The beta-Oslo method and neutron-capture rates for heavy-element nucleosynthesis

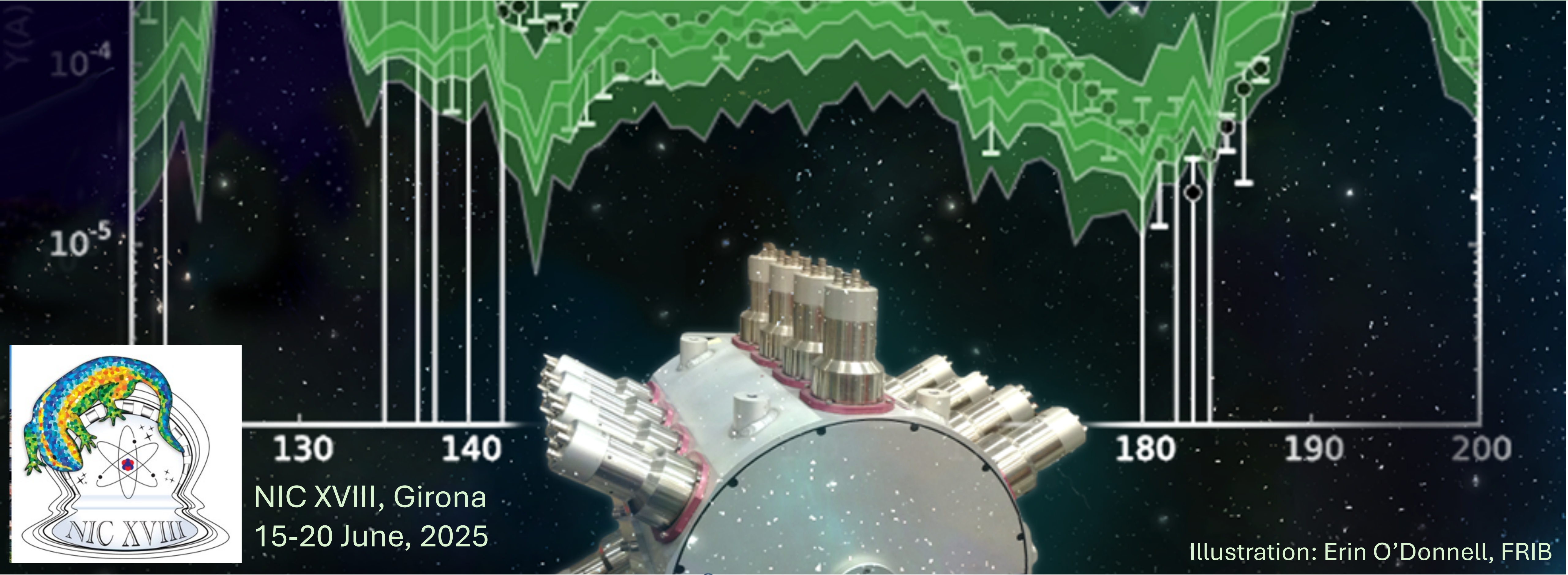


Illustration: Erin O'Donnell, FRIB

NIC XVIII, Girona
15-20 June, 2025

Ann-Cecilie Larsen

RCN Project No. 316116, NNRC Project No. 341985

UiO : Department of Physics
University of Oslo

The Research Council of Norway
Norwegian Nuclear Research Centre
NUKLEÆRSENTERET
IReNA
JINA–CEE
ChETEC INFRA

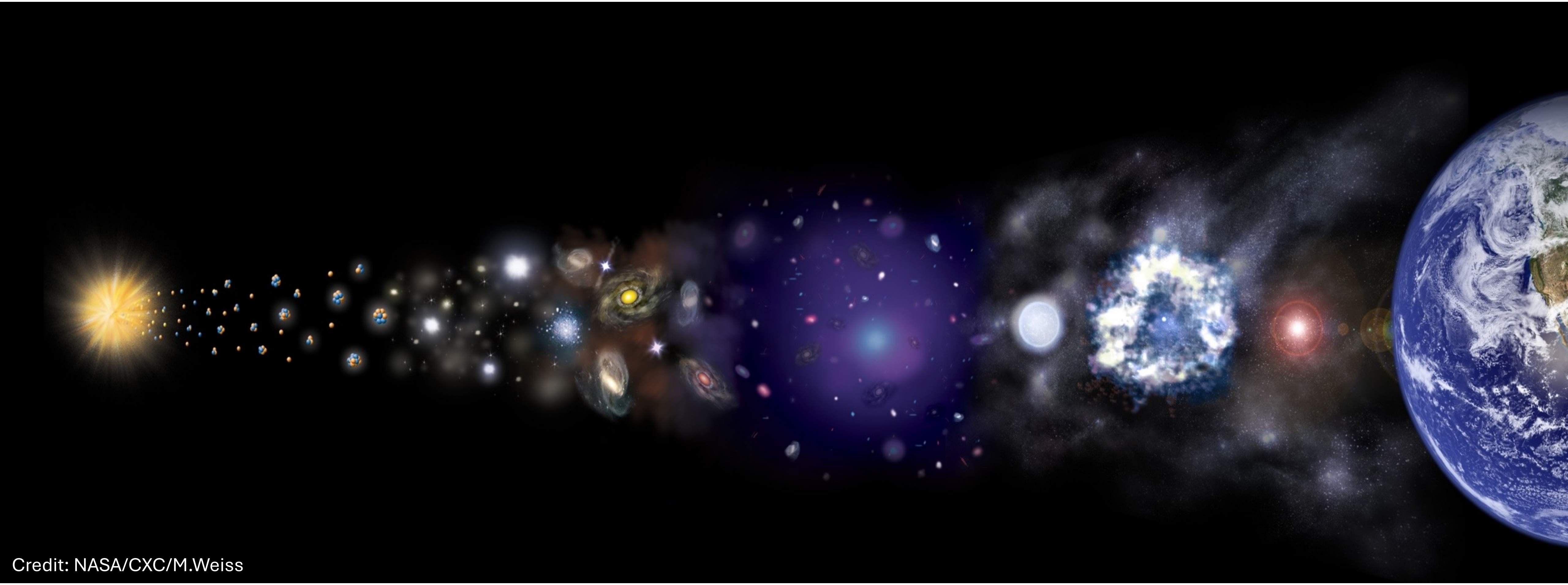
Many thanks to

- M. Guttormsen, A. Görgen, K.C.W. Li, V.W. Ingeberg, E. Sahin, S. Siem and everyone at the nuclear-physics group, Department of Physics, University of Oslo
- M. Hjorth-Jensen, A. Kvellestad, Department 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
- The CARIBU group (especially Daniel Santiago & Guy Savard), Jason Clark, Calem Hoffmann, Argonne National Lab
- Alexander Voinov, Steve Grimes (Ohio University)
- Dennis Mücher, University of Cologne
- S. Goriely (Université Libre de Bruxelles)
- S. Lyons, Pacific Northwest National Laboratory
- N. Shimizu, University of Tokyo / University of Tsukuba
- H. Utsunomiya, Konan University /Shanghai Advanced Research Institute
- M. Wiedeking (iThemba LABS)
- A. Richard, D.L. Bleuel and A. Sweet, Lawrence Livermore National Lab
- B. Greaves, University of Guelph
- T. H. Ogunbeku, Mississippi State University

From peanutsmovie.com

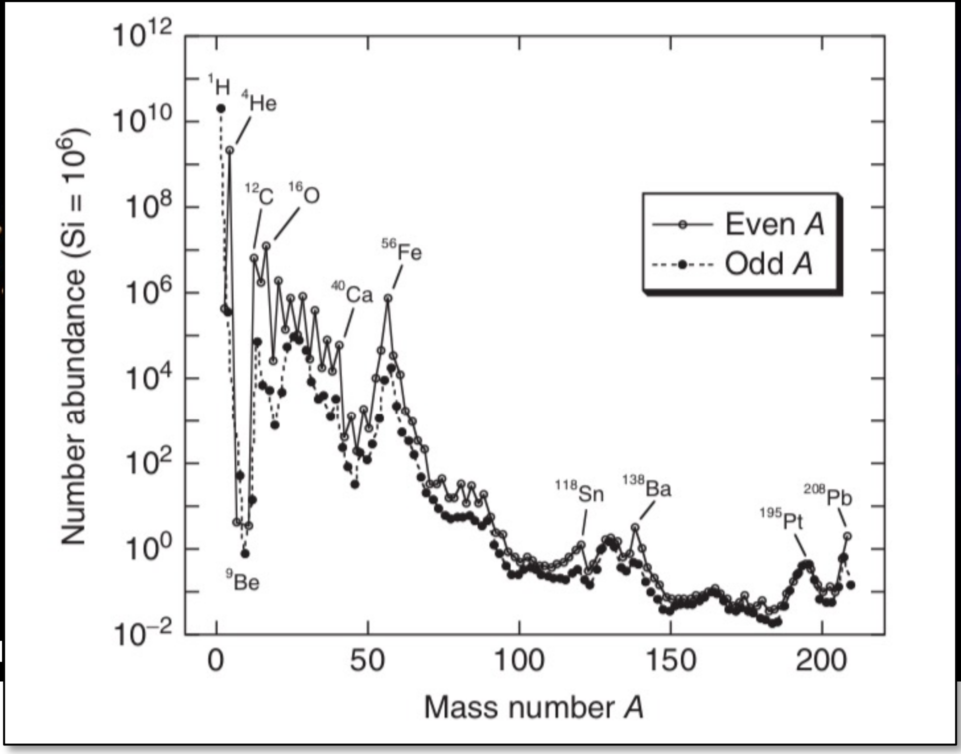
Extra-special thanks to the awesome students and postdocs!!! 🥰

What we see 👀

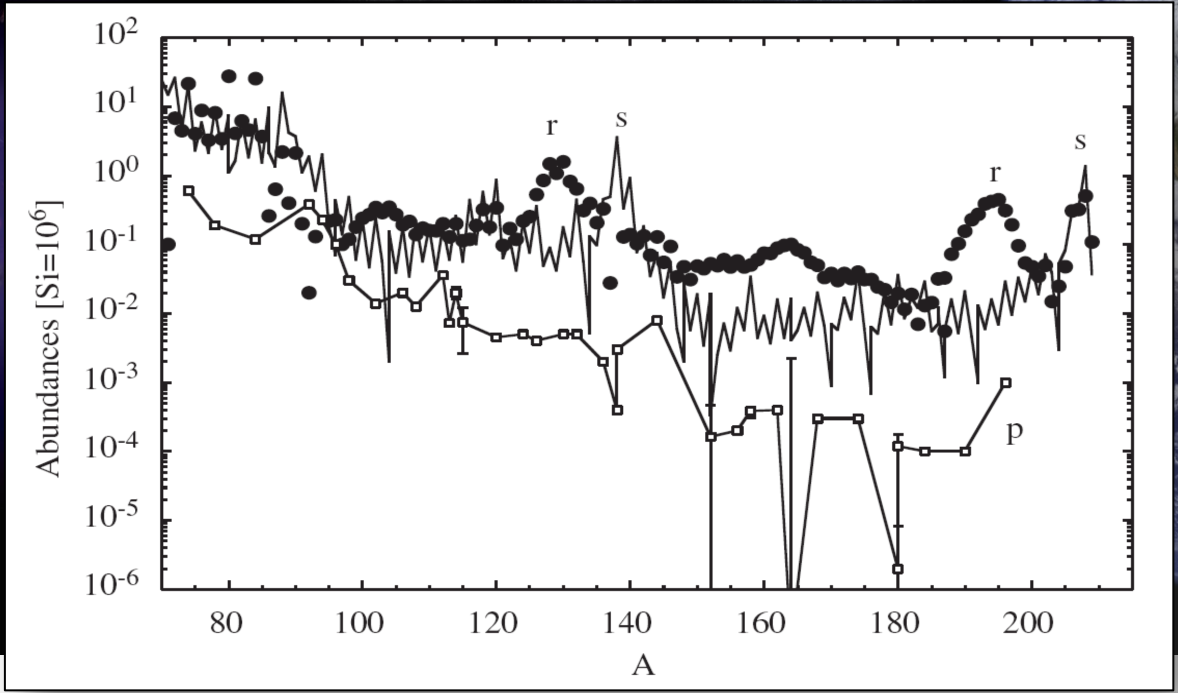


What we see 👀

Credit: NASA/CXC/M



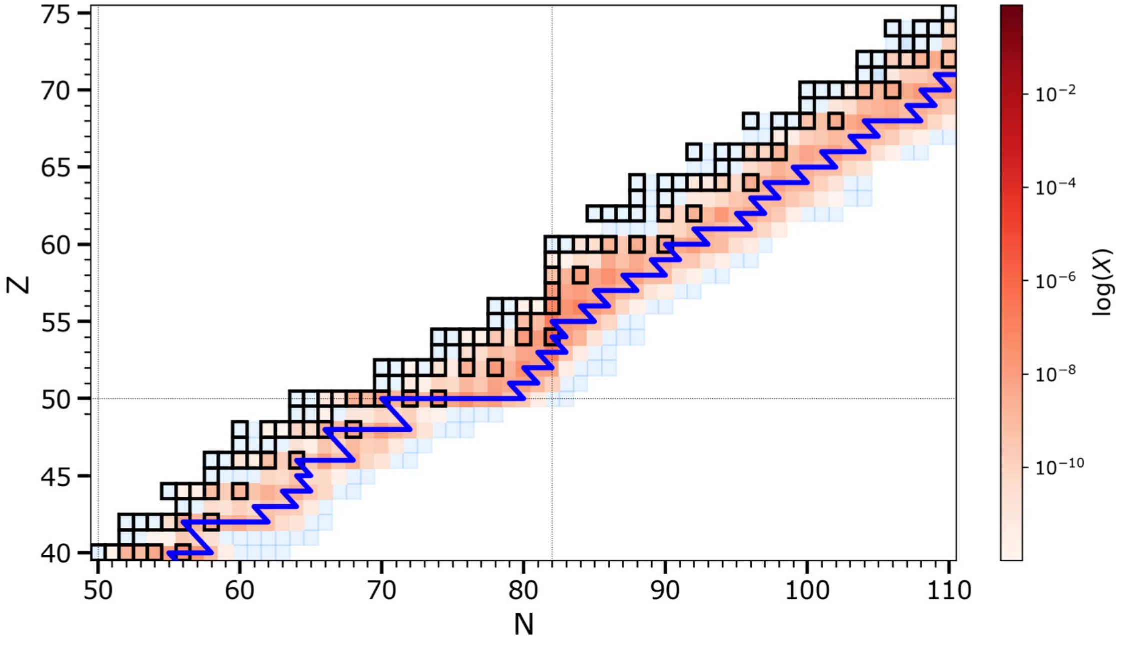
C. Iliadis “Nuclear Physics of Stars”



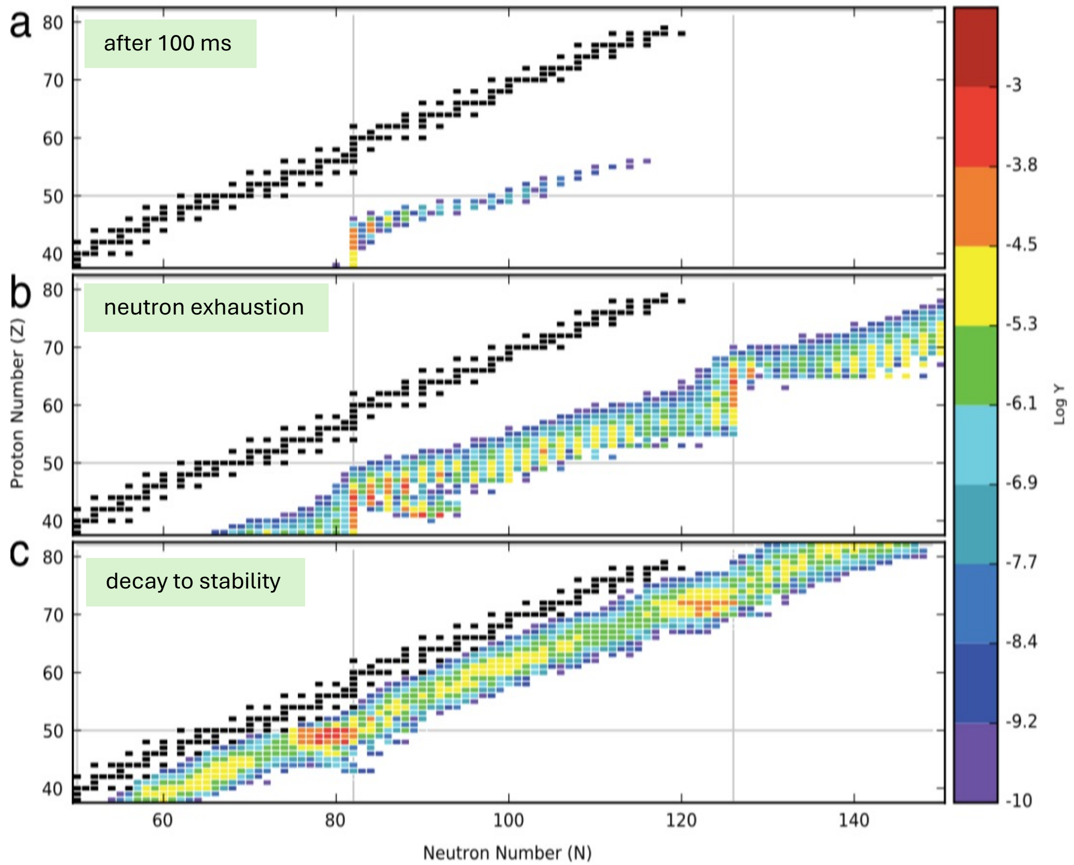
M. Arnould, S. Goriely, and K.Takahashi,
Phys. Rep. **450**, 97 (2007)

Heavy-element nucleosynthesis where neutron capture reactions are particularly important

- Slow n-cap. process
- Rapid n-cap. process
- Intermediate n-cap. process



i-process simulation, N_n = 5 x 10^{14} cm^{-3}
[Goriely, Siess, Choplin, A&A 654, A129 (2021)]

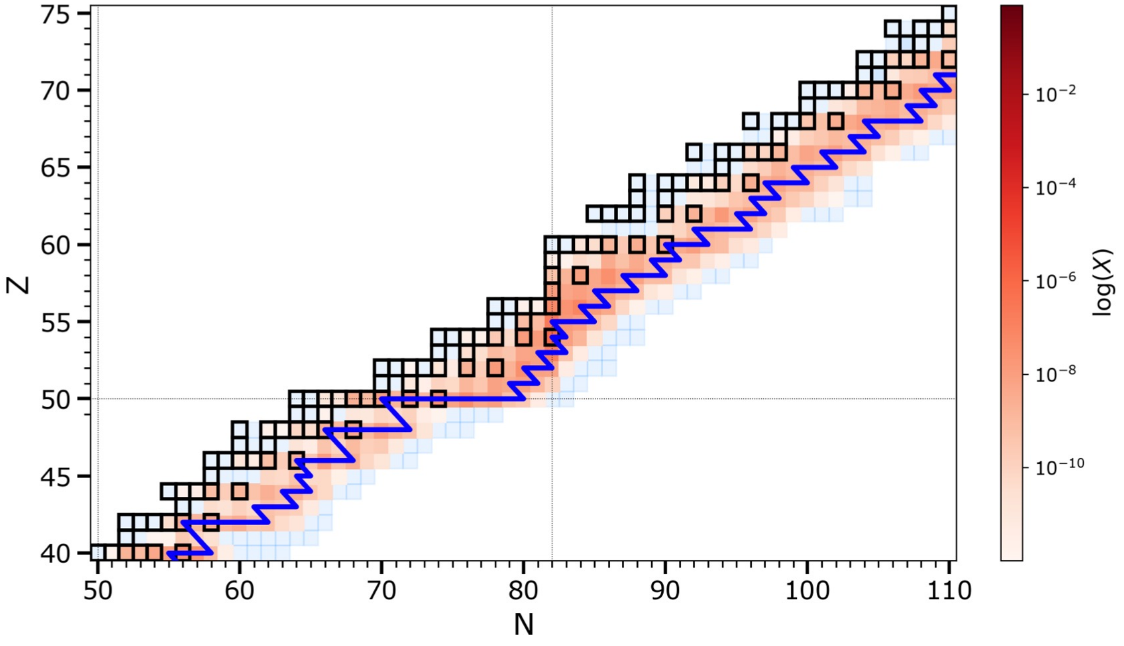


Snapshots , *r* process in neutron star collision [one trajectory!]
Mumpower, Surman, McLaughlin, Aprahamian, Prog.Part. Nucl. Phys. 86, 86 (2016)

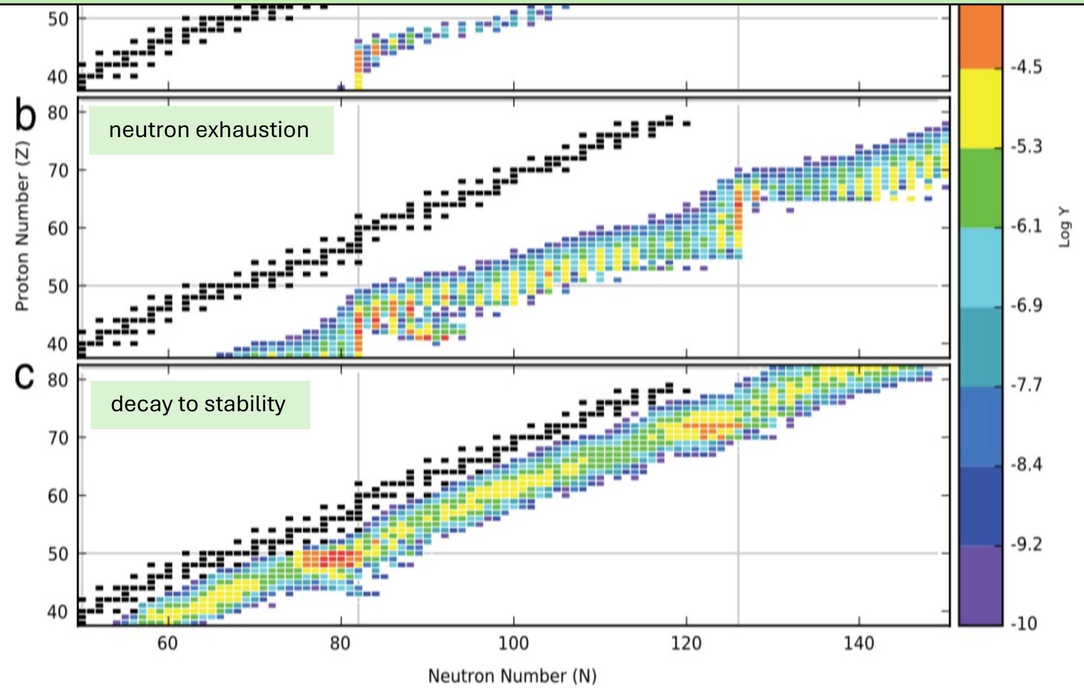
Heavy-element nucleosynthesis where neutron capture reactions are particularly important

- Slow n-cap. process
- Rapid n-cap. process
- Intermediate n-cap. process

All of them involve neutron-capture rates on unstable nuclei:
- s process: a few nuclei (branch points)
- r process: many extremely neutron rich nuclei
- i process: many moderately neutron-rich nuclei



i-process simulation, $N_n = 5 \times 10^{14}$ cm^{-3}
[Goriely, Siess, Choplin, A&A 654, A129 (2021)]



Snapshots , *r* process in neutron star collision [one trajectory!]
Mumpower, Surman, McLaughlin, Aprahamian, Prog.Part. Nucl. Phys. 86, 86 (2016)

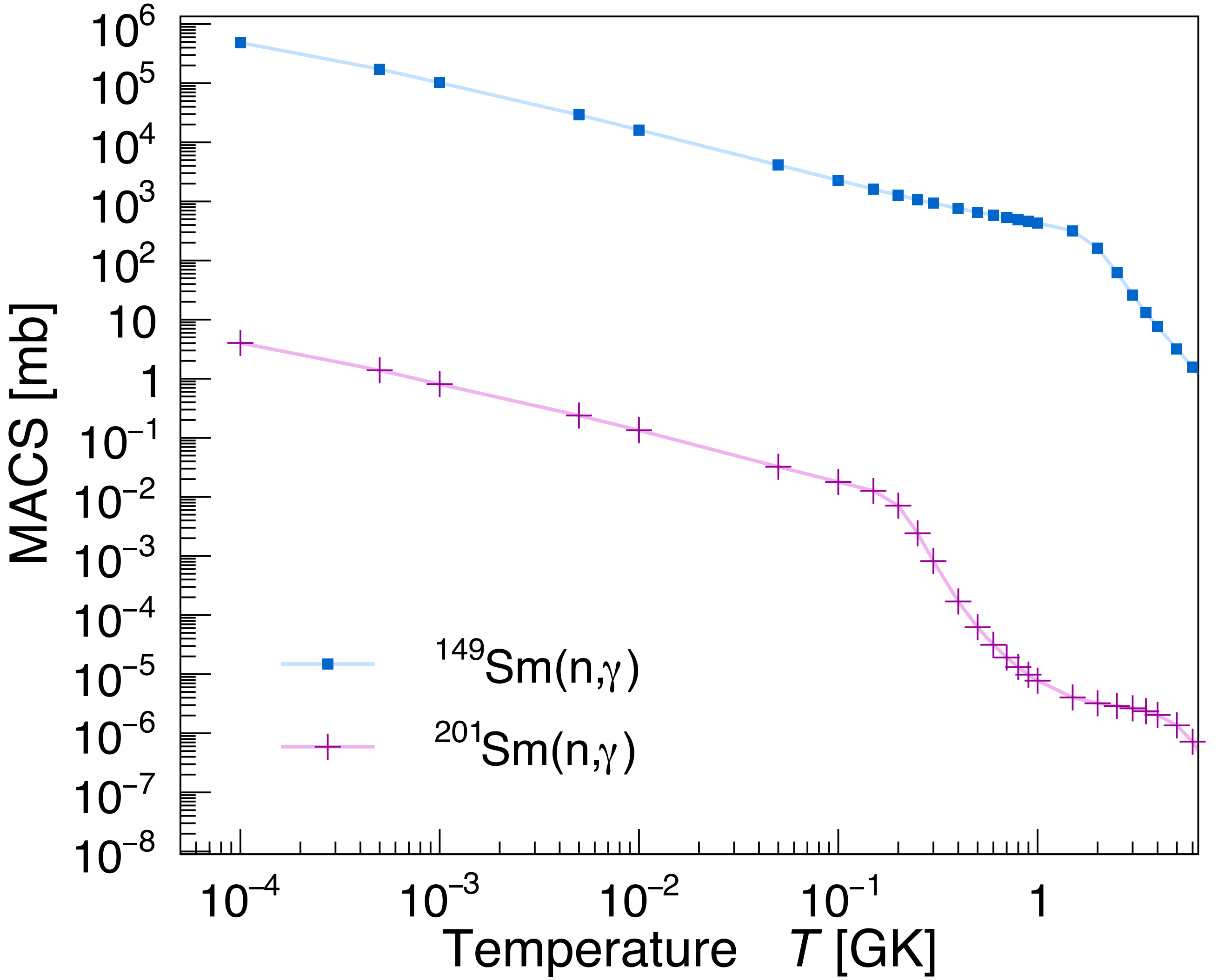
Problems 🤔

- Unstable nuclei are very difficult (or impossible) to make into proper targets for neutron-capture experiments
- Free neutrons are unstable, so we cannot easily make a neutron target for e.g. inverse-kinematics experiments

