



# Study of the 2-neutron decay of $^{13}\text{Li}$ and $^{11}\text{Li}$ via the invariant mass method @RIBF

Paul André

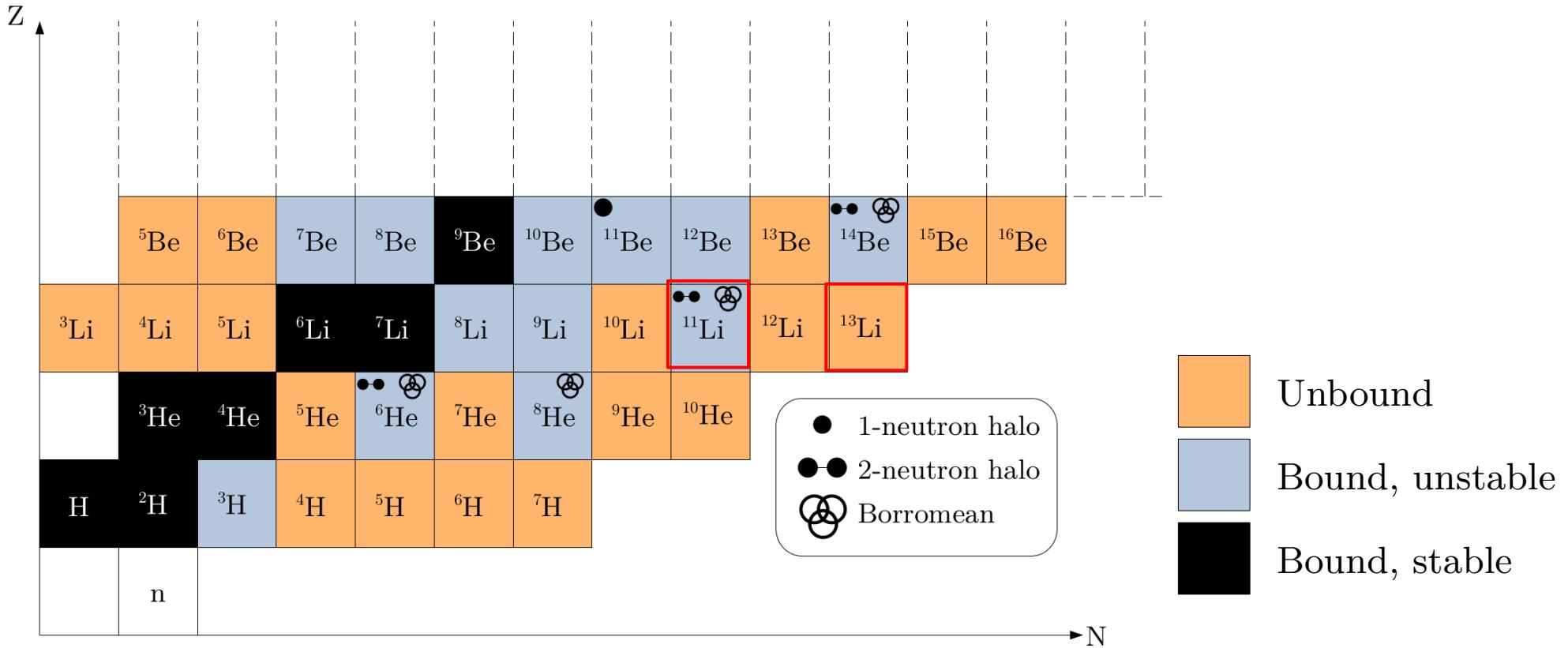
*IRFU, CEA, Université Paris-Saclay*

*Direct Reactions with Exotic Beams 2022*

*Santiago de Compostela*

*30/06/2022*

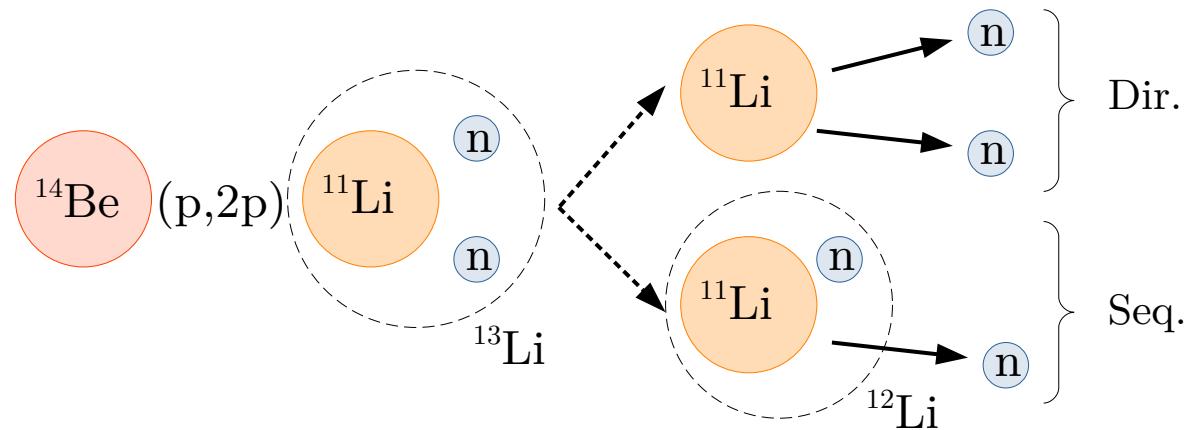
# Neutron-rich Li isotopes



- What are the limits of nuclear existence ?
- Emergence of exotic structures ? (Halo, dineutron)
- 2-neutron decay of  $^{13,11}\text{Li}$  : testing ground for n-n correlations



# How to study 2-neutron decay ?



- Direct decay : Simultaneous emission of neutrons with correlations
- Sequential decay : emission of one neutron after the other

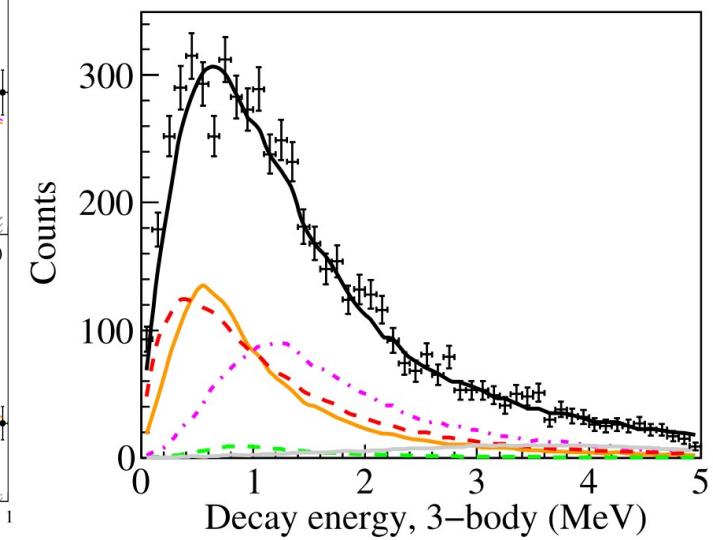
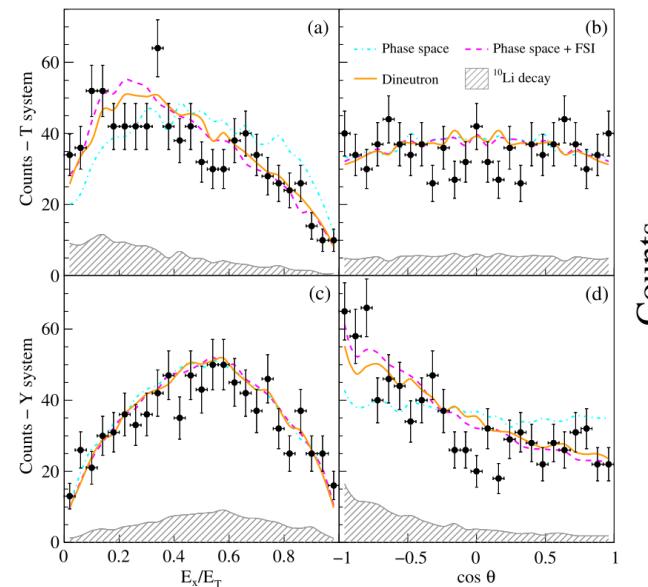
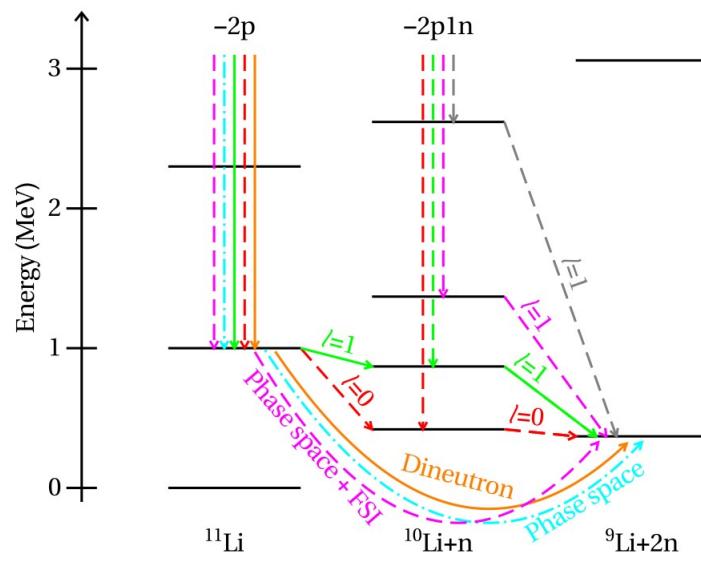
$$C_{nn} = \frac{d^2n/dp_{n_1}dp_{n_2}}{(dn/dp_{n_1})(dn/dp_{n_2})} \simeq \int W(\vec{r}, t, r_{nn}, \tau_{nn}) F(\vec{r}, q_{nn}, r_{nn}) dt d\vec{r} [1]$$

n-n distance

# State of the art for $^{11}\text{Li}$

Decay path as ansatz of the contributions in the fit

3B and 2B decay energy spectra & Jacobi coordinates

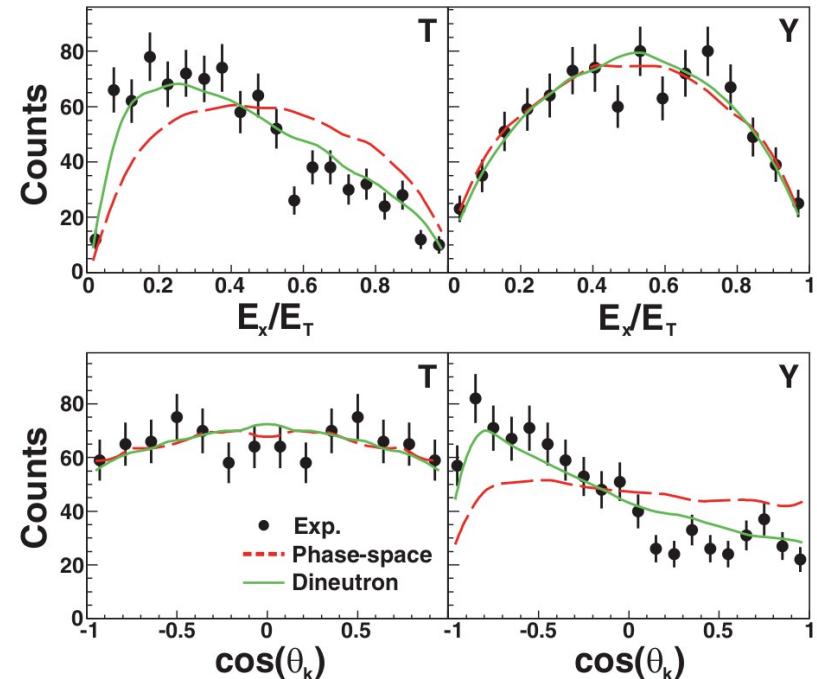
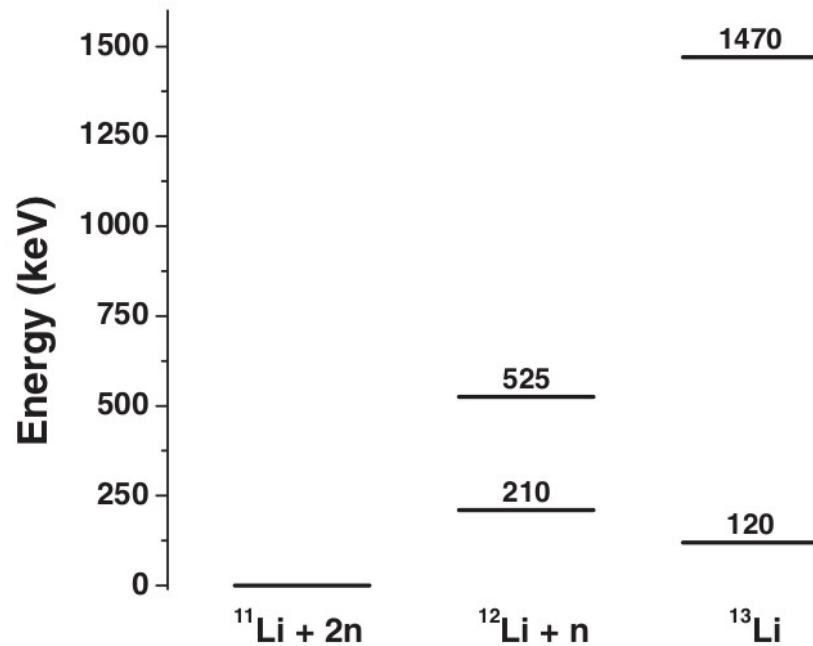


- Measurement of a  $\sim 810\text{keV}$  resonant state in  $^{11}\text{Li}$
- Best reproduction of Jacobi coordinates with direct decay



# State of the art for $^{13}\text{Li}$

3B and 2B decay energy spectra & Jacobi coordinates

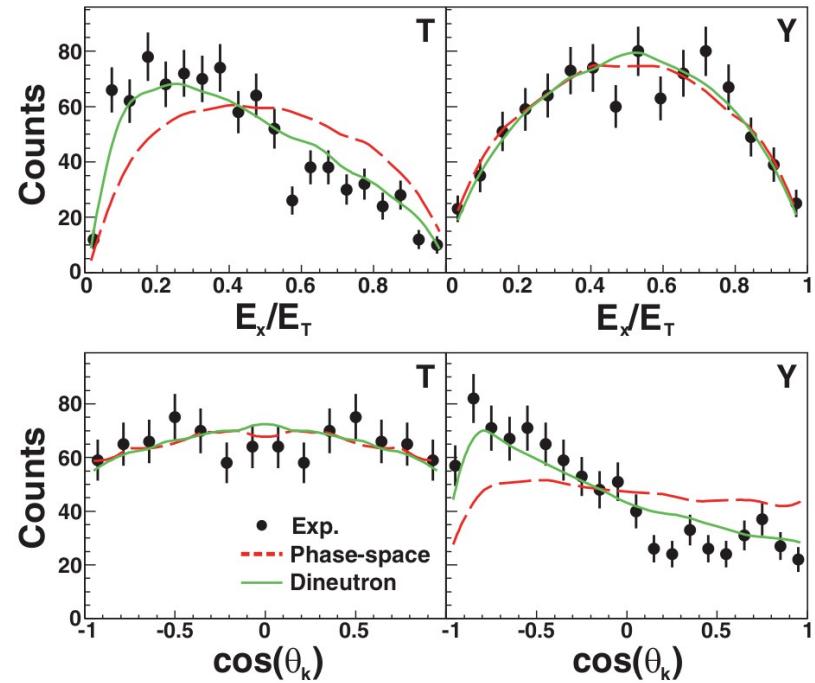
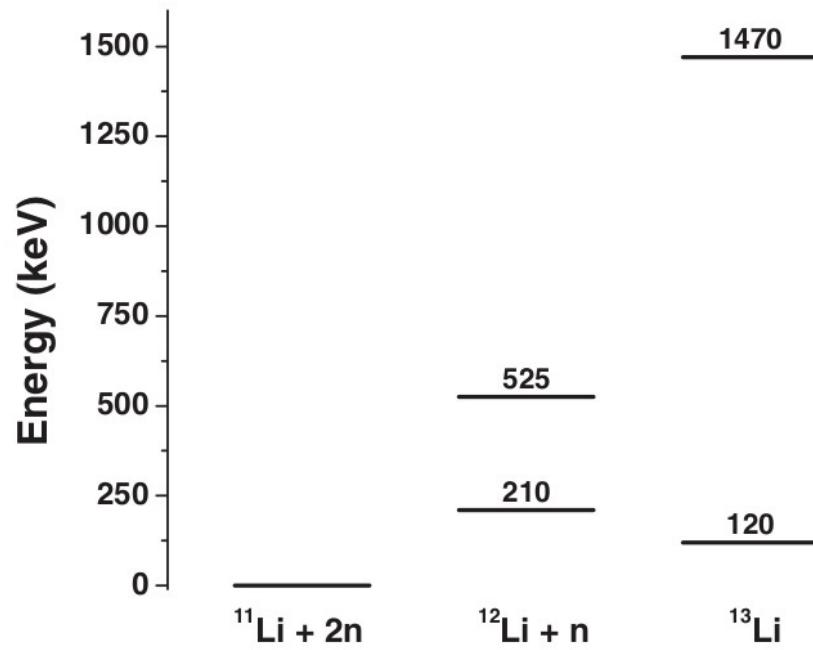


