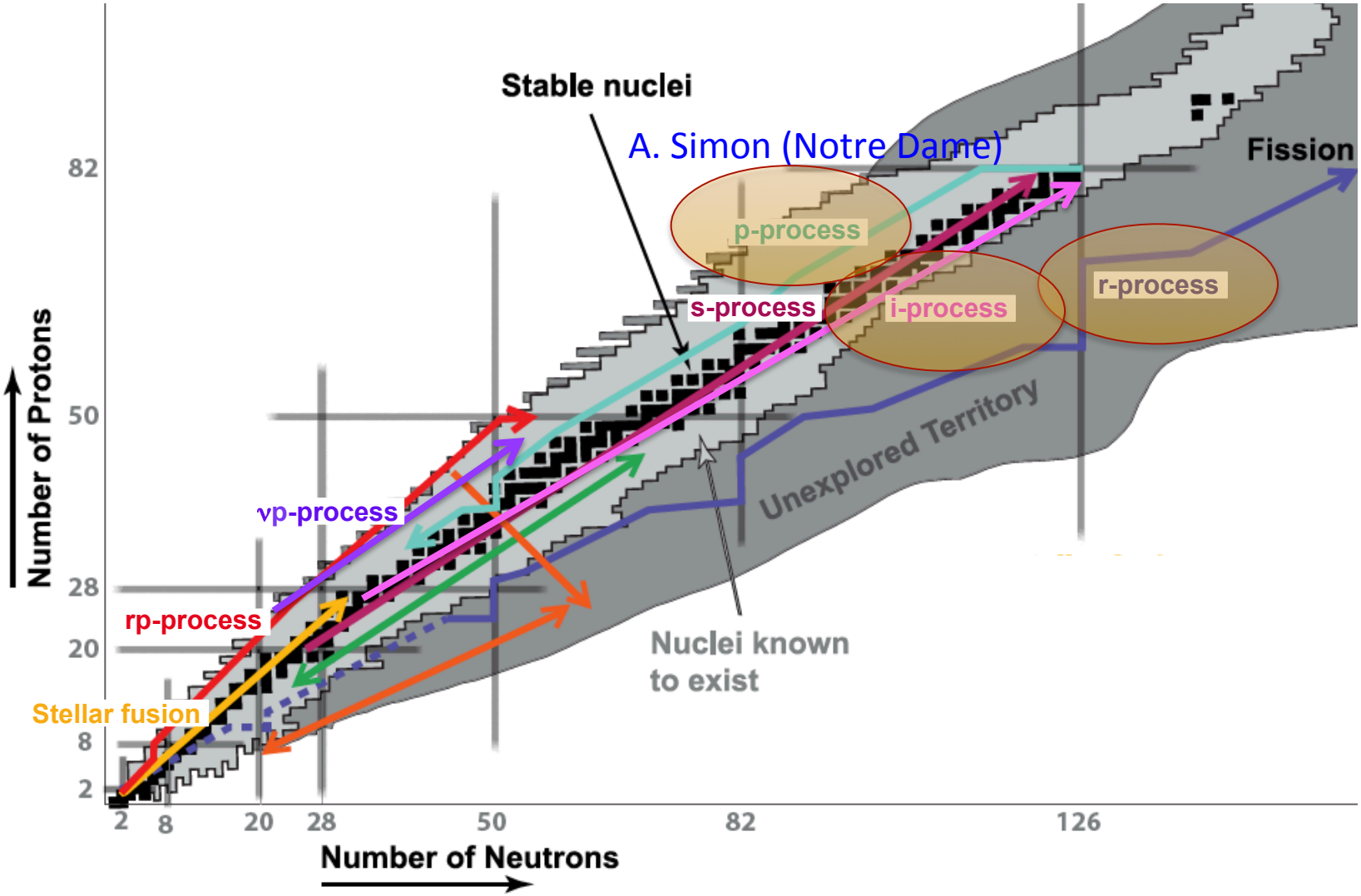
Nuclear Astrophysics Research with SuN at ATLAS

Artemis Spyrou

MICHIGAN STATE UNIVERSITY

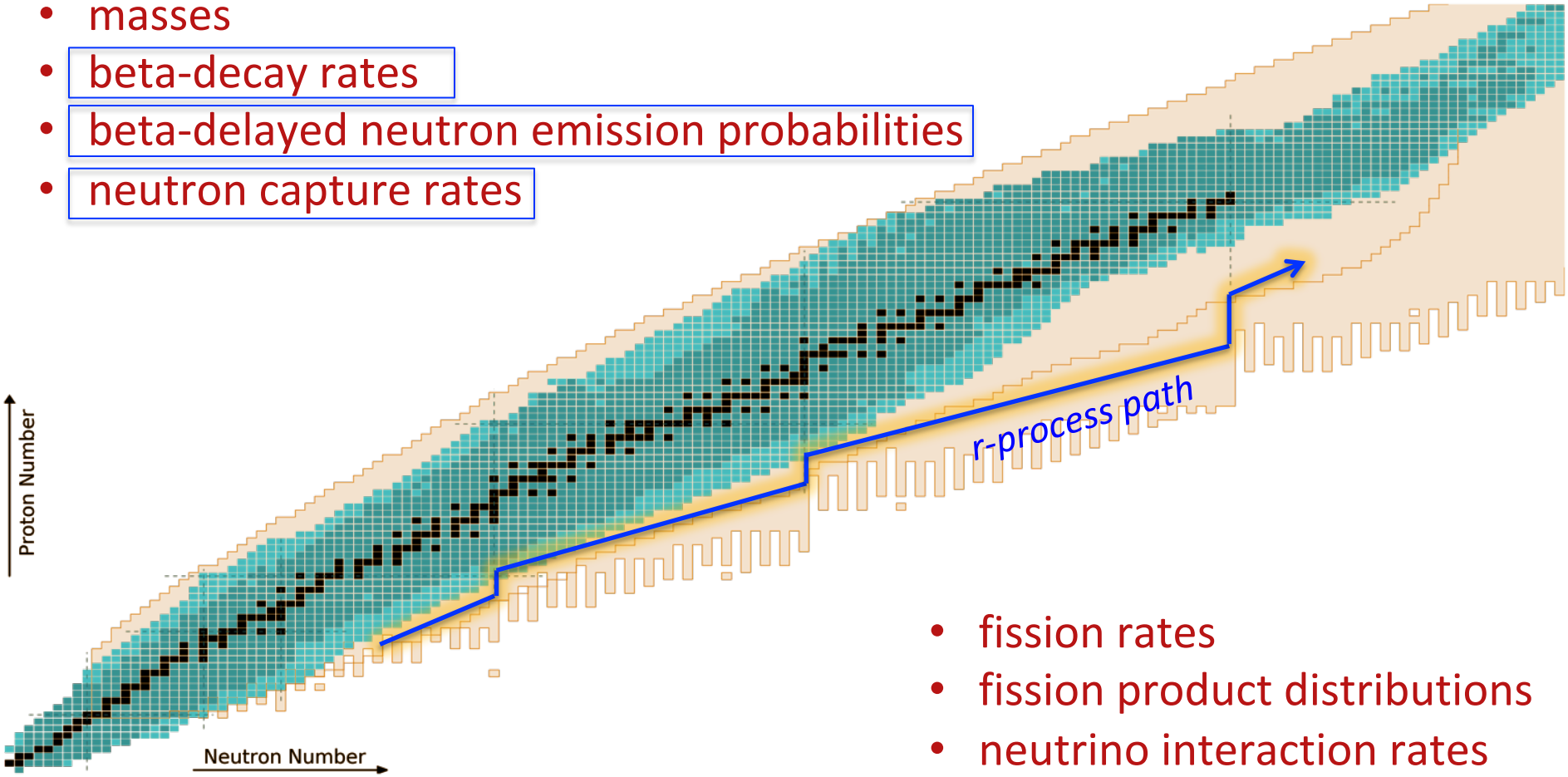
NSCL

Nucleosynthesis processes



Nuclear Input for r-process

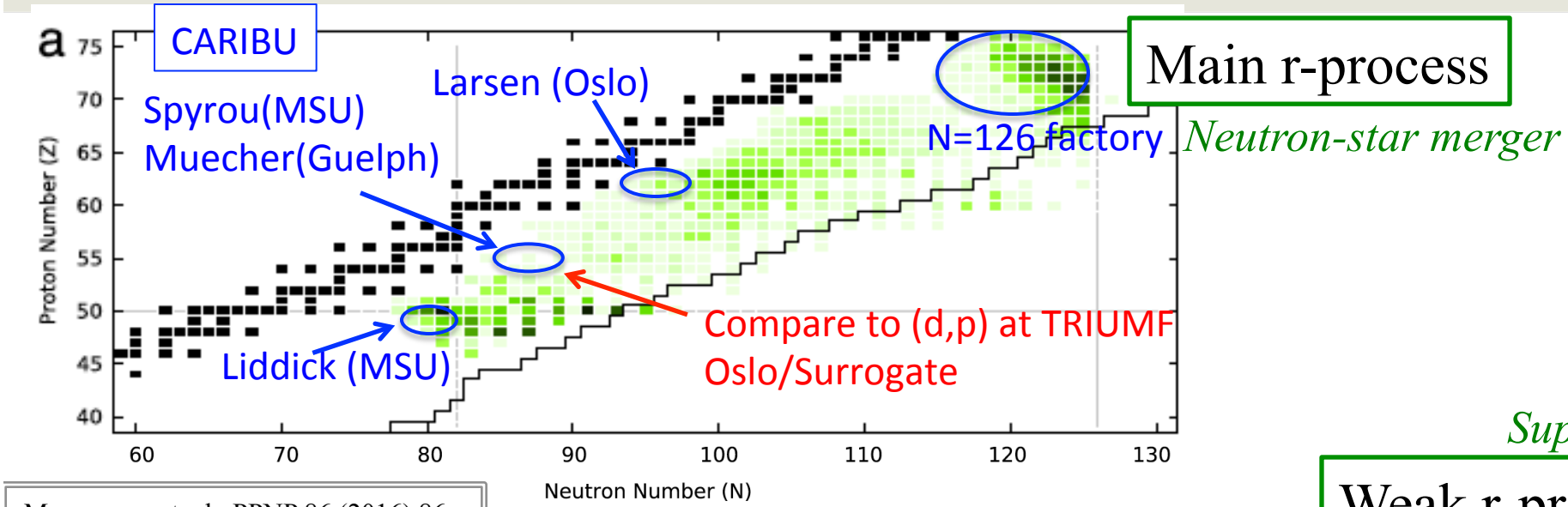
- masses
- beta-decay rates
- beta-delayed neutron emission probabilities
- neutron capture rates



