



Neutron Captures Far From Stability and Astrophysical Applications

Artemis Spyrou

MICHIGAN STATE
UNIVERSITY



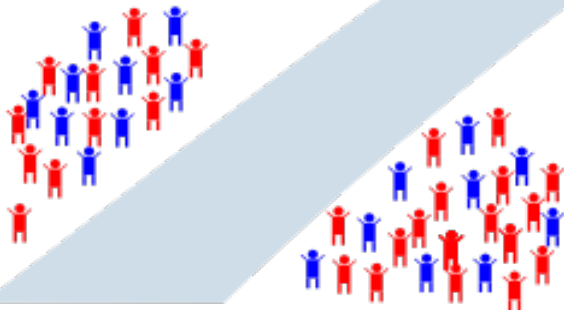
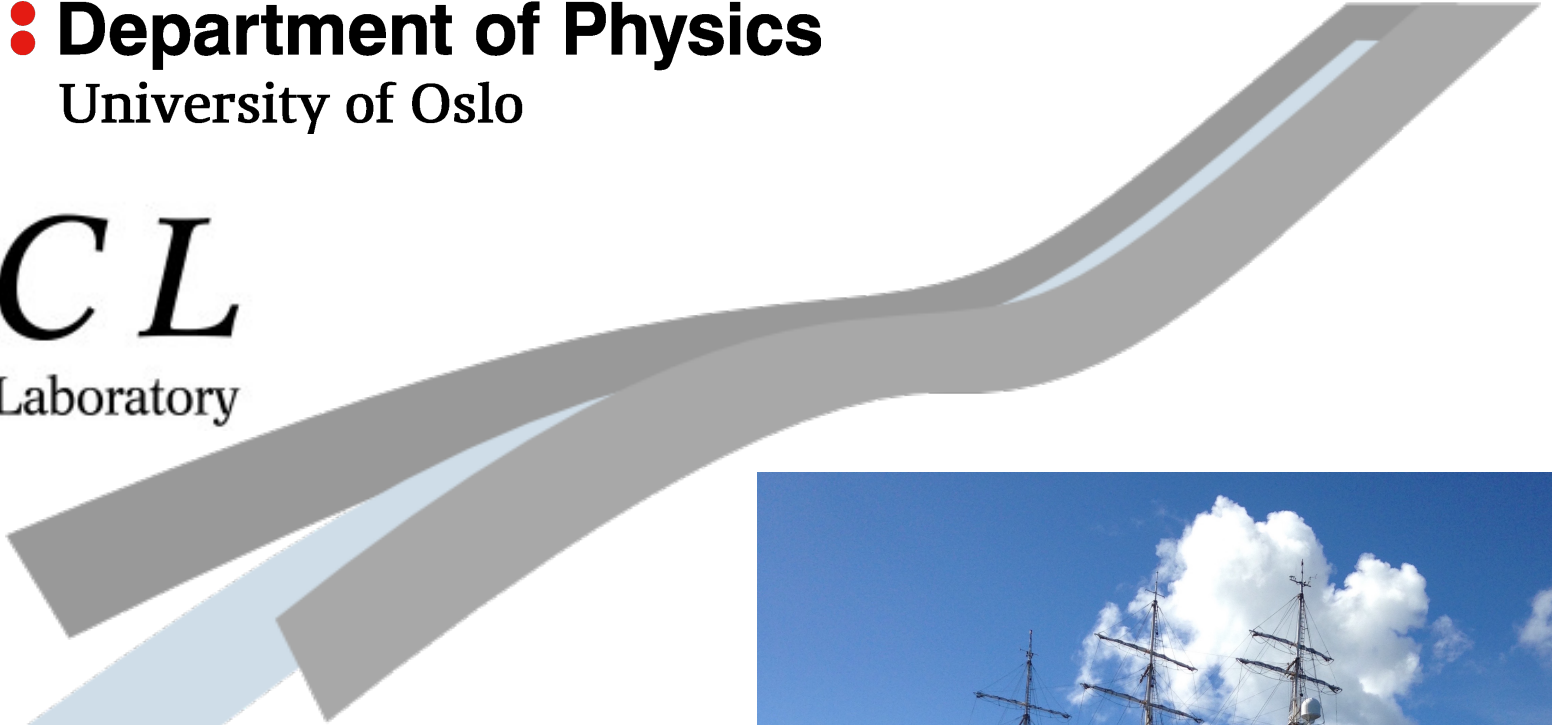
National Science Foundation
Michigan State University



10 years of Oslo Workshops



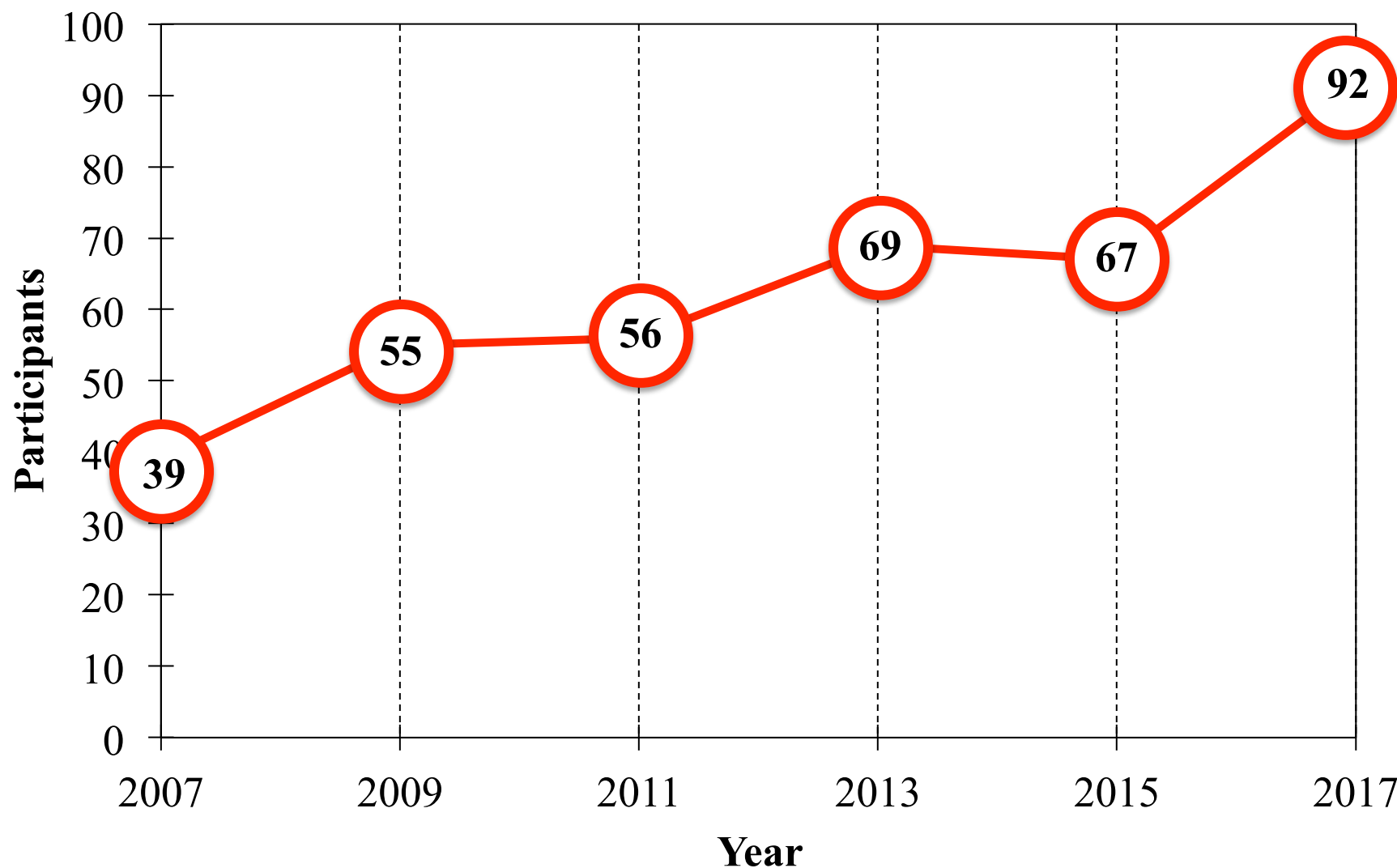
UiO : **Department of Physics**
University of Oslo



National Science Foundation
Michigan State University



10 years of Oslo Workshops





10 years of Oslo Workshops

2009



2015

2011



2013



National Science Foundation
Michigan State University

Artemis Spyrou, Oslo 2017, ...

Astrophysical Processes in the Cosmos

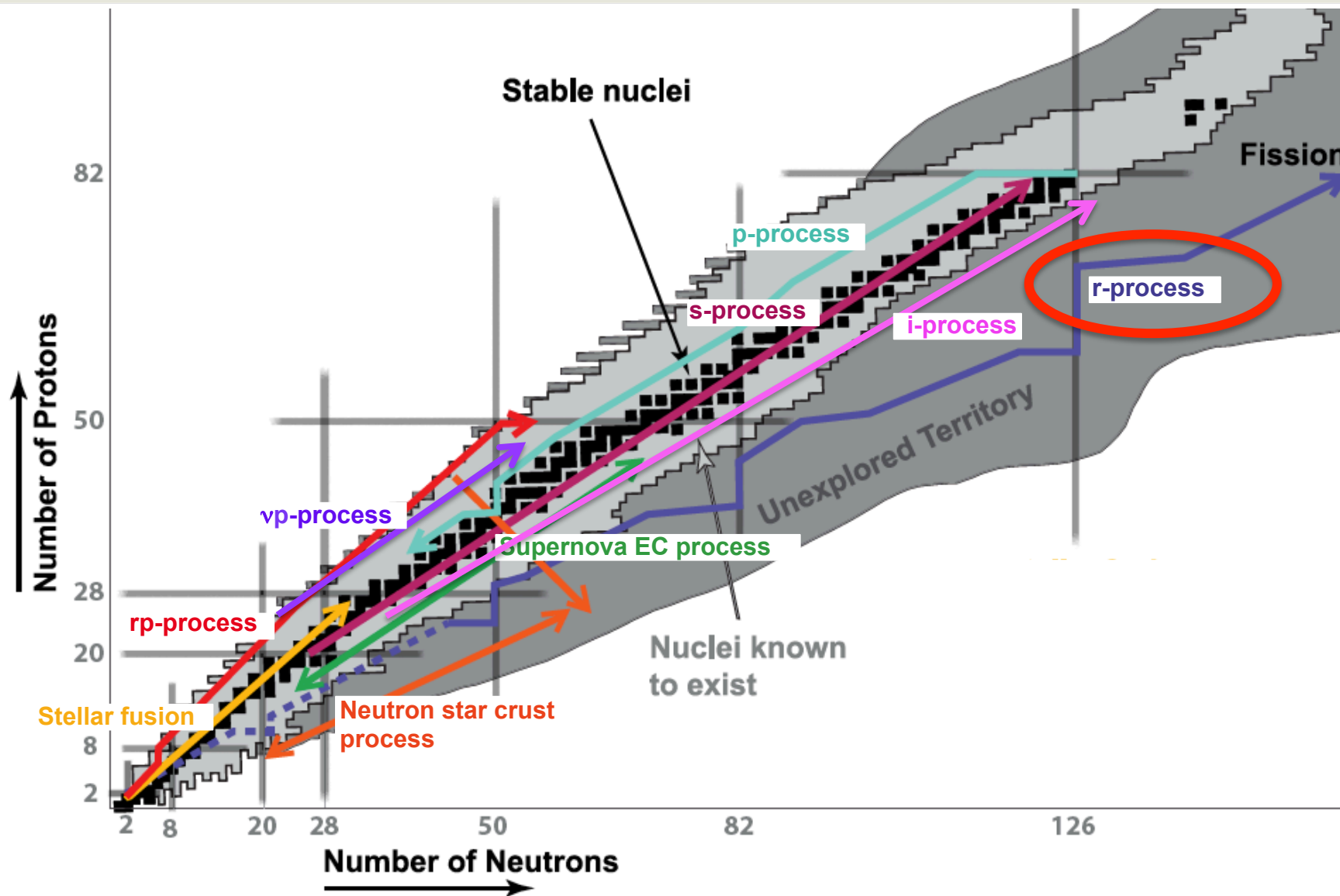
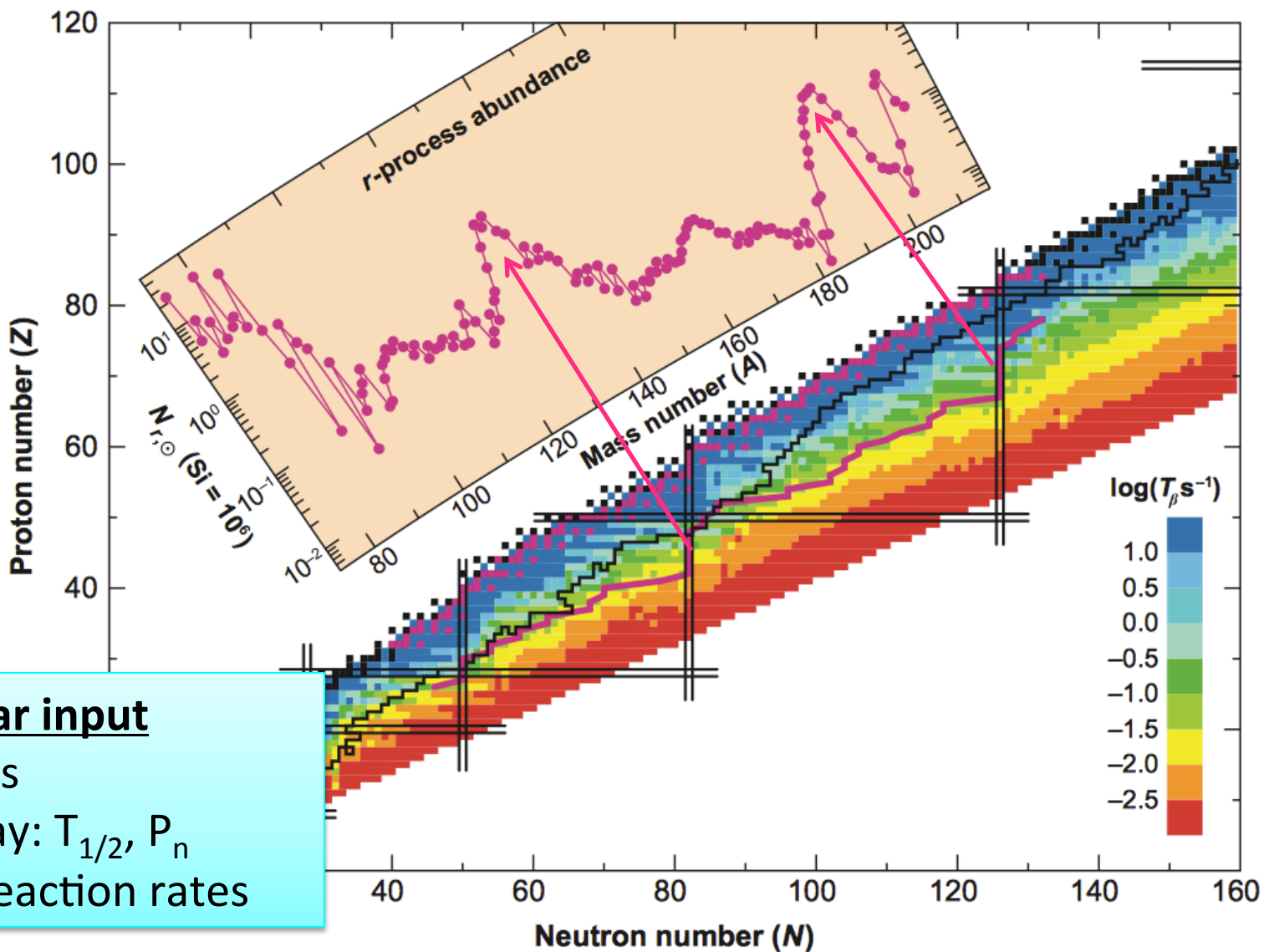


