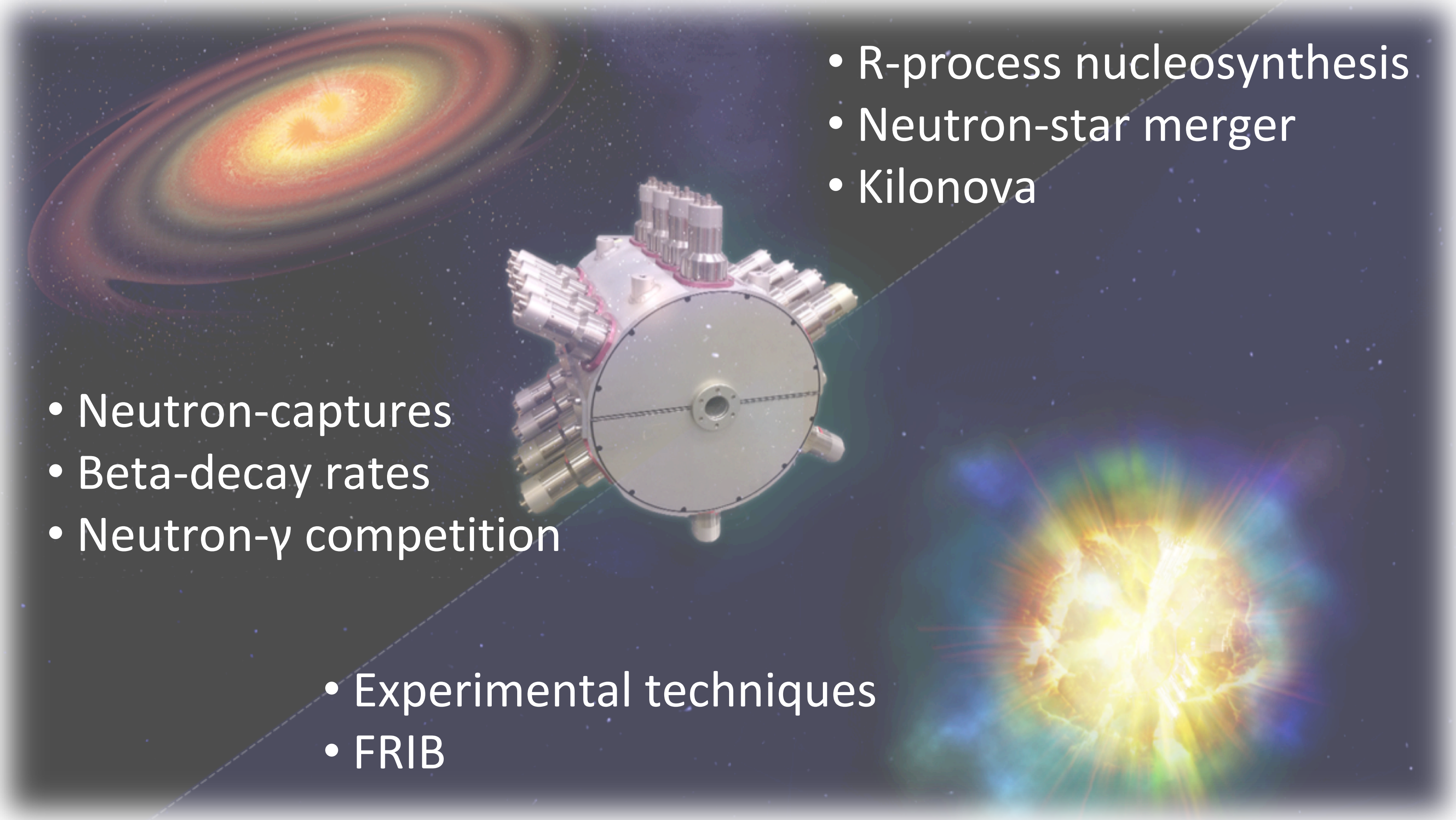
Constraining neutron-capture reactions for the astrophysical r-process

Artemis Spyrou

MICHIGAN STATE UNIVERSITY

NSCL

Overview



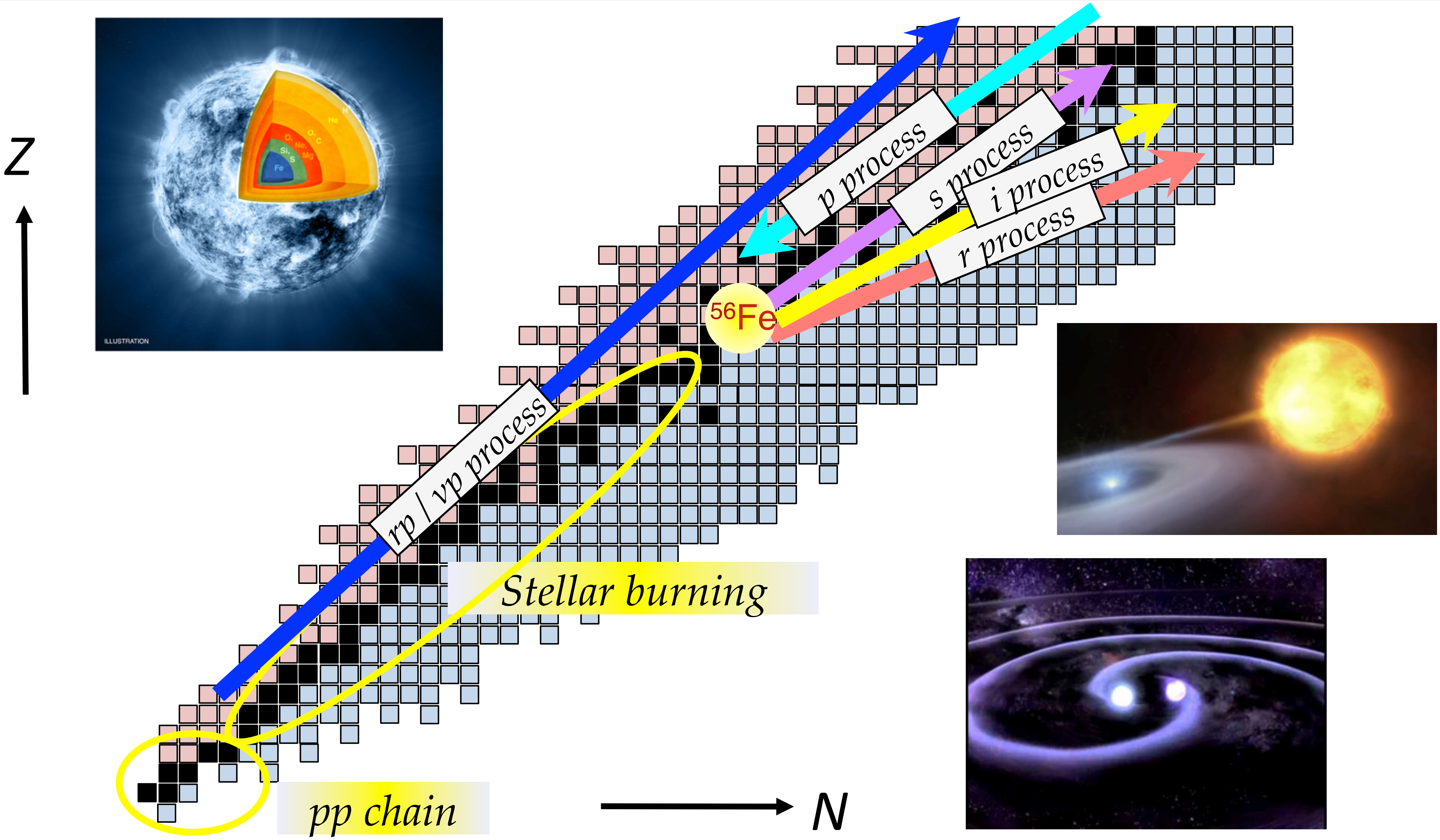
- R-process nucleosynthesis
- Neutron-star merger
- Kilonova

- Neutron-captures
- Beta-decay rates
- Neutron-γ competition

- Experimental techniques
- FRIB

Credit: Erin O'Donnel, NSCL

Stellar Nucleosynthesis



The site of the r-process ???

Credit: Erin O'Donnell, MSU

Core Collapse Supernova?

(maybe … require magnetorotation)

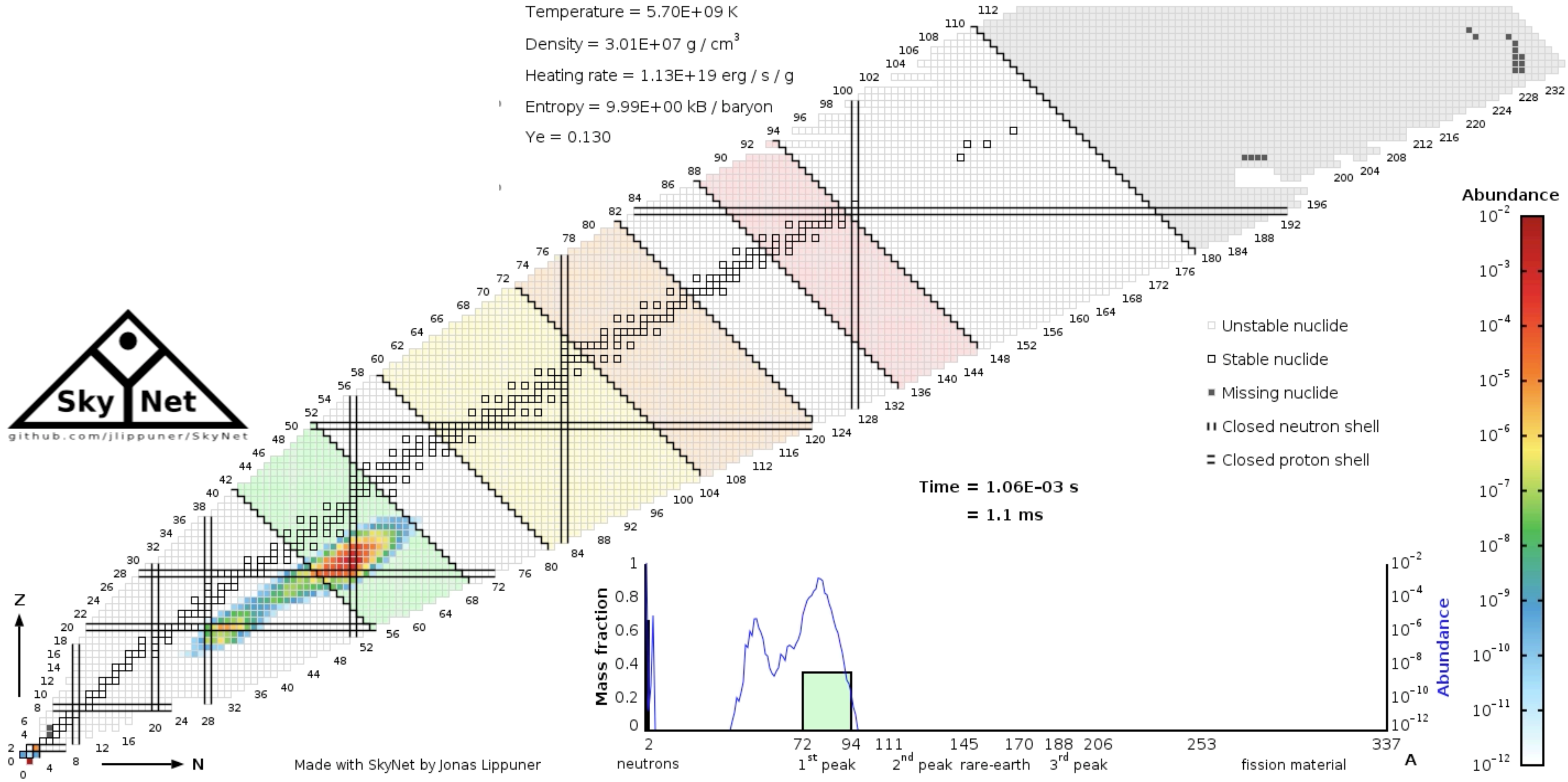
Neutron Star Merger?

Credit: NASA Goddard

Kasen et al, Nature 2017

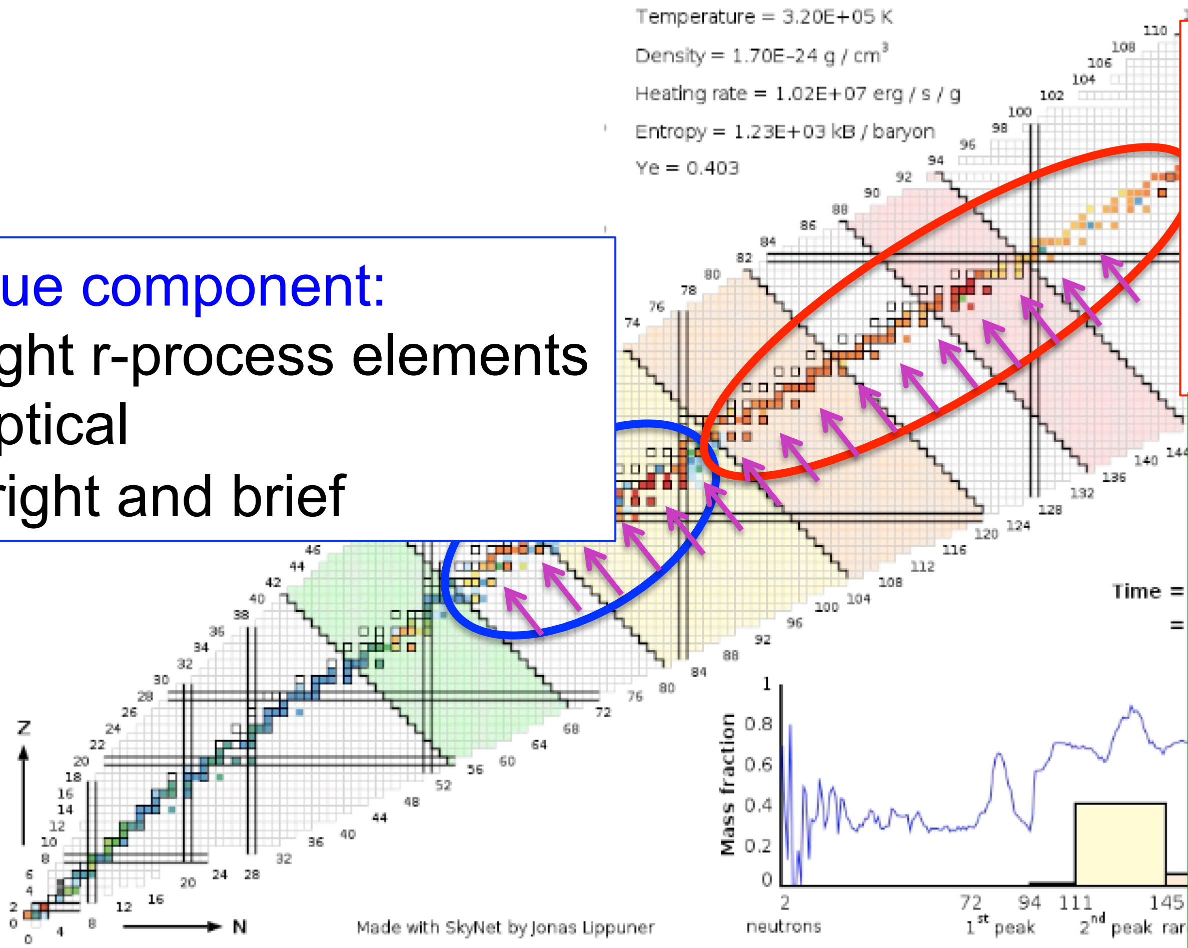
Martinez-Pinedo et al. PRL 109, 251104 (2012)

r-process in neutron-star mergers

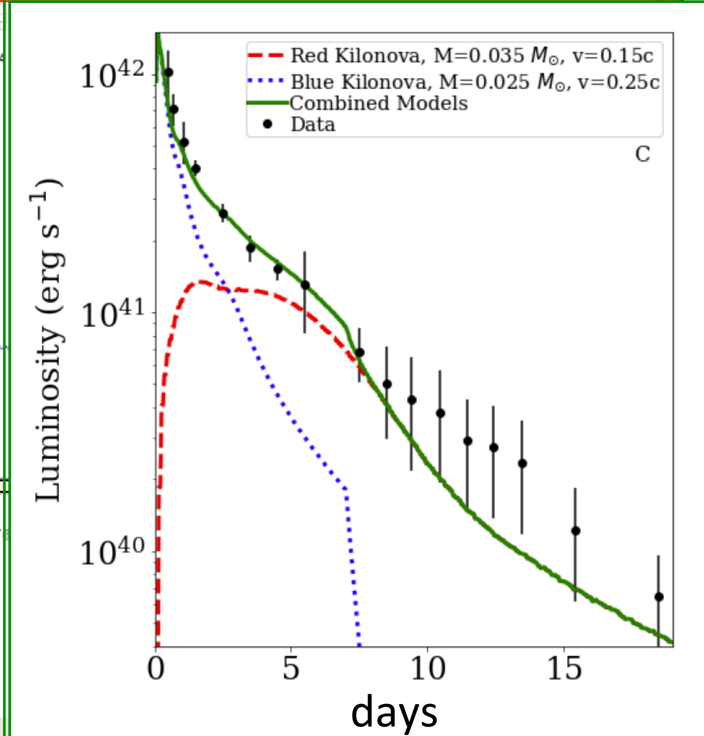


r-process in neutron-star mergers

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



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



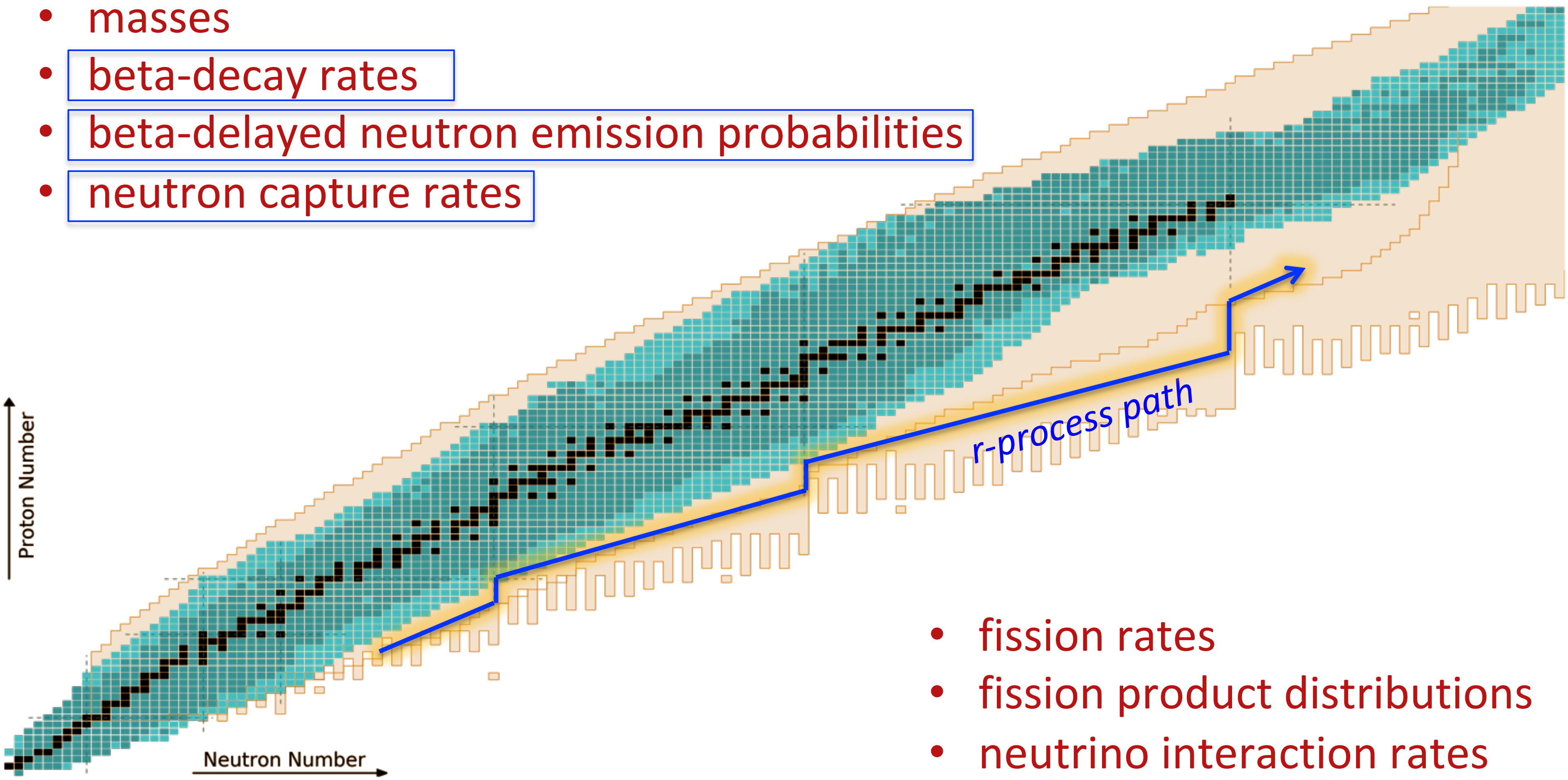
Kasen et al., Nature 2017

Made with SkyNet by Jonas Lippuner

Kilpatrick, et al, Science 2017

Nuclear Input for r-process

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

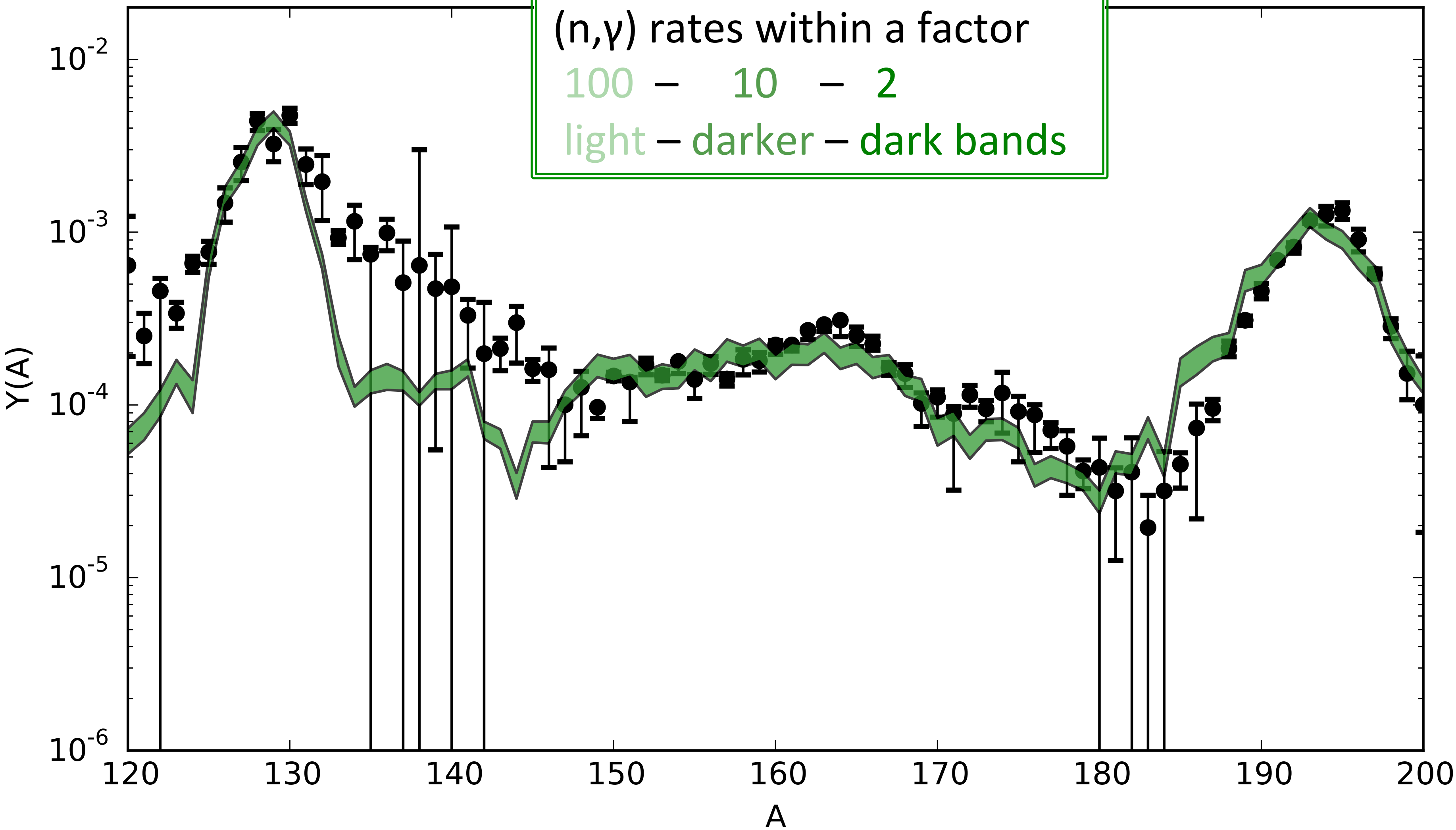


- fission rates
- fission product distributions
- neutrino interaction rates
- Equation of state

