Constraining Neutron-Induced Reactions Through the Surrogate Reaction Method

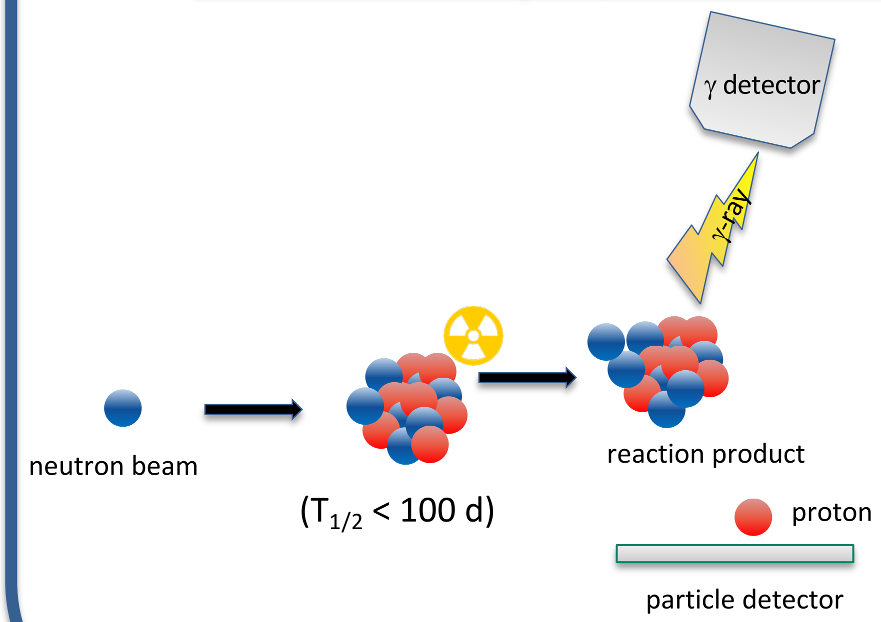
Andrew Ratkiewicz
with B. Alan, J.E. Escher, J.T. Harke, R.O. Hughes, G. Potel, C. Reingold, and A. Richards

March 01, 2022

LLNL-PRES-832051
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

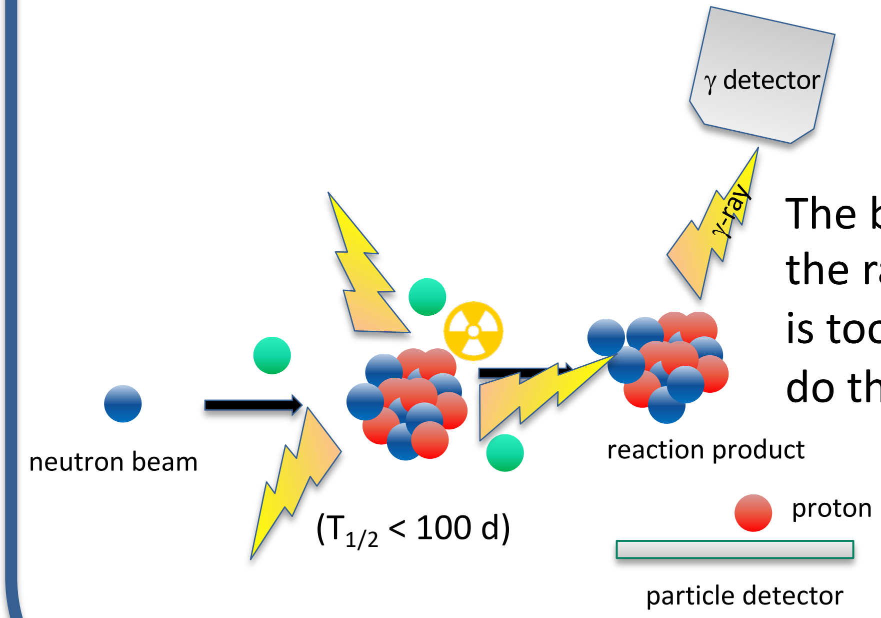
How do we measure neutron-induced reactions on short-lived radioactive targets?

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



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

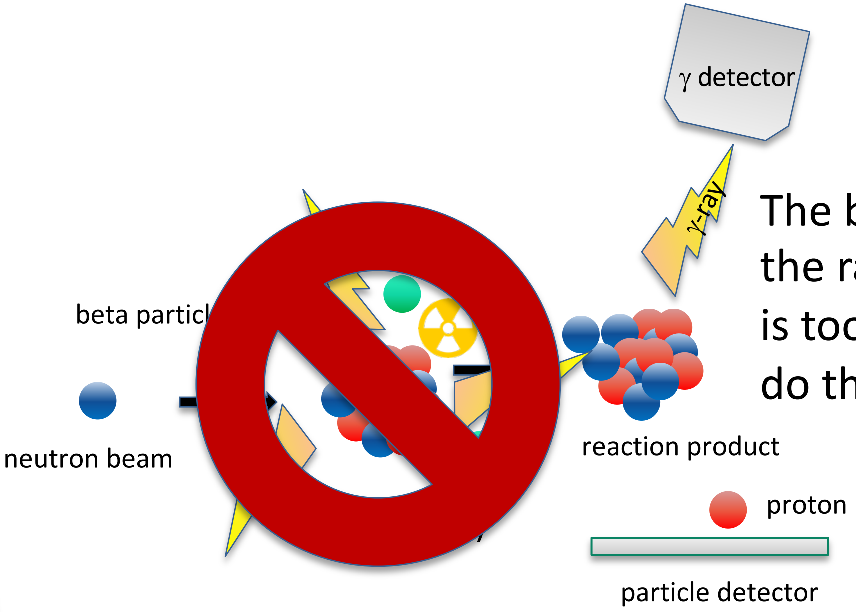
Option One: a neutron beam incident on a radioactive target ("normal kinematics")



The background from the radioactive target is too high. We can't do this.

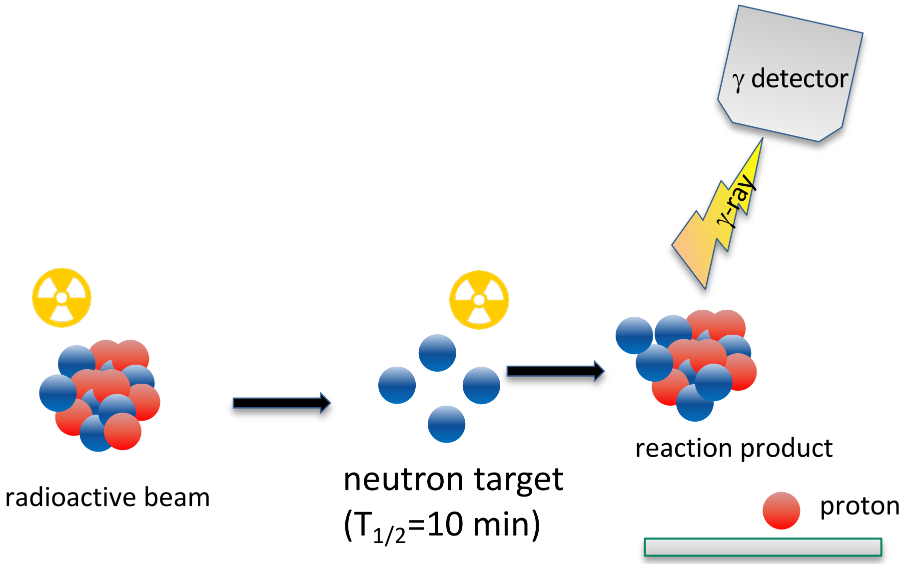
How do we measure neutron-induced reactions on short-lived radioactive targets?

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



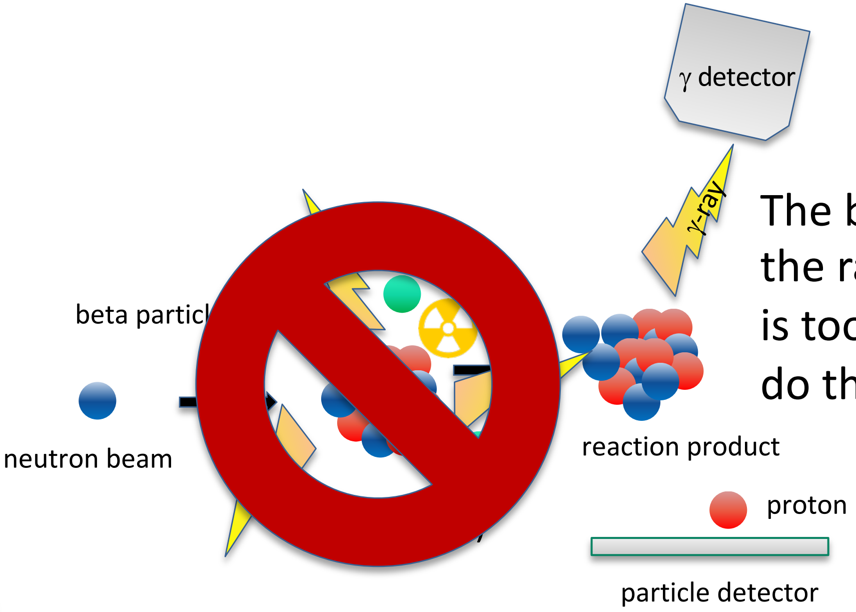
The background from the radioactive target is too high. We can’t do this.

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



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

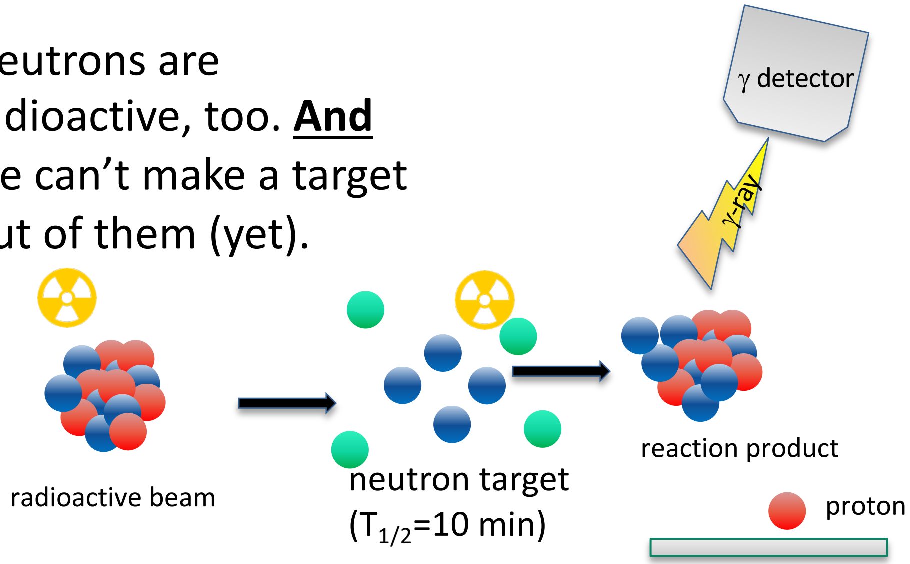
Option One: a neutron beam incident on a radioactive target ("normal kinematics")



The background from the radioactive target is too high. We can't do this.

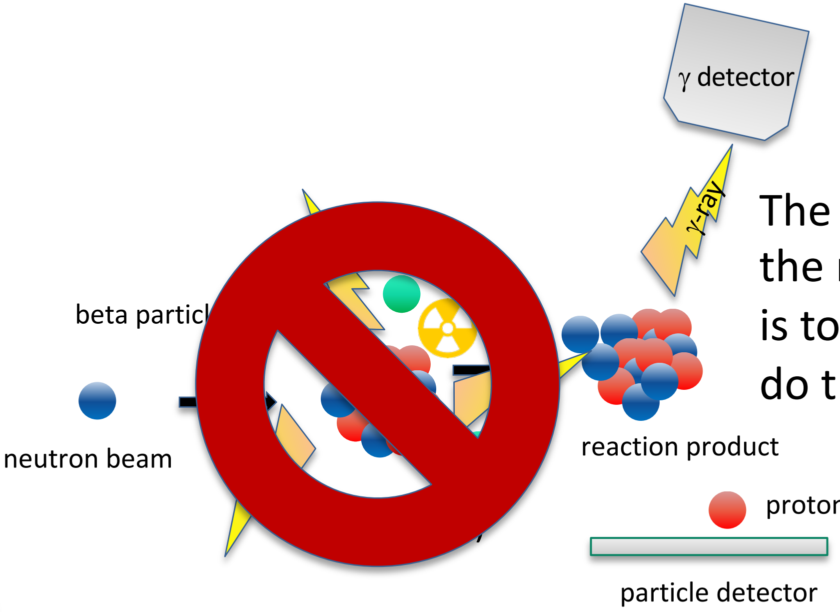
Option Two: a radioactive beam incident on a neutron target ("inverse kinematics")

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!

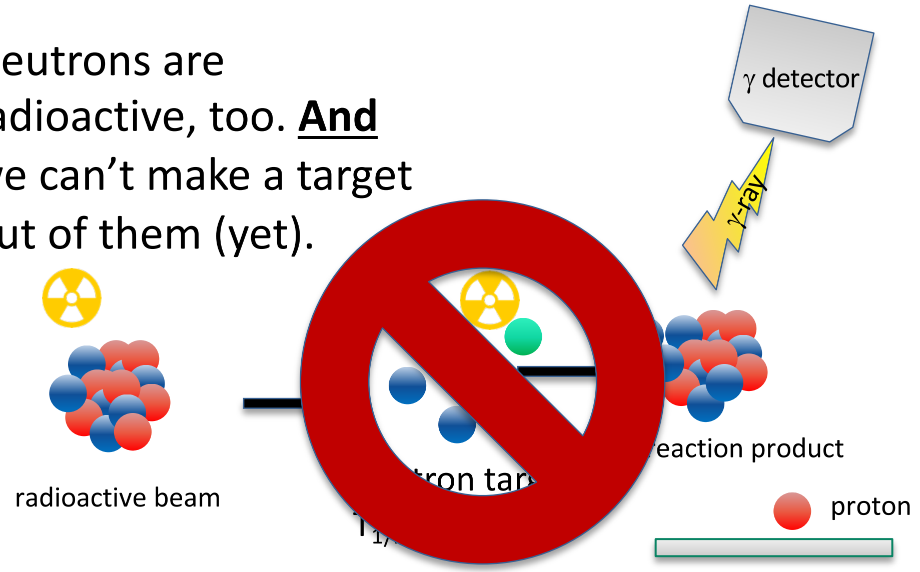
Option One: a neutron beam incident on a radioactive target ("normal kinematics")



The background from the radioactive target is too high. We can't do this.

Option Two: a radioactive beam incident on a neutron target ("inverse kinematics")

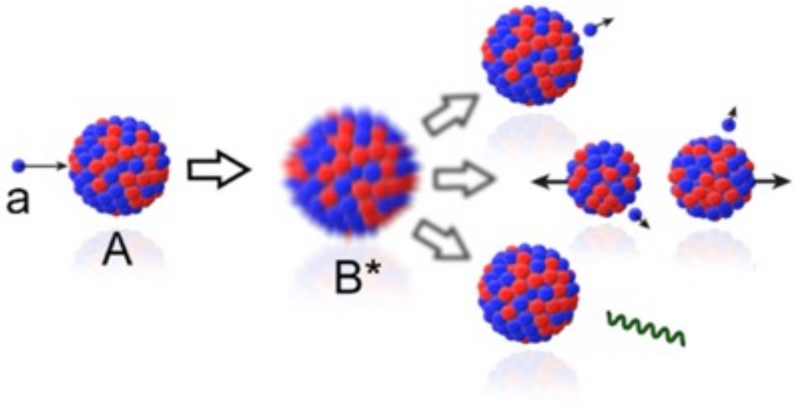
Neutrons are radioactive, too. **And** we can't make a target out of them (yet).



We need a different approach!

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

Desired Reaction: impossible to measure

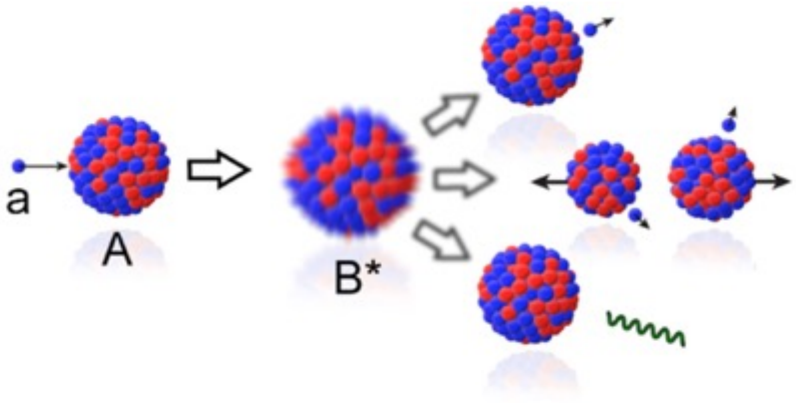


$$\sigma_{\alpha\chi}(E_a) = \sum_{J,\pi} \sigma_{\alpha}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi)$$

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

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

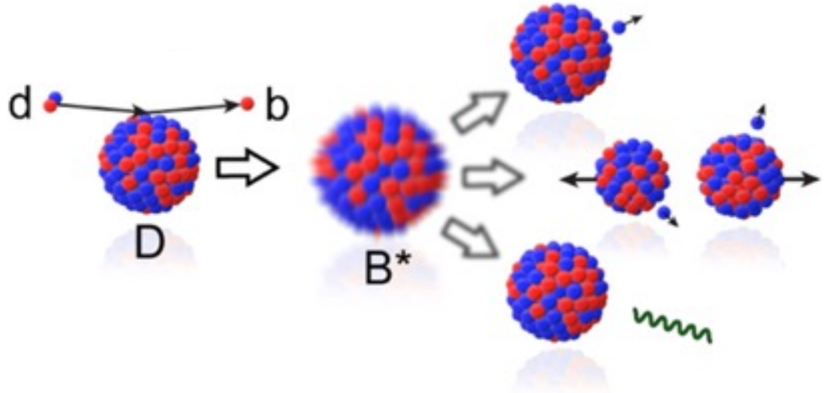
Desired Reaction: impossible to measure



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

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

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



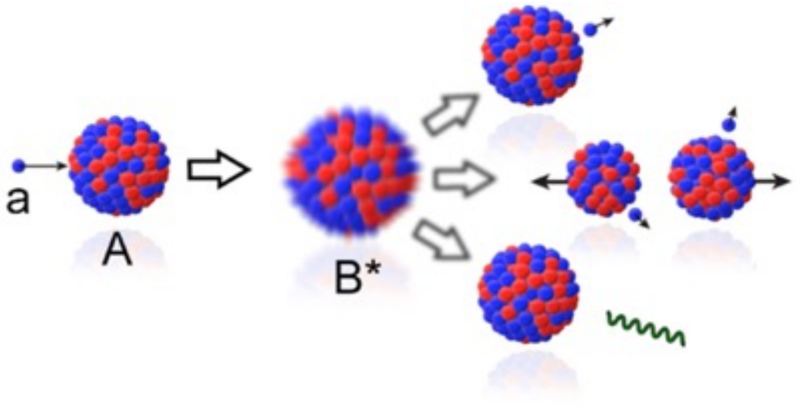
$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi)$$

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

A. Ratkiewicz *et al*. Phys. Rev. Lett. **122**, 052502 (2019).

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

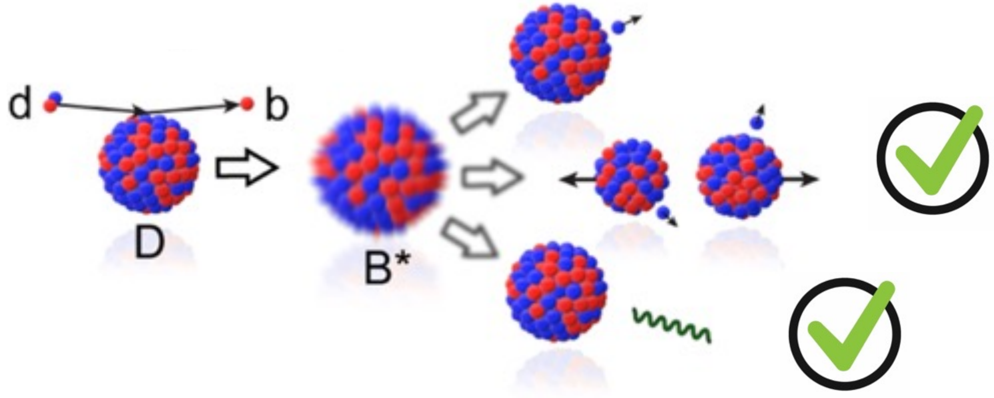
Desired Reaction: impossible to measure



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

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

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

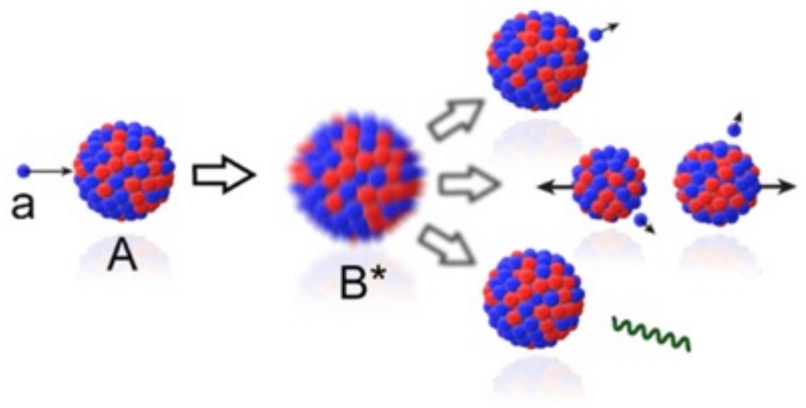


$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi)$$

J.E. Escher *et al.* Phys. Rev. Lett. **121**, 052501 (2018).
A. Ratkiewicz *et al*. Phys. Rev. Lett. **122**, 052502 (2019).

