Surrogate Reaction Studies for Nuclear Astrophysics

Andrew Ratkiewicz

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LLNL-PRES-822922

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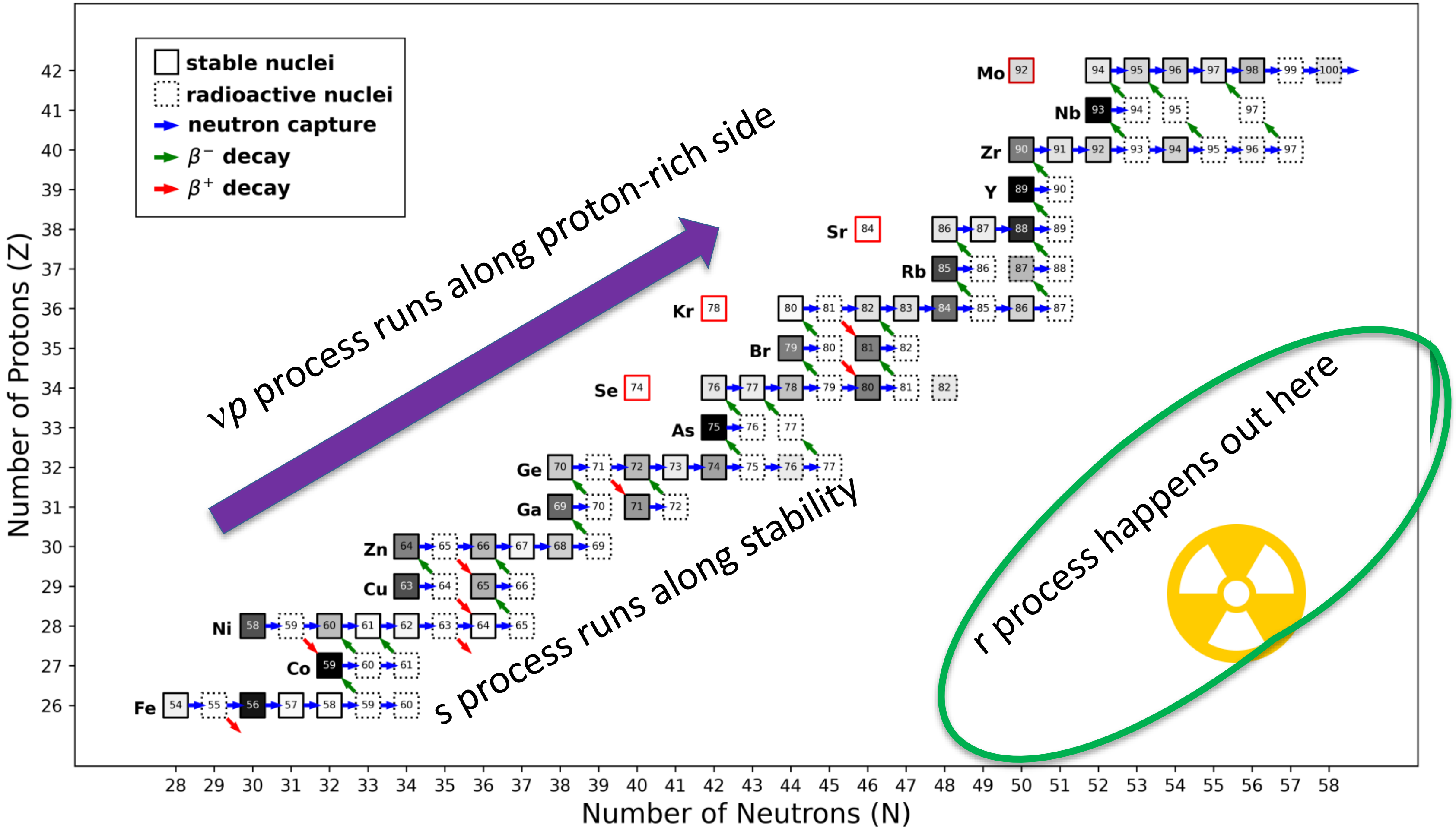
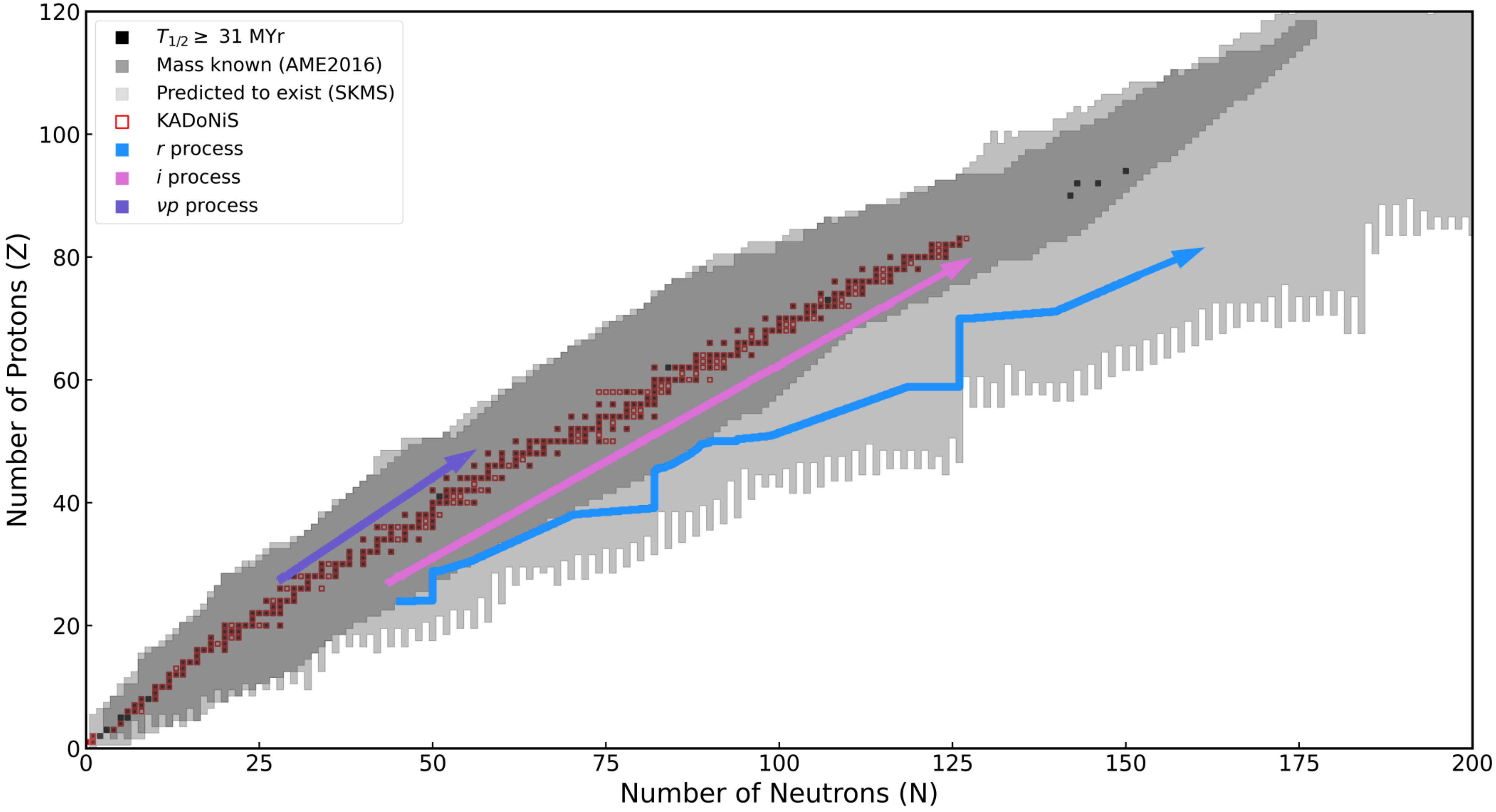
How a heavy nucleus gets made:



Neutron-induced reactions are critical!

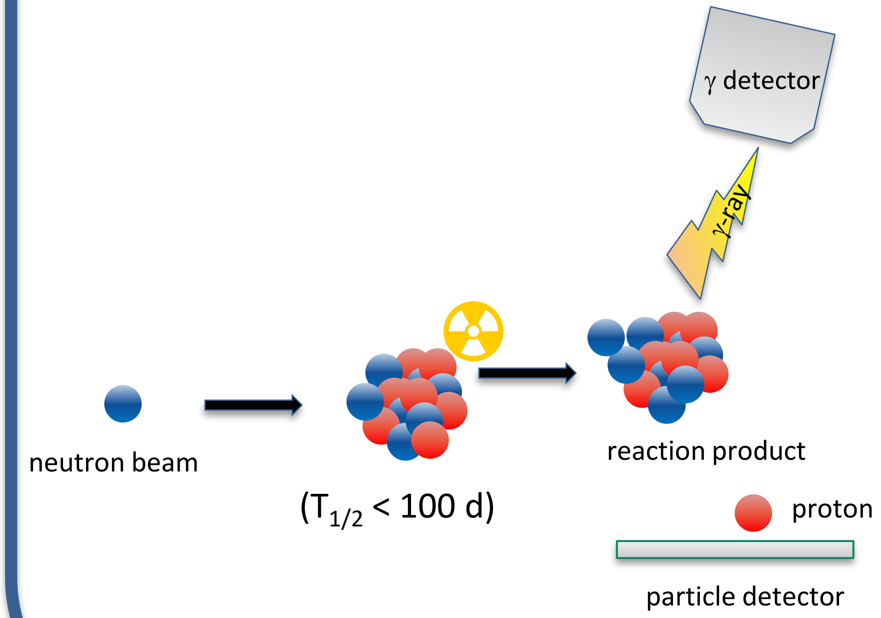
One problem – we don't know many of the neutron-induced reaction rates that matter!



[KADoNiS: I. Dillmann et al. AIP Conf. Proc. **819**, 123 (2006)]

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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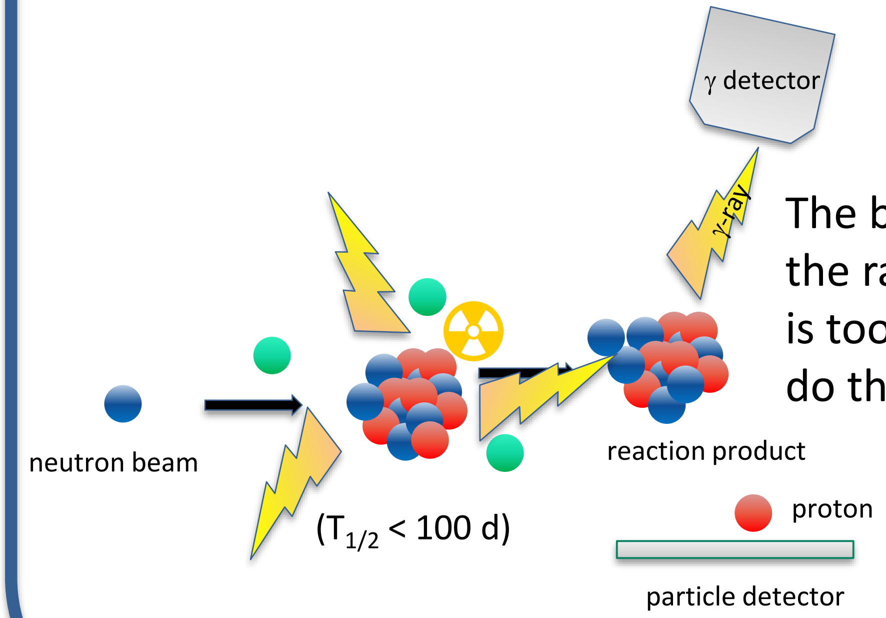

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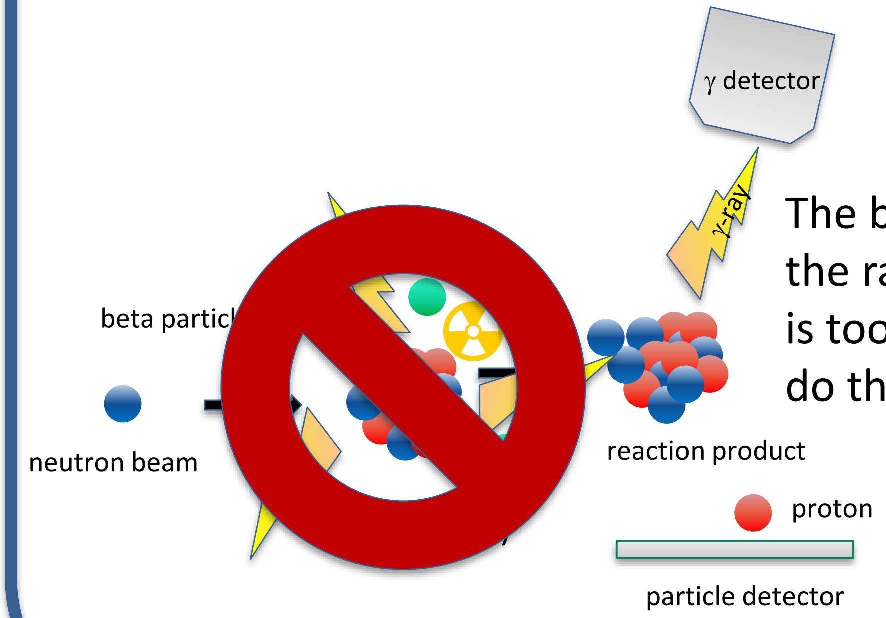

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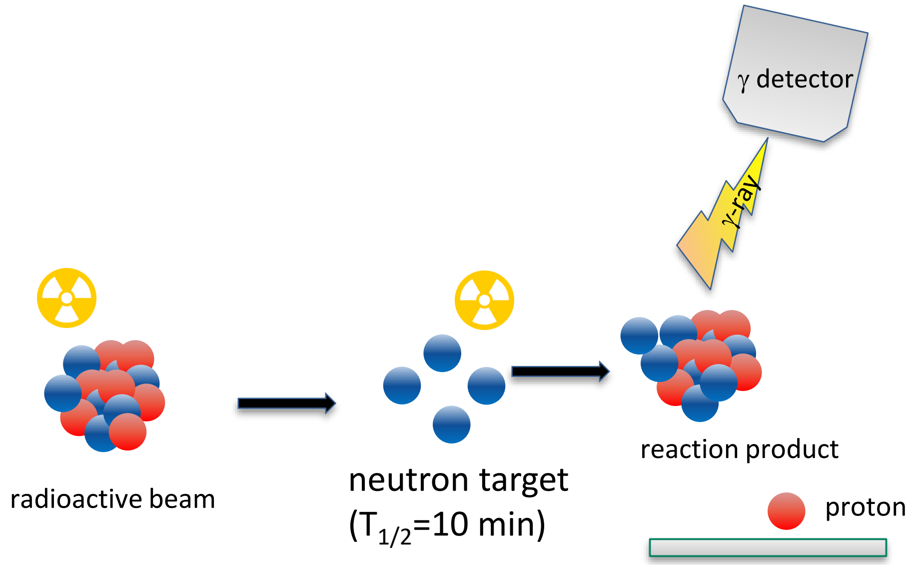

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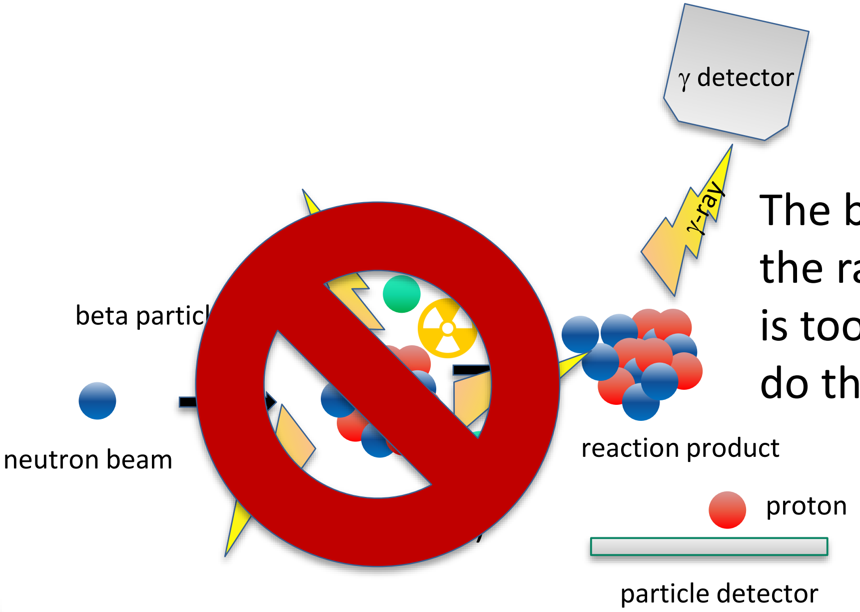

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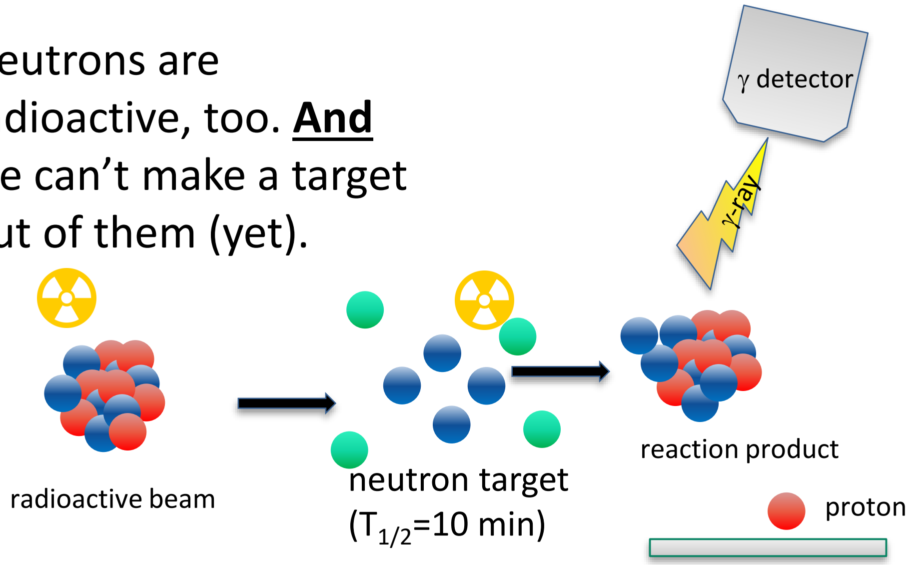

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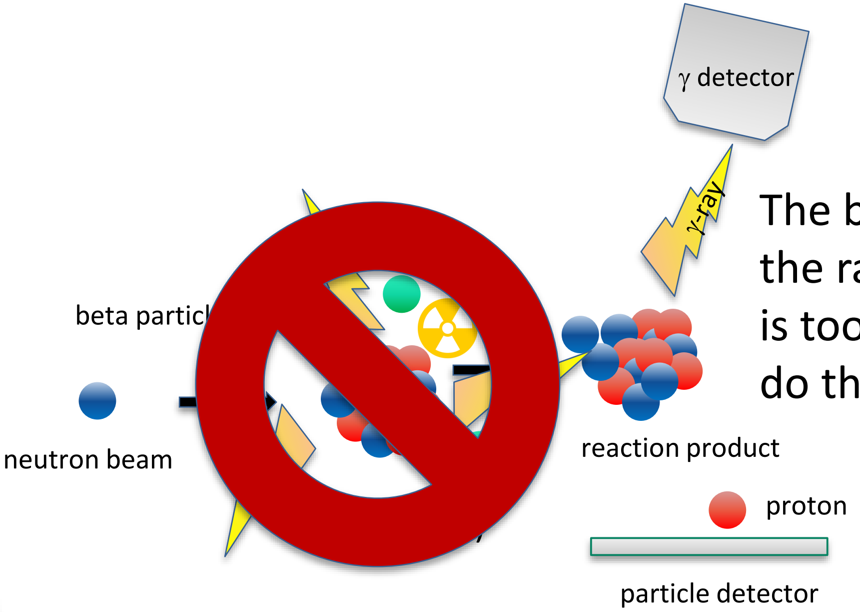

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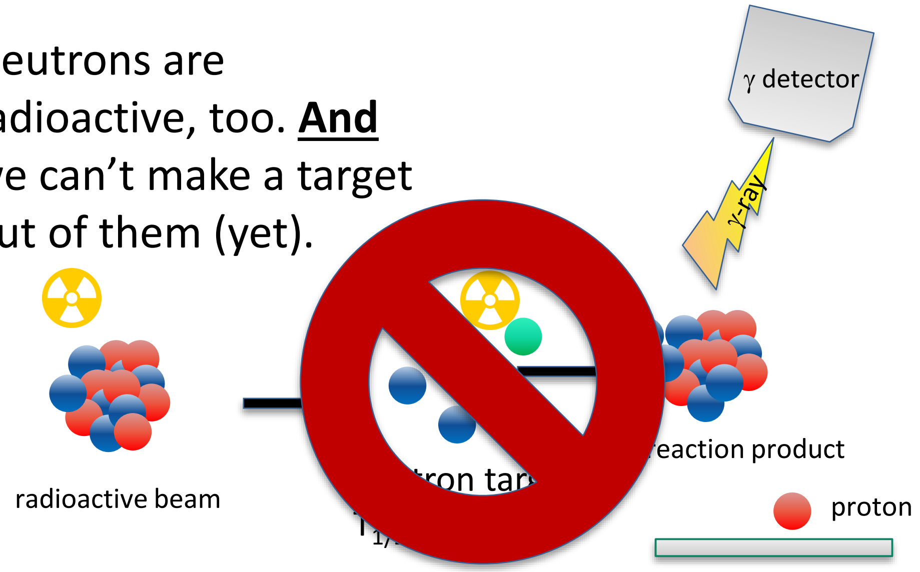
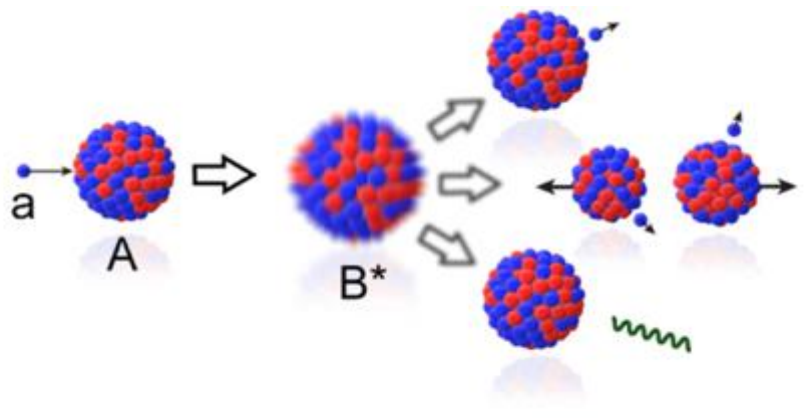


We need a different approach!

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

Desired Reaction: impossible to measure



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

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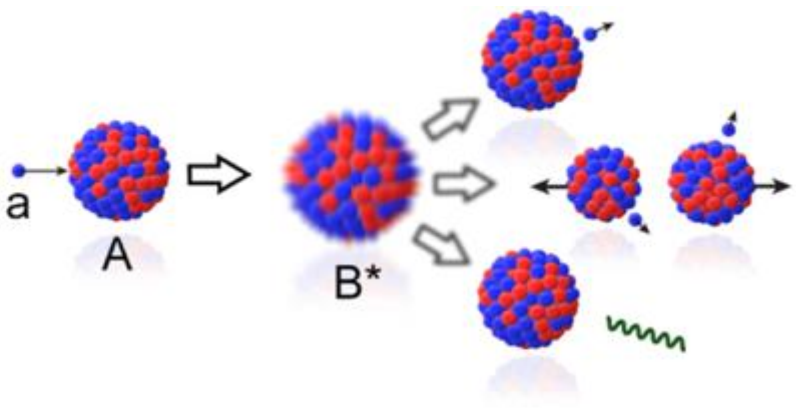

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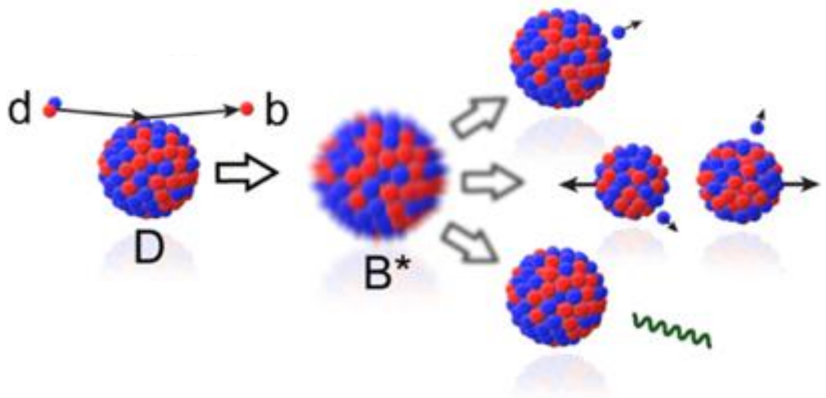
Surrogate Reaction: forms the "same" **compound nucleus** as the desired reaction.



