Using β decays to constrain (n,γ)reaction cross sections in short lived nuclei

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Workshop “Theory for open-shell nuclei near the limits of stability”, MSU 2015

Overview

- R-process nucleosynthesis
- Uncertainties
  - β-decay rates
  - Neutron capture rates

- Experiment (short)
- Results
- Future plans

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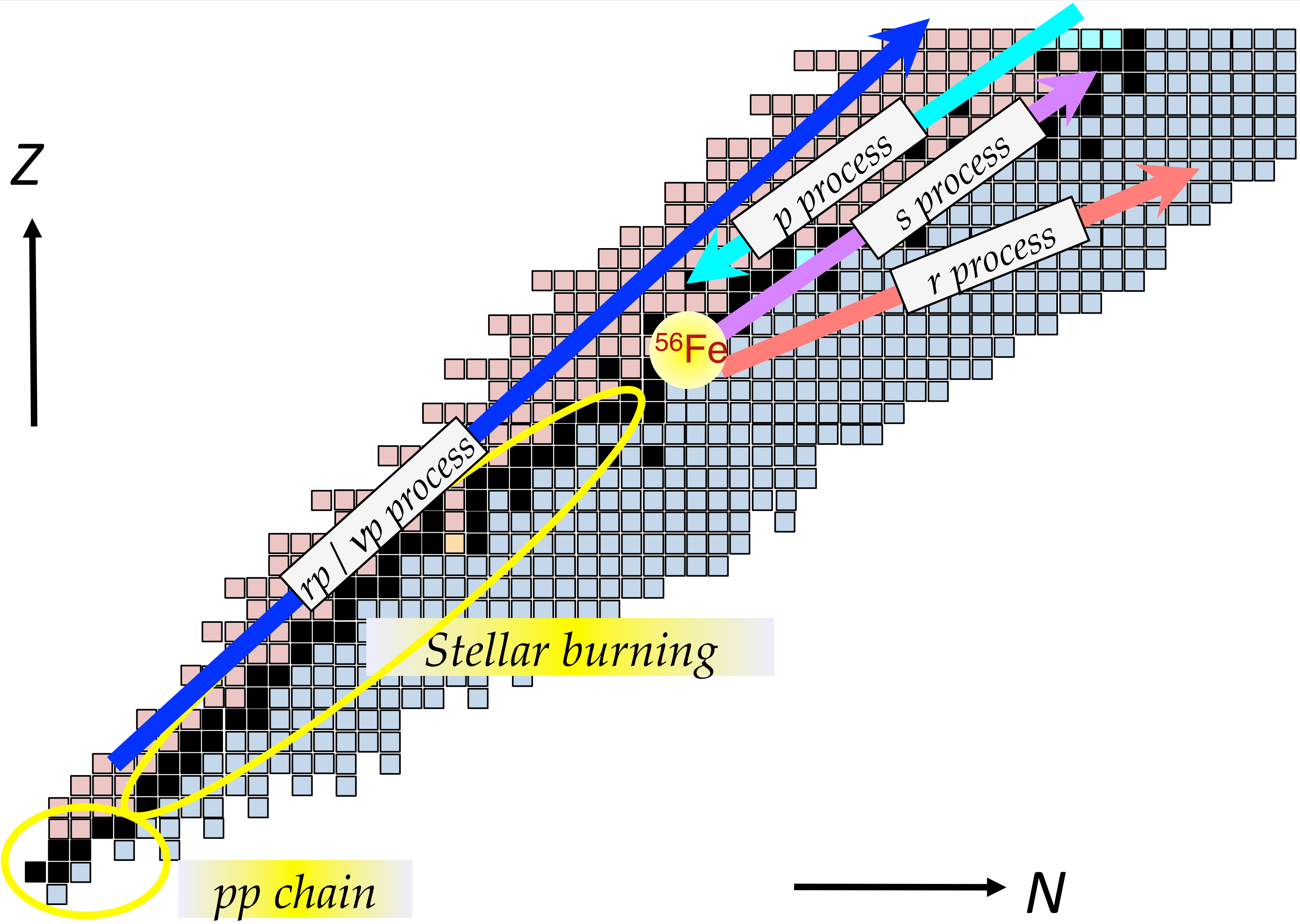
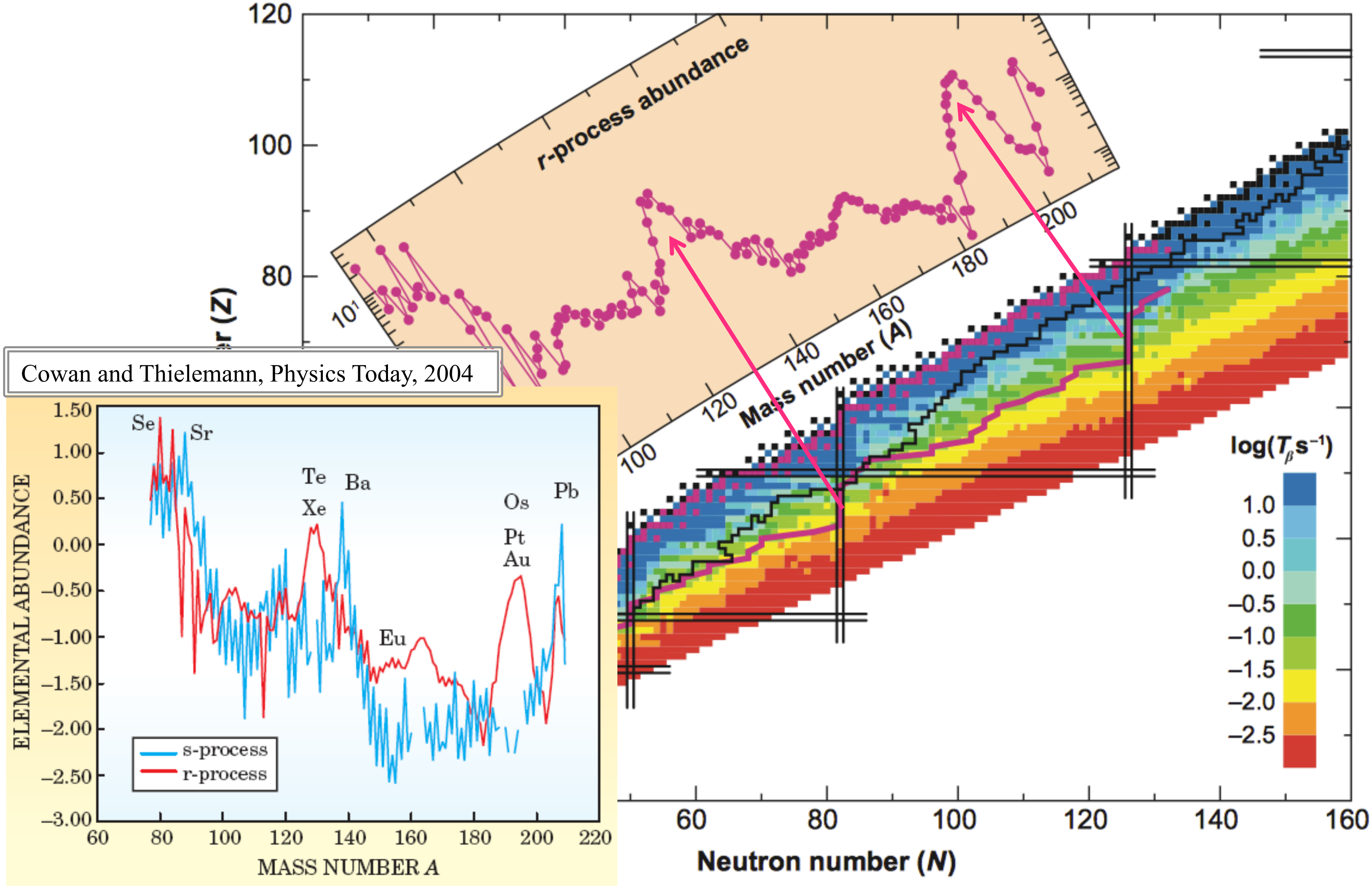
Nucleosynthesis paths



