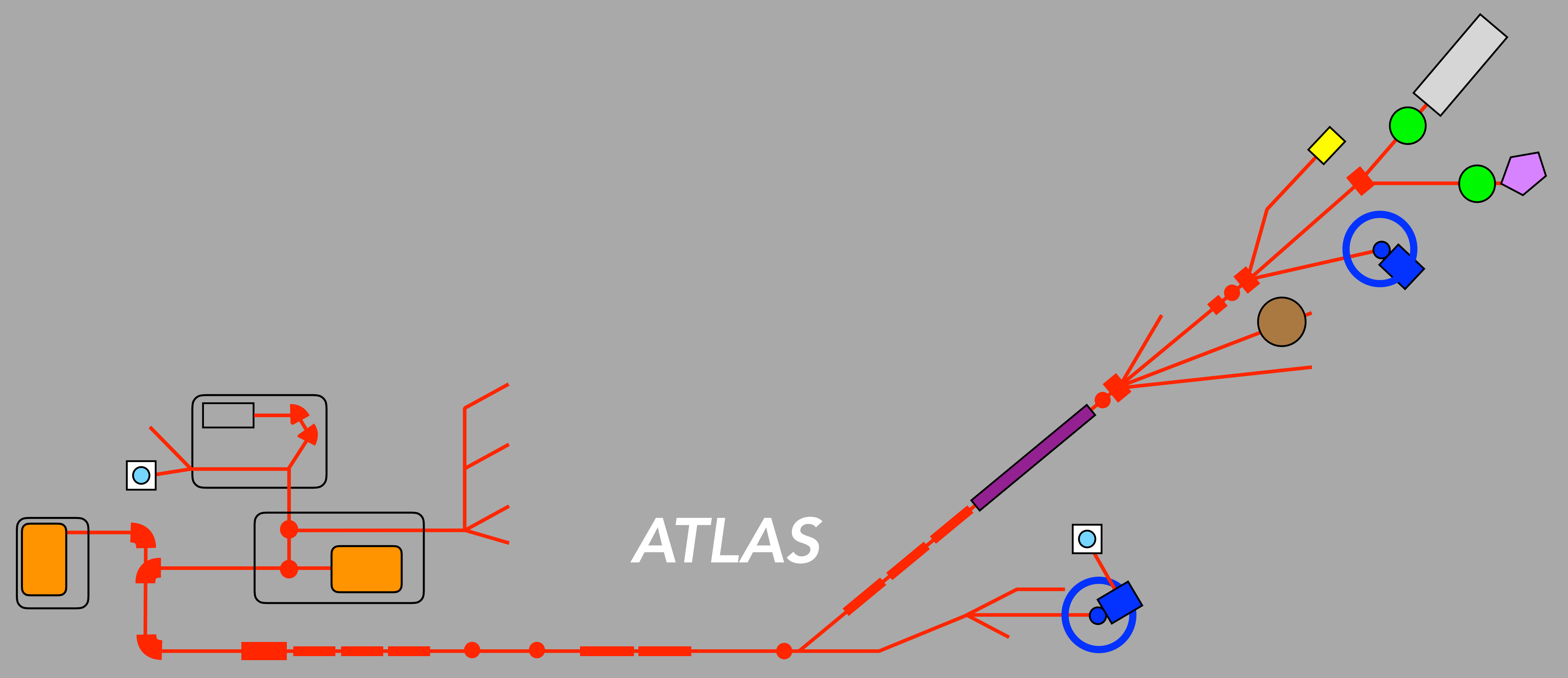
<u>HELIOS</u>: New Results and Future Developments



Benjamin P. Kay, Physics Division, Argonne National Laboratory
ISOLDE Workshop and Users Meeting, December 2017

THE UNIVERSITY *of York*

*HELIOS: a new approach to studying transfer reactions in inverse kinematics**

(and potential for the use of a HELIOS-like spectrometer at HIE-ISOLDE)

Benjamin P. Kay
The University of York

ISOLDE Workshop and Users meeting
8-10 December 2010

**This work is supported by the US Department of Energy, Office of Nuclear Physics under Contract No. DE-AC02-06CH11357 and Grant No. DE-FG02-04ER41320, NSF Grant No. PHY-02-16783, and the UK Science and Technology Facilities Council*

Overview

Inverse kinematics, HELIOS

- ➡ *Direct reactions with RI beams*
- ➡ *HELIOS at the ATLAS facility*

Recent highlights

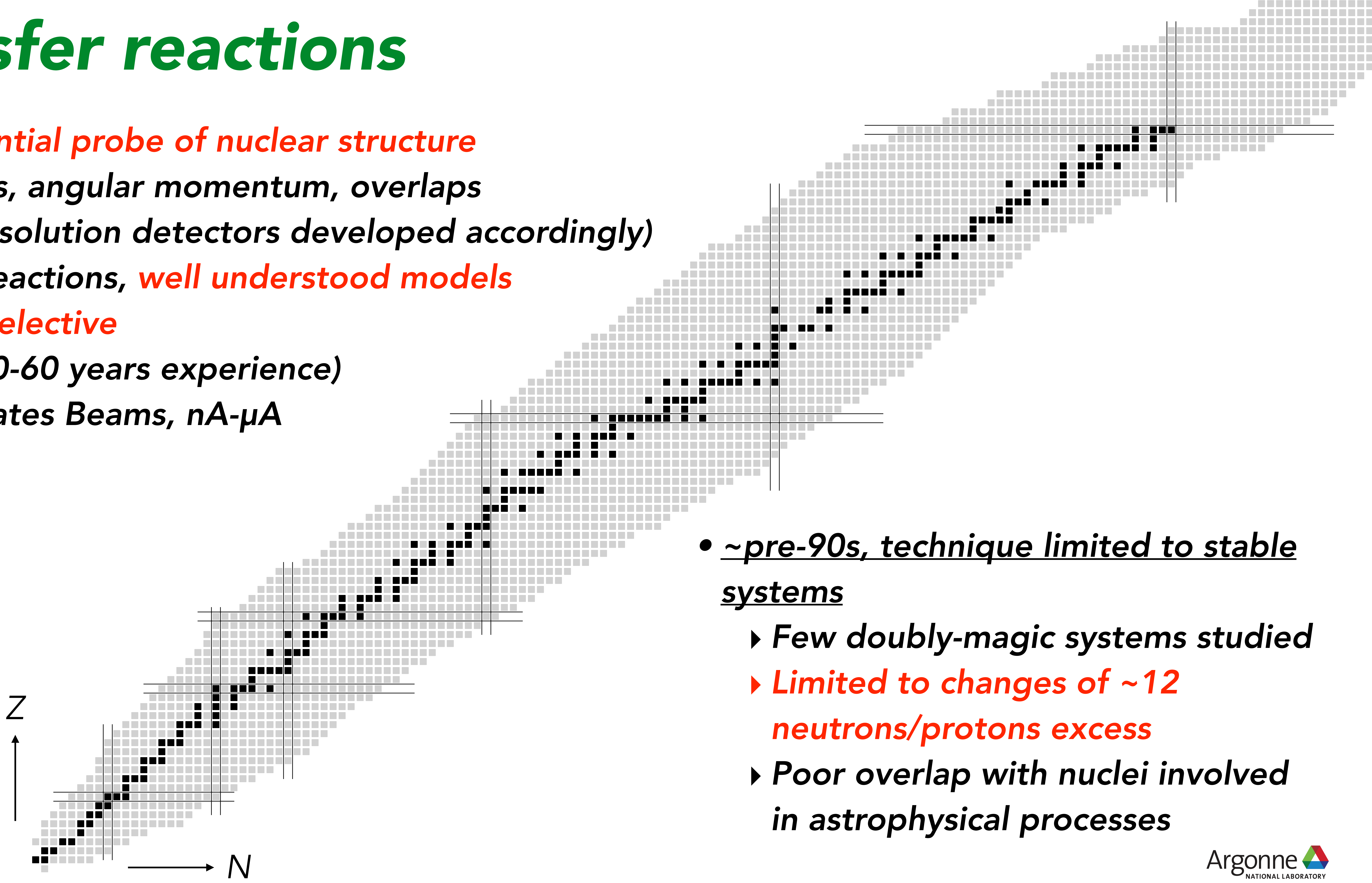
- ➡ *Inelastic scattering, Isomer beams*

Upgrades, ISS and SOLARIS

- ➡ *Better hardware: HELIOS's new siblings*

Transfer reactions

- An essential probe of nuclear structure
- Energies, angular momentum, overlaps
- (High-resolution detectors developed accordingly)
- Direct reactions, well understood models
- Highly selective
- (Over 50-60 years experience)
- Count rates Beams, nA-μA



- ~pre-90s, technique limited to stable systems
  - Few doubly-magic systems studied
  - Limited to changes of ~12 neutrons/protons excess
  - Poor overlap with nuclei involved in astrophysical processes

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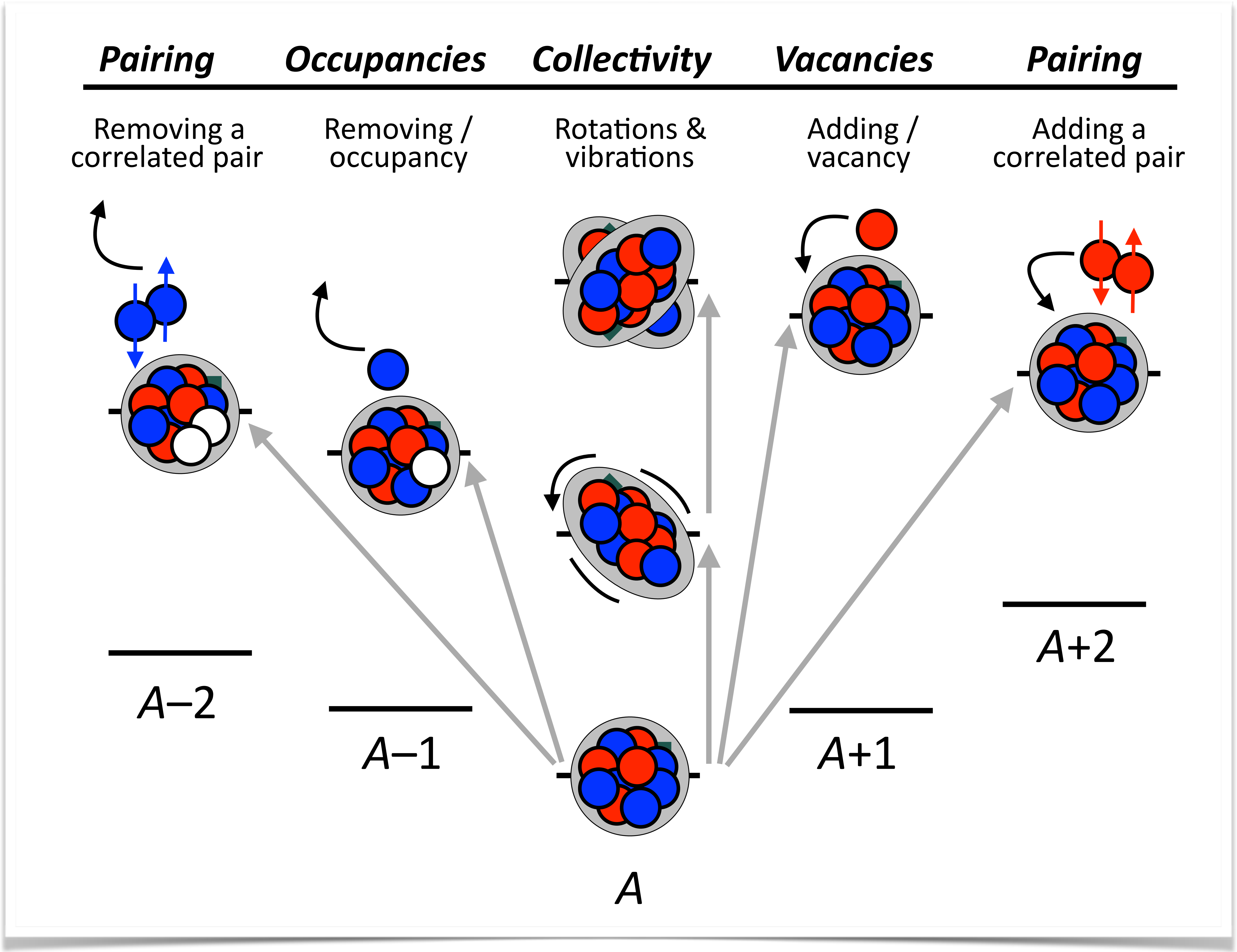
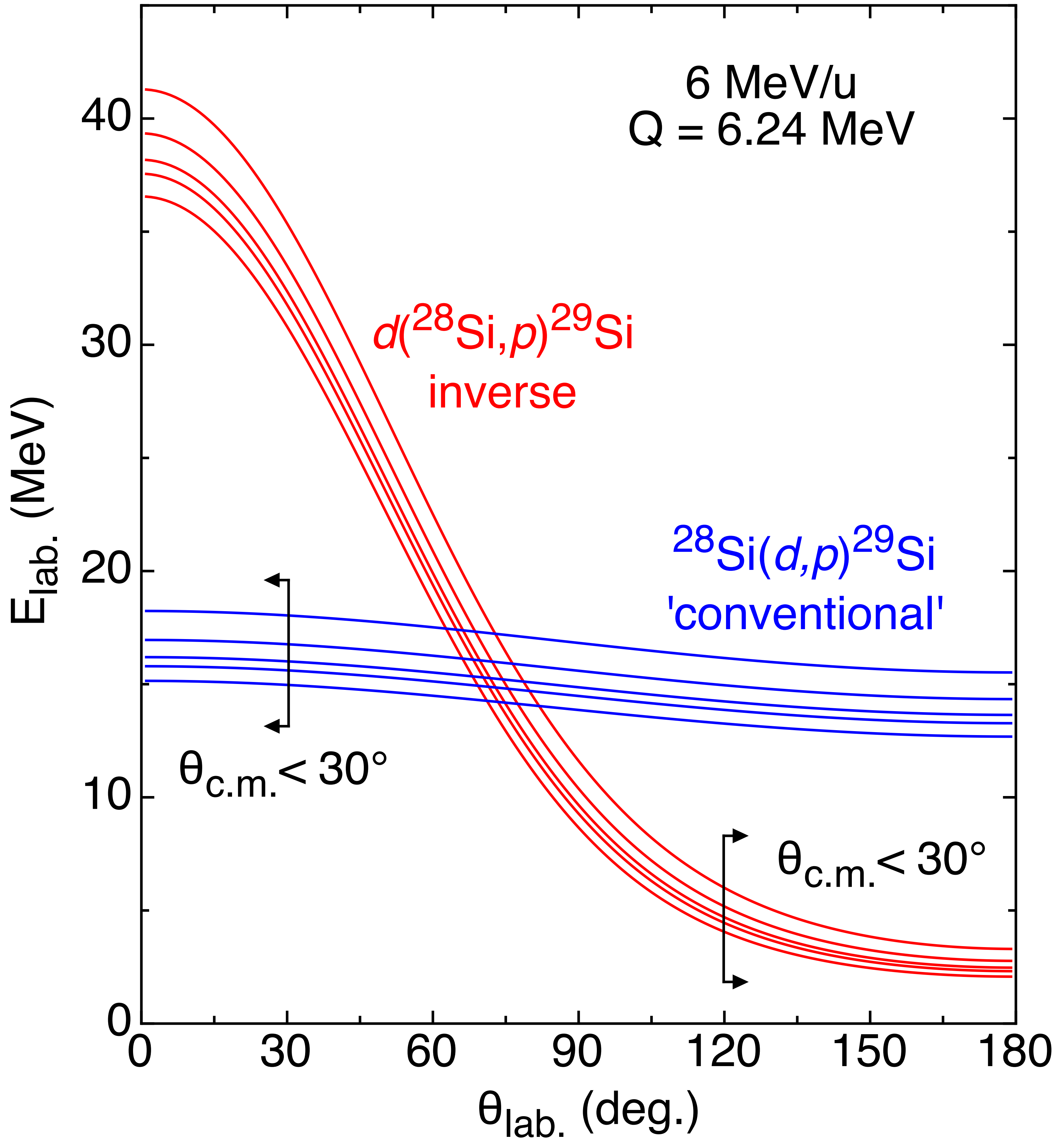
Direct reactions with RI beams

10 MeV/u (5-20 MeV/u), >10^4 pps

- single-particles states, $E_{(ex,spe)}$, *l*-values, spectroscopic factors, e.g., (*d*,*p*), …
- pair correlations, e.g., (*p*,*t*), (*t*,*p*), (^{3}He,*p*), …
- Collective properties via, e.g, (p,p’), (*d*,*d*’), (α,α’), …



Kinematics: normal vs inverse



Inverse-kinematics challenges:

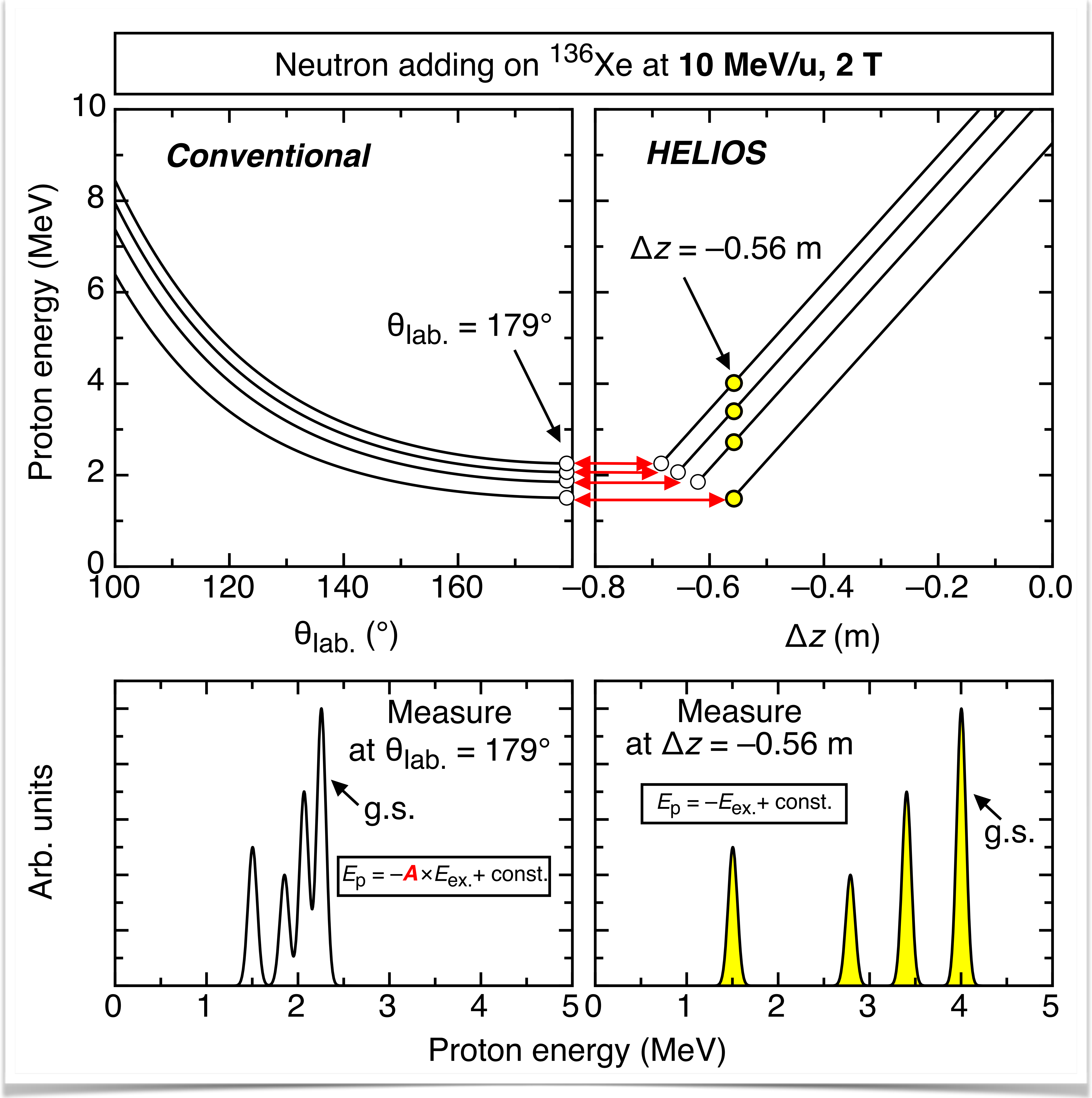
- Particle identification, ΔE-E techniques more challenging at low energies
- Strong energy dependence with respect to laboratory angle
- Kinematic compression at forward c.m. angles (in fact nearly all angles)
- Typically leading to poor resolution (100s of keV)
- … and beams a few to 10^6 orders of magnitude weaker (than stable beams)

Excellent Si arrays have been developed, with high angular granularity, large acceptance, and (often) coincident gamma-ray detection, *e.g.*, *MUST2* (GANIL), *T-REX* (ISOLDE), *SHARC* (TRIUMF), *ORRUBA* (ORNL, elsewhere), *TIARA* (GANIL, Texas A&M), etc.

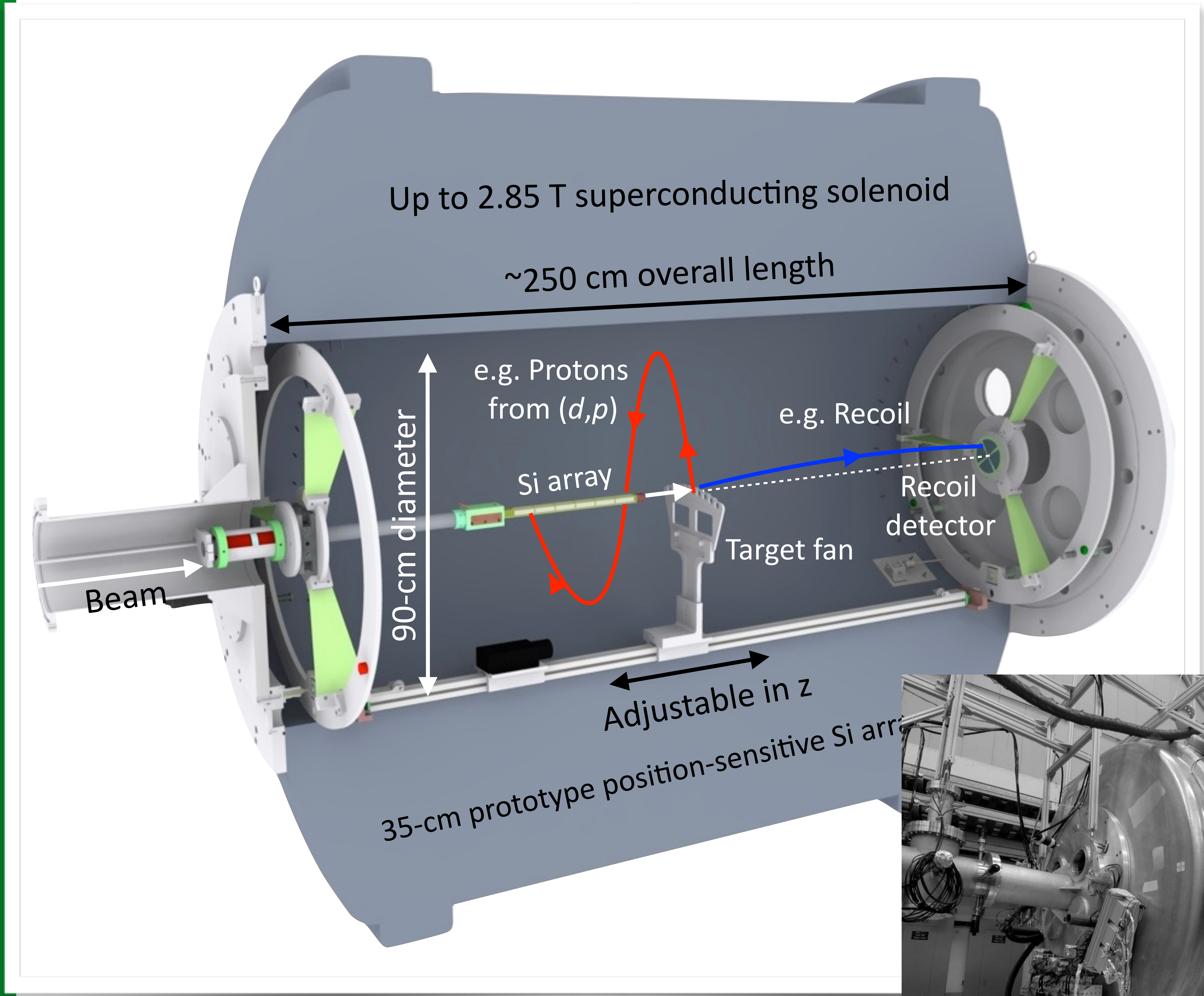
Transport through a solenoidal field

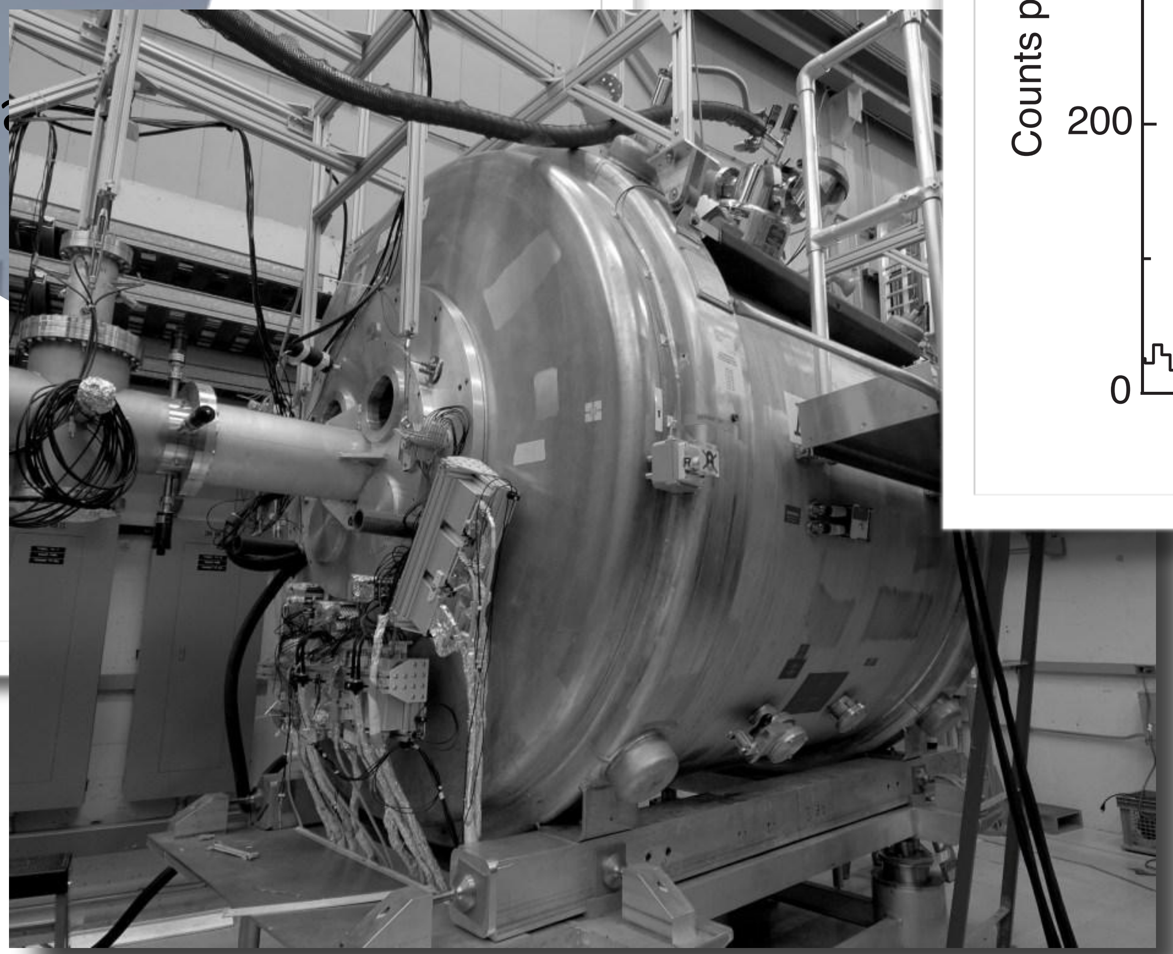
$$E_{\rm cm} = E_{\rm lab} + \frac{m}{2}V_{\rm cm}^2 - \frac{mV_{\rm cm}\,z}{T_{\rm cyc}}$$