Problems 🤔

- Unstable nuclei are very difficult (or impossible) to make into proper targets for neutron-capture experiments
- Free neutrons are unstable, so we cannot easily make a neutron target for e.g. inverse-kinematics experiments
- The more neutron-rich the target nucleus, the smaller the neutron-capture cross section → background will dominate, even if we were able to make a neutron-rich nucleus interact with neutrons for measuring neutron-capture cross sections

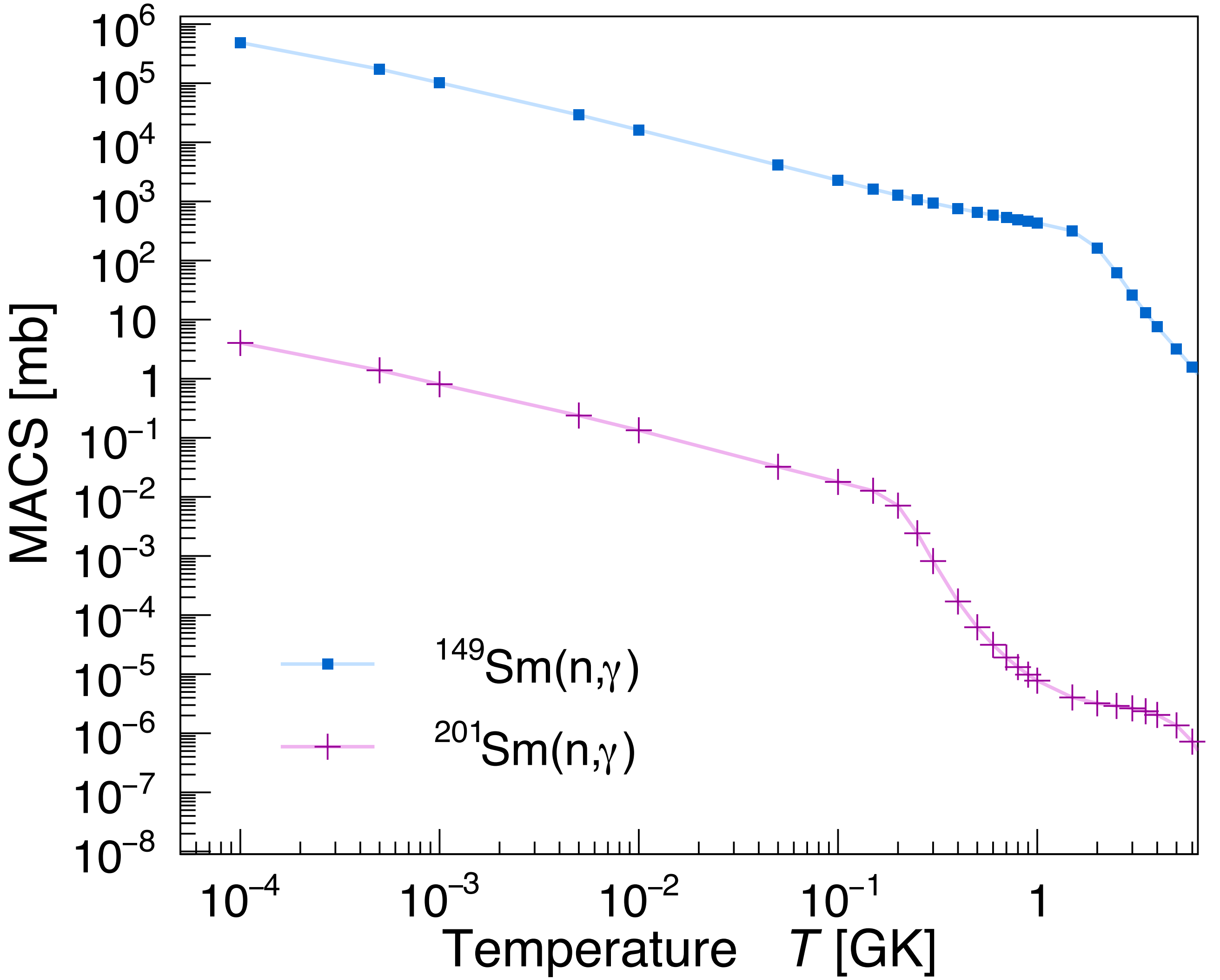
[Calculations with the TALYS reaction code]



Problems 🤔

- Unstable nuclei are very difficult (or impossible) to make into proper targets for neutron-capture experiments
- Free neutrons are unstable, so we cannot easily make a neutron target for e.g. inverse-kinematics experiments
- The more neutron-rich the target nucleus, the smaller the neutron-capture cross section → background will dominate, even if we were able to make a neutron-rich nucleus interact with neutrons for measuring neutron-capture cross sections

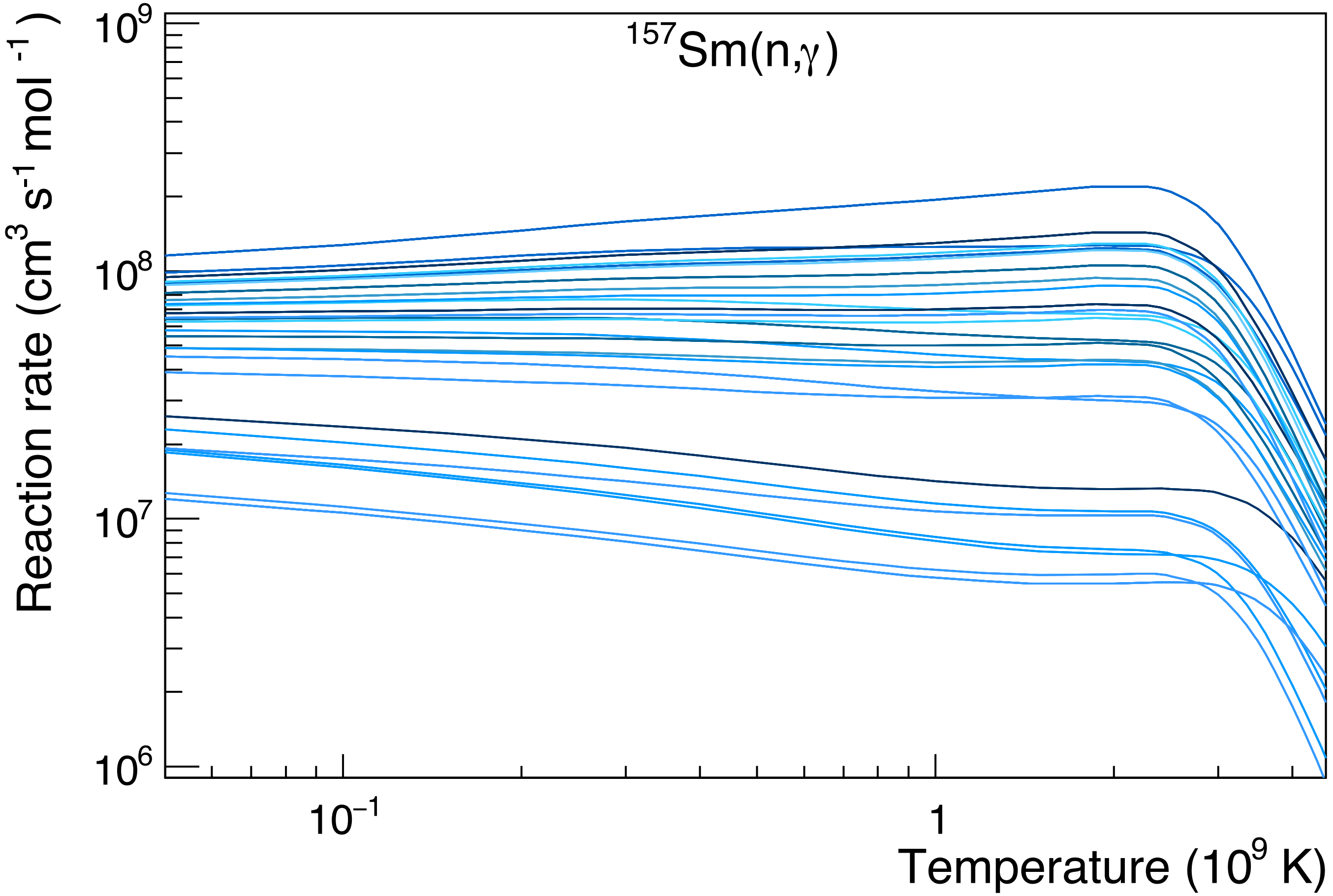
[Calculations with the TALYS reaction code]



So, let's just calculate the neutron capture rates! Or...?

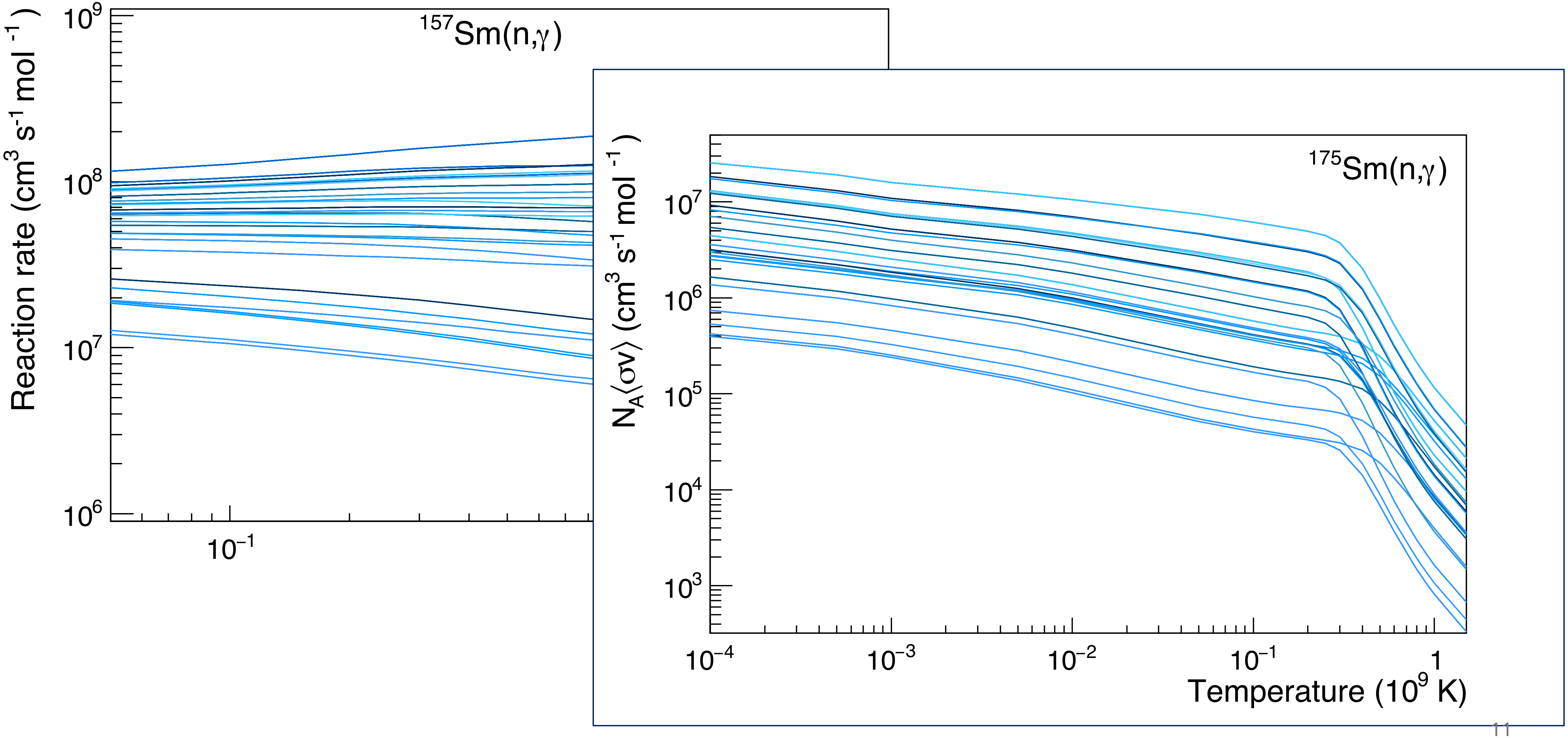
Theoretical ^{157}Sm(n,γ) and ^{175}Sm(n,γ) reaction rates

[Calculations with the TALYS reaction code]



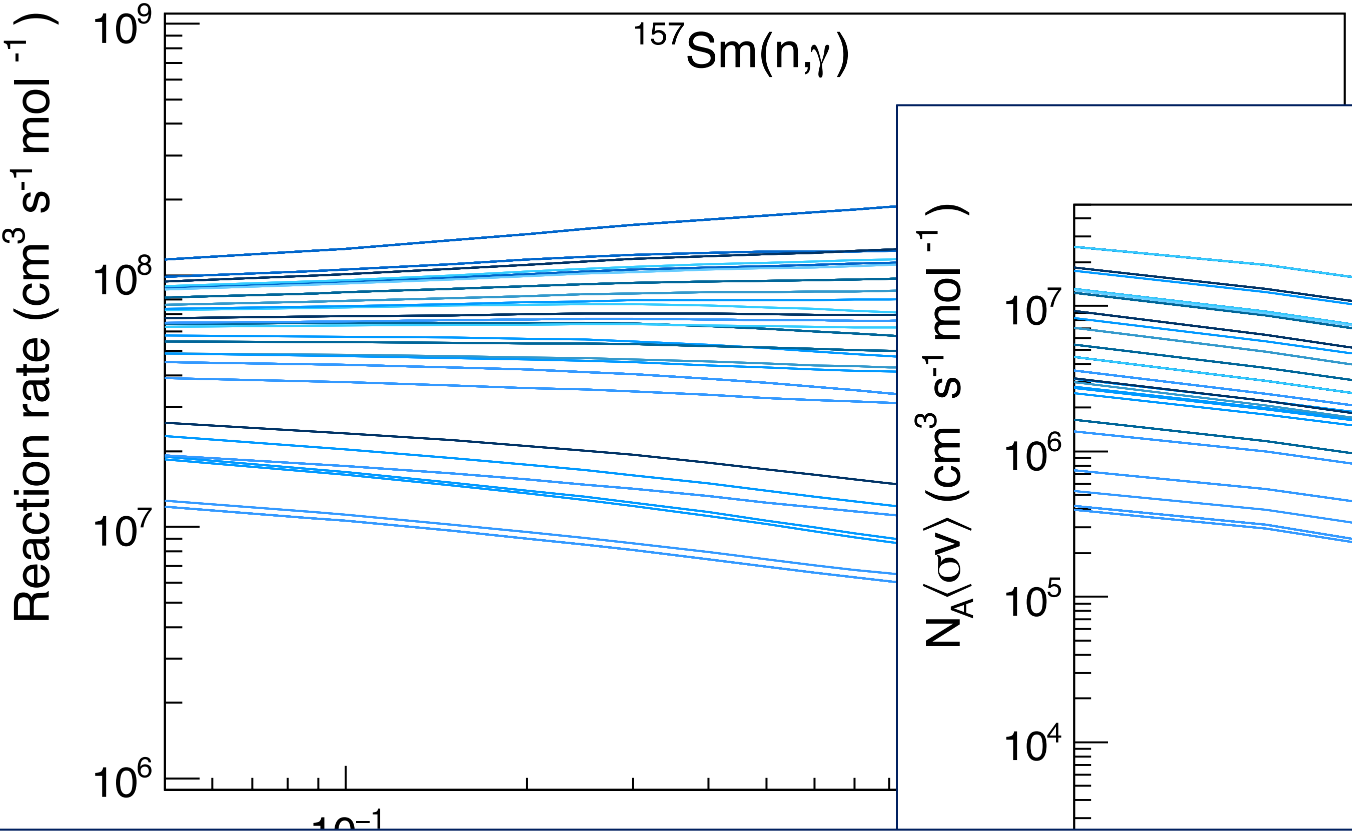
Theoretical $^{157}Sm(n,\gamma)$ and $^{175}Sm(n,\gamma)$ reaction rates

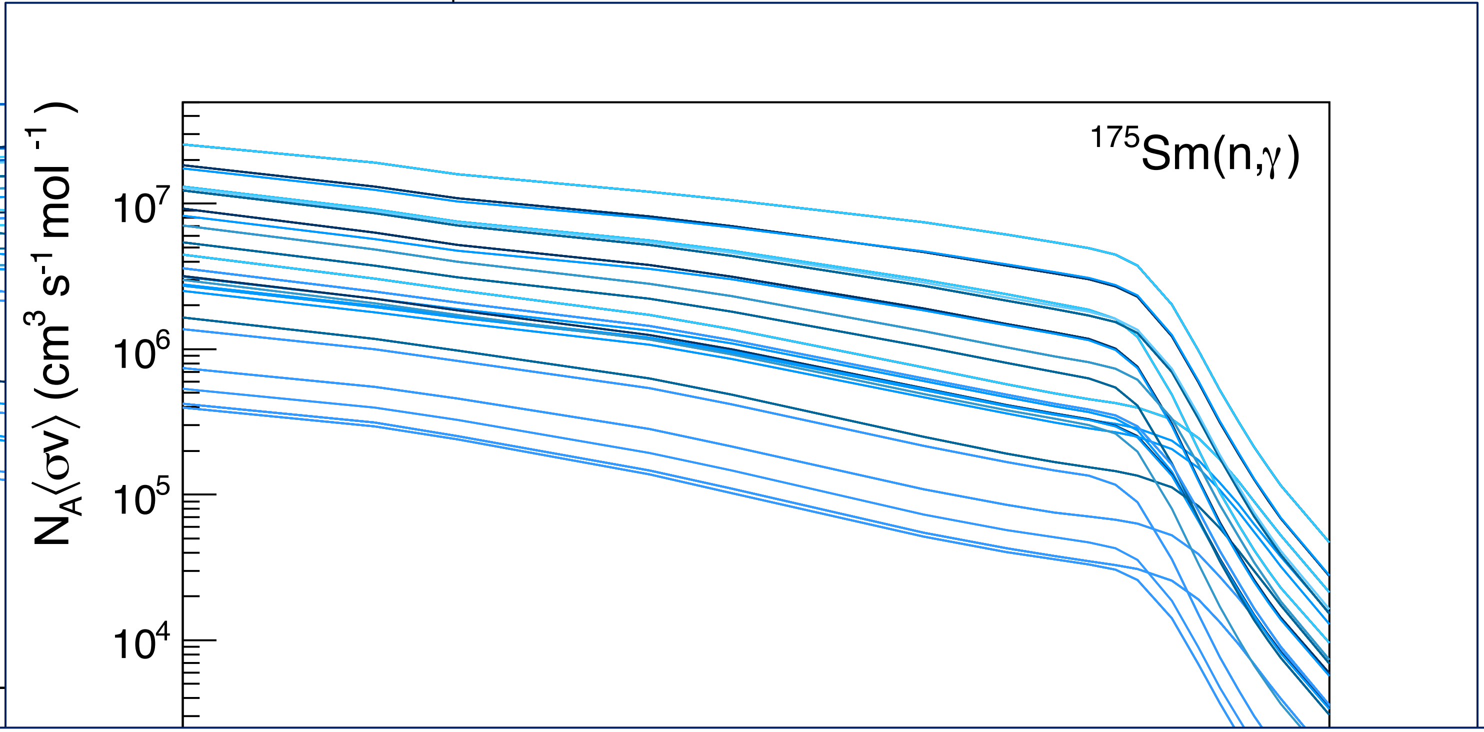
[Calculations with the TALYS reaction code]



Theoretical ^{157}Sm(n,γ) and ^{175}Sm(n,γ) reaction rates

[Calculations with the TALYS reaction code]





How to treat these uncertainties?

1) Monte Carlo approach: e.g. Mumpower et al., Prog. Part. Nucl. Phys. **86**, 86 (2016), Denissenkov et al., J. Phys. G: Nucl. Part. Phys. **45**, 055203 (2018)

2) Systematic treatment, masses & β-decay, many trajectories: Kullmann et al., MNRAS 523, 2551 (2023)

3) Systematic treatment, level density and gamma-strength: Pogliano & Larsen, PRC **108**, 025807 (2023)

The solution 💡

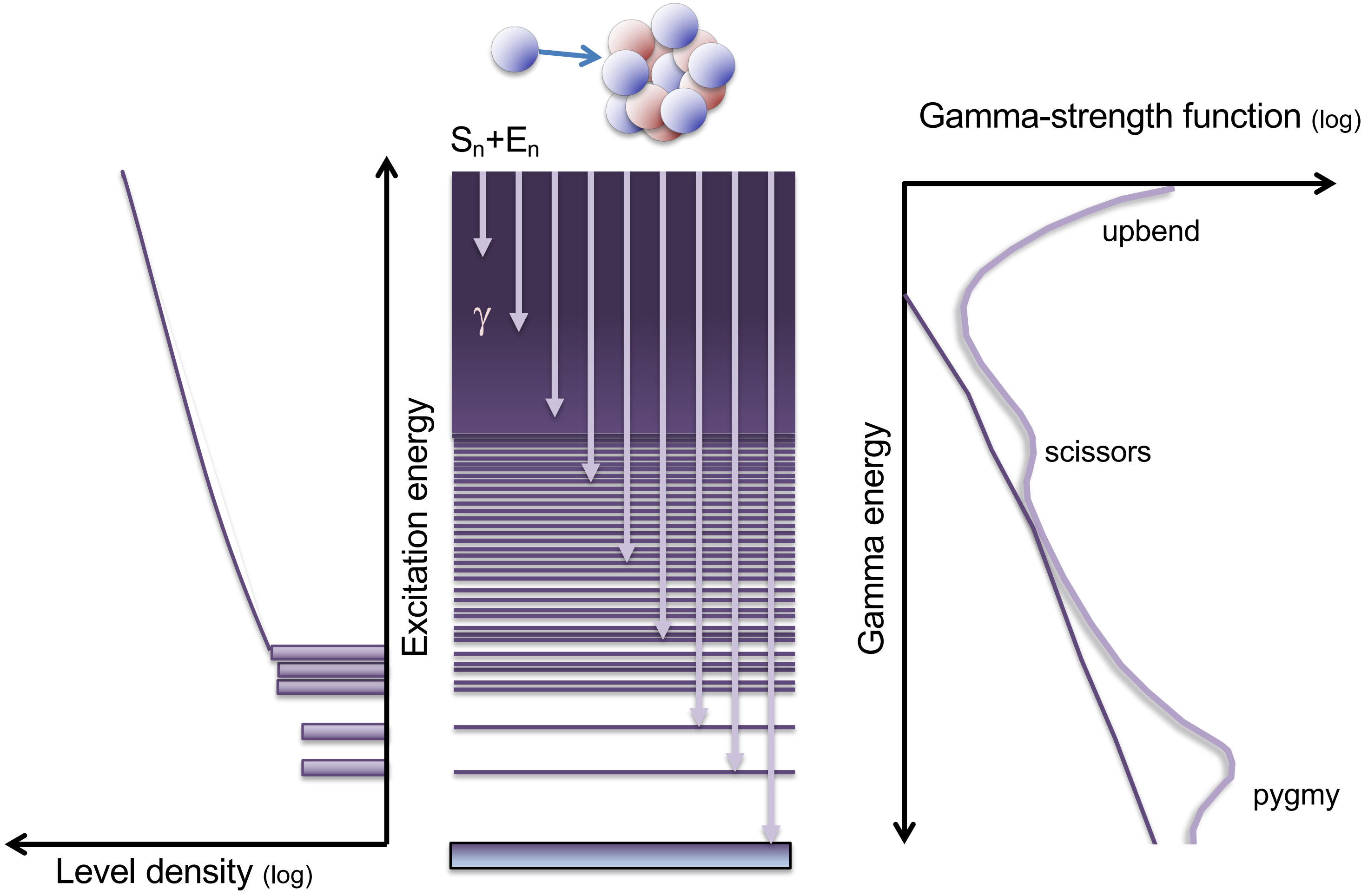
- Use ***indirect methods*** to get experimental constraints on the (n,γ) cross section
- The surrogate method, with variations:
  - direct capture: e.g. Gaudefroy et al, Eur. Phys. J. A **27**, 309 (2006), Jones et al., Nature **465**, 454 (2010), Kozub et al., PRL **109**, 172501 (2012), ...]
  - Compound-nucleus capture: e.g. Escher et al., PRL **121**, 052501 (2018), Ratkiewicz et al., PRL **122**, 052502 (2019), ...]
- Measure E1 strength with Coulomb dissociation [e.g. Uberseder et al., PRL 112, 211101 (2014)]
- Measure nuclear level density and gamma-decay strength:
  - The Oslo method (for nuclei not too far from stability) [coming slides]
  - The inverse-kinematics Oslo method [Ingeberg et al., EPJA 56, 68 (2020) and PRC **111**, 015803 (2025)]
  - **The beta-Oslo method** 🥳 [coming slides]