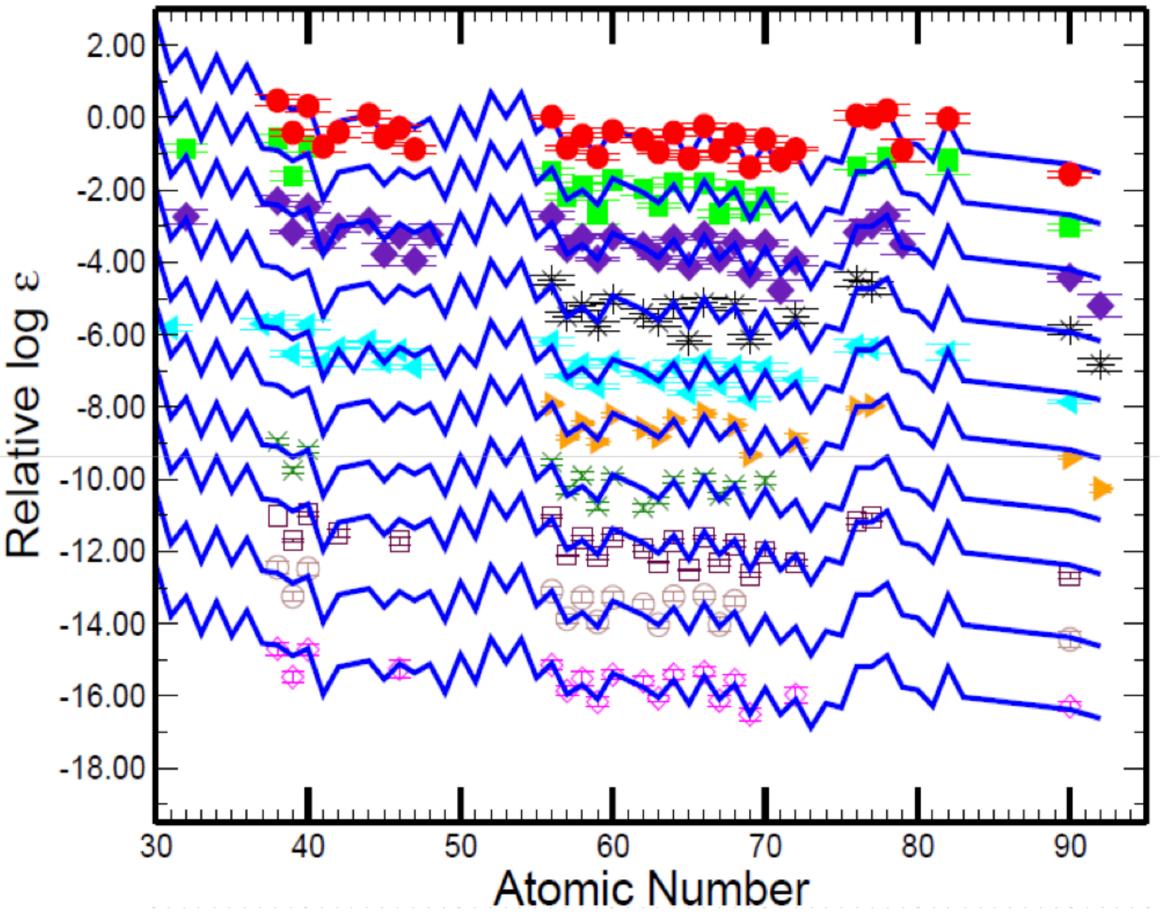
r-process path and abundances



Cowan and Thielemann, Physics Today, 2004

Sneden, C., Cowan, J. J., & Gallino, R., *Ann. Rev. Ast. Ap.* **46** (2008) 241.

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
  - ○ νp-process

Cowan, et al, 2011

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

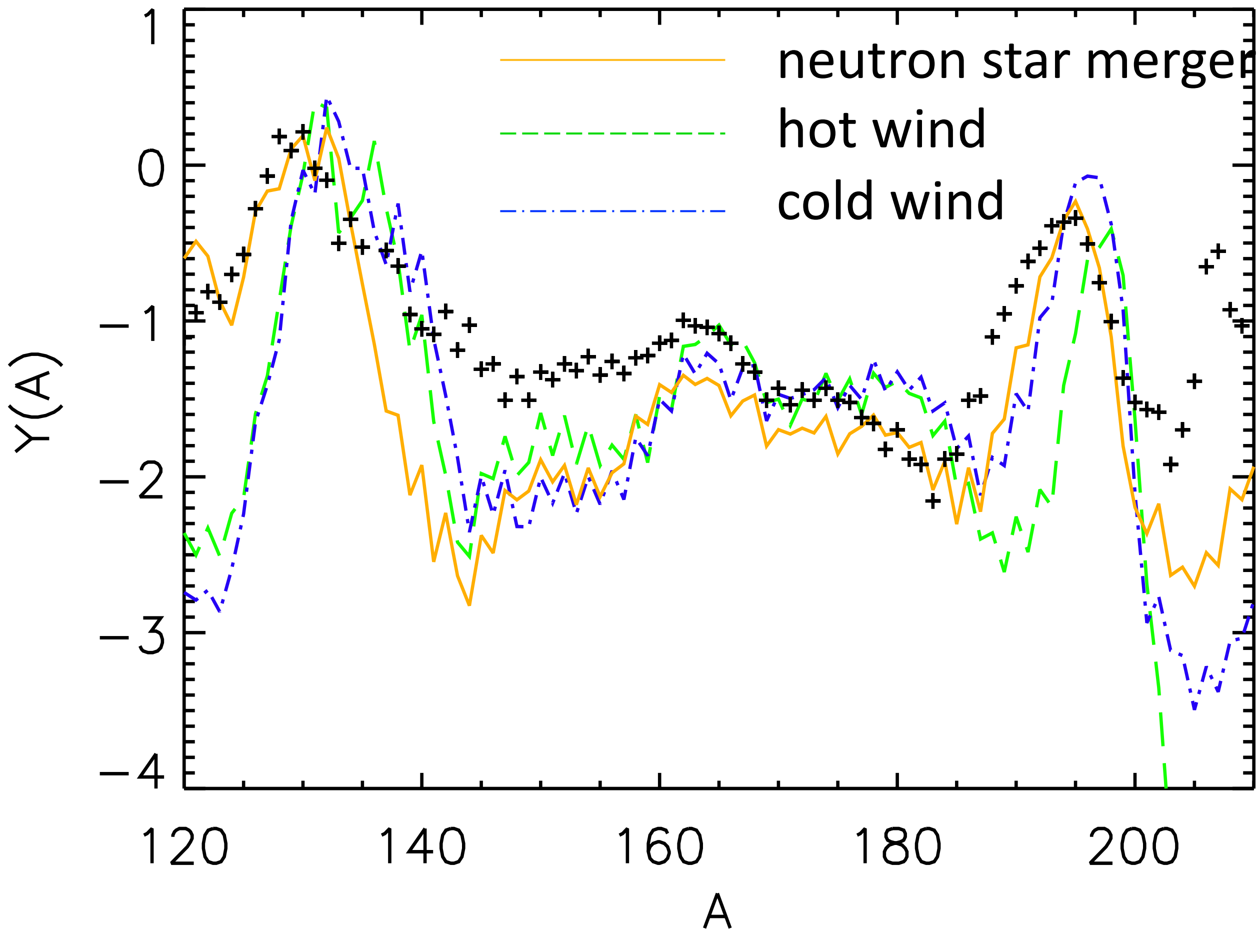
Credit: Erin O'Donnell, MSU

Core Collapse Supernova?

