Neutron-capture constraints for the astrophysical *i*-process

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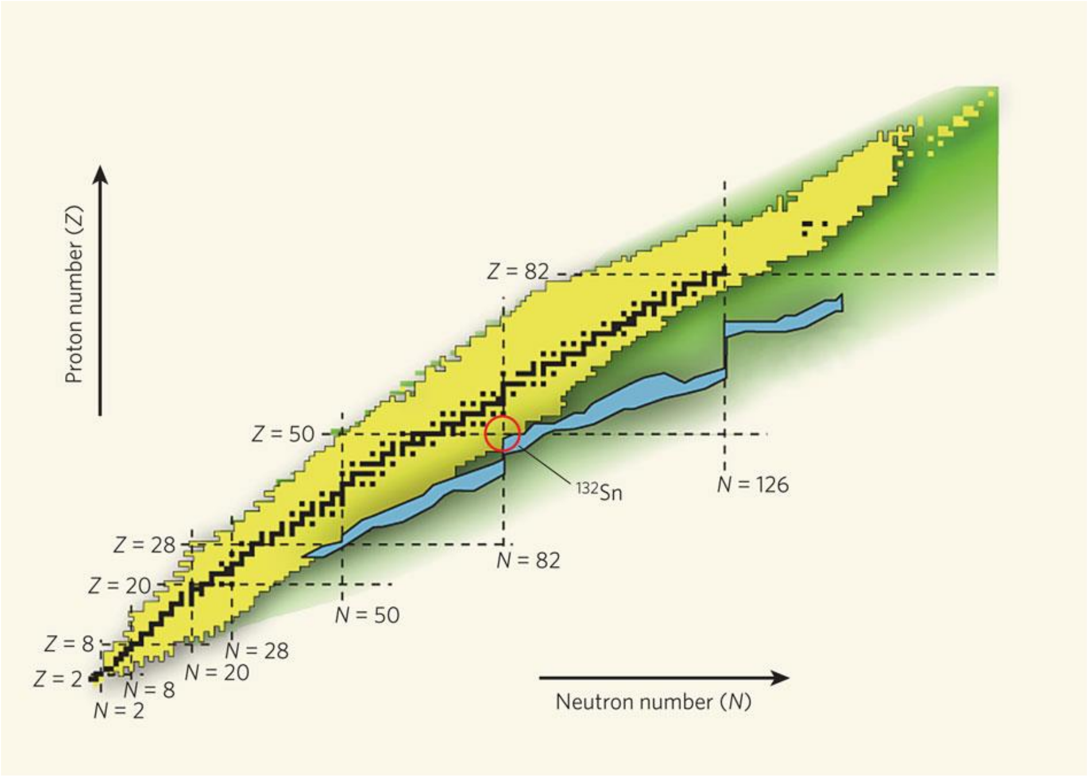
National Superconducting Cyclotron Laboratory, MSU

Outline

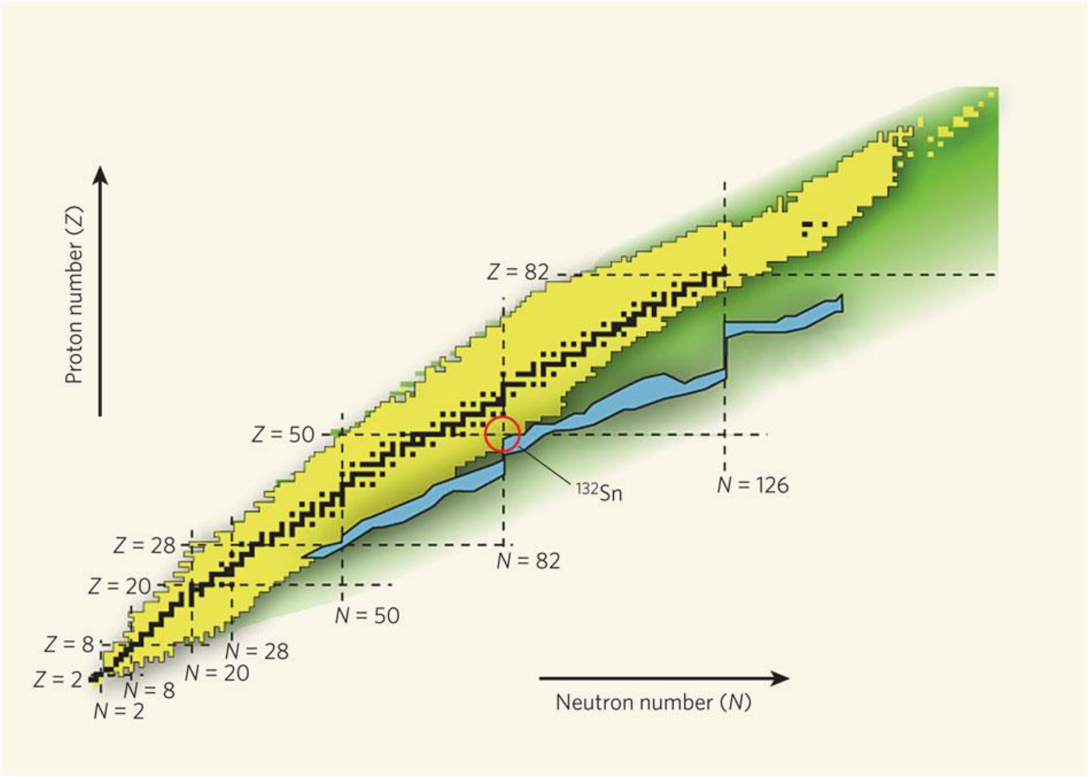
- Neutron-capture nucleosynthesis
- What is the *i*-process?
- Indirect neutron-capture constraints
  - β-Oslo method
- Fast beam experiments: $^{102\text{-}103}Mo(n,\gamma)^{103\text{-}104}Mo$
- Stopped beam experiments: $^{141}Ba(n,\gamma)^{142}Ba$
- Summary and Outlook

Open Questions in Nuclear Science



P. Cottle, *Nature* **465** (2010)
http://frib.msu.edu/_files/pdfs/frib_opening_new_frontiers_in_nuclear_science.pdf

Open Questions in Nuclear Science



Long-Range Plan in Nuclear Science:

1. How did visible matter come into being and how did it evolve?
2. How do protons and neutrons organize themselves and what phenomena emerge?
3. Are the fundamental interactions that are basic to the structure of matter fully understood?
4. How can the knowledge and technical progress provided by nuclear physics best be used to benefit society?

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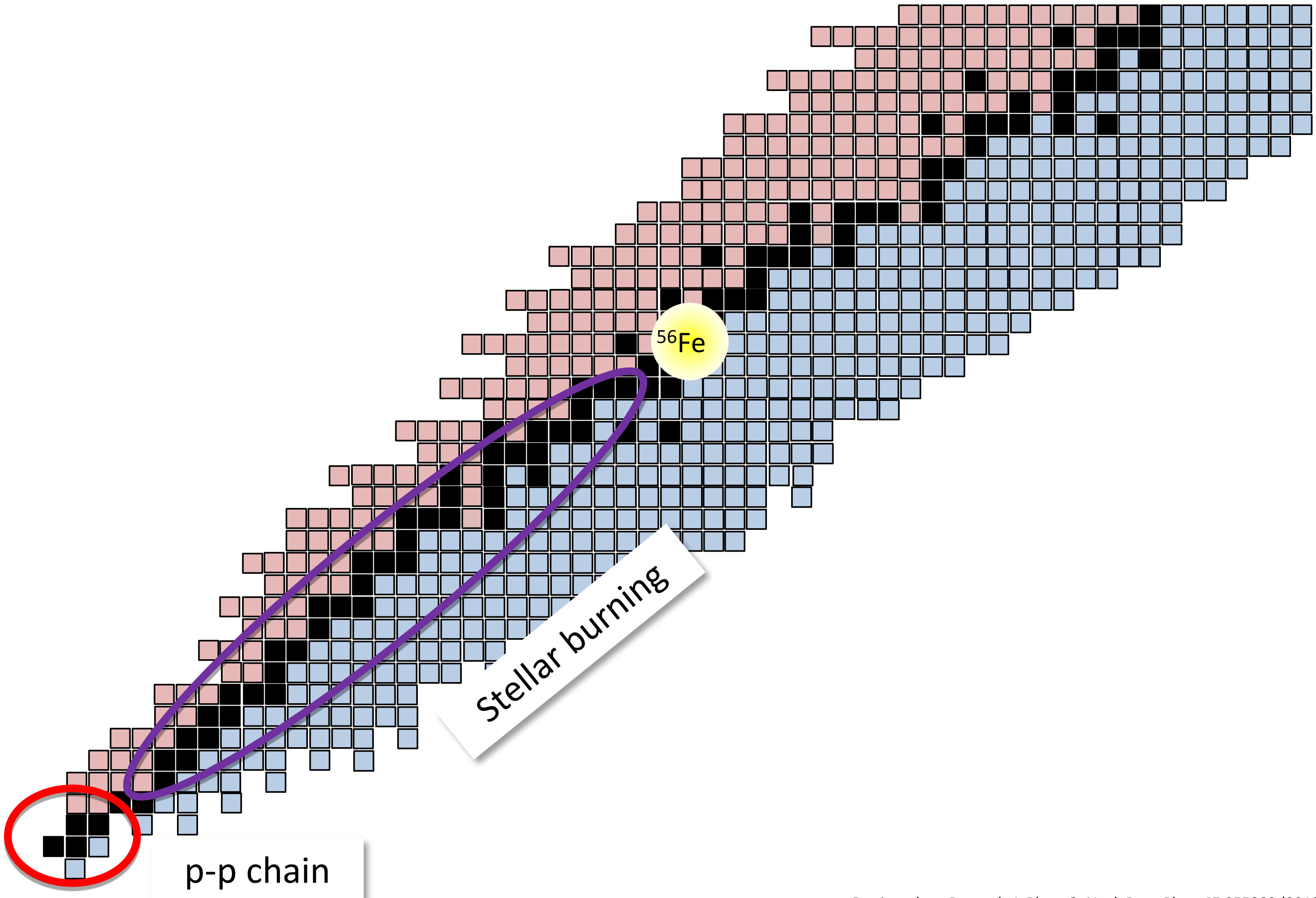
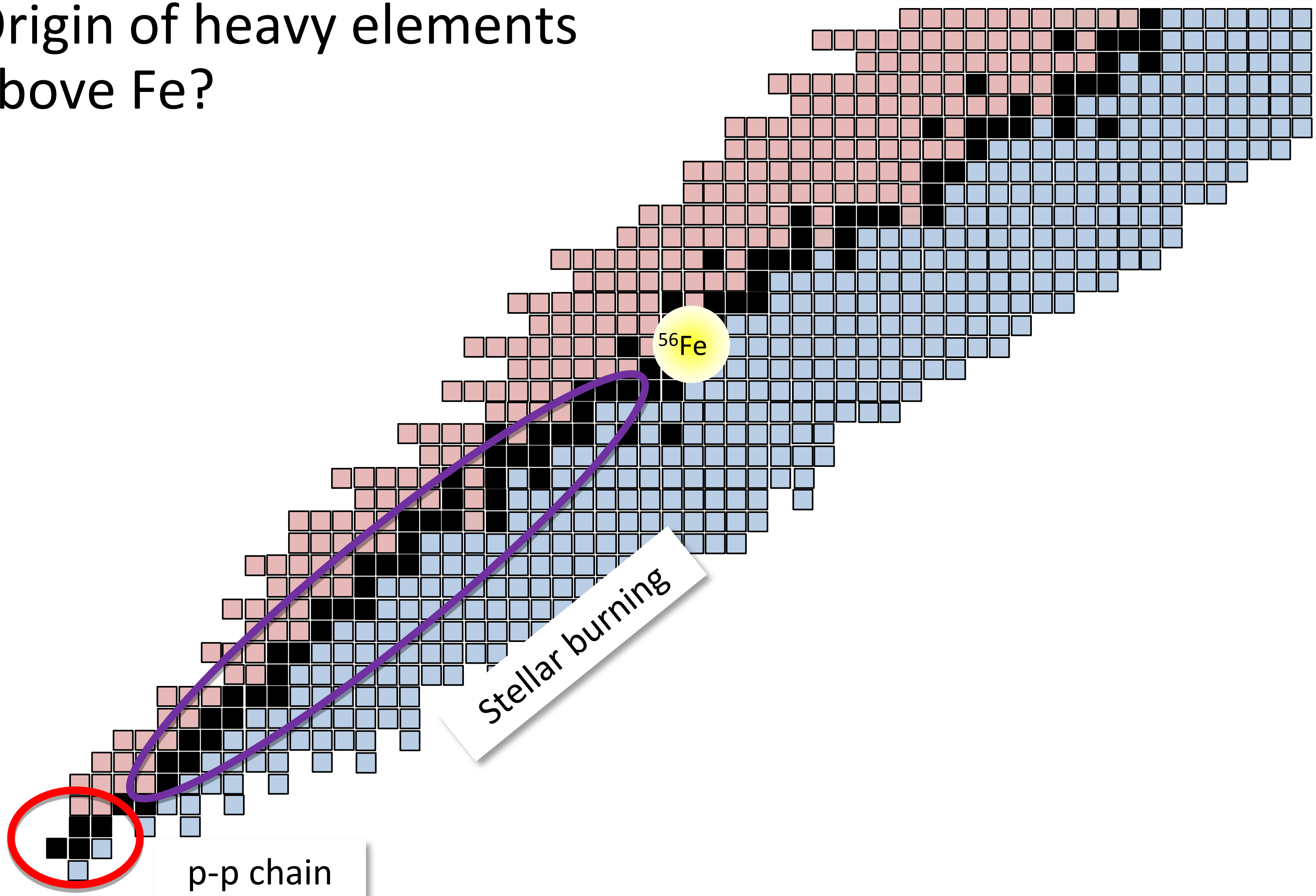
Neutron-Capture Nucleosynthesis



Denissenkov, P., *et al.*, J. Phys. G: Nucl. Part. Phys. **45** 055203 (2018)

Neutron-Capture Nucleosynthesis

- Origin of heavy elements above Fe?



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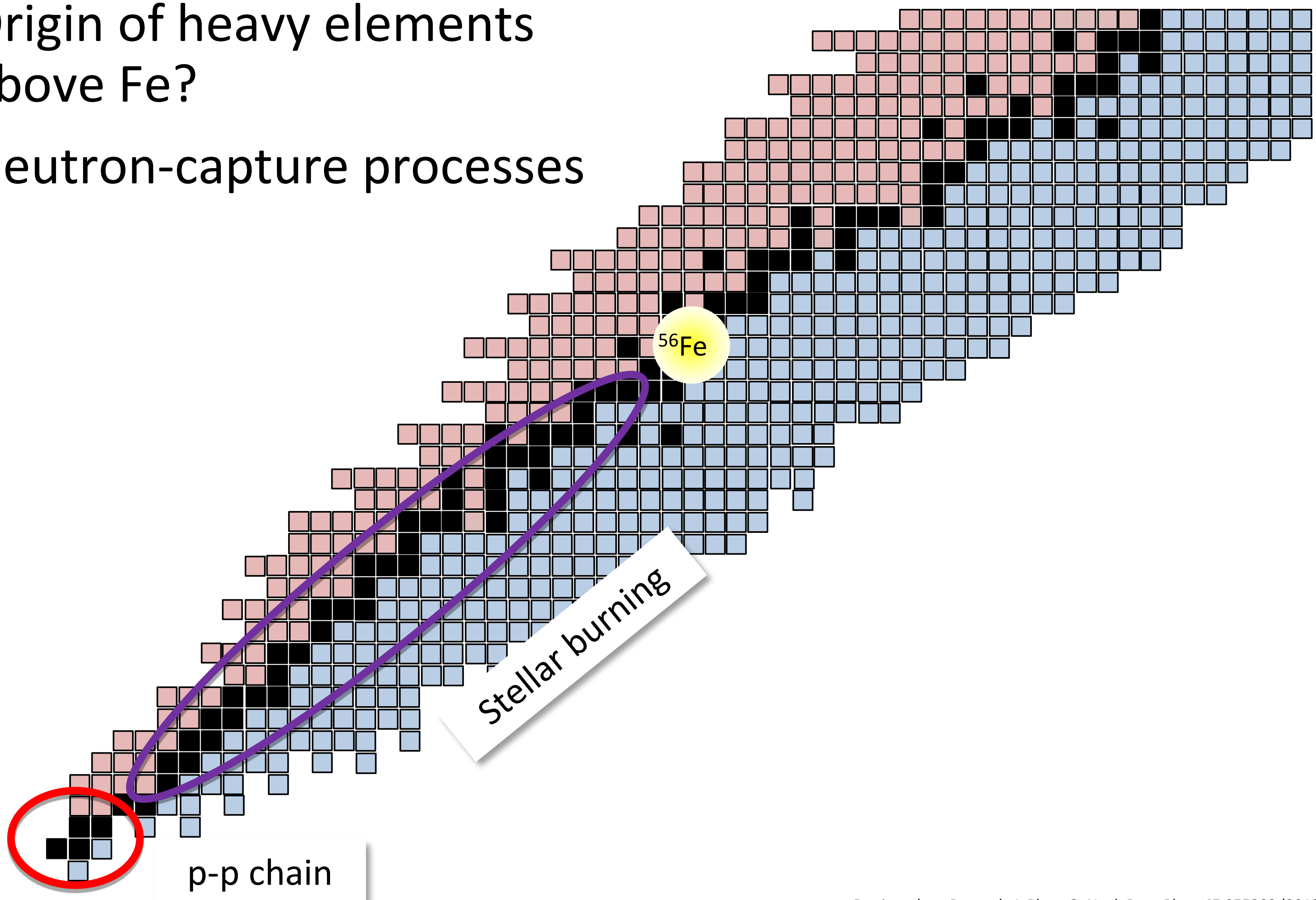

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Neutron-Capture Nucleosynthesis

- Origin of heavy elements above Fe?
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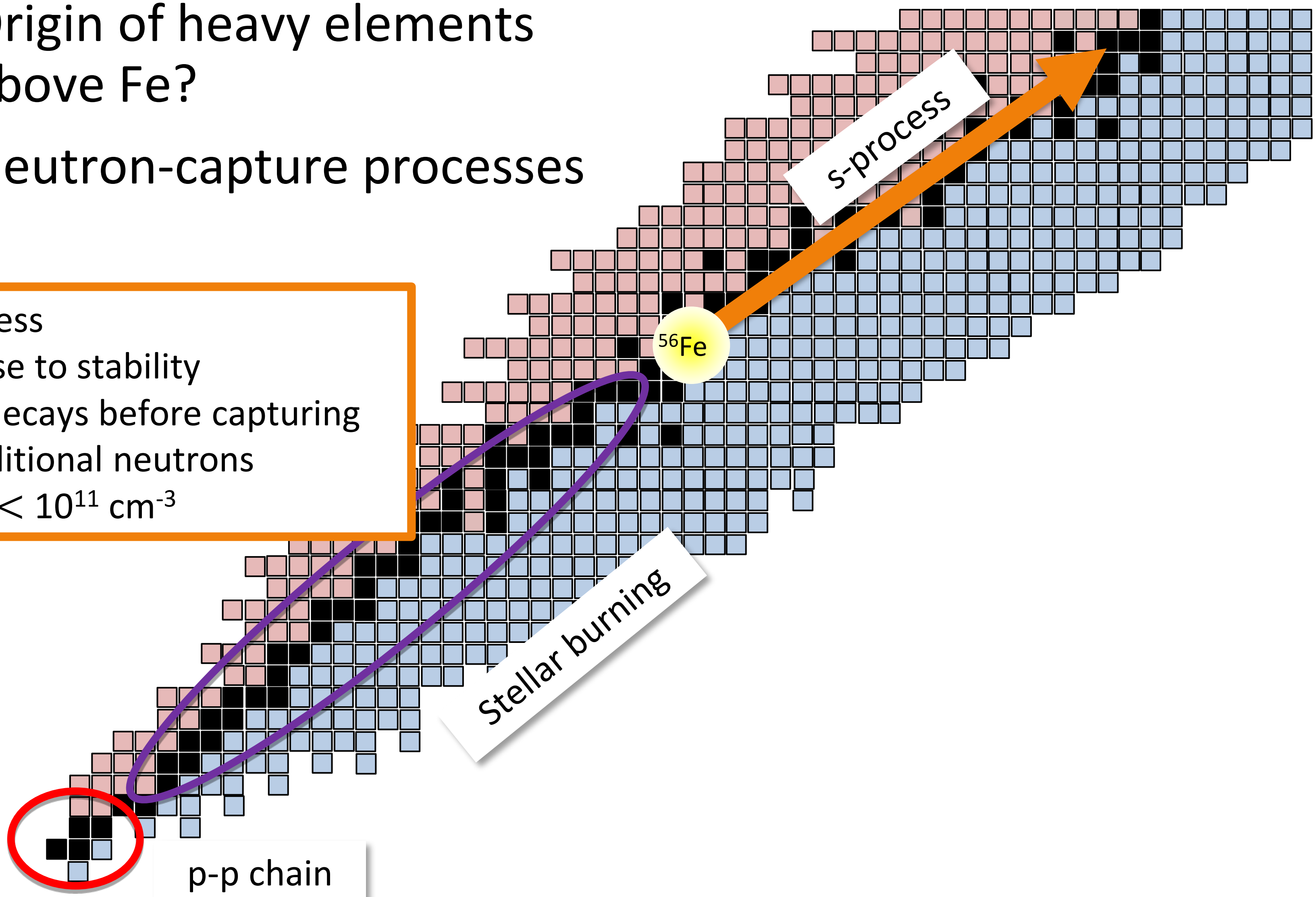
s-process
- close to stability
- β-decays before capturing additional neutrons
- $N_n < 10^{11}$ cm^{-3}



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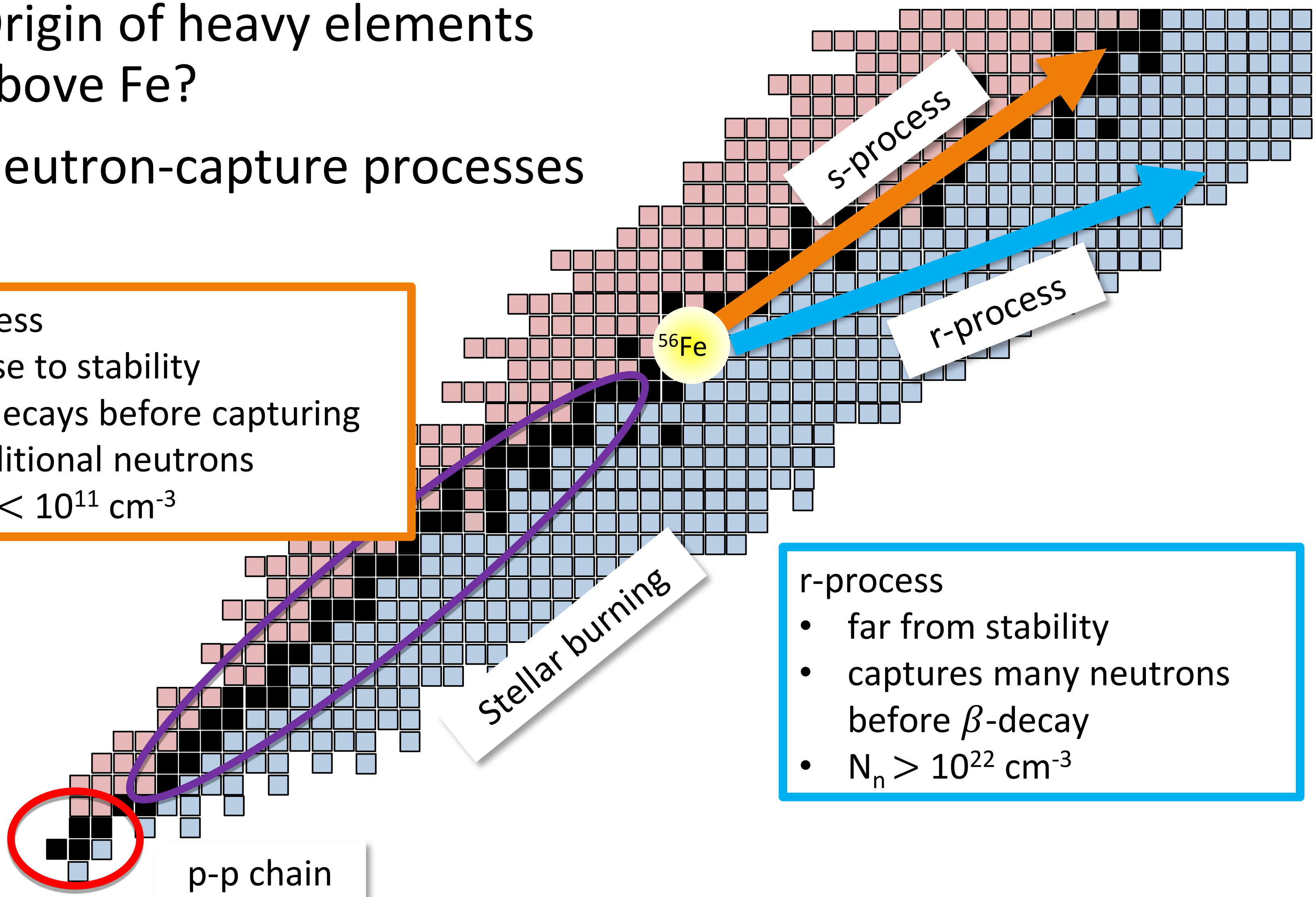

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- close to stability
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r-process
- far from stability
- captures many neutrons before β-decay
- $N_n > 10^{22}$ cm^{-3}

