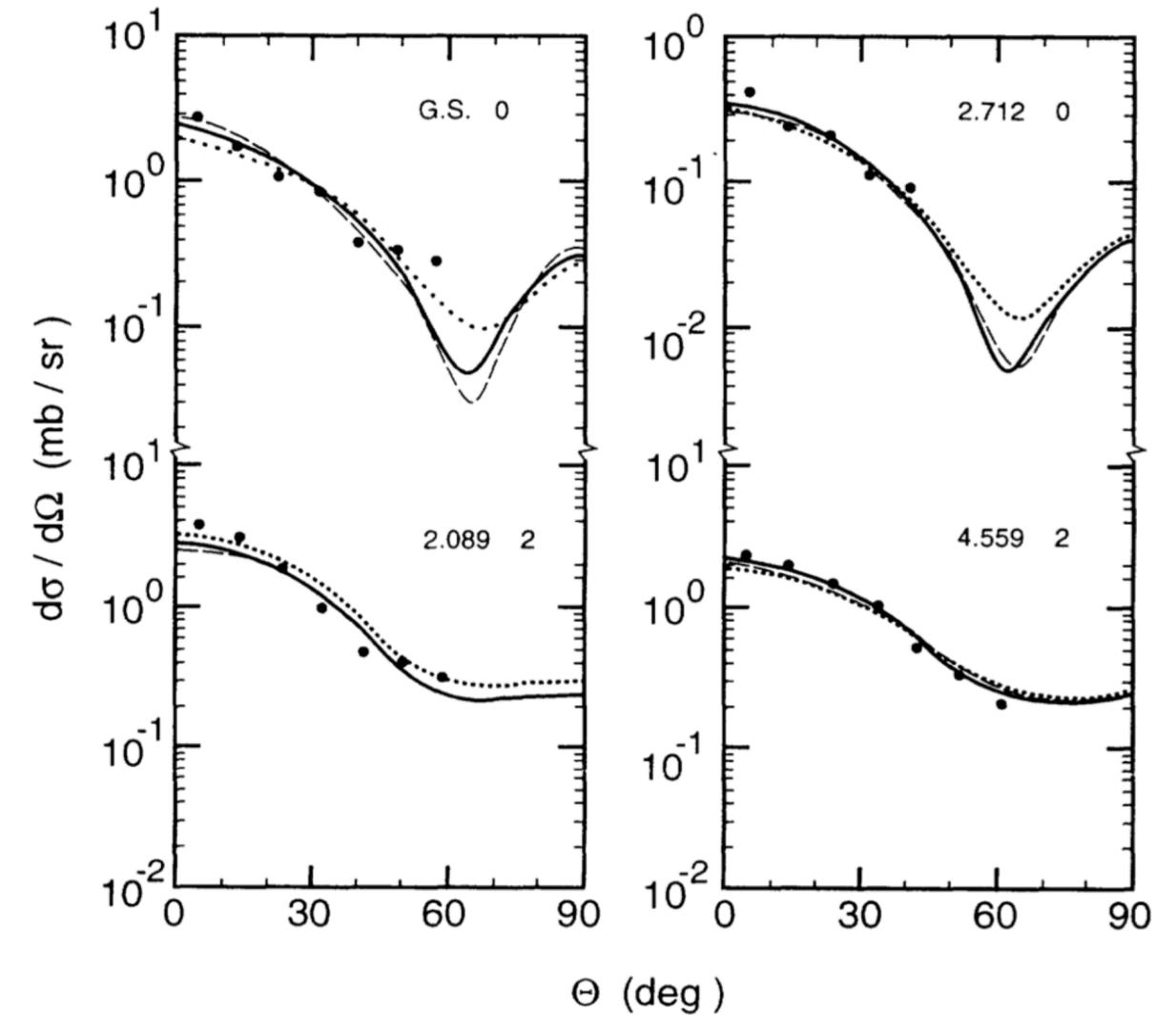


# *Study of the $^{10}\text{Be}(t,p)^{12}\text{Be}$ reaction with the SOLARIS spectrometer*

*Alicia Muñoz-Ramos, Y. Ayyad, B. P Kay, H. Alvarez-Pol, and the SOLARIS collaboration  
HIE-ISOLDE Physics Workshop, May 2023*

# Overview

- *Structure of  $^{12}\text{Be}$*
- *Why revisit with the  $(t,p)$  reaction?*
- *Challenges of inverse kinematics*
- *Solution? SOLARIS*
- *Preliminary results*
- *Future work*

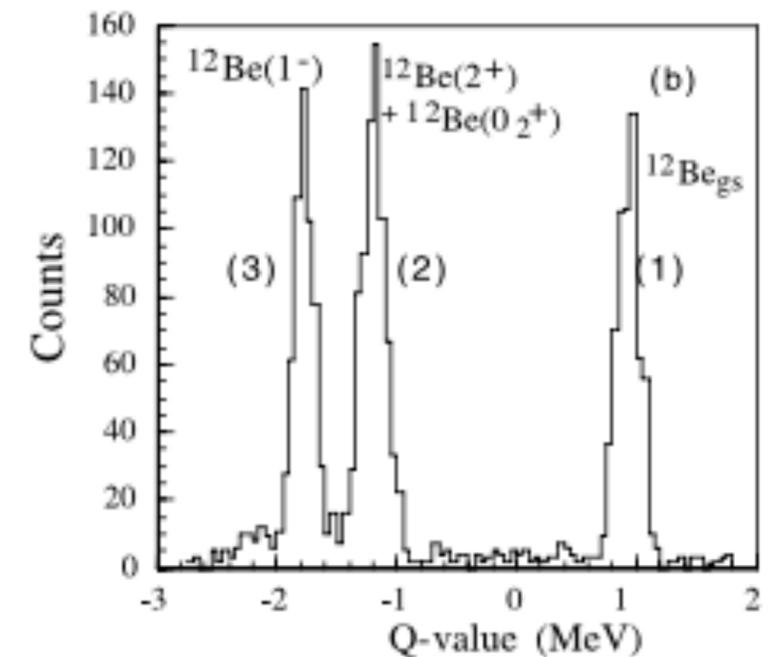


Fortune et al., Phys. Rev. C **50** (1994) 1355-1359

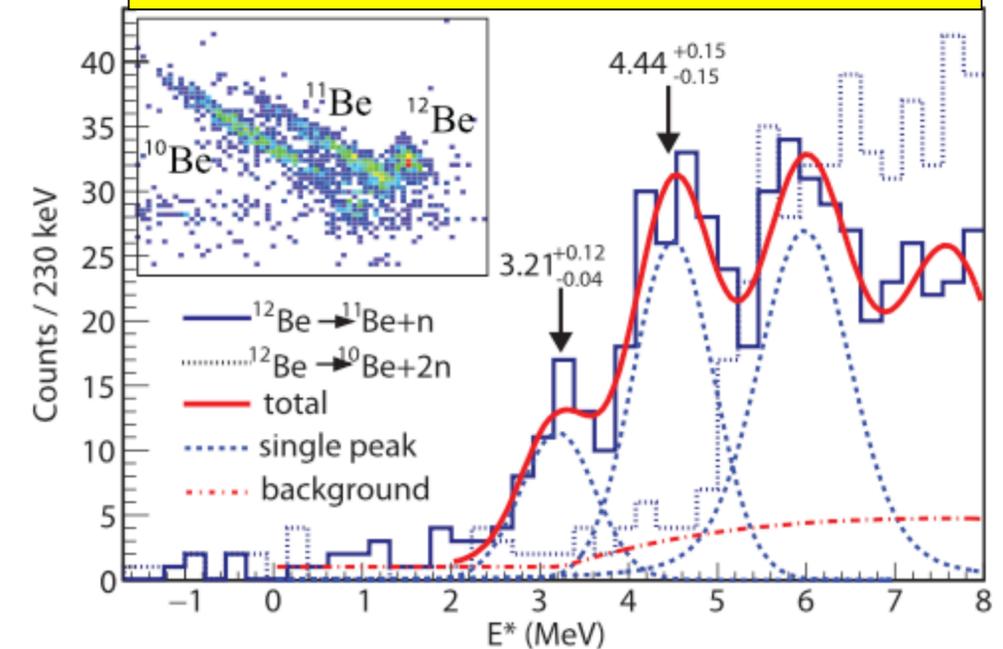
# $^{12}\text{Be}$ so far

- Several low-lying bound states known from a variety of studies
- Recent measurements of  $(d,p)$ , but still some *ambiguity as to assignment/structure of some states*
- Past  $(t,p)$ -reaction studies done at *lower energies + background from target*

$E$ (MeV)	$J^\pi$ (lit.) <sup>a</sup>	
0.0	$0^+$	
2.109	$2^+$	
2.251	$0^+$	
2.715	$1^-$	
3.21	$(0^-)$	$S_n$
4.412	$(2^-)$	
4.580	$(2^+, 3^-)$	
5.0	—	
5.724	$(4^+, 2^+, 3^-)$	
6.02	—	
6.275	—	