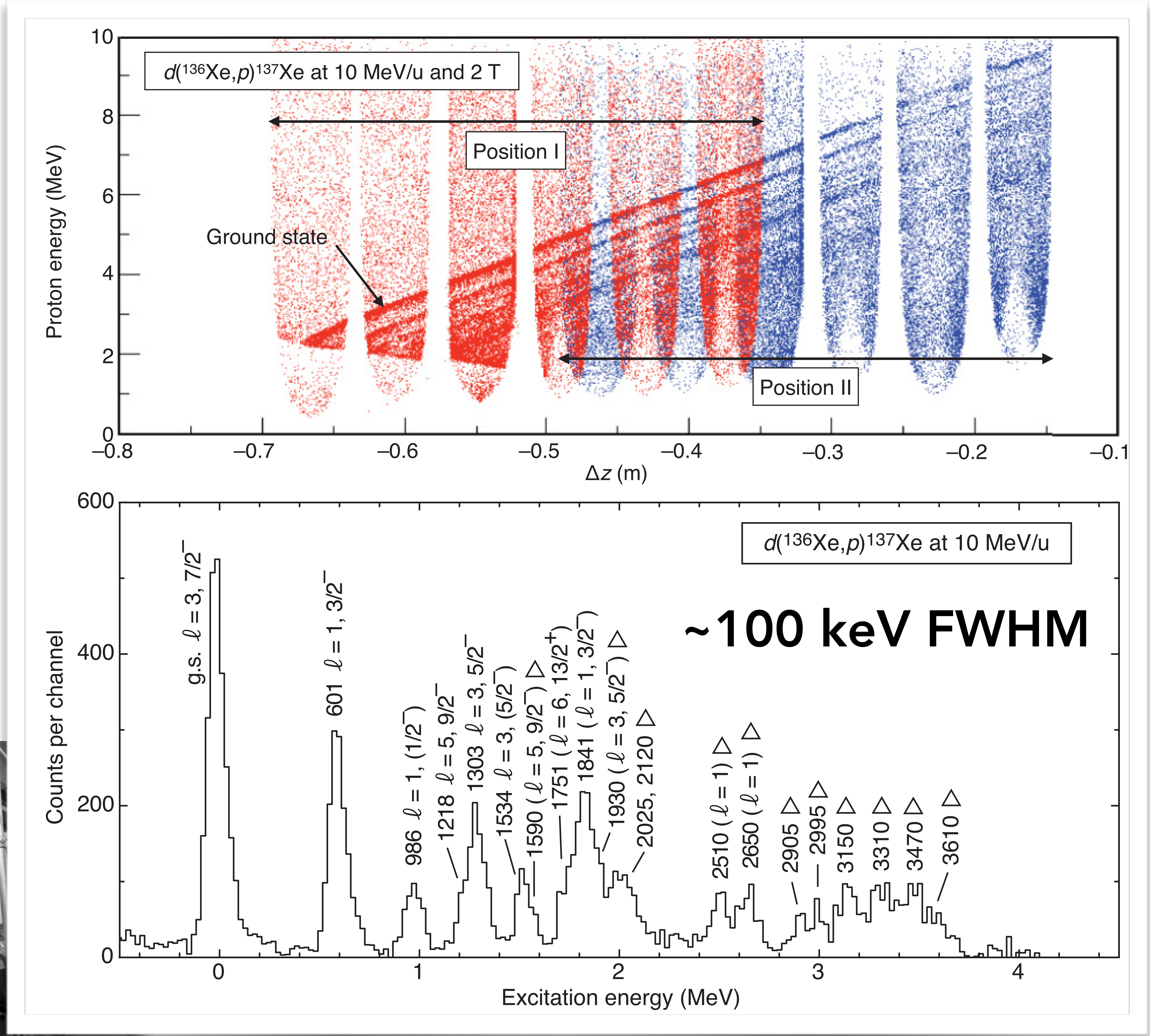
And the cyclotron period gives provides particle ID.



HELIOS *(it works)*







ATLAS, http://www.anl.gov/phy/

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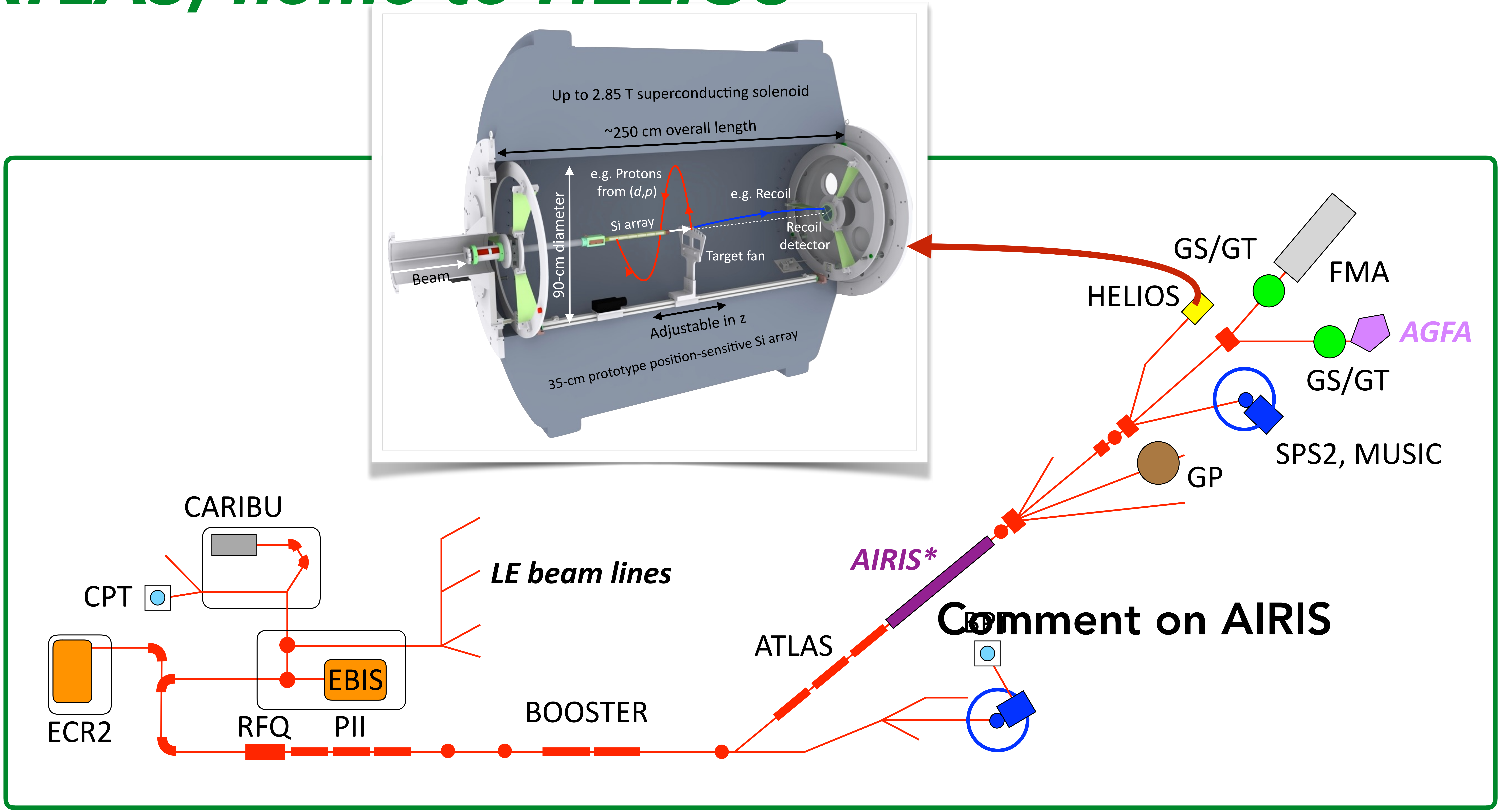
ATLAS, home to HELIOS



Comment on AIRIS

ATLAS, http://www.anl.gov/phy/

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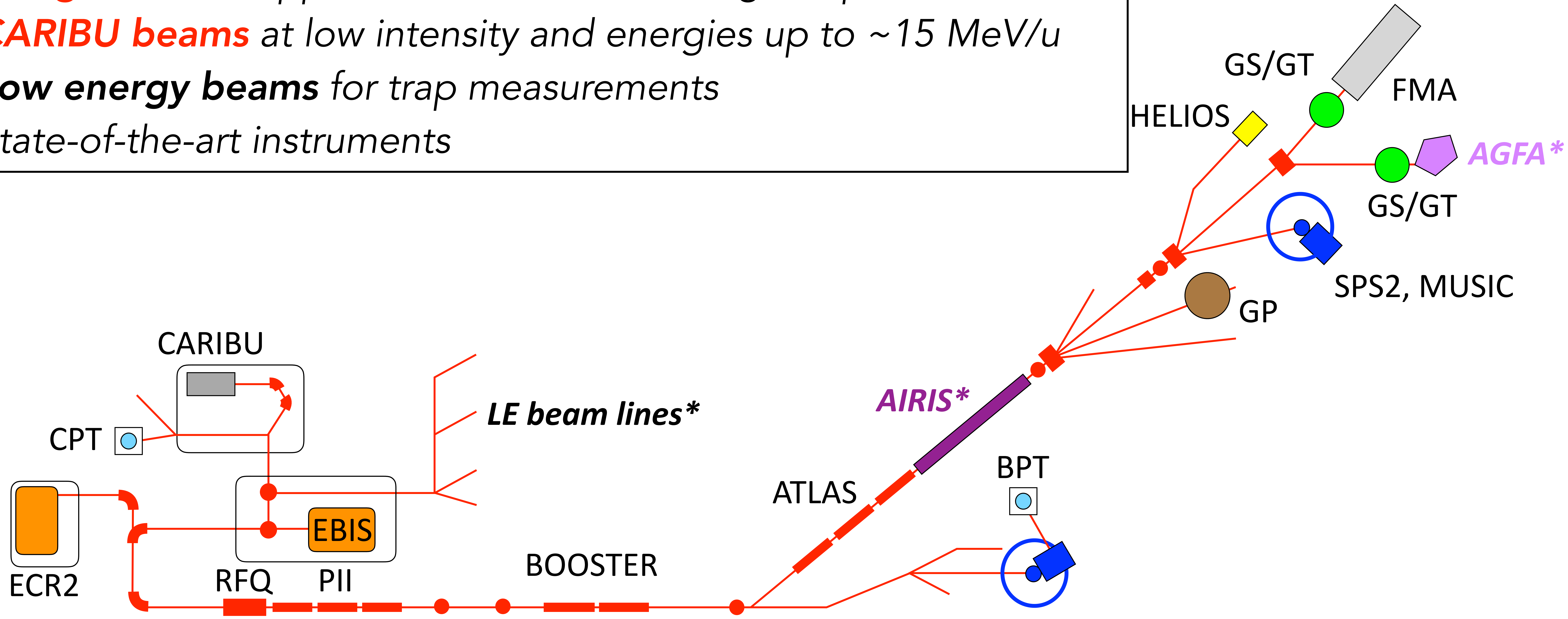
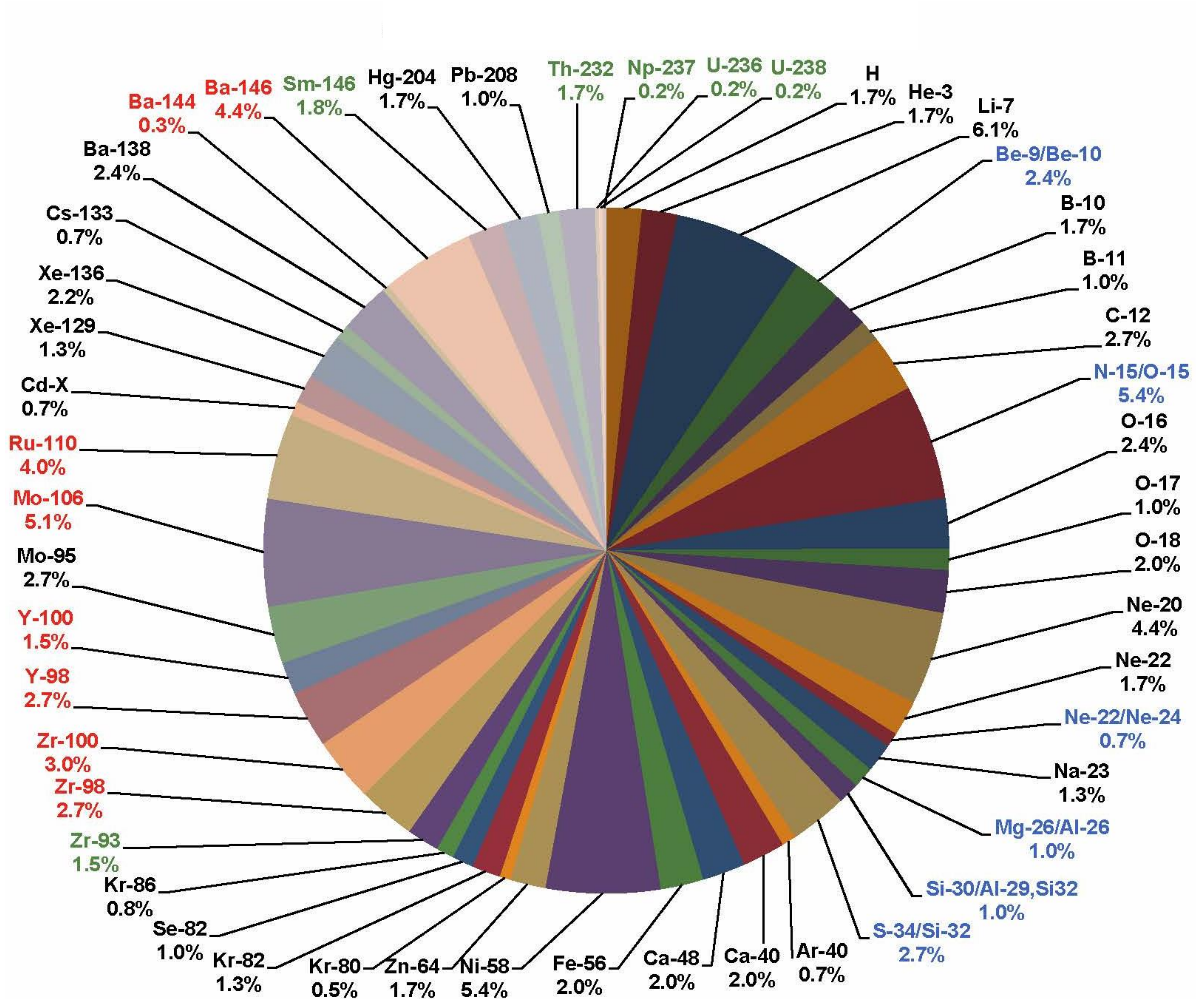
ATLAS *(today and near future)*

- ***Stable beams*** *at high intensity and energies up to ~20 MeV/u*
- ***In-flight beams*** *approx. 10 < A < 30 at energies up to ~20 MeV/u*
- ***CARIBU beams*** *at low intensity and energies up to ~15 MeV/u*
- ***Low energy beams*** *for trap measurements*
- *State-of-the-art instruments*



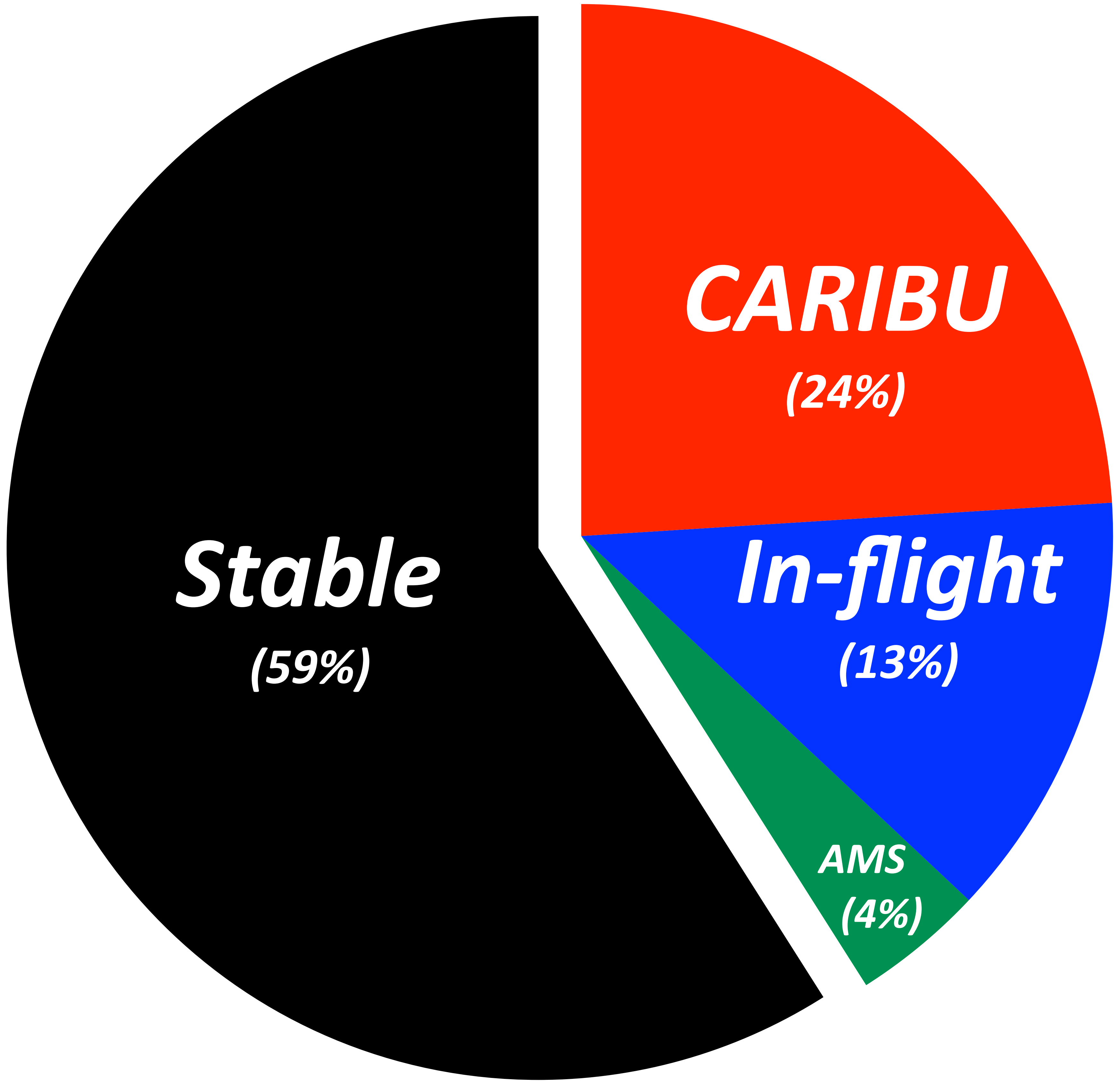
**upcoming instruments / capabilities*

ATLAS, e.g. beams (2015)



54 unique beams

37% resulting in a RIB on target



From the report on ATLAS at the Low Energy Community Meeting 2016, Notre Dame, G. Savard

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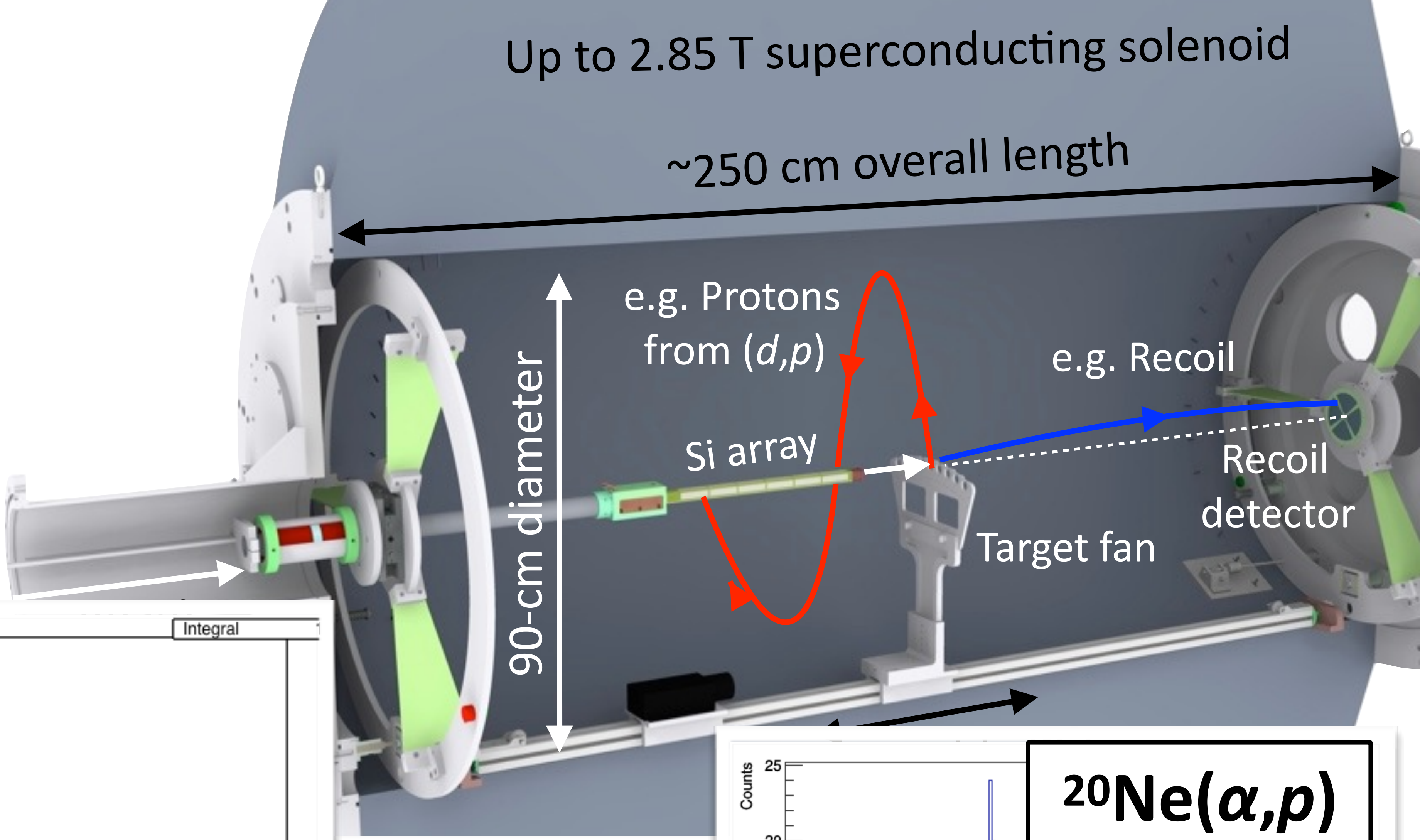
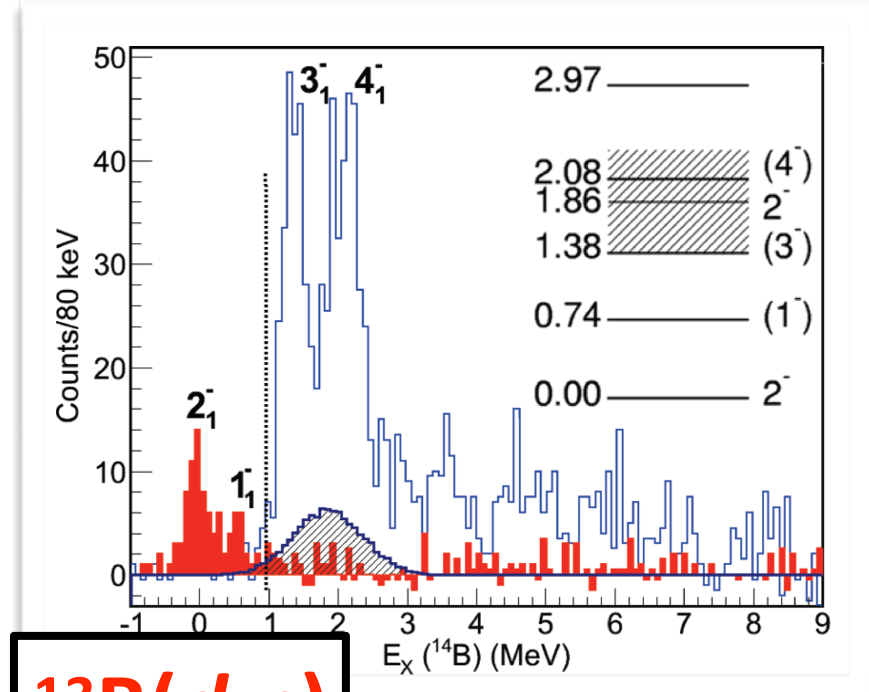
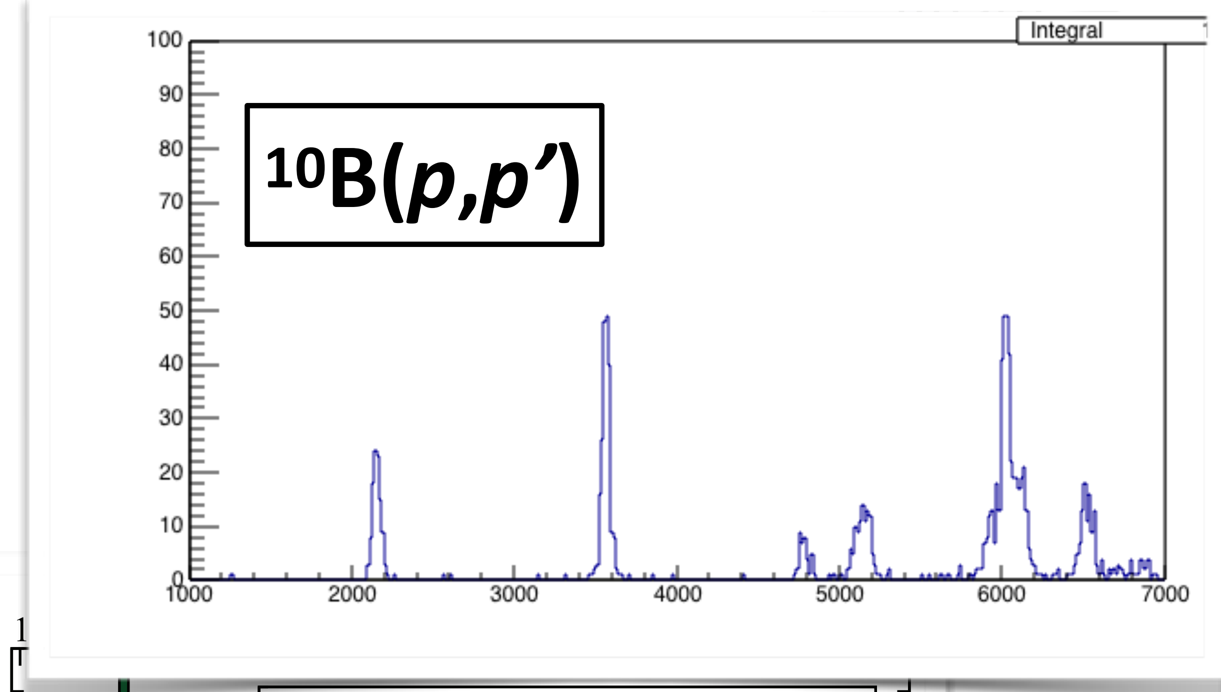
Snapshot

