Measurements of the ^{7}Be+n Big-Bang nucleosynthesis reactions at CRIB by the Trojan Horse method

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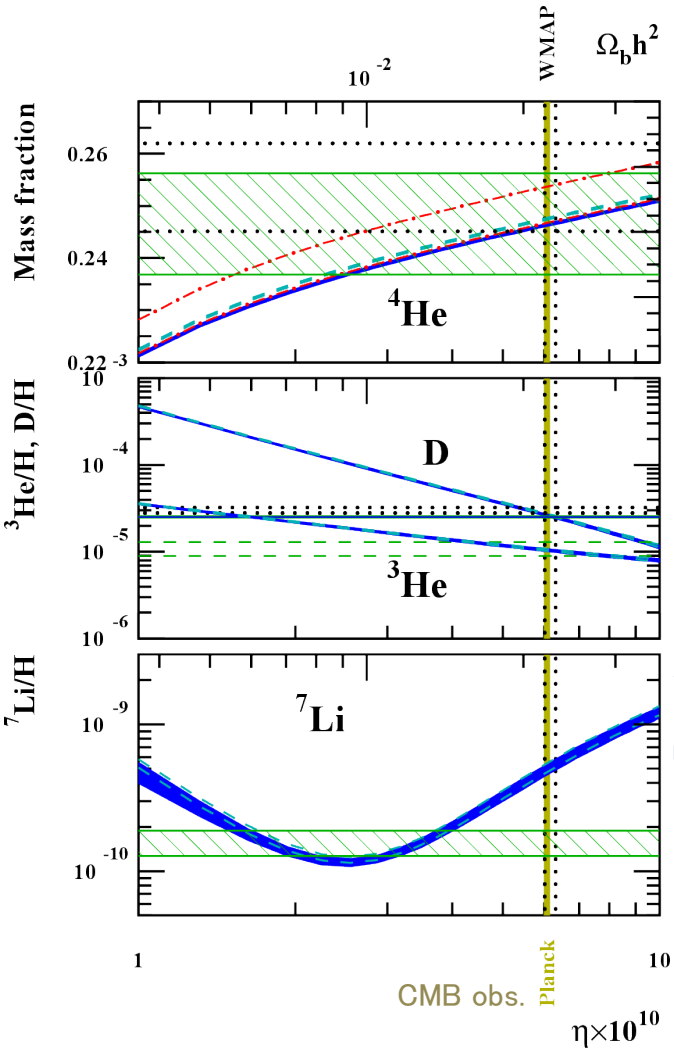
Cosmological ^{7}Li problem



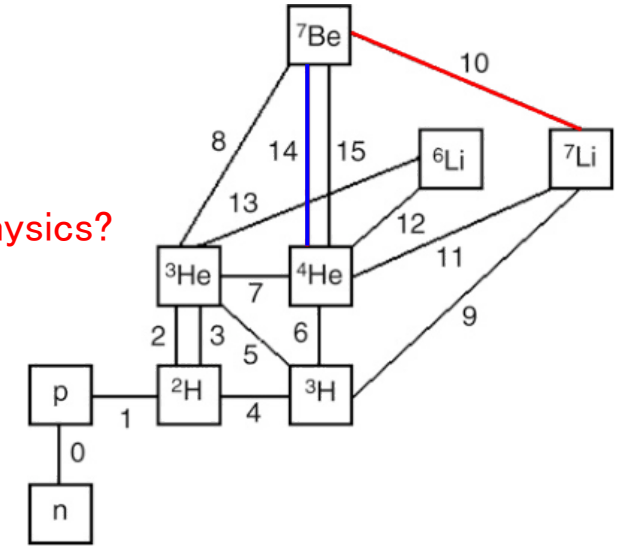
A. Coc et al. J. Cos. Astropart. Phys. 2014

Standard Big-Bang Nucleosynthesis model (BBN)

Low-metallicity star obs.

→Nuclear Physics?

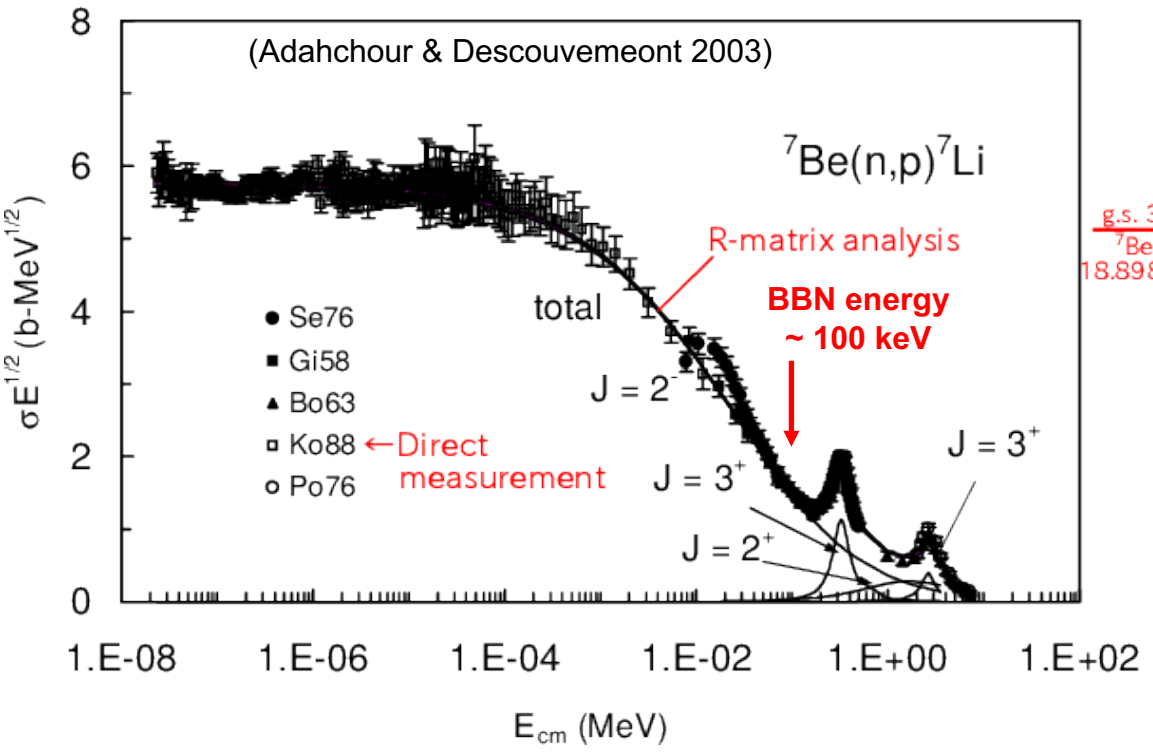
^{7}Be abundance at the end of BBN determines ^{7}Li dominantly