R. Kanungo et al., Phys. Lett. B **682** (2010) 391-395



J. Chen et al., Phys. Rev. C **103**, L031302 (2021)

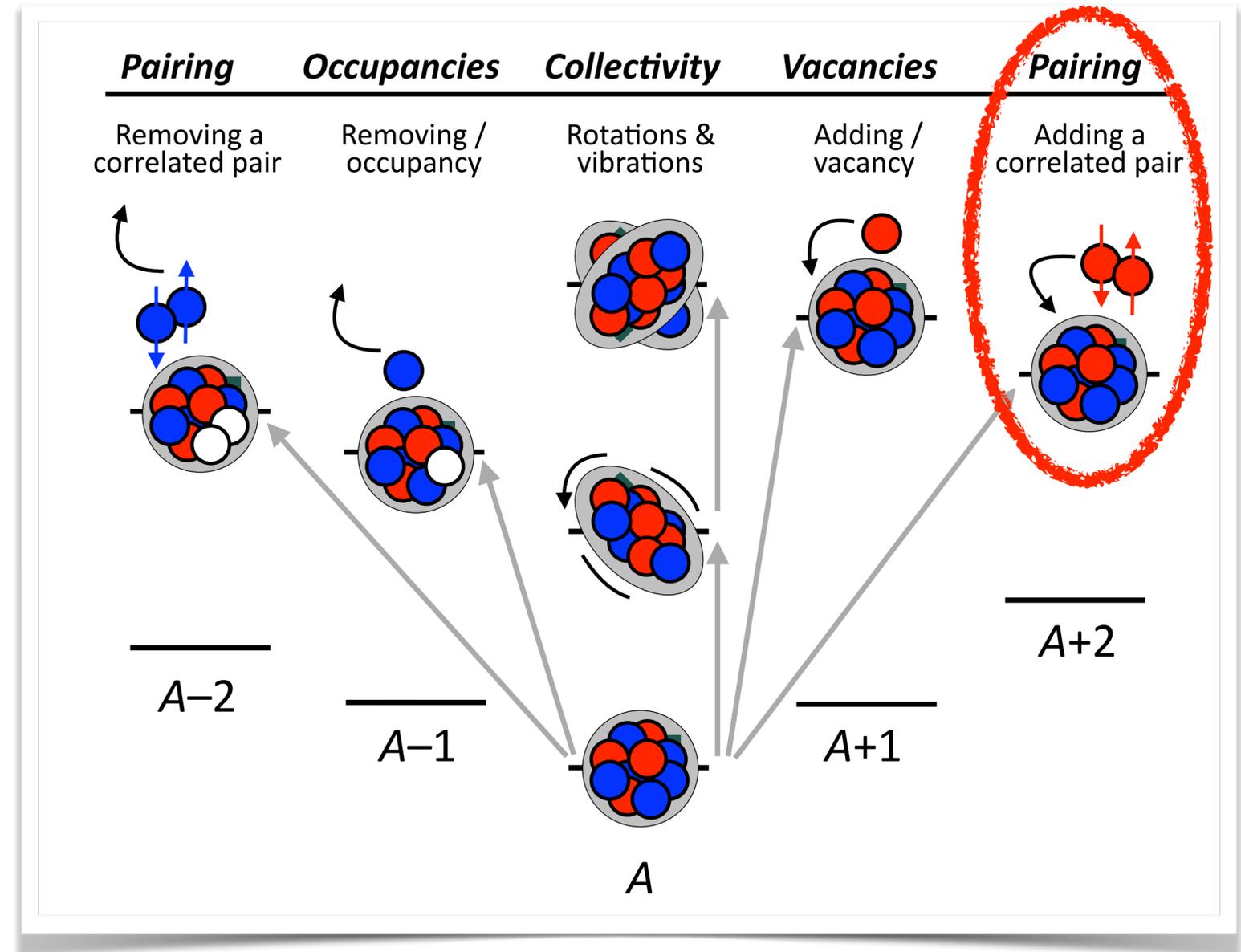
(Top) States below threshold  
(below) States above threshold

# Direct Reactions

**$\sim 10 \text{ MeV/u}$  (3-20 MeV/u)**

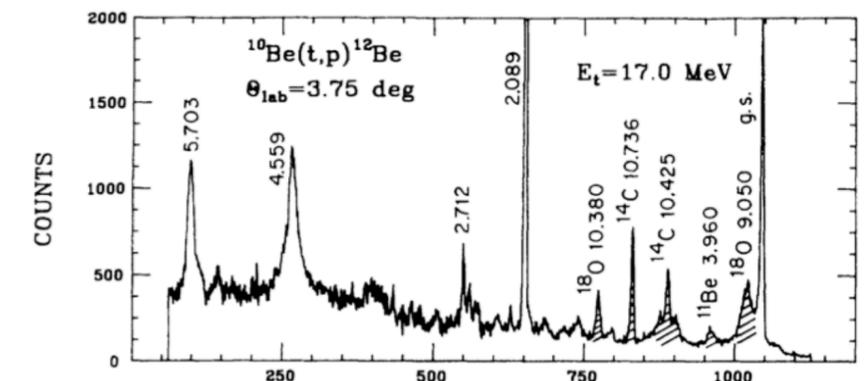
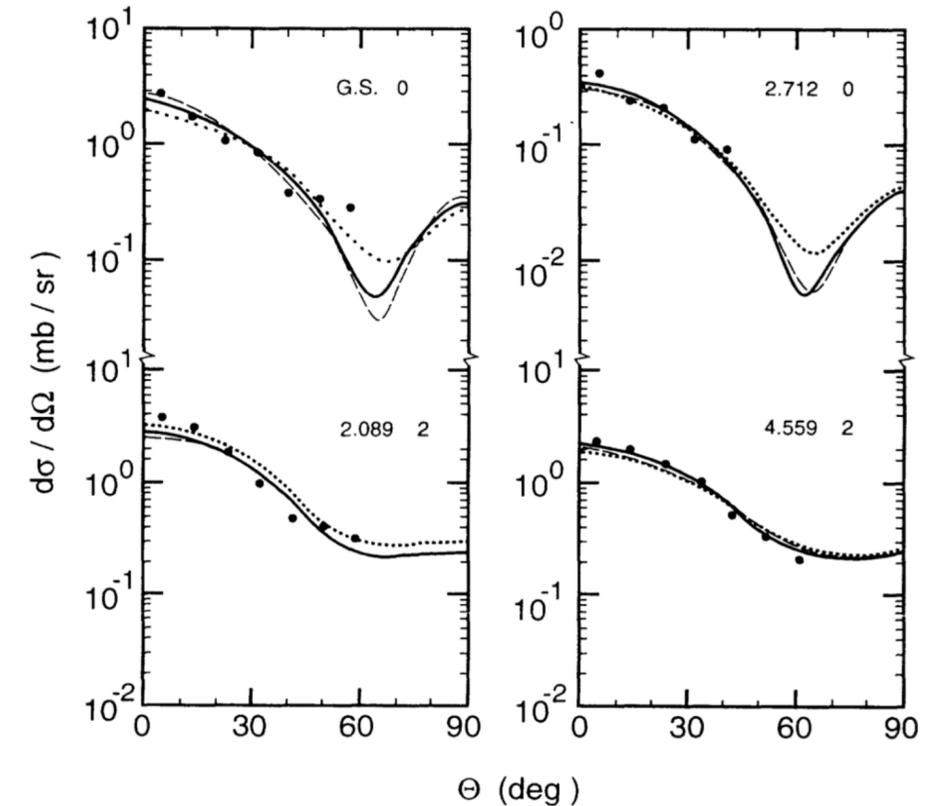
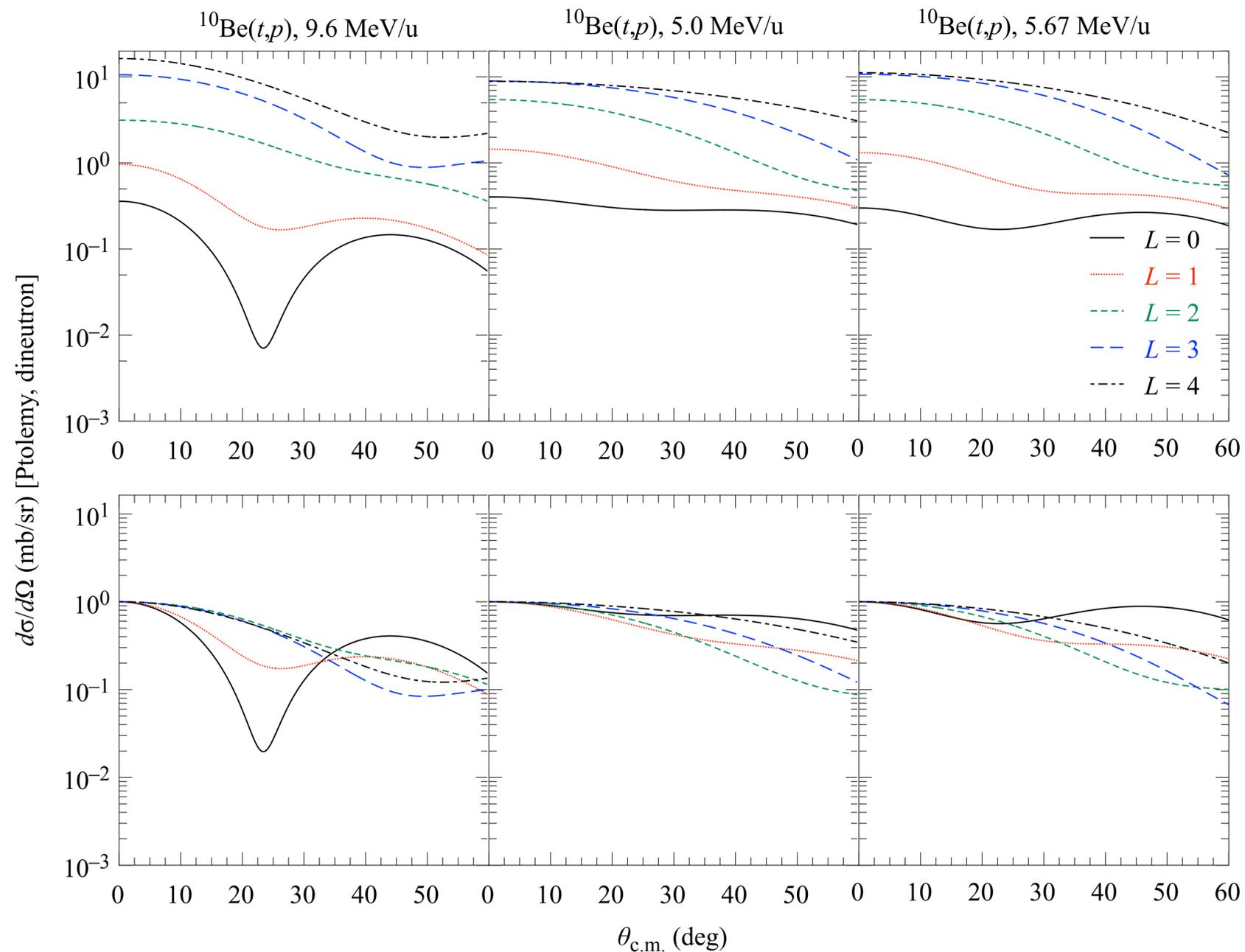
Reactions used as a tool for nuclear structure and astrophysics:

- *Selectively populate states, determine  $E, j^\pi$*
- *Inelastic, single-nucleon, two-nucleon*



# Why repeat the (t,p)?

Famous result of Fortune et al., done at lower energies around 5-5.7 MeV/u, angular distributions are broad with less features ... some advantages to higher energy ... plus, in theory a background-free measurement (removing target complications [though others remain])

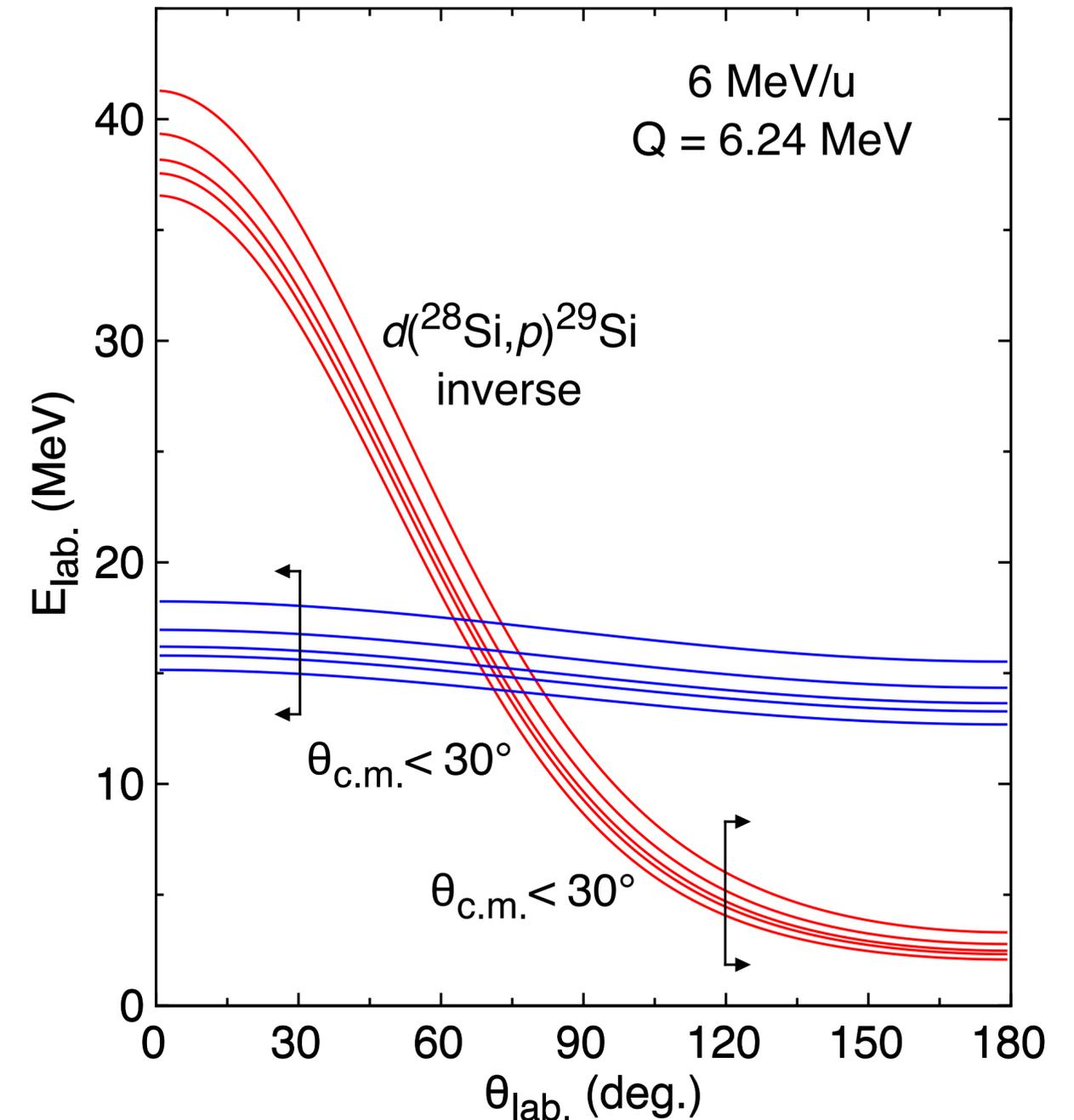


# Challenge of inverse kinematics

When compared to normal/forward kinematics, inverse kinematics suffers from:

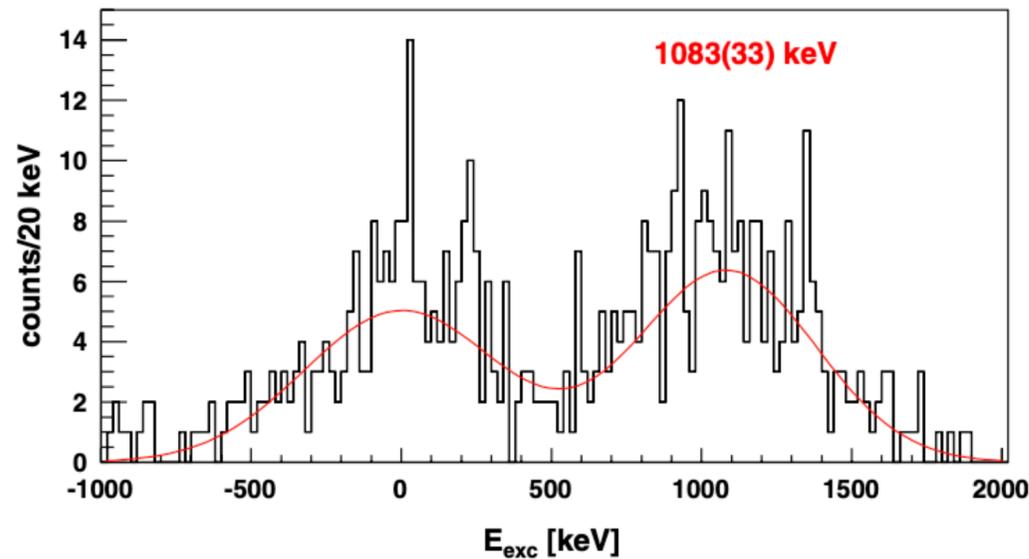
- Much **lower energy** outgoing ions, challenges for  $E$ - $\Delta E$  techniques
- Much stronger **energy dependence** with respect to laboratory angle
- A factors of 2-3 **kinematic compression** at forward c.m. angles
- ... and beams many **orders of magnitude weaker**

The result is typically very poor  $Q$ -value resolution of 100s of keV FWHM



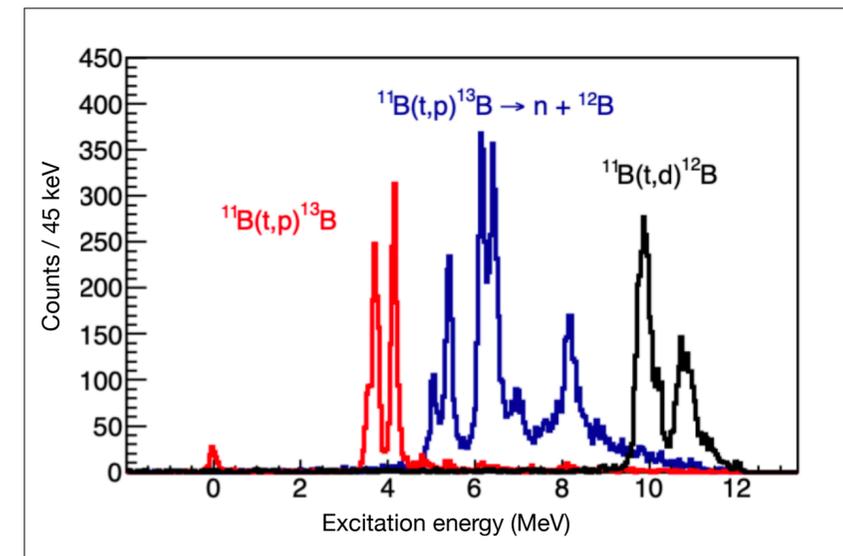
# The challenge with inverse kinematics

For examples (very few of which exist)

