Measurements of the neutron-induced reactions on ^{7}Be with CRIB by the Trojan Horse method

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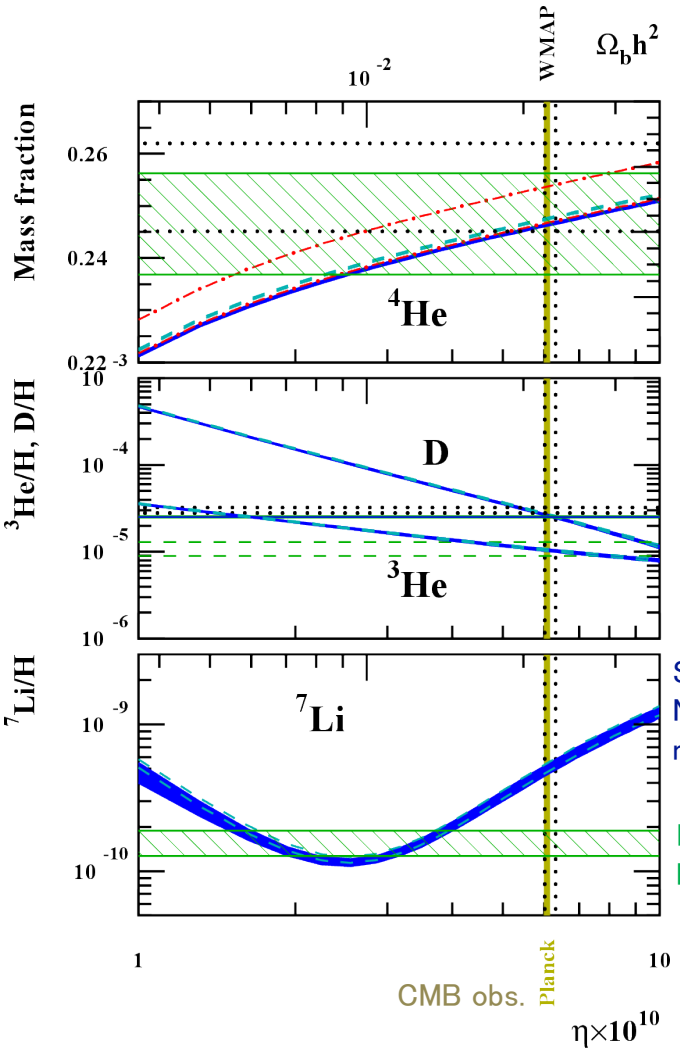
CENTER for NUCLEAR STUDY + INFN LNS + UNIVERSITÀ degli STUDI di CATANIA + SUNGKYUNKWAN UNIVERSITY + many others

Cosmological ^{7}Li problem



Standard Big-Bang Nucleosynthesis model (BBN)

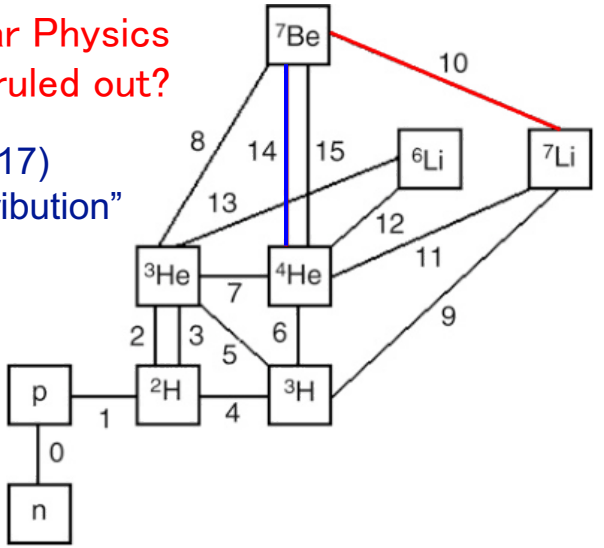
Low-metallicity star obs.
Plateau? Slope? Scatter?

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

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

→Nuclear Physics really ruled out?

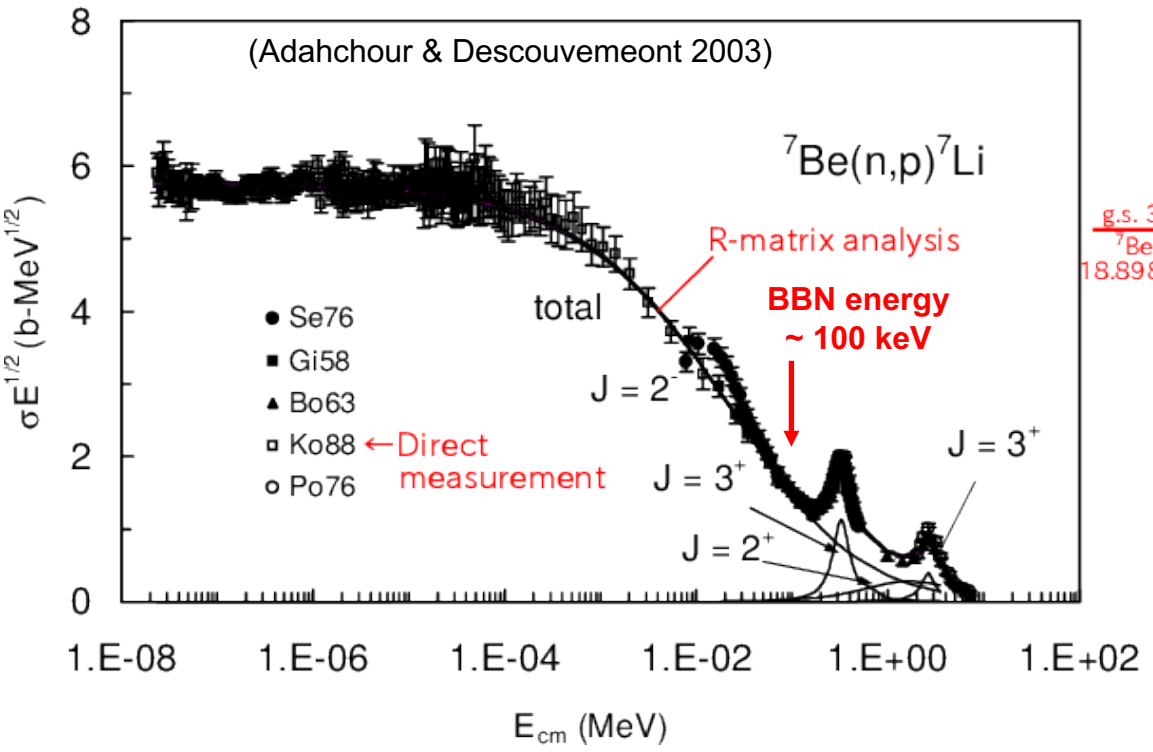
S. Q. Hou+ APJ (2017)
"Non-extensive distribution"

