even if its determination is not straightforward at all.
For a given element X, its abundance can be expressed as:

$$A(X)=12+\log(N_X/N_H)$$

where N_X is the number of atoms per cm^3 and N_H the number of hydrogen atoms per cm^3.
For a given stellar atmosphere, the metallicity represents the amount of elements heavier than helium and it can be defined as:

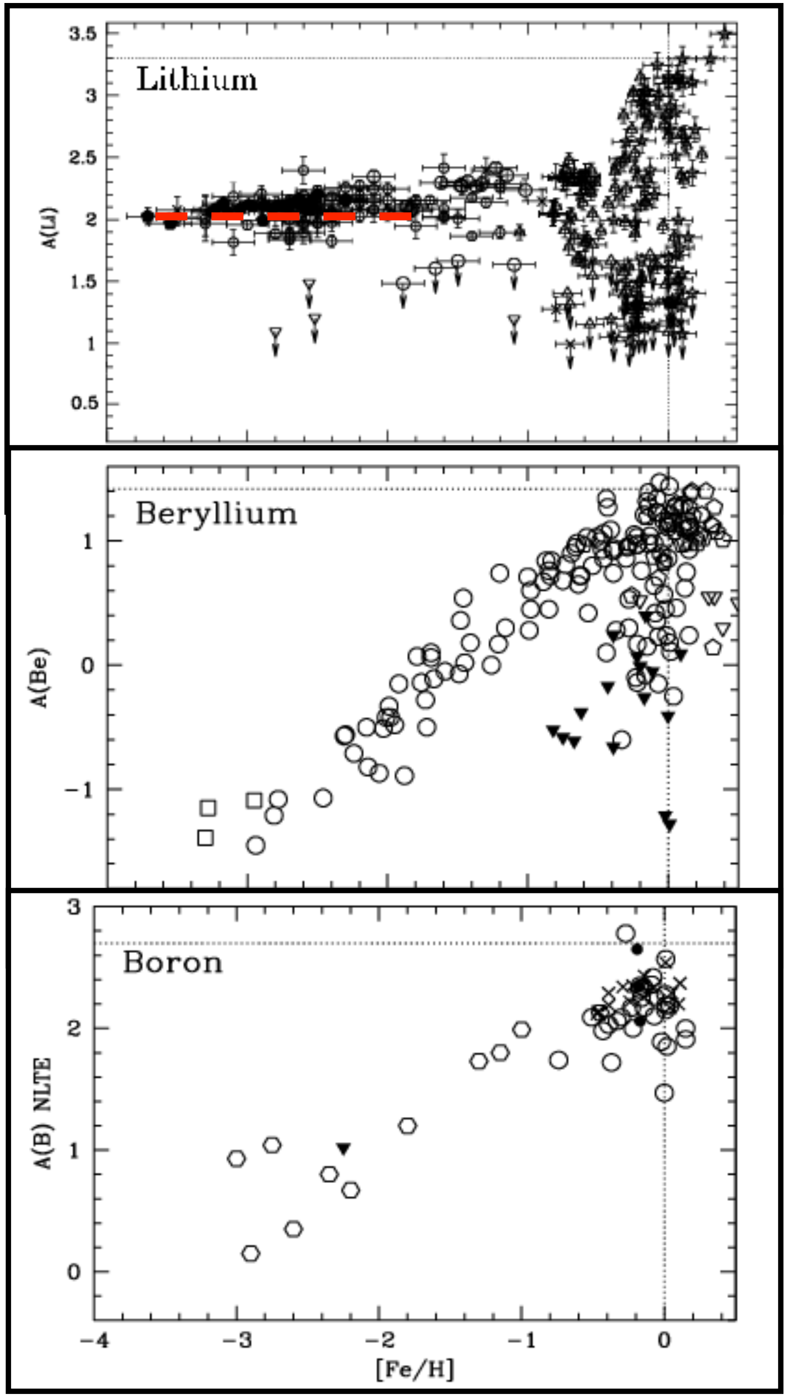
$$[Fe/H] \equiv \log(Fe/H) - \log(Fe_\odot/H_\odot)$$

(see for example Gray: "The Observation and Analysis of Stellar Photospheres" (1992))

LiBeB: A(X).vs.[Fe/H]

Different features can be extracted by studying the abundance.vs.metallicity scatter plot:

1) it is evident that the number of observations for lithium are large compared with those of beryllium and, more evident, with boron→ Region of Abs. Lines;
2) at lower metallicity, lithium abundances exhibit the so-called “Li-plateau” (Spite & Spite A&A, 1982)→ Primordial Nucleosynthesis;
3) beryllium and boron abundances are strongly related with metallicity, thus suggesting their production mainly via a synthesis occurring in a continuosly evolved ISM→ GCR’s nucleosynthesis;
4) Beryllium and boron abundances do not exhibit (until today!) any plateau→ very scarse contribution from primordial nucleosynthesis.

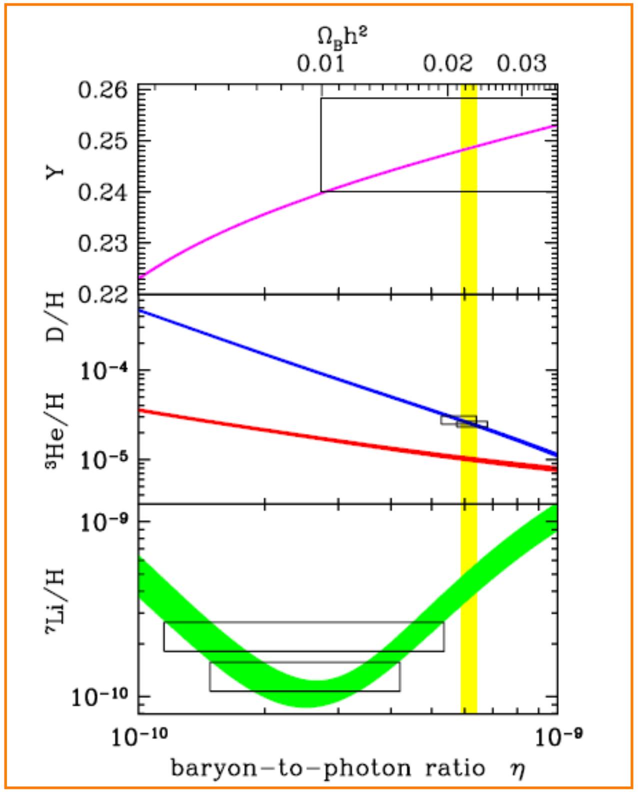


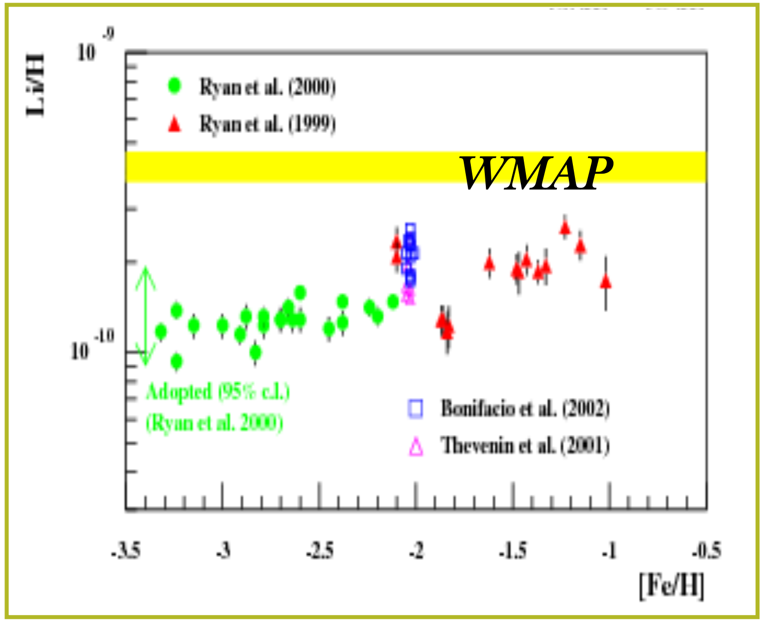
See:
“The Light elements lithium, beryllium and boron”, A.M. Boesgaard, 2004;
“Beryllium and boron in metal-poor stars”
F. Primas, 2009

Lithium and primordial nucleosynthesis (BBN)

➤ **Li-problem**: Low-metallicity Pop.II stars reveal the presence of the so-called "Li-plateau" (Spite & Spite, A&A 1982), widely assumed as the primordial one. However, the lithium abundances deduced from WMAP are in disagreement with respect the stellar ones.

➤ **SBBN**: description of primordial abundances as a function of the only free parameter $\eta = n_B/n_\gamma$ (see e.g. Coc et al., ApJ, 2012).





➤ Primordial Lithium $(Li/H)^{Stellar} \sim 1\text{-}2 * 10^{-10}$ (Fields et al., ApJ, 2005 and ref.)

➤ Primordial Lithium $(Li/H)^{WMAP} \sim 4 * 10^{-10}$ (Cyburt et al., PLB, 2005 and ref.)

Stellar Depletion?????

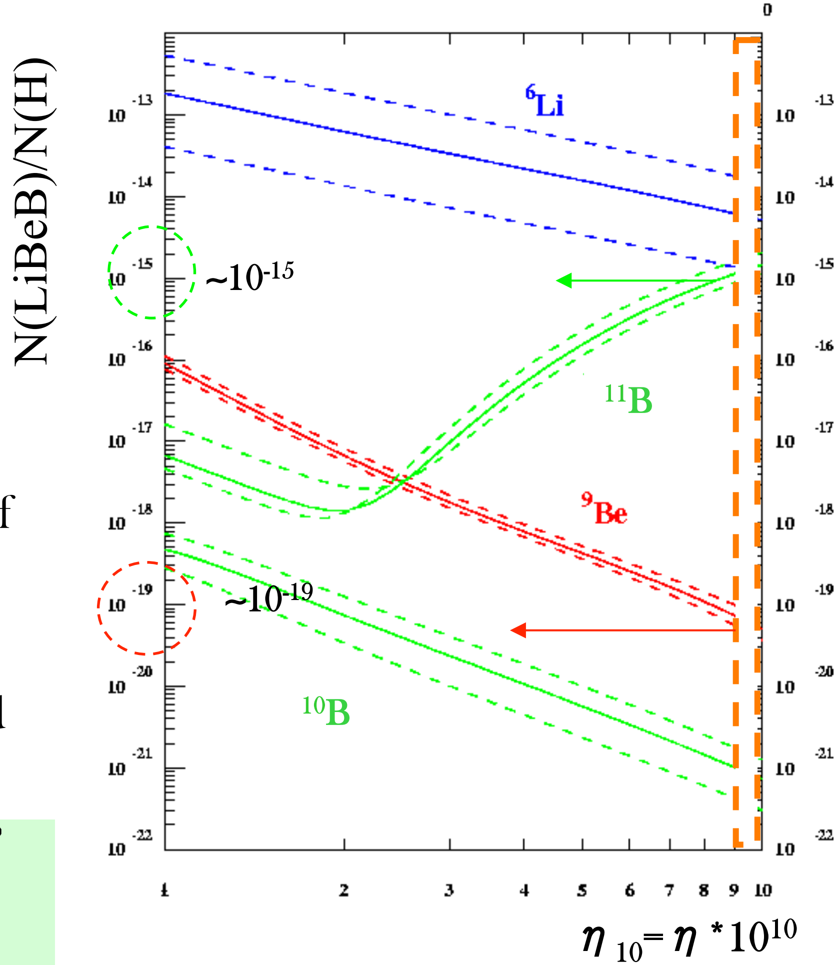
Beryllium and Boron nucleosynthesis….

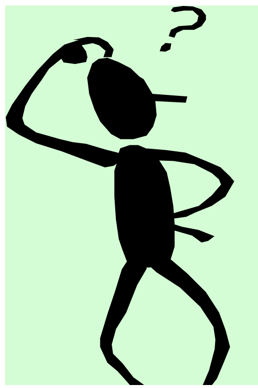
- <u>GCR-Nucleosynthesis:</u> Be and B can be produced via spallation processes (>100 MeV) from energetic protons and alpha-particles in Galactic cosmic rays (GCRs) colliding with CNO in ISM (Fields, ApJ, 2005). Effects of SN explosion have been also investigated (Kajino's talk and Suzuki et al., ApJ, 1999)

- Further, Be has been suggested as possible tracer of IBBN (Kajino & Boyd, Nature,1998).

- ν-process nucleosynthesis in SN can lead to a significant formation of ^{7}Li and ^{11}B (Kajino's talk and Mathews & Kajino, Phys.Rev. D 2012)

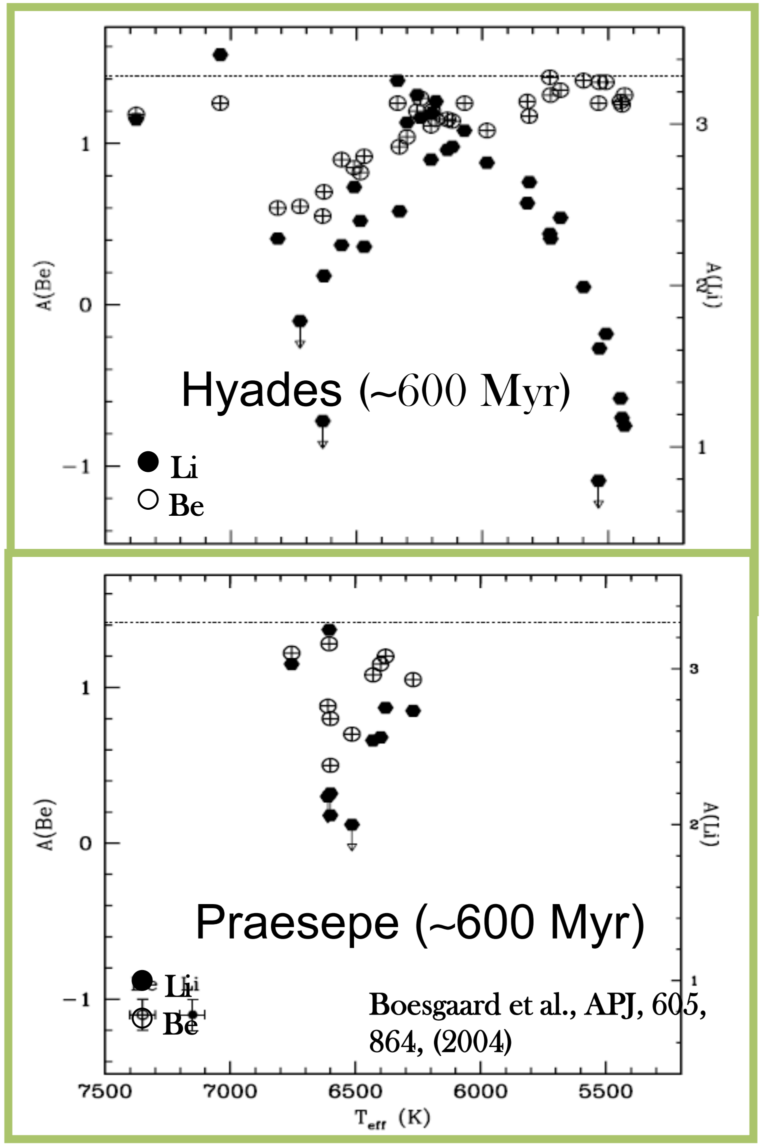
SBBN Predictions





The Lithium-Beryllium dip as signature of mixing phenomena

For MS F-G stars, standard stellar models do not predict depletion of the trio LiBeB, except during PMS (due to convection). Thus, for F-G stars, no depletion should be detected, with respect the meteoritic abundances (see details in Boesgaard et al., 2004, King et al. 2000, Pinsonneault 1997).