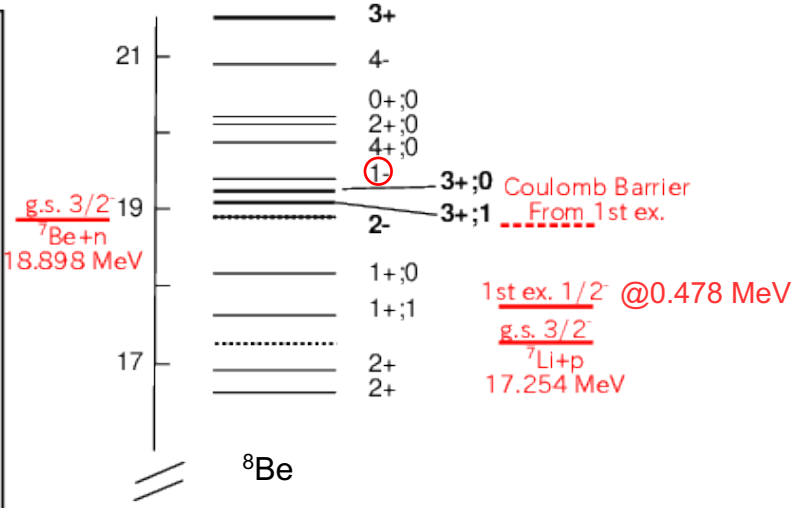


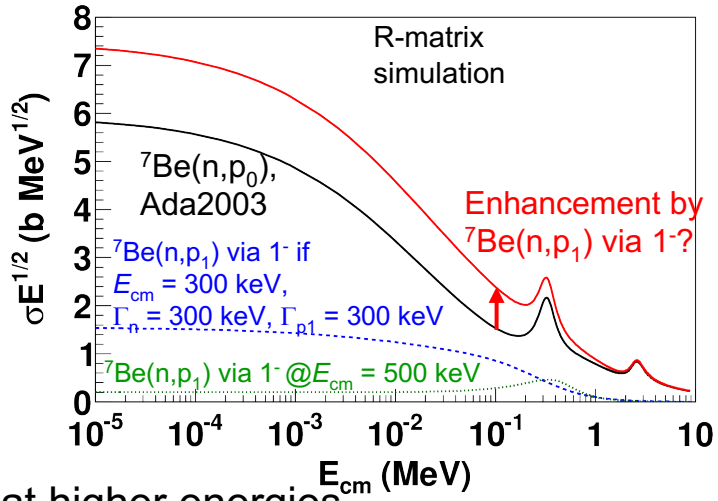
0: τ_n
1: $p(n, \gamma)d$
2: ^{2}H$(p, \gamma)^3$He
3: ^{2}H$(d, n)^3$He
4: ^{2}H$(d, p)^3$H
5: ^{3}He$(n, p)^3$H
6: ^{3}H$(d, n)^4$He
7: ^{3}He$(d, p)^4$He
8: ^{3}He$(\alpha, \gamma)^7$Be
9: ^{3}H$(\alpha, \gamma)^7$Li
10: ^{7}Be(n,p)^{7}Li
11: ^{7}Li$(p, \alpha)^4$He
12: ^{4}He$(d, \gamma)^6$Li
13: ^{6}Li$(p, \alpha)^3$He
14: ^{7}Be(n,α)^{4}He
15: ^{7}Be$(d, p)2^4$He

Iocco et al. Phys. Rep. 2009

^{7}Be(n,p)^{7}Li (Q = 1.644 MeV)

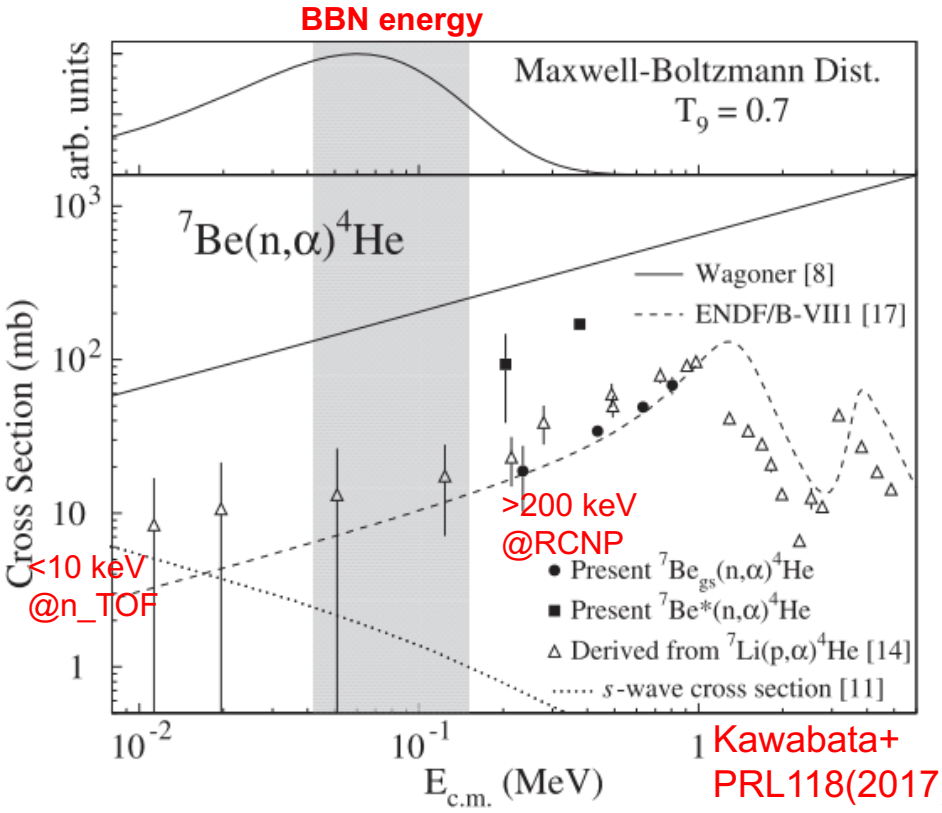


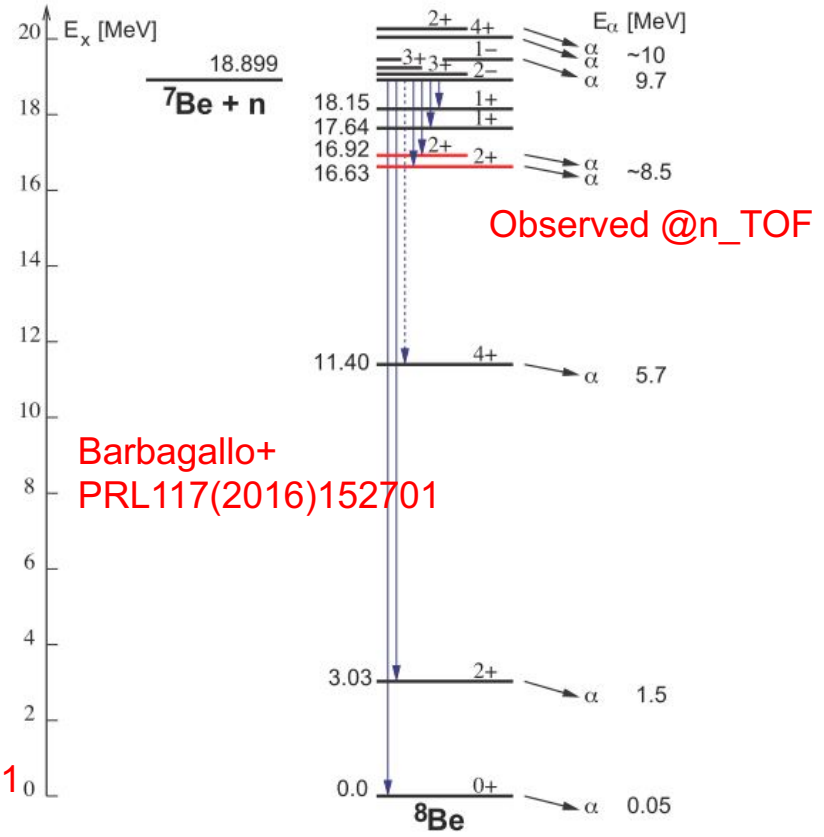




- Main ^{7}Be destruction process (>90%)
- Sensitivity: $\partial \log Y_{7Li} / \partial \log \langle \sigma v \rangle_{7Be} = -0.71$
  $\Rightarrow$ If $\langle \sigma v \rangle_{7Be} \times 2$, $Y_{7Li} \times 0.6$ (Coc & Vangioni, 2010)
- Direct measurement up to 13.5 keV, time-reversal reactions at higher energies.
- R-matrix analysis: Adahchour & Descouvemont 2003
  - One 2- close to the threshold, two 3$^+$ resonances, one non-resonant broad 2$^+$
  - Accuracy: 1σ confidence level ~ 1%

