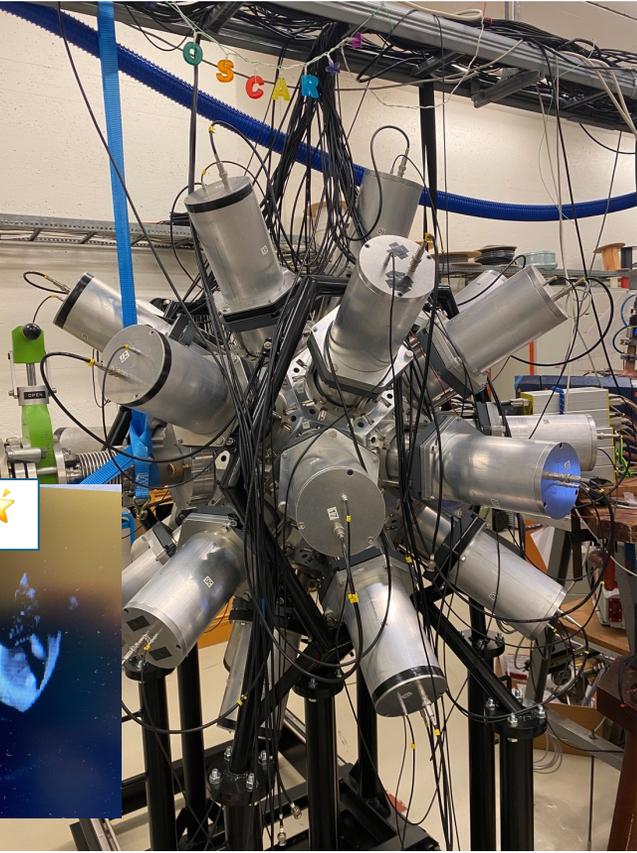


# The Oslo method for nuclear-model ingredients: Recent results and applications



OSCAR 

30 MeV alphas 



## Nuclear Data for the Next Decade

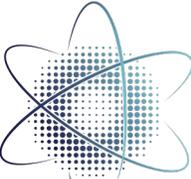
9–13 Mar 2026  
Amphithéâtre Farabeuf, Campus des Cordeliers, Paris  
Europe/Paris timezone

Ann-Cecilie Larsen

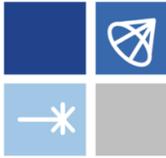
RCN Project No. 316116, NNRC Project No. 341985

UiO  Department of Physics  
University of Oslo

 The Research Council of Norway

  
NUKLEÆRSENTERET  
Norwegian Nuclear Research Centre

  
IReNA

  
JINA-CEE

  
ChETEC INFRA

# Many thanks to

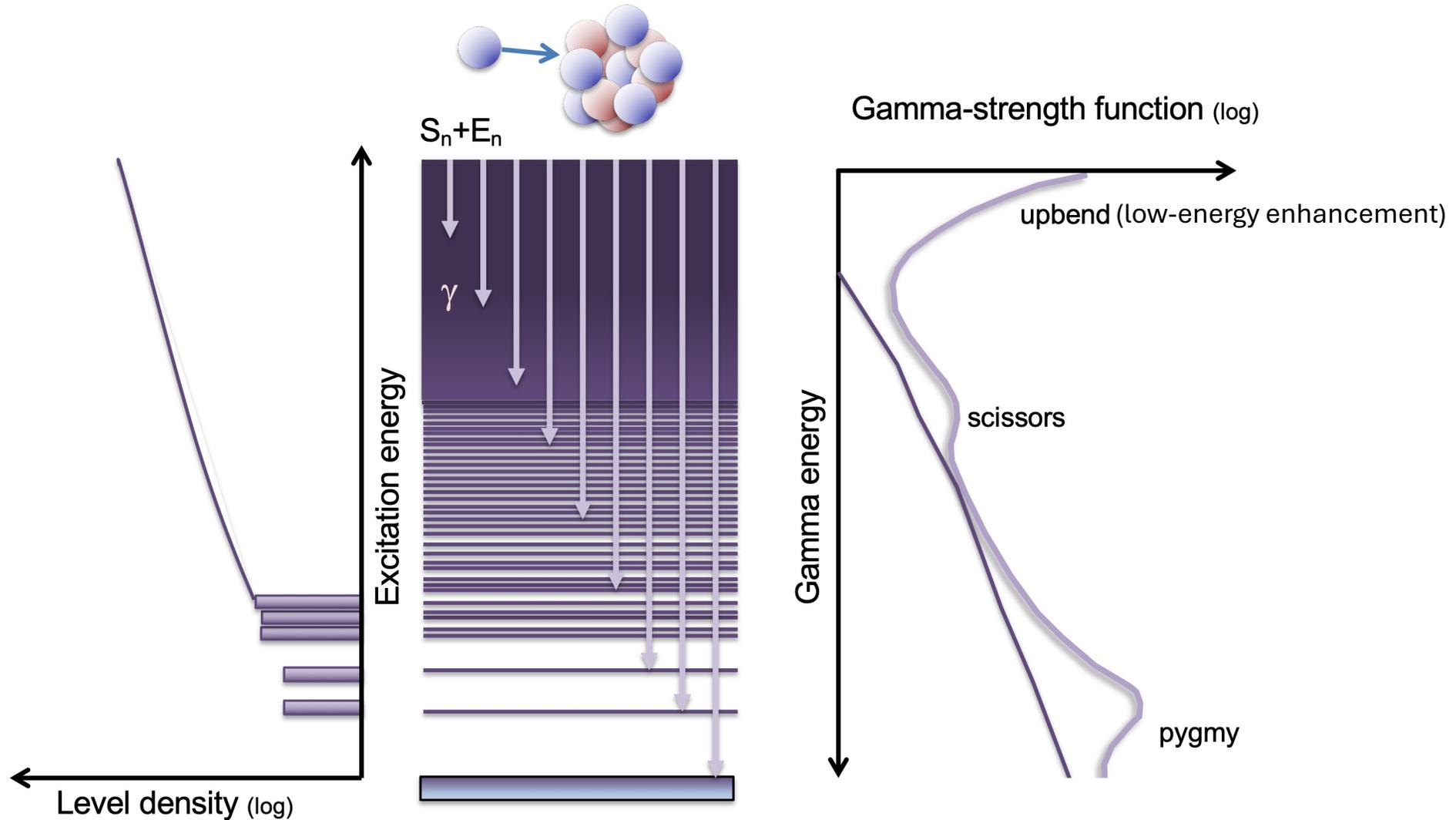
- M. Guttormsen, A. Görgen, K.C.W. Li, V.W. Ingeberg, E. Sahin, S. Siem and everyone at the nuclear-physics group, Dep. of Physics, University of Oslo
- M. Hjorth-Jensen, A. Kvellestad, Dep. of Physics, University of Oslo
- S. Shen, Institute for Theoretical Astrophysics, University of Oslo
- A. Spyrou, S. N. Liddick and their groups @ FRIB, Michigan State University
- A. L. Richard, A. V. Voinov, S. M. Grimes, Ohio University
- D. Mücher, University of Cologne
- S. Goriely, Université Libre de Bruxelles
- P. von-Neumann-Cosel and J. Isaak, TU Darmstadt
- S. Lyons, Pacific Northwest National Laboratory
- N. Shimizu, University of Tokyo and University of Tsukuba
- Y. Utsuno, University of Tokyo and Japan Atomic Energy Agency
- H. Utsunomiya, Konan University /Shanghai Advanced Research Institute
- M. Wiedeking, iThemba LABS Berkeley National Lab
- D.L. Bleuel and A. Sweet, Lawrence Livermore National Lab



From peanutsmovie.com

**Extra-special thanks to the  
awesome students and  
postdocs!!! 🥰**

# The Oslo method: measure nuclear level densities and gamma-ray strength functions



# Why are we interested in nuclear level densities and $\gamma$ -ray strength functions?



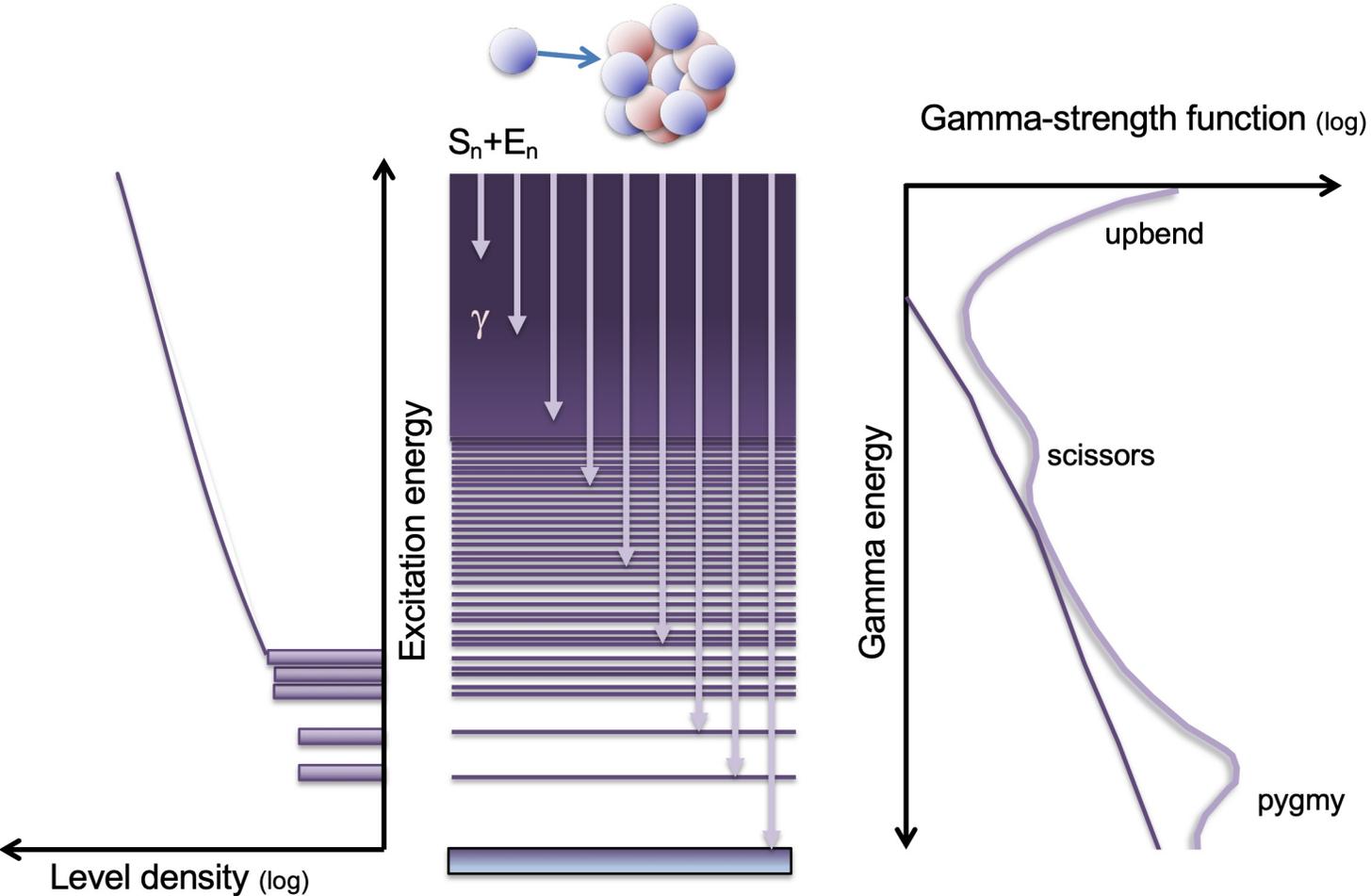
- Transition from discrete to (quasi-) continuum: “ordered” to “chaotic” many-body quantum system
- **Level density:** Pairing, shell effects, “single-particle” vs. collective behavior (collective enhancement)
- **Gamma-ray strength function:** Statistical vs. non-statistical gamma decay, Pygmy Dipole Resonance, Scissors Mode, Low-Energy Enhancement, ...
- **Applications:** cross section calculations and reaction rates (heavy-element nucleosynthesis, medical applications, next-generation reactors, ...)

# Nuclear-physics input: $(n,\gamma)$ reaction rates

🐎 The workhorse: (Wolfenstein-)Hauser-Feshbach theory

-> “Compound nucleus” picture of Bohr

[W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952)]

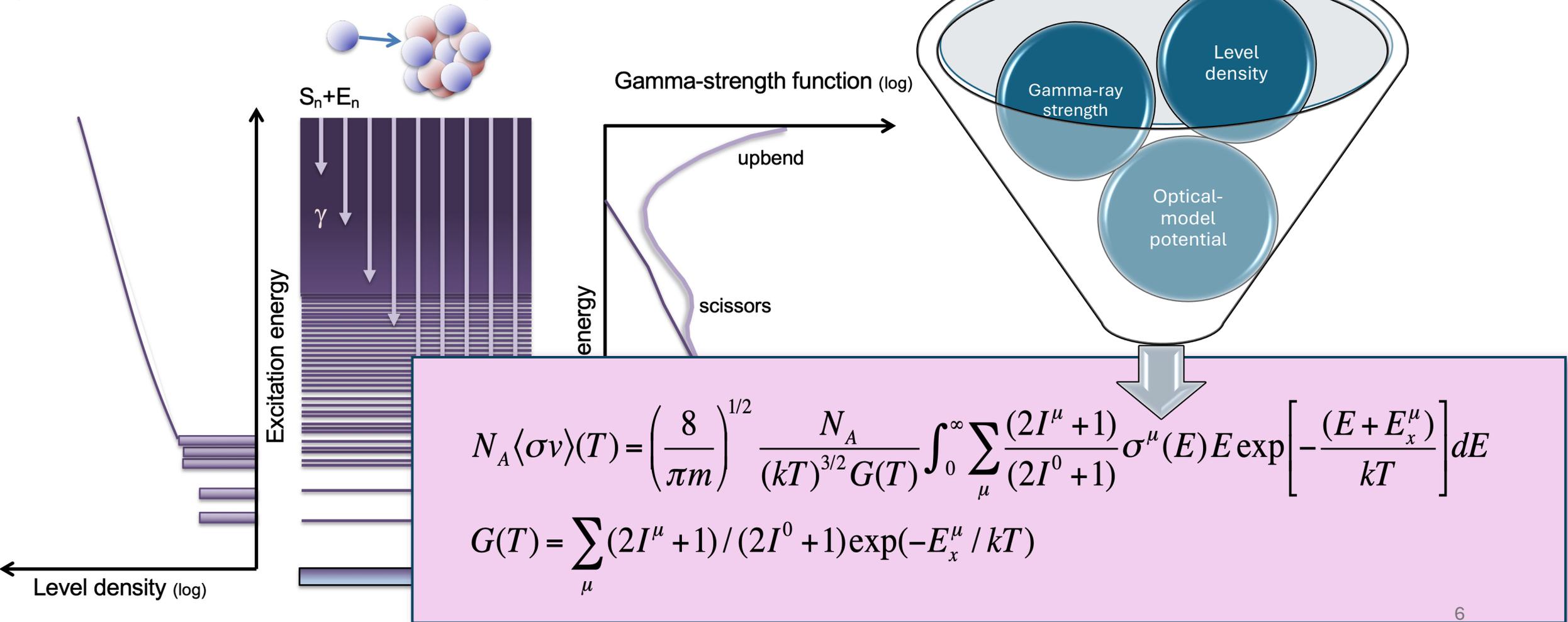


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PHILOSOPHICAL  
TRANSACTIONS A

royalsocietypublishing.org/journal/rsta



Research



**Cite this article:** Wiedeking M, Goriely S. 2024

Photon strength functions and nuclear level densities: invaluable input for nucleosynthesis.

*Phil. Trans. R. Soc. A* **382**: 20230125.

<https://doi.org/10.1098/rsta.2023.0125>

## Photon strength functions and nuclear level densities: invaluable input for nucleosynthesis

M. Wiedeking<sup>1,2,3</sup> and S. Goriely<sup>4</sup>

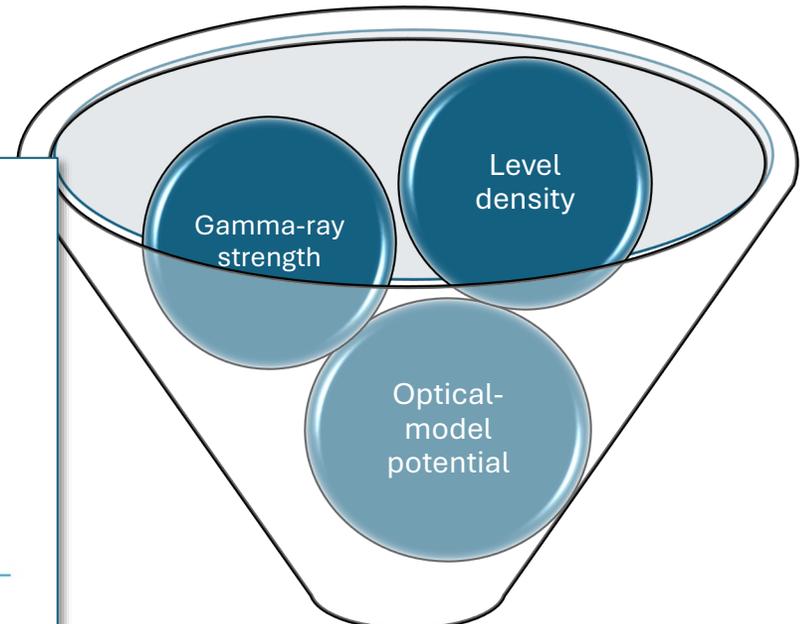
<sup>1</sup>SSC Laboratory, iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa

<sup>2</sup>School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa

<sup>3</sup>Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

<sup>4</sup>Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine CP 226, Brussels 1050, Belgium

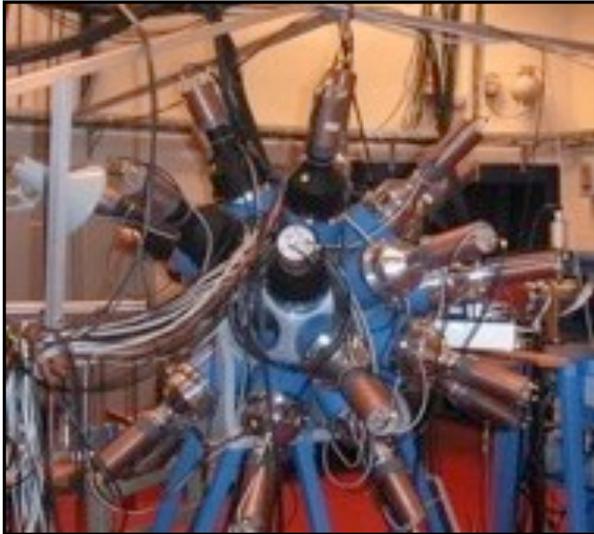
MW, 0000-0003-4983-3882



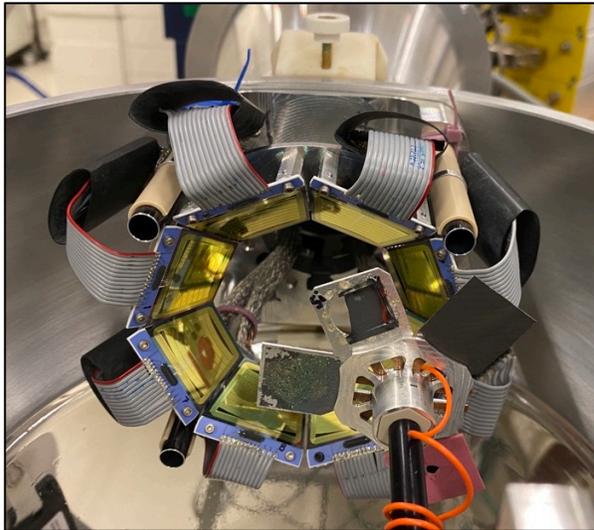
$$\sum_{\mu}^{\infty} \frac{(2I^{\mu} + 1)}{(2I^0 + 1)} \sigma^{\mu}(E) E \exp\left[-\frac{(E + E_x^{\mu})}{kT}\right] dE$$

$\sigma_x^{\mu} / kT$

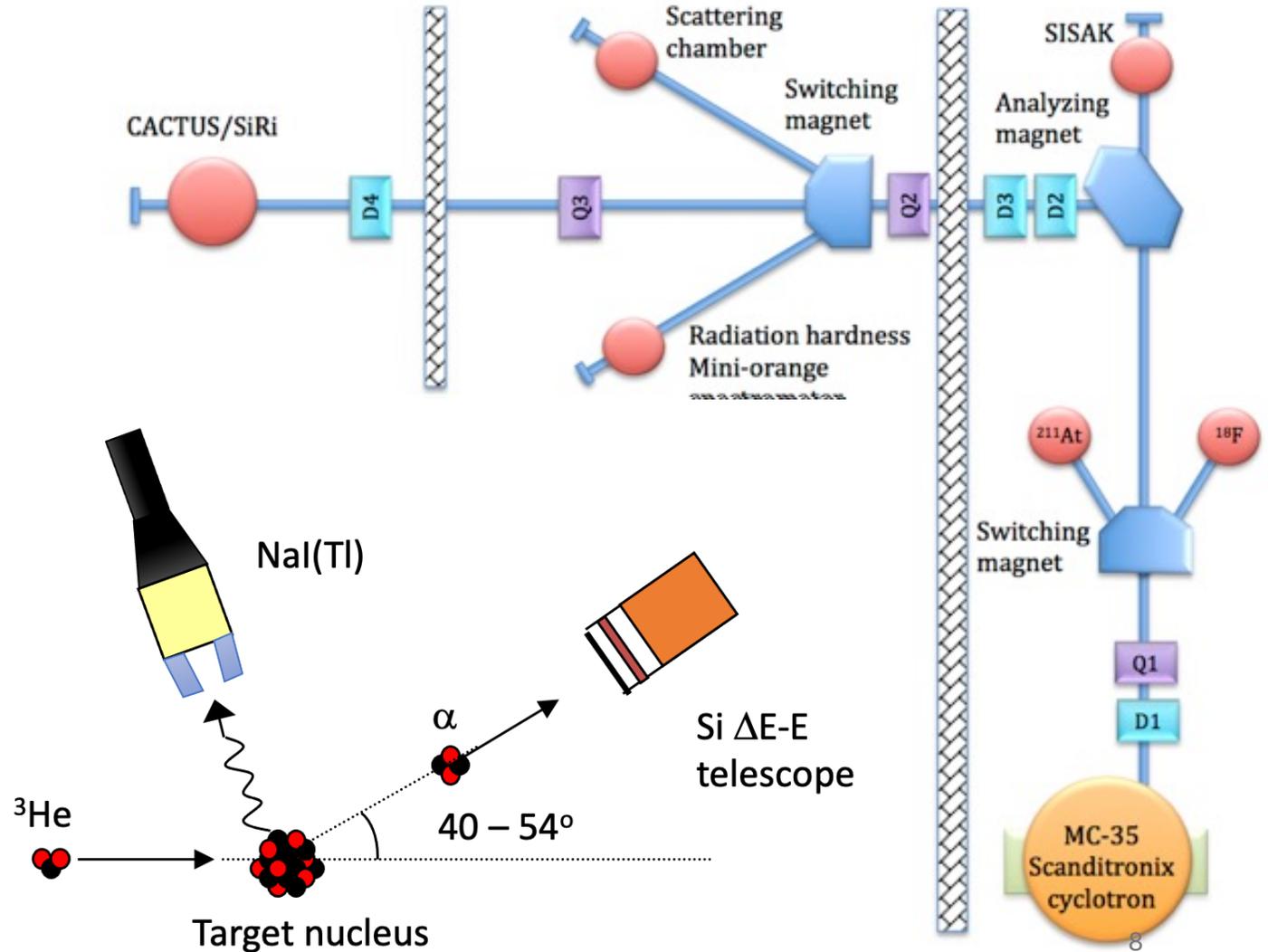
# Experiments at the Oslo Cyclotron Lab



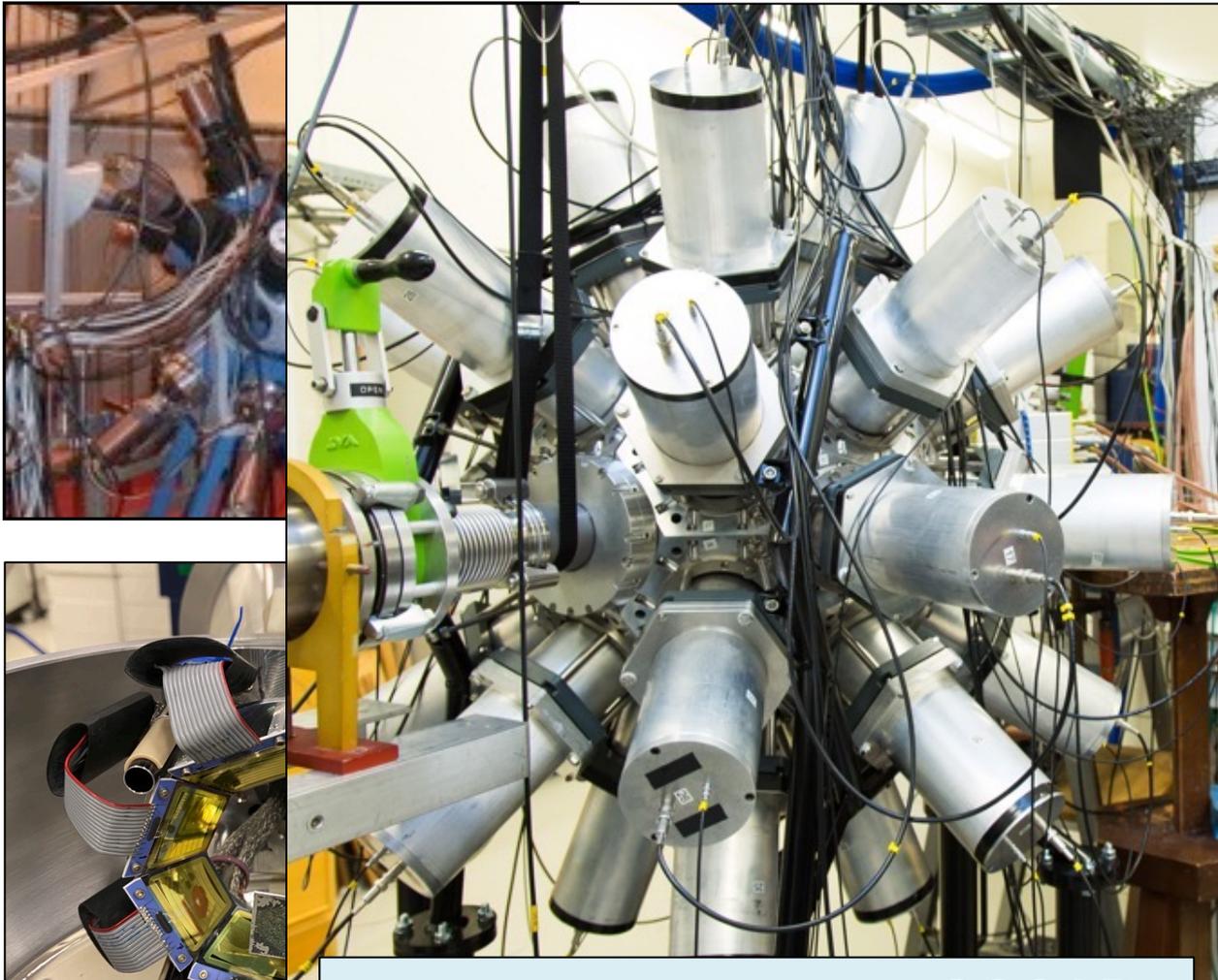
**CACTUS:**  
 26 (28)  
 collimated  
 NaI(Tl)  
 crystals,  
 5'' x 5''  
 [Guttormsen et al.,  
 Phys. Scr. T32, 54  
 (1990)]



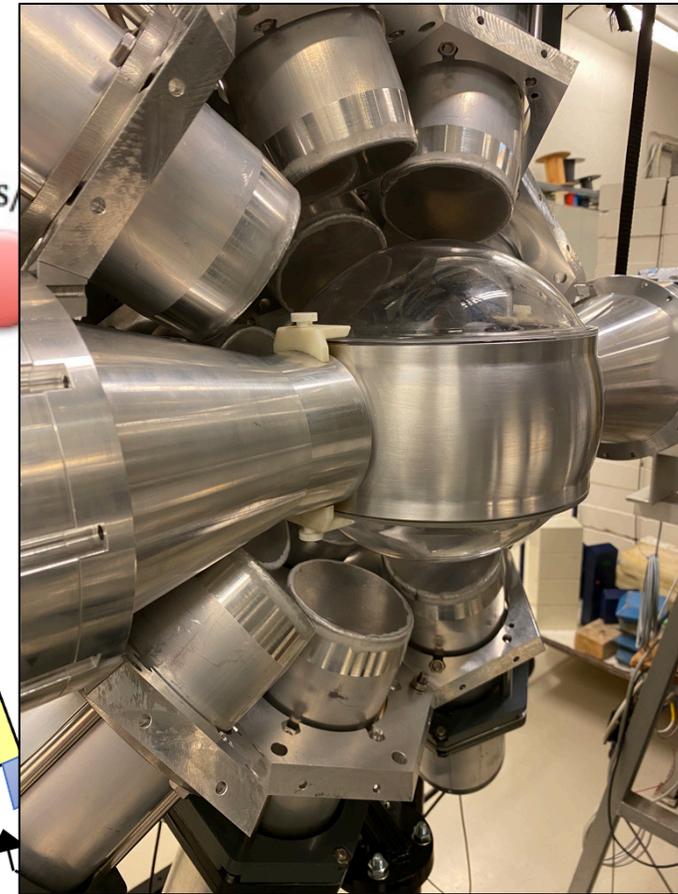
**SiRi:**  
 8x8 Si  
 $\Delta E$ - $E$  particle  
 detectors  
 (segmented  
 $\Delta E, \approx 2^\circ$ )  
 ( $\approx 9\%$  of  $4\pi$ )  
 [Guttormsen et al.,  
 NIM A 648, 168  
 (2011)]