Figure adapted from Frank Timmes / Hendrik Schatz

R-process abundances



Nuclear input

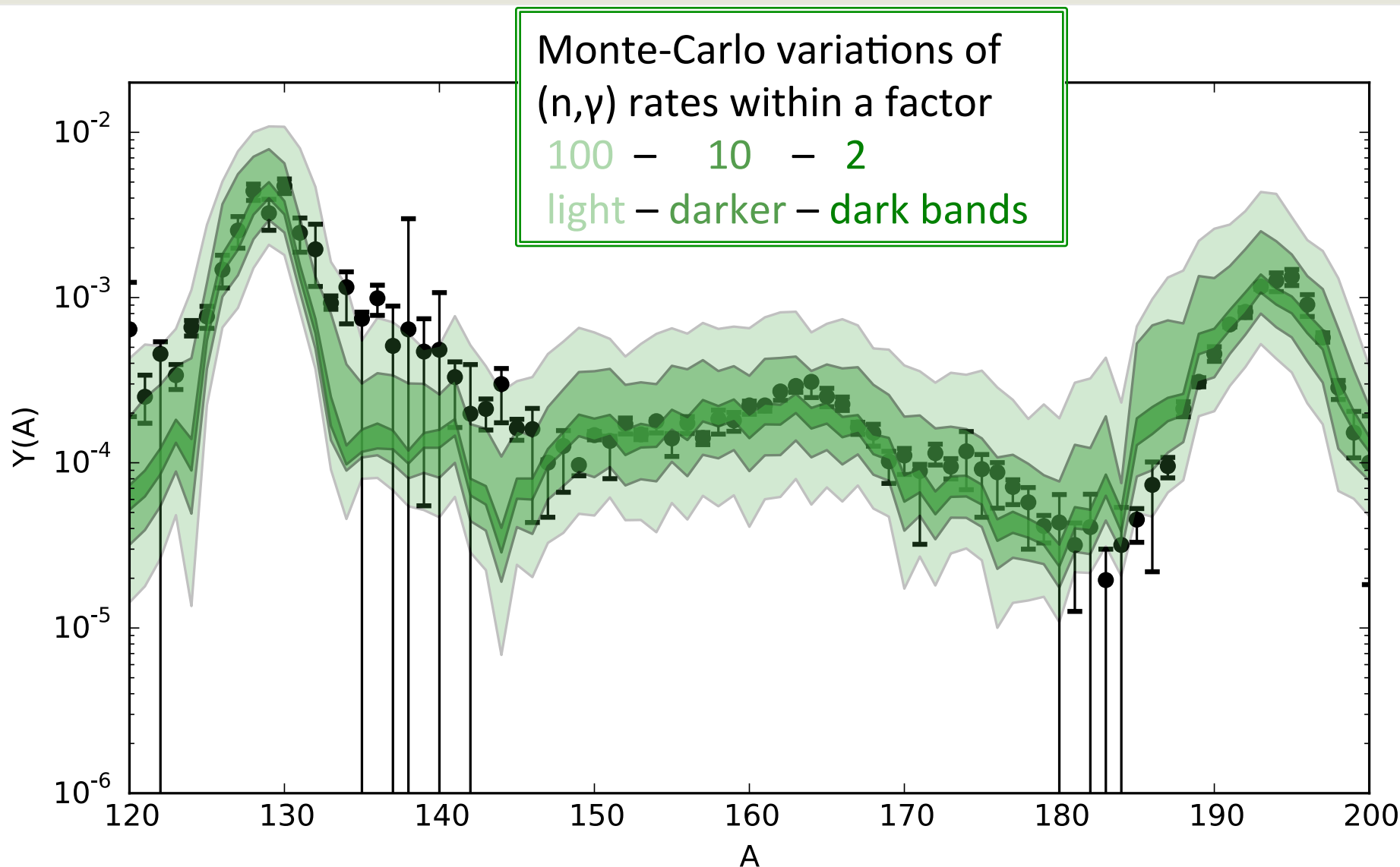
Masses

β -decay: $T_{1/2}$, P_n

(n, γ) reaction rates

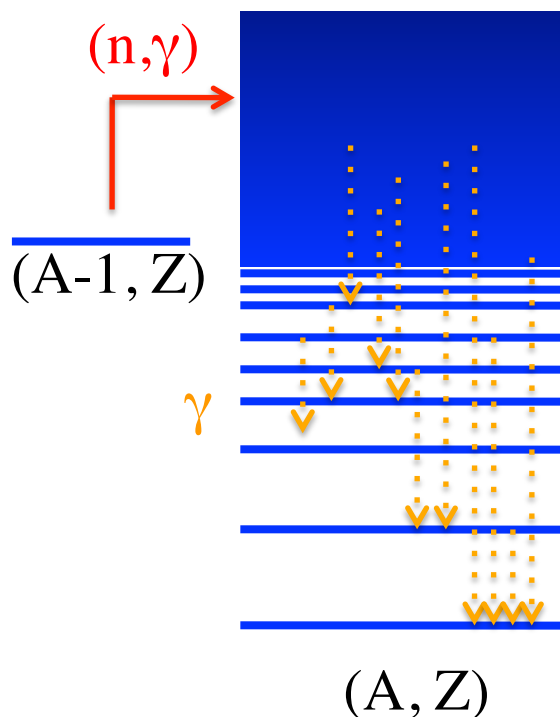


R-process sensitivity to neutron captures





Neutron Capture – Uncertainties



Hauser – Feshbach

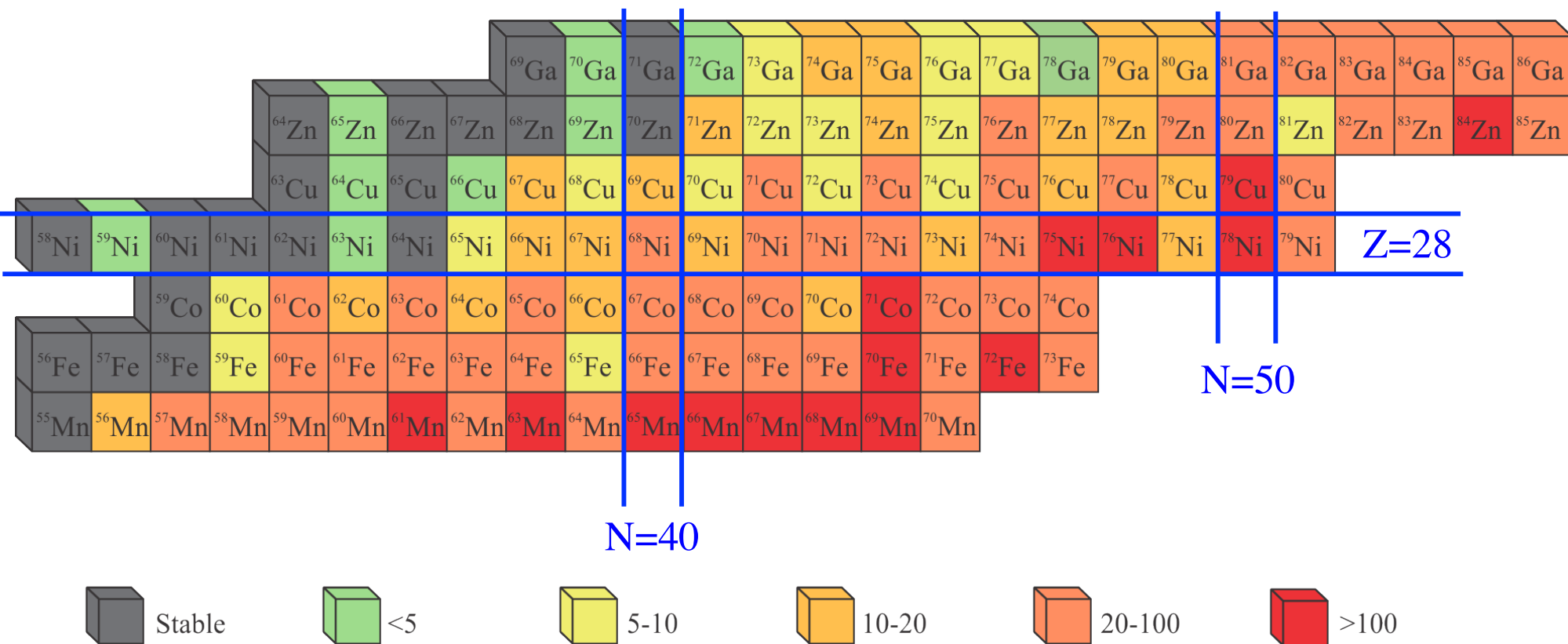
- Nuclear Level Density (NLD)
- γ -ray strength function (γ SF)
- Optical model potential

} Dominate uncertainties

Large uncertainties further from stability

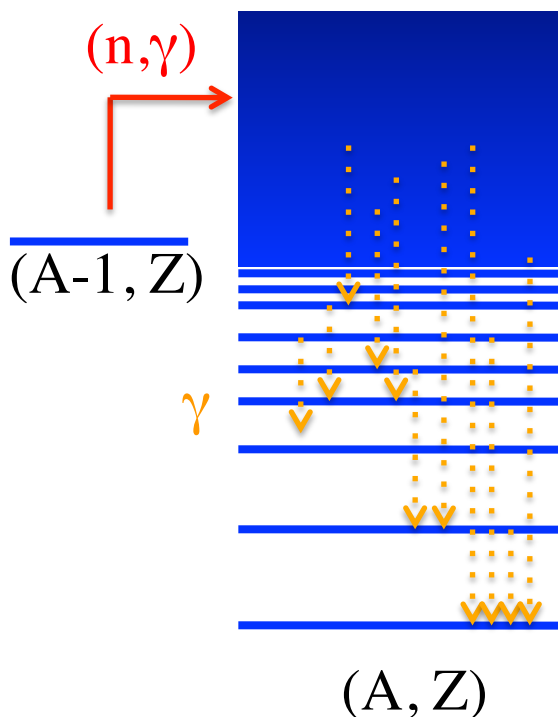


Neutron capture reactions



- Variation of theoretical predictions using TALYS, changing **NLD** and **γ SF**
- Predictions diverge moving away from stability

Neutron Capture – Uncertainties



Hauser – Feshbach

- Nuclear Level Density (NLD) } Dominate uncertainties
- γ -ray strength function (γ SF) }
- Optical model potential $\longrightarrow$ Large uncertainties further from stability