Neutron Star Merger?

Credit: NASA Goddard

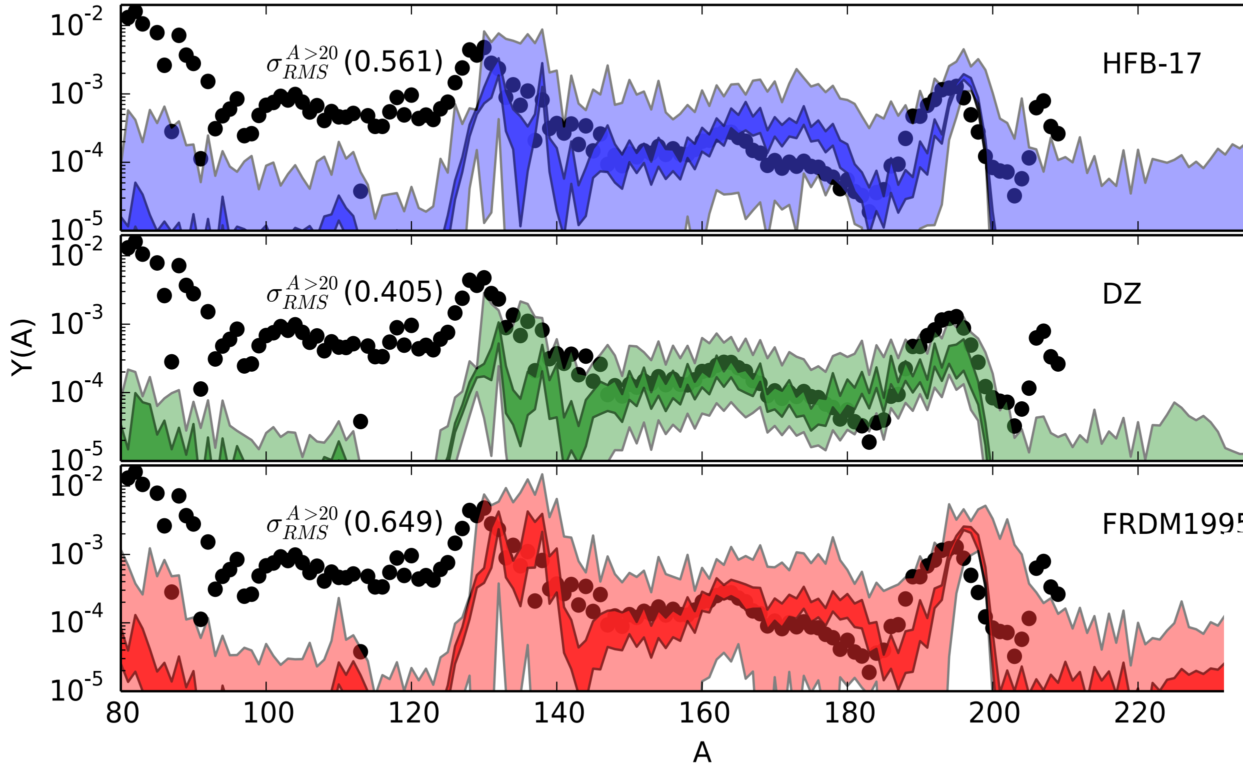
r-process calculations

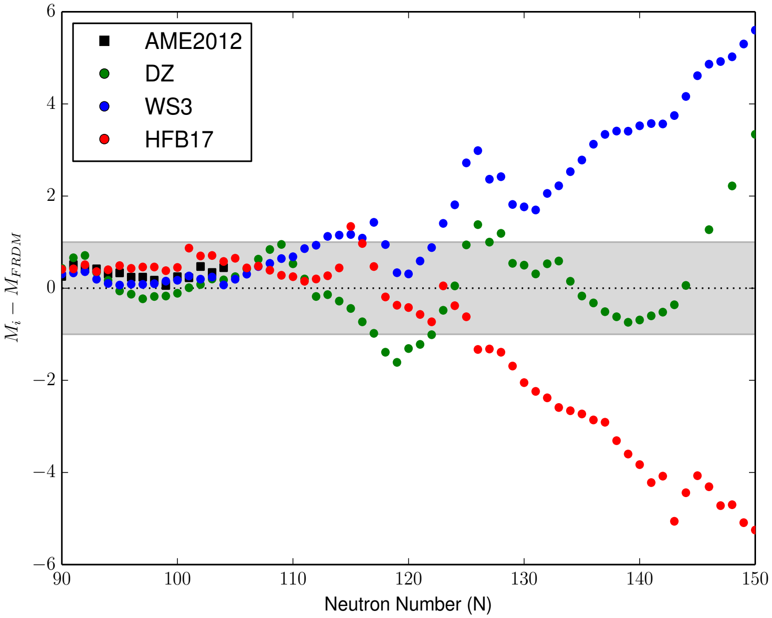


- Abundance pattern is different for the different astrophysical scenarios.
- Does one of them reproduce the observed abundances best?
- Why can't we tell?

