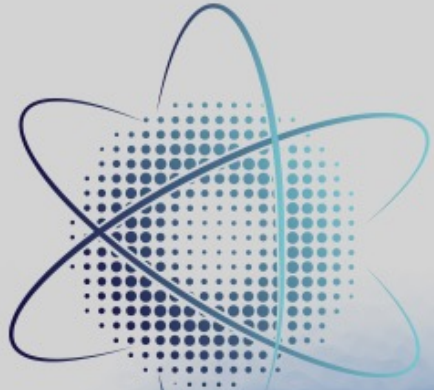




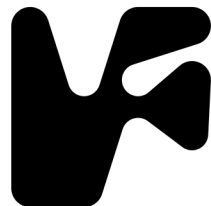
NORWEGIAN NUCLEAR
RESEARCH CENTRE

Updates from OCL

CM on Evaluation of Photon Strength Function



UNIVERSITY
OF OSLO



Funded by
The Research
Council of Norway

V. W. Ingeberg

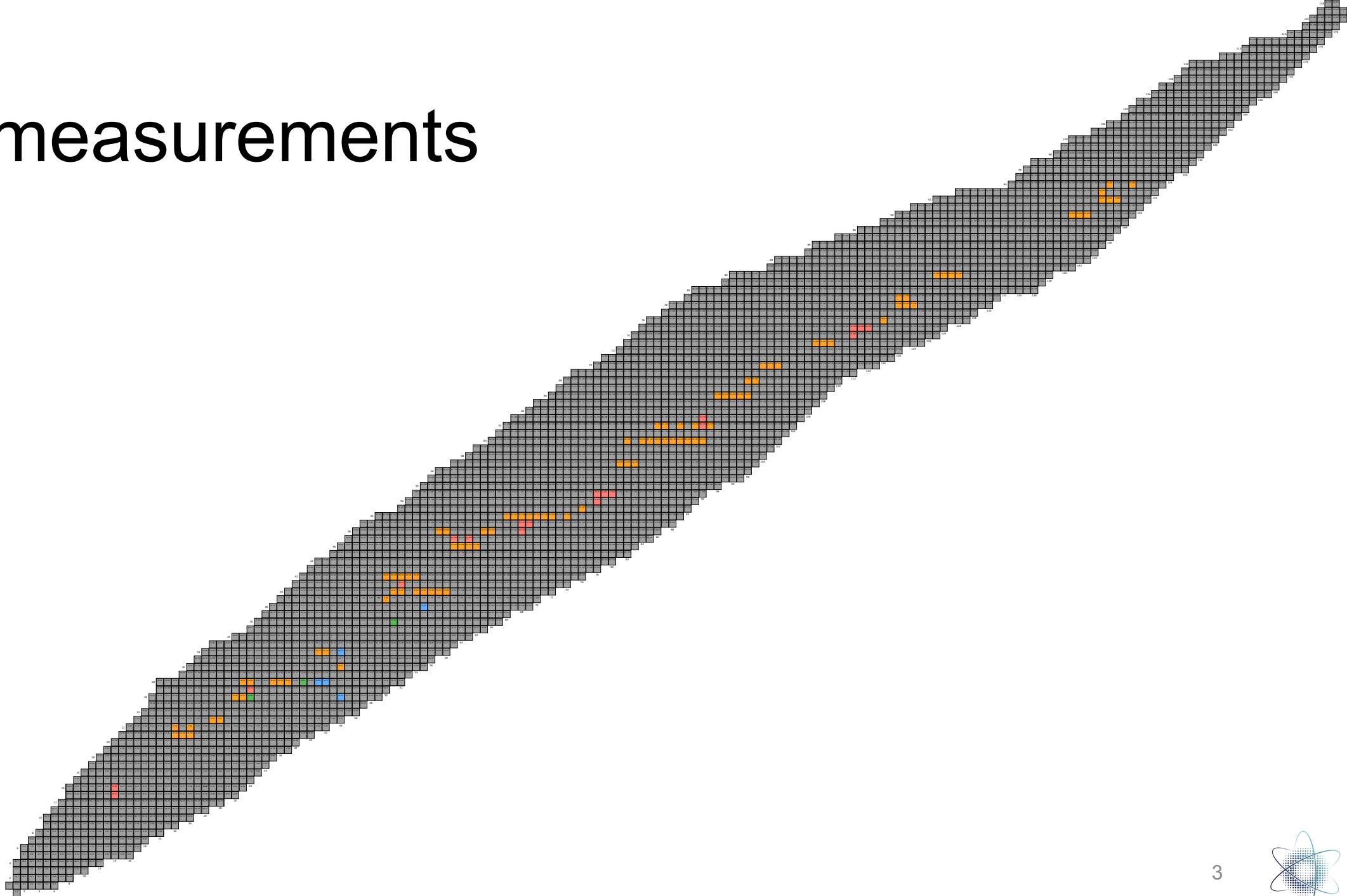
13/11/2025

Outline

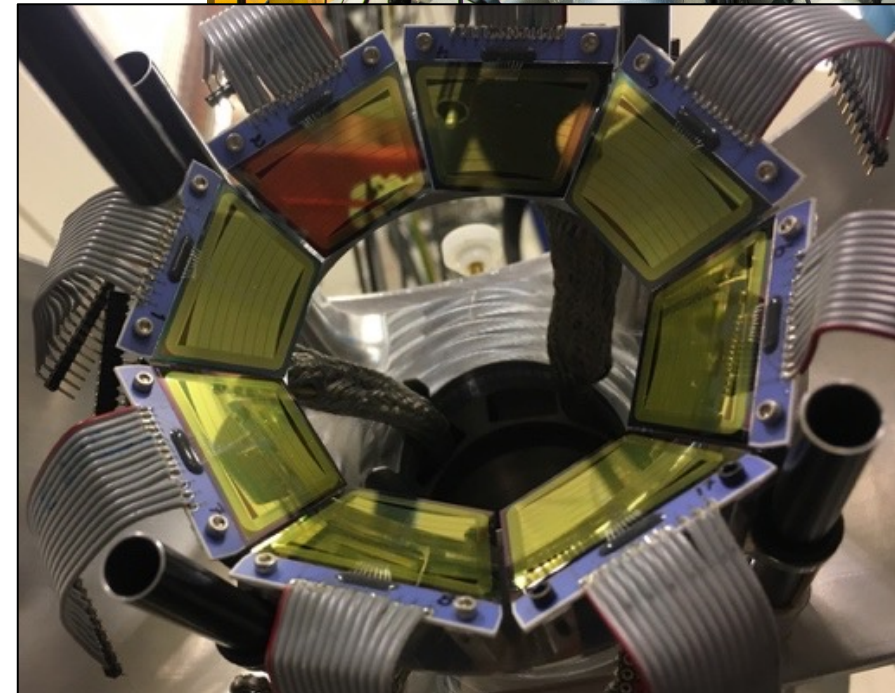
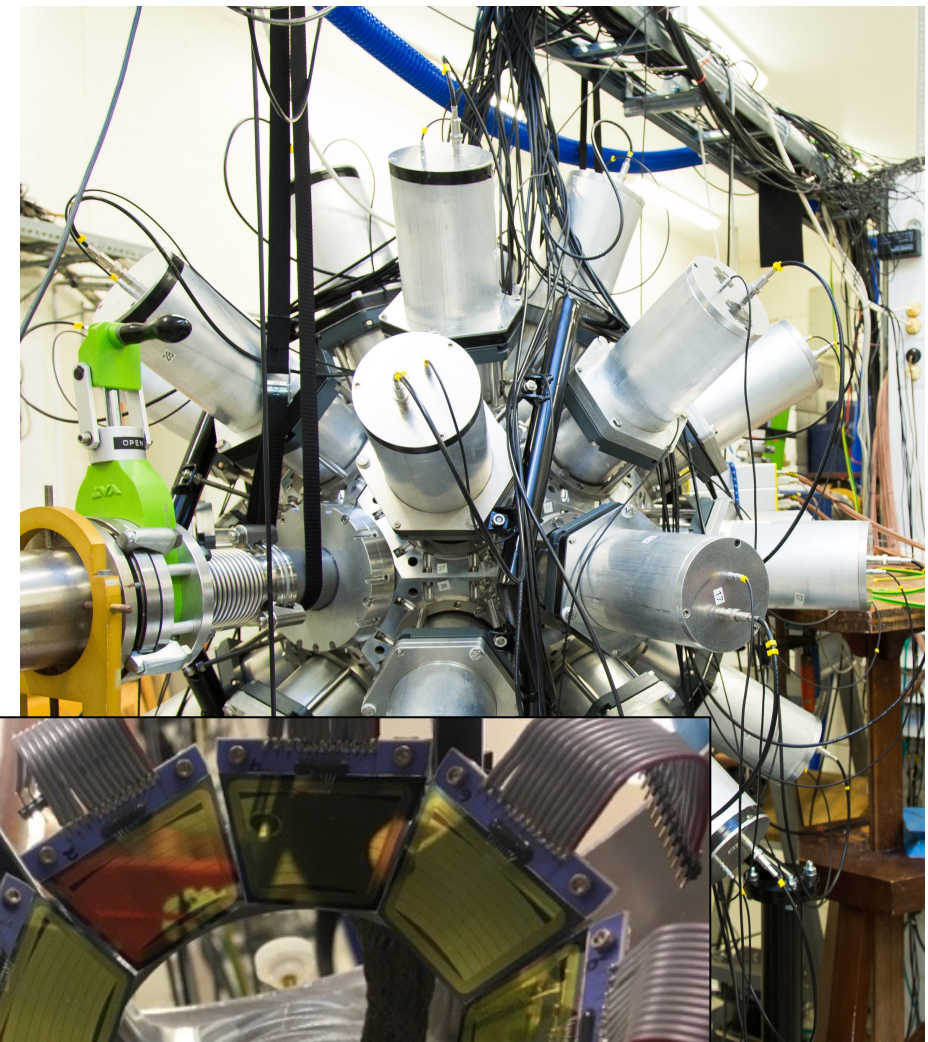
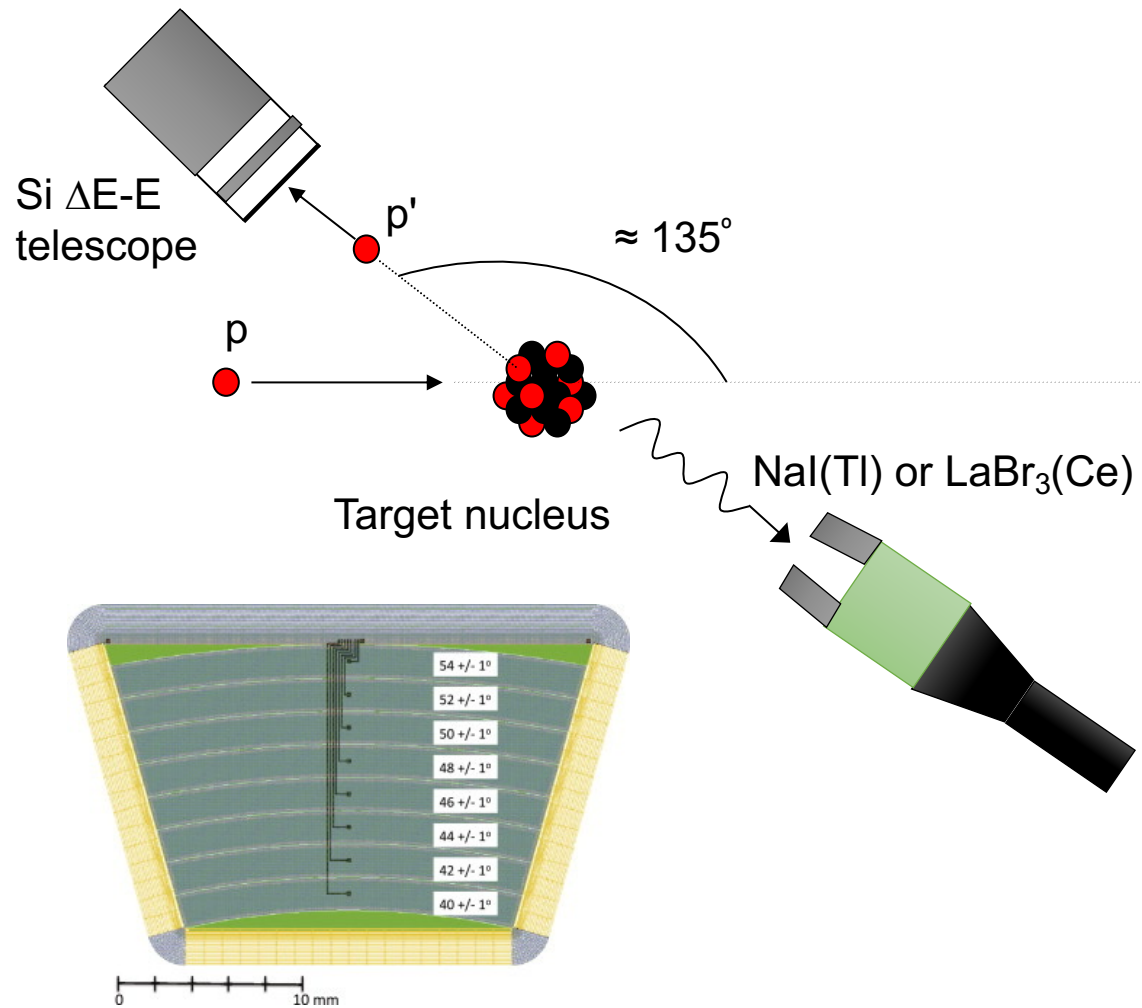
- Recently published and soon to be published
- Ongoing work
- Recent experiments