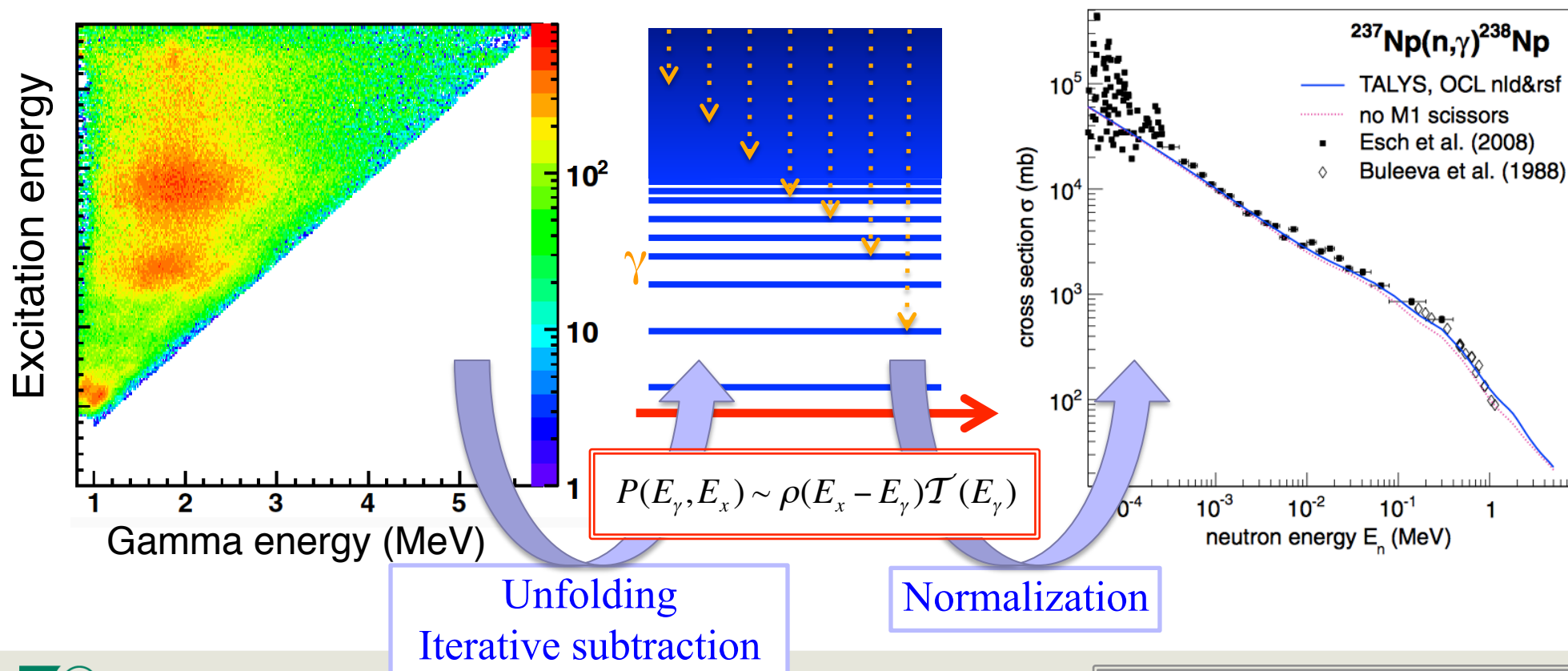
- **Direct measurements often challenging**
- Indirect techniques required
- Long list of techniques to measure NLD and γ SF
- Full week ahead of us with new results and methods
- One such technique: β -Oslo

Combine **Total Absorption Spectroscopy** with **Oslo Method**

Traditional Oslo method

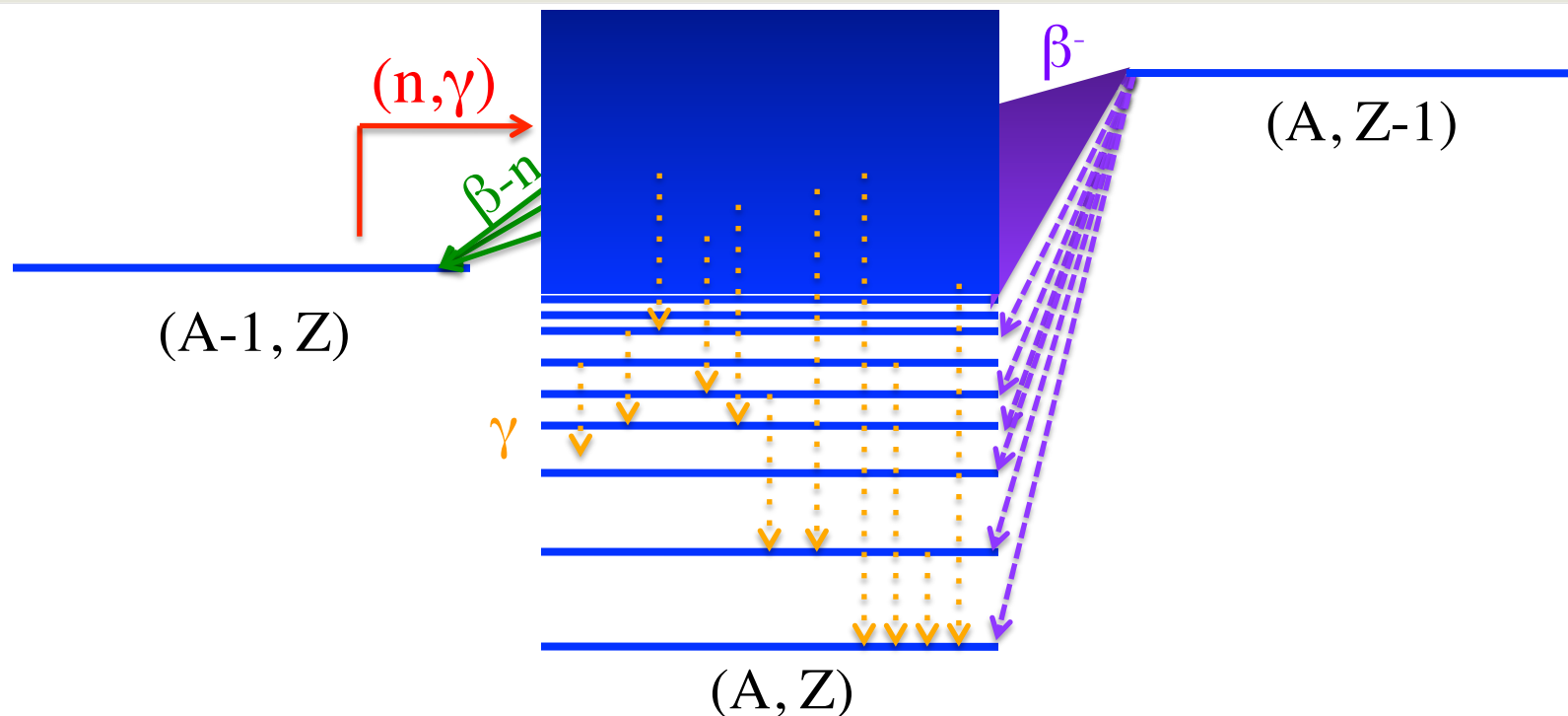
See talk by L. Crespo

- Use reaction to populate the compound nucleus of interest
- Measure excitation energy and γ-ray energy
- Extract **level density** and **γ-ray strength function**
- Calculate “semi-experimental” (n,γ) cross section
- Excellent agreement with measured (n,γ) reaction cross section



β -Oslo

Validation of β -Oslo: see talk by Sean Liddick

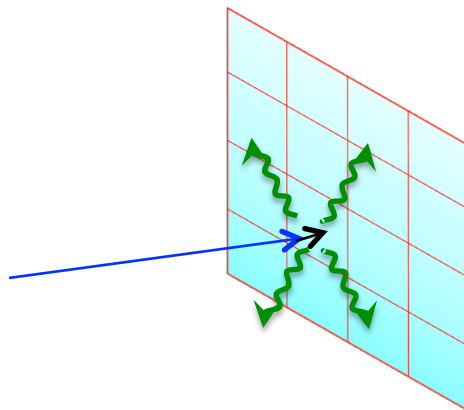
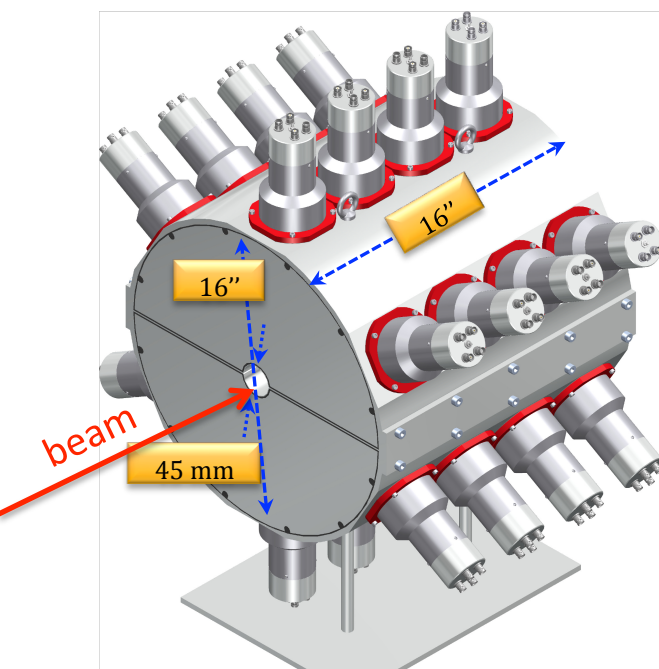


- Populate the compound nucleus via β -decay (large Q-value far from stability)
- Spin selectivity – correct for it
- Extract level density and γ -ray strength function
- **Advantage: Can reach (n,γ) reactions with beam intensity down to 1 pps.**



Total Absorption Spectroscopy

- Large size/very high efficiency γ -calorimeter – as close to 100% as possible
- Summing of all γ -rays gives the excitation energy
- Common technique for extracting β -decay strength function
- Very sensitive to the nuclear structure
- If segmented TAS detector is used - information about individual γ -rays



- ✓ 16x16 inch
- ✓ 45 mm borehole
- ✓ 2 pieces
- ✓ 8 segments
- ✓ 24 PMTs
- ✓ Efficiency > 85% for 1 MeV

J.C. Hardy *et al.*, *Phys. Lett. B* 71 (1977) 307.

E. Nacher, *et al.*, *Phys. Rev. Lett.* 92 (2004) 232501.

A. Simon, S.J. Quinn, A.S., *et al.*, *Nucl. Instr. Meth A* 703, 16 (2013)



National Science Foundation
Michigan State University

National Superconducting Cyclotron Lab

SuN

β -decay experiments with “stopped” beams

“Stopped beam area”