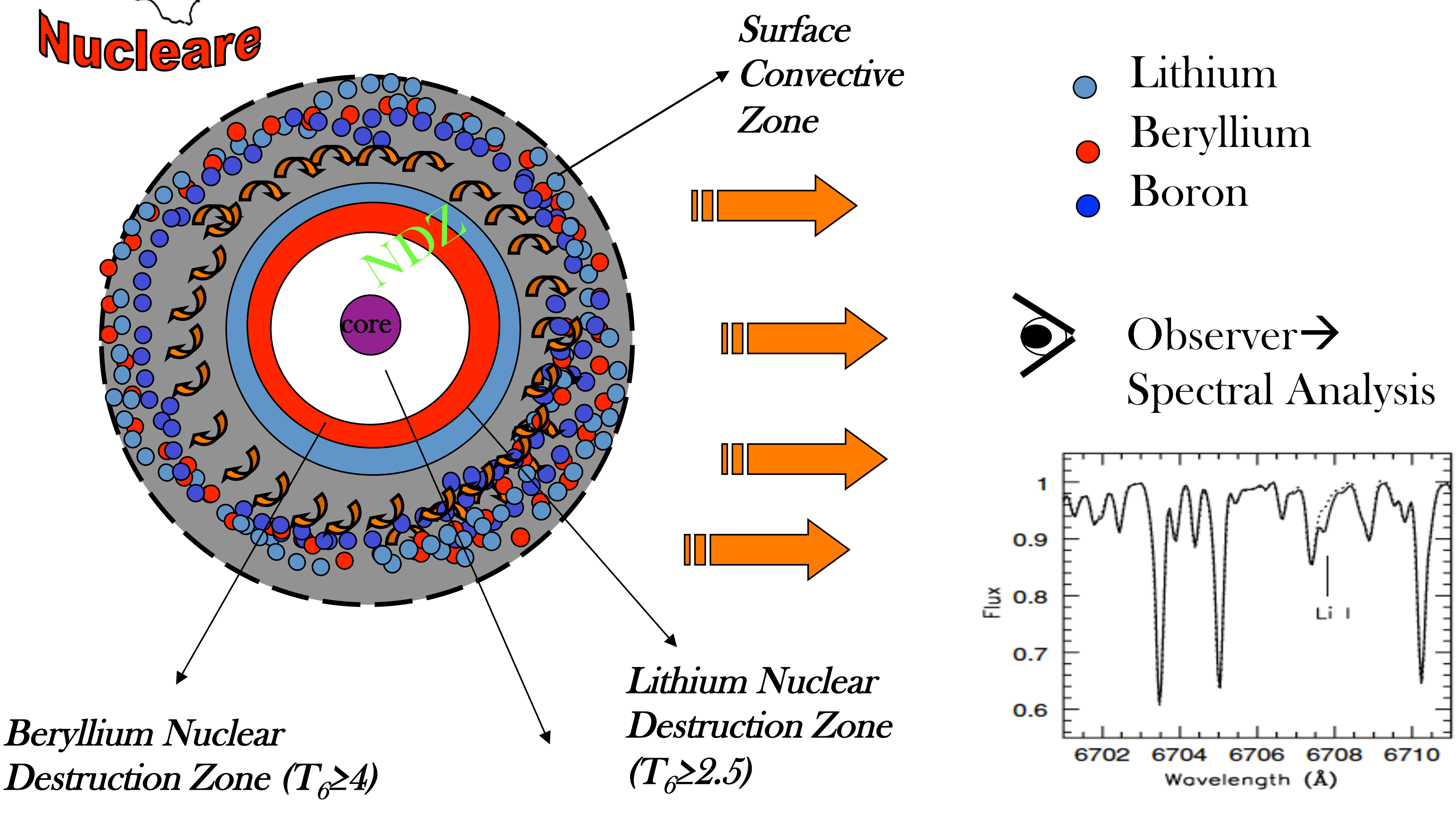
Boesgaard et al., APJ, 605, 864, (2004)

✓<u>Observational status</u>: Depletion in Open Clusters for stars with 6400<Teff(K)<6800.

✓<u>Dip di Li & Be:</u> the depth of the dip reflects the *nuclear fate* in the nuclear destruction zone (NDZ).

✓<u>Burning (p, α)</u> channel as the main contribution to their destruction at T_6=2.5 (Li), T_6=4 (Be), T_6=5 (B)

F-G stars: a very simple scheme



Lithium, Beryllium & Boron: the Li-Be correlation

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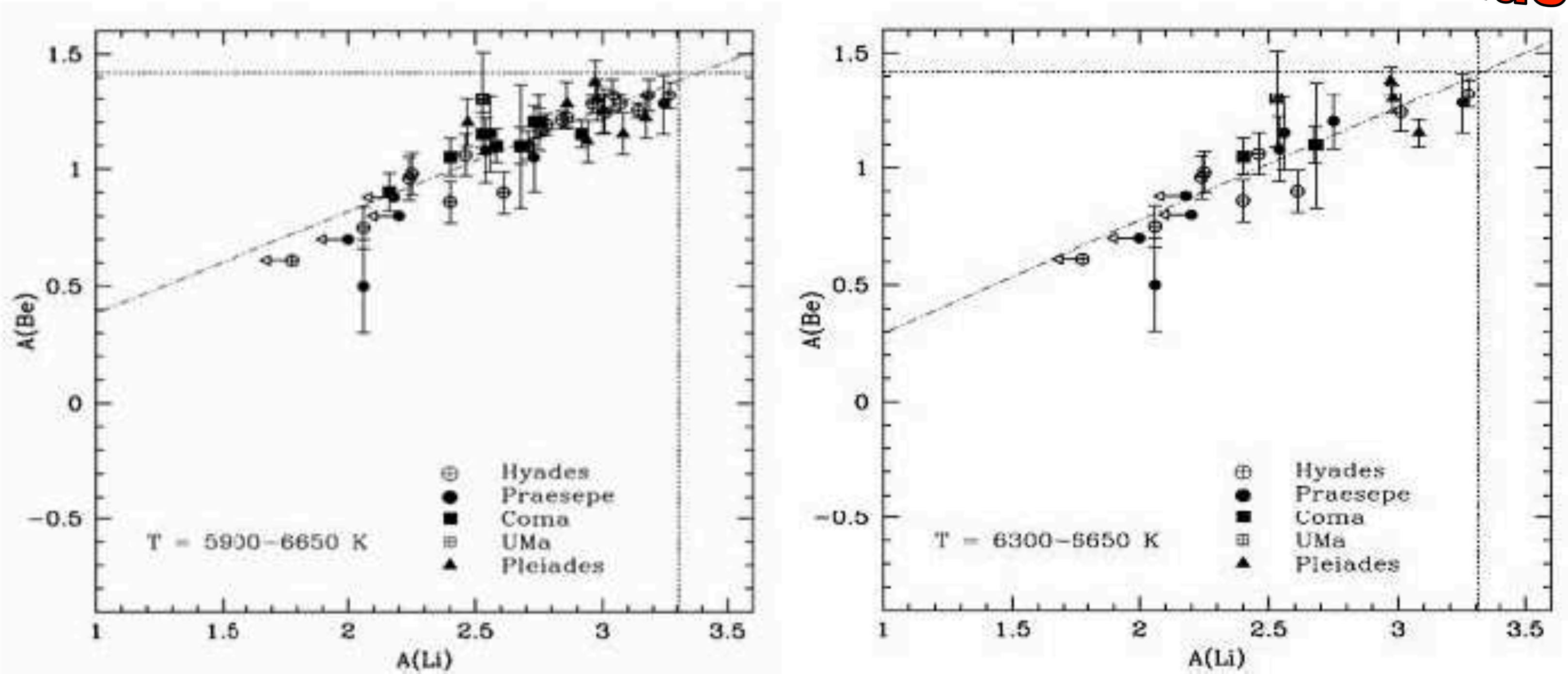
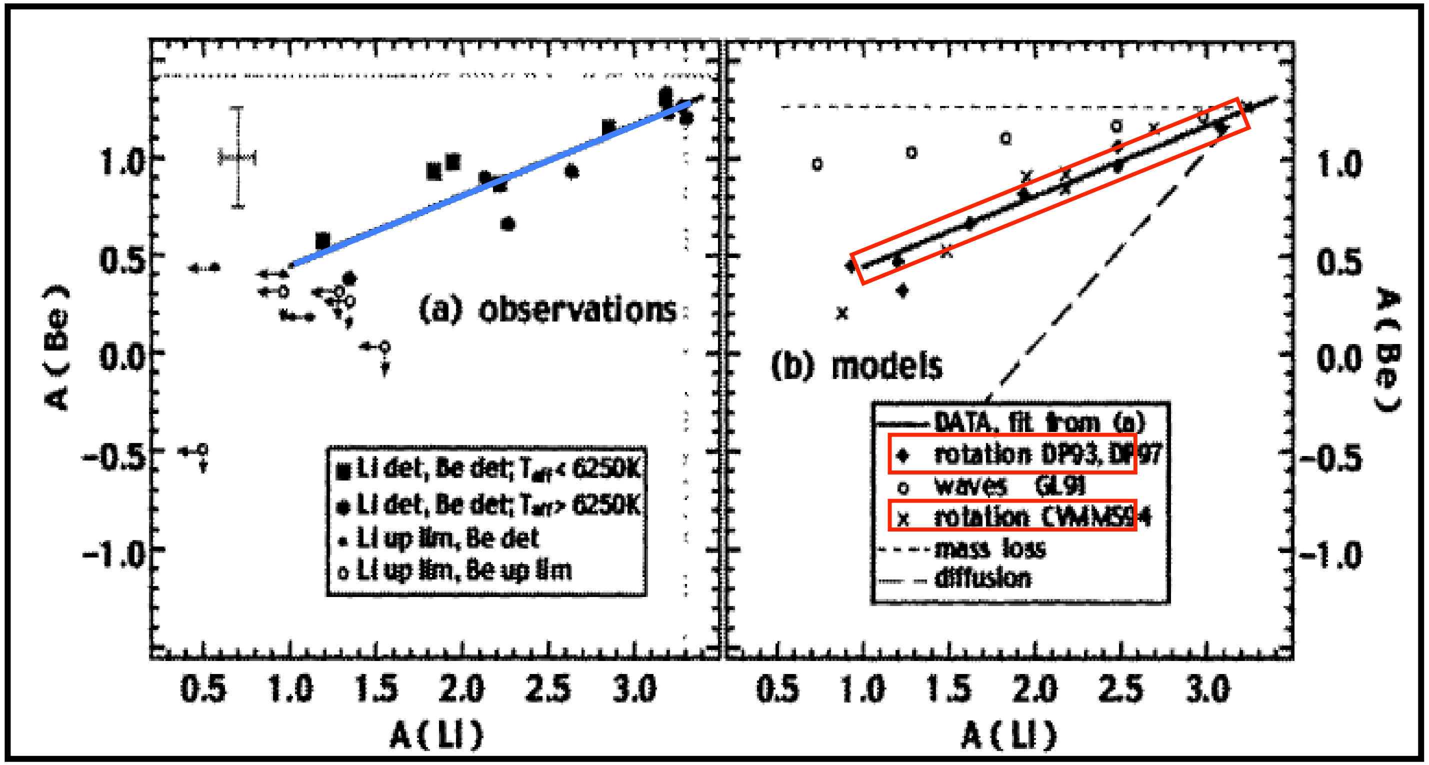


Figure 1.12: The Li-Be correlation as reported in [Boesgaard et al. (2004b)] and [Boesgaard et al. (2004c)]. Two groups are reported in this figure, corresponding to two different ranges of effective temperatures of the observed stars.

✓ <u>Li-Be & Be-B correlation</u> as signature of "rotation-induced" slow-mixing processes.