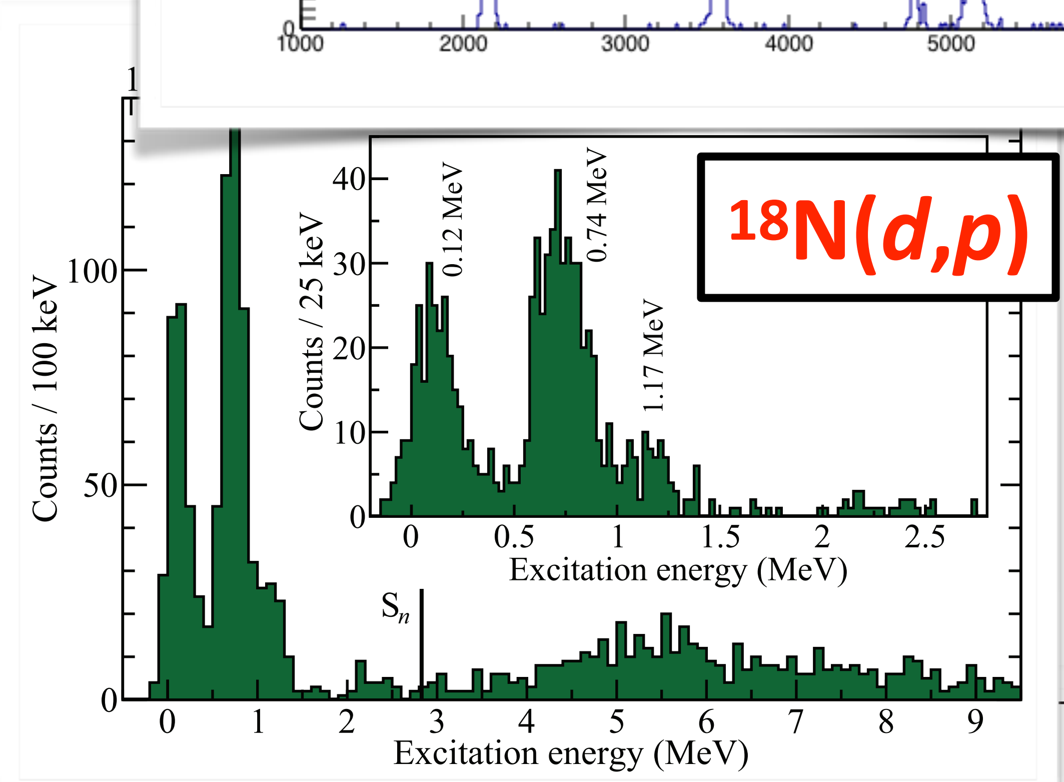
A highly versatile instrument

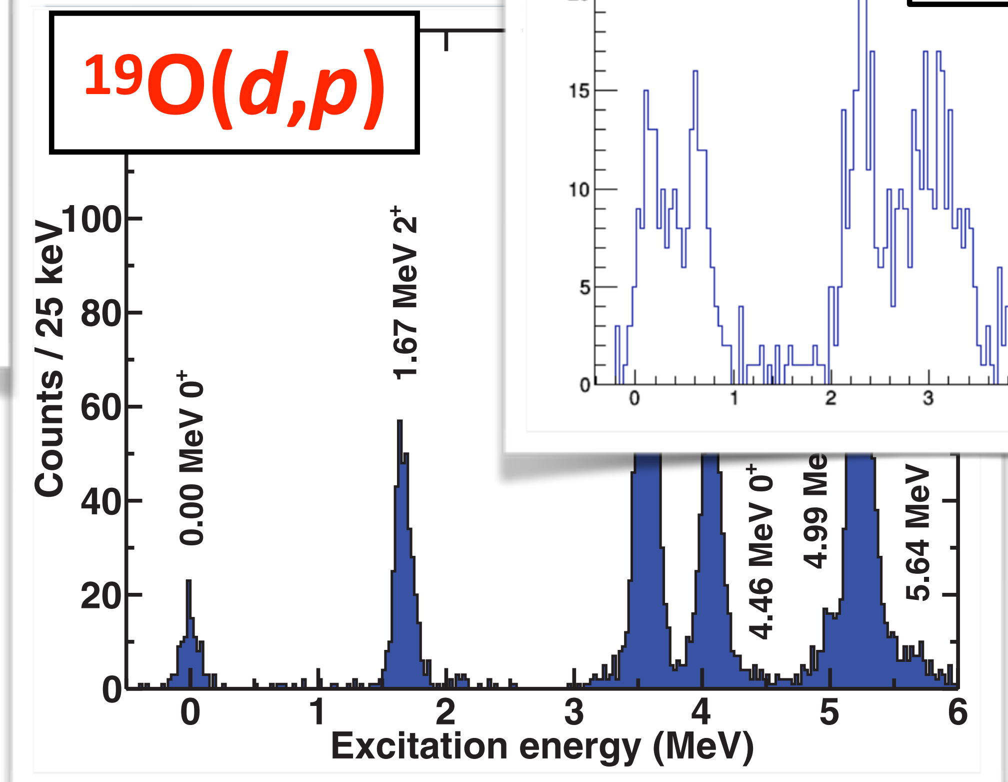
- ***Major research programs*** *from UConn, LANL, LSU, etc. Others include Berkeley, Lowell, CMU, Manchester, …*
- ***Apollo, gas target, ion chamber****, backwards / forwards / all routine*
- *Use of* ***tritium*** *target*

