Neutron capture cross sections for the astrophysical r-process

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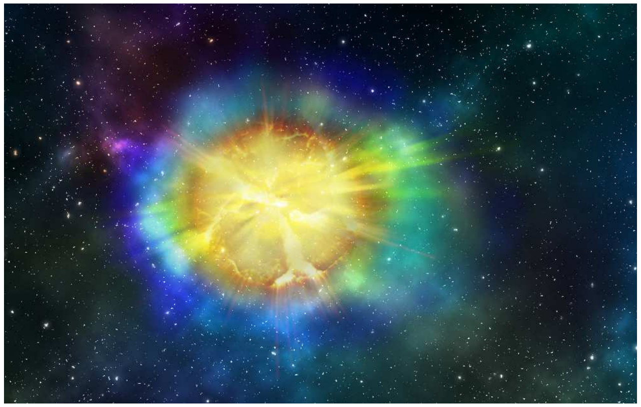
NSCL

Overview

- R-process nucleosynthesis
- Uncertainties
  - Neutron capture rates

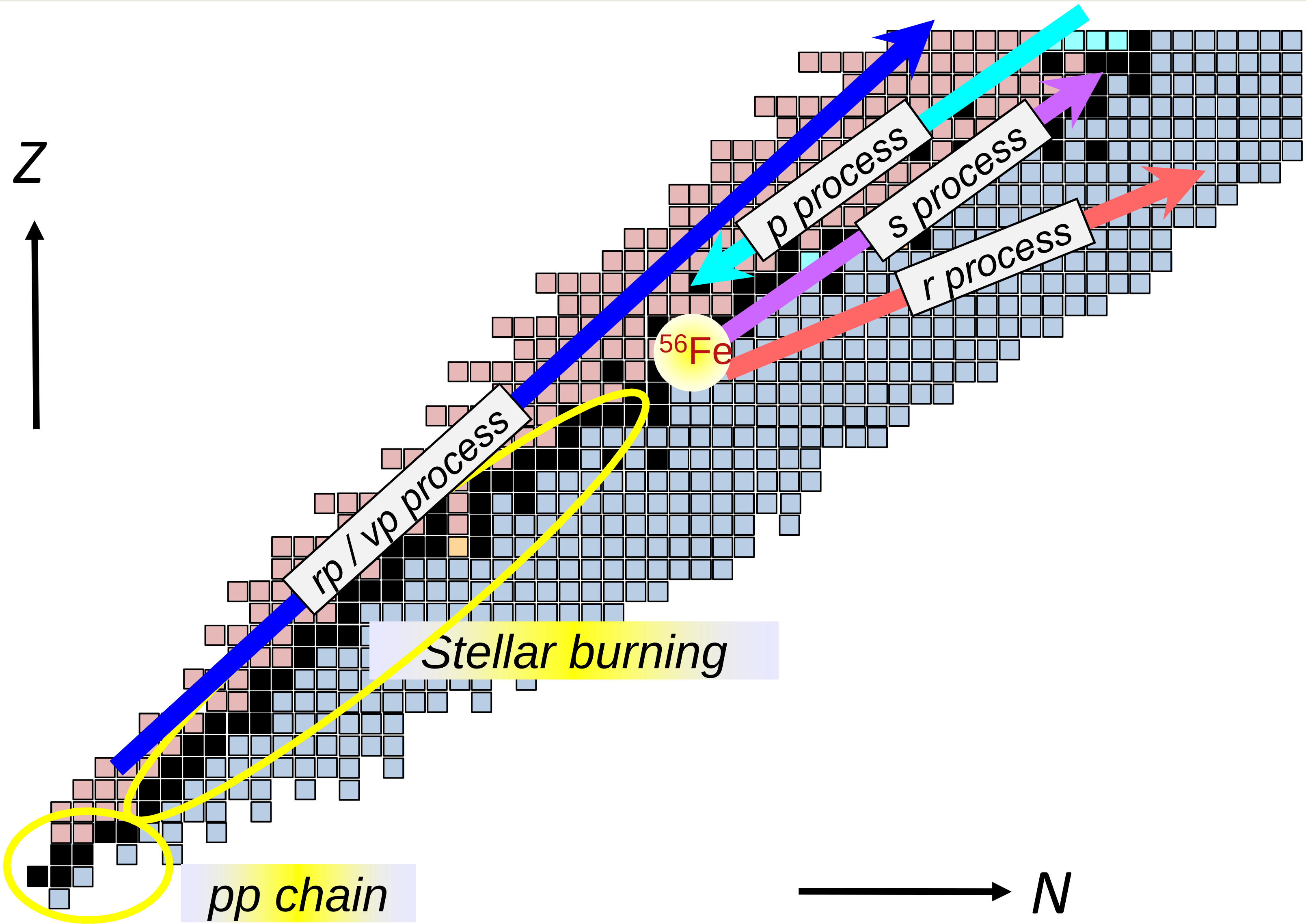
- Experiment

- Results
- Future plans



NSCL SuN

Nucleosynthesis paths



Open questions: What is the site of the r-process?

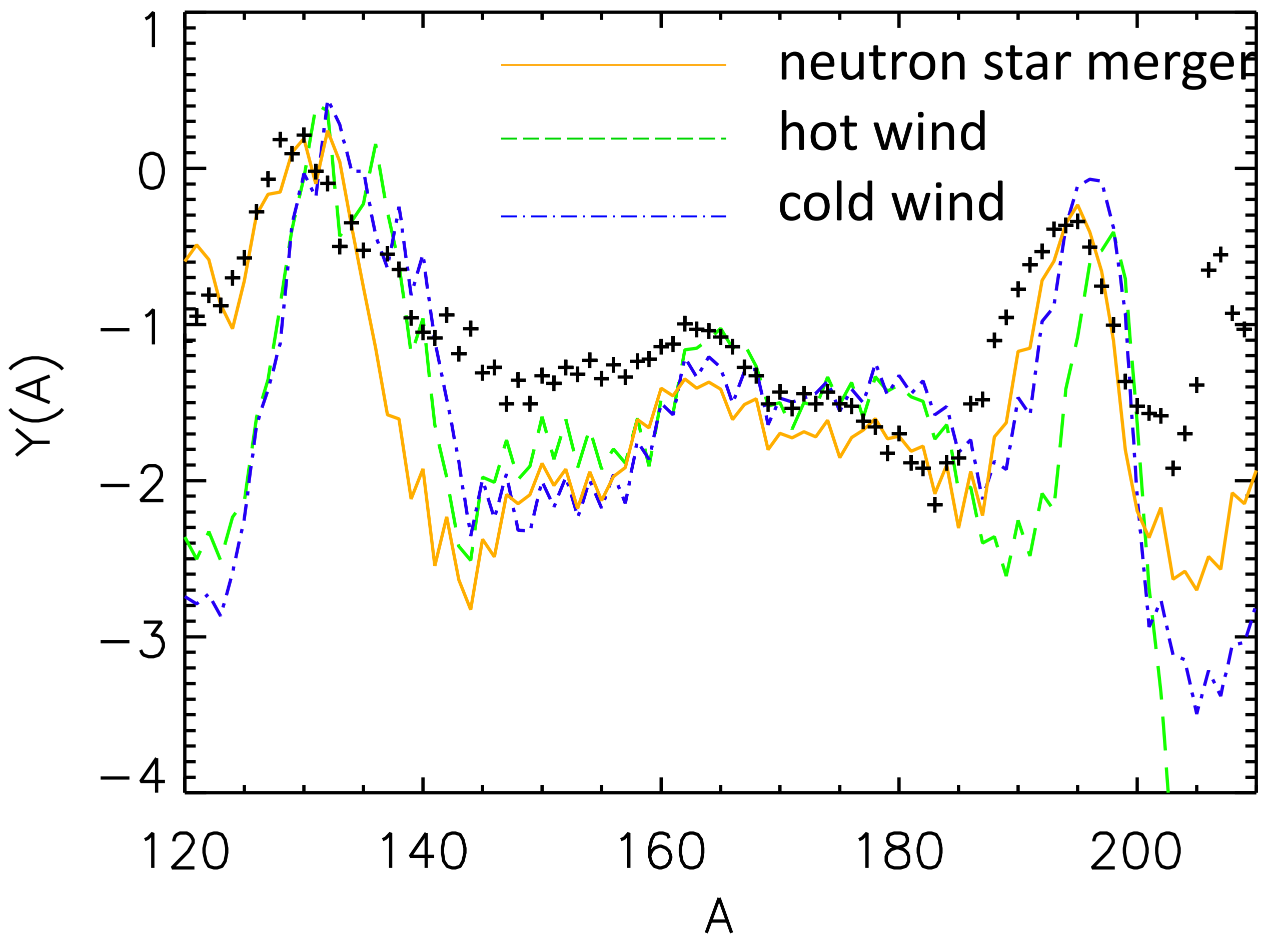
Credit: Erin O'Donnell, MSU

Core Collapse Supernova?

Neutron Star Merger?

