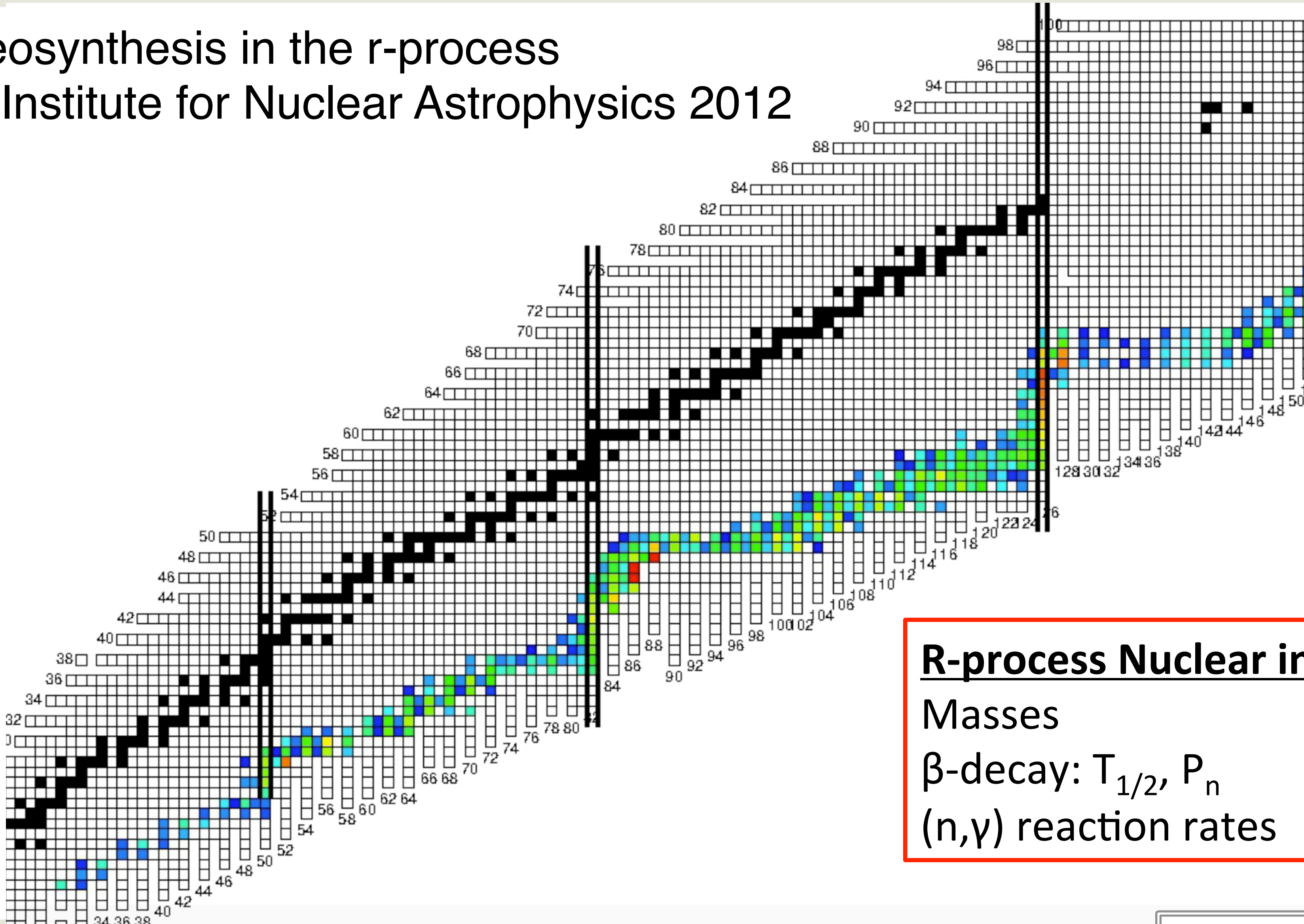
Neutron Capture rates for the astrophysical r-process

Artemis Spyrou

MICHIGAN STATE UNIVERSITY

r-process path and abundances

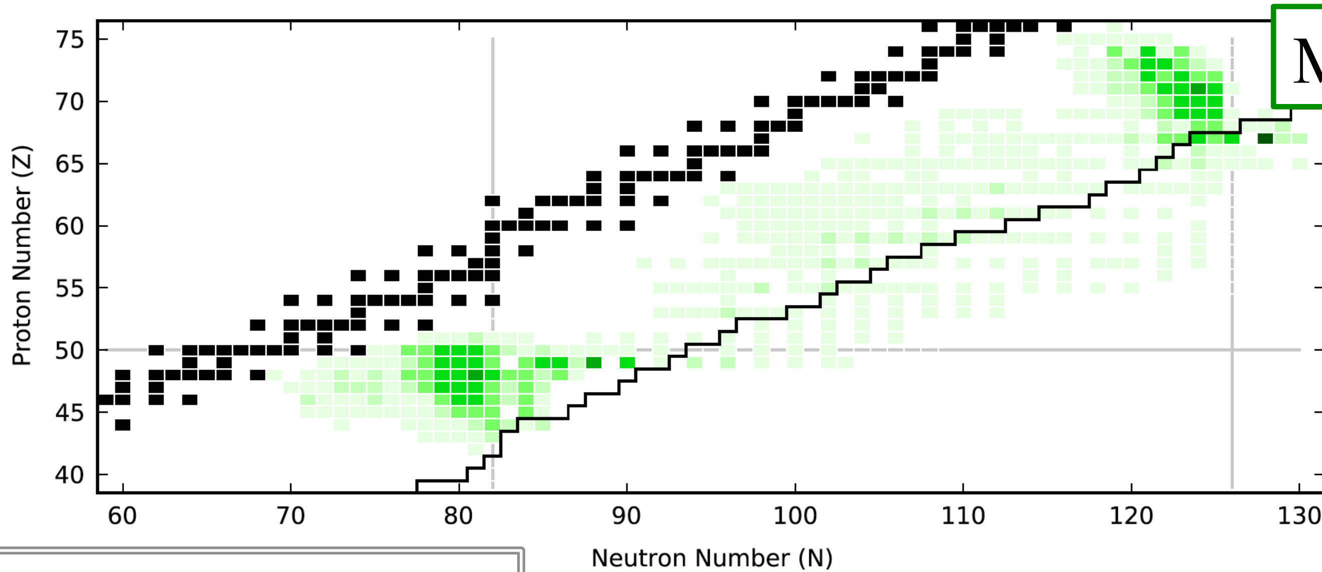
Nucleosynthesis in the r-process
Joint Institute for Nuclear Astrophysics 2012



<u>R-process Nuclear input</u>
Masses
β-decay: $T_{1/2}$, P_n
(n,γ) reaction rates