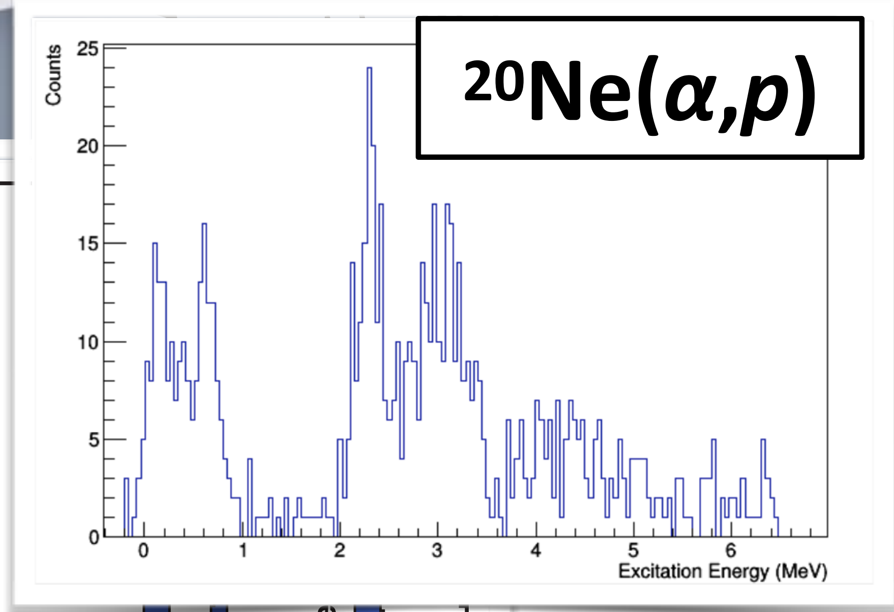


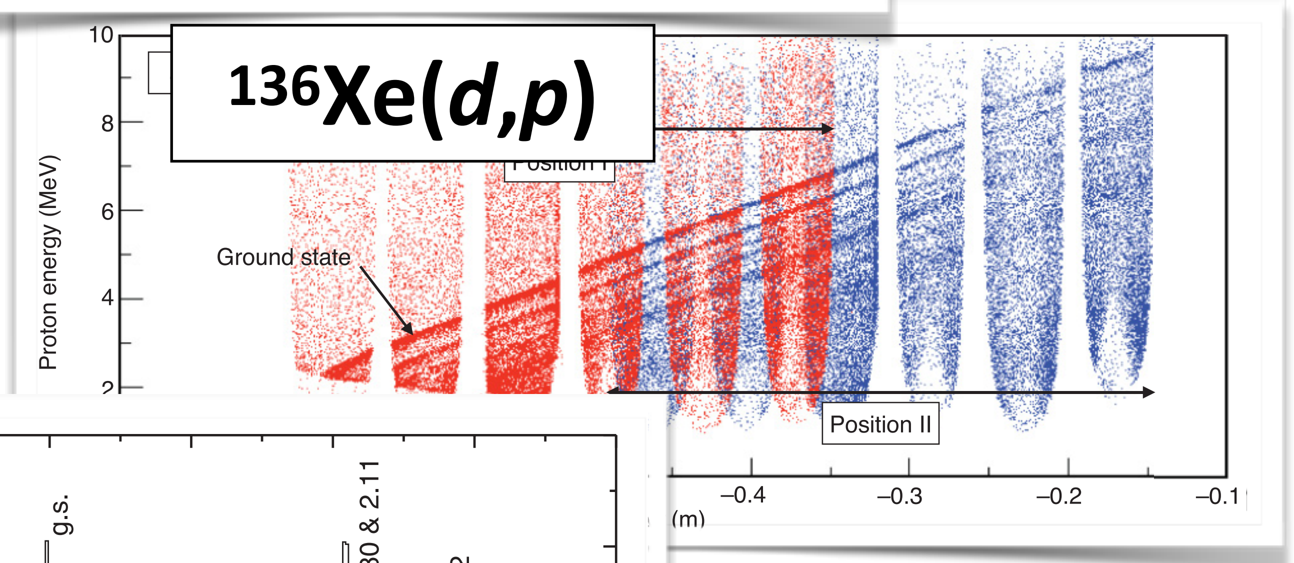


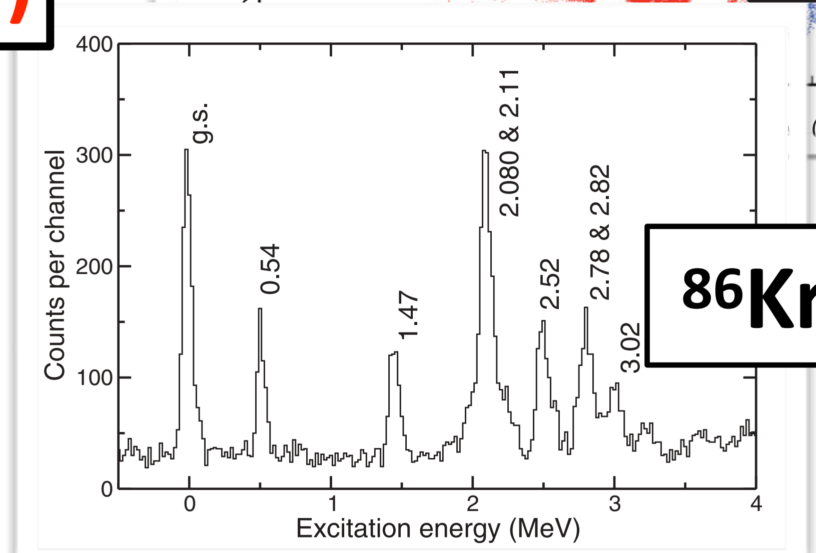


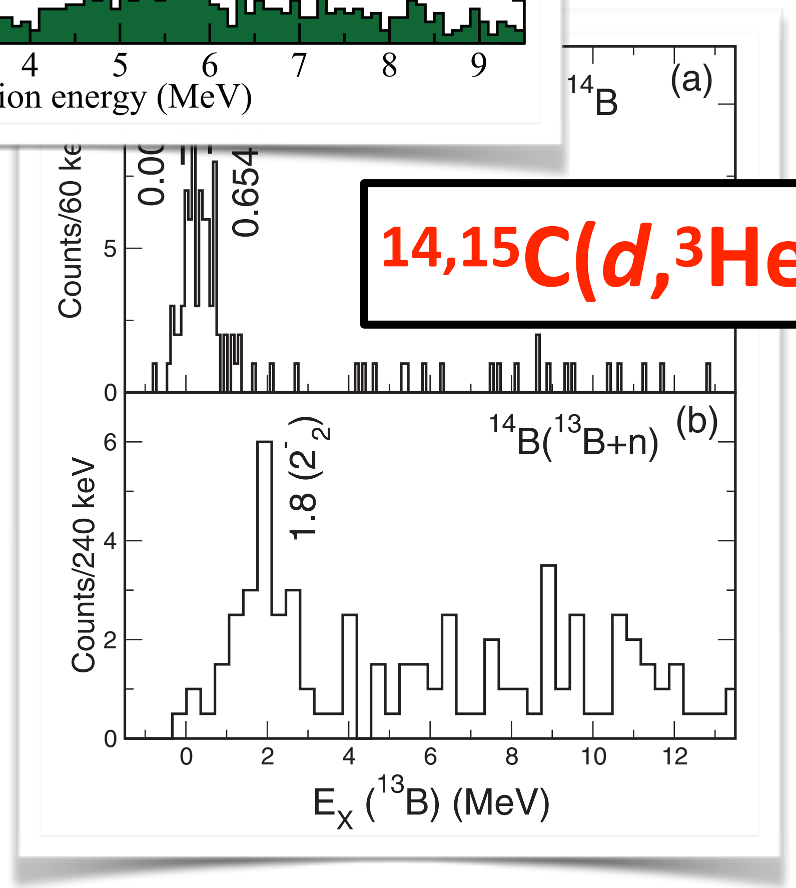


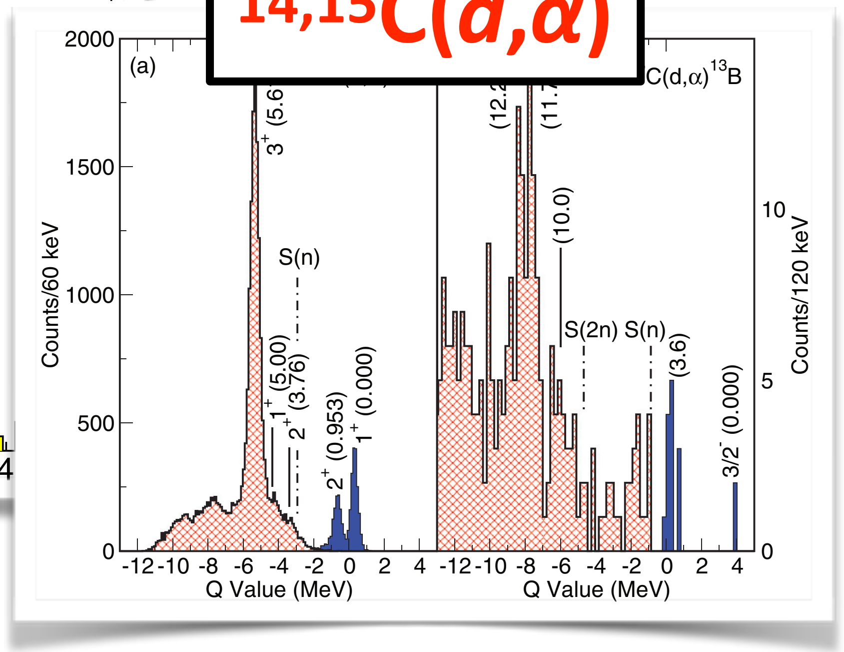


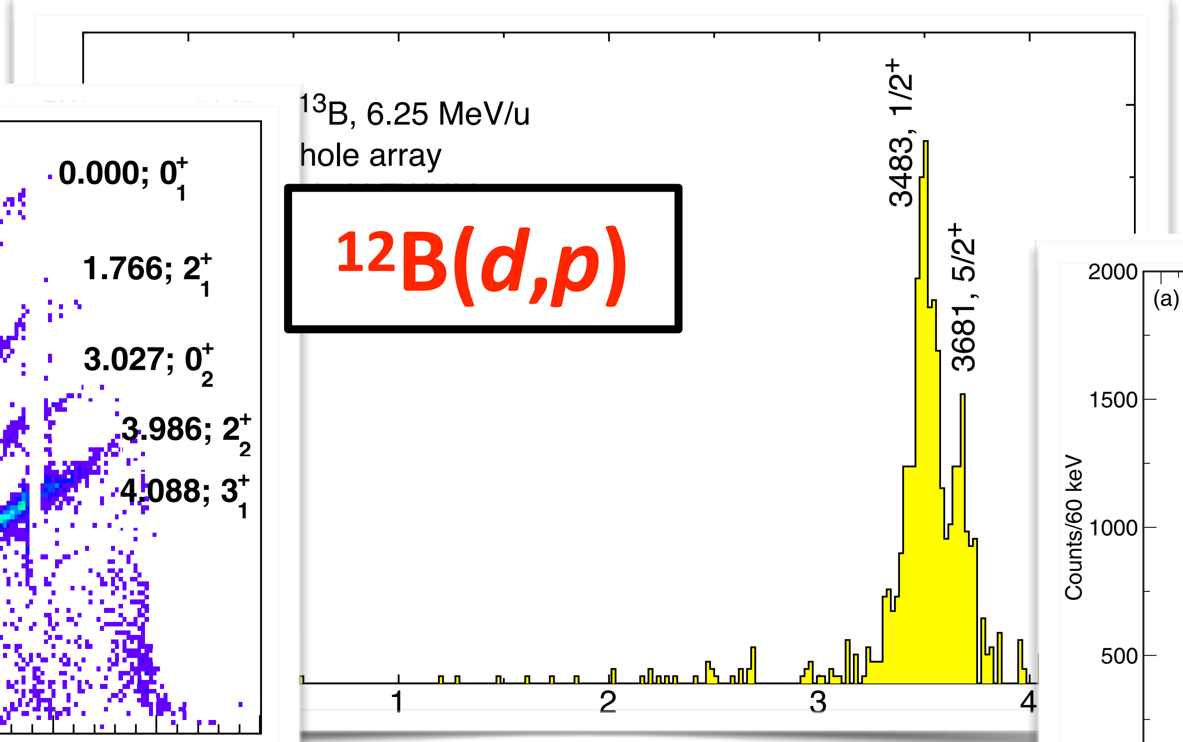


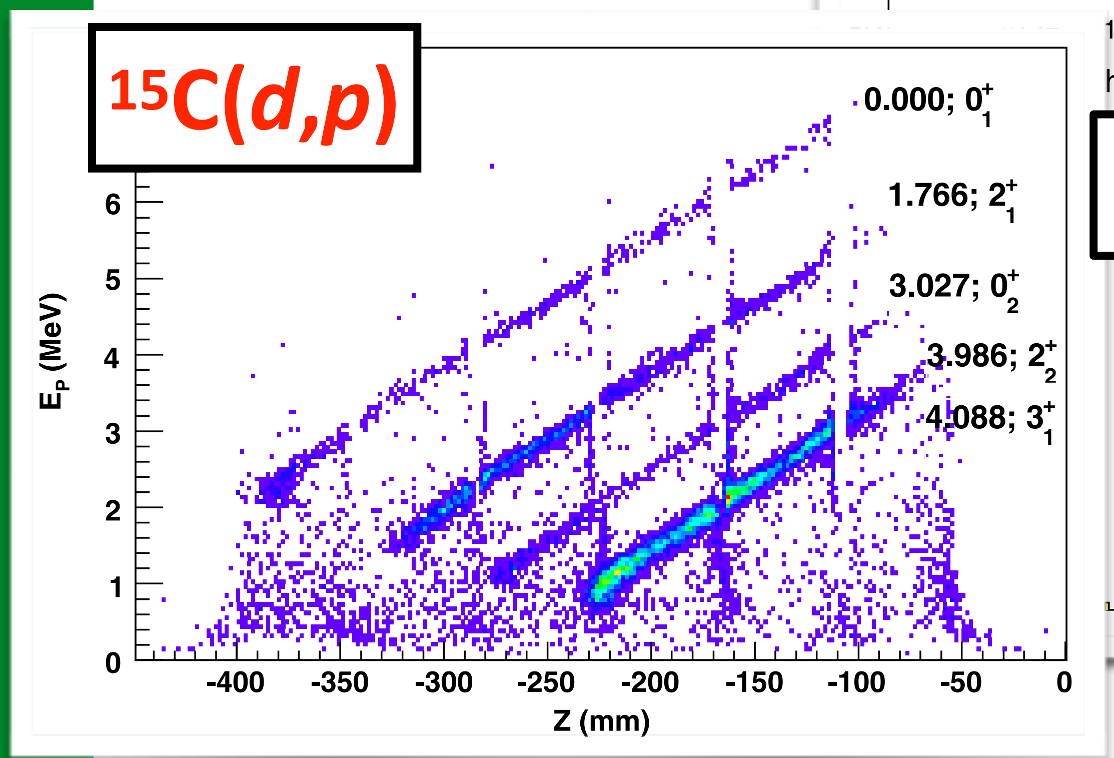










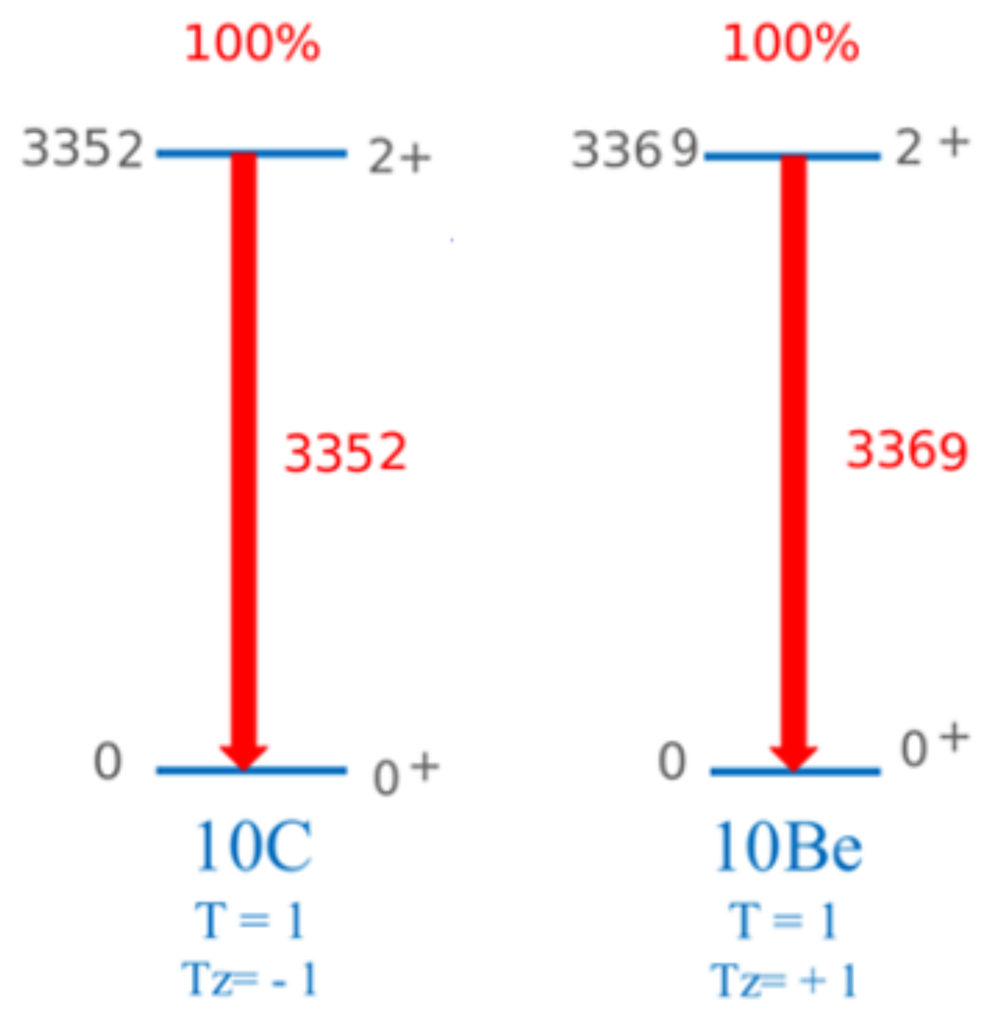


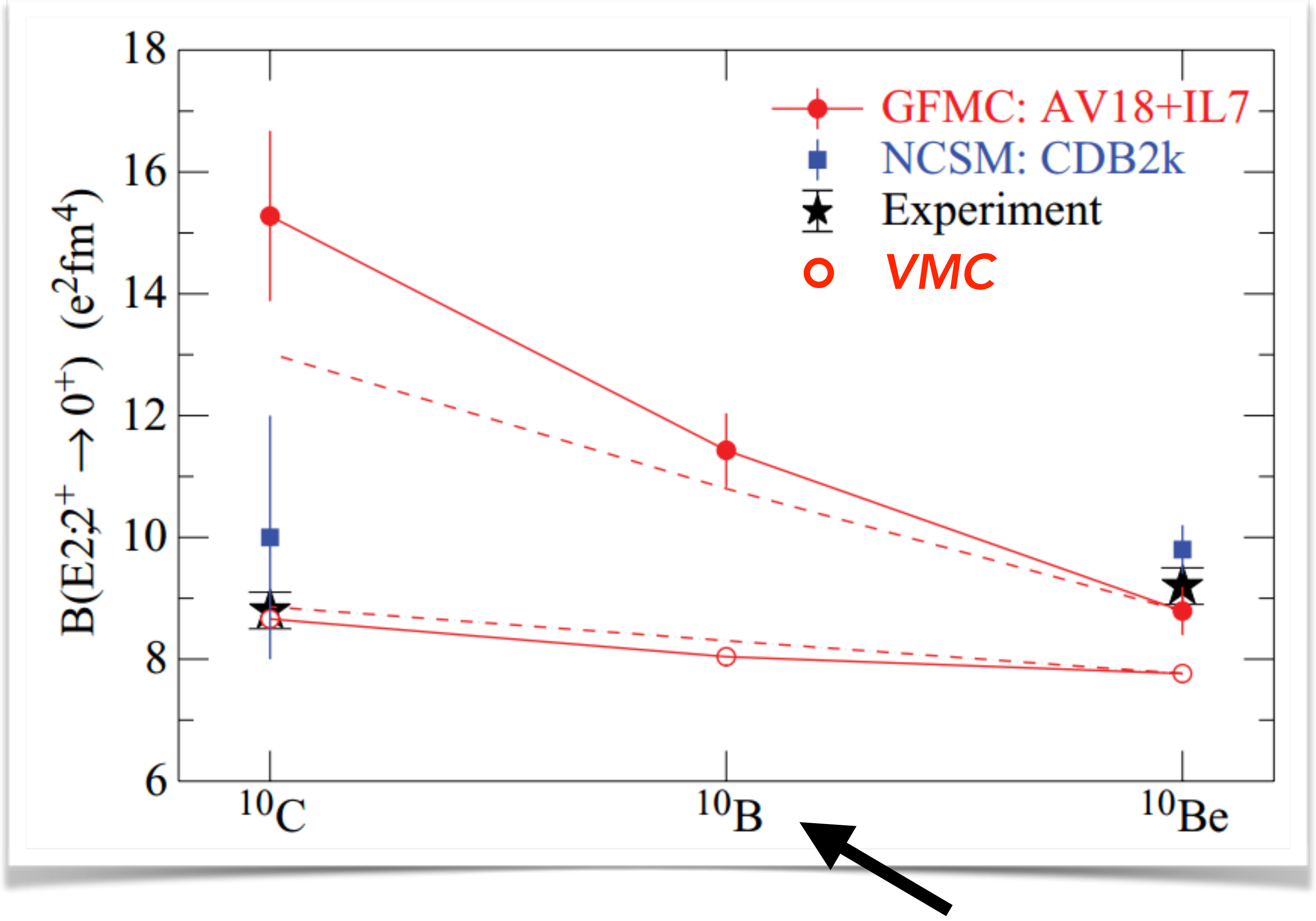
Recent highlights

<u>Goal</u>: *Improve long standing uncertainties* in the α-decay branch of the second (T=1) 2^+ state in ^{10}B

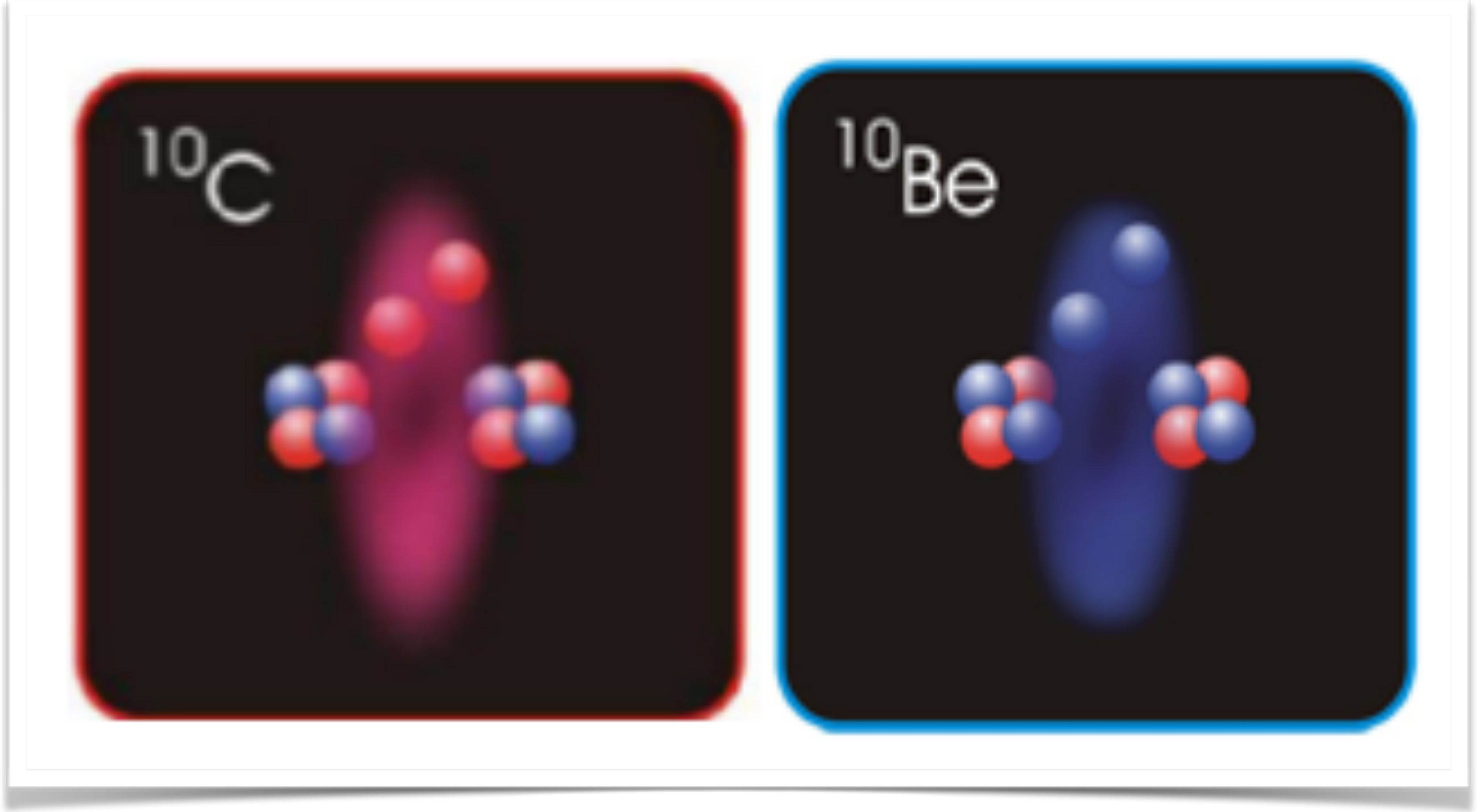
Why? Contributes to B(E2) value, which have been used as precision *tests of ab-initio calculations* of the A = 10 isospin triplet

A new technique n HELIOS …





10C 19.308 S ε: 100.00%	11C 20.364 M ε: 100.00%	12C STABLE 98.93%
9B 0.54 KeV 2α: 100.00% P: 100.00%	10B STABLE 19.9%	11B STABLE 80.1%
8Be 5.57 eV α: 100.00%	9Be STABLE 100.%	10Be 1.51E+6 Y β-: 100.00%



Sean Kuvin et al. Phys. Rev. C **96**, 041301(R) (2017)

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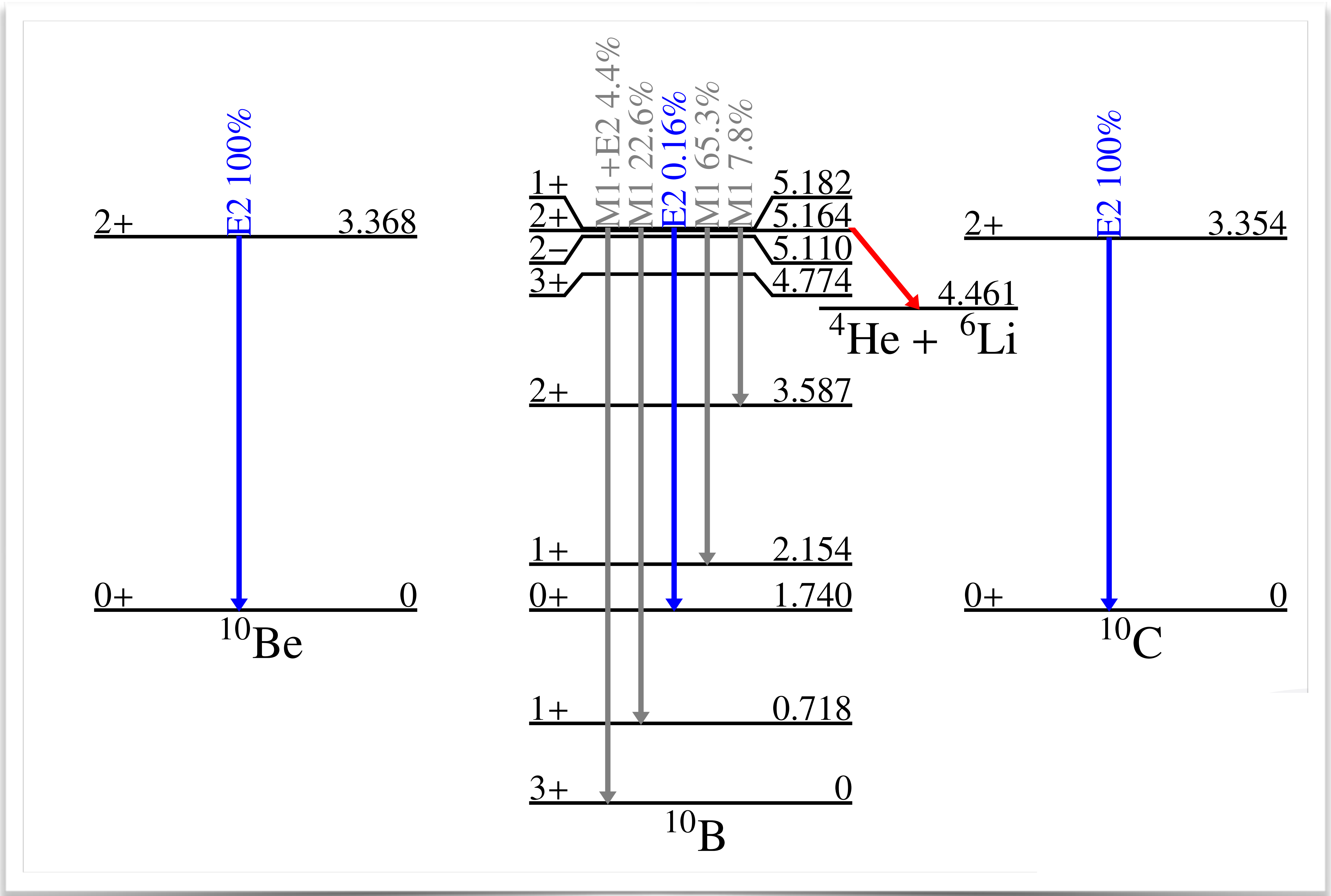
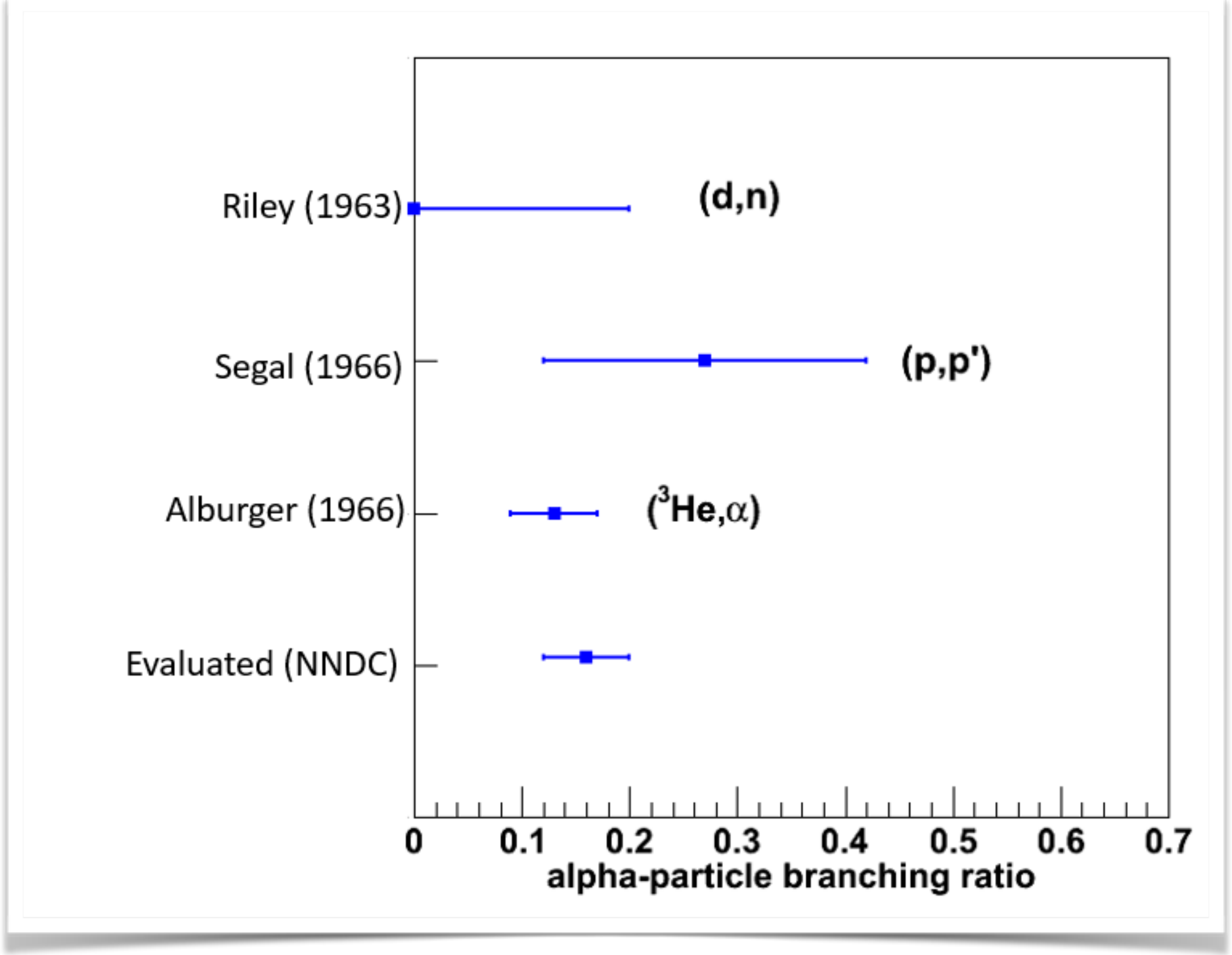
Mass 10 triplet





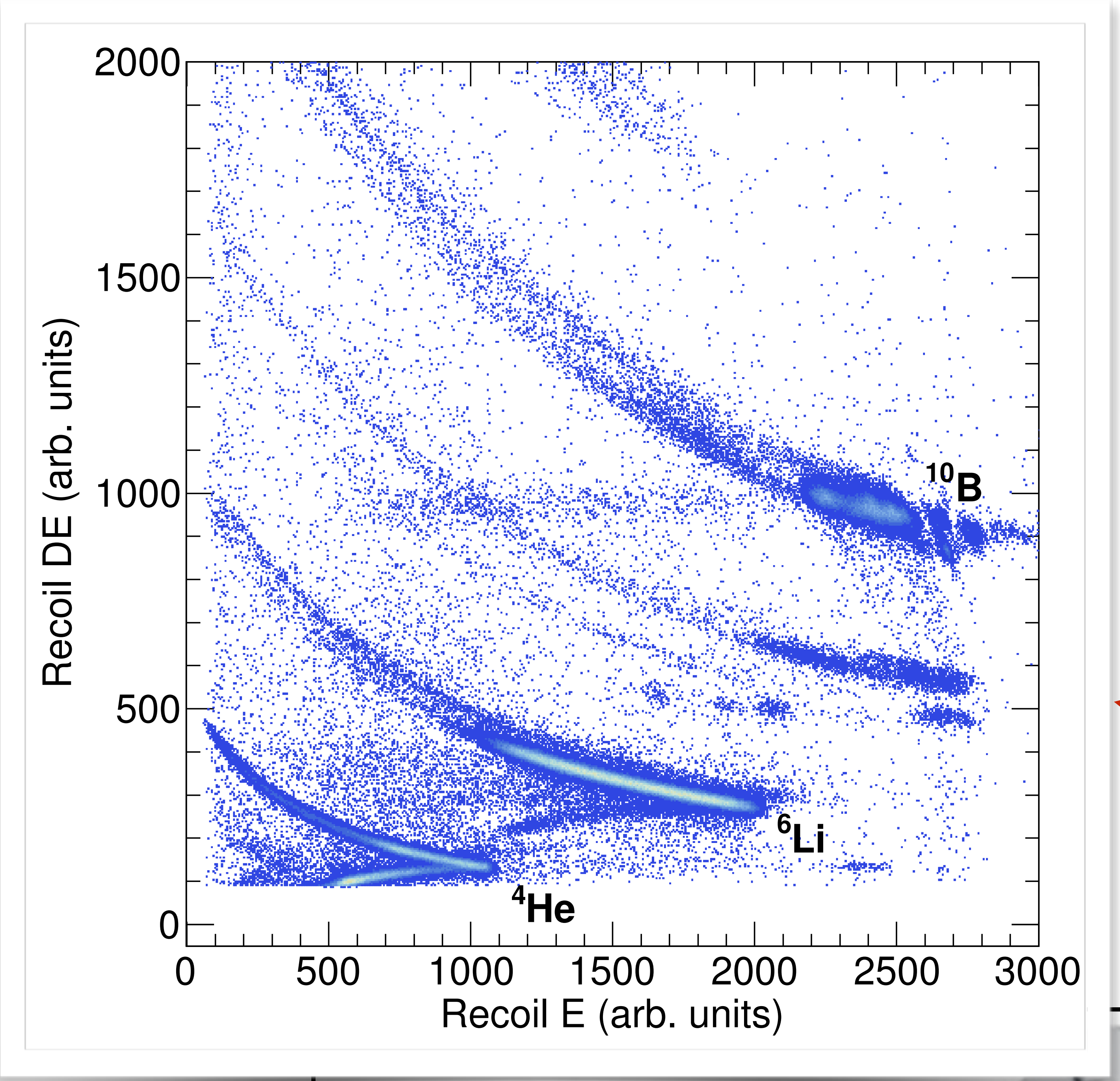
- Status of Uncertainties:
  - Width(7%)
  - Alpha-particle branching ratio (25%)
  - γ-decay branching ratio: (25%)

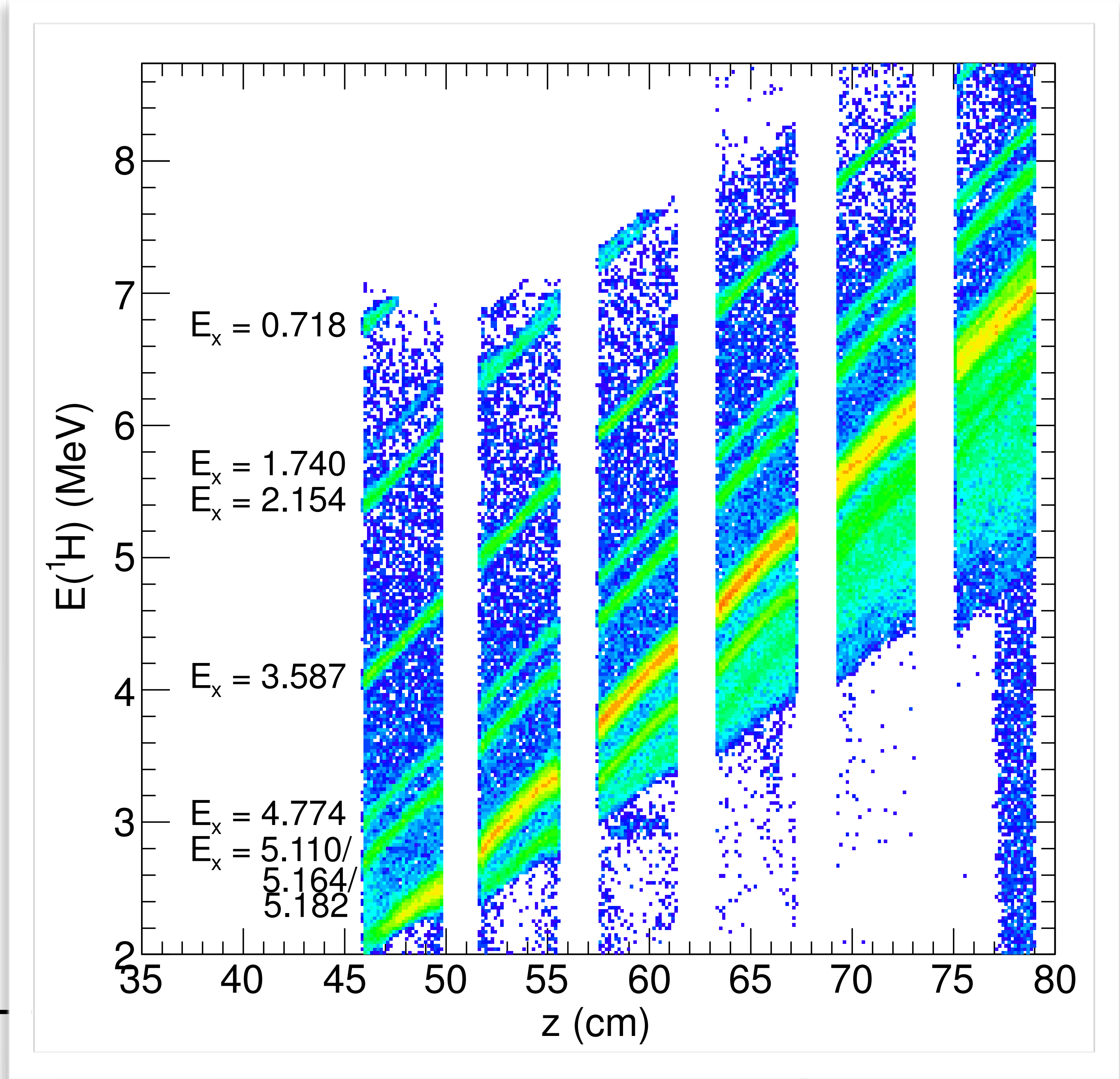
Gyürky *et al.*, EPJA **21(2)**, 355 (2004).
Tilley *et al.*, Nuclear Physics A **745(3)**, 155 (2004)
McCutchan *et al.*, Phys.Rev. C **86**, 057306 (2012).