Credit: NASA Goddard

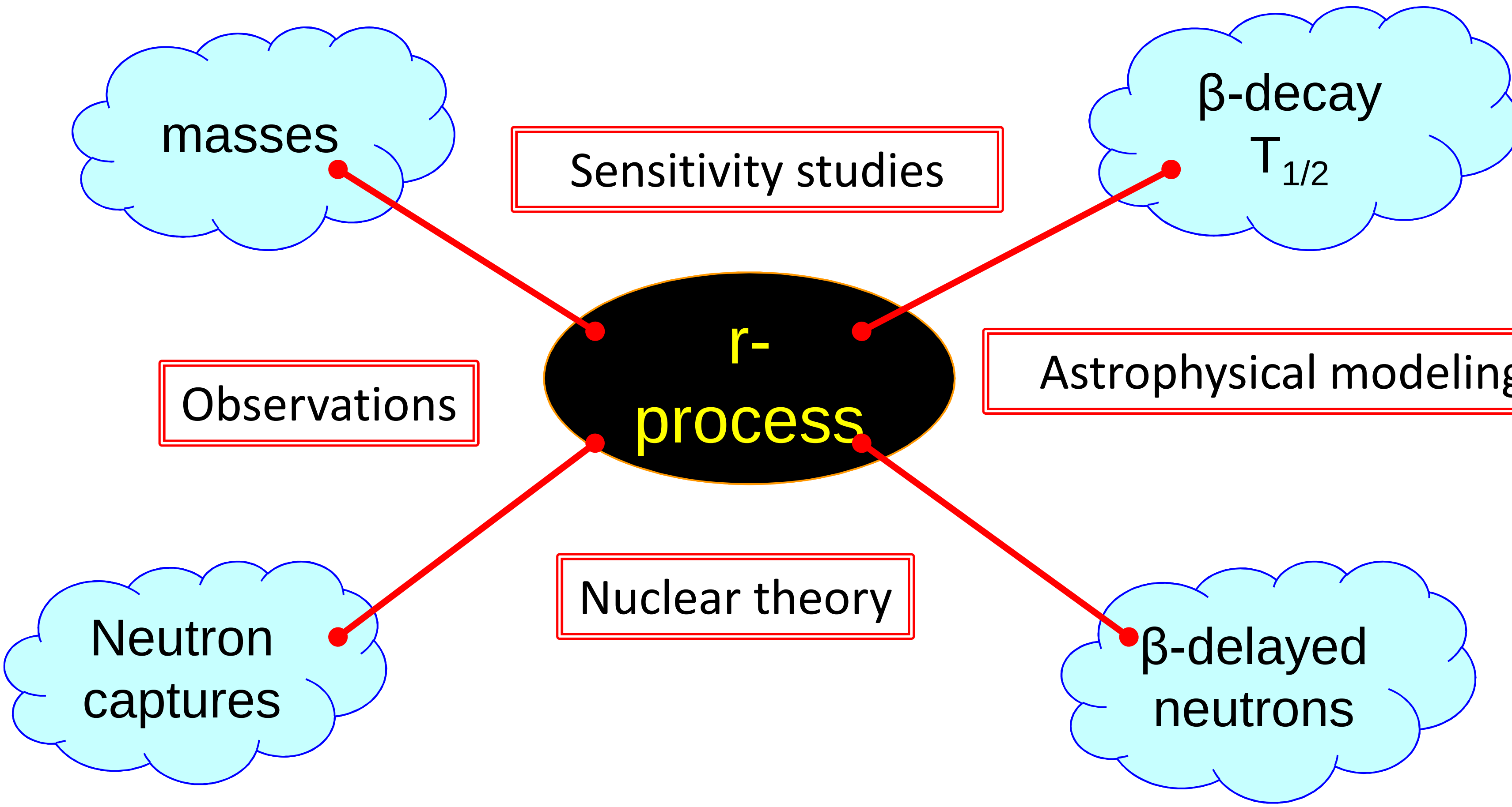
r-process calculations



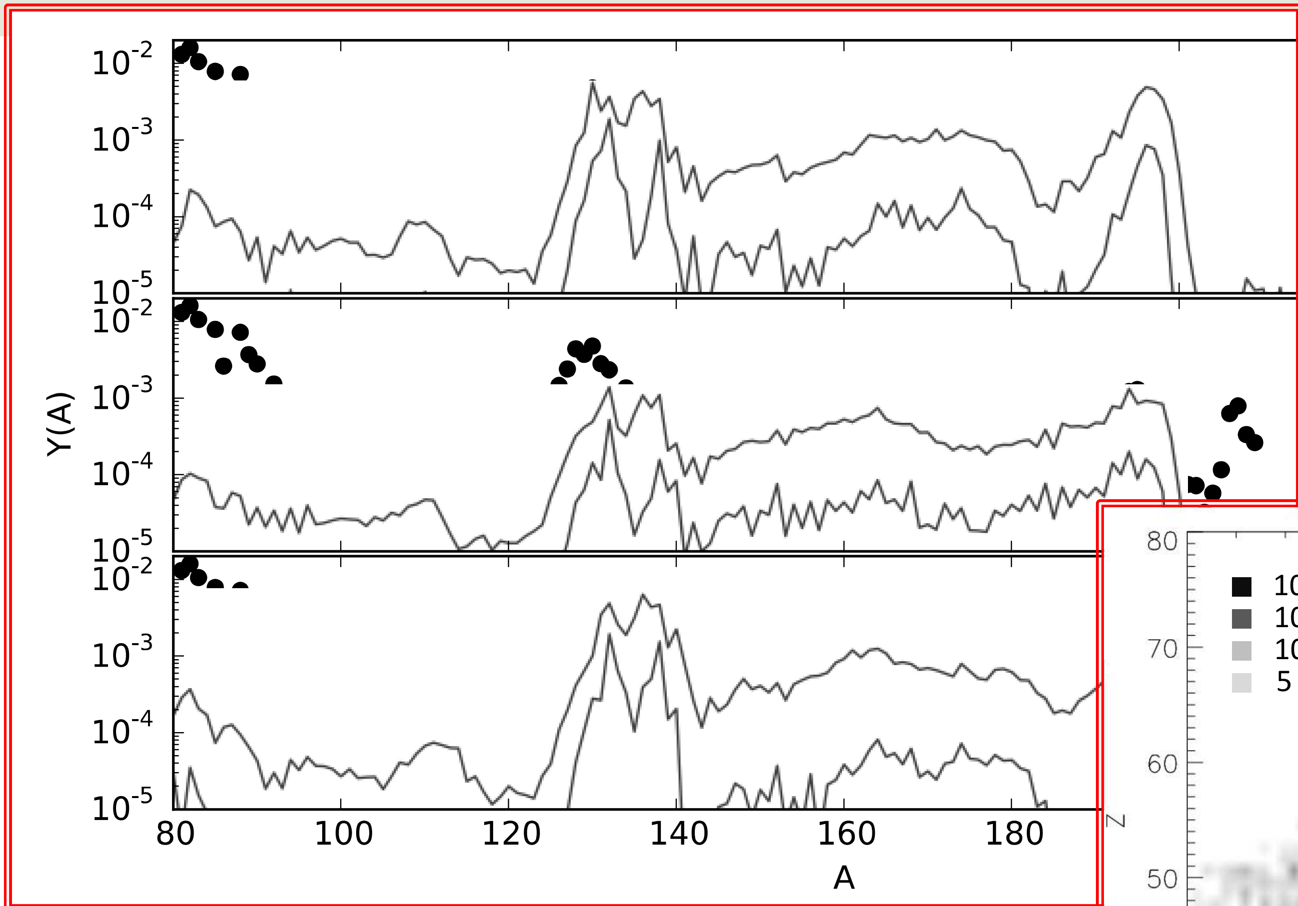
- Abundance pattern is different for the different astrophysical scenarios.
- Does one of them reproduce the observed abundances best?
- Why can't we tell?

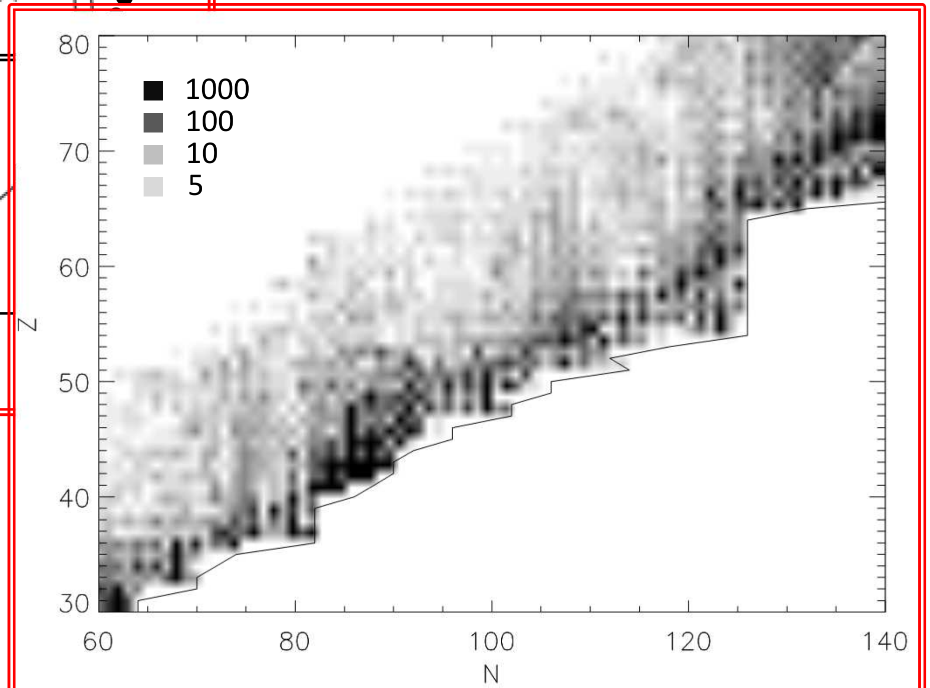
M. Mumpower, J. Cass, G. Passucci, R. Surman, A. Aprahamian, AIP Adv. **4**, 041009 (2014)

r-process


masses
β-decay
T1/2
Sensitivity studies
r-
process
Observations
Astrophysical modeling
Nuclear theory
Neutron
captures
β-delayed
neutrons

