Low Energy Nuclear Experiments

Ben Kay, Argonne National Laboratory

National Nuclear Physics Summer School, 8-19 July 2019

Overview, part 1 (*general properties of nuclei, mostly <u>macroscopic</u>*)

What can experimentalists determine about a nuclear system in the lab?

- *History … the isotopes, the facilities we use*
- *What can we measure/is observable?*
- *Questions to ask about the nucleus*
    - *How much do they weigh?*
    - *What size are they?*
    - *What shape are t* [redacted]

Attempt to [redacted] *ny accessible examples from recent literature, leaning towards the study of exotic* [redacted] *where possible*

Overview, part 2 *(mostly direct reactions, not so exotic)*

The connection between direction reactions and nuclear structure

- *History*
- *Reactions, reaction types, direct reactions*
- *Observables*
- *Energies, momentum*
- *Spectroscopic factors, occupancies (in [illegible]xt of ‘modern’ [but stable-beam] examples)*

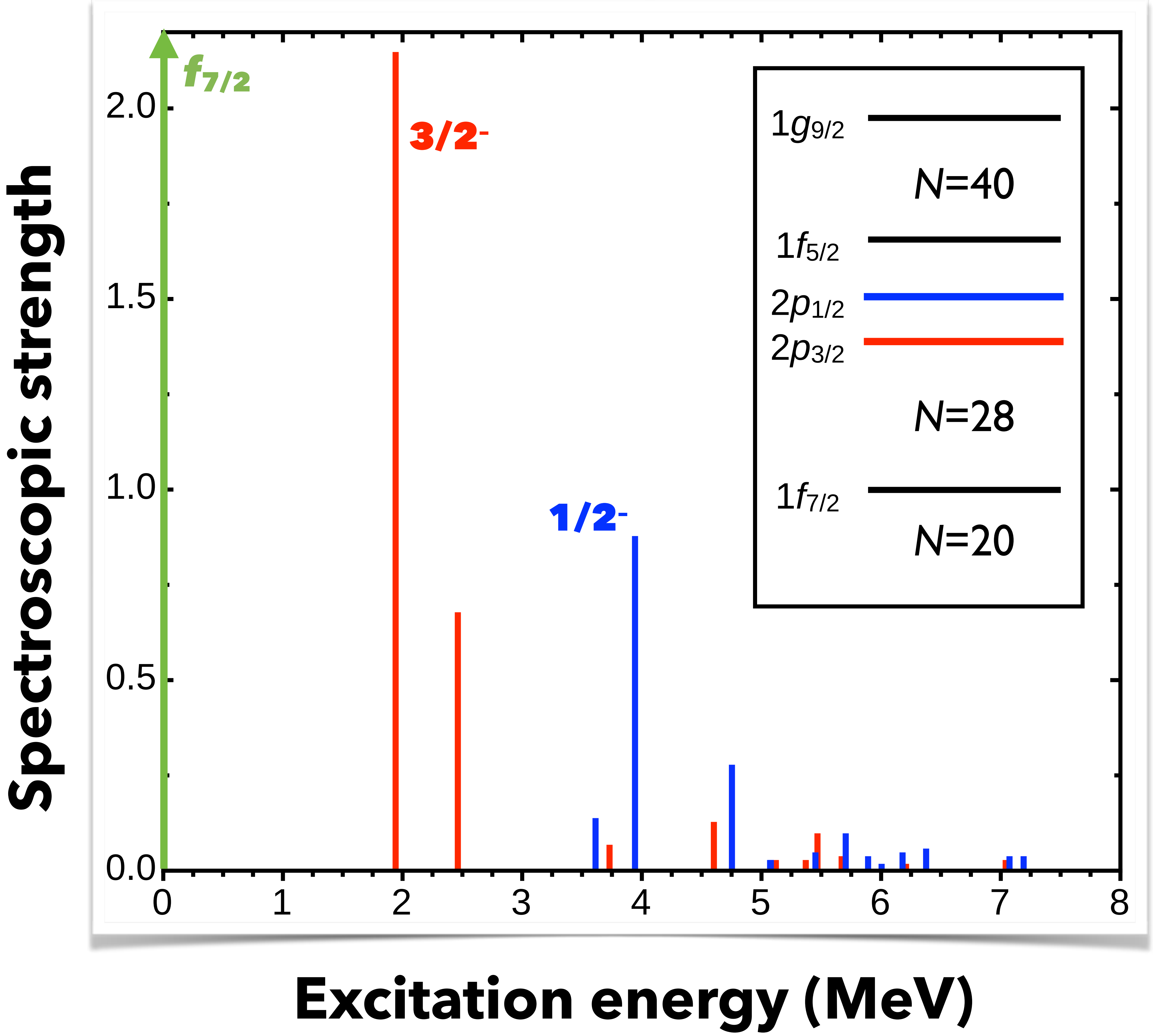
Attempt to steer c[illegible] reactions for reaction’s sake, rather using them as a meaningful tool to gain insight[illegible]opical nuclear structure properties

Single-particle energies – a 'classic' example

In many cases, single-particle strength is fragmented over several states. ^{41}Ca is an excellent example of this: just one neutron outside the doubly-magic ^{40}Ca (20 protons, 20 neutrons) …

For the (*d*,*p*) reaction …

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{measured}} = gS_j \left.\frac{d\sigma}{d\Omega}\right|_{\text{model}} \iff \sigma_{\text{exp}} = (2j+1)C^2 S_j \sigma_{\text{DWBA}}$$



The centroid of single-particle strength--weighted by its spectroscopic strength--is a good approximation to the energy of the underlying single-particle orbital.

(ESPEs, SPEs in lit., theory)

Recap …

- Reactions ***A(a,b)B*** reveal something about the atomic nucleus
- Single-nucleon transfer (shameful bias in these lectures) can:
  - populate single-particle excitations
  - allow us to deduce spectroscopic factors, ℓ
  - … and thus single-particle energies
  - … and thus occupancies / vacancies

- I showed ~two topical examples from the last ~decade, where ***reactions*** have been an ***essential tool*** in basic nuclear structure and in connection to fundamental symmetries

… and next

- Two more examples, ***exotic beams***, ***spectrometers***, …, bubbles, isomers, …

Overview, part 3 ***(mostly direct reactions, quite exotic, microscopic)***

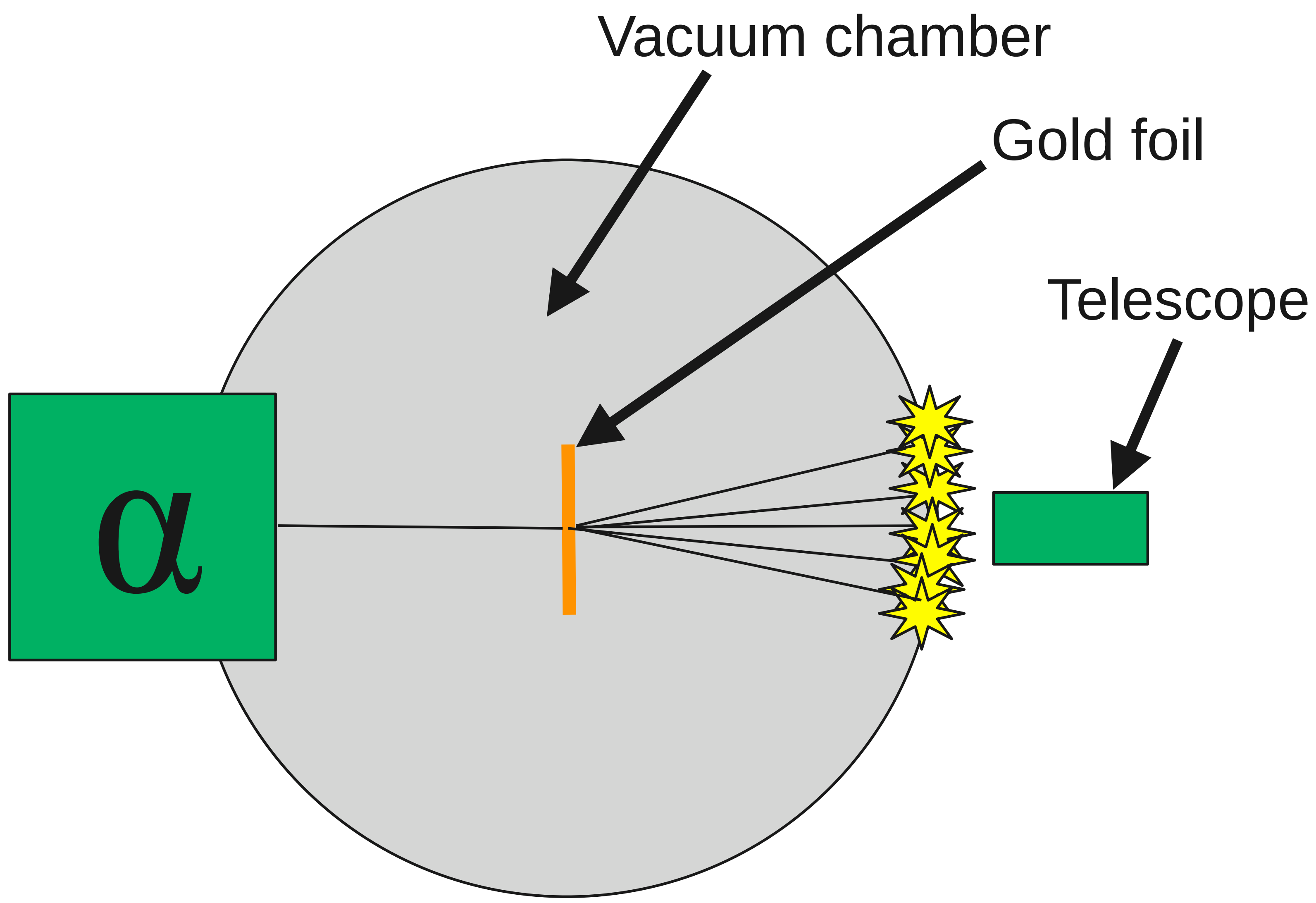
The connection between direction reactions and nuclear structure

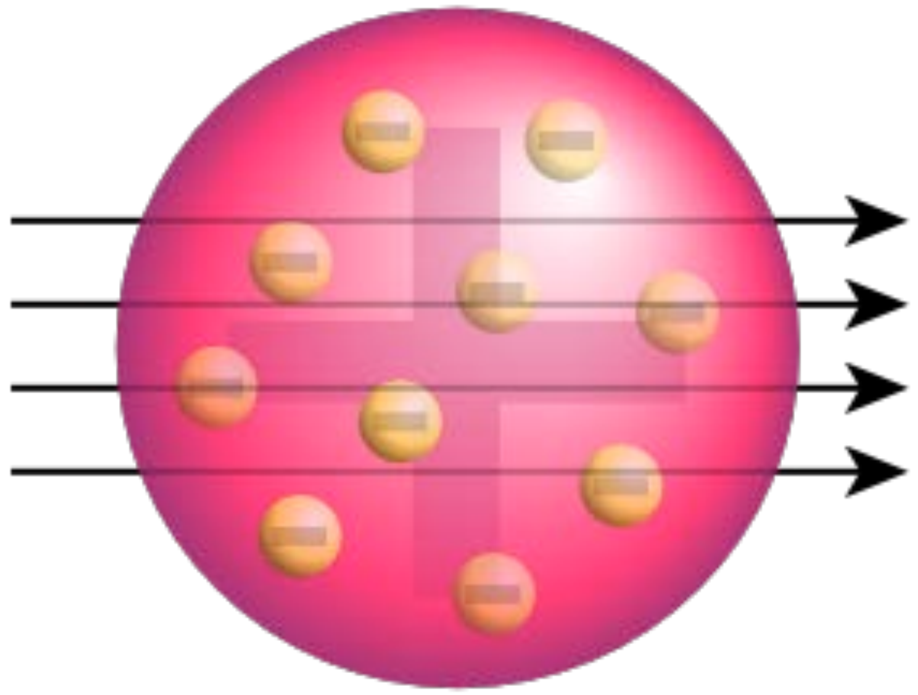
- *History*
- *Exotic beams*
- *Kinematics*
- *Spectrometers (with a focus on solenoidal spectrometers)*
- *A few examples from the last few years (2014, 2017, 2017, current) (what drove them, reaction choices, results, commentary)*

Part 3: Mostly direct reactions,… quite exotic

To begin at the beginning …

The Geiger-Marsden experiment

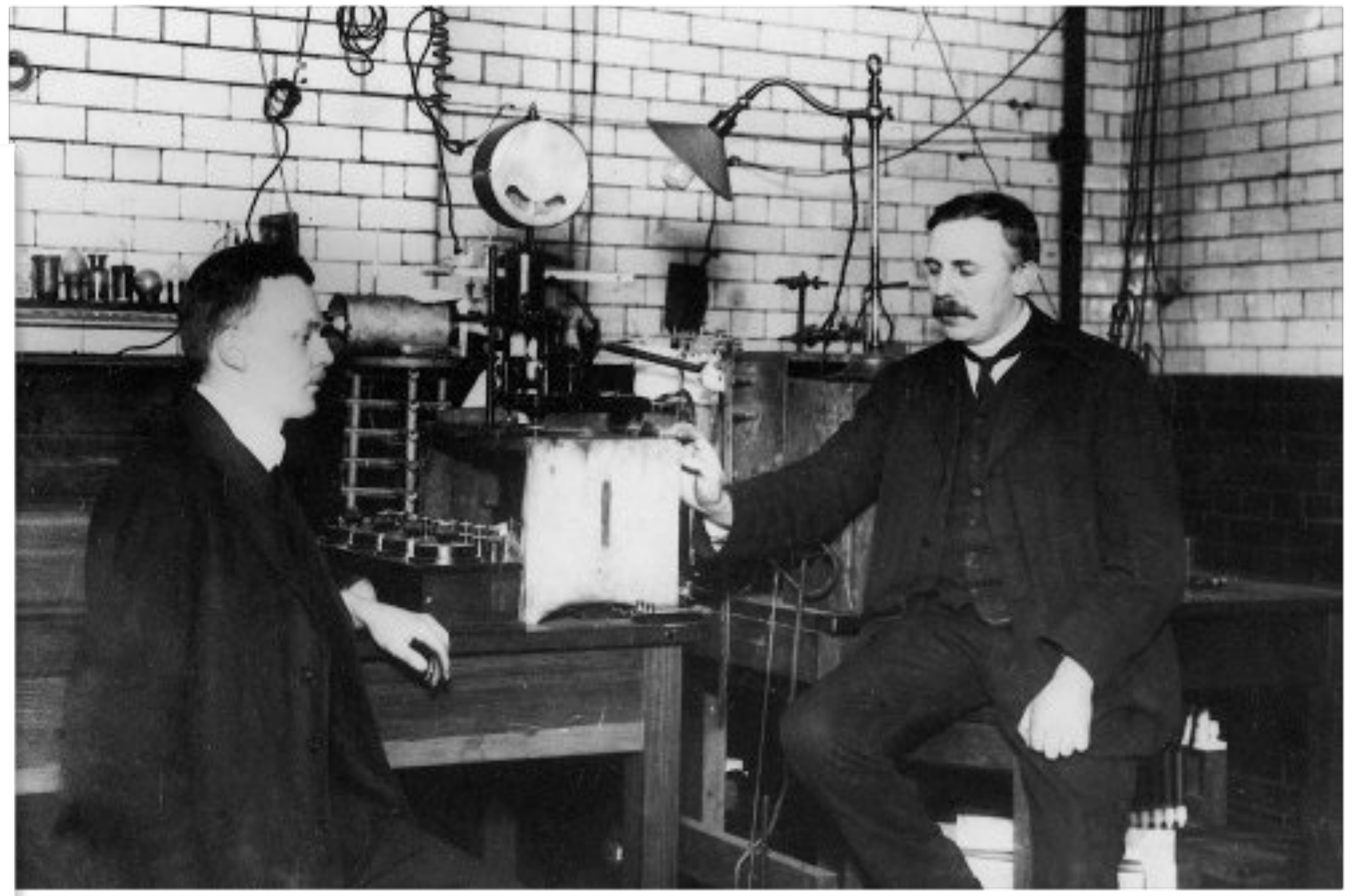




The plum-pudding idea seemed reasonable: this result would fit expectations

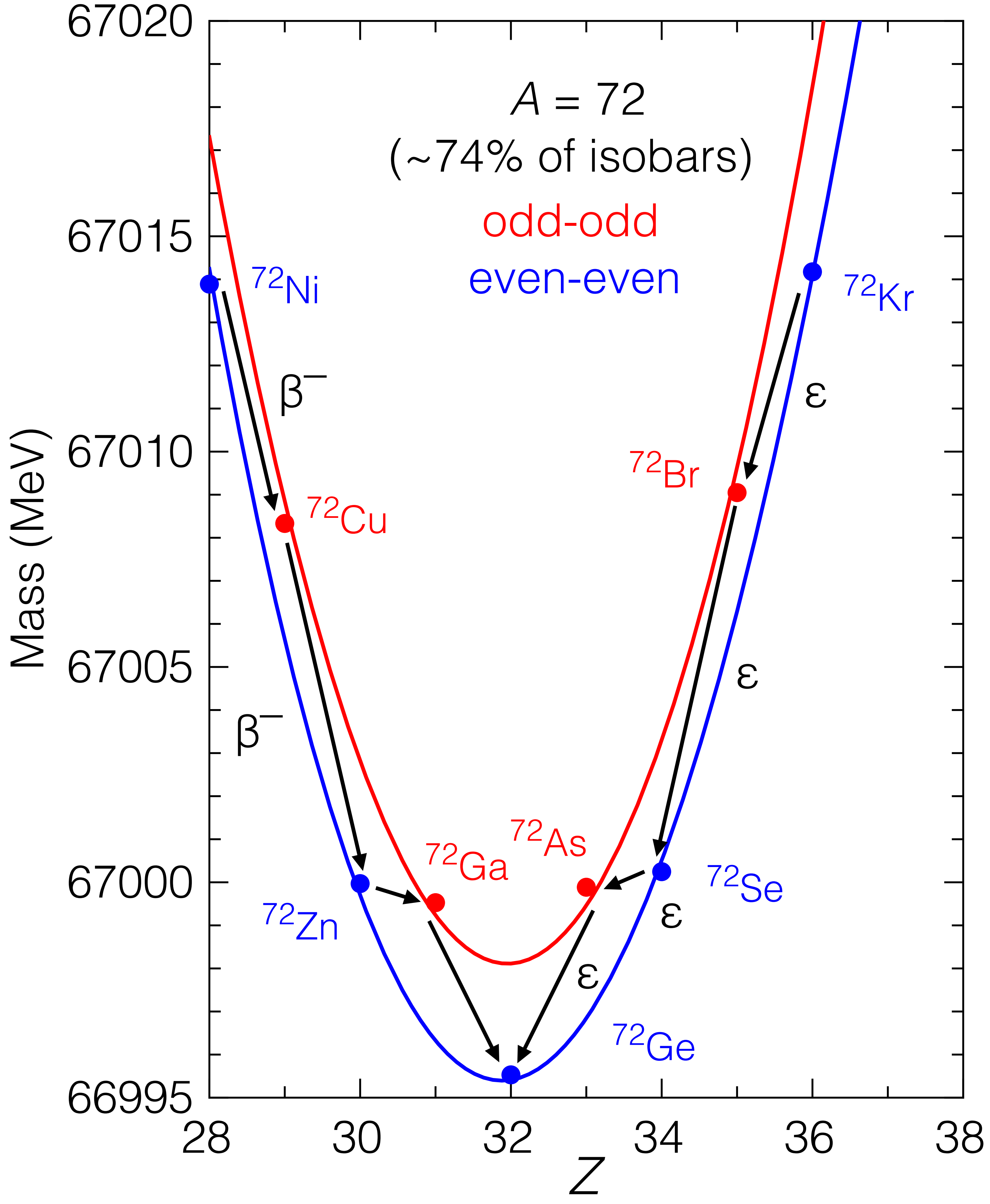
- A 0.1 Ci radium source
- ~10^{10} α particles per second (~ 1nA of ^{4}He)
- α particles of 7.7 MeV (~1.9 MeV/u)
- A gold foil of 0.00004 cm thick (~0.8 mg/cm^2)
- A telescope was used to look at flashes of light on a zinc sulphide screen

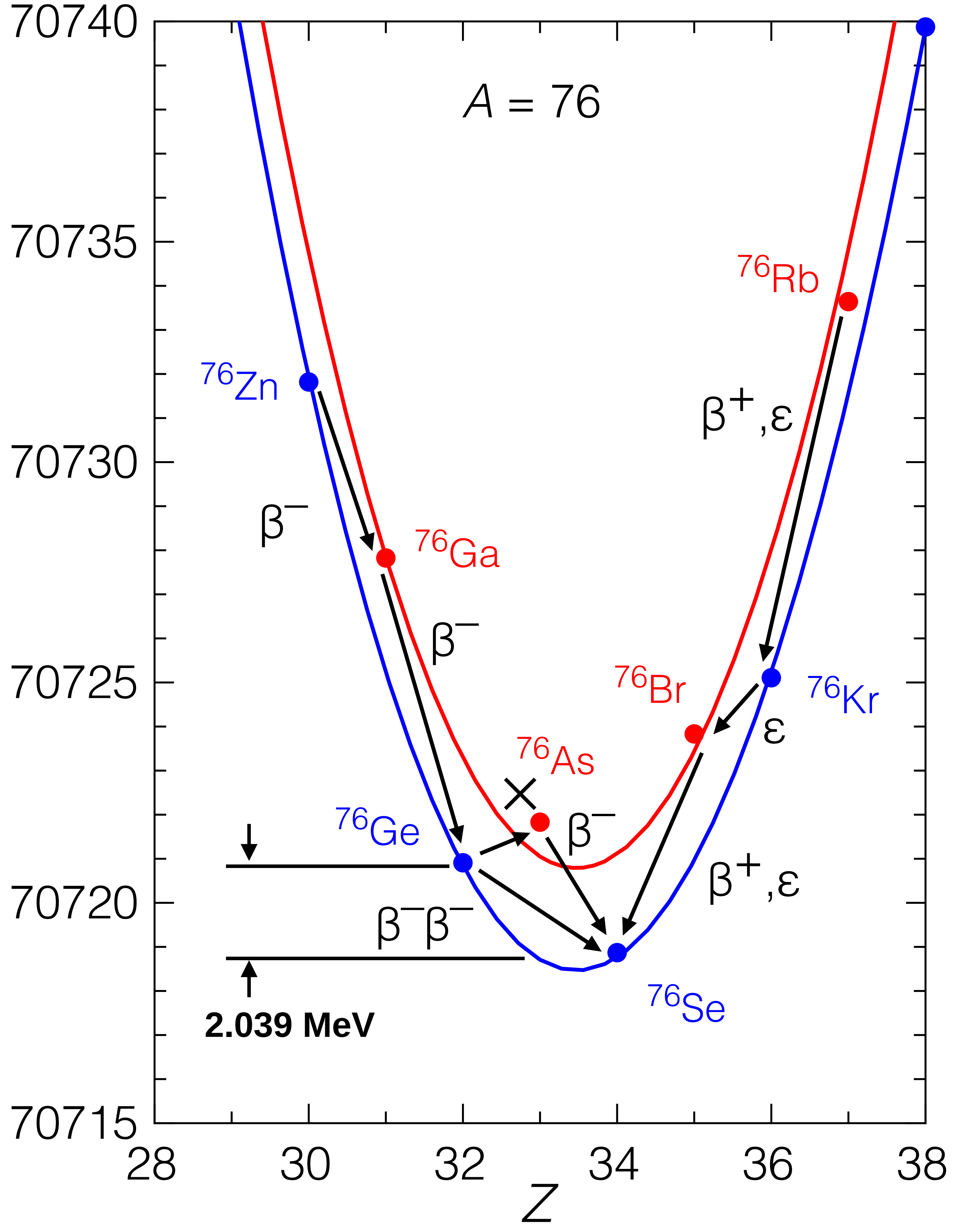
*E. Rutherford, Philosophical Magazine **21**, 669 (**1911**)*

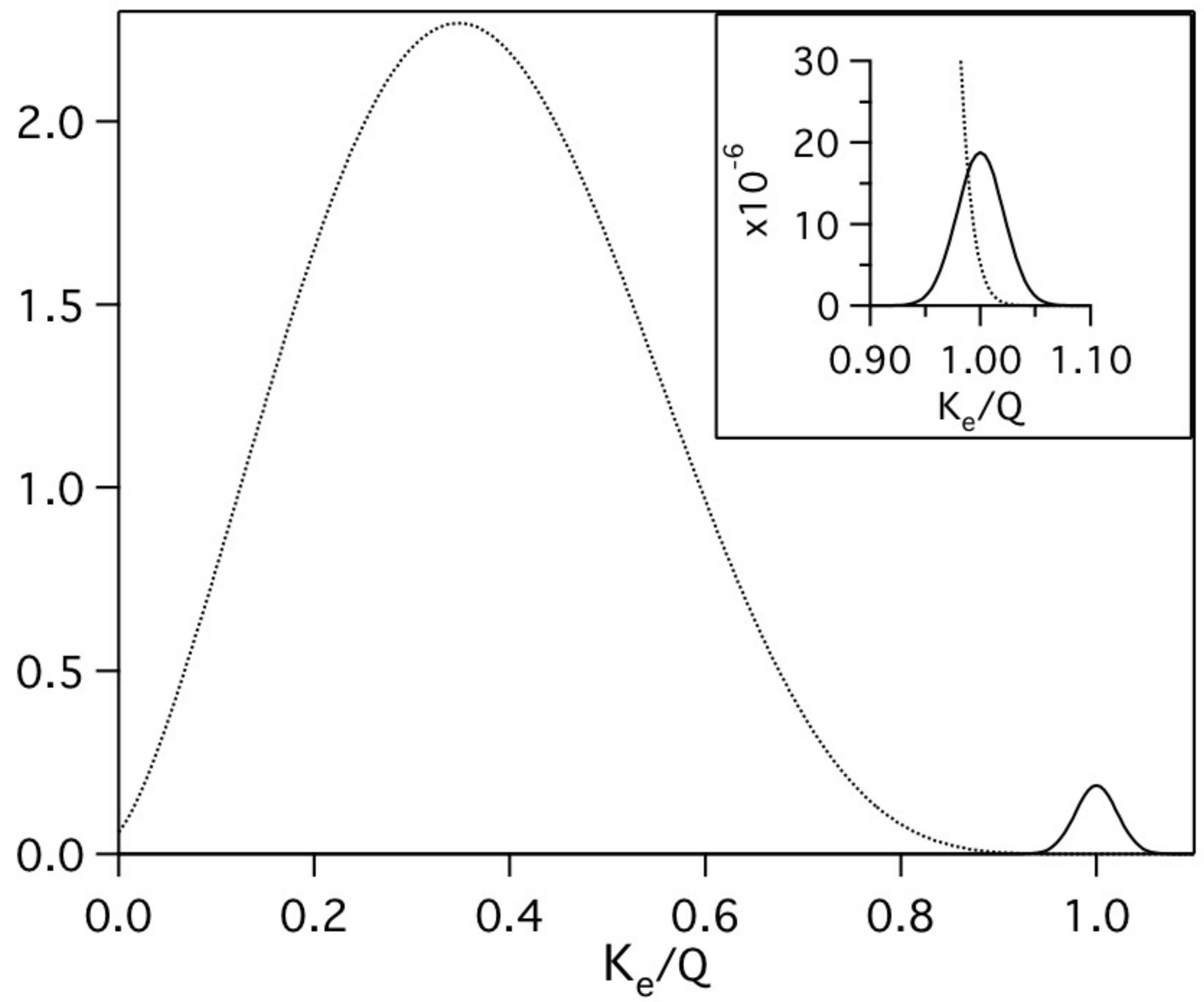


Neutrinoless double beta decay

A hypothetical decay process … made 'possible' by pairing in nuclei



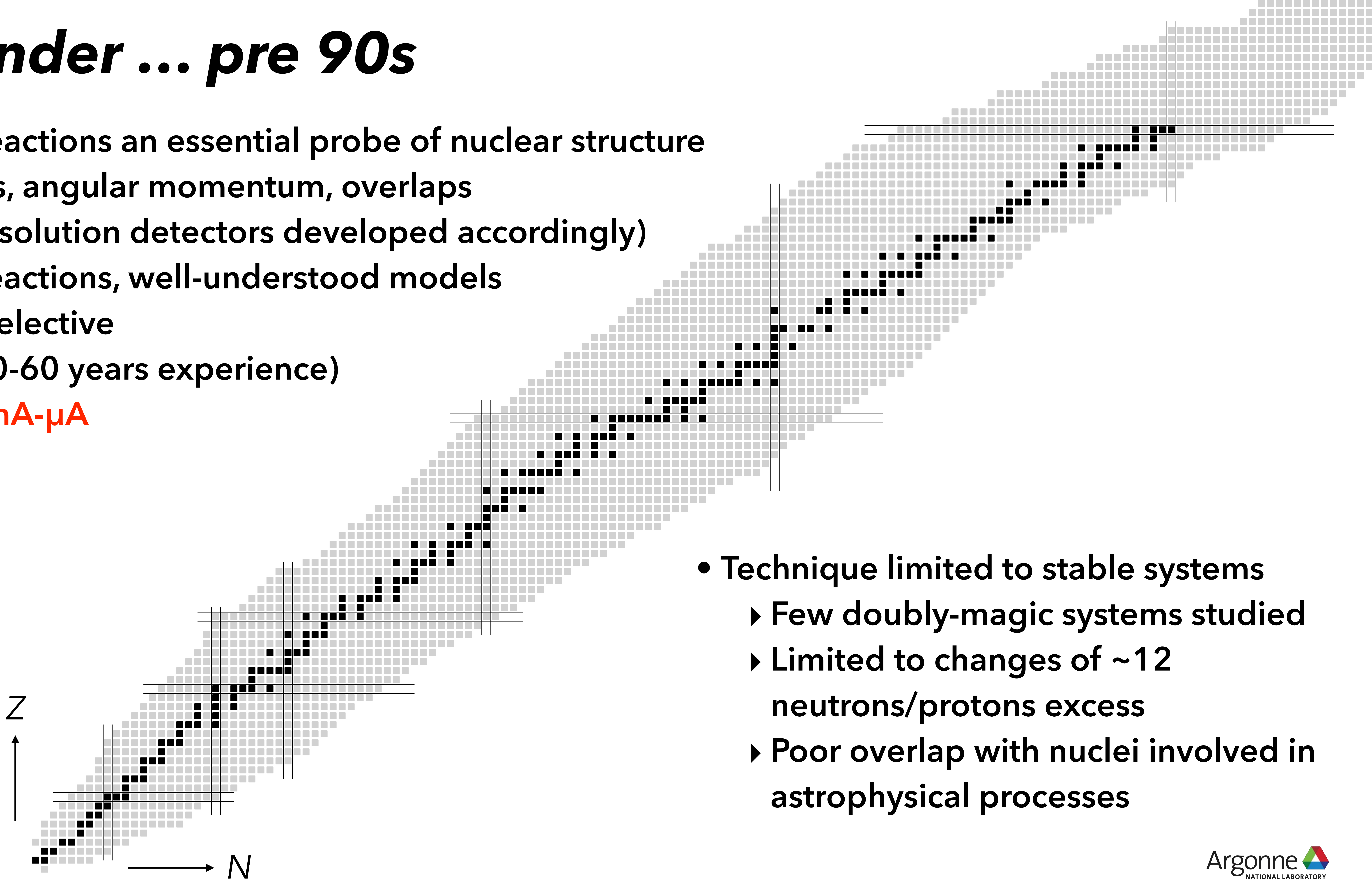




$$[T^{0\nu}_{1/2}]^{-1} = (\text{Phase Space Factor}) \times |\text{Nuclear Matrix Element}|^2 \times |\langle m_{\beta\beta}\rangle|^2$$

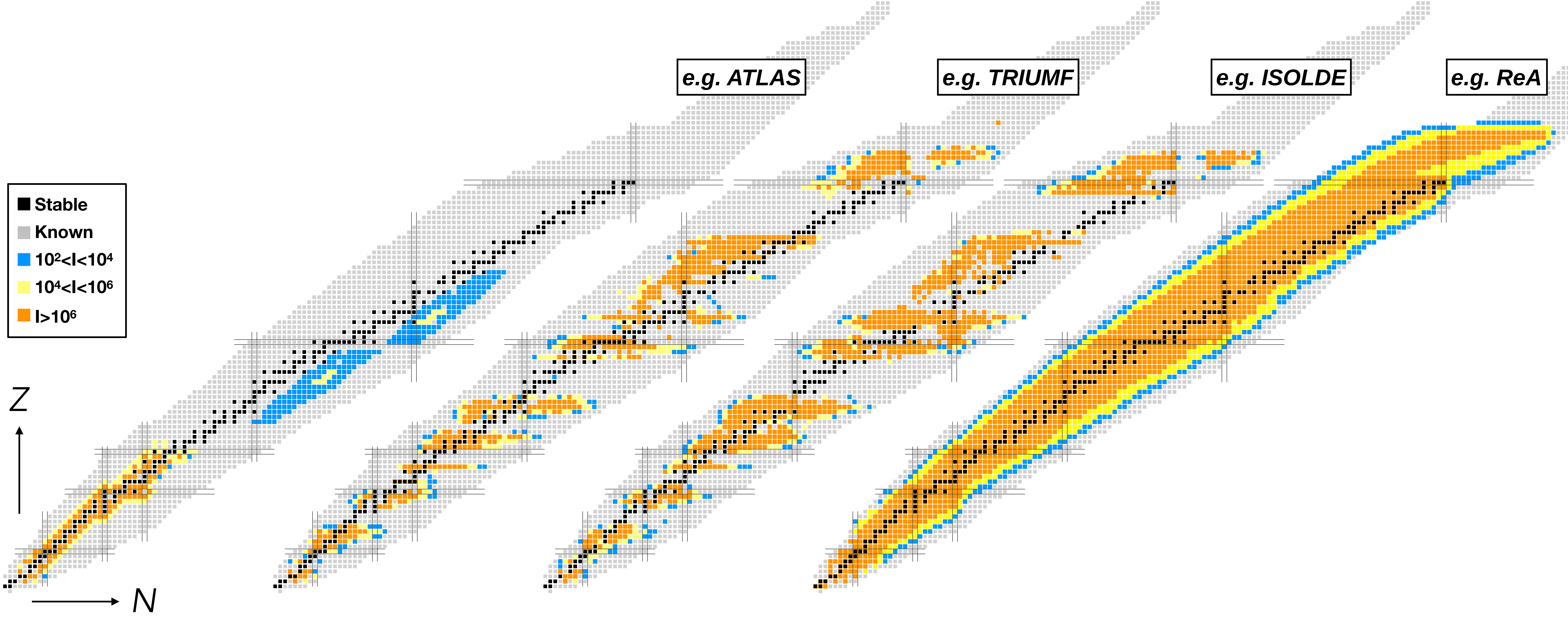
Reminder … pre 90s

- Direct 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)
- Beams, nA-μA



- 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

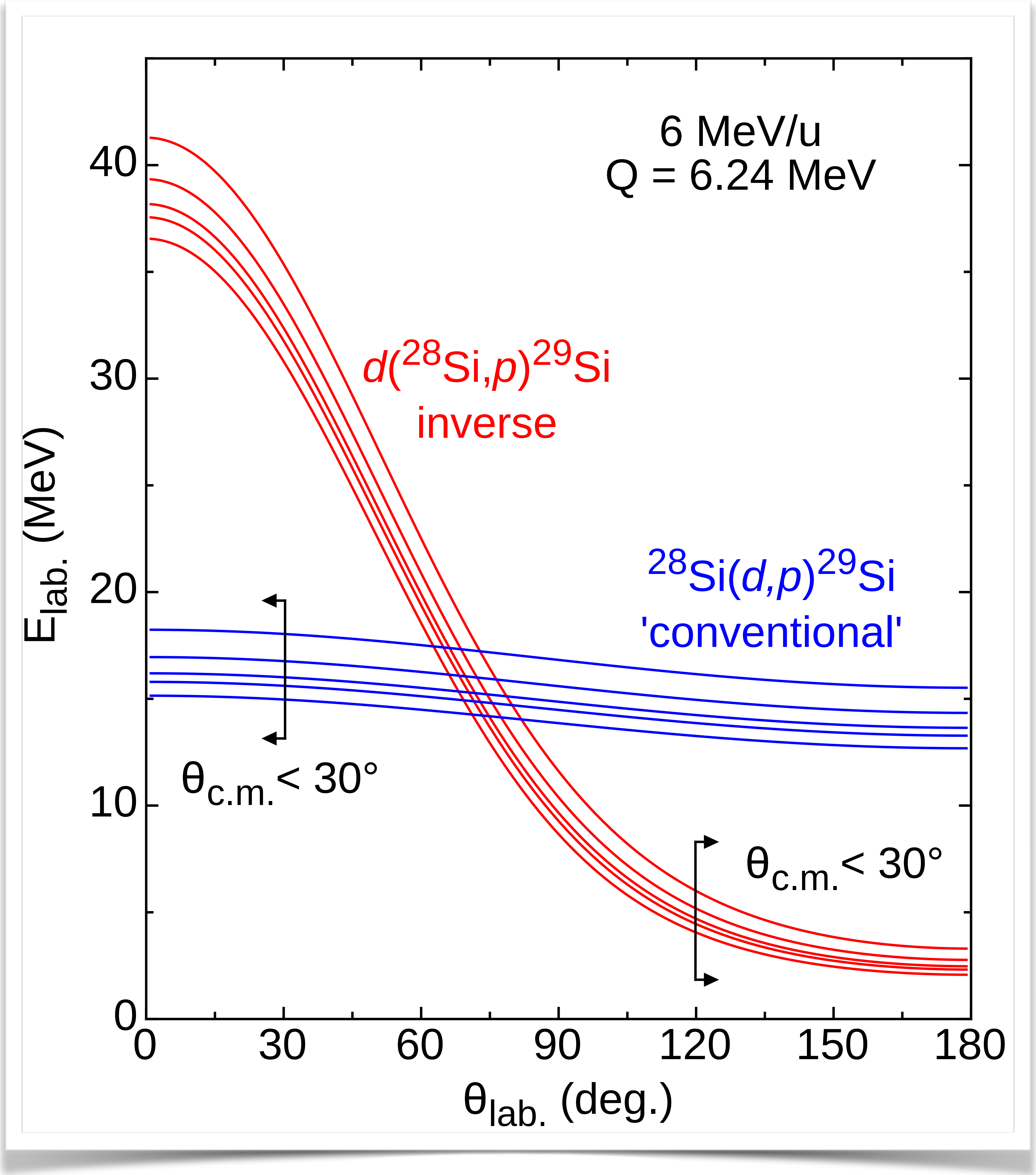
… but people have been busy



www.anl.gov/phy/helical-orbit-spectrometer

from various sources, illustrative, likely ~1-2 orders of mag. off

Kinematics: normal vs. inverse

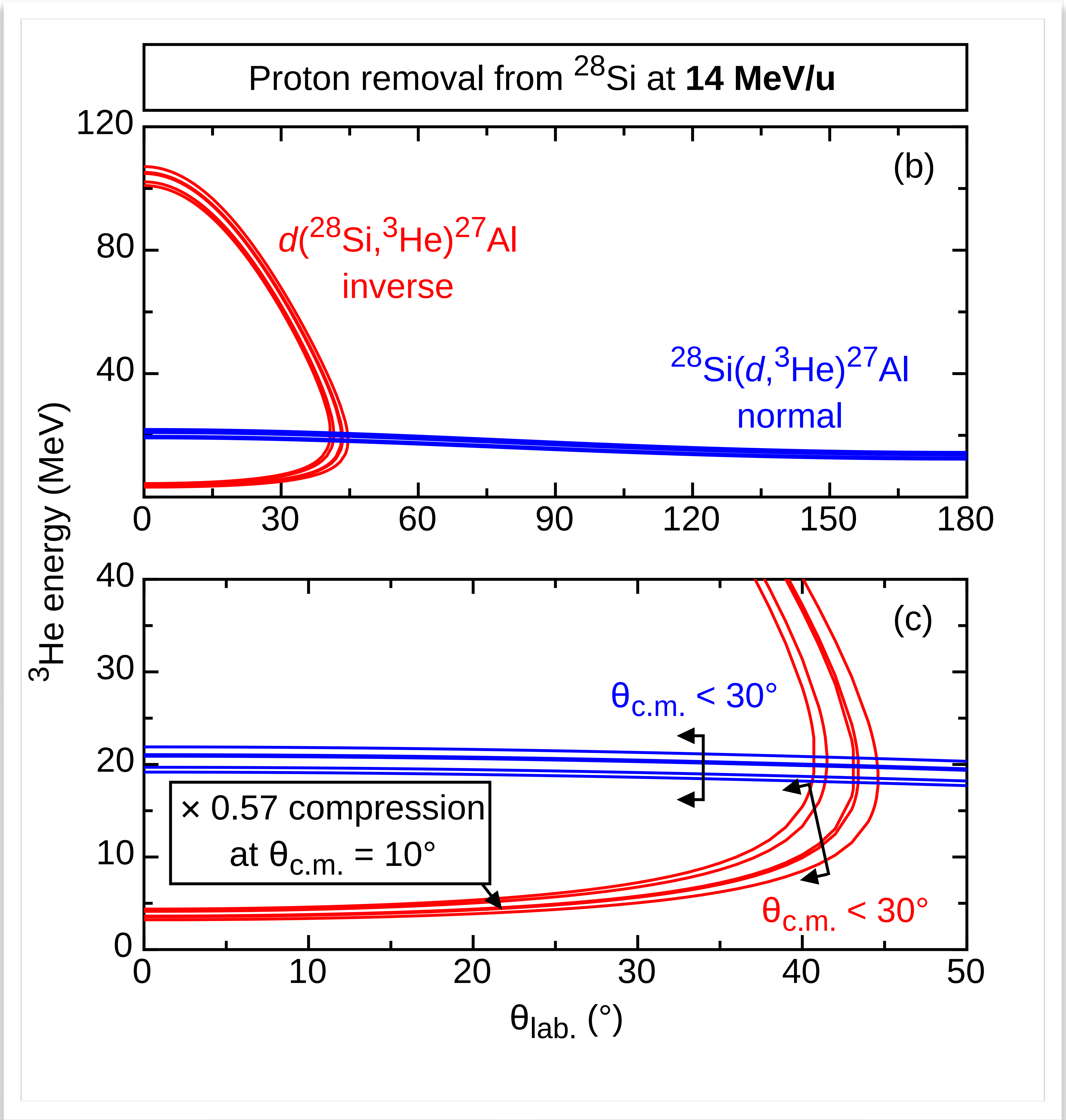


Inverse-kinematics challenges

- Particle identification, Δ*E*-*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

A. H. Wuosmaa et al. Nucl. Intrum. Methods Phys. Res. A ***580****, 1290 (****2007****), J. C. Lighthall et al. ibid.* ***622****, 97 (****2010****)*

Kinematics: normal vs. inverse



$$\tan \theta^{\text{lab}}_{\text{max.}} = 1/\sqrt{(V/\bar{v})^2 - 1}$$

V is c.m. velocity of the system, v is the velocity of the outgoing ion in the c.m. frame

- **For negative Q-value reactions e.g. (d,^{3}He) there is a double-valued kinematic solution …**
- **… ions cannot scatter beyond $\theta_{\text{max.}}$ in the laboratory, in this case $\theta_{\text{lab.}} = 44.6°$**
- **Particularly challenging for fixed lab-angle measurements, especially near $\theta_{\text{max.}}$**

Kinematics code (e.g.):

Excel based:

- *Catkin, http://personal.ph.surrey.ac.uk/~phs1wc/kinematics/ (easy, visual, intuitive)*
- *Heliomatic (for HELIOS, based on Catkin – **email me**)*

Java (old):

- *JRelkin, http://nukesim-classes.sourceforge.net/software_index.html*

Pro level:

- *LISE++ http://lise.nscl.msu.edu/lise.html*

Web based:

- *http://nrv.jinr.ru/nrv/*

Kinematics: normal vs. inverse (resolution)

Munich Q3D (Munich)

[https://arxiv.org/abs/1802.07057]

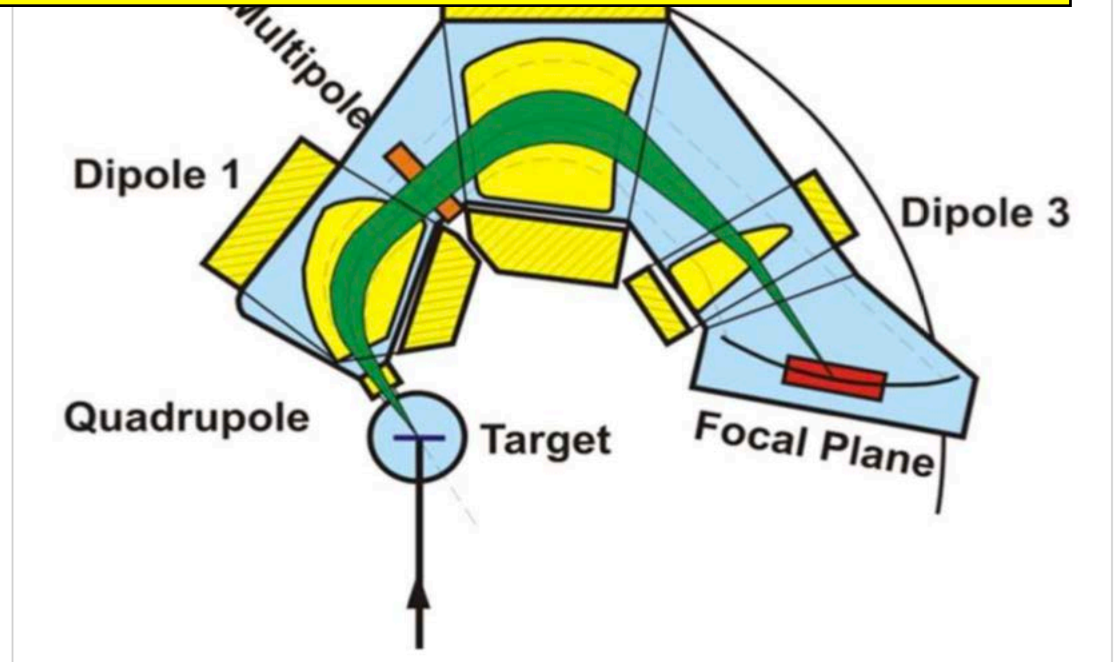


Figure 1. *Sketch of the Q3D spectrograph.*

6 keV FWHM

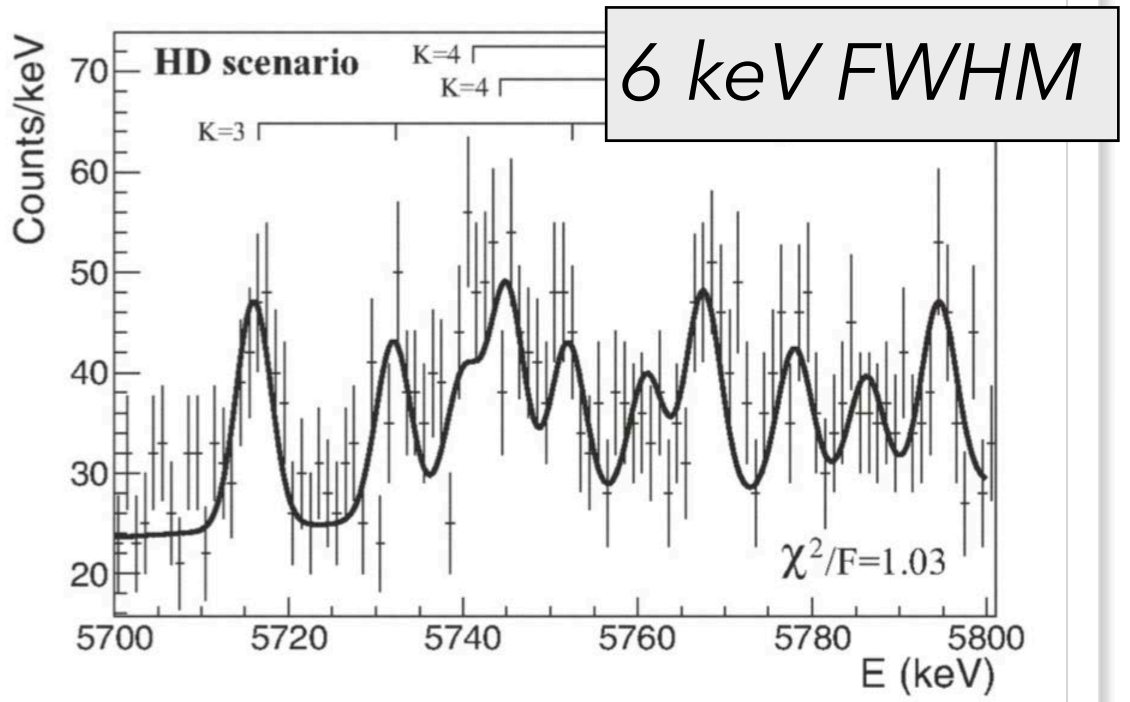
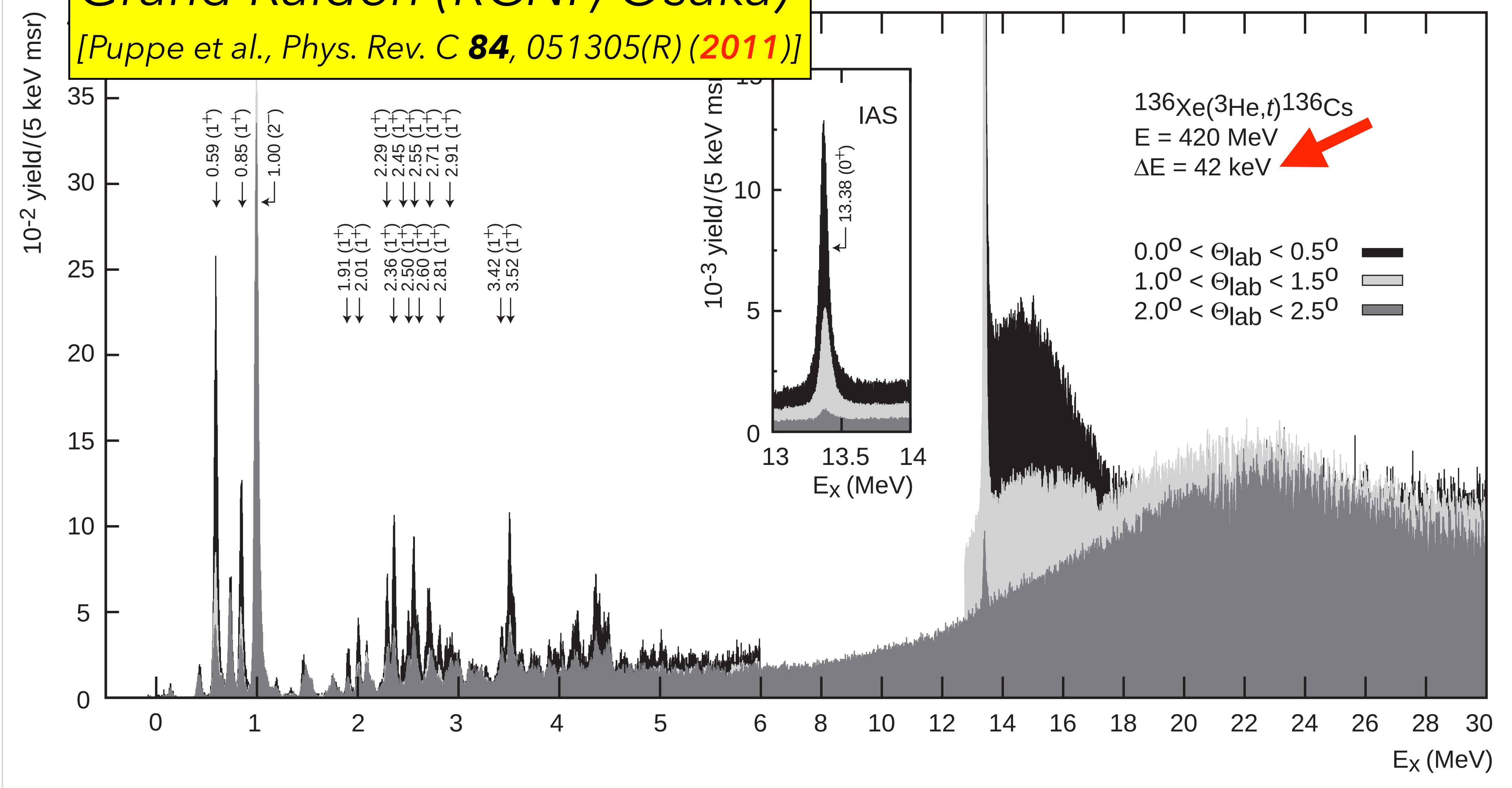


Figure 2: *Fission coincident proton spectrum for excitation energies in ^{232}Pa. Fully drawn is a fit assuming three rotational bands.*

Grand Raiden (RCNP, Osaka)

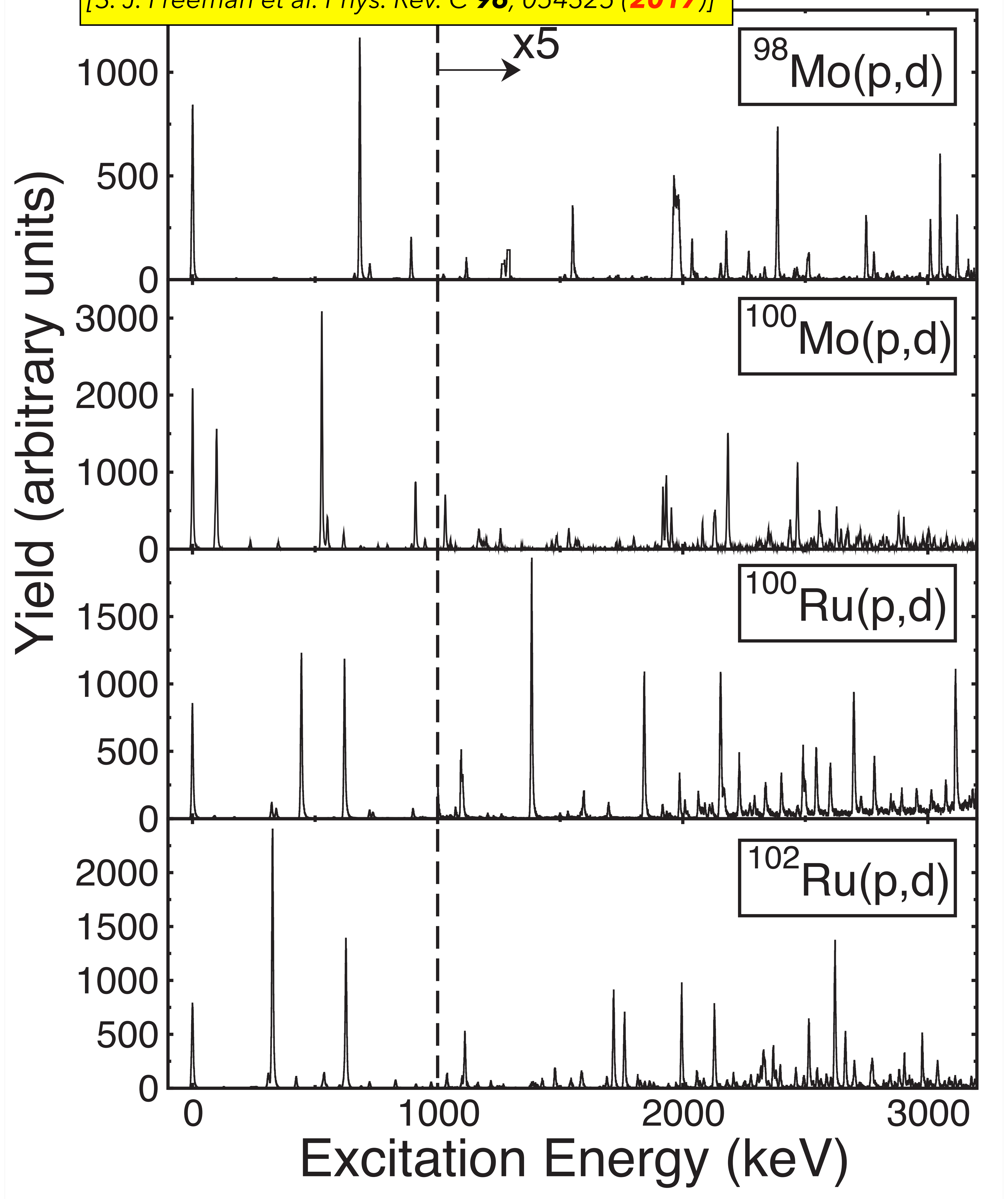
*[Puppe et al., Phys. Rev. C **84**, 051305(R) (2011)]*



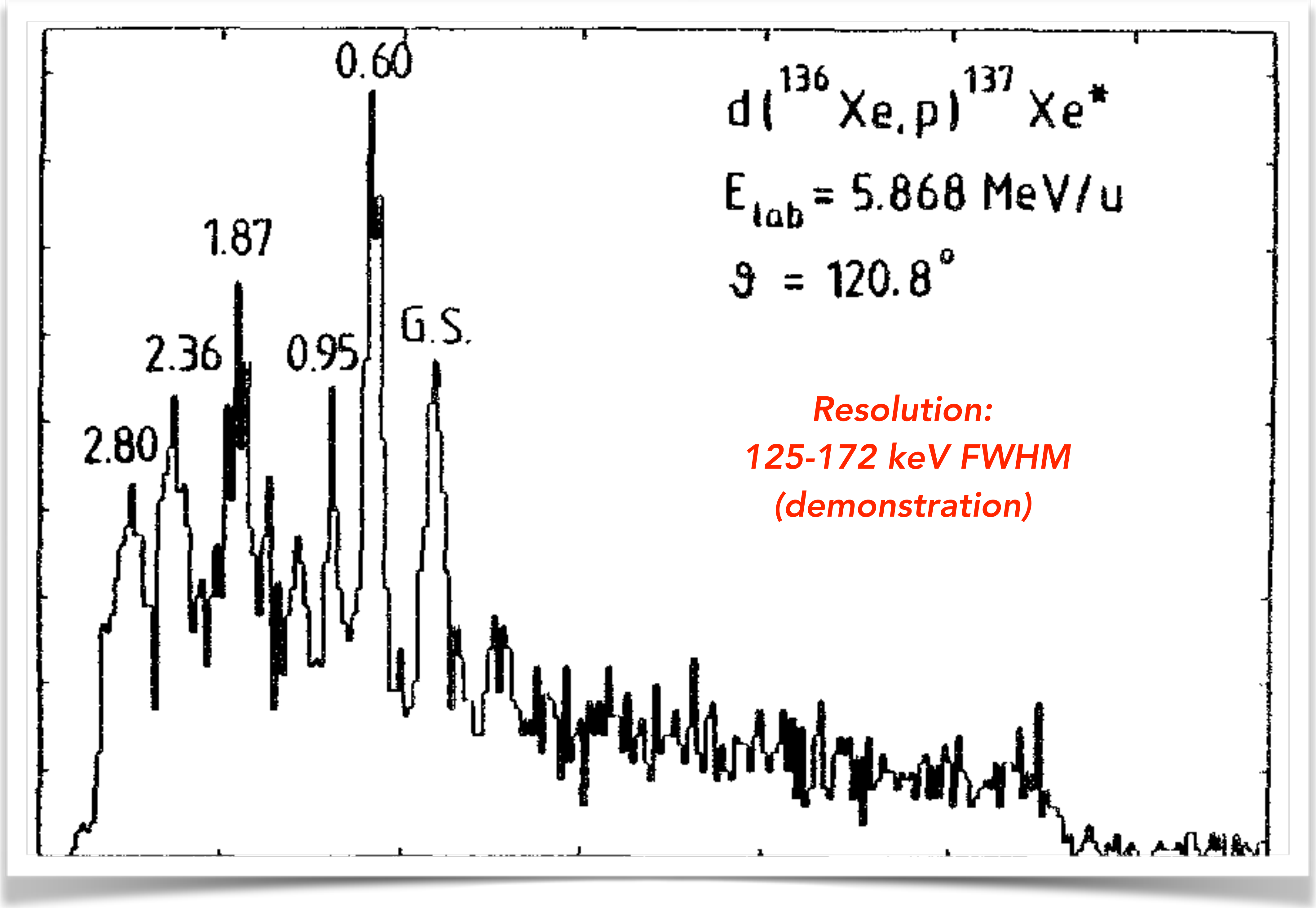
Munich Q3D (Munich)

8 keV FWHM

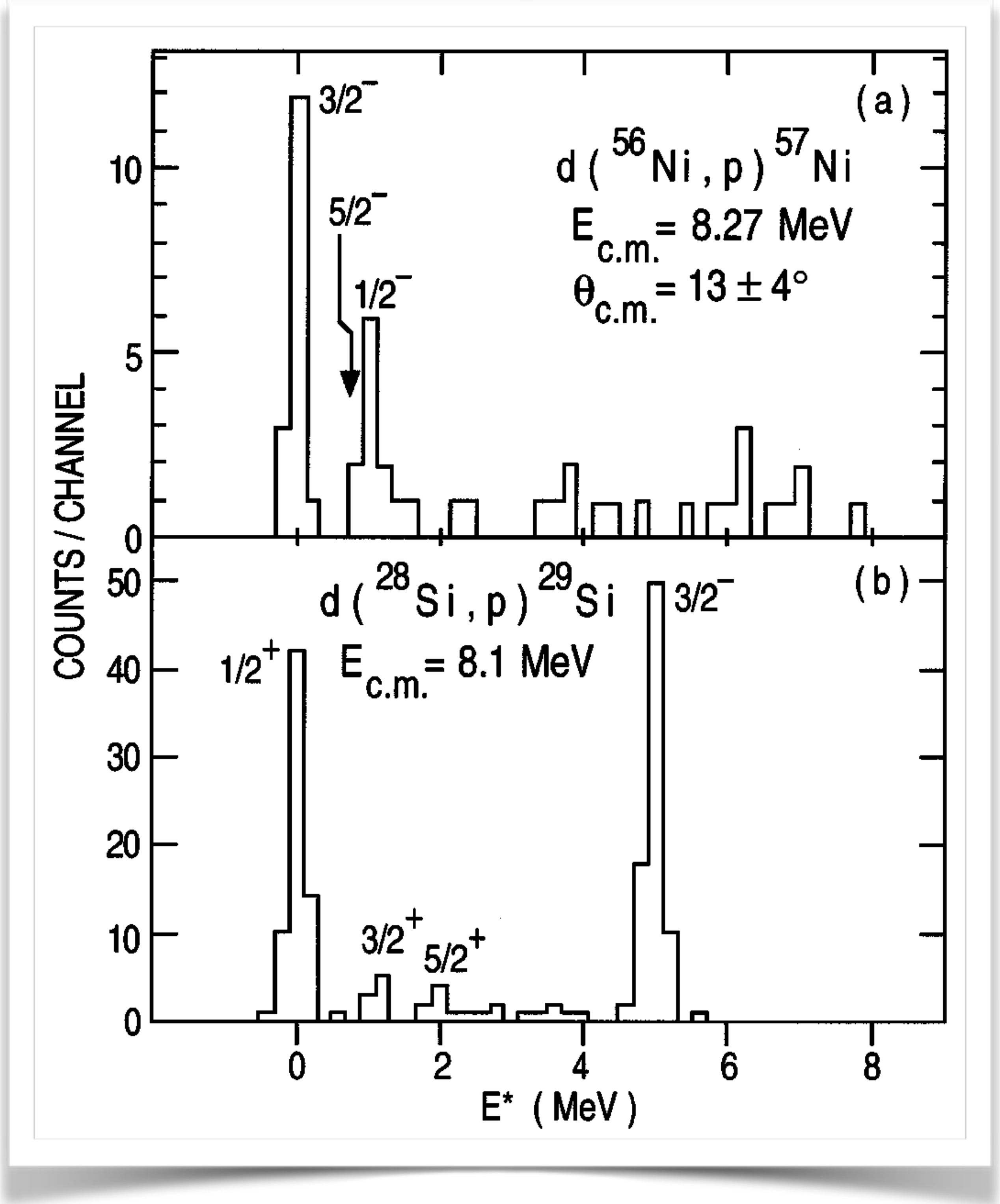
*[S. J. Freeman et al. Phys. Rev. C **96**, 054325 (2017)]*



Kinematics: normal vs. inverse (resolution)