^{7}Be(n,α)^{4}He (Q = 18.990 MeV)



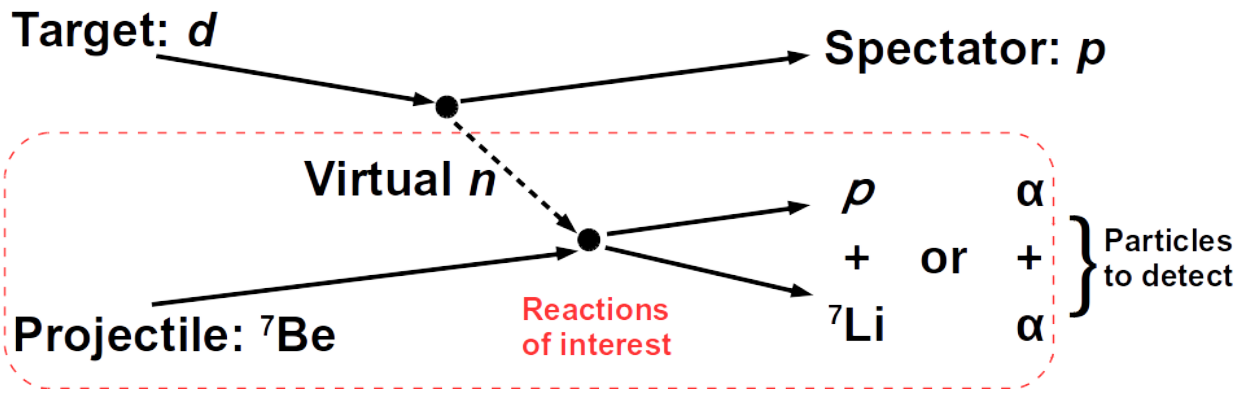


- Revised reaction rate from mirror reaction by Hou+ (2015)
- Direct measurement up to 10 keV by Barbagallo+ at n_TOF (2016)
  - Measured only α decays after γ-ray emission from ^{8}Be excited states
  - S-wave only → 1/v law
- Time-reversal reaction measurement down to 200 keV by Kawabata+ at RCNP (2017)
  - Measured p-wave neutrons → dominant at BBN energies

Trojan Horse Method for RI + *n*

Trojan Horse method: e.g. Spitaleri+ Phys. of Atom. Nucl. 74(2011)1725

^{7}Be(n,p)^{7}Li, ^{7}Be(n,α)^{4}He via ^{2}H(^{7}Be,^{7}Lip)^{1}H, ^{2}H(^{7}Be,αα)^{1}H

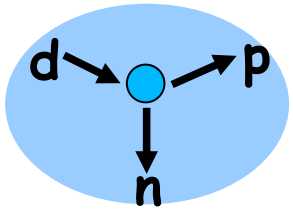


- $E_{\text{d-7Be}}$ > Coulomb barrier
- Accessible to low energy releasing deuteron binding energy
- Deuteron: low $E_{\text{bind.}}$, $L_{\text{p-n}} = 0 \Rightarrow p_{\text{p-n}}$ has maximum at 0
- Useful also as virtual neutron target

- $|p_s| < 30$ MeV/c $\Rightarrow E_{\text{c.m.}} = 0-2.5$ MeV @ $E_{\text{beam}} = 22.1$ MeV

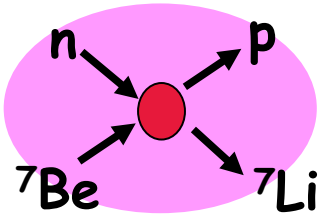
Trojan Horse Method for RI + *n*

Assuming Quasi-free mechanism is dominant, one can use (PW)IA:



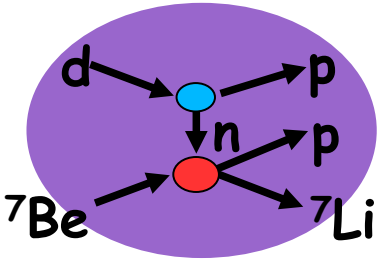
Virtual Decay

$\otimes$



Virtual reaction

$=$



3-body Reaction

$\mathbf{KF \cdot |\Phi(P_s)|^2}$ $\times$ $\dfrac{d\sigma^{HOES}}{d\Omega}$ $\propto$ $\dfrac{d^3\sigma}{d\Omega_p\, d\Omega_{7Li}\, dE_{cm}}$