Nuclear Physics Uncertainties: (n,γ)

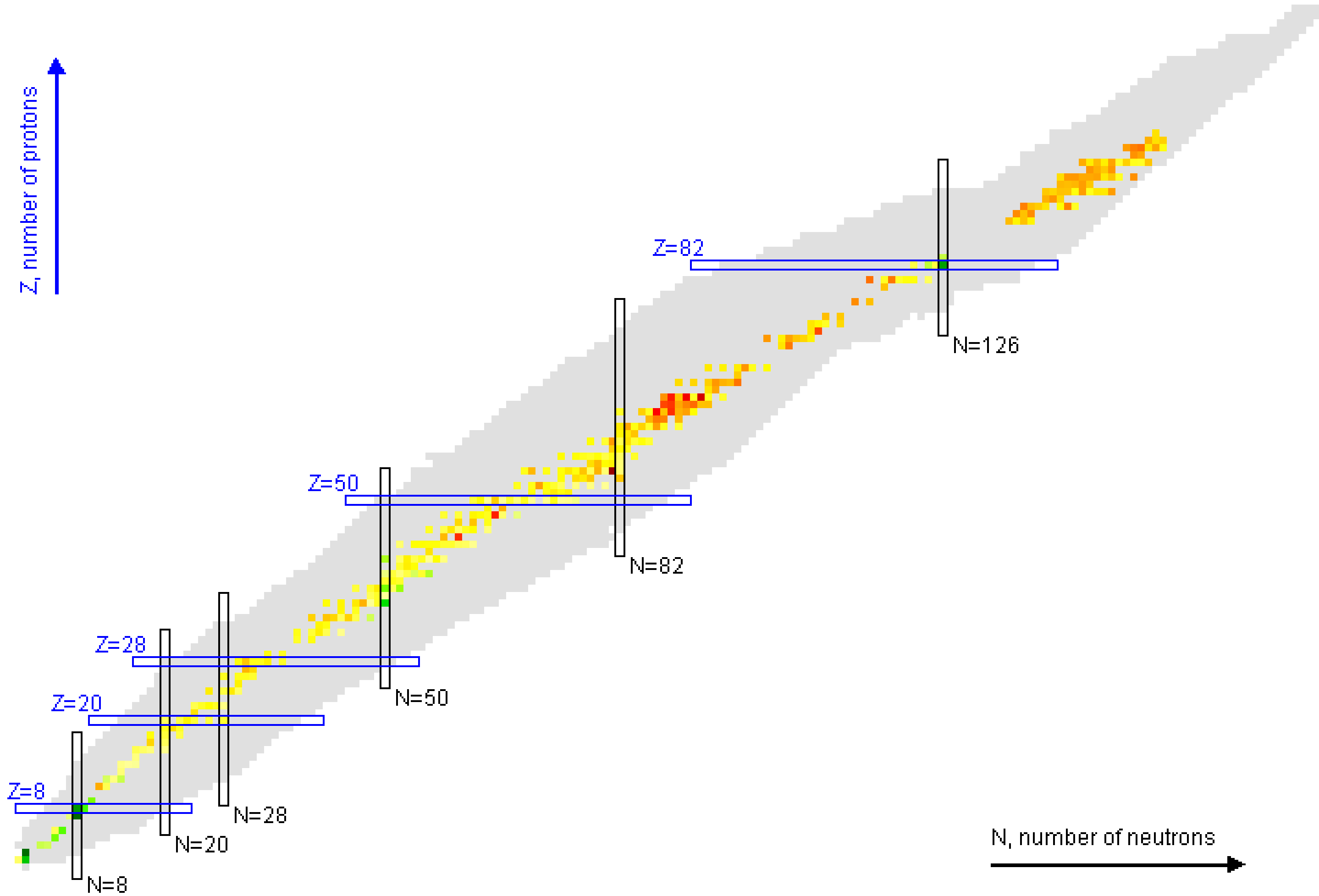




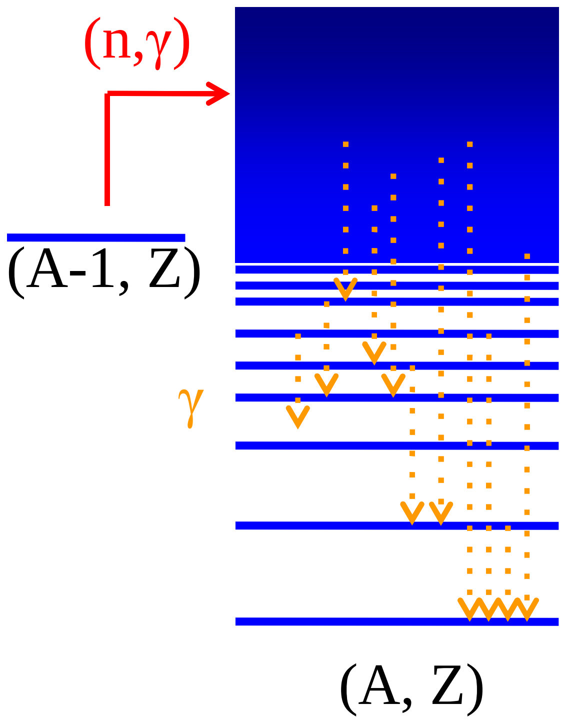
Surman and Engel PRC (2001)

Monte-Carlo variations of (n,γ) rates within a factor 100.

Current (n,γ) measurements



Neutron Capture – Uncertainties



Hauser – Feshbach

- Nuclear Level Density

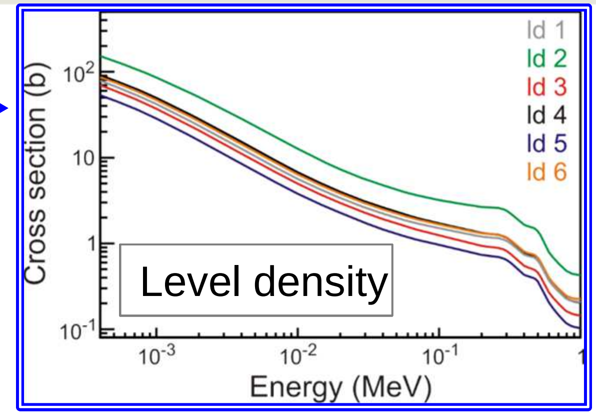
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

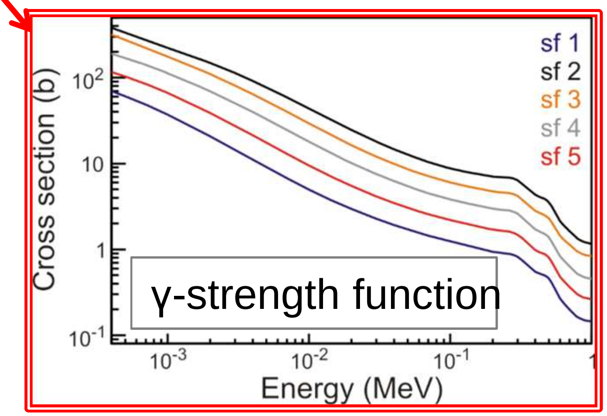
- γ-ray strength function

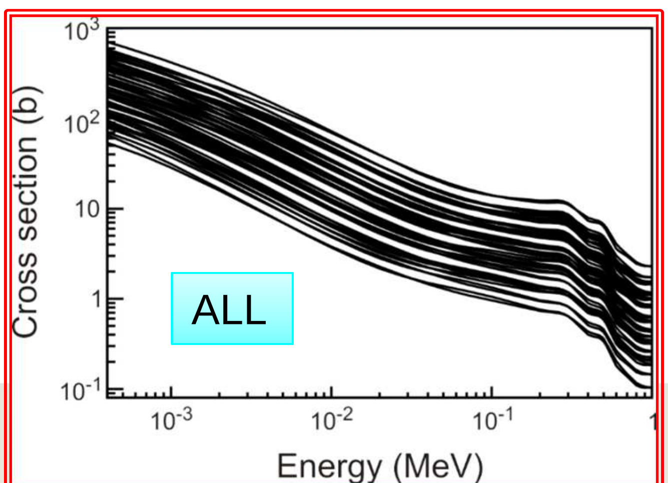
Generalized Lorentzian, Brink-Axel, various tables