Observations.vs.models: mixing induced by stellar rotation

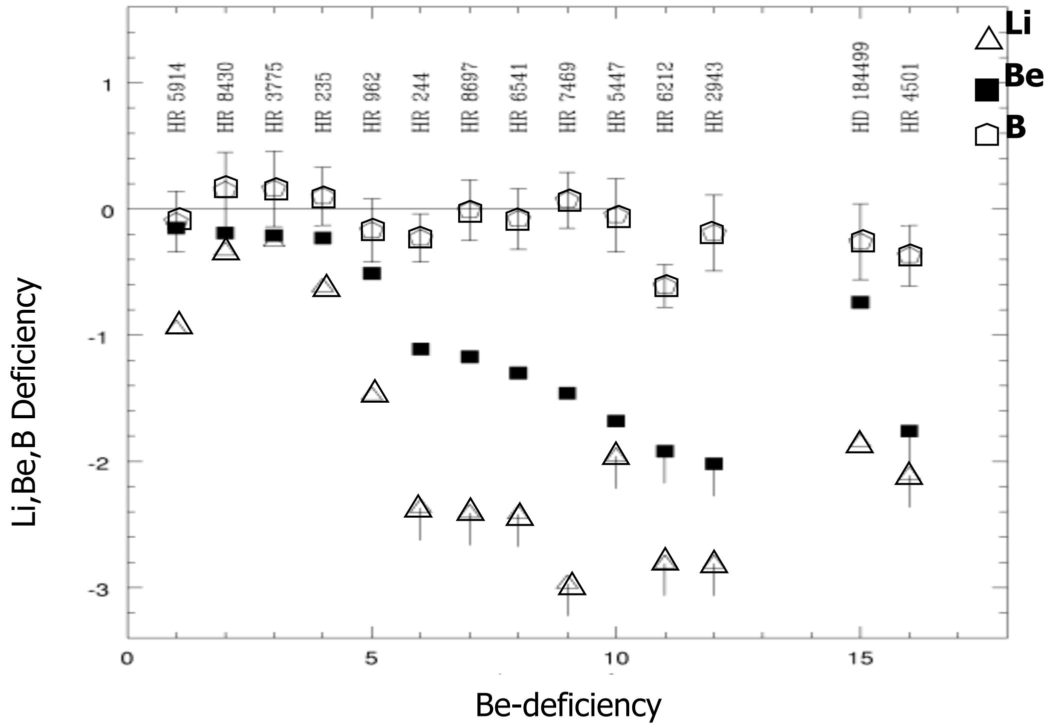
Deliyannis C.P., ASP Conf. Ser, Vol. 198, 2000



The lithium and beryllium deficiency and the boron observational trend are in agreement with "non-standard mixing process (*slow-mixing process*)" in stellar interior mainly triggered by rotation

- Stephens et al. 1997, ApJ, 491, 339
- Boesgaard 2004, ApJ, 605, 864
- Boesgaard 2005, ApJ, 621, 991

Observations of Li, Be and B abundances in young F-G stars



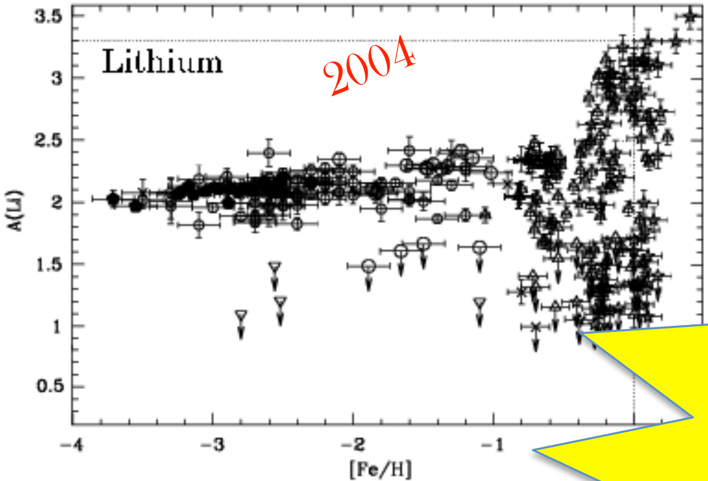
Light elements Li, Be and B abundances are shown as the Be-deficinecy varies for low-metallicity young star (-0.5<[Fe/H]<0.1, 5800< T_{eff} (K)<6500, M ~1 M_o). The variation of their abundances, with respect the metheoritic ones, has been indicated as possible "probe" for stellar structure understanding.

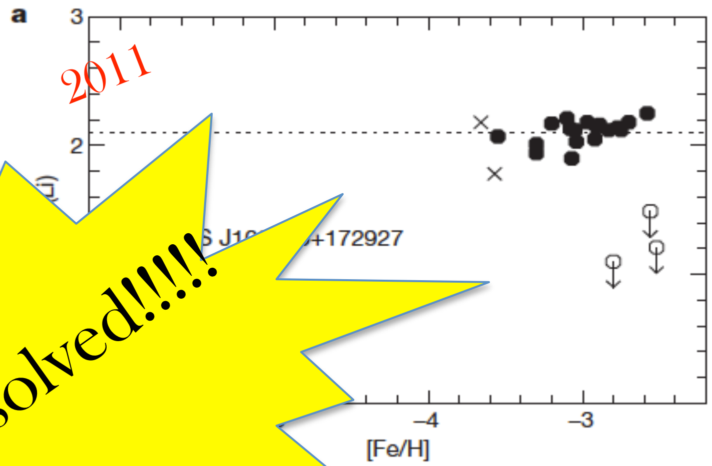
LETTER

doi:10.1038/nature10377

An extremely primitive star in the Galactic halo

Elisabetta Caffau[1,2], Piercarlo Bonifacio[2], Patrick François[2,3], Luca Sbordone[1,2,4], Lorenzo Monaco[5], Monique Spite[2], François Spite[2], Hans-G. Ludwig[1,2], Roger Cayrel[2], Simone Zaggia[6], François Hammer[2], Sofia Randich[7], Paolo Molaro[8] & Vanessa Hill[9]





Still unsolved!!!!

The most straightforward interpretation of the Sp... the Li observed in the plateau stars is the Li produ... The theoretical primordial Li abundance[1] is a factor of 2-... the value observed on the Spite plateau. A number of exp...ations of this discrepancy have been proposed, which range from stellar phenomena, such as atomic diffusion[21], to new physics leading to a different Big Bang nucleosynthesis[22]. Our upper limit implies that the Li abundance of SDSS J102915+172927 is far below the value of the Spite plateau. At extremely low metallicities, the Spite plateau displays a

Input parameters for stellar codes

- Uncertainties on some key input parameters such as *g, T_{eff}, [Fe/H]*;
- Theoretical models for stellar atmosphere and stellar opacity;
- Understanding stellar plasma physics and mixing: standard convection and/or extra-mixing phenomena (slow-mixing processes);
- Uncertainties on the nuclear cross section for the burning (p,α) reactions responsible for lithium, beryllium and boron destruction inside stars

Reaction rate determination

^{7}Li(p,α)^{4}He & ^{6}Li(p,α)^{3}He

^{9}Be(p,α)^{6}Li

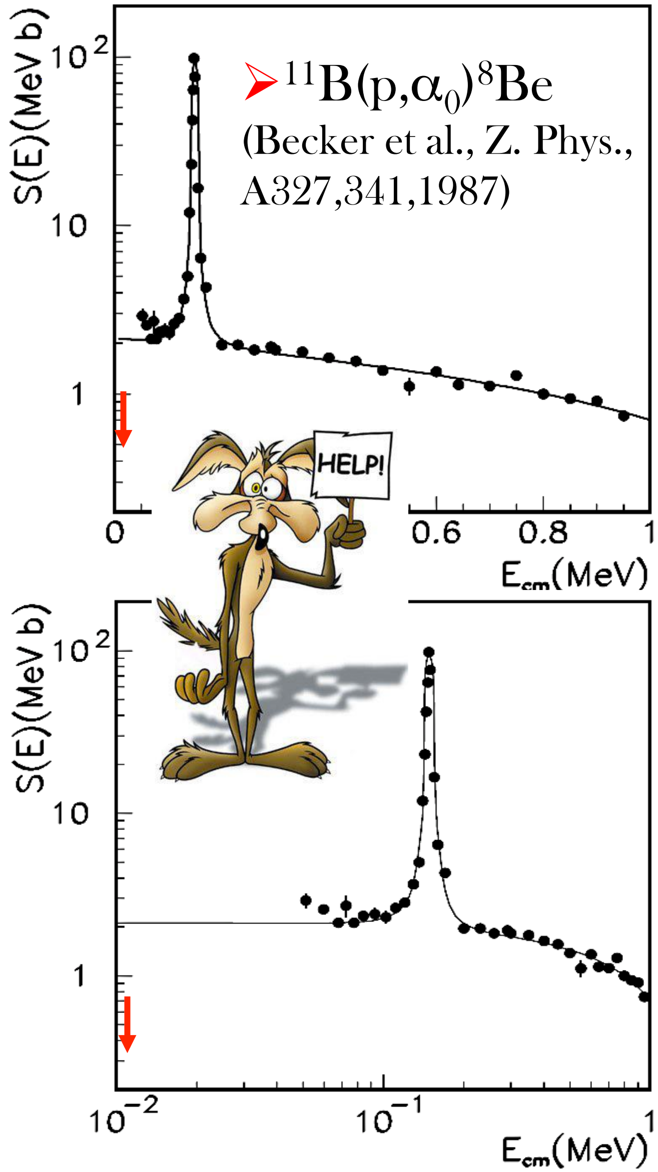
^{11}B(p,α)^{8}Be & ^{10}B(p,α)^{7}Be

From Stars to the laboratory: direct measurements of charged-particle induced reactions

By considering the typical temperatures of some 10^6 K at which burning (p,α) reactions typically occur in stellar environments, the Gamow peak is at about (for boron case)

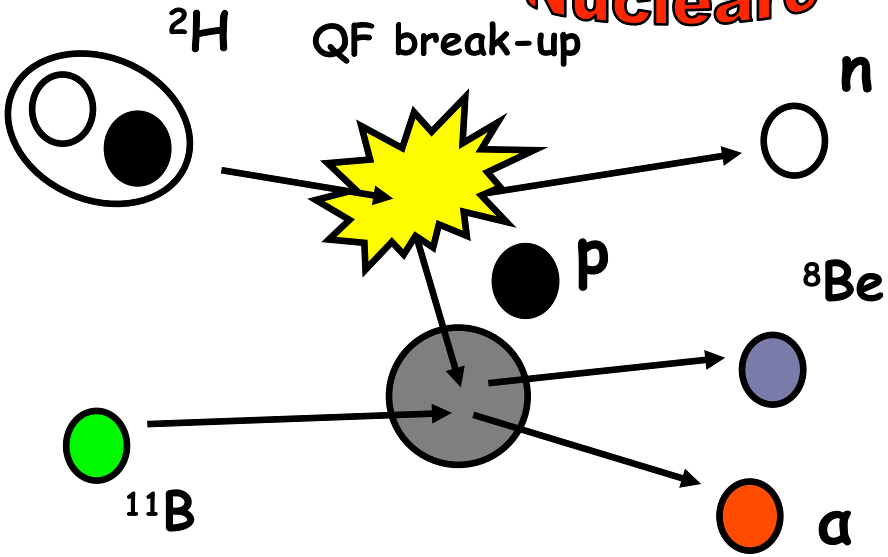
$$E_0=1.22(Z^2_x Z^2_y \mu T_6^2)^{1/3}\ \text{keV} \approx 10\ \text{keV}$$

Only extrapolations are possibl on low-energies direct data bec e el ctron screening and Co etrability effects !!!!!!



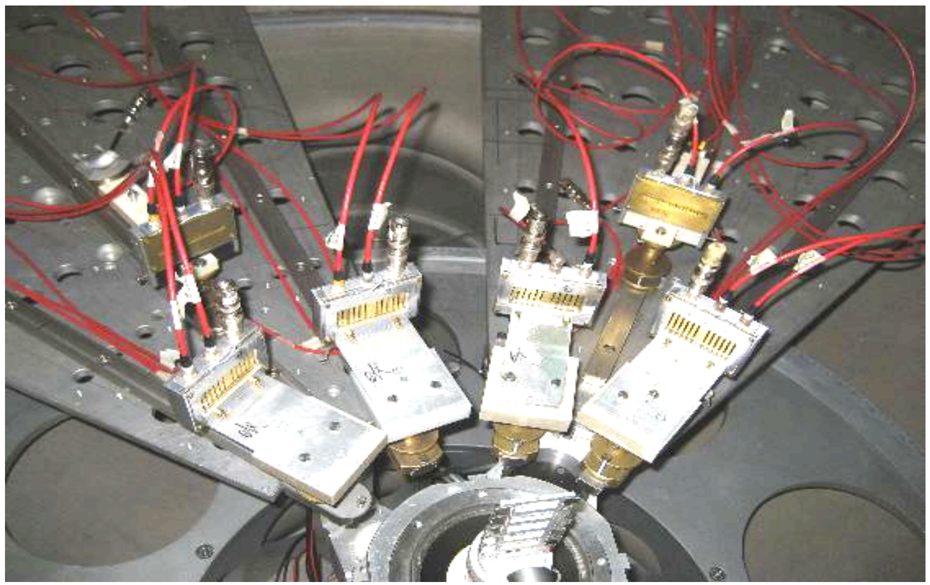
The indirect study of the $^{11}B(p,\alpha_0)\,^8Be$ via the THM applied to the $^2H(^{11}B, \alpha_0\,^8Be)n$ reaction

- Basic concepts of the method and overview already given in the previous talk of Cherubini and Pizzone;
- About the THM→ Baur et al. PLB, 1986; Cherubini et al. ApJ 1996, Spitaleri et al. PRC 1999; Tumino et al. PRC 2003, Spitaleri et al. PRC 2004........
- Experimental Review→ Spitaleri C. et al., Phys. Atom. Nuclei, 74, 2011 and ref. ther.



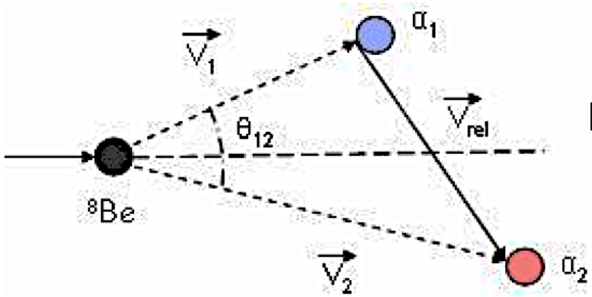
The Experiment at LNS

- Study of the $^{11}B(p,\alpha)^8Be$ reaction (Q=8.59 MeV) through the QF $^2H(^{11}B,\alpha^8Be)n$ reaction (Q=6.36 MeV);
- $E_{beam}(^{11}B)$=27 MeV & $I_{beam}(^{11}B)$=2-5 nA;
- Target thickness CD_2 ~190 μg/cm^2;
- Displacement of the detectors around the *QF-angular* range.