- First measurement of the ground state of  $^{13}\text{Li}$
- First observation of n-n correlations in  $^{13}\text{Li}$



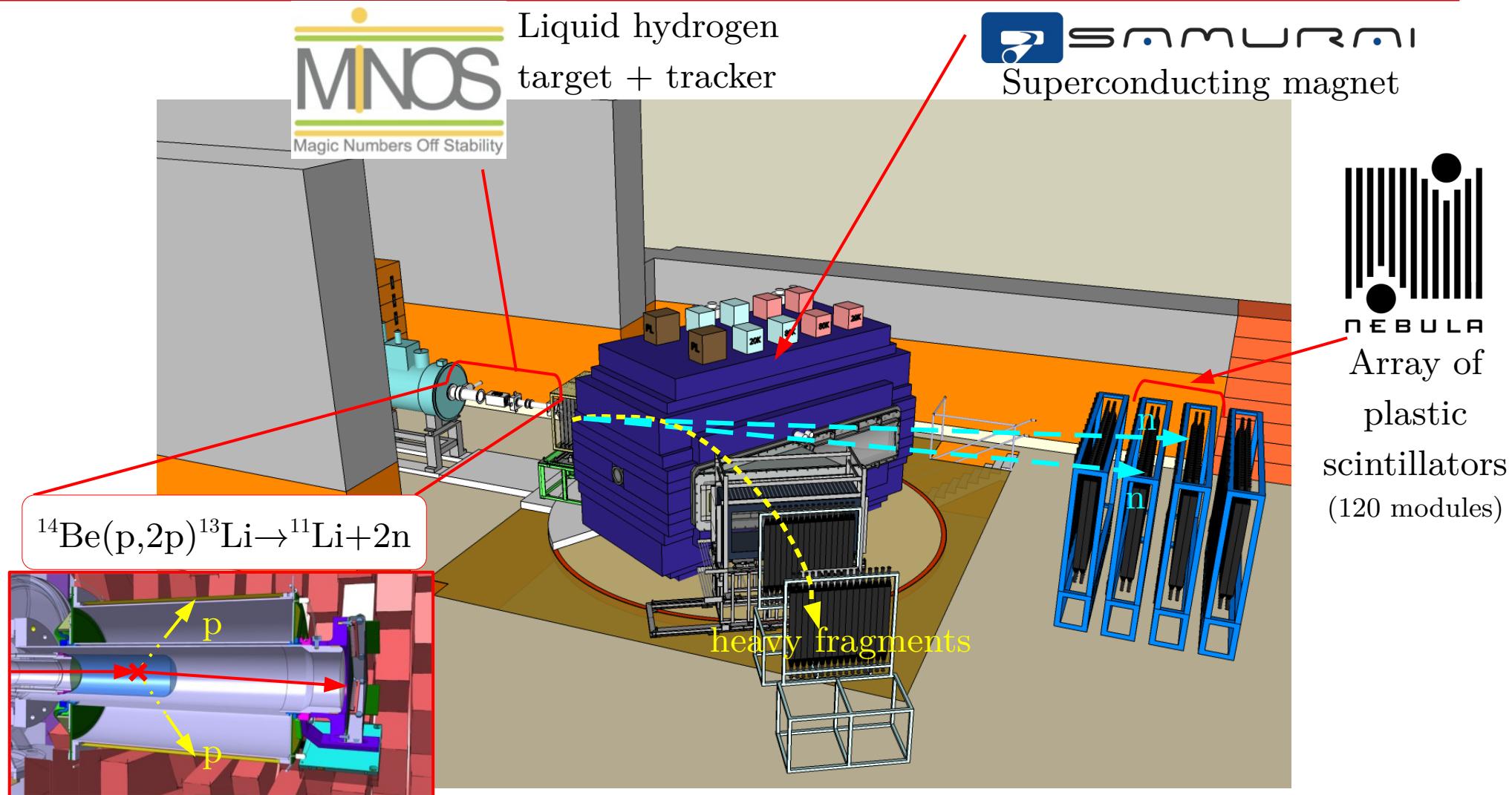
# State of the art for $^{13}\text{Li}$

3B and 2B decay energy spectra & Jacobi coordinates



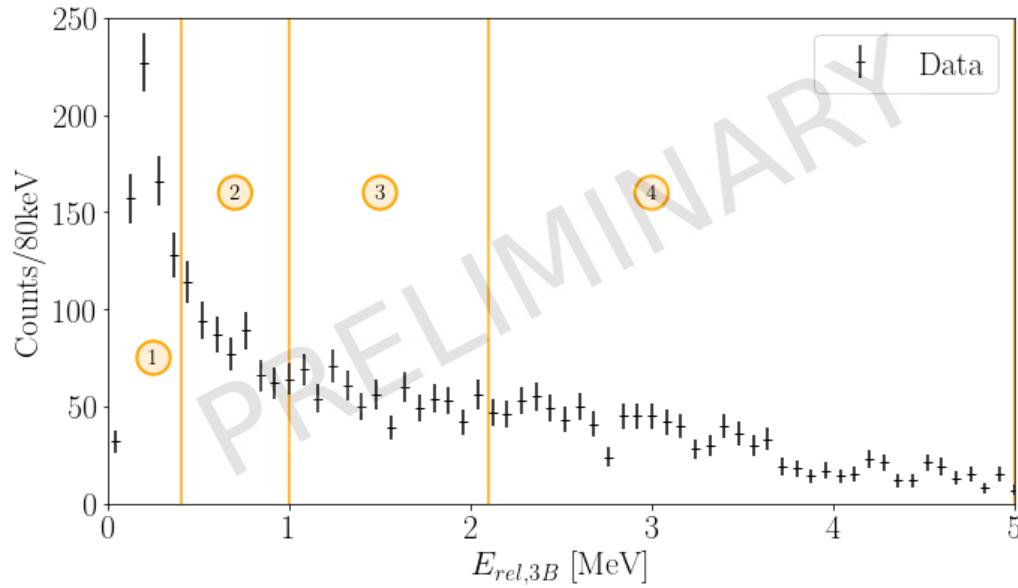
- First measurement of the ground state of  $^{13}\text{Li}$
- First observation of n-n correlations in  $^{13}\text{Li}$
- Improvement of resolution and statistics in this study

# Experimental setup

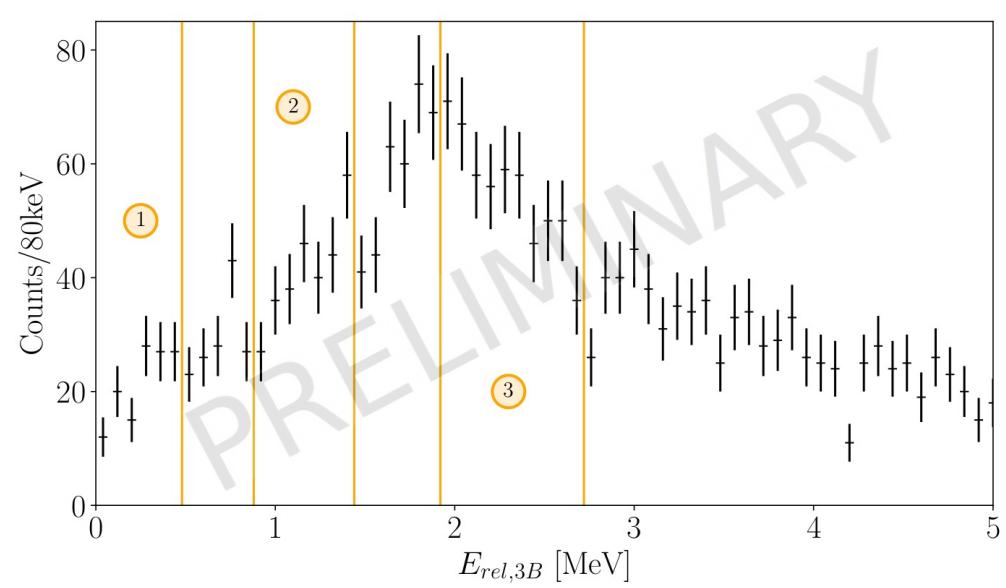


# The 3-body spectrum

For  $^{13}\text{Li}$  :



For  $^{11}\text{Li}$  :

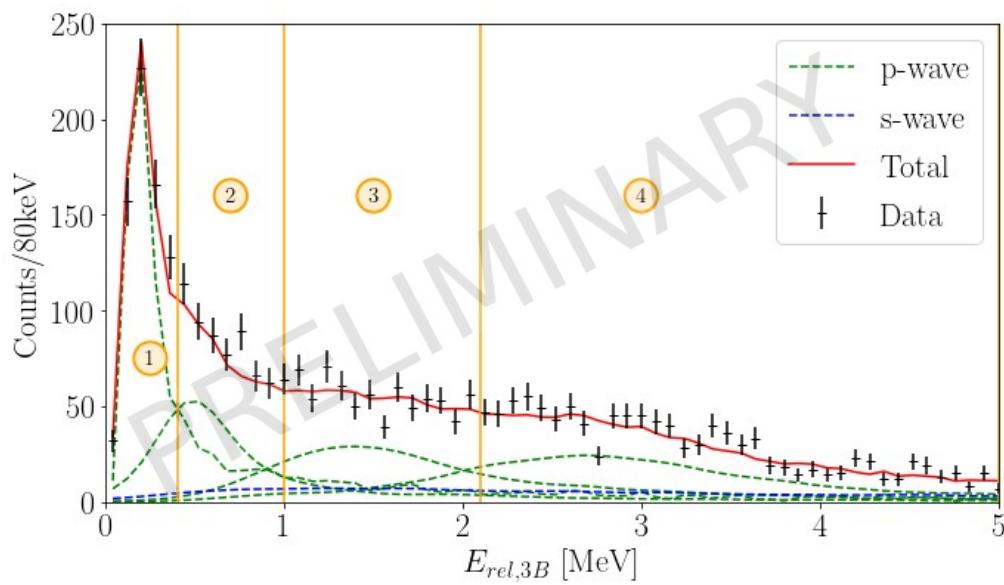


Gating on the 3B relative energy → Fitting the Jacobi coordinates for each gate  
 Constrain intermediate system with 2B relative energy spectrum



# The 3-body spectrum for $^{13}\text{Li}$

3B relative energy spectrum  
(different-wall events)



Tentative fit for  $^{13}\text{Li}$

$E_{res}$ [MeV]	$\Gamma_{res}$ [MeV]
0.16[1]	0.12
0.5	0.2
1.47[2]	1.70
2.8	1.5

$a_s$ [fm]
-4

p-wave :

s-wave :

[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

[2] Yu. Aksyutina *et al.*, Phys. Lett. B **666** (2008)

# Jacobi coordinates :

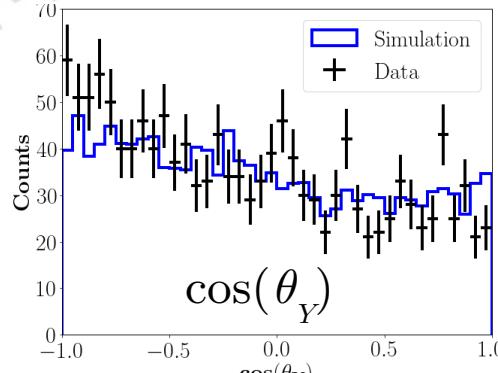
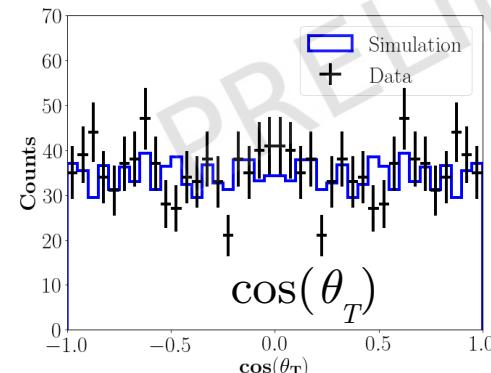
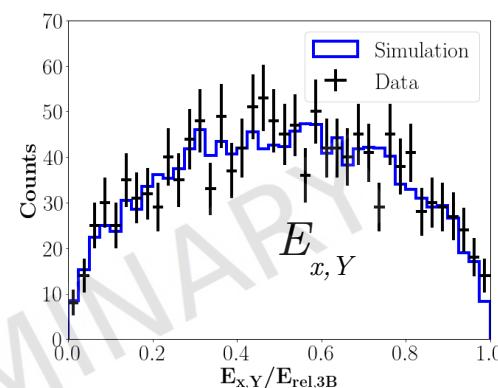
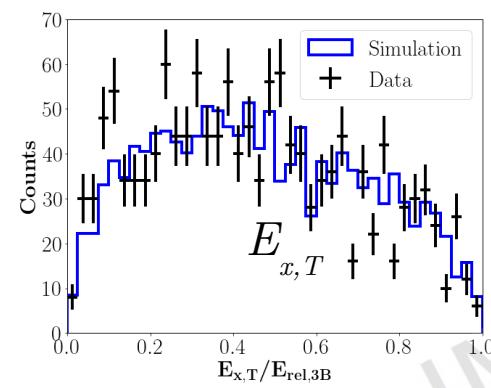
$$0 < E_{rel,3B} < 0.4 \text{ MeV}$$

$$0.4 < E_{rel,3B} < 1 \text{ MeV}$$

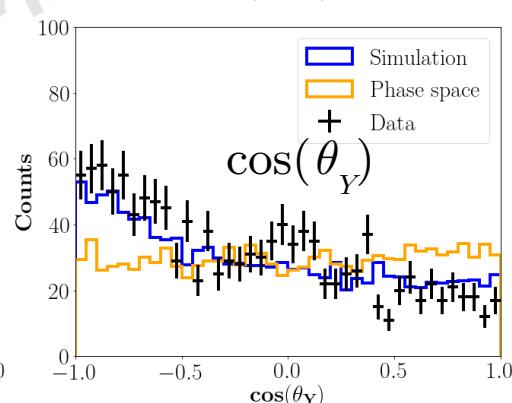
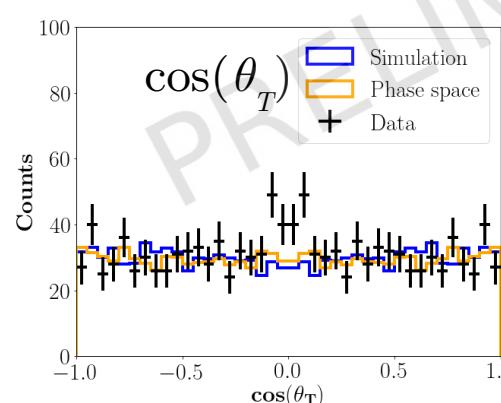
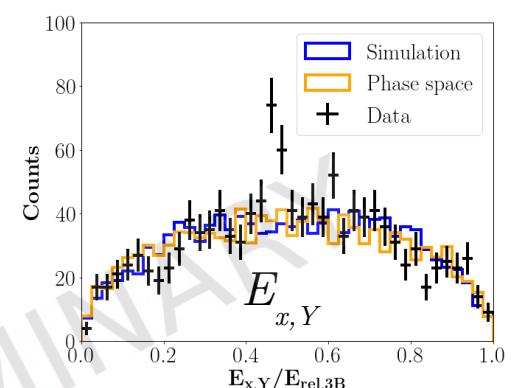
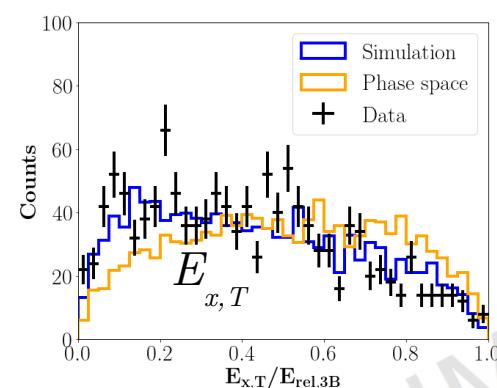


Data reproduced with direct decay only ( $r_{nn} = 5.2 \text{ fm}$ )

$$0 < E_{rel,3B} < 0.4 \text{ MeV}$$



$$0.4 \text{ MeV} < E_{rel,3B} < 1 \text{ MeV}$$



# Jacobi coordinates :

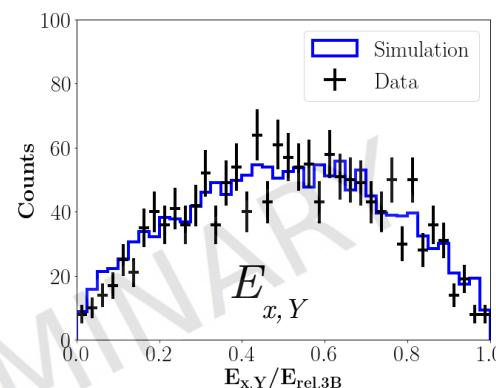
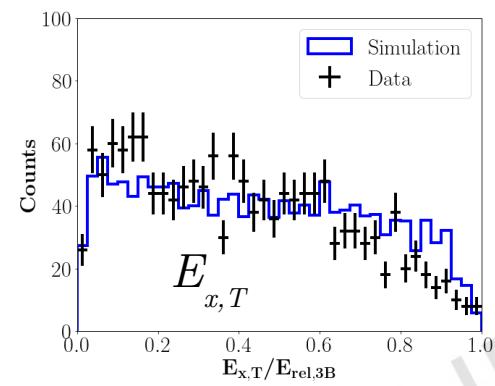
$1 < E_{rel,3B} < 2.1 \text{ MeV}$

$2.1 < E_{rel,3B} < 5 \text{ MeV}$

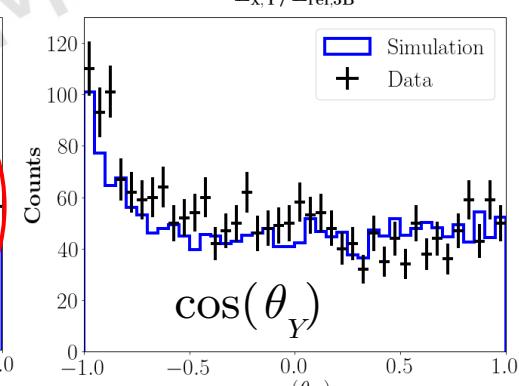
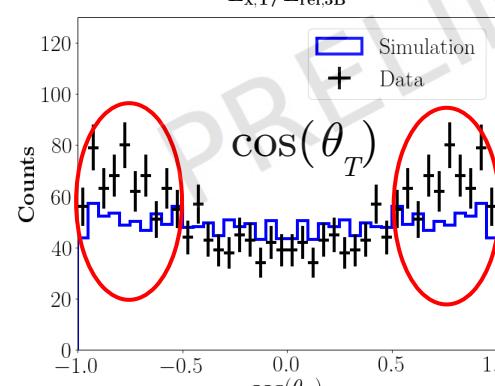
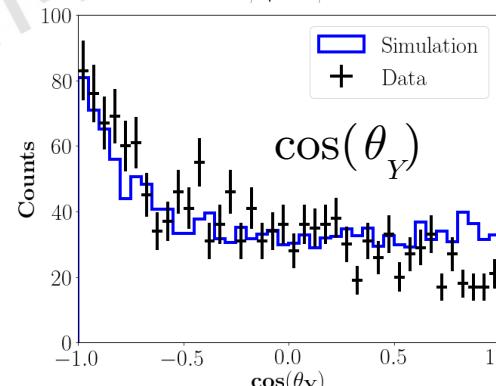
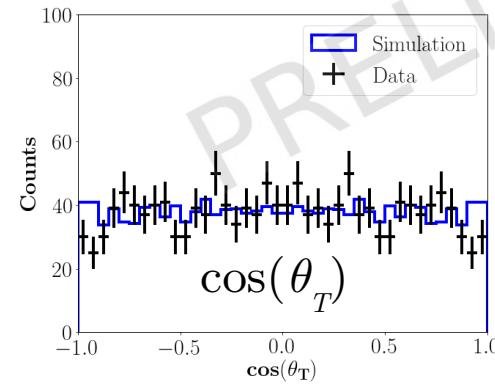
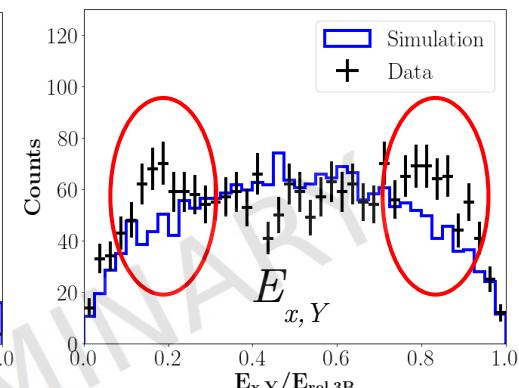
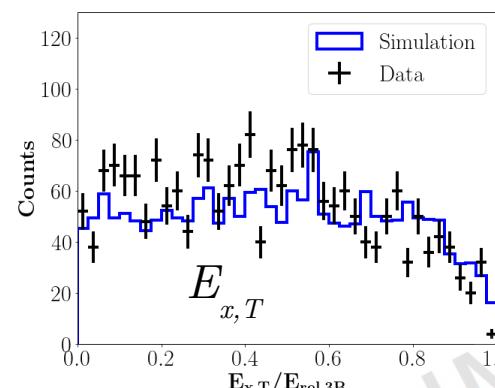


Data reproduced with direct decay only ( $r_{nn} = 5.2 \text{ fm}$ )

$1 < E_{rel,3B} < 2.1 \text{ MeV}$



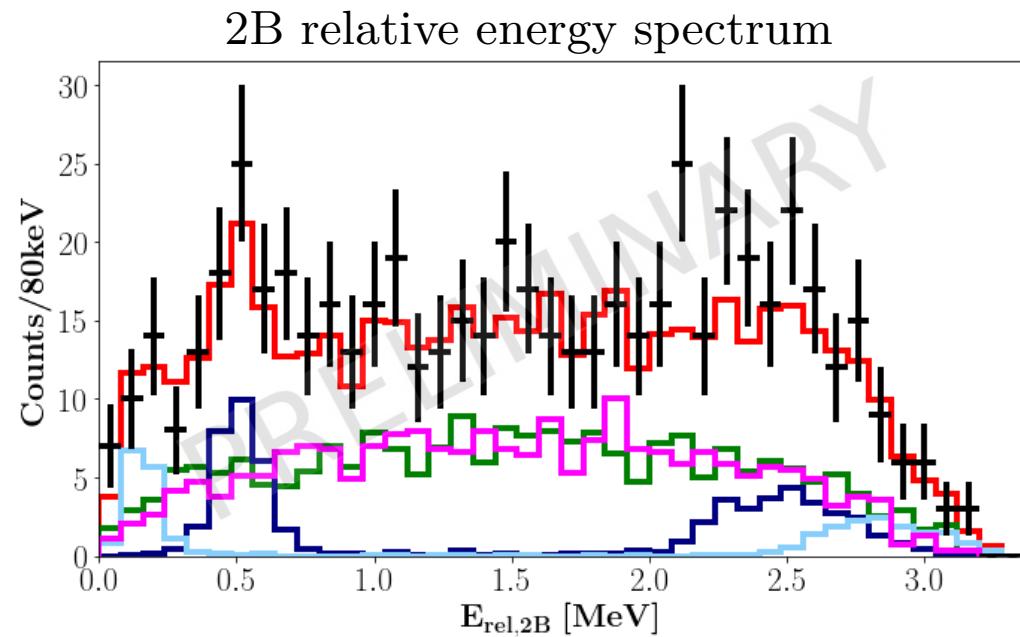
$2.1 \text{ MeV} < E_{rel,3B} < 5 \text{ MeV}$



# Adding sequential contribution

Data reproduced with direct and sequential contributions ( $r_{nn} = 5.2$  fm)

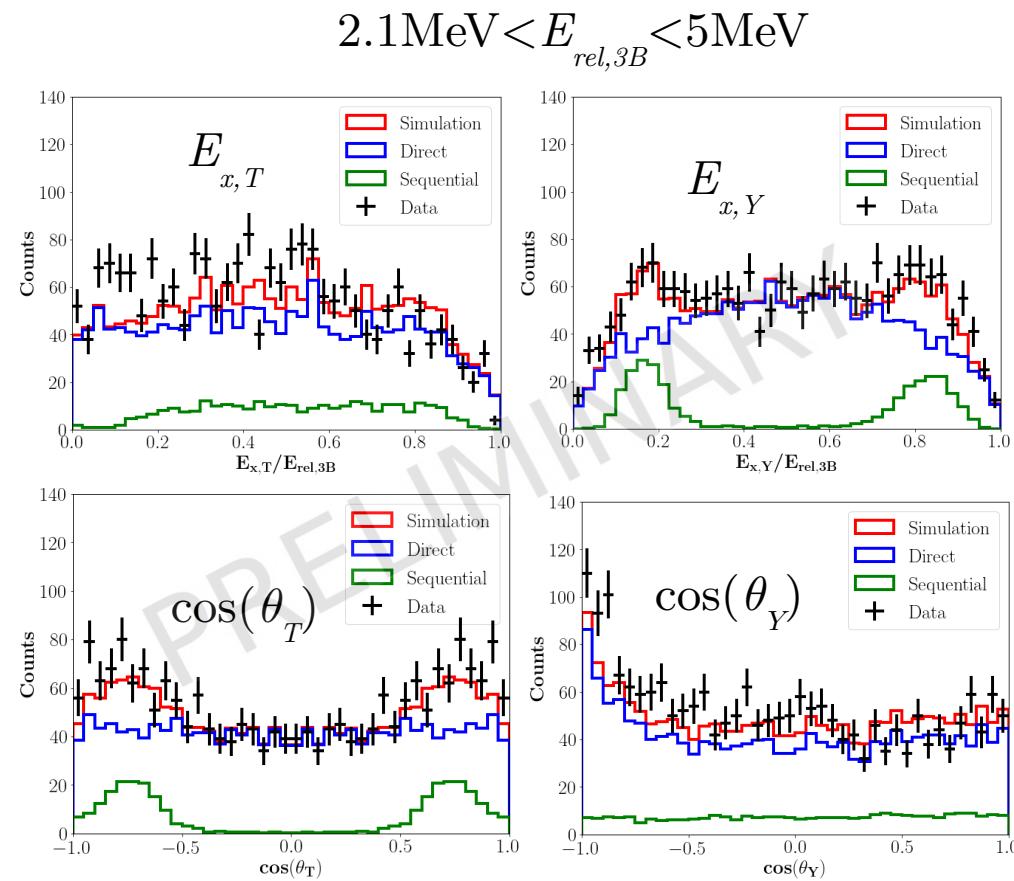
Fit proportions of each decay process (constrained by 3B spectrum integral)



2 resonances in  $^{12}\text{Li}$

Direct decay of high energy resonance in  $^{13}\text{Li}$

Direct decay of other states in  $^{13}\text{Li}$

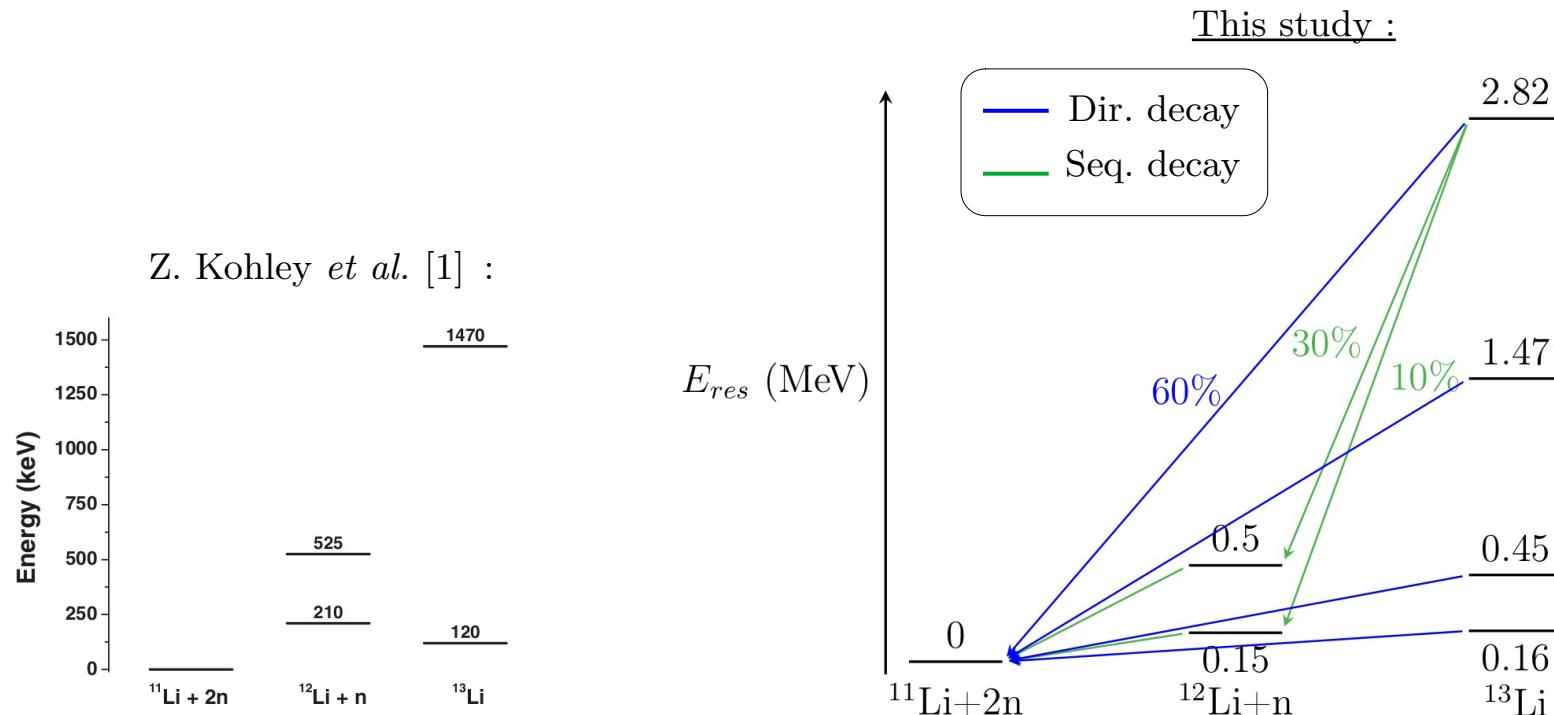


[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

[2] C.C. Hall *et al.*, Phys. Rev. C **81** (2010)



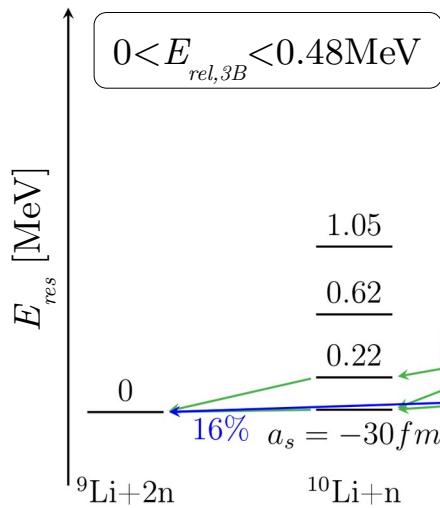
# Summary for $^{13}\text{Li}$



- First observation of sequential decay at high relative energy
- Lack of sensitivity on n-n correlation parameter  $r_{nn}$

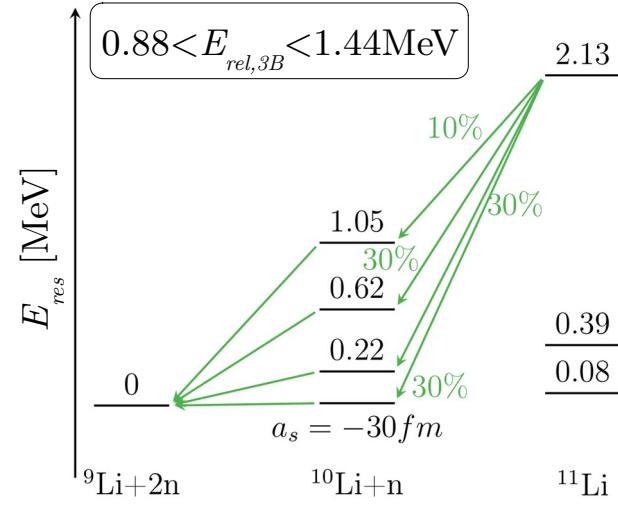


# Summary for $^{11}\text{Li}$



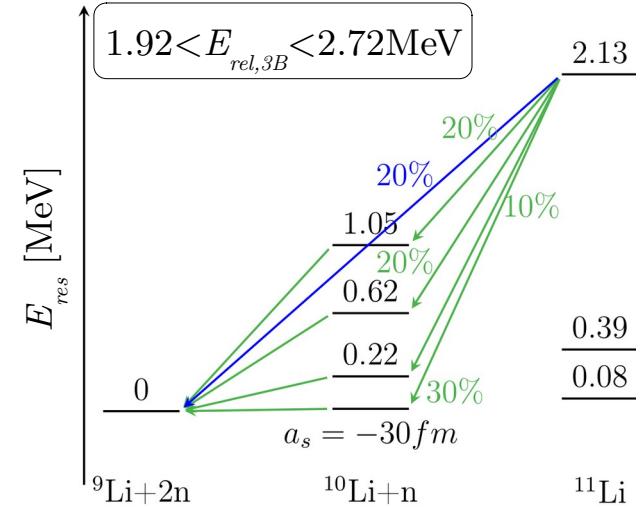
$$r_{nn} = 2 \text{ fm}$$

2.13



$$r_{nn} = 1.5 \text{ fm}$$

2.13



$$r_{nn} = 3 \text{ fm}$$

- Observation of sequential decay with 2B spectrum built with events from the 2n decay
- Small  $r_{nn}$ , strong correlations

( $r_{nn} = 1.67(16)$  fm for  $^{18}\text{C}$ , and  $r_{nn} = 1.75(24)$  fm for  $^{20}\text{O}$  [1])