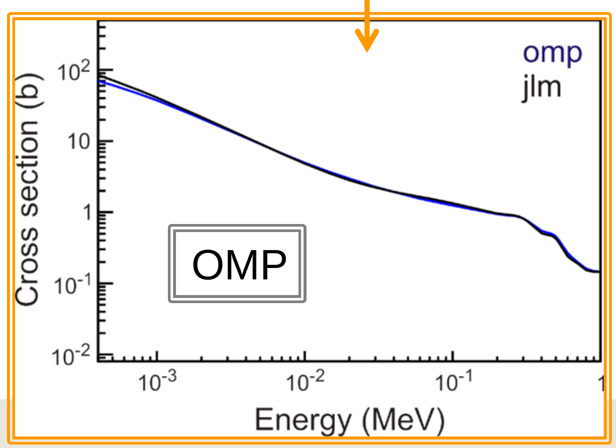
- Optical model potential

Phenomenological, Semi-microscopic







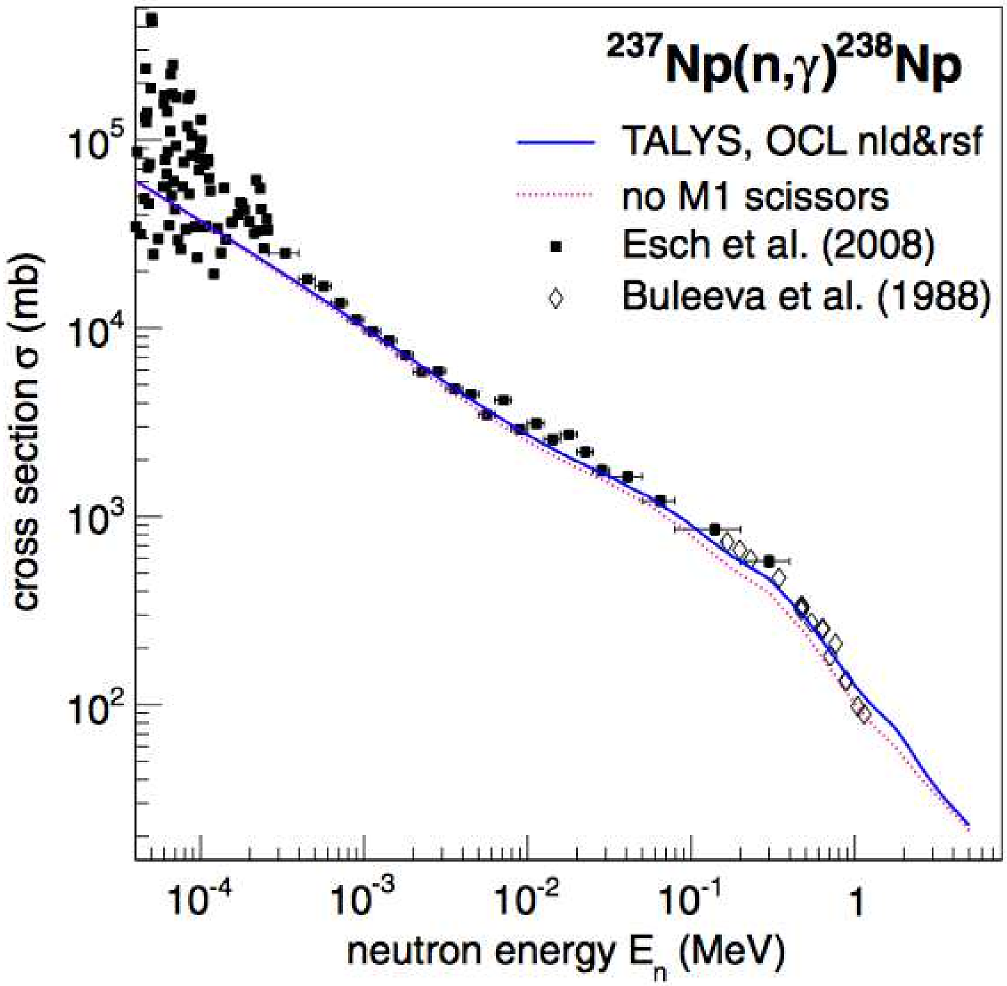


$^{95}Sr(n,\gamma)^{96}Sr$

TALYS

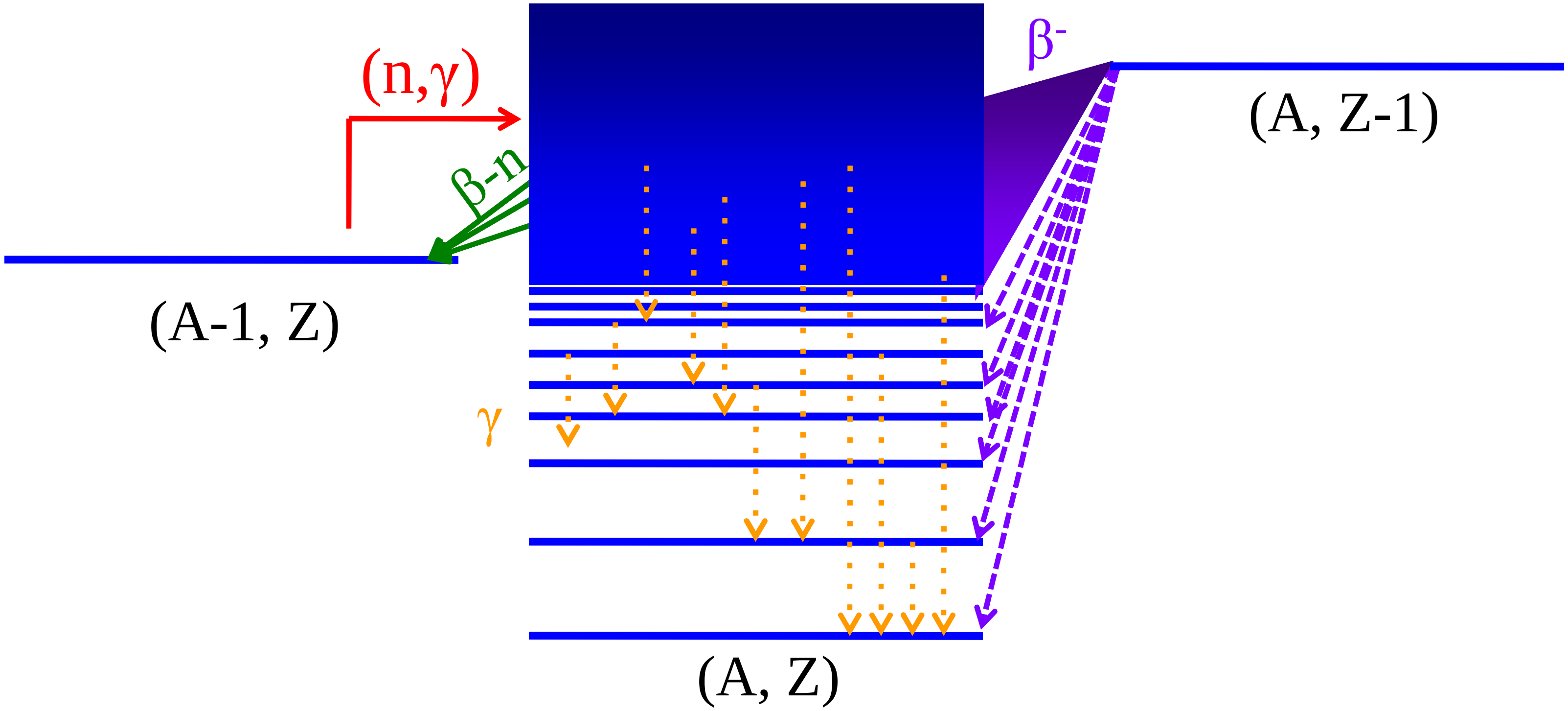
Traditional Oslo method

- Reaction based
- Applicable closer to stability
- Populate the compound nucleus of interest through a transfer or inelastic scattering
- Extract level density and γ-ray strength function
- Calculate "semi-experimental" (n,γ) cross section
- Excellent agreement with measured (n,γ) reaction cross section



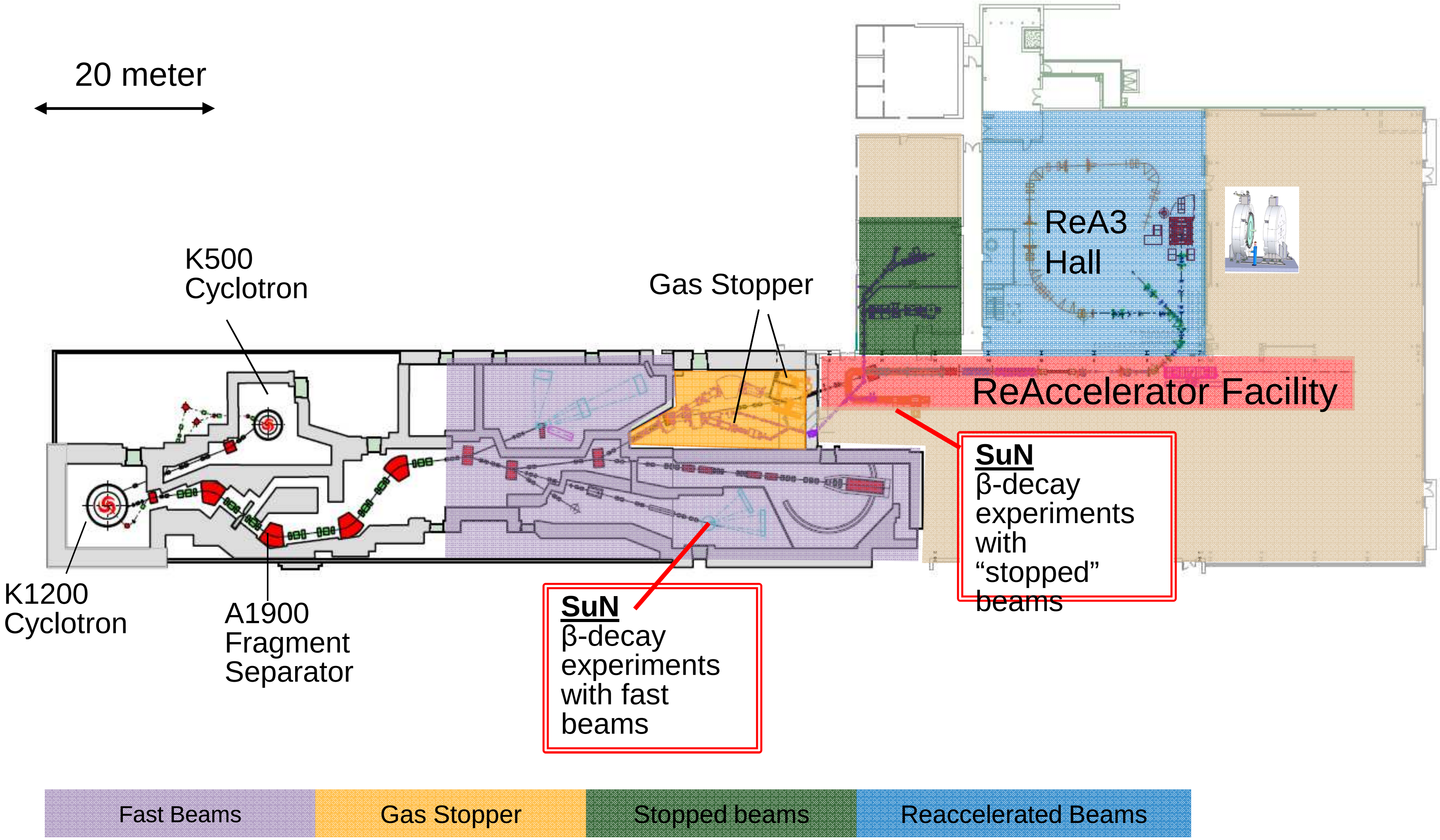
T.G. Tornyi, M. Guttormsen,et al., PRC2014