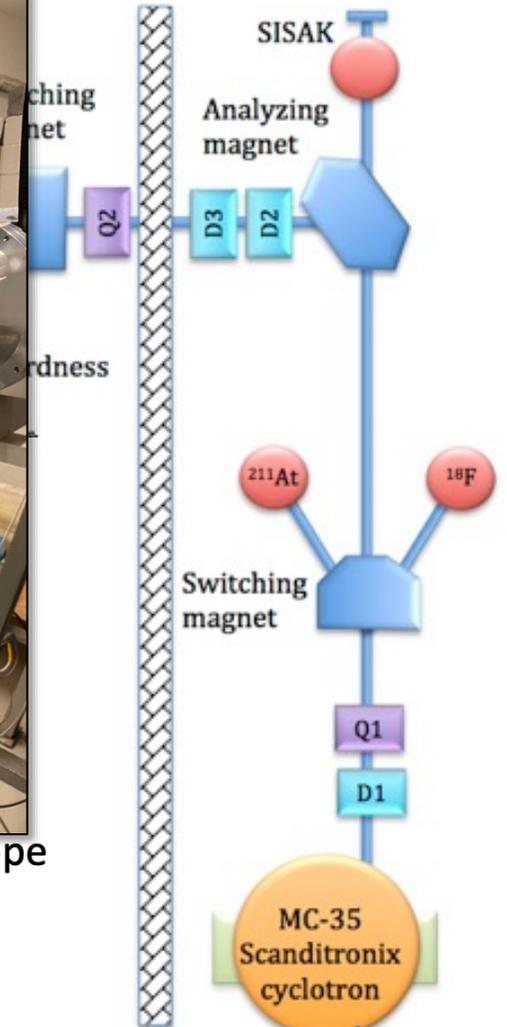
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New  $\gamma$ -ray detector system **OSCAR**  
30 LaBr<sub>3</sub>(Ce), 3.5'' x 8'' crystals  
[Zeiser et al., NIM A 985, 164678 (2021)]

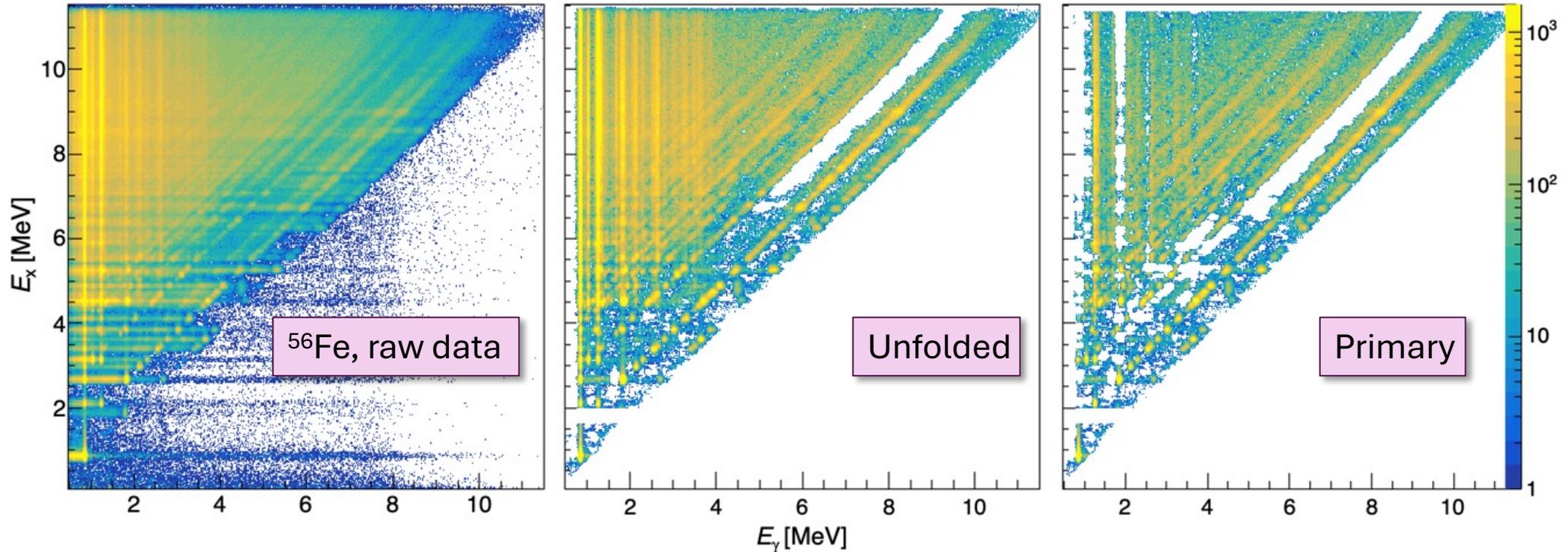


telescope  
40 – 54°  
Target nucleus



# The Oslo method in a

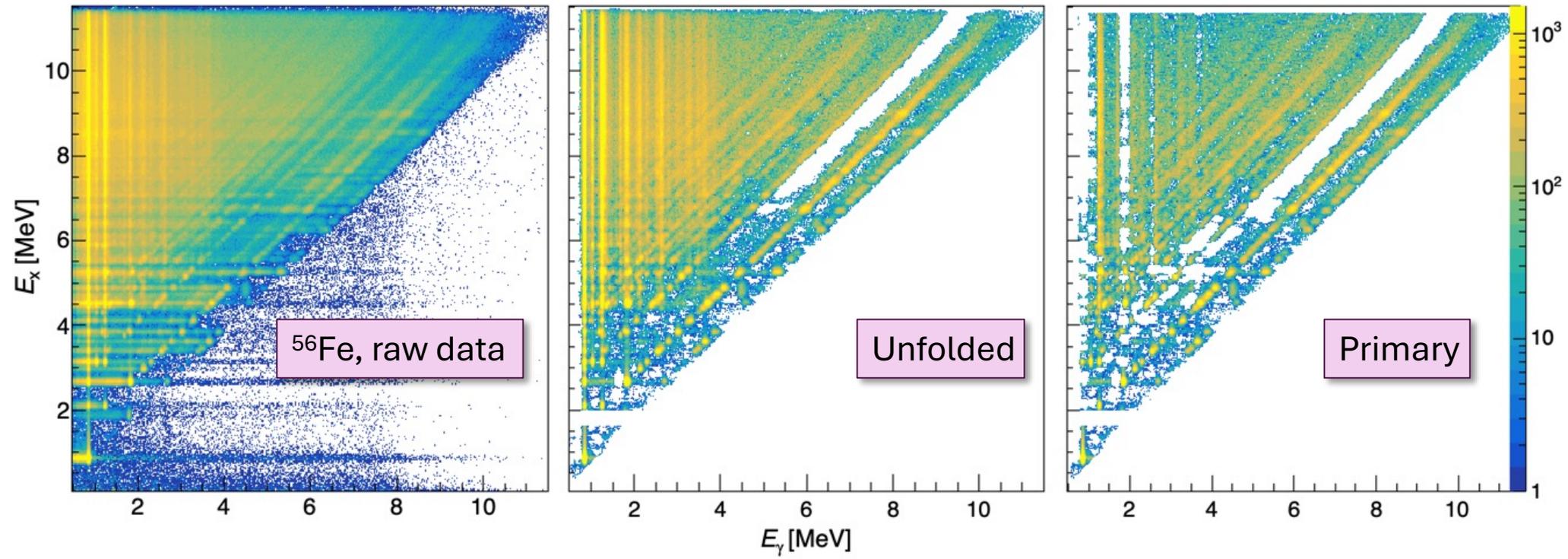
[Data from Larsen et al., PRL **111**, 242504 (2013)  
and J.Phys.G: Nucl. Part. Phys. 44, 064005 (2017)]



- [0. Get yourself an  $(E_\gamma, E_x)$  matrix (>20 000-ish coincidences)]
1. Correct for the  $\gamma$ -detector response – unfolding [Guttormsen et al., NIM A 374, 371 (1996)]
2. Extract *distribution of primary*  $\gamma$ s for each  $E_x$  [Guttormsen et al., NIM A 255, 518 (1987)]
3. Obtain level density and  $\gamma$ -strength from primary  $\gamma$  rays [Schiller et al., NIM A 447, 498 (2000)]
4. Normalize & evaluate systematic errors [Schiller et al., NIM A 447, 498 (2000), Larsen et al., PRC **83**, 034315 (2011)]

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[Data from Larsen et al., PRL **111**, 242504 (2013) and J.Phys.G: Nucl. Part. Phys. 44, 064005 (2017)]



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Data and references (if you see missing stuff, let us know!!):  
<https://ocl.uio.no/compilation/>  
 Analysis codes and tools:  
<https://github.com/oslocyclotronlab/oslo-method-software>  
 Python version OMpy (work in progress https://github.com/oslocyclotronlab/ompy

# The beta-Oslo method in a

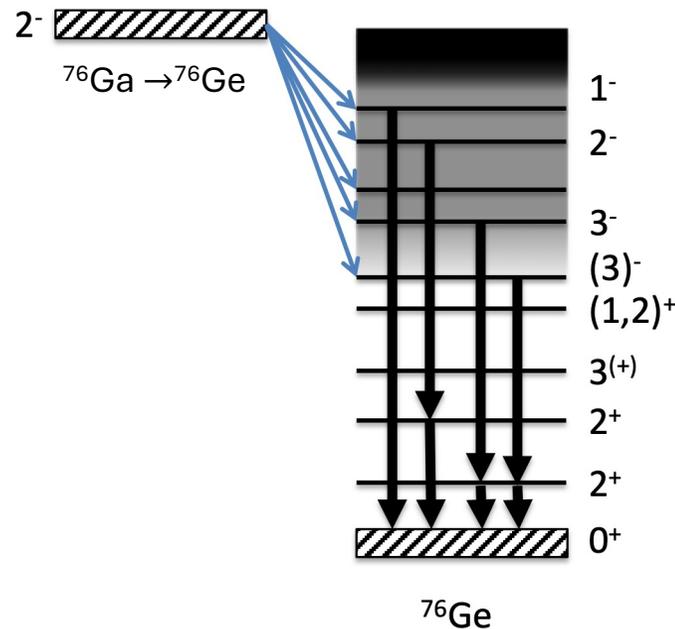
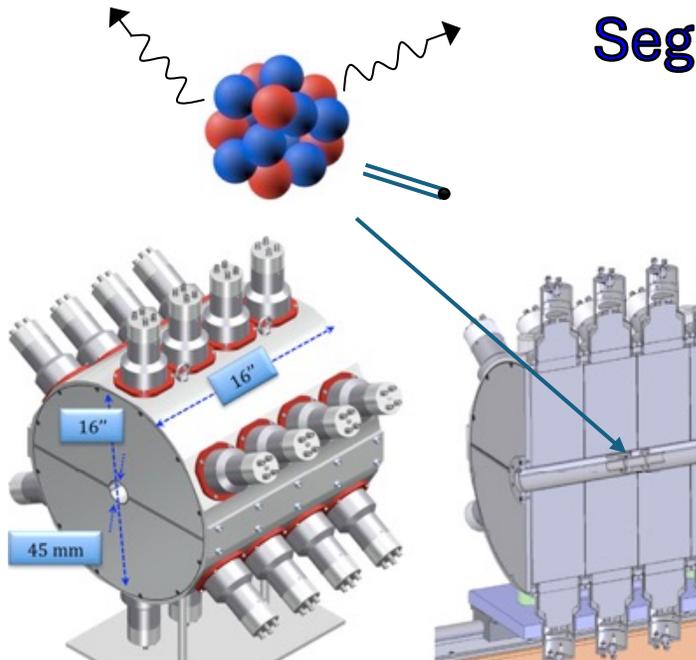


Special thanks to  
**Artemis Spyrou,**  
**Sean Liddick,**  
**Magne Guttormsen**

## Recipe:

- 1) Implant a neutron-rich nucleus inside a high-efficiency, *segmented* total-absorption spectrometer (preferably with  $Q_\beta \approx S_n$ )
- 2) Measure  $\beta^-$  in coincidence with *all*  $\gamma$  rays from the child nucleus
- 3) Apply the Oslo method to the  $(E_x, E_\gamma)$  matrix to get level density &  $\gamma$ - strength

**Segments give individual  $\gamma$  rays, the sum of all gives  $E_x$**



Segmented, total absorption spectrom  
[A. Simon, S.J. Quinn, A. Spyrou et al., NIM A 70

# The beta-Oslo method in a

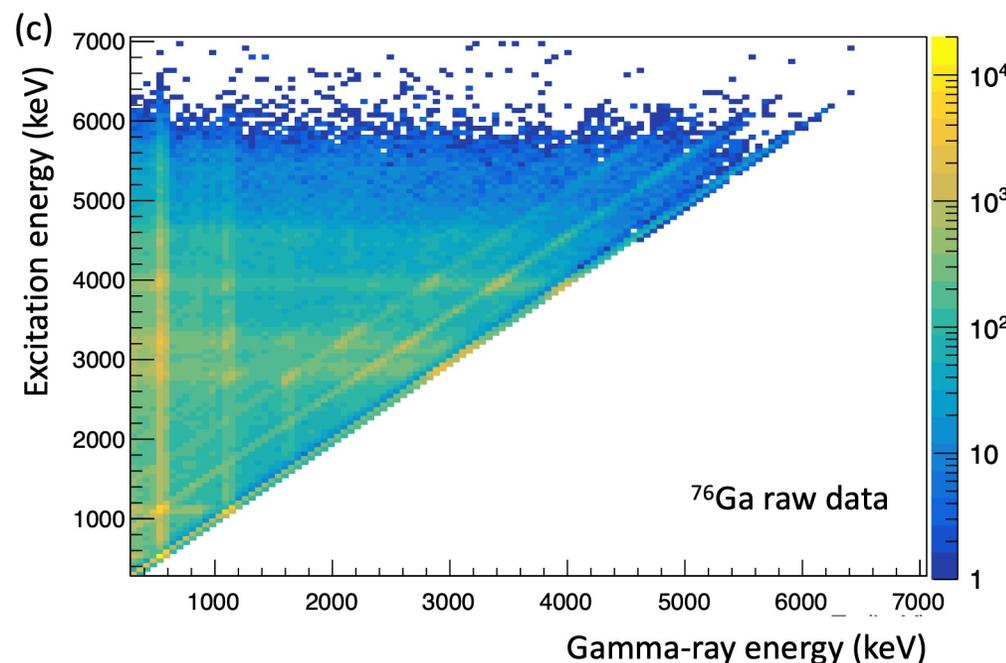
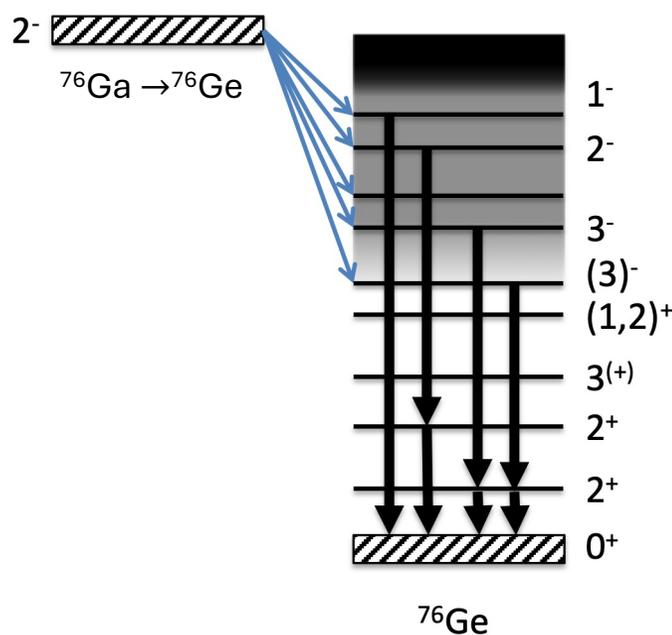
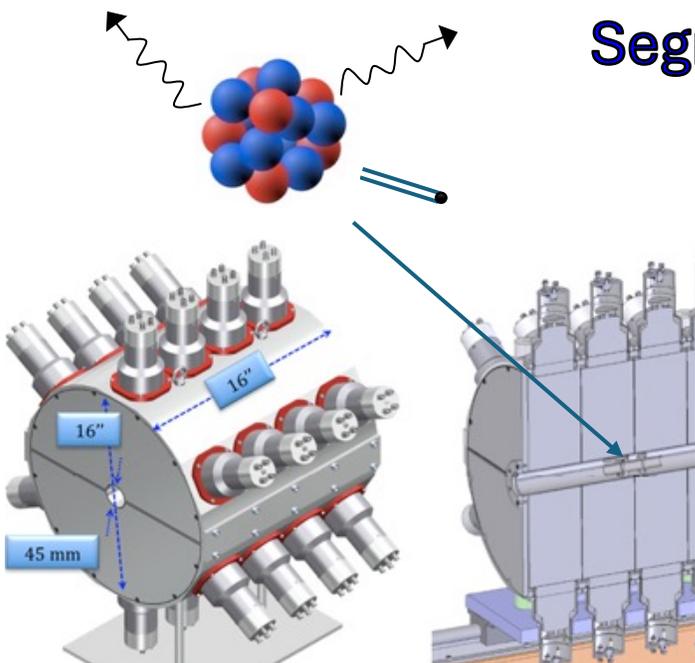


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Segmented, total absorption spectrom  
[A. Simon, S.J. Quinn, A. Spyrou et al., NIM A 70

# The beta-Oslo method in a



PRL 113, 232502 (2014)

PHYSICAL REVIEW LETTERS

week ending  
5 DECEMBER 2014

## Novel technique for Constraining $r$ -Process ( $n, \gamma$ ) Reaction Rates

A. Spyrou,<sup>1,2,3,\*</sup> S. N. Liddick,<sup>1,4,†</sup> A. C. Larsen,<sup>5,‡</sup> M. Guttormsen,<sup>5</sup> K. Cooper,<sup>1,4</sup> A. C. Dombos,<sup>1,2,3</sup>  
D. J. Morrissey,<sup>1,4</sup> F. Naqvi,<sup>1</sup> G. Perdikakis,<sup>6,1,3</sup> S. J. Quinn,<sup>1,7,3</sup> T. Renstrøm,<sup>5</sup> J. A. Rodriguez,<sup>1</sup>  
A. Simon,<sup>1,8</sup> C. S. Sumithrarachchi,<sup>1</sup> and R. G. T. Zegers<sup>1,7,3</sup>

<sup>1</sup>National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA

<sup>2</sup>Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

<sup>3</sup>Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA

<sup>4</sup>Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA

<sup>5</sup>Department of Physics, University of Oslo, NO-0316 Oslo, Norway

<sup>6</sup>Central Michigan University, Mount Pleasant, Michigan, 48859, USA

<sup>7</sup>Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA

<sup>8</sup>Department of Physics and The Joint Institute for Nuclear Astrophysics, University of Notre Dame, Notre Dame, Indiana 46556, USA

(Received 25 August 2014; published 2 December 2014)

A novel technique has been developed, which will open exciting new opportunities for studying the very neutron-rich nuclei involved in the  $r$  process. As a proof of principle, the  $\gamma$  spectra from the  $\beta$  decay of  $^{76}\text{Ge}$  have been measured with the SuN detector at the National Superconducting Cyclotron Laboratory. The nuclear level density and  $\gamma$ -ray strength function are extracted and used as input to Hauser-Feshbach calculations. The present technique is shown to strongly constrain the  $^{75}\text{Ge}(n, \gamma)^{76}\text{Ge}$  cross section and reaction rate.

DOI: 10.1103/PhysRevLett.113.232502

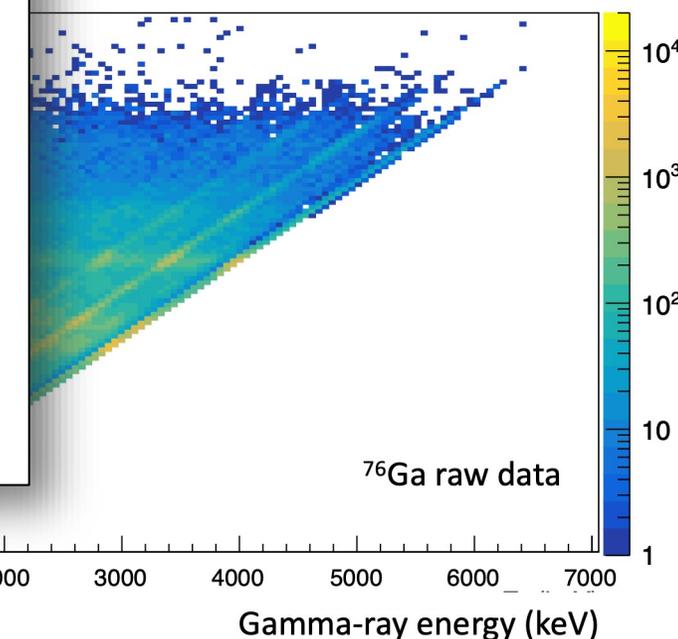
PACS numbers: 26.30.Hj, 21.10.Ma, 27.50.+e

efficiency, segmented total-

the child nucleus

et level density &  $\gamma$ - strength

all gives  $E_x$



$^{76}\text{Ge}$

0+

1000

1000 2000 3000 4000 5000 6000 7000

Gamma-ray energy (keV)

Segmented, total absorption spectrometry  
[A. Simon, S.J. Quinn, A. Spyrou et al., NIM A 70

# Step 1: Unfolding



ELSEVIER

Nuclear Instruments and Methods in Physics Research A 374 (1996) 371–376

[https://doi.org/10.1016/0168-9002\(96\)00197-0](https://doi.org/10.1016/0168-9002(96)00197-0)

**NUCLEAR  
INSTRUMENTS  
& METHODS  
IN PHYSICS  
RESEARCH**  
Section A

## The unfolding of continuum $\gamma$ -ray spectra

M. Guttormsen\*, T.S. Tveter, L. Bergholt, F. Ingebretsen, J. Rekstad

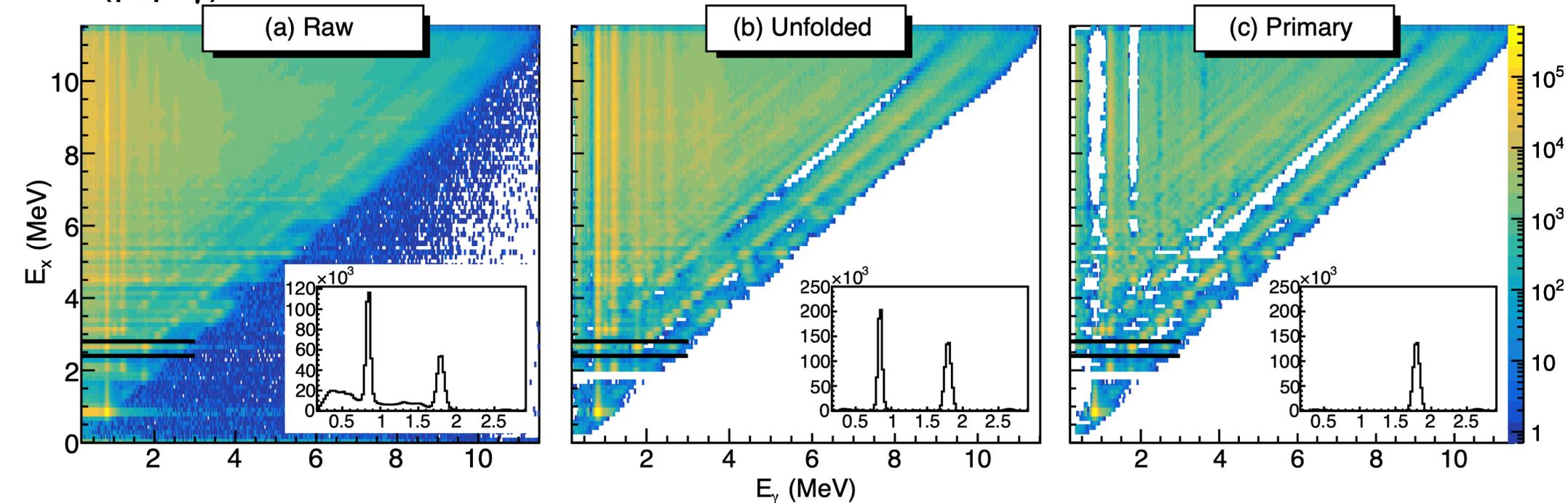
*Department of Physics, University of Oslo, Oslo, Norway*

Received 26 January 1996

### Abstract

A new method for unfolding  $\gamma$ -ray spectra is described. The method is based on the fact that the contribution of Compton scattered  $\gamma$ -rays in the spectra is a slowly varying function of energy. Thus, the Compton part can be smoothed and subtracted from the original observed spectrum giving an unfolded spectrum with the same statistical fluctuations as the observed spectrum. In particular, we show that the method works very well for poor statistics continuum  $\gamma$ -ray spectra.

$^{56}\text{Fe}(p,p'\gamma)$



# Step 1: Unfolding

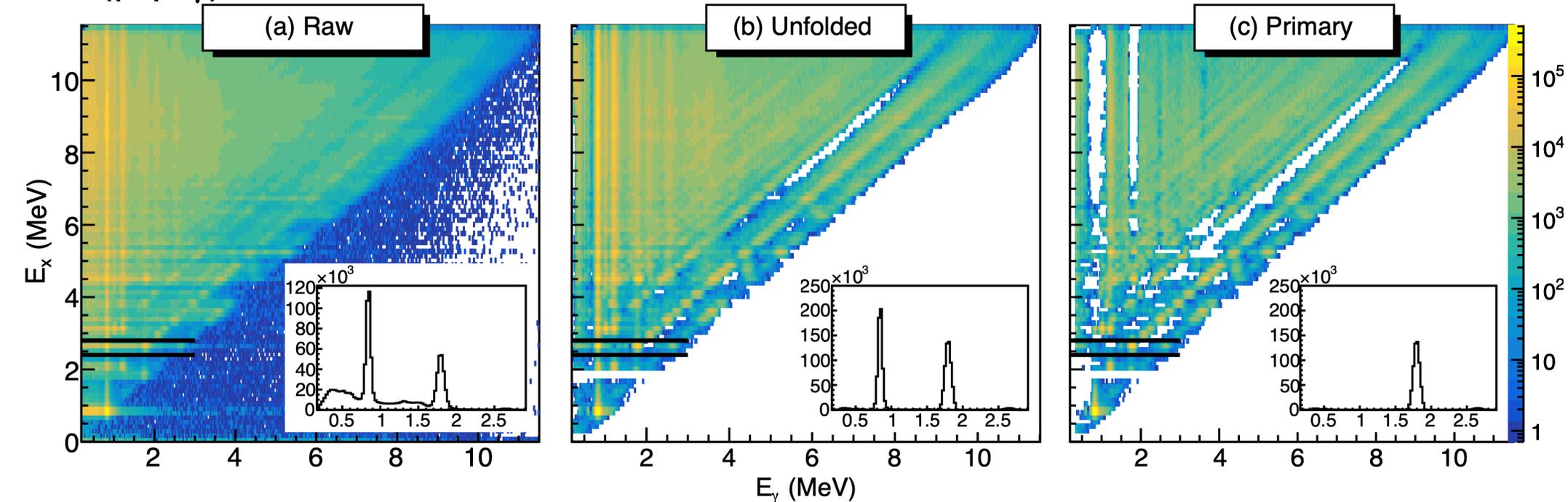
The unfolding of continuum  $\gamma$ -ray spectra

Bin-by-bin point-estimate  $\rightarrow$  Monte Carlo (MC), Midtbø et al. [Computer Physics Communications **262** (2021) 107795]

$\rightarrow$  **Improved uncertainty quantification:**

- 1) Regularized unfolding with MC [Lima et al., in review in PRC, arXiv:2511.16687]
- 2) Bayesian unfolding [Mjøs et al., to be submitted, 2026]

$^{56}\text{Fe}(p,p'\gamma)$



# Step 1: Unfolding

## The unfolding of continuum $\gamma$ -ray spectra

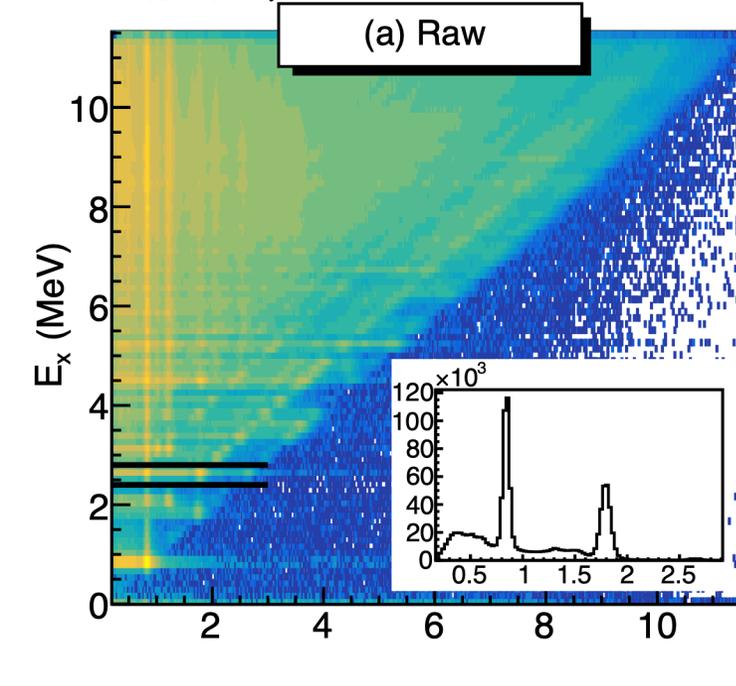
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$^{56}\text{Fe}(p,p'\gamma)$



## Regularized Unfolding of gamma-ray Spectra for Nuclear Physics Applications

E. Lima,<sup>1,2</sup> L. L. Braseth,<sup>1</sup> A. H. Mjøs,<sup>1,2</sup> M. Hjorth-Jensen,<sup>1,3</sup> A. Kvellestad,<sup>1</sup> and A. C. Larsen<sup>1,2</sup>

<sup>1</sup>Department of Physics, University of Oslo, N-0316 Oslo, Norway

<sup>2</sup>Norwegian Nuclear Research Center, Norway\*

<sup>3</sup>Center for Computing in Science Education, University of Oslo, N-0316 Oslo, Norway

(Dated: November 3, 2025)

Reconstructing gamma-ray spectra from detector measurements is an ill-posed inverse problem. Standard methods, such as Folding Iteration with Compton Subtraction (FICS), provide point estimates but lack calibrated uncertainties and may bias the spectrum. We introduce an unfolding framework based on regularized maximum-likelihood estimation (RMLE) that enforces non-negativity and detector-response constraints while explicitly modeling background and contaminant contributions. Simulations and analytical results show that RMLE yields smoother reconstructions with well-calibrated confidence intervals and outperforms existing techniques for low-complexity spectra. Although high-complexity data remain challenging, the intervals produced by RMLE maintain correct coverage.