http://www.jinaweb.org

R-process sensitivity to neutron captures



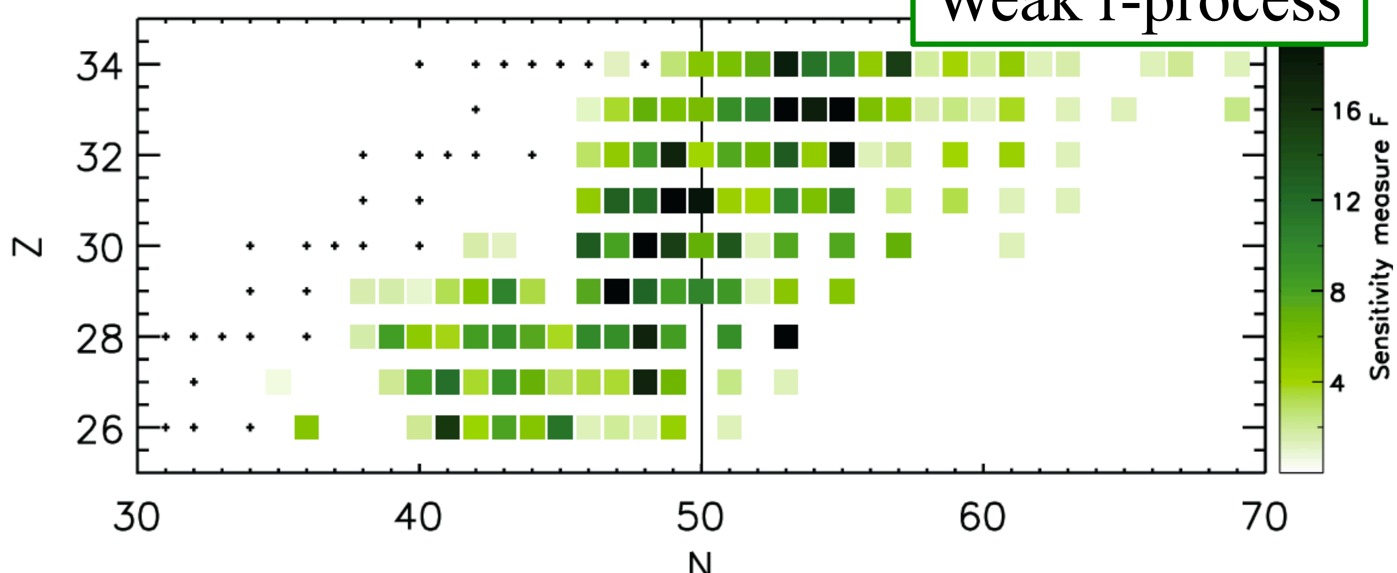
Main r-process

Neutron-star merger

Mumpower et. al., PPNP 86 (2016) 86

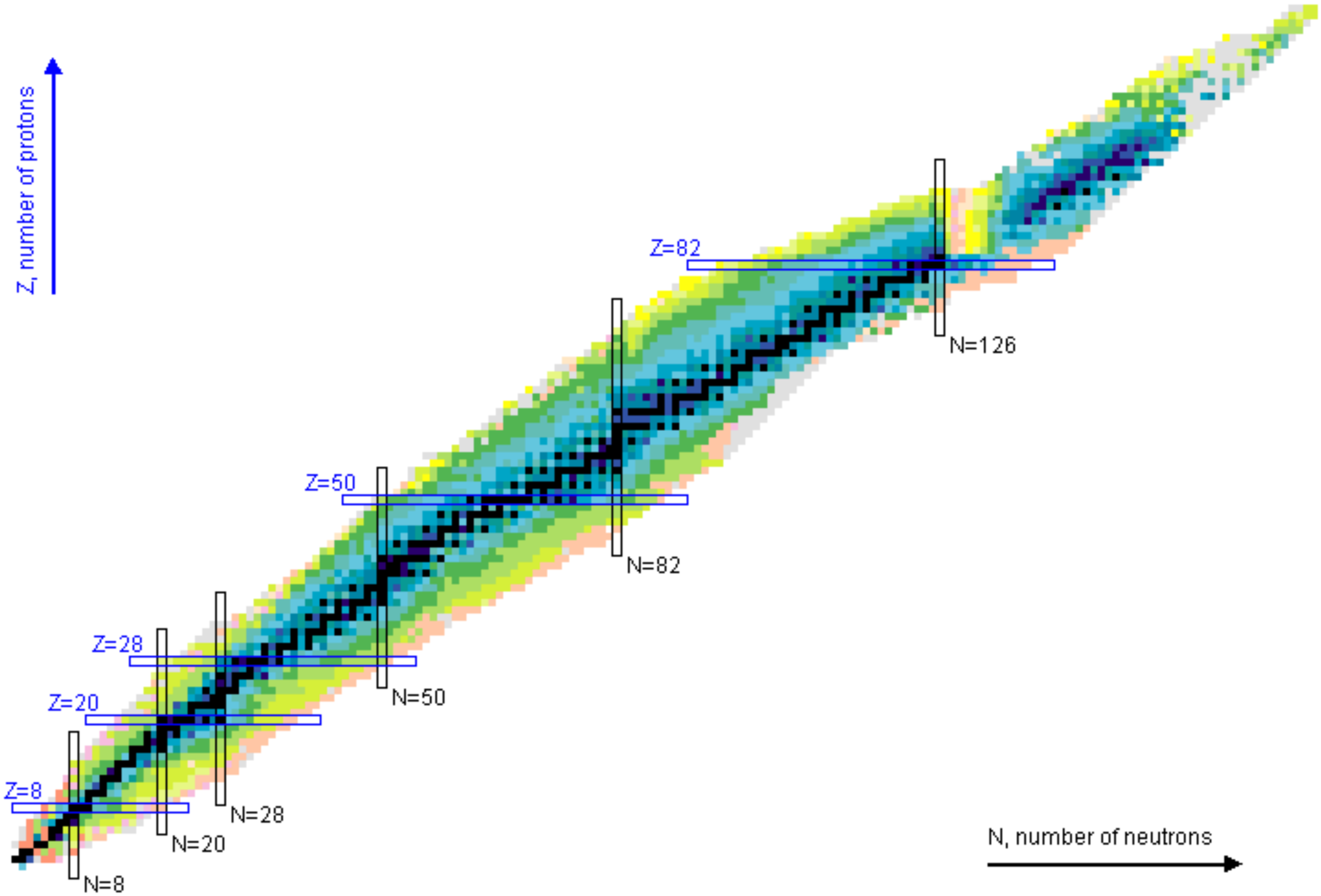
Supernova

Weak r-process

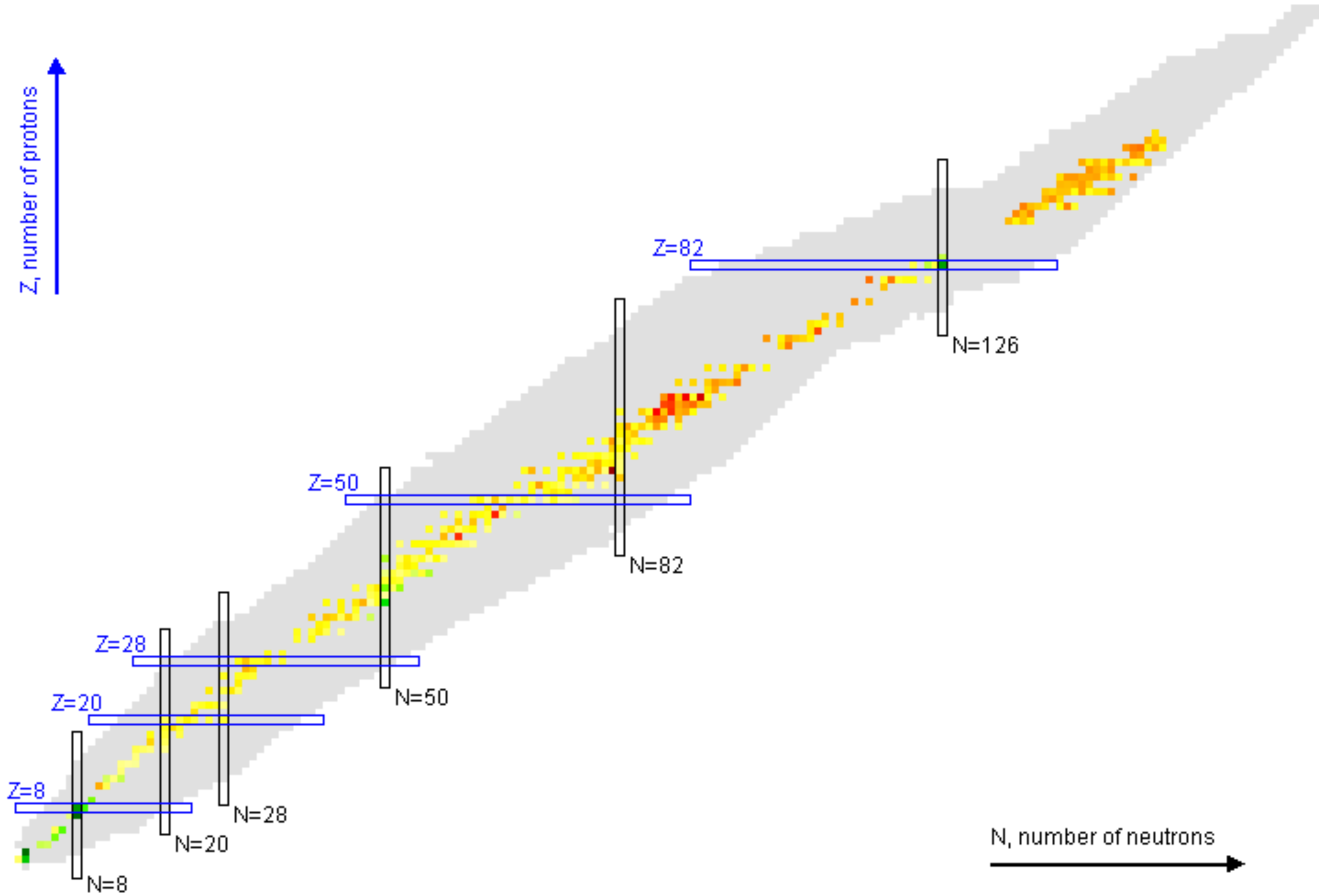


Surman, et al., , AIP Advances 4, 041008 (2014)

Current (n,γ) measurements

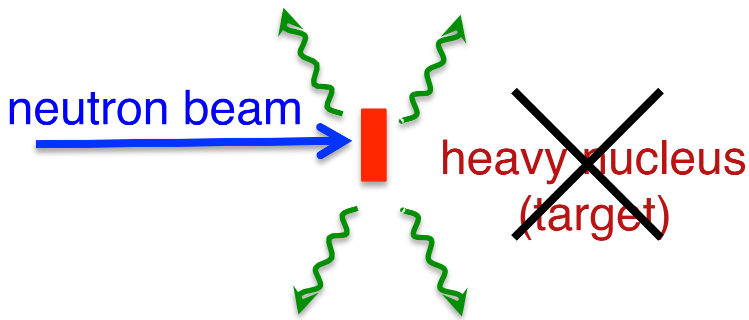


Current (n,γ) measurements



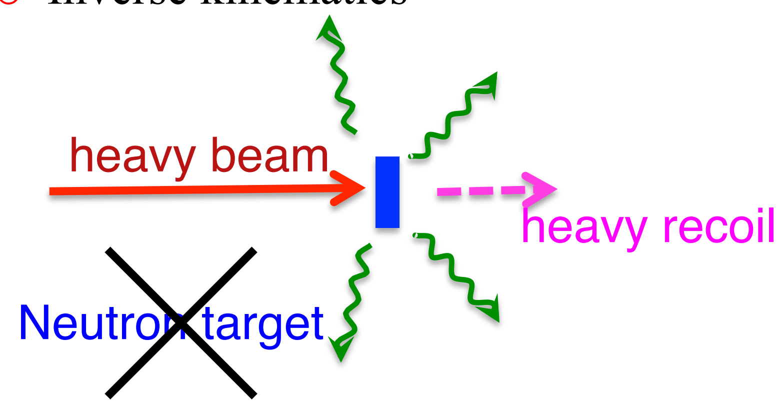
The trouble with Neutron Capture Reactions