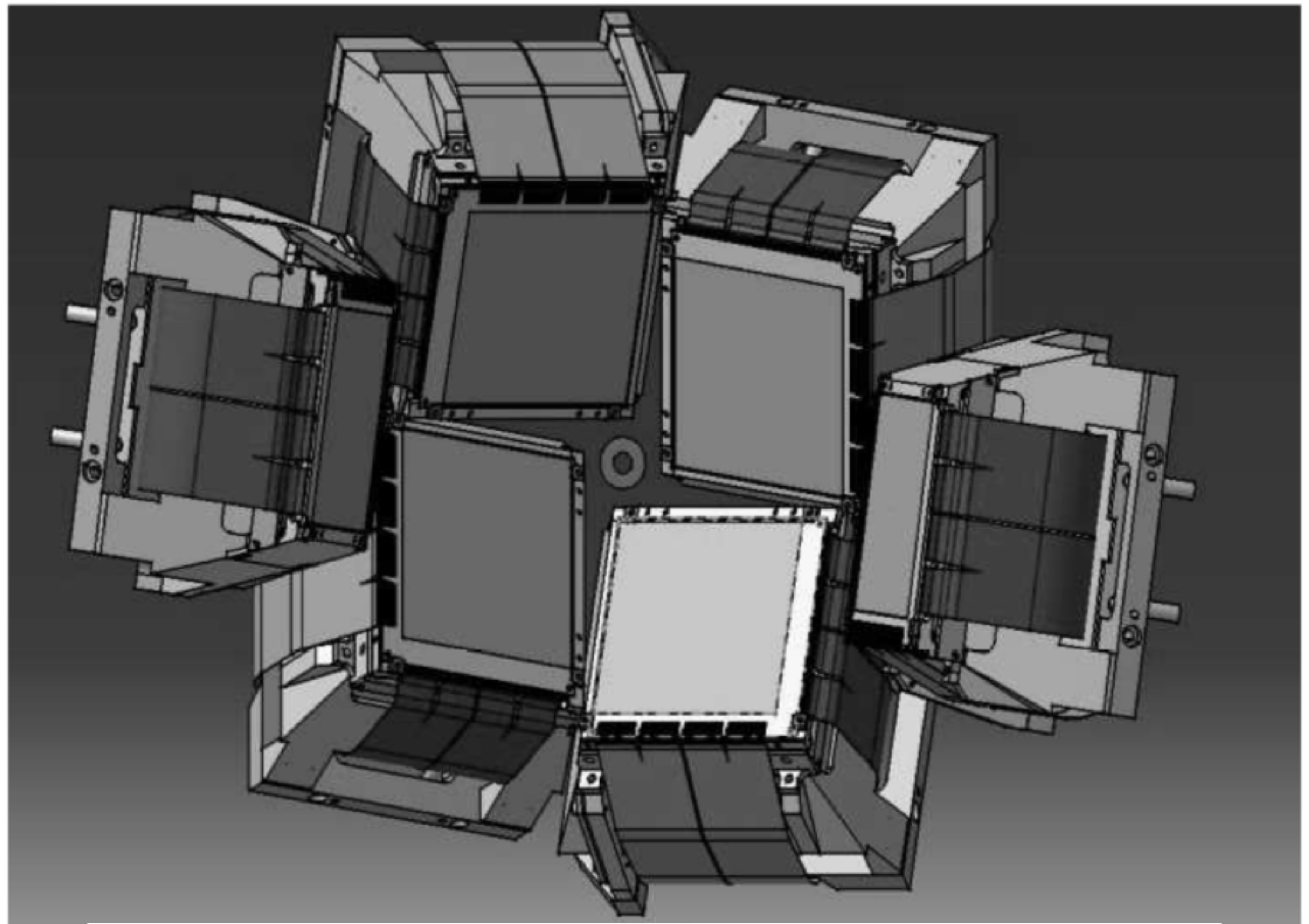


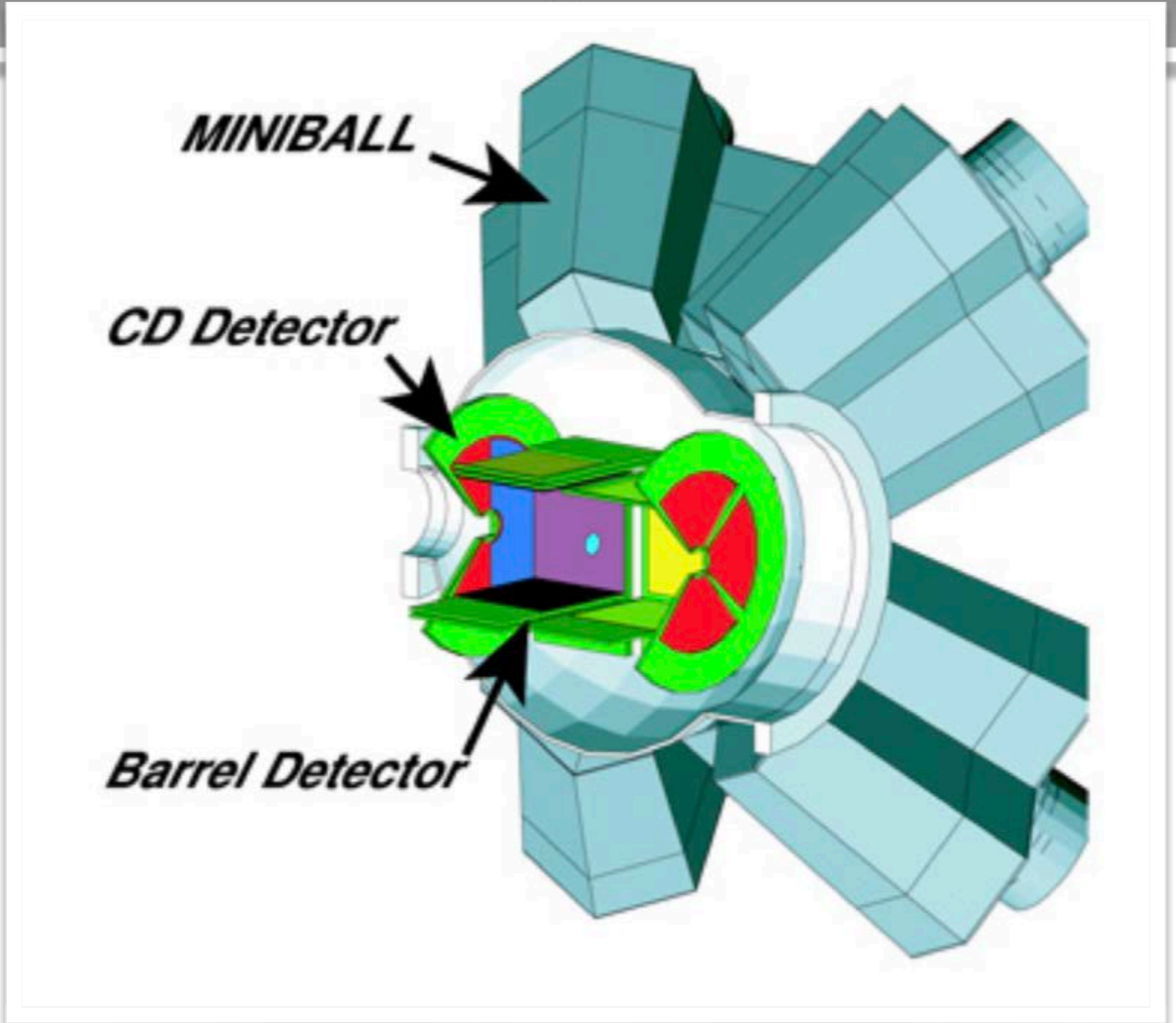
Resolution:
125-172 keV FWHM
(demonstration)

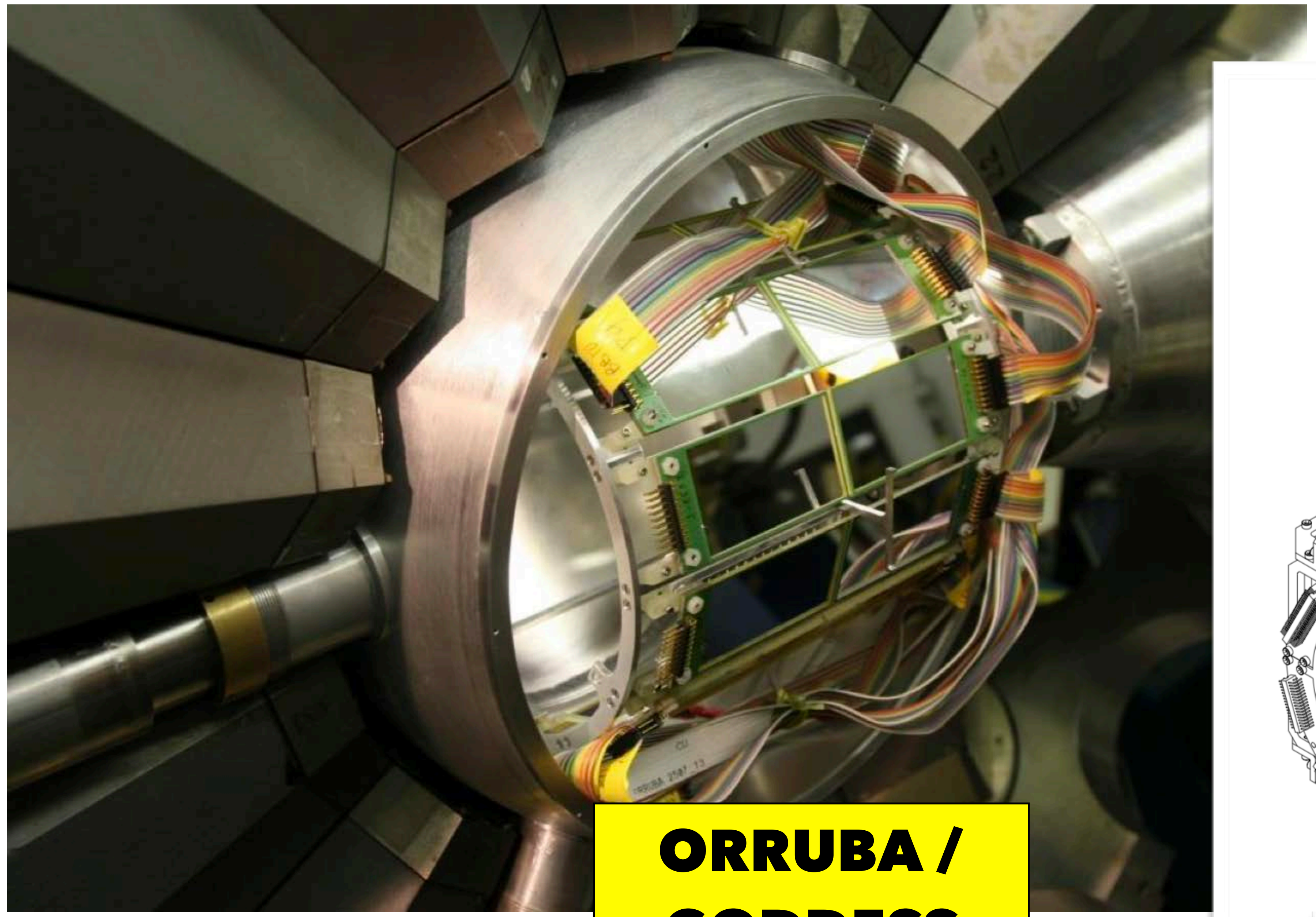


Necessities: complex Si arrays, ***high intrinsic resolution***, ***high angular granularity***, low thresholds, large acceptance, often coincident gamma-ray detection, e.g., MUST-2 (GANIL), T-REX (ISOLDE), SHARC (TRIUMF), ORRUBA (ORNL), TIARA (GANIL), etc.

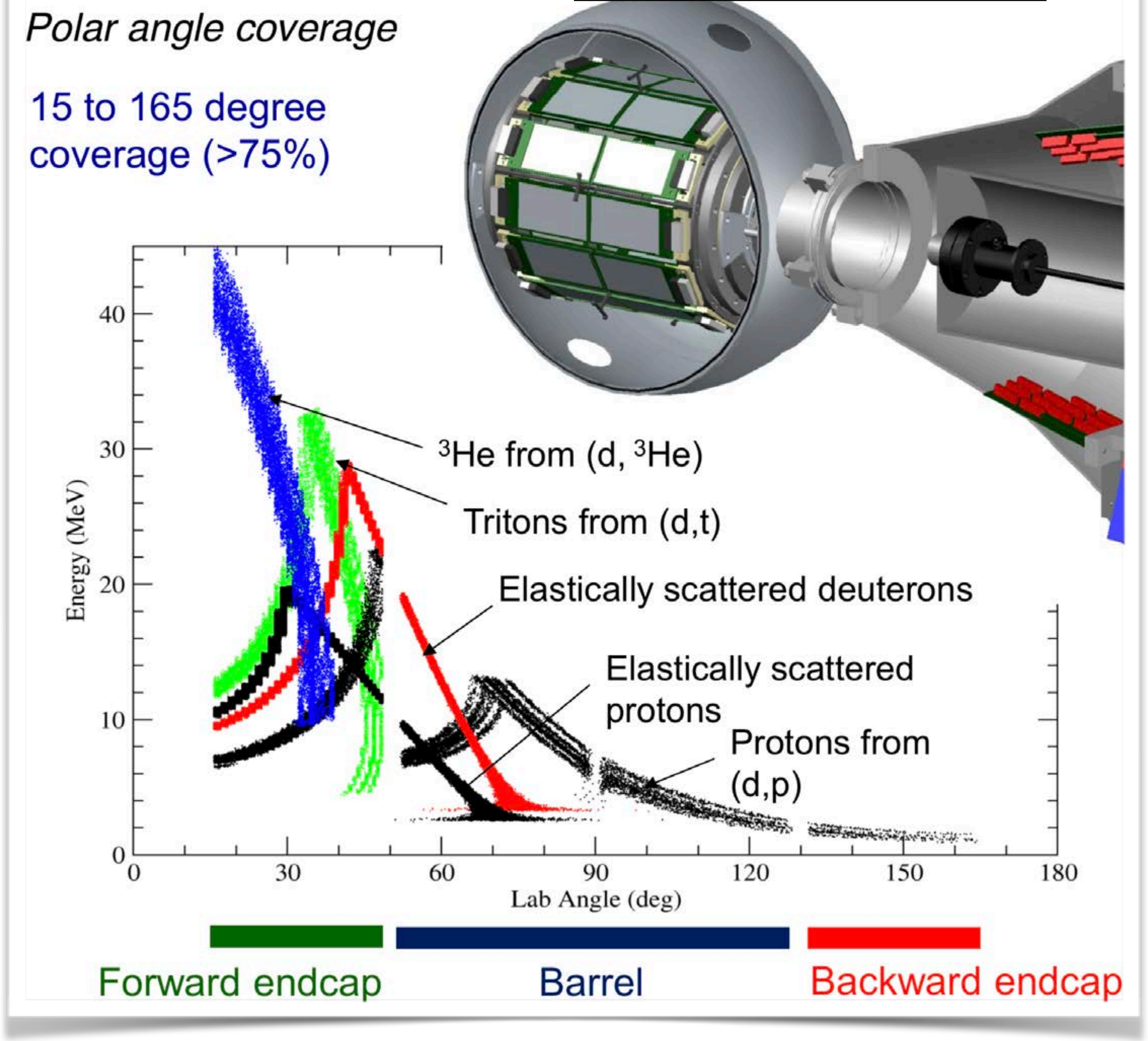
*Kraus et al., Z. Phys. A **340**, 339 (**1991**), K. E. Rehm et al., Phys. Rev. Lett. **80**, 676 (**1998**)*

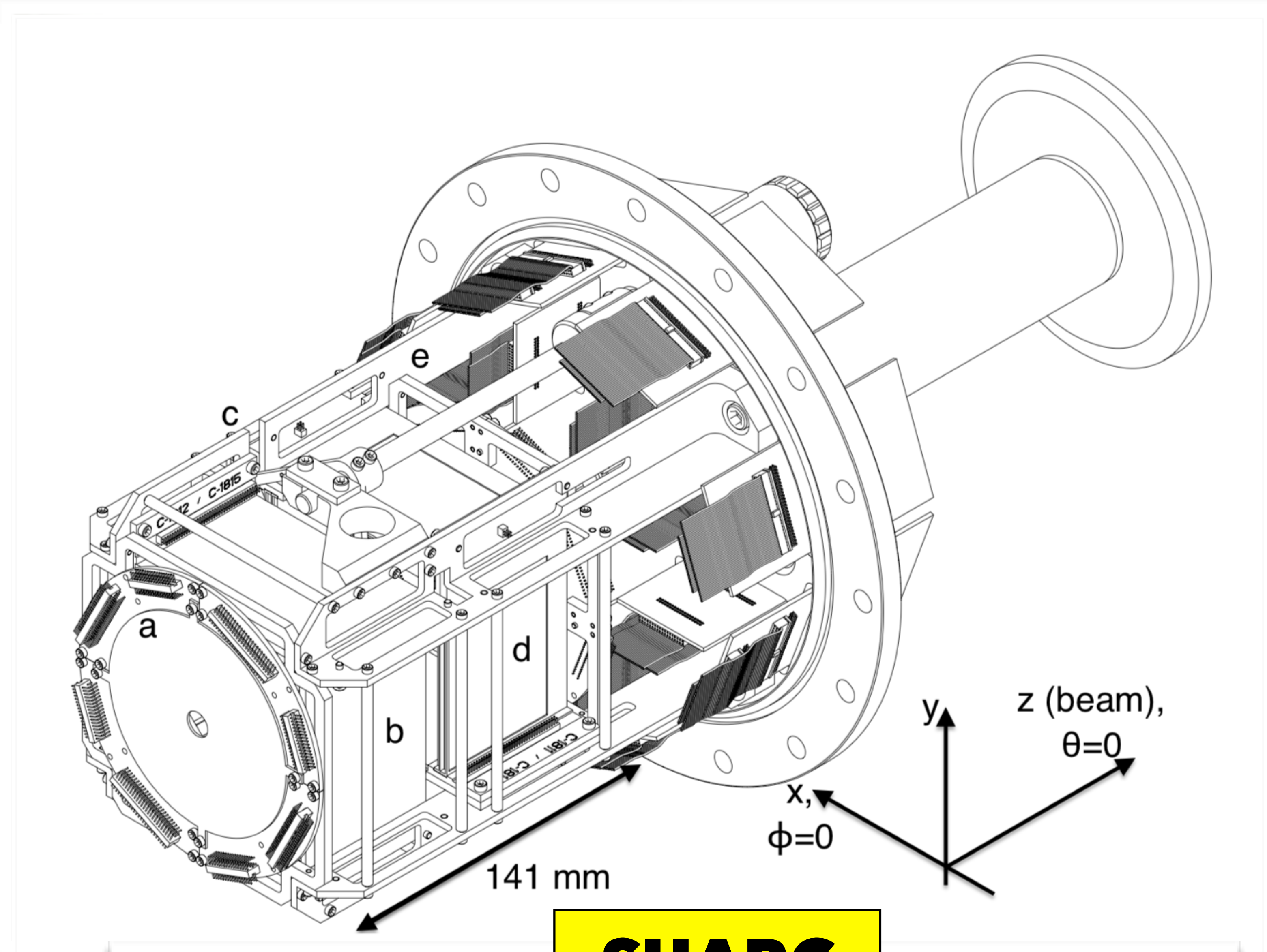




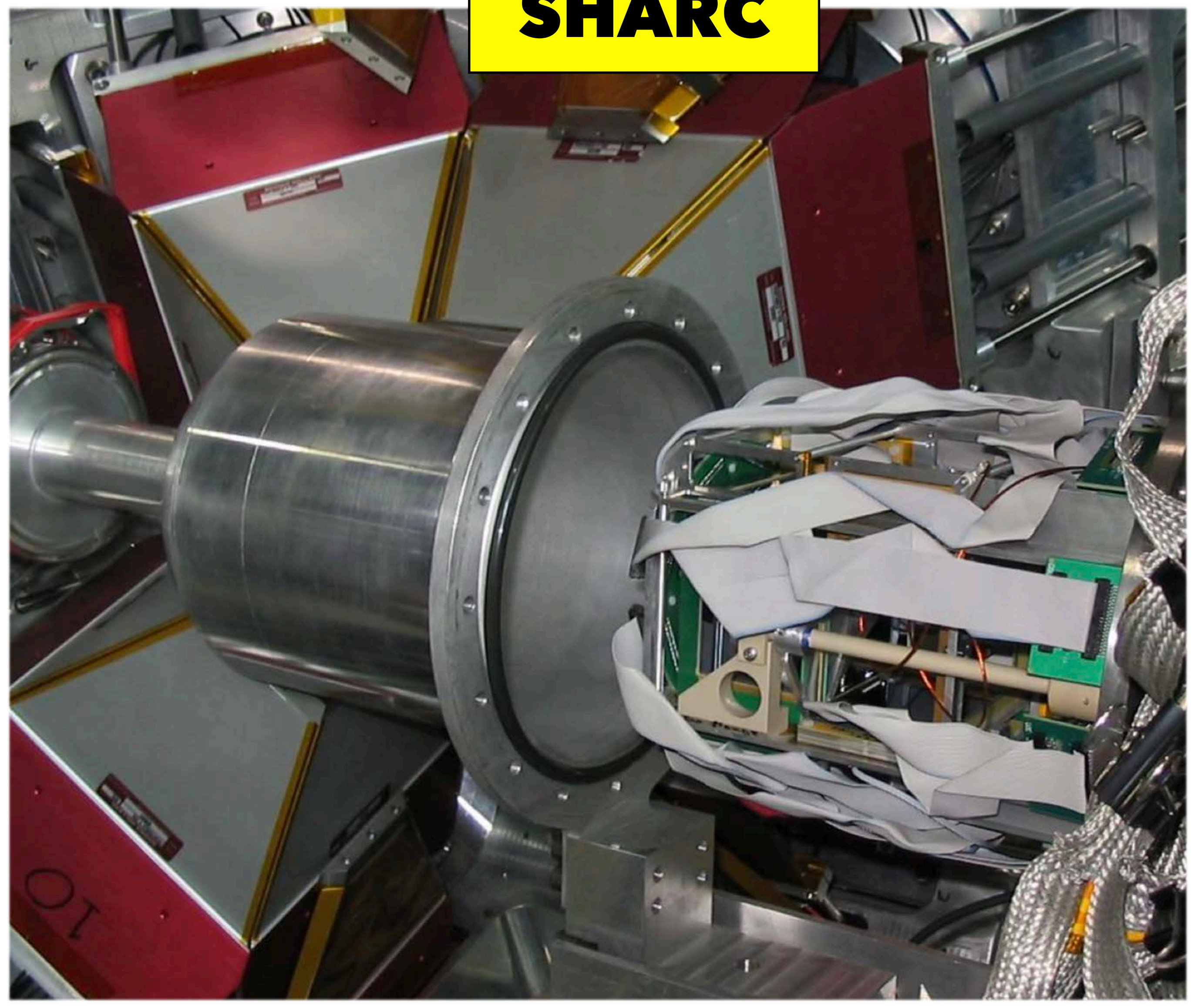


ORRUBA / GODDESS



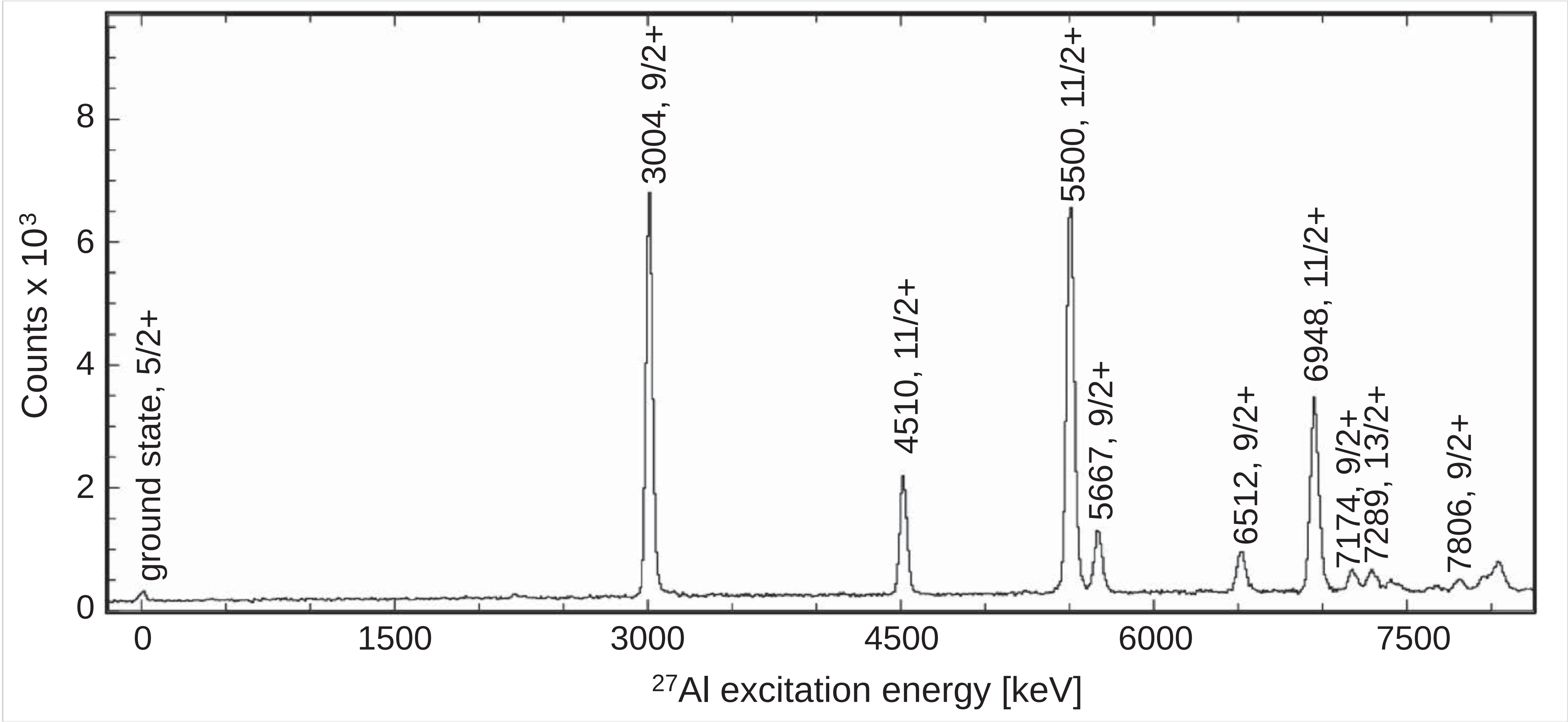


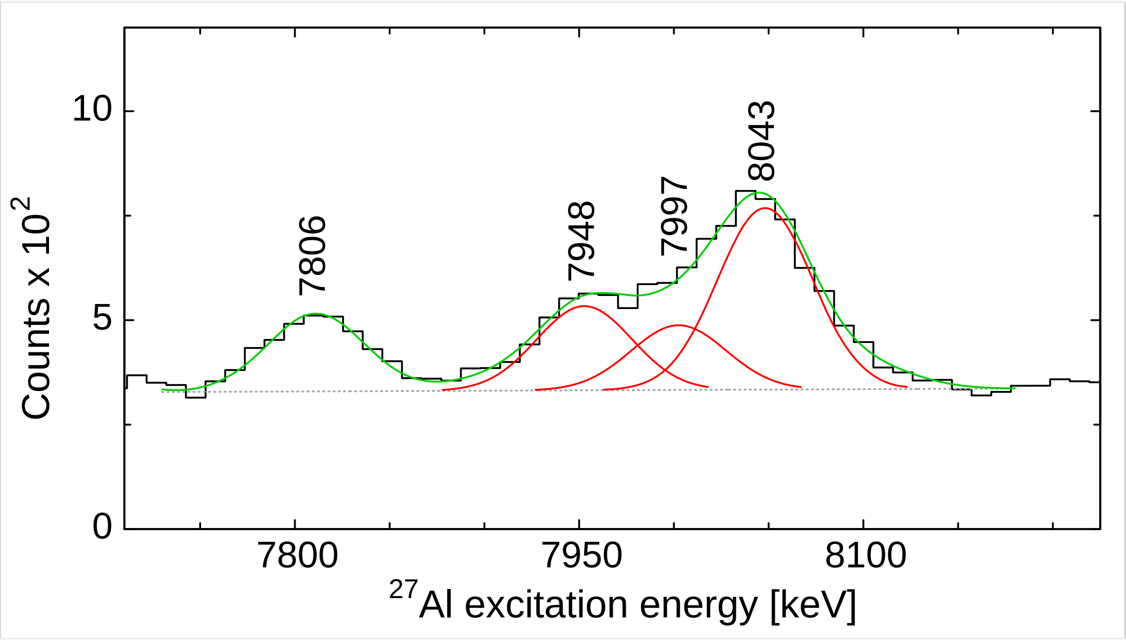
SHARC

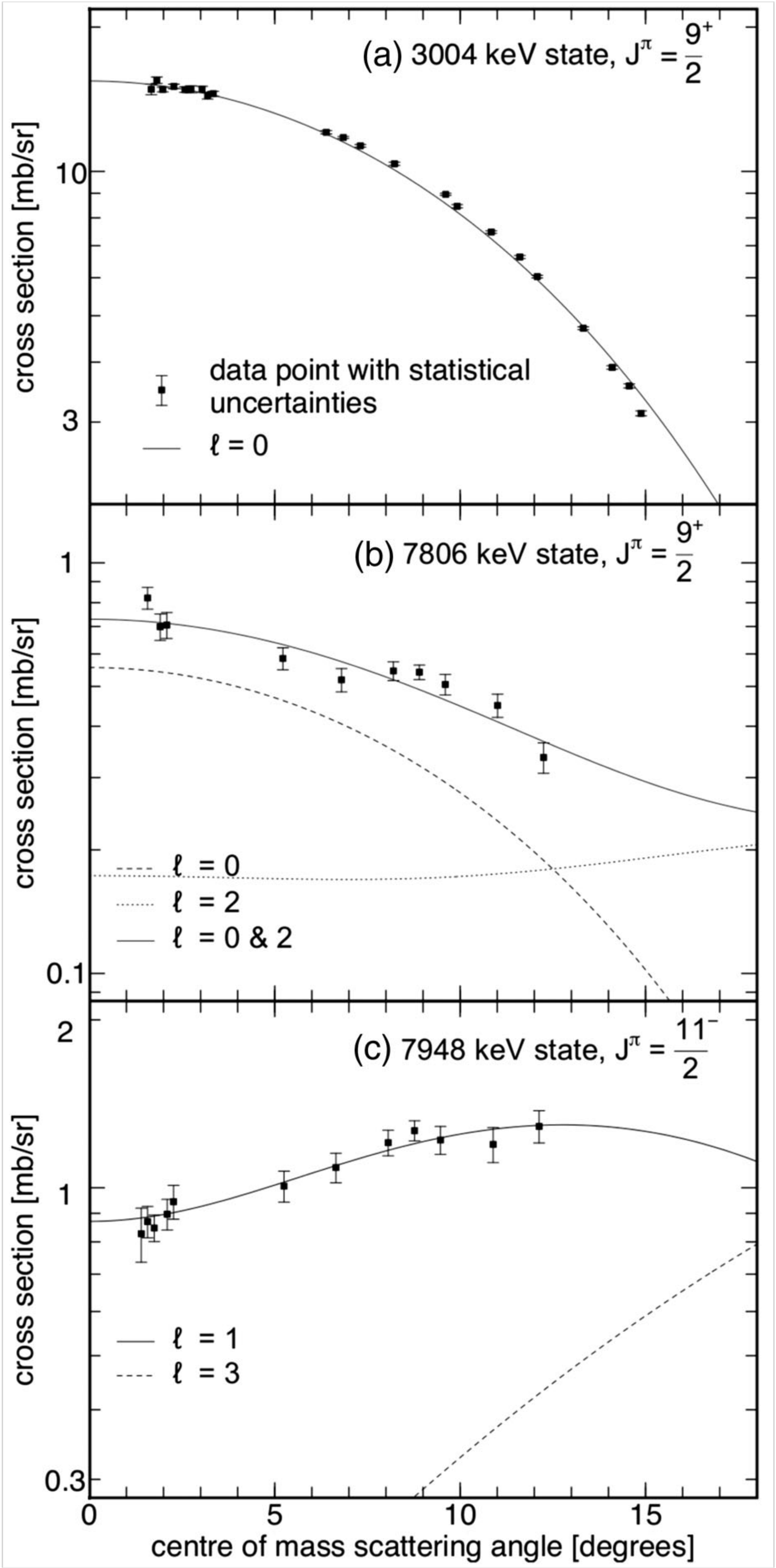


Recent 'state-of-the-art' – impressive result

Q-value resolution of 40 keV FWHM

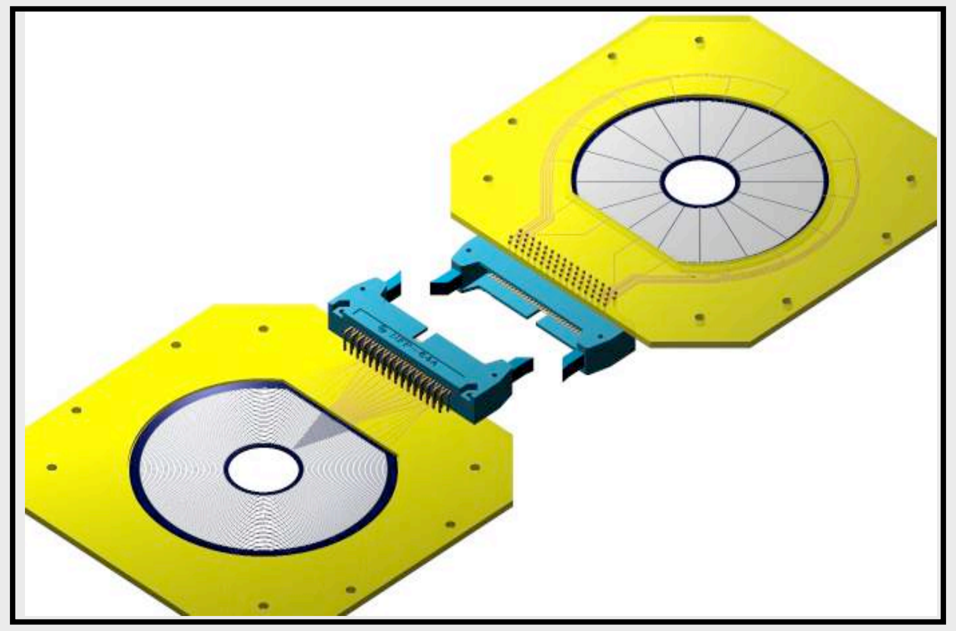


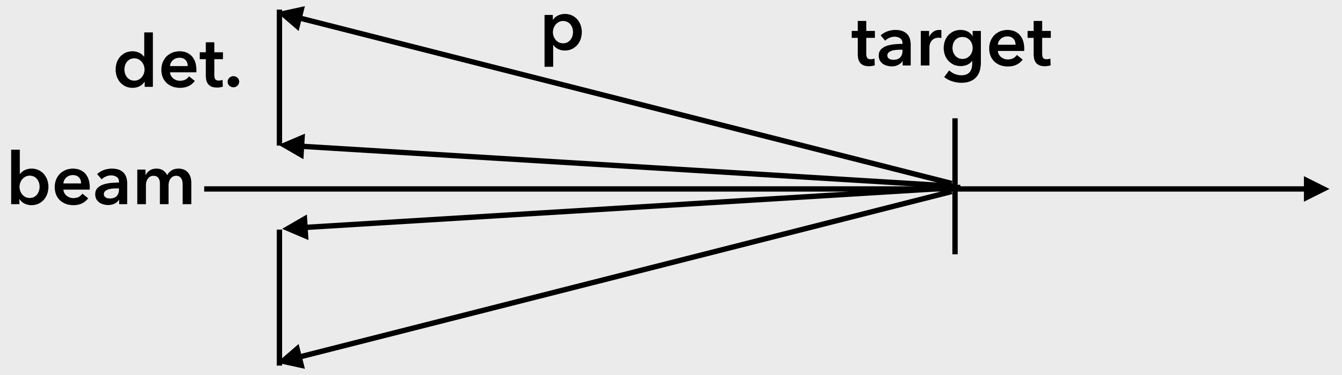




Notes

- *Beam: 6 MeV/u, 1pnA (**6.25×10^9 pps**)*
- *Target: 50 μg/cm²*
- *Highly idealized setup, afford by very intense ^{26}Al beam at TRIUMF*
- *Place detectors far way*
- *Annular Si detectors*



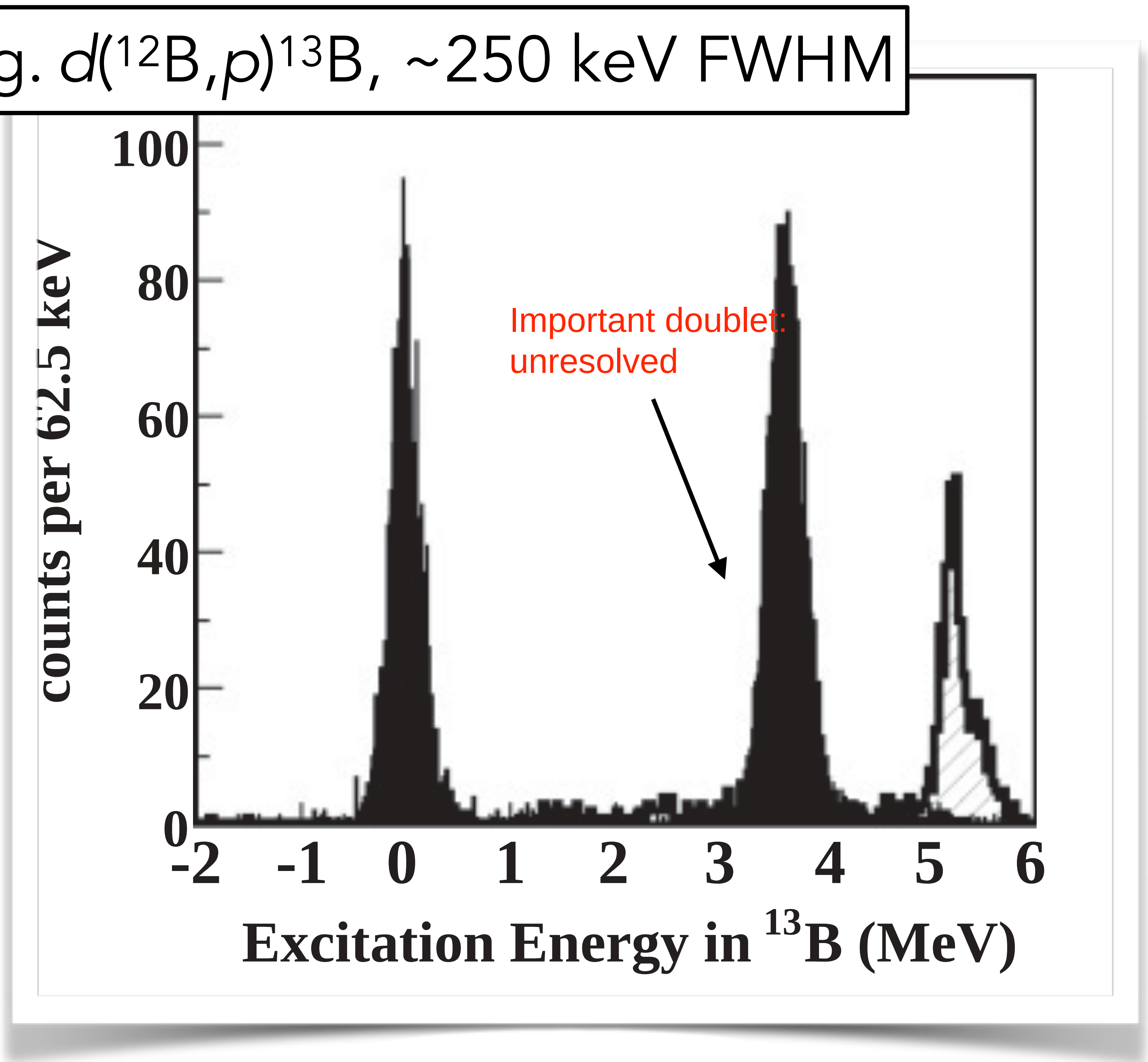


V. Margerin et al., *Phys. Rev. Lett.* **115**, 062701 (**2015**)

Typically, resolution is a challenge …

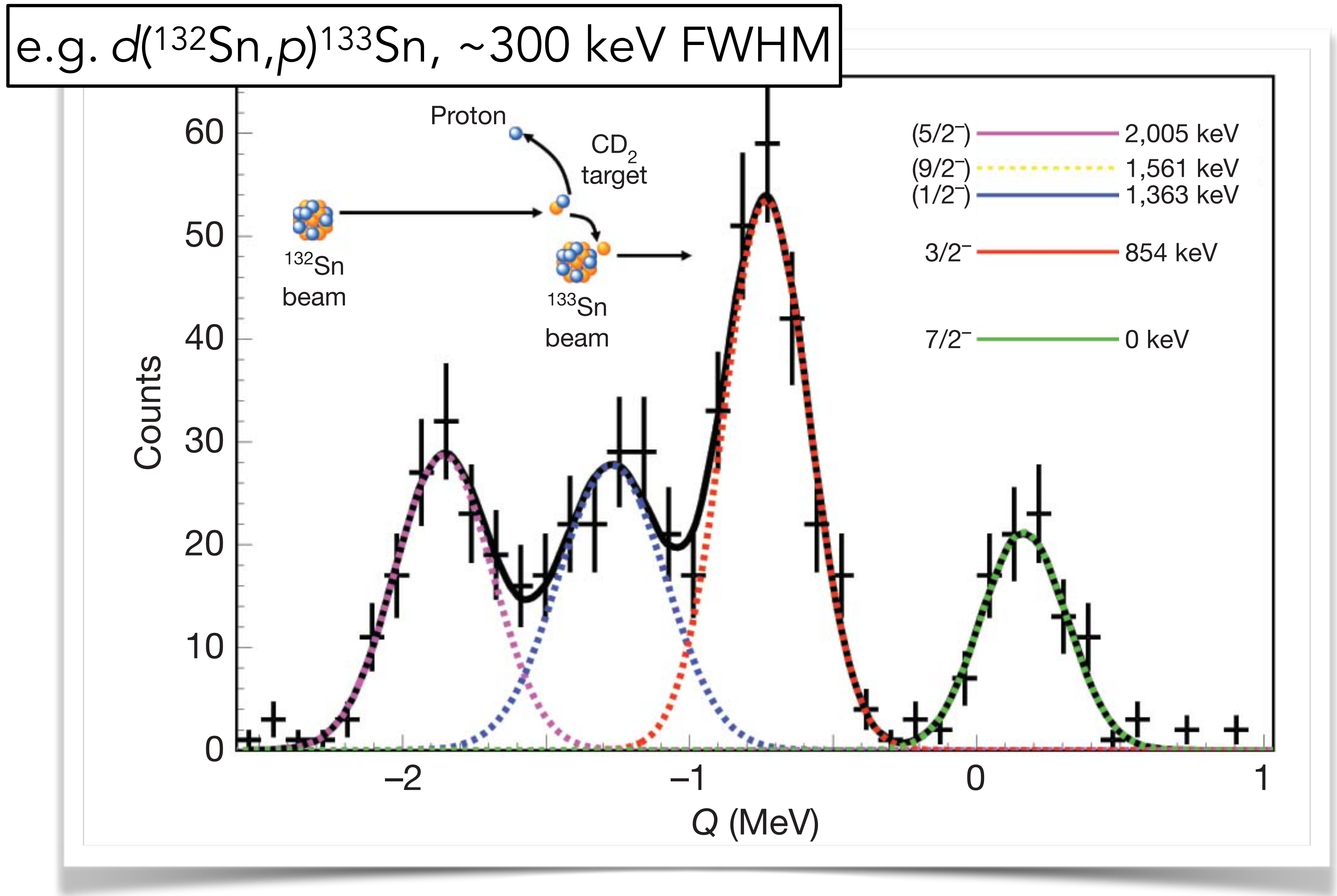
Using the traditional approach of placing a segmented Si detector at a fixed laboratory angle can result in poor excitation-energy resolution, typically of the order of ~300 keV (better can be achieved for light nuclei).

e.g. *d*(^{12}B,*p*)^{13}B, ~250 keV FWHM



Important doublet unresolved

e.g. *d*(^{132}Sn,*p*)^{133}Sn, ~300 keV FWHM

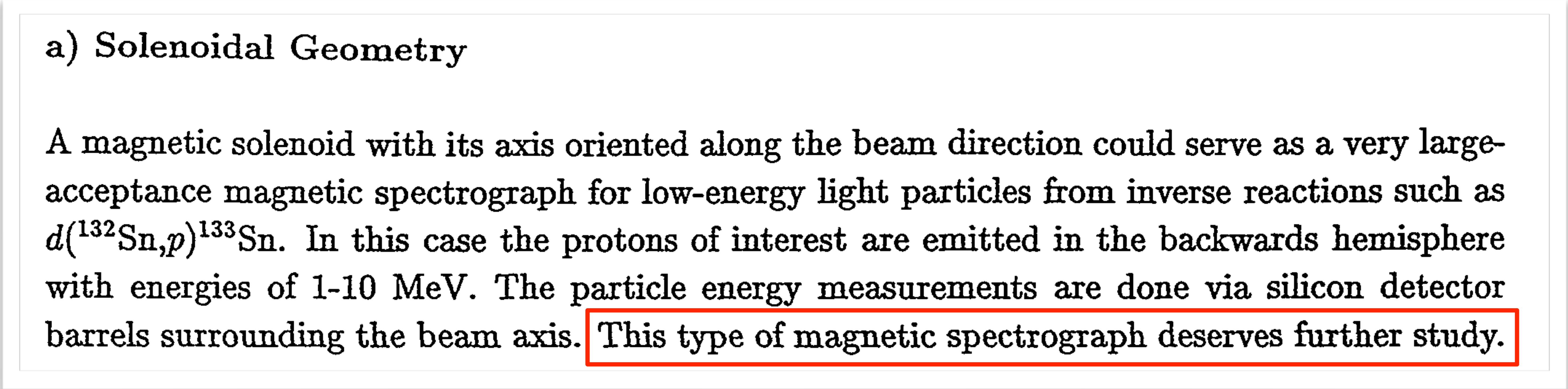


Would like an approach that consistently:

- Gives better than 100-keV FWHM resolution
- 7-10 day runs with RI beams (10^4 pps, 100 μg/cm^2 targets)

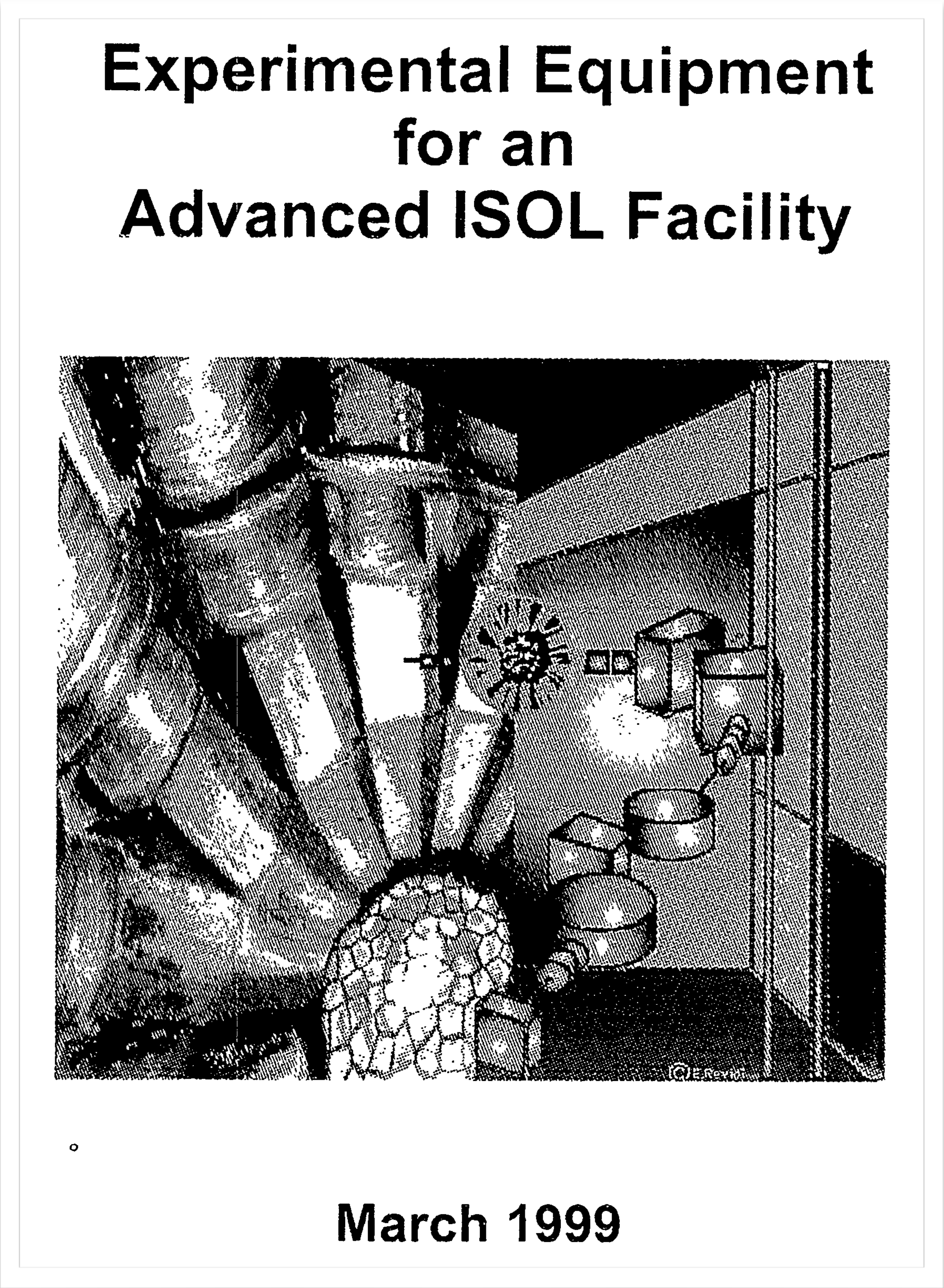
H. Y. Lee et al., Phys. Rev. C ***81****, 015802 (****2010****), K. L. Jones et al., Nature* ***465****, 454 (****2010****)*

Other approaches?



a) Solenoidal Geometry

A magnetic solenoid with its axis oriented along the beam direction could serve as a very large-acceptance magnetic spectrograph for low-energy light particles from inverse reactions such as $d(^{132}\mathrm{Sn},p)^{133}\mathrm{Sn}$. In this case the protons of interest are emitted in the backwards hemisphere with energies of 1-10 MeV. The particle energy measurements are done via silicon detector barrels surrounding the beam axis. This type of magnetic spectrograph deserves further study.



Experimental Equipment
for an
Advanced ISOL Facility

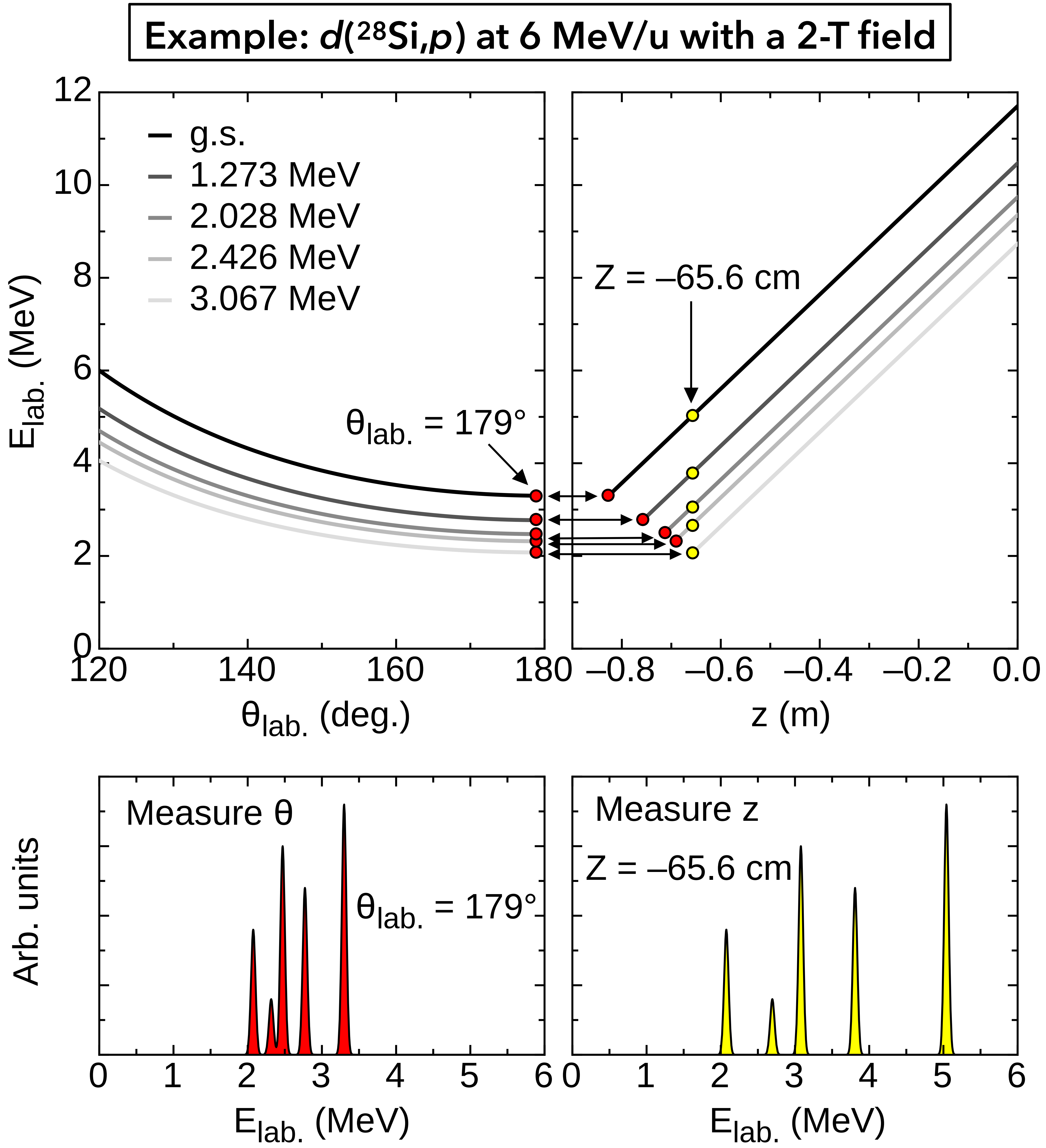
March 1999

A meeting at Berkeley in 1998 to discuss next generation facilities (to become FRIB)

Move towards 100-keV FWHM or better for transfer reactions

Comment by John P. Schiffer, Argonne, I.Y. Lee (Ed.), Proceedings of the Workshop on Experimental Equipment for an Advanced ISOL Facility, ***Lawrence Berkeley National Laboratory****, 1998, LBNL-42138, pp. 667–678.*

Transport through a solenoid

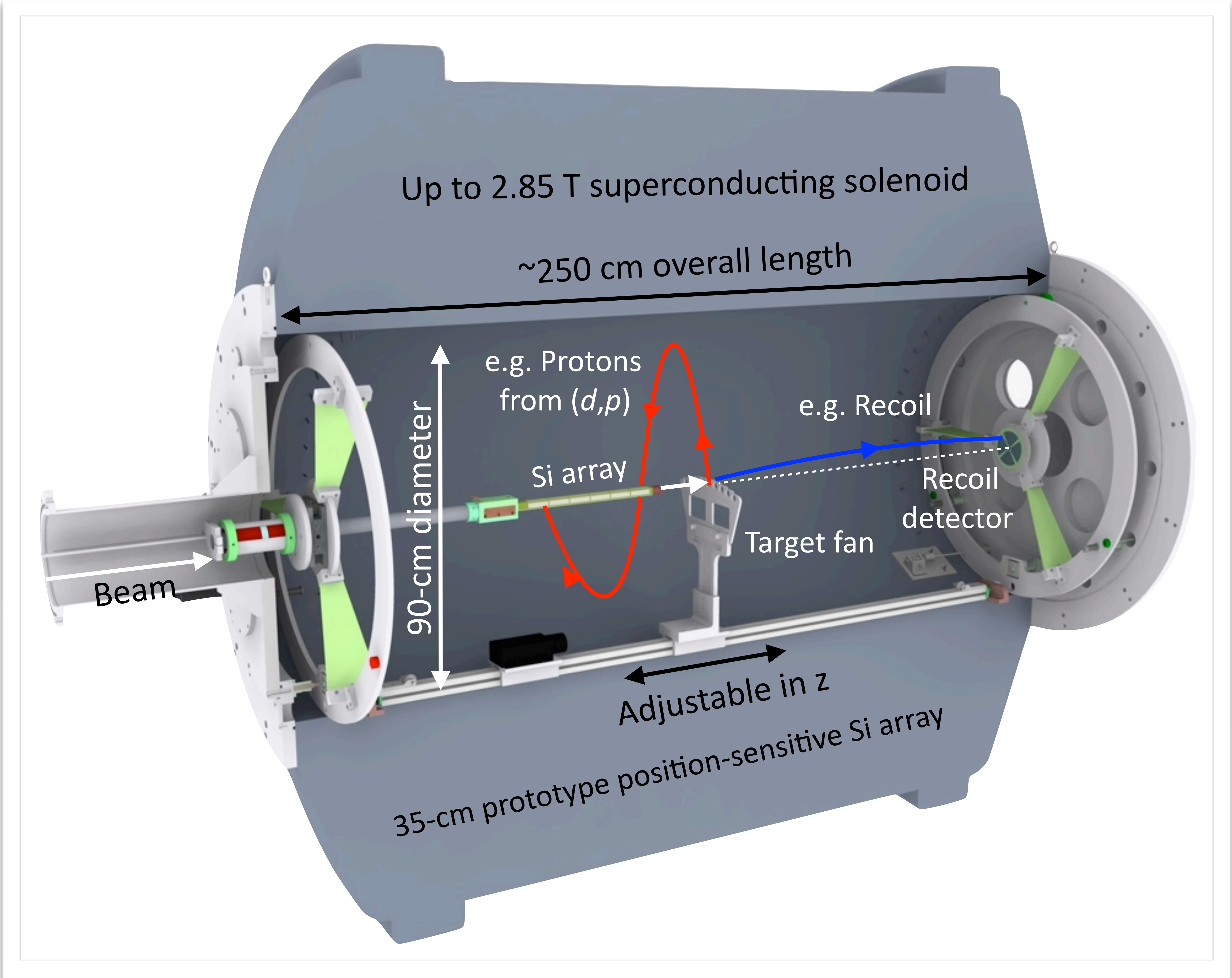


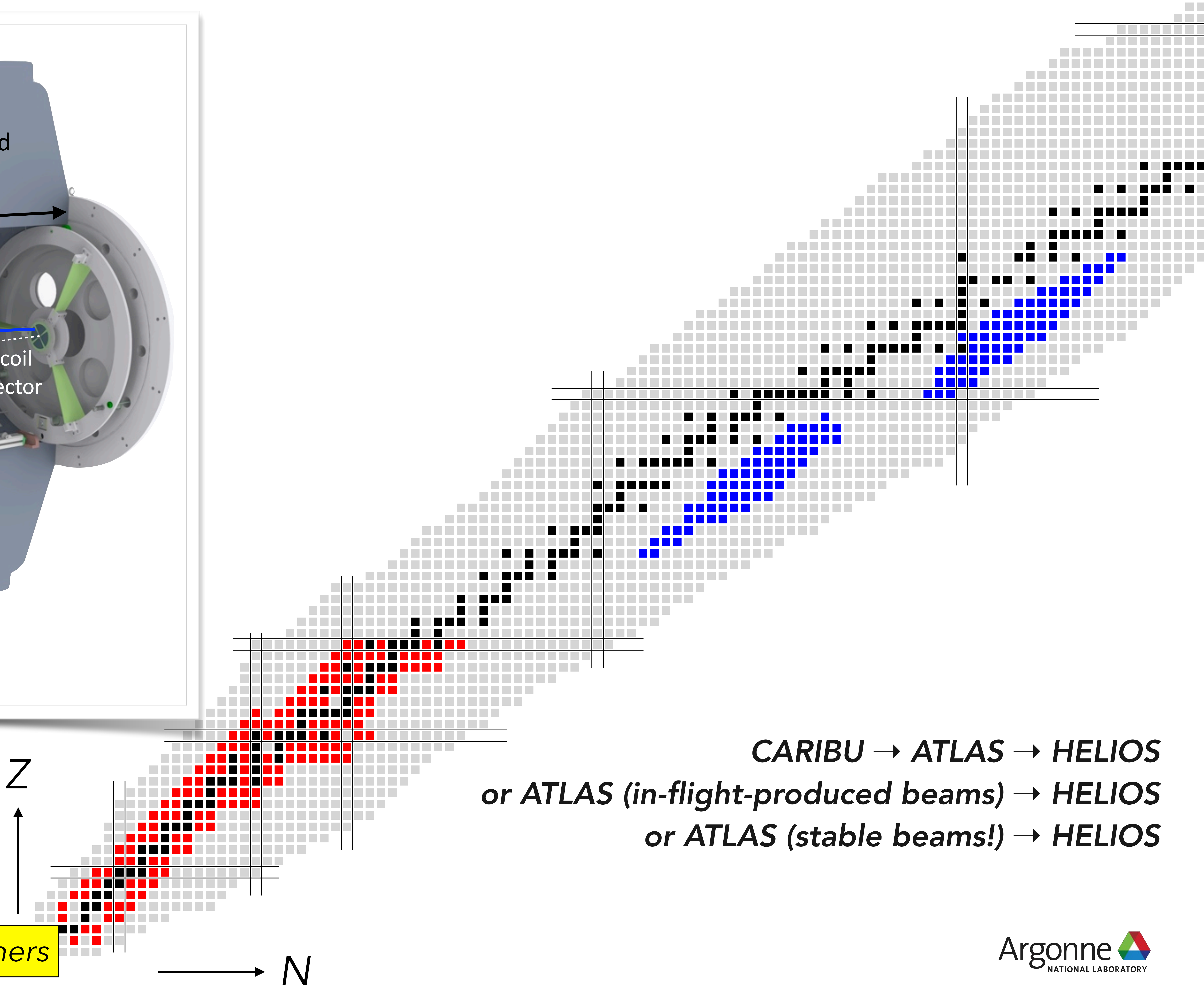
Example: *d*(^{28}Si,*p*) at 6 MeV/u with a 2-T field

- A simple linear relationship between energy and z, where the energy separation is (nearly) identical to the excitation energy in the residual nucleus.
- Removes kinematic compression.
- Factor of ~2.4 improvement in resolution (for this example)
- … and an MRI magnet seems ideal (in fact too good)

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

A helical-orbit spectrometer

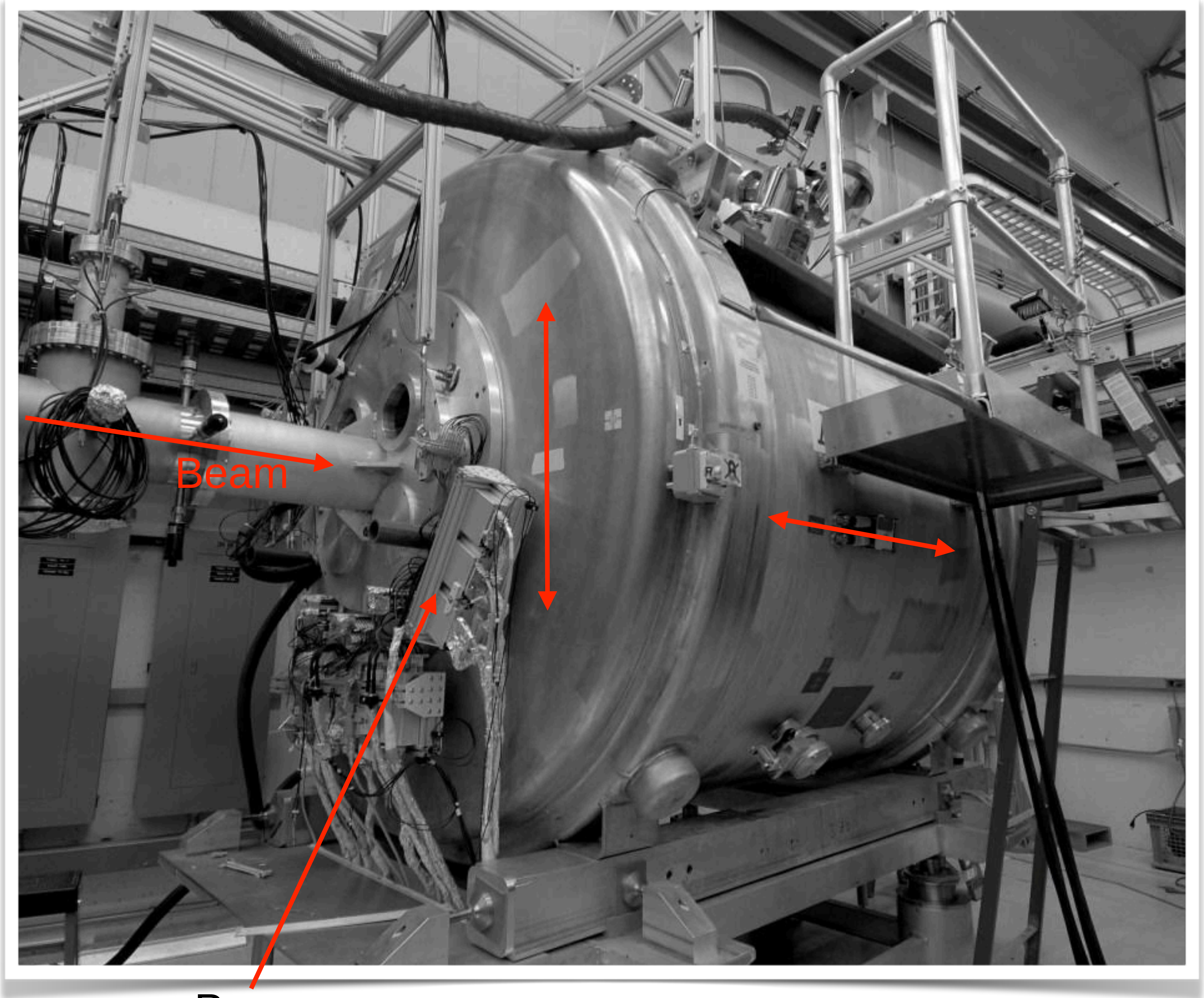




CARIBU → ATLAS → HELIOS
or ATLAS (in-flight-produced beams) → HELIOS
or ATLAS (stable beams!) → HELIOS