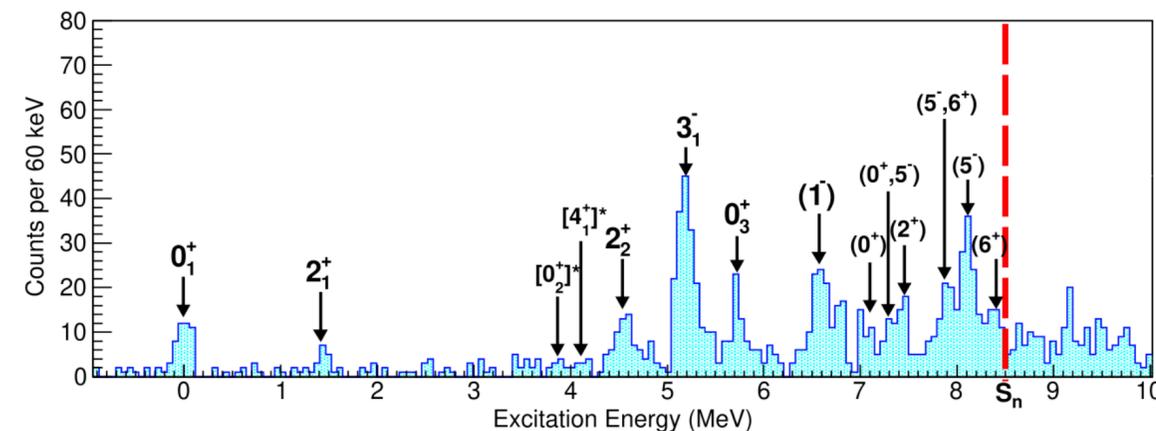


Wimmer et al., *Phys. Rev. Lett.* **105**, 252501 (2010)

Pioneering measurement of Wimmer et al. using TRES and Miniball to study the  $^{30}\text{Mg}(t,p)^{32}\text{Mg}$  reaction



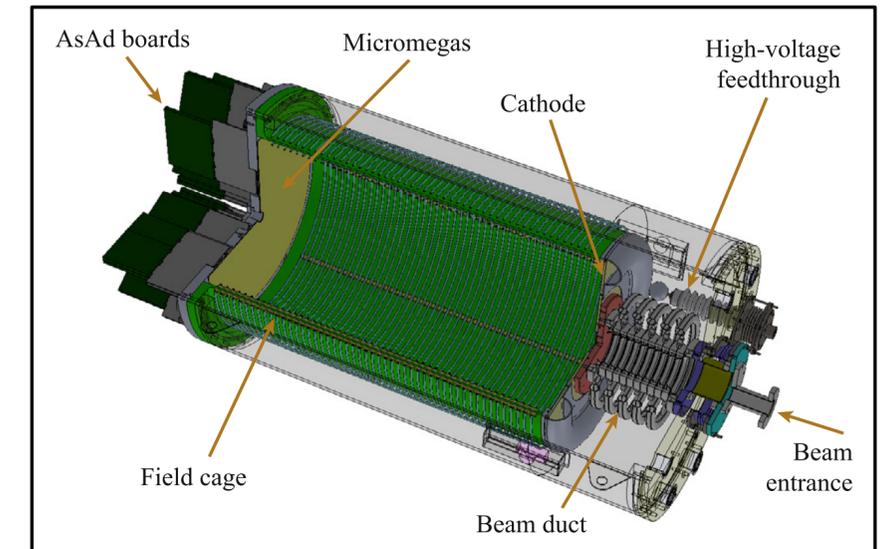
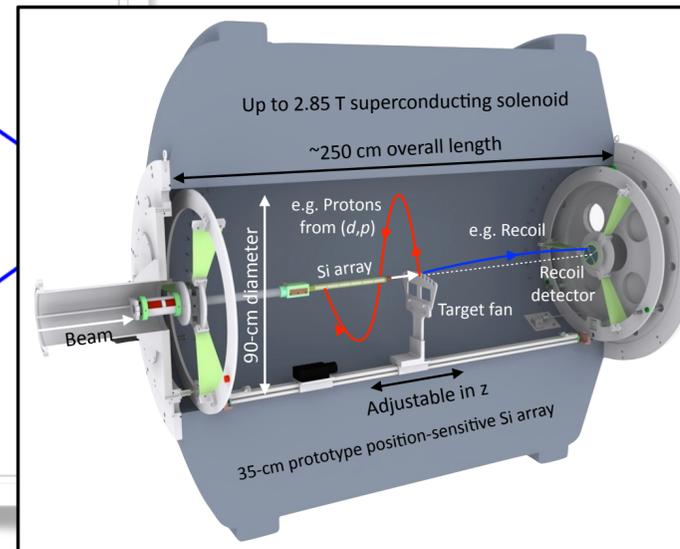
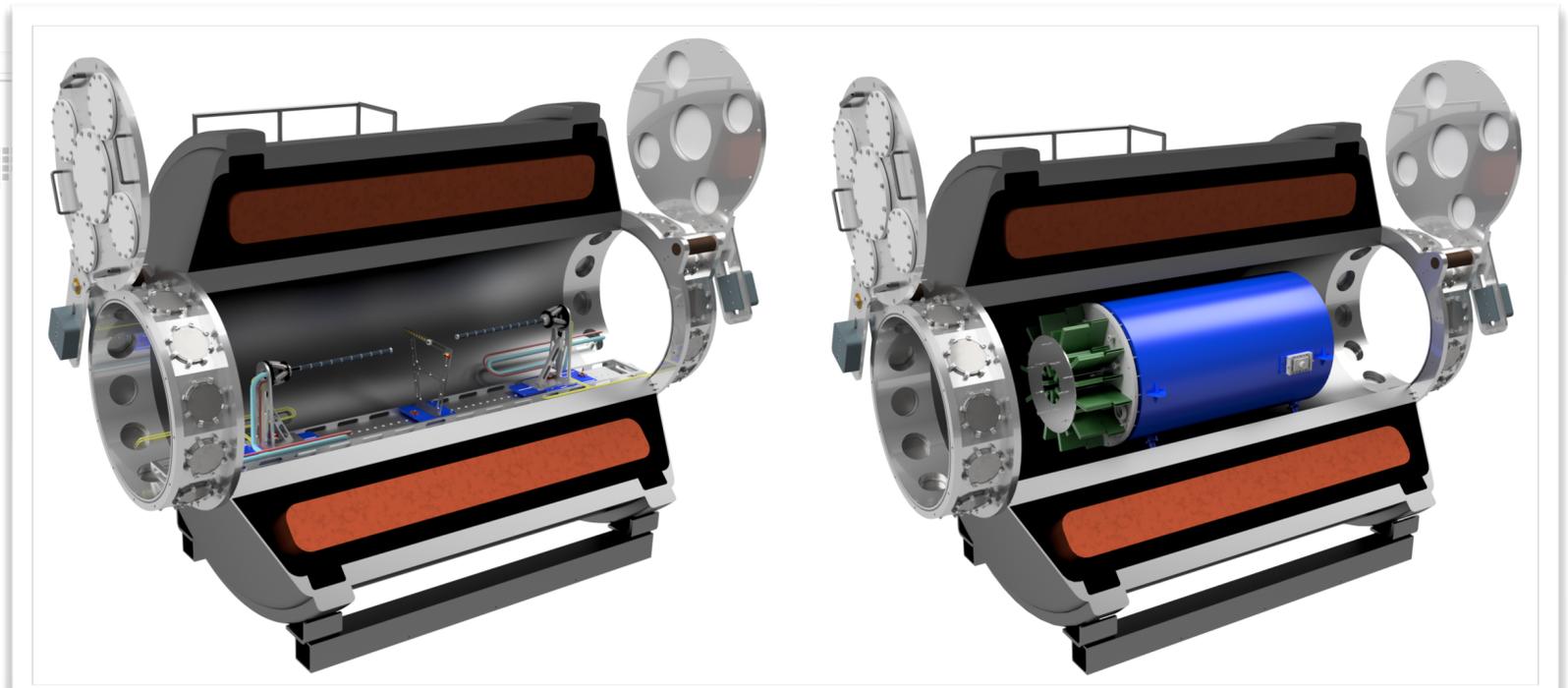
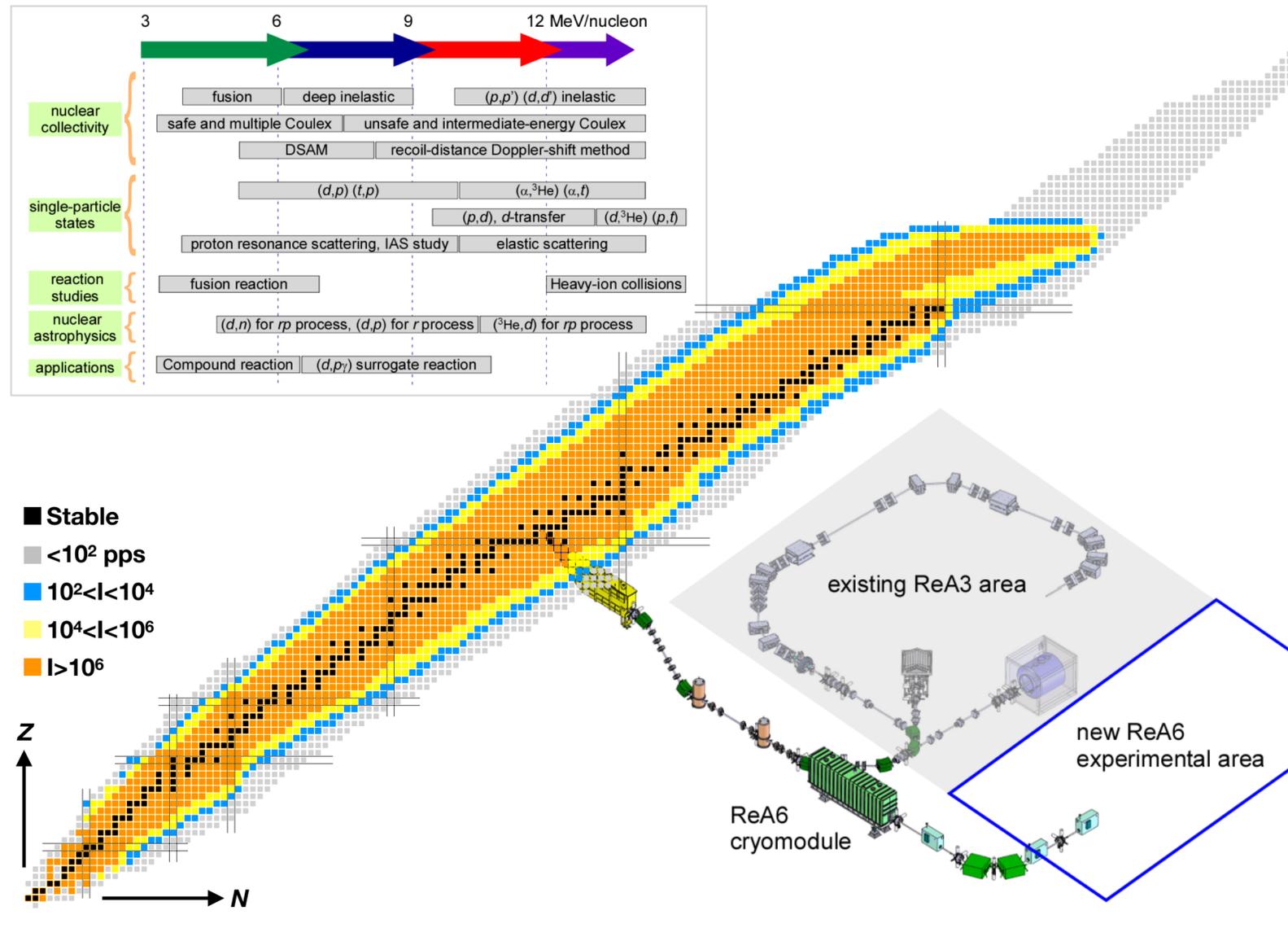
Kuvin et al., unpublished