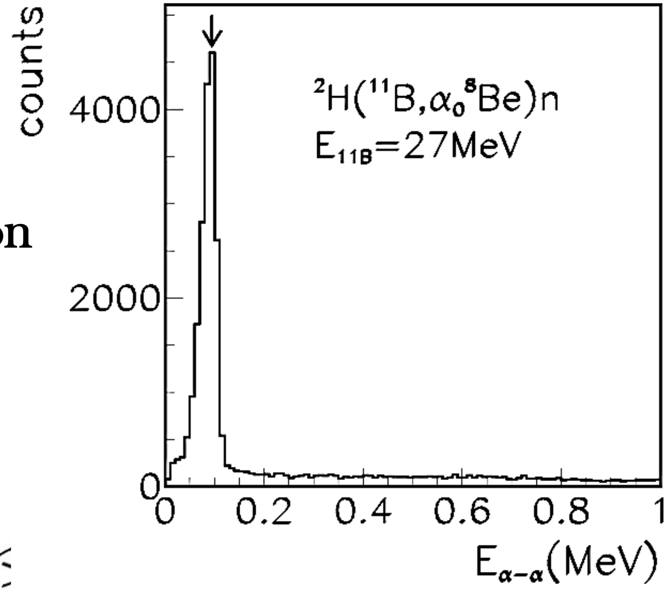


Selection of the 2->3 $^{2}H(^{11}B, \alpha_0{}^{8}Be)n$ channel: ^{8}Be determination and experimental Q-value

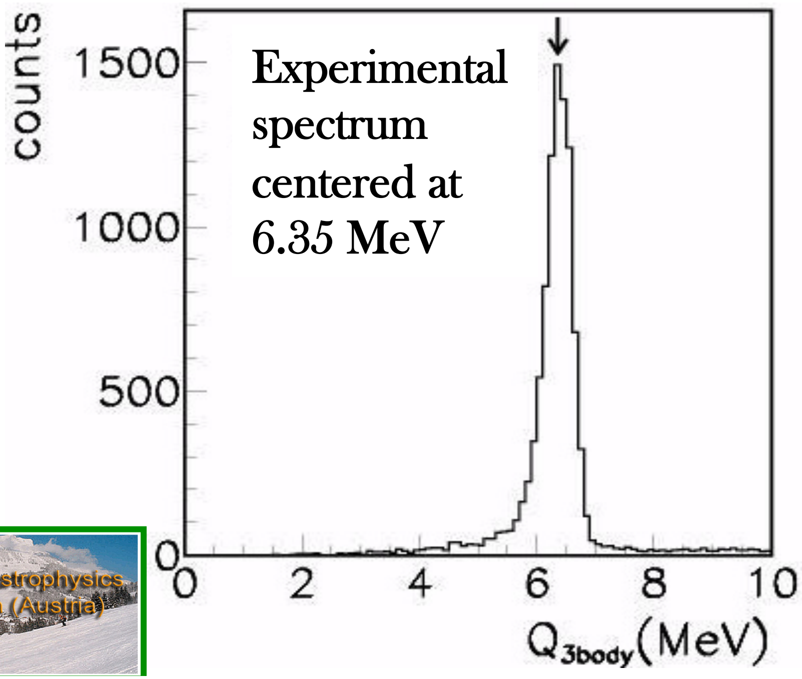
Alpha-decay of ^{8}Be(g.s.) in 2 alphas (Q^{th}_{dec} 92 keV) detected in coincidence on a Dual Position Sensitive Detector, *DPSD.*

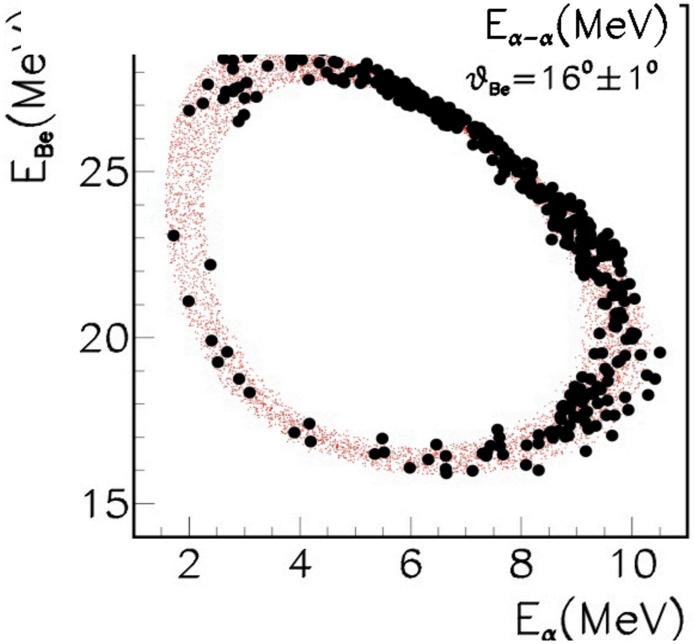


Off-line reconstruction of the relative energy between the detected α-particles



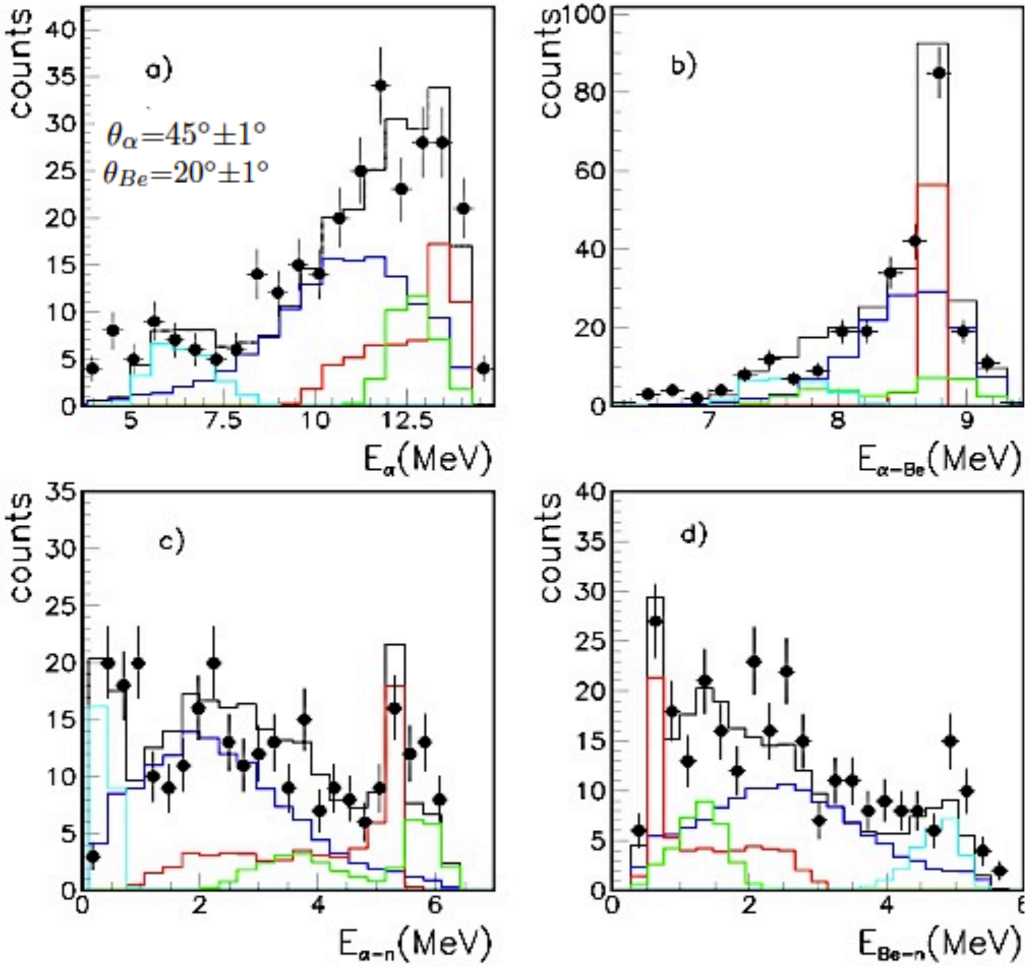
Q-value peak 2→3 reaction (Q_{th}=6.36 MeV)

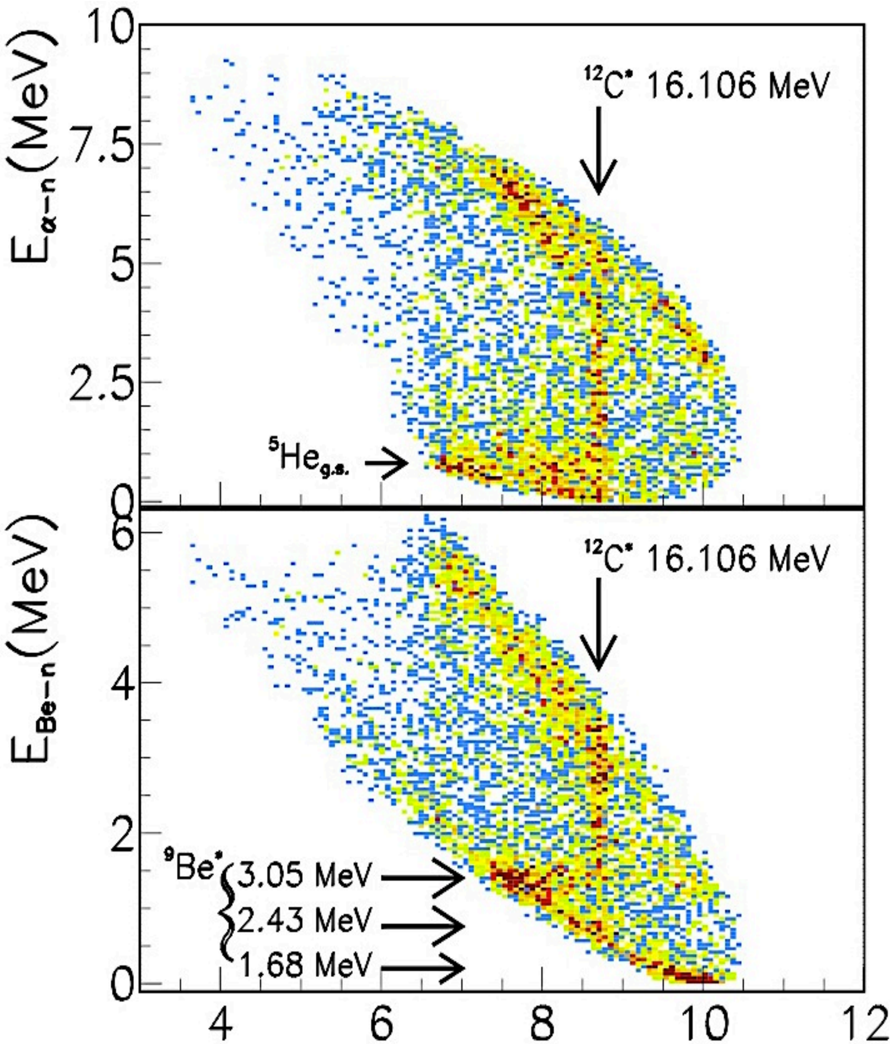




The $^{2}H(^{11}B, \alpha_0{}^{8}Be)n$ reaction channel: are the data contaminated by Sequential Mechanism (SM)?

The same particles α, ^{8}Be and neutron can be produced via the decays of intermediate nuclei. Study of the relative energies is then needed.

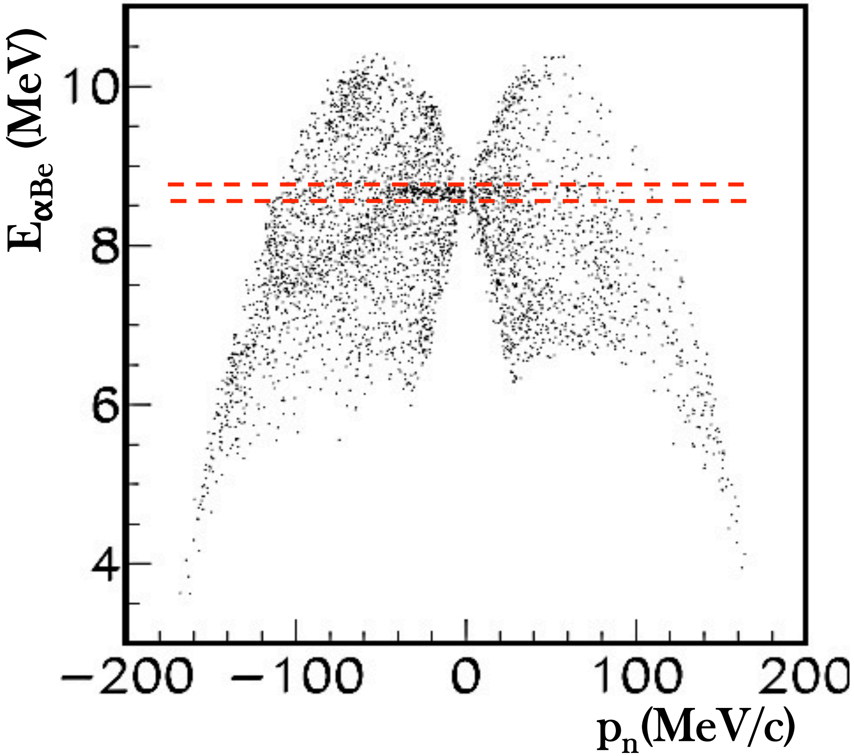


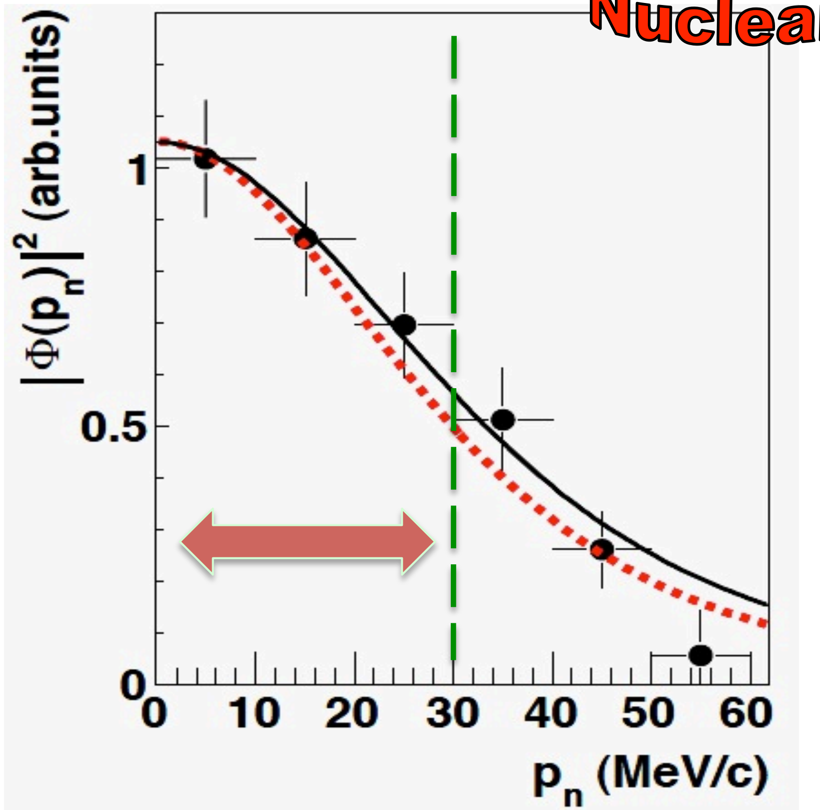


The $^2H(^{11}B, \alpha_0{}^8Be)n$ reaction: QF selection via Momentum Distribution investigation