Nuclear-physics input: (n,γ) reaction rates

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

-> "Compound nucleus" picture of Bohr

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

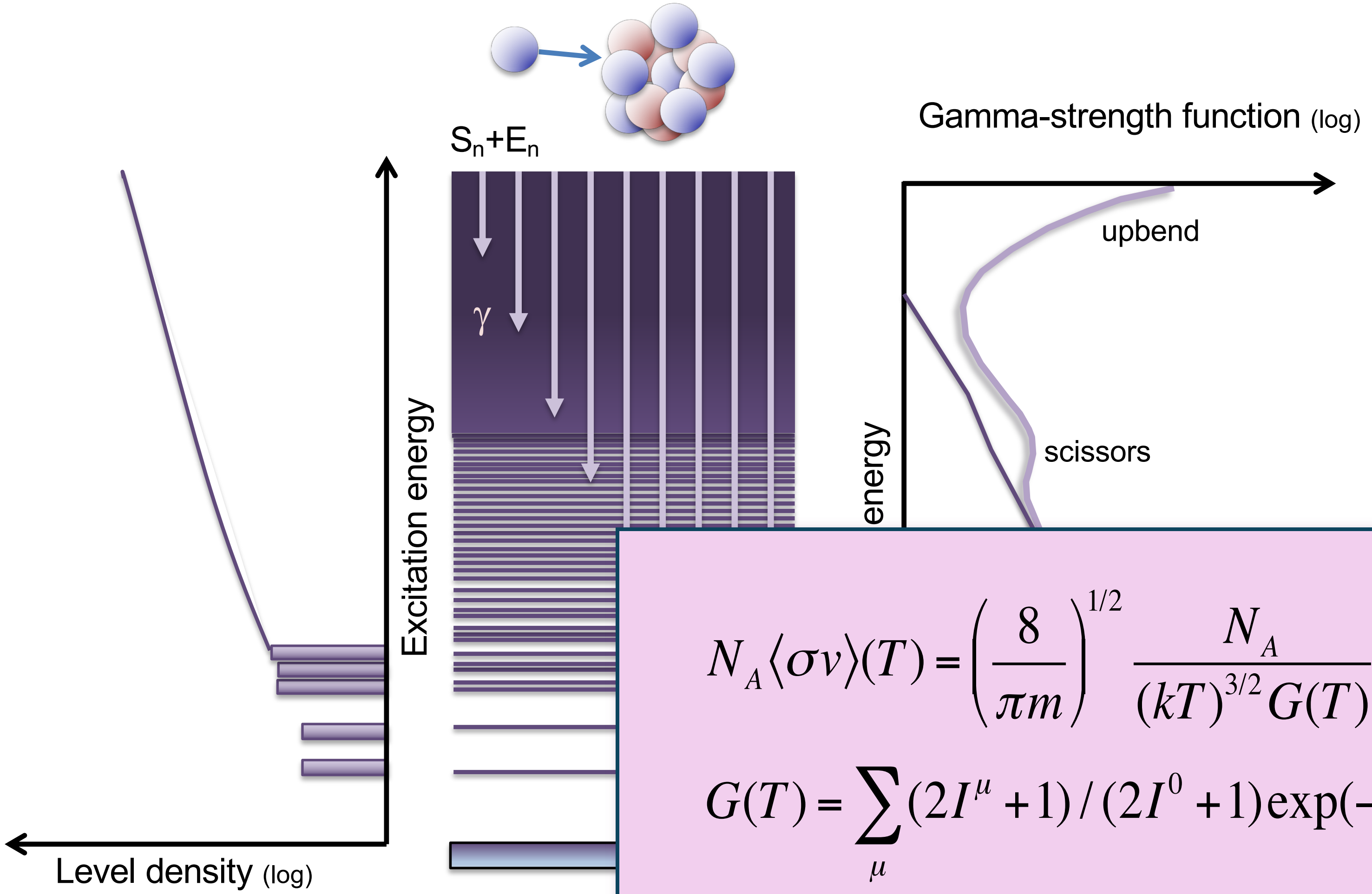


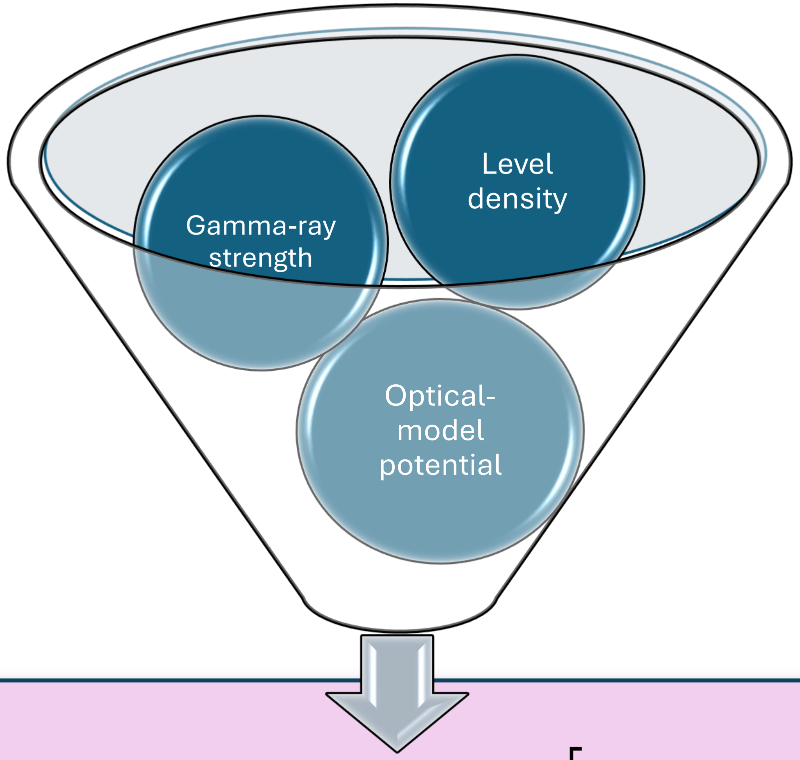
Nuclear-physics input: (n,γ) reaction rates

The workhorse: (Wolfenstein-)Hauser-Feshbach theory

-> "Compound nucleus" picture of Bohr

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



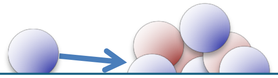


$$N_A\langle\sigma v\rangle(T)=\left(\frac{8}{\pi m}\right)^{1/2}\frac{N_A}{(kT)^{3/2}G(T)}\int_0^\infty\sum_\mu\frac{(2I^\mu+1)}{(2I^0+1)}\sigma^\mu(E)\,E\exp\left[-\frac{(E+E_x^\mu)}{kT}\right]dE$$

$$G(T)=\sum_\mu(2I^\mu+1)/(2I^0+1)\exp(-E_x^\mu/kT)$$

Nuclear-physics input: (n,γ) reaction rates

The workhorse: (Wolfenstein-)Hauser-Feshbach theory
-> “Compound nucleus” picture of Bohr
[W. Hauser and H. Feshbach, Phys. Rev. 87, 366 (1952)]



PHILOSOPHICAL TRANSACTIONS A

royalsocietypublishing.org/journal/rsta

Research

Check for updates

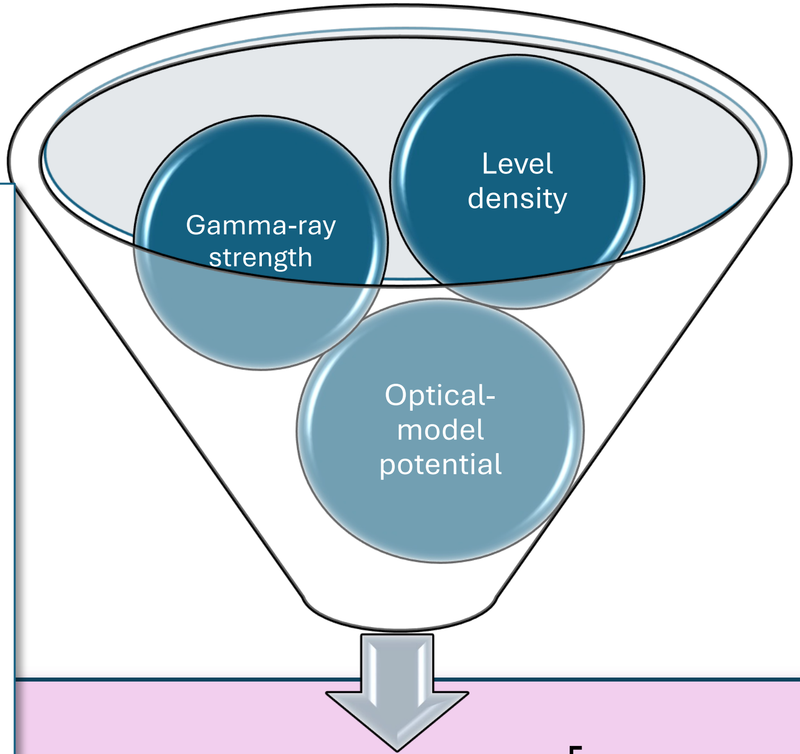
Cite this article: Wiedeking M, Goriely S. 2024 Photon strength functions and nuclear level densities: invaluable input for nucleosynthesis. *Phil. Trans. R. Soc. A* **382**: 20230125.
https://doi.org/10.1098/rsta.2023.0125

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

M. Wiedeking[1,2,3] and S. Goriely[4]

[1]SSC Laboratory, iThemba LABS, P.O. Box 722, Somerset West 7129, South Africa
[2]School of Physics, University of the Witwatersrand, Johannesburg 2050, South Africa
[3]Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[4]Institut d’Astronomie et d’Astrophysique, Université Libre de Bruxelles, Campus de la Plaine CP 226, Brussels 1050, Belgium

MW, 0000-0003-4983-3882

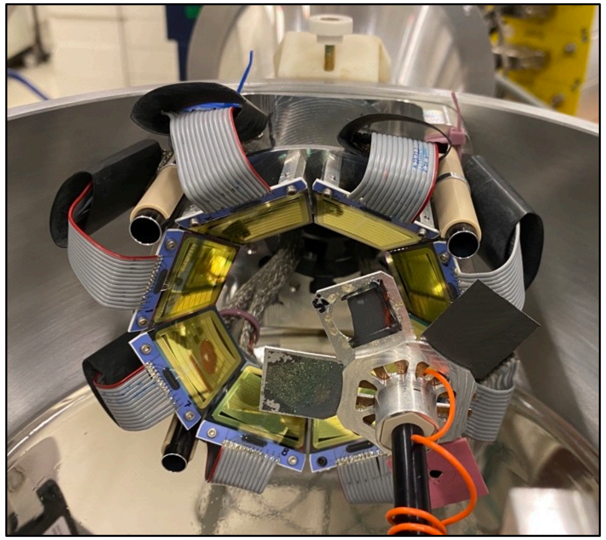


$$\cdots\int_0^{\infty}\sum_{\mu}\frac{(2I^{\mu}+1)}{(2I^{0}+1)}\sigma^{\mu}(E)\,E\exp\left[-\frac{(E+E_x^{\mu})}{kT}\right]dE$$

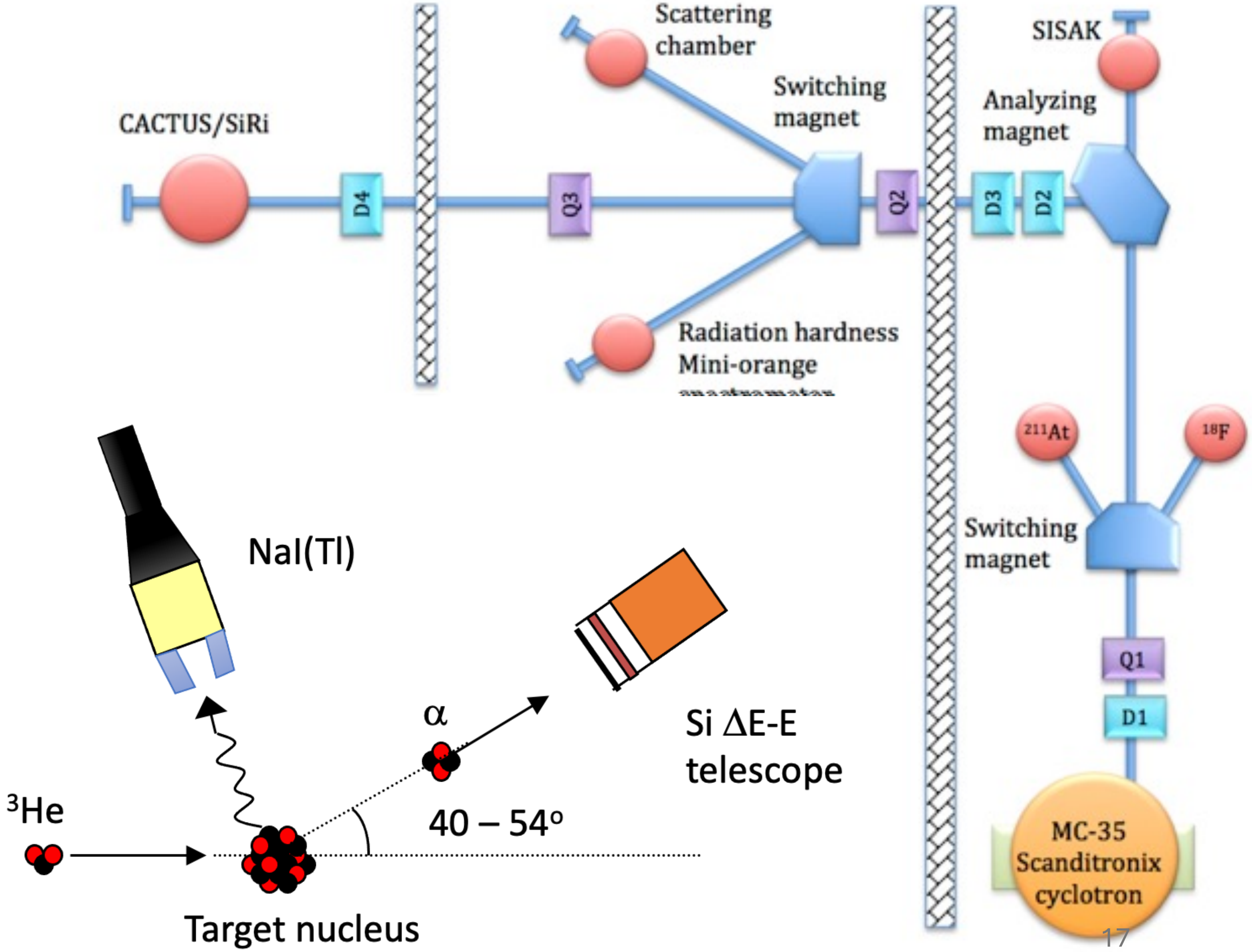
$$\cdots E_x^{\mu}/kT)$$

Experiments at the Oslo Cyclotron Lab

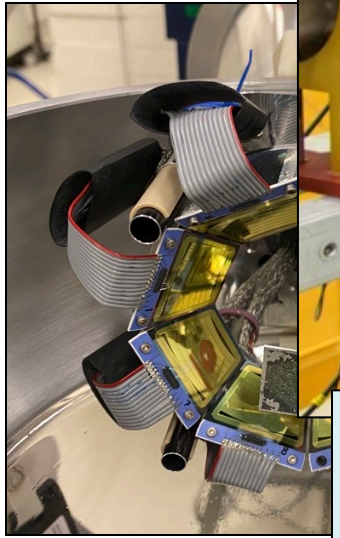
CACTUS:
26 (28) collimated NaI(Tl) crystals, 5'' x 5''
[Guttormsen et al., Phys. Scr. T32, 54 (1990]

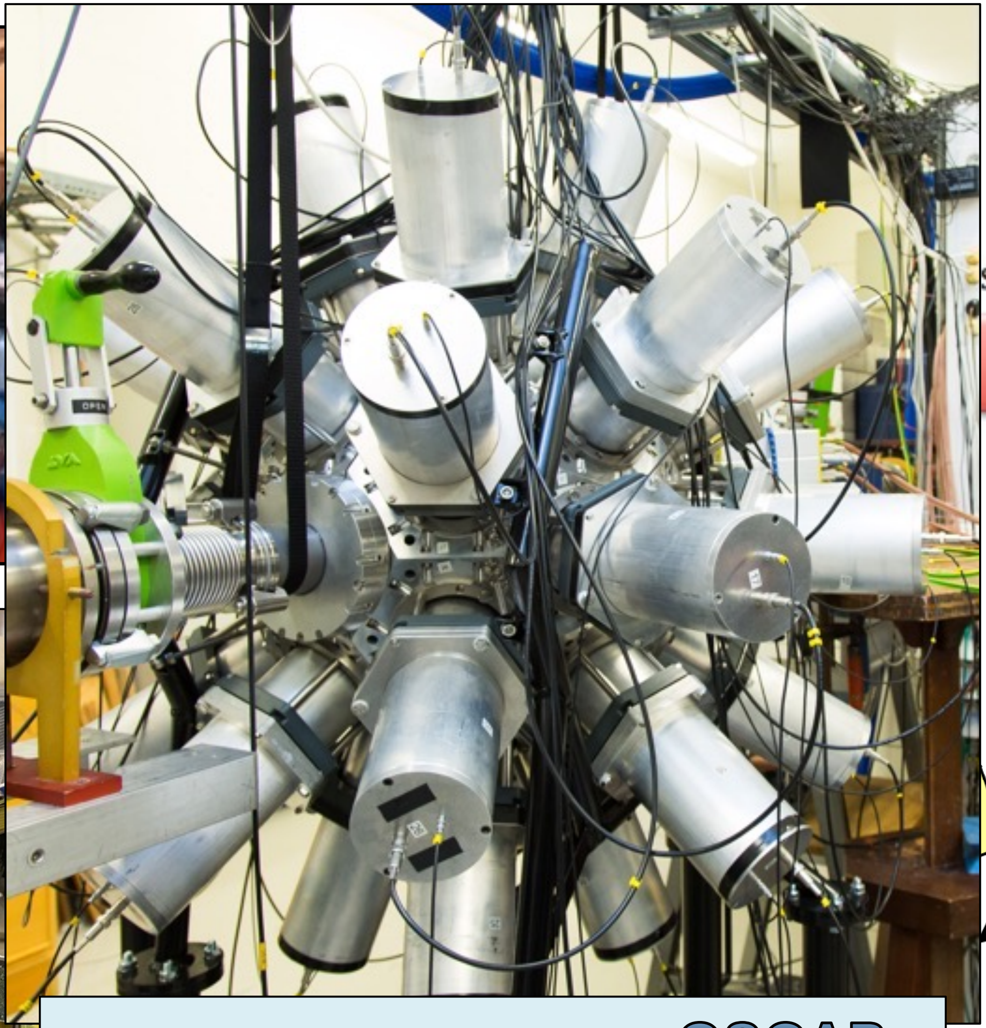


SiRi:
8x8 Si
ΔE-E particle detectors (segmented ΔE, ≈ 2^o)
(≈9% of 4π)
[Guttormsen et al., NIM A 648, 168 (2011)]

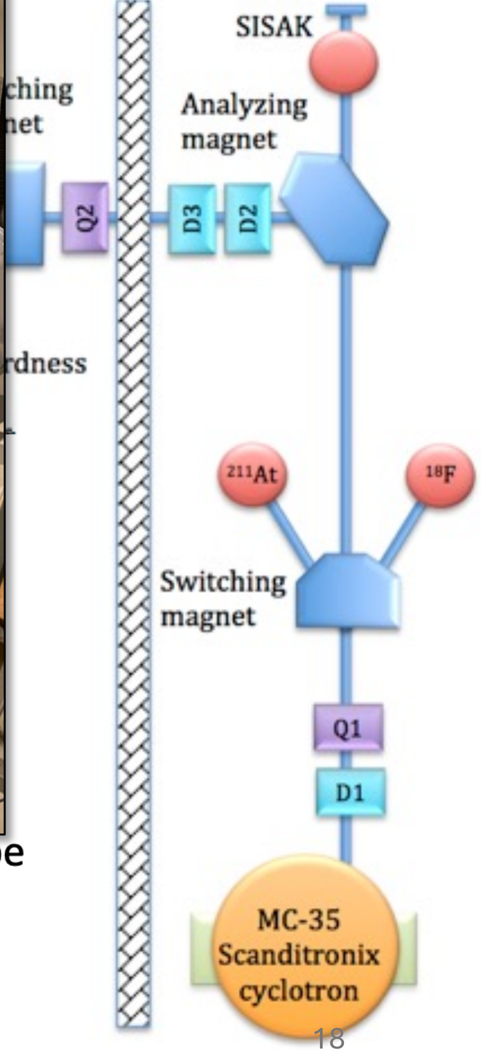


Experiments at the Oslo Cyclotron Lab



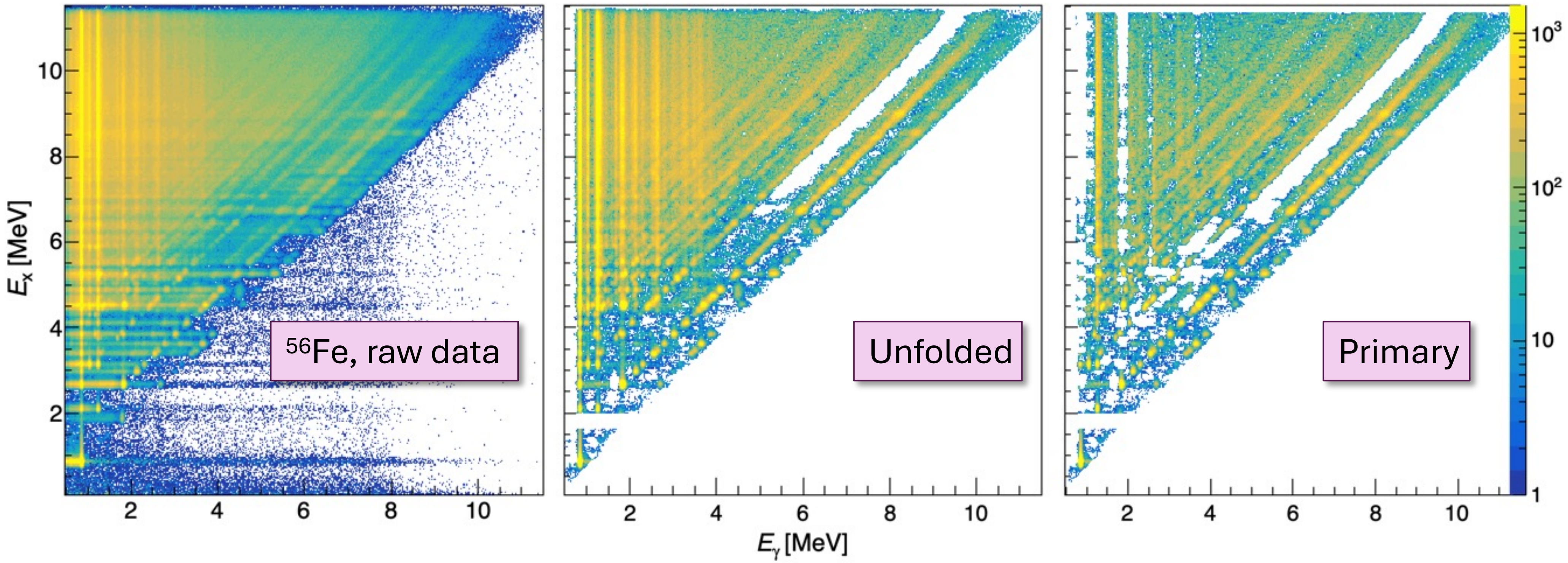


New γ-ray detector system **OSCAR**
30 $LaBr_3(Ce)$, 3.5'' x 8'' crystals
[Zeiser et al., NIM A 985, 164678 (2021)]



The Oslo method – a crash course 😎

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

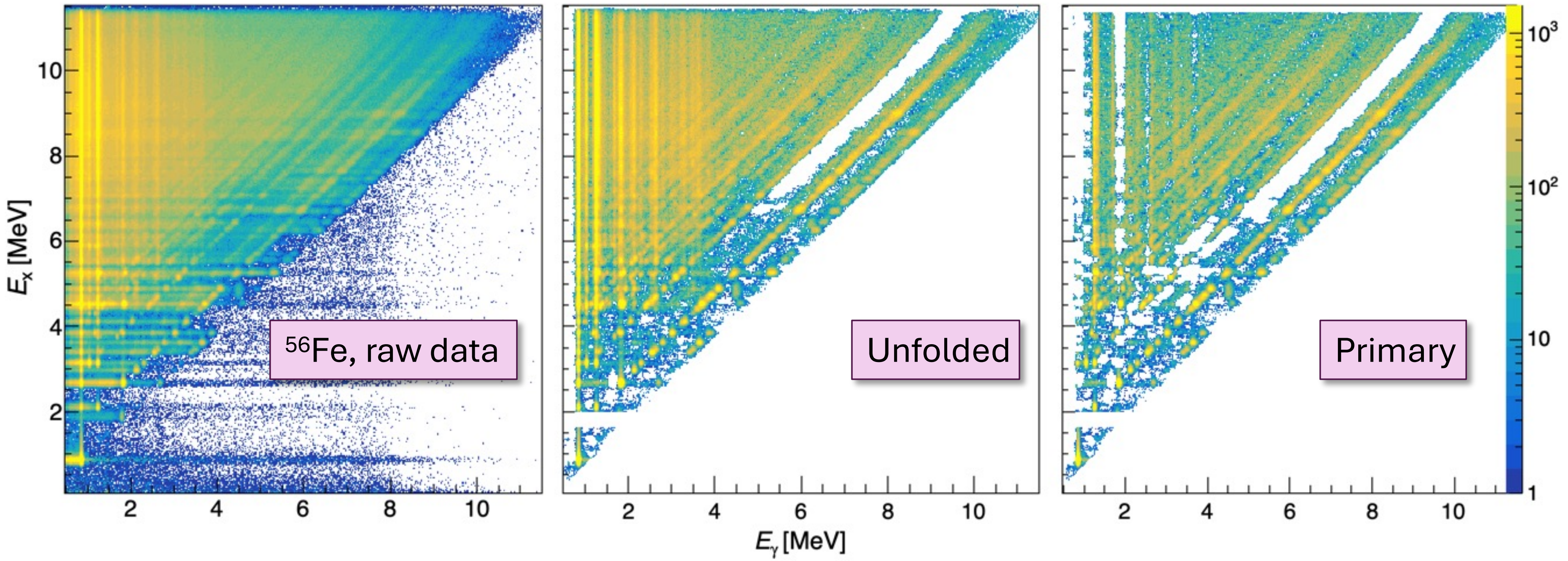


[0. Get yourself an ($E\gamma$,E_x) matrix (>20 000 coincidences)]

1. Correct for the γ-detector response [Guttormsen et al., NIM A 374, 371 (1996)]
2. Extract *distribution of* primary γs for each E_x [Guttormsen et al., NIM A 255, 518 (1987)]
3. Obtain level density and γ-strength from primary γ 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)]

The Oslo method – a crash course 😎

[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 coincidences)]

1. Correct for the γ-detector response [Guttormsen et a
2. Extract *distribution of* primary γs for each E_x [Guttor
3. Obtain level density and γ-strength from primary γ
4. Normalize & evaluate systematic errors [Schiller et a

Larsen *et al.*, PRC **83**, 034315 (2011)]

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

Step 3: NLD and γ-ray transmission coeff.