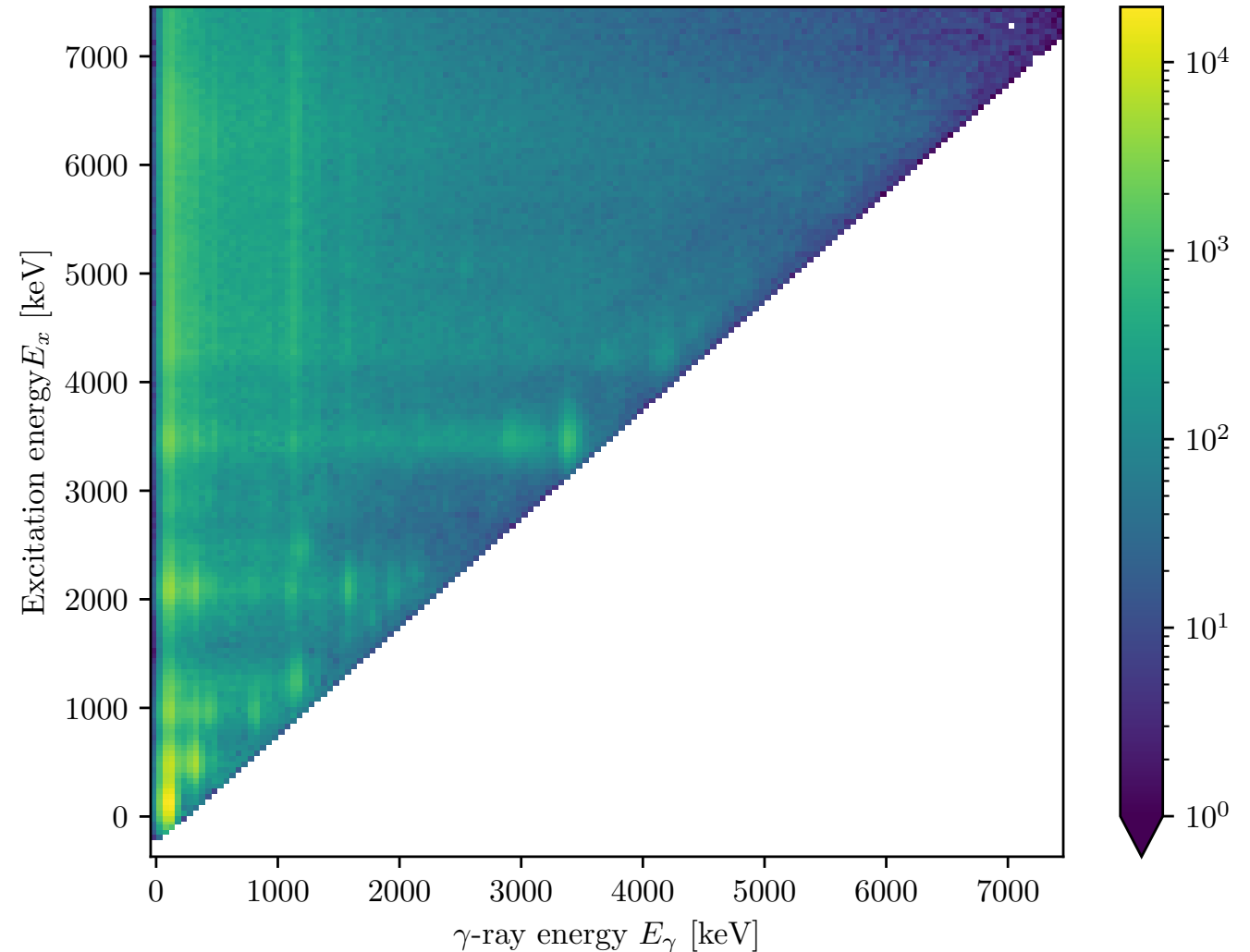
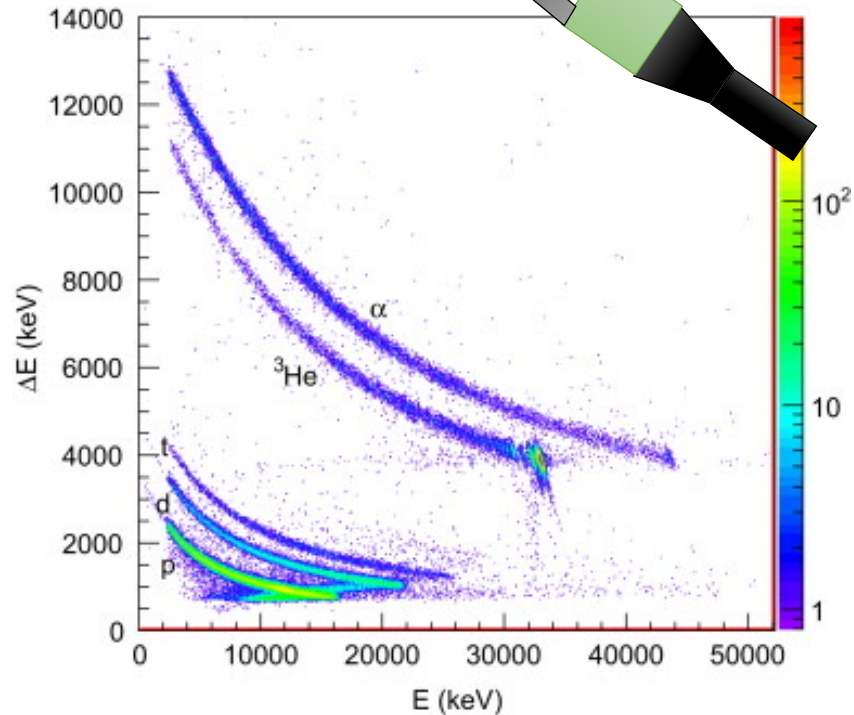
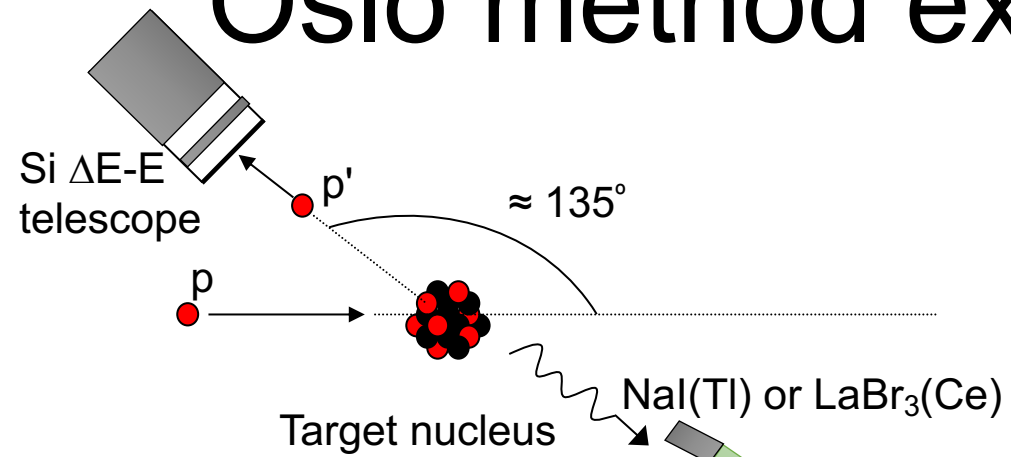
OM measurements



The Oslo Method experiment

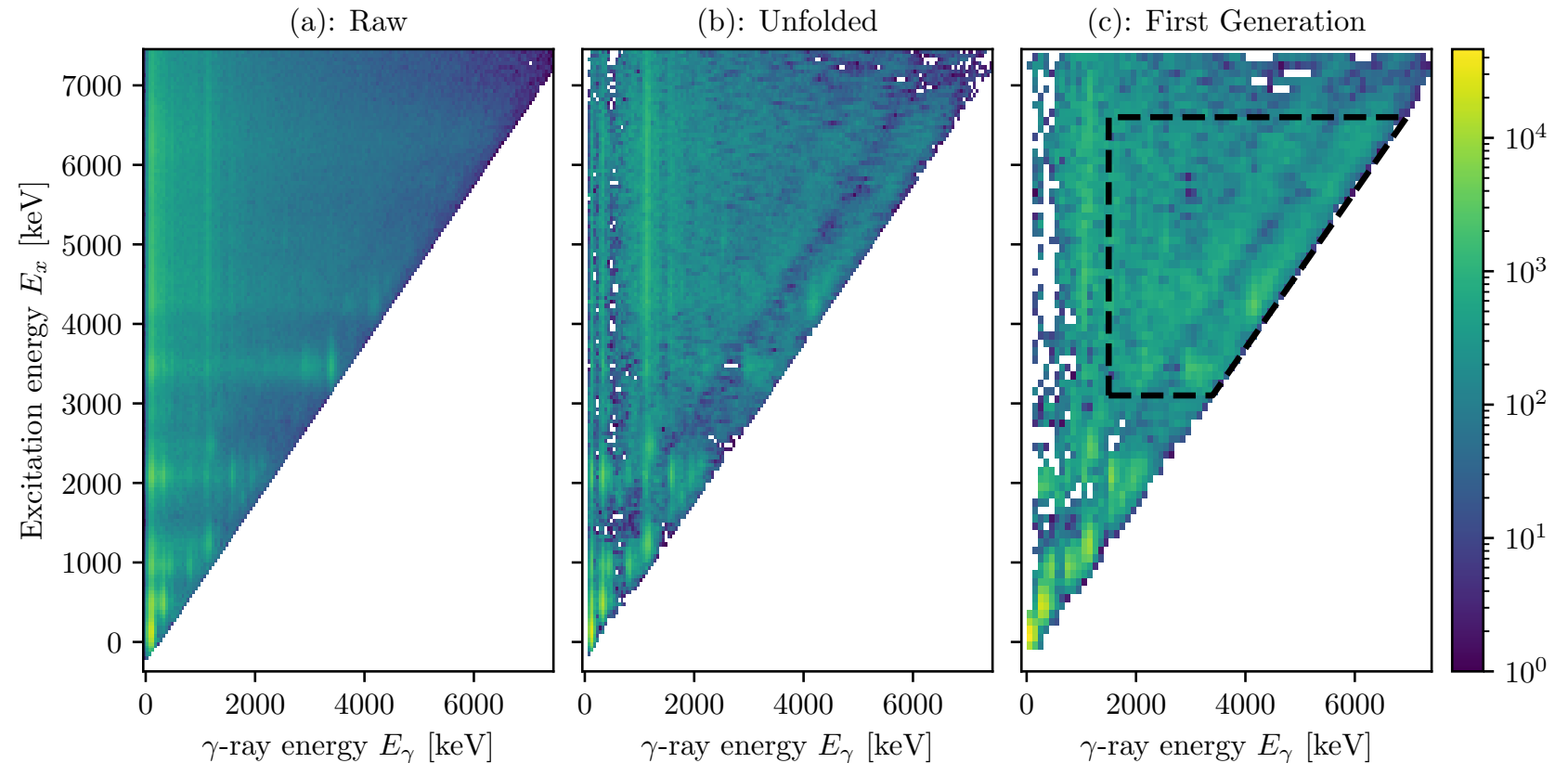


Oslo method experiment



Oslo Method in 4 (simple) steps!

1. Obtain excitation energy tagged gamma spectra
2. Unfolding method
3. First generation method
4. Extract NLD and γ SF



$$P(E_x, E_\gamma) \propto 2\pi E_\gamma^3 f(E_\gamma) \rho(E_f = E_x - E_\gamma)$$