Neutron Capture – β-Oslo

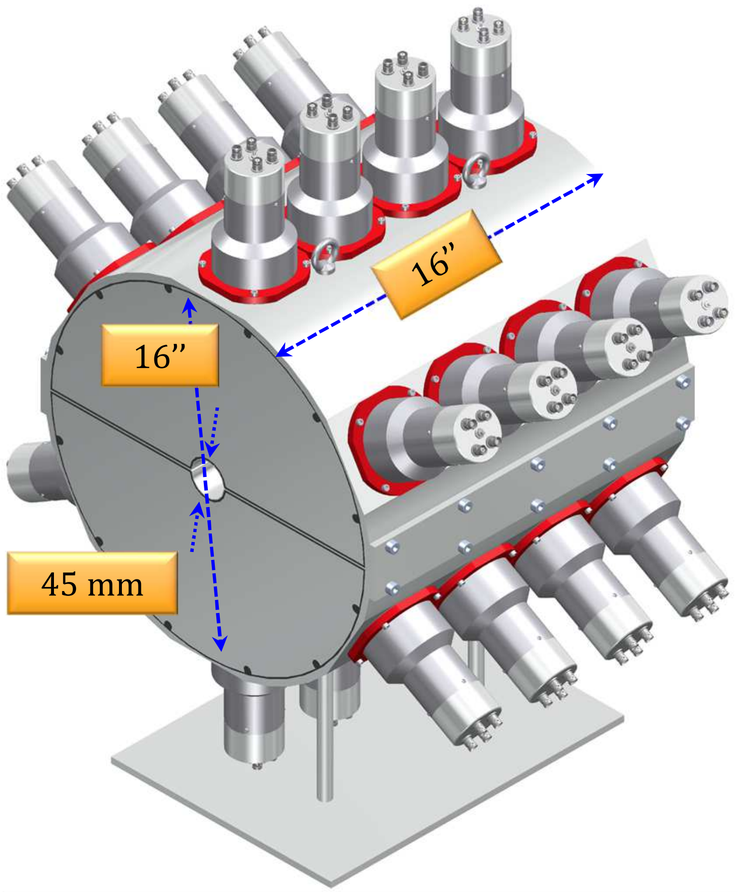


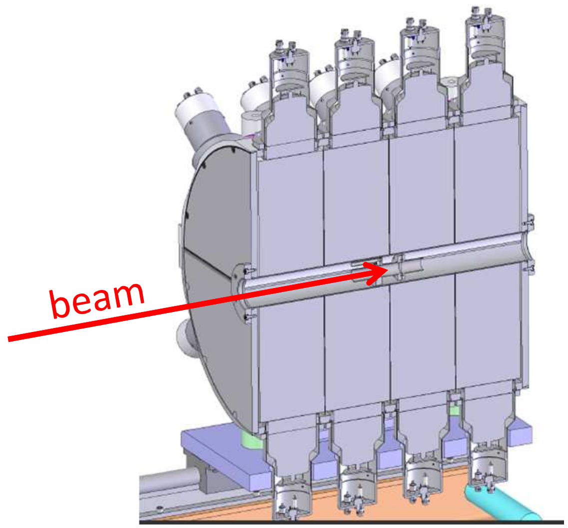
- Populate the compound nucleus via β-decay
- Spin selectivity – correct for it
- Extract level density and γ-ray strength function
- Advantage: Can reach (n,γ) reactions where beam intensity is 1 pps.

Experimental techniques



Summing NaI - SuN



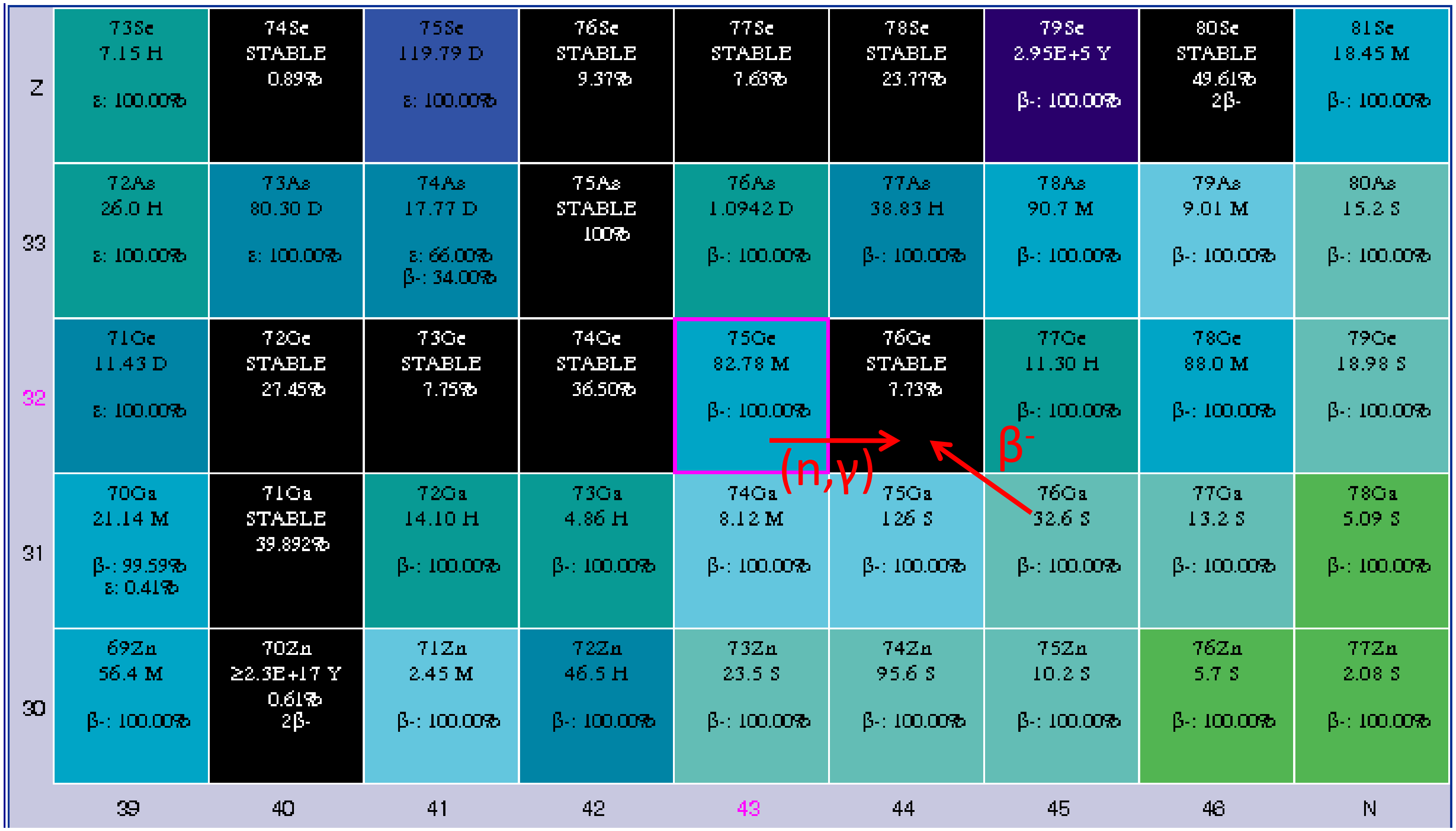


$$E_x = E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3} + E_{\gamma 4} + \ldots$$

- ✓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)