ReAccelerator Facility

Gas Stopper

K500 Cyclotron

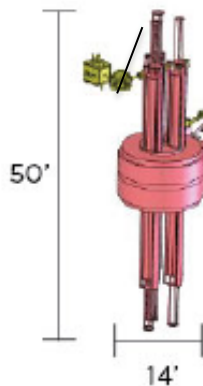
S800 Spectrograph

SuN

β -decay experiments with fast beams

A1900 Fragment Separator

K1200 Cyclotron

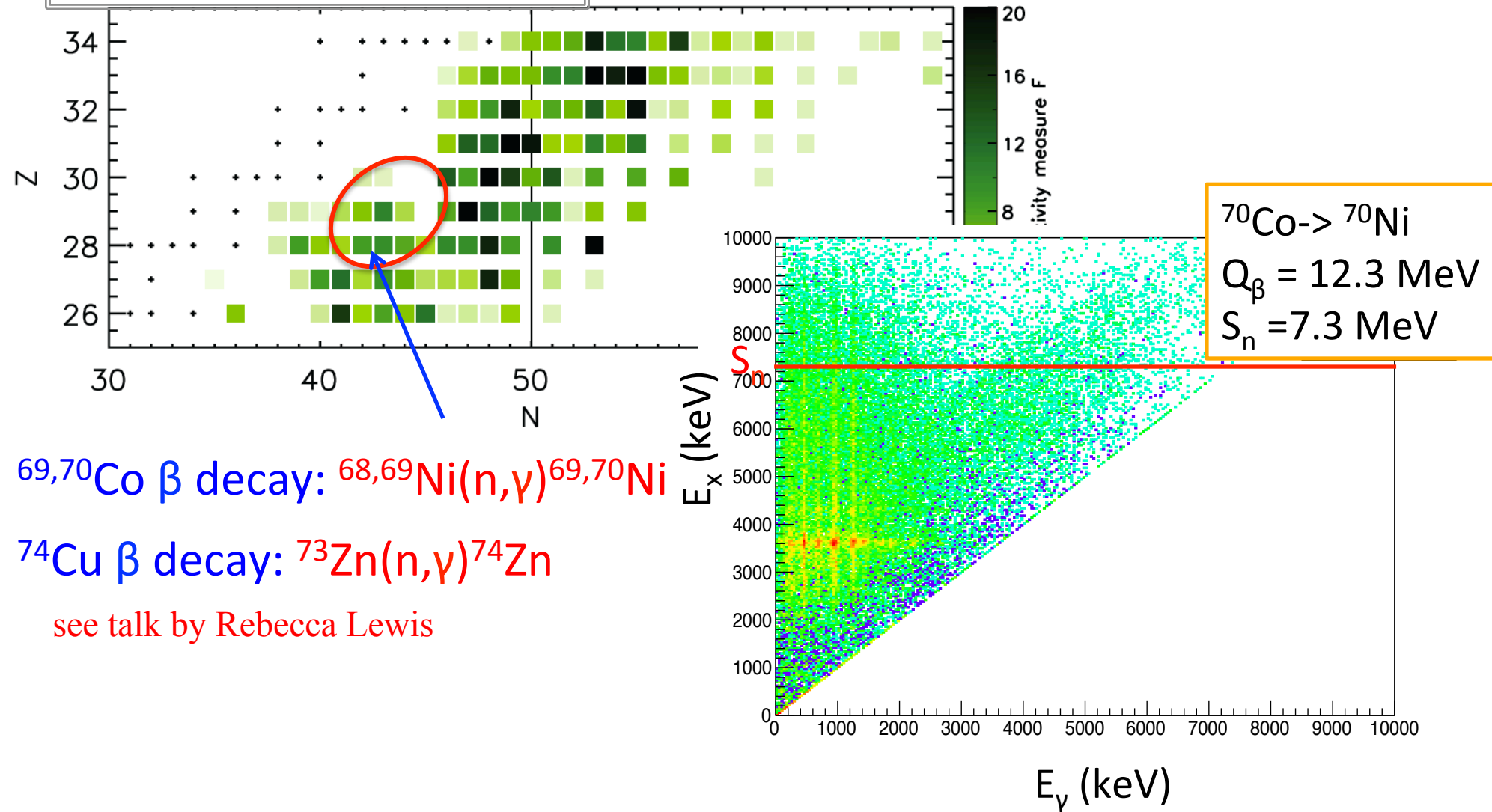


MICHIGAN STATE
UNIVERSITY

Weak r-process measurements

Neutron- γ competition: see talk by Sean Liddick

R. Surman, et al., , AIP Advances 4, 041008 (2014)



$^{69,70}\text{Co}$ β decay: $^{68,69}\text{Ni}(n,\gamma)^{69,70}\text{Ni}$

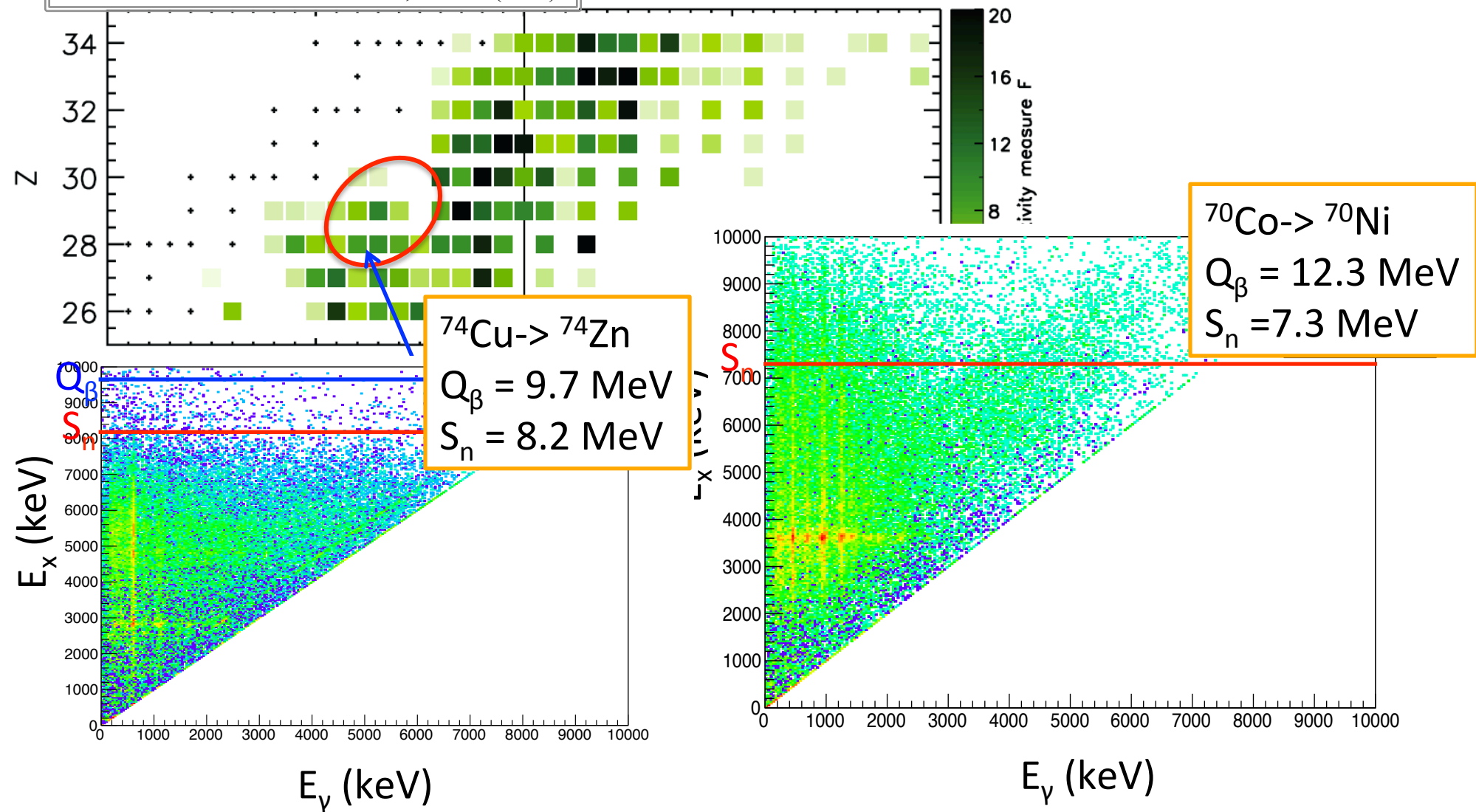
^{74}Cu β decay: $^{73}\text{Zn}(n,\gamma)^{74}\text{Zn}$

see talk by Rebecca Lewis

Weak r-process measurements

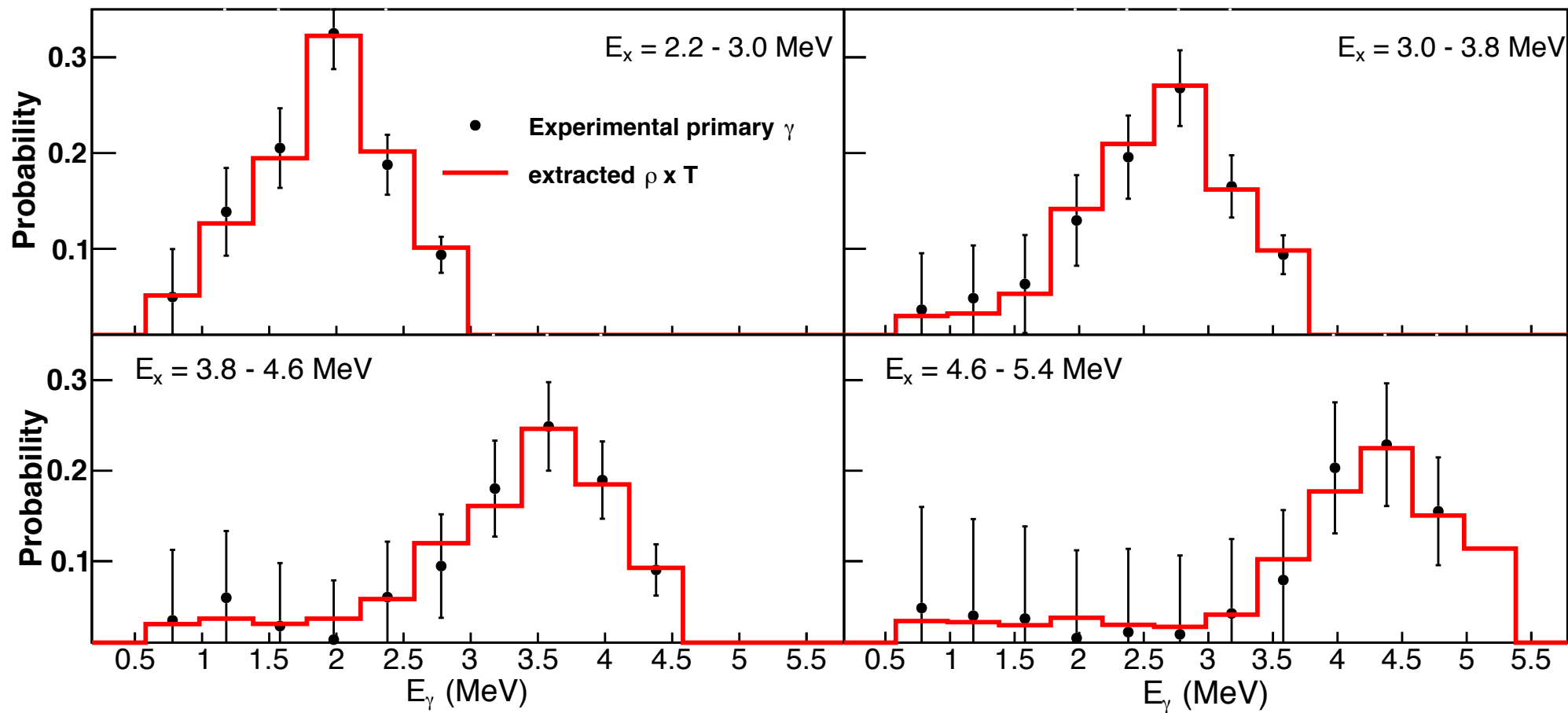
Neutron- γ competition: see talk by Sean Liddick

R. Surman, et al., , AIP Advances 4, 041008 (2014)



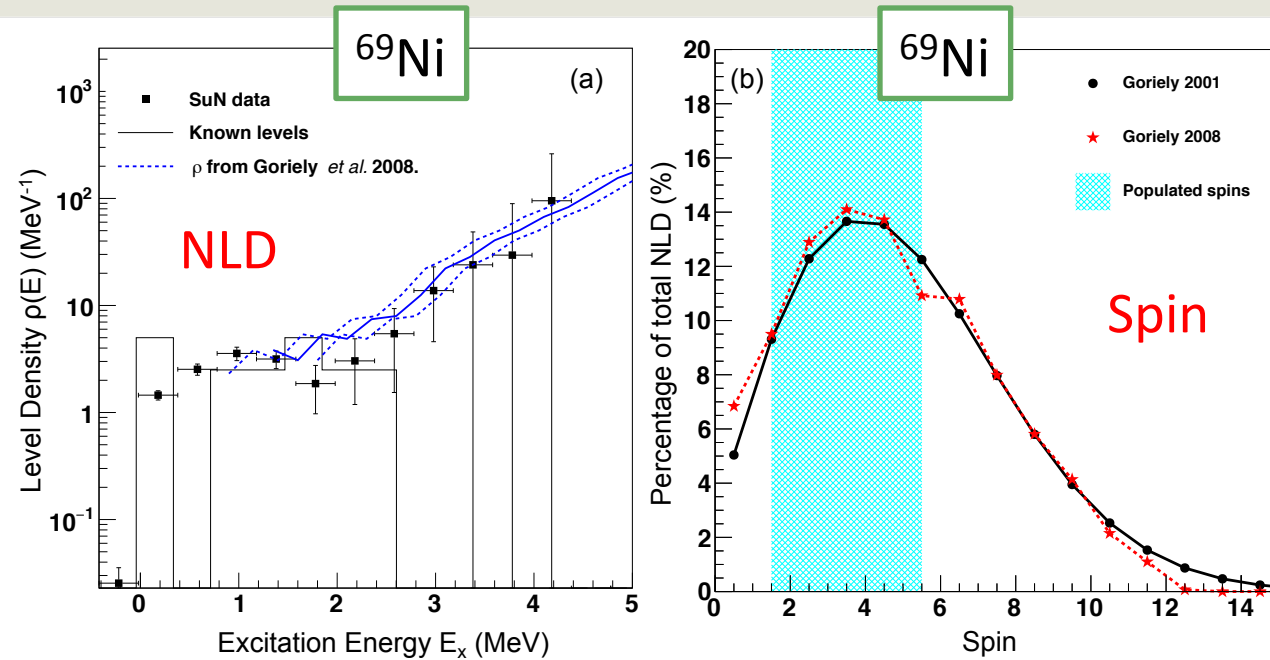
Does it work?