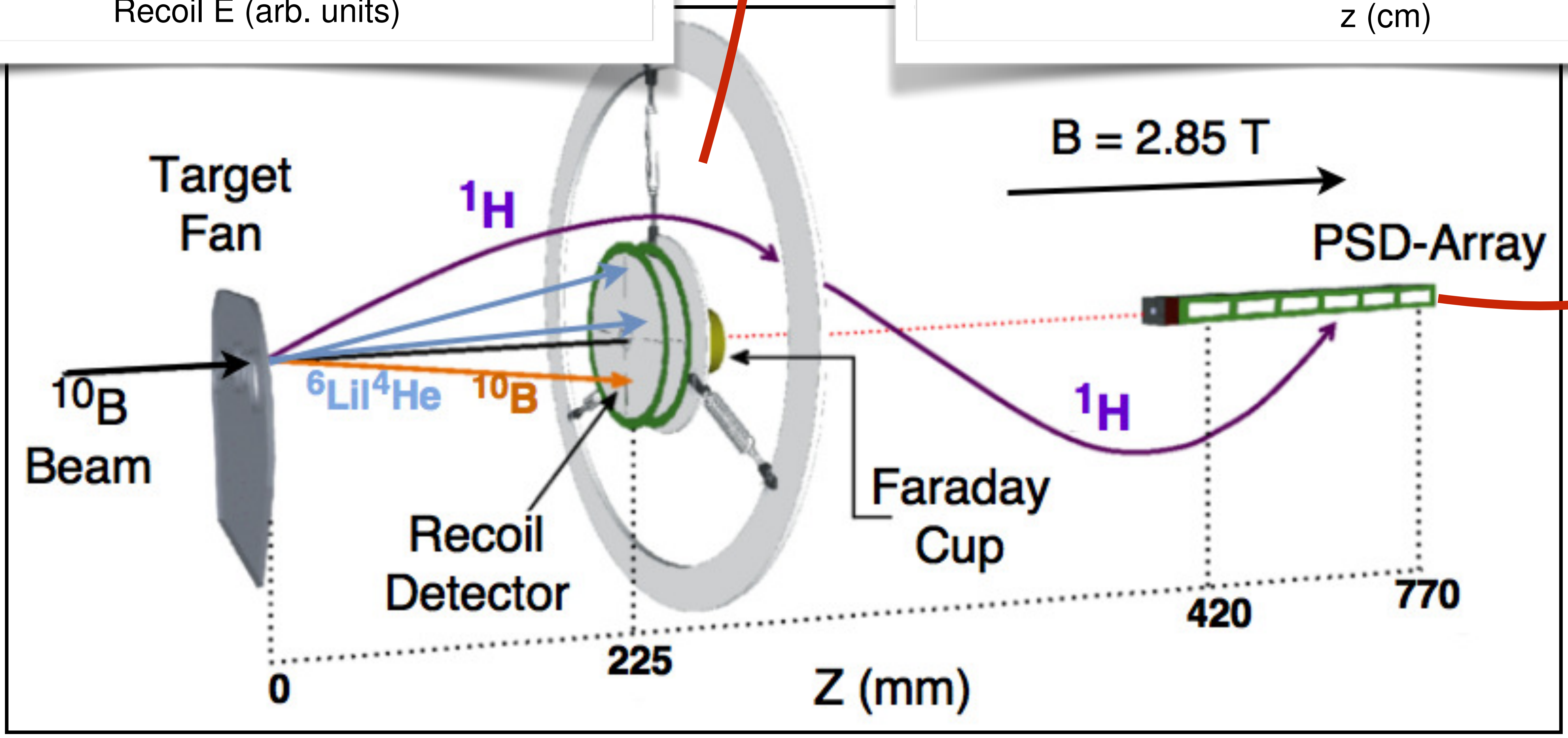
Sean Kuvin et al. Phys. Rev. C **96**, 041301(R) (2017)

‘Downstream’ mode

- ^{10}B beam (stable) at 10 MeV/u
- Thin CH_2 target
- ‘*All*’ recoils detected, including those following decay of the recoil
- Method allows multiple analysis techniques







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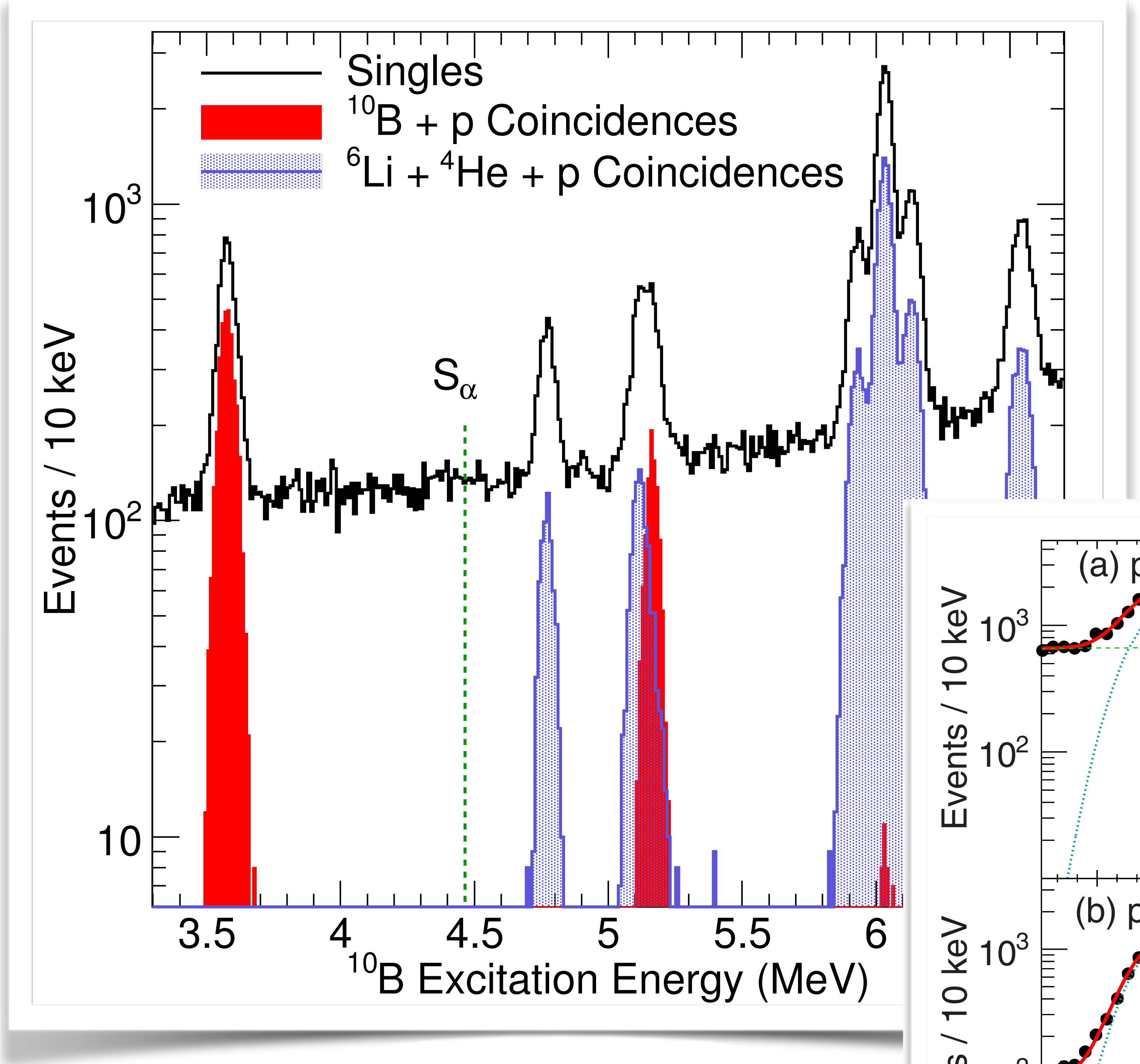
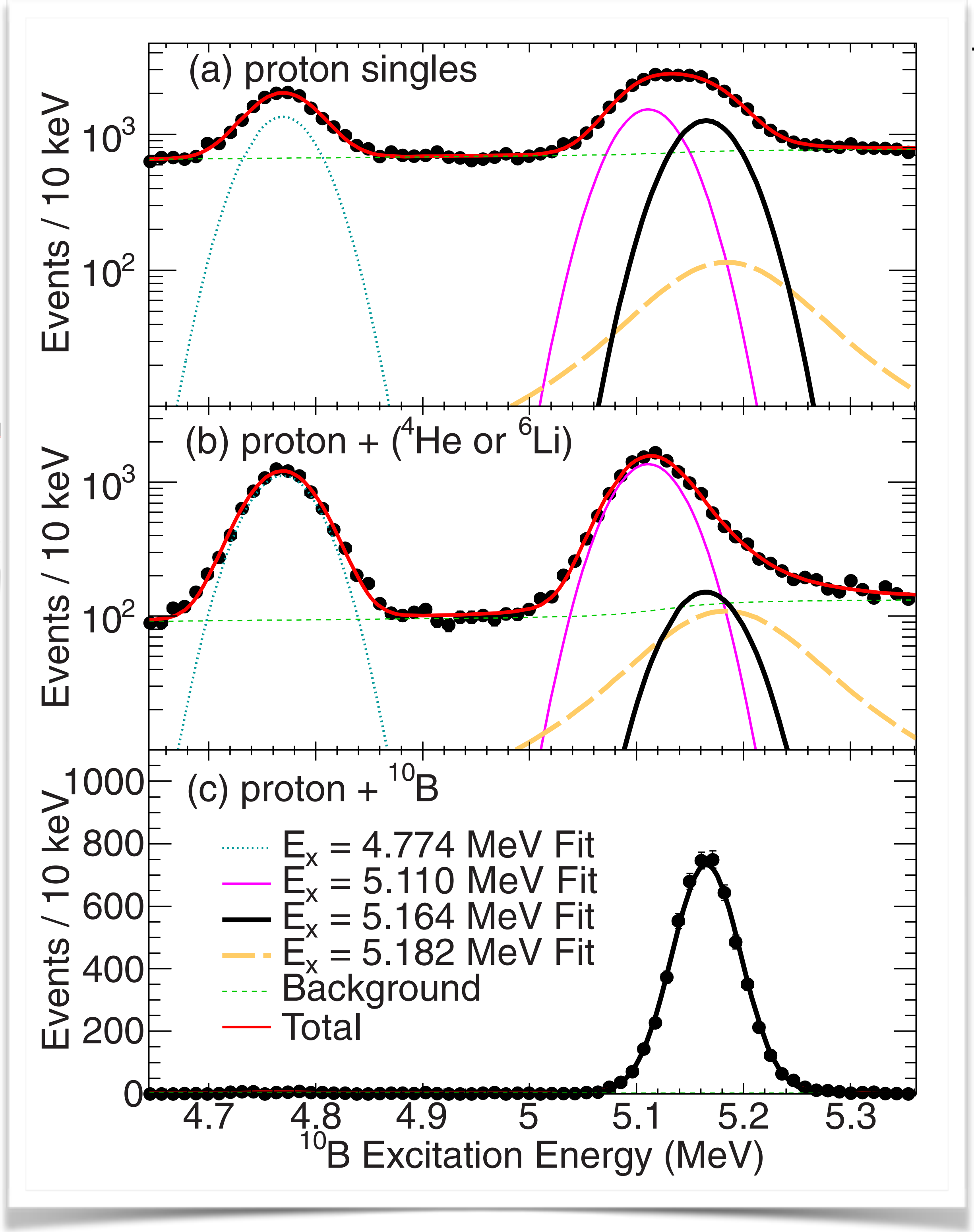
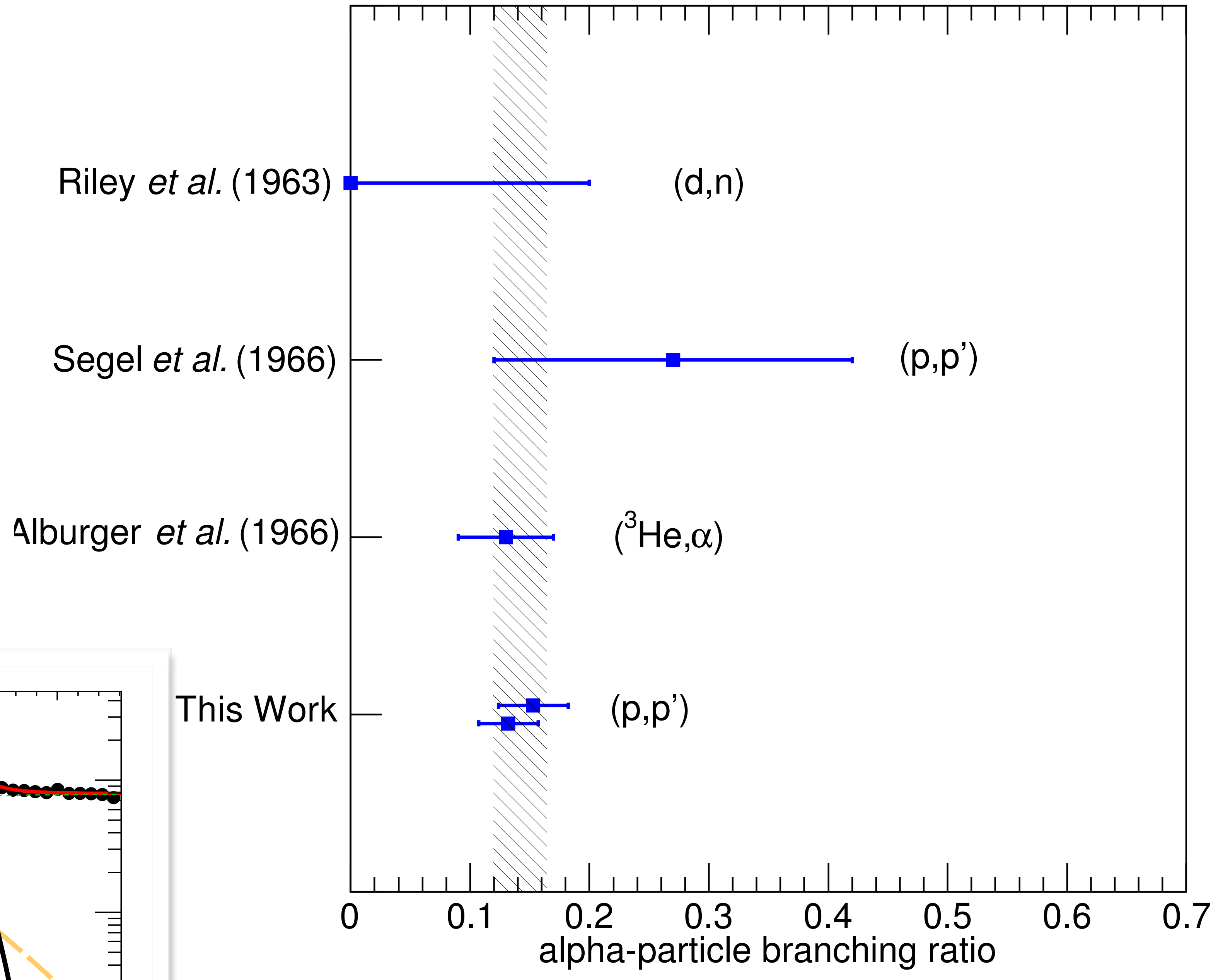
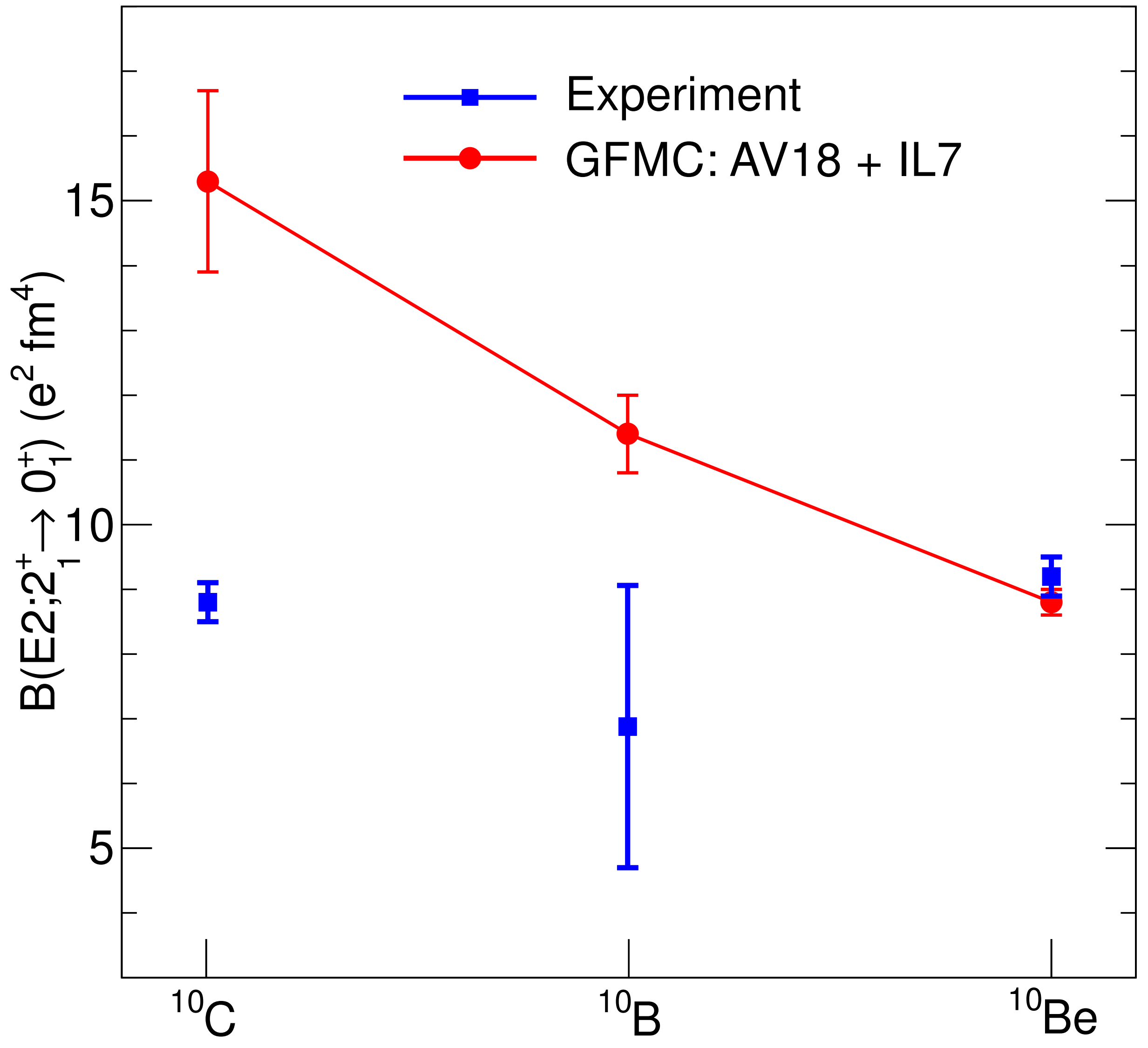
Branch ratio









Challenging measurement. Alpha branching ratio now better constrained after some 50 years …

… a follow-up measurement with Gammasphere constrain E2 gamma branch

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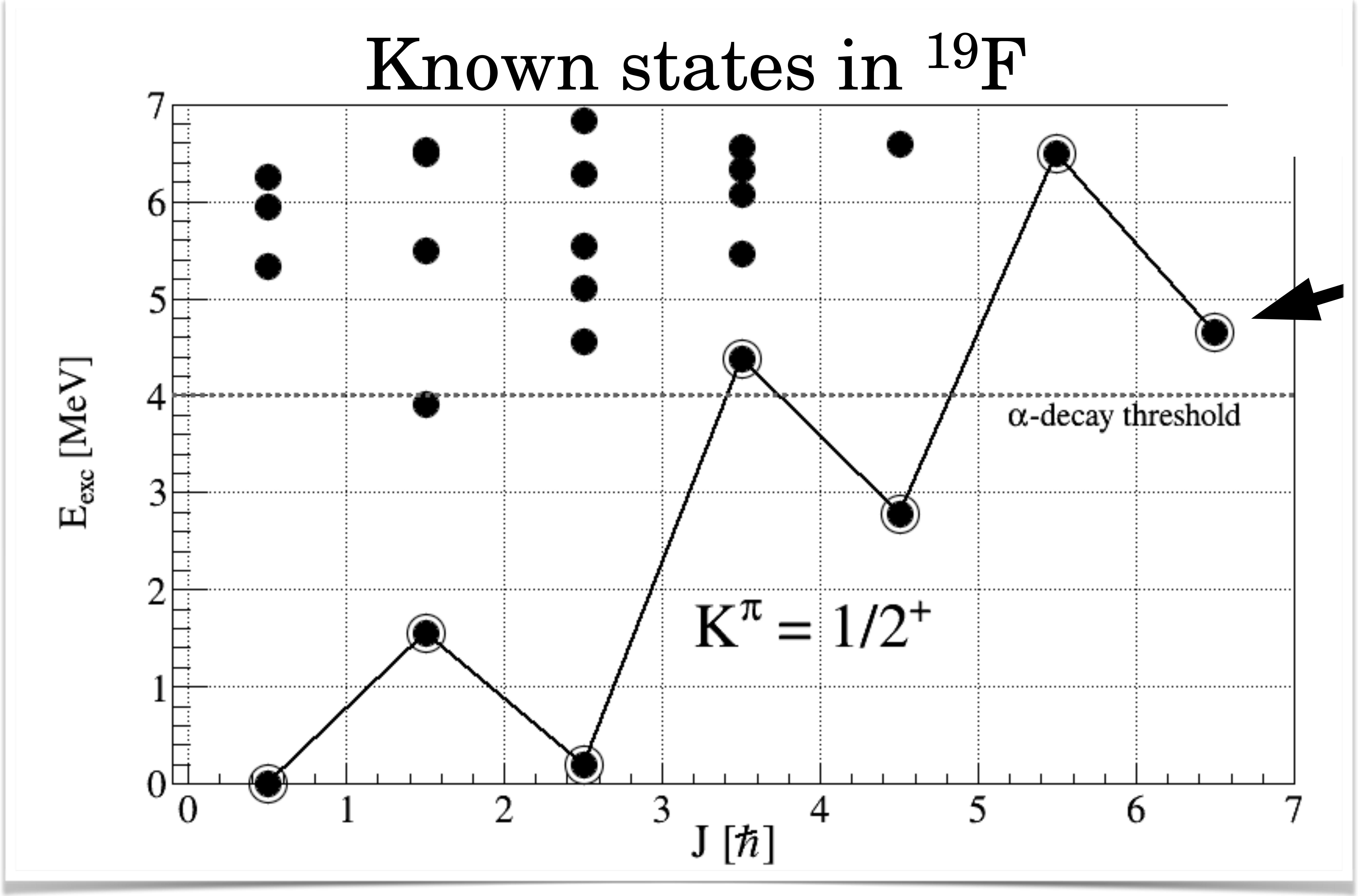
Isomer beams, studying ^{19}F

Transfer reactions are highly selective in *l* transfer

How do the valence nucleons (single-particles) contribute to each state of this rotational band?

Cannot study via transfer on the 0+ ground state of ^{18}F …



D. Santiago-Gonzalez et al. (2017)

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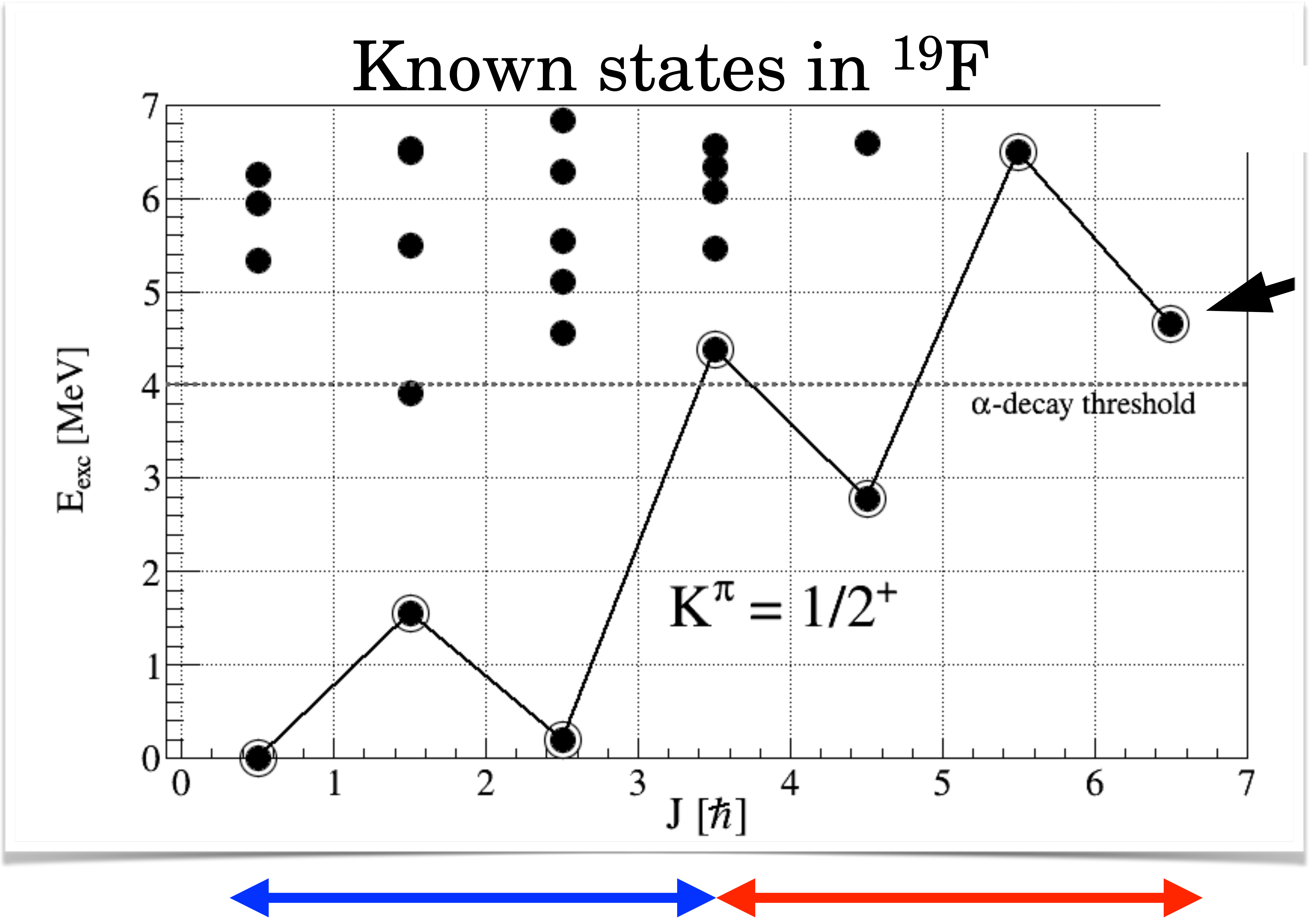
Isomer beams

^{18}F has a 5^{+} isomeric state at around 1.1 MeV.