Unfolding

1. $f^0 = \mathbf{R}u^0$

2. $u^1 = u^0 + (m - f^0)$

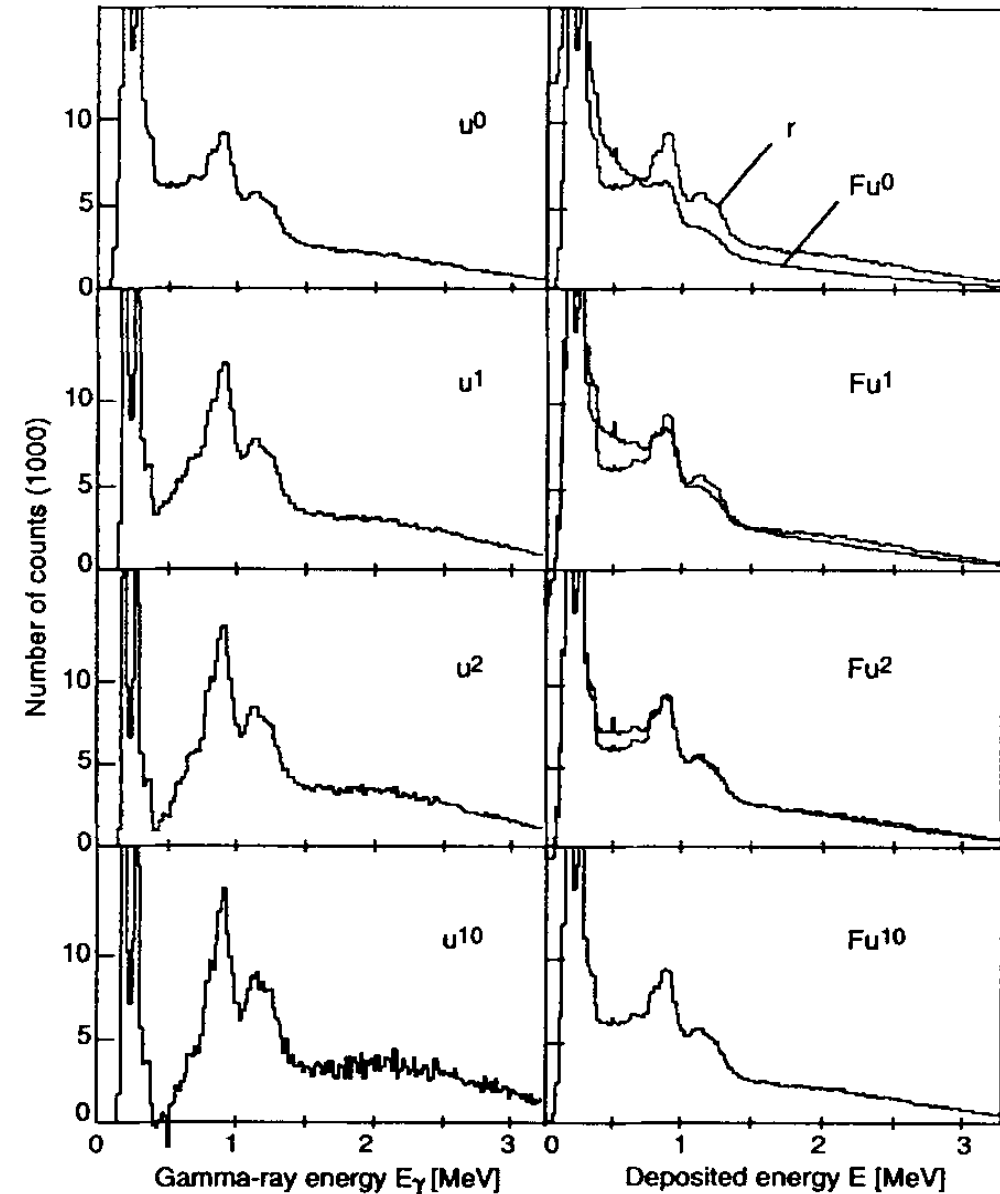
Repeat until convergence

f: Folded spectrum

u: unfolded

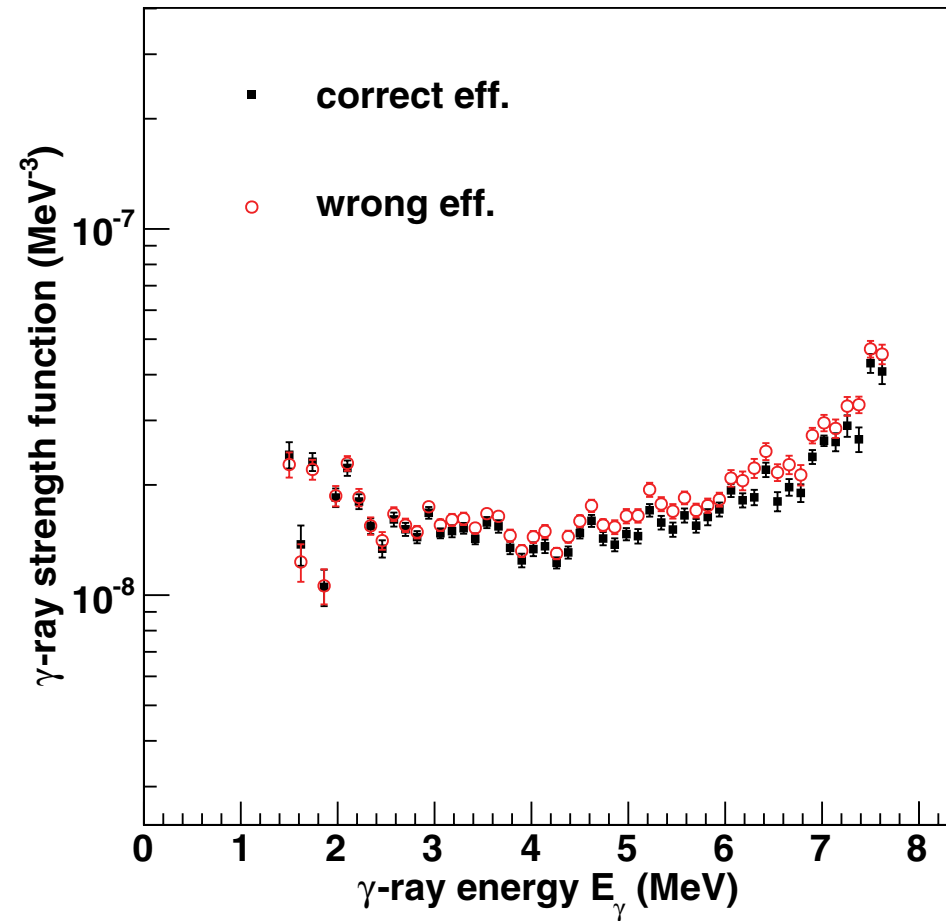
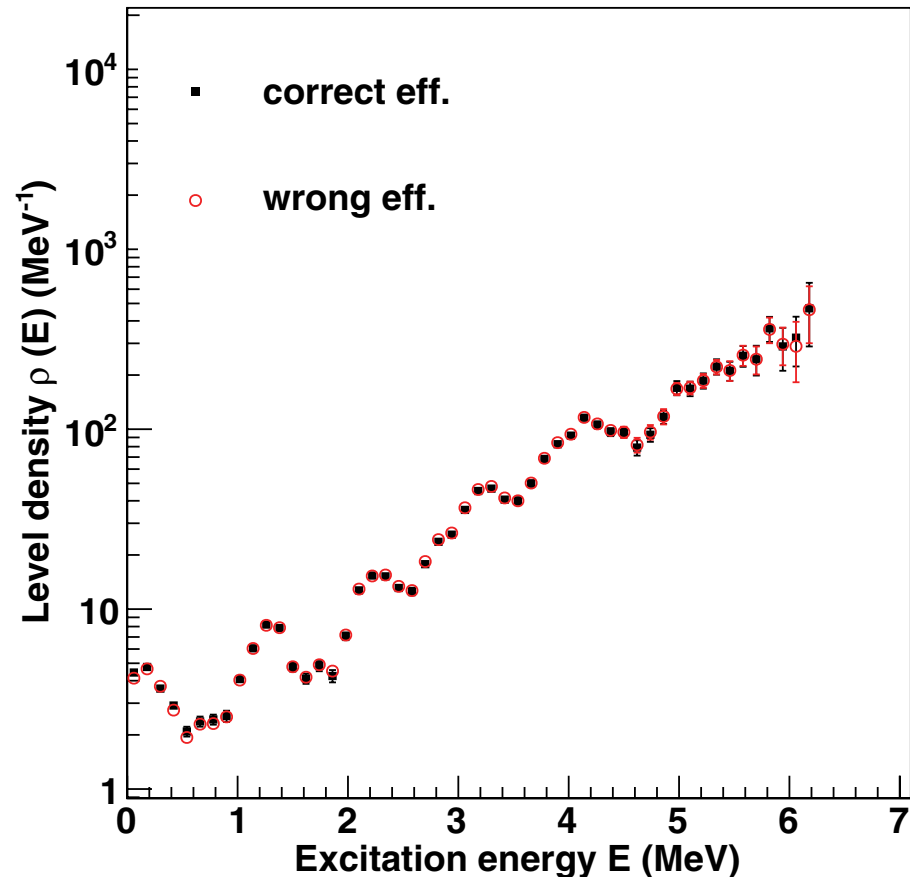
m: measured spectrum

R: response function



Sources of errors – unfolding method

Assuming a efficiency reduction of $\approx 20\%$



Uncertainty estimation

Regularized Unfolding of γ -ray Spectra for Nuclear Physics Applications

E. Lima,^{1,2} L. L. Braseth,¹ A. H. Mjøs,^{1,2} M. Hjorth-Jensen,^{3,4} A. Kvellestad,¹ and A. C. Larsen^{1,2}

¹Department of Physics, University of Oslo, N-0316 Oslo, Norway

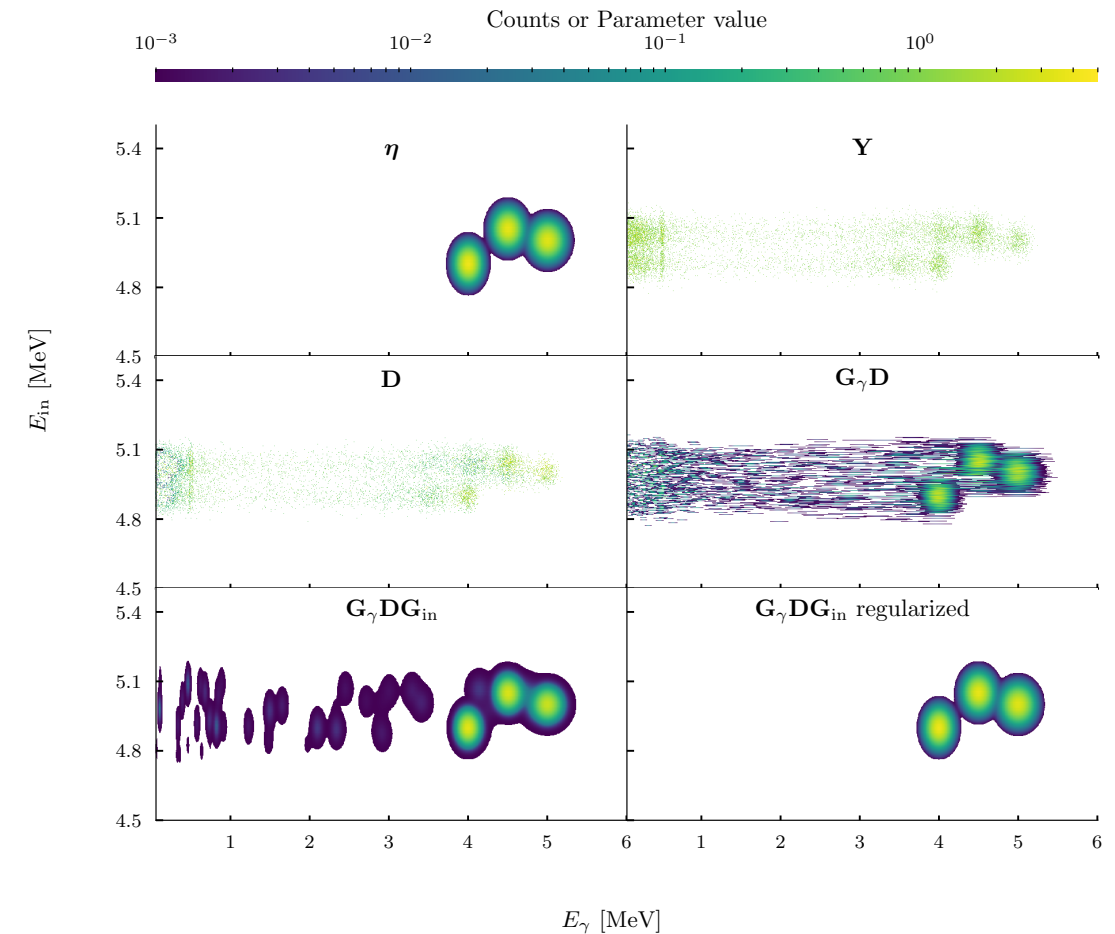
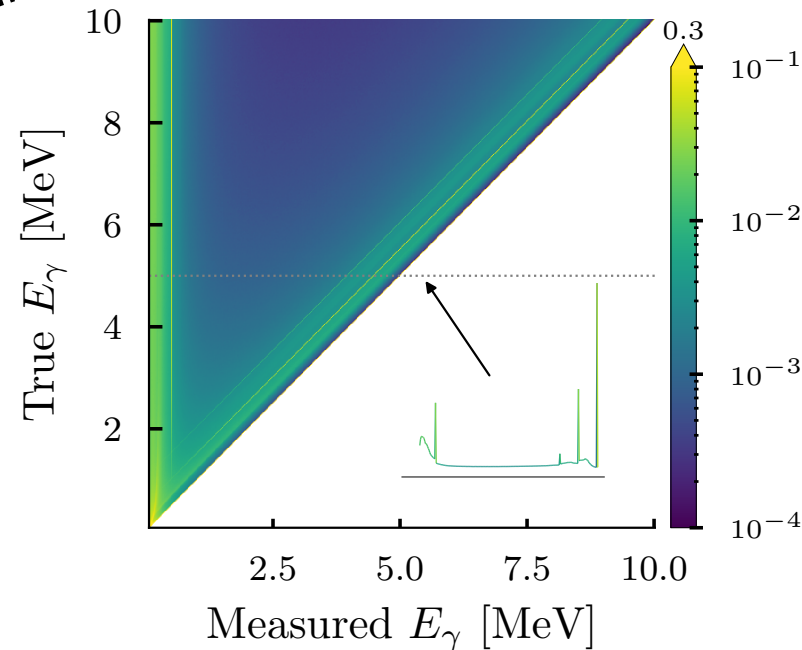
²Norwegian Nuclear Research Centre, Norway*

³Department of Physics and Center for Computing in Science Education, University of Oslo, N-0316 Oslo, Norway

⁴Department of Physics and Astronomy and Facility for Rare Isotope Beams,
Michigan State University, East Lansing, MI 48824, USA

(Dated: June 5, 2025)

Paper soon to be submitted!