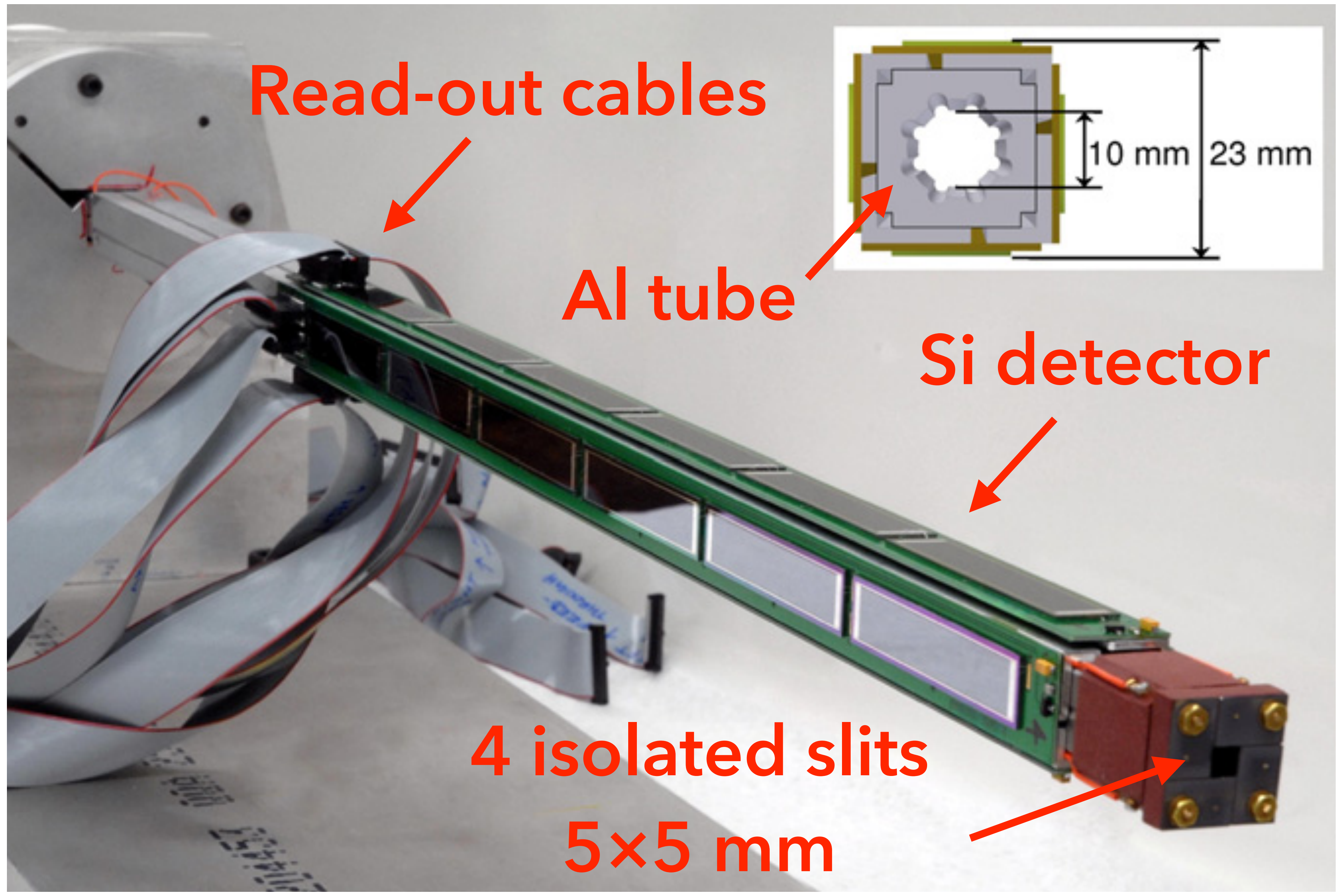
Argonne, Western Michigan, Manchester and others

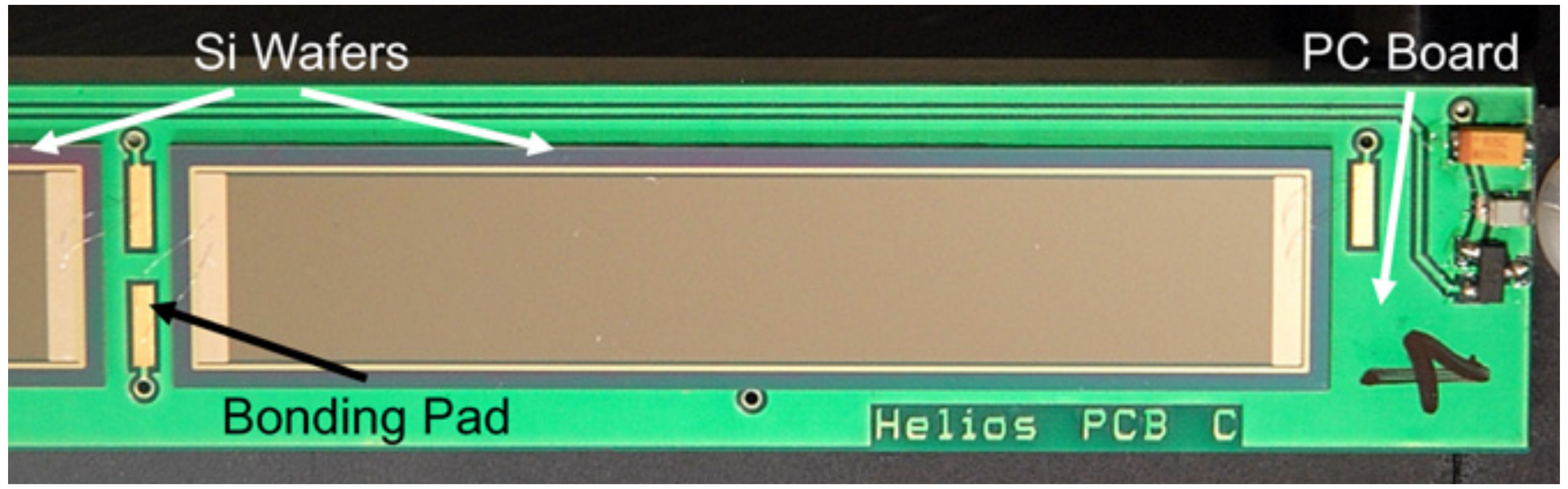
HELIOS



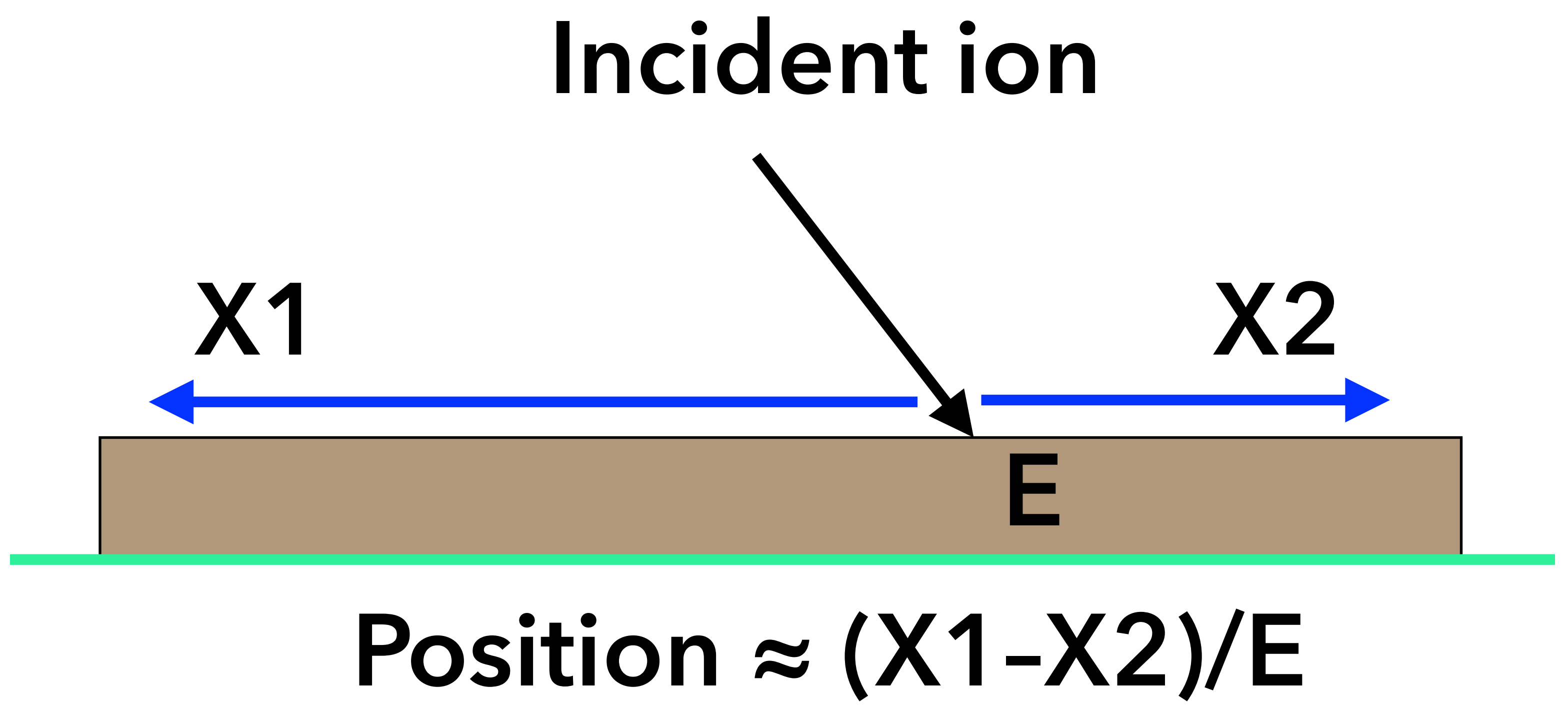
Preamps

Position sensitive Si detectors





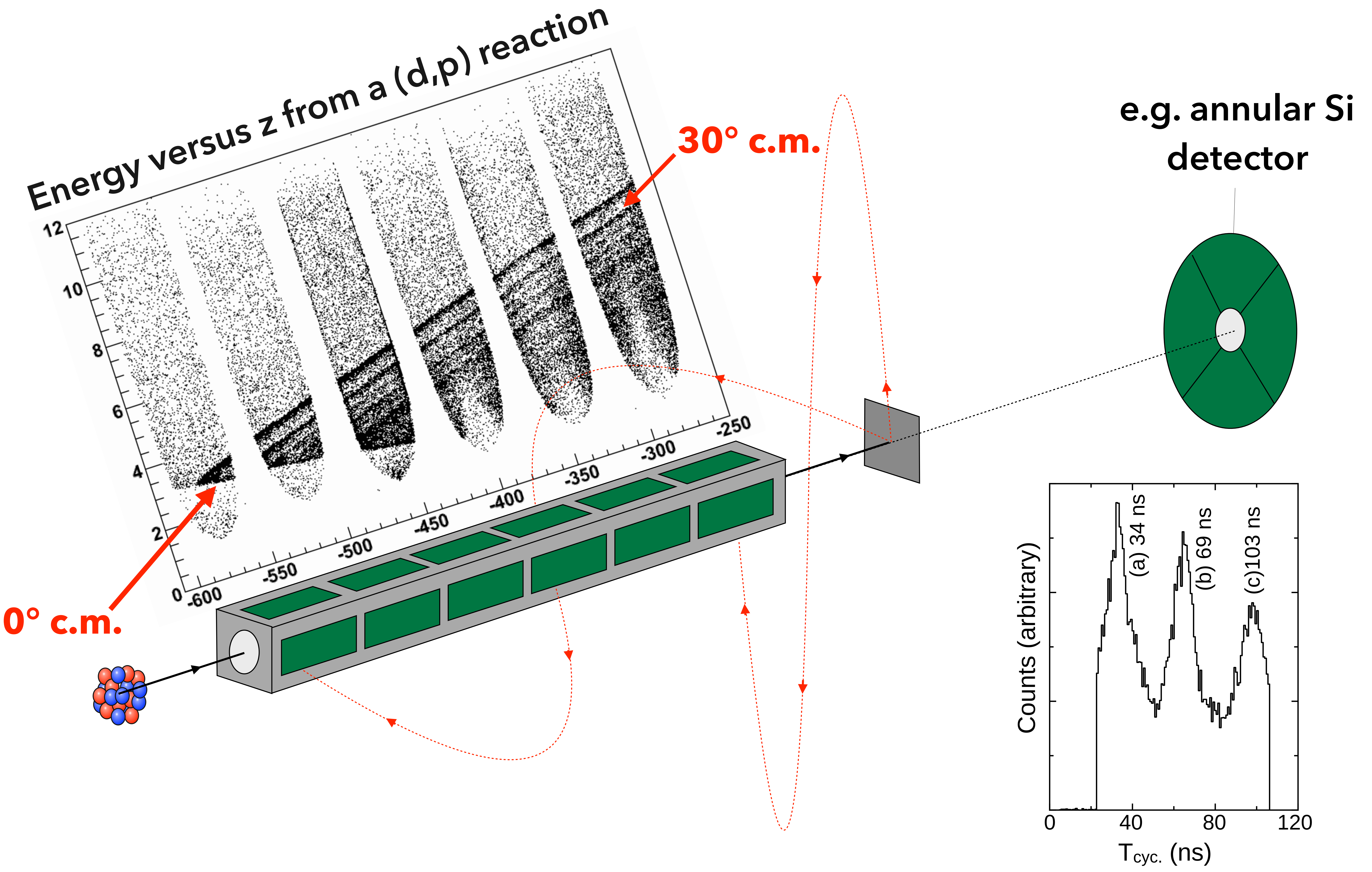
- 4 sides, 6 detectors long
- Detector size, 9×50 mm
- 700-μm thick (e.g. ~10 MeV protons)
- Φ coverage, 0.48 of 2π
- $\Omega_{detector}$ = 21 msr
- Ω_{array} = 493 msr



Position ≈ (X1–X2)/E

*J. C. Lighthall et al., Nucl. Instrum. Methods Phys. A **662**, 97 (**2010**)*

Motion of ions (bad cartoon)



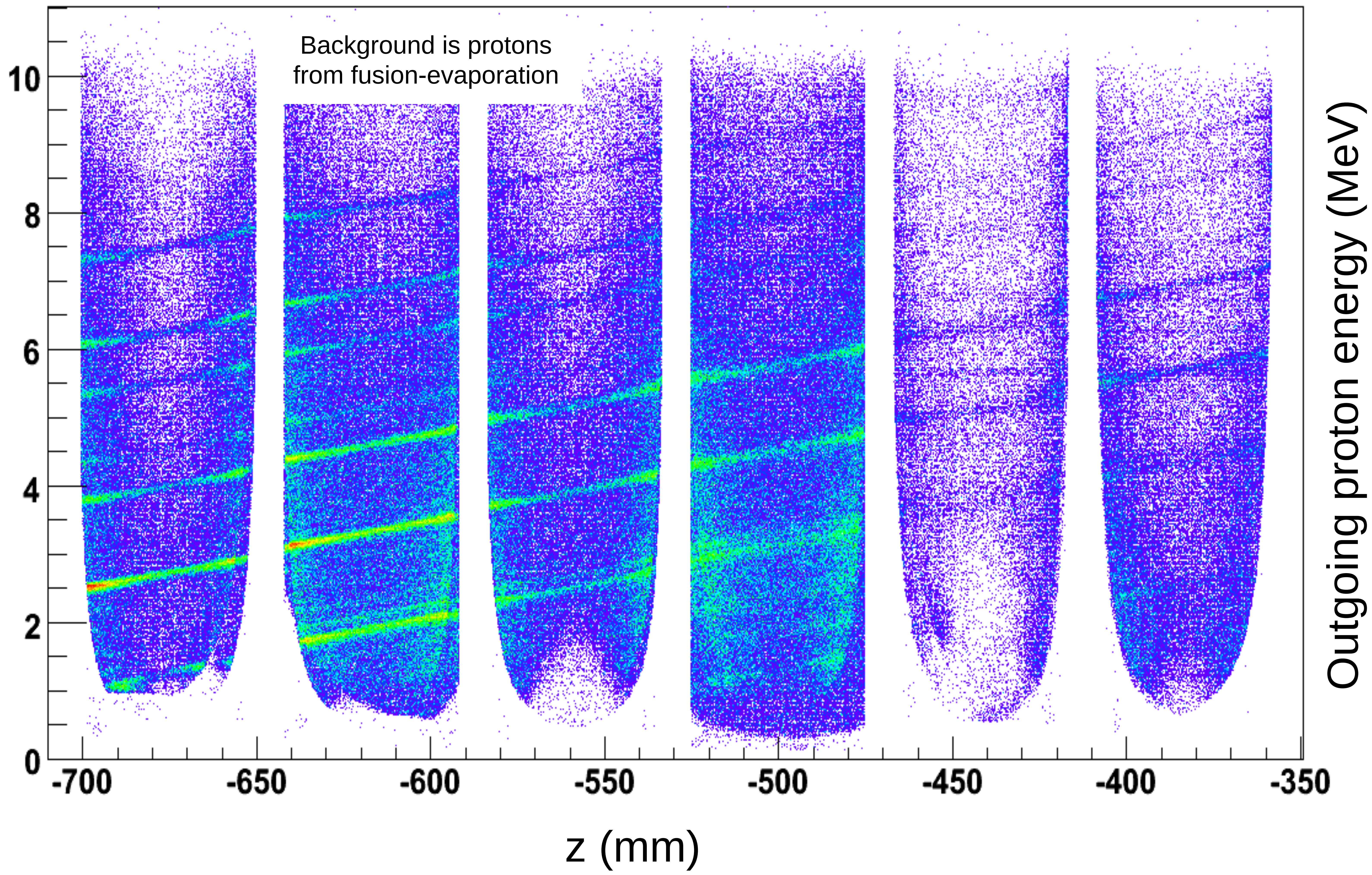
Energy versus z from a (d,p) reaction

30° c.m.

0° c.m.

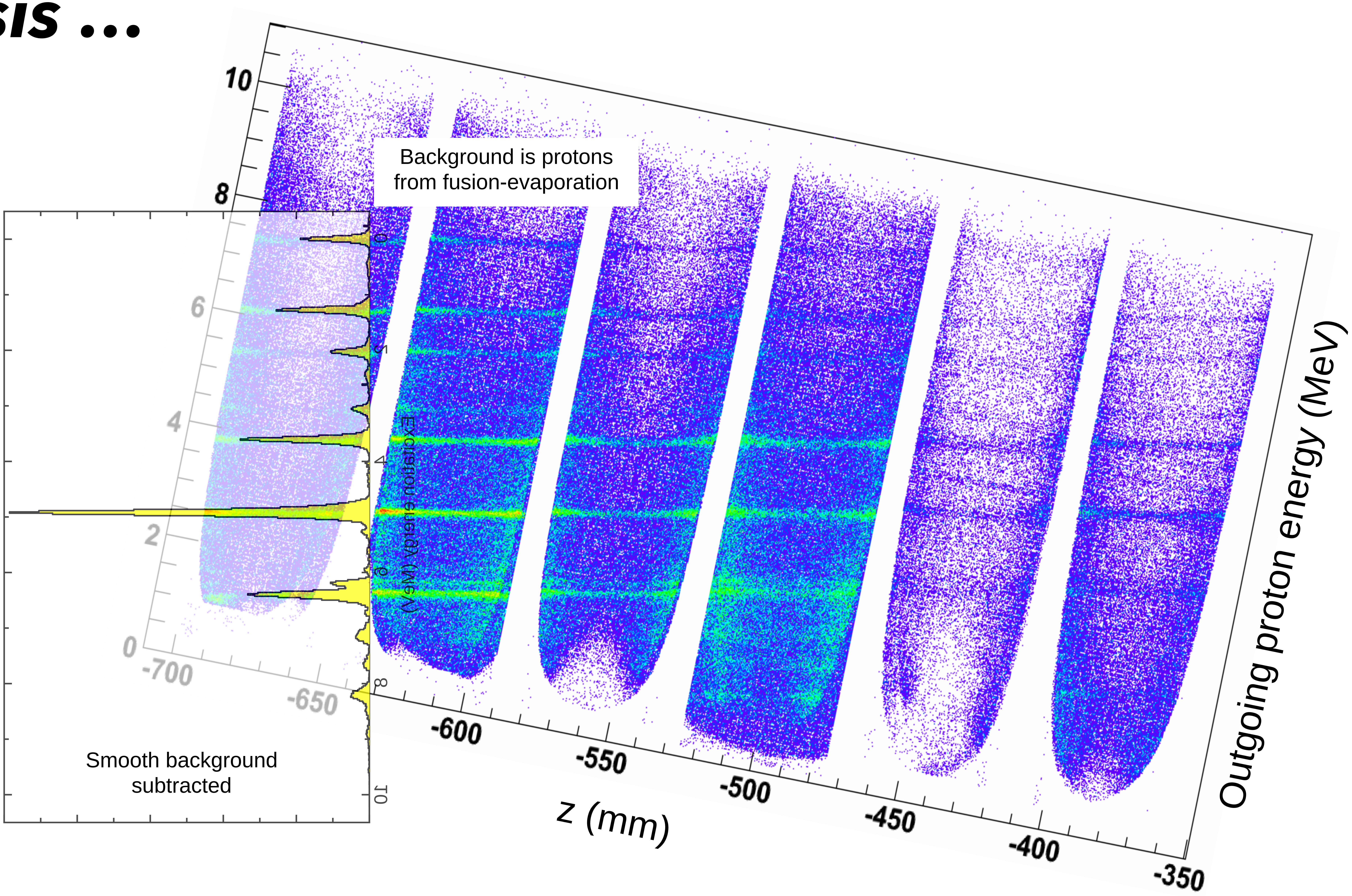
e.g. annular Si detector

Analysis …



We measure *E* vs. *z*, which is the excitation-energy spectrum of the residual nucleus

Analysis …

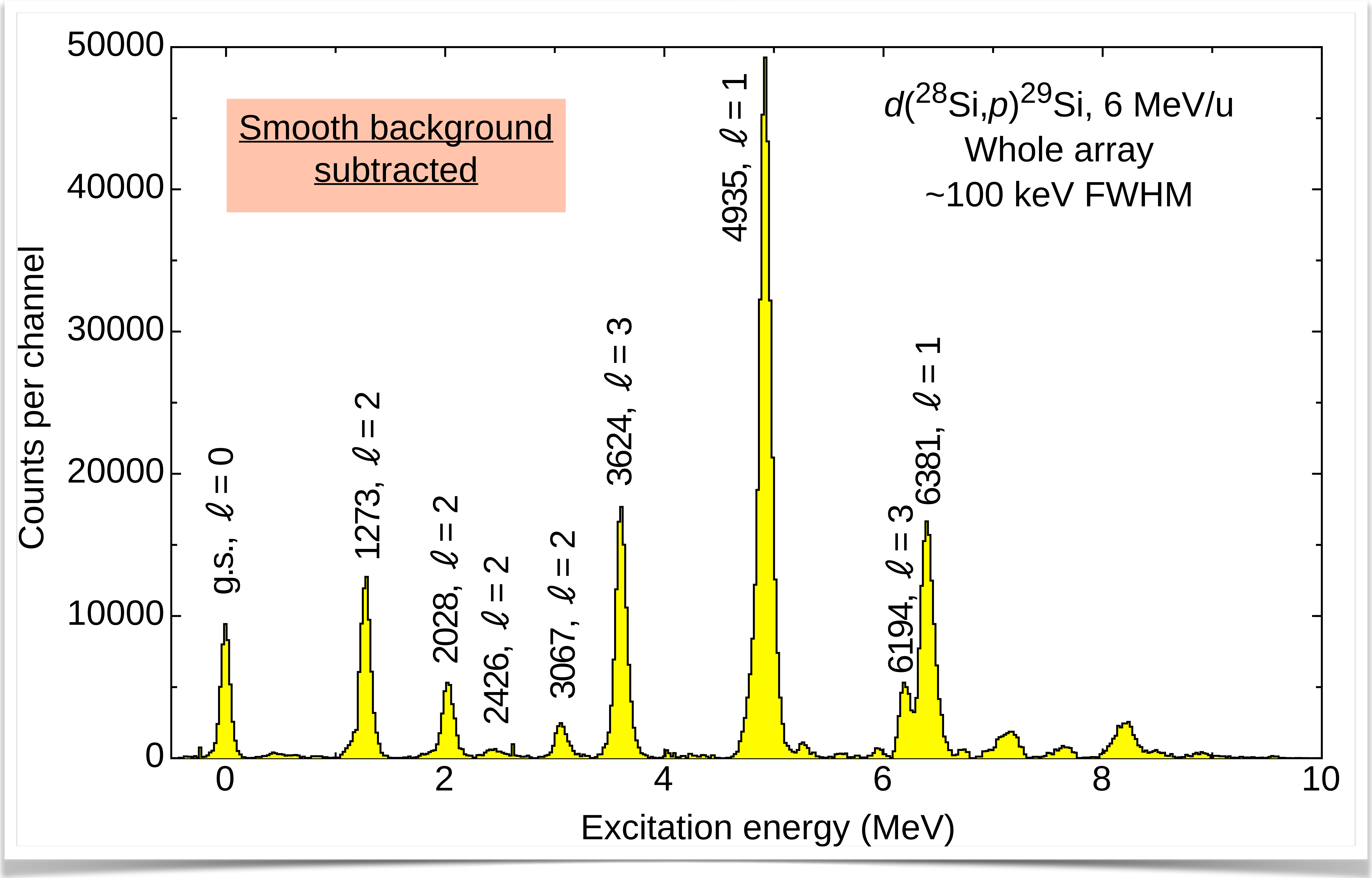


Background is protons from fusion-evaporation

Smooth background subtracted

We measure *E* vs. *z*, which is the excitation-energy spectrum of the residual nucleus

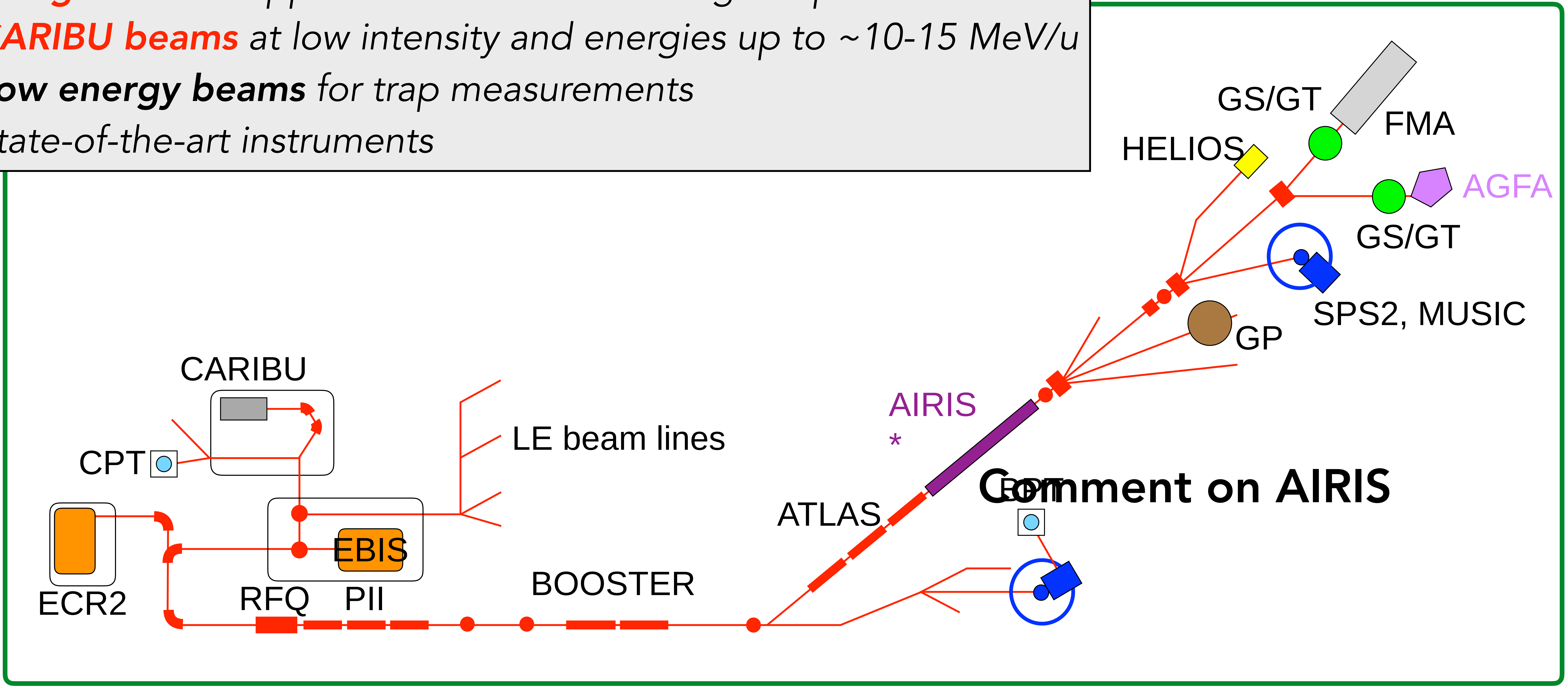
… ta-da



J. C. Lighthall et al., Nucl. Instrum. Methods Phys. A ***662****, 97 (****2010****)*

ATLAS, home to HELIOS

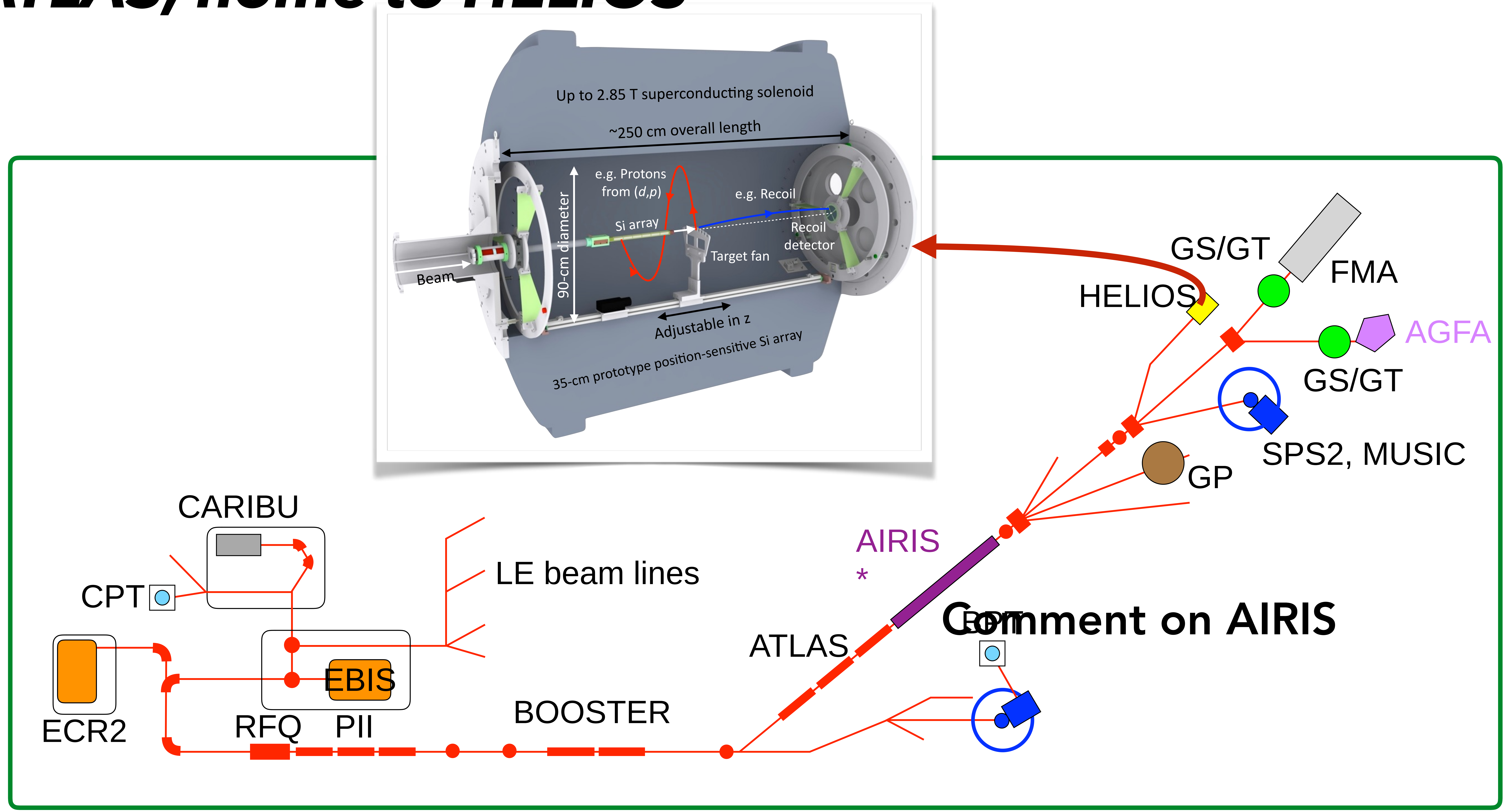
- ***Stable beams*** *at high intensity and energies up to ~20 MeV/u*
- ***In-flight beams*** *approx. 10 < A < 30 at energies up to ~20 MeV/u*
- ***CARIBU beams*** *at low intensity and energies up to ~10-15 MeV/u*
- ***Low energy beams*** *for trap measurements*
- *State-of-the-art instruments*



Comment on AIRIS

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

ATLAS, home to HELIOS



Comment on AIRIS

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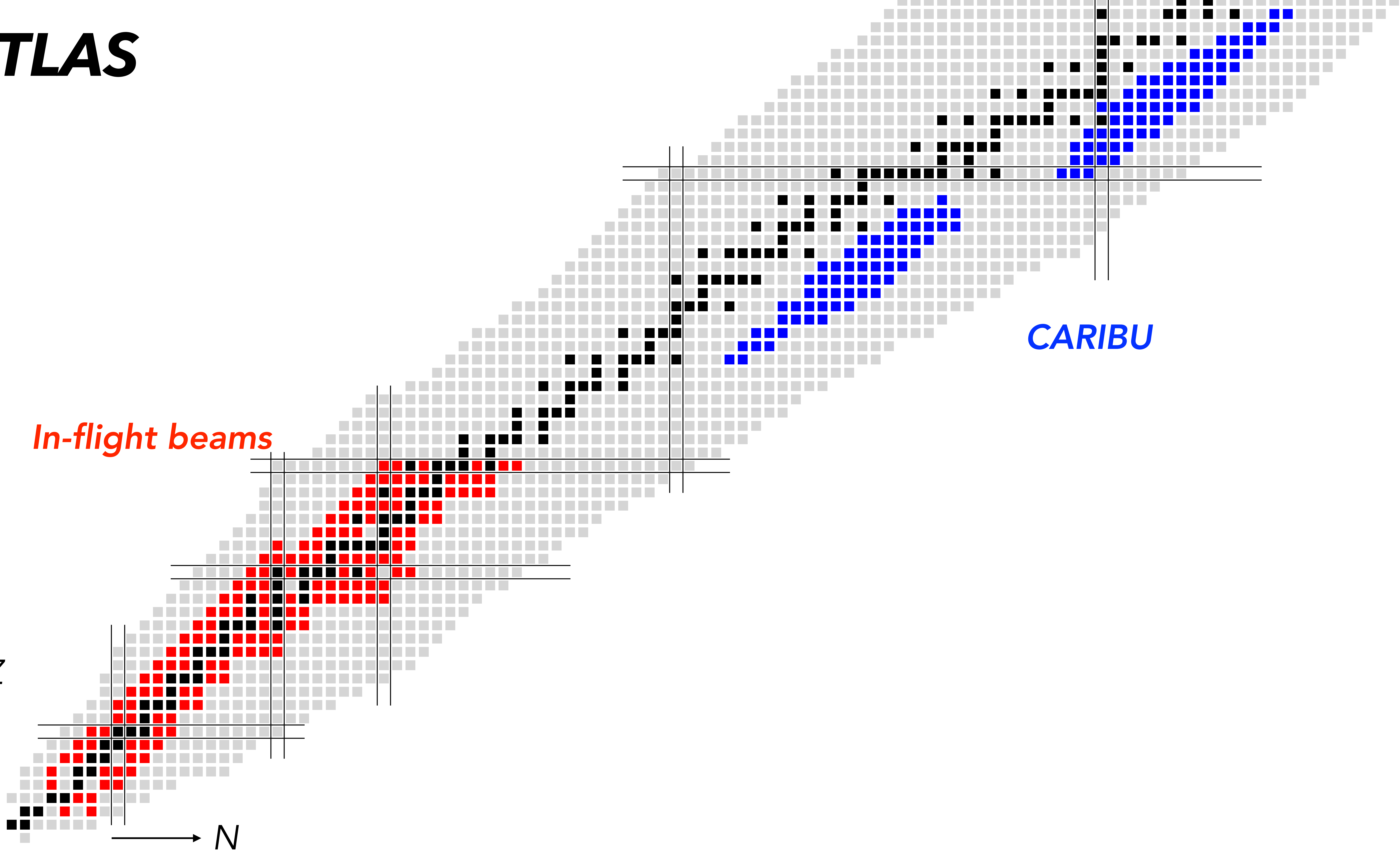
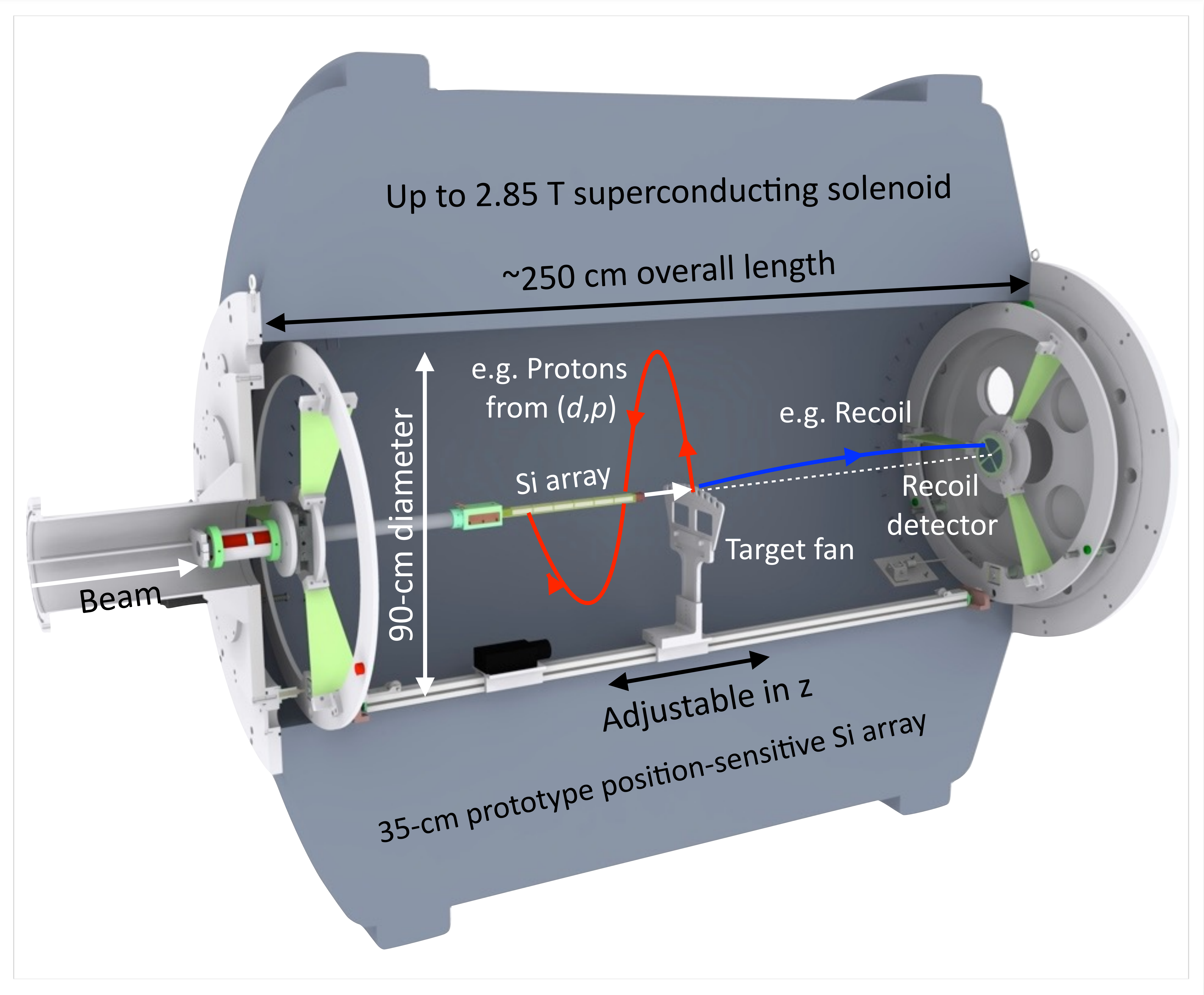
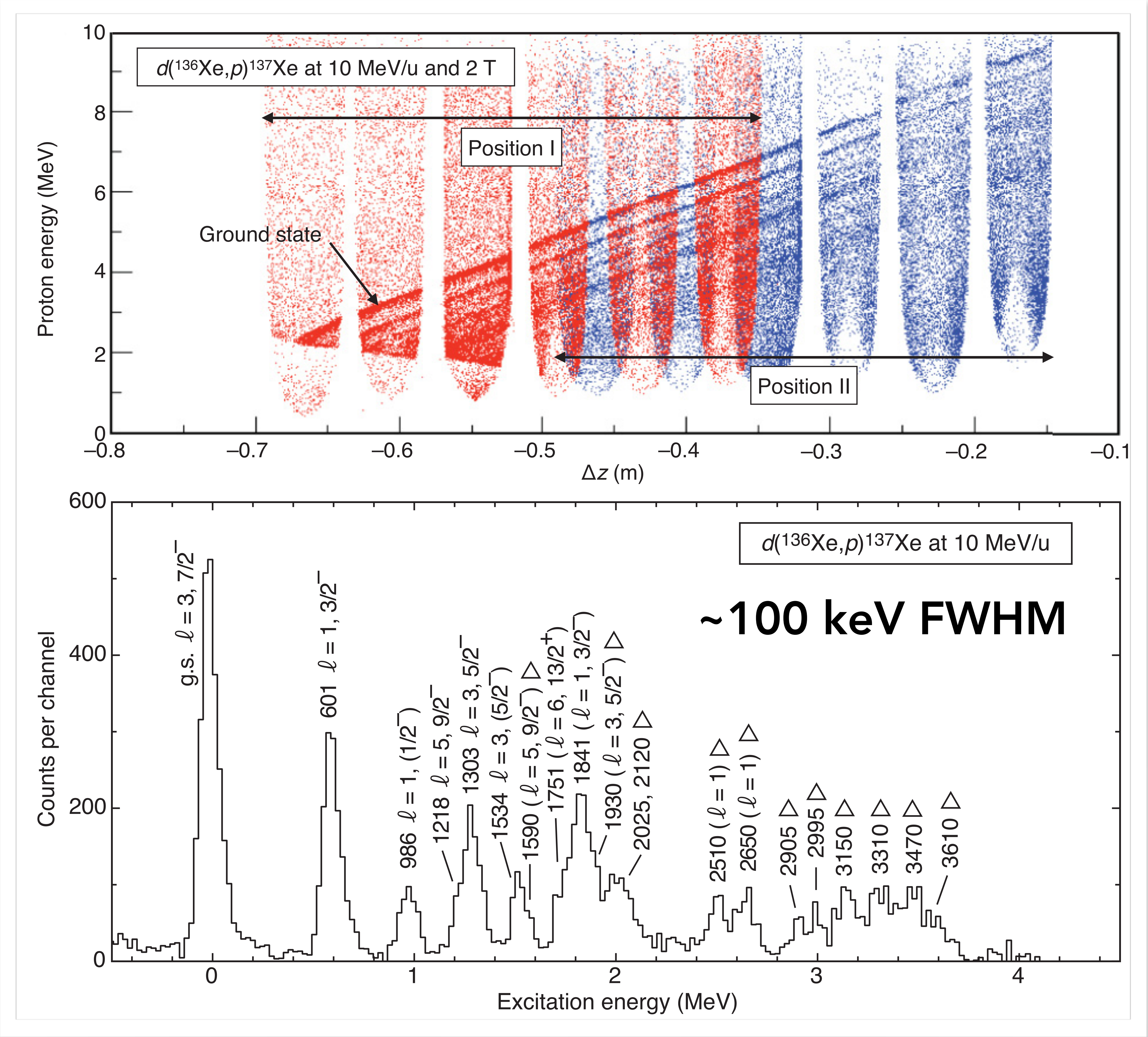
ATLAS



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

HELIOS with beams ‘near’ ^{132}Sn



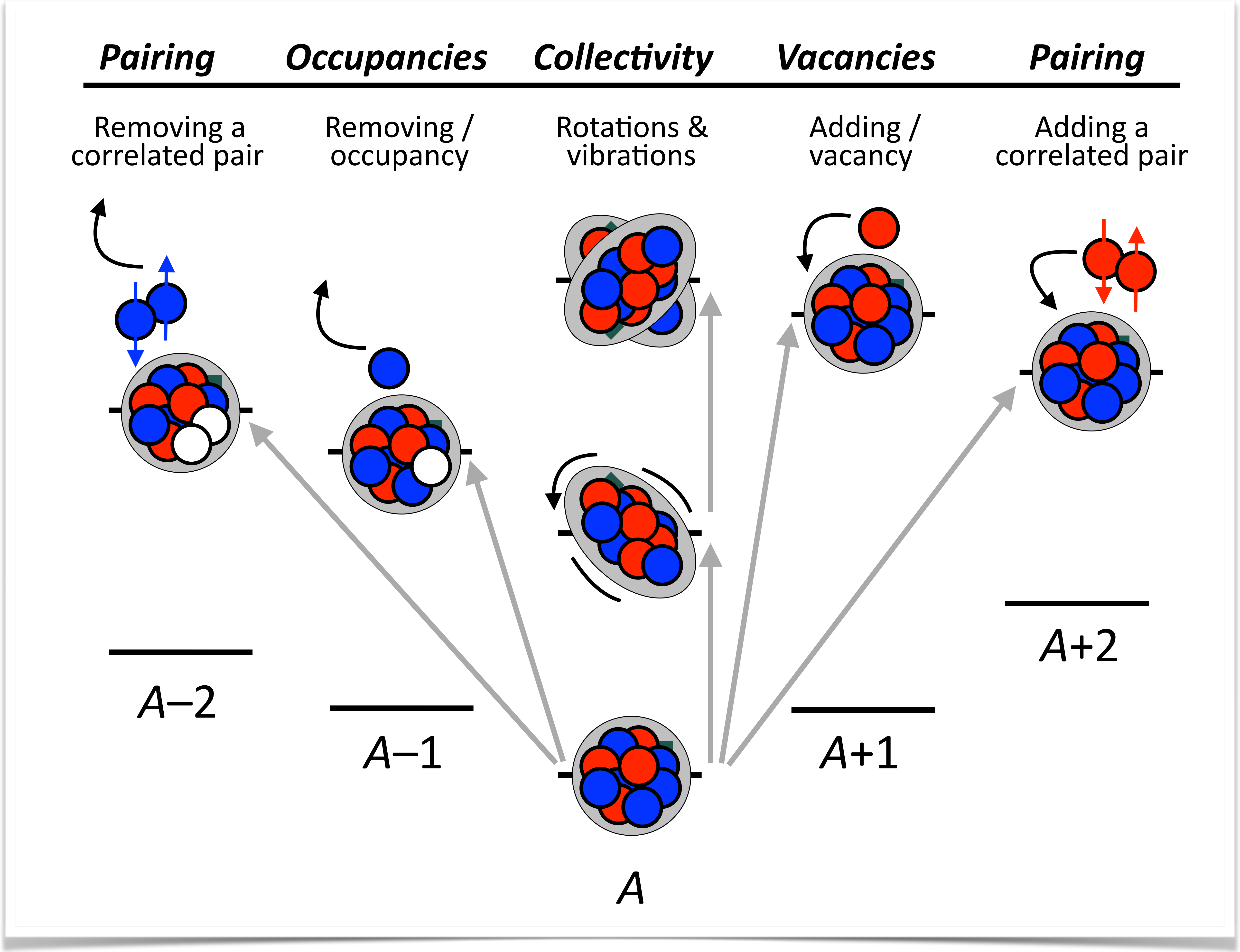


~100 keV FWHM

What would we like to do (exotic 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′), …



Snapshot

A highly versatile instrument

Apollo, gas target, ion chamber, backwards, forwards, tritium target, … all routine

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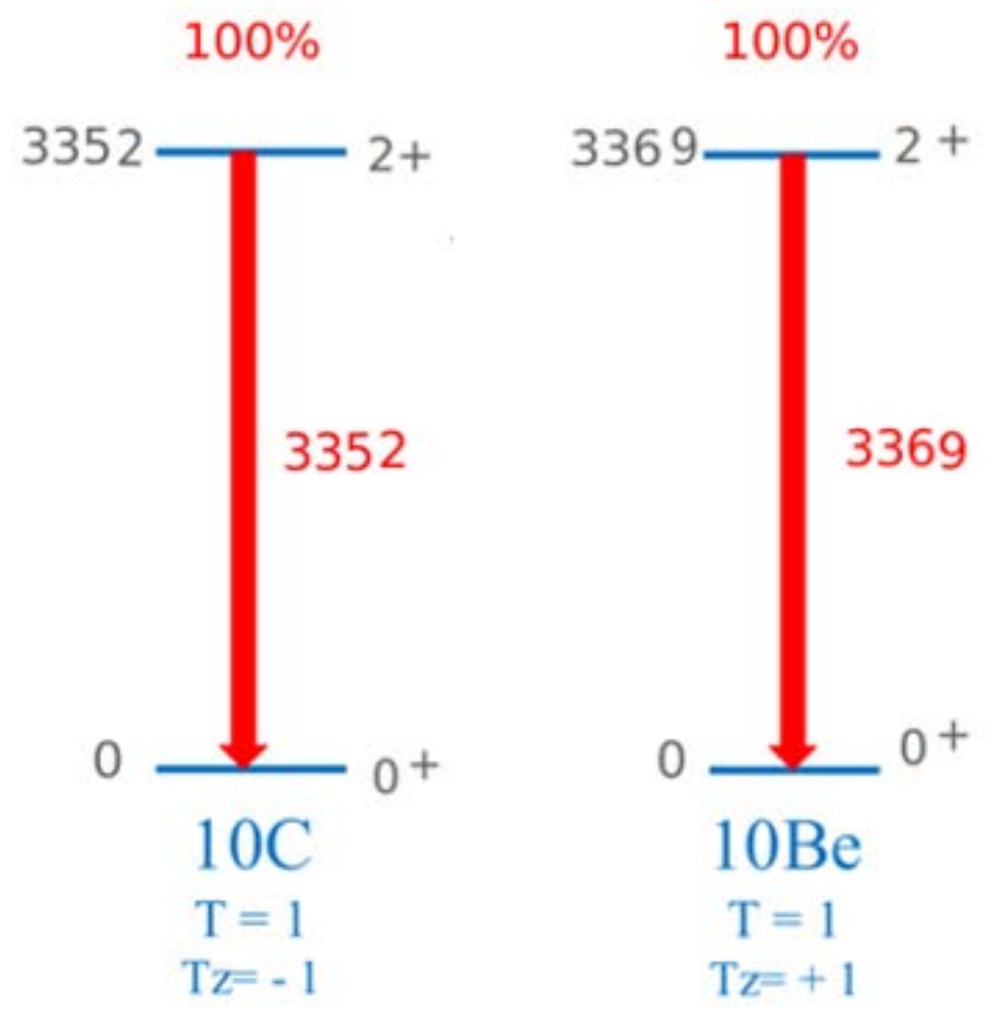
Example 1 – inelastic scattering, inverse kinematics

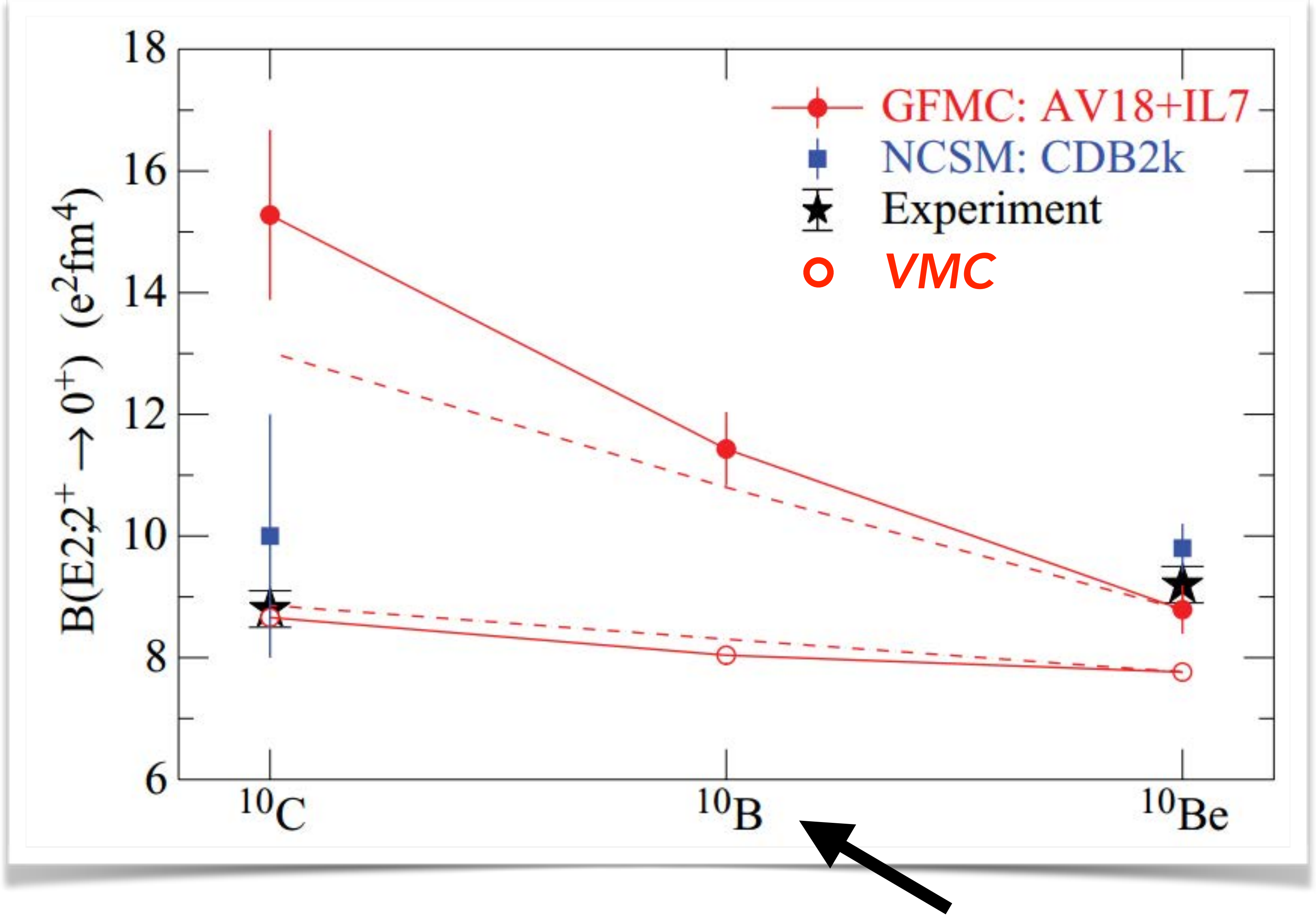
Example 1 *(exotic beam techniques, stable beams)*

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

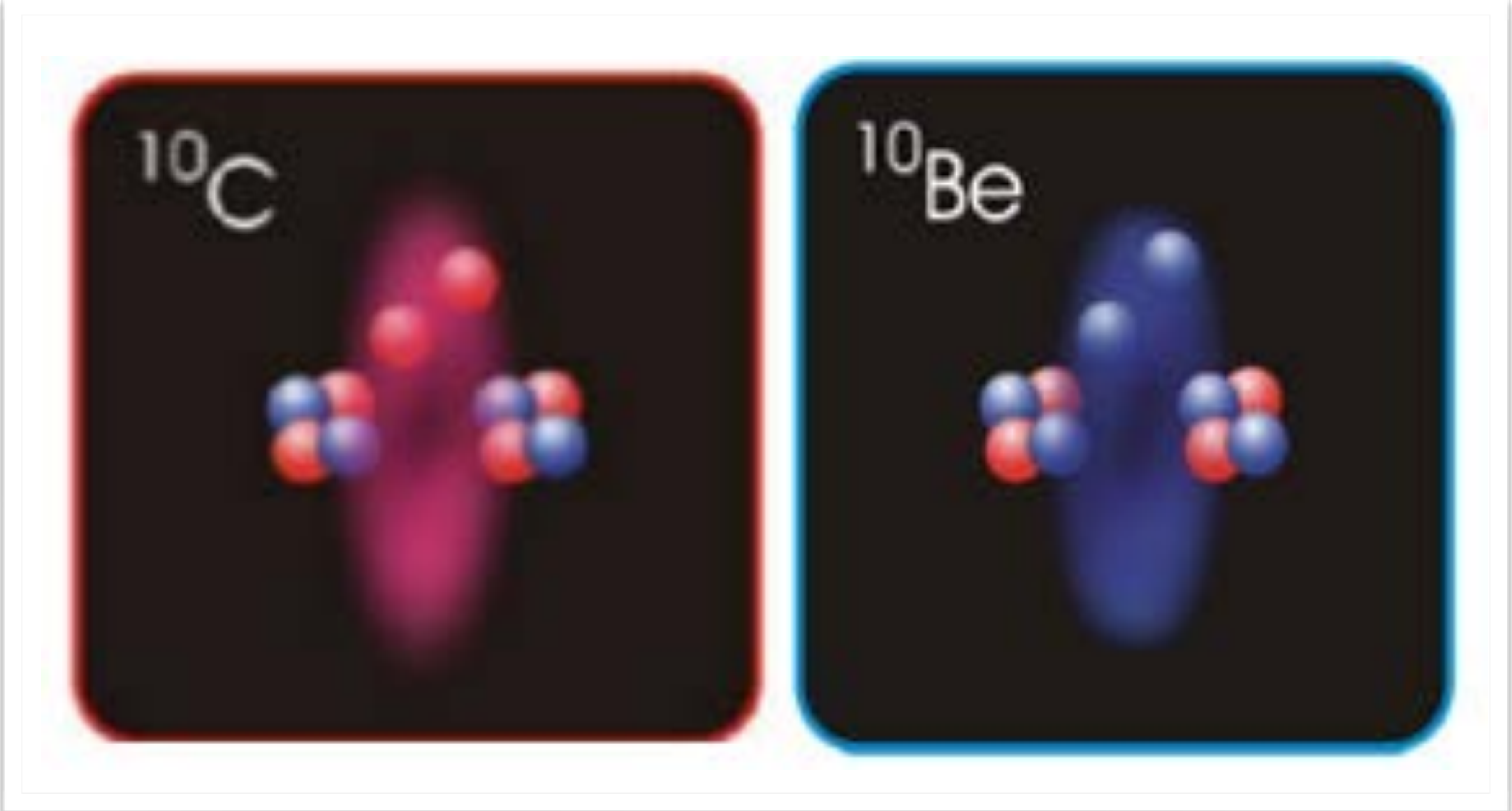
Why? Contributes to B(E2) value, which have been used as precision tests of ab-initio calculations of the A = 10 isospin triplet

A new technique in HELIOS …



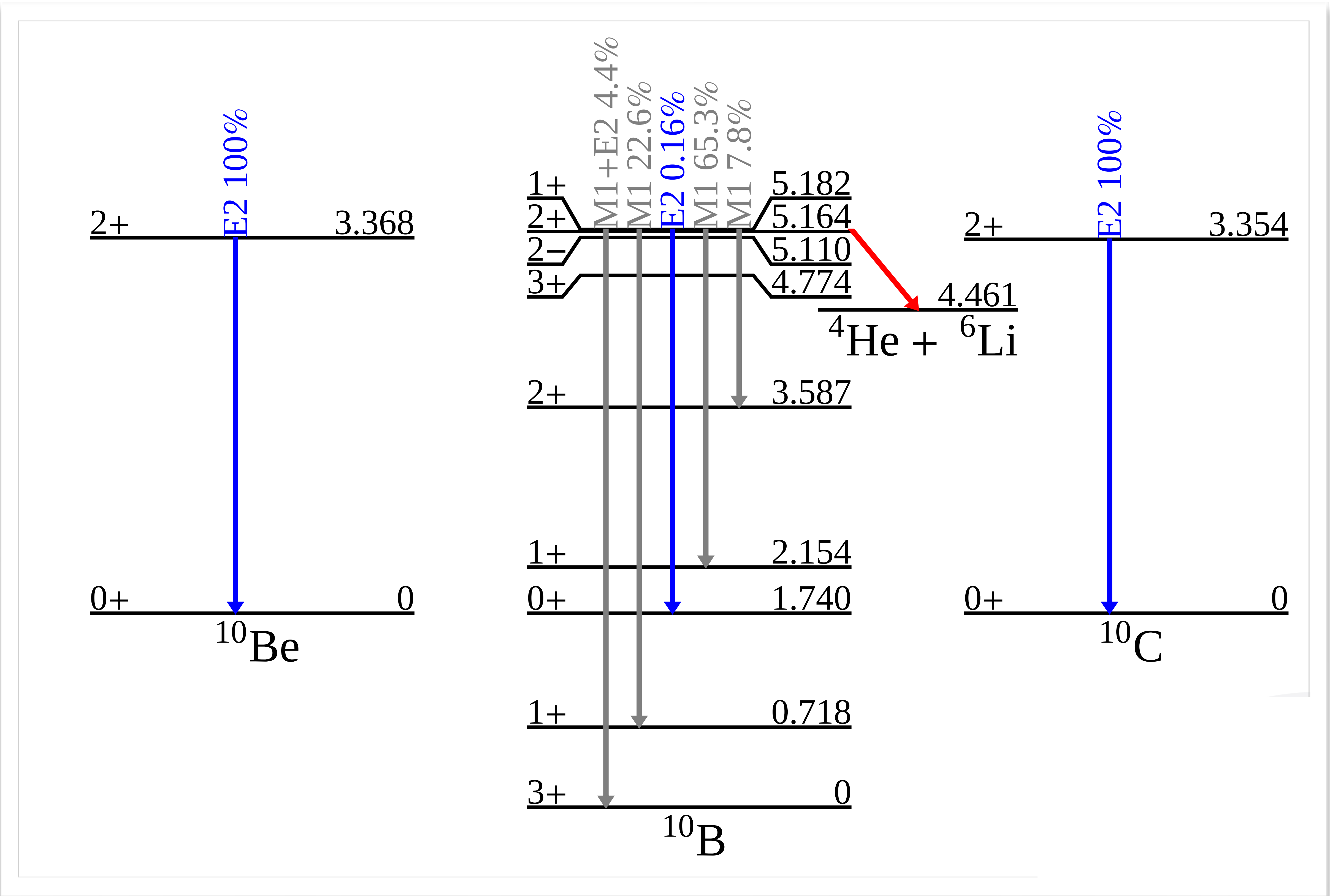


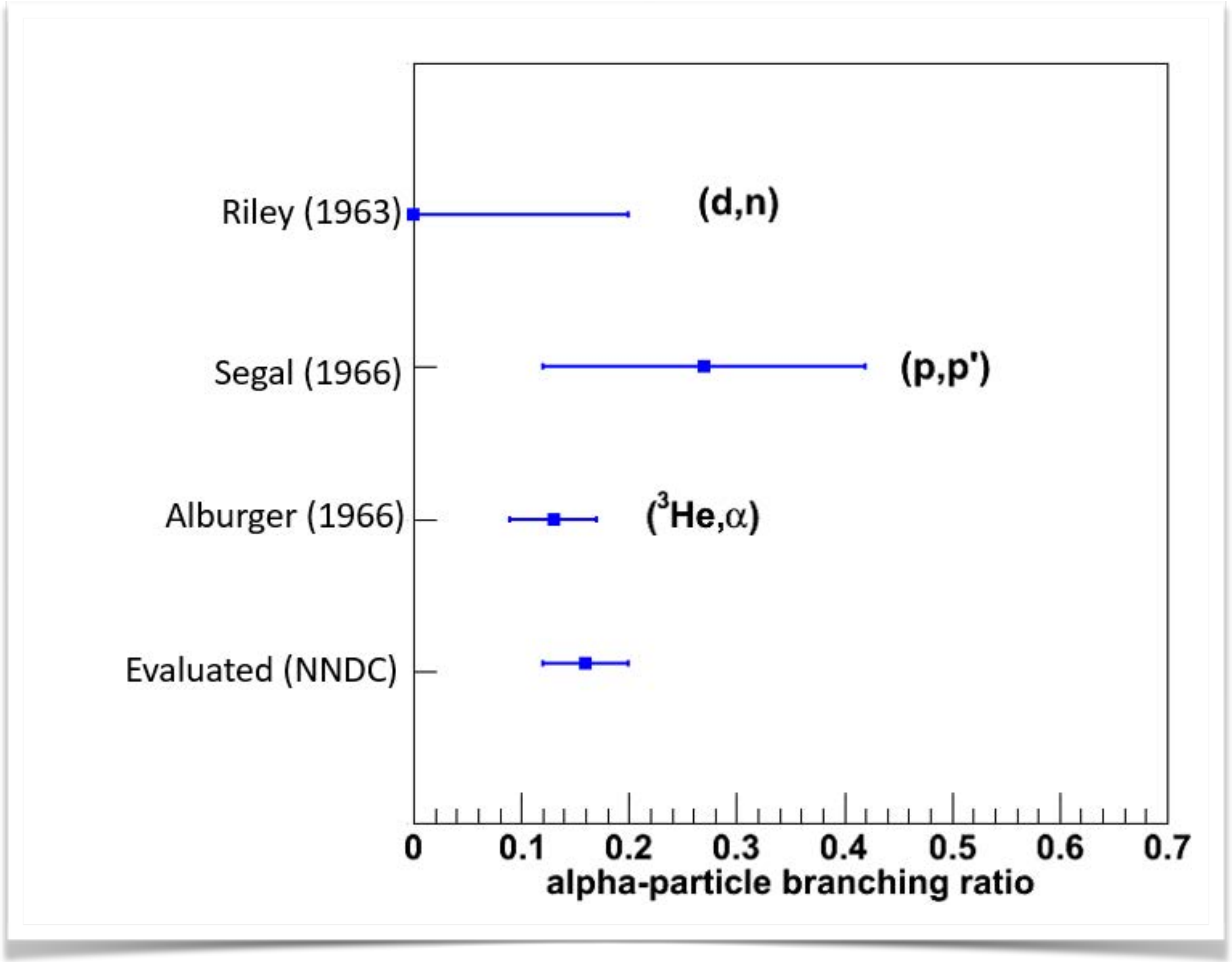
10C 19.308 S ε: 100.00%	11C 20.364 M ε: 100.00%	12C STABLE 98.93%
9B 0.54 KeV 2α: 100.00% P: 100.00%	10B STABLE 19.9%	11B STABLE 80.1%
8Be 5.57 eV α: 100.00%	9Be STABLE 100.%	10Be 1.51E+6 Y β-: 100.00%



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

Mass 10 triplet





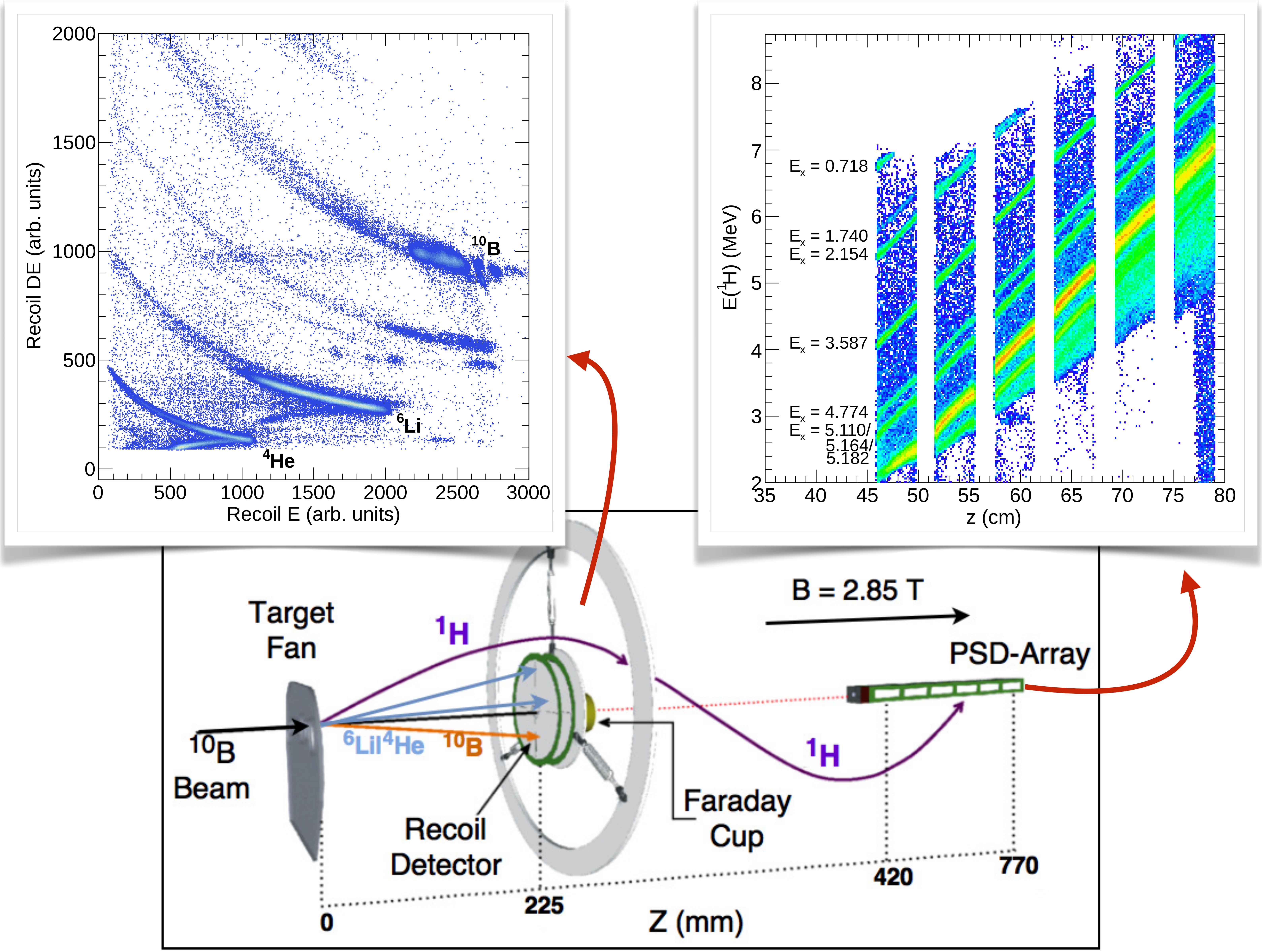
- Status of Uncertainties:
  - Width(7%)
  - Alpha-particle branching ratio (25%)
  - γ-decay branching ratio: (25%)

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).