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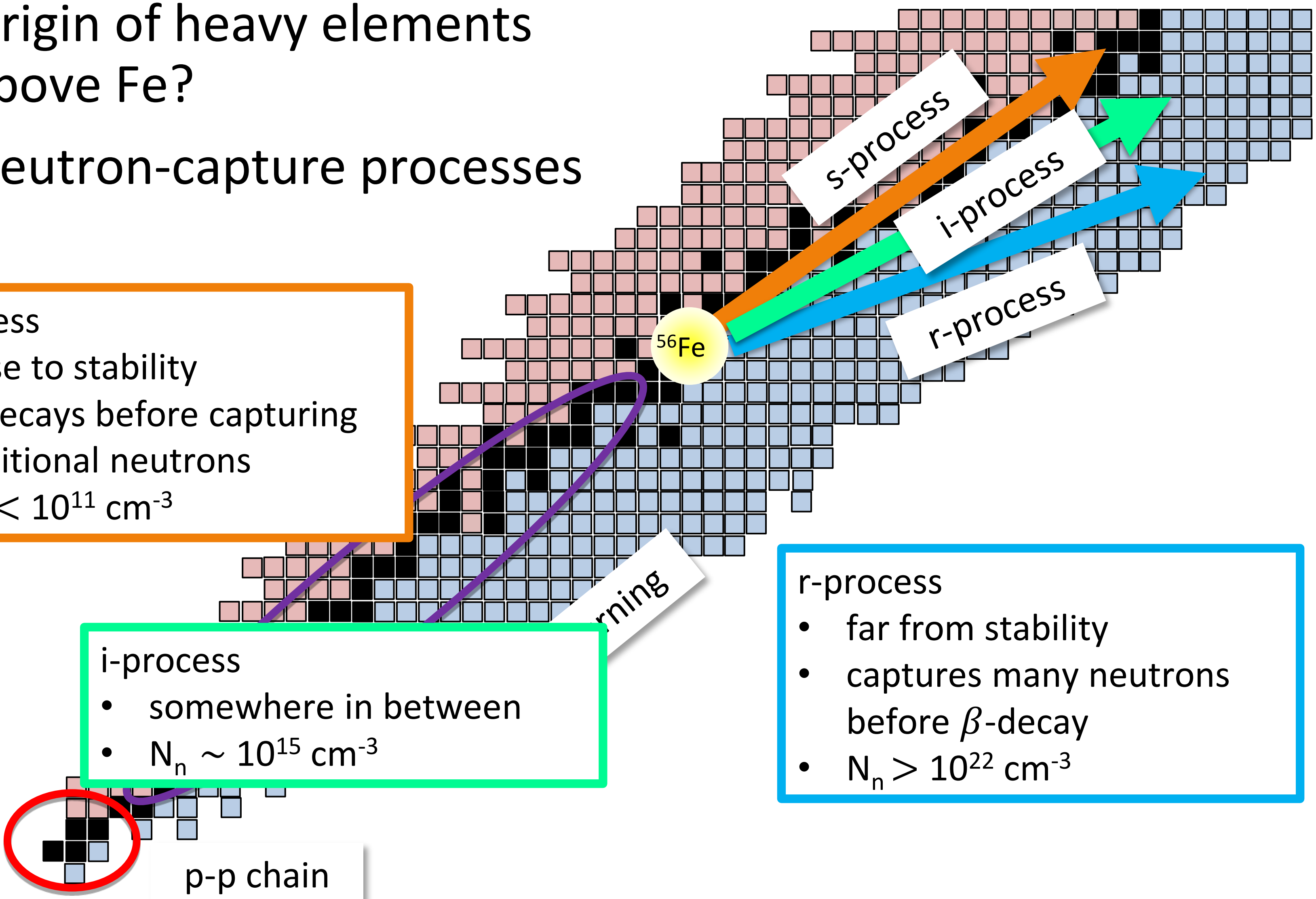

s-process
- close to stability
- β-decays before capturing additional neutrons
- $N_n < 10^{11}$ cm^{-3}

i-process
- somewhere in between
- $N_n \sim 10^{15}$ cm^{-3}

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

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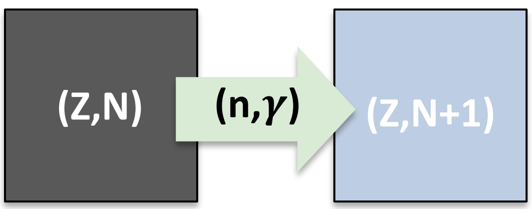

captures neutron

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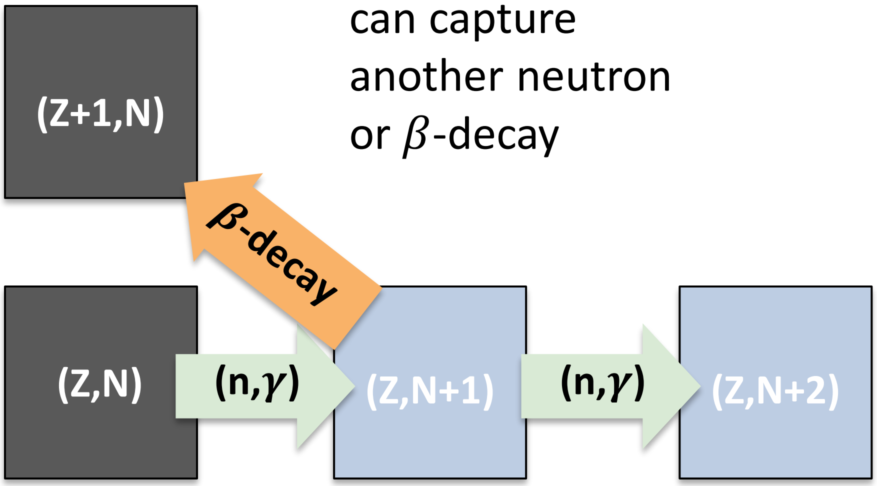
Neutron-Capture Nucleosynthesis



can capture another neutron or β-decay

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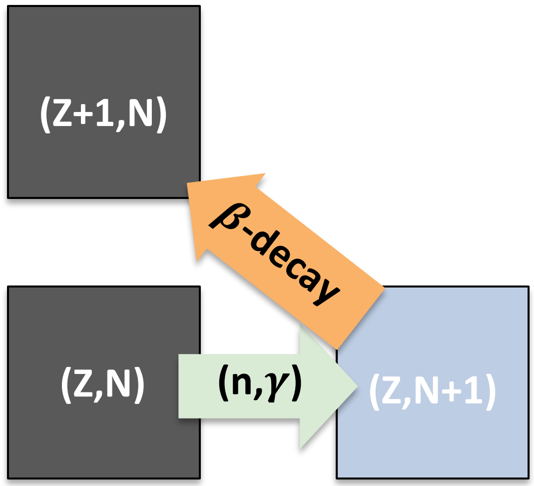
Neutron-Capture Nucleosynthesis

s-process



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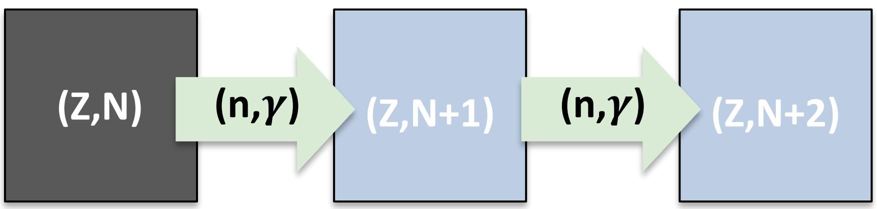

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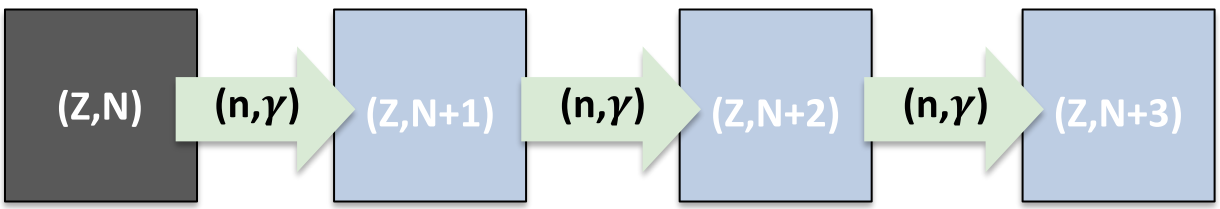

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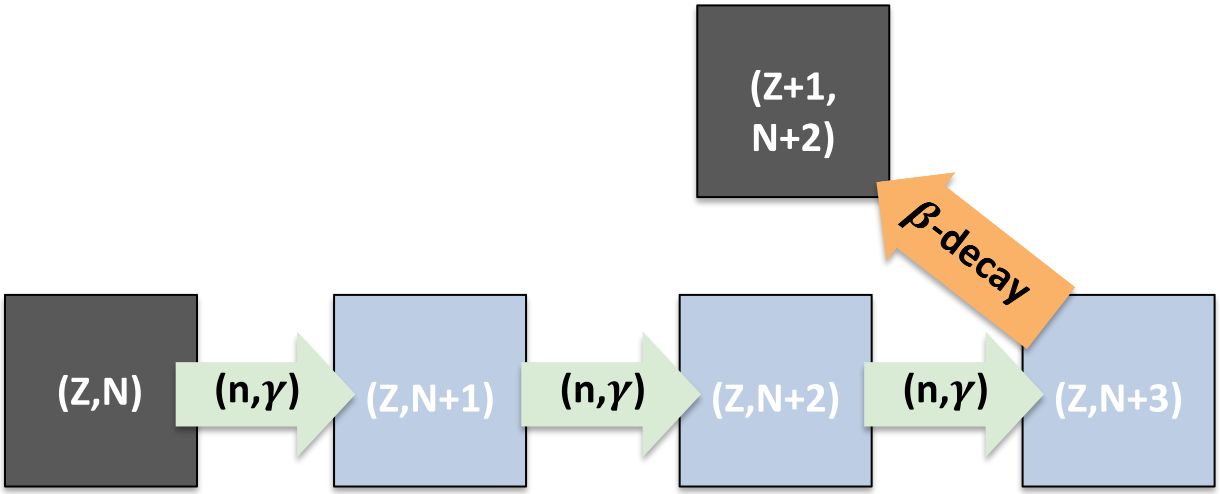

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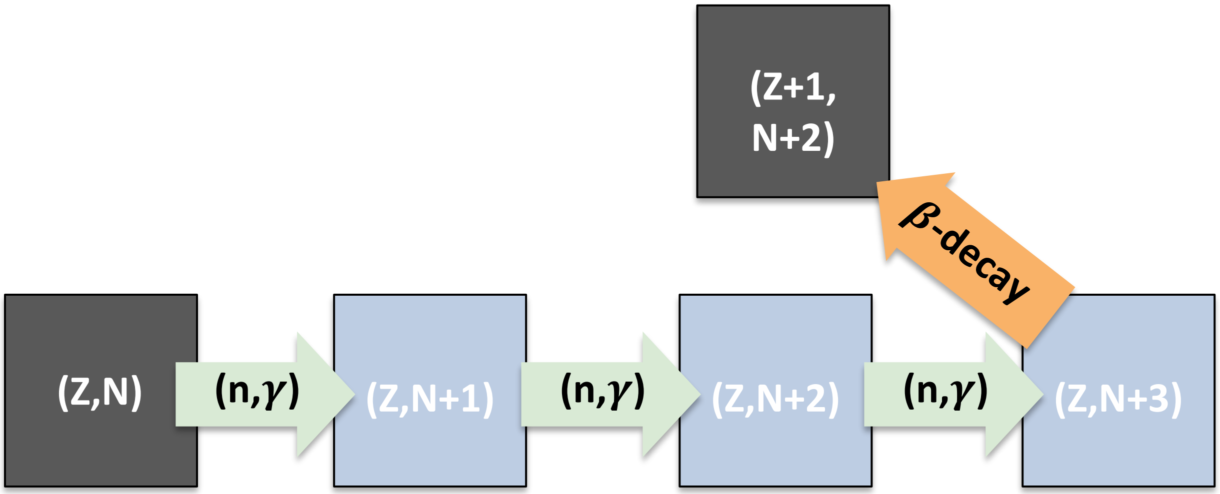
Neutron-Capture Nucleosynthesis

i-process



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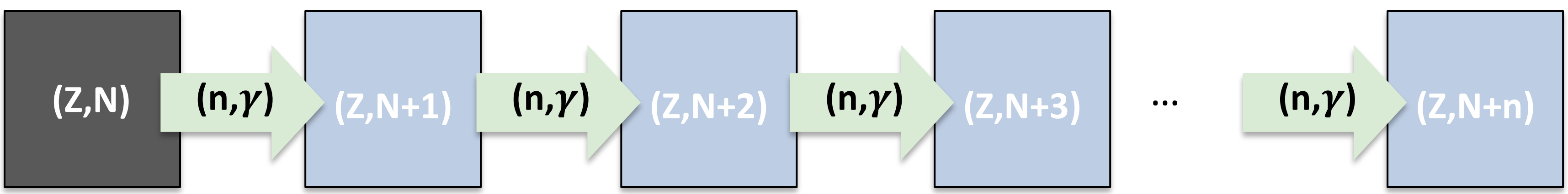
Neutron-Capture Nucleosynthesis



with high enough neutron density, nuclei can continue to capture neutrons

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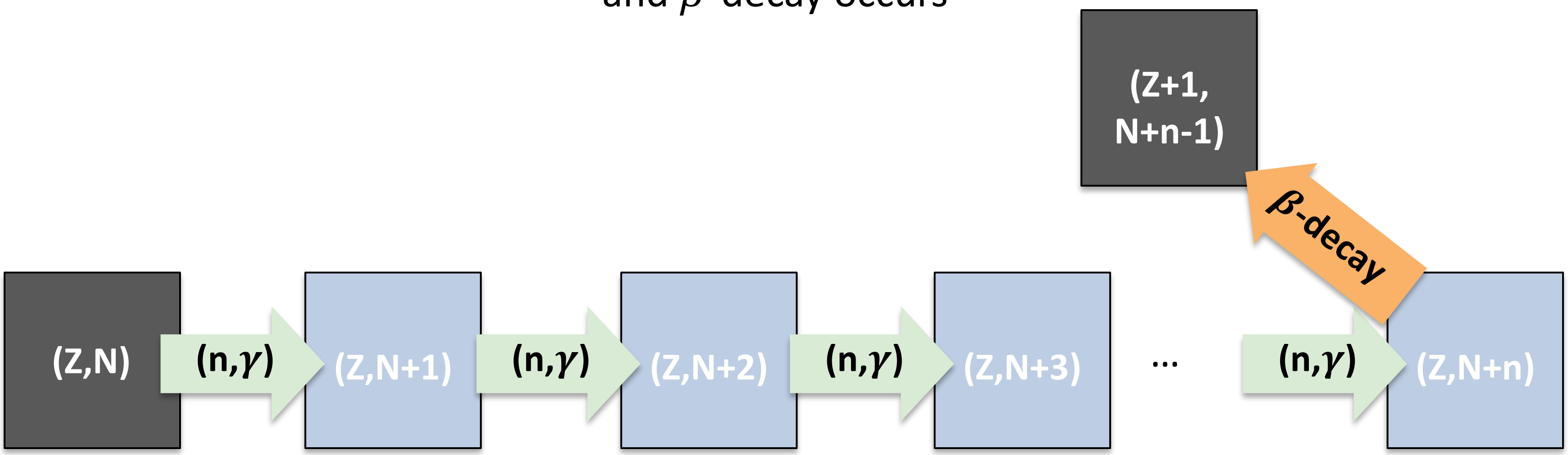
Neutron-Capture Nucleosynthesis

until neutron flux is reduced
and β-decay occurs



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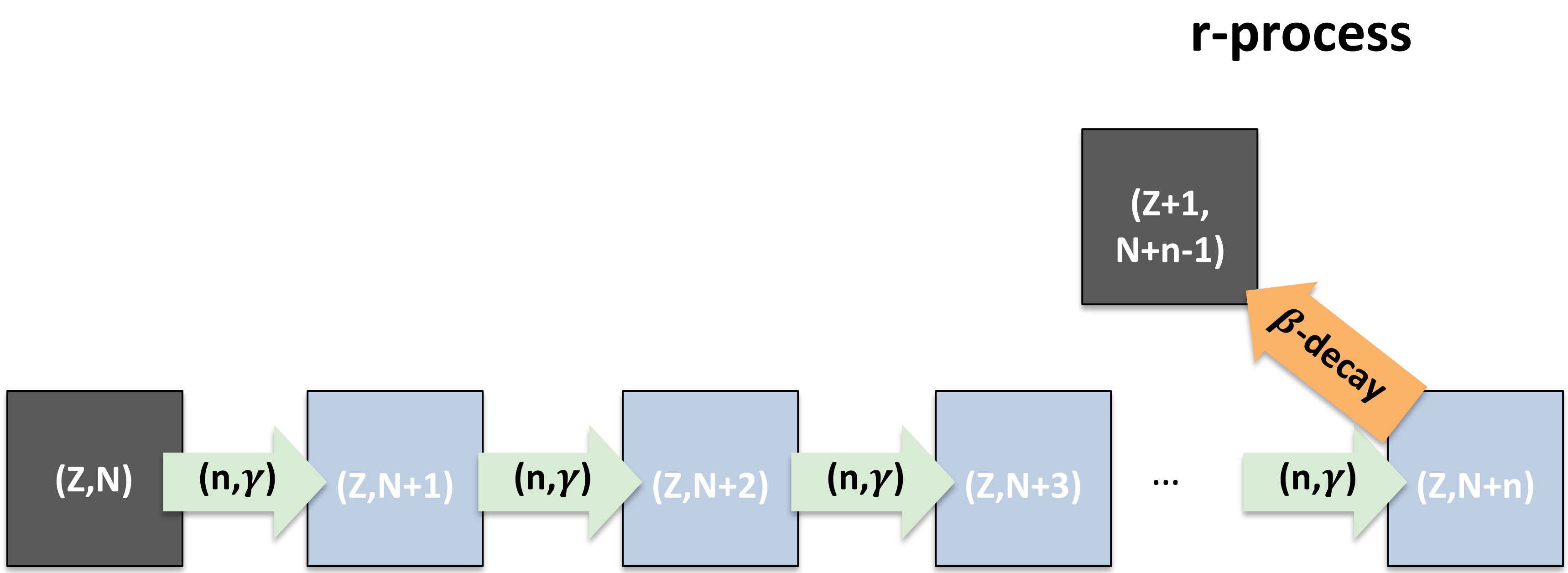

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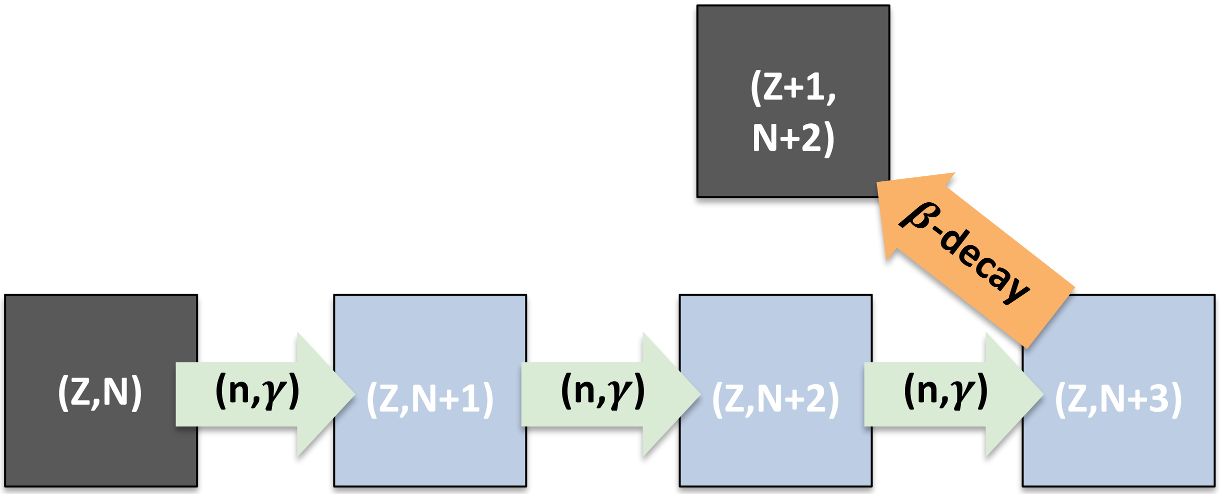
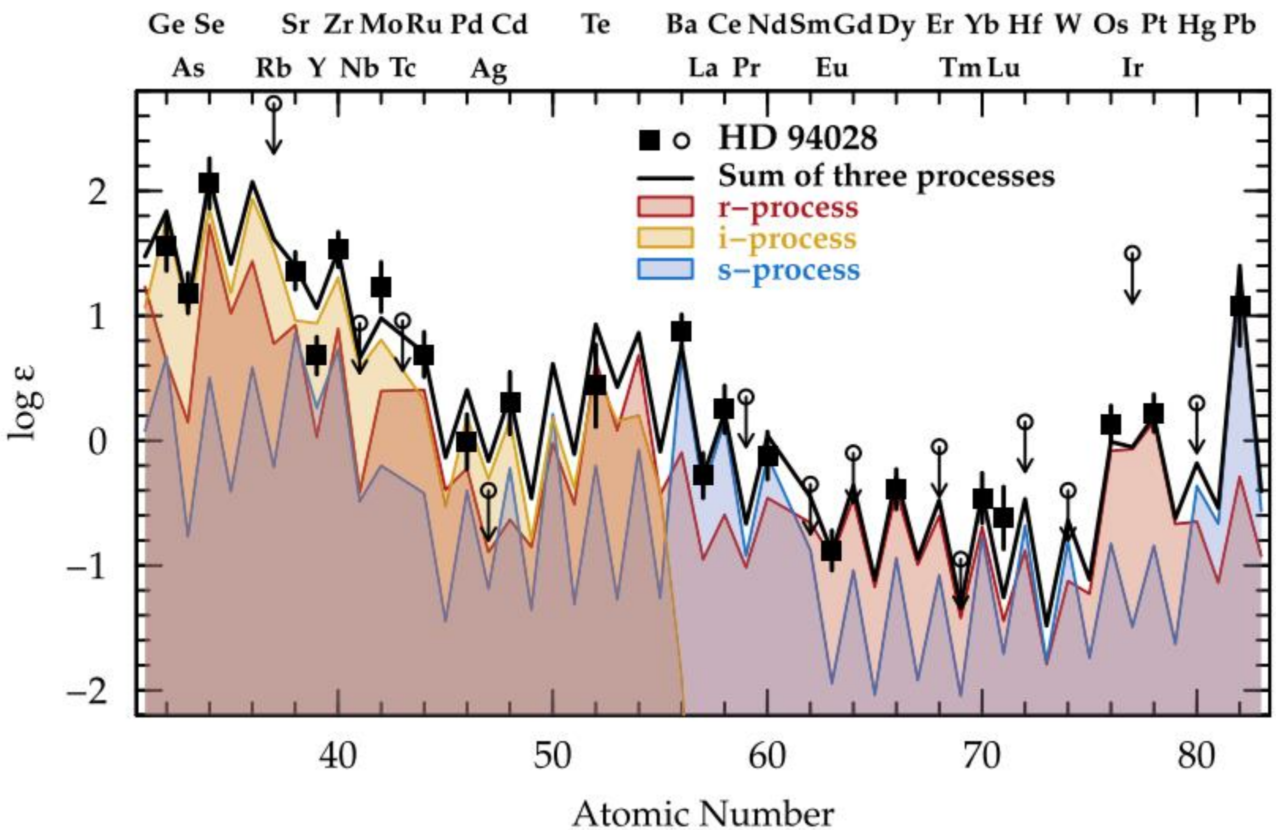
the *i*-process

i-process



few steps from stability

Nucleosynthesis in the Ge-La region

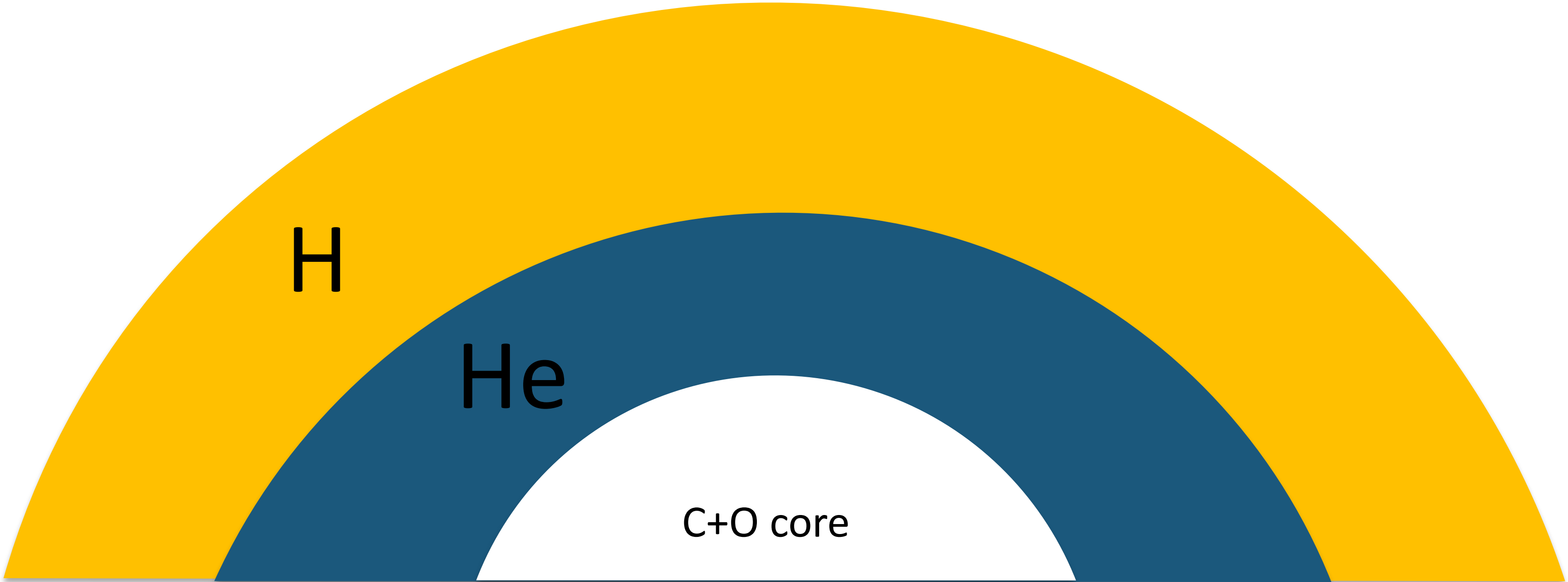


- combinations of s-process and r-process do not account for observed abundances in the Ge-La region (s + r $\neq$ i)

I. Roederer *et al.*, APJ **821**:37 (2016)

the *i*-process

- Neutron density: 10^{15} cm^{-3}, intermediate between s process, and r process
- Proposed in the 1970s and revived recently to explain observations of "strange" abundance distributions (post-AGB, CEMP stars, and RAWDs)
- Requires mixing between H and He layers of the star
- Neutron production: $^{13}C(\alpha,n)^{16}O$ reaction, like s-process
- ^{13}C replenished via $^{12}C(p,\gamma)^{13}N$, then $^{13}N(e^{+})^{13}C$, $T_{1/2}(^{13}N)$ ~ 10 minutes



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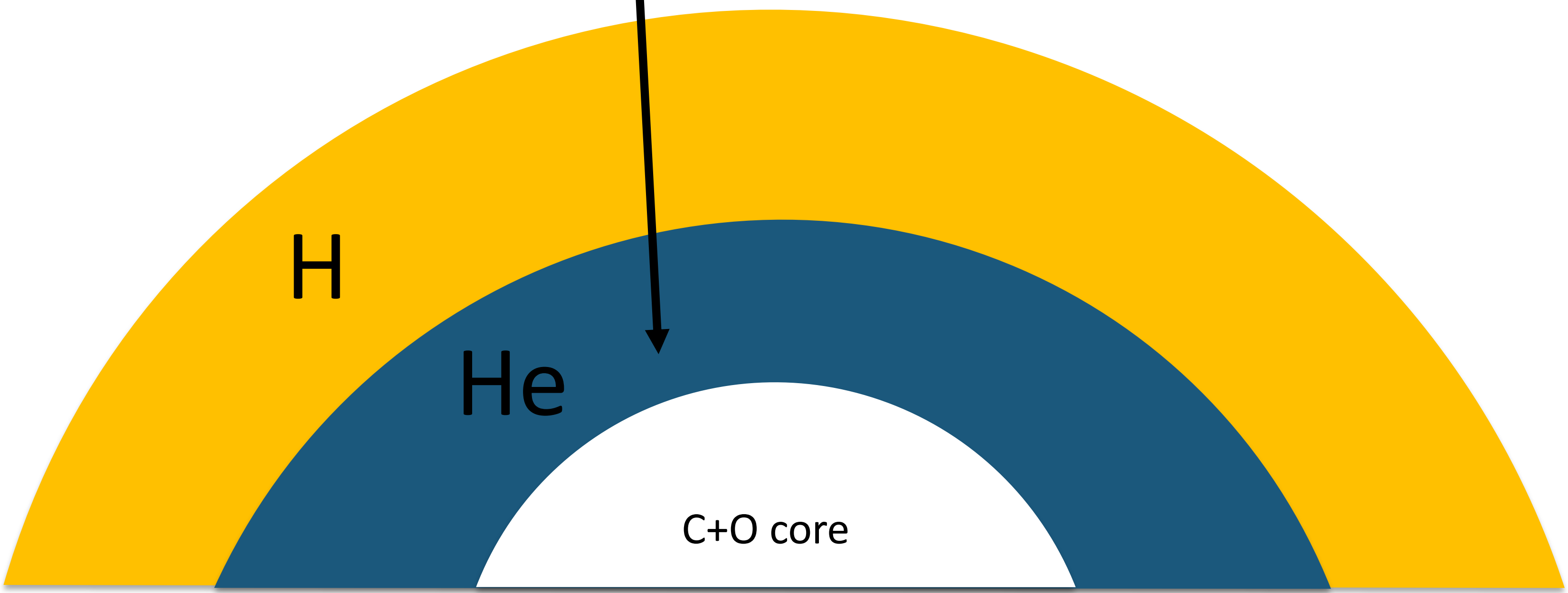