Ansatz:

[generalization of Fermi´s Golden Rule]

Factorize the primary γ matrix:

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

where the γ-decay strength (for dipole radiation)

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

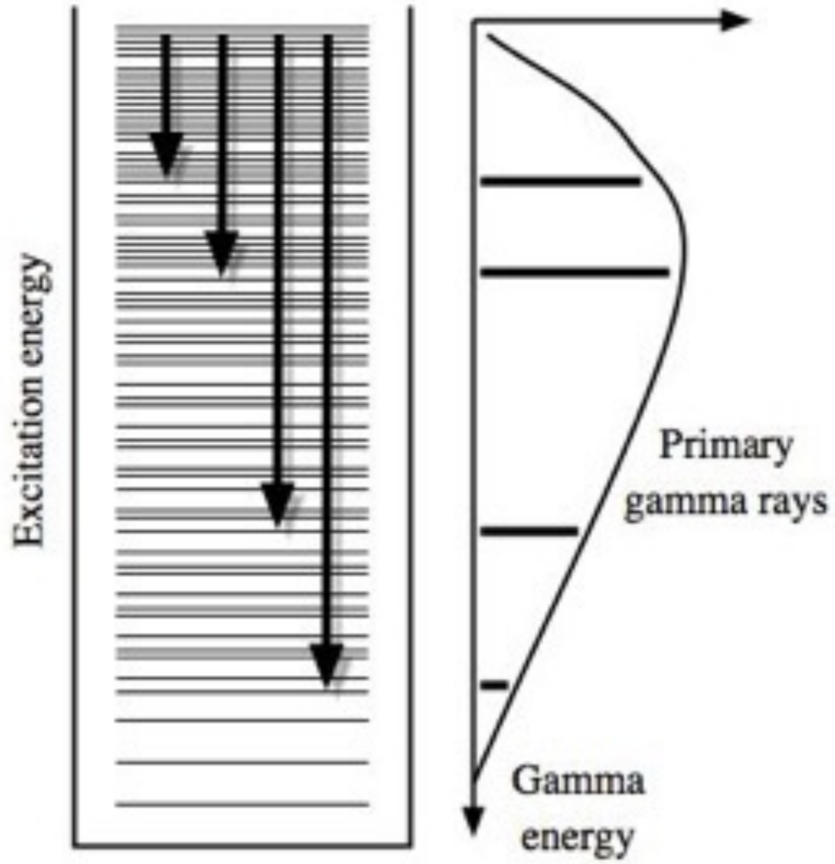
Two important assumptions:

✅ 1) The γ decay takes place a long time after the level is formed

🤔 2) The γ-ray strength function varies *slowly* with E_x (at high E_x – high level density)

➔ the ***Brink hypothesis***

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

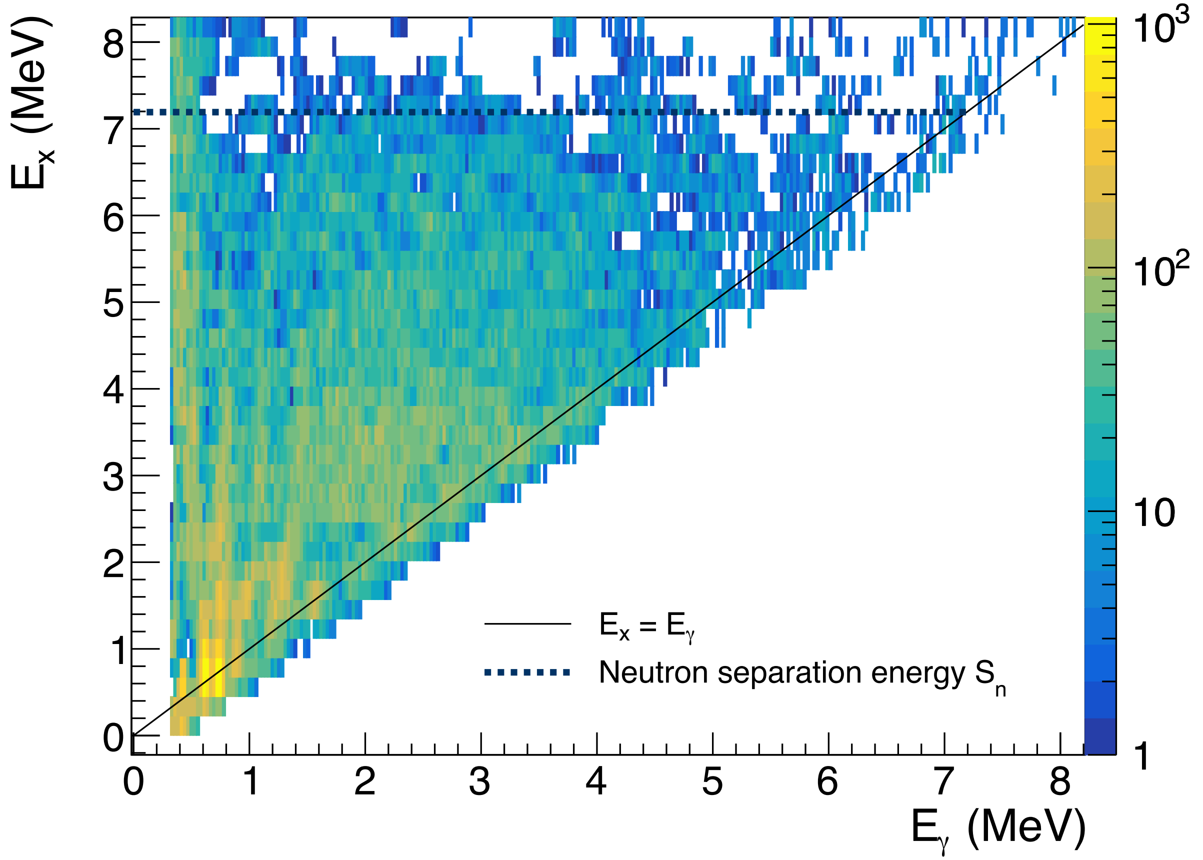


[Schiller et al., NIM A 447, 498 (2000)]
https://doi.org/10.1016/S0168-9002(99)01187-0

Using the data to calculate (n,γ) reaction rates

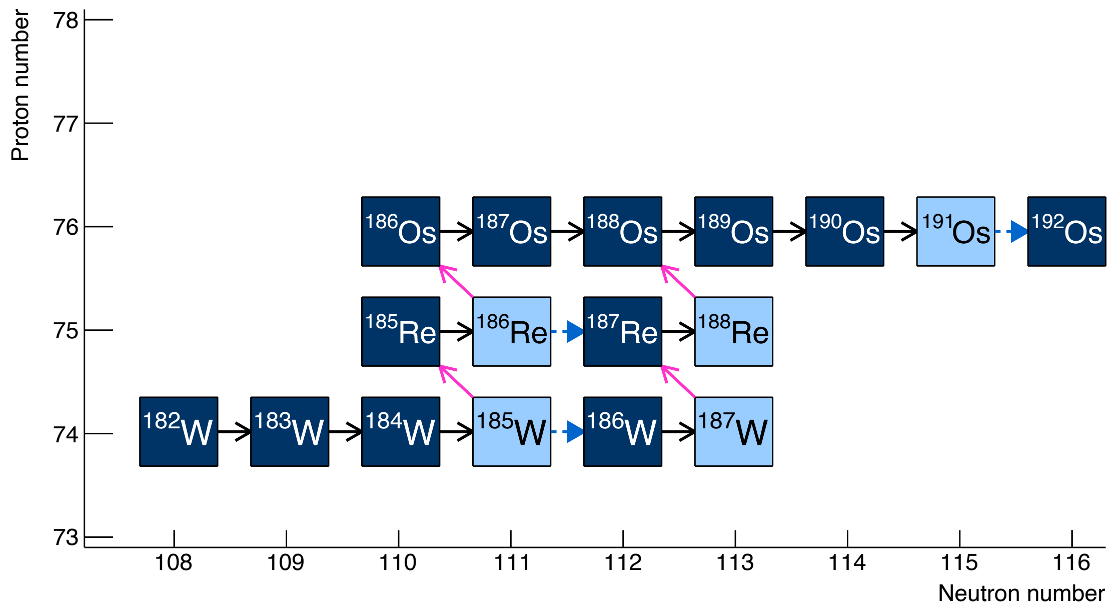
s-process branch point ^{185}W

Primary γ rays



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

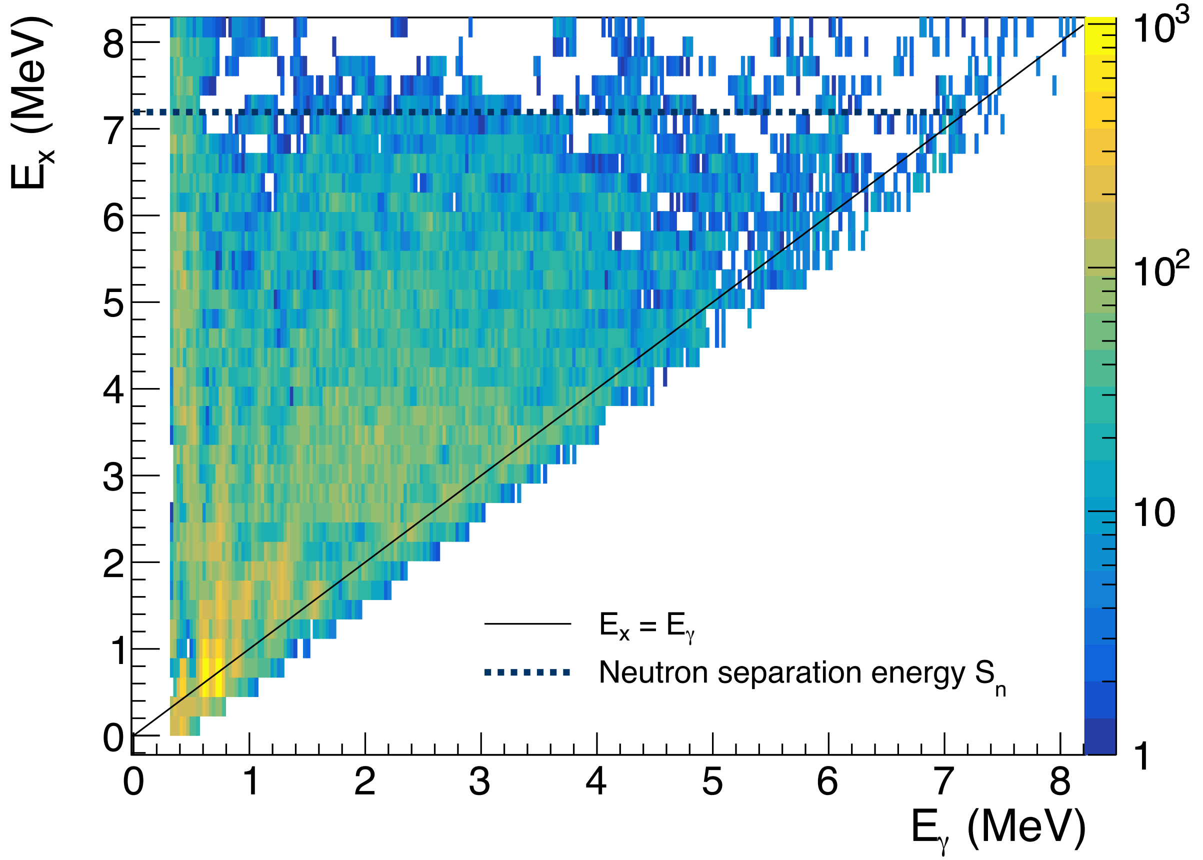
[Larsen et al., PRC **108**, 025804 (2023)]

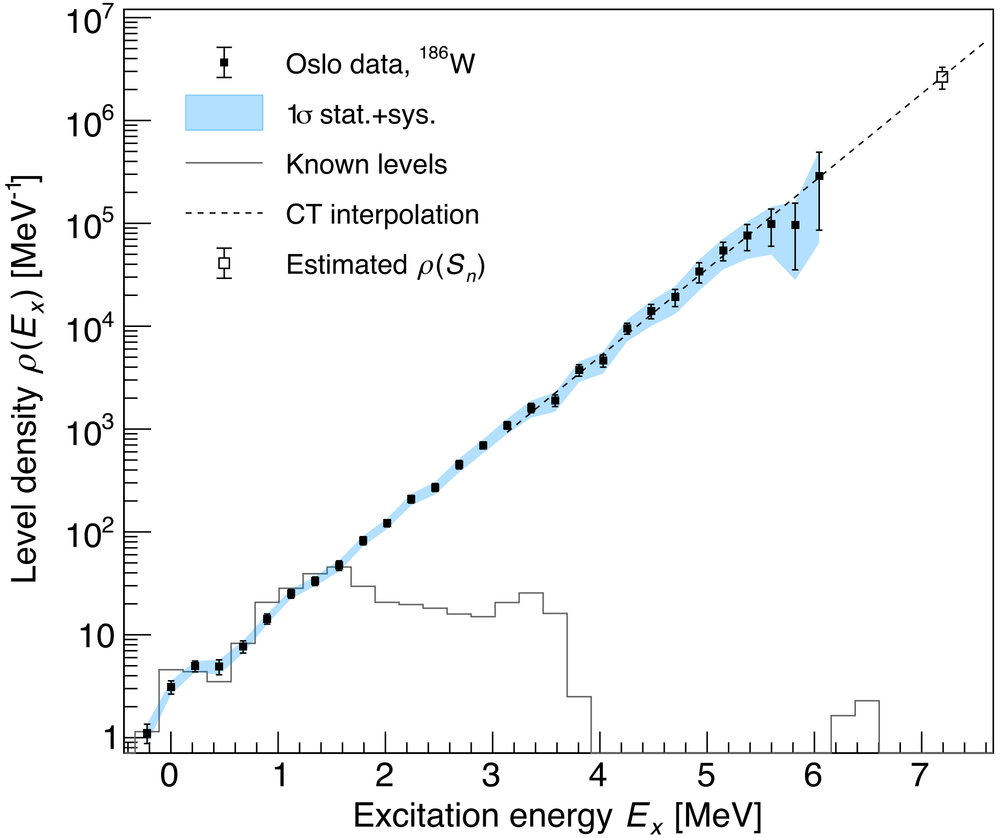


Using the data to calculate (n,γ) reaction rates

s-process branch point ^{185}W

Primary γ rays





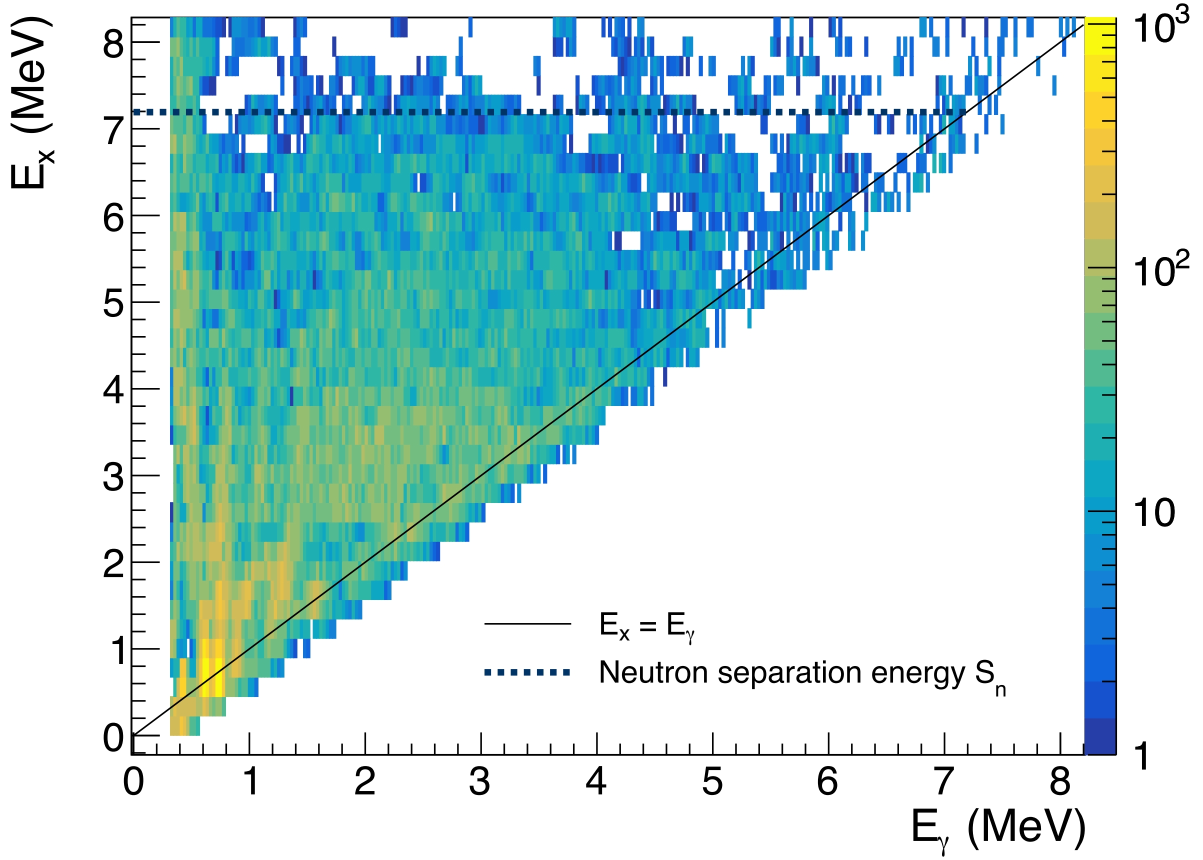
$^{186}W(\alpha,\alpha'\gamma)^{186}W$

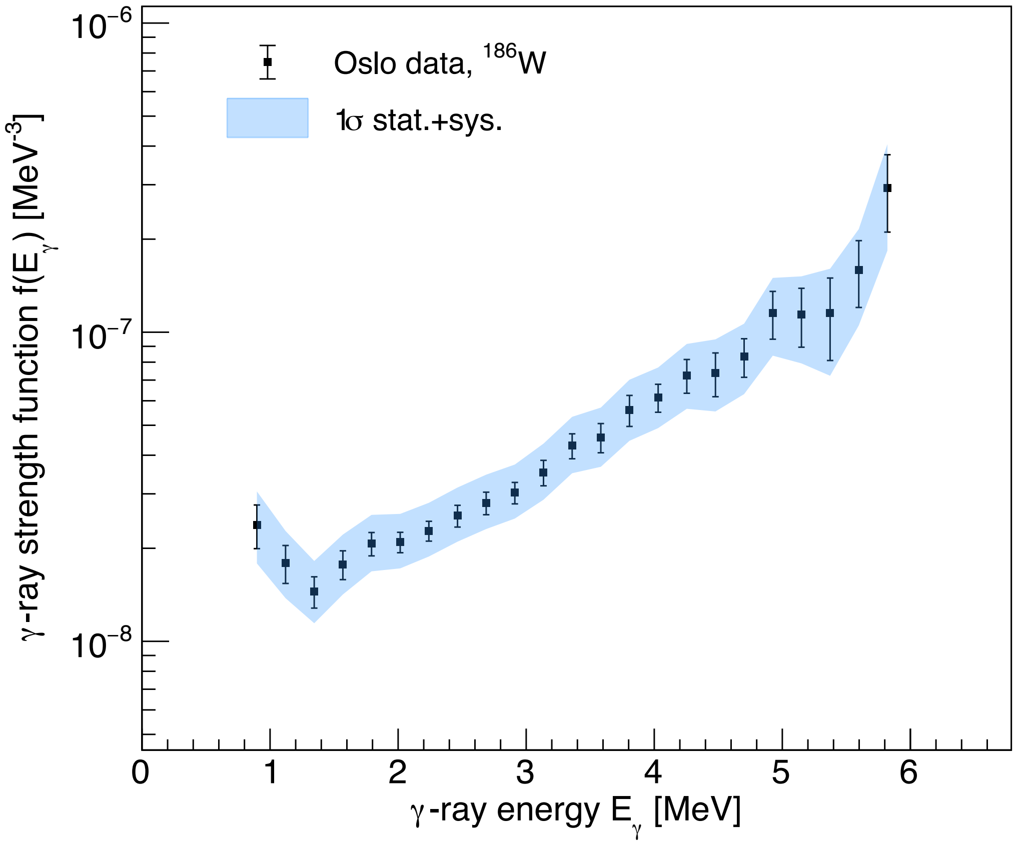
[Larsen et al., PRC **108**, 025804 (2023)]

Using the data to calculate (n,γ) reaction rates

s-process branch point ^{185}W

Primary γ rays





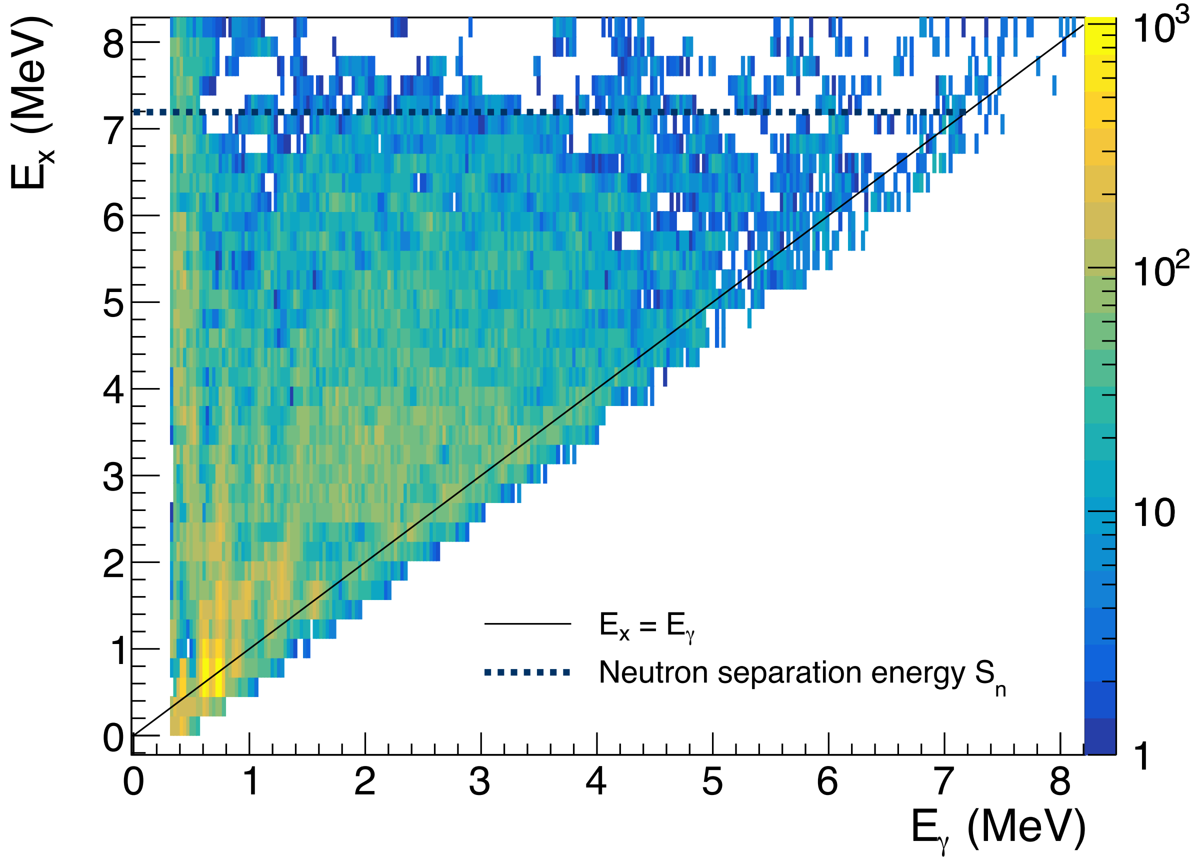
$^{186}W(\alpha,\alpha'\gamma)^{186}W$

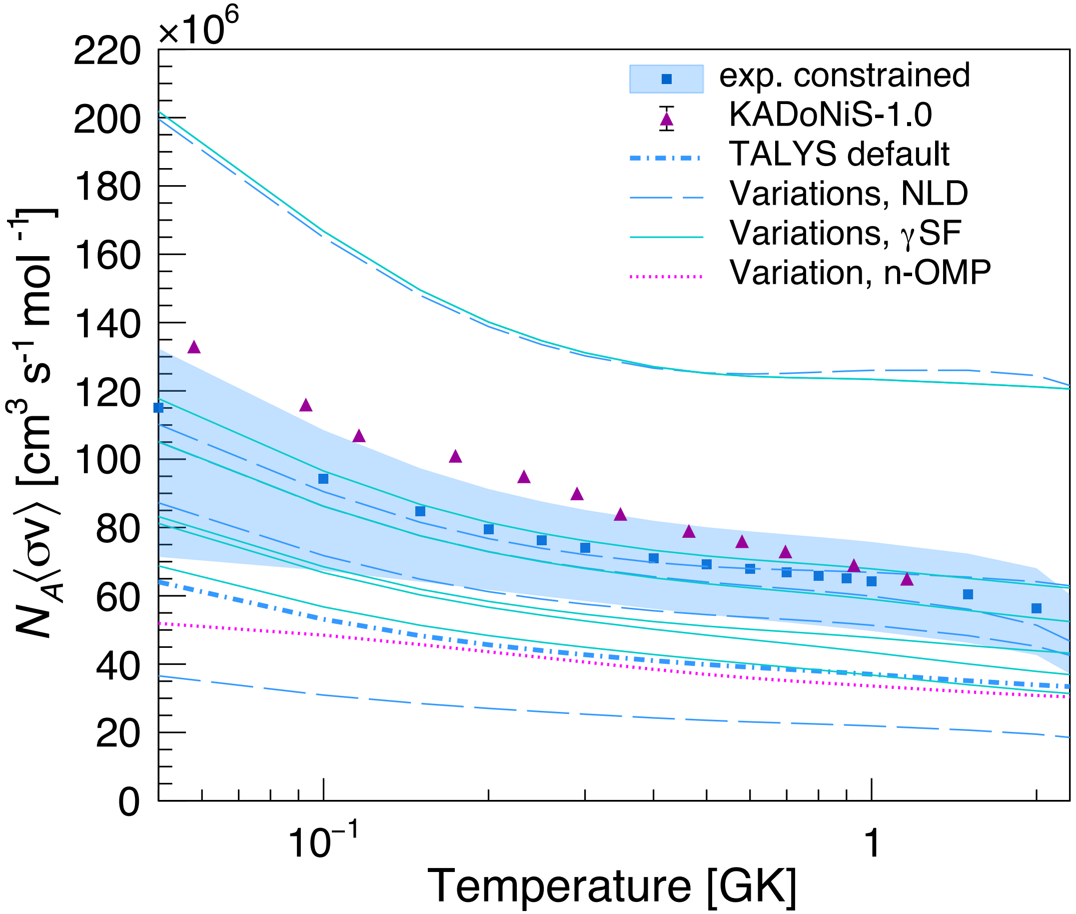
[Larsen et al., PRC **108**, 025804 (2023)]

Using the data to calculate (n,γ) reaction rates

s-process branch point ^{185}W

Primary γ rays





^{186}W(α,α'γ)^{186}W

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

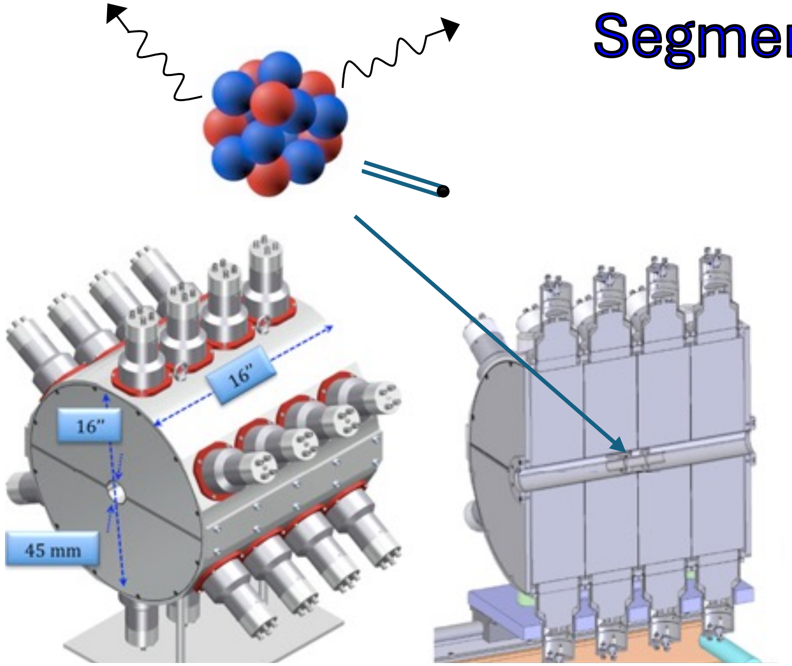
The beta-Oslo method in a 

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 β^- in coincidence with *all* γ rays from the child nucleus
3) Apply the Oslo method to the (E_x, E_γ) matrix to get level density & γ- strength