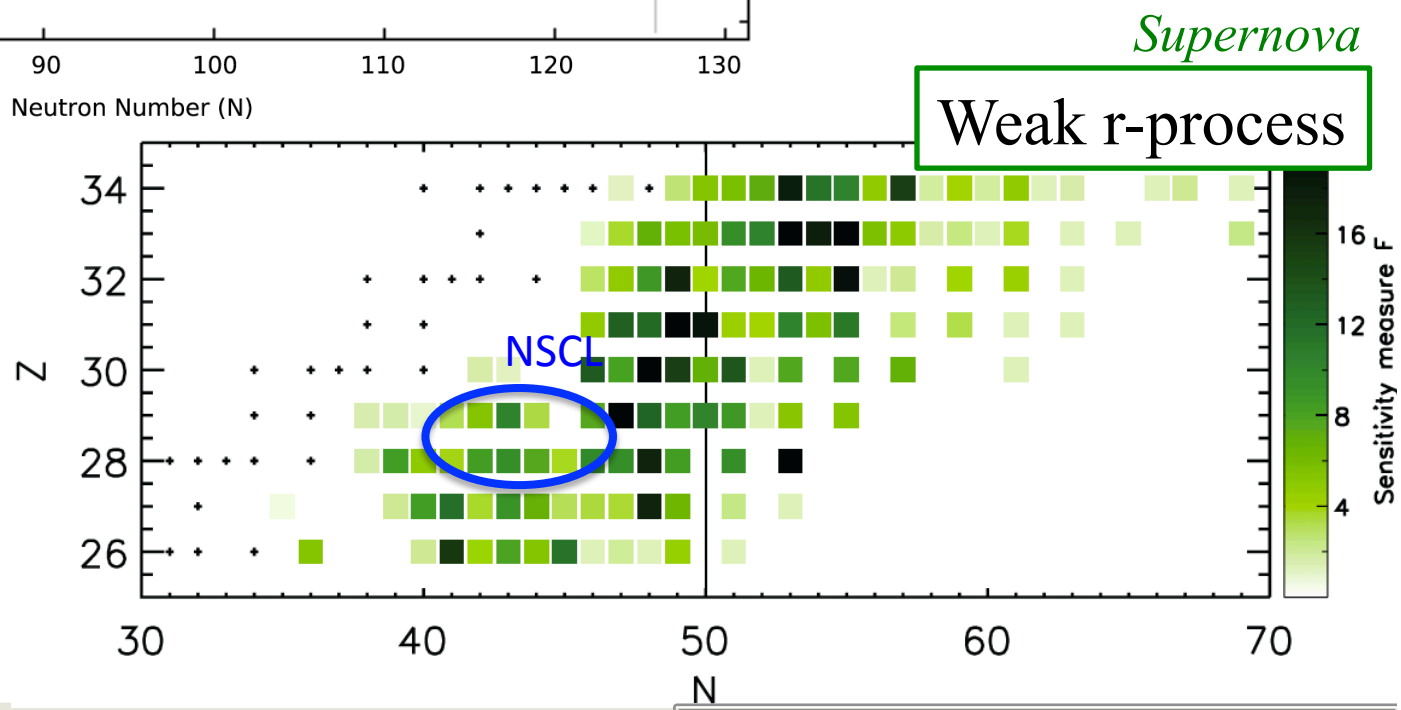
- fission rates
- fission product distributions
- neutrino interaction rates
- Equation of state

figure by M. Mumpower

Sensitivity to neutron-capture reactions



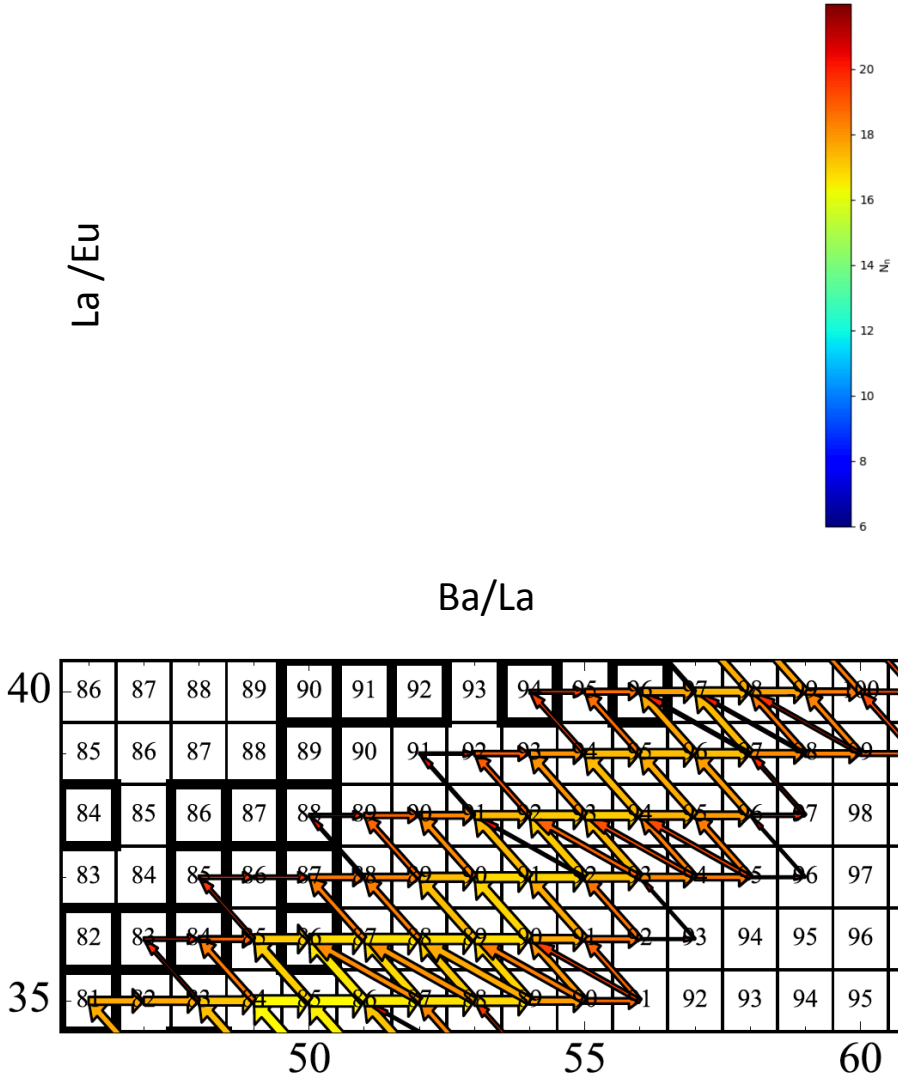
Mumpower et. al., PPNP 86 (2016) 86

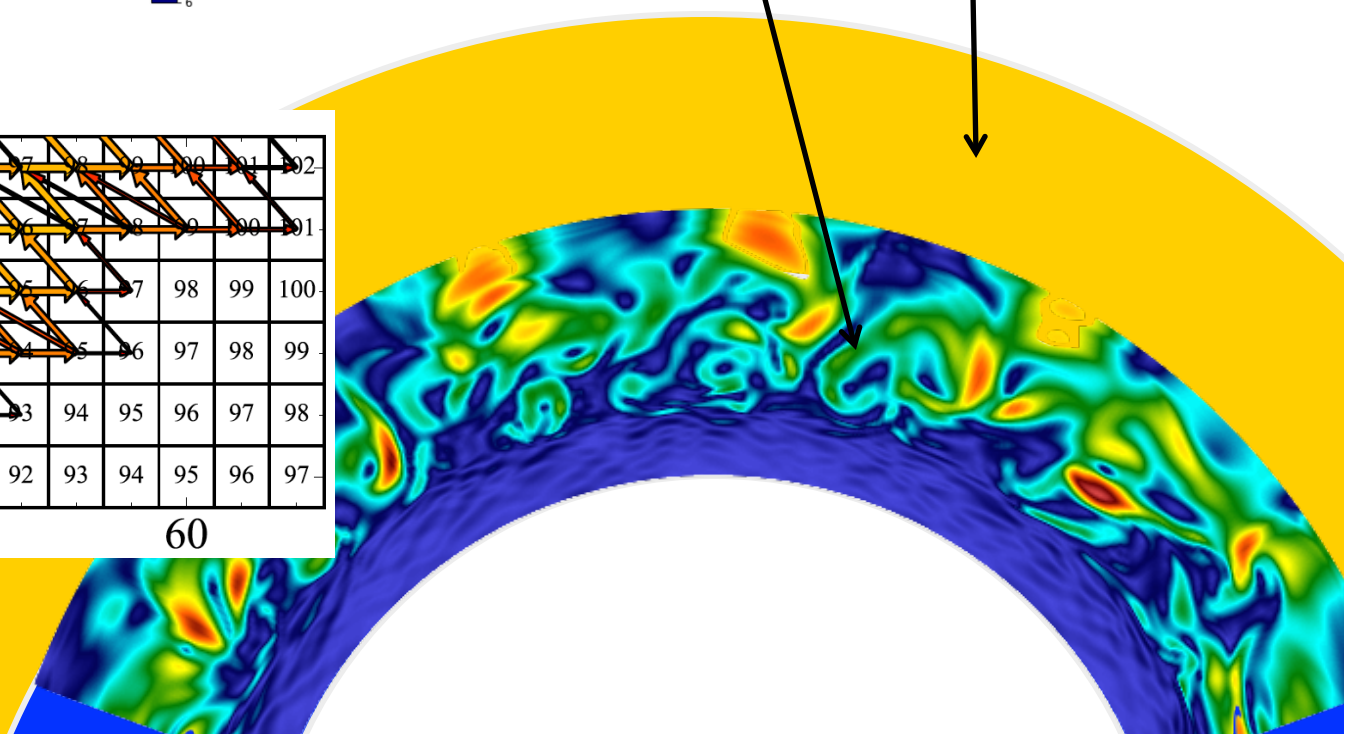


Surman, et al., , AIP Advances 4, 041008 (2014)

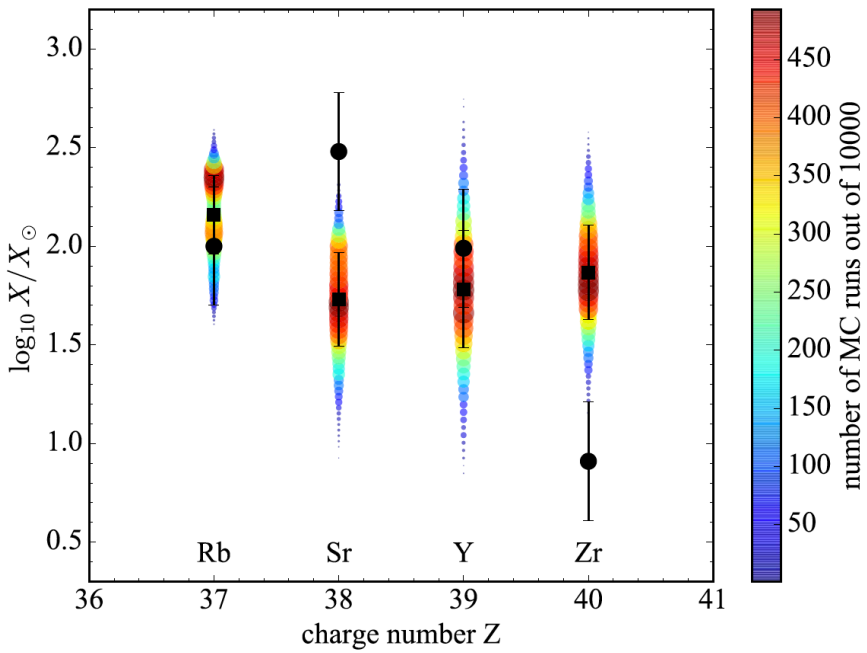
Nucleosynthesis in the i process

- **Neutron density: 10^{13} - 10^{16} cm^{-3}** (intermediate between s (<10^{11} cm^{-3}), and r process (>10^{22} cm^{-3})
- Proposed in the 1970s and revived recently to explain observations of "strange" abundance distributions (site?: post-AGB rapidly accreting white dwarf stars)
- Neutron production: $^{13}C(\alpha,n)^{16}O$ reaction like s process
- Replenishment of ^{13}C via $^{12}C(p,\gamma)^{13}N$ and $^{13}N(e^+)^{13}C$ with $T_{1/2}$~10 minutes.