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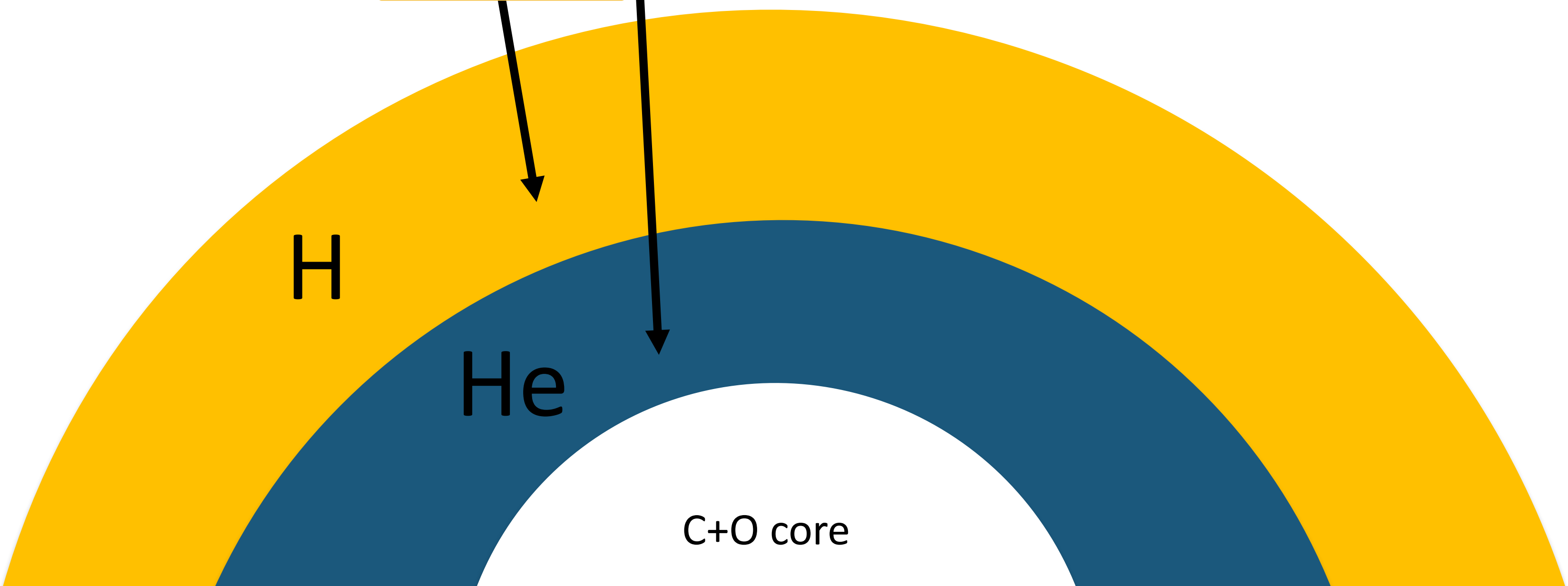

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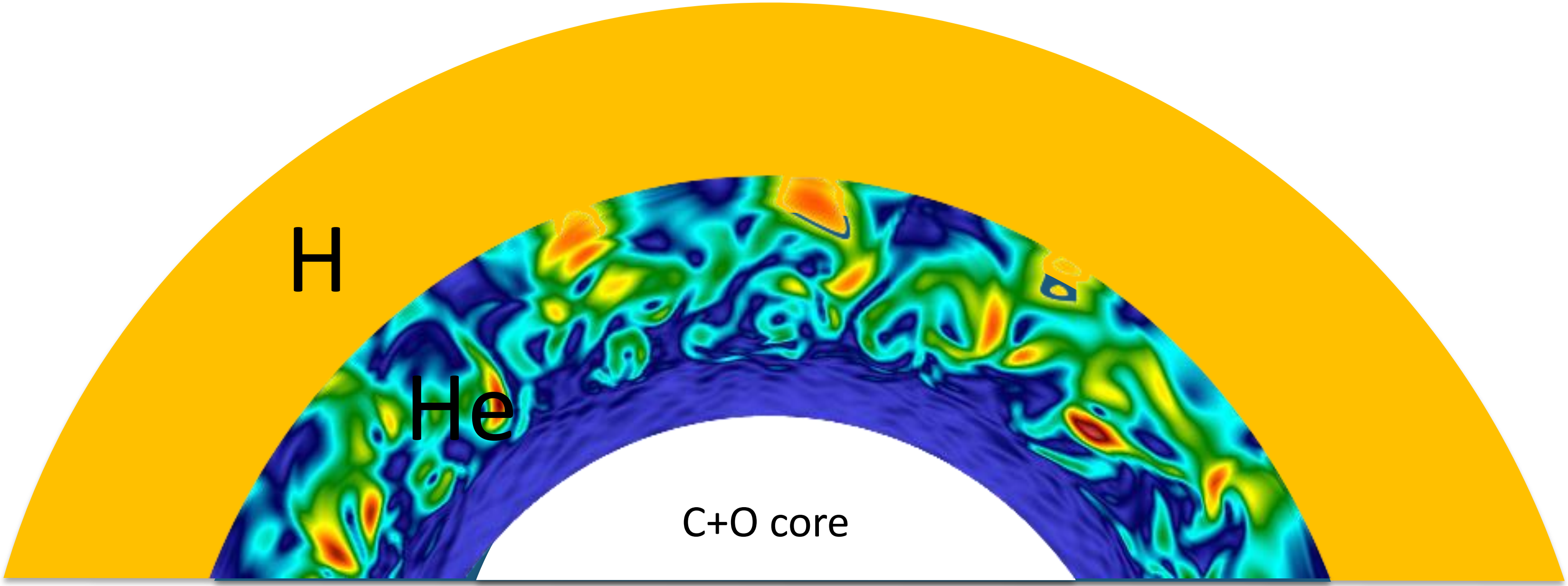

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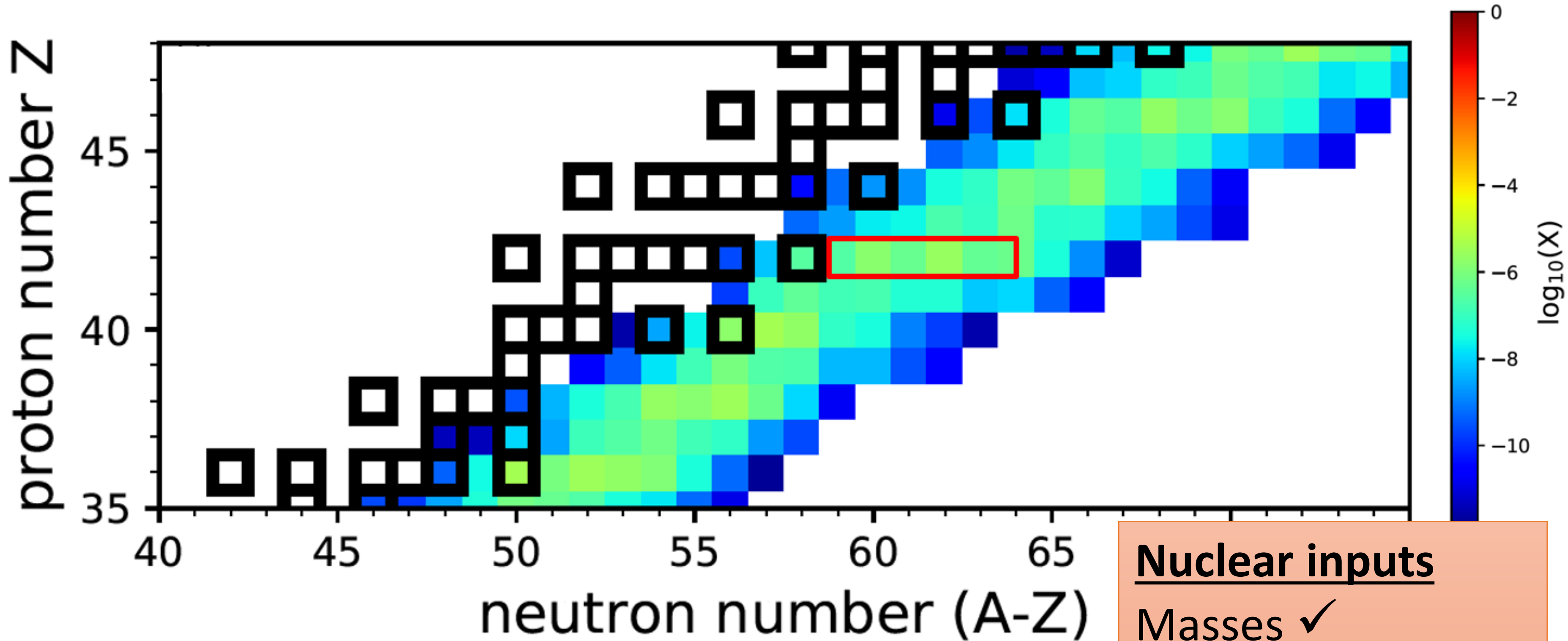
i-process: nuclear data needs



Nuclear inputs

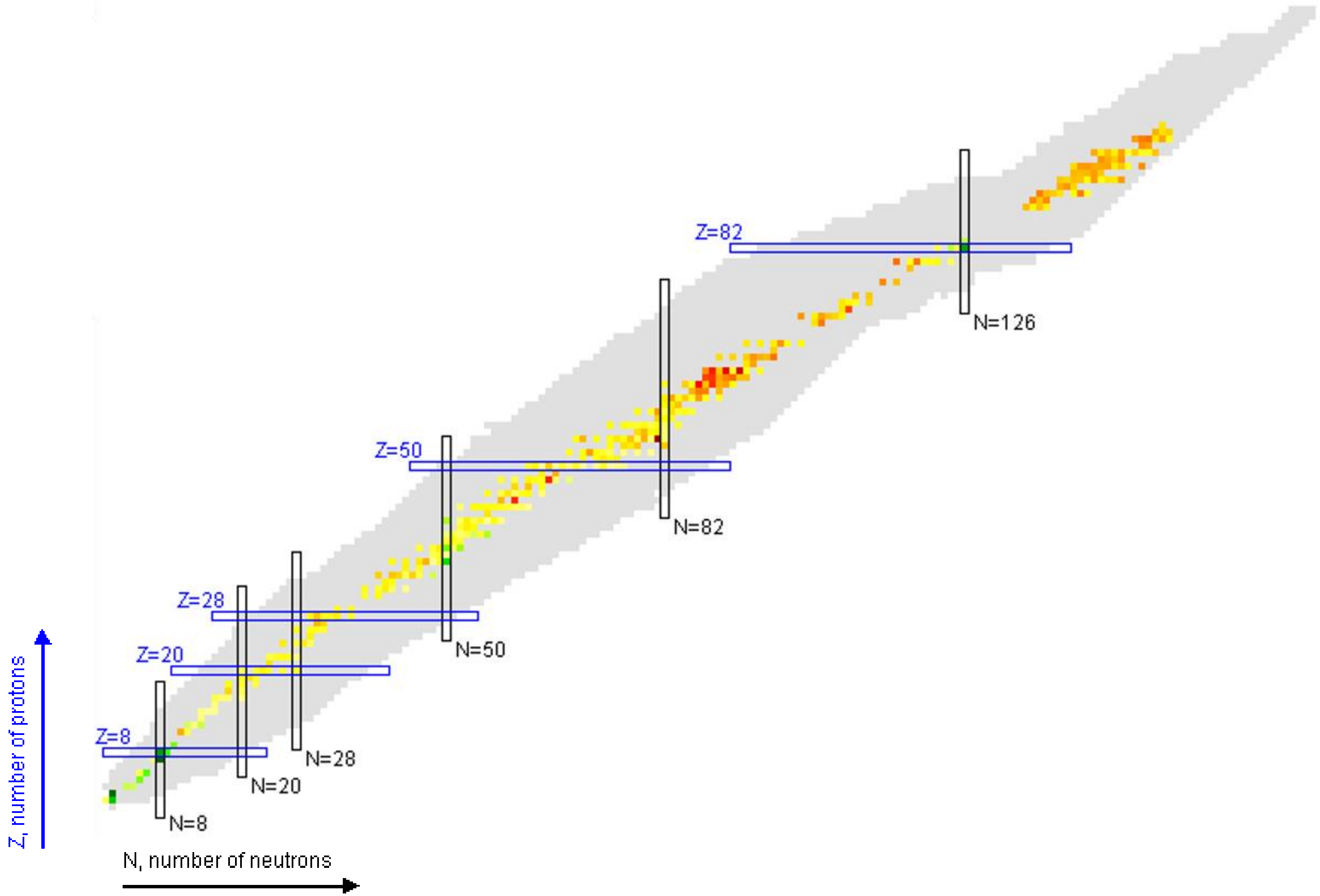
Masses ✓

β-decay: $T_{1/2}$, P_n ✓

(n,γ) reaction rates

- Reaction flow is a few steps from stability
- Nuclear properties mostly measured except **neutron-capture reactions**

Current (n,γ) measurements are limited

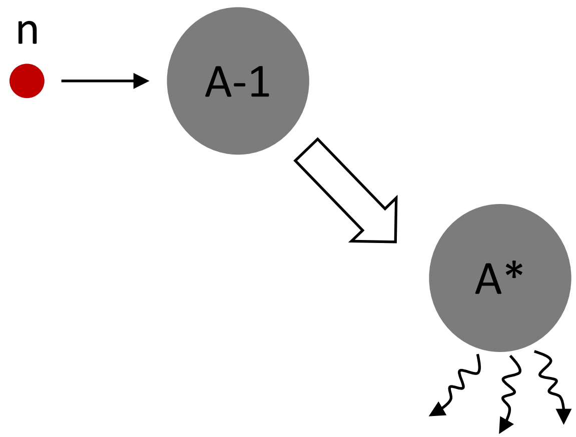


NNDC

How do you obtain (n,γ) rates for an isotope?

Direct Measurement

- Desired targets are too short-lived
- No feasible neutron target
- Not possible for rare isotopes



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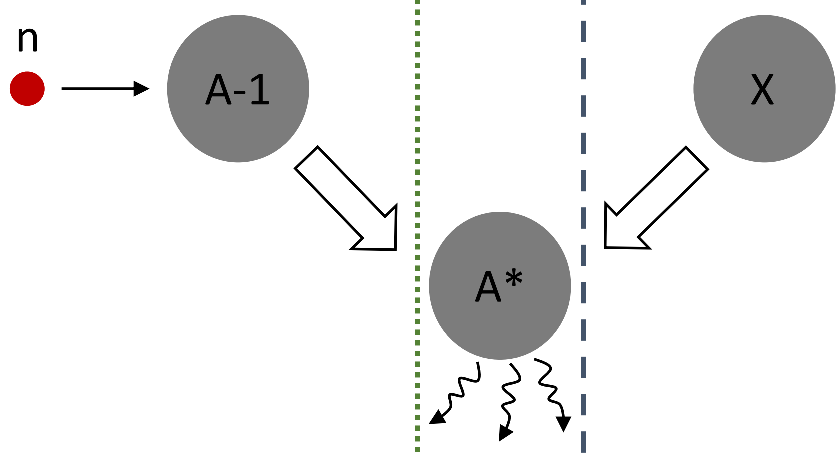

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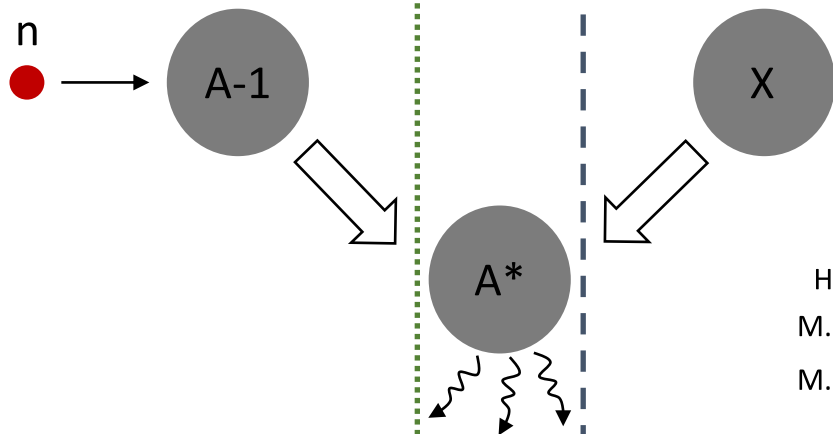
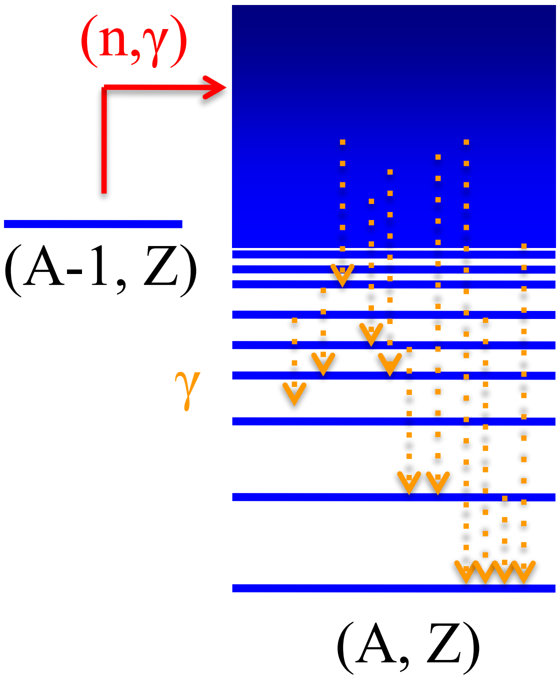
Examples:
Oslo Method
β-Oslo Method
Surrogate Method
γ-ray strength method



A. Spyrou *et al.*, PRL **113**, 232502 (2014)
J. Escher *et al.*, PRL **121**, 052501 (2018)
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)

Nuclear level densities and γ-ray strength functions dominate uncertainties in (n,γ) calculations



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)
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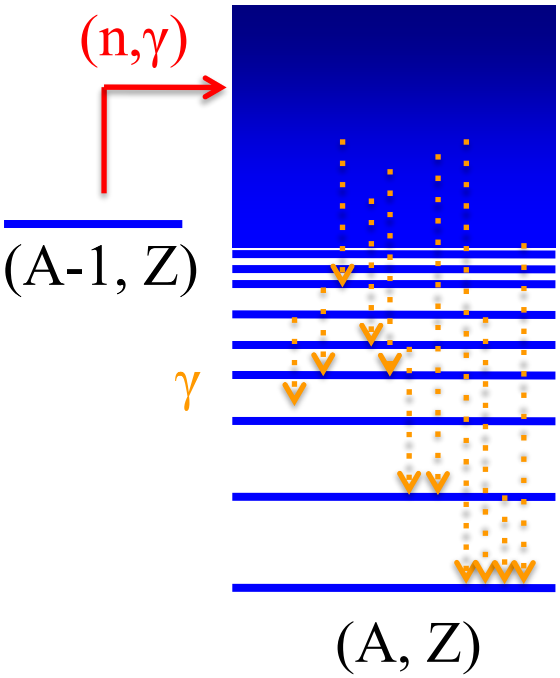

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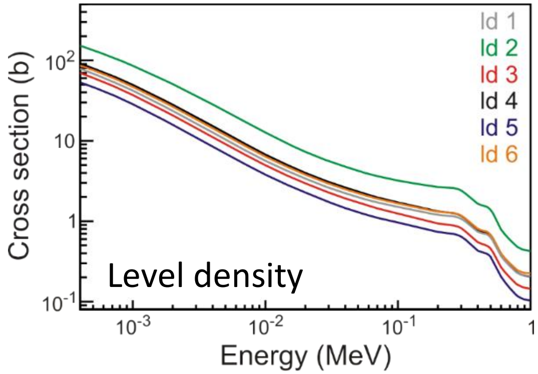

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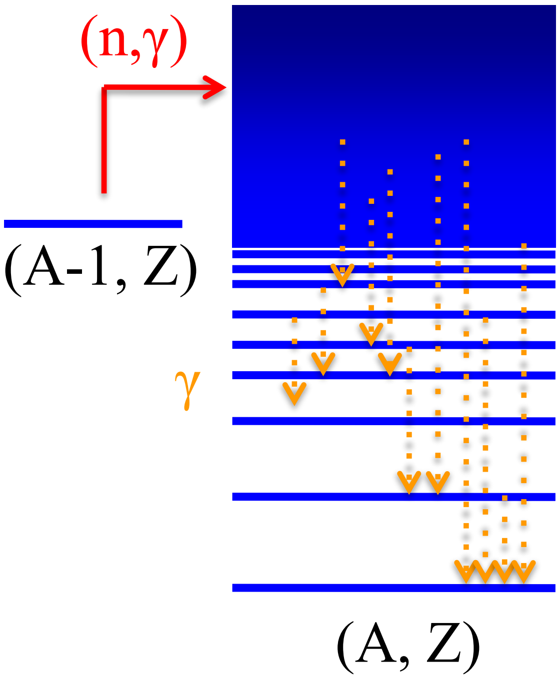

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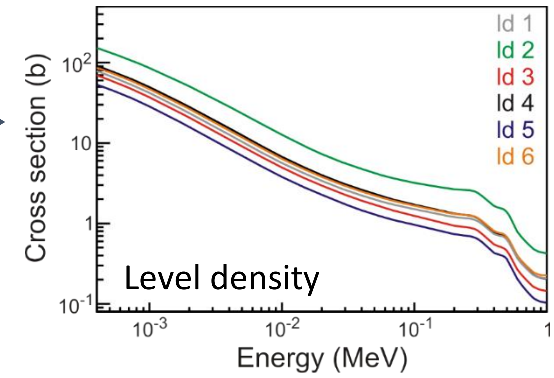

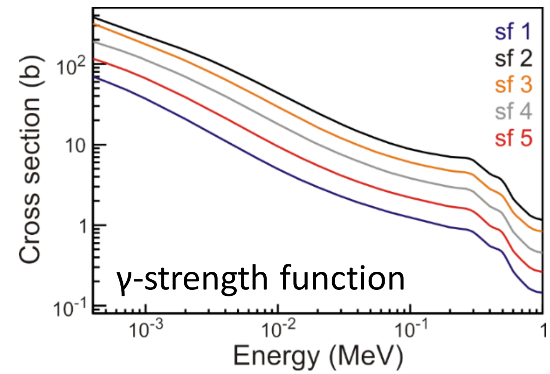

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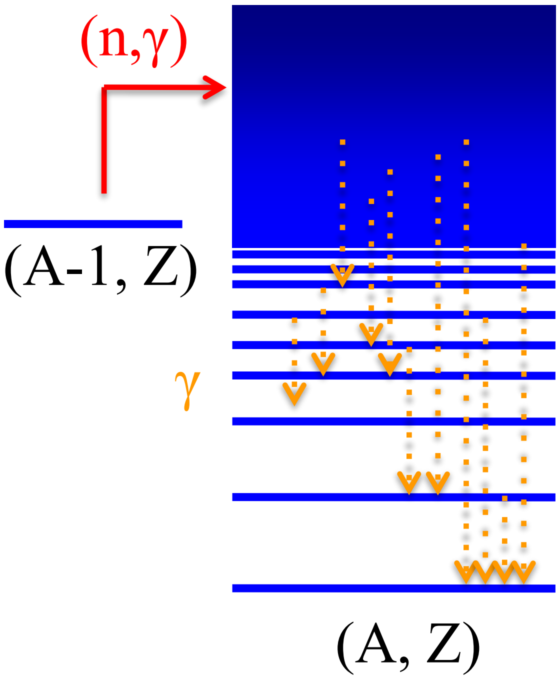

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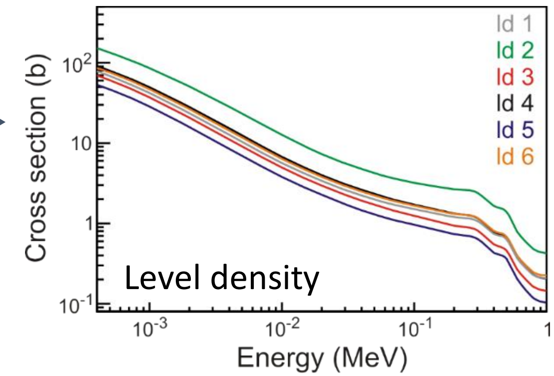

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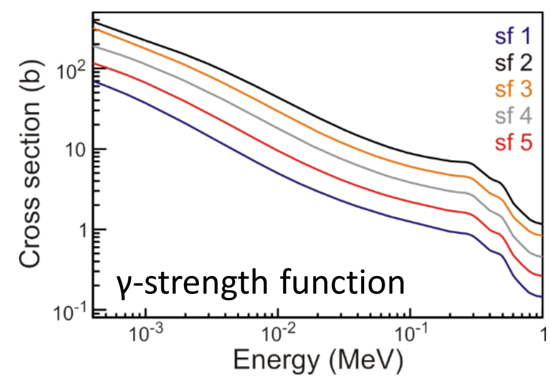

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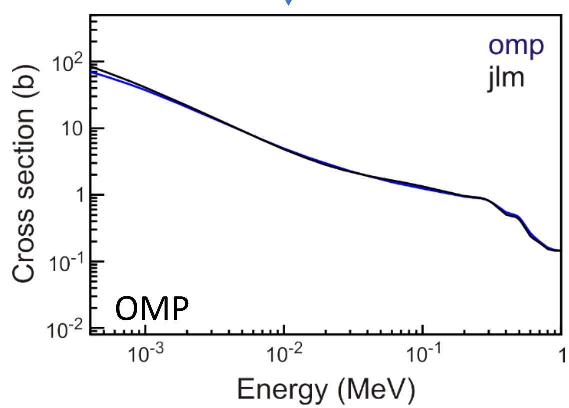
Phenomenological, Semi-microscopic



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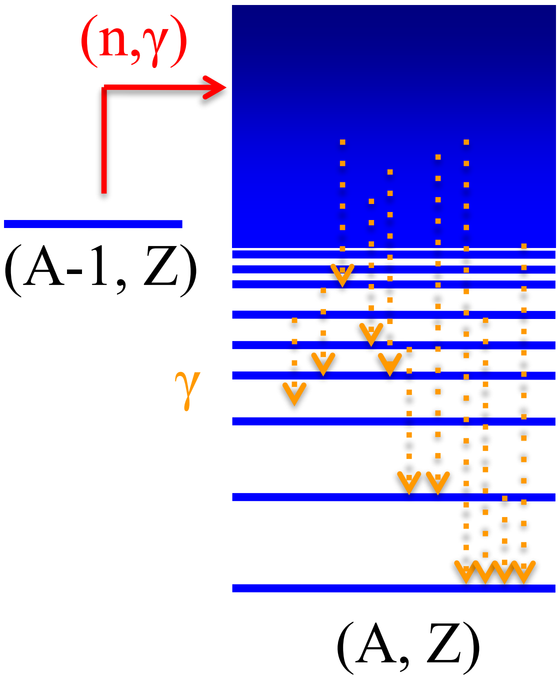

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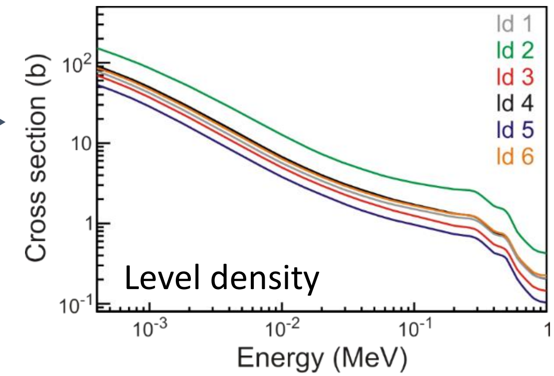