✓ The PWIA approach allows one to exctract the experimental momentum distribution via the relation:

$$|\Phi(\vec{p}_n)|^2 \propto \frac{\dfrac{d^3\sigma}{d\Omega_\alpha \, d\Omega_{8Be} \, dE_{cm}}}{KF}$$





Exp. Fit→ FWHM=65±10 MeV/c

Hulthén→FWHM=58 MeV/c

Data selection: from the $^2H(^{11}B, \alpha_0{}^8Be)n$ to the $^{11}B(p, \alpha_0)^8Be$ reaction

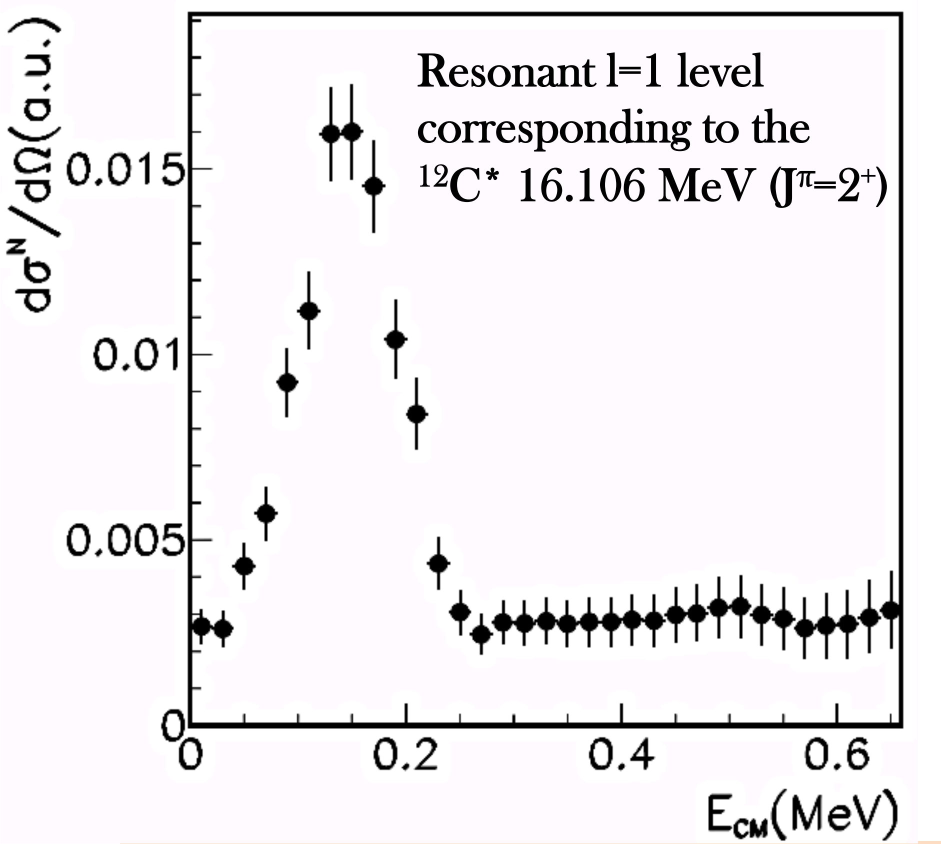
- ✓ Only the events belonging to the condition $|p_n|$<30 MeV/c (quasi-free selection) will be taken into account;

- ✓ By using the simple PWIA formulation, the HOES cross section can be obtained via the factorization:

$$\frac{d\sigma^N}{d\Omega} \propto \frac{\dfrac{d^3\sigma}{d\Omega_\alpha\, d\Omega_{8Be} dE_{cm}}}{KF \cdot |\Phi(\overrightarrow{p_n})|^2}$$

- ✓ The energy in the center-of-mass ^{11}B-p is determined by the relation:

$$E_{CM}=E_{\alpha Be}-Q_2=E_{\alpha Be}-8.59\ \text{MeV}$$



- ✓ No penetrability or electron screening effects influence the TH "bare-nucleus" cross section.

$^{11}B(p,\alpha_0)^{8}Be$: TH S(E)-factor determination

- Extraction of the bare-nucleus S(E)-factor:

$$S(E) = E^{*}P_l\sigma^{N}(E)^{*}\exp(2\pi\eta)$$

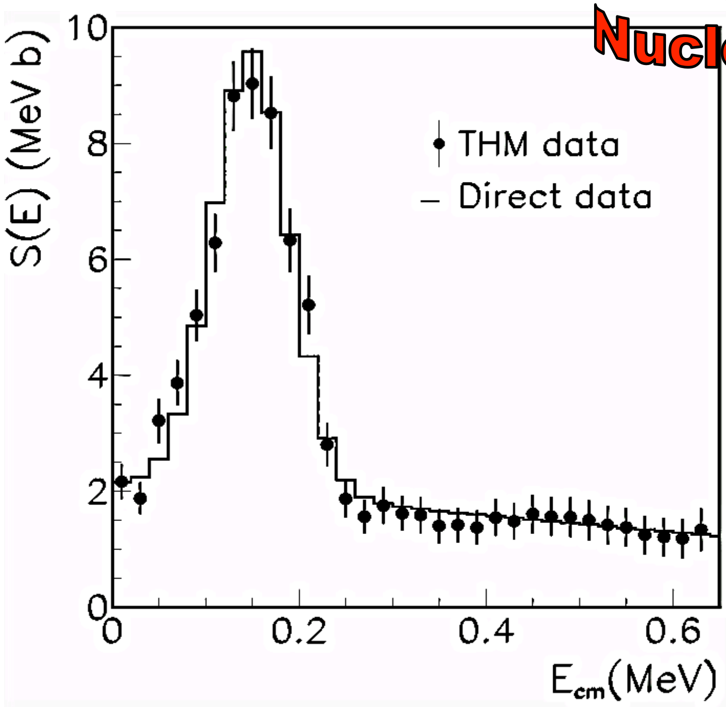
-^{9}Be & ^{5}He (SM) evaluation;

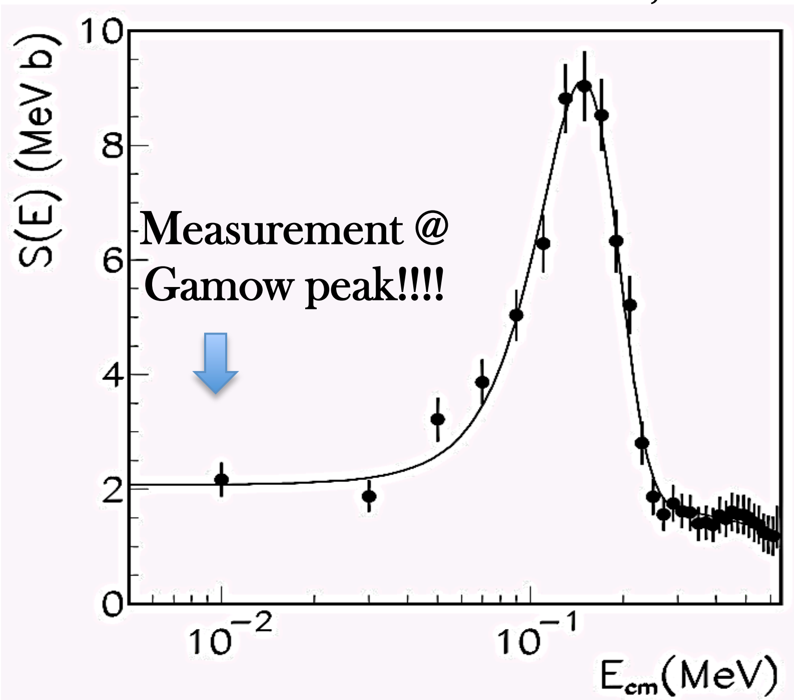
-Separation between resonant l=1 (16.106 MeV ^{12}C) and no-resonant contribution;

-Integration via angular distributions;

-Smearing procedure for the direct data (40 keV energy resolution);

-Normalization between 400-600 keV's;





- The bare-nucleus S(E)-factor has been described as:

$$S(E)_b = 2.04 - 1.37^{*}E + 0.12^{*}E^{2}$$
$$+7.28\times\exp[-0.5((E-0.148)/0.044))^{2}]$$

$\Rightarrow$ S(0)=2.07±0.41 (MeV b)

$^{11}B(p,\alpha_0)^8Be$: electron screening potential U_e determination via the TH

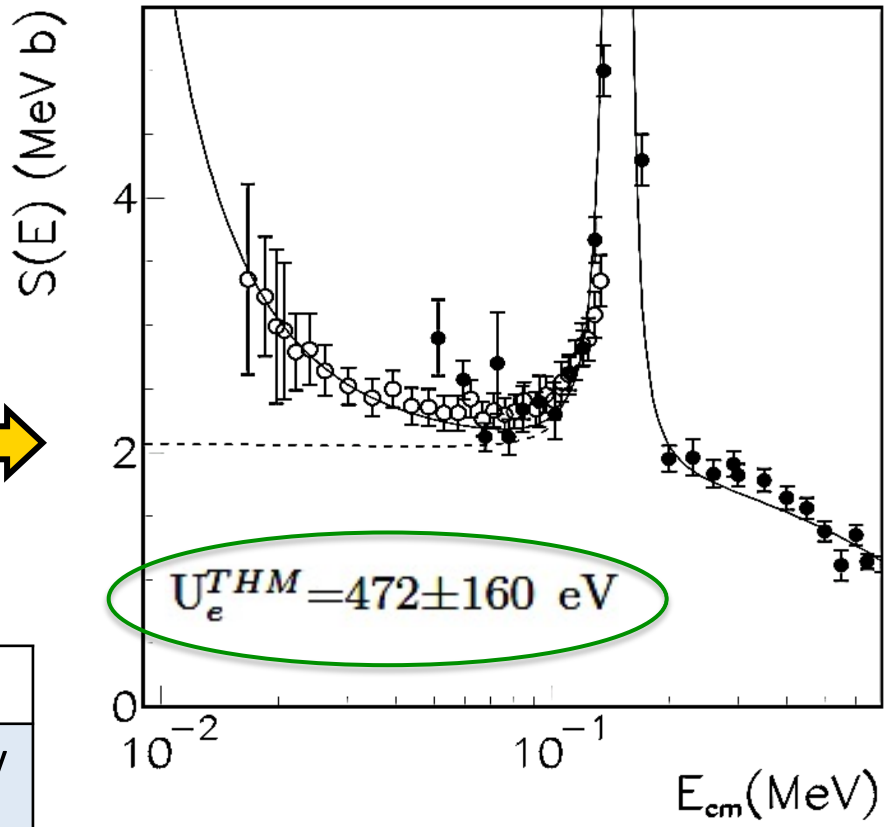
- The TH S(E)-factor (non-resonant) can be used for evaluating the electron screening potential;
- The shielded direct data can be fitted via the relation:

$$S(E)_{sh}=S(E)_b\times\exp(\pi\,\eta\,U_e/E)$$

leaving U_e as the only free parameter.