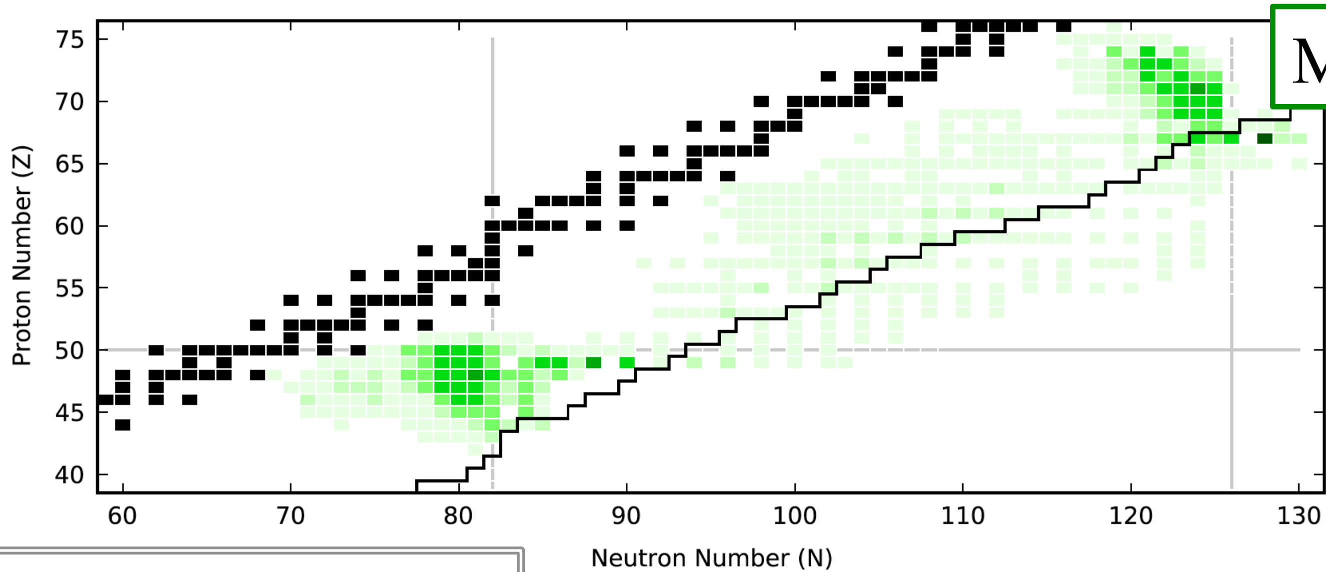
figure by M. Mumpower

R-process sensitivity to neutron-captures

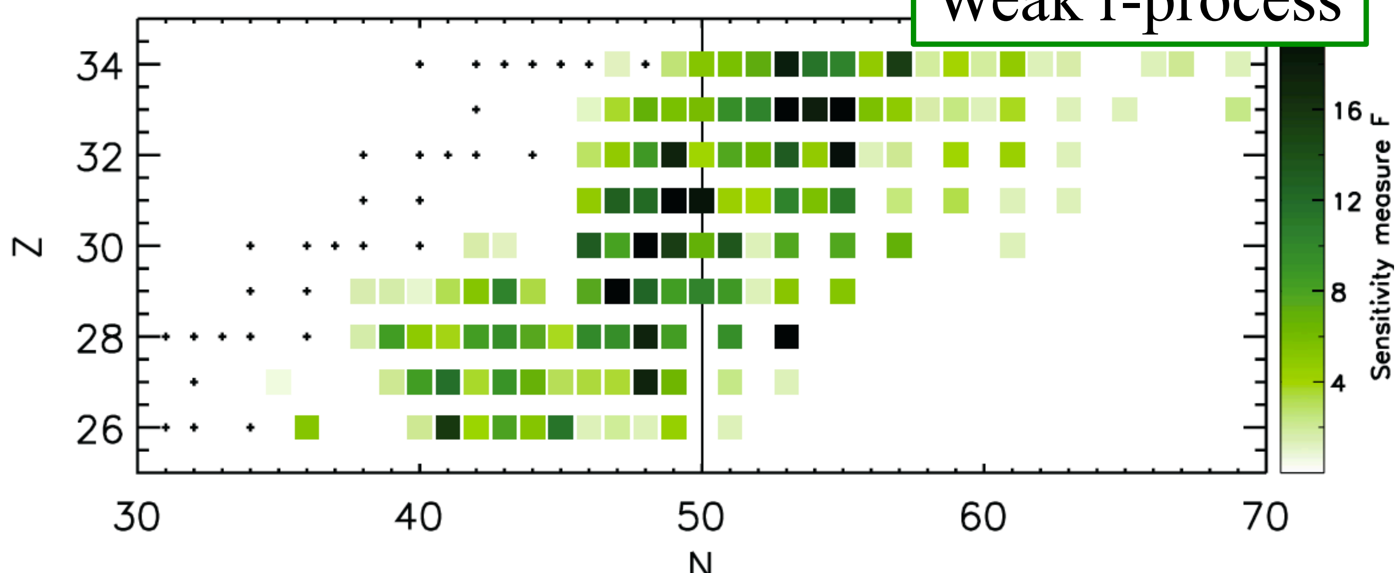
Monte-Carlo variations of (n,γ) rates within a factor
100 – 10 – 2
light – darker – dark bands



Neutron-capture sensitivity

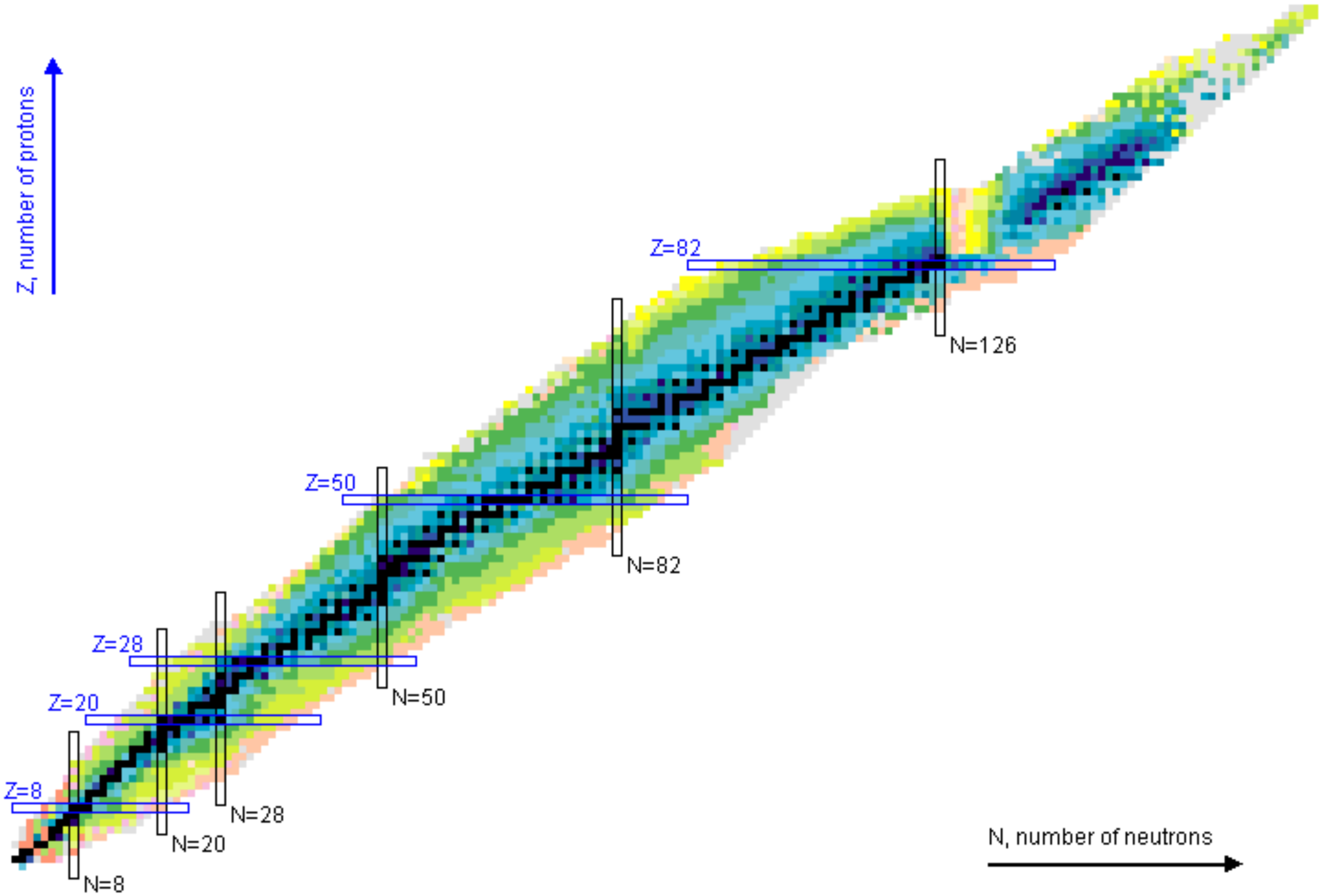


Mumpower et. al., PPNP 86 (2016) 86

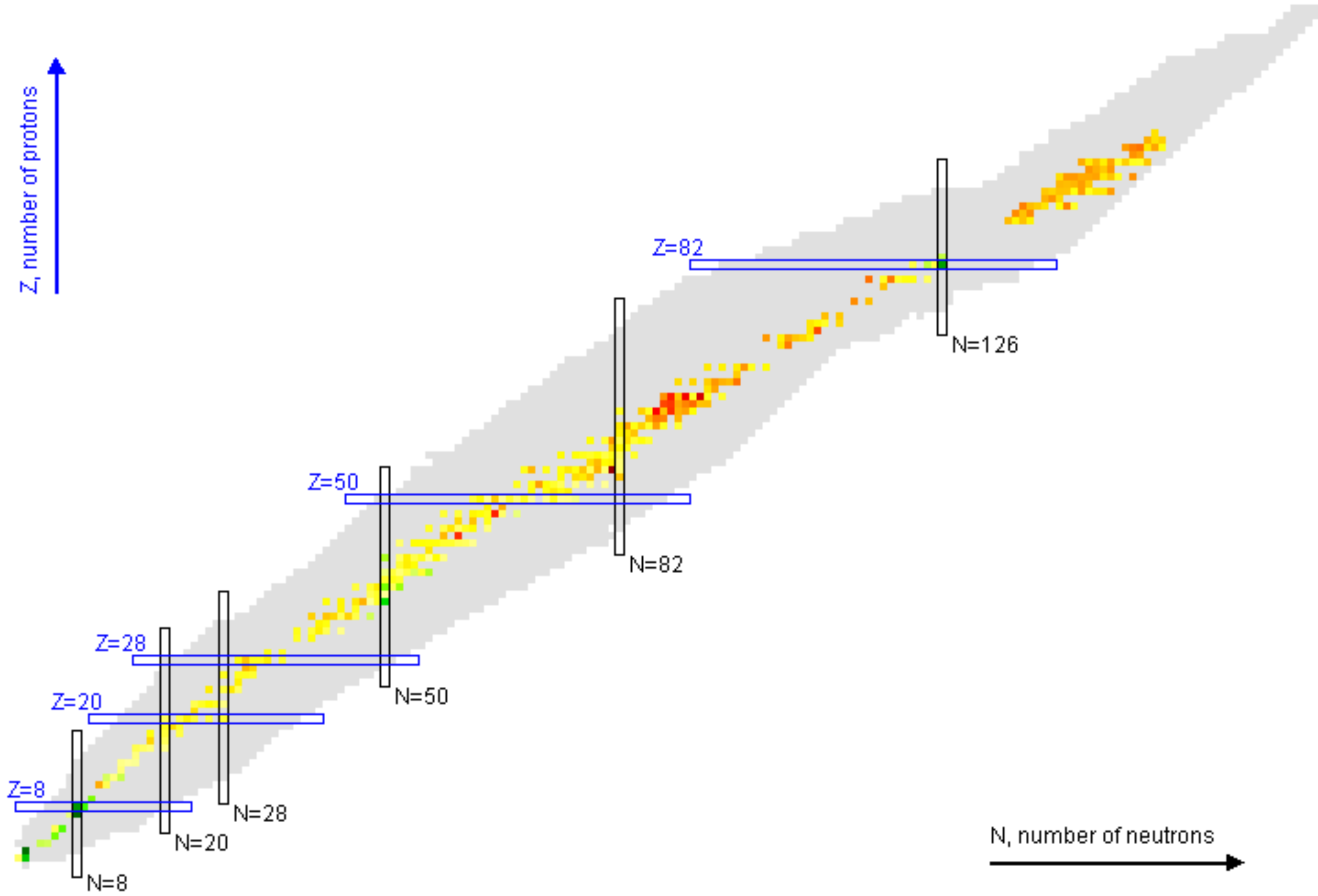


Surman, et al., , AIP Advances 4, 041008 (2014)

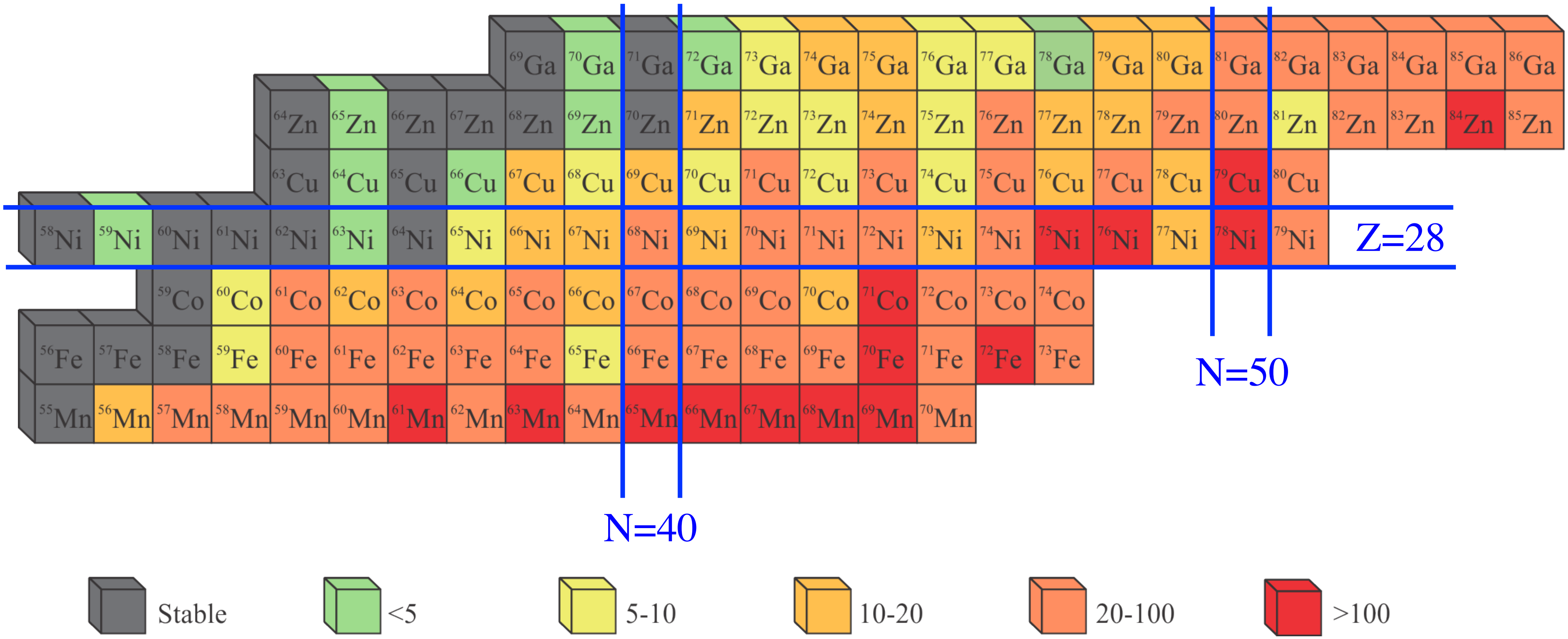
Current (n,γ) measurements



Current (n,γ) measurements



Neutron capture reactions



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

National Science Foundation
Michigan State University

NSCL

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

Liddick, Spyrou, et al., PRL 2016

Indirect Techniques for (n,γ) reactions

Coulomb Dissociation

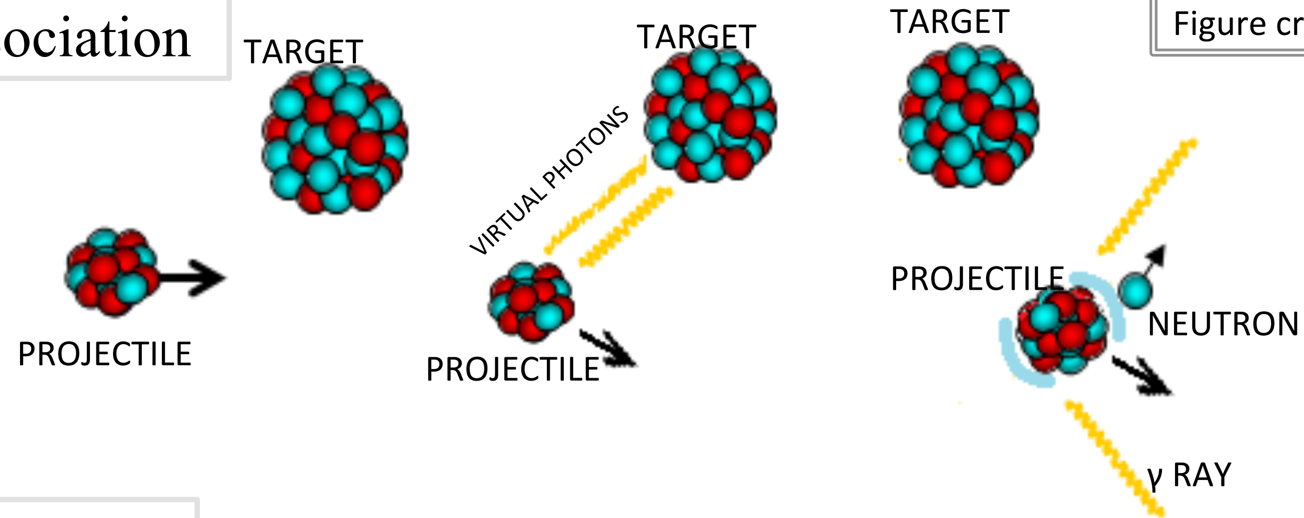
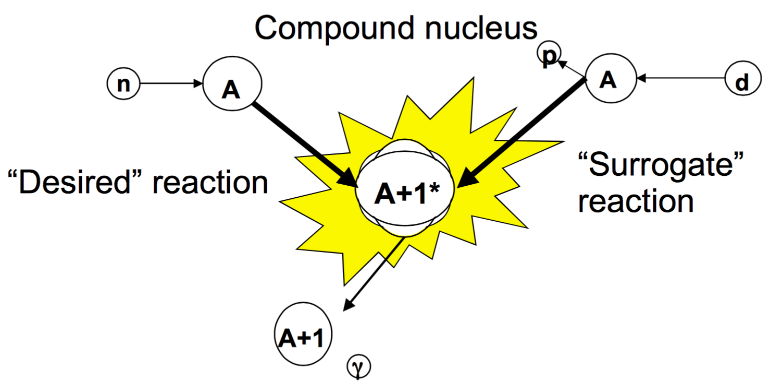


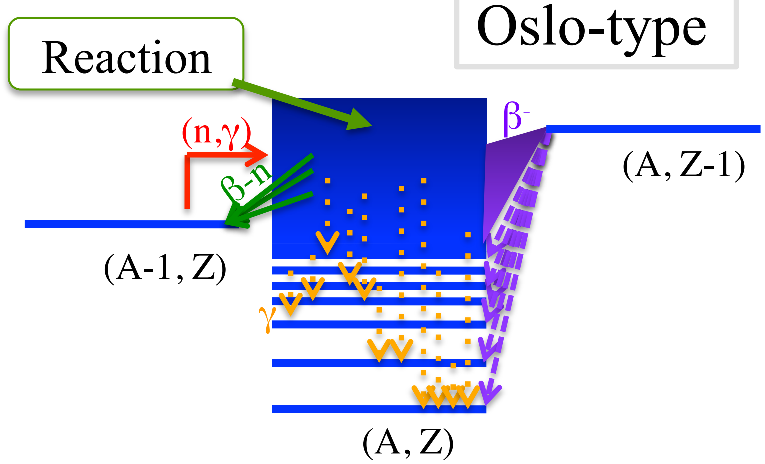
Figure credit: Riccardo Avigo

Surrogate Technique



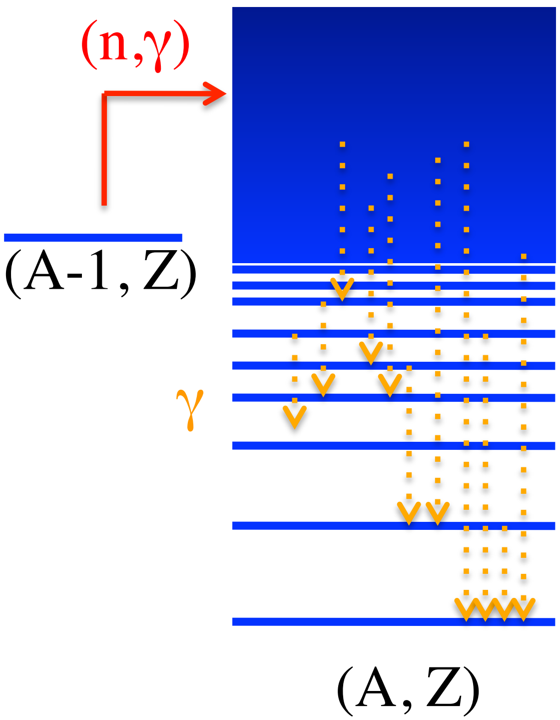
A. Ratkiewicz, J. Cizewski, et. al. EPJ WoConf. 2015
J. Escher et al. PRL 2018