^{69}Co β decay $\rightarrow$ ^{69}Ni



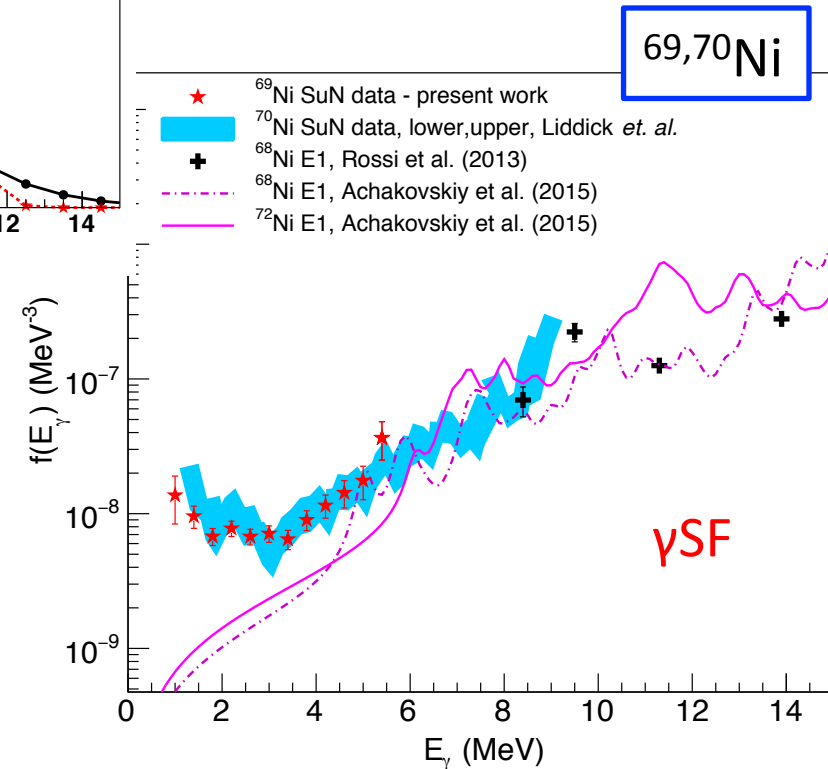
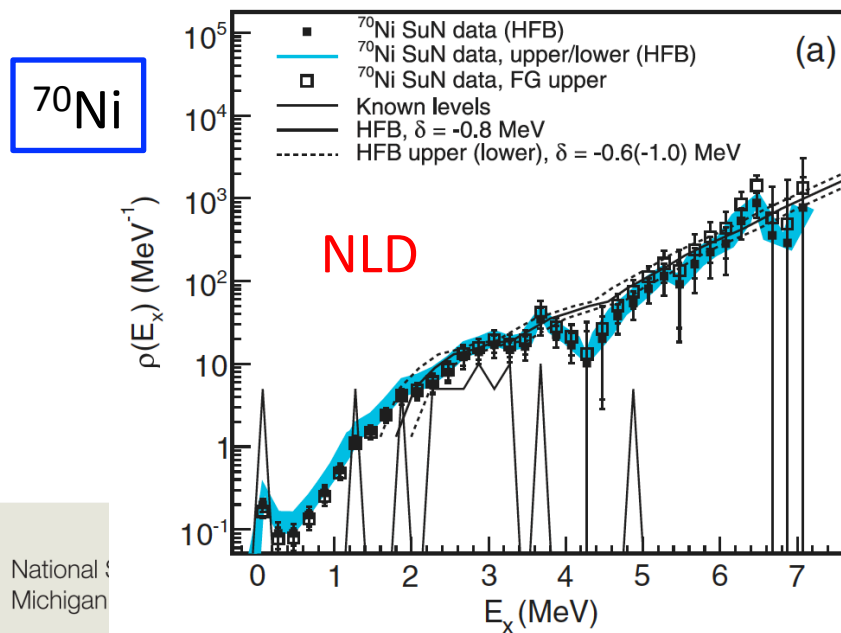
- Compare data (black points) to extracted $\rho \times T$ (red line)
- Excellent agreement

First Results $^{69,70}\text{Ni}$

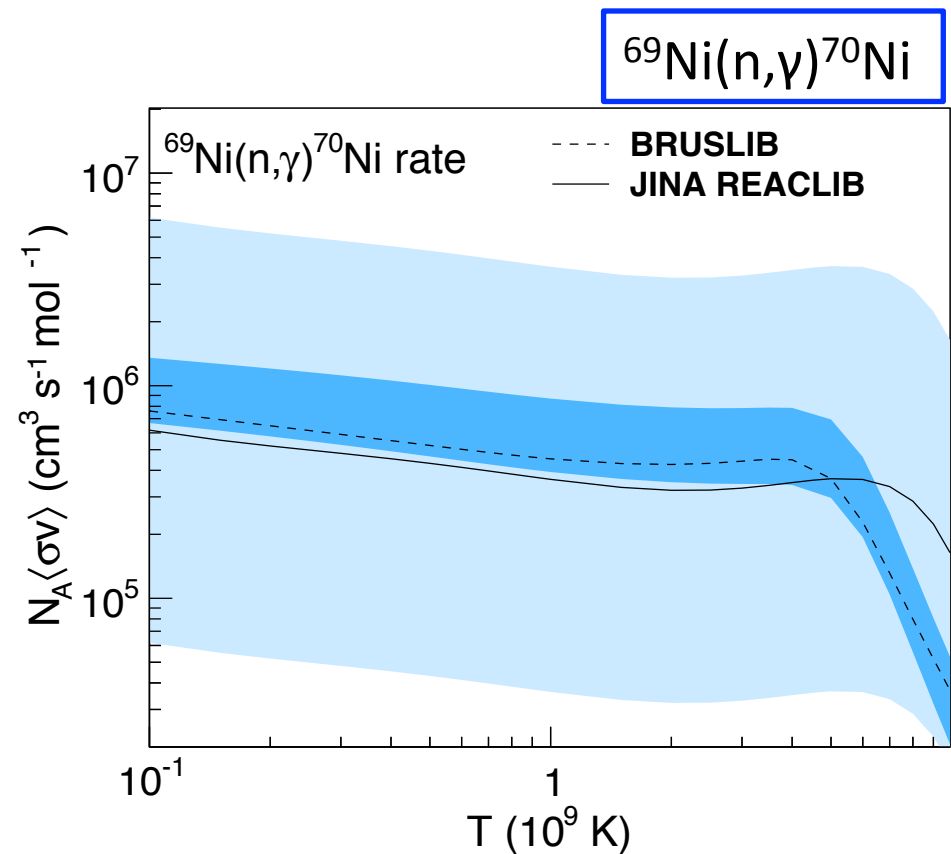
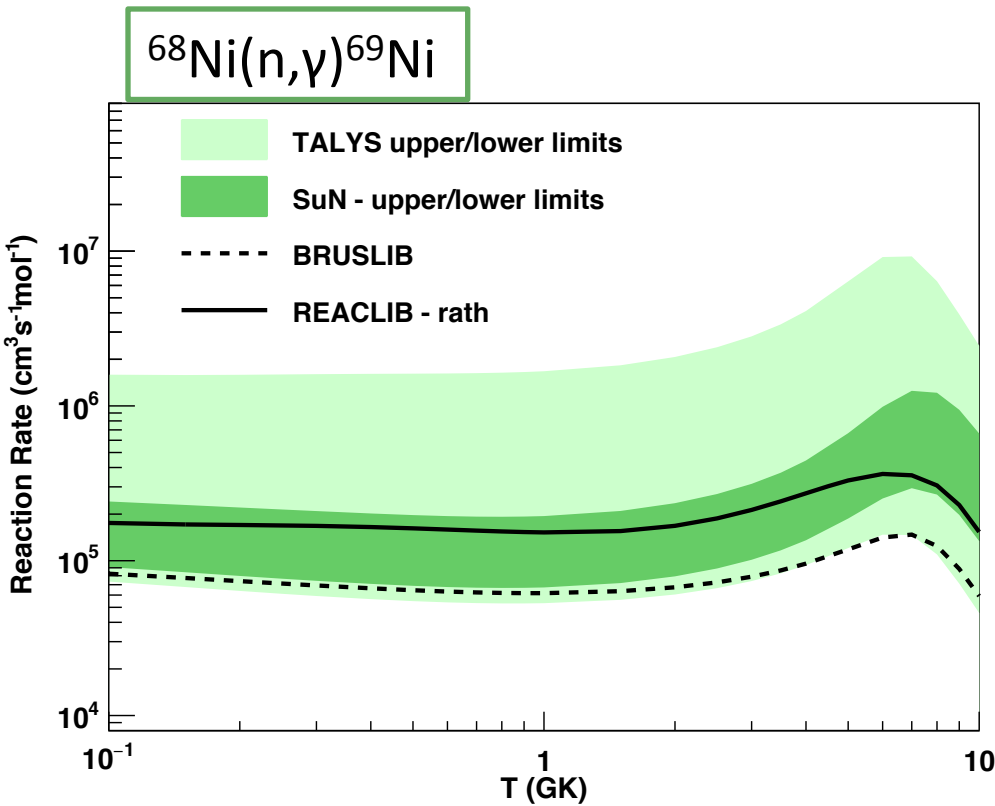


Normalizations far from stability:

- Use systematics
- Some model dependence
- Power: simultaneous extraction of NLD and γSF



First Results $^{68,69}\text{Ni}(n,\gamma)^{69,70}\text{Ni}$



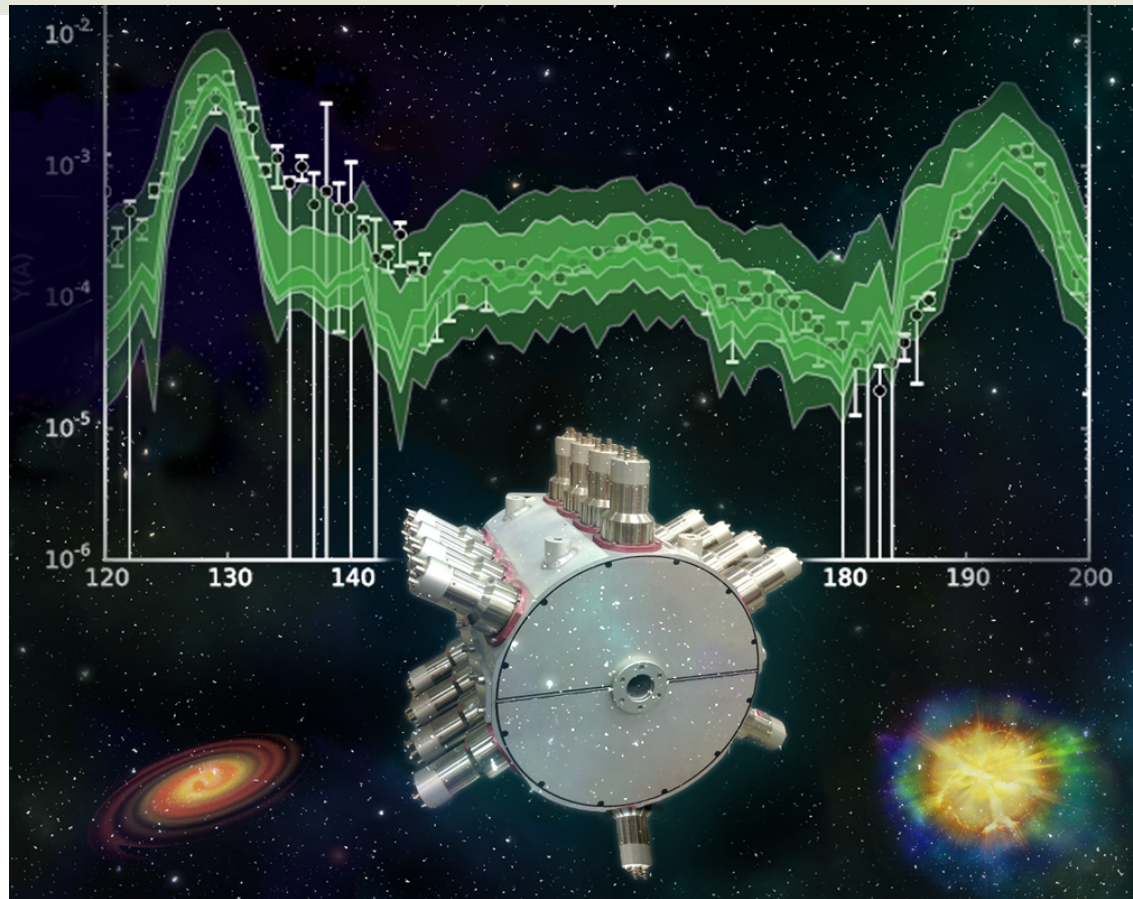
Summary

- Many astrophysical reactions cannot be measured directly
- Indirect techniques provide information where nothing known
- β -Oslo: new technique for constraining (n,γ) reactions far from stability
- β decay can be used with very low beam intensities
- Total absorption spectroscopy sensitive to nuclear structure

Collaboration

MICHIGAN STATE
UNIVERSITY

B. Crider
S.N. Liddick
K. Cooper
A.C. Dombos
R. Lewis
D.J. Morrissey
F. Naqvi
C. Prokop
S.J. Quinn
C.S. Sumithrarachchi
R.G.T. Zegers



A.C. Larsen
M. Guttormsen
T. Renstrøm
S. Siem
L. Crespo-Campo



A. Couture
S. Mosby



G. Perdikakis
S. Nikas



A. Simon



B. Rubio



D. L. Bleuel



National Science Foundation
Michigan State University



Collaboration

Michigan State University

- B. Crider
- S.N. Liddick
- K. Cooper
- A.C. Dombos
- R. Lewis
- D.J. Morrissey
- F. Naqvi
- C. Prokop
- S.J. Quinn
- C.S. Sumithrarachchi
- R.G.T. Zegers



