# Heavy Element Nucleosynthesis

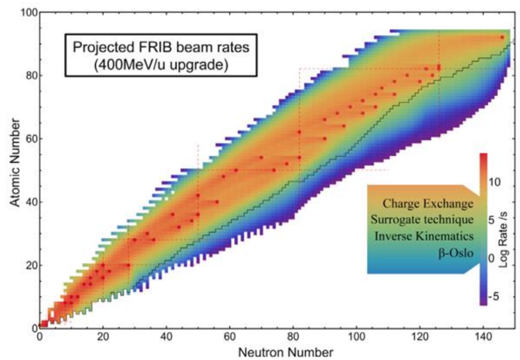
## Part II: Nuclear Data Needs and Experimental Efforts

Andrea L. Richard
Ohio University

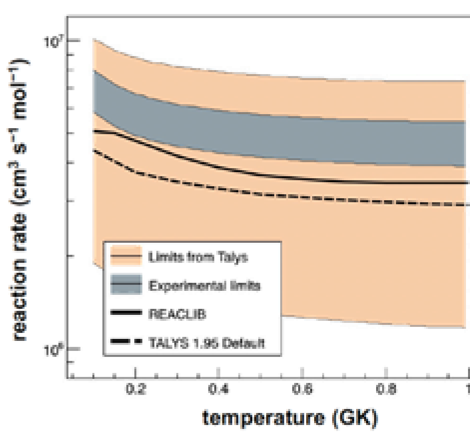
**Open Questions and Research Tools in Nuclear Astrophysics**

IReNA
IANNA
CeNAM
OHIO UNIVERSITY
FRIB
Lawrence Livermore National Laboratory

# What's the Plan?




A.C. Larsen *et al.* PPNP **107** 69 (2019)



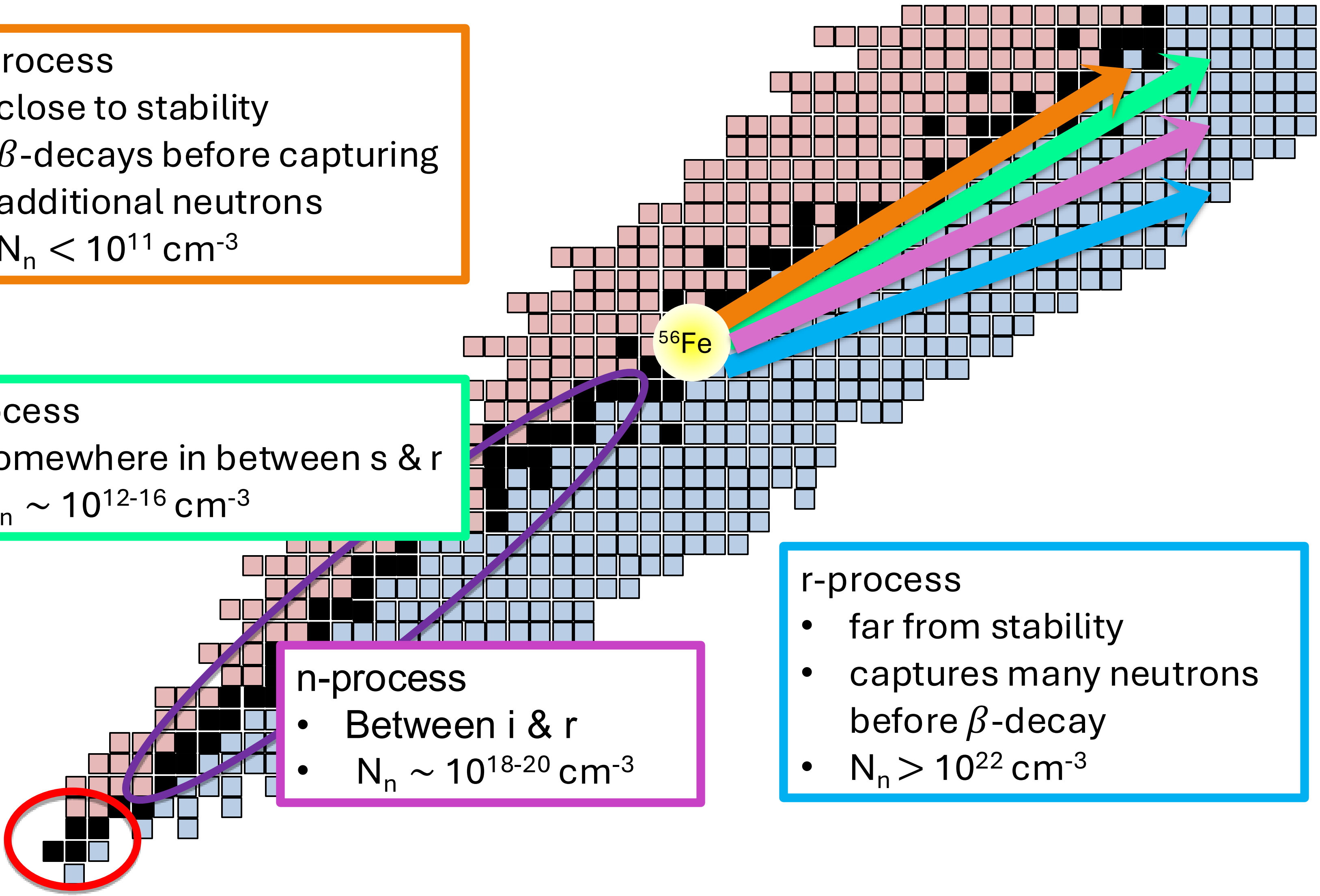

A. Spyrou *et al.*, PRL **132**, 202701 (2024)

Overview of Heavy Element Nucleosynthesis and Introduction of Nuclear Data

Nuclear Data Uncertainties and Experiments

Deep Dive into Indirect Neutron Capture and Wrap-up

# Neutron-Capture Processes Summary




s-process
- close to stability
- $\beta$-decays before capturing additional neutrons
- $N_n < 10^{11}$ cm$^{-3}$

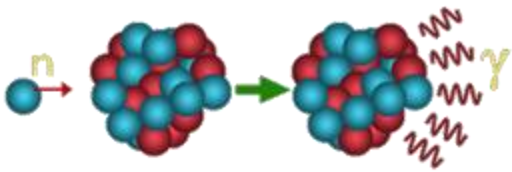
i-process
- somewhere in between s & r
- $N_n \sim 10^{12\text{-}16}$ cm$^{-3}$

n-process
- Between i & r
- $N_n \sim 10^{18\text{-}20}$ cm$^{-3}$

r-process
- far from stability
- captures many neutrons before $\beta$-decay
- $N_n > 10^{22}$ cm$^{-3}$

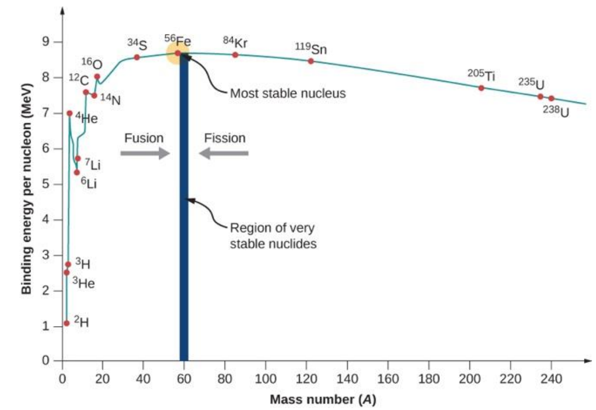
# Nuclear Data Inputs

## Neutron-Capture Rates

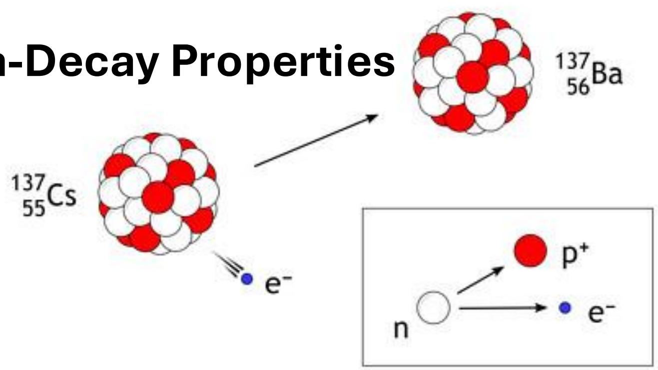


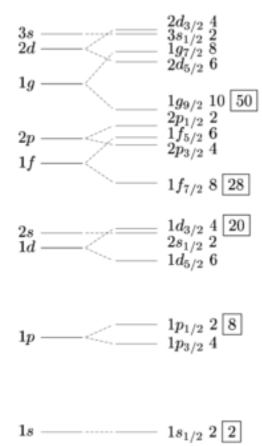

## Mass

## Binding Energy

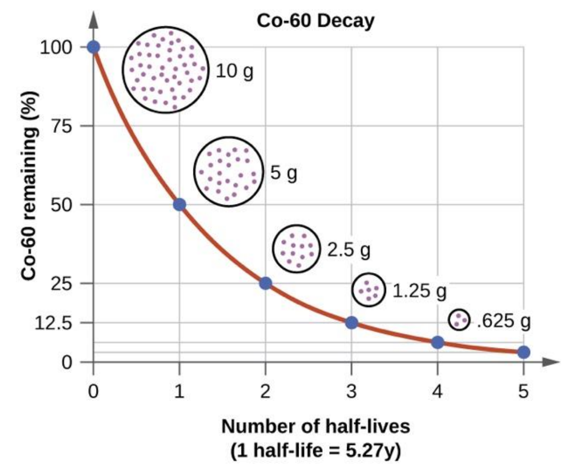



## Beta-Decay Properties

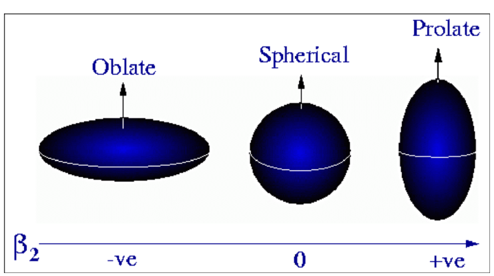



## Level structure



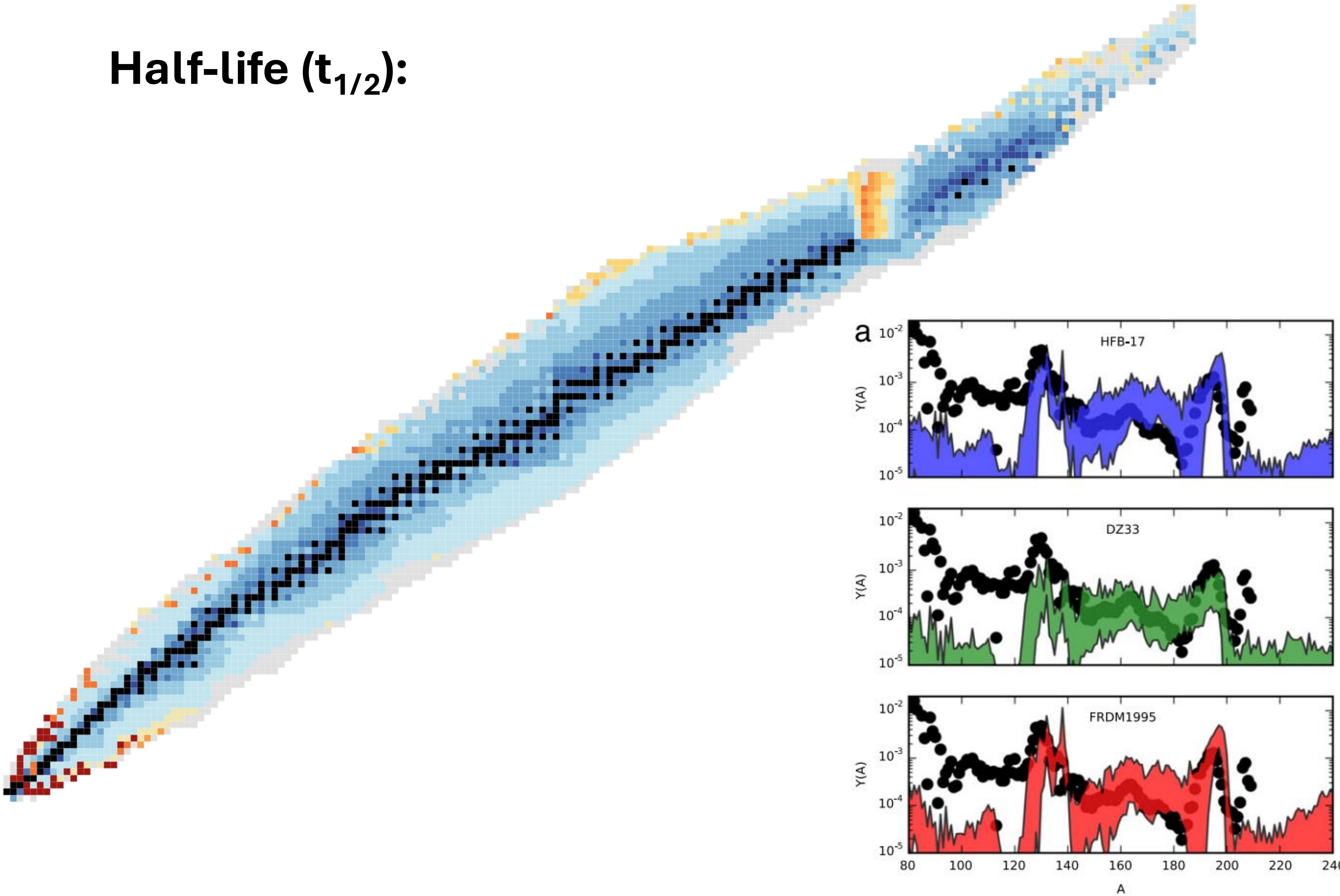

## Half-life




## Nuclear Shapes

# Nuclear data: What do we know?

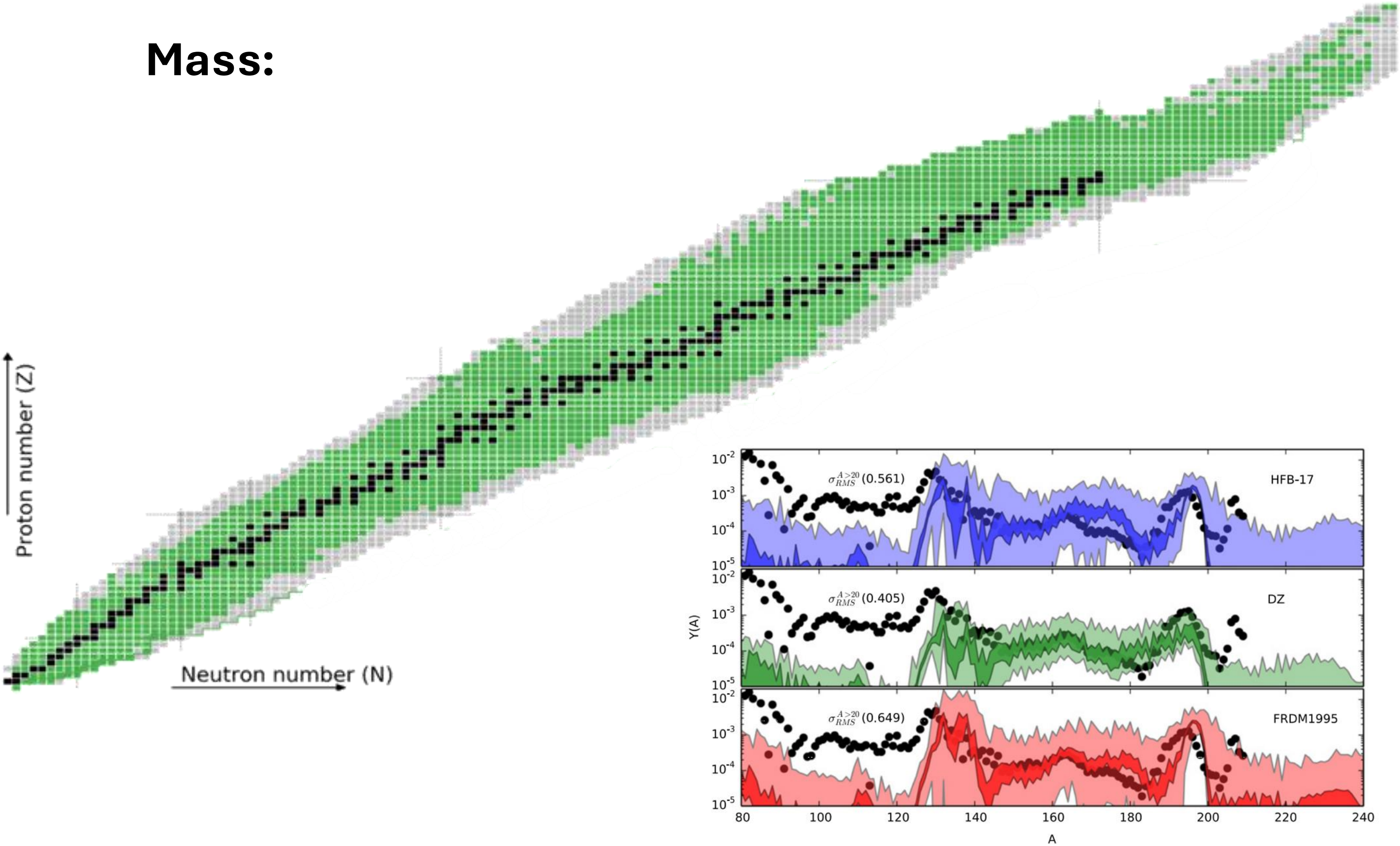
**Half-life ($t_{1/2}$):**




Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

# Nuclear data: What do we know?

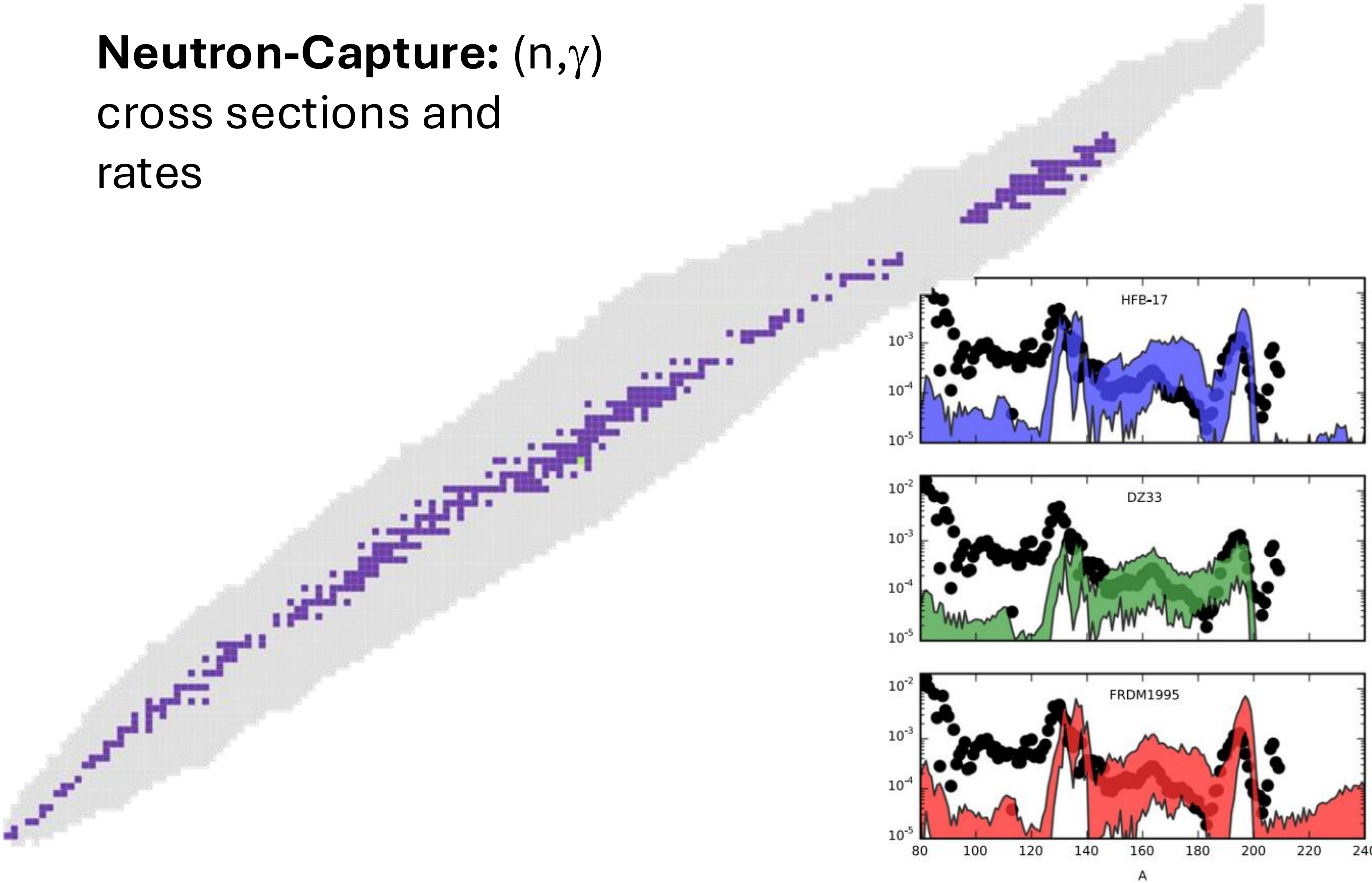
## Mass:




Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

# Nuclear data: What do we know?

**Neutron-Capture:** (n,$\gamma$) cross sections and rates

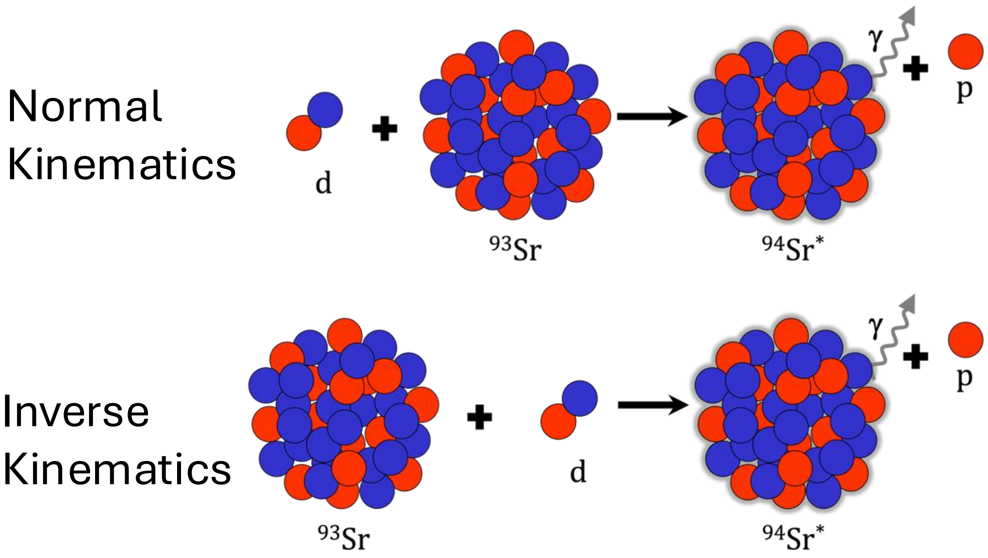



Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

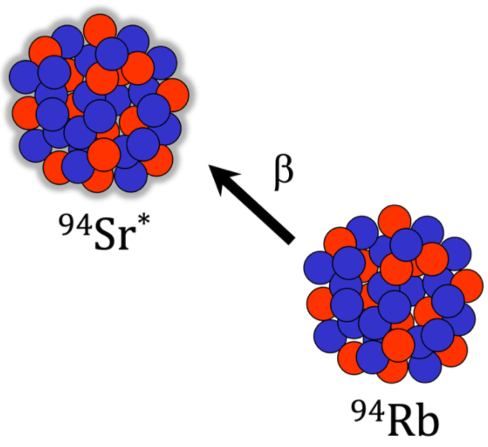
# How do we measure nuclear inputs?

- Accelerator Facilities
  - Stable beams
  - Rare Isotope Beams

**Reactions**

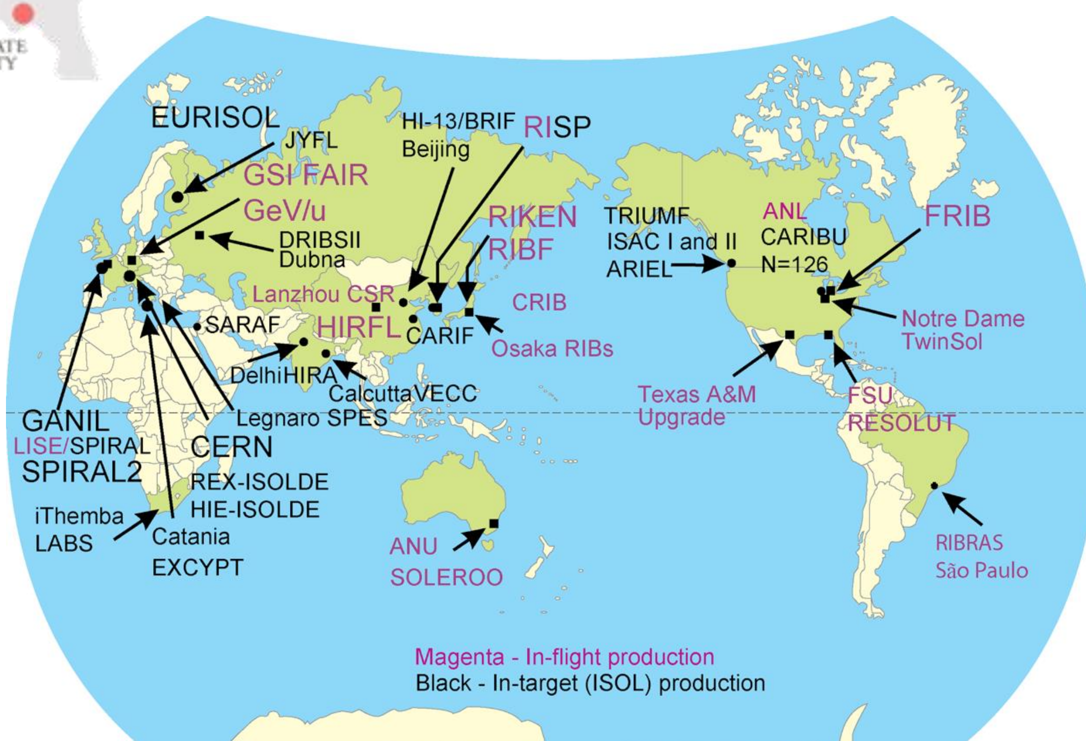



**Decay**



# Facilities

*ARUNA: Stable Beams*


*Rare Isotope Beams*

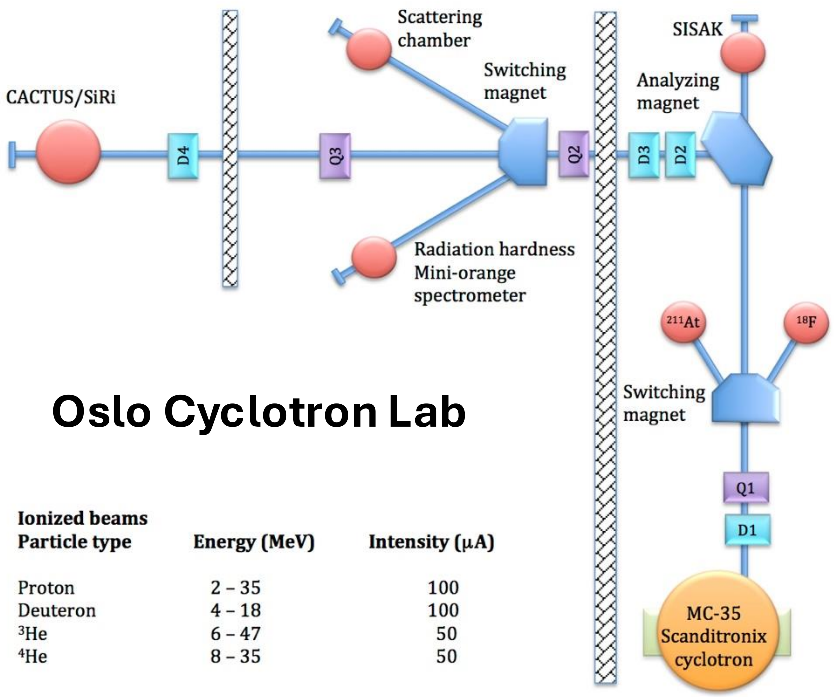
# University Accelerators in the US

## Association for Research at University Nuclear Accelerators


ARUNA

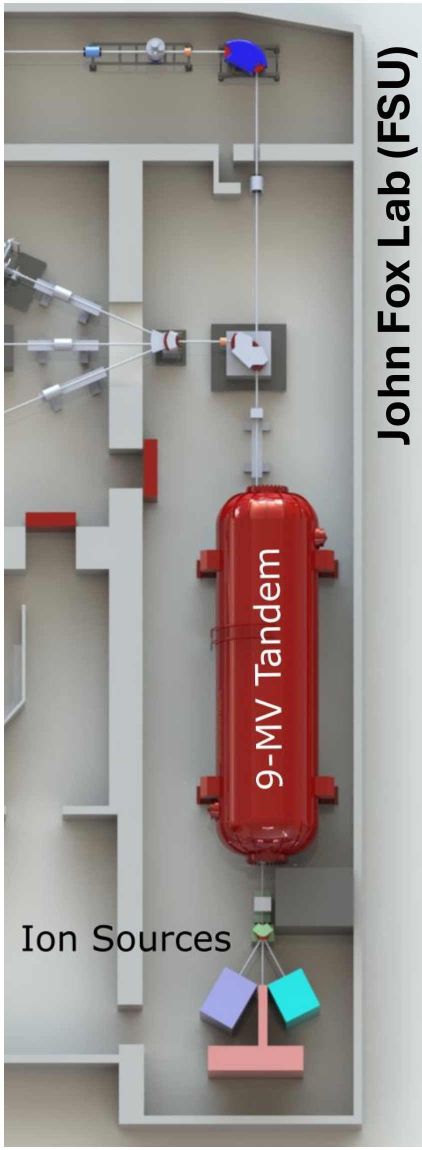
# Stable Beam Production

- Linear, Tandem, Cyclotron
- Usually normal kinematics with light ion beams



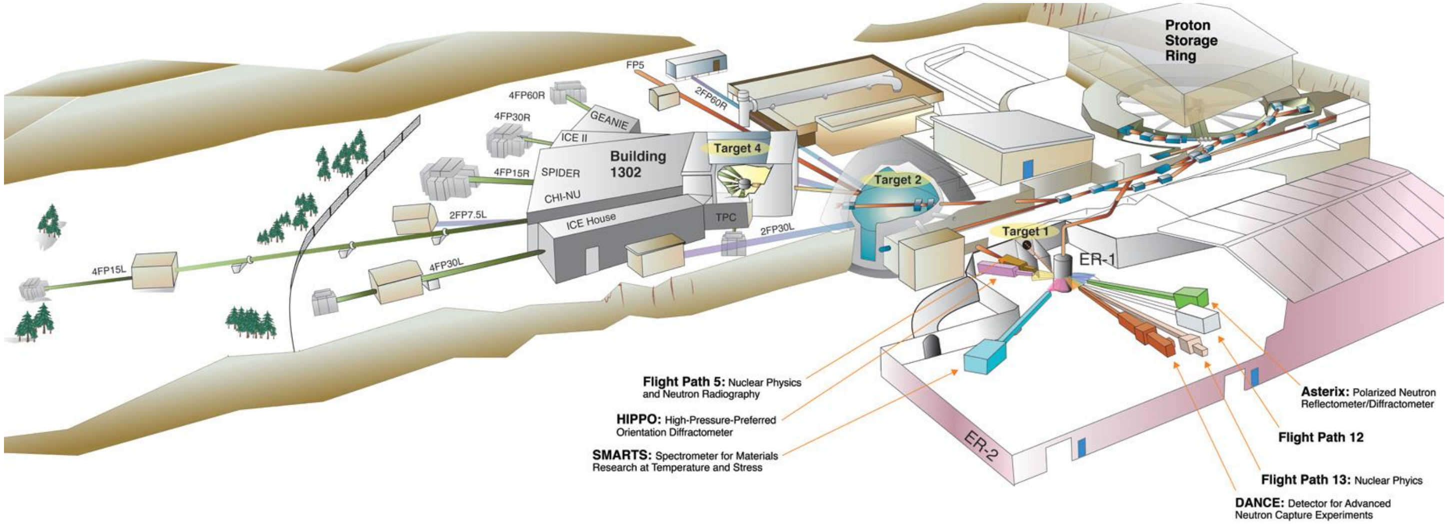

**Oslo Cyclotron Lab**

| Ionized beams Particle type | Energy (MeV) | Intensity (μA) |
|---|---|---|
| Proton | 2 – 35 | 100 |
| Deuteron | 4 – 18 | 100 |
| $^{3}$He | 6 – 47 | 50 |
| $^{4}$He | 8 – 35 | 50 |



# Neutron Beam Facilities

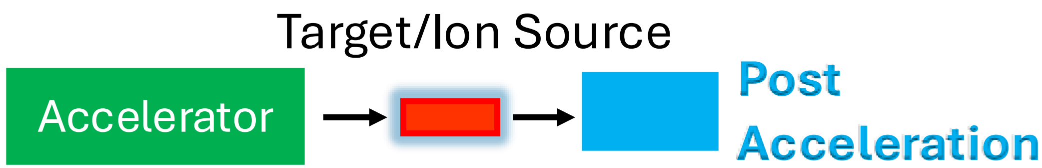
- **Time-of-Flight**: e.g. n_TOF@CERN, LANSCE@ Los Alamos, etc.
  - High energy protons on heavy target, broad energy distribution, pulsed beam.

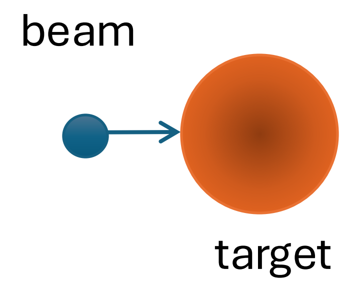



- **Reaction-based, quasi-monoenergetic**: Any low energy facility (e.g. OU)
  - $^{2}H(^{2}H,n)^{3}He$ – Q= 3.3 MeV - $E_n$= 2.5 MeV
  - $^{3}H(^{2}H,n)^{4}He$ – Q= 17.6 MeV - $E_n$ = 14.1 MeV
  - Broad spectrum too: $^{7}Li(p,n)^{7}Be$, …

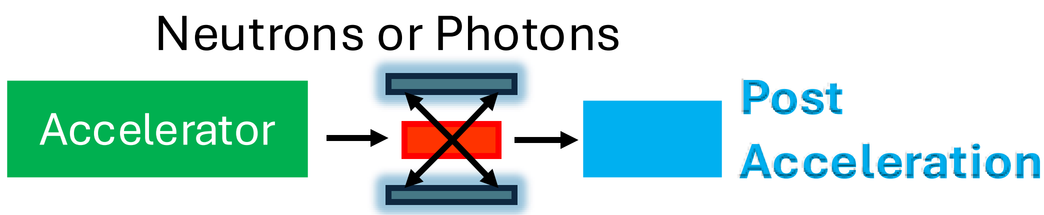
# Rare Isotope Beam Production

- Target spallation and fragmentation by light ions

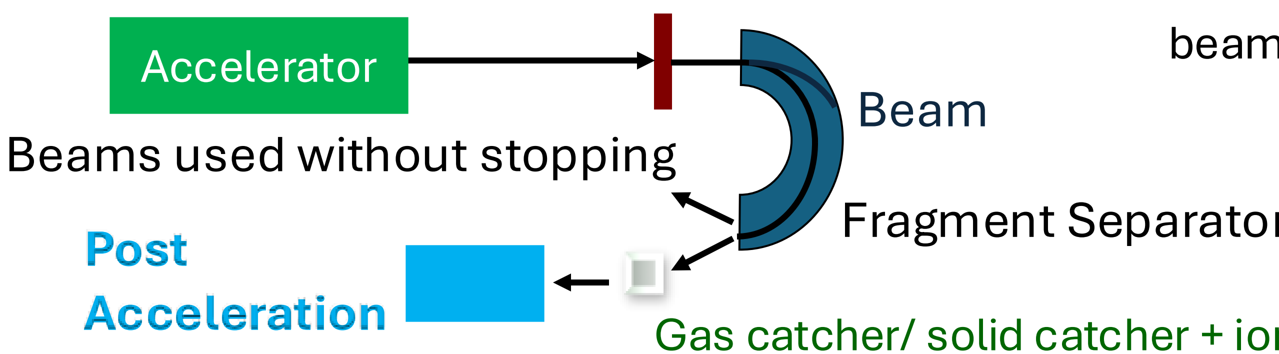


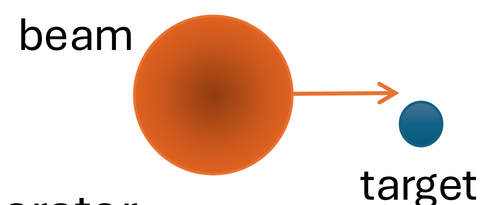




- Neutron induced fission (2-step target)




