Indirectly Constraining Neutron-Capture Reactions with the SuN Detector

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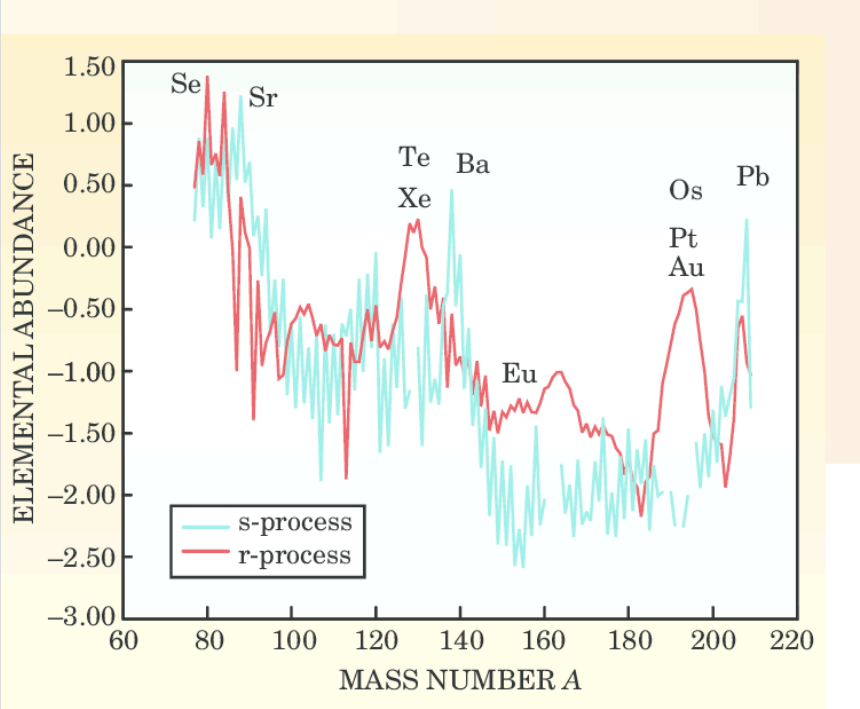
National Superconducting
Cyclotron Laboratory

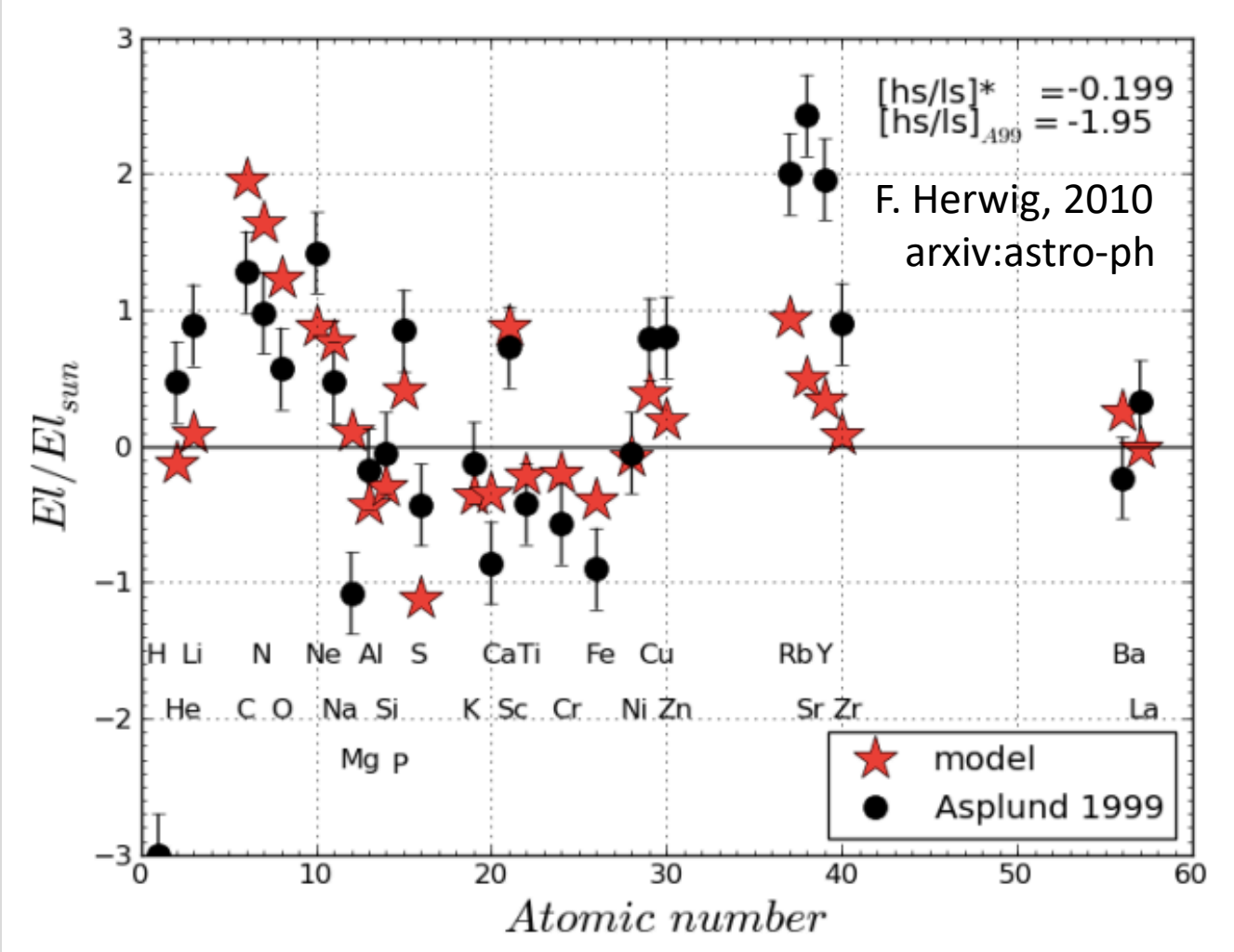
National Science Foundation
Department of Energy Office of Science
Michigan State University

Astrophysics Opportunities @ ATLAS
July 12-13 2019

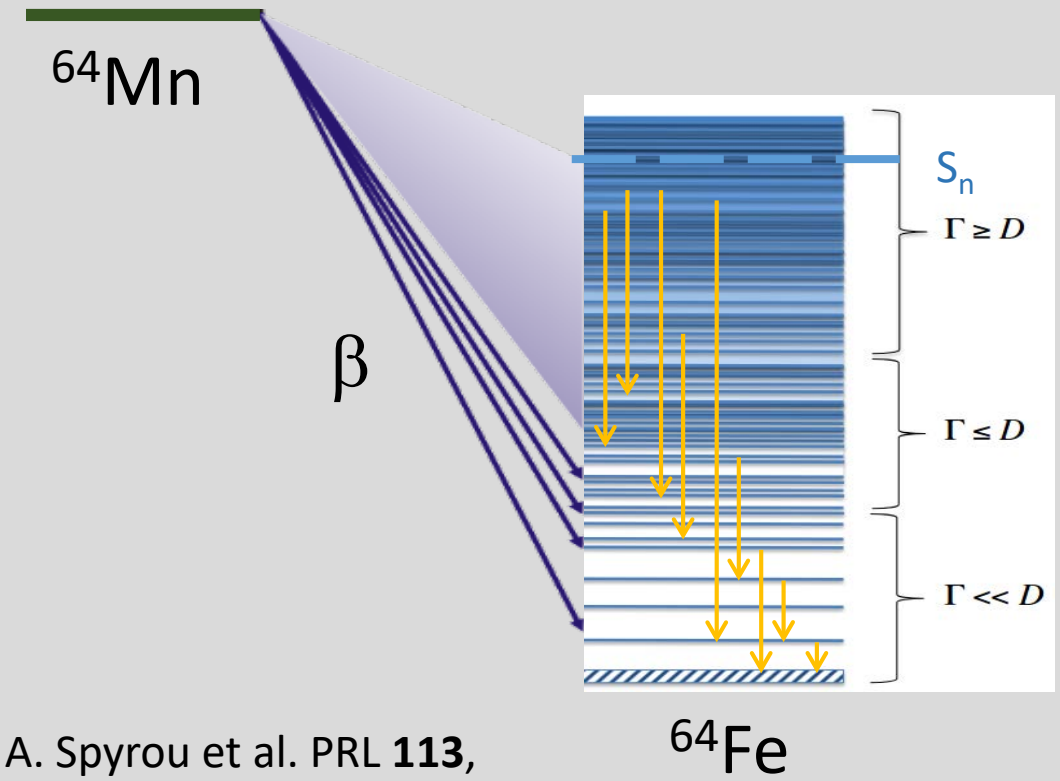
Anomalous abundance patterns…



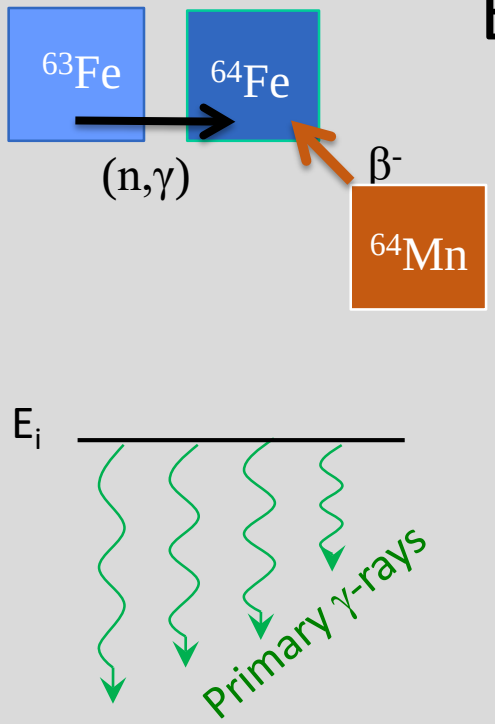
over-enhanced Sr, Y, Zr, Rb - but not Ba, La



The β-Oslo Method



A. Spyrou et al. PRL **113**, 232502 (2014)
S. N. Liddick et al. PRL **116**, 242502 (2016)



Brink-Axel Hypothesis

For γ-ray decay from the statistical (continuum) region, the probability of emitting a primary γ-ray depends on:

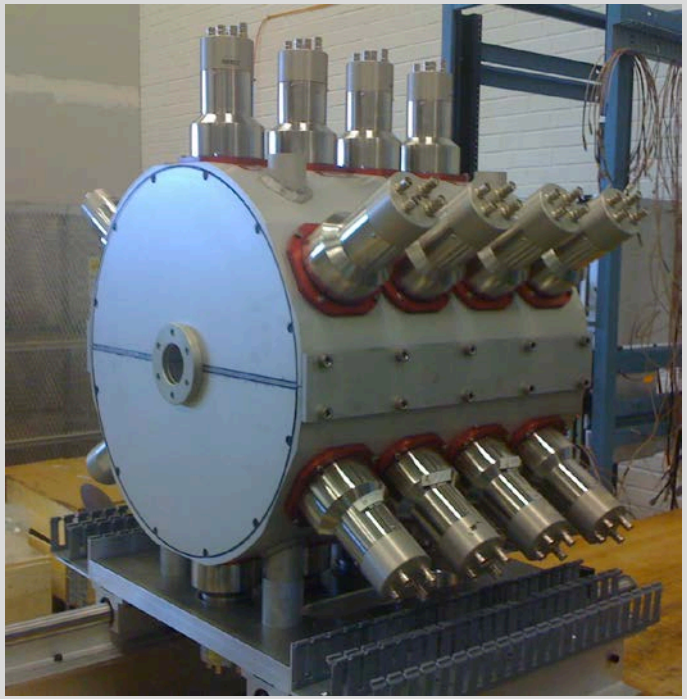
The level density at E_f
The γ–ray strength function

$$P(E_\gamma, E_X) \sim \rho(E_X - E_\gamma) T(E_\gamma)$$

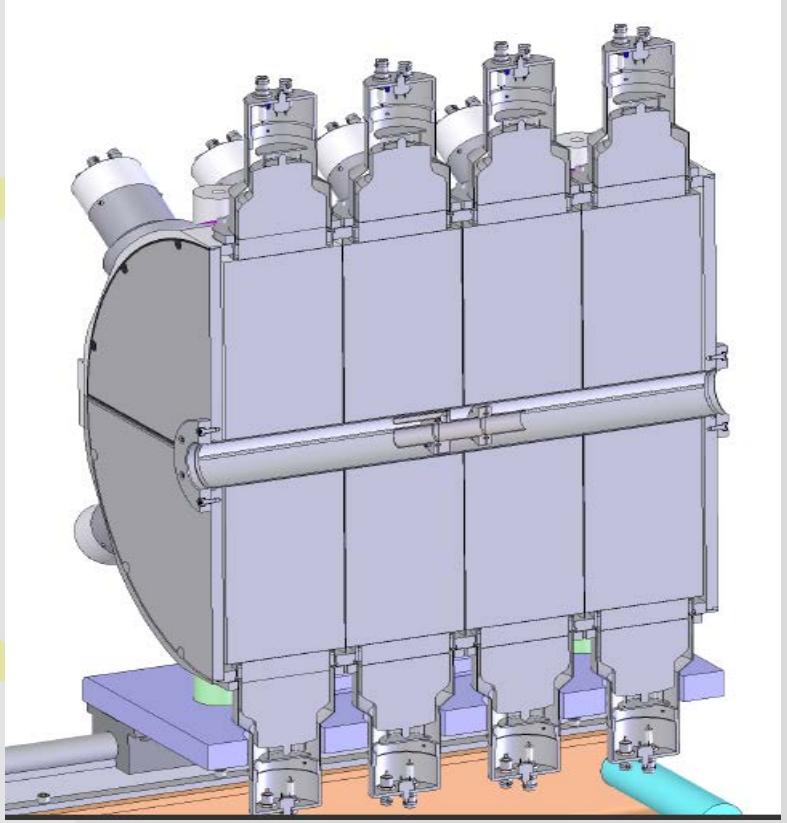
(n,γ) cross sections can be calculated using Hauser Feschbach with an appropriate optical model potential & the level density and γSF as direct inputs