# Step 1: Unfolding

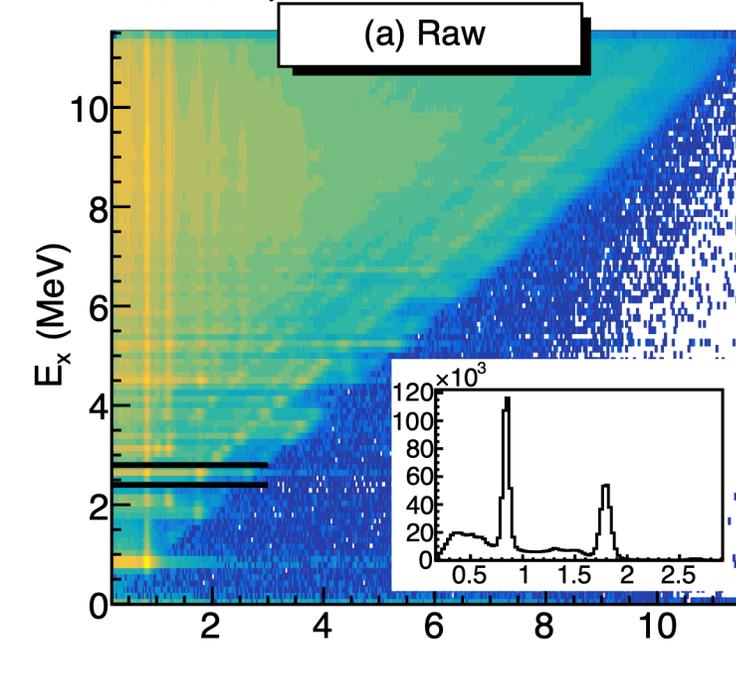
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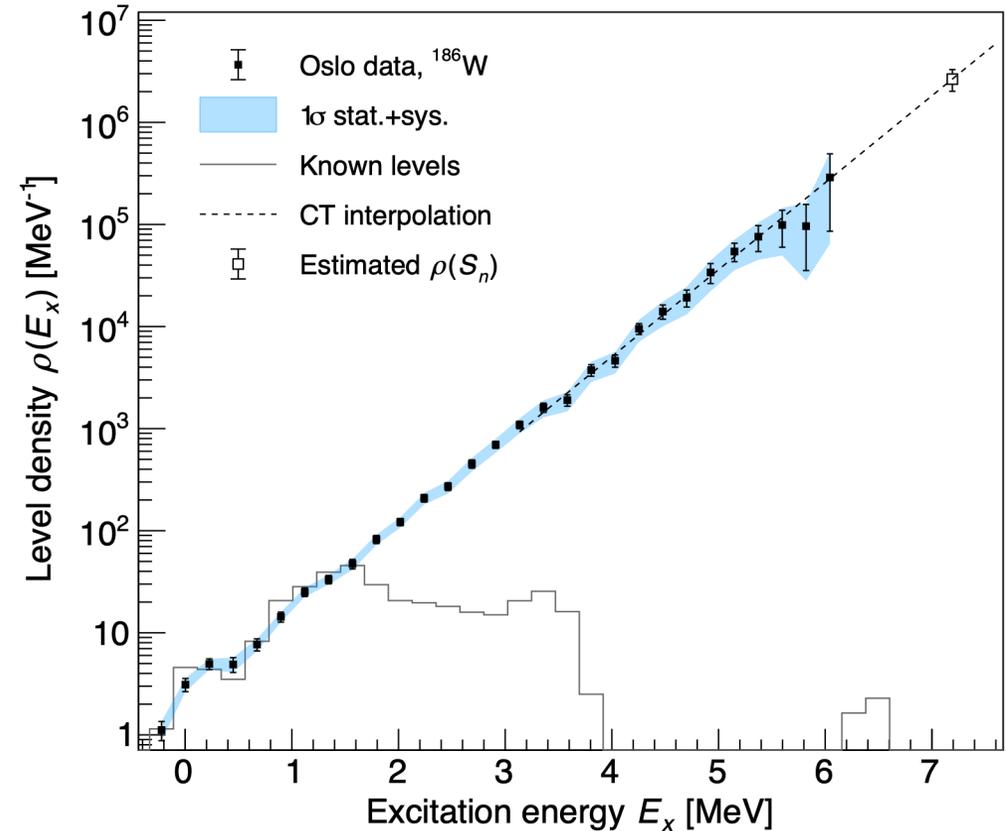
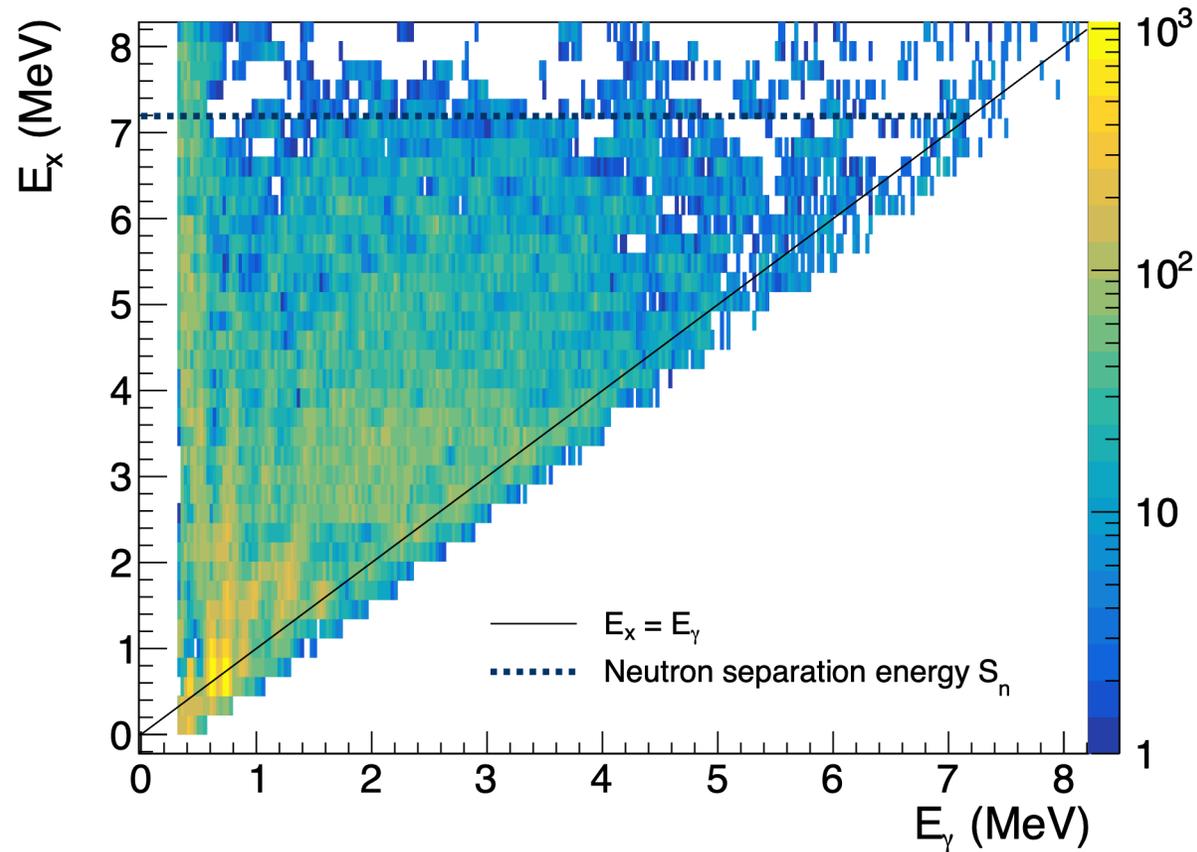
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# Using the data to calculate $(n,\gamma)$ reaction rates

s-process branch point  $^{185}\text{W}$

Primary  $\gamma$  rays



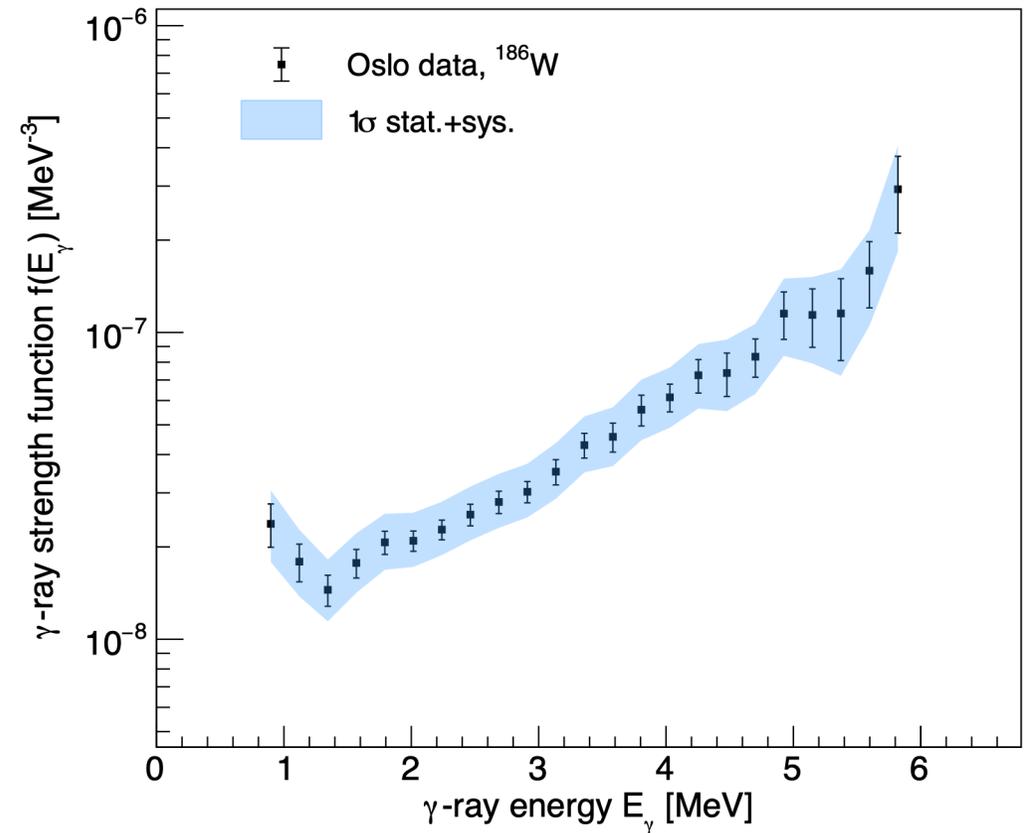
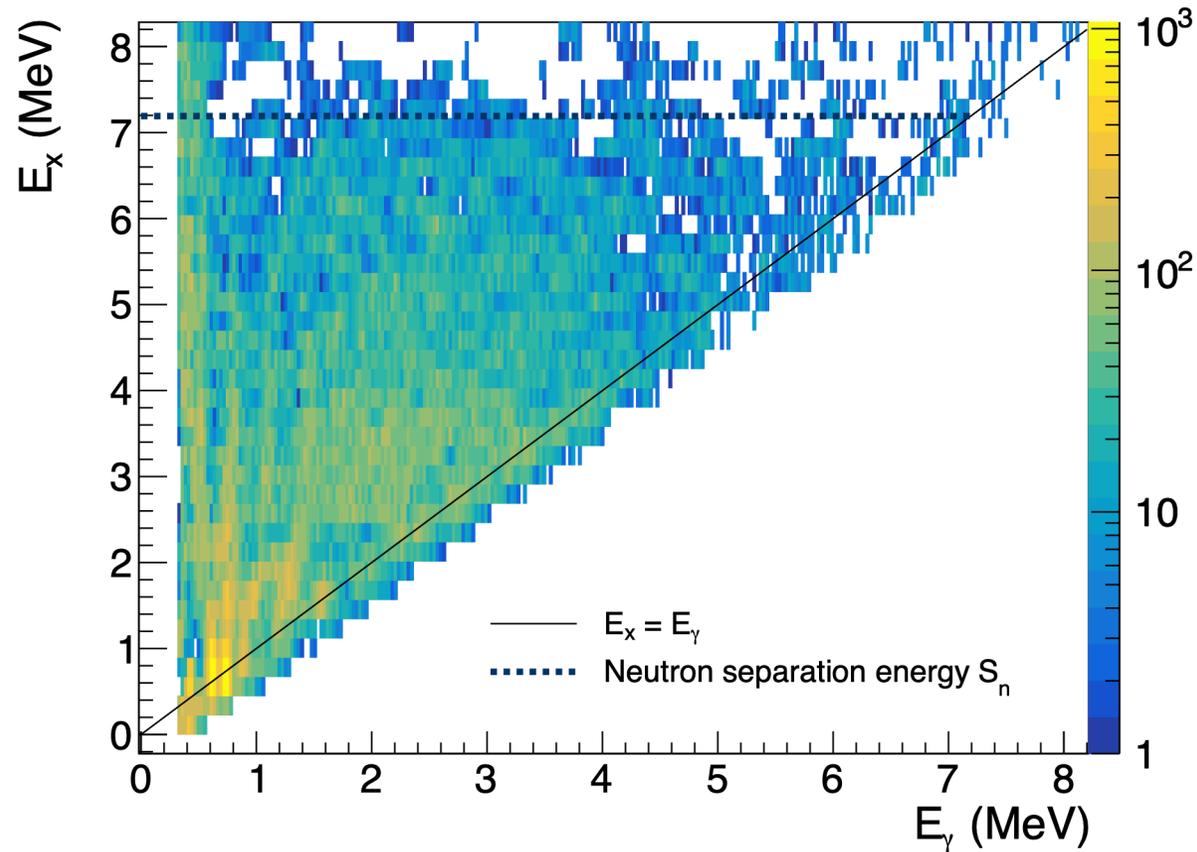
$^{186}\text{W}(\alpha, \alpha'\gamma)^{186}\text{W}$

[Larsen et al., PRC **108**, 025804 (2023)]

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s-process branch point  $^{185}\text{W}$

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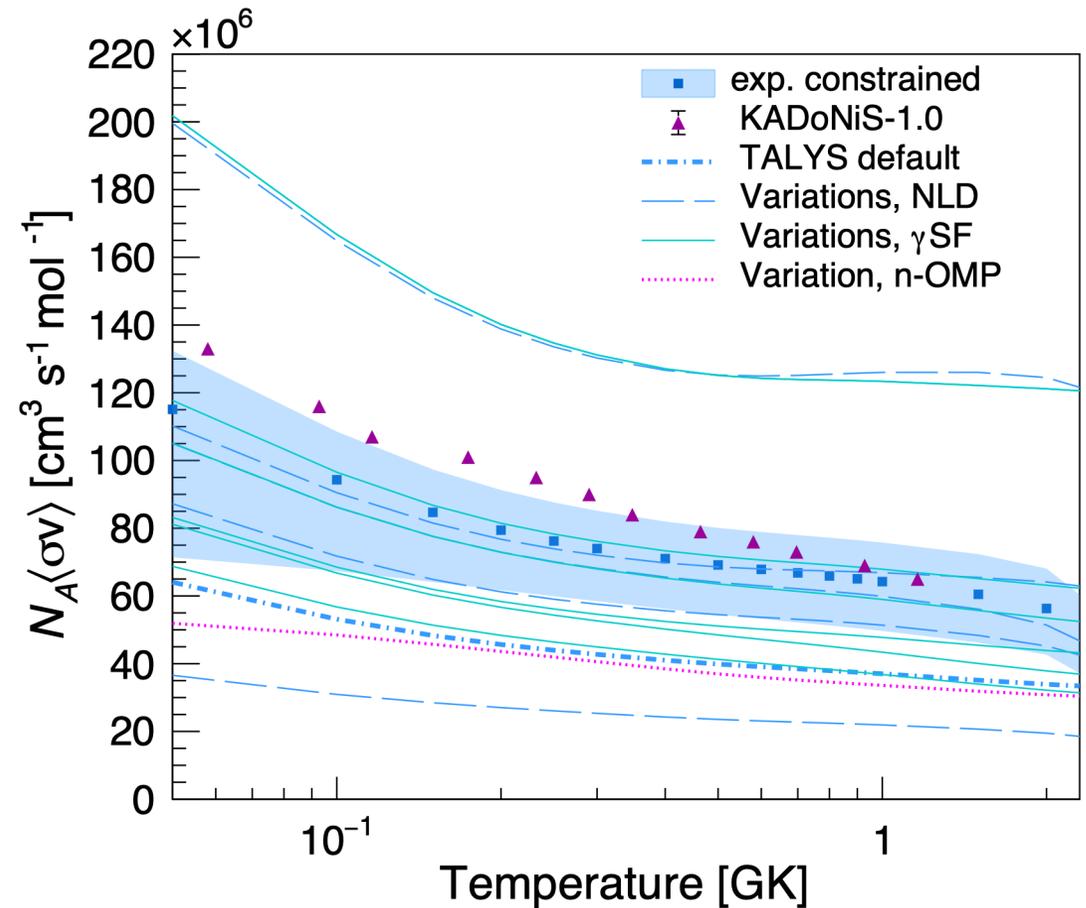
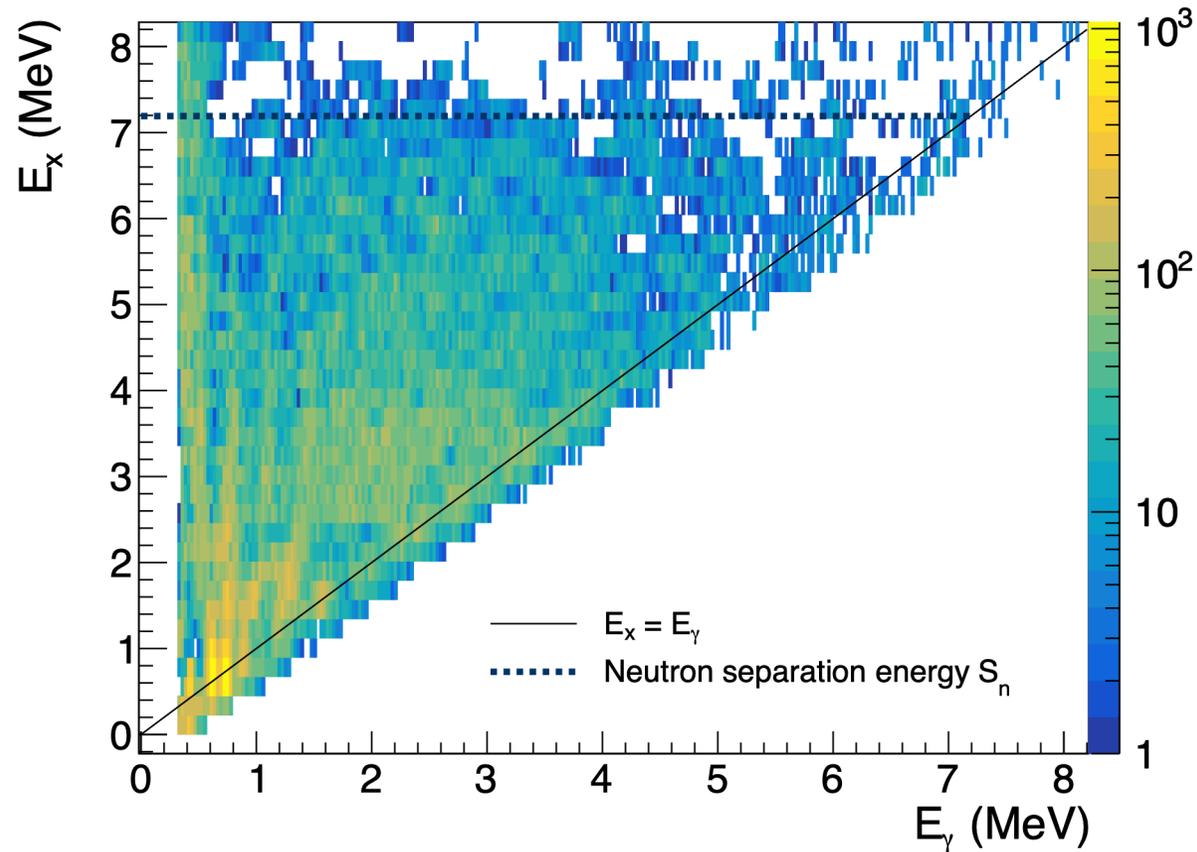
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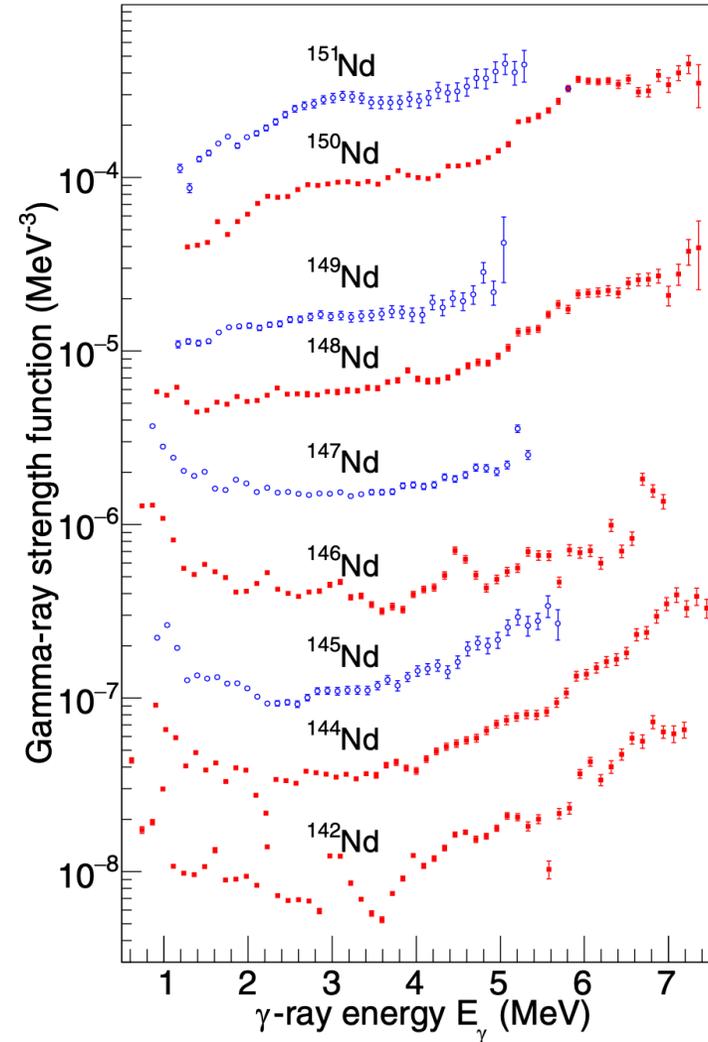
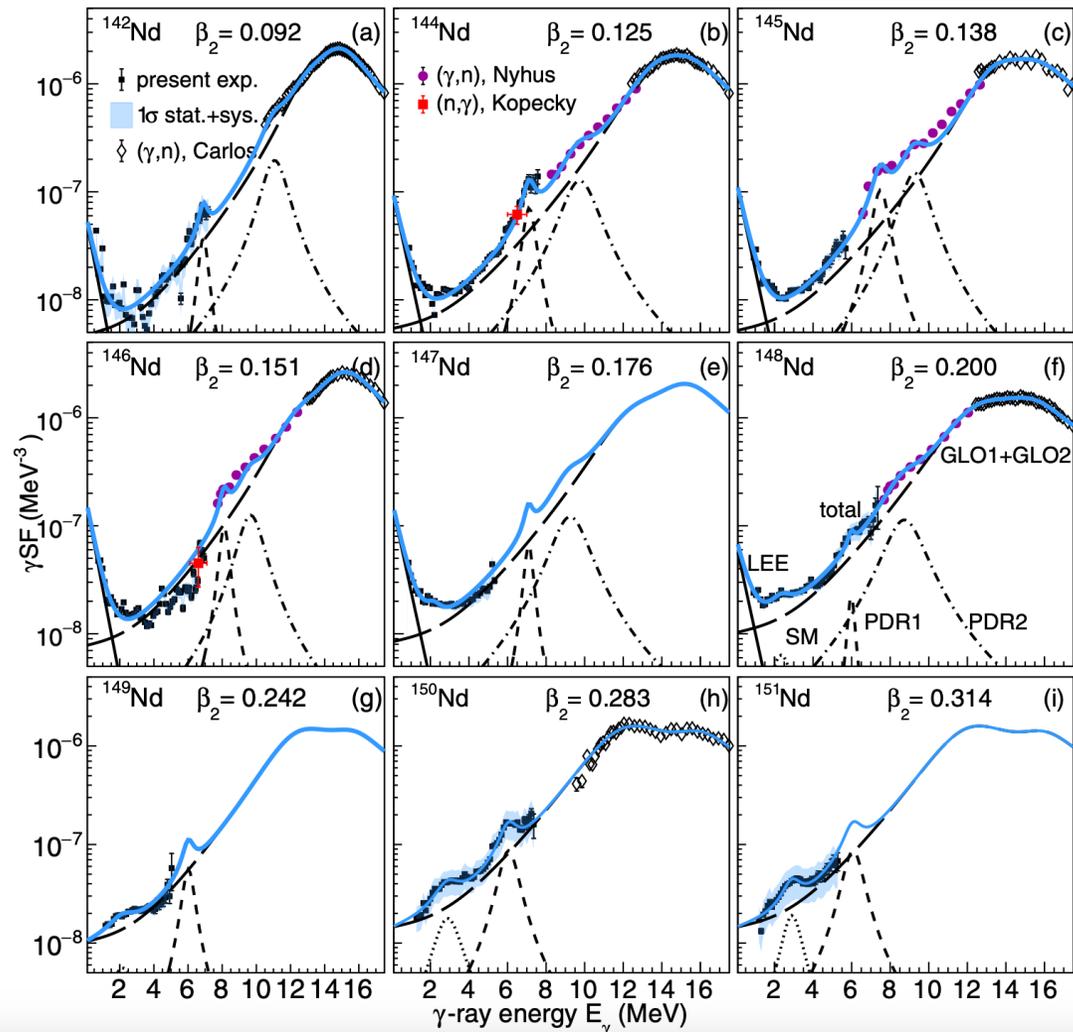
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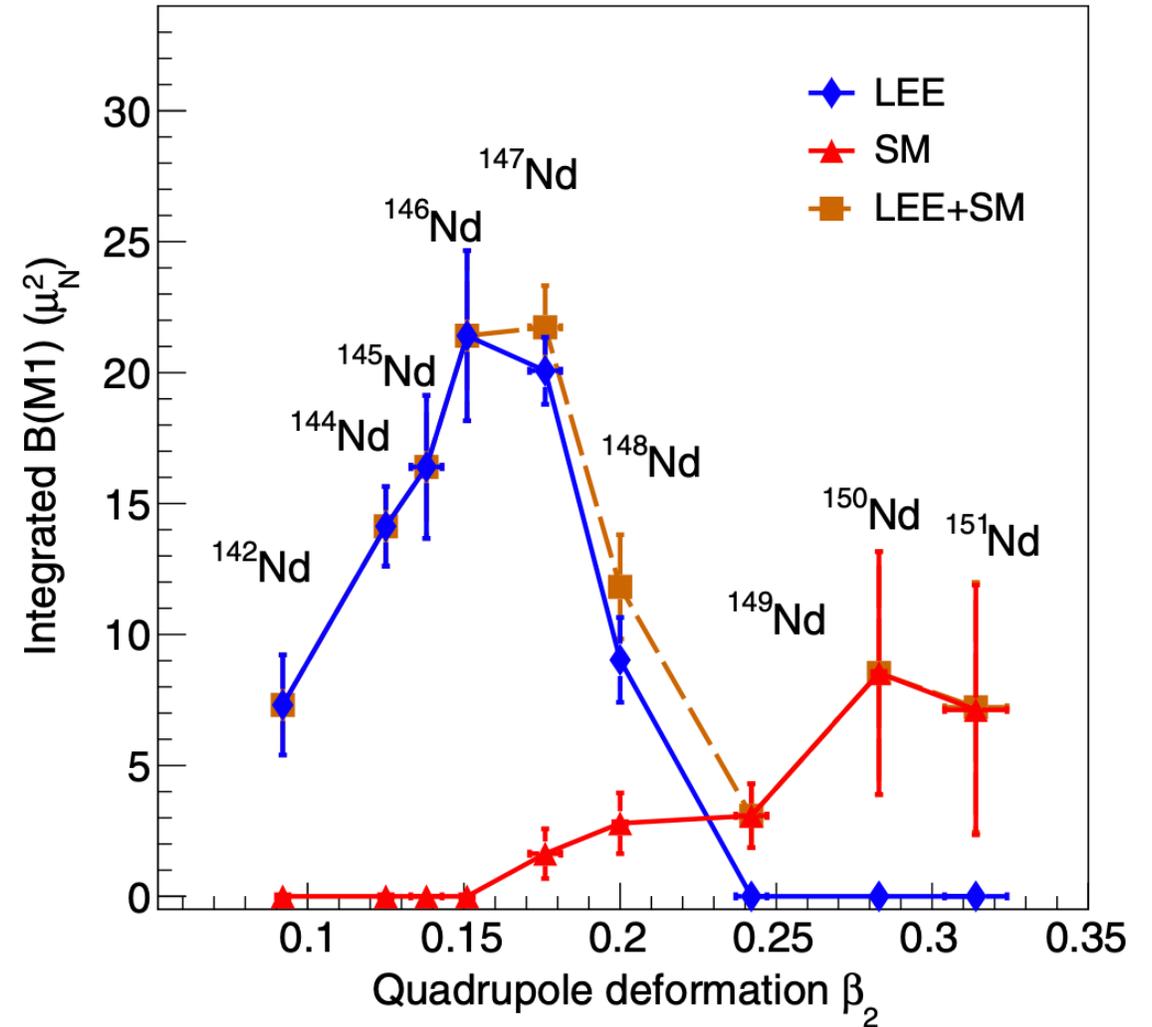
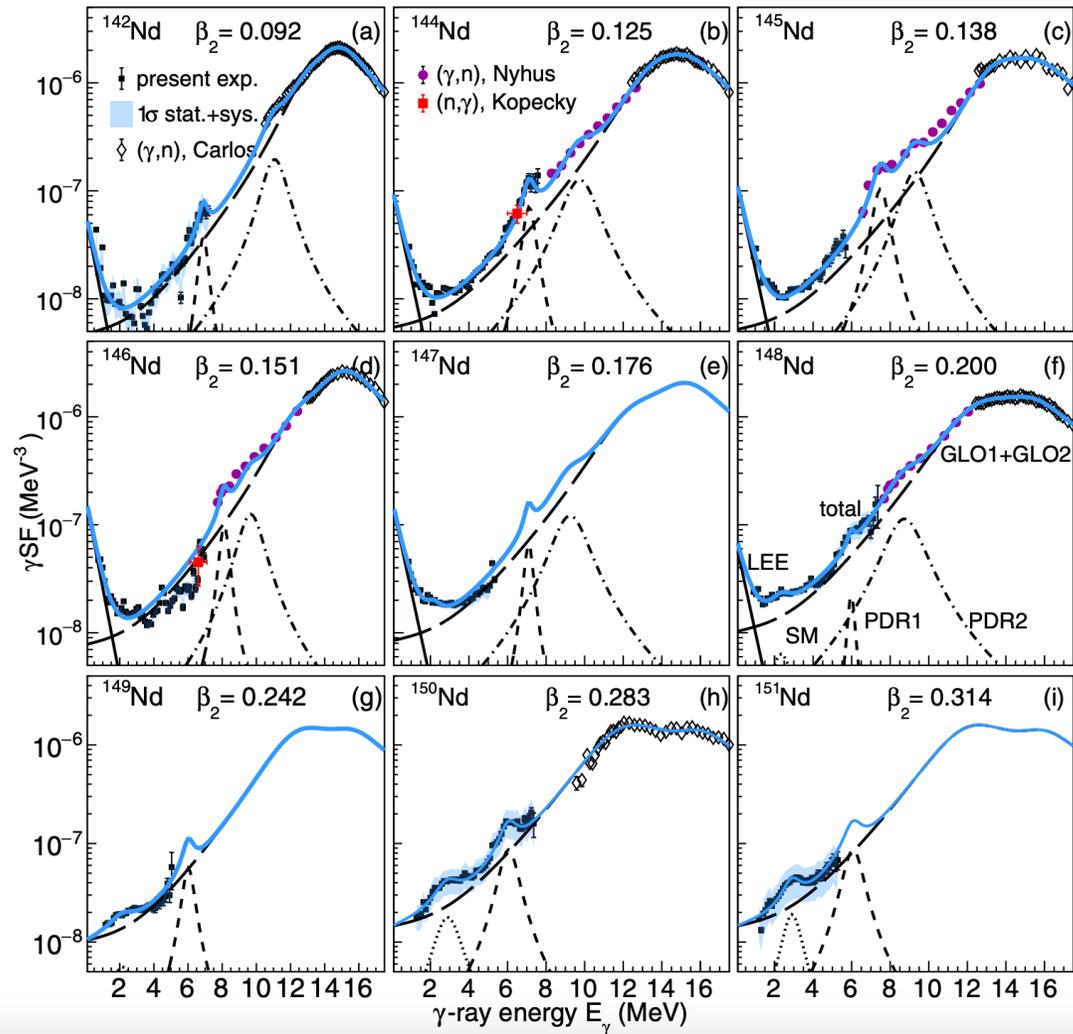
$^{186}\text{W}(\alpha, \alpha'\gamma)^{186}\text{W}$