- Regular kinematics

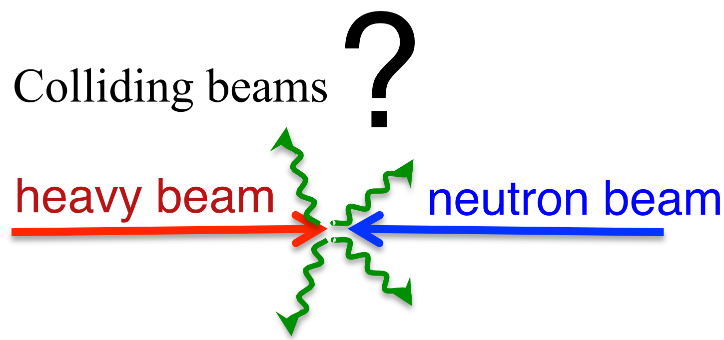


- Measuring Neutron Capture reactions on short-lived nuclei is at best challenging
- **Need indirect techniques**

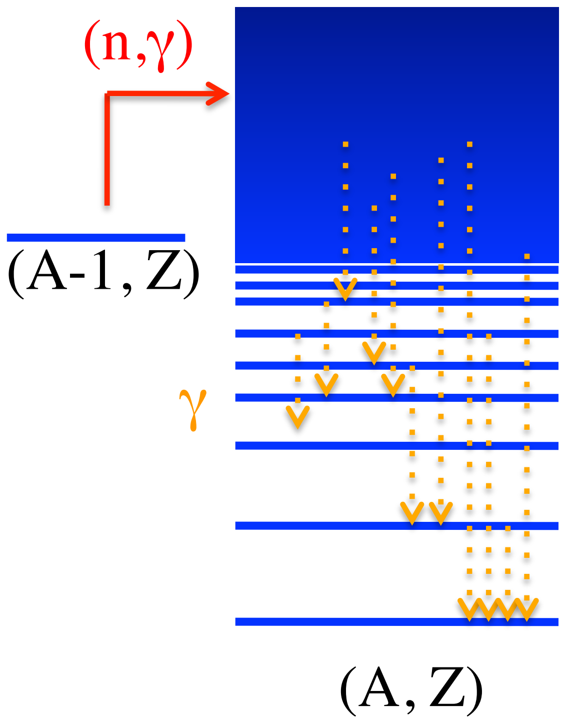
- Inverse kinematics



- Colliding beams



Neutron Capture – Uncertainties



Hauser – Feshbach

- Nuclear Level Density (NLD)
- γ-ray strength function (γSF)

} Dominate uncertainties

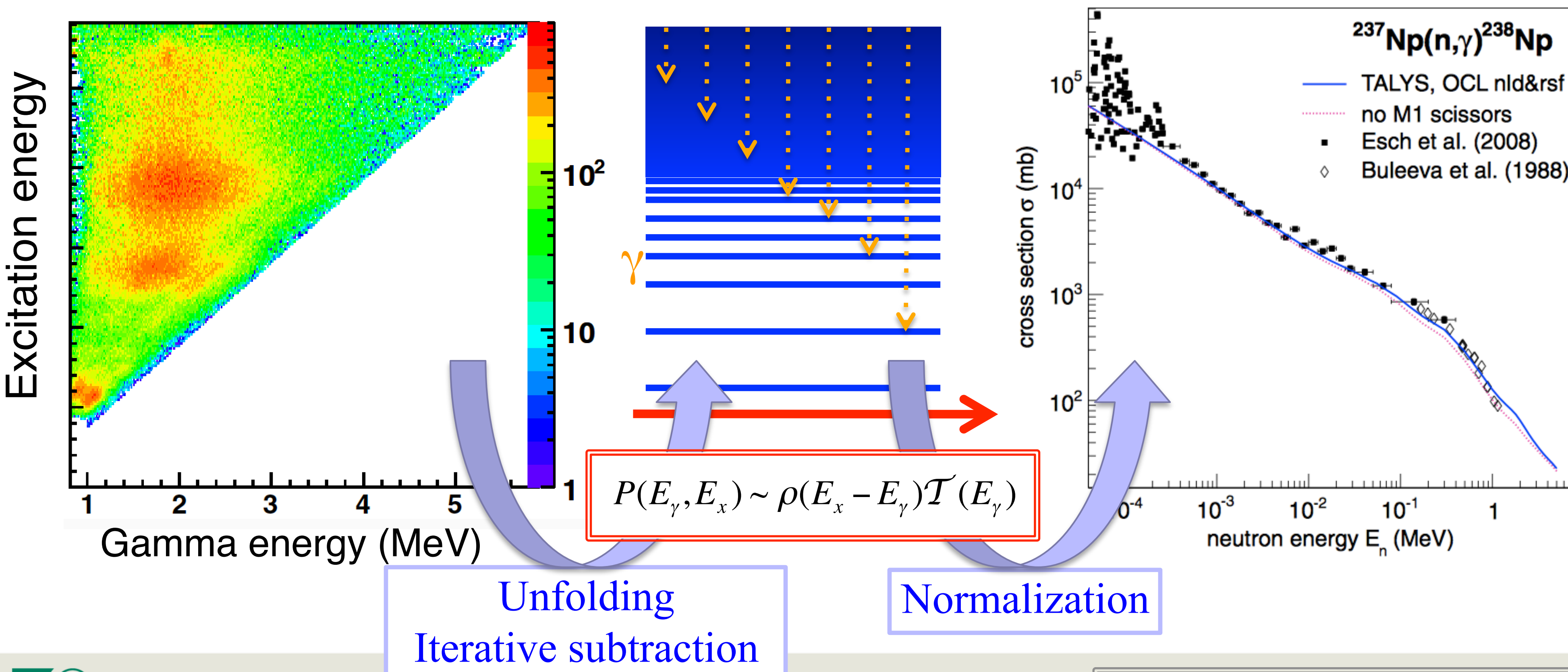
- Optical model potential → Large uncertainties further from stability

β-Oslo method:
Combine traditional **Oslo Method** with **Total Absorption Spectroscopy**