Probing high-j states via low-l transfer.

Can populate every member of the rotational band in ^{19}F via l=0 and 2 transfer.



$^{18g}F^{(0+)}(d,p)^{19}F$
l=0, 2

$^{18m}F^{(5+)}(d,p)^{19}F$
l=0, 2

D. Santiago-Gonzalez et al. (2017)

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$^{18m,g}F(d,p)^{19}F$

16.3 m, or 1.9 × half life (162 ns)

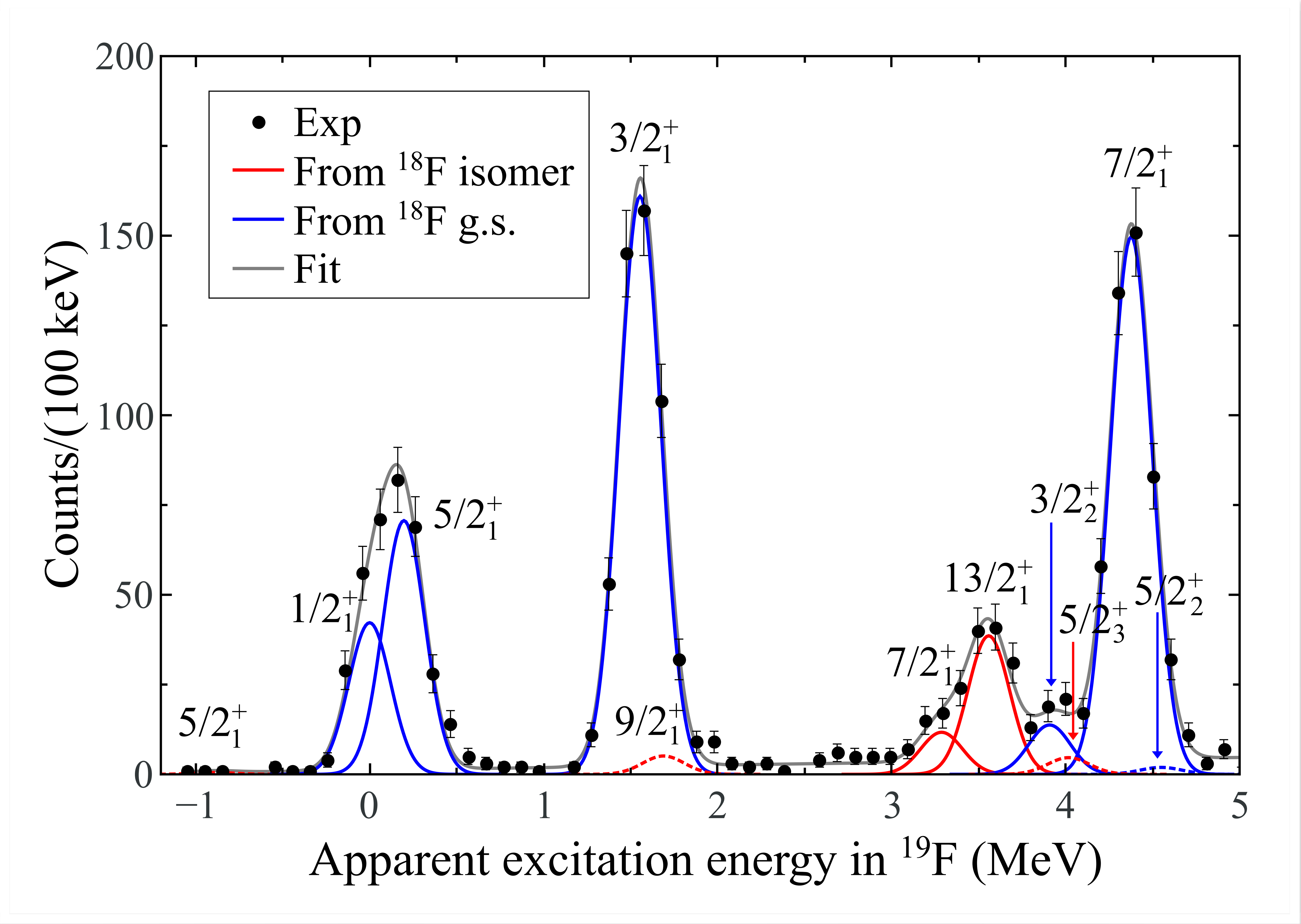
Production

$^{2}H(^{17}O,^{18}F)n$

15 MeV/u

~5×10^{5} pps

$^{18m}F/^{18g}F=0.58$



At HELIOS

$^{18m,g}F(d,p)^{19}F$

14 MeV/u

$^{18m}F/^{18g}F=0.11$

($11/2^{+}$ at higher ex)

D. Santiago-Gonzalez et al. (2017)

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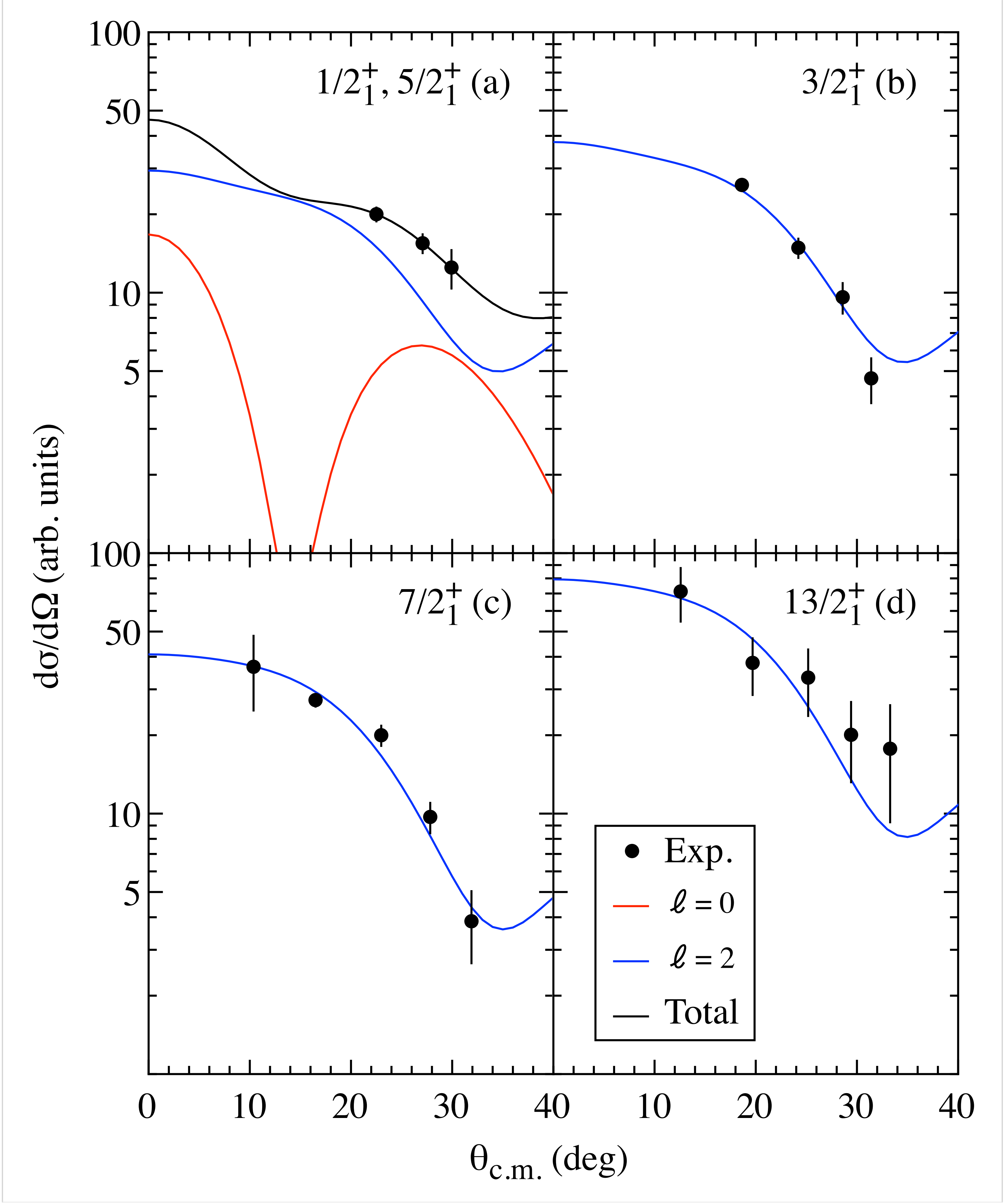
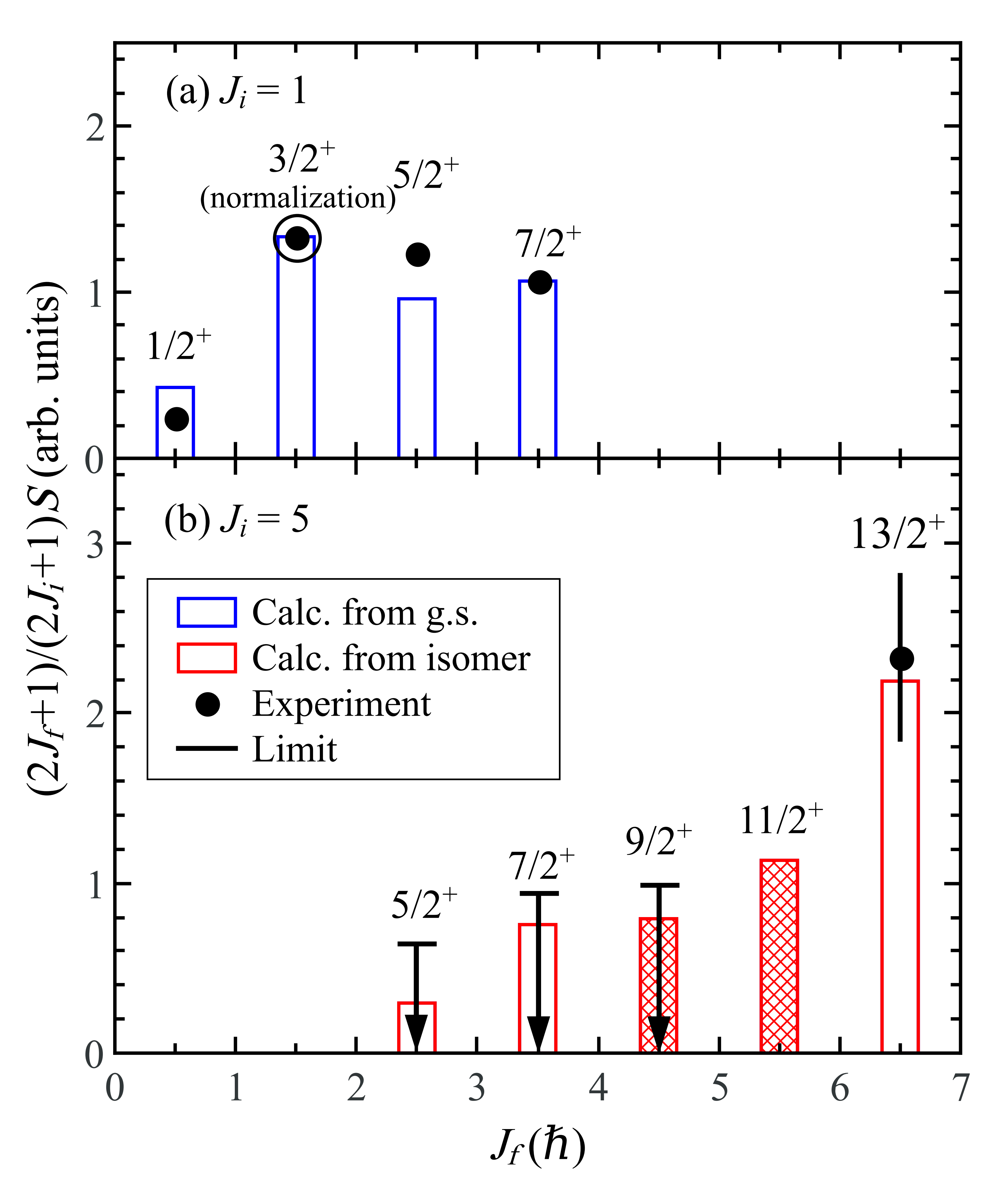
^{19}F, well understood





Excellent agreement with shell-model calculations (perhaps not surprisingly).

Powerful technique, many future possibilities (^{26}Al, ^{34}Cl, etc)

D. Santiago-Gonzalez et al. (2017)

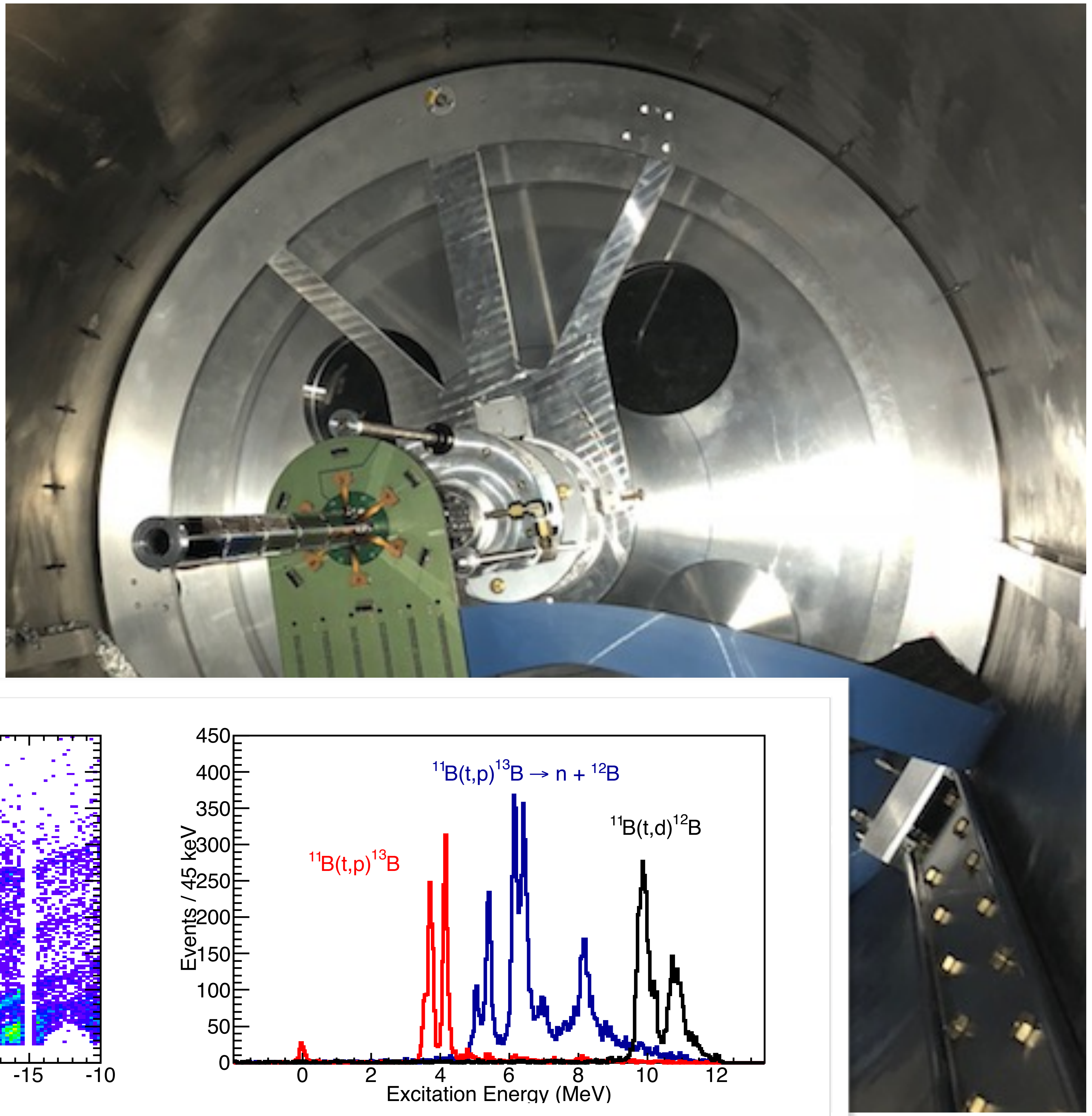
HELIOS going forwards

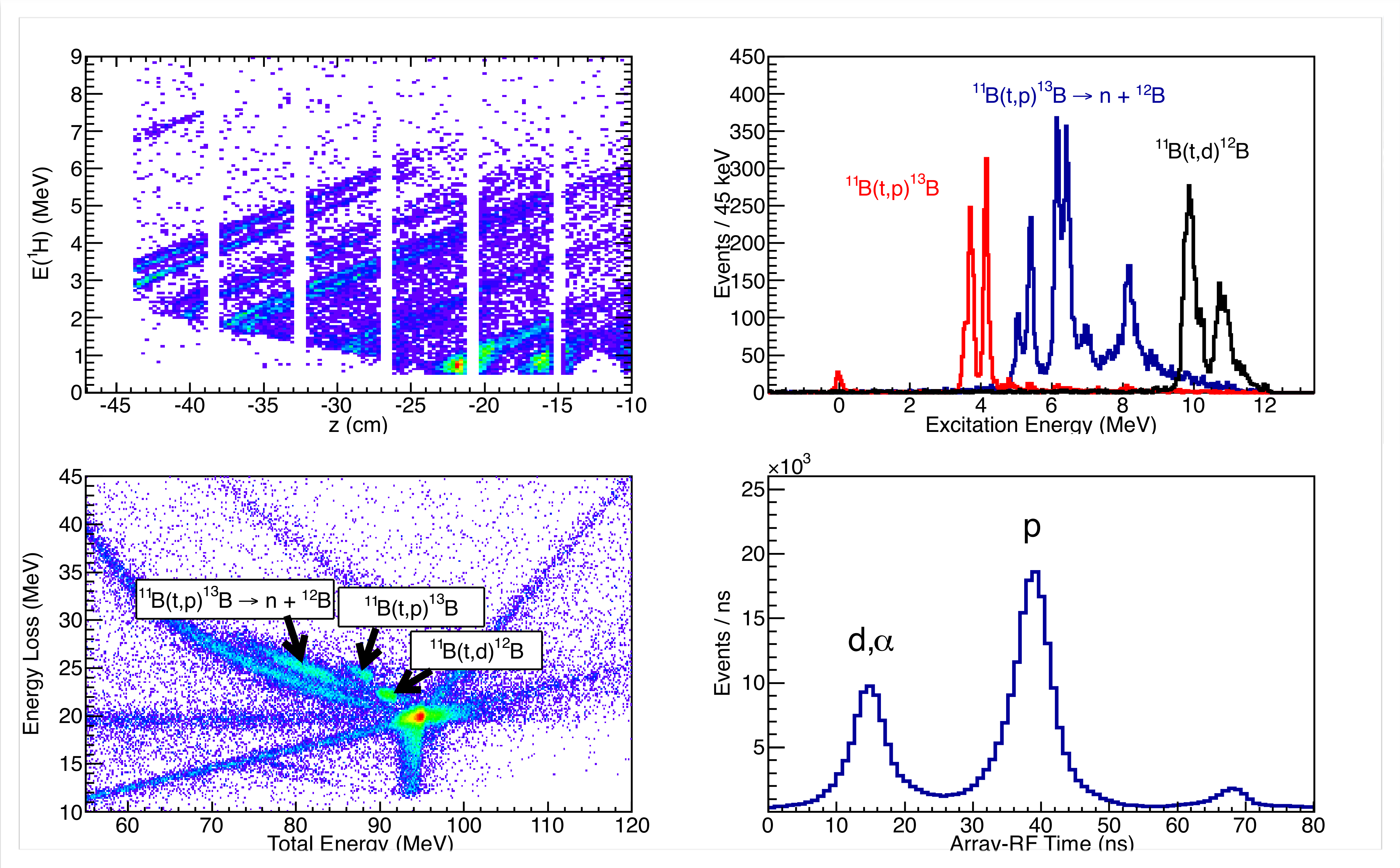
New *6-sided Si array*, new *digital DAQ* (based on Gammashpere/Gretina/GRETA digitizers)

The Argonne In-flight Radioactive Ion Separator (*AIRIS*), *improved in-flight beams*

CARIBU beams,
e.g., ^{134}Te(*d*,*p*), ^{144,146}Ba(*d*,*d*), …

Tritium target, and so on.

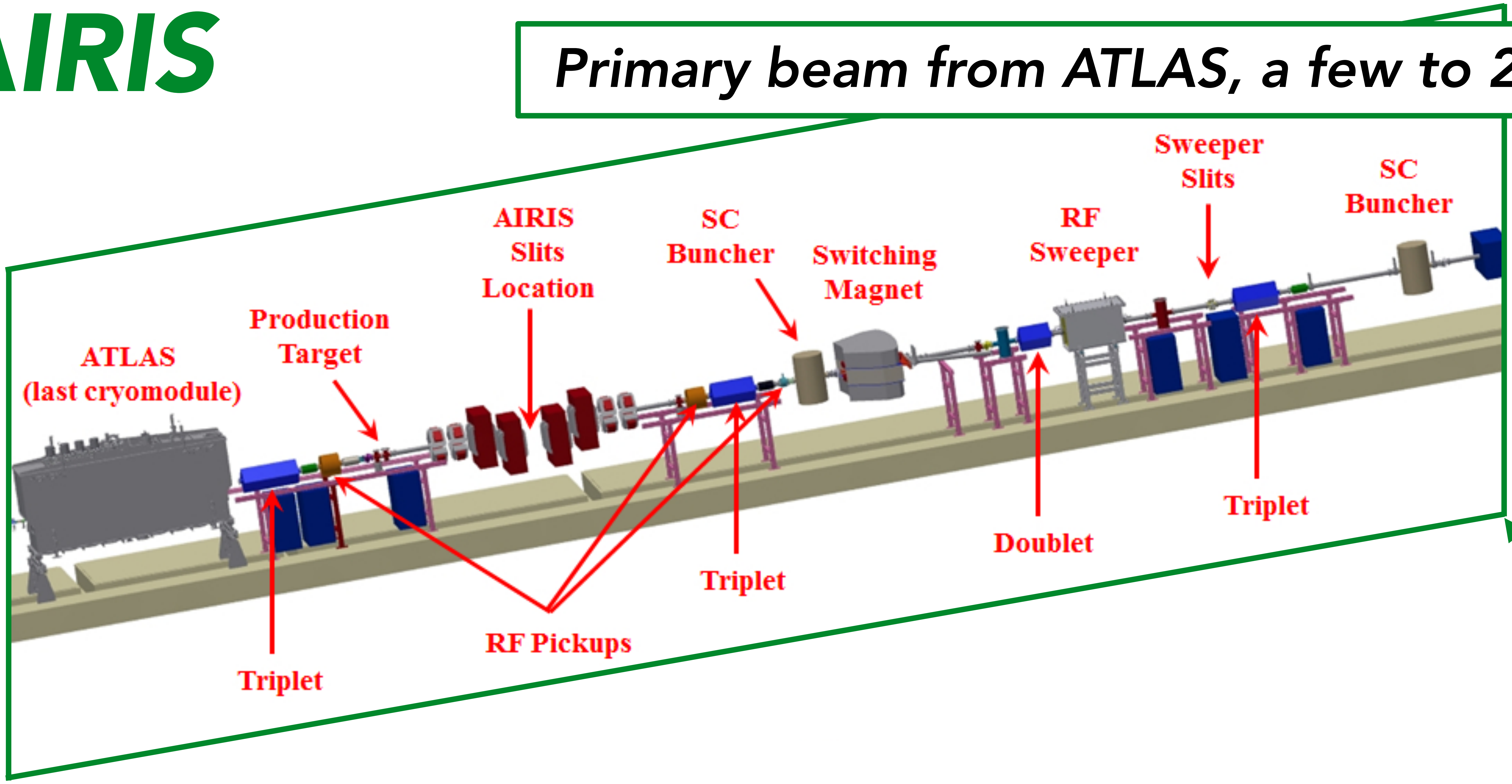


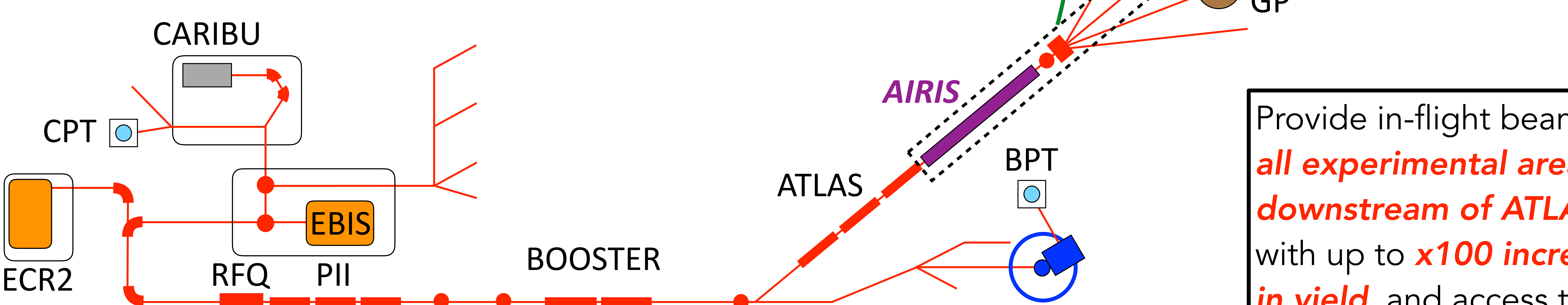


[Tritium-target tests, Kuvin, Wuosmaa (2017)]