[Larsen et al., PRC **108**, 025804 (2023)]

# Nd isotopic chain: low-energy enhancement vs. scissors mode



# Nd isotopic chain: low-energy enhancement vs. scissors mode



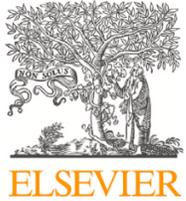
# The Sn isotopic chain: PDR

Phys. Lett. B 860 (2025) 139216

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Physics Letters B

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Letter

## Systematics of the low-energy electric dipole strength in the Sn isotopic chain



M. Markova<sup>a, , \*</sup>, P. von Neumann-Cosel<sup>b, , \*</sup>, E. Litvinova<sup>c,d,e, , \*</sup>

<sup>a</sup> Department of Physics, University of Oslo, N-0316 Oslo, Norway

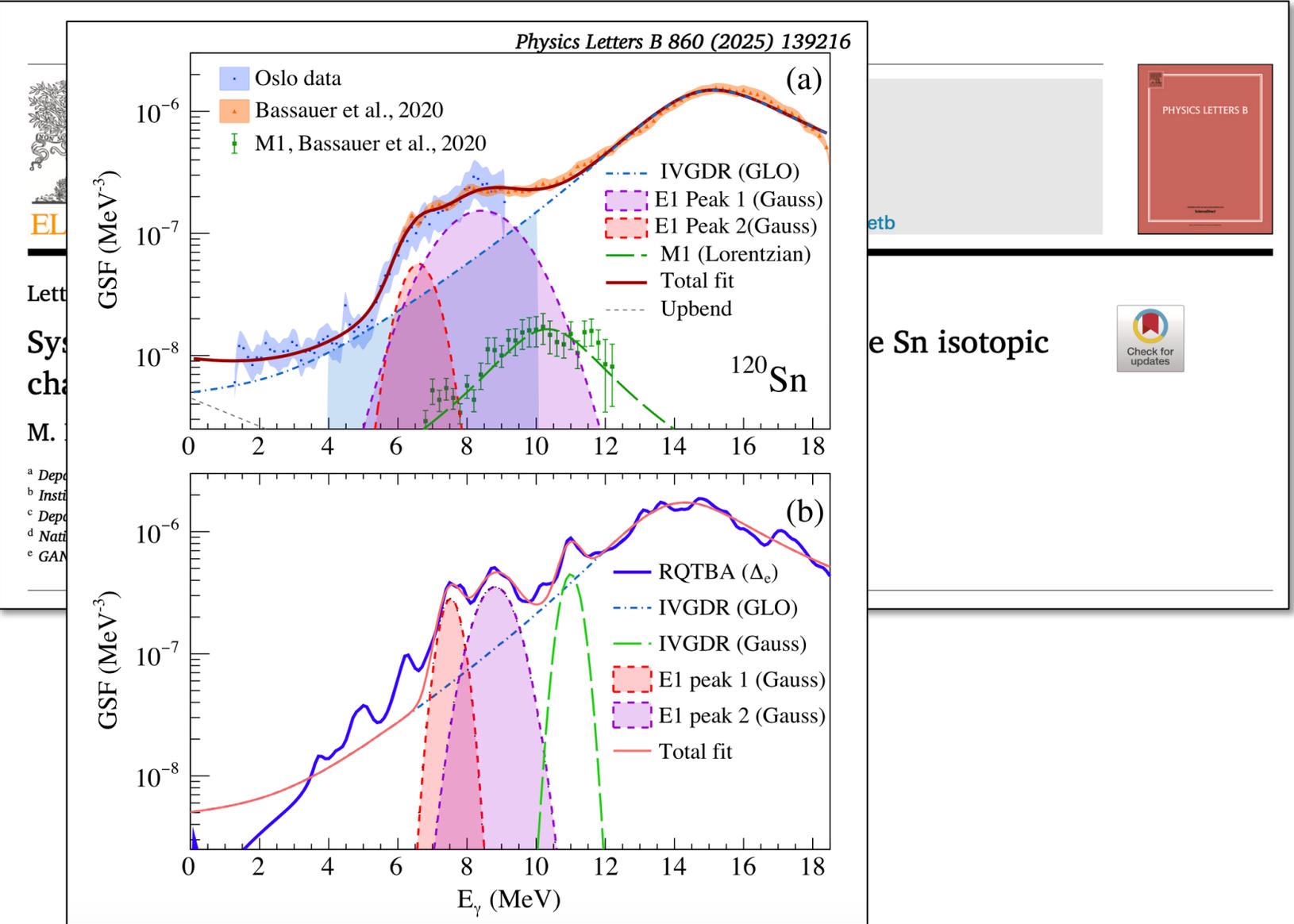
<sup>b</sup> Institut für Kernphysik, Technische Universität Darmstadt, D-64289 Darmstadt, Germany

<sup>c</sup> Department of Physics, Western Michigan University, Kalamazoo, MI 49008, USA

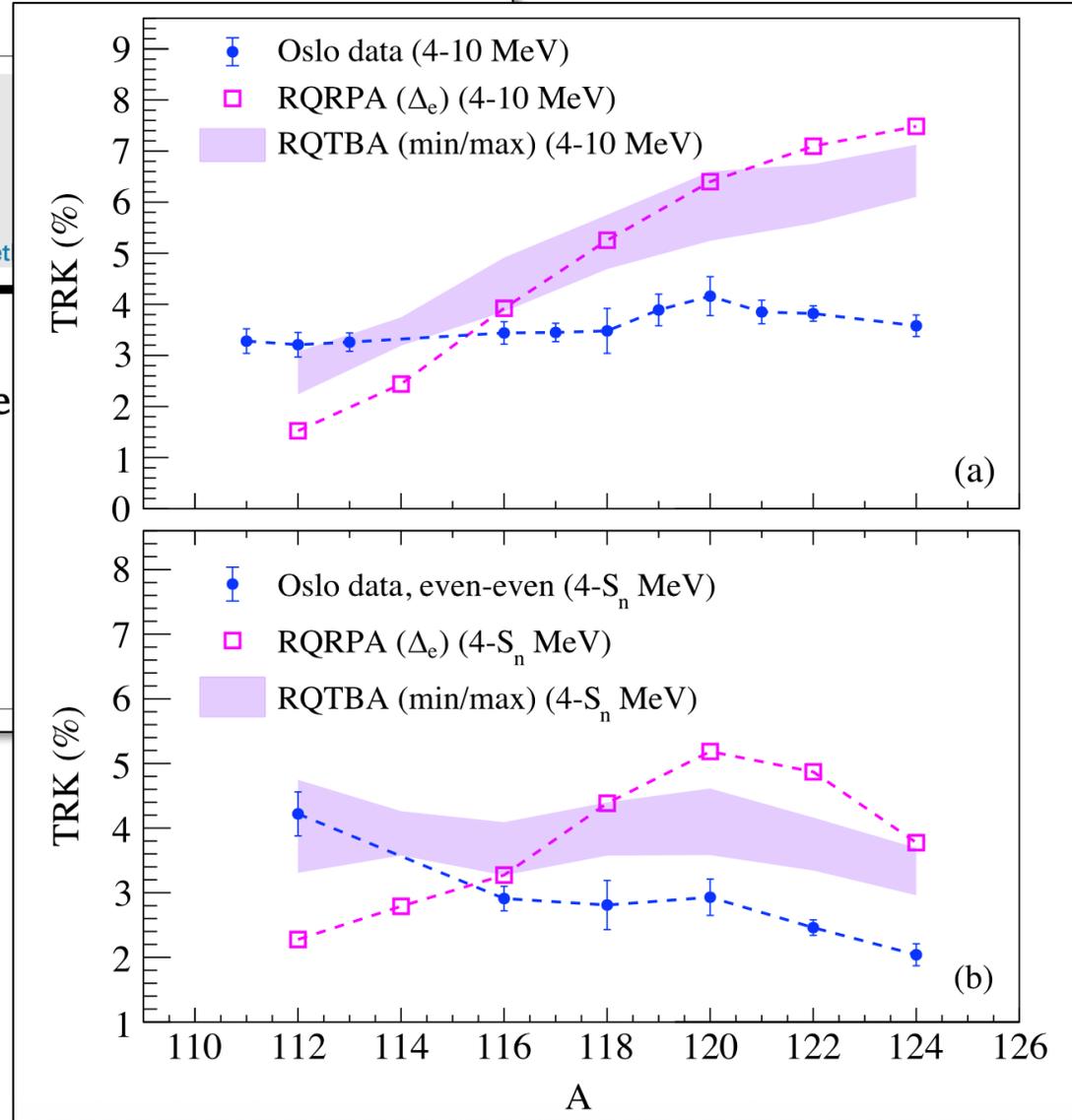
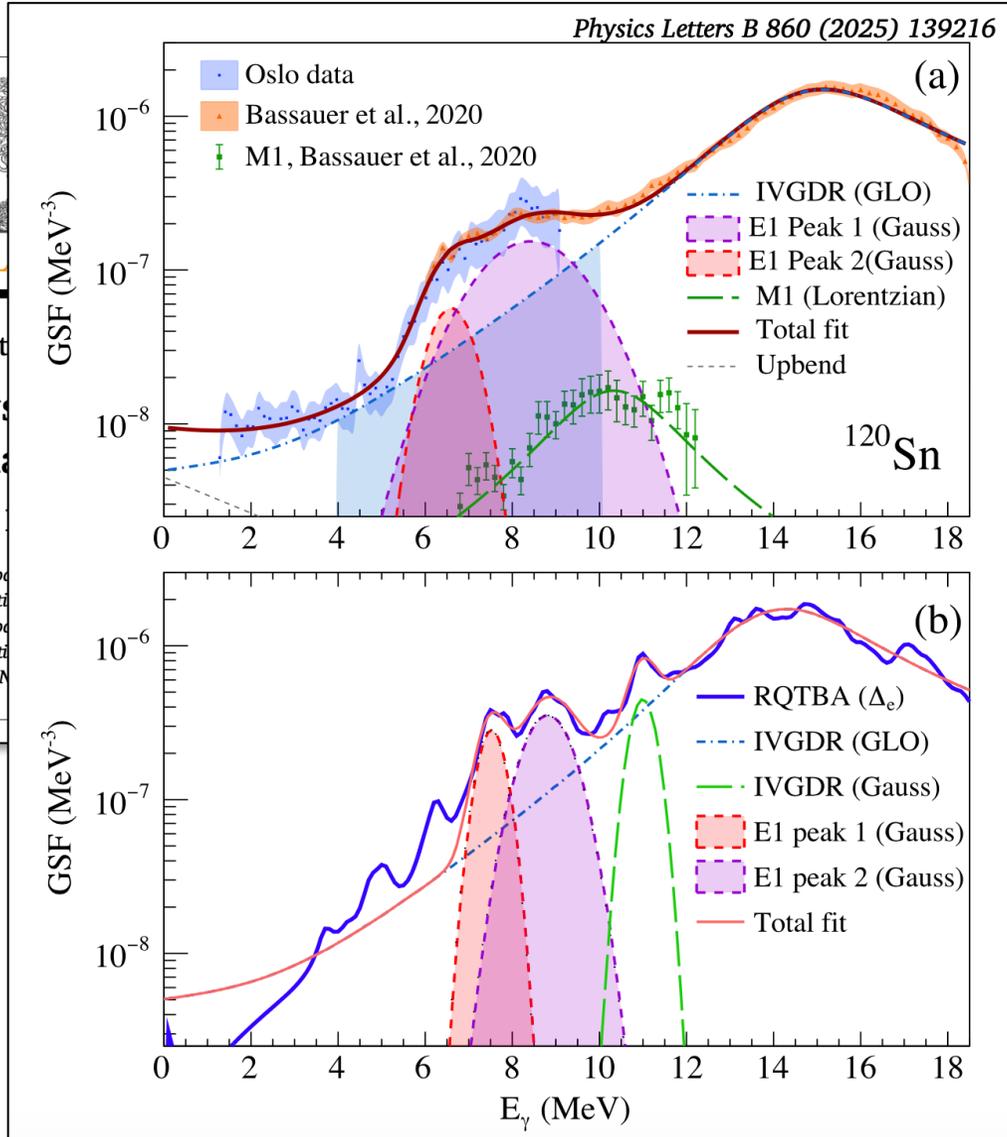
<sup>d</sup> National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, MI 48824, USA

<sup>e</sup> GANIL, CEA/DRF-CNRS/IN2P3, F-14076 Caen, France

# The Sn isotopic chain: PDR



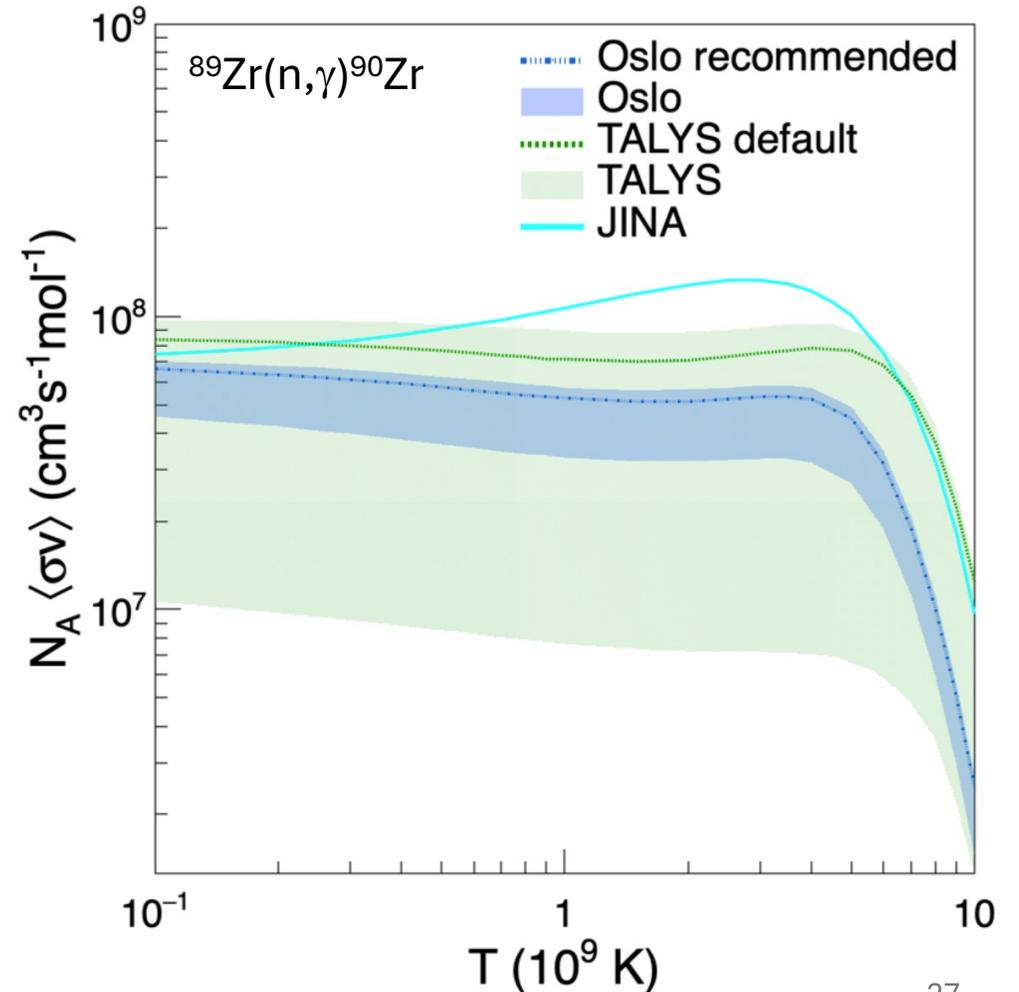
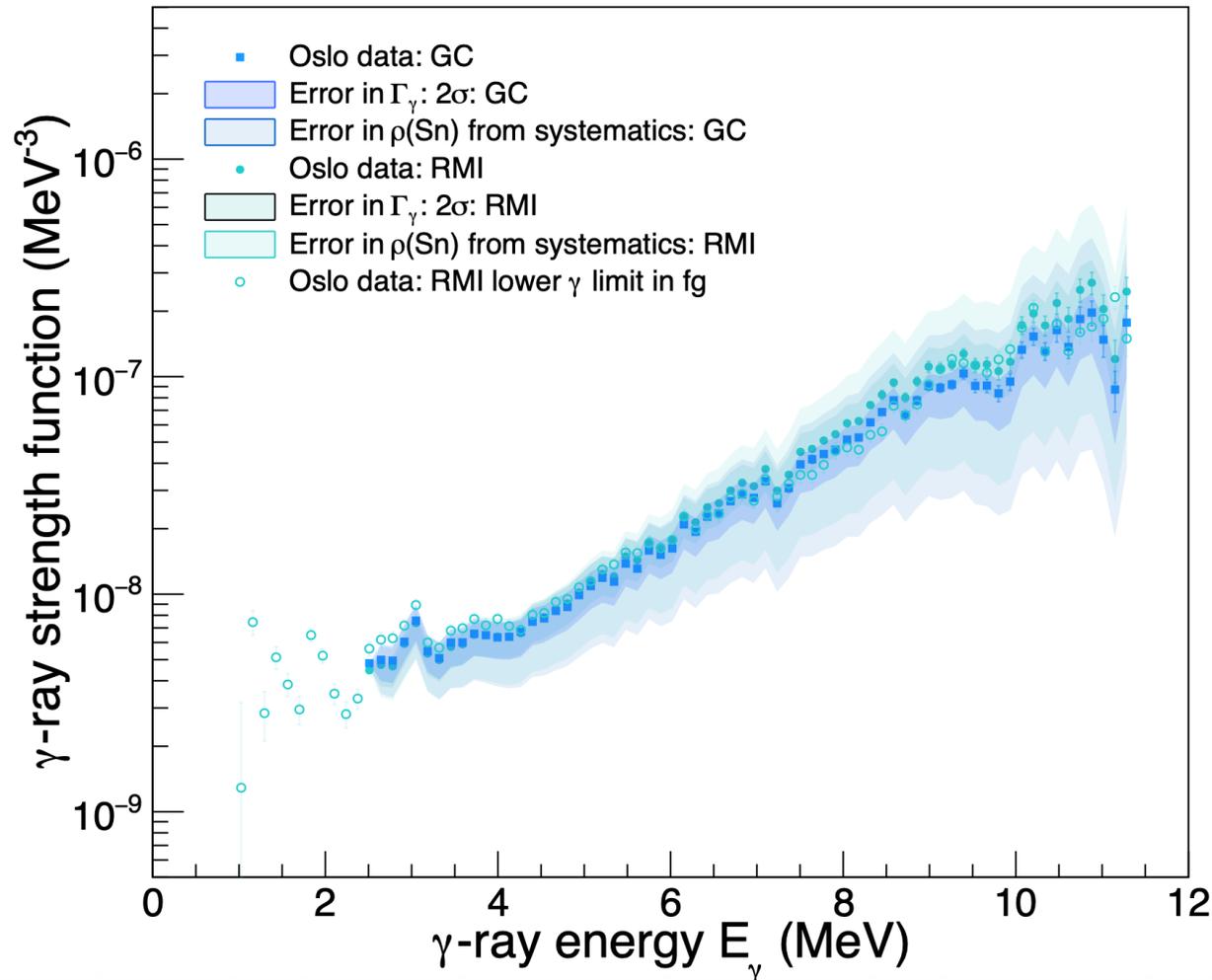
# The Sn isotopic chain: PDR



# $^{90}\text{Zr}$ : $\gamma$ -strength & reaction rate

$^{90}\text{Zr}(p,p'\gamma)^{90}\text{Zr}$ ,  $E_p = 17$  MeV [with CACTUS, experiment from 2009]. Lauren T. Bell et al, submitted to PRC (2025), in review

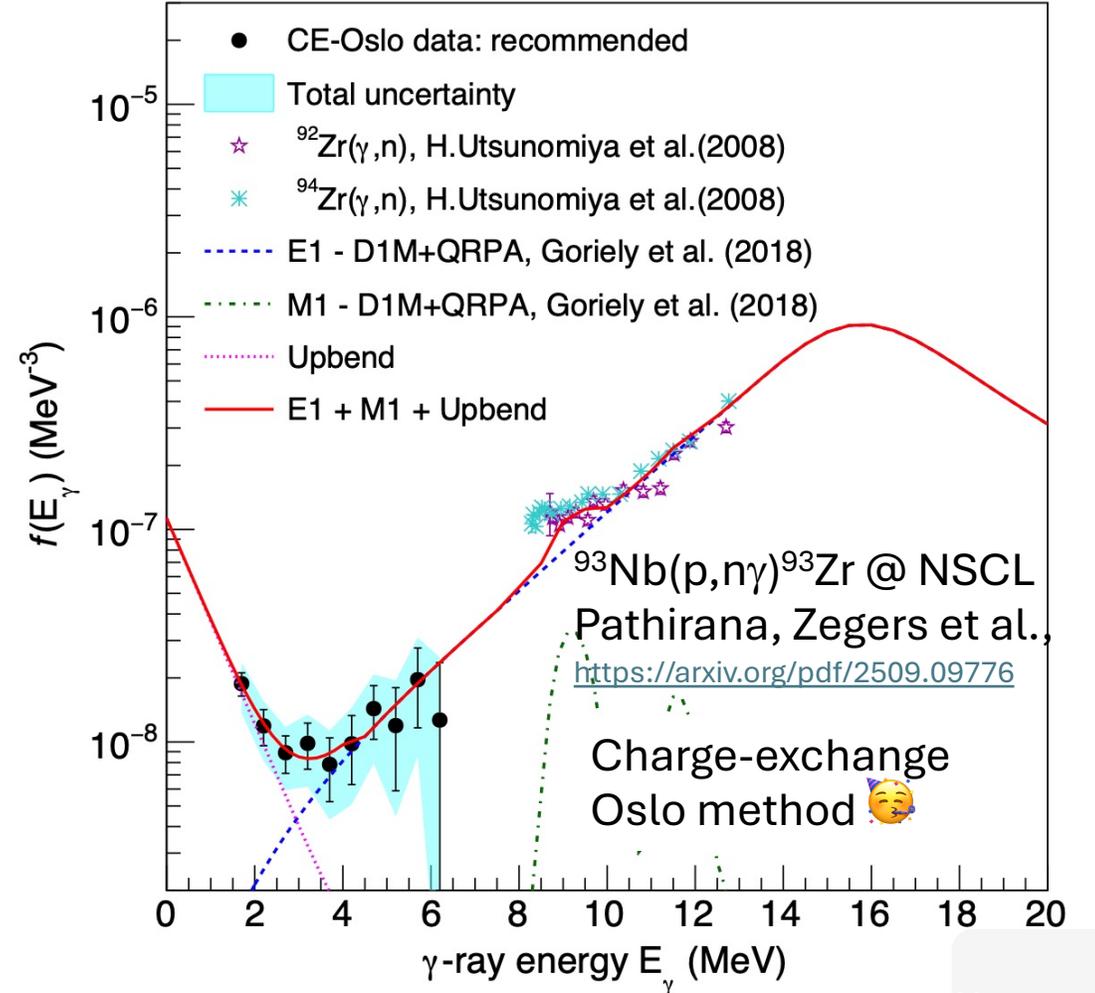
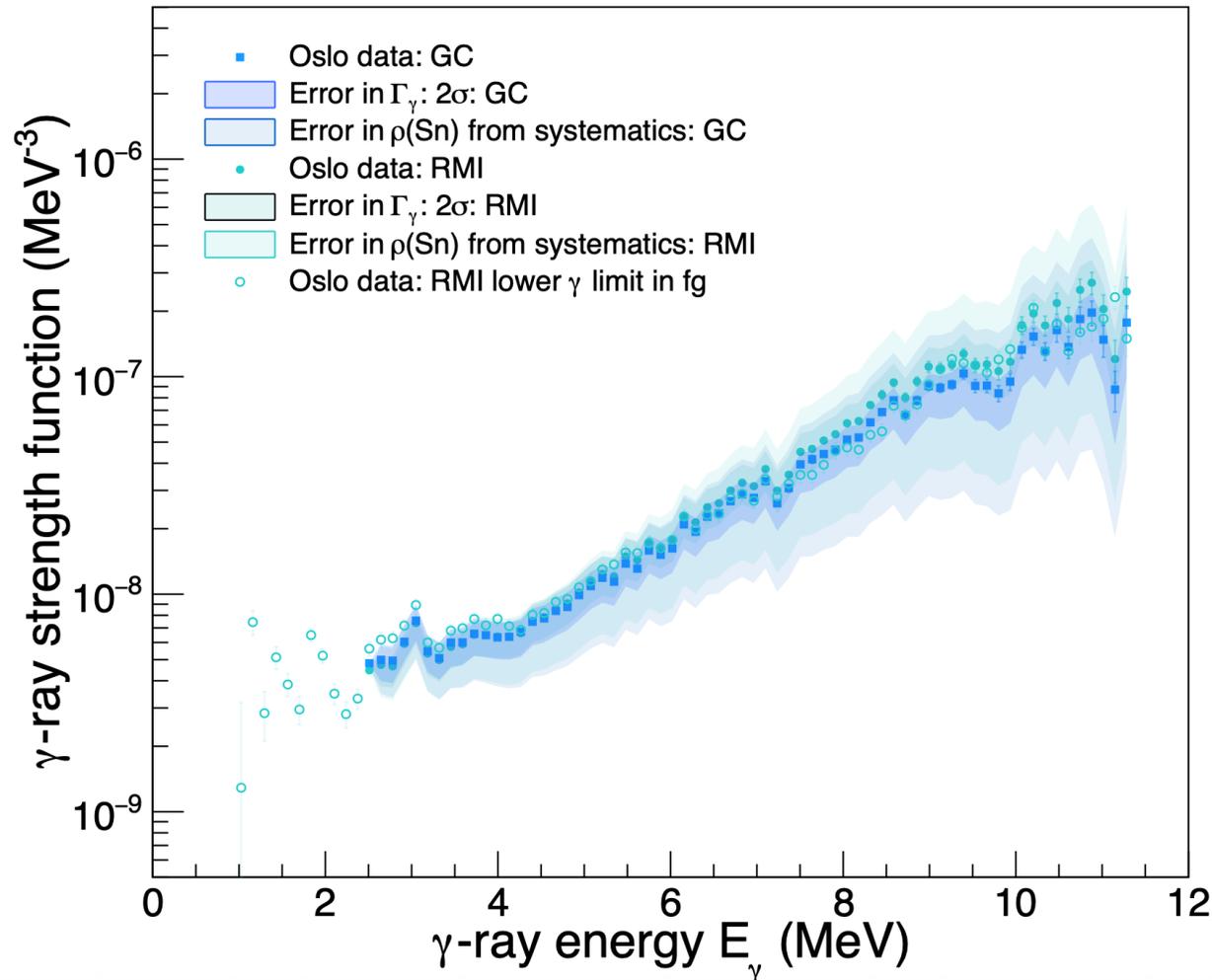
No clear low-energy enhancement (“flat”)



