

# Constraining Neutron-Induced Reactions Through the Surrogate Reaction Method

Andrew Ratkiewicz

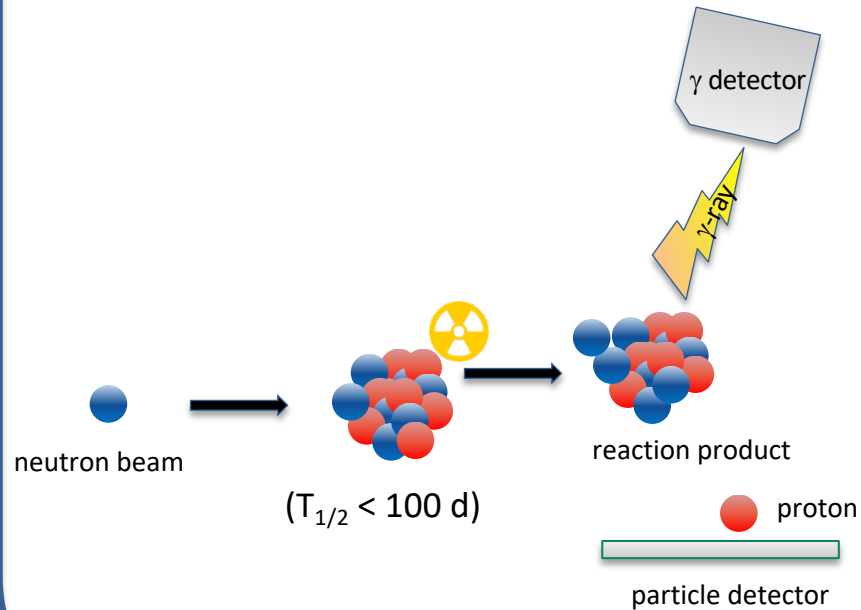
with B. Alan, J.E. Escher, J.T. Harke, R.O. Hughes, G. Potel, C. Reingold,  
and A. Richards

March 01, 2022



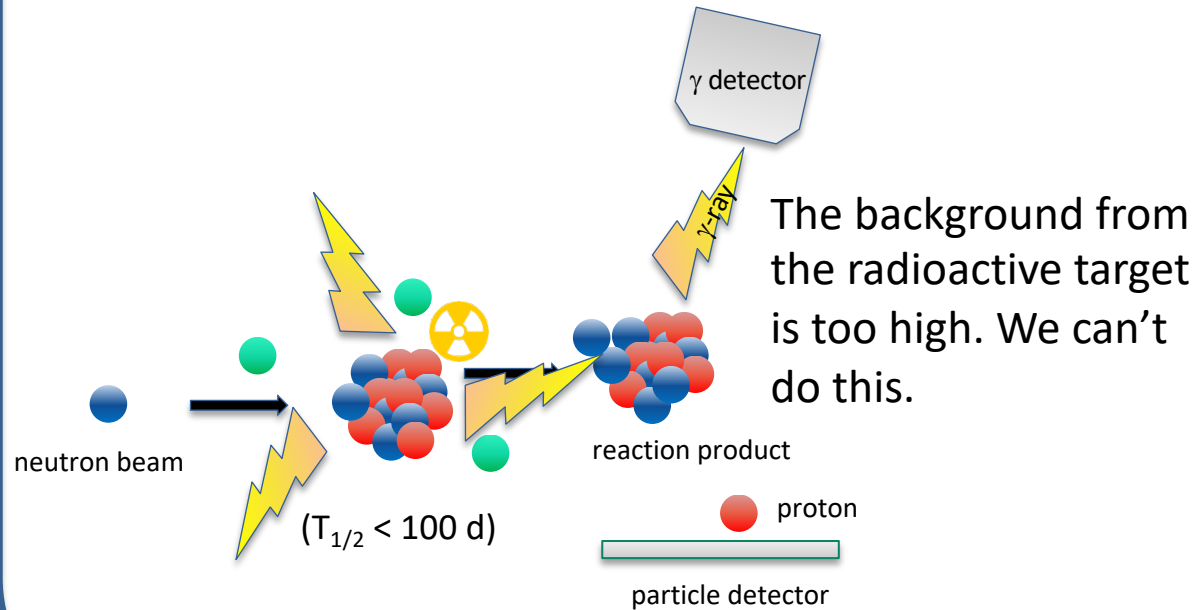
# How do we measure neutron-induced reactions on short-lived radioactive targets?

## Option One: a neutron beam incident on a radioactive target (“normal kinematics”)



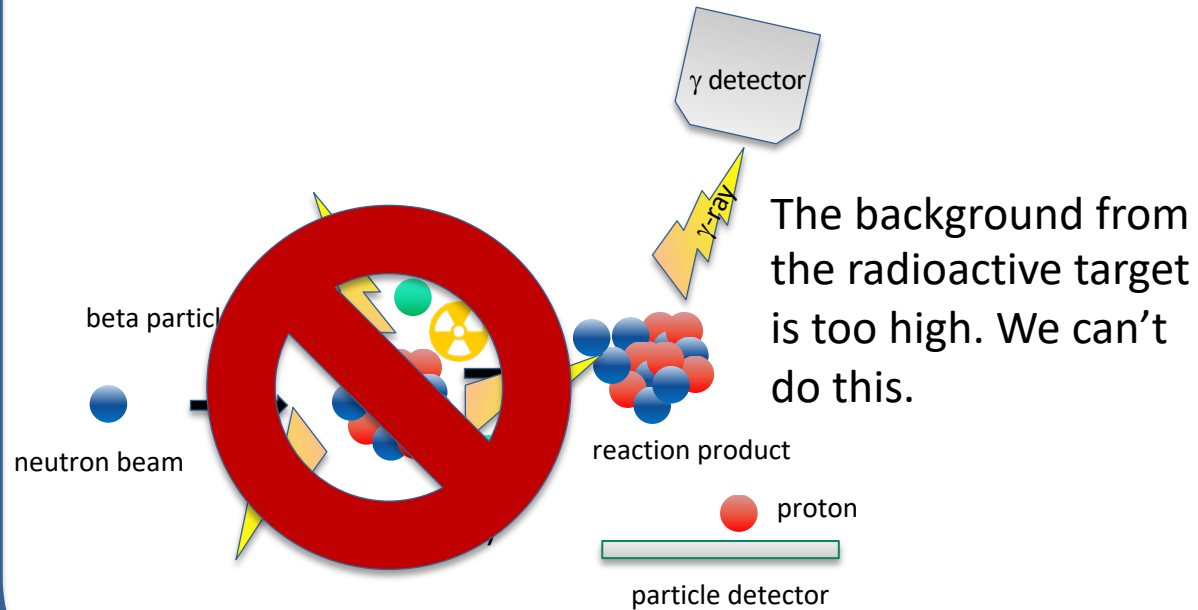
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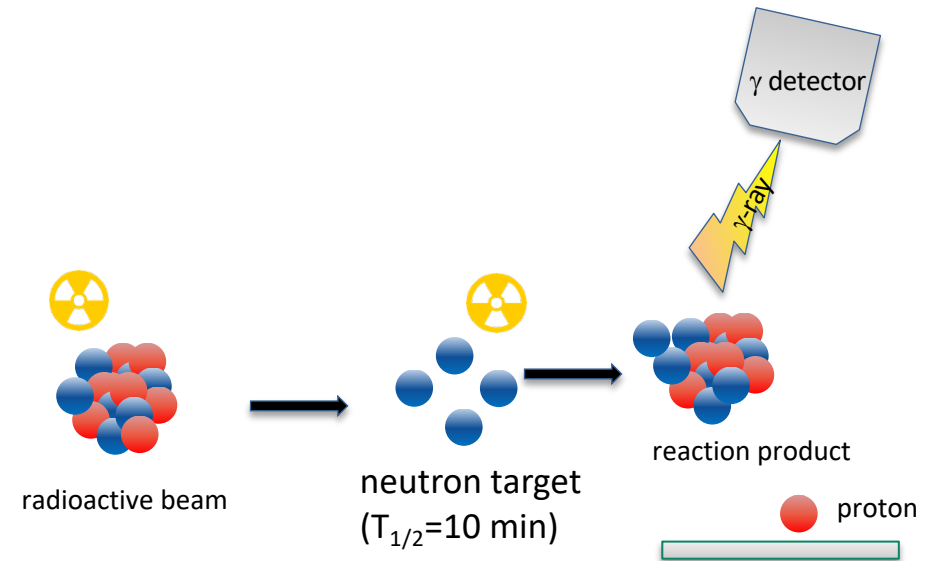


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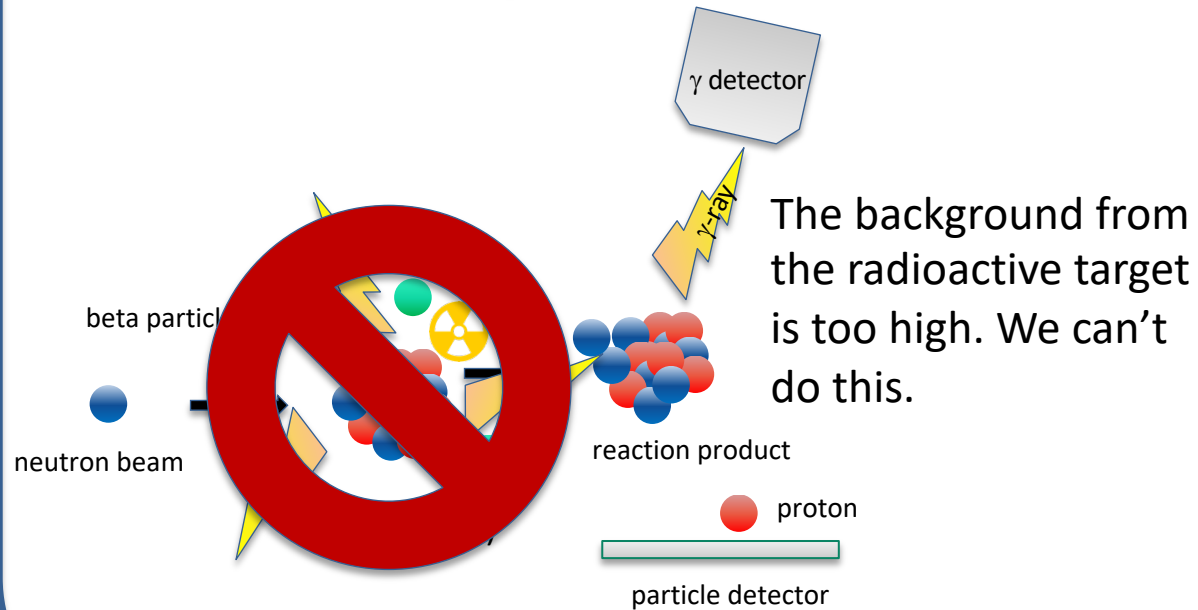


## Option Two: a radioactive beam incident on a neutron target (“inverse kinematics”)



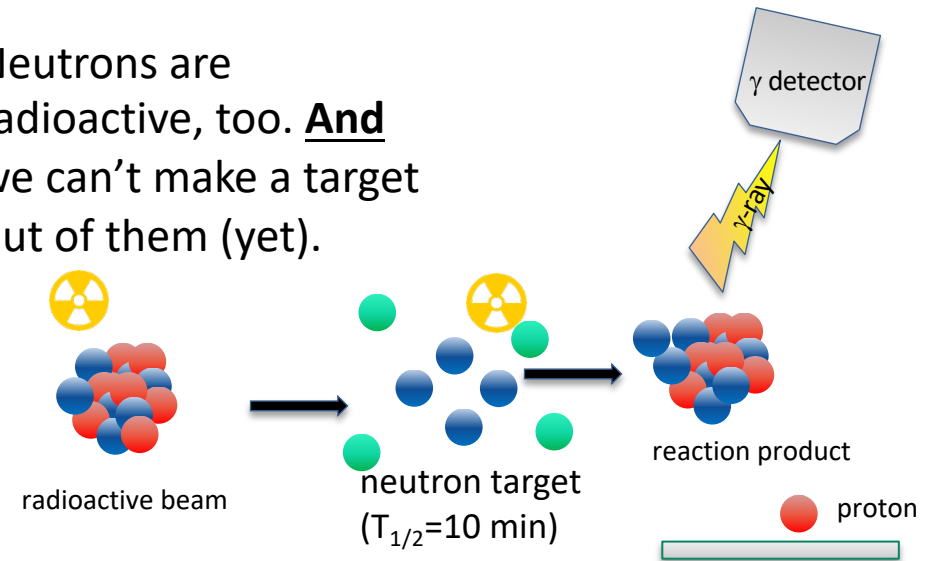
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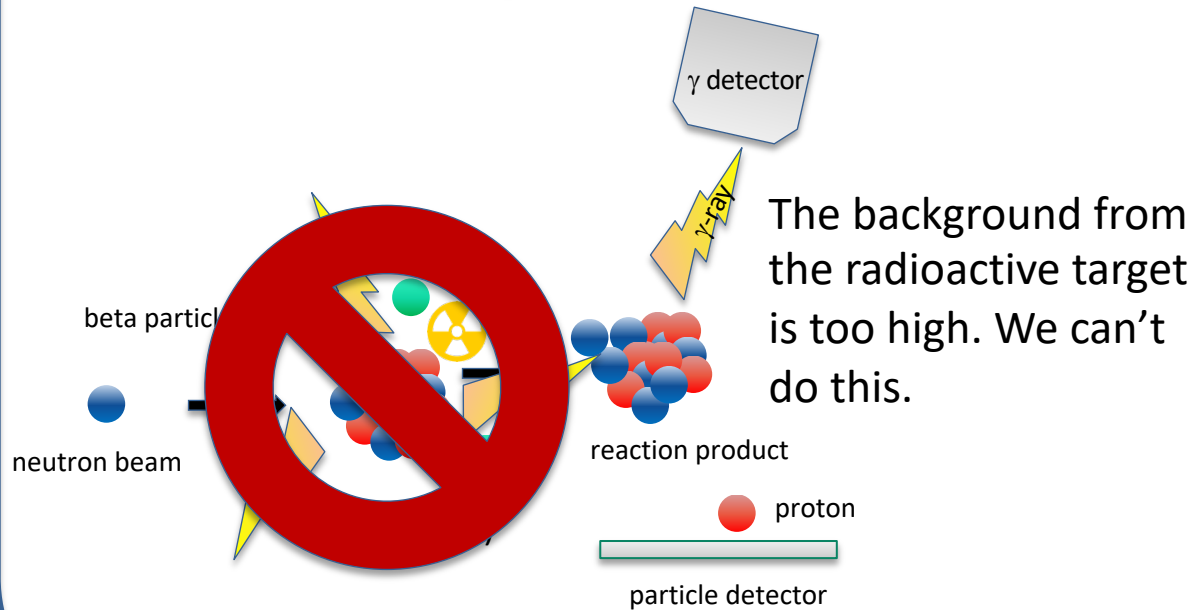
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Neutrons are radioactive, too. And we can't make a target out of them (yet).



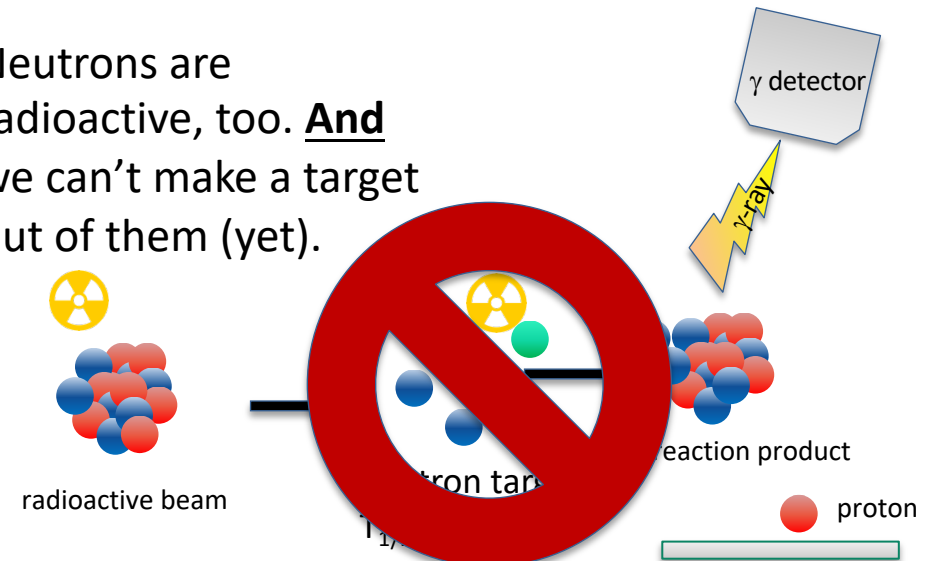
# How do we measure neutron-induced reactions on short-lived radioactive targets? – We can't!

## Option One: a neutron beam incident on a radioactive target ("normal kinematics")



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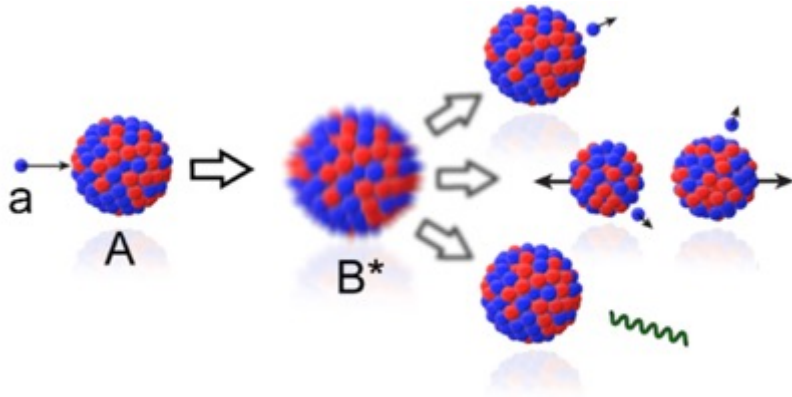
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We need a different approach!

# Using the Surrogate Reaction Method to constrain neutron-induced reactions on radioactive targets

Desired Reaction: impossible to measure

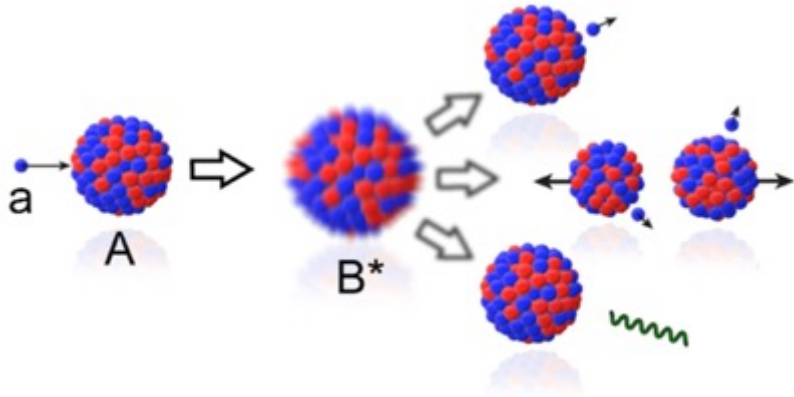


$$\sigma_{\alpha\chi}(E_a) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi)$$

[J.E. Escher \*et al.\* Rev. Mod. Phys. \*\*84\*\*, 353 \(2012\).](#)

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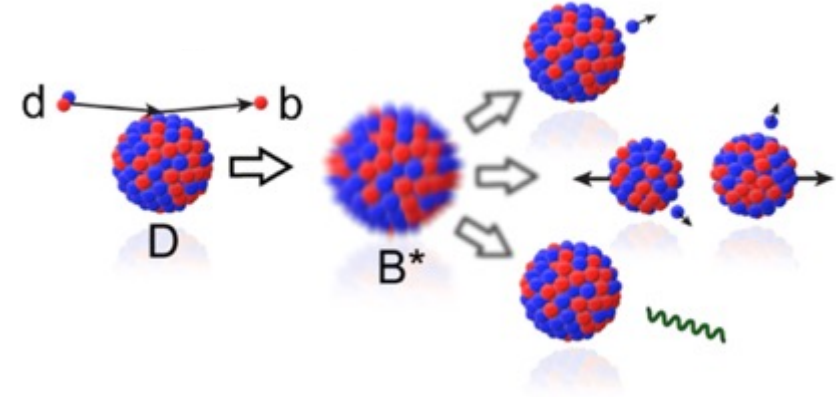
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Surrogate Reaction: forms the “same” **compound nucleus** as the desired reaction.