Goriely – Delaroche, PLB 653 (2007) 178

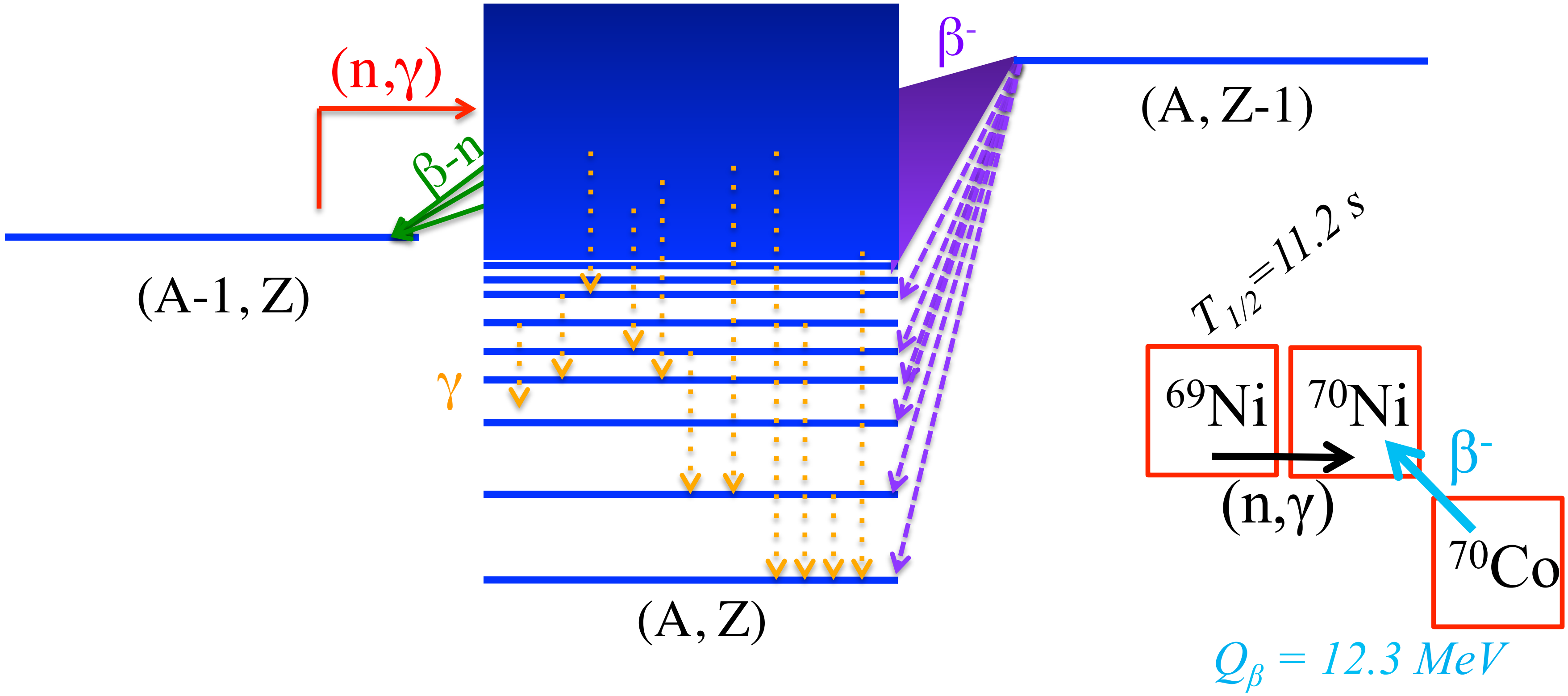
Traditional Oslo method

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



T.G. Tornyi, M. Guttormsen,et al., PRC2014

β-Oslo



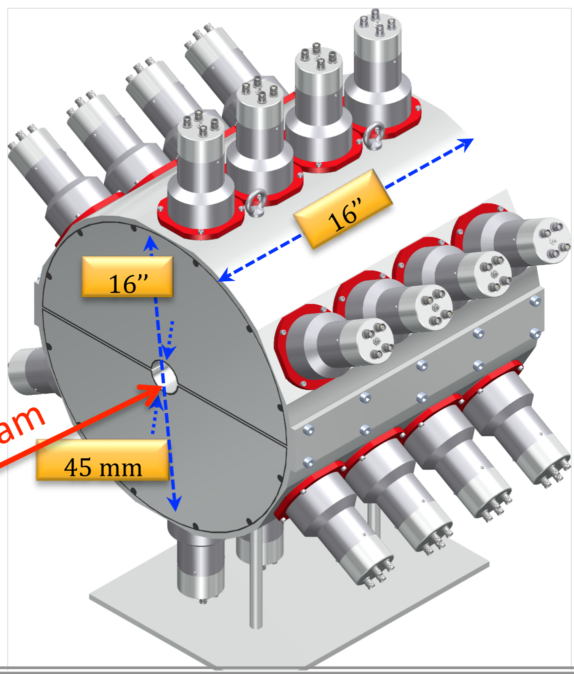
- Populate the compound nucleus via β-decay (large Q-value far from stability)
- Spin selectivity – correct for it
- Extract level density and γ-ray strength function
- Advantage: Can reach (n,γ) reactions with beam intensity down to 1 pps.

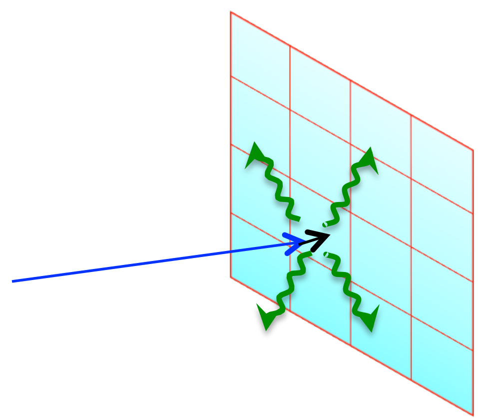
Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

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

NSCL SuN





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

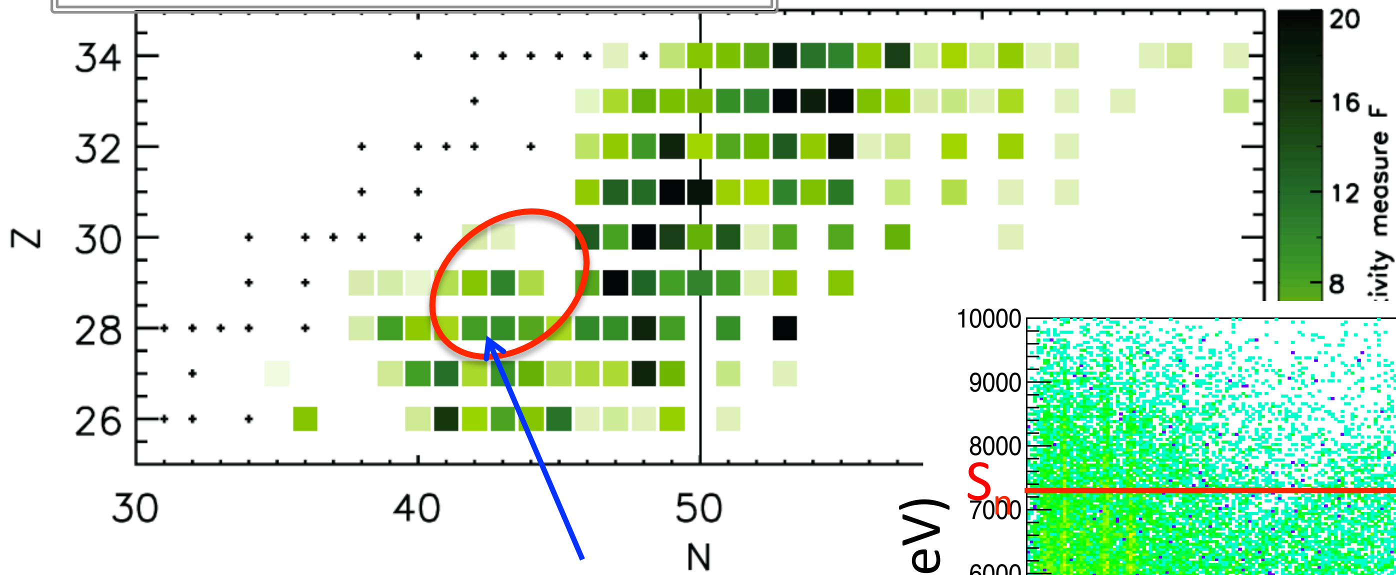
A. Simon, S.J. Quinn, A.S., et al., Nucl. Instr. Meth A 703, 16 (2013)