# Outlook

- Analysis of the core excitation for  $^{13,11}\text{Li}$
- Ab initio calculations for the mass and structure of  $^{11}\text{Li}$  and  $^{13}\text{Li}$  (K. Fossez):
  - Already done for excited states until  $^{10}\text{Li}$ , masses until  $^{11}\text{Li}$  [1]
  - Yields energies and spin assignment of ground state and excited states
  - Computationally expensive calculations
- Comparison with reaction theory (J. Casal, M. Gómez-Ramos [2]) :
  - Comparing Jacobi coordinates and reduced relative energies
  - Compare results for direct, sequential decay and structure of the isotopes

[1] X. Mao *et al.*, Phys. Rev. C **102** (2020)

[2] J. Casal, M. Gómez-Ramos, Phys. Rev. C **104** (2021)



# Thank you for your attention !

Supervision :



Anna Corsi



Aldric Revel

Acknowledgements :

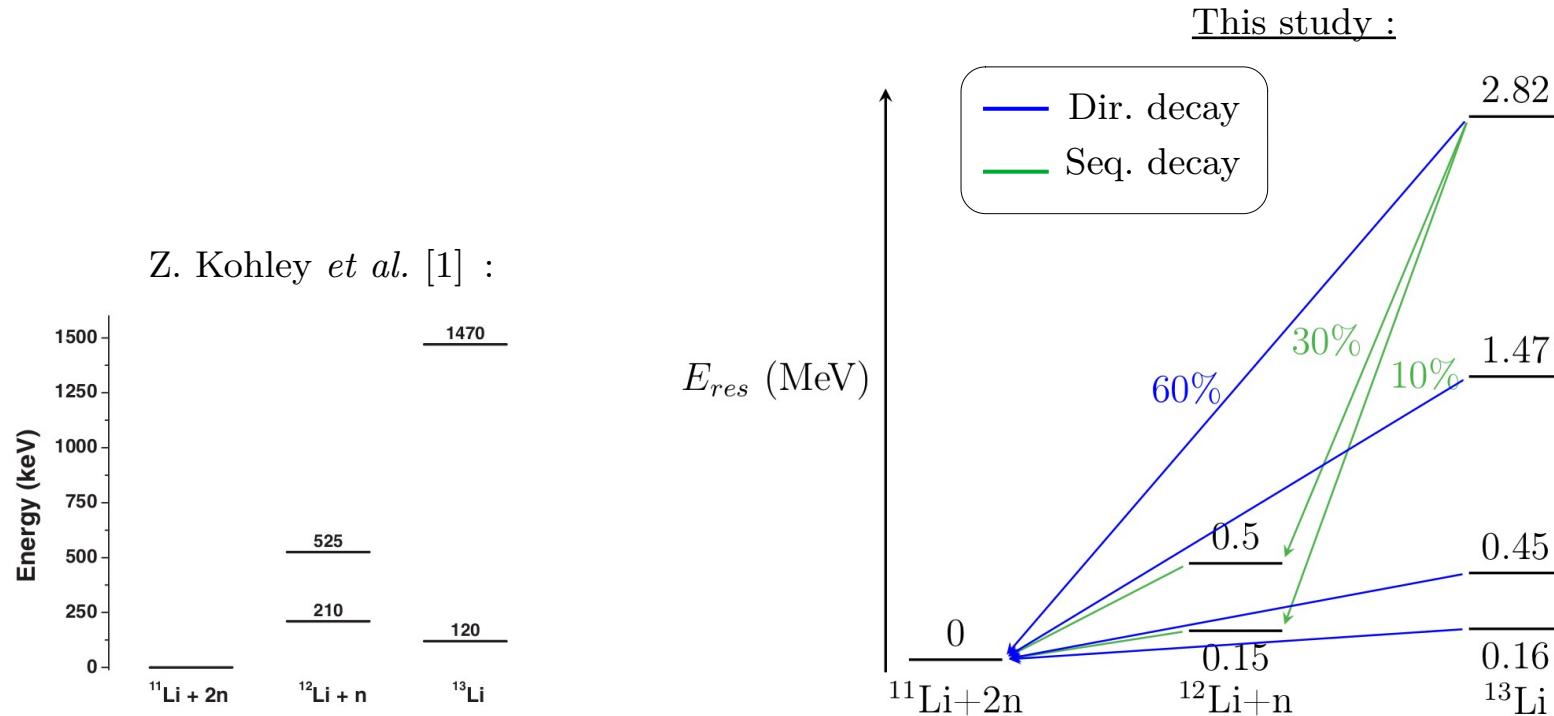


SAMURAI Collaboration



MINOS Collaboration

# Summary for $^{13}\text{Li}$



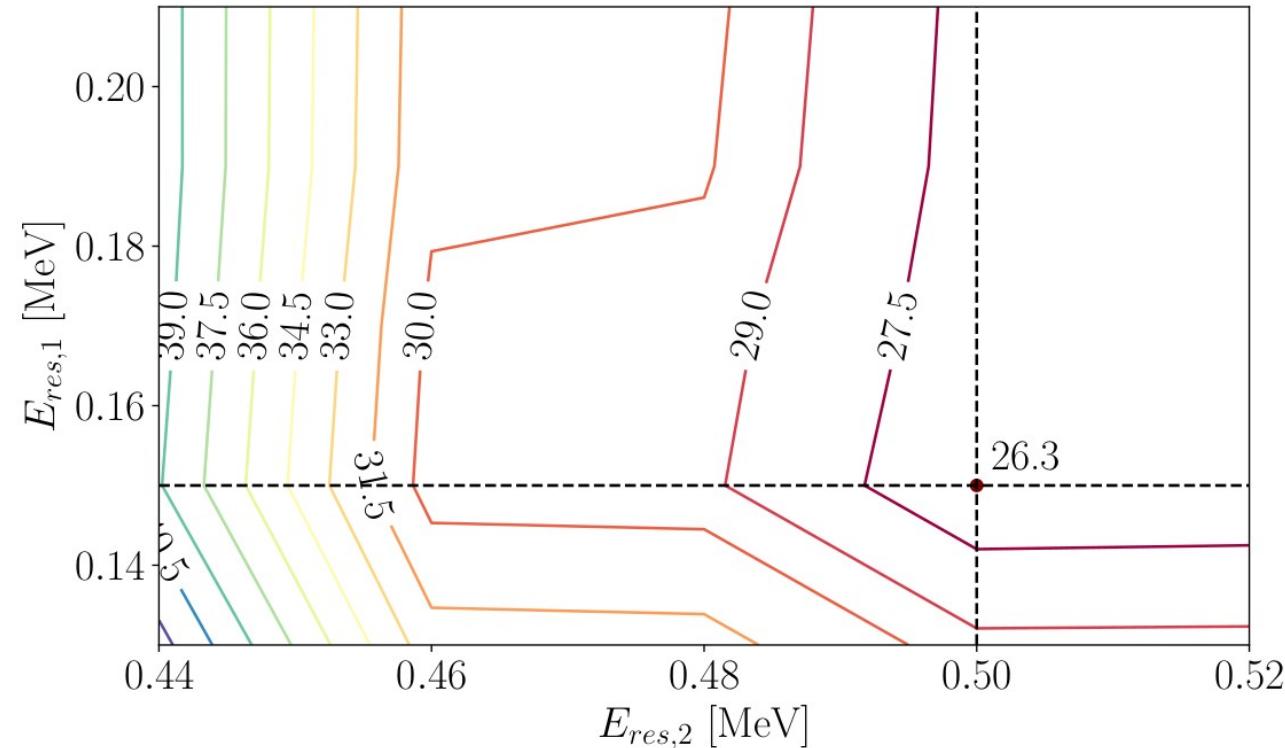
- First observation of sequential decay at high relative energy
- Lack of sensitivity on n-n correlation parameter  $r_{nn}$

# Back Up

# Constraint of the resonances in $^{12}\text{Li}$

$\chi^2$  surface with  $E_{res,1}$  and  $E_{res,2}$  as free parameters

$\Gamma_{res,1}$  and  $\Gamma_{res,2}$  fitted for a given resonance energy



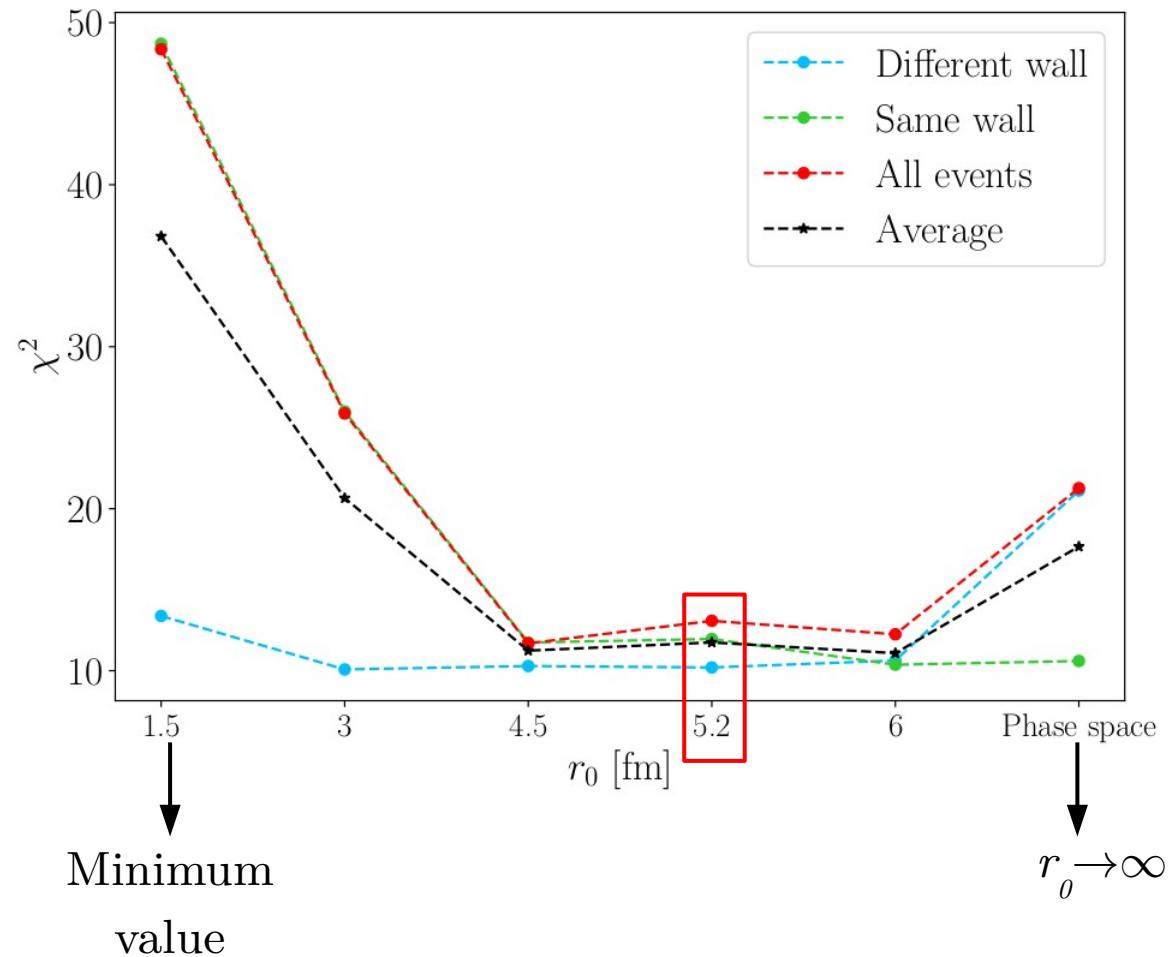
[1] Z. Kohley *et al.*, Phys. Rev. C **87** (2013)

[2] C.C. Hall *et al.*, Phys. Rev. C **81** (2010)



# Constraint of $r_0$ in $^{13}\text{Li}$

$\chi^2$  plot for fits on Jacobi coordinates with  $r_0$  as free parameters

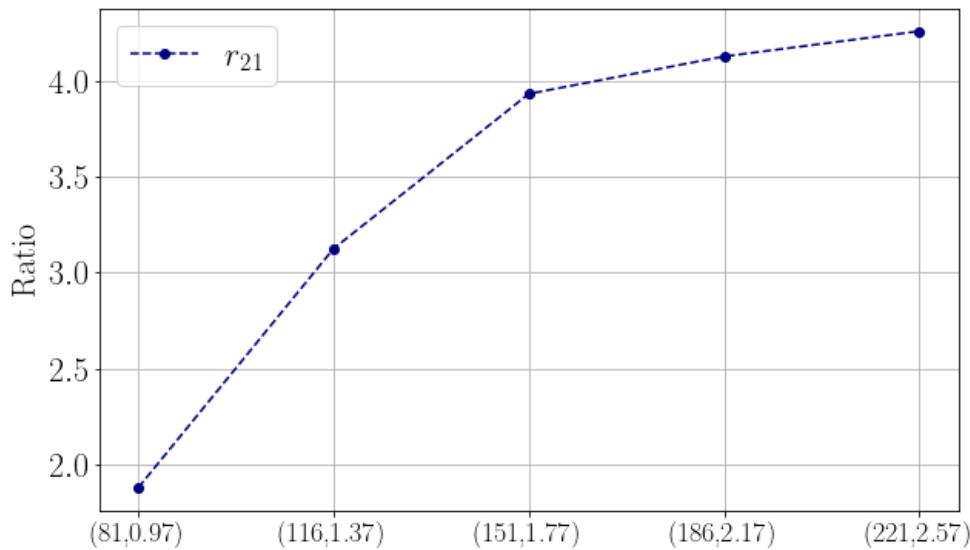


# Performances of cross-talk cuts

$$r = \frac{N(M > 1, \text{After CT rejection})}{N(M > 1, \text{Before CT rejection})}$$

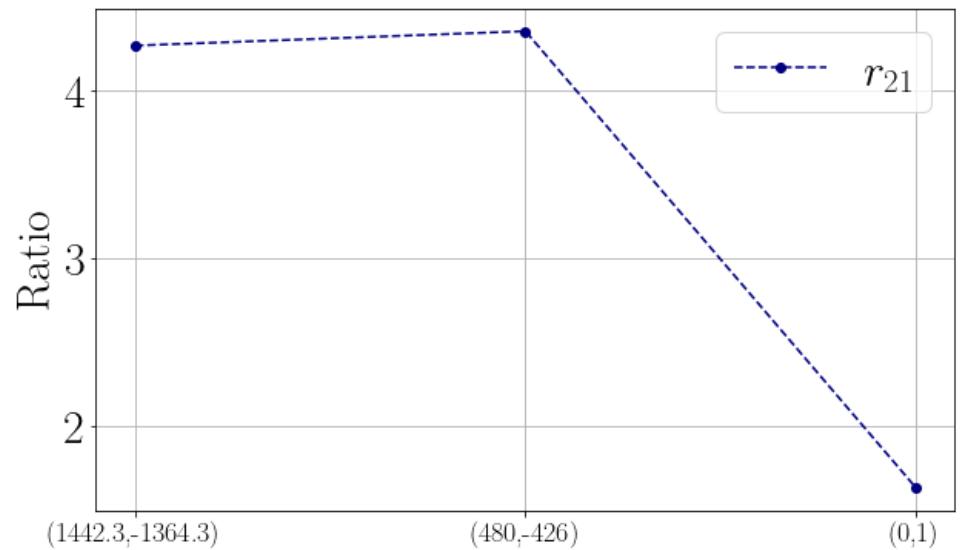
$r_1$  on 1n decay channel :  $^{11}\text{Li}(\text{p},\text{pn})^{10}\text{Li} \rightarrow ^9\text{Li} + \text{n}$   
 $r_2$  on 2n decay channel :  $^{14}\text{Be}(\text{p},2\text{p})^{13}\text{Li} \rightarrow ^{11}\text{Li} + 2\text{n}$   
 $\rightarrow r_{21} = r_2 / r_1$