Segments give individual γ rays, the sum of all gives E_x



Segmented, total absorption spectrometer SuN
[A. Simon, S.J. Quinn, A. Spyrou et al., NIM A 703, 16 (2013)]

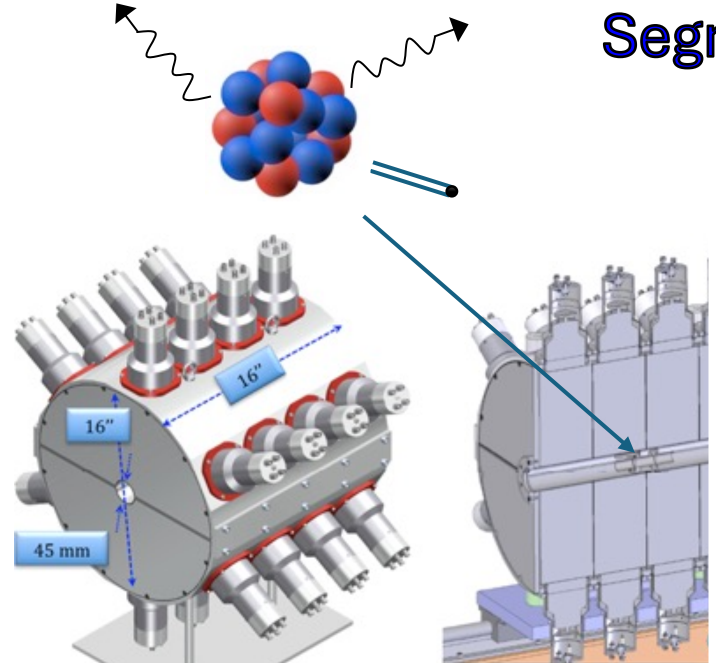
The beta-Oslo method in a 

Special thanks to
Artemis Spyrou,
Sean Liddick,
Magne Guttormsen

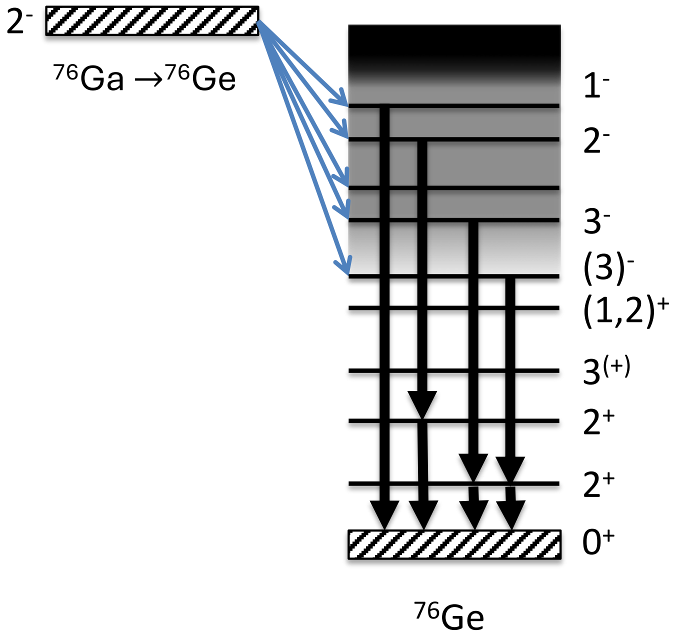
Recipe:

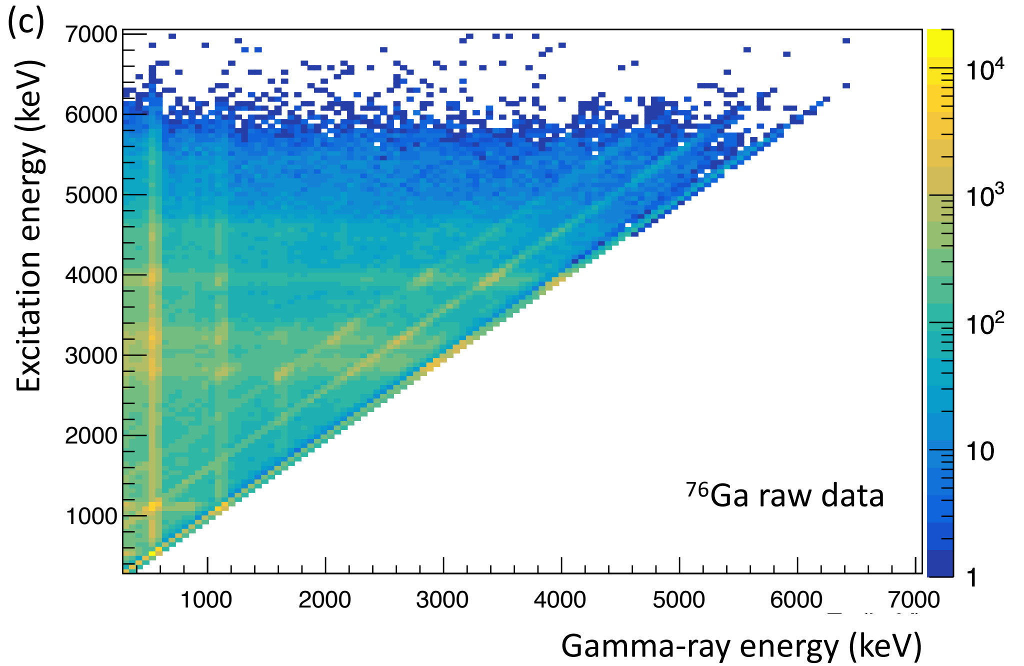
1) Implant a neutron-rich nucleus inside a high-efficiency, *segmented* total-absorption spectrometer (preferably with $Q_\beta \approx S_n$)
2) Measure β^- in coincidence with *all* γ rays from the child nucleus
3) Apply the Oslo method to the (E_x, E_γ) matrix to get level density & γ- strength

Segments give individual γ rays, the sum of all gives E_x

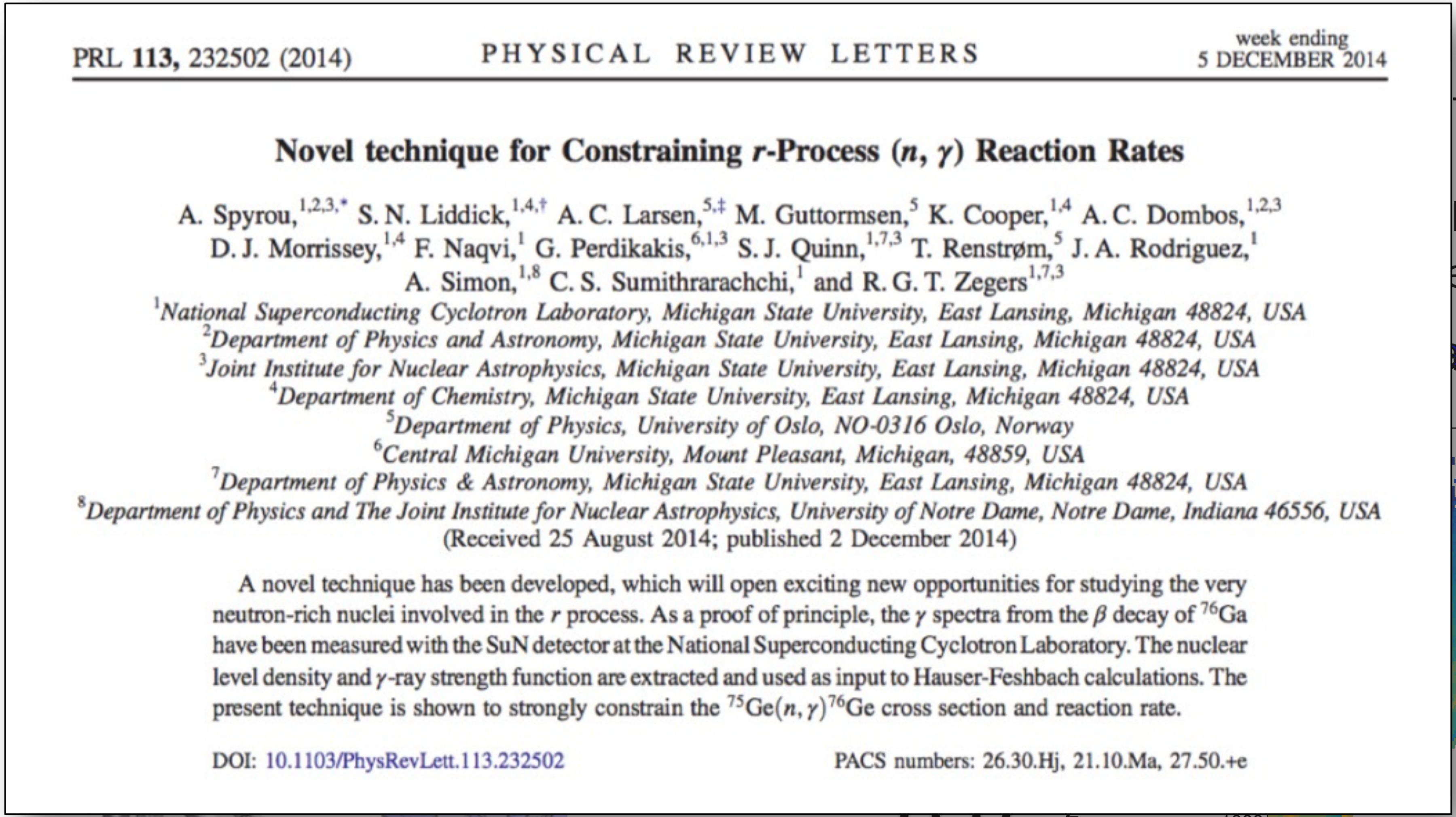


Segmented, total absorption spectrom
[A. Simon, S.J. Quinn, A. Spyrou et al., NIM A 7(





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, γ) Reaction Rates

A. Spyrou,[1,2,3,*] S. N. Liddick,[1,4,†] A. C. Larsen,[5,‡] M. Guttormsen,[5] K. Cooper,[1,4] A. C. Dombos,[1,2,3]
D. J. Morrissey,[1,4] F. Naqvi,[1] G. Perdikakis,[6,1,3] S. J. Quinn,[1,7,3] T. Renstrøm,[5] J. A. Rodriguez,[1]
A. Simon,[1,8] C. S. Sumithrarachchi,[1] and R. G. T. Zegers[1,7,3]
[1]National Superconducting Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824, USA
[2]Department of Physics and Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[3]Joint Institute for Nuclear Astrophysics, Michigan State University, East Lansing, Michigan 48824, USA
[4]Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, USA
[5]Department of Physics, University of Oslo, NO-0316 Oslo, Norway
[6]Central Michigan University, Mount Pleasant, Michigan, 48859, USA
[7]Department of Physics & Astronomy, Michigan State University, East Lansing, Michigan 48824, USA
[8]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 γ spectra from the β decay of ^{76}Ga have been measured with the SuN detector at the National Superconducting Cyclotron Laboratory. The nuclear level density and γ-ray strength function are extracted and used as input to Hauser-Feshbach calculations. The present technique is shown to strongly constrain the $^{75}Ge(n,\gamma)^{76}Ge$ cross section and reaction rate.

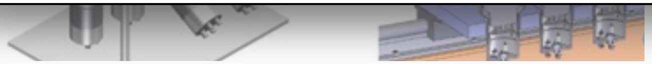
DOI: 10.1103/PhysRevLett.113.232502 PACS numbers: 26.30.Hj, 21.10.Ma, 27.50.+e

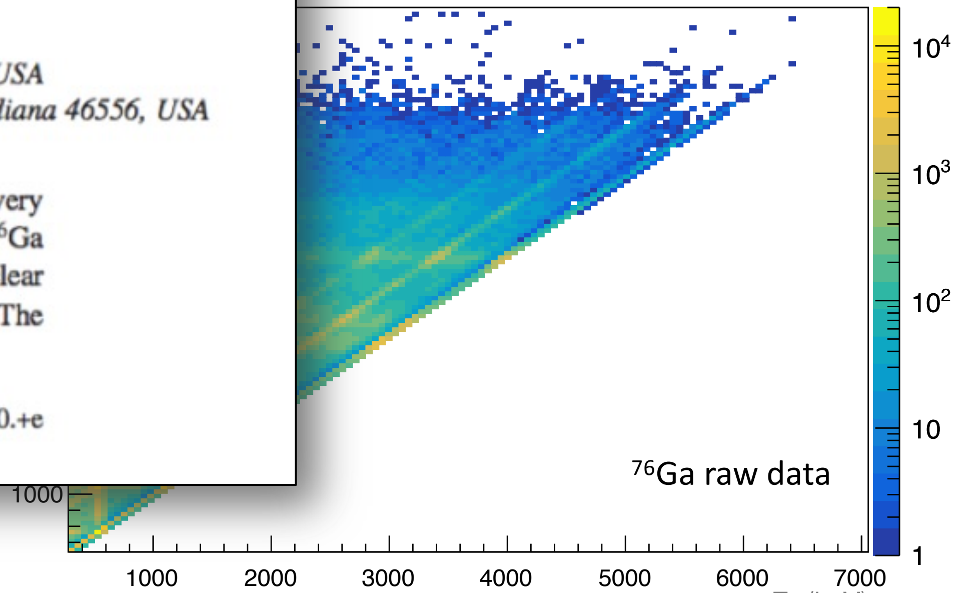
ficiency, *segmented* total-

he child nucleus

et level density & γ- strength

all gives E_x





Segmented, total absorption spectrom

[A. Simon, S.J. Quinn, A. Spyrou et al., NIM A 7(

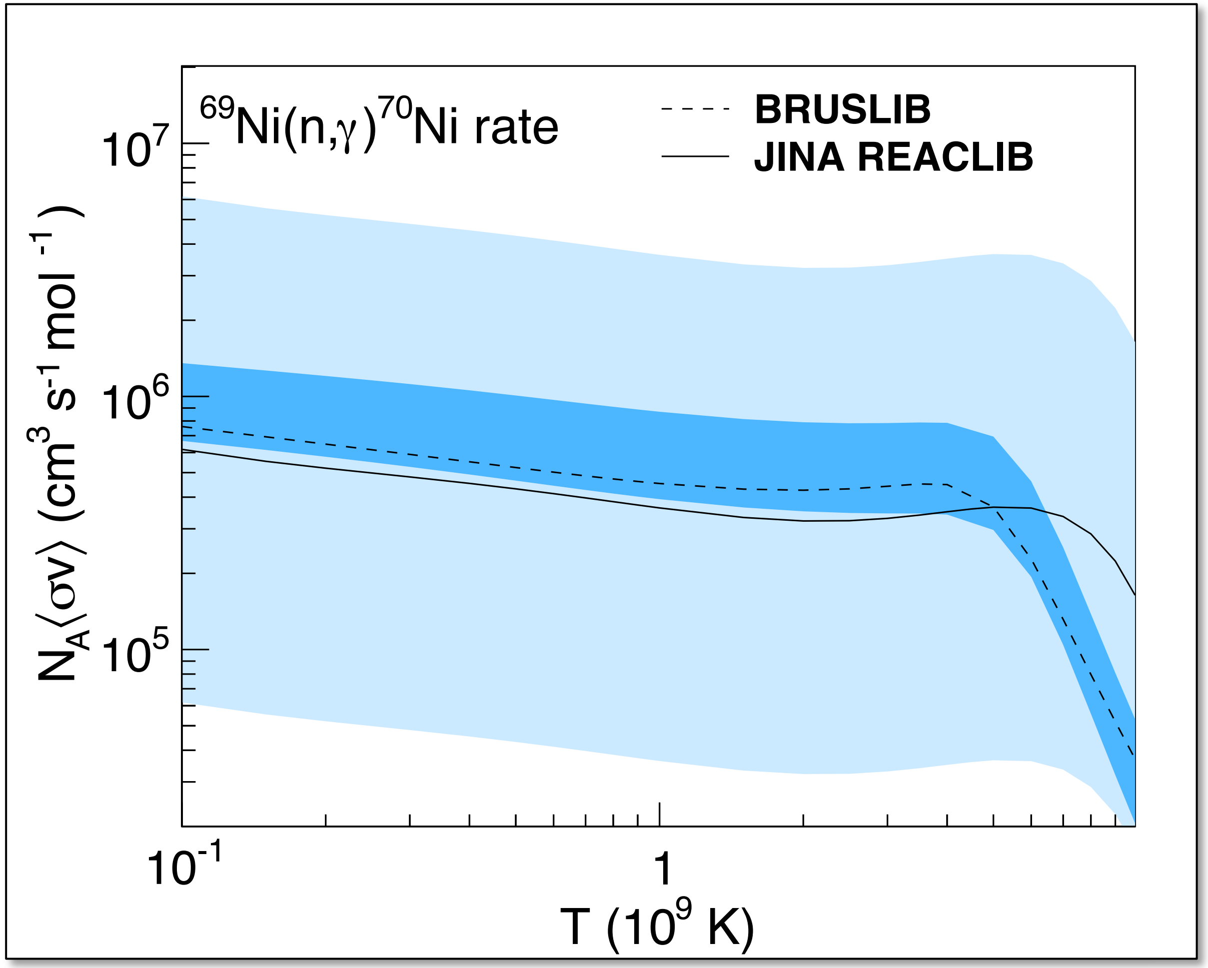
^{76}Ge

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

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

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

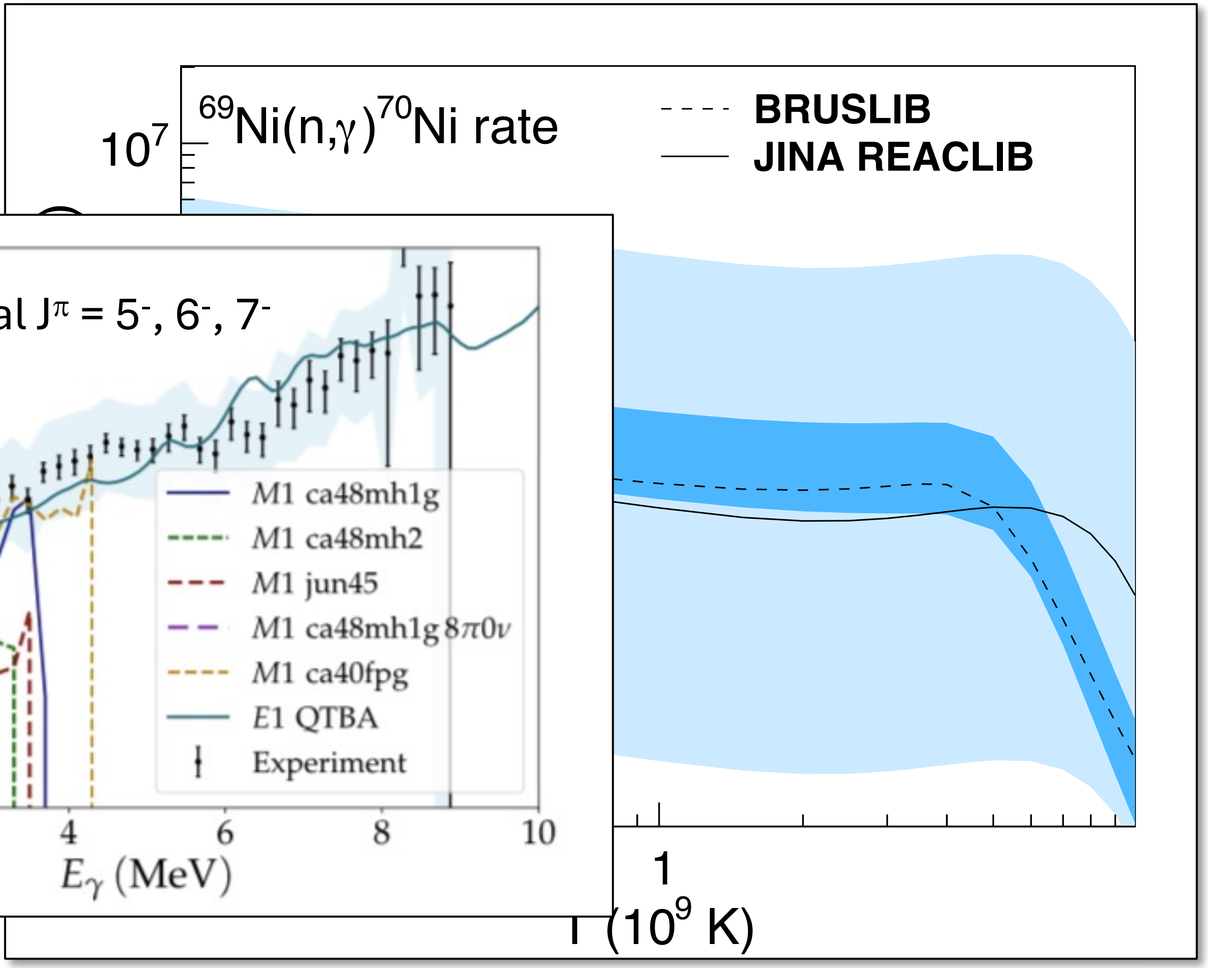
[S.N. Liddick A. Spyrou, B.P. Crider, F. Naqvi, A.C. Larsen, M. Guttormsen et al., PRL **116**, 242502 (2016)]

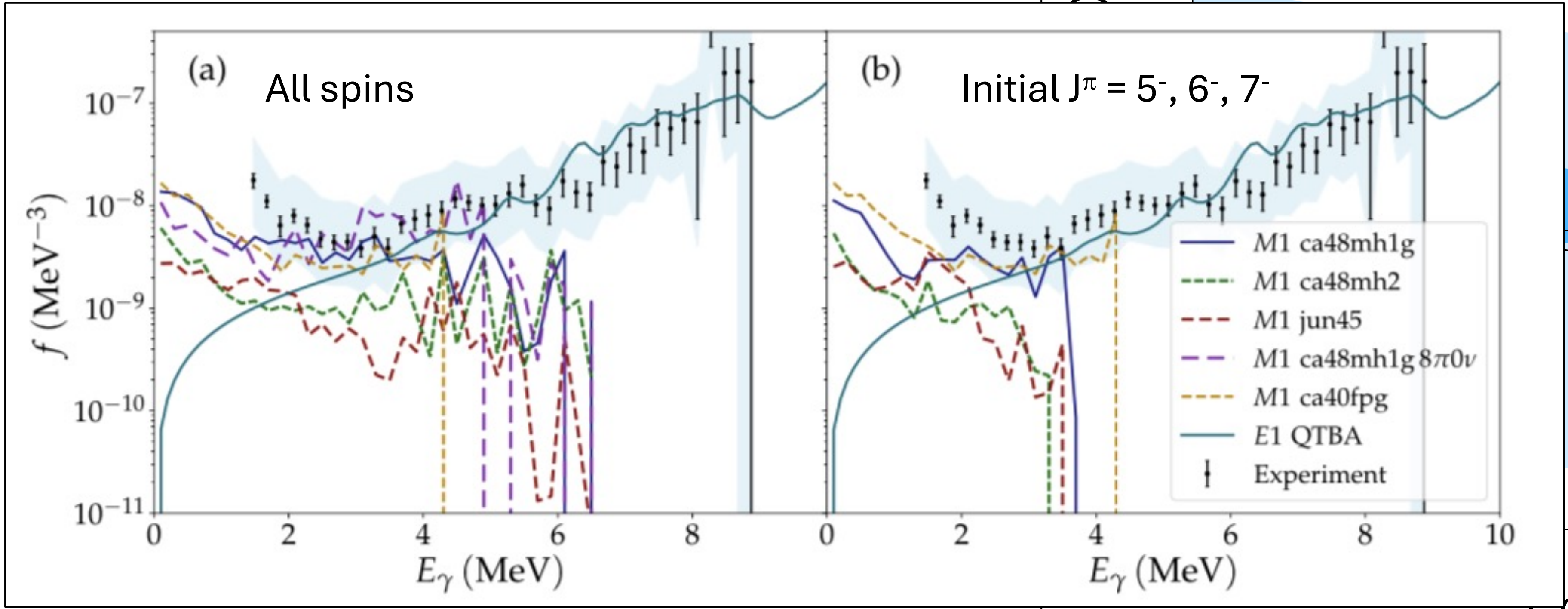


The beta-Oslo method: ^{70}Co → ^{70}Ni

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

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





Improved data analysis: unfolding of the E_x axis as well
[Larsen, Midtbø, Guttormsen, Renstrøm, Liddick, Spyrou et al., PRC **97**, 054329 (2018)]

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

nature communications

Article

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

Enhanced production of ^{60}Fe in massive stars

Received: 26 April 2024

Accepted: 30 October 2024

Published online: 07 November 2024

Check for updates

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

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}Fe (iron) and ^{26}Al (aluminum), offer unique signs of active nucleosynthesis in our galaxy. There is a long-standing discrepancy between the observed ^{60}Fe/^{26}Al ratio by γ-ray telescopes and predictions from supernova models. This discrepancy has been attributed to uncertainties in the nuclear reaction networks producing ^{60}Fe, and one reaction in particular, the neutron-capture on ^{59}Fe. Here we present experimental results that pro-