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

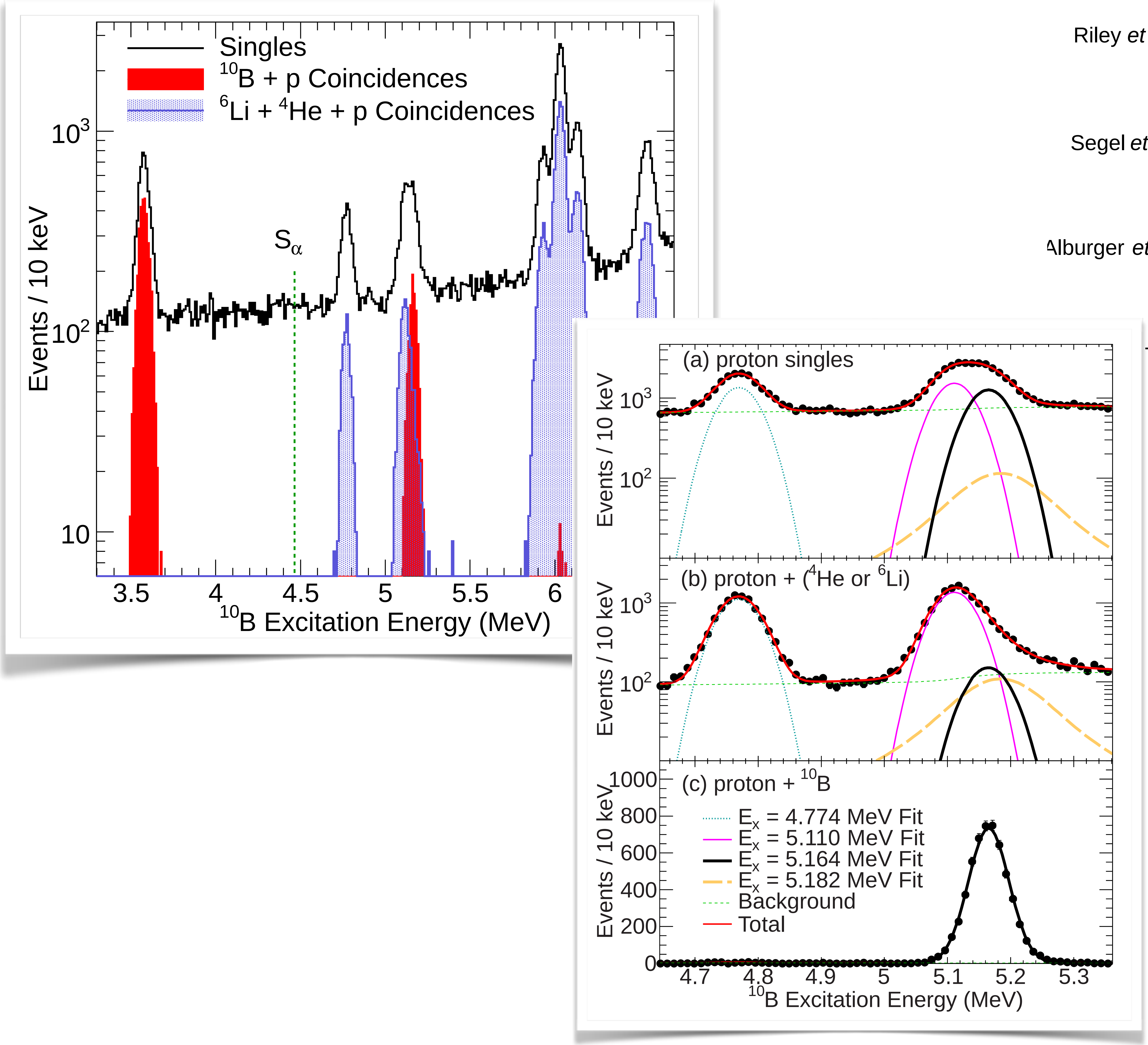
Inverse technique

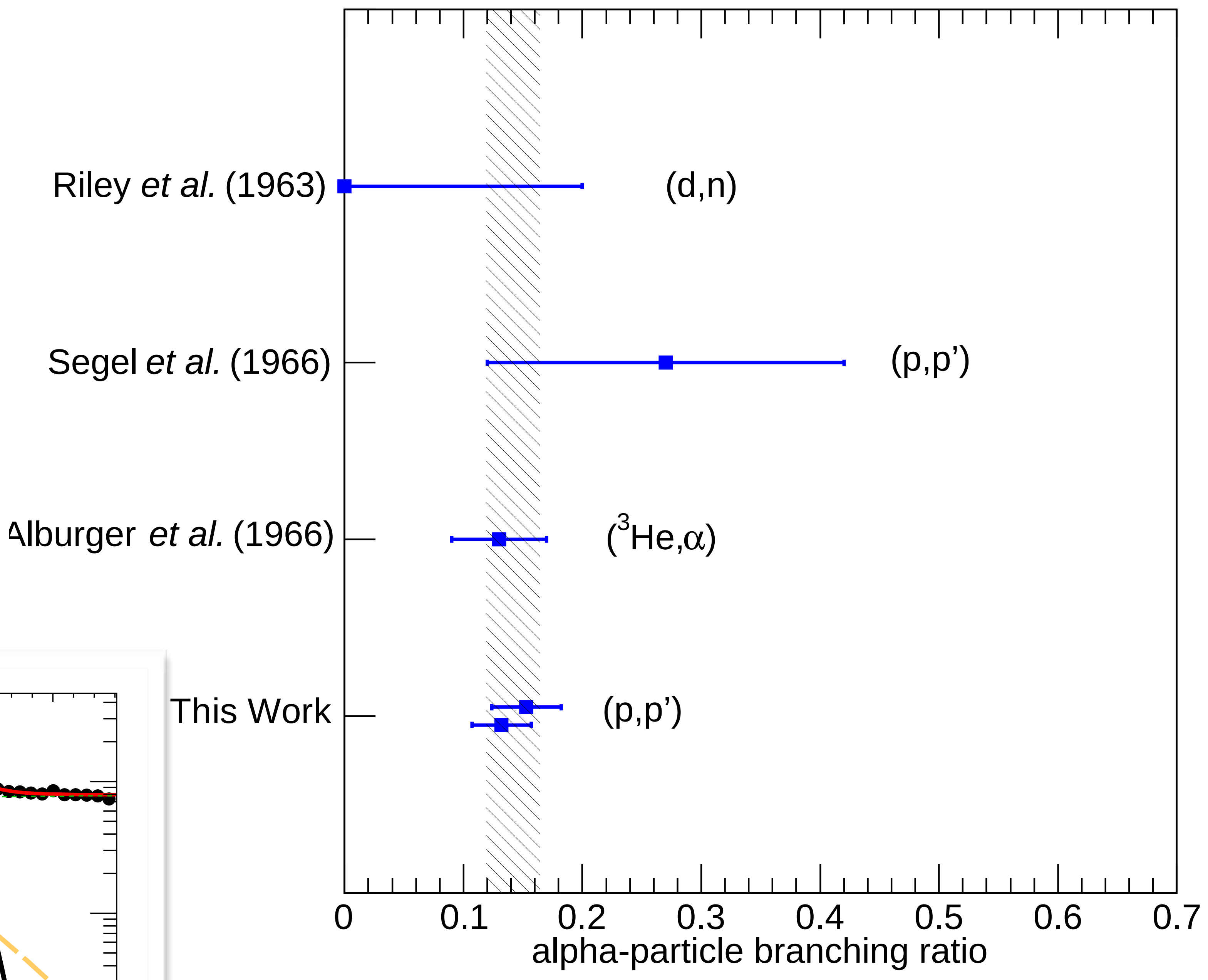
- ^{10}B beam (stable) at 10 MeV/u
- Thin CH_2 target
- 'All' recoils detected, including those following decay of the recoil
- Method allows multiple analysis techniques



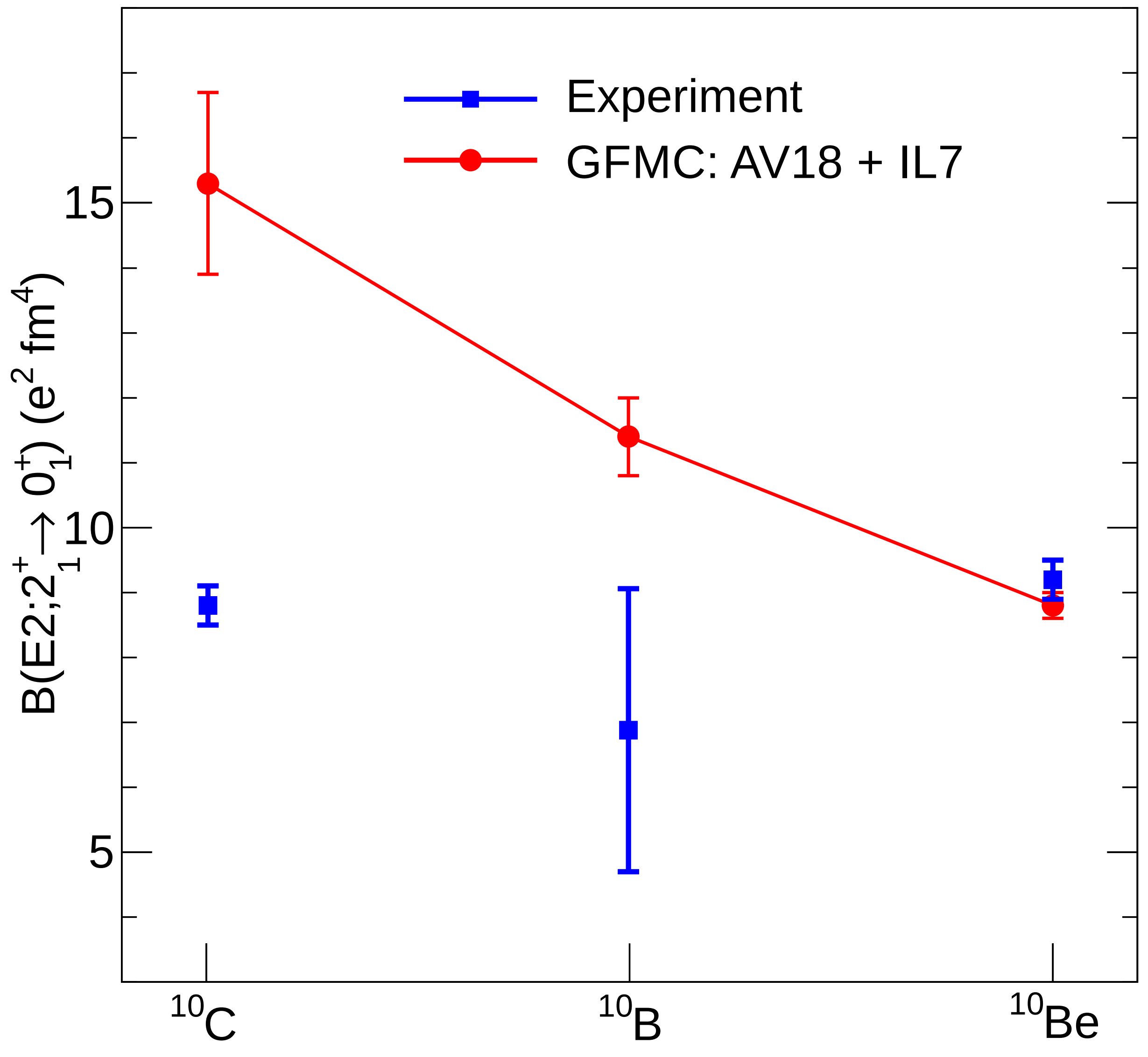
S. Kuvin et al. Phys. Rev. C ***96****, 041301(R) (****2017****)*

Branching ratio





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



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

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

Example 2 – isomeric beams

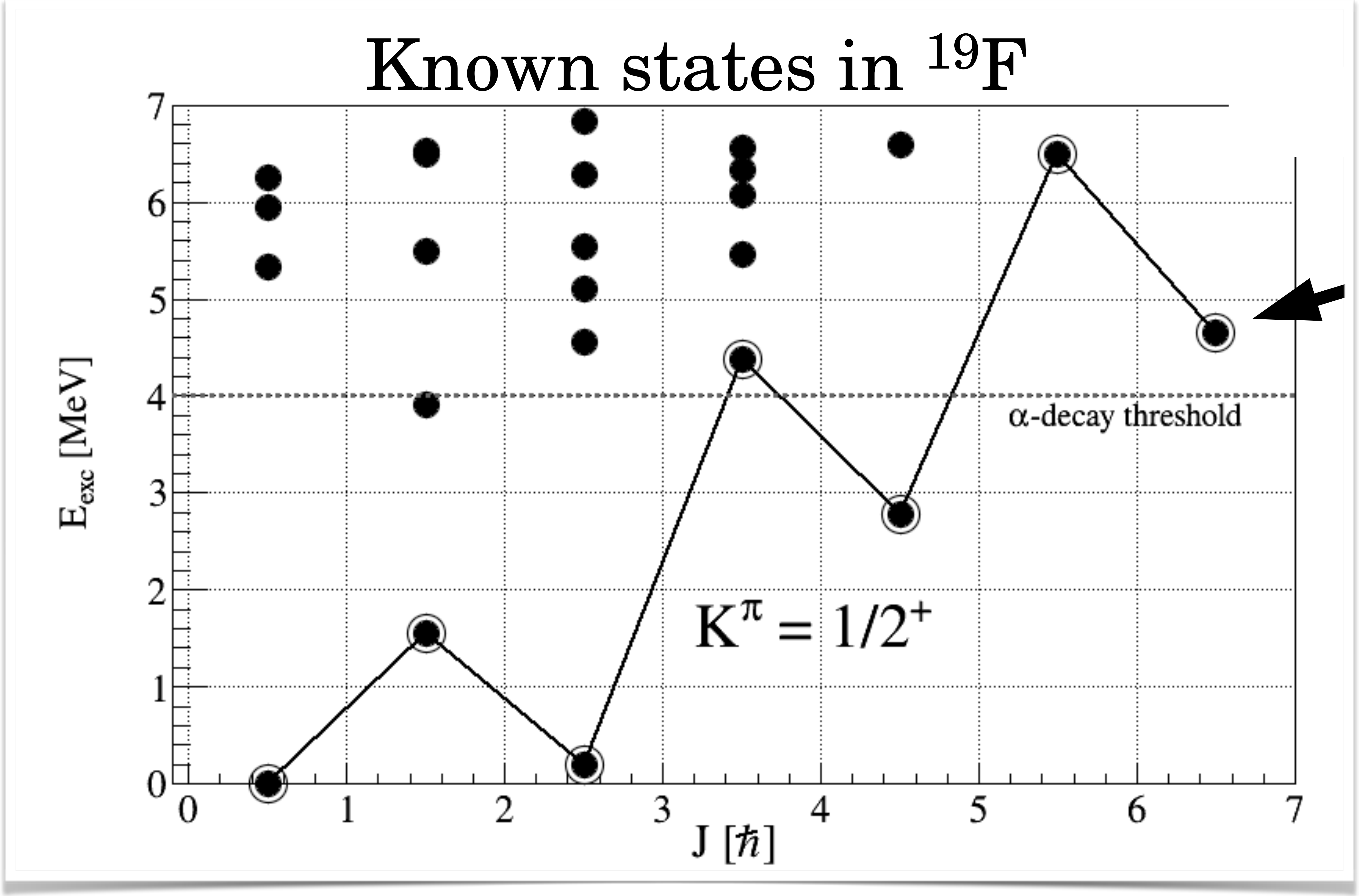
Rotational bands (and single-particles)

Transfer reactions are highly selective in ℓ transfer

Question:

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 …

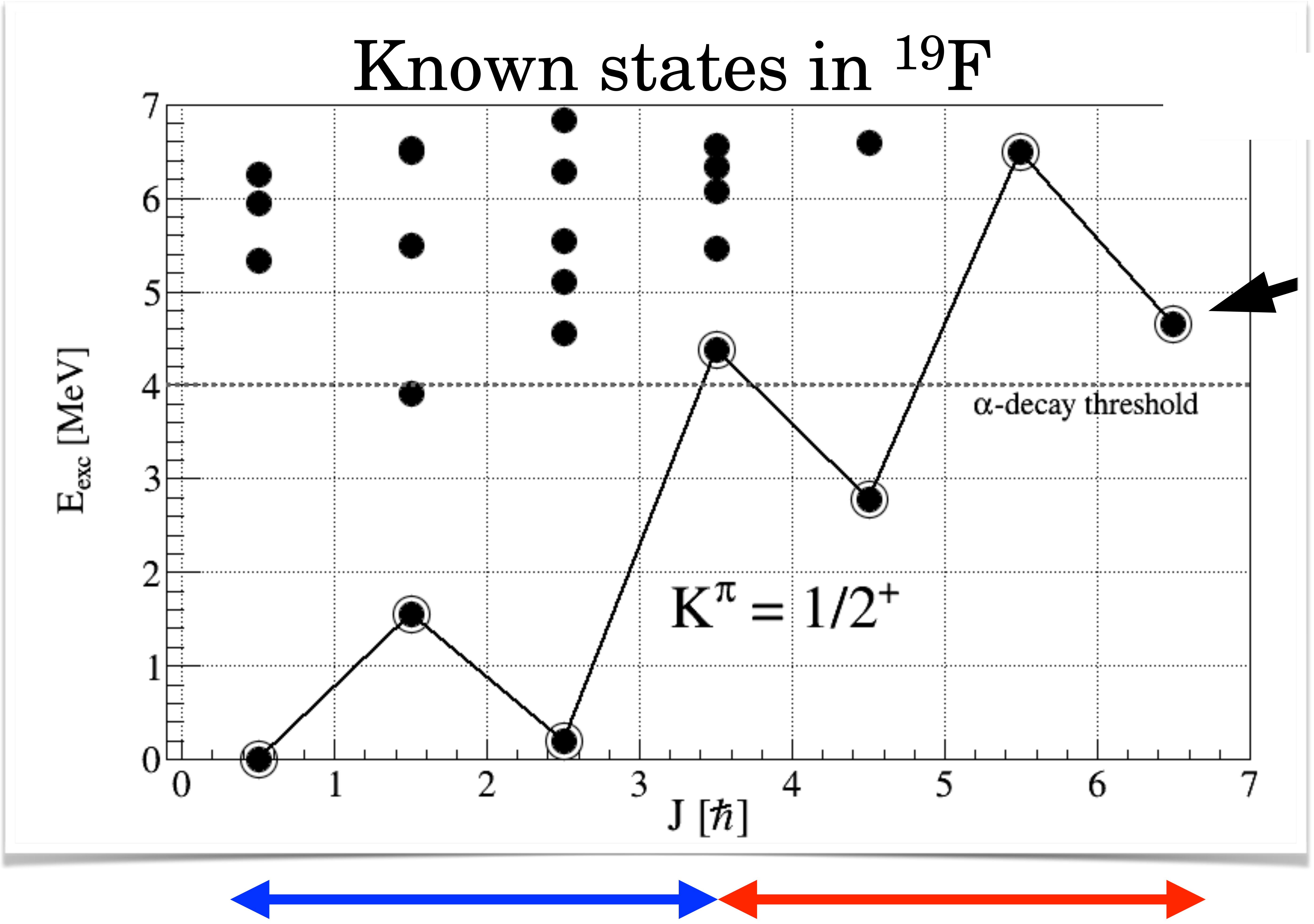


Isomeric beams

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

We can exploit this to probe high-*j* states via low-ℓ transfer.

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



$^{18g}\mathrm{F}^{(0+)}(d,p)^{19}\mathrm{F}$

ℓ=0, 2

$^{18m}\mathrm{F}^{(5+)}(d,p)^{19}\mathrm{F}$

ℓ=0, 2

D. Santiago-Gonzalez et al., Phys. Rev. Lett. ***120****, 122503 (****2018****)*

^{18}F(d,p) two ways

16.3 m, or 1.9 × half life (162 ns)

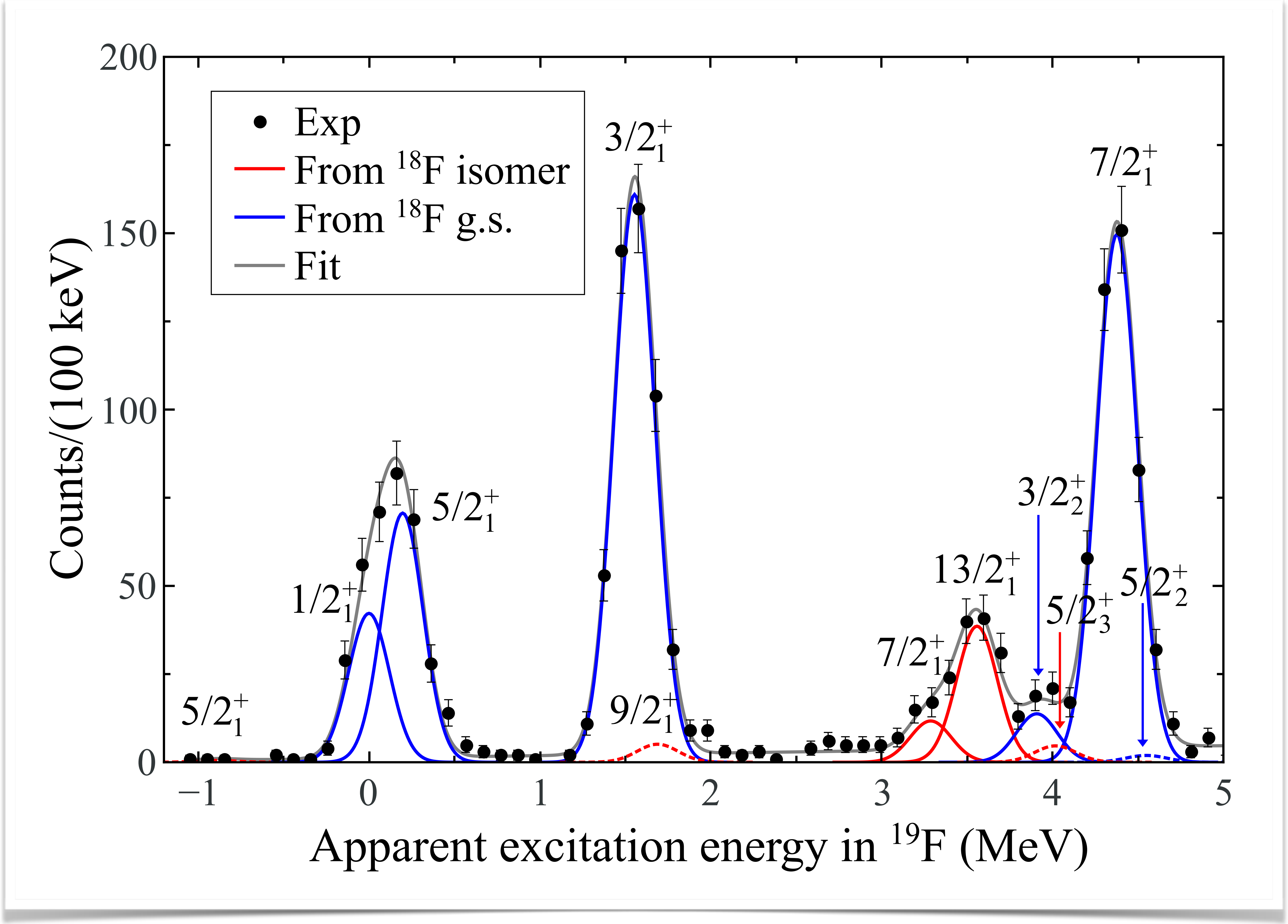
Production

^{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., Phys. Rev. Lett. ***120****, 122503 (****2018****)*

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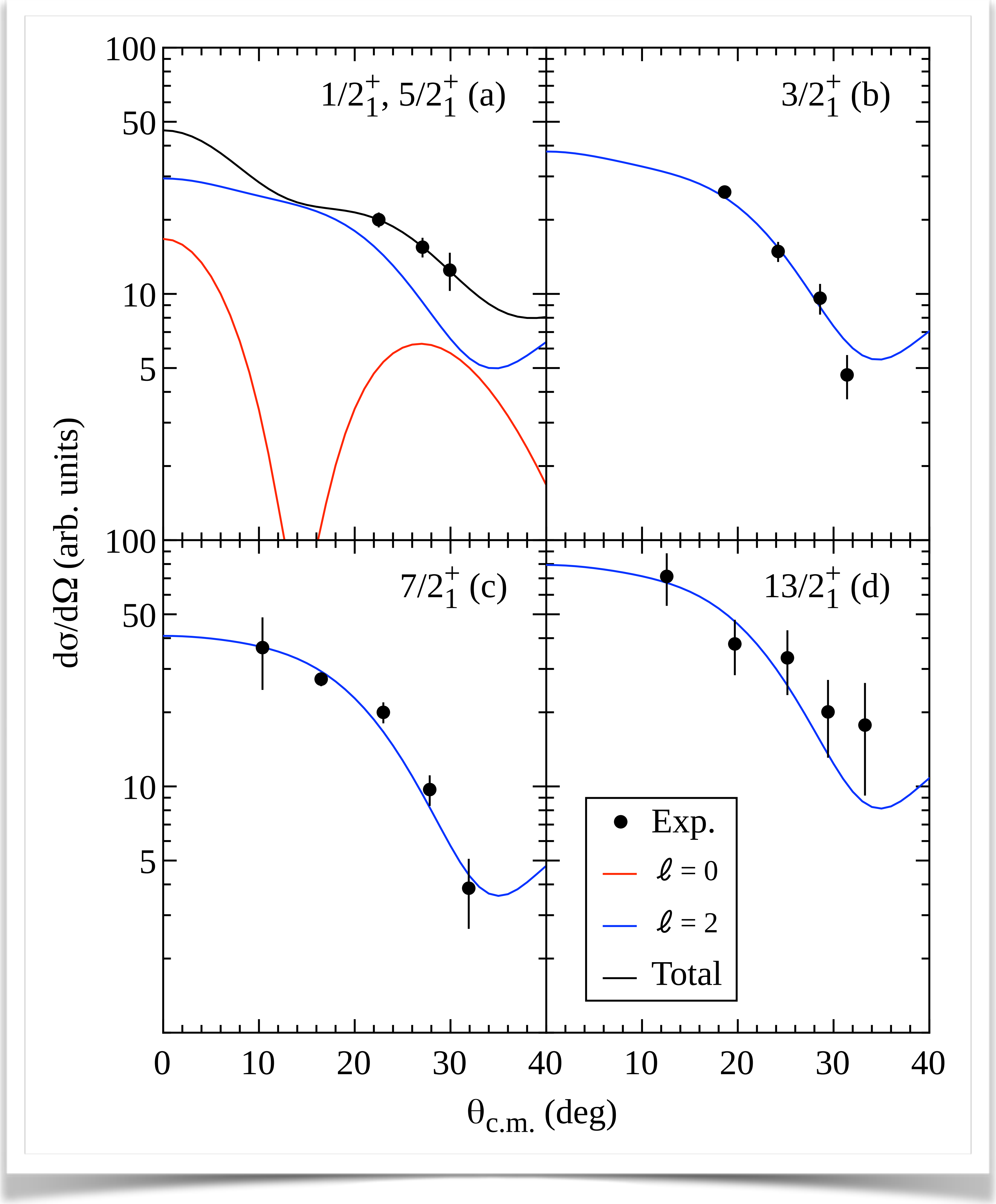
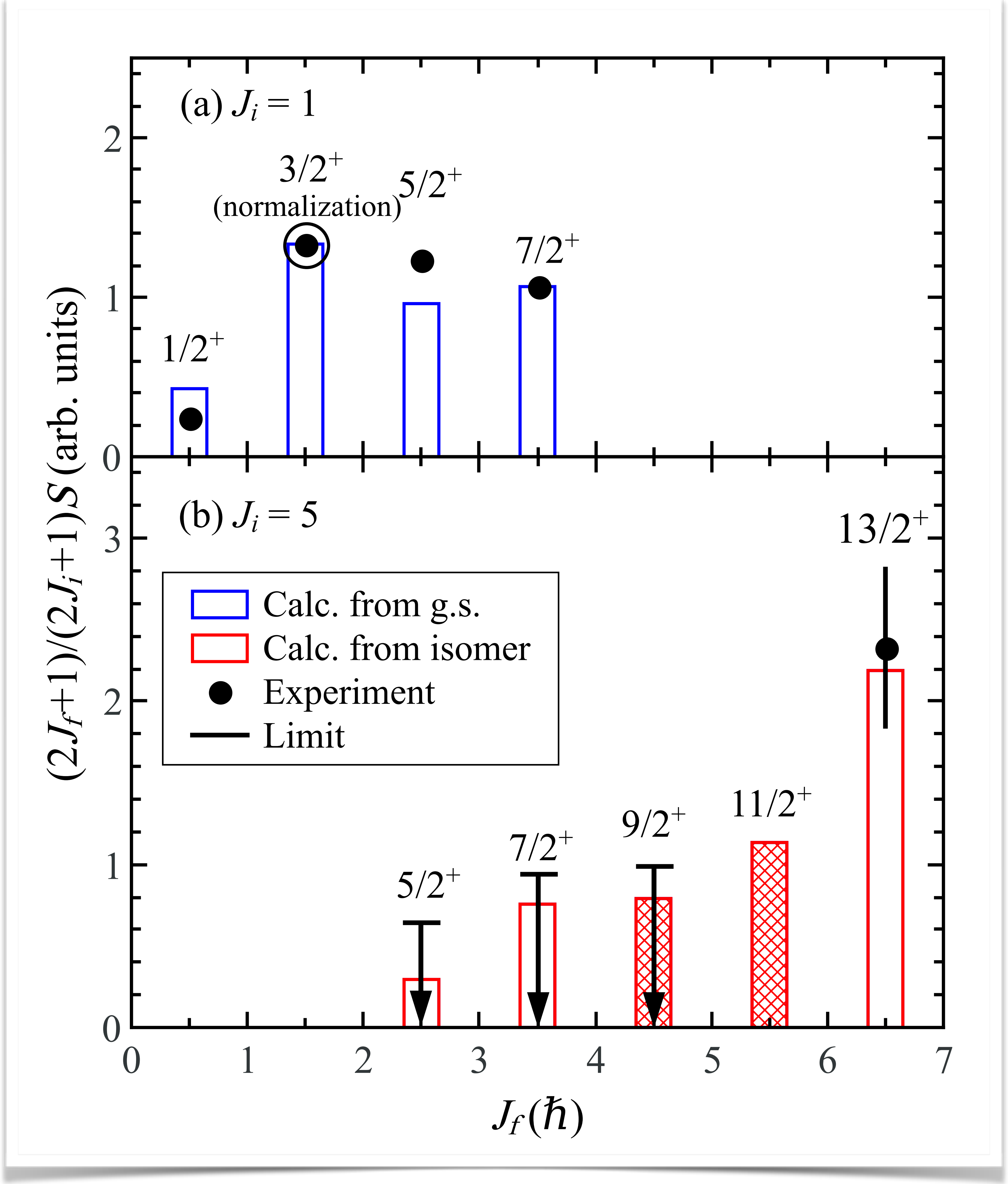
Reactions confirm ^{19}F well understood



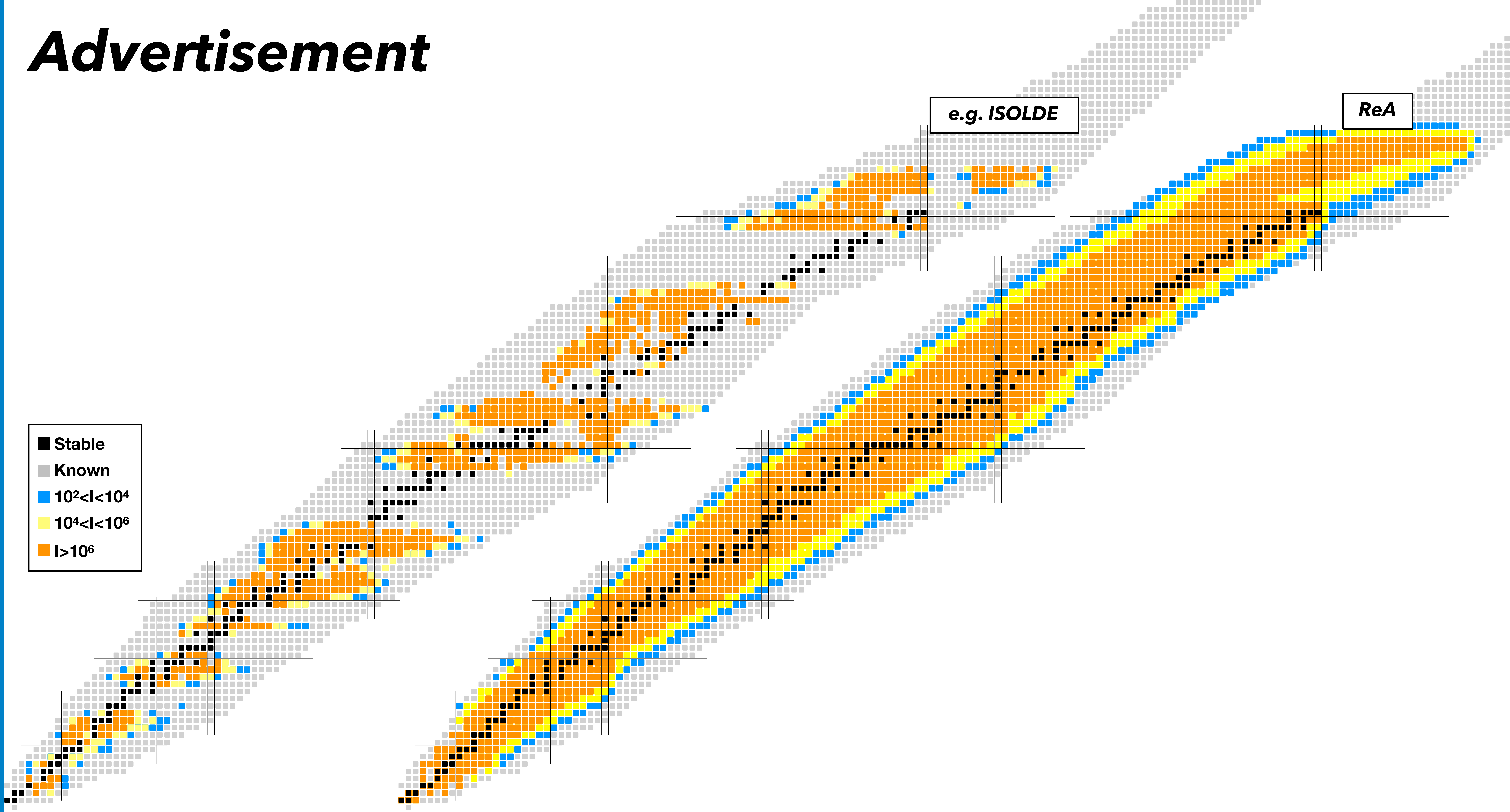


Excellent agreement with shell-model calculations (perhaps not surprisingly).

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

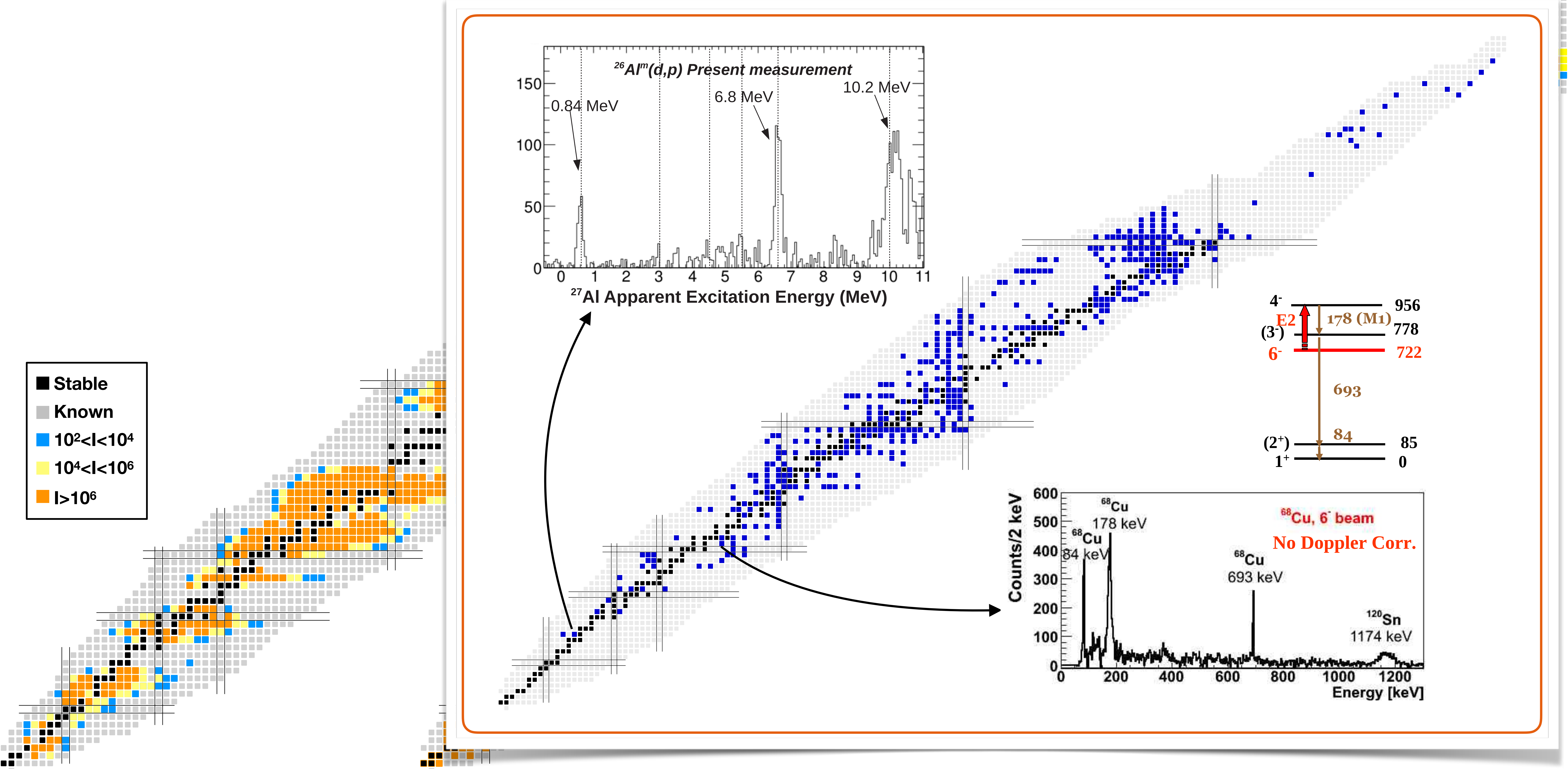
D. Santiago-Gonzalez et al., Phys. Rev. Lett. ***120****, 122503 (****2018****)*

Advertisement



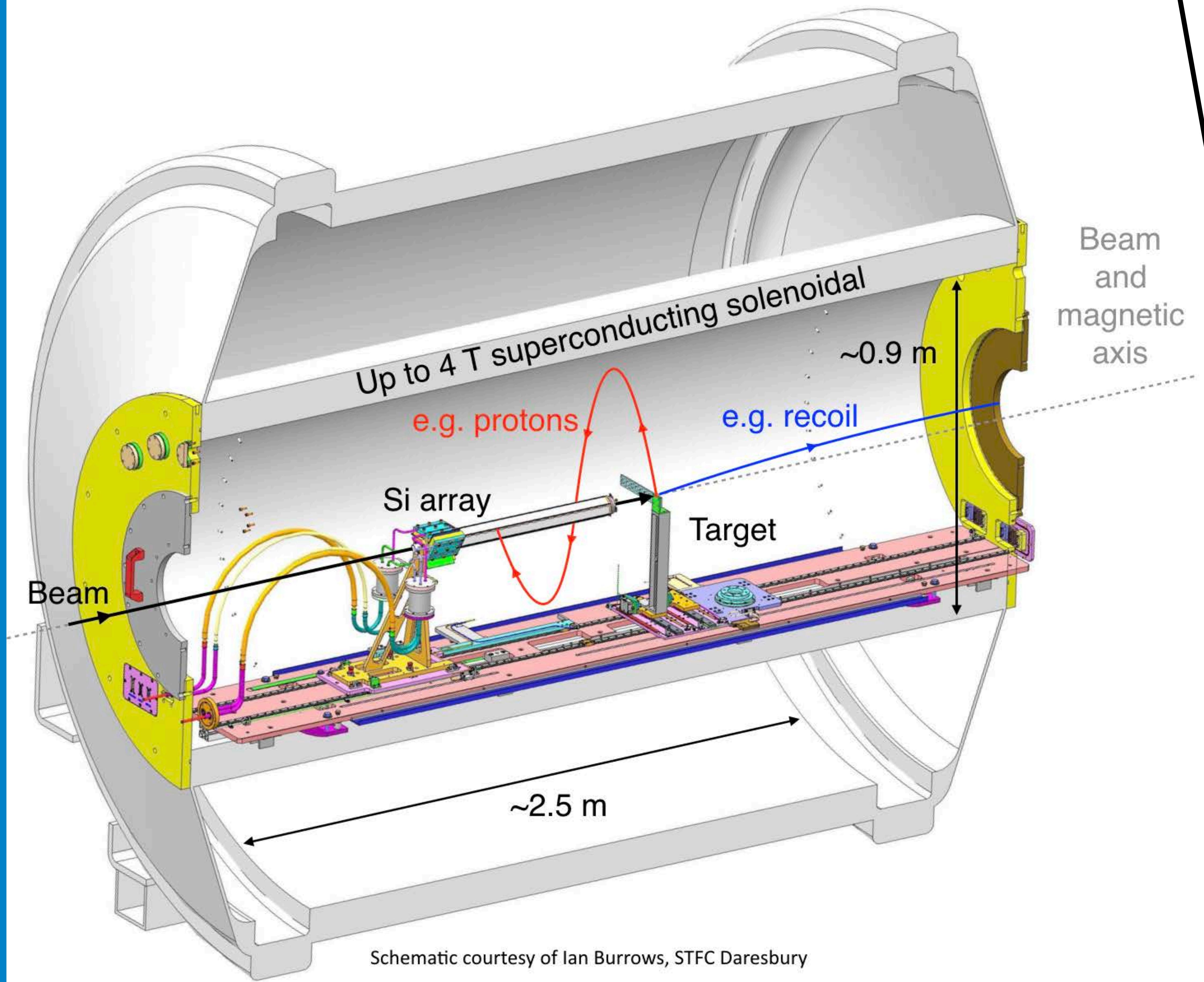
(Beam rates crude estimates from various sources, illustrative)

Advertisement



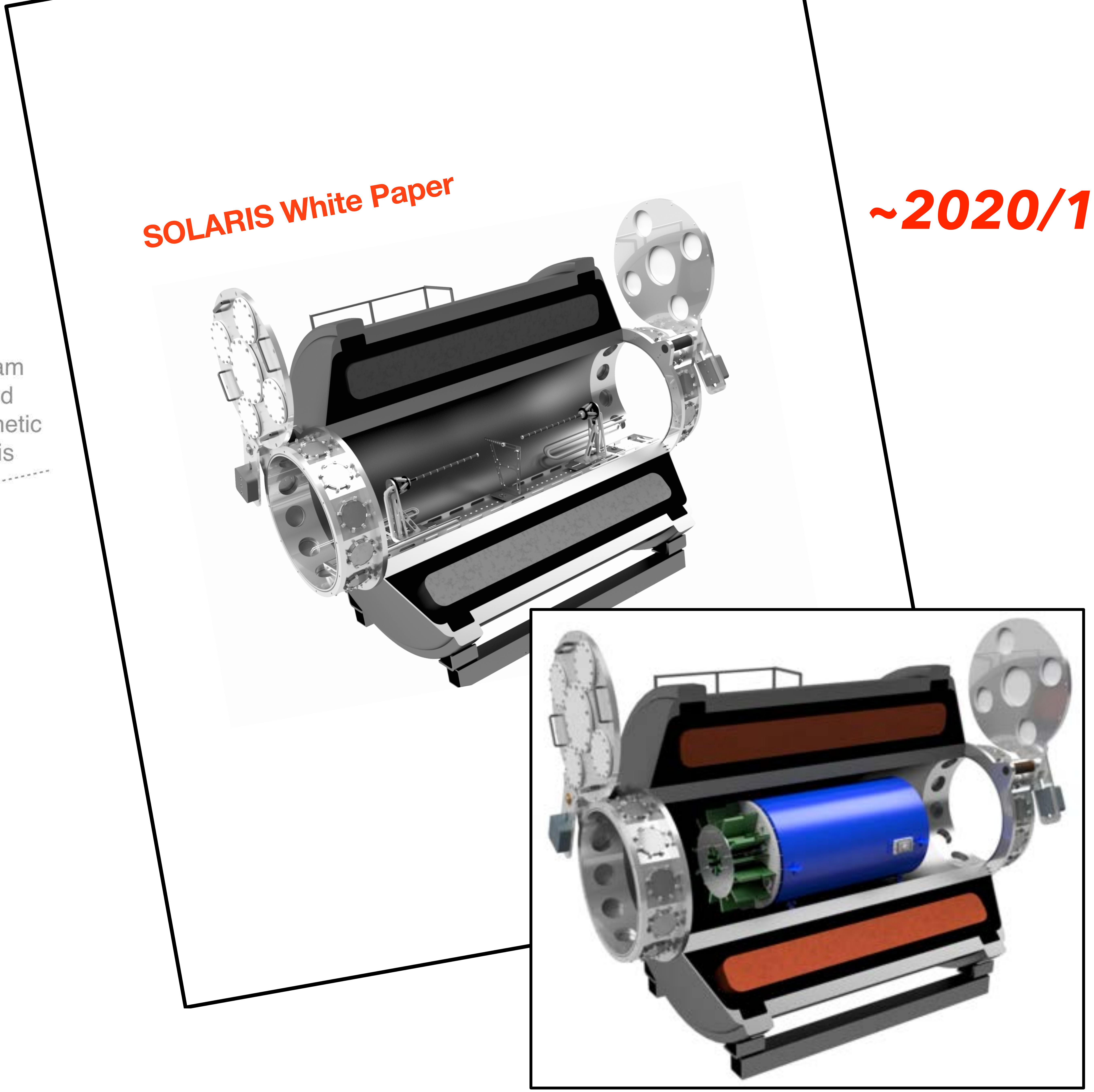
(Beam rates crude estimates from various sources, illustrative)

Advertisement



Schematic courtesy of Ian Burrows, STFC Daresbury

~now

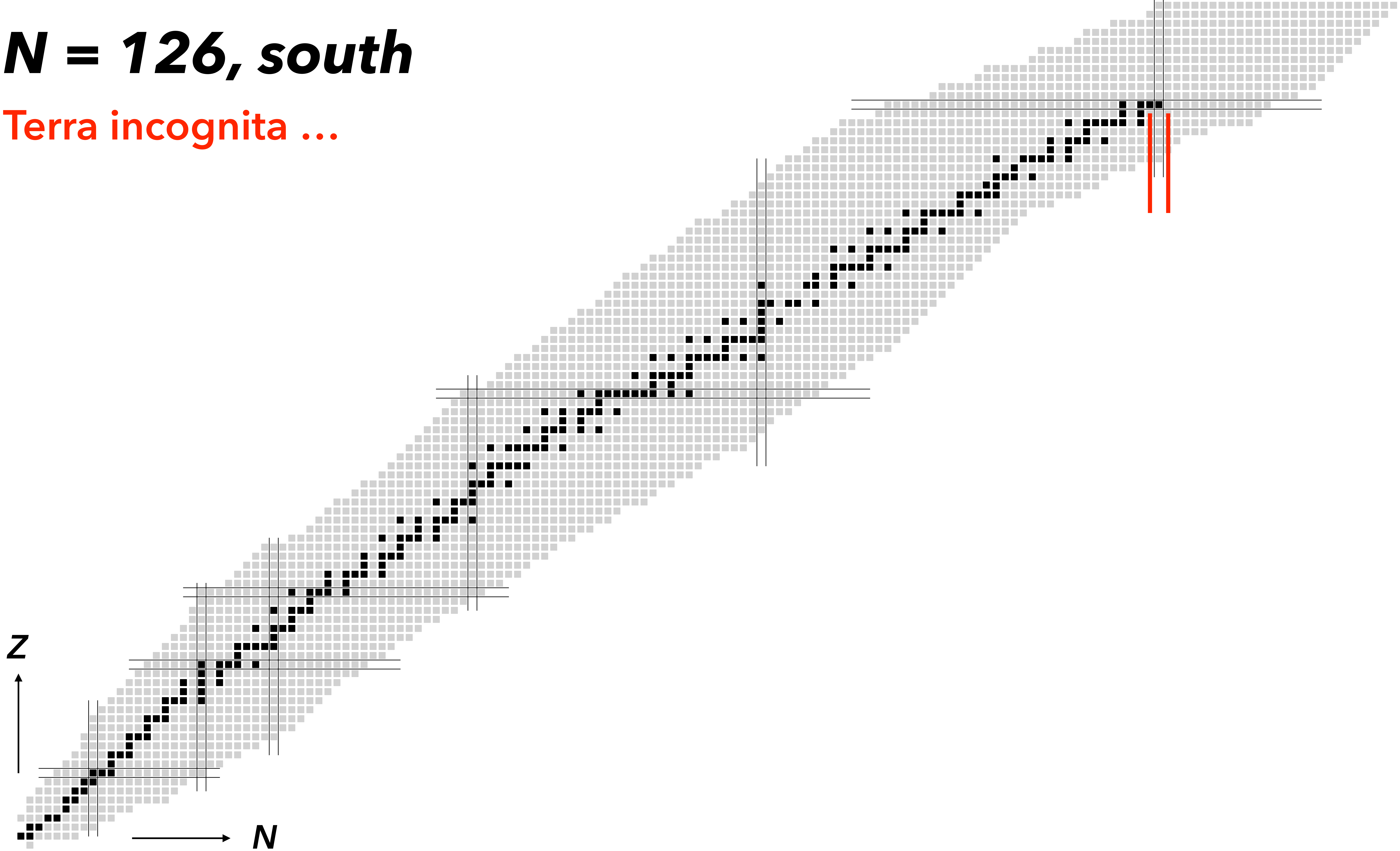


~2020/1

SOLARIS: http://www.anl.gov/phy/group/solaris (white paper link)

N = 126, south

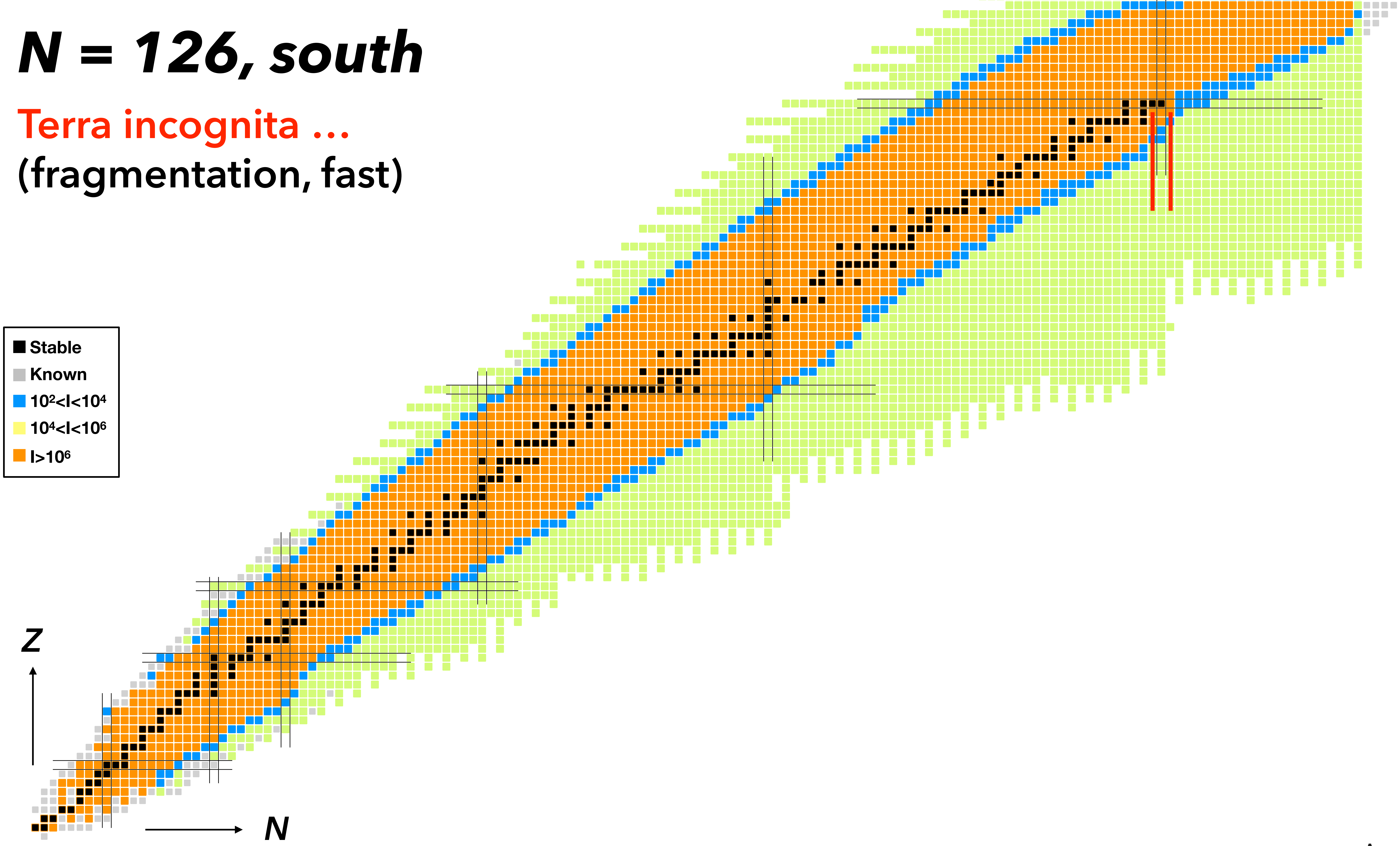
Terra incognita …



***N* = 126, south**

Terra incognita …

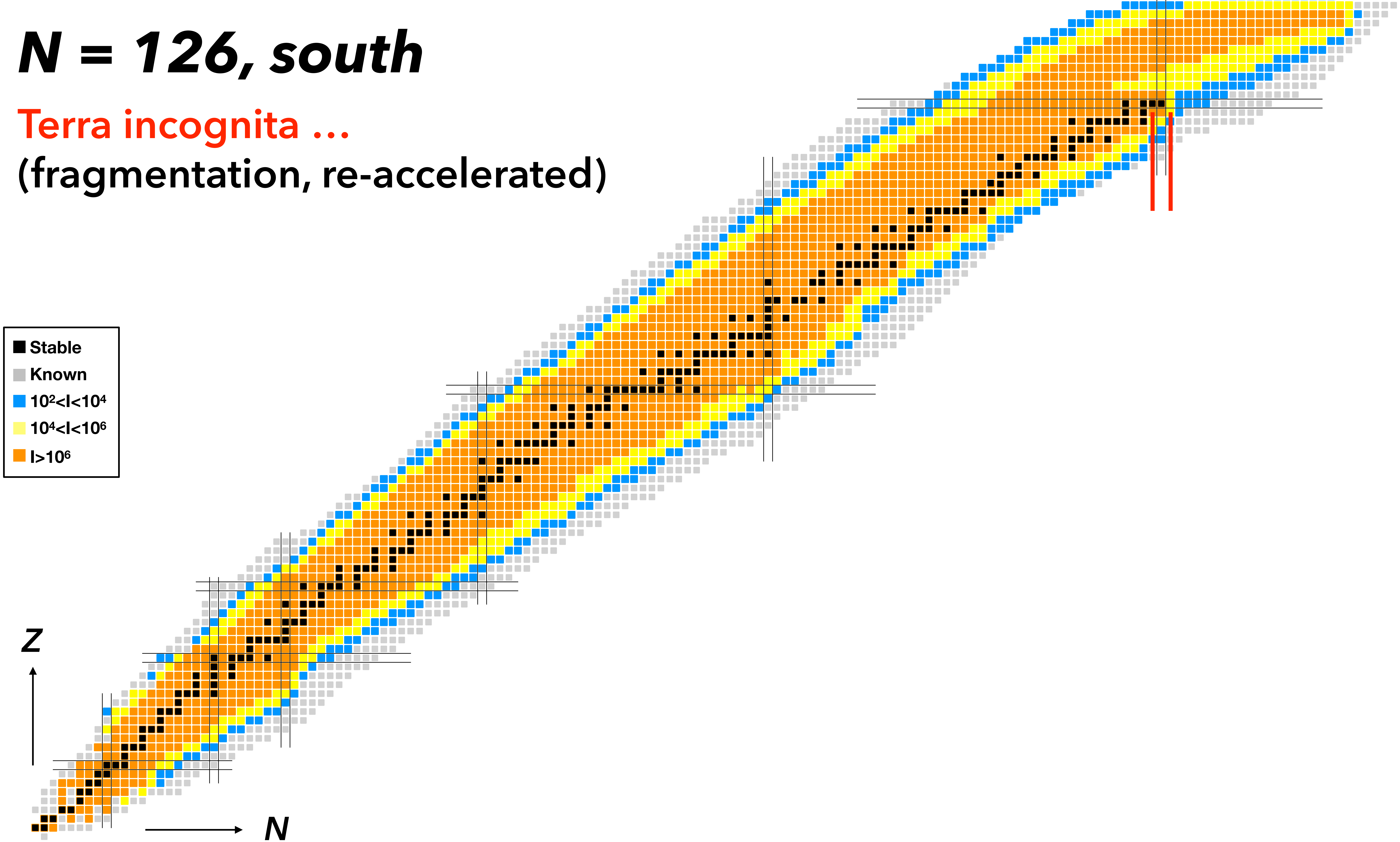
(fragmentation, fast)



N = 126, south

Terra incognita …

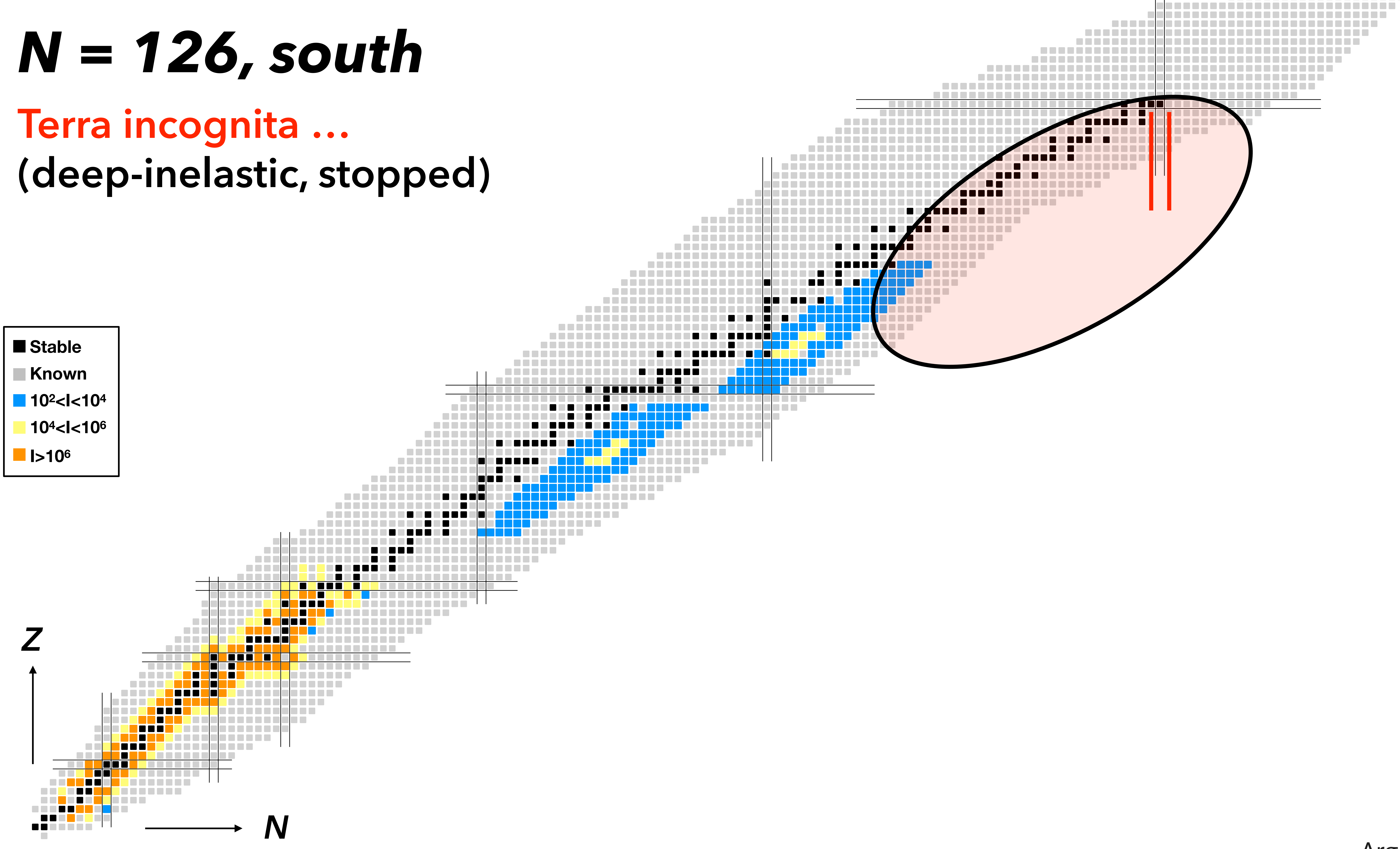
(fragmentation, re-accelerated)