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

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

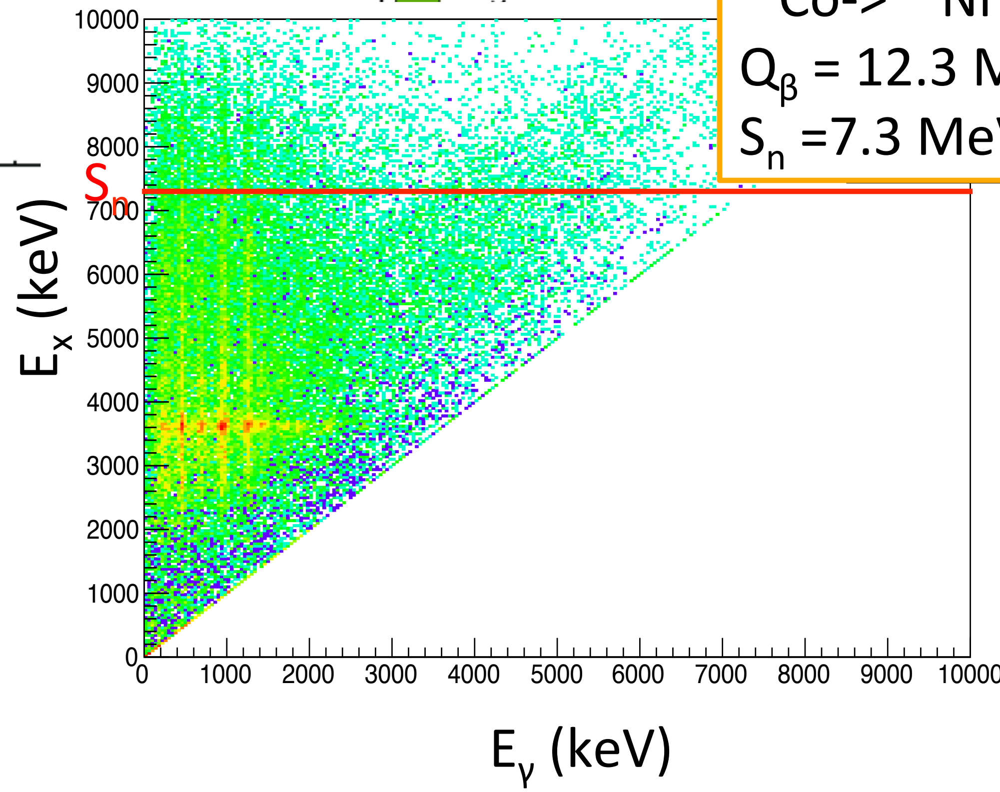
Weak r-process measurements

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



^{69,70}Co β decay: ^{68,69}Ni(n,γ)^{69,70}Ni

^{74}Cu β decay: ^{73}Zn(n,γ)^{74}Zn



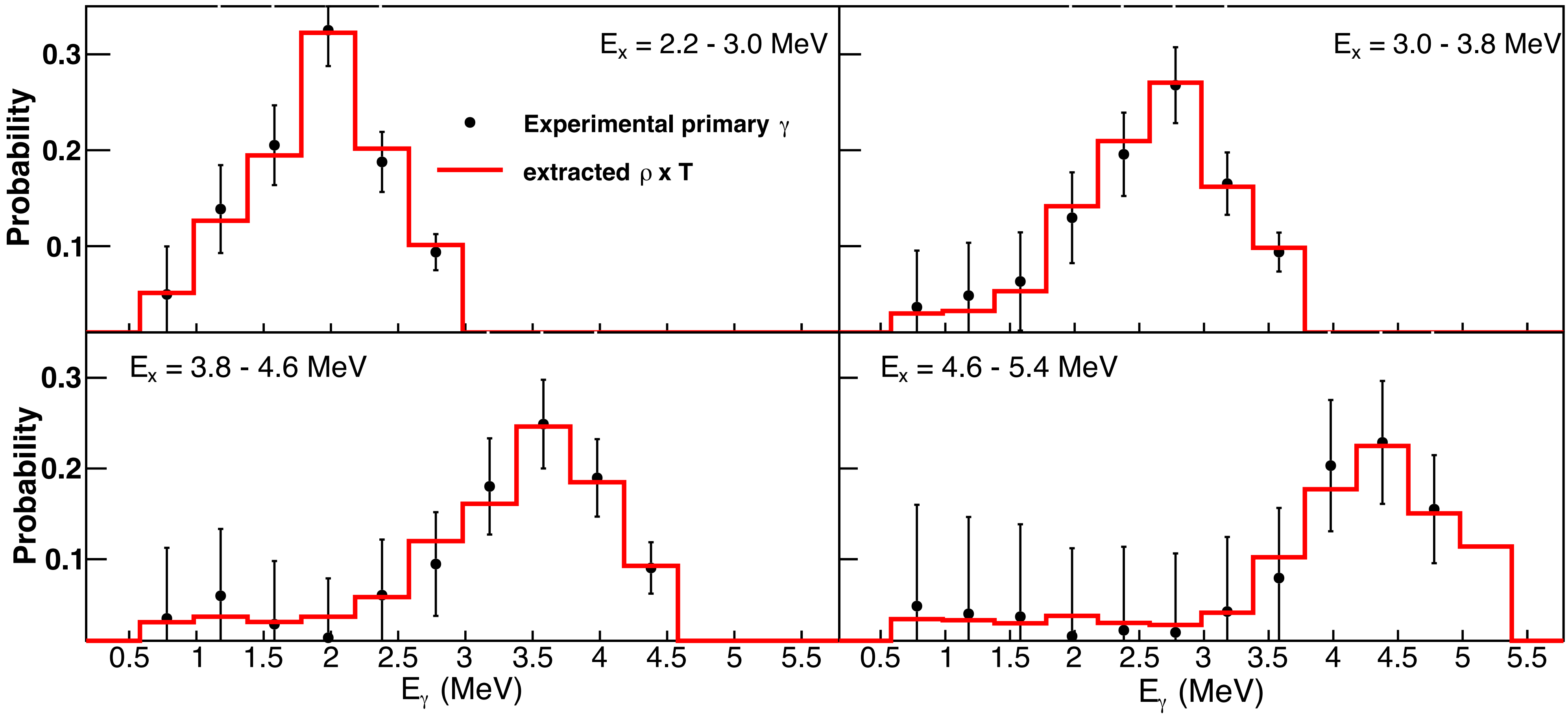
^{70}Co-> ^{70}Ni

Q_β = 12.3 MeV

S_n =7.3 MeV

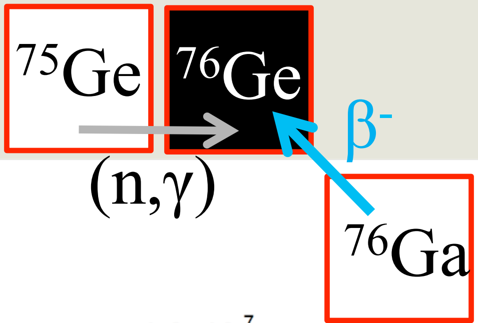
Does it work?

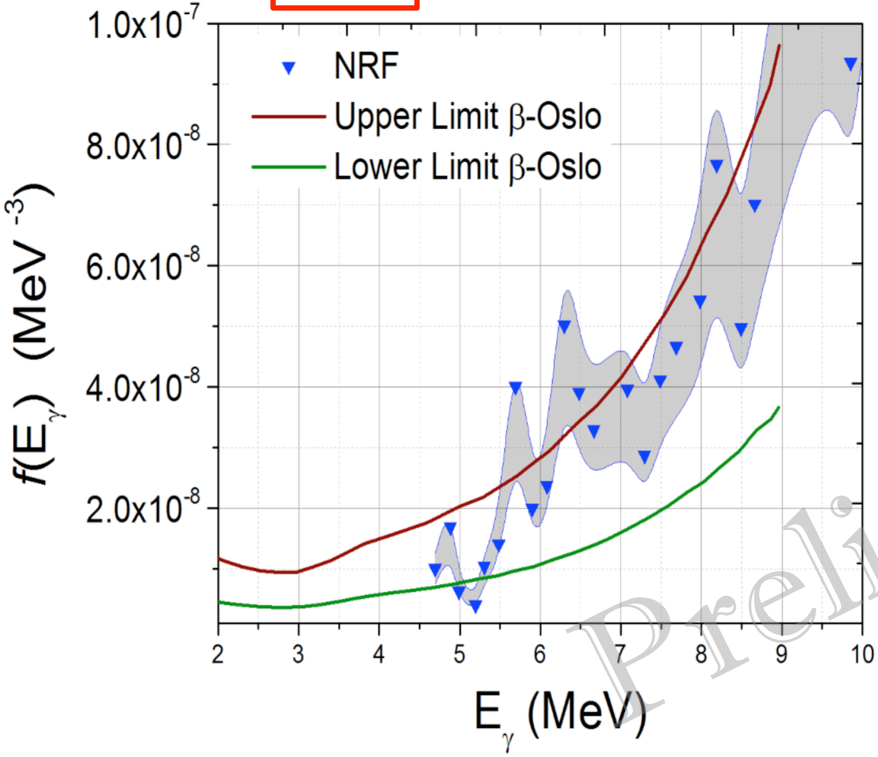
^{69}Co β decay -> ^{69}Ni

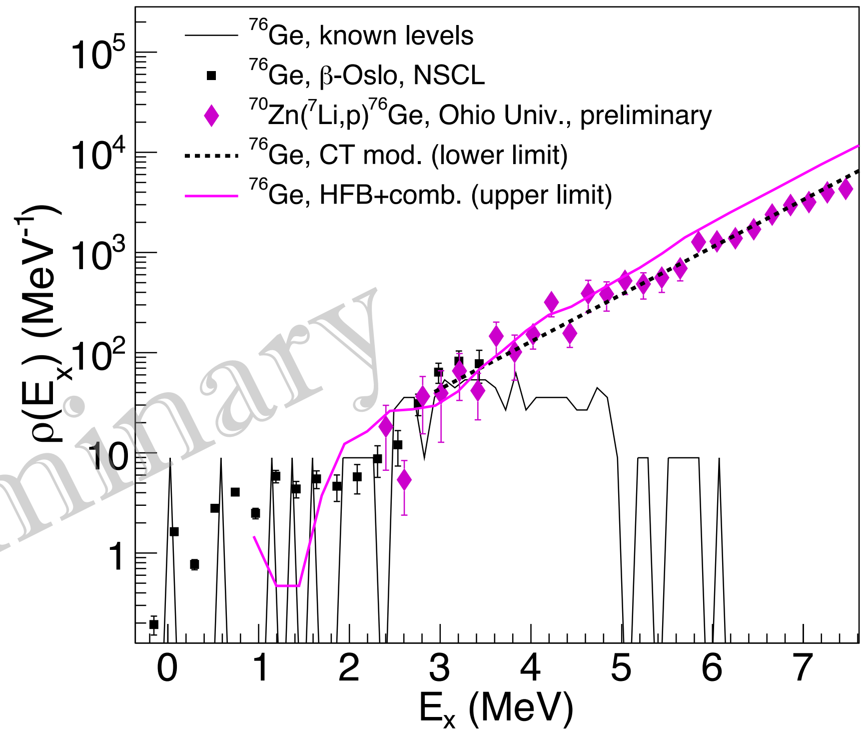


- Compare data (black points) to extracted ρ x T (red line)
- Excellent agreement