University of Oslo

- A.C. Larsen
- M. Guttormsen
- T. Renstrøm
- S. Siem
- L. Crespo-Campo

Los Alamos National Lab

A. Couture
S. Mosby



Lawrence Livermore National Lab

D.L. Bleuel



Central Michigan University

- G. Perdikakis



Notre Dame

- A. Simon



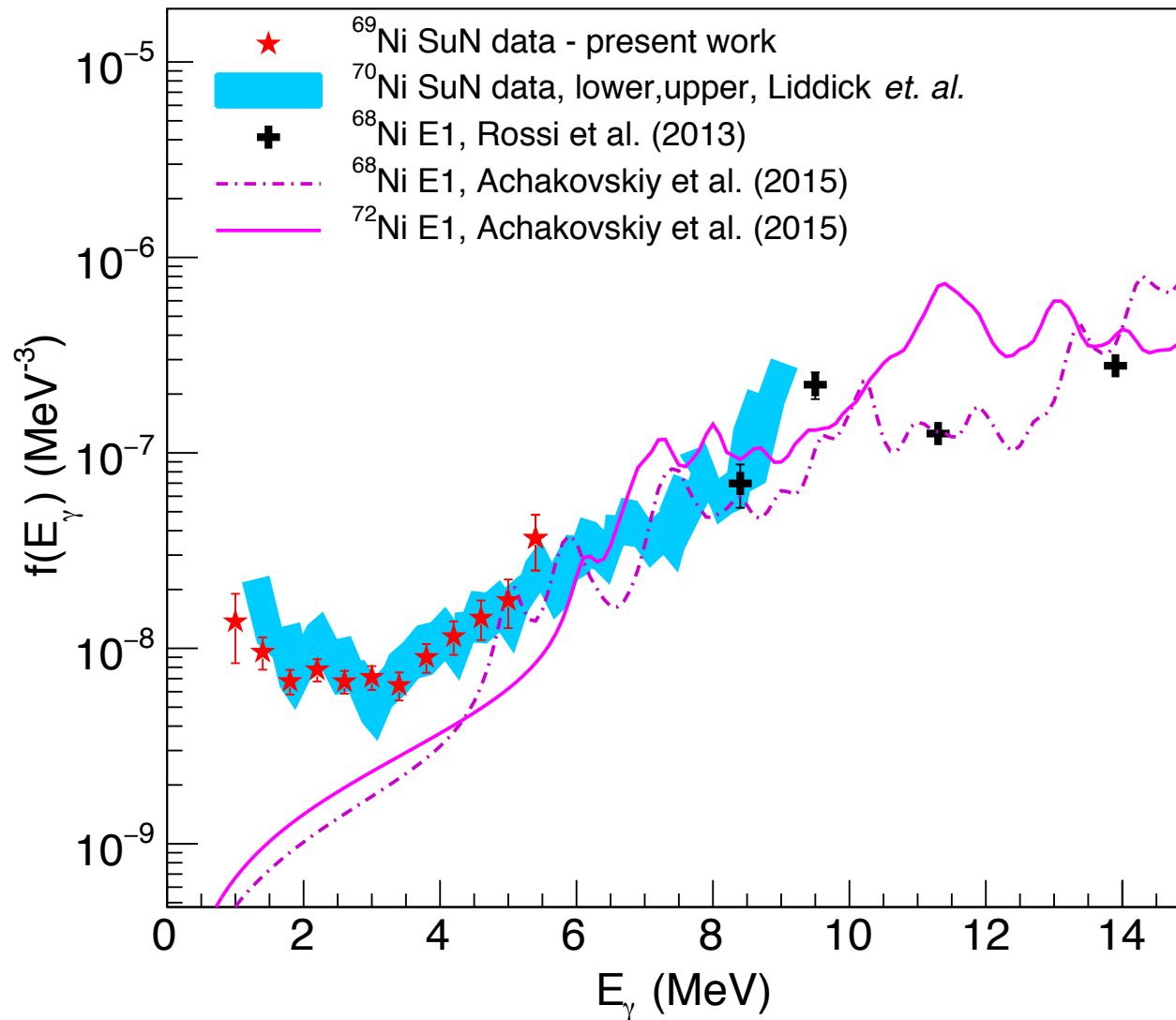
University of Valencia

B. Rubio

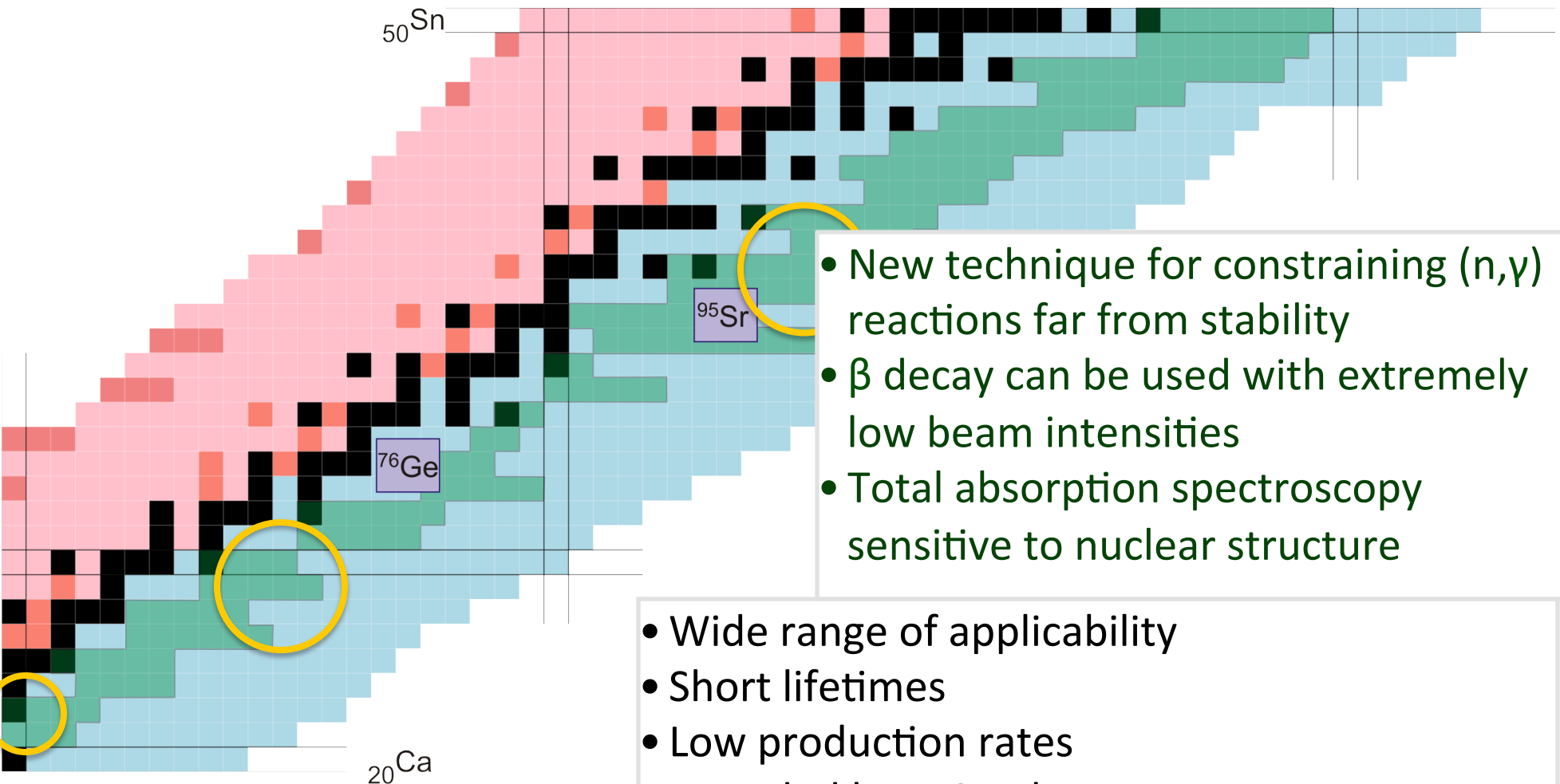


A. C. L. and M. G. acknowledge financial support from the Research Council of Norway, project grant no. 205528. This work was supported by the National Science Foundation under Grants No. PHY 102511, and No. PHY 0822648, and PHY 1350234.

First Results – γ strength $^{69,70}\text{Ni}$



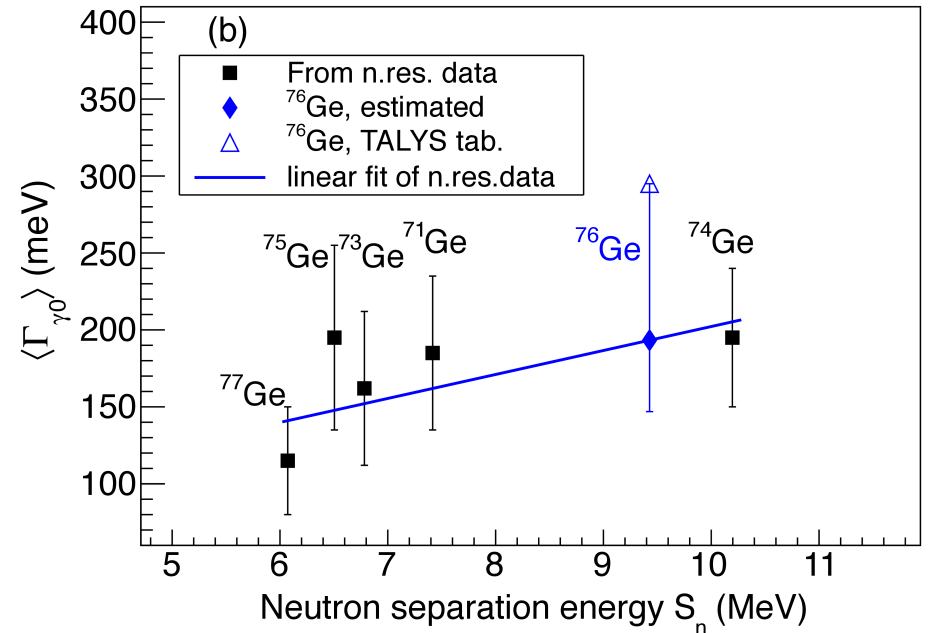
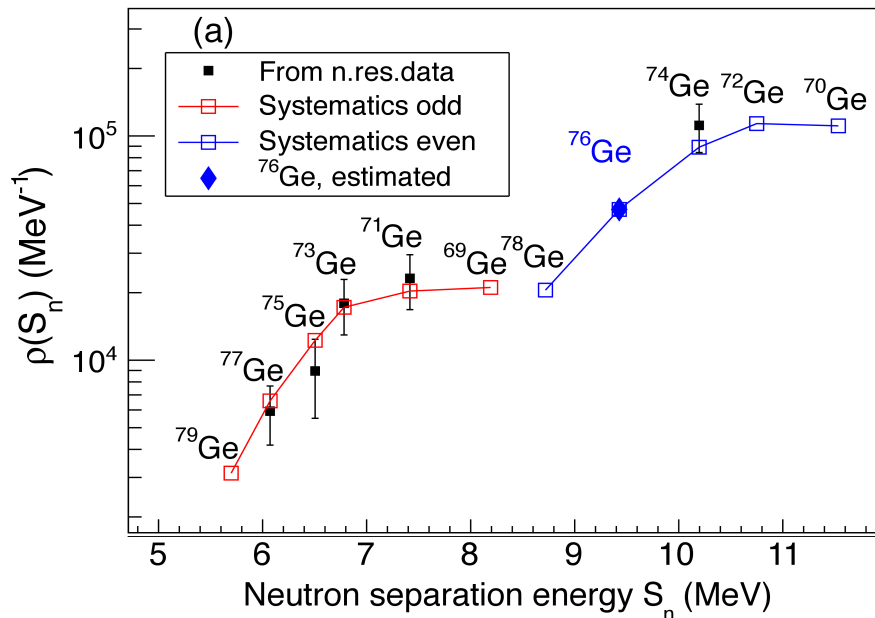
Summary and Applicability



- Wide range of applicability
- Short lifetimes
- Low production rates
- Bounded by: - Q values
- Delayed neutron emission

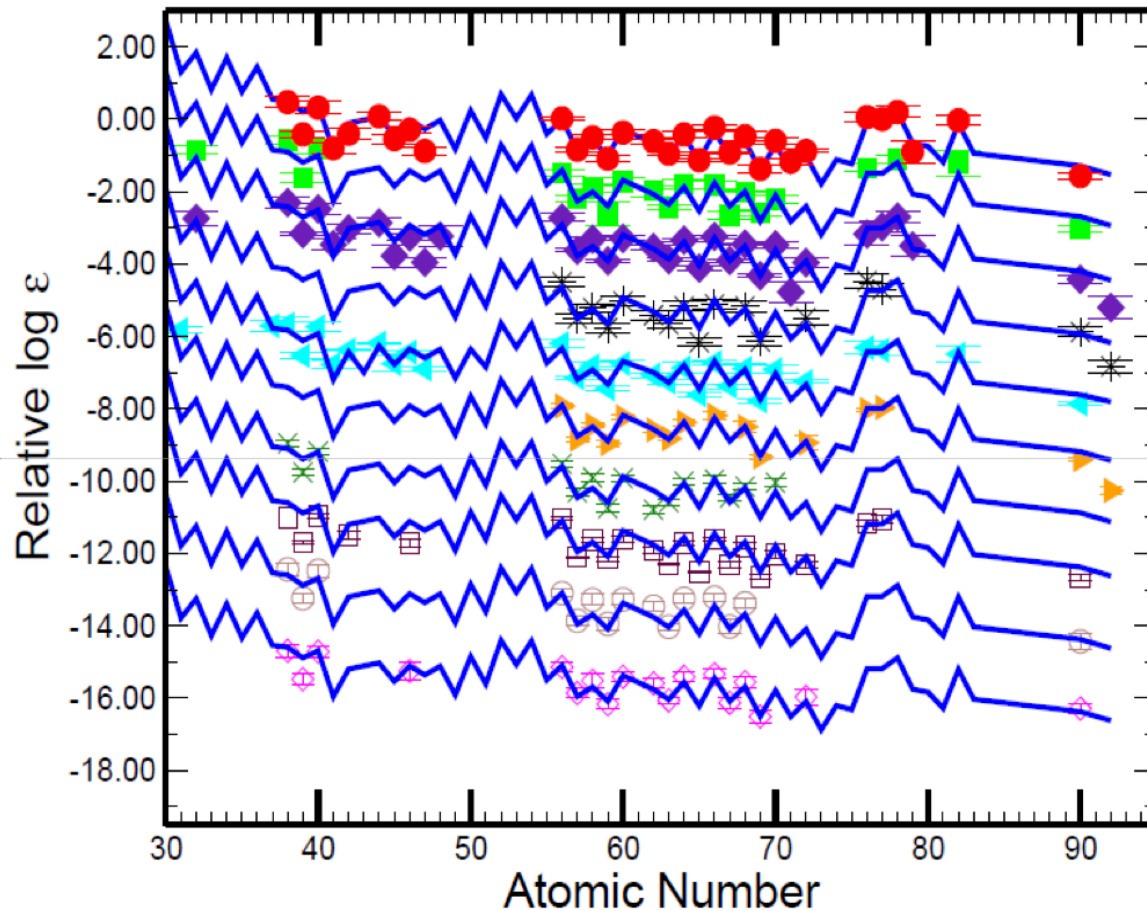
Normalizations

- Functional form of level density and strength function
- Three normalization points
 - Low-energy level density.
 - Level density at S_n .
 - Average radiative width at S_n .