***N* = 126, south**

Terra incognita …

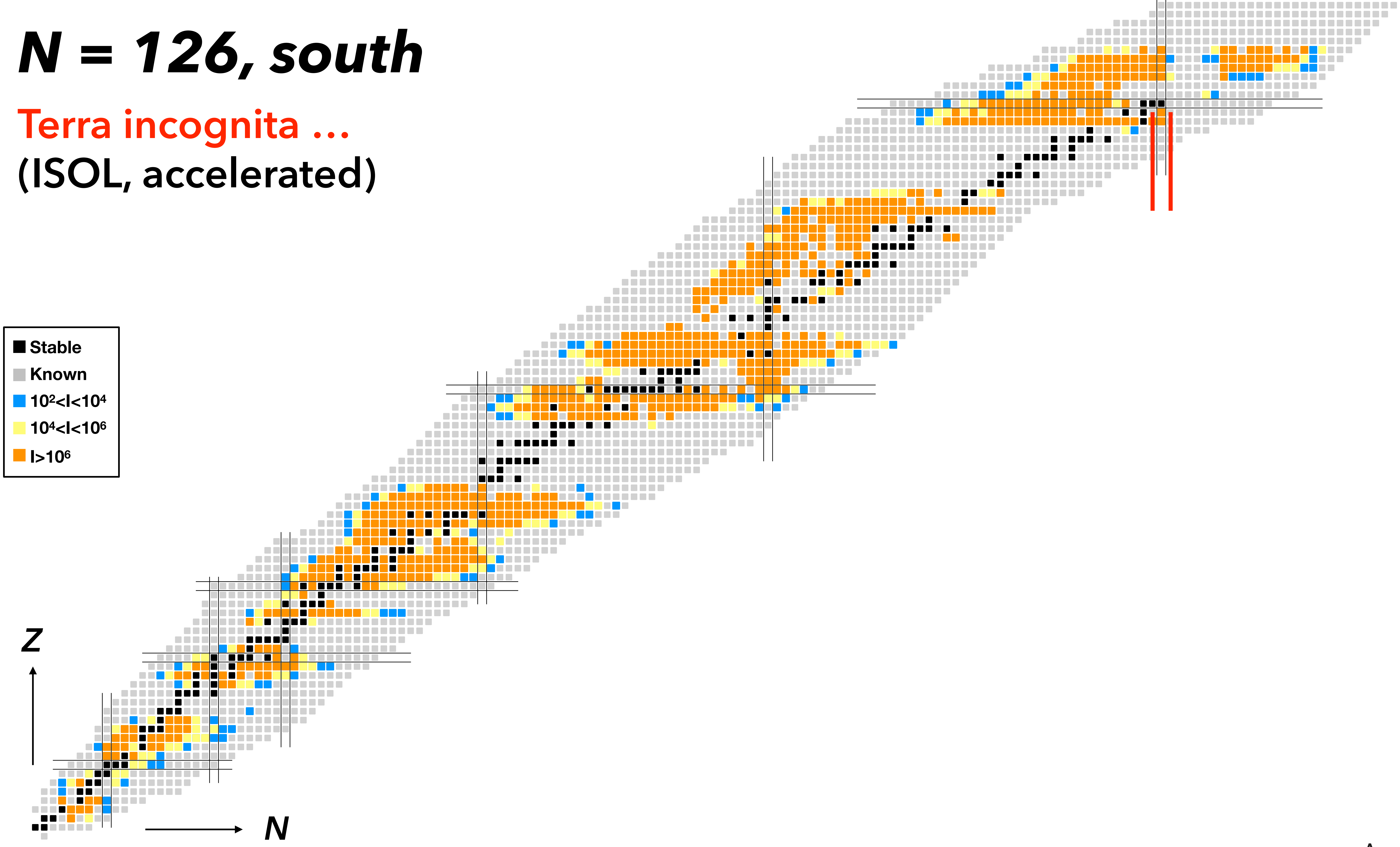
(deep-inelastic, stopped)



N = 126, south

Terra incognita …

(ISOL, accelerated)



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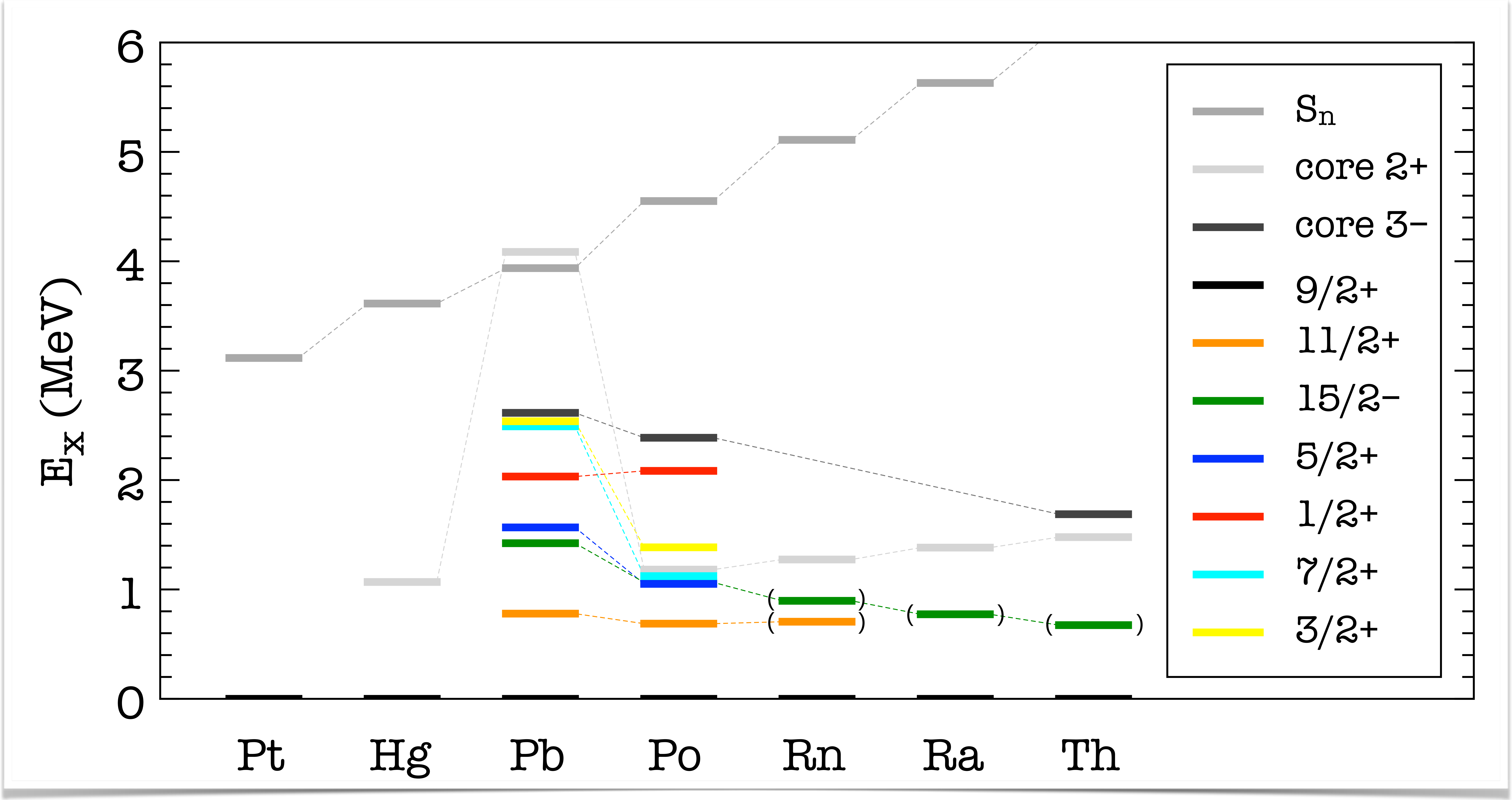
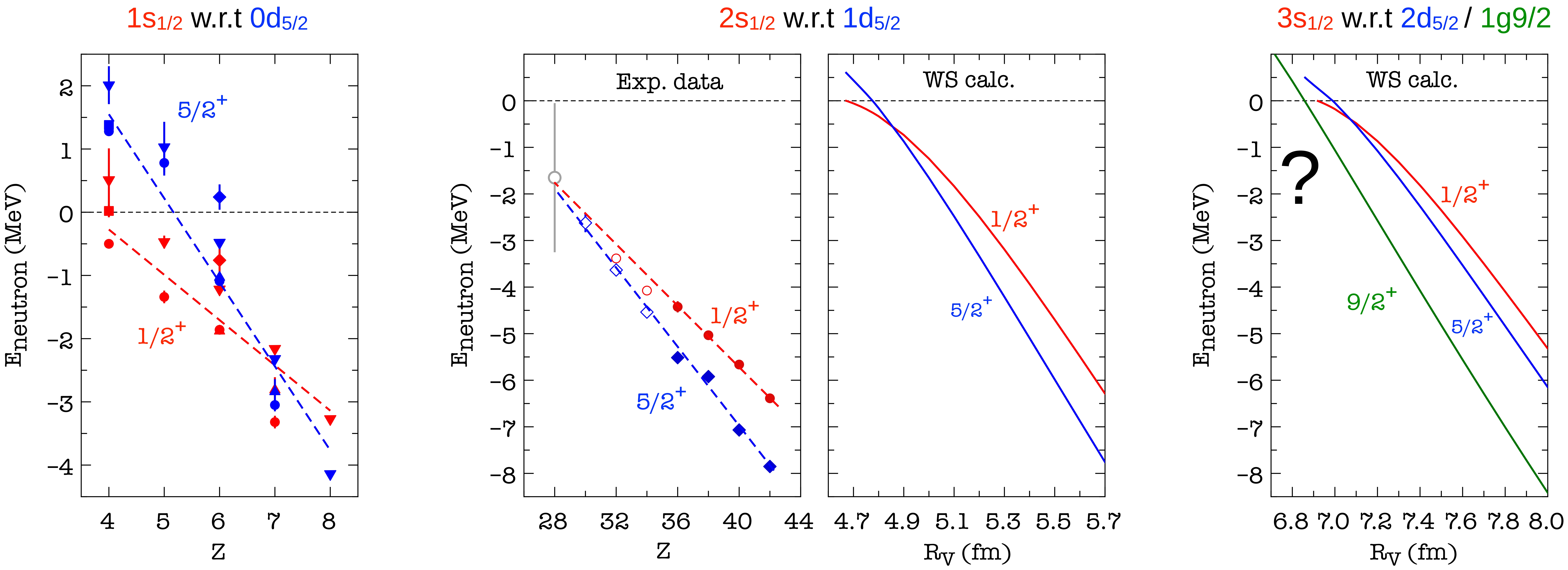
Motivation – single-neutron excitations

N = 126 excitations, N = 127 single-neutron excitations



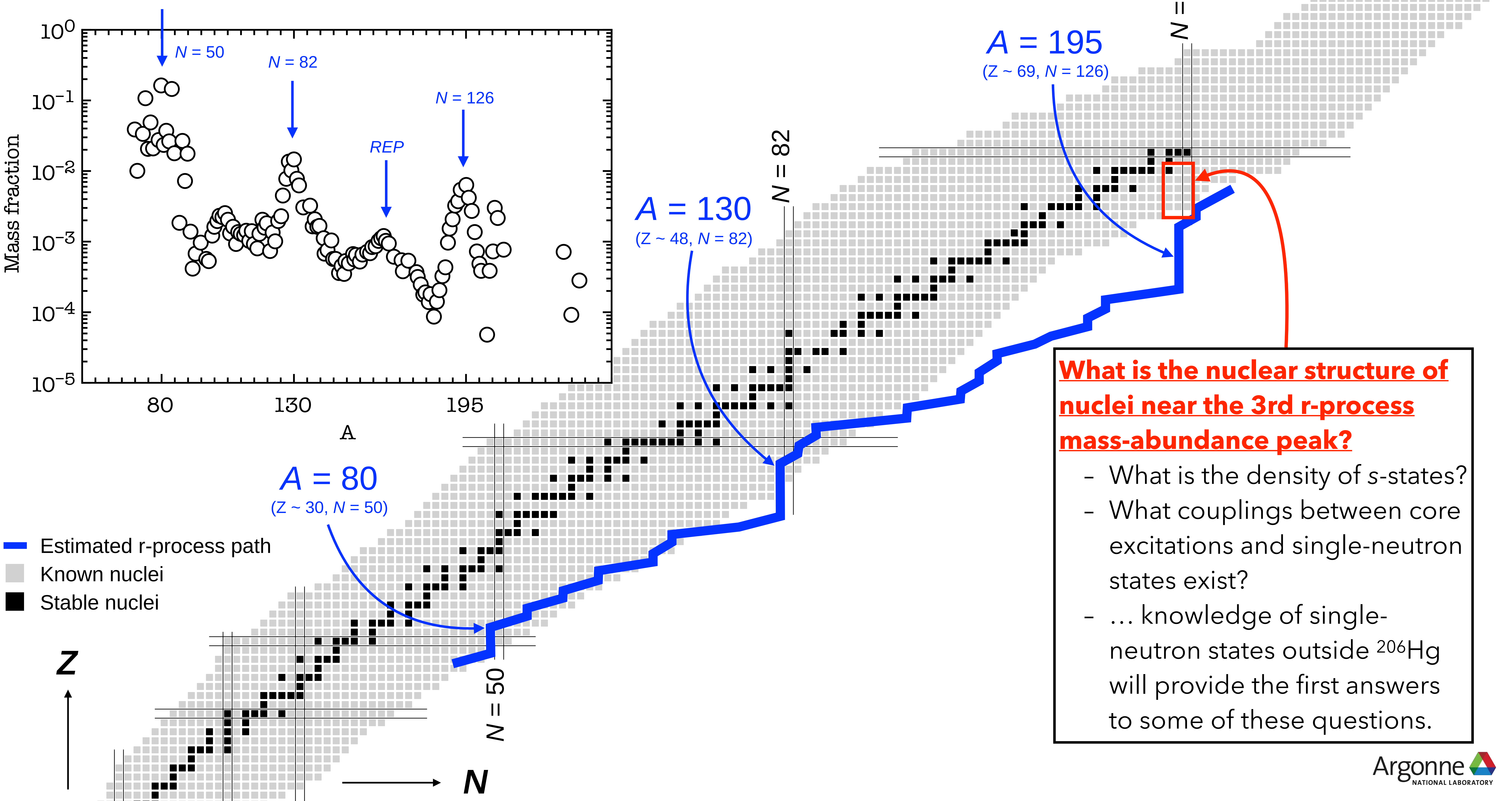
Motivation – weak binding

s[and other]-states in loosely bound systems tend to linger below their [respective] barriers– this feature seems to ***dominate the structural changes in light nuclei***, and results in e.g., ***halo structures***. Does this characteristic of *s*-states play a role in loosely bound heavier systems?



C. R. Hoffman, B. P. Kay, J. P. Schiffer, Phys Rev. C 89, 061305(R) (2014), C. R. Hoffman, B. P. Kay, J. P .Schiffer, submitted (2016). X. F. Yang et al., Phys. Rev. Lett. 116, 182501 (2016) [Recent ISOLDE measurement suggests the 1/2+ isomeric state could potentially be below the 5/2+ state in the N = 49 system at Z = 30.]

Motivation – r-process physics



What is the nuclear structure of nuclei near the 3rd r-process mass-abundance peak?

- What is the density of *s*-states?
- What couplings between core excitations and single-neutron states exist?
- … knowledge of single-neutron states outside ^{206}Hg will provide the first answers to some of these questions.

Proposed measurement *(as presented in 2016)*

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

Why 10 MeV/u?

- Cross sections
- Angular momentum matching
- Angular distributions

Why ISS?

Resolution

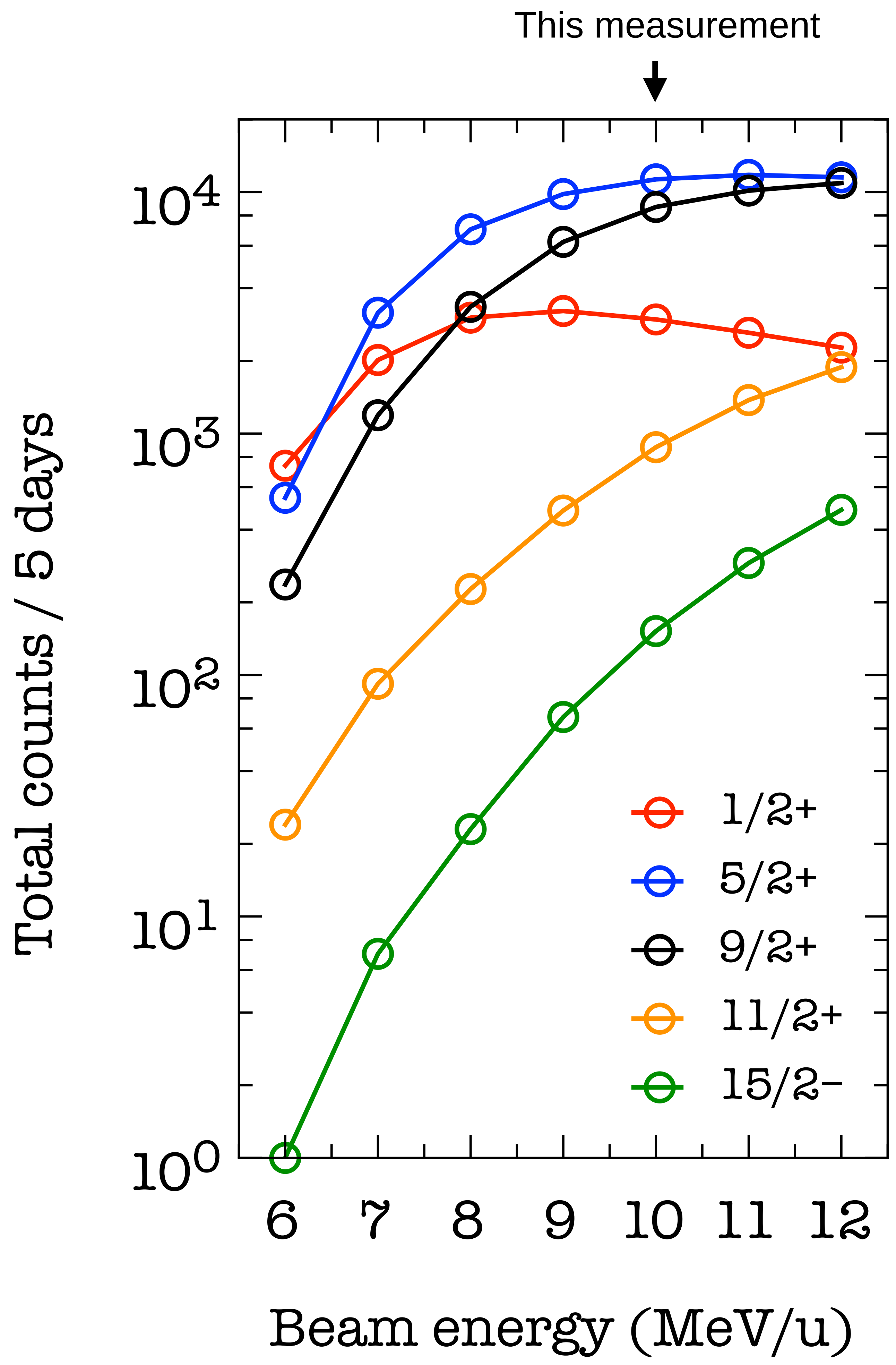
- Charged-particle spectroscopy with ***<100-keV Q-value resolution*** using thin targets

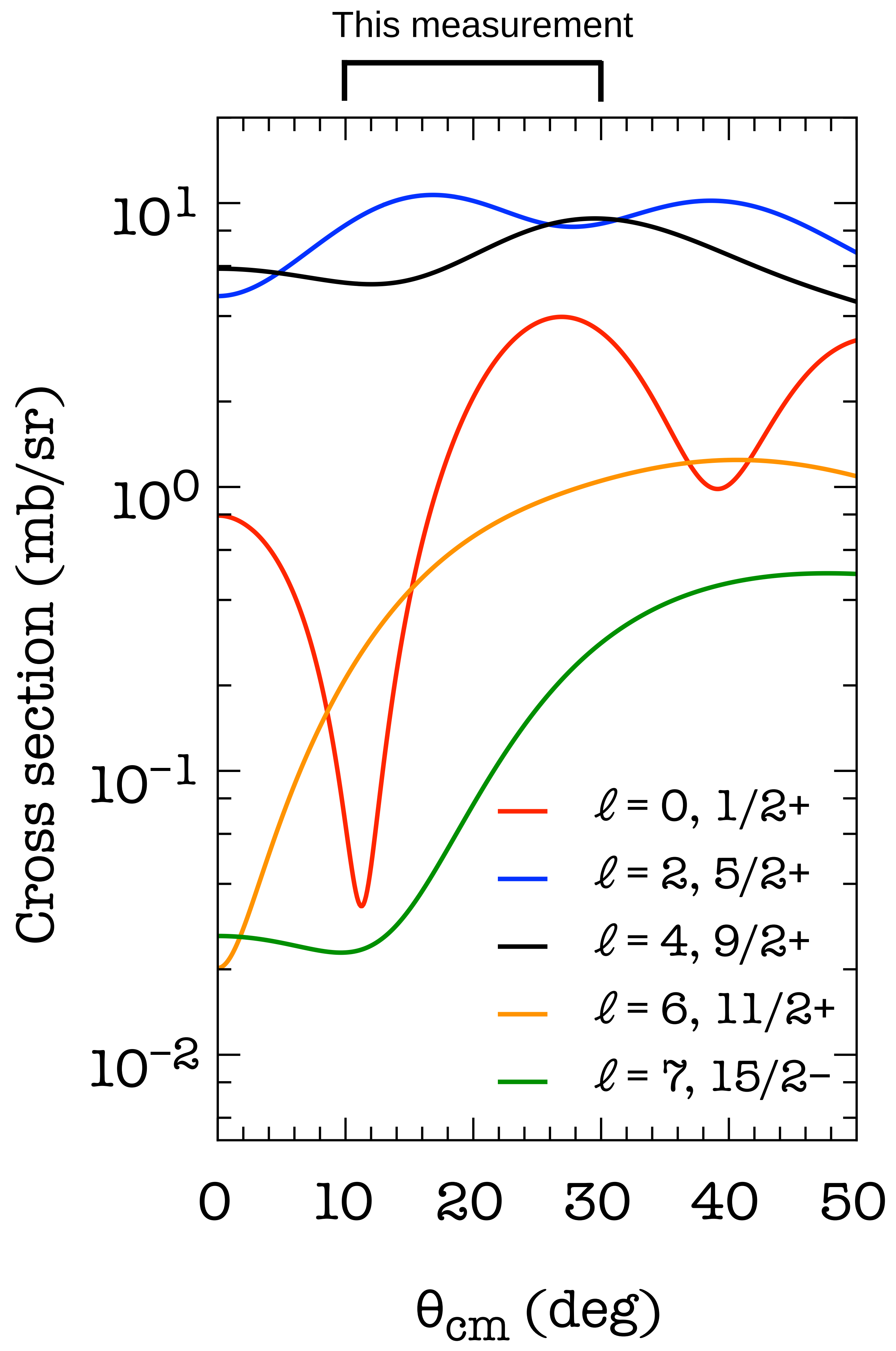
Efficiency

- 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).





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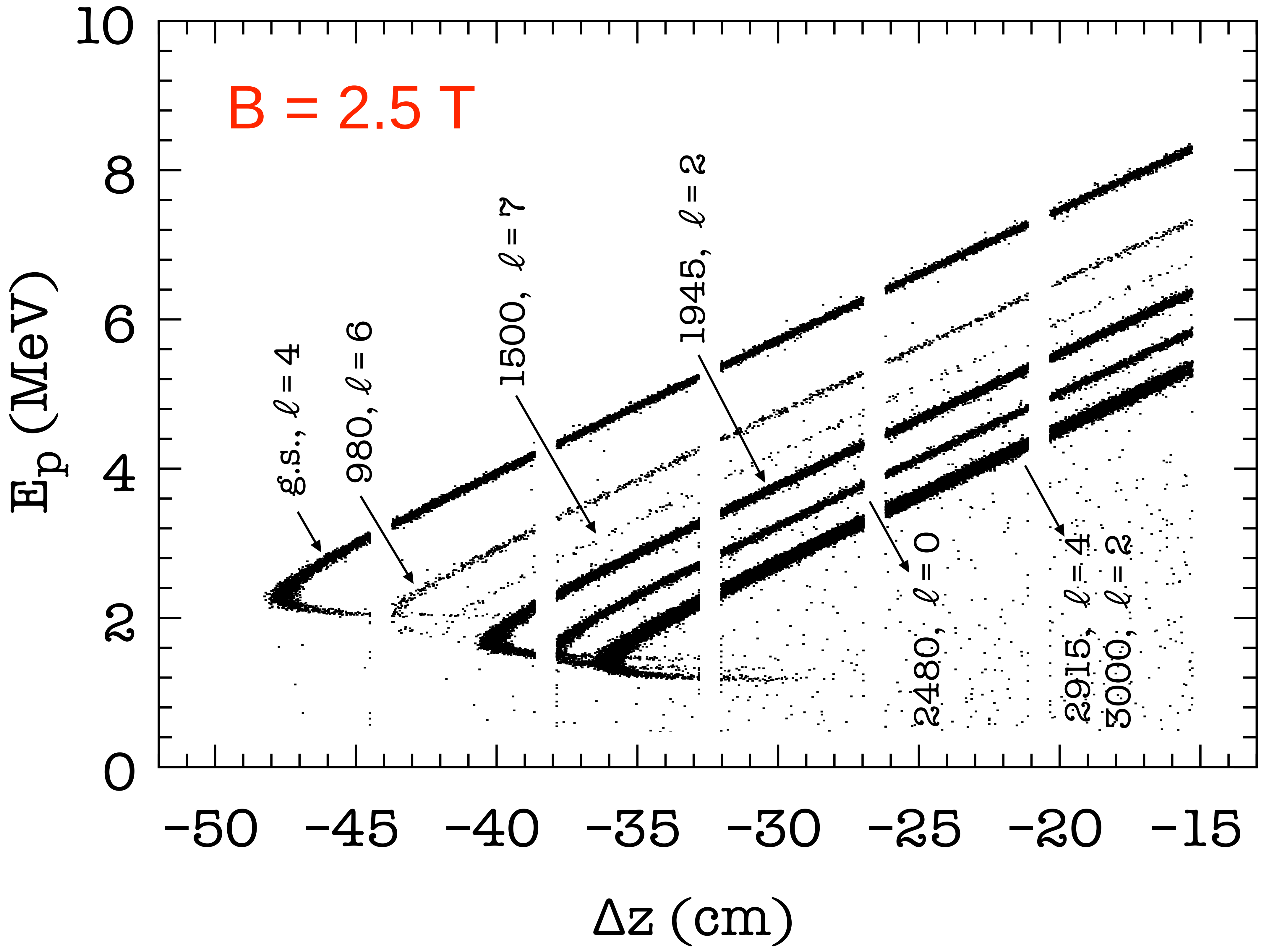
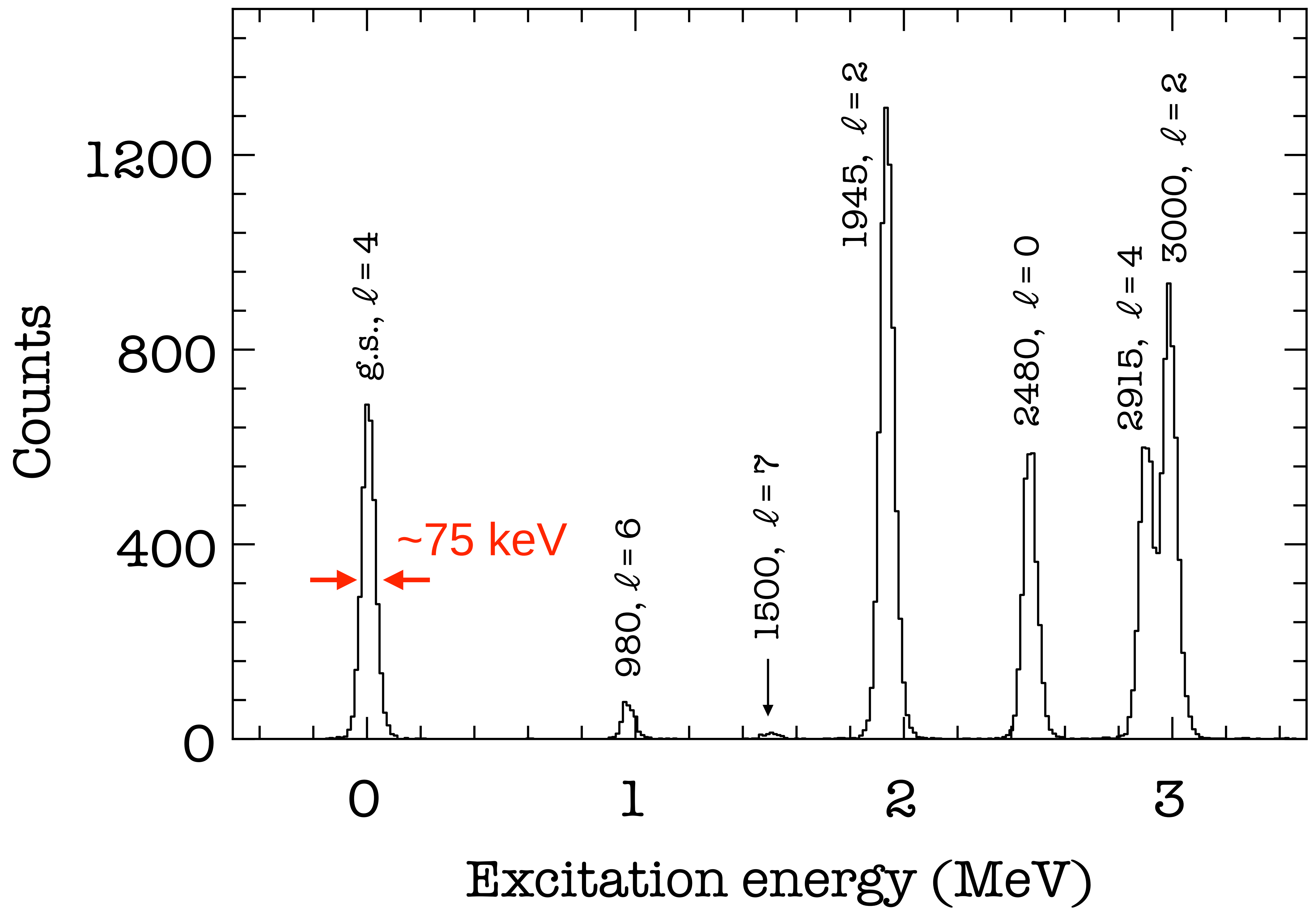
*Isomers prevalent in the region around Pb
Cross sections estimated using DWBA code Ptolemy using standard parameterizations.

The solenoidal-spectrometer technique





Simulation:

Marc Labiche, STFC Daresbury, using NPTool, assuming 40-keV intrinsic Si resolution[1] and the geometry of the ANL array, beam properties of the linac[2]. Comparable to actual performance of the HELIOS spectrometer at ANL. Location of states states in ^{207}Hg estimated from Woods-Saxon calculations[3].

[1] Mean value for ANL Si array, J. C. Lighthall et al., Nucl. Instrum. Methods Phys. Res. A 622, 97 (2010).

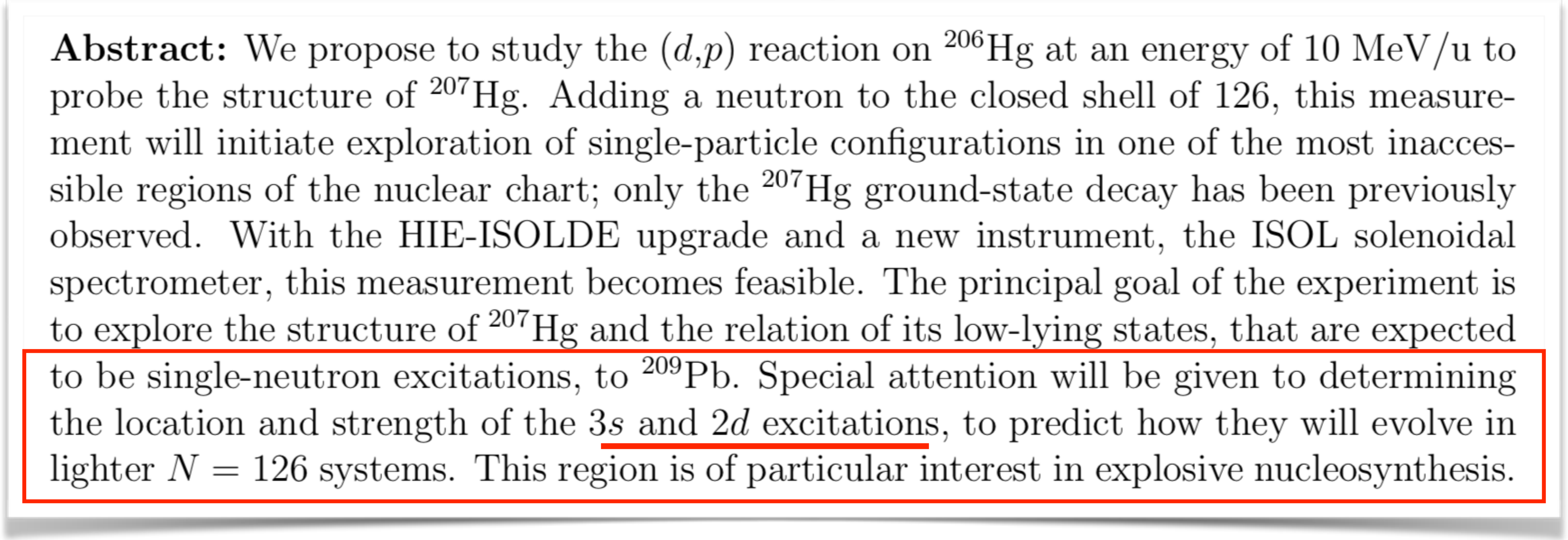
[2] Beam spot: 2.3 mm FWHM, Beam divergence: 1.8 mrad, Beam energy spread: 0.26%

[3] http://www.volya.net

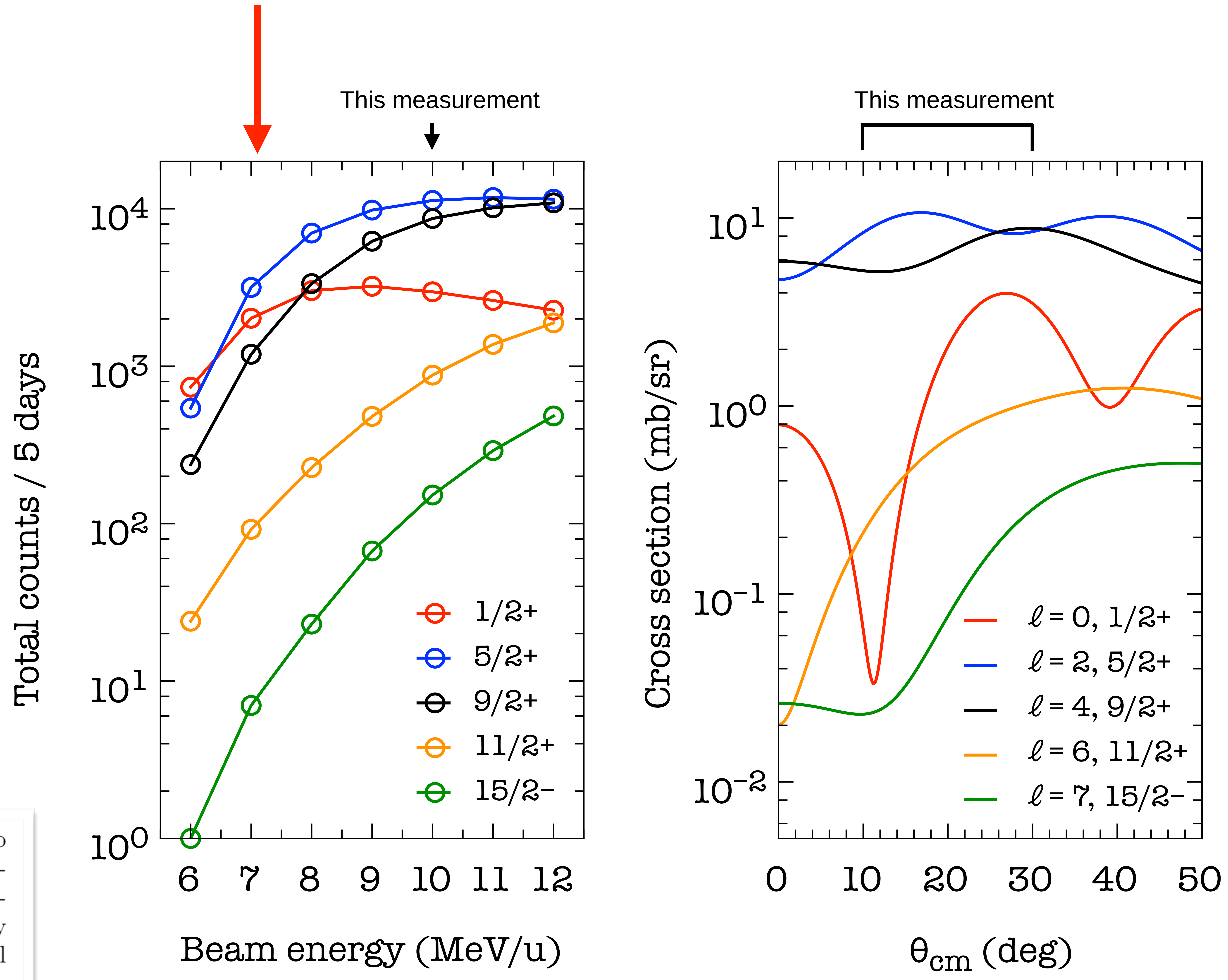
Some changes …

The beam energy will be lower than 10 MeV/u, … 9 MeV/u, … 8 MeV/u, … 7.3 MeV/u (maybe 7 MeV/u)

This is not ideal, but is just above barrier for the low-excitation energy, low-l states, which is the focus of this initial exploration of ^{207}Hg

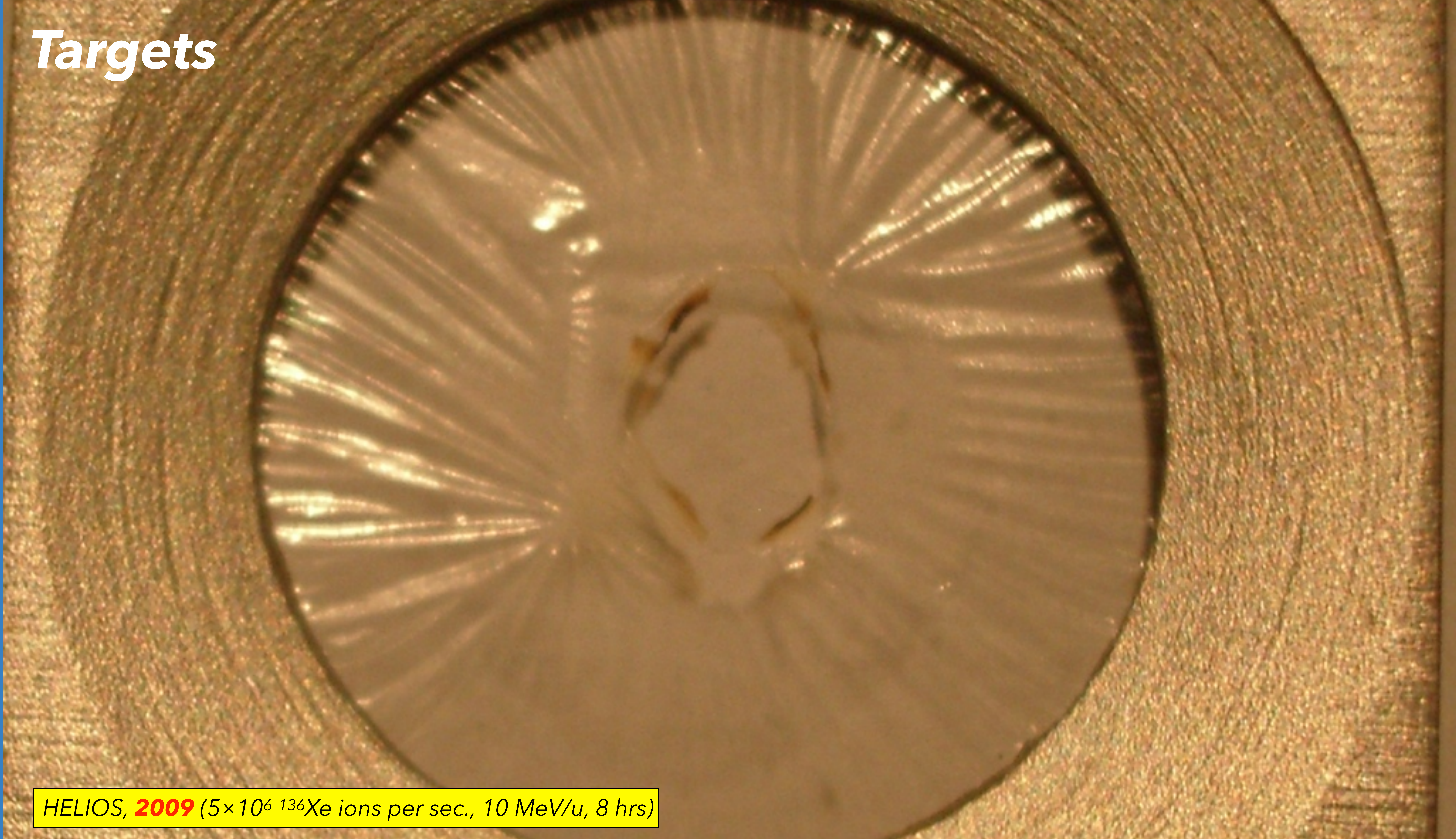


Abstract: We propose to study the (d,p) reaction on ^{206}Hg at an energy of 10 MeV/u to probe the structure of ^{207}Hg. Adding a neutron to the closed shell of 126, this measurement will initiate exploration of single-particle configurations in one of the most inaccessible regions of the nuclear chart; only the ^{207}Hg ground-state decay has been previously observed. With the HIE-ISOLDE upgrade and a new instrument, the ISOL solenoidal spectrometer, this measurement becomes feasible. The principal goal of the experiment is to explore the structure of ^{207}Hg and the relation of its low-lying states, that are expected to be single-neutron excitations, to ^{209}Pb. Special attention will be given to determining the location and strength of the $3s$ and $2d$ excitations, to predict how they will evolve in lighter $N = 126$ systems. This region is of particular interest in explosive nucleosynthesis.



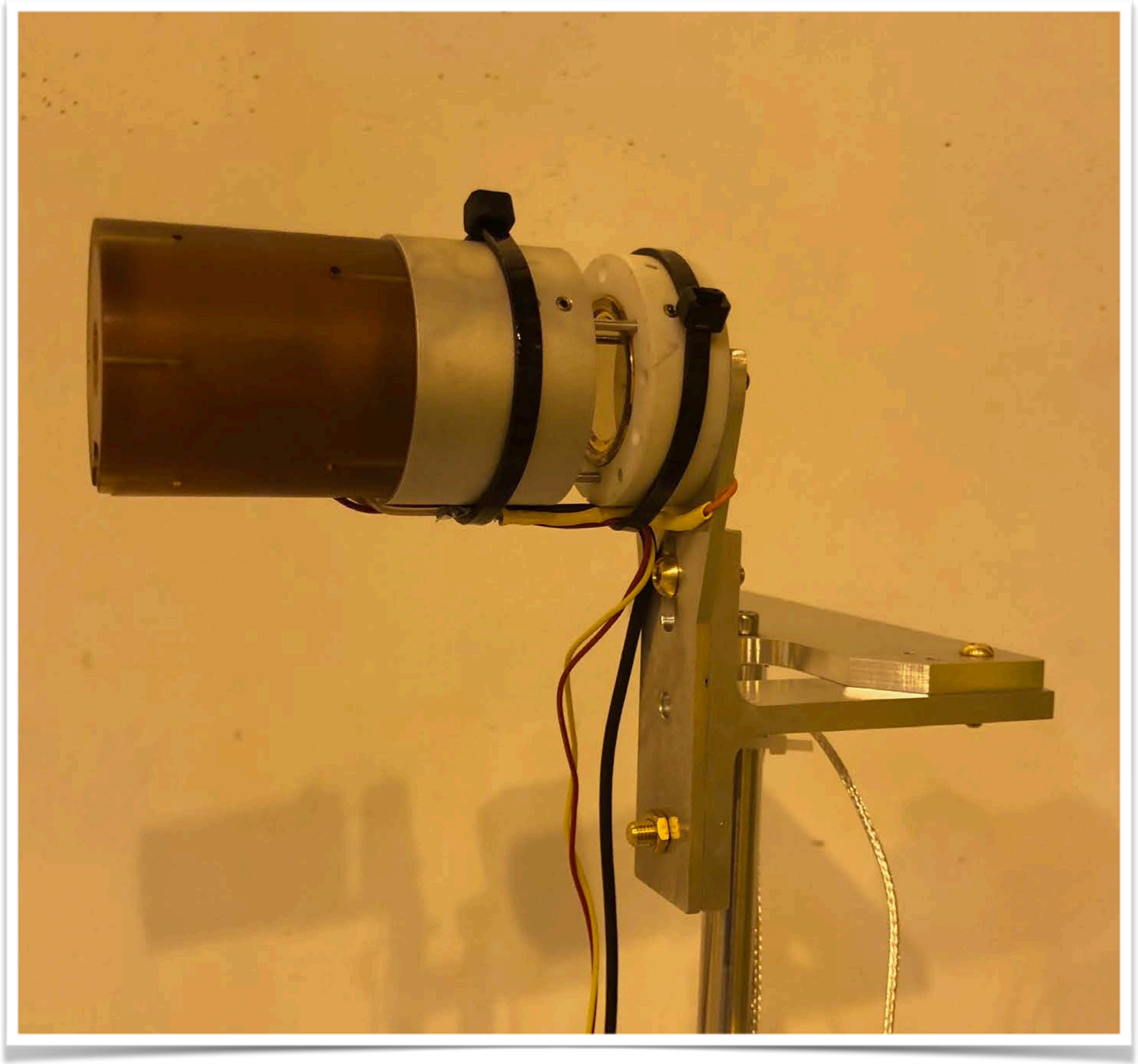
ADs for l=0,2 and 4 still distinct at 7 MeV/u, and still relatively forward focused

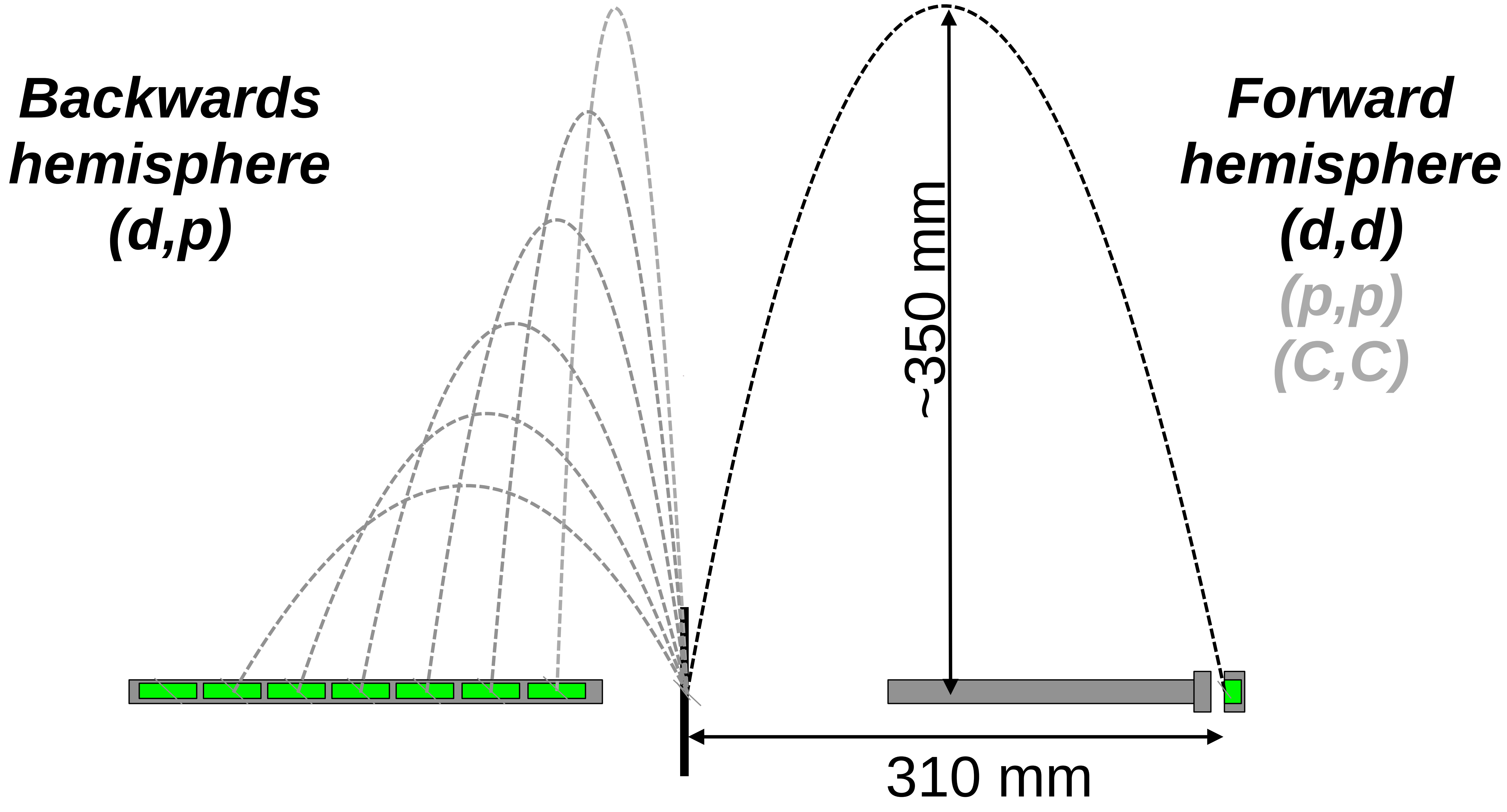
Targets



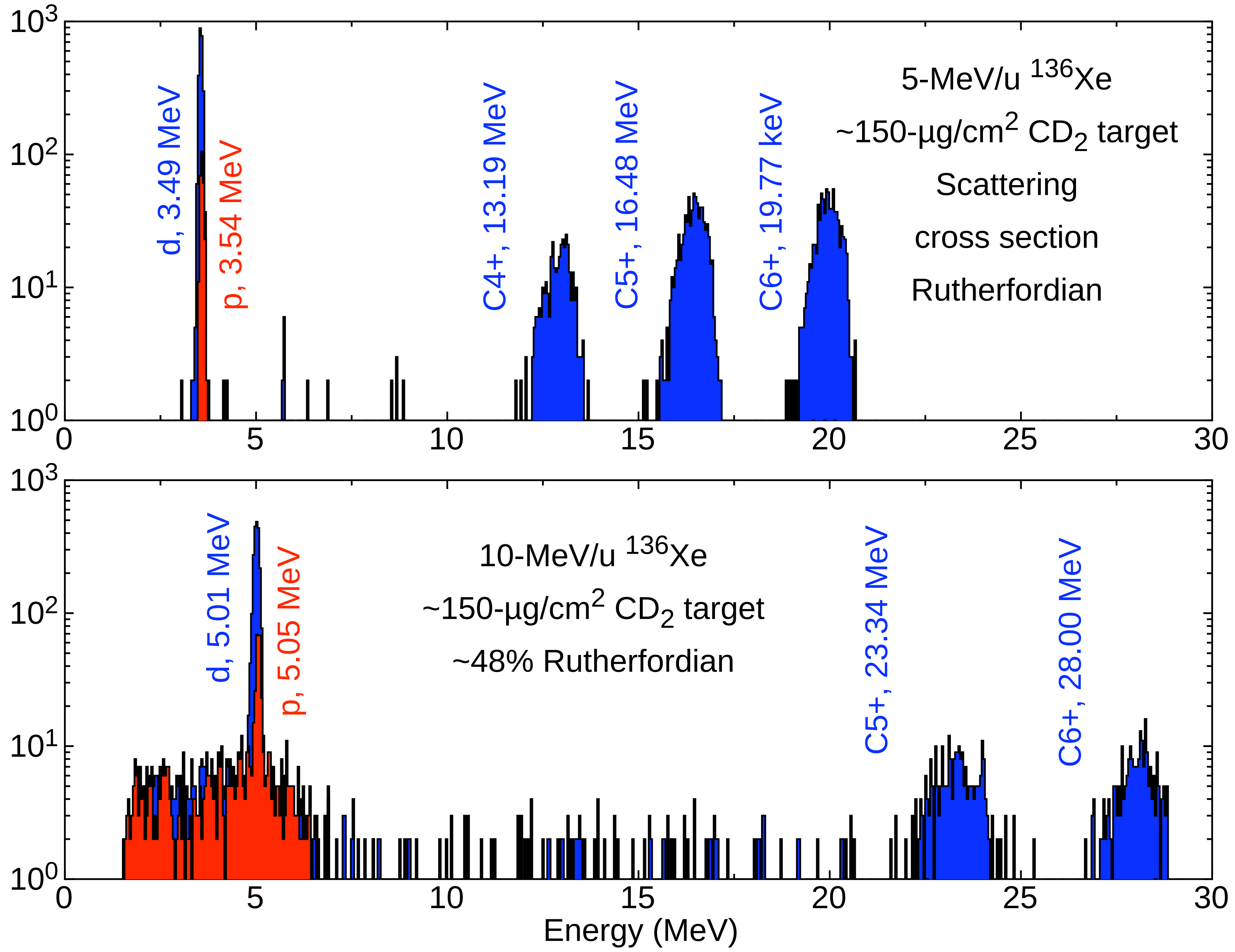
*HELIOS, **2009** (5×10^{6} ^{136}Xe ions per sec., 10 MeV/u, 8 hrs)*

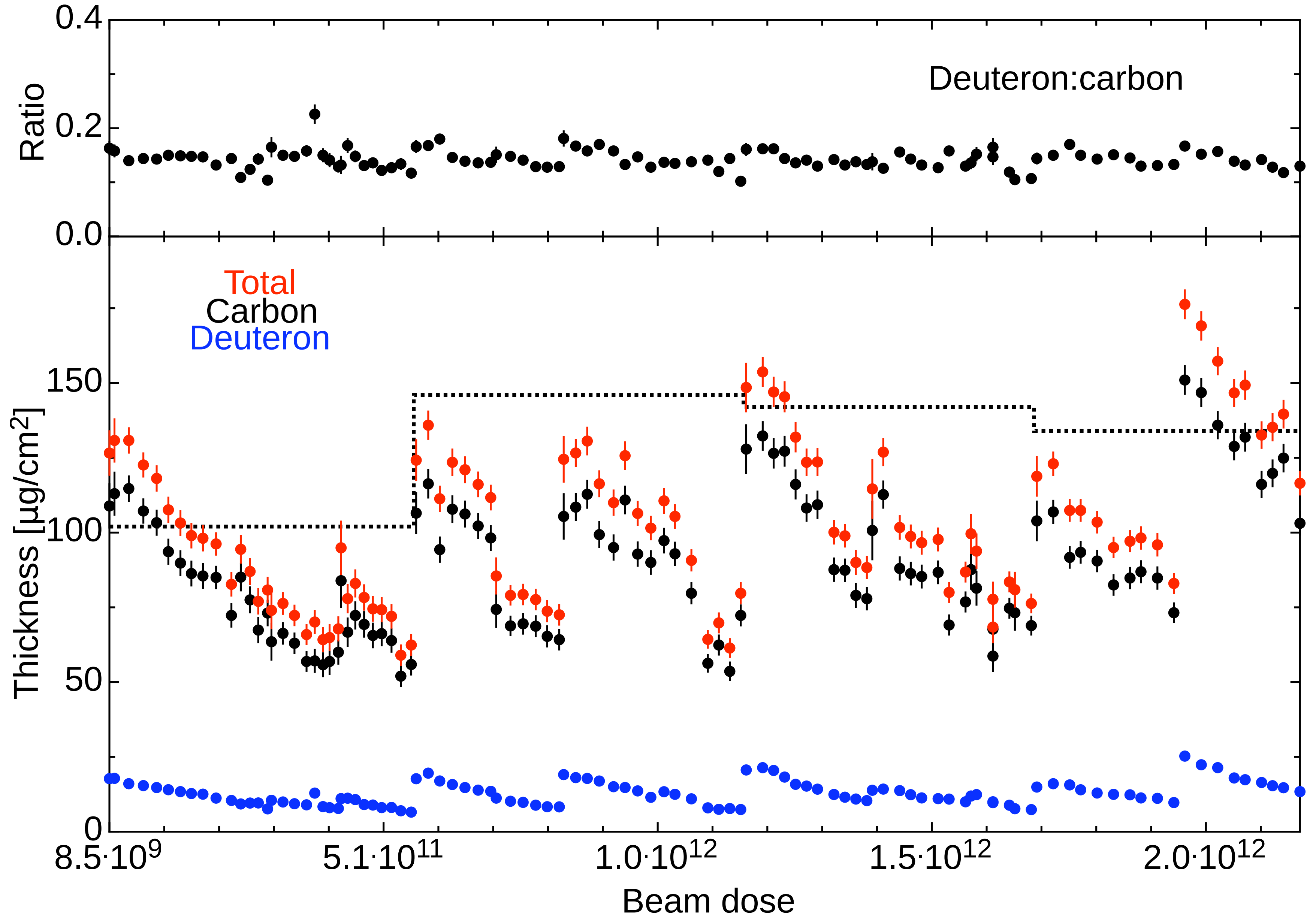
“ELUM” (luminosity detector)