- In-flight Separation following projectile fragmentation/fission

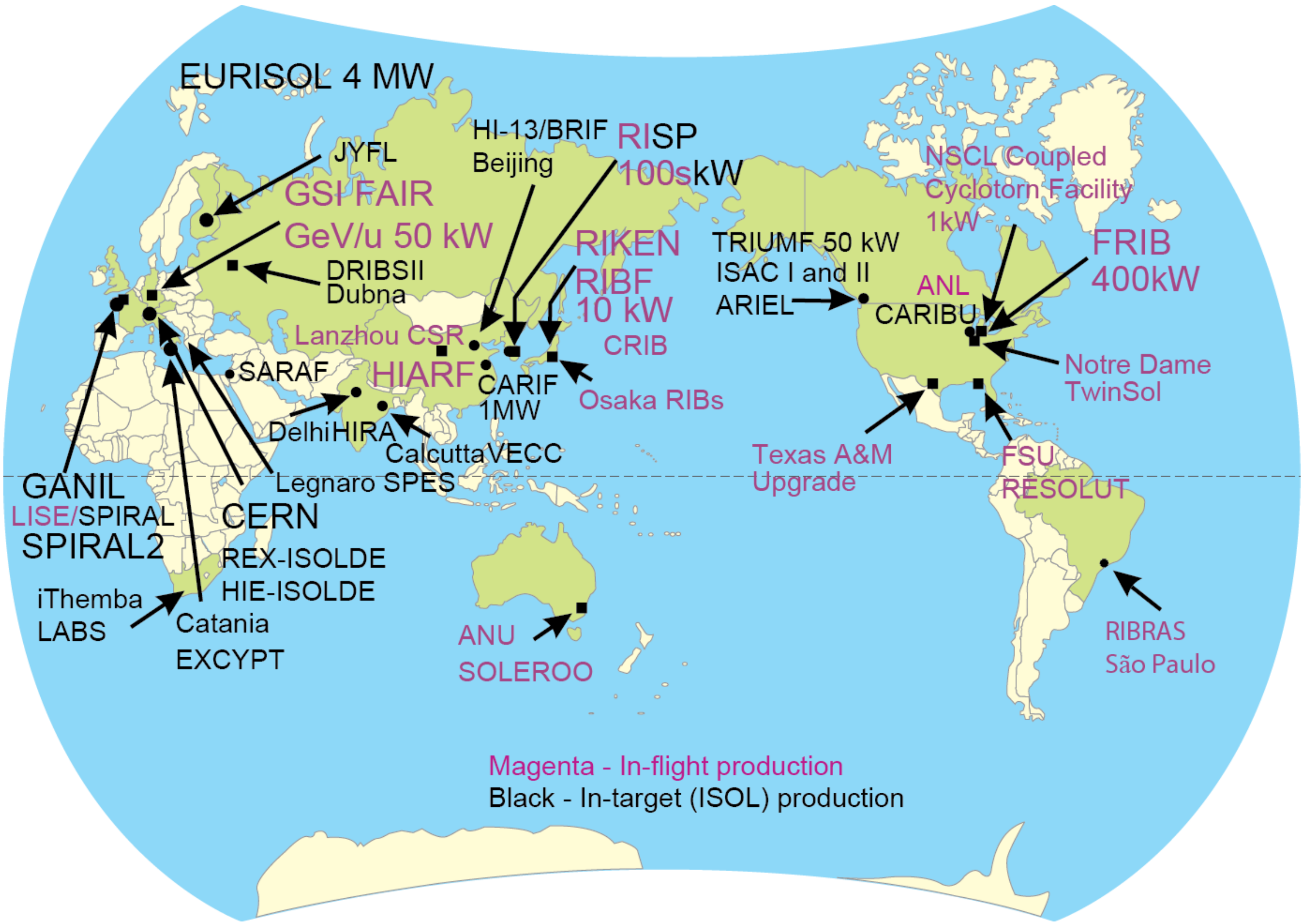


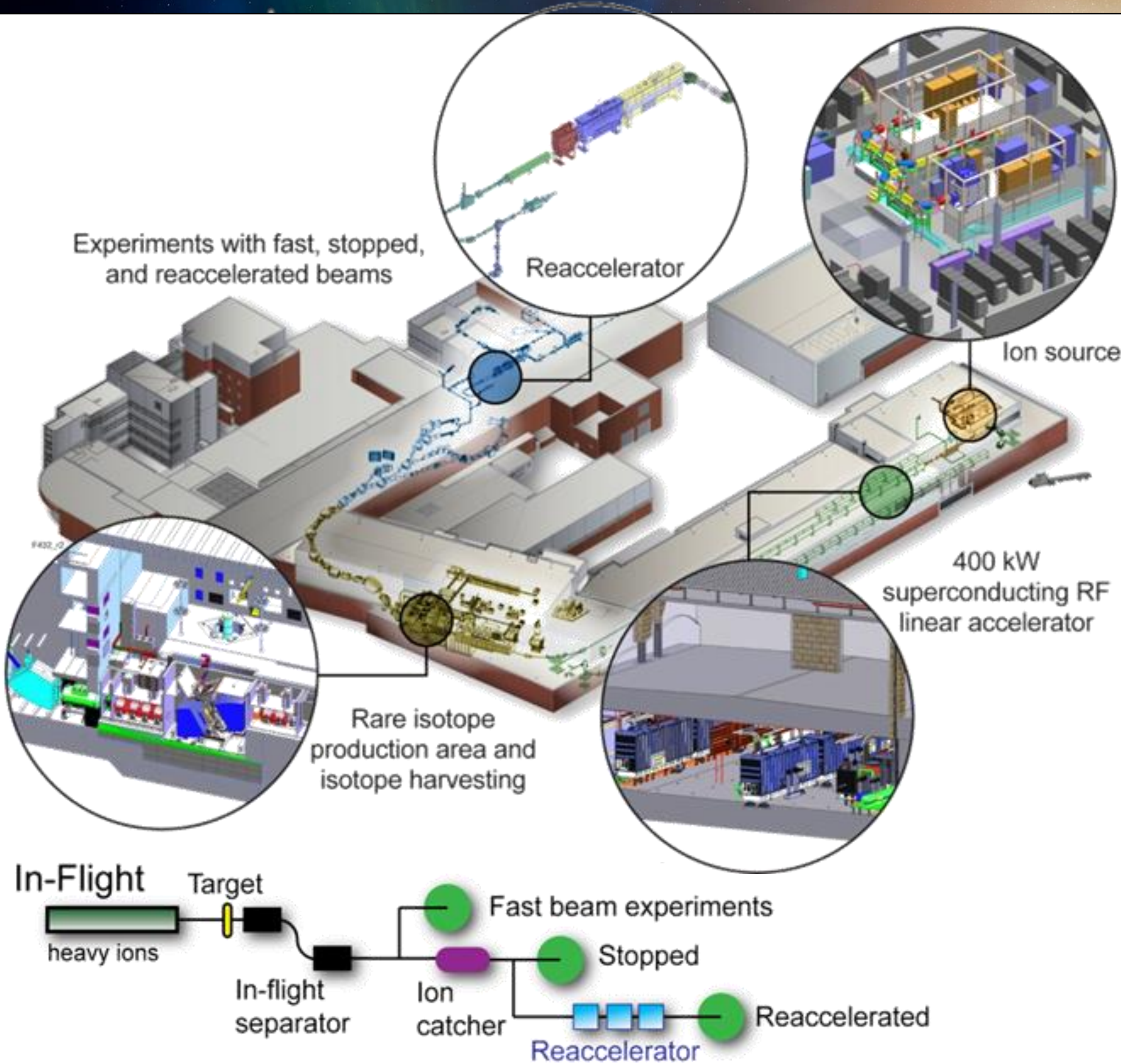



Slide courtesy of Brad Sherrill

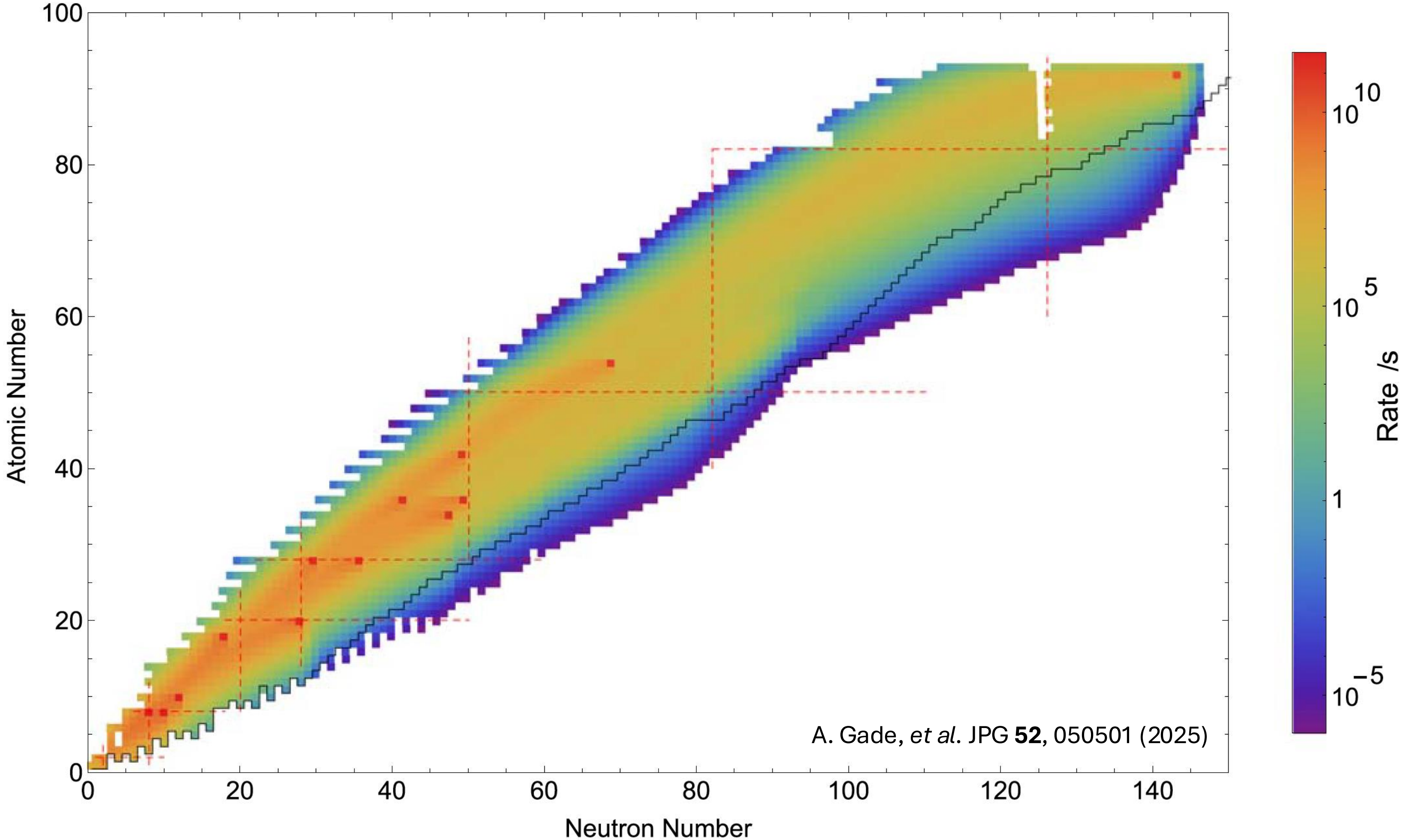
# Rare Isotope Beam (RIB) Facilities



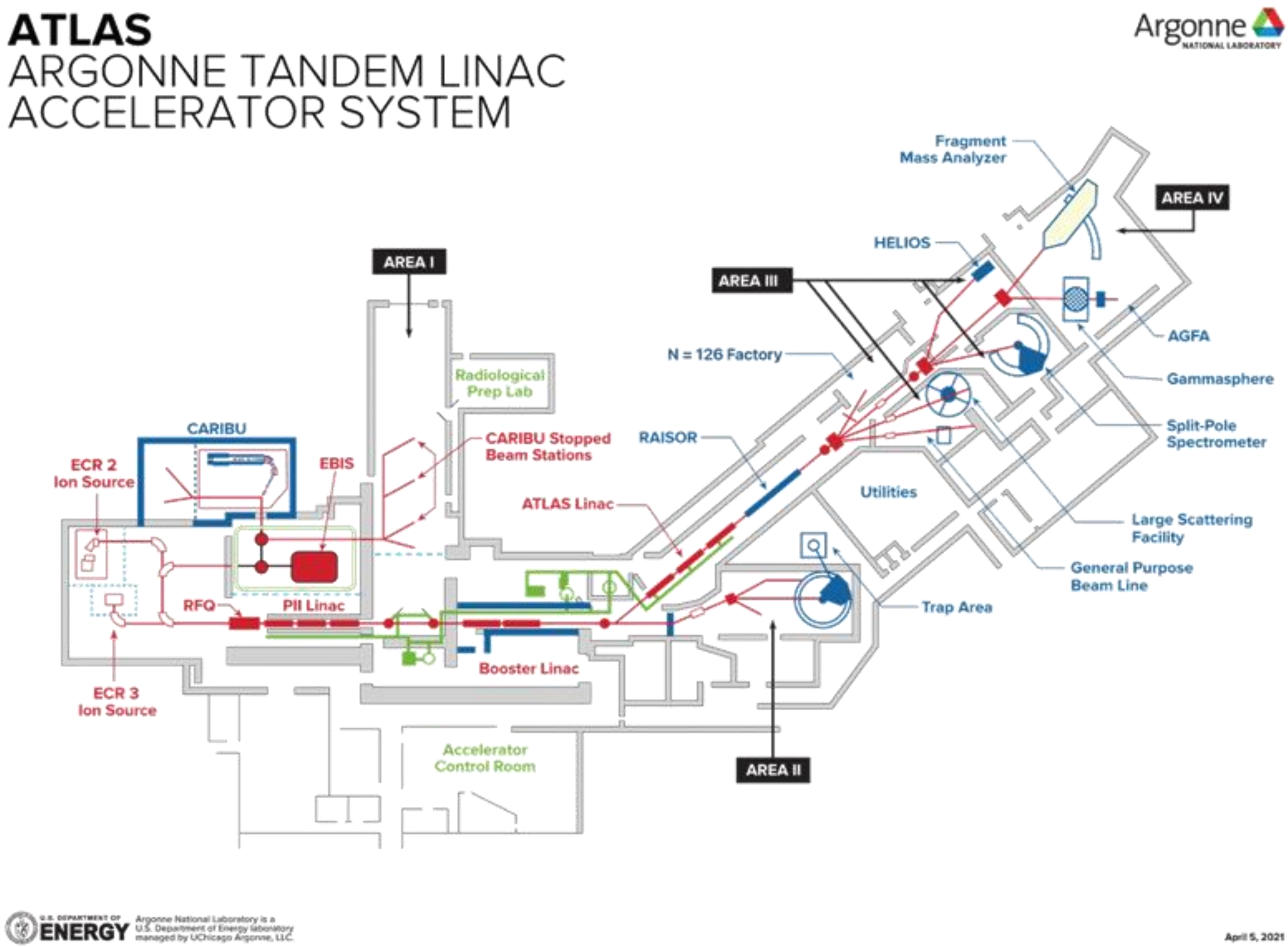
# Facility for Rare Isotope Beams



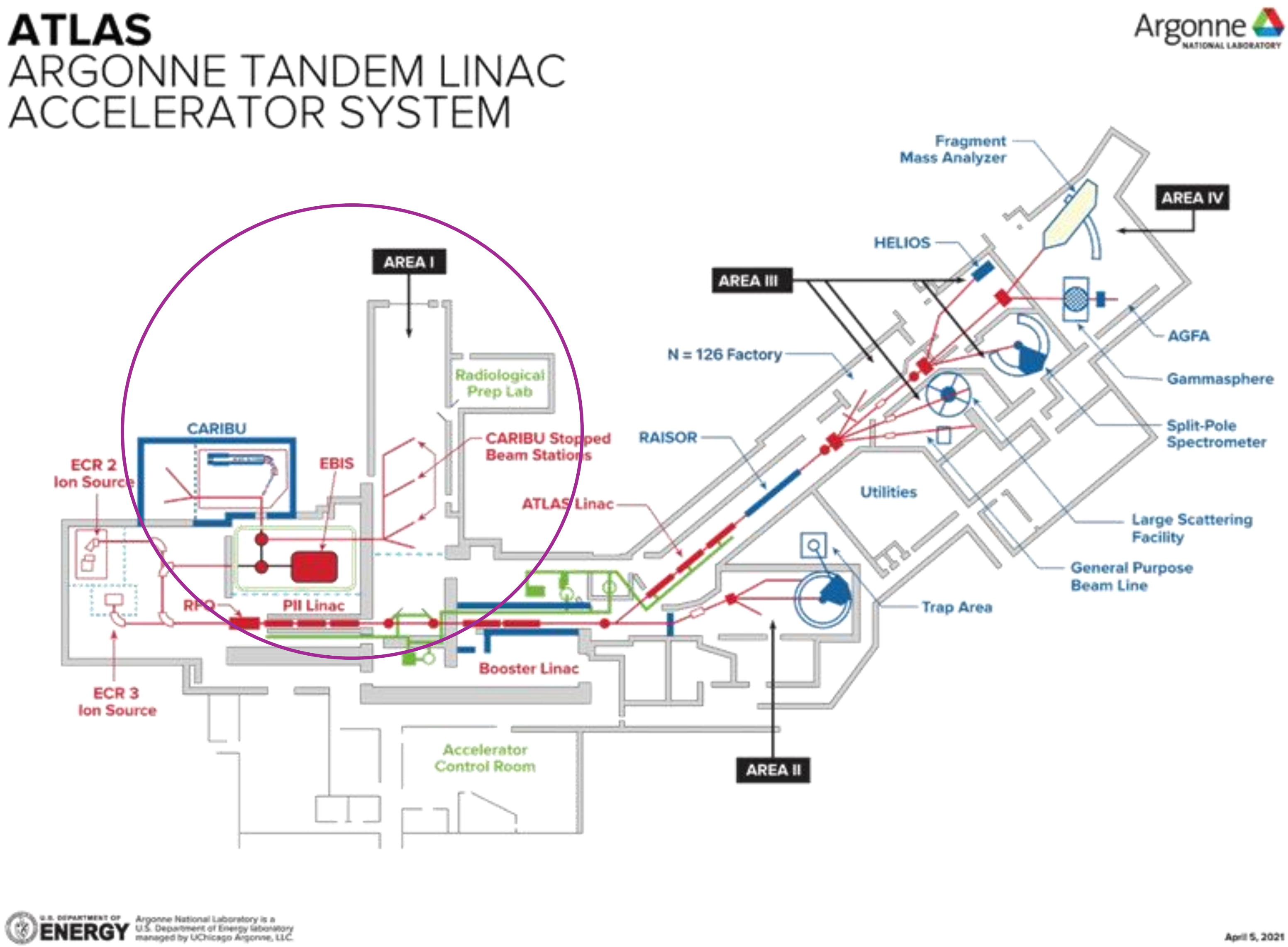
# FRIB Beam Rates



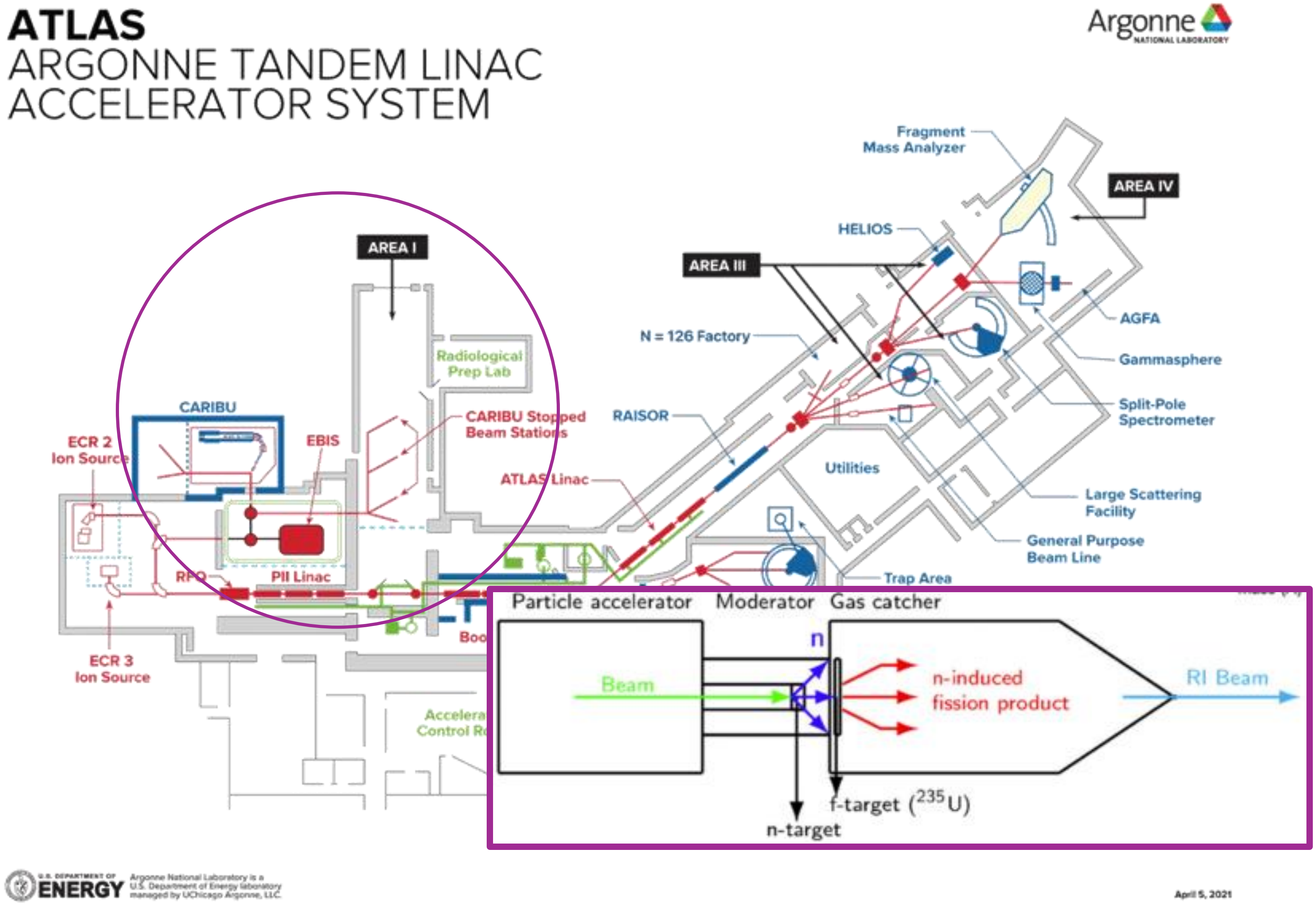
# Argonne National Lab: ATLAS + nuCARIBU