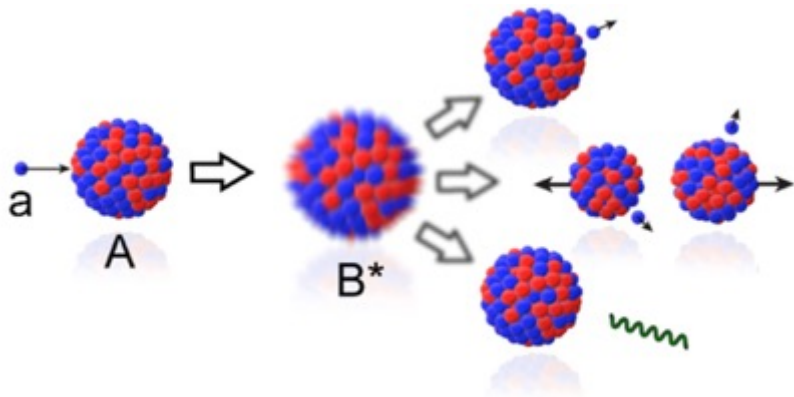
$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi)$$

[J.E. Escher \*et al.\* Phys. Rev. Lett. \*\*121\*\*, 052501 \(2018\).](#)

[A. Ratkiewicz \*et al.\* Phys. Rev. Lett. \*\*122\*\*, 052502 \(2019\).](#)

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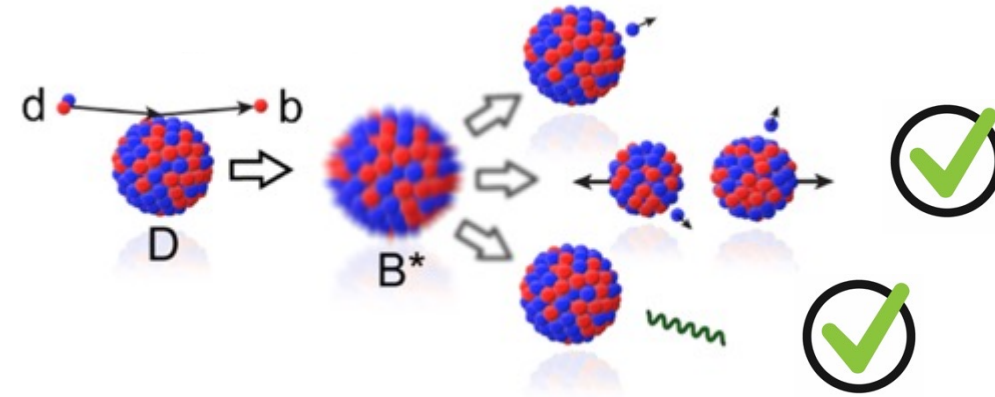
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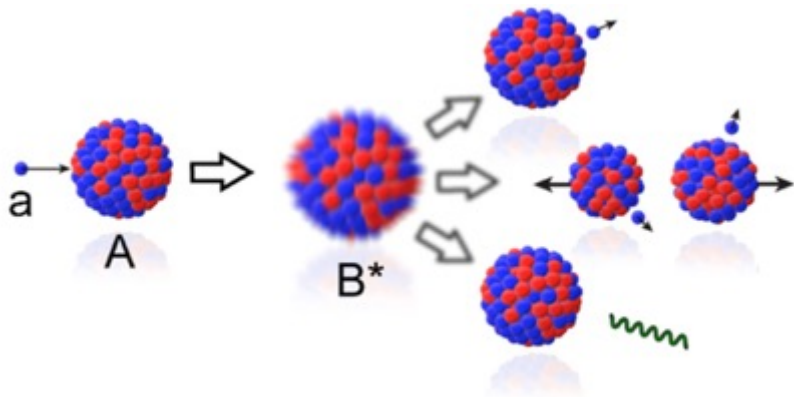
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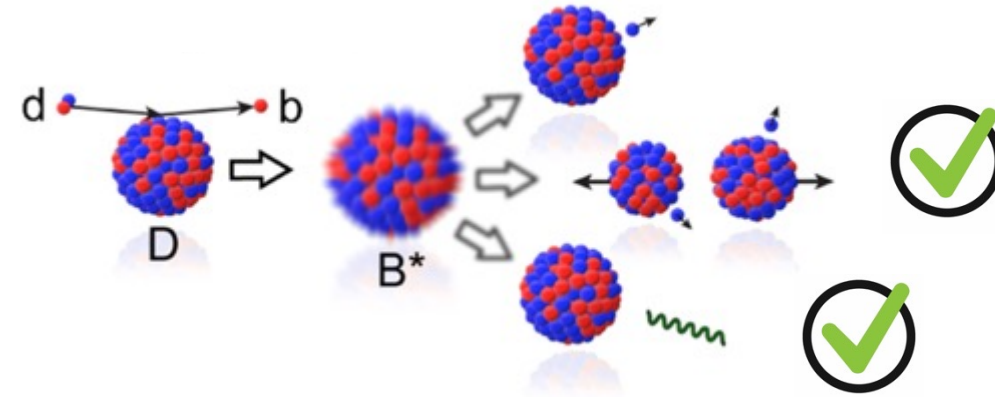
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# Benchmarking (d,p $\gamma$ ) as an (n, $\gamma$ ) surrogate

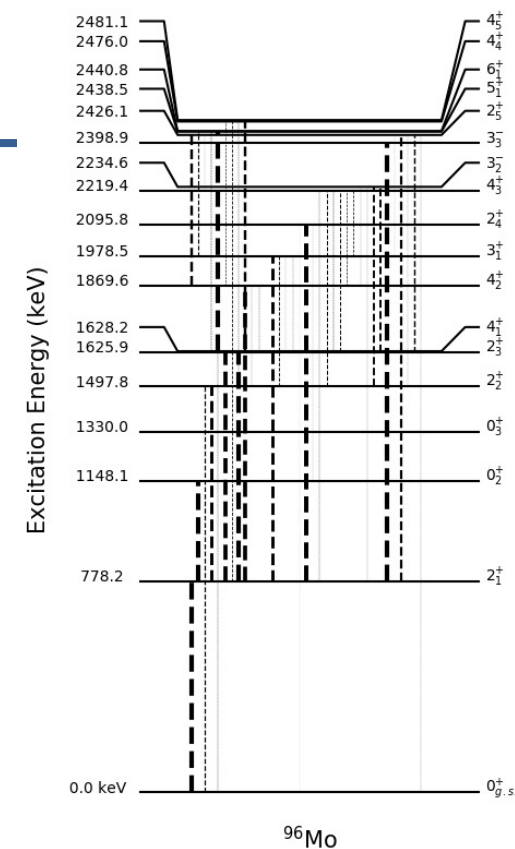
- Requirements for a target:
  - Stable.

Z	93Ru 59.7 S ε: 100.00%	94Ru 51.8 M ε: 100.00%	95Ru 1.643 H ε: 100.00%	96Ru STABLE 5.54%	97Ru 2.83 D ε: 100.00%	98Ru STABLE 1.87%	99Ru STABLE 12.76%	100Ru STABLE 12.80%	101Ru STABLE 17.06%
	92Tc 4.25 M ε: 100.00%	93Tc 2.75 H ε: 100.00%	94Tc 293 M ε: 100.00%	95Tc 20.0 H ε: 100.00%	96Tc 4.28 D ε: 100.00%	97Tc 4.21E+6 Y ε: 100.00%	98Tc 4.2E+6 Y β: 100.00%	99Tc 2.111E+5 Y β: 100.00%	100Tc 15.46 S β: 100.00%
	91Mo 15.49 M ε: 100.00%	92Mo STABLE 14.53%	93Mo 4.0E+3 Y ε: 100.00%	94Mo STABLE 9.15%	95Mo STABLE 15.84%	96Mo STABLE 16.67%	97Mo STABLE 9.60%	98Mo STABLE 24.39%	99Mo 65.976 H ε: 100.00%
	90Nb 14.60 H ε: 100.00%	91Nb 6.8E+2 Y ε: 100.00%	92Nb 3.47E+7 Y ε: 100.00%	93Nb STABLE 100%	94Nb 2.03E+4 Y β: 100.00%	95Nb 34.991 D β: 100.00%	96Nb 23.35 H β: 100.00%	97Nb 72.1 β: 100.00%	98Nb 0.0 β: 100.00%
	89Zr 78.41 H ε: 100.00%	90Zr STABLE 51.45%	91Zr STABLE 11.22%	92Zr STABLE 17.15%	93Zr 1.61E+6 Y β: 100.00%	94Zr STABLE 17.38%	95Zr 64.032 D β: 100.00%	96Zr 2.35E+19 Y 2.80% β: 100.00%	97Zr 16.749 H β: 100.00%
	49	50	51	52	53	54	55	56	N

# Benchmarking (d,p $\gamma$ ) as an (n, $\gamma$ ) surrogate

- Requirements for a target:
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  - Product of (n, $\gamma$ ) is an even-even nucleus, strong  $2^+ \rightarrow 0^+$  collecting transition.

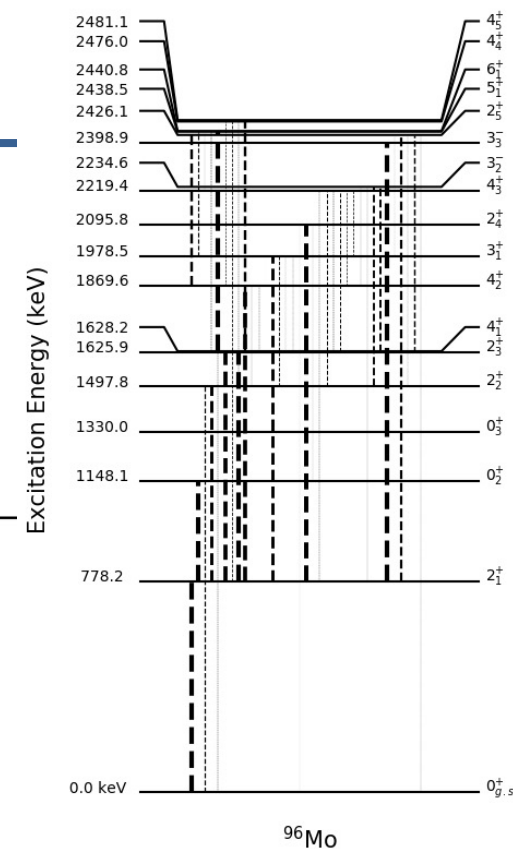
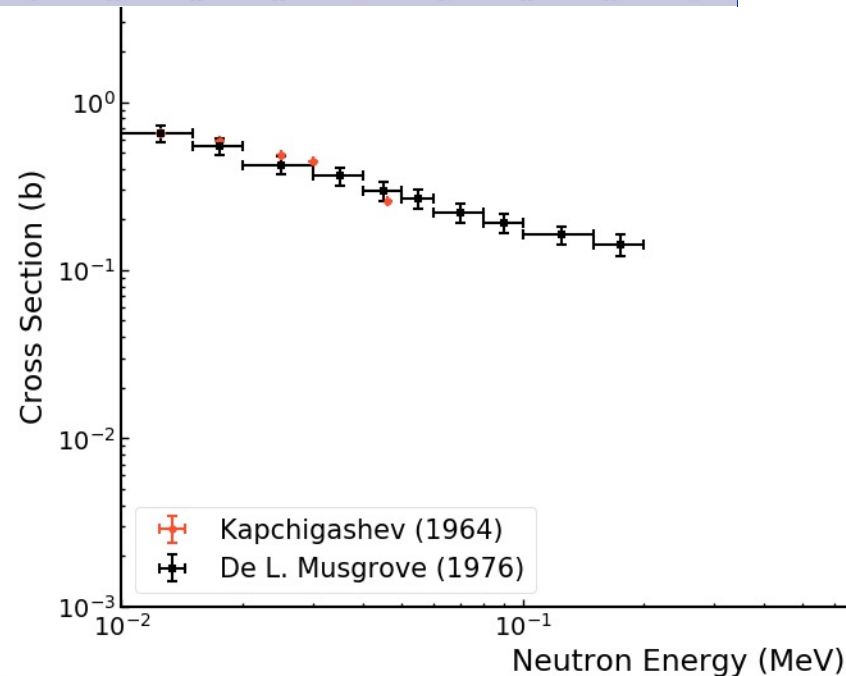
Z	93Ru	94Ru	95Ru	96Ru	97Ru	98Ru	99Ru	100Ru	101Ru
	59.7 S	51.8 M	1.643 H	STABLE	2.83 D	STABLE	STABLE	STABLE	STABLE
	$\approx 100.00\%$	$\approx 100.00\%$	$\approx 100.00\%$	5.54%	$\approx 100.00\%$	1.87%	12.76%	12.80%	17.06%
43	92Tc	93Tc	94Tc	95Tc	96Tc	97Tc	98Tc	99Tc	100Tc
	4.25 M	2.75 H	293 M	20.0 H	4.28 D	4.21E+6 Y	4.2E+6 Y	2.111E+5 Y	15.46 S
	$\approx 100.00\%$	$\approx 100.00\%$	$\approx 100.00\%$	$\approx 100.00\%$	$\approx 100.00\%$	$\approx 100.00\%$	$\beta^- 100.00\%$	$\beta^- 100.00\%$	$\beta^- 100.00\%$
42	91Mo	92Mo	93Mo	94Mo	95Mo	96Mo	97Mo	98Mo	99Mo
	15.49 M	STABLE	4.0E+3 Y	STABLE	STABLE	STABLE	STABLE	STABLE	65.976 H
	$\approx 100.00\%$	14.53%	$\approx 100.00\%$	9.15%	15.84%	16.67%	9.60%	24.39%	$\approx 100.00\%$
41	90Nb	91Nb	92Nb	93Nb	94Nb	95Nb	96Nb	97Nb	98Nb
	14.60 H	6.8E+2 Y	3.47E+7 Y	STABLE	2.03E+4 Y	34.991 D	23.35 H	72.1	72.1
	$\approx 100.00\%$	$\approx 100.00\%$	$\approx 100.00\%$	100%	$\beta^- 100.00\%$	$\beta^- 100.00\%$	$\beta^- 100.00\%$	$\beta^- 100.00\%$	$\beta^- 100.00\%$
40	89Zr	90Zr	91Zr	92Zr	93Zr	94Zr	95Zr	96Zr	97Zr
	78.41 H	STABLE	STABLE	STABLE	1.61E+6 Y	STABLE	64.032 D	2.35E+19 Y	16.749 H
	$\approx 100.00\%$	51.45%	11.22%	17.15%	$\beta^- 100.00\%$	17.38%	$\beta^- 100.00\%$	2.80% $\beta^-$	$\beta^- 100.00\%$
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# Benchmarking (d,p $\gamma$ ) as an (n, $\gamma$ ) surrogate

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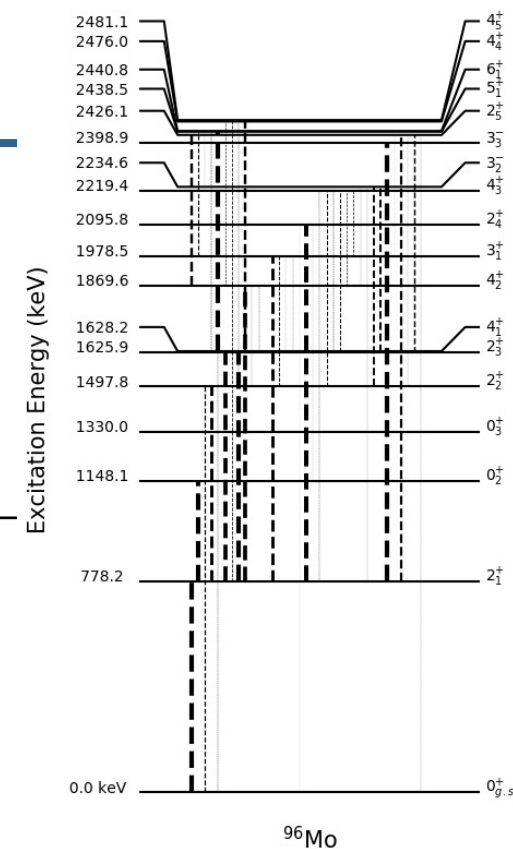
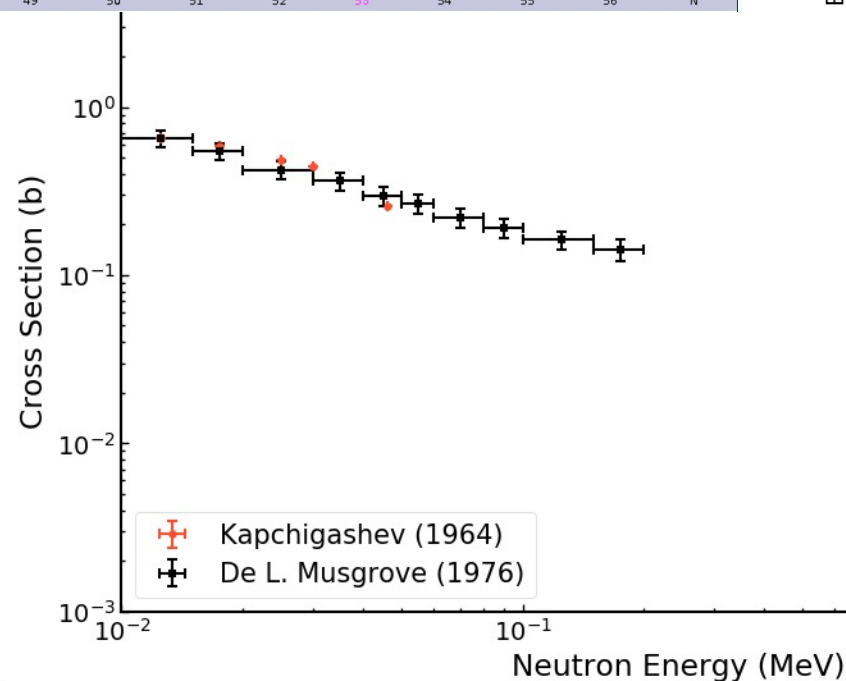
$^{96}\text{Mo}$  levels from [RIPL-3](#) (R. Capote *et al.*)

# Benchmarking (d,p $\gamma$ ) as an (n, $\gamma$ ) surrogate

- Requirements for a target:
  - Stable.
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  - Product of (n, $\gamma$ ) is an even-even nucleus, strong  $2^+ \rightarrow 0^+$  collecting transition.
  - Known (n, $\gamma$ ) cross section as a function of neutron energy.
- Need to understand:
  - ☐ Reaction mechanism.
  - ☐ Entry spin distribution.