# $^{90,93}\text{Zr}$ : $\gamma$ -strength

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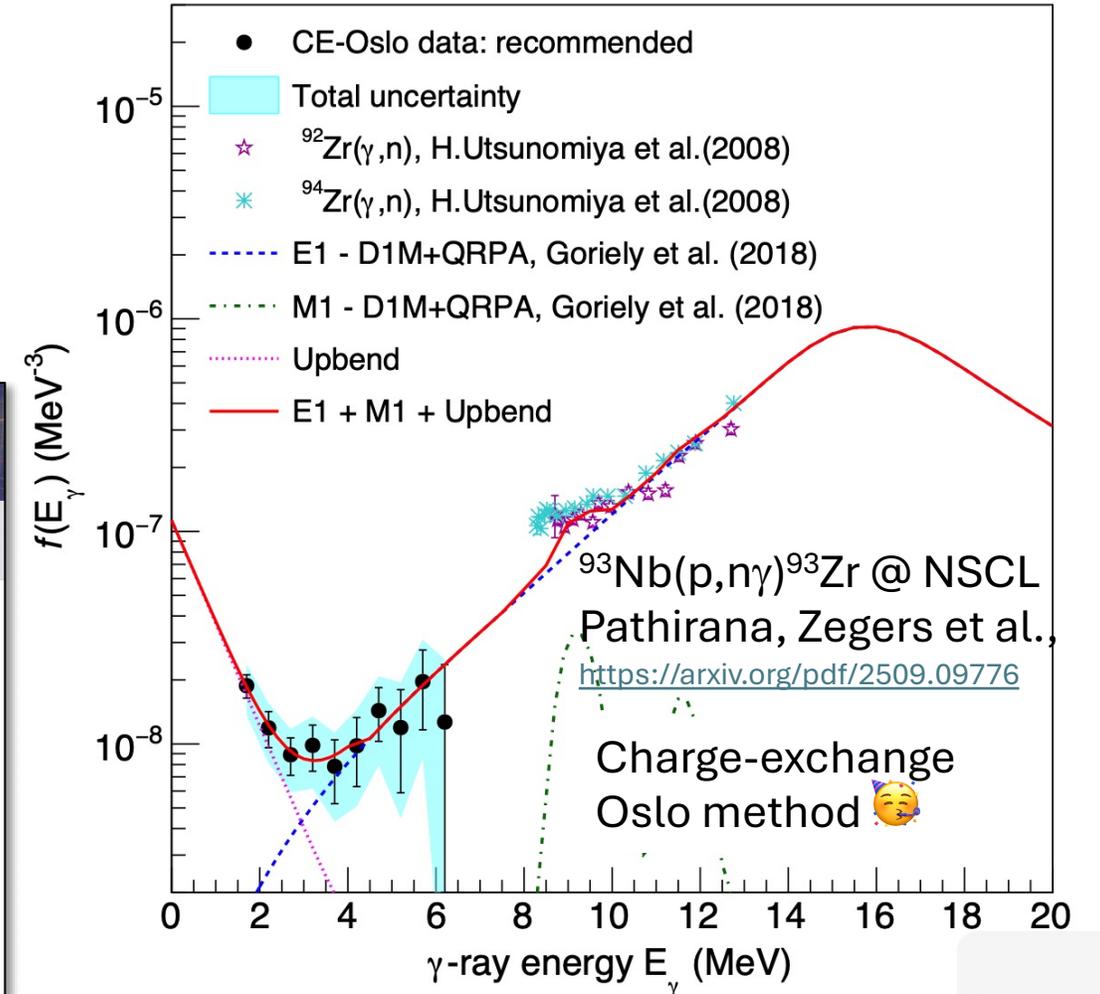
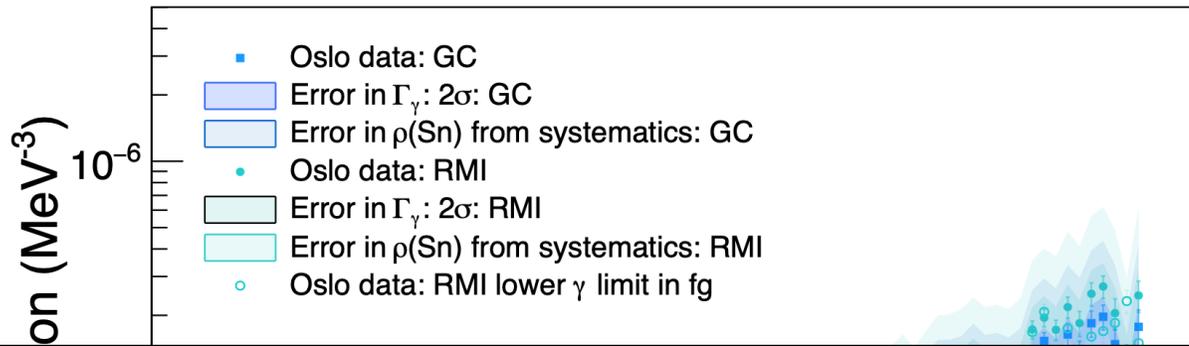
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No clear low-energy enhancement (“flat”)



## Physical Review C

Highlights Recent Accepted Collections Authors Referees Press About Editorial Team RSS

### Extraction of neutron-capture cross sections on $^{92}\text{Zr}$ using the charge-exchange Oslo method

N. D. Pathirana <sup>1,2,\*</sup>, R. G. T. Zegers <sup>1,2,†</sup>, B. Gao <sup>3</sup>, A. Spyrou <sup>1,2</sup>, A. C. Larsen <sup>4</sup>, H. Berg <sup>1,2</sup>, D. Bazin <sup>1,2</sup>, H. L. Crawford <sup>5</sup>, A. Gade <sup>1,2</sup> et al.

Show more

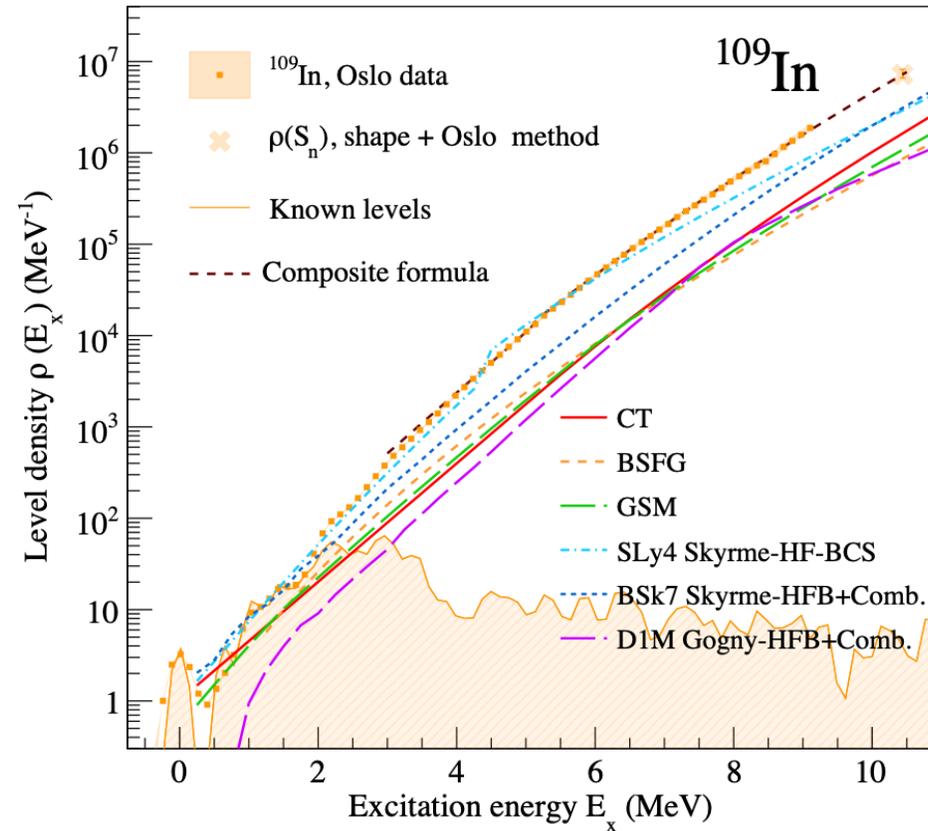
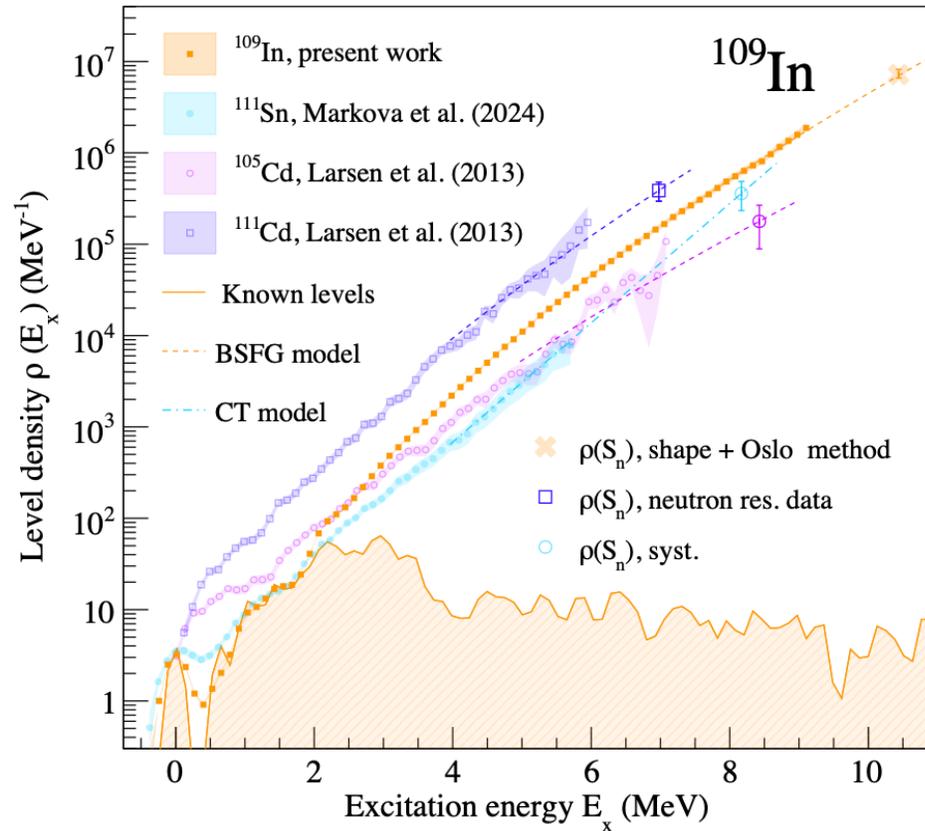
Phys. Rev. C **113**, 015801 – Published 6 January, 2026

DOI: <https://doi.org/10.1103/qdsh-ygry>

Export Citation

# $^{109}\text{In}$ : level density

$^{106}\text{Cd}(\alpha, p\gamma)^{109}\text{In}$ ,  $E_\alpha = 23$  MeV. Maria Markova et al., submitted to PRC (2025), in review (arXiv:2511.20206)

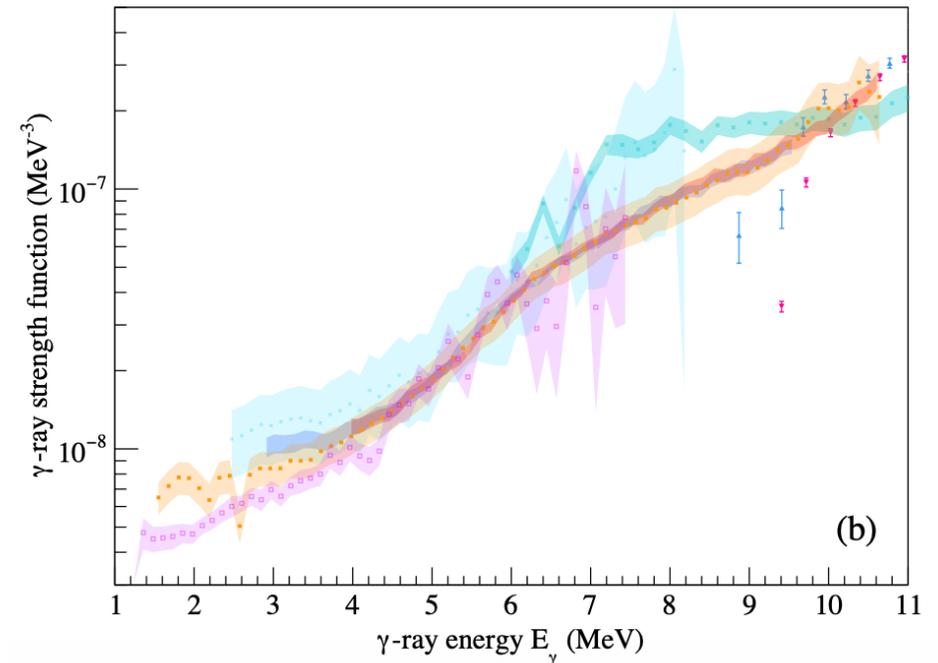
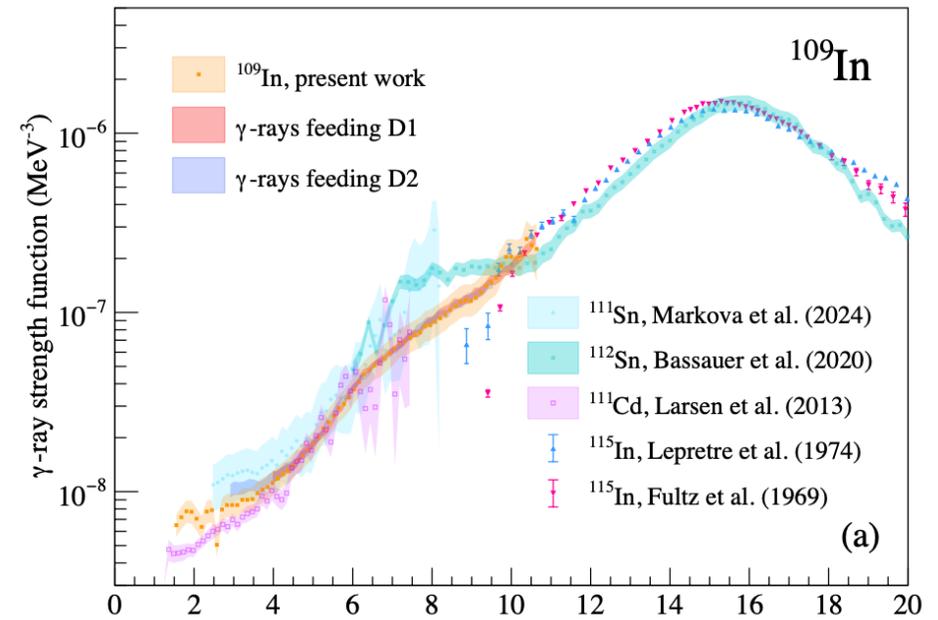
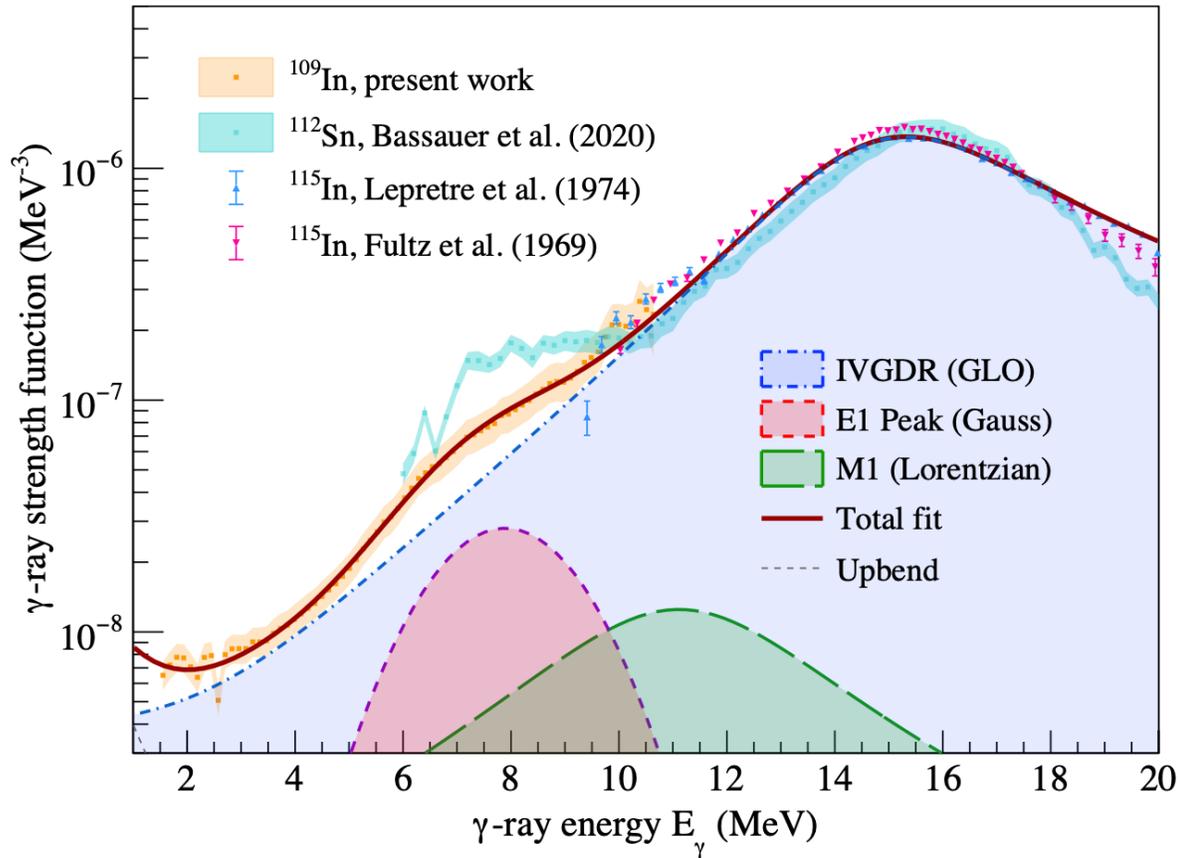


👻 Myth: The Oslo method always gives a “constant-temperature-like” shape of the NLD

🧐 Truth: The data can also show a “Fermi-gas-like” shape; e.g., for the odd  $^{109}\text{In}$  and odd-odd  $^{44}\text{Sc}$ ,  $^{166}\text{Ho}$

# $^{109}\text{In}$ : $\gamma$ -ray strength

$^{106}\text{Cd}(\alpha, p\gamma)^{109}\text{In}$ ,  $E_\alpha = 23$  MeV. Maria Markova et al.,  
submitted to PRC (2025), in review (arXiv:2511.20206)



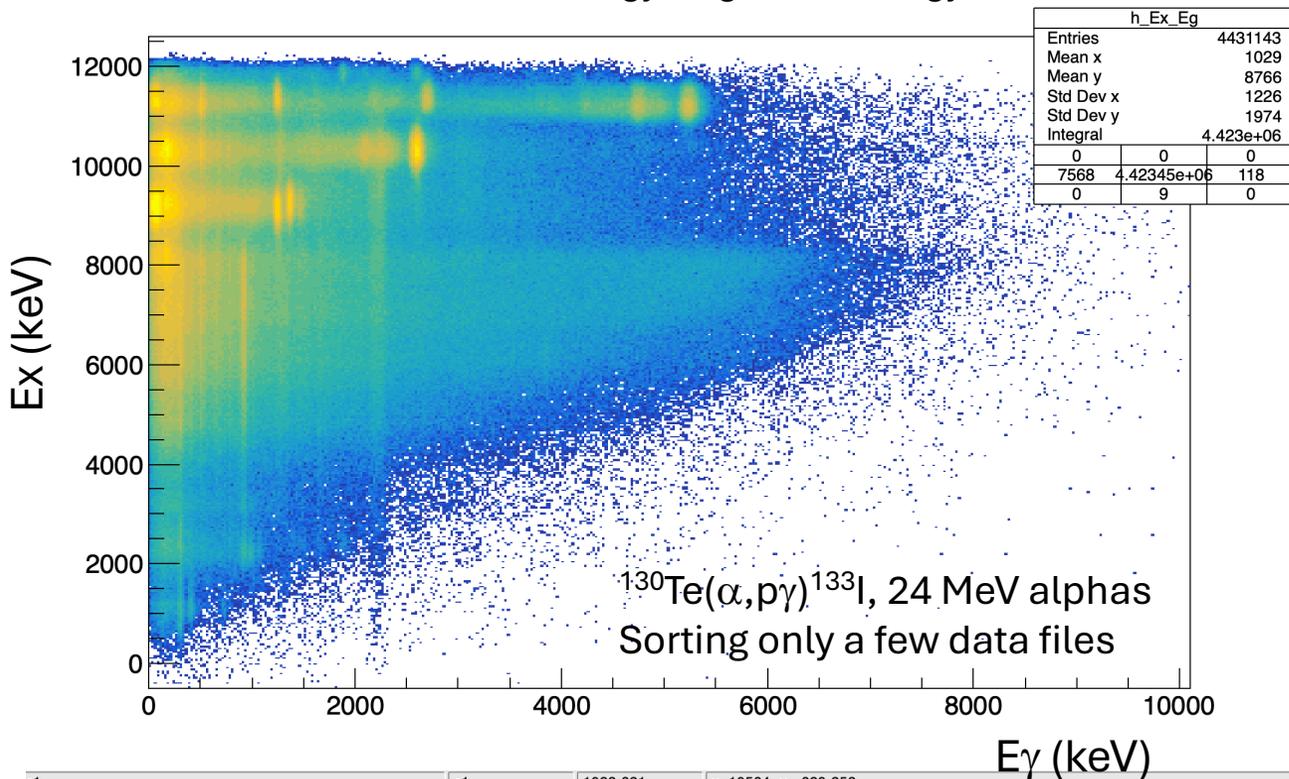
# $^{132,133}\text{I}$ (experiments at OCL fall 2025)

Analyzed by our Master students Claudia Emilia Grieg and Therese Einskau Mørk

$^{130}\text{Te}(\alpha, p\gamma)^{133}\text{I}$ ,  $E_\alpha = 24 \text{ MeV}$ ,  $^{130}\text{Te}(\alpha, d\gamma)^{132}\text{I}$ ,  $E_\alpha = 30 \text{ MeV}$

**Goal:** indirectly extract  $(n, \gamma)^{132,133}\text{I}$  cross sections and reaction rates

Excitation energy vs gamma energy



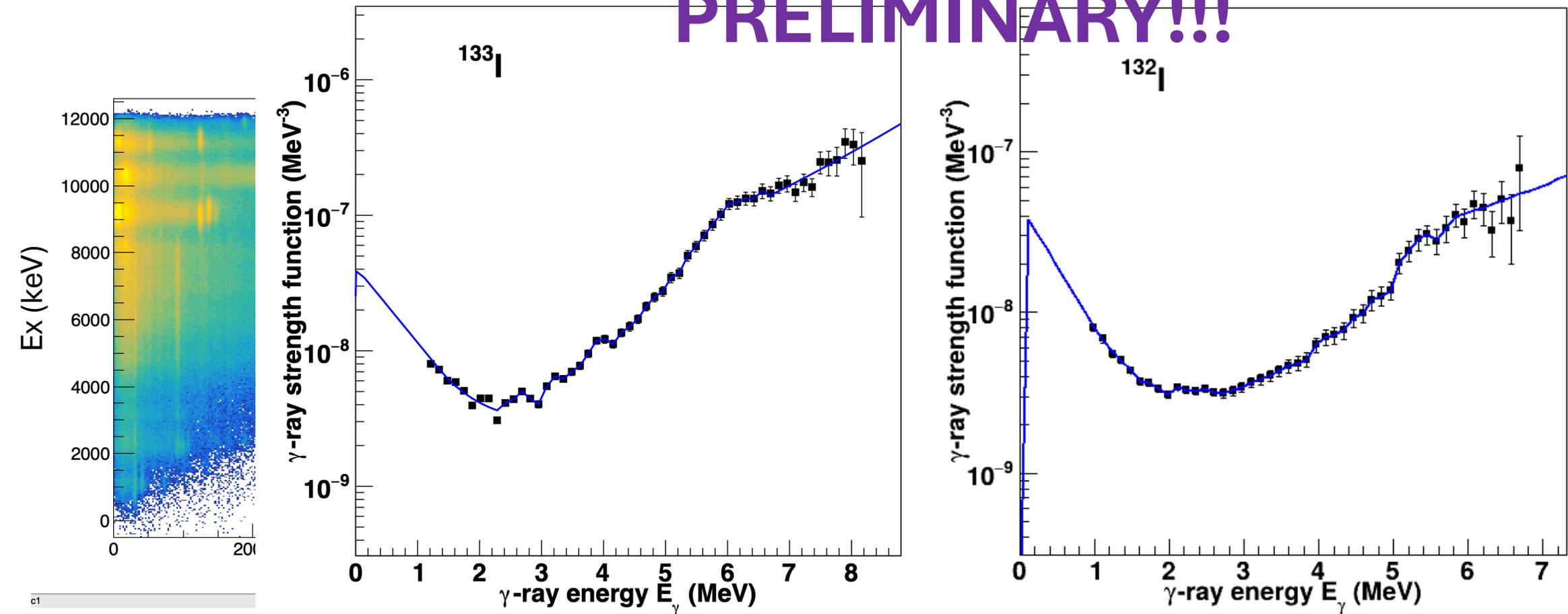
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**Goal:** indirectly extract  $(n, \gamma)^{132,133}\text{I}$  cross sections and reaction rates

**PRELIMINARY!!!**



# Recent beta-Oslo results: $^{59}\text{Fe}(n,\gamma)^{60}\text{Fe}$

nature communications



Article

<https://doi.org/10.1038/s41467-024-54040-4>

## Enhanced production of $^{60}\text{Fe}$ in massive stars

Received: 26 April 2024

Accepted: 30 October 2024

Published online: 07 November 2024

Check for updates

A. Spyrou<sup>1,2</sup>✉, D. Richman<sup>1,2</sup>, A. Couture<sup>3</sup>, C. E. Fields<sup>3,4</sup>, S. N. Liddick<sup>1,5</sup>, K. Childers<sup>1,5</sup>, B. P. Crider<sup>1,6</sup>, P. A. DeYoung<sup>7</sup>, A. C. Dombos<sup>1,2</sup>, P. Gastis<sup>3,8</sup>, M. Guttormsen<sup>9</sup>, K. Hermansen<sup>1,2</sup>, A. C. Larsen<sup>9</sup>, R. Lewis<sup>1,5</sup>, S. Lyons<sup>1,10</sup>, J. E. Midtbø<sup>9</sup>, S. Mosby<sup>3</sup>, D. Muecher<sup>11</sup>, F. Naqvi<sup>1,12</sup>, A. Palmisano-Kyle<sup>1,2,13</sup>, G. Perdikakis<sup>8</sup>, C. Prokop<sup>1,3</sup>, H. Schatz<sup>1,2</sup>, M. K. Smith<sup>1</sup>, C. Sumithrarachchi<sup>1</sup> & A. Sweet<sup>14</sup>

Massive stars are a major source of chemical elements in the cosmos, ejecting freshly produced nuclei through winds and core-collapse supernova explosions into the interstellar medium. Among the material ejected, long-lived radioisotopes, such as  $^{60}\text{Fe}$  (iron) and  $^{26}\text{Al}$  (aluminum), offer unique signs of active nucleosynthesis in our galaxy. There is a long-standing discrepancy between the observed  $^{60}\text{Fe}/^{26}\text{Al}$  ratio by  $\gamma$ -ray telescopes and predictions from supernova models. This discrepancy has been attributed to uncertainties in the nuclear reaction networks producing  $^{60}\text{Fe}$ , and one reaction in particular, the neutron-capture on  $^{59}\text{Fe}$ . Here we present experimental results that pro-

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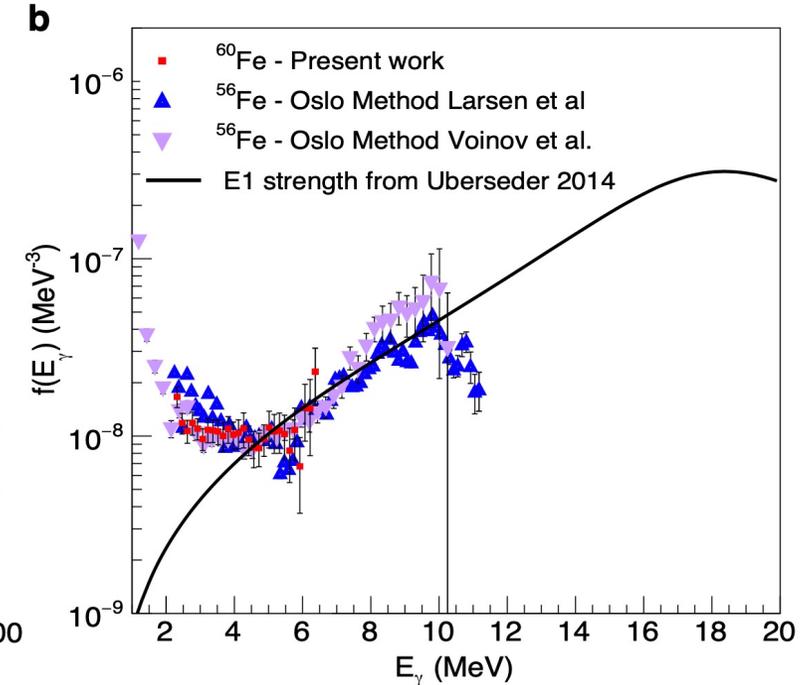
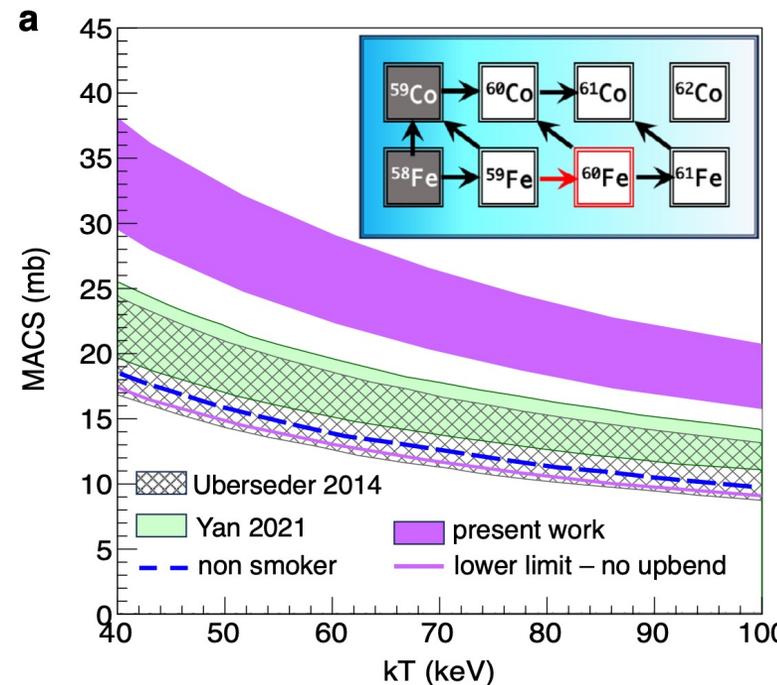
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A. Spyrou<sup>1,2</sup>,  
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Massive stars freshly produce  $^{60}\text{Fe}$  into the interstellar medium through the production of active nucleosynthesis between the core and the supernova maximum.

the nuclear reaction networks producing  $^{60}\text{Fe}$ , and one reaction in particular, the neutron-capture on  $^{59}\text{Fe}$ . Here we present experimental results that pro-

“While uncertainties in the nuclear physics aspects still remain, our result removes one of the most significant uncertainties in the  $^{60}\text{Fe}$  production. **However, the discrepancy persists and is even larger.** The solution to the puzzle must come from stellar modeling...”