- ***RESULTS***

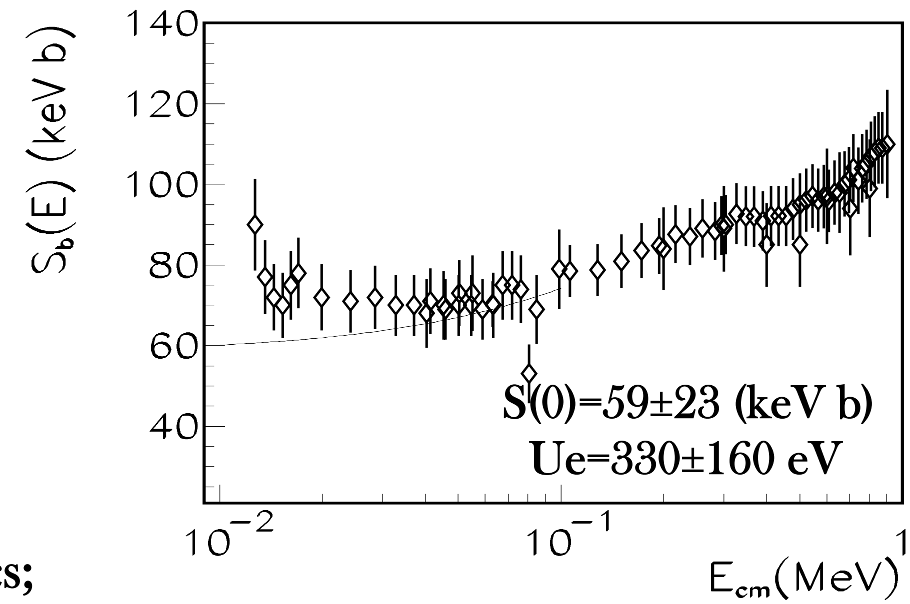
$^{11}B(p,\alpha_0)^8Be$	S(0)	U_e
THM	2.07±0.41 (MeV b)	472±160 eV
Becker et al., 1987	2.10±0.13 (MeV b)	-----------
Angulo et al., 1993	------------	430±80 eV

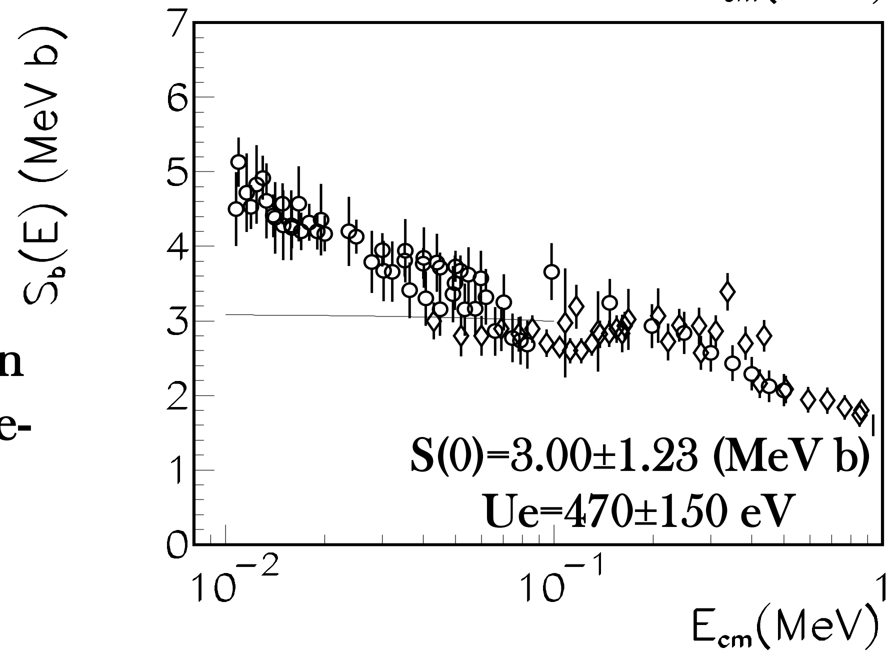


Lamia L. et al, JpG, 2012

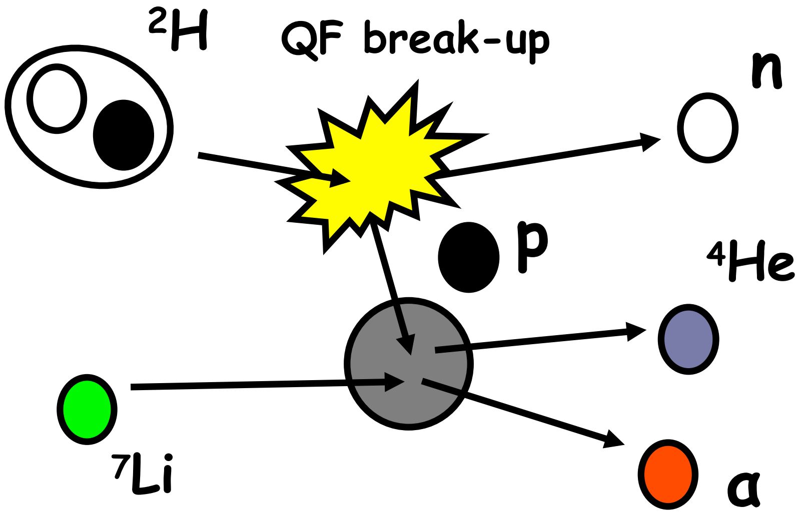
Why ^{6,7}Li(p, α) TH measurements?

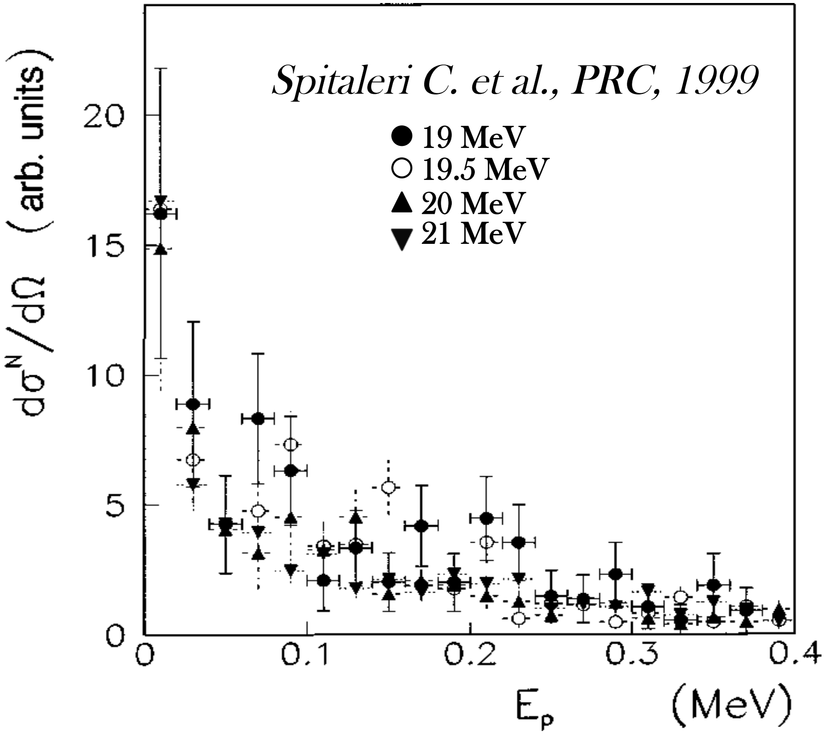
- The direct measurements at low-energies have been performed and discussed by Engstler et al., Z.Phys., 1992;
- Only extrapolations have been performed in correspondence of the energy window relevant for astrophysics;
- These measurements allowed to shed light on the electron-screening phenomena (Rolf's group);
- Thus, the first THM approach has been performed in order to measure the bare-nucleus S(E)-factor at astrophysical energies.......



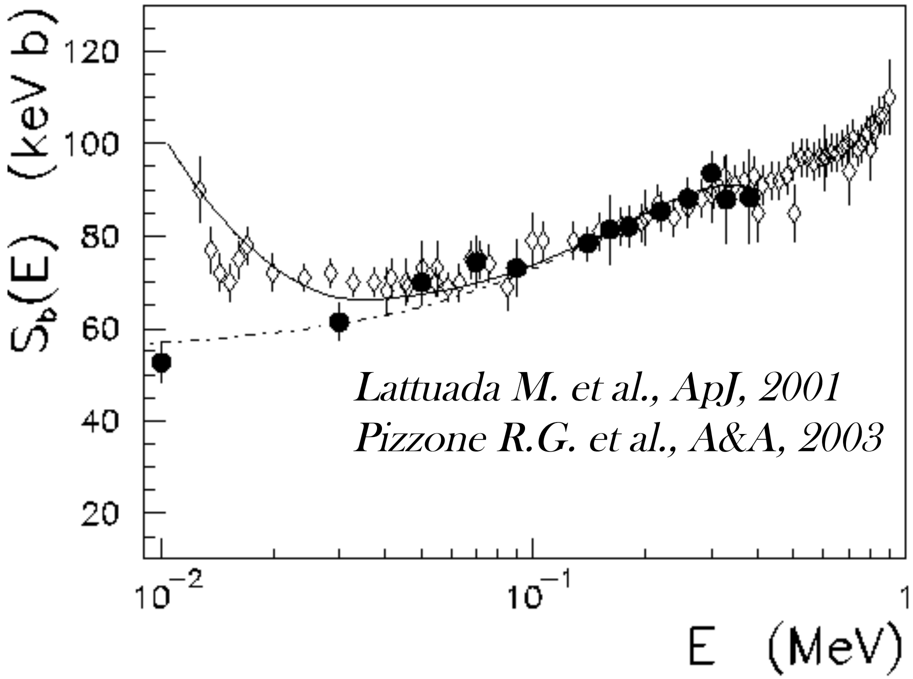


The ^{7}Li(p, α)^{4}He reaction via the ^{2}H(^{7}Li, α ^{4}He)n QF-reaction

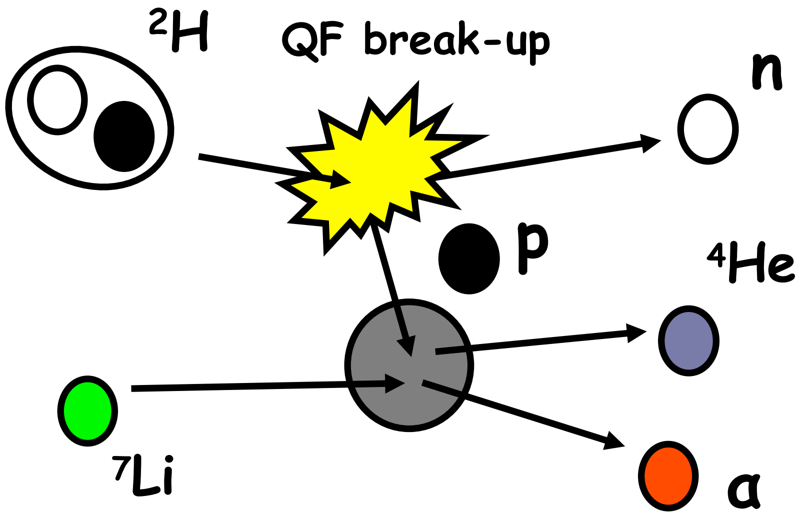




- Study of the ^{7}Li(p,α)^{4}He reaction (Q=17.35 MeV) through the QF ^{2}H(^{7}Li,α^{4}He)n reaction (Q=15.12 MeV);
- E_{beam}(^{7}Li)=19, 19.5 and 20 MeV ;
- S(0)=55±3 (keV b) and Ue=330±40 eV;



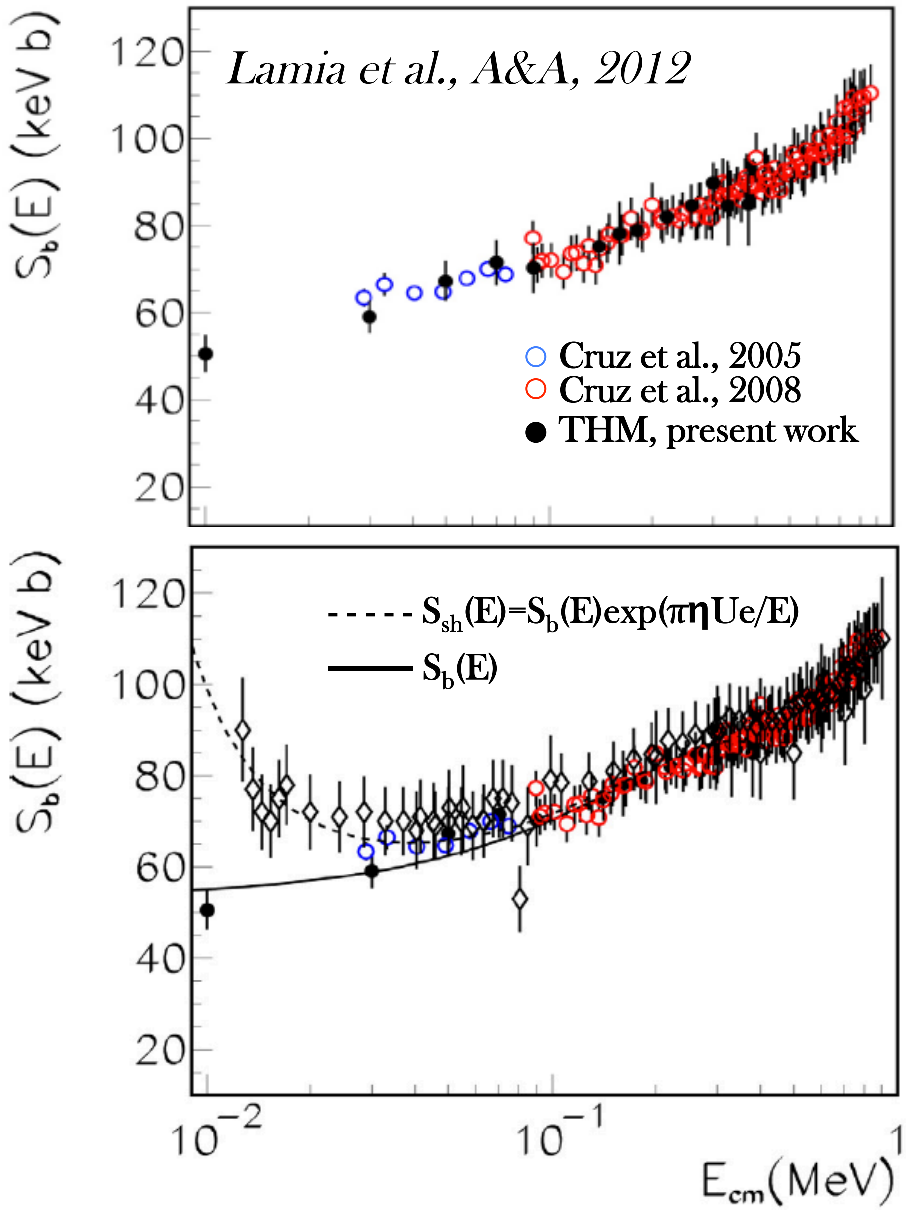
The updated ^{7}Li(p, α)^{4}He TH reaction rate