Total Absorption Spectroscopy with SuN

Summing **N**aI(Th) Detector

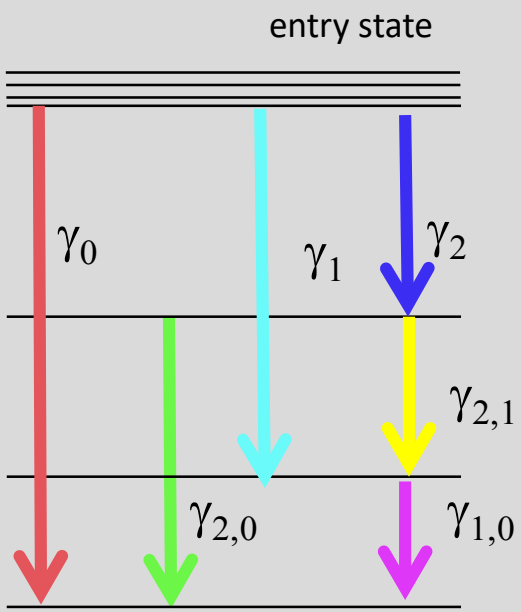


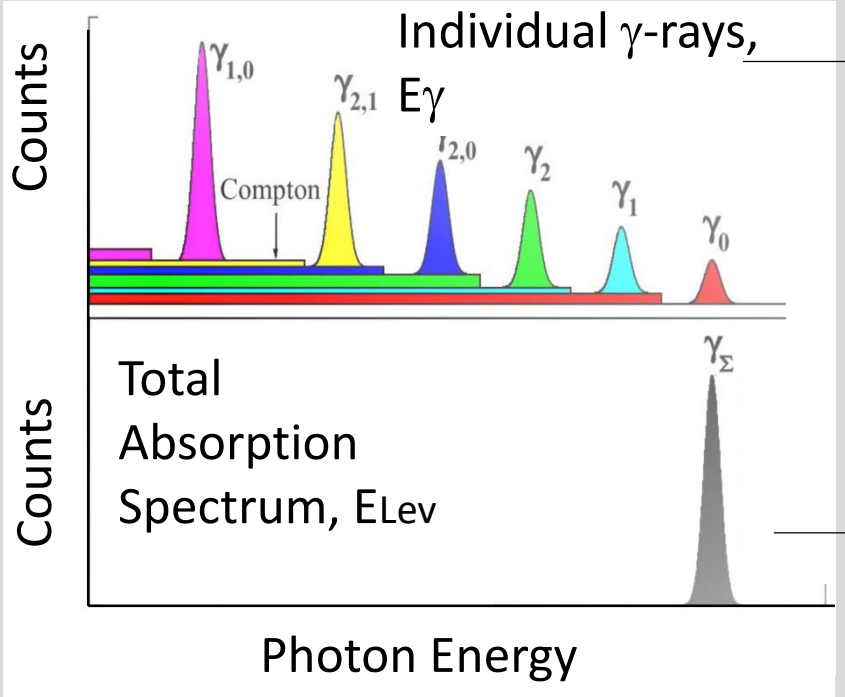
16” x 16”
1.5” (45 mm) borehole
2 halves
4 segments per half
3 PMTs per segment → 24 PMTs
Efficiency > 85% @ 1MeV

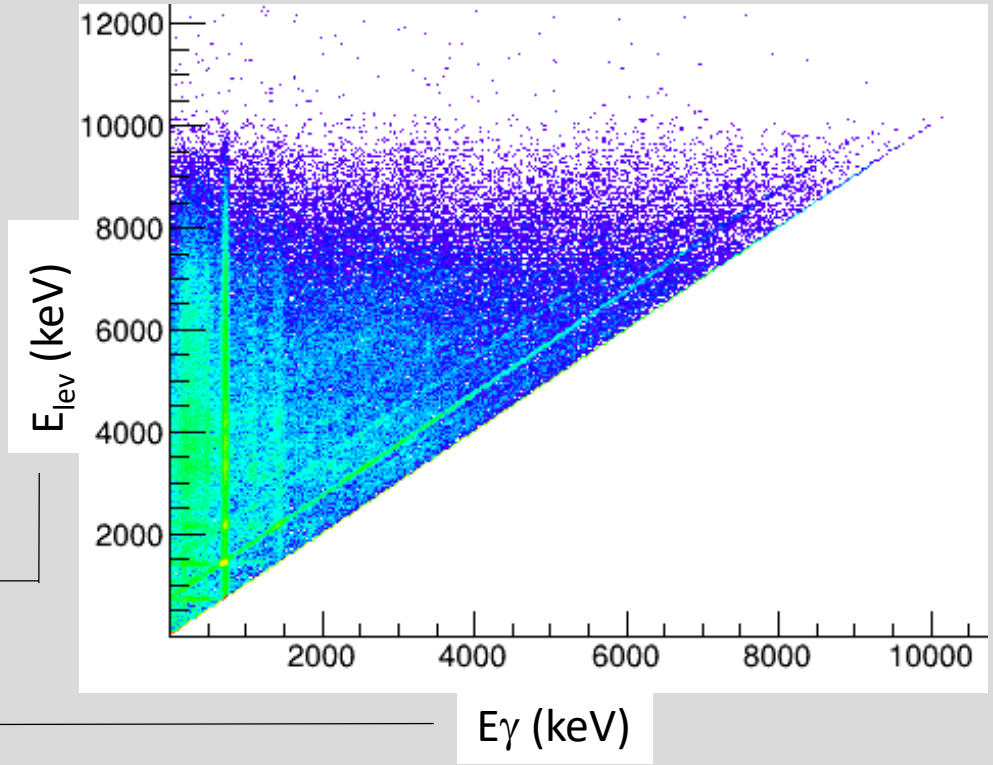


A. Simon, et al., Nucl. Instr. Meth A 703, 16 (2013)

β-Oslo with SuN

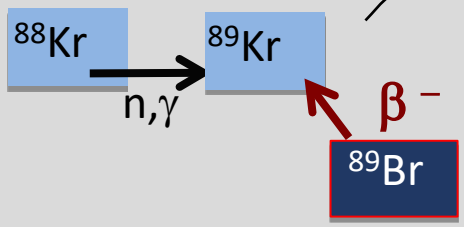






Designing a β-Oslo experiment

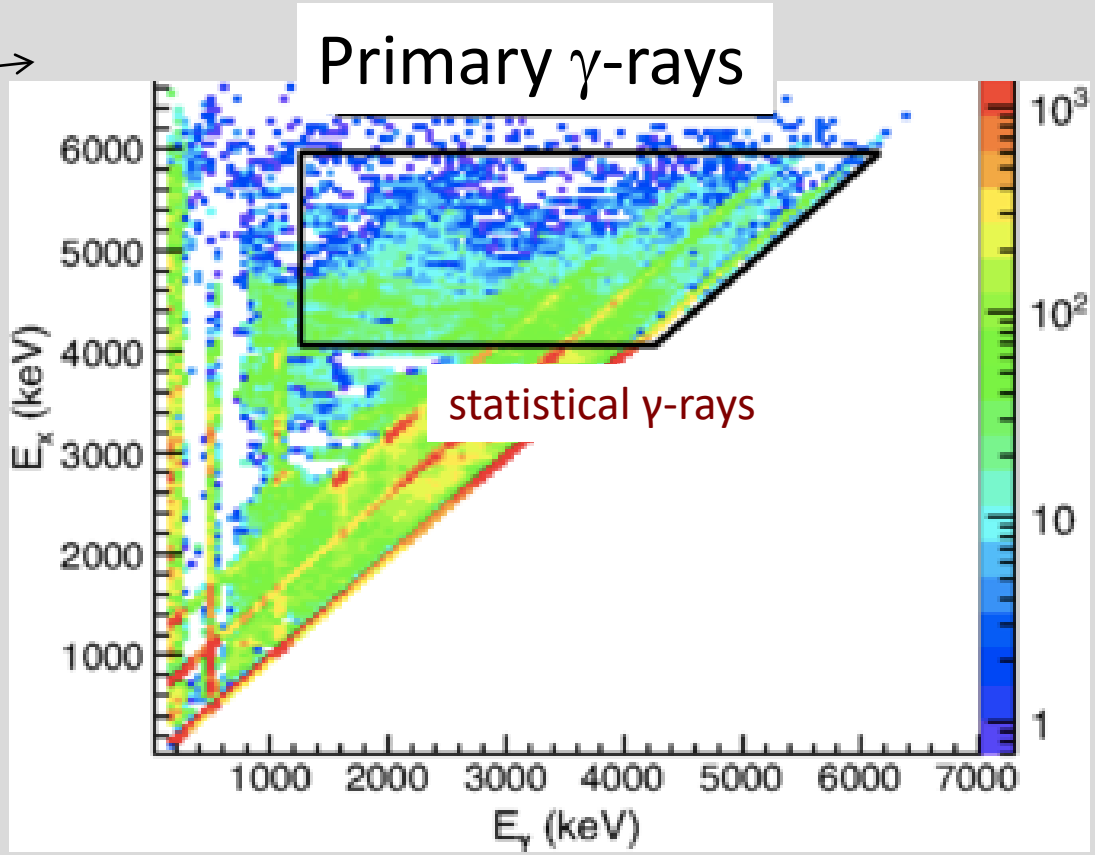
B-Oslo Method



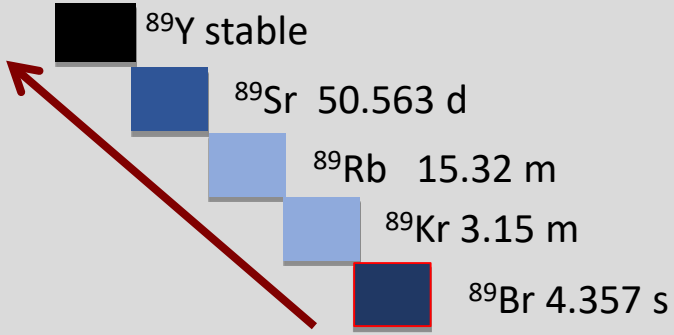
Raw matrix

↓

Unfolding



Even with pure beams, the decay chain causes a build up of radioactive nuclei

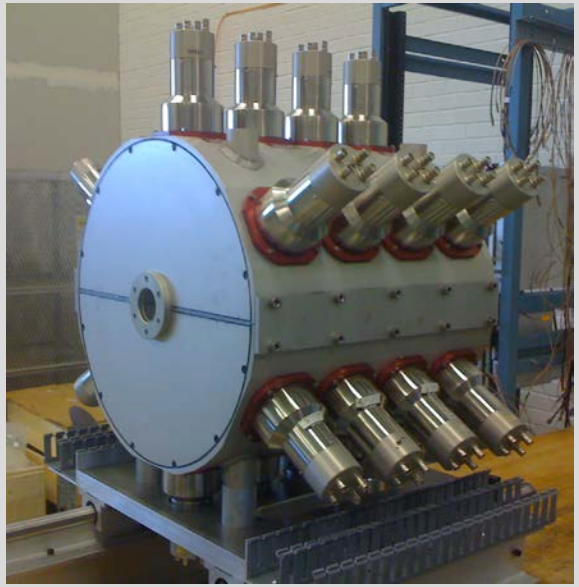


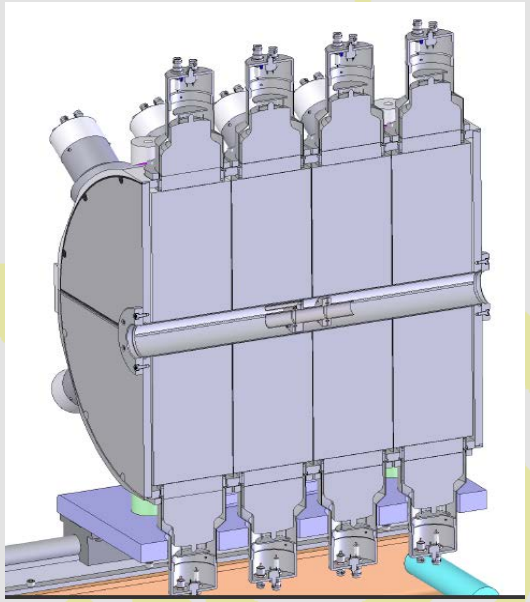
Isotope production rate ~1000 pps

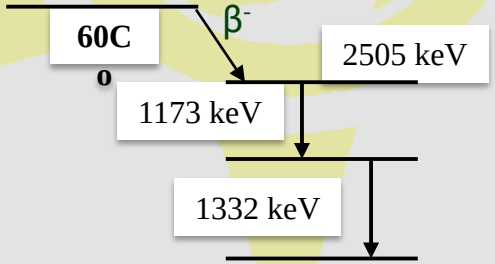
Detection rate ~10ct/s

Total Absorption Spectroscopy with SuN

Summing **N**al(Th) Detector







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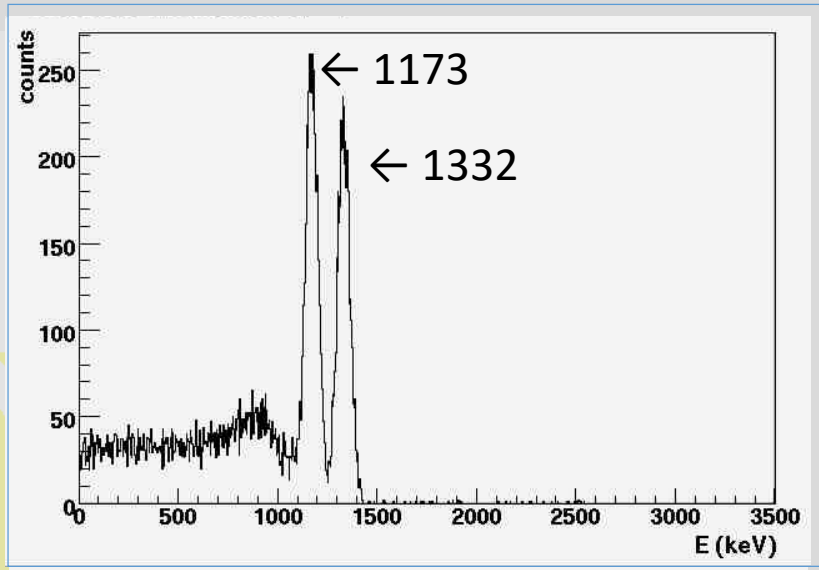
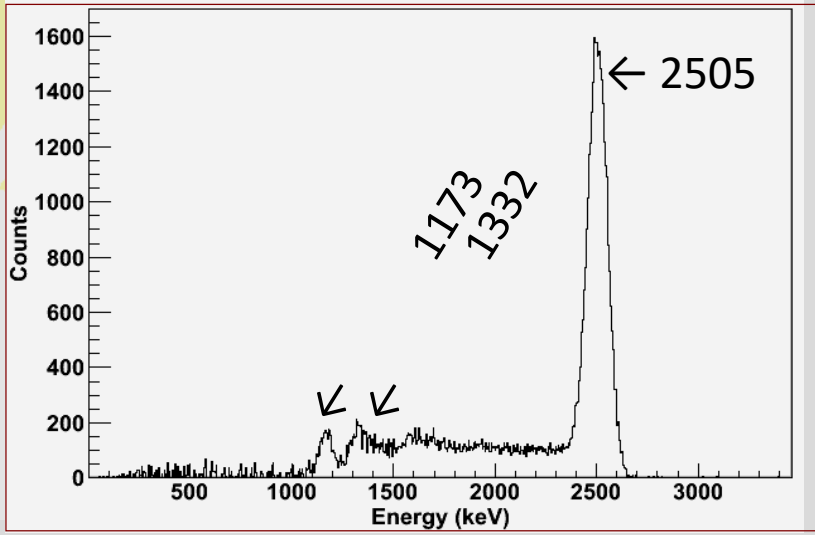
A. Simon, et al., Nucl. Instr. Meth A 703, 16 (2013)