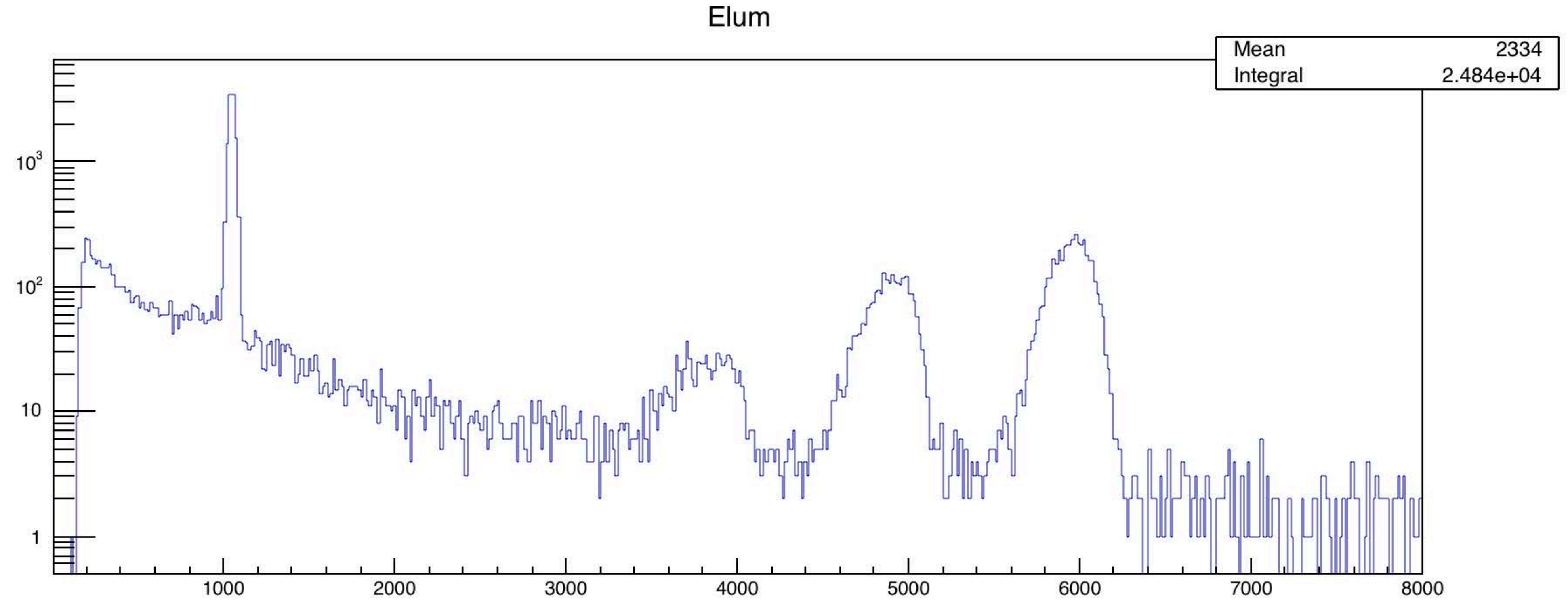


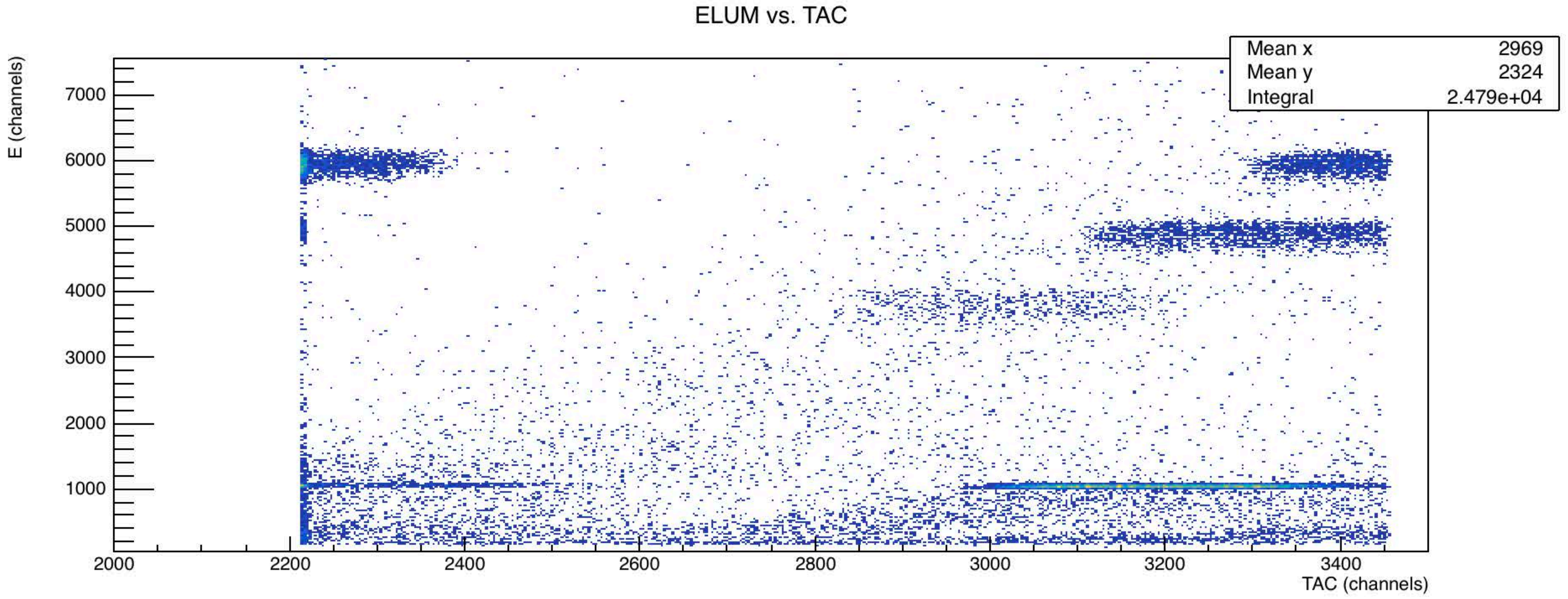


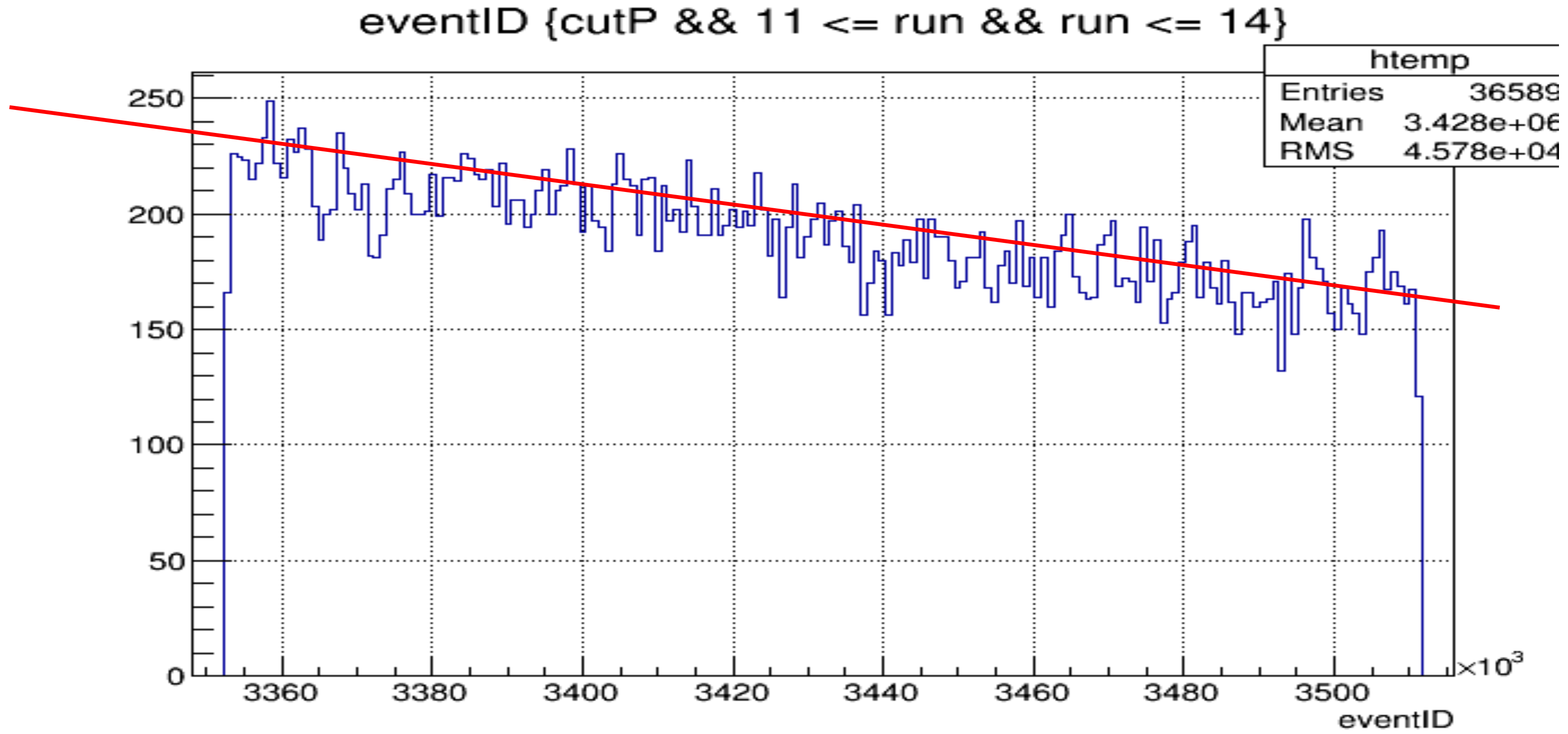
Target degradation

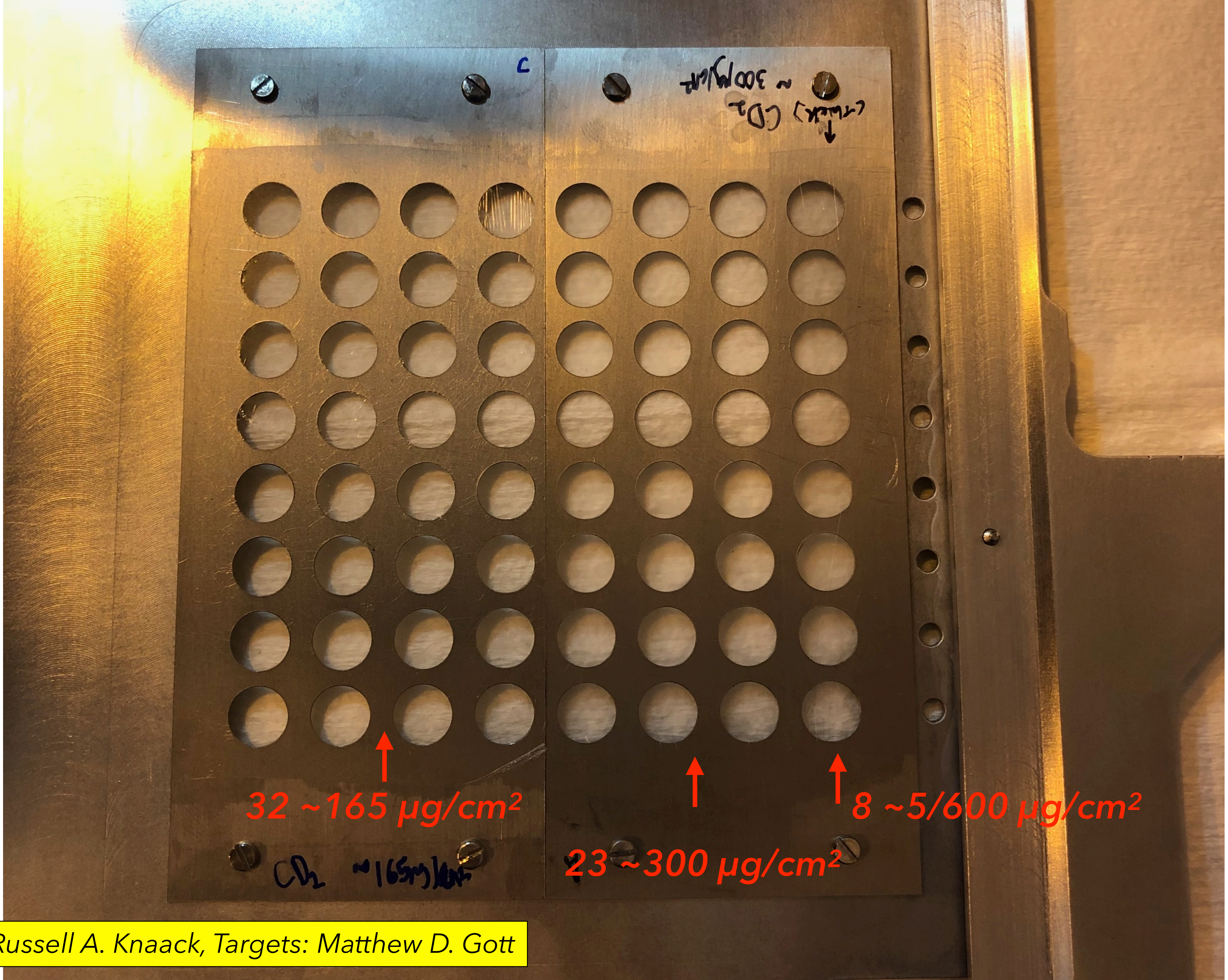












32 ~165 μg/cm^2

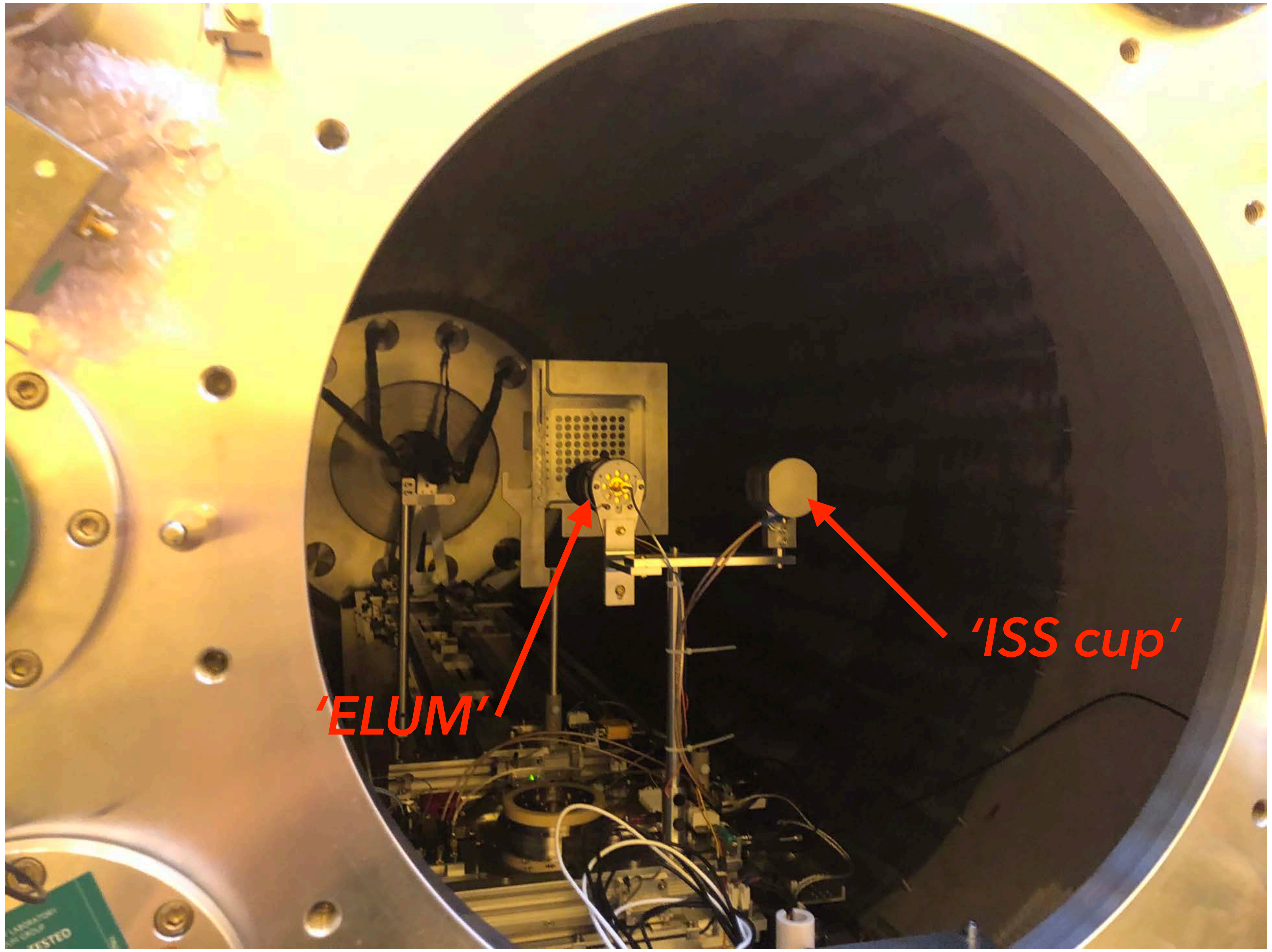
23 ~300 μg/cm^2

8 ~5/600 μg/cm^2

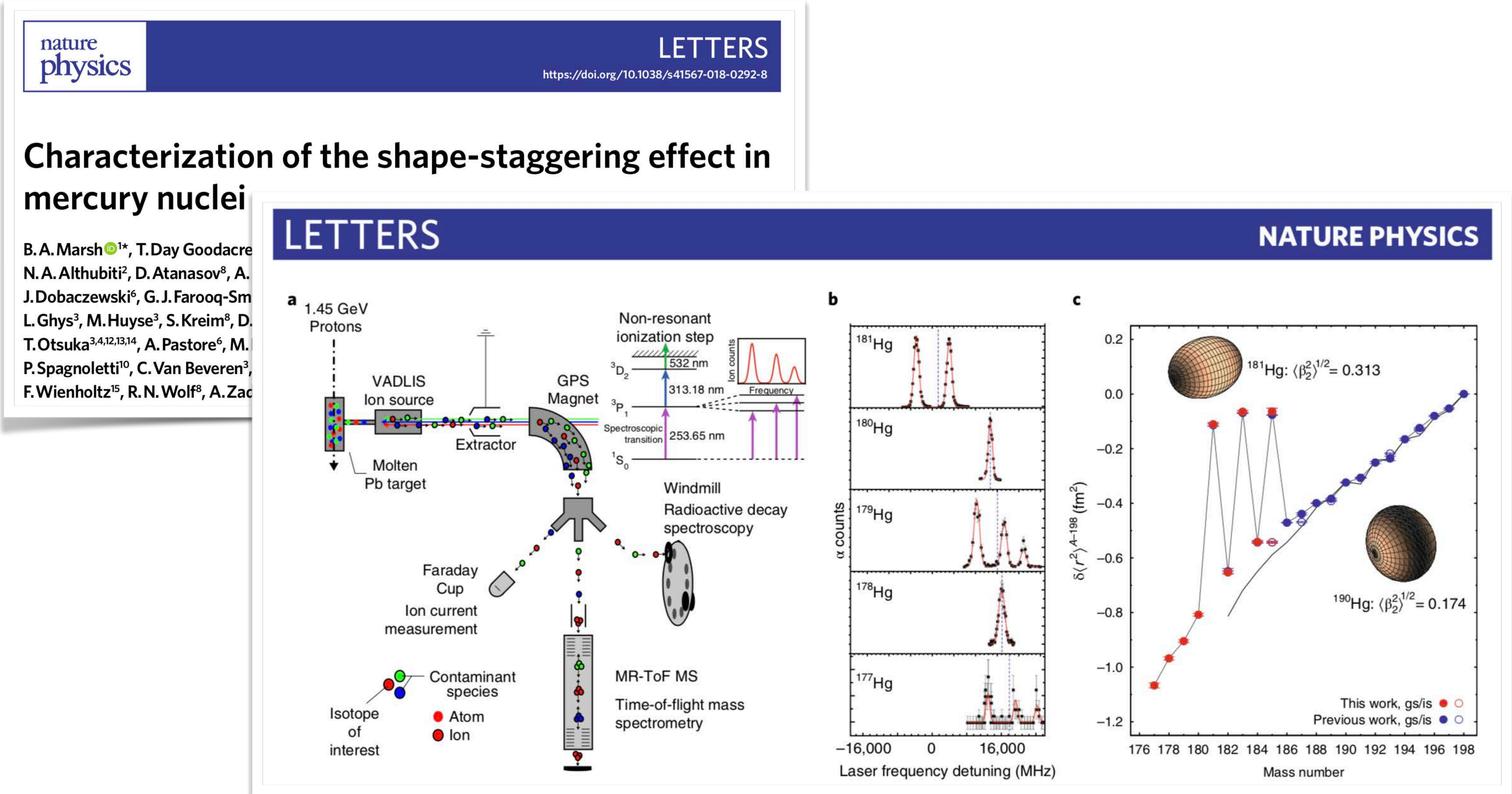
Mechanical: Russell A. Knaack, Targets: Matthew D. Gott

Cups, tuning, luminosity

We had two cups, one as part of the luminosity detector, the other the ISS standard



ISOLDE and Hg beams



nature physics

LETTERS

https://doi.org/10.1038/s41567-018-0292-8

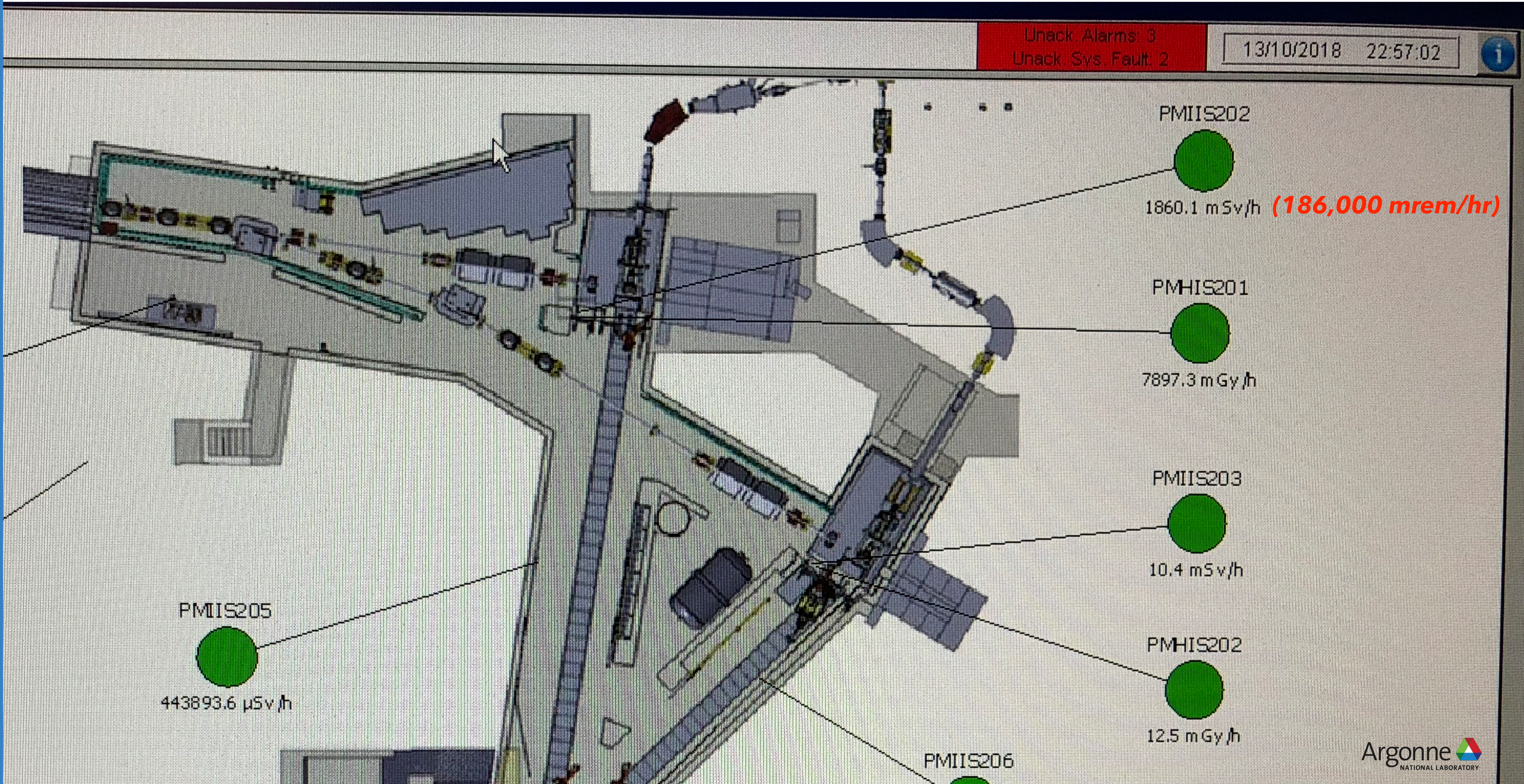
Characterization of the shape-staggering effect in mercury nuclei

B. A. Marsh[1*], T. Day Goodacre
N. A. Althubiti[2], D. Atanasov[8], A.
J. Dobaczewski[6], G. J. Farooq-Sm
L. Ghys[3], M. Huyse[3], S. Kreim[8], D.
T. Otsuka[3,4,12,13,14], A. Pastore[6], M.
P. Spagnoletti[10], C. Van Beveren[3],
F. Wienholtz[15], R. N. Wolf[8], A. Zad

LETTERS NATURE PHYSICS

*Nature Physics, October 10, **2018***

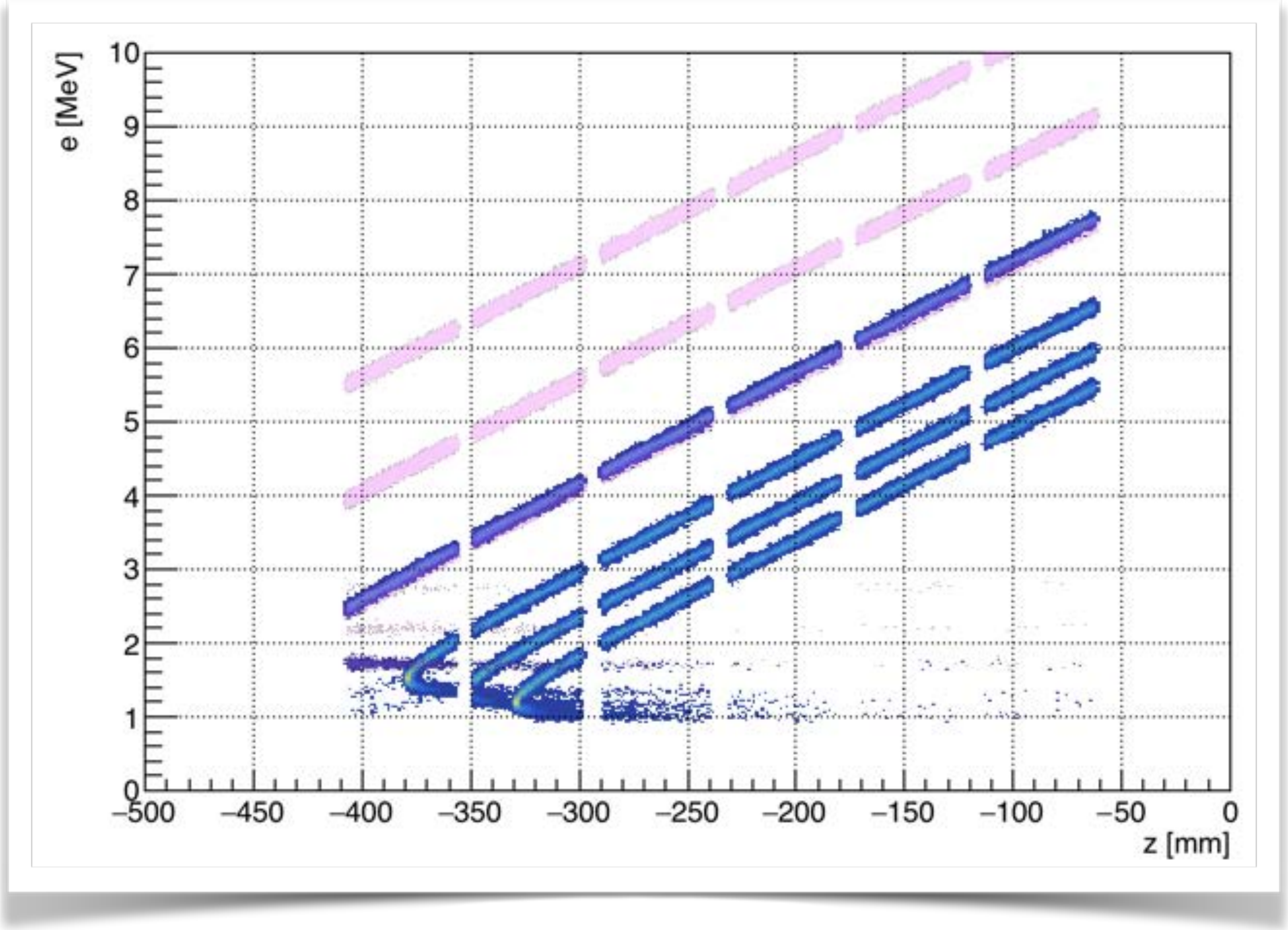
ISS at ISOLDE

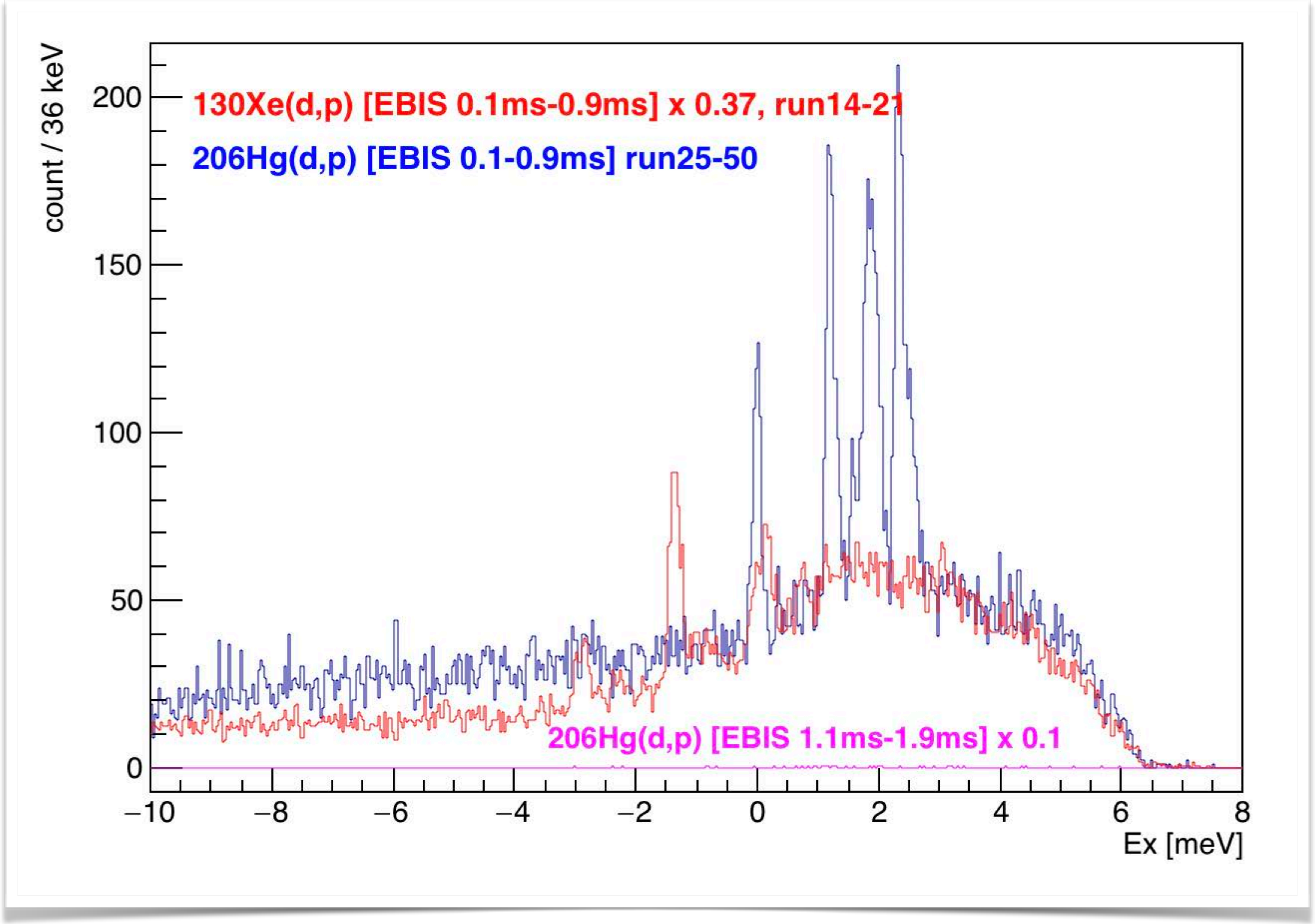


(186,000 mrem/hr)

Xe in the vacuum, ^{130}Xe(29+) *[^{206}Hg(46+)]*

Transpired to be negligible, but initial concerns it was substantial
… <few thousand ions per second





(We had studied ^{130}Xe(d,p) with HELIOS in 2009)

OR …

A study of the hitherto unknown single-neutron structure of ^{207}Hg was carried out using a ***7.4 MeV/u ^{206}Hg beam*** and the ***ISOLDE Solenoidal Spectrometer*** to momentum analyze the protons following the neutron-adding (*d*,*p*) reaction

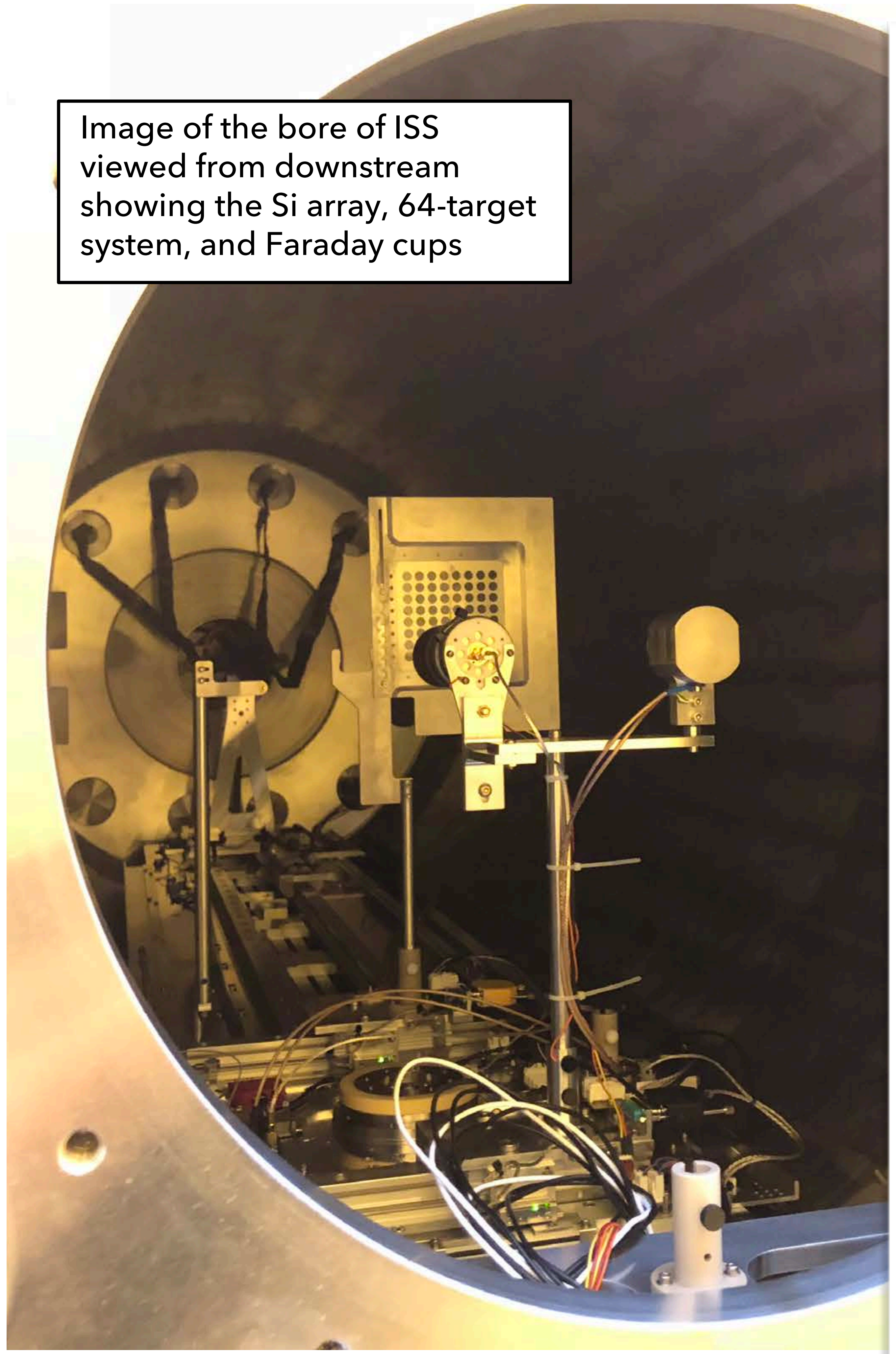
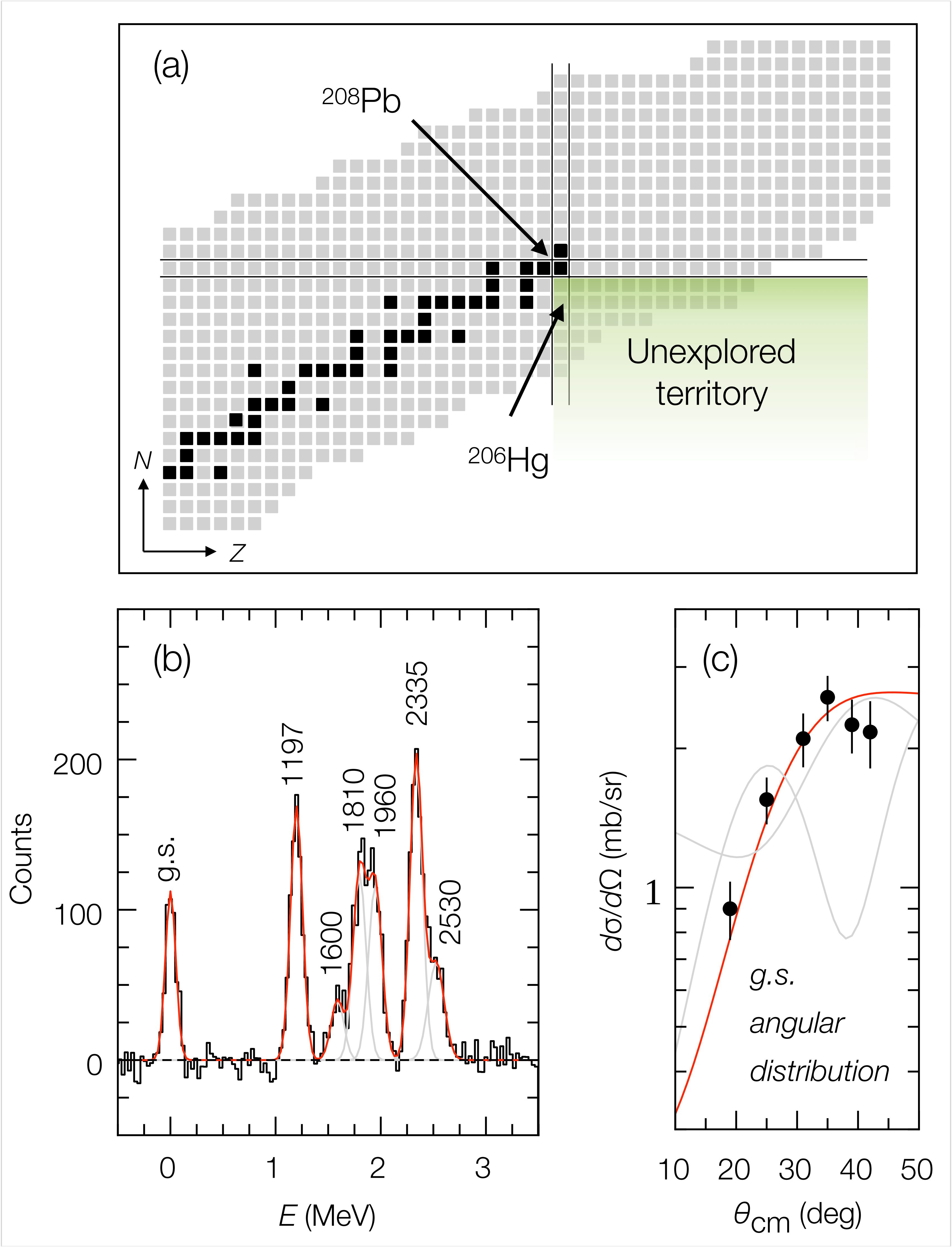


Image of the bore of ISS viewed from downstream showing the Si array, 64-target system, and Faraday cups



First exploration of single-particle states outside *N* = 126, south of Pb, made possible by ISS.

Experimental info:

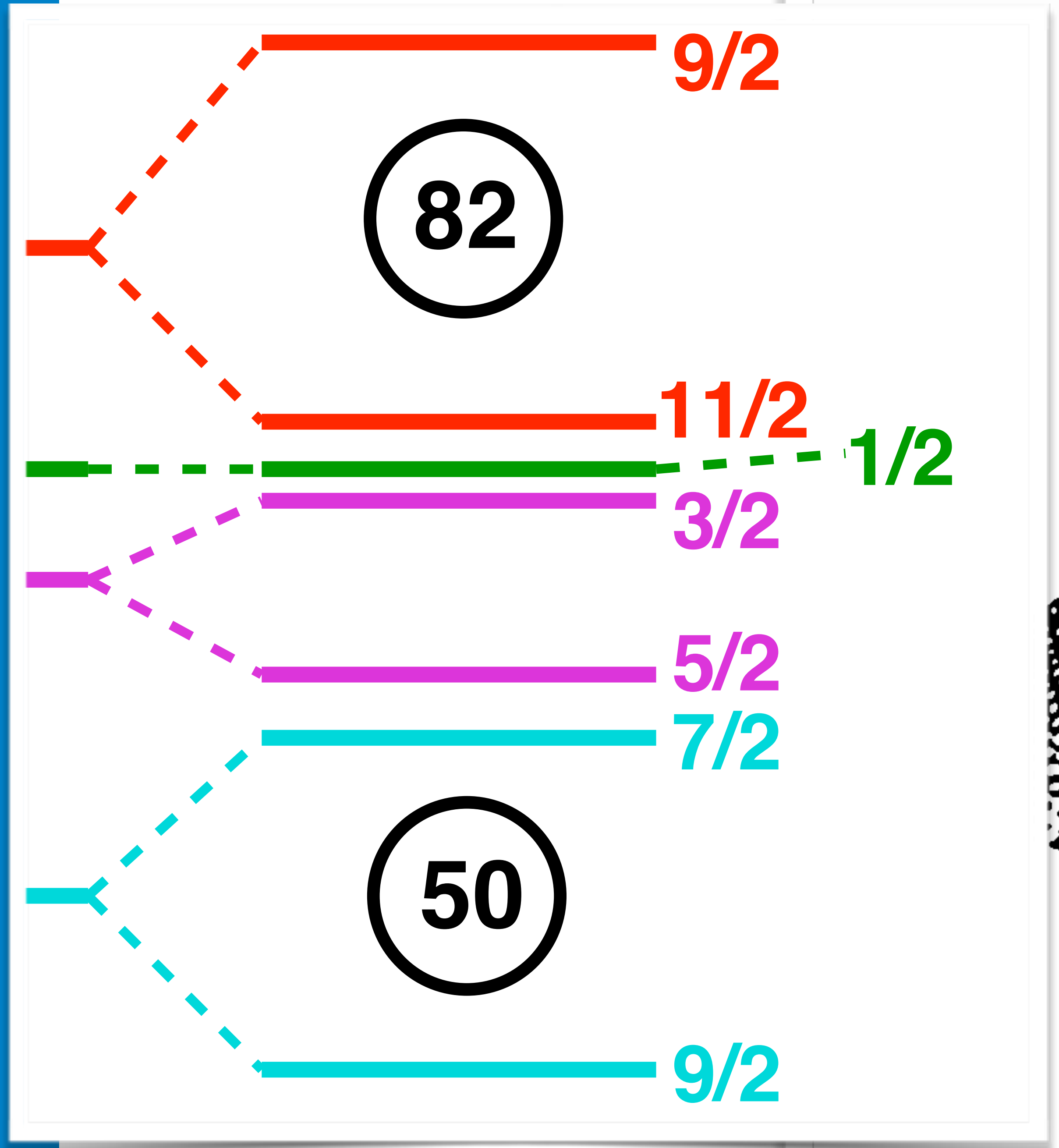
- ~***5×10^5 ions per second*** of ^{206}Hg for ~***82 hours***
- Beam ***purity of >98%***
- Measured in singles mode
- Using ***>30*** deuterated polyethylene ***targets*** of thickness around 165 μg/cm^2 (to deal with target degradation)
- ISS set to a B-field of 2.5 T

*Tang, Kay et al., (**2018**)*

Example 3 – N = 20 isotones

Requires a little setup, so please be patient

Electron scattering, charge density (remember sizes?!)



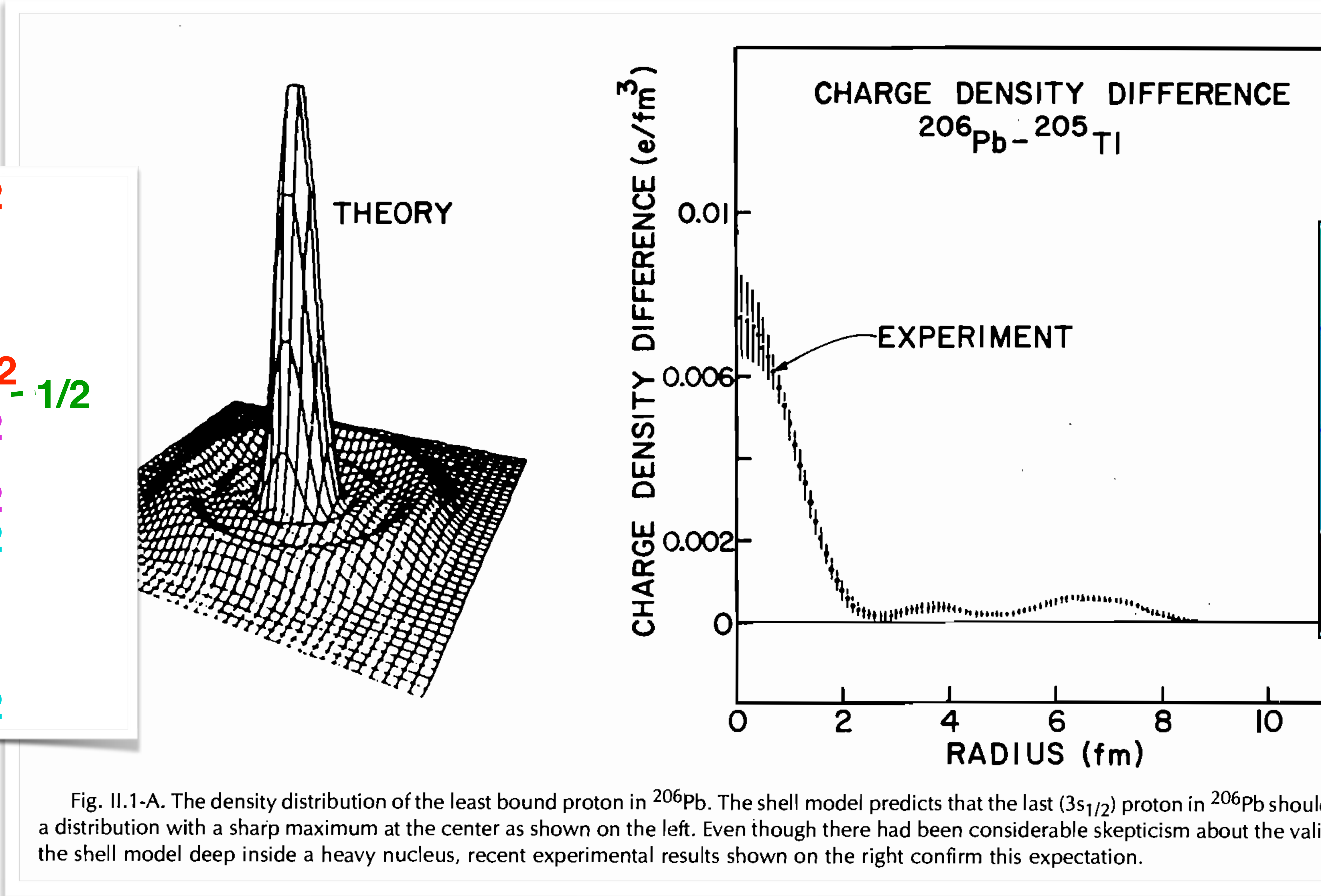
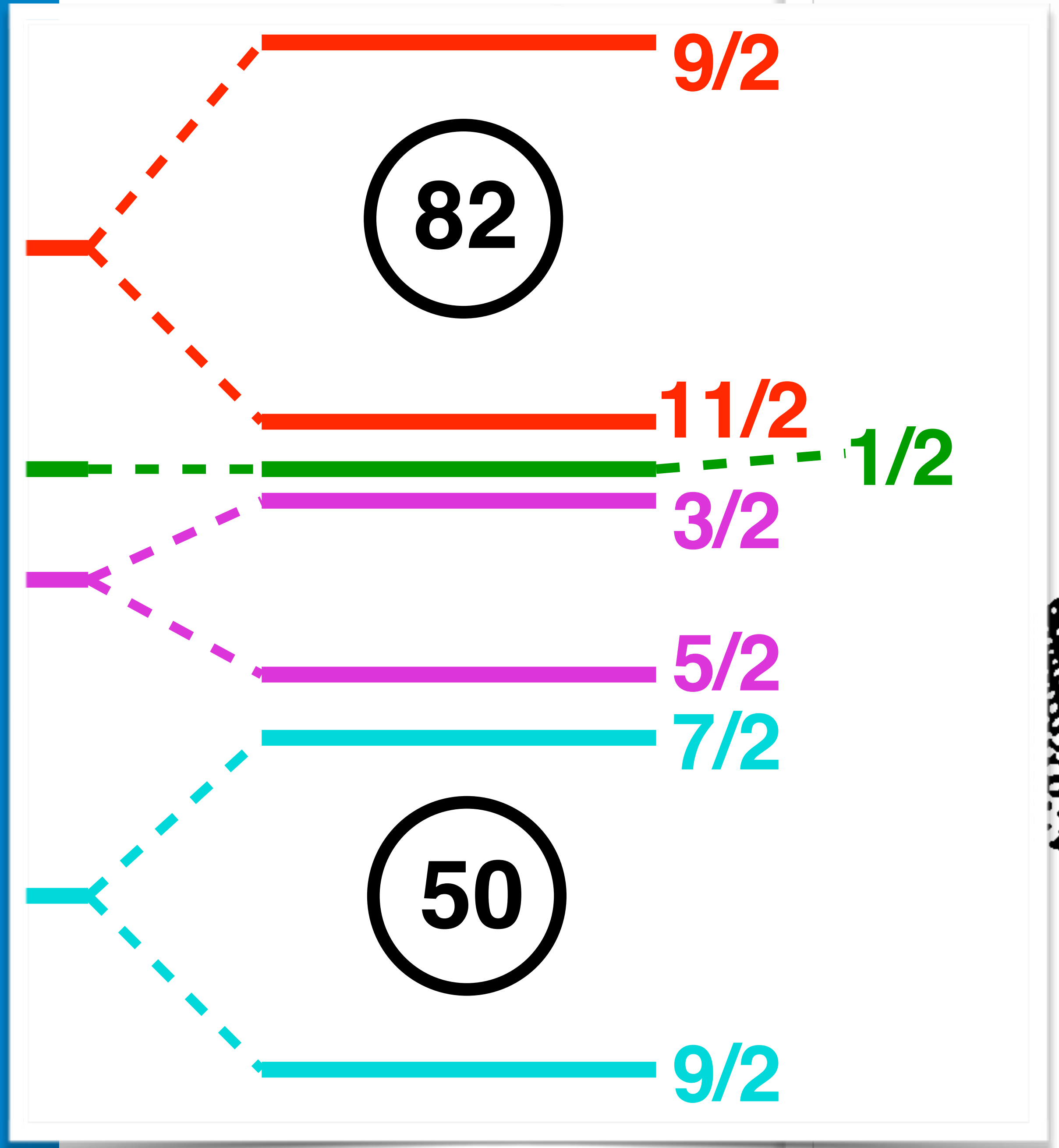


Fig. II.1-A. The density distribution of the least bound proton in ^{206}Pb. The shell model predicts that the last ($3s_{1/2}$) proton in ^{206}Pb should have a distribution with a sharp maximum at the center as shown on the left. Even though there had been considerable skepticism about the validity of the shell model deep inside a heavy nucleus, recent experimental results shown on the right confirm this expectation.

205Bi	206Bi	207Bi	208Bi	209Bi
204Pb	205Pb	206Pb	207Pb	208Pb
203Tl	204Tl	205Tl	206Tl	207Tl
202Hg	203Hg	204Hg	205Hg	206Hg

From 1983 NSAC Long Range Plan referring to J. M. Cavedon et al., Phys. Rev. Lett. ***49****, 978 (****1982****)*

Electron scattering, charge density (remember sizes?!)



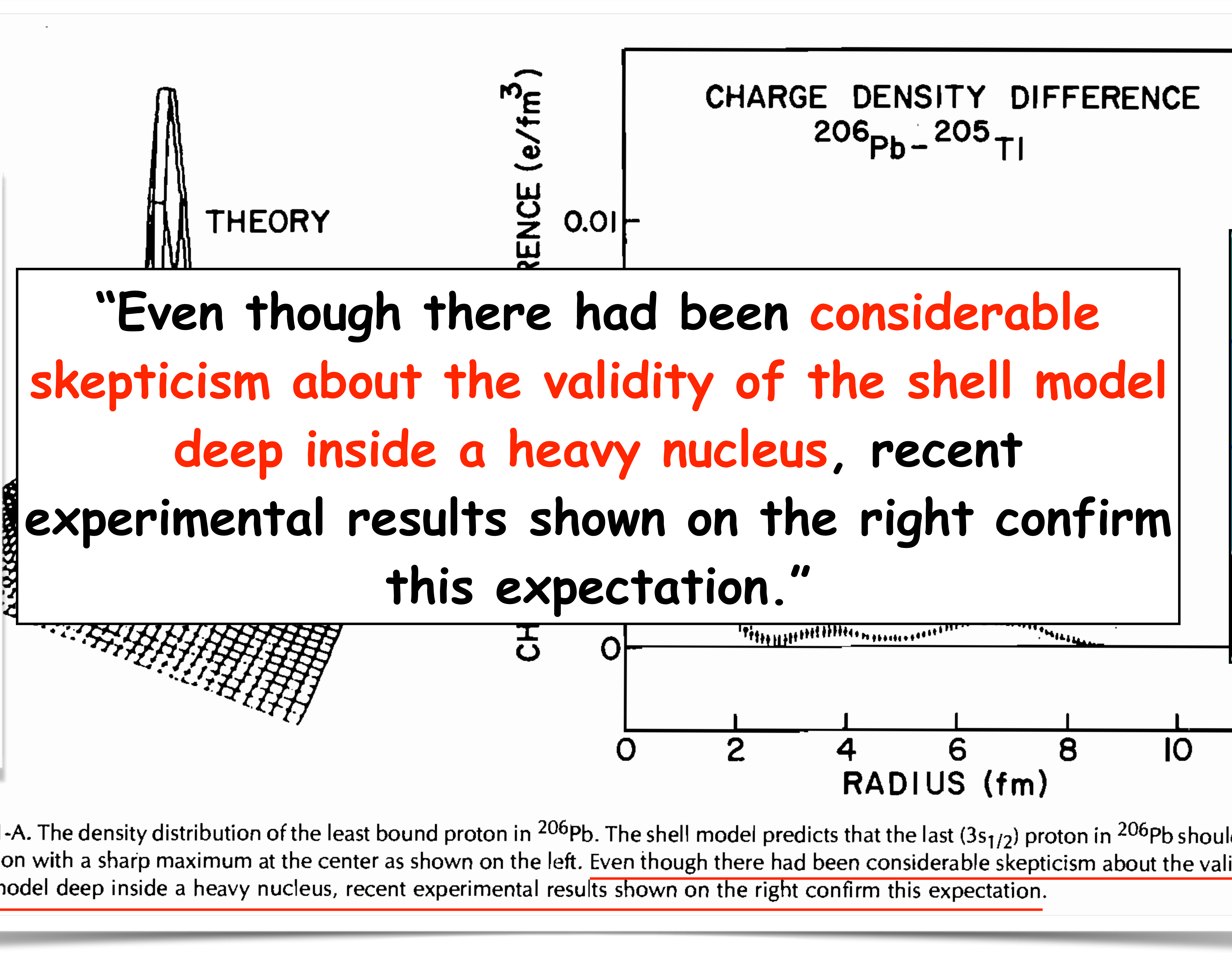


Fig. II.1-A. The density distribution of the least bound proton in ^{206}Pb. The shell model predicts that the last ($3s_{1/2}$) proton in ^{206}Pb should have a distribution with a sharp maximum at the center as shown on the left. Even though there had been considerable skepticism about the validity of the shell model deep inside a heavy nucleus, recent experimental results shown on the right confirm this expectation.

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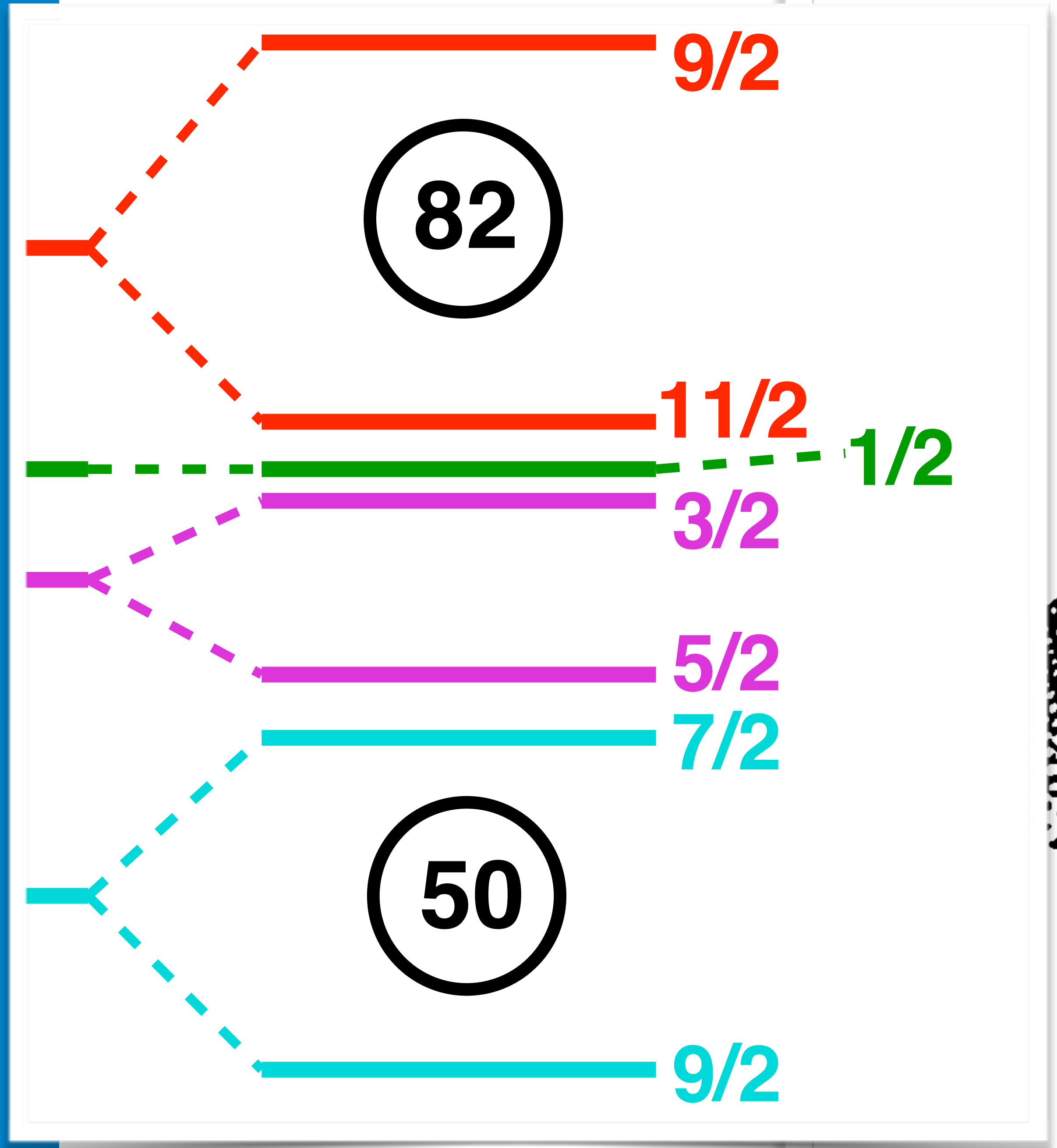
Electron scatte mber sizes?!)



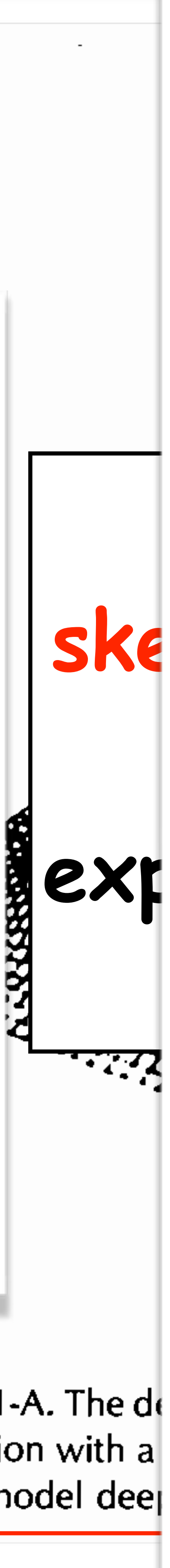

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Fig. II.1-A. The d
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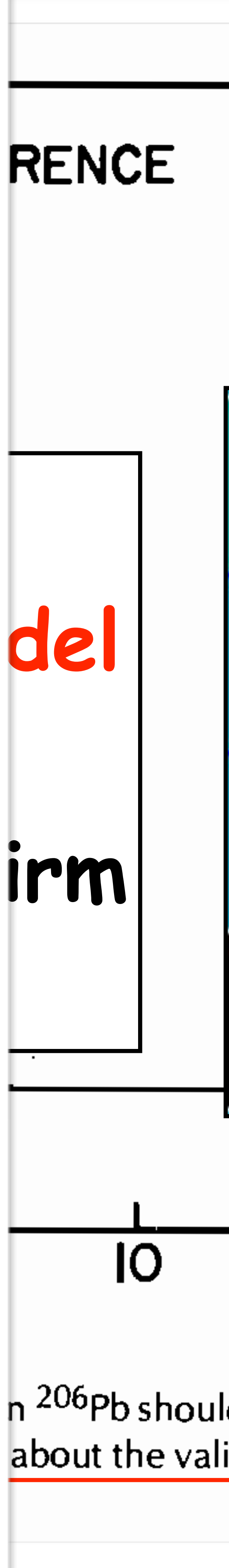
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n ^{206}Pb should have
about the validity of

205Bi	206Bi	207Bi	208Bi	209Bi
204Pb	205Pb	206Pb	207Pb	208Pb
203Tl	204Tl	205Tl	206Tl	207Tl
202Hg	203Hg	204Hg	205Hg	206Hg

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In the vicinity of ^{34}Si

Why could ^{34}Si be a bubble nucleus? And what can reactions tell us?