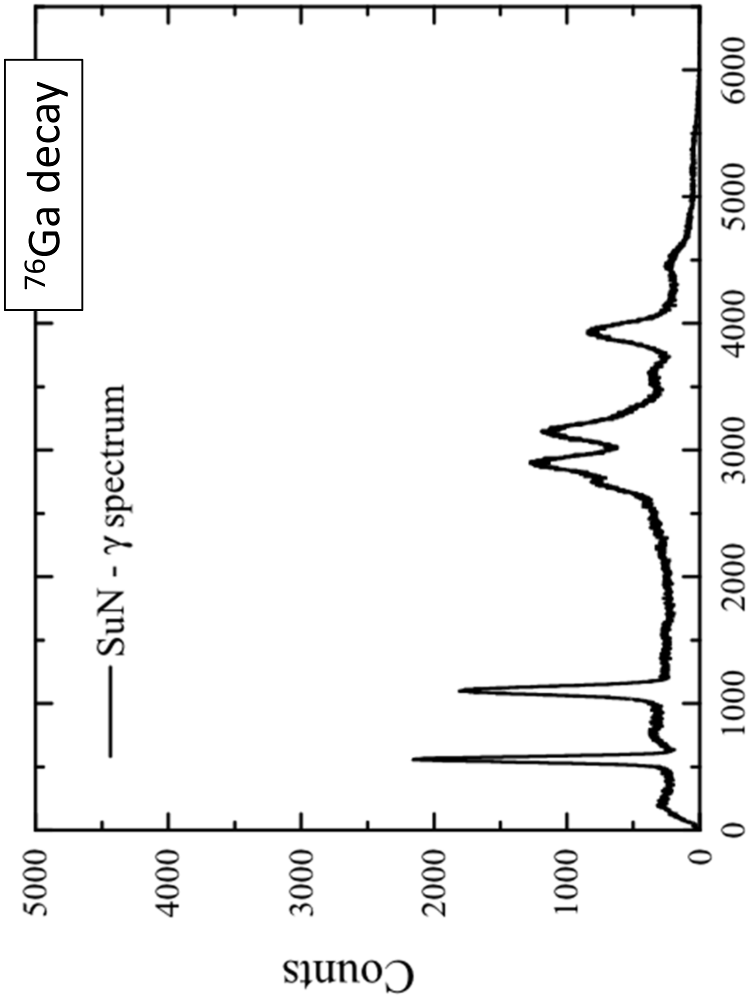
Proof-of-principle: $^{75}Ge(n,\gamma)^{76}Ge$

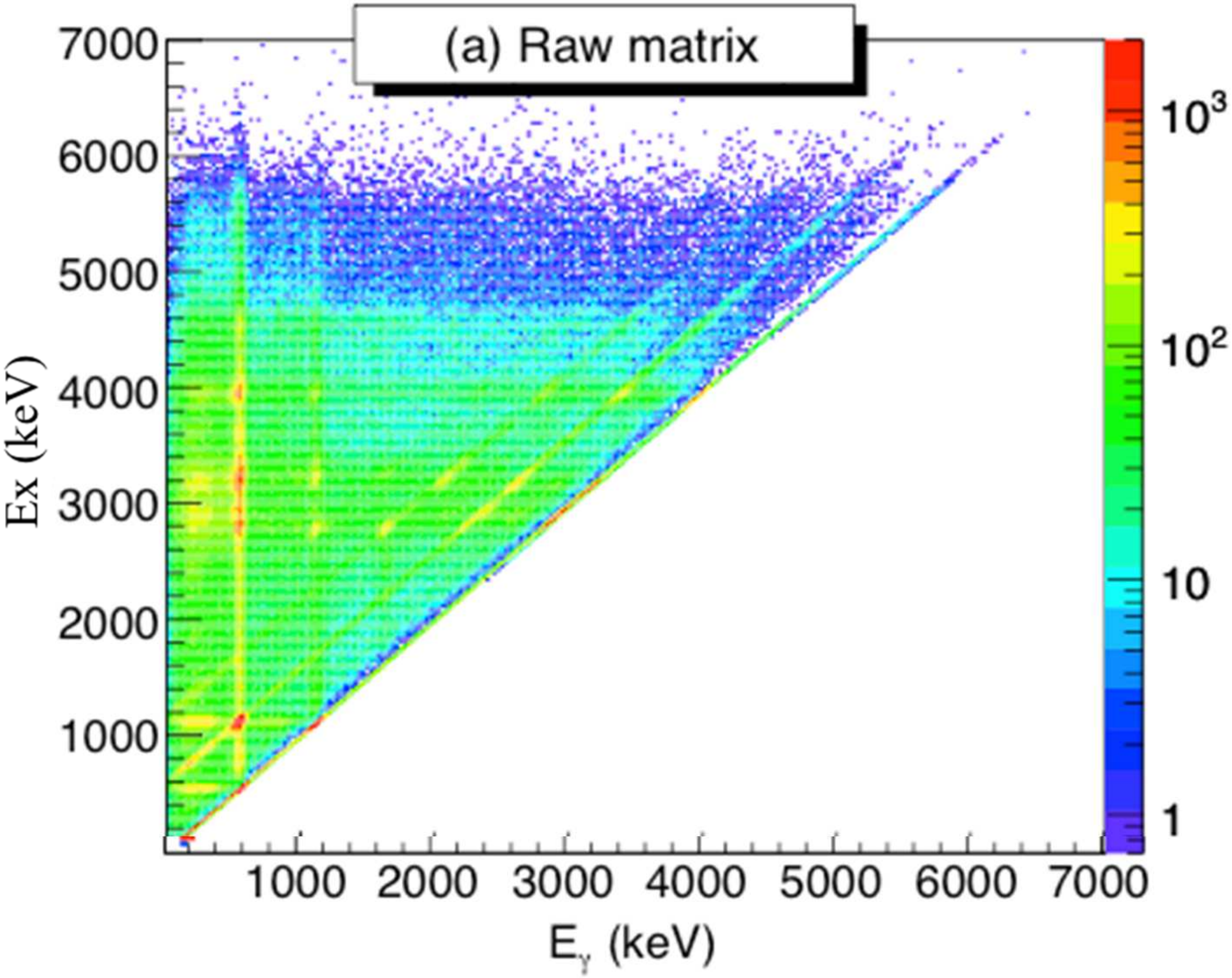


^{76}Ga: $T_{1/2}$ = 32.6 s
$Q_{\beta-}$ = 7.0 MeV
S_n (^{76}Ge) = 9.4 MeV

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

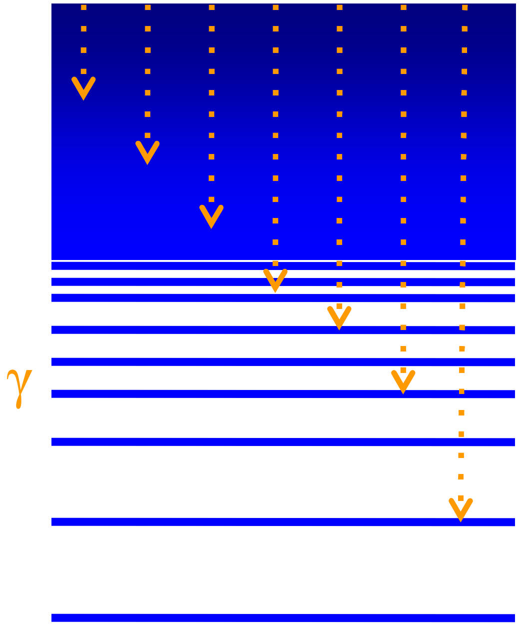
Proof-of-principle: $^{75}Ge(n,\gamma)^{76}Ge$