Small detector
- eg, Ge, single crystal scintillator



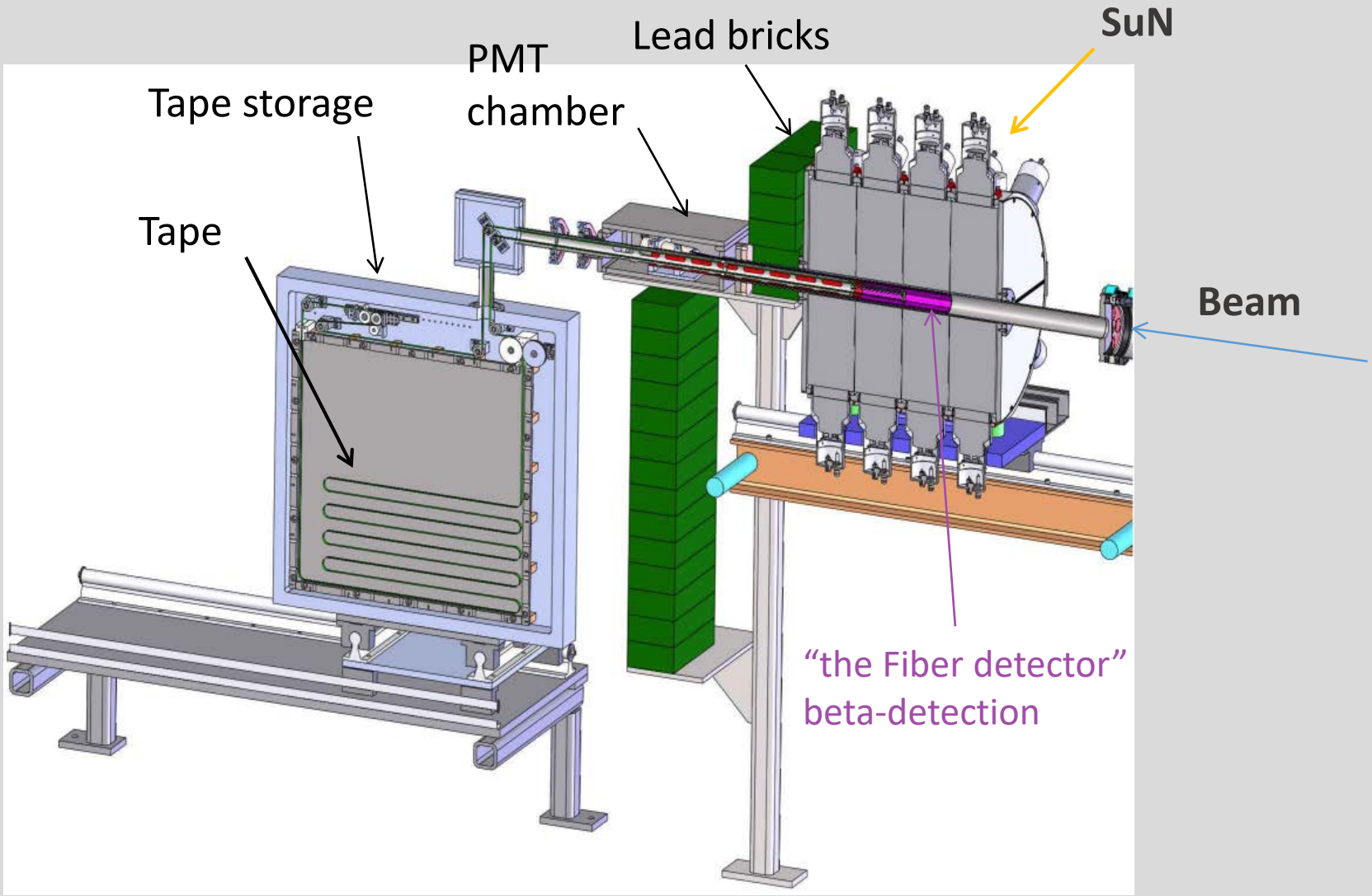
SuN Total Absorption Spectrum (TAS)

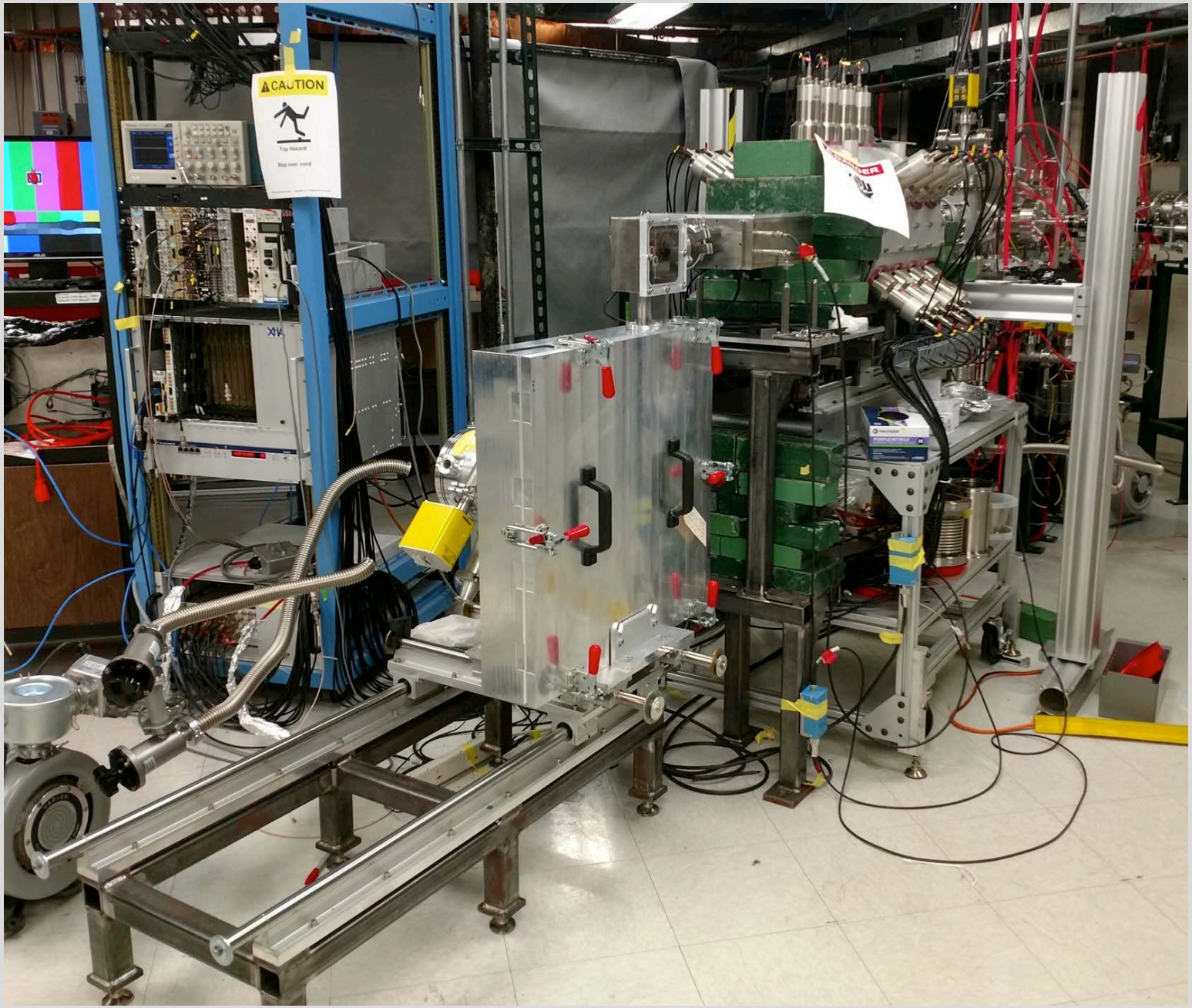
SuNTAN:
Summing **N**aI(Th) [SuN] detector + **T**ape system for **A**ctive **N**uclei

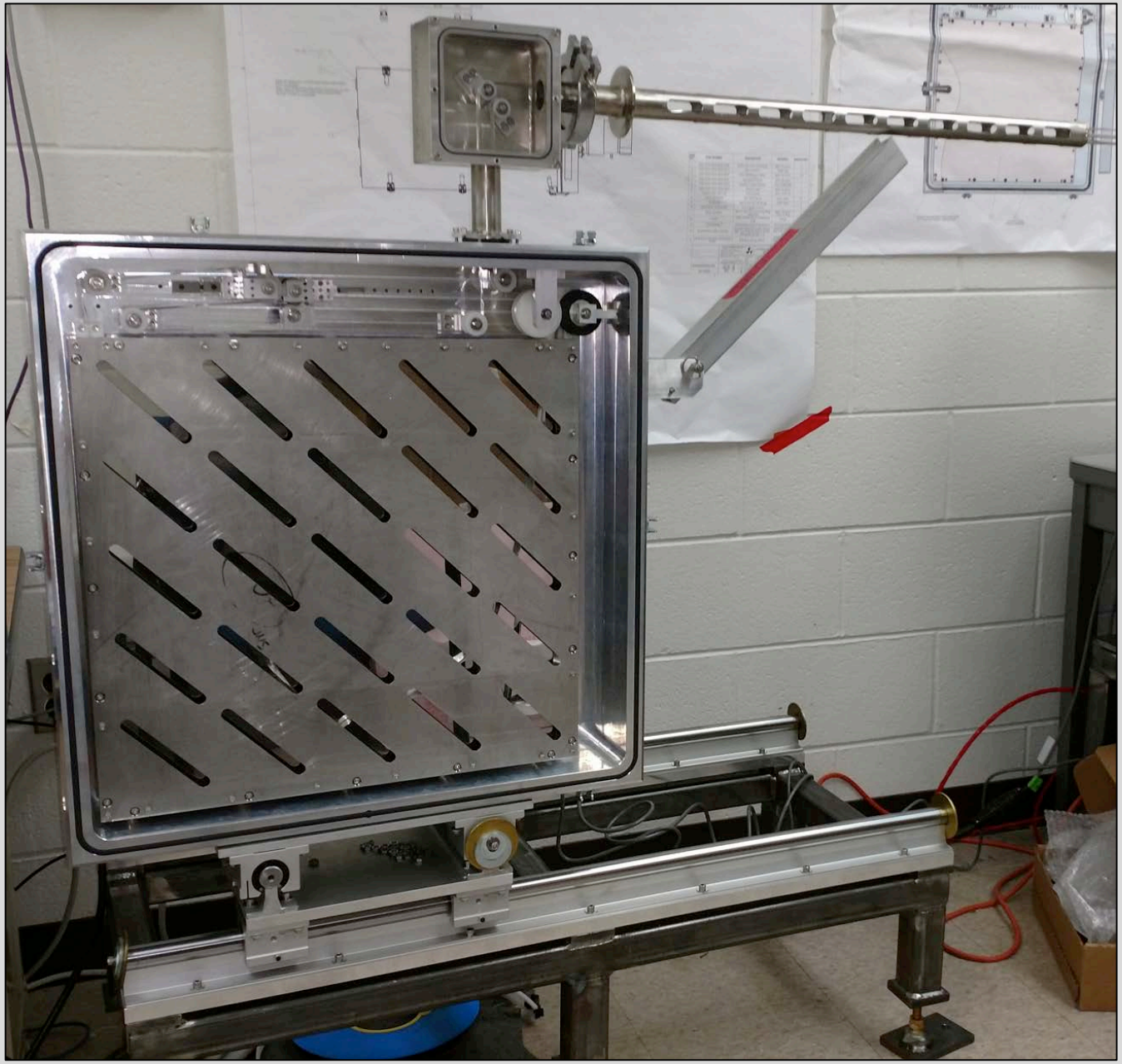
Based on design by E. Zganjer, LSU, and ANL's X-array tape station