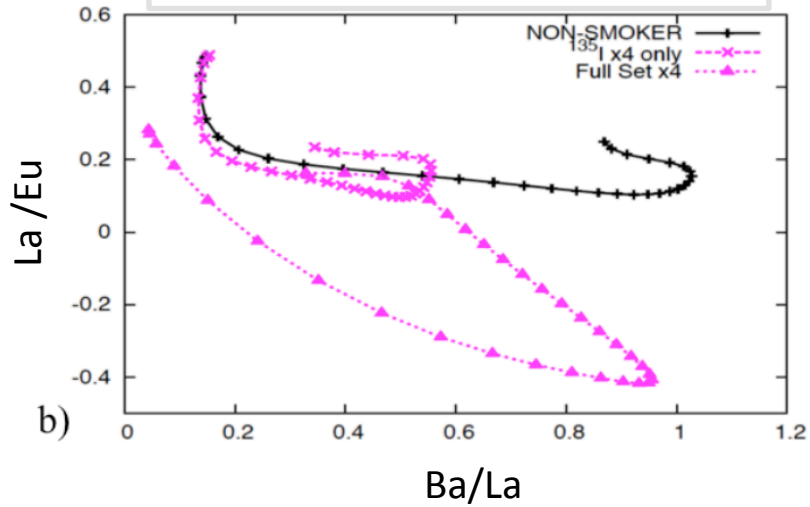




Sensitivity to neutron-captures



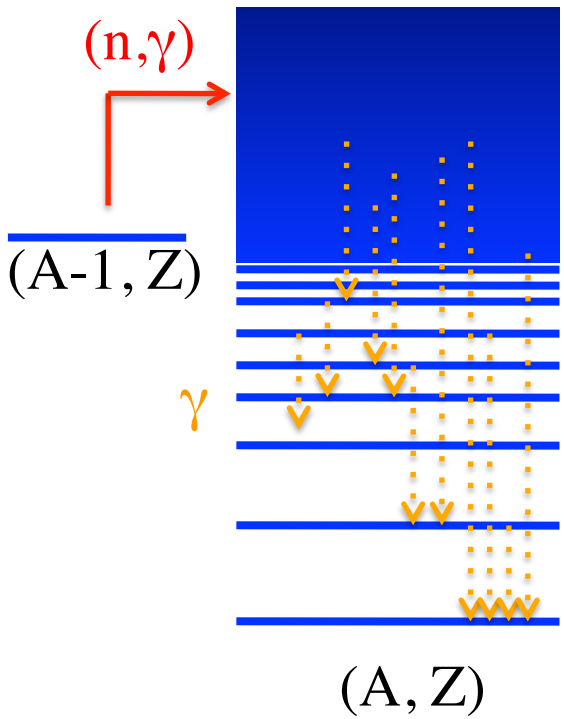
Sensitivity to $^{135}I(n,\gamma)^{136}I$



	Reaction	Rb	Sr	Y	Zr	Rb/Sr	Sr/Y	Y/Zr
NSCL	^{85}Br(n, γ)	−0.18	+0.27	+0.23	+0.32	−0.22		
	^{86}Br(n, γ)		+0.21	+0.18	+0.24			
ANL	^{87}Kr(n, γ)	−0.81	+0.41	+0.23	+0.28	−0.60		
ANL	^{88}Kr(n, γ)		−0.60	+0.36	+0.49	+0.42	−0.59	
ANL	^{89}Kr(n, γ)			−0.34			+0.27	−0.37
	^{89}Rb(n, γ)			−0.46			+0.42	−0.54
	^{89}Sr(n, γ)			−0.23			+0.21	−0.30
NSCL	^{92}Sr(n, γ)				−0.26			+0.21

Dennissenkov, et al., JPG 2018, Bertolli, et al. 2014

Neutron Captures within the Statistical Model



Hauser – Feshbach

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

} Dominate uncertainties

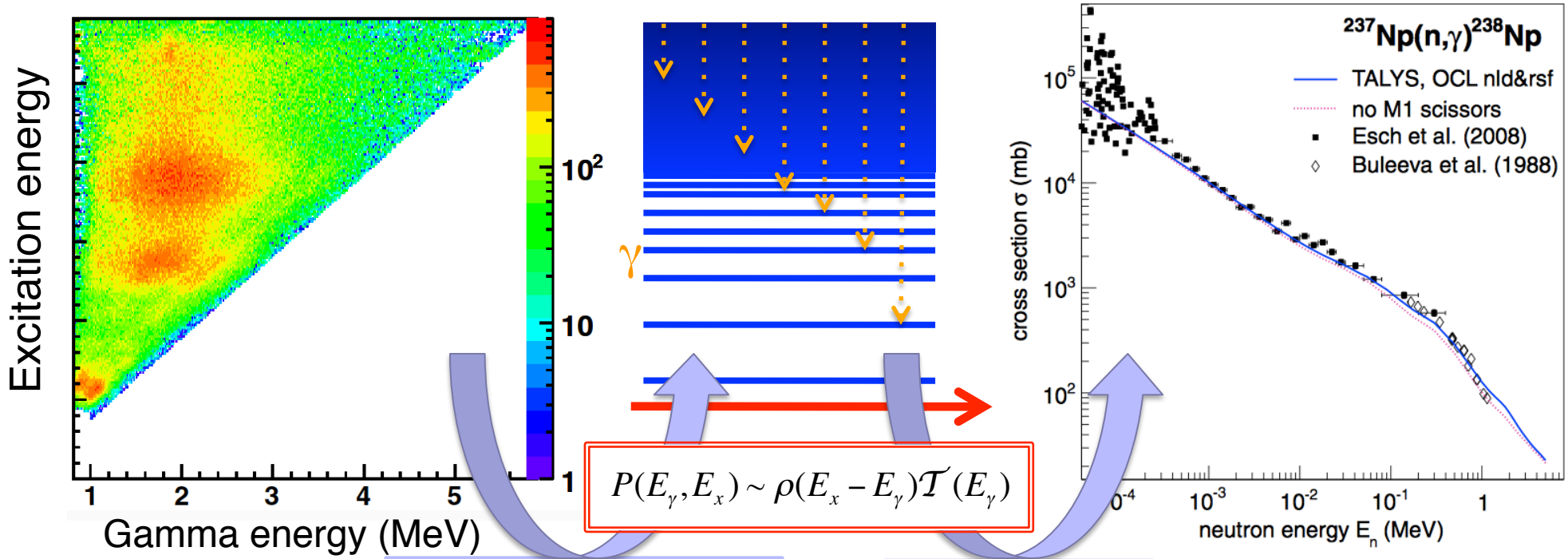
- Optical model potential → Large uncertainties further from stability

β-Oslo method:

- Combine traditional **Oslo Method** with **Total Absorption Spectroscopy**
- Use β-decay to populate the compound nucleus of interest
- Advantage: study nuclei far from stability

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



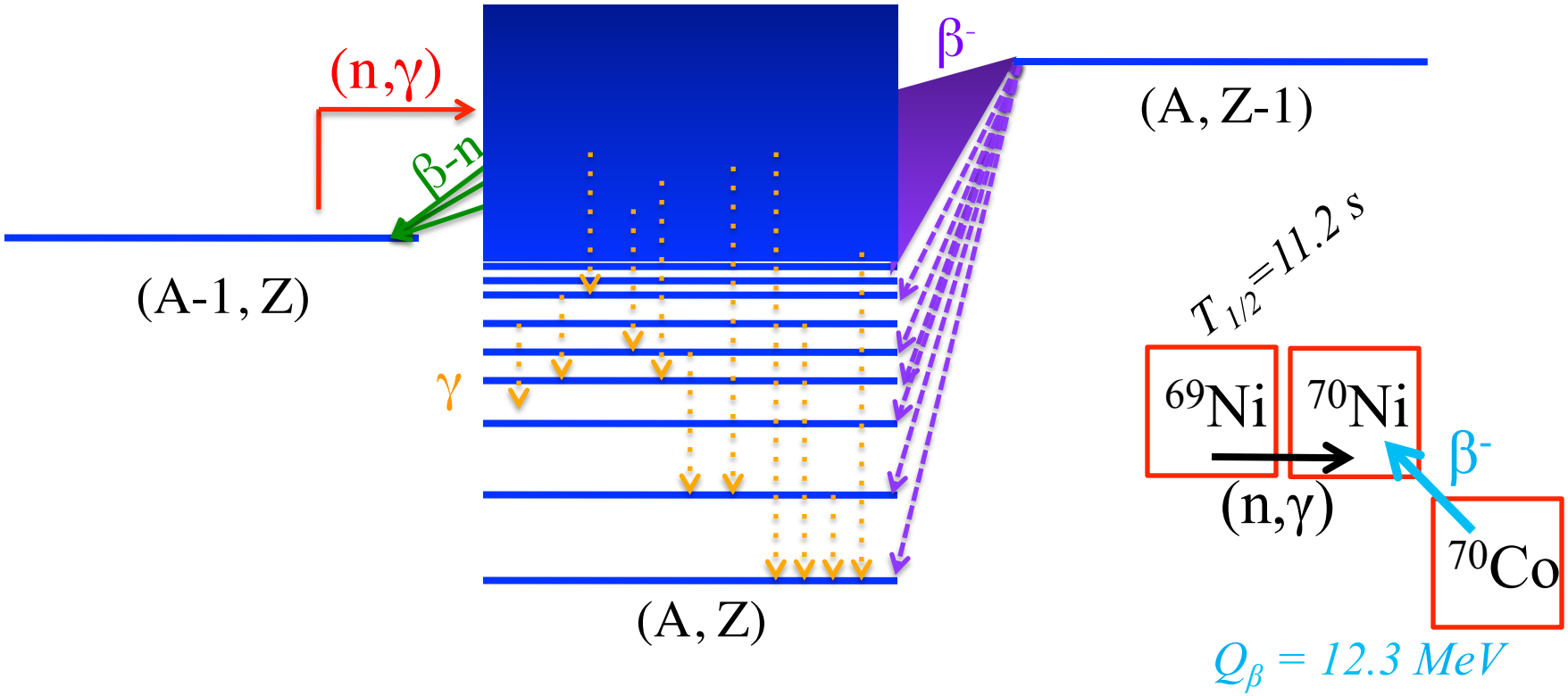
Unfolding
Iterative subtraction

Normalization

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

β-Oslo

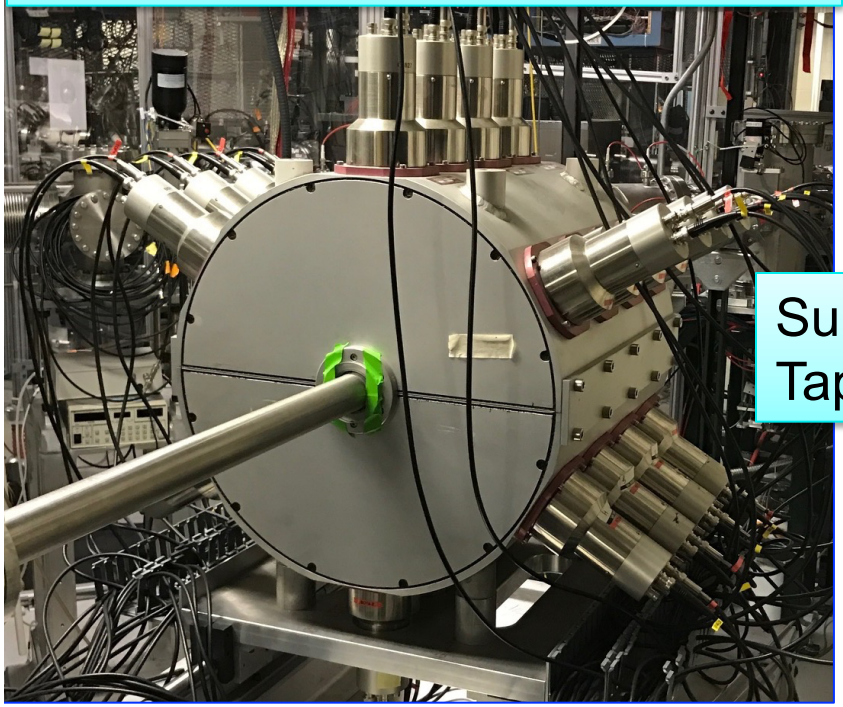
Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014