- Recent direct measurements by Cruz et al. (2005, 2008) allowed for a new normalization;
- Fit of the TH data→

$$S_b(E)=53+213*E-336*E^2$$

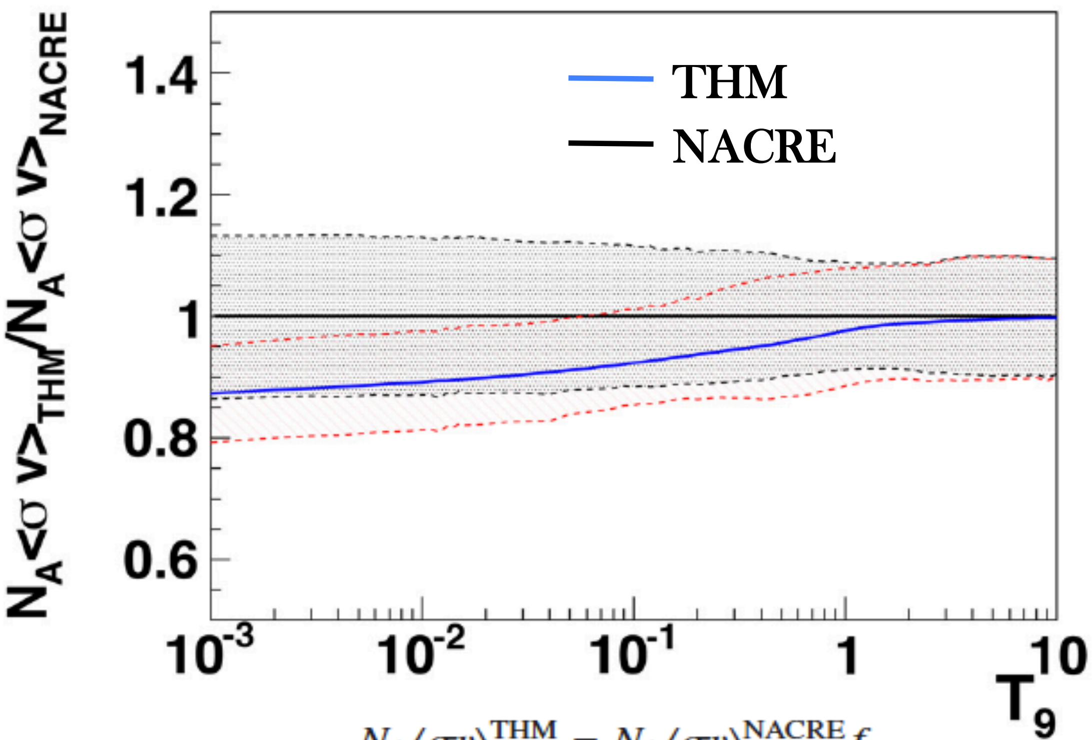
- S(0)=53±5 (keV b) and Ue=425±60 eV;



The updated $^{7}Li(p,\alpha)^{4}He$ TH reaction rate

Reaction rate determination by means of the formula (Rolfs & Rodney, 1988)

$$N_A < \sigma v > = \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty S_b(E) e^{-2\pi\eta - \frac{E}{kT}} dE \qquad (cm^3 mol^{-1} s^{-1})$$



$$N_A\langle\sigma v\rangle^{THM} = N_A\langle\sigma v\rangle^{NACRE} f_{corr}$$

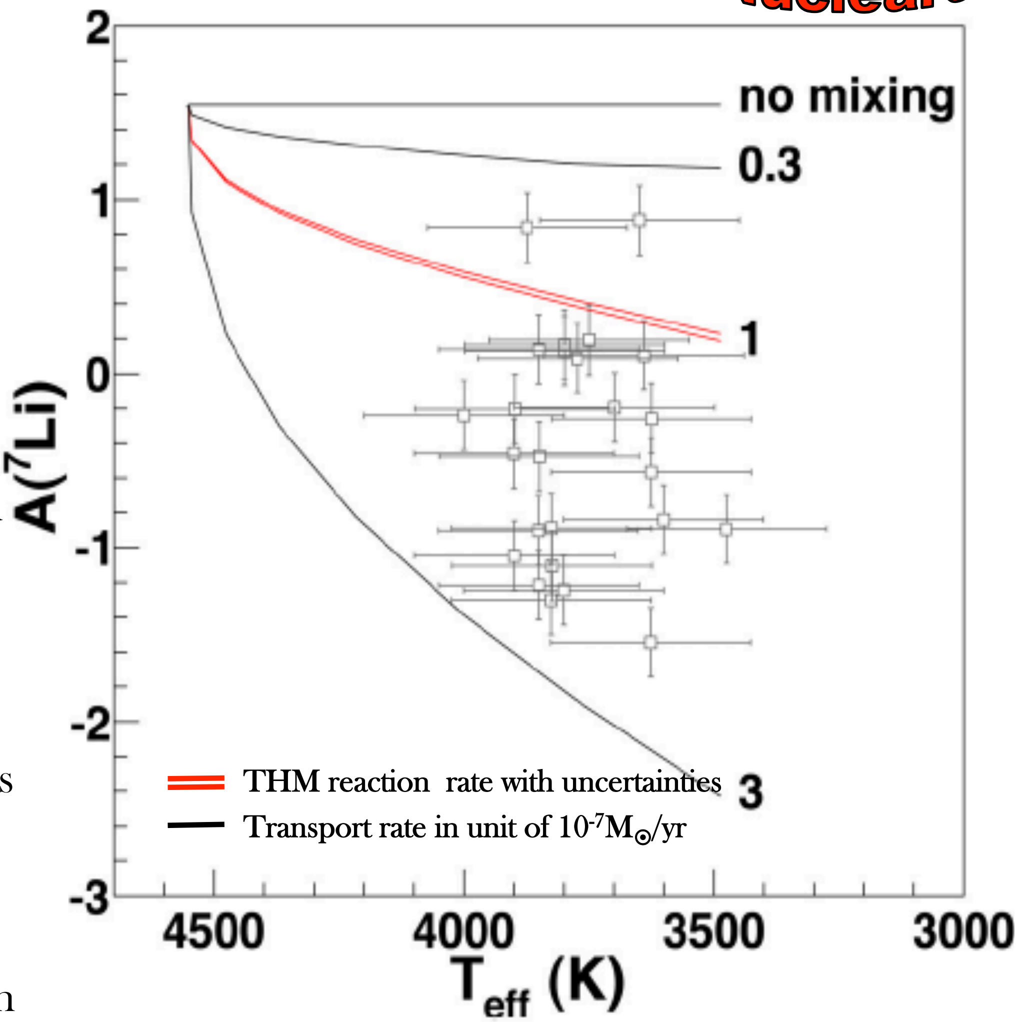
with

$$f_{corr}(T_9) = 0.966 + 0.184\times10^{-1} \ln T_9 + 0.545\times10^{-3}(\ln T_9)^2$$

- The $S_b(E)$ used has been measured, overcoming the extrapolation procedures;
- A simply correction factor has been derived, $f_{corr}(T_9)$

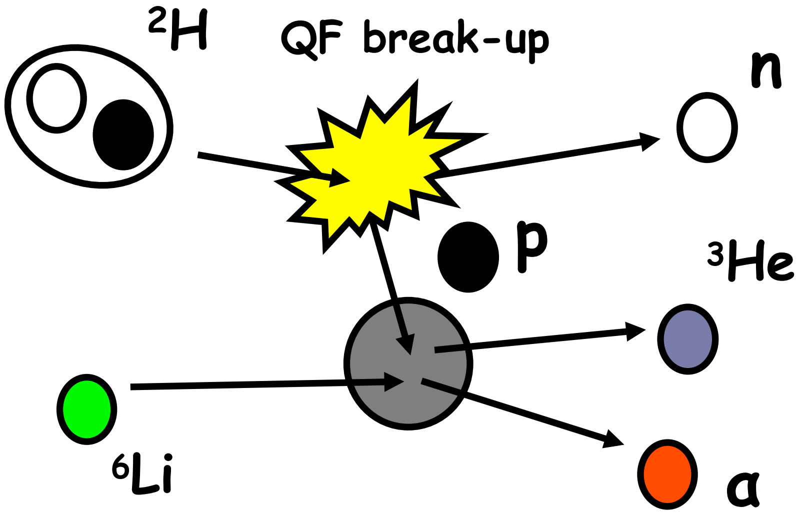
Impact on ^{7}Li nucleosynthesis in RGB phase

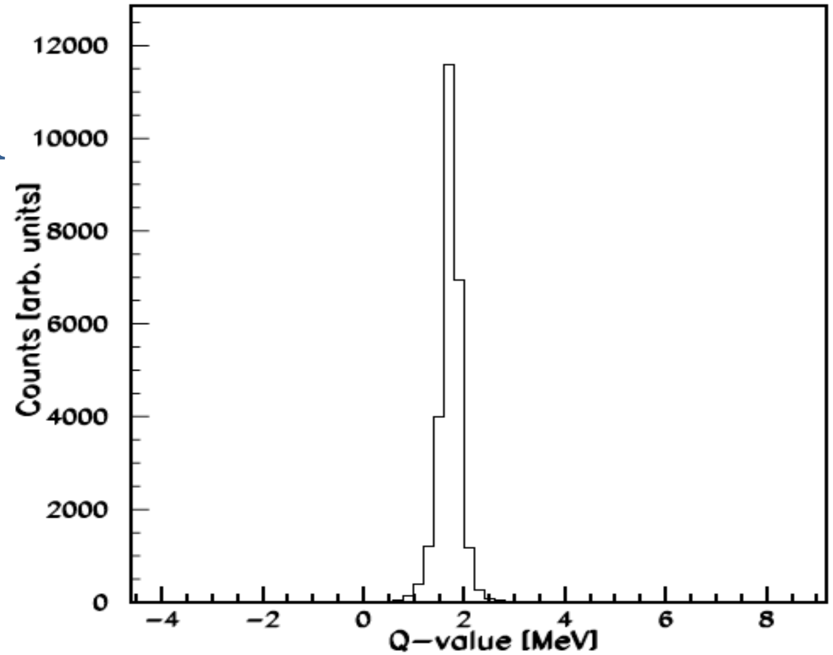
- Standard STellar Models (SSTMs) predict a Li depletion at the beginning of the red giant branch (RGB) phase (Pinsonneault 1997; Sestito et al. 2005), when the deepening convective envelope mixes the external layers with hydrogen-processed material.
- The difficulty in understanding the Li abundance in giant stars is increased by the observation of both Li-rich and Li-poor, for which different mixing mechanism (with different mass transport rate) are still discussed (Sackmann & Boothroyd 1999; Guandalini et al. 2007; Palmerini et al. 2011).
- Thus, we evaluate the impact of the TH reaction rate on ^{7}Li abundance evolution for a 1.5 M and solar-metallicity RGB star, by means of the code discussed and developed by Palmerini et al. 2011.
- The uncertainties on THM reaction rate (red lines) doesn't introduce any significant variation in the Li abundance. If any modification occurs, this is negligible compared to the other uncertainties.



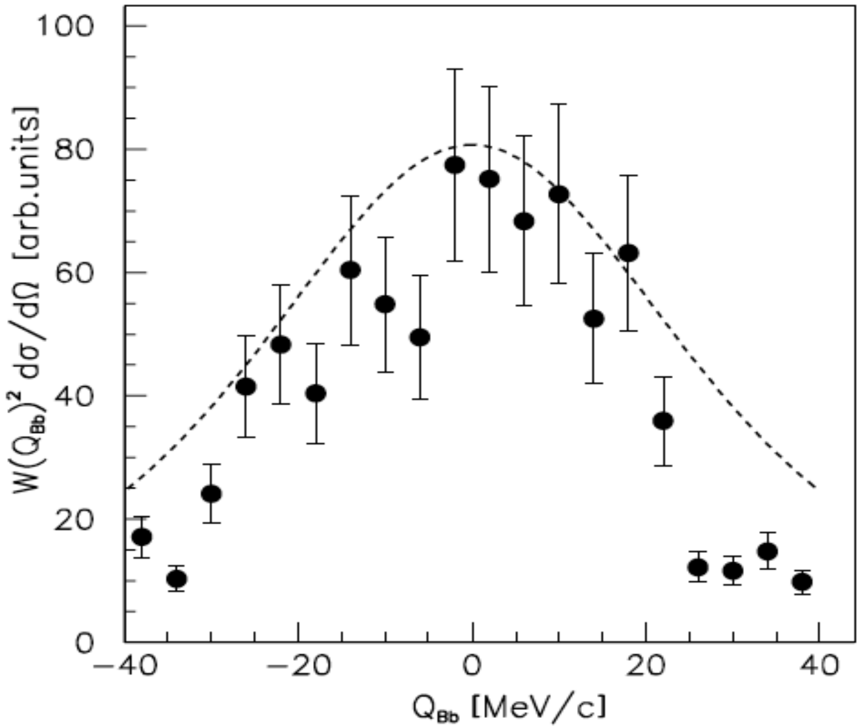
(Lamia L. et al. A&A 2012; Palmerini et al. ApJ, 2011)

The $^{6}Li(p,\alpha)^{3}He$ reaction via the $^{2}H(^{6}Li,\alpha\,^{3}He)n$ QF-reaction