Same-wall cut



$x$ -axis : semi-axis of ellipse

Different-wall cut



$x$ -axis : parameters for the straight line

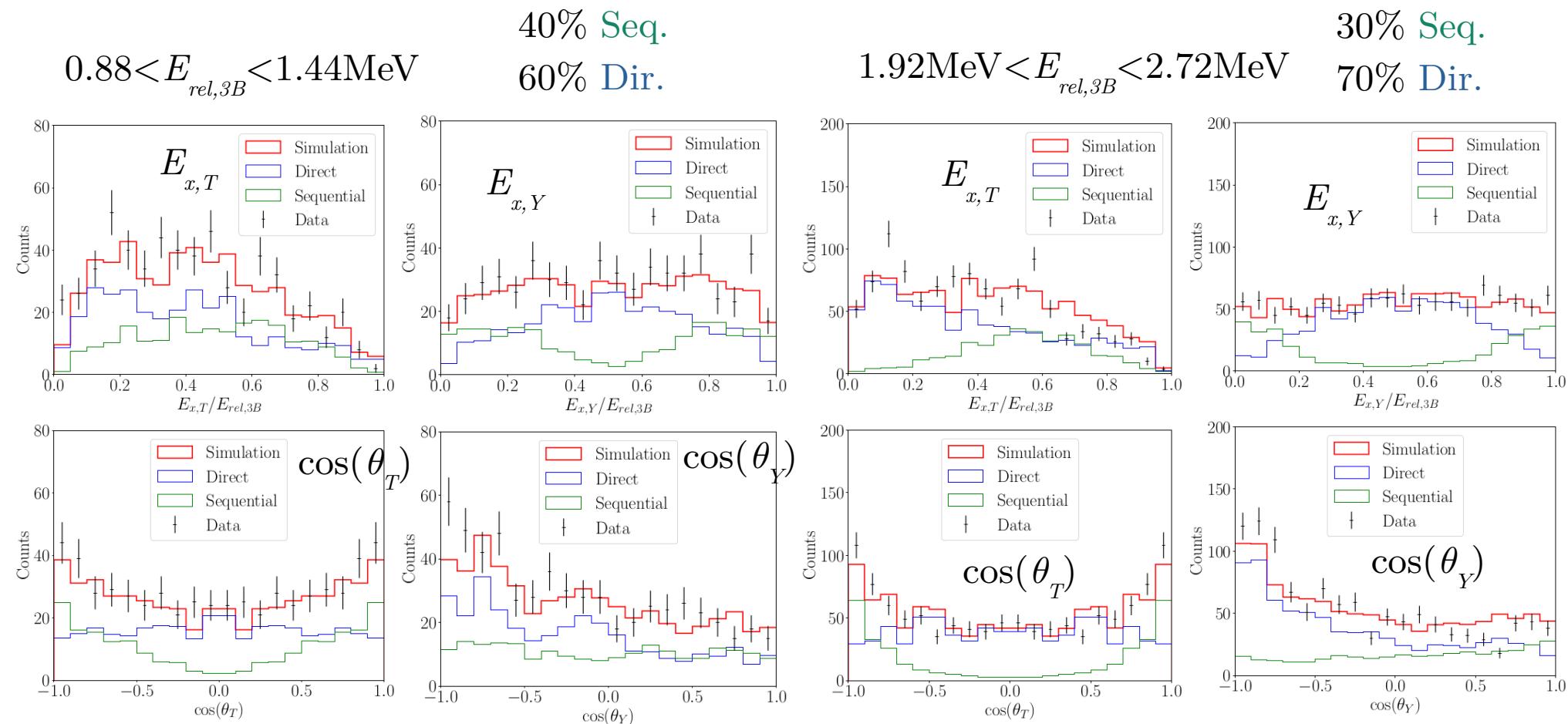
Survival rate for 1n channel : 2.32% ; Survival rate for 2n channel : 10.1%

$0.88 < E_{rel,3B} < 1.44 \text{ MeV}$

$1.92 < E_{rel,3B} < 2.72 \text{ MeV}$



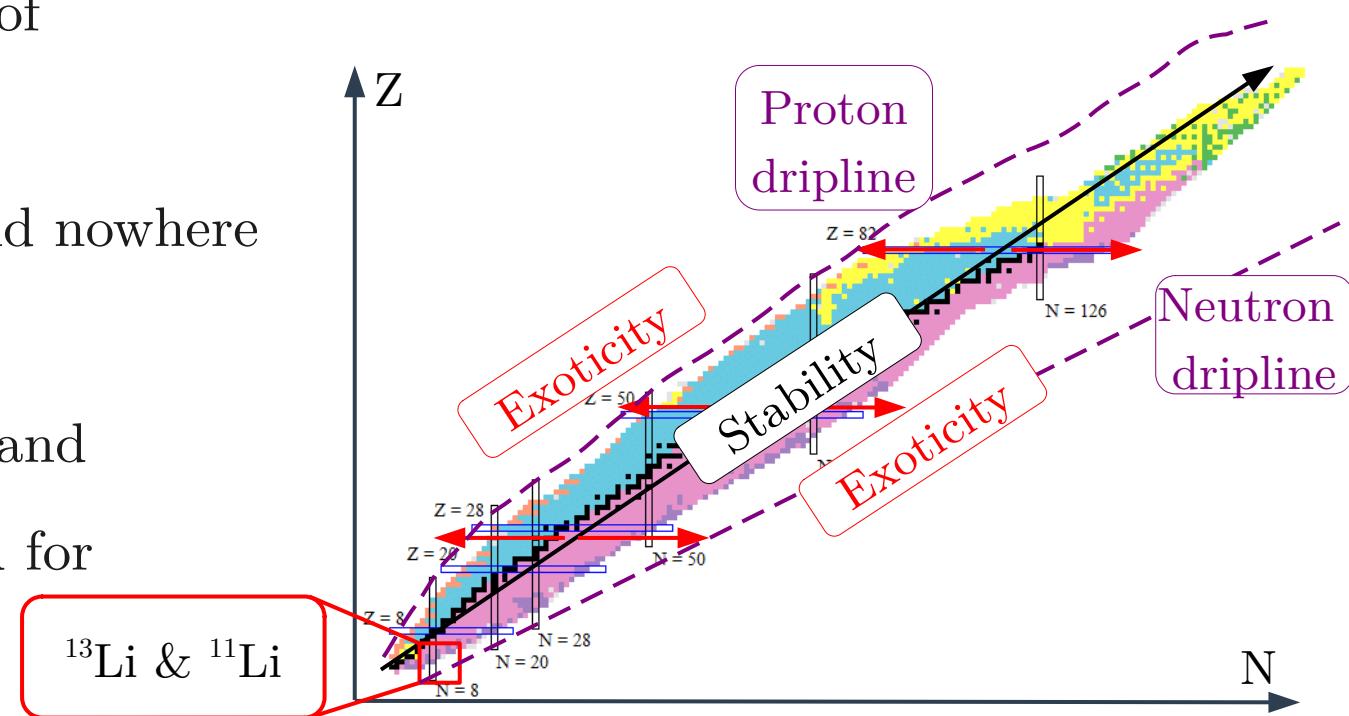
## Minimization on the Jacobi coordinates



# Studying exotic nuclei in inverse kinematics



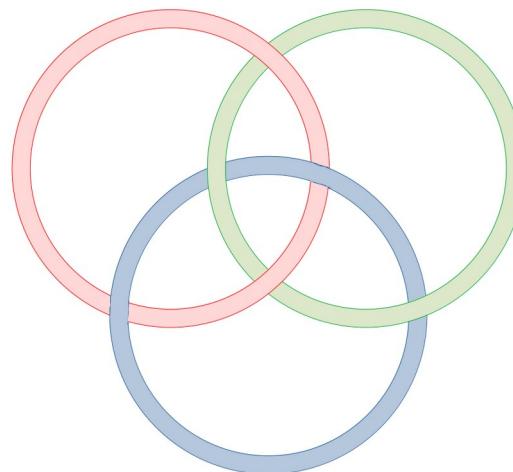
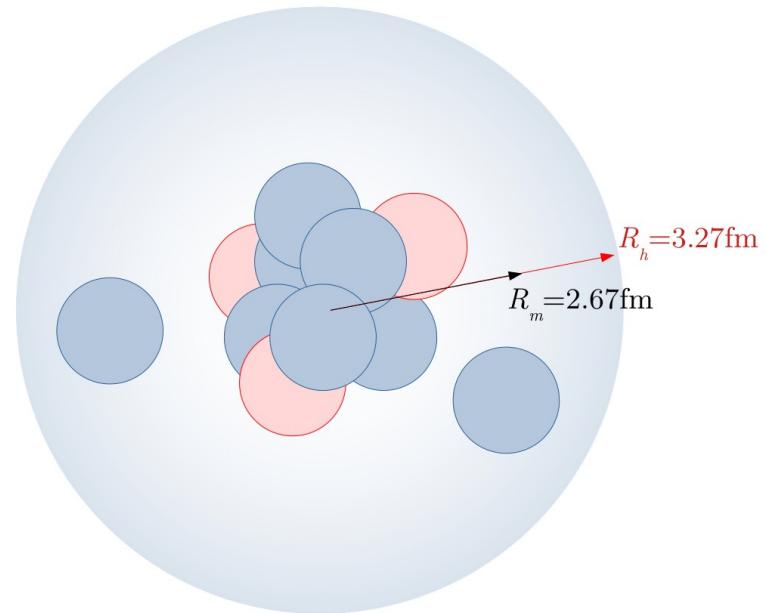
- Study of nuclei far from stability → short-lived systems
- Inverse kinematics technique : exotic nuclei in beam on target
- Interest of studying exotic nuclei :
  - Testing our knowledge of nuclear interaction
  - Special structures, found nowhere else in the nuclide chart
  - Finding fundamental and universal properties valid for the whole chart



# Halo and Borromean nuclei

Special structure of  $^{11}\text{Li}$  : halo nuclei[1][2] and Borromean[3]

→ Effective radius  $> R_m = r_0 \cdot A^{1/3}$  &  $^{11}\text{Li}$  bound while  $^{10}\text{Li}$  unbound



→ Good testing ground for n-n correlations



# How to study n-n correlations ?

- Coulomb dissociation

T. Nakamura *et al.*, PRL **96** (2006)

- 2n interferometry

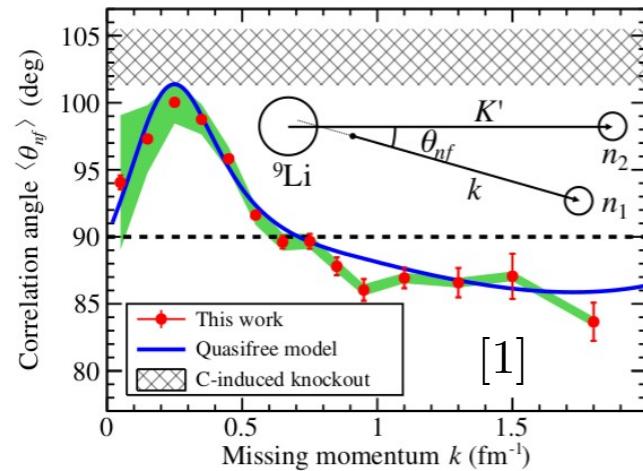
F.M. Marques *et al.*, Phys. Lett. B **476** (2000)

- Neutron transfer reactions

I. Tanihata *et al.*, PRL **100** (2008)

- Fragmentation reactions

H. Simon *et al.*, Nucl. Phys. A **791** (2007)



- Quasi-free scattering reactions

[1] Y. Kubota *et al.*, PRL **125** (2020)

-2n decay

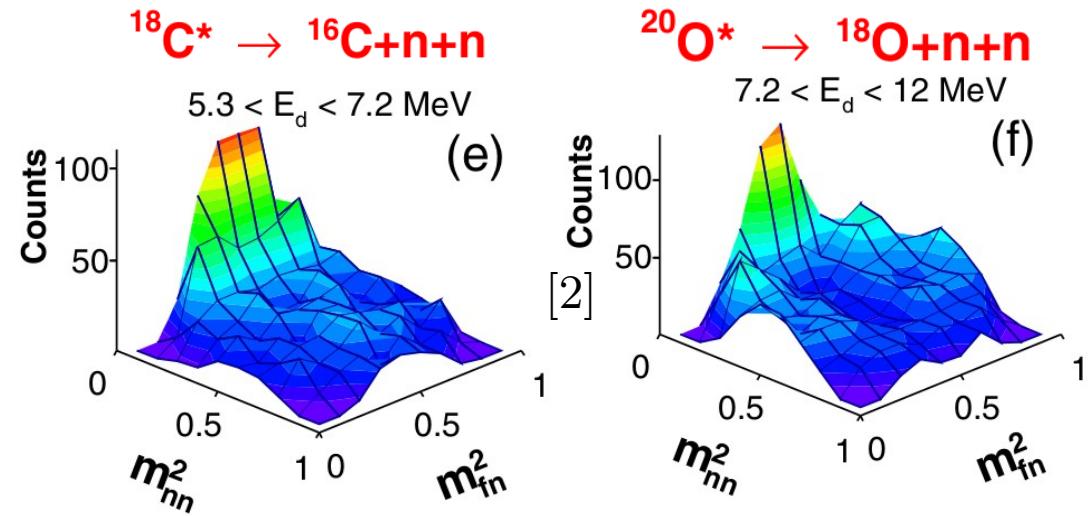
of  $^{26}\text{O}$

Y. Kondo *et al.*, PRL **116** (2016)

K. Hagino, H. Sagawa, Phys. Rev. C **90** (2016)

of  $^{18}\text{C}$  and  $^{20}\text{O}$

[2] A. Revel *et al.*, PRL **120** (2018)

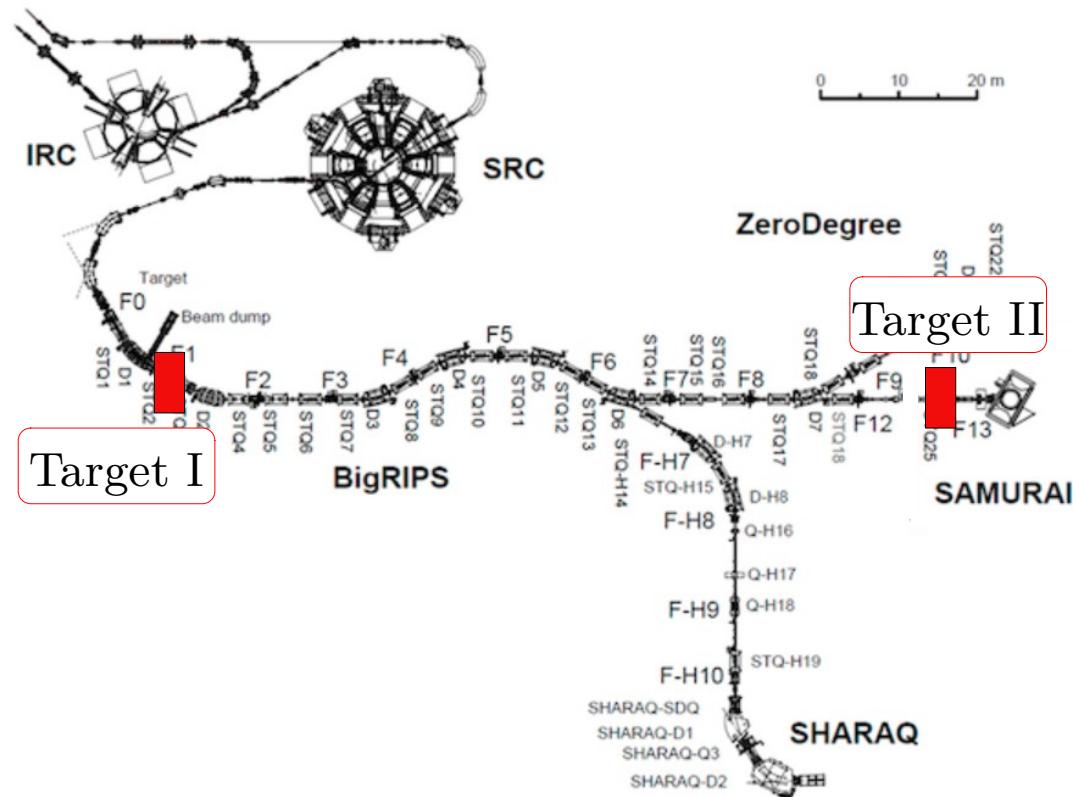




# RIBF @ Riken Nishina Center

## Radioactive Isotope Beam Factory

**RIBF**  
RIKEN NISHINA CENTER  
Introduction to RI Beam Factory and Users' Information

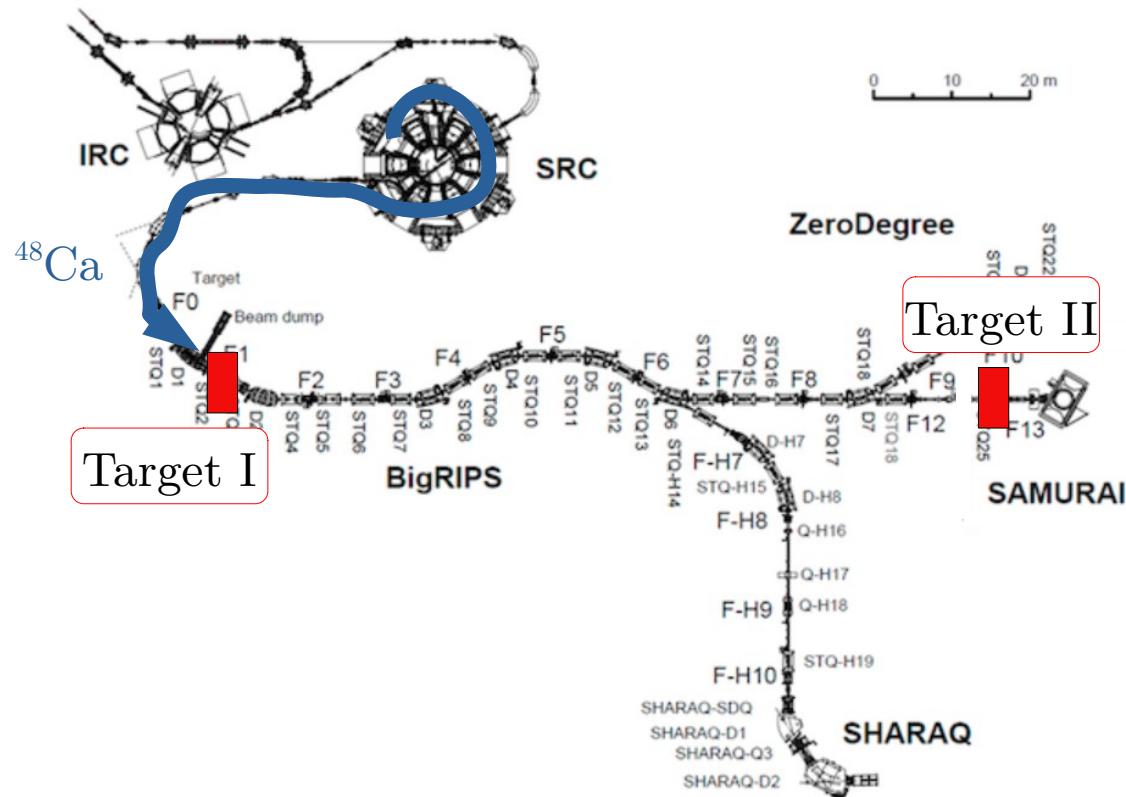




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## Radioactive Isotope Beam Factory