Confirm momentum distribution then use Monte Carlo simulation

2-body cross section of interest

Measured at high energy

Normalization needed

$\sigma^{OES} \propto \sigma^{HOES} \times$ **Penetrability**

Collaboration with BELICOS project

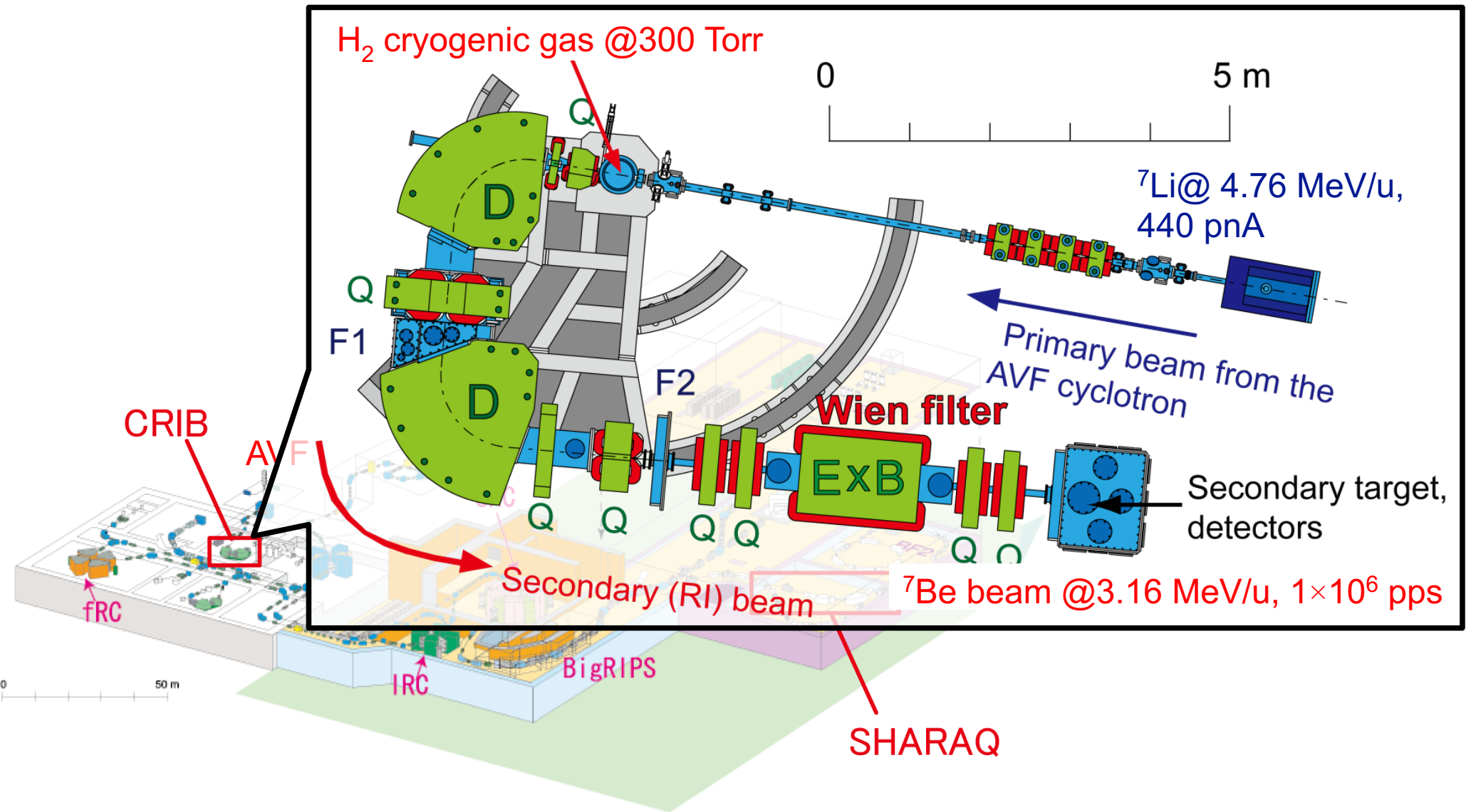
- BELICOS project: Beryllium and Lithium in the Cosmos
  - ^{7}Be+d THM experiment for ^{7}Be(n,α)^{4}He
    (L. Lamia, C. Spitaleri, Catania − M. Mazzocco, Padova)
  - Done at EXOTIC, INFN-LNL

- BELICOS: better statistics, only ^{7}Be(n,α)
  ⇔ CRIB: better resolution, both ^{7}Be(n,p) and ^{7}Be(n,α)

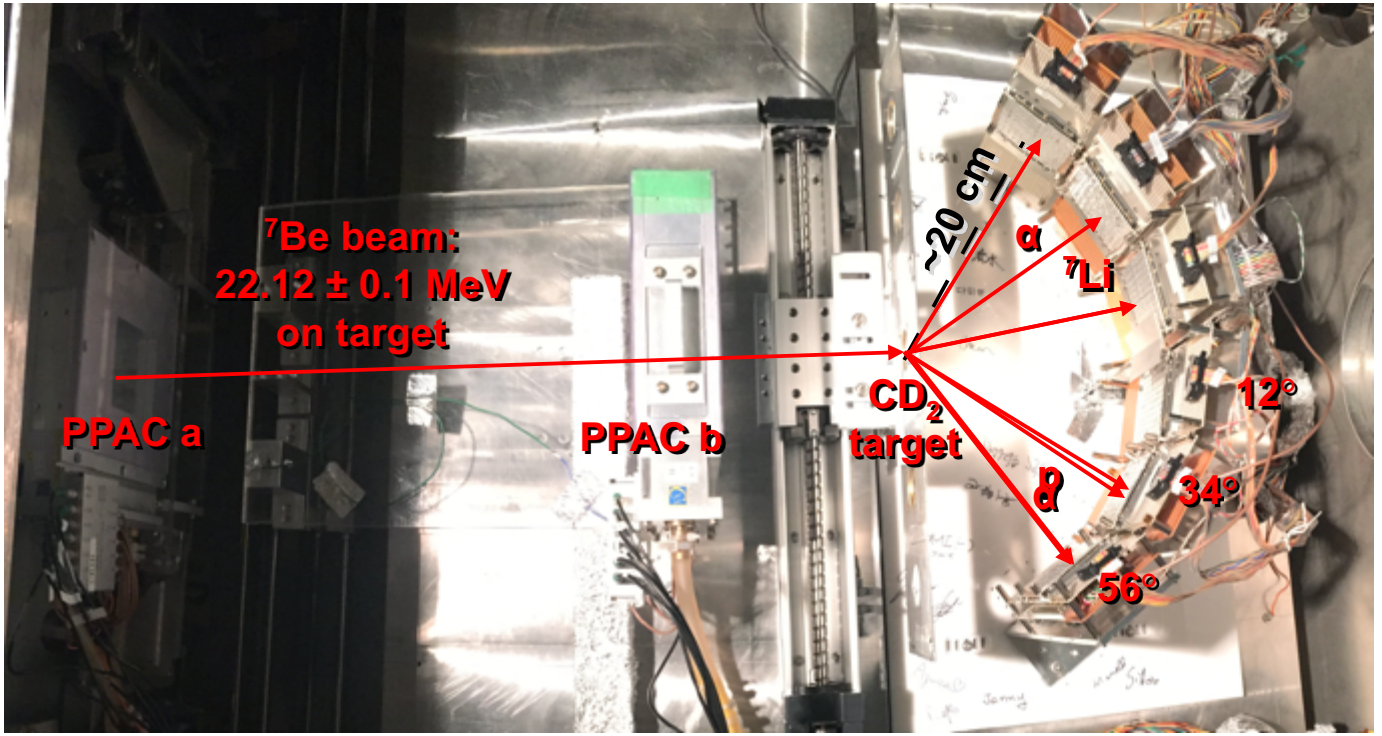
- See L. Lamia's talk (14:30, Thr., "Indirect methods 1")

^{7}Be beam production at CRIB

CRIB: CNS Radioactive-Isotope Beam separator (in-flight technique), managed by Center for Nuclear Study, Univ. of Tokyo, located at RIBF, RIKEN.