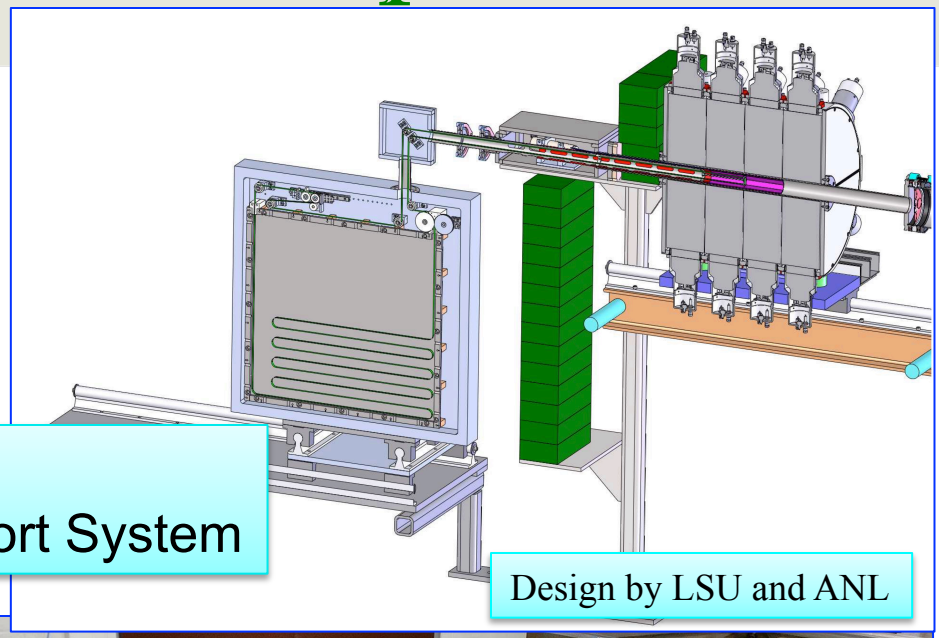
- Populate the compound nucleus via β-decay (large Q-value far from stability)
- Spin selectivity – correct for it
- Extract level density and γ-ray strength function
- Advantage: Can reach (n,γ) reactions with beam intensity down to 1 pps.