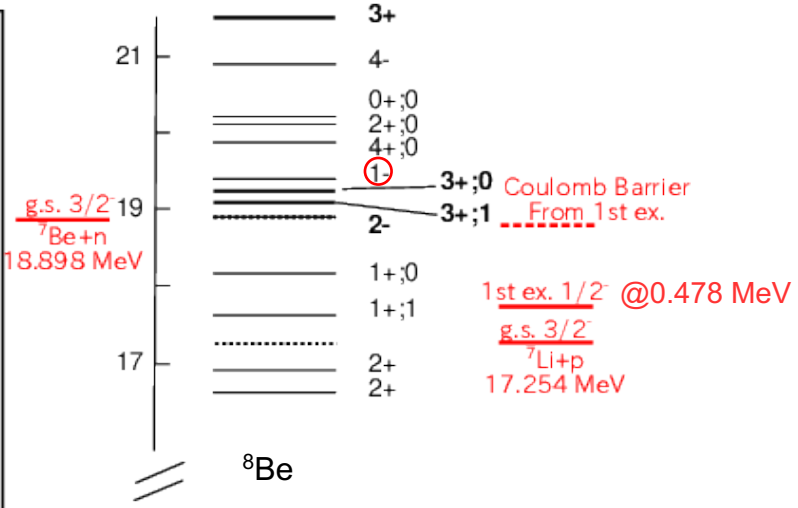


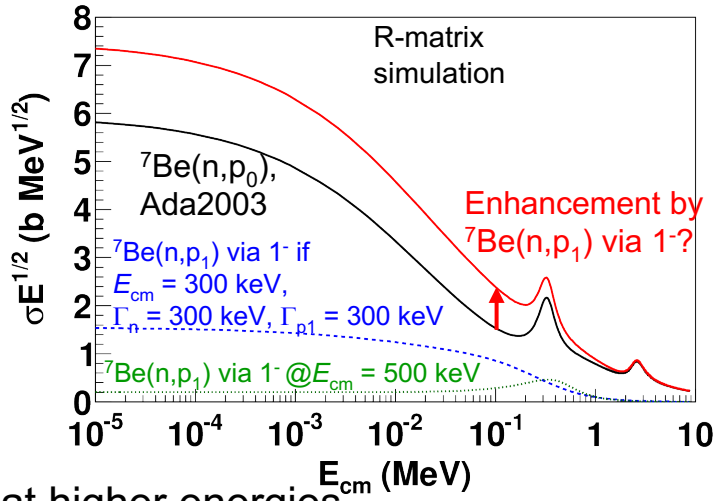
0: τ_n
1: $p(n, \gamma)d$
2: ^{2}H$(p, \gamma)^3$He
3: ^{2}H$(d, n)^3$He
4: ^{2}H$(d, p)^3$H
5: ^{3}He$(n, p)^3$H
6: ^{3}H$(d, n)^4$He
7: ^{3}He$(d, p)^4$He
8: ^{3}He$(\alpha, \gamma)^7$Be
9: ^{3}H$(\alpha, \gamma)^7$Li
10: ^{7}Be(n,p)^{7}Li
11: ^{7}Li$(p, \alpha)^4$He
12: ^{4}He$(d, \gamma)^6$Li
13: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

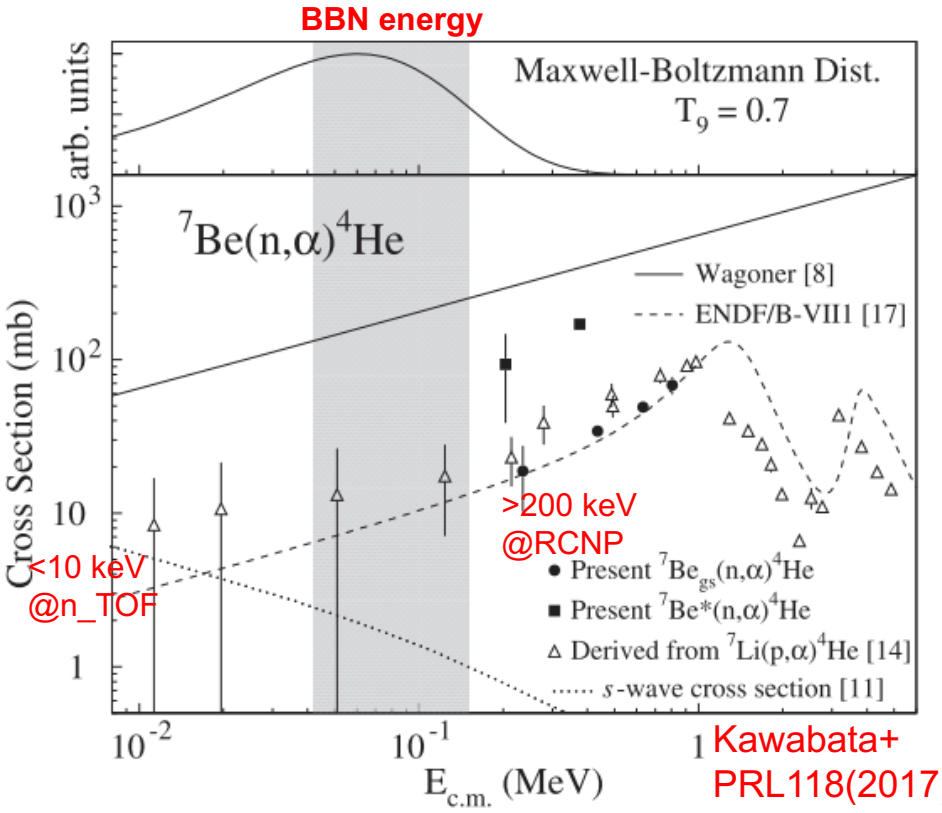


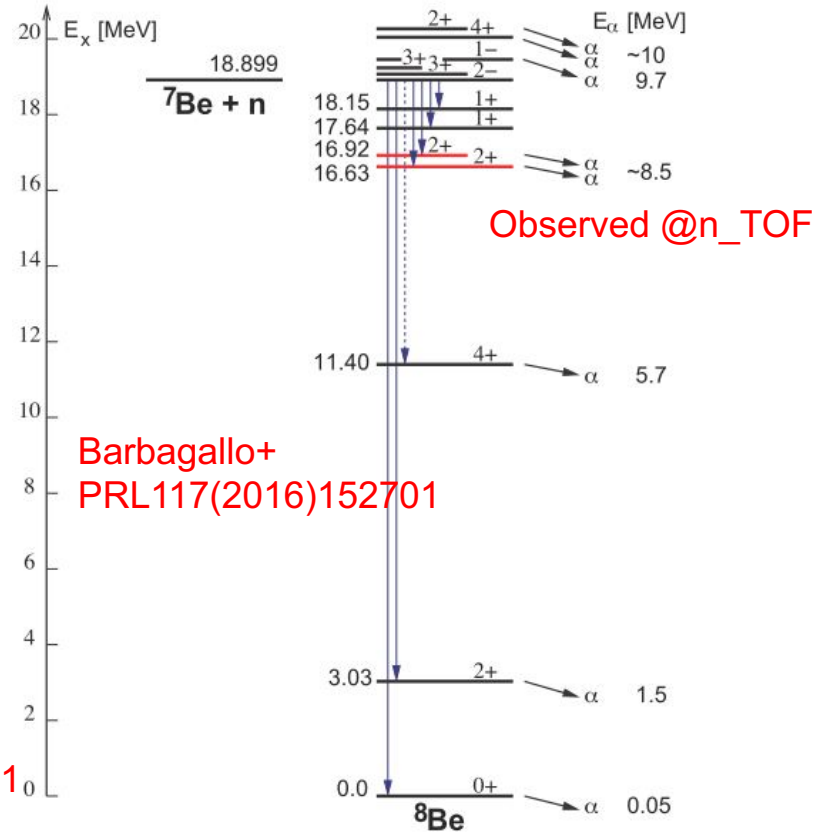




- Main ^{7}Be destruction process (>90%)
- Sensitivity: $\partial \log Y_{7Li} / \partial \log \langle \sigma v \rangle_{7Be} = -0.71$
  $\Rightarrow$ If $\langle \sigma v \rangle_{7Be} \times 2$, $Y_{7Li} \times 0.6$ (Coc & Vangioni, 2010)
- Direct measurement up to 13.5 keV, time-reversal reactions 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)