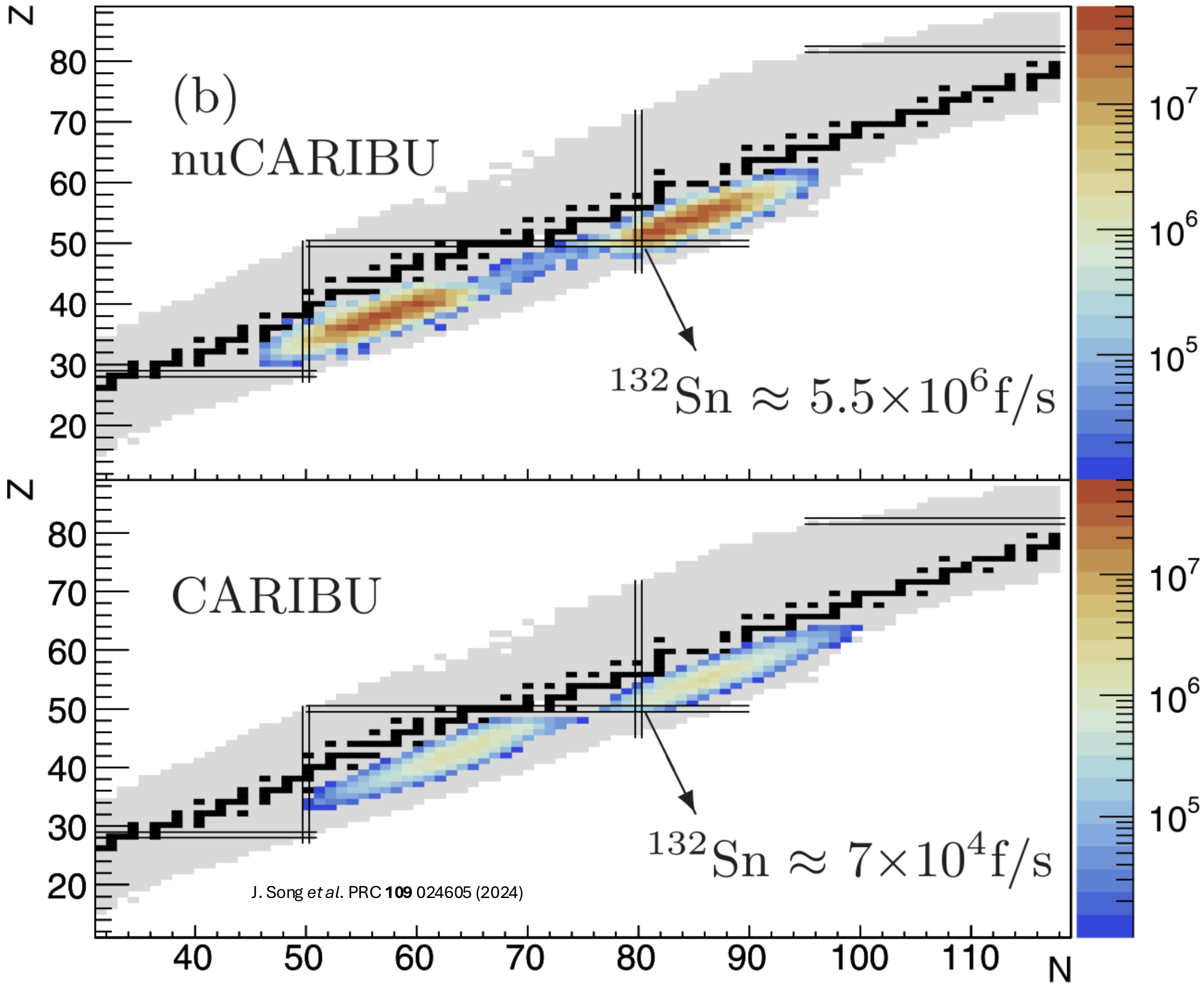
# Argonne National Lab: ATLAS + nuCARIBU



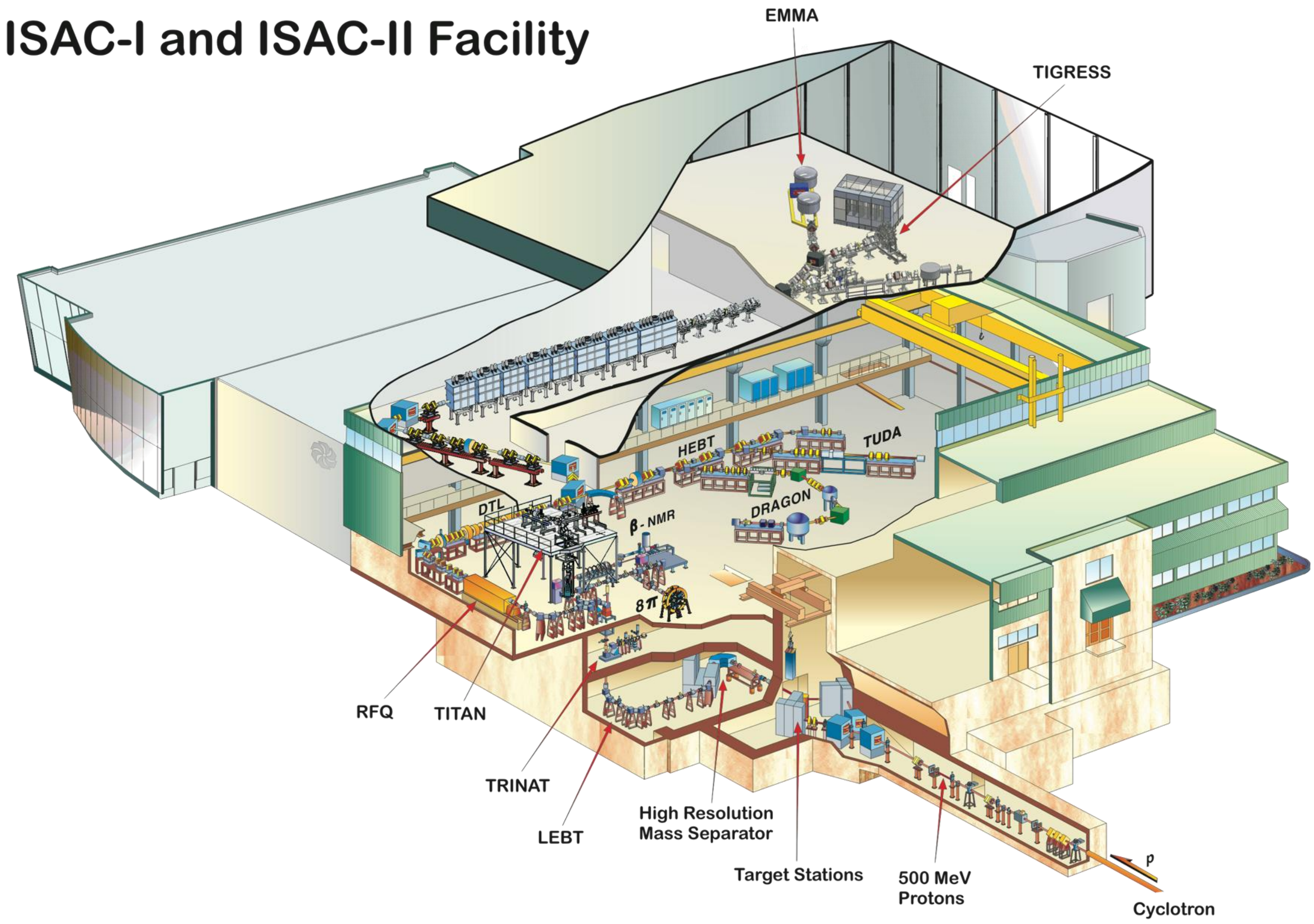
# Argonne National Lab: ATLAS + nuCARIBU



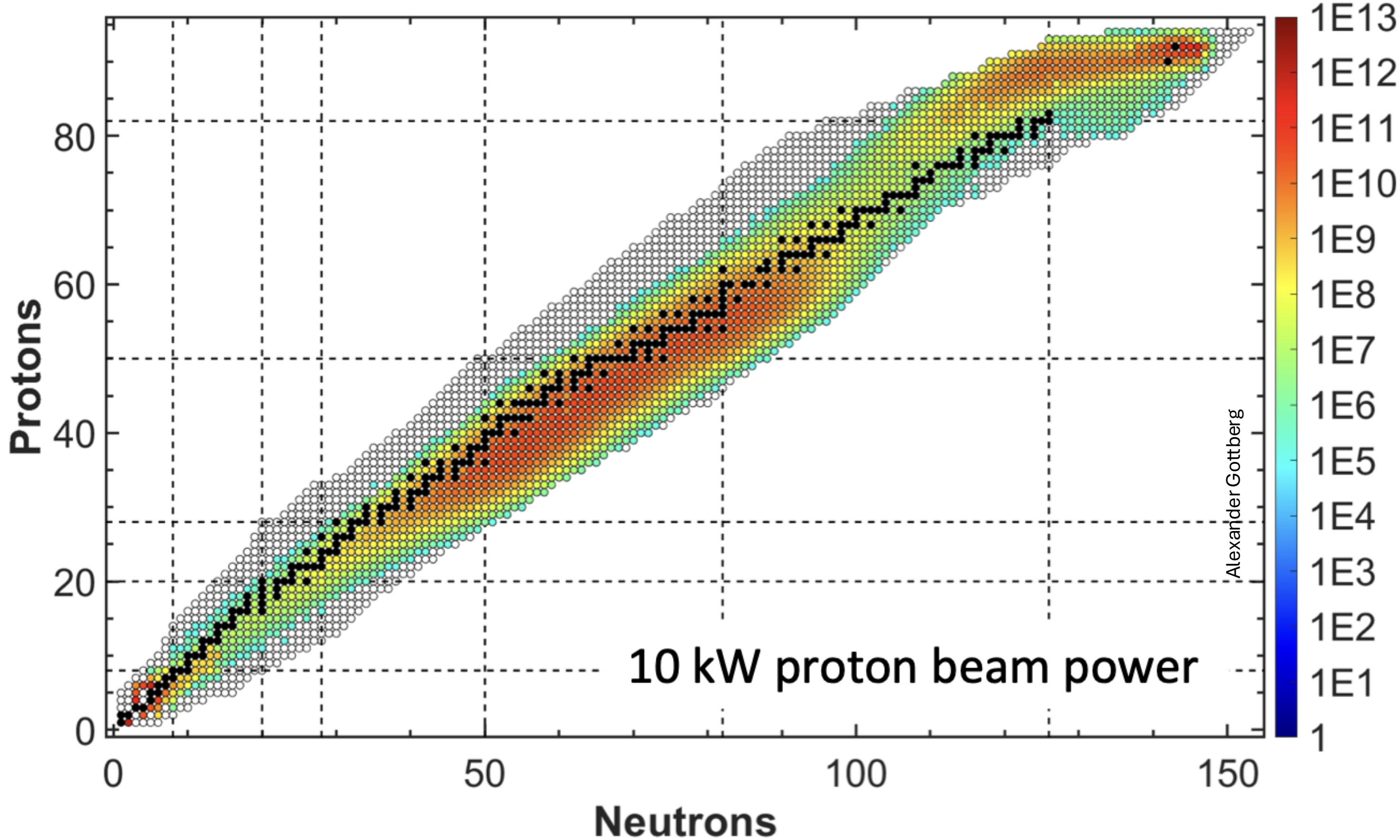
# nuCARIBU Beam Rates



# TRIUMF

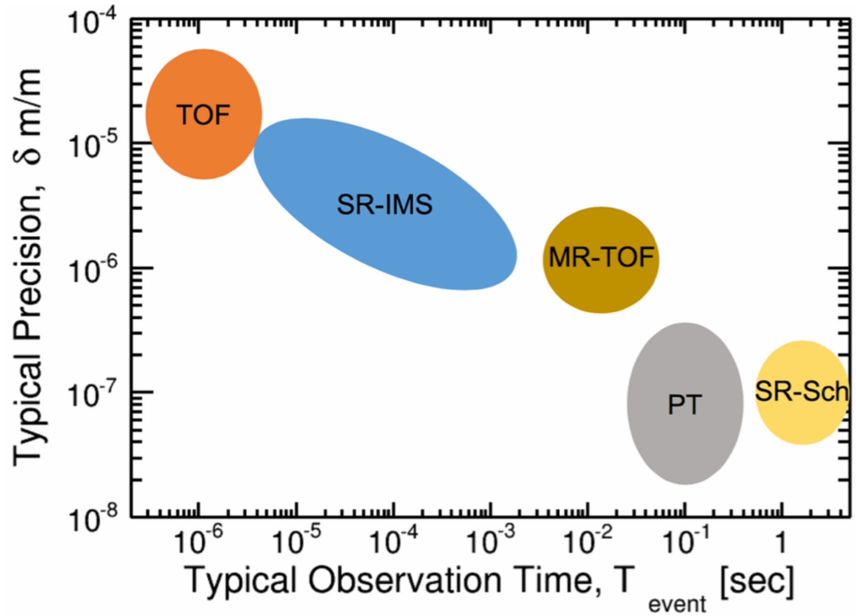

ISAC-I and ISAC-II Facility
EMMA
TIGRESS
HEBT
TUDA
DTL
β - NMR
DRAGON
8π
RFQ
TITAN
TRINAT
LEBT
High Resolution
Mass Separator
Target Stations
500 MeV
Protons
p
Cyclotron

# TRIUMF Upgrade to ARIEL

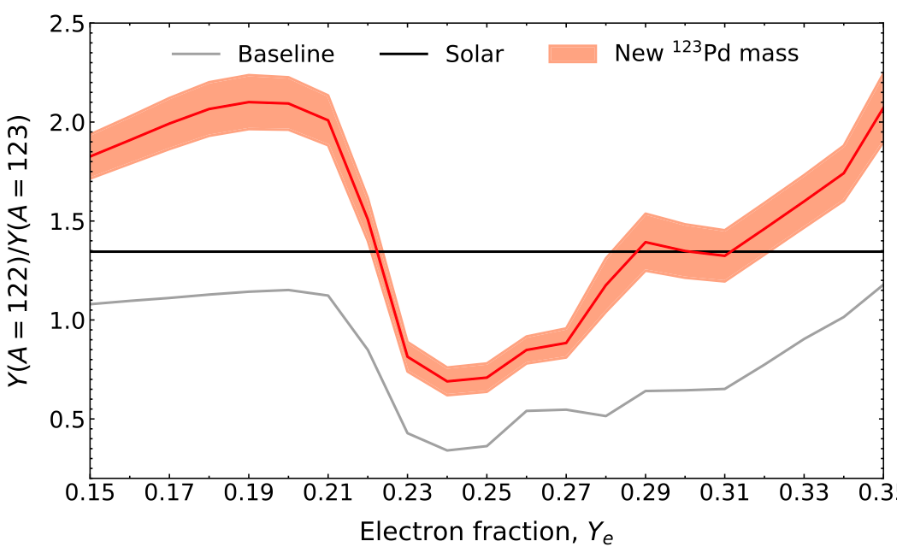


# Mass Measurement Techniques

- Time-of-Flight (ToF)
- Multi-reflection ToF (MR ToF)
- Penning Traps
- Storage Rings: Schottky (SR-Sch)
- Storage Rings: Isochronous Mass Spectrometry (SR-IMS)

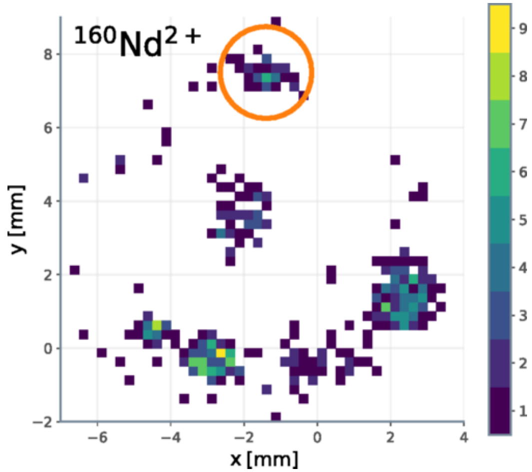


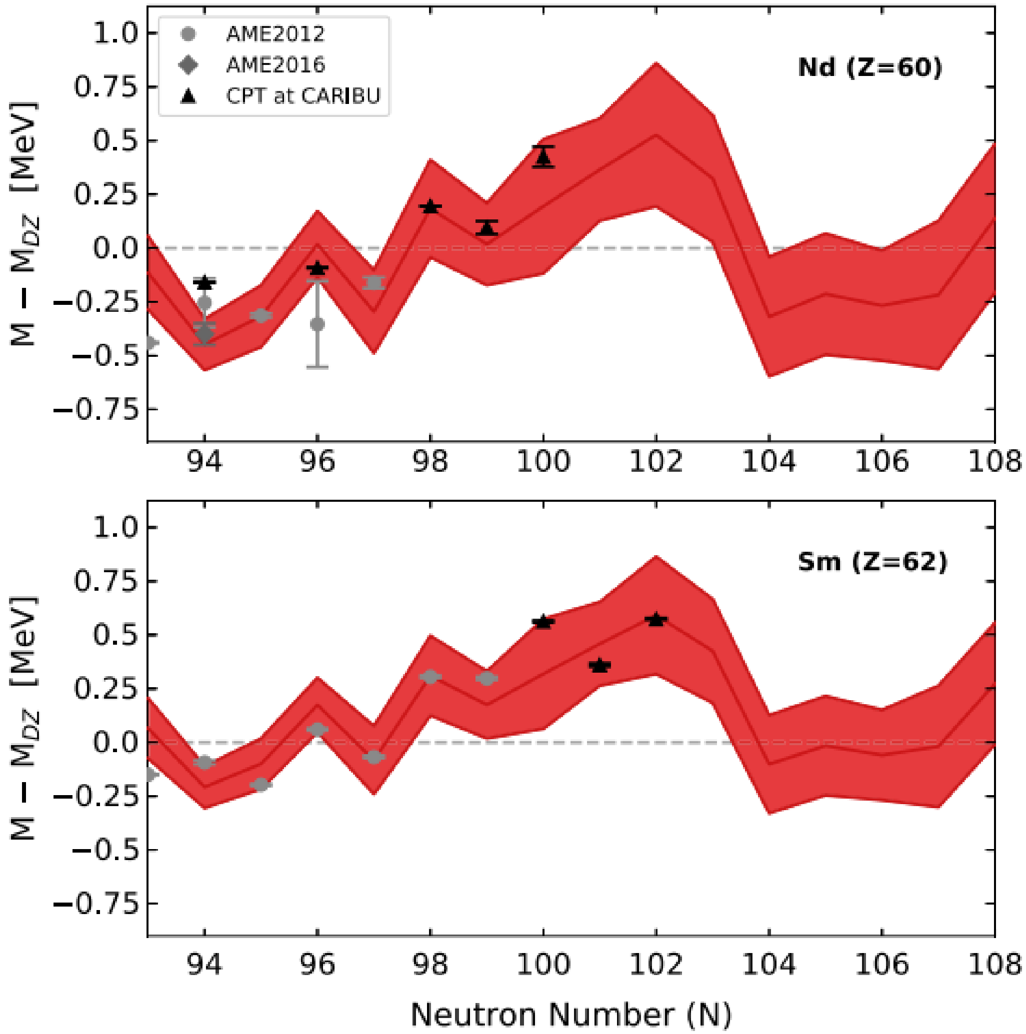

Z. Meisel, Ph.D thesis, Michigan State University (2015)




Clark, *et al*. European Physical Journal A, (2023) 59:204

# Mass Measurements using the CPT @ ANL



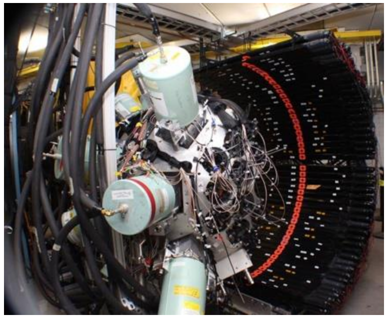

R. Orford et al. PRL 120, 262702 (2018)

# Beta-Decay Properties

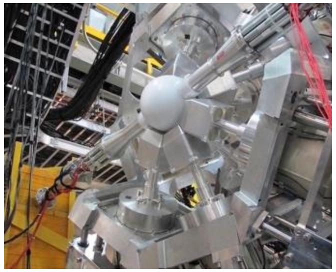
## $\beta$-decay information is important for neutron-capture nucleosynthesis