AIRIS

Primary beam from ATLAS, a few to 20 MeV/u, <few pμA

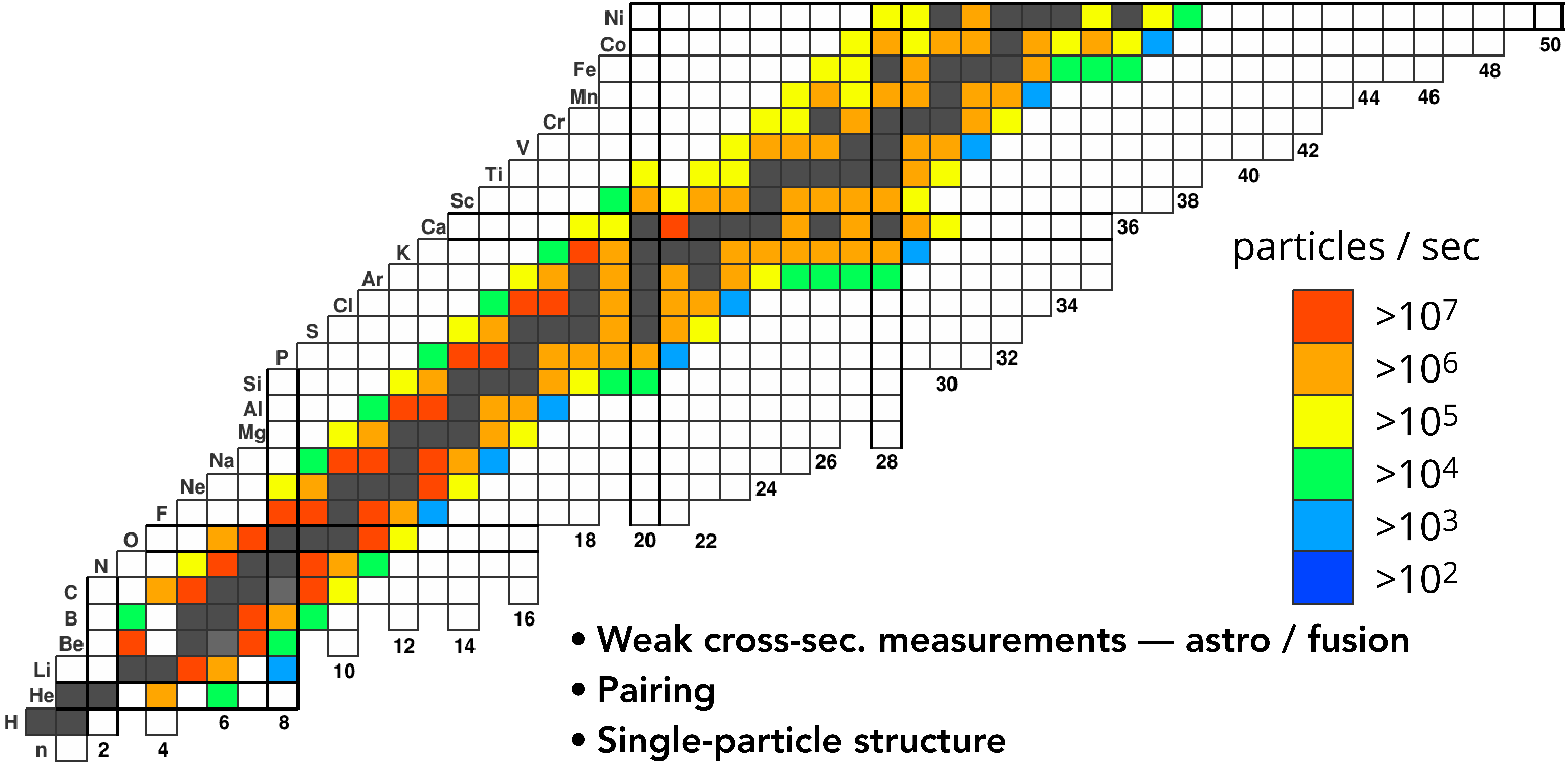




Provide in-flight beams to ***all experimental areas downstream of ATLAS***, with up to ***x100 increase in yield***, and access to ***higher mass beams***

See e.g. http://www.anl.gov/phy/group/argonne-flight-radioactive-ion-separator-airis

AIRIS beams, 2018

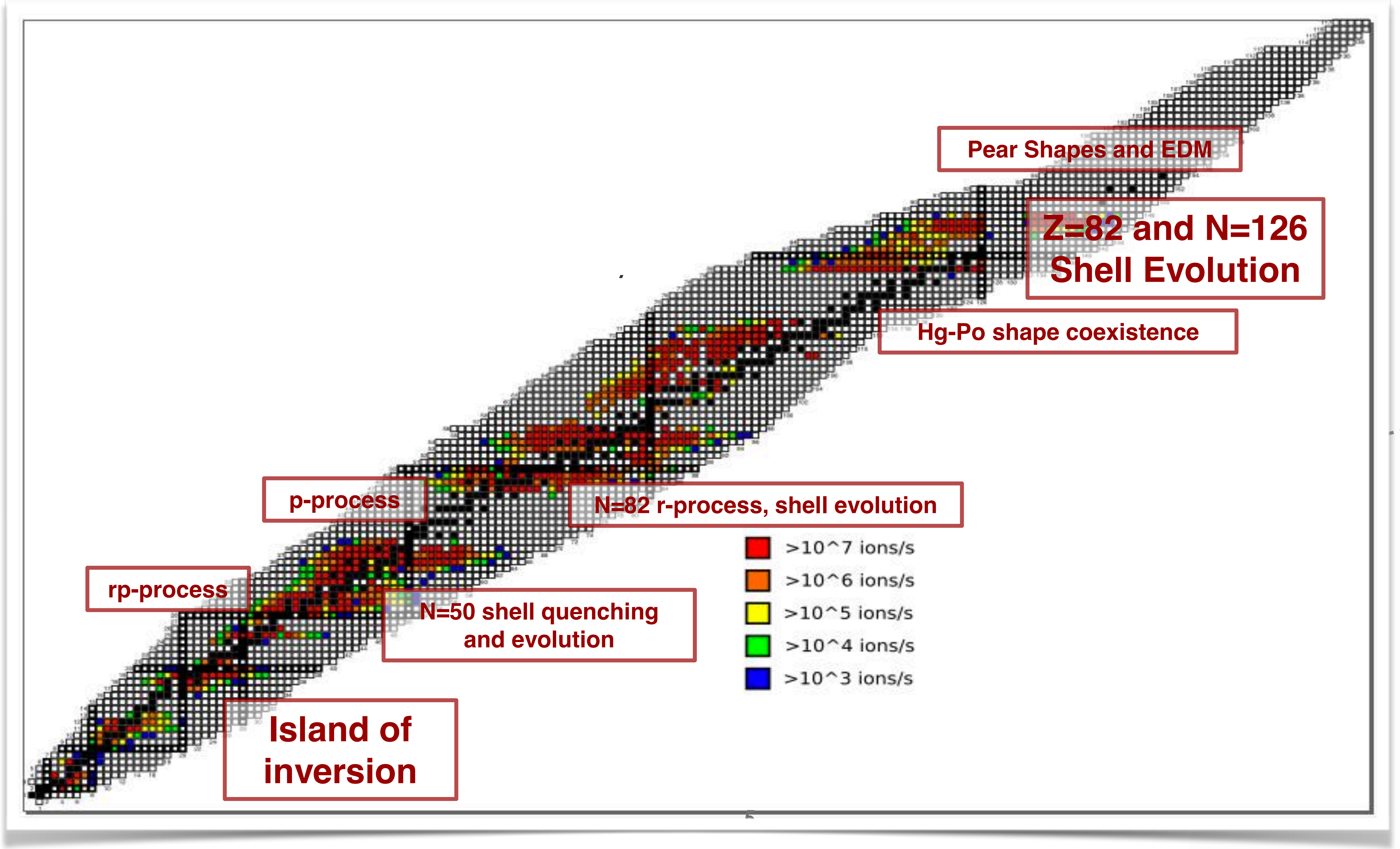


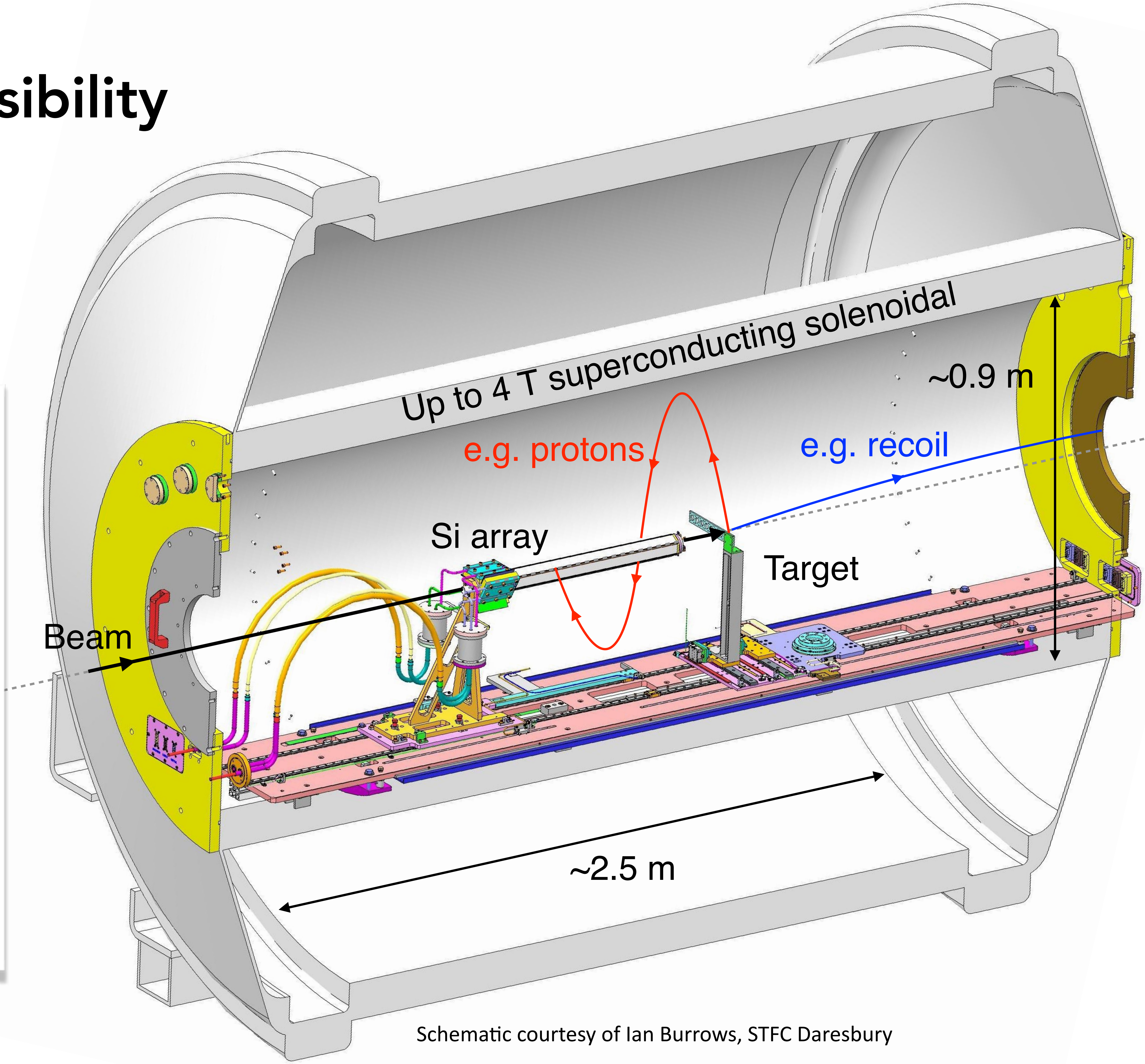
- Weak cross-sec. measurements — astro / fusion
- Pairing
- Single-particle structure
- Possibly fusion-evap. with e.g. ^{38}Ca, ^{42}Ti, ^{56}Ni beams

See e.g. http://www.anl.gov/phy/group/argonne-flight-radioactive-ion-separator-airis

ISS @ HIE-ISOLDE

10 MeV/u beams opens up the possibility of a major direct-reaction program at ISOLDE … ISS being developed





Schematic courtesy of Ian Burrows, STFC Daresbury

Chart of nuclides taken from talk by Liam Gaffney

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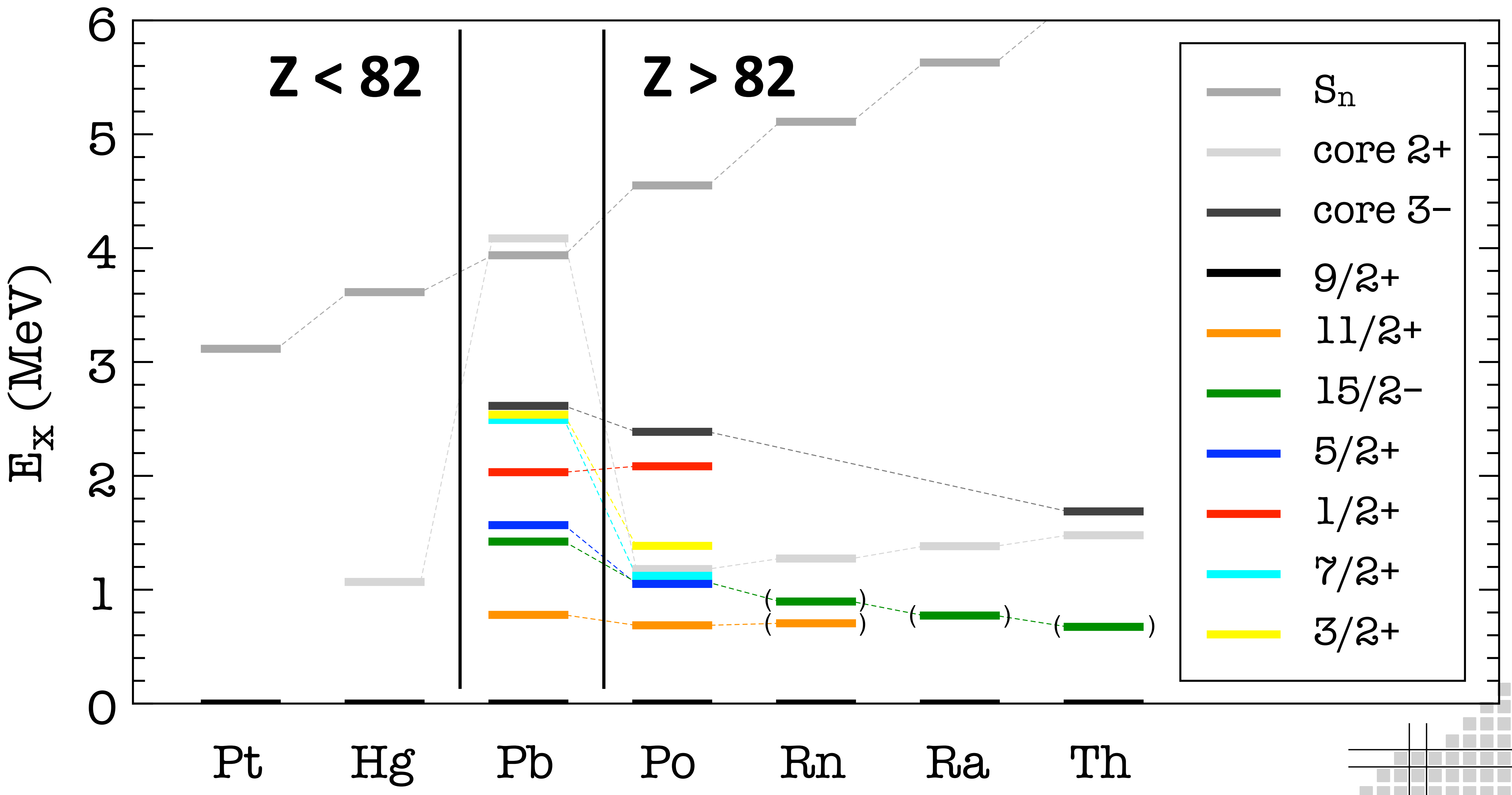
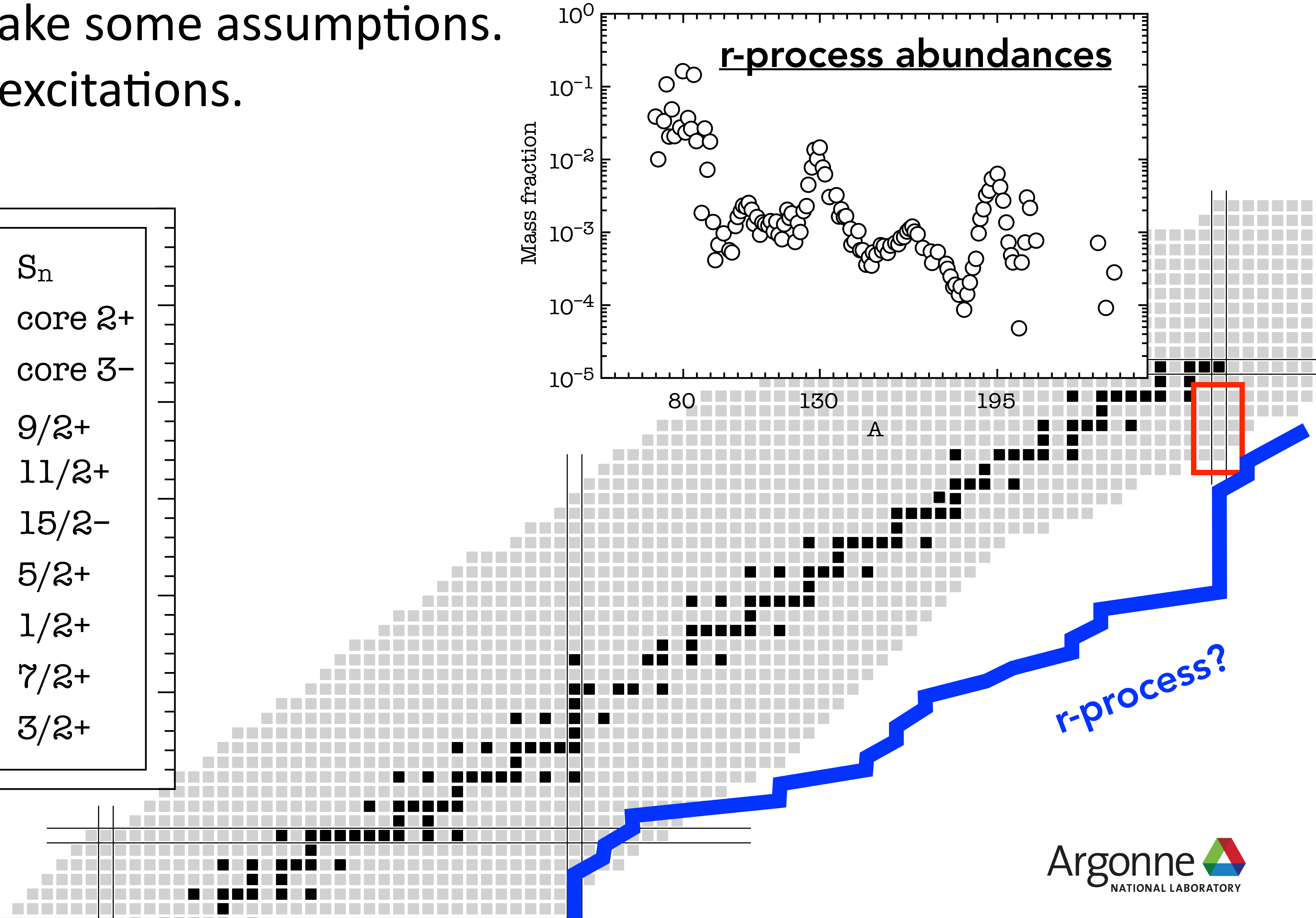
Early physics opportunities

<u>***N* = 127 isotones below Pb**</u>

- ***Terra incognita***. Below Pb, around *N* = 126, ***very little known*** (limited knowledge on masses, decays).
- ***Evolution of single-particle states*** has ***not been explored*** in nuclei around ^{208}Pb as these require ***radioactive ion beams***.
- Data on 2^+ and 3^- in even nuclei allows us to make some assumptions.
- ***Few / no theoretical studies*** on single-particle excitations.





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Early physics opportunities

The ^{206}Hg(*d*,*p*) reaction at 10 MeV/u using the ISOL Solenoidal Spectrometer (ISS)

Why (close to) 10 MeV/u?

- Cross sections
- Angular momentum matching
- Angular distributions

Why ISS?

Resolution

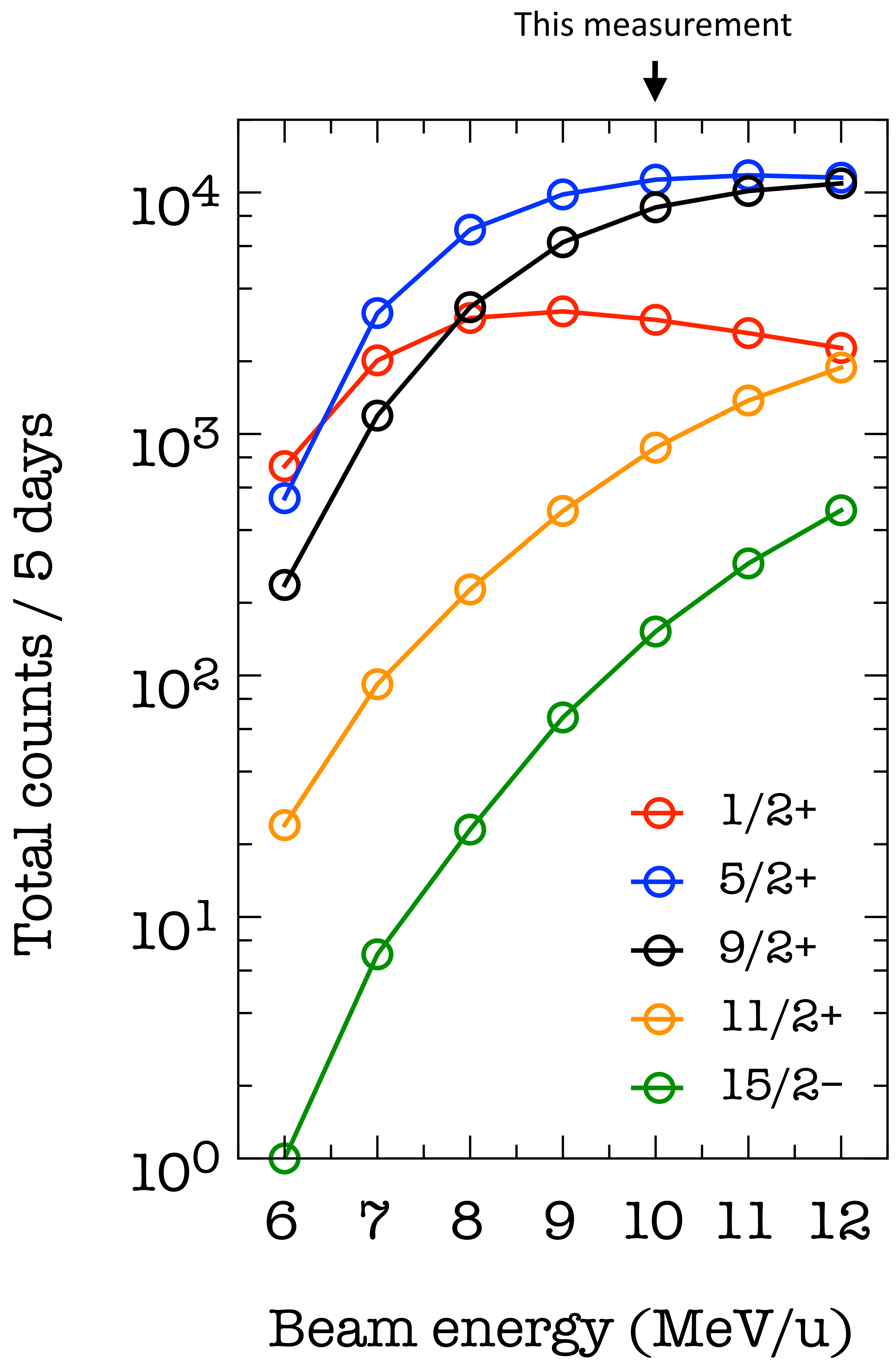
- Charged-particle spectroscopy with ***<100-keV Q-value resolution*** using thin targets

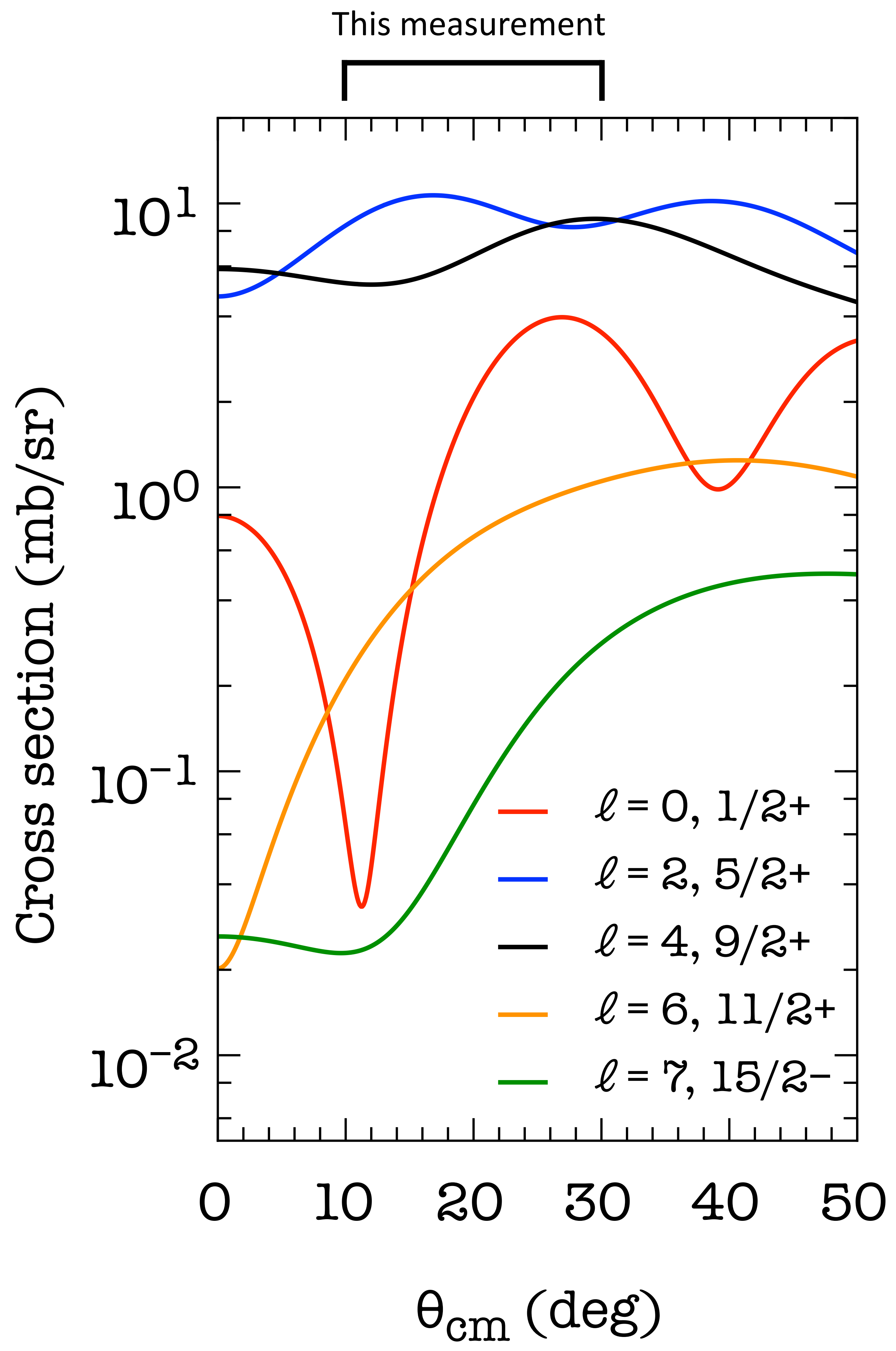
Efficiency

- Limited only by geometrical acceptance, not intrinsic efficiency of the detectors.