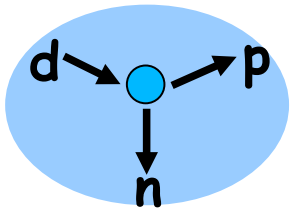
- Revised reaction rate from reverse mirror reaction by Hou+ (2015)
- Direct measurement up to 10 keV by Barbagallo+ at n_TOF (2016)
  - Measured only α decays after γ-ray emission from ^{8}Be excited states
  - S-wave only → 1/v law
- Time-reversal reaction measurement down to 200 keV by Kawabata+ at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

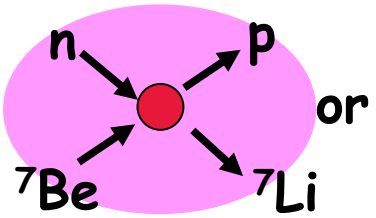
^{7}Be(n,p)^{7}Li, ^{7}Be(n,α)^{4}He via ^{2}H(^{7}Be,^{7}Lip)^{1}H, ^{2}H(^{7}Be,αα)^{1}H

✓ PWIA works well when Quasi-free mechanism is dominant



Virtual Decay

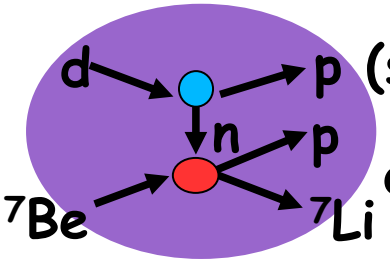
⊗



α or α

Virtual reaction

=



p (spectator)

α or α

3-body Reaction

(Kinematic Factor)·$|\Phi(P_s)|^2$ × $\frac{d\sigma^{HOES}}{d\Omega}$ ∝ $\frac{d^3\sigma}{d\Omega_p\, d\Omega_{7Li}\, dE_{cm}}$

Calculated by Monte Carlo simulation

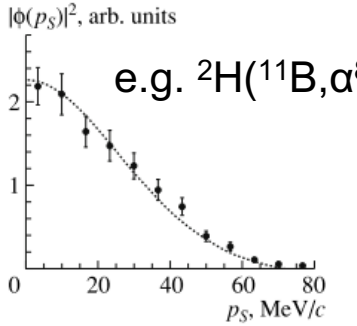
Half-off energy-shell 2-body cross section of interest

Measured at $E_{d\text{-}7Be}$ > Coulomb barrier

Need to confirm QF dominance

Normalization needed

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



e.g. ^{2}H(^{11}B,α^{8}Be)n

✓ Deuteron: low $E_{bind.}$, $L_{p\text{-}n} = 0 \Rightarrow p_{p\text{-}n}$ has maximum at 0

✓ Accessible to low energy releasing deuteron binding energy

✓ Useful also as virtual neutron target

Collaboration with BELICOS project

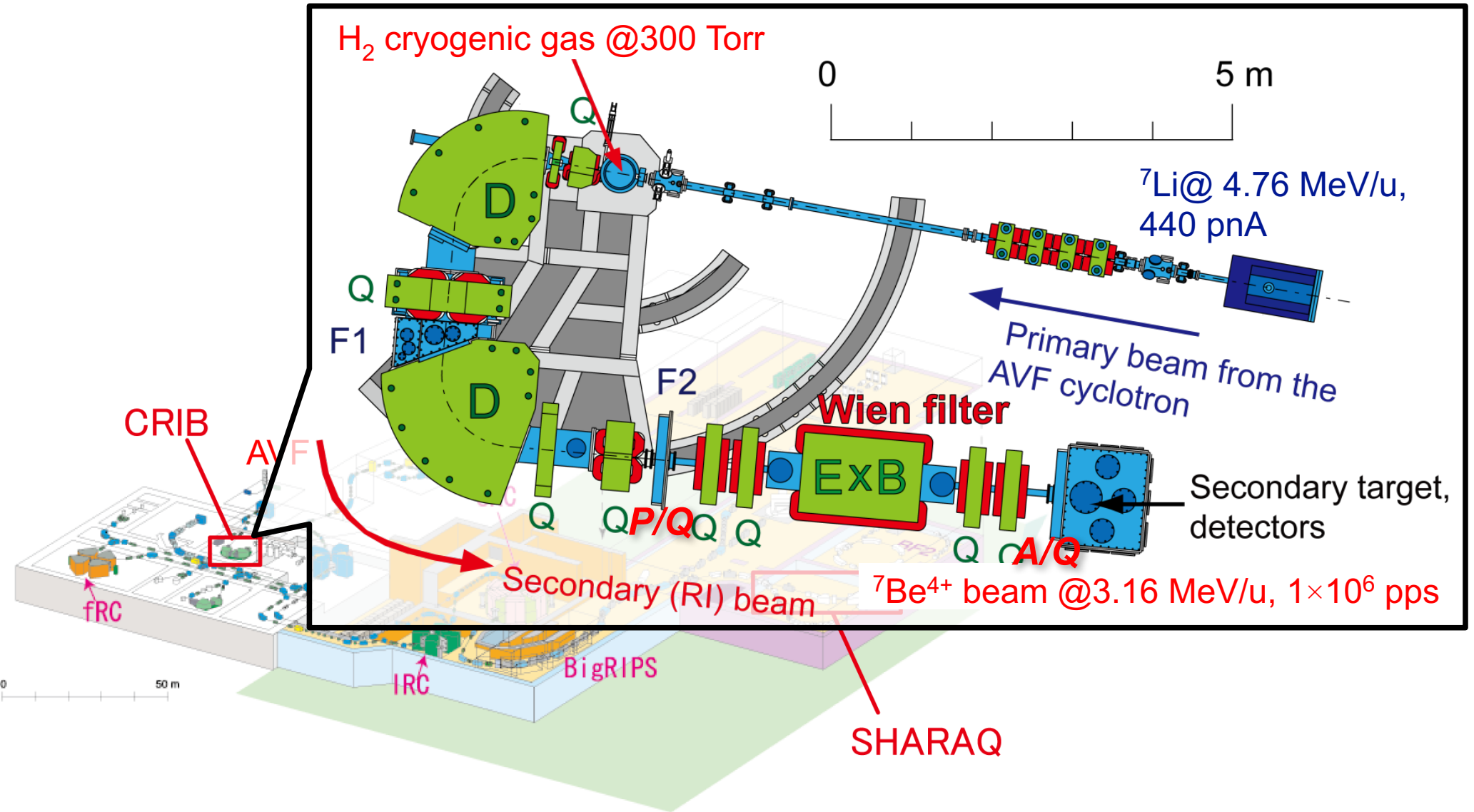
- BELICOS project: Beryllium and Lithium in the Cosmos
  - ^{7}Be+d THM experiment for ^{7}Be(n,α)^{4}He
    (L. Lamia, C. Spitaleri, Catania − M. Mazzocco, Padova)
  - Done at EXOTIC, INFN-LNL