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RIKEN NISHINA CENTER  
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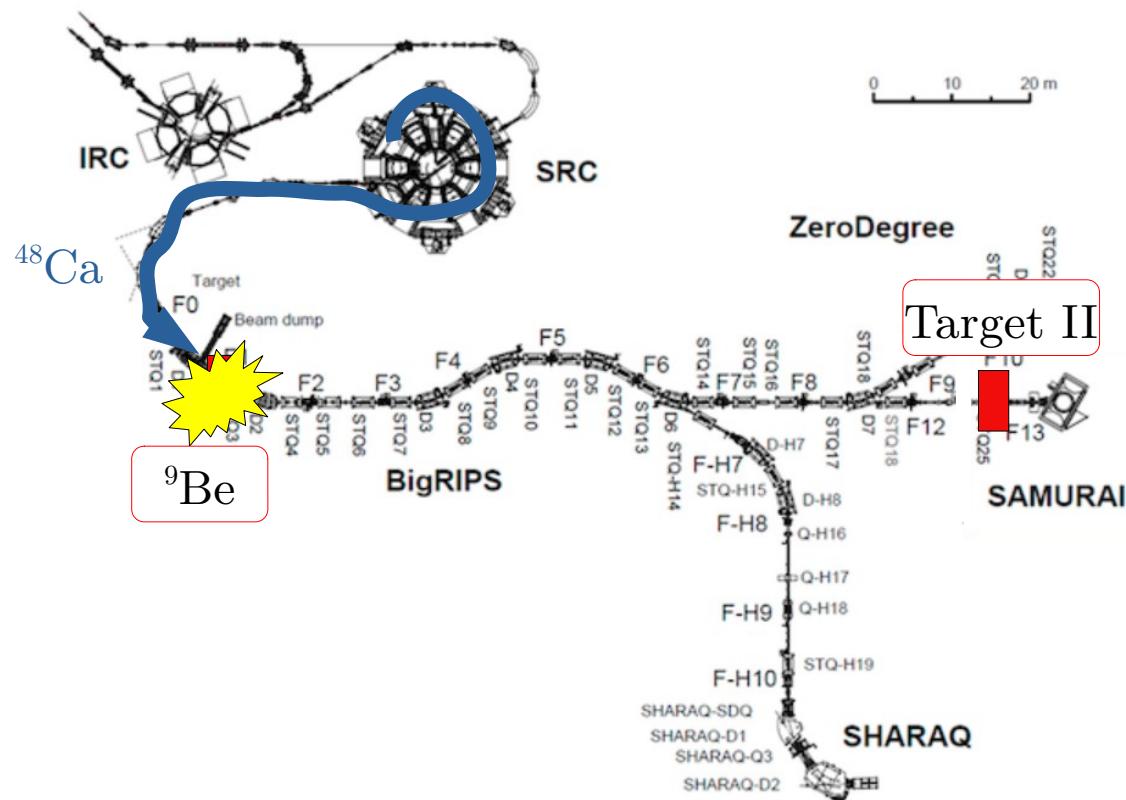




# RIBF @ Riken Nishina Center

## Radioactive Isotope Beam Factory

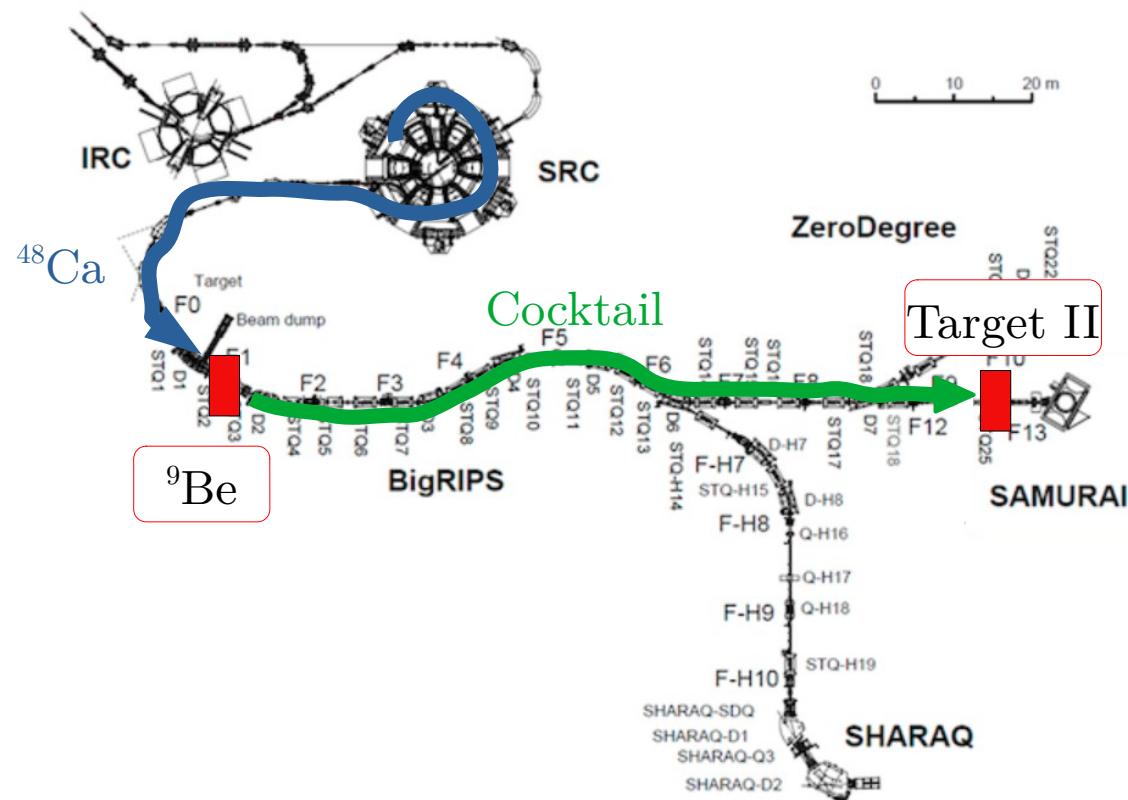
**RIBF**  
RIKEN NISHINA CENTER  
Introduction to RI Beam Factory and Users' Information





# RIBF @ Riken Nishina Center

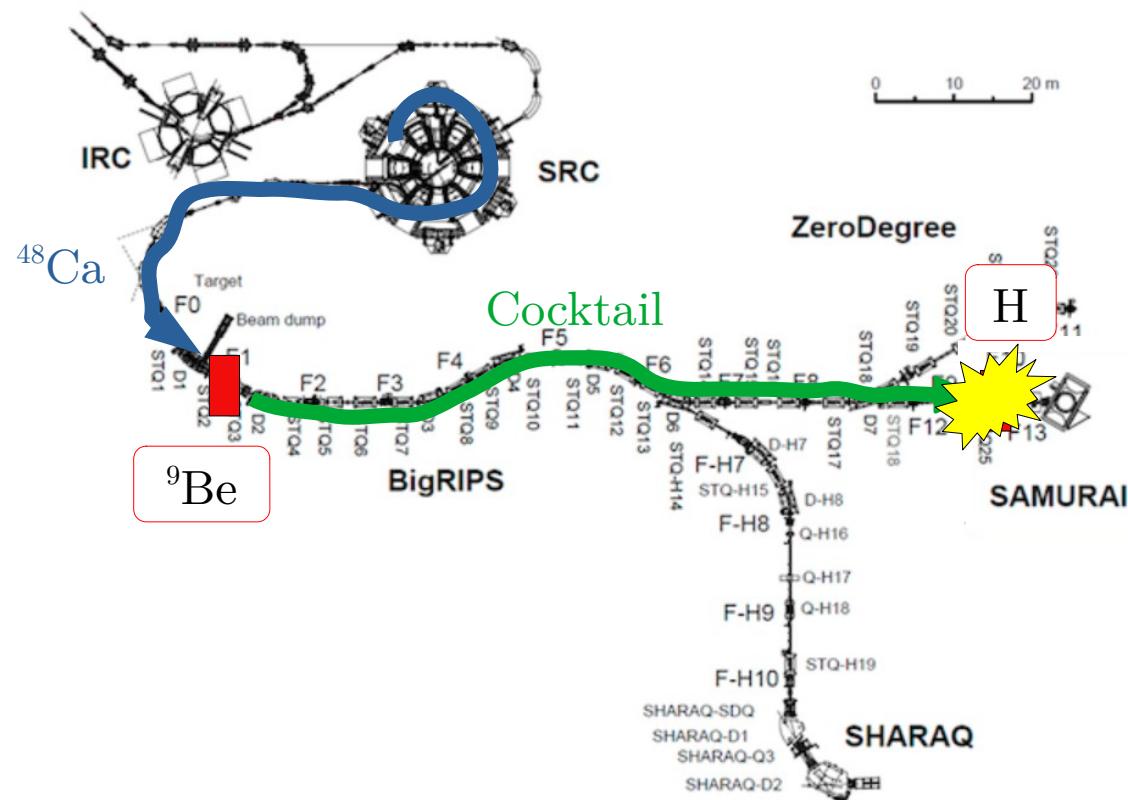
## Radioactive Isotope Beam Factory





# RIBF @ Riken Nishina Center

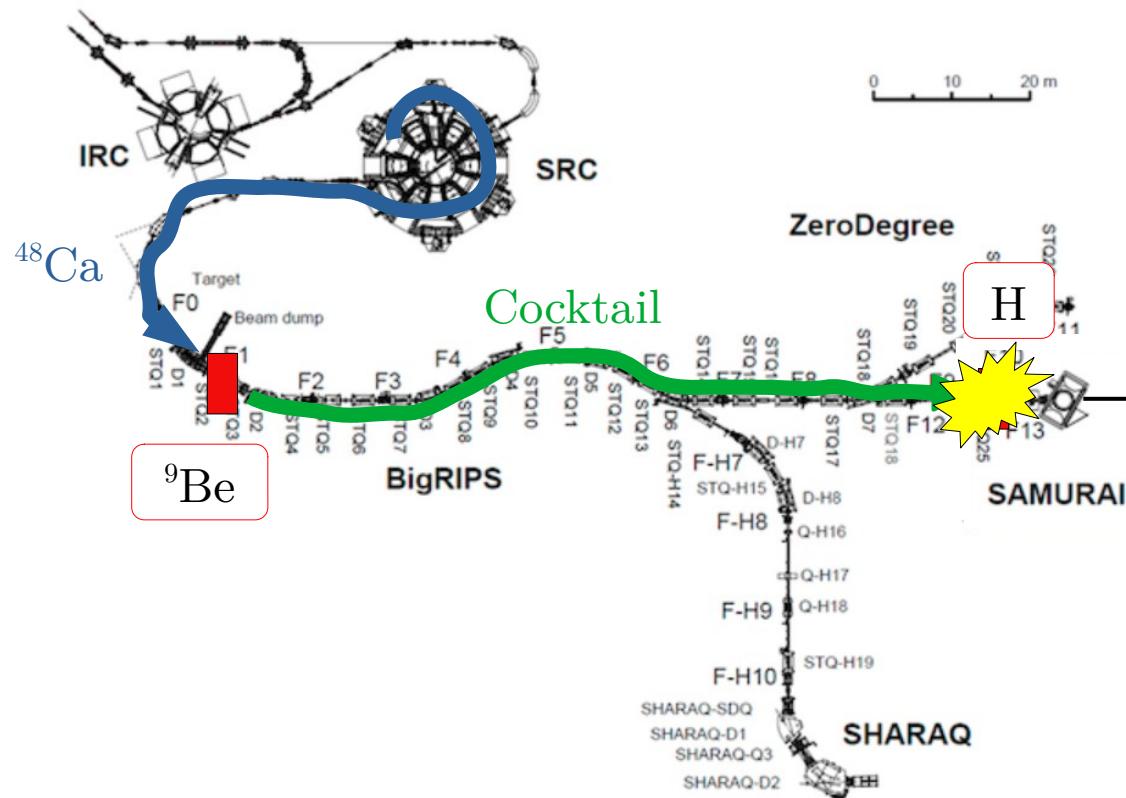
## Radioactive Isotope Beam Factory





# RIBF @ Riken Nishina Center

## Radioactive Isotope Beam Factory



In the **cocktail** beam :

- 80% of  $^{11}\text{Li}$
- 12% of  $^{14}\text{Be}$
- 8% of  $^{17}\text{B}$

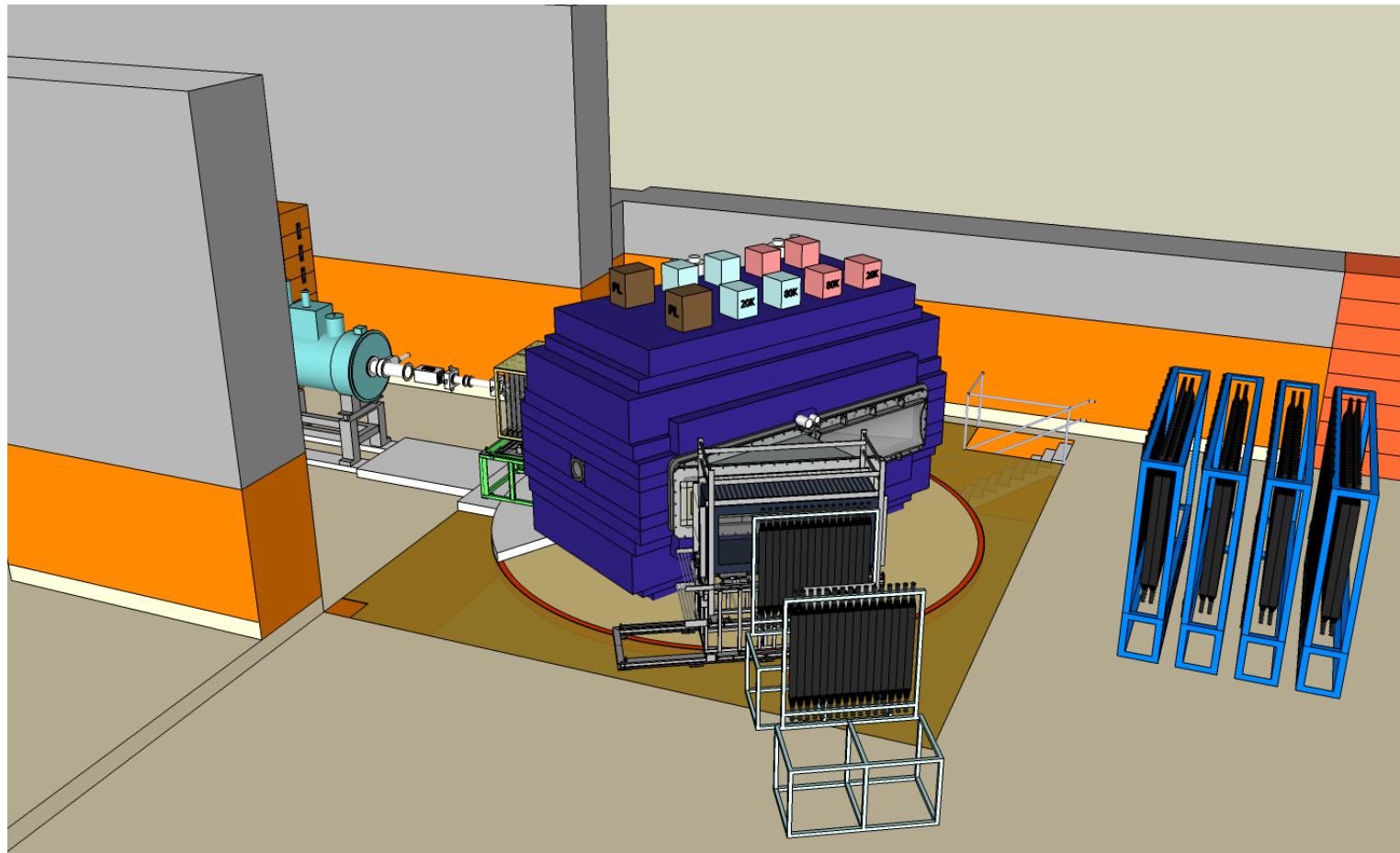
Detection of  
decay products

Reactions of interest :