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

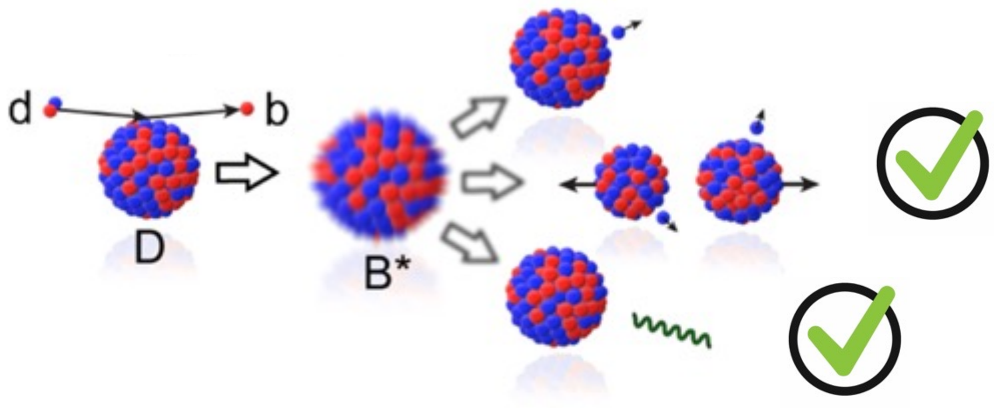
Desired Reaction: impossible to measure



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

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

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

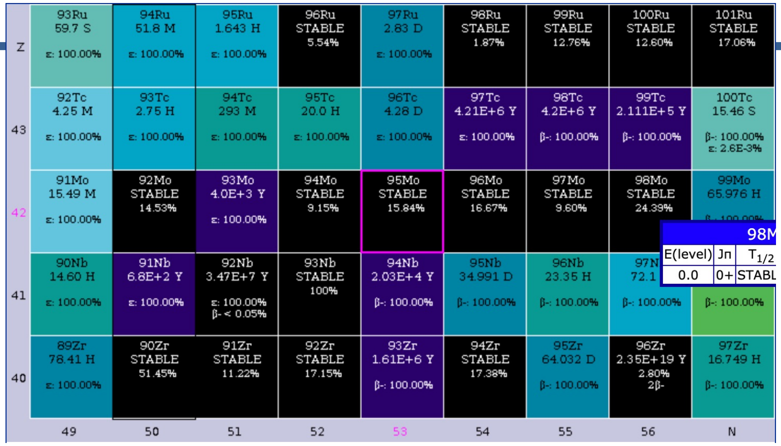


$$P_{\delta\chi}(E_{ex}) = \sum_{J,\pi} F_{\delta}^{CN}(E_{ex}, J, \pi) G_{\chi}^{CN}(E_{ex}, J, \pi)$$

J.E. Escher *et al.* Phys. Rev. Lett. **121**, 052501 (2018).
A. Ratkiewicz *et al*. Phys. Rev. Lett. **122**, 052502 (2019).

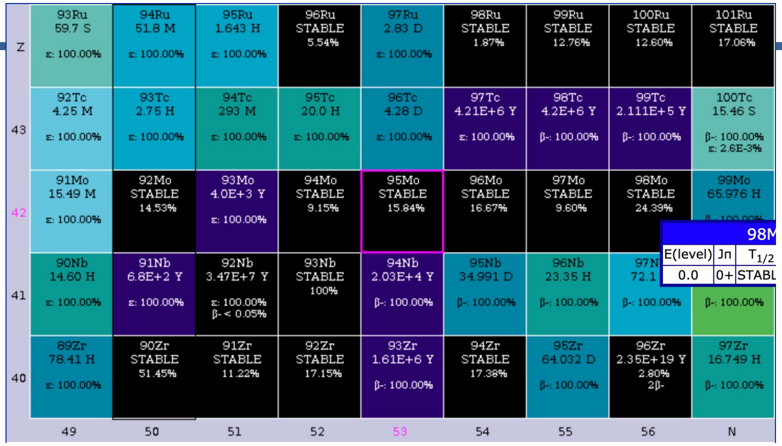
Benchmarking (d,pγ) as an (n,γ) surrogate

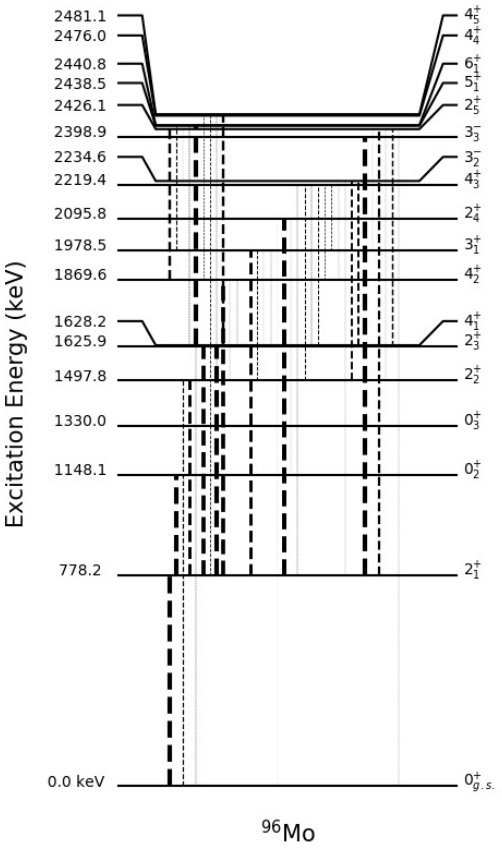
- Requirements for a target:
  - Stable.



Benchmarking (d,pγ) as an (n,γ) surrogate

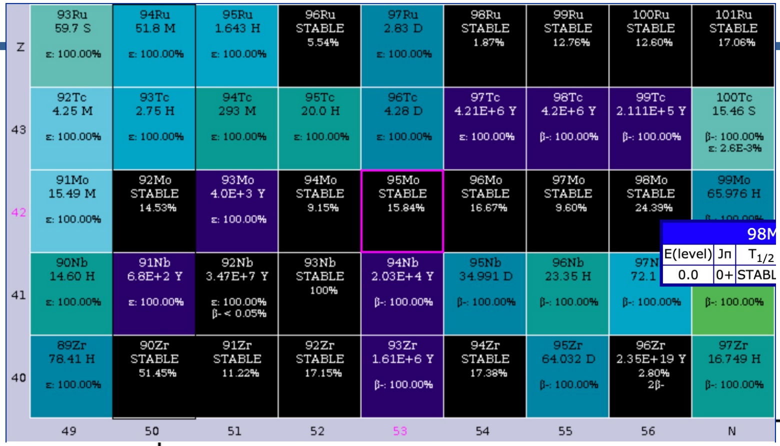
- Requirements for a target:
  - Stable.
  - Structure is well understood.
  - Product of (n,γ) is an even-even nucleus, strong $2^+ \rightarrow 0^+$ collecting transition.

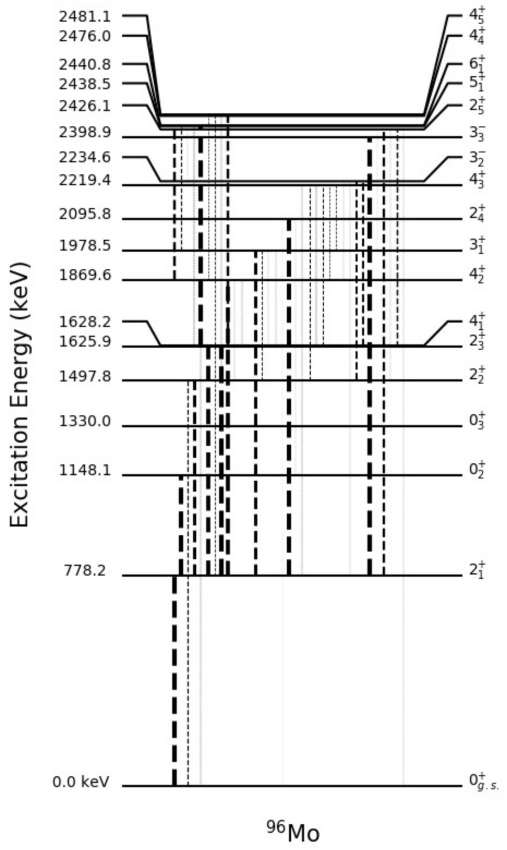


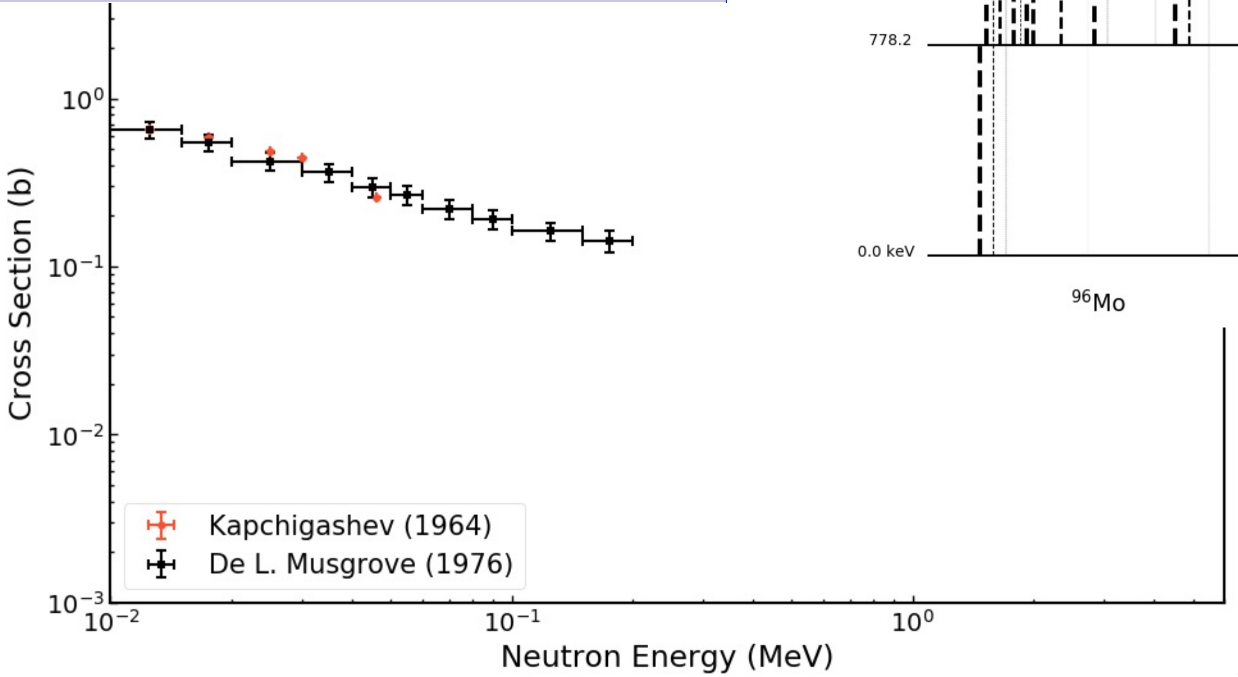


Benchmarking (d,pγ) as an (n,γ) surrogate

- Requirements for a target:
  - Stable.
  - Structure is well understood.
  - Product of (n,γ) is an even-even nucleus, strong $2^+ \rightarrow 0^+$ collecting transition.
  - Known (n,γ) cross section as a function of neutron energy.





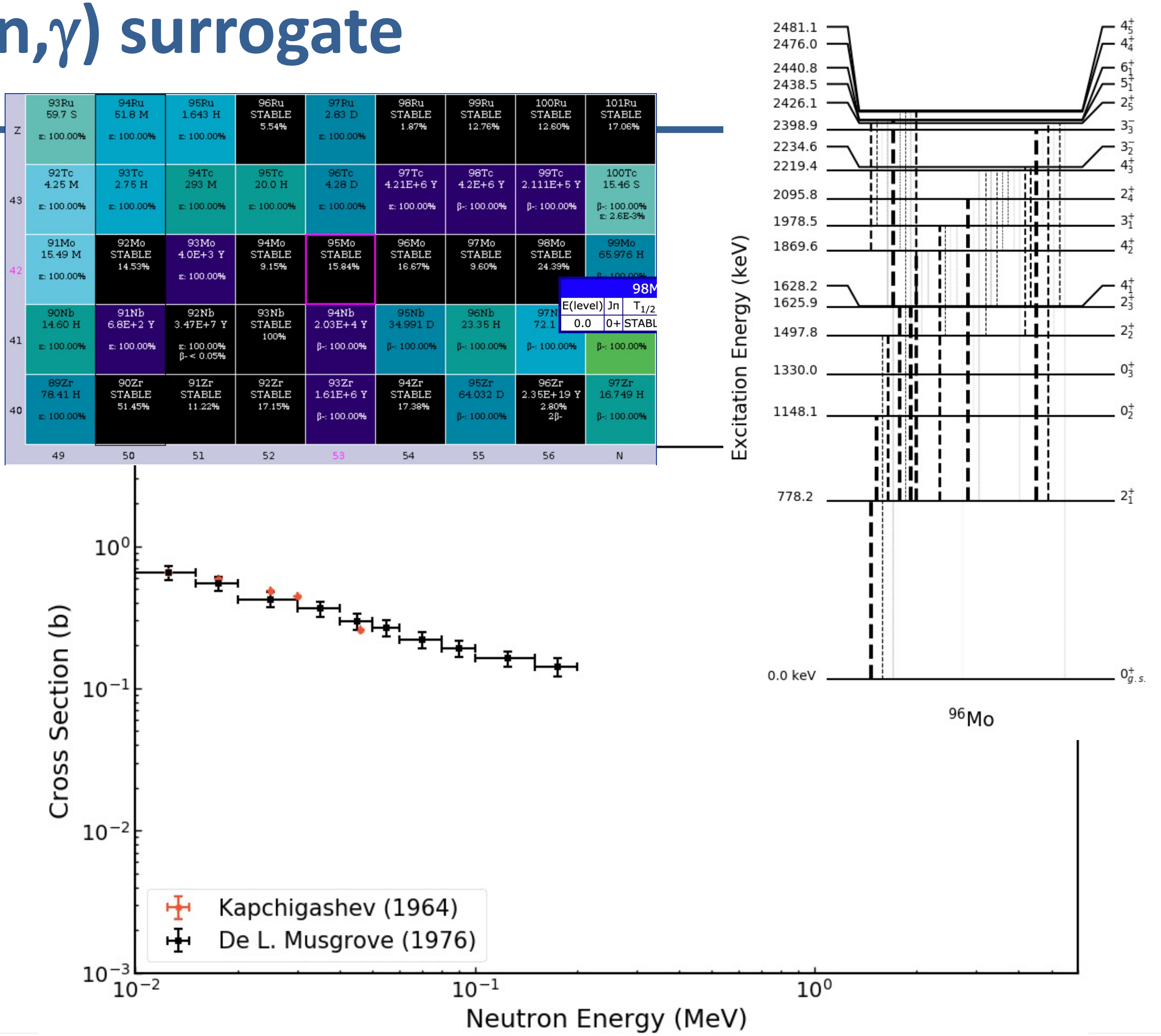


^{96}Mo levels from RIPL-3 (R. Capote *et al.*)

Benchmarking (d,pγ) as an (n,γ) surrogate

- Requirements for a target:
  - Stable.
  - Structure is well understood.
  - Product of (n,γ) is an even-even nucleus, strong $2^+ \rightarrow 0^+$ collecting transition.
  - Known (n,γ) cross section as a function of neutron energy.

- Need to understand:
  - ❑ Reaction mechanism.
  - ❑ Entry spin distribution.