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

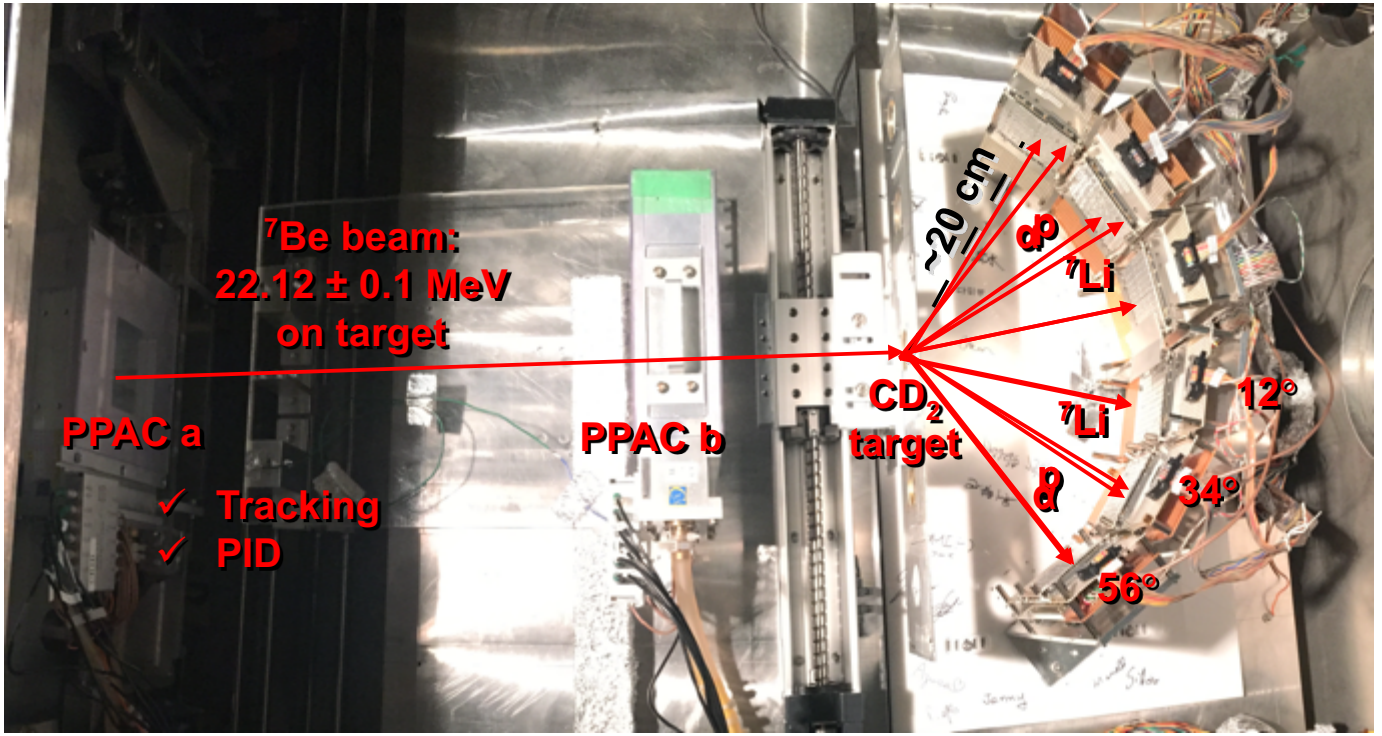
- Consistent results
  - Talk in Nuclear Physics in Astrophysics IIX, last week

^{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.

