NORWEGIAN NUCLEAR RESEARCH CENTRE

The Oslo Scintillator Array

The OSCAR Array

UNIVERSITY OF OSLO

Funded by The Research Council of Norway

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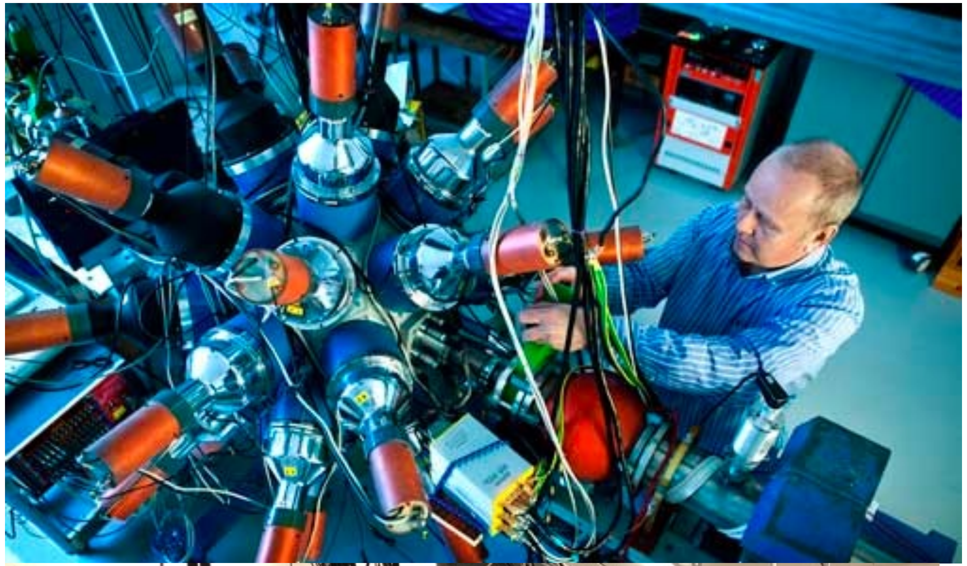
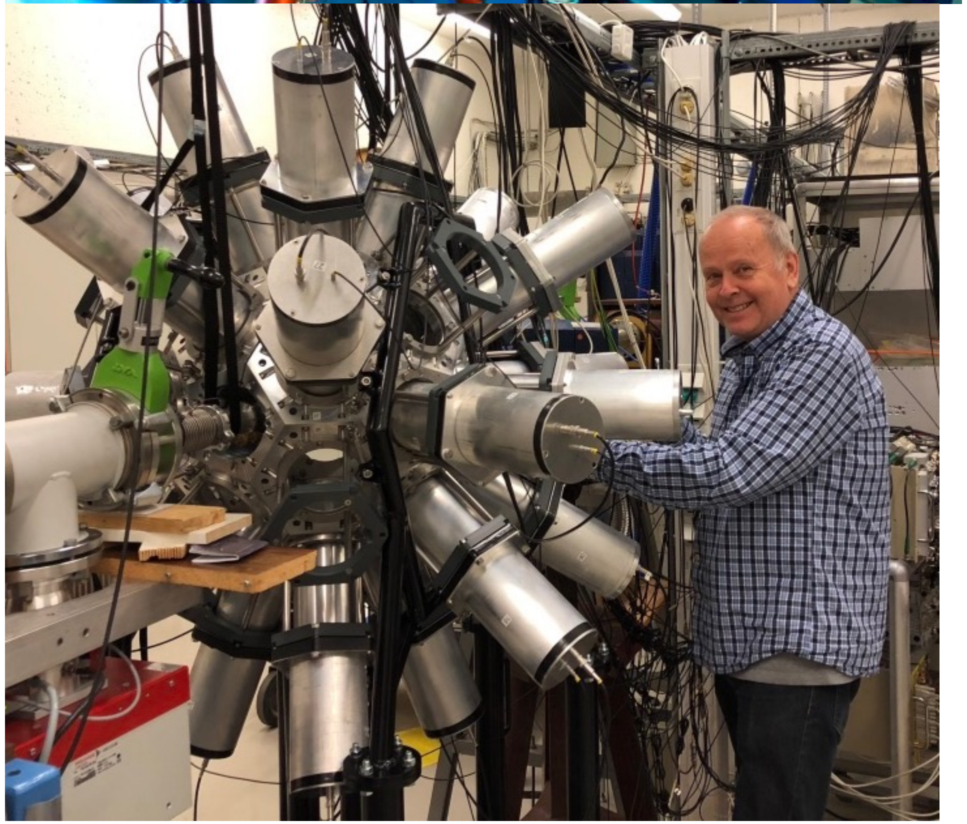
INTRANS Workshop 22-25 January 2024

Outline

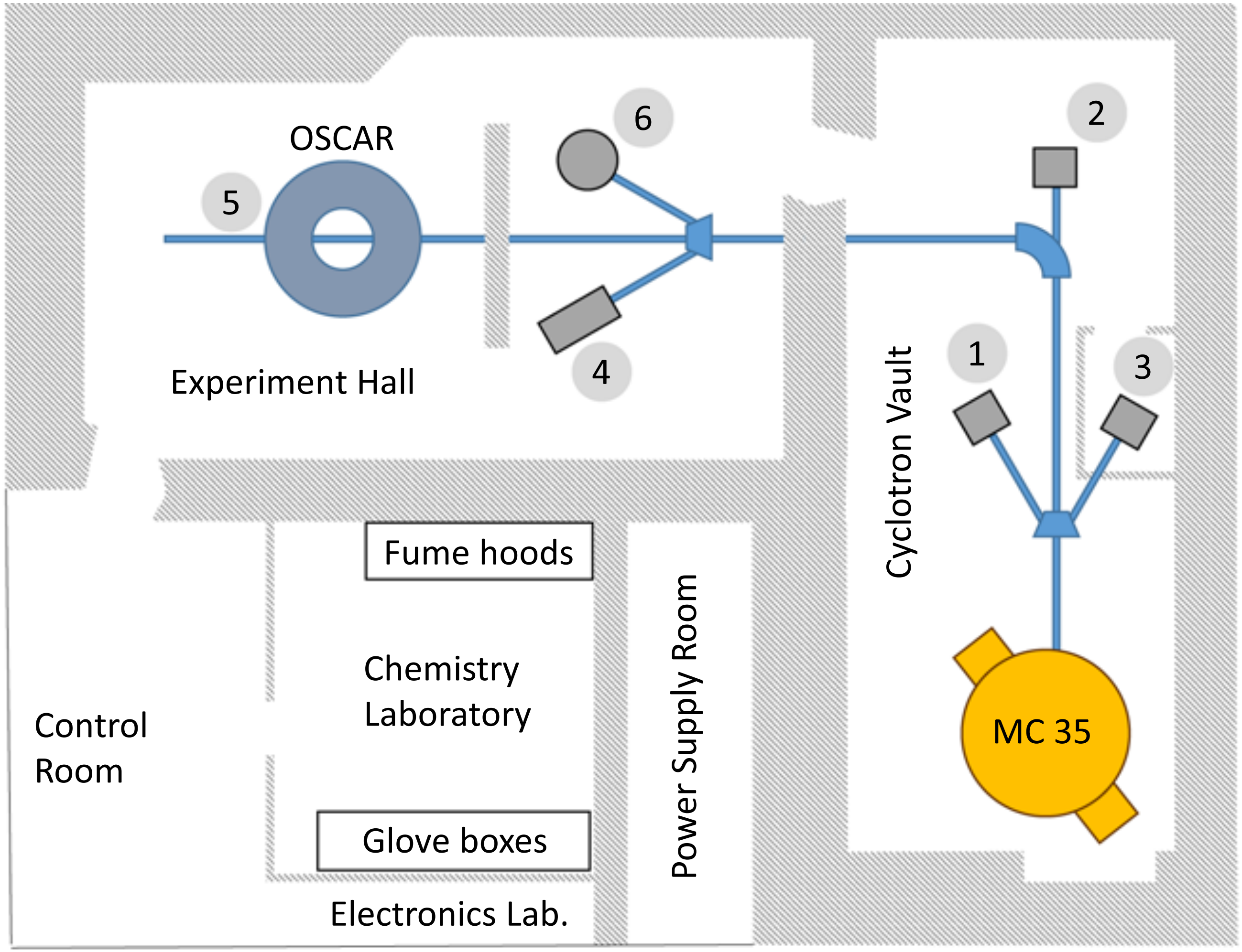
- The Oslo Cyclotron Laboratory (OCL)
- The OSCAR array
  - The $LaBr_3$:Ce detectors
  - Data Acquisition System
  - Characteristics
- Physics Results
  - Statistical nuclear properties
  - Nuclear astrophysics
  - Fission properties





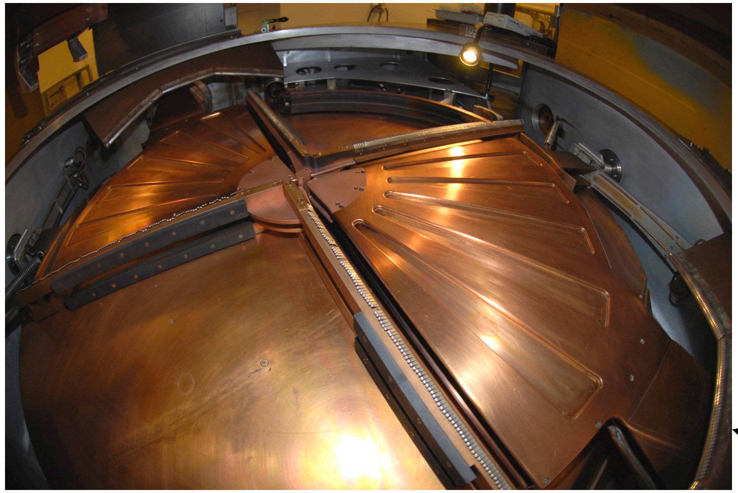
The Oslo Cyclotron Laboratory (OCL)

- Basement of the Department of Physics, University of Oslo
- Scientific programme:
  - Statistical properties of nuclei
  - Nuclear structure
  - Nuclear astrophysics
  - Fission
  - Nuclear chemistry
  - Radiation biology and medical applications
  - Material science and radiation hardening of electronics



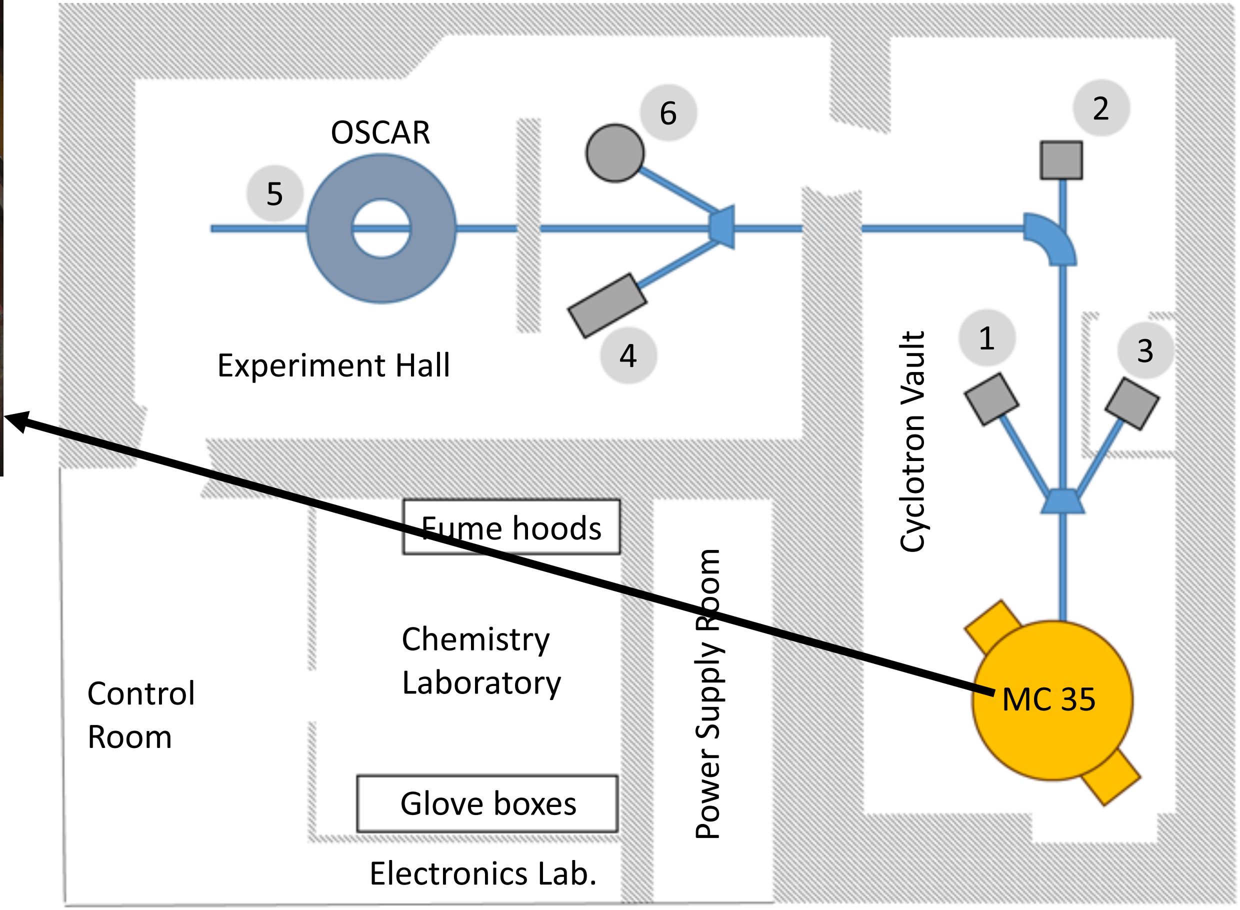
A. Görgen *et al.*, Eur. Phys. J Plus **136**, 181 (2021)

The Oslo Cyclotron Laboratory (OCL)



Scanditronix MC-35

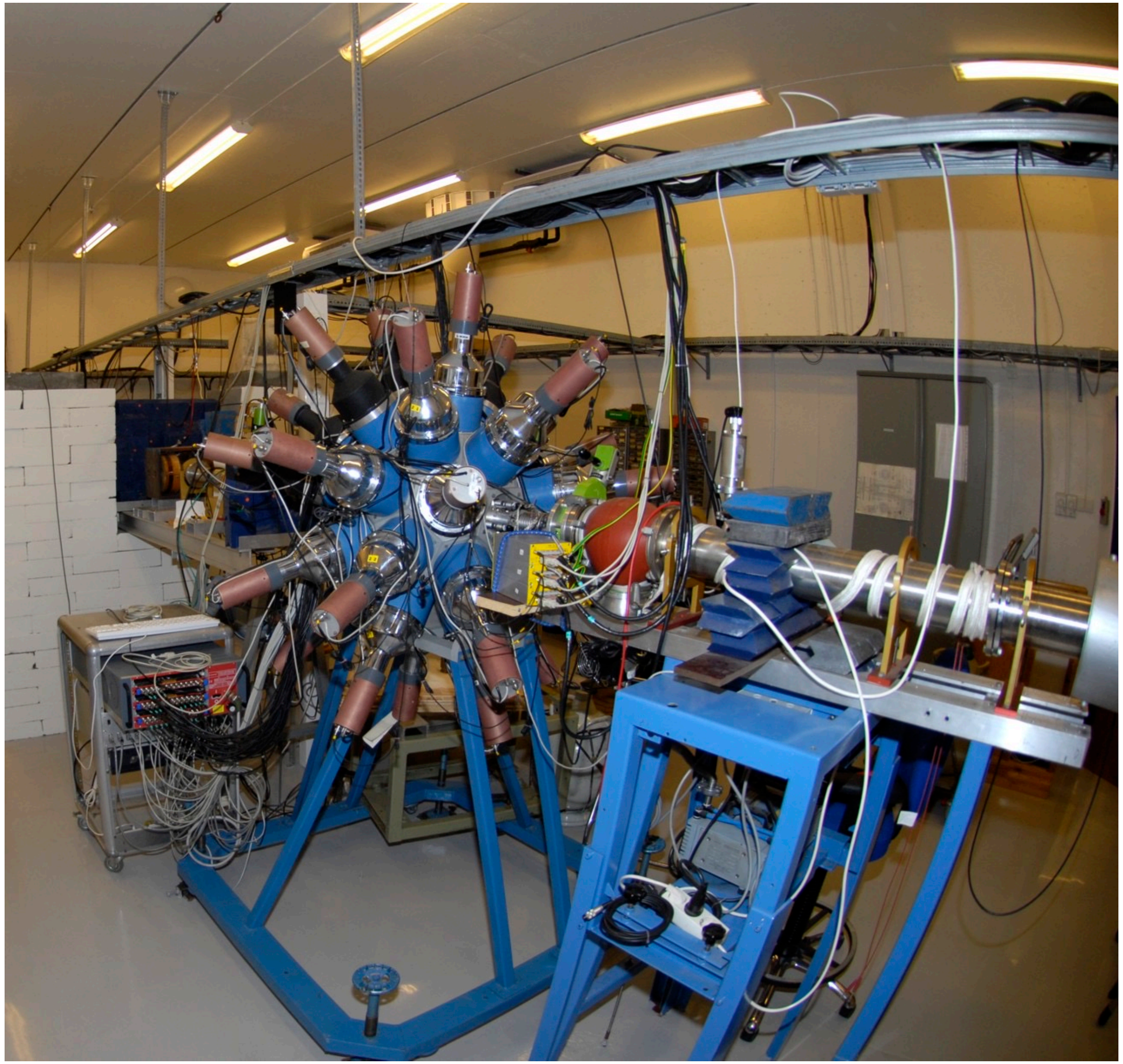
- Commissioned in 1979
- Light ion beams
  - $^{1}H^{+}$: 8-35 MeV
  - $^{2}H^{+}$: 4-18 MeV
  - $^{3}He^{2+}$: 6-47 MeV
  - $^{4}He^{2+}$: 8-35 MeV
- ^{3}He recovery system
- ≈ 2500 hours of beam/year



A. Görgen *et al.*, Eur. Phys. J Plus **136**, 181 (2021)

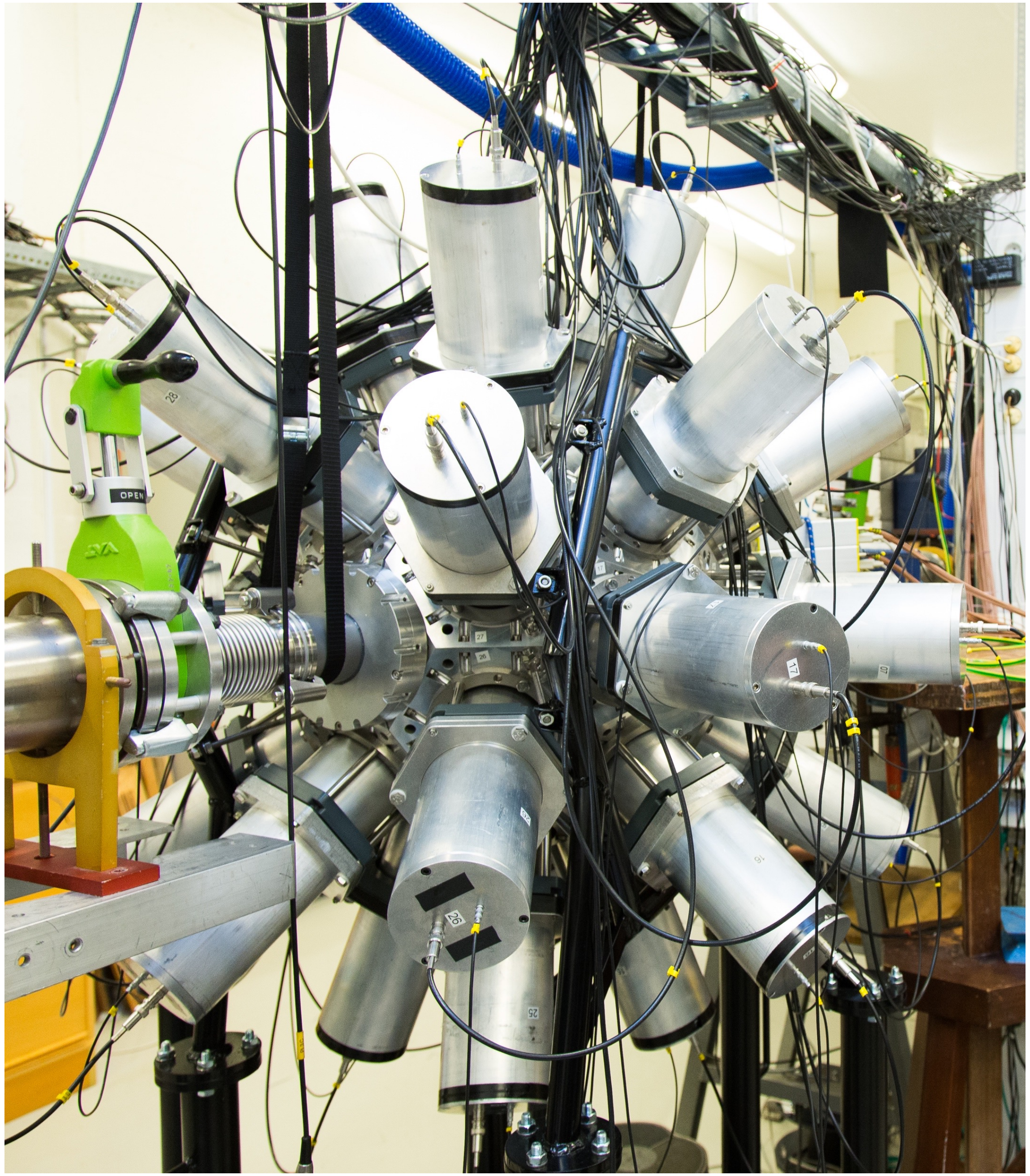
The CACTUS array

- Commission ≈ 1990
- 28 large NaI:Tl detectors
  - 5x5-inch detectors
- Collimated detectors
- Analog electrons
- Energy resolution ≈ 7% (1332 keV)
- Time resolution ≈ 17 ns
- Total efficiency 15.2% at 1332 keV
  - Full energy efficiency≈4.5%,1332 keV



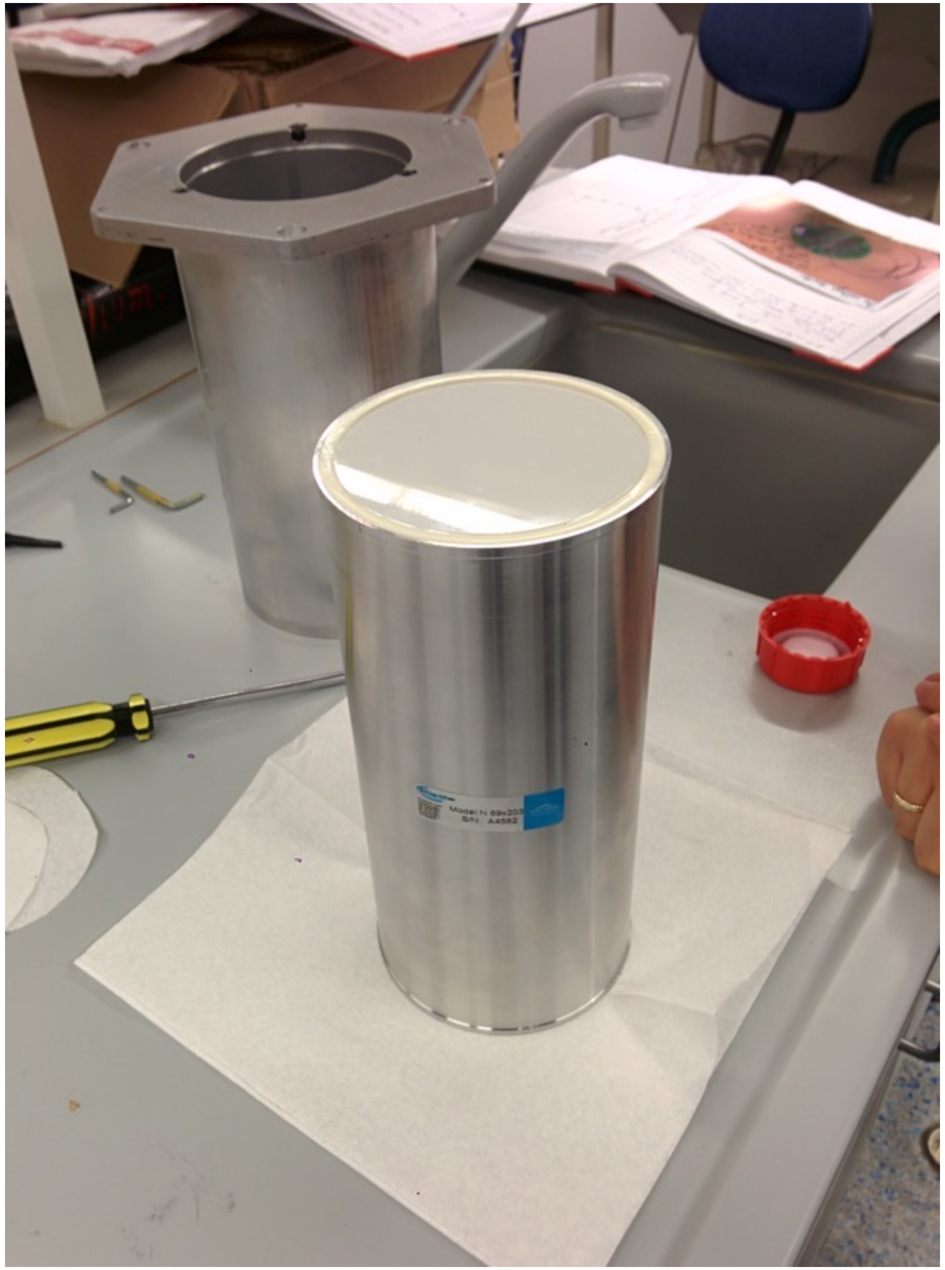
The OSCAR array

- Commissioned 2018
- Largest $LaBr_3$:Ce array
- Budget ≈ 23.3 MNOK (≈ 2.3 M€)
- 30 large volume LaBr3:Ce detectors
  - 3.5x8-inch detectors
- National Research Infrastructure
- Digital Data Acquisition
- Improves resolution by
  - Energy ≈ 3-5
  - Time > 10x
- Efficiency > 3x



The OSCAR detectors

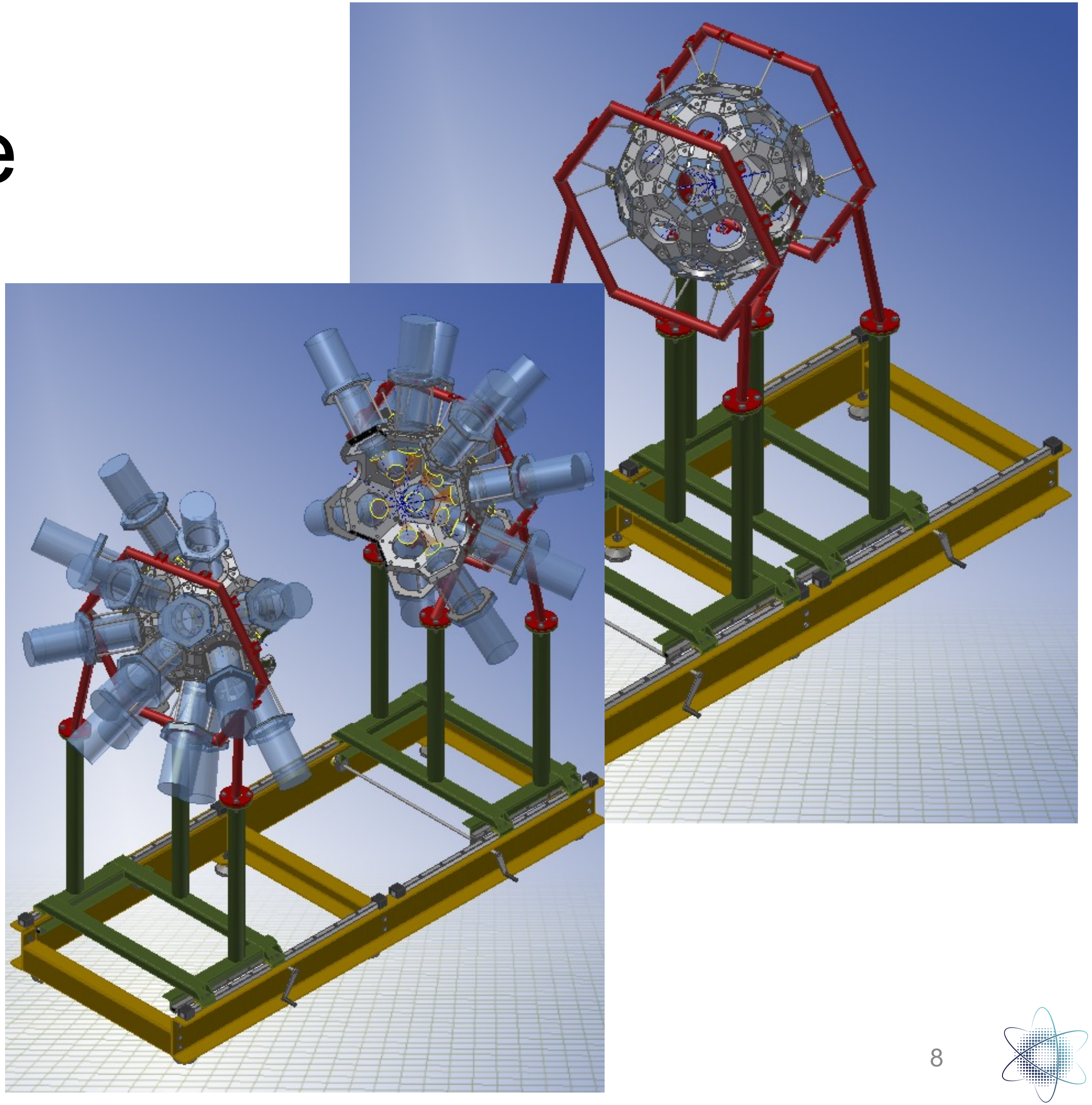
- Built at OCL
- Design based on the HECTOR+ array
- Large volume $LaBr_3:Ce$
  - BrilianCe 380 from Saint-Gobain Crystals[1]
- Redesigned housing with thin Al window
- Hammamatsu R10233-100 PMT
  - Maximum gain 2.5x10^4
  - Minimum quantum efficiency 41%
- Active voltage dividers `LABRVD` designed by the Milano Group



[1]Now Luxium Solutions

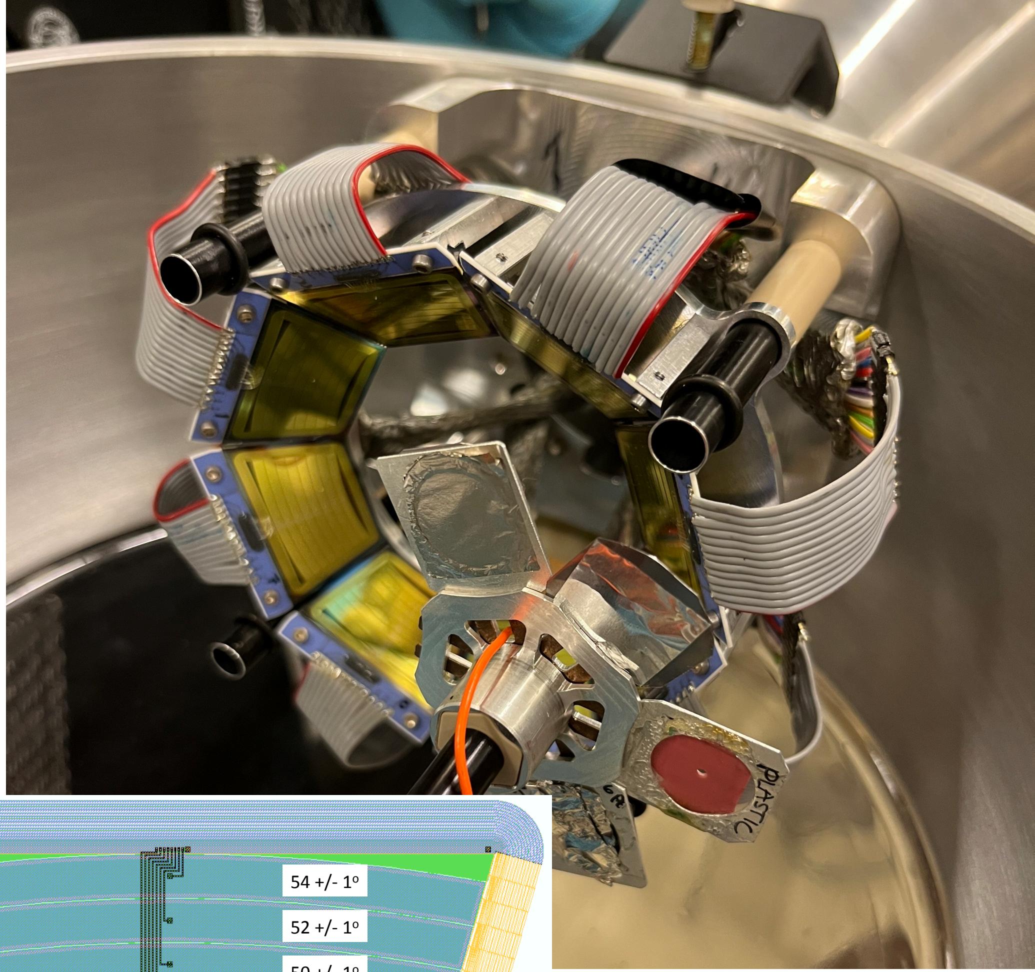
The OSCAR frame

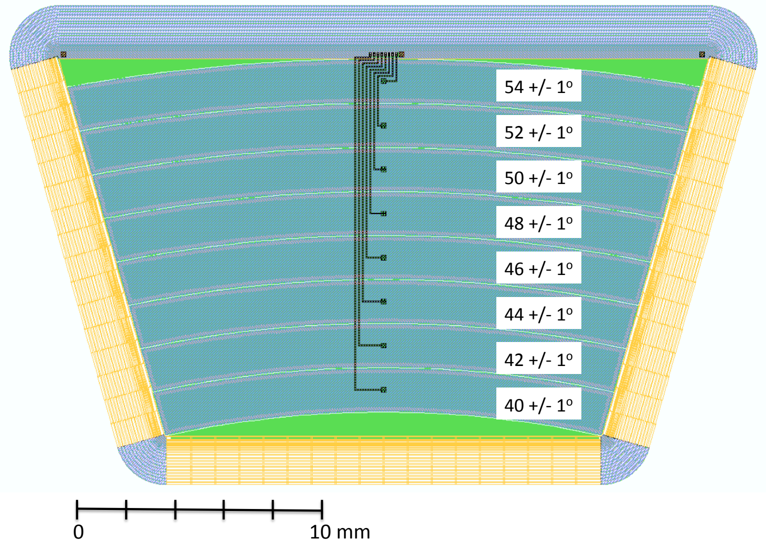
- Aluminum frame
- Approximate isotropic
- Three different detector distances
    - 16.3 cm: 57% of 4π
    - 22.0 cm: 30% of 4π
    - 42.0 cm: 8.4% of 4π
- Designed by Jan Mierzejewski, Component3D, Poland



OSCAR+SiRi

- Silicon Ring Array – SiRi
- Eight trapezoidal assemblies
- Each trapezoid: ΔE-E telescopes
- Covers angles:
  - Forward: 40° to 58°
  - Backwards: 126° to 140°
- ΔE:
  - Eight segments, 2° each
  - Thickness: 130 μm
- E:
  - Single crystal, thickness: 1550 μm
- Designed and manufactured in collaboration with SINTEF MiNaLab, Norway

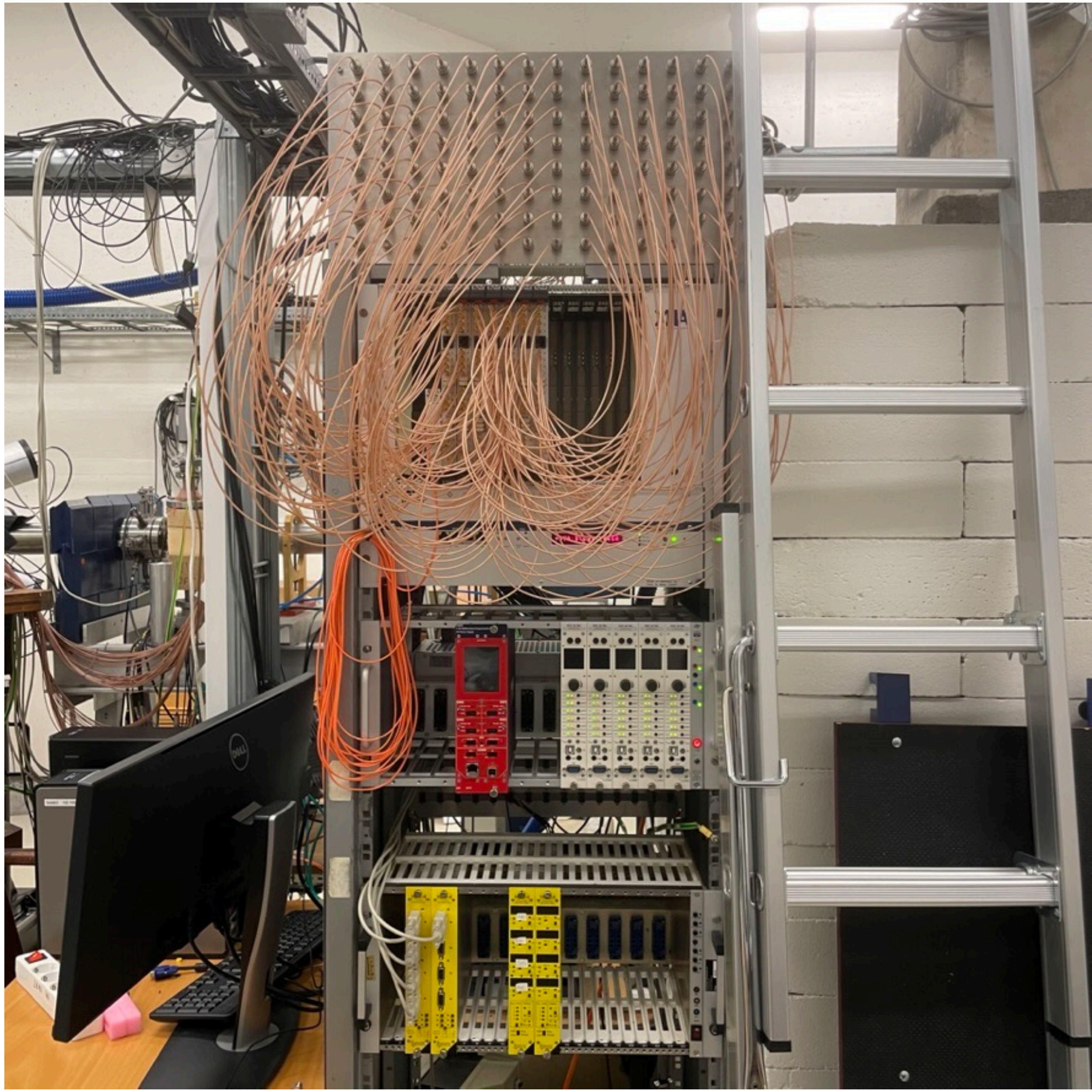




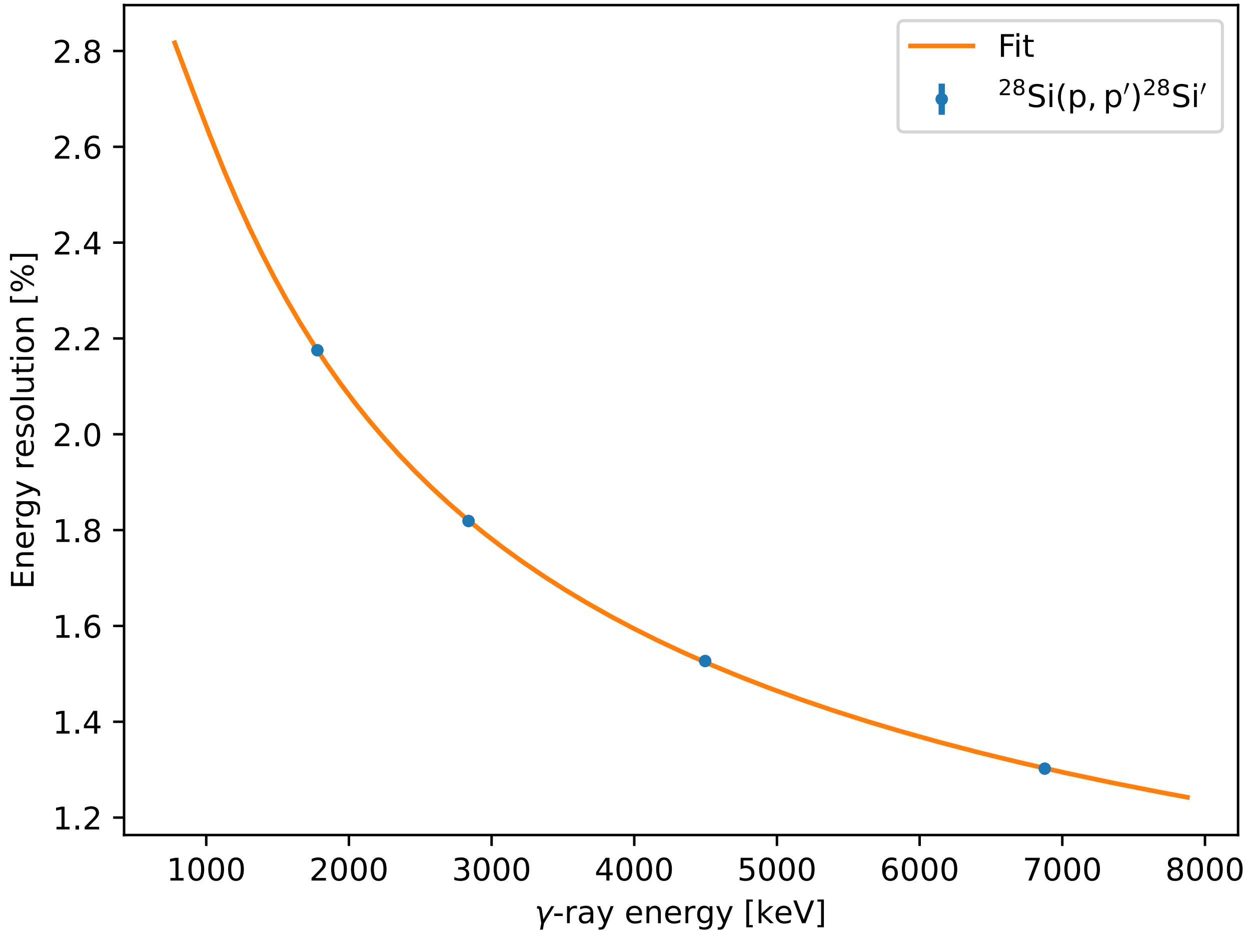
M. Guttormsen *et al.*, Nucl. Inst. and Meth. Phys. Res. A **648**, 168 (2011)

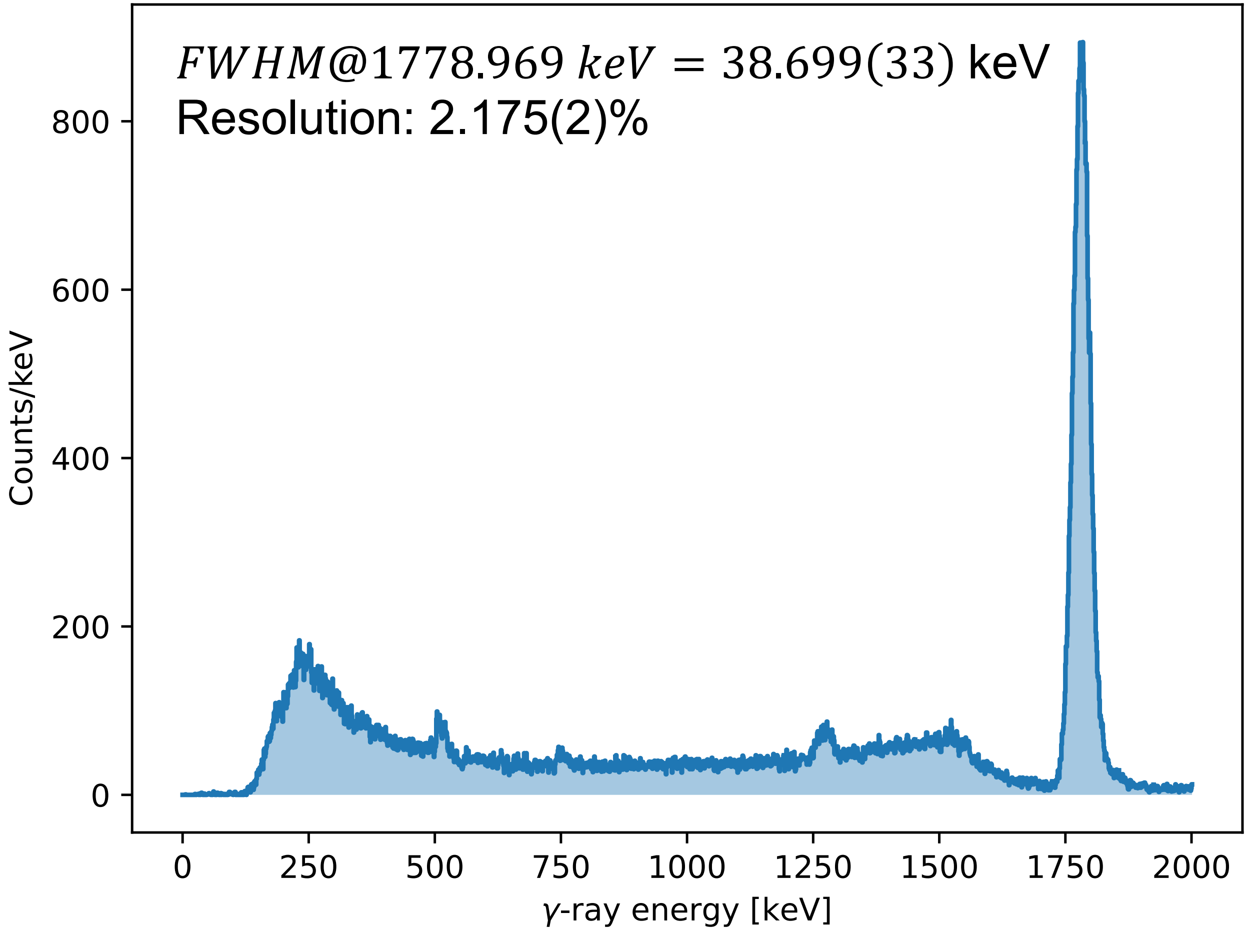
Data Acquisition System

- Digital system from XIA LLC
- Based around the Pixie-16 modular system
- Single crate:
  - $LaBr_3$:Ce: 14-bit, 500 MHz (2 + 1 spare)
  - SiRi: 16-bit, 250 MHz (5 + 1 spare)
- Each channel individually triggered
- Storing only gamma events within 500 ns of a particle event
- Virtually no deadtime
- Improves throughput significantly (> 10x)
- Optimized for throughput

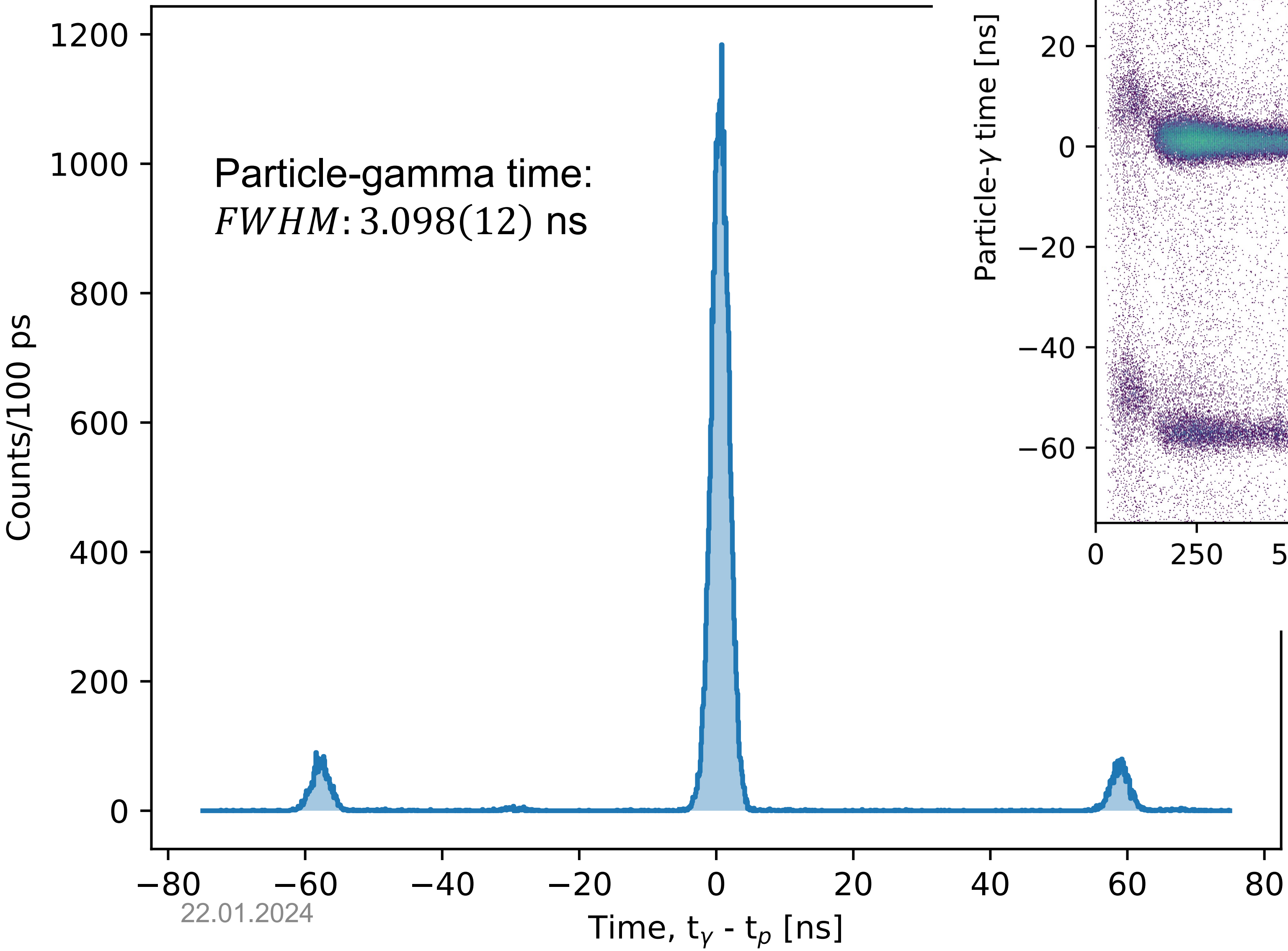


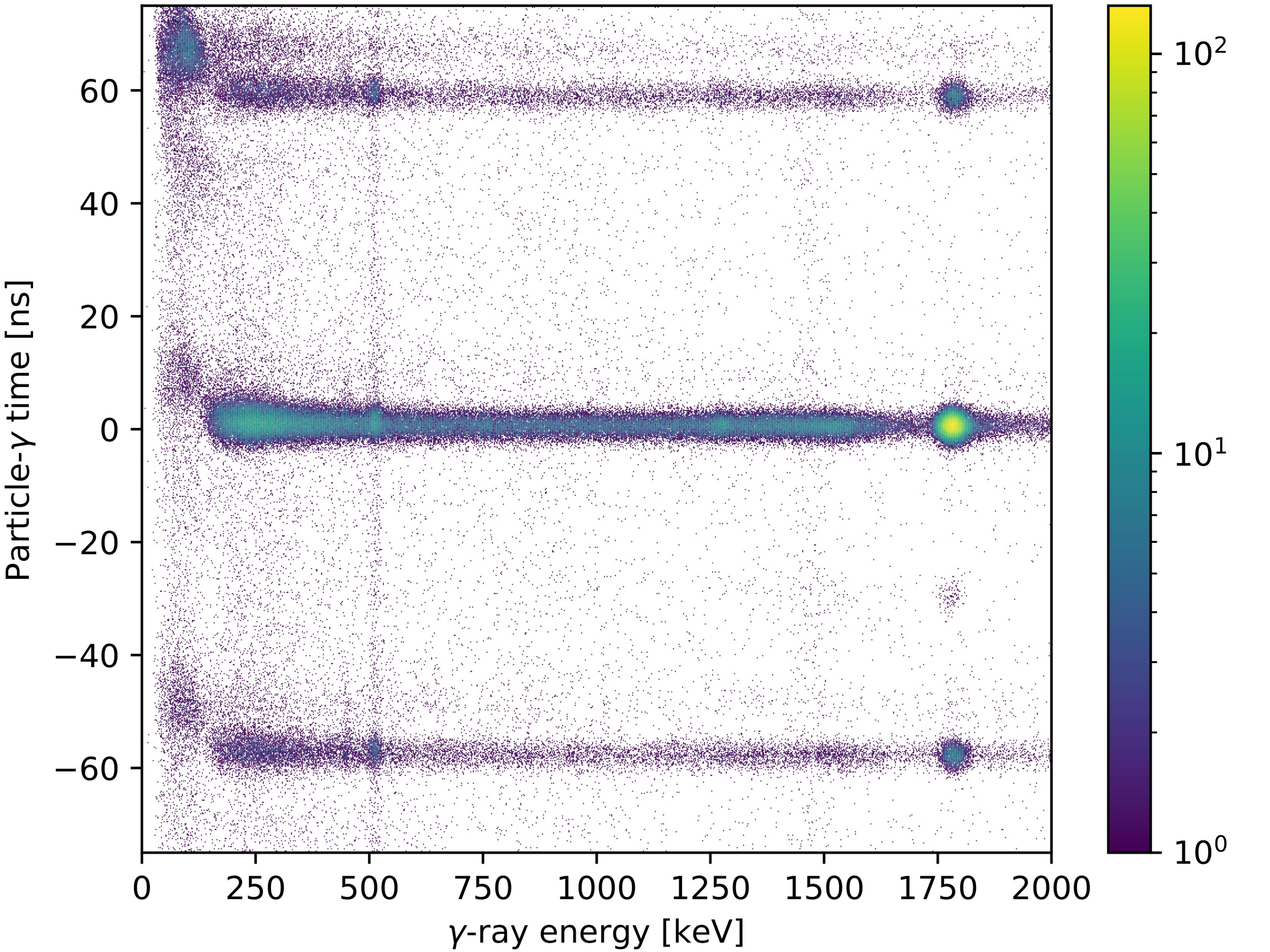
Energy Resolution



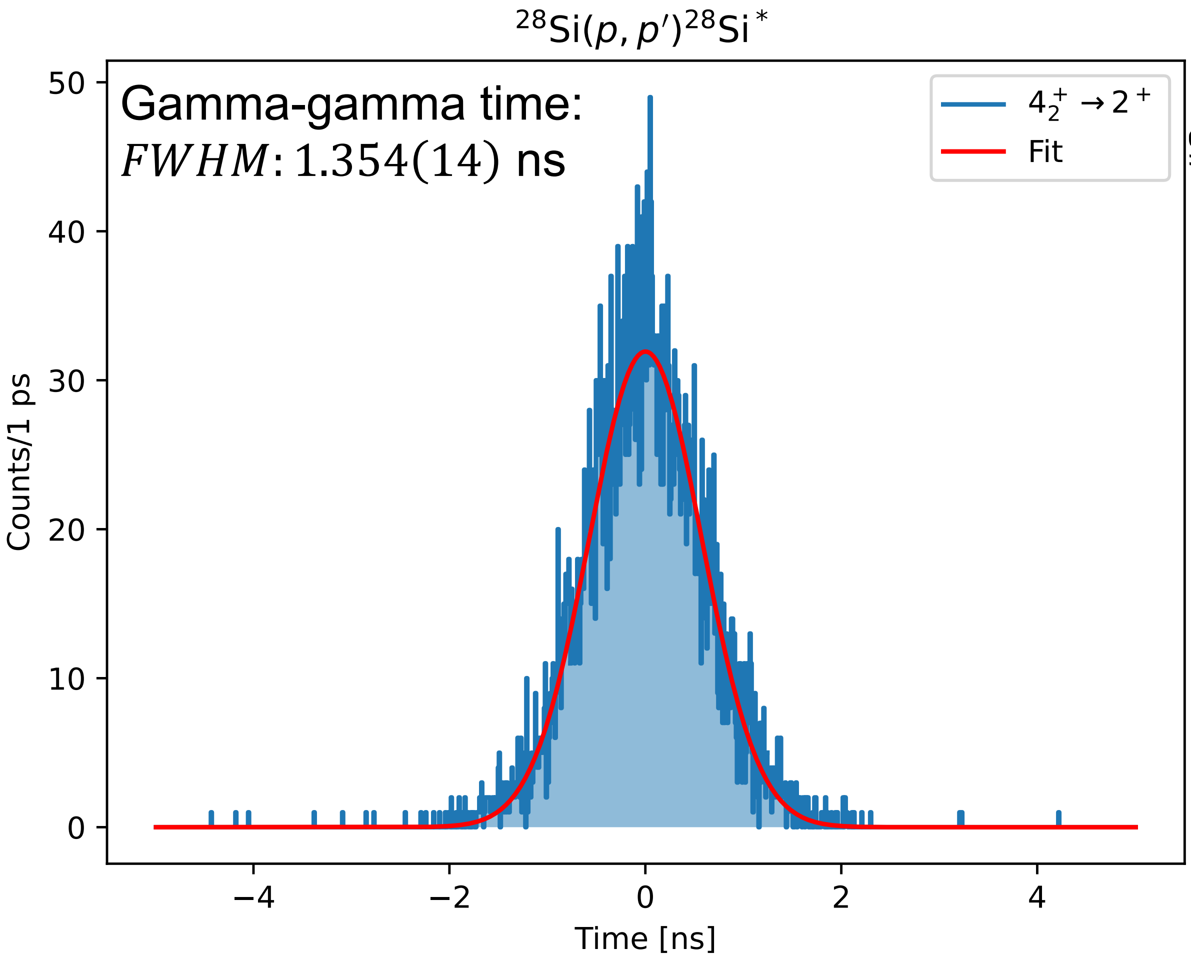


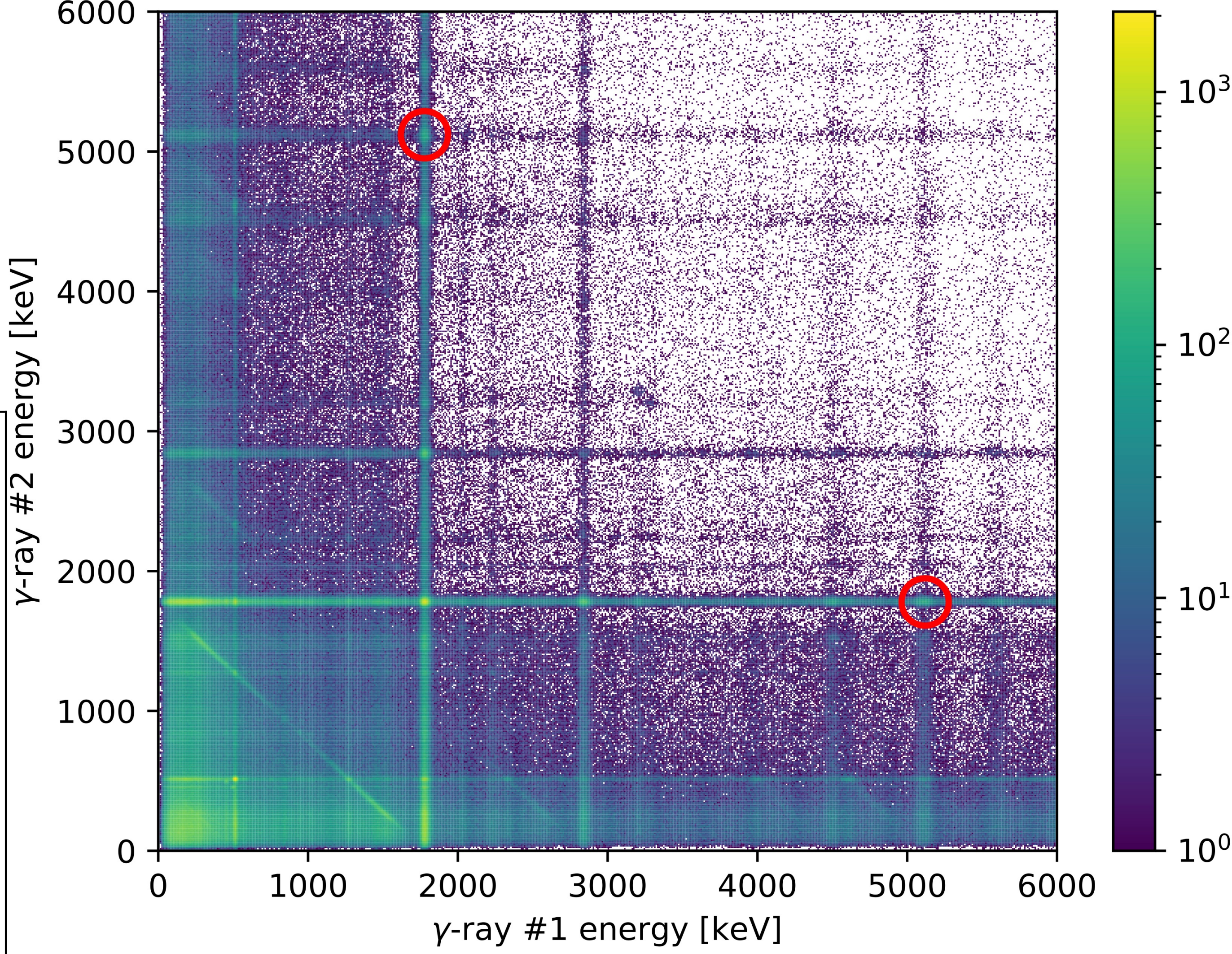
Time Resolution

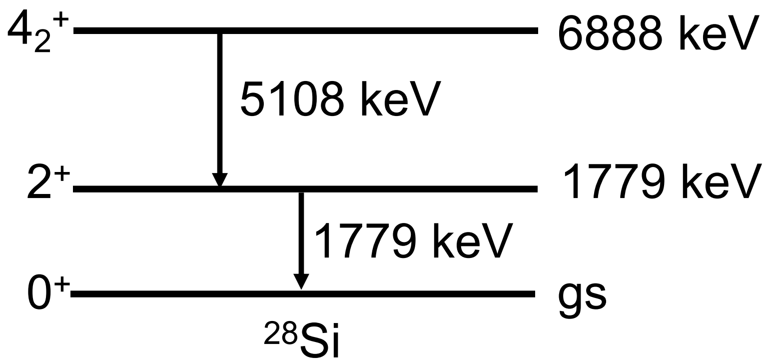




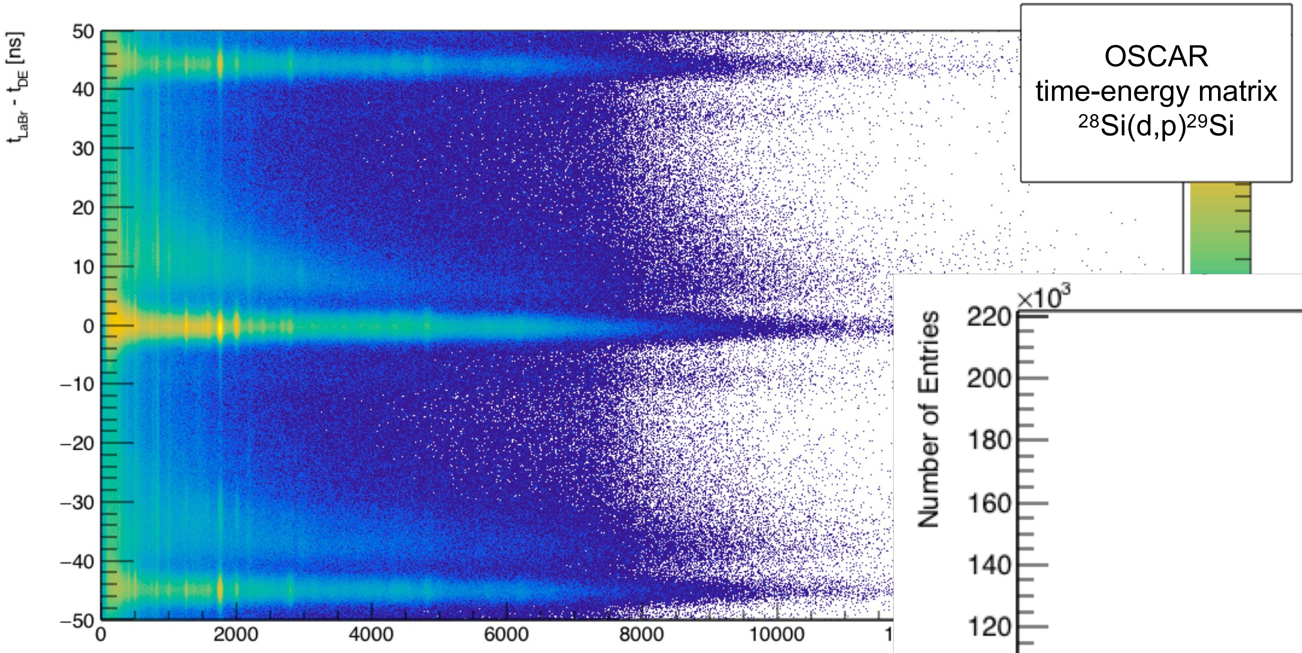
Time Resolution



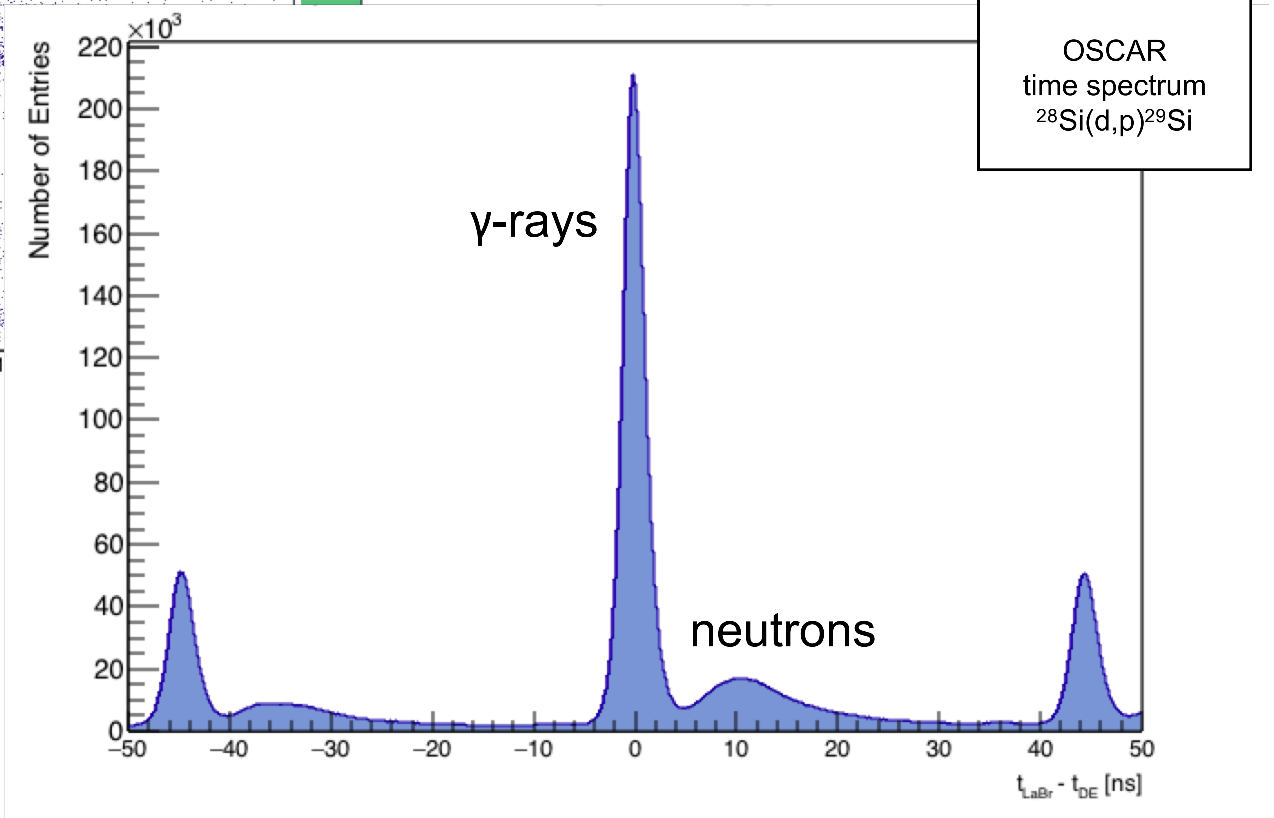




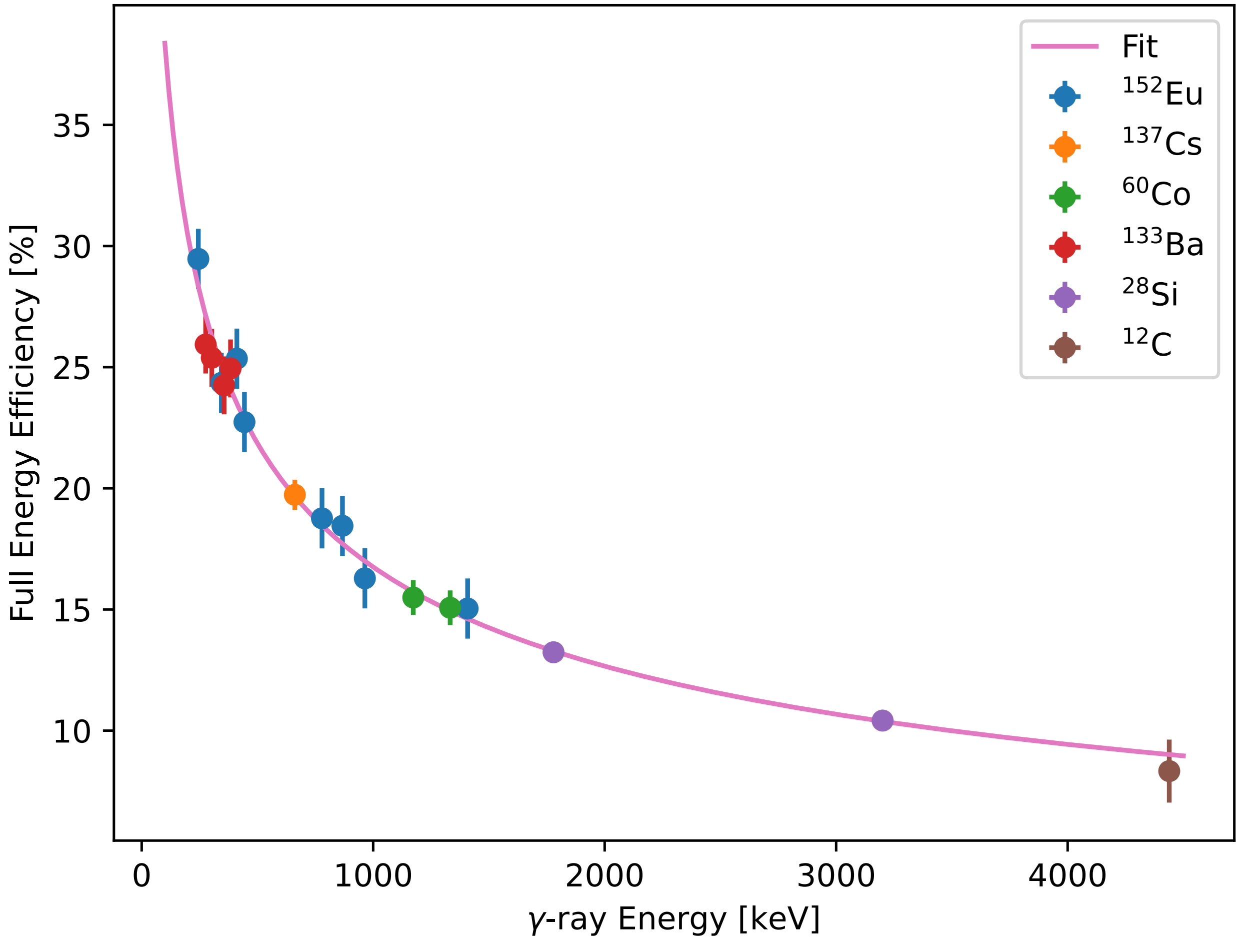
TOF neutron/gamma discrimination

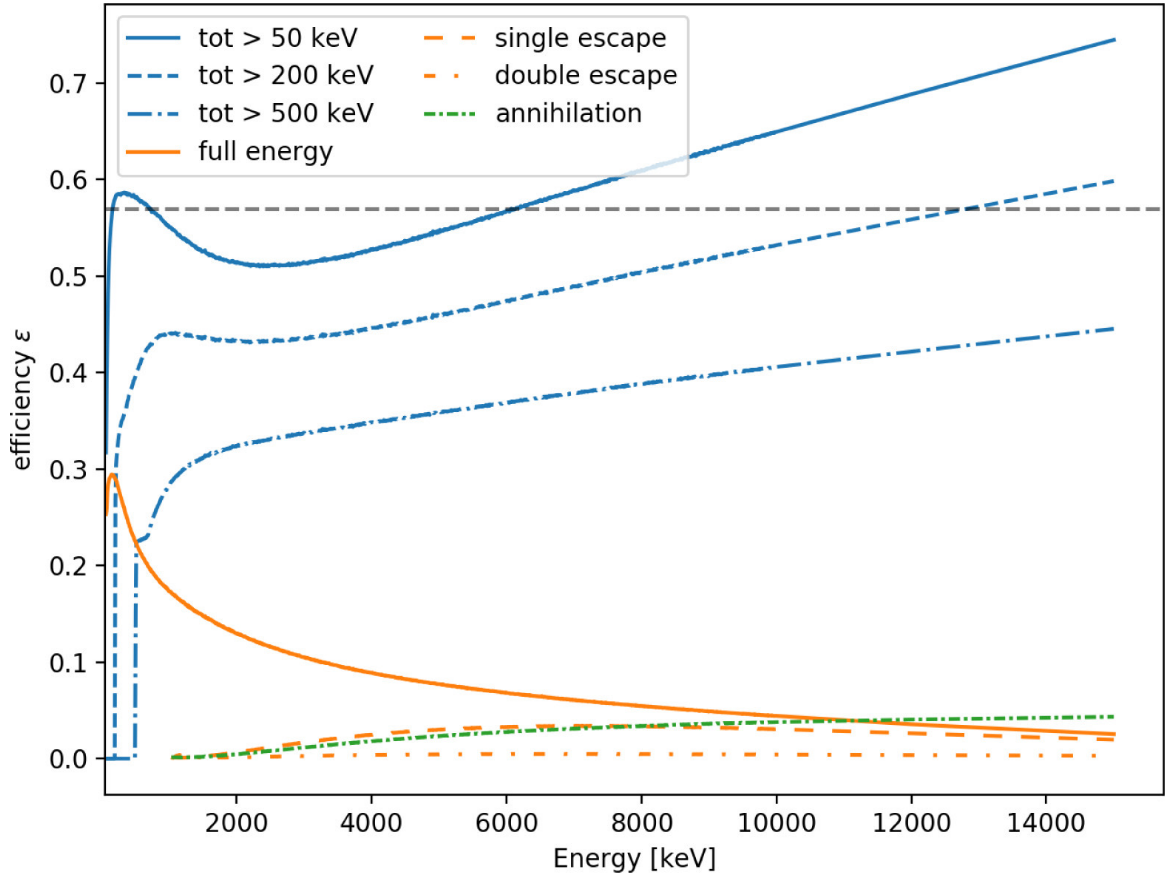


Detector at 42 cm from target



Efficiency

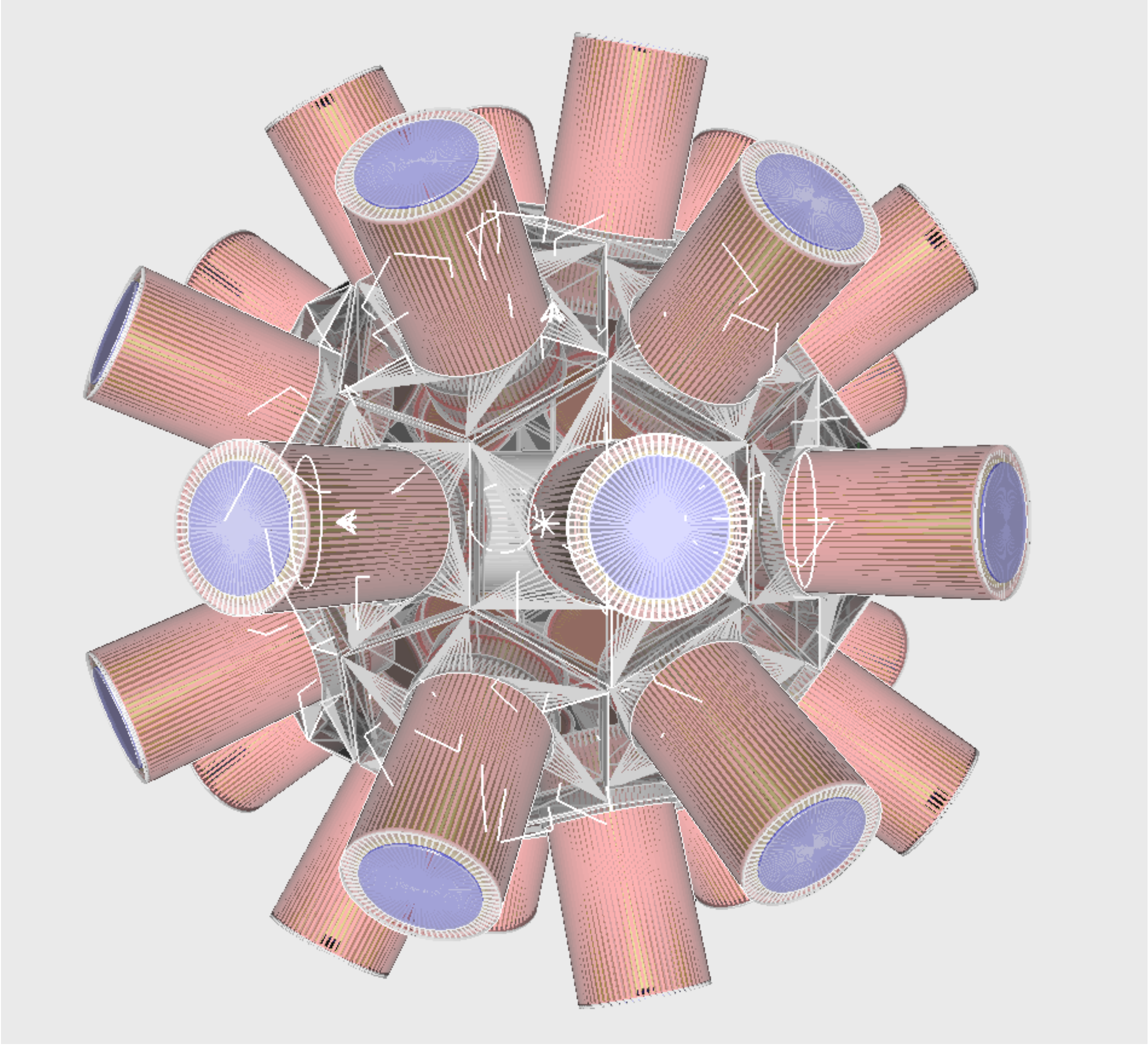




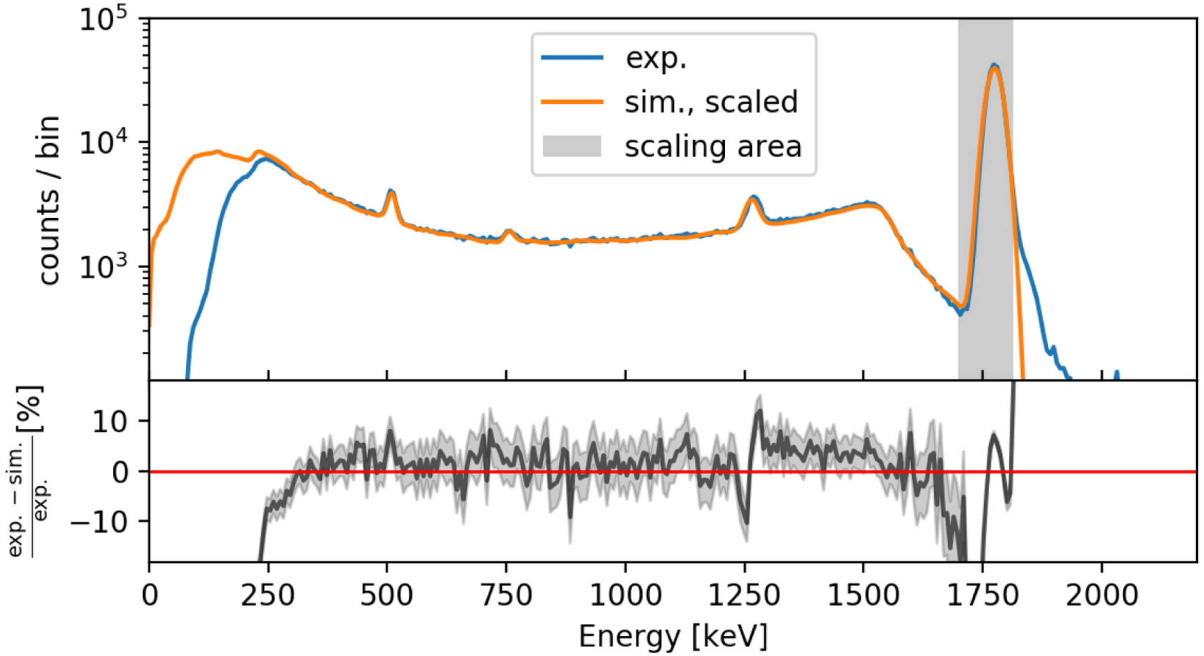
F. Zeiser *et al.*, Nucl. Inst. Meth. Phys. Res. A **985**, 164678 (2021)

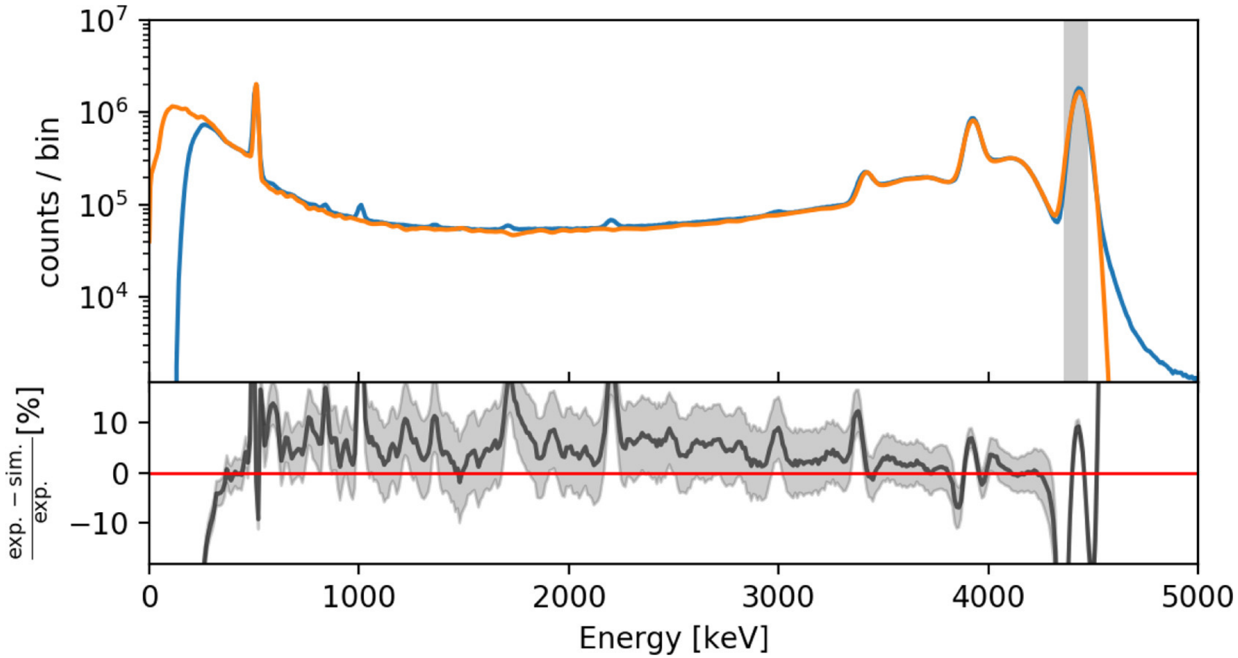
Geant4 model

- Entire array implemented in Geant4
  - Crystal, housing, PMT
  - Frame and support structure
- Simulated response function for energies between 100 keV and 20 MeV
- Model published in F. Zeiser *et al.*, Nucl. Inst. Meth. Phys. Res. A **985**, 164678 (2021)



Geant4 model

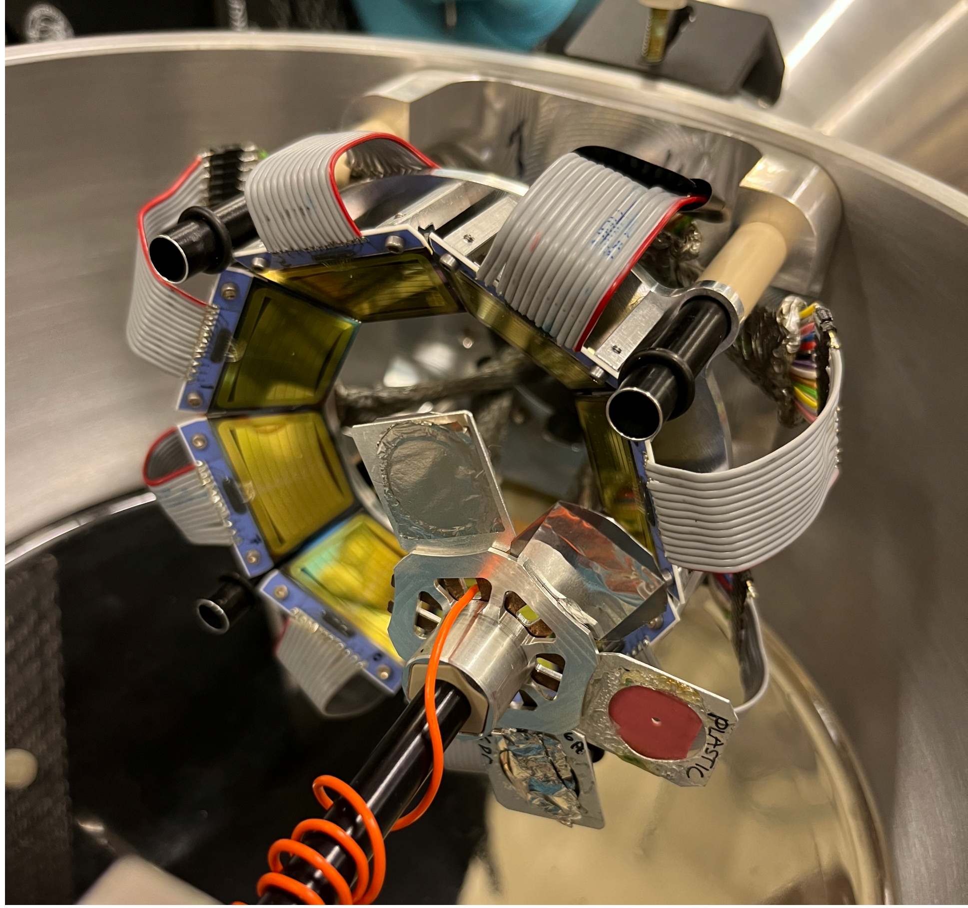


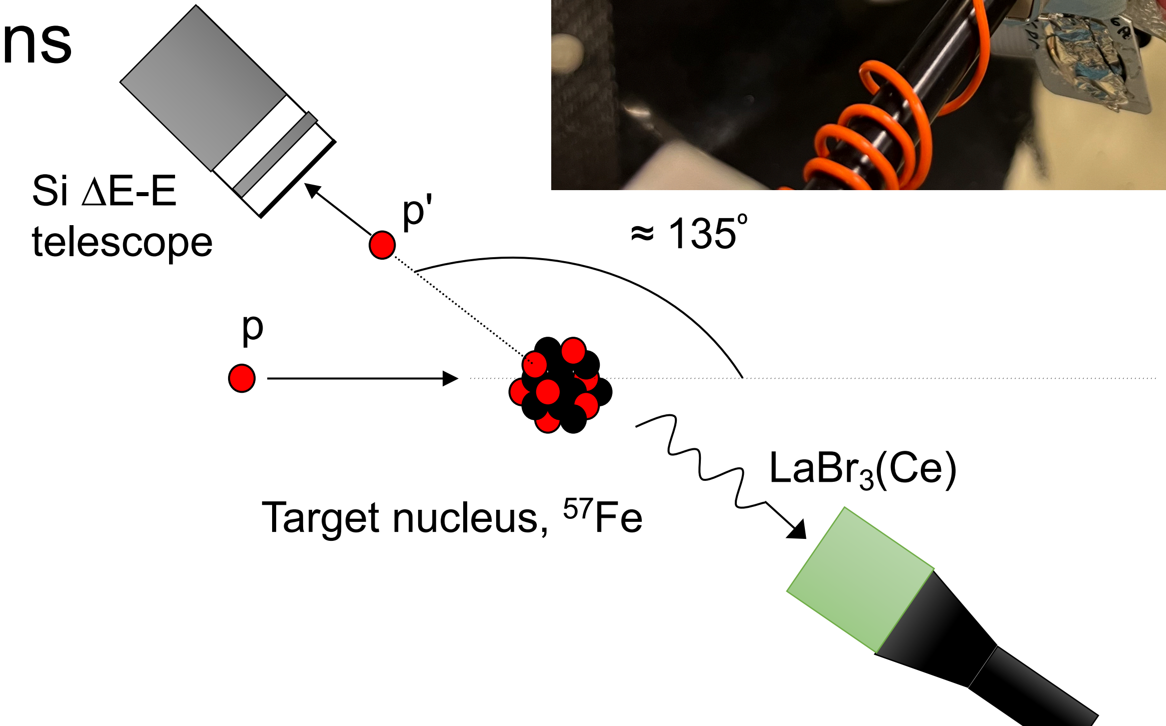


F. Zeiser et al., Nucl. Inst. Meth. Phys. Res. A **985**, 164678 (2021)

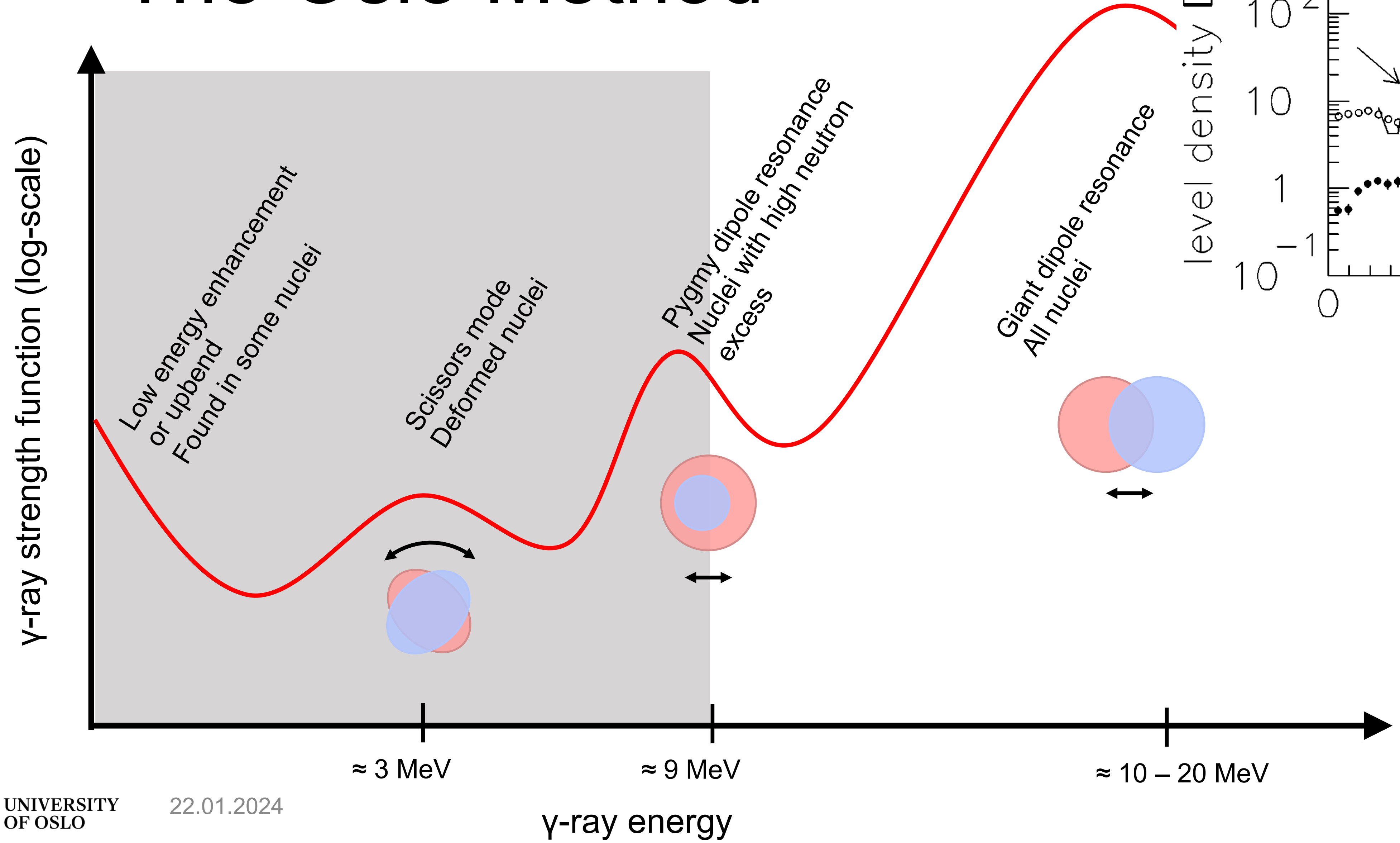
The Oslo Method

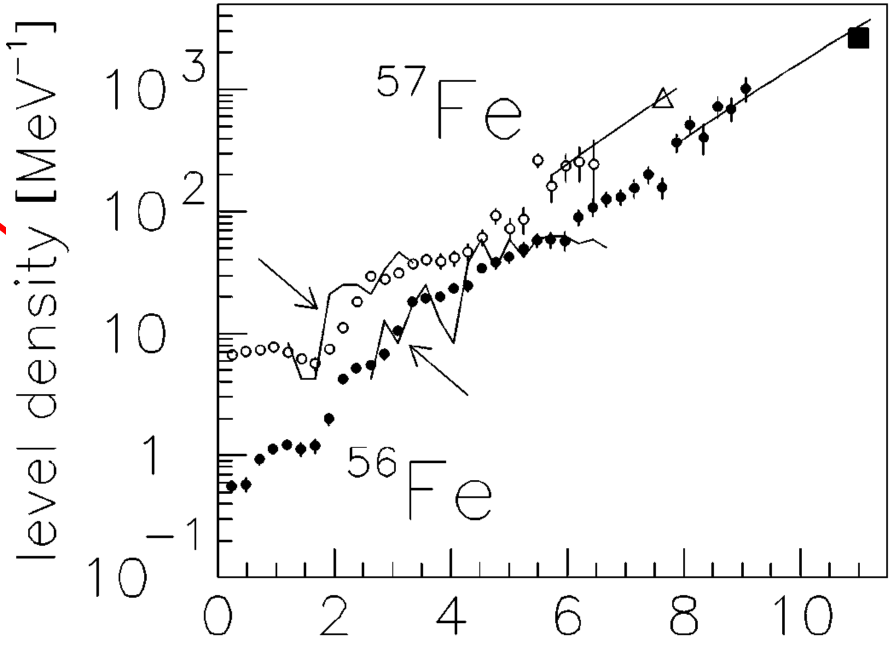
- Measure the Nuclear Level Density and gamma-ray strength function simultaneously
- Important parameters for nuclear reaction calculations
  - Nuclear astrophysics
  - Nuclear reactors
  - Isotope production
- Input for the Oslo Method: Excitation versus gamma energy matrices





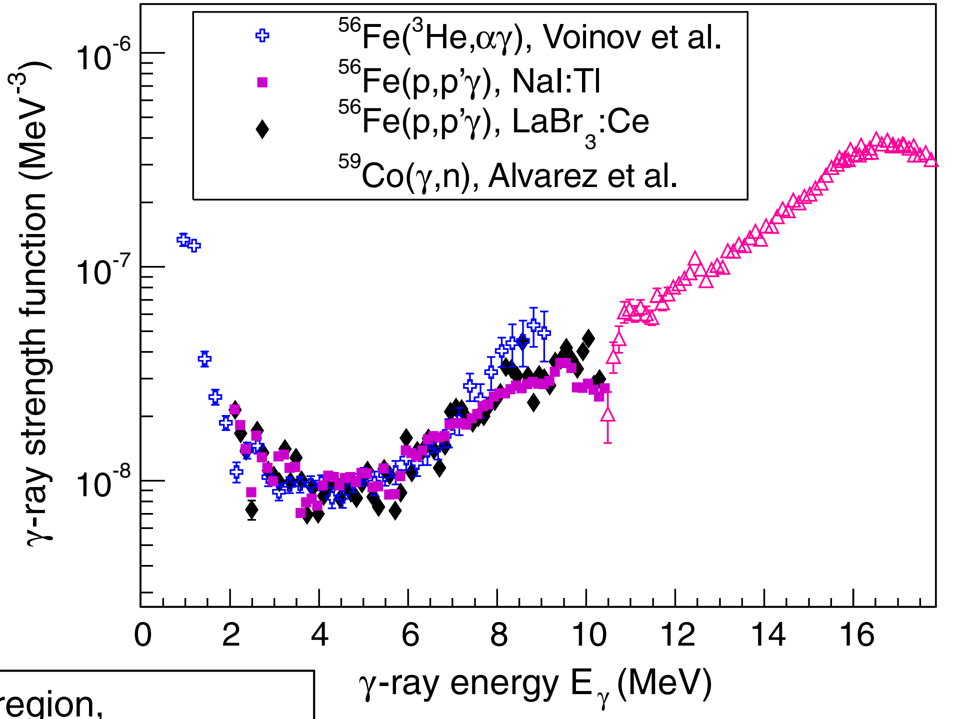
The Oslo Method

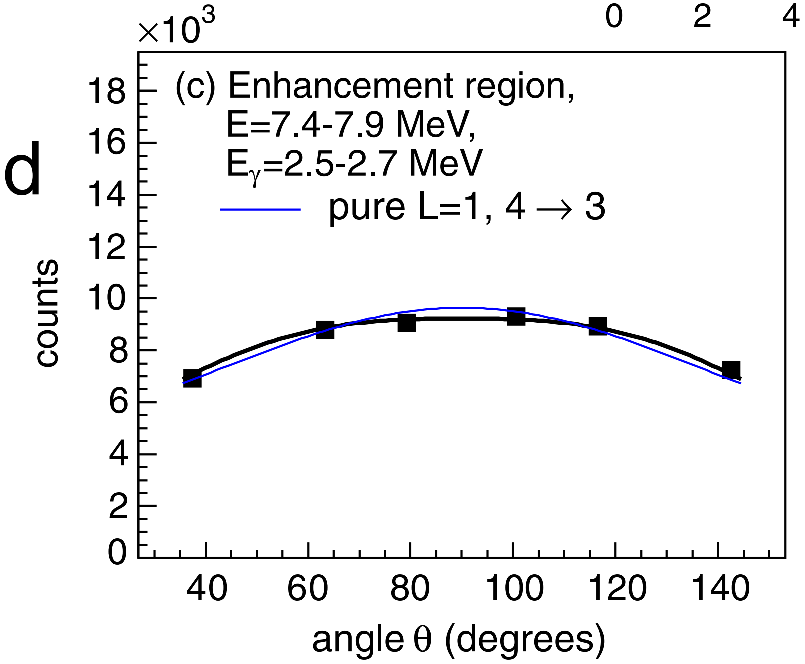




Low Energy Enhancement

- First measured with the Oslo Method in ^{56}Fe
- Measured to be dipole
- E1/M1 not yet experiementally determined



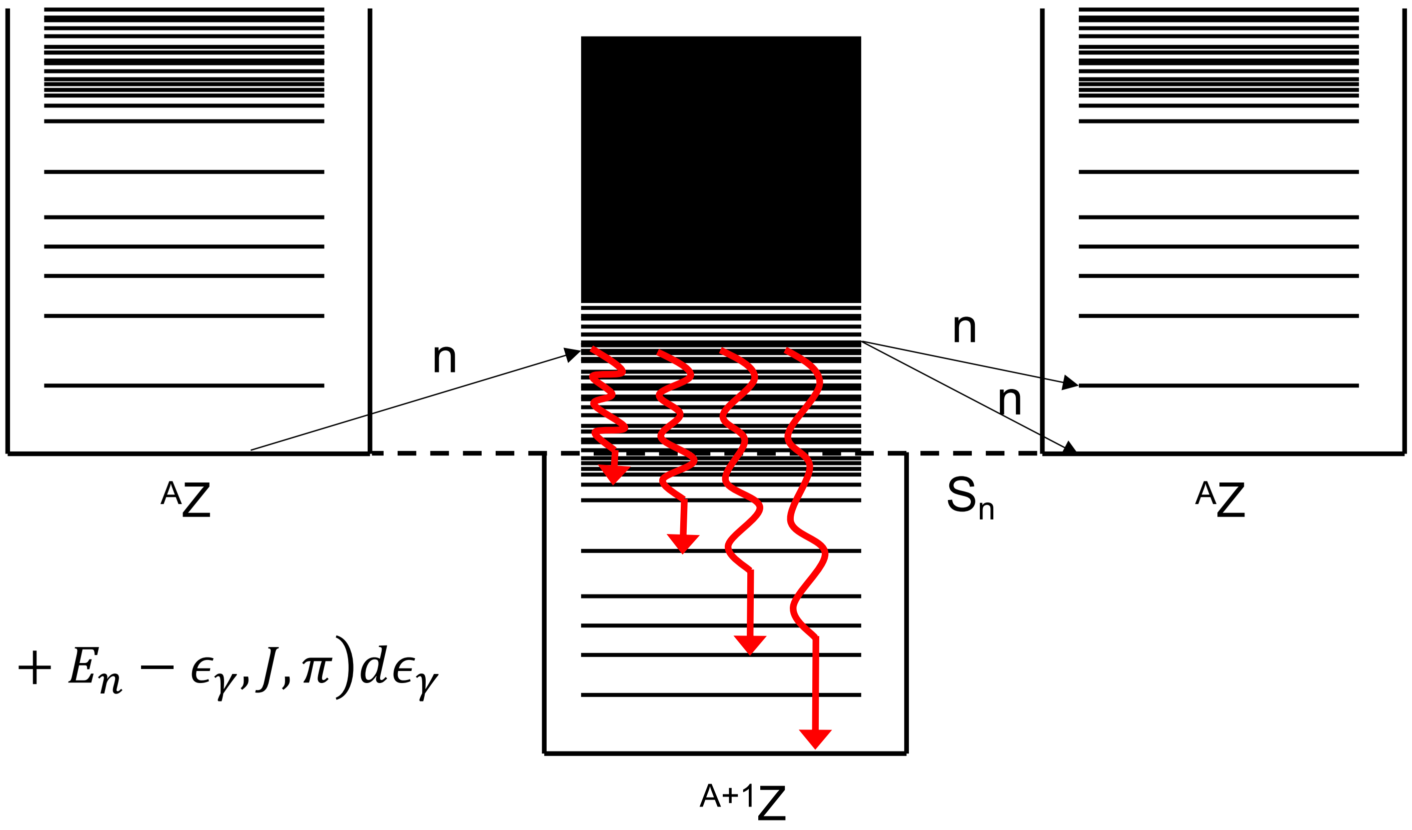


A. C. Larsen *et al.*, Phys. Rev. Lett. **111**, 242504 (2013)

The Oslo Method – Nuclear Astrophysics

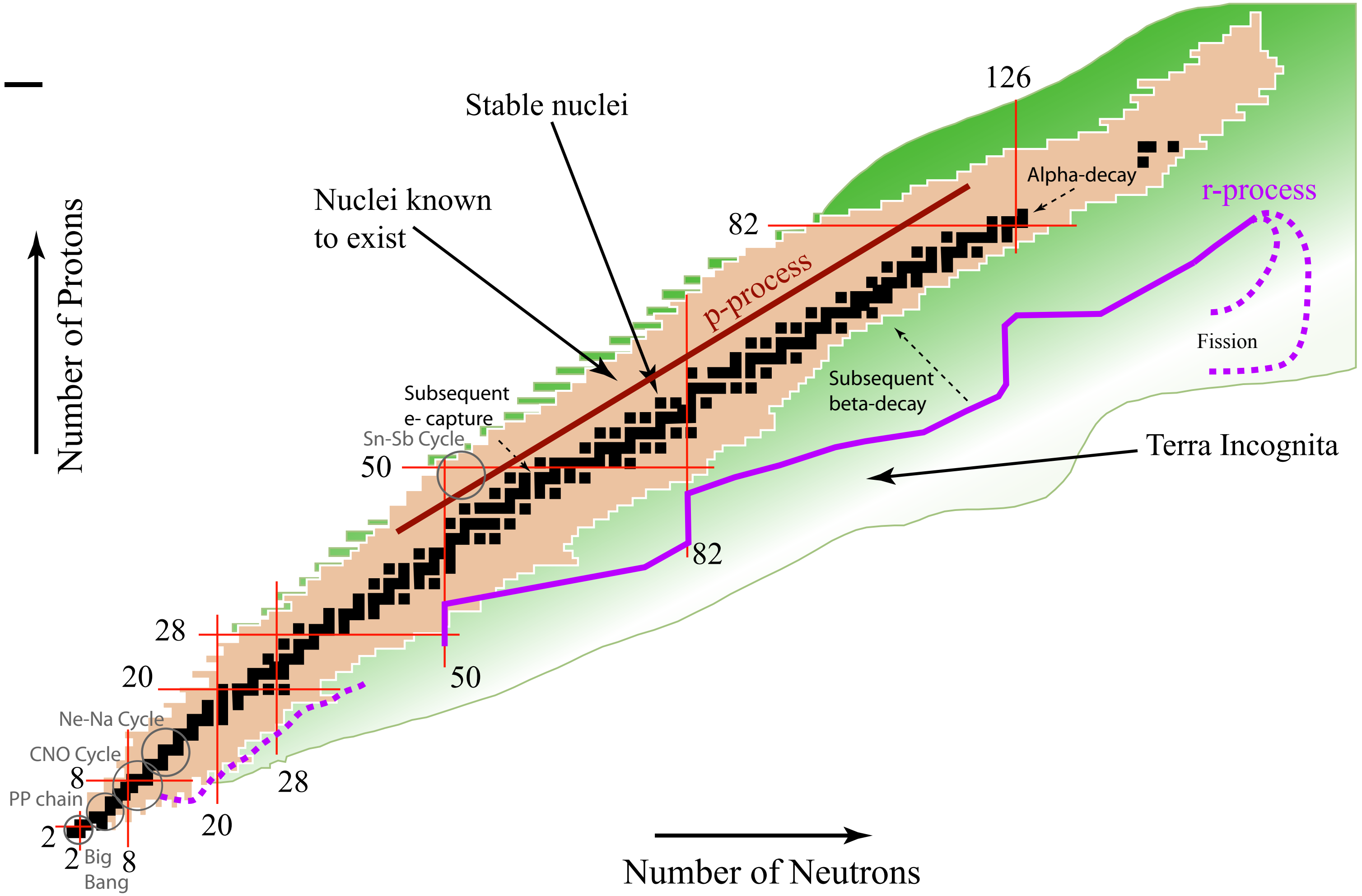
$$\sigma_{n,\gamma} \propto \sum_{J,\pi} \frac{T_n(J^\pi)T_\gamma(J^\pi)}{T_n(J^\pi) + T_\gamma(J^\pi)} \approx \sum_{J,\pi} T_\gamma(J^\pi)$$

$$T_\gamma = \sum_{XL} \sum_{J,\pi} \int_0^{S_n+E_n} 2\pi\epsilon_\gamma^{2L+1} f_{XL}(\epsilon_\gamma)\rho(S_n + E_n - \epsilon_\gamma, J, \pi)d\epsilon_\gamma$$

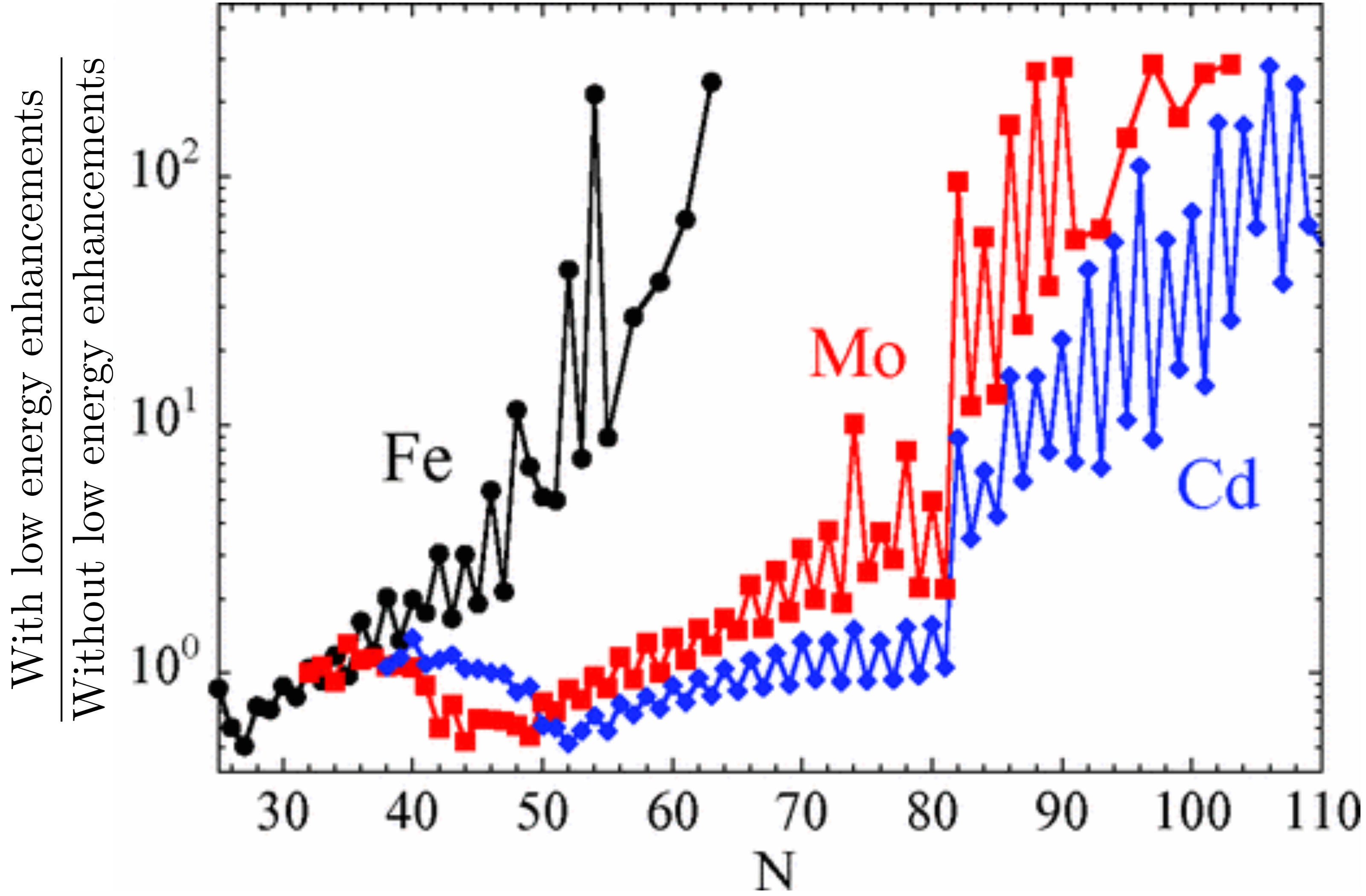


Nuclear Astrophysics

- Elements heavier than iron – neutron capture processes
  - s-process
  - i-process
  - r-process
- The Oslo Method:
  - Indirect method to measure neutron capture rates



Nuclear Astrophysics



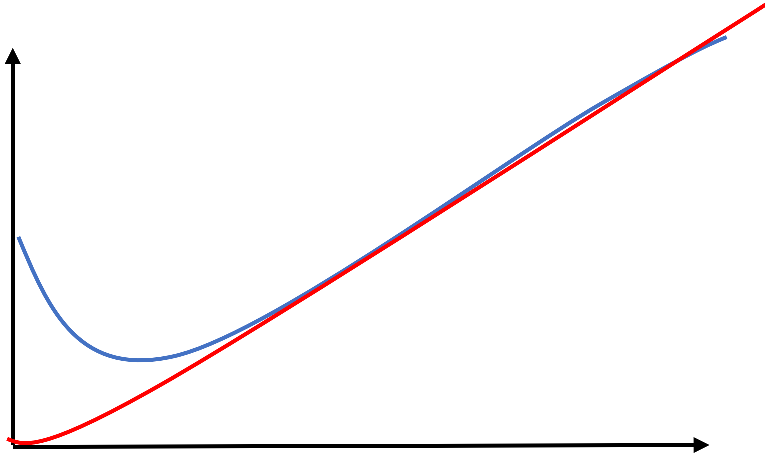
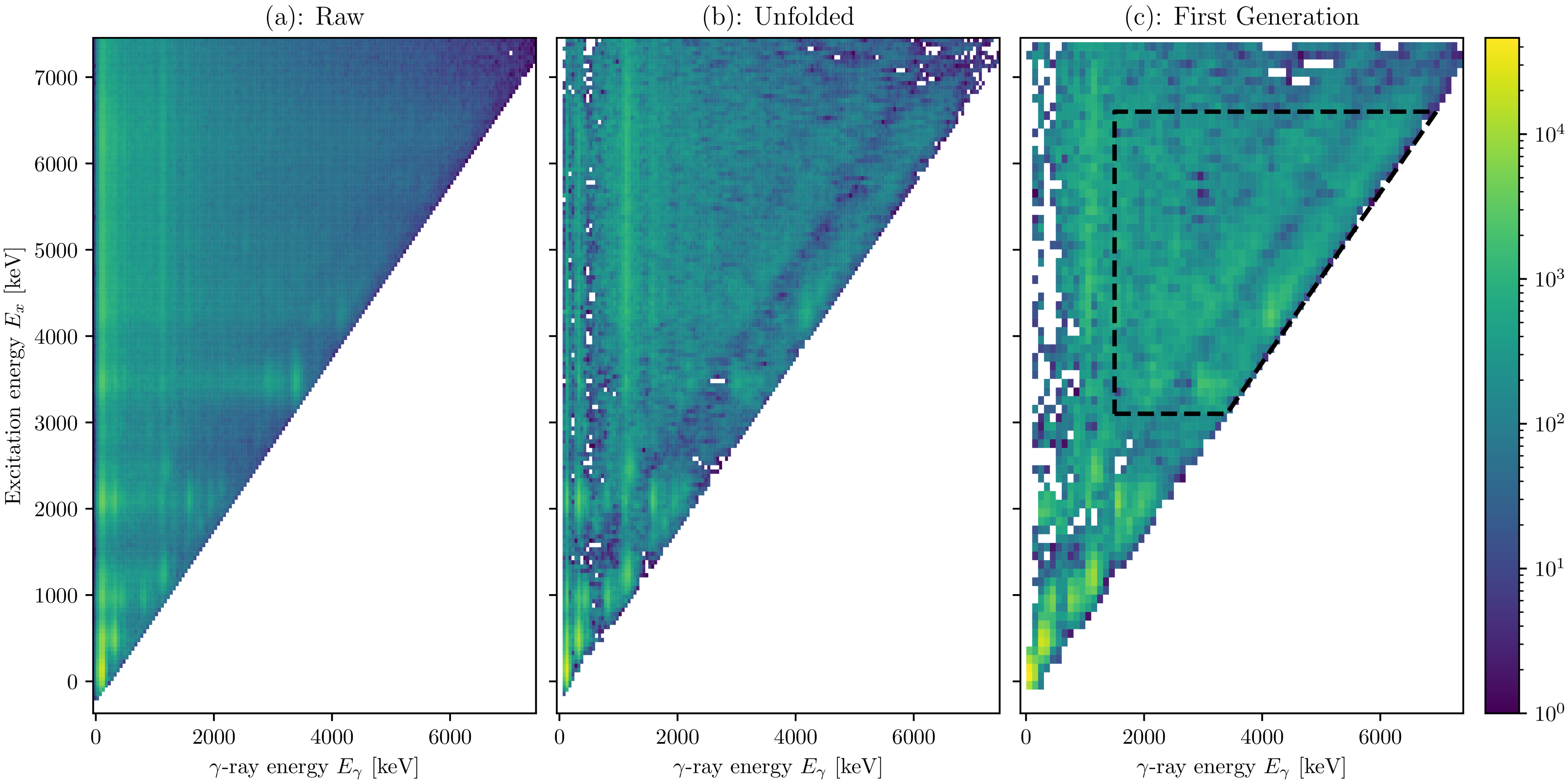


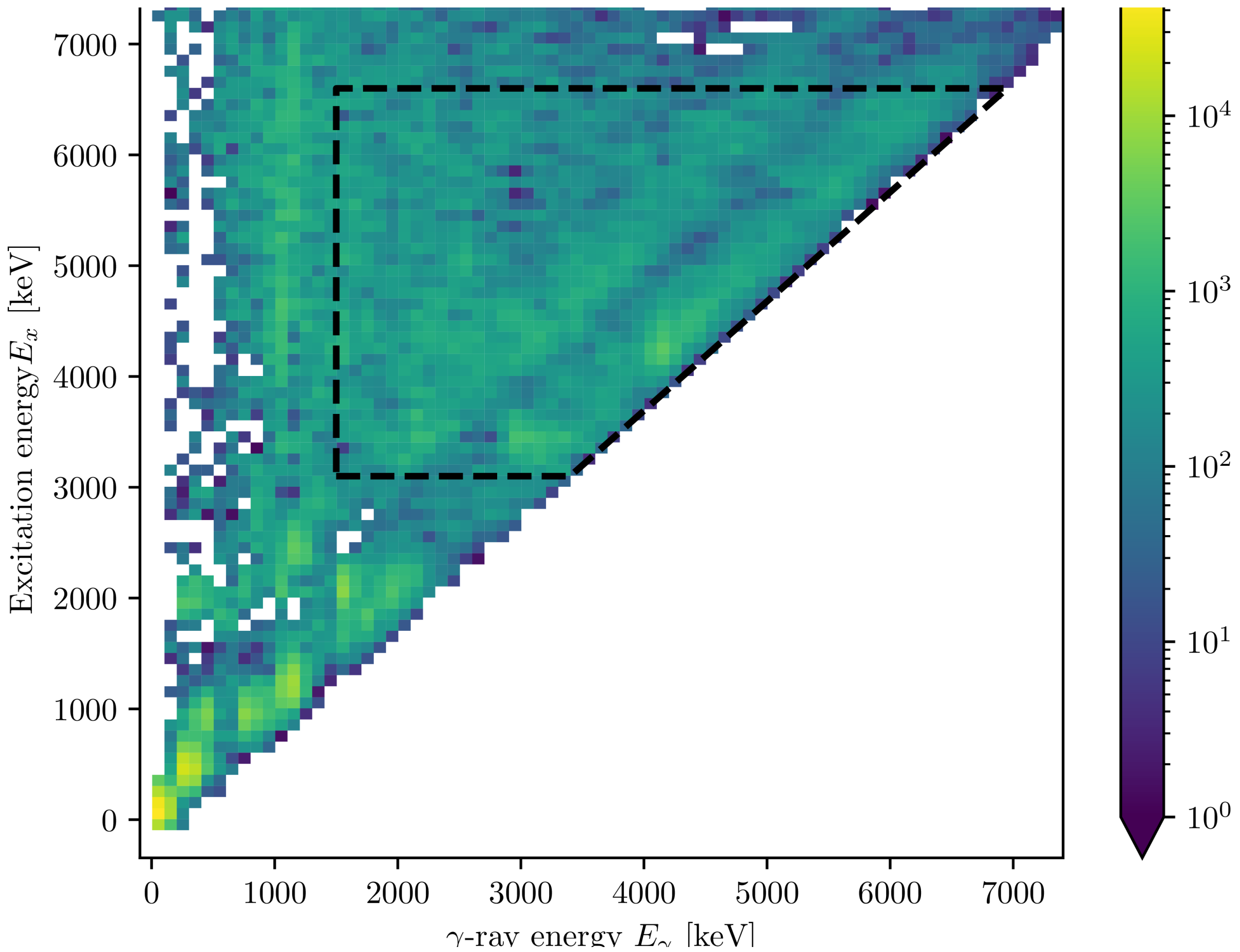
Figure credit: A. C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

The Oslo Method



V. W. Ingeberg *et al.*, Phys. Rev. C **106**, 054315 (2022)

The Oslo Method



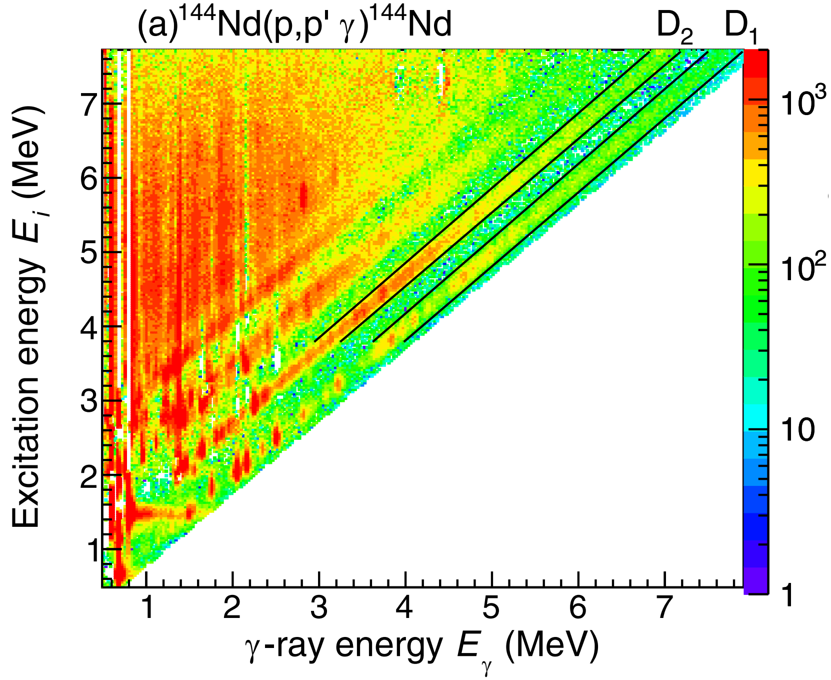
- First Generation Matrix
- Proportional to NLD & gamma transmission coefficients
  - $P(E_i, E_\gamma) \propto \mathcal{T}(E_\gamma) \cdot \rho(E_f = E_i - E_\gamma)$
- $P_{th}(E_x E_\gamma) = \dfrac{\mathcal{T}(E_\gamma)\rho(E_x - E_\gamma)}{\sum_{E_\gamma = E_\gamma^{min}}^{E_x} \mathcal{T}(E_\gamma)\rho(E_x - E_\gamma)}$
- $f_{L=1}(E_\gamma) = [f_{E1}(E_\gamma) + f_{M1}(E_\gamma)] \approx \dfrac{\mathcal{T}(E_\gamma)}{2\pi E_\gamma^3}$

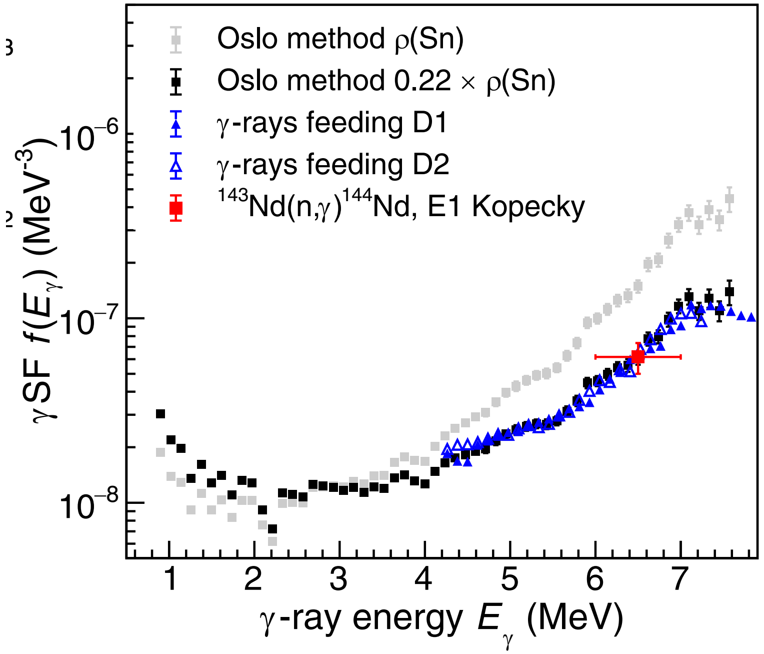
V. W. Ingeberg *et al.*, Phys Rev C **106**, 054315 (2022)

The Shape Method

- Model independent method
- Provides external data constrining the slope of Oslo Method data

$$N_D \propto f(E_\gamma)E_\gamma^3 \sum_{[J_f]} \sum_{J_i=J_f-1}^{J_i=J_f+1} p^{\text{level}}(E_i, J_i)\, g(E_i, J_i)_{\text{tot}},$$

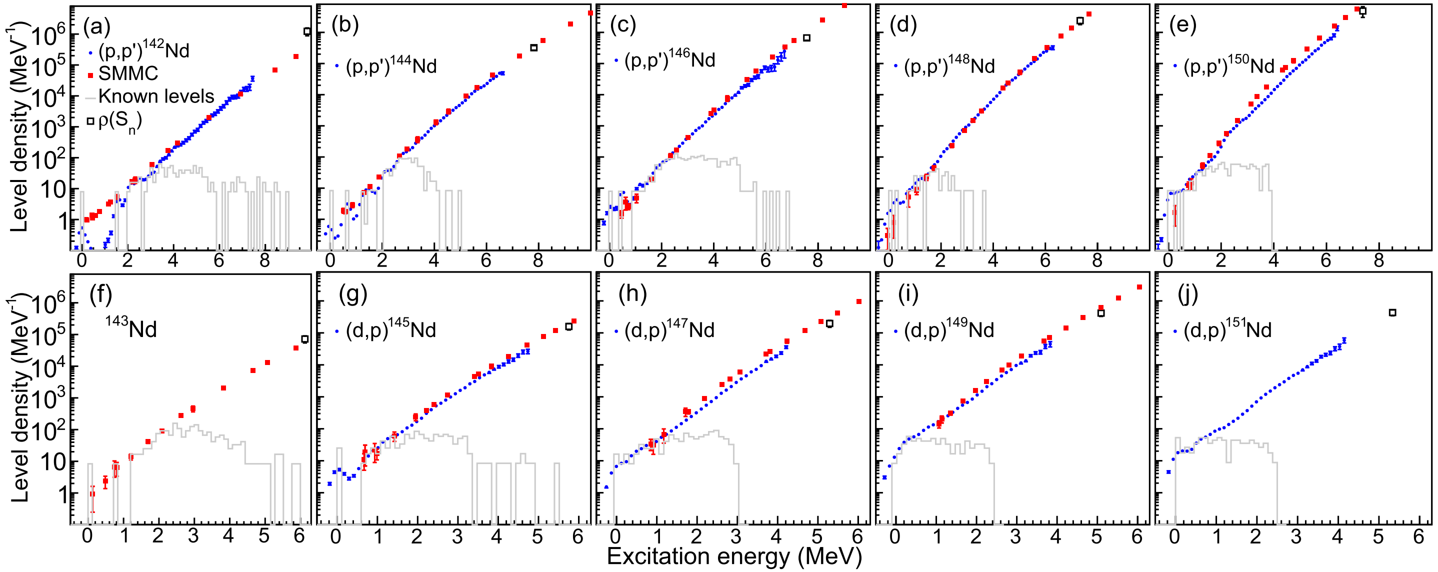




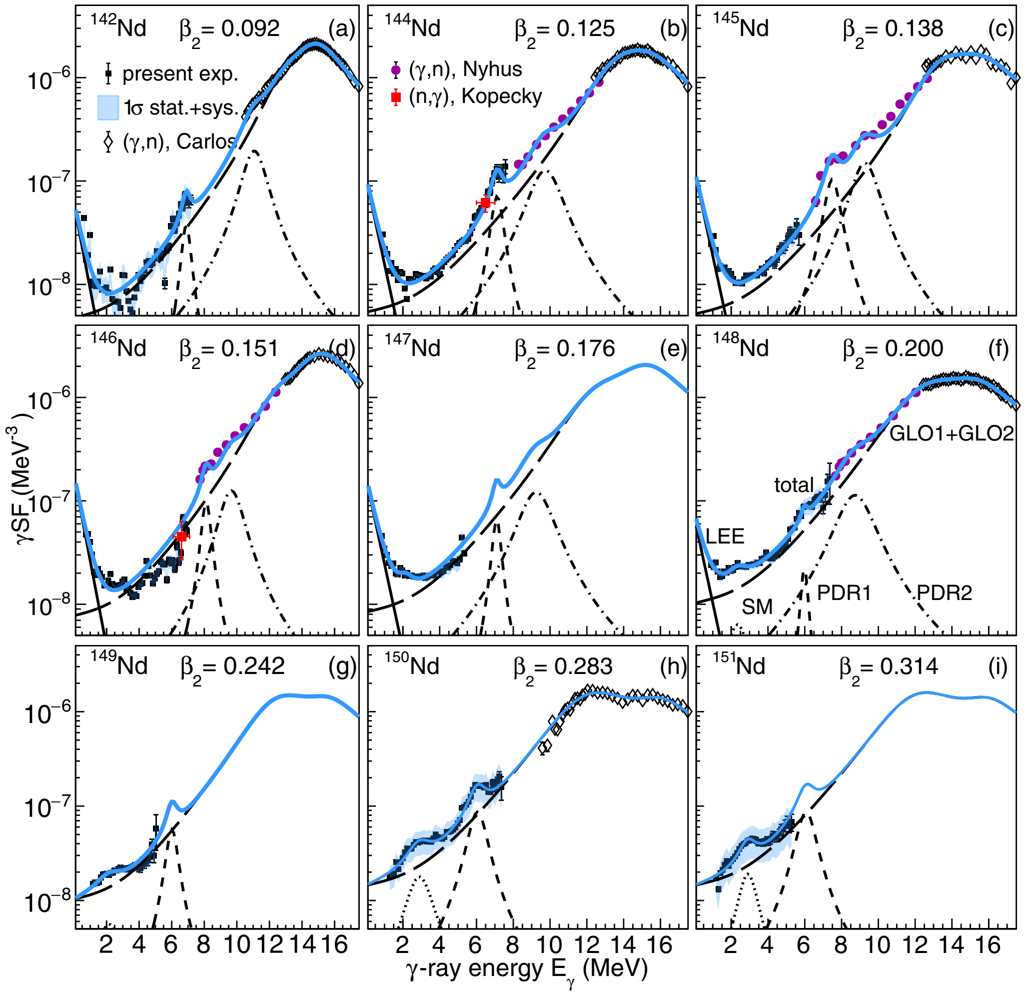
M. Guttormsen *et al.*, Phys. Rev. C **106**, 034314 (2022)

Systematic studies of Nd isotopes

- Is there a connection between the LEE and the SM? Deformation?
- NLD & gSF measured for $^{142,144\text{-}151}$Nd
- First obervation of LEE & SM in same nucleus

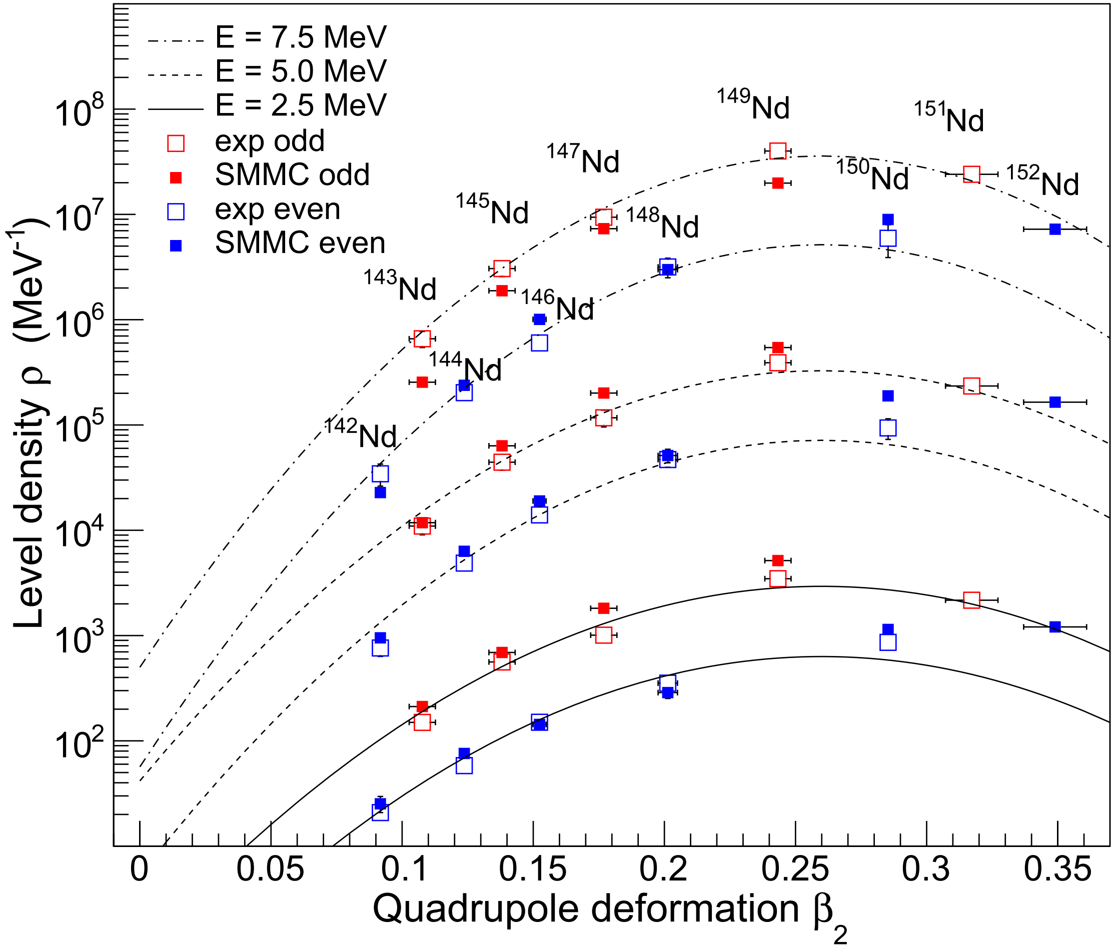


M. Guttormsen *et al.*, Phys. Lett. B **816**, 136206 (2021)

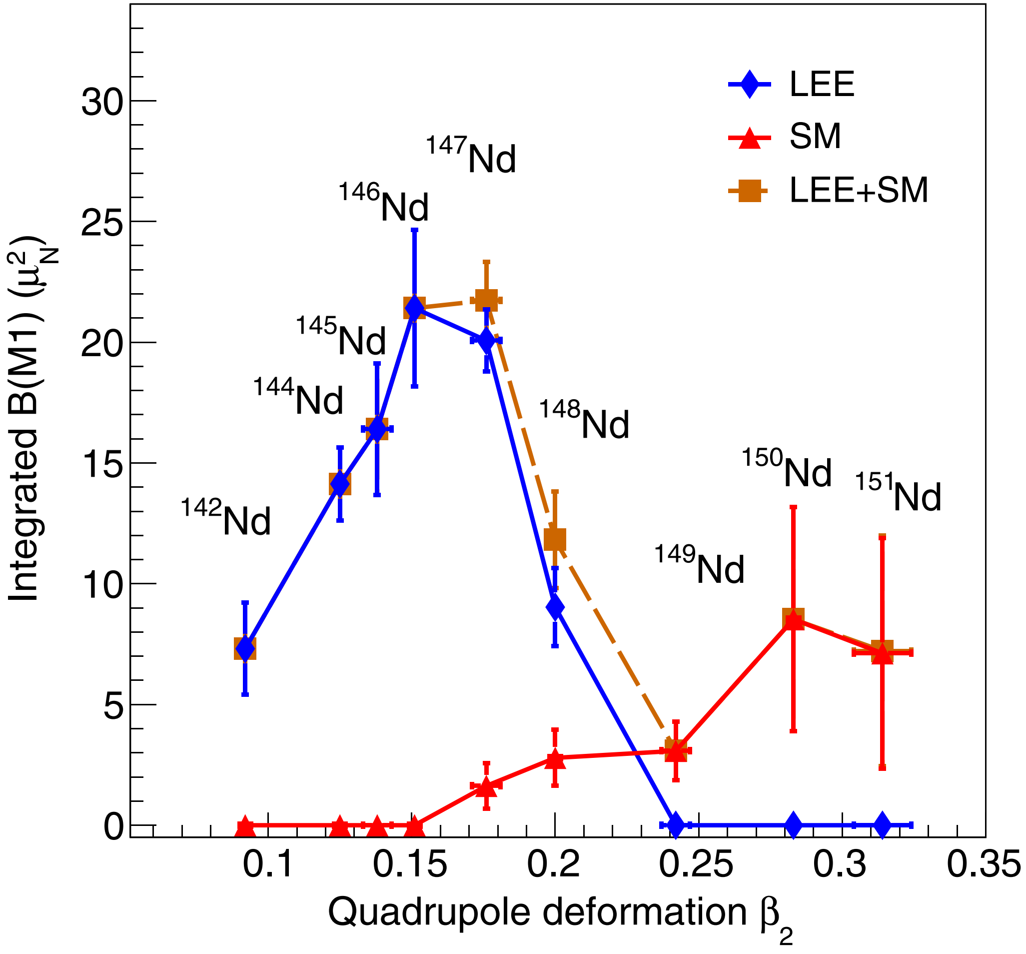


M. Guttormsen *et al.*, Phys. Rev. C **106**, 034314 (2022)

Systematic studies of Nd isotopes



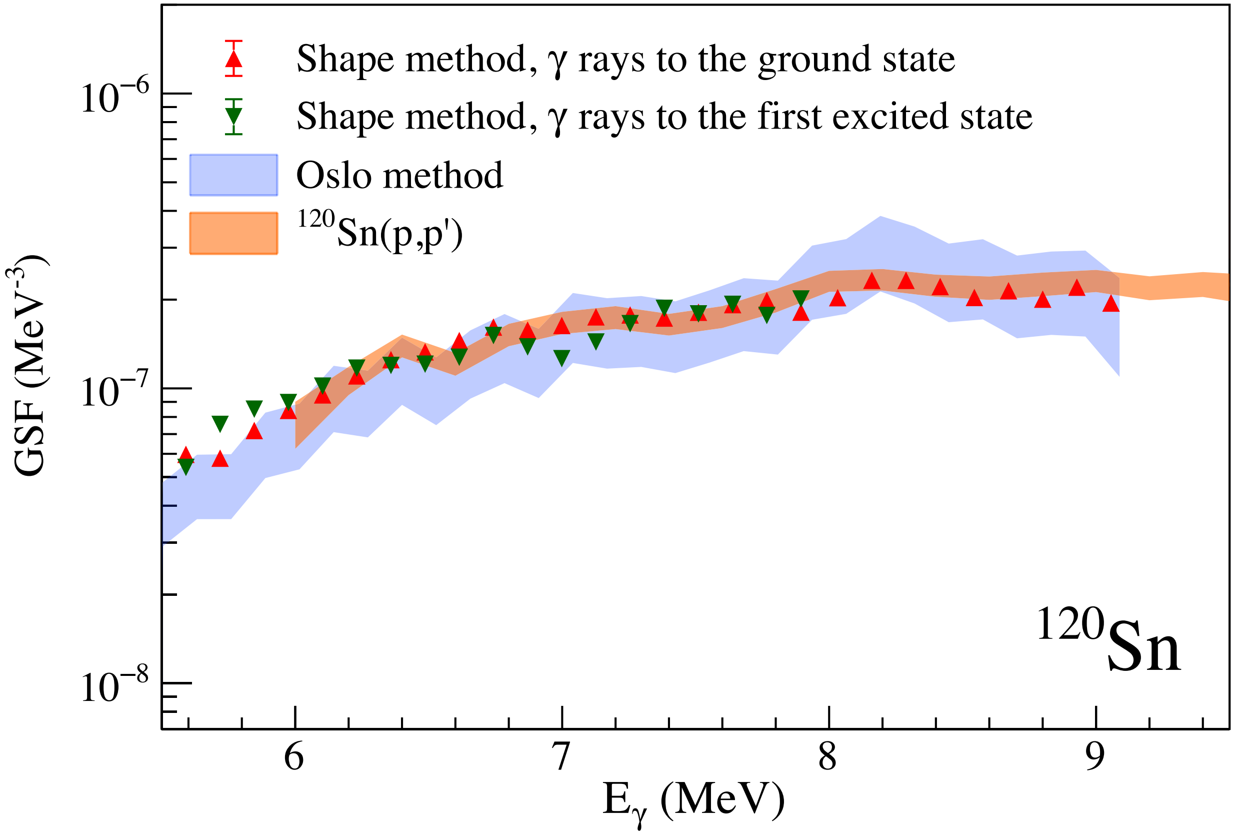
M. Guttormsen *et al.*, Phys. Lett. B **816**, 136206 (2021)



M. Guttormsen *et al.*, Phys. Rev. C **106**, 034314 (2022)

Test of Brink-Axel in Sn Isotopes

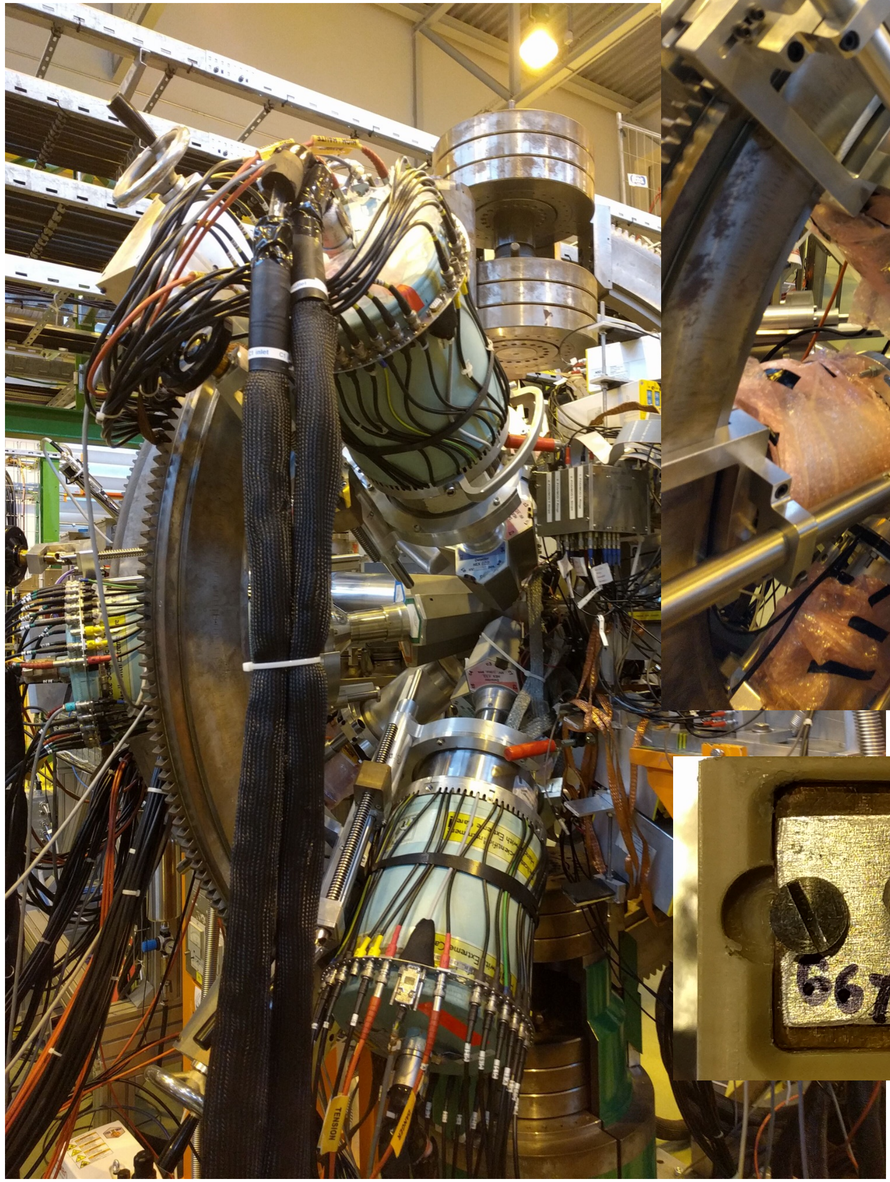
- Collective modes of excitation can be built on excited levels the same way as for the ground state
- Consequences:
  - No dependence of spin/parity of the GSF
  - No dependency on initial and final excitation energy
- GSF extracted with Oslo Method & Shape Method in ^{120}Sn and comparison to (p,p') Coulex data

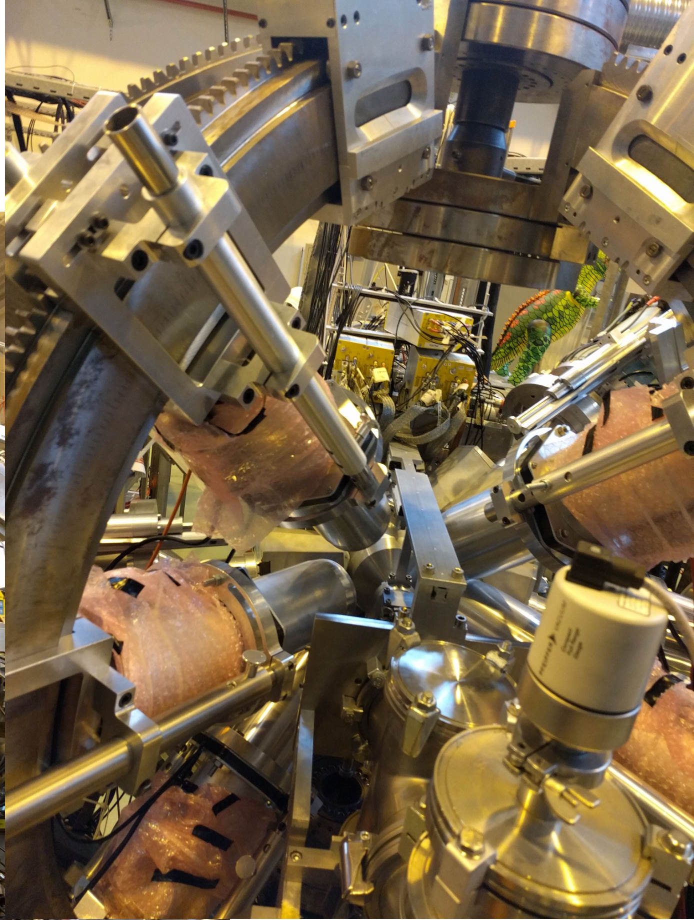


M. Markova *et al.*, Phys. Rev. Lett. **127**, 182501 (2021)

Inverse Kinematics

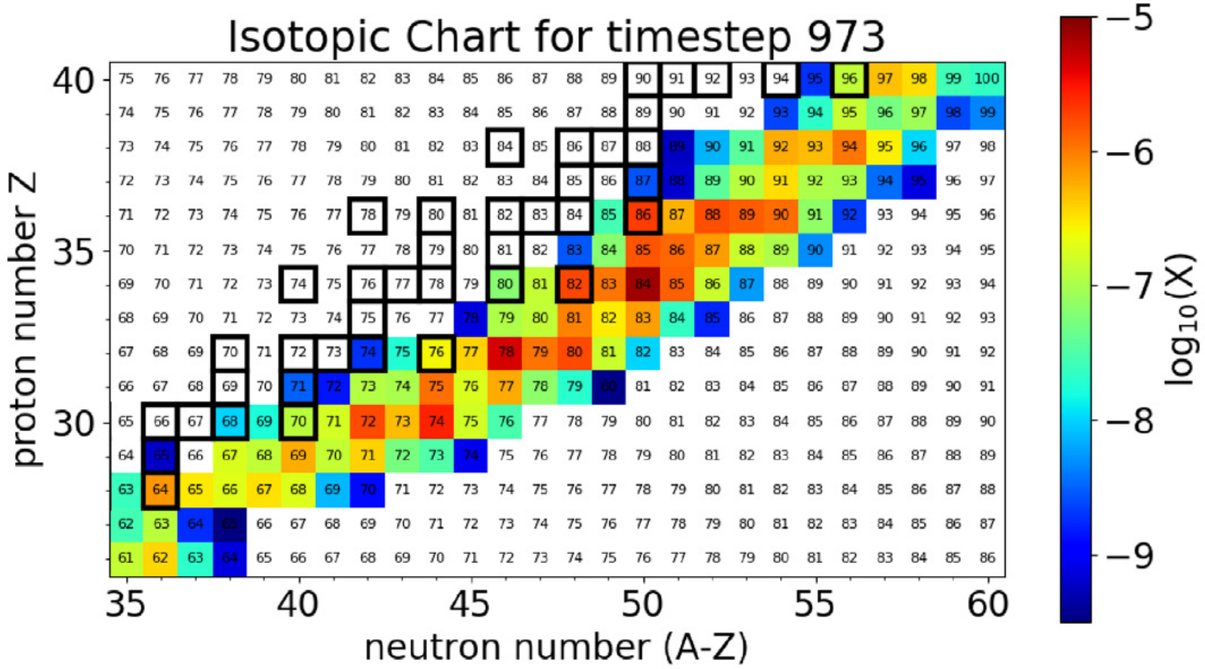
- The Oslo Method with inverse kinematics
- Radioactive beam
- Low beam rate – need high efficiency
- First ever experiment:
  - d(^{66}Ni,p)^{67}Ni
  - Deuterated polyethylene target
- Important for understanding the weak i-process
- CERN ISOLDE



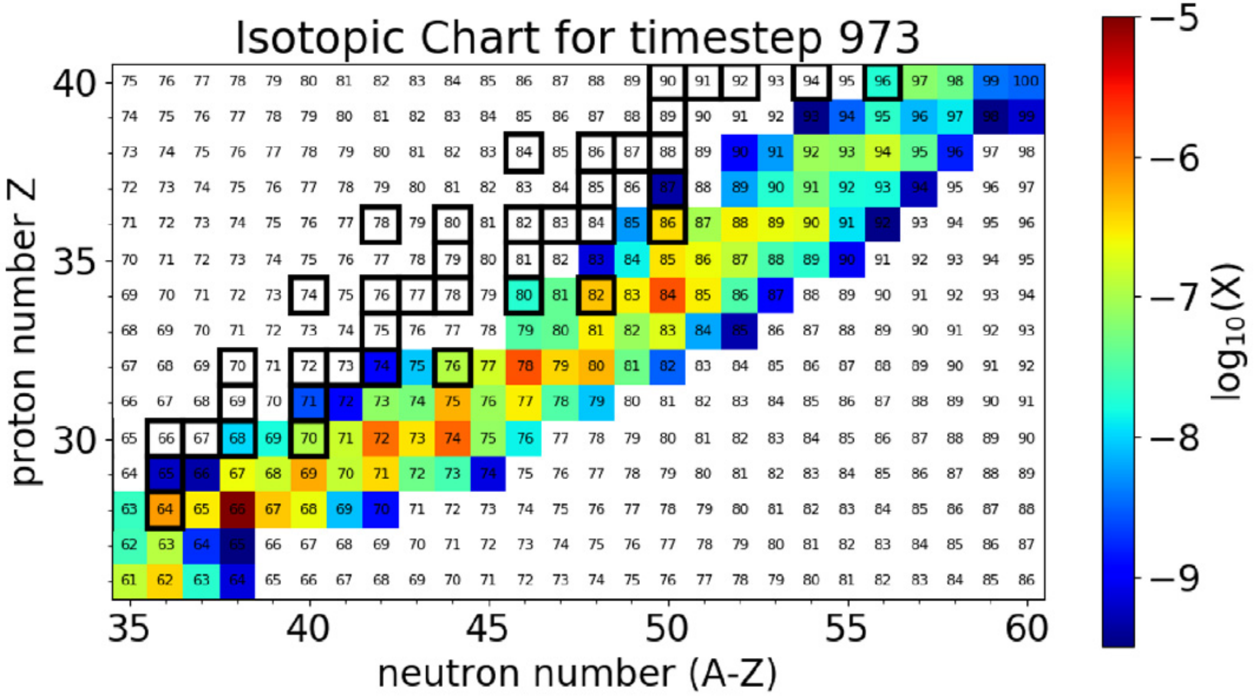


66Ni(n,g) and the i-process

High ^{66}Ni(n, γ) cross section

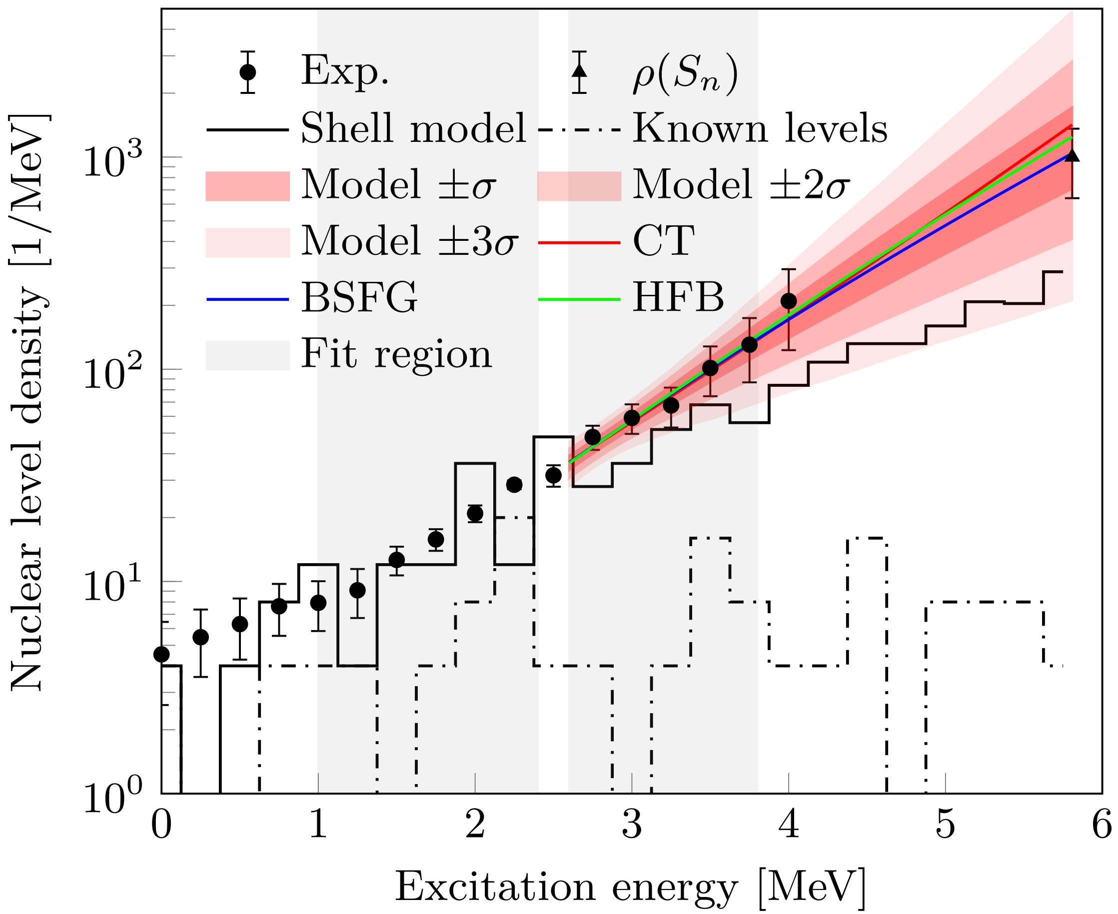


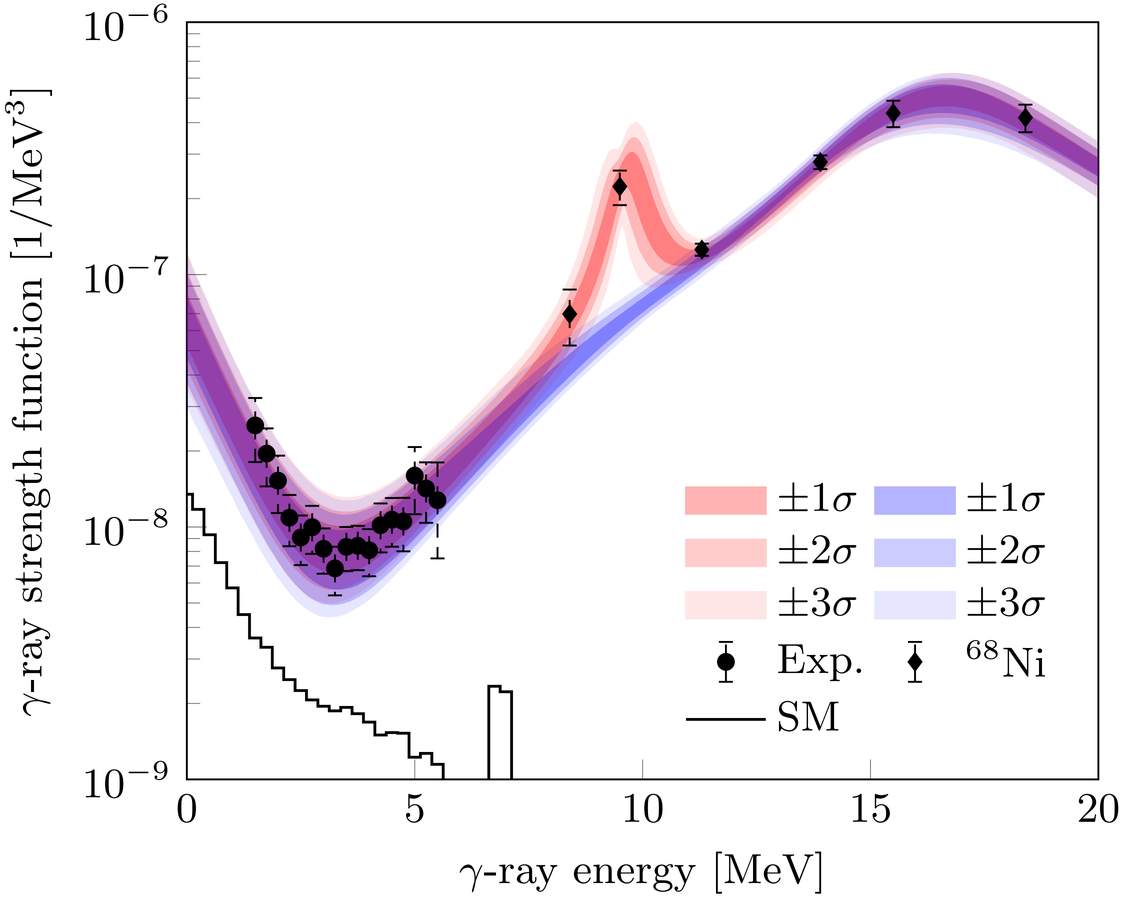
Low ^{66}Ni(n, γ) cross section



J. McKay *et al.*, MNRAS **491**, 5179 (2020)

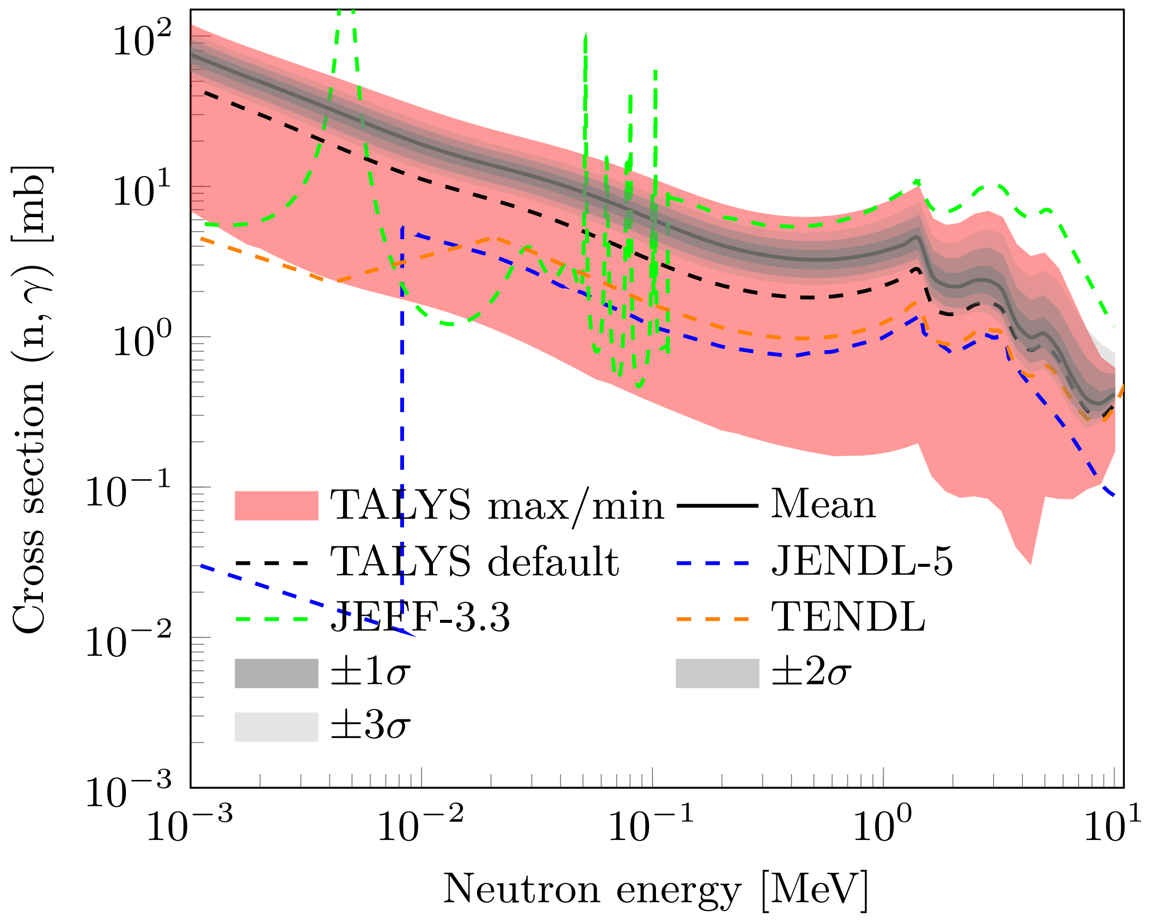
Inverse Kinematics

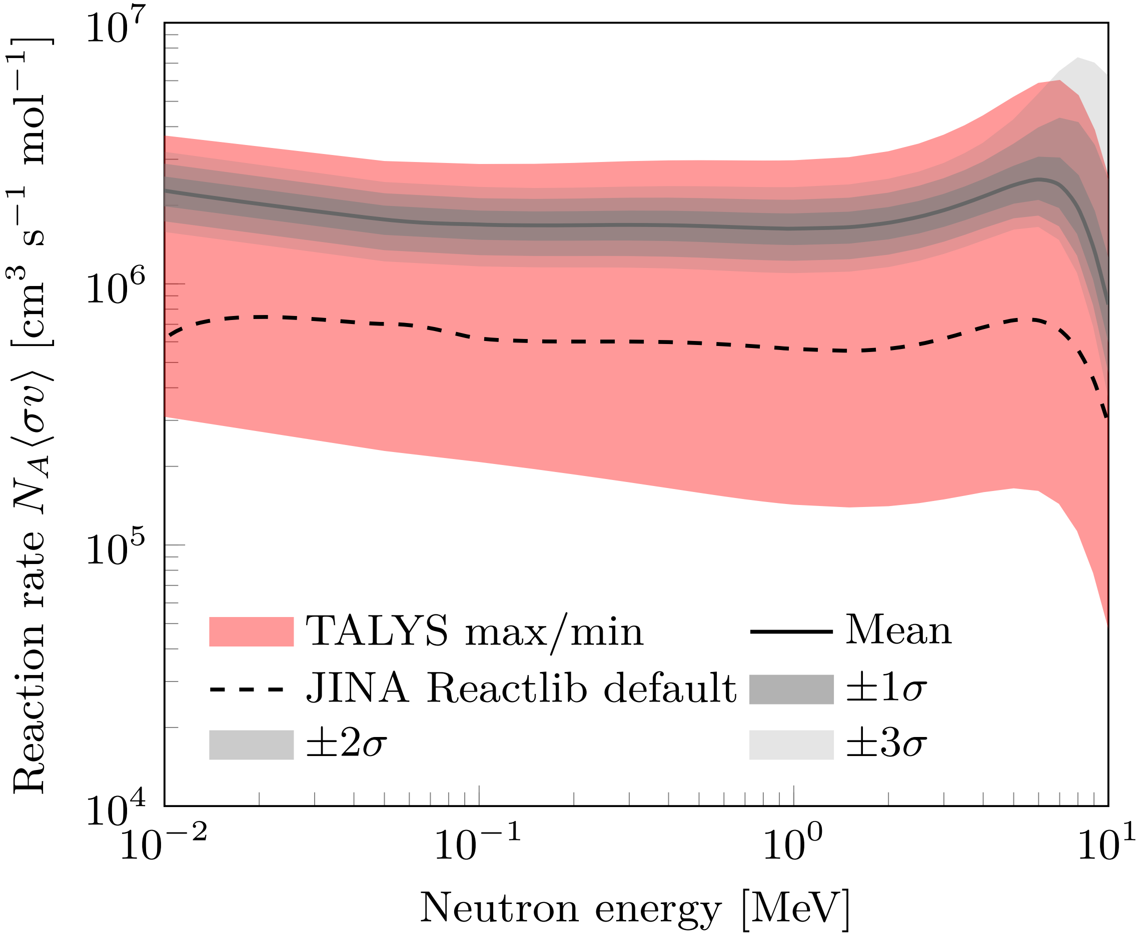




V. W. Ingeberg *et al.*, Phys. Rev. C (in review)

Neutron capture rate: ^{66}Ni(n,γ)



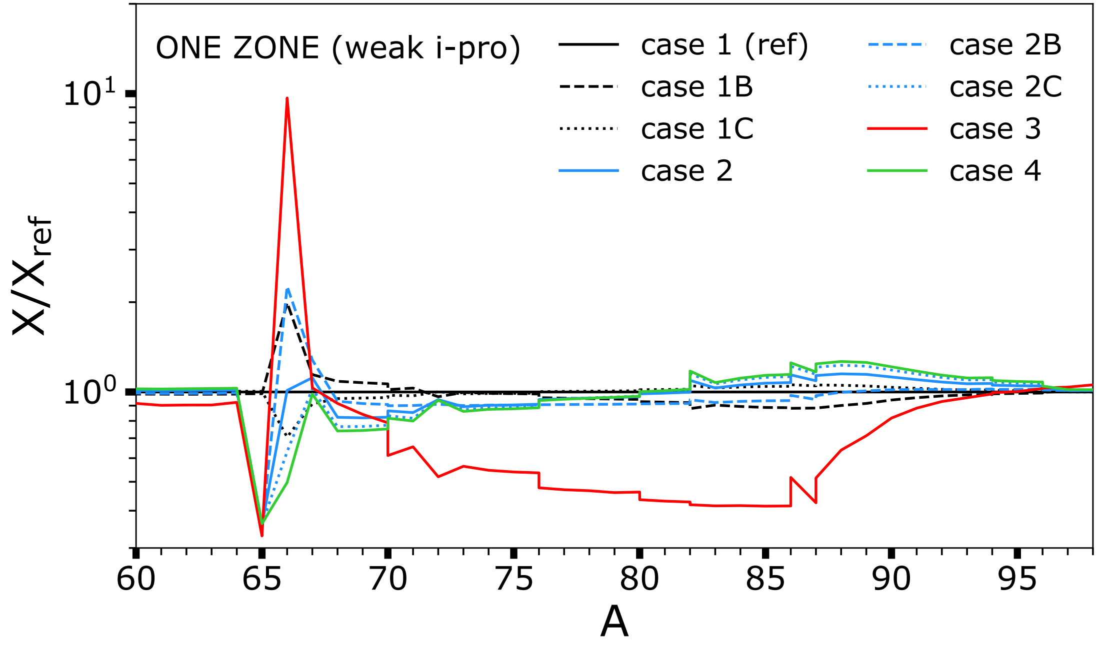


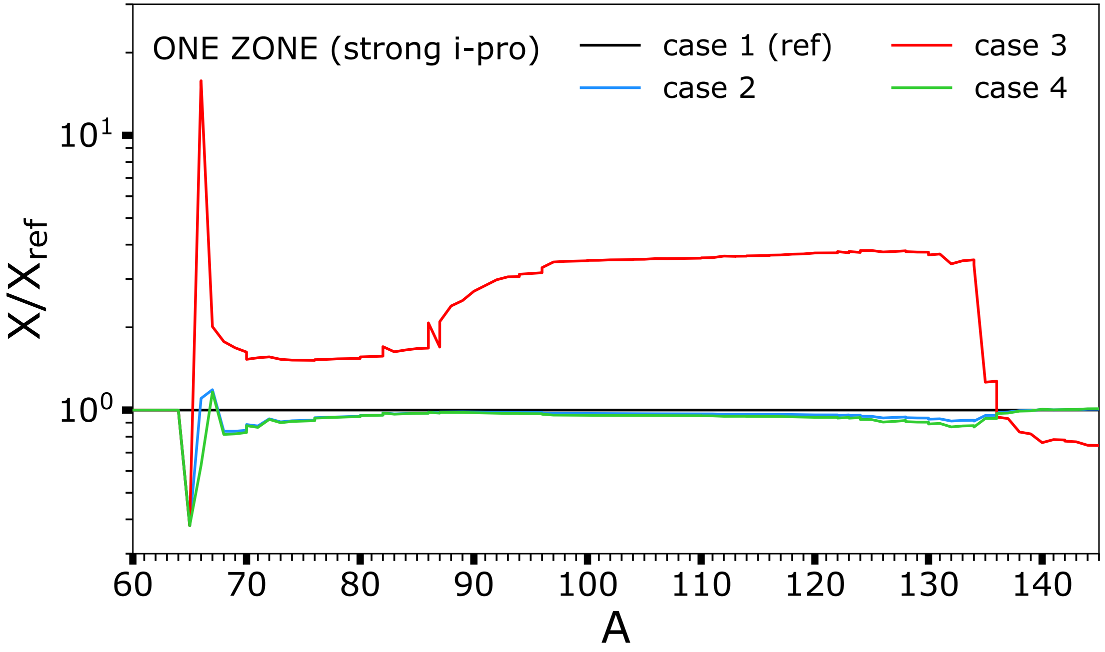
V. W. Ingeberg *et al.*, Phys. Rev. C (in review)

Impact of ^{66}Ni(n, γ)?

- Nucleosynthesis calculations by A. Choplin, S. Goriely and L. Siess
- One-zone model & multi-zone model
- Consider four scenarios:

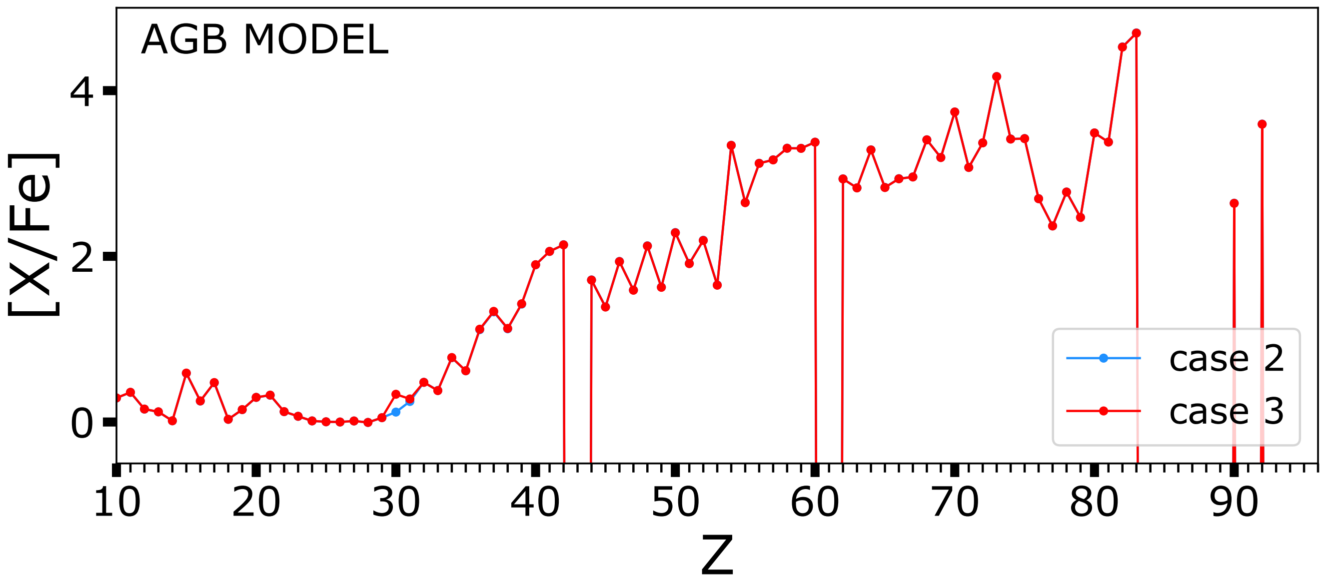
	65Ni(n, γ)	66Ni(n, γ)
Case 1	TALYS min	10.7 mb (MACS, this work)
Case 2	TALYS max	10.7 mb (MACS, this work)
Case 3	TALYS max	TALYS min
Case 4	TALYS max	TALYS max

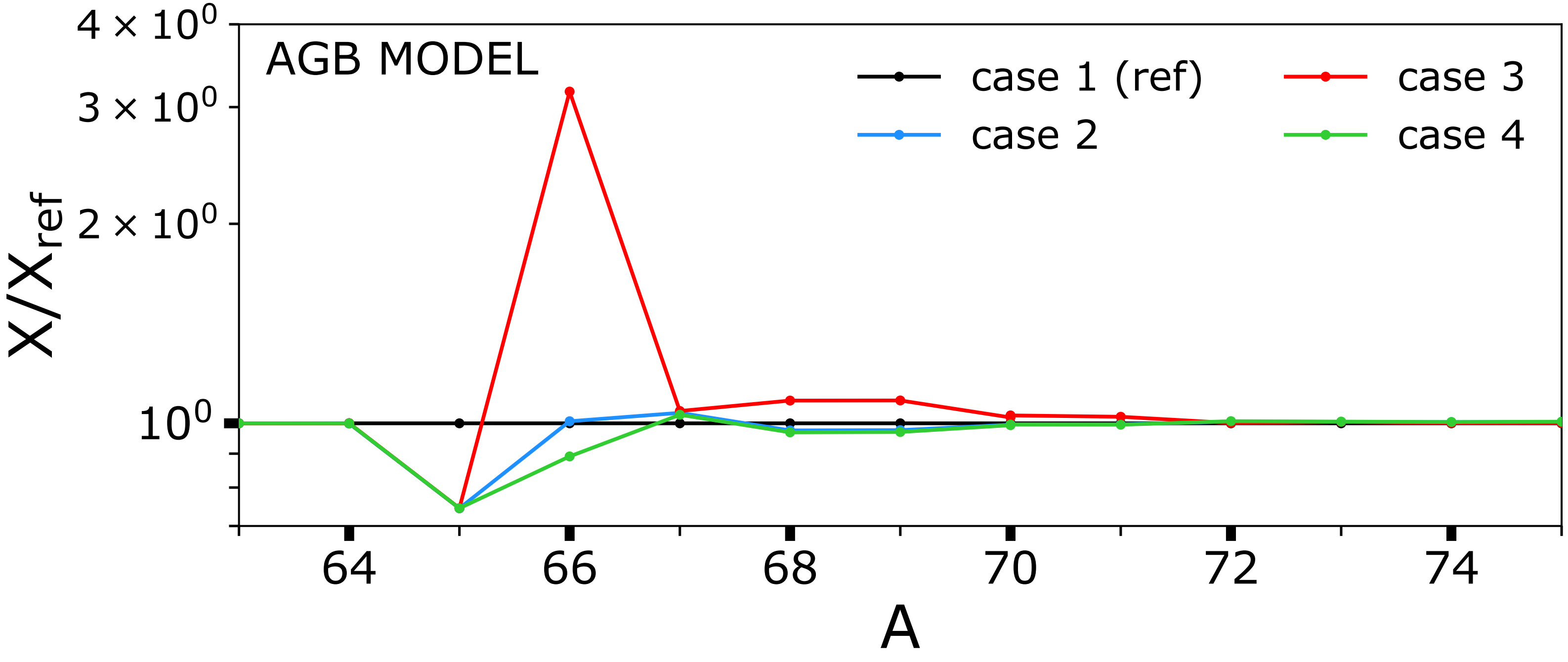




Impact of ^{66}Ni(n, γ)?

	65Ni(n, γ)	66Ni(n, γ)
Case 1	TALYS min	10.7 mb (MACS, this work)
Case 2	TALYS max	10.7 mb (MACS, this work)
Case 3	TALYS max	TALYS min
Case 4	TALYS max	TALYS max

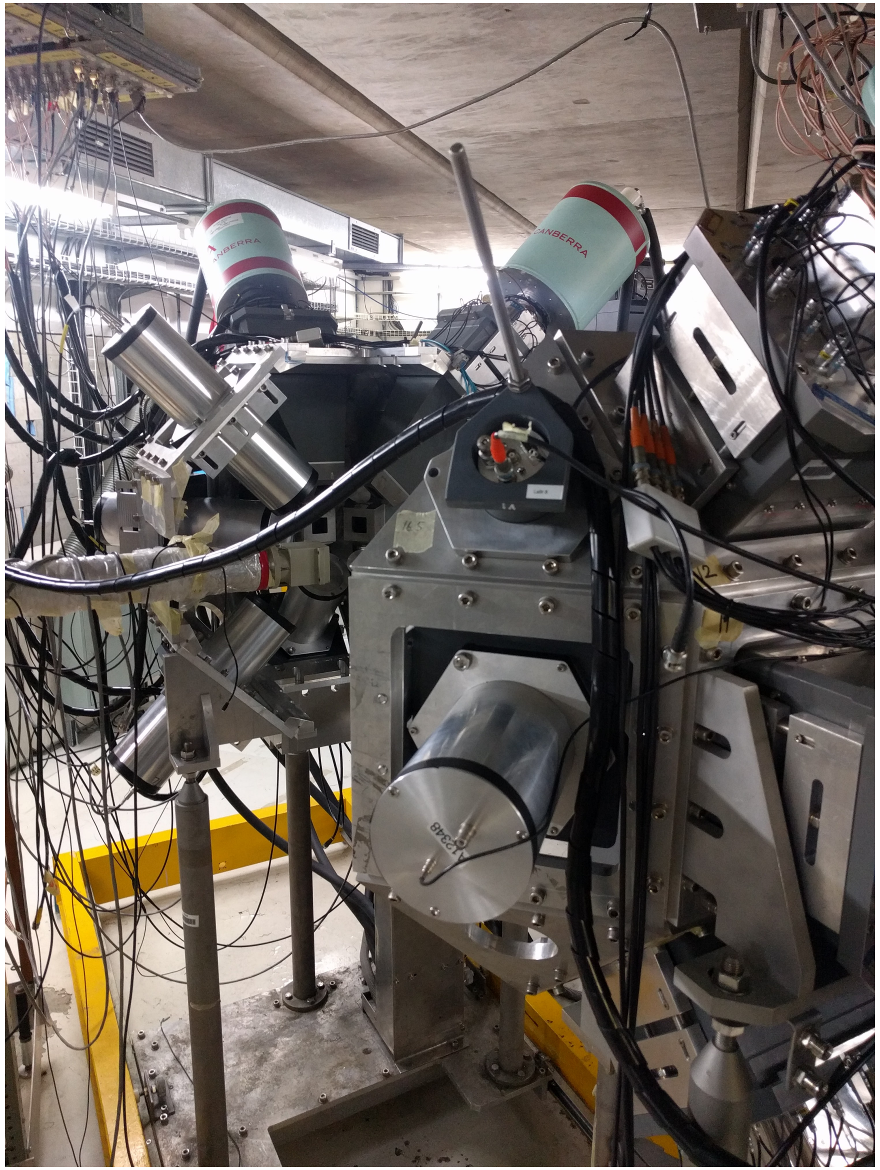




V. W. Ingeberg *et al.*, Phys. Rev. C (in review)

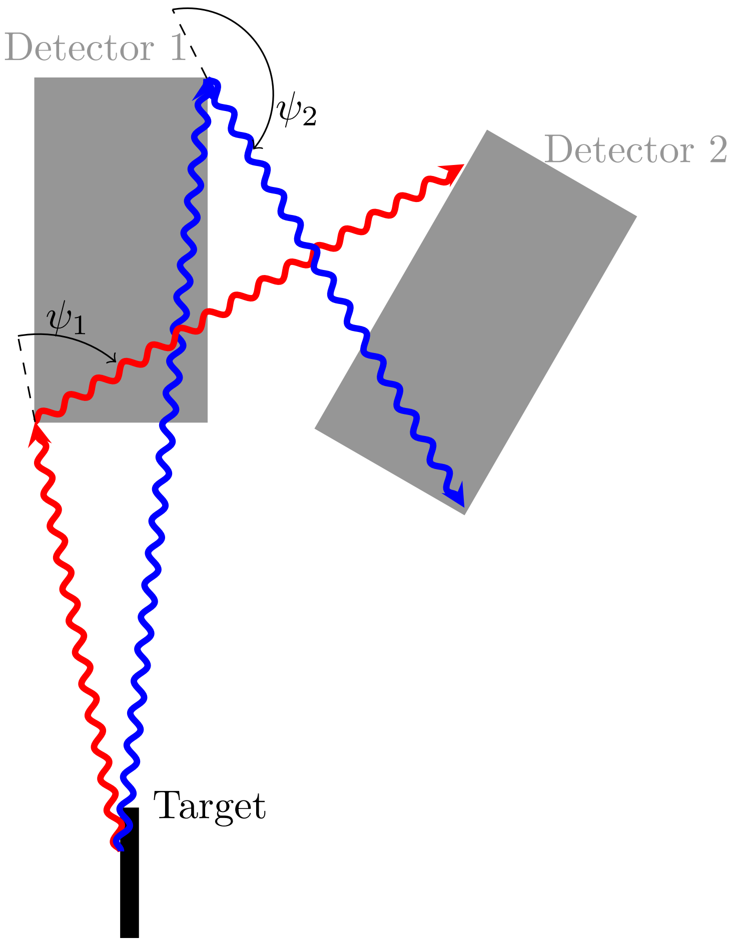
Inverse Kinematics at iThemba LABS

- AFRODITE array
- $d(^{86}Kr, p)^{87}Kr$ with 2 $LaBr_3$:Ce detectors
- $d(^{84}Kr, p)^{85}Kr$
- $d(^{132}Xe, p)^{133}Xe$
  - 6 $LaBr_3$:Ce
- 8 CLOVER detectors
- Particle DE-E detectors



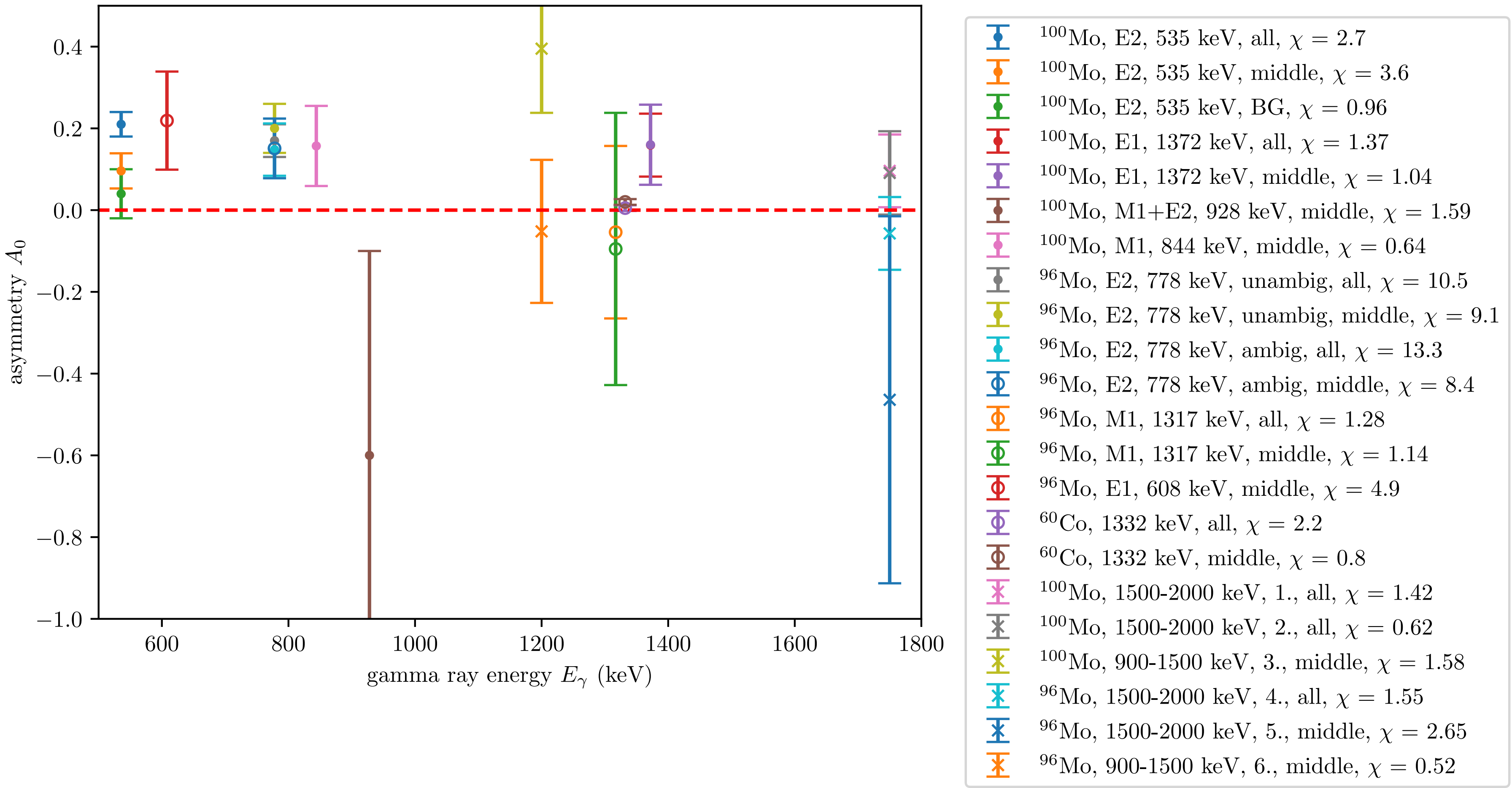
OSCAR as a Polariometer

- What is the nature of the LEE?
  - M1 or E1
- Can use Compton scattering to measure polarization?
- $W(\psi) = b(1 - A_0 \cos(2\psi))$
  - $A_0 > 0$: Electric
  - $A_0 < 0$: Magnetic
- Explored in MSc of Johan Emil Larsson



Johan Emil L. Larsen, *"Statistical properties of Mo-96 and Mo-100"*, Master's Thesis, University of Oslo (2022)

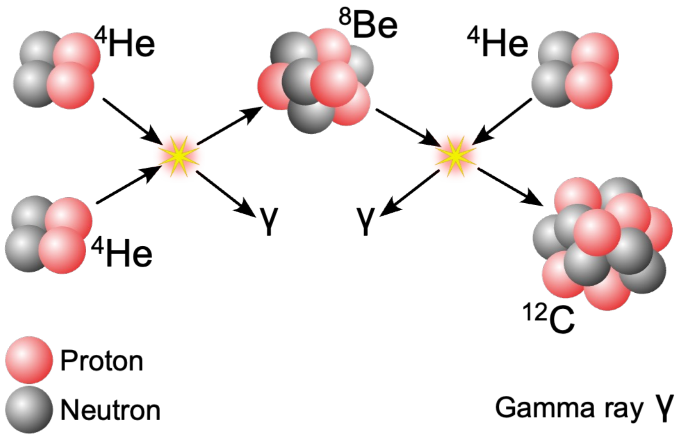
OSCAR as a Polariometer

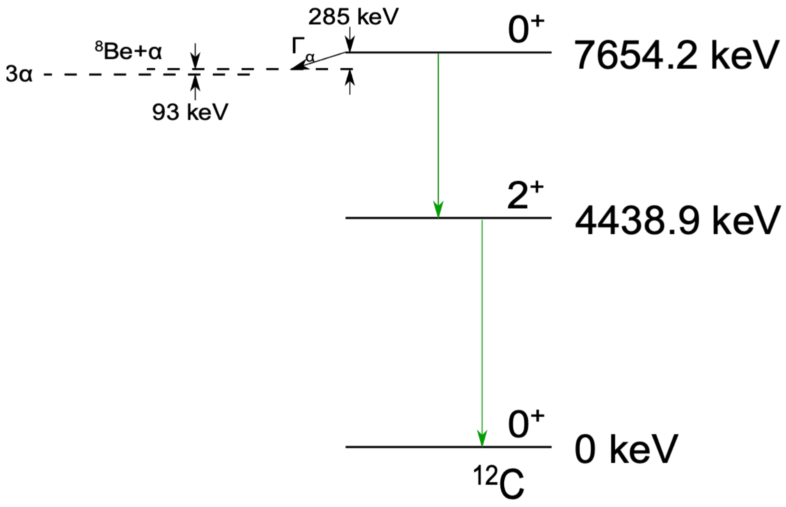


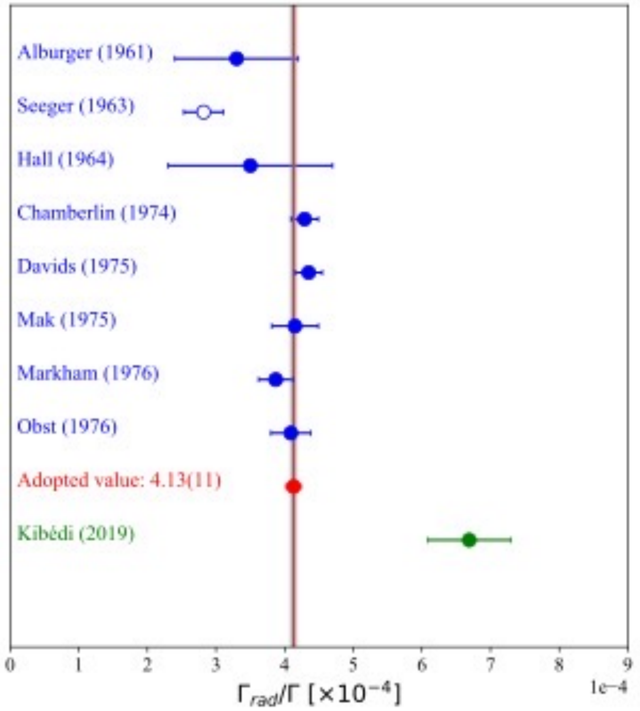
Johan Emil L. Larsen, *“Statistical properties of Mo-96 and Mo-100”*, Master’s Thesis, University of Oslo (2022)

The Hoyle State

- Radiative width of the Hoyle State in ^{12}C
- Important for the reaction rate of the tripple-α
- Measure particle-γ-γ coincidences, ^{12}C(p,p'γγ)
- Experiment performed in 2019 and 2020



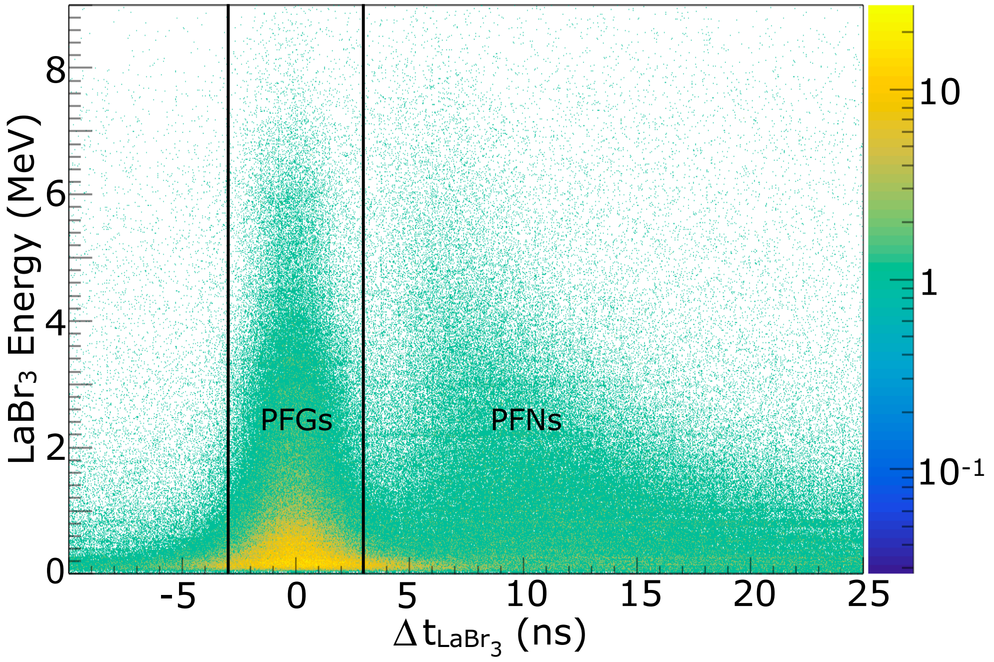


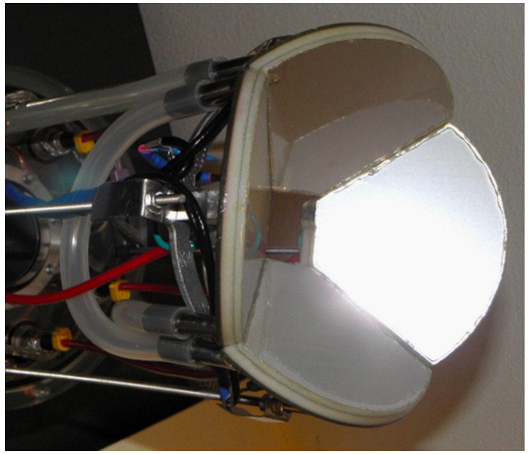


W. Paulsen, "*Reassessment of the radiative width of the Hoyle state from gamma ray spectroscopy using OSCAR*", Master's thesis (2020)

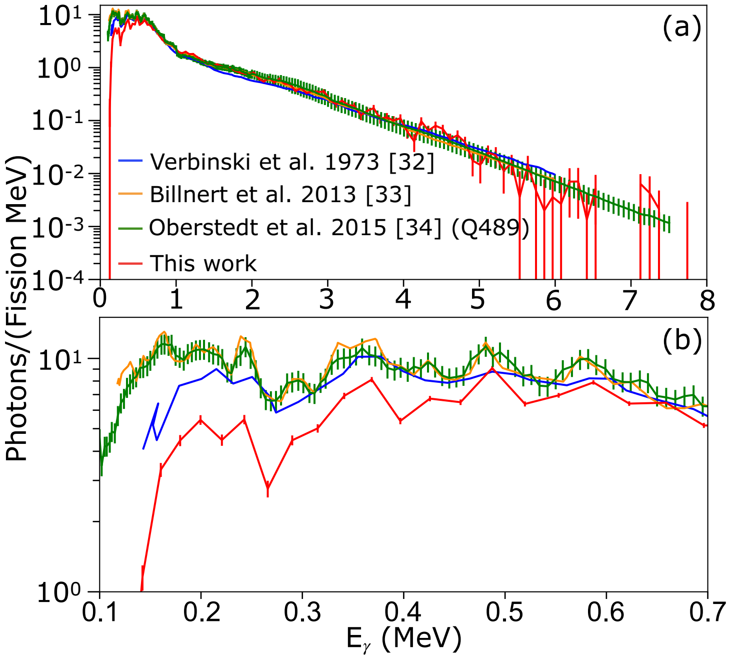
Physics cases – Fission studies

- Currently building a dedicated fission setup
- Newly developed scintillator-based fission detectors
- Expected to be commissioned this fall
- Measure excitation dependent prompt fission gamma-rays
- TOF to distinguish fission neutrons





T.G. Tornyi *et al.*, Nucl. Inst. and Meth. in Phys. Res. A **738**, 6-12 (2014)



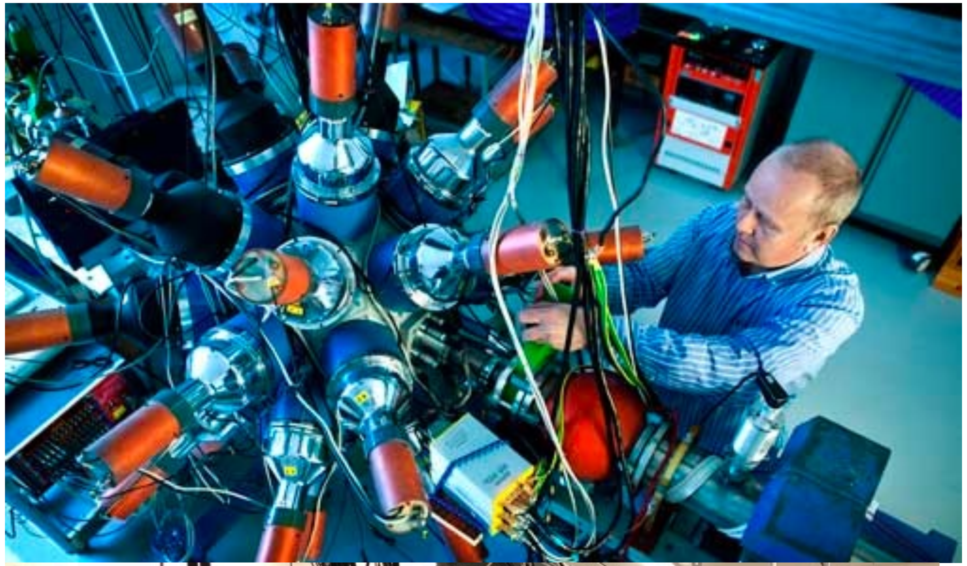
D. Gjestvang *et al.*, Phys. Rev. C **103**, 034609 (2021)

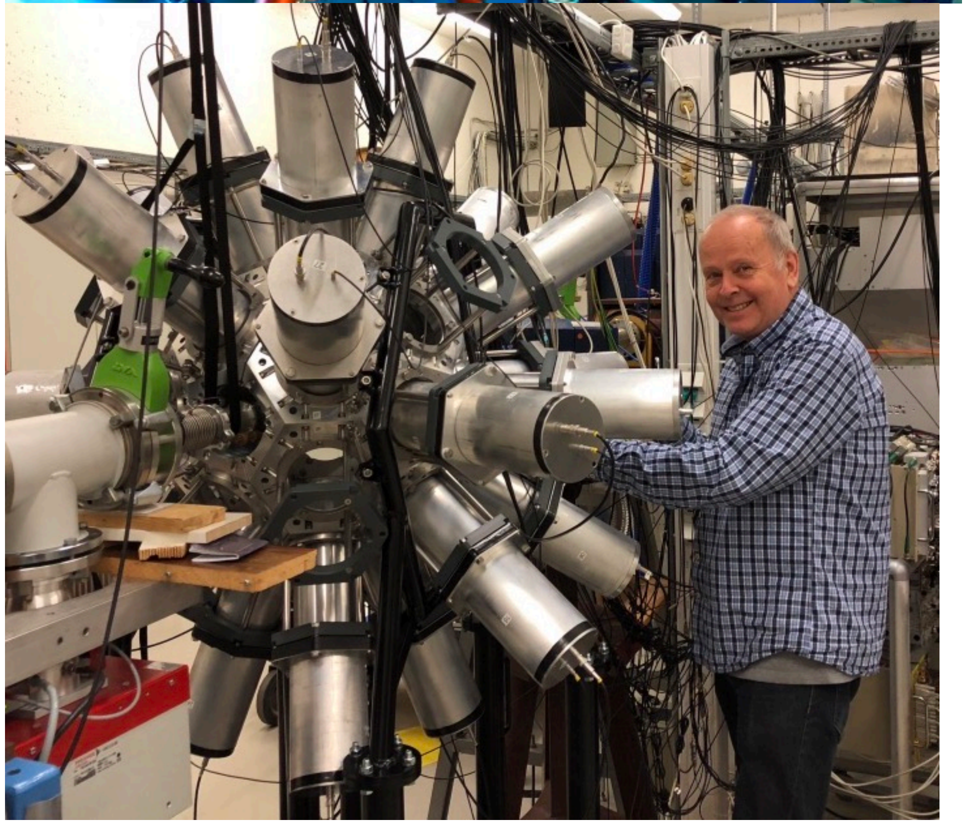
Future Prospects?

Photo credits: ISOLDE Collaboration

Summary

- Large $LaBr_3$:Ce array
- Excellent efficiency
- Excellent energy & time resolution
- Enables new studies
  - Systematic measurements with the Oslo Method
  - Reactions with low cross section such as (a,p), (a,d), etc.
- Great tool for low yield/rare events





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