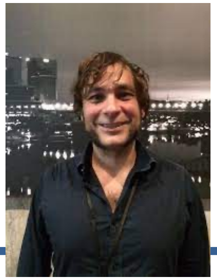


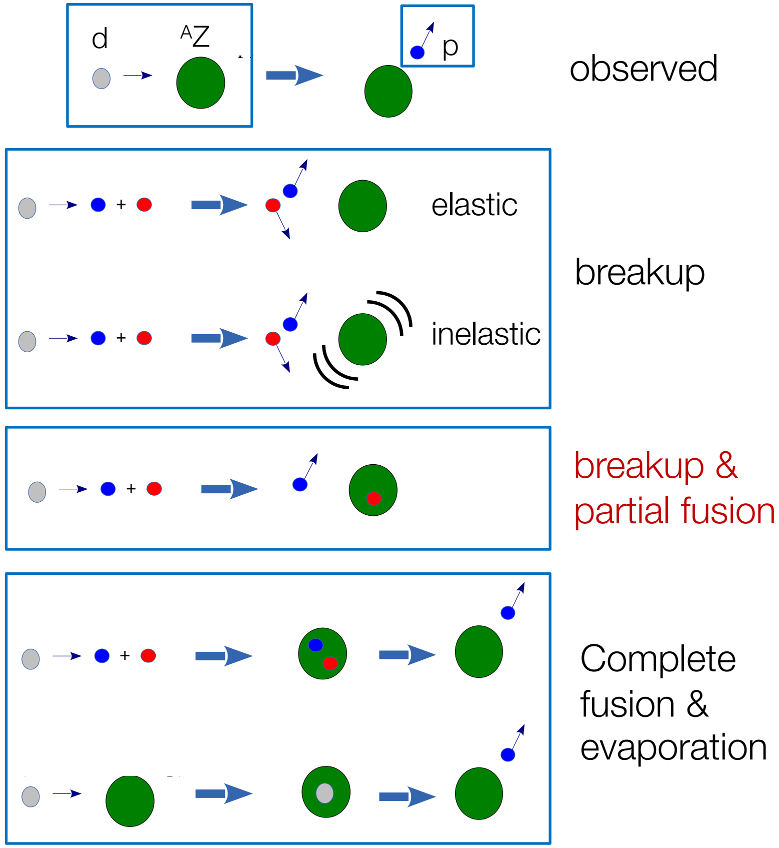
^{96}Mo levels from RIPL-3 (R. Capote *et al.*)

Reaction Mechanism: (d,p)

revisited for the FRIB era

G. Potel et al.





Inclusive (d,p) reactions recently revisited: formalism

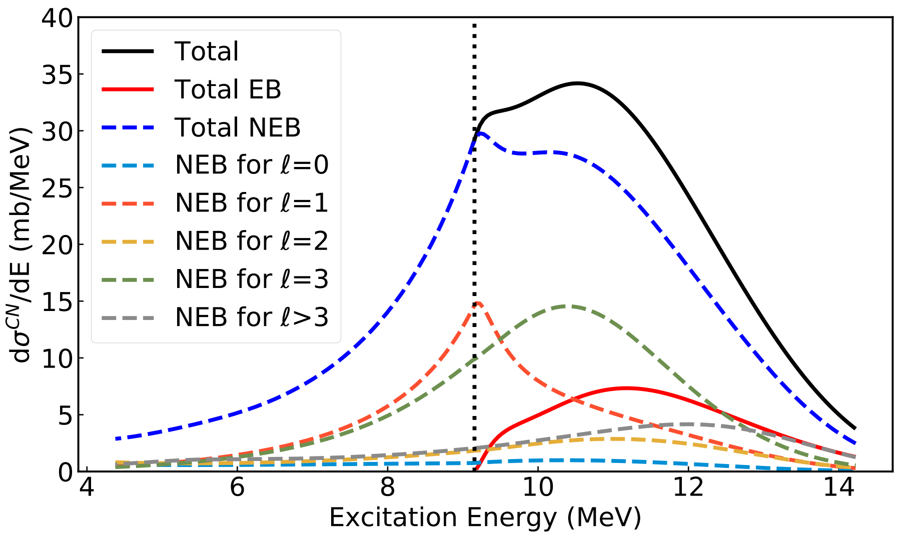
- Based on earlier work by Udagawa & Tamura and Ichimura, Austern & Vincent
- Goal: describe breakup-fusion, which contains CN formation
- Potel et al, PRC 92, 034611 (2015)
- Lei & Moro, PRC 92, 044616 (2015)
- Carlson et al, Few-Body Syst 57, 307 (2016), arxiv:1508.01466

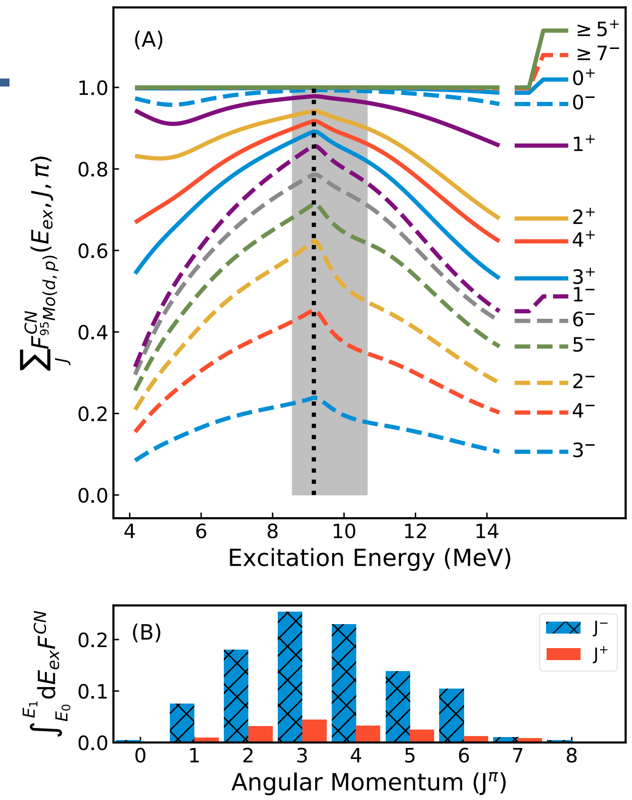
Applications:

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

Thanks to Jutta Escher for this slide!

Reaction Mechanism and Entry Spin Distribution





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

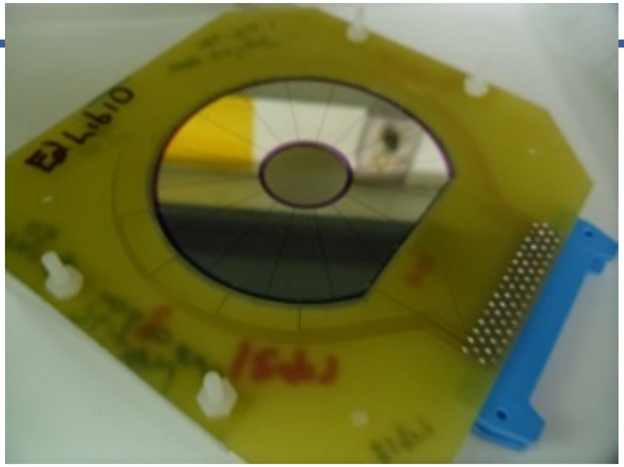
Correct theoretical description of the CN formation cross section and entry spin distribution are ***essential***!

See G. Potel *et al.* PRC **92** 034611 (2015)

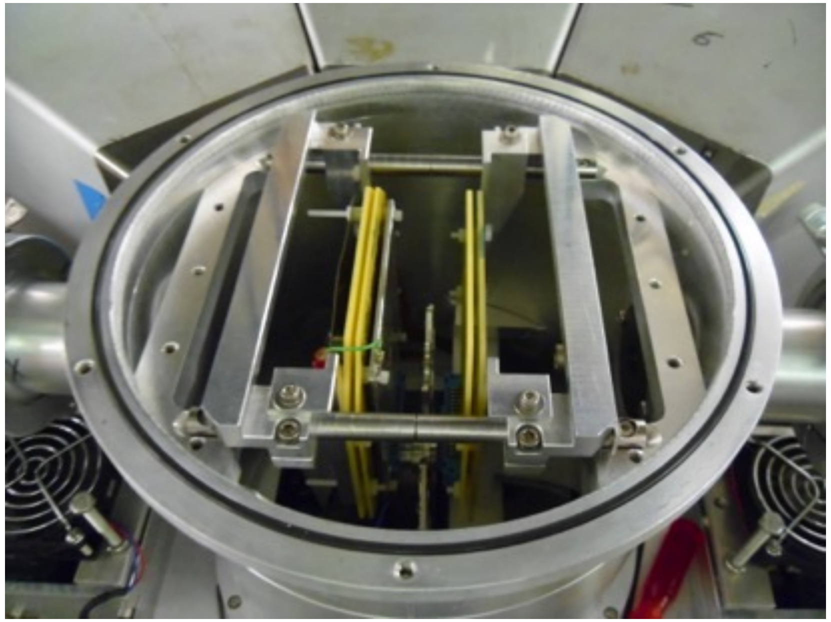
The Experiment: ^{95}Mo(d,pγ)

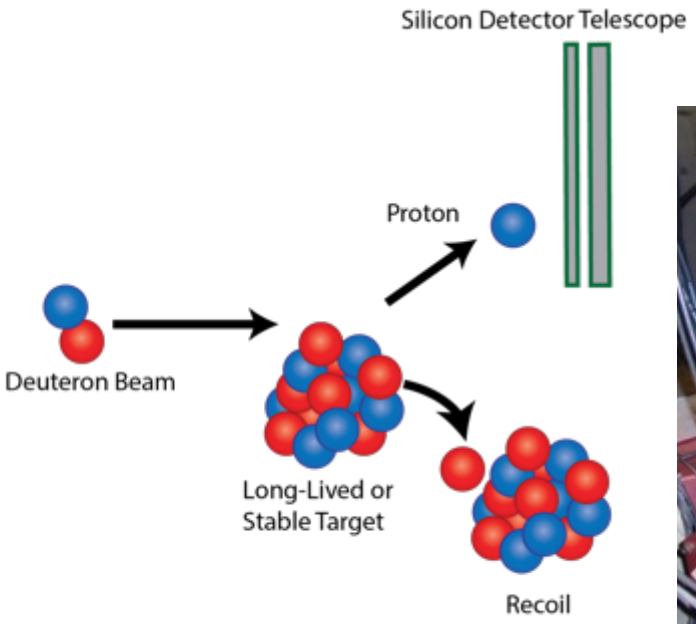
A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).

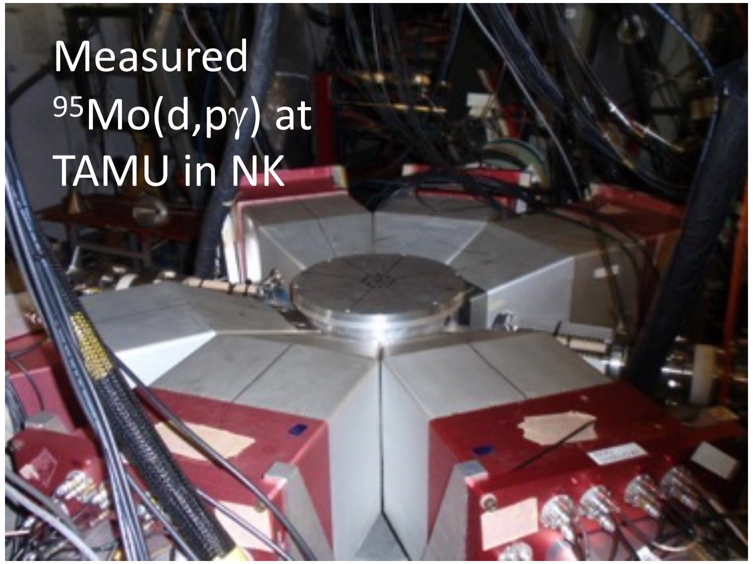
$$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_\gamma}$$



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



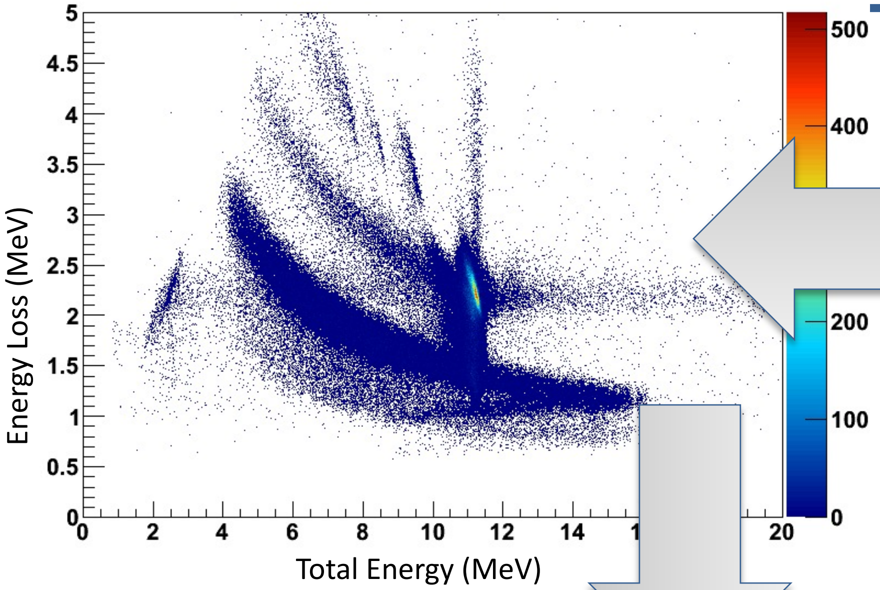


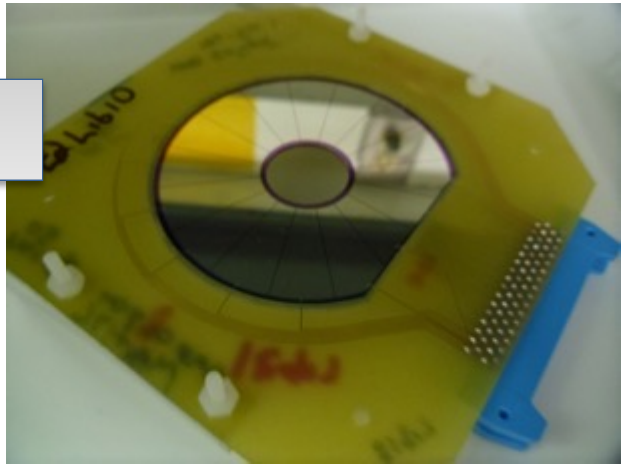


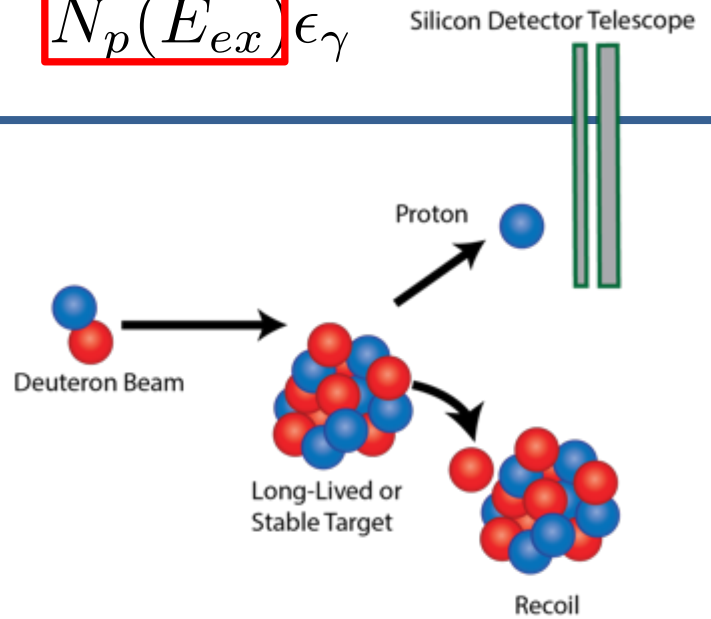
The Experiment: $^{95}Mo(d,p\gamma)$

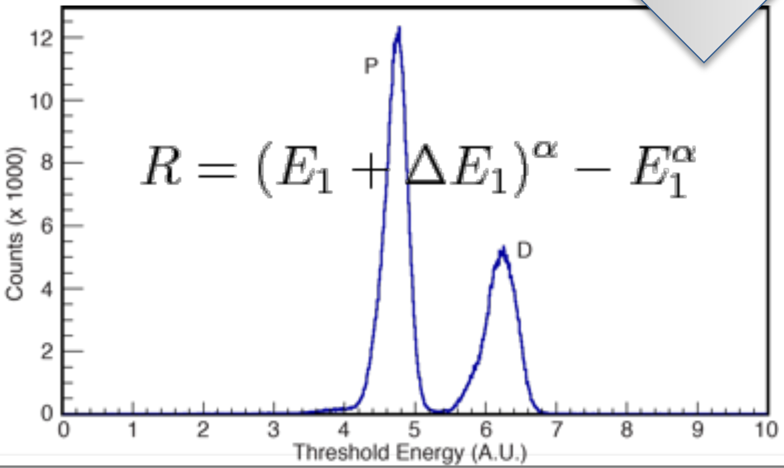
A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).

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

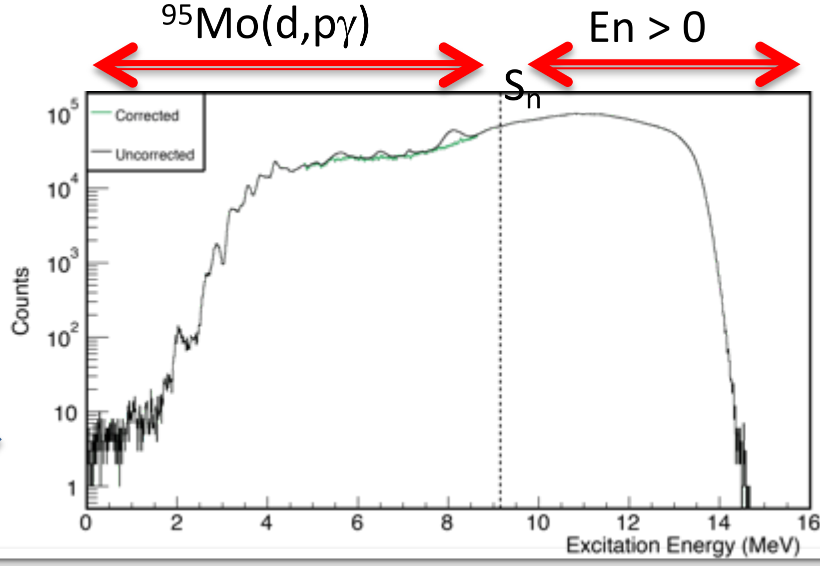








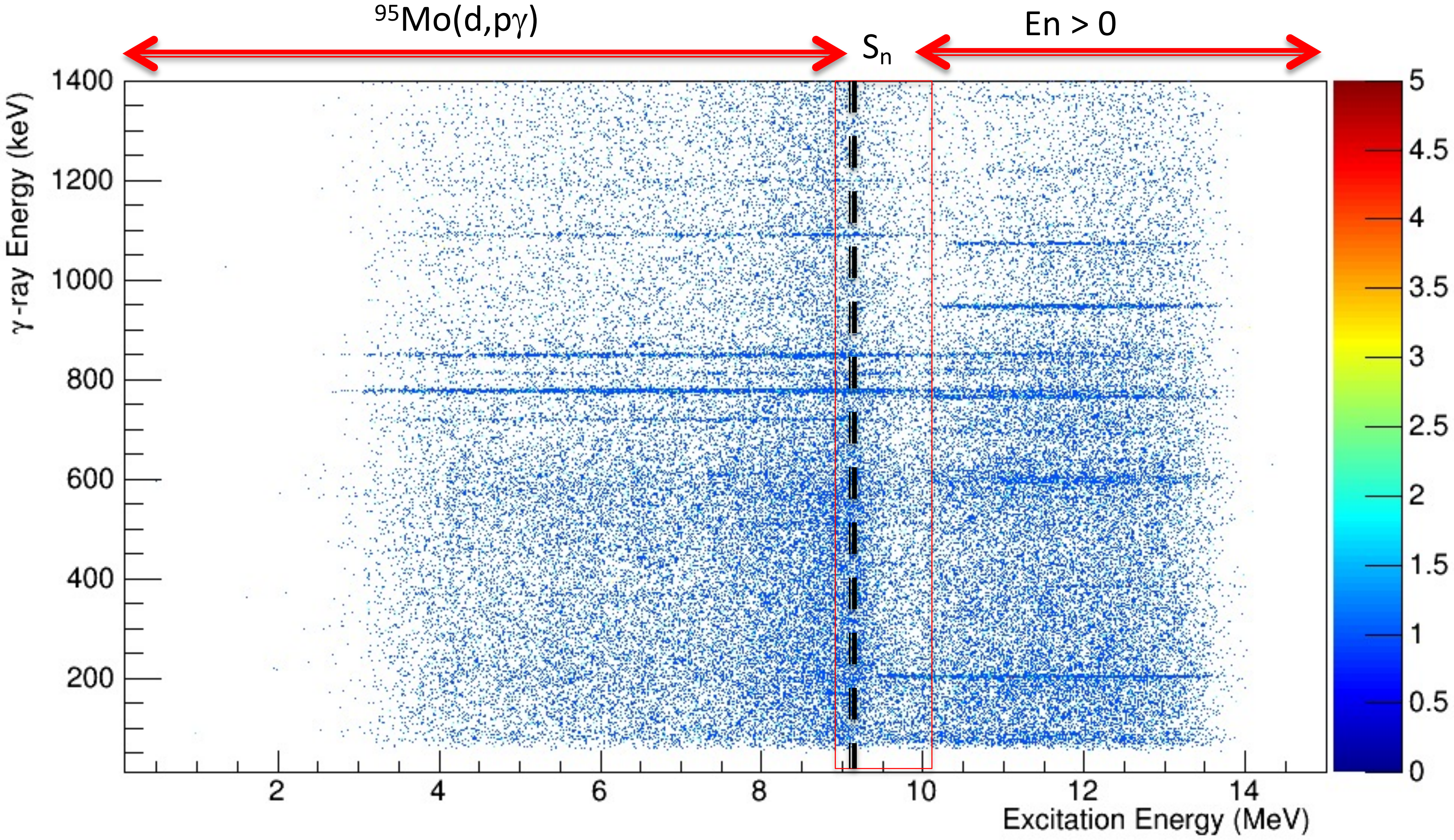
$$R = (E_1 + \Delta E_1)^\alpha - E_1^\alpha$$



The Experiment: ^{95}Mo(d,pγ)