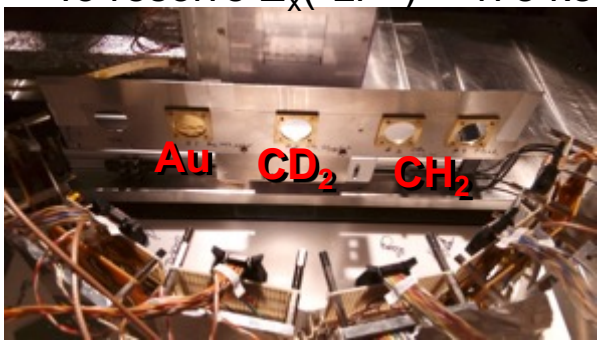


Experimental setup

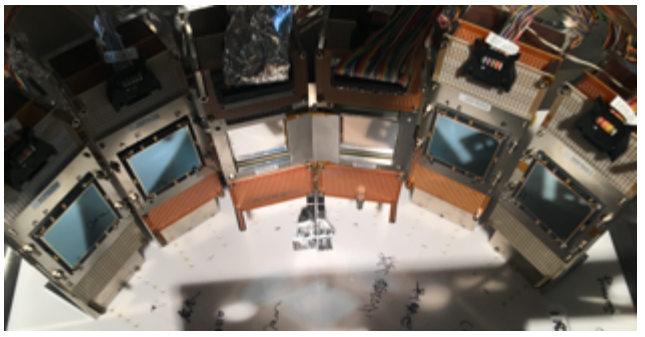


6 ΔE-E position sensitive silicon telescopes

CD_2: 64 μg/cm^2
→ ΔE_{beam} ~ 150 keV
→ To resolve $E_x(^7Li^{1st})$ = 478 keV

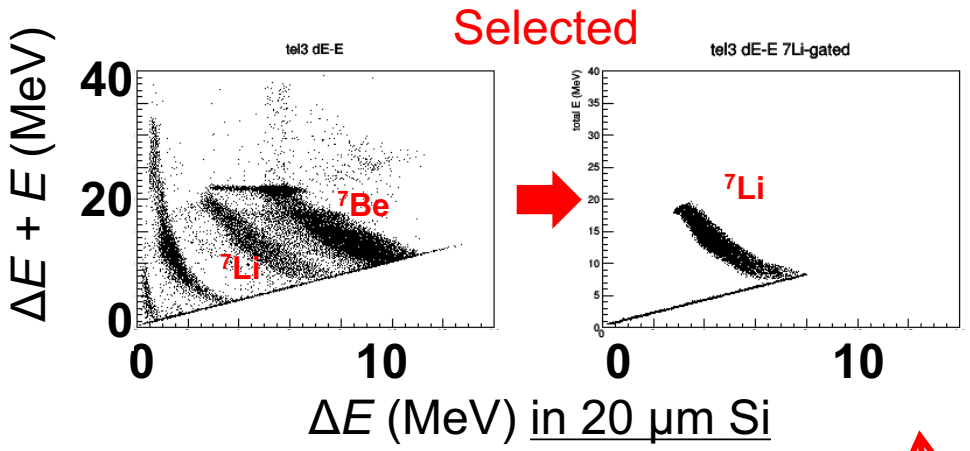


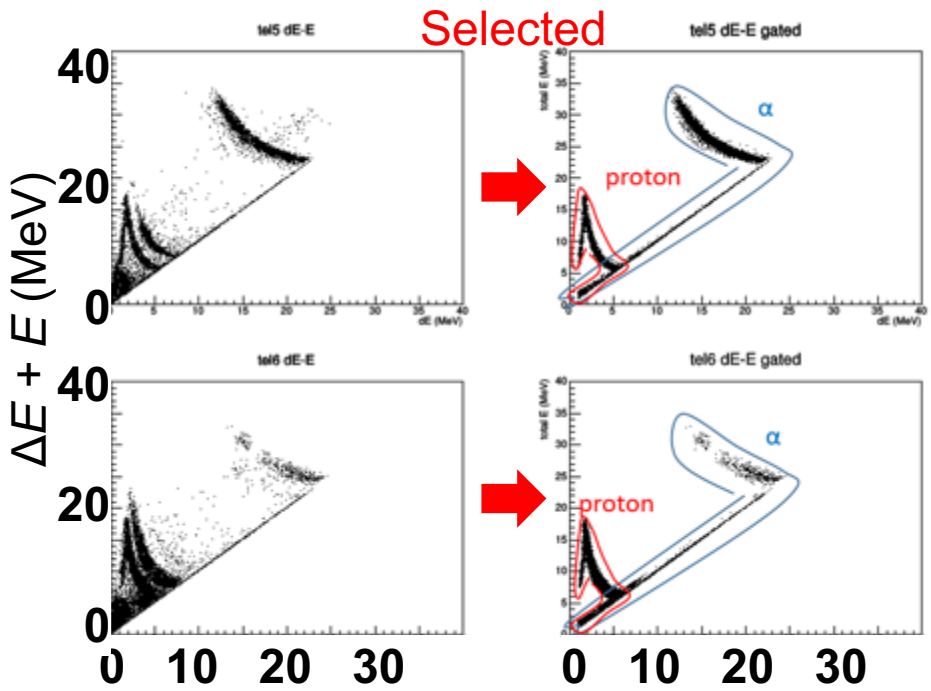
Hamamatsu Charge-division PSD: position resolution ~ 0.5 mm