- **Half-lives**
- $\beta$-delayed neutron emission probabilities
- $\beta$-decay feeding intensities

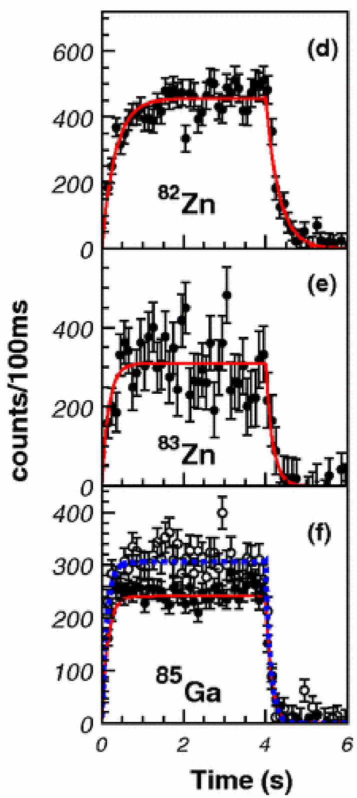
FDSi at FRIB

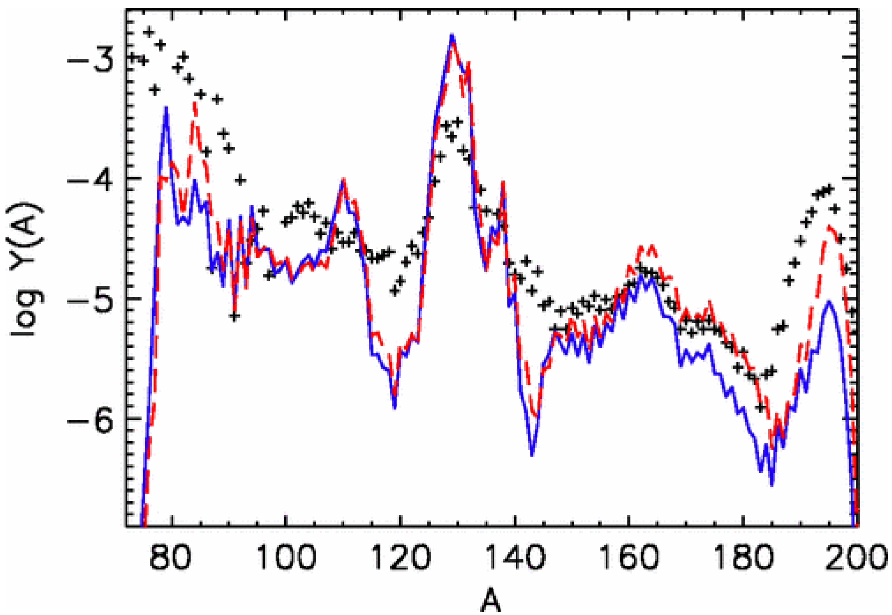


GRIFFIN at TRIUMF



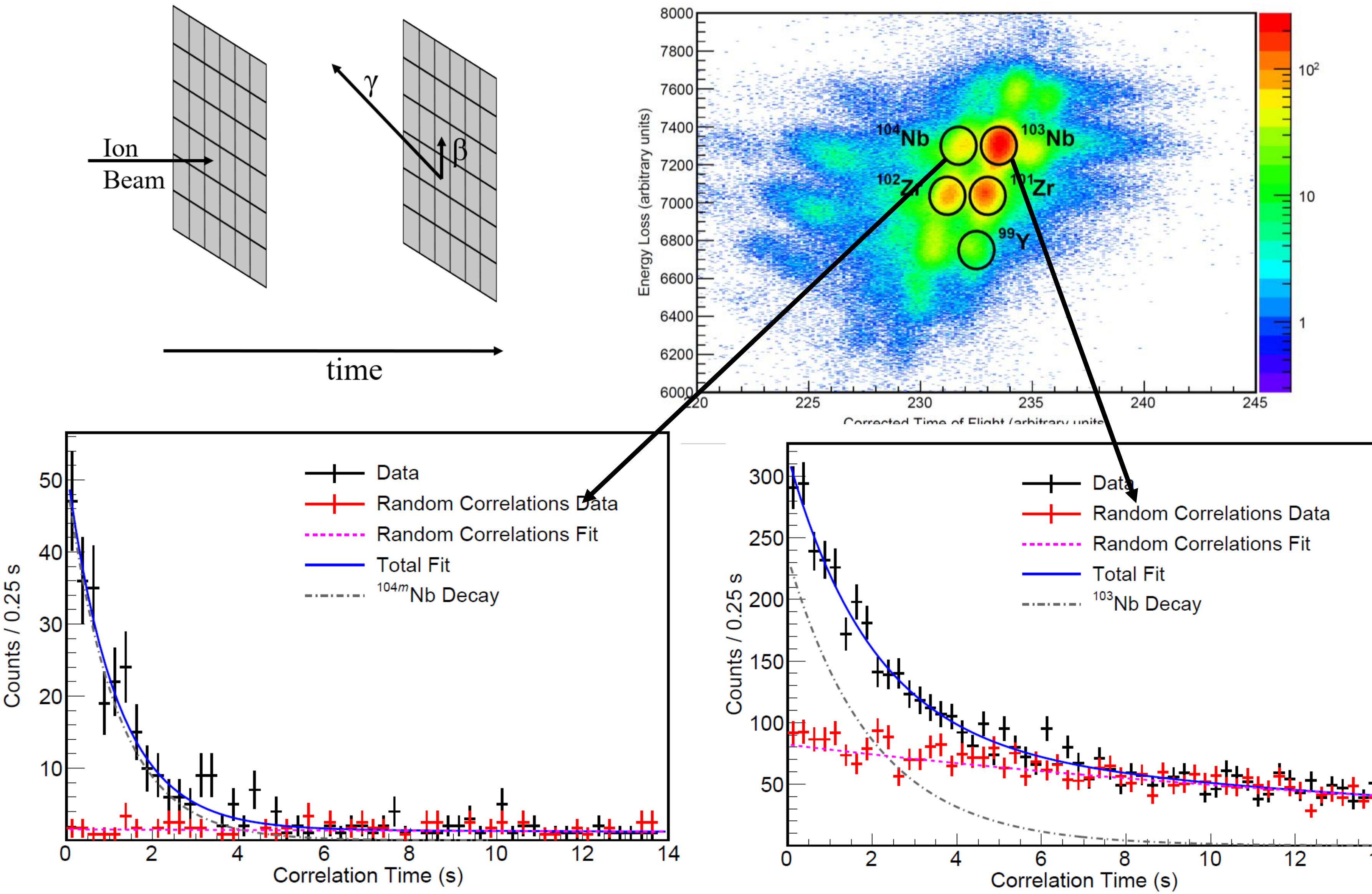
Garnsworthy, *et al.* NIM-A **918**, 2019




M. Madurga, Phys. Rev. Lett. **109**, 112501 (2012)

# Half-Life Determination



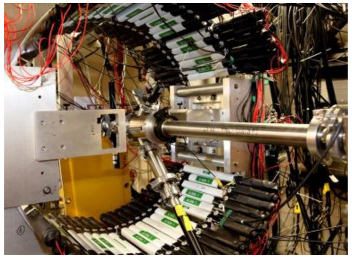

A. C. Dombos Dissertation

# Beta-Decay Properties

$\beta$-decay information is important for neutron capture nucleosynthesis

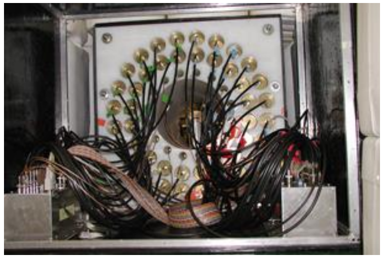
- Half-lives
- **$\beta$-delayed neutron emission probabilities**
- $\beta$-decay feeding intensities

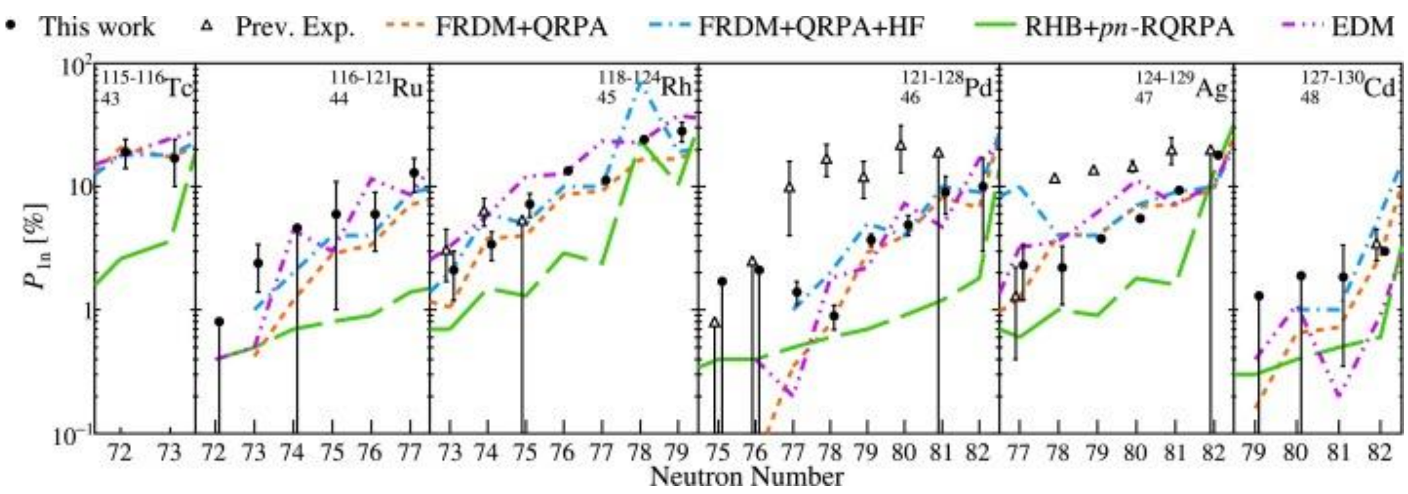
VANDLE at UTK



Peters, *et al.* NIM-A **816**, 2016, pages 122-133

NERO at FRIB



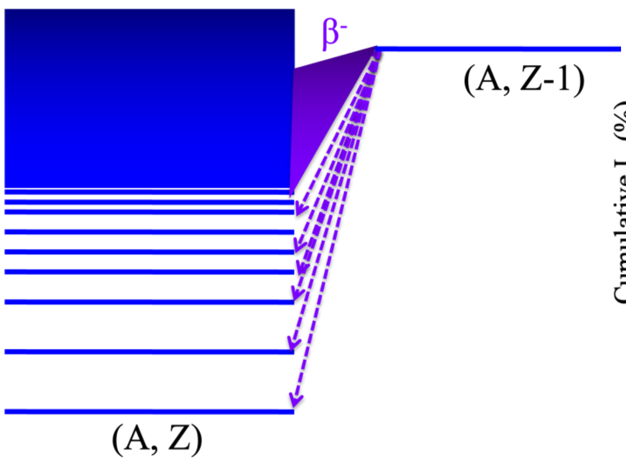


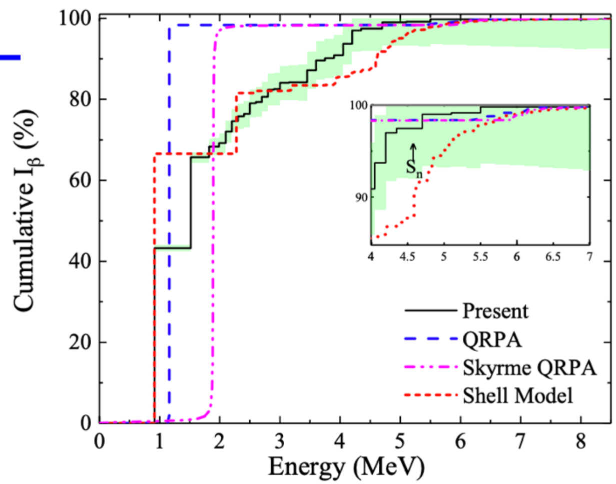

O. Hall, Phys. Lett. B **816**, 136266 (2021)

# Beta-Decay Properties

## $\beta$-decay information is important for neutron capture nucleosynthesis

- Half-lives
- $\beta$-delayed neutron emission probabilities
- **$\beta$-decay feeding intensities**




(a) Cumulative $I_\beta$ results for $^{69}$Co decay.

Lyons *et al.* PRC **100**, 025806 (2019)

MTAS at ORNL

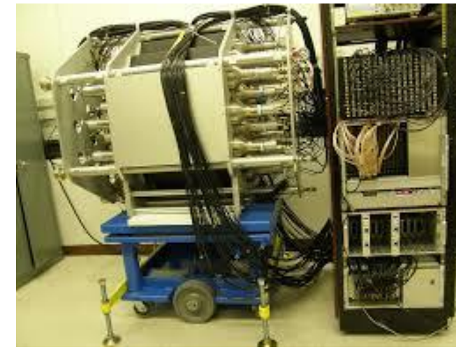
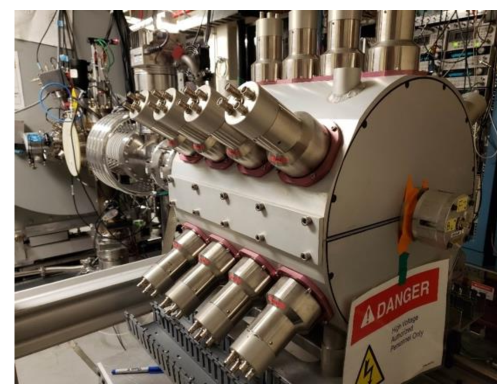


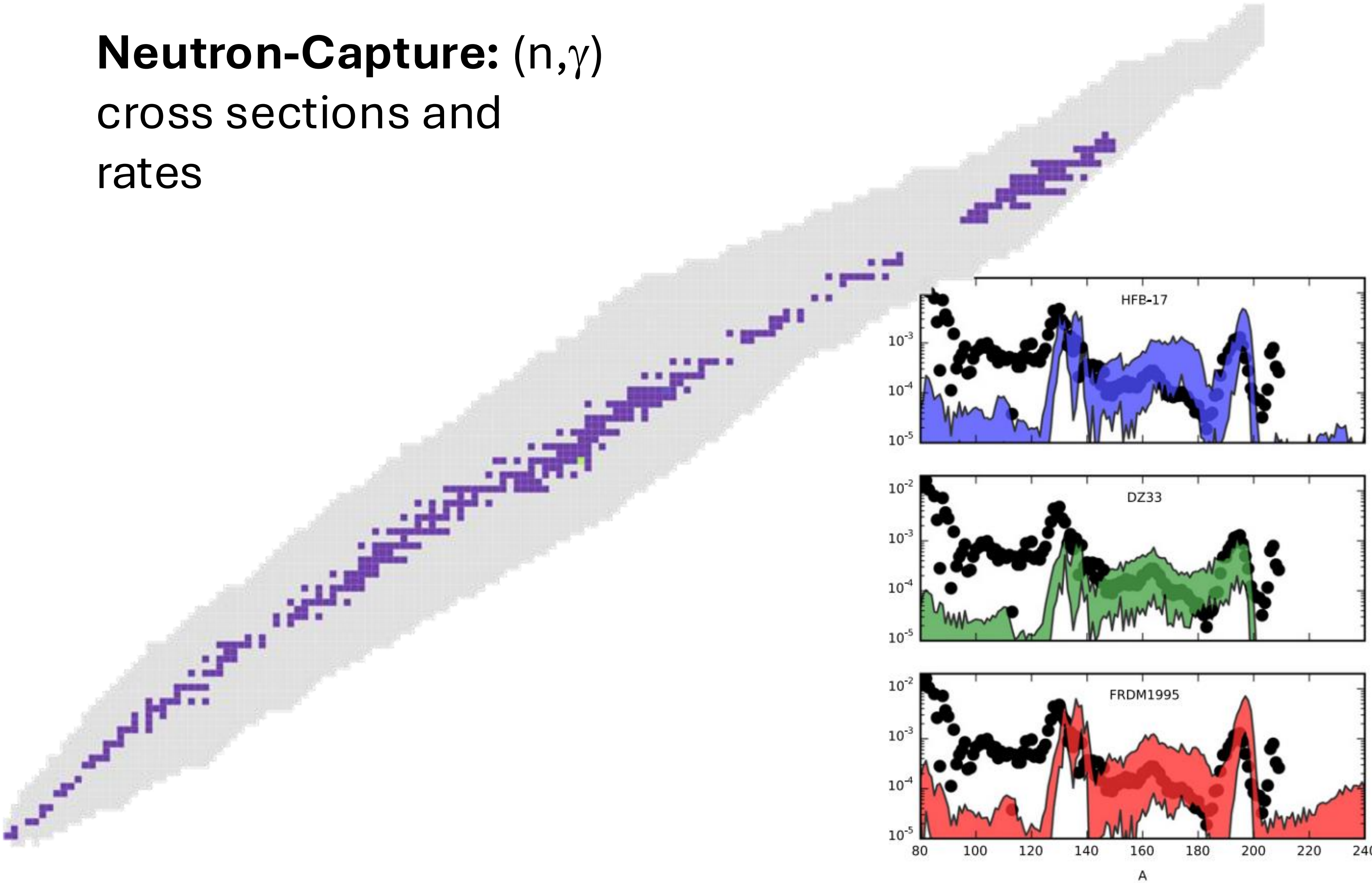
Photo from M. Karny

SuN at FRIB



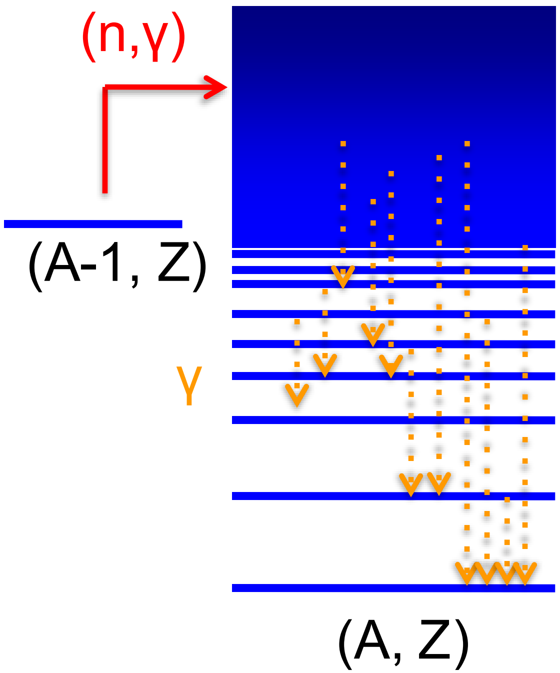
# Recall the Status of Neutron-Capture

**Neutron-Capture:** (n,$\gamma$) cross sections and rates




Mumpower *et al.* Prog. Part. Nucl. Phys. **86**, 86 (2016)