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

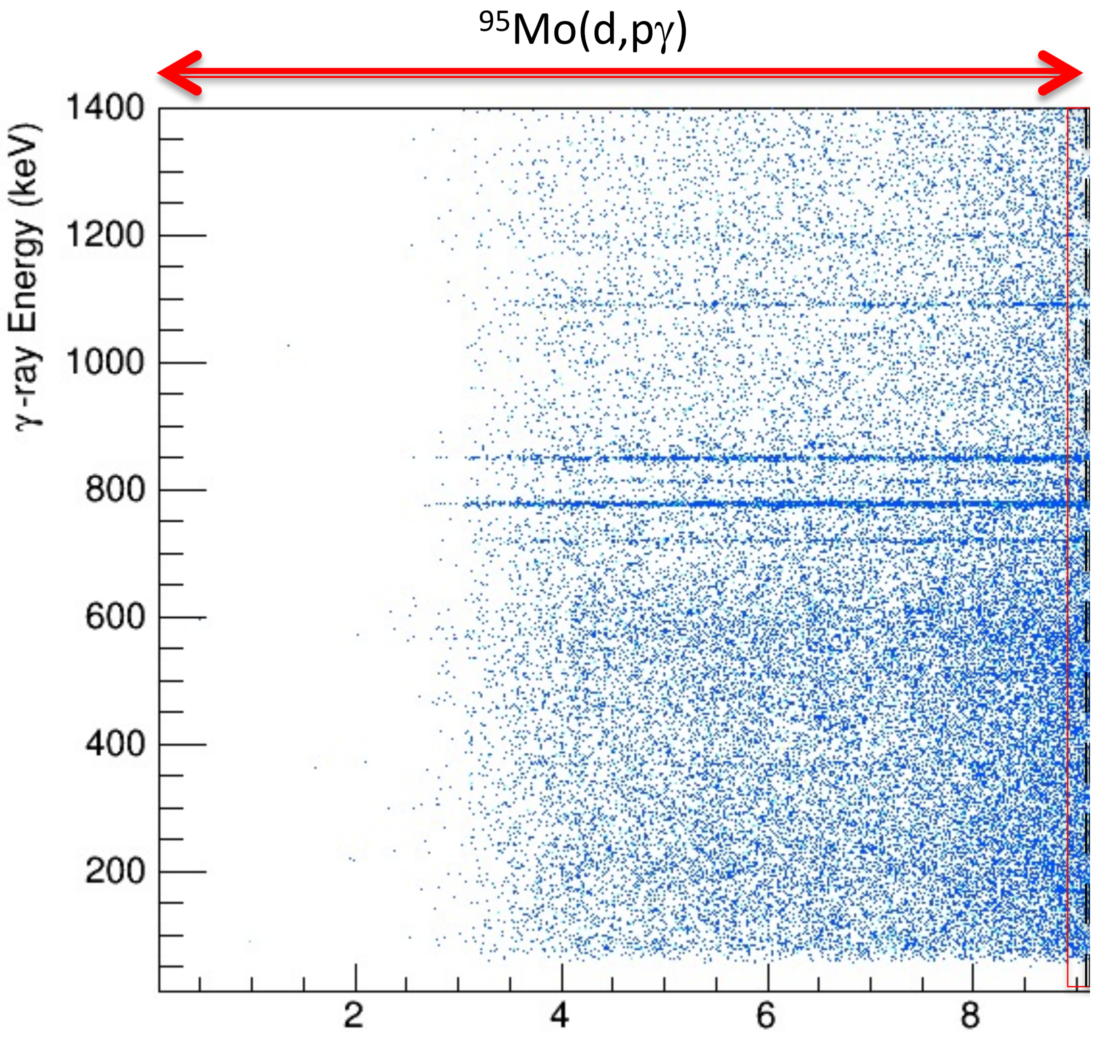
$$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_\gamma}$$

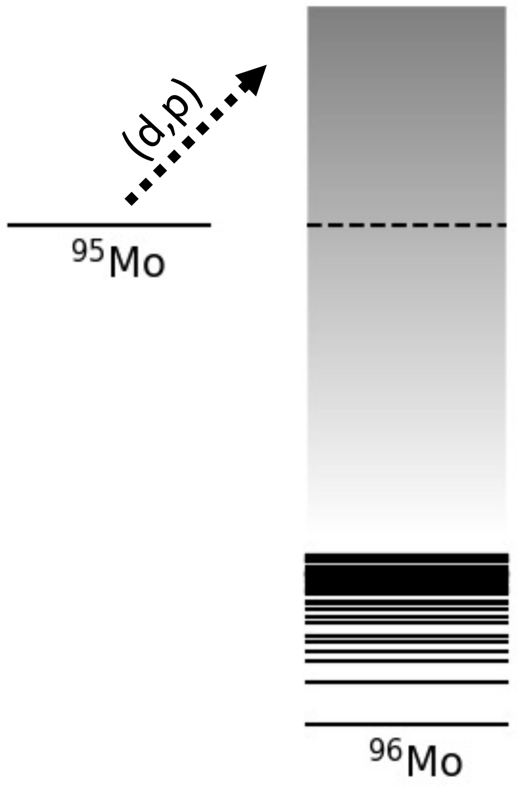


The Experiment: ^{95}Mo(d,pγ)

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

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



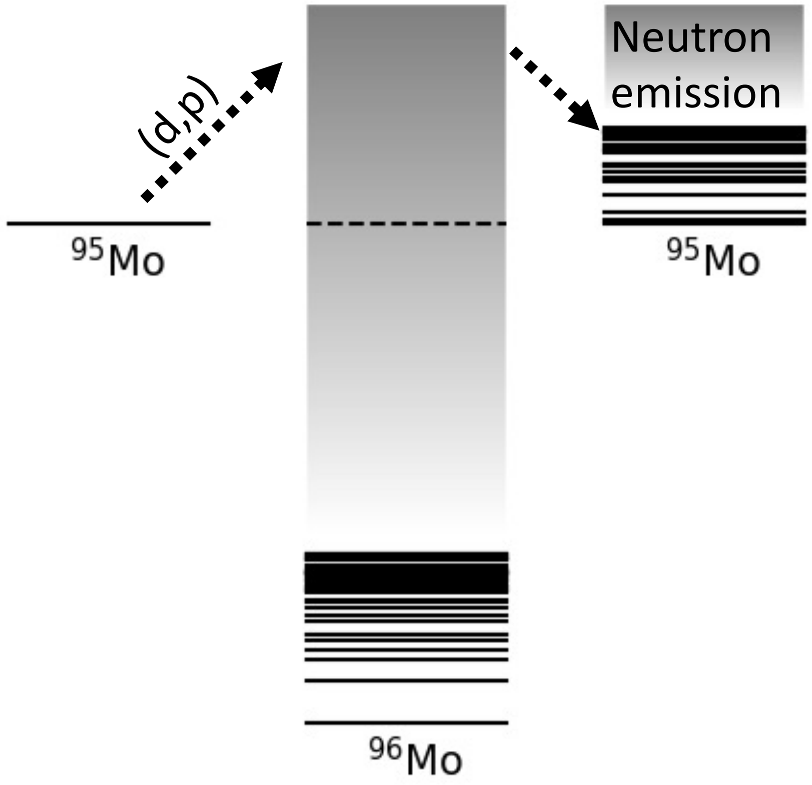


^{96}Mo levels from RIPL-3 (R. Capote et al.)

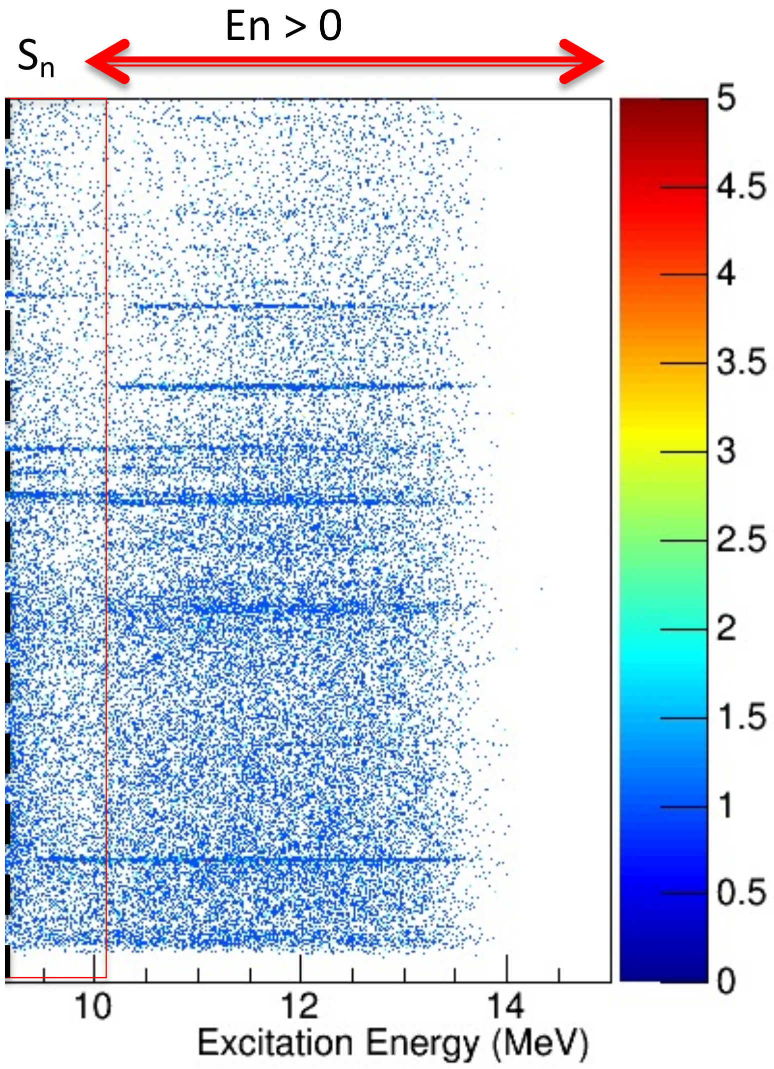
The Experiment: ^{95}Mo(d,pγ)

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

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



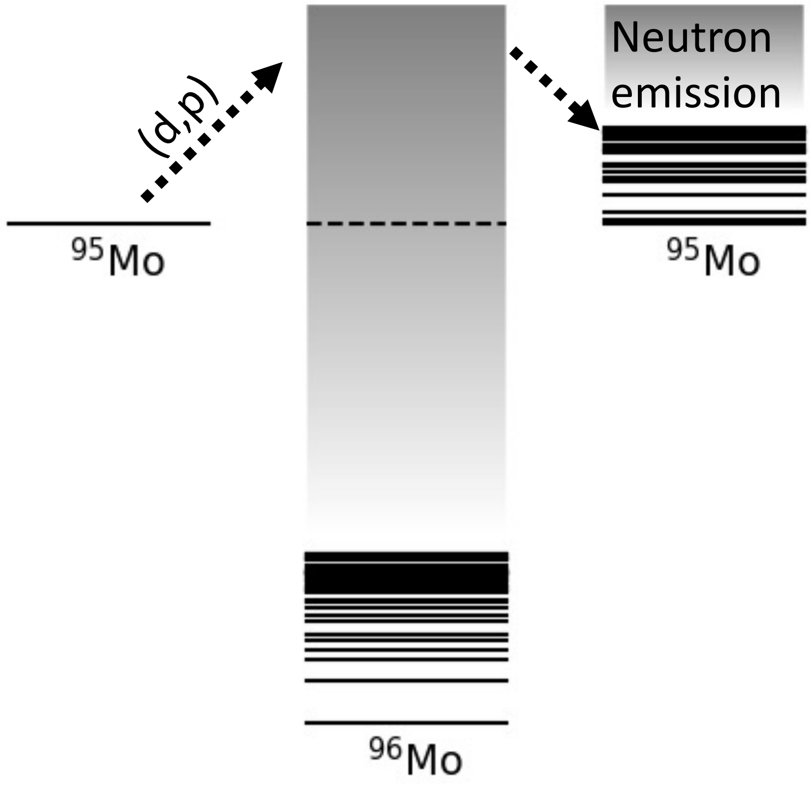
^{95,96}Mo levels from RIPL-3 (R. Capote et al.)



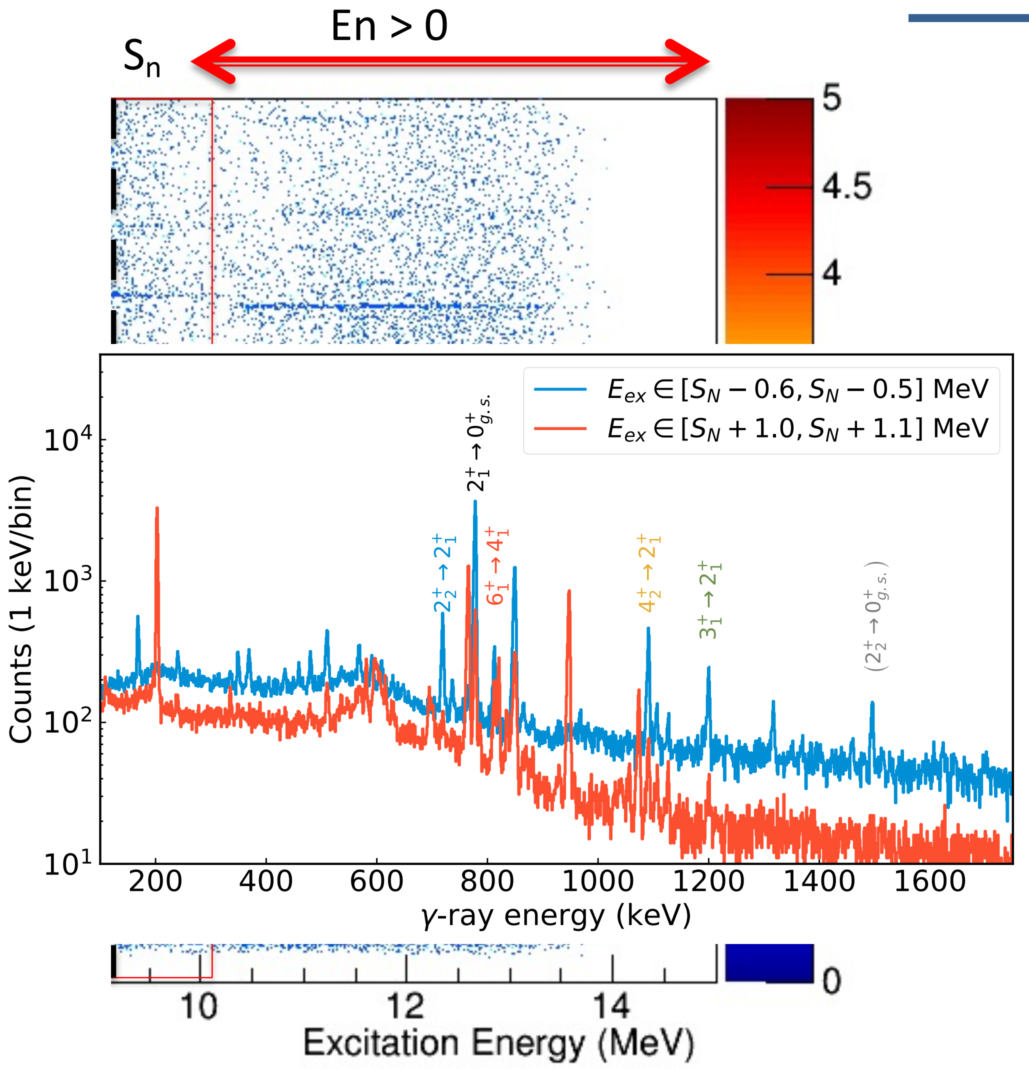
The Experiment: ^{95}Mo(d,pγ)

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

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



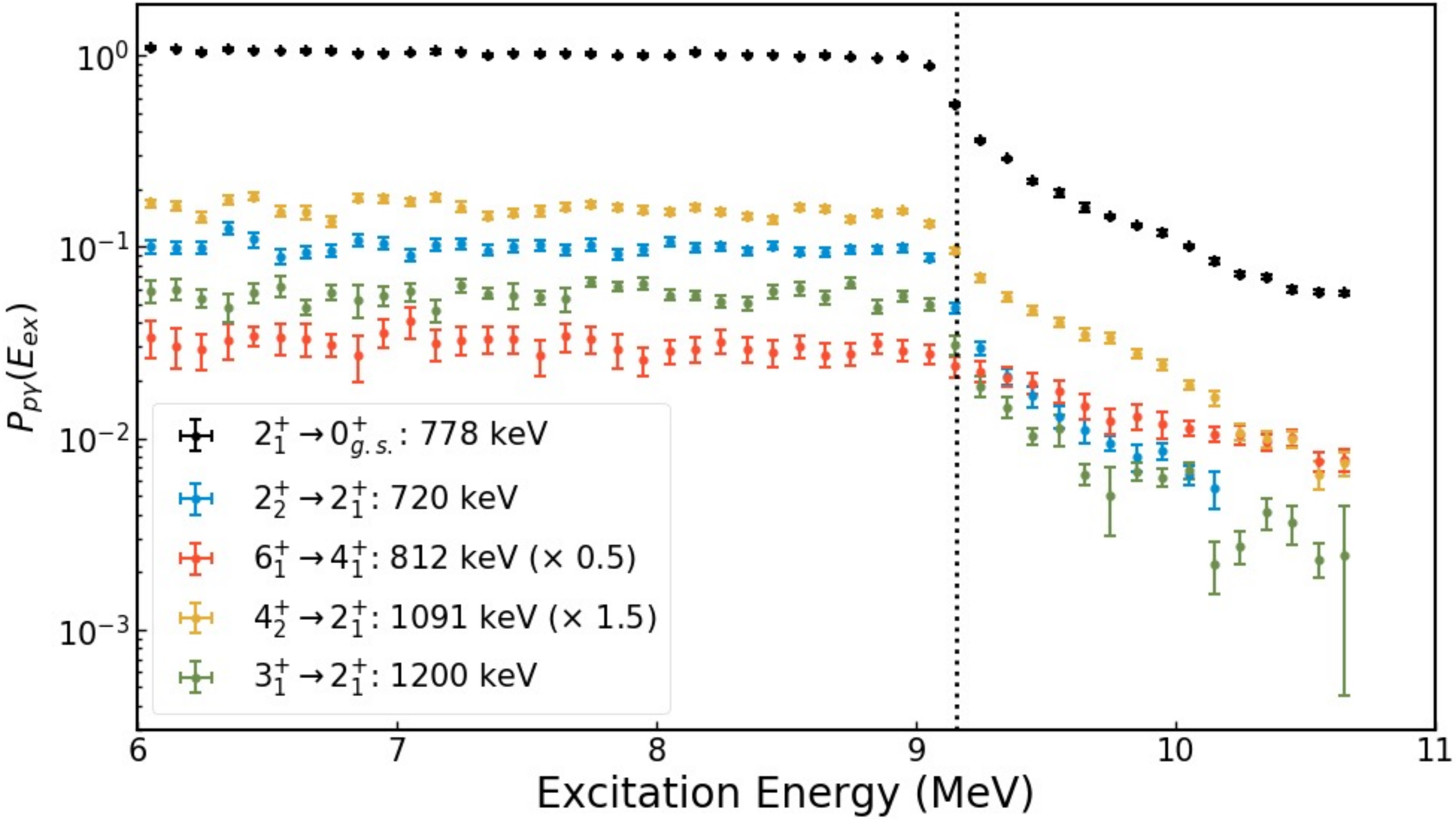
^{95,96}Mo levels from RIPL-3 (R. Capote et al.)