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

Nuclear Physics Uncertainties: masses





Mumpower, Surman, Aprahamian (2015)

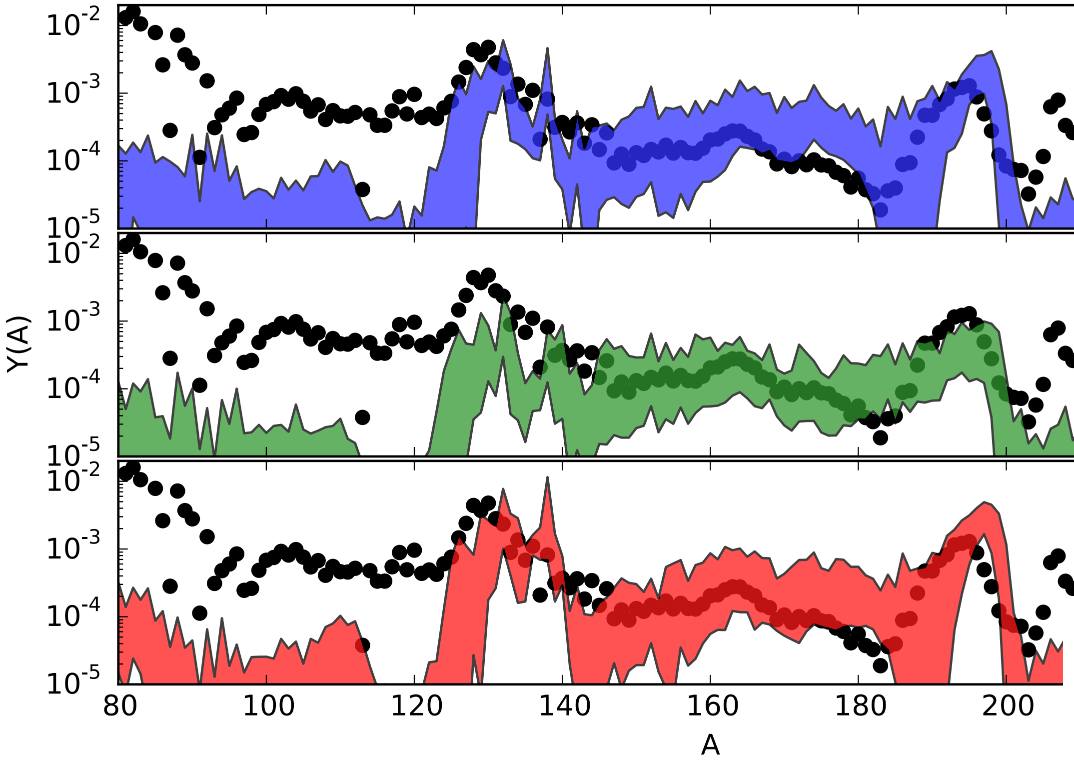
Monte-Carlo mass variations within:

mass model s_{RMS} :wide light-shaded band

100 keV :narrow dark-shaded band

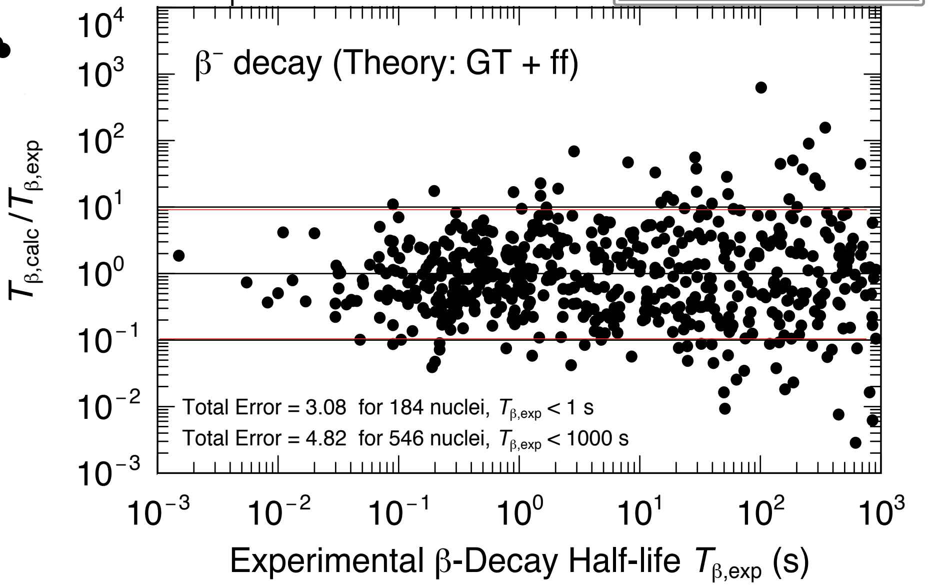
Nuclear Physics Uncertainties: β - decay

Mumpower, Surman, Aprahamian (2015)



Monte-Carlo mass variations of half lives

Möller et al (2003)



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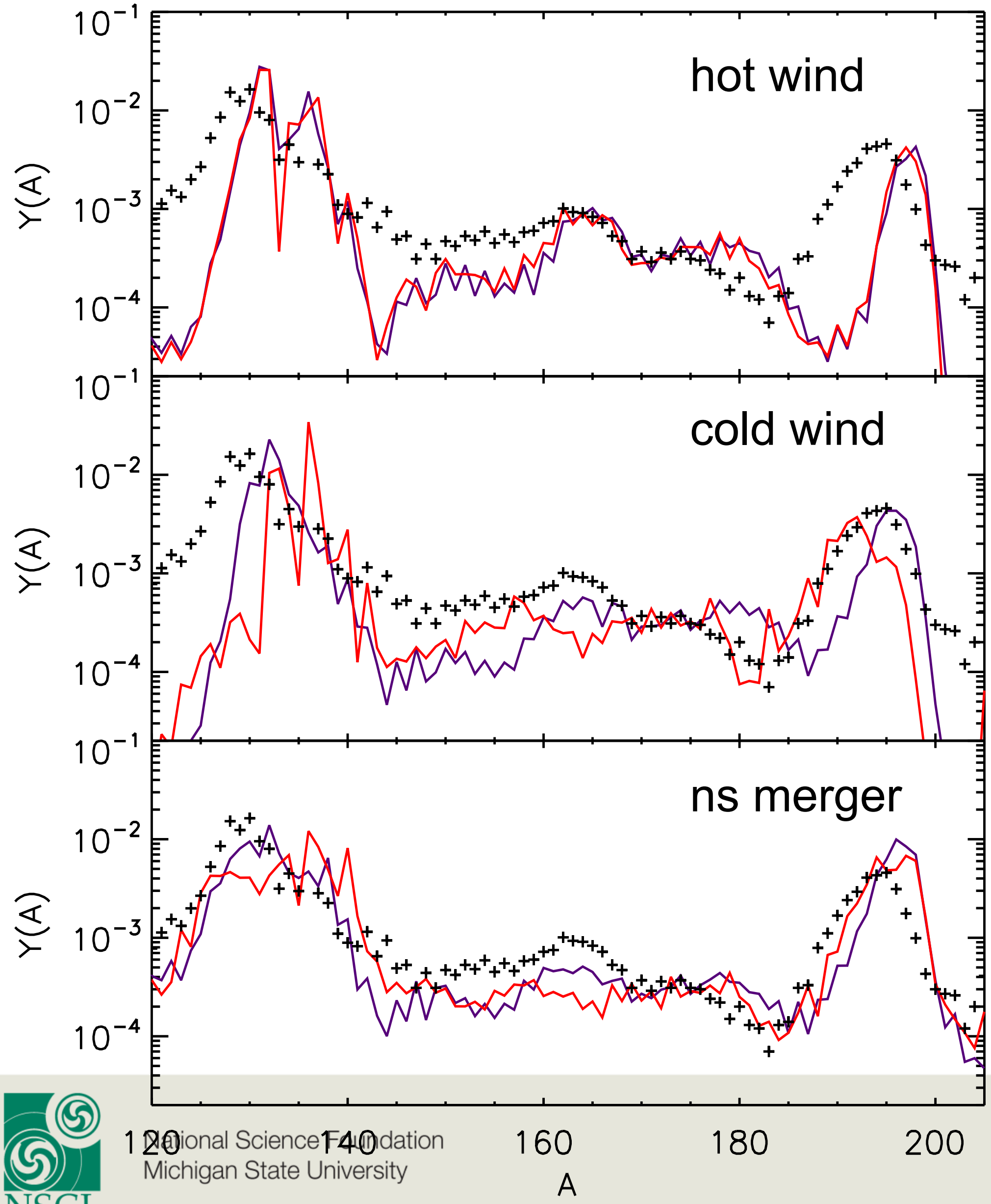
Nuclear Physics Uncertainties: βn



r-process simulation results with and without *β*-delayed neutron emission

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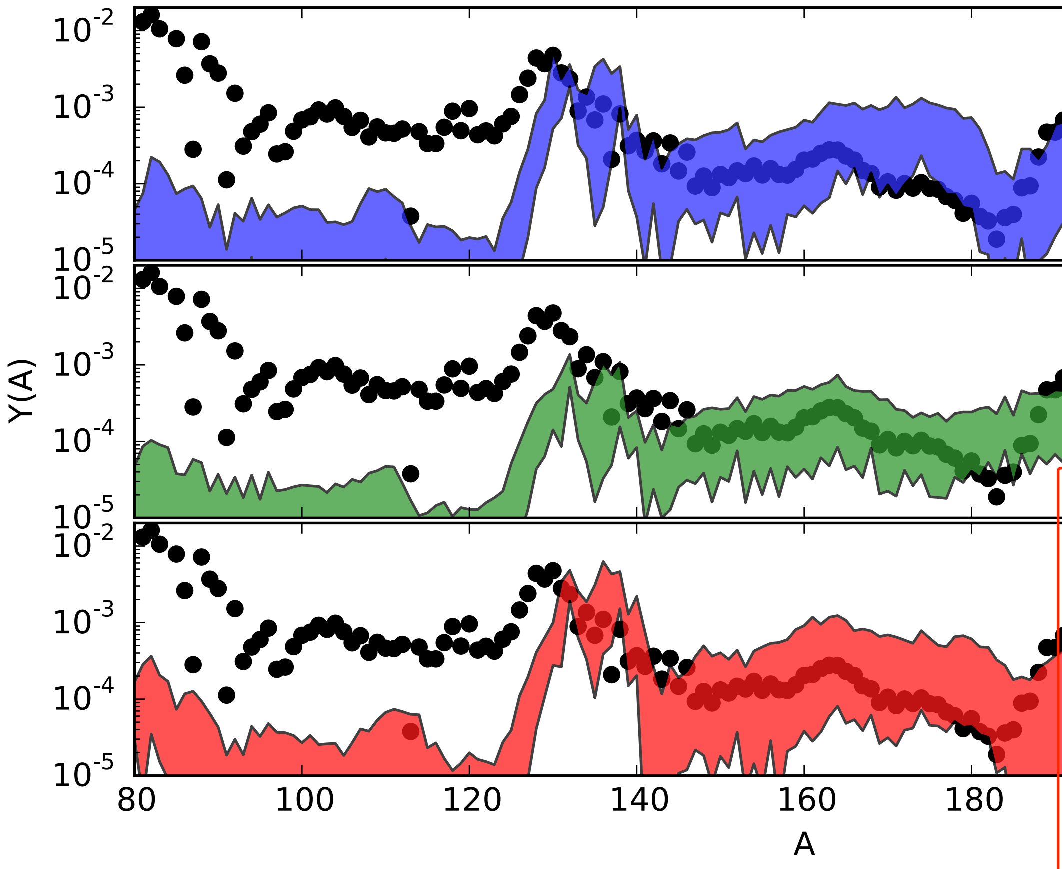
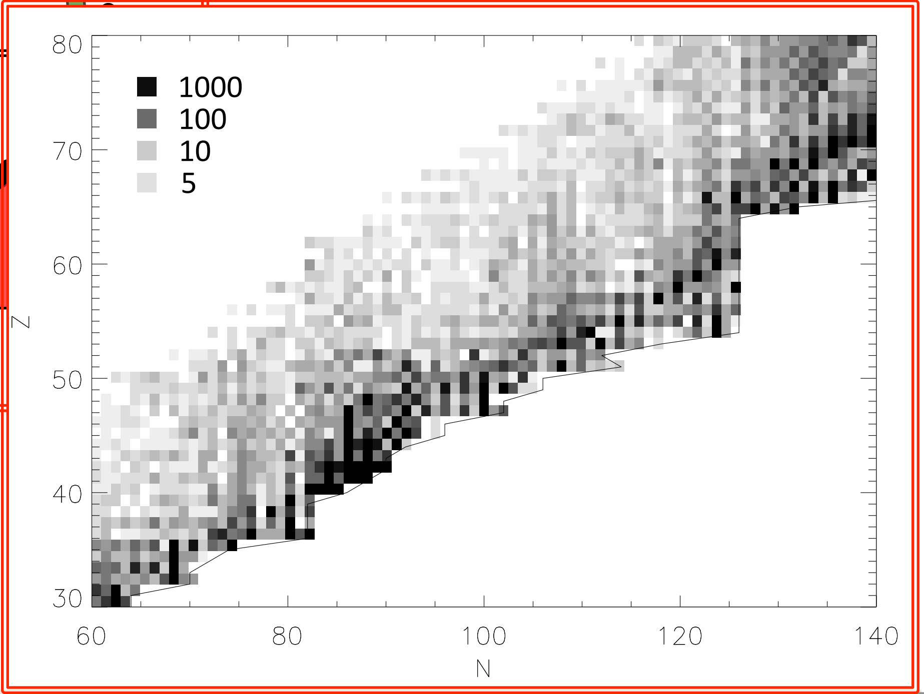
Nuclear Physics Uncertainties: (n,γ)