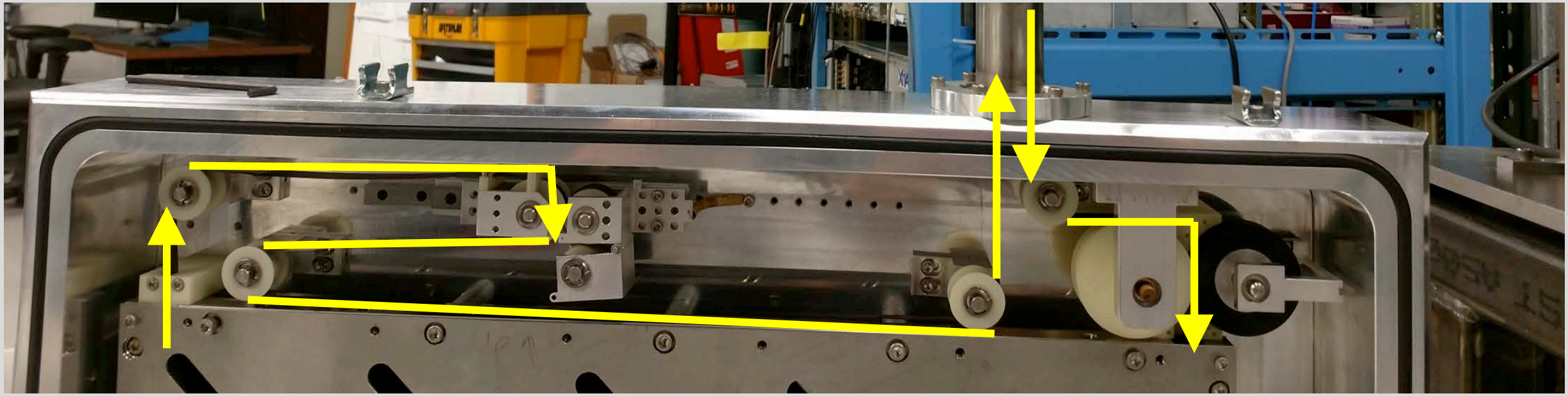
No reel

Feeding, tensioner, motor driver optimized over several generations of design



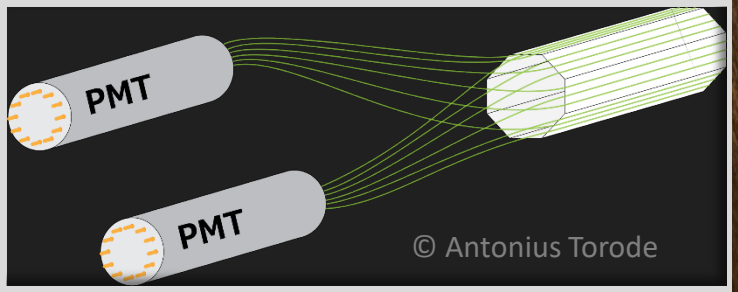

CAUTION
Trip Hazard
Step over cord

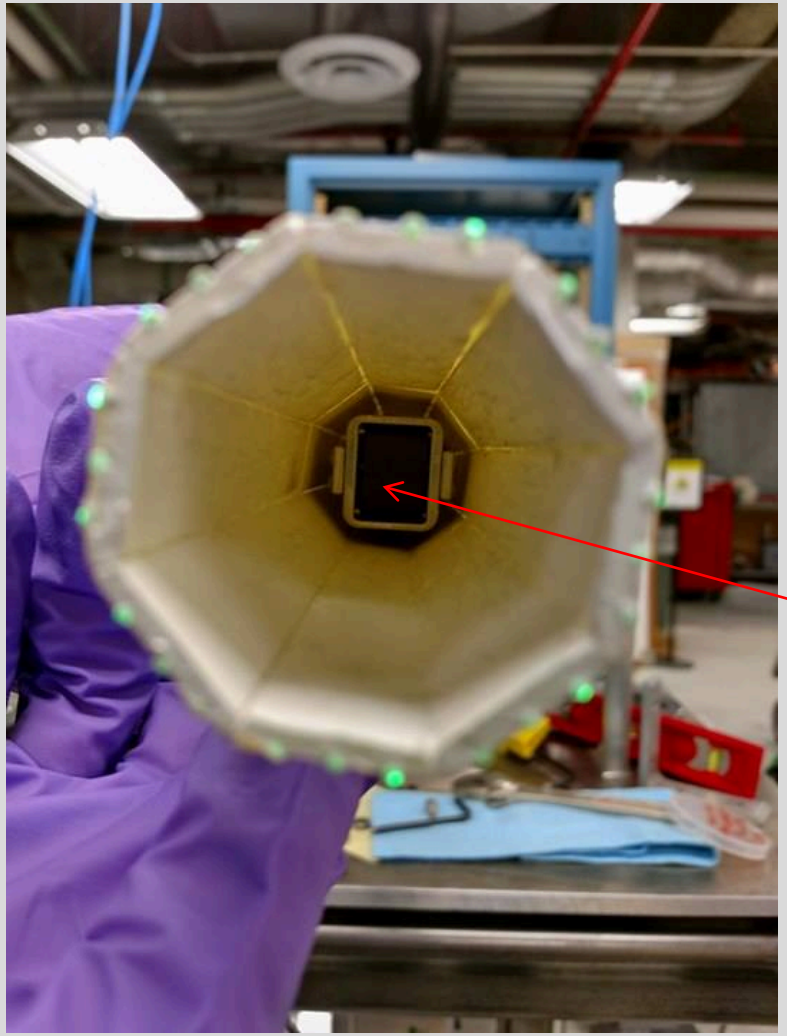




Beta Scintillator – The ‘Fiber detector’

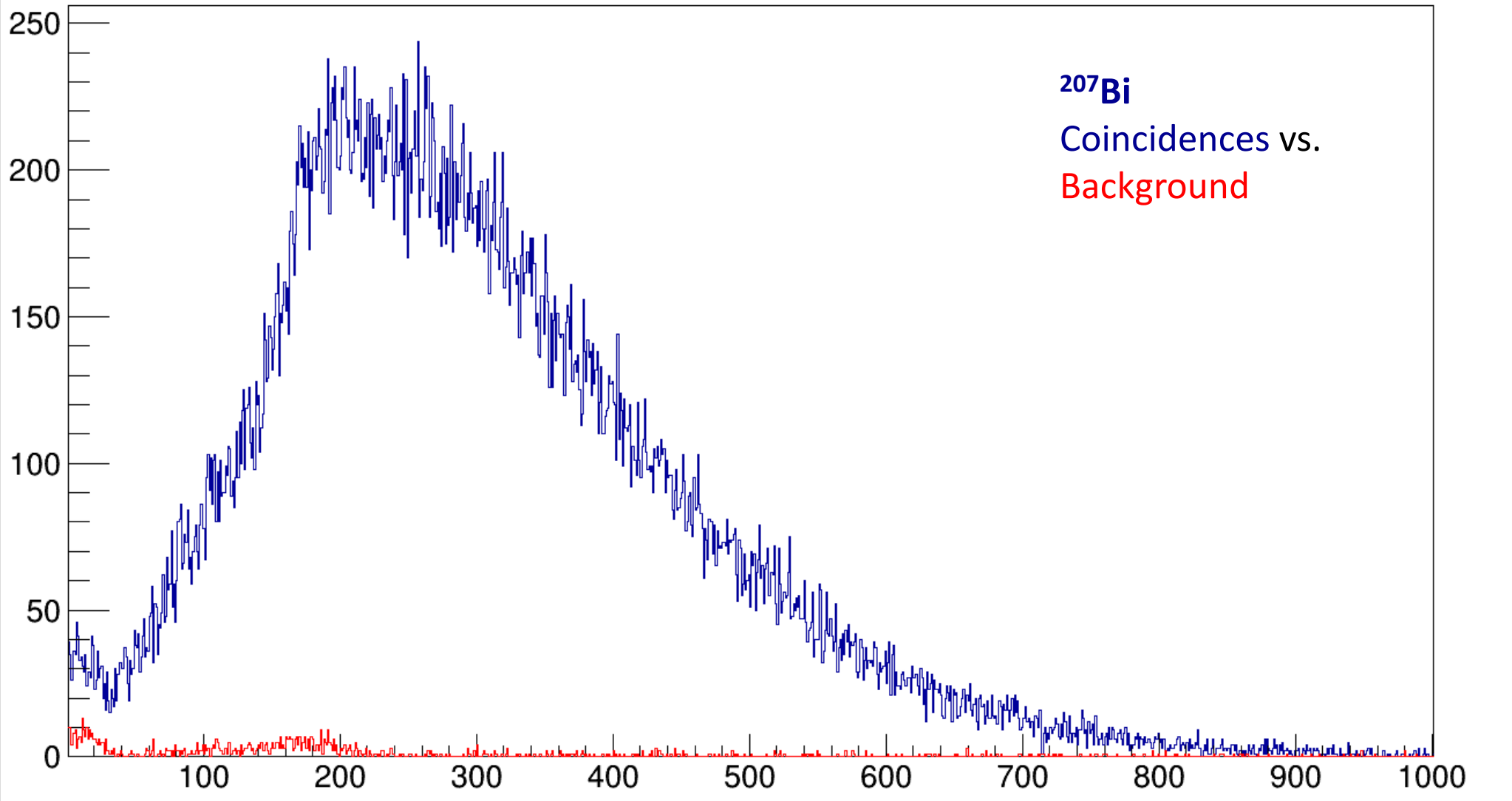
Fiber optic signal transport
Octogon, 4 fibers per side
2 PMTs - every other fiber



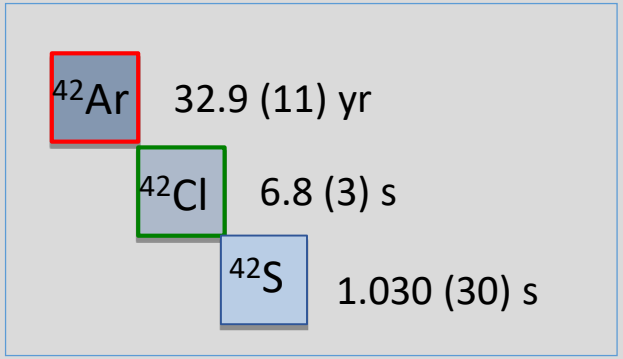


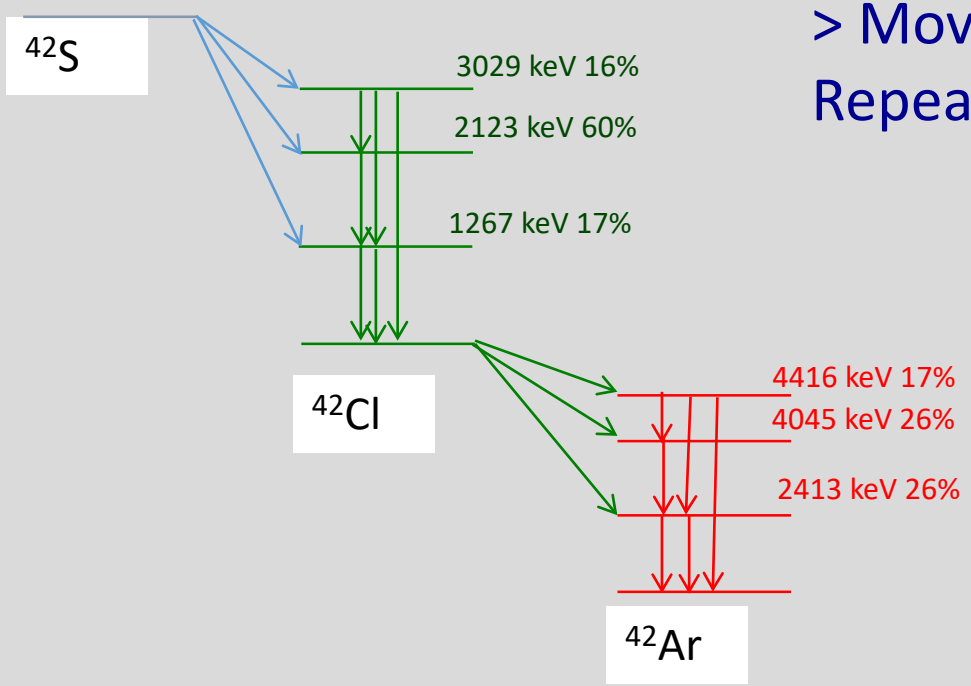
Tape
“catcher target”

Beta Scintillator – The ‘Fiber detector’



^{42}S Experiment - Commissioning





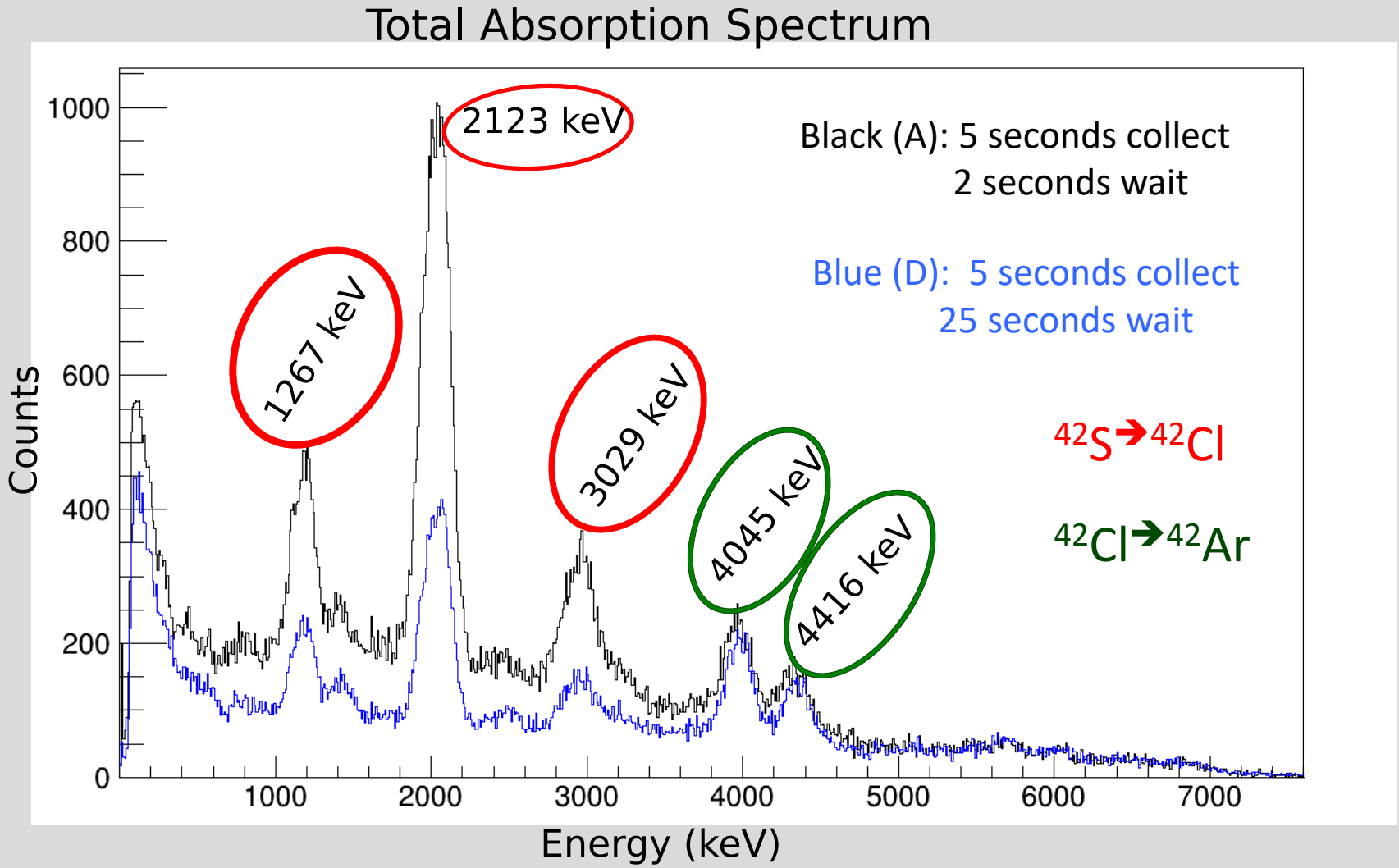
Control Sequence:

> Beam on, collect implants
> Beam off – wait
> Move tape
Repeat

Setting	Collect Beam	Wait
A	5 s	2 s
B	25 s	25 s
C	2 s	2 s
D	5 s	25 s
E	5 s	0 s
F	10 s	20 s

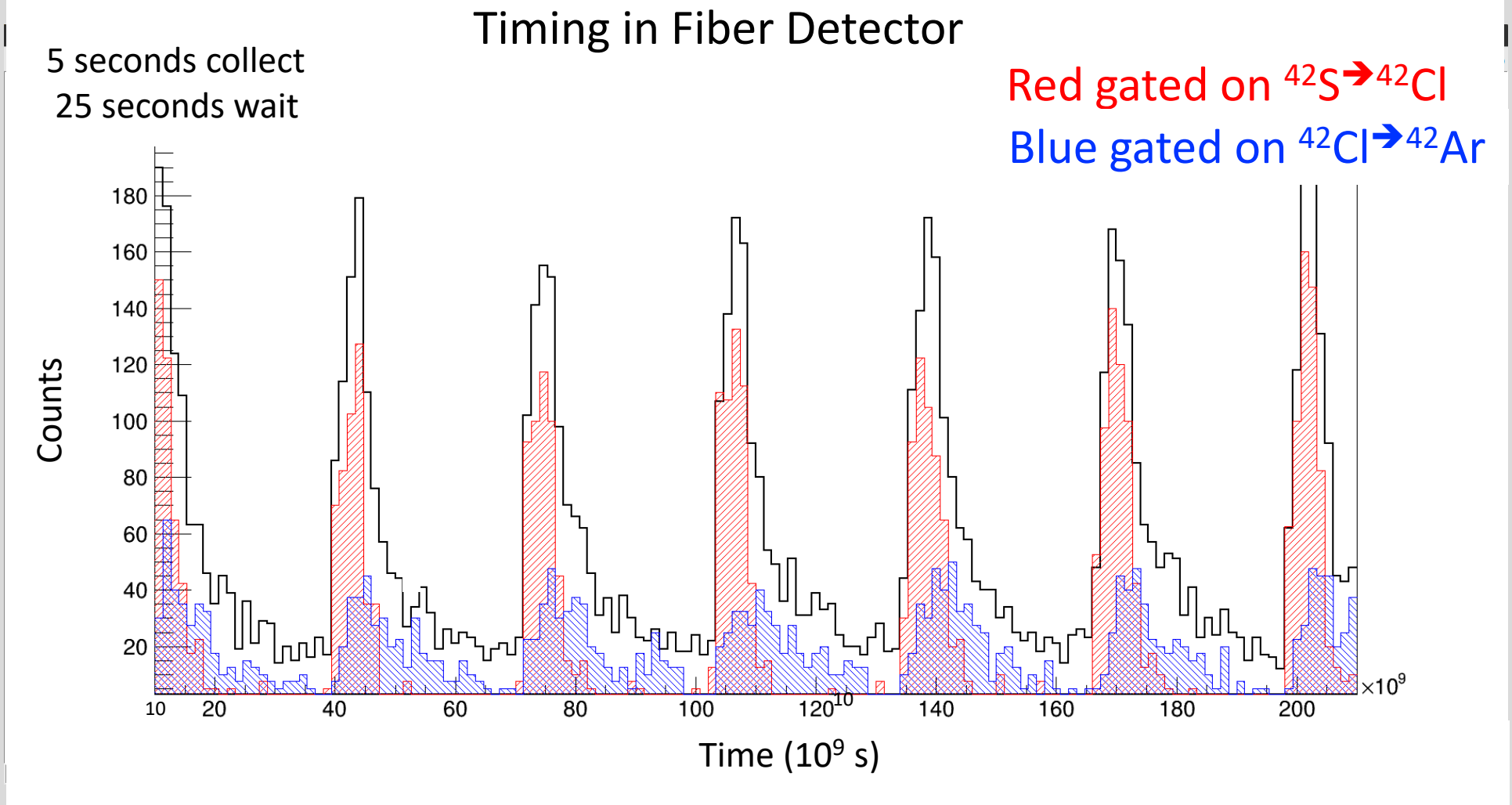
SunTAN Commissioning Experiment

TAS: Energy Levels Observed with SuN



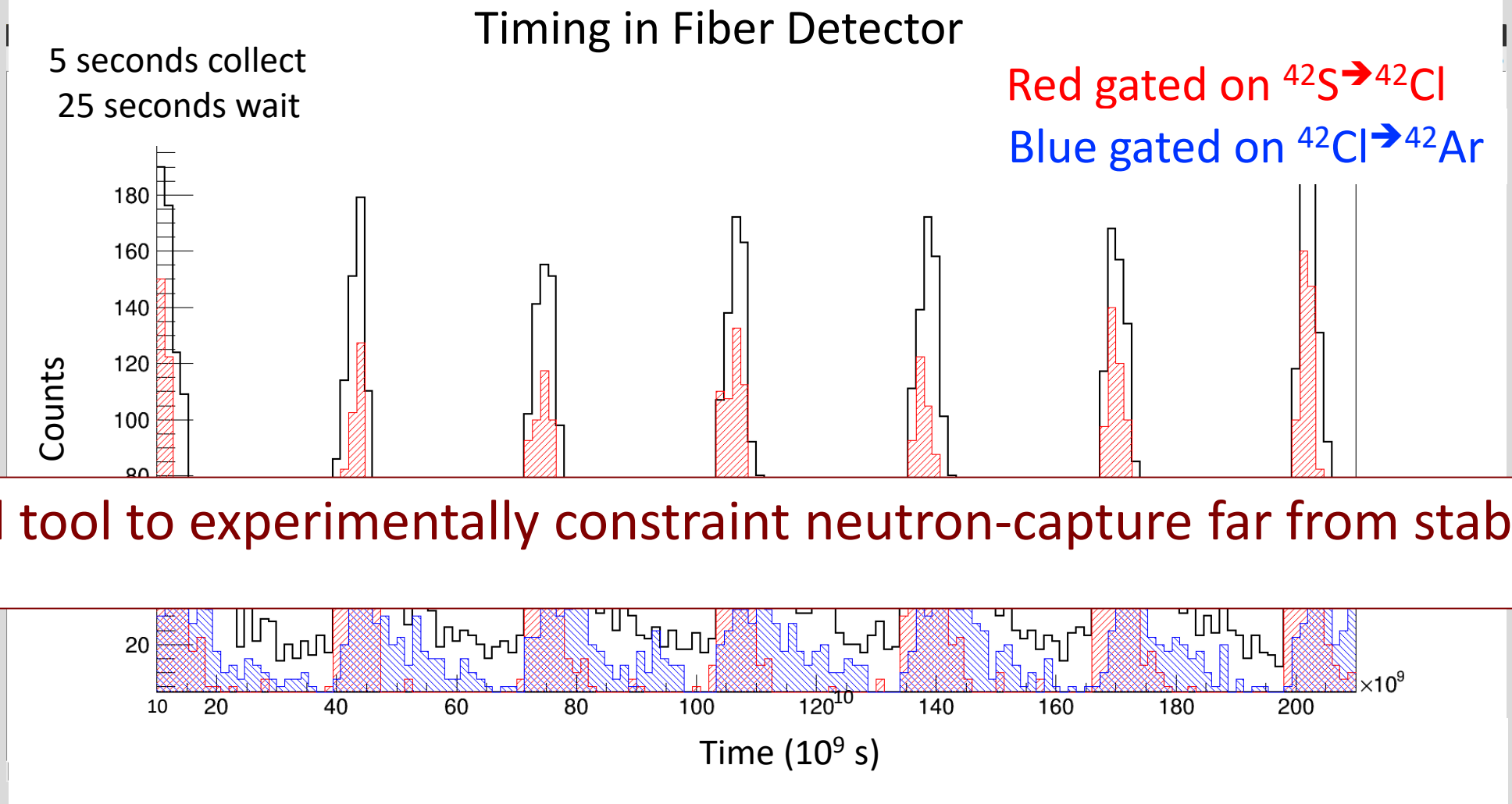
SunTAN Commissioning Experiment

Time Spectrum from the Fiber Detector



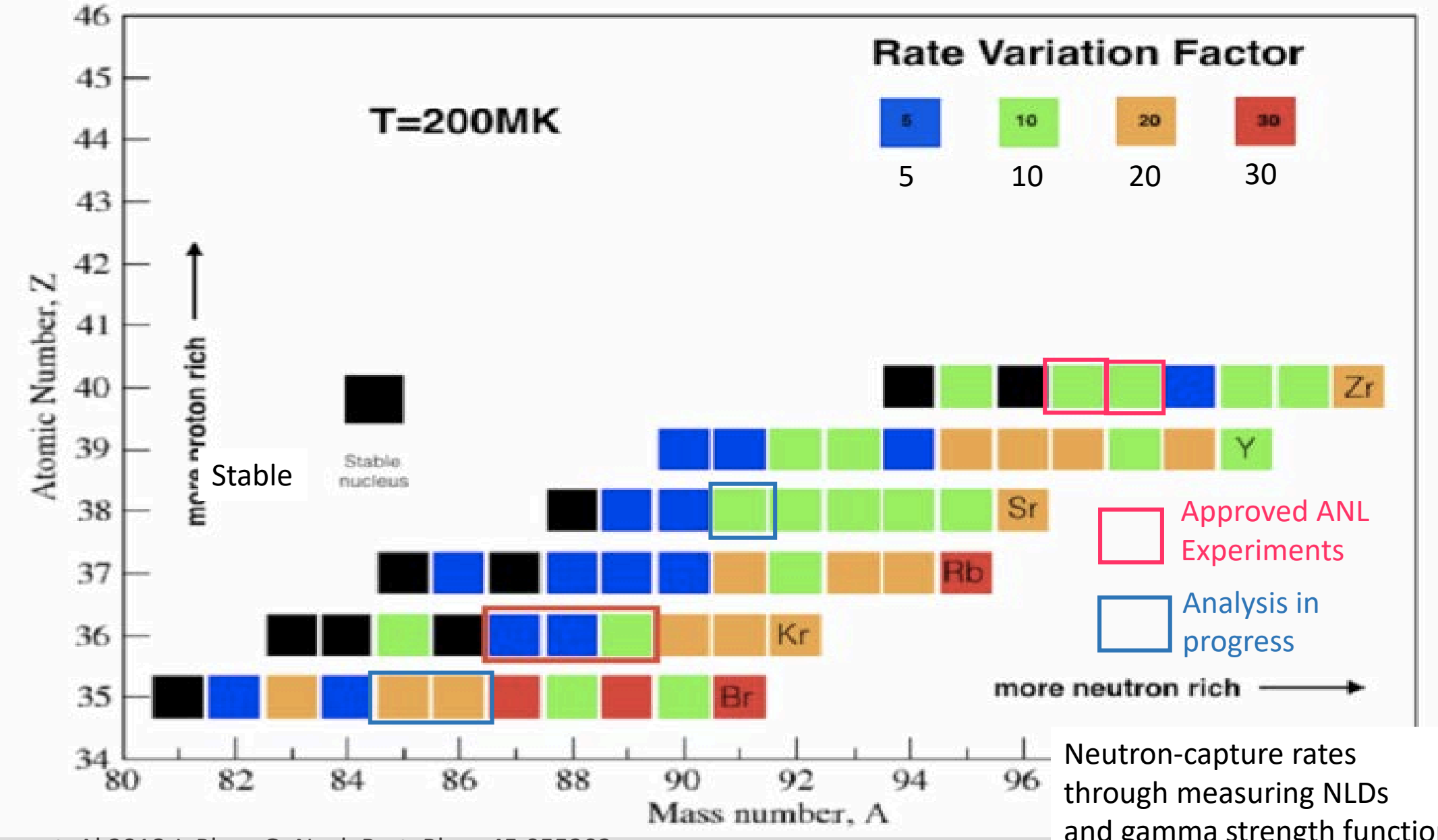
SunTAN Commissioning Experiment

Time Spectrum from the Fiber Detector



Ideal tool to experimentally constraint neutron-capture far from stability

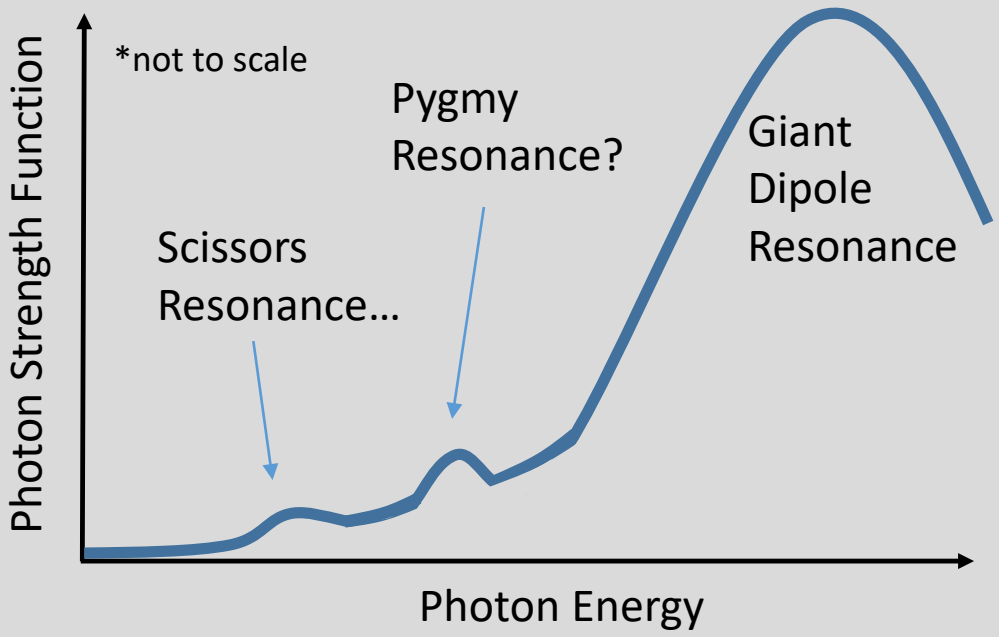
Summary: SunTAN + i-process neutron capture