$^{96}\text{Mo}$  levels from [RIPL-3](#) (R. Capote *et al.*)

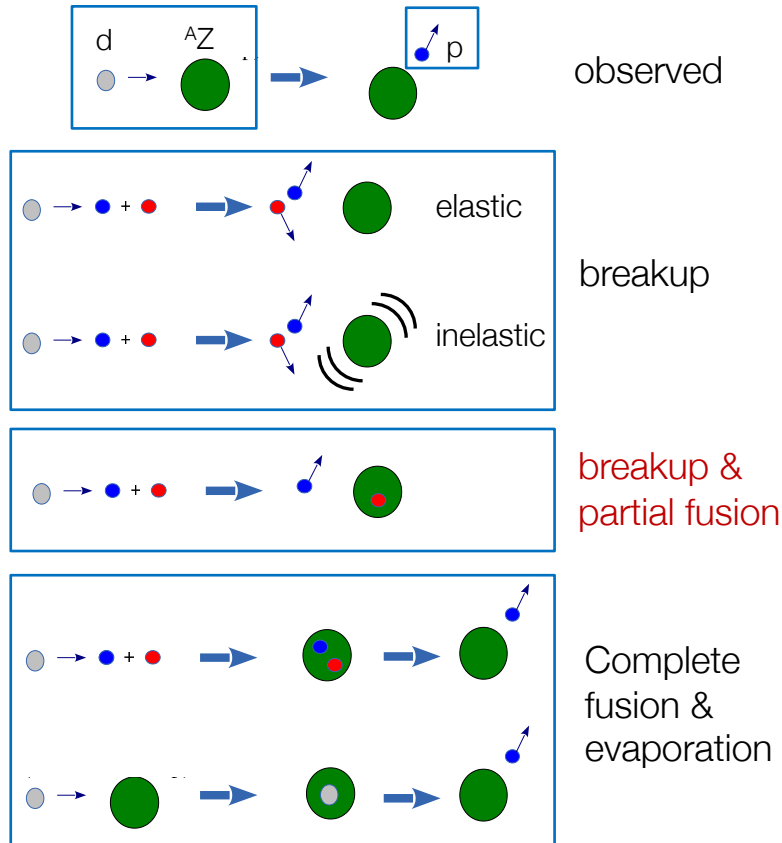
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# Reaction Mechanism: (d,p)

## revisited for the FRIB era

G. Potel et al.



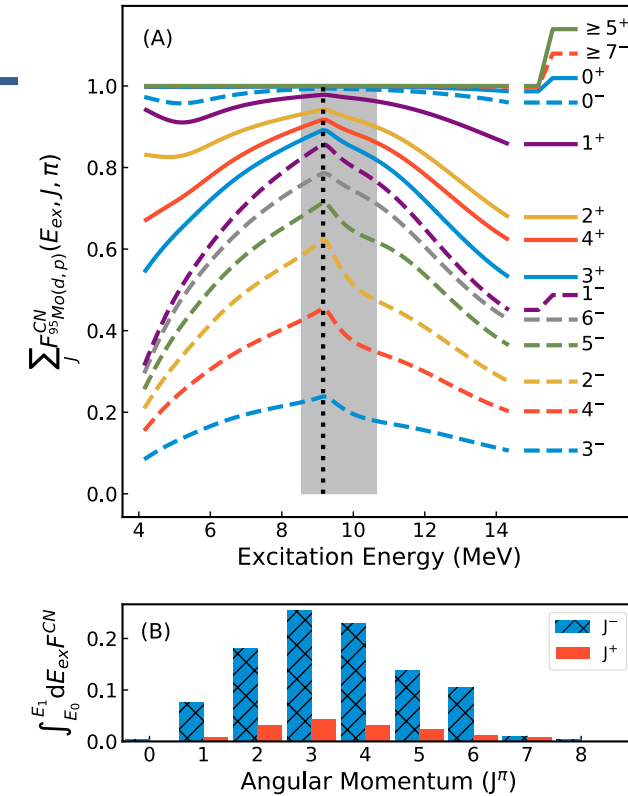
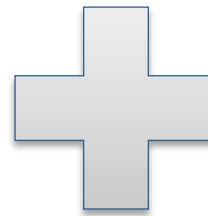
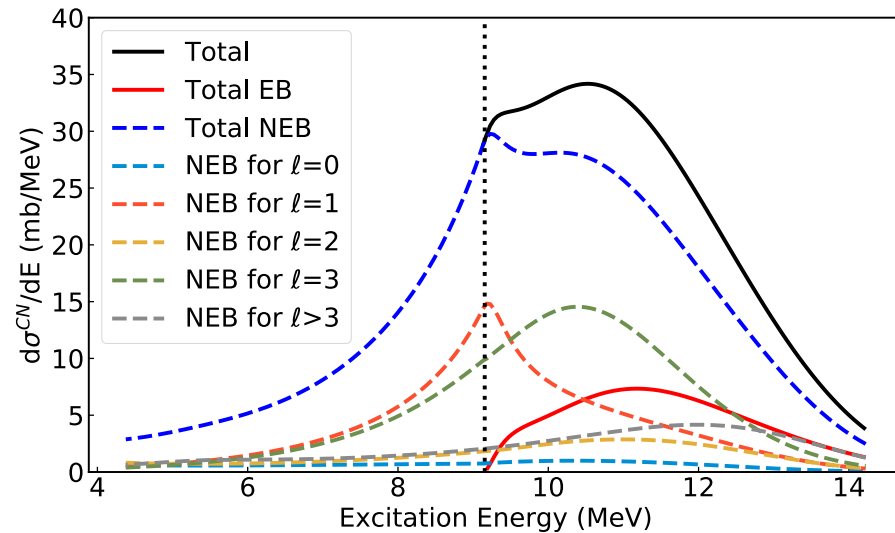
### Inclusive (d,p) reactions recently revisited: formalism

- Based on earlier work by [Udagawa & Tamura](#) and [Ichimura, Austern & Vincent](#)
- Goal: describe breakup-fusion, which contains CN formation
- [Potel et al, PRC 92, 034611 \(2015\)](#)
- [Lei & Moro, PRC 92, 044616 \(2015\)](#)
- [Carlson et al, Few-Body Syst 57, 307 \(2016\)](#), [arxiv:1508.01466](#)

### Applications:

- Comparison to  $^{93}\text{Nb}(d,p)$  inclusive cross sections - [Potel et al., PRC 92, 034611 \(2015\)](#)
- Predictions for  $^{40,48,60}\text{Ca}(d,p\gamma)$  - [Potel et al., EPJ 53, 178 \(2017\)](#)
- Application: **Surrogate for  $^{95}\text{Mo}(n,\gamma)$**  with Ratkiewicz, Cizewski, Escher, et al.: Measurements in regular and inverse kinematics, at Texas A&M and ANL, respectively

# Reaction Mechanism and Entry Spin Distribution



$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi)$$

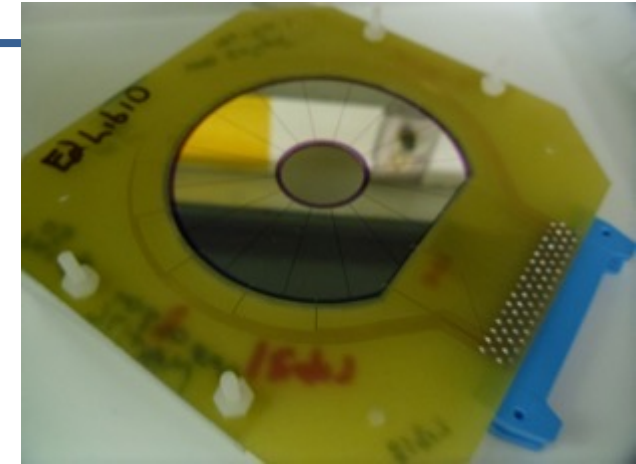
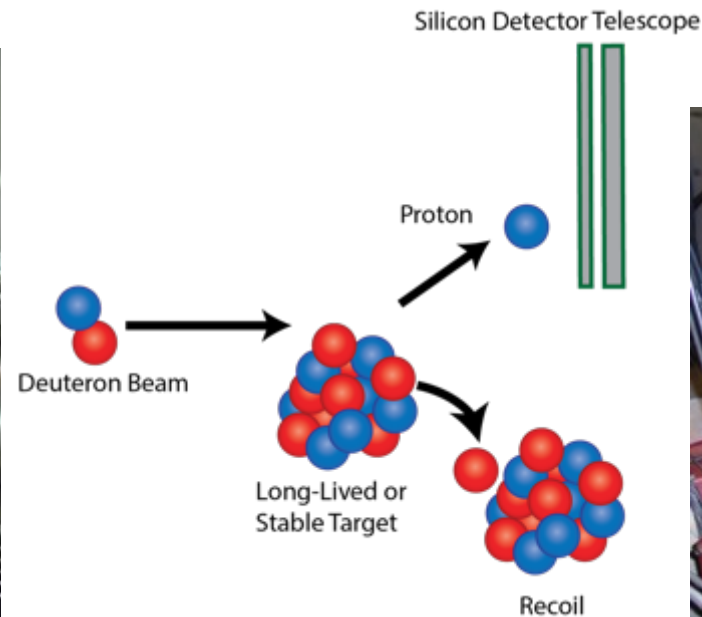
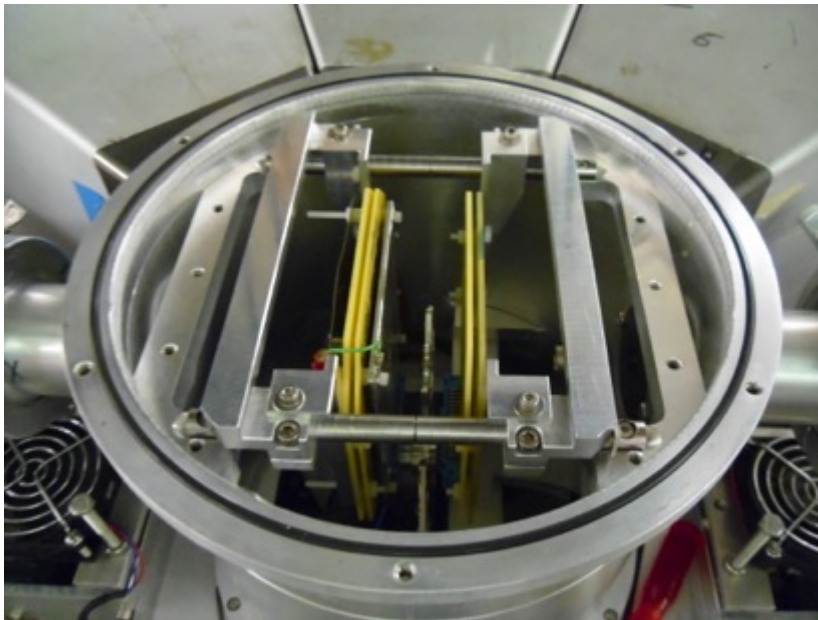
Correct theoretical description of the CN formation cross section and entry spin distribution are essential!

# The Experiment: $^{95}\text{Mo}(\text{d},\text{p}\gamma)$

A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).

$$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_{\gamma}}$$

- 140  $\mu\text{m}$  + 1000  $\mu\text{m}$  segmented telescopes at forward, backward angles.
- Beam energy of 12.5 MeV.
- 0.960  $\text{mg}/\text{cm}^2$  thick  $^{95}\text{Mo}$  target ( $\sim 97\%$   $^{95}\text{Mo}$ , 1.5%  $^{96}\text{Mo}$ ).
- Four Compton-suppressed HPGe clovers at 90, 220, 270, 320 degrees (lab frame).

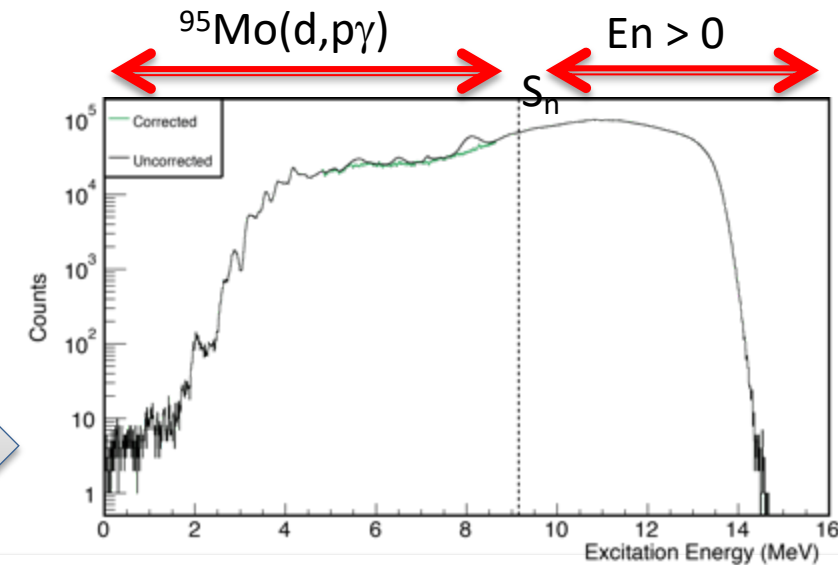
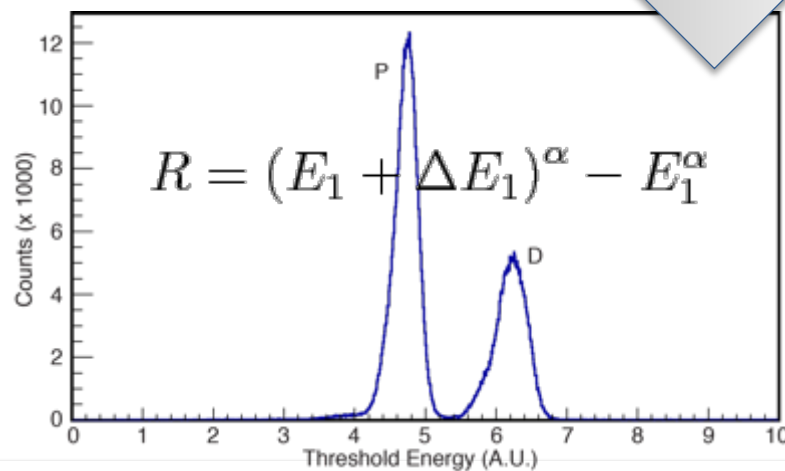
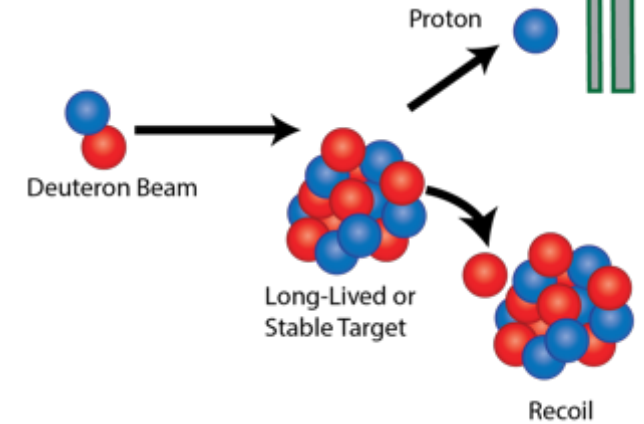
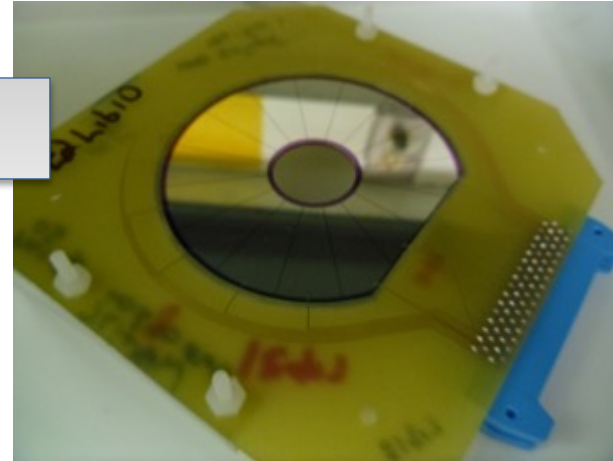
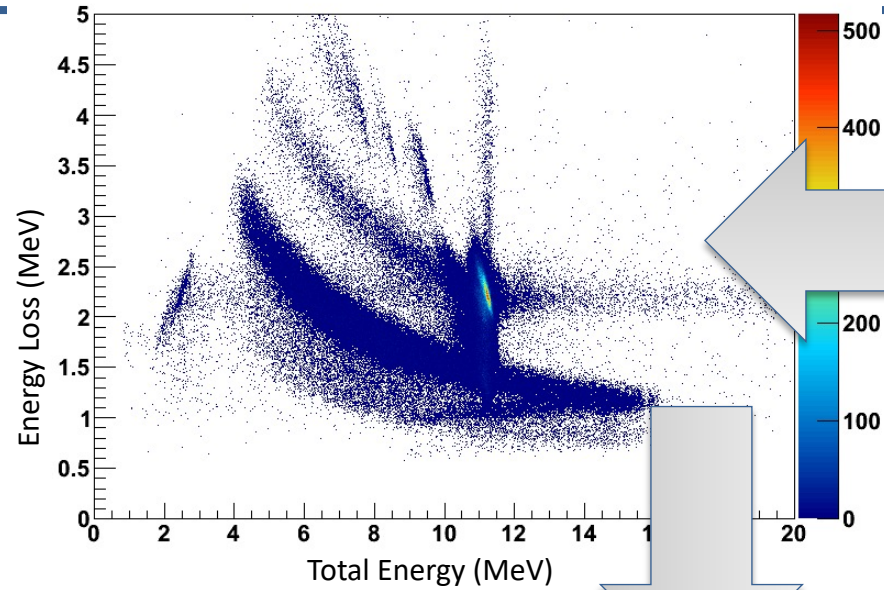


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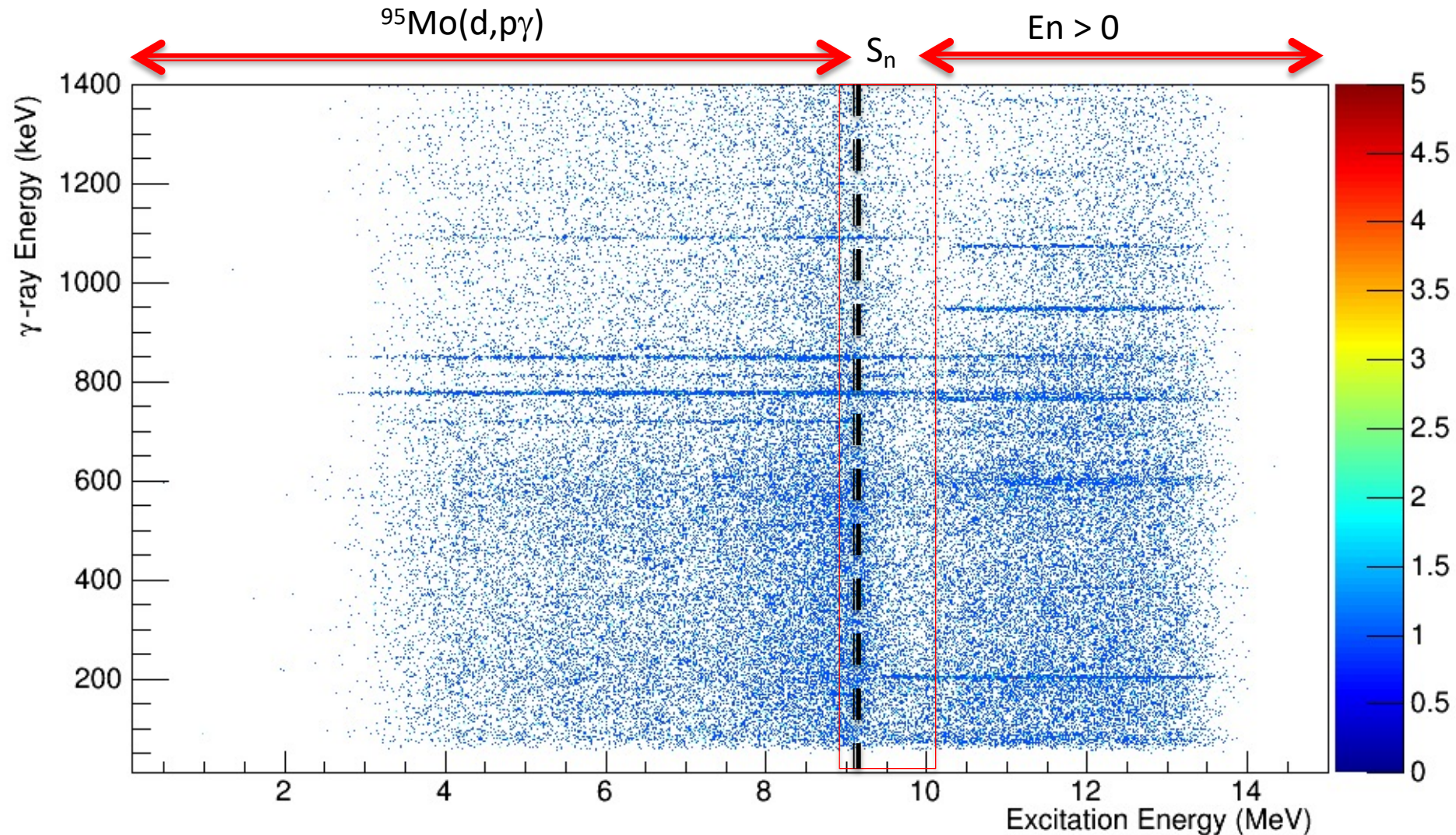
Silicon Detector Telescope