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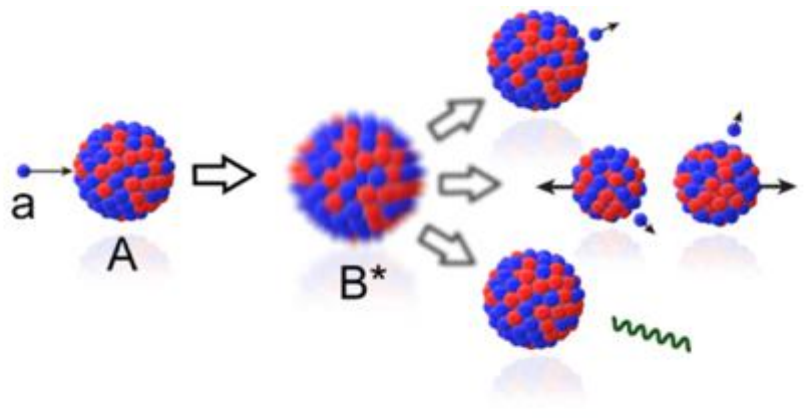

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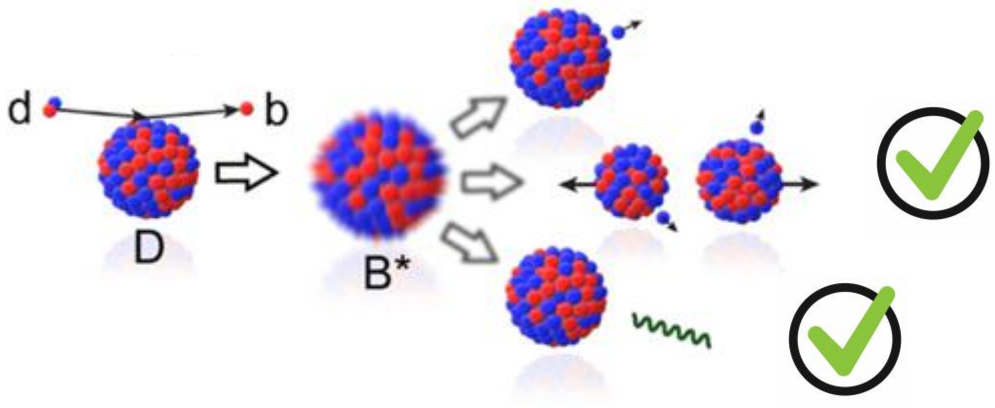

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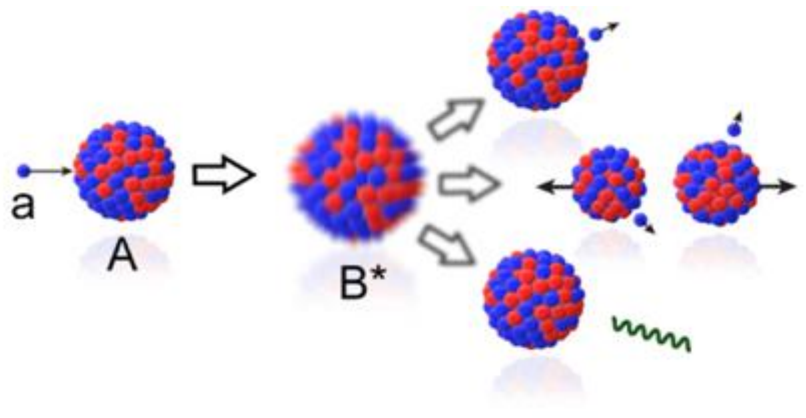

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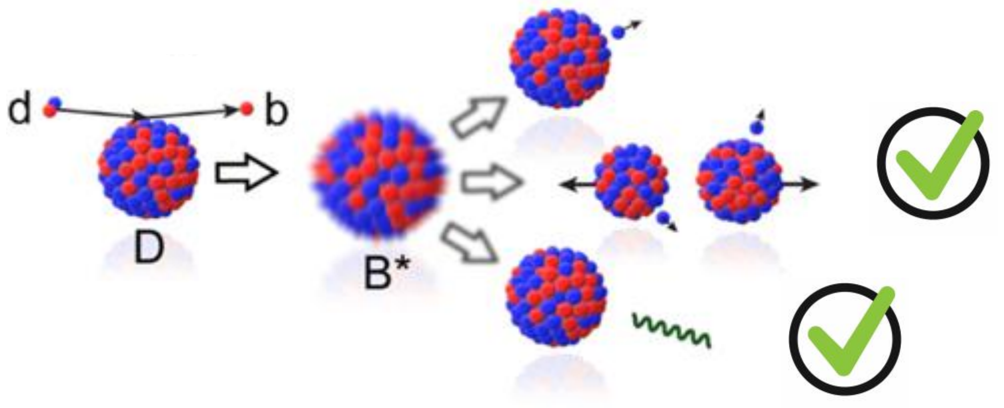

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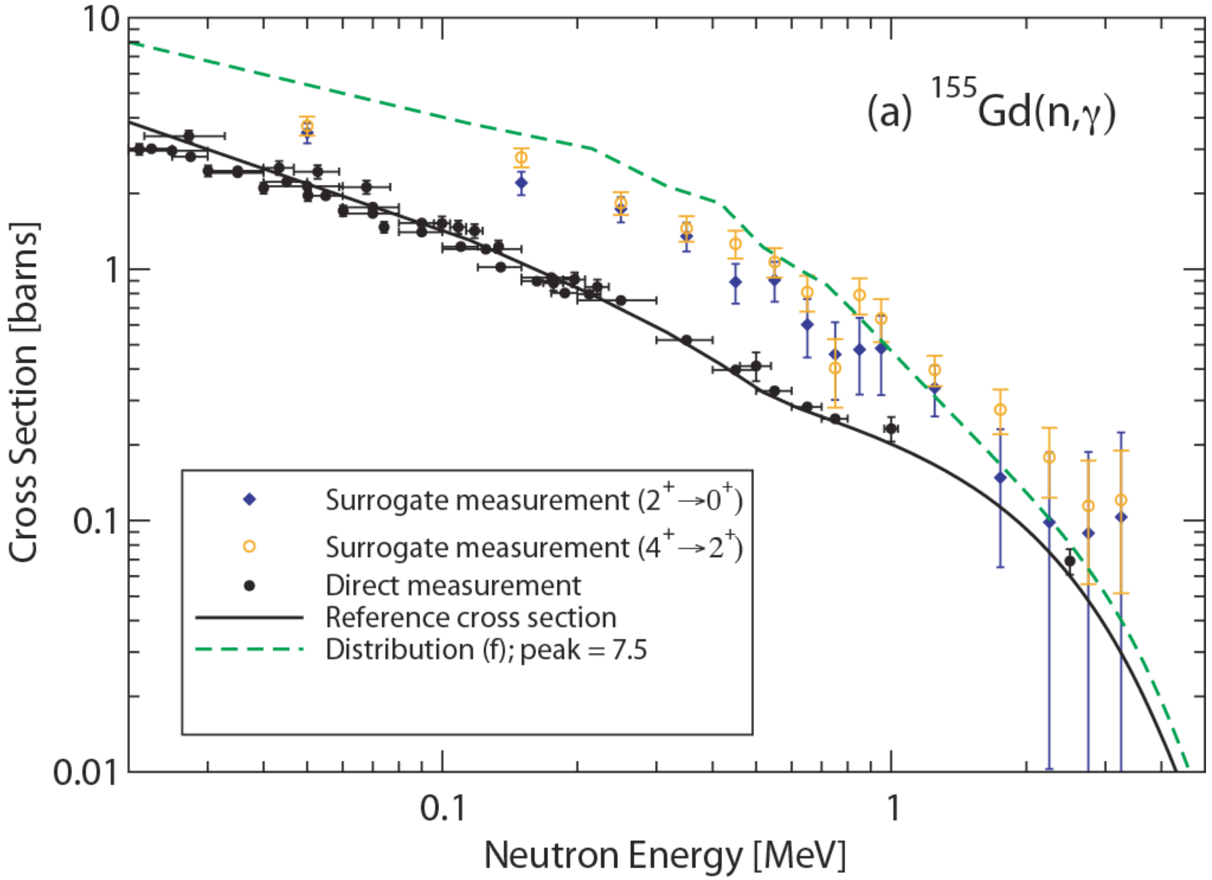
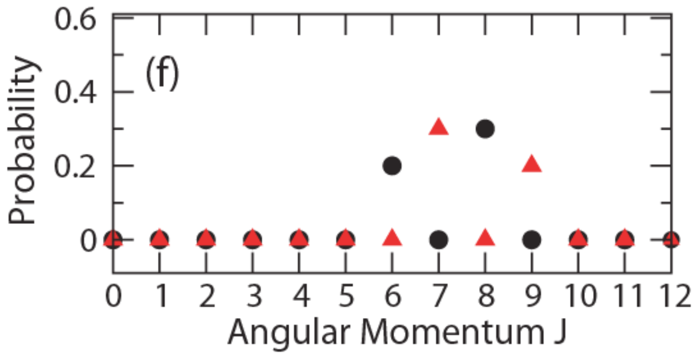
The Weisskopf-Ewing Approximation

“What if the hard stuff doesn’t matter?”

$$G_\chi^{CN}(E_{ex}, J, \pi) \rightarrow \mathcal{G}_\chi^{CN}(E_{ex})$$





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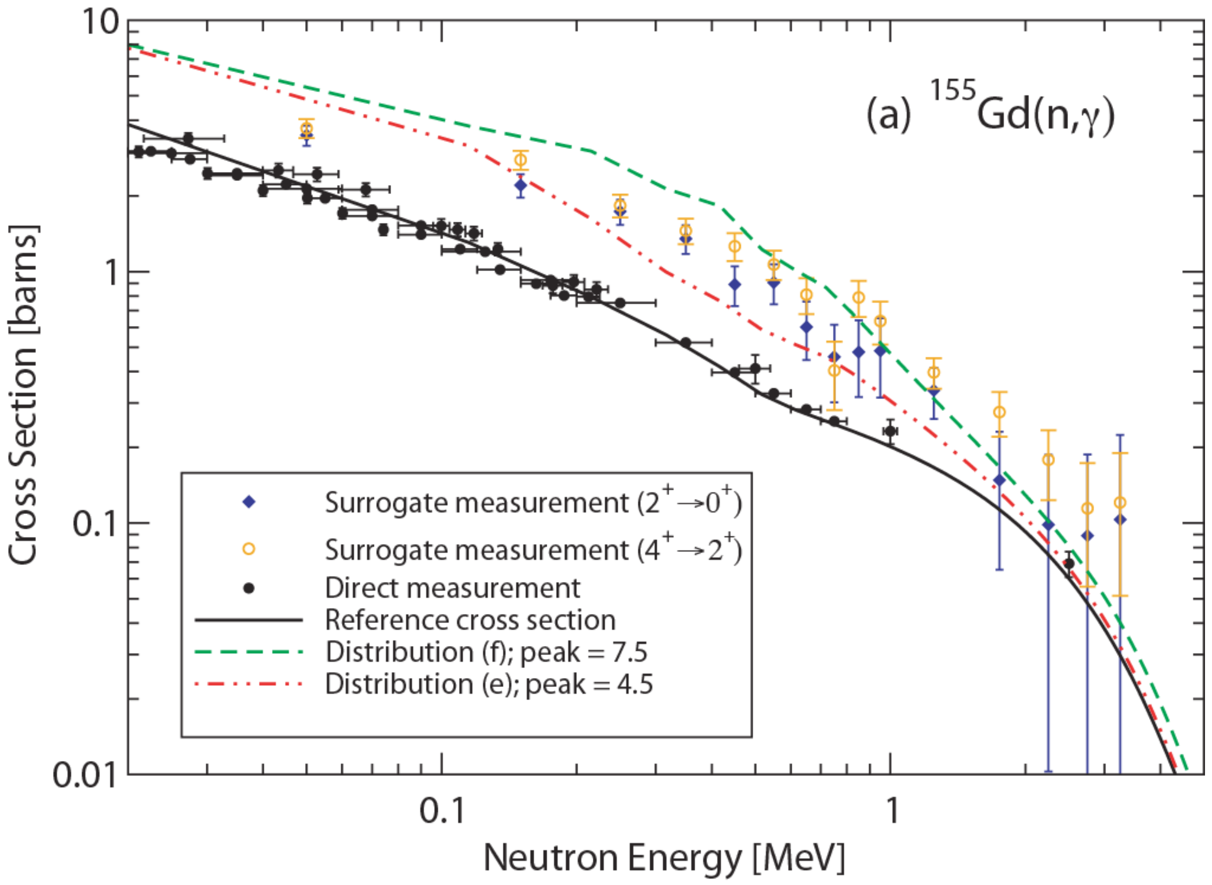

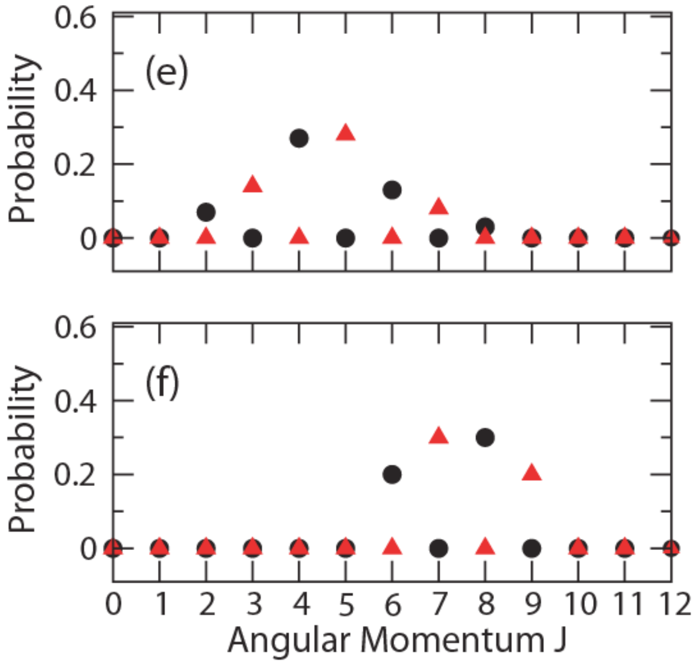

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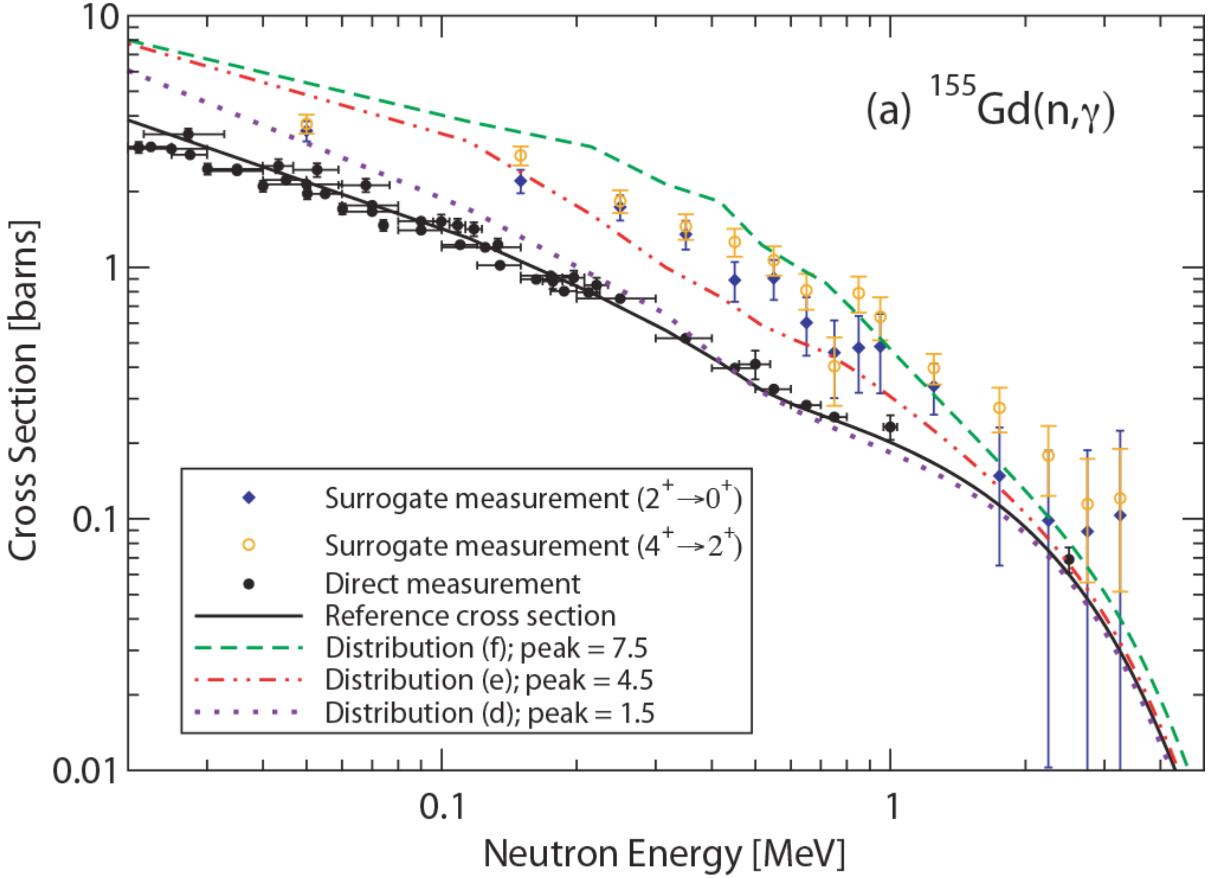

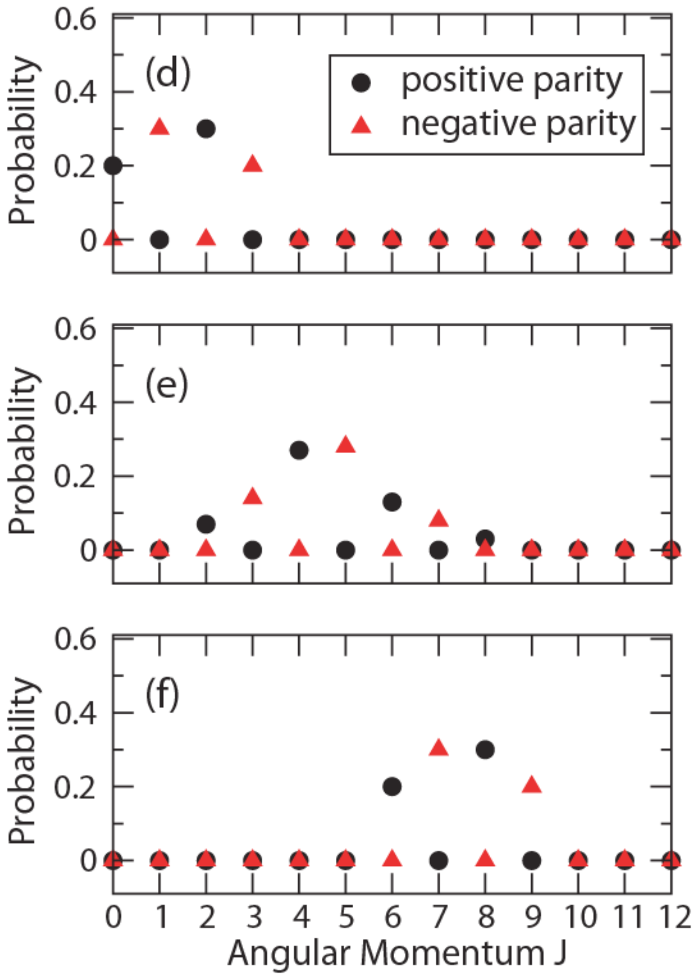

N.D. Scielzo *et al.* PRC **81** 034608 (2010)

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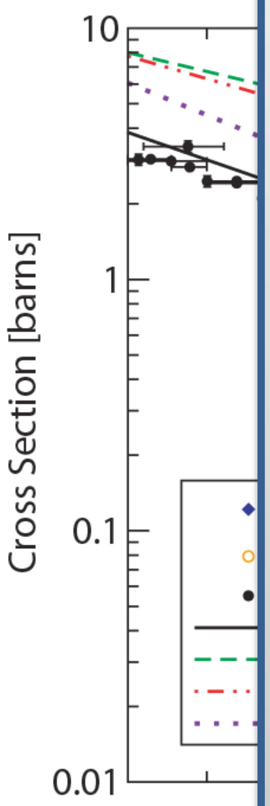
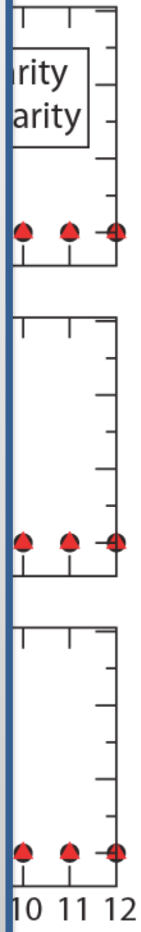
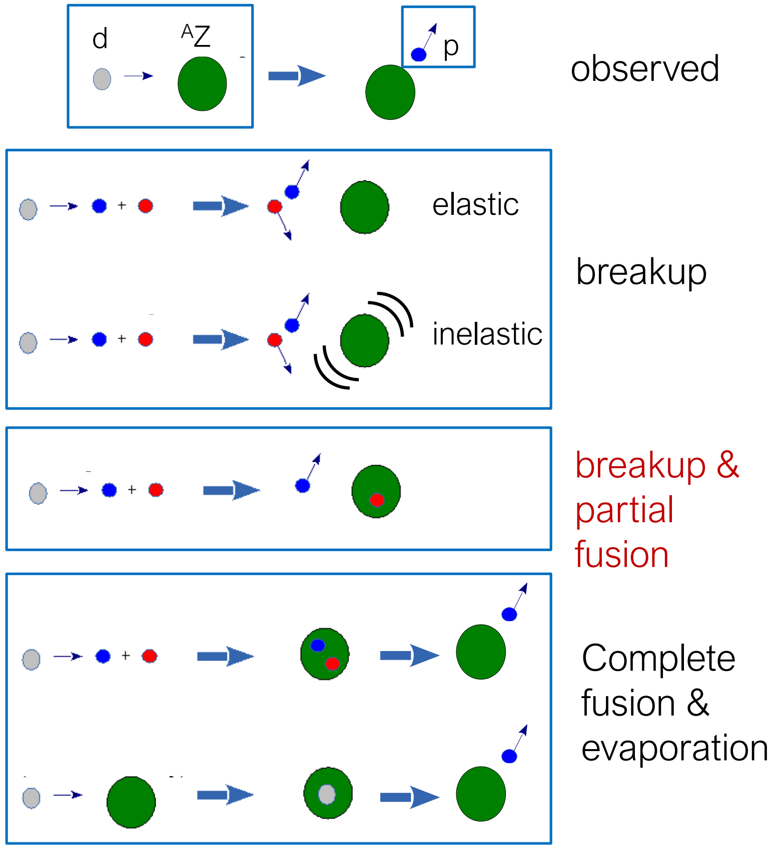


<u>What have we learned?</u>

- Dependence of surrogate cross section on entry spin distribution suggests that the Weisskopf-Ewing approximation is not justified in all cases.
- Clearly, we need to understand the entry spin distribution of the compound nucleus, which means we need to understand the reaction mechanism.