Direct probe of excited states

- ***Does not*** require coincident γ-rays de-exciting the states ($\therefore$ no concerns with isomers*, ground state, states not connected by γ-ray decay, etc).

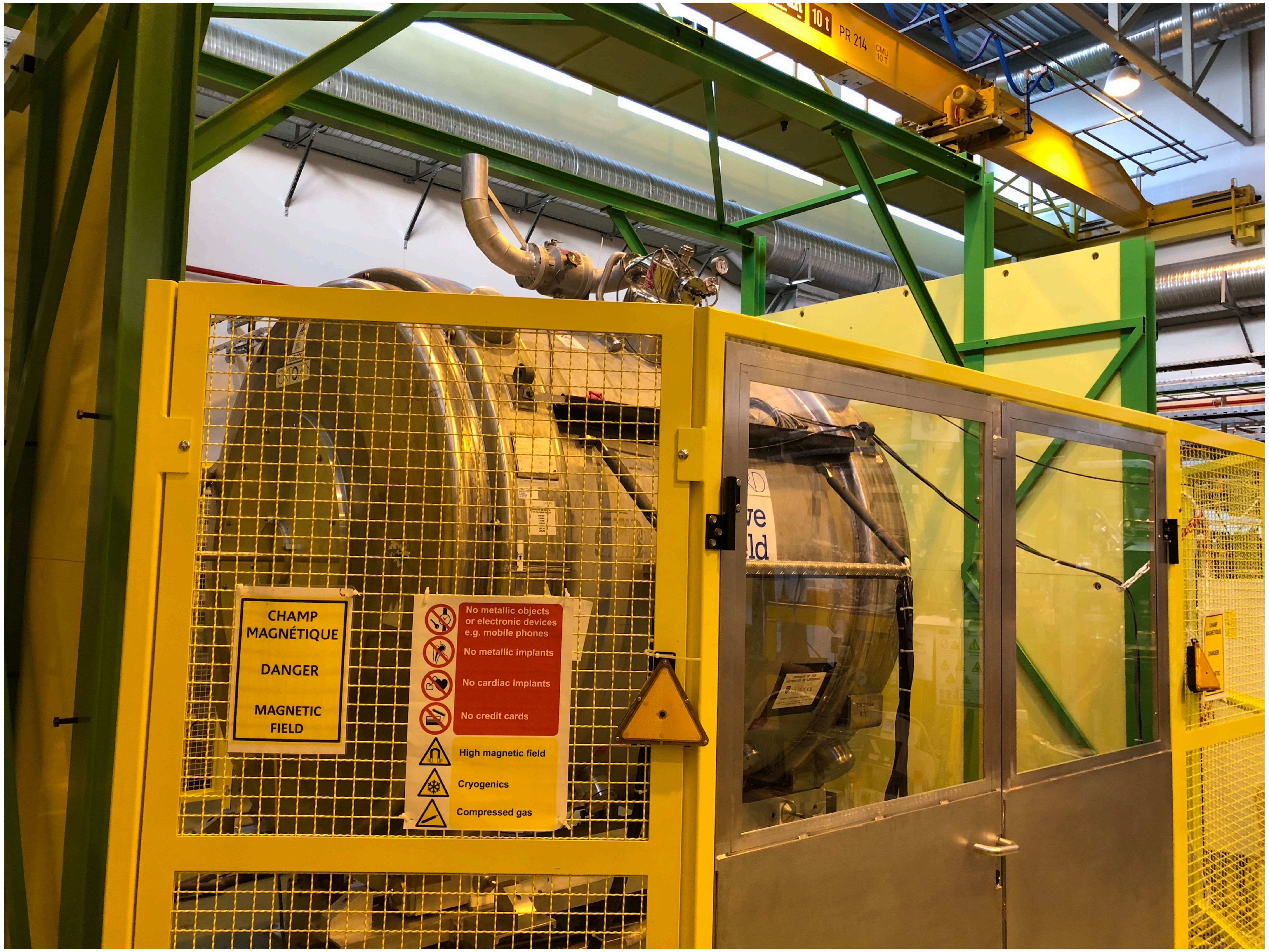




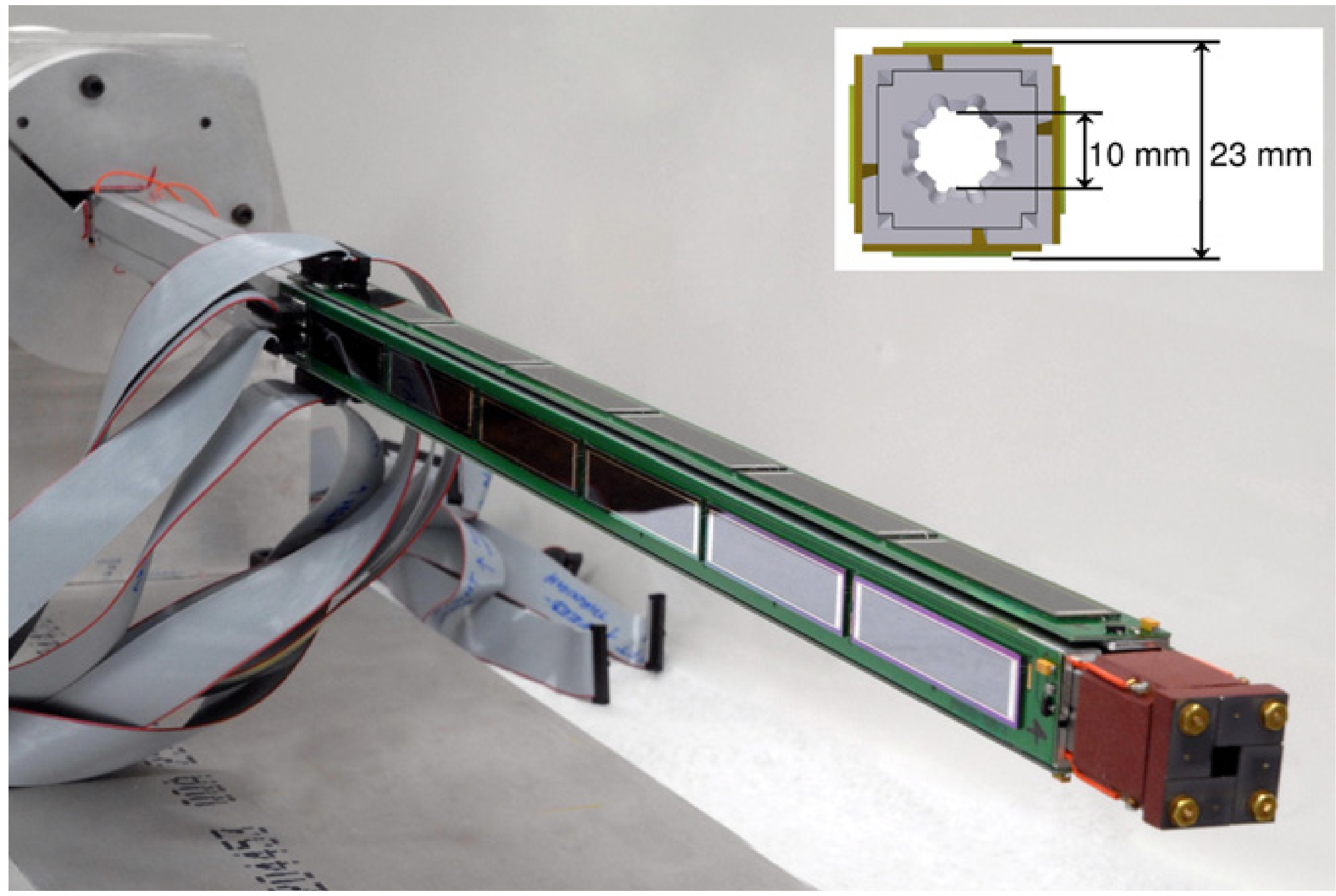
*Isomers prevalent in the region around Pb

Cross sections estimated using DWBA code Ptolemy using standard parameterizations.

In collaboration with ANL



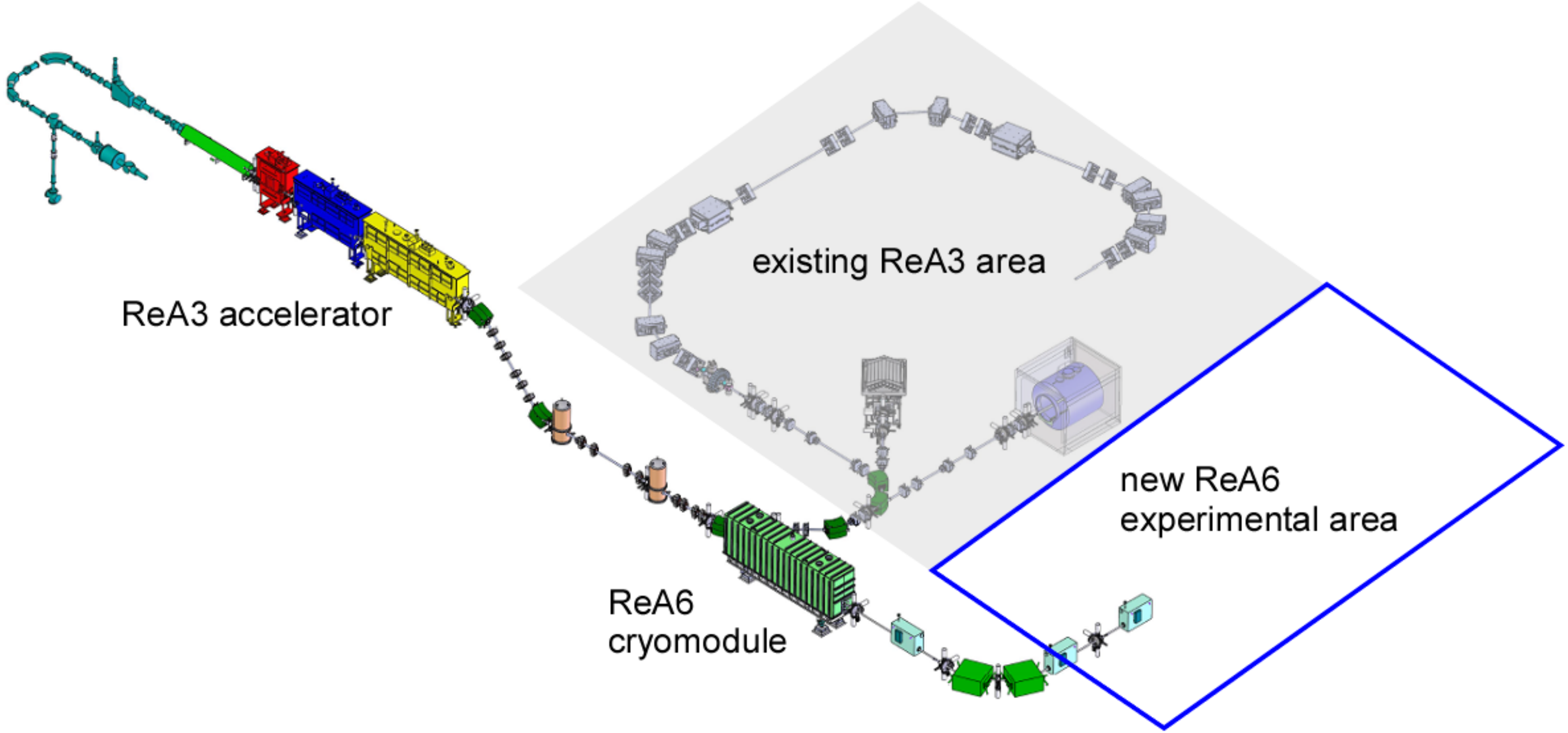
ISOLDE, December 3, 2017



For potential 2018 experiments, <u>^{28}Mg(*d,p*) and ^{206}Hg(*d,p*)</u>, *the HELIOS digital DAQ and Si array will be shipped to CERN in <u>2018</u>*

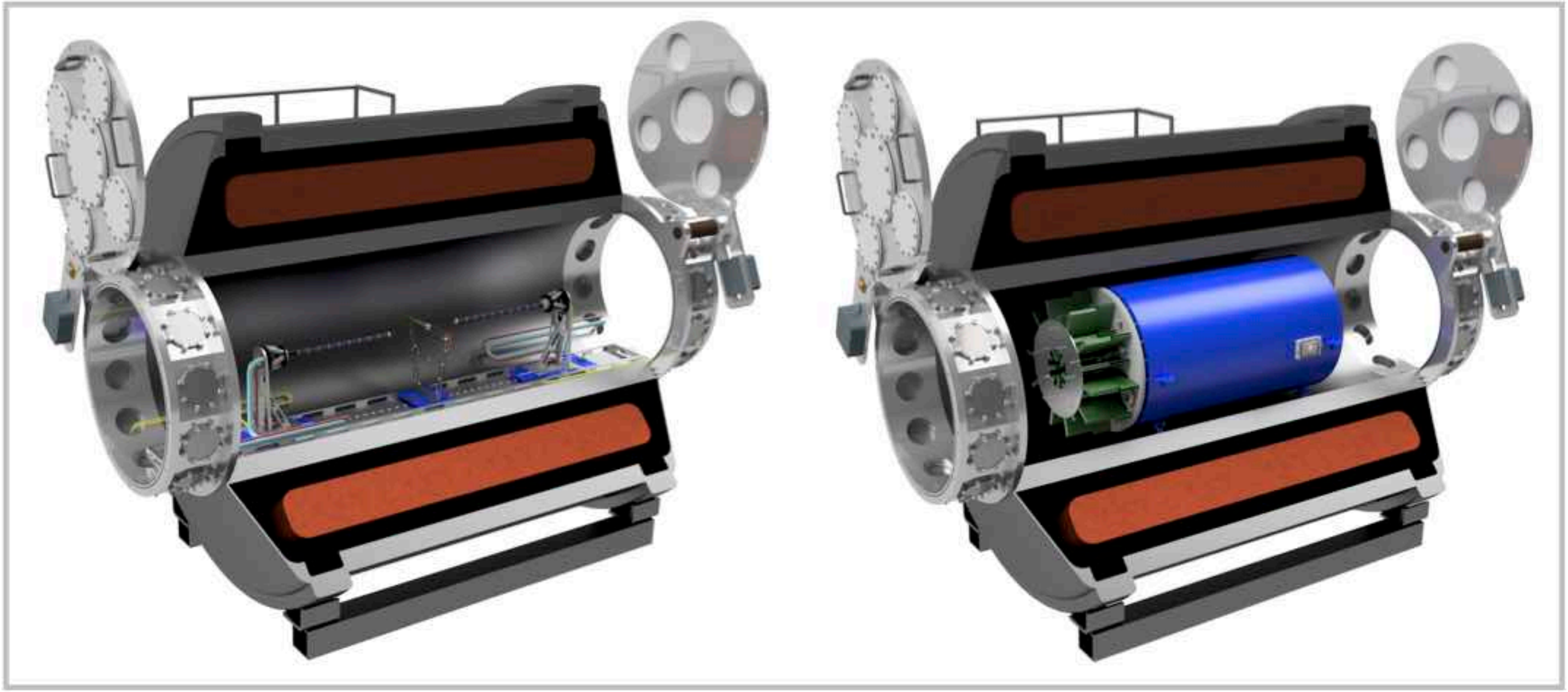
Shorter 'test' Si-array to be shipped in spring/summer for stable beam tests.

SOLARIS at NSCL/FRIB



*Estimated, http://www.anl.gov/phy/group/argonne-flight-radioactive-ion-separator-airis

SOLARIS

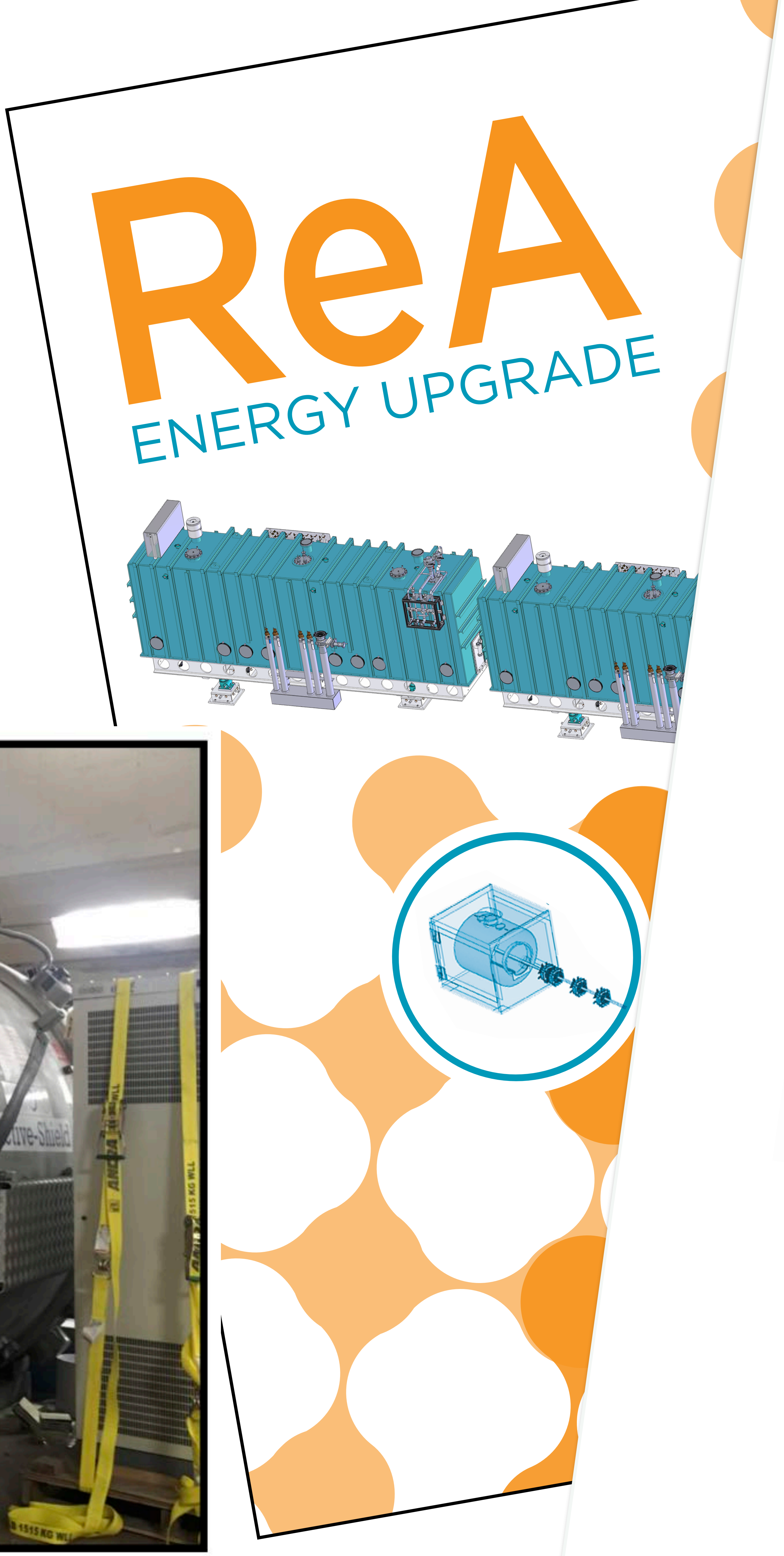


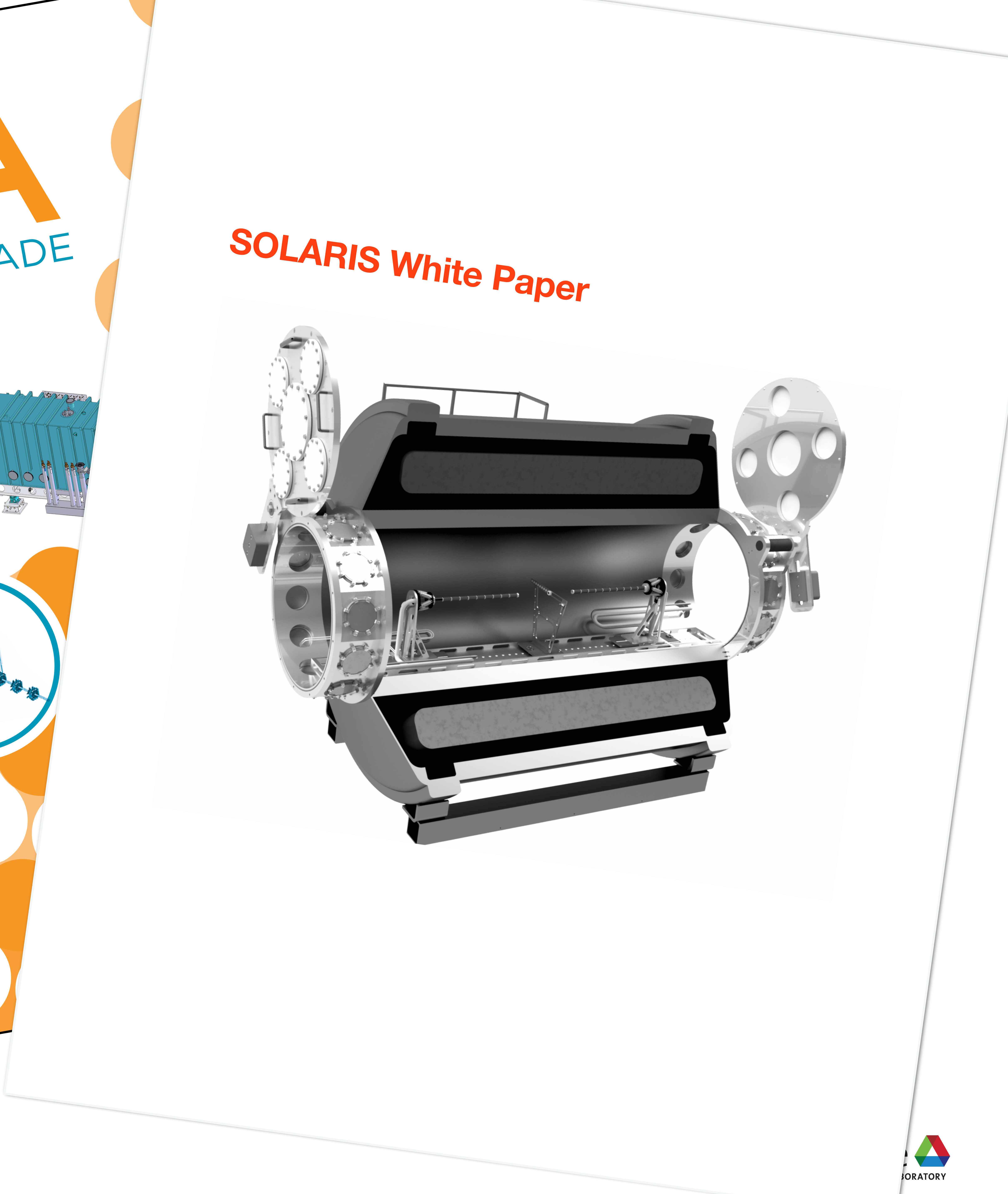
Will operate in dual modes, like the ISS.

http://www.anl.gov/phy/group/solaris

SOLARIS

Website and white paper available shortly (email me if interested). Anyone is welcome to join us.





http://www.anl.gov/phy/group/solaris

Summary

Solenoidal spectrometers are a valuable tool for studying direct reactions in inverse kinematics with Q-value good resolution

- 'Simplicity'
- Efficiency
- Versatility
- Resolution

Demonstrated with a ~10-year program with HELIOS at ATLAS

… BUT, the beams are king

- AIRIS upgrade at ATLAS, CARIBU beams …

… ISS at HIE-ISOLDE and SOLARIS at FRIB (ReA)