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

nature communications

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

Enhanced production of ^{60}Fe in massive stars

Received: 26 April 2024

Accepted: 30 October 2024

Published online: 07 November 2024

Check for updates

A. Spyrou[1,2]

K. Childers[1,5],

M. Guttormse

J. E. Midtbø[9],

G. Perdikakis[8]

A. Sweet[14]

Massive stars

freshly produ

sions into the

radioisotopes

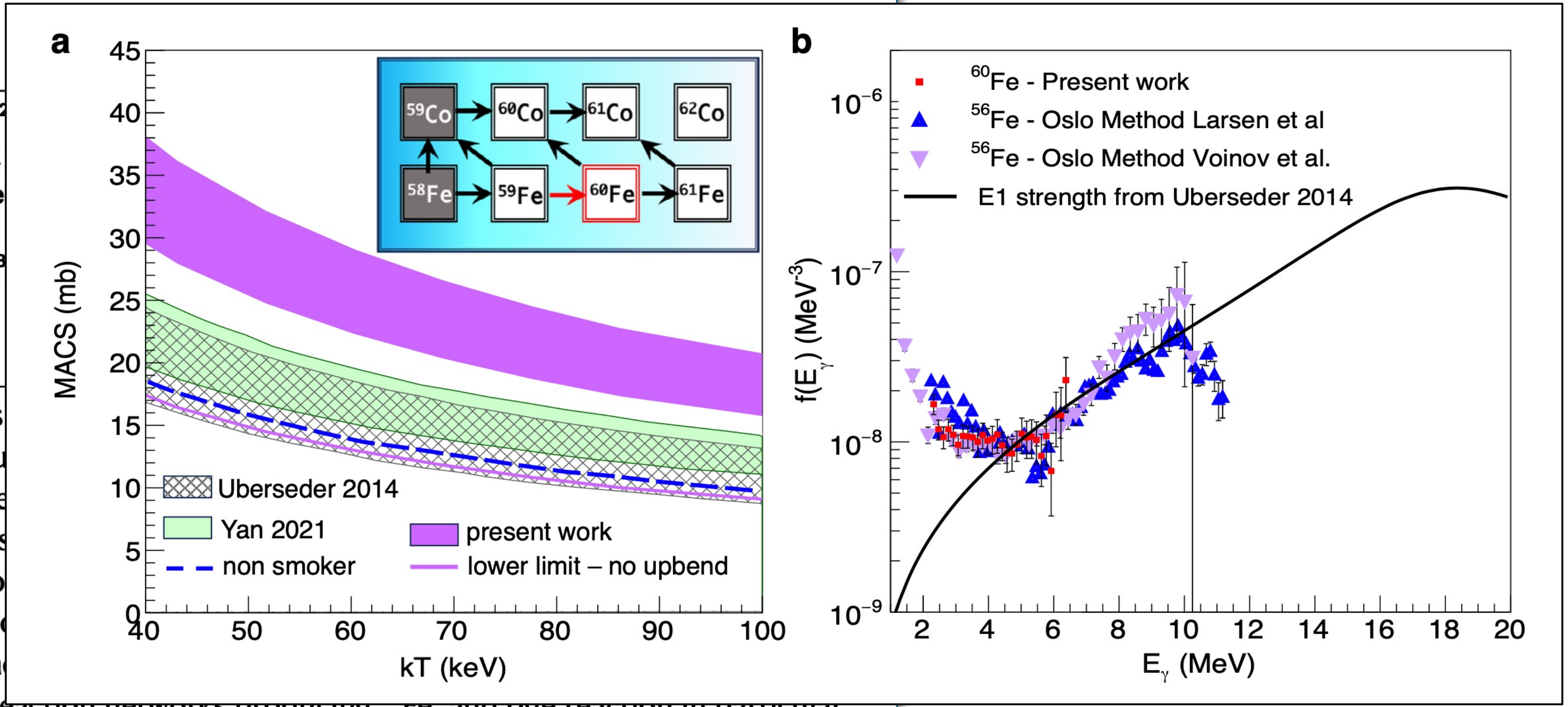
active nucleo

between the

supernova m

the nuclear reaction networks producing ^{60}Fe, and one reaction in particular,

the neutron-capture on ^{59}Fe. Here we present experimental results that pro-



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

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

nature communications

Article

Enhanced production of ^{60}Fe in massive stars

Received: 26 April 2024

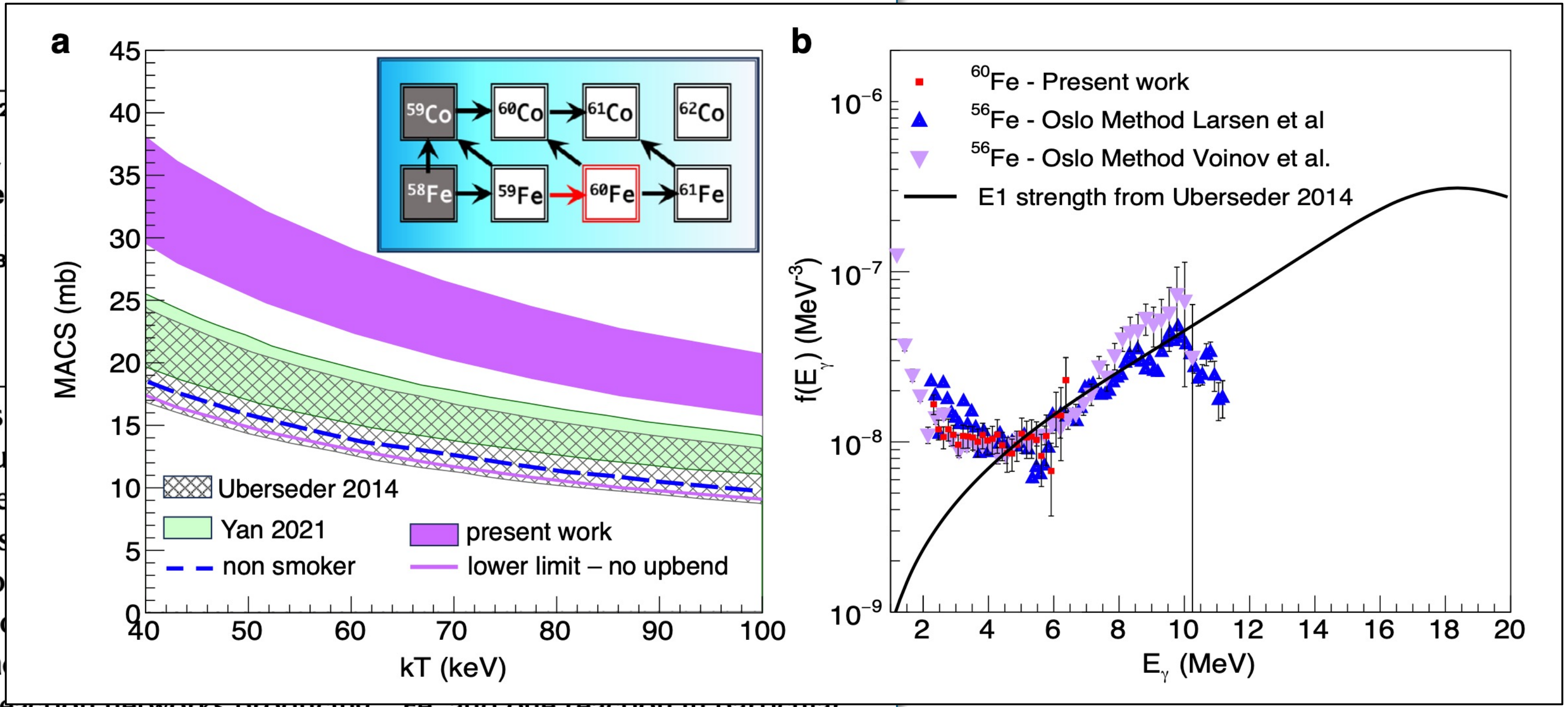
Accepted: 30 October 2024

Published online: 07 November 2024

Check for updates

A. Spyrou 1,2
K. Childers[1,5],
M. Guttormse
J. E. Midtbø[9],
G. Perdikakis[8]
A. Sweet[14]

Massive stars
freshly produ
sions into the
radioisotopes
active nucleo
between the
supernova m
the nuclear reaction networks producing ^{60}Fe, and one reaction in particular,
the neutron-capture on ^{59}Fe. Here we present experimental results that pro-



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

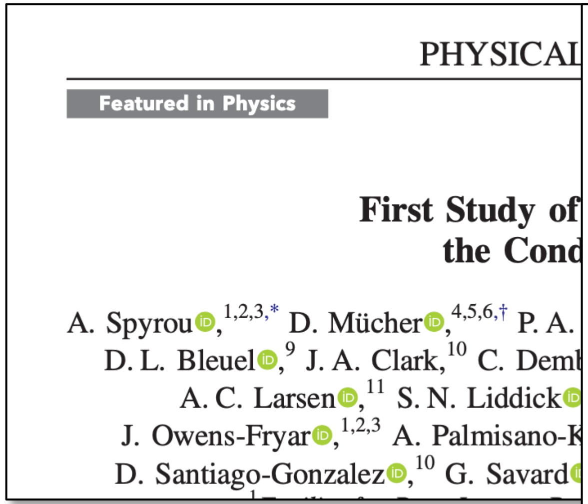
PHYSICAL REVIEW LETTERS **132,** 202701 (2024)

Featured in Physics

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

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

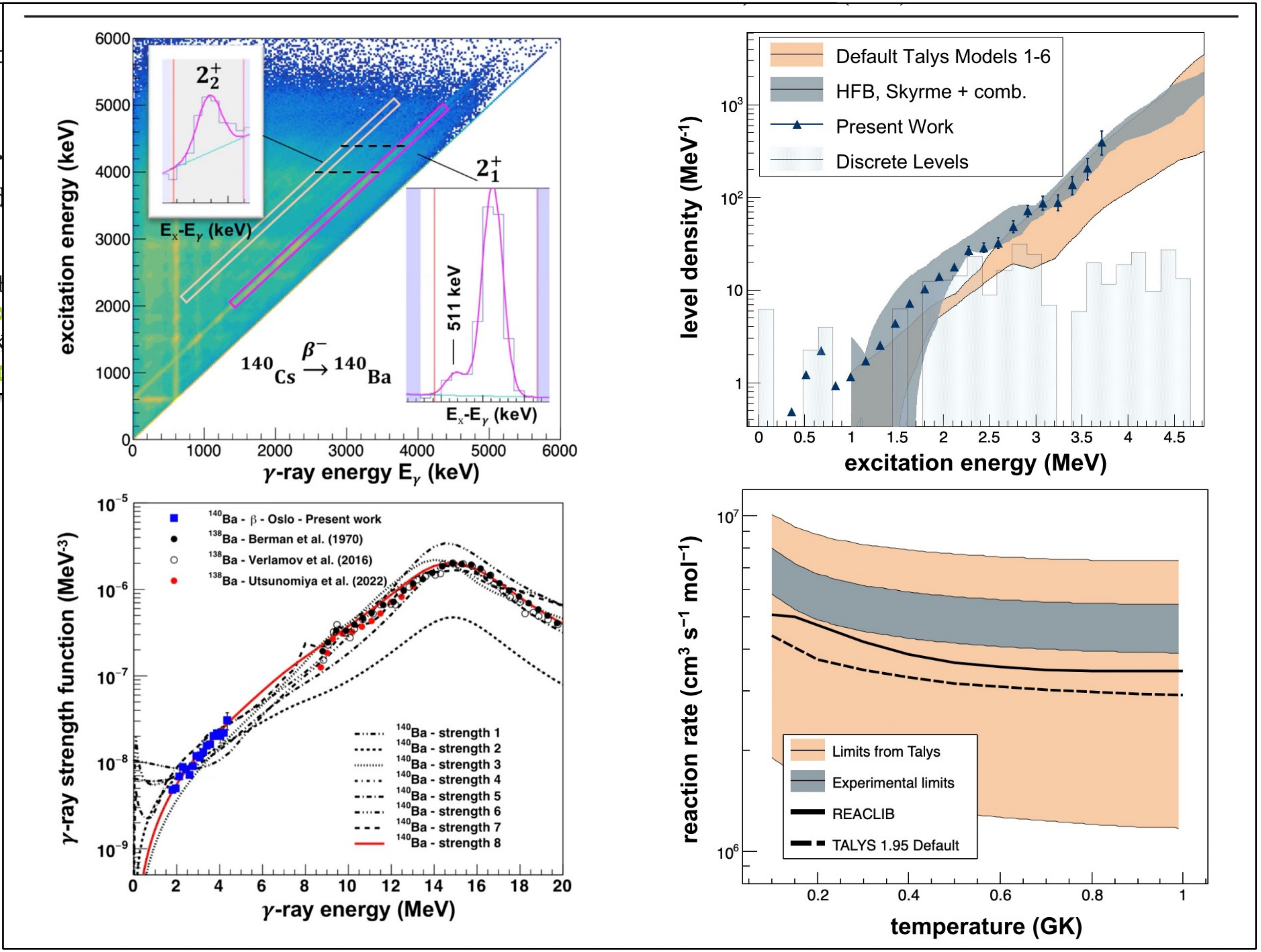
Recent beta-Oslo results: $^{139}Ba(n,\gamma)^{140}Ba$


PHYSICAL

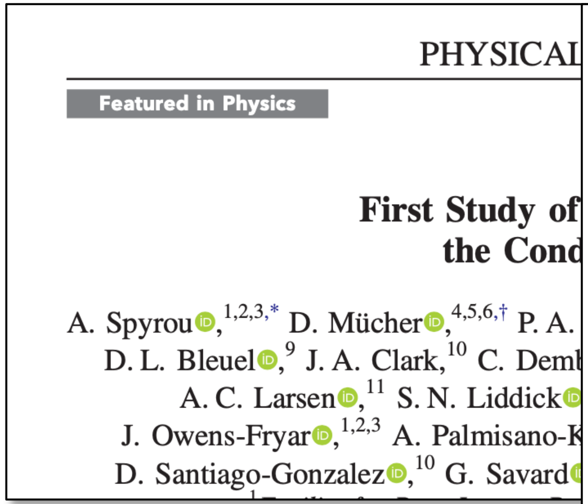
Featured in Physics

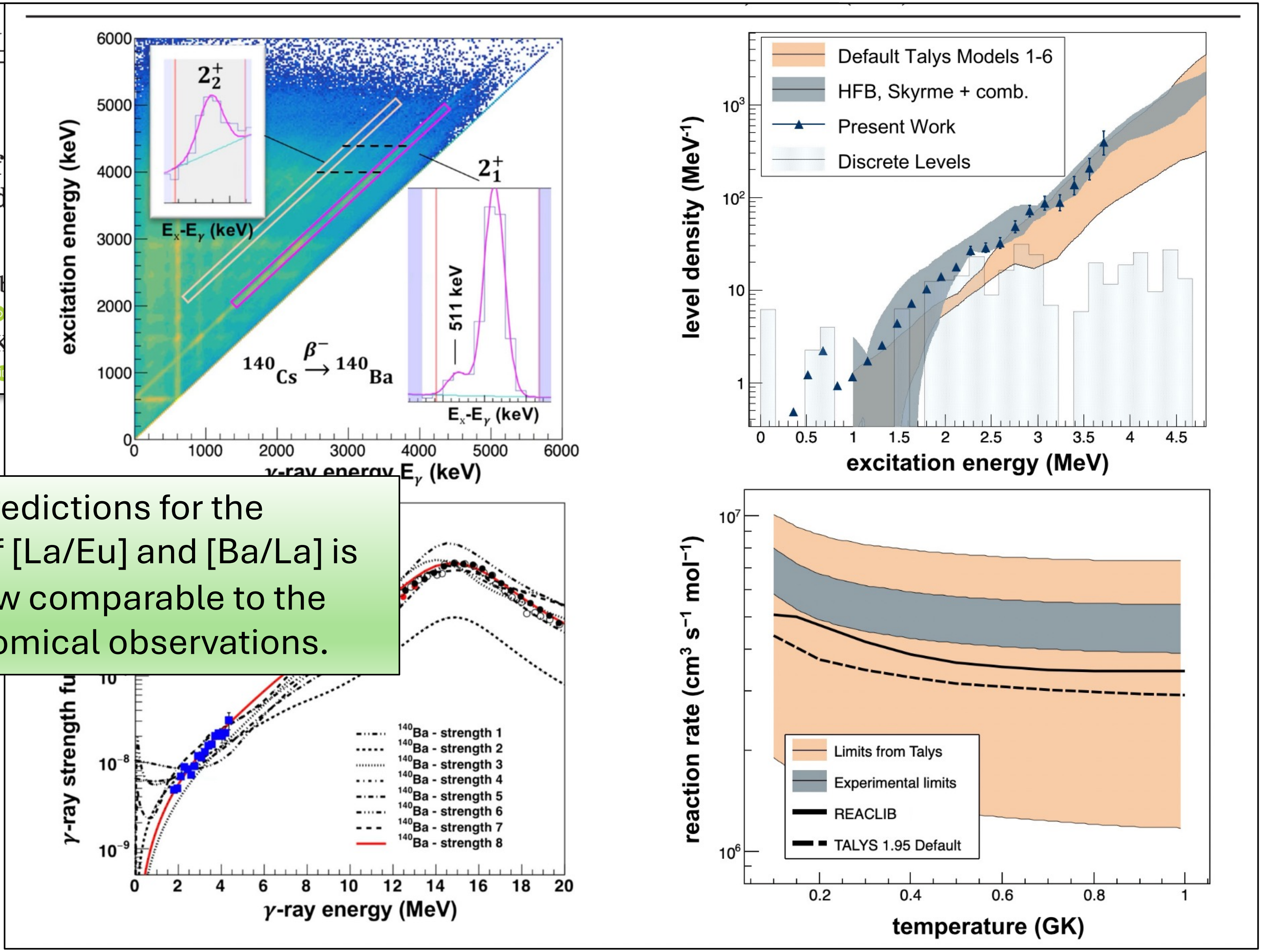
First Study of
the Cond

A. Spyrou,[1,2,3,*] D. Mücher,[4,5,6,†] P. A.
D. L. Bleuel,[9] J. A. Clark,[10] C. Demb
A. C. Larsen,[11] S. N. Liddick
J. Owens-Fryar,[1,2,3] A. Palmisano-K
D. Santiago-Gonzalez,[10] G. Savard



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


PHYSICAL
Featured in Physics
First Study of
the Cond
A. Spyrou,[1,2,3,*] D. Mücher,[4,5,6,†] P. A.
D. L. Bleuel,[9] J. A. Clark,[10] C. Demb
A. C. Larsen,[11] S. N. Liddick
J. Owens-Fryar,[1,2,3] A. Palmisano-K
D. Santiago-Gonzalez,[10] G. Savard

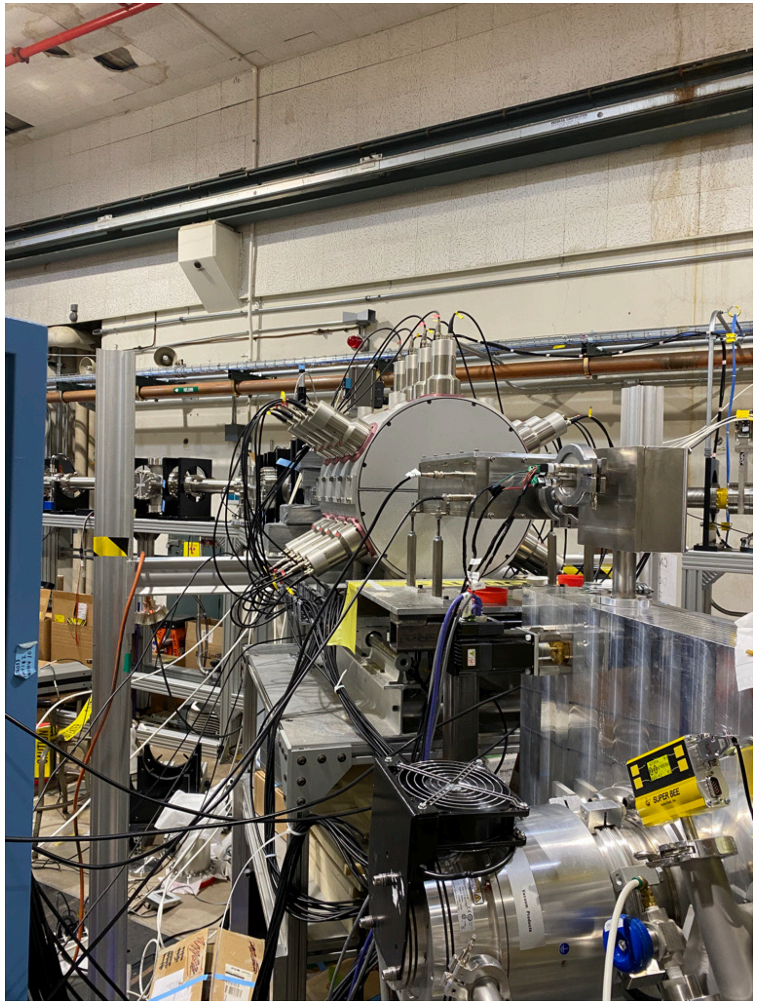


... the uncertainty in the predictions for the double abundance ratio of [La/Eu] and [Ba/La] is greatly reduced, and is now comparable to the uncertainties from astronomical observations.

The samarium experiment @ Argonne National Lab

CARIBU: ^{252}Cf spontaneous fission source → $^{156,158}Pm$. SuN with SuNTAN (tape station), fiber detector for the electrons

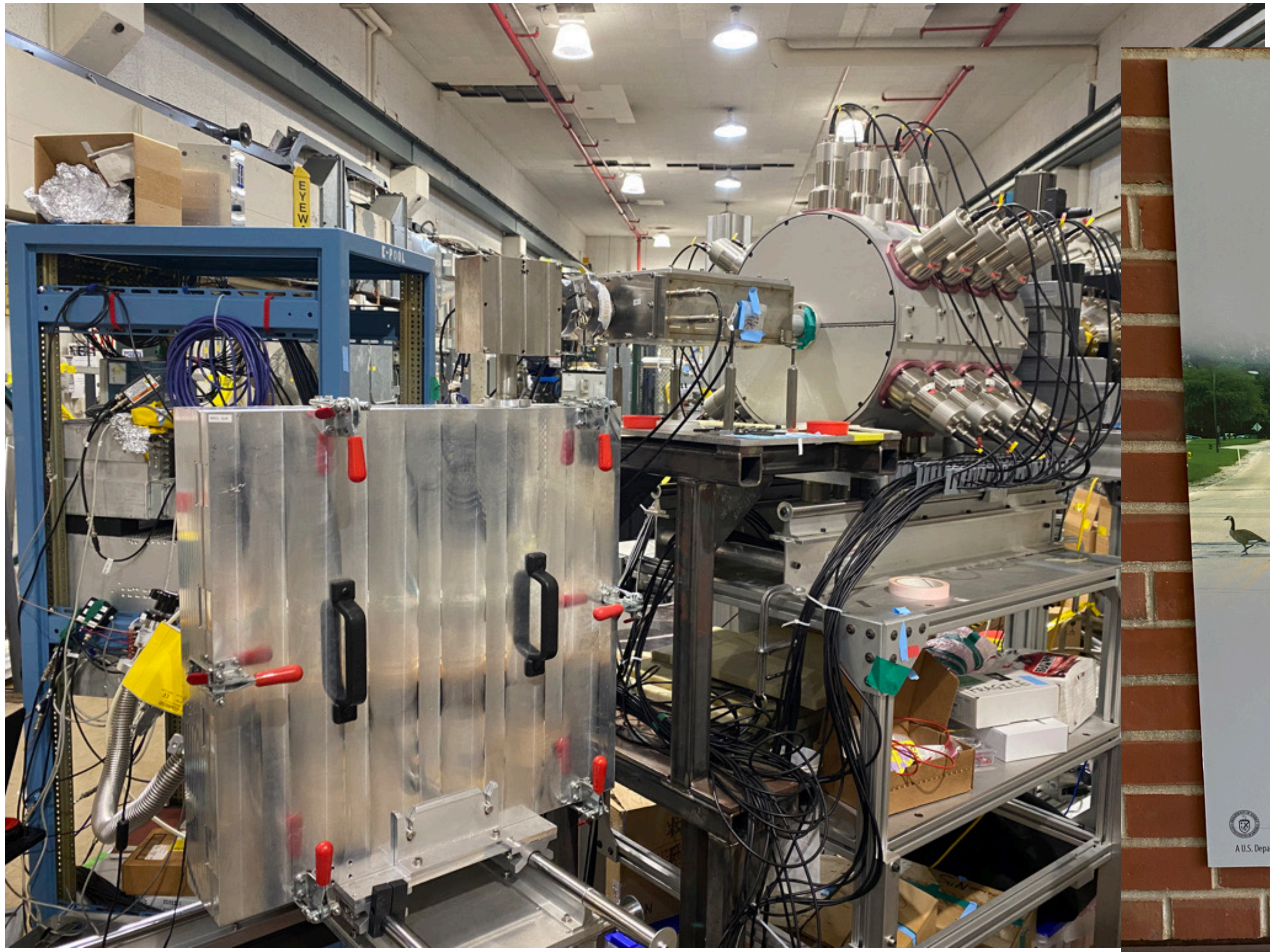
[CARIBU: G. Savard, et al, Nucl. Instr. Methods Phys. Res. B 266, 4086 (2008)]

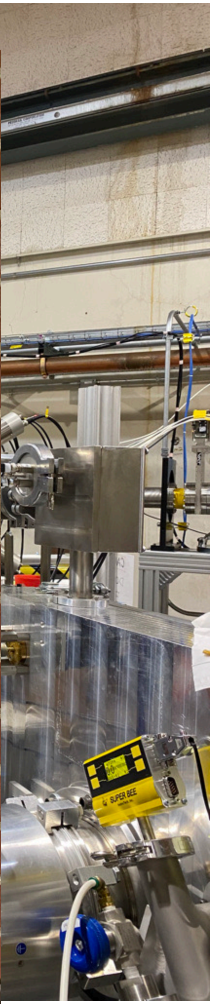


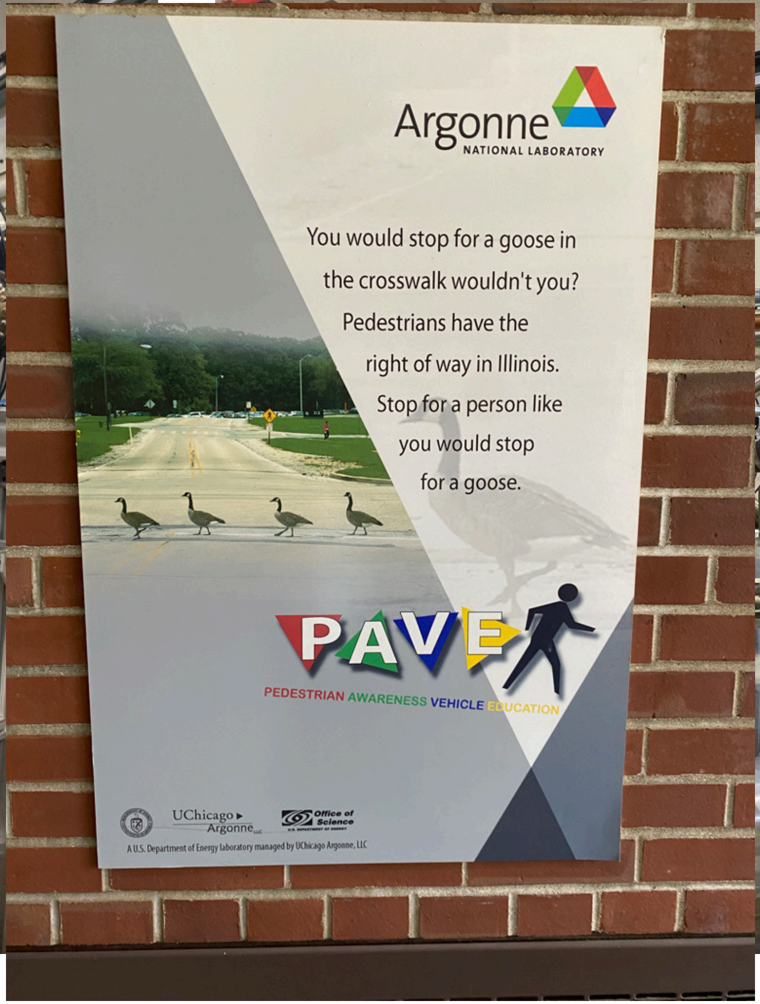
The samarium experiment @ Argonne National Lab