Bayesian Unfolding in the Oslo Method

- Model outline:
 - Factorize total detector response R : discrete response D and Gaussian response kernel G from the finite detector resolution
 - Forward model: $\mu \rightarrow \eta = G\mu \rightarrow \nu = D\eta$
(μ = counts in true space, η = counts smeared by G , ν = expected counts in observed space)
 - Likelihood: $n_i \sim \text{Poisson}(\nu_i)$ – captures counting-statistics uncertainty
 - Prior: log-normal on μ with hierarchical hyperpriors
 - Posterior exploration with *No-U-Turn Sampler* (NUTS, PyMC 5)
- Capabilities & benefits
 - Supports spectra up to 1000 energy bins
 - Delivers full Bayesian uncertainty bands per bin (+ correlation between bins)
 - Reproducible: open-source code & data
- *Planned journal submission: early autumn 2025*
- Co-authors: Erlend Lima, Ann-Cecilie Larsen, Anders Kvellerstad, Morten Hjort-Jensen



Extraction of NLD and GSF

Higher order estimates through a least χ^2 -minimization:

$$P_{th}(E_x, E_\gamma) = \frac{2\pi E_\gamma^3 f(E_\gamma) \rho(E_x - E_\gamma)}{\sum_{E_\gamma} 2\pi E_\gamma^3 f(E_\gamma) \rho(E_x - E_\gamma)}$$

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

Each vector element in ρ and f is treated as a free parameter

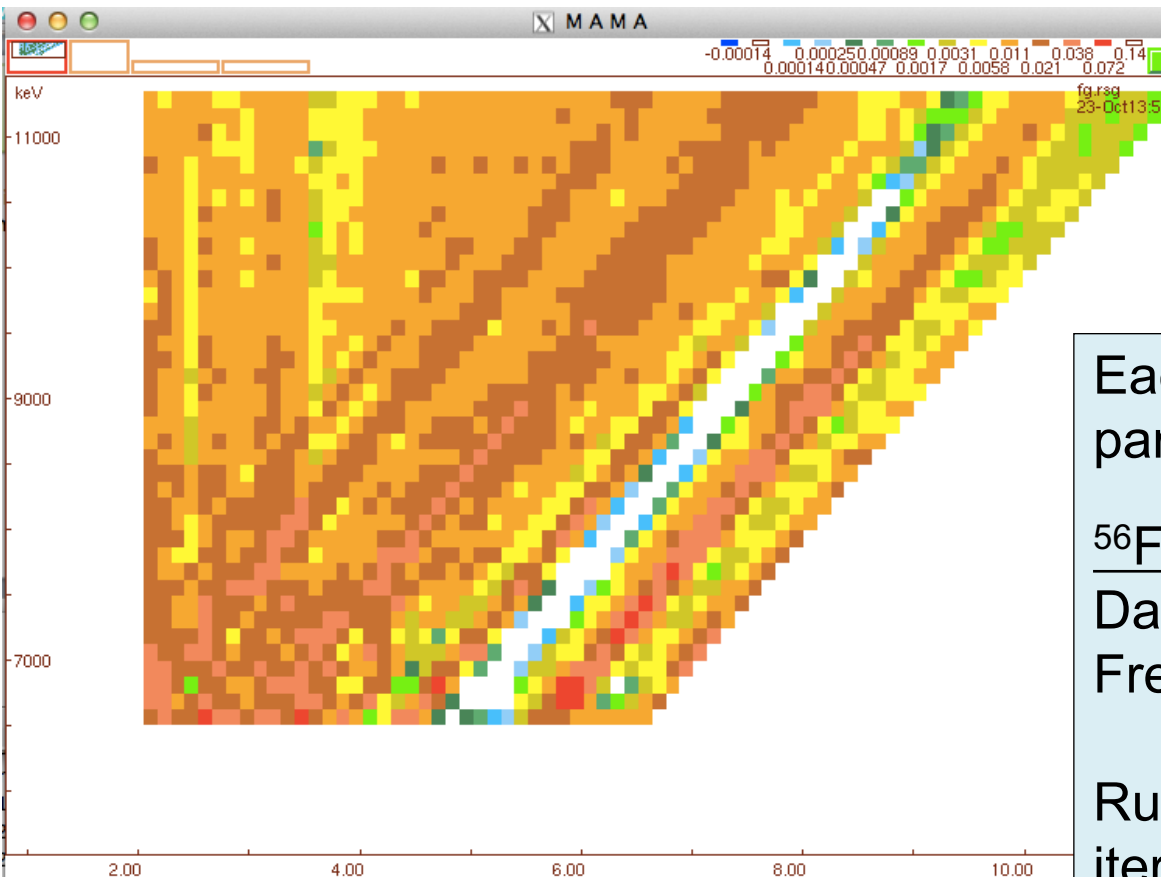
$^{56}\text{Fe}(p, p')$ example:

Data points ("pixels"): 2052

Free parameters: 184

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

Runs 50 iterations, but converges often at 10-20 iterations (depending on the case)

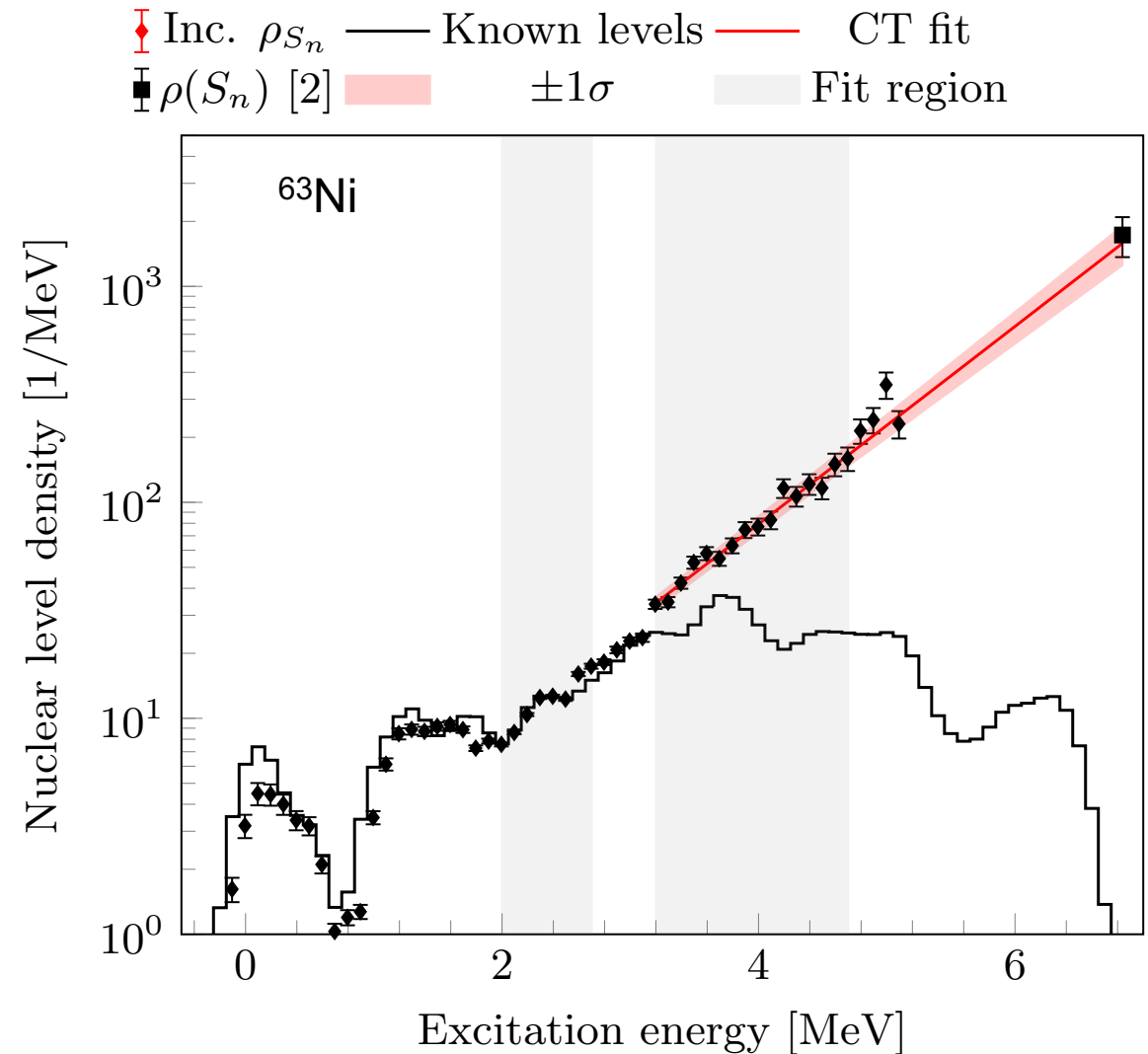


Normalization of NLD

- Comparison to NLD from tabulated discrete levels
- Comparison to NLD at neutron separation energy

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

- D_0 : Average s-wave resonance spacing
- α_π : Parity asymmetry
- σ : Spin-cutoff parameter
- Between S_n and data: Interpolation with some model (usually CT)
- Gives the absolute value of the NLD, A , and the slope α



Normalization of NLD – NLD at particle threshold

- Use resonance spacing at particle threshold to determine NLD:

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

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

- Where:
 - D_0 : s-wave resonance spacing, most often neutron resonances, sources such as RIPL-3 and Mughabghab
 - I_t : Ground state spin of the A-1 nucleus
 - α_π : Parity asymmetry
 - σ : Spin-cutoff parameter



Normalization of GSF

$$\begin{aligned}\tilde{\rho}(E_i - E_\gamma) &= A\rho(E_i - E_\gamma)e^{\alpha(E_i - E_\gamma)} \\ \tilde{\mathcal{T}}(E_\gamma) &= B\mathcal{T}(E_\gamma)e^{\alpha E_\gamma}\end{aligned}$$

Slope parameter α determined by normalized NLD

Now assuming dipole transitions dominate:

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

Next step: Average total radiative width:

$$\langle \Gamma_\gamma(E, J, \pi) \rangle = \frac{1}{4\pi\rho(E, J, \pi)} \sum_{XL} \sum_{J_f, \pi_f} \int_0^E dE_\gamma \mathcal{T}_{XL}(E_\gamma) \rho(E - E_\gamma, J_f, \pi_f)$$

Normalization integral (normalize to $\langle \Gamma_{\gamma 0} \rangle$, average radiative of s-wave capture res.)

$$\langle \Gamma_\gamma \left(S_n, I_t \pm \frac{1}{2}, \pi_t \right) \rangle = \frac{BD_0}{2\pi} \int_0^{S_n} dE_\gamma \mathcal{T}_{XL}(E_\gamma) \rho(S_n - E_\gamma) \sum_{J=-1}^1 g(S_n - E_\gamma, I_t \pm \frac{1}{2} + J)$$

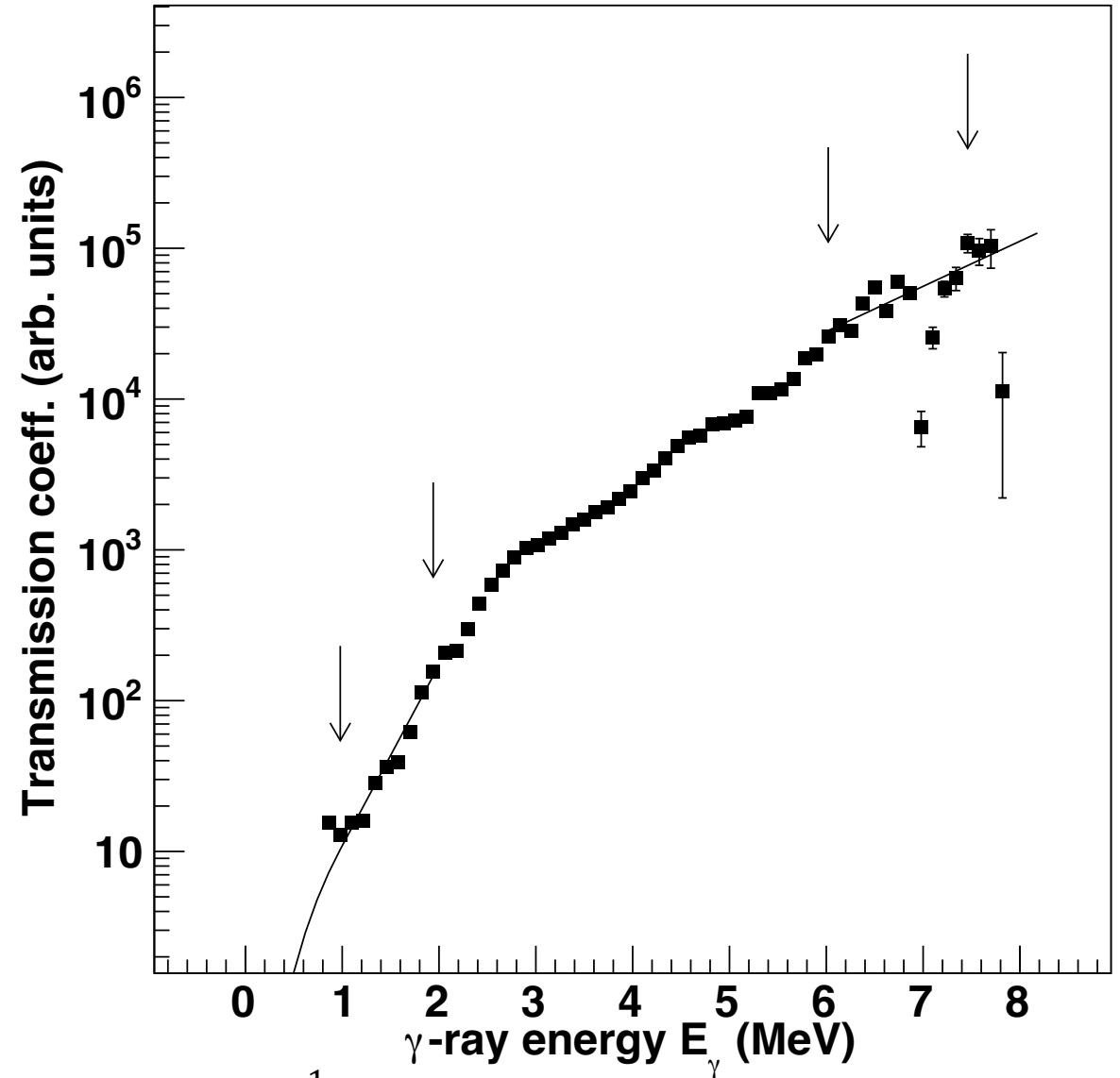


Normalization of GSF

- GSF covers energies between E_γ^{min} and E_x^{max}
- Need to extrapolate between
 - $E_\gamma = 0$ and E_γ^{min}
 - E_x^{max} and S_n
- Between $E_\gamma = 0$ and E_γ^{min} :

$$\mathcal{T}(E_\gamma) = \frac{\exp(aE_\gamma + b)}{E_\gamma^3}$$
- Between E_x^{max} and S_n :

$$\mathcal{T}(E_\gamma) = \exp(cE_\gamma + d)$$



$$\langle \Gamma_\gamma \left(S_n, I_t \pm \frac{1}{2}, \pi_t \right) \rangle = \frac{BD_0}{2\pi} \int_0^{S_n} dE_\gamma \mathcal{T}_{XL}(E_\gamma) \rho(S_n - E_\gamma) \sum_{J=-1}^1 g(S_n - E_\gamma, I_t \pm \frac{1}{2} + J)$$