McNeel et al., *Phys. Rev. C* **103**, 064320 (2021)

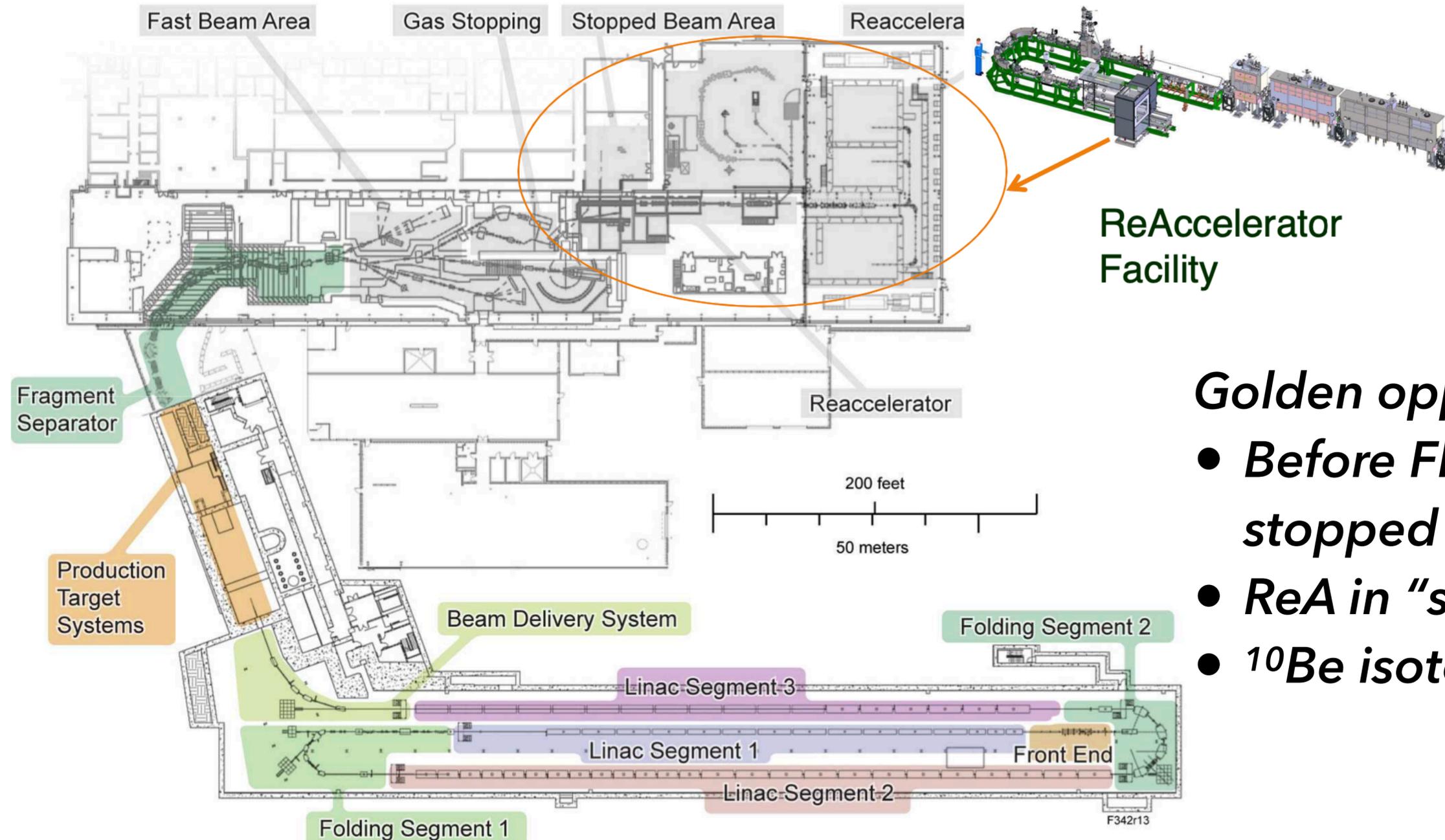
(Top) Example of the  $^{11}\text{B}(t,p)$  reaction in HELIOS (below) and the  $^{26}\text{Mg}(t,p)$  reaction

# Solution? SOLARIS



*A dual-mode solenoidal spectrometer to exploit the full dynamic range of the ReA facility at FRIB*