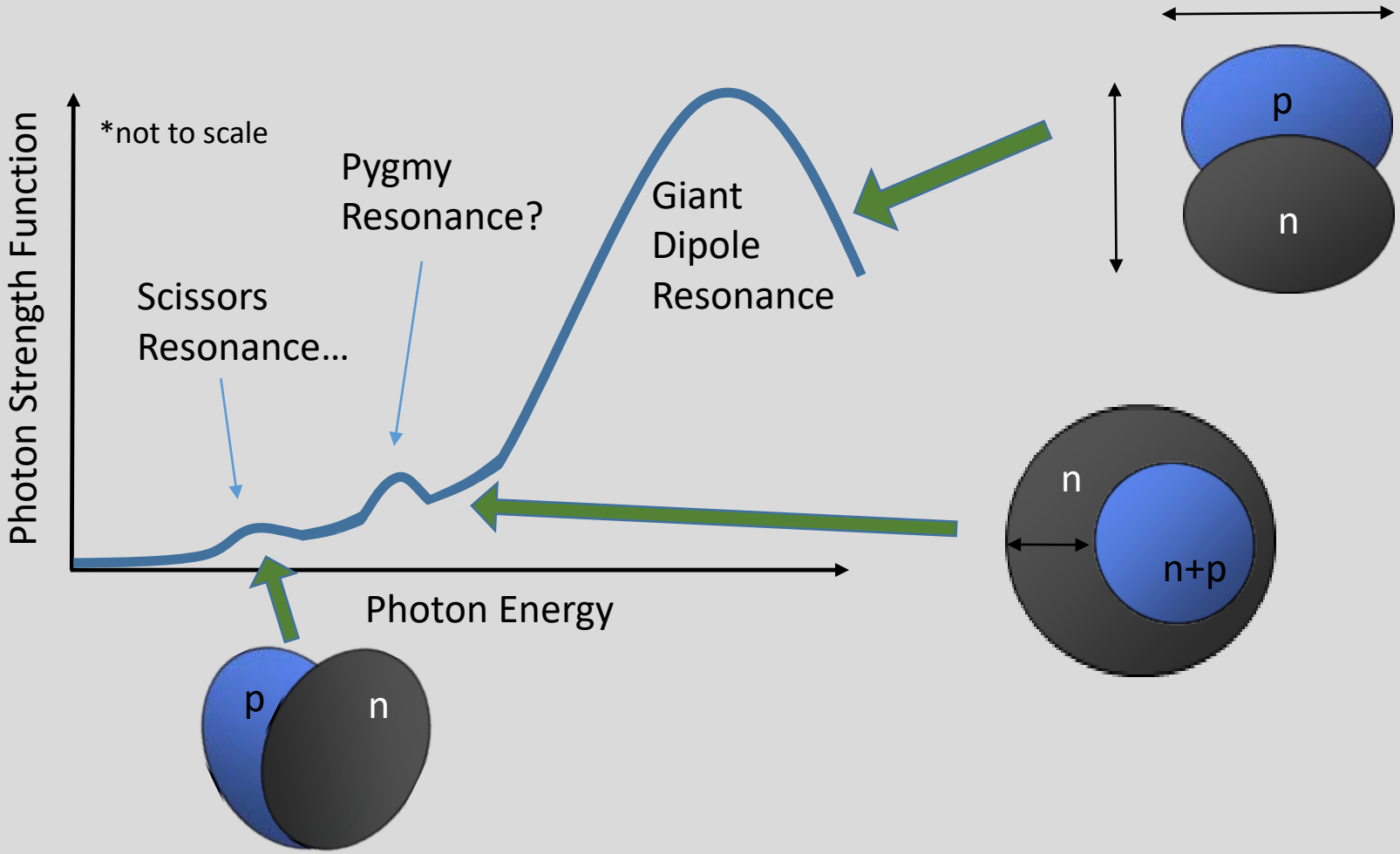
Neutron-capture rates through measuring NLDs and gamma strength functions…

P. Denissenkov, et. Al 2018 J. Phys. G: Nucl. Part. Phys. 45 055203

Features in γ–raySFs

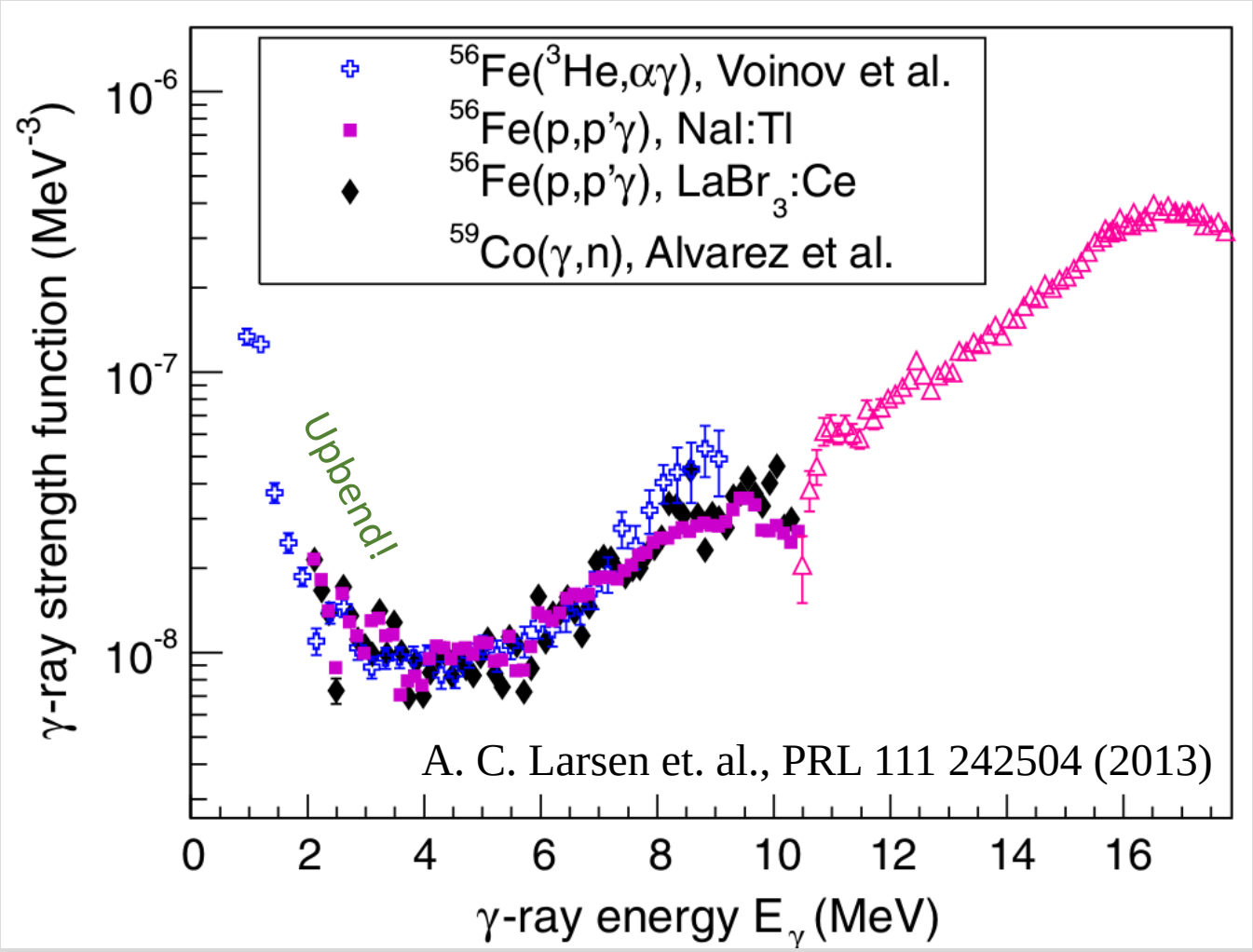


Features in γ–raySFs

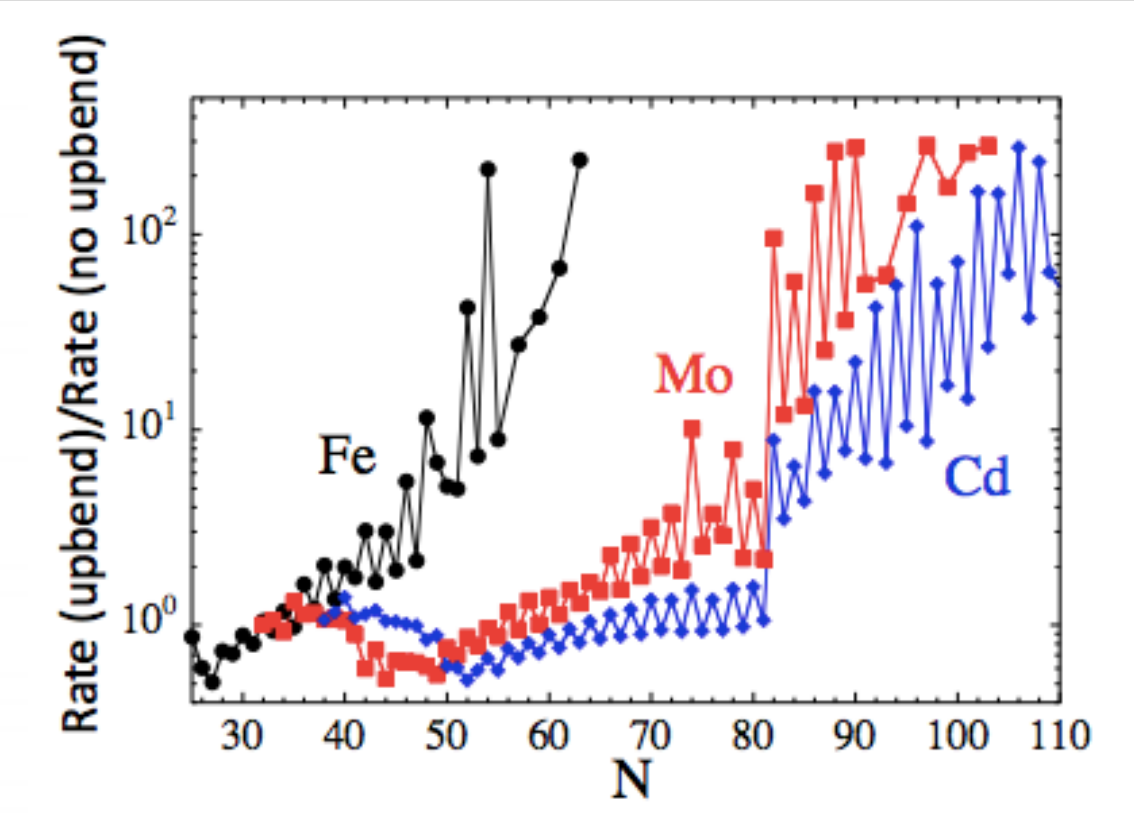


Low Energy Enhancement: ^{56}Fe

A.Voinov et al, PRL. 93, 142504 (2004)



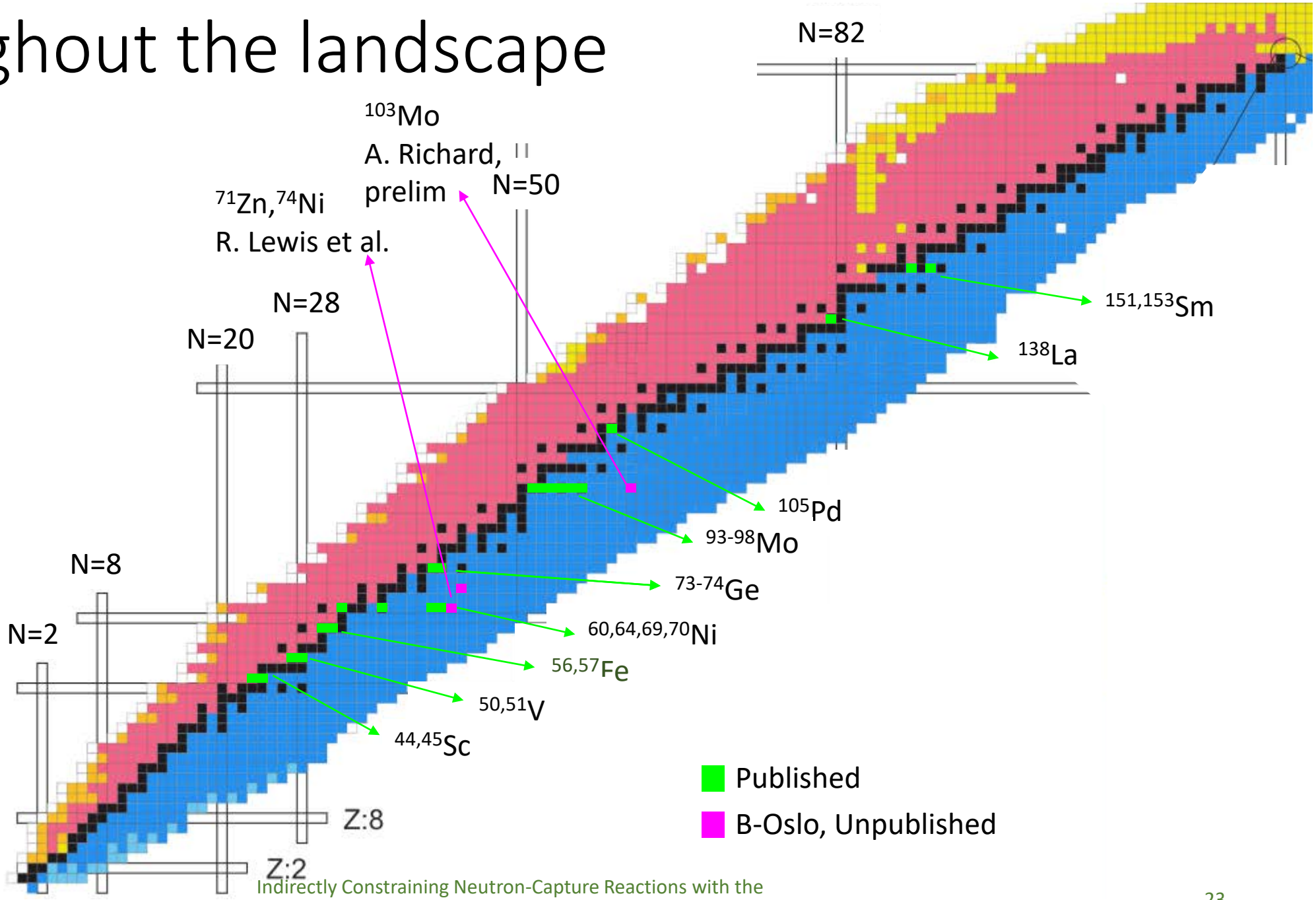
Potential Impact on Neutron Capture Rates