Oslo-type



Spyrou, Liddick, et. al., PRL 2014
Guttormsen et al, NIMA, 1987

Neutron Captures within the Statistical Model



<u>Hauser – Feshbach</u>

- Nuclear Level Density

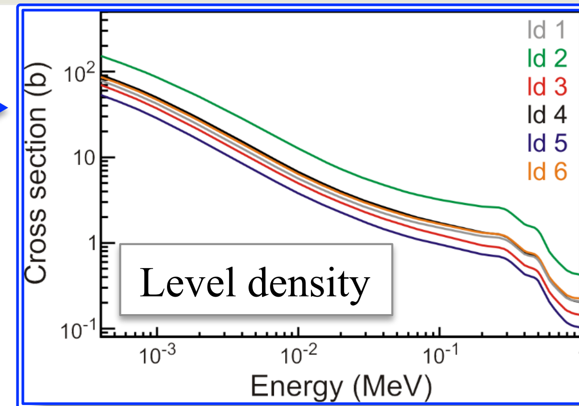
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

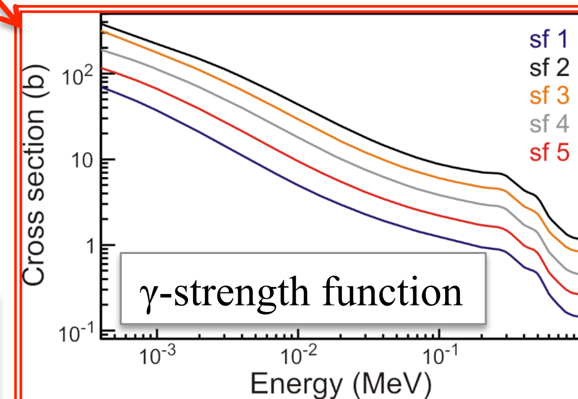
- γ-ray strength function

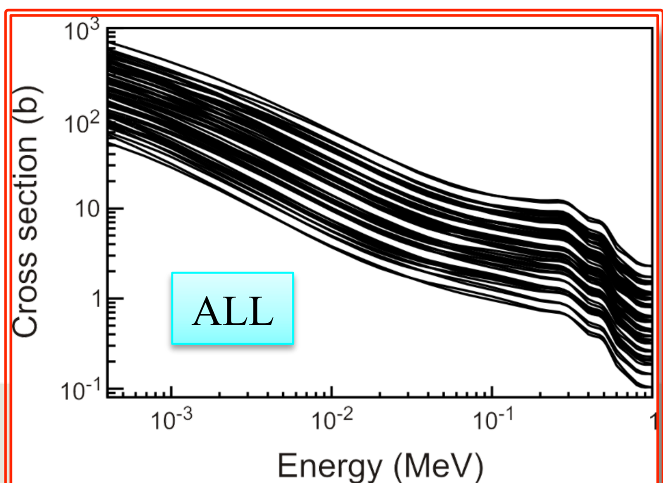
Generalized Lorentzian, Brink-Axel, various tables

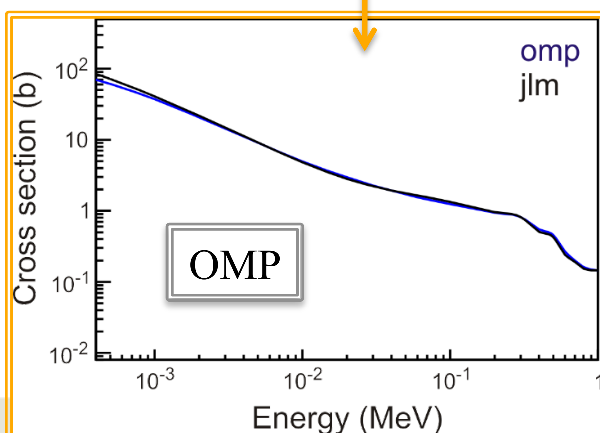
- Optical model potential

Phenomenological, Semi-microscopic







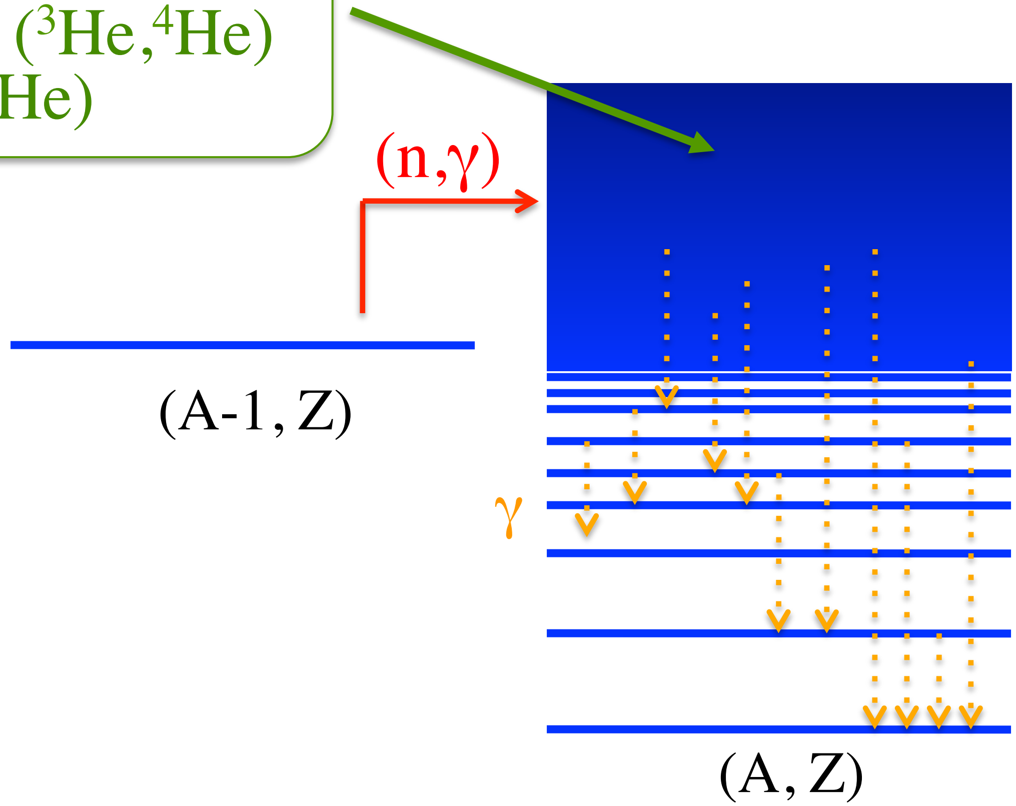


$^{95}Sr(n,\gamma)^{96}Sr$

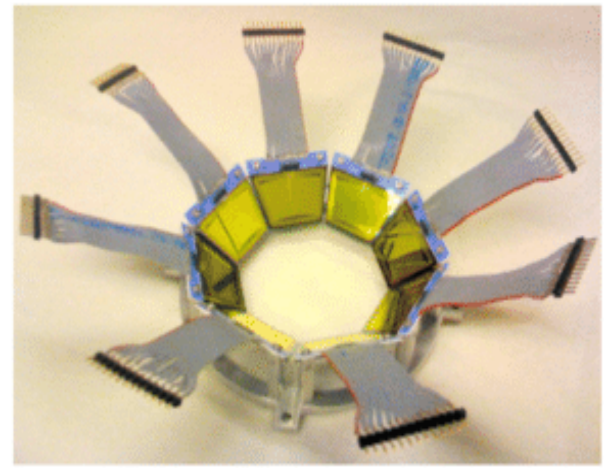
TALYS

Oslo method

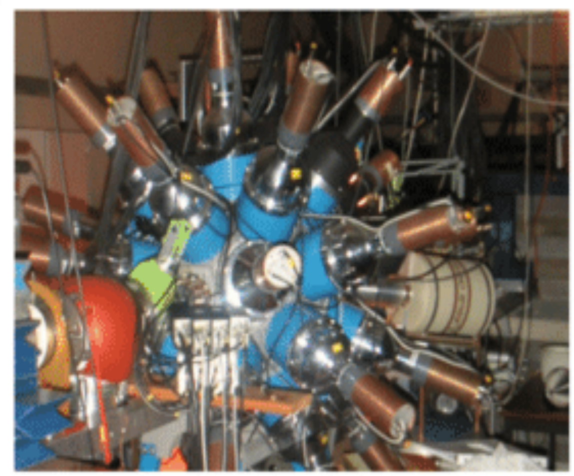
(d,p) (^{3}He,^{3}He)
(p,t) (^{3}He,^{4}He)
(p,^{4}He)



SiRi



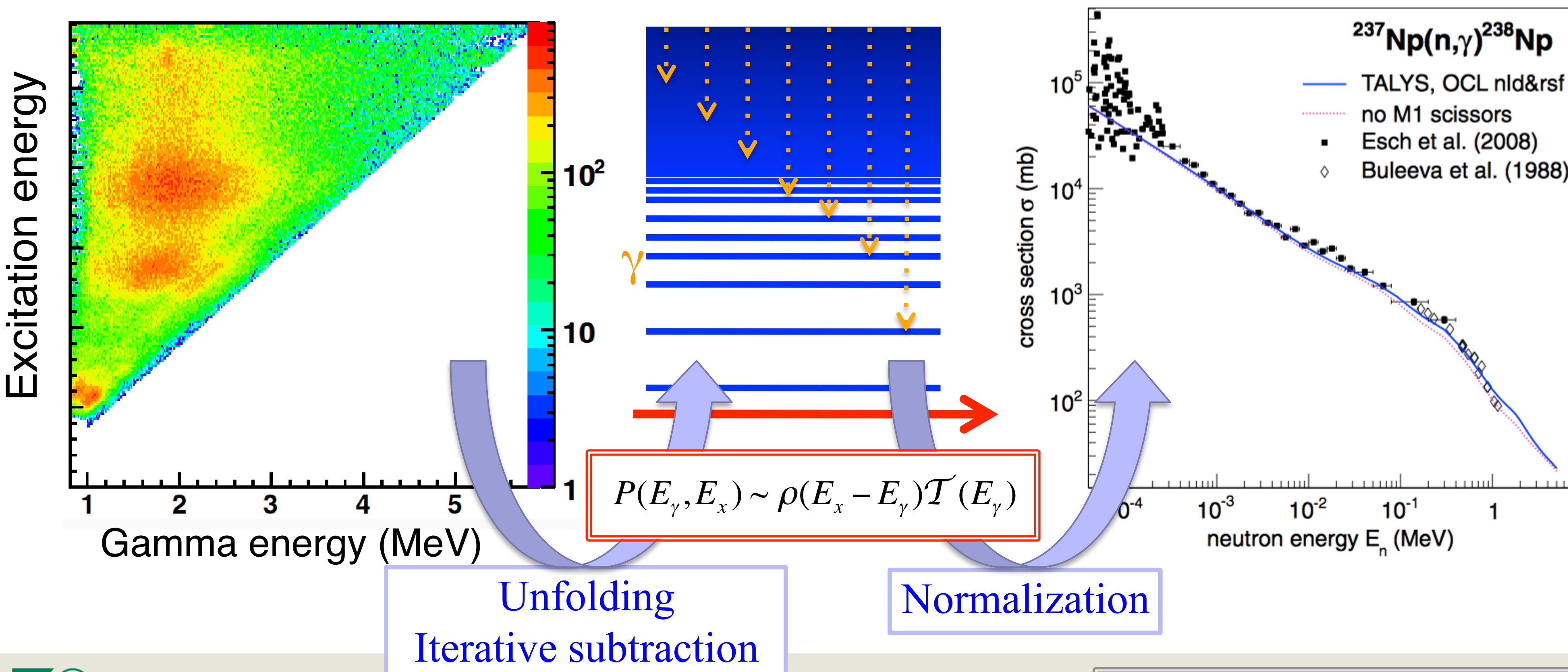
CACTUS



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

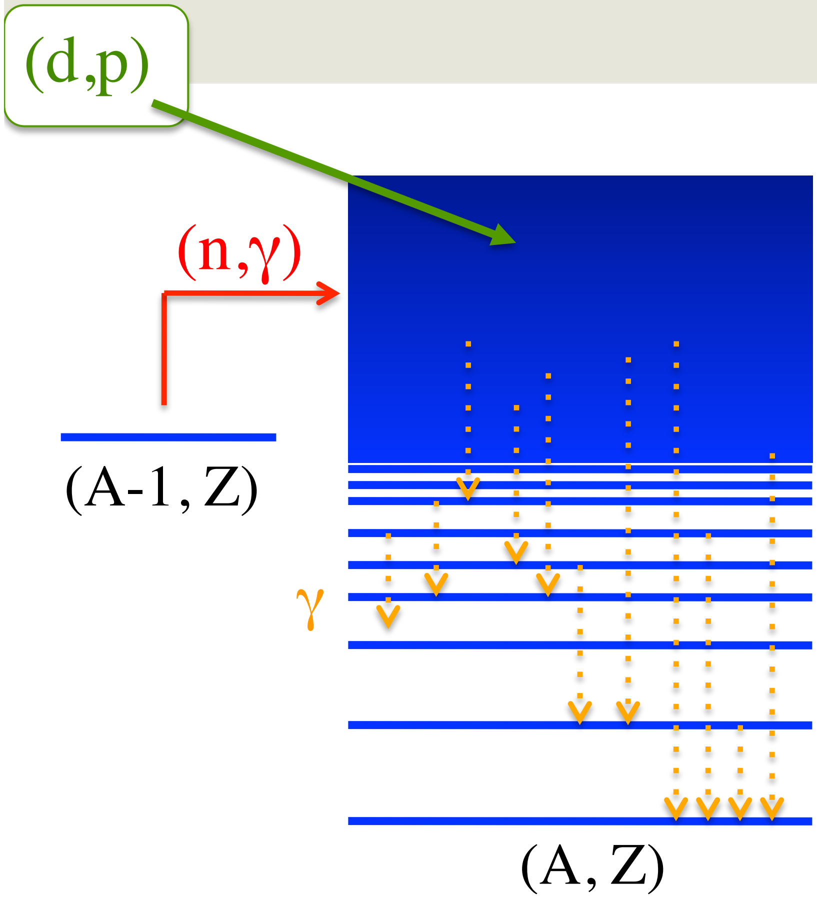
Traditional Oslo method

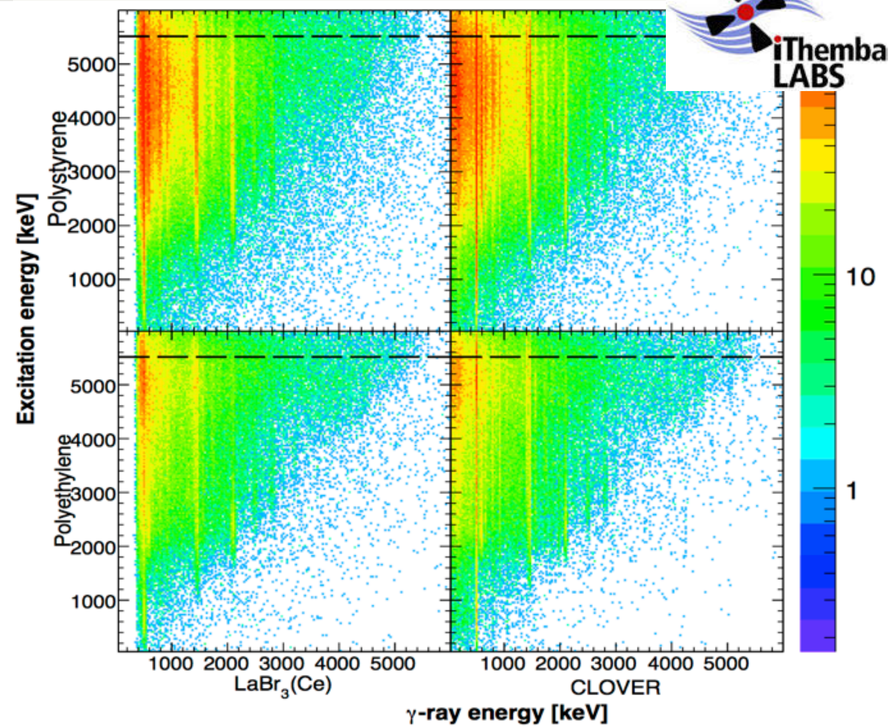
- Use reaction to populate the compound nucleus of interest
- Measure excitation energy and γ-ray energy
- Extract **level density** and **γ-ray strength function** (external normalizations)
- Calculate "semi-experimental" (n,γ) cross section
- Excellent agreement with measured (n,γ) reaction cross sections



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

Oslo method in inverse kinematics





- First radioactive beam experiment @ ISOLDE
- ^{66}Ni(d,p)^{67}Ni
- Under analysis (Vetle Wegner)

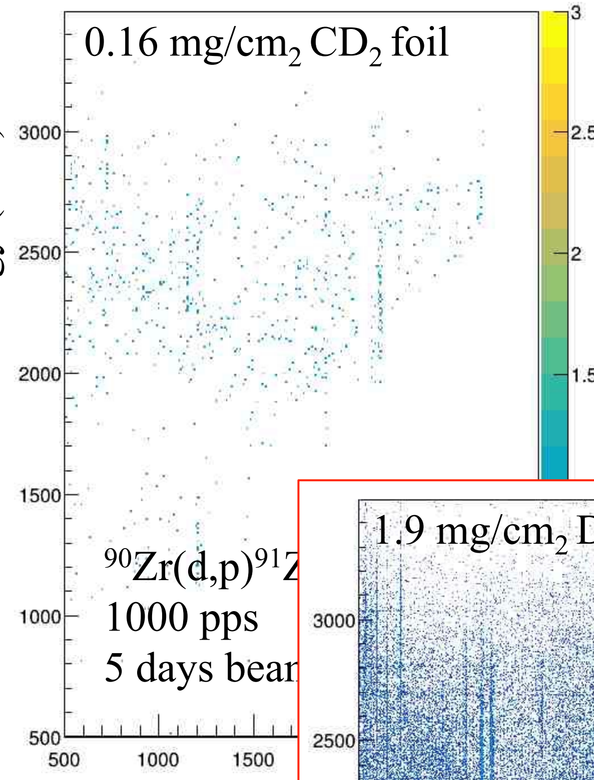
- Proof of principle: ^{86}Kr(d,pg)^{87}Kr,
- inverse kinematics @ iThemba LABS,
- 300-MeV ^{86}Kr beam on CD_2
- AFRODITE (Ge clovers) array + two 3.5" x 8" LaBr3 detectors from Oslo

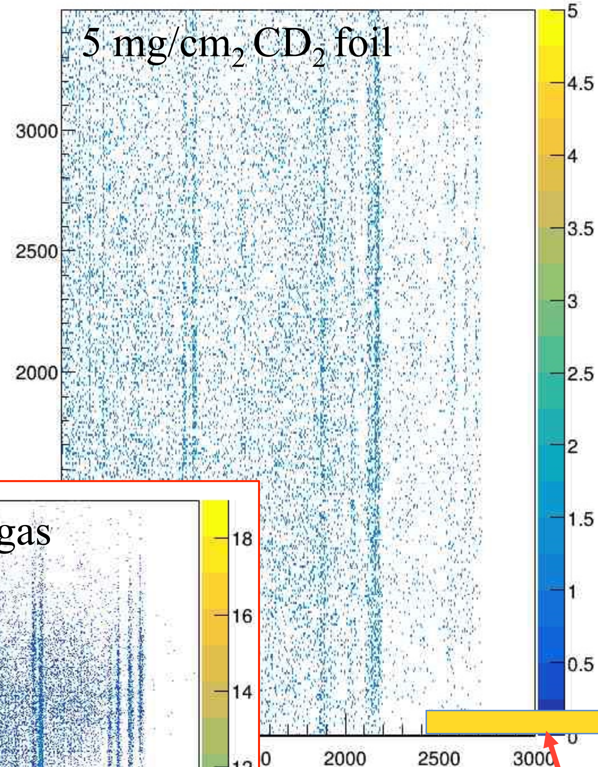
Siem, Wiedeking, Larsen, Guttormsen, Wegner

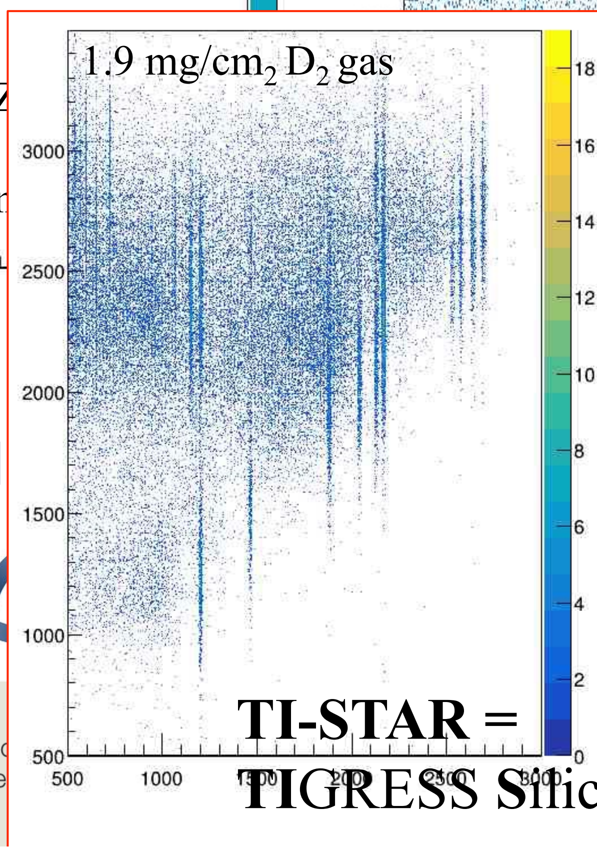
Oslo method in inverse kinematics

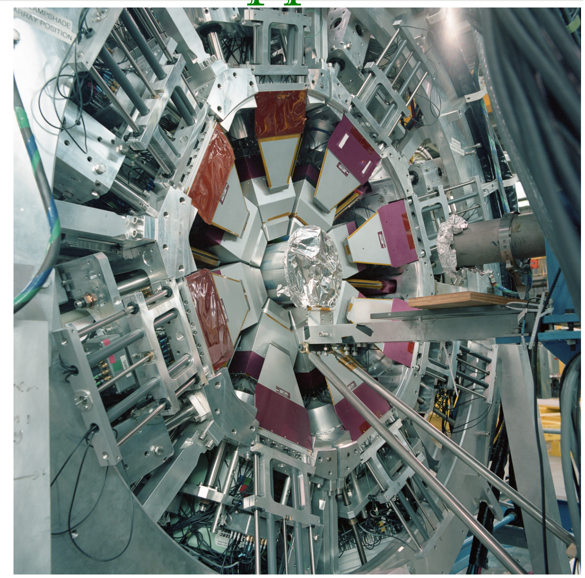
Yield vs Resolution

new approach

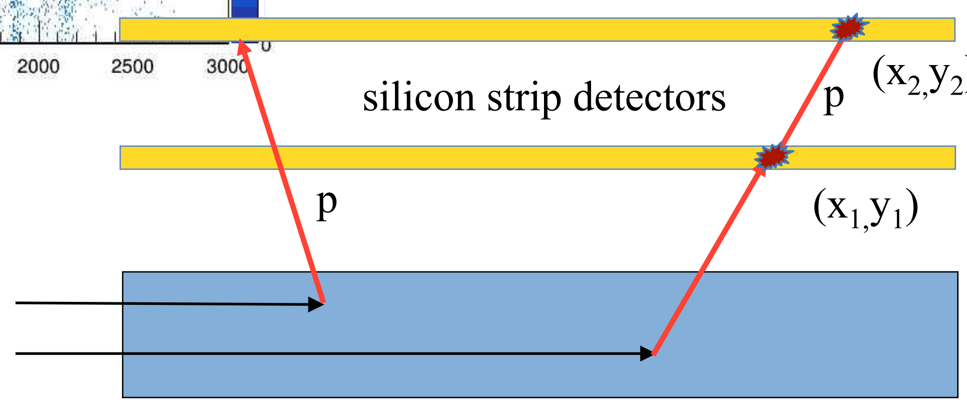








TIGRESS



TRIUM

UNIVERSITY of GUELPH

TI-STAR =

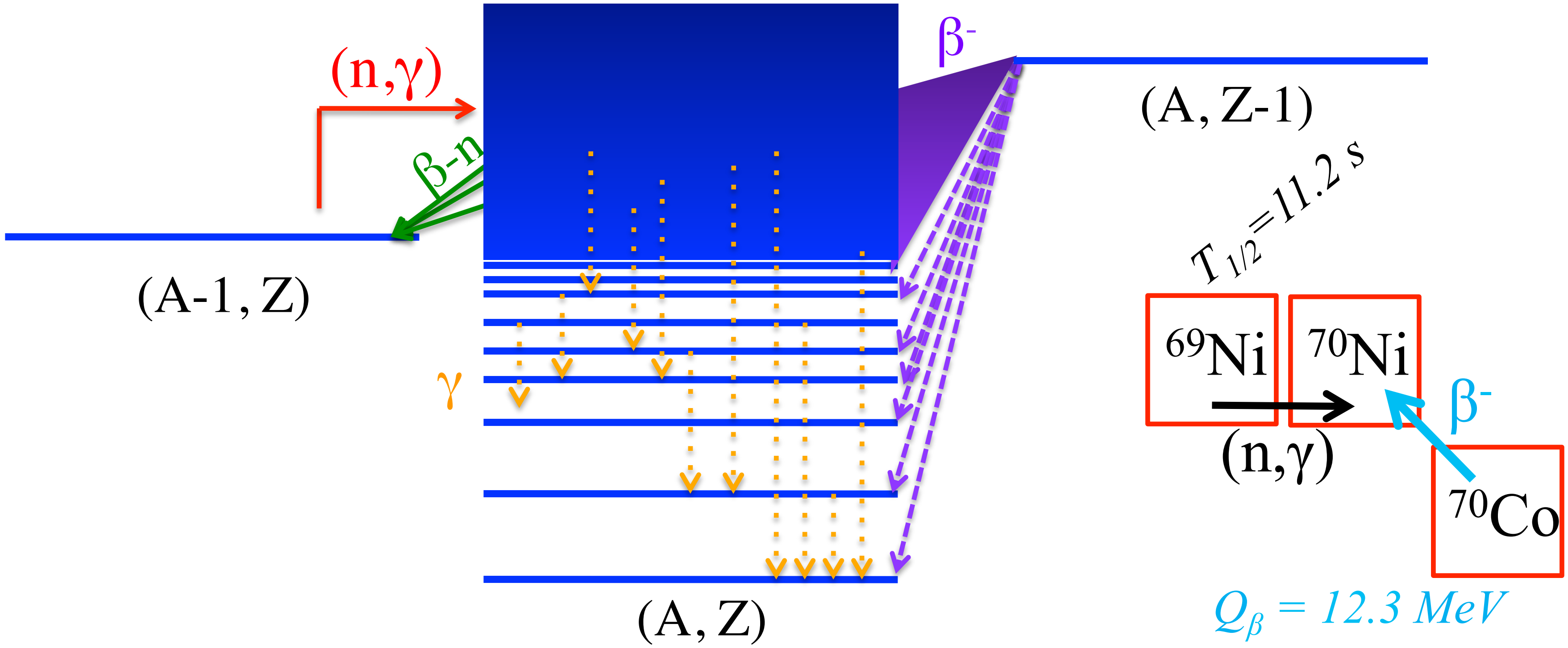
TIGRESS **S**ilicon **T**racker **AR**ray