Reaction Mechanism: (d,p)
revisited for the FRIB era



Inclusive (d,p) reactions recently revisited: formalism

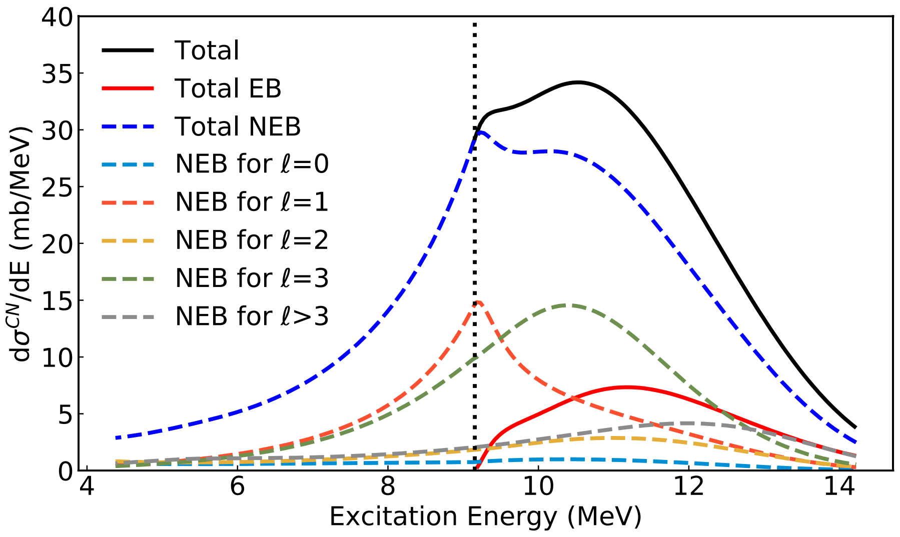
- Based on earlier work by Udagawa & Tamura and Ichimura, Austern & Vincent
- Goal: describe breakup-fusion, which contains CN formation
- Potel et al, PRC 92, 034611 (2015)
- Lei & Moro, PRC 92, 044616 (2015)
- Carlson et al, Few-Body Syst 57, 307 (2016), arxiv:1508.01466

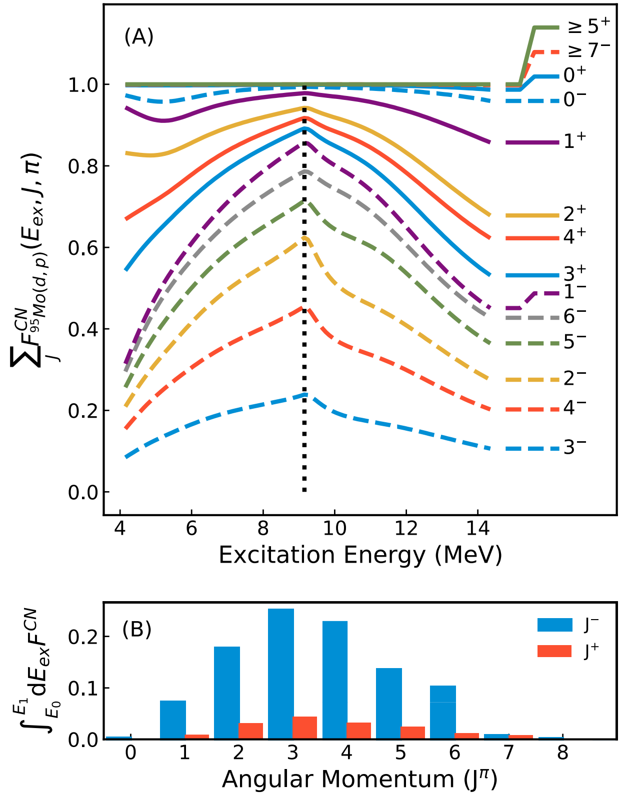
Applications:

- 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





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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).

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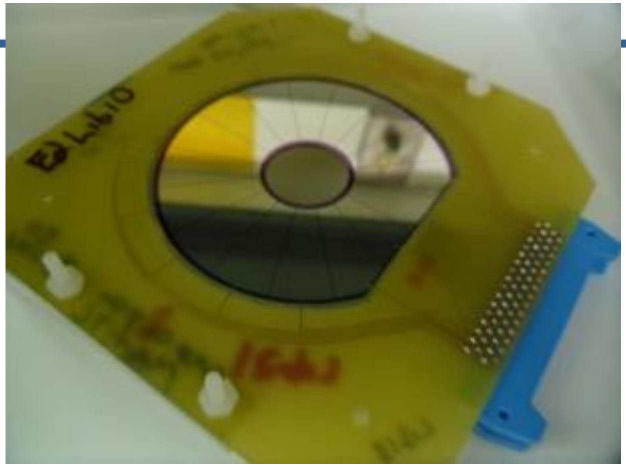
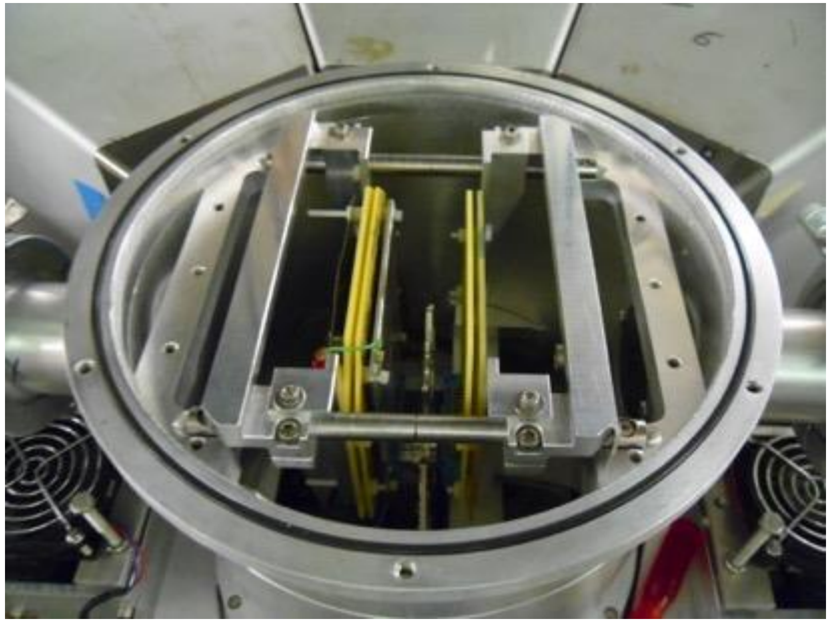
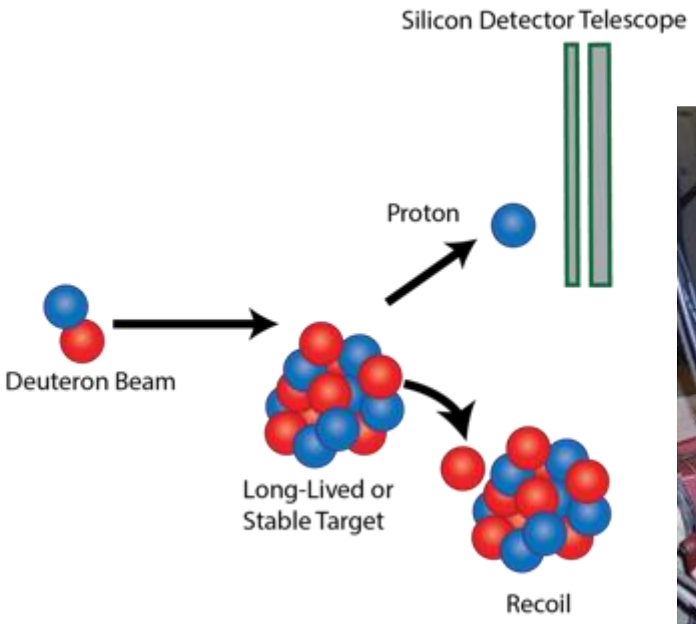


- 140 μm +1000 μm segmented telescopes at forward, backward angles.
- Beam energy of 12.5 MeV.
- 0.960 mg/cm^2 thick ^{95}Mo target (~97% ^{95}Mo, 1.5% ^{96}Mo).
- Four Compton-suppressed HPGe clovers at 90, 220, 270, 320 degrees (lab frame).





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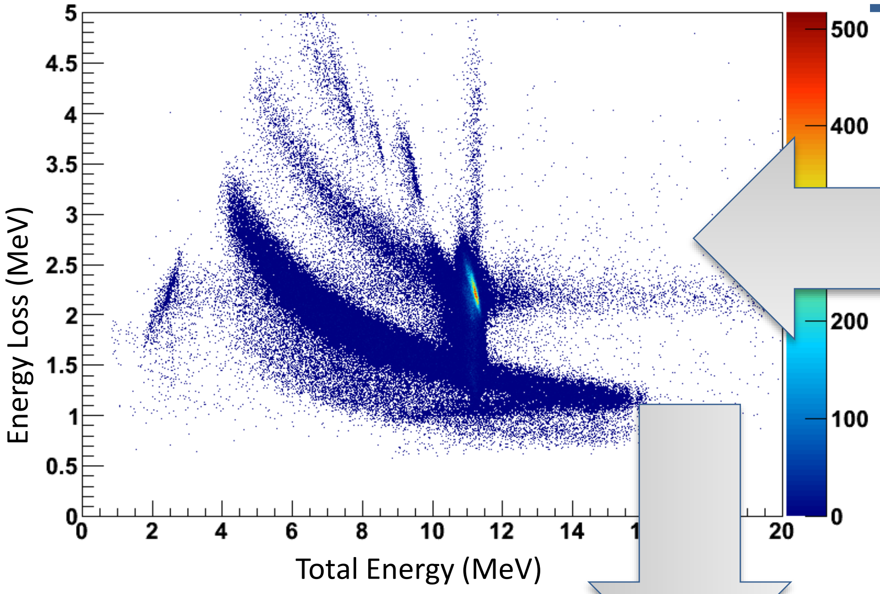
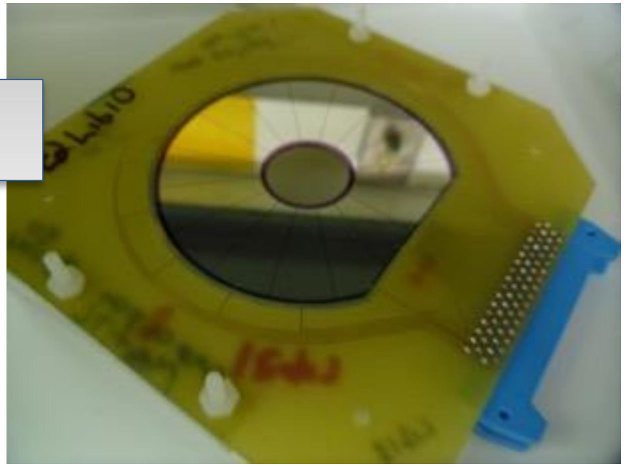
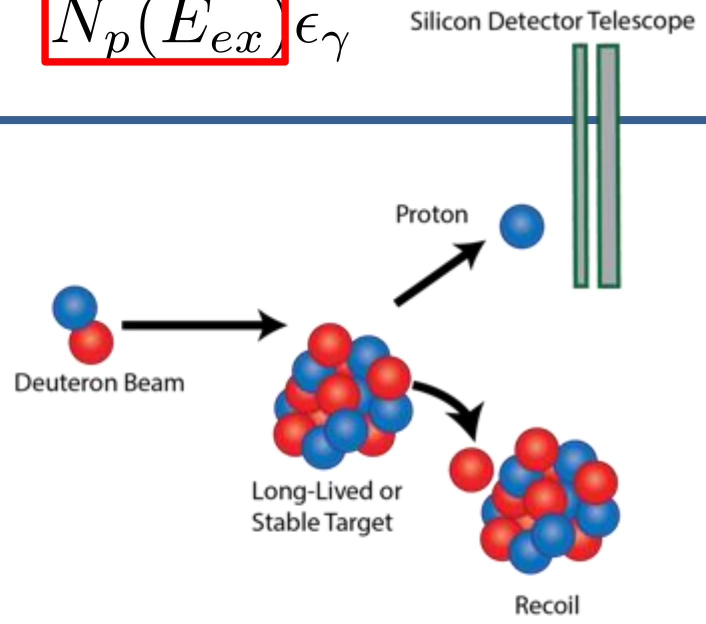
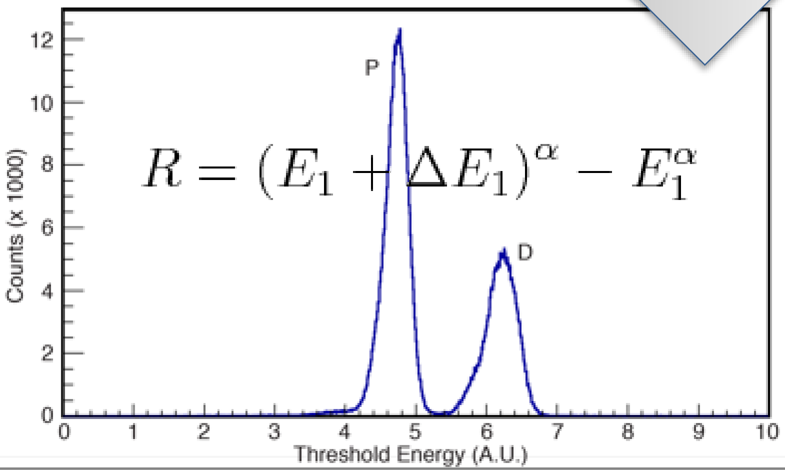
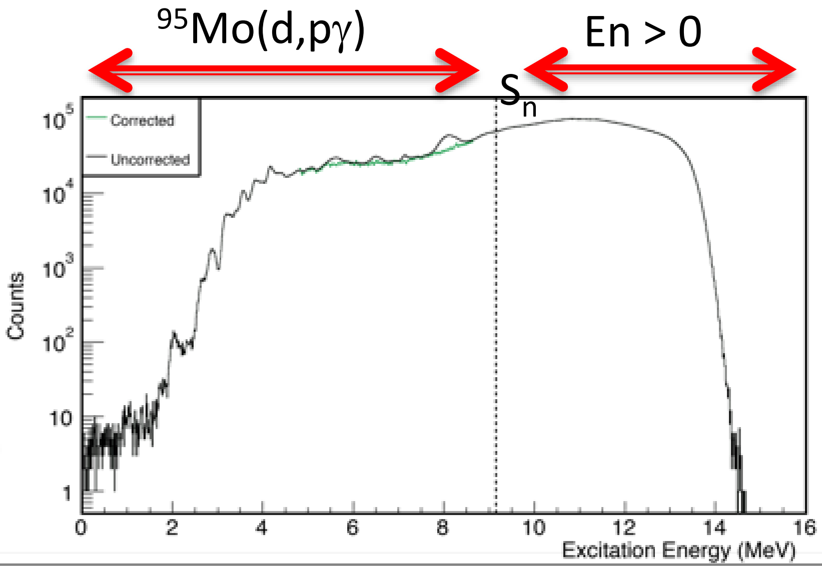








$$R = (E_1 + \Delta E_1)^\alpha - E_1^\alpha$$



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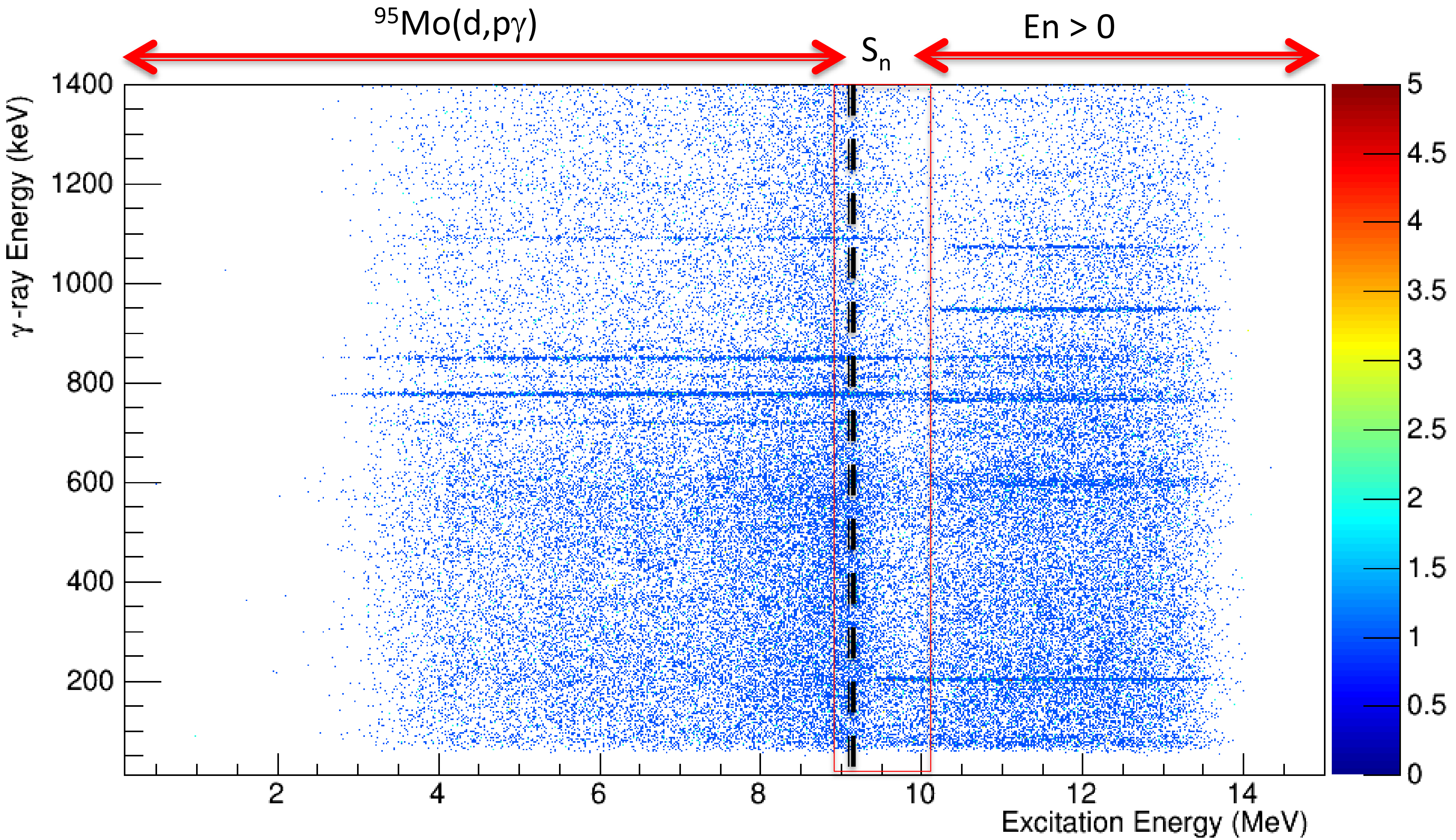

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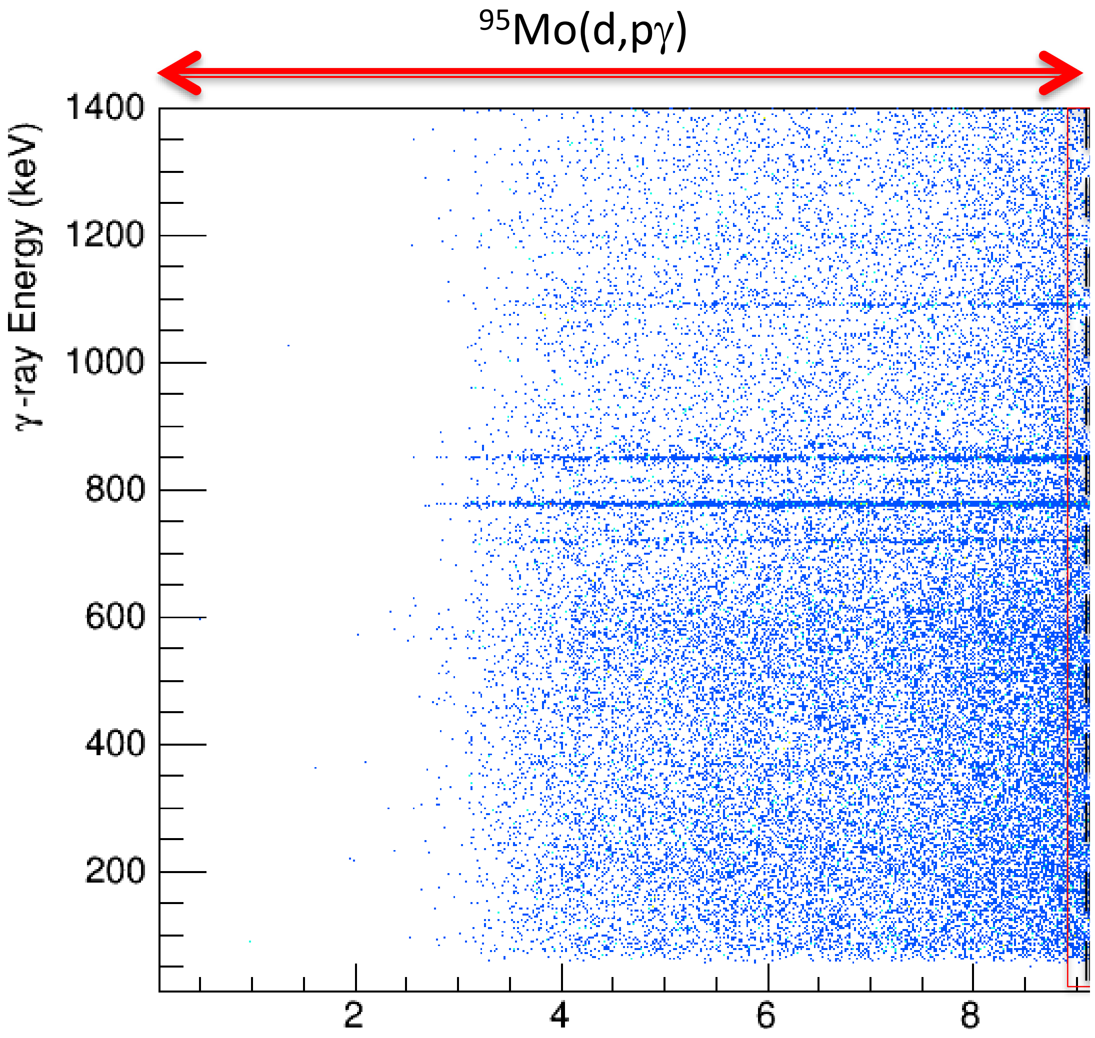

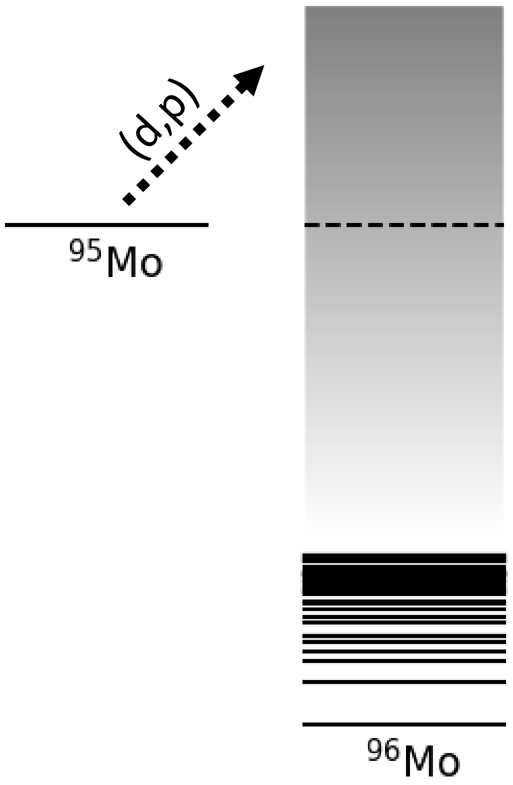

^{96}Mo levels from RIPL-3 (R. Capote et al.)

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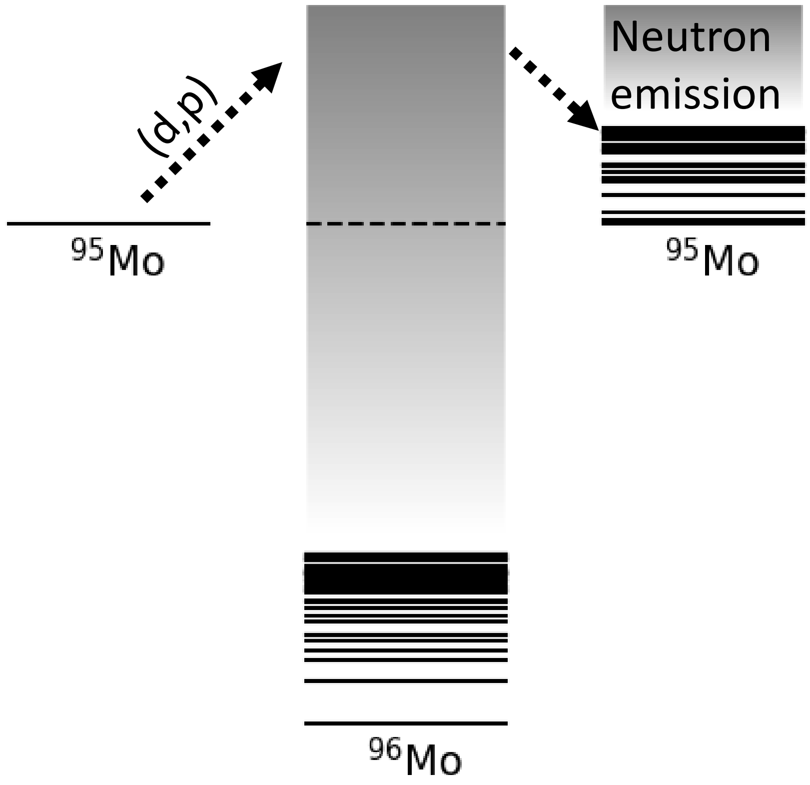

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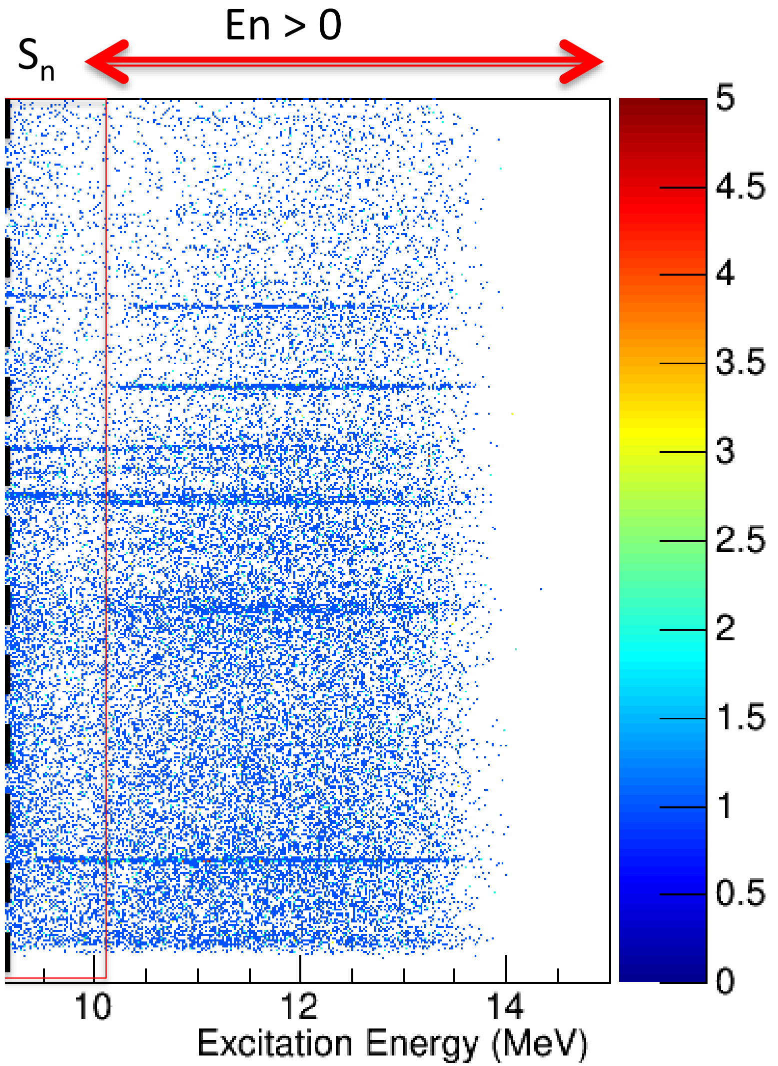

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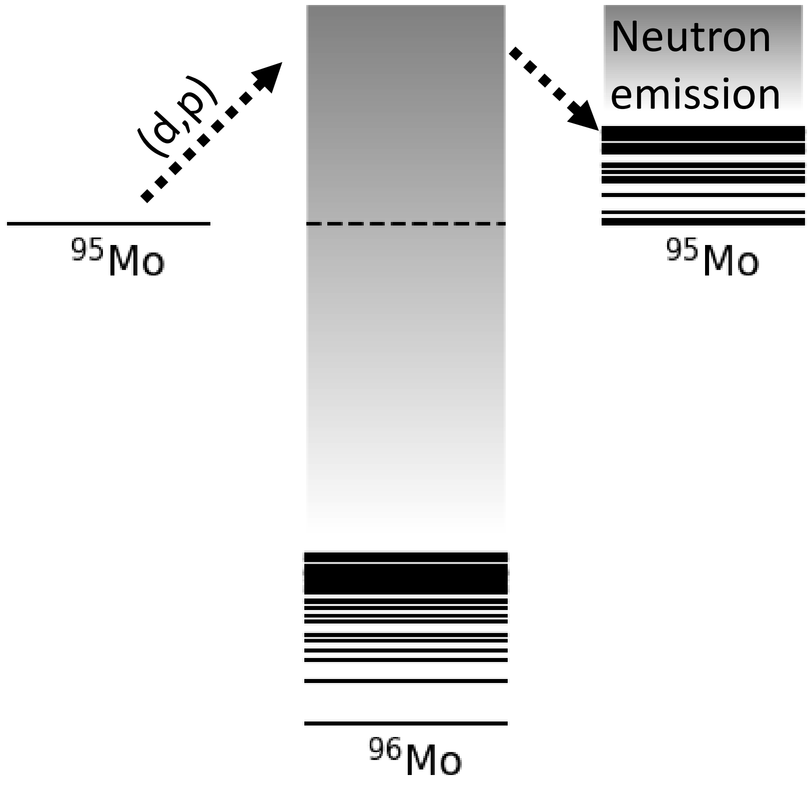

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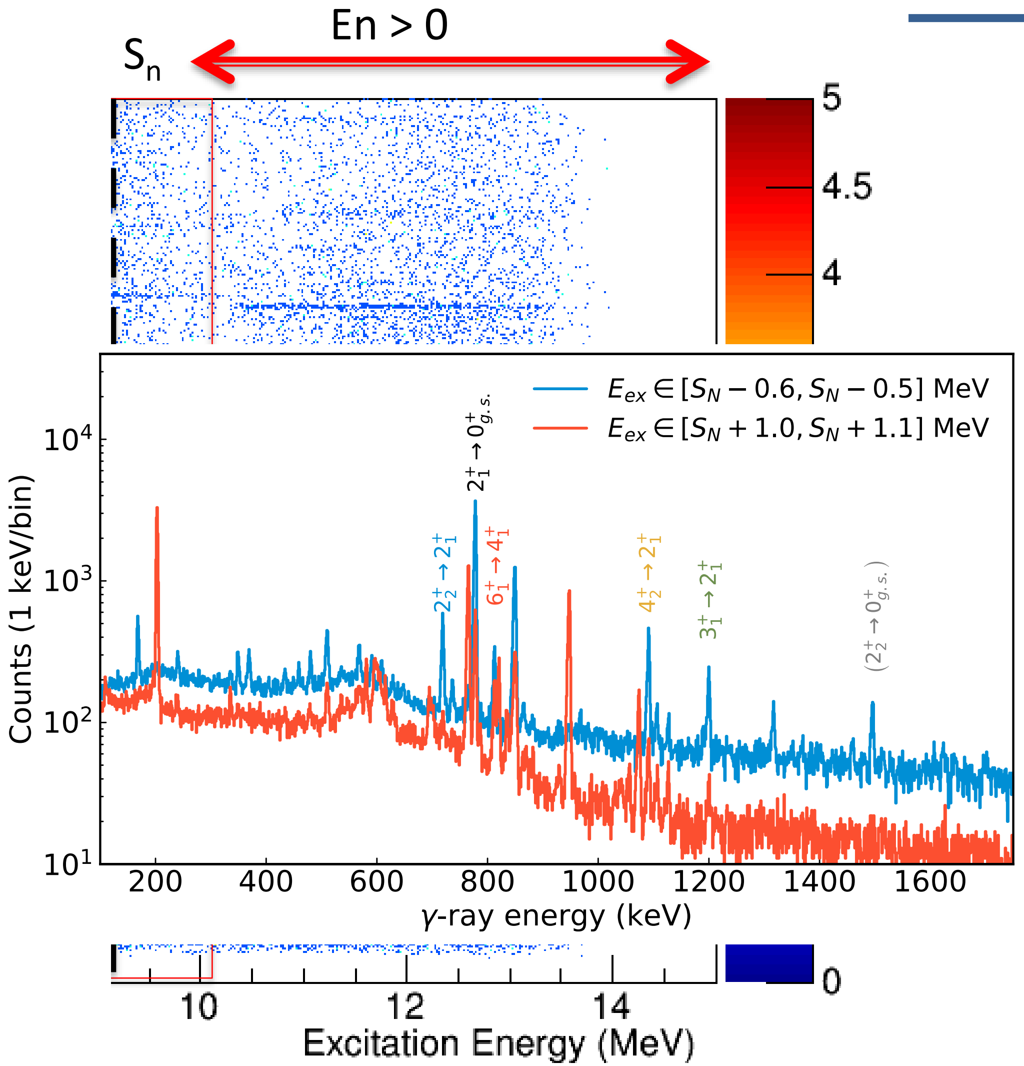

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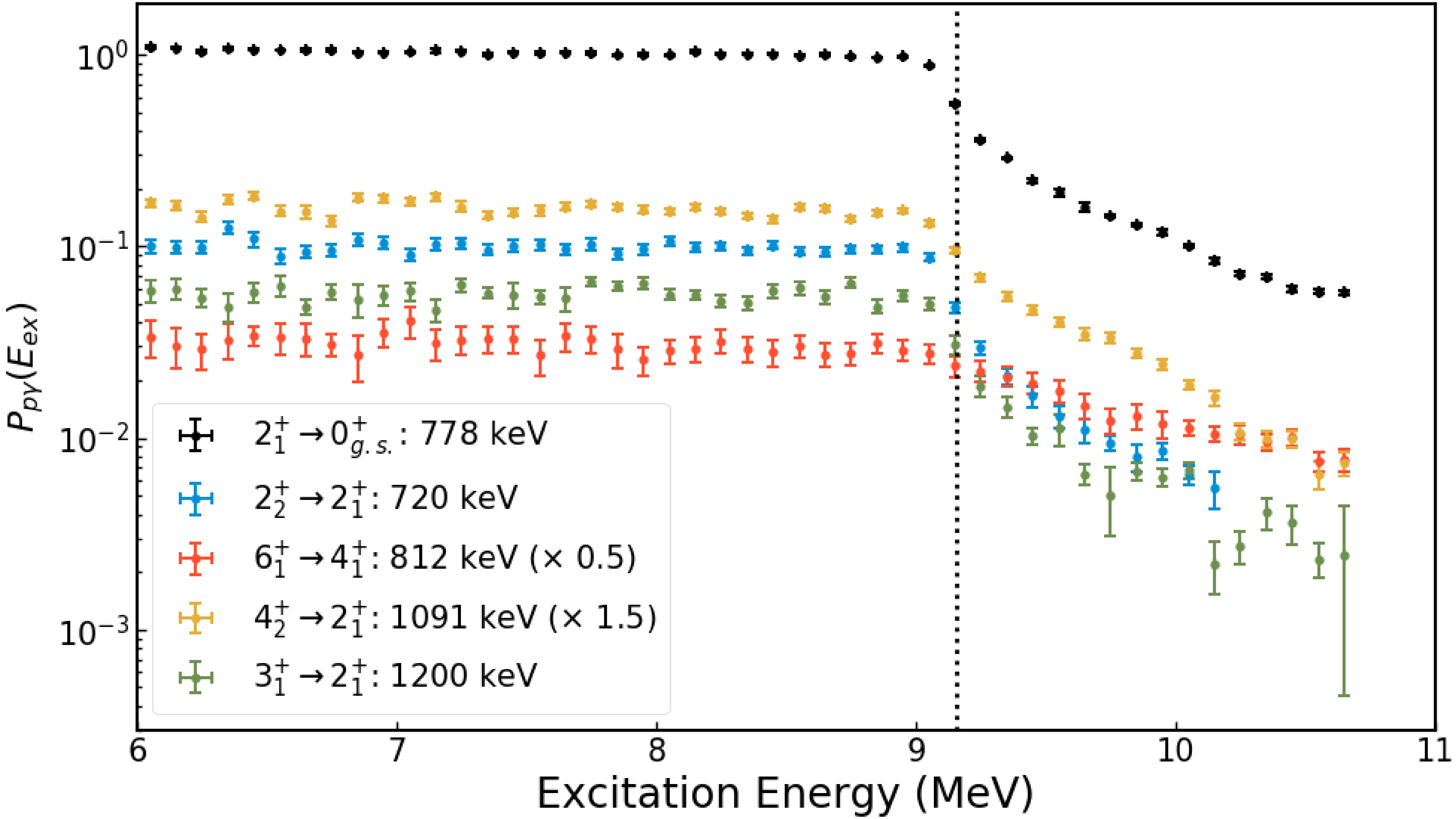

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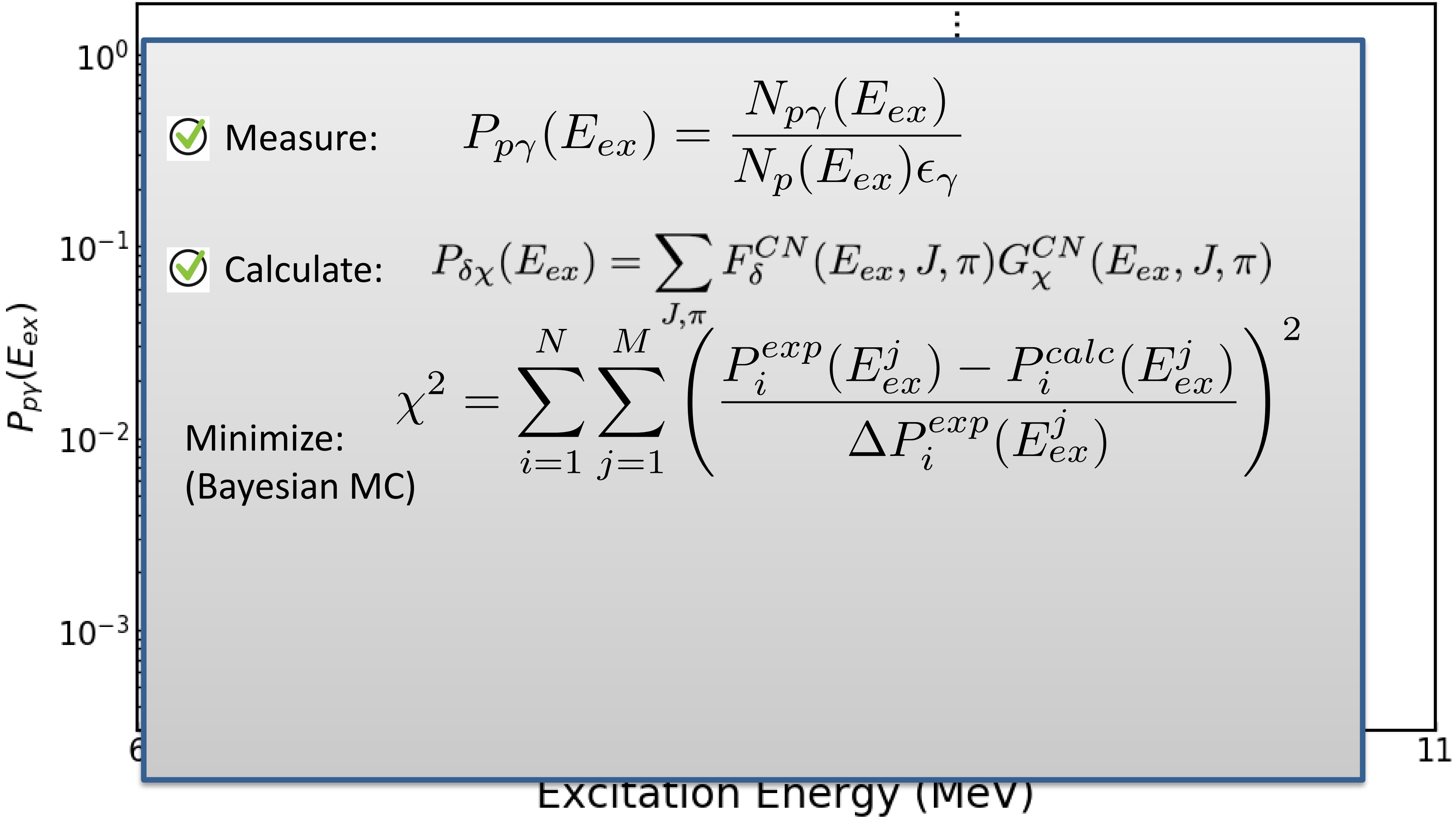

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Minimize:
(Bayesian MC)

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

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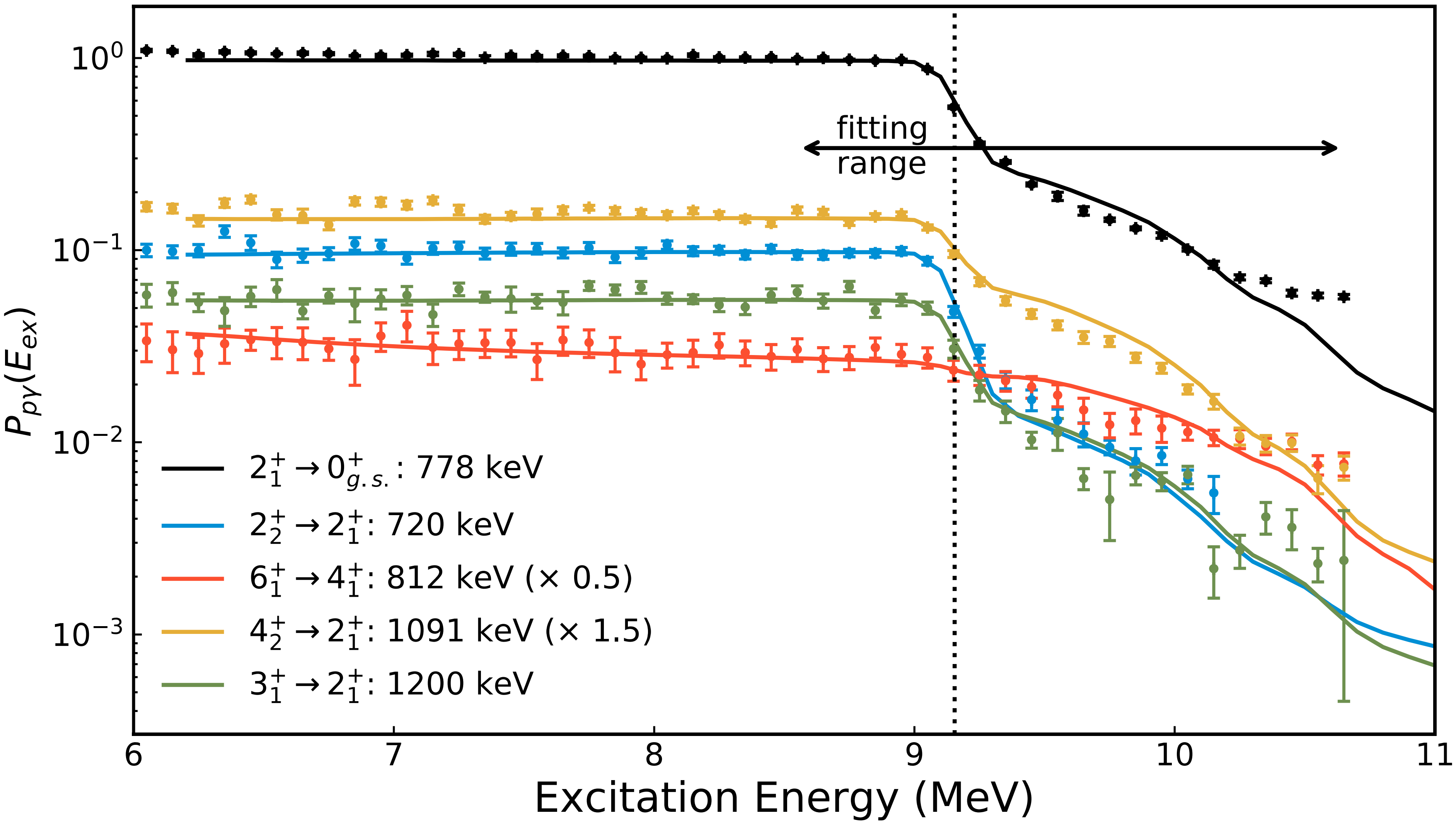

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NLD, GSF

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

Does not depend on D_0, <Γ>!

The Experiment: ^{95}Mo(d,pγ)

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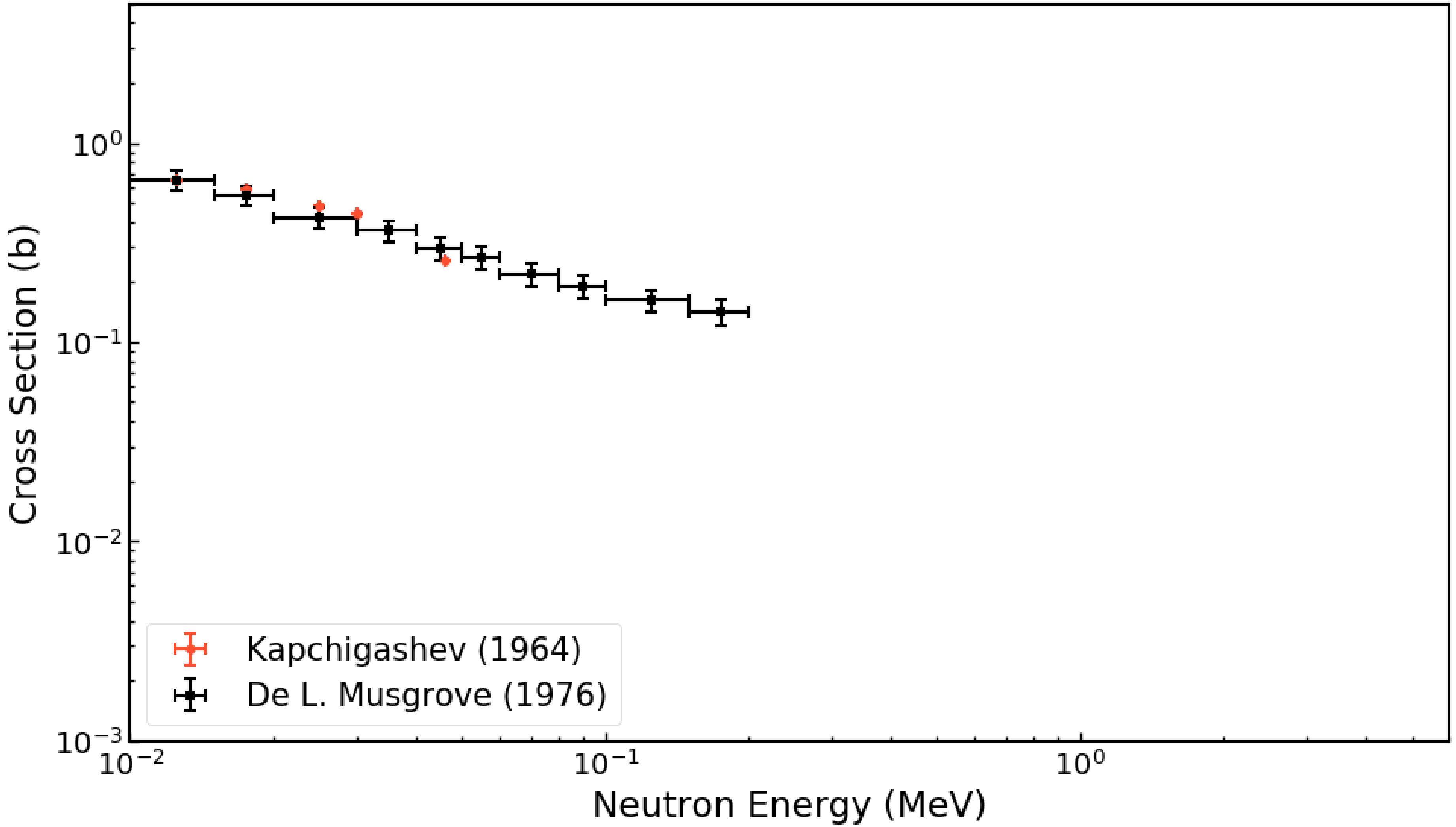

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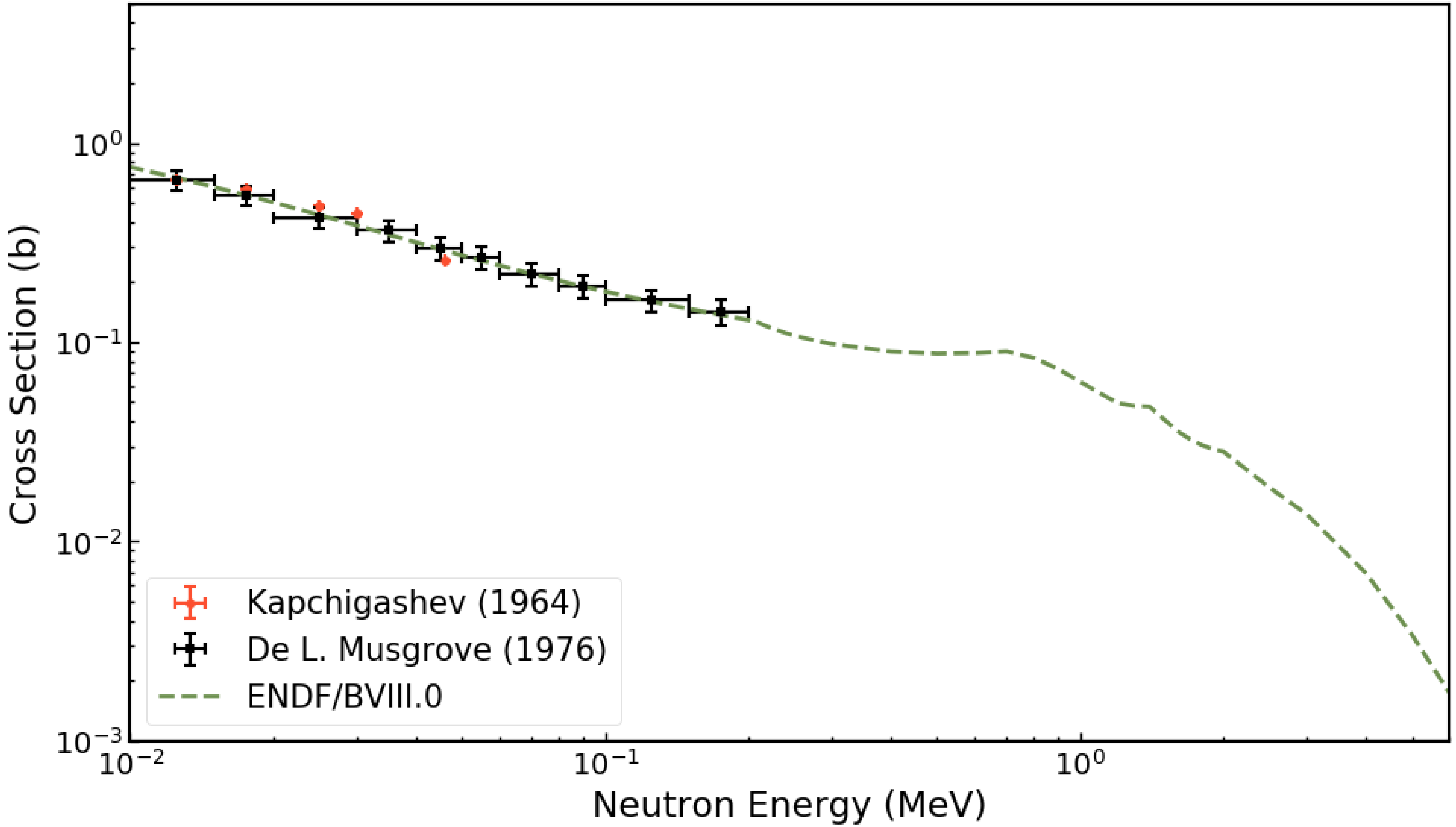

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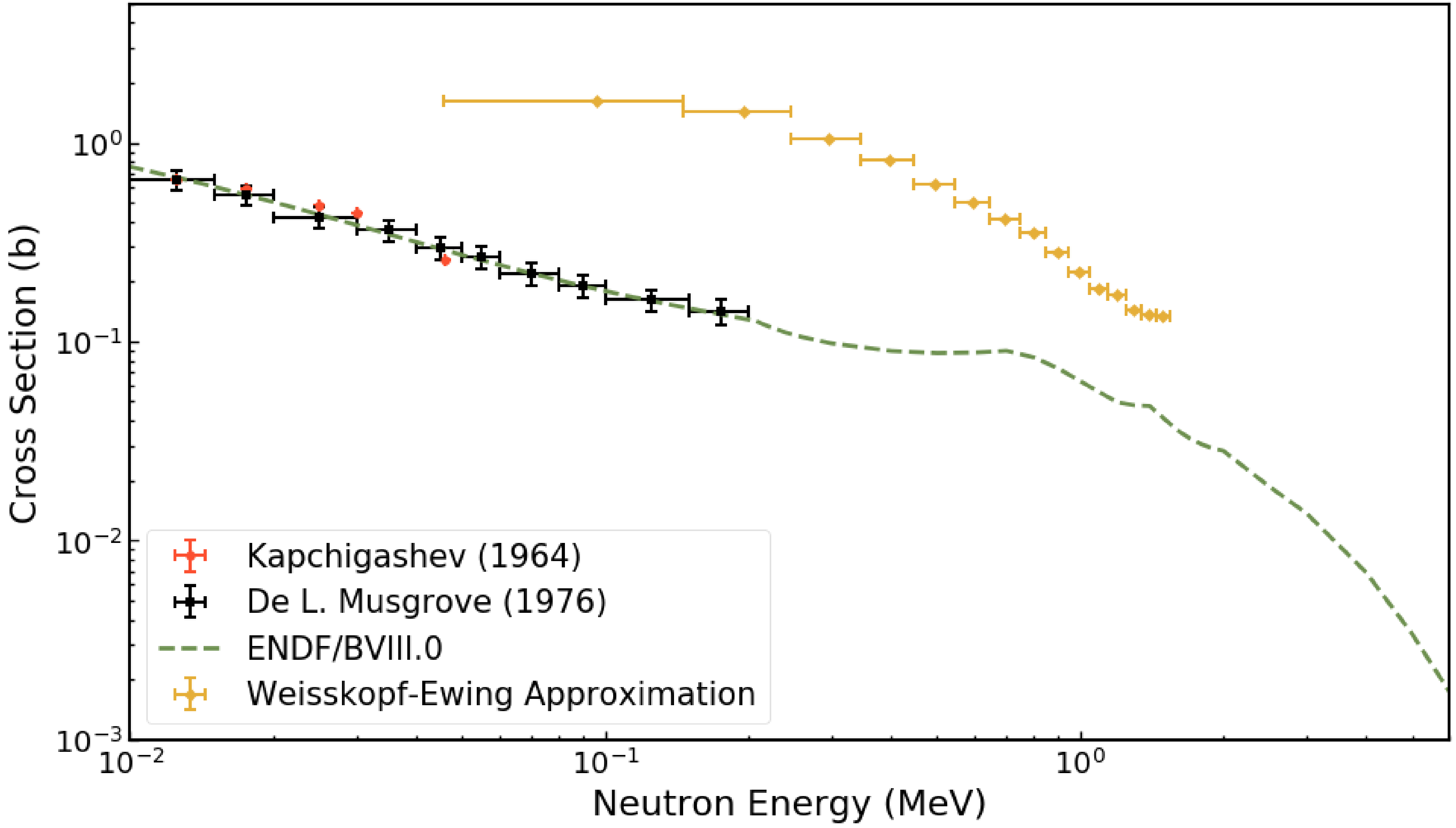

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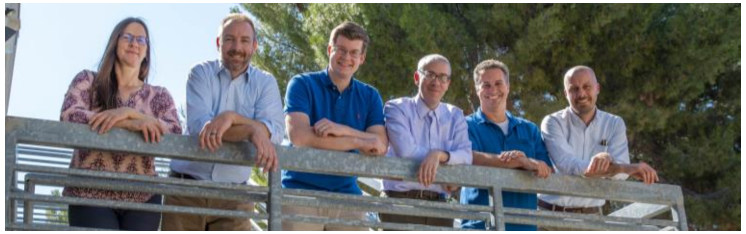
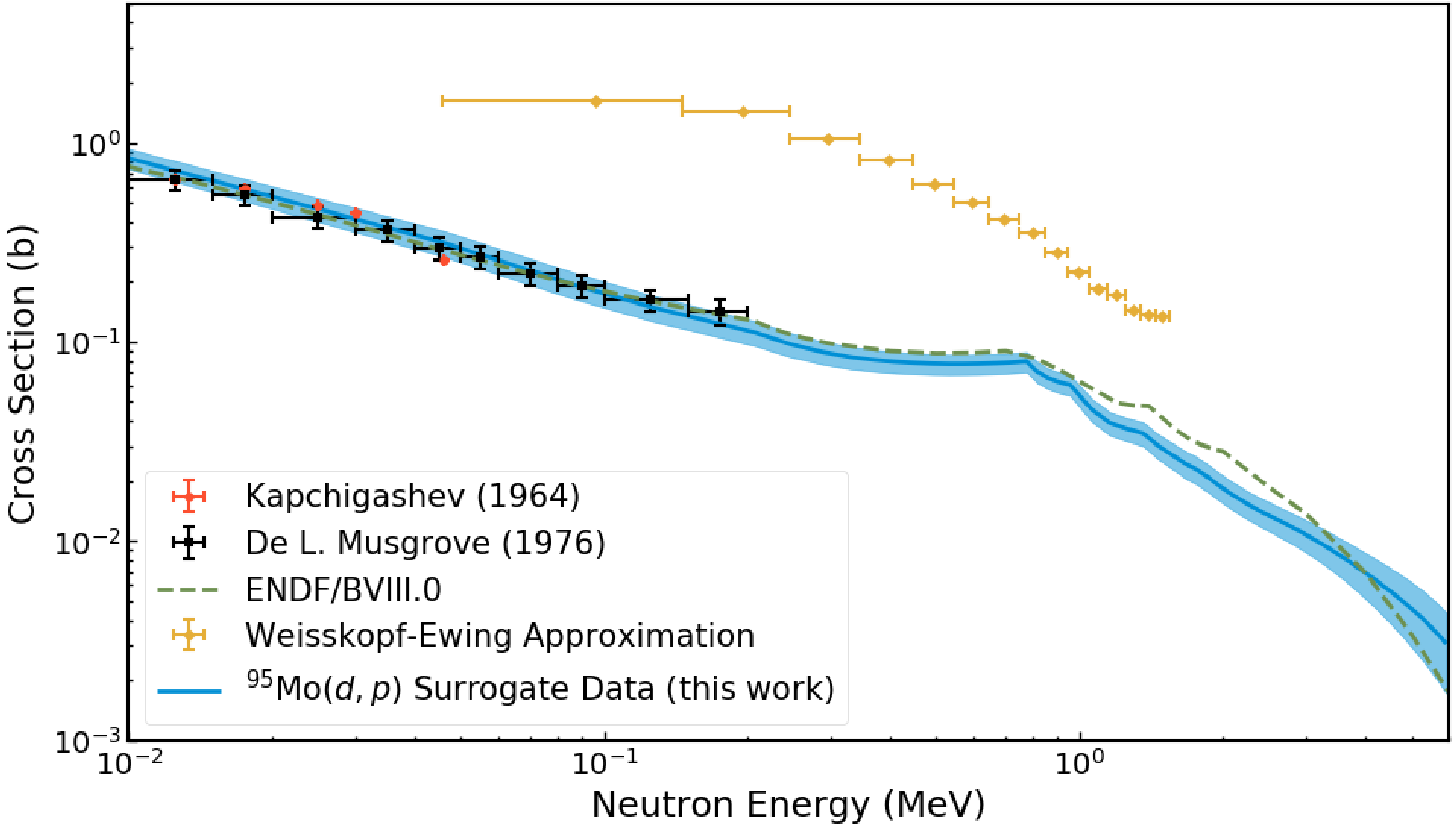
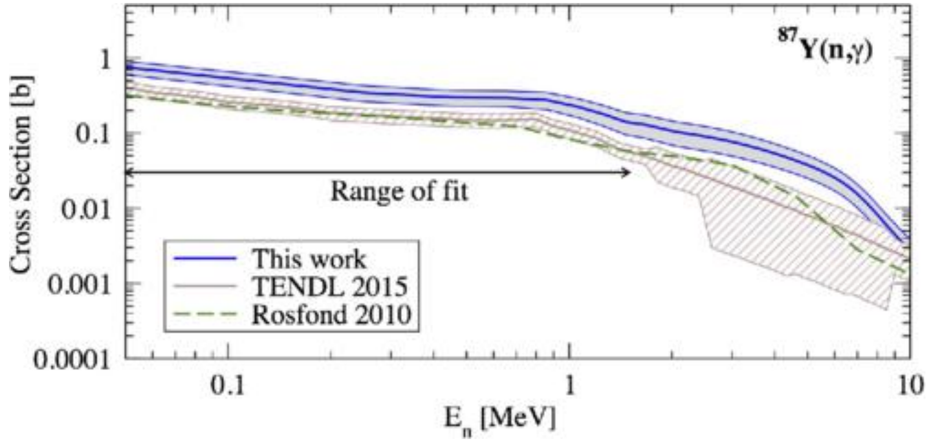




Neutron-capture surrogates work – but at present, particle-γ coincidences rays are essential!

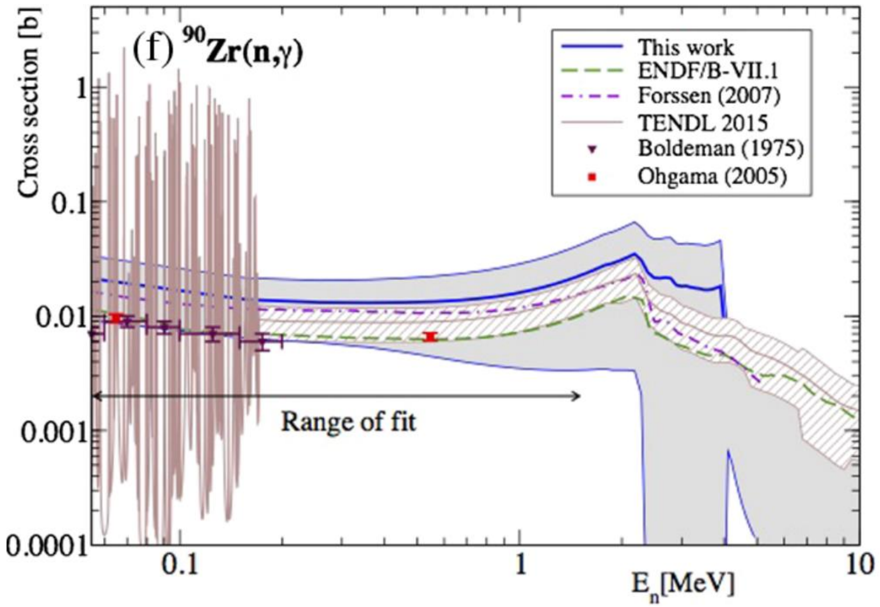
Ratkiewicz et al., Phys. Rev. Lett. **122**, 052502 (2019)

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

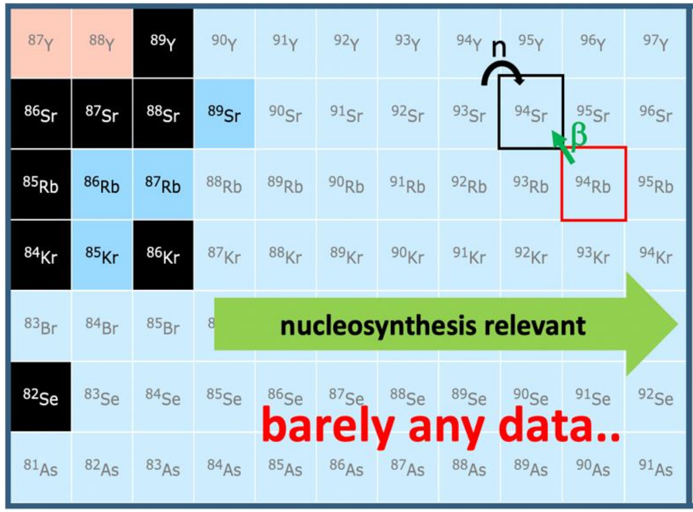


J.E. Escher et al., PRL **121**, 052501 (2018).

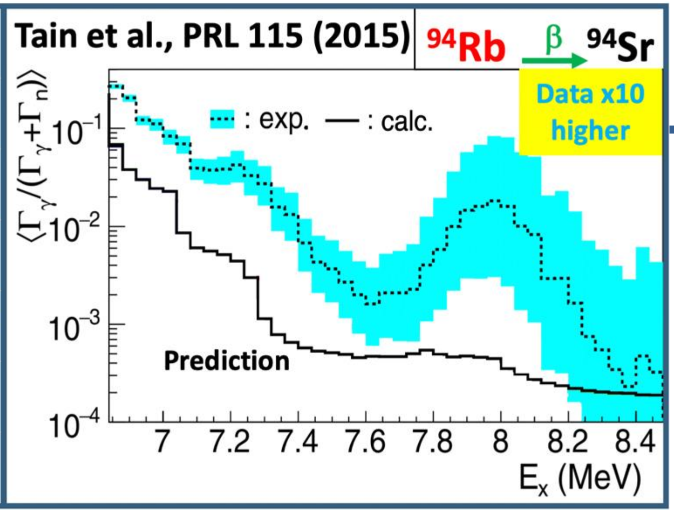
Determining the n-capture rate for unstable ^{93}Sr via the Surrogate Reaction Method

R.O. Hughes, A. Richard, 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 $\sigma(^{93}\mathrm{Sr}(n,\gamma))$ 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.

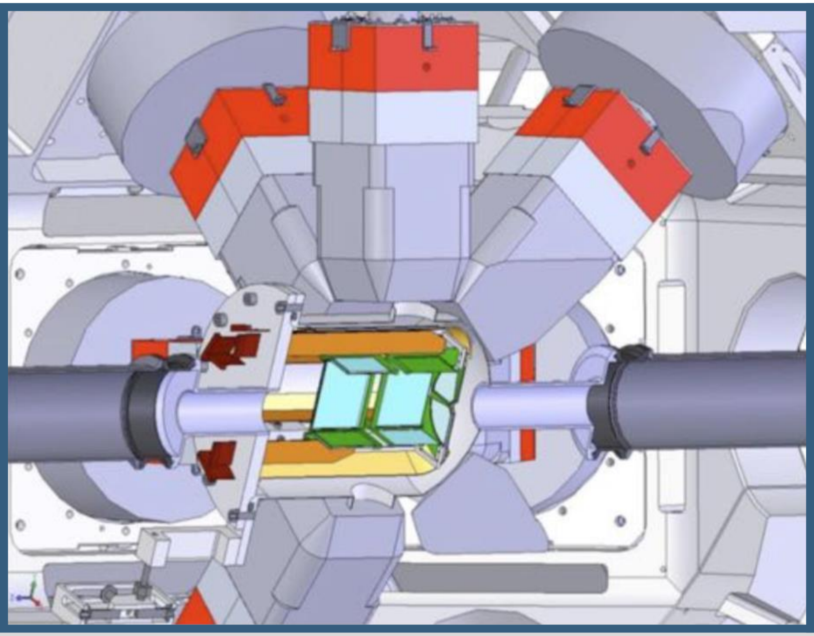


capture data limited for n-rich Sr region

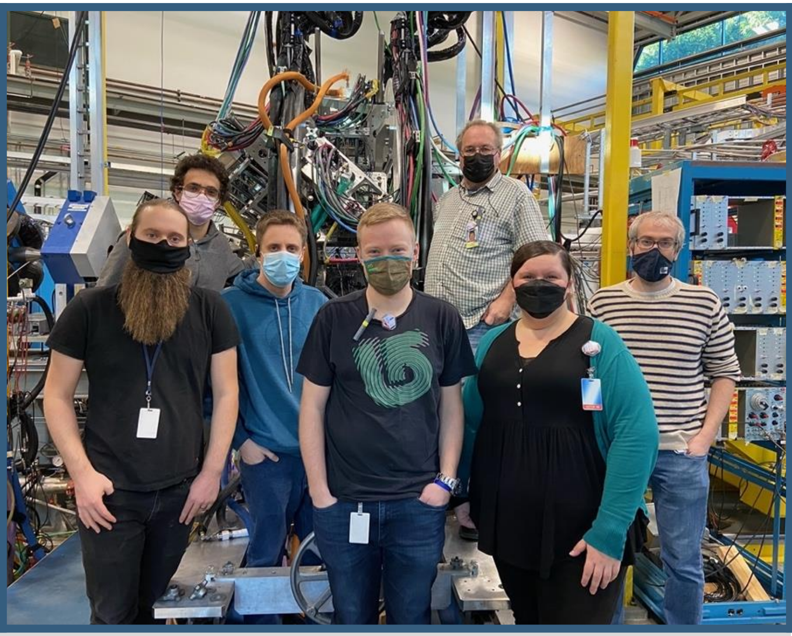


TAGS results hint at n-capture enhancement

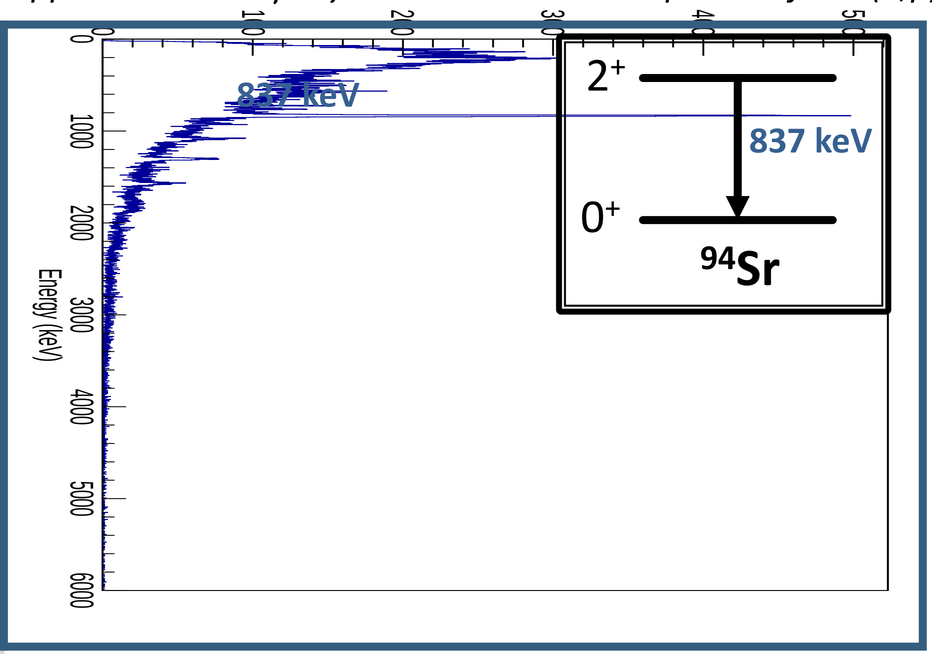
TIGRESS HPGe array & SHARC Si array @ TRIUMF



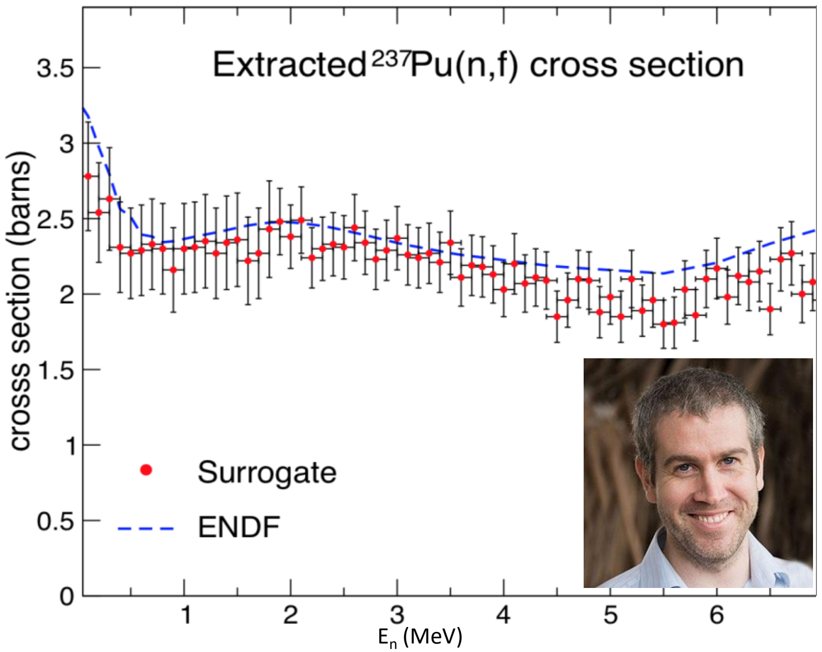
LLNL/TRIUMF experiment team



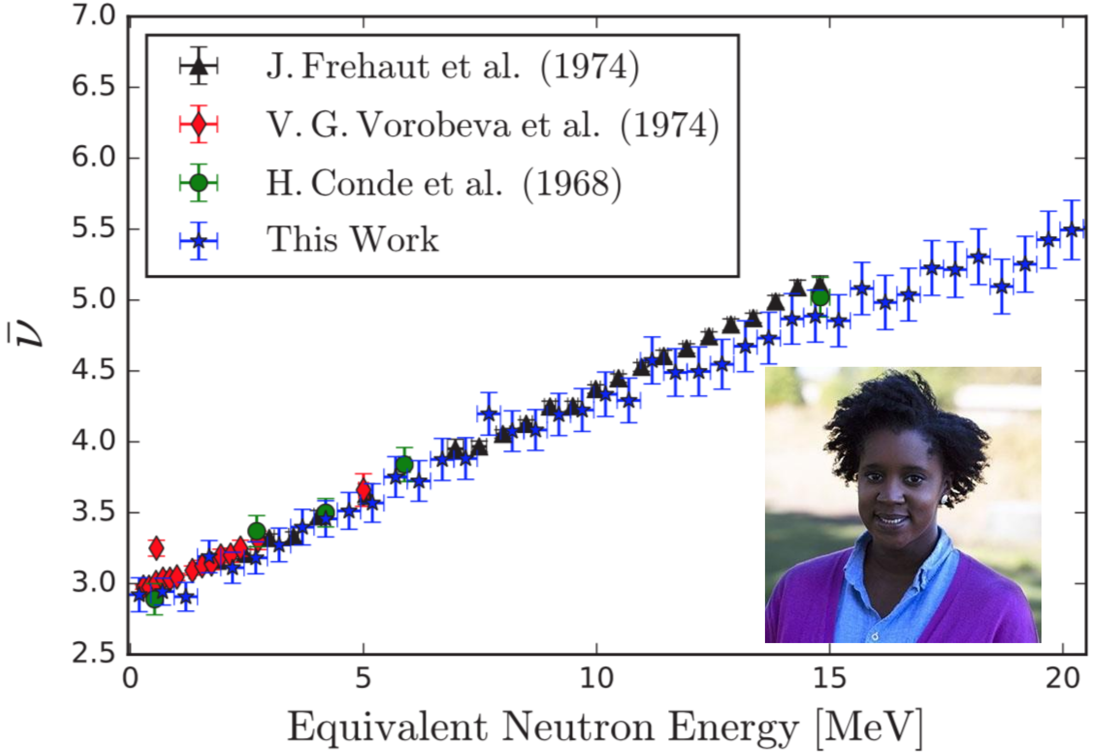
Doppler-corrected γ-rays in coincidence with protons from (d,p)



The Surrogate Reaction Method is not just for constraining neutron-capture cross sections



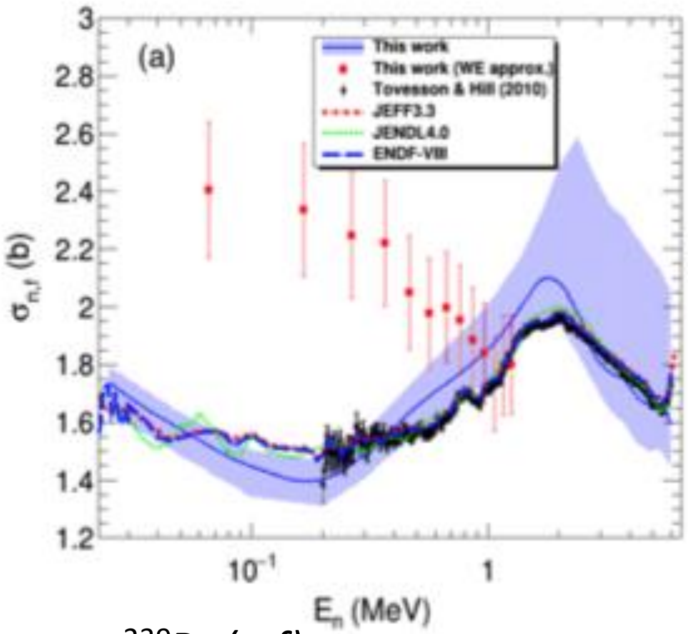
(n,f) cross section for ^{237}Pu ($T_{1/2}$ = 46 days), determined via (p,d) Hughes et al., PRC 90, 014304 (2014).



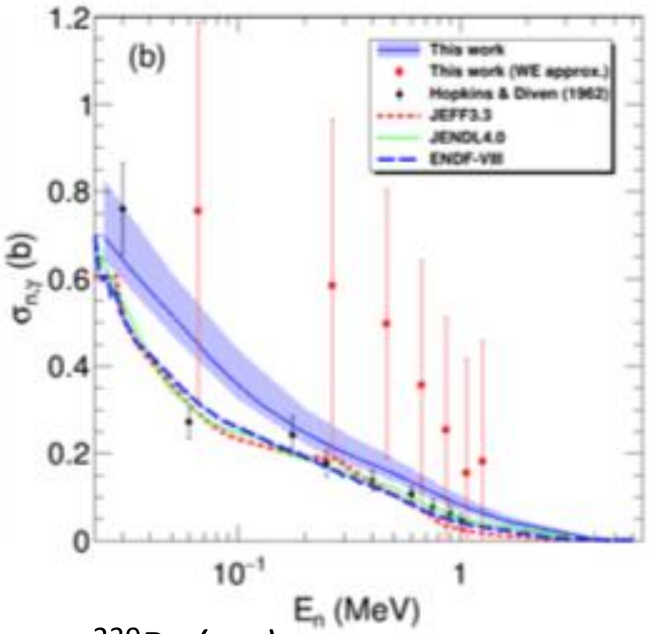
Fission neutron multiplicity obtained as a function of energy for ^{241}Pu(n,f) Akindele et al., PRC 99, 054601 (2019).

Thanks to R.O. Hughes for material on this slide

Other applications: simultaneous *(n,f)*, *(n,γ)* constraints and fission-fragment mass distributions

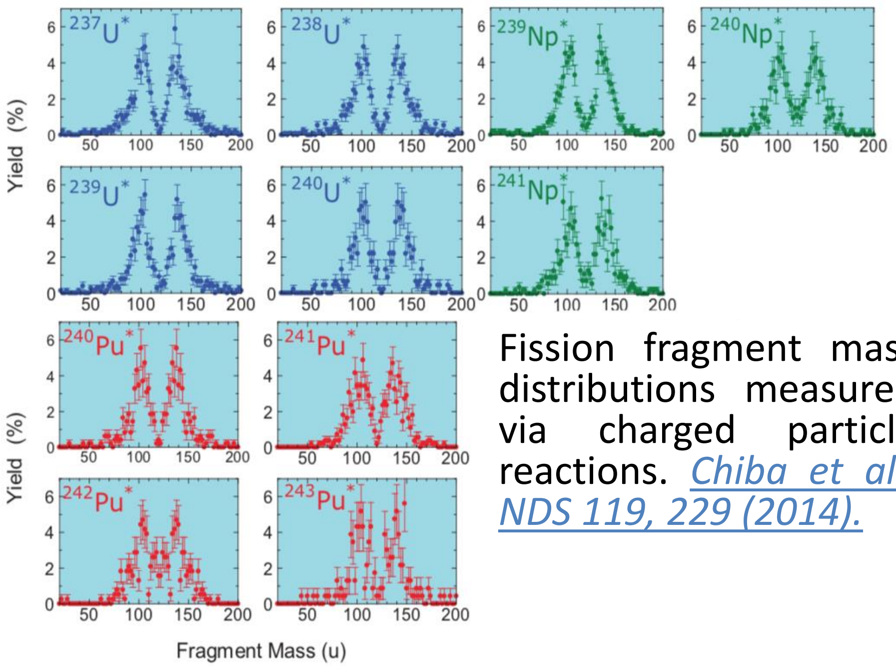


^{239}Pu*(n,f)*



^{239}Pu*(n,γ)*

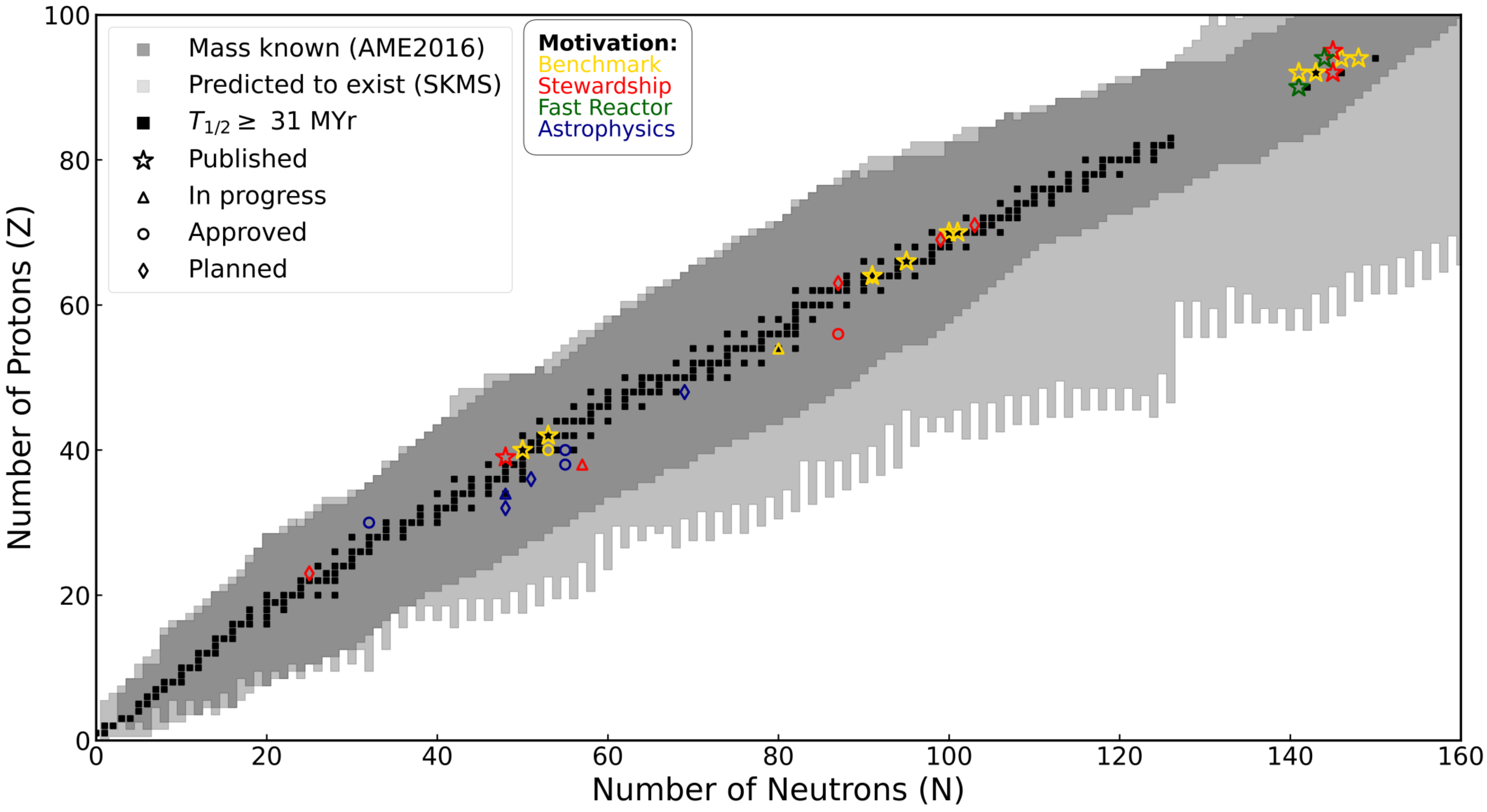
Simultaneous constraint of capture and fission on ^{239}Pu using ^{240}Pu$(\alpha,\alpha`)$ *R. Pérez Sánchez et al., PRL* ***125****, 122502 (2020)*



Fission fragment mass distributions measured via charged particle reactions. *Chiba et al., NDS 119, 229 (2014).*

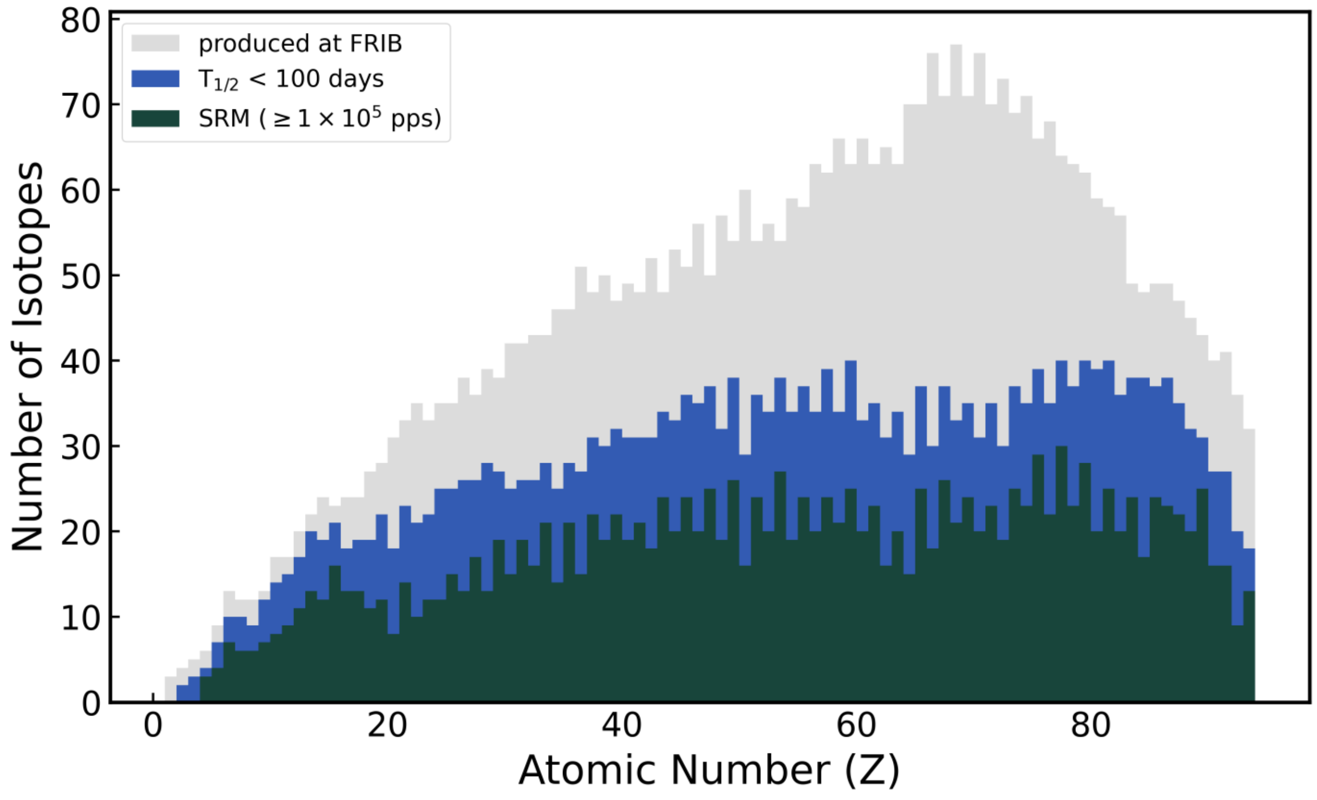
Exciting future for surrogate measurements – many neutron-induced reactions available for constraint.

The Surrogate Method has been widely exercised.



The FRIB era brings new opportunities and challenges:

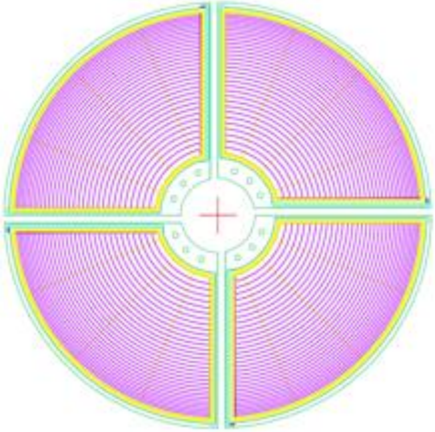
- Every γ ray is precious.
  - Need to maximize γ efficiency ***without*** compromising angular resolution for particles.
- In-flight beams (80 MeV/u) are too fast for transfer reactions.
  - Can degrade the beam to ~40 MeV/u.
  - Inelastic scattering?
  - Degraded beams have raggedy beam spots.
    - This will blow up our energy resolution. How big of a problem is it? How can we mitigate it?

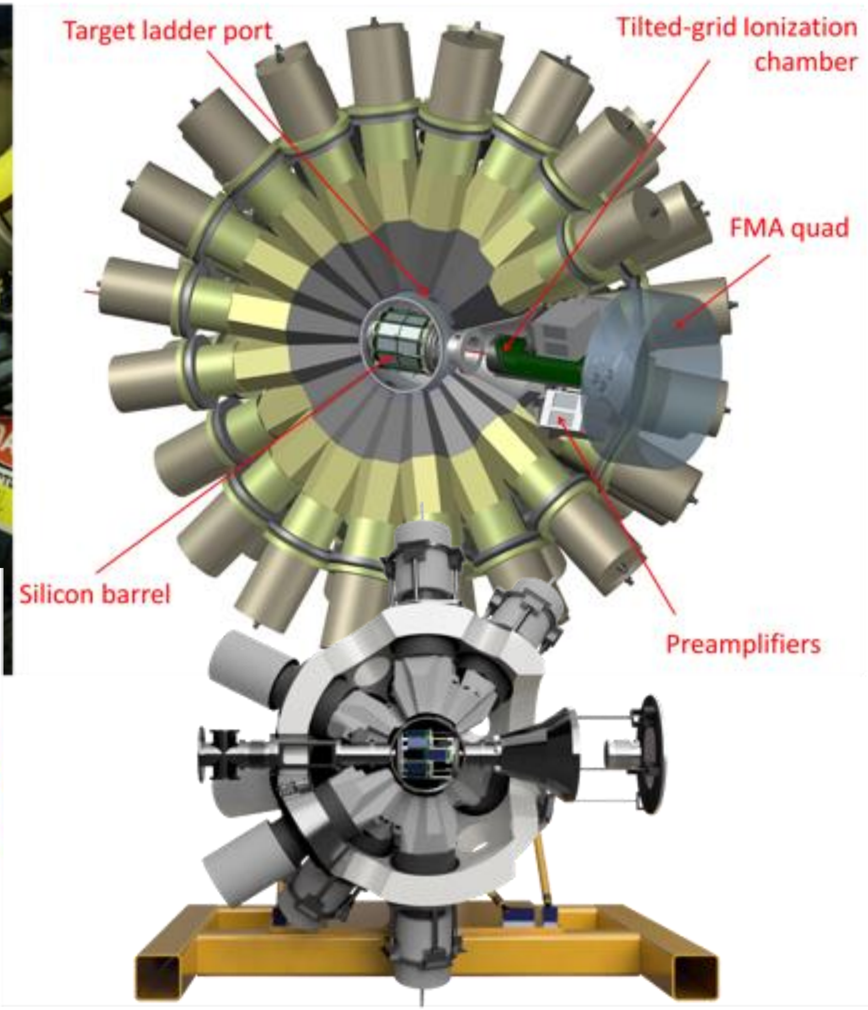


Problem 1: Maximize γ–ray efficiency w/o sacrificing particle resolution Solution: large-scale γ-ray spectrometers like GODDESS

- GODDESS is composed of:
  - ORRUBA, a barrel array of Si strip detectors augmented with annular endcap detectors:
    - Up to 720 channels.
    - mm-precision for particles → 1 degree polar resolution.
    - Covers ~75% of the angle between 18-163 degrees.
    - dE (BB10, 65 μm) and E (sX3 1000 μm, resistive) are available.
  - Augmented by QQQ5 (100 and 1000 μm) annular detectors DS and US.
    - Design work on-going for new detectors that will extend polar angle coverage for fast-beam measurements.
  - An auxiliary array for detecting γ rays.

- Has been implemented with GAMMASPHERE (2015) and GRETINA (2019, 2021) at ATLAS. Work on-going to implement with GRETINA/S800.





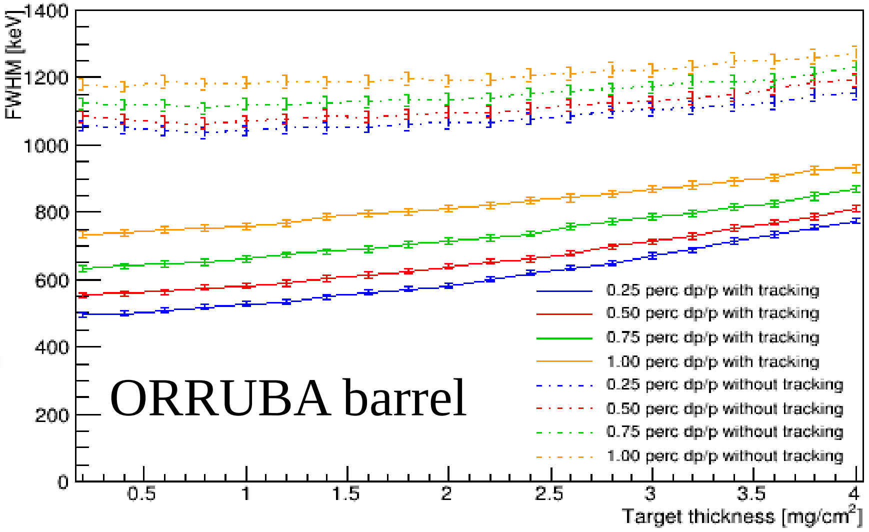
A. Ratkiewicz, *et al.*, AIP Conf. Proc. **1525**, 487 (2013)
S.D. Pain, AR, *et al.*, Phys. Proc. **90**, 455 (2017).

Problem 2: resolution degraded by large beam spots.
Solution: Beam tracking

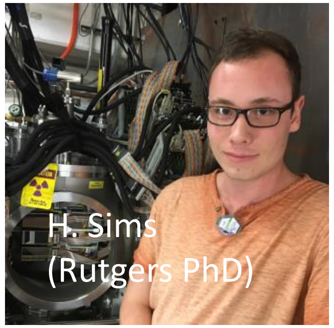
<u>Important to simulate the Q value resolution for all detector types</u>

- Simulation performed using the Monte Carlo approach in VIKAR v4.2
- Assumed the following parameters:
  - Beam spot size: **5mm**
  - Beam divergence: **1°**
  - Beam tracking position resolution: **1.9mm**
  - Beam tracking angular resolution: **0.12°**

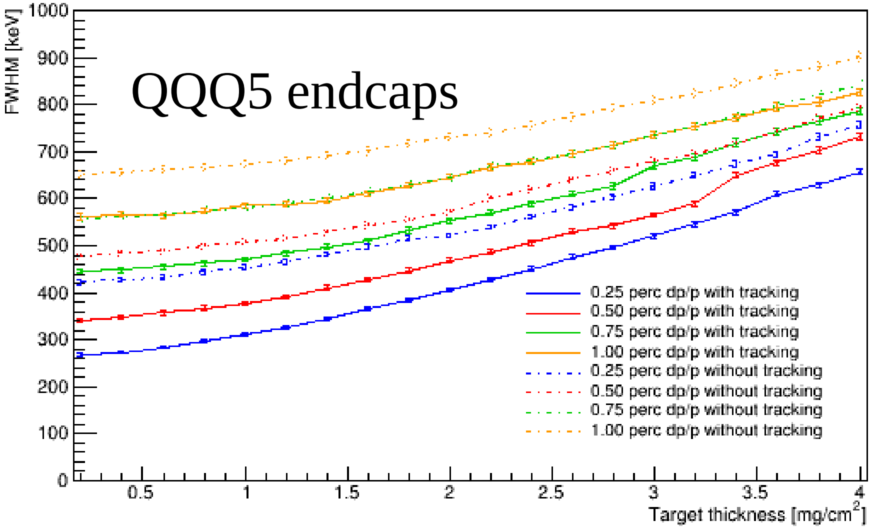
better



Sensitivity:
Tracking
dp/p
Target thickness

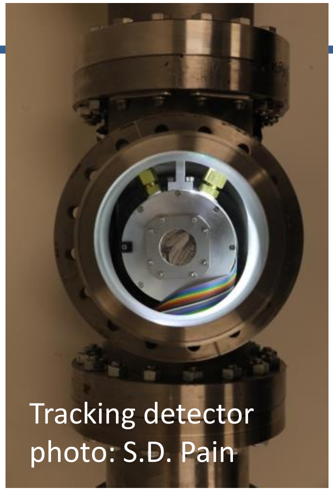


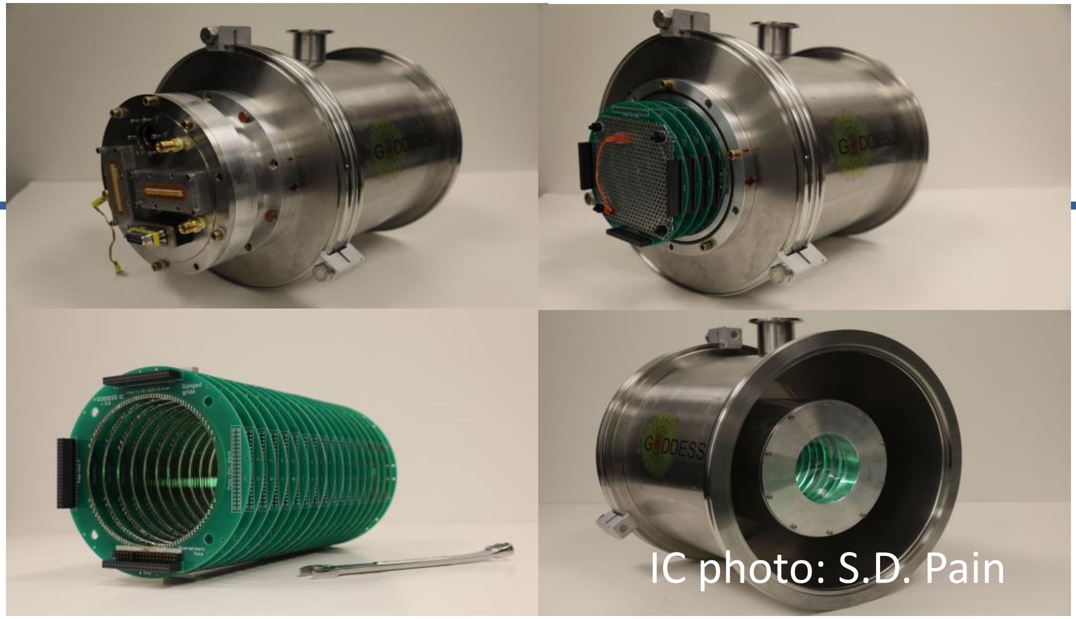
better



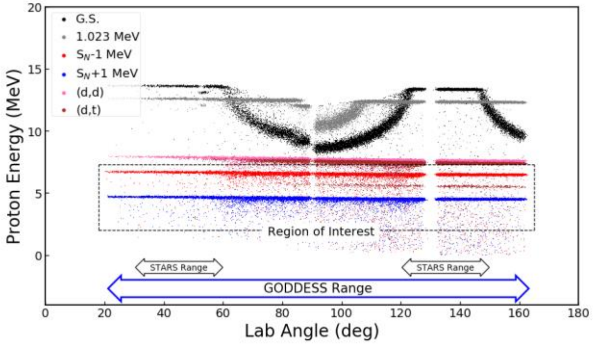
GODDESS Tools: IC, tracking detectors, VIKAR

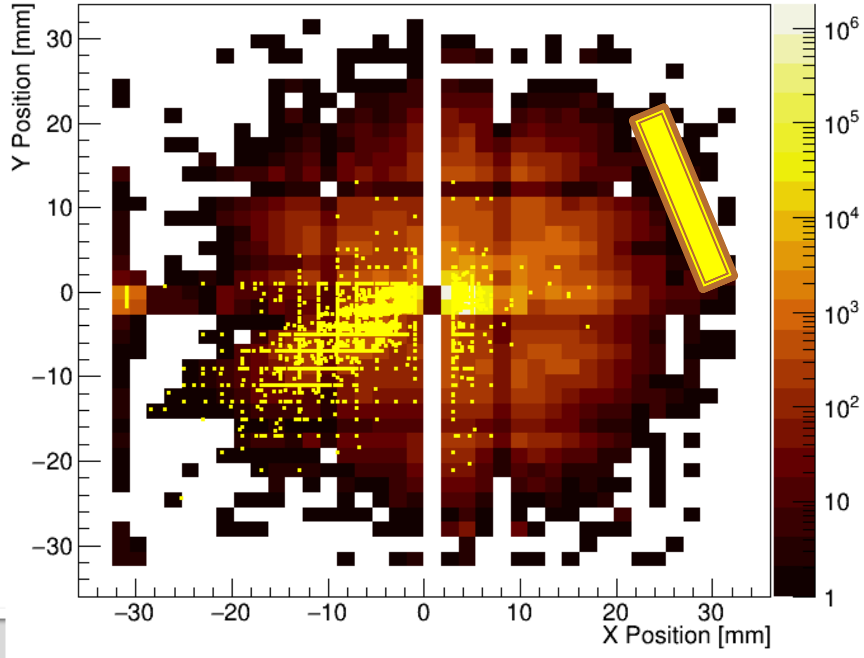
- Several tools and auxiliary detectors are available for GODDESS:
  - A fast (~500kHz), position-sensitive ionization chamber (dE + E, 32 X, 32 Y), can separate d*A*=1 isobars at *A*=130, 10 MeV/A.
  - Beam-tracking detectors (16 X, 16 Y).
  - A Monte-Carlo kinematics code (VIKAR, S.D. Pain) to simulate the performance of the silicon detectors.
  - A website: https://orruba.org/goddess/


Tracking detector photo: S.D. Pain



IC photo: S.D. Pain

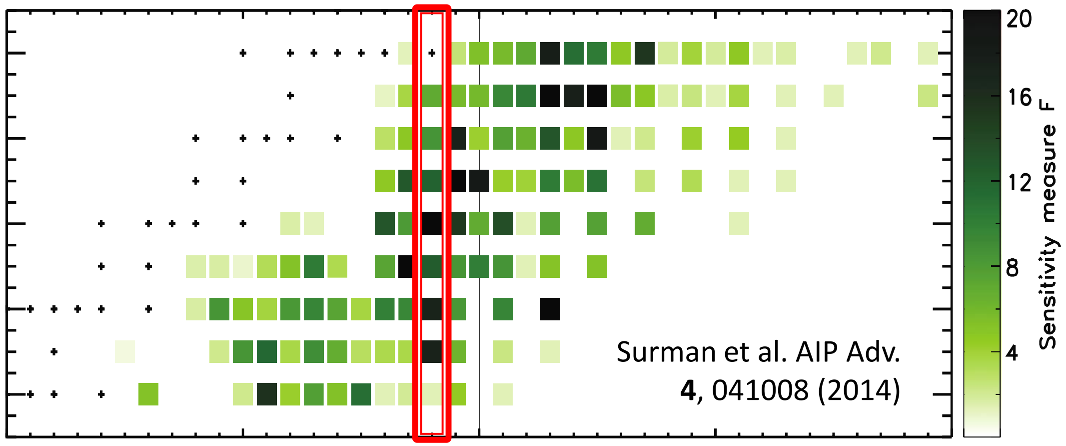




Highlight: Competition between direct-semi direct and compound neutron capture near the N=50 shell closure

^{82}Se(d,pγ)

Sensitivities of neutron capture rates are high around N=50 shell closure, in particular the N=48 isotones, Surman *et al:*



Around closed shells, neutron capture can proceed via two processes:

Direct (& Semi-direct, via the GDR)

Via a Compound Nucleus

DSD:

- Informed by spectroscopic information of the state
- Extract spectroscopic factors through comparison of observed angular distribution to FR-ADWA

$$S_{\ell j} = \langle \Psi_f(J_f) | a_j^{\dagger} | \Psi_i(J_i) \rangle$$

$$S = \left(\frac{d\sigma}{d\Omega}\right)^{\exp} \Big/ \left(\frac{d\sigma}{d\Omega}\right)^{theory}$$

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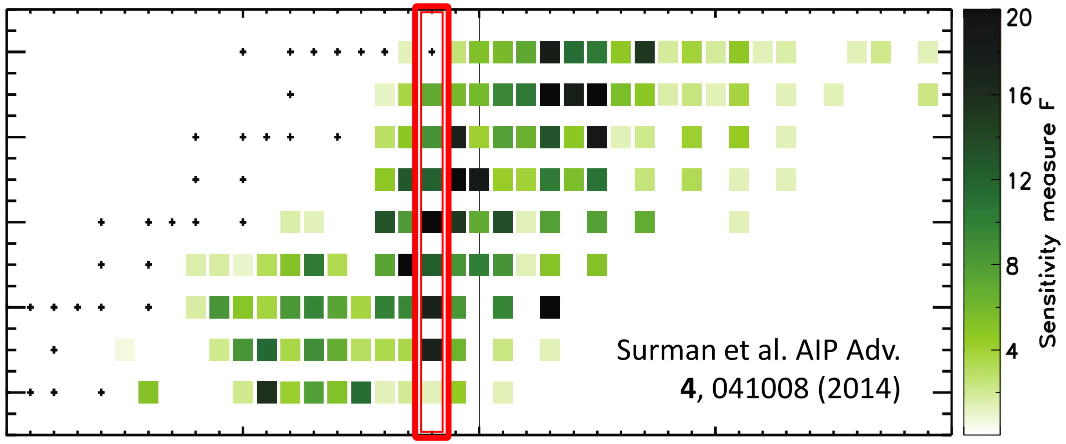

Around closed shells, neutron capture can proceed via two processes:

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(& Semi-direct, via the GDR)

Via a Compound Nucleus

CN:

- Cross section depends on the formation cross section, and subsequent decay

$$\sigma_{\alpha\chi}(E_n) = \sum_{J,\pi} \boxed{\sigma_\alpha^{\mathrm{CN}}(E_{ex}, J, \pi)}\boxed{G_\chi^{\mathrm{CN}}(E_{ex}, J, \pi)}.$$

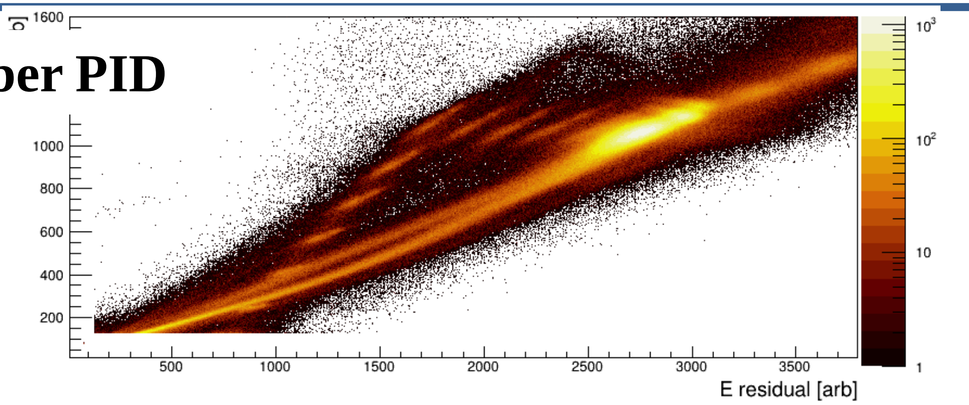
$$\boxed{P_{\delta\chi}(E_{ex}, \theta_p)} = \sum_{J,\pi} \boxed{F_\delta^{\mathrm{CN}}(E_{ex}, J, \pi, \theta_p)}\boxed{G_\chi^{\mathrm{CN}}(E_{ex}, J, \pi)}.$$

$$\boxed{P_{p\gamma}(E_{ex})} = N_{p\gamma}(E_{ex})/[N_p(E_{ex})\epsilon_\gamma].$$

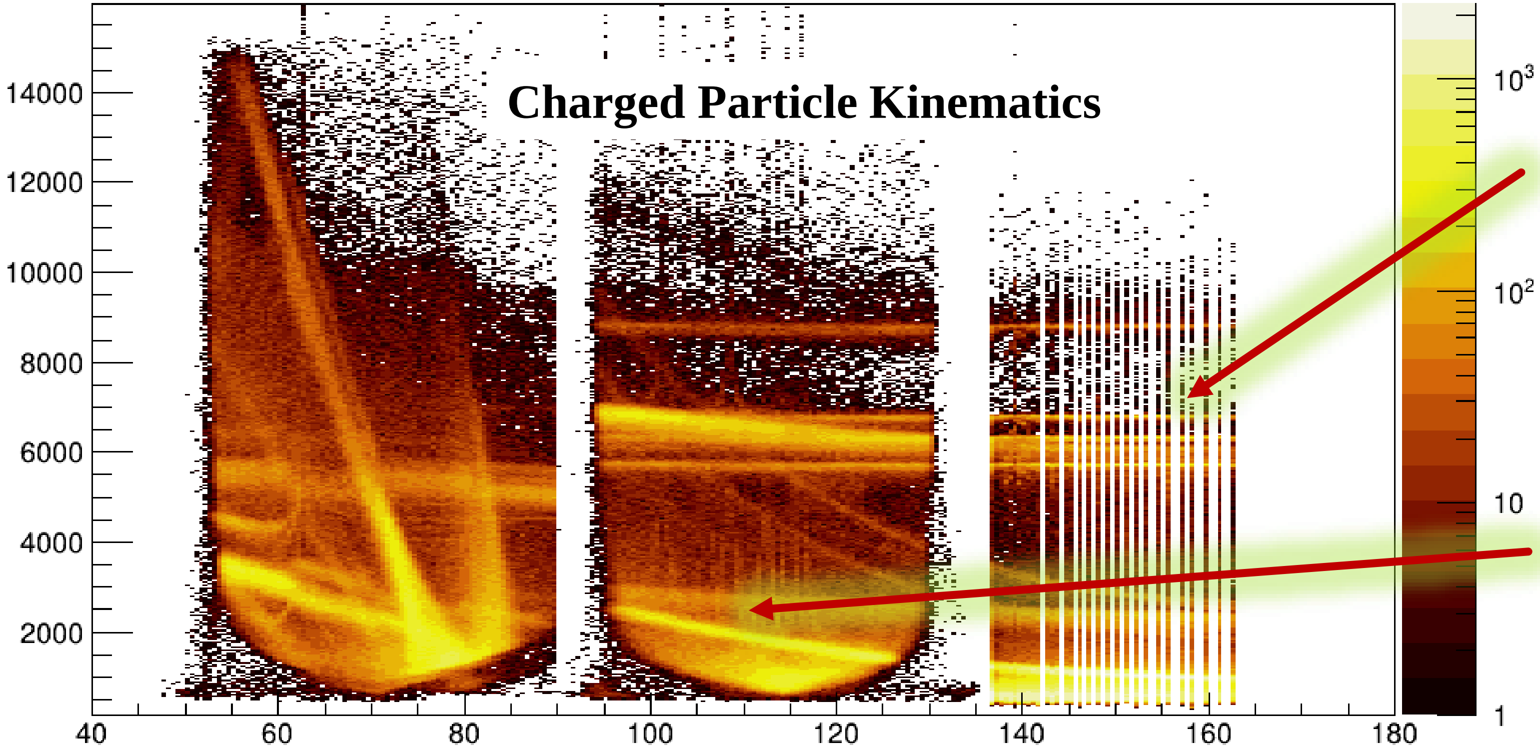
Preliminary results for ^{82}Se(d,pγ)

- Light-ion contaminants in beam dominate spectra
- Also see residual alpha contamination in chamber
- Need recoil coincidence in the IC

Ion Chamber PID



Charged Particle Kinematics



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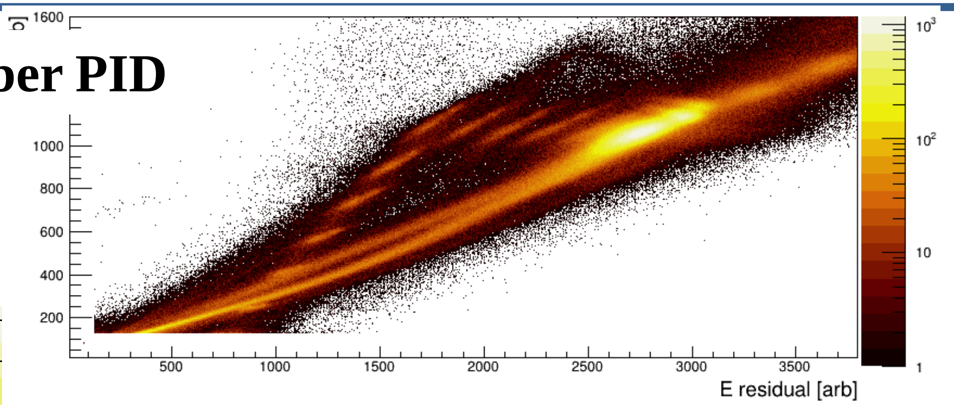

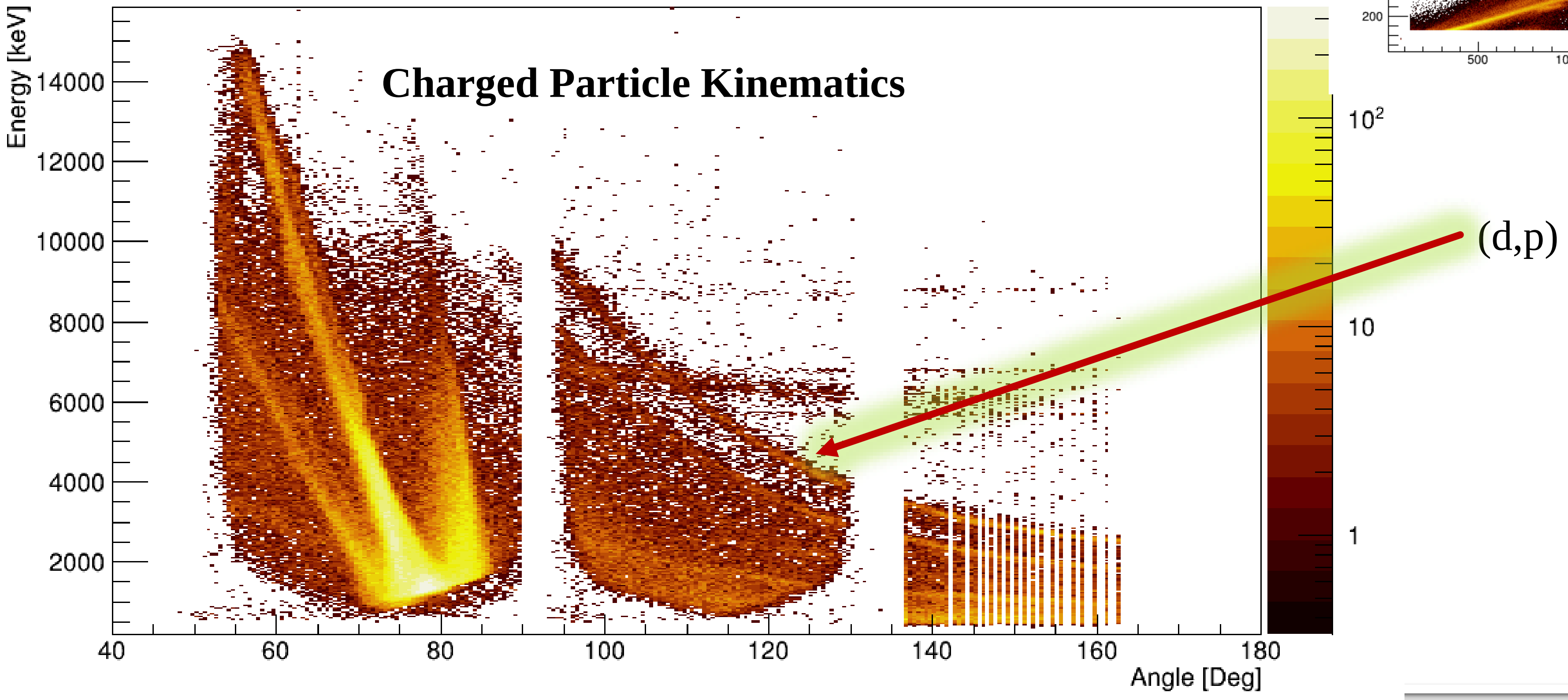

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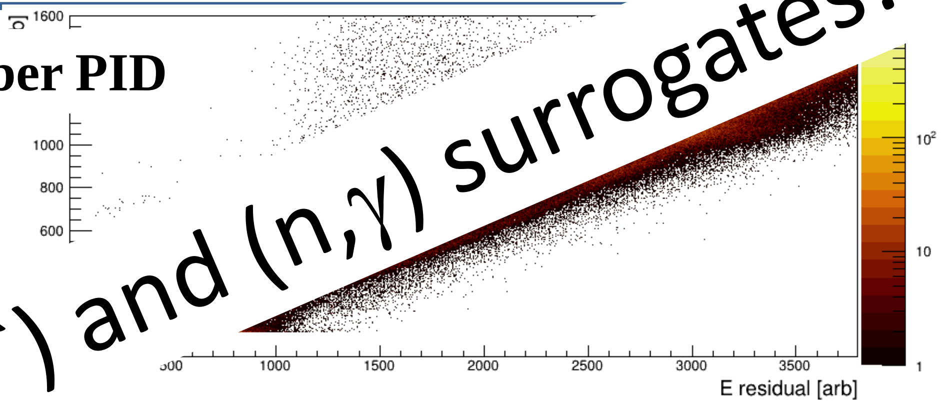

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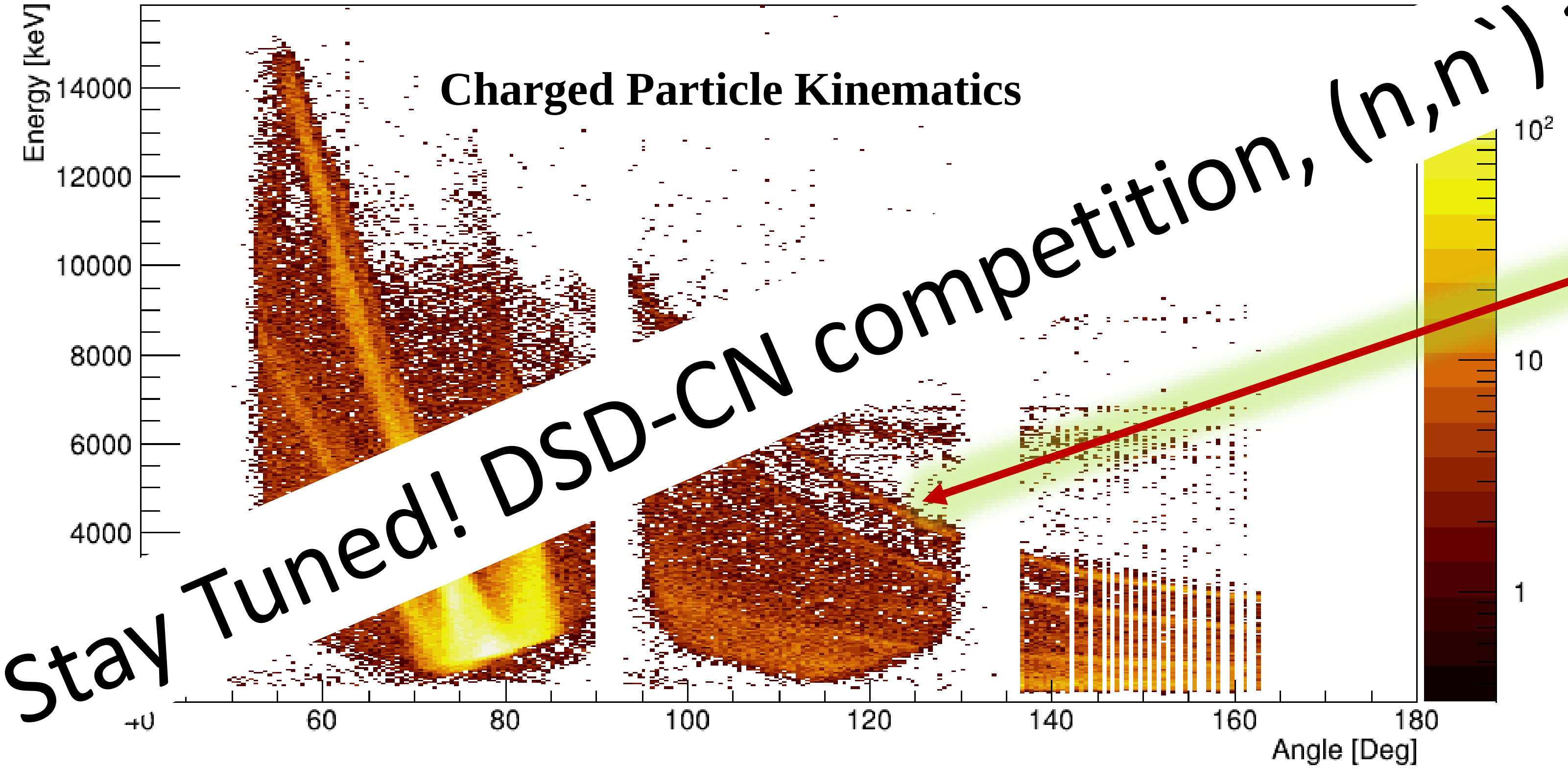
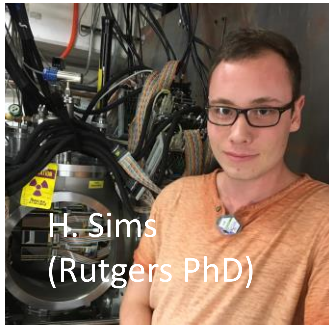
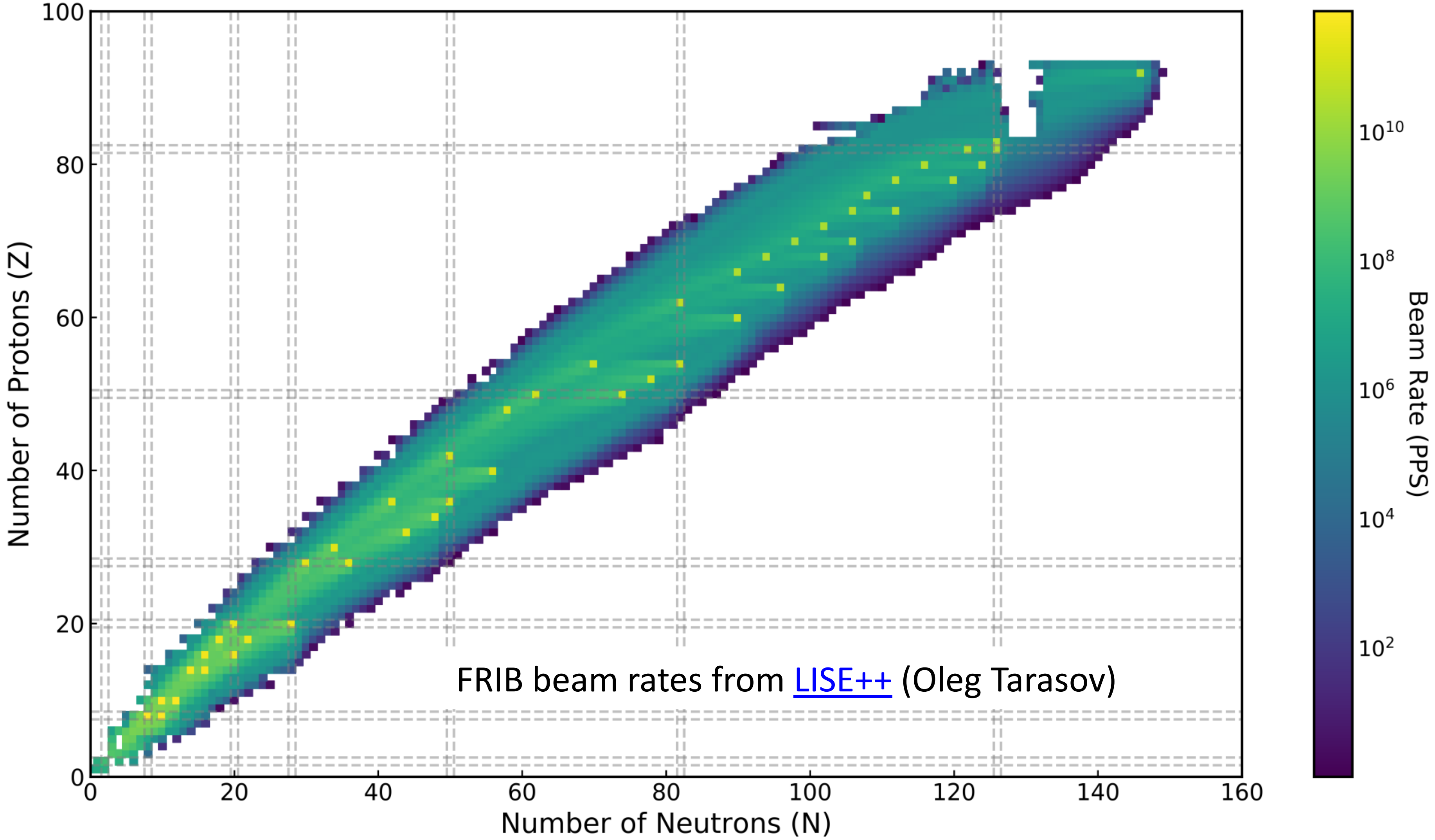


Stay Tuned! DSD-CN competition, (n,n`) and (n,γ) surrogates!