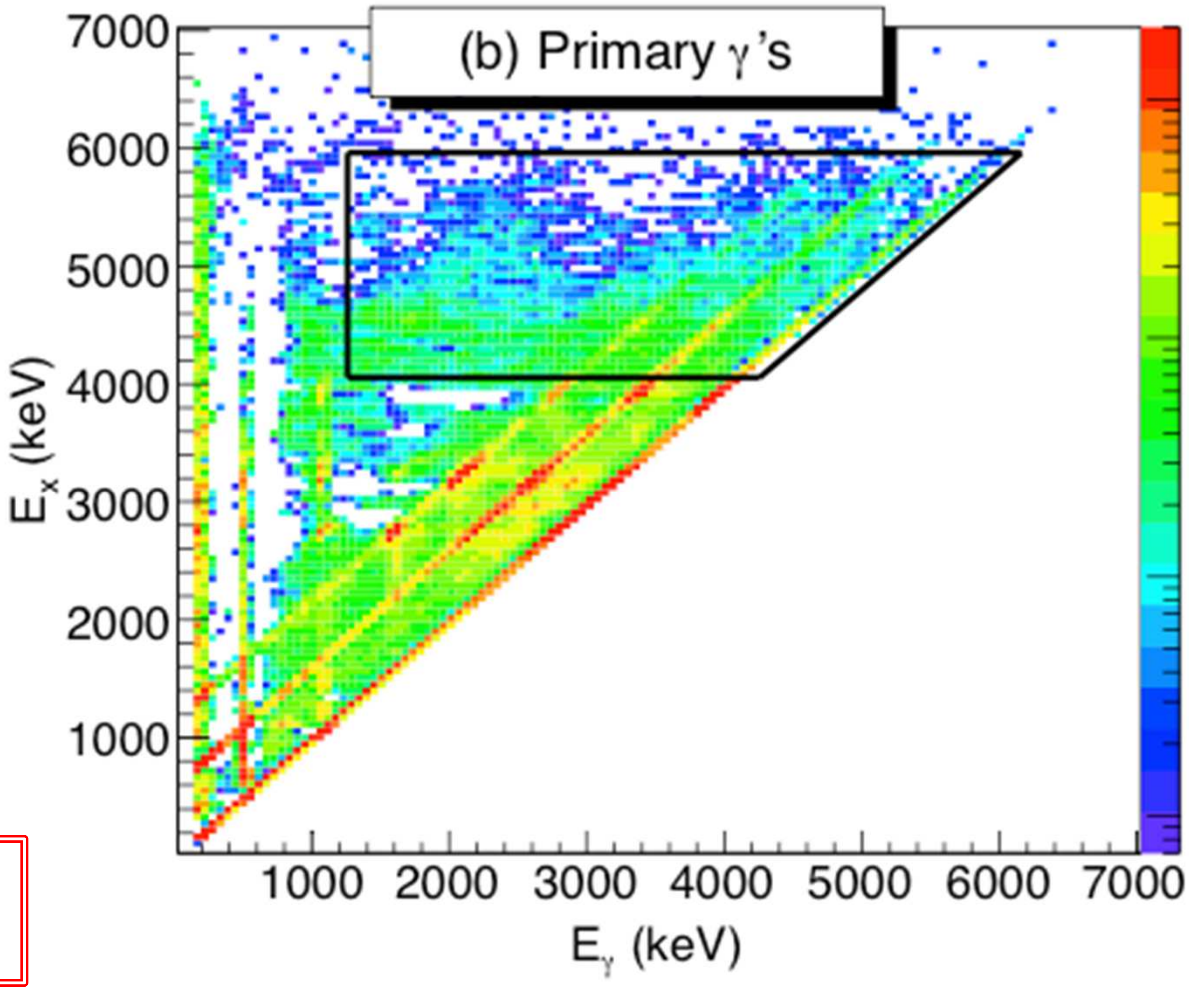




Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

Proof-of-principle: $^{75}Ge(n,\gamma)^{76}Ge$

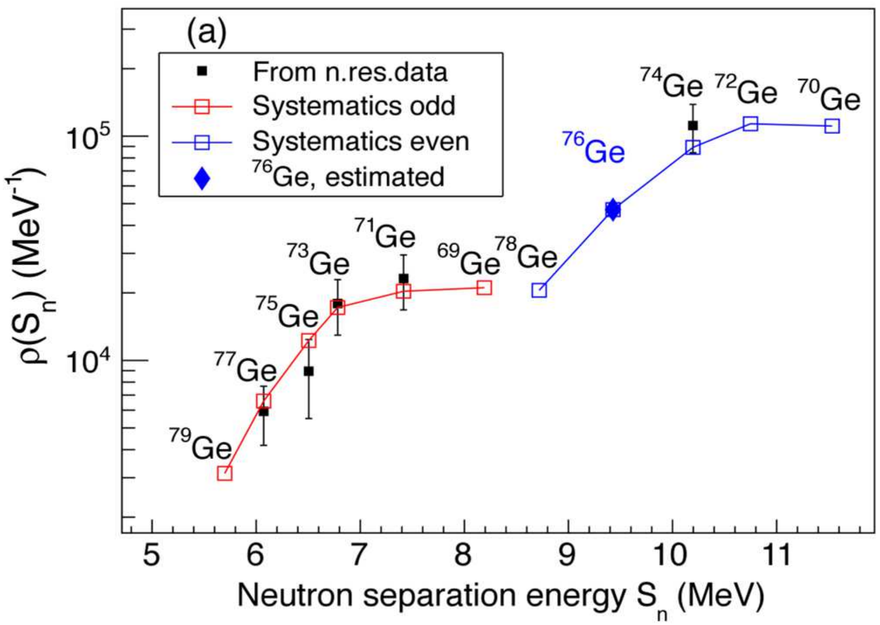


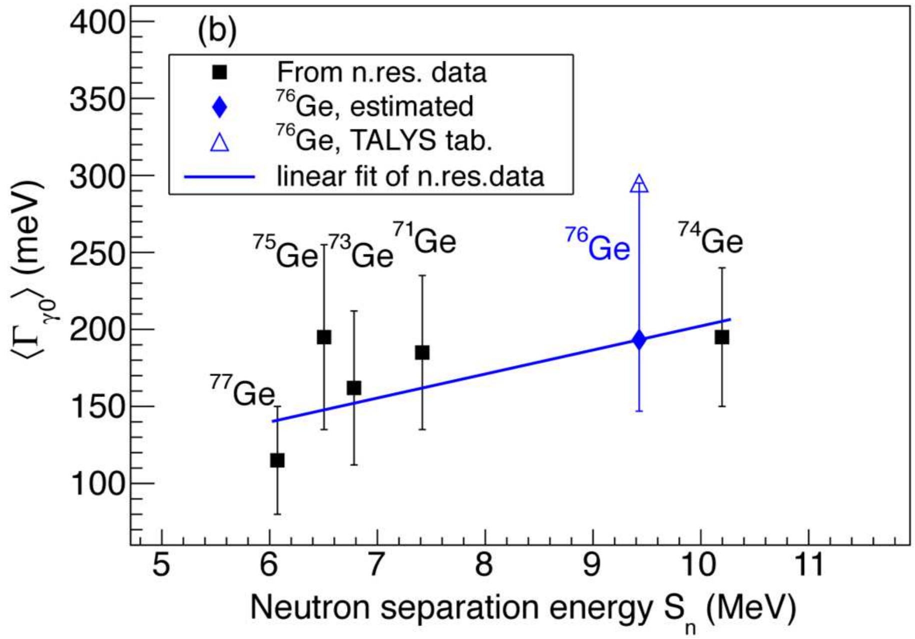


$$P(E_\gamma, E_x) = \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

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.

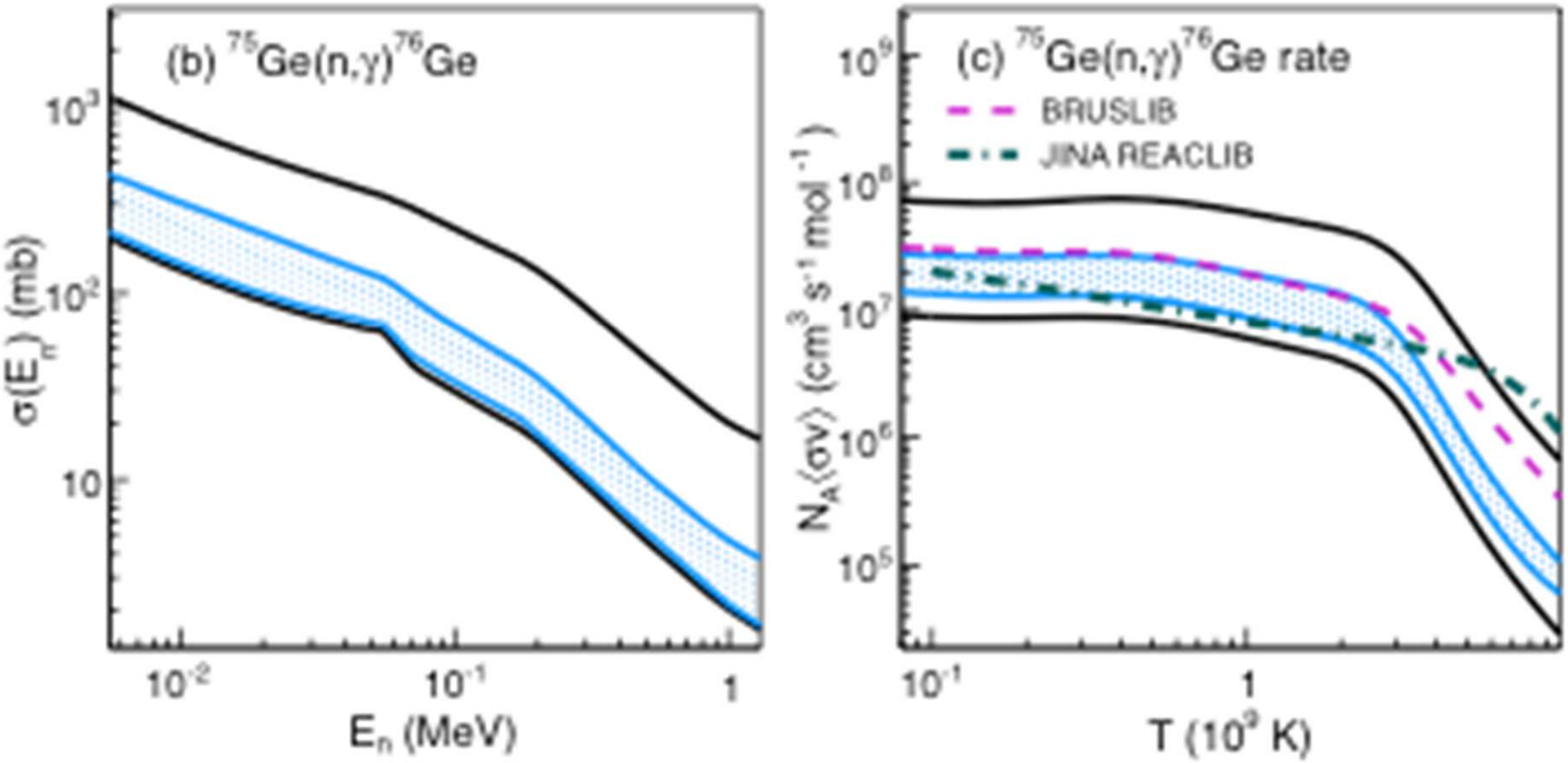




- 〉(S_n) from
  - Systematics
  - Microscopic calculations
- <℘©> normalized from systematics