Experimental Setup

SuN
γ-Total Absorption Spectrometer



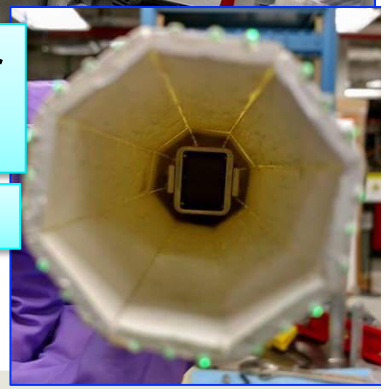
SuNTAN
Tape Transport System



Design by LSU and ANL

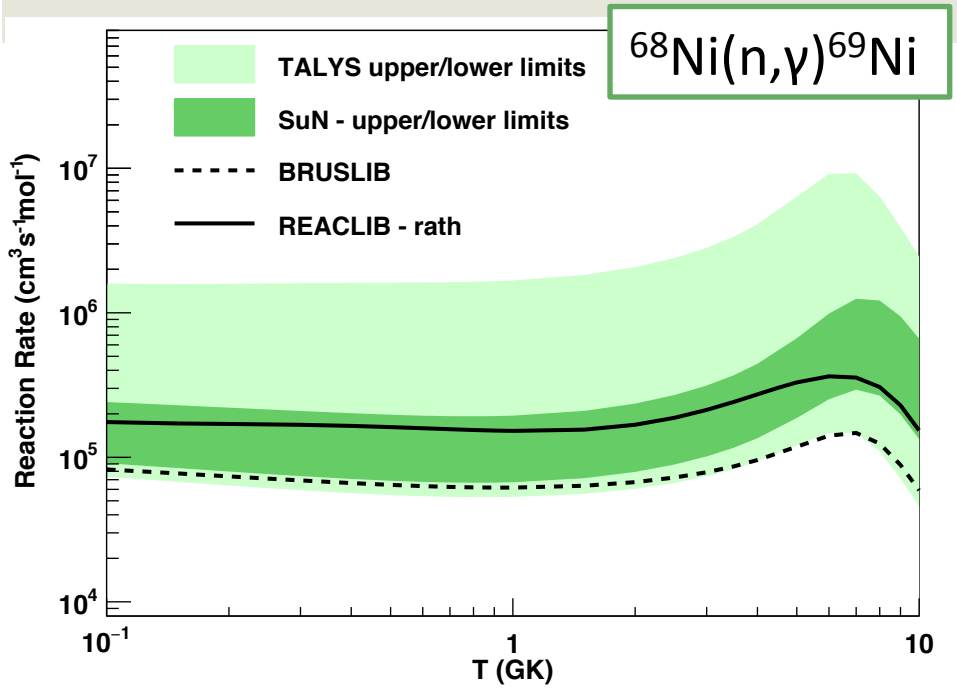
Fiber Detector
β-detection

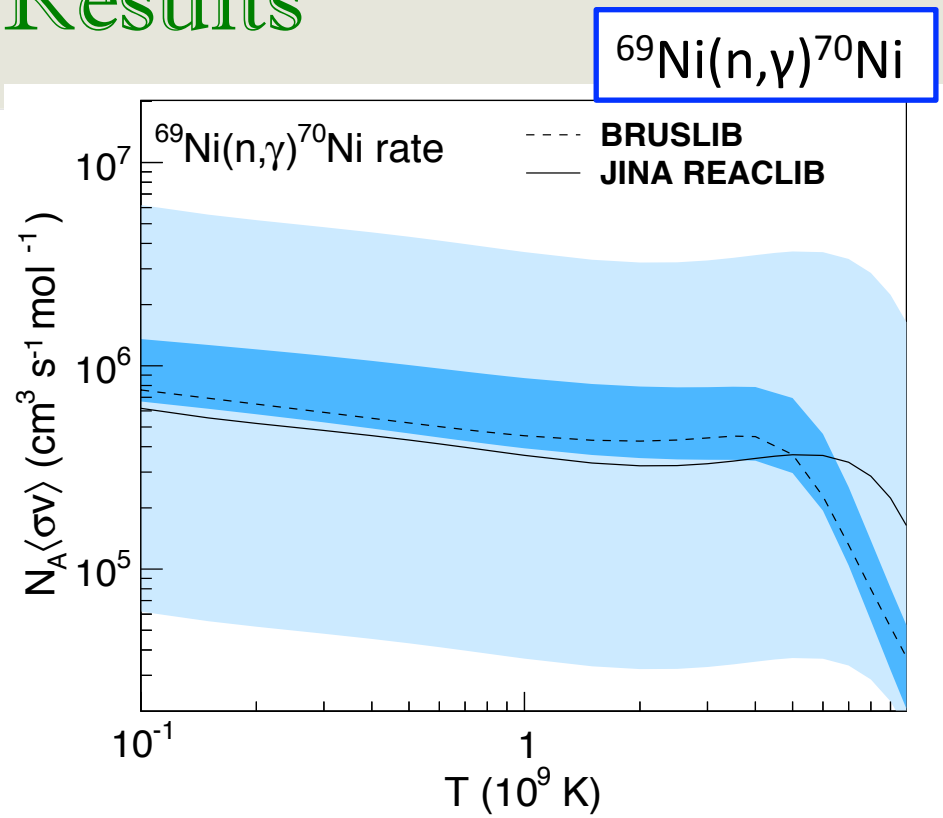
Hope College

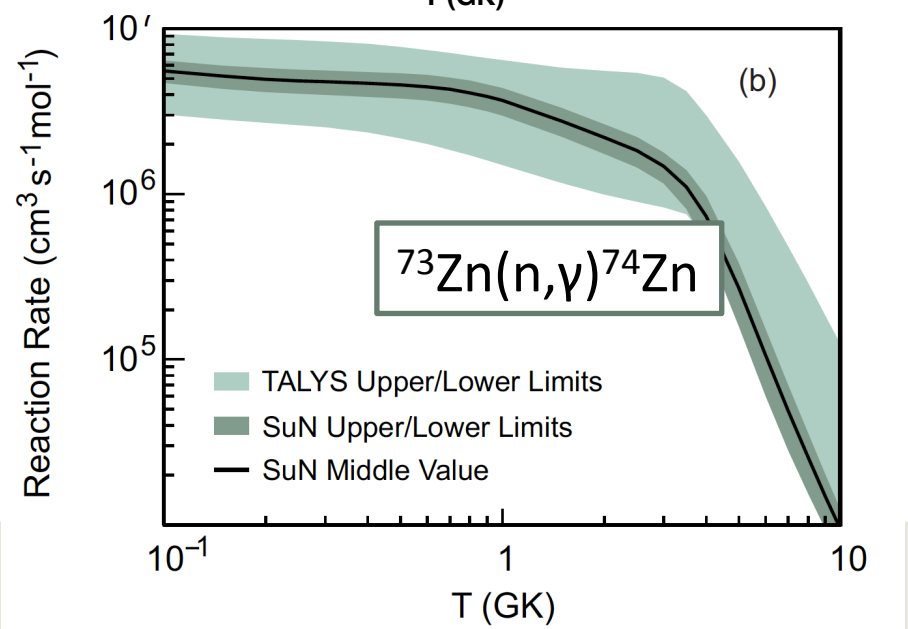


see Mallory Smith's talk

First (n,γ) Results





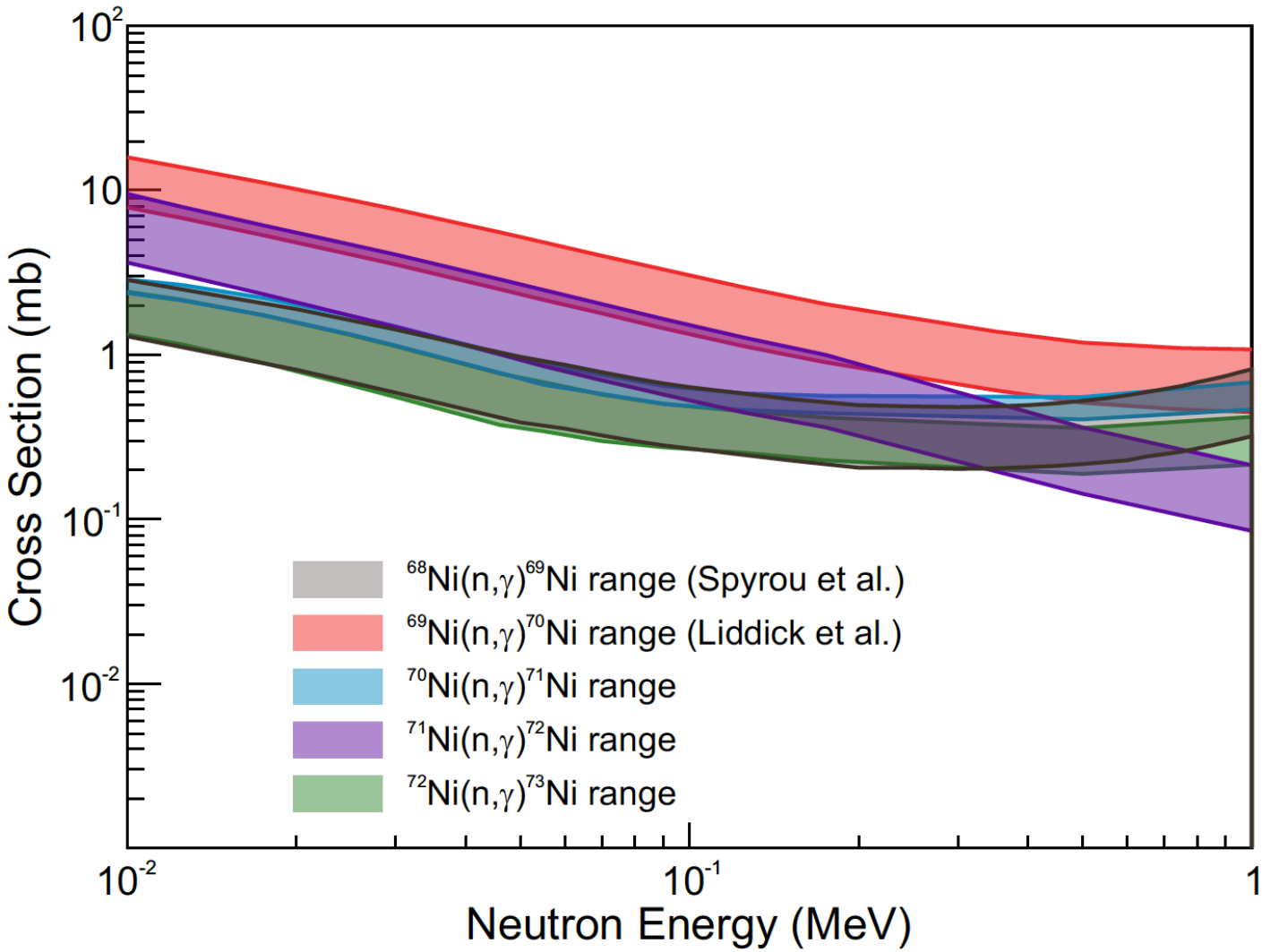


Liddick, Spyrou, et al, PRL 2016

Spyrou, Larsen, et al, JPG 2017

Lewis, et al, PRC 2019

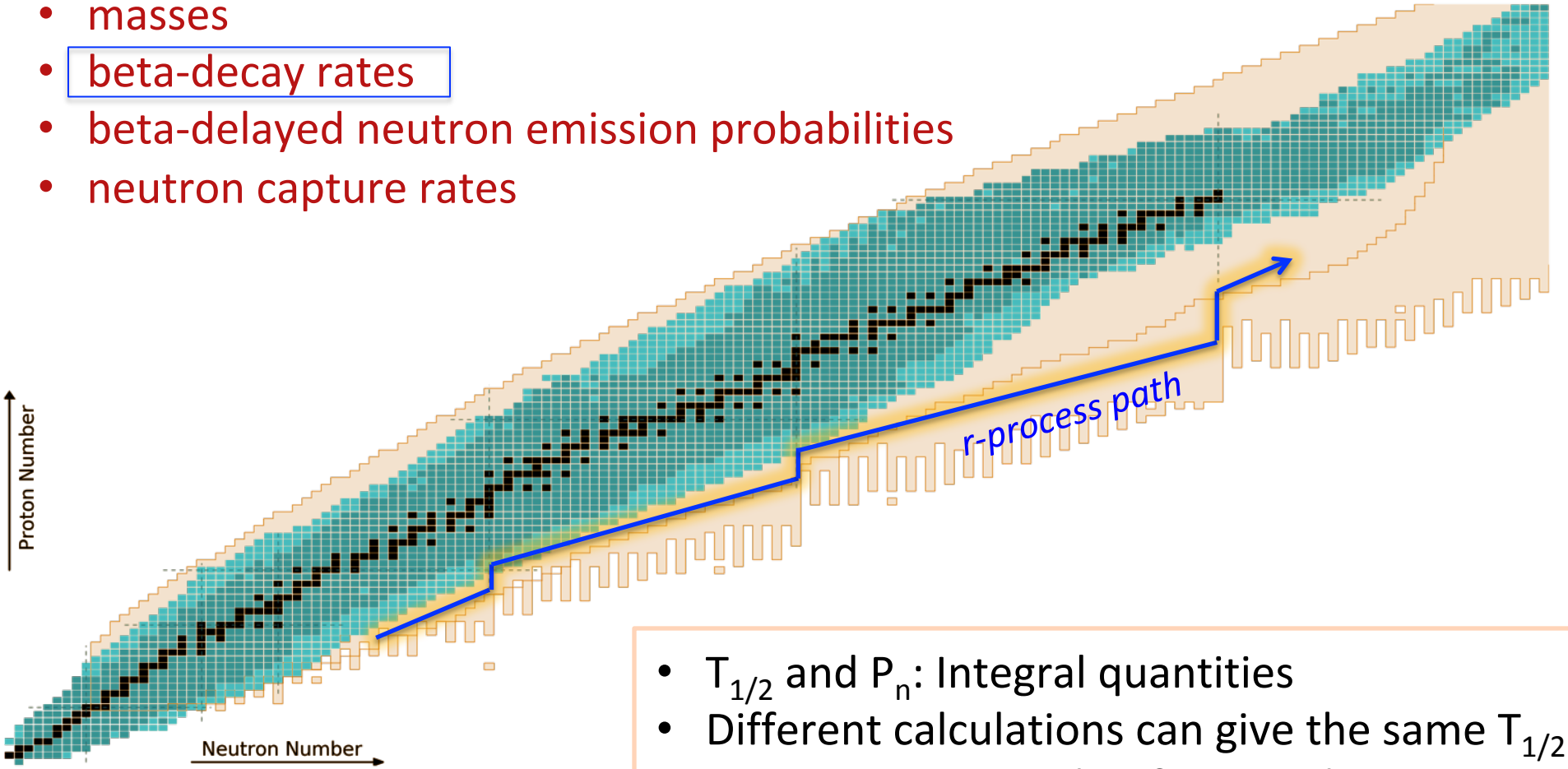
Ni(n,γ) systematcis



Lewis, et al, PhD thesis 2019

Nuclear Input for r-process

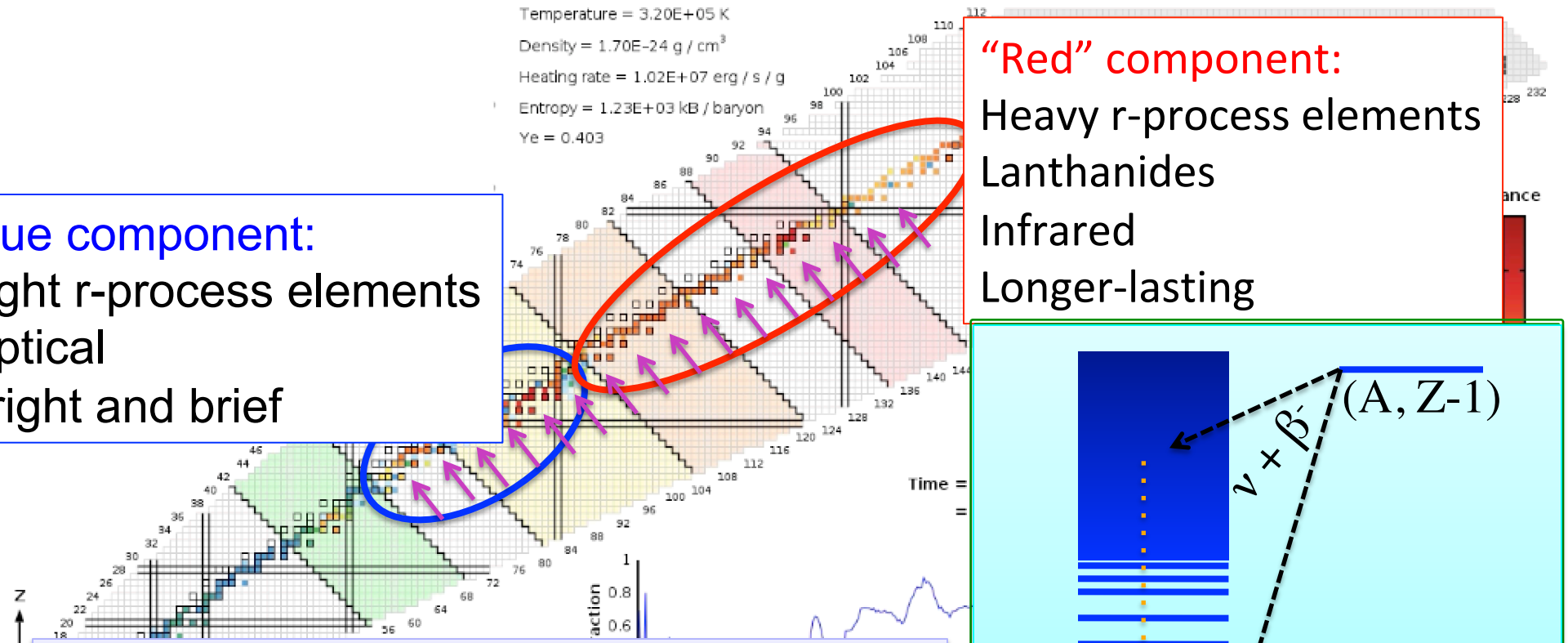
- masses
- beta-decay rates
- beta-delayed neutron emission probabilities
- neutron capture rates



- $T_{1/2}$ and P_n: Integral quantities
- Different calculations can give the same $T_{1/2}$
- More sensitive probe: β strength