Validation – ^{76}Ge





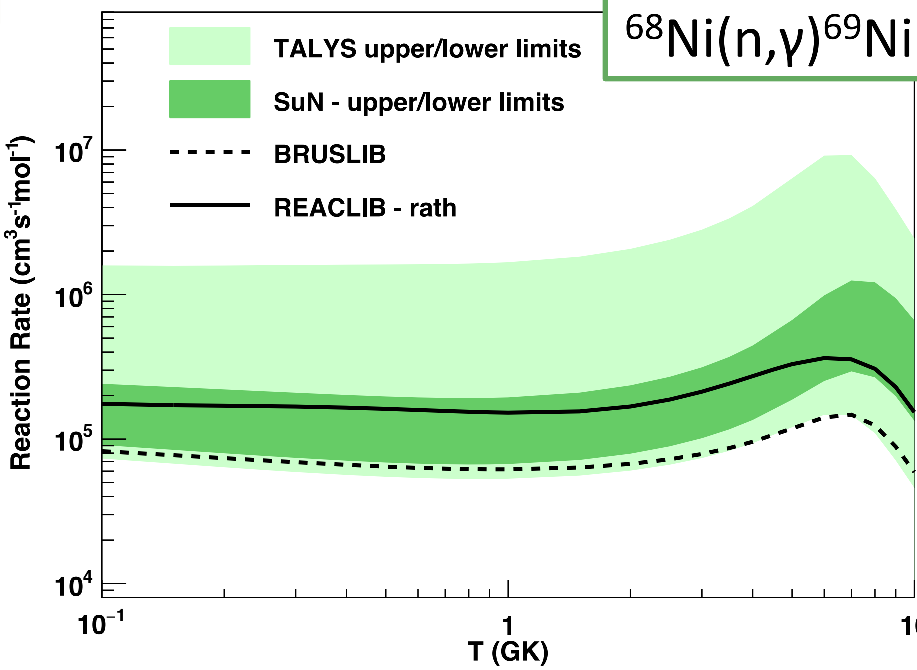


A. Tonchev, *et al.*
Photoscattering exeriment – HIγS
Talk at Oslo workshop 2015

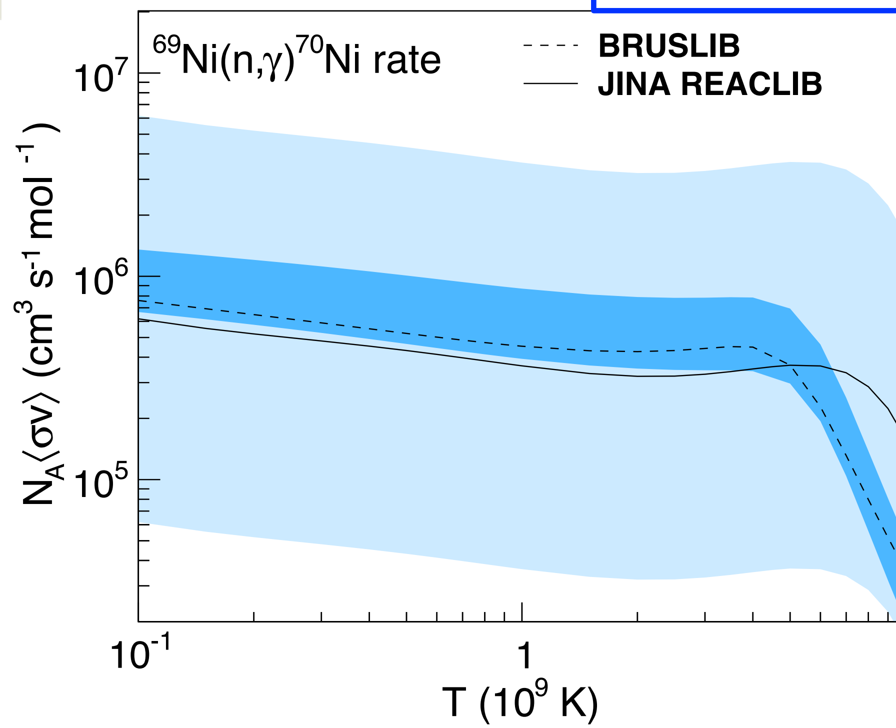
A. Voinov, T. Renstrom, A.-C. Larsen, *et al.*
Preliminary Analysis - *^{70}Zn(^{7}Li,p)^{76}Ge reaction*
Experiment at Ohio University

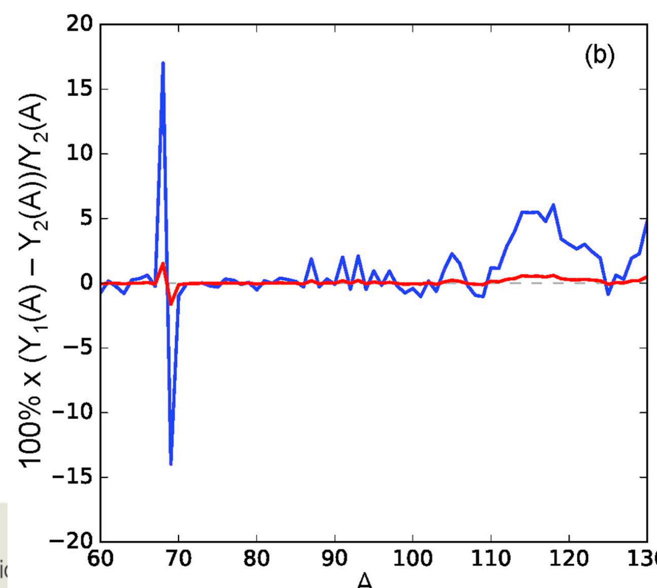
First Results $^{68,69}Ni(n,\gamma)^{69,70}Ni$

$^{68}Ni(n,\gamma)^{69}Ni$



$^{69}Ni(n,\gamma)^{70}Ni$





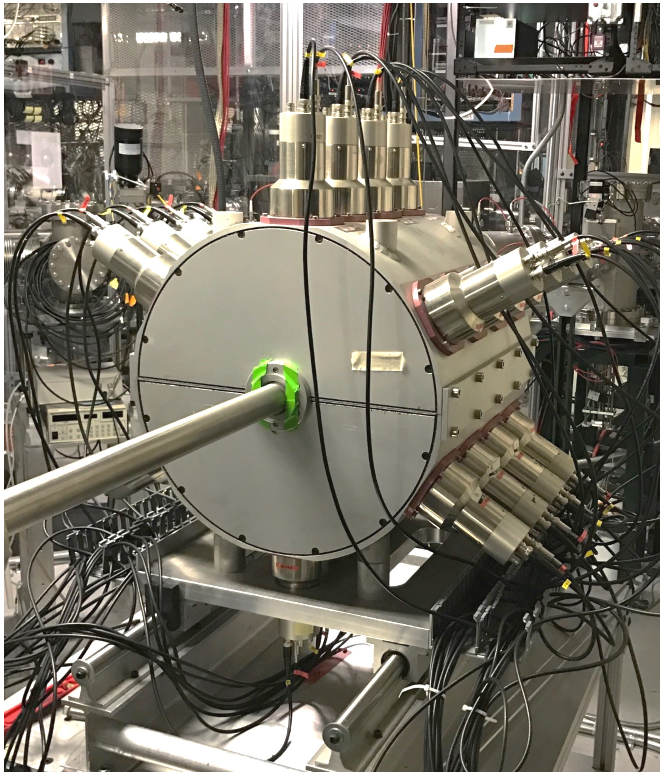
Impact on weak r-process abundance calculations