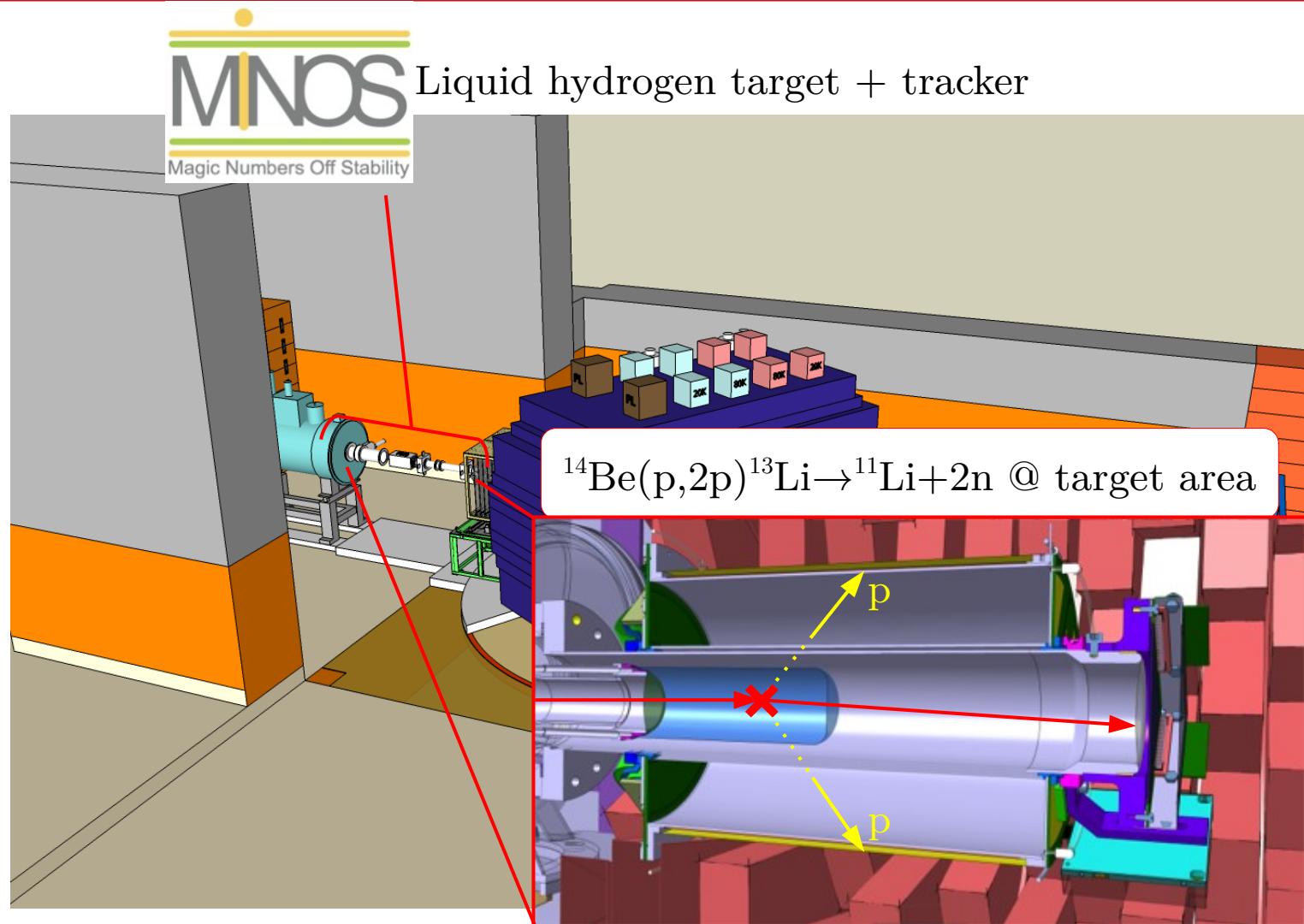
- $^{14}\text{Be}(\text{p},2\text{p})^{13}\text{Li}$
- $^{12}\text{Be}(\text{p},2\text{p})^{11}\text{Li}$



# MINOS, NEBULA & SAMURAI



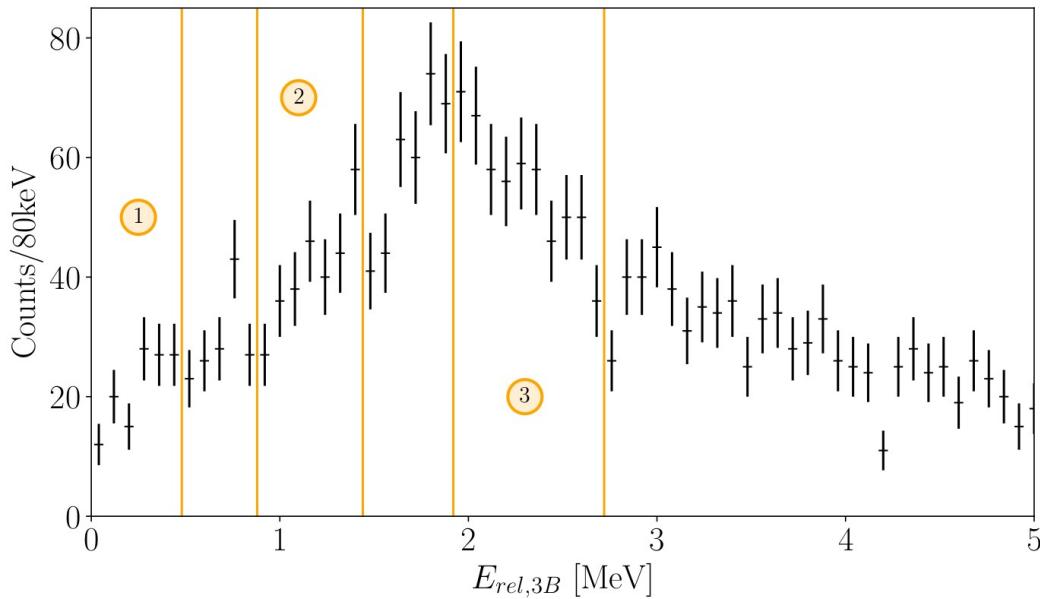
# MINOS, NEBULA & SAMURAI



**Results :  $^{11}\text{Li}$**

# The 3-body spectrum for $^{11}\text{Li}$

3B relative energy spectrum  
(different-wall events)



Gating in the 3B relative energy  
 → Fitting the Jacobi coordinates  
 for each gate  
 → Fitting the 2B relative energy  
 spectrum

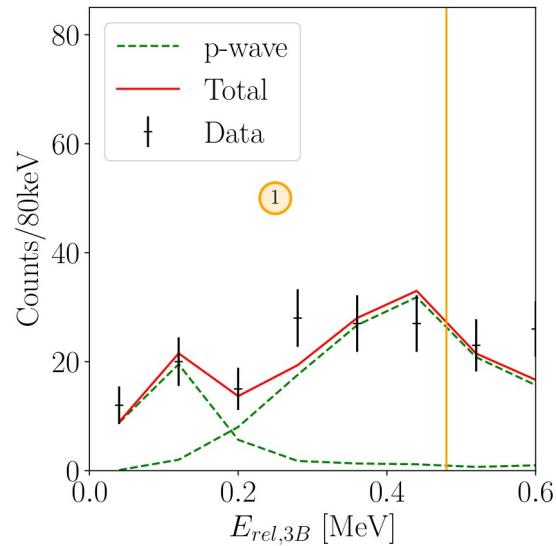
Constraining with the integral in the 3B spectrum for the integral of  
 the response functions in the other observables

# The 3-body spectrum for $^{11}\text{Li}$ :

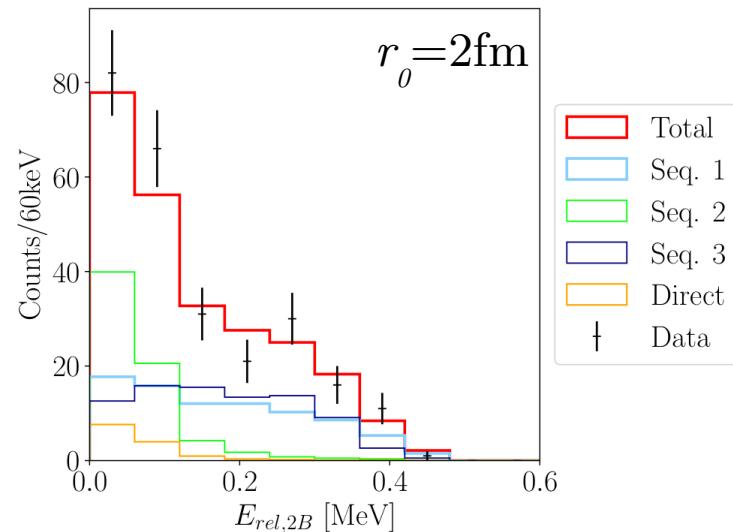
$0 < E_{rel,3B} < 0.48\text{MeV}$



3B relative energy :



2B relative energy :

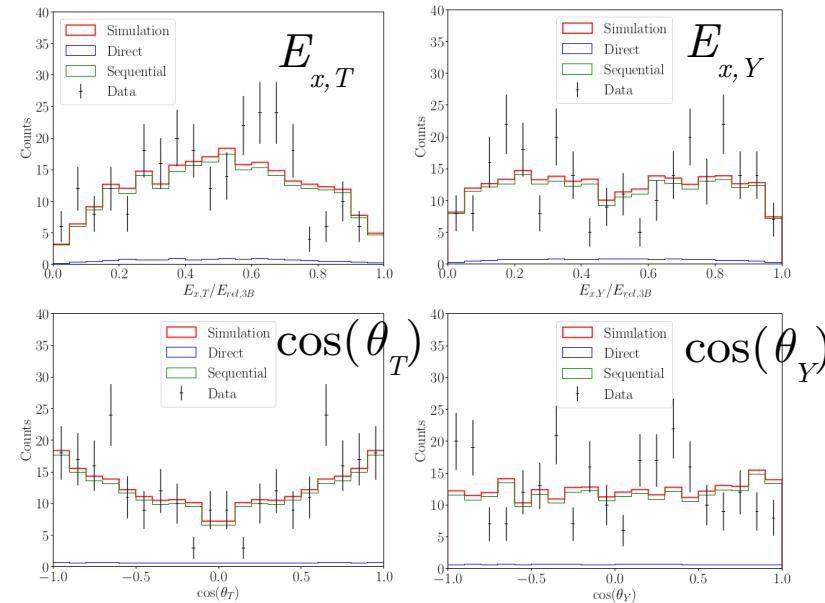


Resonances in  $^{11}\text{Li}$  :

	1	2
$E_{res}$ (MeV)	0.08	0.39
$\Gamma_{res}$ (MeV)	0.01	0.71

Resonances in  $^{10}\text{Li}$  :

	1	2	
$a_s$ (fm)	-30	$E_{res}$ (MeV)	0.3
		$\Gamma_{res}$ (MeV)	0.14



[1] M. Zinser *et al.*, Nucl. Phys. A **619** (1997)

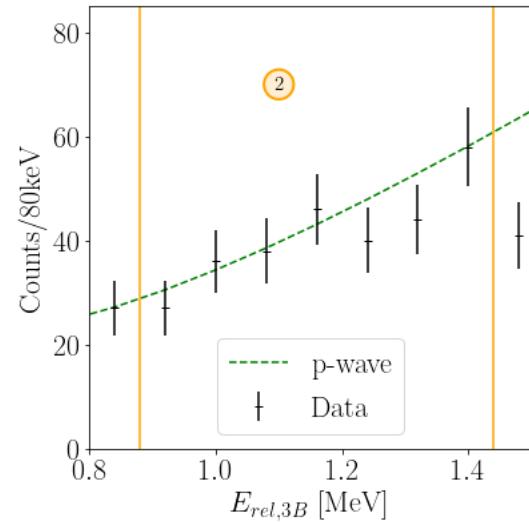
[2] T. Nakamura *et al.*, PRL **96** (2006) [3] H. Simon *et al.*, Nucl. Phys. A **791** (2007)

# The 3-body spectrum for $^{11}\text{Li}$ :

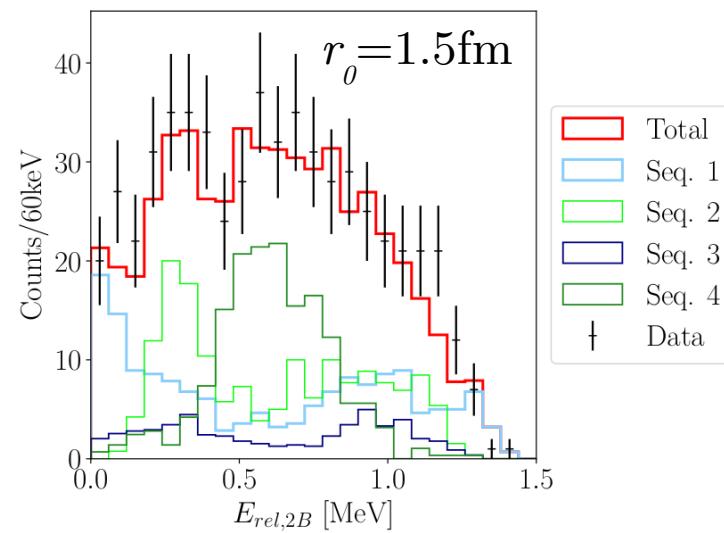
$0.88 < E_{rel,3B} < 1.44 \text{ MeV}$



3B relative energy :



2B relative energy :

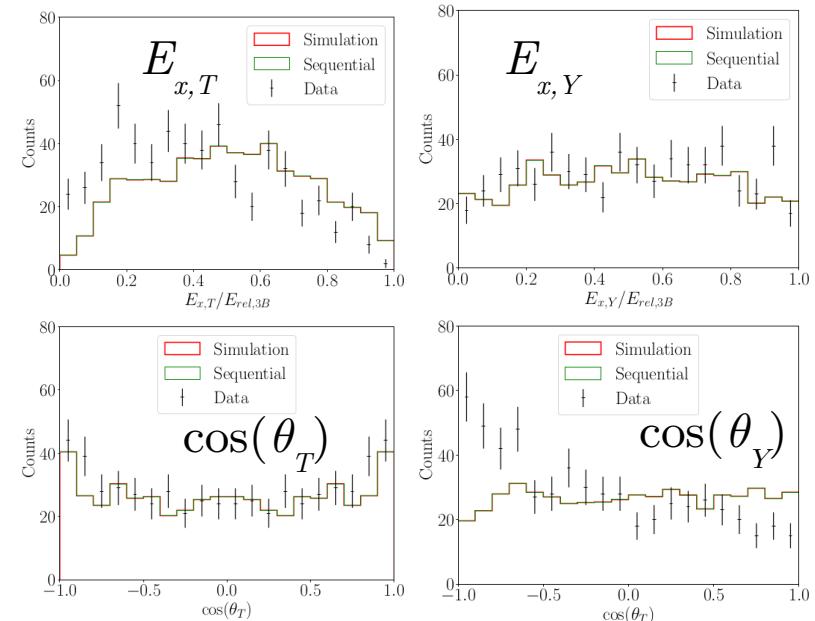


Resonances in  $^{11}\text{Li}$  :

	1	2	3	4	
$a_s$ (fm)	-30	$E_{res}$ (MeV)	0.3	0.62	1.05
		$\Gamma_{res}$ (MeV)	0.14	0.06	0.03

Resonances in  $^{10}\text{Li}$  :

	1	2	3	4
$E_{res}$ (MeV)	2.13			
$\Gamma_{res}$ (MeV)	2.65			



[1] M. Zinser *et al.*, Nucl. Phys. A **619** (1997)

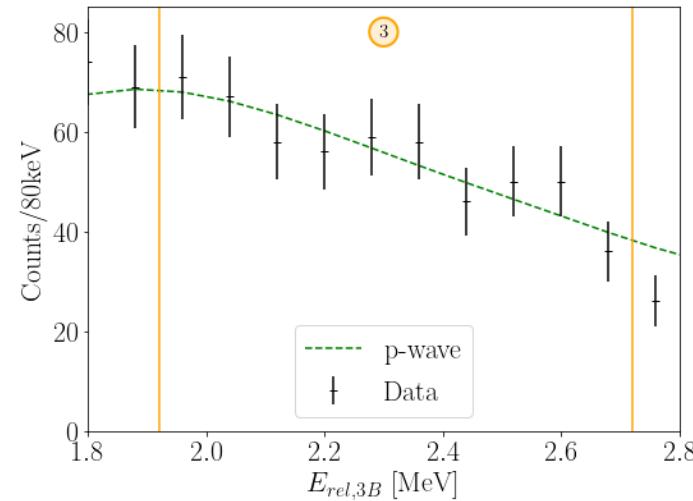
[2] J.K. Smith *et al.*, Nucl. Phys. A **940** (2015)

# The 3-body spectrum for $^{11}\text{Li}$ :

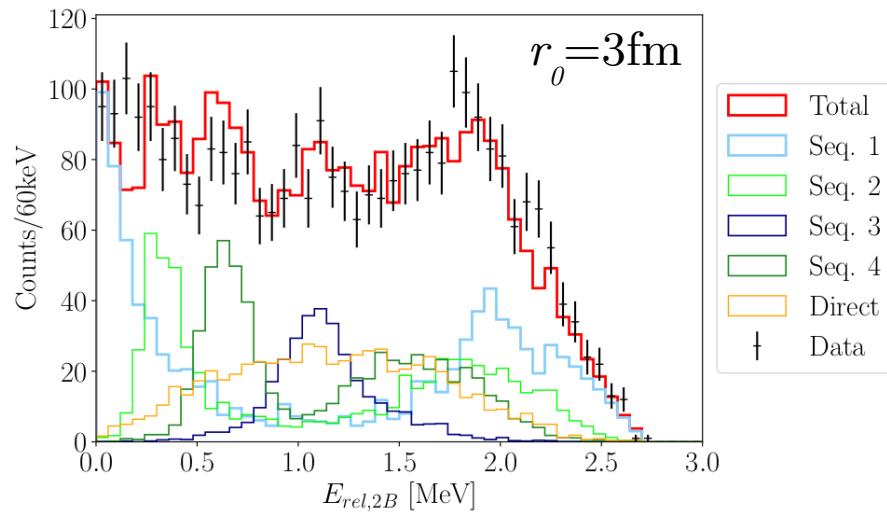
$1.92 < E_{rel,3B} < 2.72 \text{ MeV}$



3B relative energy :