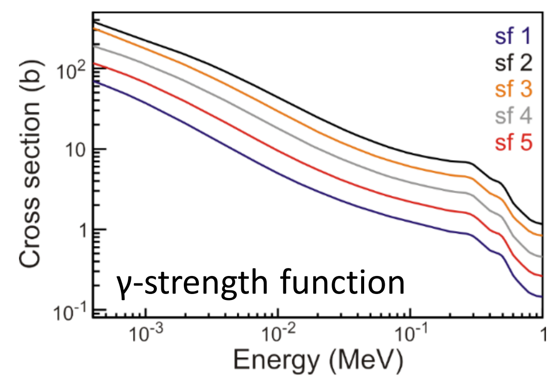

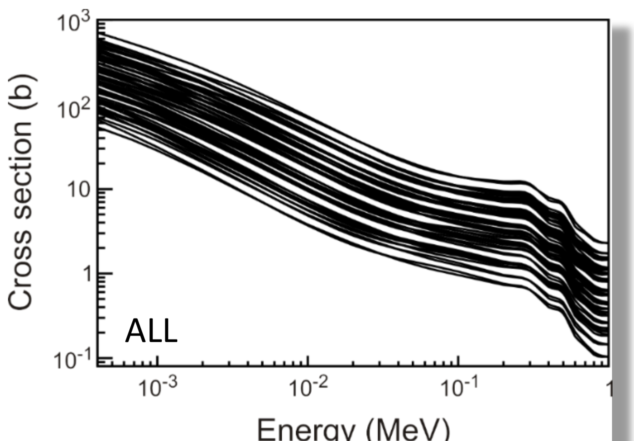

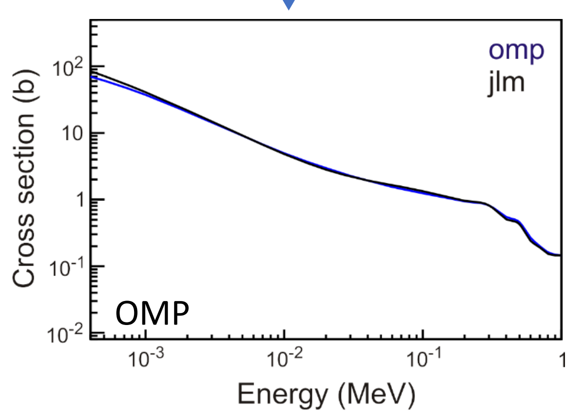

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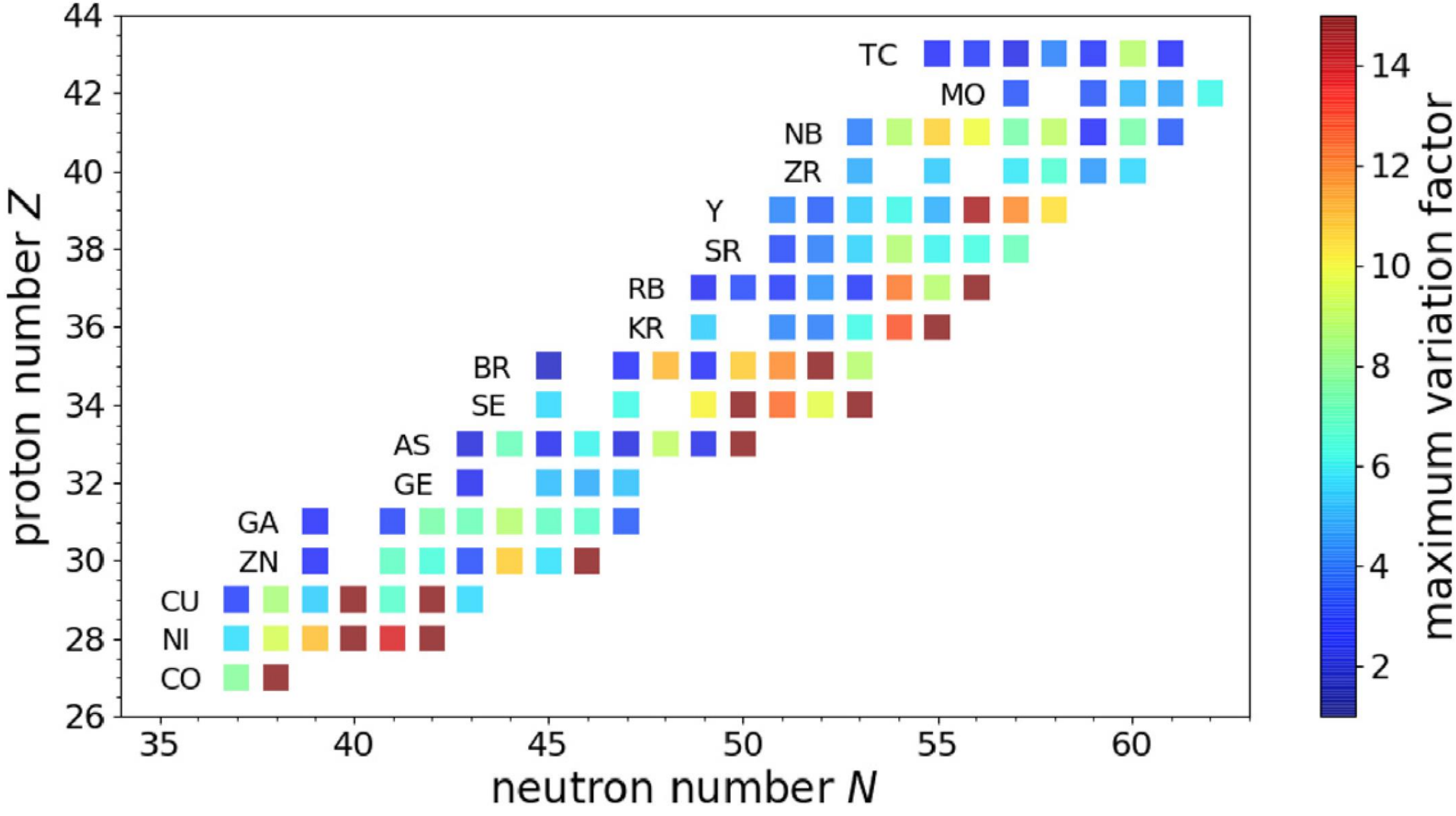
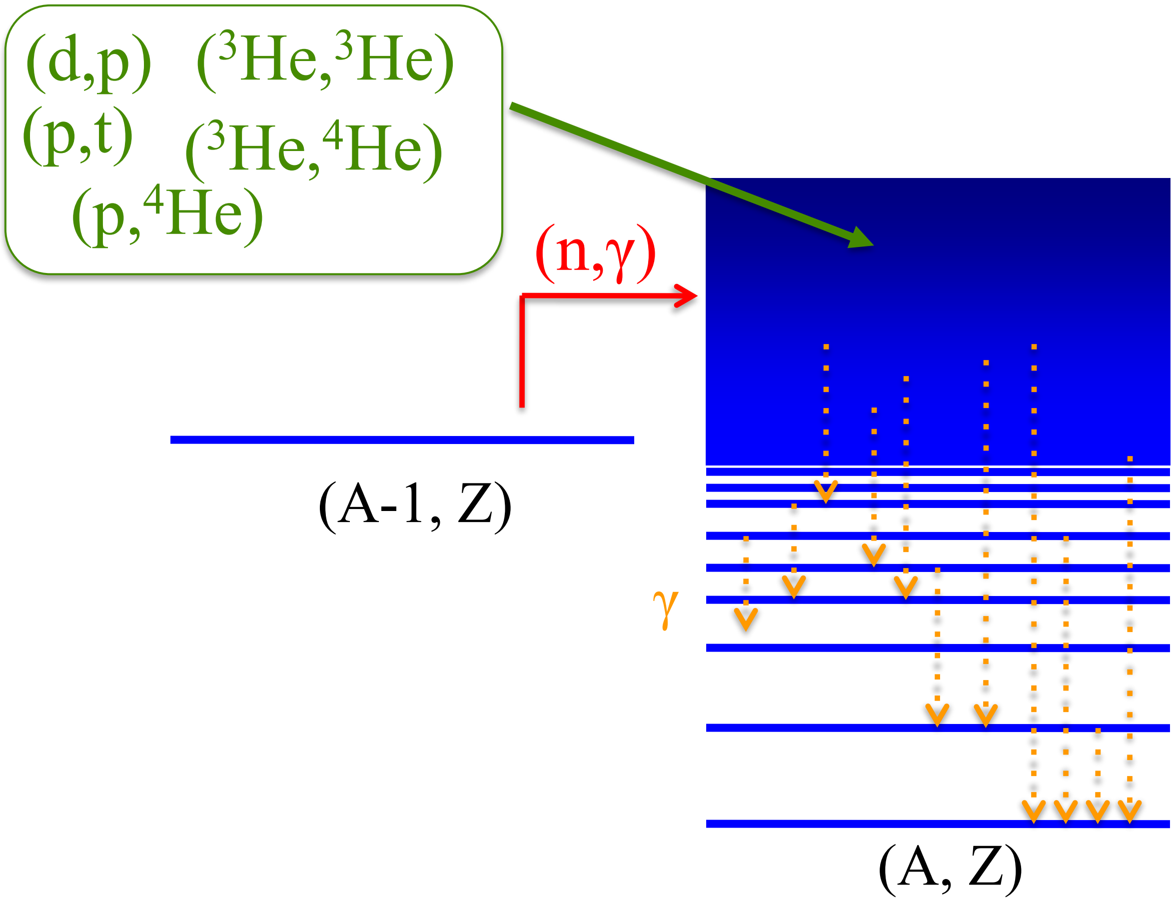
(n,γ) uncertainties impact heavy element creation



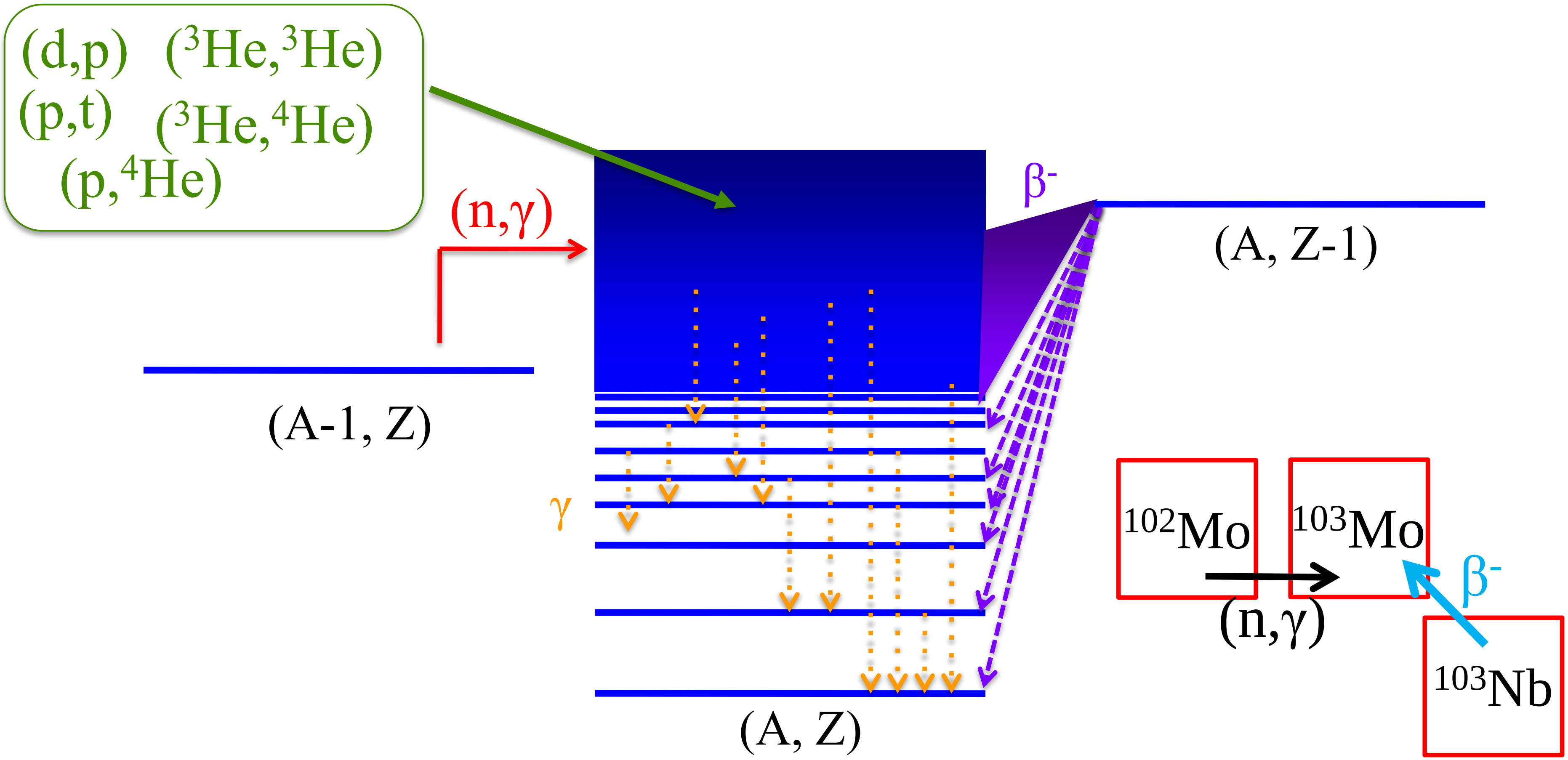
J. McKay *et al.*, MNRAS **491**, 5179–5187 (2020)

Indirect Studies



A. Spyrou *et al.* PRL **113**, 232502 (2014)

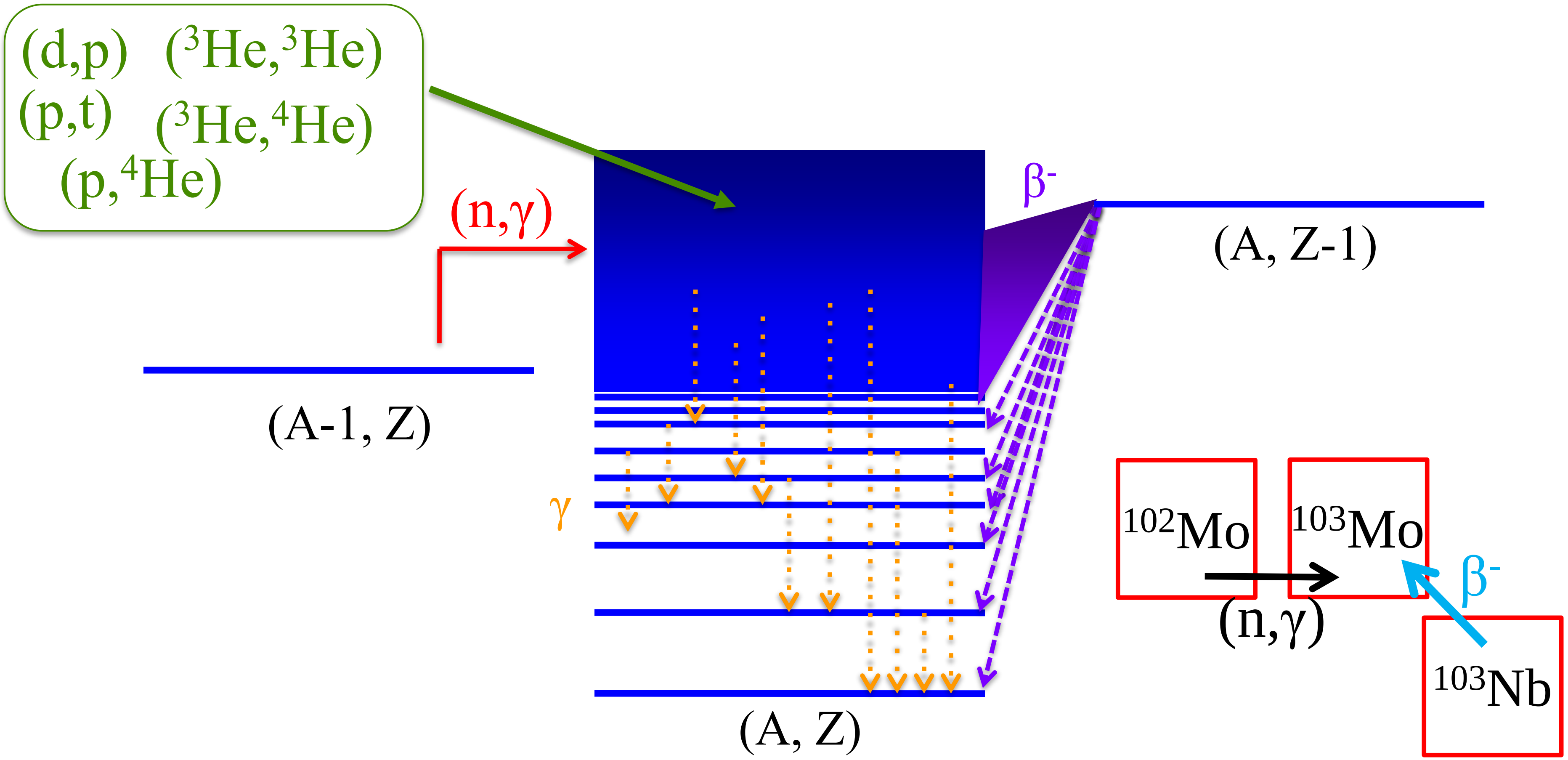
Indirect Studies



- Populate the compound nucleus via β-decay
- Study nuclei far from stability
- Feasible with low beam intensities

A. Spyrou *et al.* PRL **113**, 232502 (2014)

Indirect Studies



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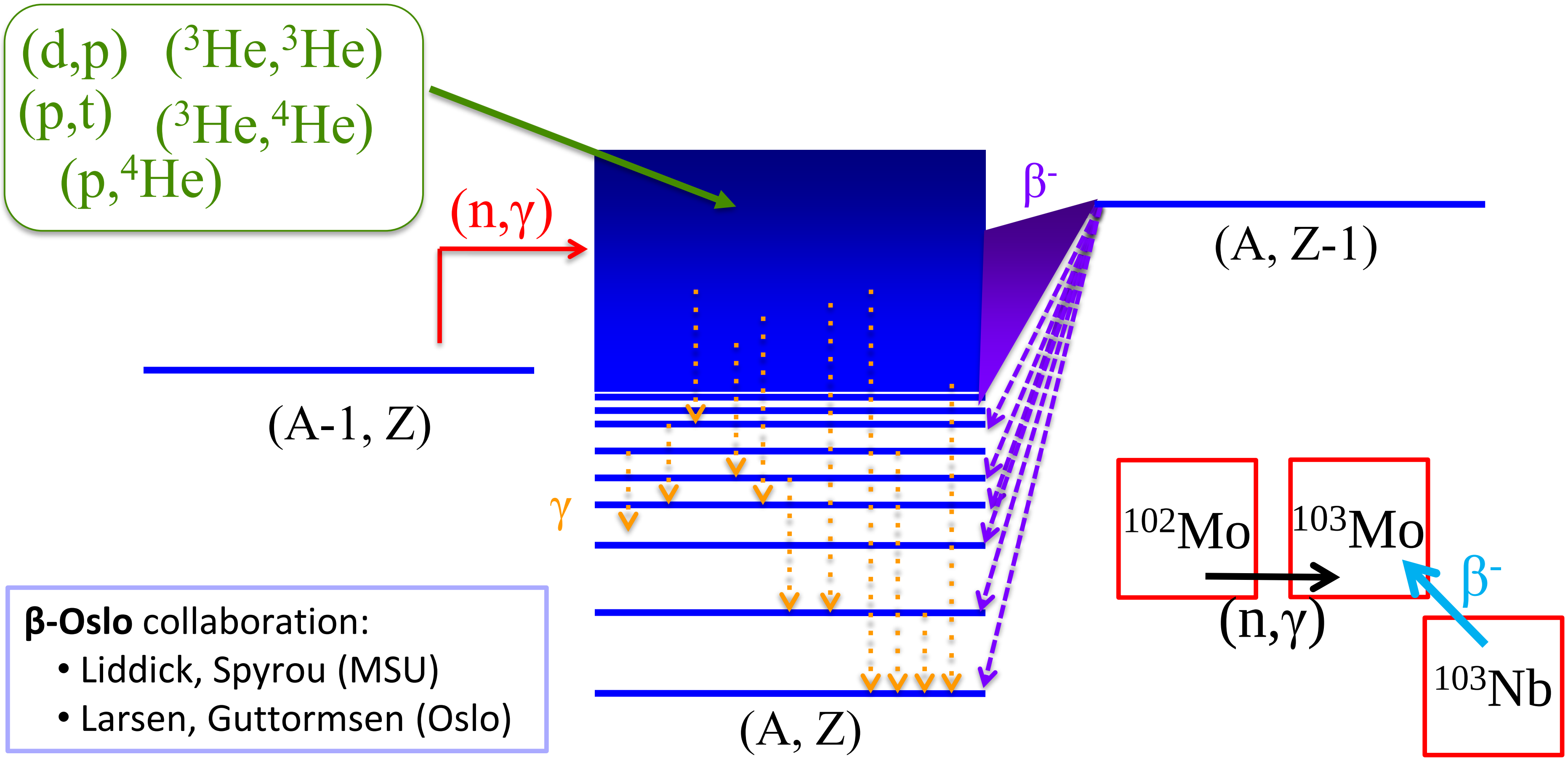
•Need:

✓ Radioactive Beam

✓ Segmented γ-ray calorimeter

A. Spyrou *et al.* PRL **113**, 232502 (2014)

Indirect Studies



β-Oslo collaboration:
- Liddick, Spyrou (MSU)
- Larsen, Guttormsen (Oslo)

- Populate the compound nucleus via β-decay
- Study nuclei far from stability
- Feasible with low beam intensities

•Need:
✓ Radioactive Beam
✓ Segmented γ-ray calorimeter

A. Spyrou *et al.* PRL **113**, 232502 (2014)

The β-Oslo Method

- Use β-decay to populate the compound nucleus of interest
- Measure excitation energy and γ-ray energy
- Extract **level density** and **γ-ray strength function** (external normalizations)
    - Three normalization points:
        - Low-lying levels (from NNDC)
        - Level density at neutron-separation energy (from previous data or from theory)
        - Average radiative width or giant dipole resonance (GDR) data
- Calculate "semi-experimental" (n,γ) cross section

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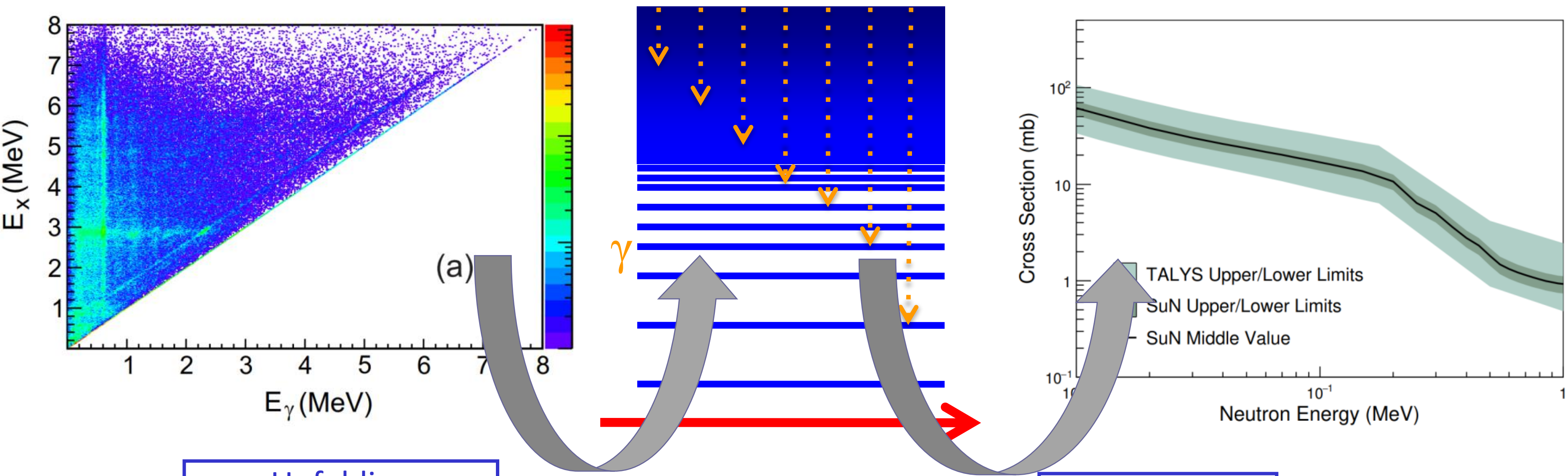


Unfolding
Iterative subtraction

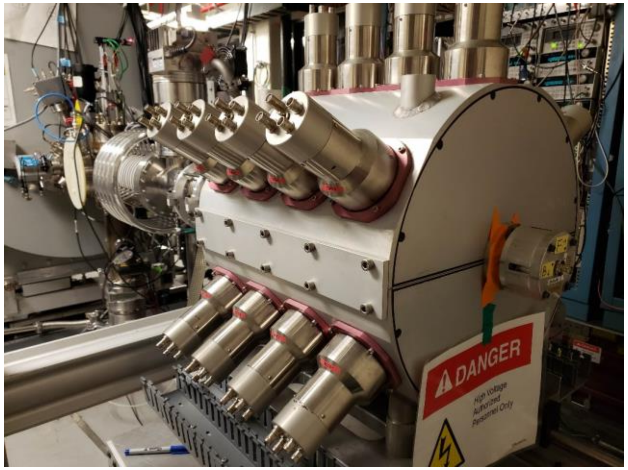
$$P(E_g, E_x) \sim r(E_x - E_g)\mathcal{T}(E_g)$$

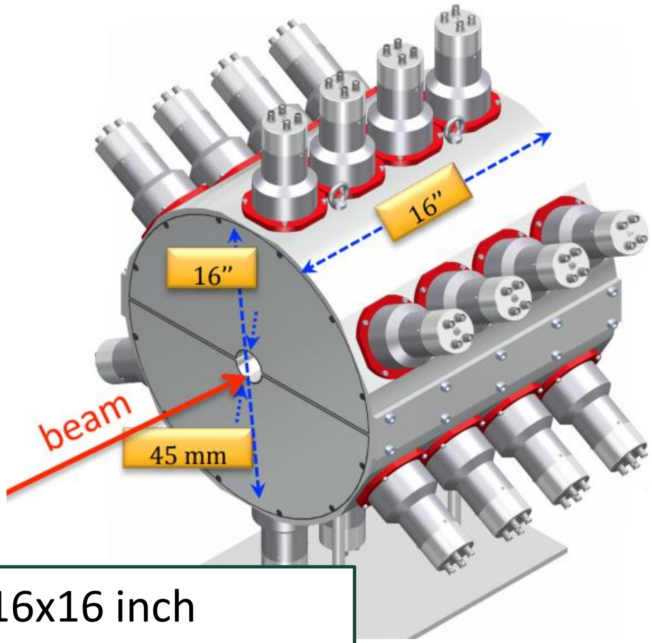
Normalization

R. Lewis *et al.*, PRC **99**, 034604 (2019)

The Summing NaI(Tl) Detector as a total absorption spectrometer

- Large size, high efficiency γ-ray detector
- Summing of all γ-rays gives the excitation energy
- Segmentation provides information about individual γ-rays
- Resolution at 1 MeV – 6%
- Efficiency at 1 MeV – 85%



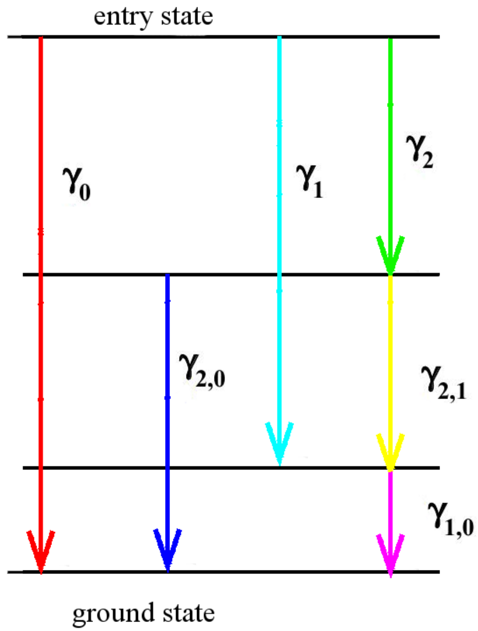


- ✓ 16x16 inch
- ✓ 45 mm borehole
- ✓ 8 segments
- ✓ 24 PMTs

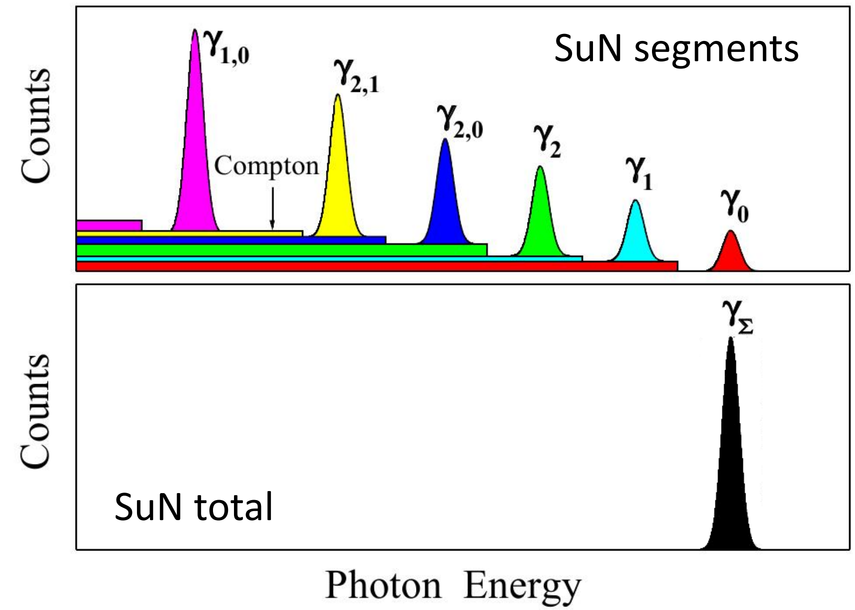
Simon, A., et al. *NIM A* 703 (2013): 16-21

Total Absorption Spectroscopy: Cartoon Example

Cartoon Decay Scheme



Energy Spectrum



Sensitive to initial excited energies + individual gamma rays!