# Hauser Feshbach Formalism




**Hauser – Feshbach**

- Nuclear Level Density

Constant T + Fermi gas, back-shifted Fermi gas, super-fluid, microscopic

- γ-ray strength function

Generalized Lorentzian, Brink-Axel, various tables

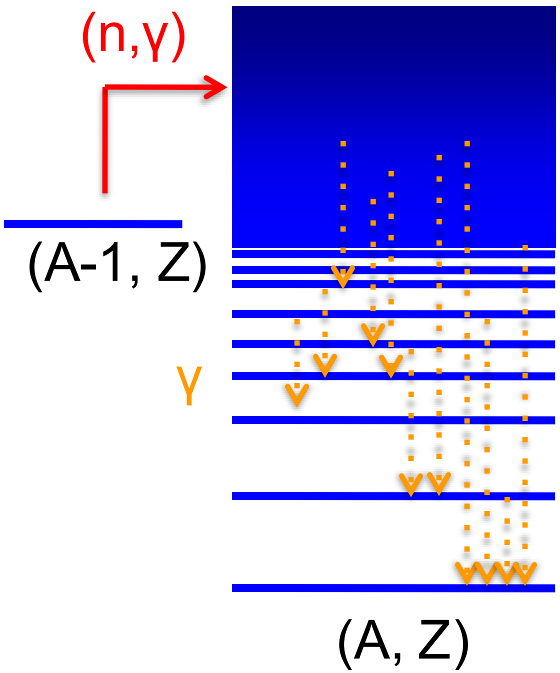
- Optical model potential

Phenomenological, Semi-microscopic

$^{95}Sr(n,\gamma)^{96}Sr$

Koning and Rochman, Nucl. Data Sheets **113**, 2841 (2012)
Hauser and Feshbach, Phys. Rev. **87**, 366 (1952)

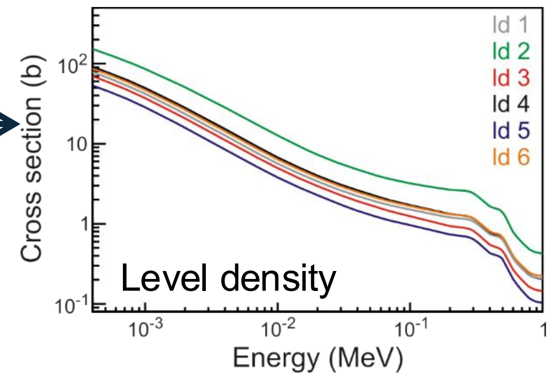
# Hauser Feshbach Formalism




**Hauser – Feshbach**

- Nuclear Level Density

Constant T + Fermi gas, back-shifted
Fermi gas, super-fluid, microscopic




- γ-ray strength function

Generalized Lorentzian, Brink-Axel,
various tables

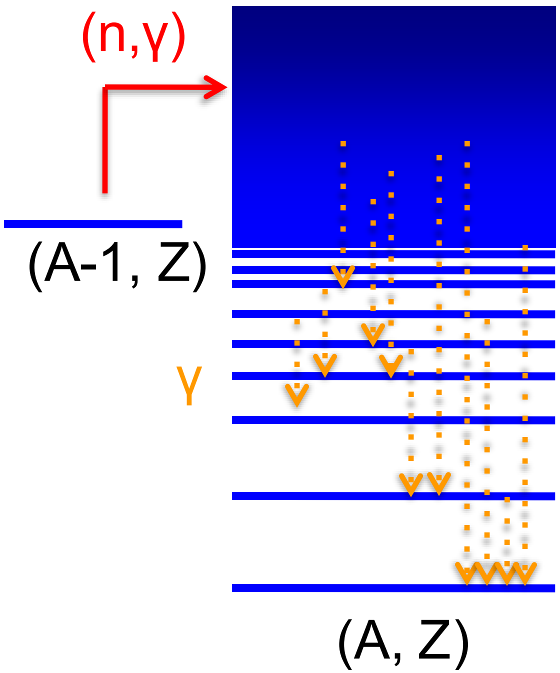
- Optical model potential

Phenomenological, Semi-microscopic

$^{95}Sr(n,\gamma)^{96}Sr$

Koning and Rochman, Nucl. Data Sheets **113**, 2841 (2012)
Hauser and Feshbach, Phys. Rev. **87**, 366 (1952)

# Hauser Feshbach Formalism




## Hauser – Feshbach

- Nuclear Level Density

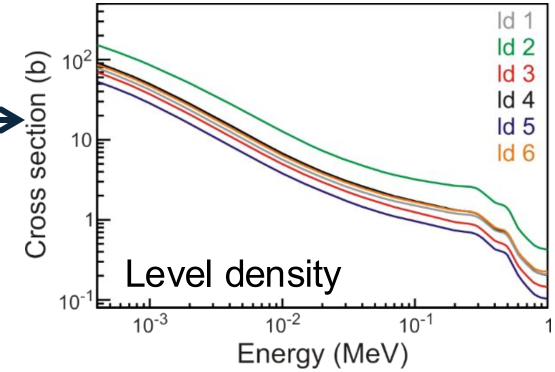
Constant T + Fermi gas, back-shifted Fermi gas, super-fluid, microscopic

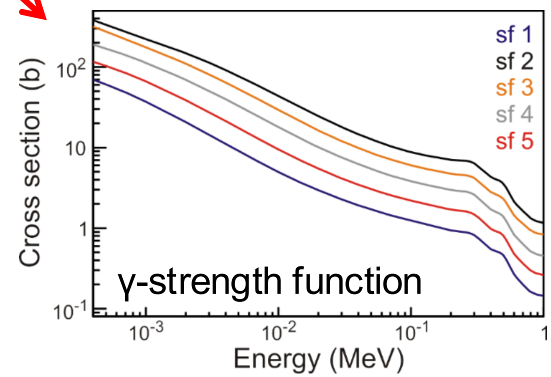
- γ-ray strength function

Generalized Lorentzian, Brink-Axel, various tables

- Optical model potential

Phenomenological, Semi-microscopic

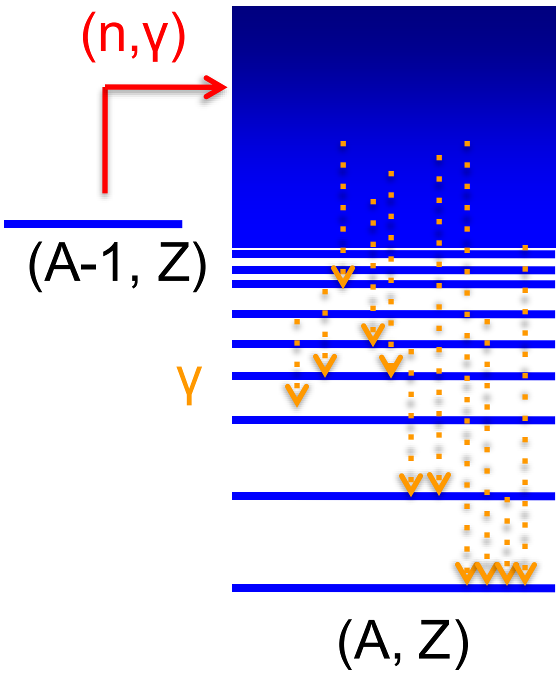



$^{95}Sr(n,\gamma)^{96}Sr$


Koning and Rochman, Nucl. Data Sheets **113**, 2841 (2012)
Hauser and Feshbach, Phys. Rev. **87**, 366 (1952)

# Hauser Feshbach Formalism




**Hauser – Feshbach**

- Nuclear Level Density

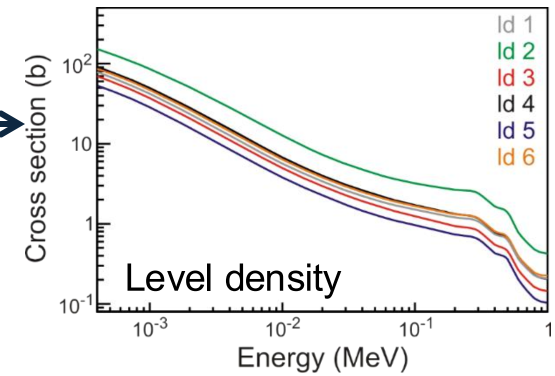
Constant T + Fermi gas, back-shifted Fermi gas, super-fluid, microscopic

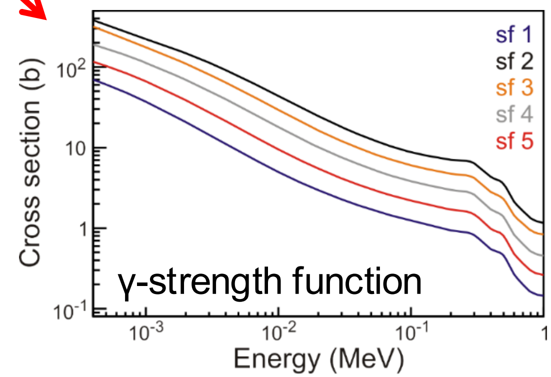
- γ-ray strength function

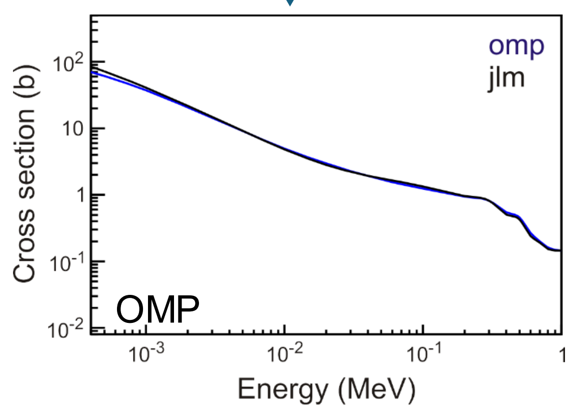
Generalized Lorentzian, Brink-Axel, various tables

- Optical model potential

Phenomenological, Semi-microscopic



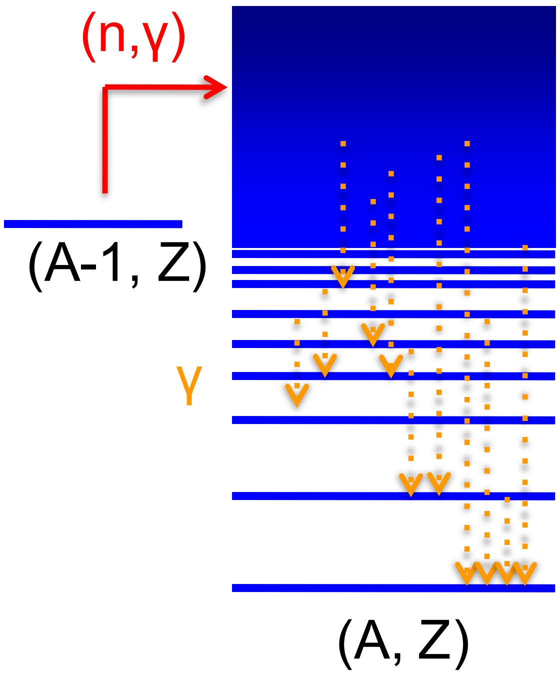




$^{95}Sr(n,\gamma)^{96}Sr$

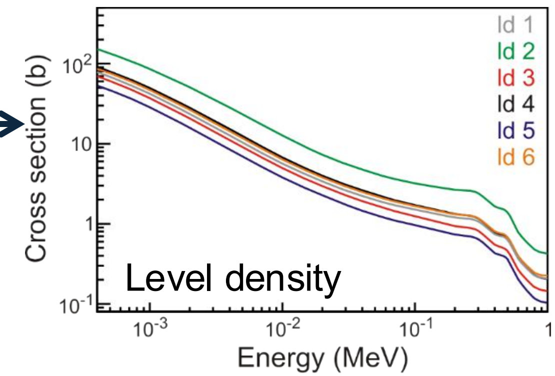

Koning and Rochman, Nucl. Data Sheets **113**, 2841 (2012)
Hauser and Feshbach, Phys. Rev. **87**, 366 (1952)

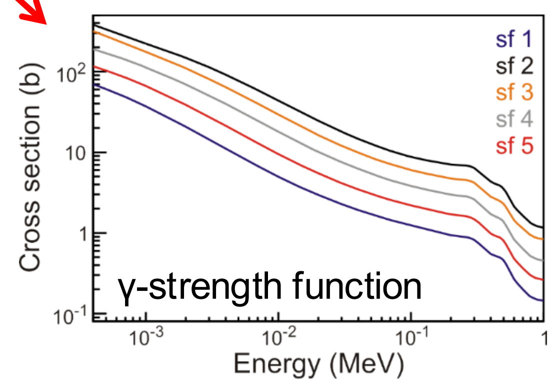
# Hauser Feshbach Formalism

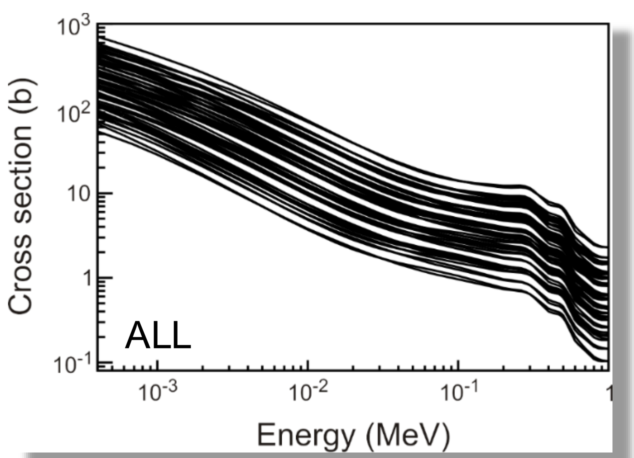


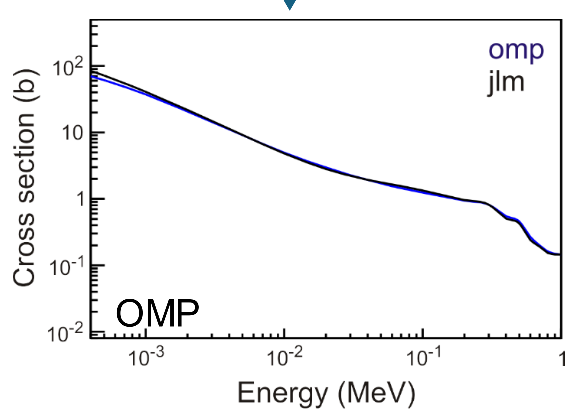

## Hauser – Feshbach

- Nuclear Level Density
  Constant T + Fermi gas, back-shifted Fermi gas, super-fluid, microscopic
- γ-ray strength function
  Generalized Lorentzian, Brink-Axel, various tables
- Optical model potential
  Phenomenological, Semi-microscopic



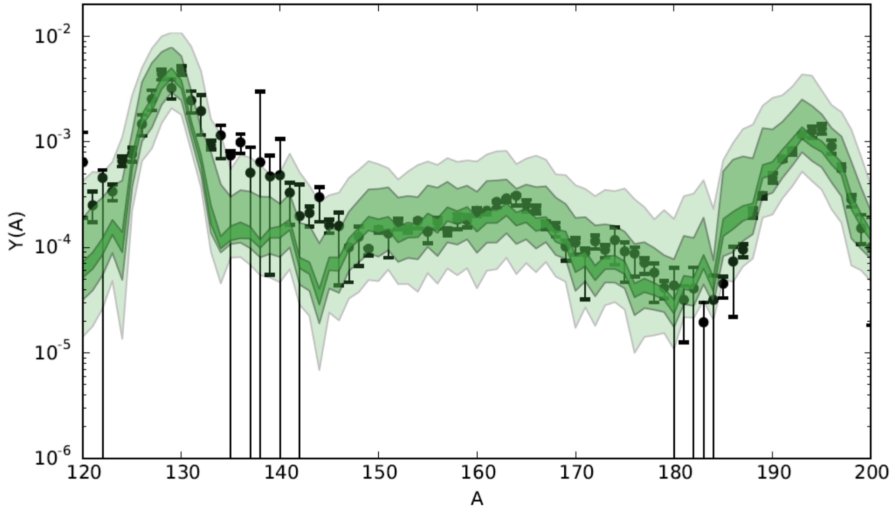




$^{95}Sr(n,\gamma)^{96}Sr$


Koning and Rochman, Nucl. Data Sheets **113**, 2841 (2012)
Hauser and Feshbach, Phys. Rev. **87**, 366 (1952)

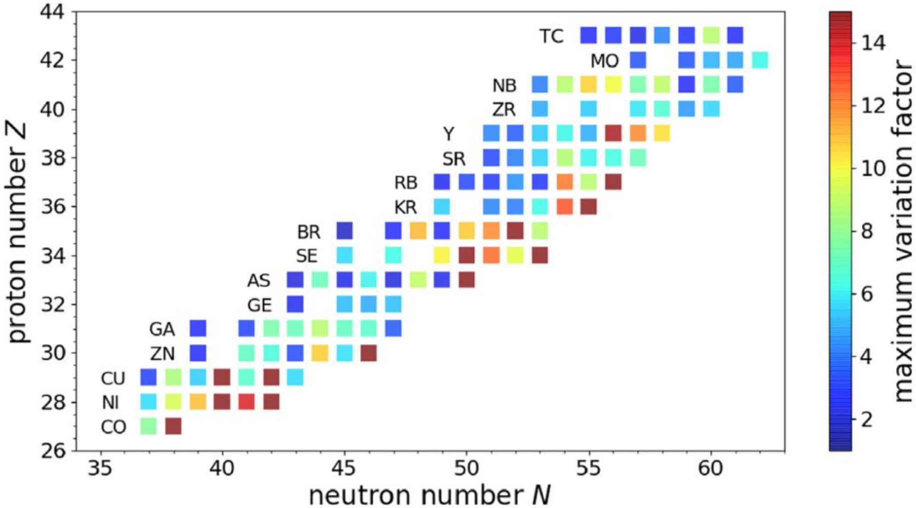
# (n,γ) uncertainties impact heavy element creation

r-process



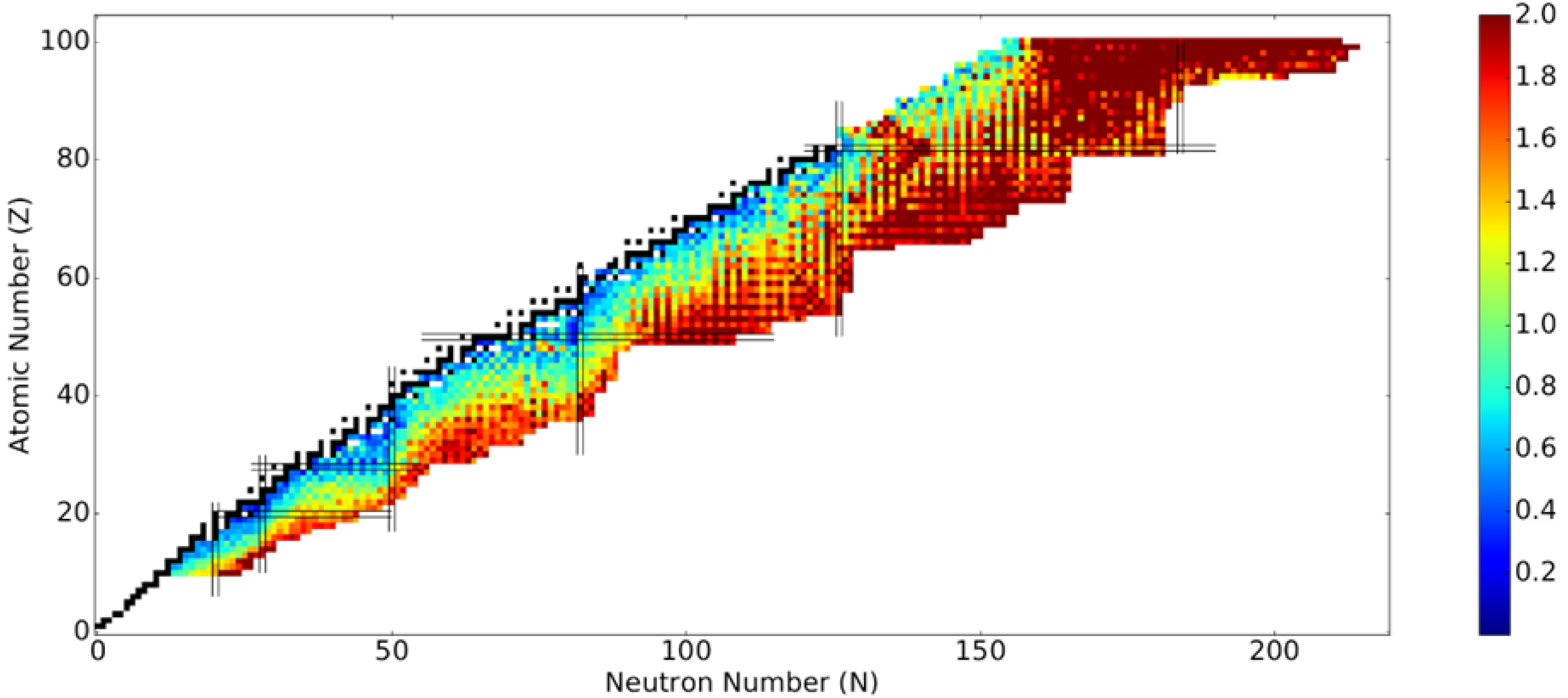

S.N. Liddick, A. Spyrou, *et al.*, Phys. Rev. Lett. **116**, 242502 (2016)