Looking ahead to FRIB:

This is the opportunity with which we are presented



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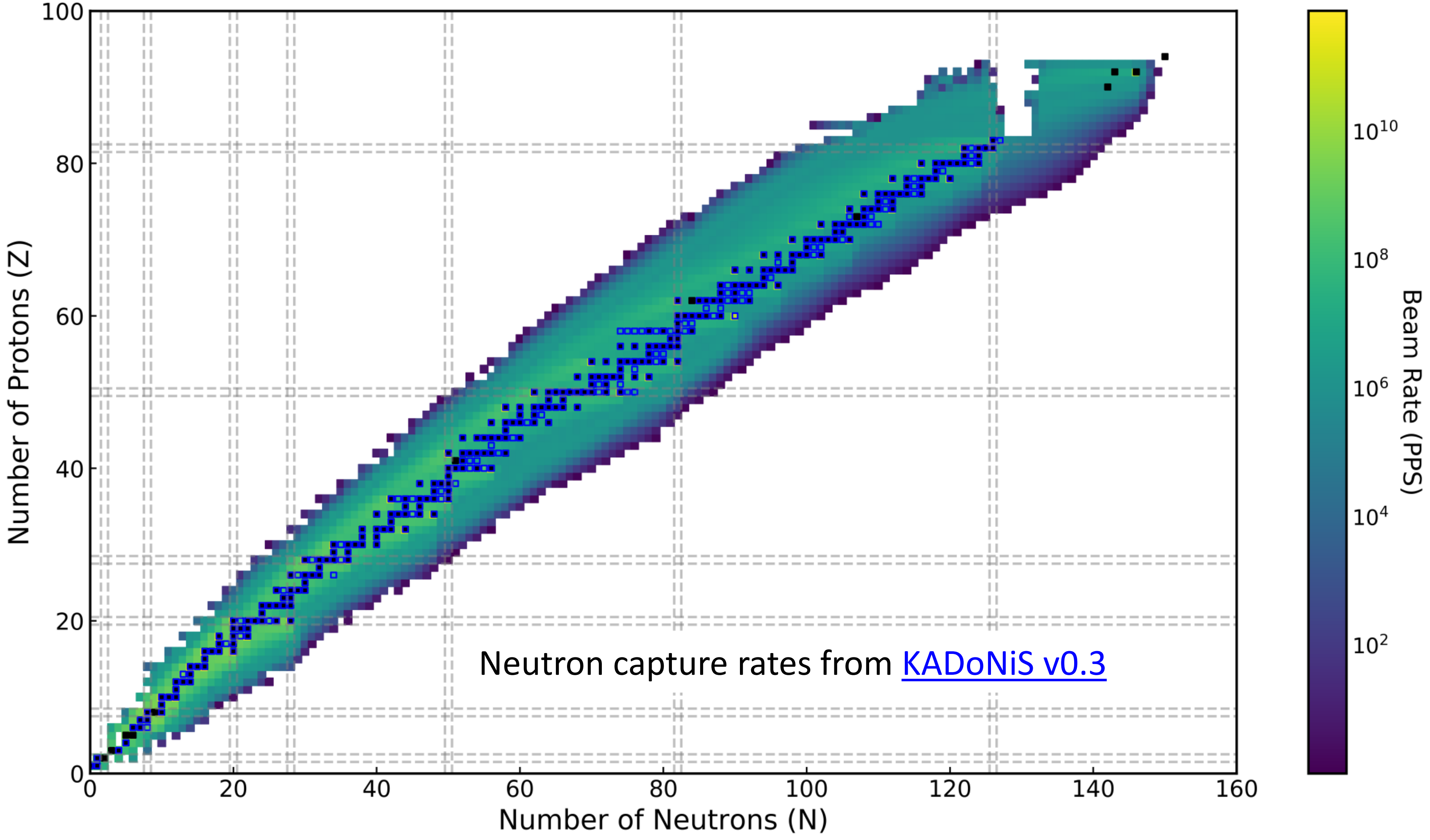

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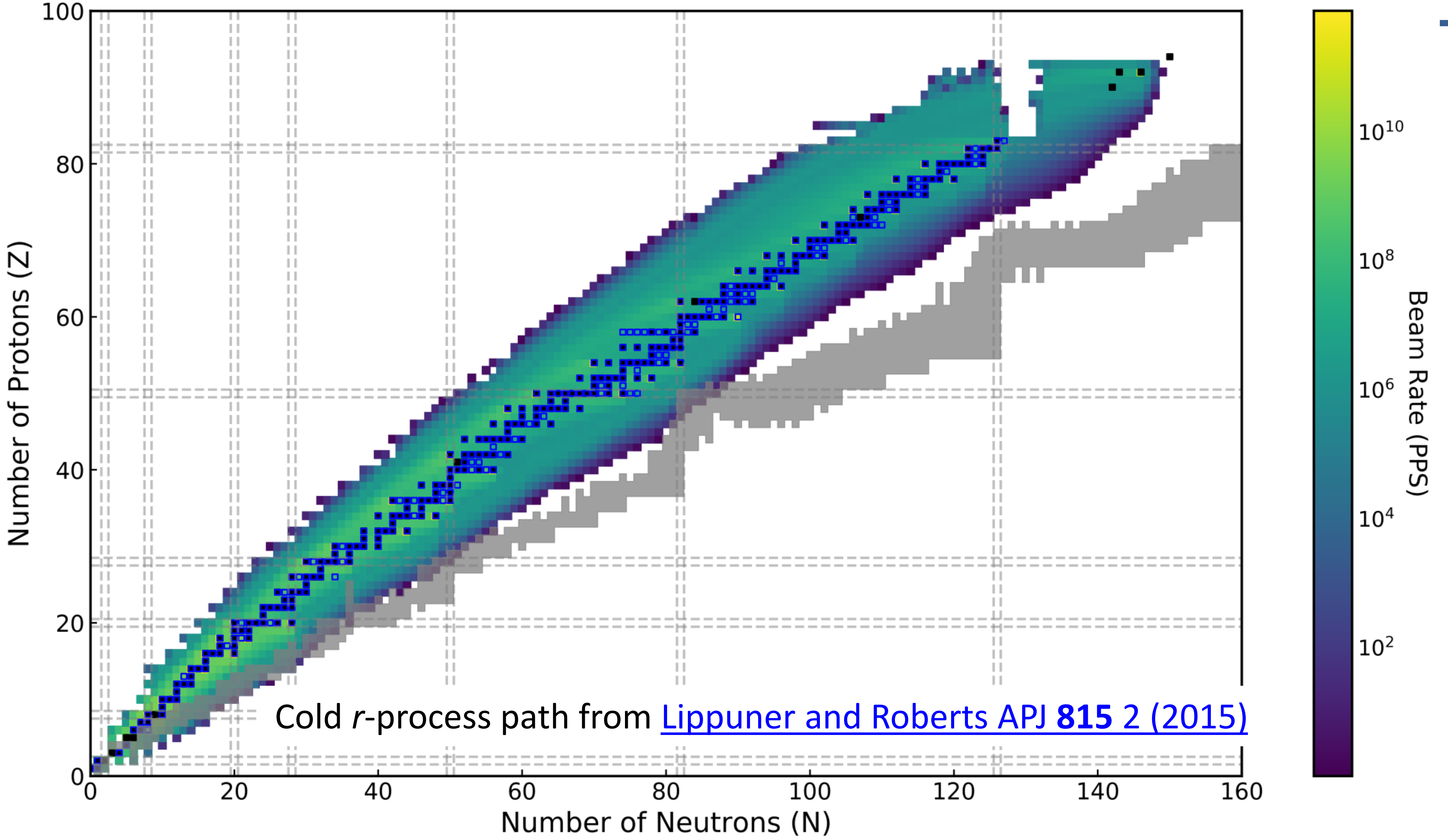

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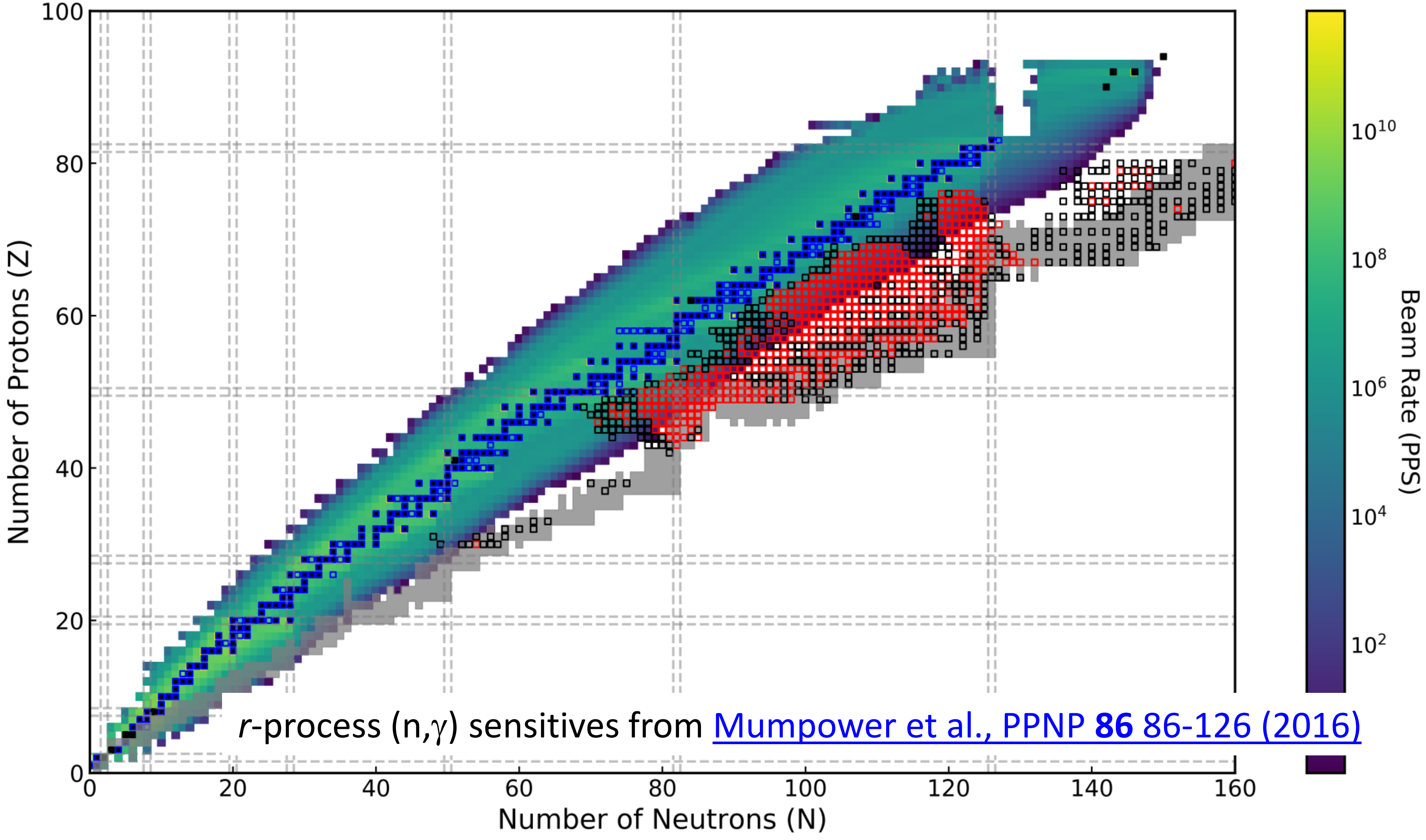

r-process (n,γ) sensitives from [Mumpower et al., PPNP **86** 86-126 (2016)]

Looking ahead to FRIB:

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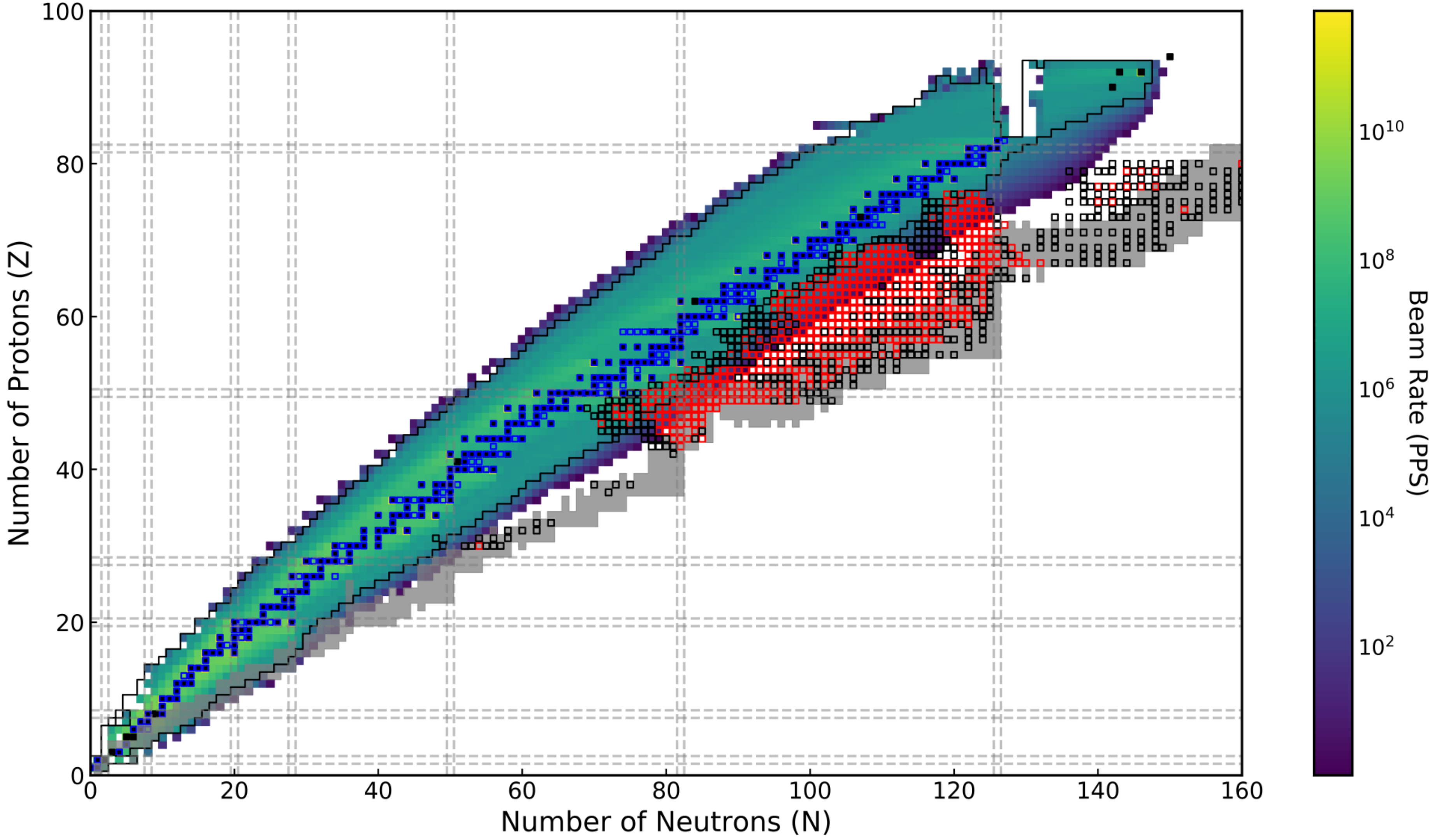

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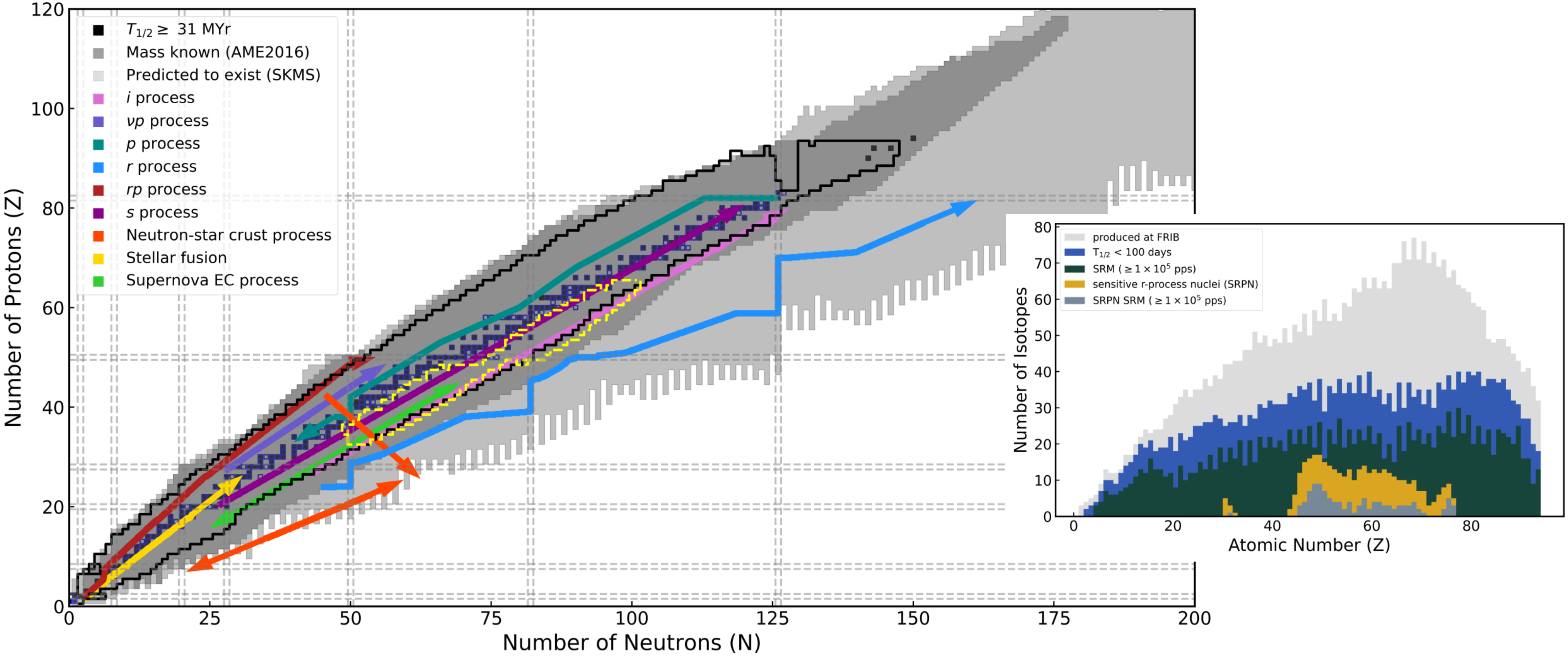

GODDESS

S.D. Pain, K.A. Chipps, M. Febbraro, ***M.R. Hall (PD)***, **R.L. Varner**, A. Walsh (GS)
Oak Ridge National Laboratory

A. Ratkiewicz, *J. Henderson*, R. Hughes, N.D. Scielzo
LLNL

S. Zhu
Brookhaven National Laboratory

J.A. Cizewski, **C. Ummel**, **H. Garland, *A. Lepailleur*, H. Sims, *G. Seymour***, R. Toomey
Rutgers University

R. Ghimire, **S. Burcher**, M. Cantrell, ***J. Hooker***, **K.L. Jones**, J. Kovoor
University of Tennessee

G.L. Wilson, J.C. Blackmon
Louisiana State University

C. Campbell, H. Crawford, P. Fallon, A. Macchiavelli, *C. Morse*, *C. Santamaria*
LBNL

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B. Nardi (ANL)
C. Snow (NSCL/FRIB)

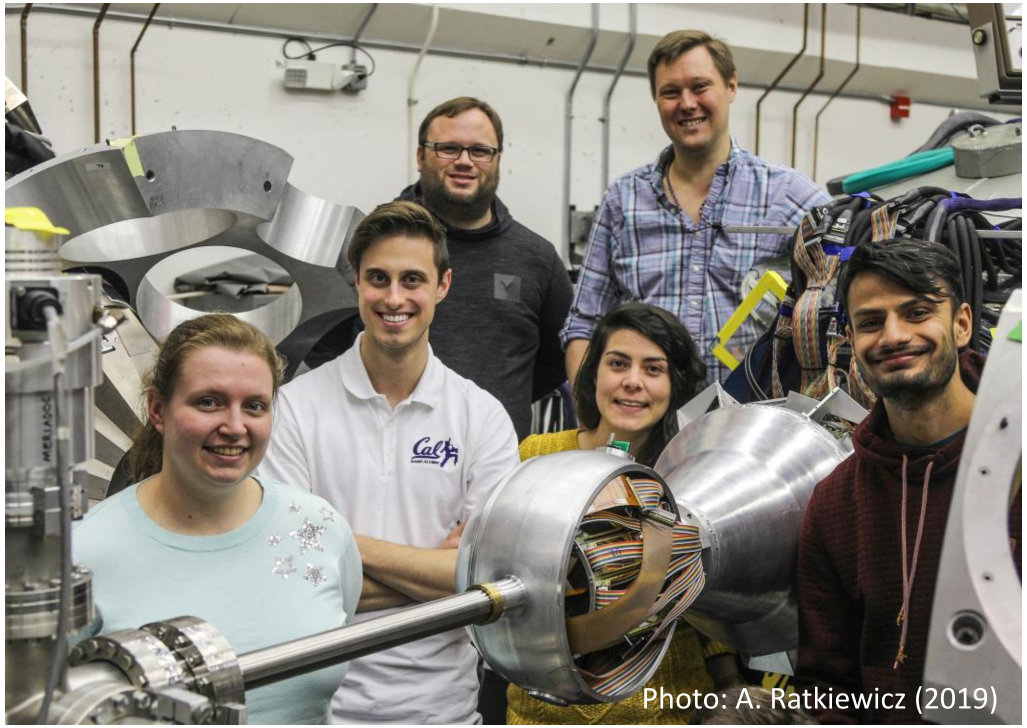
Photo: A. Ratkiewicz (2019)

J. Anderson, *K. Auranen*, M. Carpenter, C. Dickerson, *M. Gott*, J. Greene, C. Hoffman, T. Lauritsen, *J. Li*, D. Santiago-Gonzales, D. Seweryniak, G. Savard, *S. Stolze*, *R. Vondrasek*
Argonne National Laboratory

D. Bardayan, D. Blankstein, **P.D. O'Malley**
University of Notre Dame

W.N. Catford, D.T. Doherty, G. Lotay
University of Surrey

And others in the GODDESS collaboration

Slide stolen from S.D. Pain

Thanks to J.E. Escher, R.O. Hughes, S.D. Pain, and H. Sims for slides and figures.

Thanks for your attention!

Lawrence Livermore National Laboratory