# FRIB Accelerator Complex Subsystems

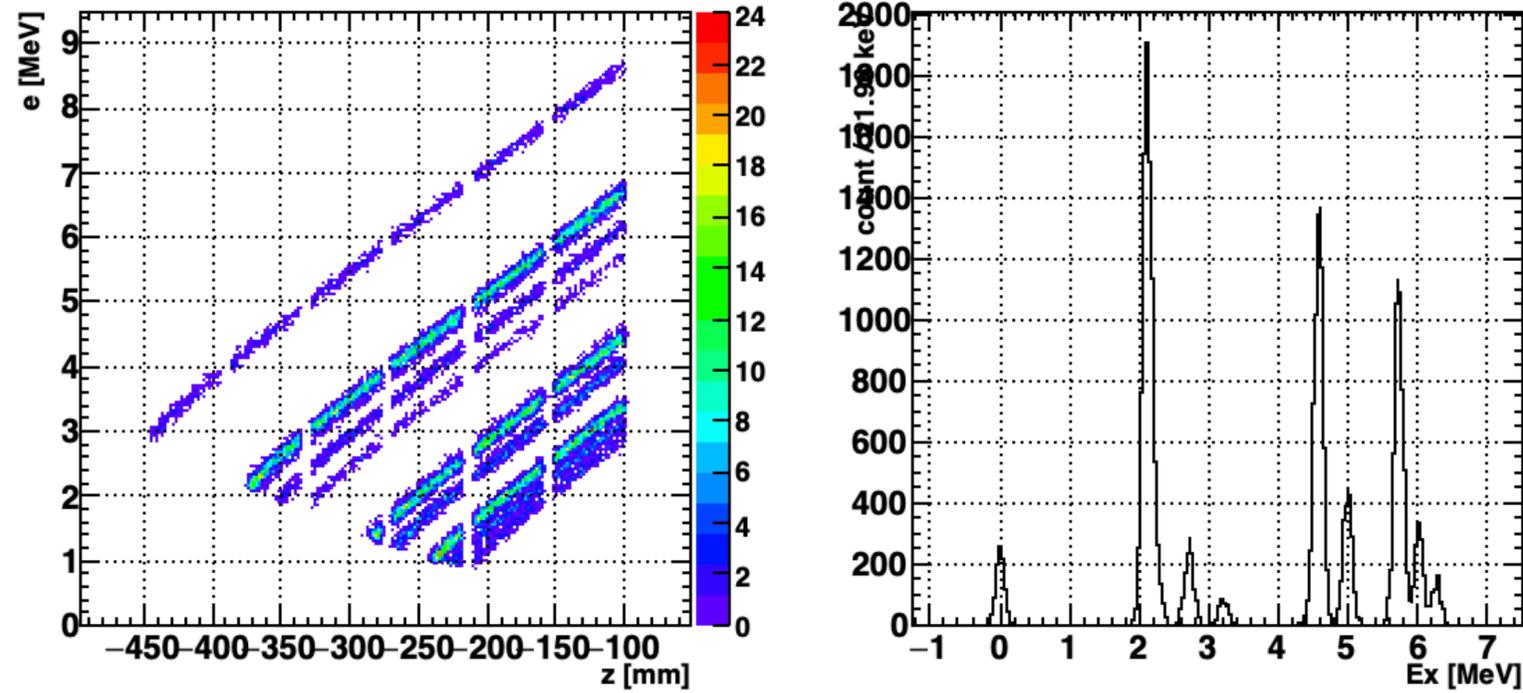


**Golden opportunity in 2021:**

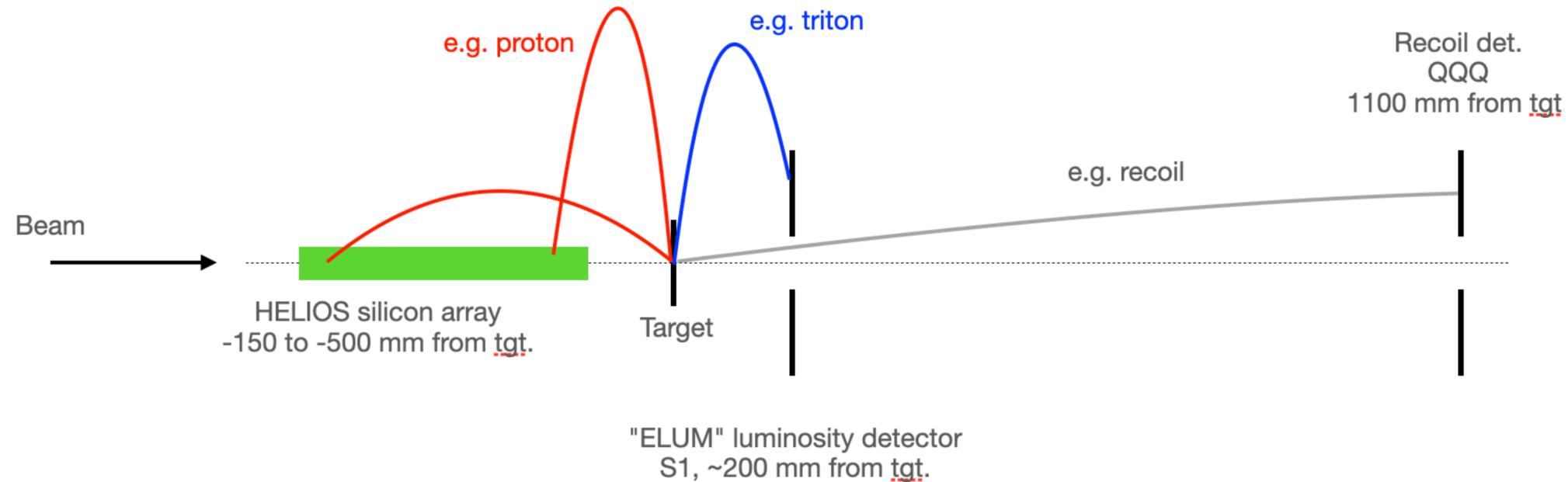
- *Before FRIB started, NSCL stopped*
- *ReA in "standalone" mode*
- *$^{10}\text{Be}$  isotope by PSI*