Z = 20

		36Sc	37Sc	38Sc	39Sc	40Sc	41Sc	42Sc	43Sc	44Sc	45Sc	46Sc	47Sc	48Sc	49Sc	50Sc
	34Ca	35Ca	36Ca	37Ca	38Ca	39Ca	40Ca	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca	49Ca
32K	33K	34K	35K	36K	37K	38K	39K	40K	41K	42K	43K	44K	45K	46K	47K	48K
31Ar	32Ar	33Ar	34Ar	35Ar	36Ar	37Ar	38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar	45Ar	46Ar	47Ar
30Cl	31Cl	32Cl	33Cl	34Cl	35Cl	36Cl	37Cl	38Cl	39Cl	40Cl	41Cl	42Cl	43Cl	44Cl	45Cl	46Cl
29S	30S	31S	32S	33S	34S	35S	36S	37S	38S	39S	40S	41S	42S	43S	44S	45S
28P	29P	30P	31P	32P	33P	34P	35P	36P	37P	38P	39P	40P	41P	42P	43P	44P
27Si	28Si	29Si	30Si	31Si	32Si	33Si	34Si	35Si	36Si	37Si	38Si	39Si	40Si	41Si	42Si	43Si
26Al	27Al	28Al	29Al	30Al	31Al	32Al	33Al	34Al	35Al	36Al	37Al	38Al	39Al	40Al	41Al	42Al

N = 20

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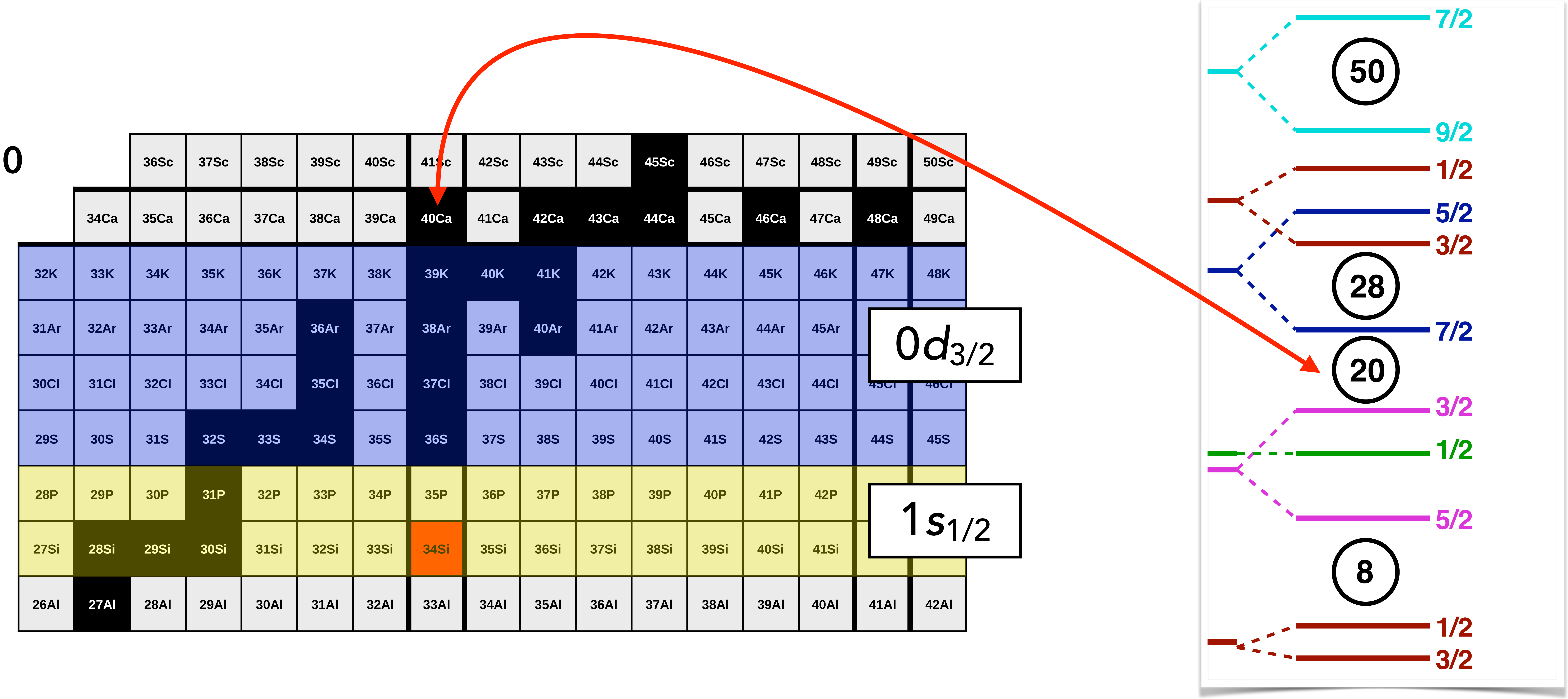


		36Sc	37Sc	38Sc	39Sc	40Sc	41Sc	42Sc	43Sc	44Sc	45Sc	46Sc	47Sc	48Sc	49Sc	50Sc
	34Ca	35Ca	36Ca	37Ca	38Ca	39Ca	40Ca	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca	49Ca
32K	33K	34K	35K	36K	37K	38K	39K	40K	41K	42K	43K	44K	45K	46K	47K	48K
31Ar	32Ar	33Ar	34Ar	35Ar	36Ar	37Ar	38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar	45Ar		
30Cl	31Cl	32Cl	33Cl	34Cl	35Cl	36Cl	37Cl	38Cl	39Cl	40Cl	41Cl	42Cl	43Cl	44Cl		
29S	30S	31S	32S	33S	34S	35S	36S	37S	38S	39S	40S	41S	42S	43S	44S	45S
28P	29P	30P	31P	32P	33P	34P	35P	36P	37P	38P	39P	40P	41P	42P		
27Si	28Si	29Si	30Si	31Si	32Si	33Si	34Si	35Si	36Si	37Si	38Si	39Si	40Si	41Si		
26Al	27Al	28Al	29Al	30Al	31Al	32Al	33Al	34Al	35Al	36Al	37Al	38Al	39Al	40Al	41Al	42Al

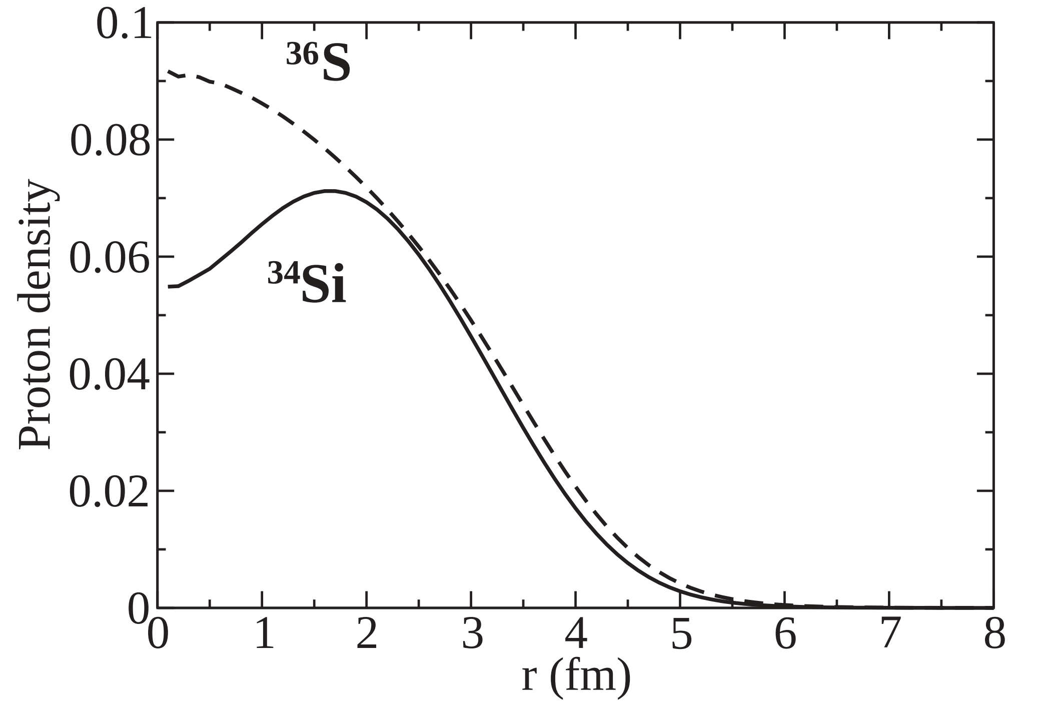
$0d_{3/2}$

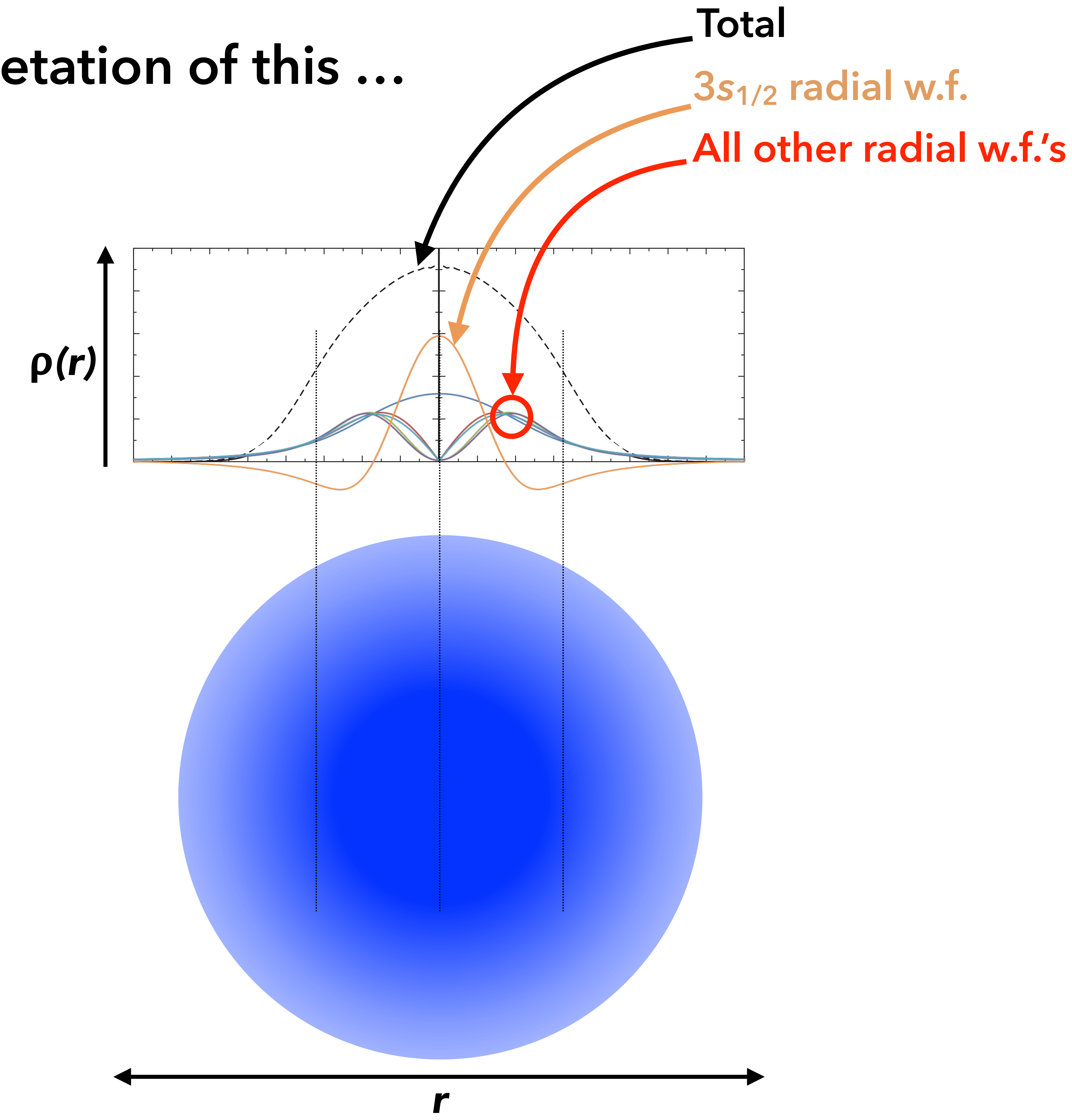
$1s_{1/2}$

N = 20

Central density

A (bad) cartoon interpretation of this …



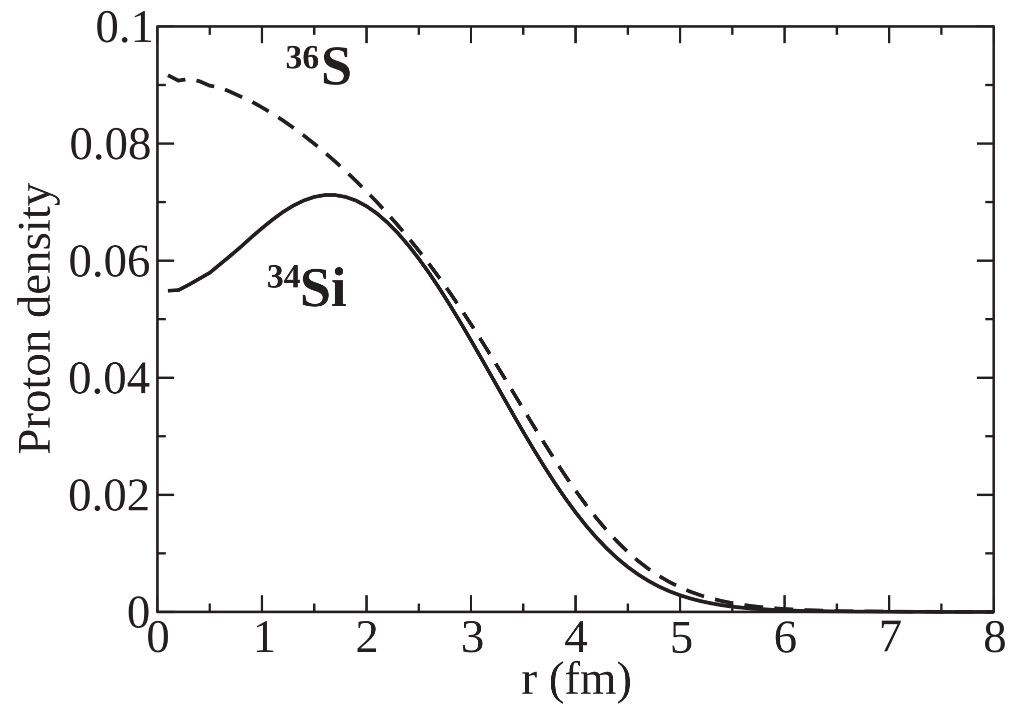


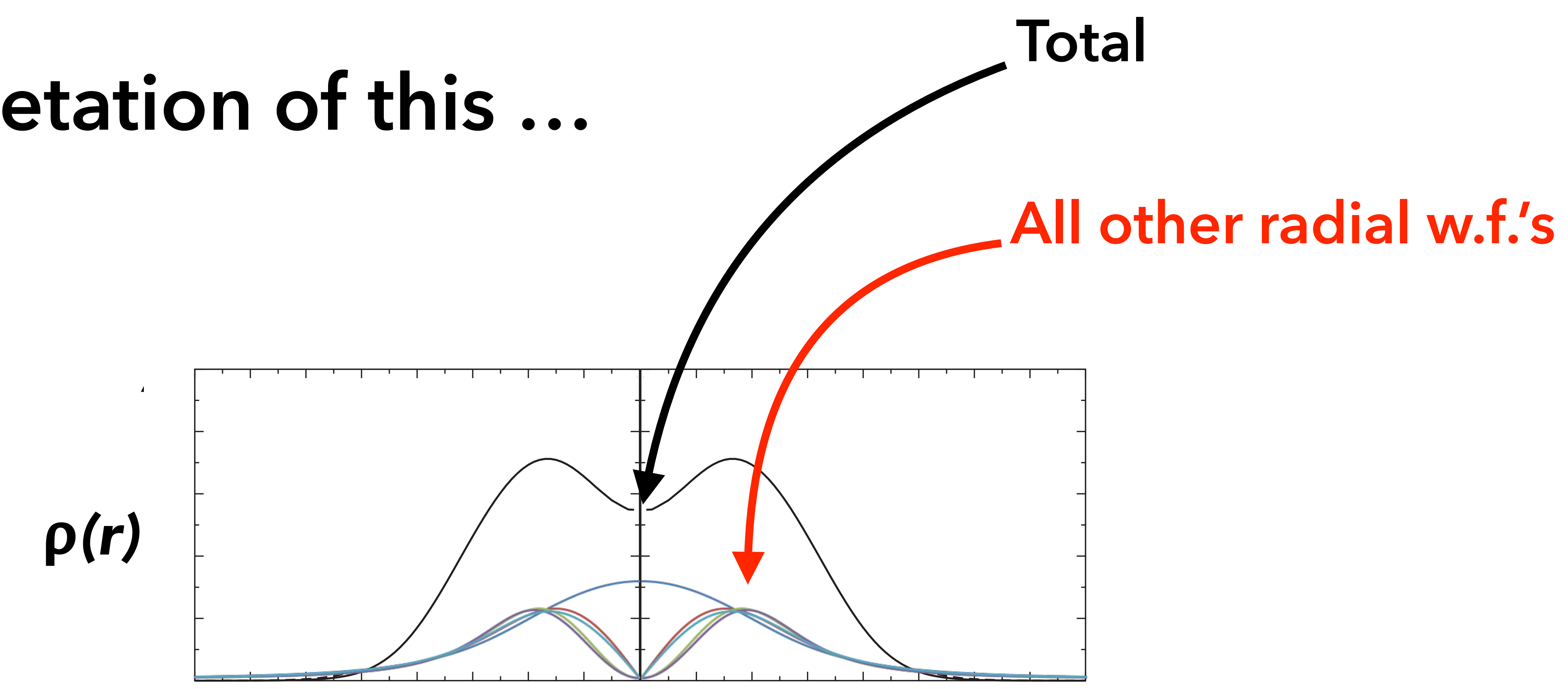
density, slice thru middle

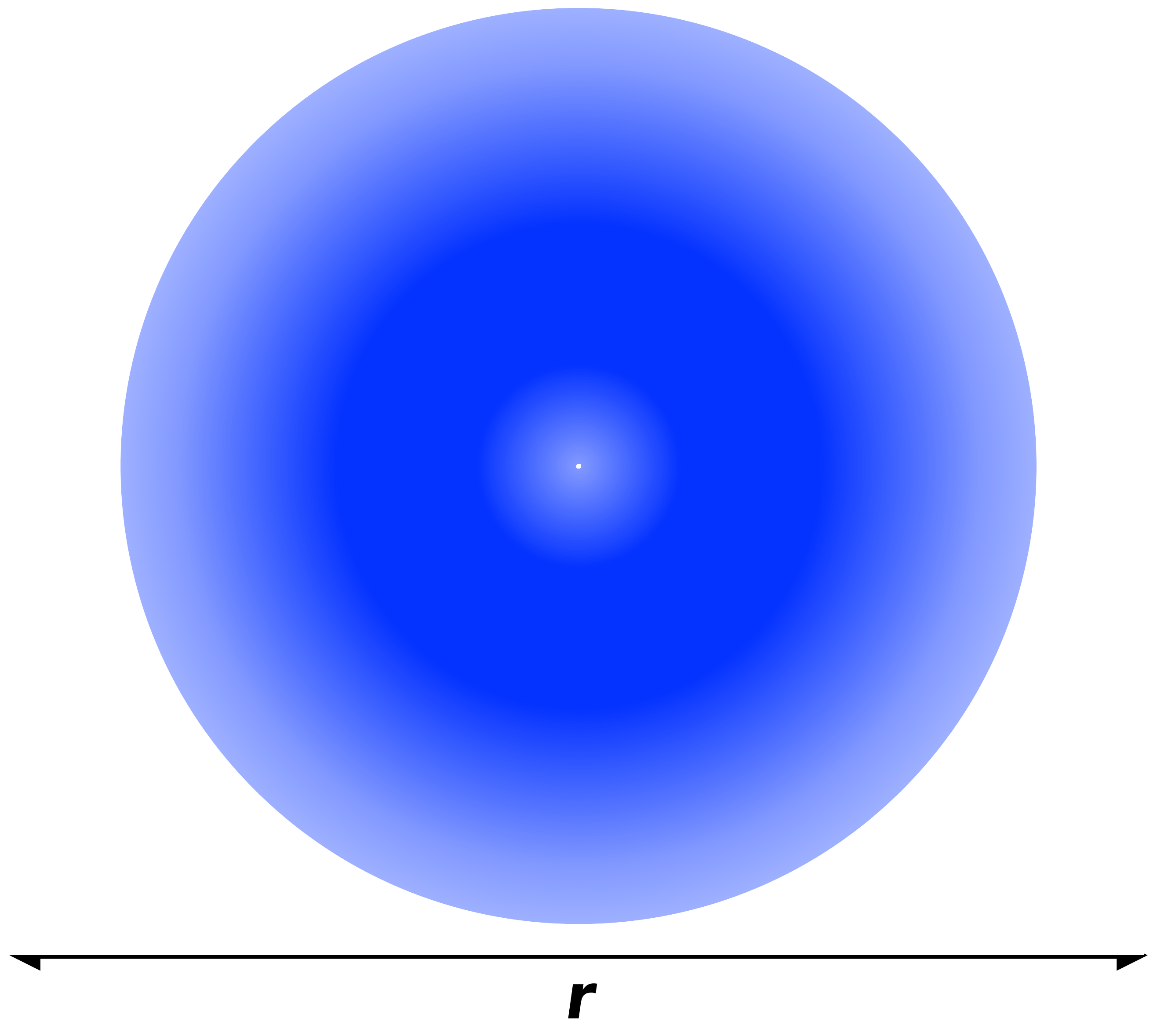
(dark=dense, less dark=less so

Central density

A (bad) cartoon interpretation of this …







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Central density

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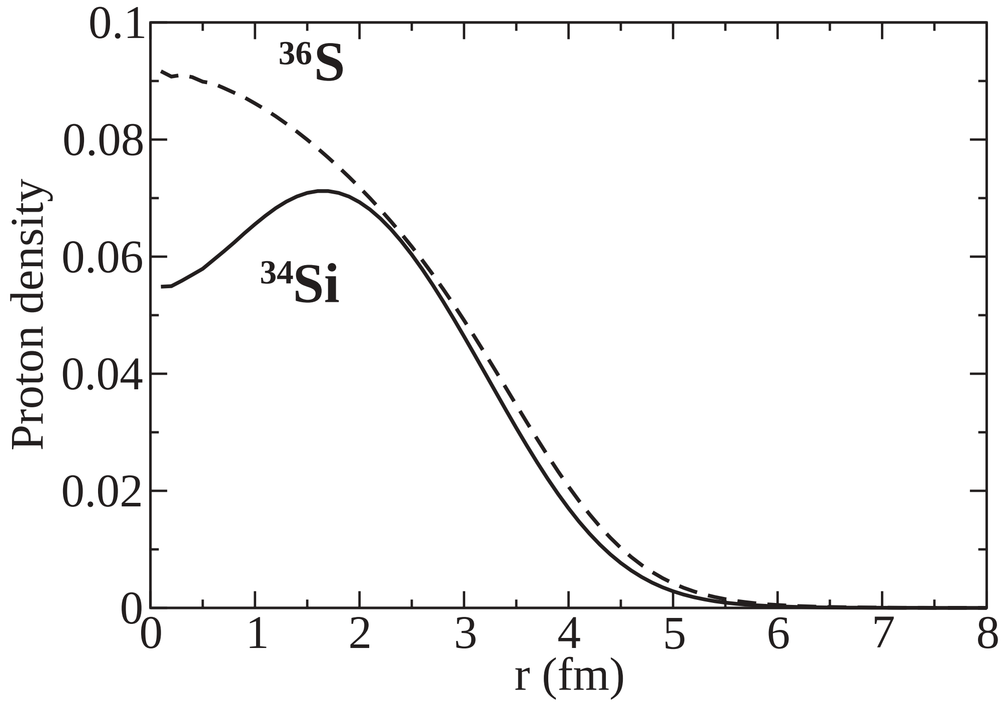
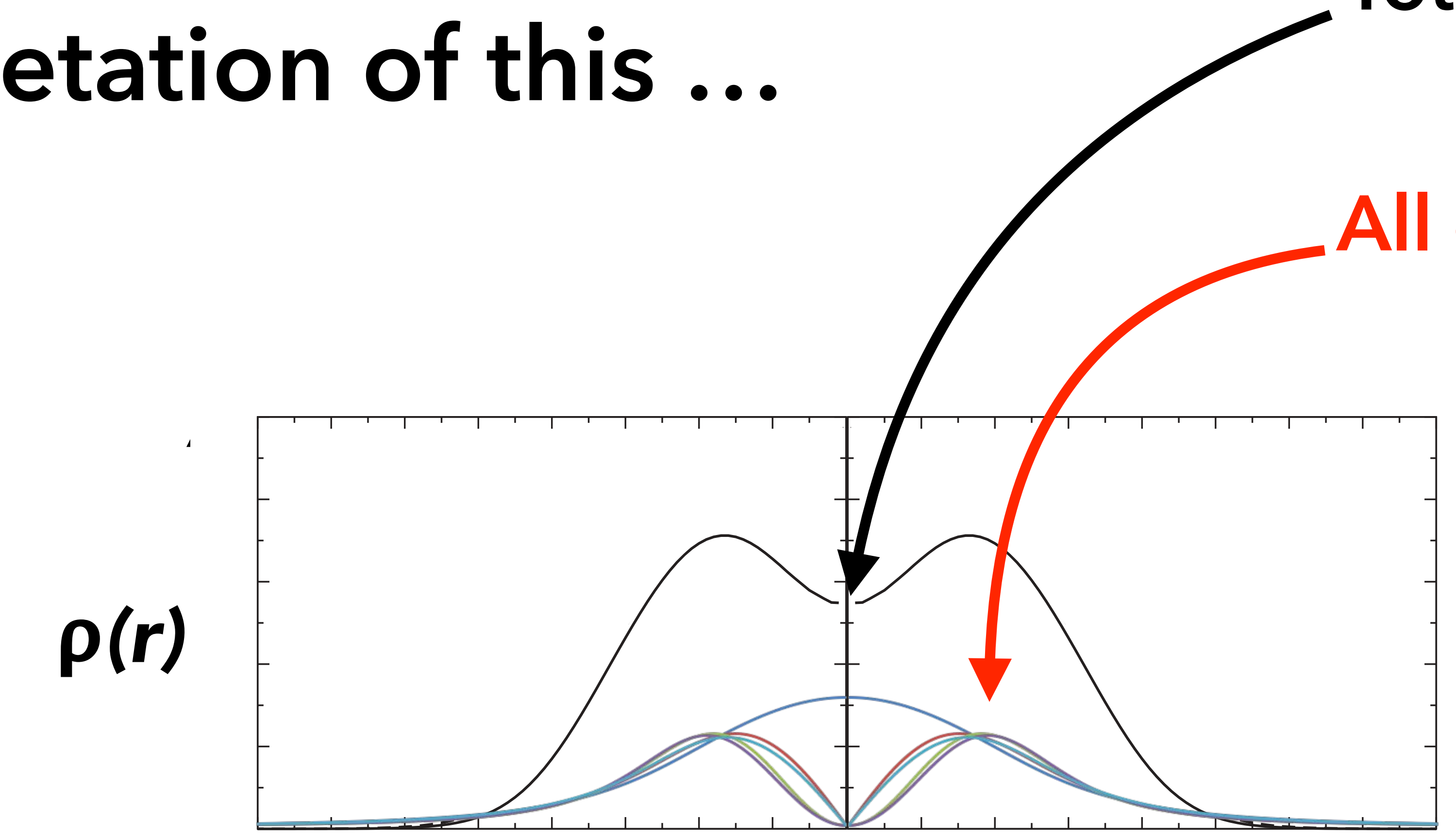
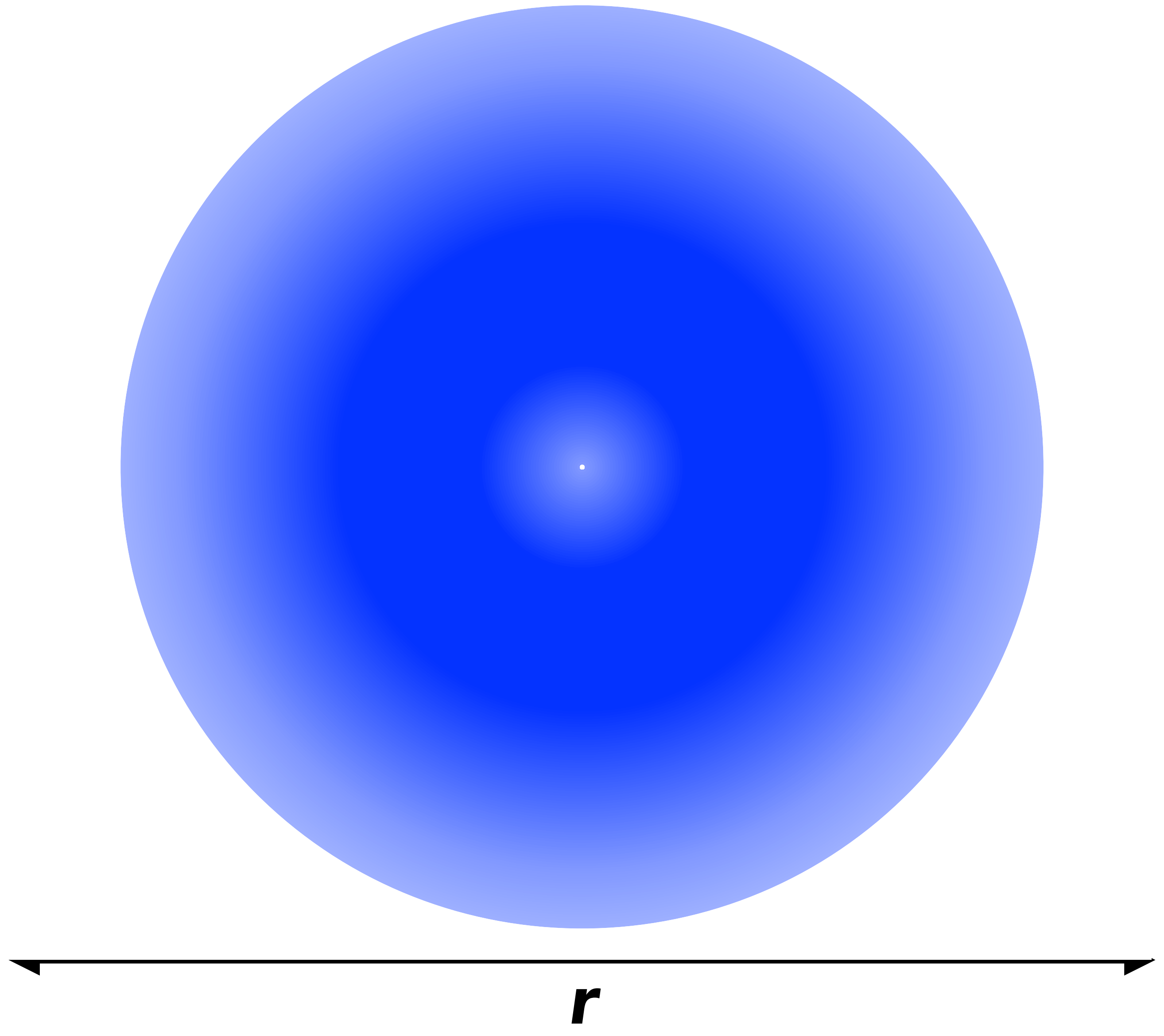


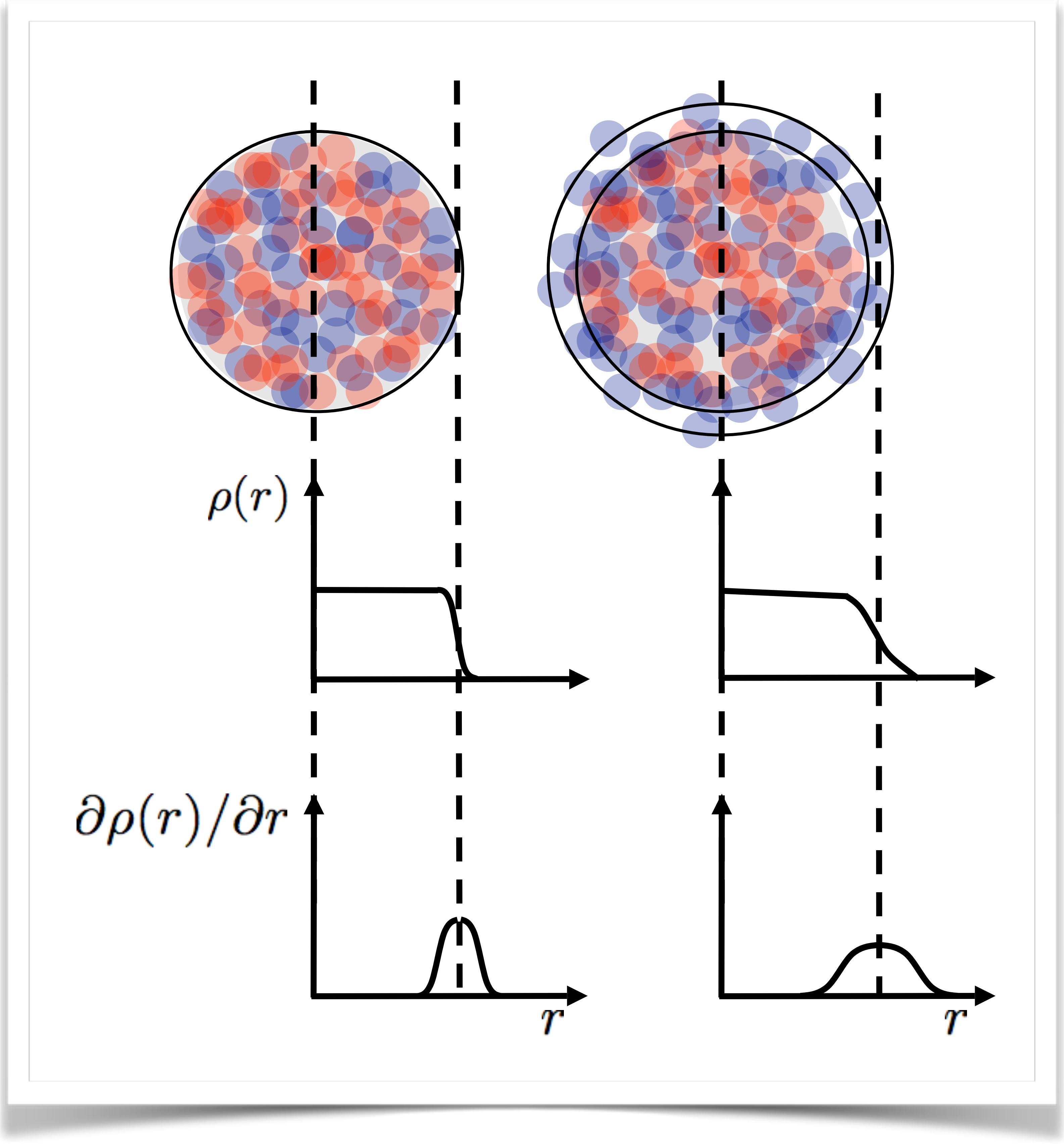


Total

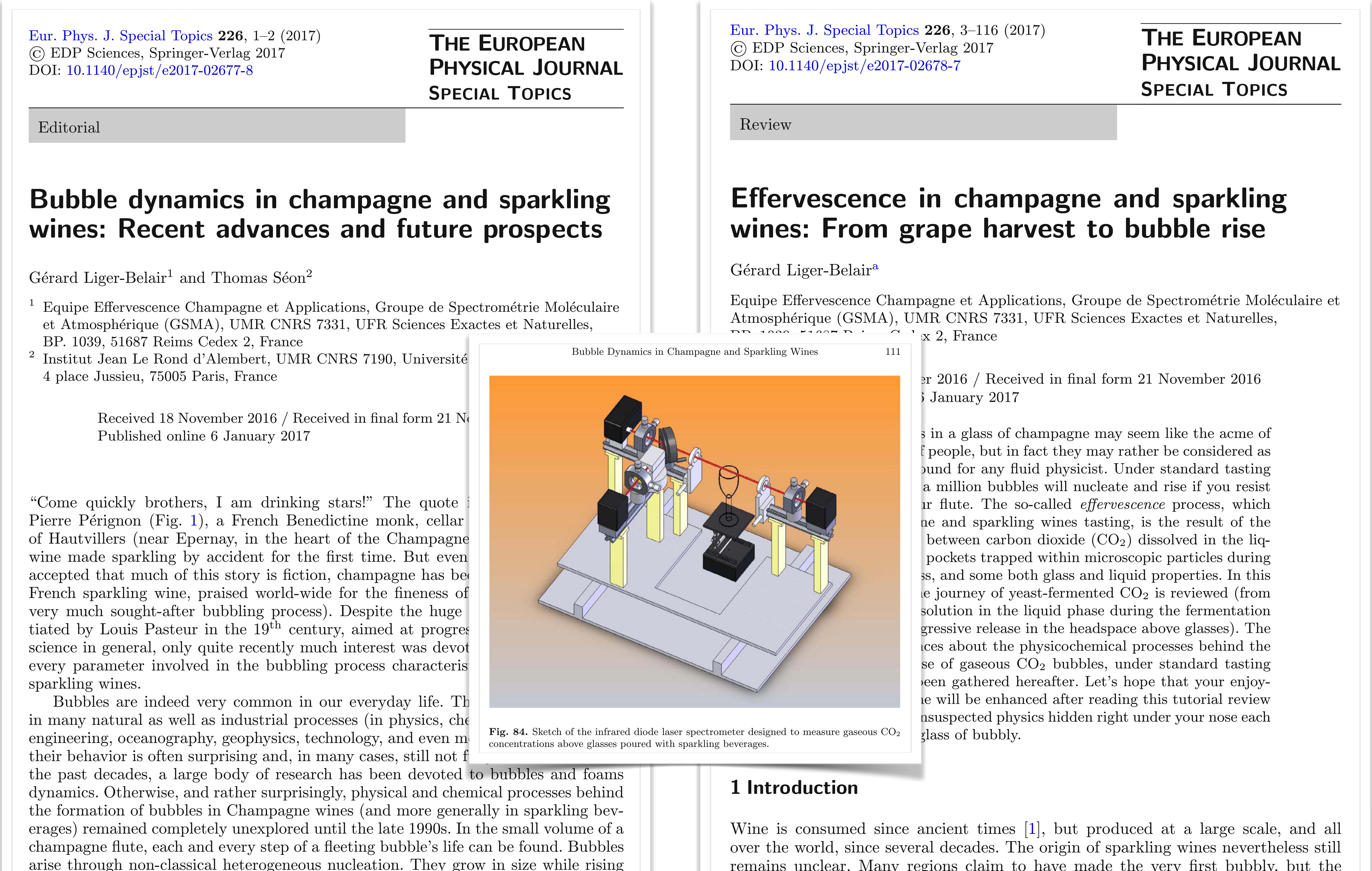
All other radial w.f.'s



density, slice thru middle
(dark=dense, less dark=less so



Density, spin-orbit



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THE EUROPEAN
PHYSICAL JOURNAL
SPECIAL TOPICS

Editorial

Bubble dynamics in champagne and sparkling wines: Recent advances and future prospects

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"Come quickly brothers, I am drinking stars!" The quote i
Pierre Pérignon (Fig. 1), a French Benedictine monk, cellar
of Hautvillers (near Epernay, in the heart of the Champagne
wine made sparkling by accident for the first time. But even
accepted that much of this story is fiction, champagne has be
French sparkling wine, praised world-wide for the fineness of
very much sought-after bubbling process). Despite the huge
tiated by Louis Pasteur in the 19th century, aimed at progres
science in general, only quite recently much interest was devot
every parameter involved in the bubbling process characteris
sparkling wines.

Bubbles are indeed very common in our everyday life. Th
in many natural as well as industrial processes (in physics, che
engineering, oceanography, geophysics, technology, and even m
their behavior is often surprising and, in many cases, still not f
the past decades, a large body of research has been devoted to bubbles and foams dynamics. Otherwise, and rather surprisingly, physical and chemical processes behind the formation of bubbles in Champagne wines (and more generally in sparkling beverages) remained completely unexplored until the late 1990s. In the small volume of a champagne flute, each and every step of a fleeting bubble's life can be found. Bubbles arise through non-classical heterogeneous nucleation. They grow in size while rising

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THE EUROPEAN
PHYSICAL JOURNAL
SPECIAL TOPICS

Review

Effervescence in champagne and sparkling wines: From grape harvest to bubble rise

Gérard Liger-Belair[a]

Equipe Effervescence Champagne et Applications, Groupe de Spectrométrie Moléculaire et Atmosphérique (GSMA), UMR CNRS 7331, UFR Sciences Exactes et Naturelles,
x 2, France

er 2016 / Received in final form 21 November 2016
January 2017

s in a glass of champagne may seem like the acme of
f people, but in fact they may rather be considered as
ound for any fluid physicist. Under standard tasting
a million bubbles will nucleate and rise if you resist
ur flute. The so-called *effervescence* process, which
ne and sparkling wines tasting, is the result of the
between carbon dioxide (CO_2) dissolved in the liq-
pockets trapped within microscopic particles during
ss, and some both glass and liquid properties. In this
e journey of yeast-fermented CO_2 is reviewed (from
solution in the liquid phase during the fermentation
gressive release in the headspace above glasses). The
ces about the physicochemical processes behind the
se of gaseous CO_2 bubbles, under standard tasting
een gathered hereafter. Let's hope that your enjoy-
e will be enhanced after reading this tutorial review
nsuspected physics hidden right under your nose each
glass of bubbly.

1 Introduction

Wine is consumed since ancient times [1], but produced at a large scale, and all over the world, since several decades. The origin of sparkling wines nevertheless still remains unclear. Many regions claim to have made the very first bubbly, but the

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Bubble Dynamics in Champagne and Sparkling Wines 111

Fig. 84. Sketch of the infrared diode laser spectrometer designed to measure gaseous CO_2 concentrations above glasses poured with sparkling beverages.

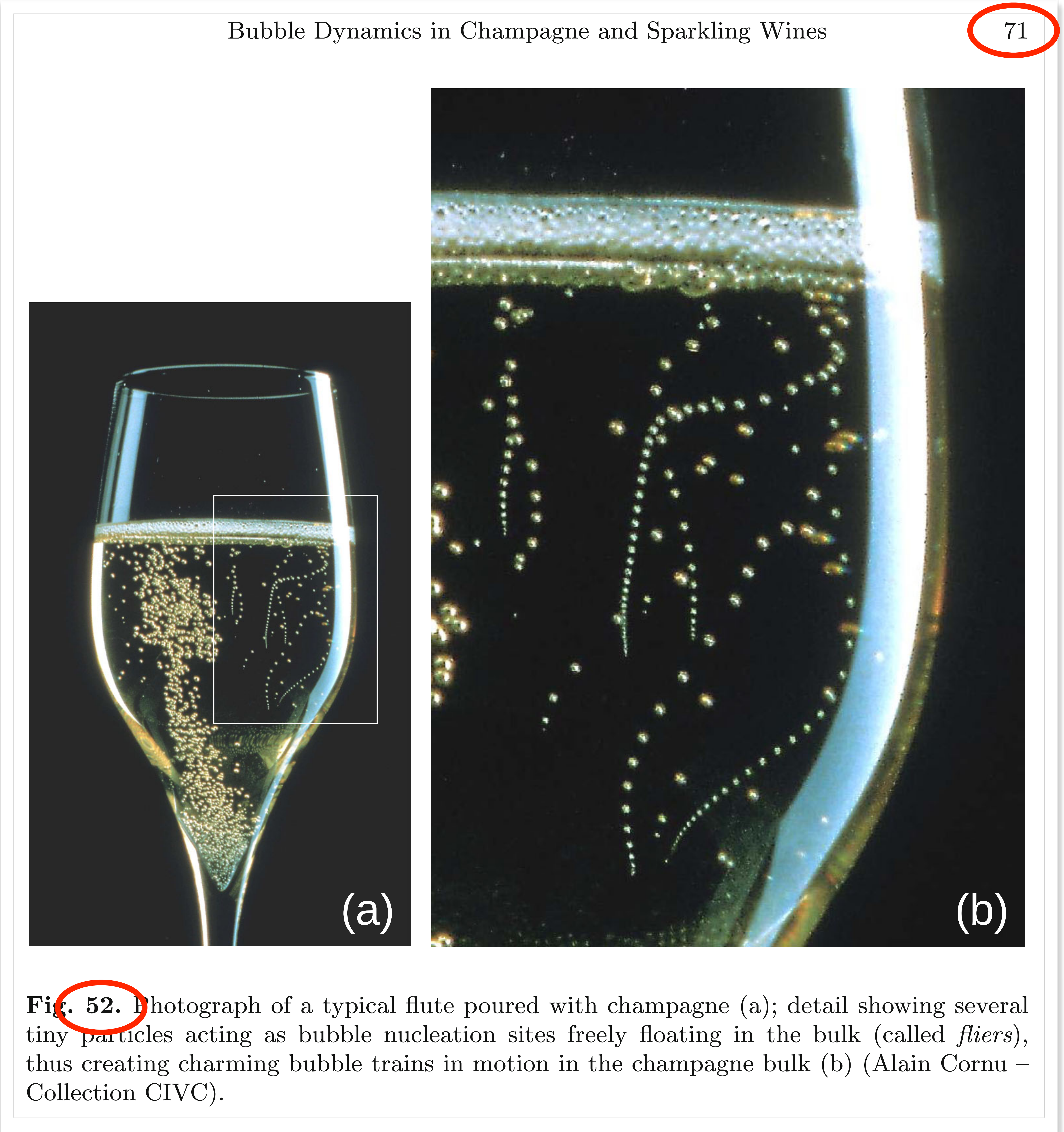
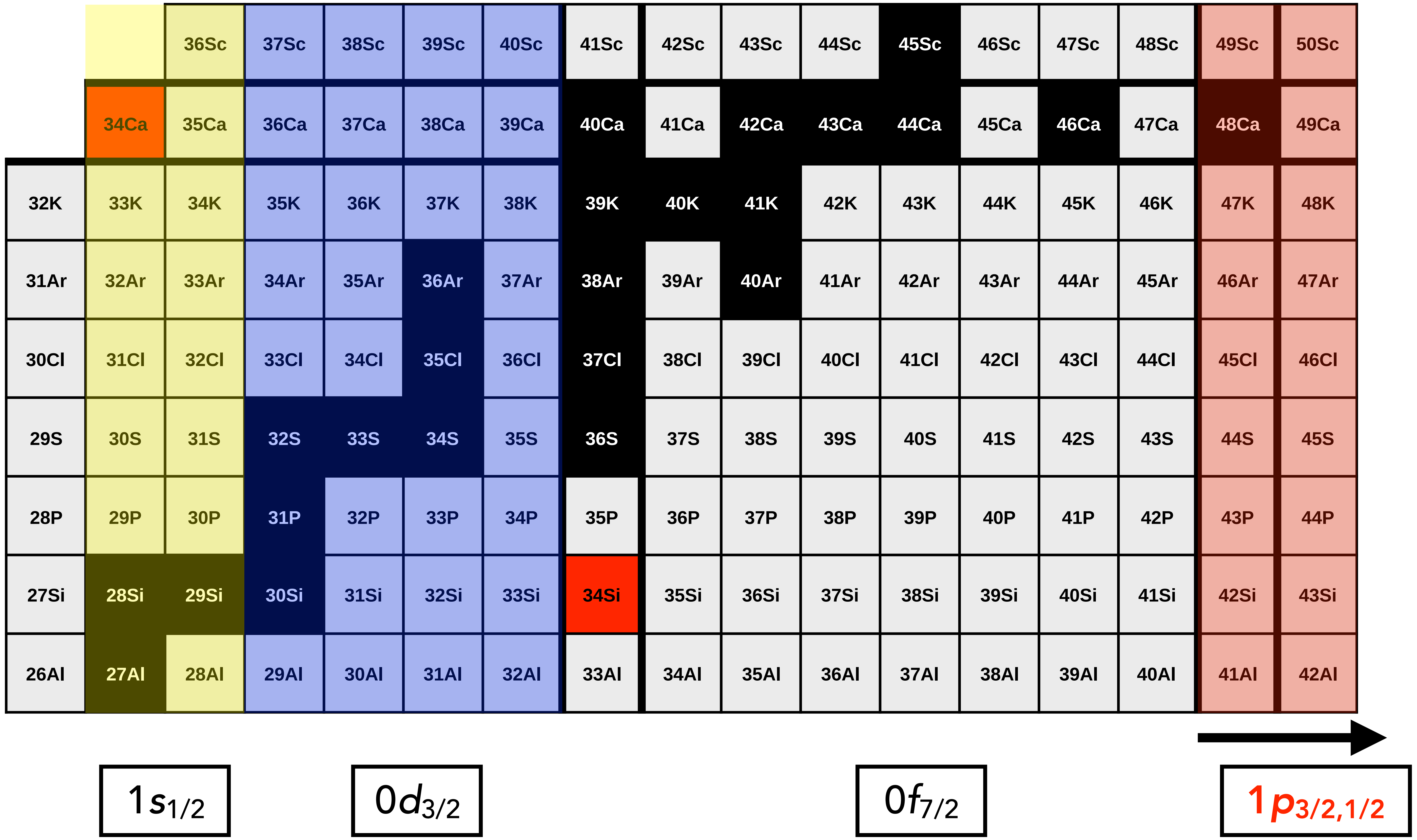


Fig. 52. Photograph of a typical flute poured with champagne (a); detail showing several tiny particles acting as bubble nucleation sites freely floating in the bulk (called *fliers*), thus creating charming bubble trains in motion in the champagne bulk (b) (Alain Cornu – Collection CIVC).

And how would this affect the neutron levels?



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	34Ca	35Ca	36Ca	37Ca	38Ca	39Ca	40Ca	41Ca	42Ca	43Ca	44Ca	45Ca	46Ca	47Ca	48Ca	49Ca
32K	33K	34K	35K	36K	37K	38K	39K	40K	41K	42K	43K	44K	45K	46K	47K	48K
31Ar	32Ar	33Ar	34Ar	35Ar	36Ar	37Ar	38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar	45Ar	46Ar	47Ar
30Cl	31Cl	32Cl	33Cl	34Cl	35Cl	36Cl	37Cl	38Cl	39Cl	40Cl	41Cl	42Cl	43Cl	44Cl	45Cl	46Cl
29S	30S	31S	32S	33S	34S	35S	36S	37S	38S	39S	40S	41S	42S	43S	44S	45S
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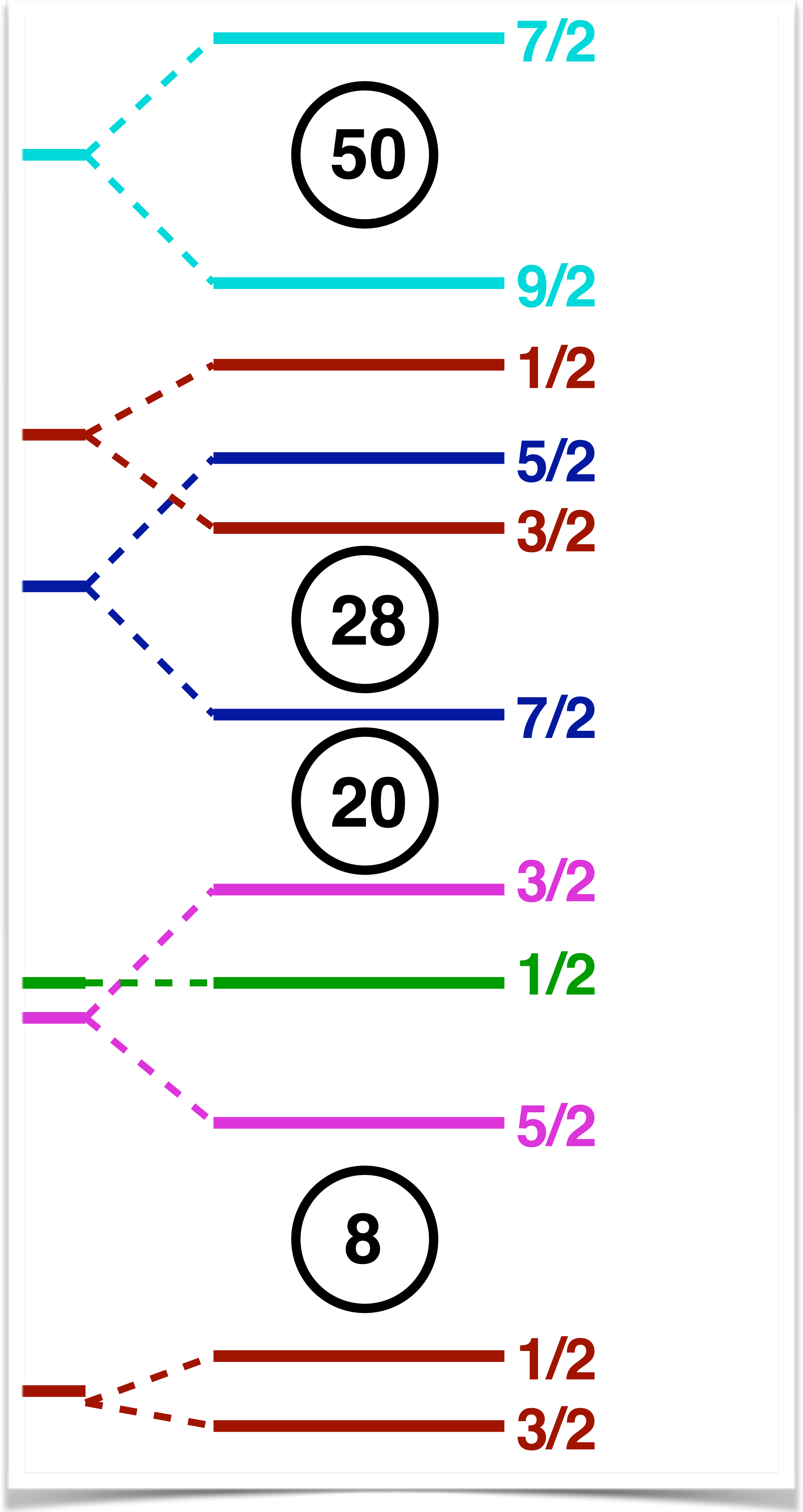
26Al	27Al	28Al	29Al	30Al	31Al	32Al	33Al	34Al	35Al	36Al	37Al	38Al	39Al	40Al	41Al	42Al

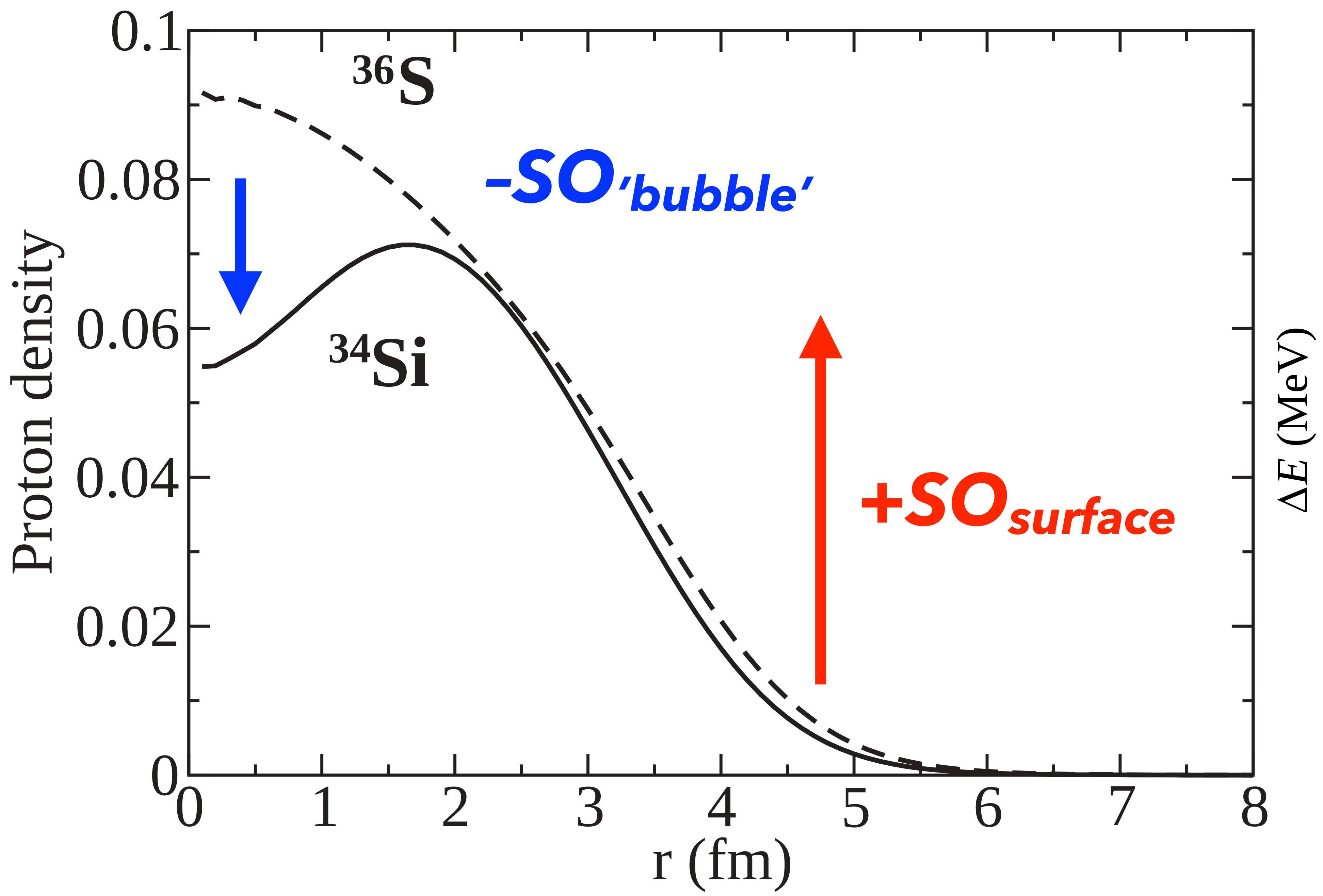
$1s_{1/2}$ $0d_{3/2}$ $0f_{7/2}$ $1p_{3/2,1/2}$



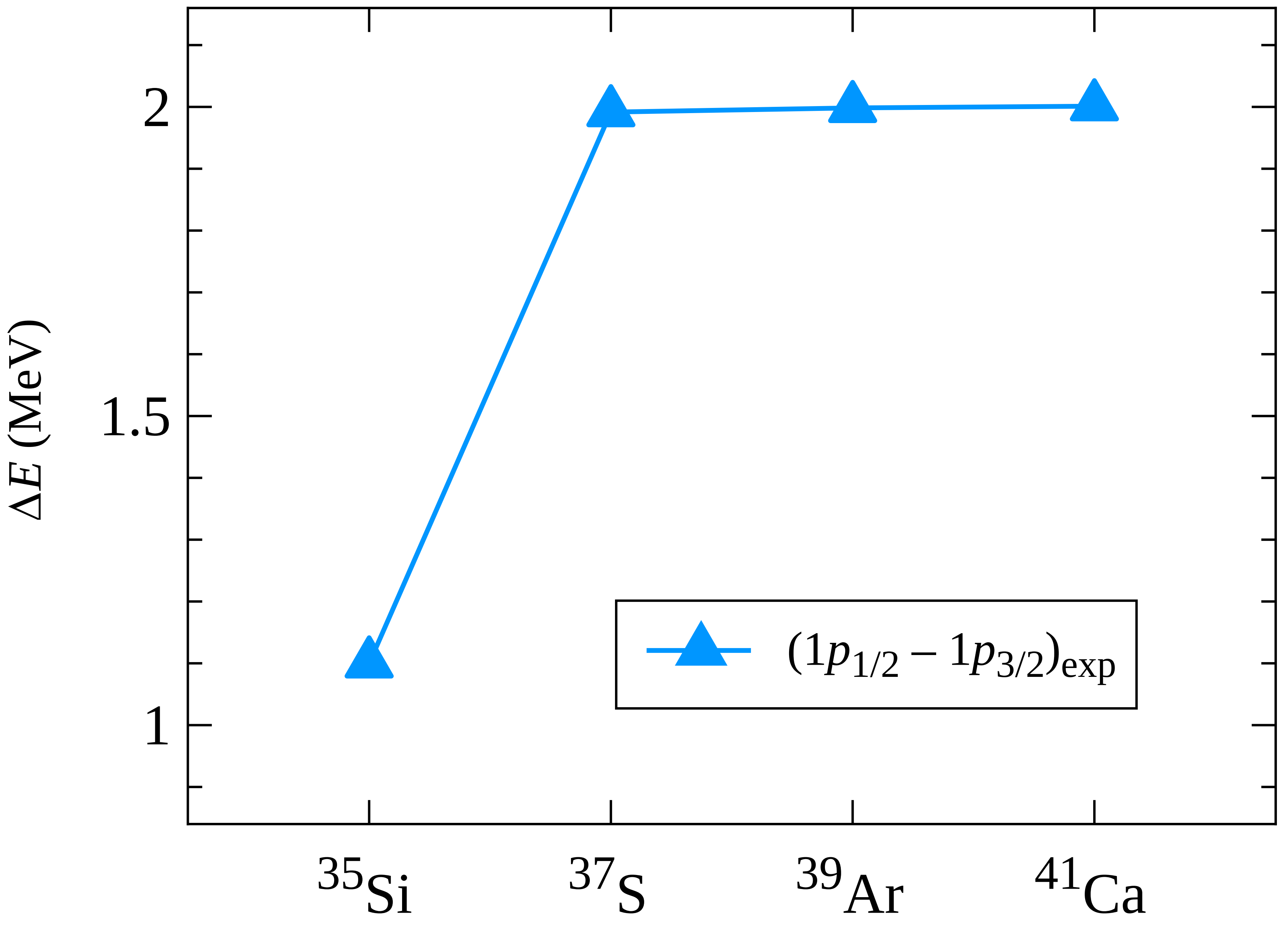
Argonne NATIONAL LABORATORY

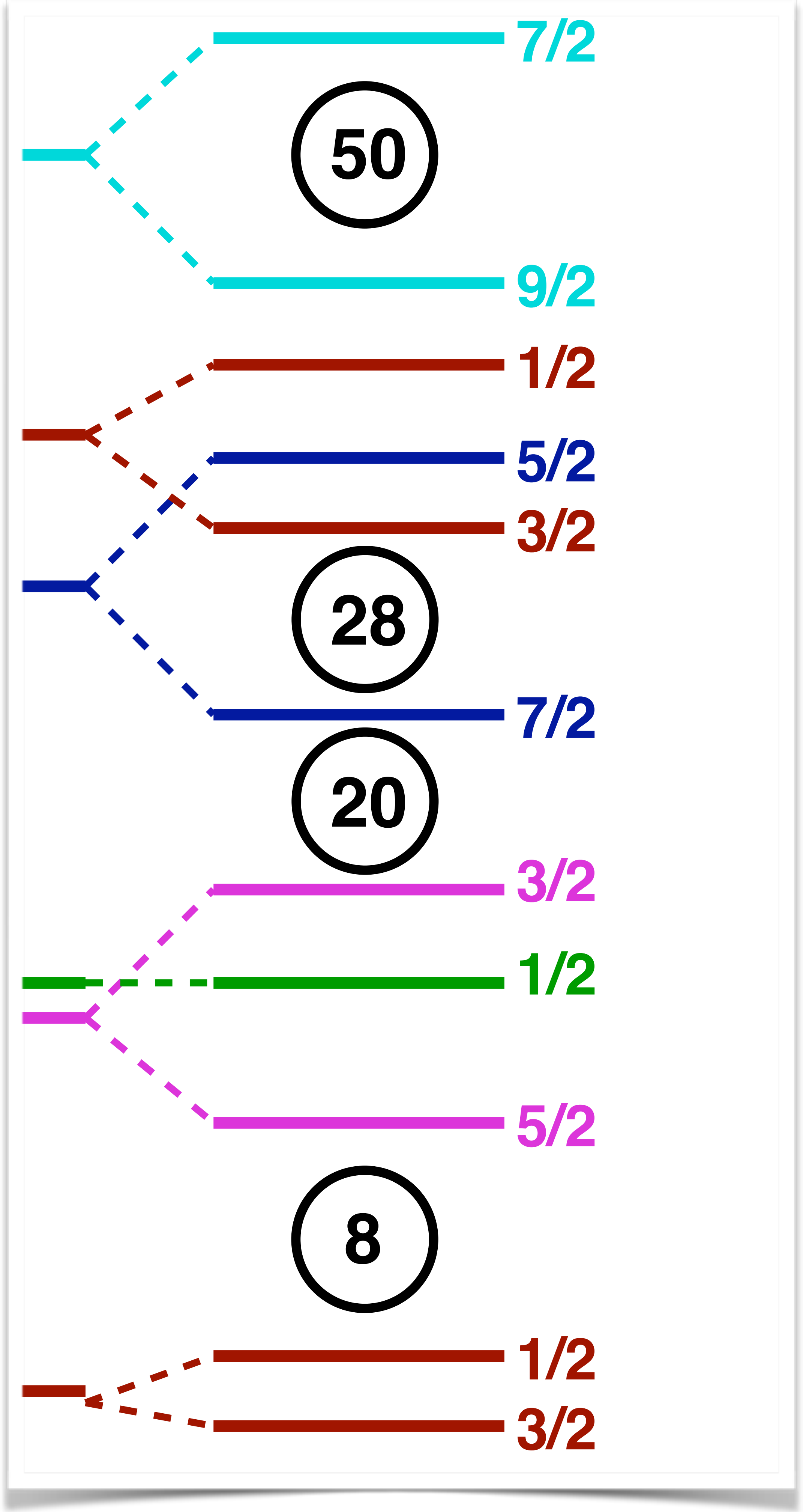
And how would this affect the neutron levels?

Protons?



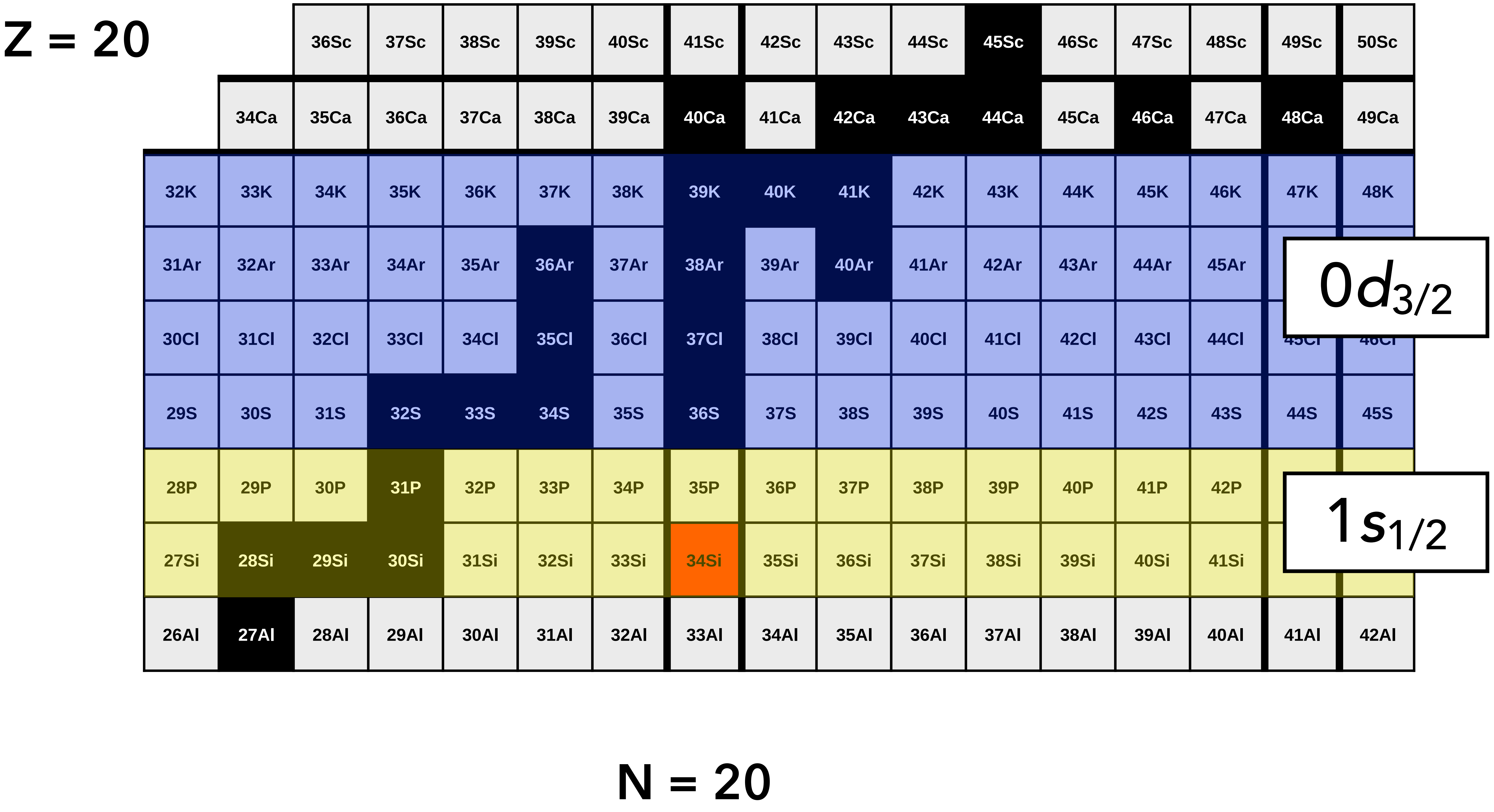
Neutrons?