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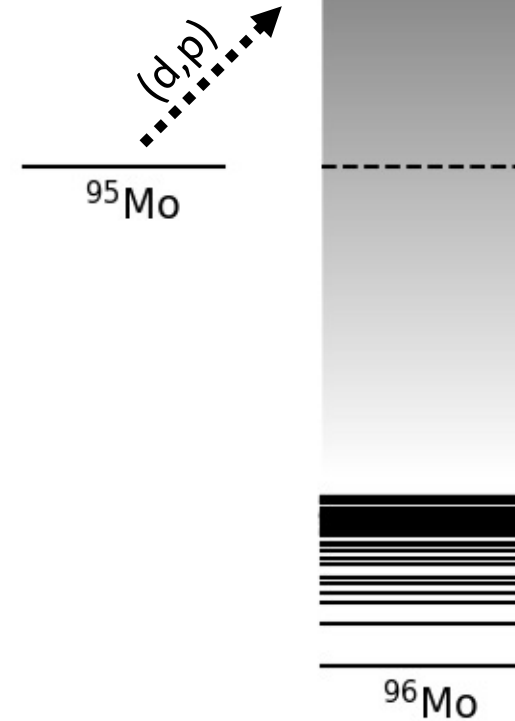
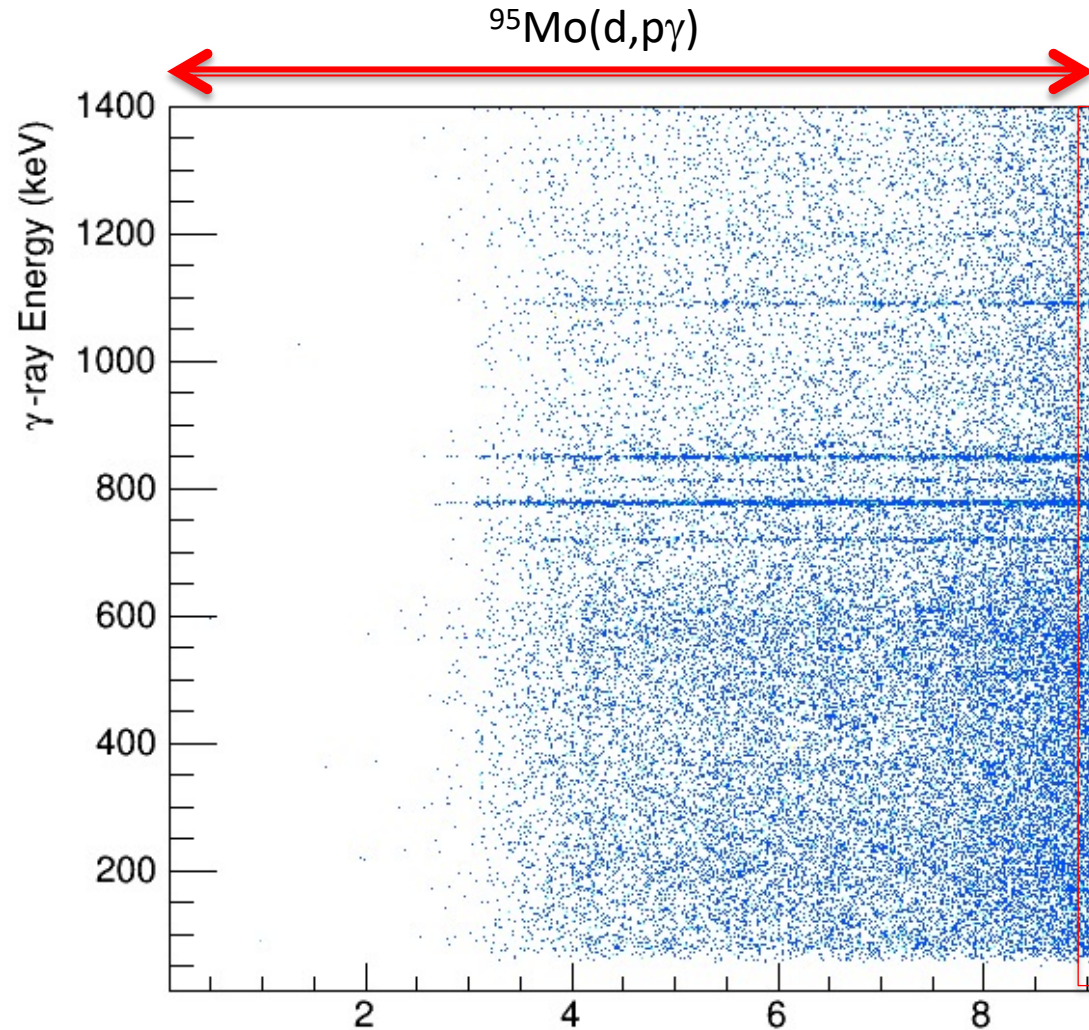
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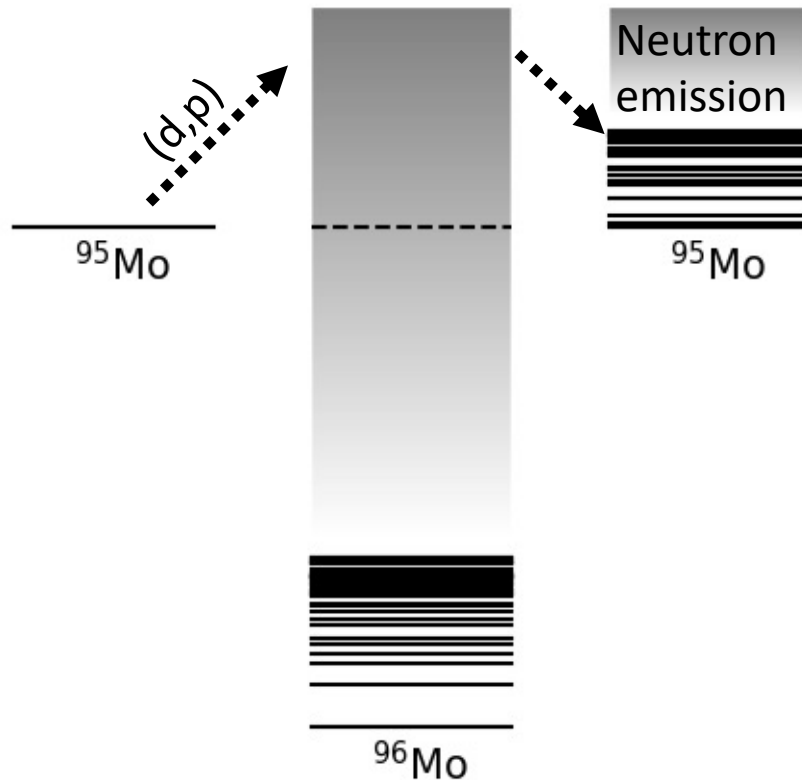
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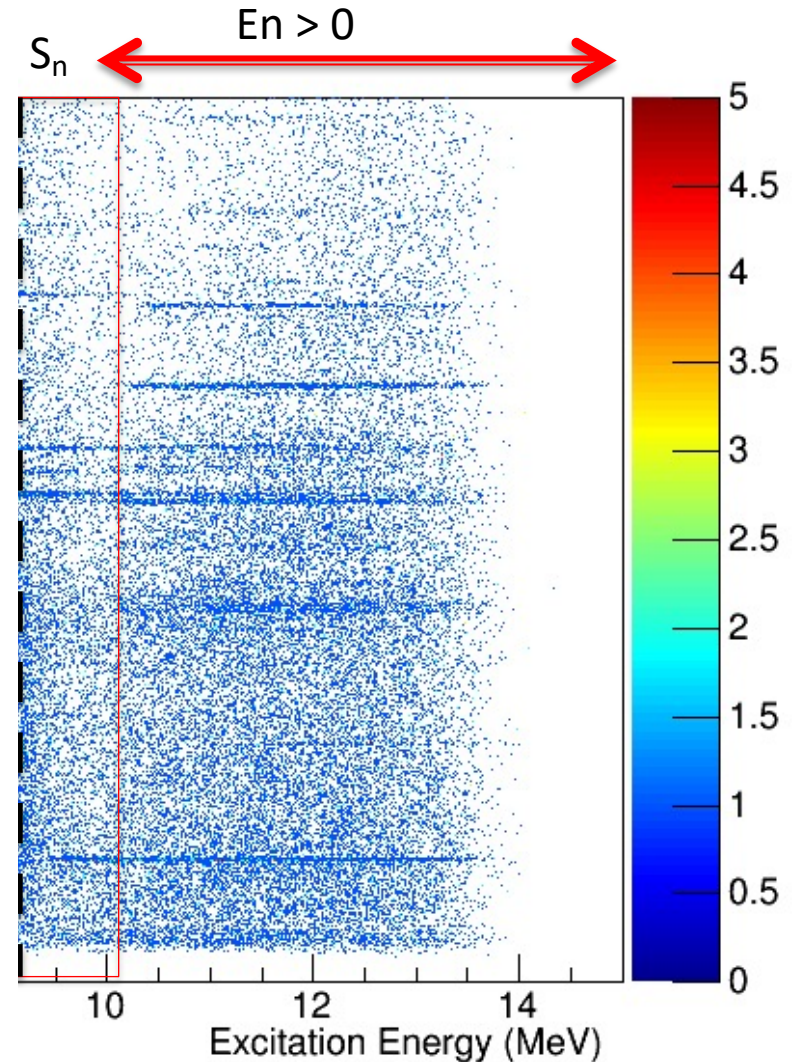
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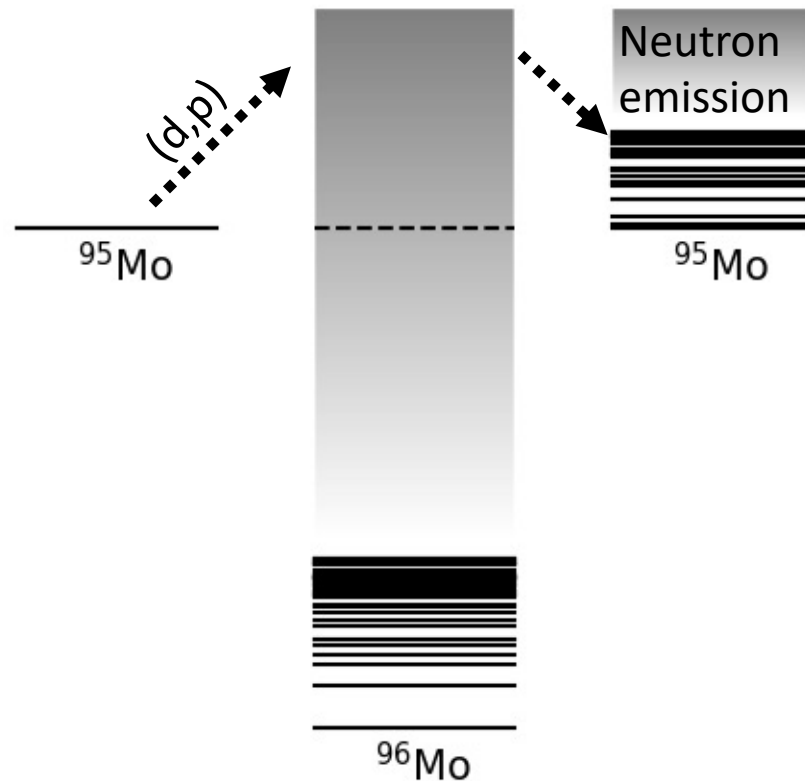
$^{95,96}\text{Mo}$  levels from [RIPL-3](#) (R. Capote et al.)

$$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_\gamma}$$



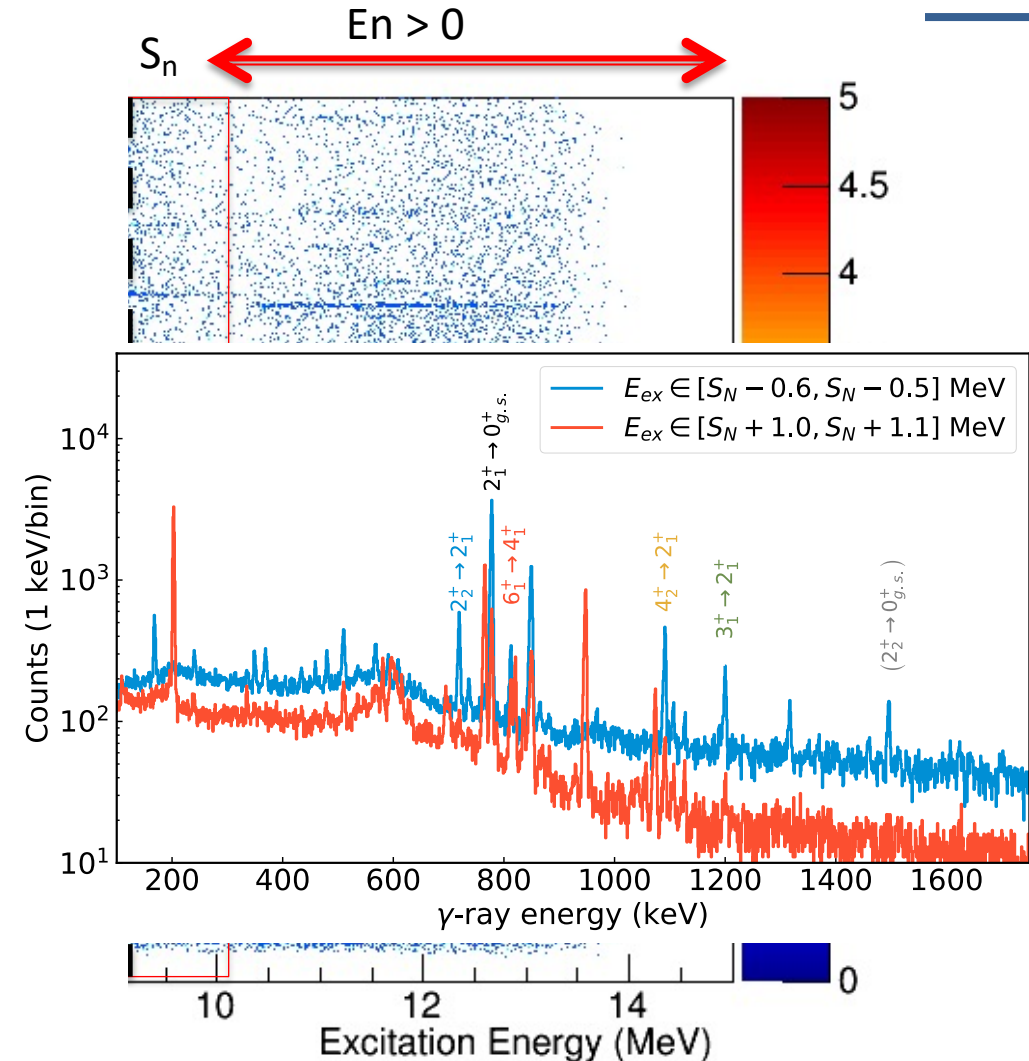
# The Experiment: $^{95}\text{Mo}(d,p\gamma)$

A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



$^{95,96}\text{Mo}$  levels from [RIPL-3](#) (R. Capote et al.)

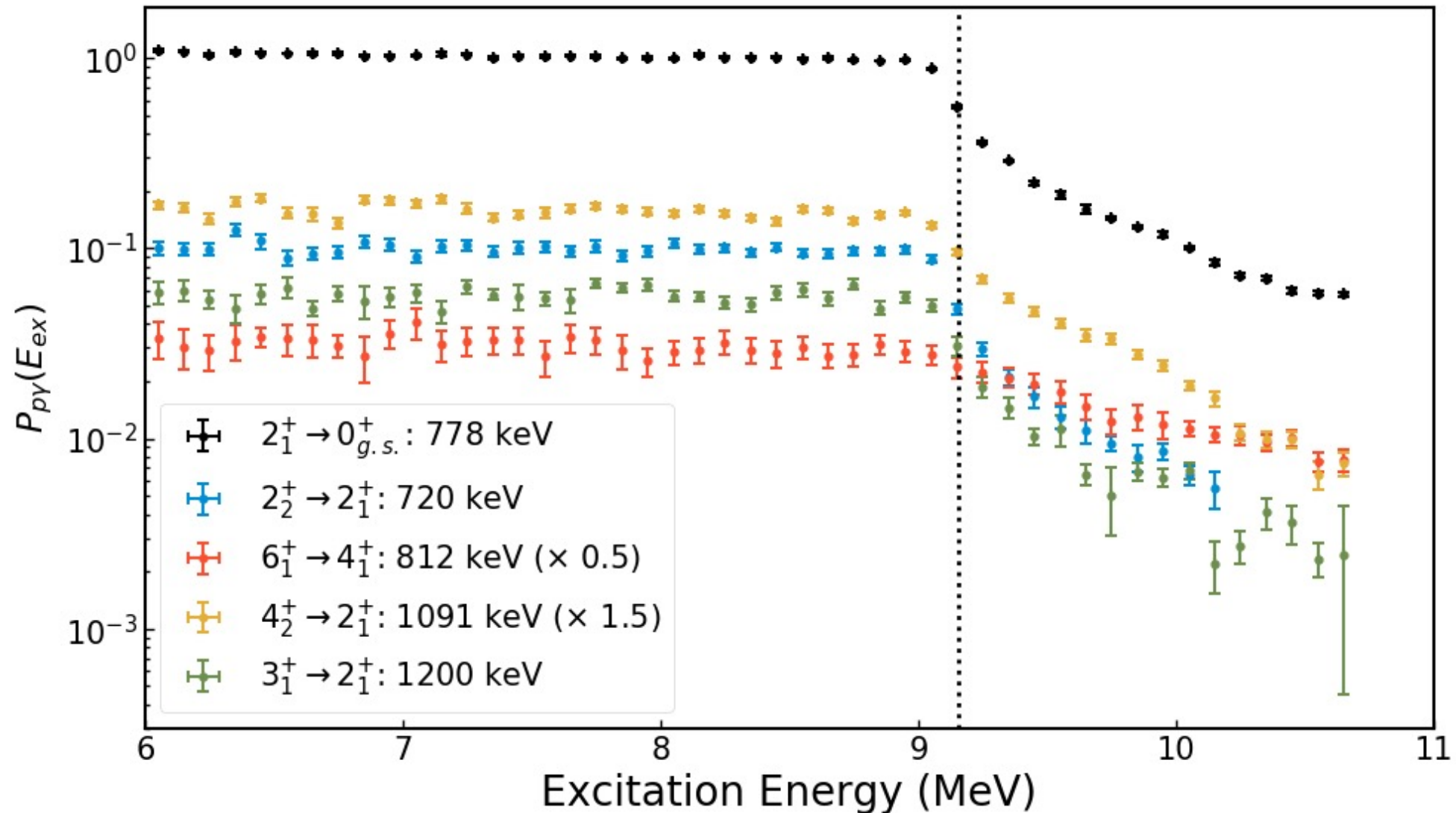
$$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_\gamma}$$