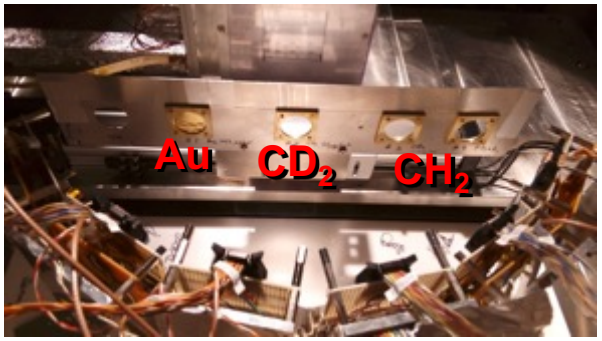
Experimental setup

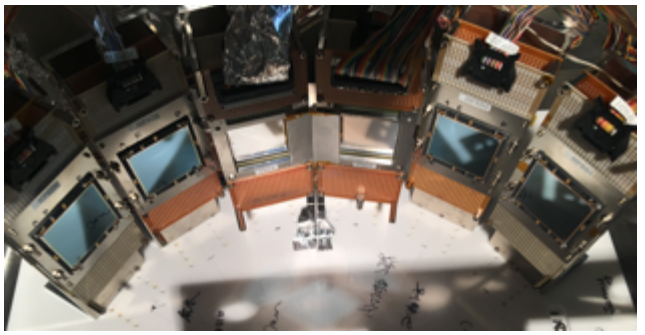


6 ΔE-E position sensitive silicon telescopes

CD_2: 64 µg/cm^2
→ ΔE_{beam} ~ 150 keV

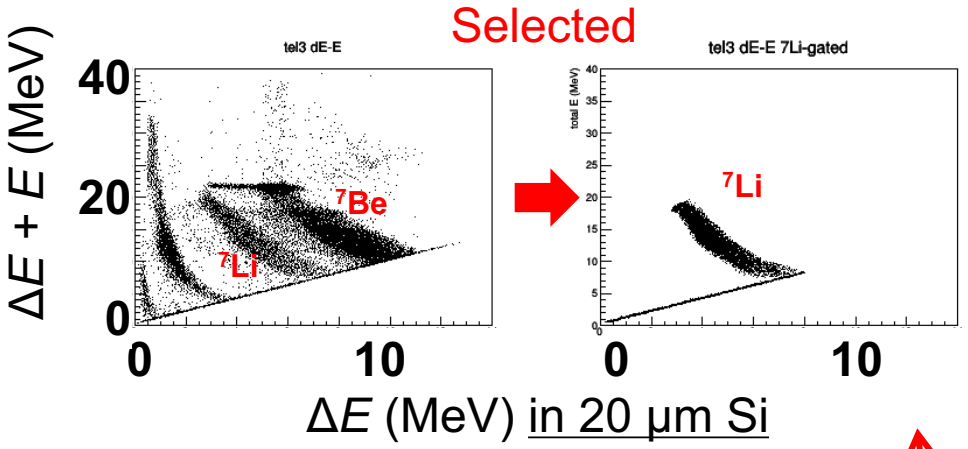
Hamamatsu Charge-division PSD: position resolution ~ 0.5 mm