Systematic effects of the normalization

- Selection of spin-cutoff parameter:
 - If spin-cutoff is too big $\rightarrow$ steep slope
 - Will affect the strength abs. value
- Large parity asymmetry
 - Will give wrong abs. Strength
 - Average total radiative width of s-wave resonances integral no longer valid

$$\begin{aligned} \langle \Gamma_\gamma(S_n, I_t \pm 1/2, \pi_t) \rangle &= \frac{B}{2\pi\rho(S_n, I_t \pm 1/2, \pi_t)} \\ &\times \int_0^{S_n} dE_\gamma [\mathcal{T}_{E1}(E_\gamma)\mathcal{P}_\mp + \mathcal{T}_{M1}(E_\gamma)\mathcal{P}_\pm] \\ &\times \rho(S_n - E_\gamma) \sum_{J=-1}^1 g(S_n - E_\gamma, I_t \pm 1/2 + J) \end{aligned}$$



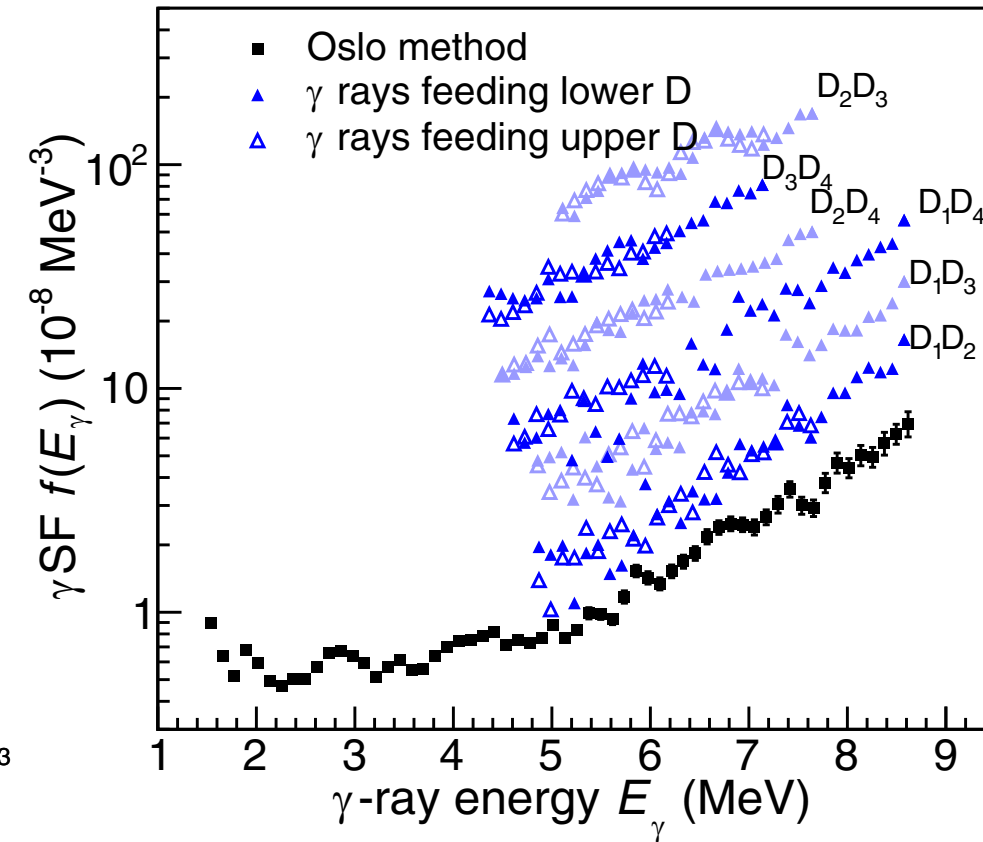
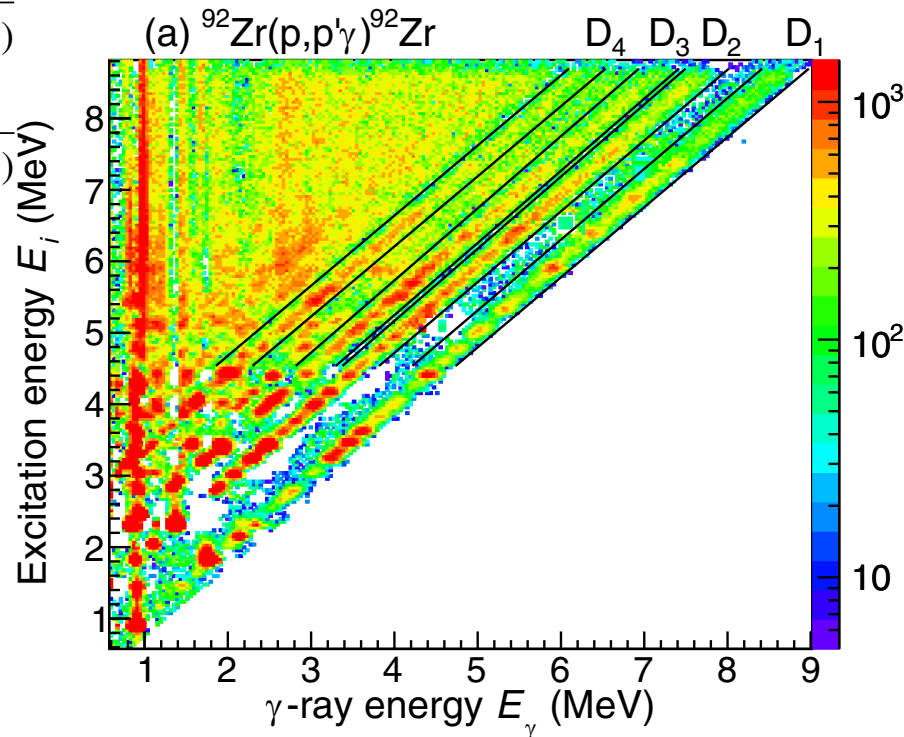
Shape method

- Decay to discrete levels
- Can obtain the shape of the γ SF
- Constrains the slope of OM data

$$N_D \propto f(E_\gamma) E_\gamma^3 \sum_{[J_f]} \sum_{J_i=J_f-1}^{J_i=J_f+1} \sigma(E_i, J_i) g(E_i, J_i).$$

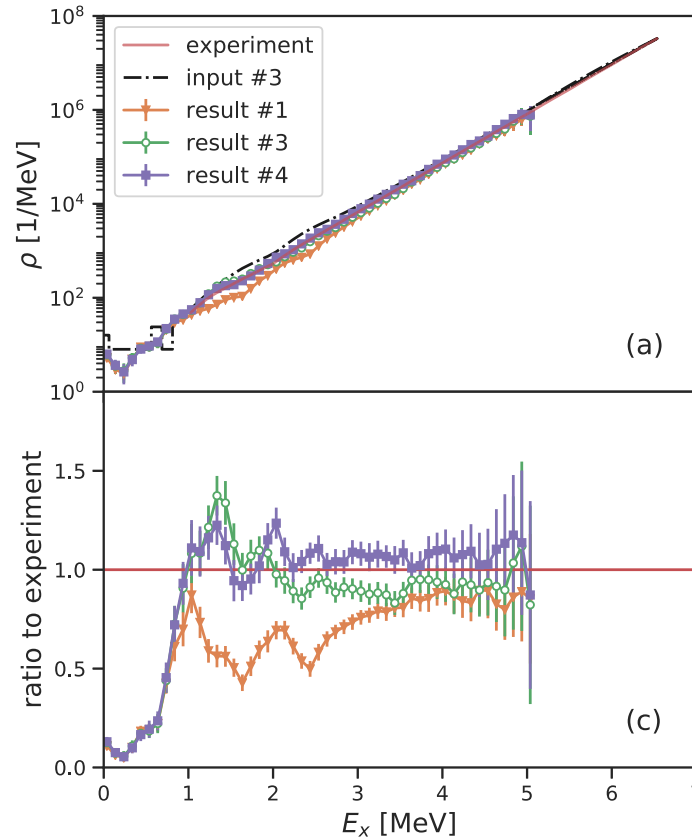
$$f(E_{\gamma 1}) \propto \frac{N_{D1}}{E_{\gamma 1}^3 \sum_{[J_{f1}]} \sum_{J_i=J_{f1}-1}^{J_i=J_{f1}+1} g(E_i, J_i)}$$

$$f(E_{\gamma 2}) \propto \frac{N_{D2}}{E_{\gamma 2}^3 \sum_{[J_{f2}]} \sum_{J_i=J_{f2}-1}^{J_i=J_{f2}+1} g(E_i, J_i)}$$

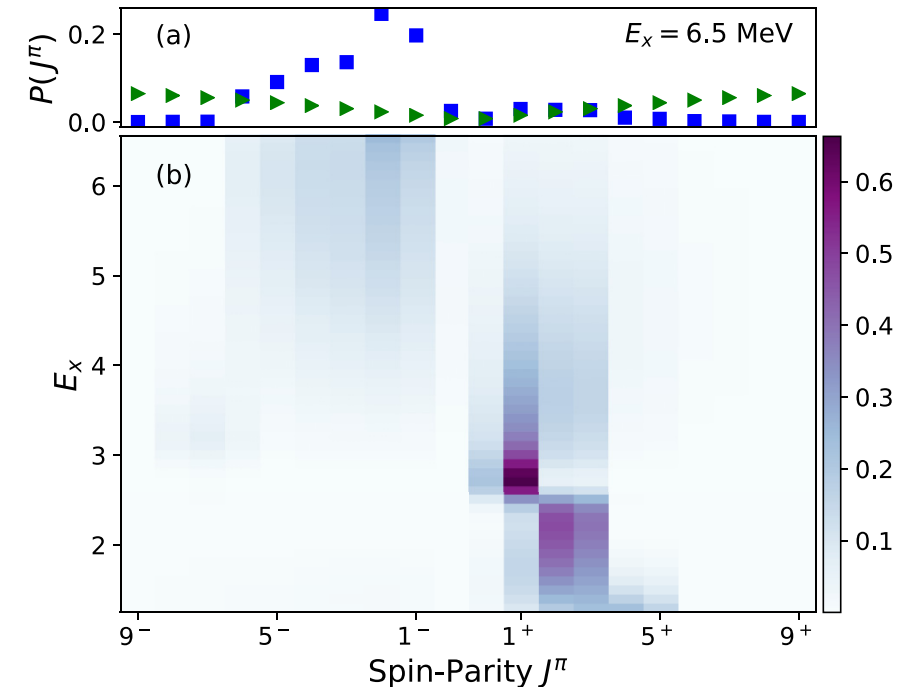


Reaction dependent systematic errors

- (d, p) reaction
 - Close to Coulomb barrier – reaction resembles a deuteron breakup + neutron absorption
 - Limited spin window populated
- Test with RAINIER (DICEBOX)