- $\rho(S_n)$ from
 - Systematics
 - Microscopic calculations
- $\langle \Gamma_\gamma \rangle$ normalized from systematics

Open questions: Origin of elements Sr-Y-Zr



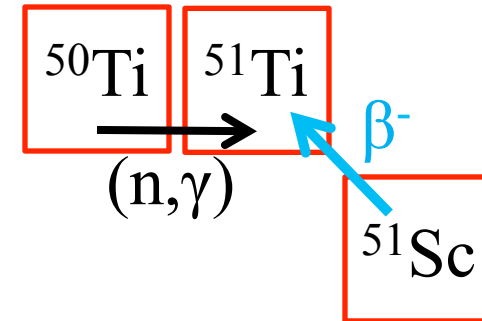
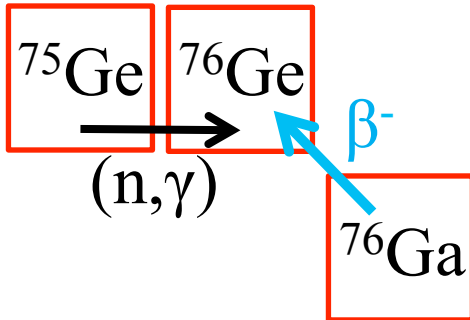
- Abundance pattern robust above Ba
- Variations in the Sr-Y-Zr mass region
- Alternative processes proposed
 - LEPP
 - weak r-process
 - vp-process

Cowan, et al, 2011

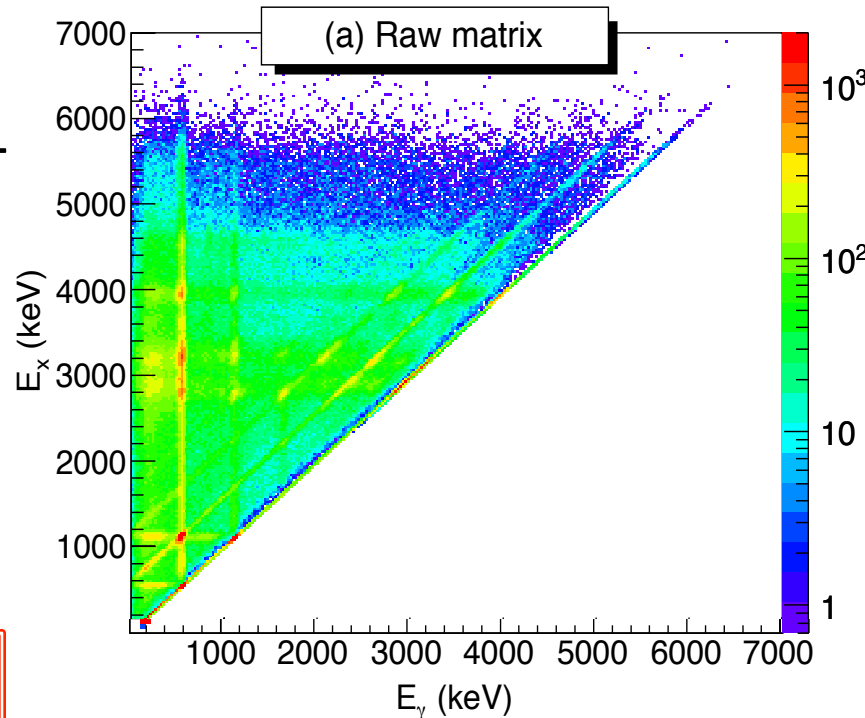
Validations: $^{75}\text{Ge}(n,\gamma)^{76}\text{Ge}$ and $^{50}\text{Ti}(n,\gamma)^{51}\text{Ti}$

^{76}Ga : $T_{1/2} = 32.6 \text{ s}$
 $Q_{\beta^-} = 7.0 \text{ MeV}$
 $S_n(^{76}\text{Ge}) = 9.4 \text{ MeV}$

^{51}Sc : $T_{1/2} = 12.4 \text{ s}$
 $Q_{\beta^-} = 6.5 \text{ MeV}$
 $S_n(^{51}\text{Ti}) = 6.7 \text{ MeV}$



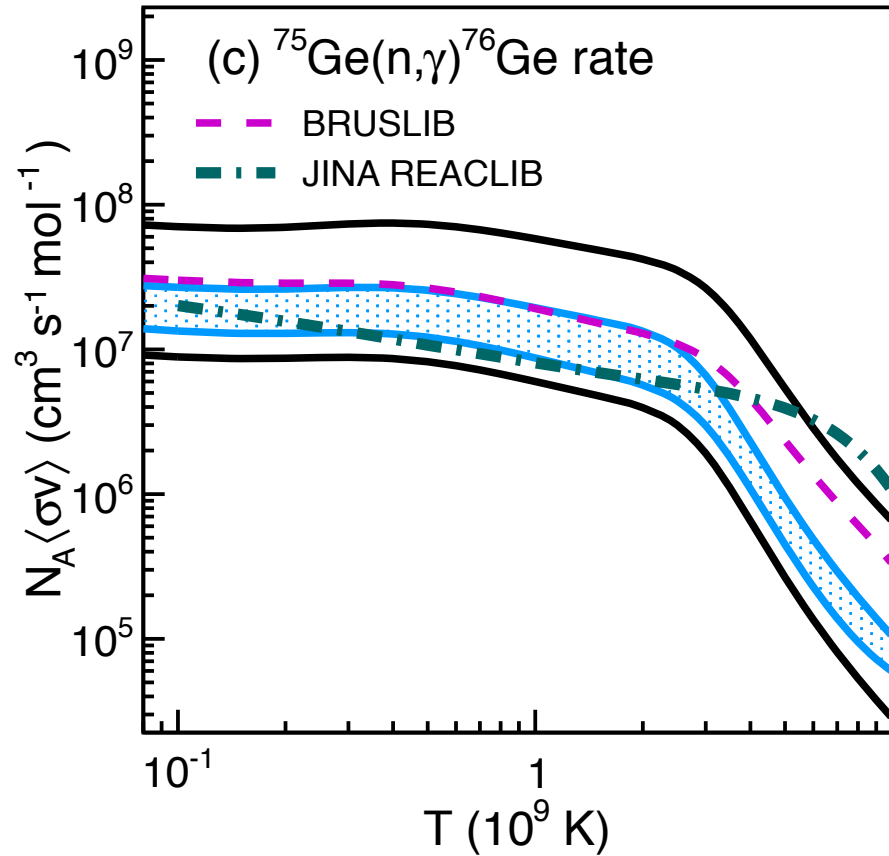
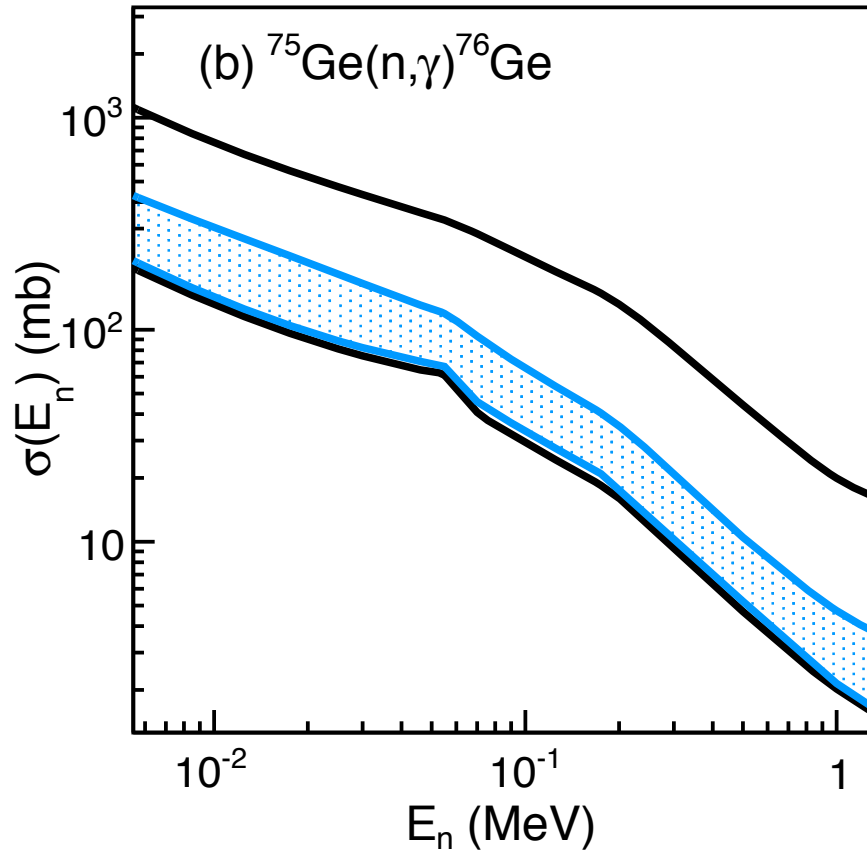
SuN – Total Absorption



SuN – Individual Segments

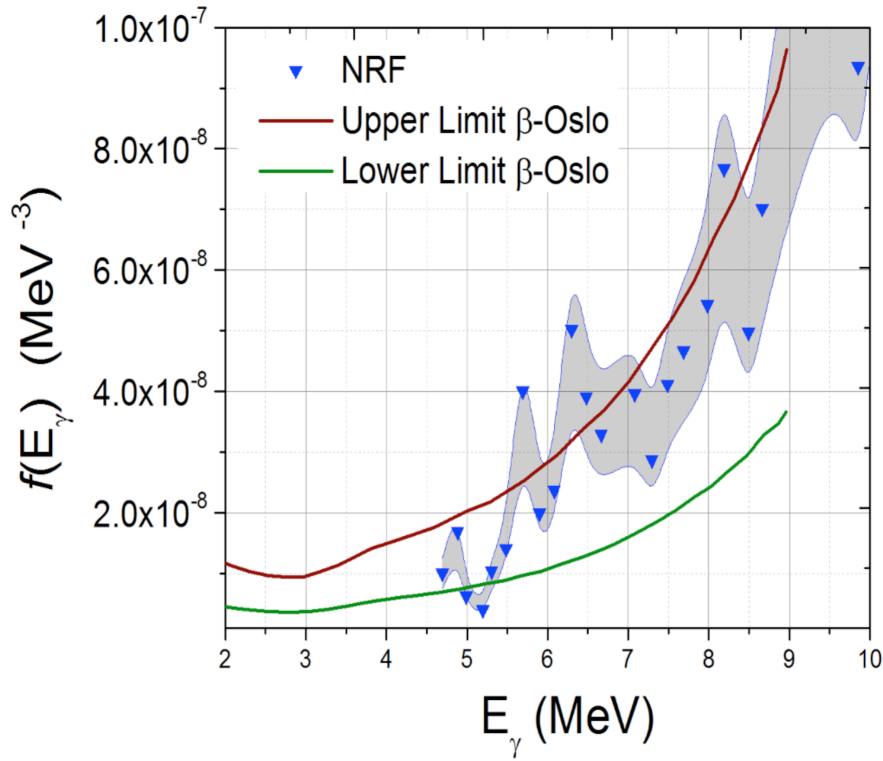
$$P(E_\gamma, E_x) \sim \rho(E_x - E_\gamma) \mathcal{T}(E_\gamma)$$