# Recent beta-Oslo results: $^{139}\text{Ba}(n,\gamma)^{140}\text{Ba}$

PHYSICAL REVIEW LETTERS **132**, 202701 (2024)

Featured in Physics

## First Study of the $^{139}\text{Ba}(n,\gamma)^{140}\text{Ba}$ Reaction to Constrain the Conditions for the Astrophysical *i* Process

A. Spyrou<sup>1,2,3,\*</sup>, D. Mücher<sup>4,5,6,†</sup>, P. A. Denissenkov<sup>7,‡</sup>, F. Herwig<sup>7,‡</sup>, E. C. Good<sup>1,3</sup>, G. Balk<sup>8</sup>, H. C. Berg<sup>1,2,3</sup>, D. L. Bleuel<sup>9</sup>, J. A. Clark<sup>10</sup>, C. Dembski<sup>1,2,3</sup>, P. A. DeYoung<sup>8</sup>, B. Greaves<sup>5</sup>, M. Guttormsen<sup>11</sup>, C. Harris<sup>1,2,3</sup>, A. C. Larsen<sup>11</sup>, S. N. Liddick<sup>1,12</sup>, S. Lyons<sup>13</sup>, M. Markova<sup>11</sup>, M. J. Mogannam<sup>1,12</sup>, S. Nikas<sup>14</sup>, J. Owens-Fryar<sup>1,2,3</sup>, A. Palmisano-Kyle<sup>15</sup>, G. Perdikakis<sup>16</sup>, F. Pogliano<sup>11</sup>, M. Quintieri<sup>1,2</sup>, A. L. Richard<sup>9</sup>, D. Santiago-Gonzalez<sup>10</sup>, G. Savard<sup>10</sup>, M. K. Smith<sup>1,3</sup>, A. Sweet<sup>9</sup>, A. Tsantiri<sup>1,2,3</sup> and M. Wiedeking<sup>17,18</sup>



# The Oslo method in France



Nuclear Instruments and Methods in Physics Research A 1073 (2025) 170243

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Nuclear Inst. and Methods in Physics Research, A

journal homepage: [www.elsevier.com/locate/nima](http://www.elsevier.com/locate/nima)



Full Length Article

## SF $\gamma$ NCS, a multi-detector to characterize $\gamma$ -ray cascades from nuclear reactions

O. Roig <sup>a,b</sup> \*, M. Pottier <sup>a,b</sup> , V. Méot <sup>a,b</sup> , L. Gaudefroy <sup>a,b</sup> , C. Fougères <sup>a,b</sup> , A. Ebran <sup>a</sup>

<sup>a</sup> CEA, DAM, DIF, F-91297 Arpajon, France

<sup>b</sup> Université Paris-Saclay, CEA, Laboratoire Matière en Conditions Extrêmes, F-91680, Bruyères-le-Chatel, France



# The Oslo method in France

Nuclear Instruments and Methods in Physics Research A 1073 (2025) 170243



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Full Length  
SF $\gamma$ NCS  
reaction

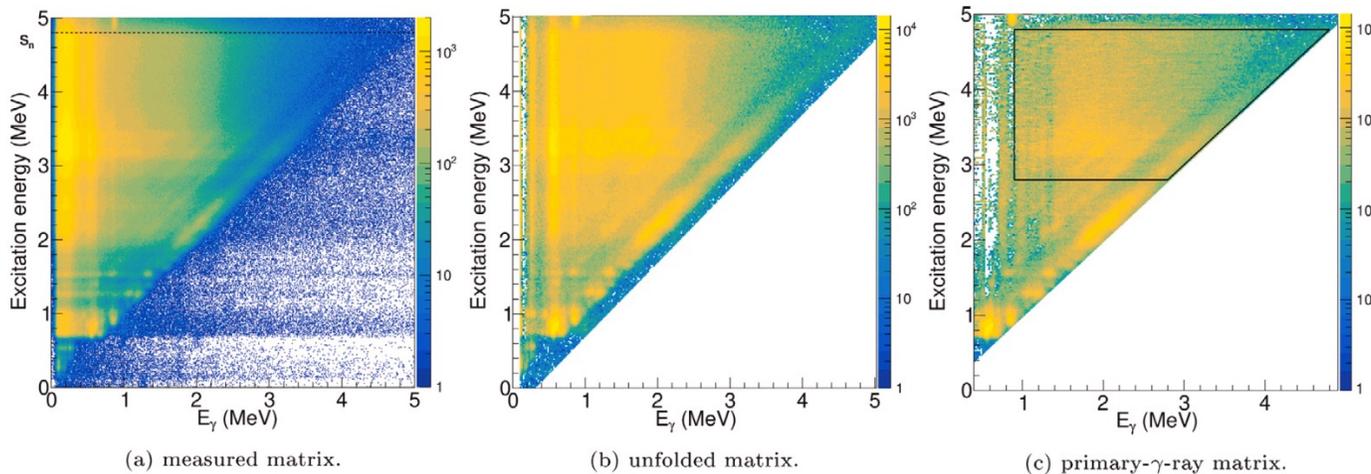
O. Roig <sup>a,b</sup>

<sup>a</sup> CEA, DAM, DIF

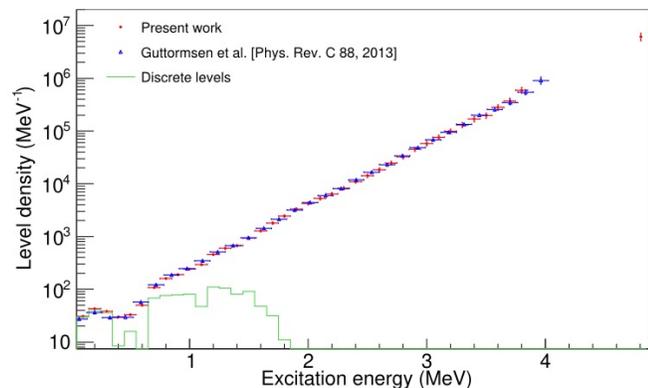
<sup>b</sup> Université Paris

O. Roig et al.

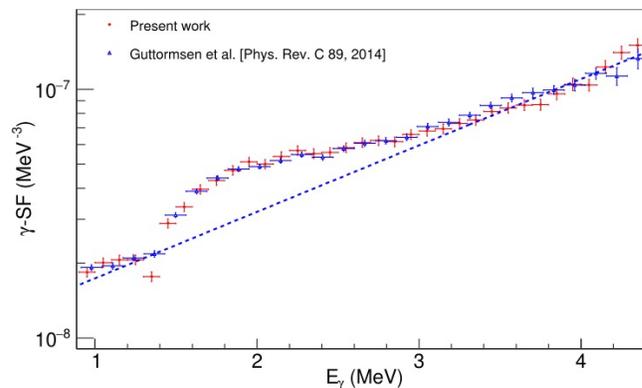
Nuclear Inst. and Methods in Physics Research, A 1073 (2025) 170243



**Fig. 9.**  $[E_\gamma, E_{exc}]$  matrix, measured (left part), unfolded (middle part) and primary- $\gamma$ -rays (right part) for the  $^{238}\text{U}(d, p)$  reaction. The neutron binding energy of compound  $^{239}\text{U}$ , at  $S_n = 4.8064(2)$  MeV [26], is shown with the black dotted line in Fig. 9(a). Black lines in Fig. 9(c) mark the area of the primary- $\gamma$ -ray matrix which was used in the Oslo method.



(a) nuclear level density.



(b)  $\gamma$ -ray strength function.

# The Oslo method in France 🎉🇫🇷

Nuclear Instruments and Methods in Physics Research A 1073 (2025) 170243



ELSEVIER

Full Length  
SF $\gamma$ NCS  
reaction

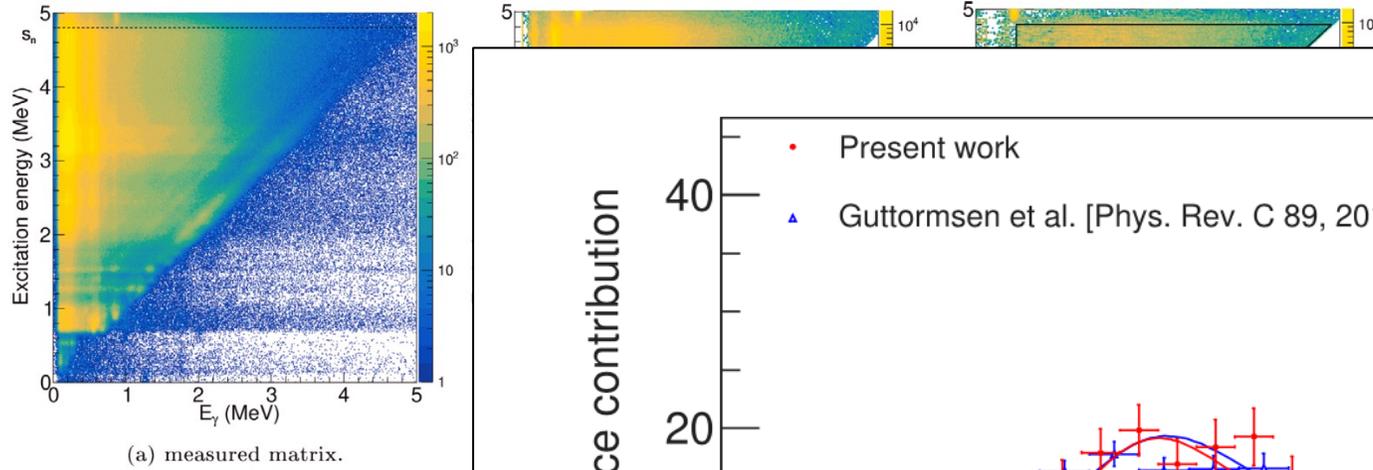
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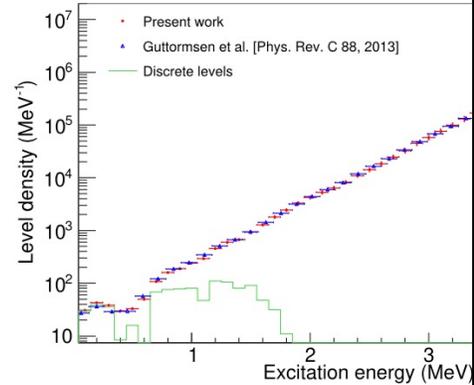
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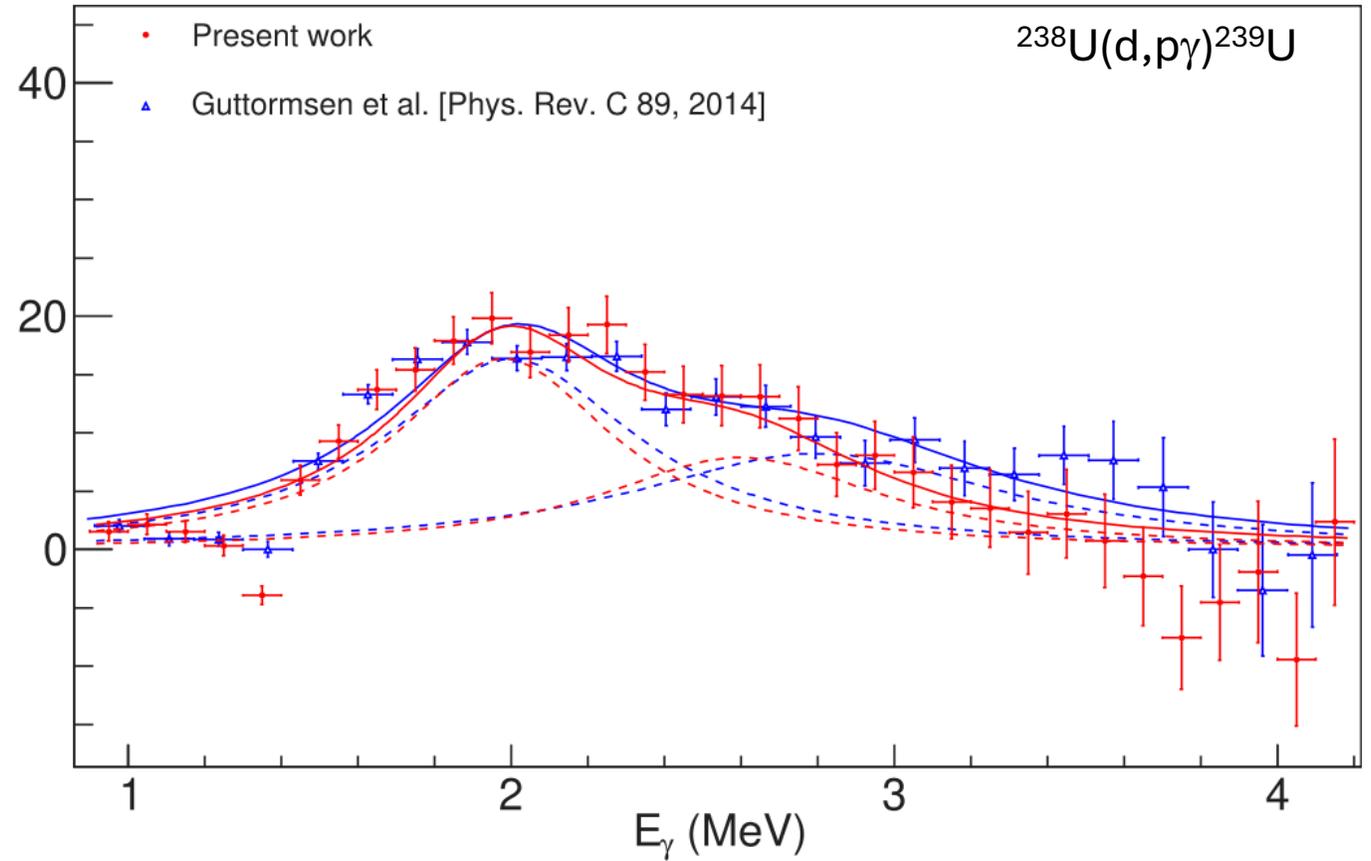
(a) measured matrix.

Fig. 9.  $[E_\gamma, E_{exc}]$  matrix, measured (left part), unfolded (middle part),  $S_n = 4.8064(2)$  MeV [26], is shown with the black dotted line in



(a) nuclear level density

Scissor resonance contribution



(b)  $\gamma$  strength function

# Summary & outlook

## Take-home message:

The Oslo method and the beta-Oslo method make it possible to extract level densities and  $\gamma$ -ray strength functions from  $E_x$ - $E_\gamma$  matrices

## Challenges (AKA to-do list):

- (i) For astrophysics applications, we need to go much more neutron-rich  $\rightarrow$  beta-delayed neutron emission... Also, higher  $\gamma$  multiplicity! (well-deformed nuclei) 🤔
- (ii) Better normalizations for the level density and  $\gamma$ -ray strength of neutron-rich, unstable nuclei
- (iii) Uncertainty quantification!
- (iv) +++

# Summary & outlook

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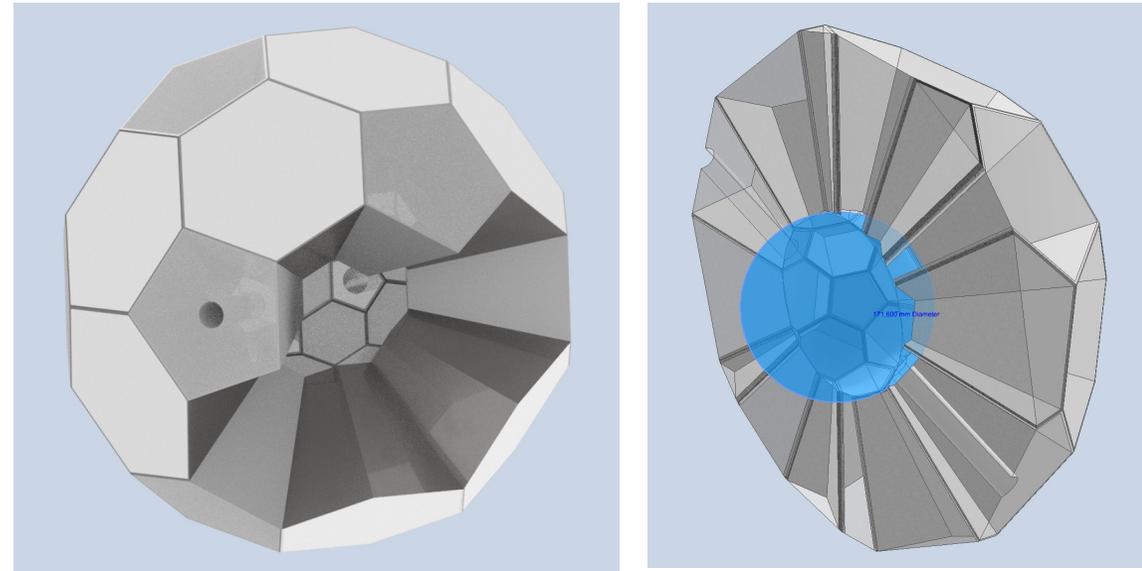
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## R&D funded by AVIT grant, Univ. of Oslo:

A highly segmented total-absorption spectrometer, NaI(Tl+Li) from Luxium Solutions. Milestones 1&2 underway (smaller crystals 🙇)



Design drawings by Maren Lithun, UiO

# Summary & outlook

## Take-home message:

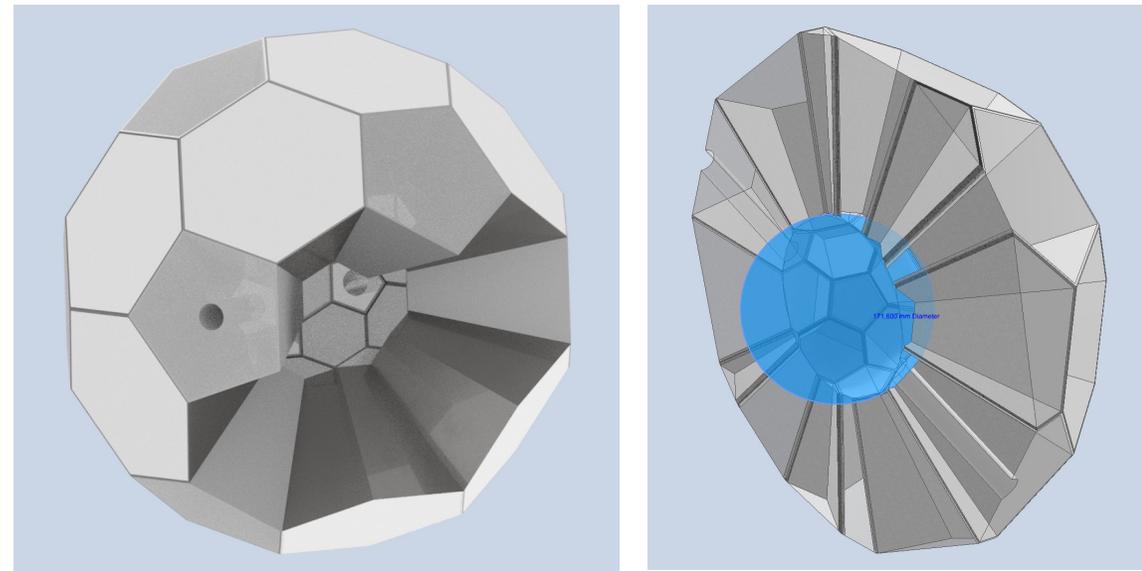
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**Many thanks for your attention!**

# Extra stuff

# Level density and $\gamma$ -ray strength function

## Level density:

$$\rho(E_x, J, \pi) = \frac{\Delta N(E_x, J, \pi)}{\Delta E_x}$$

$$\rho(E_x) = \sum_{J, \pi} \rho(E_x, J, \pi)$$

Excitation-energy bin  $E_x$

Spin  $J$

Parity  $\pi$

## Gamma strength function:

$$f_{XL}(E_\gamma, E_i, J_i, \pi_i) = \frac{\langle \Gamma_\gamma^{XL}(E_\gamma, E_i, J_i, \pi_i) \rangle}{E_\gamma^{2L+1}} \rho(E_i, J_i, \pi_i)$$

Electromagnetic character  $X$

Multipolarity  $L$

Average, **partial** radiative width  $\langle \Gamma_\gamma^{XL} \rangle$

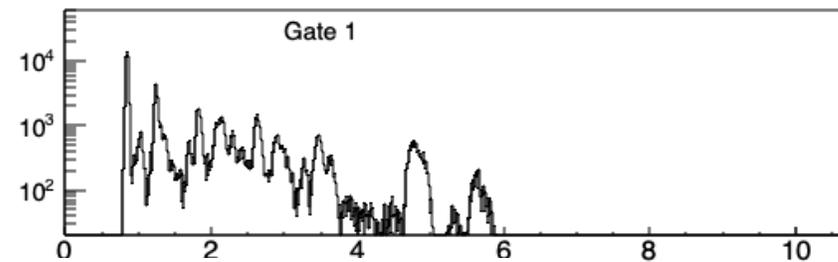
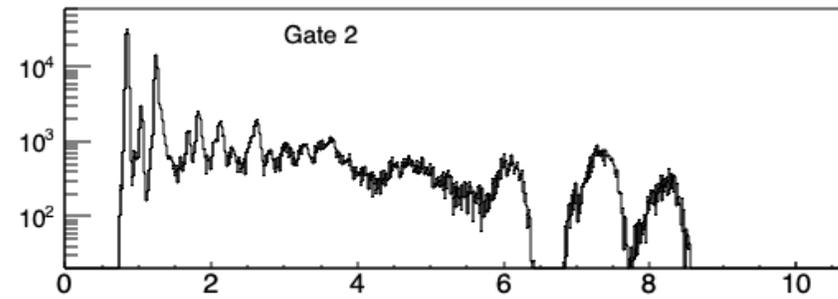
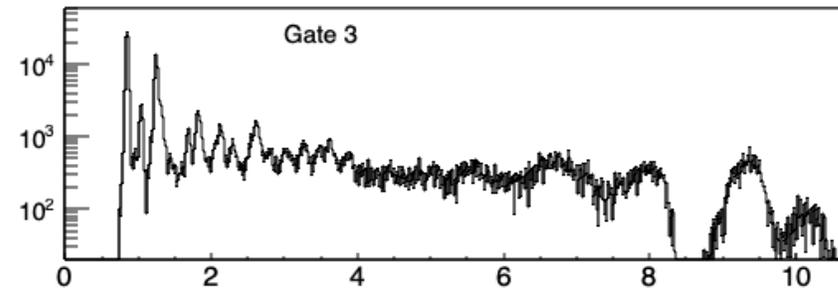
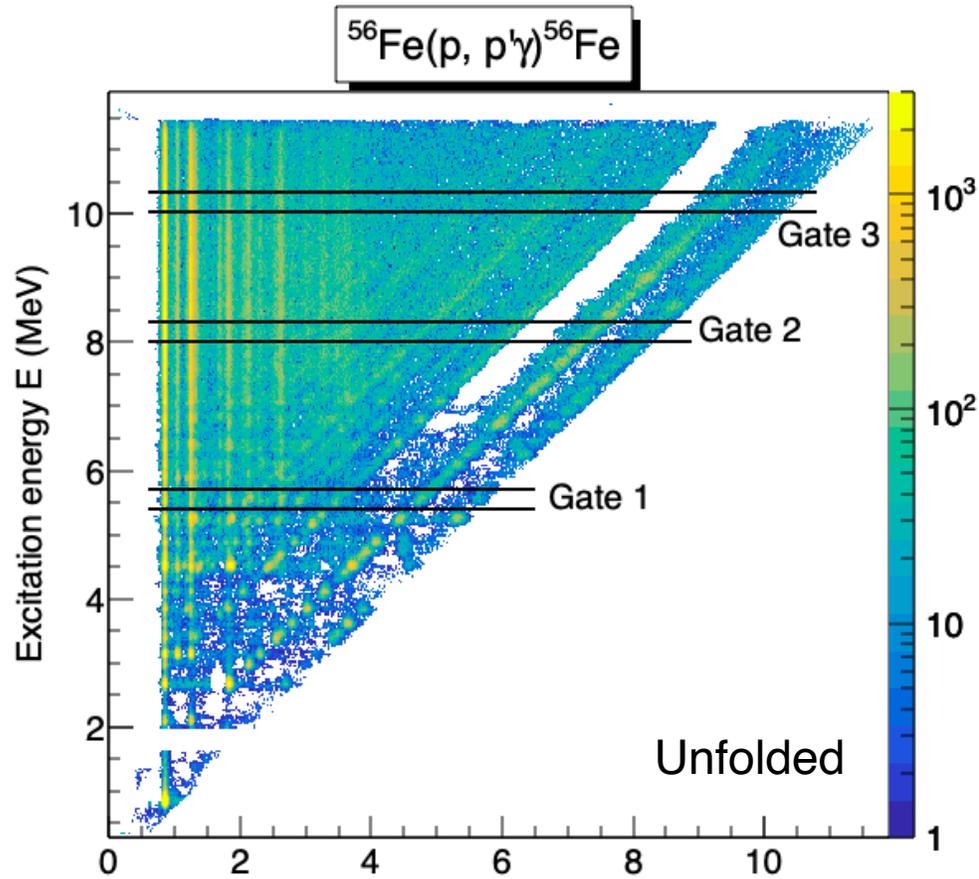
Initial excitation energy  $E_i$