# The Experiment: $^{95}\text{Mo}(\text{d},\text{p}\gamma)$

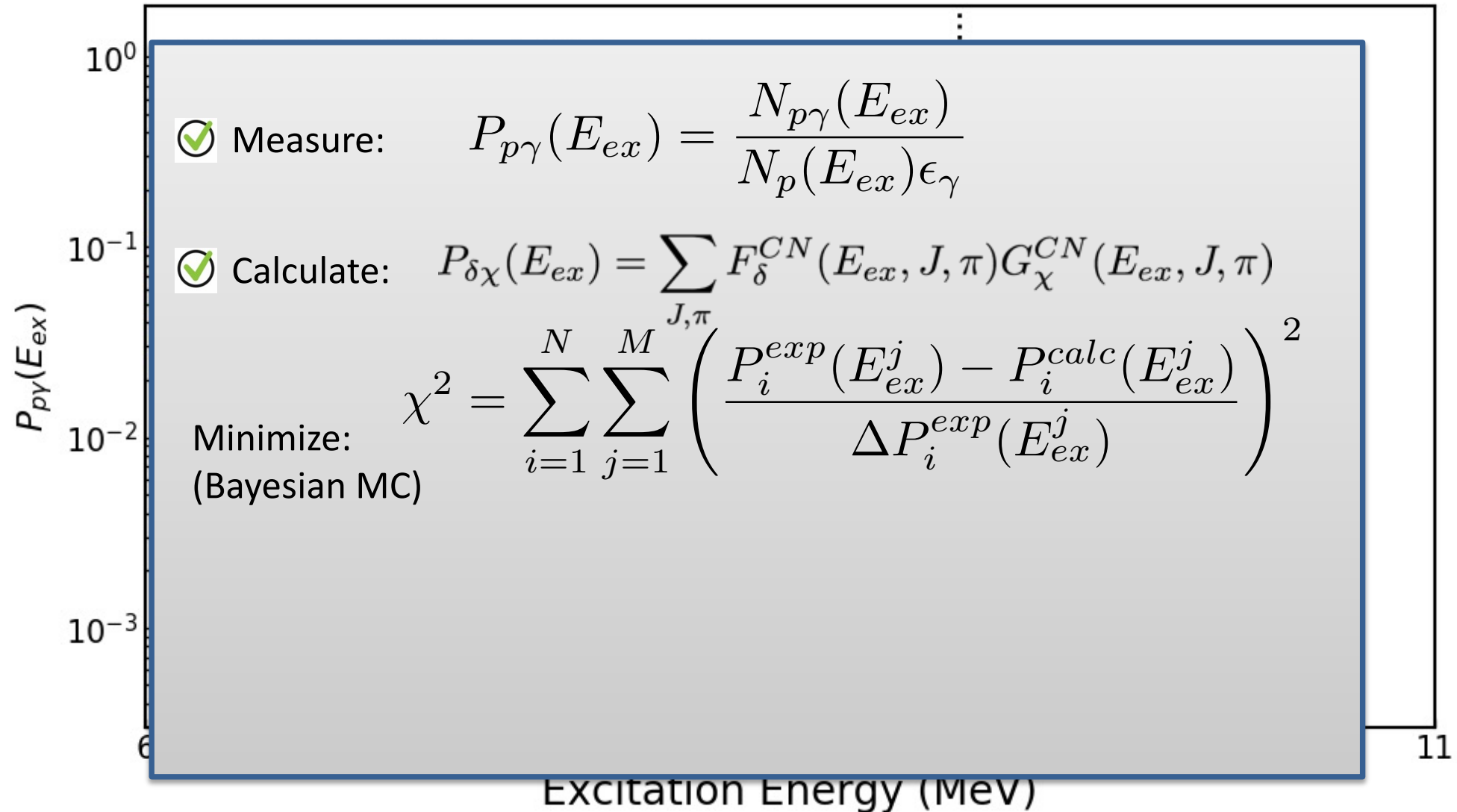
A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).

$$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_\gamma}$$



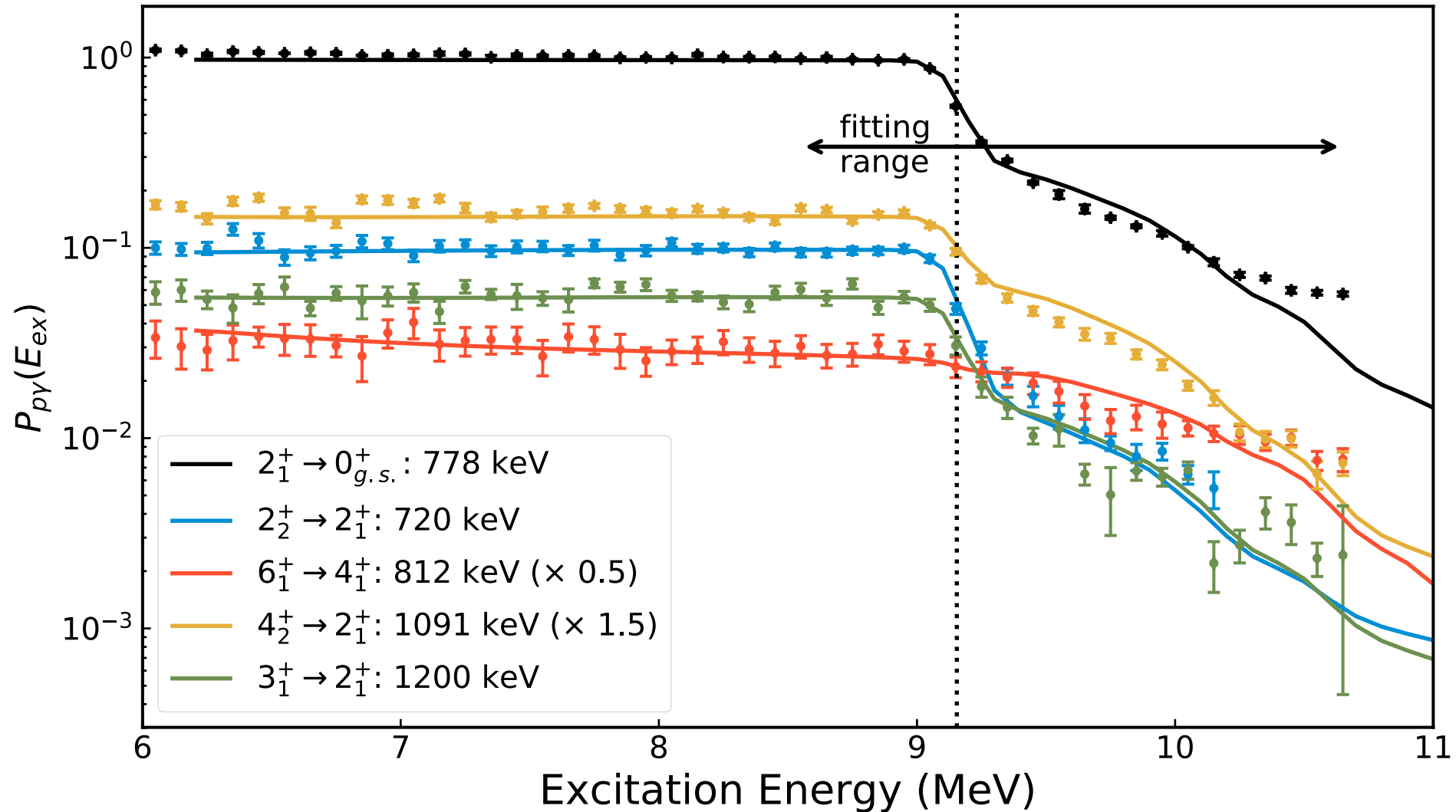
# The Experiment: $^{95}\text{Mo}(\text{d},\text{p}\gamma)$

A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



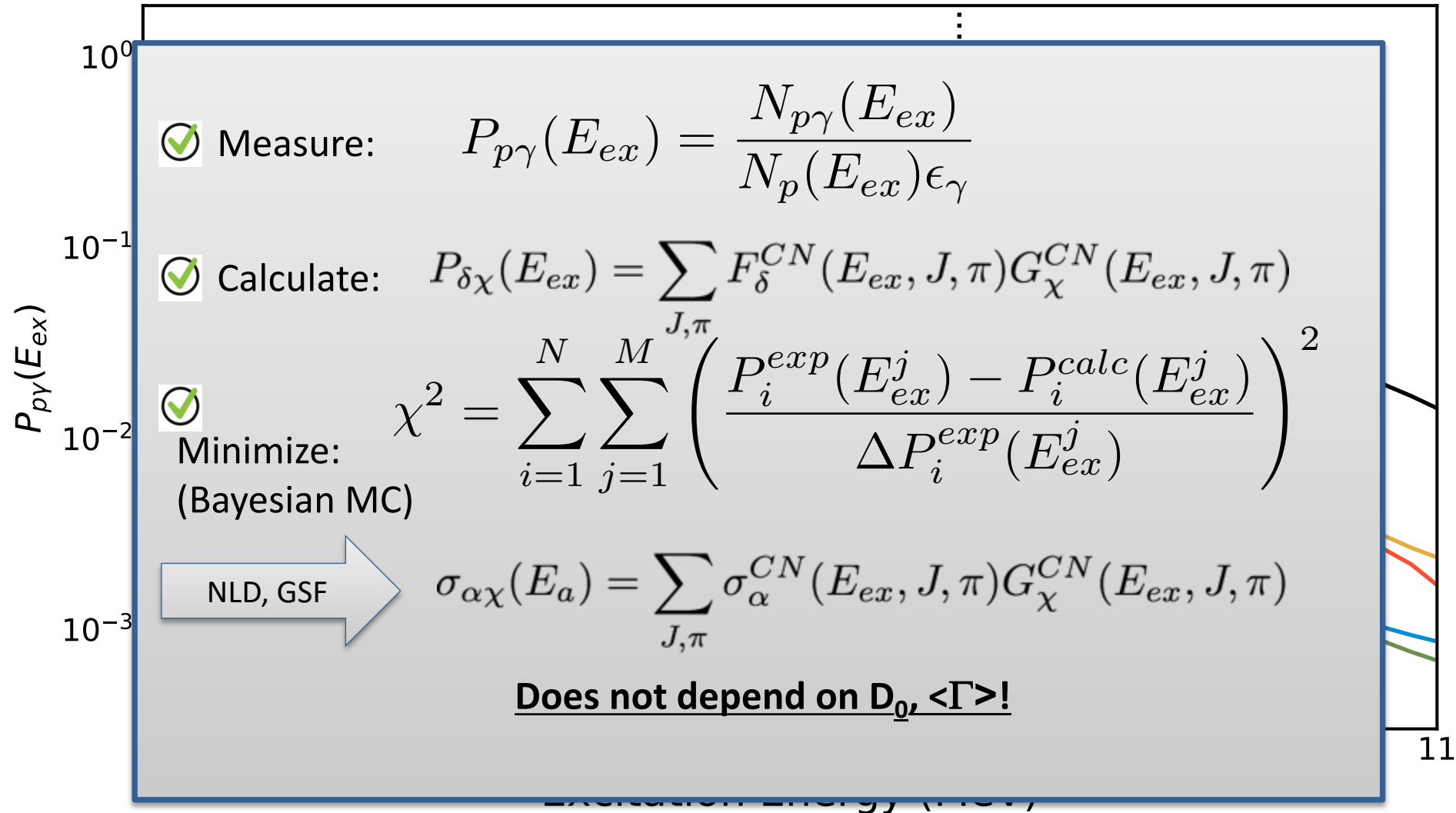
# The Experiment: $^{95}\text{Mo}(\text{d},\text{p}\gamma)$

A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



# The Experiment: $^{95}\text{Mo}(\text{d},\text{p}\gamma)$

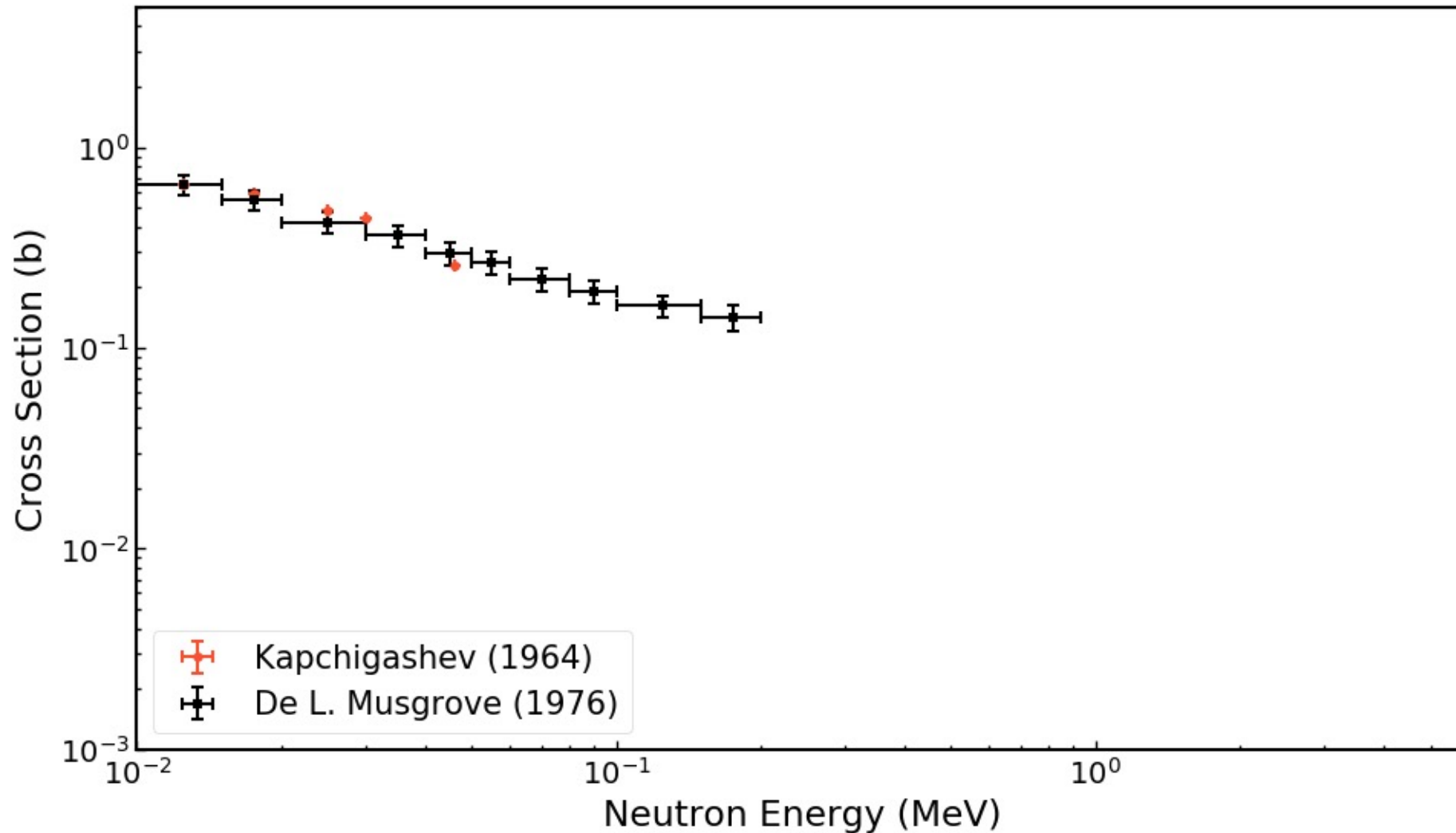
A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



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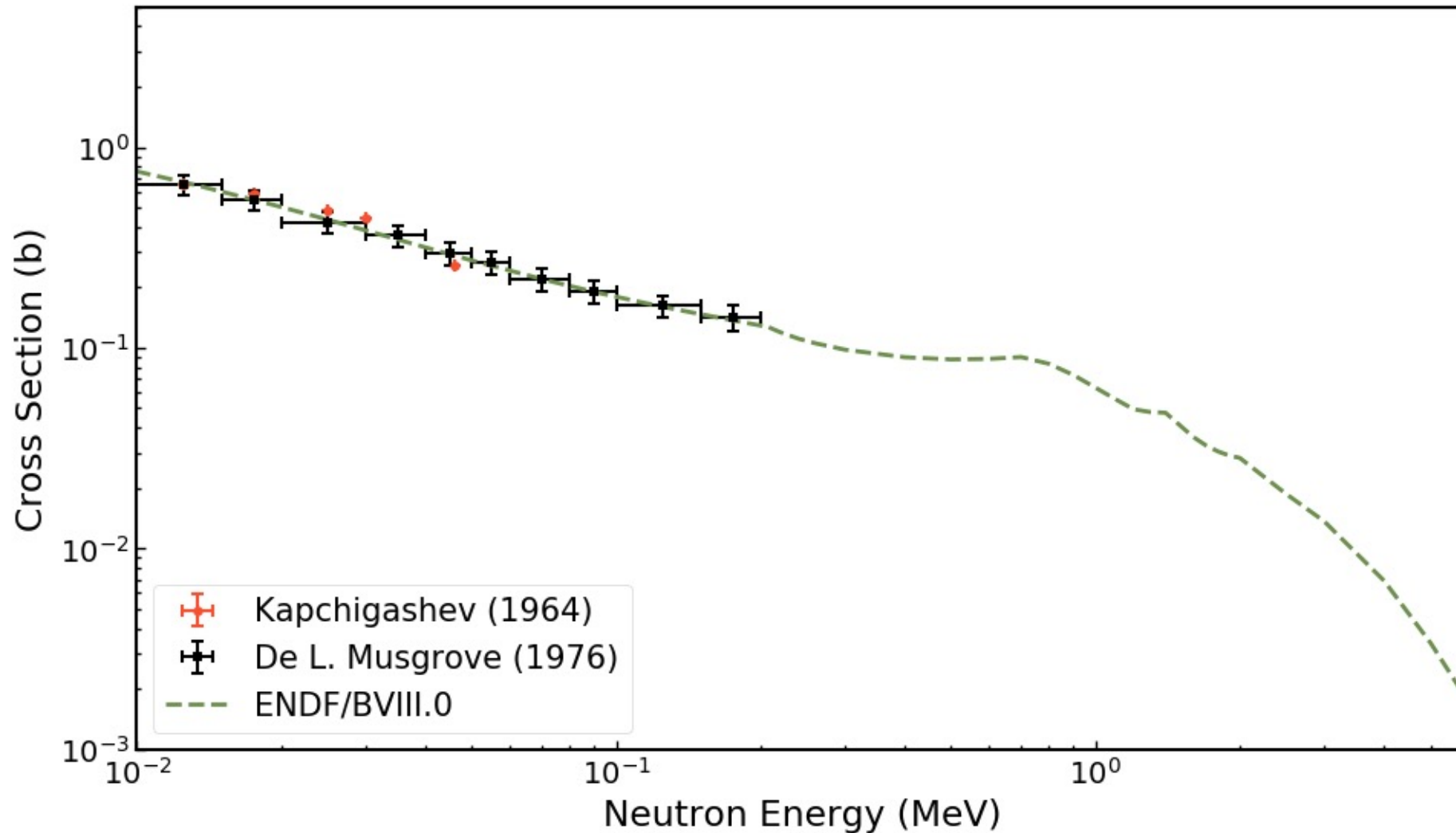
# The Experiment: $^{95}\text{Mo}(\text{d},\text{p}\gamma)$