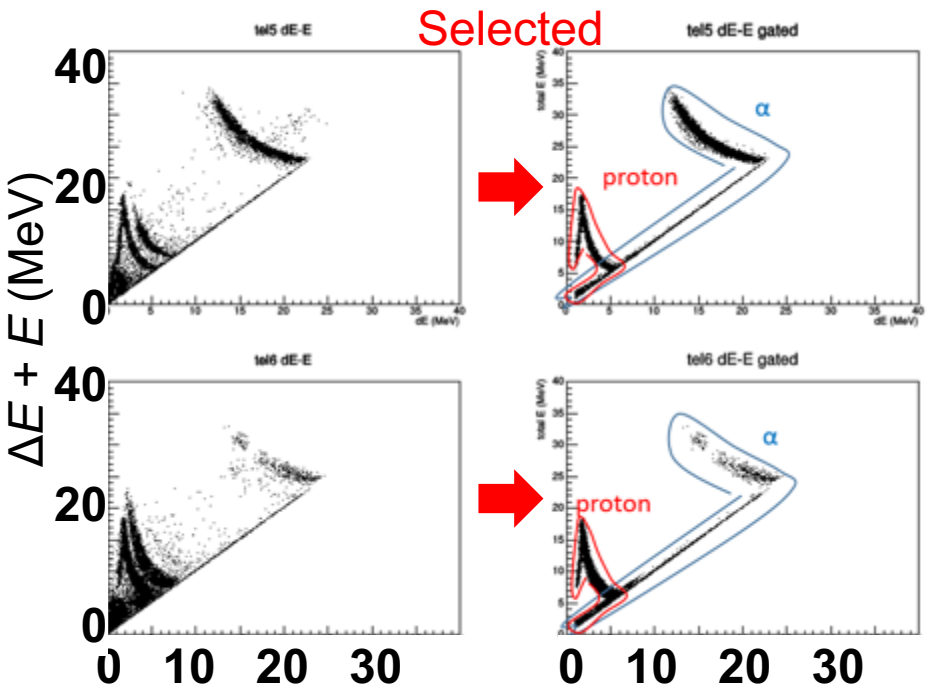




→ Total angular resolution
~ 0.5° ⇒ ΔE_{cm} ~ 60 keV

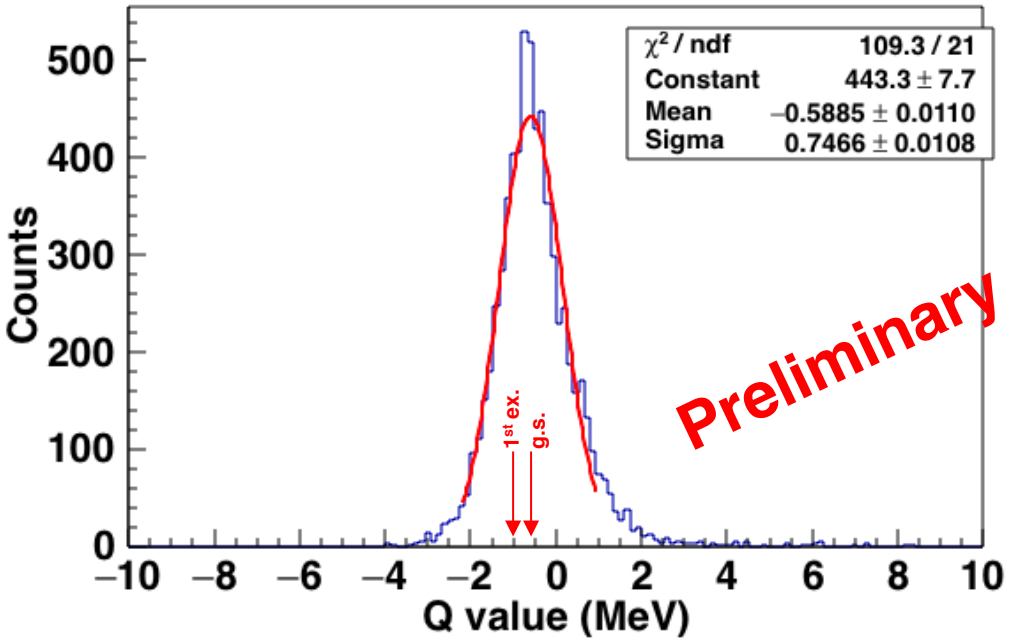
Particle identification



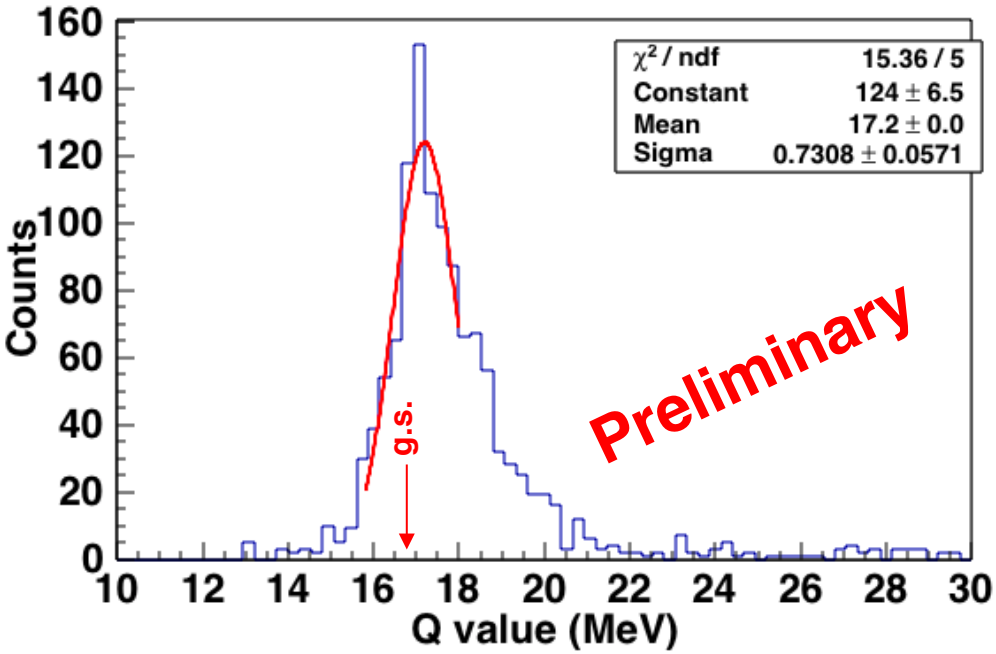


Q-value spectra of the 3-body channels

^{7}Be(d,^{7}Lip)p



^{7}Be(d,2α)p



Known value:
Q(g.s.) = -0.589 MeV
Q(1st) = -1.058 Mev

Reaction	*Q*-value (MeV)
p+2α	16.766
^{7}Li+2*p*	-0.589
^{7}Be+*n*+*p*	-2.225
^{5}He+*p*+^{3}He	-4.547

Known value:
Q(g.s.) = 16.766 MeV

$Q_{3body} = E_1 + E_2 + E_3 - E_{beam}$

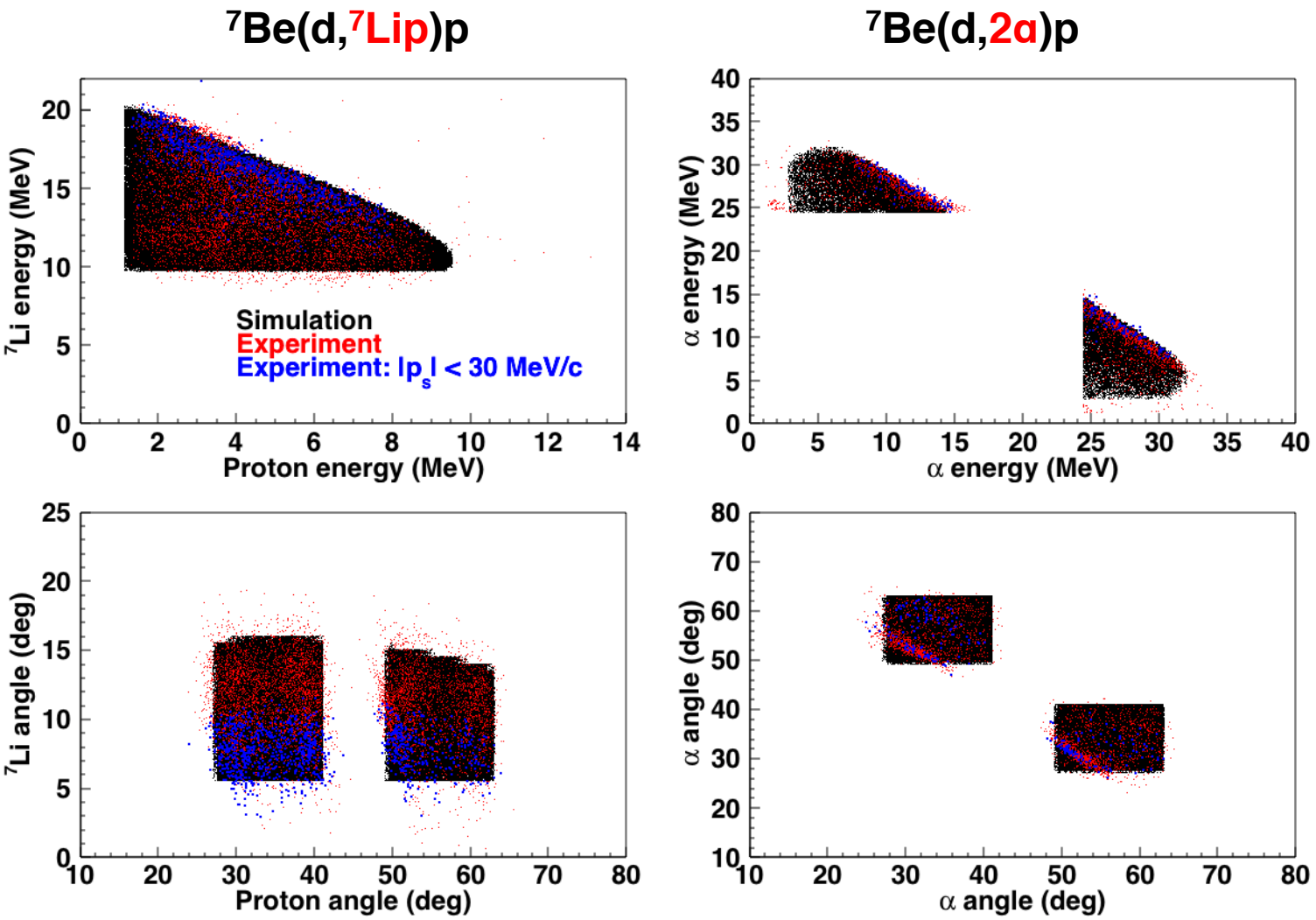
$\Delta Q_{3body} \sim \sqrt{(\Delta E_1^2 + \Delta E_2^2 + \Delta E_3^2 + \Delta E_{beam}^2)}$