CARIBU: ^{252}Cf spontaneous fission source → ^{156,158}Pm. SuN with SuNTAN (tape station), fiber detector for the electrons

[CARIBU: G. Savard, et al, Nucl. Instr. Methods Phys. Res. B 266, 4086 (2008)]

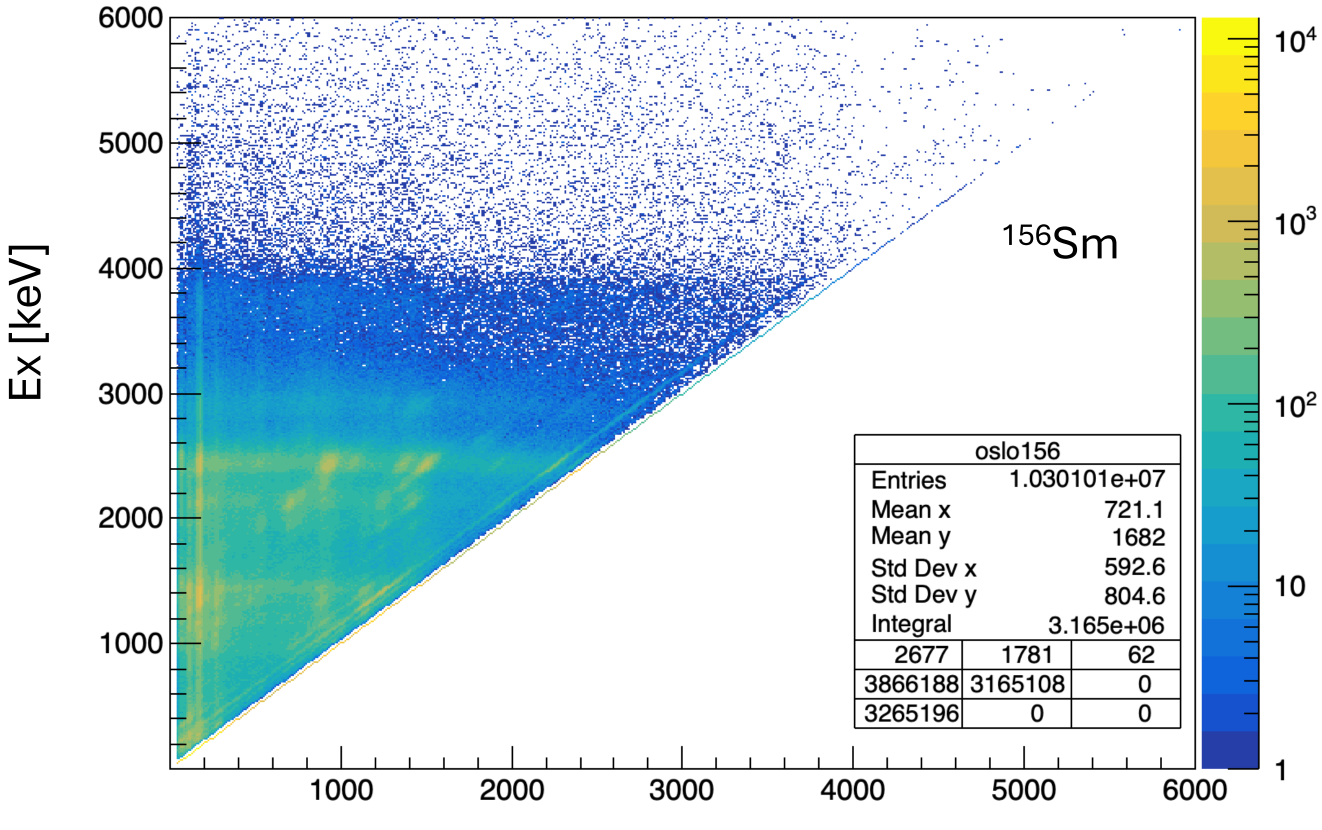


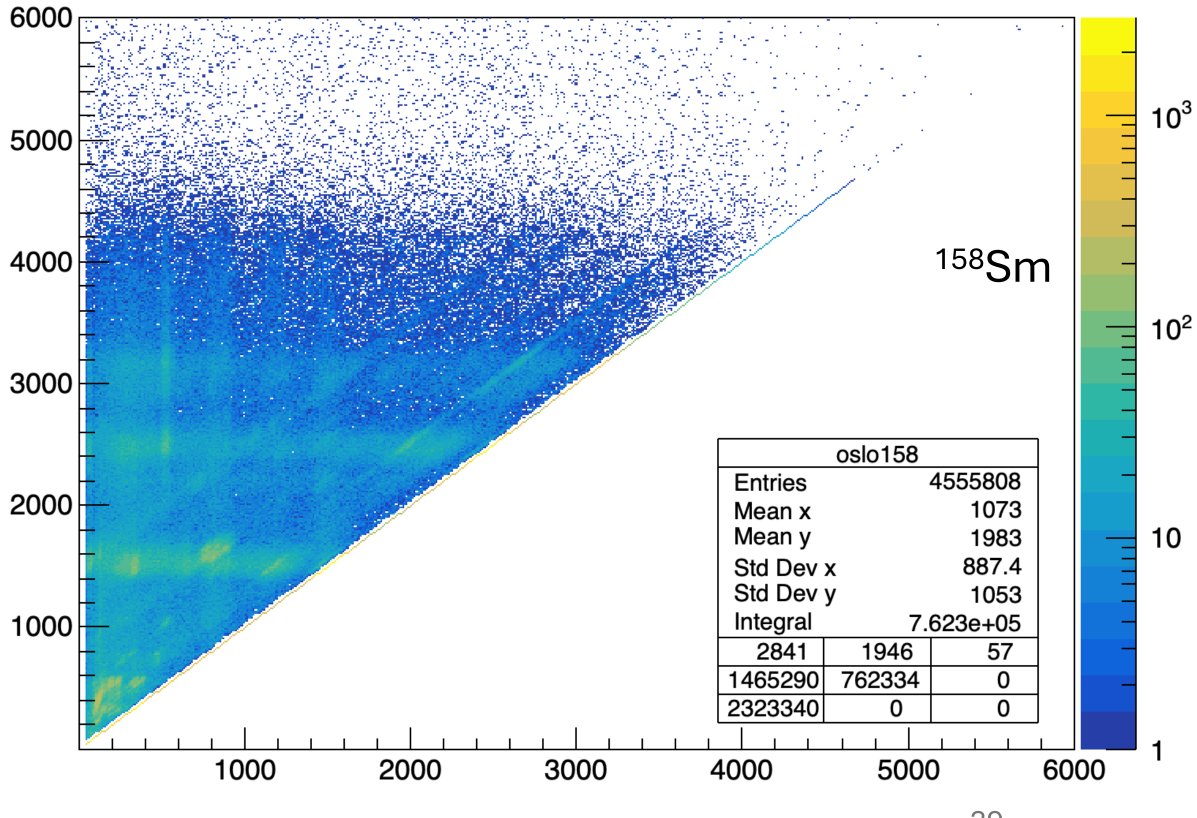




The samarium experiment @ Argonne National Lab

^{156}Pm -> ^{156}Sm: Q-value = 5.20 MeV, S_n = 7.24 MeV, $T_{1/2}$ = 26.7s
^{158}Pm -> ^{158}Sm: Q-value = 6.16 MeV, S_n = 6.64 MeV, $T_{1/2}$ = 4.8 s

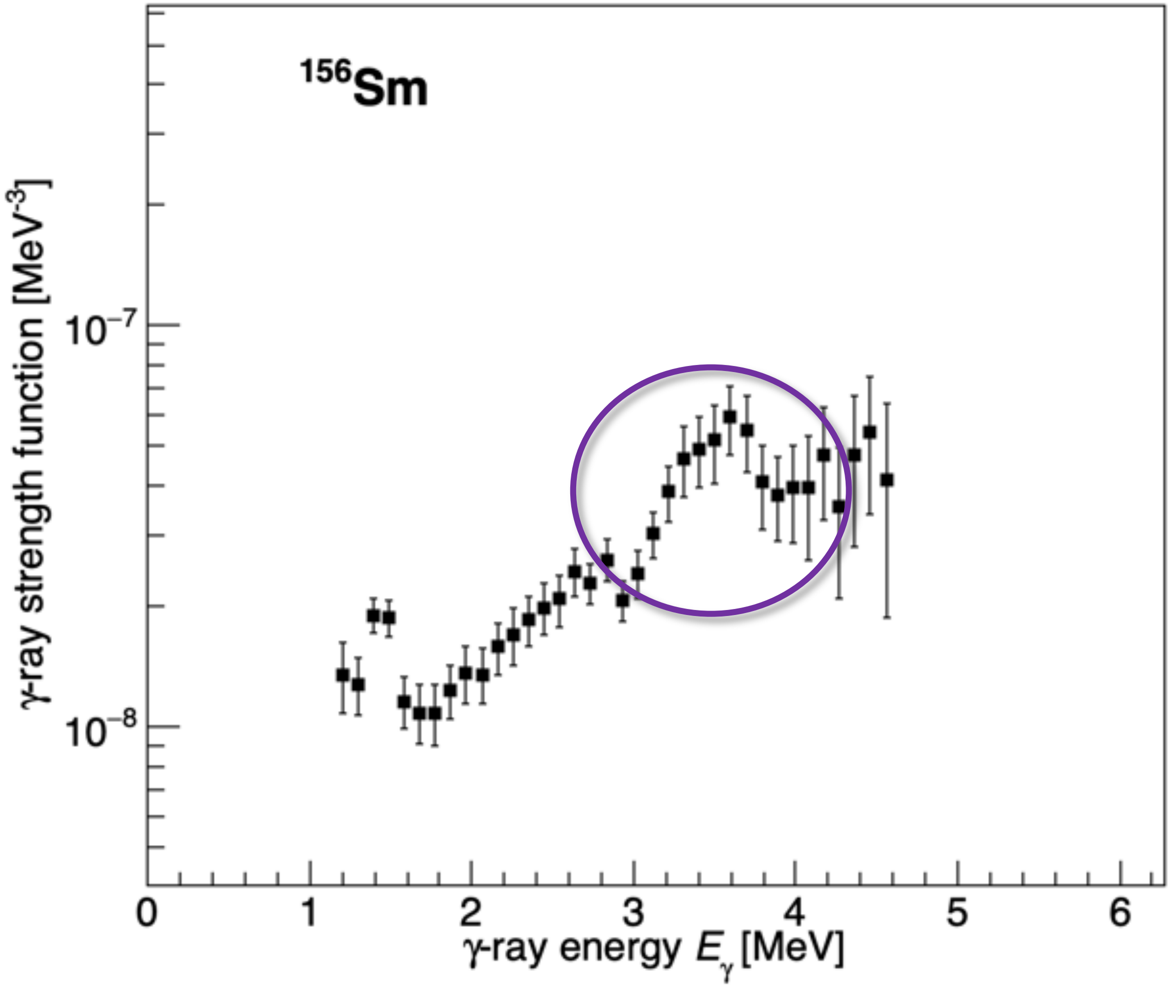


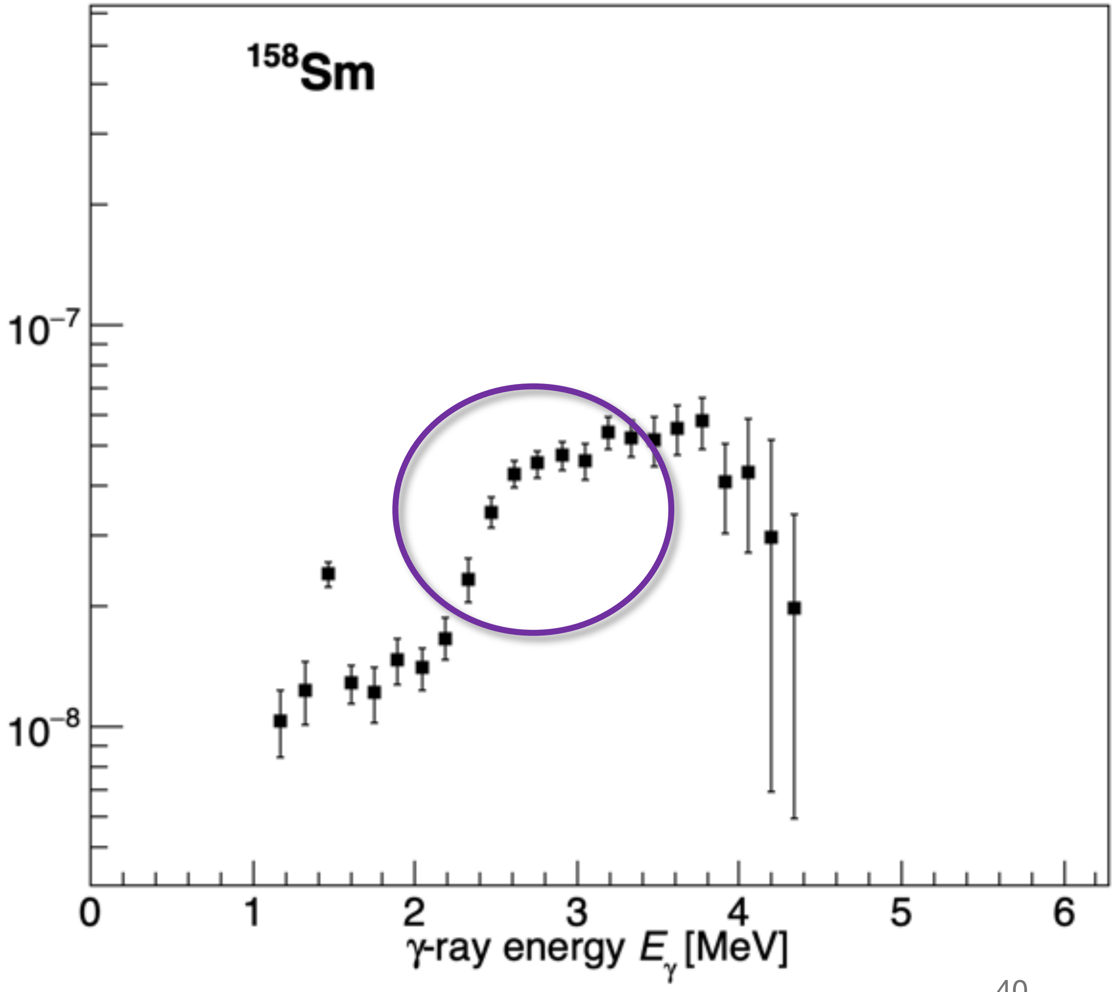


[Larsen et al., data analysis ongoing]

Preliminary results, $^{156,158}Sm$

Deformation (β_2) ≈ 0.34-0.35 [Goriely, Chamel, and Pearson, PRL **102**, 152503 (2009)]

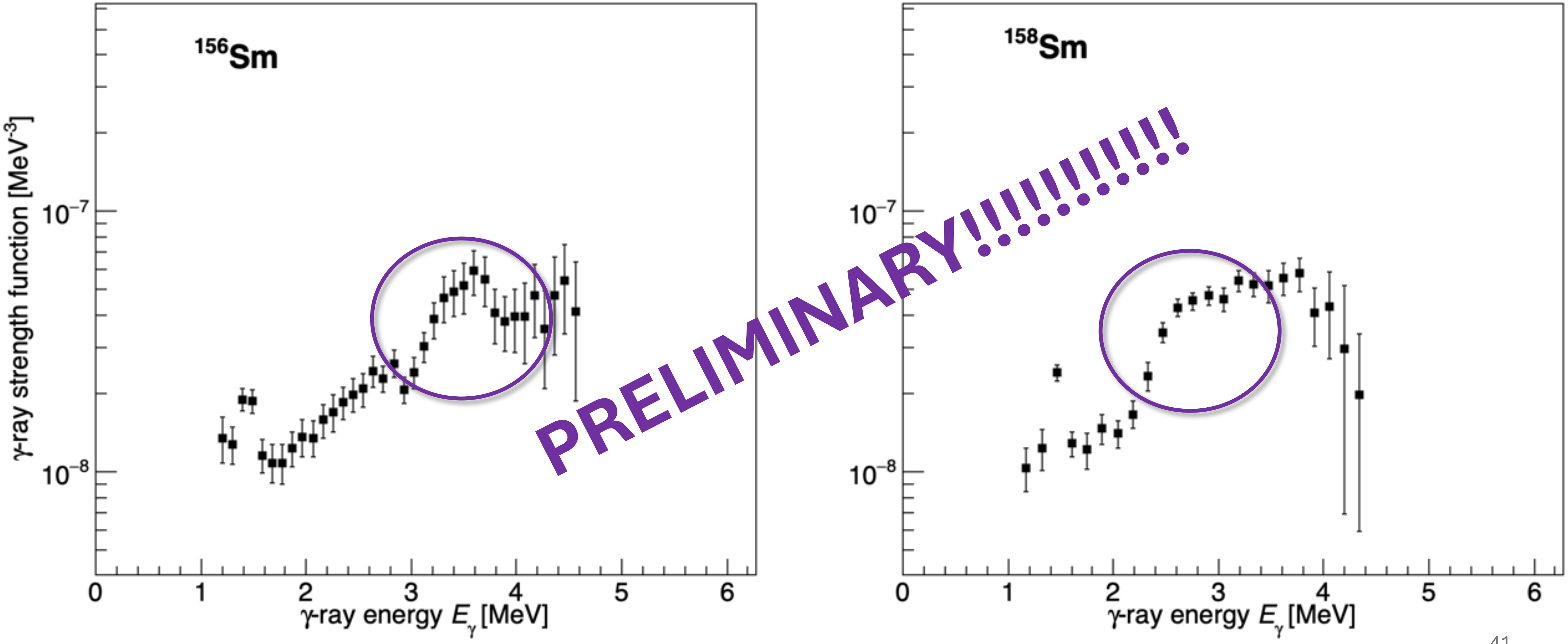




[Larsen et al., data analysis ongoing]

Preliminary results, ^{156,158}Sm

Deformation (β_2) ≈ 0.34-0.35 [Goriely, Chamel, and Pearson, PRL **102**, 152503 (2009)]



[Larsen et al., data analysis ongoing]

Summary & outlook

From plusquotes.com

Take-home message:

Indirect methods are often the only way to determine (n,γ) reaction rates for the *i* and *r* process → (beta-)Oslo method!

Challenges:

(i) We need to go much more neutron-rich → beta-delayed neutron emission opens up! Also, higher γ multiplicity, especially for well-deformed nuclei 🤔

(ii) We need to get better normalizations for the level density and γ-ray strength for neutron-rich, unstable nuclei!

Summary & outlook

From plusquotes.com

<u>Take-home message</u>:

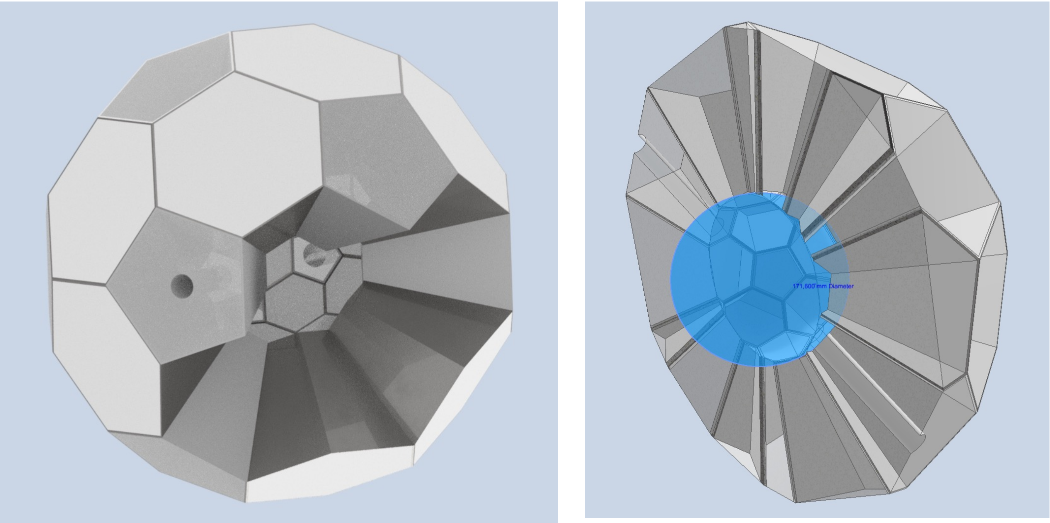
Indirect methods are often the only way to determine (n,γ) reaction rates for the *i* and *r* process → (beta-)Oslo method!

<u>Challenges</u>:

(i) We need to go much more neutron-rich → beta-delayed neutron emission opens up! Also, higher γ multiplicity, especially for well-deformed nuclei 🤔

(ii) We need to get better normalizations for the level density and γ-ray strength for neutron-rich, unstable nuclei!

<u>My dream</u>:
A highly segmented total-absorption spectrometer made of NaI(Tl+Li) 🤩



Design drawings by Maren Lithun, UiO

Summary & outlook

From plusquotes.com

Take-home message:

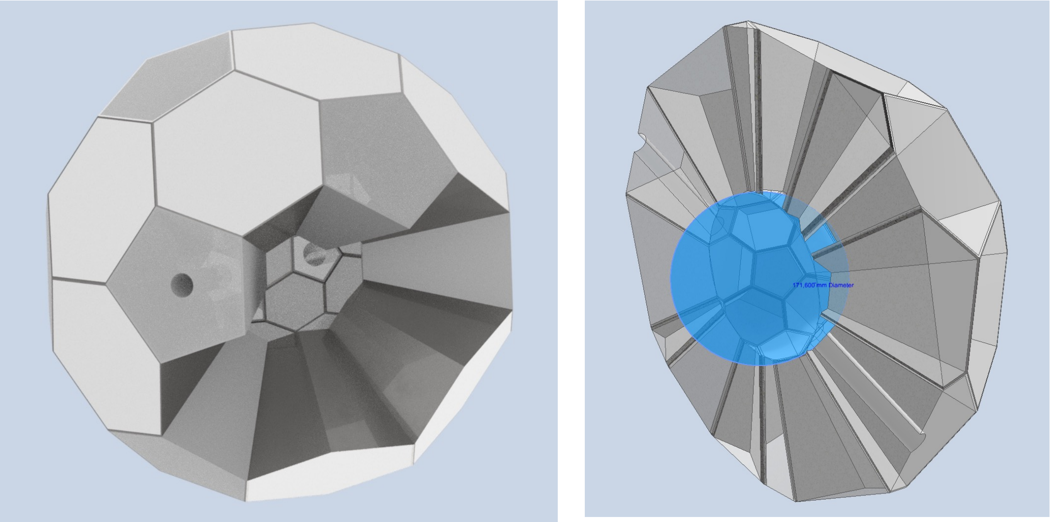
Indirect methods are often the only way to determine (n,γ) reaction rates for the *i* and *r* process → (beta-)Oslo method!

Challenges:

(i) We need to go much more neutron-rich → beta-delayed neutron emission opens up! Also, higher γ multiplicity, especially for well-deformed nuclei 🤔

(ii) We need to get better normalizations for the level density and γ-ray strength for neutron-rich, unstable nuclei!