Dennis Muecher – TI-STAR Collaboration

National Scienc
Michigan State

NSCL

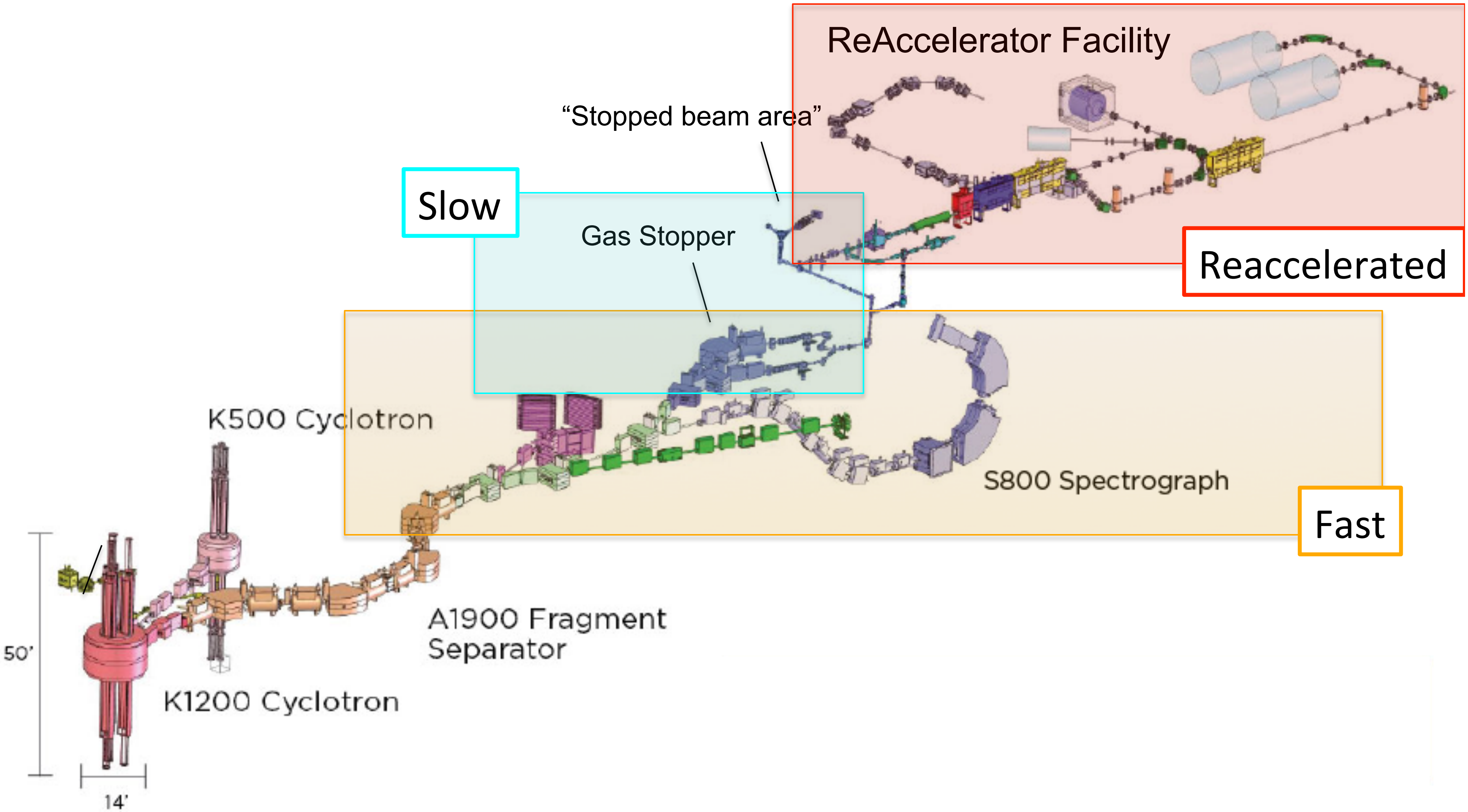
β-Oslo



- 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.
- Need Total Absorption Spectroscopy

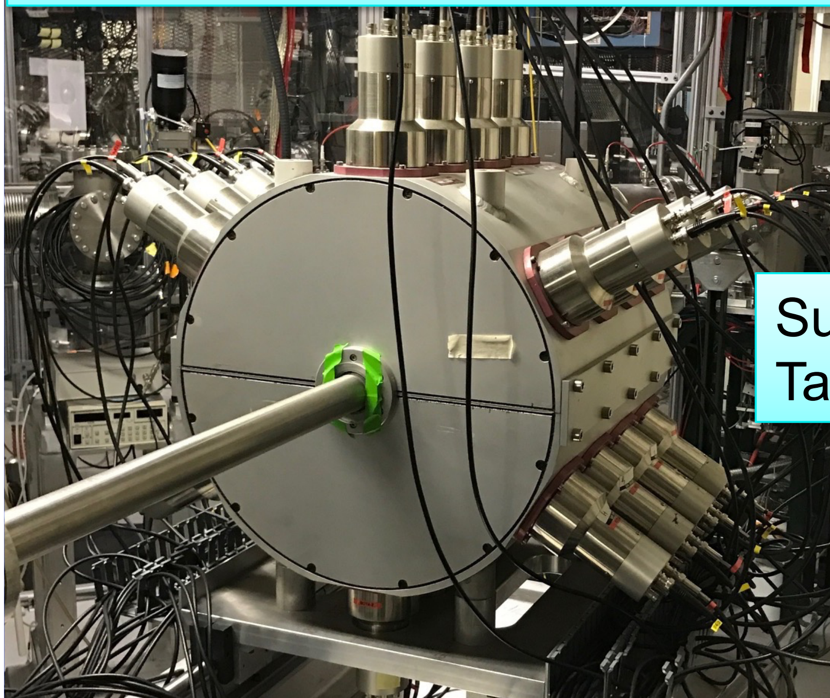
Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

National Superconducting Cyclotron Lab

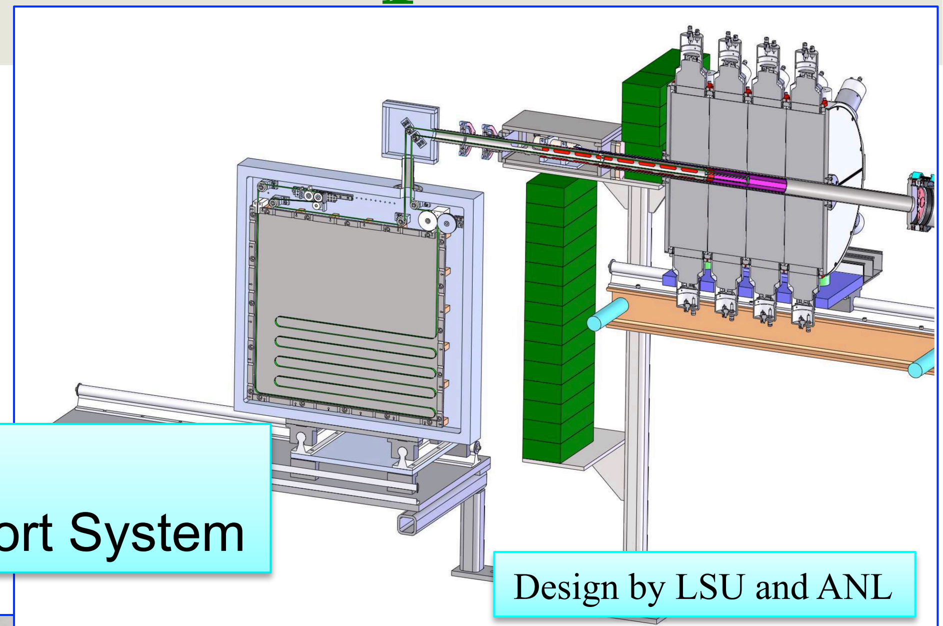


Experimental Setup

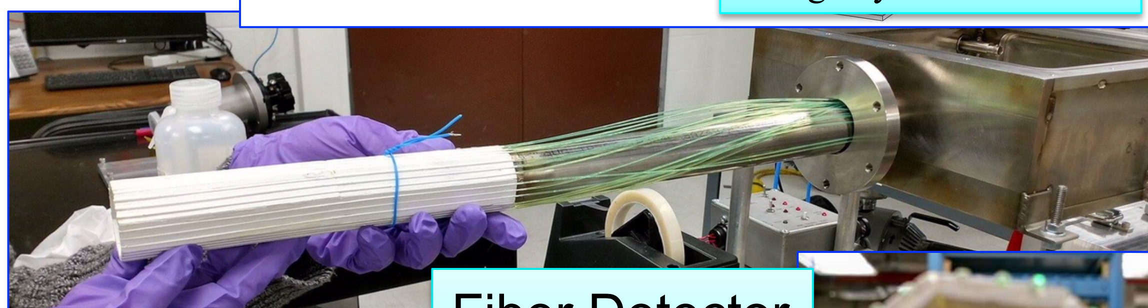
SuN
γ-Total Absorption Spectrometer



SuNTAN
Tape Transport System

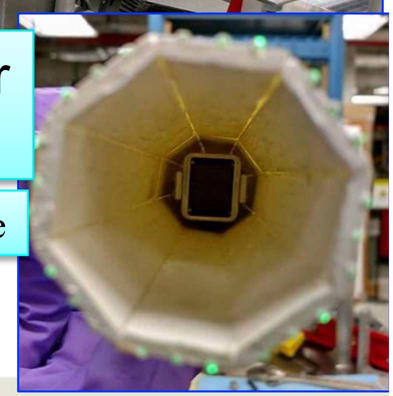


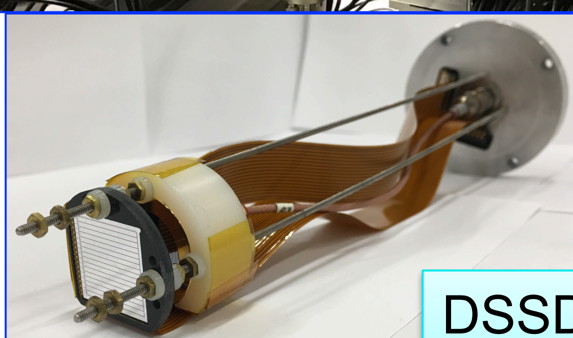
Design by LSU and ANL



Fiber Detector
β-detection

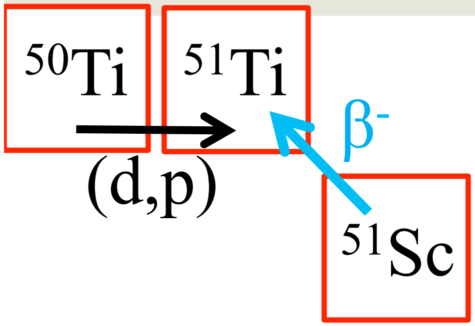
Hope College



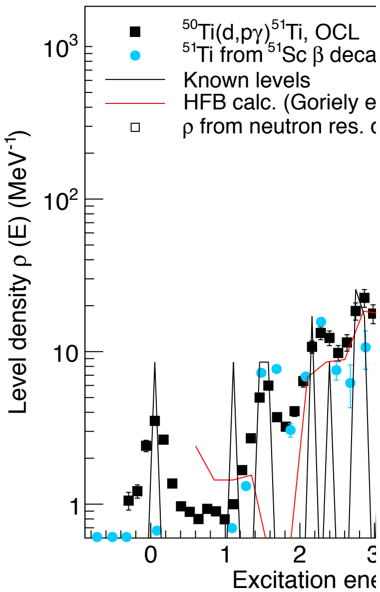


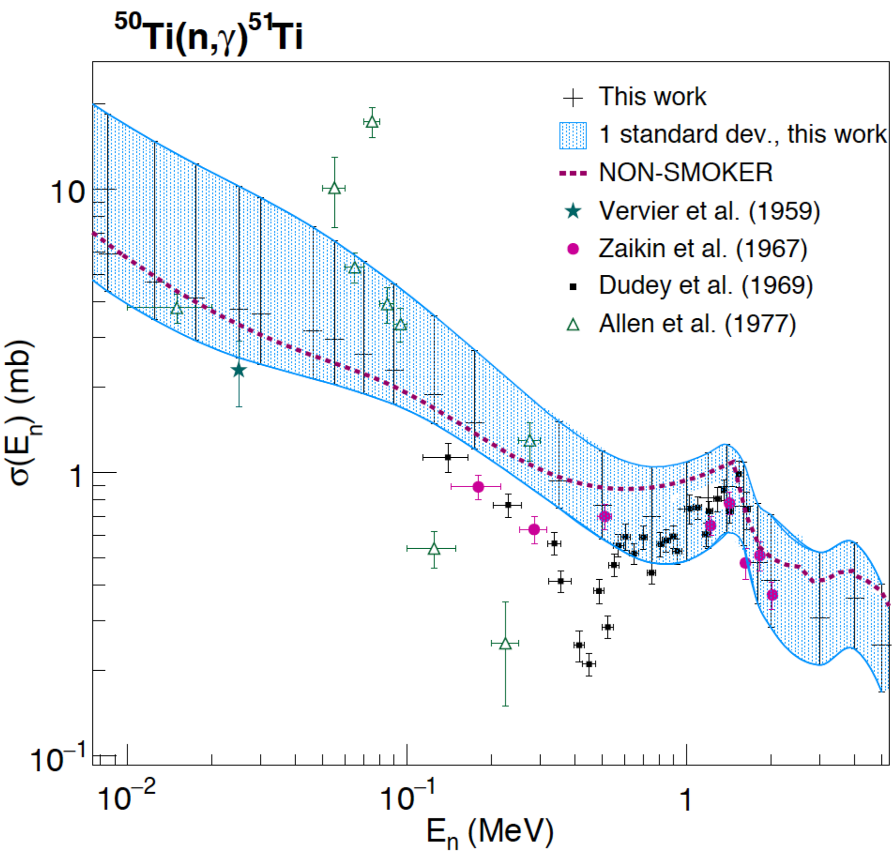
DSSD
Implantation-decay correlation

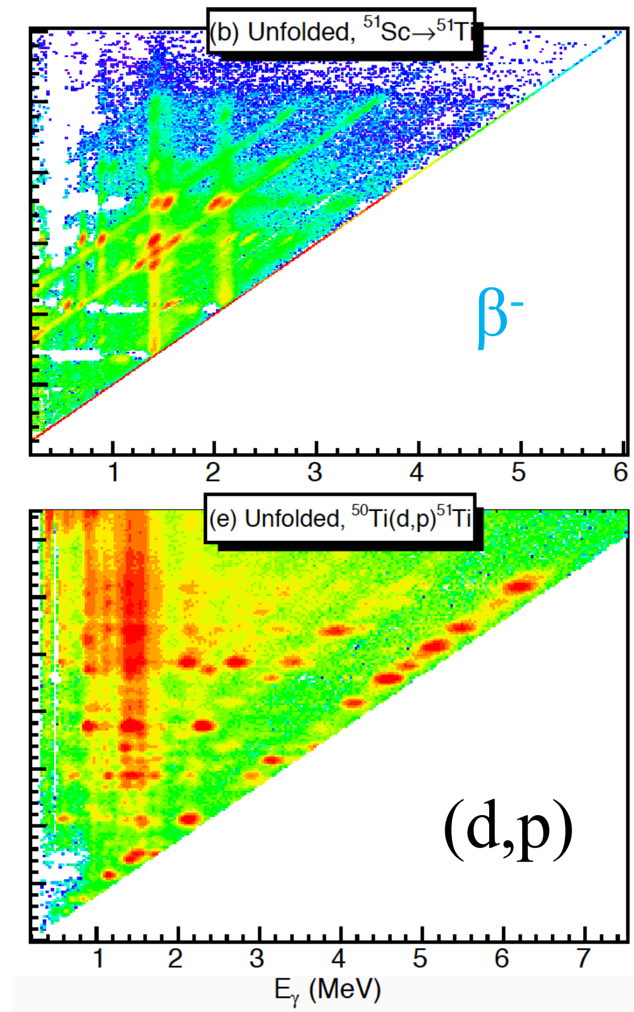
β-Oslo validation



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



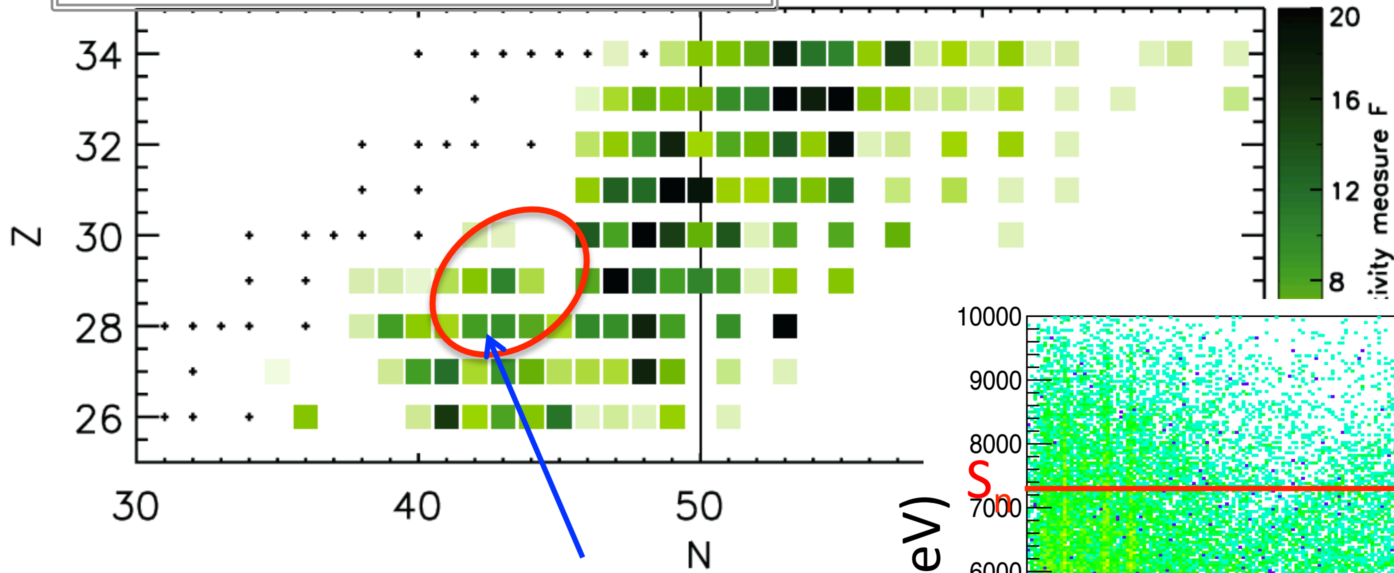




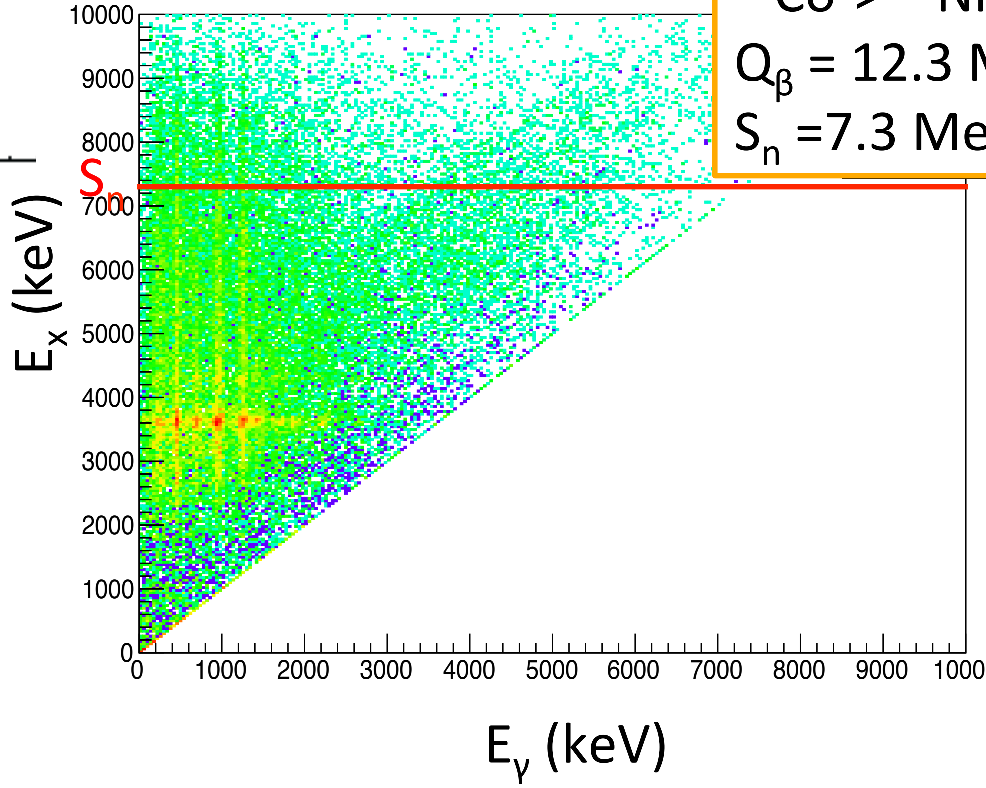
Liddick, Larsen,, et al, PRC2018-submitted

Weak r-process measurements

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



^{70}Co-> ^{70}Ni
Q_{β} = 12.3 MeV
S_n =7.3 MeV

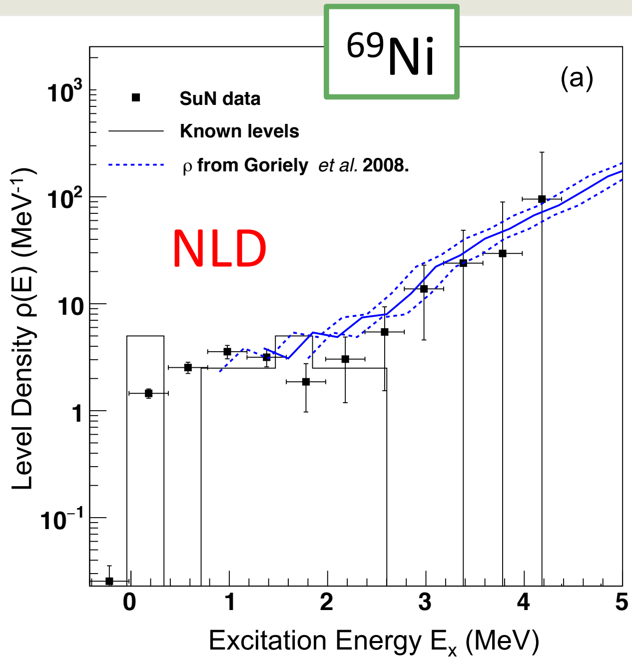


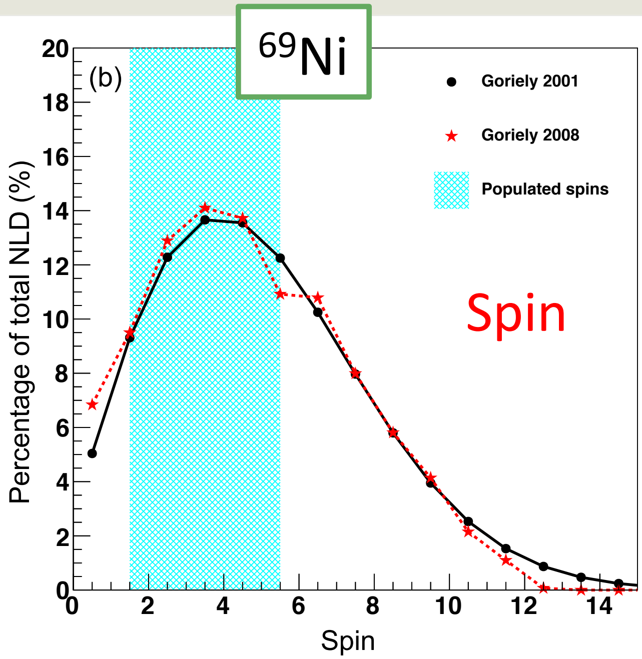
^{69,70}Co β decay: ^{68,69}Ni(n,γ)^{69,70}Ni

^{74}Cu β decay: ^{73}Zn(n,γ)^{74}Zn

Liddick, Spyrou et al, PRL 2016
Spyrou et al., JPG 2017

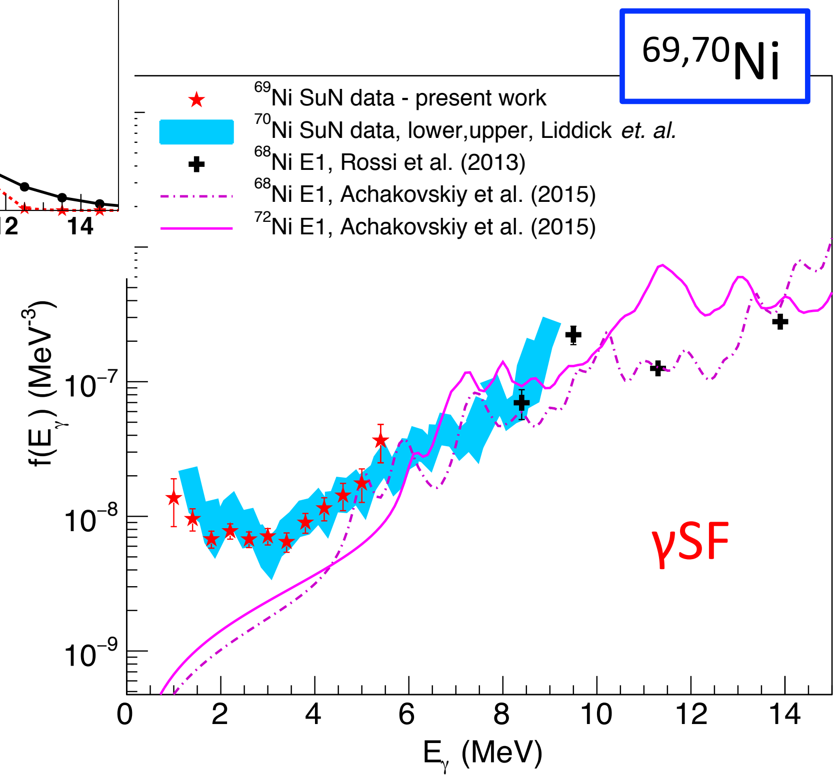
First Results ^{69,70}Ni

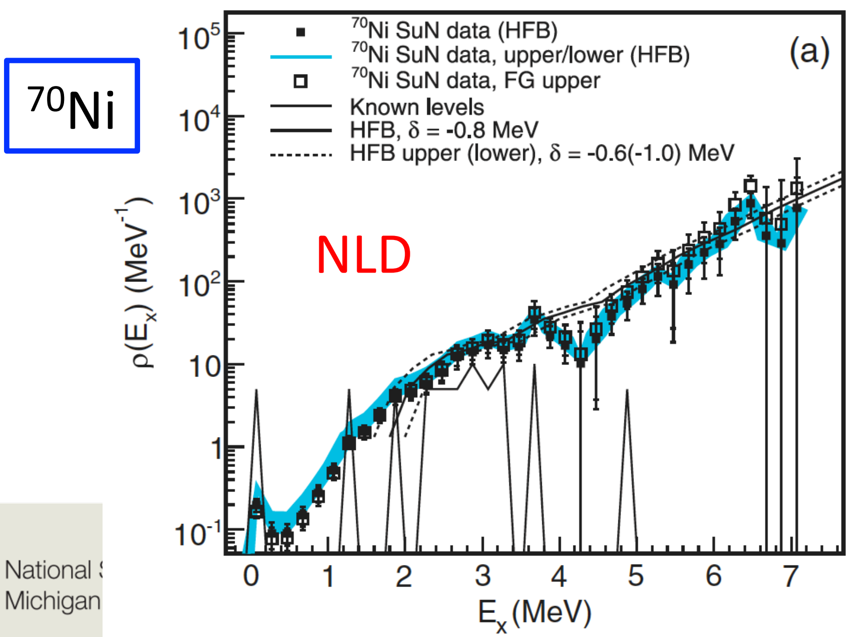




Normalizations far from stability:

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





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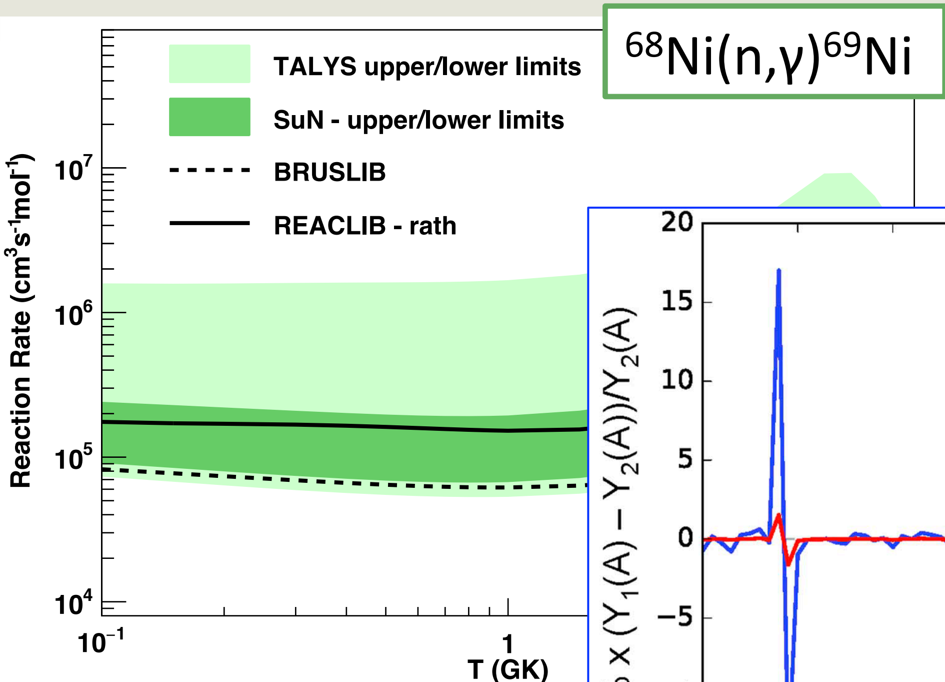
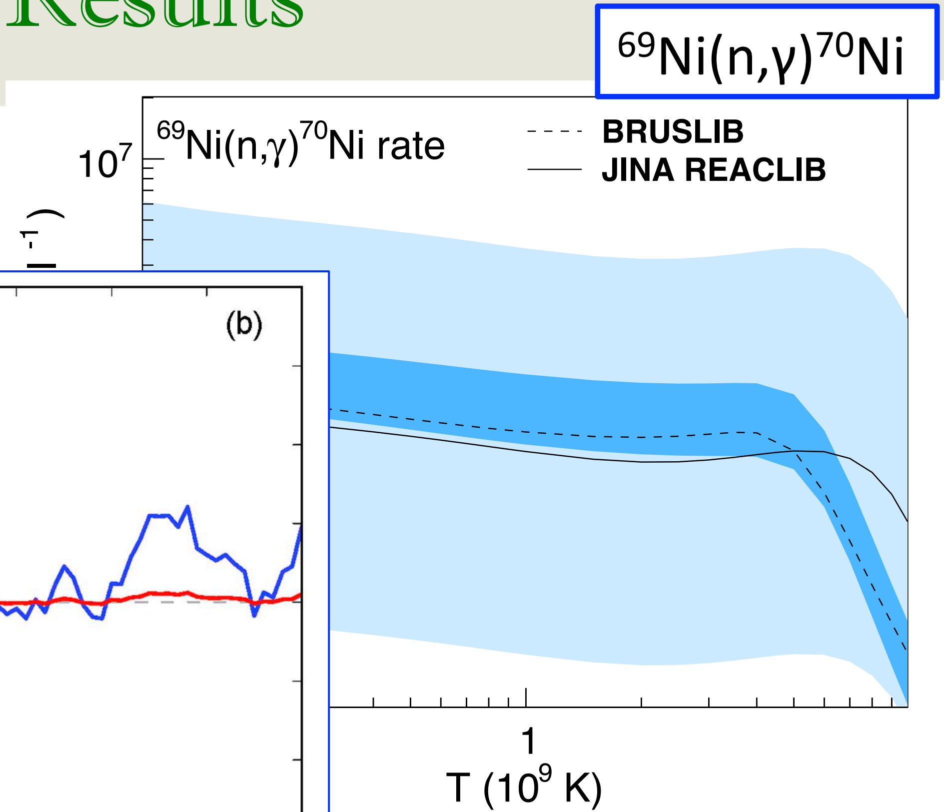
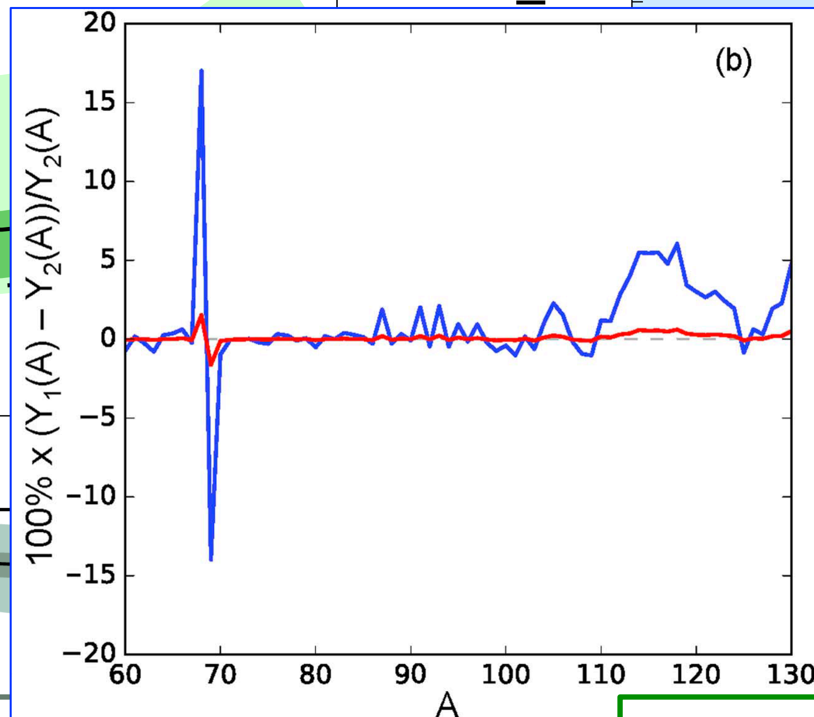
Liddick, Spyrou, et al, PRL 2016

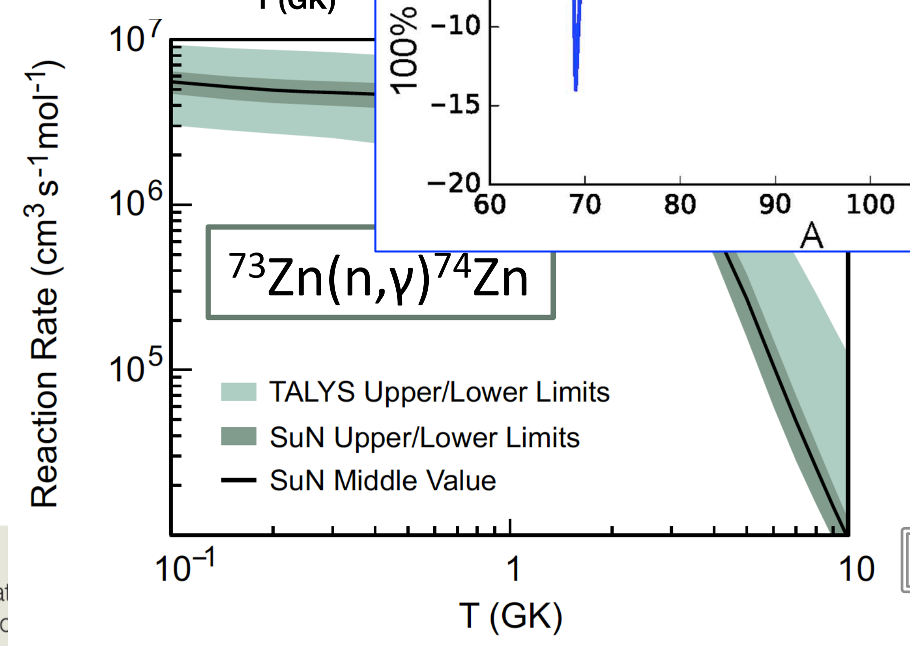
Spyrou, Larsen, et al, JPG 2017

First (n,γ) Results









Impact on weak r-process abundance calculations

Liddick, Spyrou, et al, PRL 2016

Lewis, et al, Submitted 2018

Spyrou, Larsen, et al, JPG 2017

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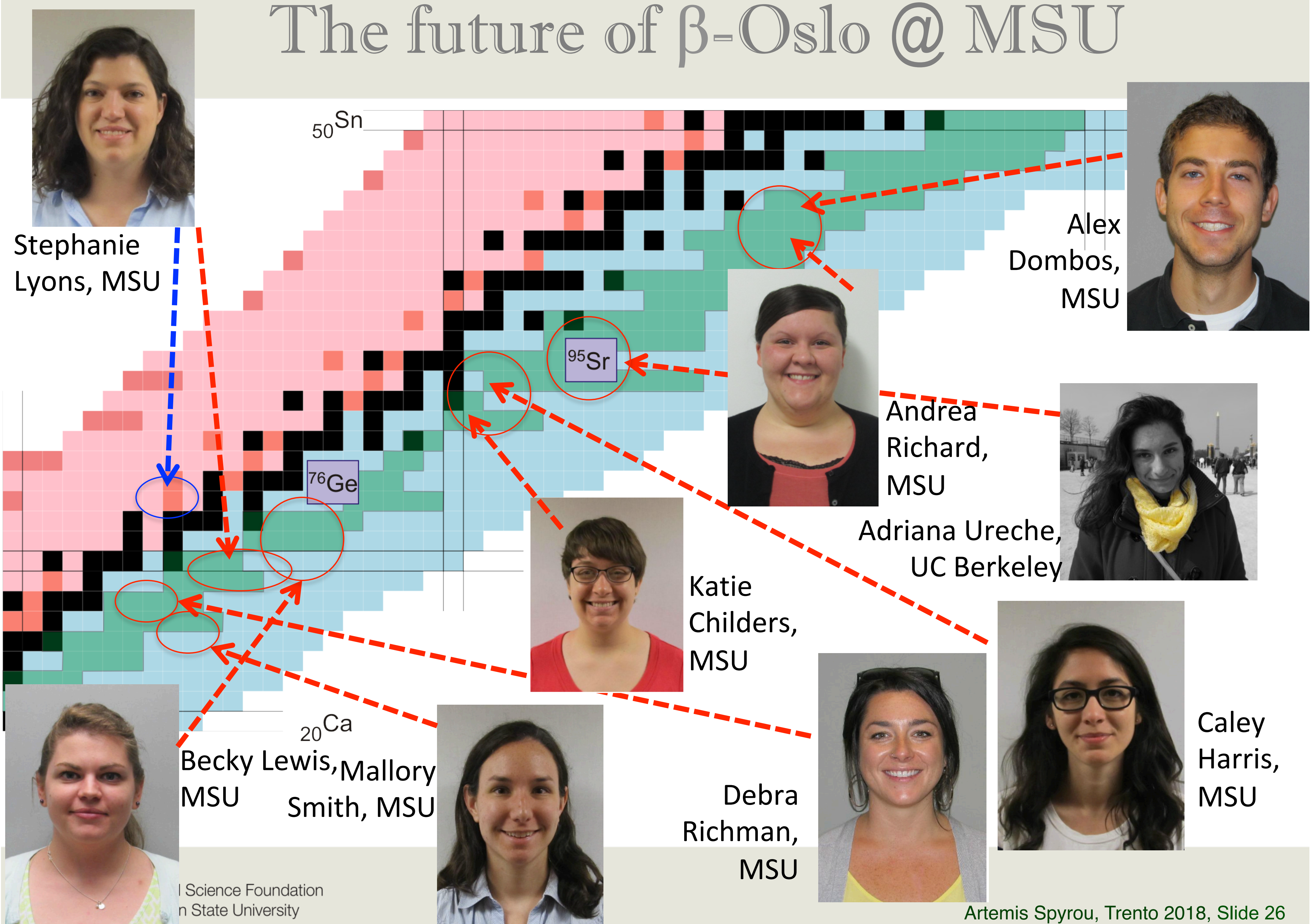
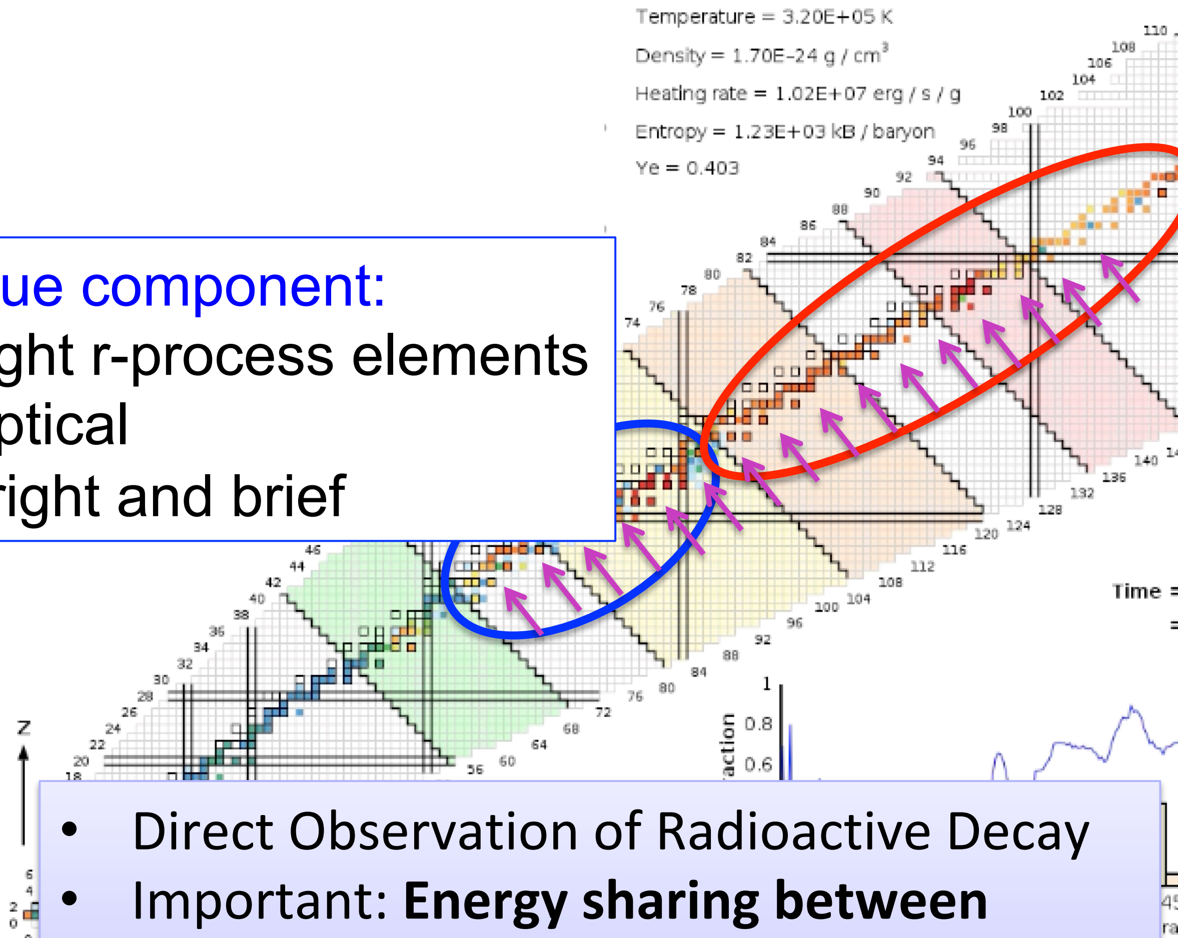
The future of β-Oslo @ MSU

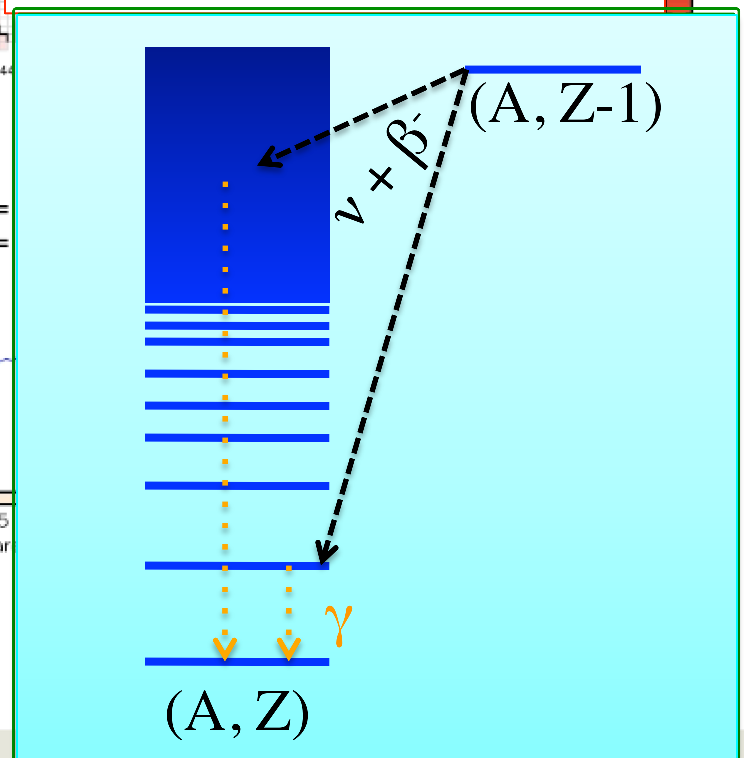


r-process in neutron-star mergers



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!!!