Gamma energy  $E_\gamma$

Spin of initial levels  $J_i$

Parity of initial levels  $\pi_i$

# Step 2: Distribution of first-generation $\gamma$ rays



$f_{i+1}(E_\gamma)$

$g_i(E_\gamma)$

$$h_{i+1}(E_\gamma) = f_{i+1}(E_\gamma) - \sum_{i'=1}^i c_{i'} w_{i'} f_{i'}(E_\gamma) = f_{i+1}(E_\gamma) - g_i(E_\gamma)$$

# Step 3: Extraction of level density and $\gamma$ -ray transmission coefficient

- Normalize  $P(E_i, E_\gamma)$  so that 
$$\sum_{E_\gamma=E_\gamma^{\min}}^{E_i} P(E_i, E_\gamma) = 1.$$

- “Theoretical” estimate of experimental primary  $\gamma$  matrix:

$$P_{th} = \frac{\tau(E_\gamma)\rho(E_i - E_\gamma)}{\sum_{E_\gamma=E_\gamma^{\min}}^{E_i} \tau(E_\gamma)\rho(E_i - E_\gamma)}$$

- First trial function:

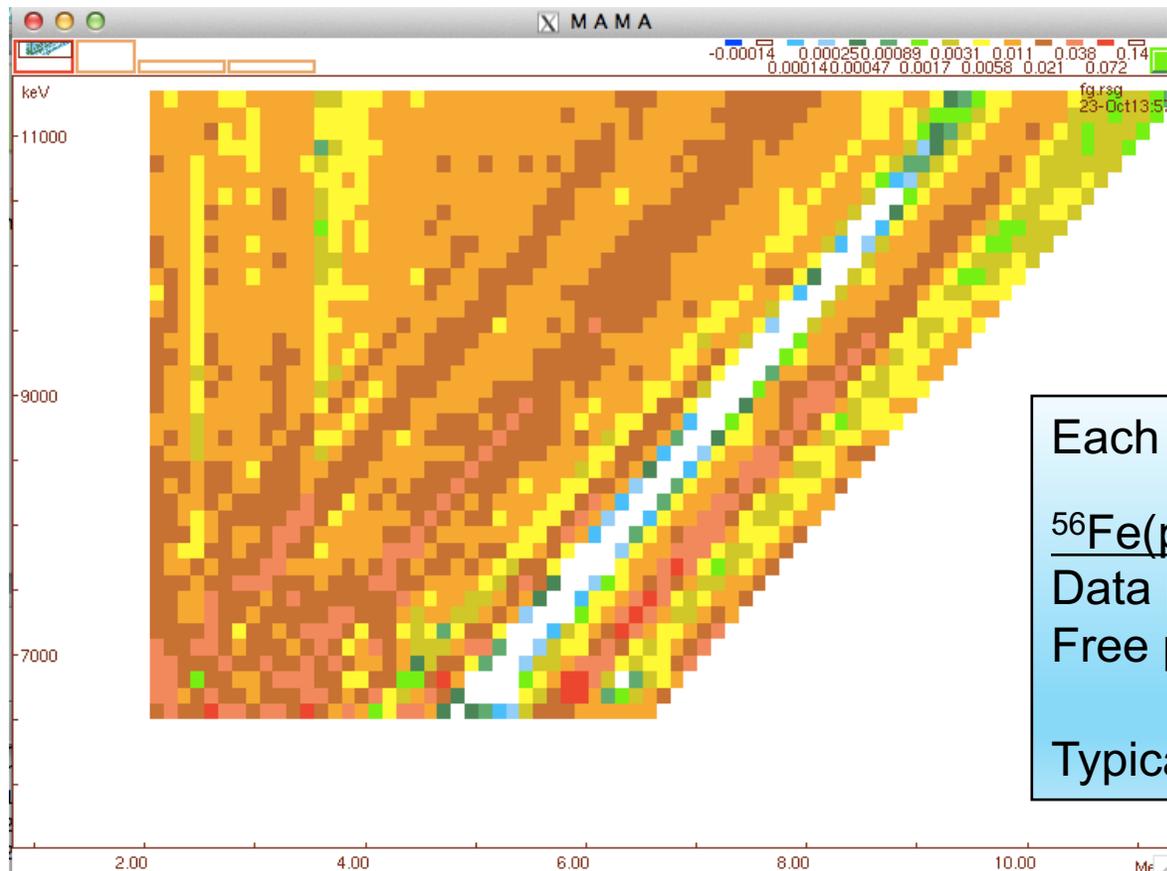
$$\rho^{(0)} = 1,$$

$$P(E_i, E_\gamma) = \frac{\tau^{(0)}(E_\gamma)}{\sum_{E_\gamma=E_\gamma^{\min}}^{E_i} \tau^{(0)}(E_\gamma)}$$

Note: there is no *a priori* assumption that the level density has a Fermi gas or constant-temperature shape!

# Step 3: Extraction of level density and $\gamma$ -ray transmission coefficient

- Higher-order estimates through a least  $\chi^2$ - minimization:



$$\chi^2 = \frac{1}{N_{free}} \sum_{E_i=E_{min}}^{E_{max}} \sum_{E_\gamma=E_\gamma^{min}}^{E_i} \left[ \frac{P_{th}(E_i, E_\gamma) - P(E_i, E_\gamma)}{\Delta P(E_i, E_\gamma)} \right]^2$$

Each vector element in  $\rho$  and  $\tau$  is treated as a free parameter

$^{56}\text{Fe}(p,p')$  example:

Data points (“pixels”): 2052

Free parameters: 184

$$N_{free} \ll N_{data}$$

Typically  $\approx 10$ -20 iterations, but often converges after  $\sim 4$ -5 iterations

# Step 3: NLD and $\gamma$ -ray transmission coeff.

**Ansatz:**

[generalization of Fermi's Golden Rule]

Factorize the primary  $\gamma$  matrix:

$$P(E_i, E_\gamma) \propto \rho(E_x - E_\gamma) \mathcal{T}(E_\gamma)$$

where the  $\gamma$ -decay strength (for dipole radiation) is

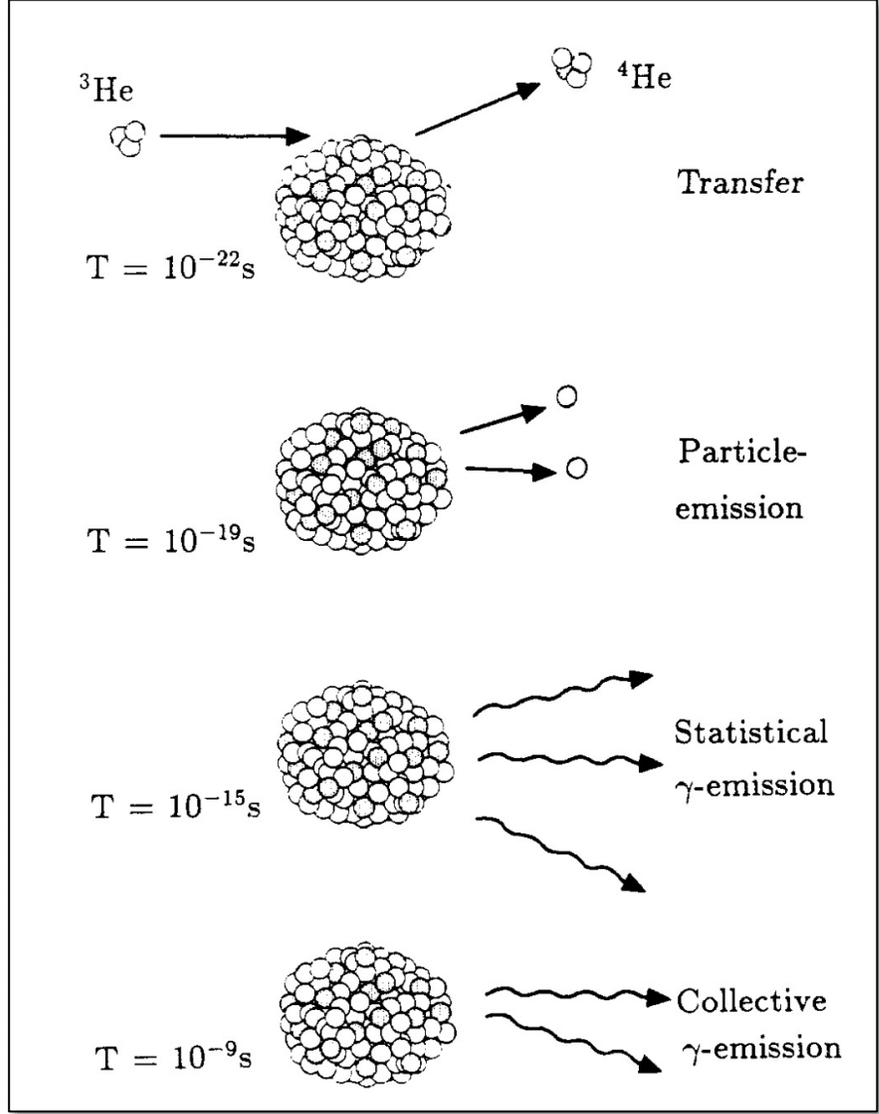
$$f(E_\gamma) = \mathcal{T}(E_\gamma) / 2\pi E_\gamma^3$$

**Two important assumptions:**

- ✓ 1) The  $\gamma$  decay takes place a long time after the level is formed
- 🤔 2) The  $\gamma$ -ray strength function varies *slowly* with  $E_x$  (at high  $E_x$  – high level density), and we can apply an *average* dipole strength for all spins and both parities

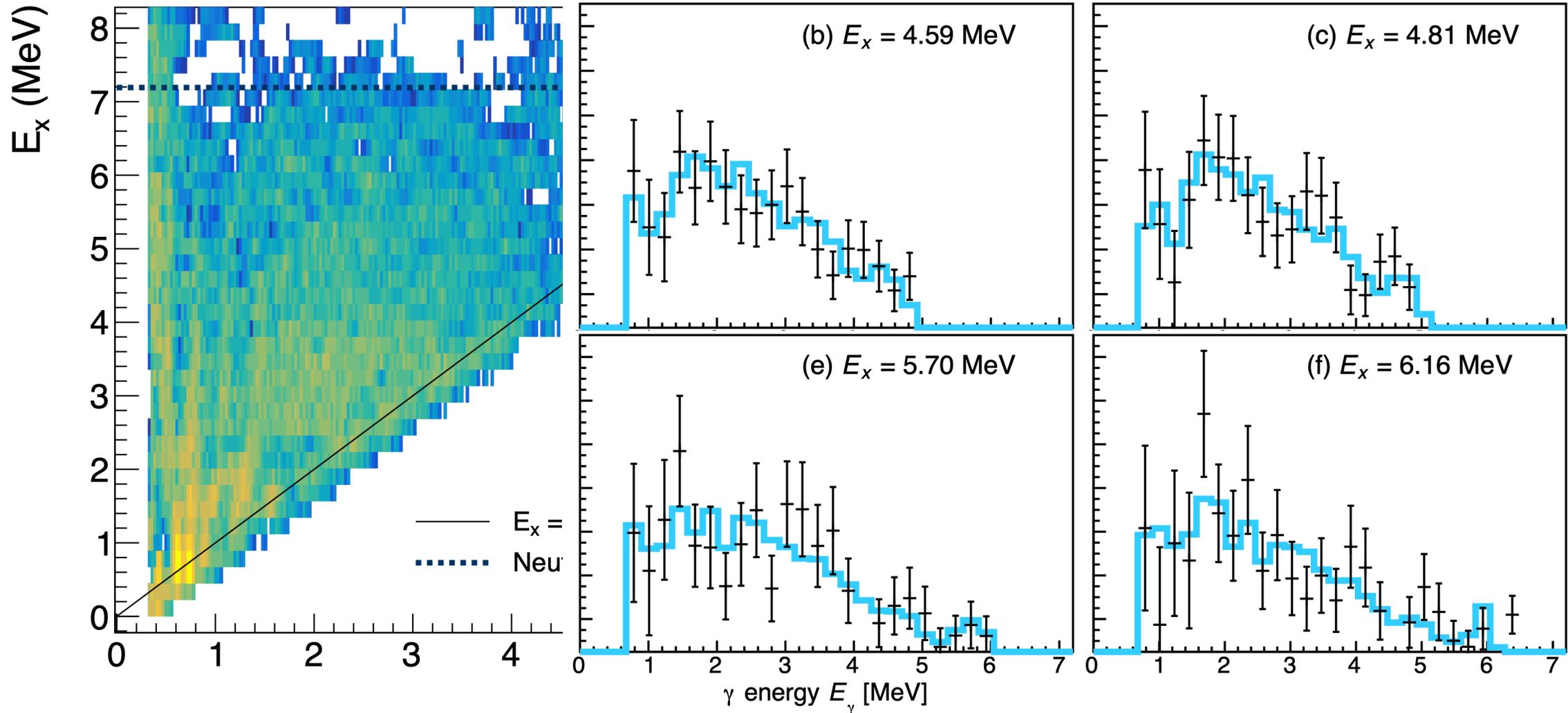
➔ the **Brink hypothesis**

[Brink, Doctoral thesis, Oxford (1955), Axel, Phys. Rev. **126**, 671 (1962)]



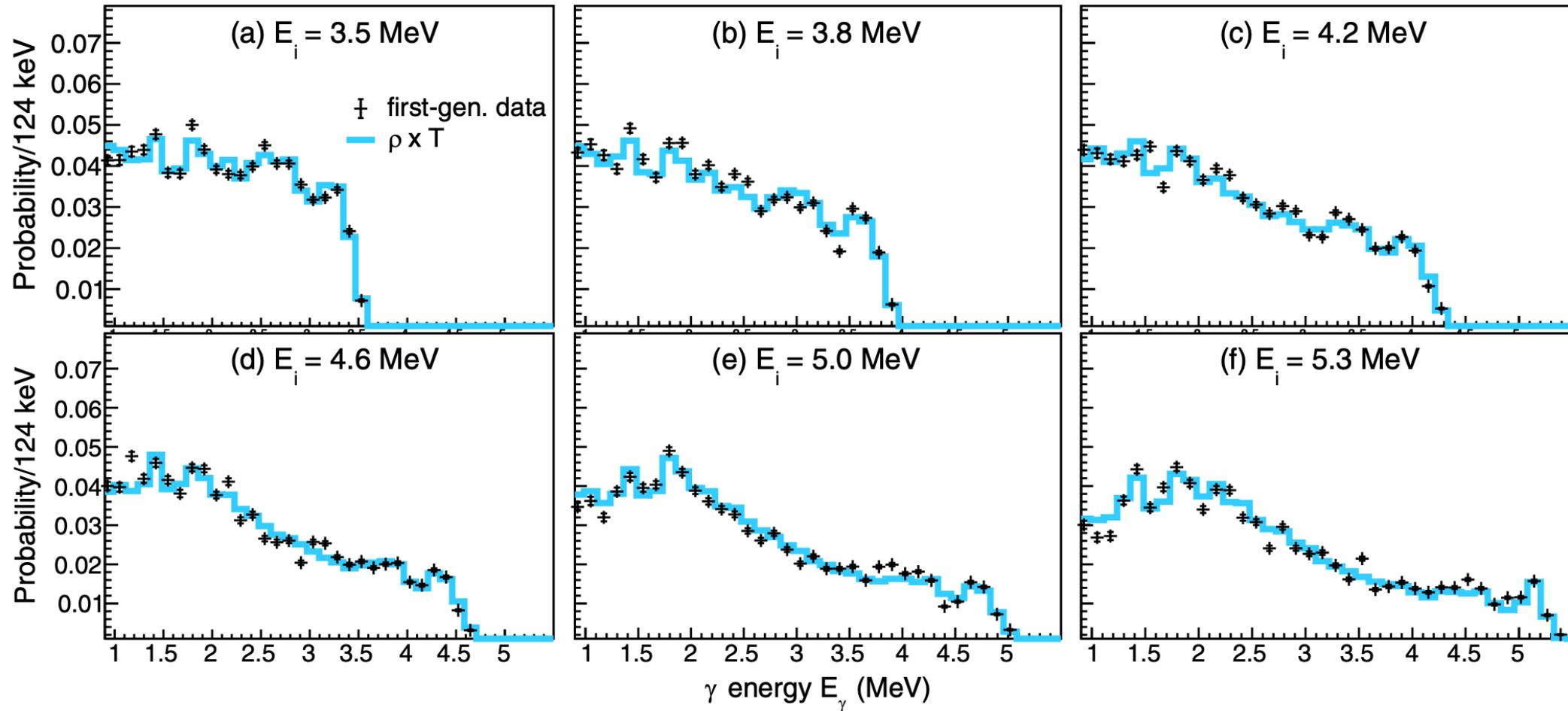
Guttormsen et al, Phys. Scr. T32, 54 (1990)

# ... but does it work? Let's check!



From  $^{186}\text{W}(\alpha, \alpha'\gamma)^{186}\text{W}$  with CACTUS [Larsen et al., PRC **108**, 025804 (2023)] – reduced  $\chi^2 = 0.85$

... but does it work? Let's check!



From  $^{146}\text{Nd}(d, p\gamma)^{147}\text{Nd}$  with OSCAR [Guttormsen et al., PRC **106**, 034314 (2022)]

# Step 4: Normalization

- The extracted  $\rho(E_f)$  and  $\tau(E_\gamma)$  vectors have a functional form that is ***uniquely determined*** by the  $\chi^2$  minimization (e.g. bumps, dips, ...)
- The absolute normalizations and slopes are not known. Equally good solutions are found with all functions of the form (continuous 3-parameter Lie group transformation)

$$\tilde{\rho}(E - E_\gamma) = \rho(E - E_\gamma) A \exp[\alpha(E - E_\gamma)]$$

$$\tilde{\tau}(E_\gamma) = \tau(E_\gamma) B \exp(\alpha E_\gamma)$$

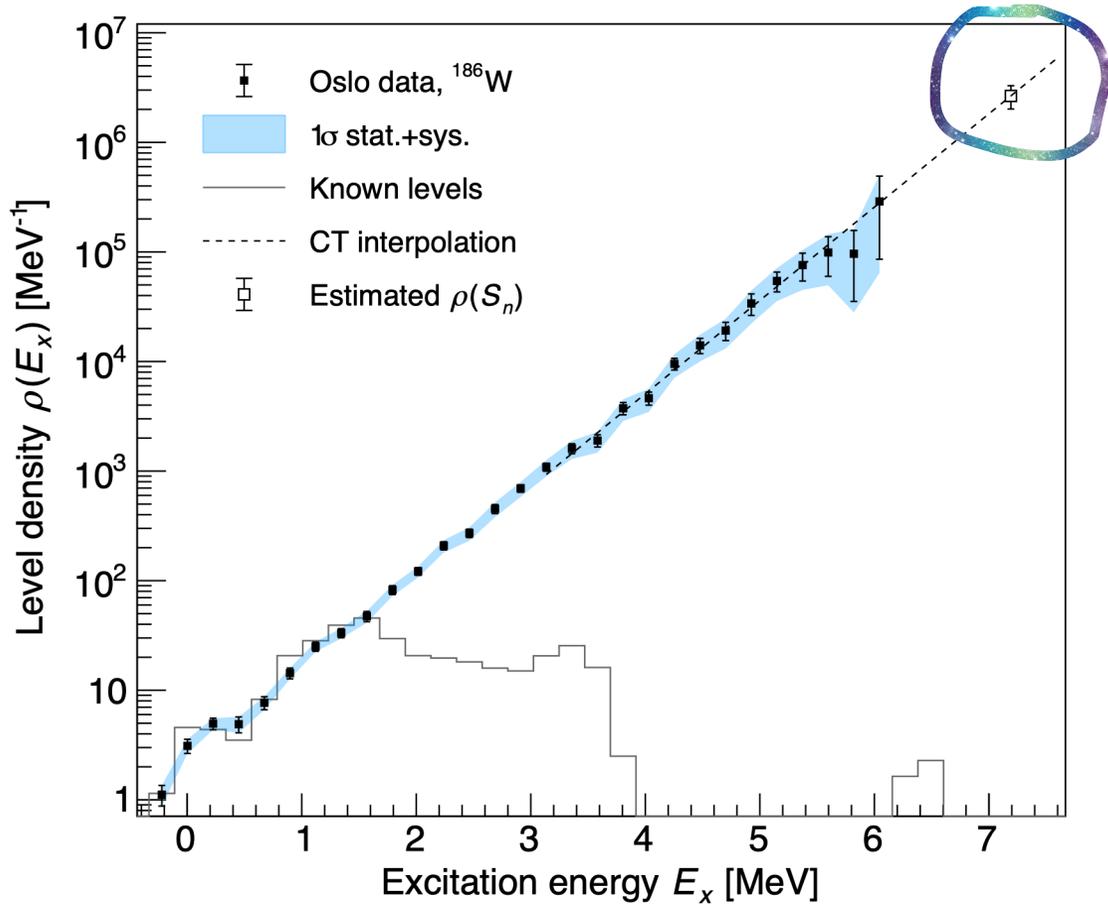
- The parameters  $A$ ,  $B$ , and  $\alpha$  must be determined from external data
- The parameter  $\alpha$  can be found ***from the Oslo data set*** by applying the ***Shape method***

# Step 4: Normalization, NLD

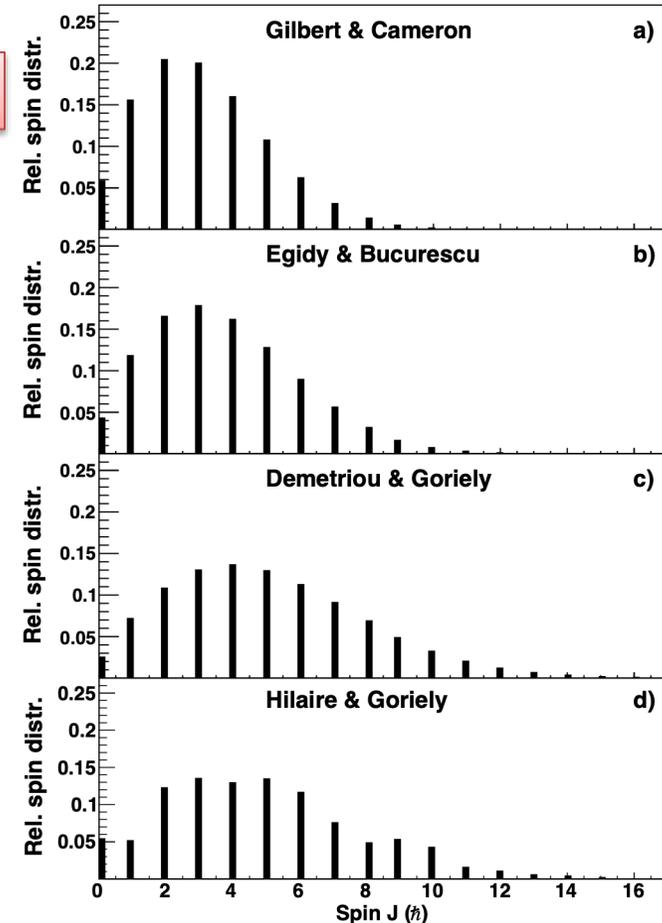
$D_0$ : neutron s-wave spacing;  
 $I_t$ : target spin in  $(n,\gamma)$  reaction;  
 $\sigma$ : spin cutoff parameter

$$\tilde{\rho}(E - E_\gamma) = A \exp[\alpha(E - E_\gamma)] \rho(E - E_\gamma)$$

$$\rho(S_n) = \frac{2\sigma^2}{D_0} \frac{1}{(I_t + 1)\exp[-(I_t + 1)^2 / 2\sigma^2] + I_t \exp[-I_t^2 / 2\sigma^2]}$$



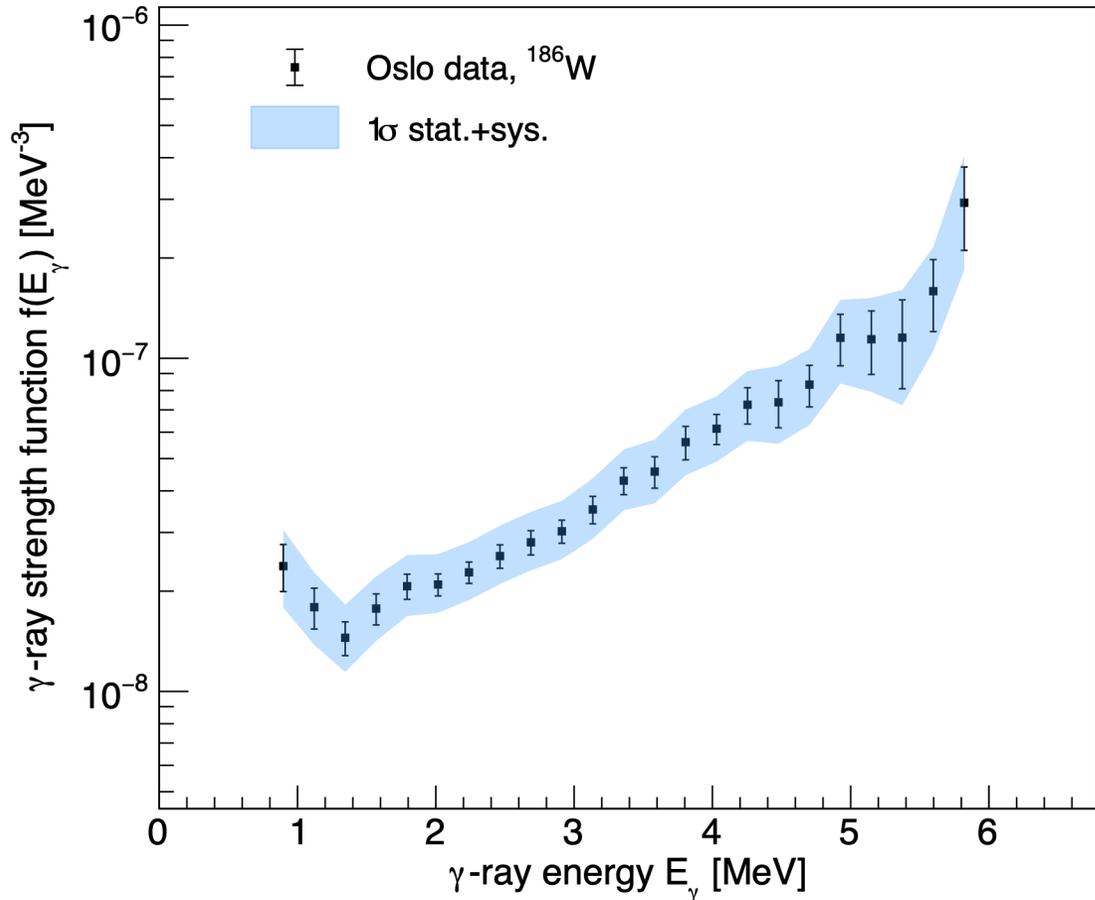
<sup>44</sup>Sc,  $E_x = 8$  MeV



<sup>186</sup>W( $\alpha,\alpha'\gamma$ )<sup>186</sup>W [Larsen et al., PRC **108**, 025804 (2023)]

# Step 4: Normalization, $\gamma$ SF

$$\tilde{\mathcal{I}}(E_\gamma) = B \exp(\alpha E_\gamma) \mathcal{I}(E_\gamma)$$



$^{186}\text{W}(\alpha, \alpha'\gamma)^{186}\text{W}$  [Larsen et al., PRC **108**, 025804 (2023)]

- The slope is already given by the level-density normalization
- Now we assume:

$$B \mathcal{I}(E_\gamma) = B \sum_{XL} \mathcal{I}_{XL}(E_\gamma) \approx B[\mathcal{I}_{E1}(E_\gamma) + \mathcal{I}_{M1}(E_\gamma)]$$

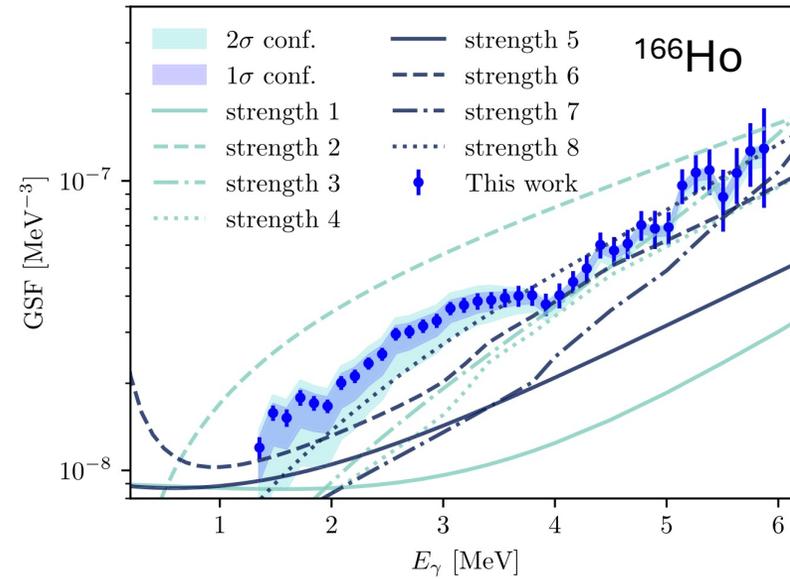
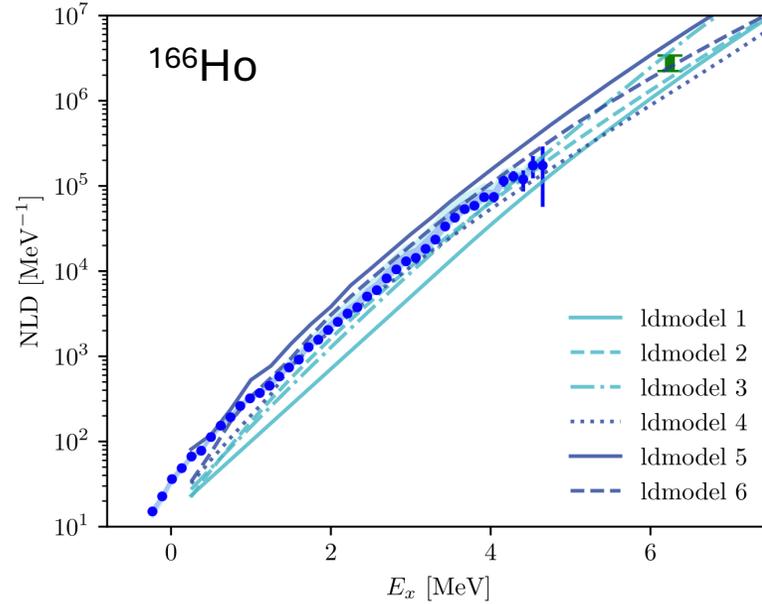
- Then we can use:

$$\begin{aligned} &\langle \Gamma_\gamma(S_n, I_t \pm 1/2, \pi_t) \rangle \\ &= \frac{B}{4\pi\rho(S_n, I_t \pm 1/2, \pi_t)} \int_{E_\gamma=0}^{S_n} dE_\gamma \mathcal{I}(E_\gamma) \\ &\quad \times \rho(S_n - E_\gamma) \sum_{J=-1}^1 g(S_n - E_\gamma, I_t \pm 1/2 + J). \end{aligned}$$