My dream:
A highly segmented total-absorption spectrometer made of NaI(Tl+Li) 🤩

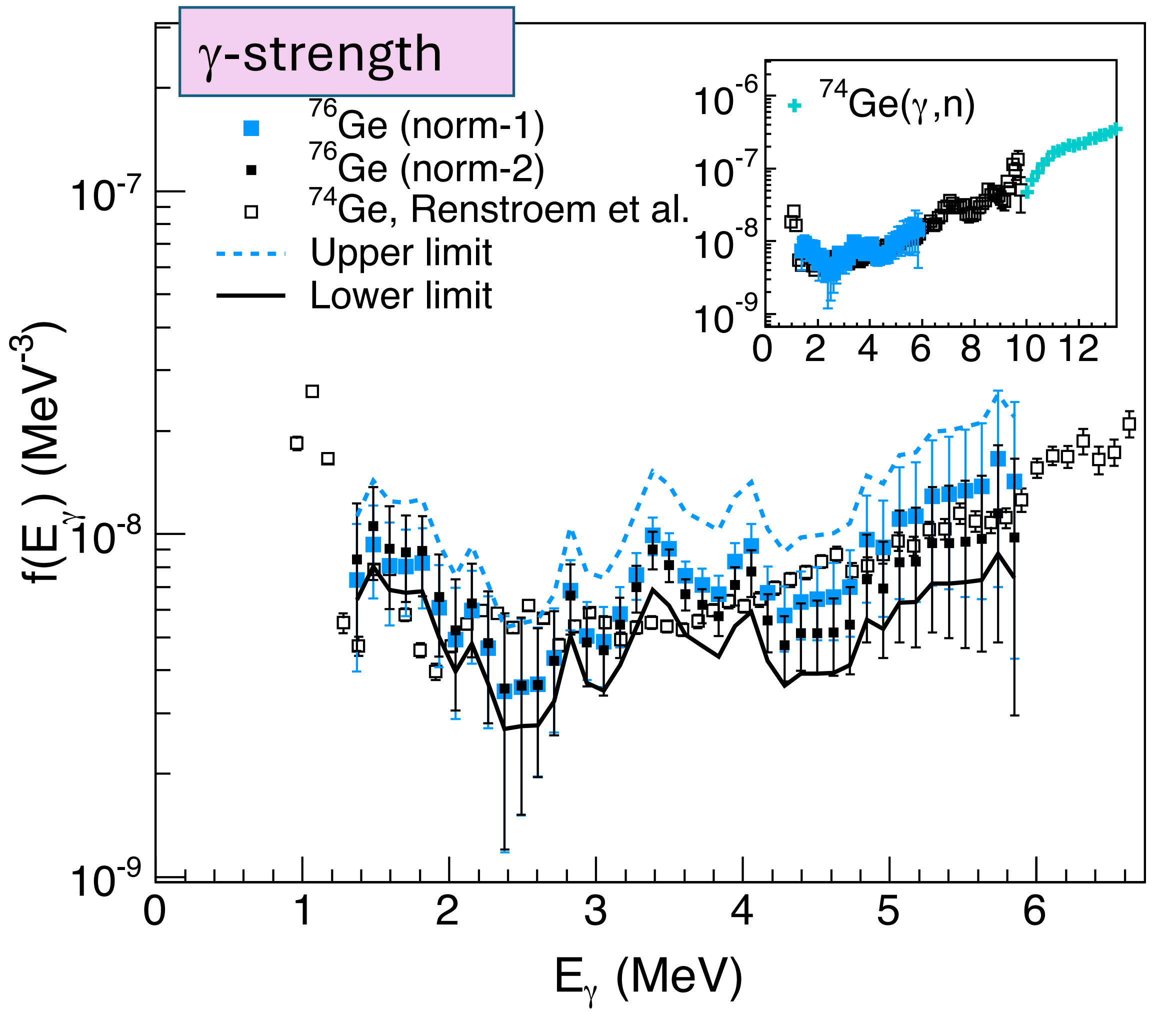


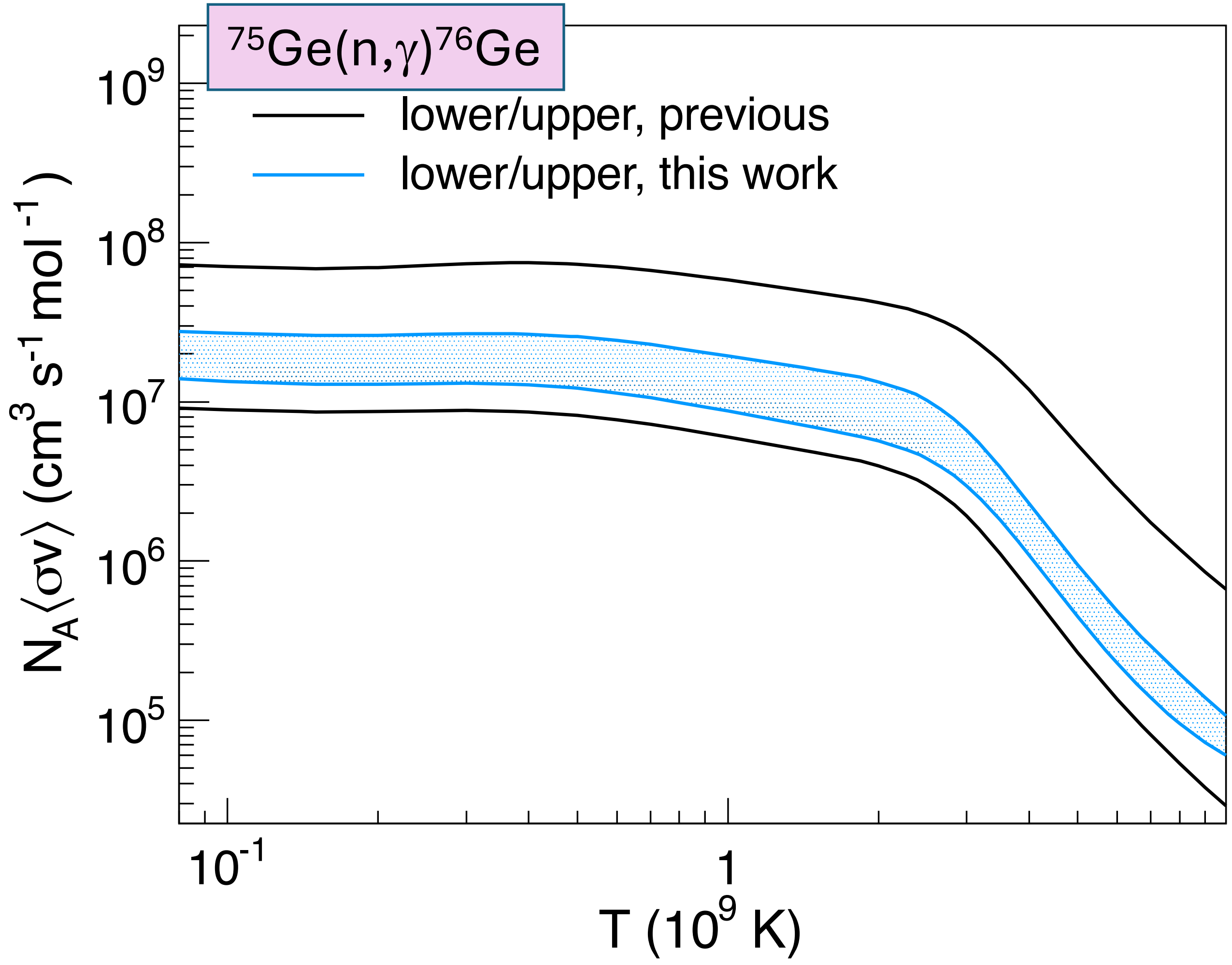
Design drawings by Maren Lithun, UiO

Many thanks for your attention!

Extra stuff

The beta-Oslo method: ^{76}Ge results

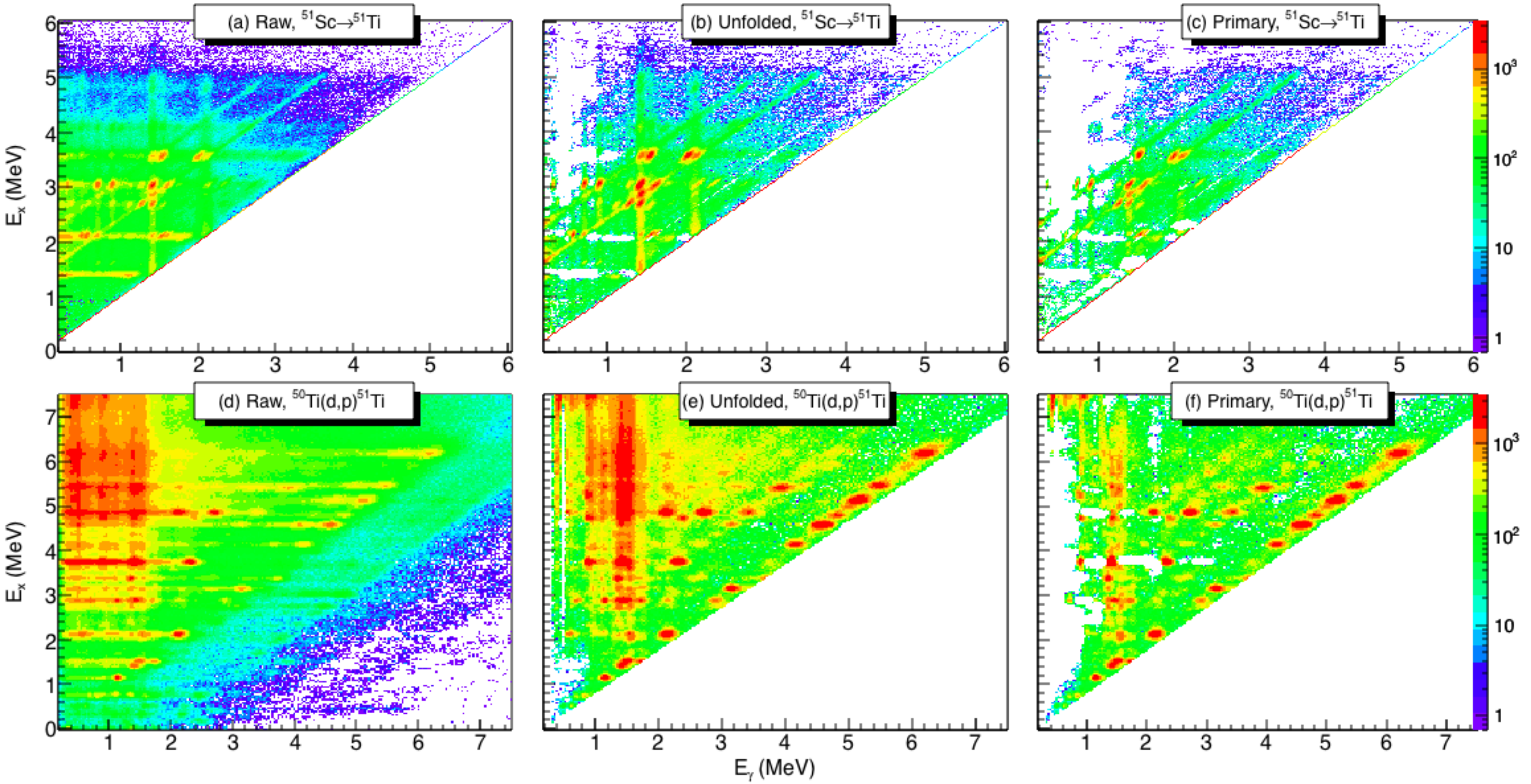




[A. Spyrou, S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRL **113**, 232502 (2014)]

Benchmarking Oslo and beta-Oslo methods

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

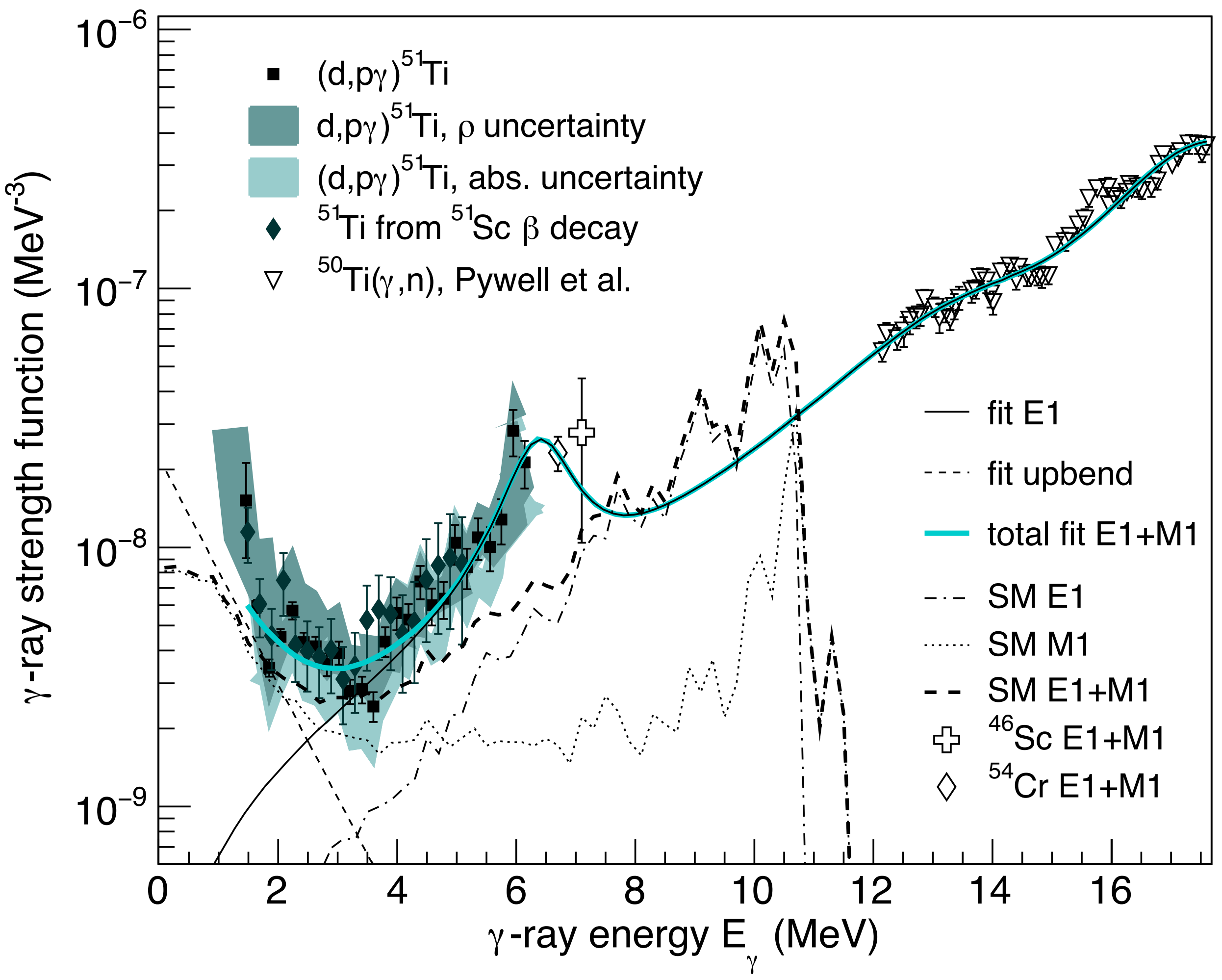


[S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRC **100**, 024624 (2019)]

Benchmarking Oslo and beta-Oslo methods

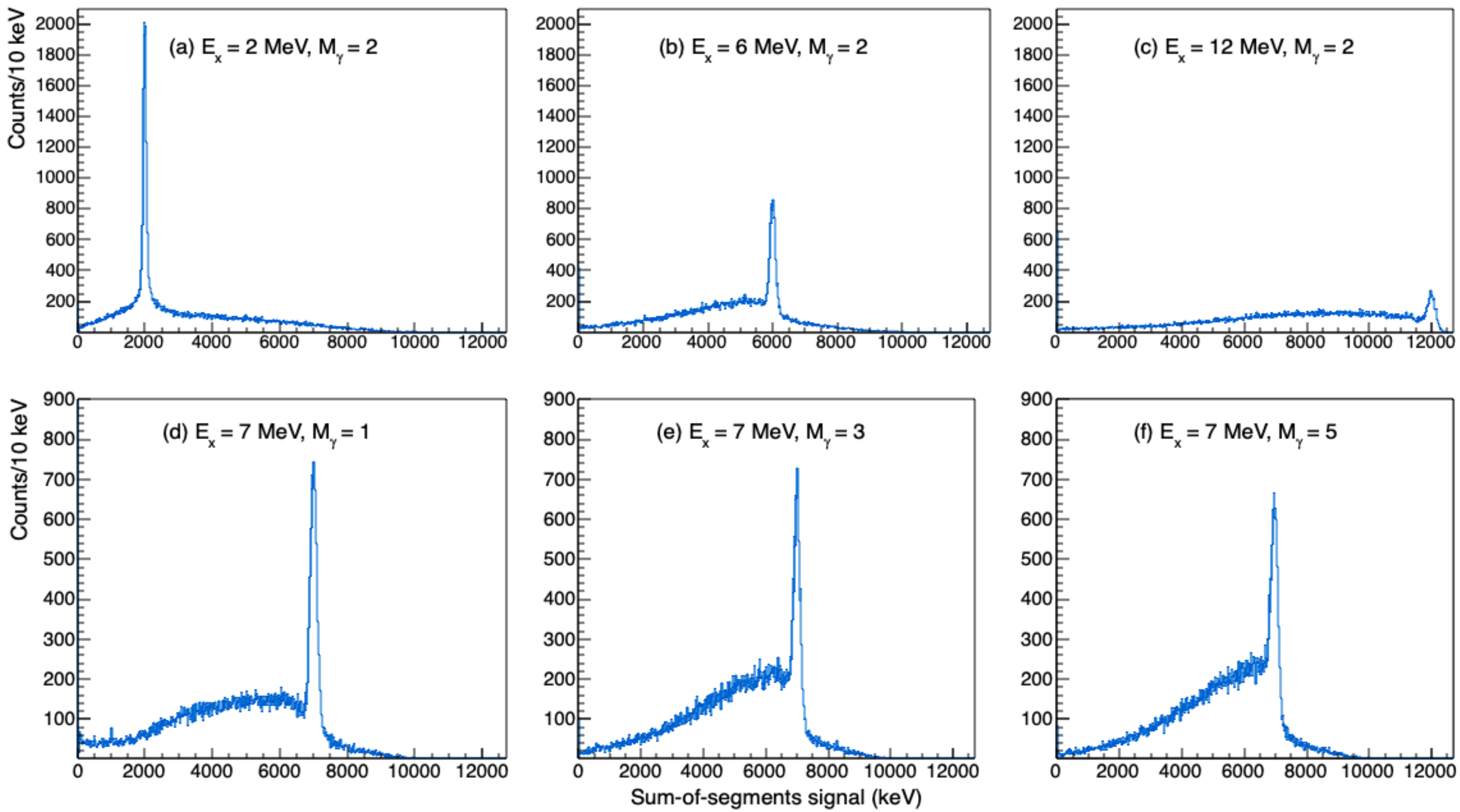
Almost the same spin range of final levels

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



[S.N. Liddick, A.C. Larsen, M. Guttormsen et al., PRC **100**, 024624 (2019)]

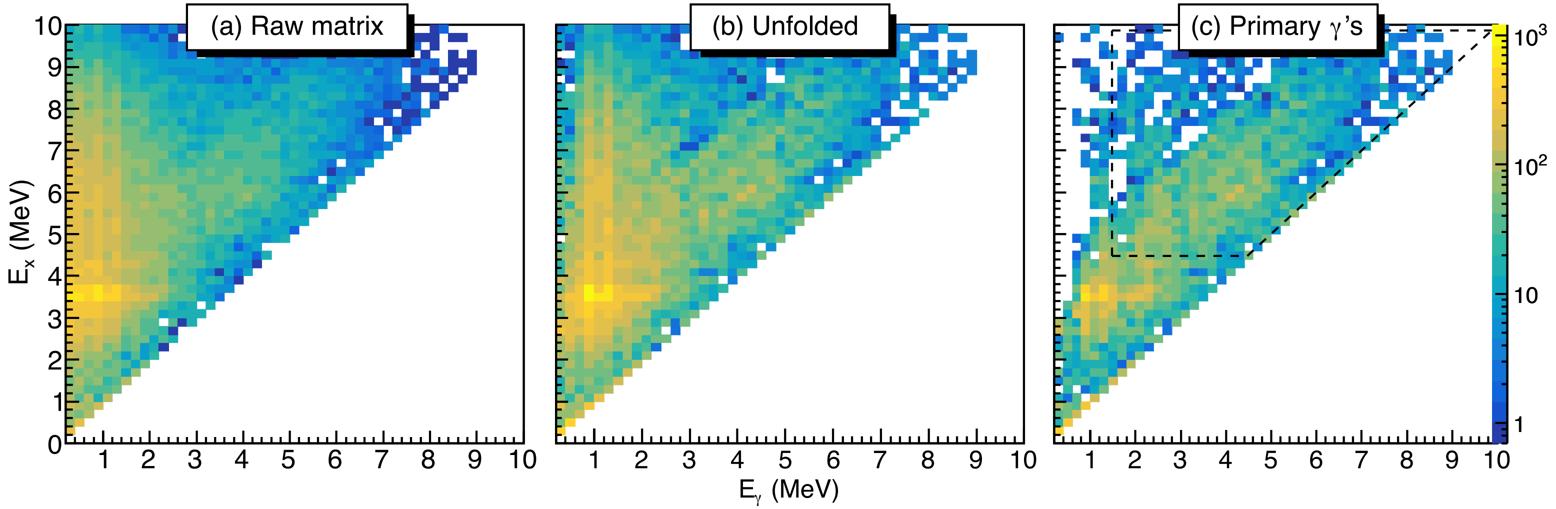
Unfolding of Ex axis: ^{70}Ni Ex response function



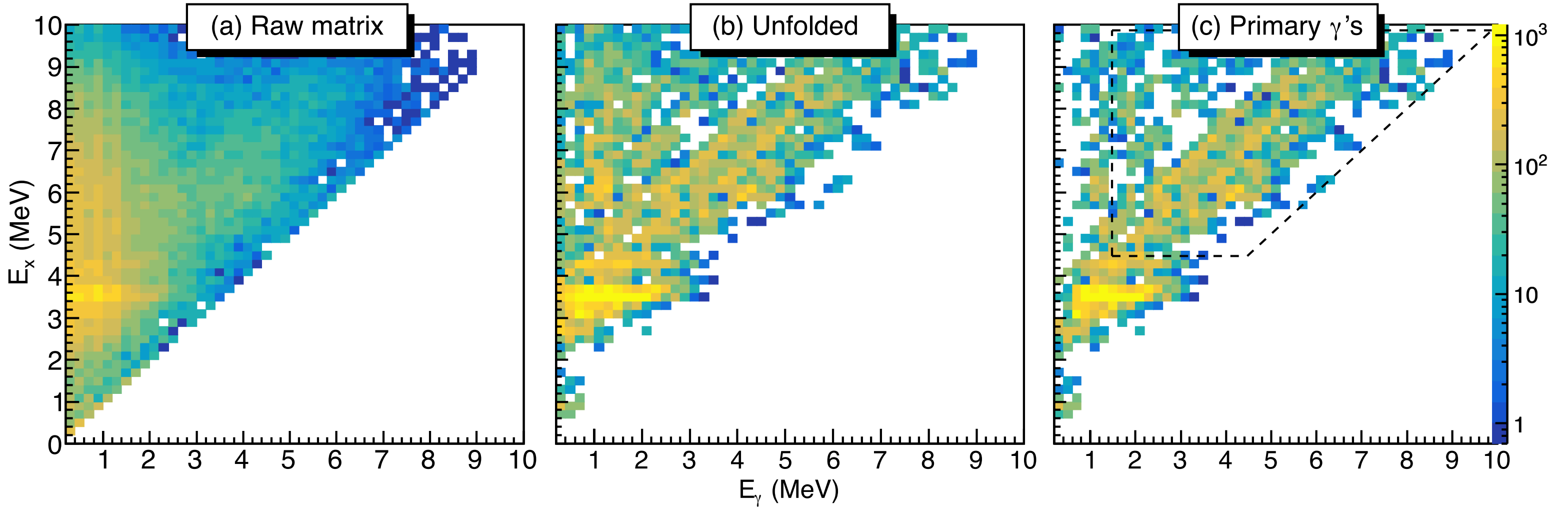
Unfolding of Ex axis: ^{70}Ni

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

Old:

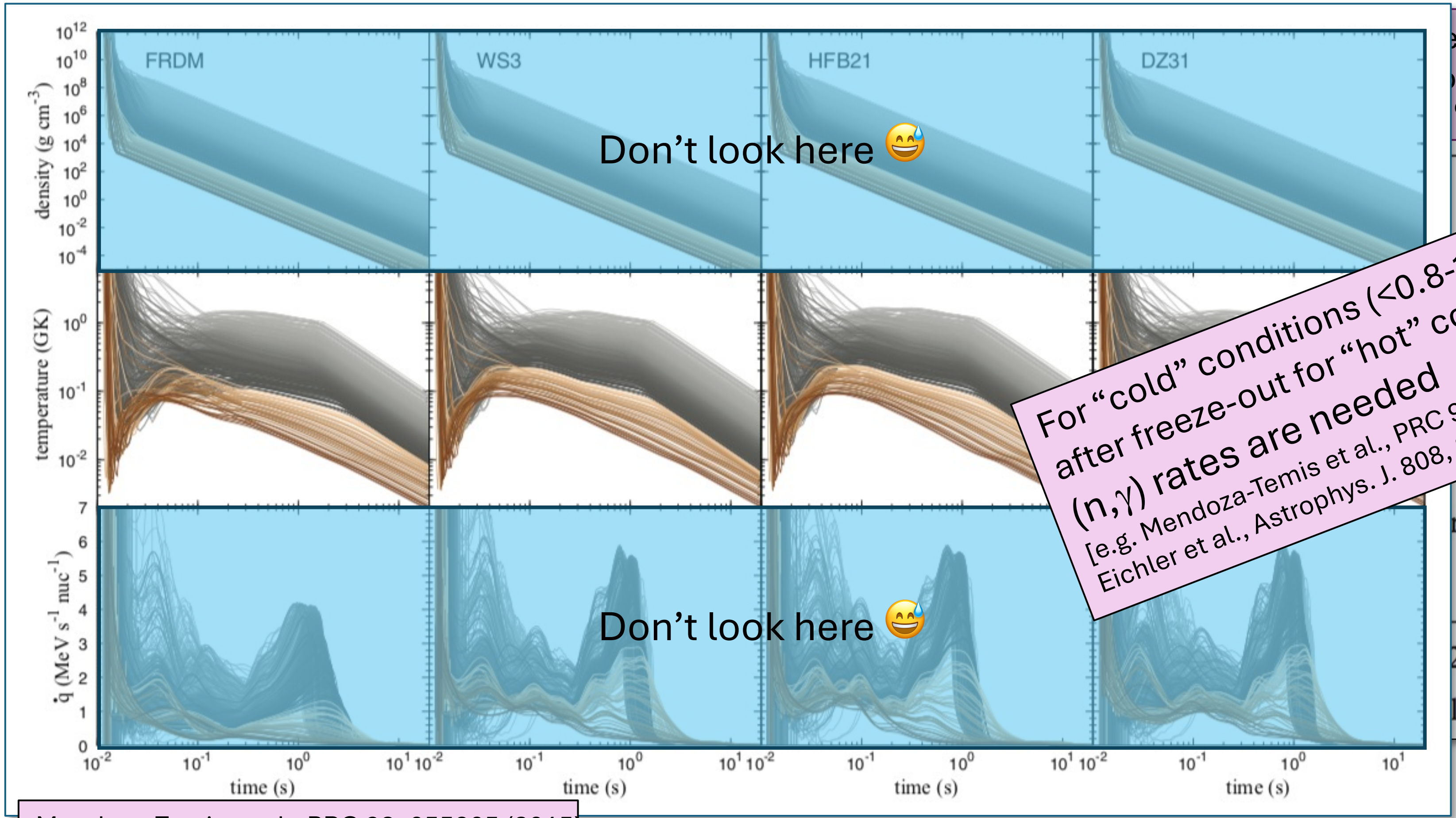


New:



Neutron-star merger *r*-process trajectories

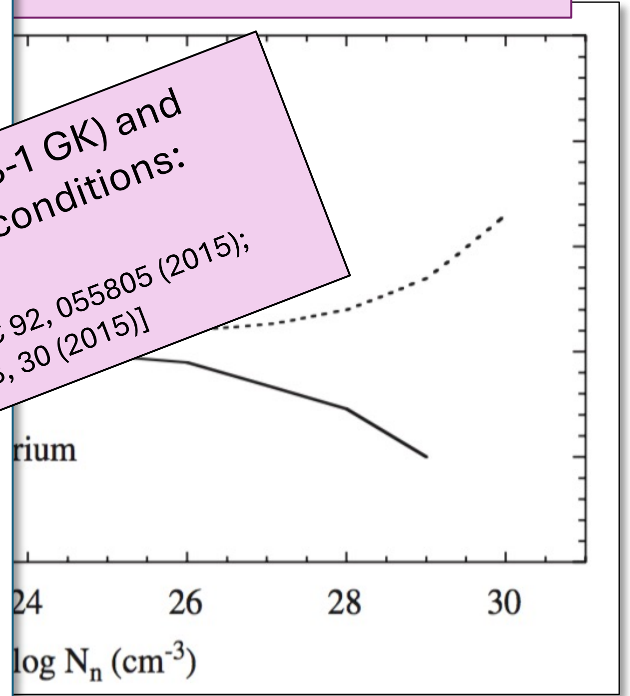
⚖️ (n,γ)-(γ,n) equilibrium: to be or not to be



Mendoza-Temis et al., PRC 92, 055805 (2015)

...: pure Hauser-Feshbach; dashed ... **direct capture**

[... Goriely and K. Takahashi, Phys. Rep. 450, 97 (2007)]



For "cold" conditions (<0.8-1 GK) and after freeze-out for "hot" conditions: (n,γ) rates are needed

[e.g. Mendoza-Temis et al., PRC 92, 055805 (2015); Eichler et al., Astrophys. J. 808, 30 (2015)]