The Experiment: ^{95}Mo(d,pγ)

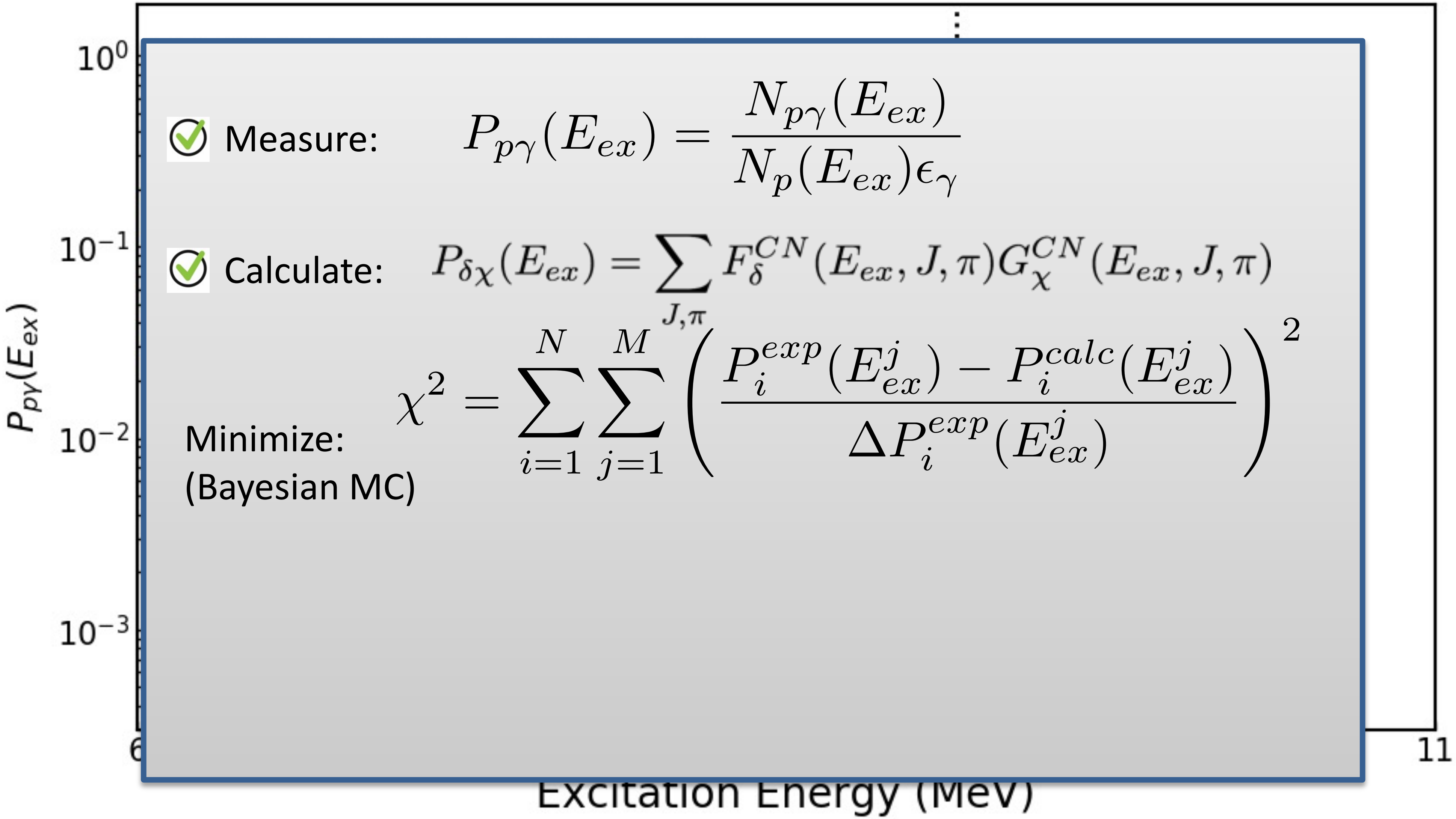
A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).

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



The Experiment: ^{95}Mo(d,pγ)

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



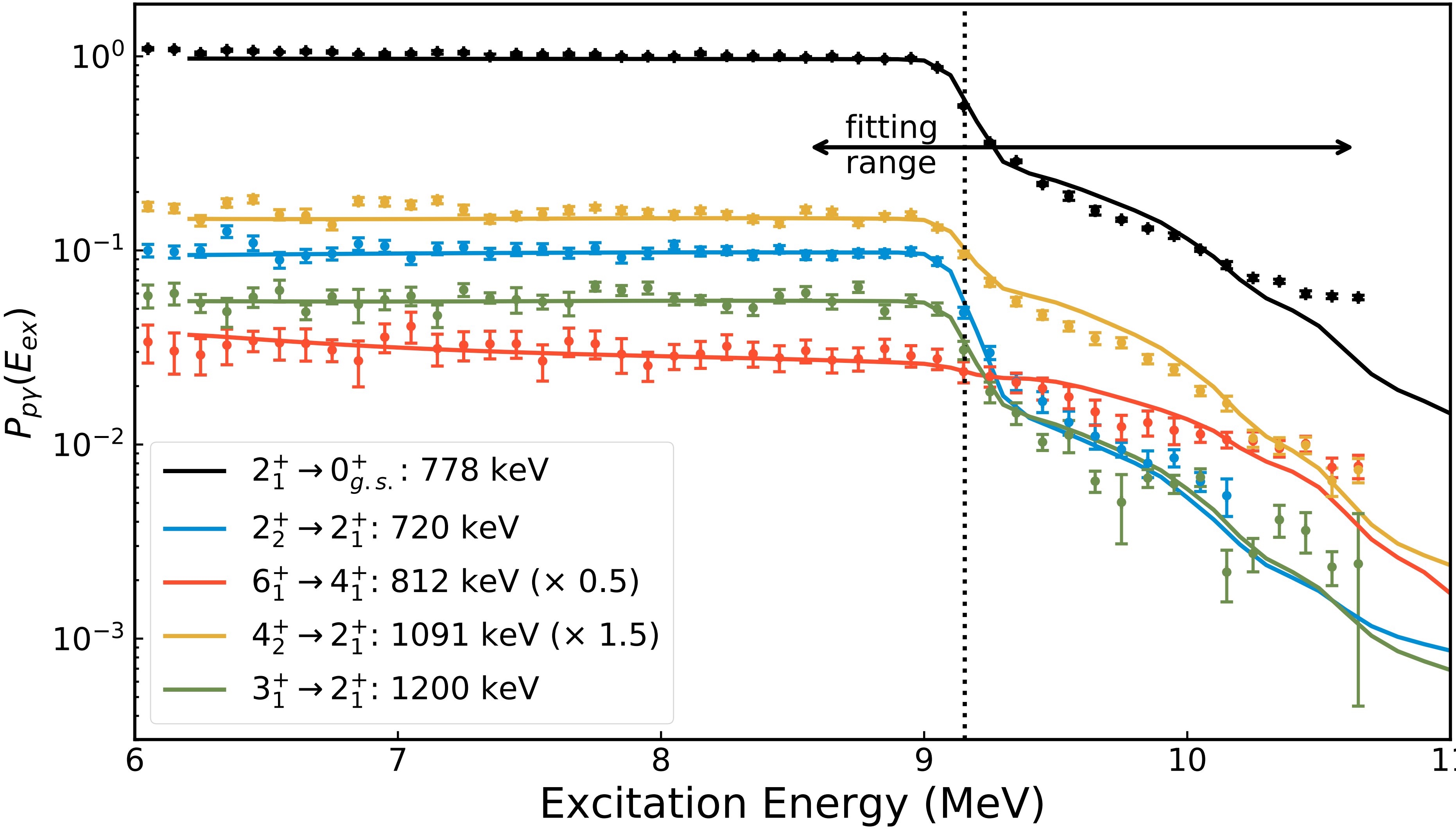
Measure: $$P_{p\gamma}(E_{ex}) = \frac{N_{p\gamma}(E_{ex})}{N_p(E_{ex})\epsilon_\gamma}$$

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

Minimize: (Bayesian MC) $$\chi^2 = \sum_{i=1}^{N} \sum_{j=1}^{M} \left(\frac{P_i^{exp}(E_{ex}^j) - P_i^{calc}(E_{ex}^j)}{\Delta P_i^{exp}(E_{ex}^j)} \right)^2$$

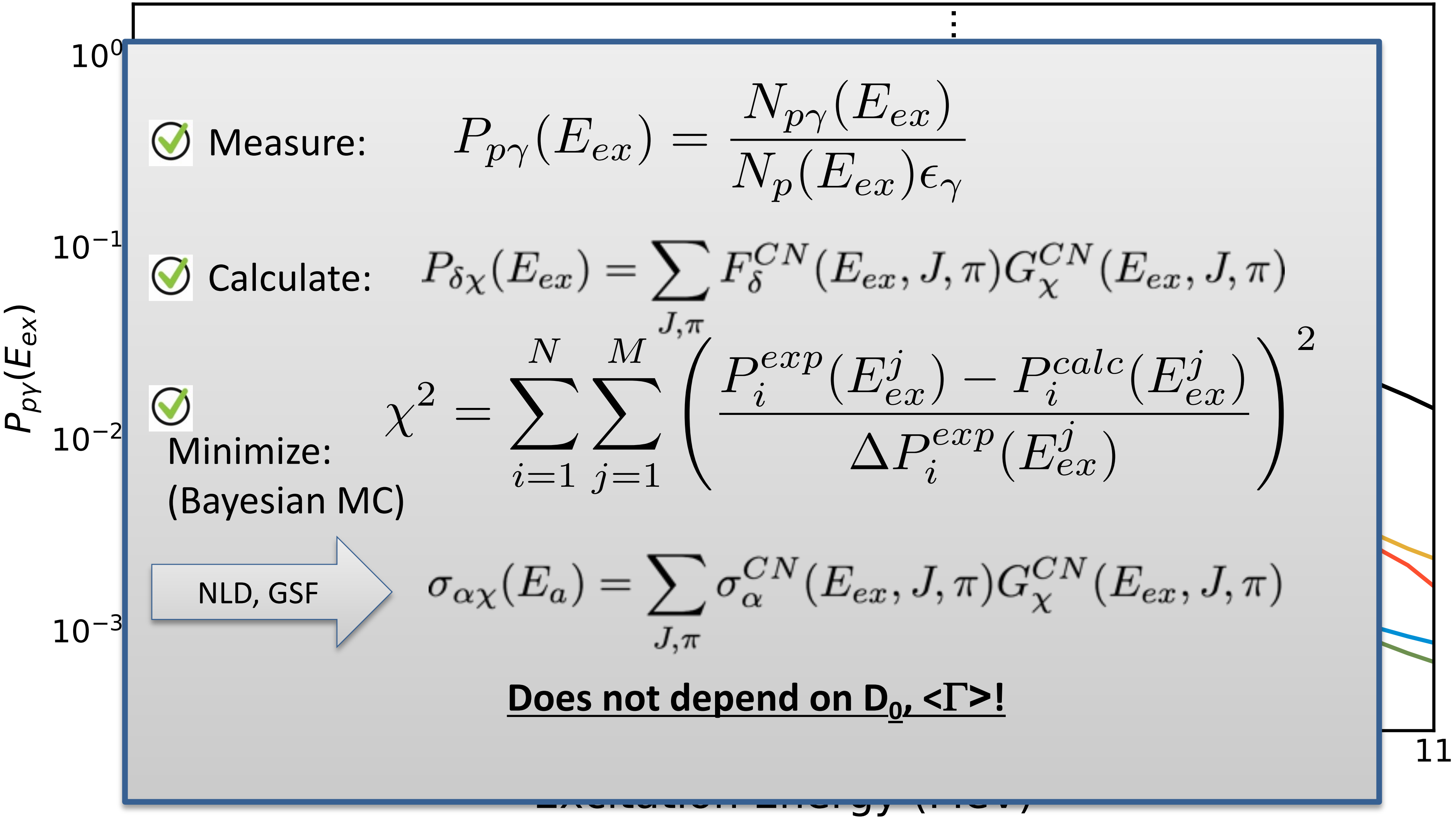
The Experiment: ^{95}Mo(d,pγ)

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



The Experiment: ^{95}Mo(d,pγ)

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



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

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

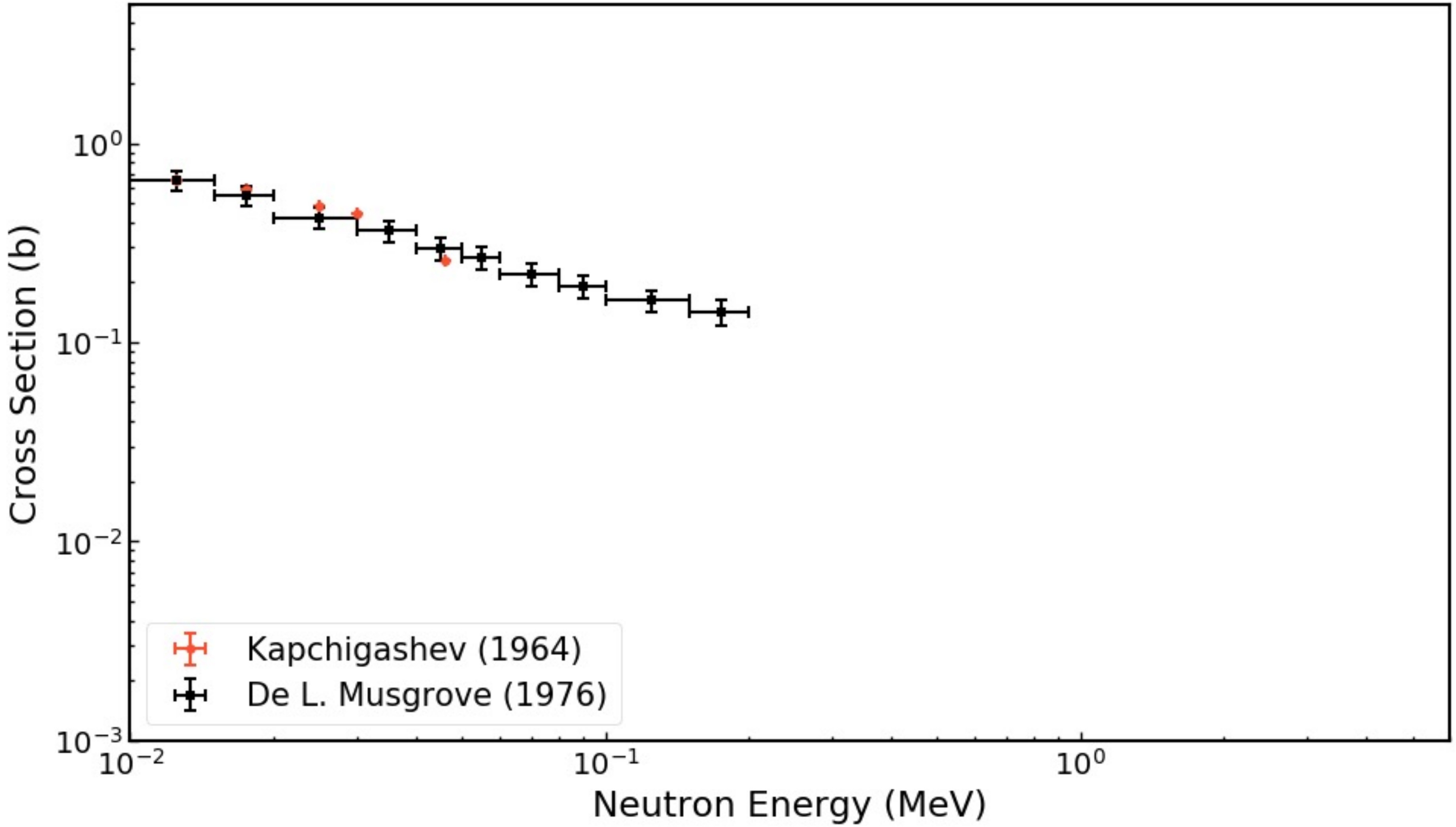
✅ Minimize: (Bayesian MC) $$\chi^2 = \sum_{i=1}^{N} \sum_{j=1}^{M} \left(\frac{P_i^{exp}(E_{ex}^j) - P_i^{calc}(E_{ex}^j)}{\Delta P_i^{exp}(E_{ex}^j)} \right)^2$$

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

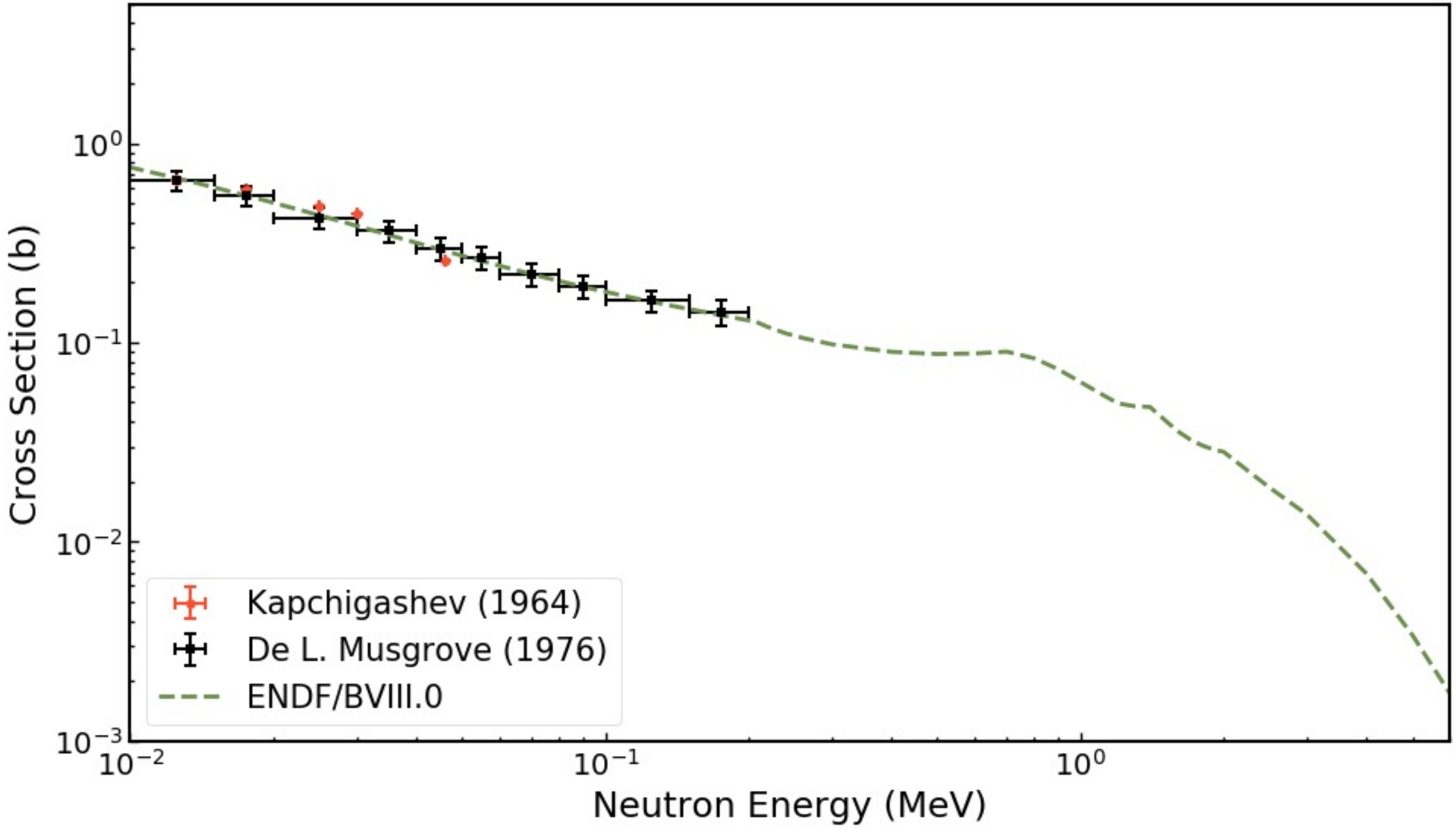
Does not depend on D_0, <Γ>!