Results: $^{75}\text{Ge}(n,\gamma)^{76}\text{Ge}$

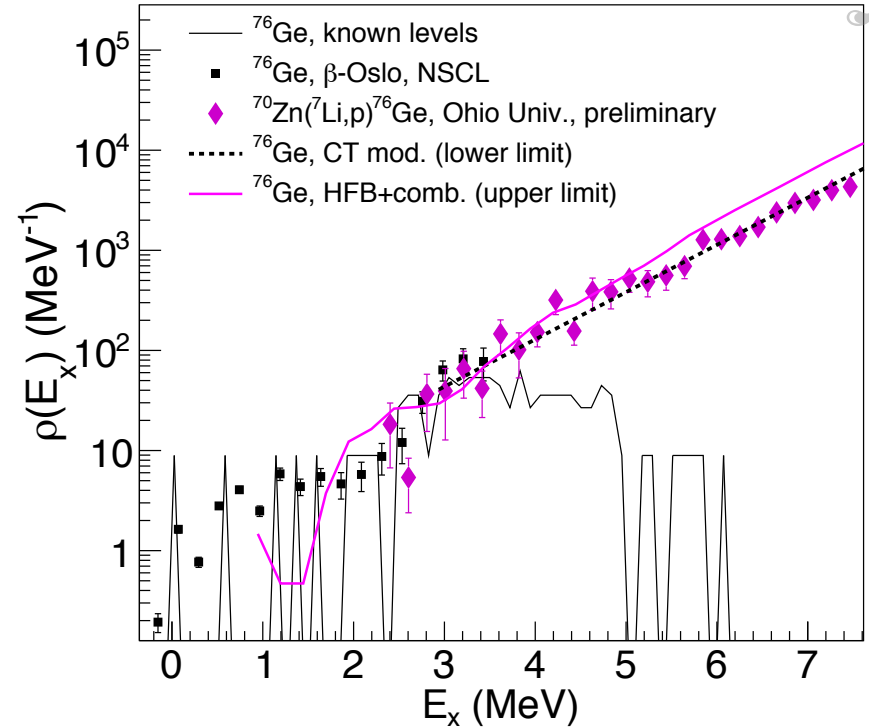


Validation – ^{76}Ge

Preliminary

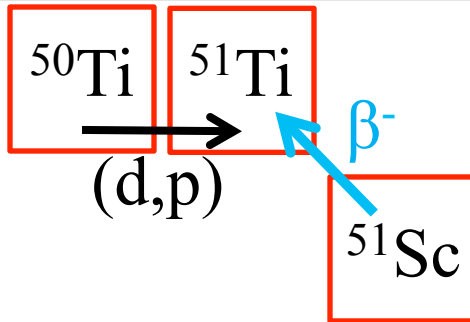


A. Tonchev, *et al.*
 Photoscattering experiment – HlyS
 Talk at Oslo workshop 2015

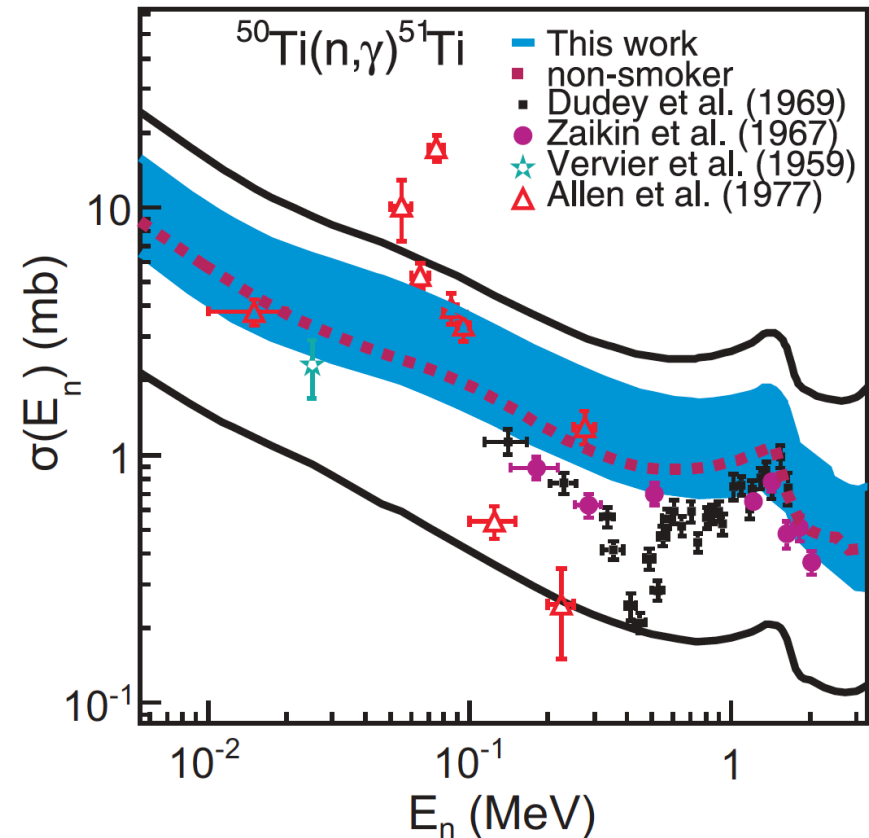
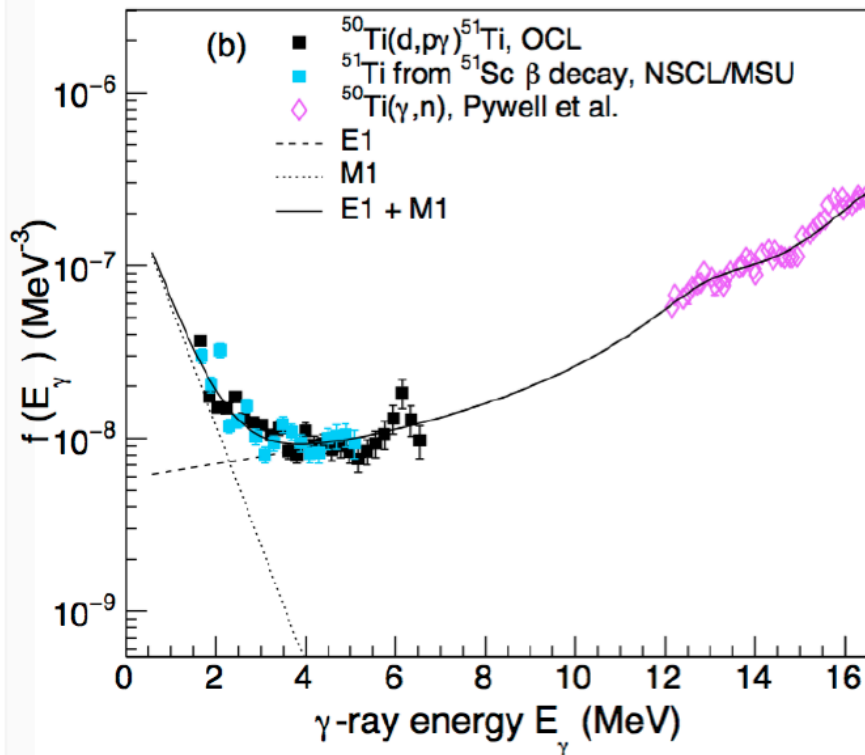


A. Voinov, T. Renstrom, A.-C. Larsen, *et al.*
 Preliminary Analysis - $^{70}\text{Zn}(^7\text{Li},p)^{76}\text{Ge}$ reaction
 Experiment at Ohio University

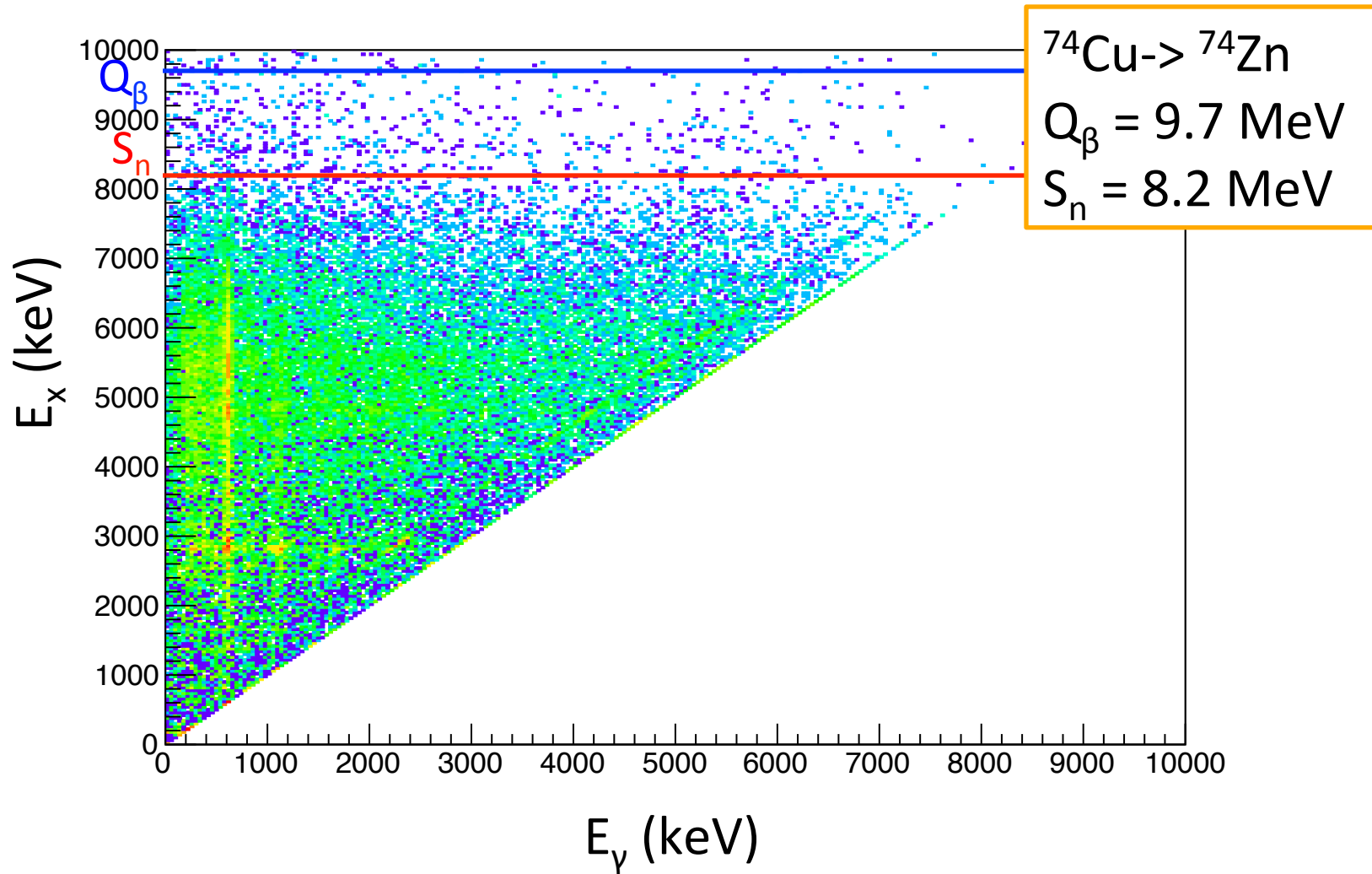
Validation – ^{51}Ti



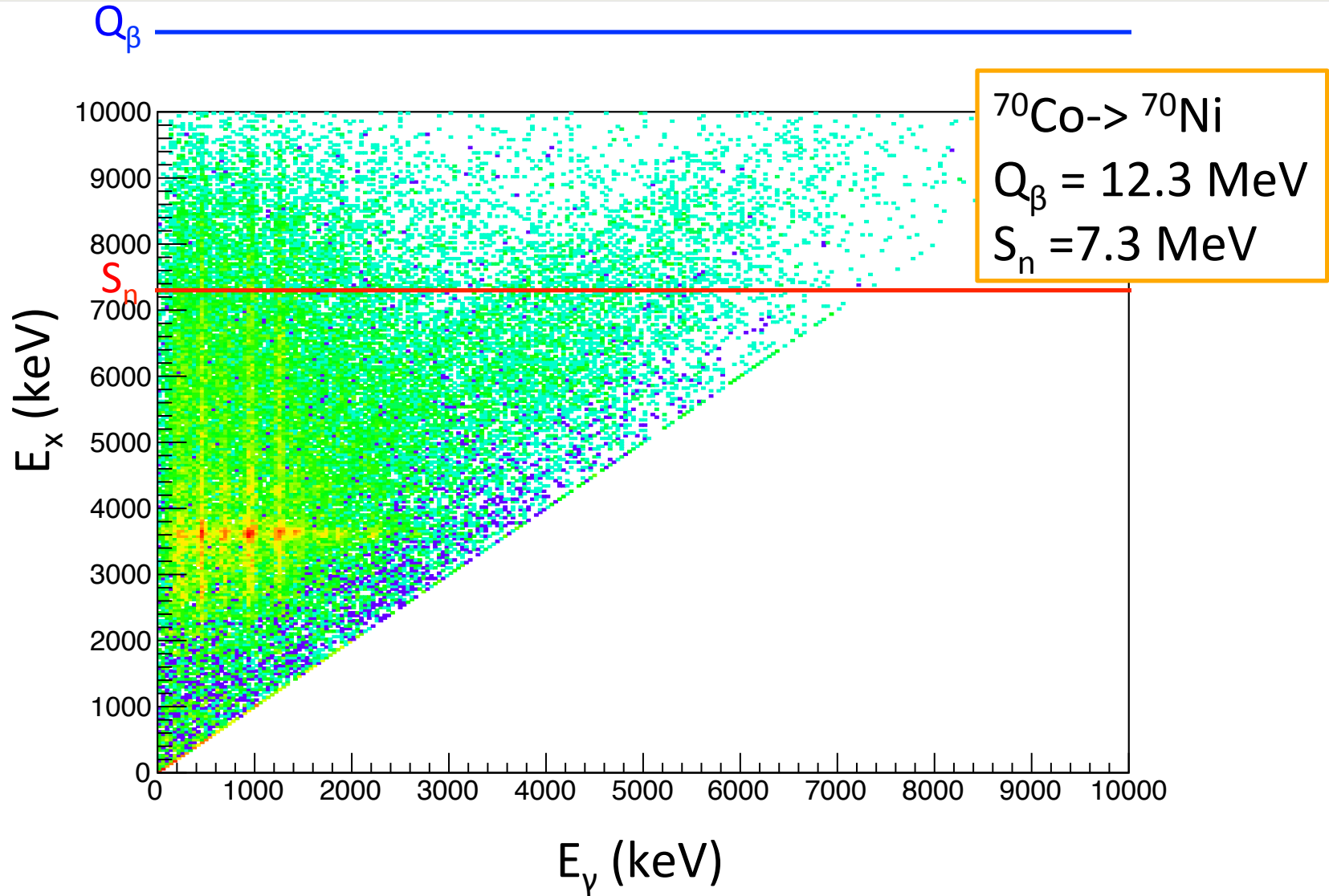
^{51}Sc : $T_{1/2} = 12.4 \text{ s}$
 $Q_{\beta^-} = 6.5 \text{ MeV}$
 $S_n(^{51}\text{Ti}) = 6.7 \text{ MeV}$



$^{74}\text{Cu} \rightarrow \beta$ -decay



^{70}Co β -decay



^{69}Co β -decay