Liddick, Spyrou, et al, PRL 2016

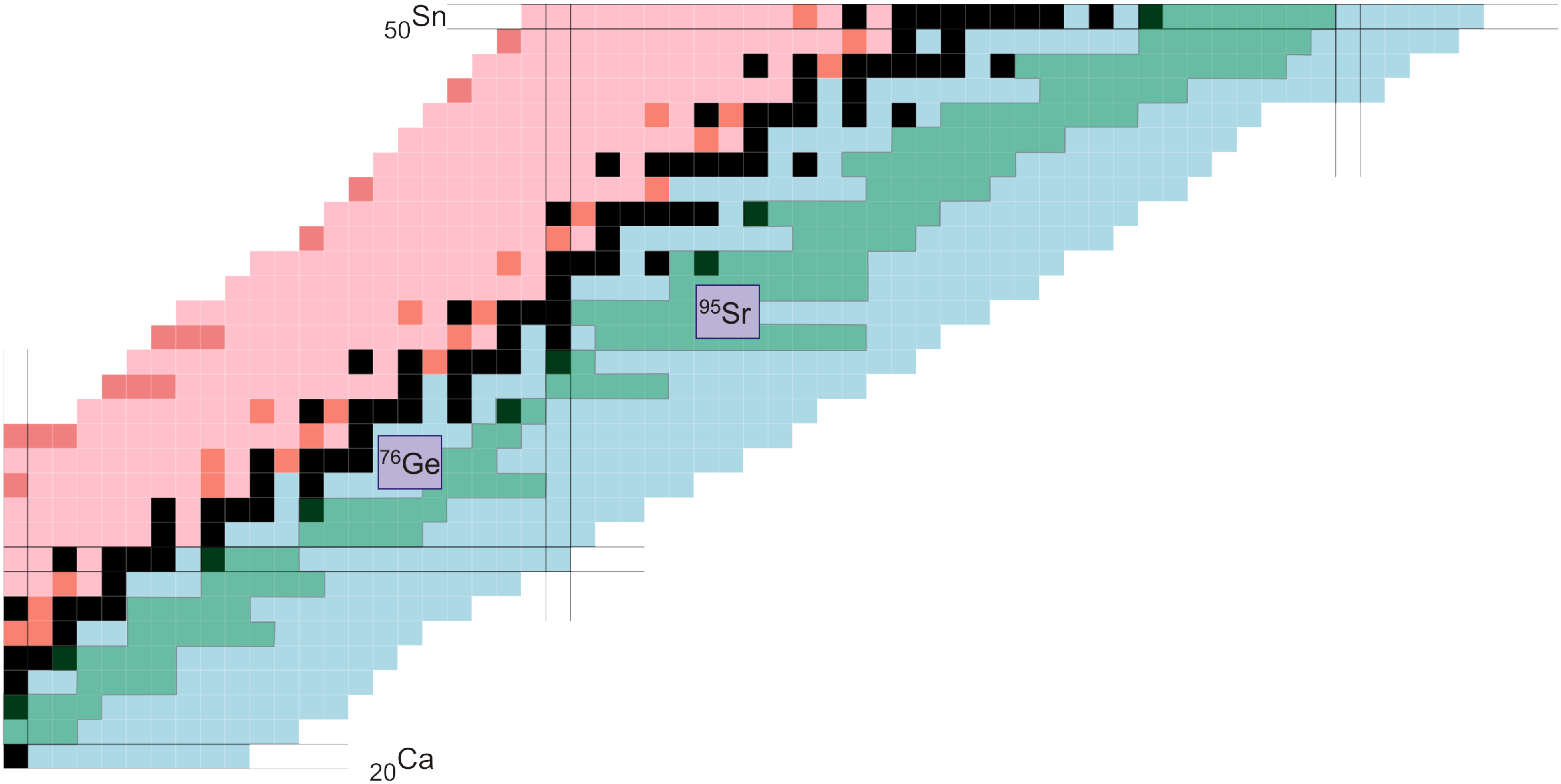
Spyrou, Larsen, et al, JPG 2017

Summary

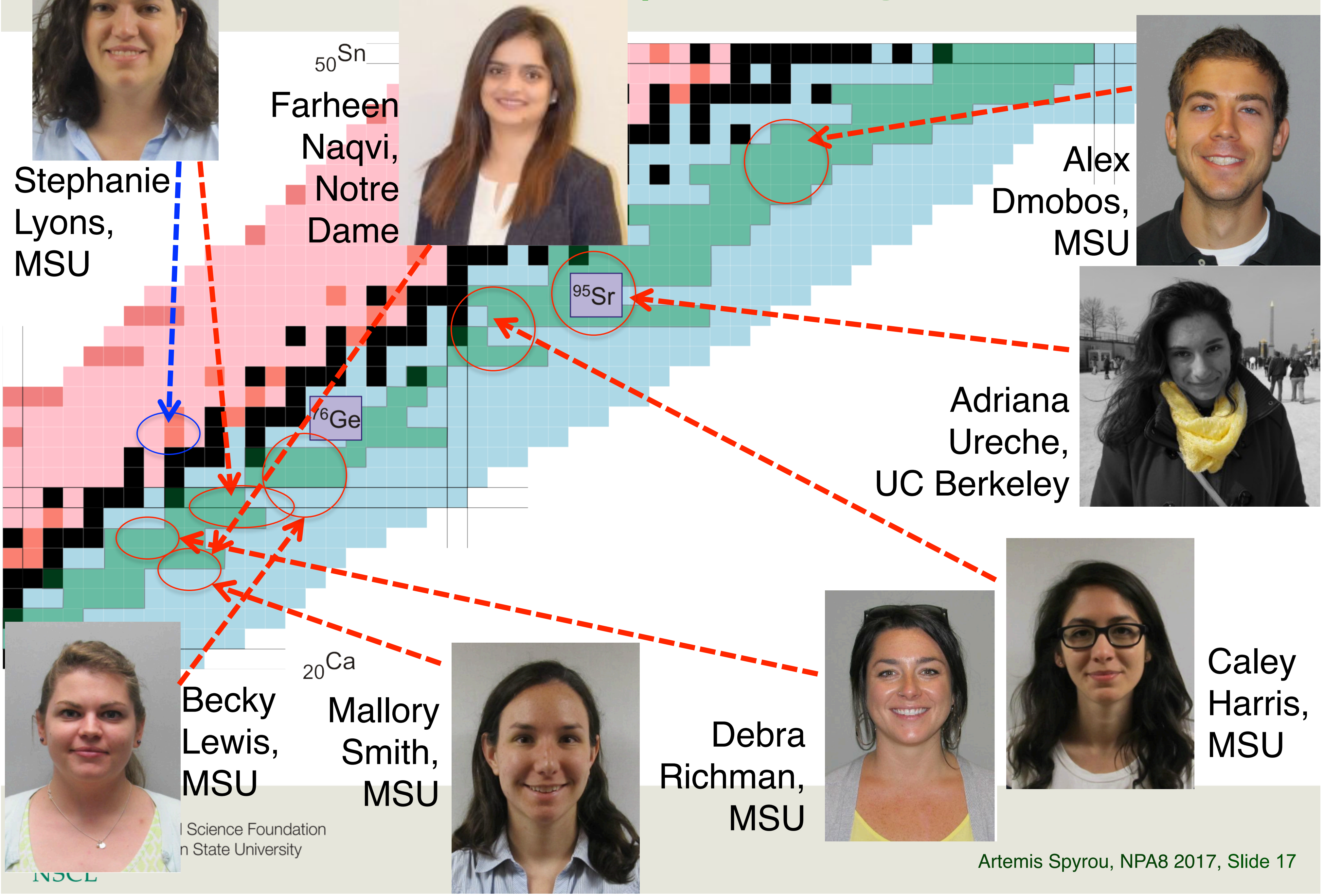
- Many astrophysical reactions cannot be measured directly
- Indirect techniques provide information where nothing is known
- β-Oslo: new technique for constraining (n,γ) reactions far from stability
- β decay can be used with very low beam intensities
- **Future**: Apply to more cases along the r-process path, learn from systematics