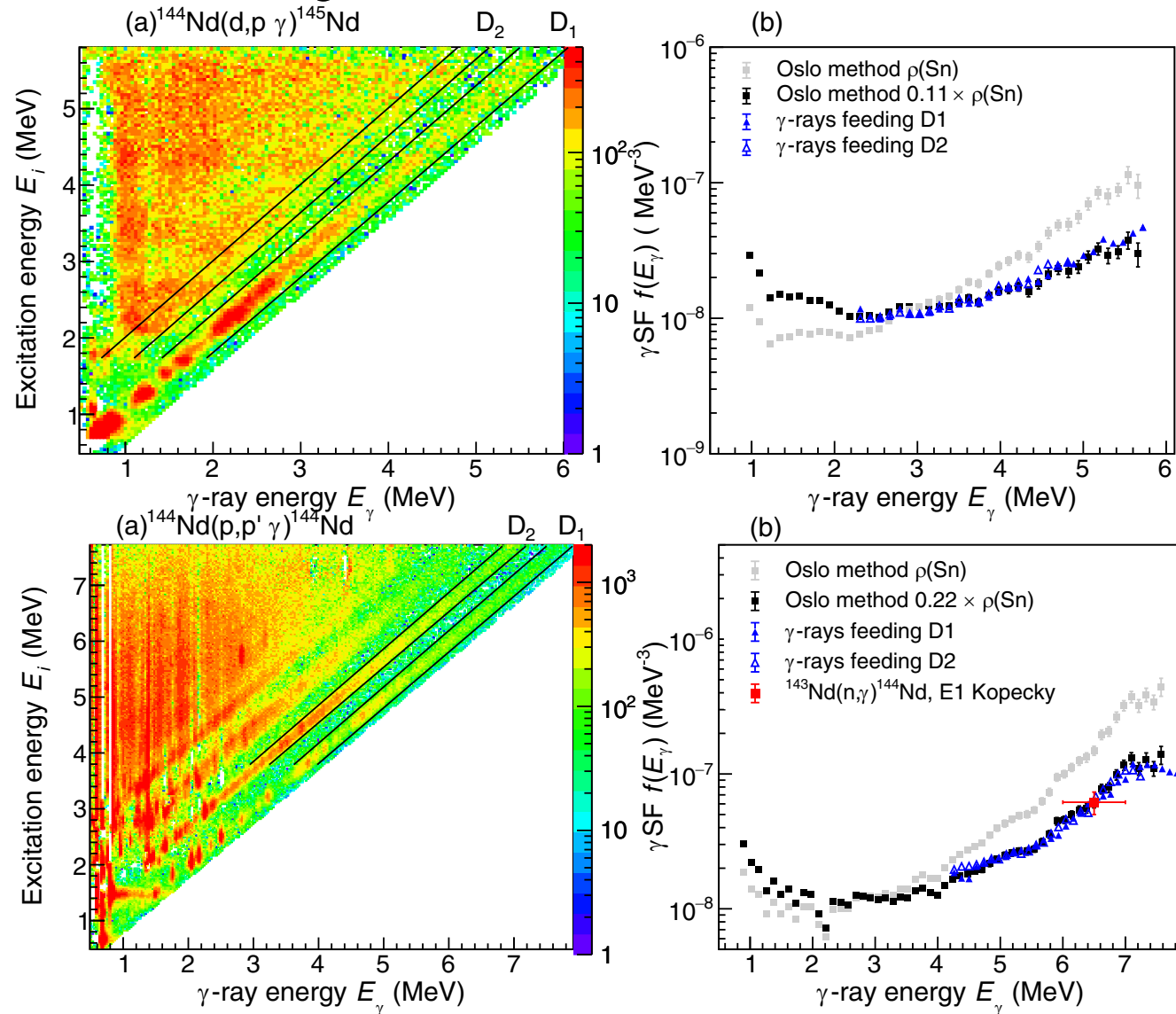
Theoretical spin-parity population Green's function transfer formalism



Reaction dependent systematic errors

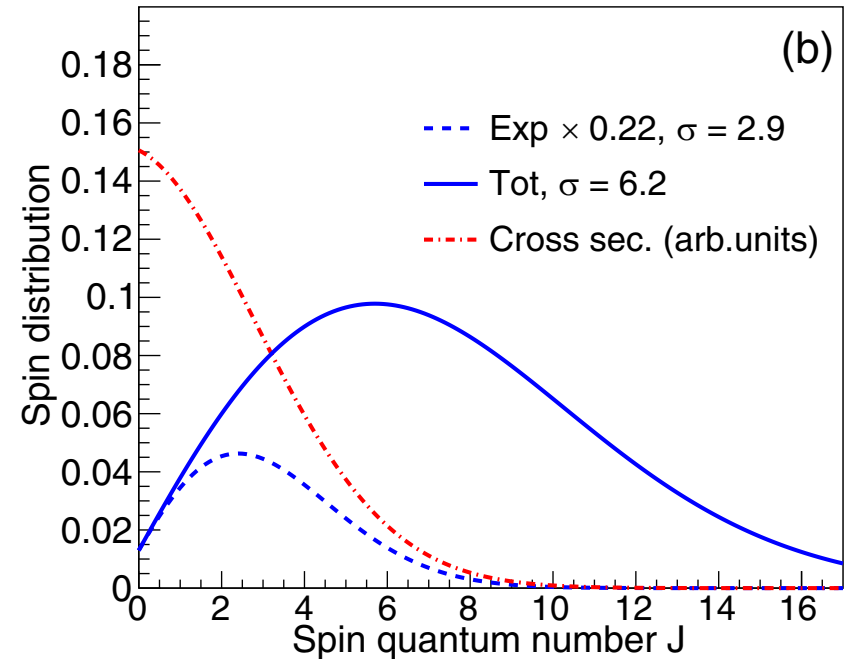
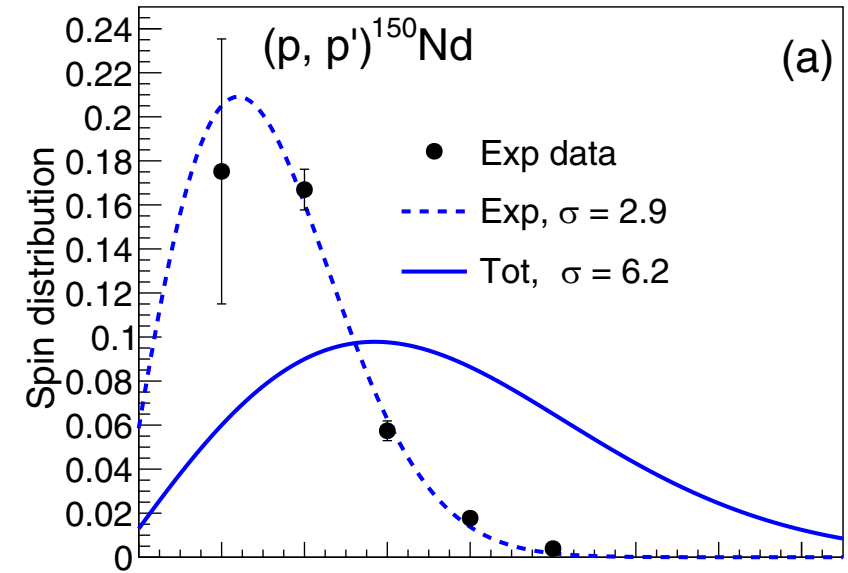
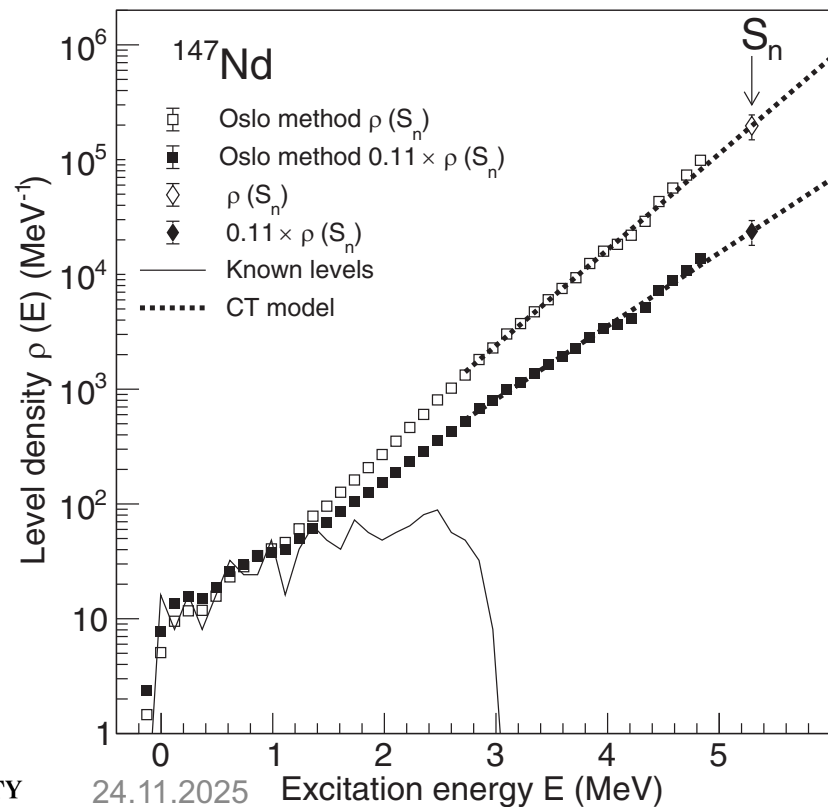
Nd chain: (p,p) and (d,p)

- Limited spin population
- Shape method indicates that OM overestimates the slope significantly
- For (d,p): 11% of full NLD observed
- For (p,p): 22% of full NLD observed
- Independently confirmed by measurements of ground state band feeding
- M. Guttormsen et al., Phys. Rev. C **106**, 034314 (2022)