# Physics

$^{10}\text{Be}(t,p) @ 9.6 \text{ MeV/u}$

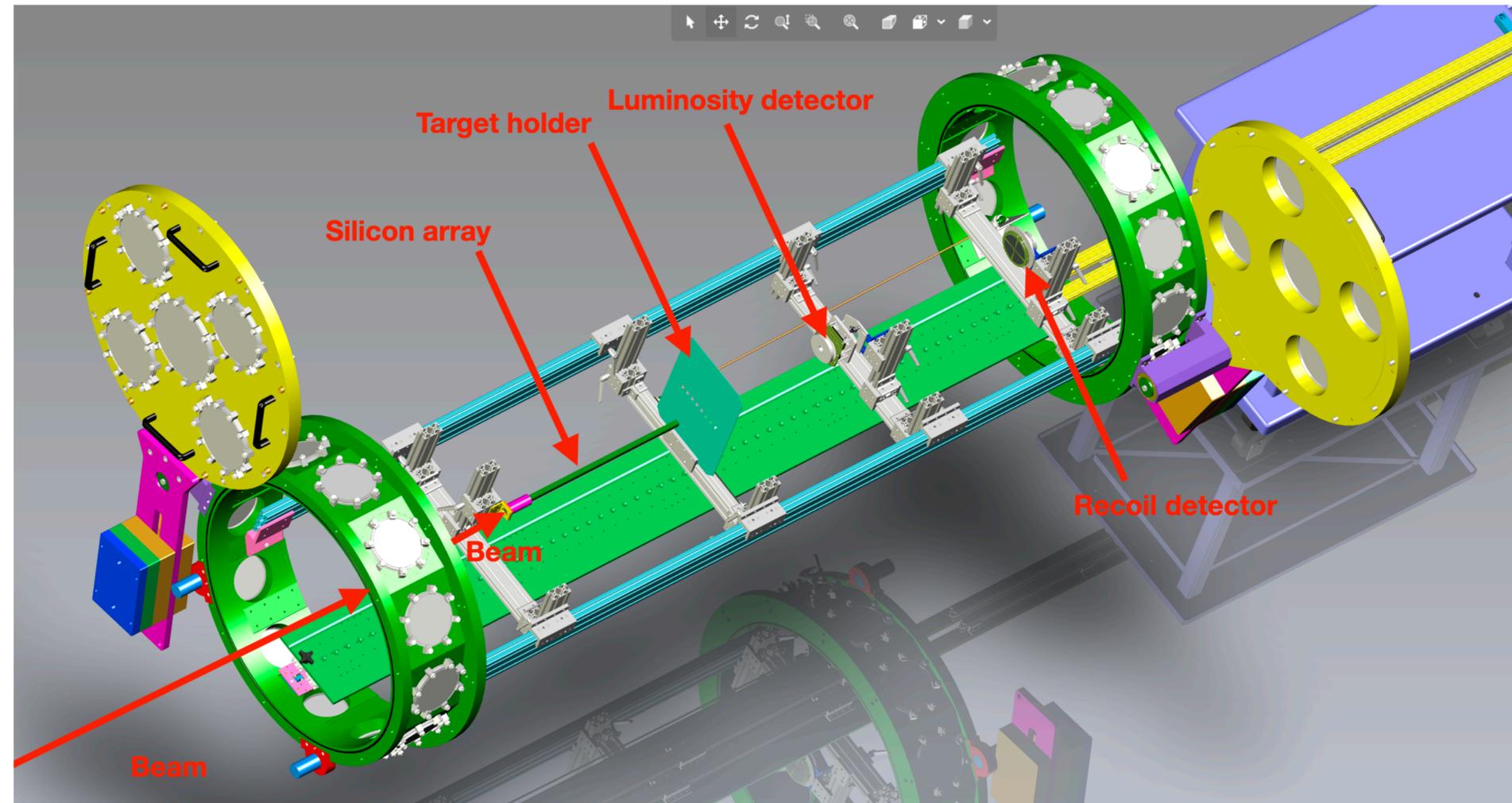


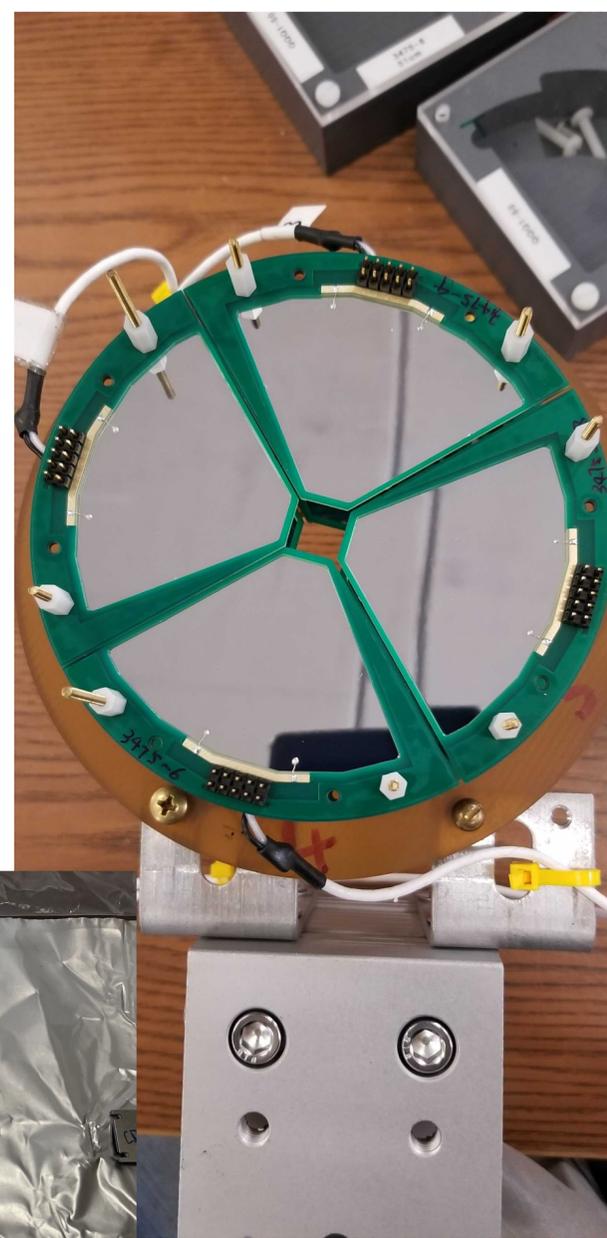
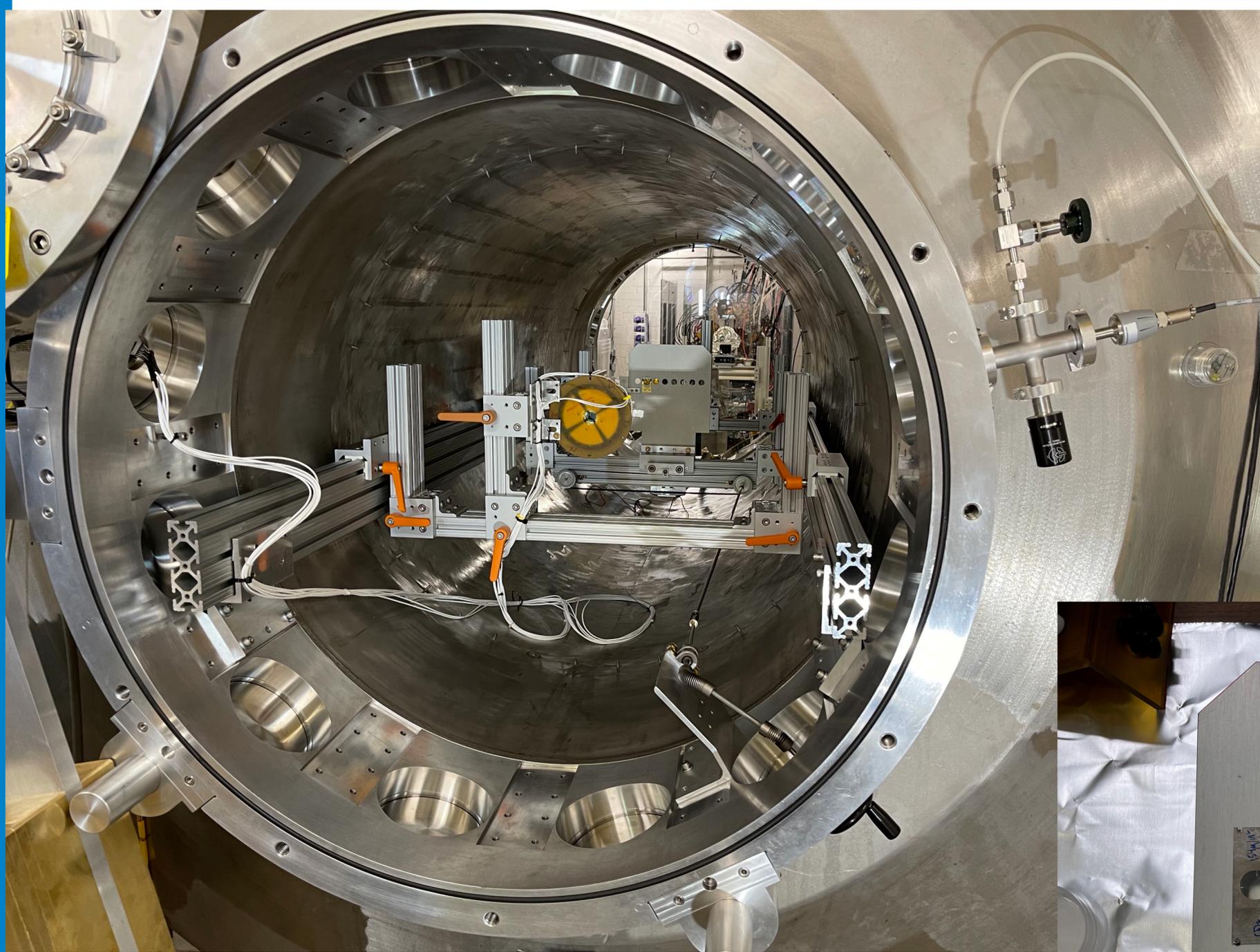
$$E_{lab} = E_{cm} - \frac{1}{2} m V_{cm}^2 + \left( \frac{m V_{cm}}{T_{cyc}} \right) z$$



# Using SOLARIS

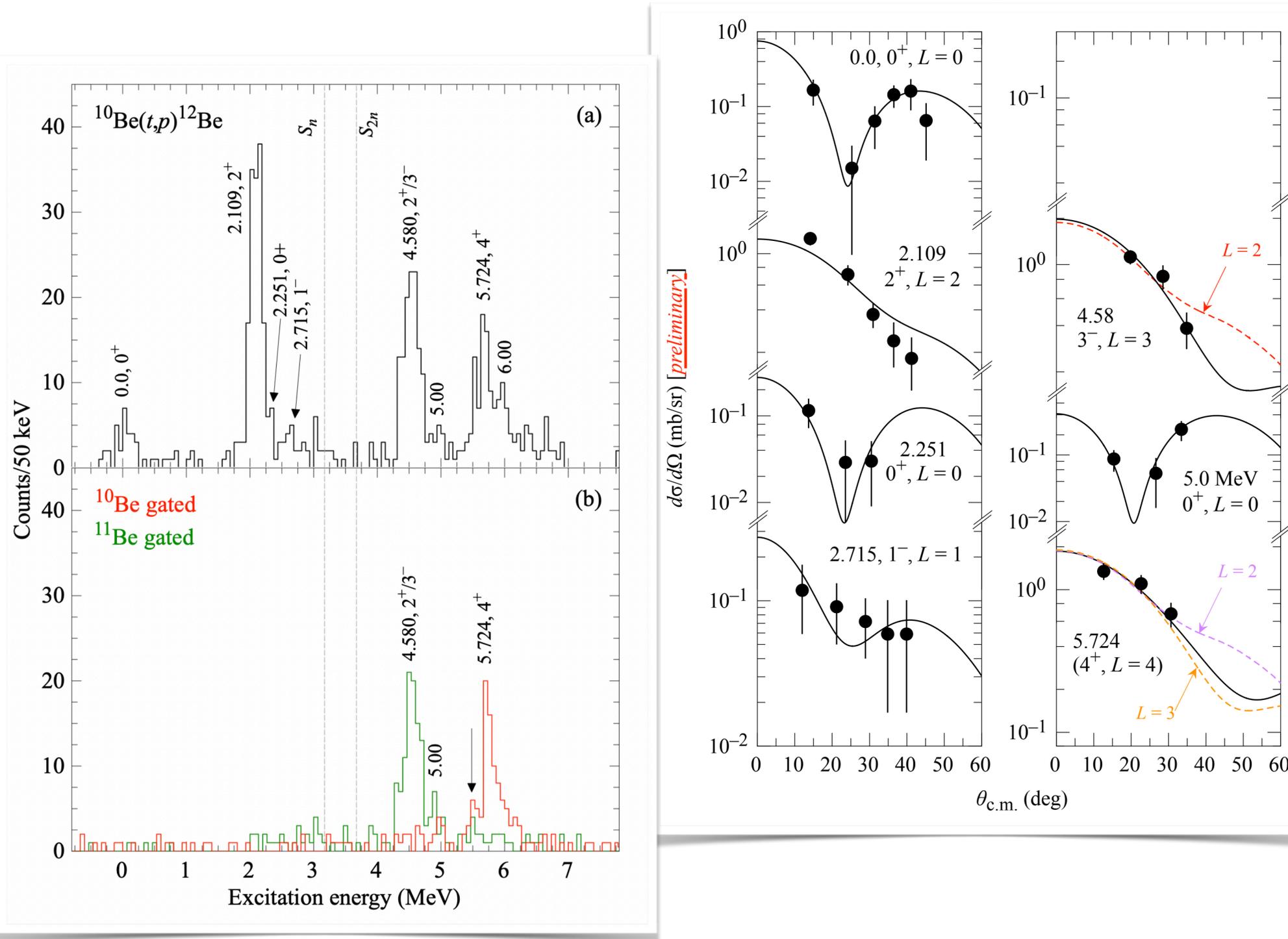
- $^{10}\text{Be}$  beam at **9.6 MeV/u** on titanium tritide target ( $2\text{-}5\ \mu\text{g}/\text{cm}^2$ !!!)
- Helios Si-array for protons
- Recoil detection: annular Si detectors
- B field of **3T**
- Q-value resolution  $\sim 150\ \text{keV FWHM}$