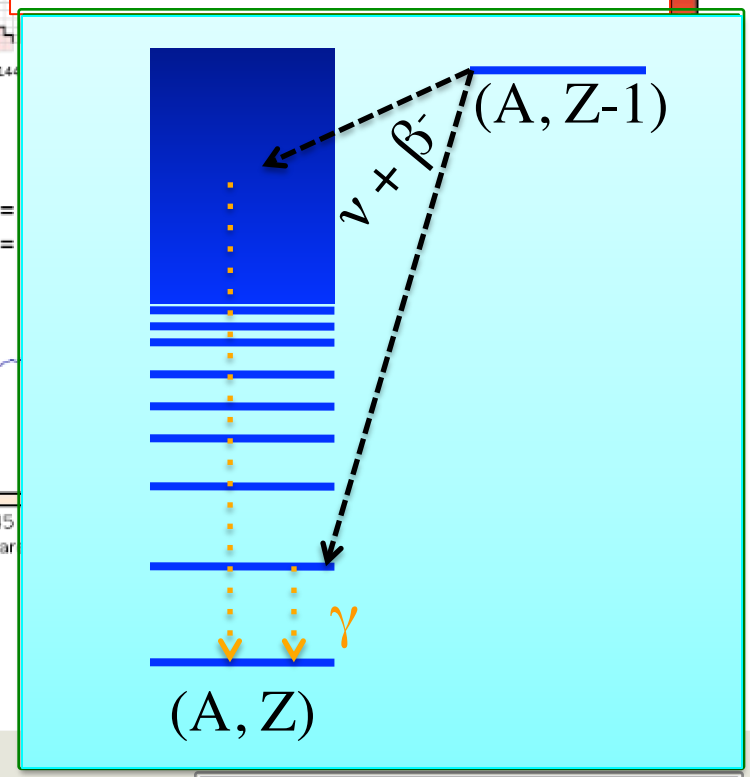
figure by M. Mumpower

r-process in neutron-star mergers



Blue component:
Light r-process elements
Optical
Bright and brief

"Red" component:
Heavy r-process elements
Lanthanides
Infrared
Longer-lasting



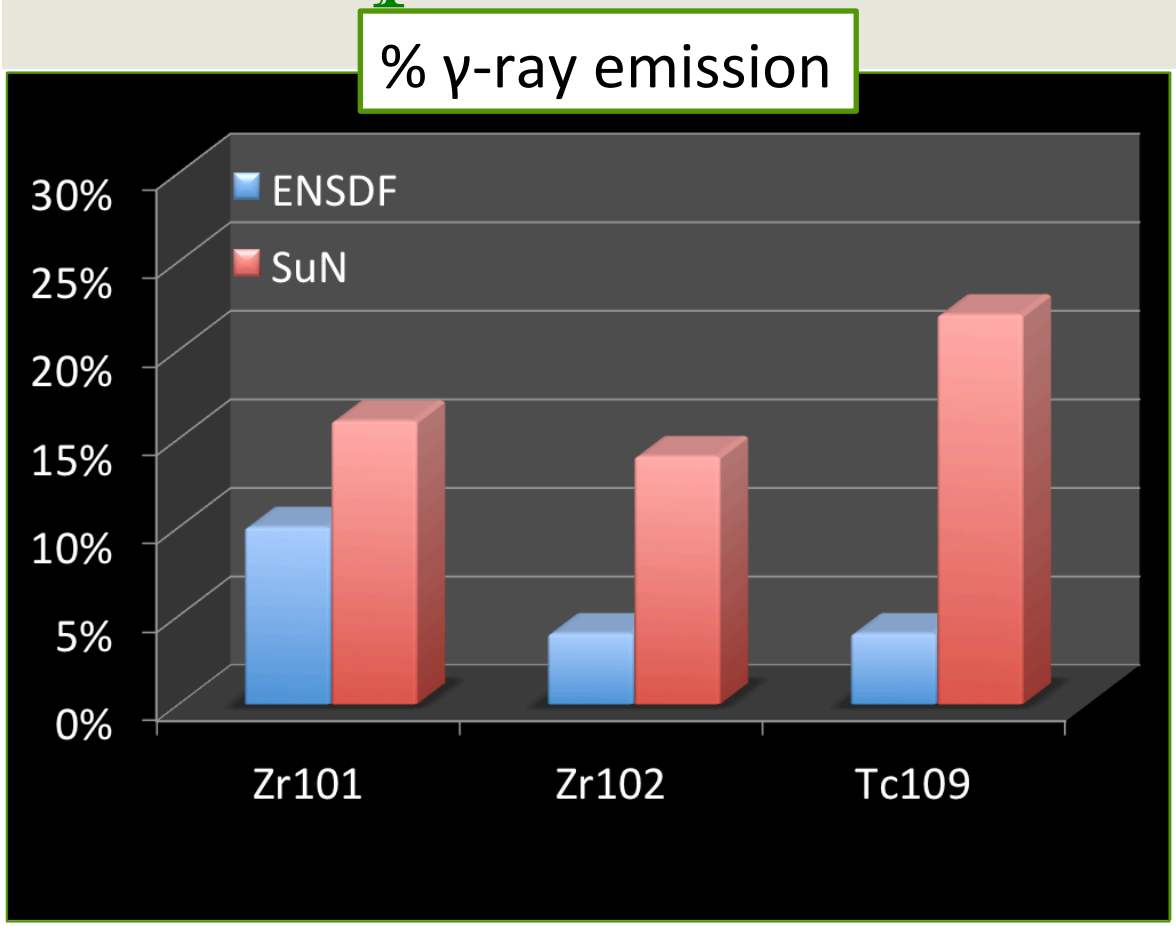
- Direct Observation of Radioactive Decay
- Important: **Energy sharing between decay particles**
- Existing Data is often misleading!!!

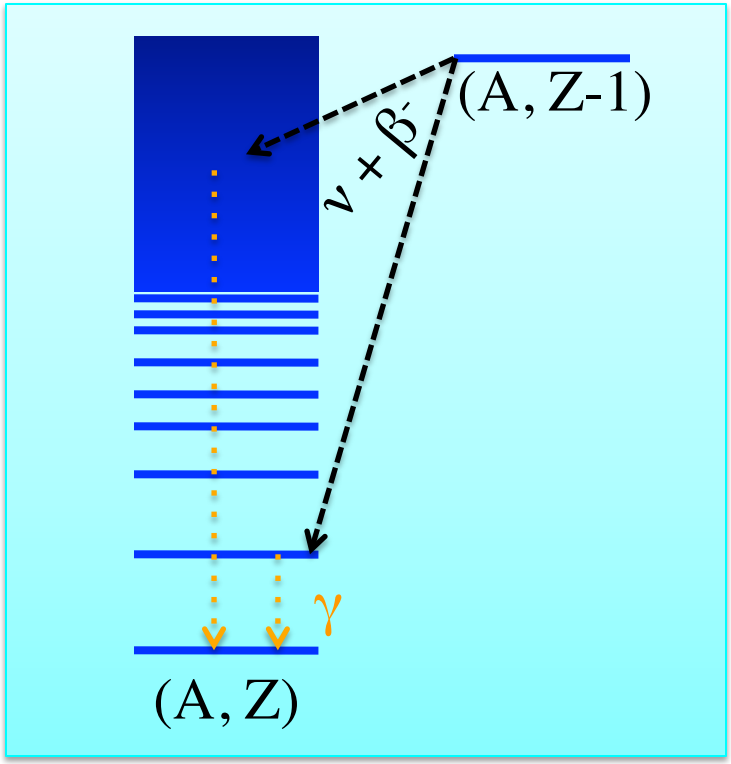
Kasen et al., Nature 2017

Made with SkyNet by Jonas Lippuner

Kilpatrick, et al, Science 2017

The pandemonium effect in action

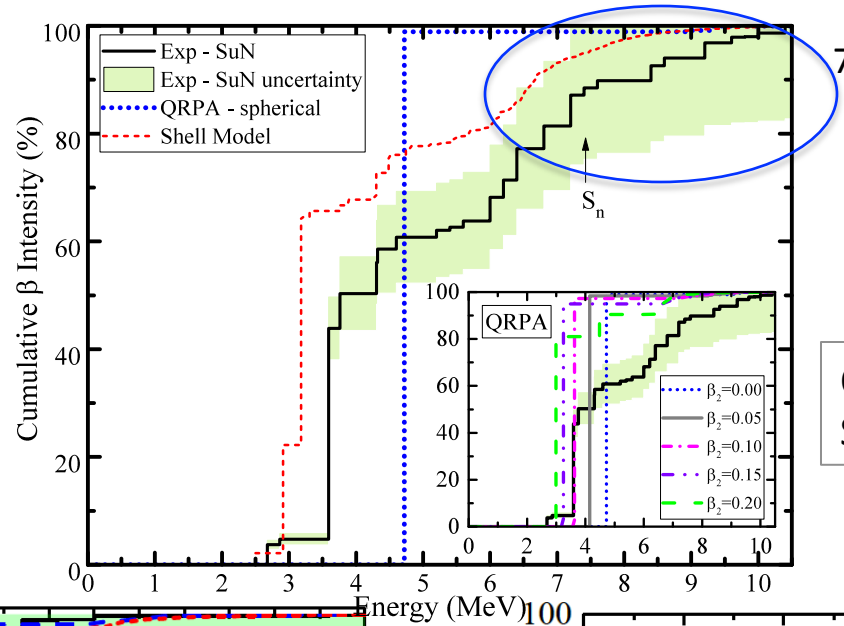




- Sensitivity study to identify important nuclei
- More measurements needed
- Impact on kilonova observations?

β-decay Intensity

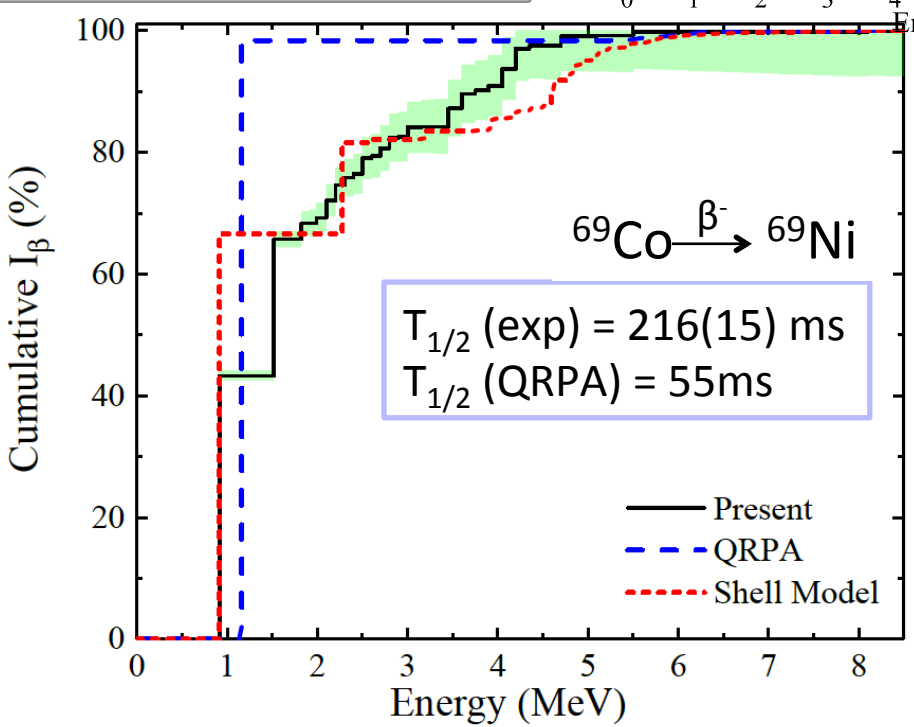
A. Spyrou, S.N. Liddick, et al.
Phys. Rev. Lett. 2016