i-process



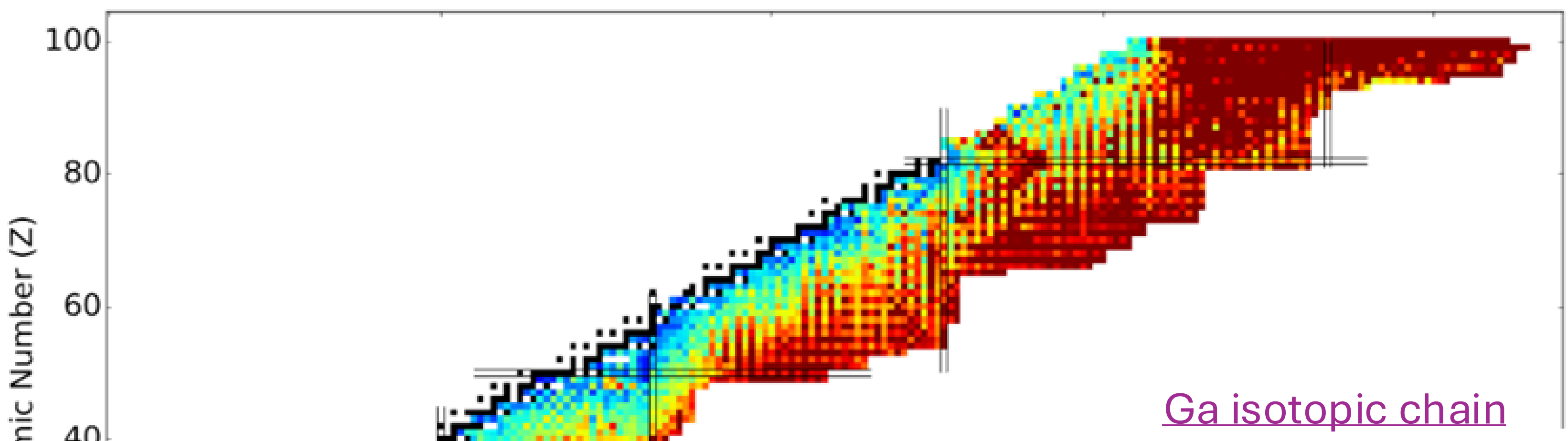

J. McKay *et al.*, MNRAS **491**, 5179–5187 (2020)

# NLD and $\gamma$SF uncertainties lead to large (n,$\gamma$) uncertainties

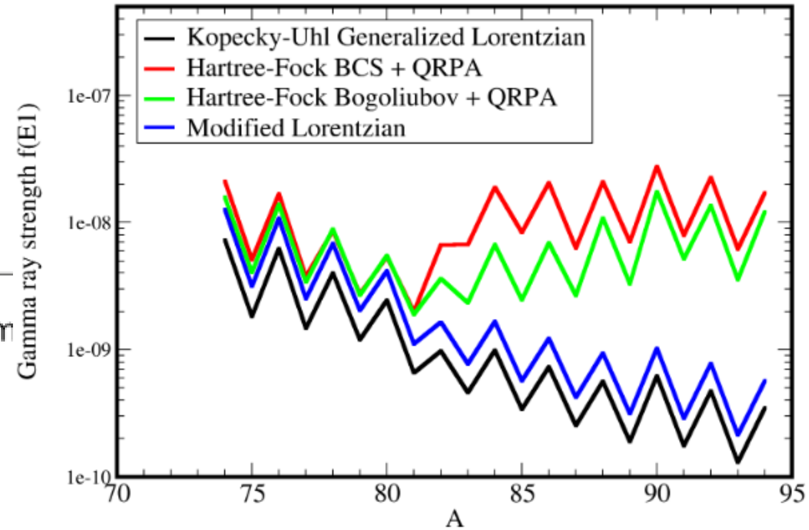



S. Nikas, arXiv:2010.01698
R. Lewis, private comm.

# NLD and γSF uncertainties lead to large (n,γ) uncertainties

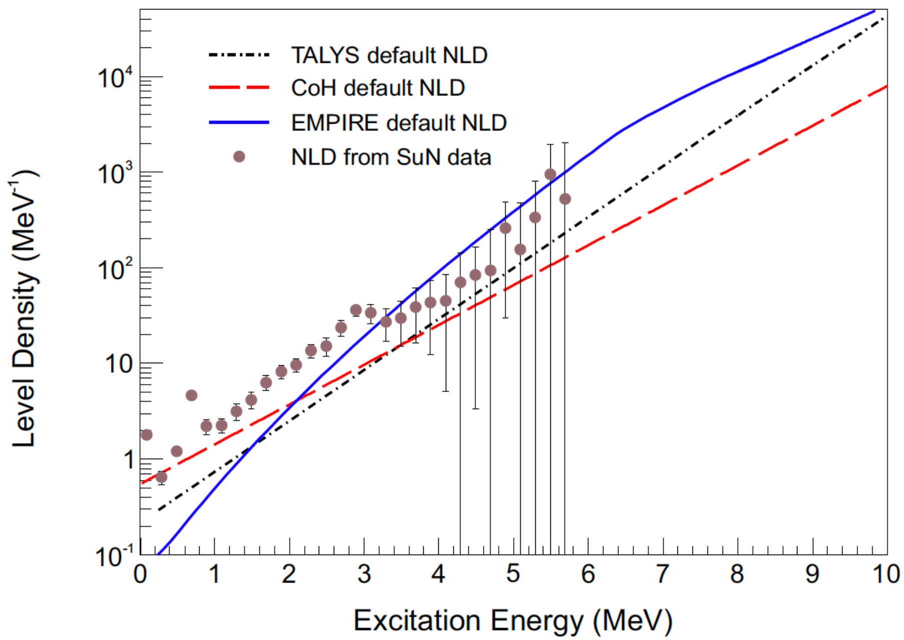


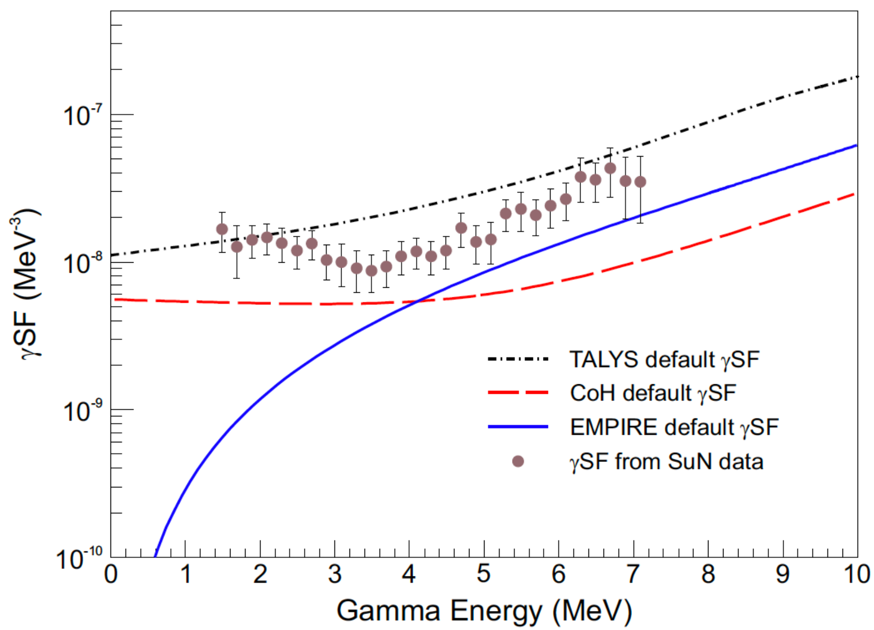

Ga isotopic chain




01698
m.

# NLD and γSF uncertainties lead to large (n,γ) uncertainties



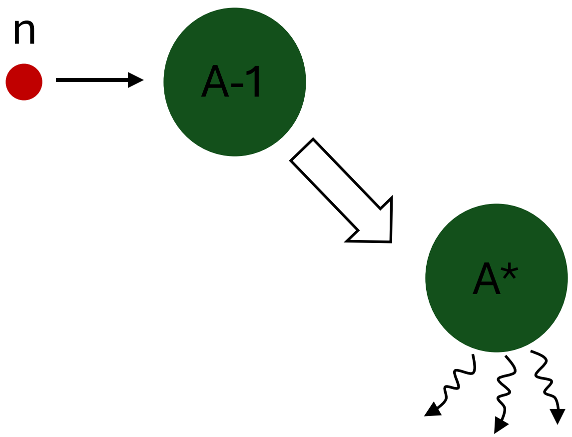

**Codes used to calculate NLD and γSF show large variations**

S. Nikas, arXiv:2010.01698
R. Lewis, private comm.

# How do we measure neutron-capture reactions?

**Direct Measurement**

- Only feasible for stable or long-lived nuclei
- For i/n/r-process, desired targets are too short-lived
- No feasible neutron target…
- Not possible for rare isotopes



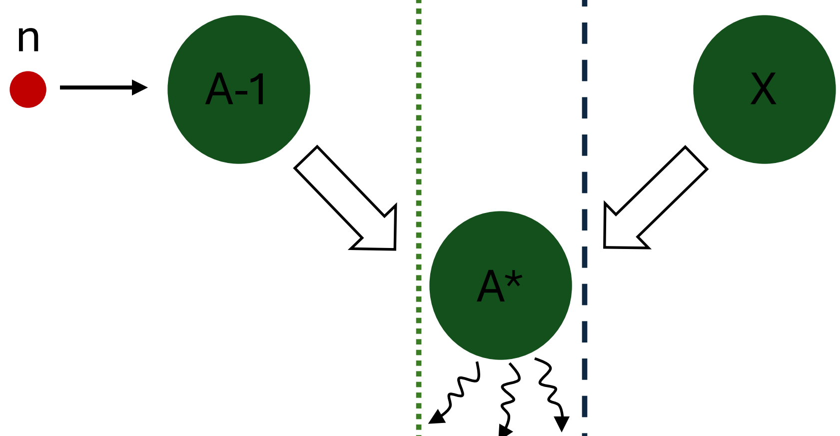
# How do we measure neutron-capture reactions?

**Direct Measurement**

- Only feasible for stable or long-lived nuclei
- For i/n/r-process, desired targets are too short-lived
- No feasible neutron target…
- Not possible for rare isotopes

**Indirect Measurement**

- Access same nucleus through different pathway
- Can utilize short half-lives



# How do we measure neutron-capture reactions?

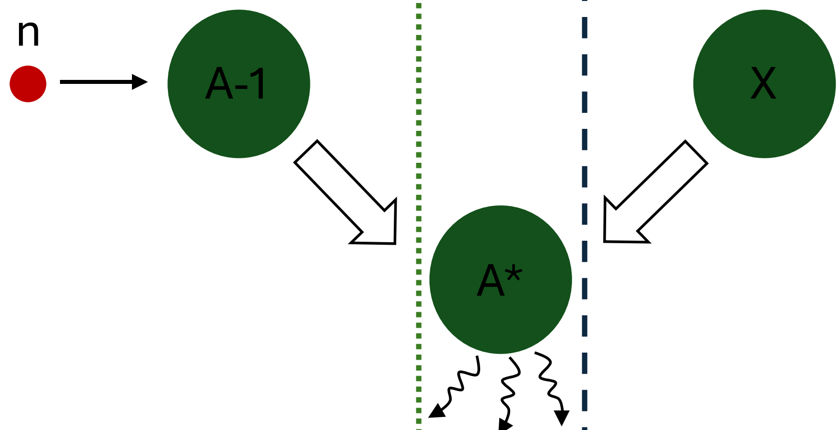
**Direct Measurement**

- Only feasible for stable or long-lived nuclei
- For i/n/r-process, desired targets are too short-lived
- No feasible neutron target…
- Not possible for rare isotopes

**Indirect Measurement**

- Access same nucleus through different pathway
- Can utilize short half-lives

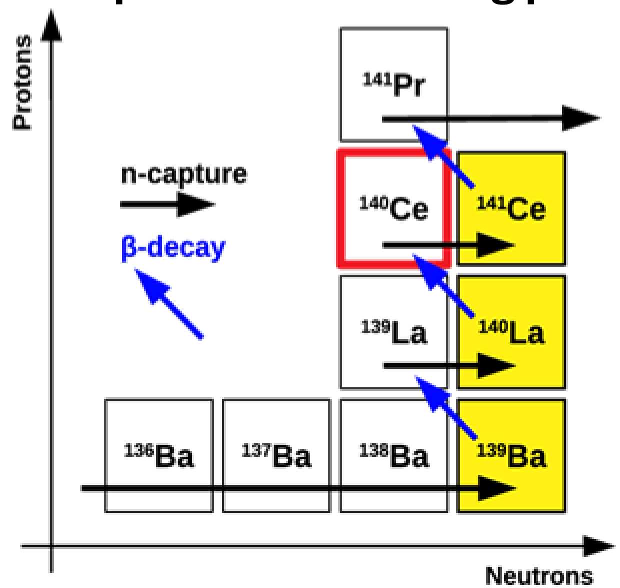
*Some Examples*:
Oslo Method
**β-Oslo Method**
**Surrogate Method**
**Inverse Oslo Method**
γ-ray strength method
**Particle Evaporation Method**

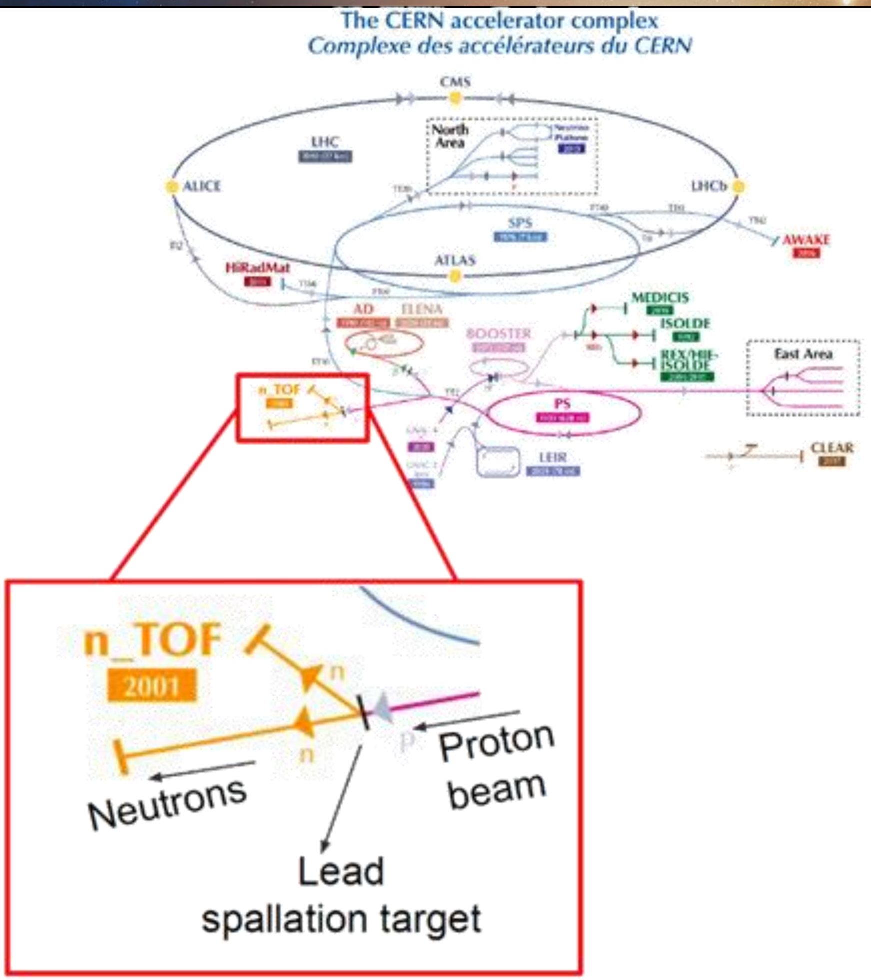



A. Spyrou *et al.*, PRL **113**, 232502 (2014)
J. Escher *et al.*, PRL **121**, 052501 (2018)
A. Ratkiewicz *et al.*, PRL **122**, 052502 (2019)
H. Utsunomiya *et al.*, PRC **82**, 064610 (2010)
M. Guttormsen *et al.*, NIMA **255**, 518 (1987)
M. Guttormsen *et al.*, NIMA **374**, 371 (1996)
A. Schiller *et al.*, NIMA **447**, 498 (2000)
A.C. Larsen *et al.*, PRC **83**, 034315 (2011)
V. Ingeberg *et al.*, EPJA **56**, 68 (2020)
V. Ingeberg *et al.*, PRC **106**, 054315 (2022)
A. Voinov, *et al.*, PRC **99**, 054609 (2019).