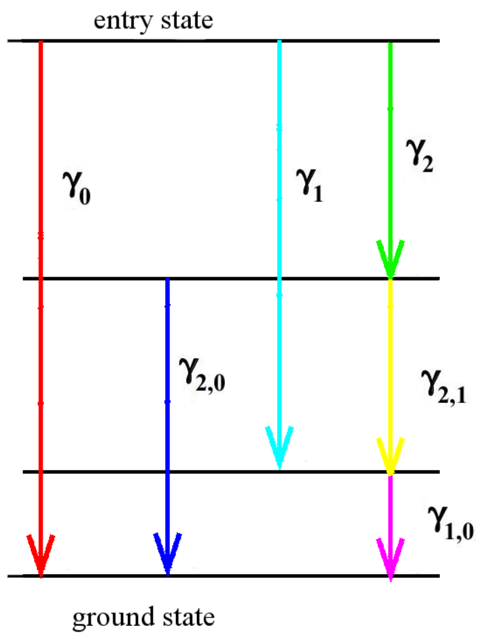
TAS = initial excited energies

Segments = individual gamma rays

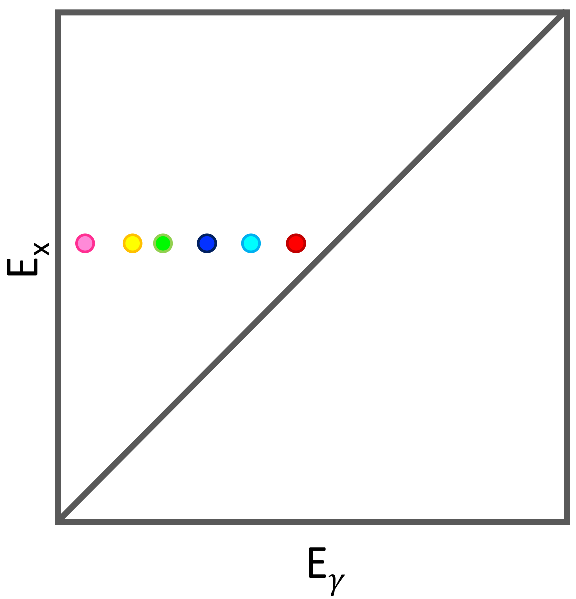
Slide modified from C. Harris

Total Absorption Spectroscopy: Cartoon Example

Cartoon Decay Scheme



βOslo Matrix



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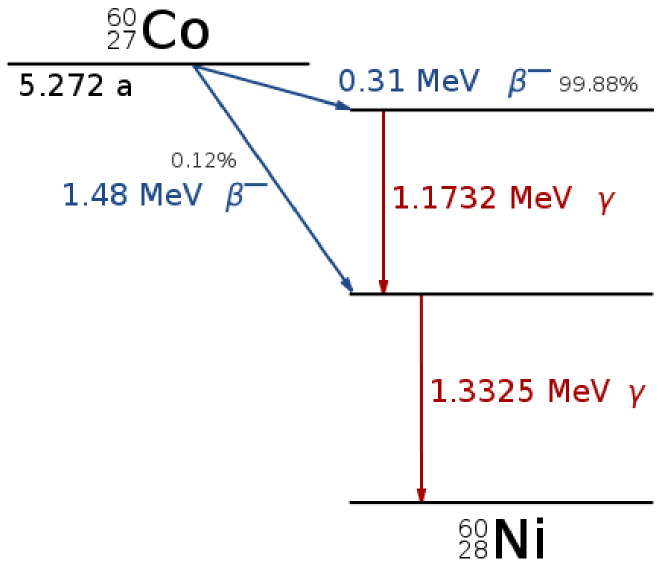
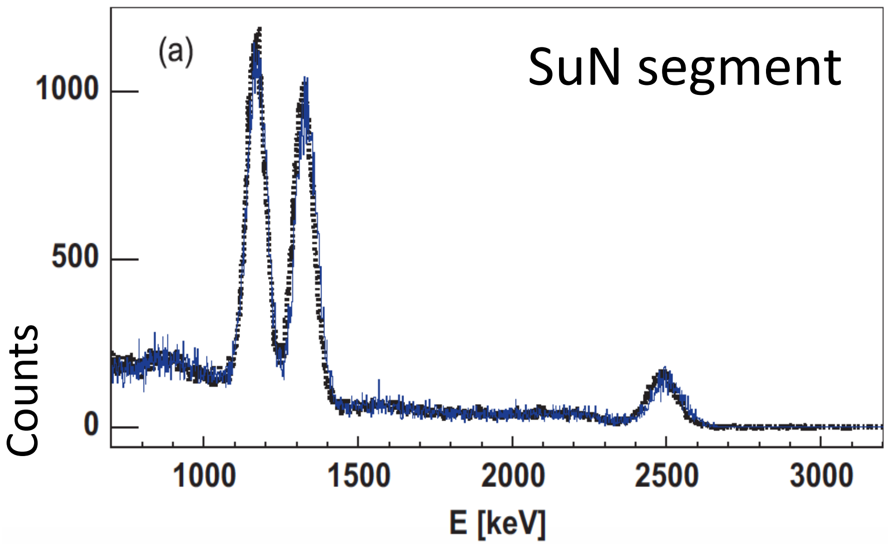
Slide modified from C. Harris

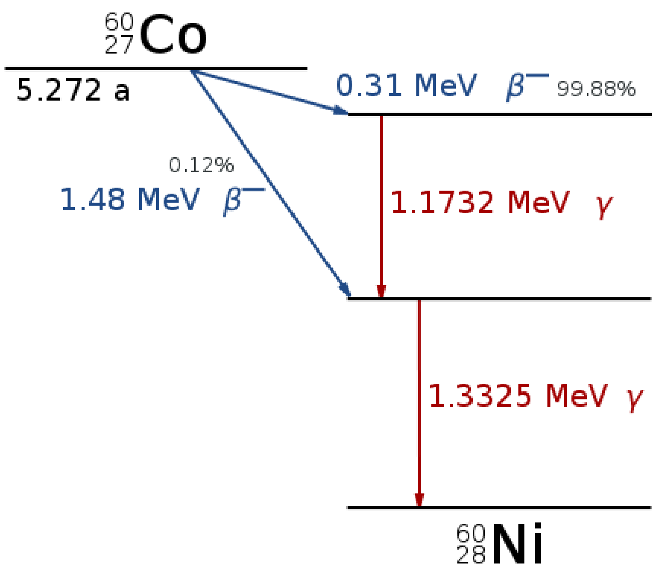
Total Absorption Spectroscopy

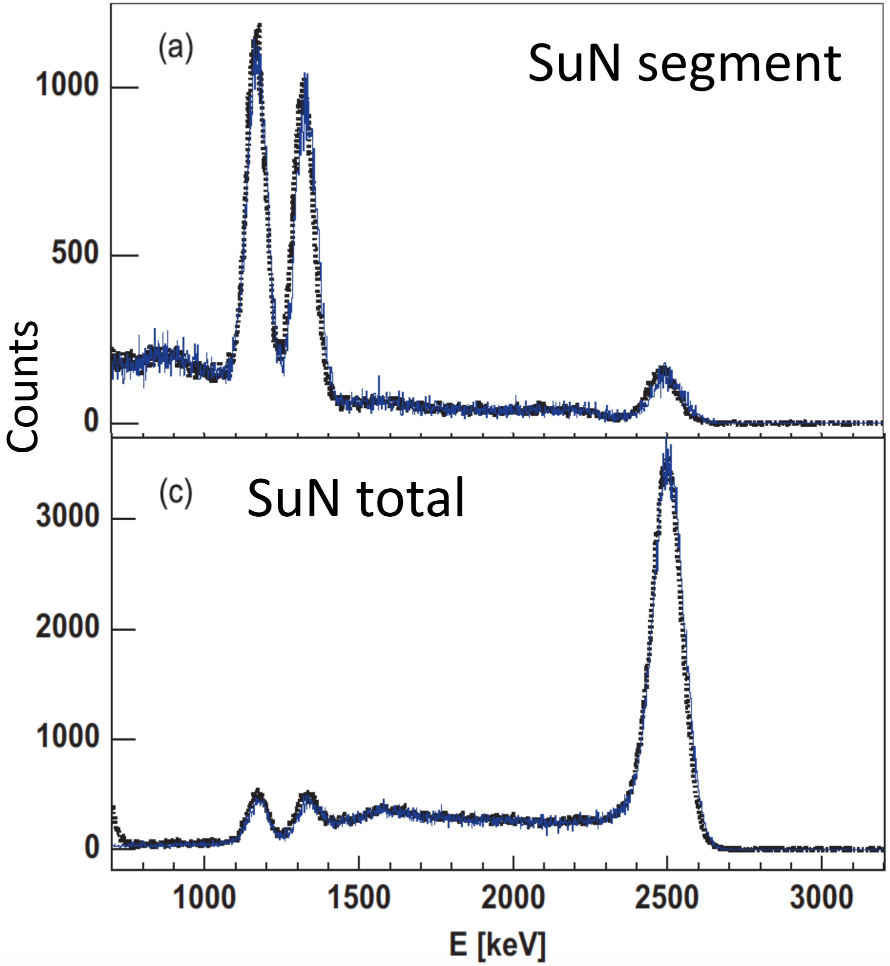




Simon, A., et al. *NIM A* 703 (2013): 16-21

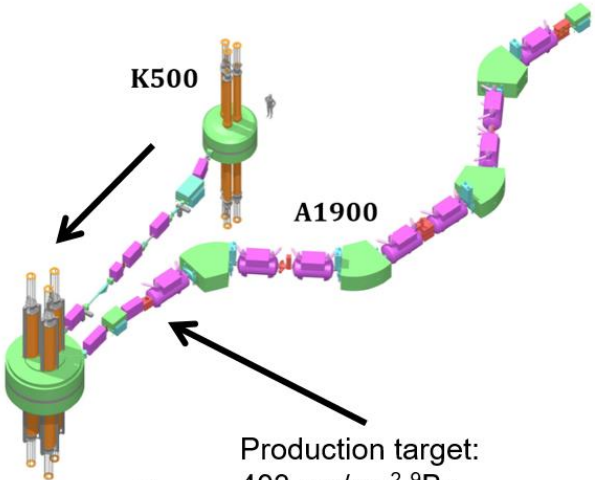
Total Absorption Spectroscopy





Simon, A., et al. *NIM A* 703 (2013): 16-21

β-Oslo at the NSCL – fast beams



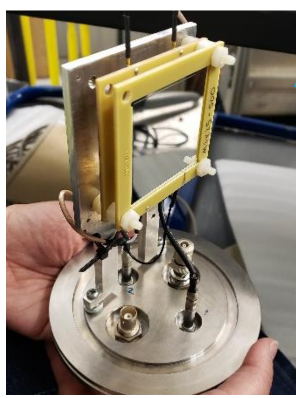
To S2 vault

$\Delta p/p \sim 5\%$
Cocktail beam of Y, Zr, Nb, Mo, and Tc isotopes

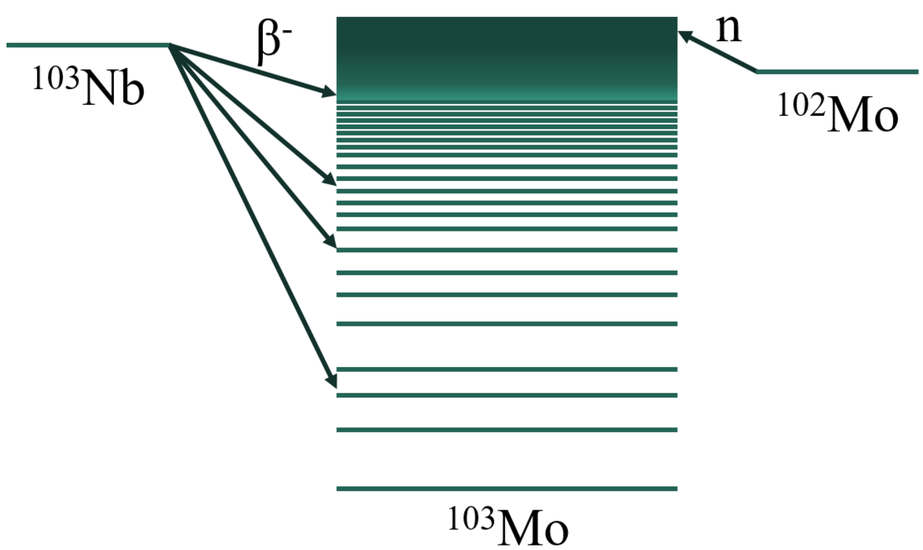
Production target:
403 mg/cm^2 ^{9}Be

$^{124}Sn^{45+}$ at
120 MeV/u

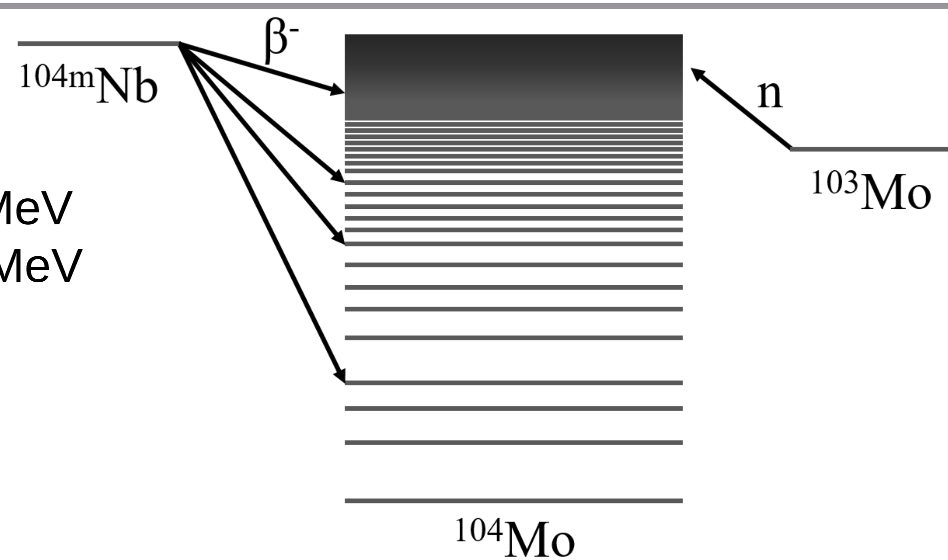
SuN



Decay of ^{103}Nb, ^{104m}Nb

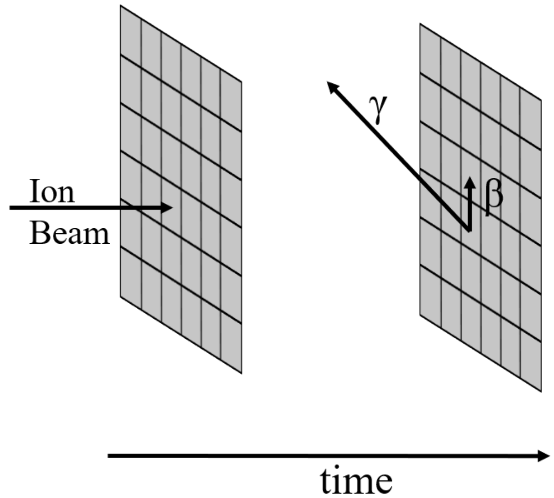


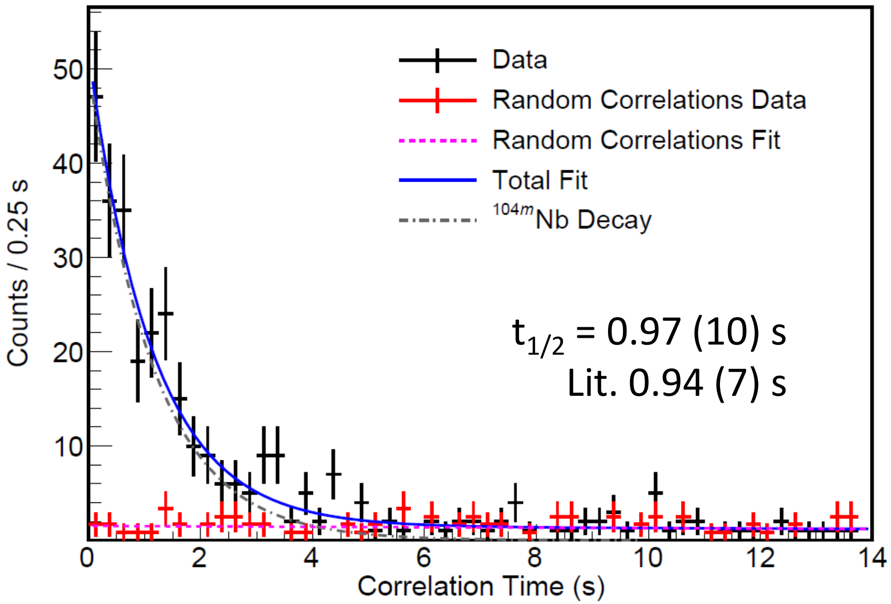
$Q_{\beta-}$ = 5.932 (10) MeV
S_n = 5.466 (12) MeV
J^π = $(5/2^+)$
$t_{1/2}$ = 1.5 (2) s

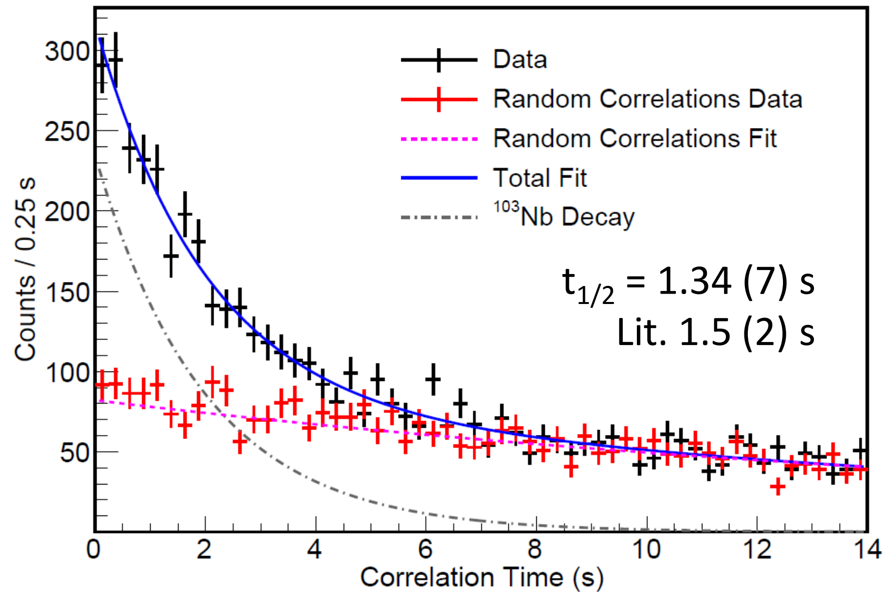


$Q_{\beta-}$ = 8.531 (9) MeV
S_n = 7.461 (13) MeV
J^π = (4^-)
$t_{1/2}$ = 0.97 (10) s

Correlation technique for fast β-decay spectroscopy

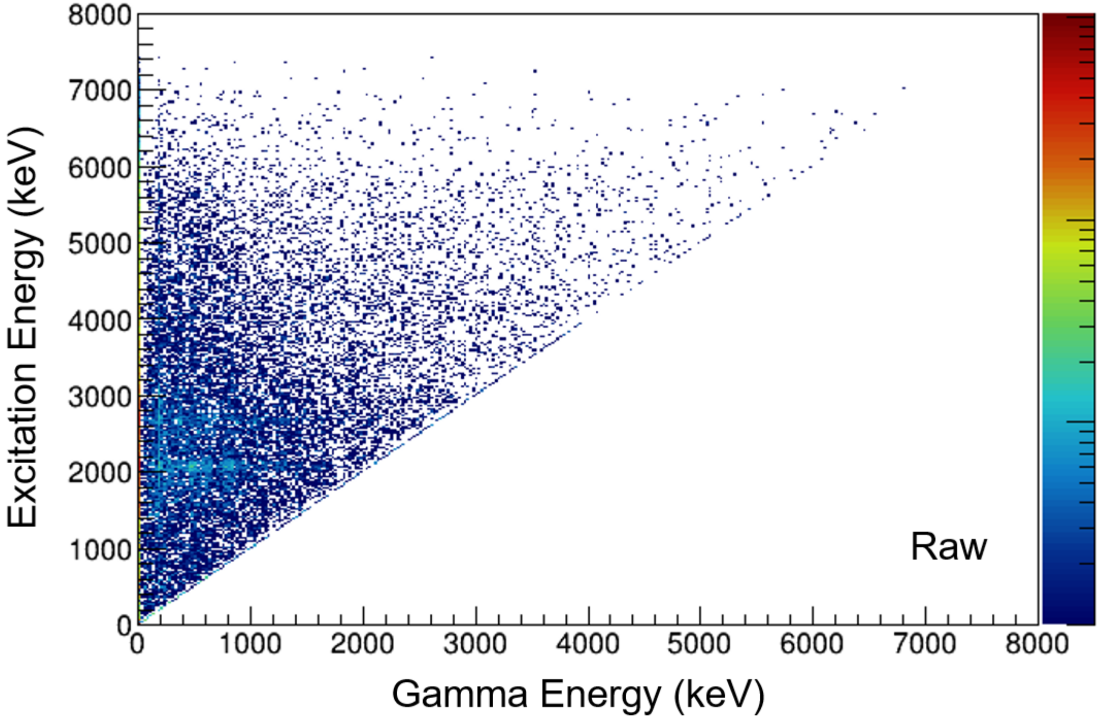






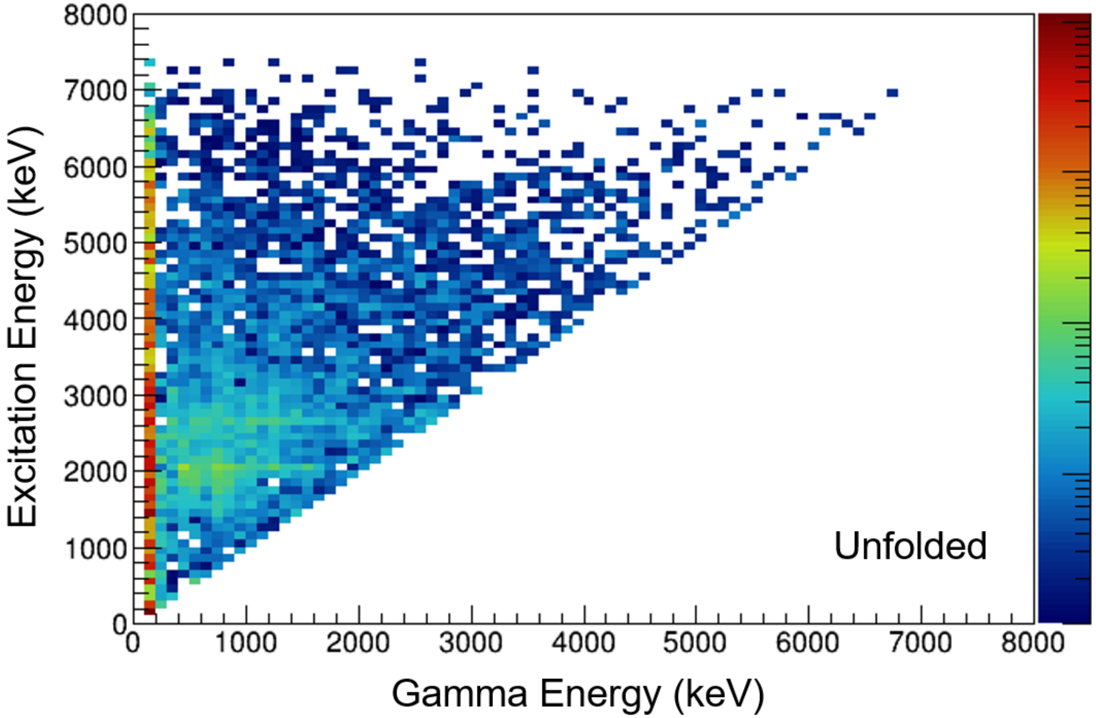
A. C. Dombos Dissertation

Raw E_x vs. E_γ Matrix: ^{104m}Nb



- Strongly populated levels at ~2MeV and 3MeV consistent with known data

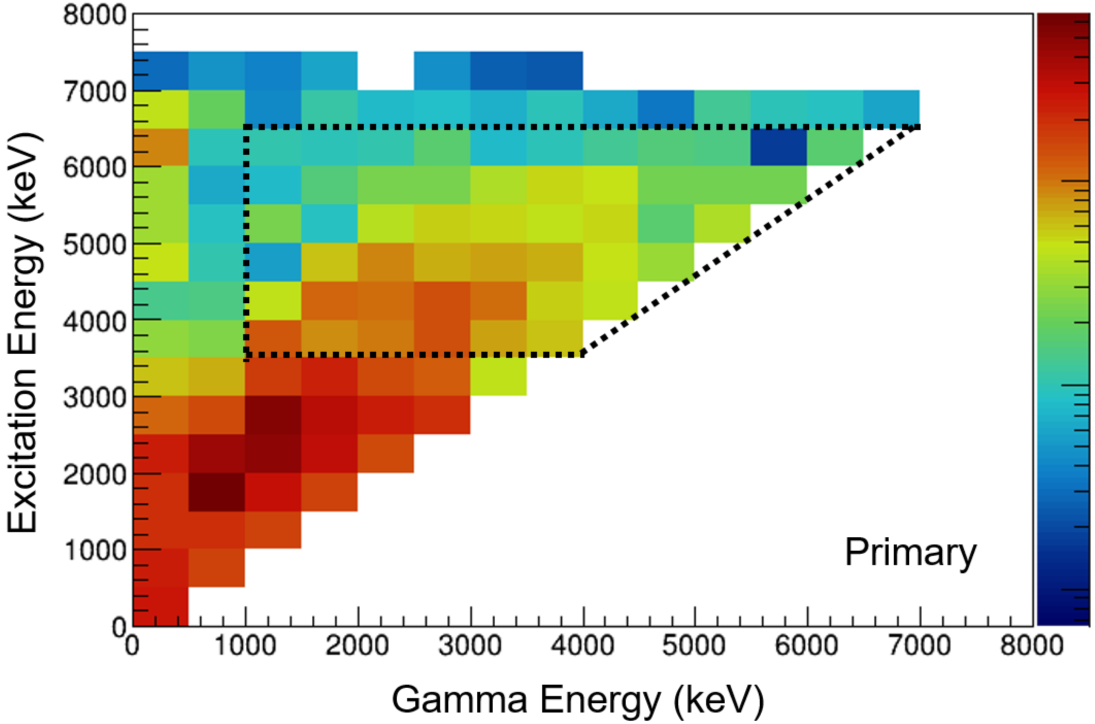
Unfolded E_x vs. E_γ Matrix: ^{104m}Nb



- Need to account for the interaction of γ-rays in the detector
- Generate response function for SuN in GEANT4
- Iterative procedure to determine the incoming energy

Guttormsen *et al.*, NIMA **255**, 518 (1987)
Allison *et al.*, NIMA **835**, 186 (2016)