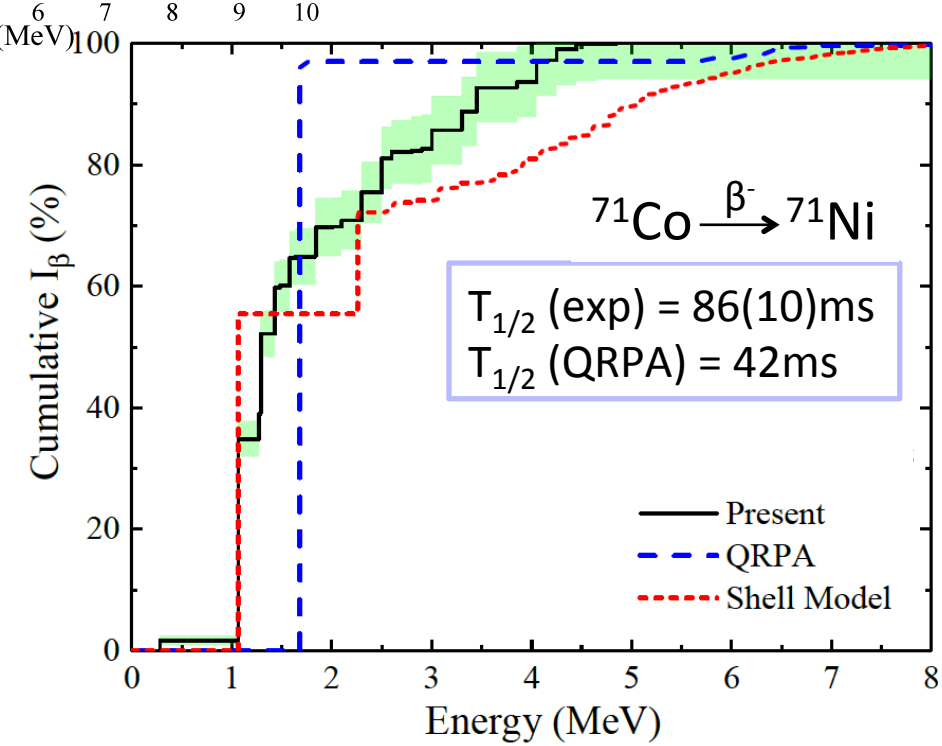


$^{70}Co \xrightarrow{\beta^-} {}^{70}Ni$

QRPA: P. Moller, LANL
Shell model: B. A. Brown, MSU

S. Lyons, A. Spyrou, S.N. Liddick, et al.
Phys. Rev. C. 2019 (submitted)





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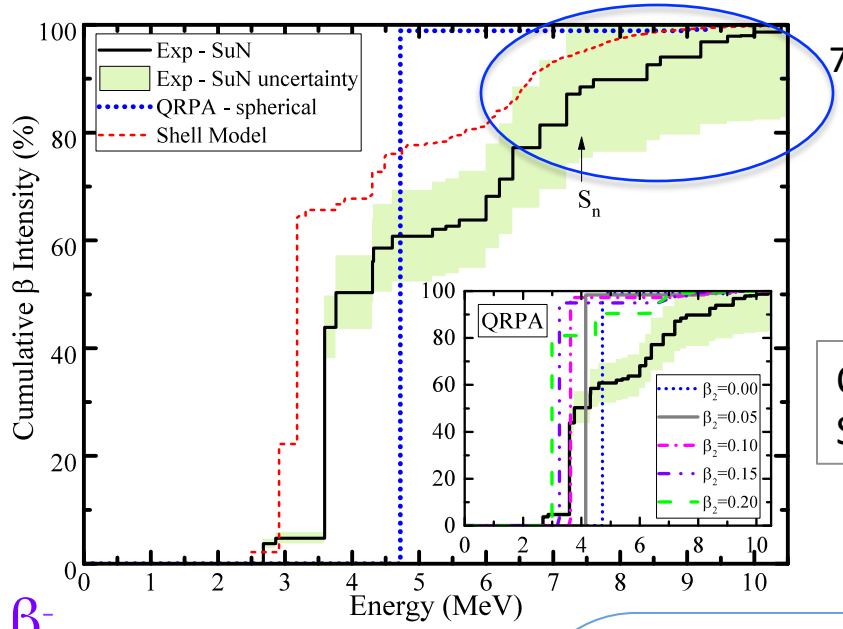

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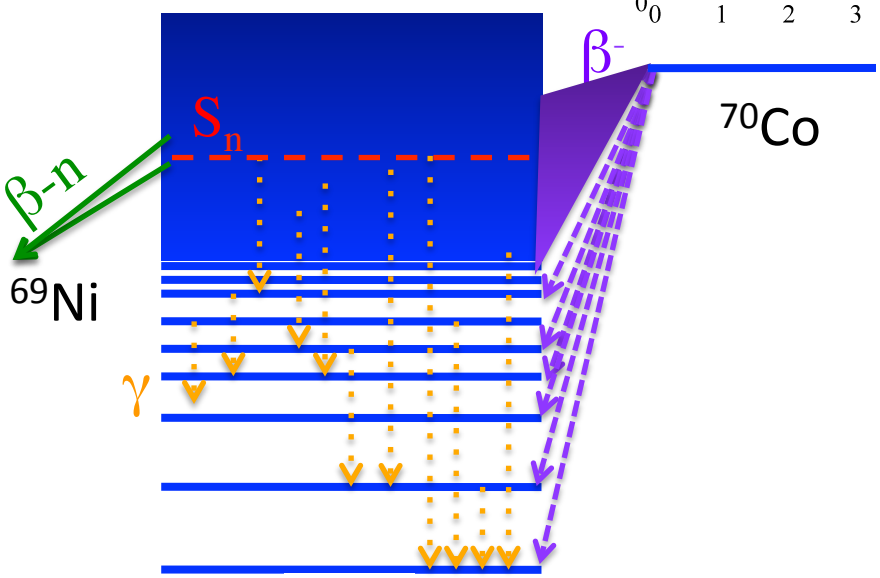
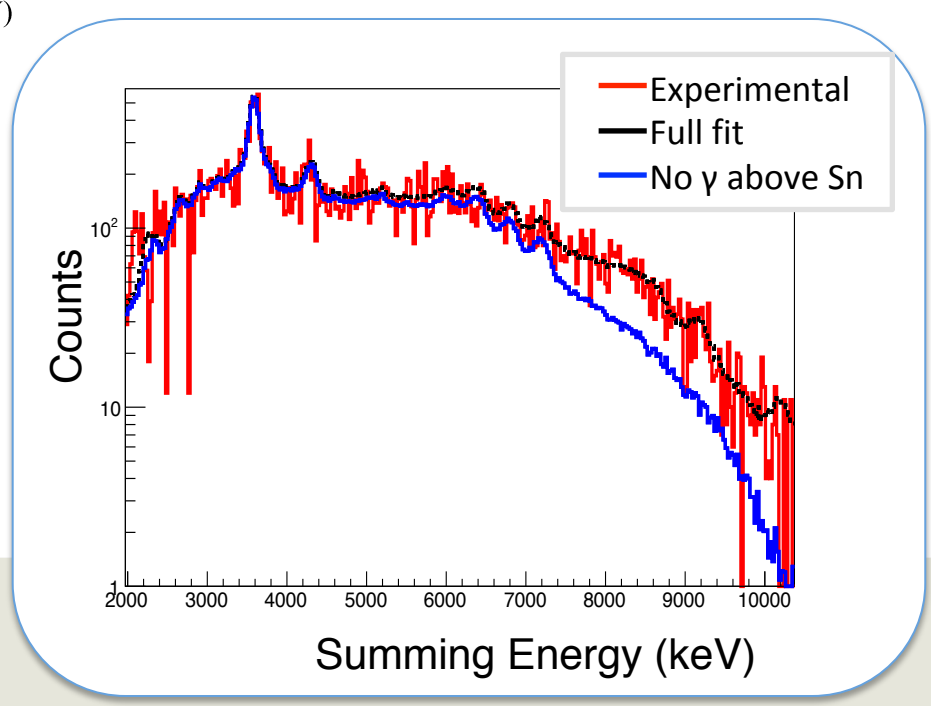
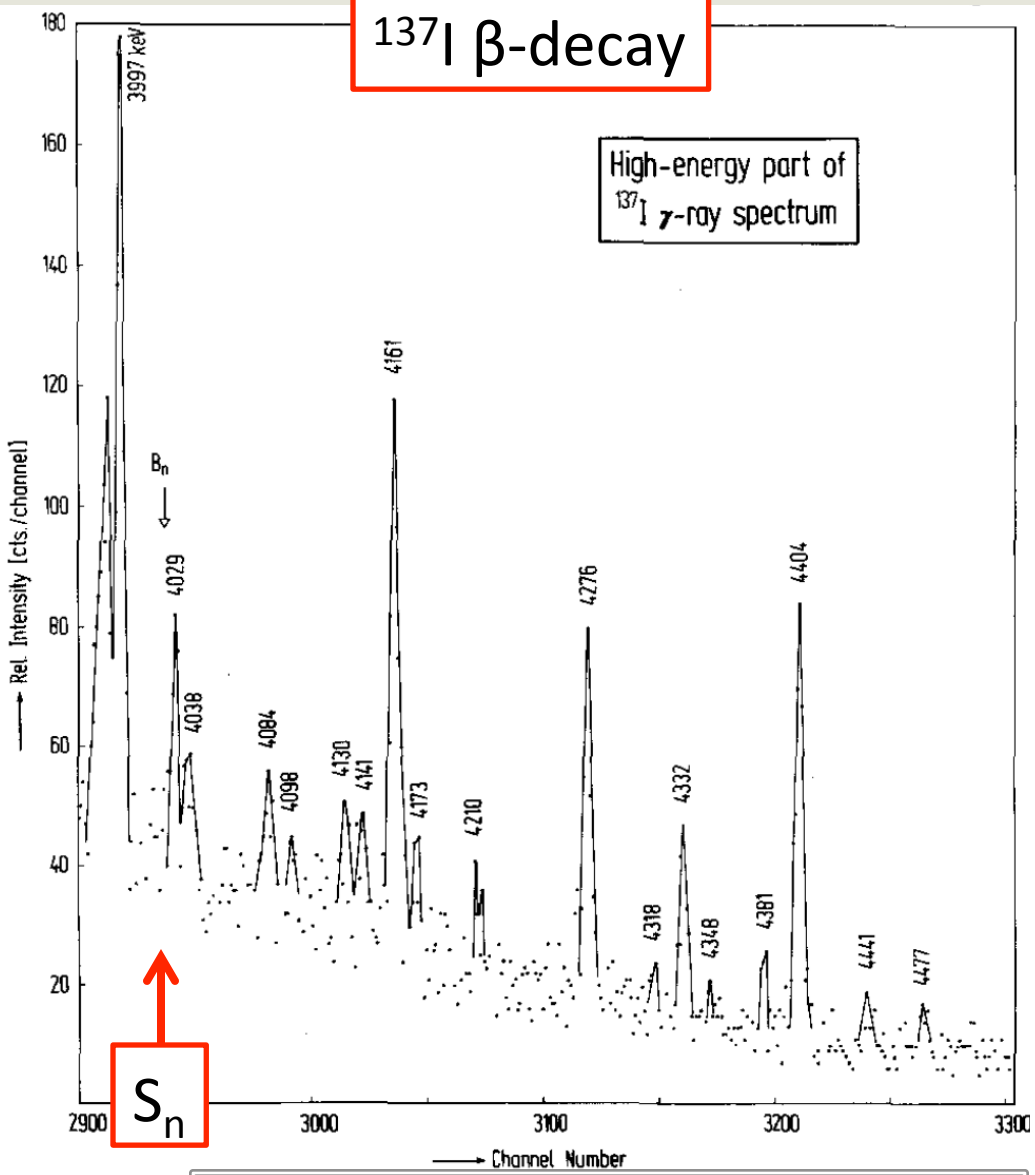




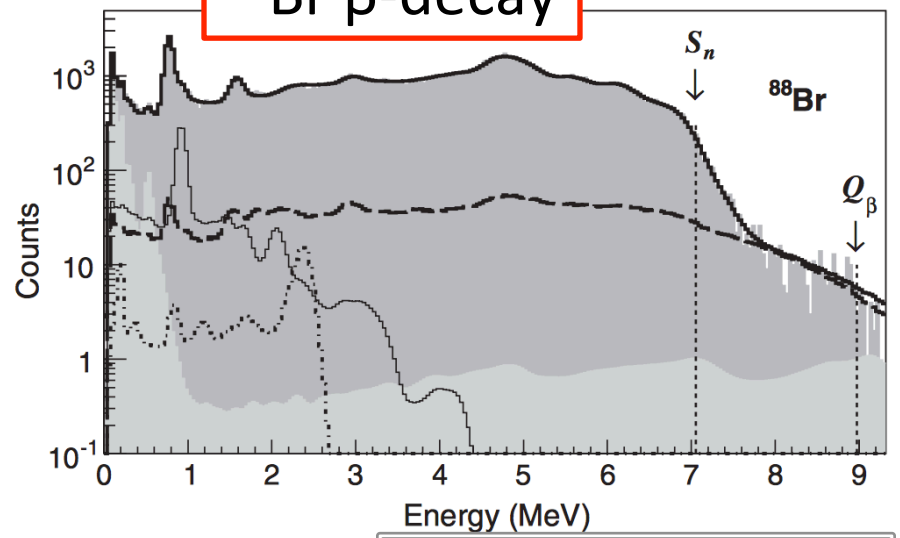
Neutron – γ competition

^{137}I β-decay



H. Ohm, et al.,,Physik A - Atoms and Nuclei 296, 23 (1980).

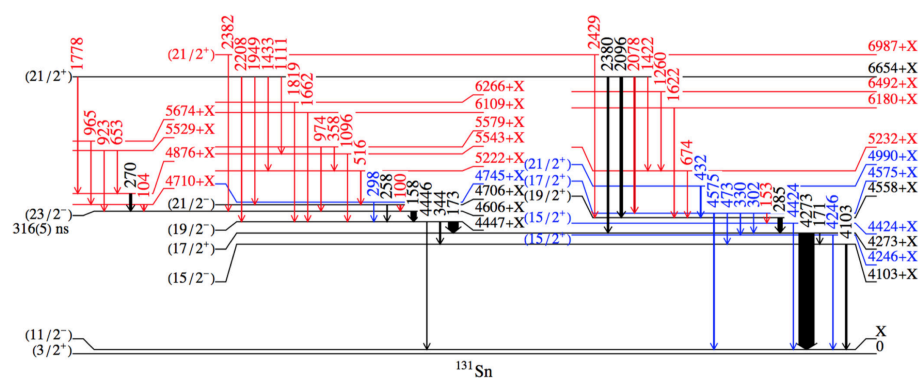
^{88}Br β-decay



Tain et al, PRL 115, 062502 (2015)