# Direct Measurements: $^{140}$Ce(n,$\gamma$) at n_TOF

**s-process branching point**

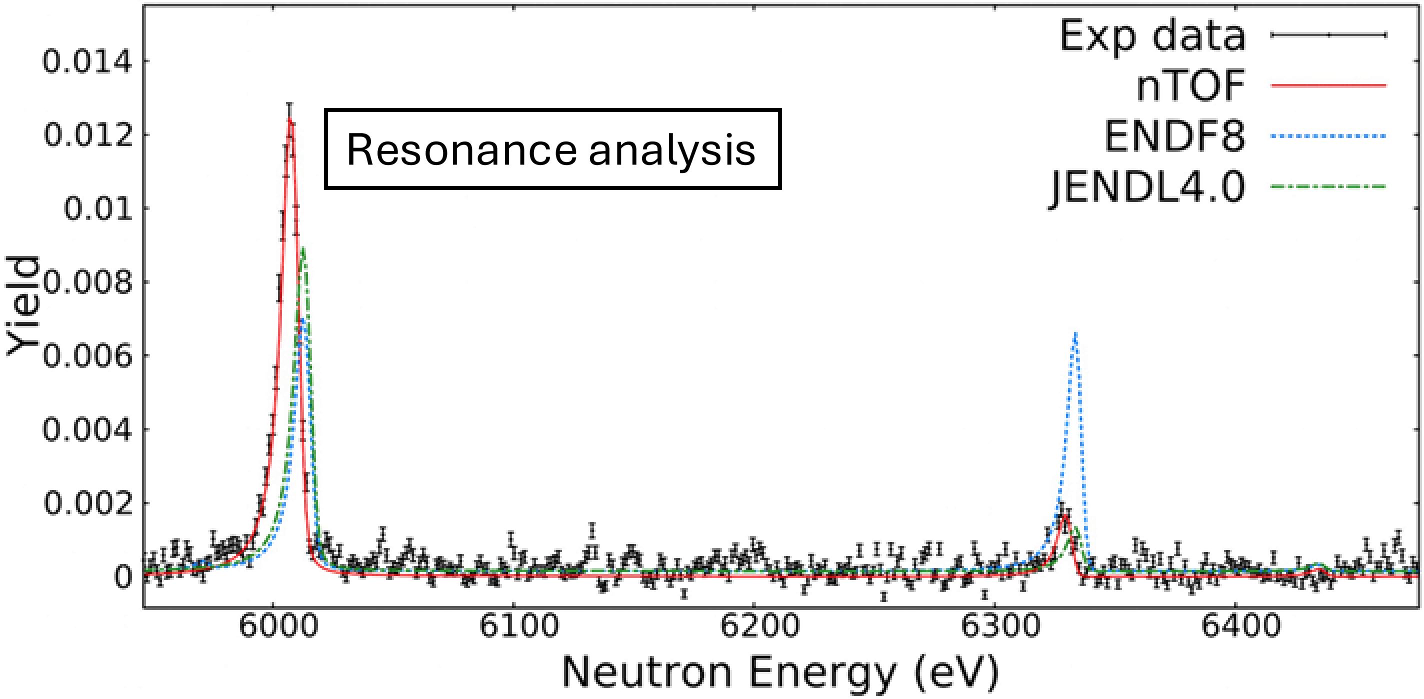



- CERN's n_TOF facility
  - Spallation neutrons
- ~185 m flight path
- Prompt gamma cascade analysis using 4 deuterated scintillators and a pure $^{140}$Ce target

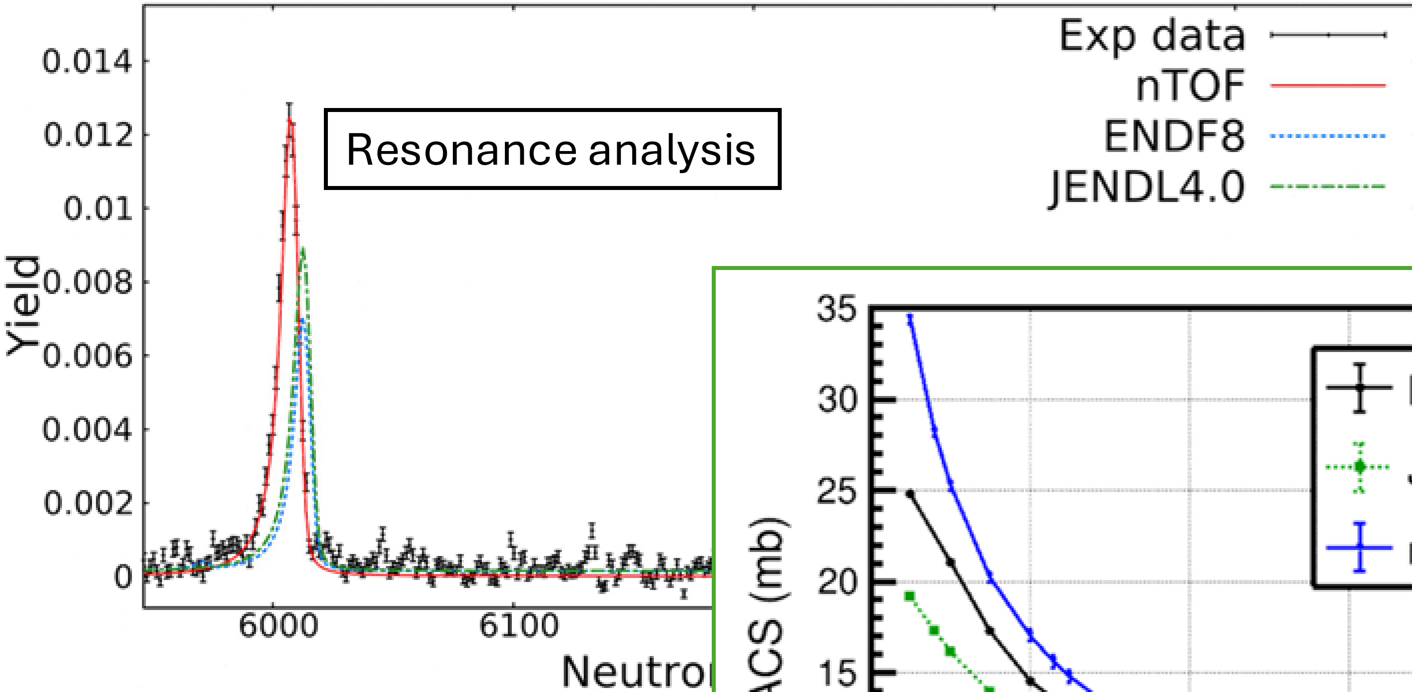
S. Amaducci, *et al*. PRL **132**, 122701 (2024)

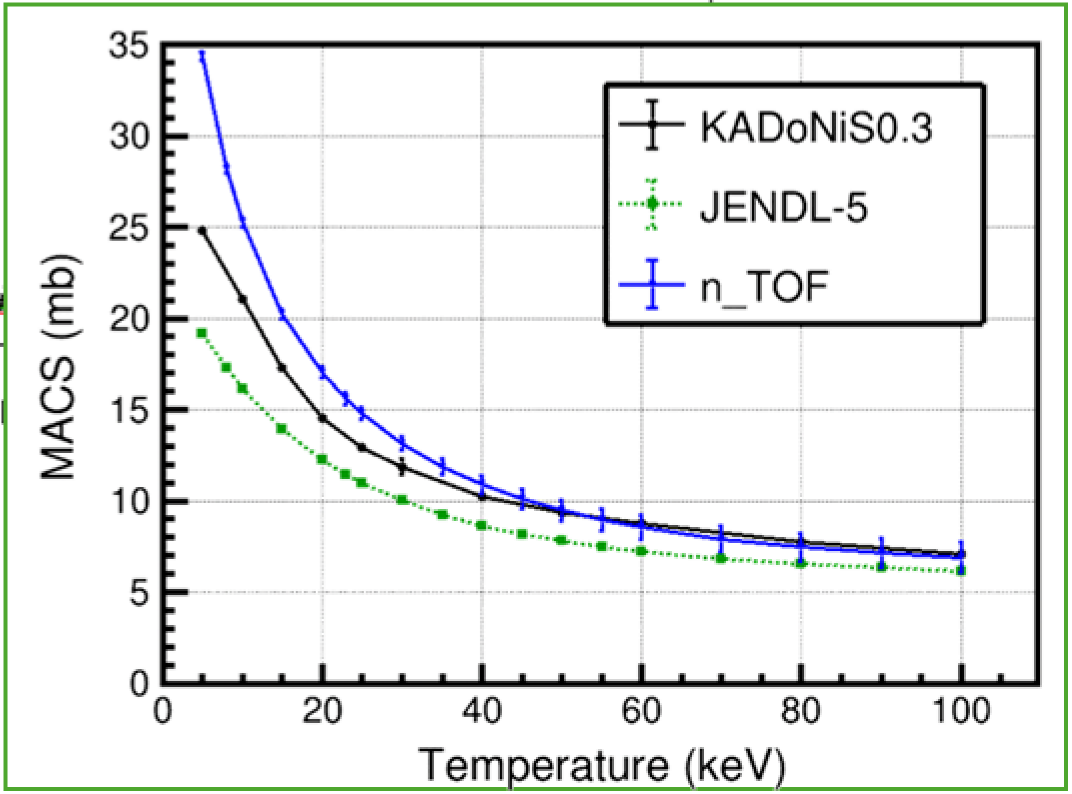
# Direct Measurements: $^{140}Ce(n,\gamma)$ at n_TOF




S. Amaducci, *et al*. PRL **132**, 122701 (2024)

# Direct Measurements: $^{140}Ce(n,\gamma)$ at n_TOF



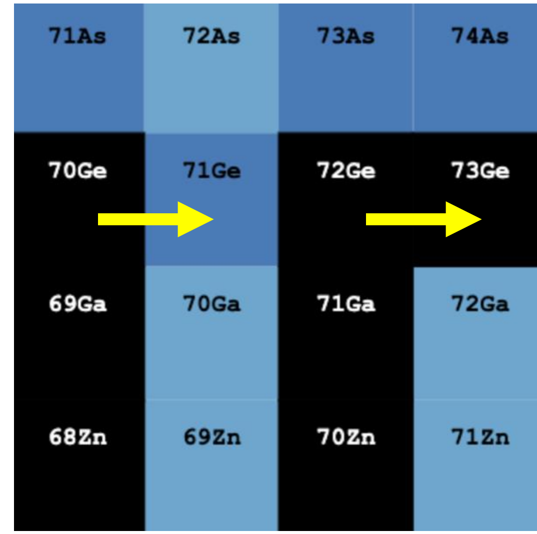



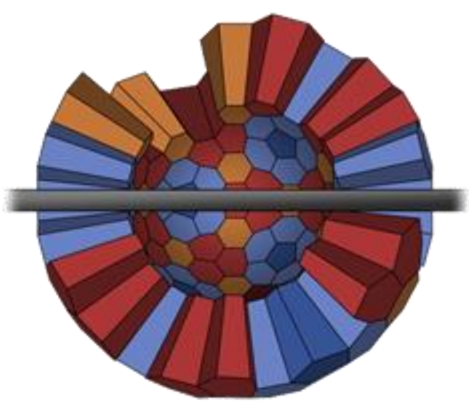

S. Amaducci, *et al*. PRL **132**, 122701 (2024)

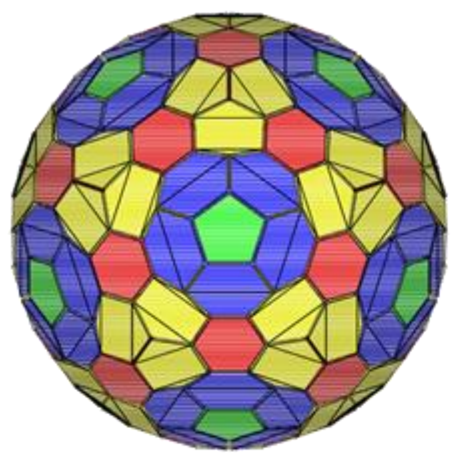
New MACS values lead to lower cerium production in AGB stars

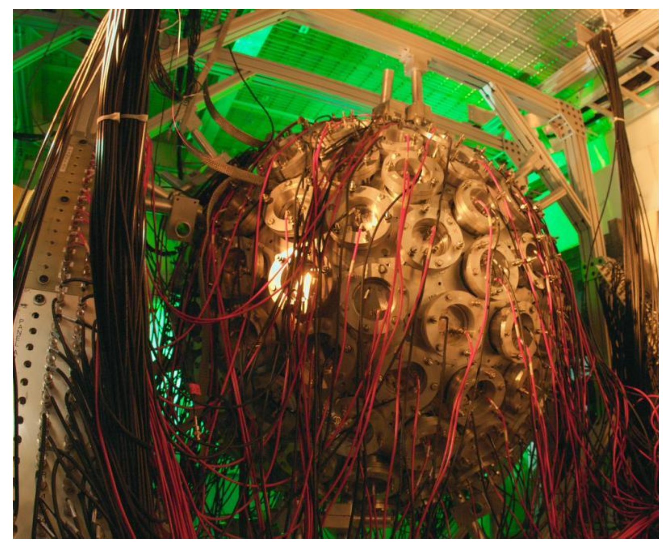
# Direct Measurements: $^{70,72}$Ge(n,$\gamma$) @ DANCE

- 800-MeV proton beam on tungsten target
- $^{70,72}$Ge targets
- Gamma-rays detected in DANCE (Detector for Advanced Neutron Capture Experiments): 160 $BaF_2$ detectors



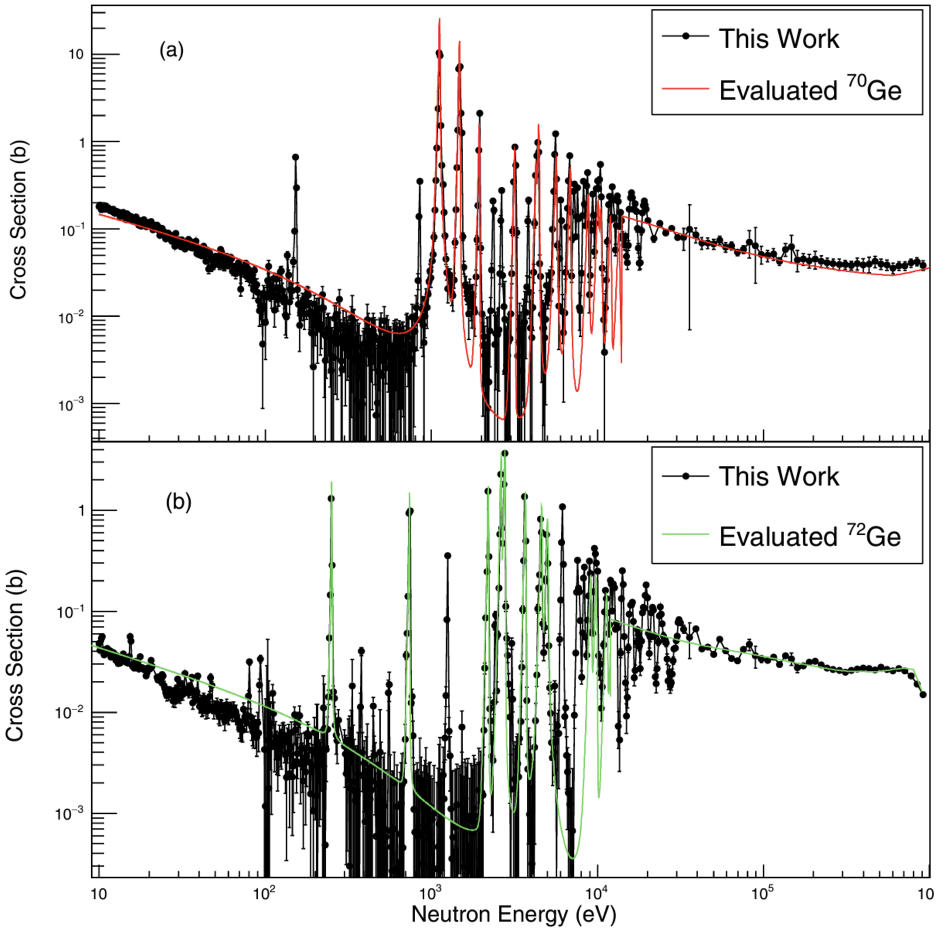



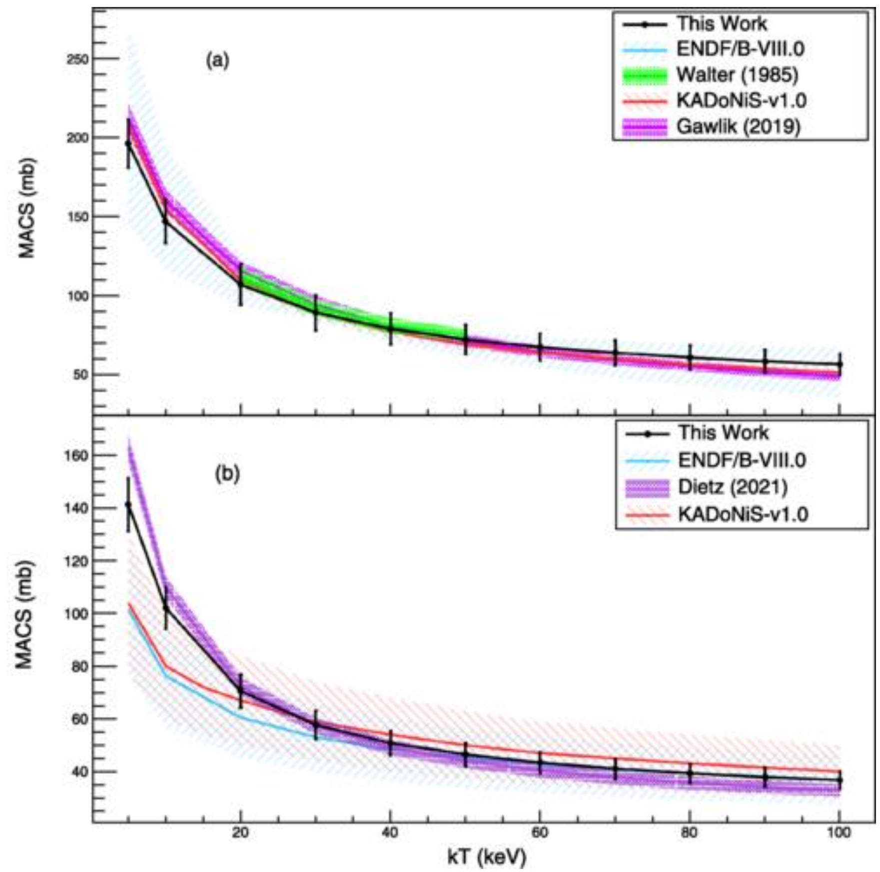




A. Laminack, *et al*. PRC **106**,025802(2022)

# Direct Measurements: $^{70,72}Ge(n,\gamma)$ @ DANCE

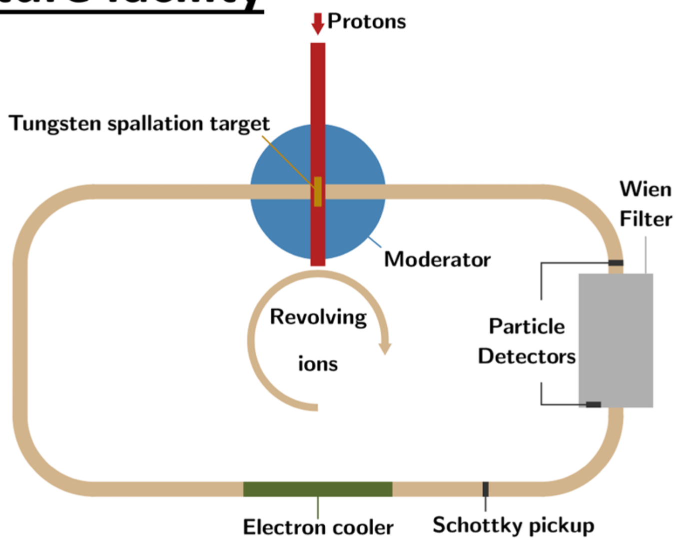


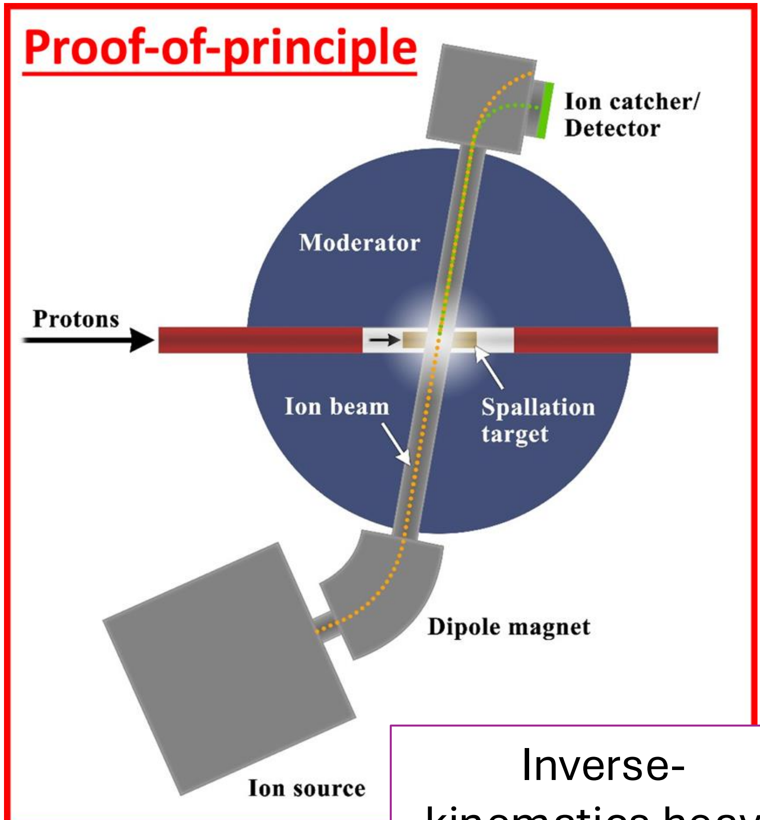




A. Laminack, *et al*. PRC **106**,025802 (2022)

# Novel Direct Technique at LANL

**Future facility**




Inverse-kinematics heavy ion beam impinging a neutron field

- **Goal**: Measure neutron reactions on unstable isotopes with $t_{1/2}$~minutes

Concept in R. Reifarth, et al. Phys. Rev. Accel. Beams 20, 044701 (2017).

Figures courtesy R. Reifarth

# Wrapping Up for Today

- Most elements heavier than iron synthesized in capture processes
- Many nuclear properties need to be measured – focus on $(n,\gamma)$ for these lectures
- Direct measurements only feasible for stable elements or long-lived isotopes (mostly s-process)

- Tomorrow:
  - Indirect neutron-capture methods for s, i, and r-process

# Thank you!

Questions?

Thanks to A. Spyrou for slide suggestions!