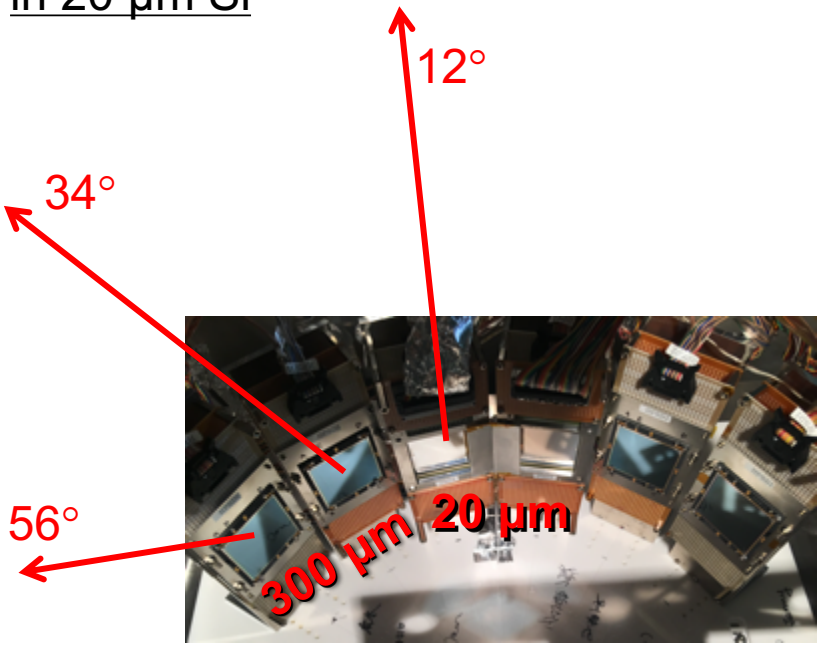


→ Total angular resolution (PPACs & PSDs & alignment) ~ 0.5° ⇒ ΔE_{cm} ~ 60 keV

Particle identification

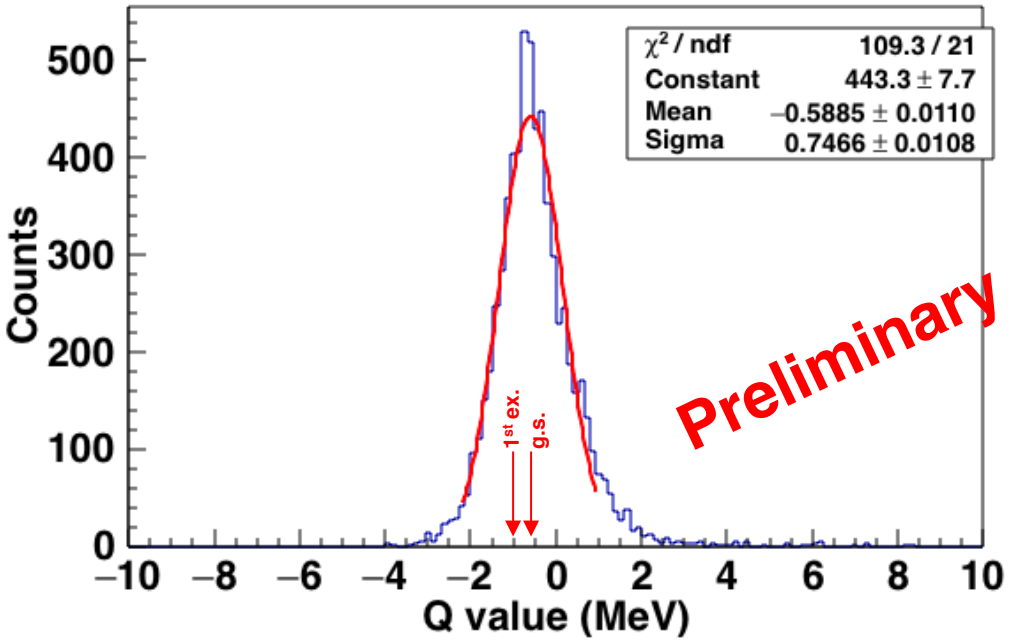




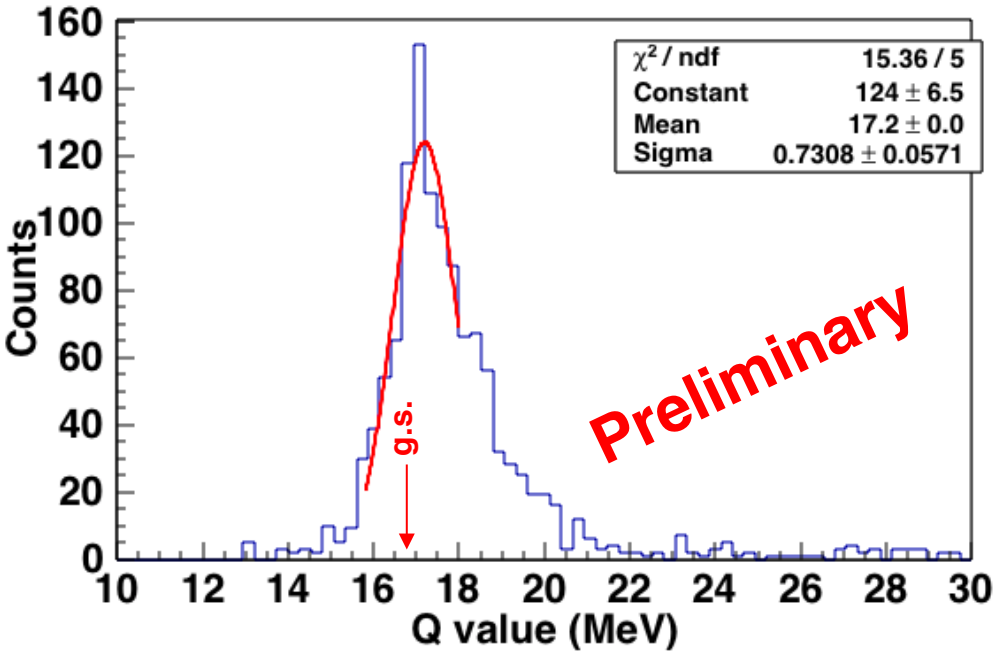


Q-value spectra of the 3-body channels

^{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

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

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

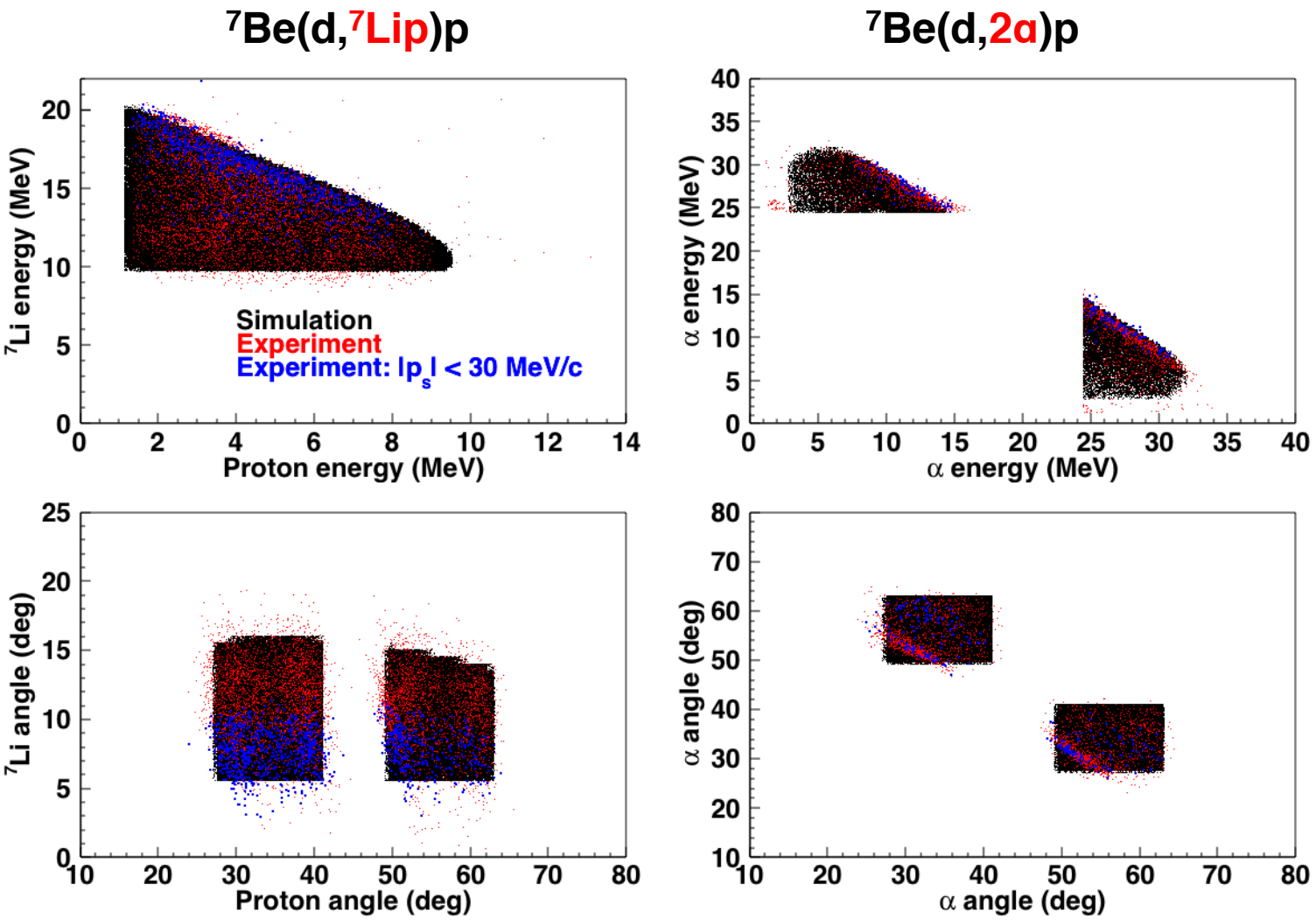
~ 200 keV expected with 64 μg/cm^2 CD_2

→ Gain variation correction needed

Kinematics check

E_{lab}-E_{lab} correlation