TALYS: Comparison of predicted SF with and without upbend

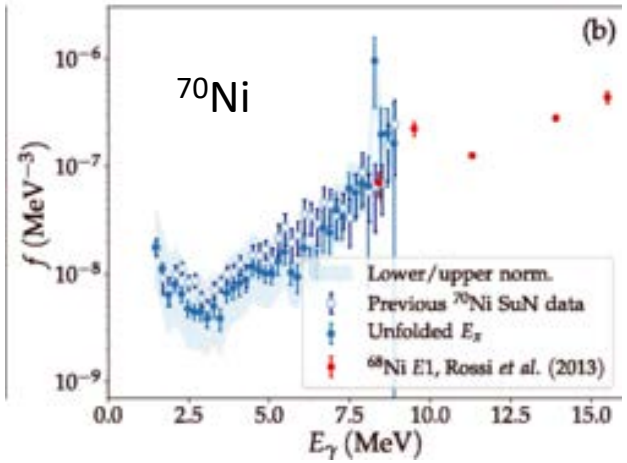
A. C. Larsen et. al., EPJA 66 (2014)
A. C. Larsen, S. Goriely, PRC **82** 014318 (2010)

LEE throughout the landscape

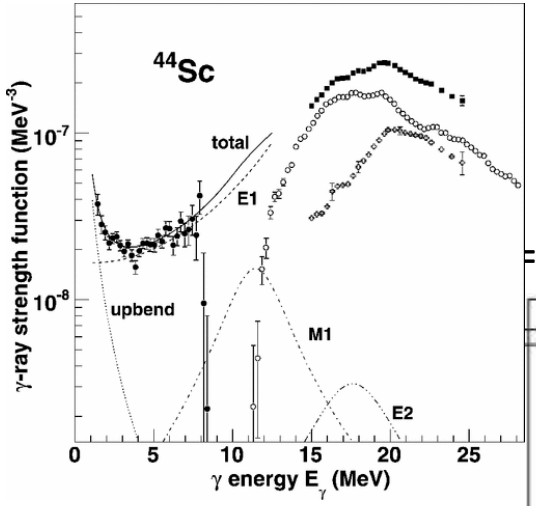


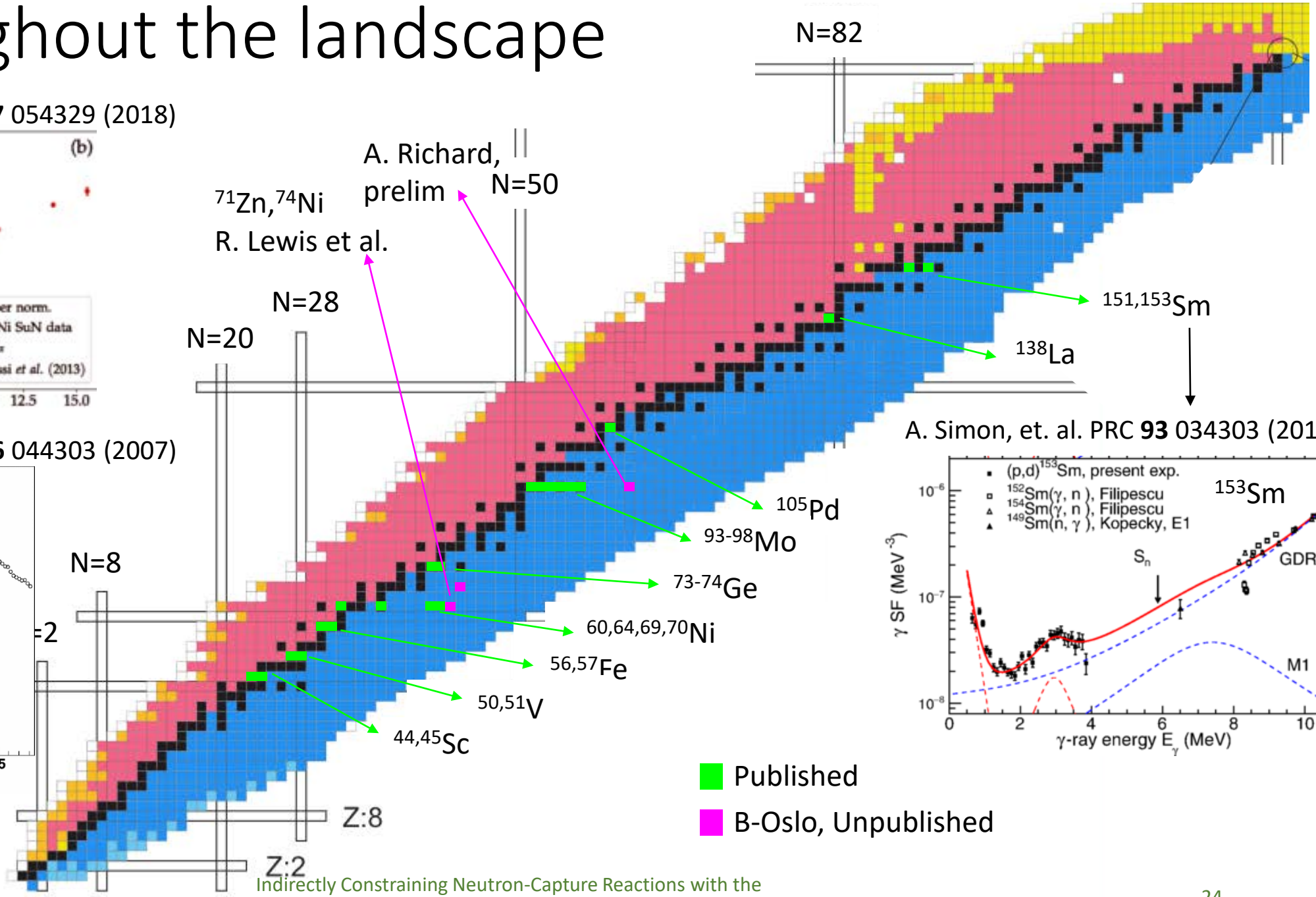
LEE throughout the landscape

A. C. Larsen, et. al. PRC **97** 054329 (2018)



A. C. Larsen, et. al. PRC **76** 044303 (2007)

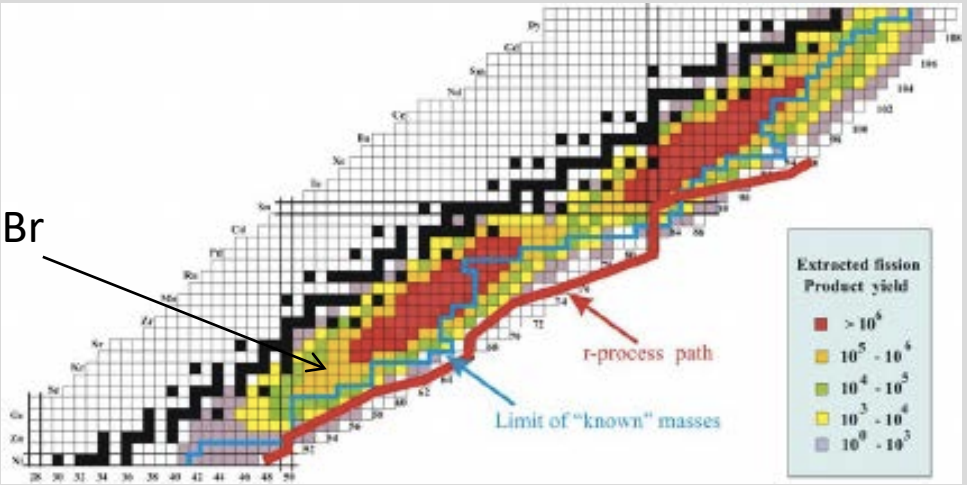




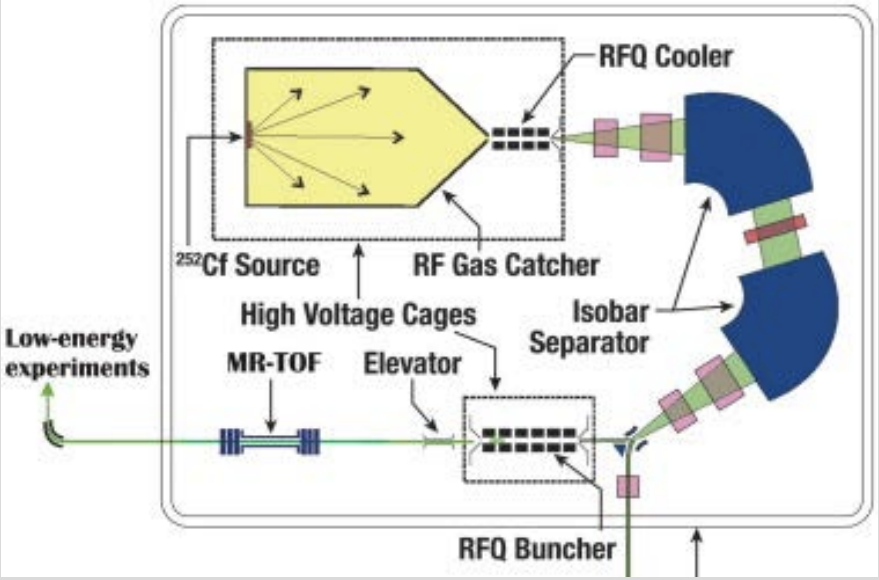
A. Simon, et. al. PRC **93** 034303 (2016)

Future SunTAN Experiments

- ^{87,88,89}Kr(n,γ) – beams ^{88,89,90}Br
  i-process
- ^{93,94,95}Sr(n,γ) - beams ^{94,95,96}Y
  stockpile stewardship
- ^{96,97,99}Zr – beams ^{97,98,100}Y
  i-process & search for LEE and scissors mode
- ^{127,128}Sn(n,γ) – beams ^{128,129}In
  ^{132,133}Sb(n,γ) – beams ^{133,134}Sn
  r-process
- ^{140,142,145}Cs(n,γ) – beams 141,143,145Xe
  r-process
- $^{135\text{-}138}$I(n,γ) – beams $^{136\text{-}139}$Te
  i-process bottleneck & r-process
- $^{155\text{-}158}$Sm(n,γ) – beams $^{156\text{-}159}$Pm
  search for LEE and scissors mode



Savard et. al



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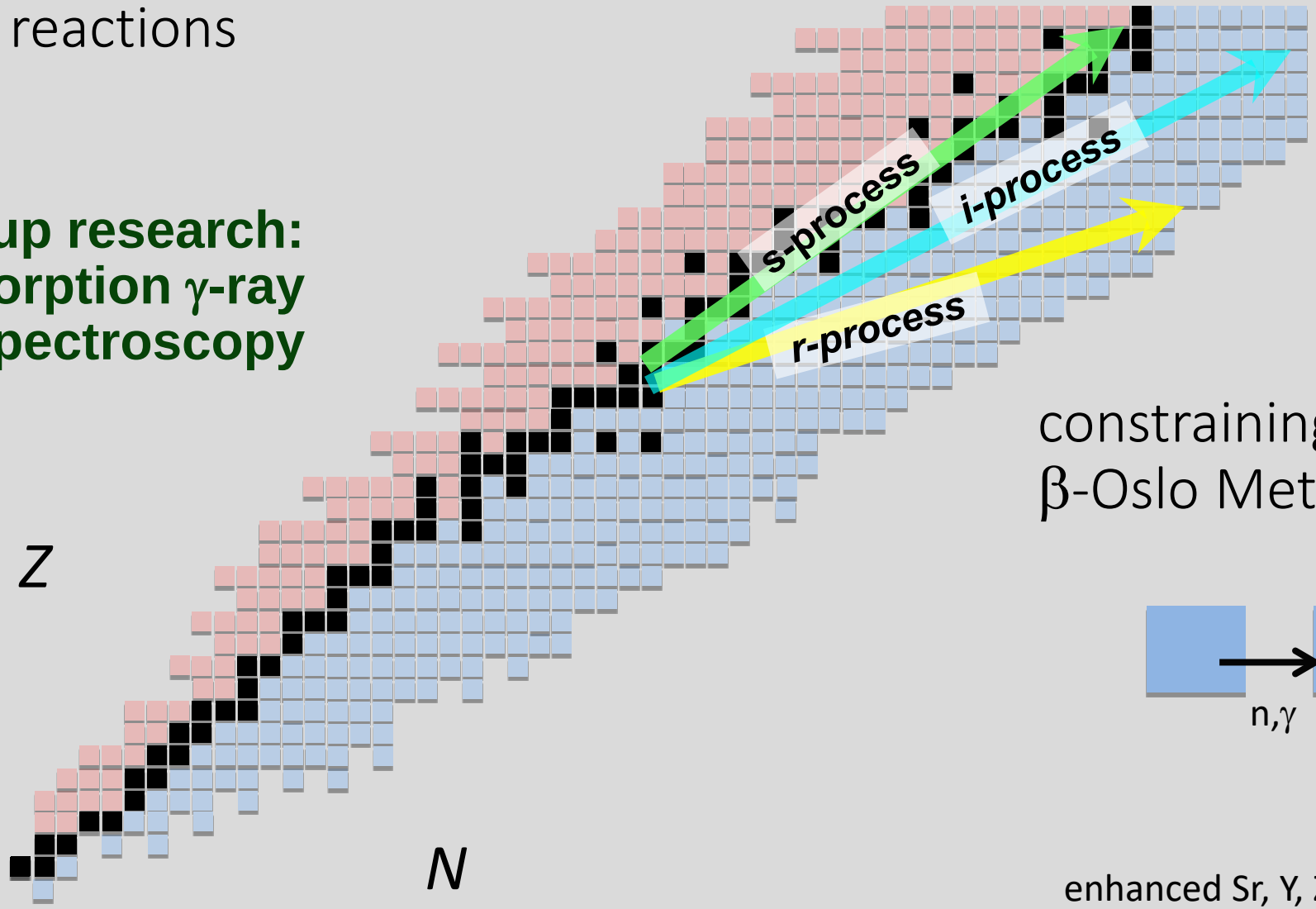
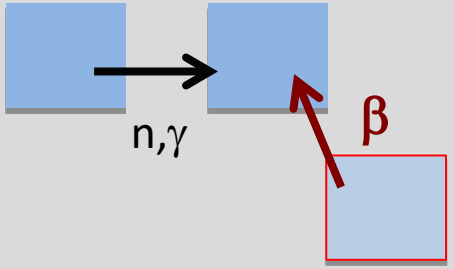
Backup Slides