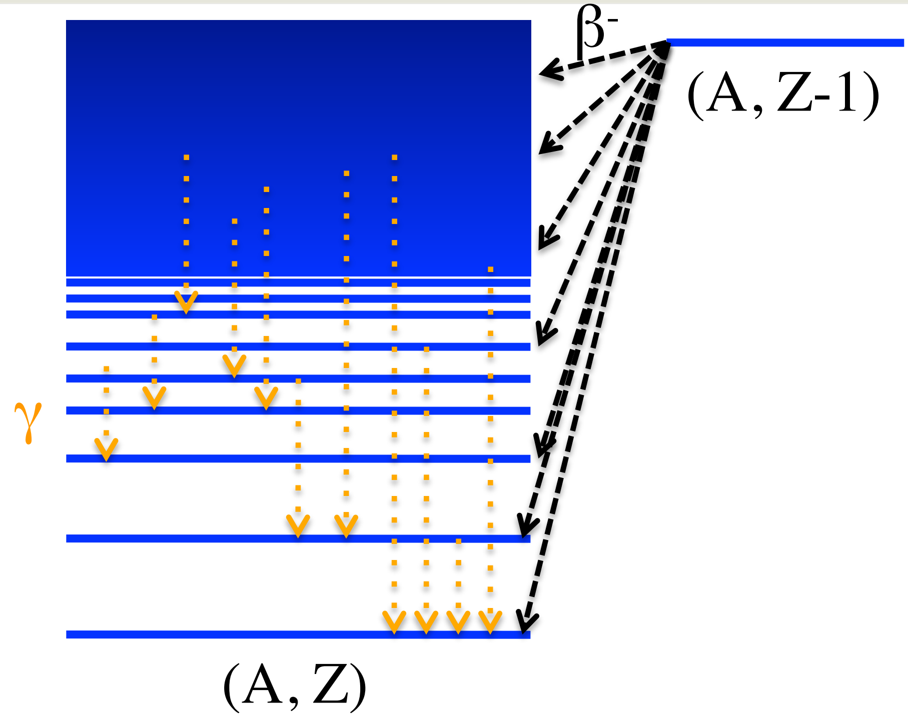
Kasen et al., Nature 2017

Made with SkyNet by Jonas Lippuner

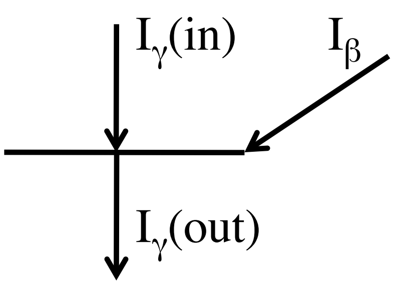
Kilpatrick, et al, Science 2017

The pandemonium effect

John Milton's "Paradise Lost



Small size – low efficiency detector

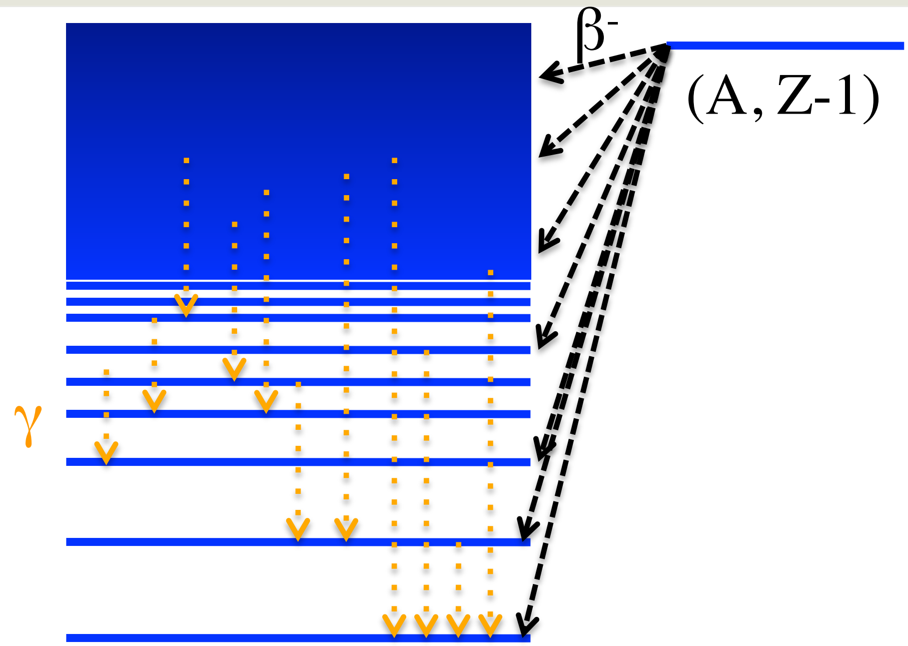


$I_\beta = I_\gamma(\text{out}) - I_\gamma(\text{in})$

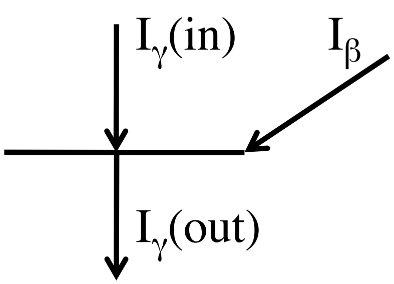
J.C. Hardy *et al*., *Phys. Lett. B 71 (1977) 307.*

The pandemonium effect: solution

John Milton's "Paradise Lost

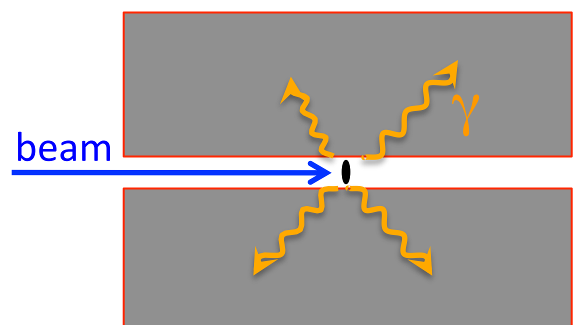


Small size – low efficiency detector



$$I_\beta = I_\gamma(\text{out}) - I_\gamma(\text{in})$$

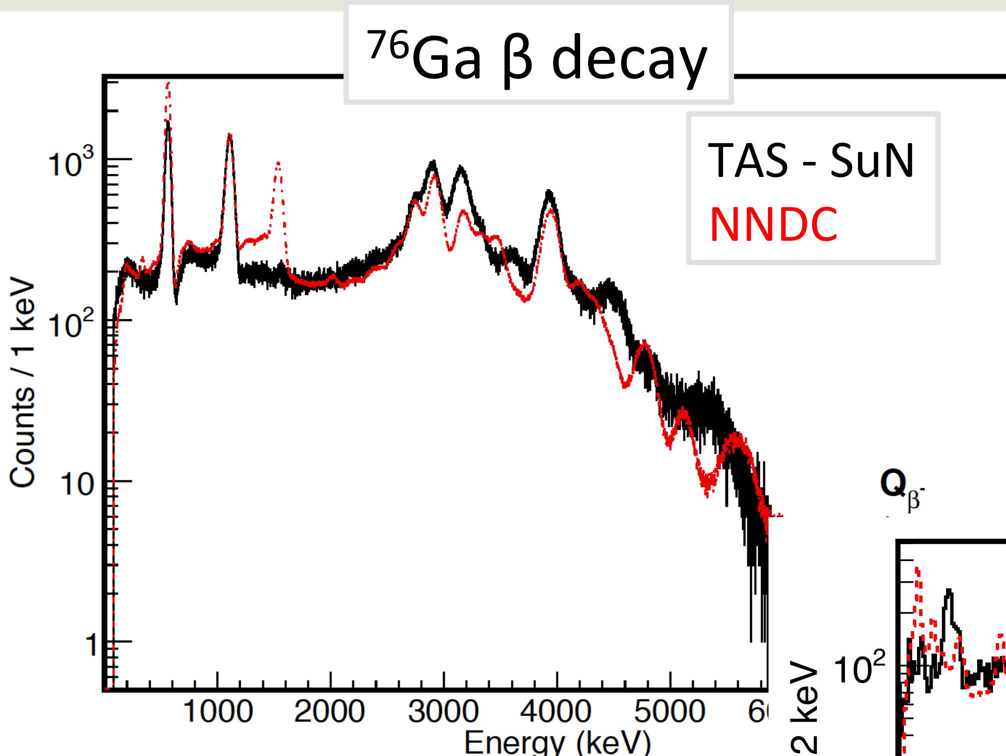
Large size - high efficiency detector

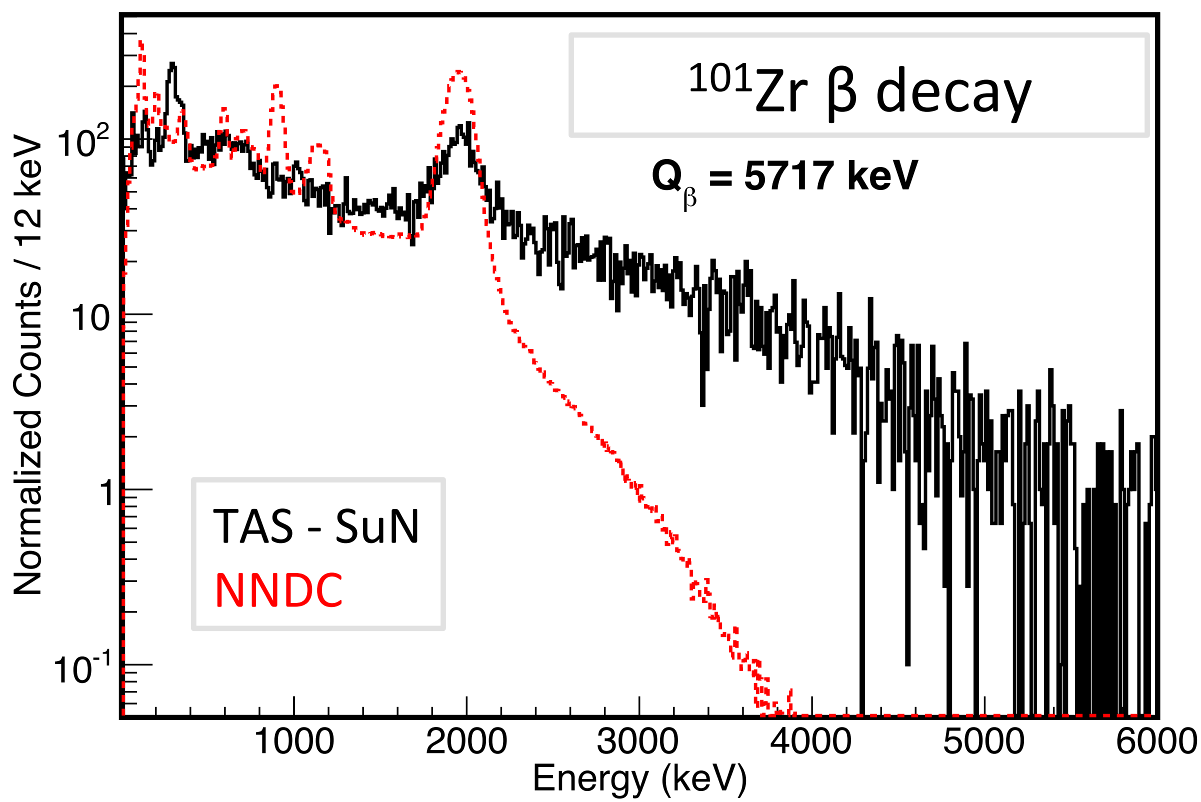


$$E_x = E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3} + E_{\gamma 4} + \ldots$$

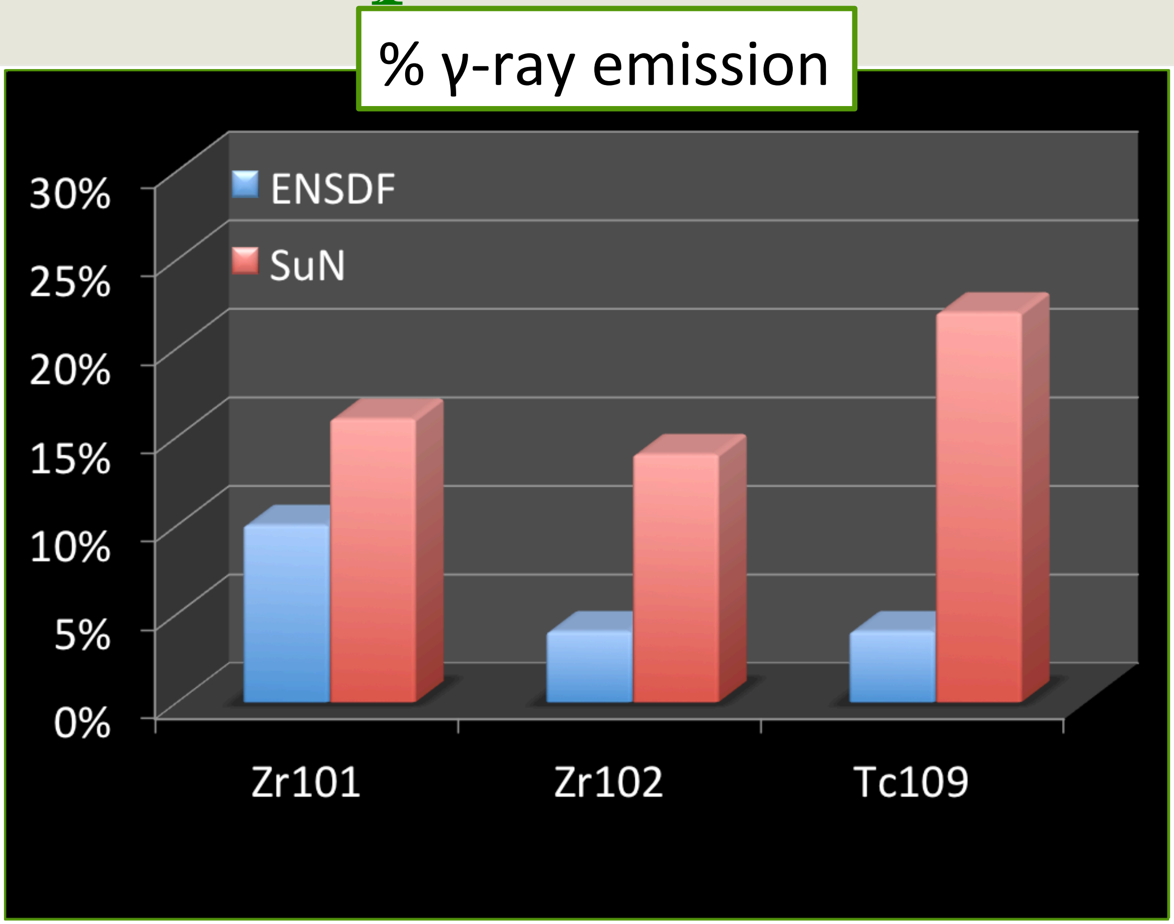
Total Absorption Spectroscopy - TAS

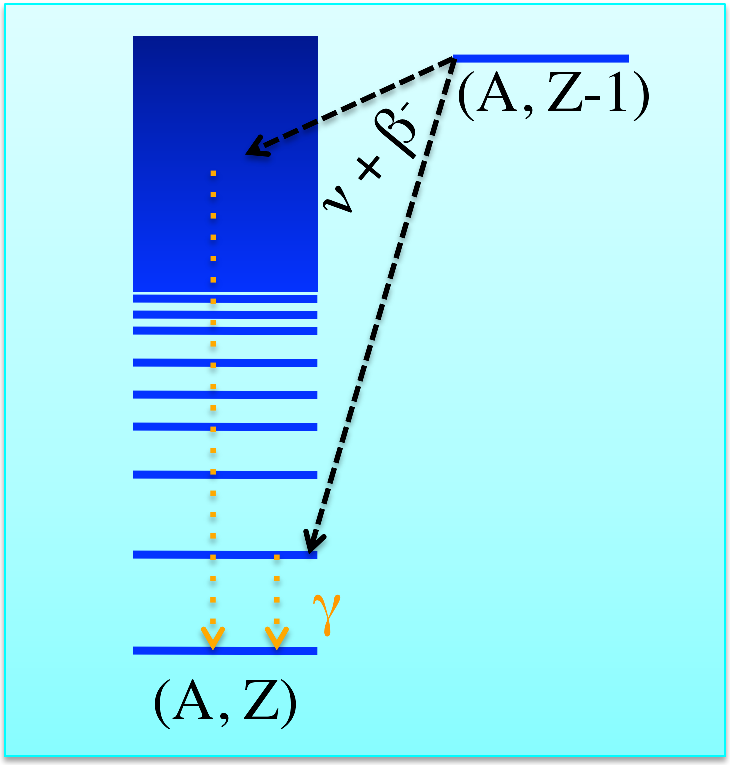
The pandemonium effect in action





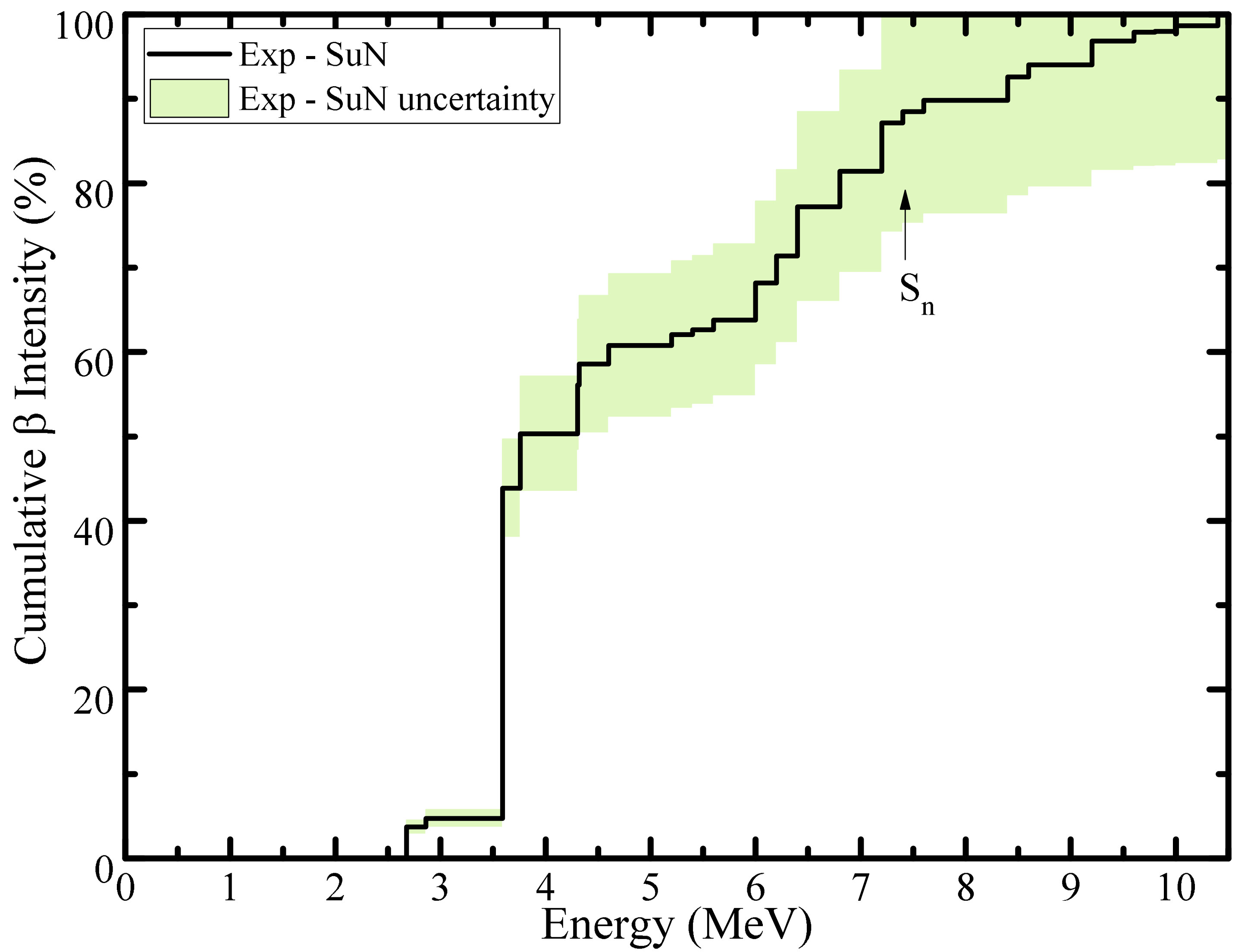
The pandemonium effect in action





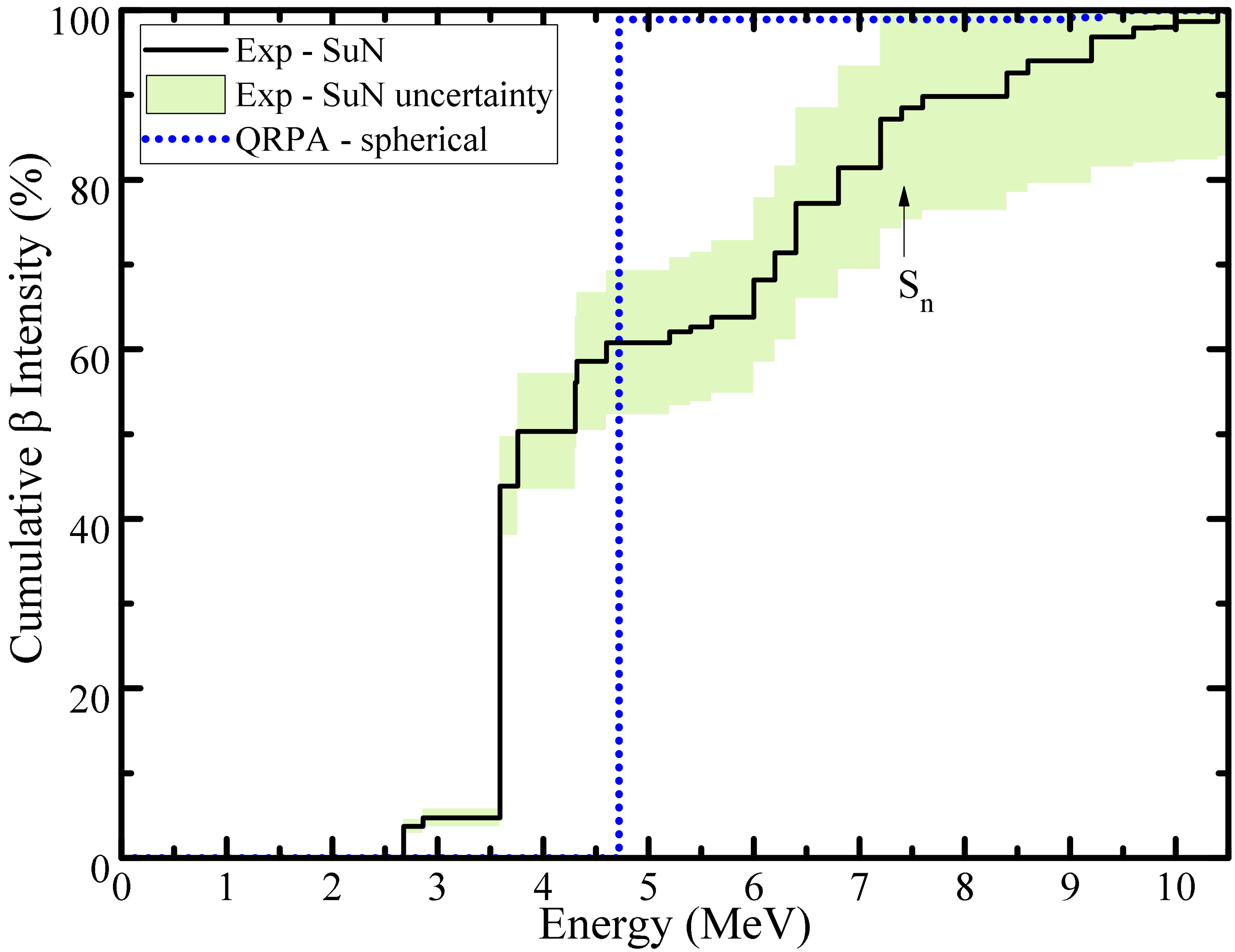
- Sensitivity study to identify important nuclei
- More measurements needed
- Impact on kilonova observations?

^{70}Co β-decay Intensity



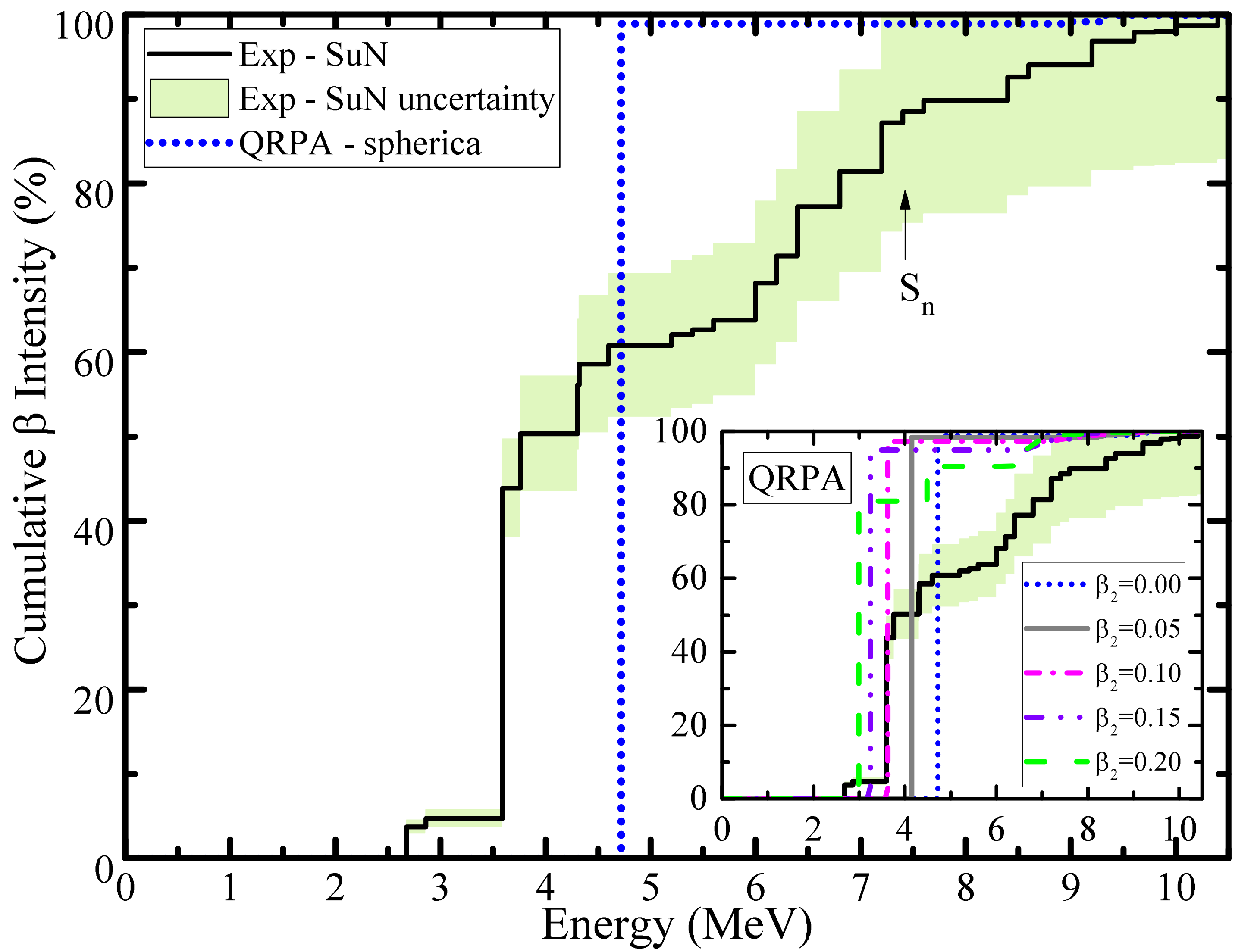
A. Spyrou, S.N. Liddick, et al. *Phys. Rev. Lett. 2016*

^{70}Co β-decay Intensity



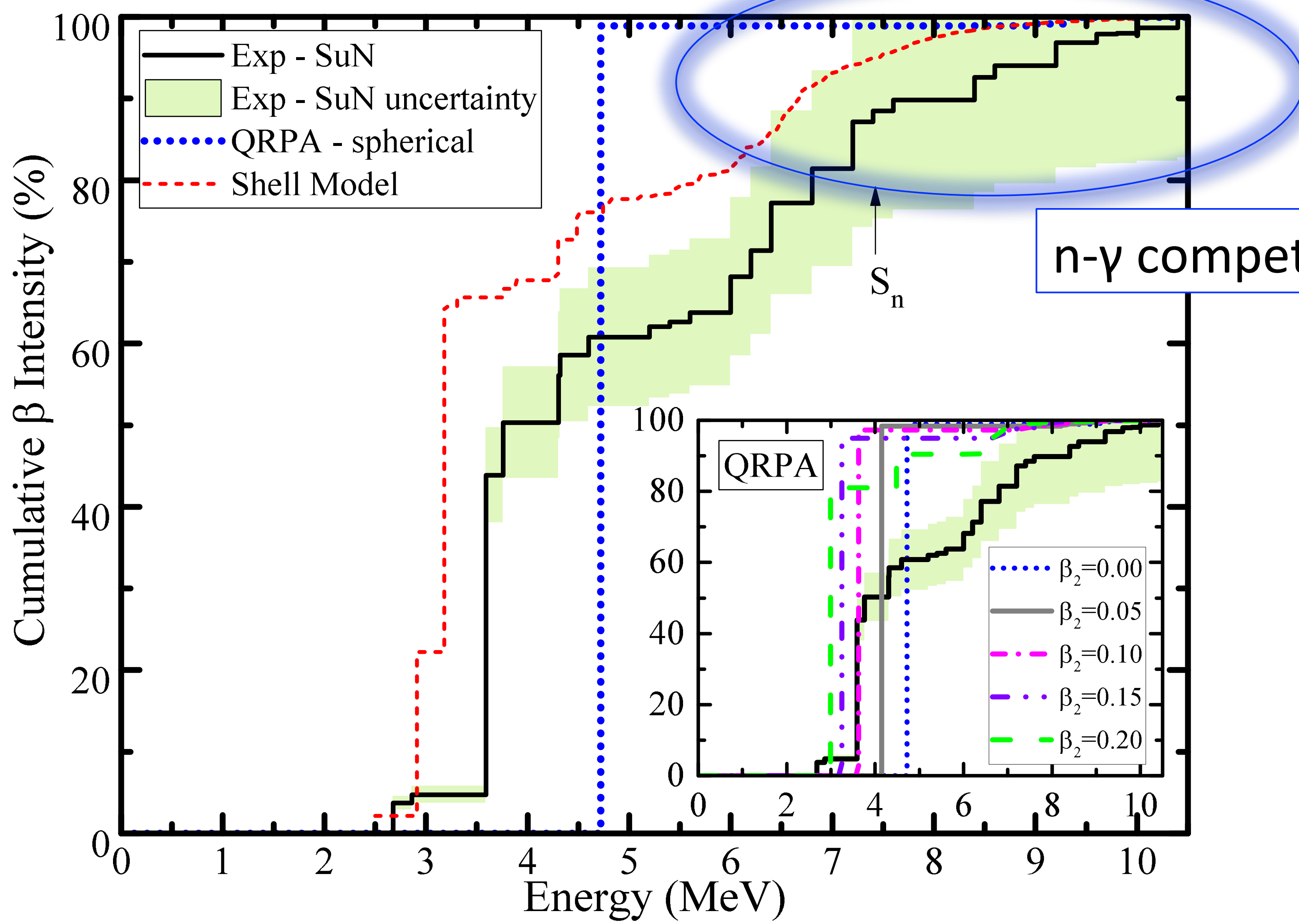
A. Spyrou, S.N. Liddick, et al. *Phys. Rev. Lett. 2016*

^{70}Co β-decay Intensity



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

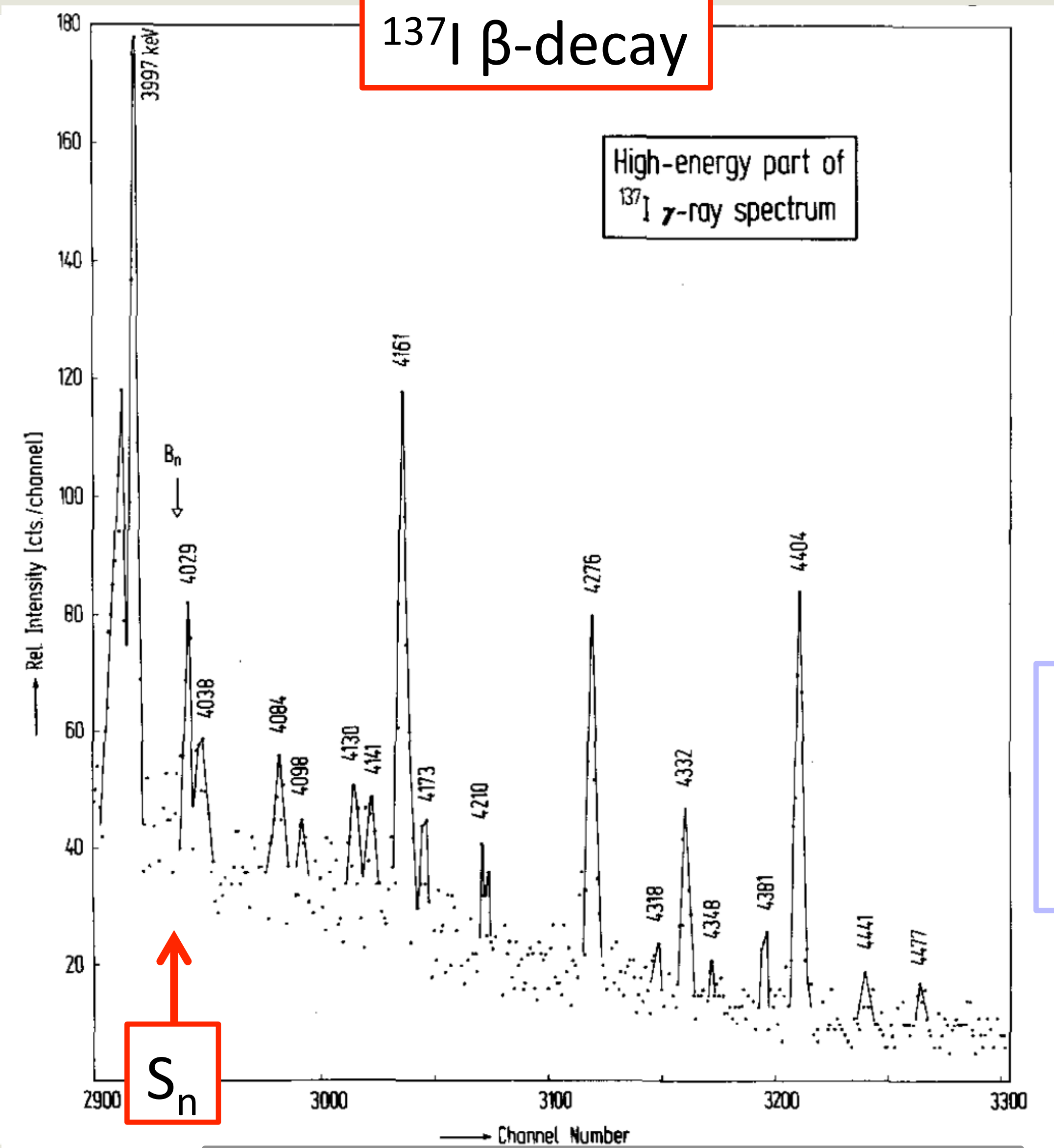
^{70}Co β-decay Intensity



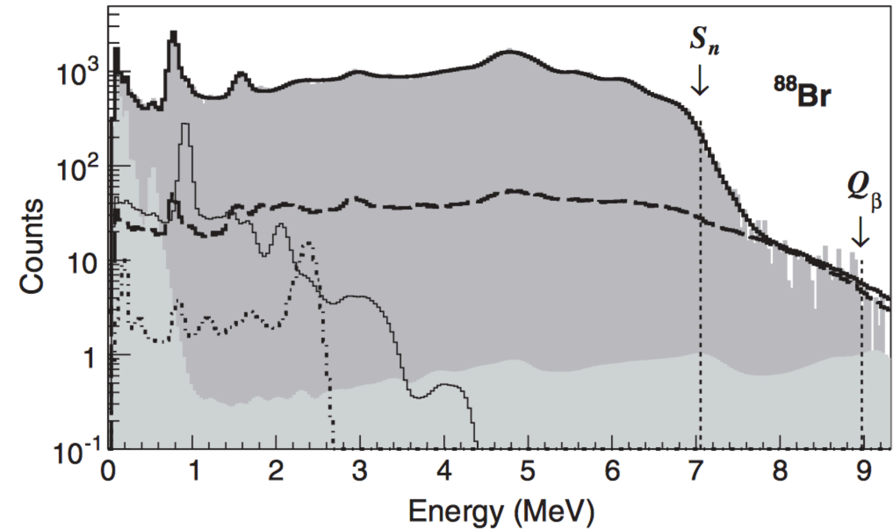
n-γ competition

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

γ emission – the competition / Neutron – γ competition threshold



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



Tain et al, PRL 115, 062502 (2015)

Reason

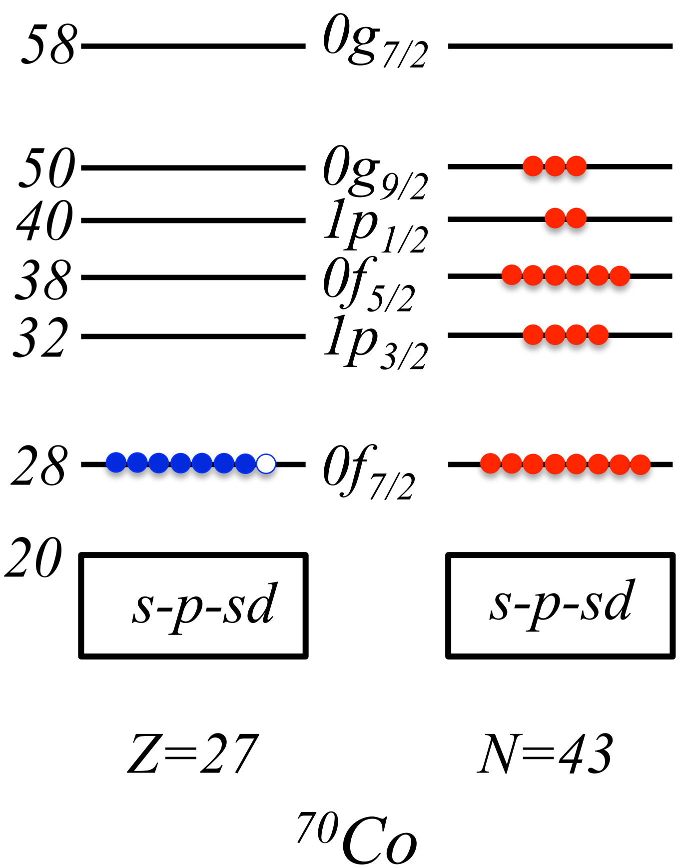
High angular momentum barrier for neutron emission

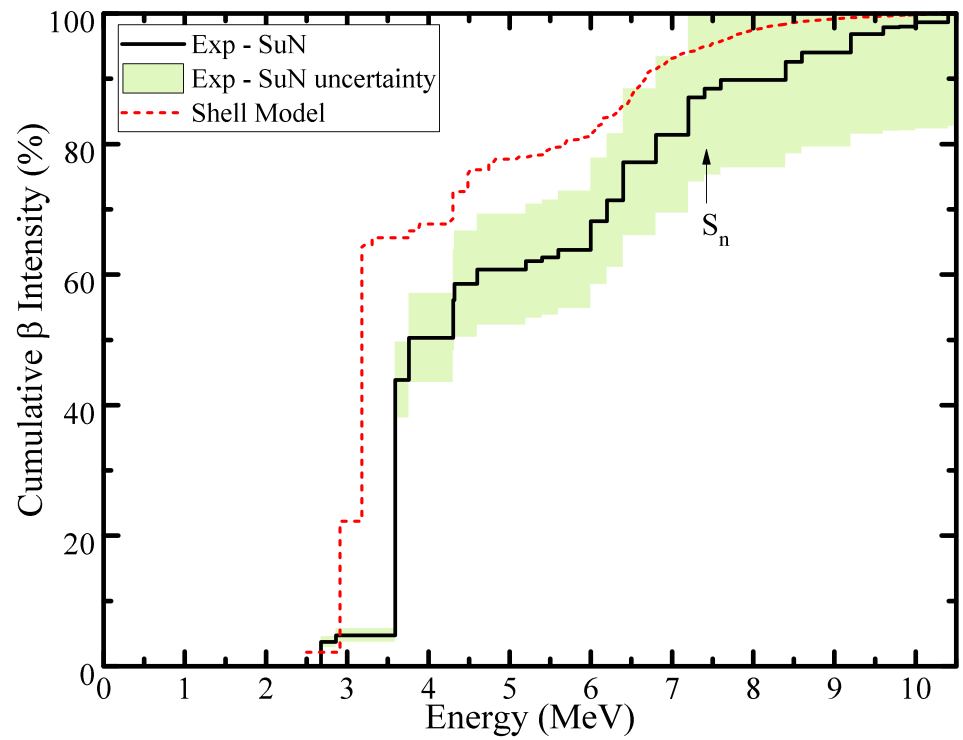
^{70}Co (6,7$^-$) —β$^-$→ ^{70}Ni (5,6,7,8$^-$) —n→ ^{69}Ni (9/2$^+$)