# Odd rare-earth nuclei: $^{166,167}\text{Ho}$

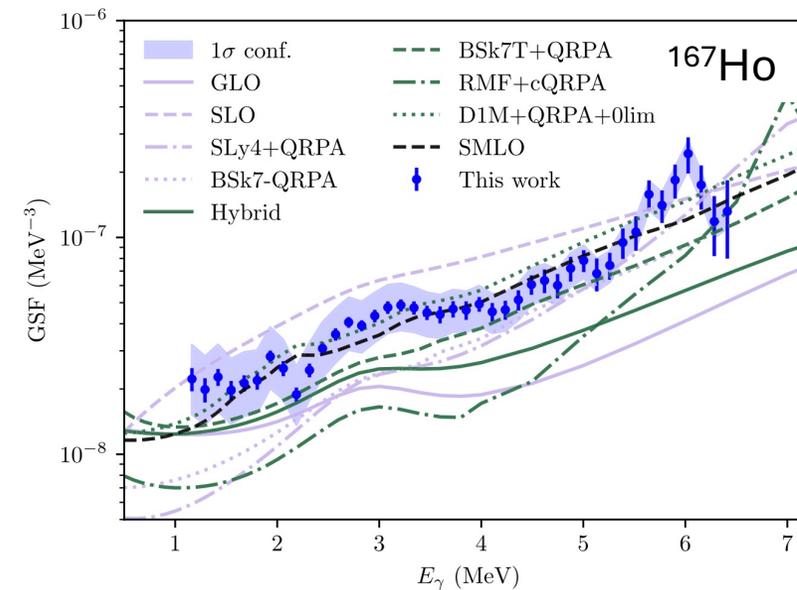
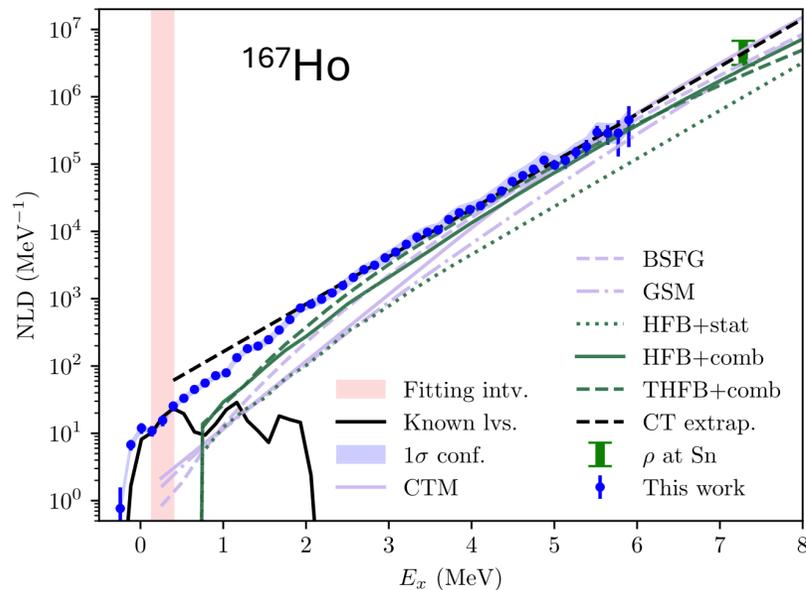
$^{163}\text{Dy}(\alpha, p\gamma)^{166}\text{Ho}$

Pogliano et al.,  
Phys. Rev. C. **107**,  
034605 (2023)



$^{164}\text{Dy}(\alpha, p\gamma)^{167}\text{Ho}$

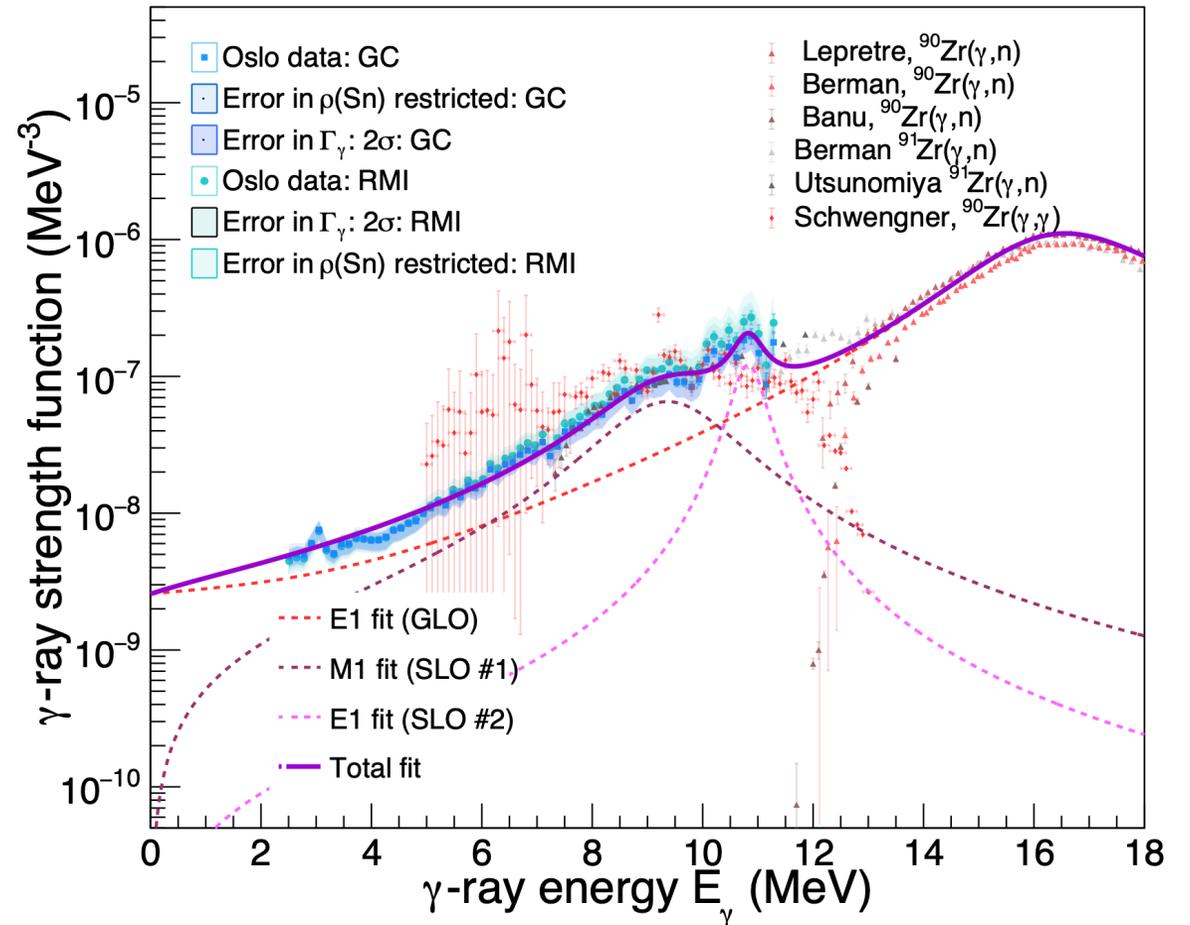
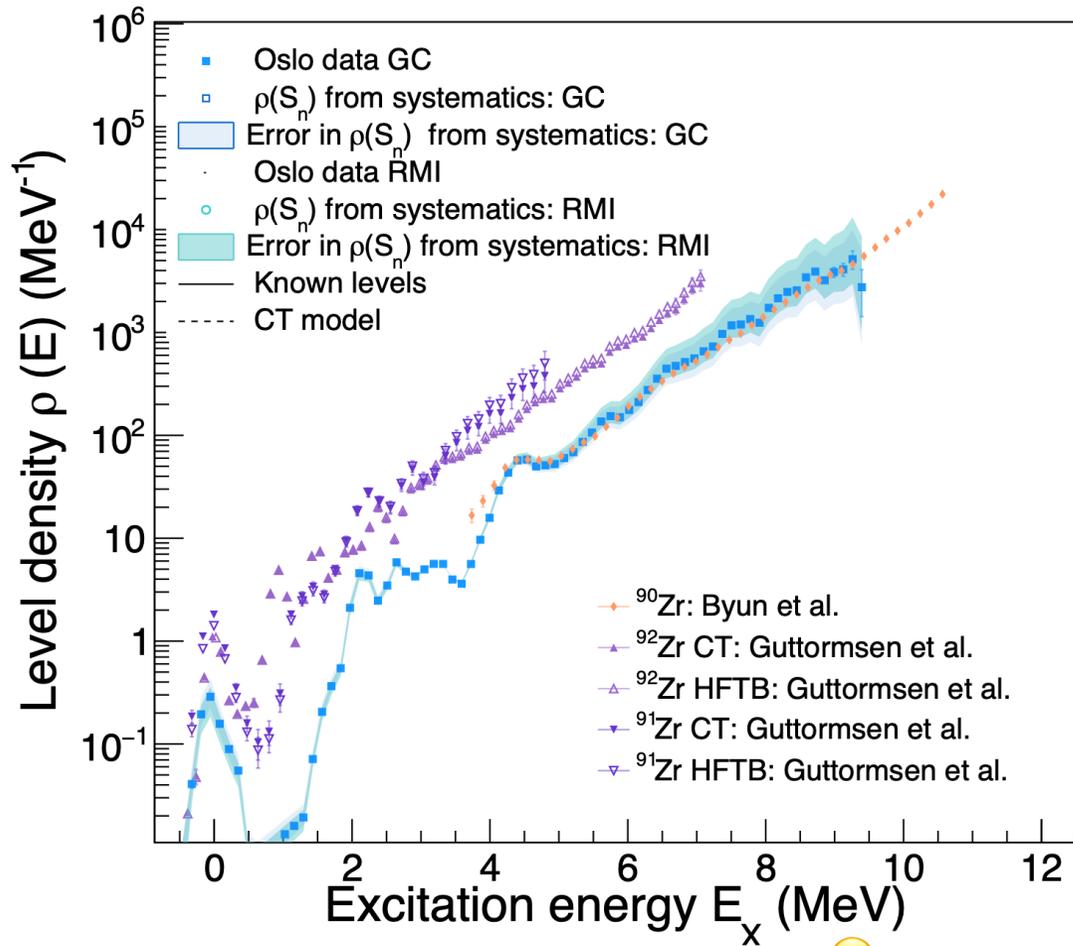
Pogliano et al.,  
Phys. Rev. C. **107**,  
064614 (2023)



TALYS 1.96

# $^{90}\text{Zr}$

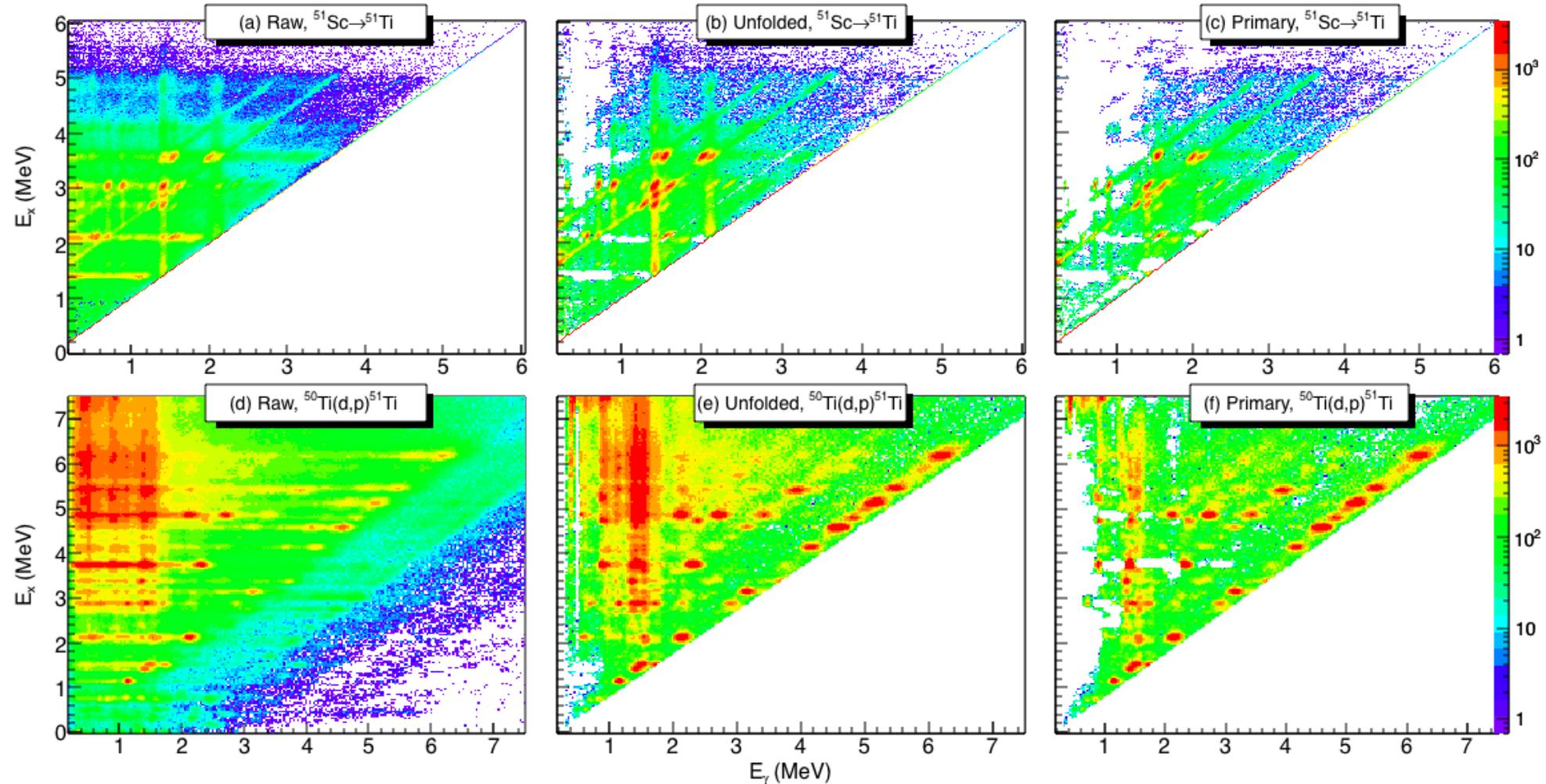
$^{90}\text{Zr}(p,p'\gamma)^{90}\text{Zr}$ ,  $E_p = 17$  MeV [with CACTUS, experiment from 2009]. Lauren T. Bell et al, submitted to PRC (2025), in review



NLD in good agreement with Ohio data! 😊

# Benchmarking Oslo and beta-Oslo methods

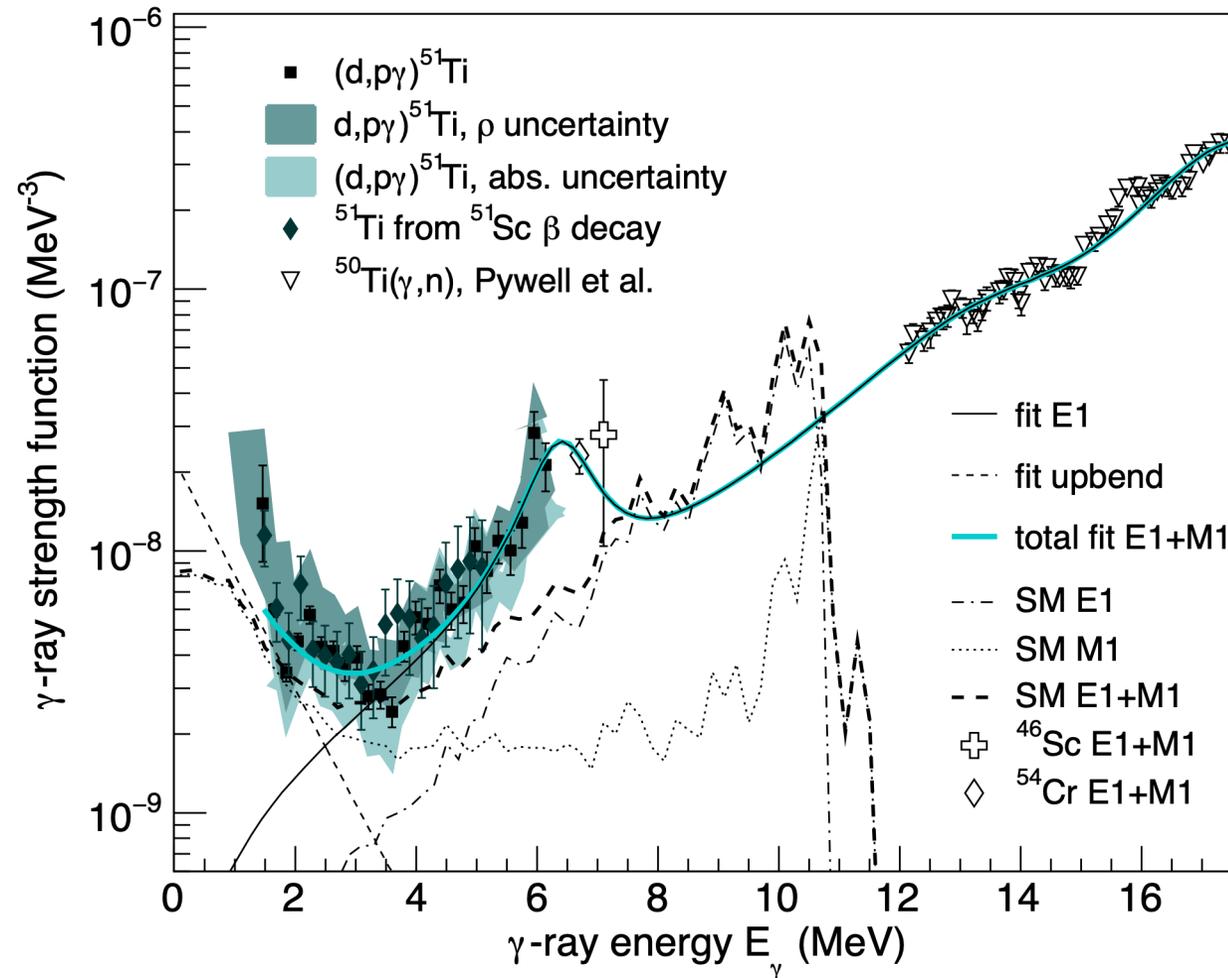
Discretionary beam time @ NSCL/MSU, February 2015;  $^{51}\text{Sc}$  beta-decaying into  $^{51}\text{Ti}$   
Q-value, beta-decay: 6.503 MeV;  $S_n = 6.372$  MeV. Also:  $^{50}\text{Ti}(d,p\gamma)^{51}\text{Ti}$  @ OCL.



# Benchmarking Oslo and beta-Oslo methods

Almost the same spin range of final levels

Shell-model calculations by Jørgen E. Midtbø using KSHELL (Shimizu, <https://arxiv.org/abs/1310.5431>)



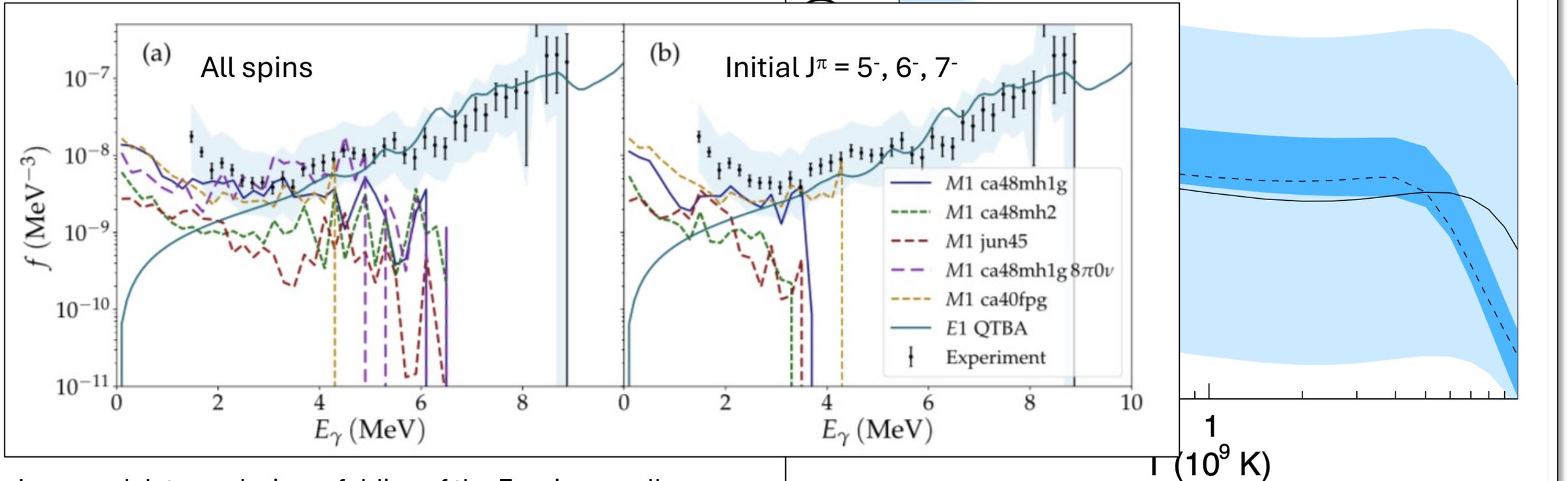
# The beta-Oslo method: $^{70}\text{Co} \rightarrow ^{70}\text{Ni}$

Discretionary beam time @ NSCL/MSU, Feb 2015;  $^{70}\text{Co}$  beta-decaying into  $^{70}\text{Ni}$

$^{70}\text{Co}$  g.s.  $T_{1/2}$ : 105 ms,  $I^\pi = 6^-$ ,  $Q_\beta = 12.3$  MeV  
 $S_n$  of  $^{70}\text{Ni}$ : 7.3 MeV  
 Initial spins,  $^{70}\text{Ni}$ :  $5^-, 6^-, 7^-$

$10^7$   $^{69}\text{Ni}(n,\gamma)^{70}\text{Ni}$  rate

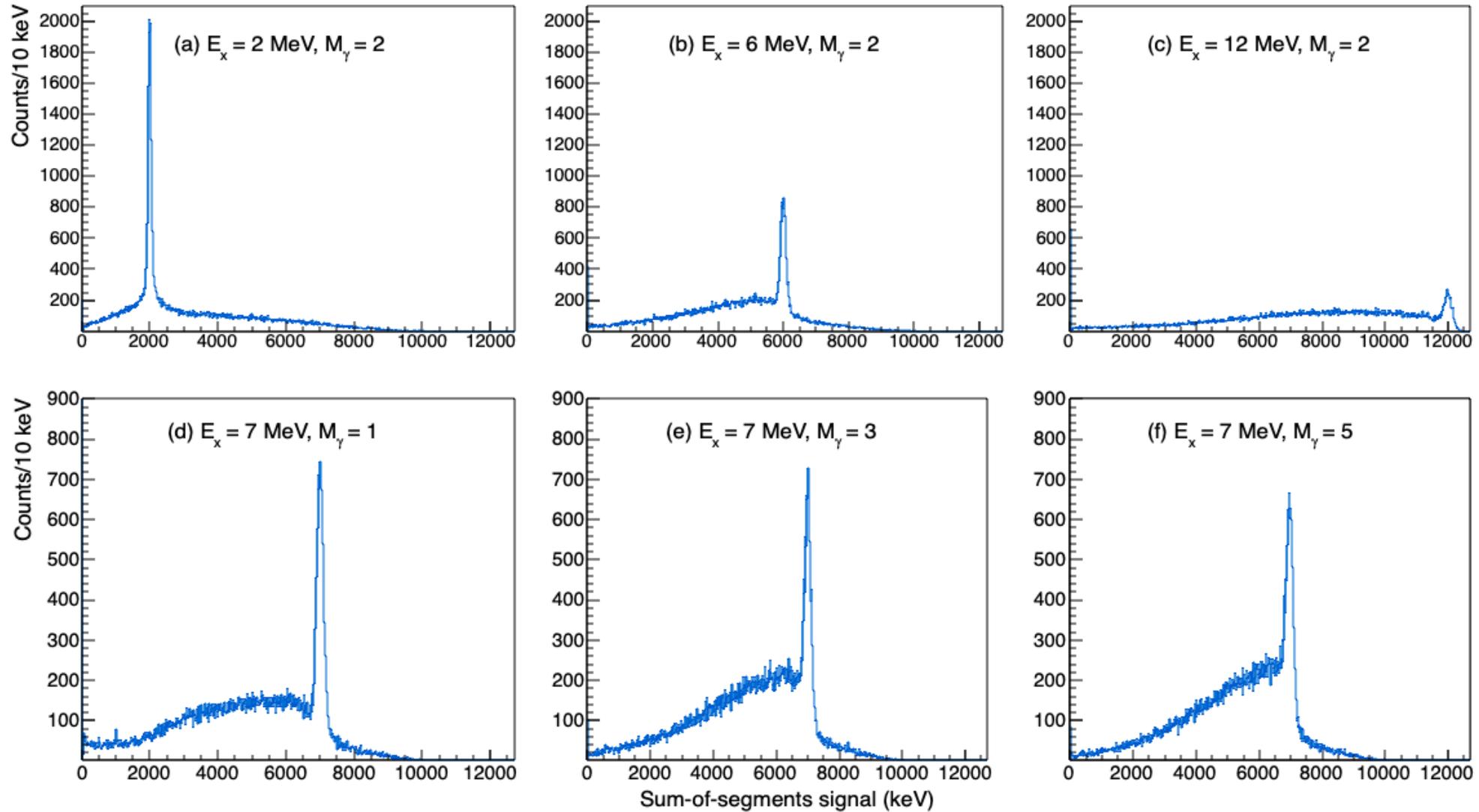
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Improved data analysis: unfolding of the  $E_x$  axis as well

[Larsen, Midtbø, Guttormsen, Renstrøm, Liddick, Spyrou et al., PRC **97**, 054329 (2018)]

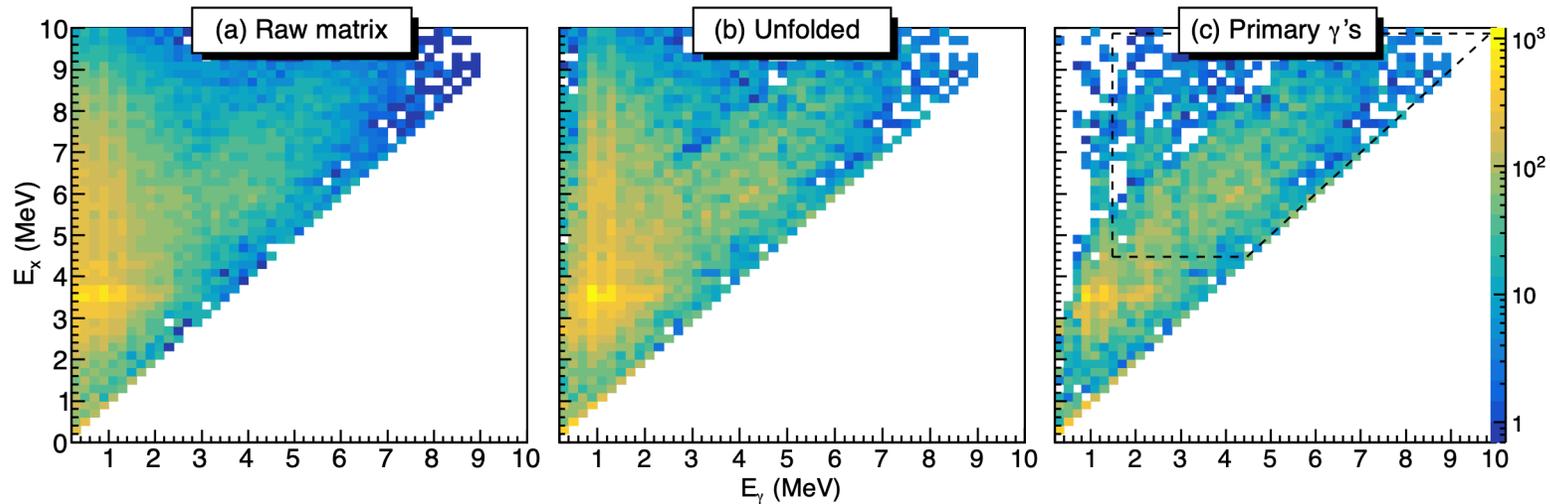
# Unfolding of Ex axis: $^{70}\text{Ni}$ Ex response function



# Unfolding of Ex axis: $^{70}\text{Ni}$

Correction for incomplete summing and electron background [M. Guttormsen et al., in preparation (2025)]

Old:



New:

