Pacific Northwest NATIONAL LABORATORY
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The University of North Carolina at Chapel Hill
Lawrence Livermore National Laboratory

Systematic Study of Neutron-Capture Reactions on Peak Fission Products

Stephanie Lyons, PNNL

Anthony Ramirez, Anton Tonchev, LLNL

Andrea Richard, Alexander Voinov, Ohio U

Akaa Daniel Ayangeakaa, UNC

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

This work was supported by the Office of Defense Nuclear Nonproliferation Research and Development within the U.S. Department of Energy's National Nuclear Security Administration.

Meet the Team

Stephanie Lyons
PNNL- Lead PI

Andrea Richard
Ohio U PI

Anthony Ramirez
LLNL PI

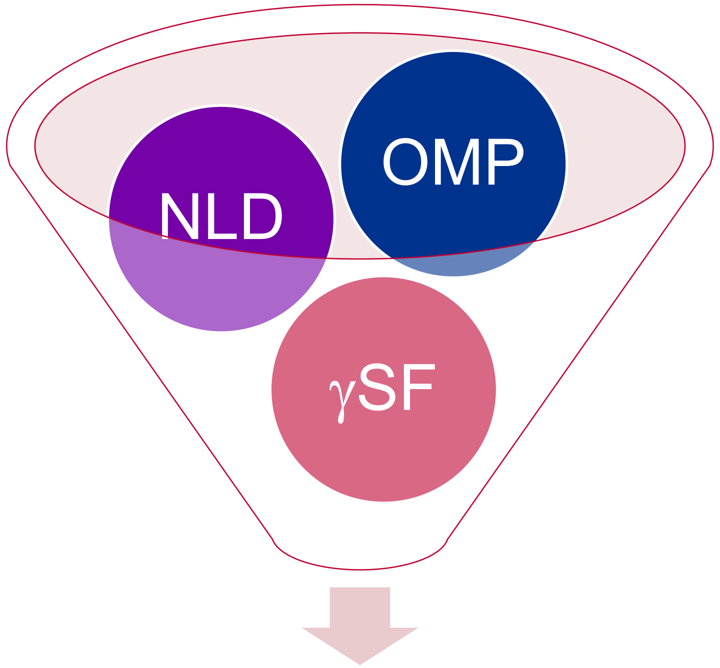
Akaa D. Ayangeakaa
UNC/TUNL PI

Alexander Voinov
Ohio U

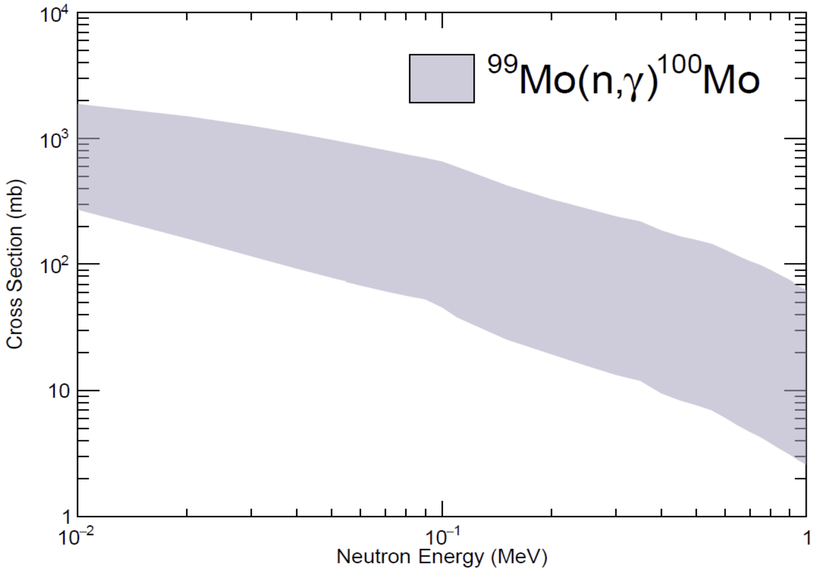
Anton Tonchev
LLNL

Amadie Wijenarayana (Ohio U)
Logan Schaedig (UNC)

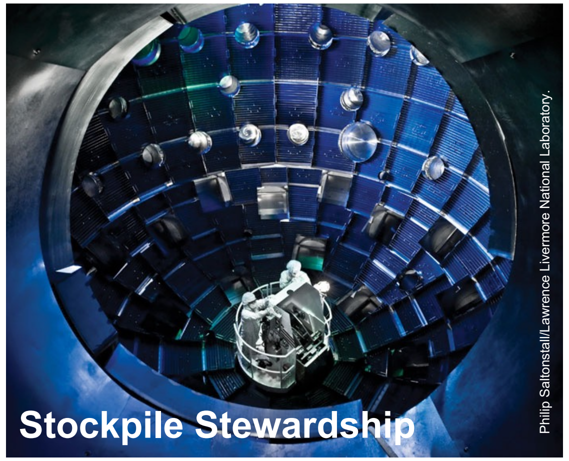
Statistical properties are necessary to calculate reaction cross-sections, especially far from stability

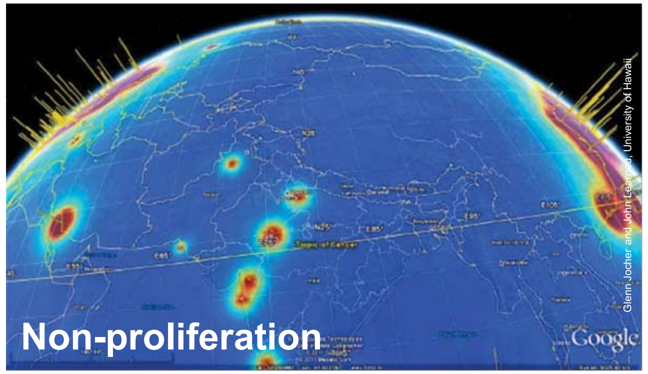


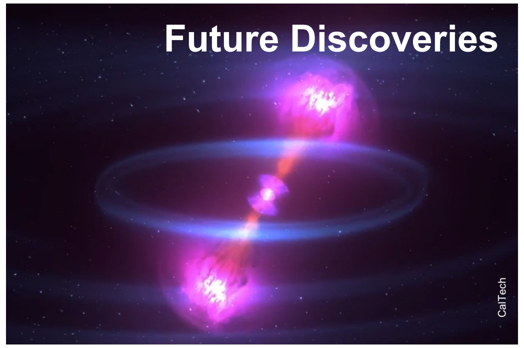
Hauser-Feshbach
calculated cross sections



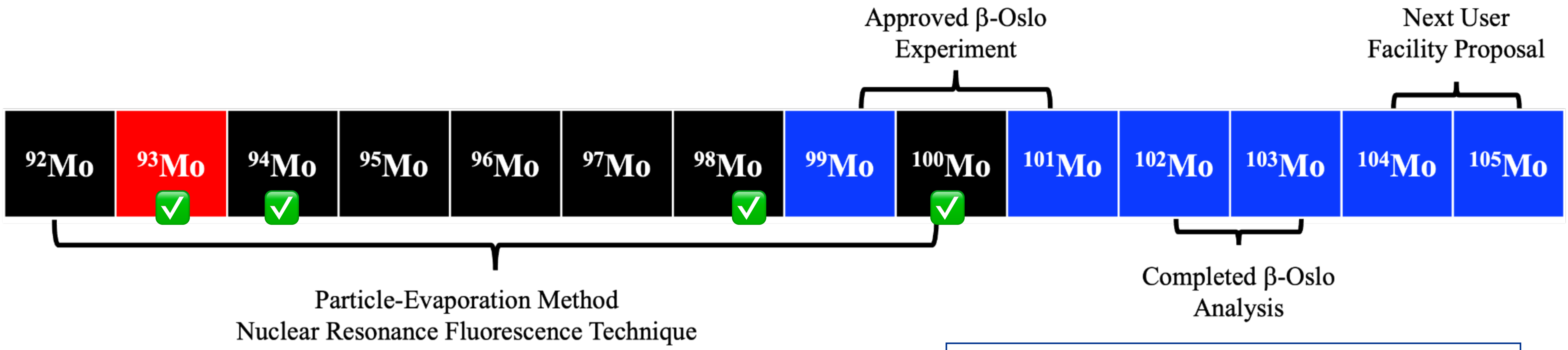
Nuclear level densities (NLD) and gamma-ray strength functions (gSF) are critical inputs for calculations of neutron-induced cross sections across mission spaces







Improving the Understanding of Statistical Nuclear Properties through a Systematic Study of Mo Isotopes



Ohio U.
NLD at EAL via Part. Evap.

LLNL/UNC
gSF at HIGS via NRF

PNNL/Ohio U
^{99,101}Mo at nuCARIBU
^{104,105}Mo at FRIB/nuCARIBU
via Beta-Oslo Method

Compile results to generate systematic study of statistical property evolution and resolve uncertainties from previous approaches. Provide rich dataset for theory development.

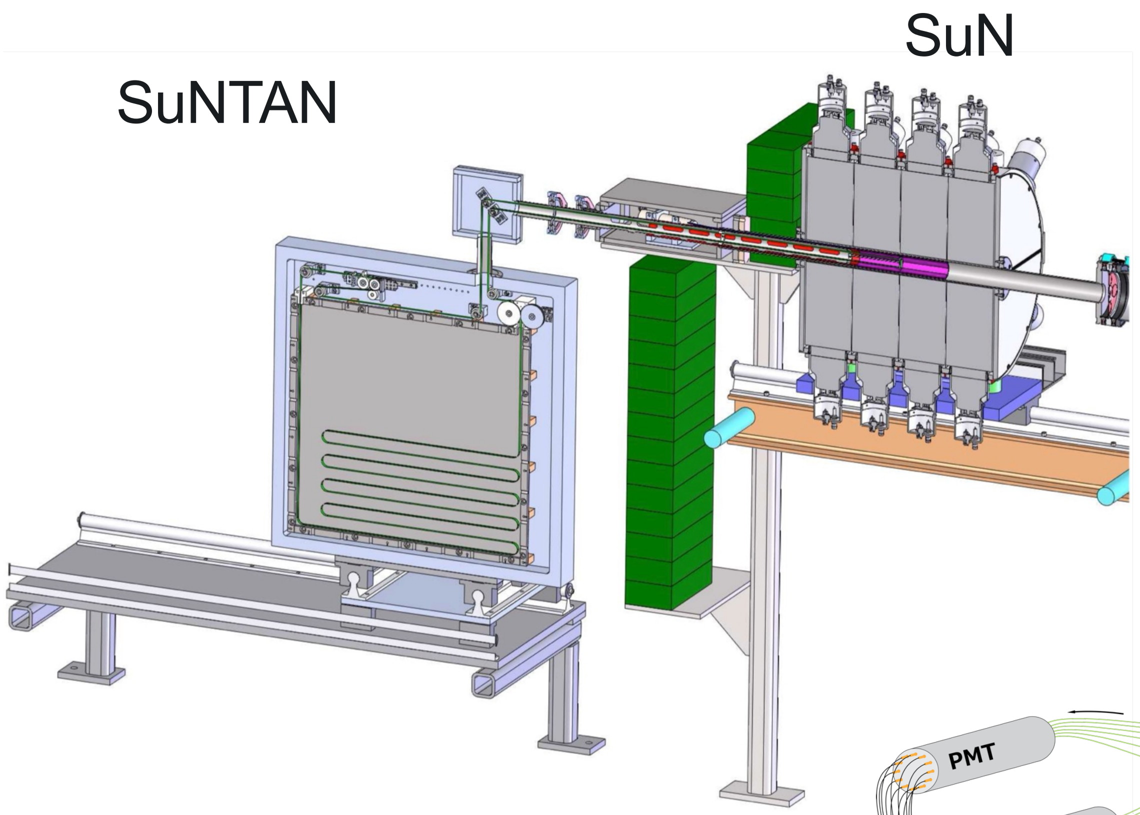
Radioactive Ion Beams: ANL Experiment Updates

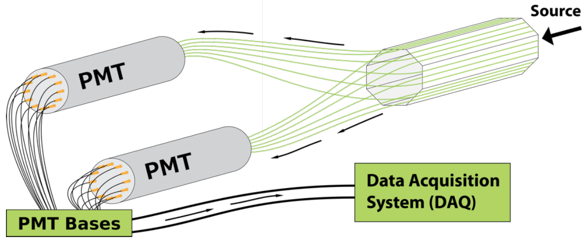
- nuCARIBU experiments are planned for this summer
- Summing NaI (SuN) is being moved back to ANL this April

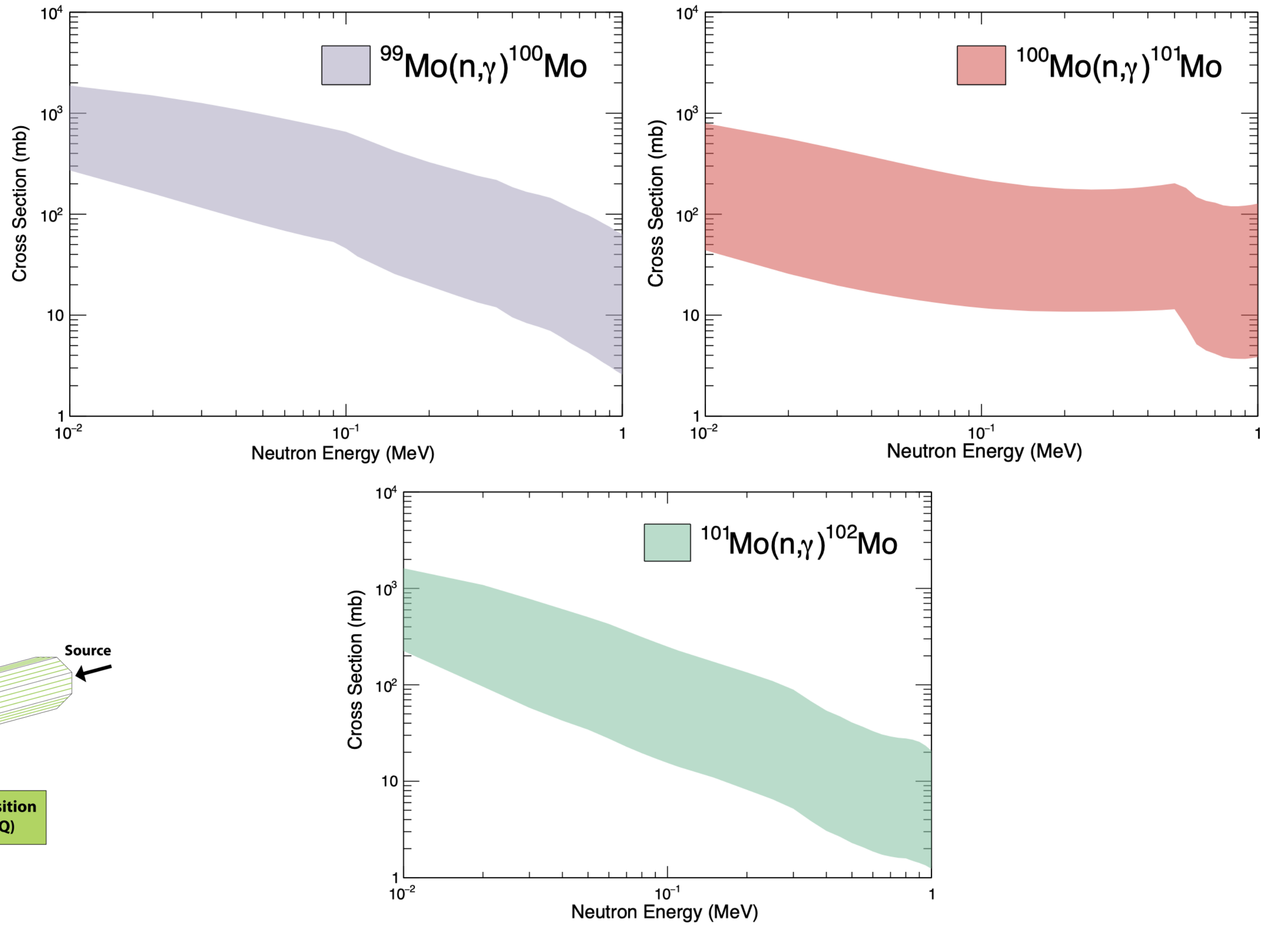
Approved experiment for this summer:

β-decay of neutron-rich $^{100\text{-}102}$Nb

- β-Oslo Method: NLDs, gSFs, and (n,γ) rates
- Total Absorption Spectroscopy: β-decay strength







FRIB NSCL Argonne NATIONAL LABORATORY

Stable Beam Measurements

Ohio U. (EAL): Particle Evaporation Experiments for NLD

- First experiments performed FY25
- Next experiment: FY26

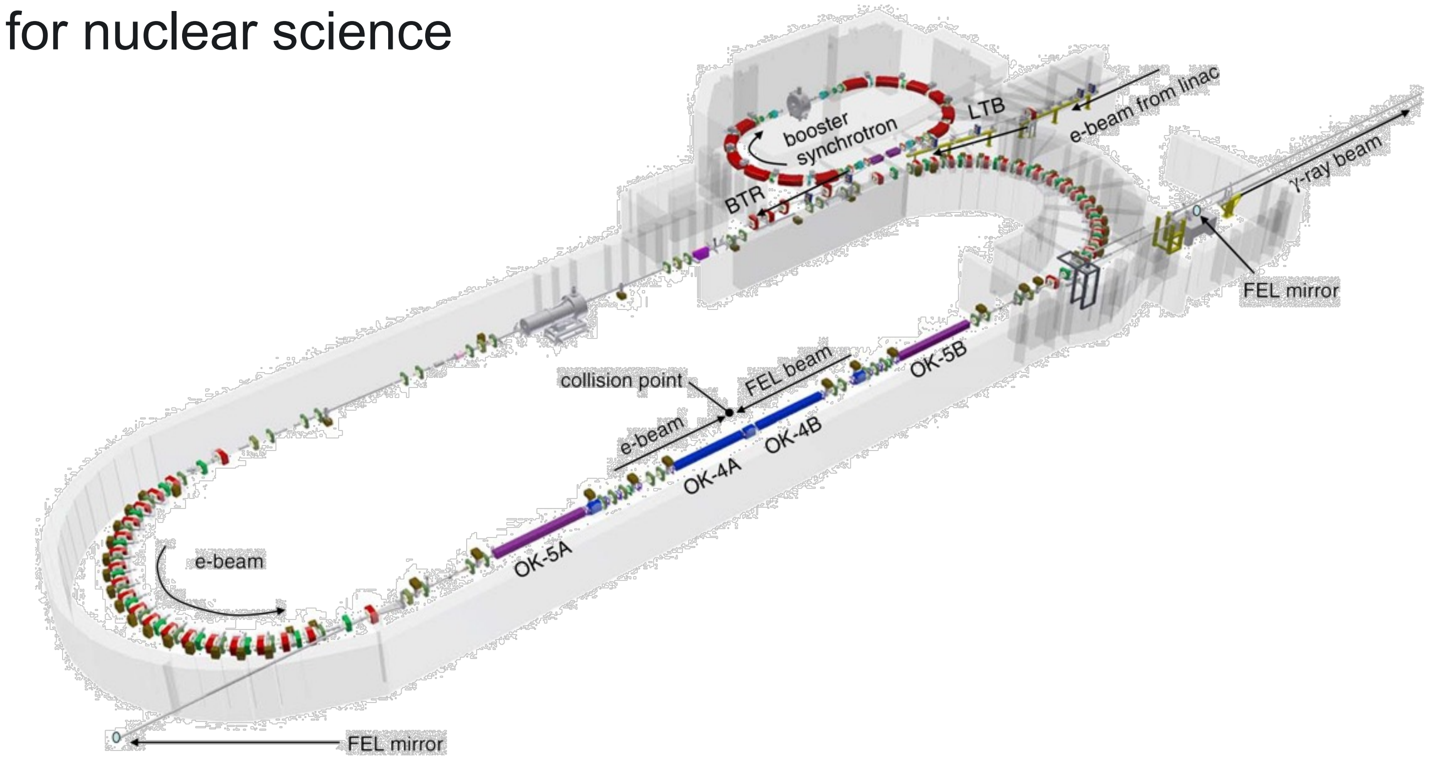
UNC/TUNL (HIγS): NRF Technique for γSF

- First experiments performed in FY25: ^{98,100}Mo
- Next experiments → extend to ^{92}Mo

Association for **R**esearch at **U**niversity **N**uclear **A**ccelerators

The HIγS Facility

The High Intensity Gamma-ray Source is a **Compton-backscattering** γ-ray source dedicated for nuclear science research.



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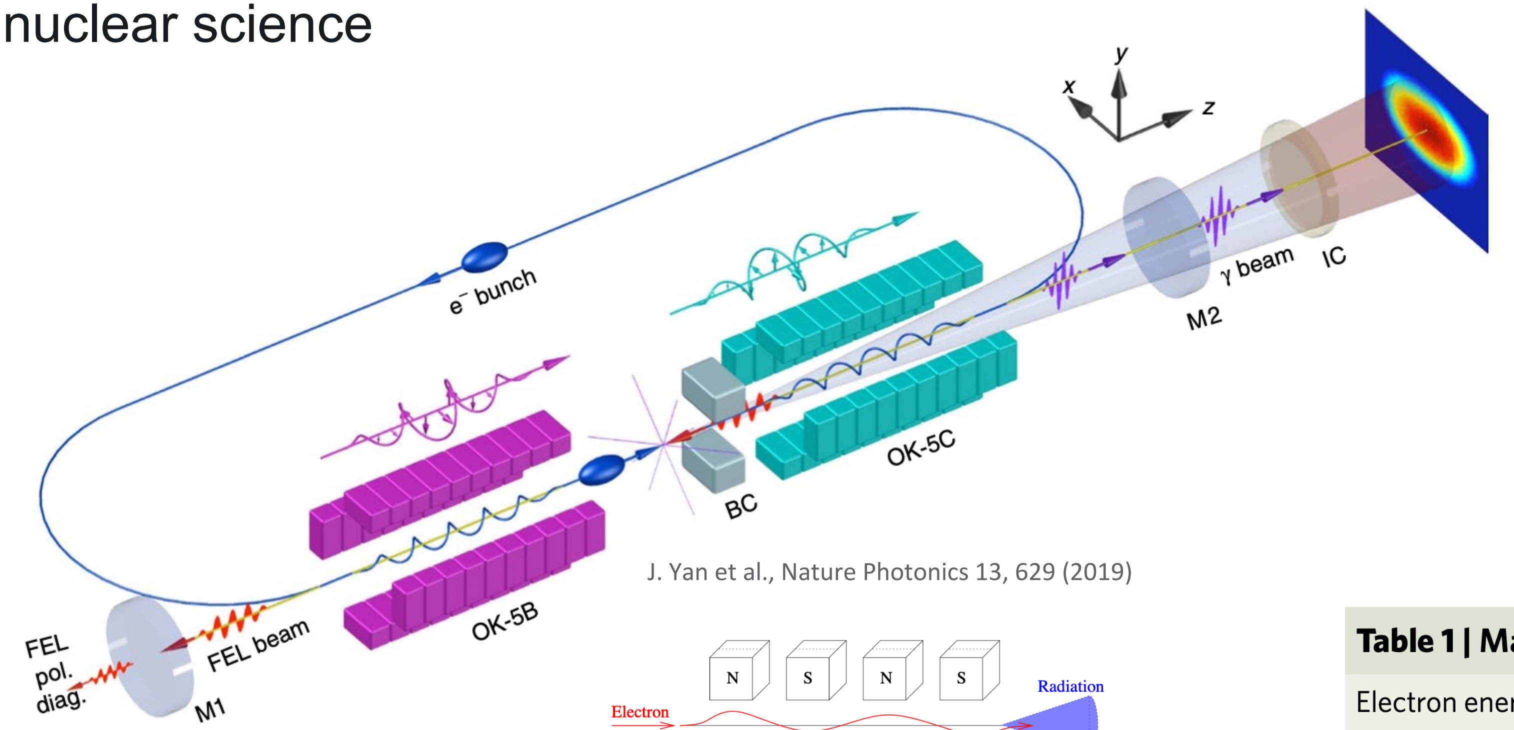
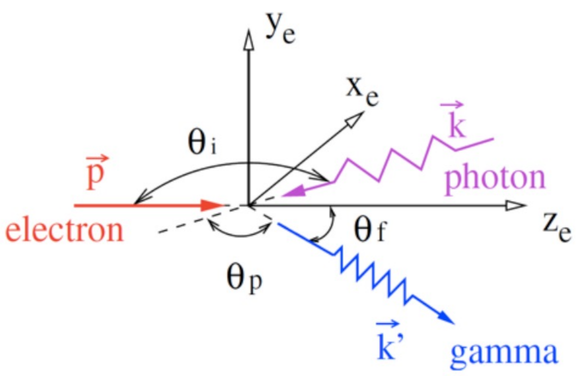
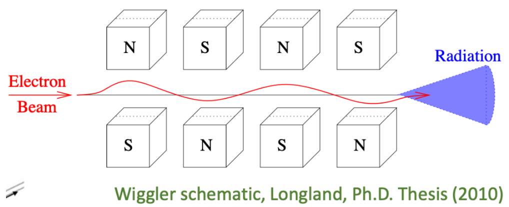


J. Yan et al., Nature Photonics 13, 629 (2019)





Wiggler schematic, Longland, Ph.D. Thesis (2010)

Table 1 | Main operation parameters of the Duke FEL and HIGS

Electron energy (GeV)	0.24–1.2
Electron beam current (two-bunch) (mA)	50–120
FEL wavelength (nm)	190–1,060
Gamma-ray energy (MeV)	1–100
Total gamma flux in 4π solid angle ($\gamma\,s^{-1}$)	1×10^{8}–3×10^{10}
FEL and gamma-ray beam polarization	Flexible linear; left-, right-circular
Gamma pulse repetition rate (MHz)	5.58

See poster by L Schaedig

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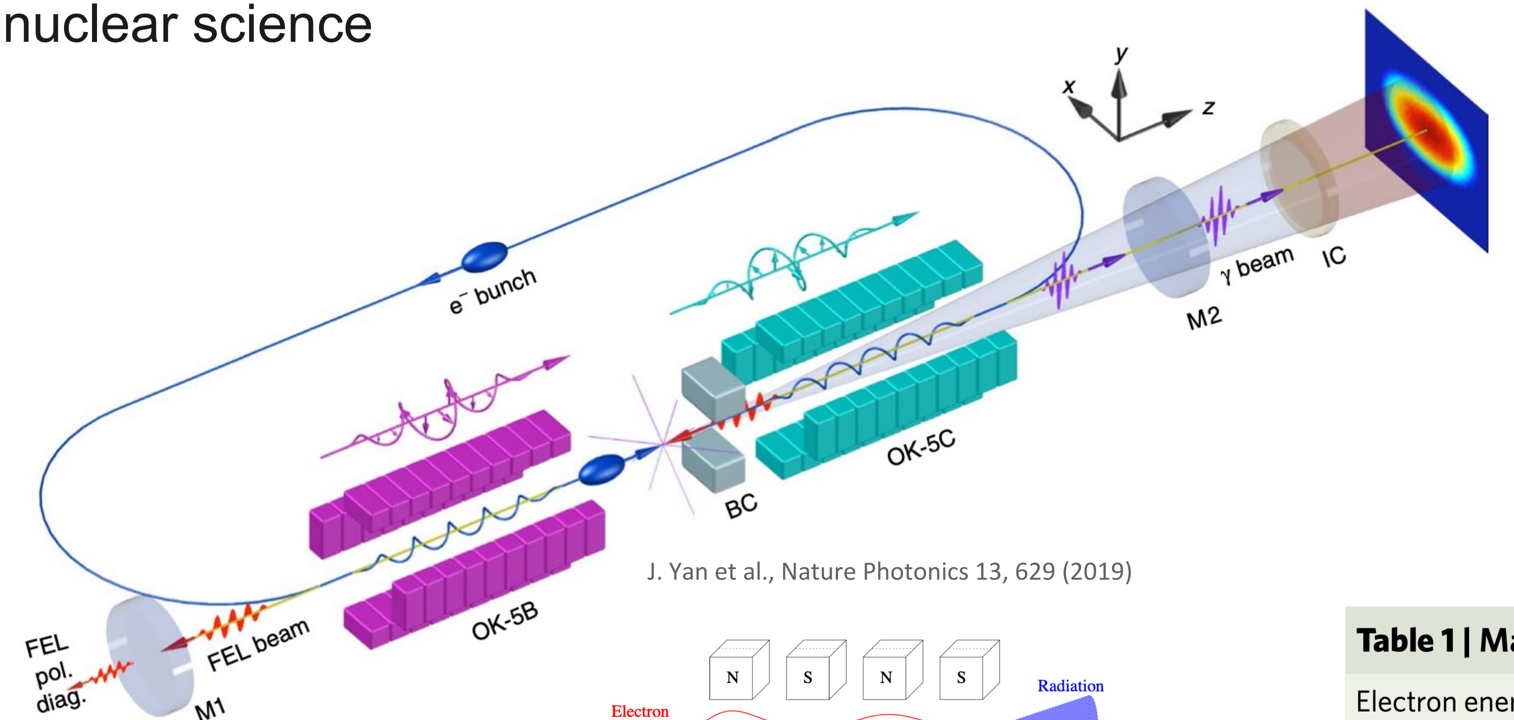

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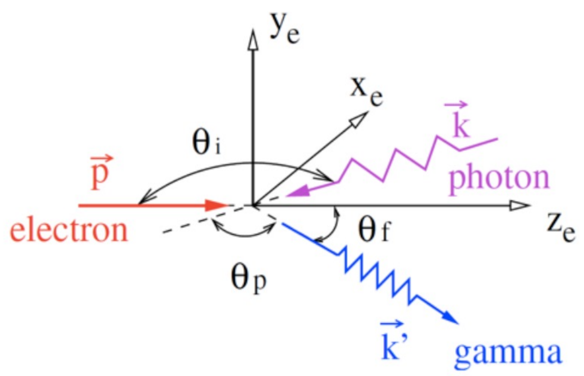

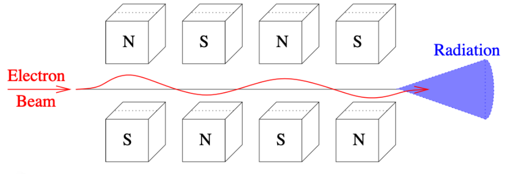

Wiggler schematic, Longland, Ph.D. Thesis (2010)

- **Linear** polarization: ≈ 99 %
- **Circular** polarization: > 93 %
- **Photon flux**: 10^9 γ s^{-1}
- **Bandwidth**: 2-5 % of beam energy

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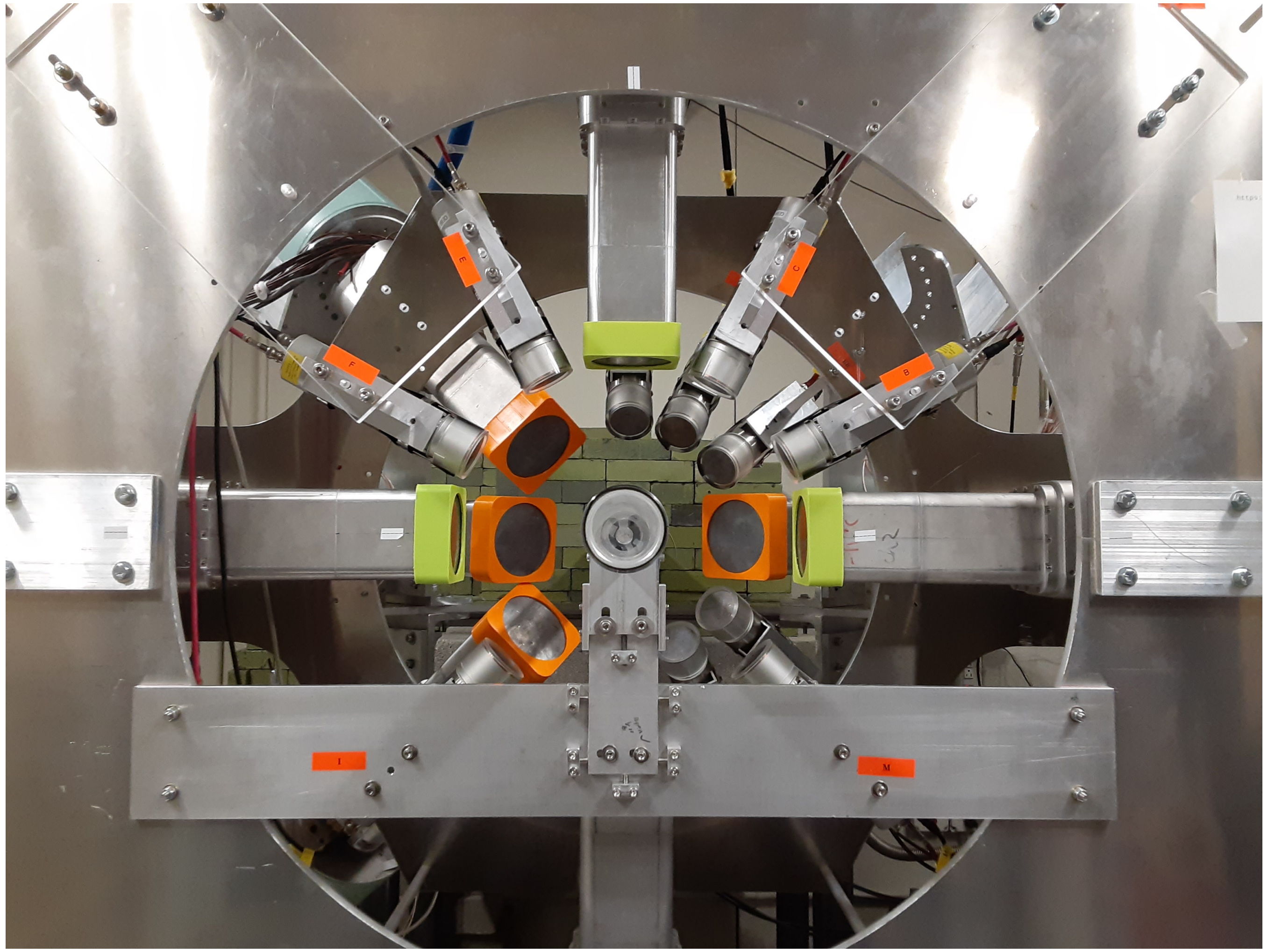
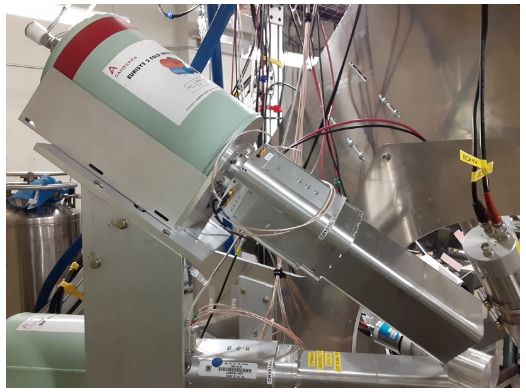
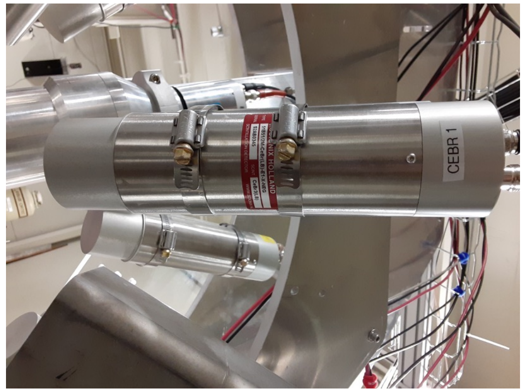
Detection Capabilities at HIγS: The Clover Array



A. D. Ayangeakaa, U. Friman-Gayer, and R. V. F. Janssens
Innovation News Network:
https://www.innovationnewsnetwork.com/nuclear-structure/10491/



HPGe



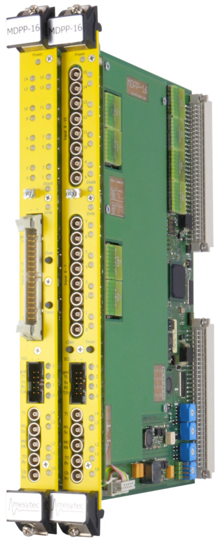
CeBr

- 10 (16) clover-type HPGe** and 12 (2″ × 2″) CeBr detectors.
- Higher HPGe rates due to segmentation.
- Higher granularity.
- No intrinsic radioactivity.
- Solid angle coverage: 14%

**Provided by the Clovershare Consortium, the US Naval Academy, the US Army Research Lab, and TUNL

For certain applications: $LaBr_3$

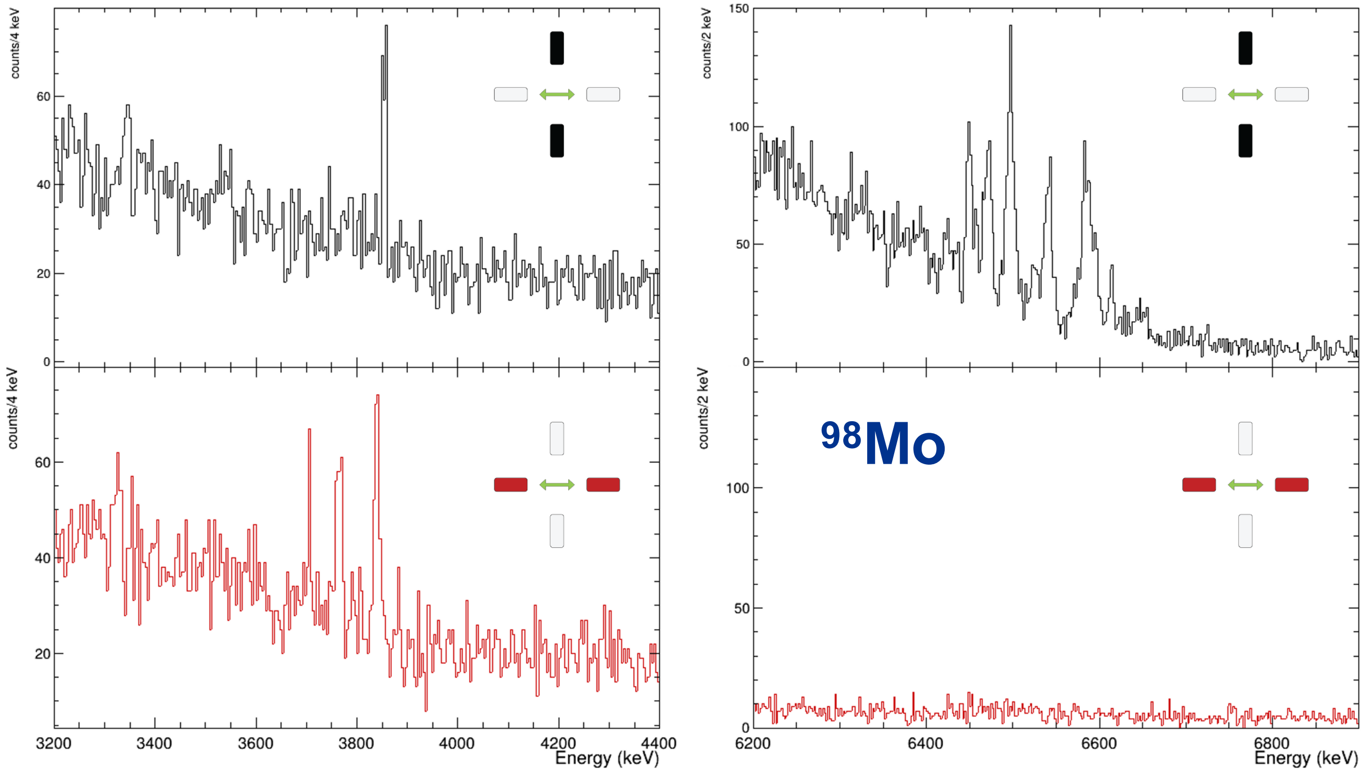
- **Mesytec** Hardware



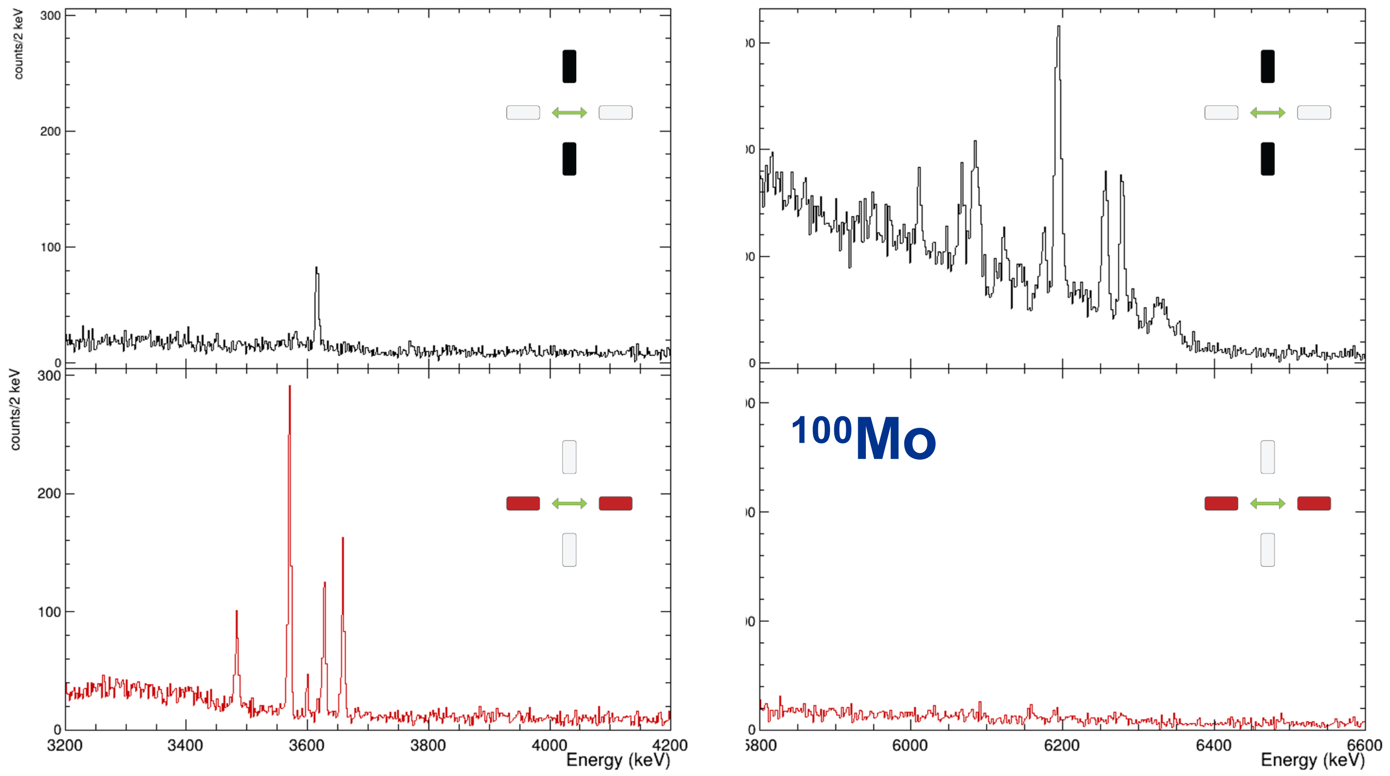
See poster by L Schaedig

NRF spectra from $^{98}Mo(\gamma,\gamma')$ and $^{100}Mo(\gamma,\gamma')$ reactions

Beam energy: 3.77 MeV   **Beam energy**: 6.50 MeV



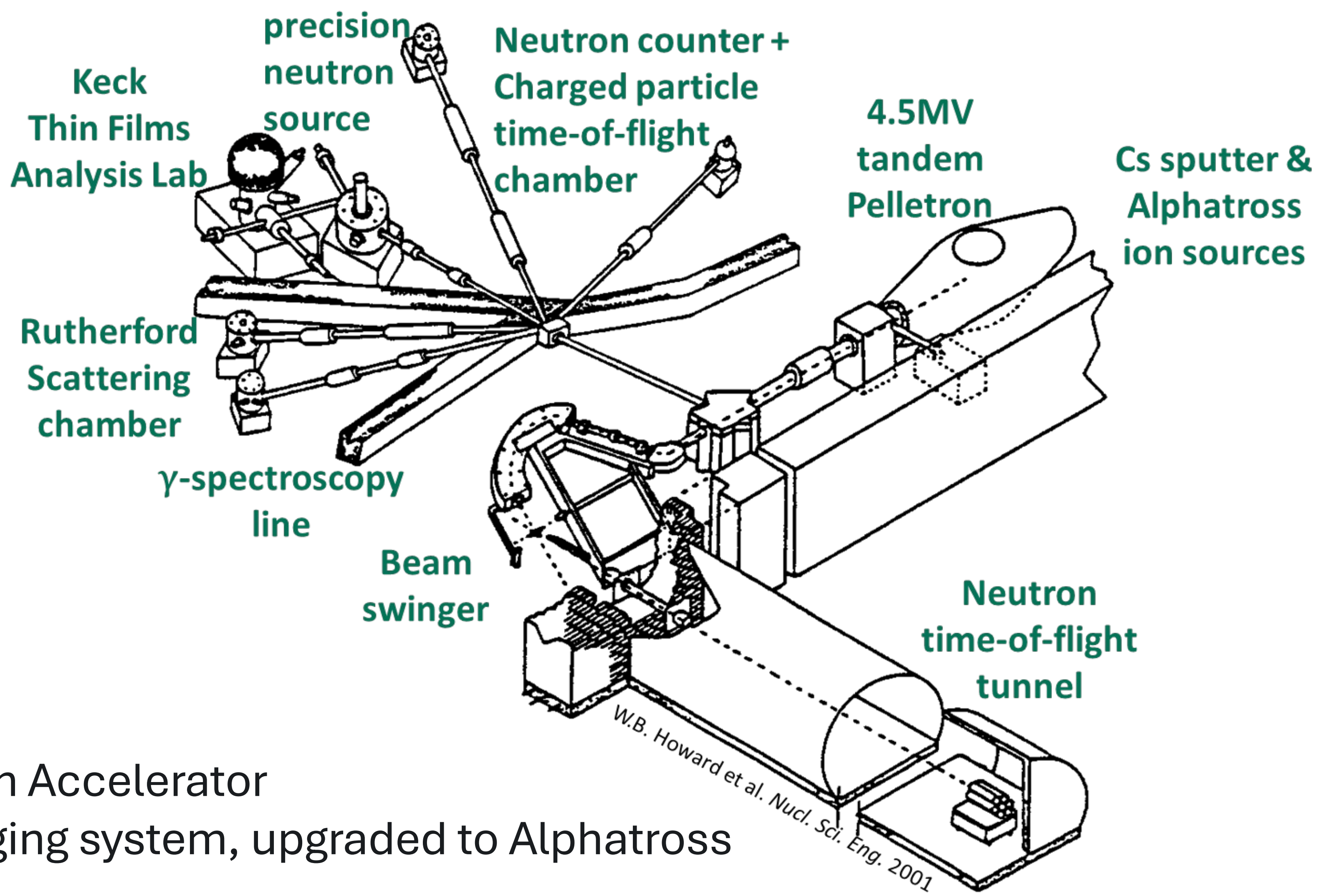
Beam energy: 3.60 MeV   **Beam energy**: 6.21 MeV



NRF spectra taken at different beam energies show a clear distinction between **electric** and **magnetic** dipole transitions with respect to a horizontally linearly polarized photon beam

See poster by L Schaedig

Statistical Nuclear Physics at Ohio University



- 4.5-MV Tandem Accelerator
- Pelletron charging system, upgraded to Alphatross He ion source
- Unique beam swinger and 30-m TOF tunnel
- Specializations: TOF techniques, neutrons

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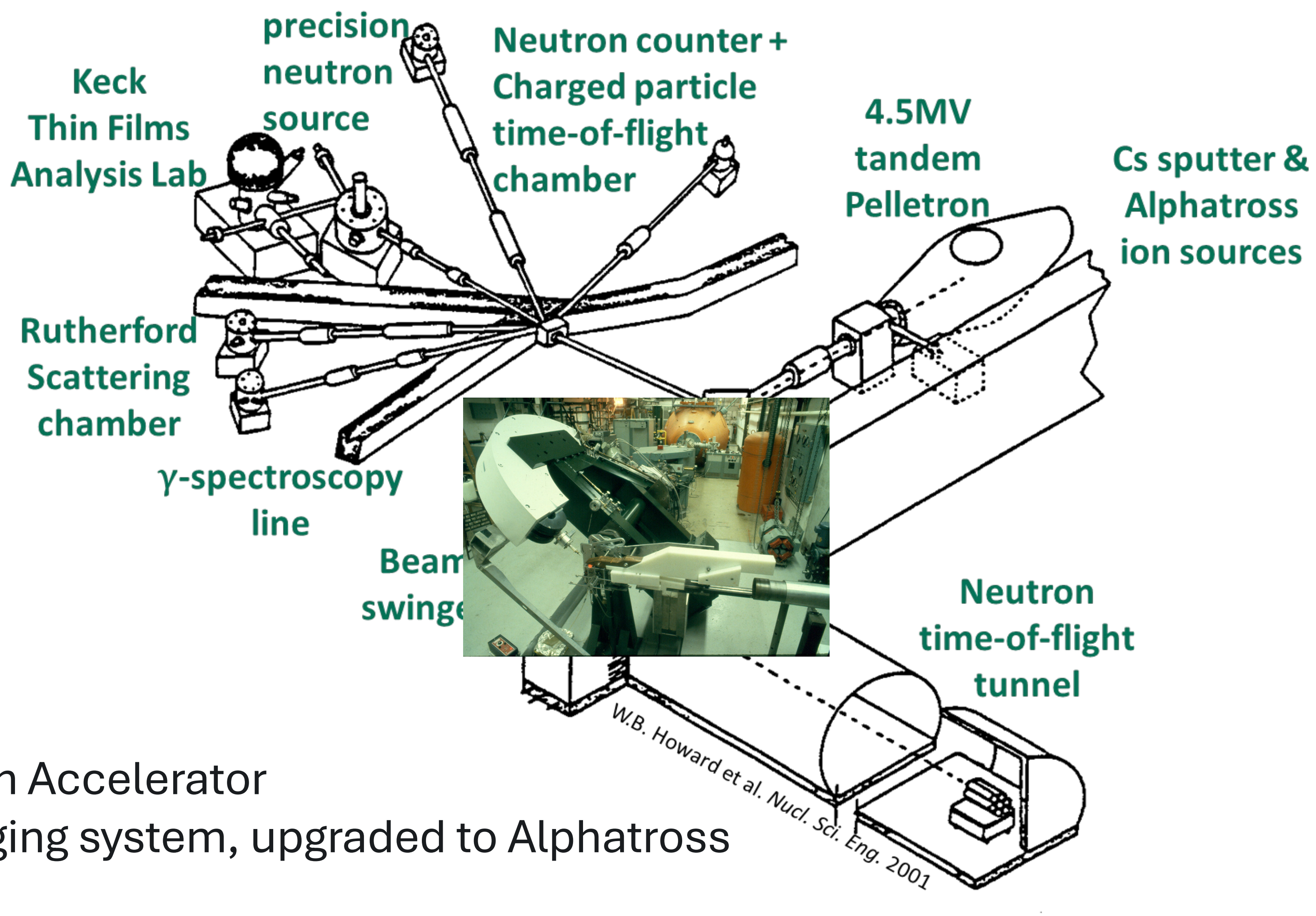

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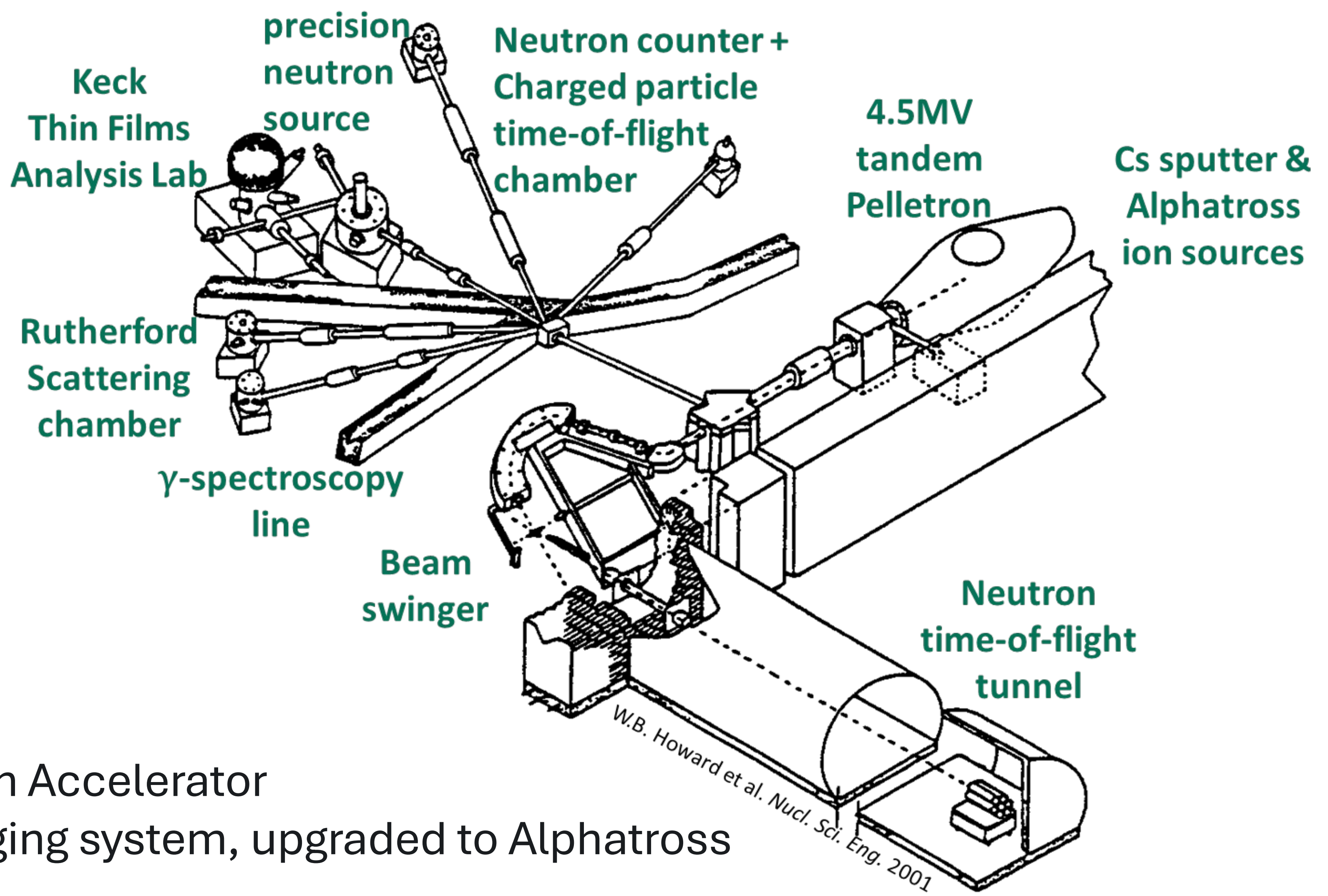

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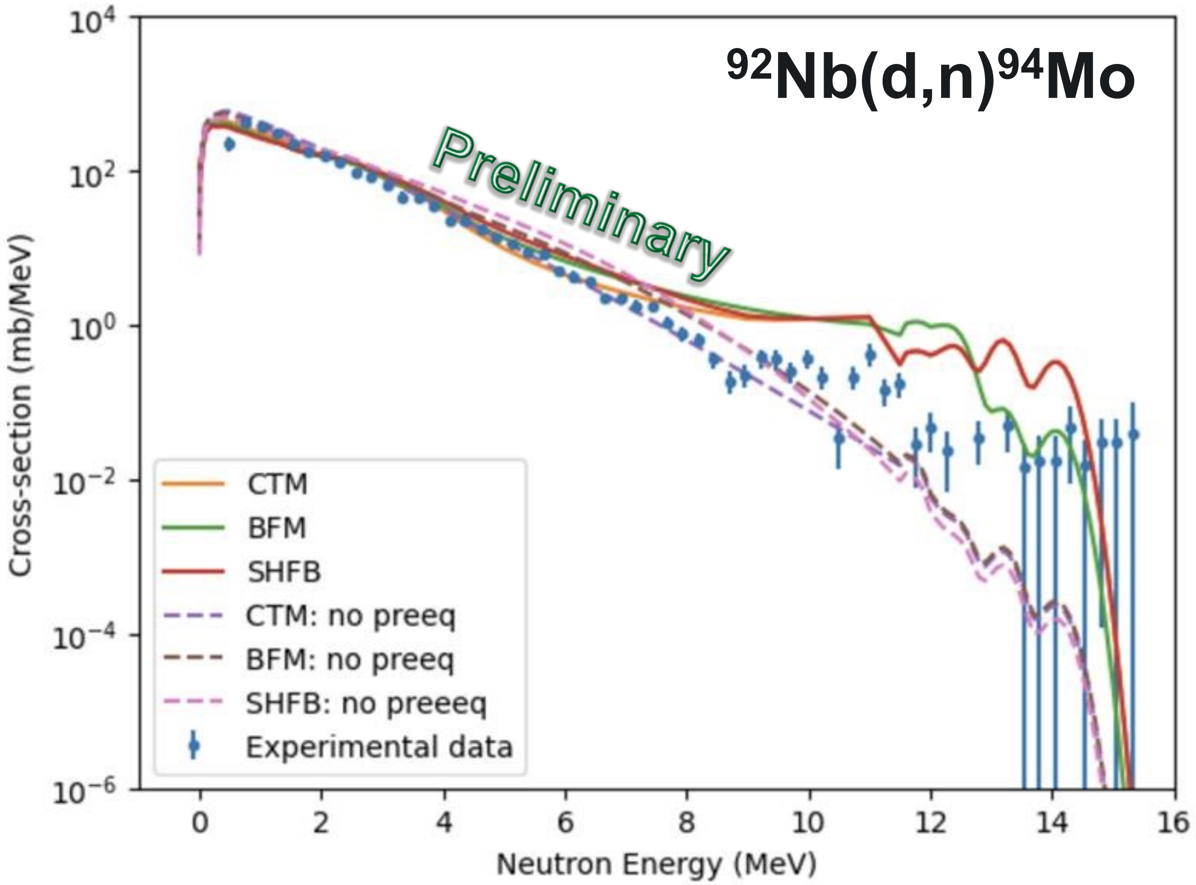
Statistical Nuclear Physics at Ohio University

Measure particle spectra (p, n, ...) using TOF → Obtain differential cross sections → Extract NLD from shape of cross section → Input NLD into Hauser Feshbach calculation

- ^{92}Nb(p,n)^{93}Mo and **^{92}Nb(d,n)^{94}Mo** experiments performed at the EAL in August 2025
- Analysis underway by A. Wijenarayana (OU)



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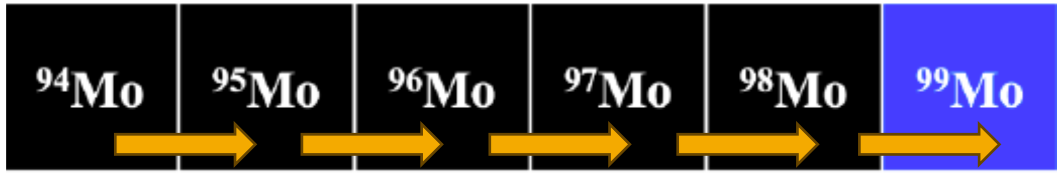
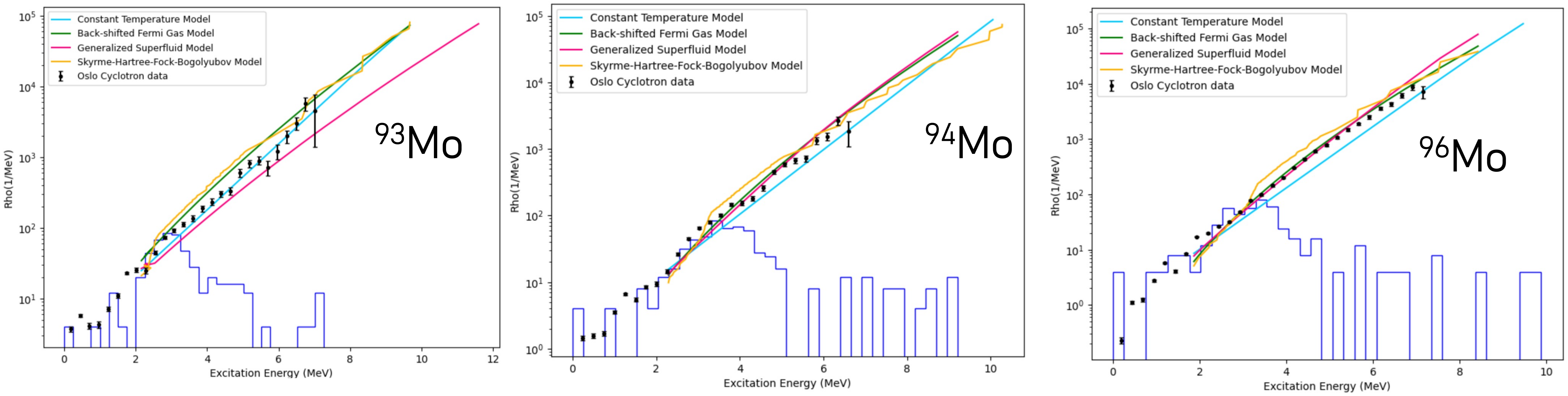
Follow-up measurements:



(d,p), (p,p'), (n,n') reaction mechanisms being explored

See poster by A. Wijenarayana

Systematic Studies of the Molybdenum Isotopes



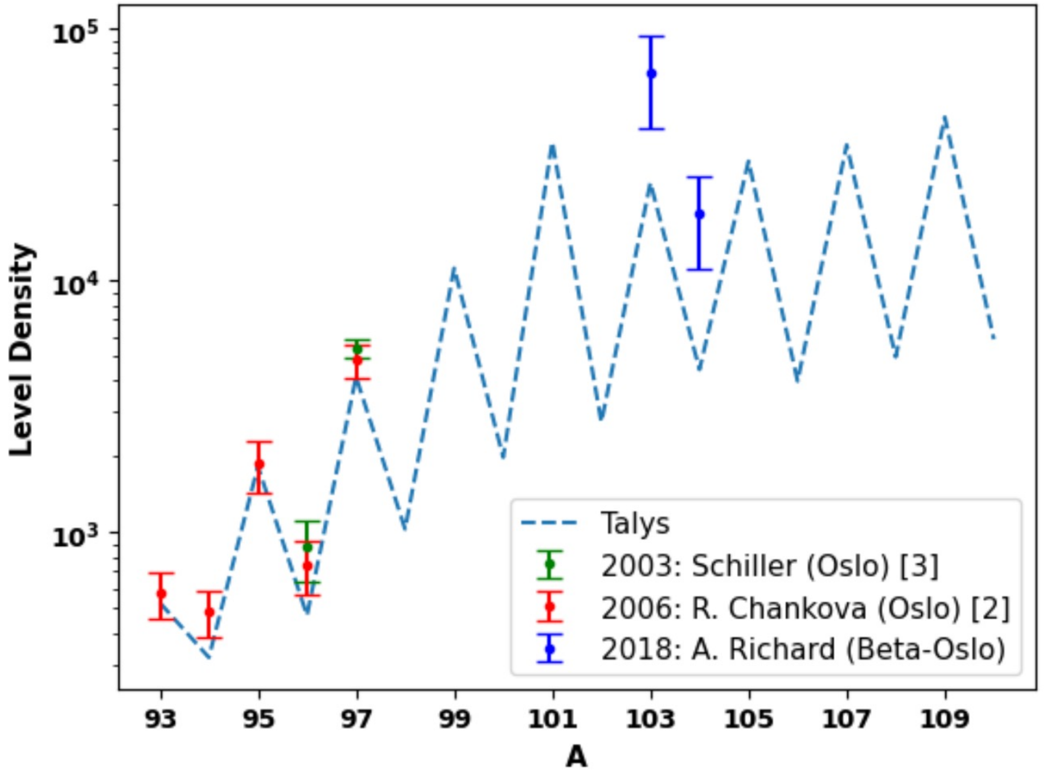
- Oslo Method data available for $^{93\text{-}98}$Mo
- No single model can reproduce all NLDs using default parameters
- Explore existing NLD data using Bayesian Optimization
  - Are there trends in the data?

See poster by A. Wijenarayana

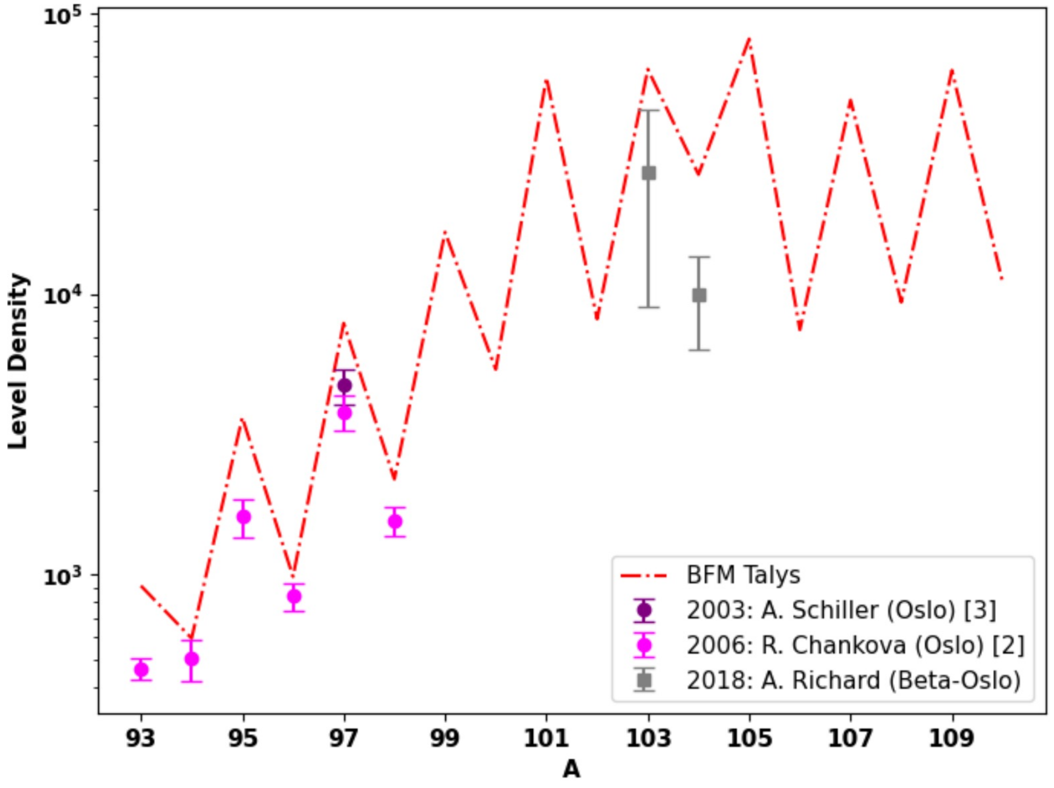
Systematic Studies of the Molybdenum Isotopes

Parameters extracted from Bayesian analysis provide trends across the Mo isotopic chain