p-wave

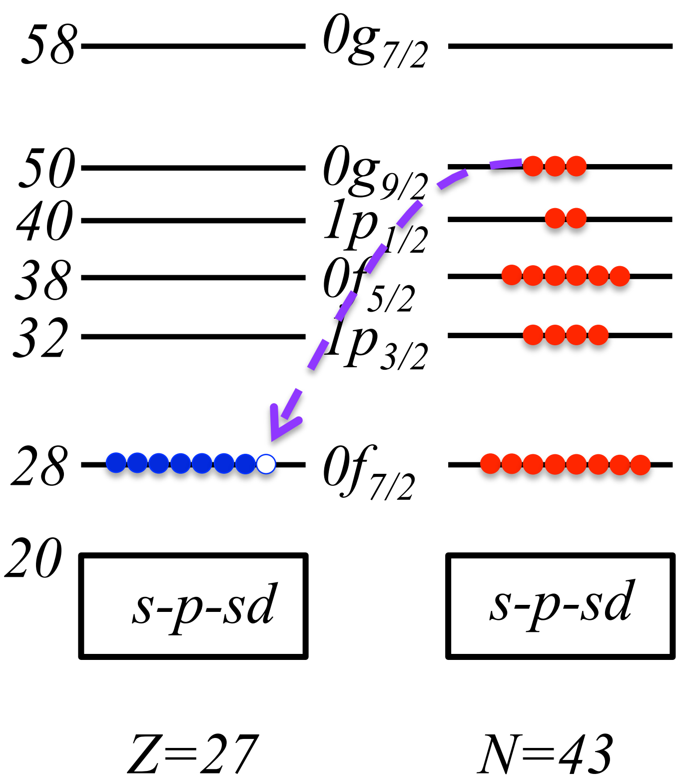
Spyrou, Liddick et al, PRL 2016

Neutron – γ competition

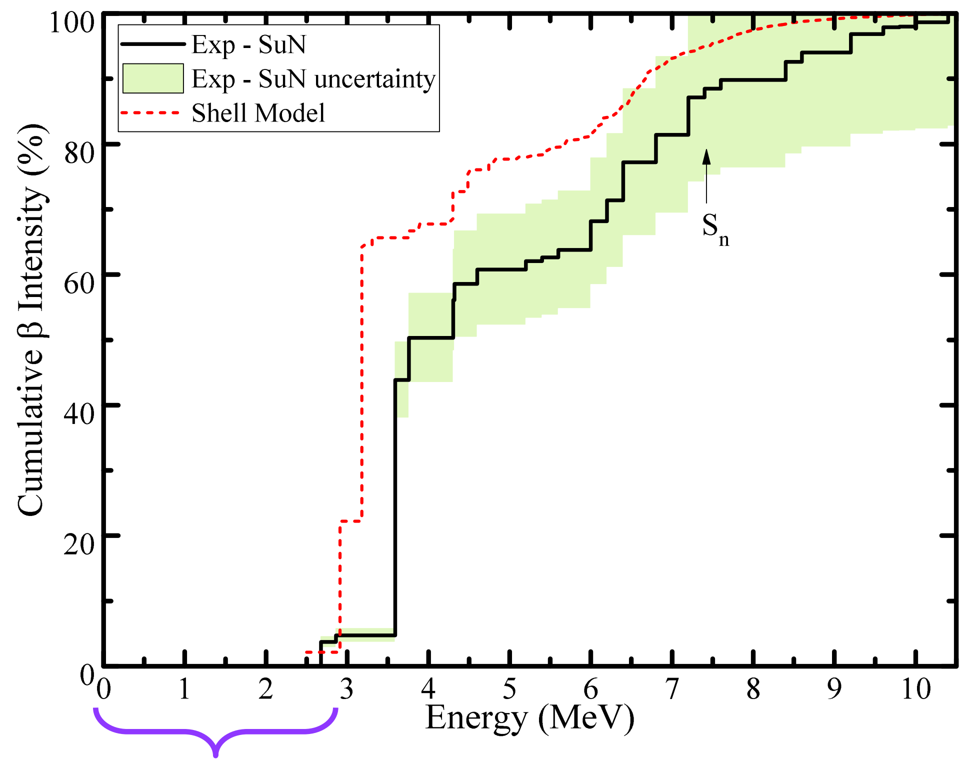




Neutron – γ competition



$^{70}Co \longrightarrow {}^{70}Ni$

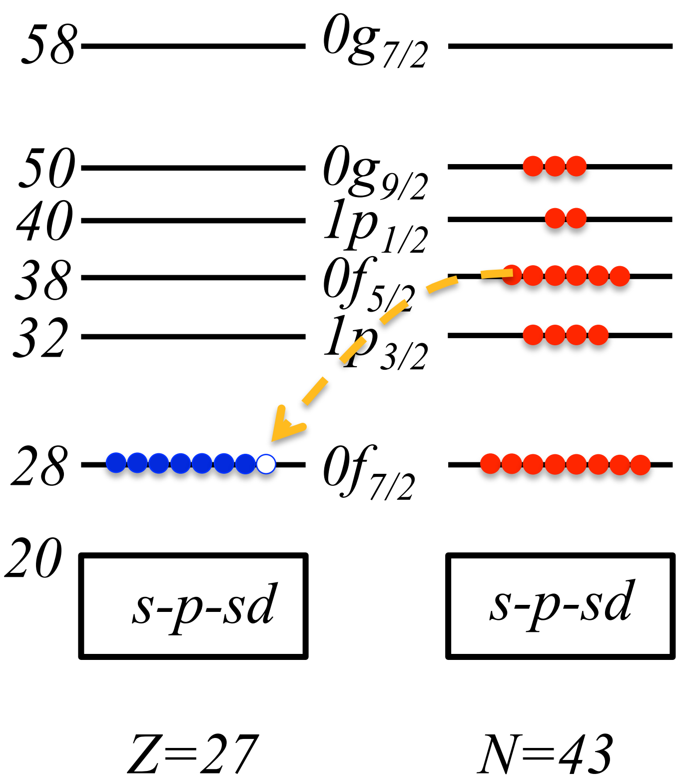


$\nu(0g_{9/2}) \longrightarrow \pi(0f_{7/2})$

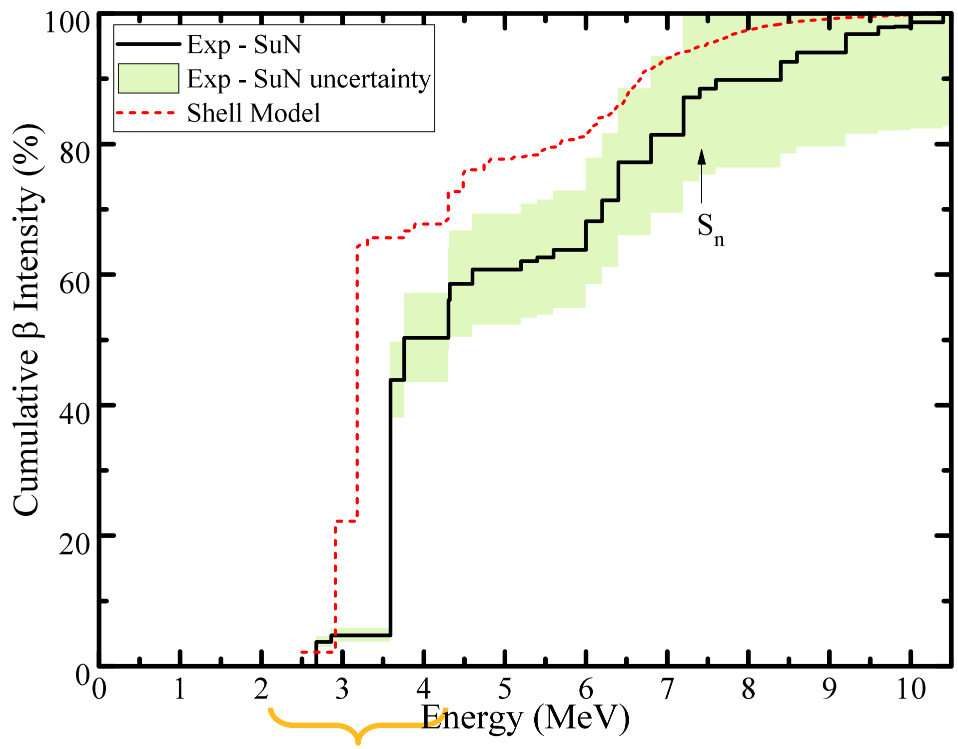
$6^- \longrightarrow 0^+$

Fifth forbidden

Neutron – γ competition



$^{70}Co \longrightarrow {}^{70}Ni$

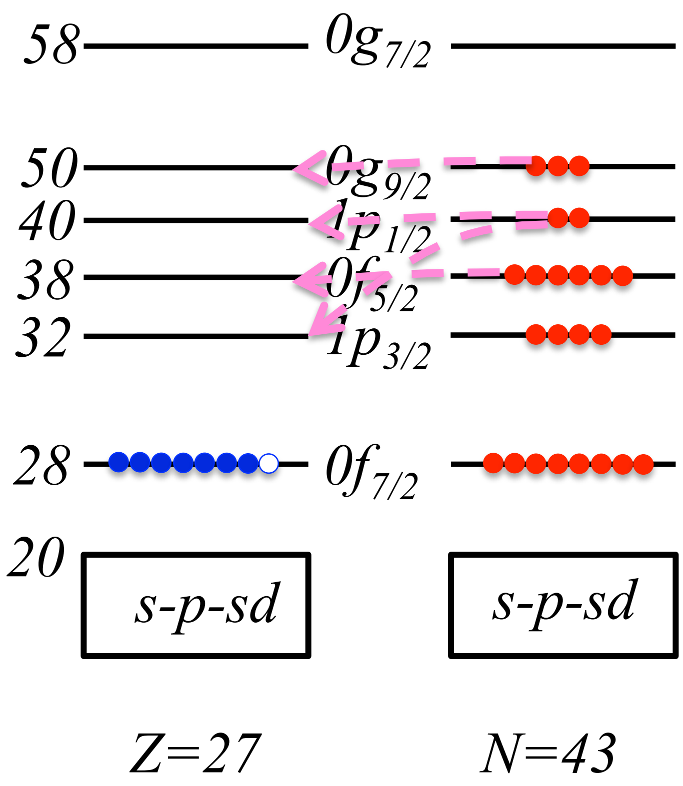


$\nu(0f_{5/2}) \longrightarrow \pi(0f_{7/2})$

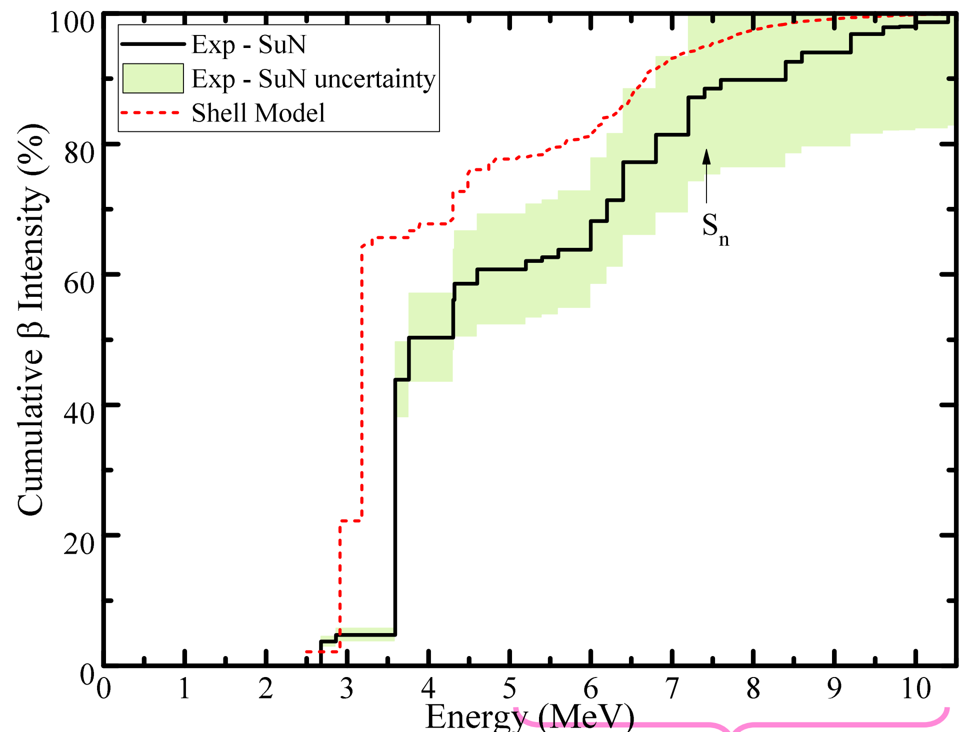
$6^- \longrightarrow 5,6,7^-$

Allowed

Neutron – γ competition



$^{70}Co \longrightarrow {}^{70}Ni$

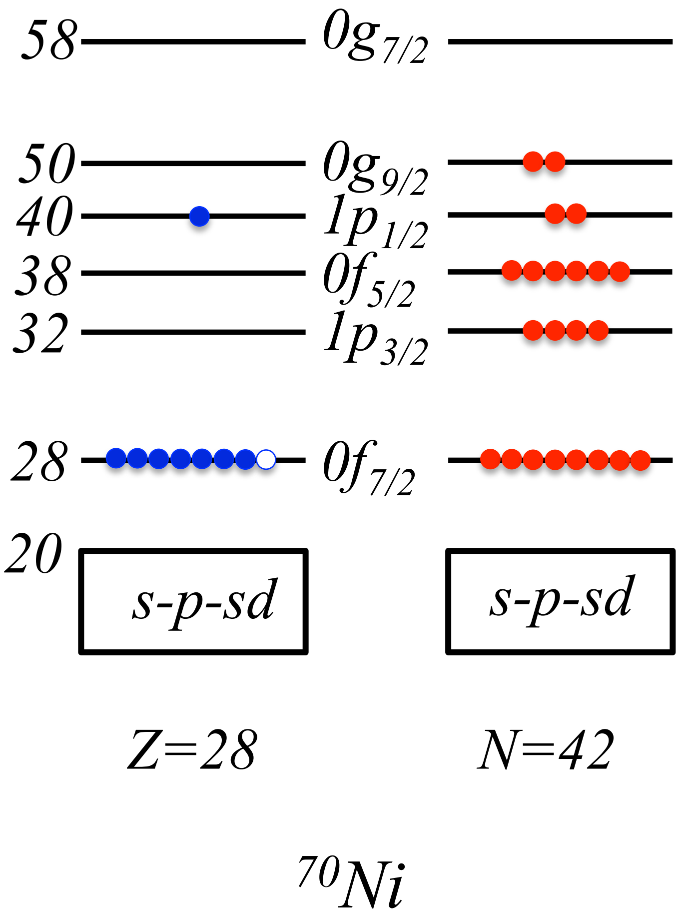


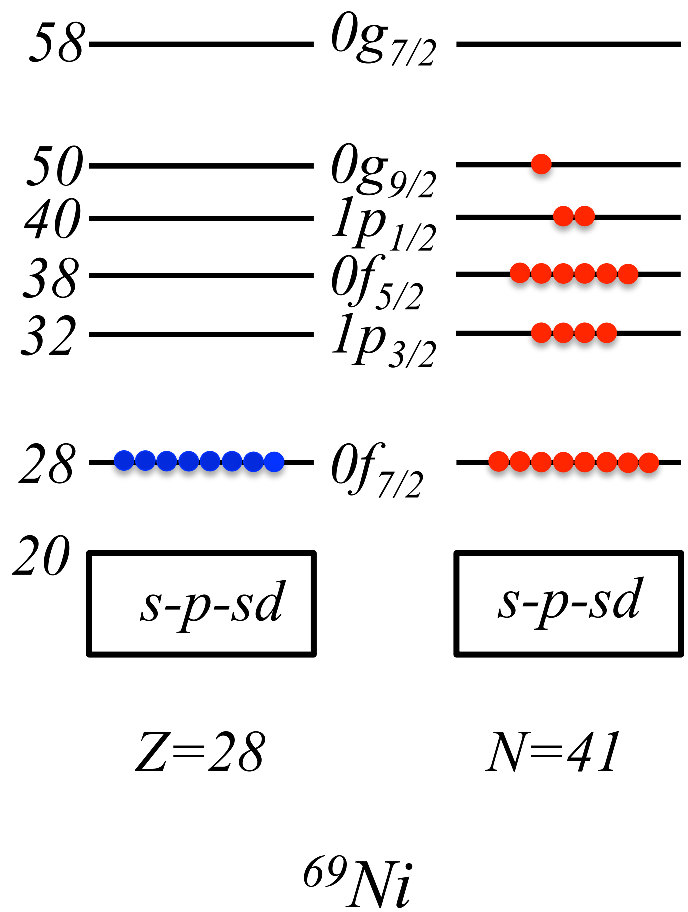
Proton excited across Z=28

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

Allowed

Neutron – γ competition

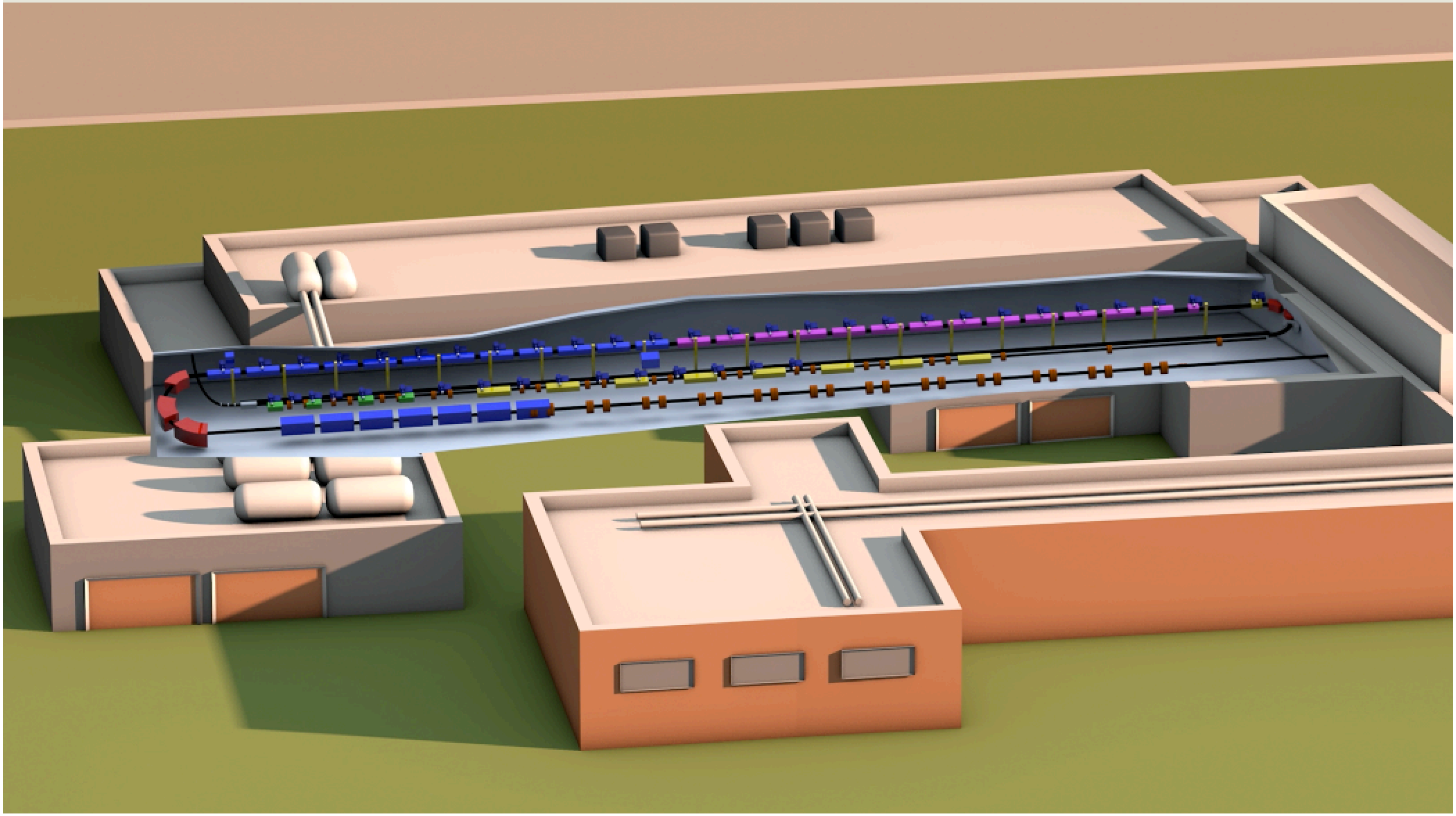




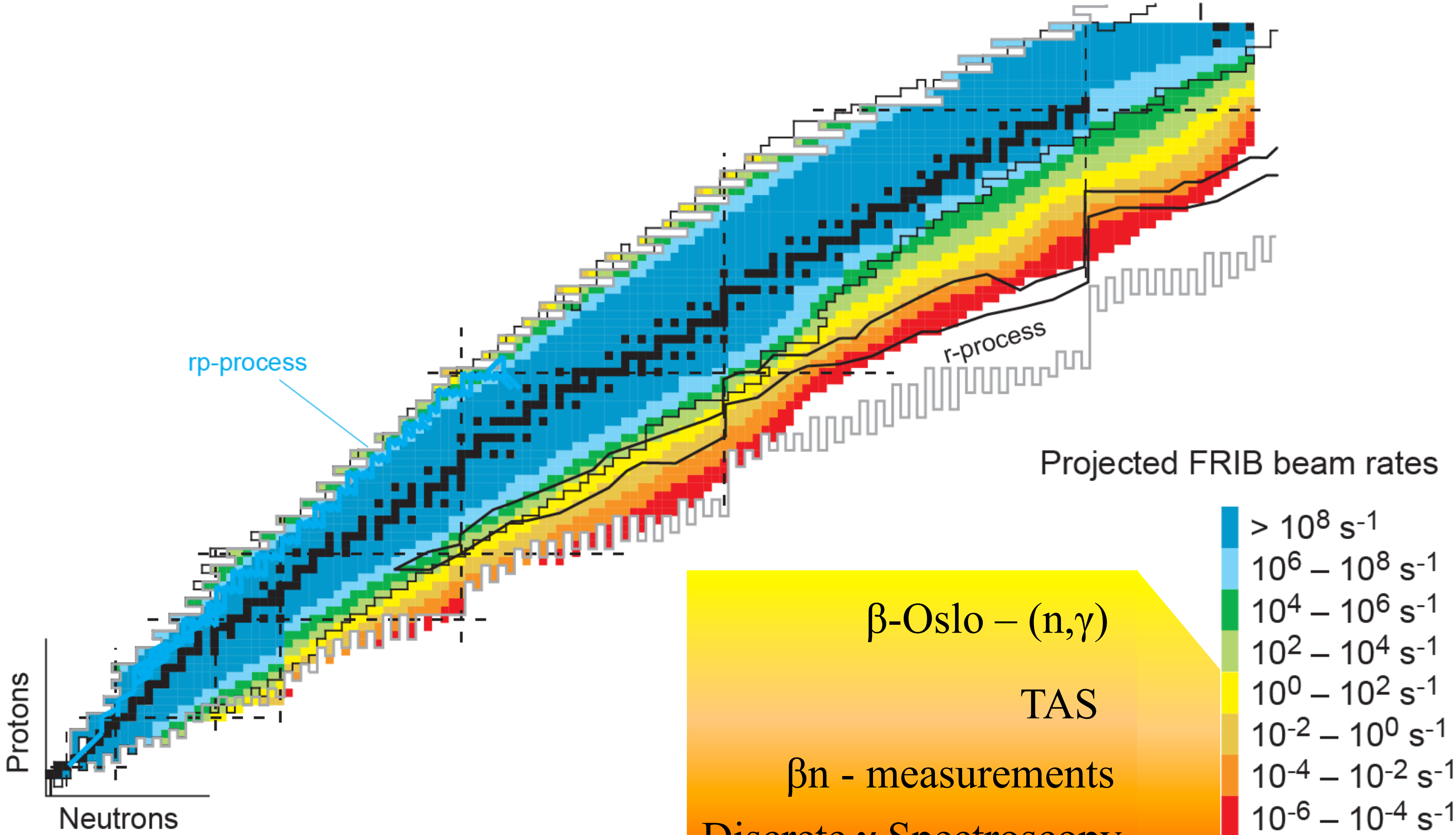
Summary

- Nuclear Physics input is essential for understanding the r process
- β-Oslo: Indirect Technique to constrain neutron-capture reactions
- Kilonova: More data needed to interpret the observations
- Neutron-gamma competition – how important is it?
- Future…

Facility for Rare Isotope Beams



FRIB Rates



β-Oslo – (n,γ)

TAS

βn - measurements

Discrete γ Spectroscopy

Half-life

Collaboration

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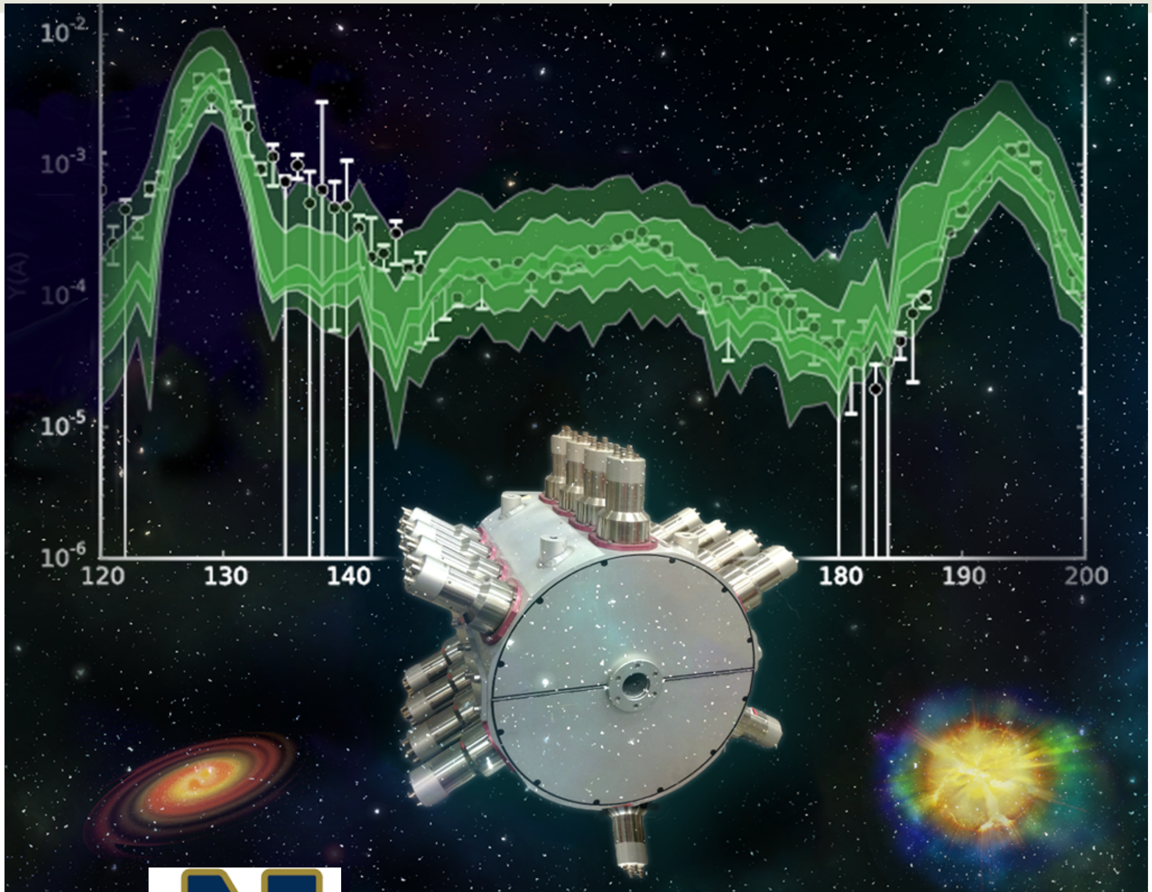

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