Primary E_x vs. E_γ Matrix: ^{104m}Nb



- Isolate the first γ-ray to be emitted from each excited state
- Iterative subtraction of the γ-rays emitted from lower excited states
- When normalized, becomes the probability matrix needed to extract NLD and γSF:

$$P(E_\gamma, E_x) \propto \rho(E_x - E_\gamma) \cdot T(E_\gamma)$$

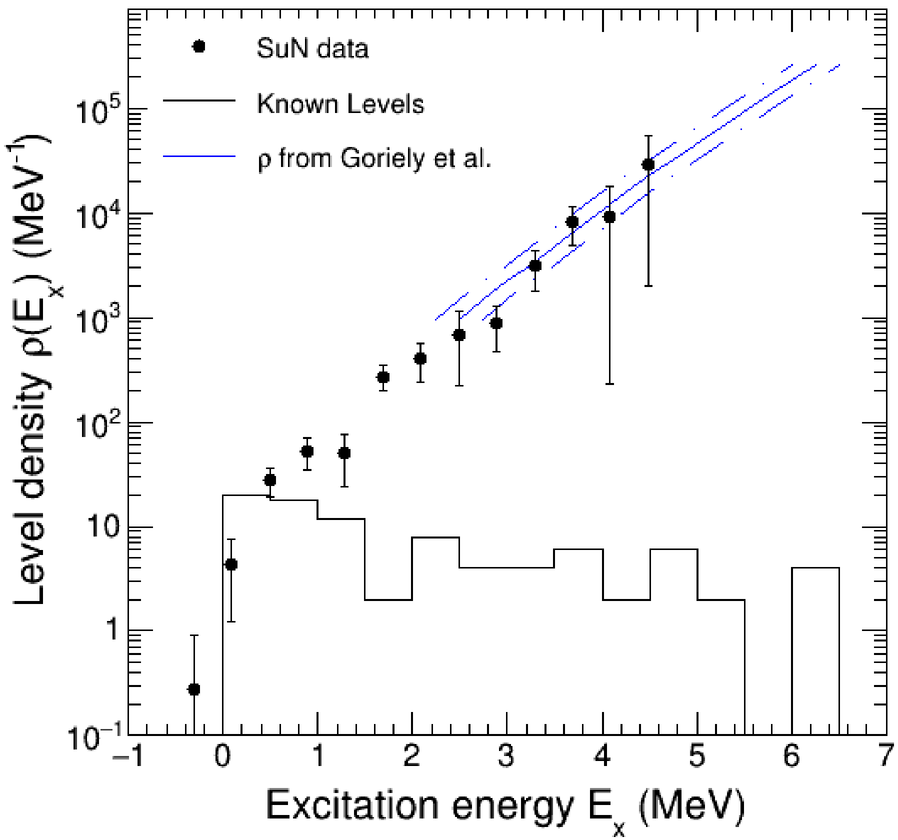
$$\gamma SF(E_\gamma) = \frac{1}{2\pi} \frac{T(E_\gamma)}{E_\gamma^3}$$

Schiller *et al.*, NIMA **447**, 498 (2000)

Guttormsen *et al.*, NIMA **374**, 371 (1996)

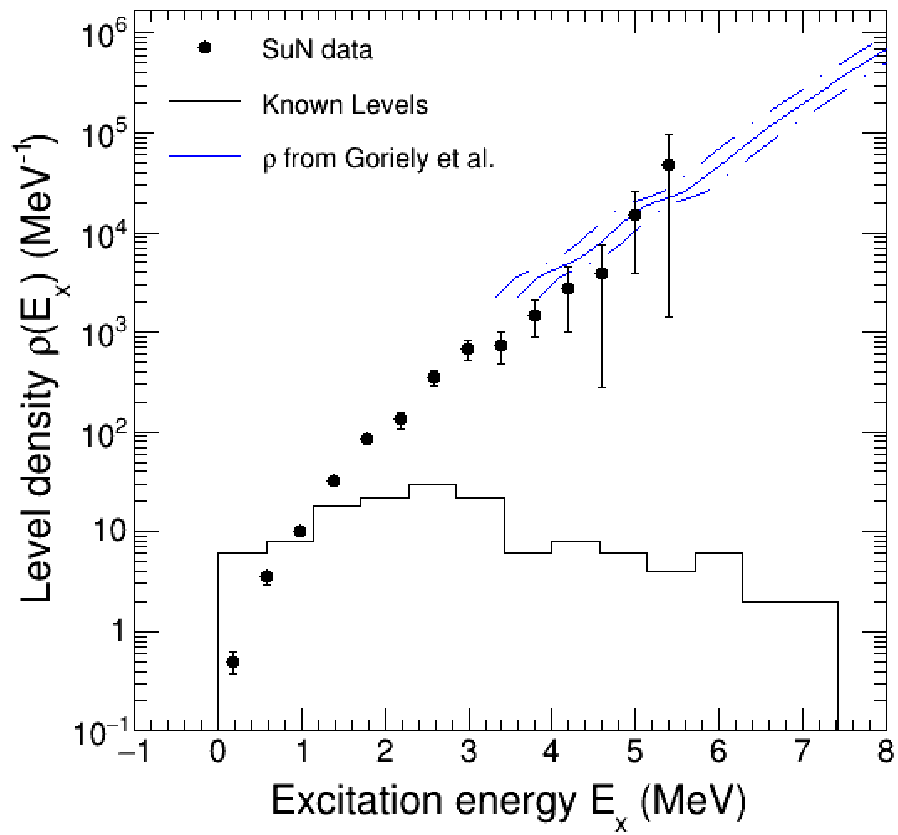
Normalized Level Densities for ^{103}Mo, ^{104}Mo

^{103}Mo



Shift value: -0.25 ± 0.25 MeV

^{104}Mo

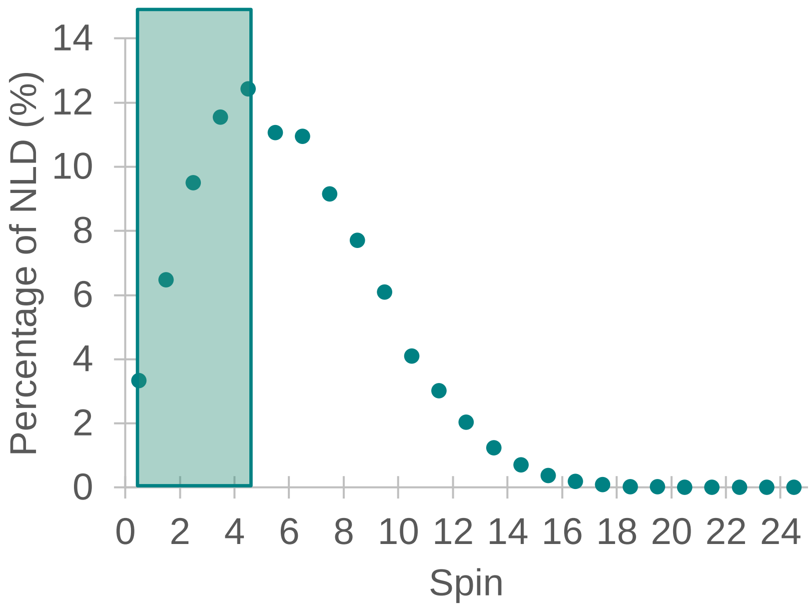


Shift value: 0.1 ± 0.35 MeV

Goriely, Hilaire, and Koning, PRC **78**, 064307 (2008)

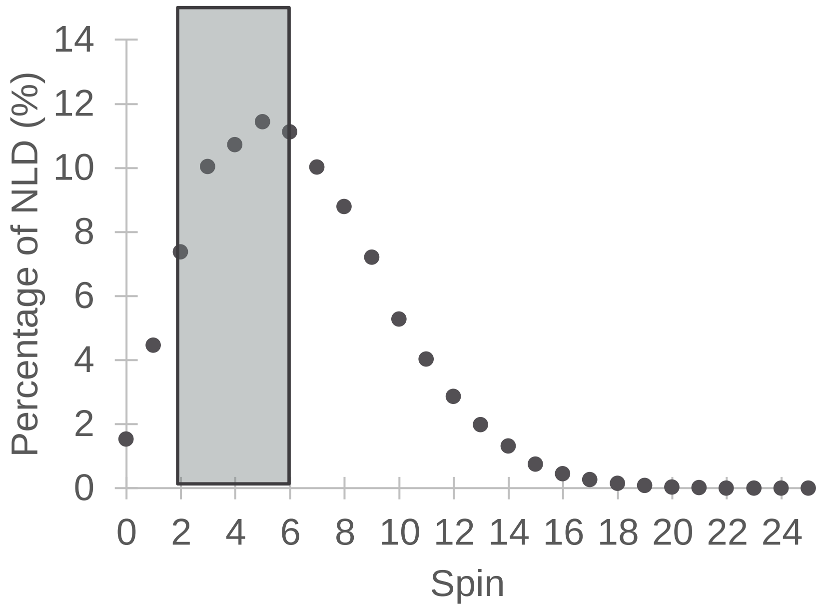
Spin Reduction from β-decay Selection Rules

^{103}Mo



- From ^{103}Nb – $5/2^+$
  - Spin range: $1/2^{\pm}$ - $9/2^{\pm}$
- 43% population

^{104}Mo

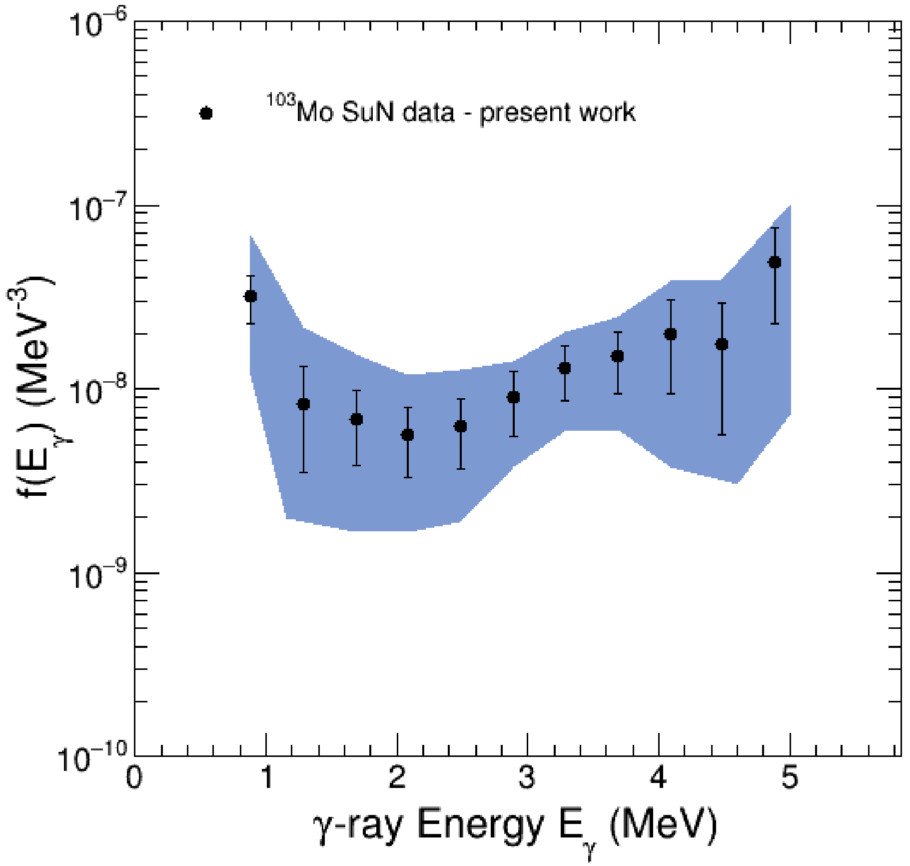


- From ^{104m}Nb – (4^-)
  - Spin range: $2^{\pm}$ - $6^{\pm}$
- 51% population

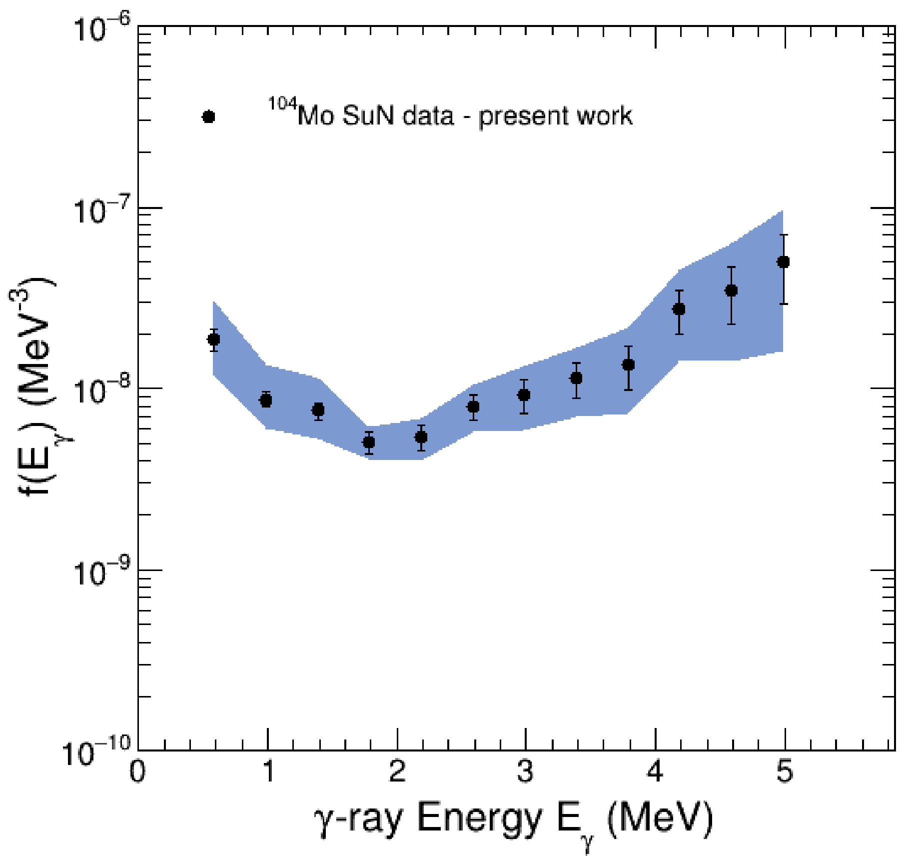
Goriely, Hilaire, and Koning, PRC **78**, 064307 (2008)

Reduced γ-ray Strength Functions for ^{103}Mo, ^{104}Mo

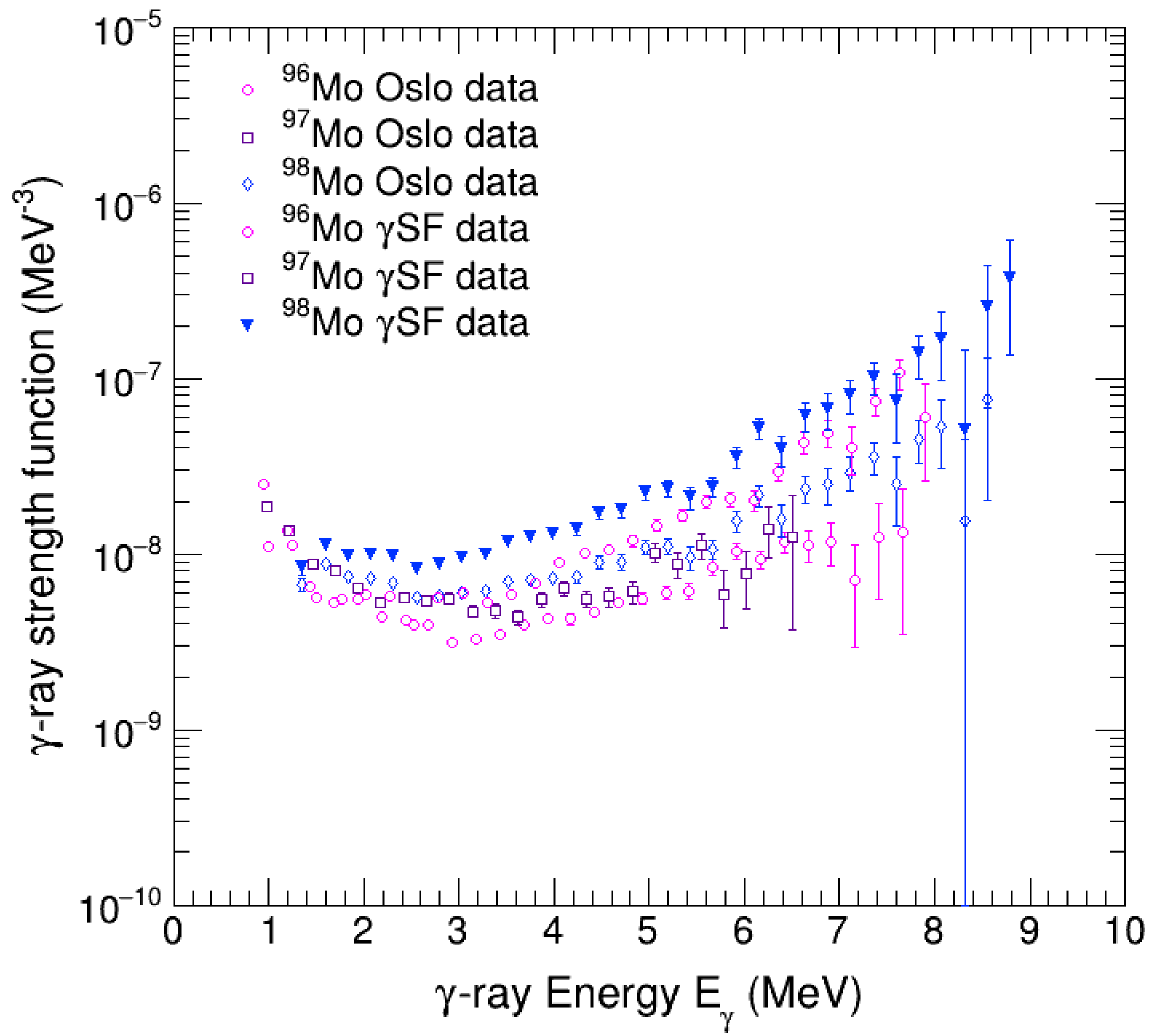
^{103}Mo



^{104}Mo

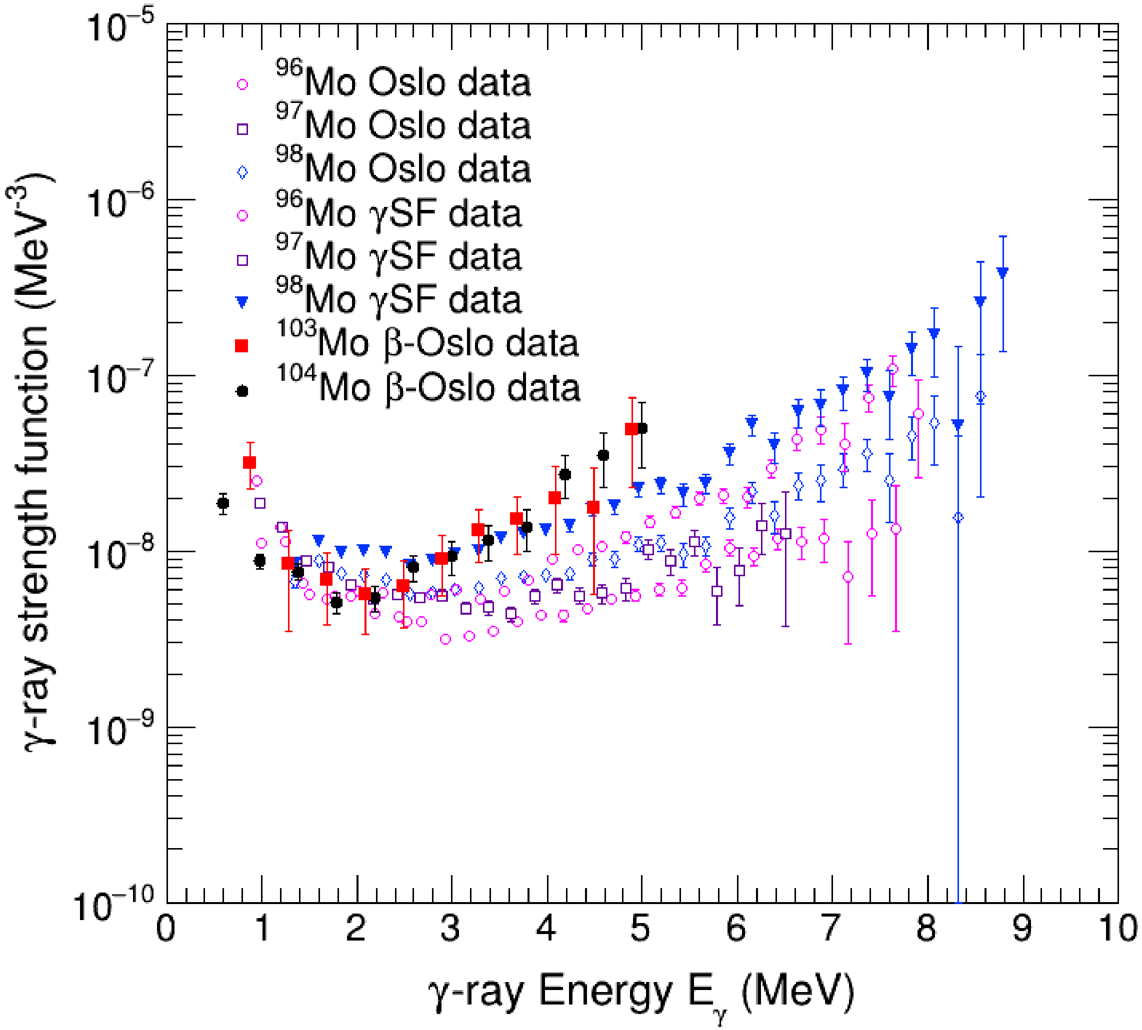


Comparison to $^{96-98}$Mo



M. Guttormsen, PRC 71, 044307 (2005)
H. Utsunomiya, PRC 88, 015805 (2013)

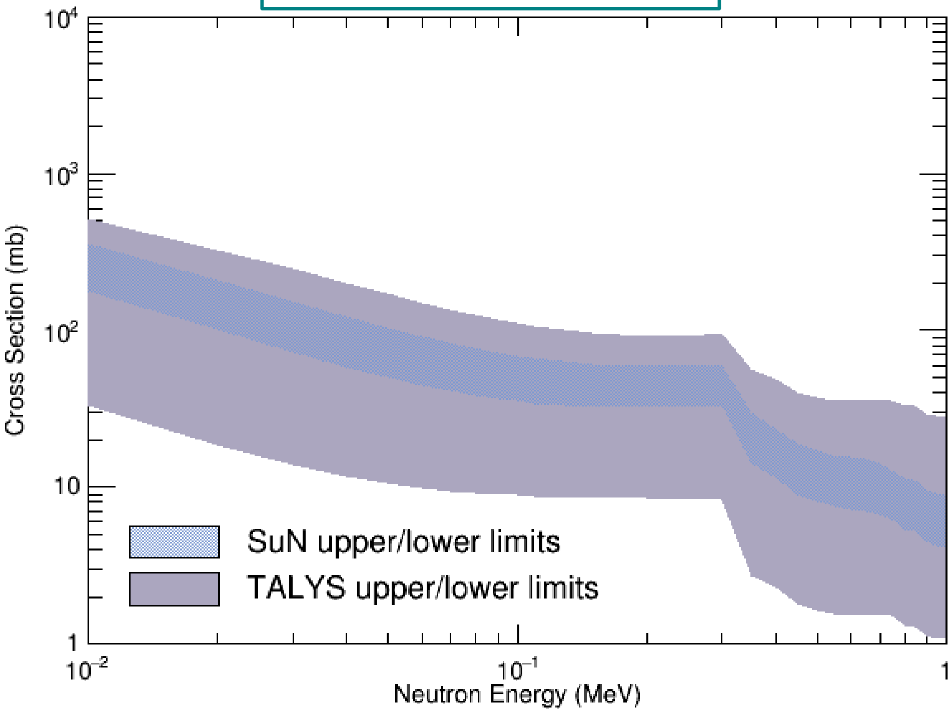
Comparison to $^{96-98}$Mo



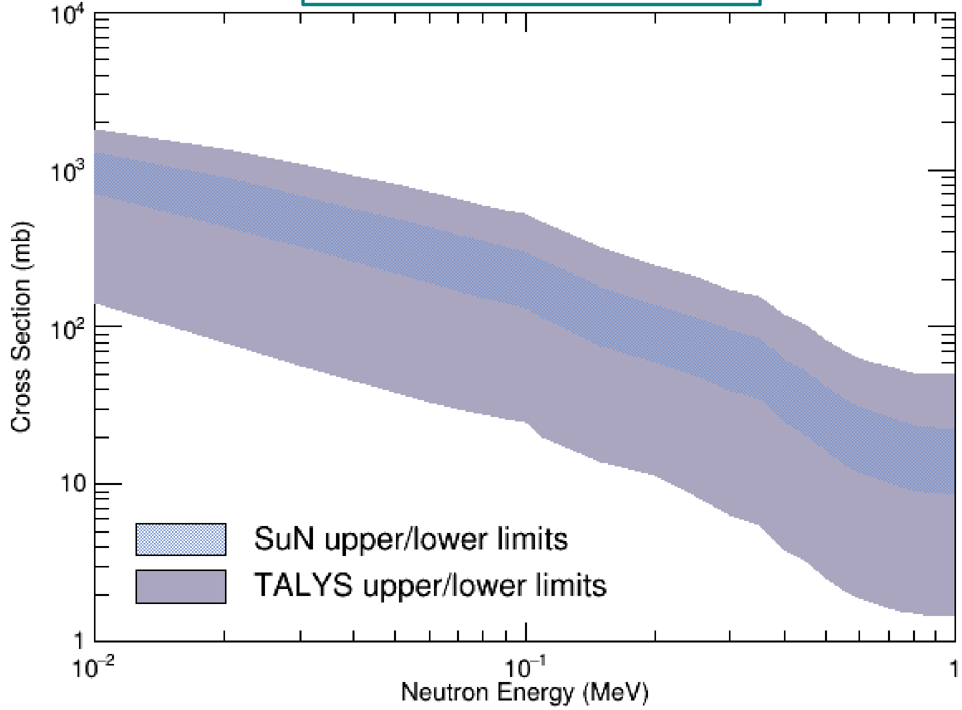
M. Guttormsen, PRC 71, 044307 (2005)
H. Utsunomiya, PRC 88, 015805 (2013)

Experimentally constrained cross sections for $^{102}Mo(n,\gamma)^{103}Mo$ and $^{103}Mo(n,\gamma)^{104}Mo$