A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



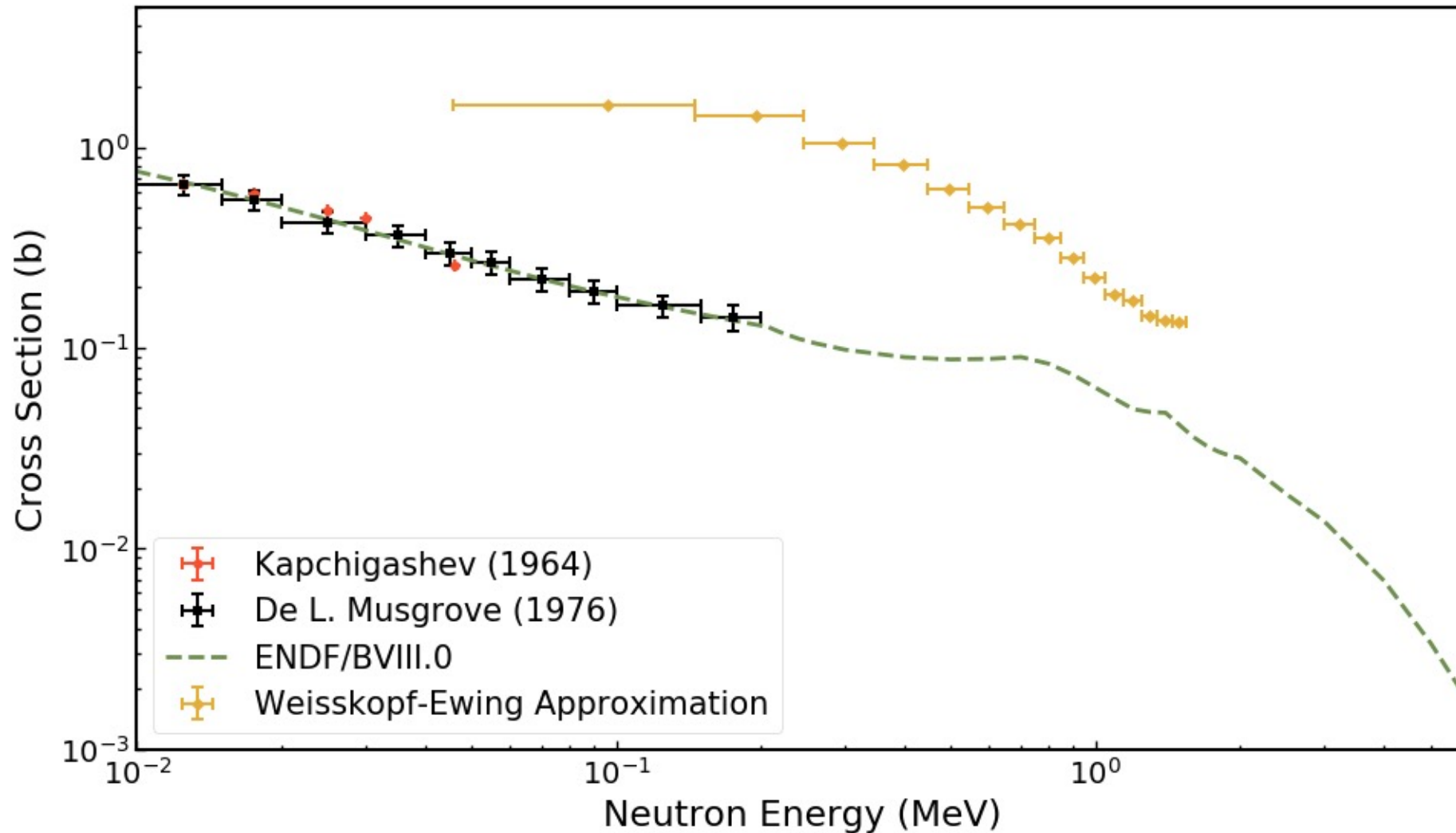
# The Experiment: $^{95}\text{Mo}(d,p\gamma)$

A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



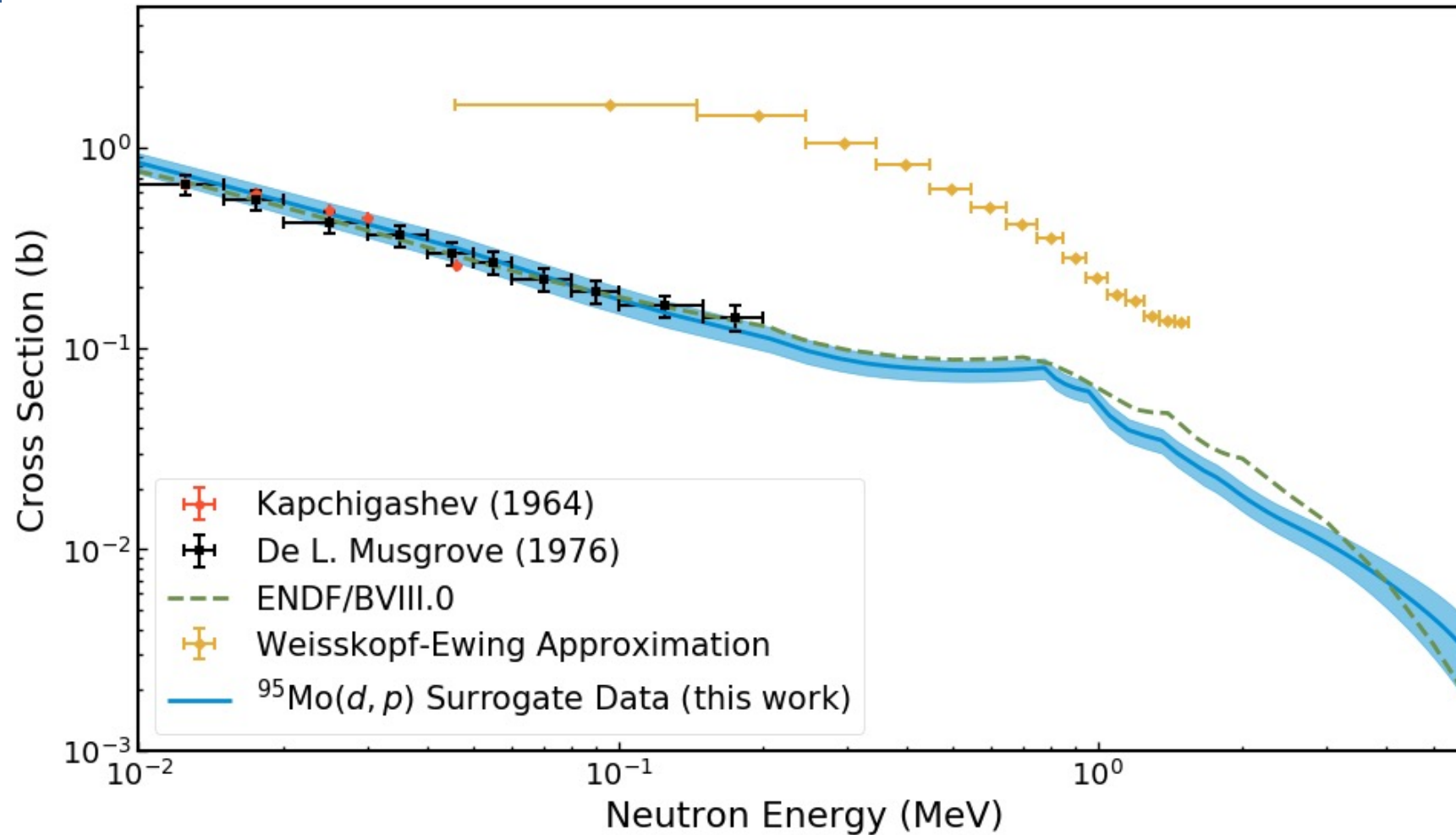
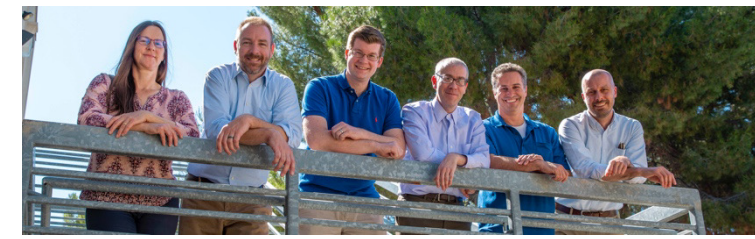
# The Experiment: $^{95}\text{Mo}(d,p\gamma)$

A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



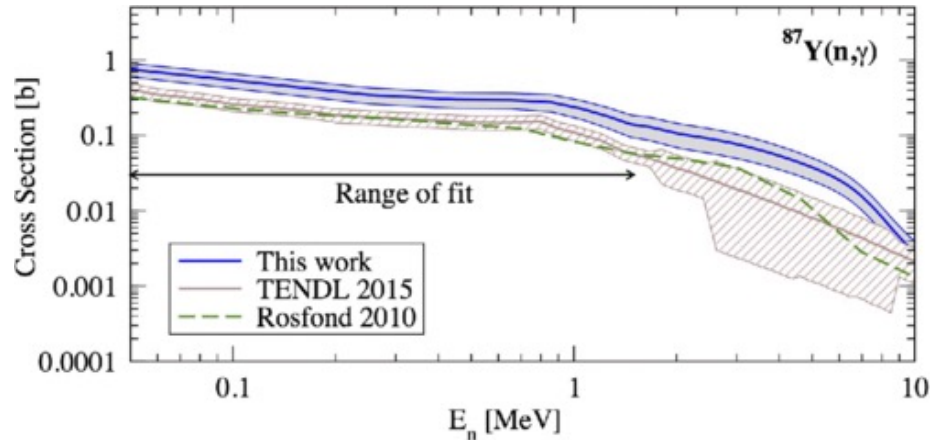
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A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



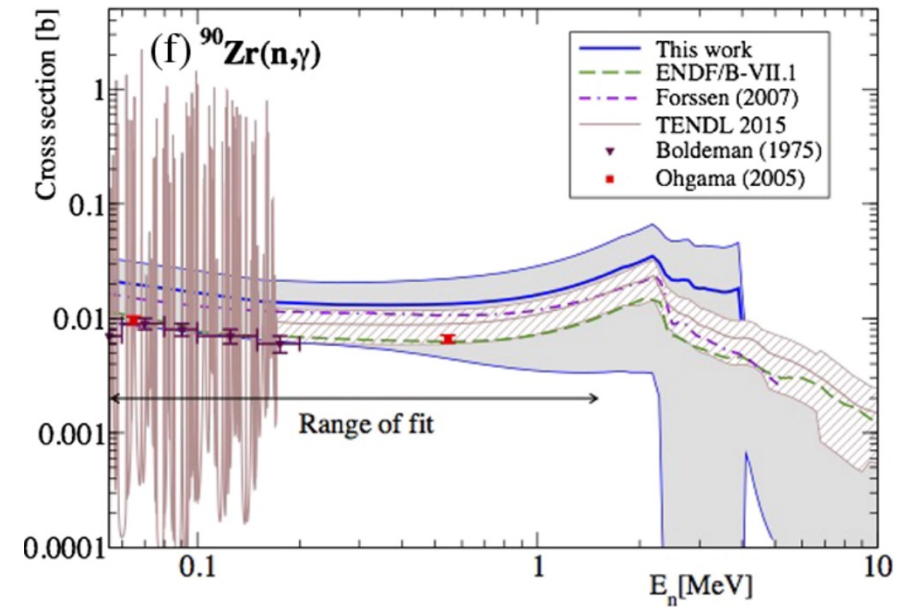
Successful Surrogate constraints are only possible through close collaboration between theory and experiment.

# Surrogate Reaction Method works on odd-odd & odd-even systems and with different reaction mechanisms:



- Includes full treatment of theoretical uncertainty in entry spin distribution.
- Requires two-step reaction mechanism.
- Agreement with data is good.

- Same experimental apparatus.
- Surrogate reactions:
  - $^{89}\text{Y}(p,d)$  for  $^{87}\text{Y}(n,\gamma)^{88}\text{Y}$
  - $^{92}\text{Zr}(p,d)$  for  $^{90}\text{Zr}(n,\gamma)^{91}\text{Zr}$



[J.E. Escher et al., PRL \*\*121\*\*, 052501 \(2018\).](#)

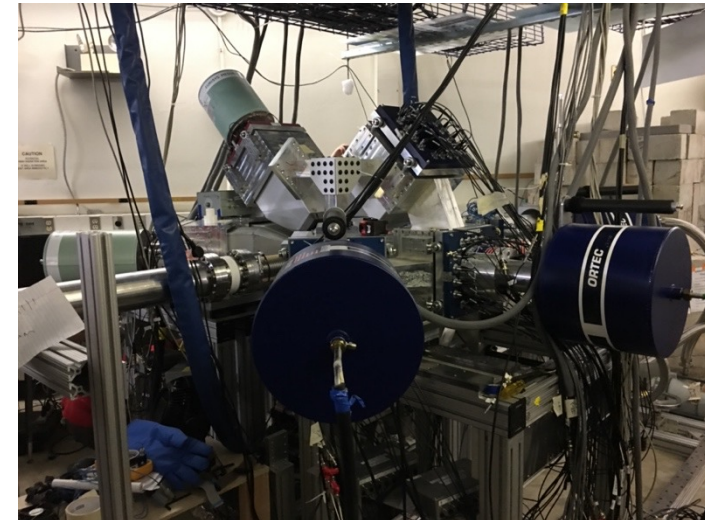
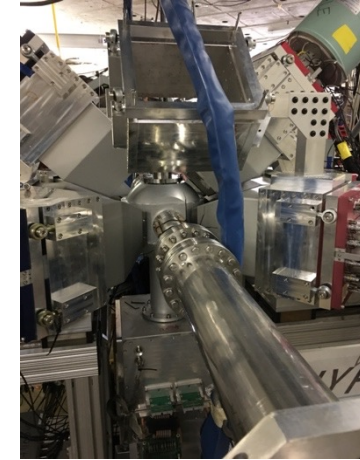


# $^{95}\text{Zr}(n,\gamma)$ cross-section measurement

*B. Alan, et al.*



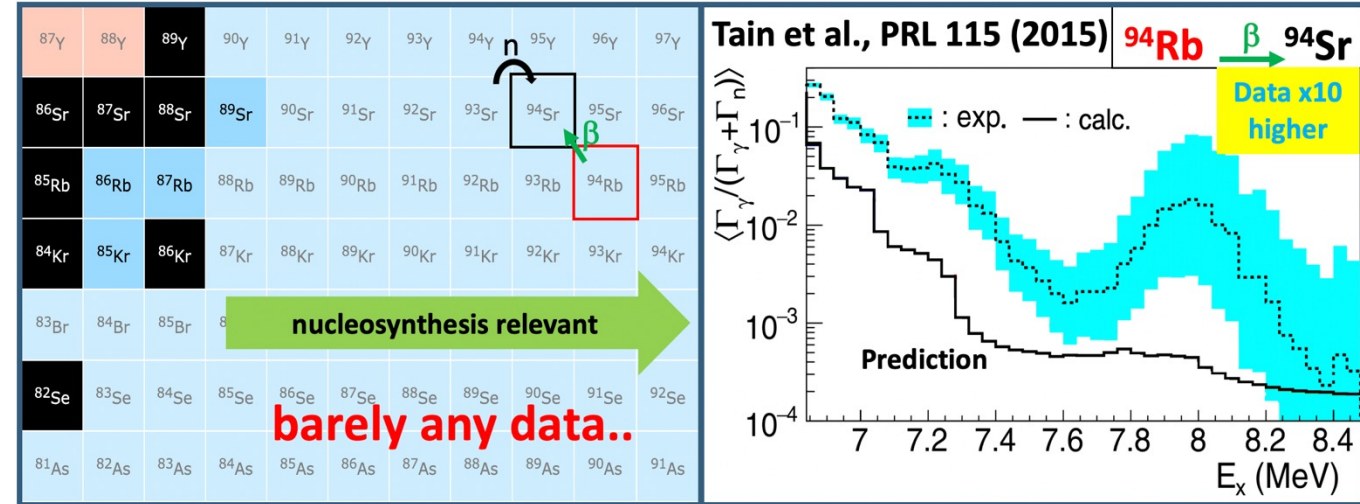
- **Branching points are powerful probes of the astrophysical environments of the s-process**
  - The abundance of  $^{96}\text{Zr}$  in AGB stars is very sensitive to the neutron density during the s-process because of the **branching point at  $^{95}\text{Zr}$** .
  - The  $^{96}\text{Zr}$  isotopic ratios derived from stellar models of AGB stars depend on the  **$^{95}\text{Zr}(n,\gamma)$  cross section**.
- **Measurements were performed at the Texas A&M Cyclotron Institute in Aug-Oct 2021**
  - Measured  $^{95}\text{Zr}(n,\gamma)$  using the surrogate reaction  $^{96}\text{Zr}(p,p')$
  - Benchmark: measured  $^{93}\text{Zr}(n,\gamma)$  using the surrogate reaction  $^{94}\text{Zr}(p,p')$ 
    - $^{93}\text{Zr}(n,\gamma)$  cross section measured directly by Macklin (1985).
  - Cave 4, K150 beamline
  - Nominal 21-MeV-proton beam incident on target
  - LLNL Hyperion detector array
    - Particles measured using 3 segmented double-sided silicon detectors in dE-E1-E2 configuration
    - Gamma rays measured using 7 HPGe Clover detectors



# Determining the n-capture rate for unstable $^{93}\text{Sr}$ via the Surrogate Reaction Method

R.O. Hughes, A. Richards, et al.

- Very limited experimental data exist for n-capture rates off-stability but needed for applications & astrophysics.
- Early hints for n-rich strontium suggest possible enhancements of a factor of ten.
- We intend to constrain  $\sigma(^{93}\text{Sr}(n,\gamma))$  with SRM and RIBs
- Experiment fielded at TRIUMF in Nov. 2021:
  - $^{93}\text{Sr}(d,p-\gamma)$  with TIGRESS & SHARC, 8MeV/A  $^{93}\text{Sr}$ .
- Analysis underway led by LLNL postdoc Andrea Richard.

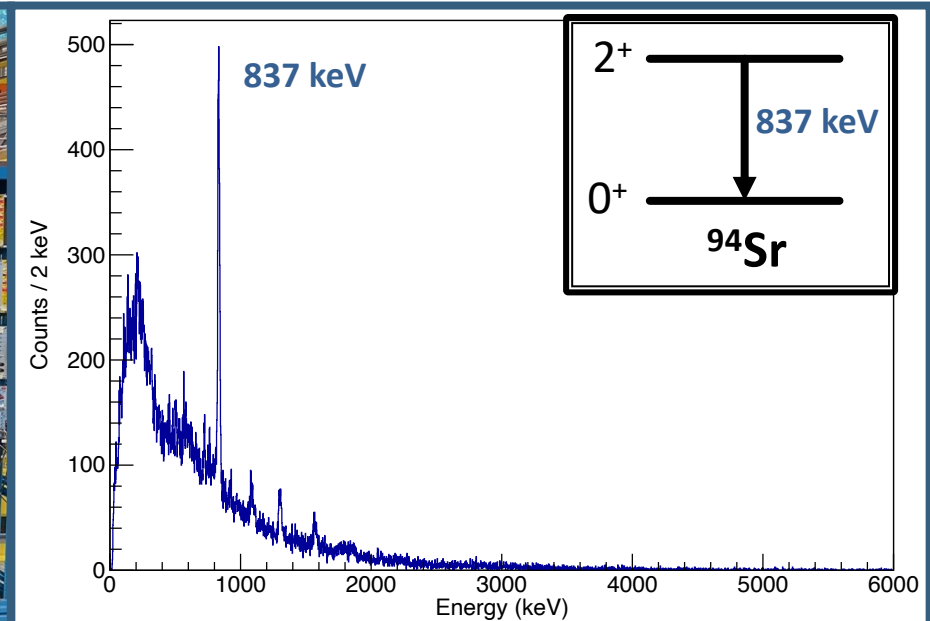
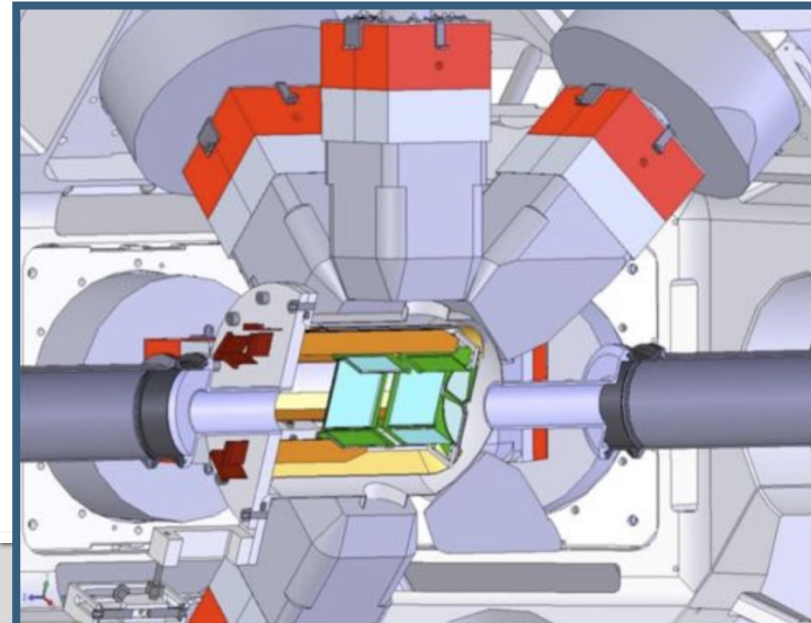


capture data limited for n-rich Sr region TAGS results hint at n-capture enhancement