More than 50% of elements with Z>26 were created through neutron-capture reactions

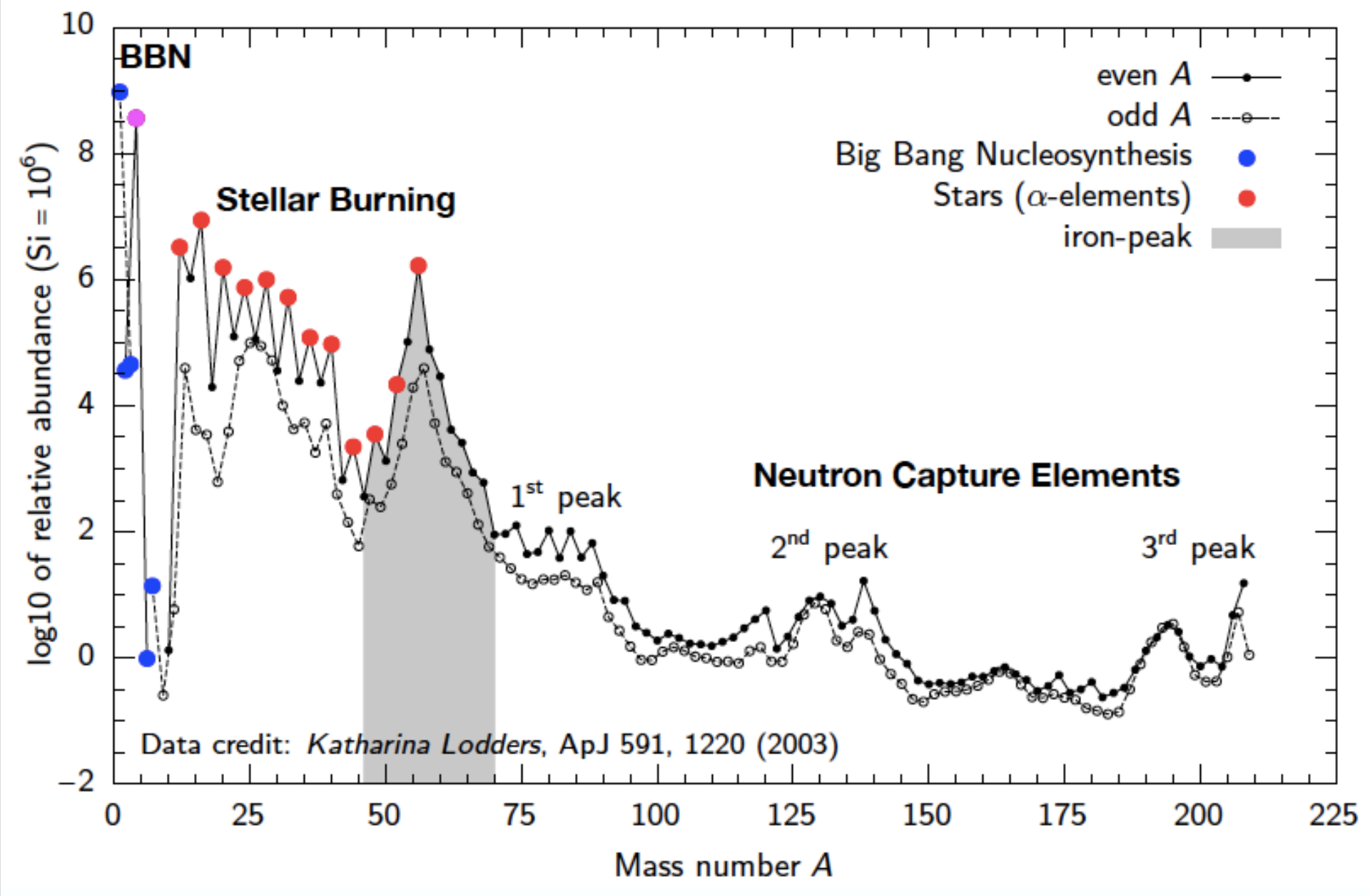
SuN Group research: total absorption γ-ray spectroscopy

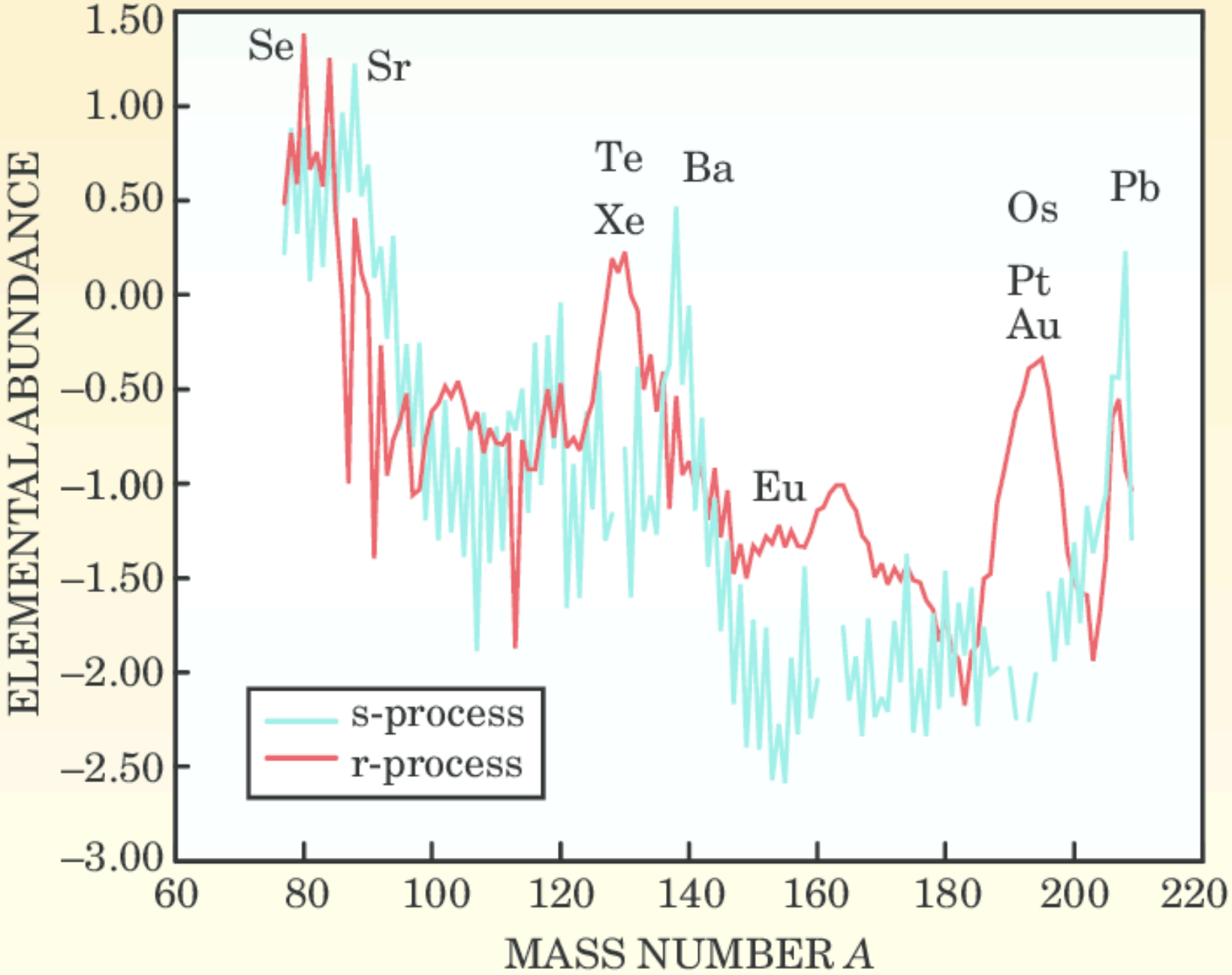


constraining (n.g) rates via the β-Oslo Method



enhanced Sr, Y, Zr, Rb- but not Ba, La


BBN
Stellar Burning
Neutron Capture Elements
1st peak
2nd peak
3rd peak
even A
odd A
Big Bang Nucleosynthesis
Stars (α-elements)
iron-peak
Data credit: Katharina Lodders, ApJ 591, 1220 (2003)
log10 of relative abundance (Si = 10^6)
Mass number A
10
8
6
4
2
0
−2
0
25
50
75
100
125
150
175
200
225


ELEMENTAL ABUNDANCE
1.50
1.00
0.50
0.00
–0.50
–1.00
–1.50
–2.00
–2.50
–3.00
60
80
100
120
140
160
180
200
220
MASS NUMBER A
Se
Sr
Te
Xe
Ba
Eu
Os
Pt
Au
Pb
s-process
r-process

Calculating Nuclear Cross Sections

Hauser-Feshbach theory

$$\sigma_{\alpha\beta} = \pi\lambda\!\!\!^{-}_{a} \frac{1}{(2i_a+1)(2J_a+1)} \sum_{J,\pi} (2J_C^{\pi}+1) \frac{T_a^{J^{\pi}} T_\beta^{J^{\pi}}}{\sum_e T_e^{J^{\pi}}}$$

Transmission coefficients

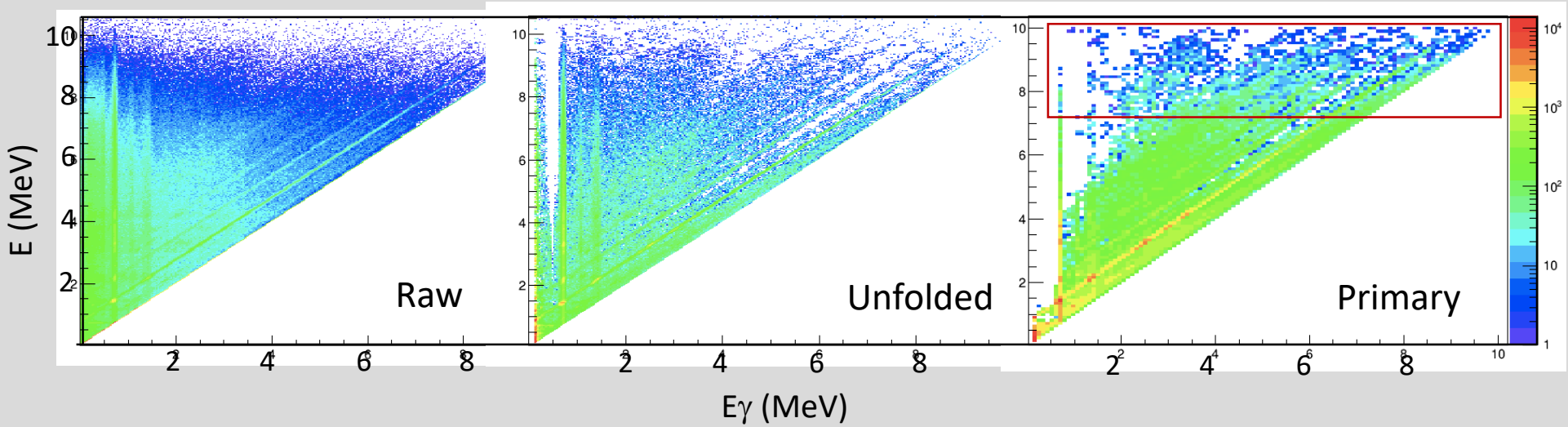
γSF — γ ray strength function

OMP — Optical model potential

NLD — Nuclear level densities

$$T_\beta^{J^\pi}(E) = \sum_{i=1}^{w} T_\beta^{J^\pi}(E) + \int_{E_w}^{U} T_\beta^{J^\pi}(E)\,\rho(E,J)\,dE$$

β-Oslo Analysis



Raw coincidence matrix from the SuN detector

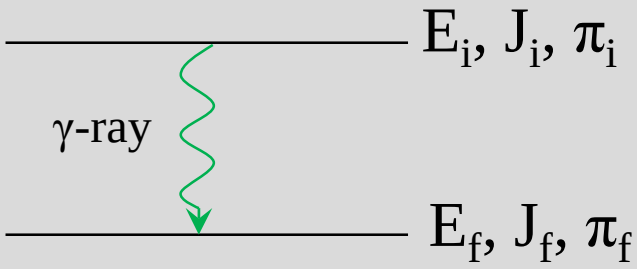
Compton scattering removed, aka “unfolded”

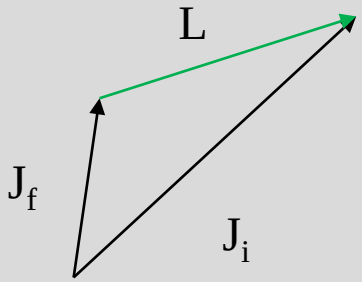
Iterative subtraction technique applied to the unfolded matrix

Background – Gamma Strength Function?

Discrete States (Low Energy Nuclear Structure)

Transition Probability depends on γ-ray energy, lifetime of i, and decay





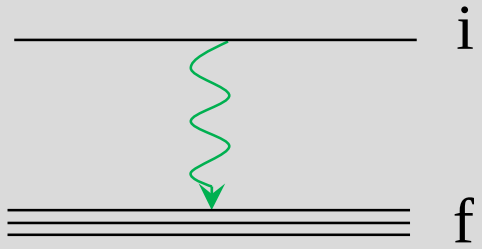
Each photon carries a definite angular momentum, L > 0

Selection Rules:

$$|J_i - J_f| \leq L \leq |J_i + J_f|$$

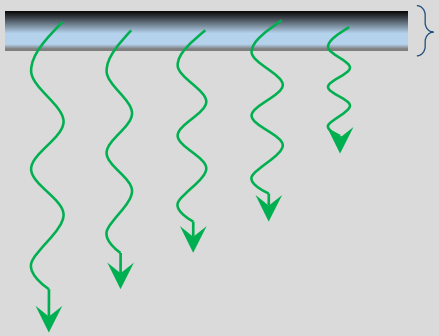
Electric multipole radiation
$\Delta\pi = (-1)^L$
Magnetic multipole radiation
$\Delta\pi = (-1)^{L+1}$

High Density of States – Overlapping of states (High Energy Nuclear Structure)



Transition Probability

$$\lambda = \frac{2\pi}{\hbar}\left|\langle f|H|i\rangle\right|^2 \rho(E_f)$$



$\Gamma = \Delta E$

Average over several states

$$\langle \lambda \rangle \langle \Gamma \rangle$$