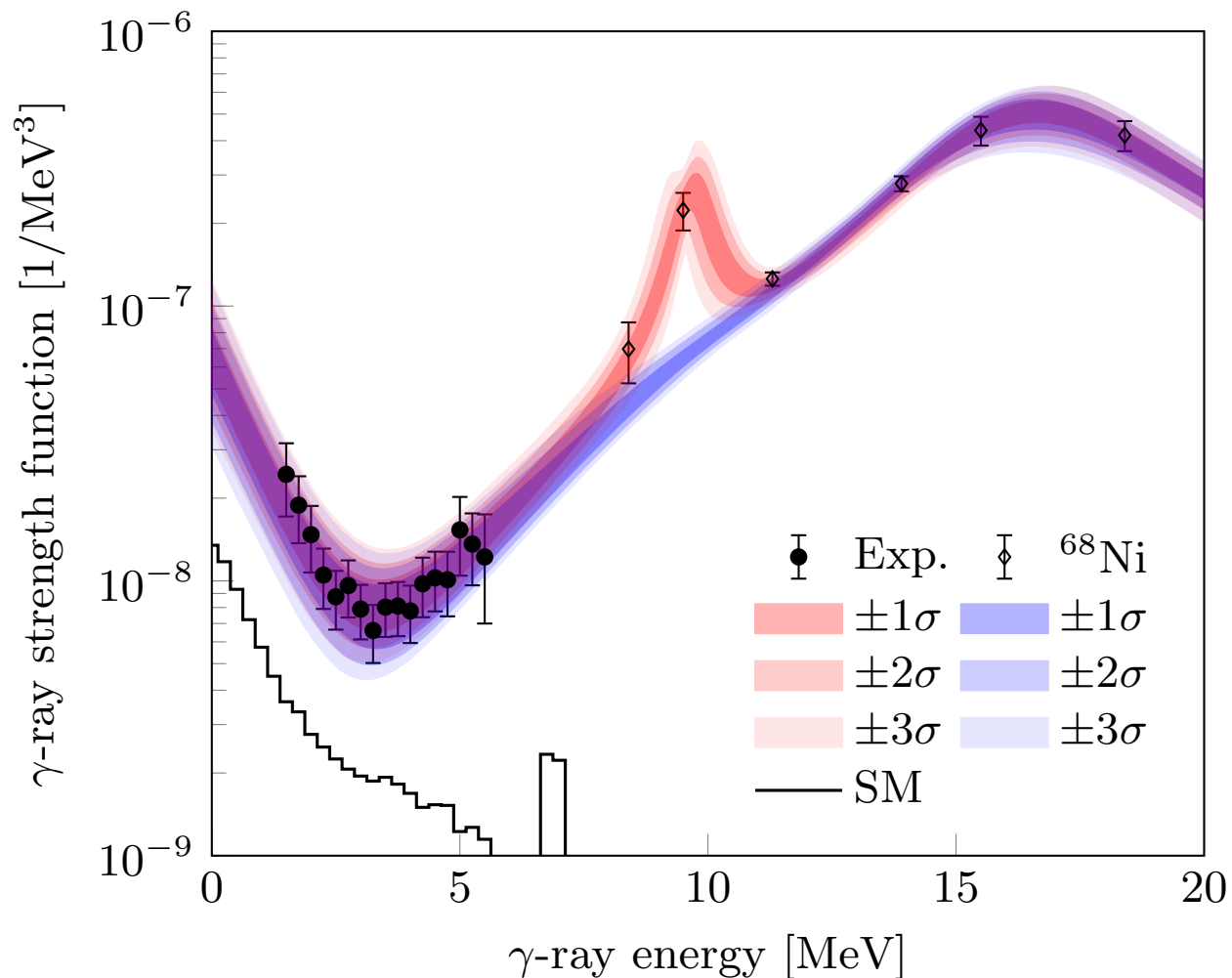


Reaction Specific Errors

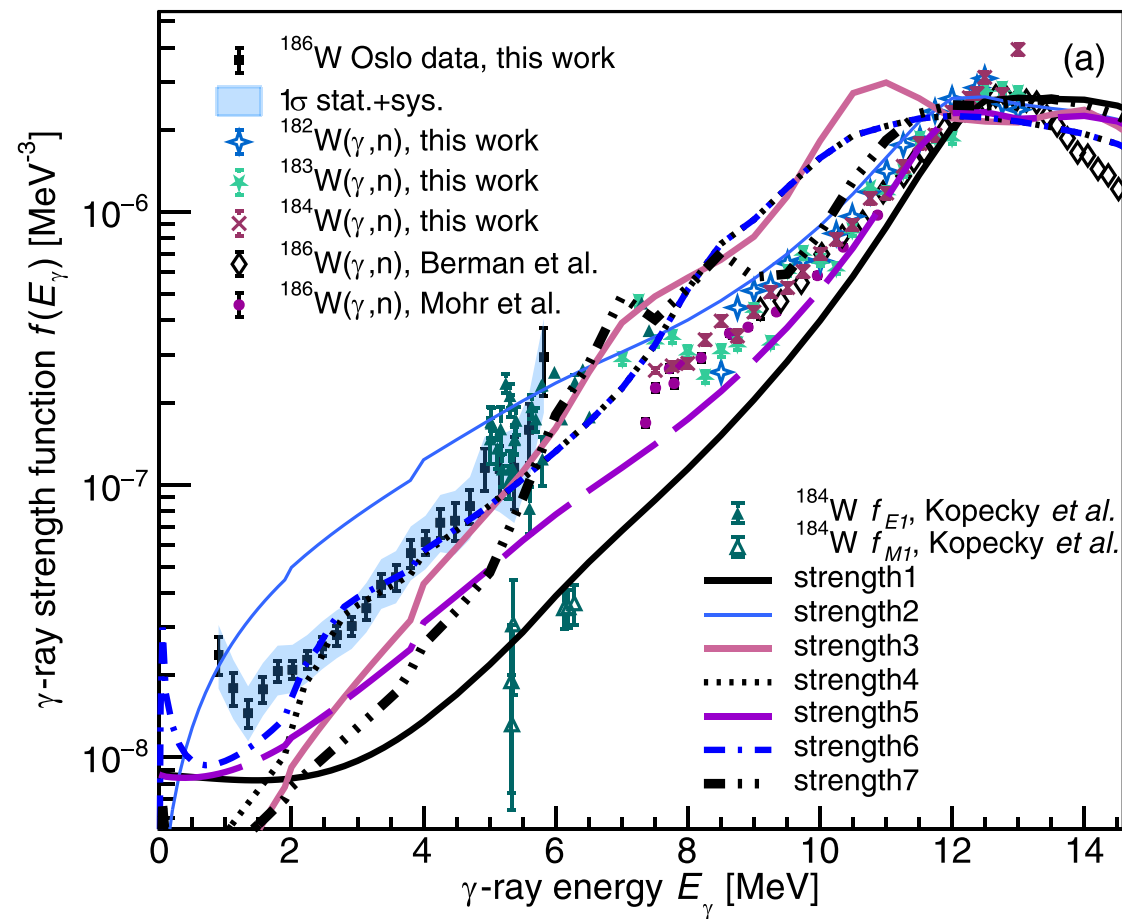
- Initial population determined by side-feeding



Recent results

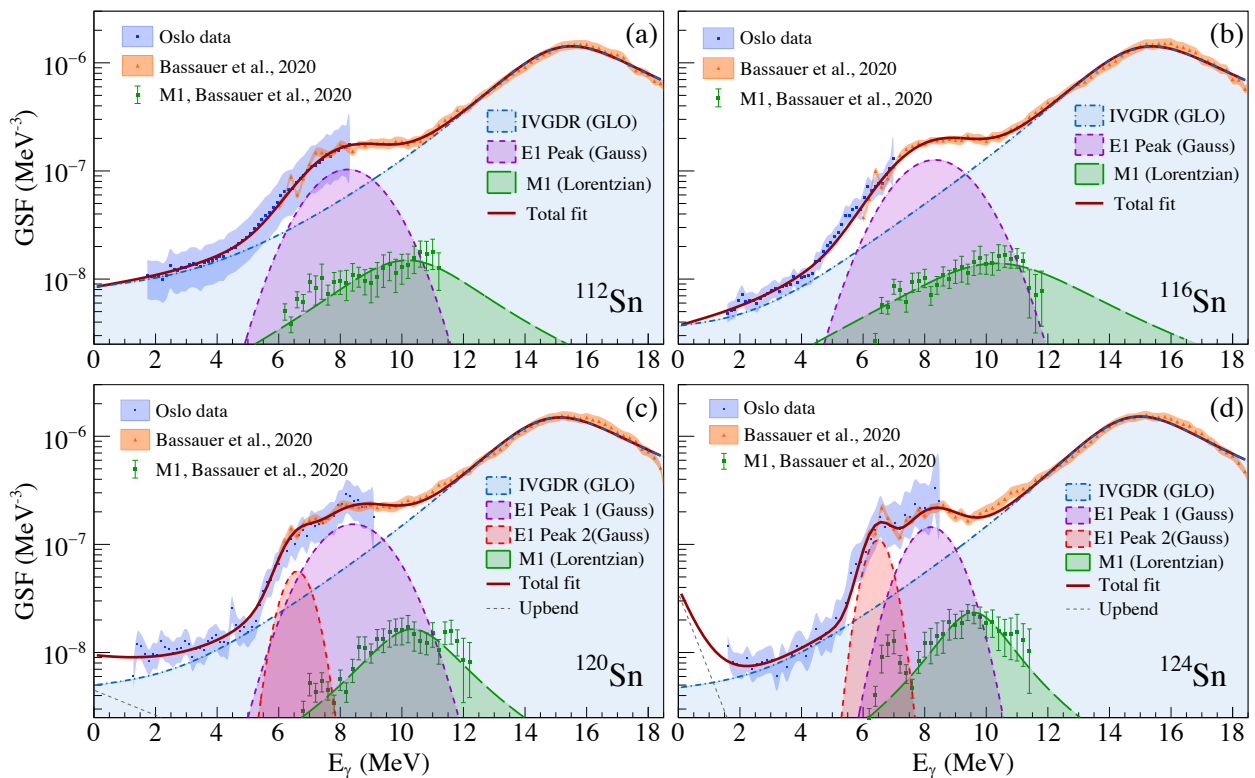
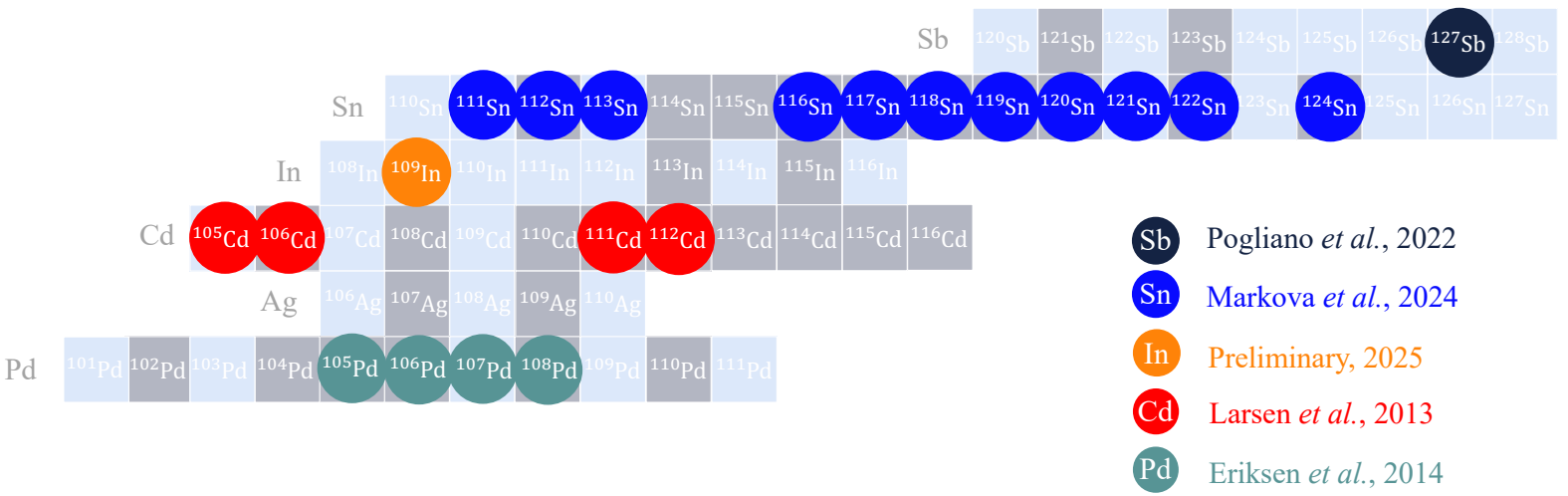


V. W. Ingeberg *et al.*, Phys. Rev. C **111**, 015803 (2025)



A. C. Larsen *et al.*, Phys. Rev C **108**, 025804 (2023)





Recent experiments at OCL

a) $^{93}\text{Nb} + 16\text{-MeV protons}$, April 2025

PI: Sivahami Uthayakumaar (FRIB), Ann-Cecile Larsen

Motivation: The $^{92}\text{Nb}(n,\gamma)^{93}\text{Nb}$ is one of the most important reactions for the destruction of ^{92}Nb in the p-process nucleosynthesis. We aim to constrain this un-measured reaction cross section and astrophysical reaction rate by using the level density and gamma strength function from the Oslo method on the $^{93}\text{Nb}(p,p'\gamma)$ data set.

b) ^{106}Pd , ^{59}Co , $^{27}\text{Al} + 16\text{-MeV protons}$, June 2025

PI: Vette W. Ingeberg, Ann-Cecilie Larsen, Kevin Li

Motivation: The PSF of ^{59}Co was recently published from a NRF experiment and has an unusual shape. The ^{27}Al is of interest in supernova nucleosynthesis and are close to the limit of the Oslo method. In ^{106}Pd there are discrepancies in the nuclear level density and between the models of the NLD.

c) $^{154}\text{Sm} + 30\text{ MeV alphas}$, August 2025

PI: Lauren T. Bell, Sunniva, Ann-Cecilie Larsen

Motivation: We want to investigate the impact of angular-momentum transfer on the level density and gamma strength function of ^{154}Sm by comparing the $^{154}\text{Sm}(a,a'g)$ data to previously taken data on $^{154}\text{Sm}(p,p'g)$

Bonus: We also got data on the exotic, n-rich ^{155}Eu through the $^{154}\text{Sm}(a,tg)^{155}\text{Eu}$ and $^{154}\text{Sm}(a,dg)^{156}\text{Eu}$ reaction channels, respectively, of interest for the intermediate neutron-capture process

d) $^{130}\text{Te} + 30\text{ MeV alphas}$ & $^{130}\text{Te} + 24\text{ MeV alphas}$, September 2025

PI: Claudia, Therese (Master students), Ann-Cecilie, Maria

Motivation: to get level densities and gamma strength for ^{132}I and ^{131}I through the reaction channels $^{130}\text{Te}(a,pg)^{133}\text{I}$, $^{130}\text{Te}(a,dg)^{132}\text{I}$, $^{130}\text{Te}(a,tg)^{131}\text{I}$ respectively, for the i-process nucleosynthesis

Bonus: we also have a super nice $^{130}\text{Te}(a,a'g)$ data set, for nuclear structure (oblate deformation, looking for the M1 scissors mode in an oblate nucleus for the first time)

e) $^{116}\text{Cd} + 30\text{ MeV alphas}$, October 2025

PI: Maria Markova, Ann-Cecile Larsen

Motivation: to get level densities and gamma strength for ^{116}Cd through the reaction channel $^{116}\text{Cd}(a,a'g)^{116}\text{Cd}$, to get a data-constrained $^{115}\text{Cd}(n,g)$ reaction rate, of critical importance for the i-process nucleosynthesis

Bonus: we also got data on the exotic, n-rich $^{117,118}\text{In}$ through the $^{116}\text{Cd}(a,tg)^{117}\text{In}$ and $^{116}\text{Cd}(a,dg)^{118}\text{In}$ reaction channels, respectively, also of interest for the intermediate neutron-capture process, and to investigate the pygmy dipole resonance for indium isotopes, as ^{109}In shows almost no sign of a PDR

f) $^{107,109}\text{Ag} + 16\text{-MeV protons}$, November 2025

PI: Henrik D. Andrews, Ann-Cecilie Larsen, Sunniva Siem

Motivation: Study level densities and gamma strength functions in silver isotopes for the first time. Search for the pygmy dipole resonance. Also, i-process relevant.