TIGRESS HPGe array & SHARC Si array @ TRIUMF

LLNL/TRIUMF experiment team

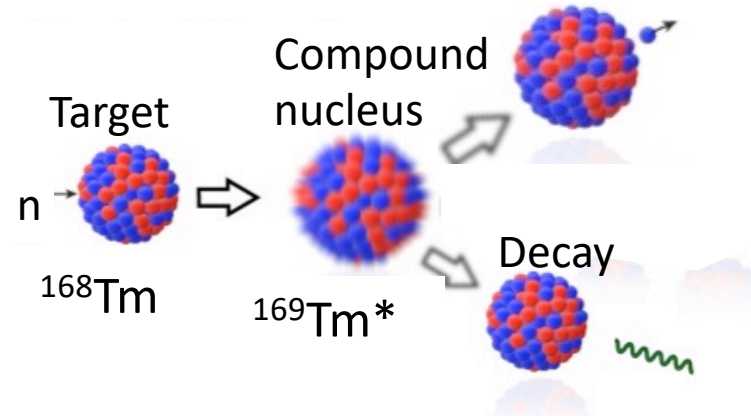
Doppler-corrected  $\gamma$ -rays in coincidence with protons from (d,p)



# The surrogate method allows us to measure the cross section of unstable nuclei (ex: $^{168}\text{Tm}(n,2n)$ which has never been measured)

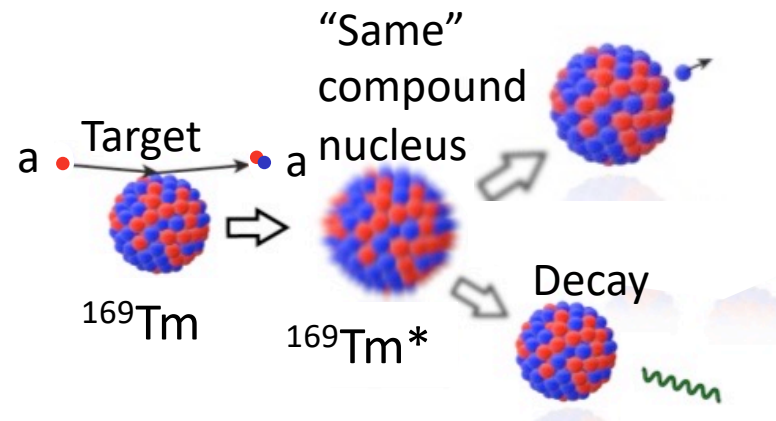
*J. Harke, et al.*

Desired Reaction



$^{168}\text{Tm}$  half-life = 93.1 days  
100 milligram target  
839 Curies or  $3 \times 10^{11}$  dps

Surrogate Reaction



OR

$^{169}\text{Tm} == \text{stable}$



# NeutronSTARS: 3.7-ton active volume neutron detector

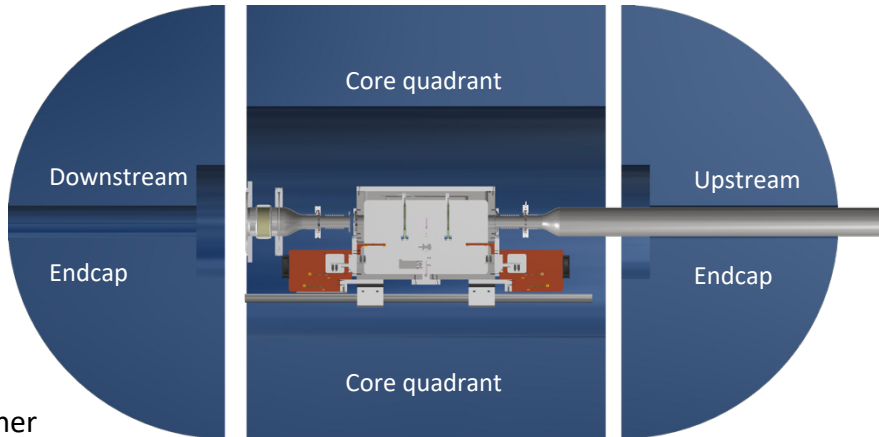
*J. Harke et al.*



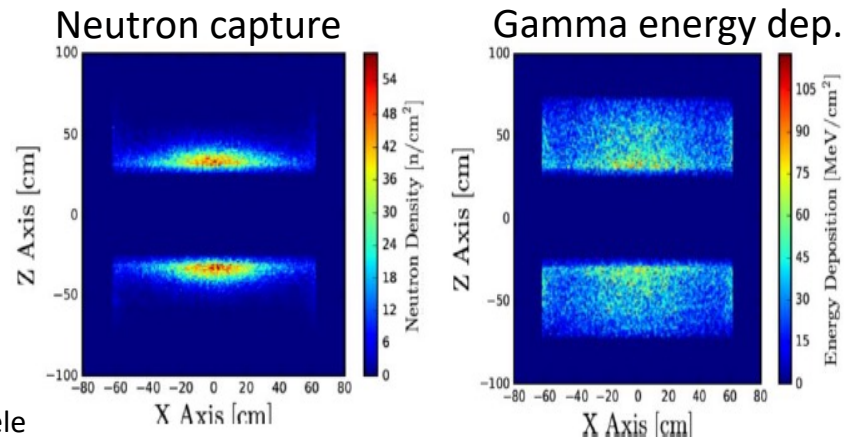
NeutronSTARS is the largest neutron detector in the NNSA complex and the US. 3.7t liquid scintillator + Gd 0.25%. Fission neutron multiplicity ( $\bar{\nu}$ ), fission neutron distribution, surrogate ( $n, n'$ ) and ( $n, 2n$ ).

Commissioned January-April 2017

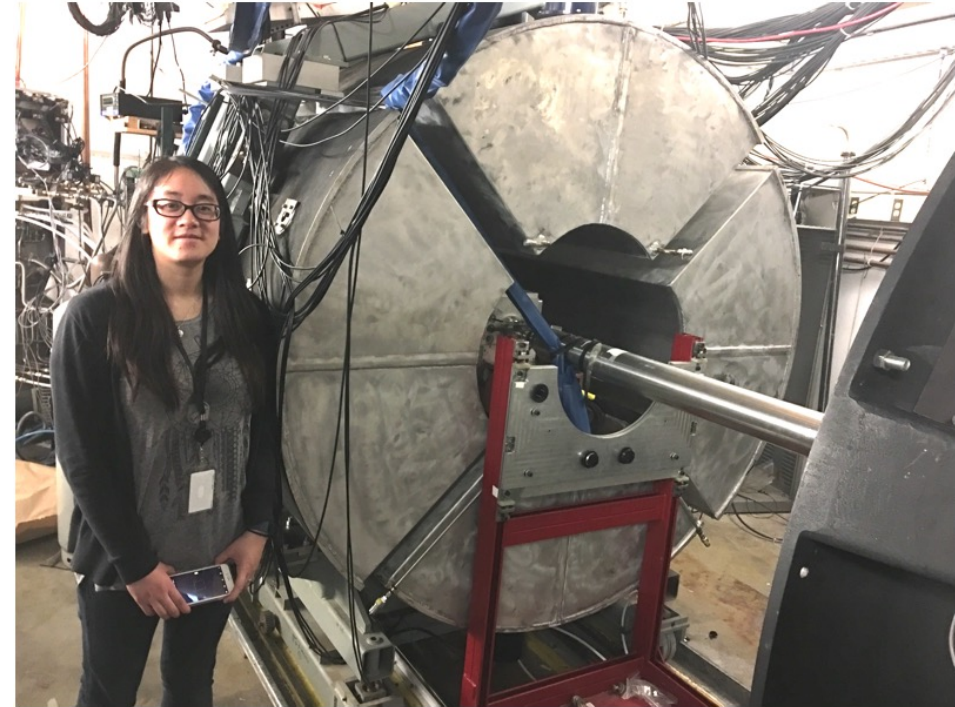
J.T.Harke , R.J. Casperson, R.O.Hughes,  
B.S. Alan, S.Fisher, O.Akindele, A.Tamashiro, A. Padilla



Courtesy S. Fisher



Courtesy O. Akindele

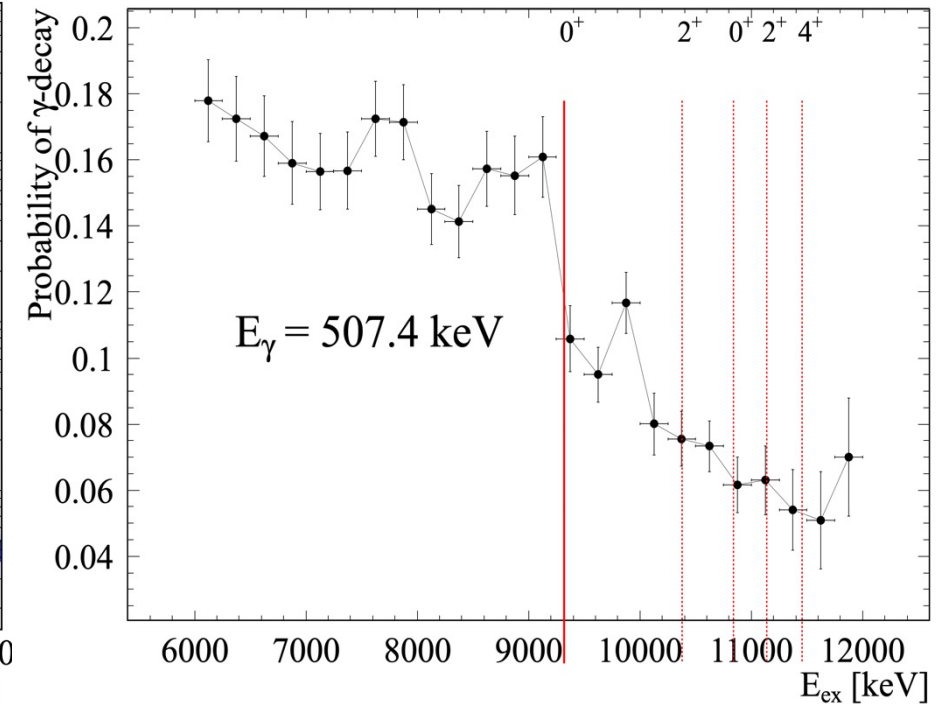
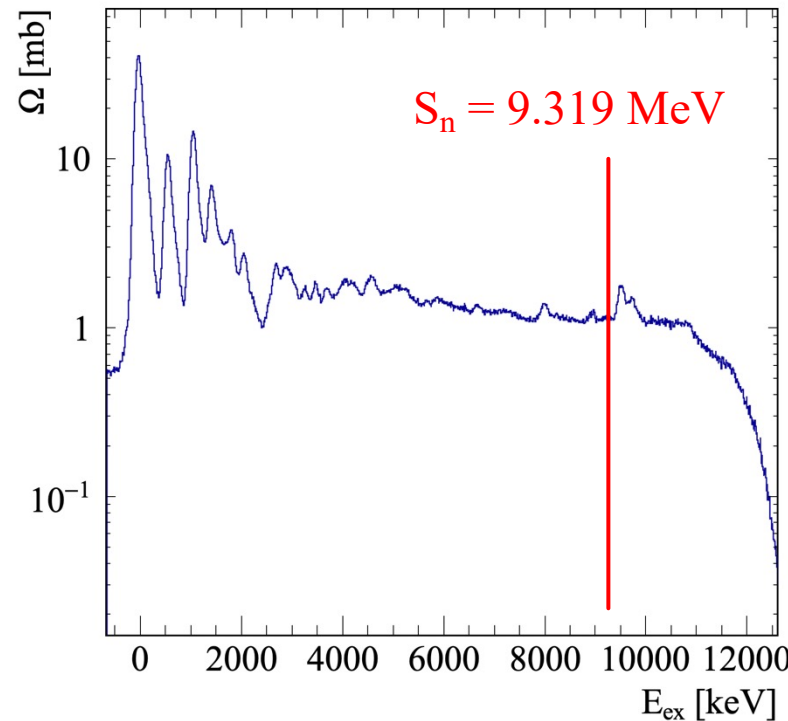


# Using $^{90}\text{Zr}(p,d)^{89}\text{Zr}$ as a surrogate for $^{88}\text{Zr}(n,\gamma)^{89}\text{Zr}$

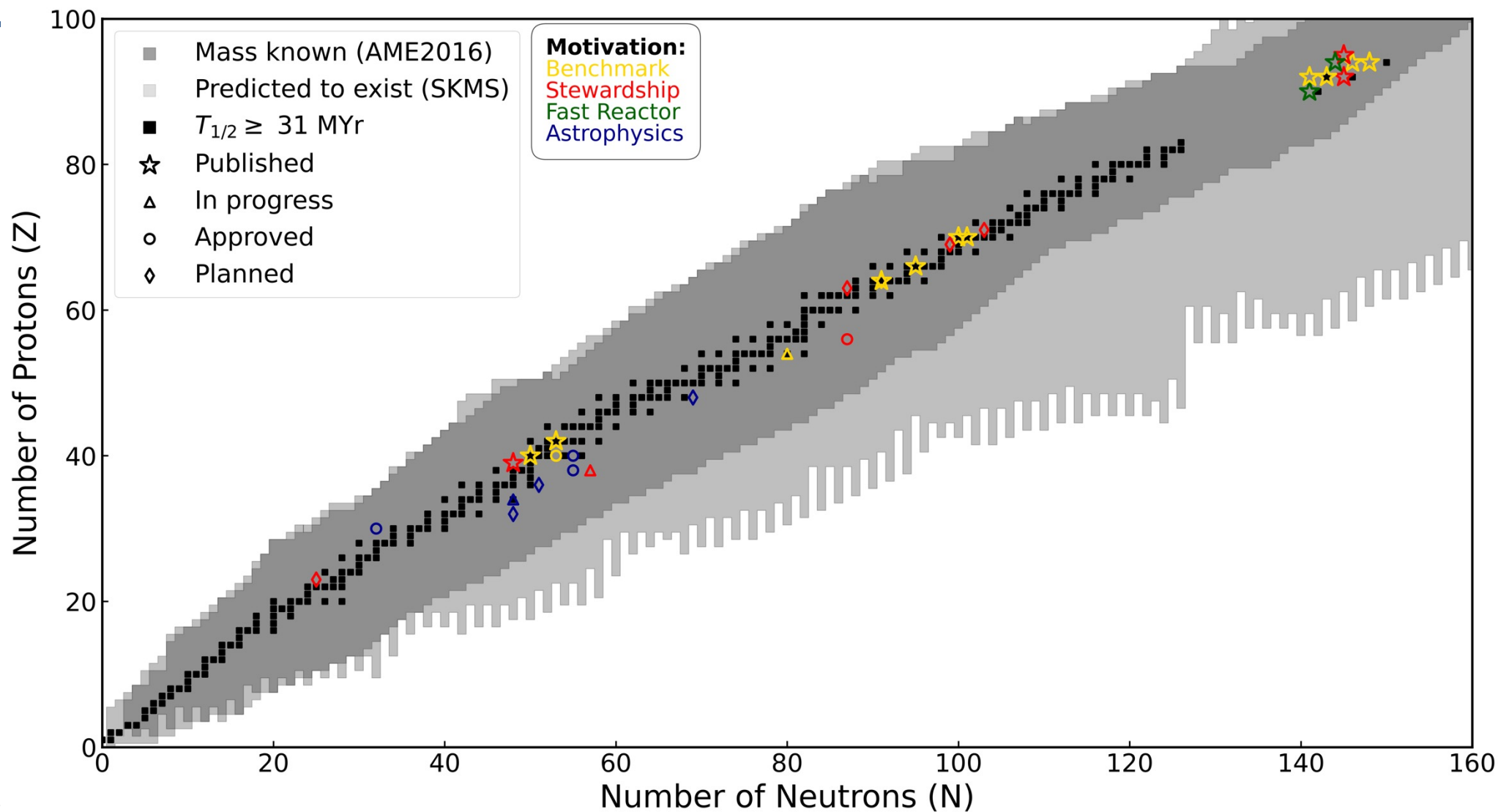
*C. Reingold et al.*



- Applications-driven measurement.
- Measured with StarLiTeR detector array, comprised of 6 Compton-suppressed HPGe clover detectors coupled to an S2 silicon telescope
- Currently extracting the  $(n,\gamma)$  cross section from the  $(p,d)$  cross section (left) and  $\gamma$ -decay probabilities (right)