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

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

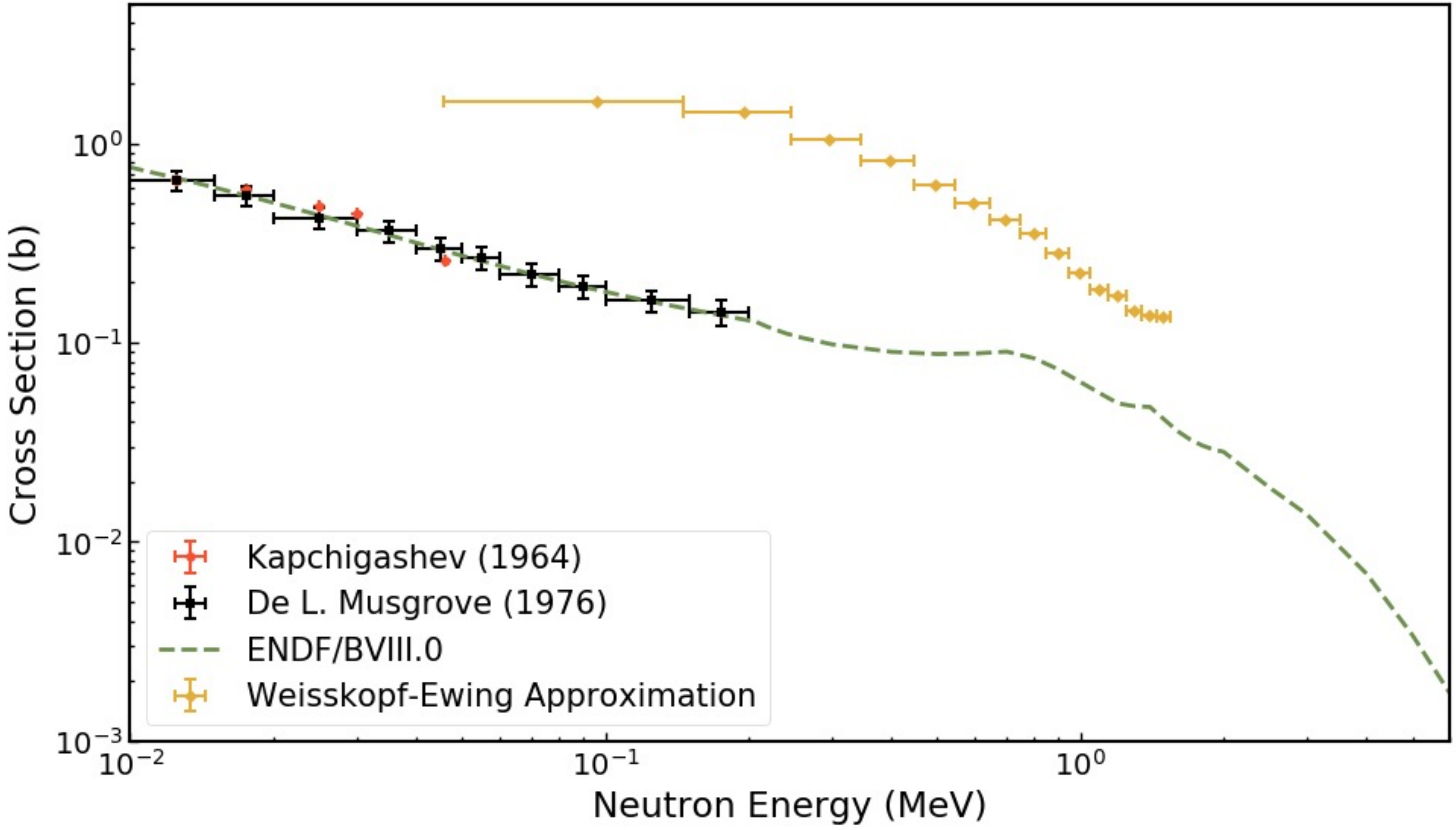


The Experiment: $^{95}Mo(d,p\gamma)$
A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



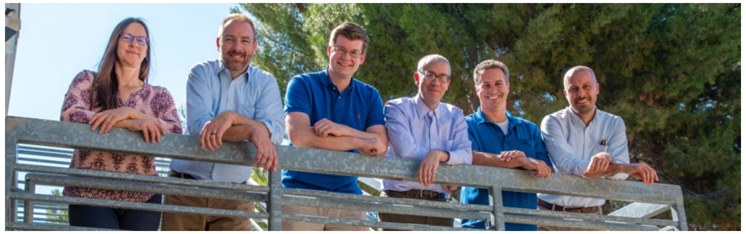
The Experiment: $^{95}Mo(d,p\gamma)$

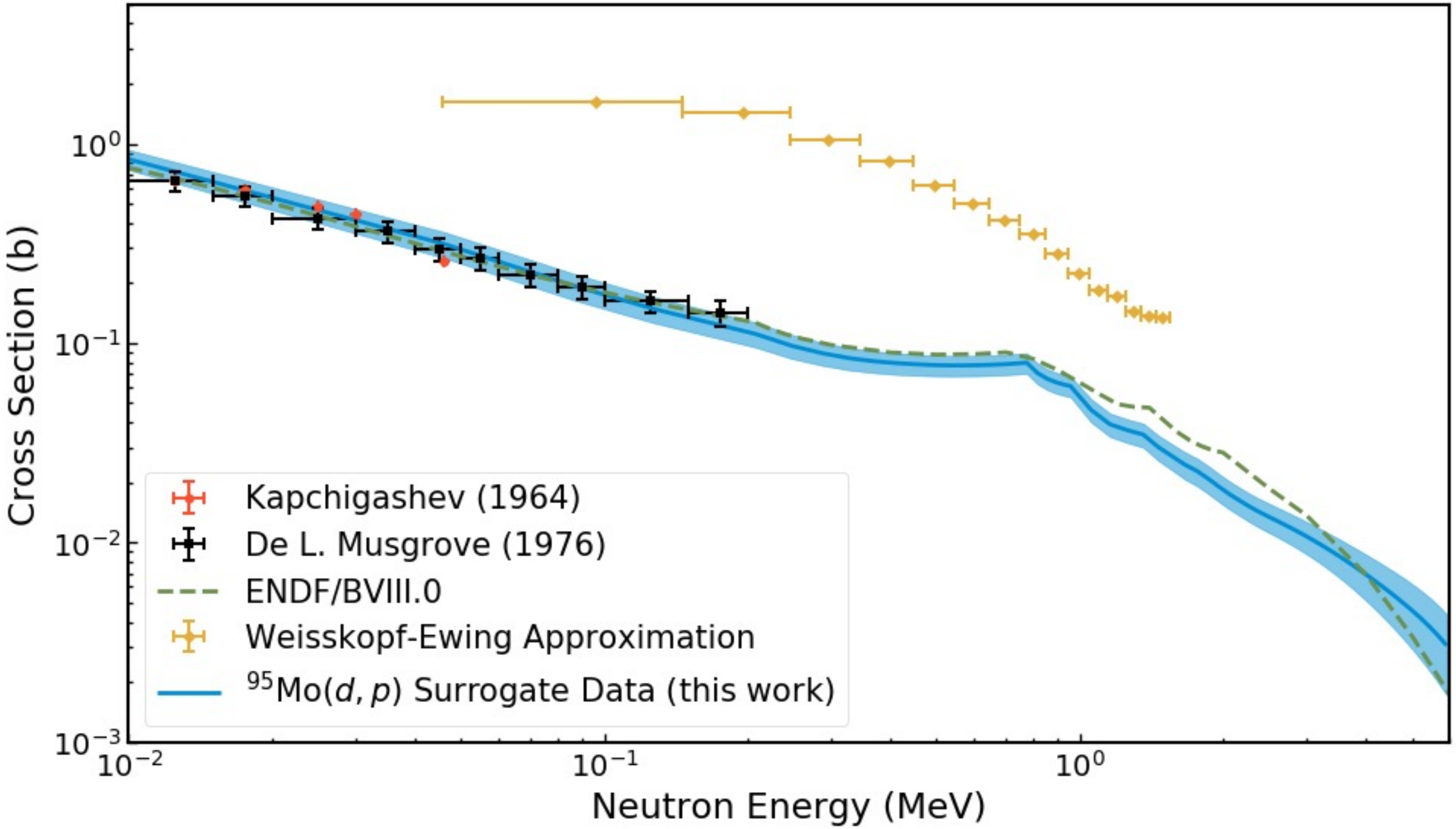
A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).



The Experiment: ^{95}Mo(d,pγ)

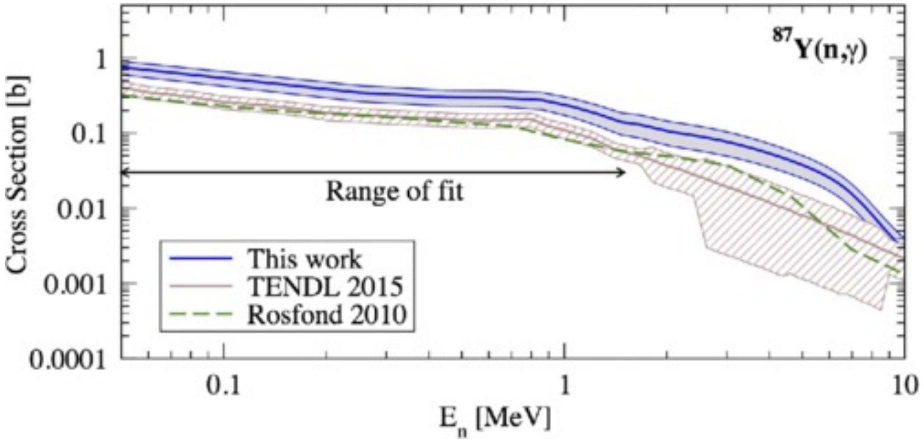
A. Ratkiewicz *et al.*, PRL 122, 052502 (2019).





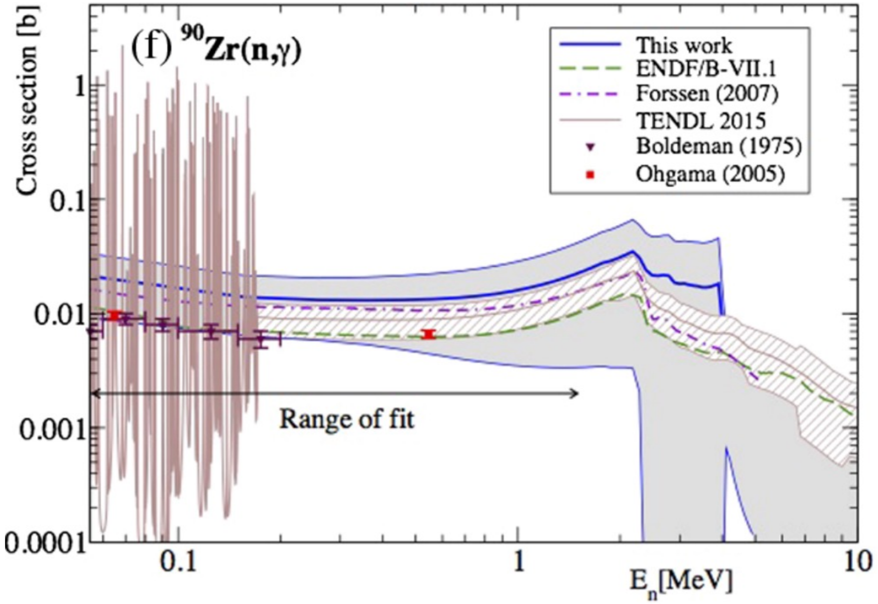
Successful Surrogate constraints are ***only*** possible through close collaboration between theory and experiment.

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}Y(p,d) for ^{87}Y(n,γ)^{88}Y
  - — ^{92}Zr(p,d) for ^{90}Zr(n,γ)^{91}Zr

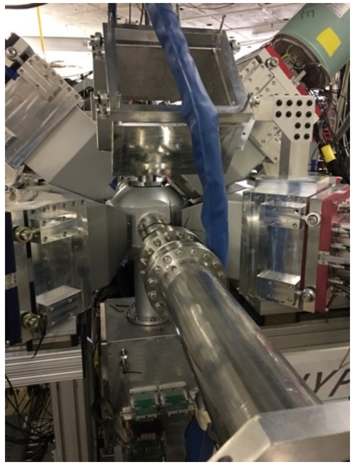


J.E. Escher et al., PRL **121**, 052501 (2018).

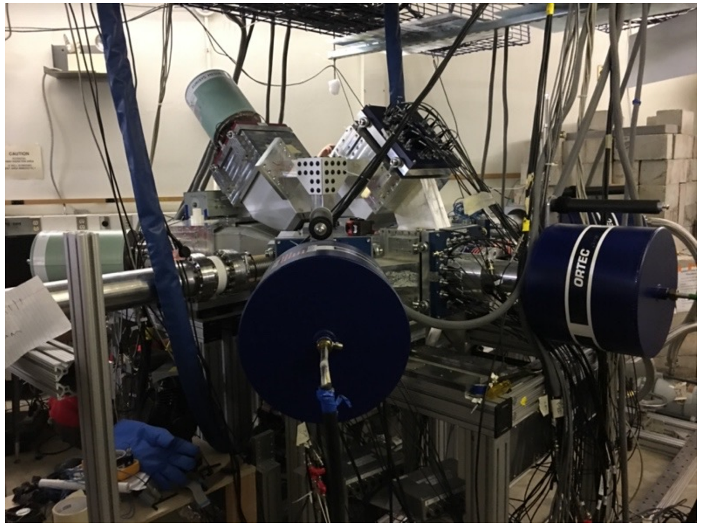
$^{95}Zr(n,\gamma)$ cross-section measurement

B. Alan, et al.

- **Branching points are powerful probes of the astrophysical environments of the *s*-process**
  - The abundance of ^{96}Zr in AGB stars is very sensitive to the neutron density during the *s*-process because of the **branching point at ^{95}Zr.**
  - The ^{96}Zr isotopic ratios derived from stellar models of AGB stars depend on the **$^{95}Zr(n,\gamma)$ cross section.**



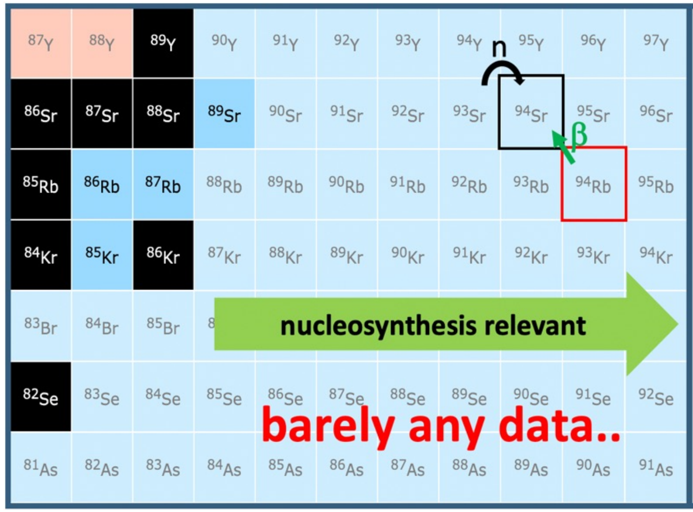
- **Measurements were performed at the Texas A&M Cyclotron Institute in Aug-Oct 2021**
  - Measured $^{95}Zr(n,\gamma)$ using the surrogate reaction $^{96}Zr(p,p')$
  - Benchmark: measured $^{93}Zr(n,\gamma)$ using the surrogate reaction $^{94}Zr(p,p')$
    - $^{93}Zr(n,\gamma)$ cross section measured 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



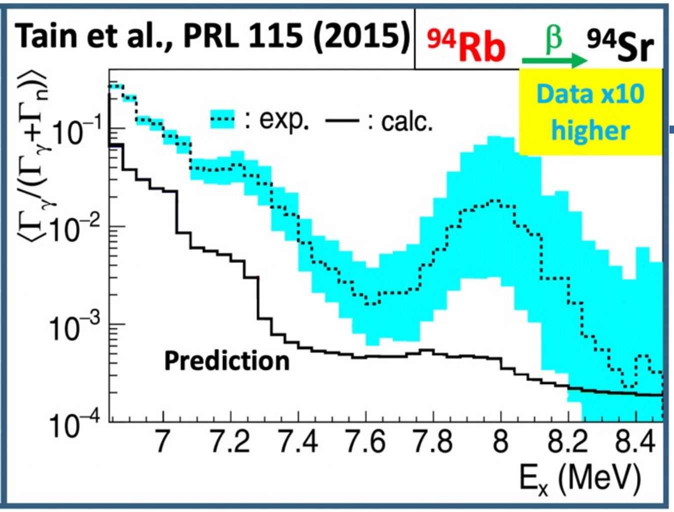
Determining the n-capture rate for unstable ^{93}Sr via the Surrogate Reaction Method

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 σ(^{93}Sr(n,γ)) with SRM and RIBs
- Experiment fielded at TRIUMF in Nov. 2021:
  - ^{93}Sr(d,p-γ) with TIGRESS & SHARC, 8MeV/A ^{93}Sr.
- Analysis underway led by LLNL postdoc Andrea Richard.

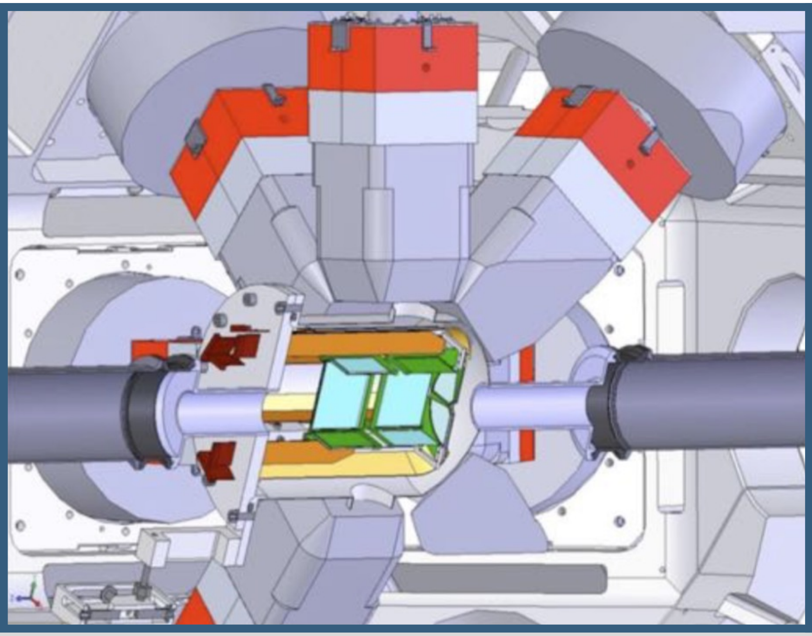


capture data limited for n-rich Sr region

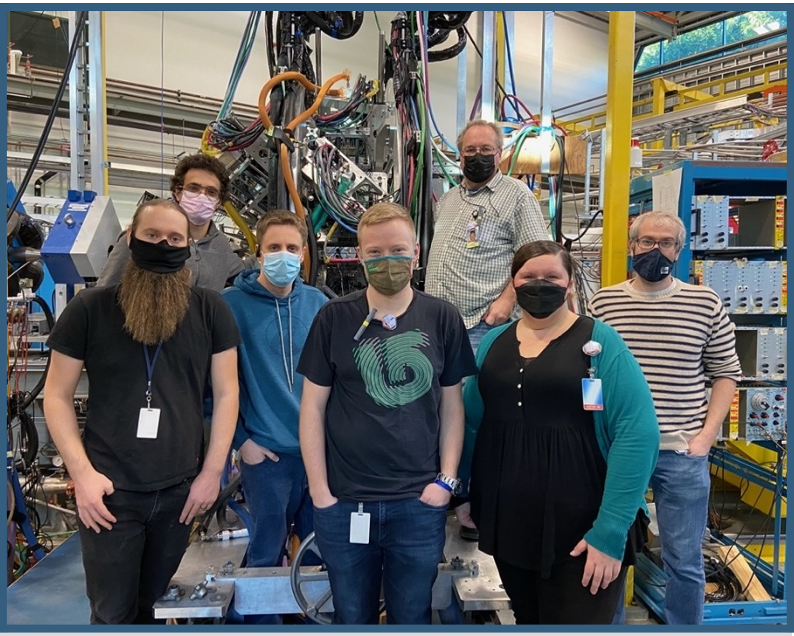


TAGS results hint at n-capture enhancement

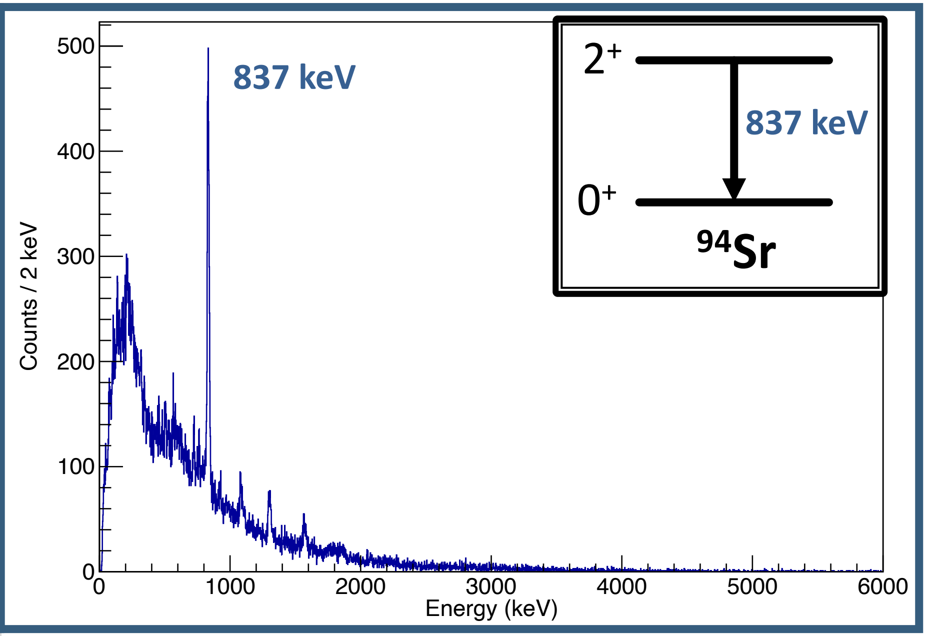
TIGRESS HPGe array & SHARC Si array @ TRIUMF