What experiments, reactions? (protons first)

Does the $0d_{3/2}$ orbitals empty, then the $1s_{1/2}$? Sounds like a question about *occupancies* …



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32K	33K	34K	35K	36K	37K	38K	39K	40K	41K	42K	43K	44K	45K	46K	47K	48K
31Ar	32Ar	33Ar	34Ar	35Ar	36Ar	37Ar	38Ar	39Ar	40Ar	41Ar	42Ar	43Ar	44Ar	45Ar		
30Cl	31Cl	32Cl	33Cl	34Cl	35Cl	36Cl	37Cl	38Cl	39Cl	40Cl	41Cl	42Cl	43Cl	44Cl	45Cl	46Cl
29S	30S	31S	32S	33S	34S	35S	36S	37S	38S	39S	40S	41S	42S	43S	44S	45S
28P	29P	30P	31P	32P	33P	34P	35P	36P	37P	38P	39P	40P	41P	42P		
27Si	28Si	29Si	30Si	31Si	32Si	33Si	34Si	35Si	36Si	37Si	38Si	39Si	40Si	41Si		
26Al	27Al	28Al	29Al	30Al	31Al	32Al	33Al	34Al	35Al	36Al	37Al	38Al	39Al	40Al	41Al	42Al

Historical data for the stable nuclei … very crudely …

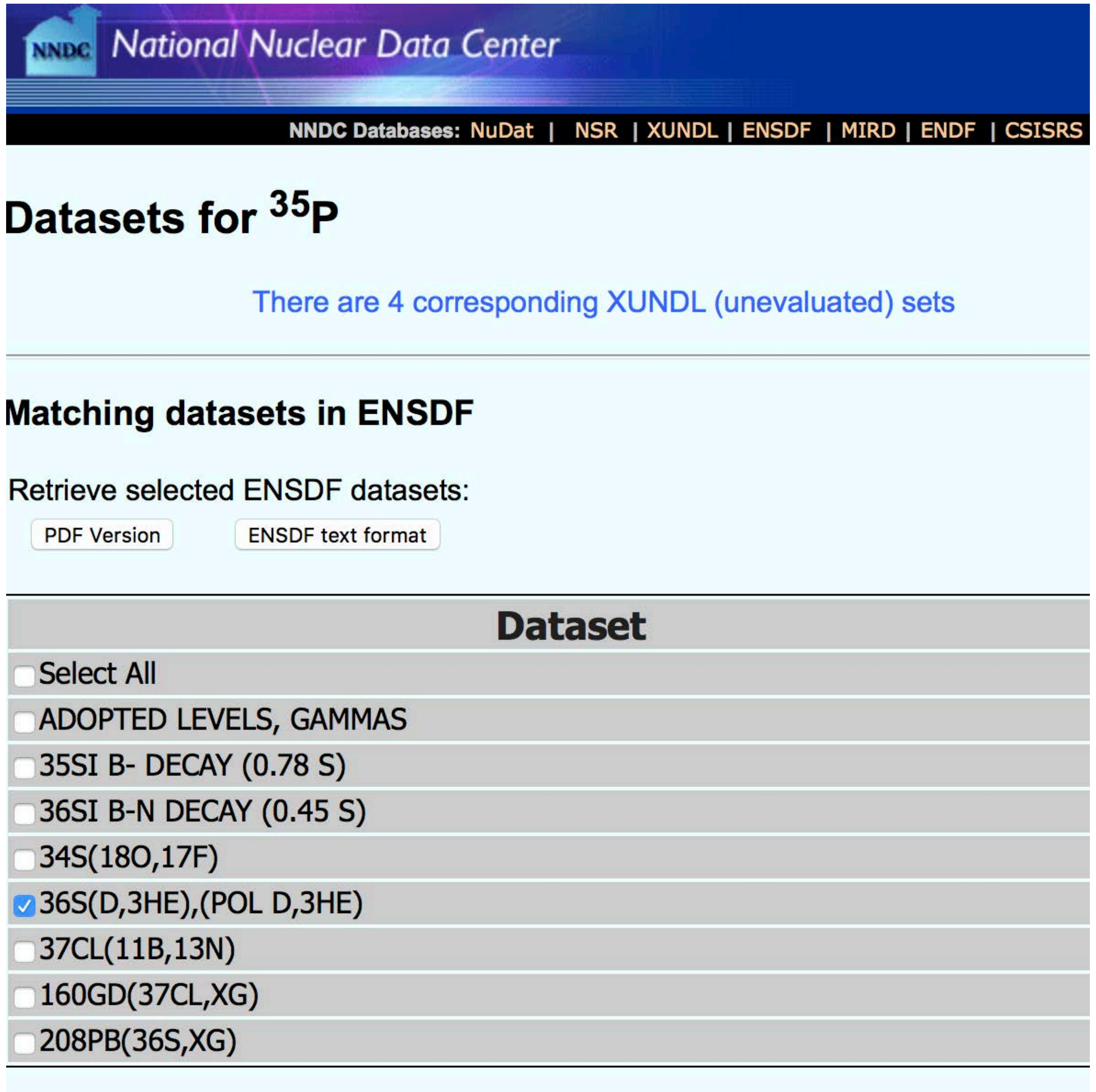
e.g. ^{40}Ca(d,^{3}He) should imply 4 protons in the $0d_{3/2}$ orbital, and 2 in the $1s_{1/2}$

e.g. ^{38}Ar(d,^{3}He) might imply 2 protons in the $0d_{3/2}$ orbital, and 2 holes …

e.g. ^{36}S(d,^{3}He) might imply 0 protons in the $0d_{3/2}$ orbital, and 4 holes … 2 in the $1s_{1/2}$

The stable-beam bit

Very quick glance at *ENSDF*, confirms suspicions about ^{36}S



Datasets for ^{35}P

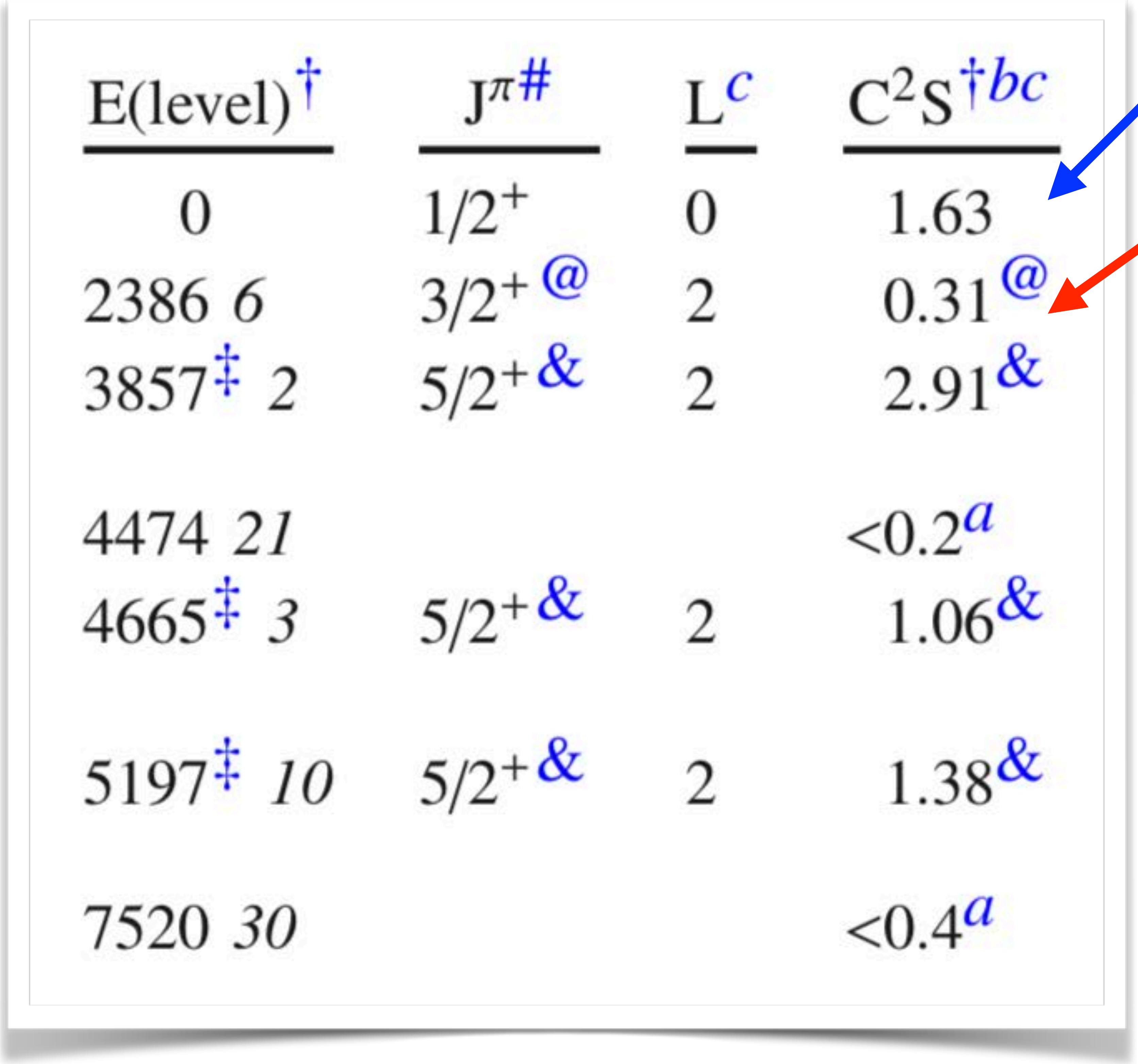
There are 4 corresponding XUNDL (unevaluated) sets

Matching datasets in ENSDF

Retrieve selected ENSDF datasets:

Dataset
☐ Select All
☐ ADOPTED LEVELS, GAMMAS
☐ 35SI B- DECAY (0.78 S)
☐ 36SI B-N DECAY (0.45 S)
☐ 34S(18O,17F)
☑ 36S(D,3HE),(POL D,3HE)
☐ 37CL(11B,13N)
☐ 160GD(37CL,XG)
☐ 208PB(36S,XG)

→



E(level)†	Jπ#	L^{c}	C^{2}S†^{bc}
0	1/2$^+$	0	1.63
2386 *6*	3/2$^+$@	2	0.31@
3857‡ *2*	5/2$^+$&	2	2.91&
4474 *21*			<0.2^a
4665‡ *3*	5/2$^+$&	2	1.06&
5197‡ *10*	5/2$^+$&	2	1.38&
7520 *30*			<0.4^a

1.63 out of 2 present (full-ish)

Only 0.31 out of 4 present (empty-ish)

(Be careful though, always read the original works to double check)

The exotic-beam bit

Need a ^{34}Si beam … not many choices

Need a reaction sensitive to occupancies … (d,^{3}He), proton knockout?

Need a suitable spectrometer system … again, not many choices

nature physics

ARTICLES

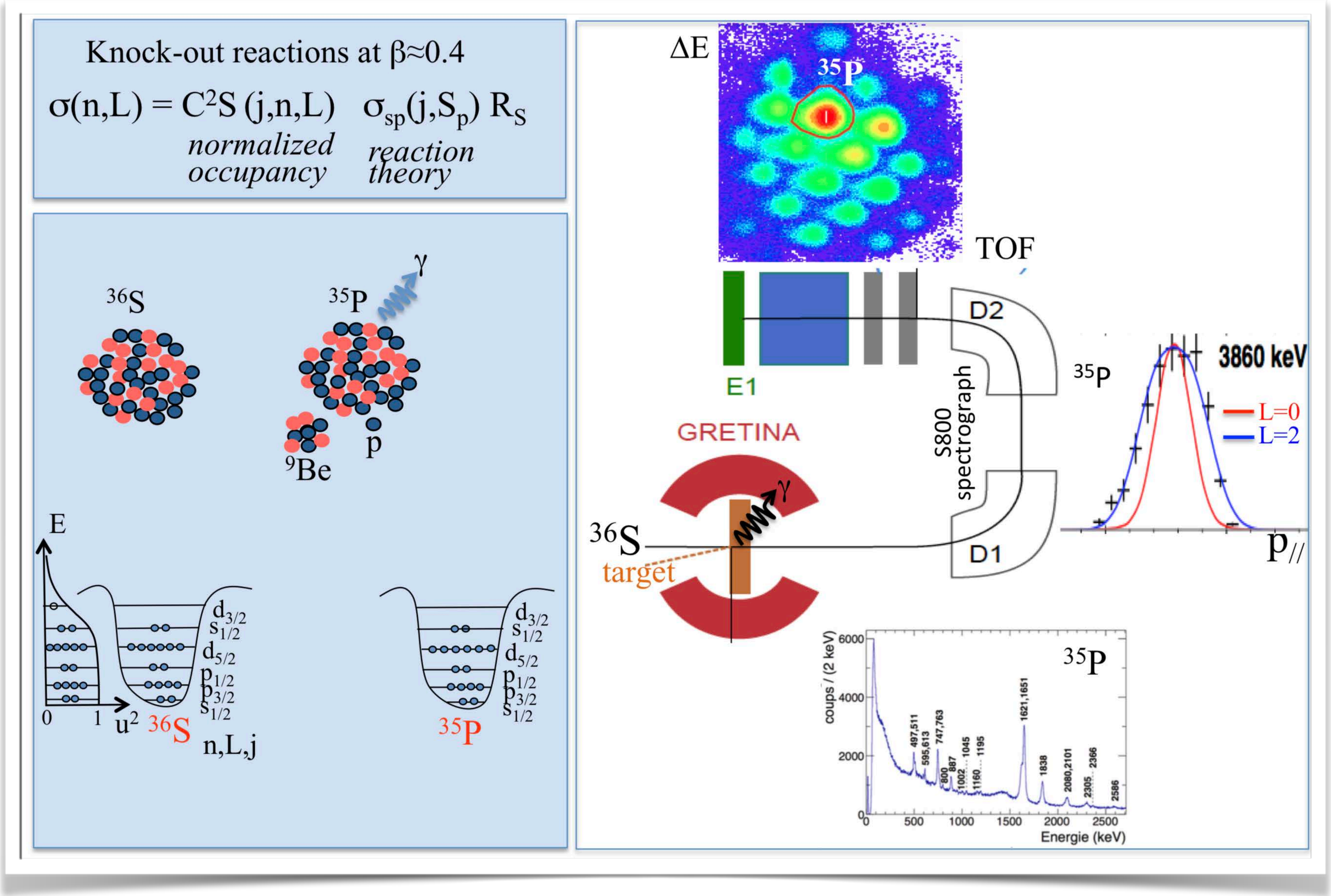
PUBLISHED ONLINE: 24 OCTOBER 2016 | DOI: 10.1038/NPHYS3916

A proton density bubble in the doubly magic ^{34}Si nucleus

A. Mutschler[1,2], A. Lemasson[2,3], O. Sorlin[2★], D. Bazin[4], C. Borcea[5], R. Borcea[5], Z. Dombrádi[6], J.-P. Ebran[7], A. Gade[4], H. Iwasaki[4], E. Khan[1], A. Lepailleur[2], F. Recchia[3], T. Roger[2], F. Rotaru[5], D. Sohler[6], M. Stanoiu[5], S. R. Stroberg[4,8], J. A. Tostevin[9], M. Vandebrouck[1], D. Weisshaar[3] and K. Wimmer[3,10,11]

S800 and GRETINA

Proton knockout on a ^{9}Be target (e.g. of test case ^{36}S – *remember checklist?*)



Knock-out reactions at $\beta \approx 0.4$

$\sigma(n,L) = C^2S\,(j,n,L)\ \ \sigma_{sp}(j,S_p)\ R_S$

normalized occupancy *reaction theory*

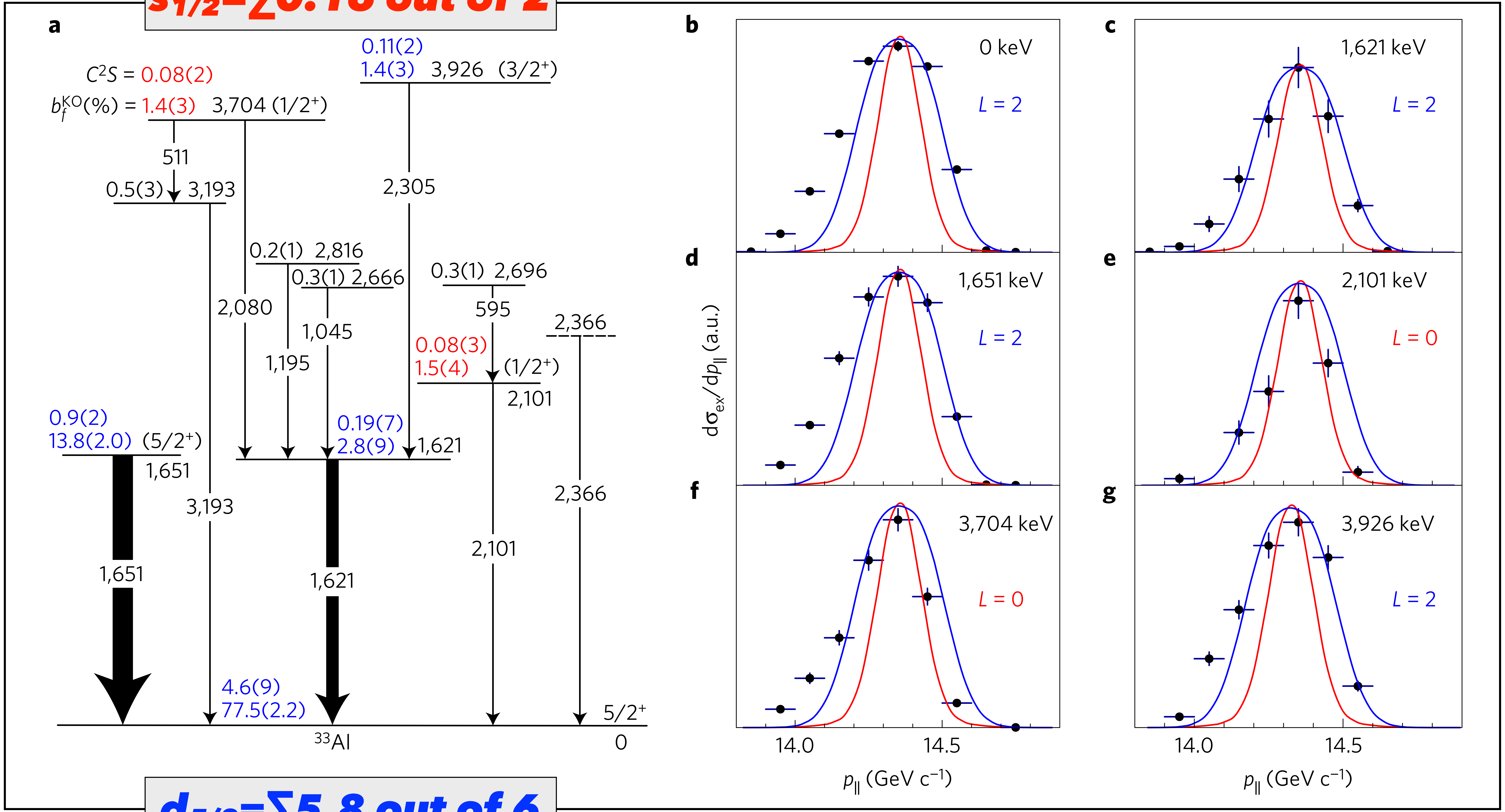
Notes

- *Beam: ~40 MeV/u, 1pnA (4×10^5 pps)*
- *Target: 100 **mg**/cm^2*
- *Prompt gamma-rays in GRETINA*
- *S800 identifies residues, used for longitudinal momentum distributions of resides (can determine ℓ value of knocked out proton), and, with γ-gating, the cross sections*
- *Good consistency checks*

Stolen from Sorlin's slides at https://indico.cern.ch/event/505871/attachments/1250569/1843685/seminaire_CERN-OS.pdf

Indeed, the $1s_{1/2}$ is ~empty

$s_{1/2}=\sum 0.16$ out of 2



$d_{5/2}=\sum 5.8$ out of 6

A. Mutschler et al., Nat. Phys. ***13****, 152 (****2017****)*

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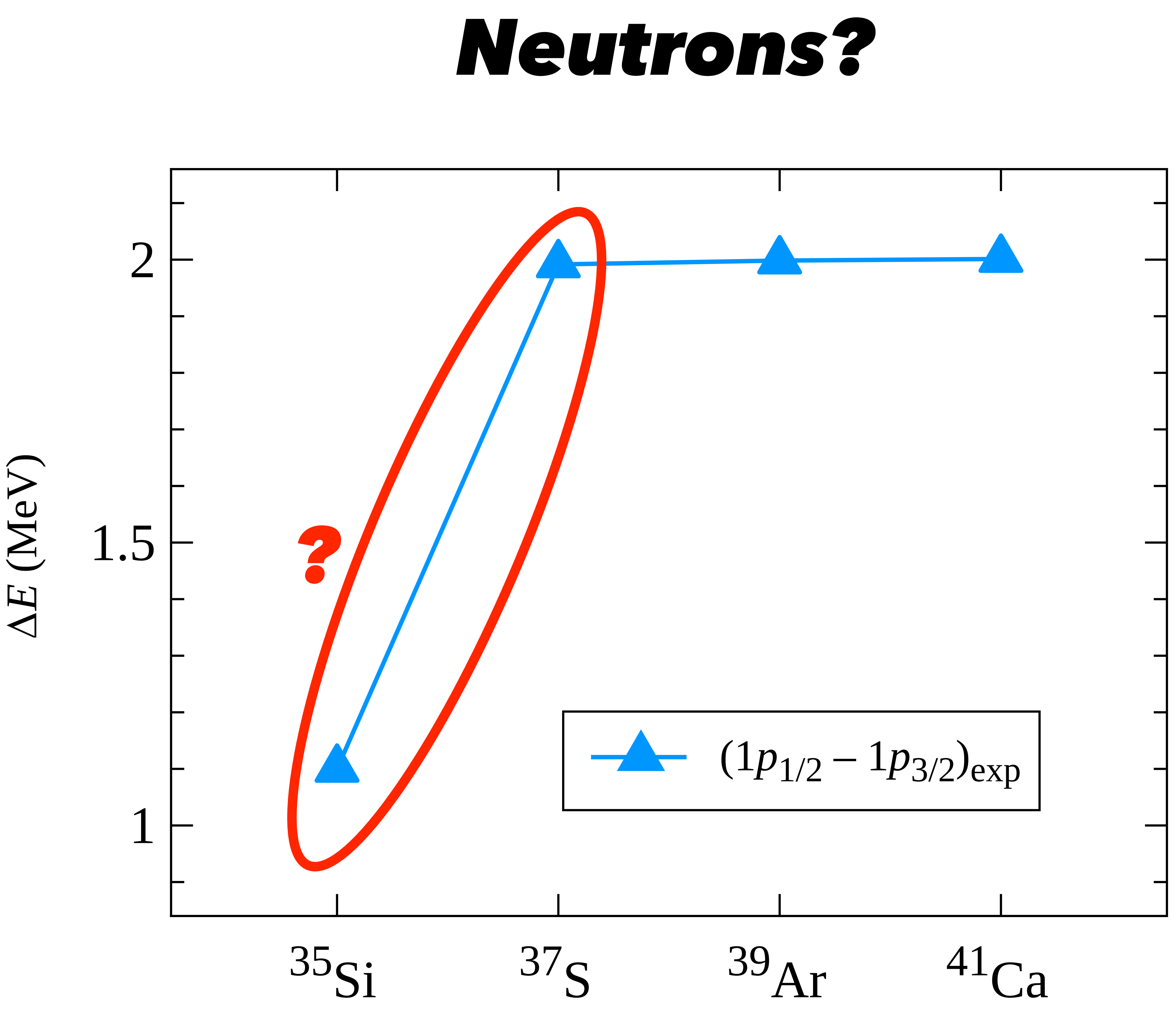
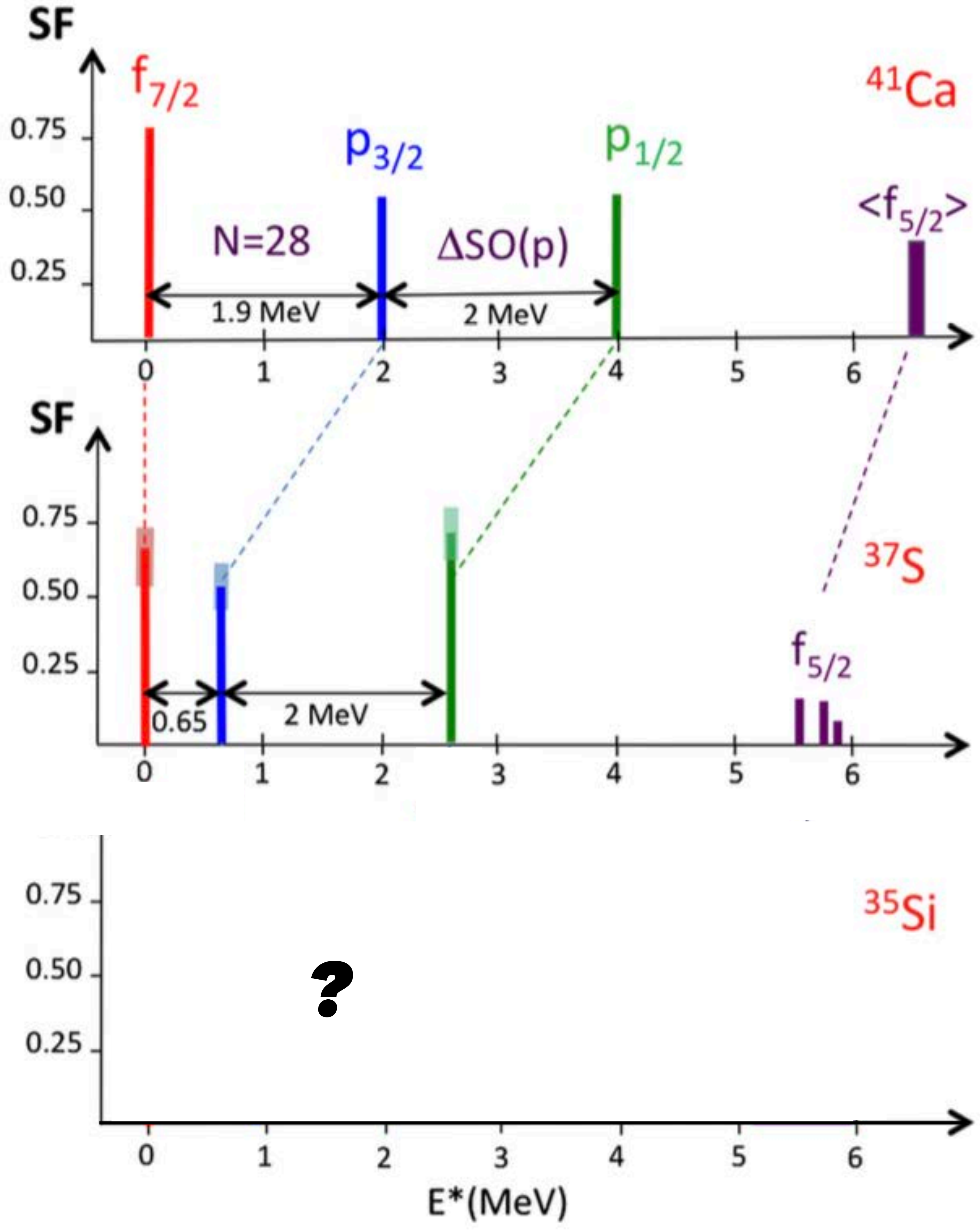
What experiments, reactions? (neutrons next)





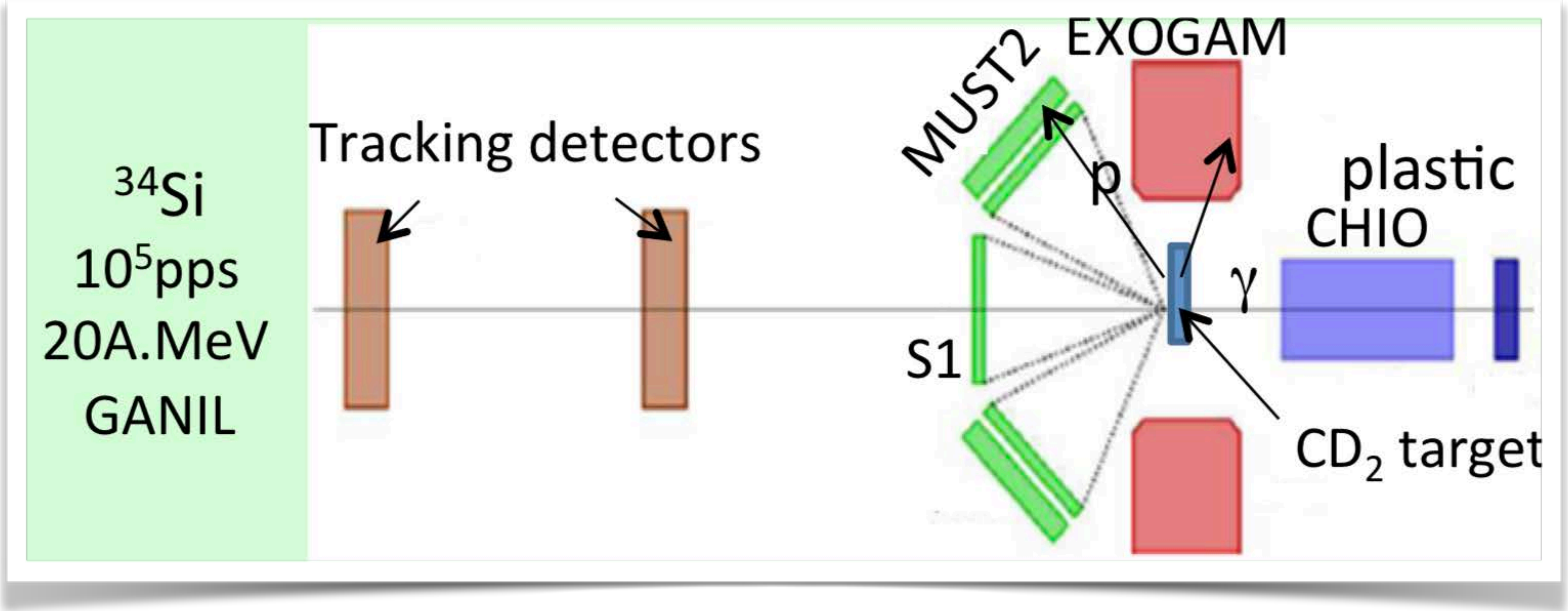
G. Burgunder et al., Phys. Rev. Lett. **112**, 042502 (**2014**)

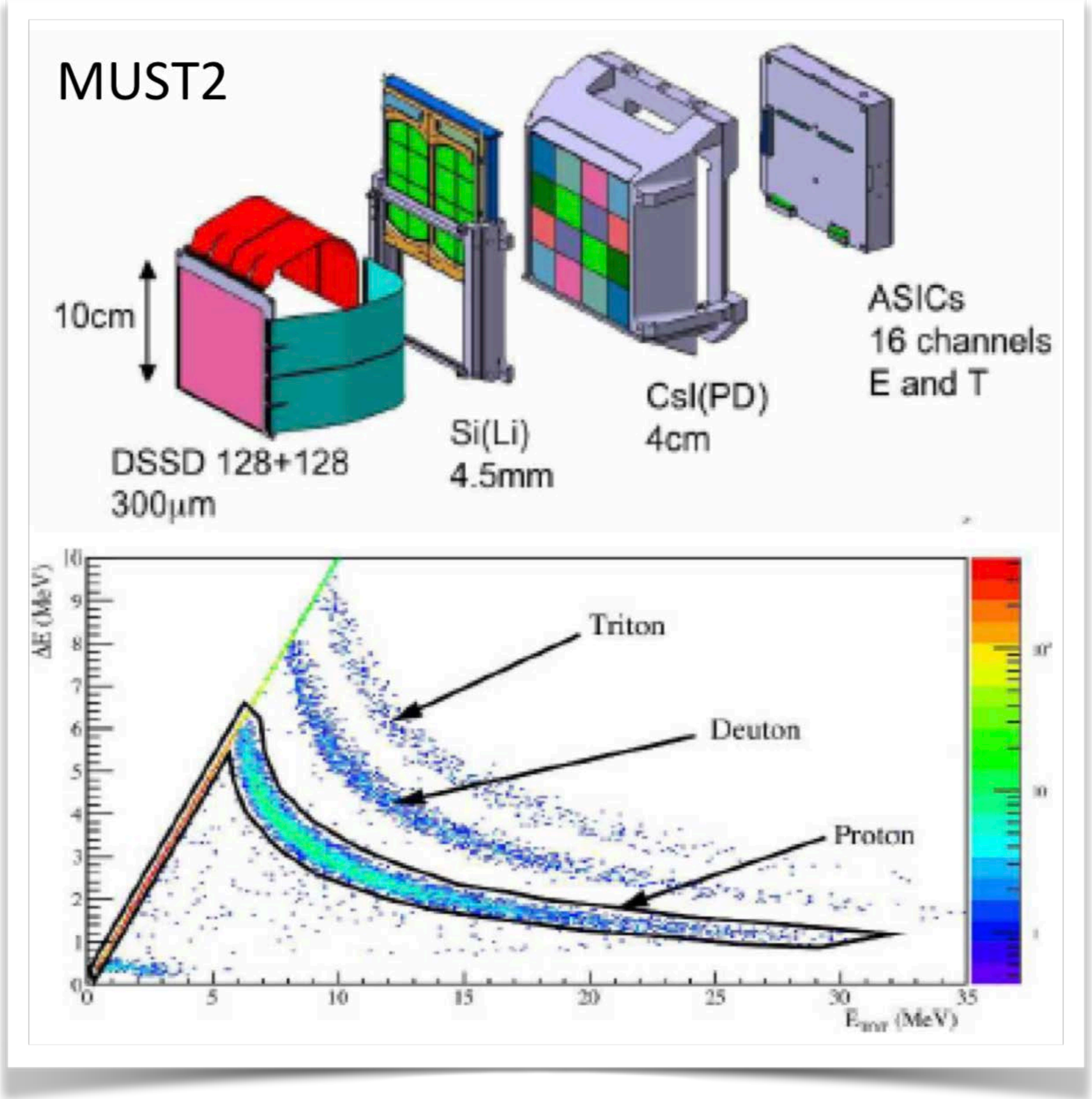
(d,p) reaction to find 1p strength

Need a ^{34}Si beam … not many choices

Need a reaction sensitive to occupancies … (*d*,*p*)?

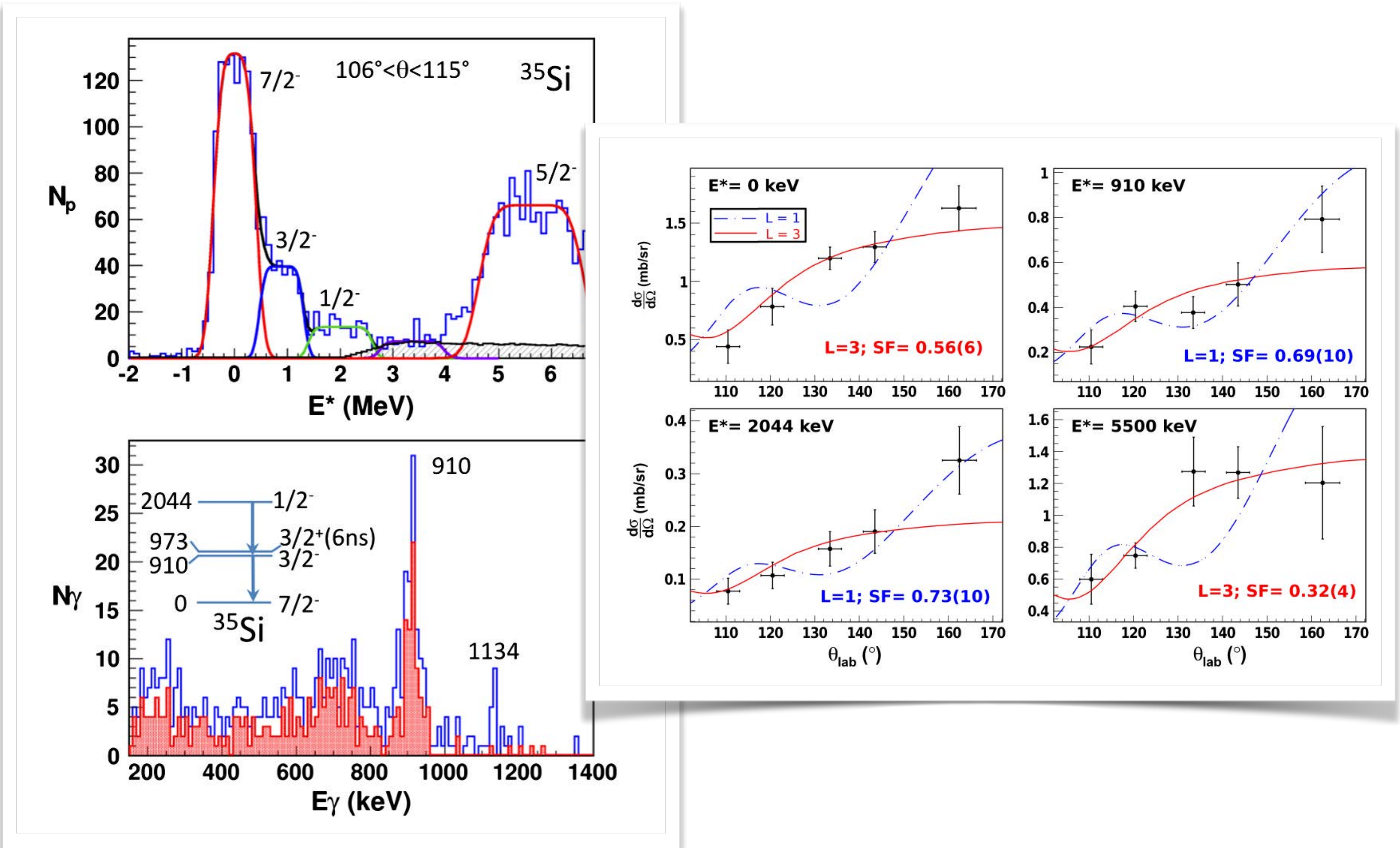
Need a suitable spectrometer system … again, not many choices

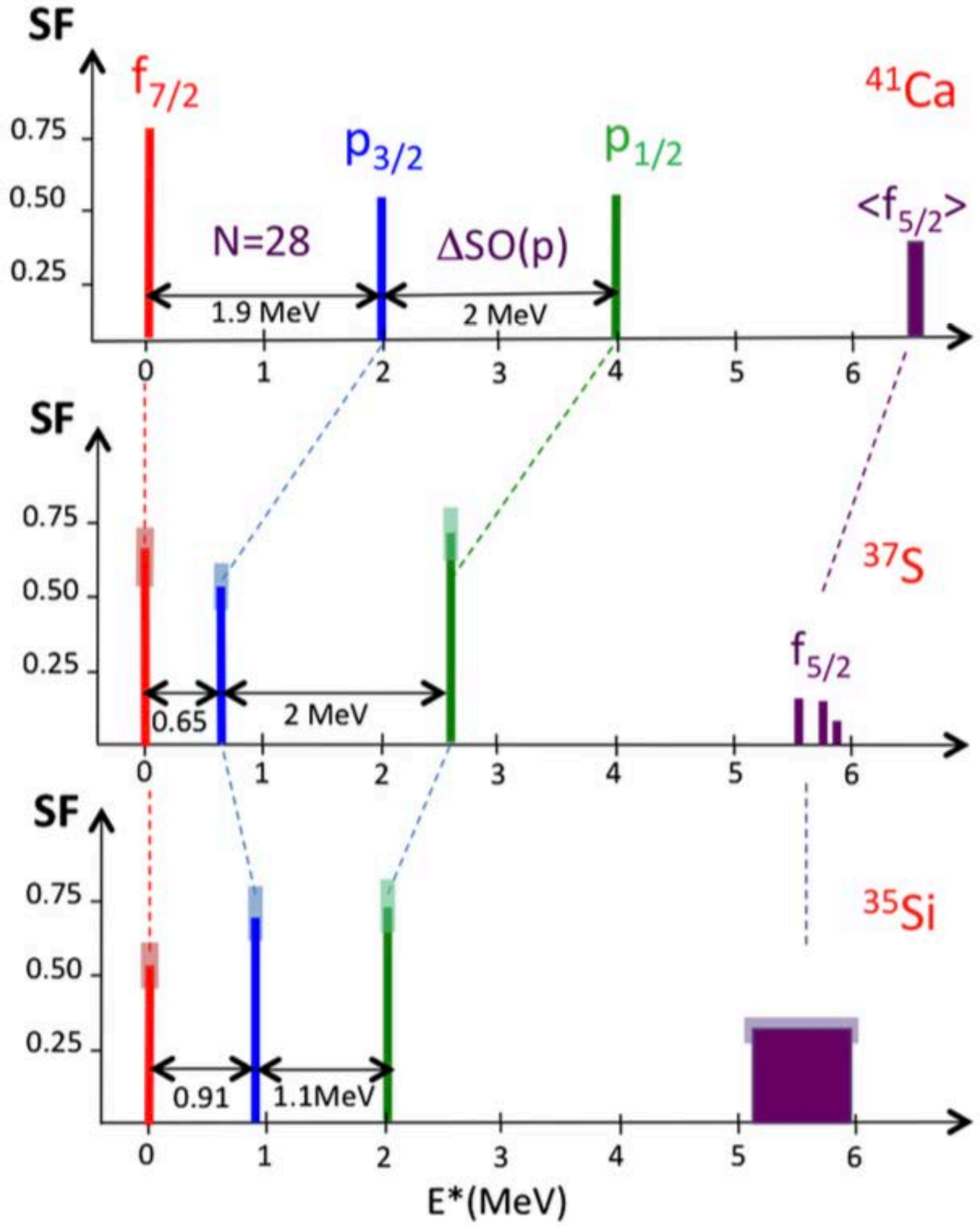




Stolen from Sorlin's slides at https://indico.cern.ch/event/505871/attachments/1250569/1843685/seminaire_CERN-OS.pdf

(d,p) reaction to find 1p strength



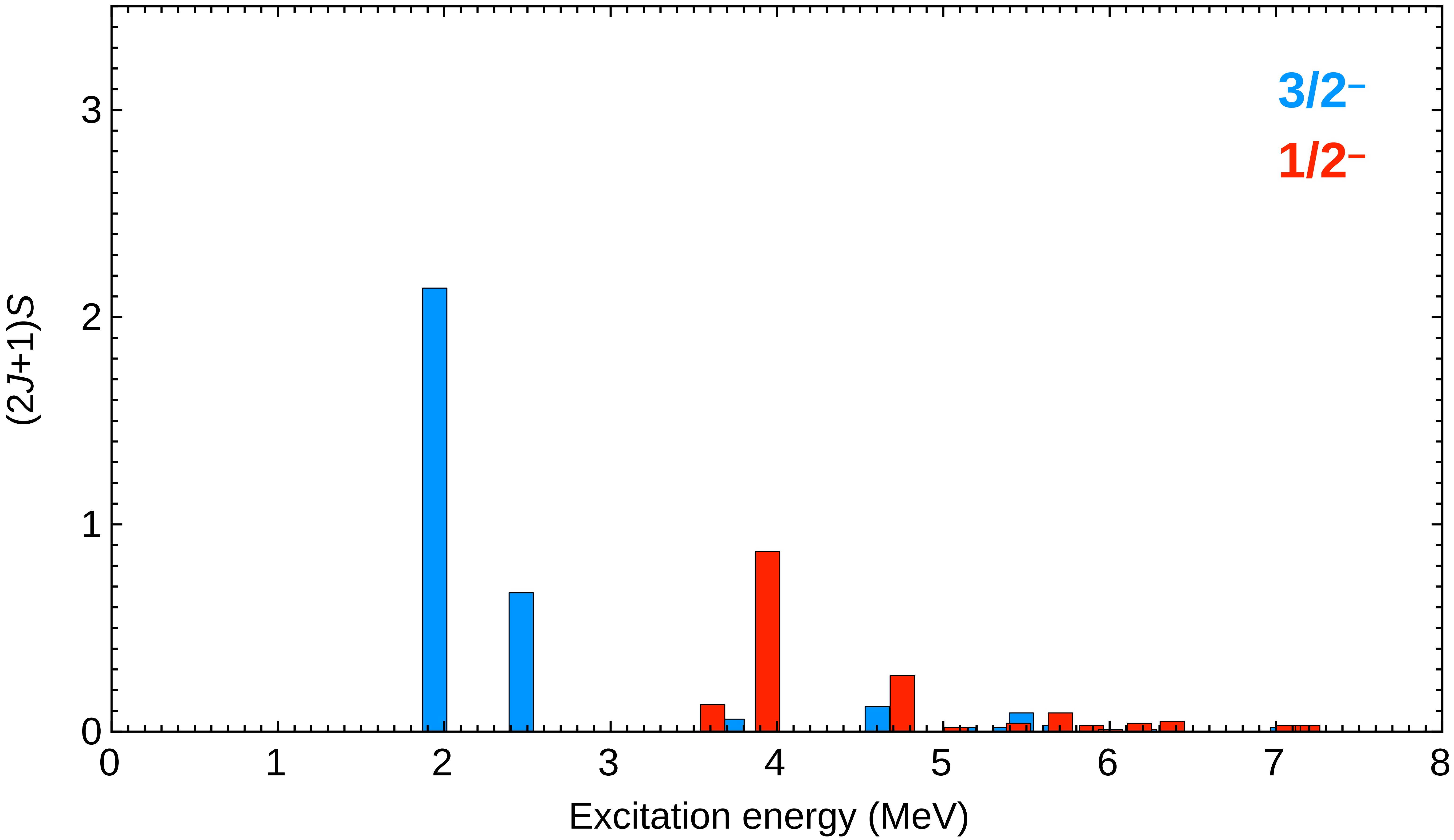


HAPPY … ?

G. Burgunder et al., Phys. Rev. Lett. ***112****, 042502 (****2014****)*

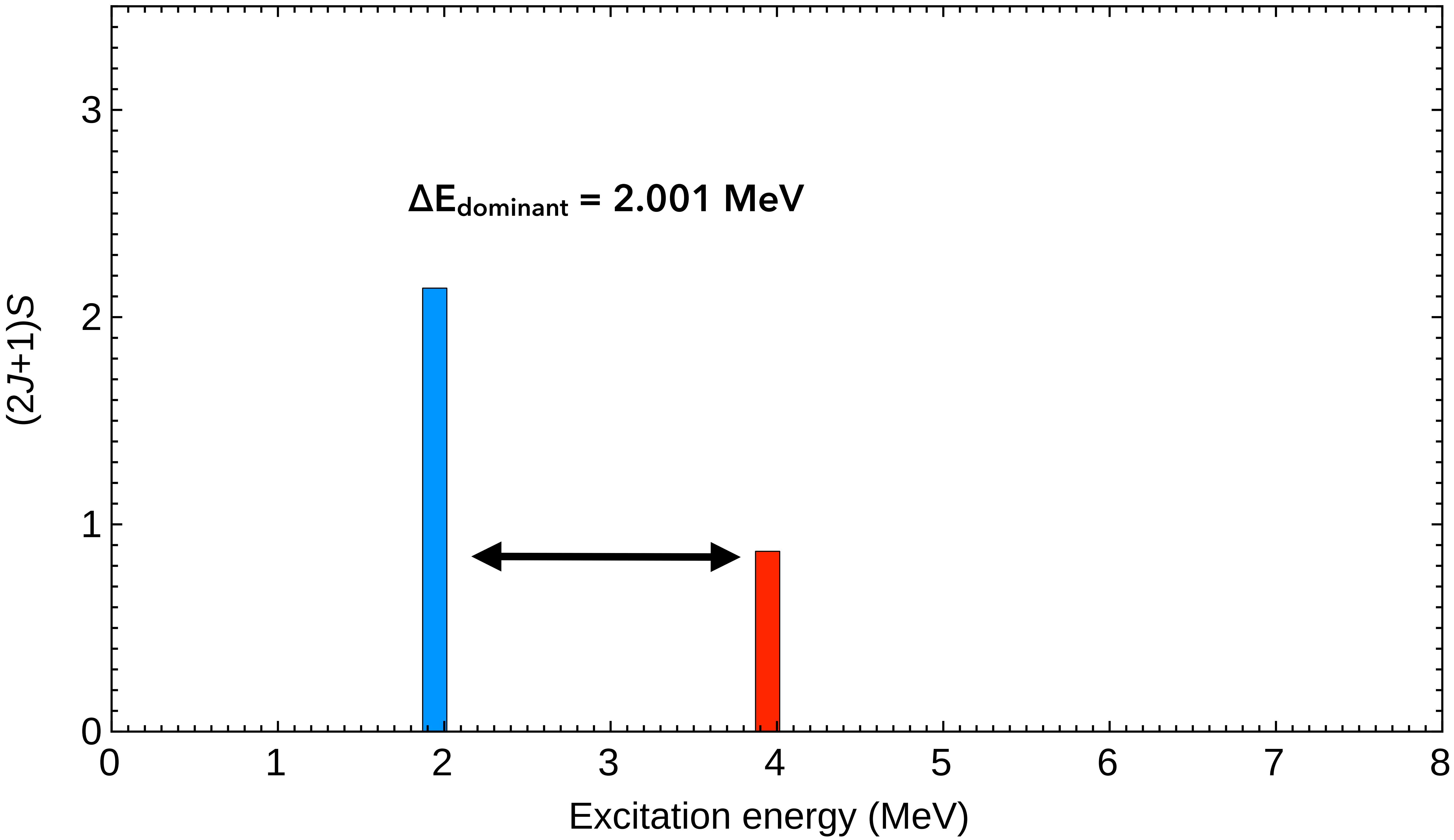
But these aren't the centroids …

Remember – Ca was our 'classic' example



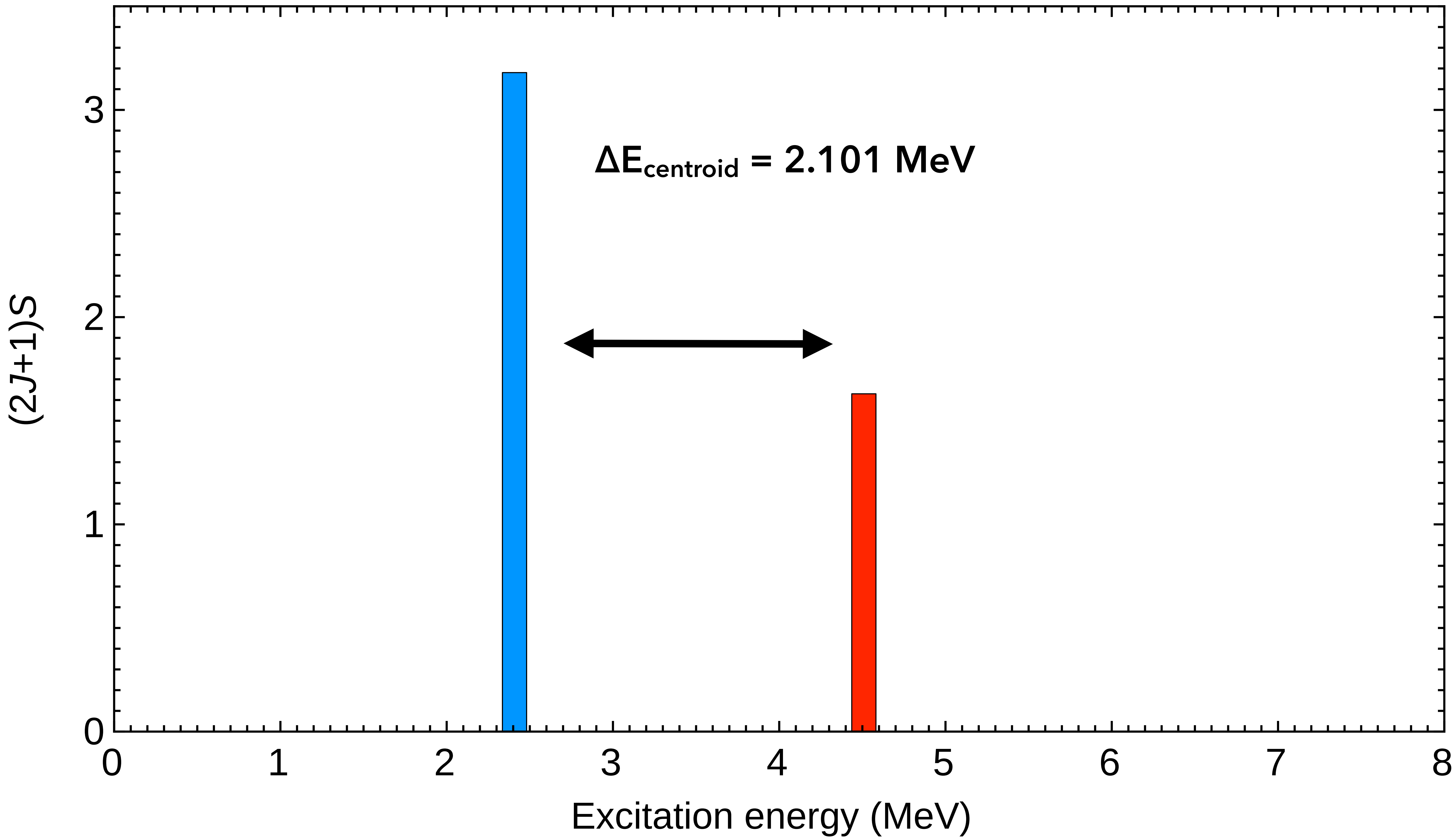
Dominant states

Dominant neutron $1p_{3/2}$ and $1p_{1/2}$ states in ^{41}Ca
(those with largest SF, typically lowest lying)



Centroids

Centroids of the neutron $1p_{3/2}$ and $1p_{1/2}$ orbitals in ^{41}Ca



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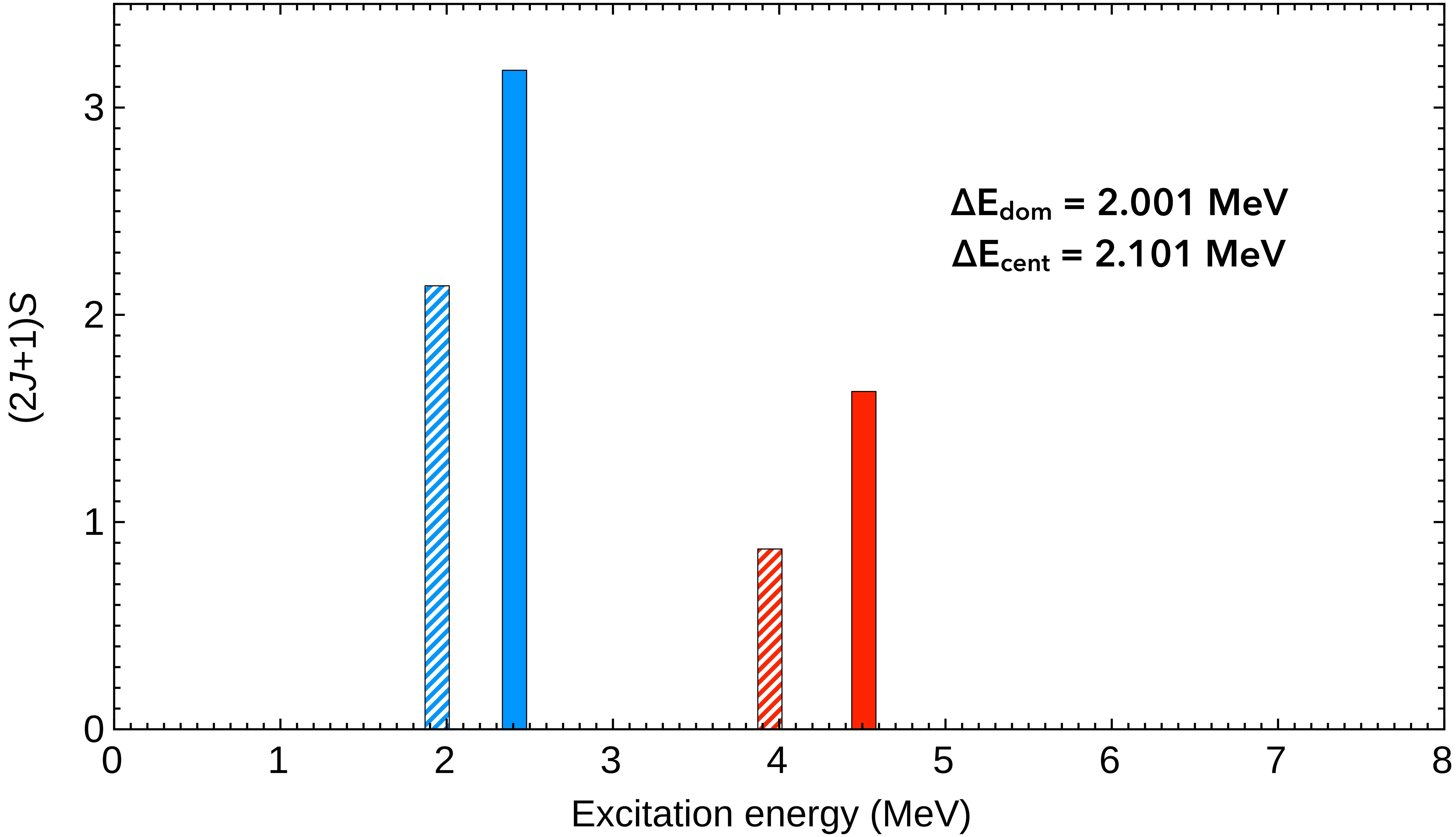
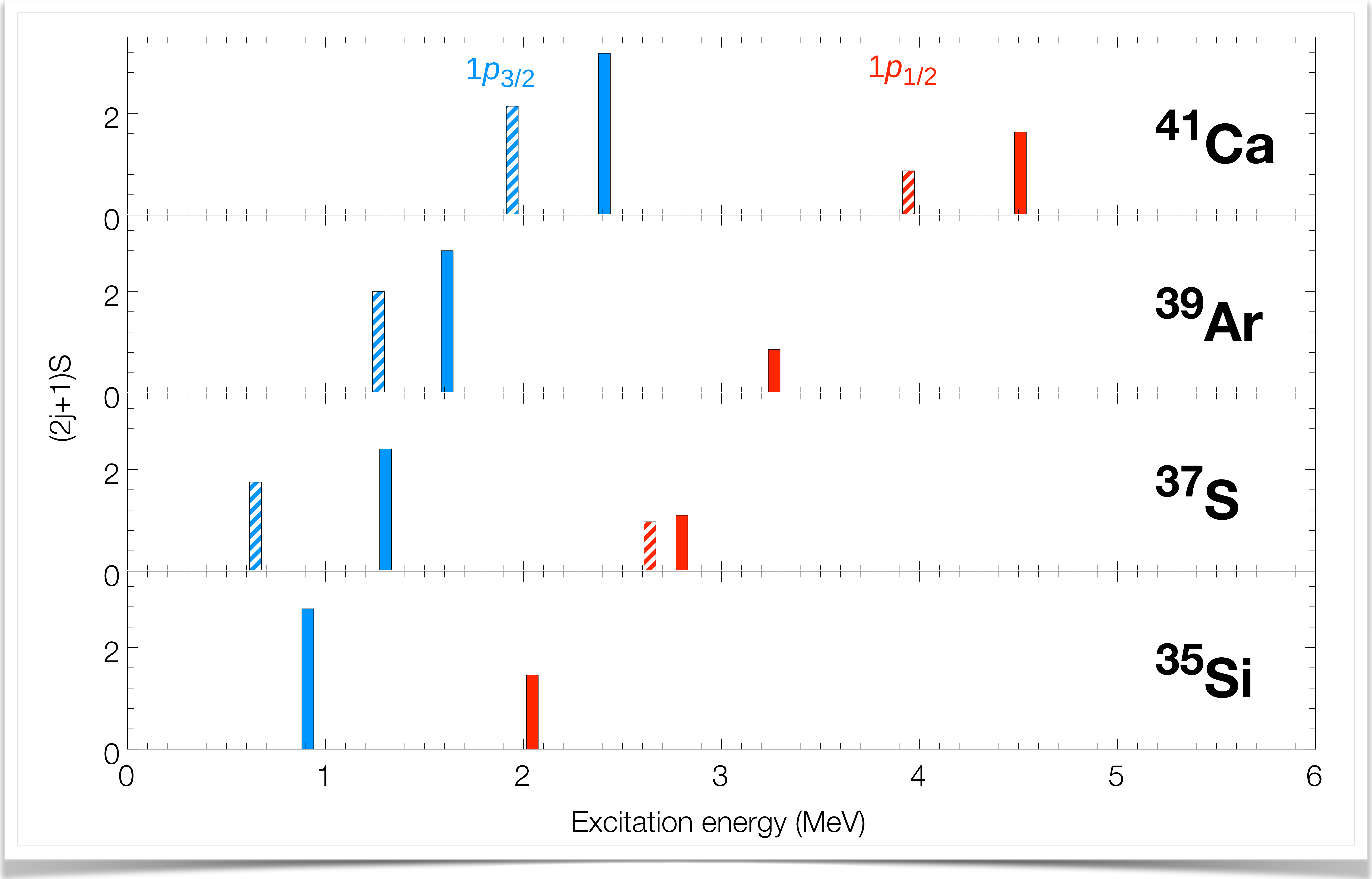
Actually the same separation, just offset … what about the rest?



All together … [all from (d,p)-reaction data]



	$\Delta 1p_{\mathrm{dom}}$ (MeV)	$\Delta 1p_{\mathrm{cent}}$ (MeV)
^{41}Ca	2.00	2.10
^{39}Ar	2.00	1.61
^{37}S	2.00	1.50
^{35}Si	1.13	1.13

Same net change, but different trend …

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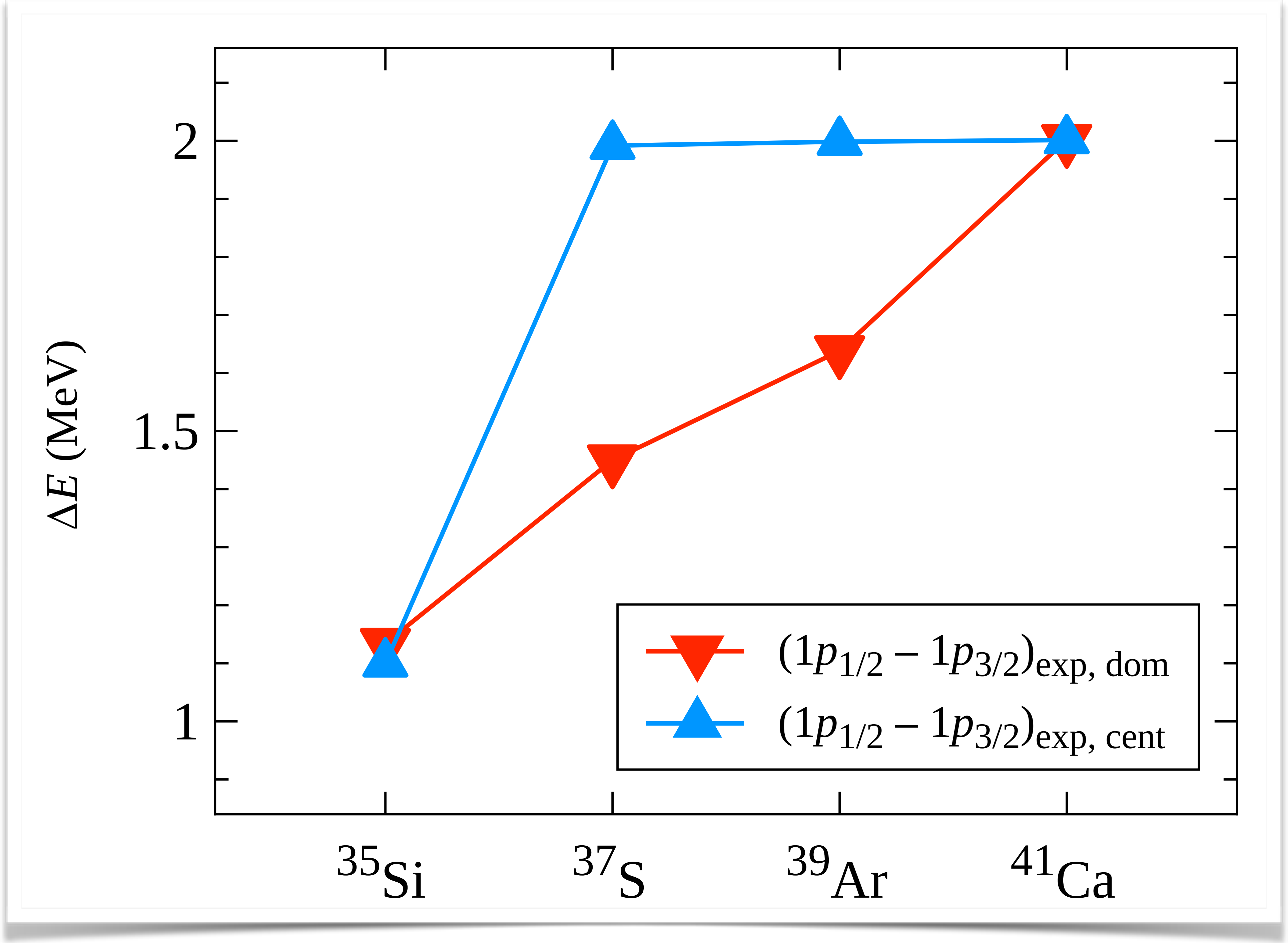

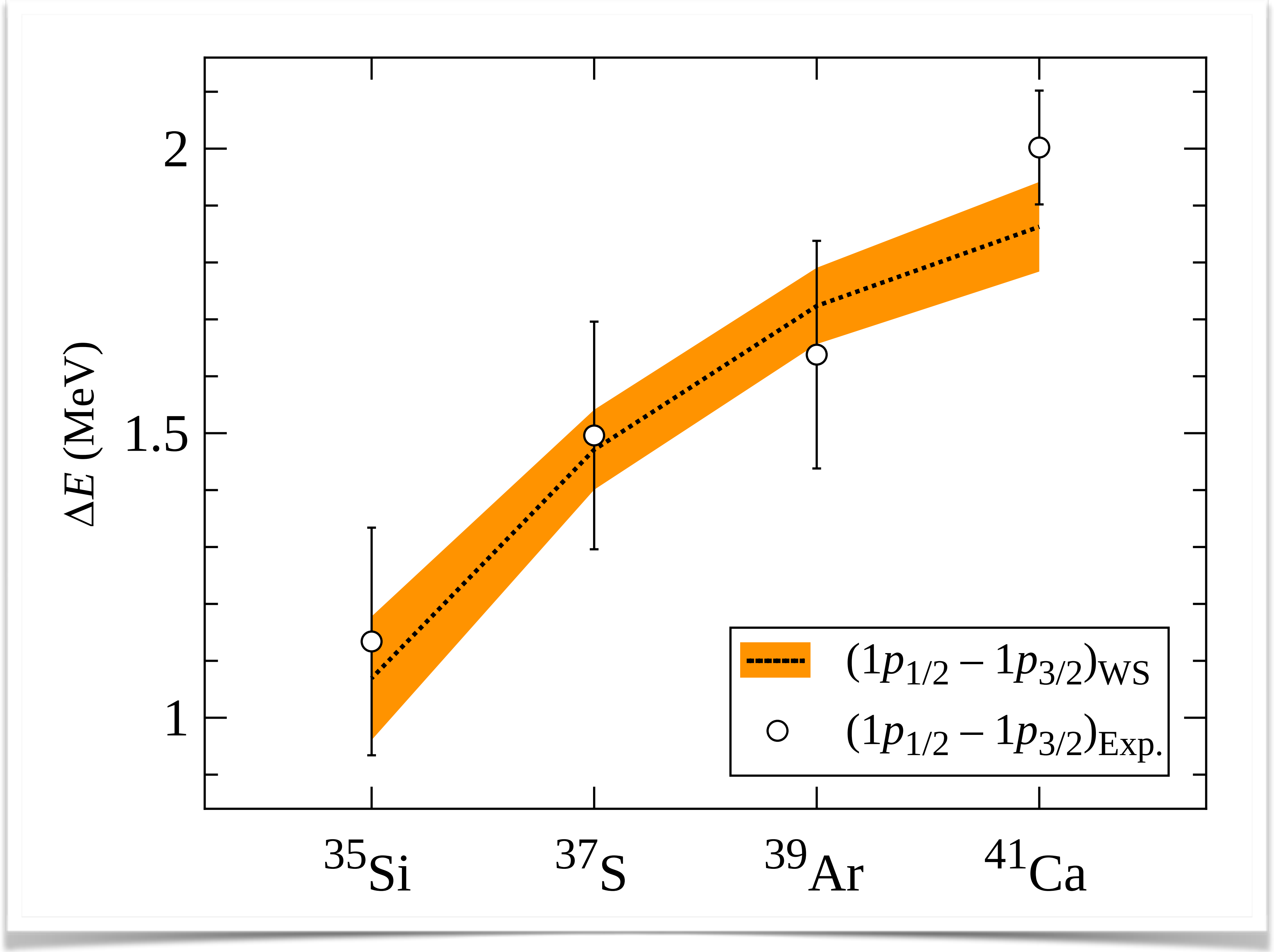

These lectures ends here, the ‘^{34}Si story’ is a great example of well-targeted nuclear-reaction studies and wonderfully well done measurements, given the obstacles.

(However, the story doesn’t end here. You can read the original papers and an interesting follow up [BPK, C. R. Hoffman, and A. O. Macchiavelli, Phys. Rev. Lett. ***119****, 182502 (2017)])*

Closing remarks

The future: facilities in the US and elsewhere have worked to develop exotic beams, we on the precipice an era of exotic-beam physics – the next decade or so will be very exciting as, e.g., FRIB comes on line, other facilities too

(We should not forget, many major works in the last decade or so have also been done with more modest set ups, facilities … exotic beams are not the be-all and end-all.)

How we practice physics is important. *Models have to be understood, their limitations appreciated, and marginal data not pushed too far. Precision and clarity is essential.*

Closing remarks

Transfer reactions, especially those induced by 'simple' projectiles and carried out at energies a few MeV/u above the Coulomb barrier, allow us to infer a great deal about nuclear structure.

The reduced cross sections provide consistent, quantitative nuclear-structure information.

Major text books, monographs, conferences, and 1000s of paper have been dedicated this subject over the 50 years. (In just a few hours I missed out on 99% of the it, I suspect.)

I hope I showed you a few interesting examples, with techniques directly applicable to exciting new measurements with the available/anticipated EBs here in the US and elsewhere – already there are many obvious questions to ask / address.

A major challenge is to bring our instrumentation up to date in order to exploit the weakest exotic beams, to be able to do detailed charged-particle spectroscopy as was done yesteryear.

Closing remarks

It takes a community
The vitality of nuclear physics, in the US and internationally, depends on a vibrant and diverse community … small labs, to behemoths, are all essential parts of the puzzle

…and YOU!