$^{102}Mo(n,\gamma)^{103}Mo$

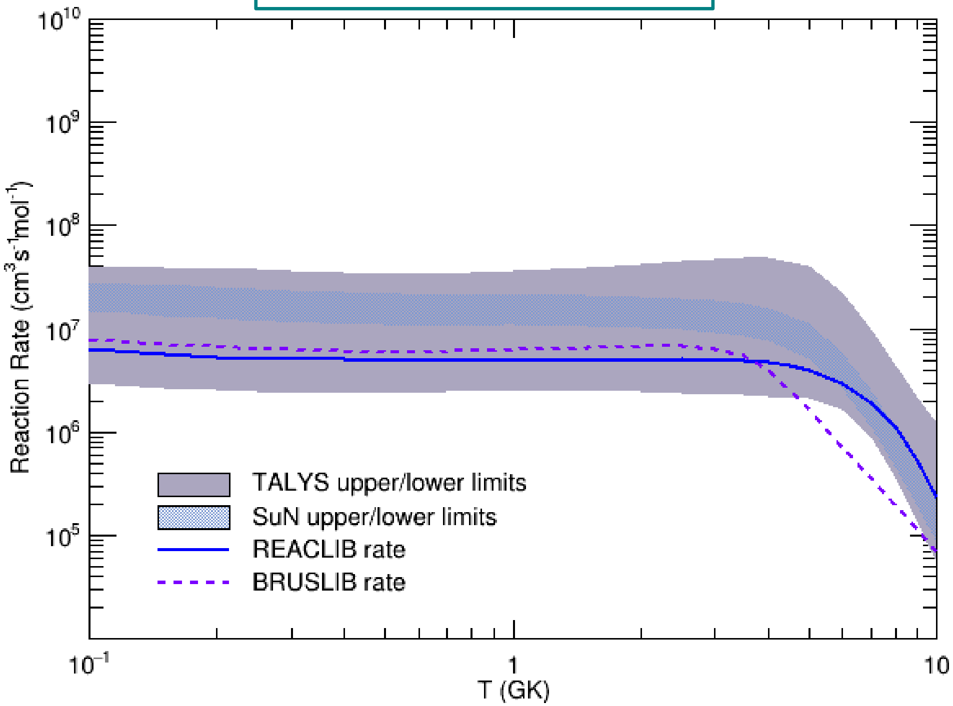


$^{103}Mo(n,\gamma)^{104}Mo$

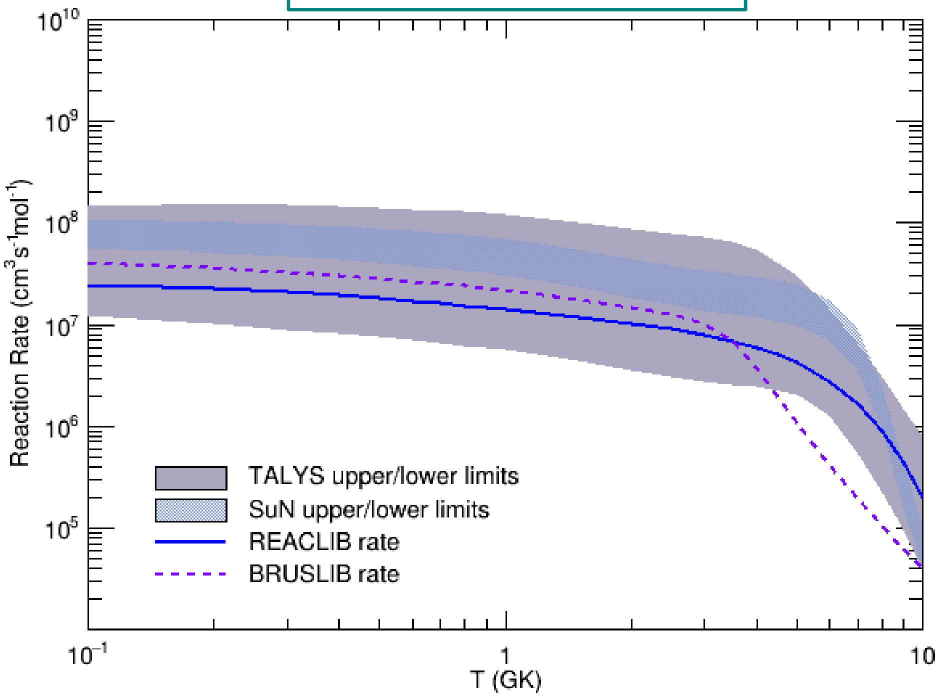


Experimentally constrained reaction rates for $^{102}Mo(n,\gamma)^{103}Mo$ and $^{103}Mo(n,\gamma)^{104}Mo$

$^{102}Mo(n,\gamma)^{103}Mo$

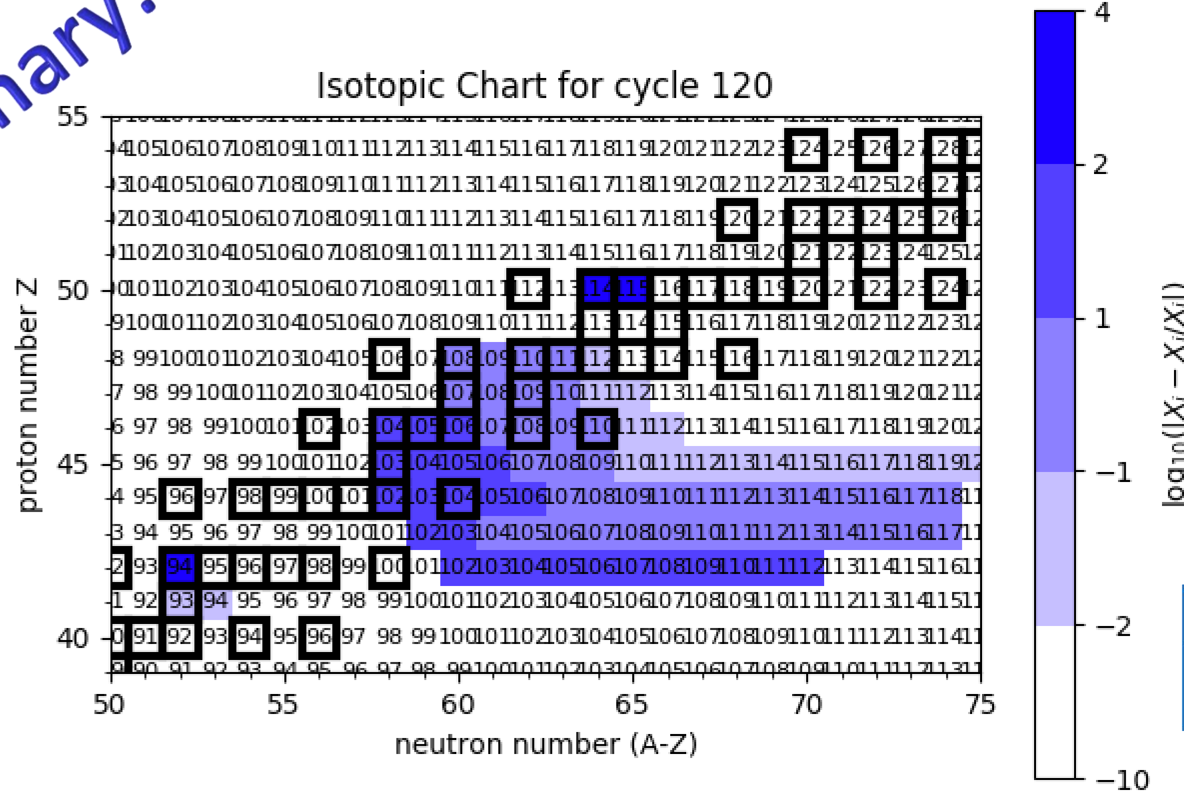


$^{103}Mo(n,\gamma)^{104}Mo$



Impact of neutron-capture constraints

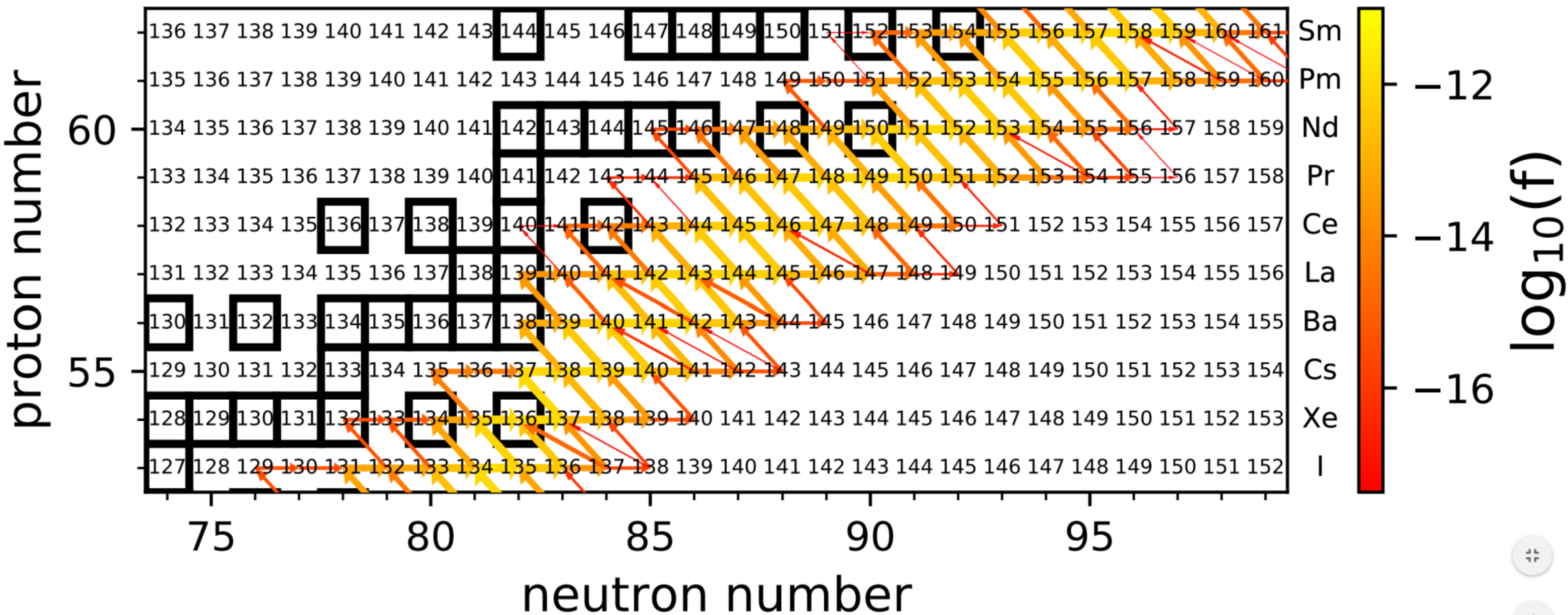
Preliminary!



- Nucleosynthesis Grid (NuGrid) Collaboration
- Relative difference between constrained rates and non-smoker
- Comparison with CEMP stars underway

Ondrea Clarkson, University of Victoria, NuGrid

i-process sensitivity studies attribute highest impact to ^{141}Ba(n,γ)^{142}Ba

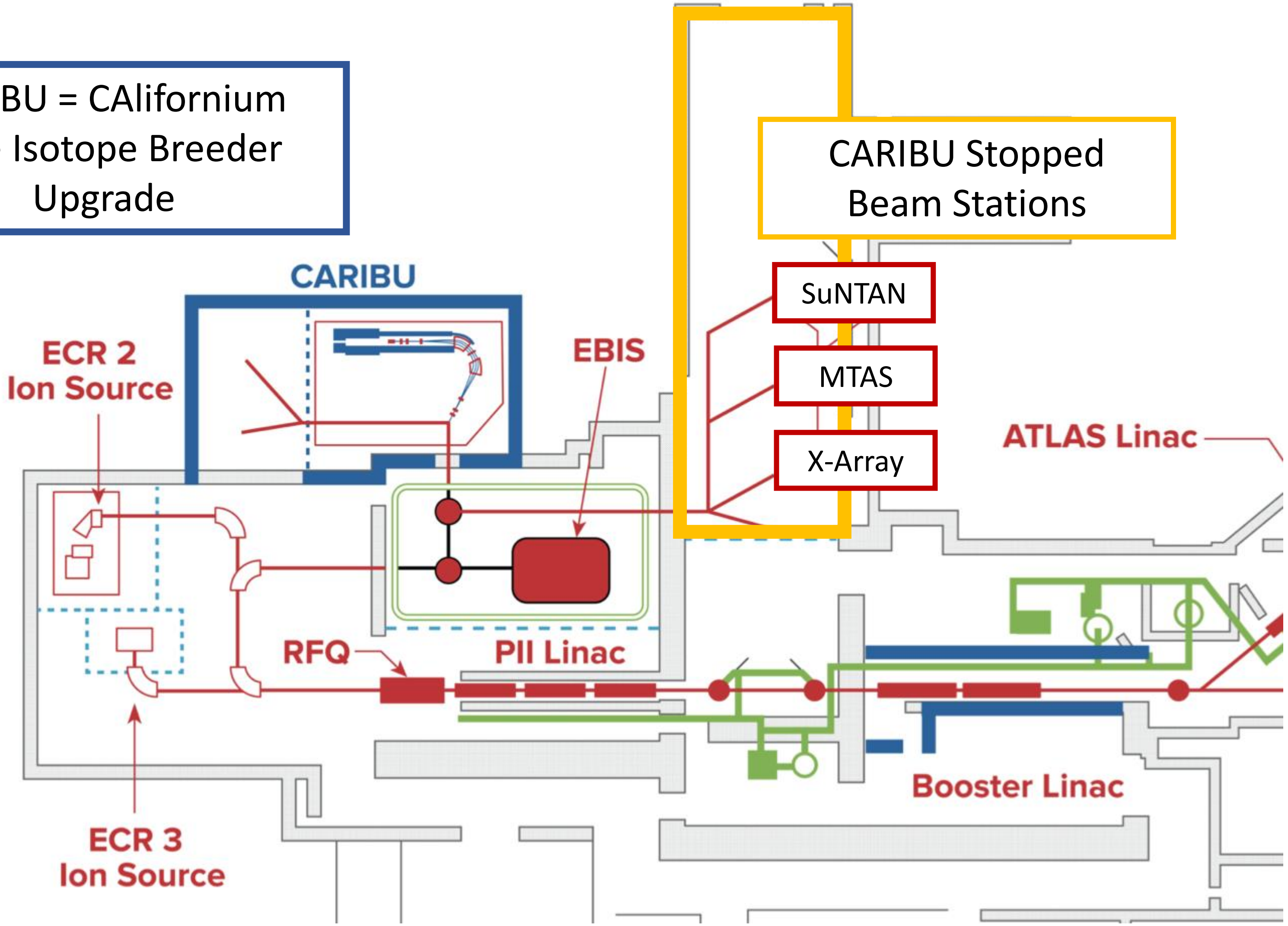


- Recent study by NuGrid highlights the significance of ^{141}Ba(n,γ)^{142}Ba uncertainties on Pr production in CEMP stars

Denissenkov, arXiV:2010.15798

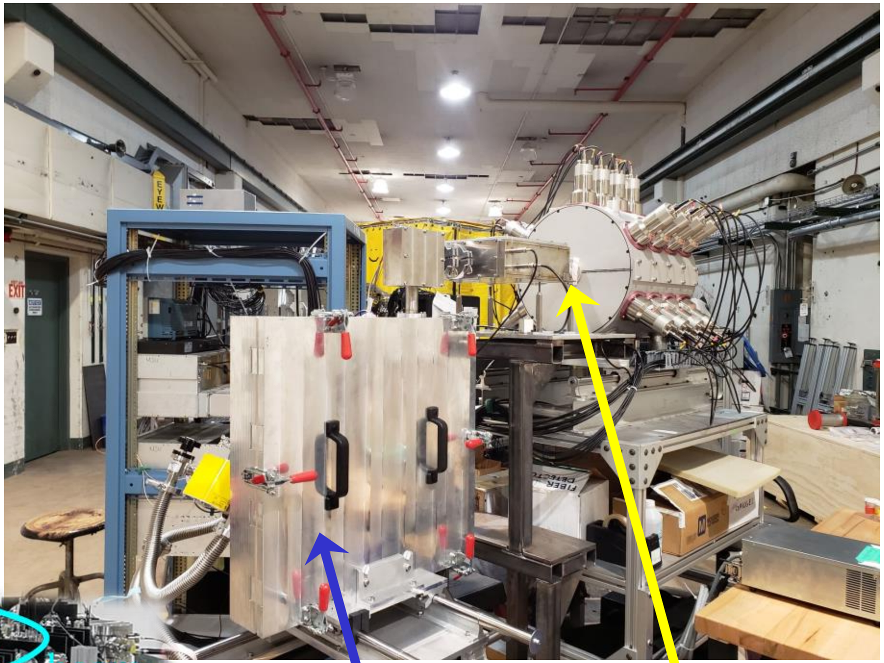
SuNTAN at CARIBU

CARIBU = CAlifornium Rare Isotope Breeder Upgrade

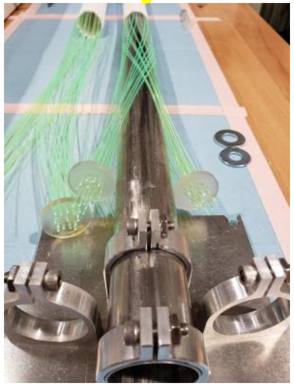


β-Oslo at ANL – stopped beams

- CARIBU + low-energy area
- Nov. 2019: SuNTAN moved to ANL
- Feb. 2020: Commissioning
  $^{141}Ba(n,\gamma)^{142}Ba$
- Feb. 2020: First experiment
  $^{87\text{-}89}Kr(n,\gamma)^{88\text{-}90}Kr$
- Additional experiments delayed due to COVID-19



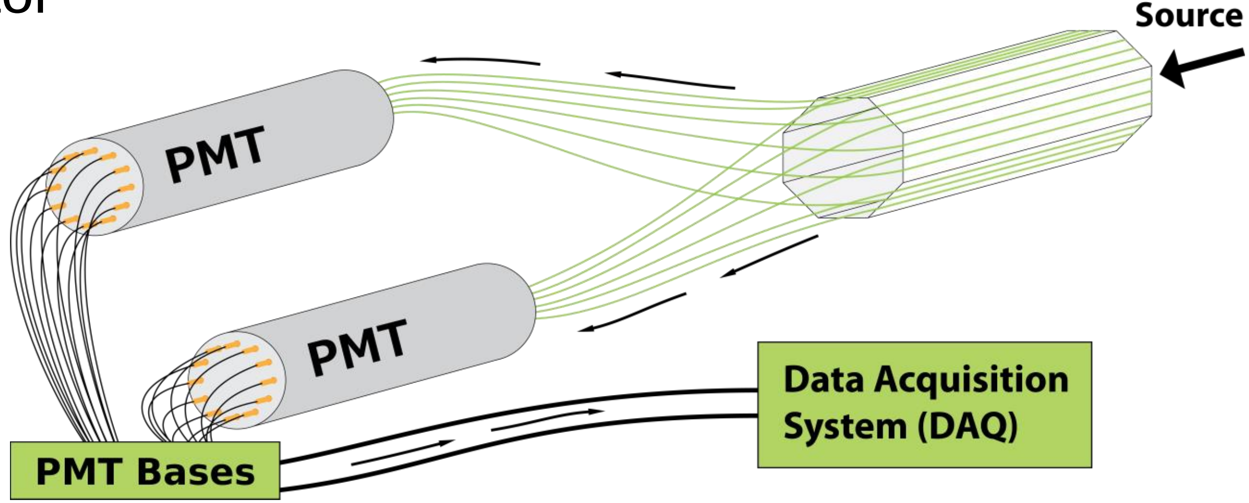
Tape Station



Fiber detector: β detector

Scintillating Plastic Optical Transport Detector

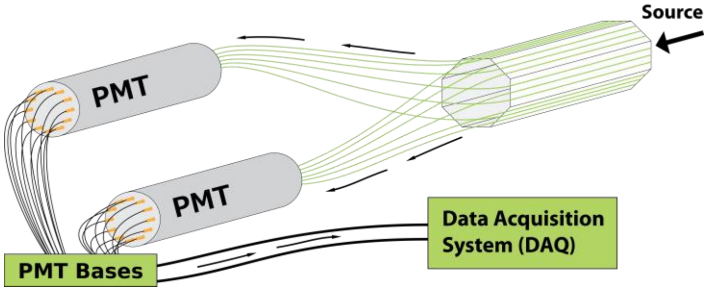
- 8 panels of scintillating plastic
- alternating optical fibers transport signal to PMTs
- ΔE detector