LLNL/TRIUMF experiment team



Doppler-corrected γ-rays in coincidence with protons from (d,p)

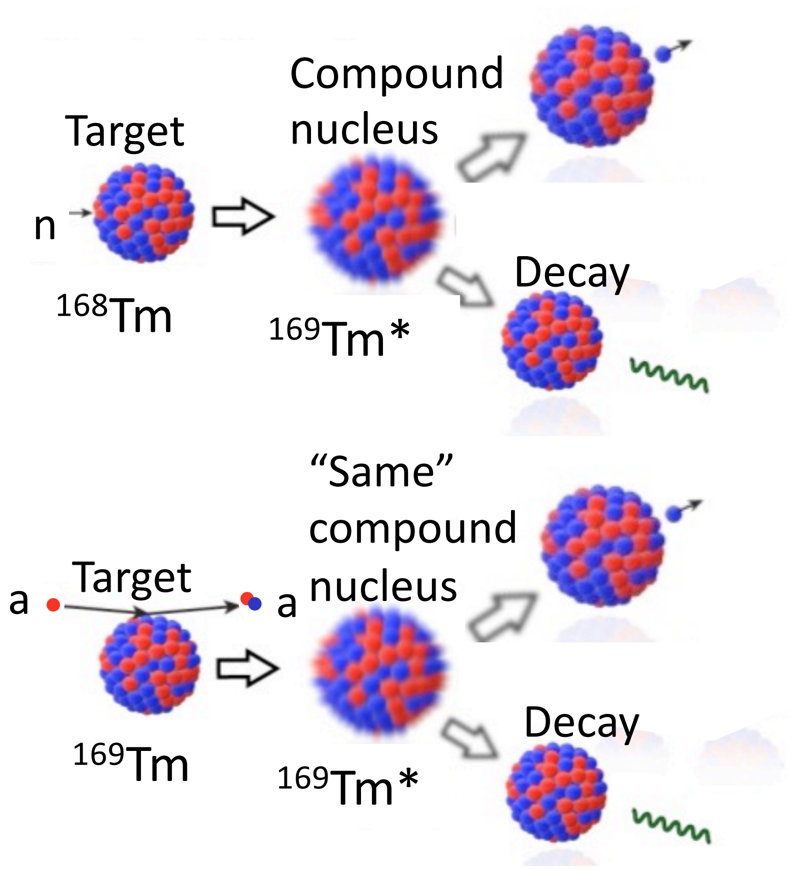


The surrogate method allows us to measure the cross section of unstable nuclei (ex: 168Tm(n,2n) which has never been measured)

J. Harke, et al.

Desired Reaction

Surrogate Reaction



^{168}Tm half-life = 93.1 days
100 milligram target
839 Curies or 3e11 dps

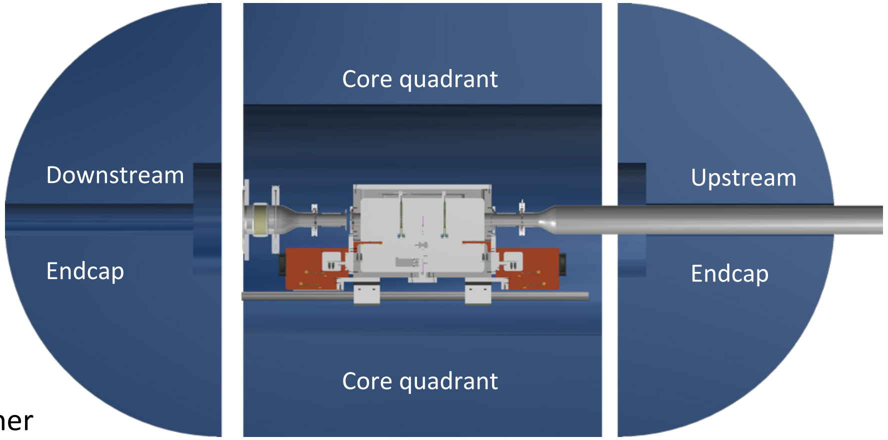
OR

^{169}Tm == stable

NeutronSTARS: 3.7-ton active volume neutron detector

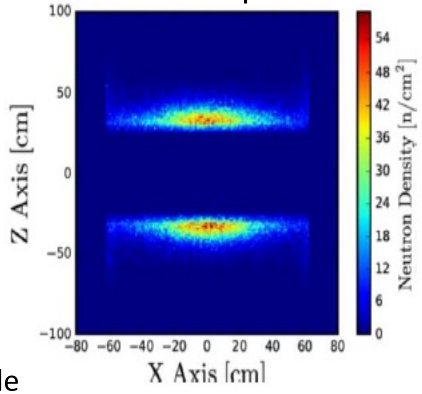
J. Harke et al.

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

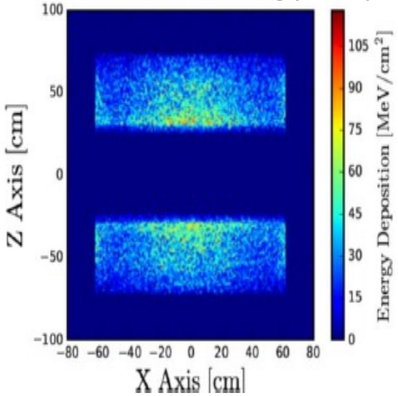


Courtesy S. Fisher

Neutron capture

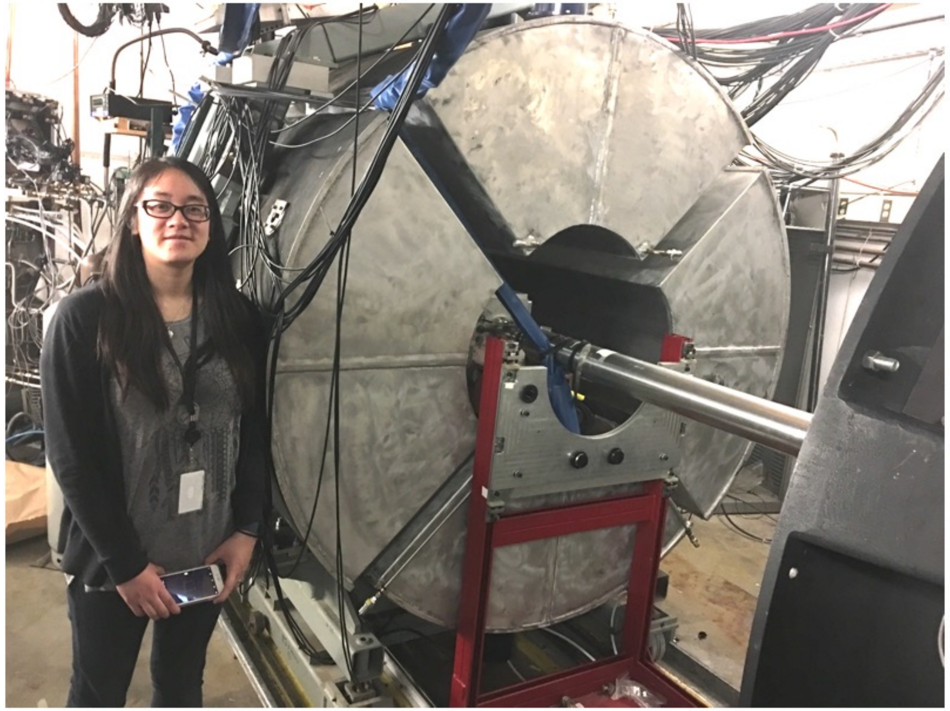


Gamma energy dep.



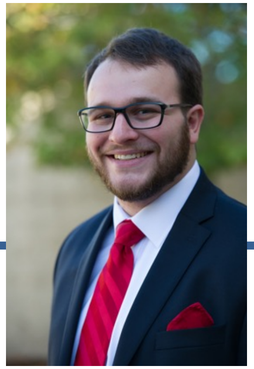
Courtesy O. Akindele

Commissioned January-April 2017
J.T.Harke , R.J. Casperson, R.O.Hughes,
B.S. Alan, S.Fisher, O.Akindele, A.Tamashiro, A. Padilla

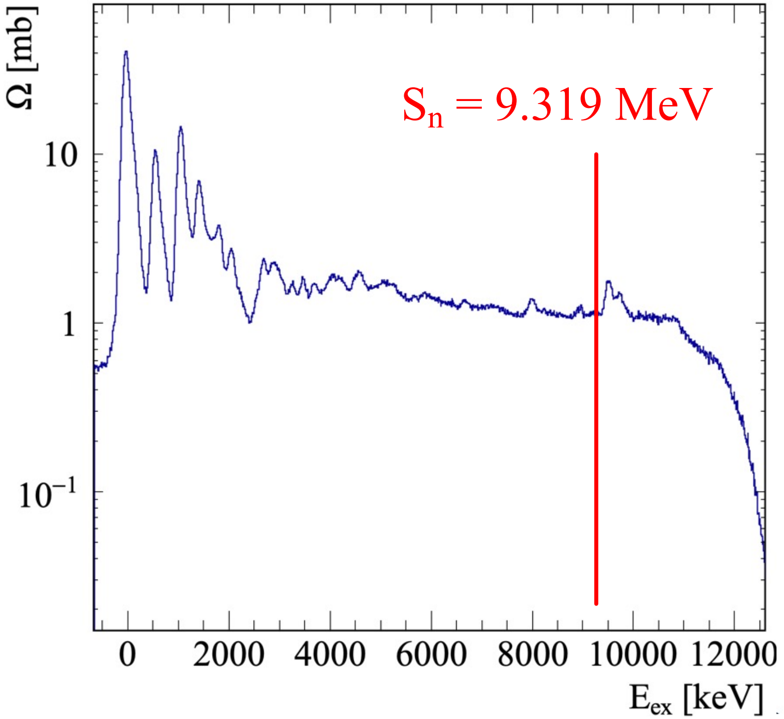


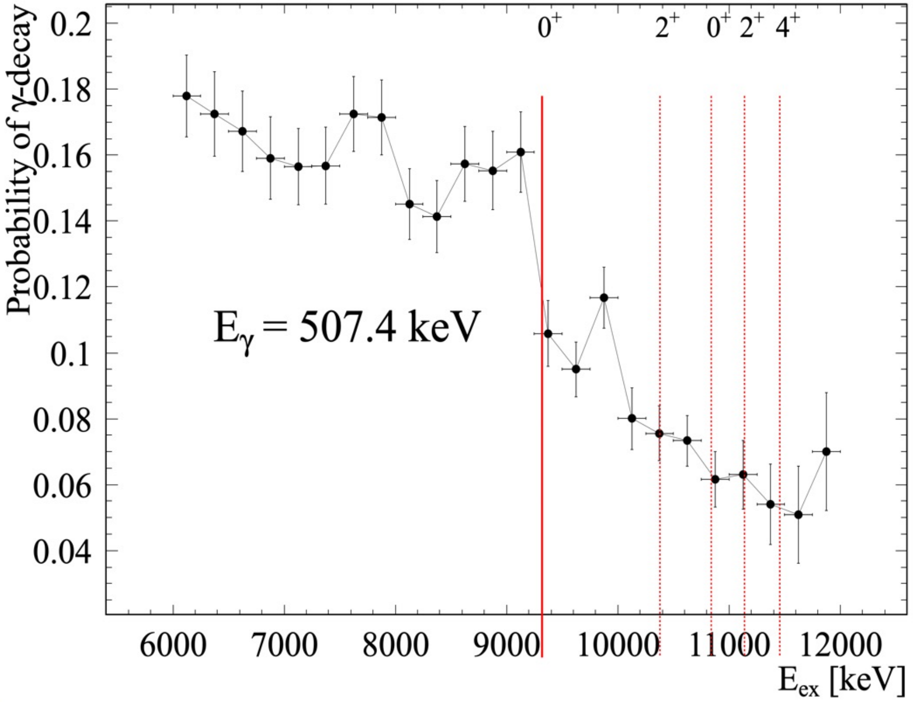
Using $^{90}Zr(p,d)^{89}Zr$ as a surrogate for $^{88}Zr(n,\gamma)^{89}Zr$

C. Reingold et al.

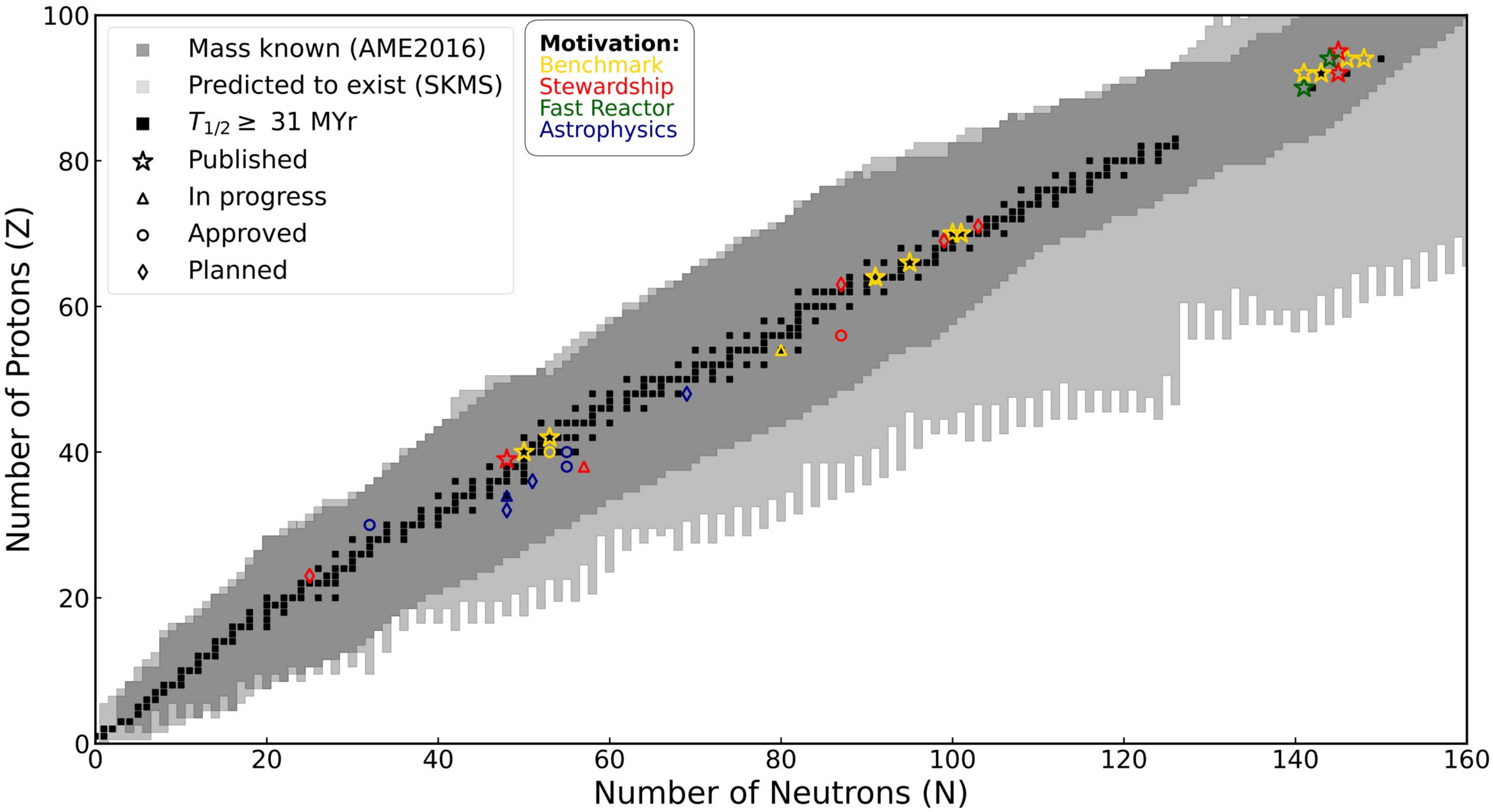


- Applications-driven measurement.
- Measured with StarLiTeR detector array, comprised of 6 Compton-suppressed HPGe clover detectors coupled to an S2 silicon telescope
- Currently extracting the (n,γ) cross section from the (p,d) cross section (left) and γ-decay probabilities (right)



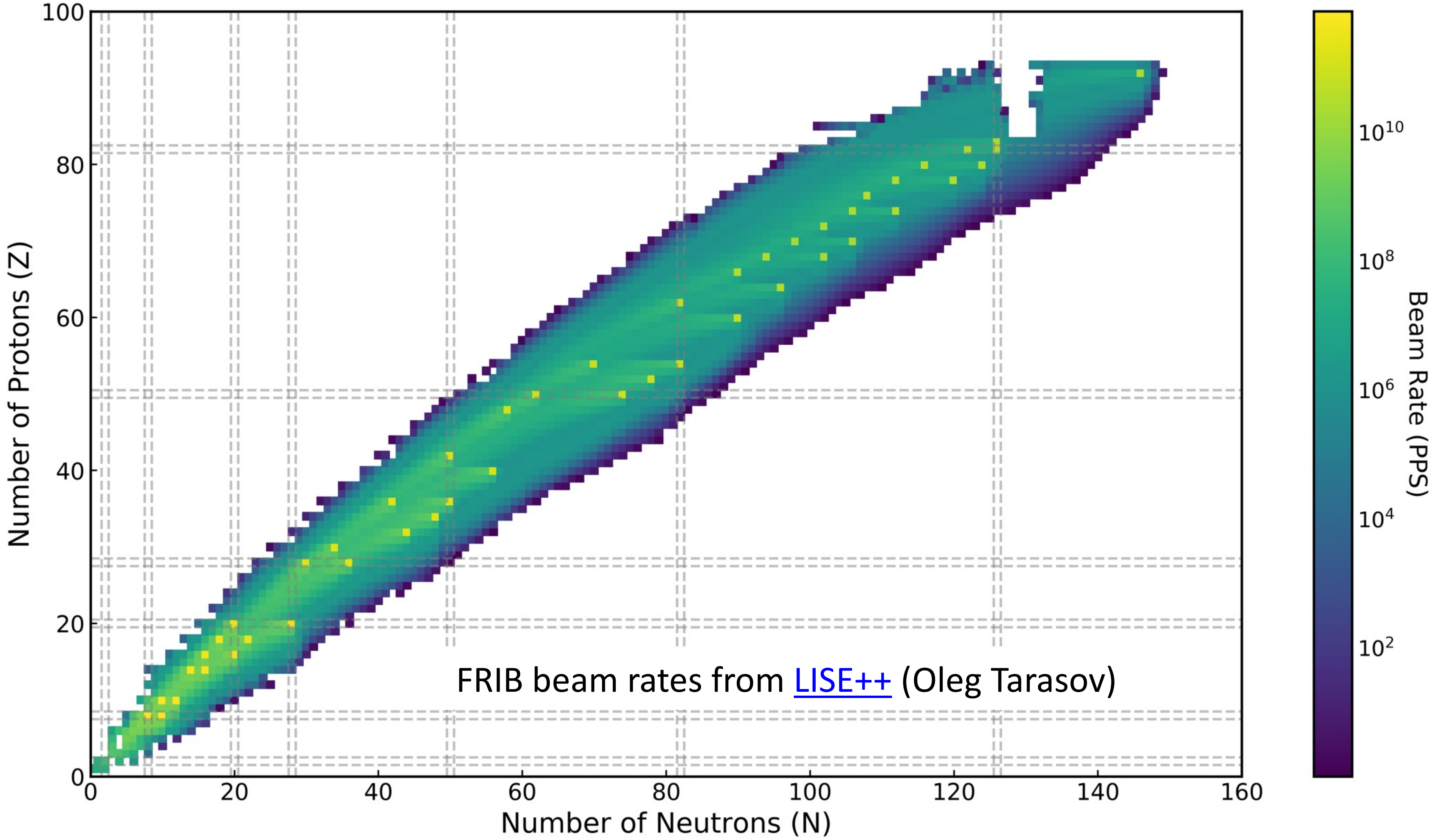


The Surrogate Method has been widely exercised.