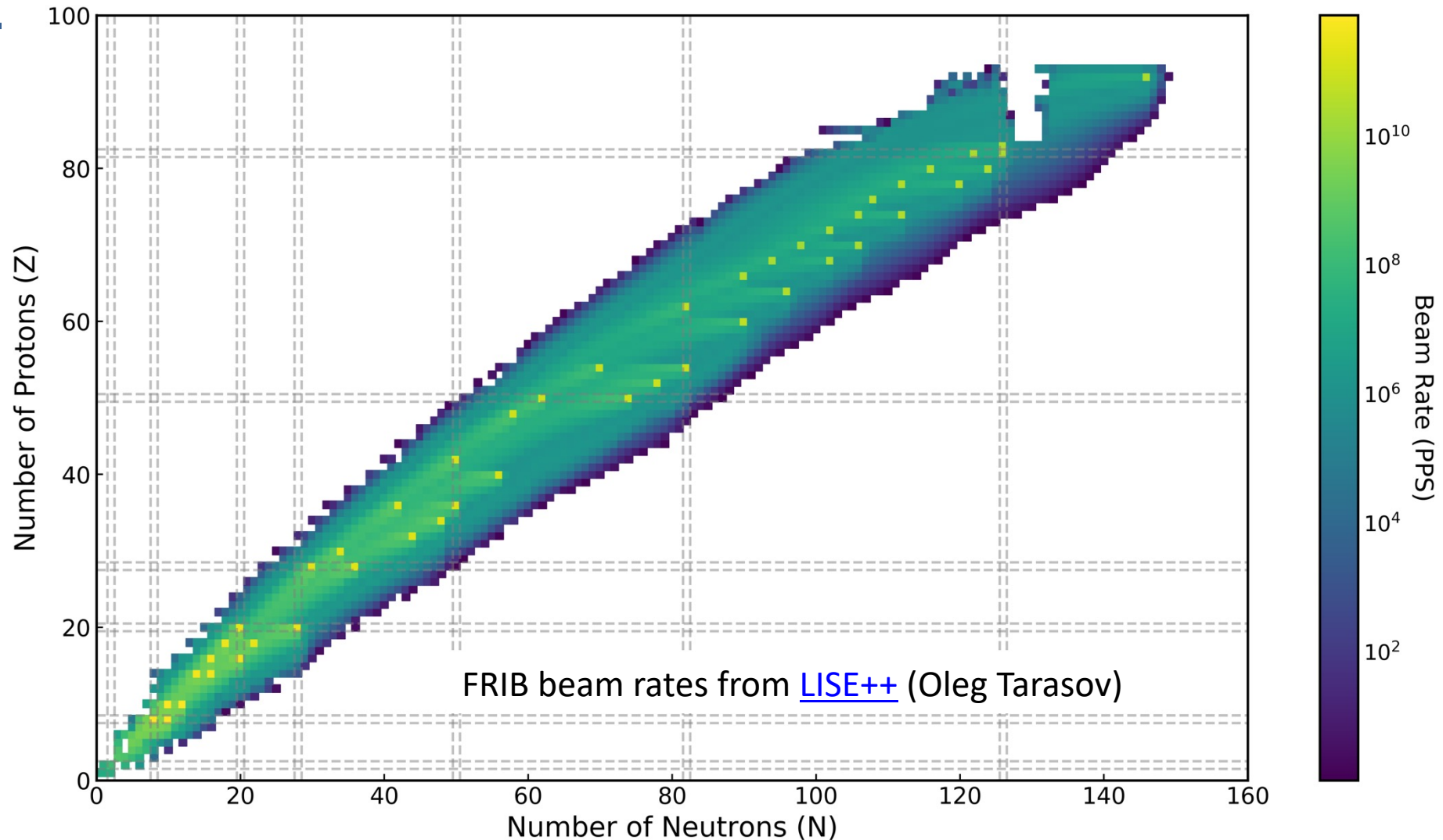


# The Surrogate Method has been widely exercised.



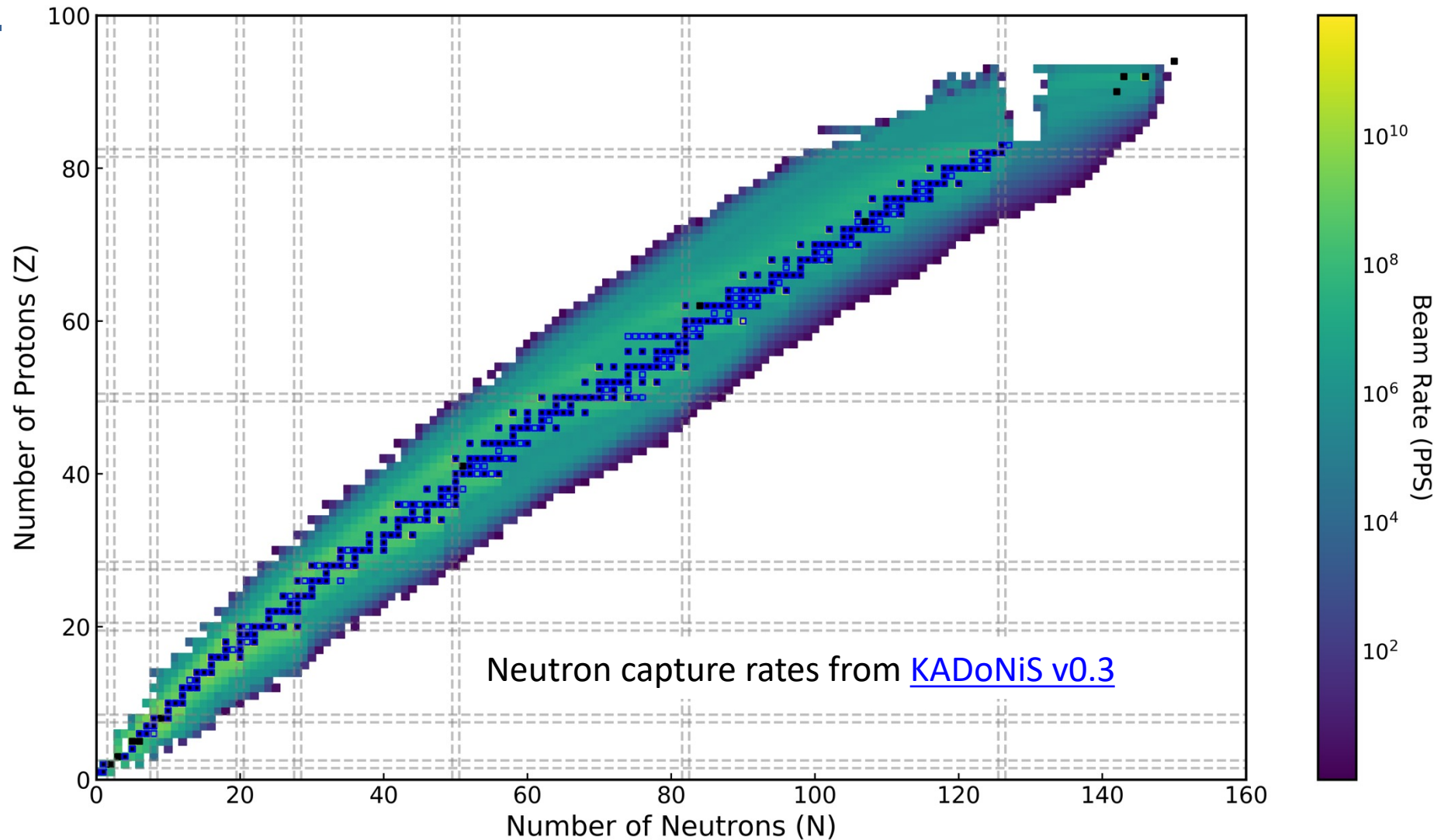
# Looking ahead to FRIB:

*This is the opportunity with which we are presented*



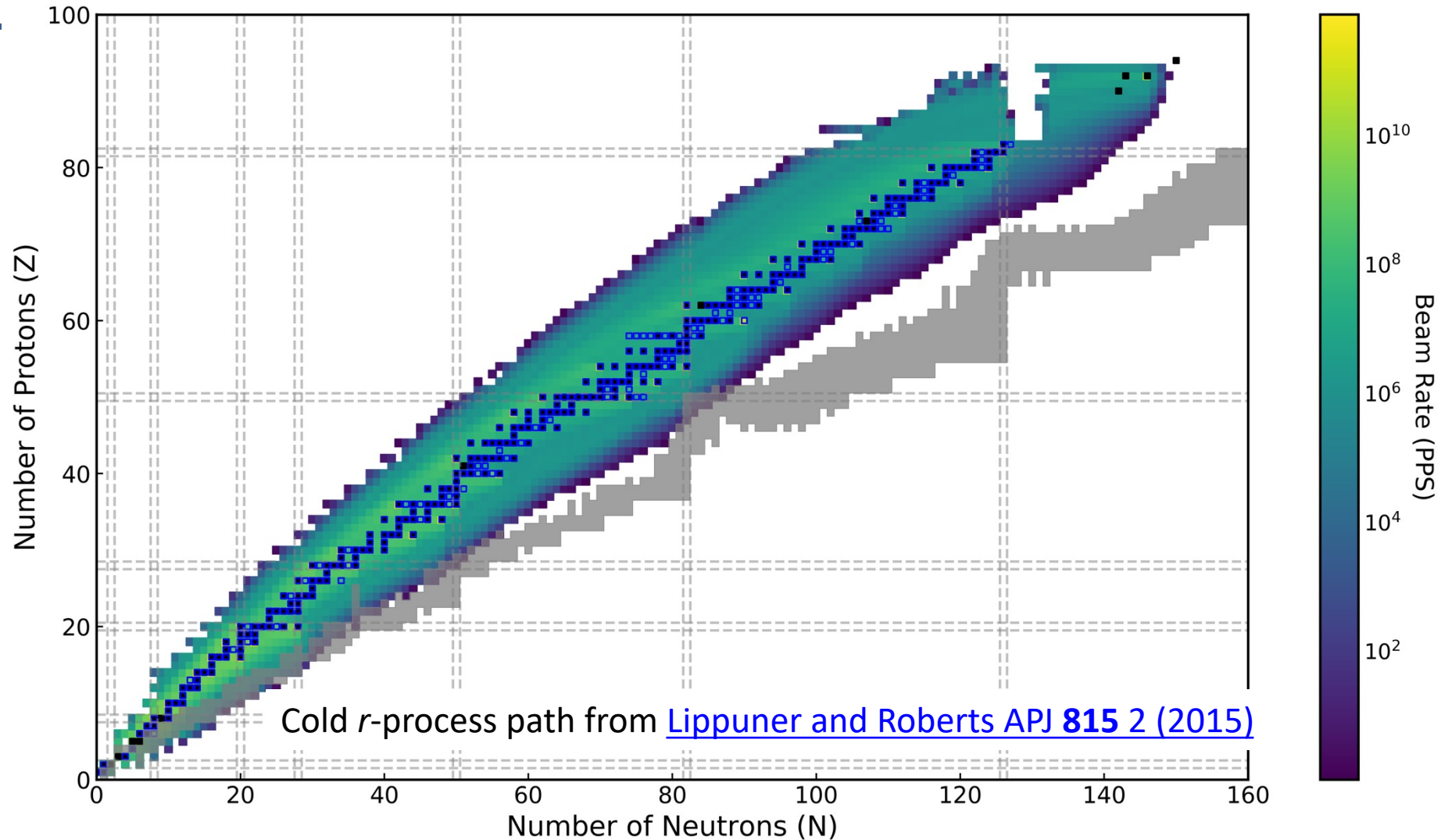
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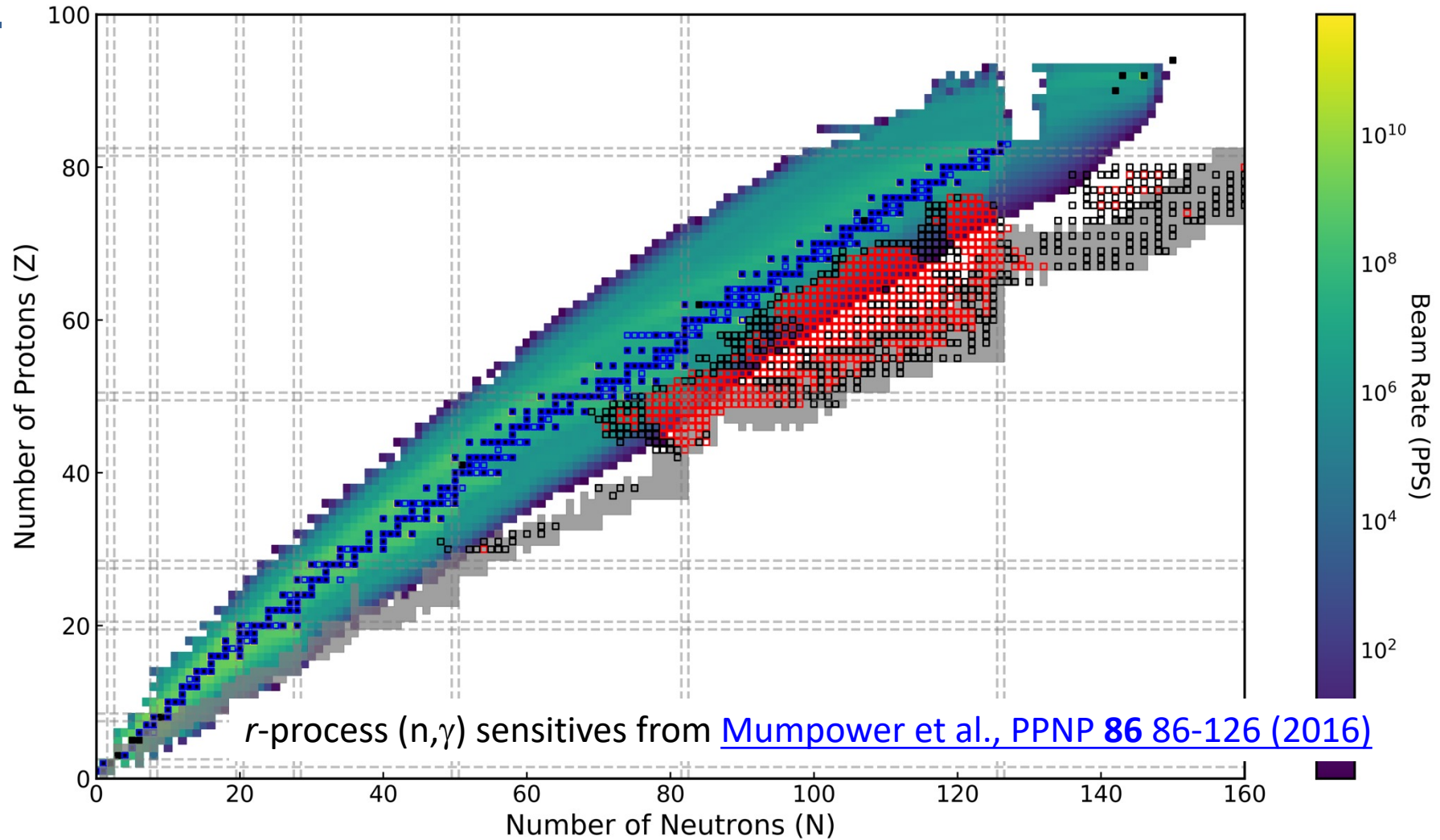
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*This is the opportunity with which we are presented*



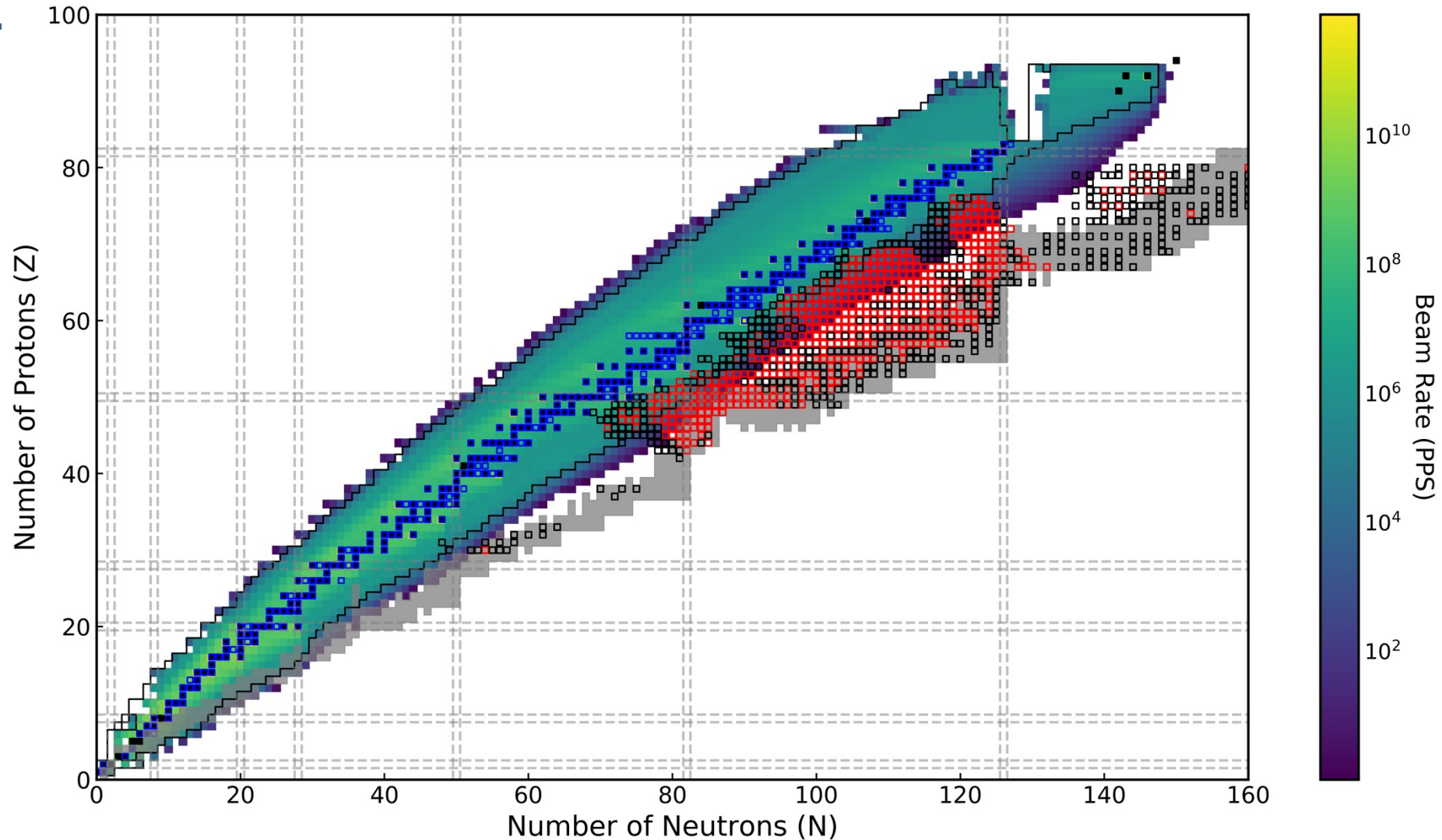
# Looking ahead to FRIB:

*This is the opportunity with which we are presented*



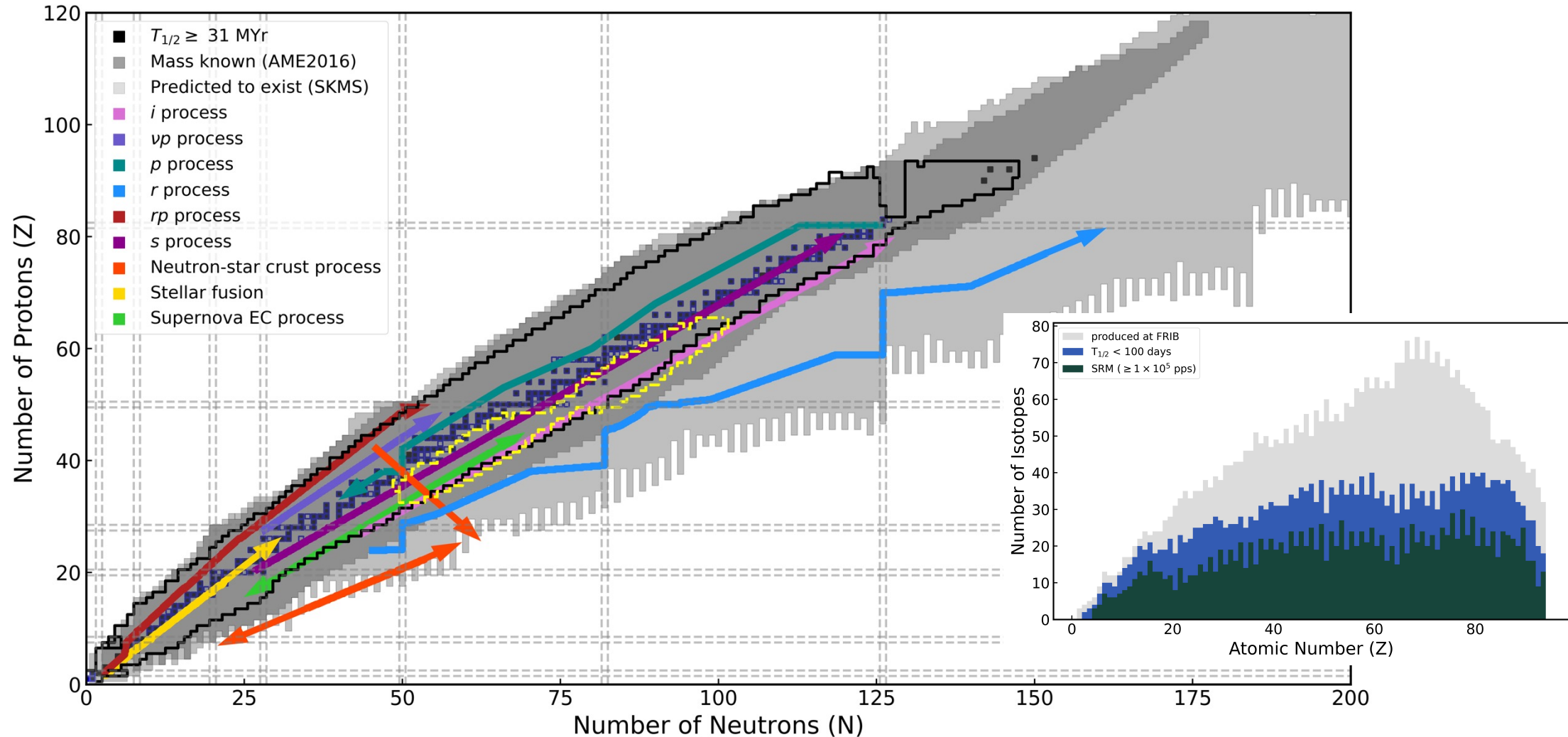
# Looking ahead to FRIB:

*This is the opportunity with which we are presented*



# Looking ahead to FRIB and nuCARIBU:

*This is the opportunity with which we are presented – maximizing it requires investments in theory and experiment.*



Thanks to B. Alan, J.E. Escher, J.T. Harke, R.O. Hughes, and C. Reingold for slides and figures.

Thank you for your attention!



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