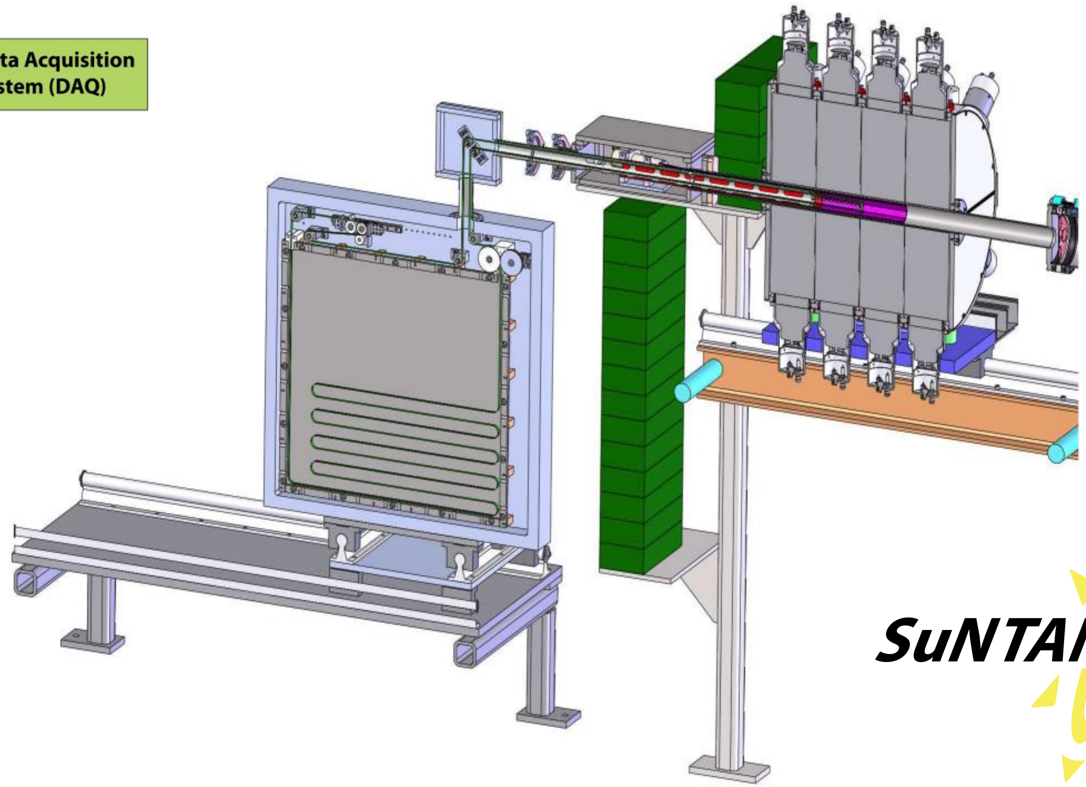


Hope COLLEGE

SuNTAN at ANL – stopped beams

- Tape system for Active Nuclei: SuNTAN
  - i-process, nuclear security

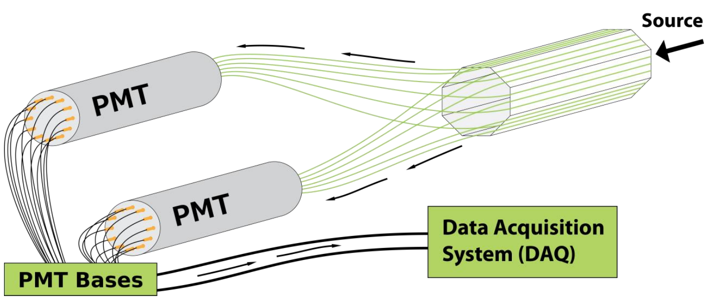


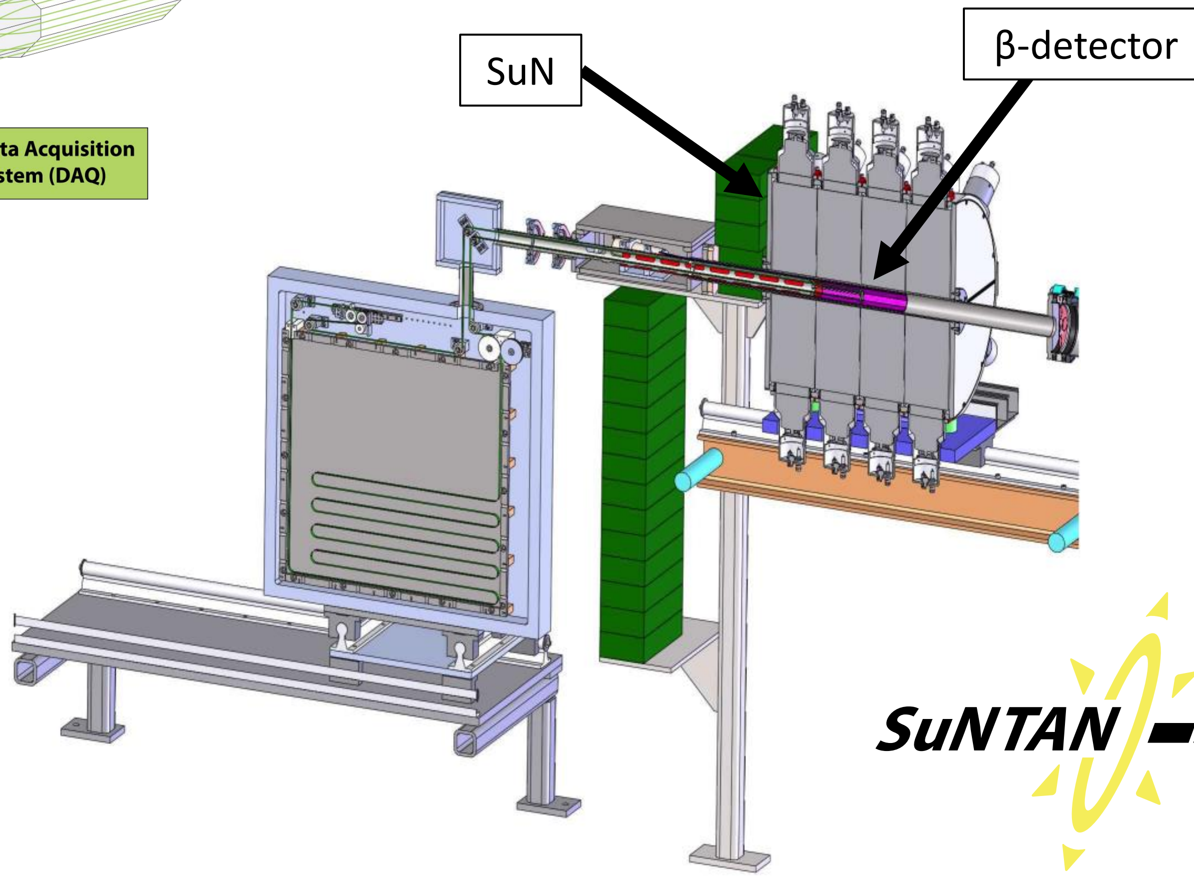


SuNTAN

SuNTAN at ANL – stopped beams

- Tape system for Active Nuclei: SuNTAN
  - i-process, nuclear security



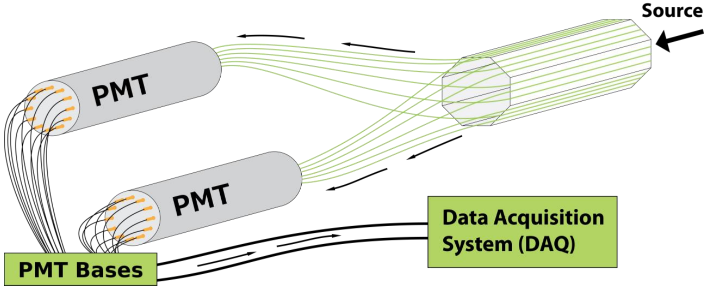


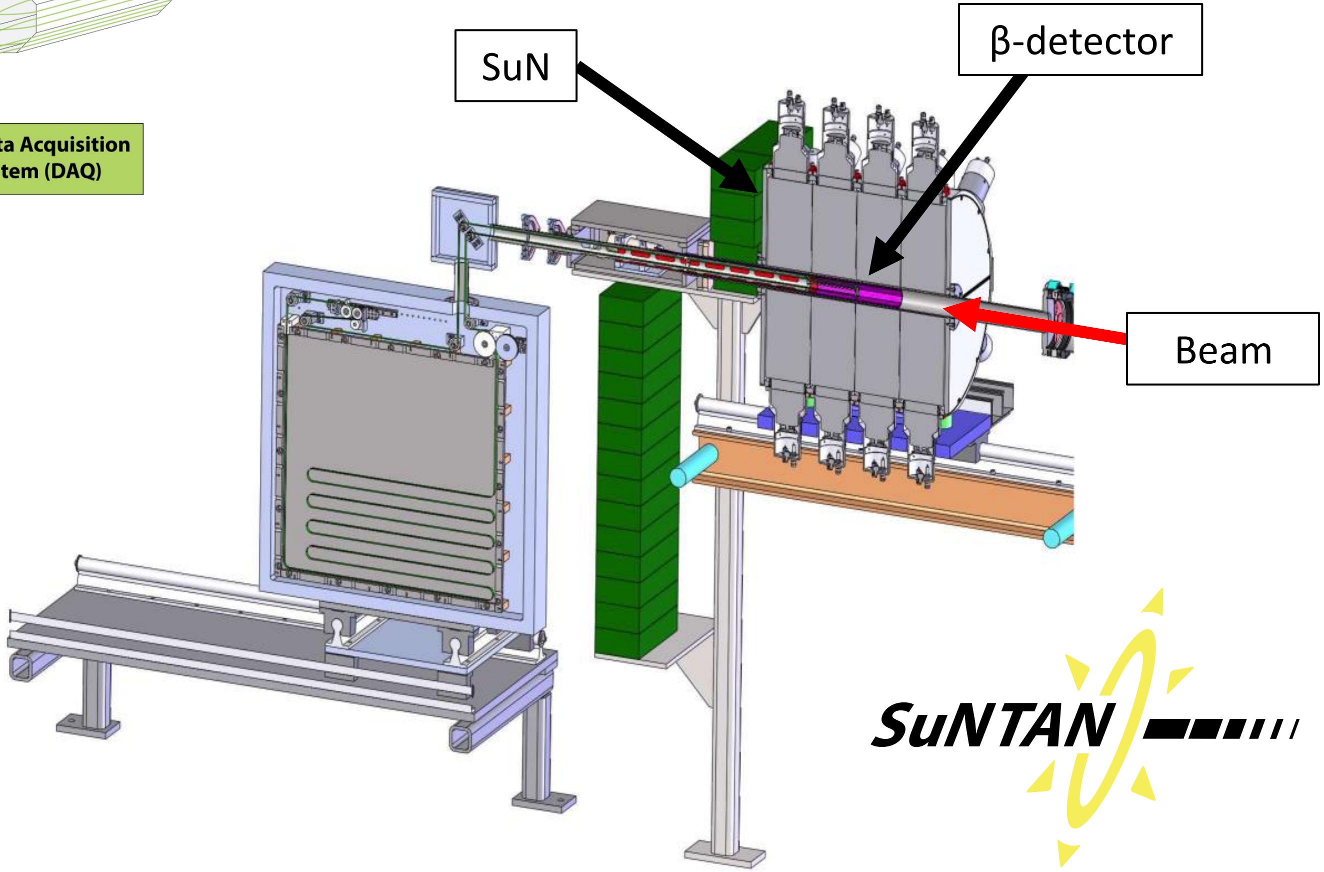
SuNTAN

Slide modified from C. Harris

SuNTAN at ANL – stopped beams

- Tape system for Active Nuclei: SuNTAN
  - i-process, nuclear security

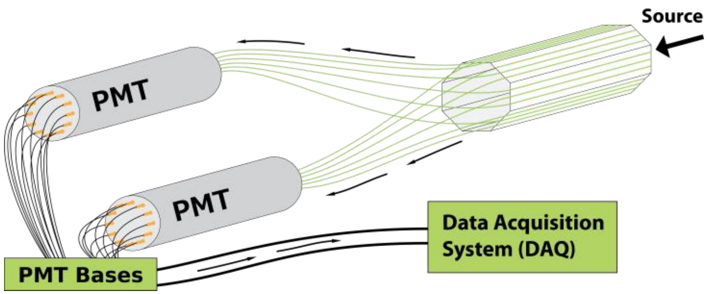


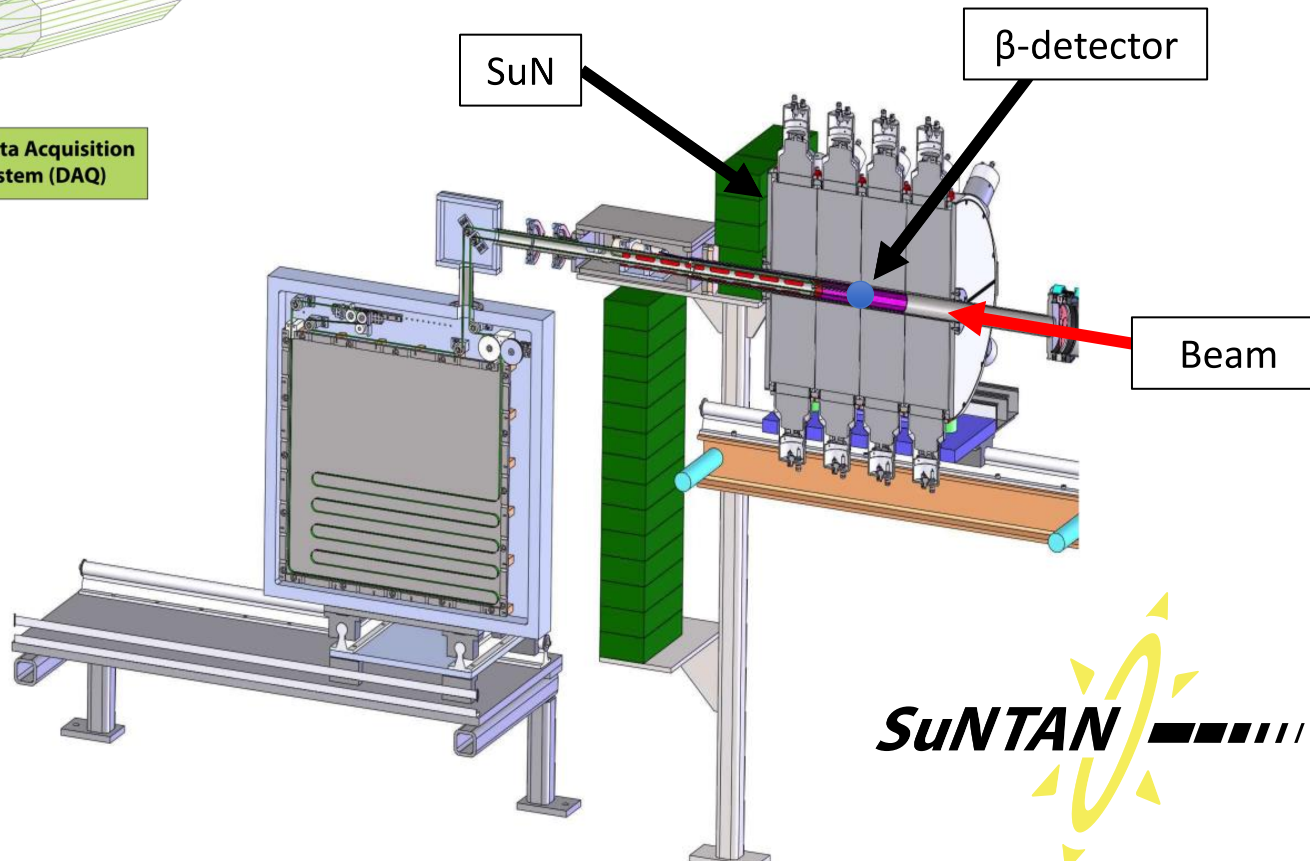


SuNTAN

SuNTAN at ANL – stopped beams

- Tape system for Active Nuclei: SuNTAN
  - i-process, nuclear security





SuNTAN

Slide modified from C. Harris

SuNTAN at ANL – stopped beams

- Tape system for Active Nuclei: SuNTAN
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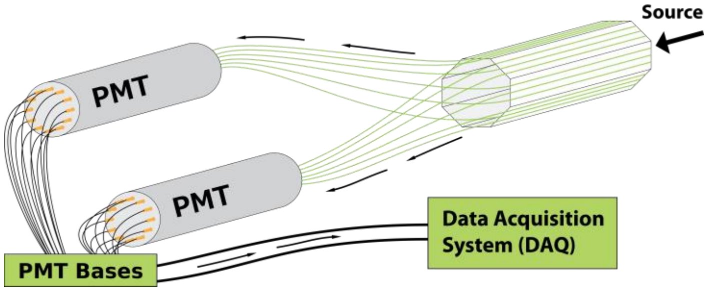
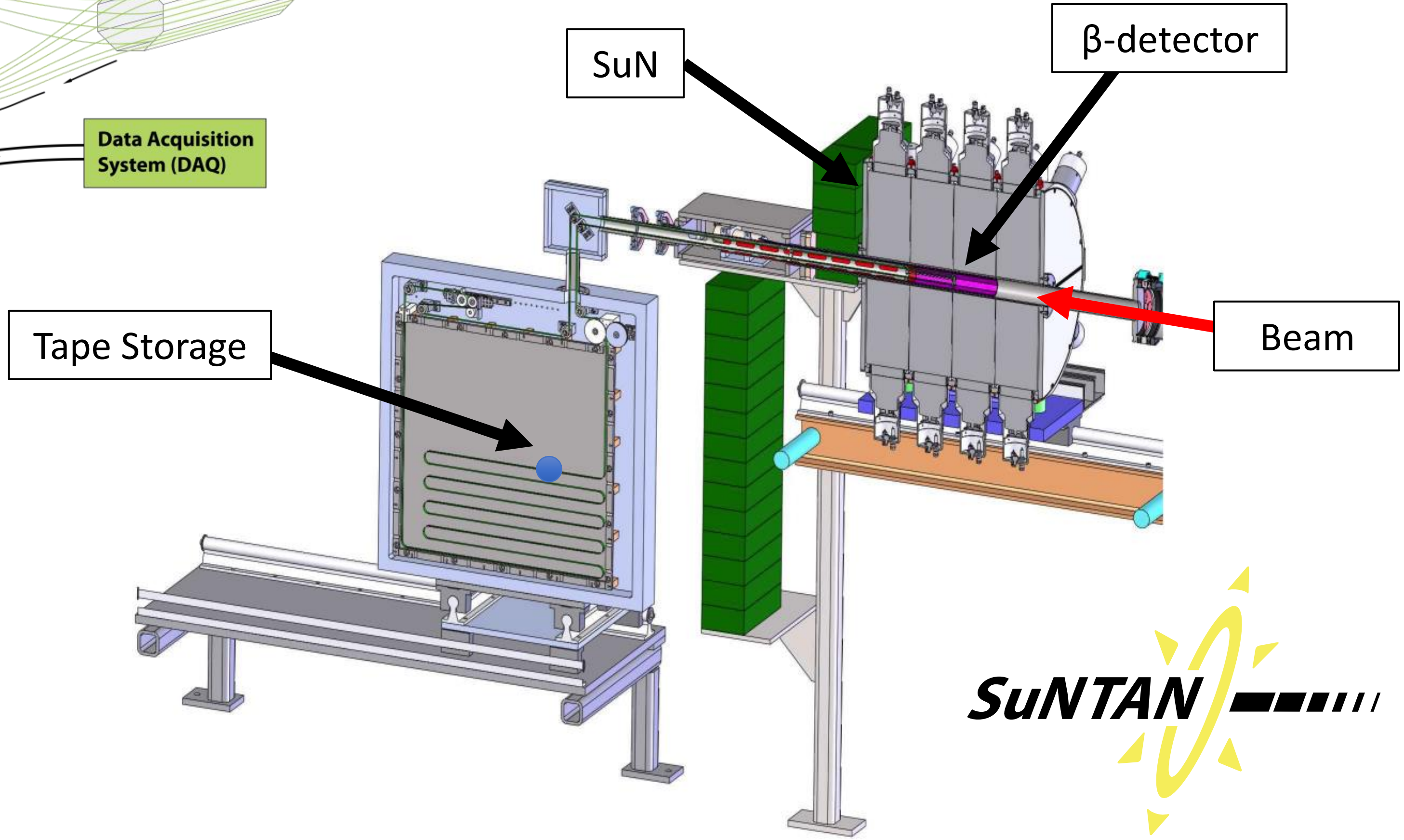
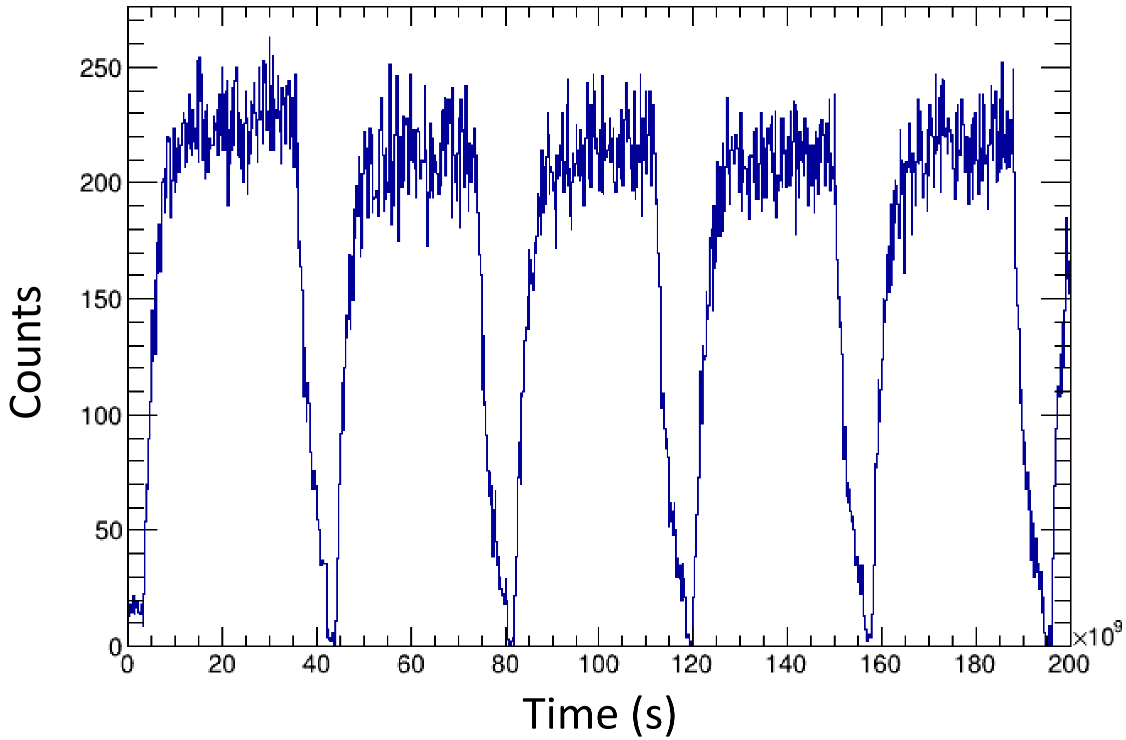
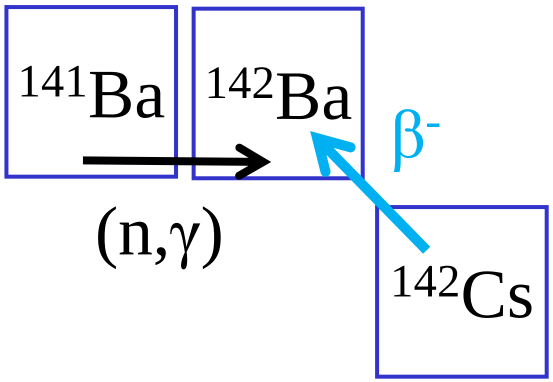




ANL Commissioning: $^{141}Ba(n,\gamma)^{142}Ba$ from ^{142}Cs β-decay

Tape Cycle: 30s on, 5s off





$^{142}Cs \rightarrow {}^{142}Ba$

$t_{1/2}$ = 1.684 (14) s

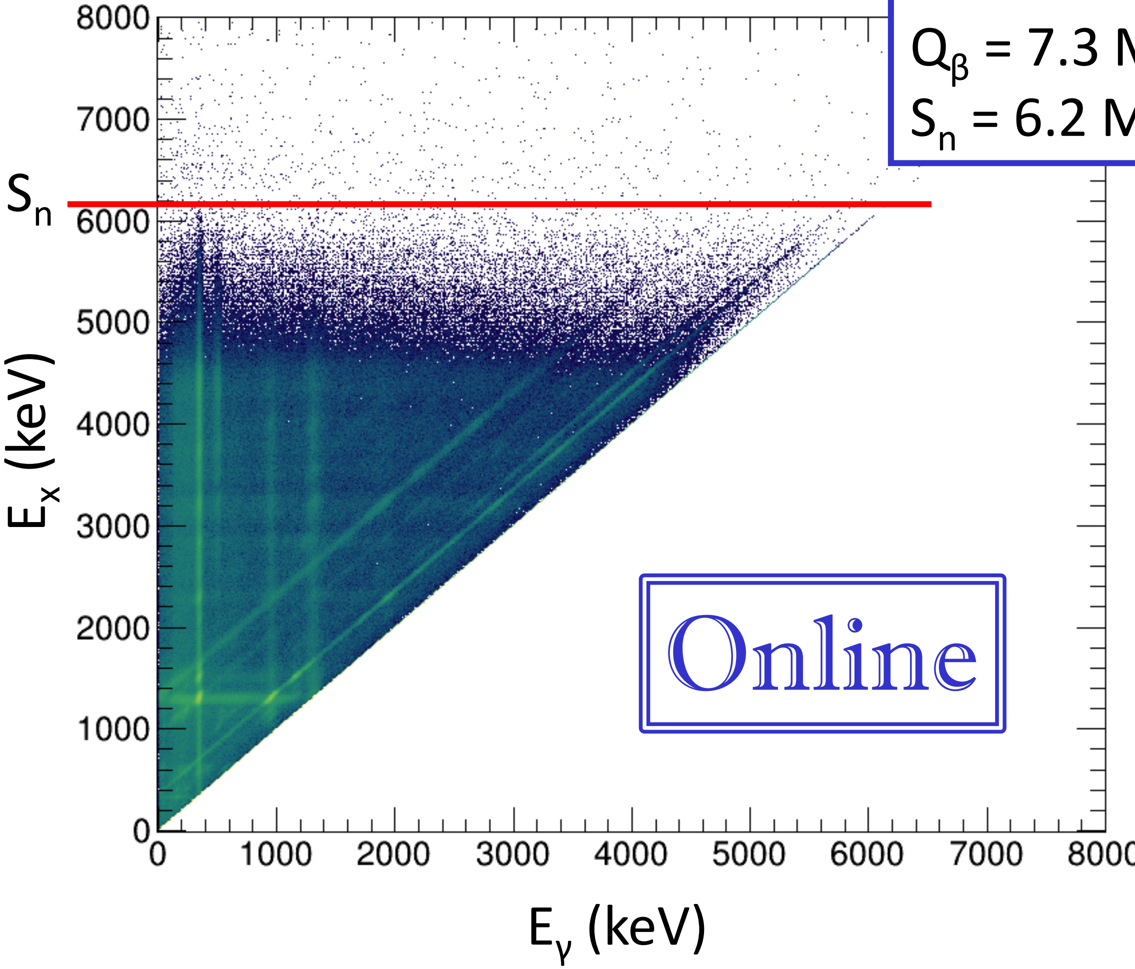
$^{142}Ba \rightarrow {}^{142}La$

$t_{1/2}$ = 10.6(2) min

- Isolate parent decay and remove daughter contribution

ANL Commissioning: $^{141}Ba(n,\gamma)^{142}Ba$ from ^{142}Cs β-decay

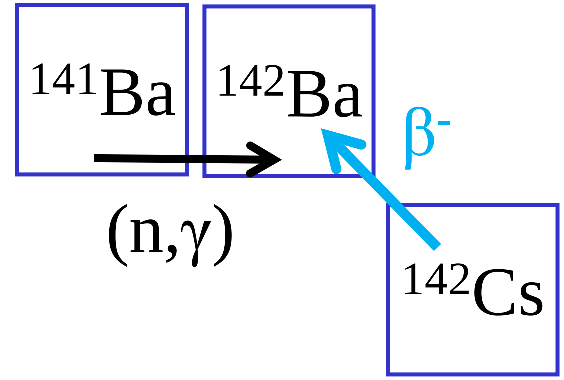
Preliminary!



$^{142}Cs \rightarrow {}^{142}Ba$

Q_β = 7.3 MeV

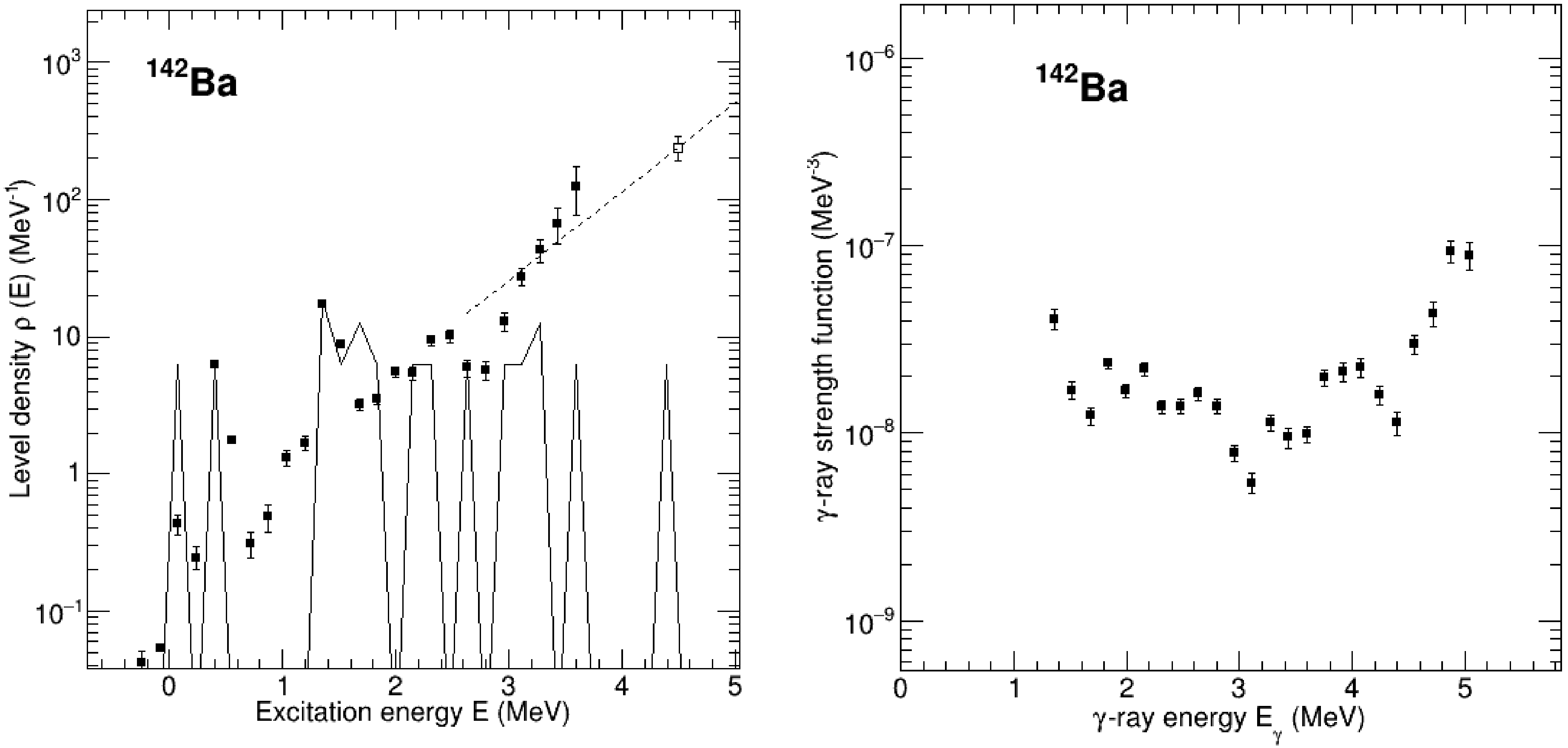
S_n = 6.2 MeV



Experiment performed at ANL in Feb. 2020

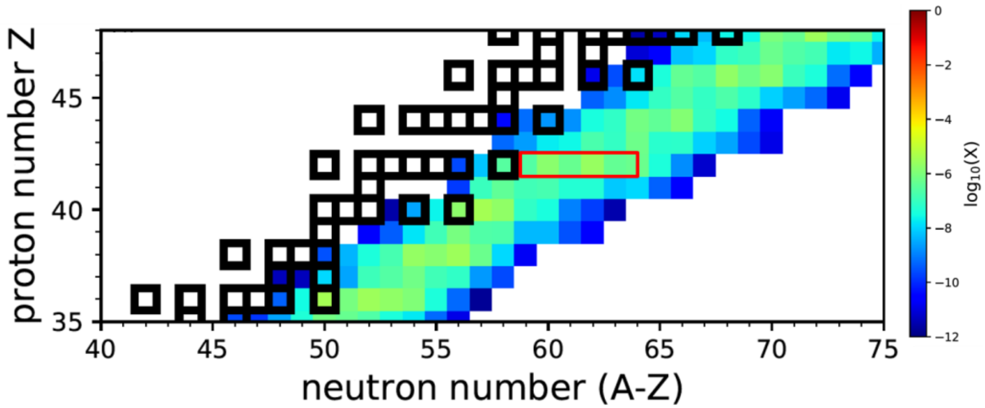
Preliminary nuclear level density and γ-ray strength function for ^{142}Ba

Preliminary!

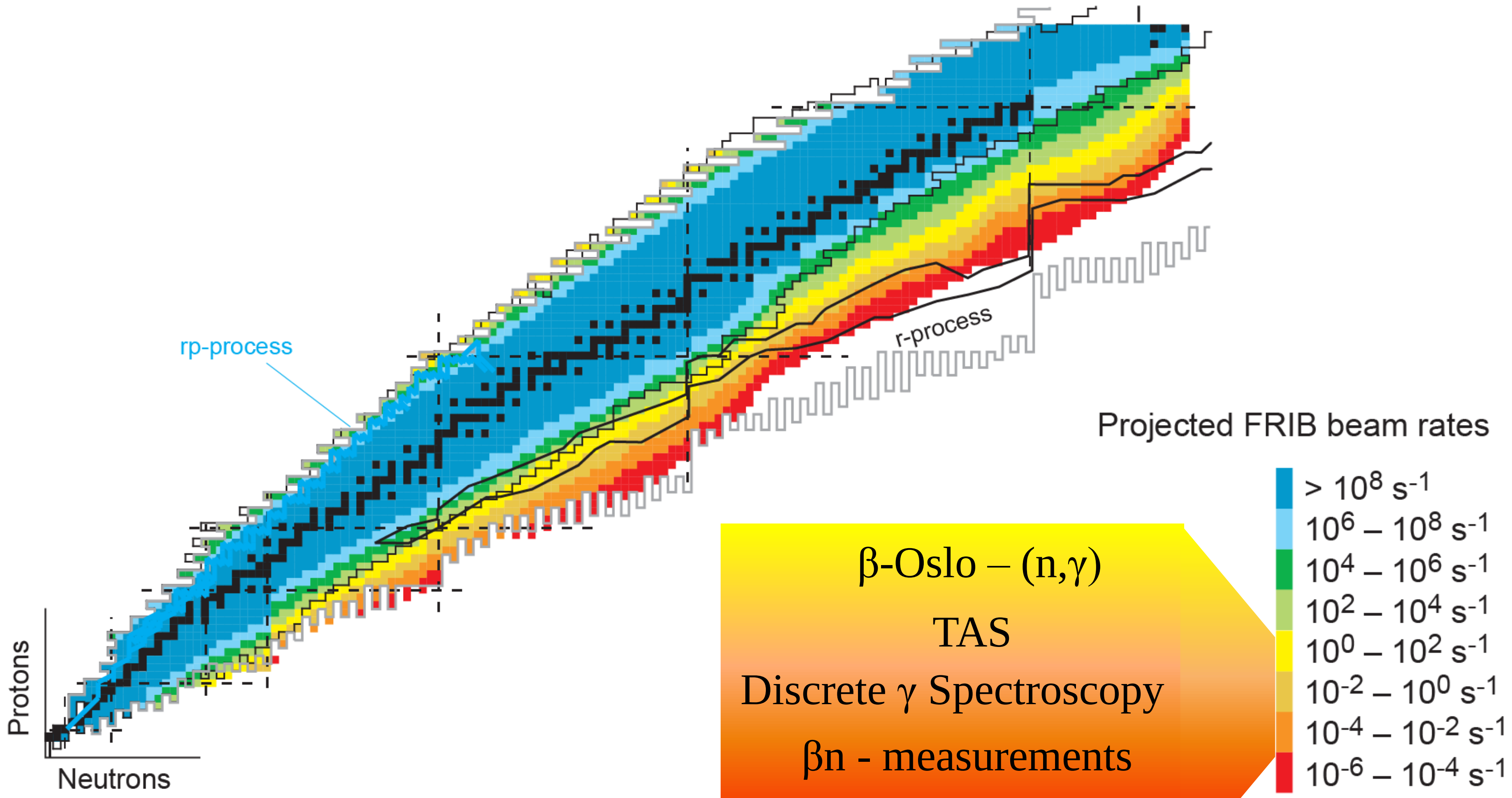


Summary and Outlook

- i-process nucleosynthesis uncertainties are dominated by neutron-capture cross sections
- β-Oslo method for constraining neutron-capture reactions
- Experimental campaigns at NSCL using fast beams, and ANL using stopped beams
- Collaboration with NuGrid to determine the impact of our constrained cross sections



Prospects for β-decay studies at FRIB



β-Oslo – (n,γ)

TAS

Discrete γ Spectroscopy

βn - measurements

Half-life

Collaborators

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Thank you!
Questions?