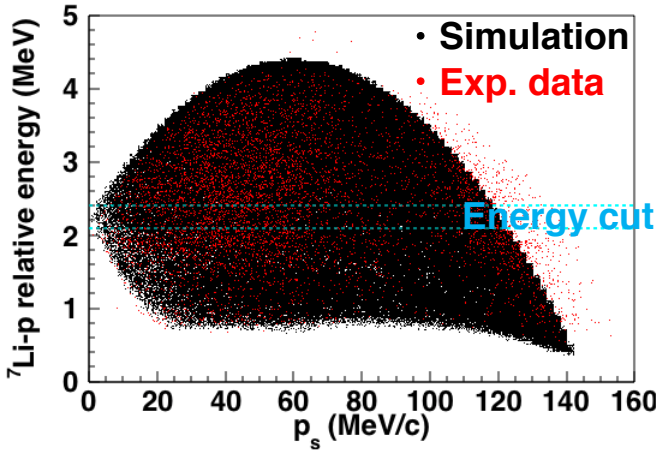
θ_{lab}-θ_{lab} correlation

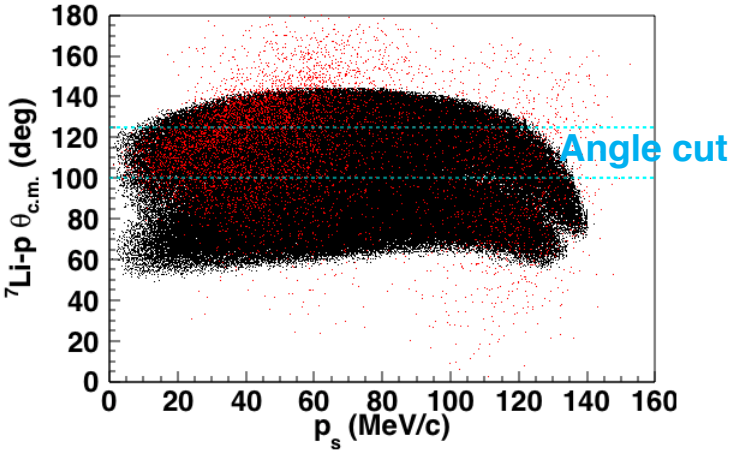


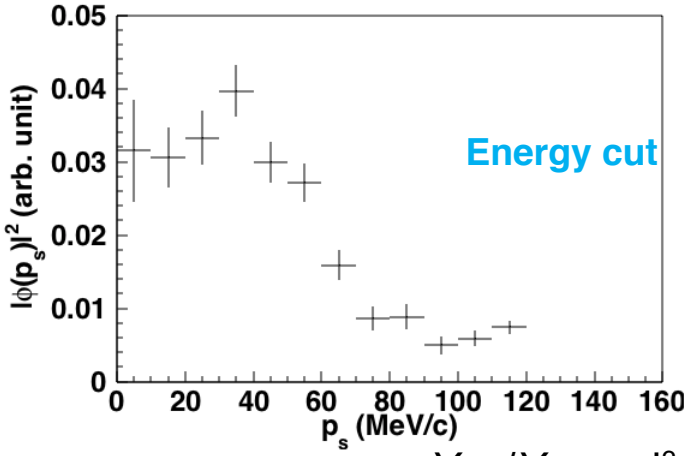
Monte Carlo simulation and experimental data are in a good agreement.
The simulation does not include uncertainties yet → The data is broader.

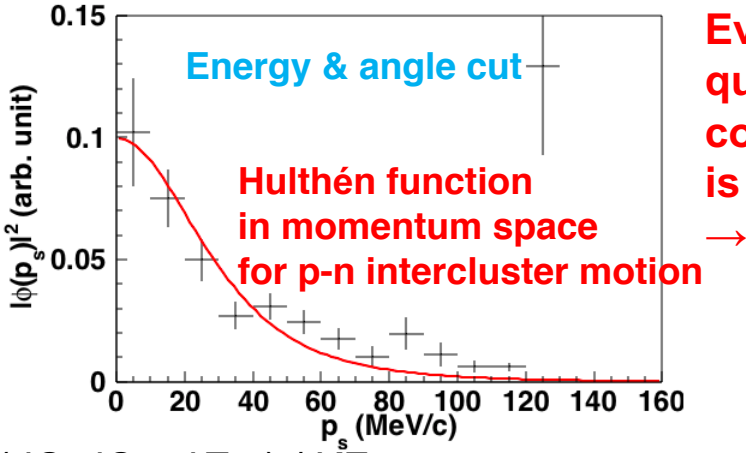
Energy, angle vs. spectator's momentum

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









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

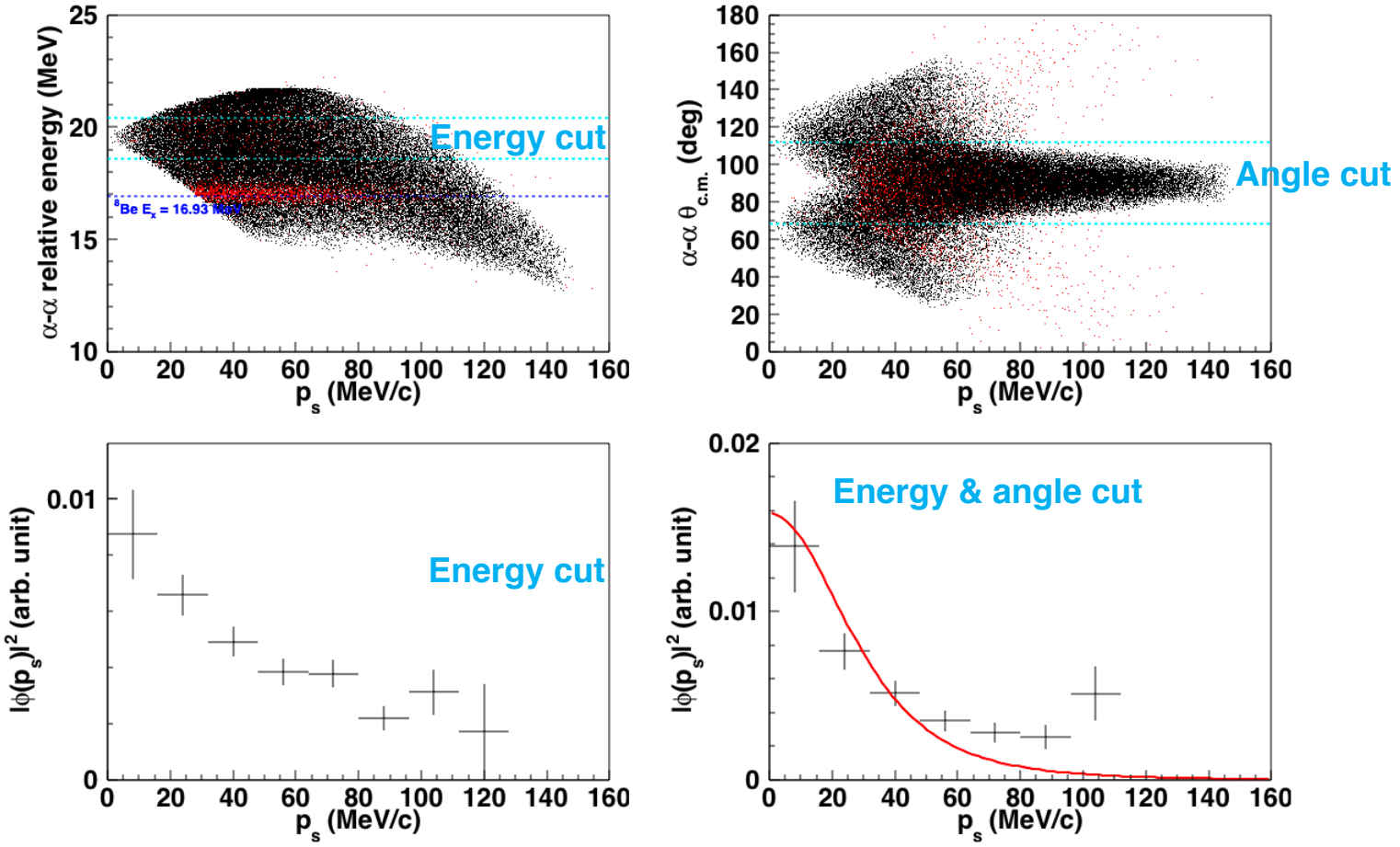
$$Y_{exp}/Y_{sim} = d^3\sigma/(d\Omega_p d\Omega_{7Li} dE_{cm}) \,/\, KF$$