~ 200 keV expected with 64 μg/cm^2 CD_2

Kinematics check

Energy correlation

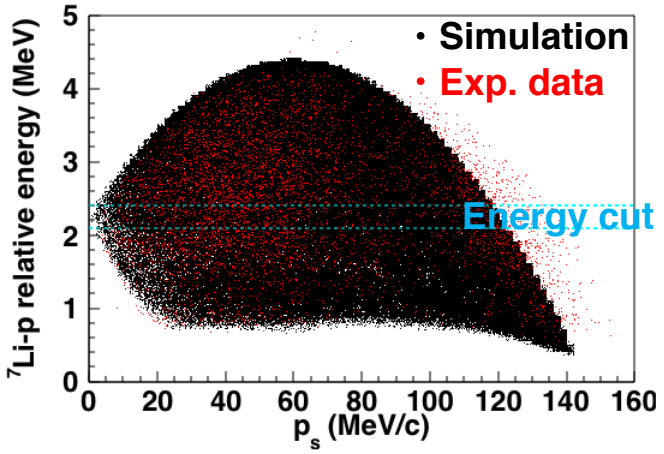
Angular correlation

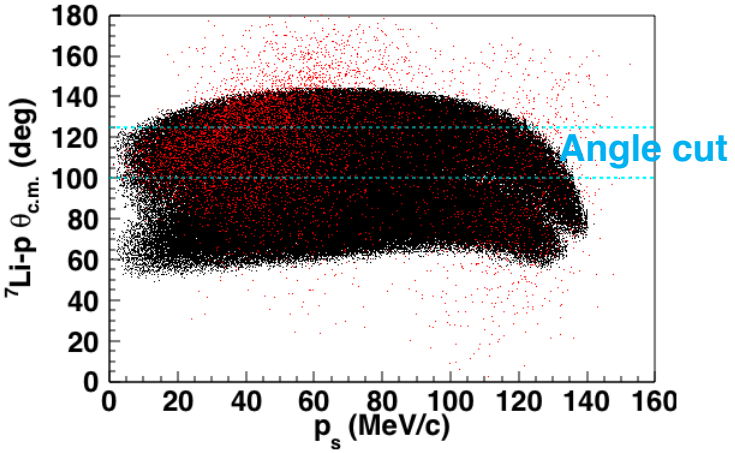


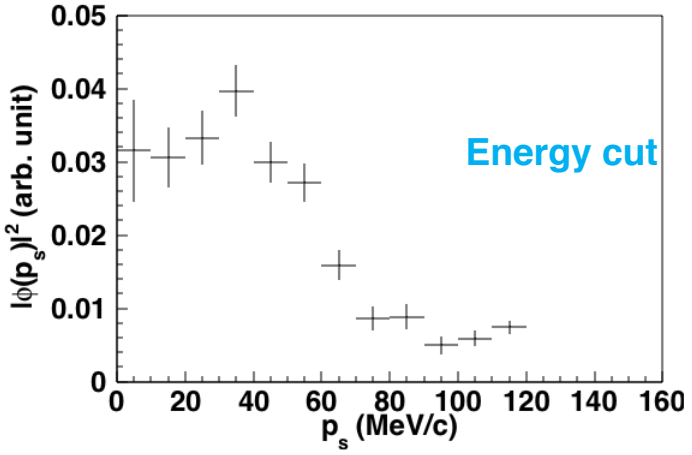
Monte Carlo simulation and experimental data are in a good agreement.
The simulation does not include uncertainties yet → The data is broader.

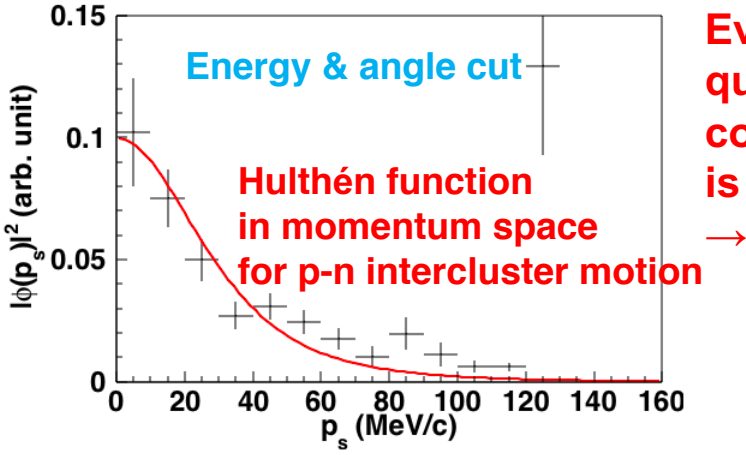
Energy, angle vs. spectator's momentum

^{7}Be(d,^{7}Lip)p









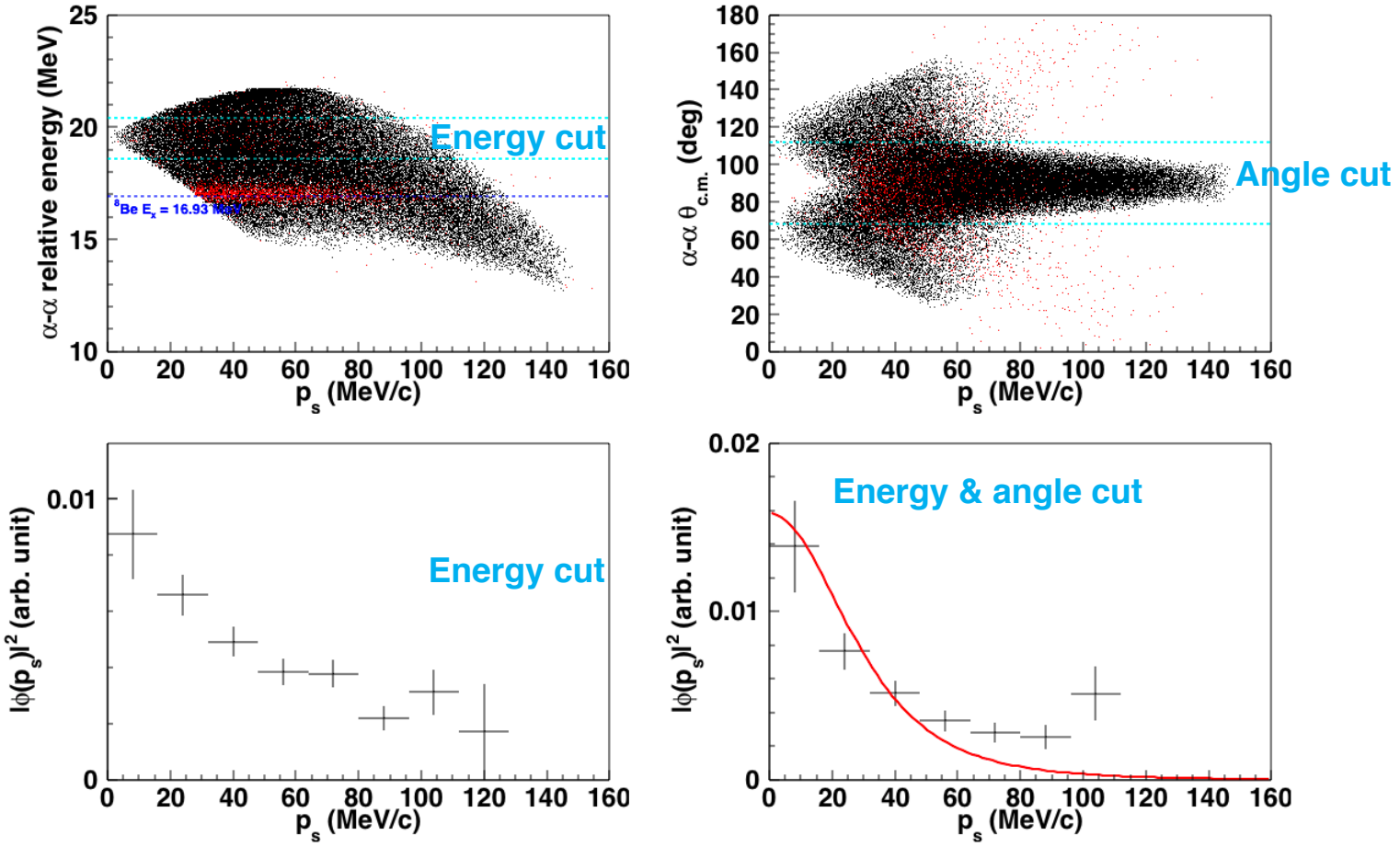
Evidence that quasi-free contribution is dominant.
→ THM is valid!