The future of β-Oslo @ MSU



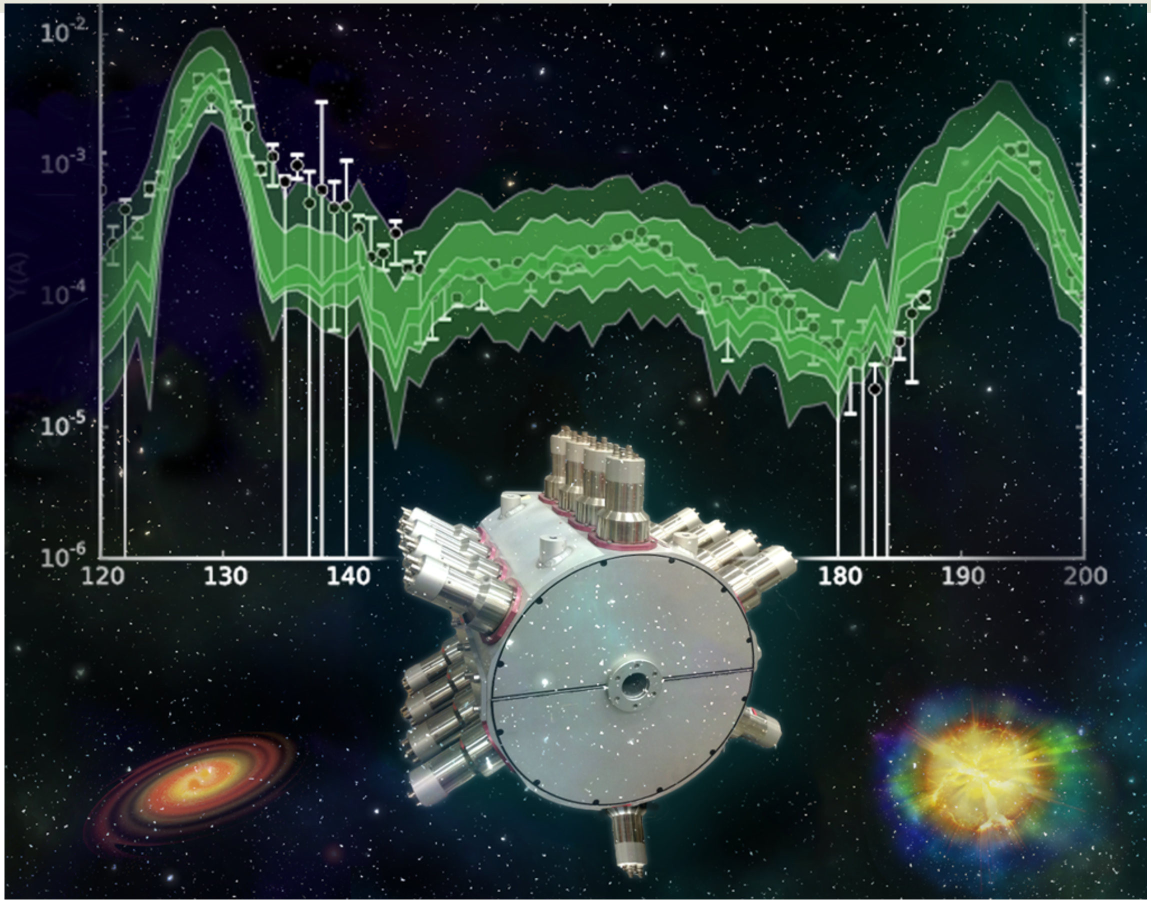
The future of β-Oslo @ MSU



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

Los Alamos NATIONAL LABORATORY EST.1943

A. Couture
S. Mosby
M. Mumpower

G. Perdikakis
S. Nikas

R. Surman
A. Simon

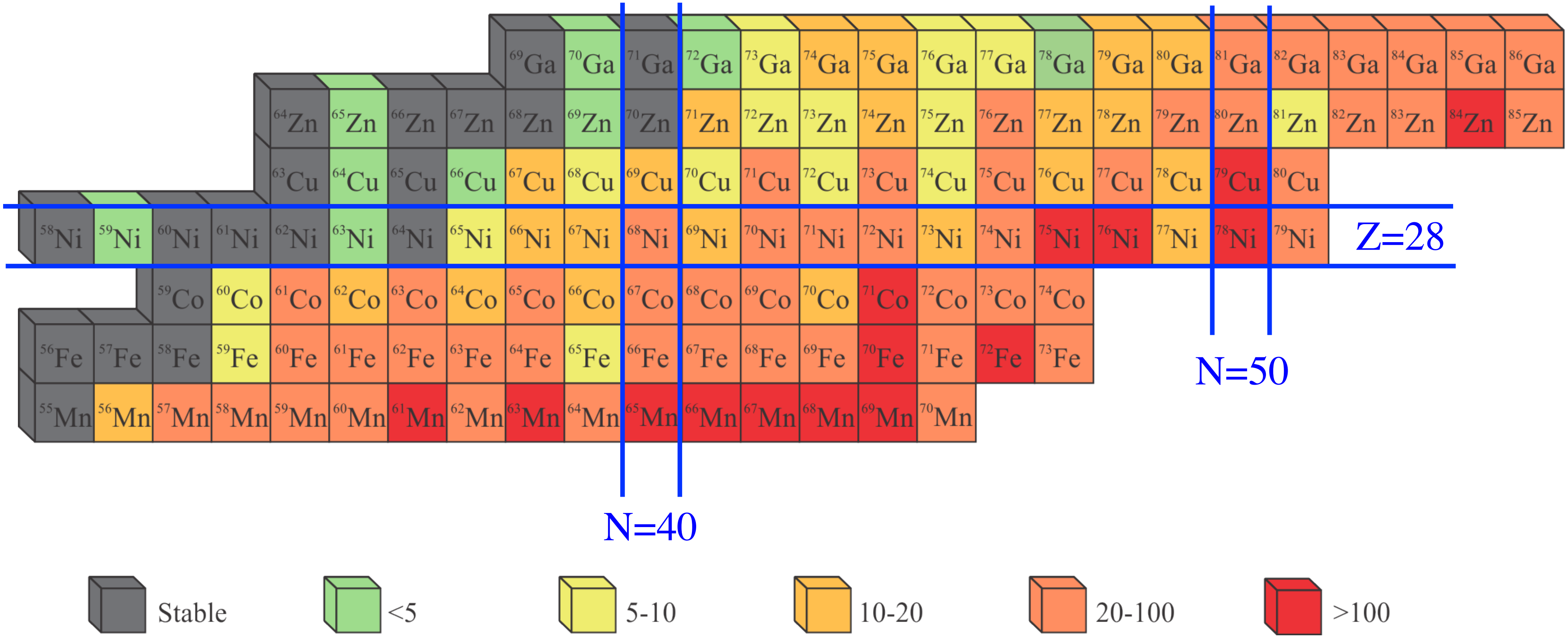
VNIVERSITAT DE VALÈNCIA

B. Rubio

Lawrence Livermore National Laboratory

D. L. Bleuel

Neutron capture reactions



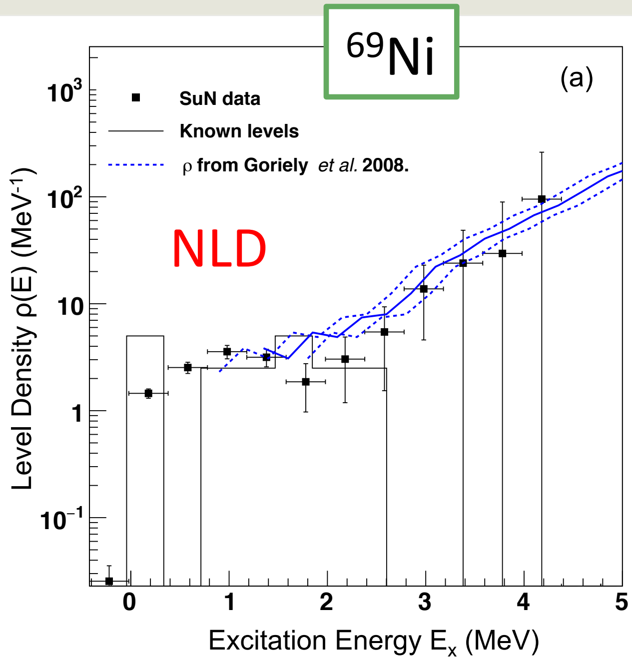
- Variation of theoretical predictions using TALYS, changing NLD and γSF
- Predictions diverge moving away from stability

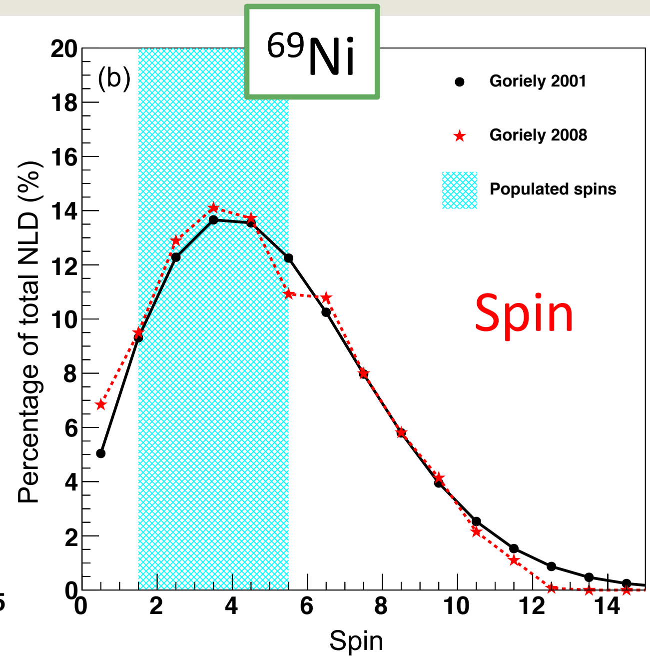
Calculations by G. Perdikakis, S. Nikas
Central Michigan University

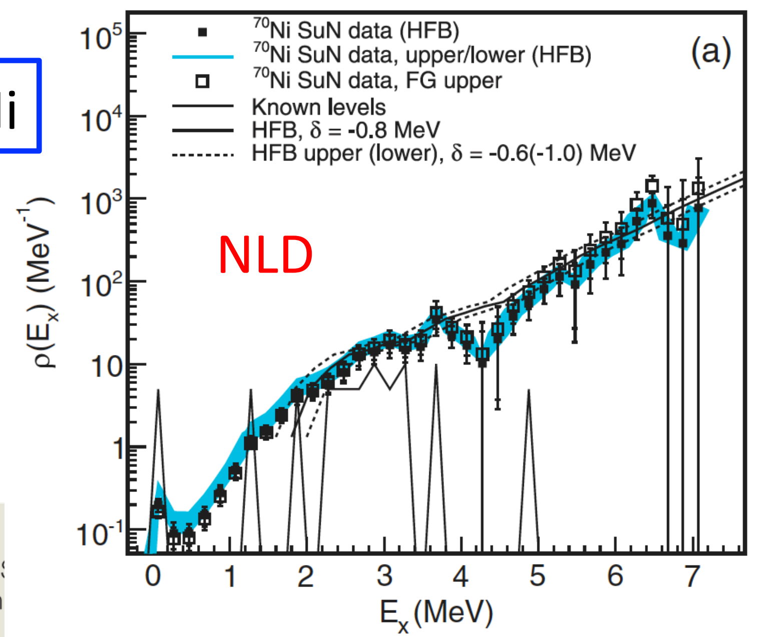
Liddick, Spyrou, et al., PRL 2016

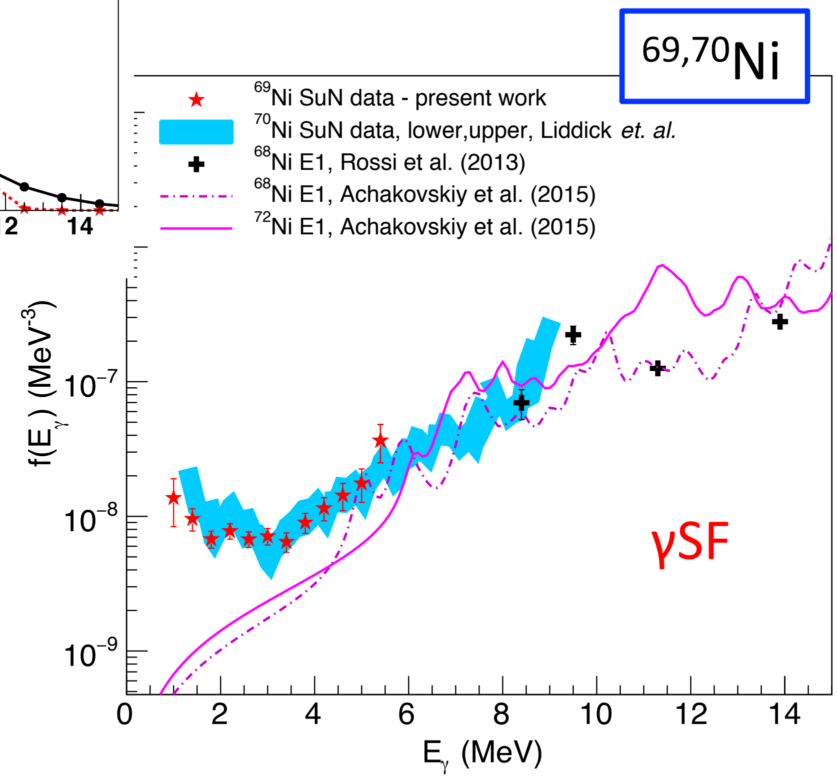
First Results ^{69,70}Ni

Normalizations far from stability:
- Use systematics
- Some model dependence
- Power: simultaneous extraction of NLD and γSF









Liddick, Spyrou, et al, PRL 2016

Spyrou, Larsen, et al, JPG 2017