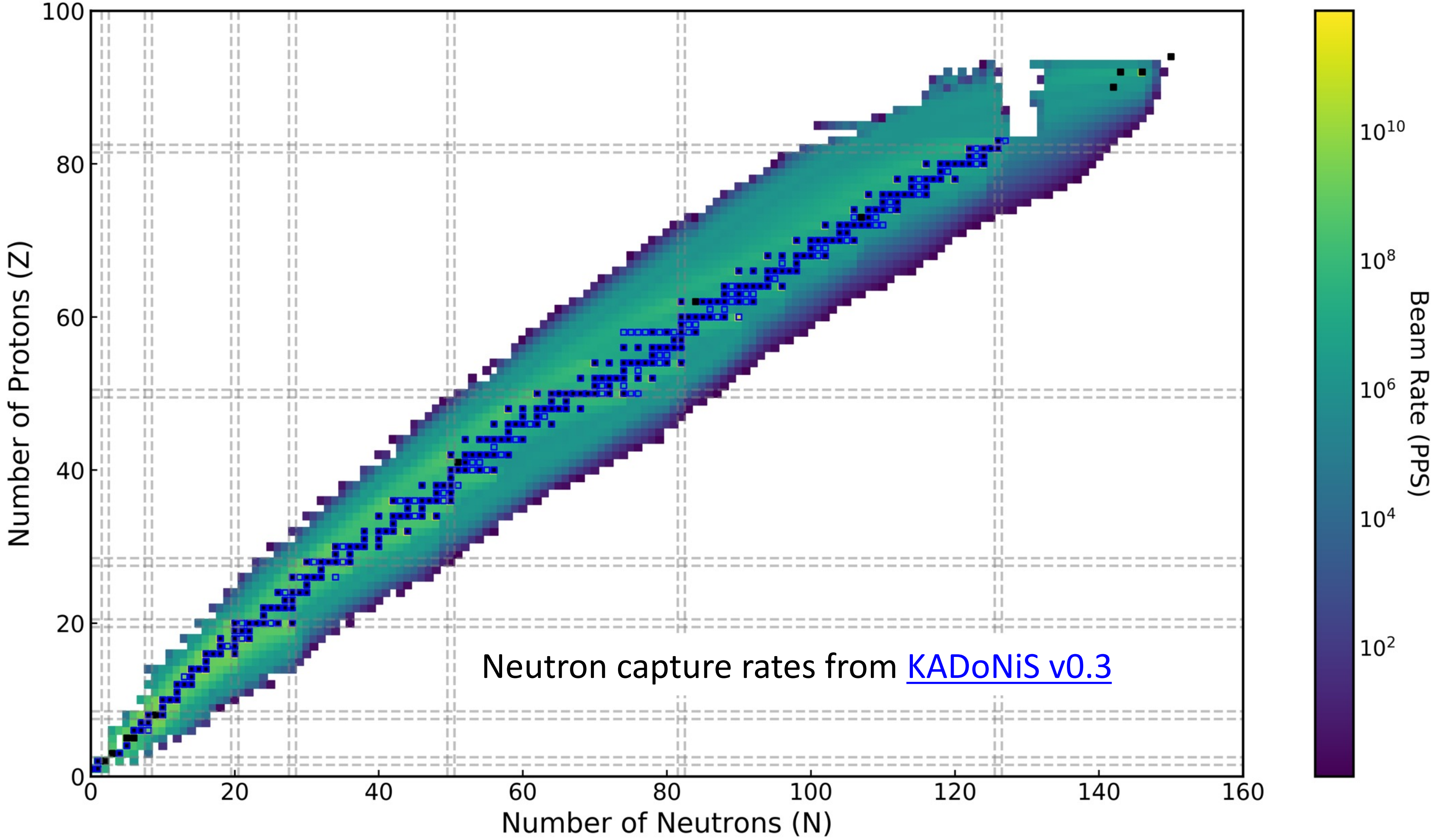
Looking ahead to FRIB:

This is the opportunity with which we are presented



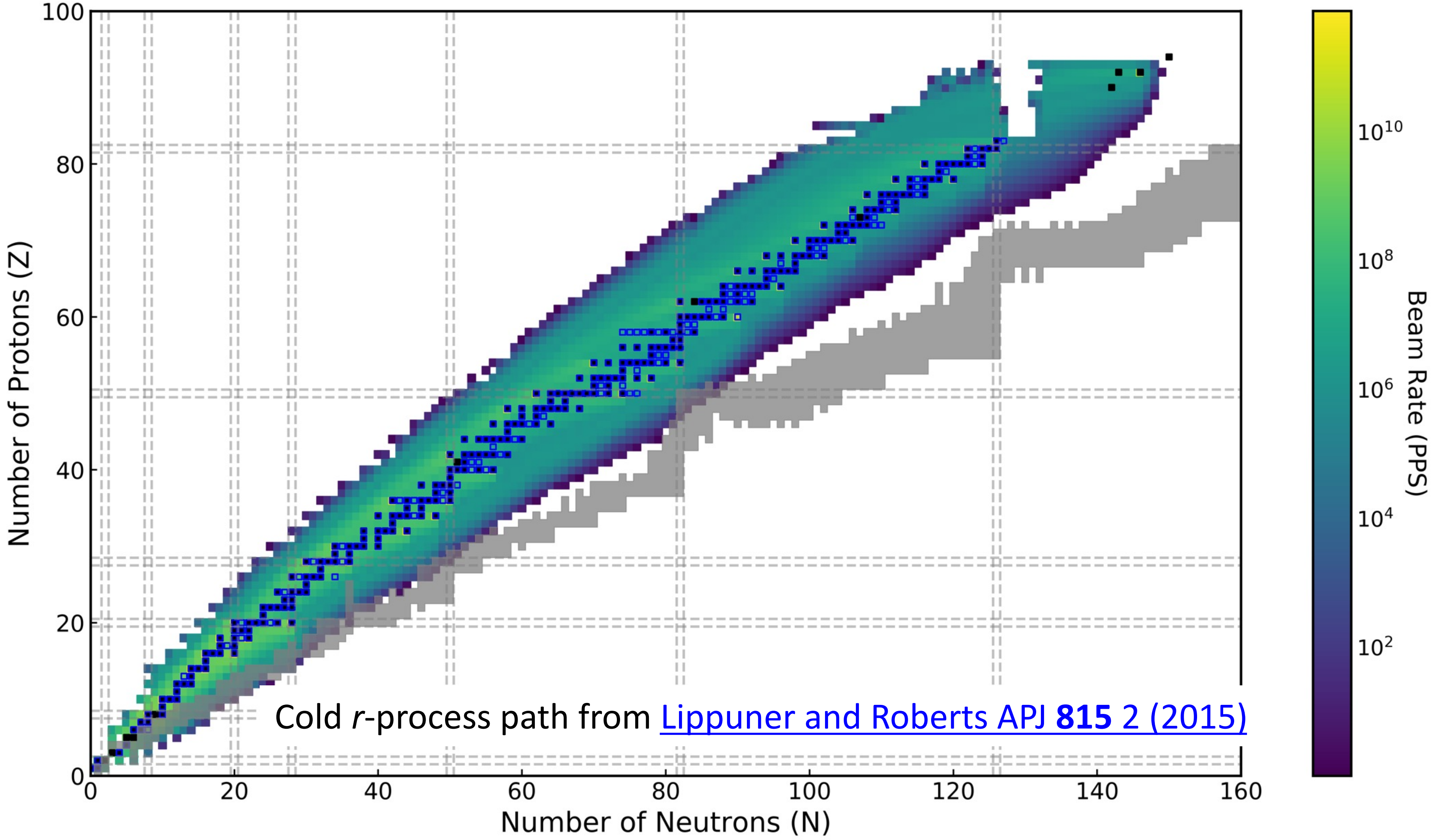
Looking ahead to FRIB:

This is the opportunity with which we are presented



Looking ahead to FRIB:

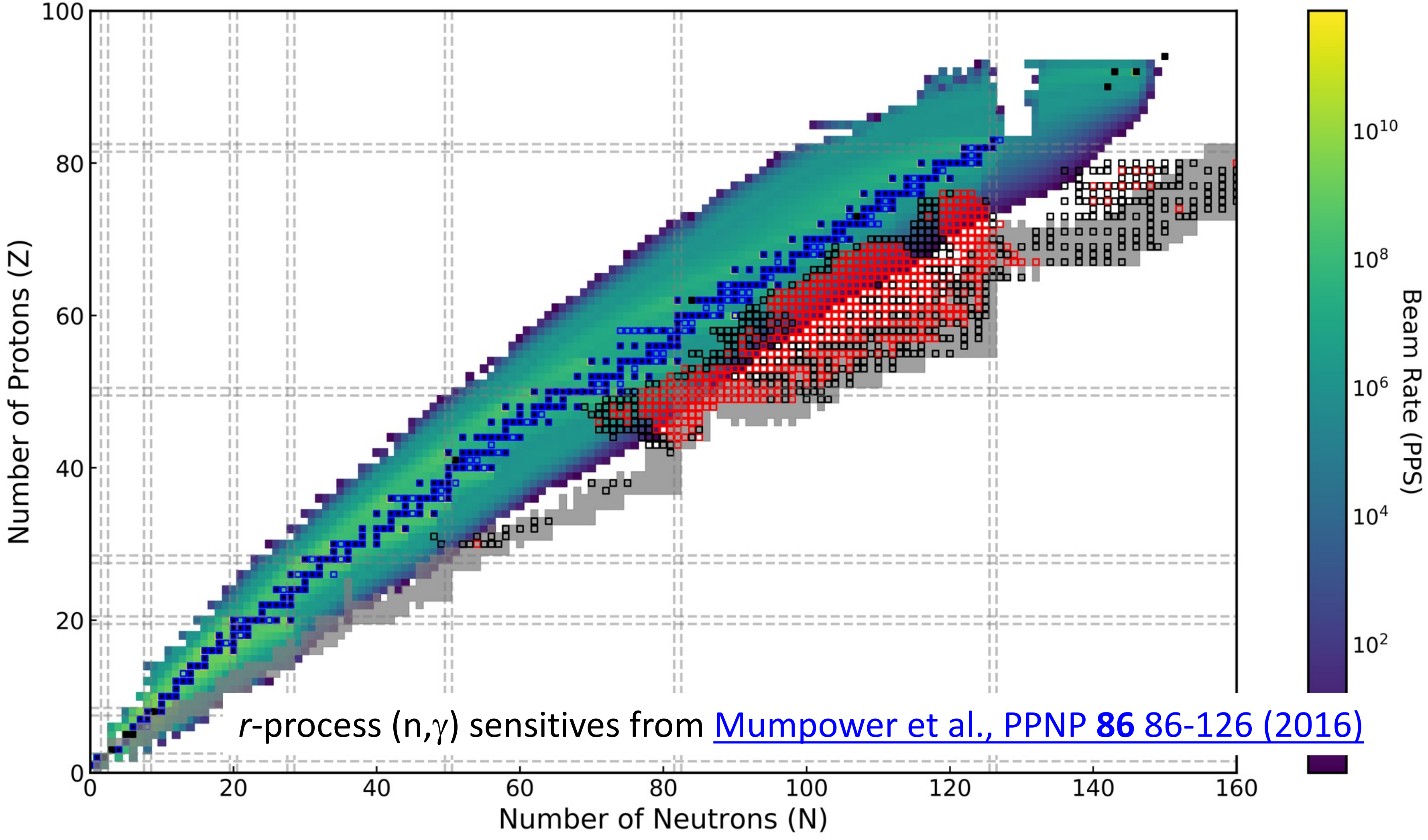
This is the opportunity with which we are presented



Cold *r*-process path from Lippuner and Roberts APJ **815** 2 (2015)

Looking ahead to FRIB:

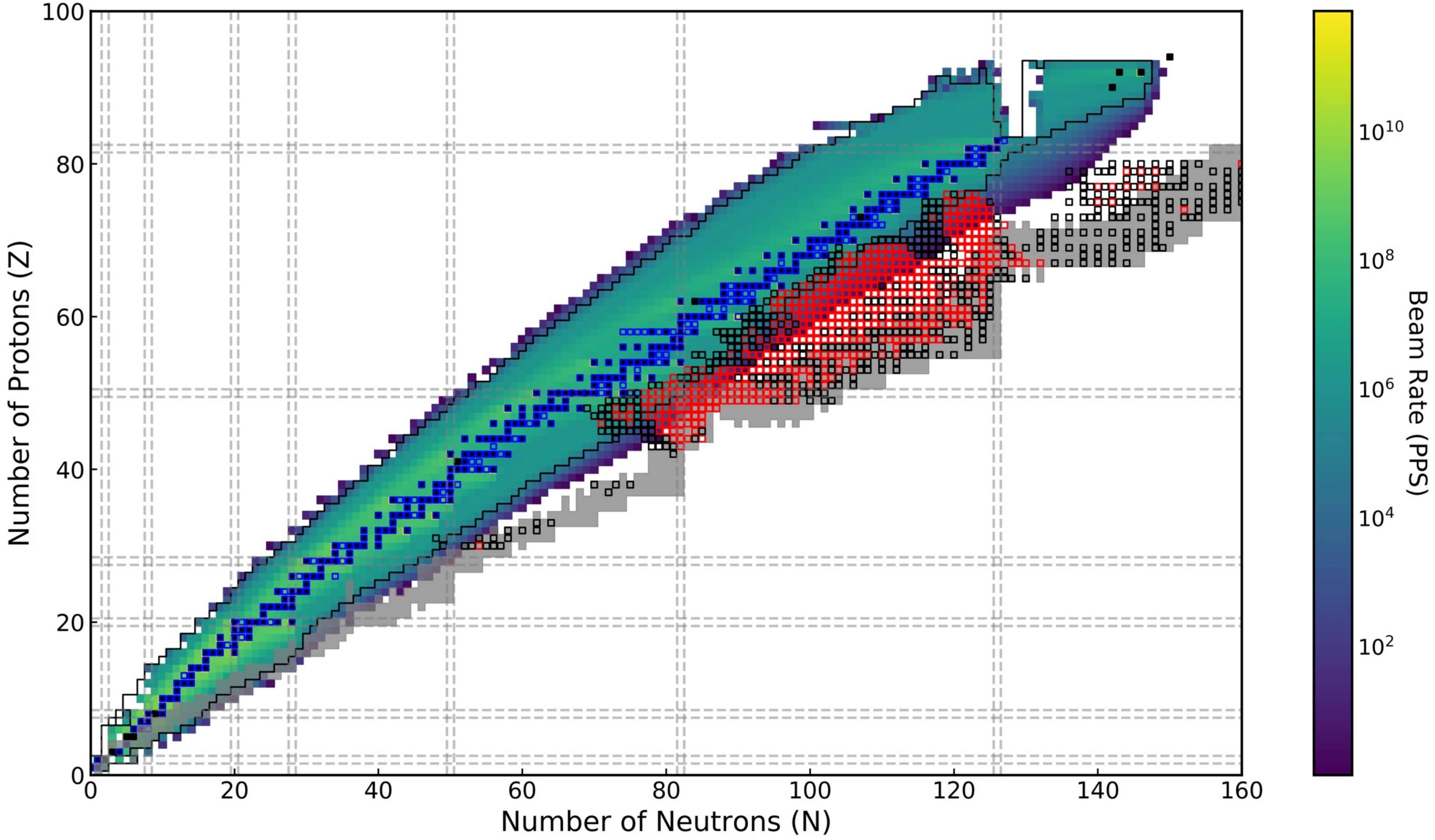
This is the opportunity with which we are presented



r-process (n,γ) sensitives from Mumpower et al., PPNP **86** 86-126 (2016)

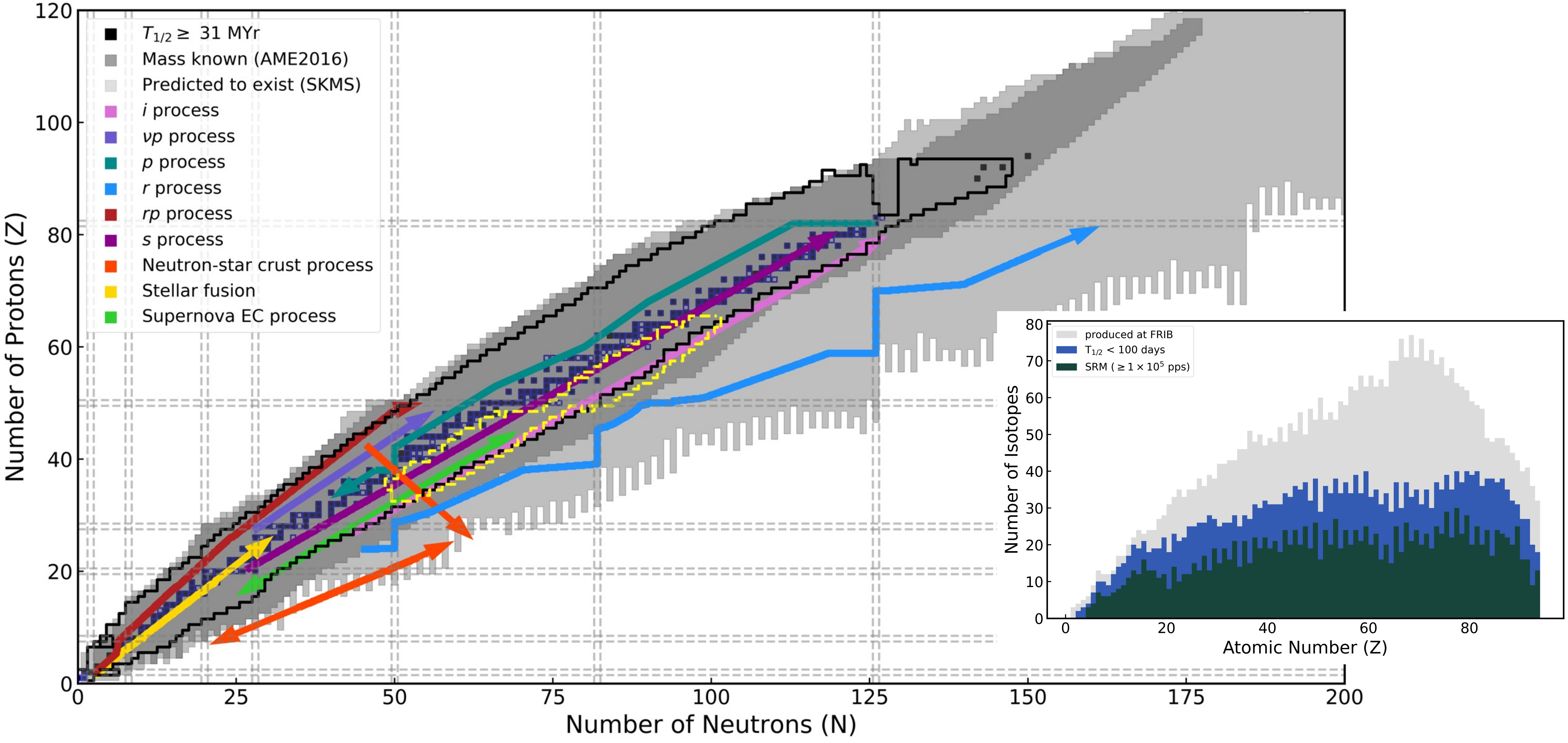
Looking ahead to FRIB:

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!

Lawrence Livermore National Laboratory