$$\propto |\Phi(p_s)|^2$$

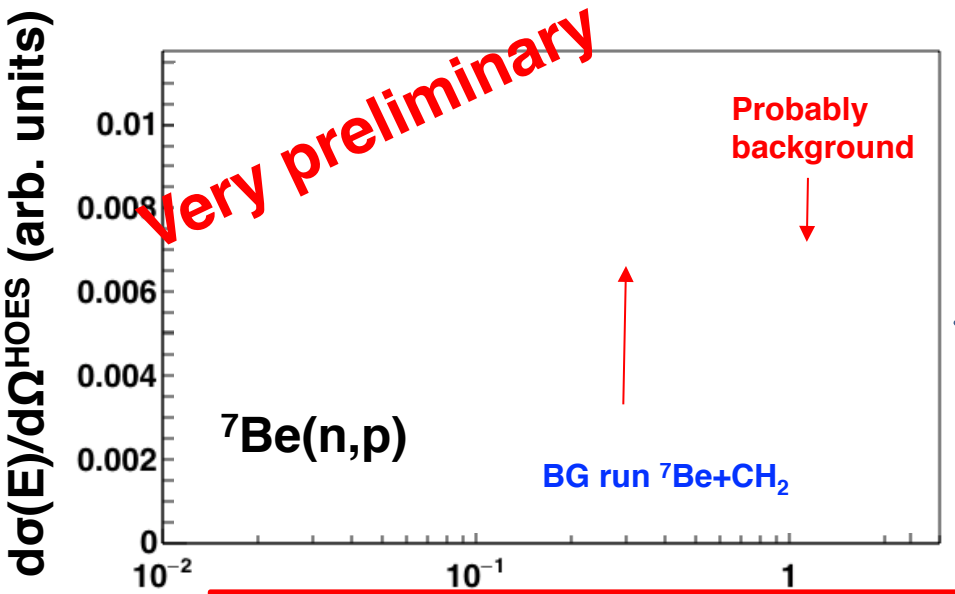
at a fixed $E_{c.m.}$ and $\theta_{c.m.}$ ($\Leftrightarrow$ 2-body cross section is const.)

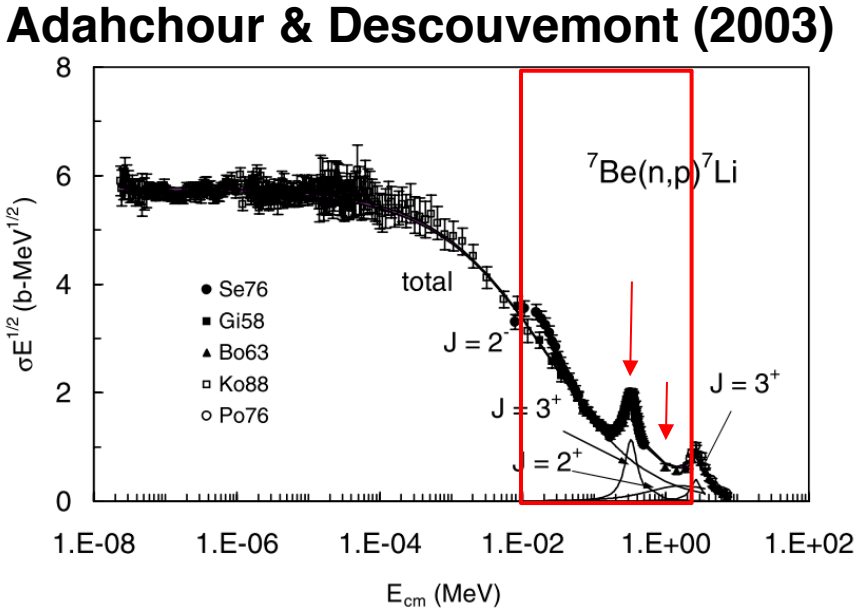
Energy, angle vs. spectator's momentum

^{7}Be(d,2α)p

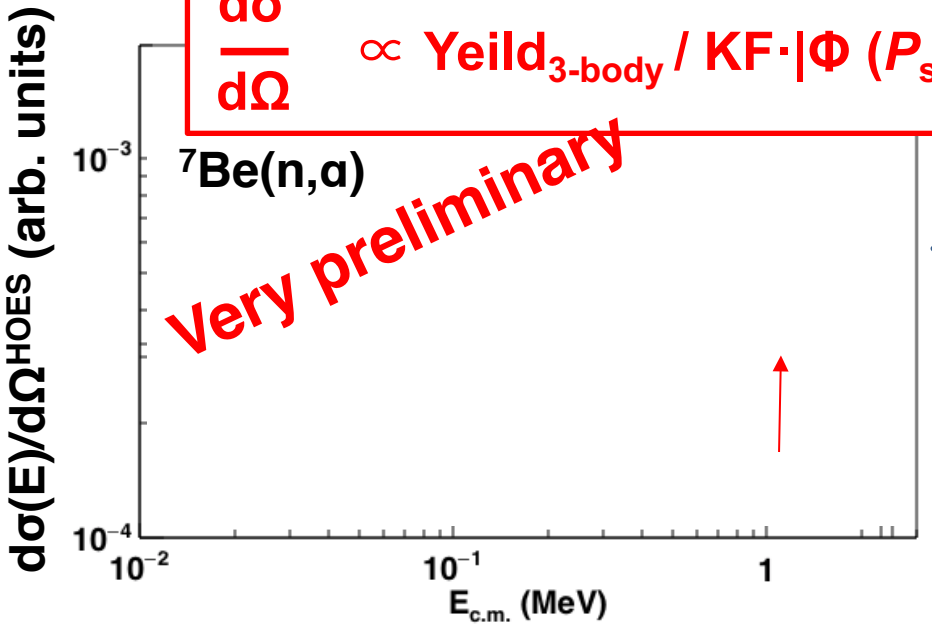


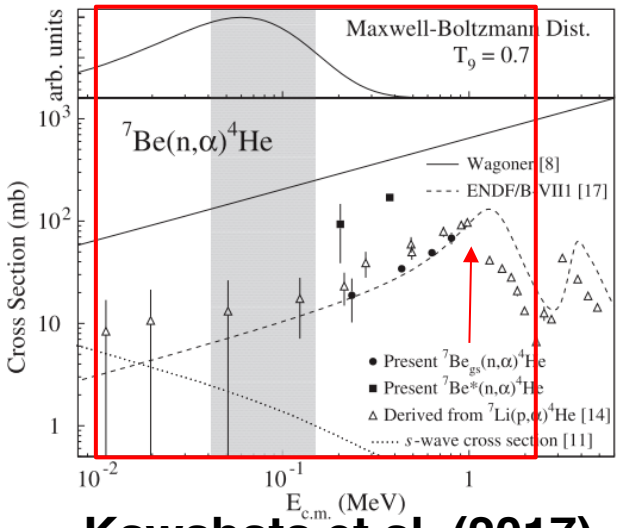
HOES cross sections for $|p_s| < 40$ MeV/c





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





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... not clear yet: Q-value resolution?
- Upper limit of p_1 contribution from p_0 spectrum?