2B relative energy :

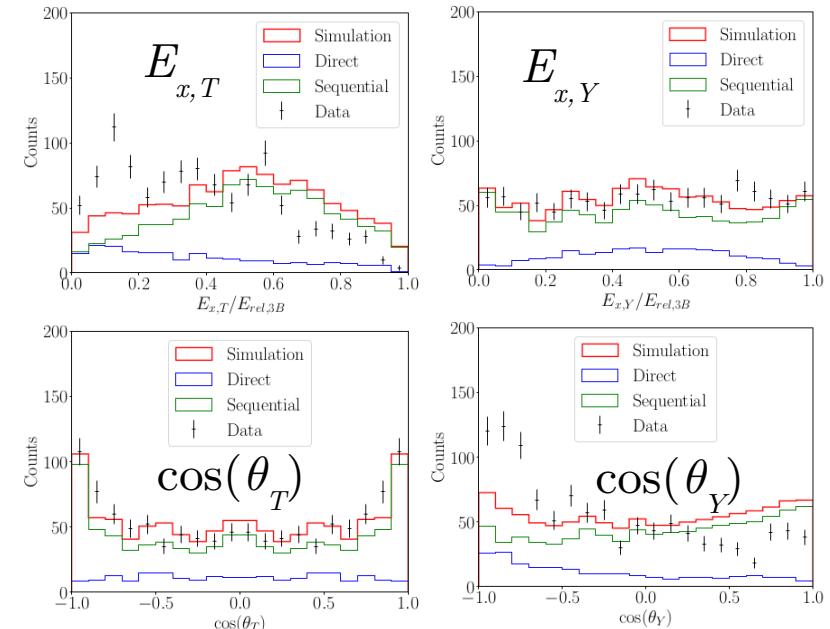


Resonances in  $^{11}\text{Li}$  :

		3	
$E_{res}$ (MeV)	2.13		
$\Gamma_{res}$ (MeV)	2.65		

Resonances in  $^{10}\text{Li}$  :

	1	2	3	4	
$a_s$ (fm)	-30	$E_{res}$ (MeV)	0.3	0.62	1.05
		$\Gamma_{res}$ (MeV)	0.14	0.06	0.03



[1] M. Zinser *et al.*, Nucl. Phys. A **619** (1997)

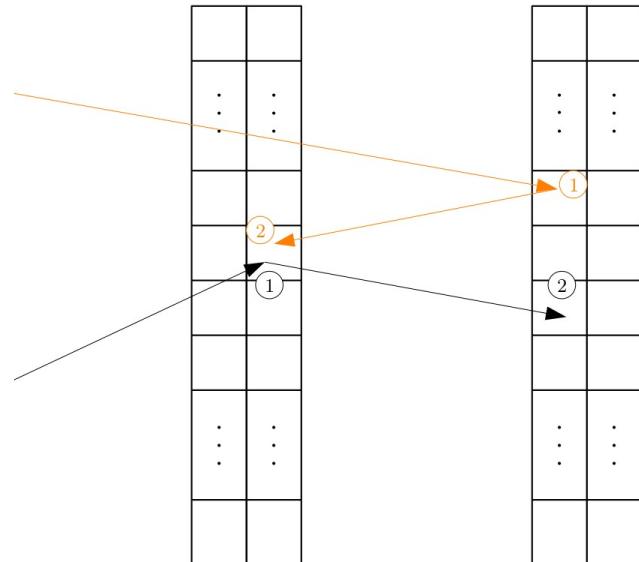
[2] J.K. Smith *et al.*, Nucl. Phys. A **940** (2015)



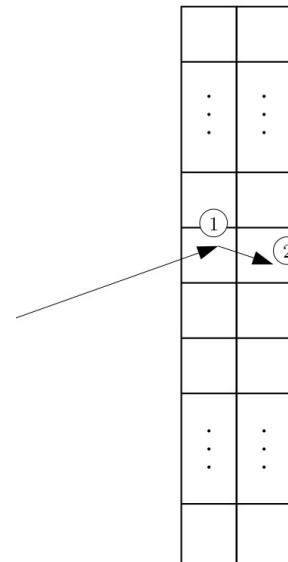
# Neutron cross-talk

Removing 1n events that yield 2 signals in NEBULA

Different-wall events :



Same-wall events :



+  $\gamma$  ray cut : removing all events below 6MeVee

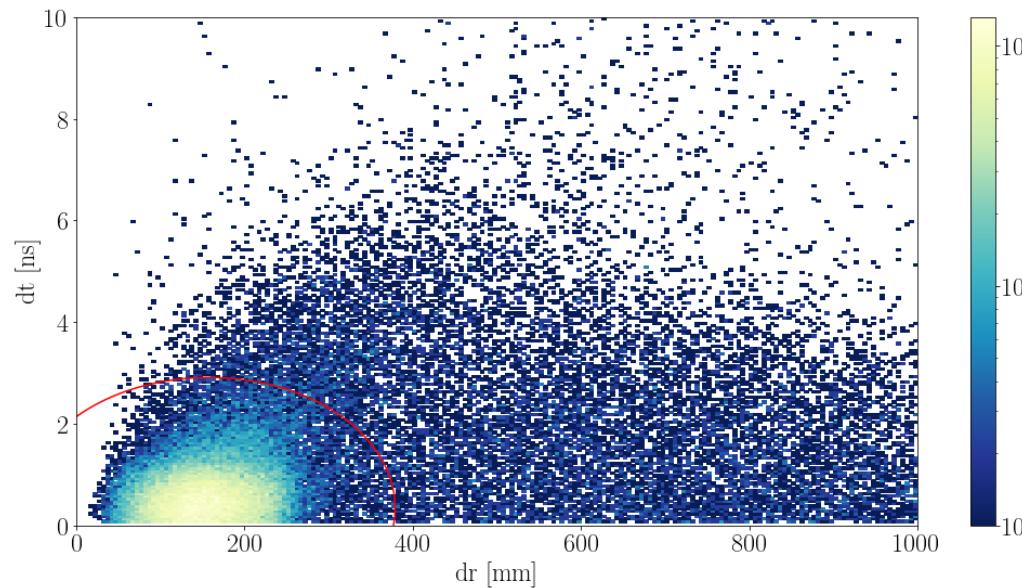
# Same-wall events

Removing hits too close to each other :

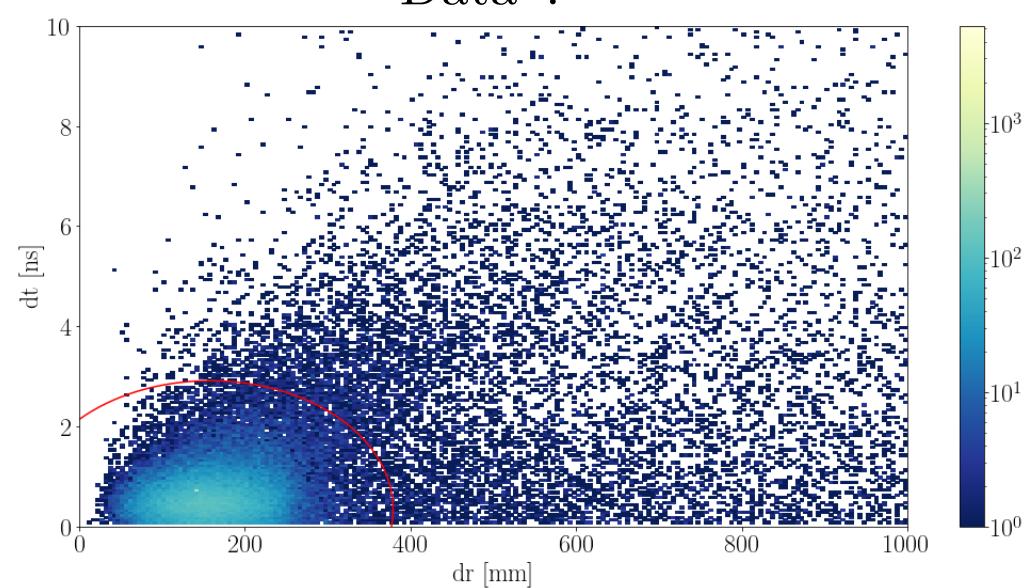
- spatially
- temporally

$dt = t_2 - t_1$  ;  $dr = |\mathbf{r}_2 - \mathbf{r}_1|$  :  $(\mathbf{r}_1, t_1)$  &  $(\mathbf{r}_2, t_2)$  coordinates for both signals

Simulation :



Data :



# Different-wall events : causality cuts

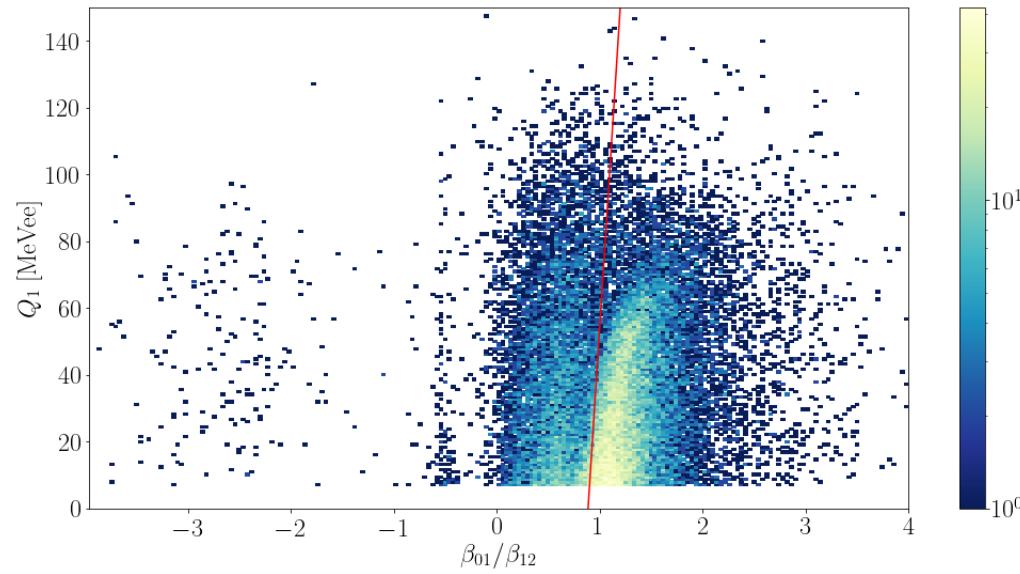
Checking causality between events with using energy loss

$\beta_{01}$  : velocity between target and 1<sup>st</sup> hit scintillator

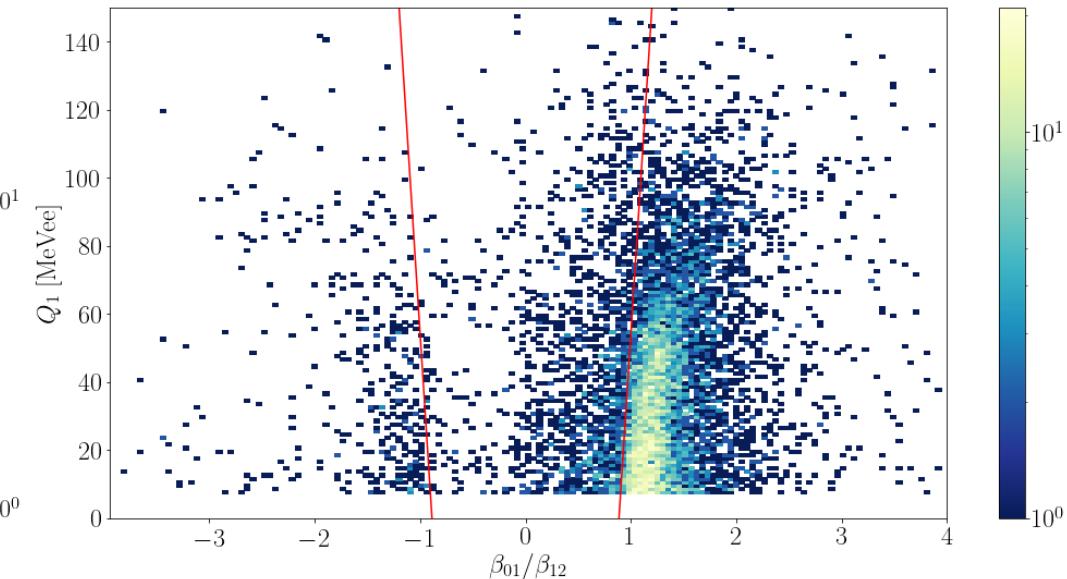
$\beta_{12}$  : velocity between 1<sup>st</sup> and 2<sup>nd</sup> hit scintillator

→ Removing events with  $\beta_{01}/\beta_{12} > 1$

Simulation :



Data :



# Observables

Invariant mass for a 3B system :

$$M_{inv,3B} = \sqrt{E_{tot,3B}^2 - \vec{P}_{tot,3B}^2}$$

Relative energy :

$$E_{rel,3B} = M_{inv,3B} - 2m_n - m_f$$

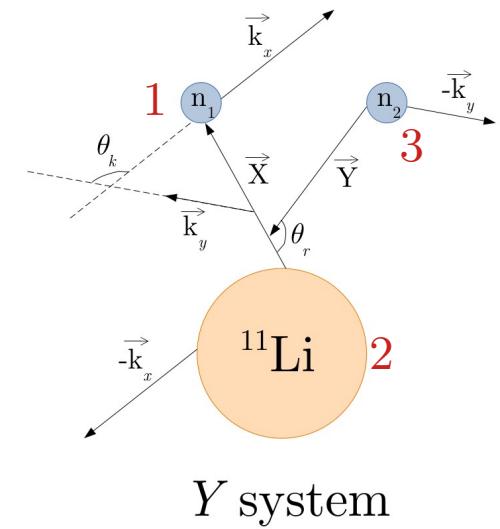
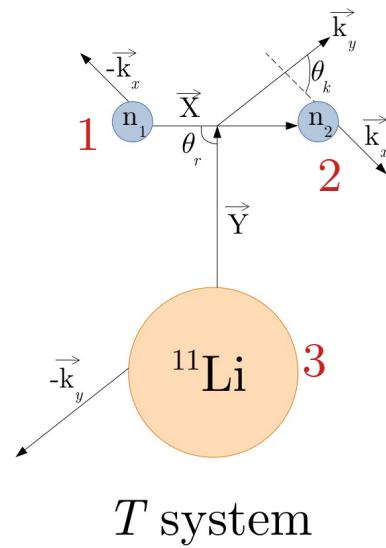
with  $E_{tot,3B} = E_f + E_{n_1} + E_{n_2}$

$$\vec{P}_{tot,3B} = \vec{P}_f + \vec{P}_{n_1} + \vec{P}_{n_2}$$

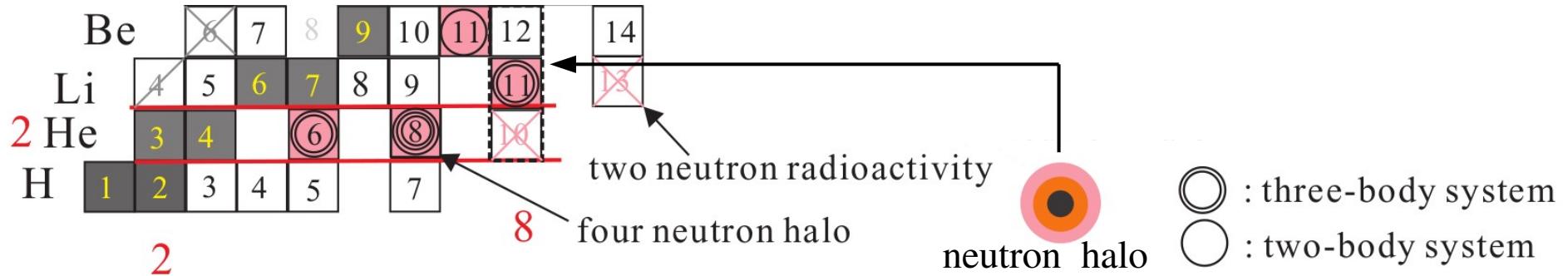
Jacobi coordinates :

$$E_{x,T} = \frac{k_{x,T}^2}{m_n} \quad E_{x,Y} = \frac{(m_n + m_{^{11}\text{Li}}) k_{x,Y}^2}{2m_n m_{^{11}\text{Li}}}$$

$$\cos \theta_k = \frac{\vec{k}_x \cdot \vec{k}_y}{k_x k_y}$$



# How to study n-n correlations ?



- What are the limits of nuclear existence ?
  - What is the role of exotic structures ? (Halo, dineutron)

$^{13,11}\text{Li}$  : testing ground for n-n correlations