# Preliminary results

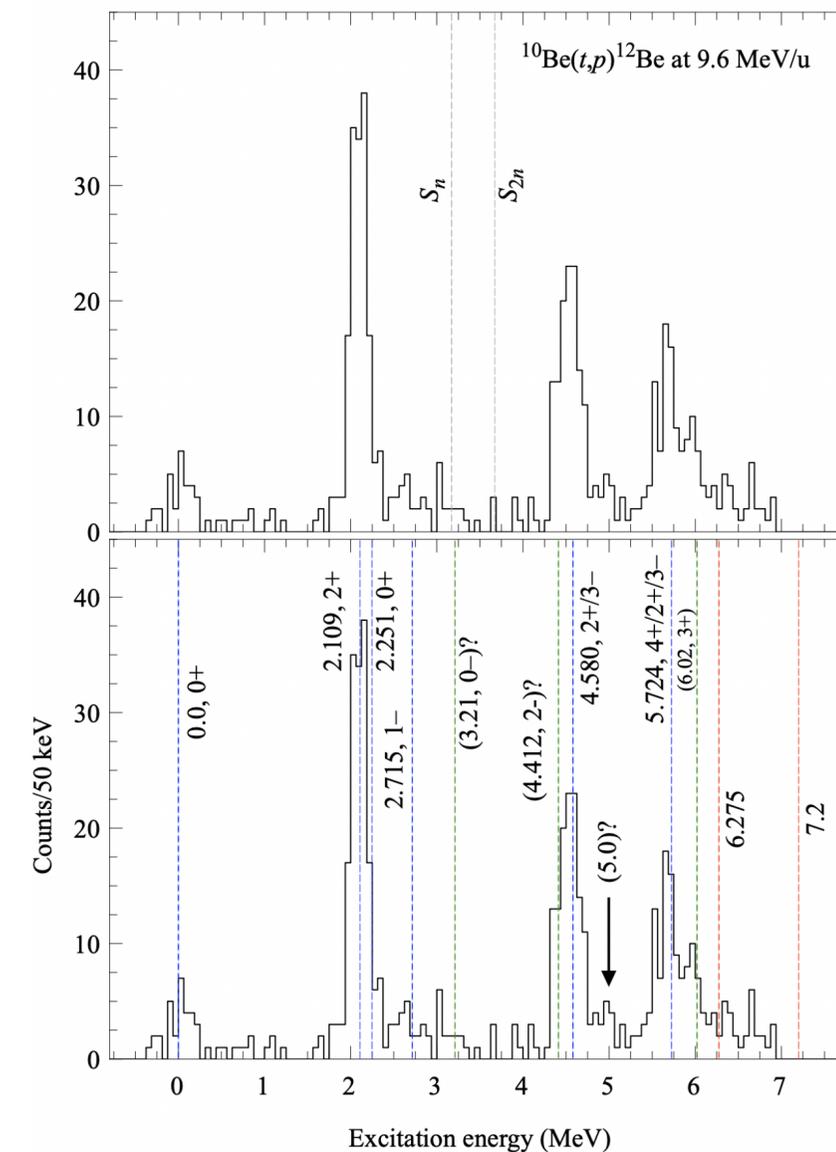
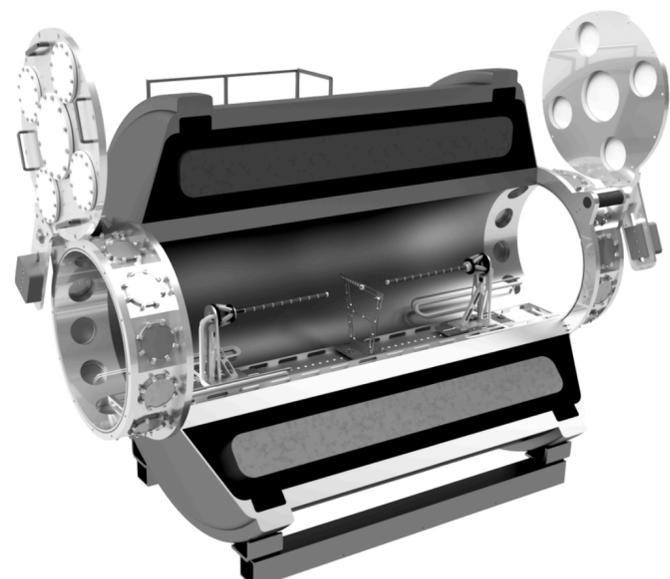
- Limited statistics (very [effectively] thin target), but also very low background



- Confirm** previous results from  $(t,p)$ , below  $S_n/S_{2n}$  (2nd  $0^+$  challenging to fit)
- See some **strength at 3.2 MeV**, recently postulated to be  $0^-$  in  $(d,p)$  -- no firm conclusions yet
- Possibly confirm** the long speculated  $3^-$  at 4.6 MeV is consistent with a  $3^-$  (but could be doublet)
- Clear strength at 5.0 MeV**, with shape **compatible with  $0^+$**  (3rd  $0^+$  predicted to be weak and at around  $\sim 5$  MeV)
- The 5.724 MeV state must be  $4^+$ , **some strength at 6.0 MeV** and at 6.275 MeV

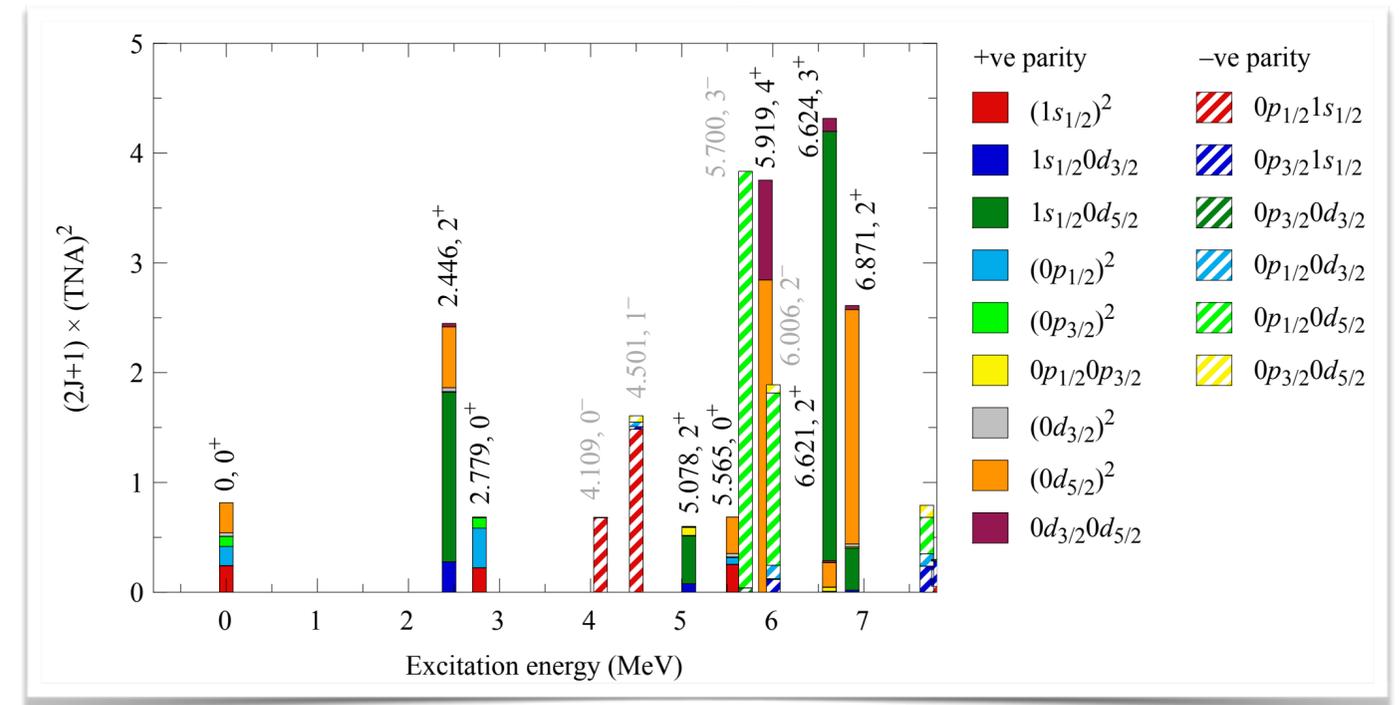
# Conclusions

1. *Powerful demonstration of ReA and SOLARIS*
2. *Agreement with previous results from (t,p) below  $S_n$*
3. *Possibly confirmation of  $3^-$  at 4.6 MeV*
4. *Clear strength at 5.0 MeV with compatible shape with  $0^+$*
5. *Some strength at 3.2 MeV and significant strength at 6.0 MeV and 6.275 MeV*



# Future work

- *Full DWBA (Fresco) analysis with shell-model two-nucleon amplitudes*
- *Future  $^{14}\text{C}$  in ATLAS*
- *$^9\text{Li}(t,p)$  run at CERN by Y. Ayyad et al.*
- *The study of  $^{11}\text{Be}(d,p)$  at CERN complements this work (Jie's talk from earlier)*



## SOLARIS collaboration:

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