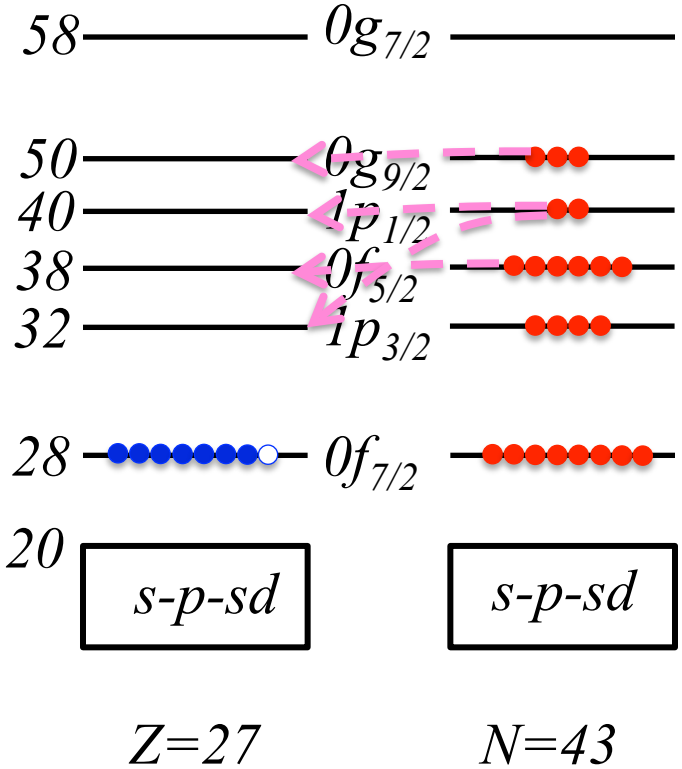
^{131}In β-decay

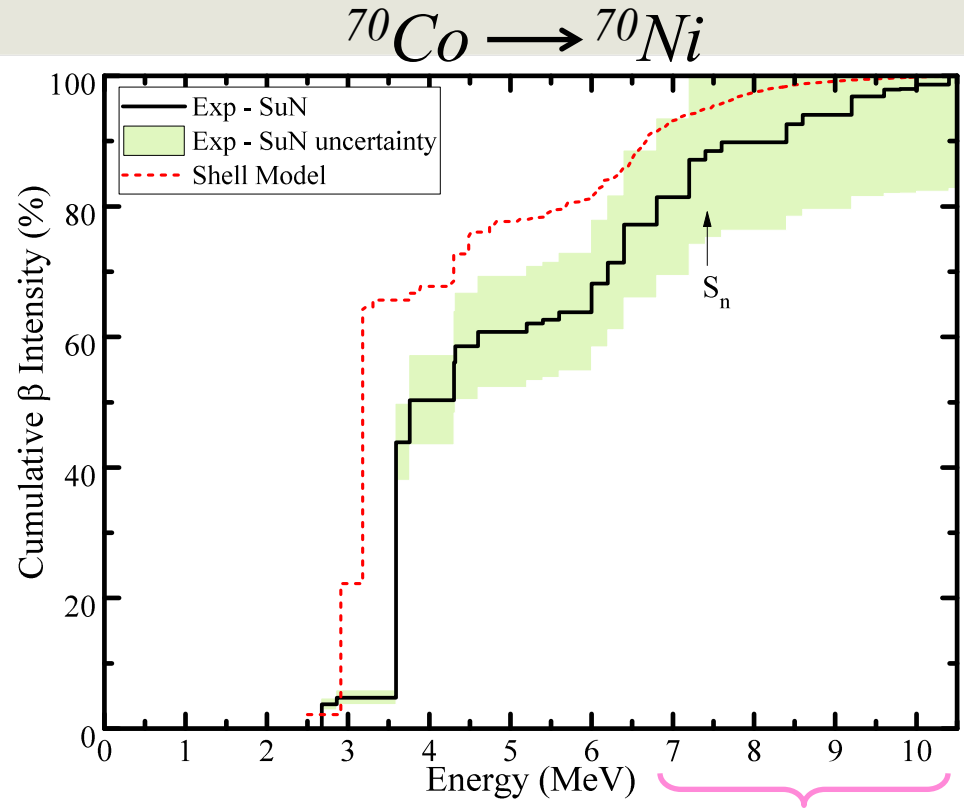
21/2+



Dunlop, Svensson, et al. PRC 2019

Neutron – γ competition





Proton excited across Z=28

$6^- \longrightarrow 5,6,7^-$

Allowed

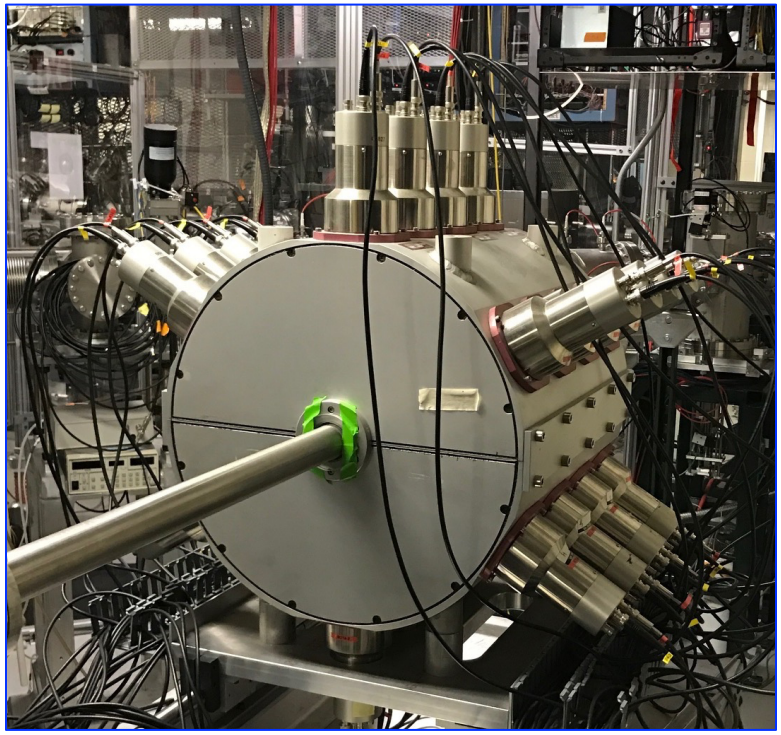
Reasons

- High spin
- Low spectroscopic overlaps
- High gamma-ray strength function

Spyrou, Liddick, et al, PRL2016

Summary

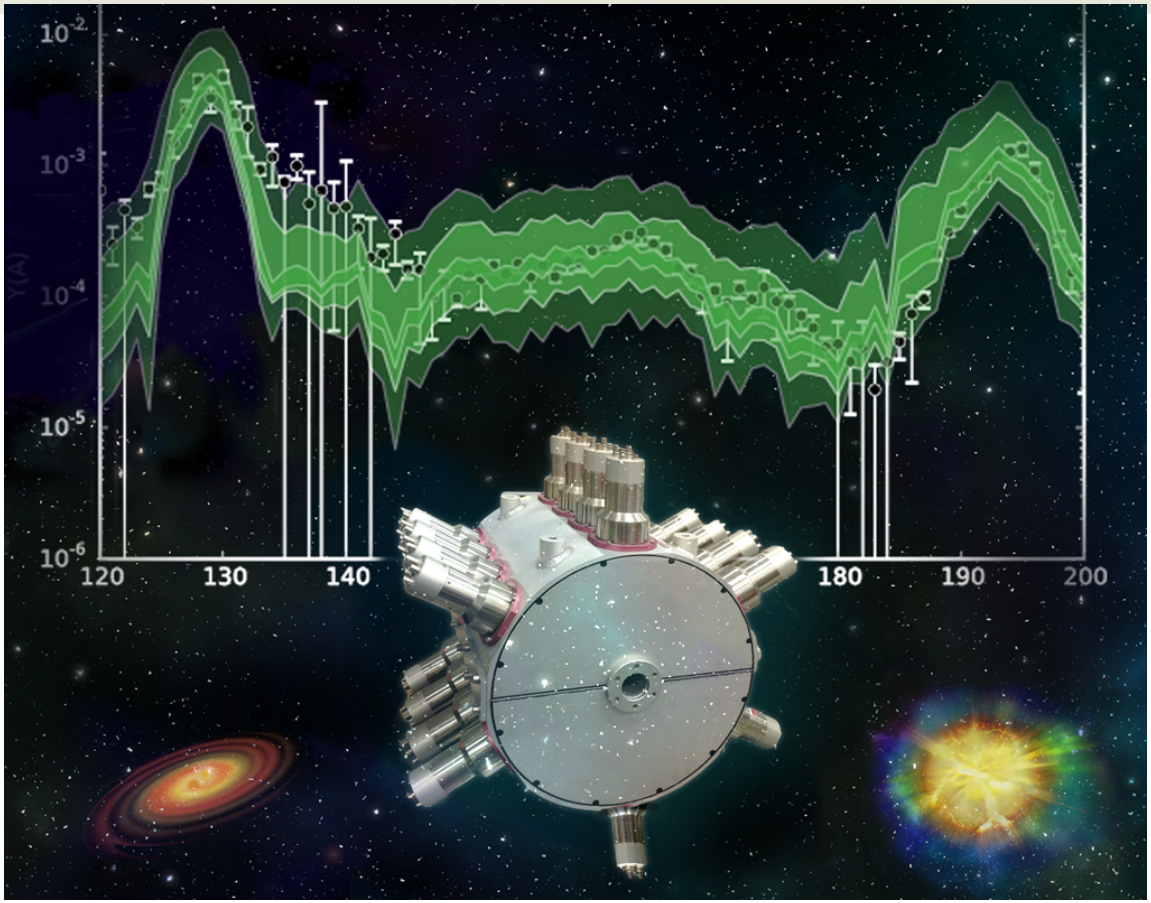
- Exciting opportunities with SuN at ANL
- β-Oslo provides experimental constraints far from stability.
- Radioactive decay for kilonova – Pandemonium
- Neutron-gamma competition



Collaboration

MICHIGAN STATE UNIVERSITY

B. Crider
S.N. Liddick
K. Childers
A.C. Dombos
C. Harris
R. Lewis
S. Lyons
F. Naqvi
C. Prokop
A. Palmisano
S.J. Quinn
A. Richard
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

Lawrence Livermore National Laboratory

D. L. Bleuel

A. Simon

VNIVERSITAT DE VALÈNCIA

B. Rubio

G. Perdikakis
S. Nikas

D. Muecher

UNIVERSITY of GUELPH

University of Victoria

F. Herwig
P. Denissenkov

NSCL

National Science Foundation
Michigan State University