$Y_{exp}/Y_{sim} = d^3\sigma/(d\Omega_p d\Omega_{7Li} dE_{cm})$ / KF

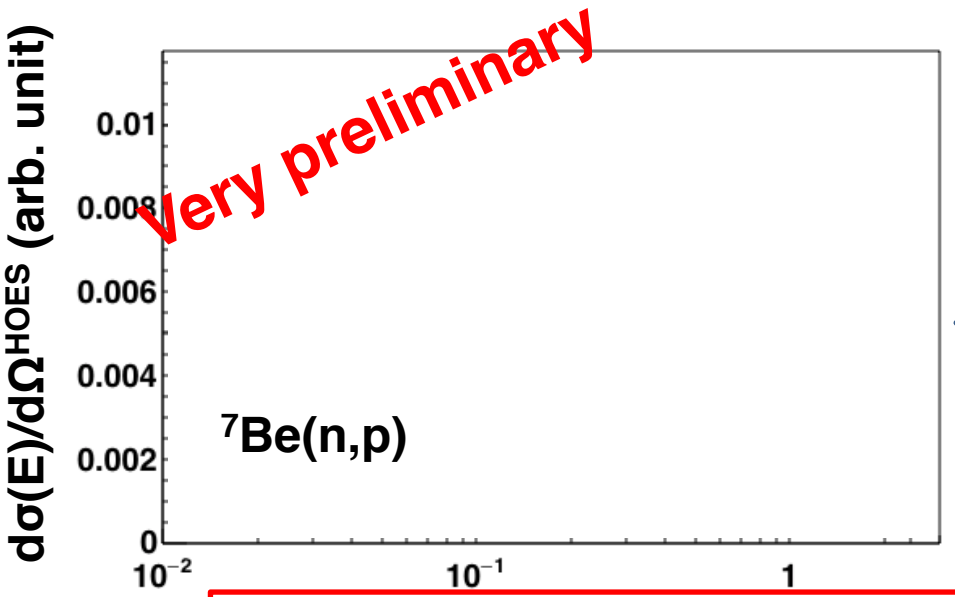
$\propto |\Phi(p_s)|^2$ at a fixed $E_{c.m.}$ and $\theta_{c.m.}$.

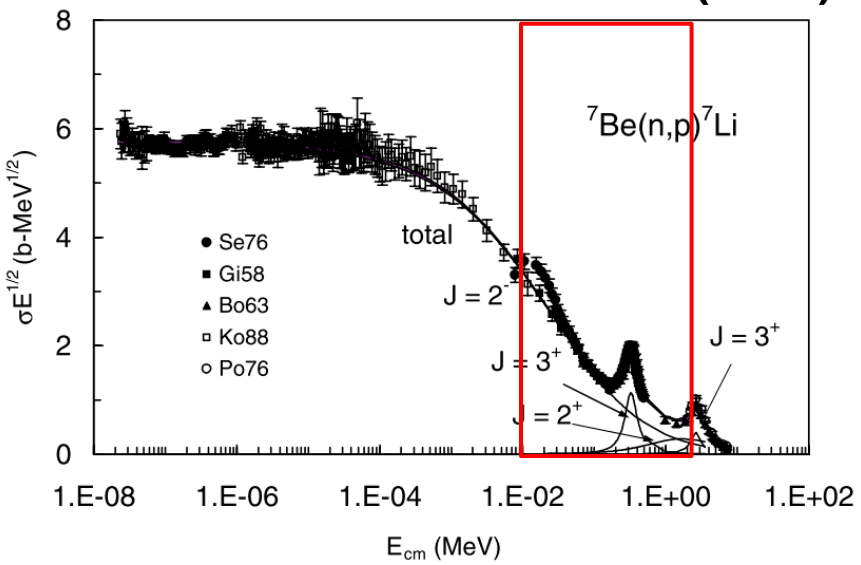
Energy, angle vs. spectator's momentum

^{7}Be(d,2α)p

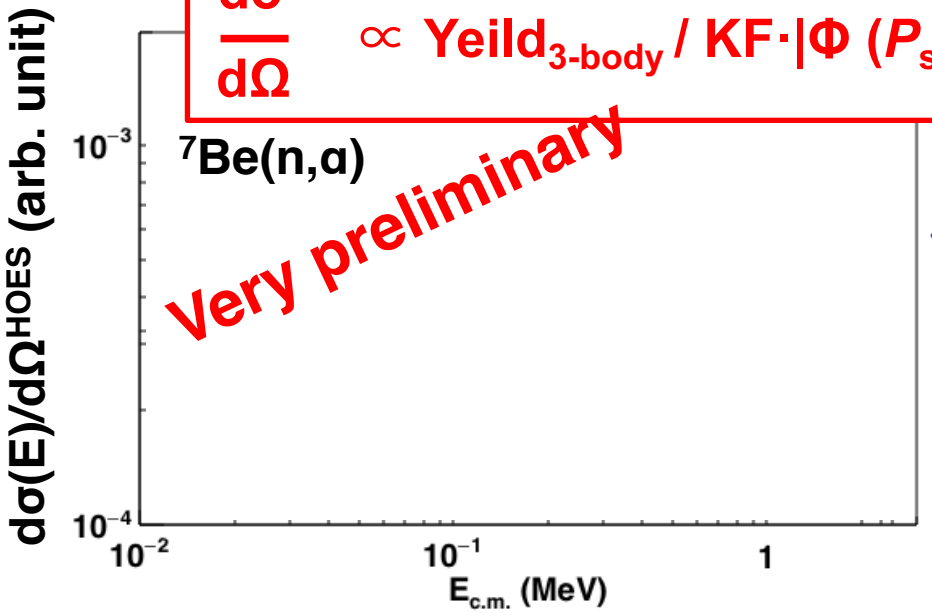


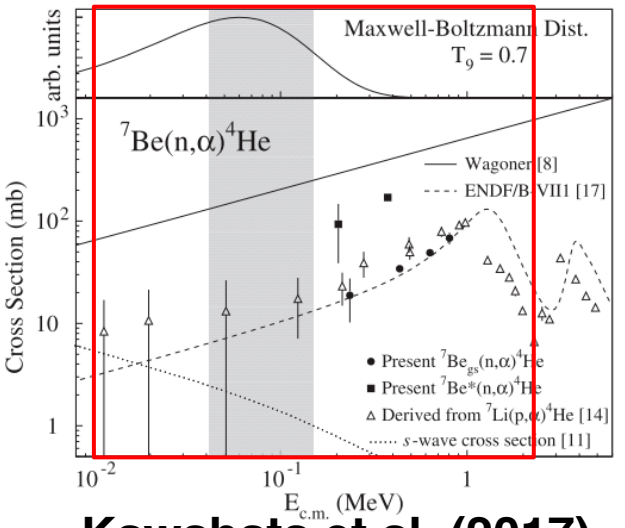
HOES cross sections for $|p_s| < 40$ MeV/c





$$\frac{d\sigma^{HOES}}{d\Omega} \propto Yeild_{3\text{-}body} / KF \cdot |\Phi(P_s)|^2$$





Kawabata et al. (2017)

Summary

- Measured $^{7}Be(n,p)^{7}Li$ and $^{7}Be(n,\alpha)^{4}He$ by THM
- Evidence of quasi-free reaction mechanism: validity of THM
- Excitation functions: roughly consistent with the previous data
- Able to approach the BBN energies ~ 100 keV
- $^{7}Be(n,p_1)^{7}Li^*$ contribution is not clear: better Q-value resolution?
- Upper limit of p_1 contribution from p_0 spectrum?