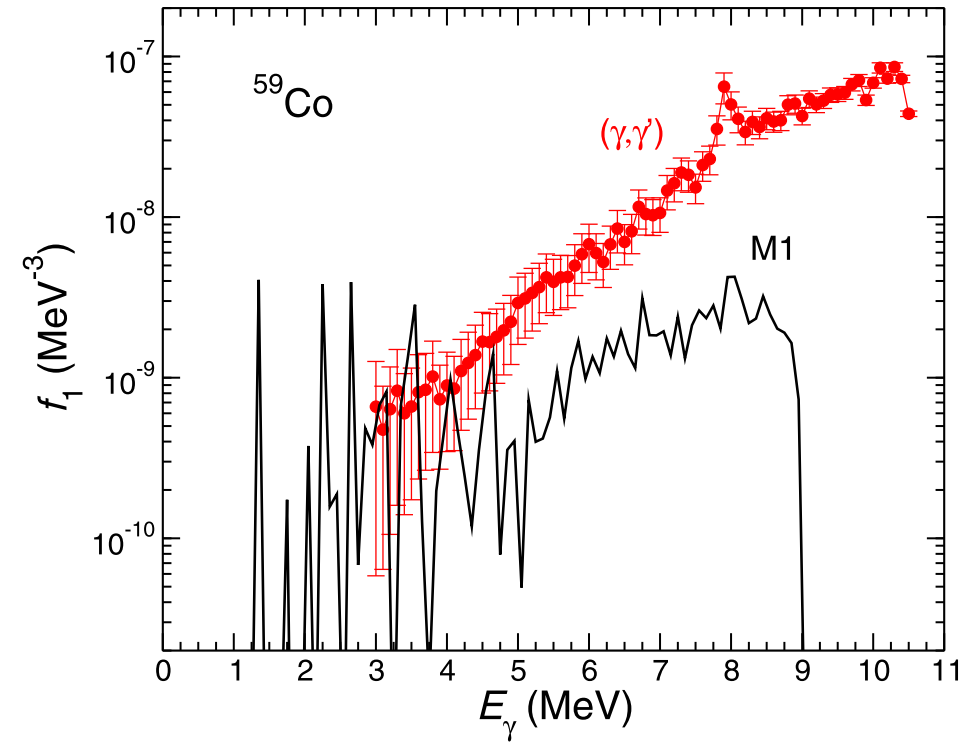
g) $^{186}\text{W} + 30\text{ MeV alphas}$, November 2025

PI: Rahul Jain (LLNL), Richard Hughes (LLNL), Andrea Richard (Ohio Univ.), Ann-Cecilie Larsen

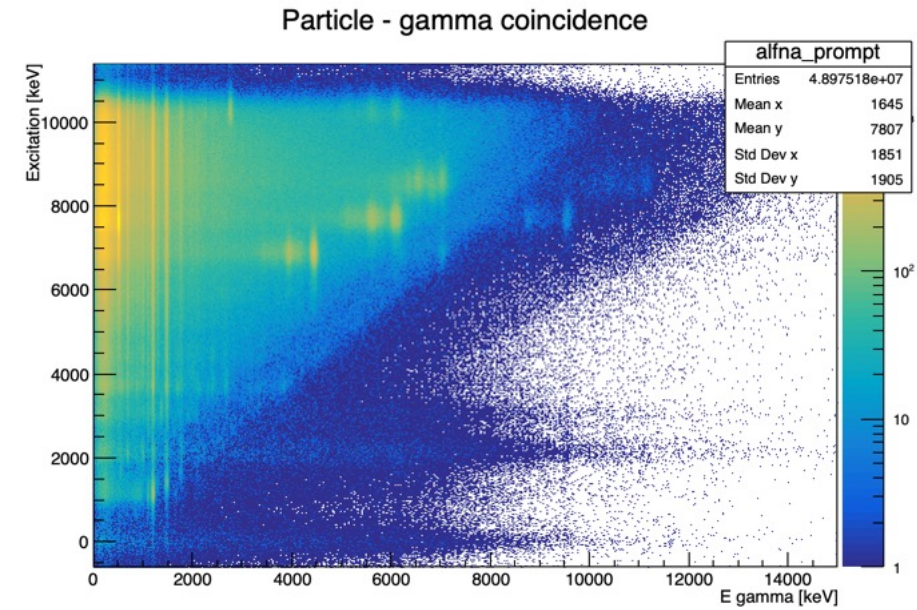
Motivation: Aim was to reach ^{189}Re and ^{188}Re with the $^{186}\text{W}(a,p)$ and $^{186}\text{W}(a,d)$ reactions.



GSF of ^{59}Co



Will measure with both (p,p')
and (a,a')



~ 2-3 hours of data

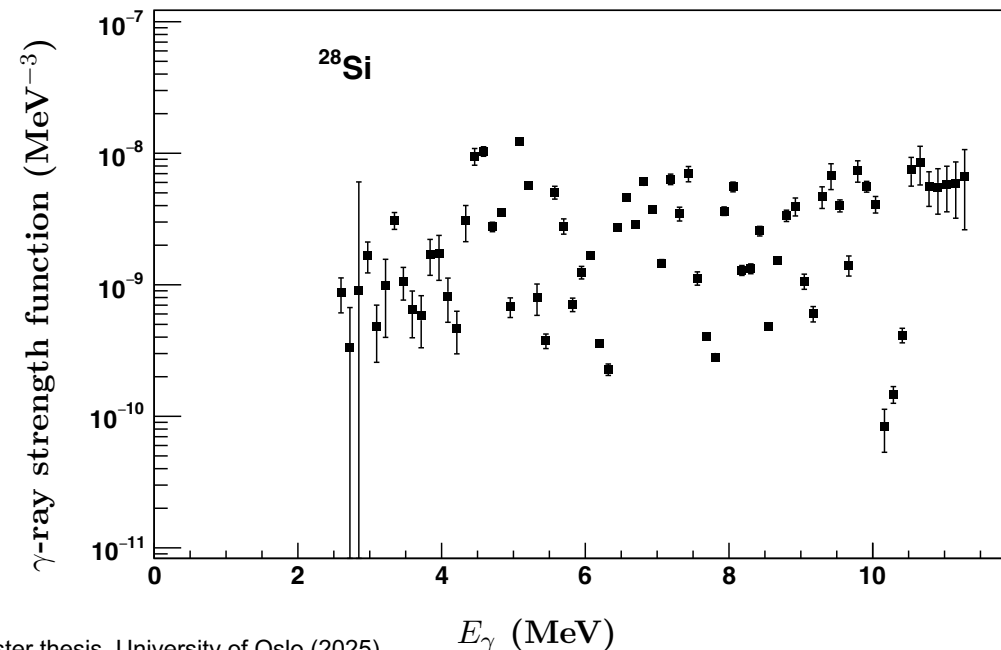
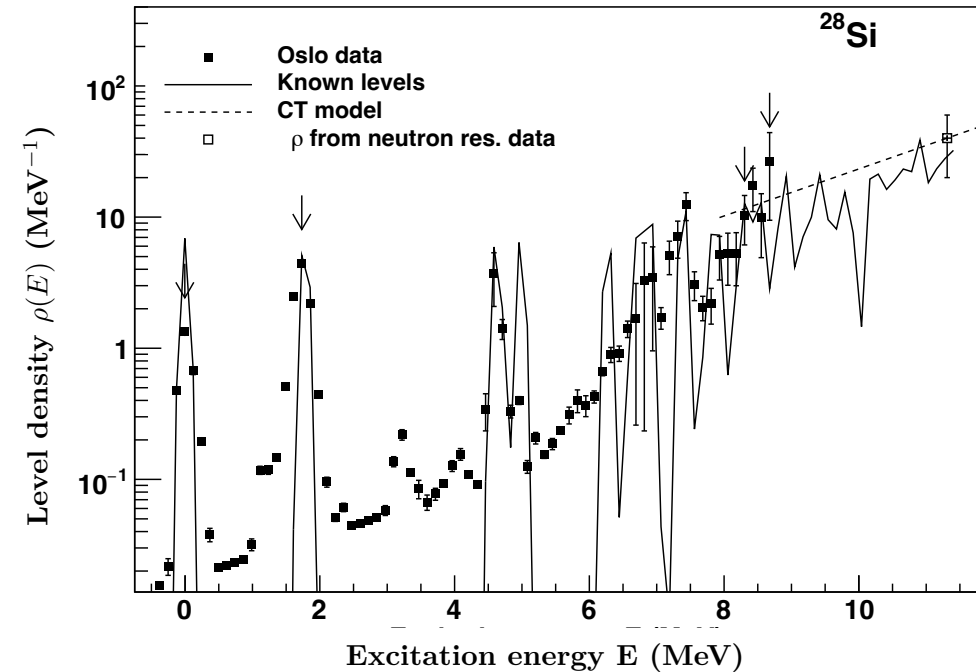
SUPER
Preliminary

R. Schwengner *et al.*, Phys. Rev. C **111**, 014312 (2025)



Limits of the Oslo Method

- MSc project of Lise Granheim
- Can you extract GSF from ^{28}Si
- Can you extract GSF and NLD in ^{27}Al ?
 - We have measured (p, p')

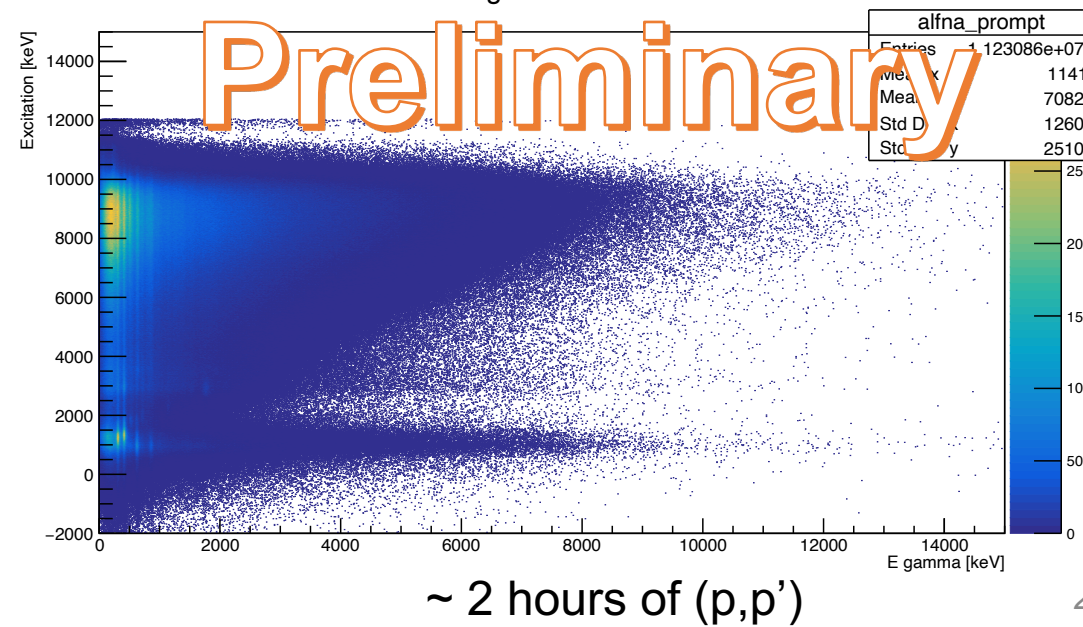
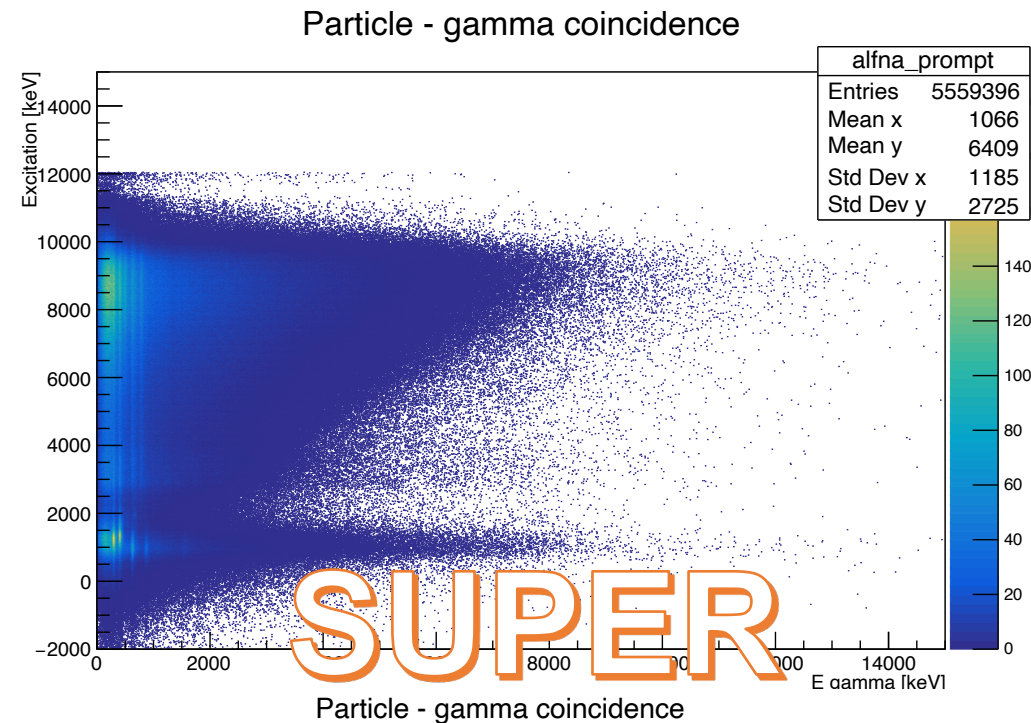


New project on Ag

	In 106 6.2 m	In 107 32.4 m	In 108 58.0 m	In 109 4.167 h	In 110 4.92 h	In 111 2.8063 d	In 112 14.88 m	In 113 4.29	In 114 71.9 s	In 115 95.71
48	Cd 105 55.5 m	Cd 106 1.25	Cd 107 6.50 h	Cd 108 0.89	Cd 109 461.6 d	Cd 110 12.49	Cd 111 12.80	Cd 112 24.13	Cd 113 12.22	Cd 114 28.73
	Ag 104 69.2 m	Ag 105 41.29 d	Ag 106 23.96 m	Ag 107 51.839	Ag 108 2.382 m	Ag 109 48.161	Ag 110 24.56 s	Ag 111 7.433 d	Ag 112 3.130 h	Ag 113 5.37 h
46	Pd 103 16.991 d	Pd 104 11.14	Pd 105 22.33	Pd 106 27.33	Pd 107 6.5 My	Pd 108 26.46	Pd 109 13.7012 h	Pd 110 11.72	Pd 111 23.4 m	Pd 112 21.04 h
	Rh 102 207.0 d	Rh 103 100.	Rh 104 42.3 s	Rh 105 35.357 h	Rh 106 30.07 s	Rh 107 21.7 m	Rh 108 16.8 s	Rh 109 80 s	Rh 110 3.35 s	Rh 111 11 s
	58	60	62	64	66					

Plan to investigate Ag nuclei with several probes

PhD project of Henrik Andrews



AVIT application, StarLight prototype ✨

- 3 hexagonal-shaped scintillator crystals made of NaI(Tl+Li) that can separate neutrons and gammas through pulse-shape discrimination
- Testing & characterization at OCL
- Full array financed hopefully through a grant in 2026/2027 [PI Ann-Cecilie Larsen]