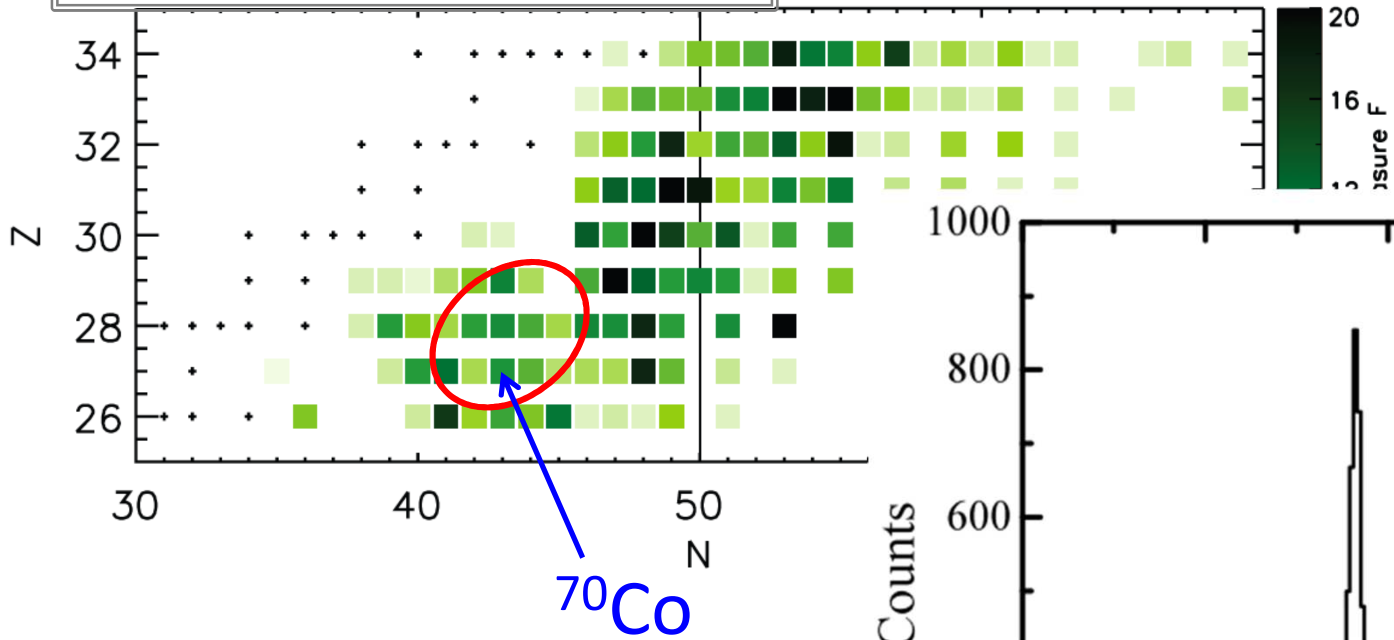
Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

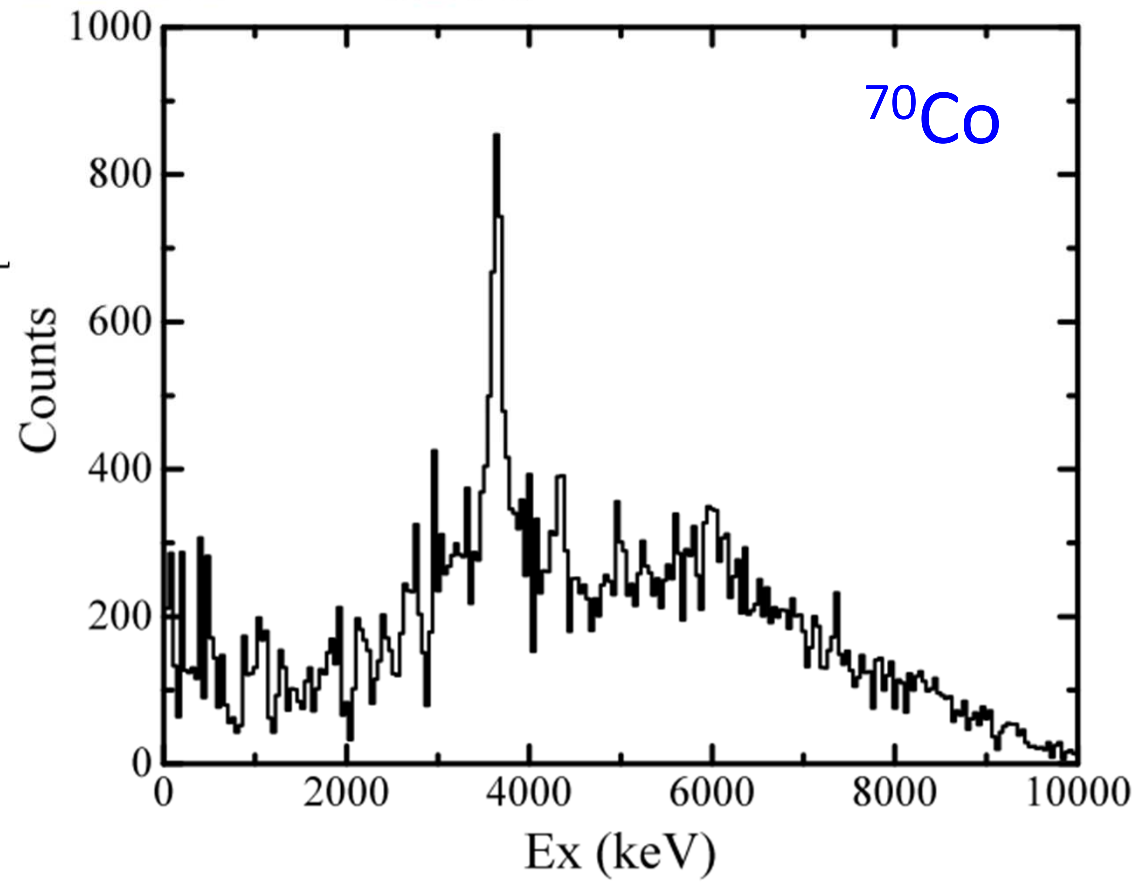
Results: $^{75}Ge(n,\gamma)^{76}Ge$



Weak r-process measurements

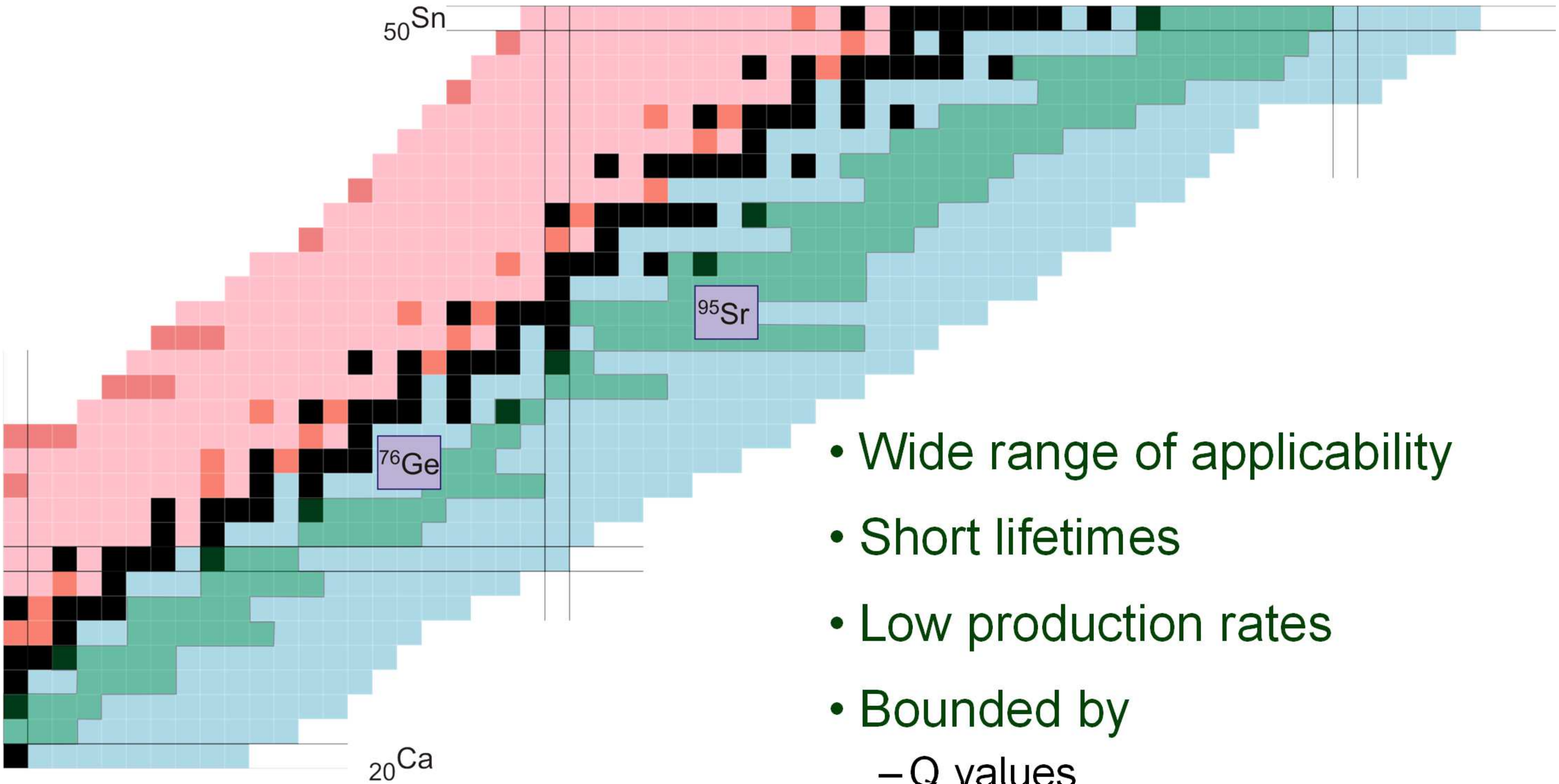
R. Surman, et al., , AIP Advances 4, 041008 (2014)





^{70}Co: $T_{1/2}$ = 108 ms
$Q_{\beta-}$ = 12.3 MeV
S_n (^{70}Ni) = 7.3 MeV

Applicability



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

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
- A. Rodriguez
- C.S. Sumithrarachchi
- R.G.T. Zegers

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

Central Michigan University
- G. Perdikakis

Notre Dame
- A. Simon

Los Alamos National Lab
A. Couture

S. Mosby

Lawrence Livermore National Lab
D.L. Bleuel

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