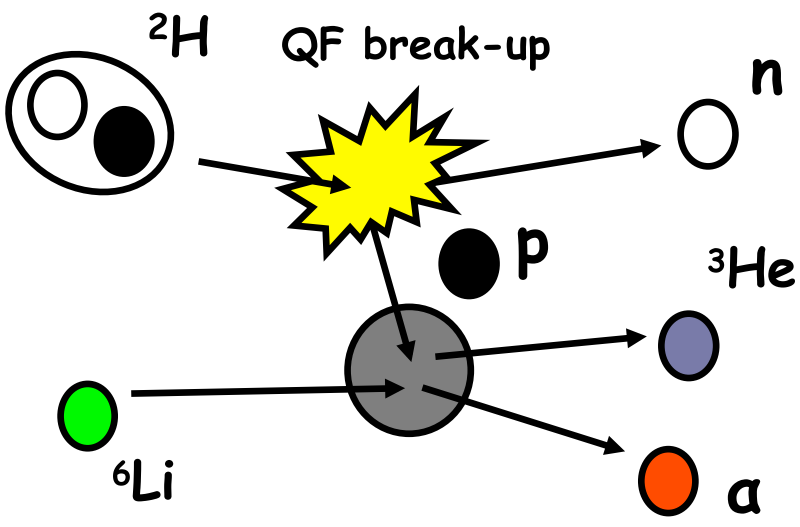


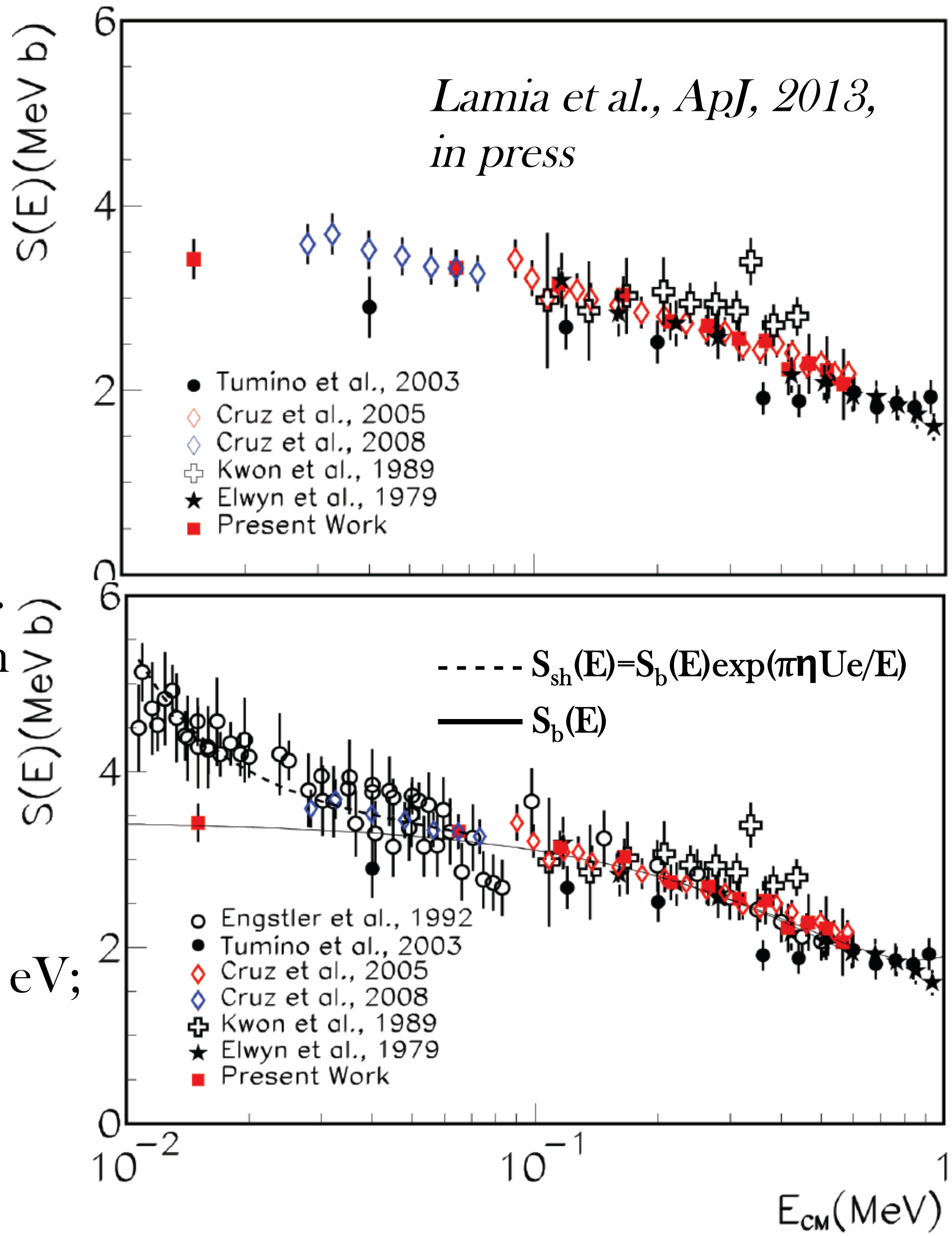


- Earlier investigation Tumino et al. Phys.Rev.C 2003, Pizzone et al. A&A 2005
- Study of the $^{6}Li(p,\alpha)^{3}He$ reaction ($Q=17.35$ MeV) through the QF $^{2}H(^{6}Li,\alpha^{3}He)n$ reaction ($Q=15.12$ MeV);
- $E_{beam}(^{6}Li)$ @ LNS = 25 MeV ;



The updated ^{6}Li(p, α)^{3}He TH reaction rate





- Recent direct measurements by Cruz et al. (2005, 2008) allowed for a new normalization
- Fit of the TH data in **(MeV b)** →

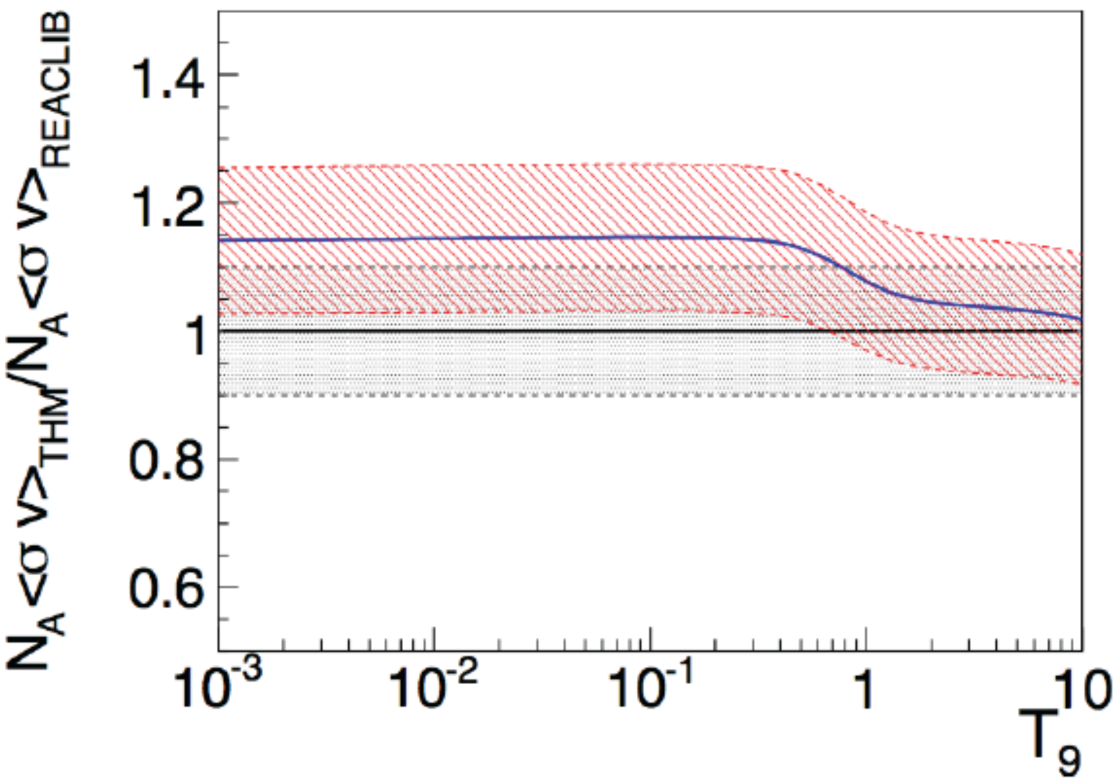
$$S_b(E)=3.44-3.50*E+1.74*E^2+0.23*E^3$$

- S(0)=3.44±0.35 (MeV b) and Ue=355±100 eV;

The updated ^{6}Li(p, α)^{3}He TH reaction rate

Reaction rate determination by means of the formula (Rolfs & Rodney, 1988)

$$N_A < \sigma v >= \left(\frac{8}{\pi\mu}\right)^{1/2} \frac{N_A}{(kT)^{3/2}} \int_0^\infty S_b(E) e^{-2\pi\eta - \frac{E}{kT}} dE \qquad (cm^3 mol^{-1} s^{-1})$$



TH reaction rate compared with the calculation of Cyburt et al., ApJ, 189, 2010 (REACLIB, website):

- Variation of about 15% at astrophysical temperatures relevant for Li-burning in stars!!!

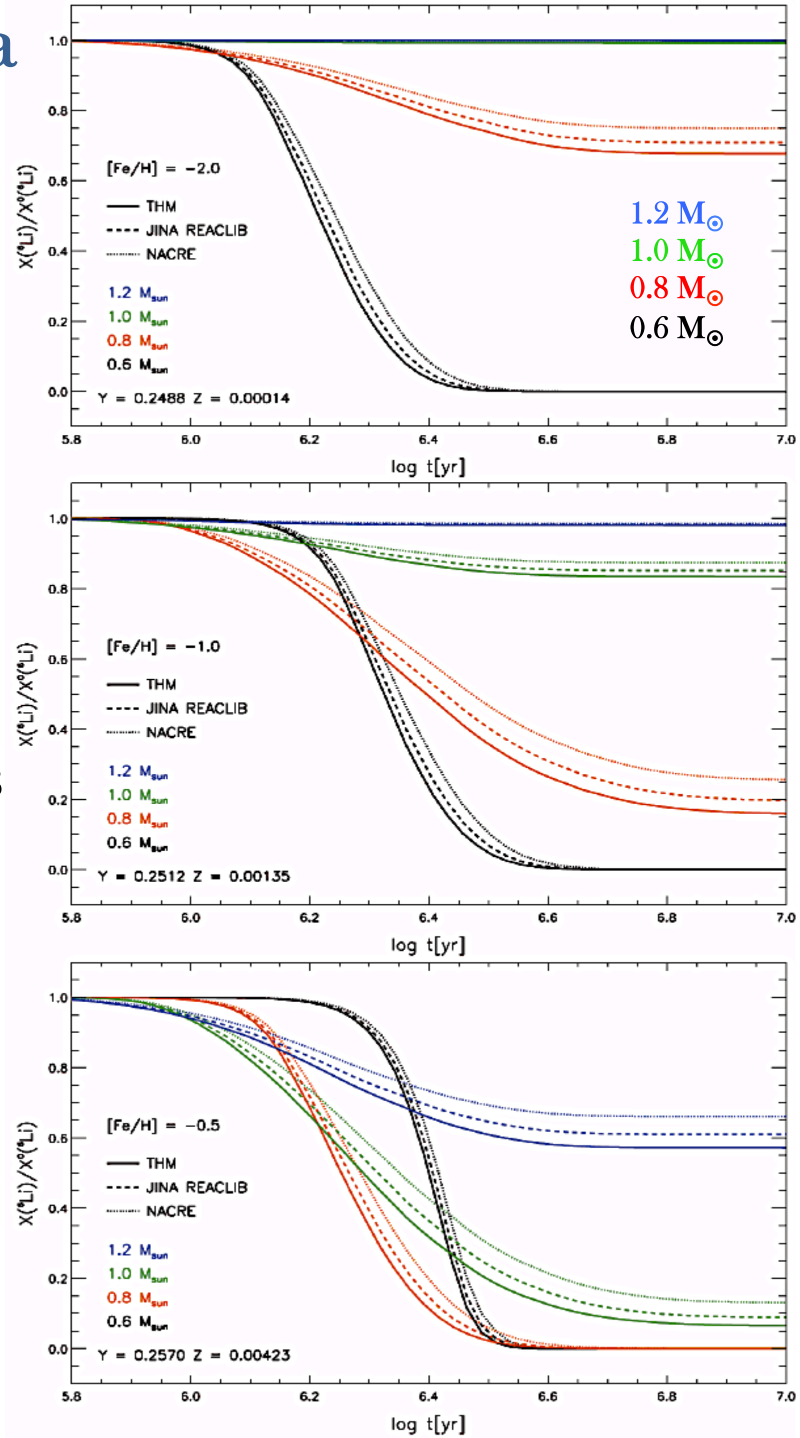
Astrophysical implications in PMS via the updated FRANEC code

- The observation of ^{6}Li in stars is affected by observational difficulties mainly due to the scarse ^{6}Li abundances in stellar envelopes, thus requiring high-quality spectra and spectral analysis based on updated atmospheric models (see e.g. Asplund et al. (2006); Steen et al. (2012)).

- Present models have been computed with a version of the FRANEC evolutionary code (Degl'Innocenti et al. (2008); Dell'Omodarme et al. (2012)) recently updated with particular attention to the physical inputs relevant for the Pre Main Sequence (PMS) phase (see Tognelli et al. (2011) for details). We did model calculations for four dierent masses (0.6 M, 0.8 M,1.0 M, 1.2 M) and three different metallicities, namely [Fe/H] = -0.5, -1.0, and -2.0.

- The higher the metallicity, or the lower the stellar mass, the deeper and hotter the base of the convective envelope. This qualitatively explains the different ^{6}Li depletion for various masses and metallicities.

- Uncertainties on ^{6}Li abundance observations (stellar masses, input parameters....) make difficult any comparison with the obtained results, thus leaving 6Li in PMS as an open problem.



CONCLUSIONS

The THM (see Spitaleri et al. At.Phy.Nucl. 2011, PRC 2004) provides a valid alternative to the direct measurements for the evaluation of the low-energy region of astrophysically relevant reactions.

- It allowed us to measure the $^{11}B(p,\alpha_0)^8Be$ S(0)=2.07±0.41 (MeV b) and Ue=472±160 eV, without any extrapolation (see Lamia, Spitaleri et al. JpG, 2012);
- Thanks to the most recent direct measurements, an updated $^7Li(p,\alpha)^4He$ TH reaction rate has been deduced, with variation of about 10% in correspondence of the astrophysical temperatures. Evaluation on RGB nucleosynthesis;
- The direct measurements of Cruz et al. 2005-2008 allowed us to update the $^6Li(p,\alpha)^3He$ TH reaction. Astrophysical application on PMS star nucleosynthesis via the recent FRANEC code version (even if no observational data have been used for comparison);

PERSPECTIVES

- Application of the updated THM reaction rate to different astrophysical context;
- Extraction of the $^{10}B(p,\alpha)^7Be$ S(E)-factor and its measurement in correspondence of the 10 keV resonance (data analysis in progress);
- Extraction of the Ue from the TH $^{10}B(p,\alpha)^7Be$ measure ... ta to test the so-called "isotopic-independence", i.e. the Ue does n ... charge Z of the istopes ^{10}B or ^{11}B (Assembaum et al., 1987 or Engstl

Thank you....