Constant Temperature Model



Back-Shifted Fermi Gas Model



See poster by A. Wijenarayana

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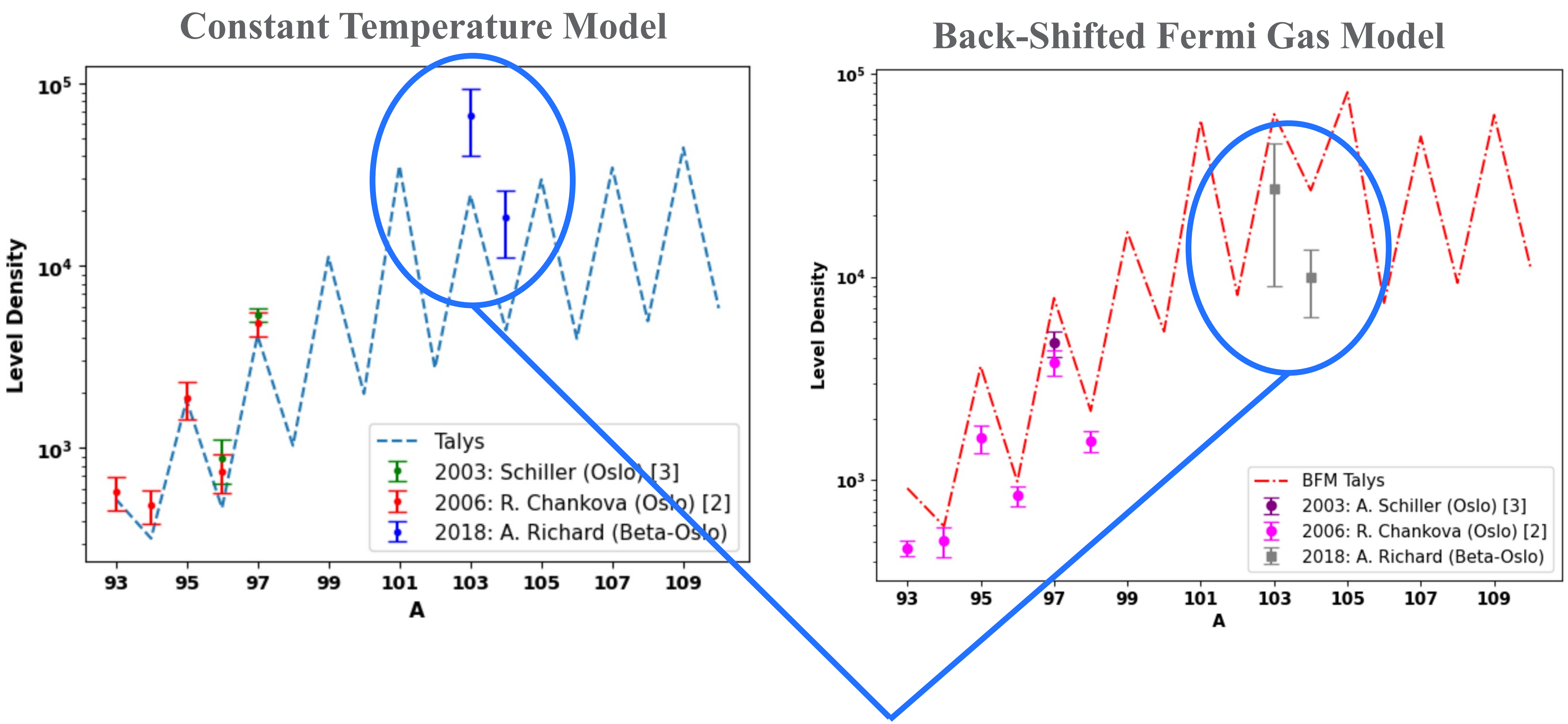
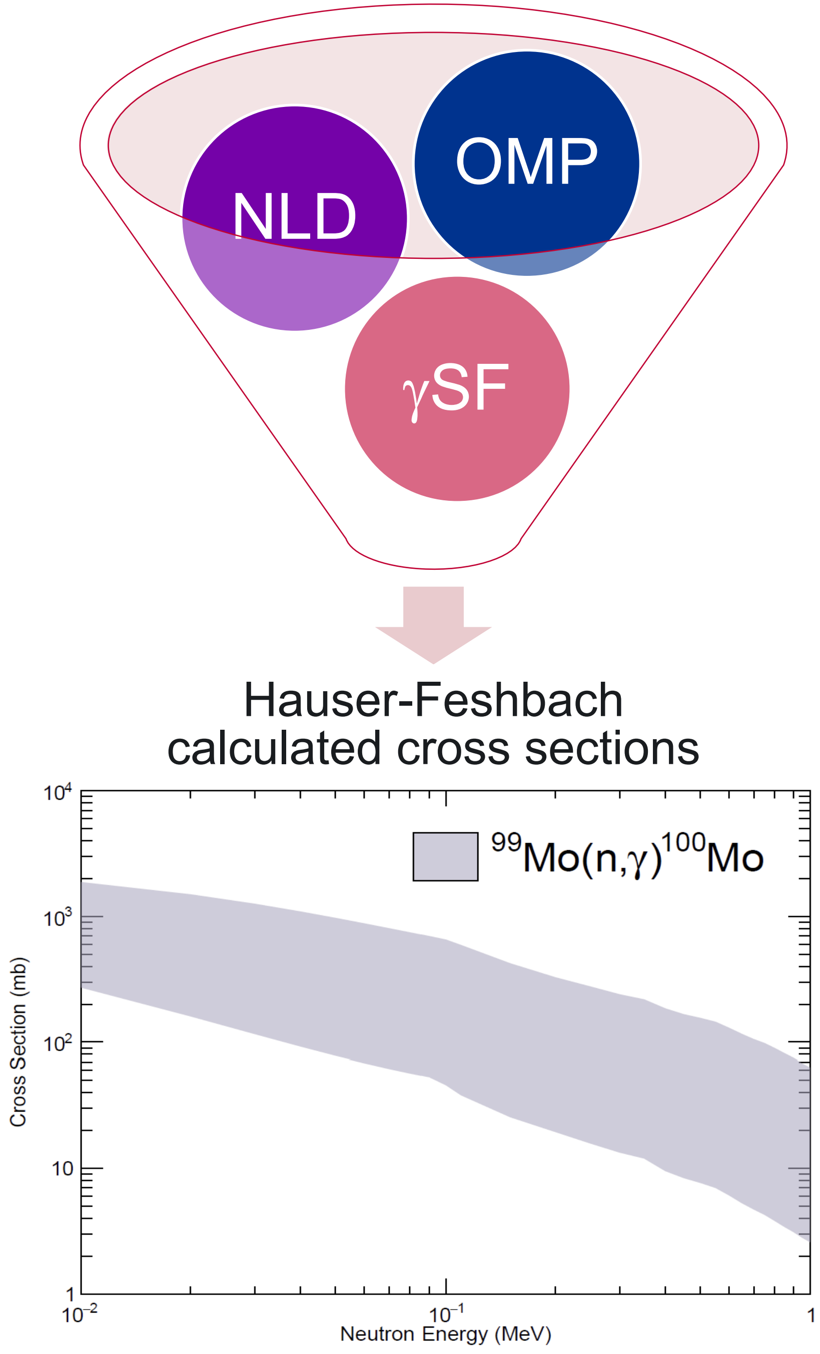


Observed deviation from trend for radioactive ^{103,104}Mo NLDs

See poster by A. Wijenarayana

Summary & Future Work

- Statistical properties of nuclei (NLDs, gSFs) play important roles in nuclear data for non-proliferation, stewardship, energy, astrophysics and beyond
- Systematic studies of NLDs and gSFs can provide increased confidence in evaluations of nuclear data off stability
- Ongoing experimental efforts at ANL, EAL, and HIγS to study the Mo isotopic chain from stable to radioactive isotopes
- Preliminary Bayesian analysis of Mo NLDs show odd-even trends that appear to deviate for short-lived nuclei



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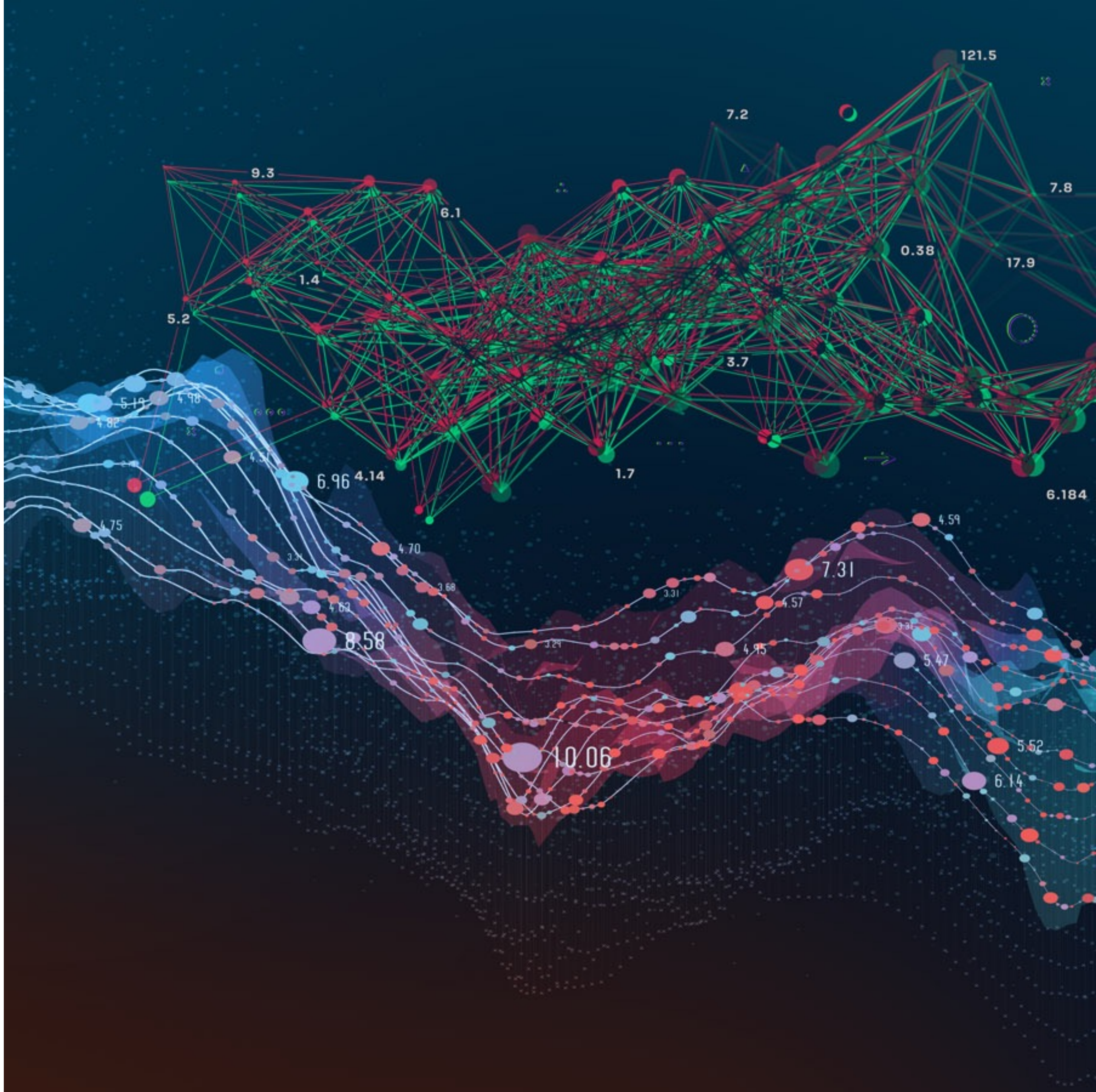

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