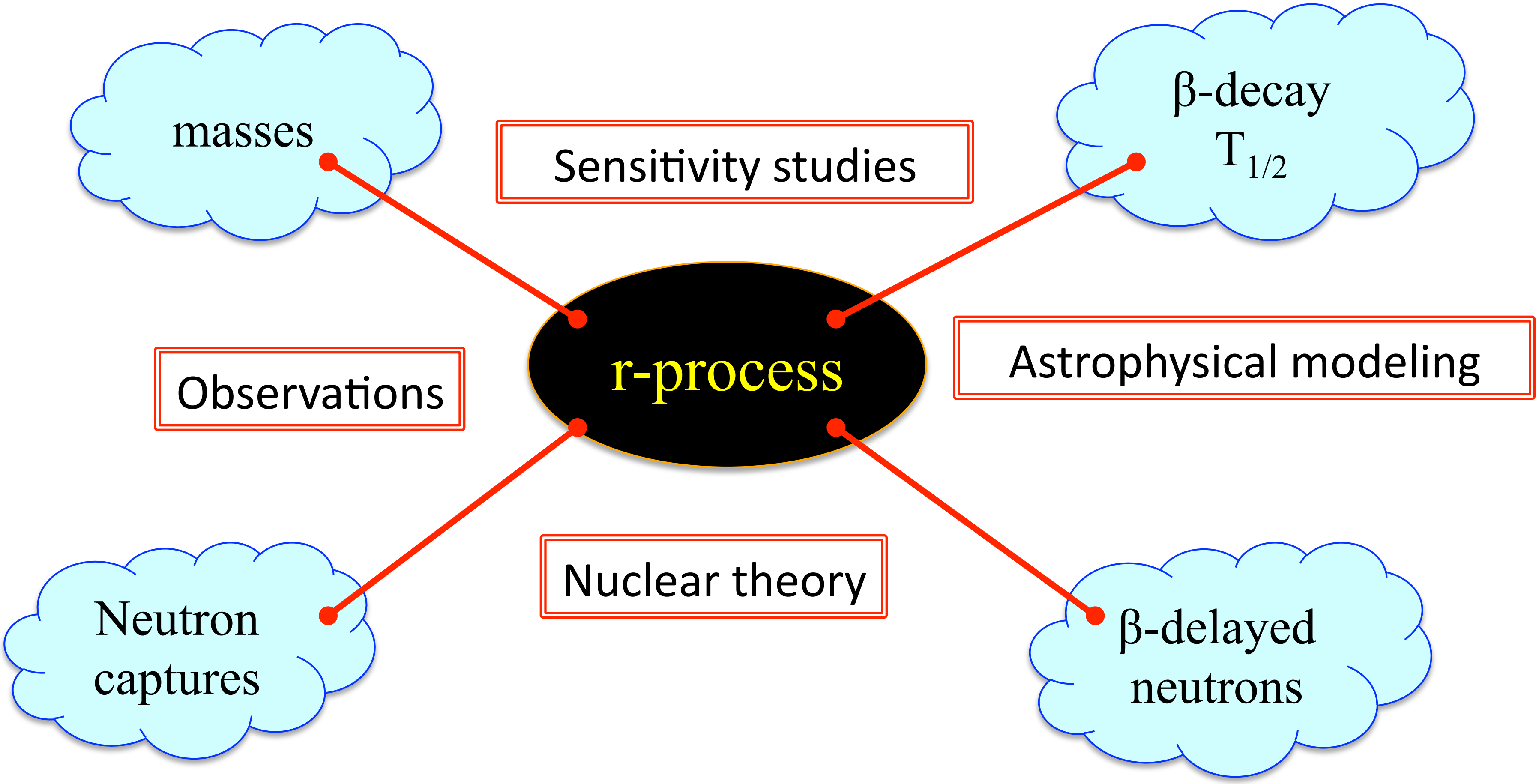




Monte-Carlo variations of (n,γ) rates within a factor 100.

Surman and Engel PRC (2001)

r-process



masses

Sensitivity studies

β-decay

$T_{1/2}$

Observations

r-process

Astrophysical modeling

Neutron captures

Nuclear theory

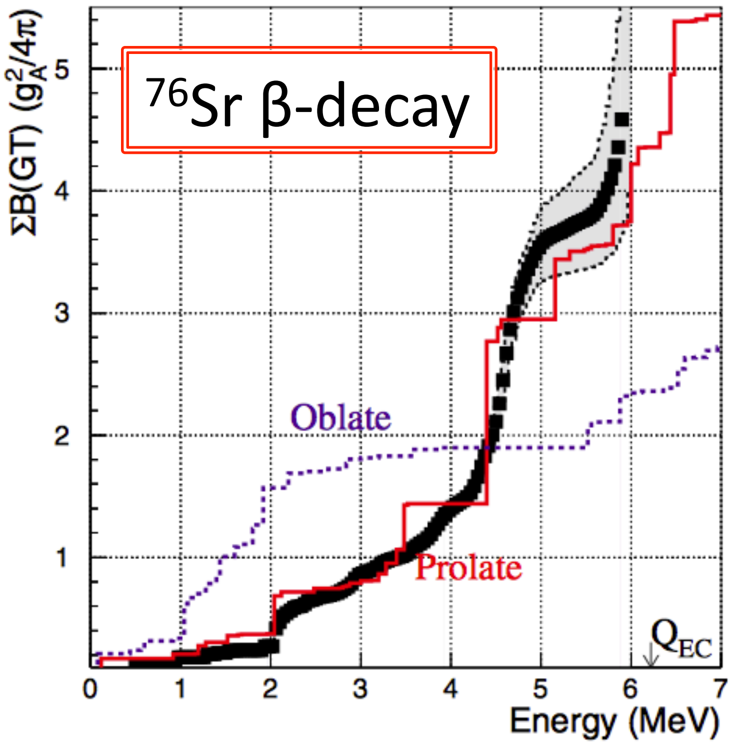
β-delayed neutrons

Why measure the β decay strength

- Model constraints for better input in r-process calculations

(Cannot measure everything - we need to rely on model predictions)

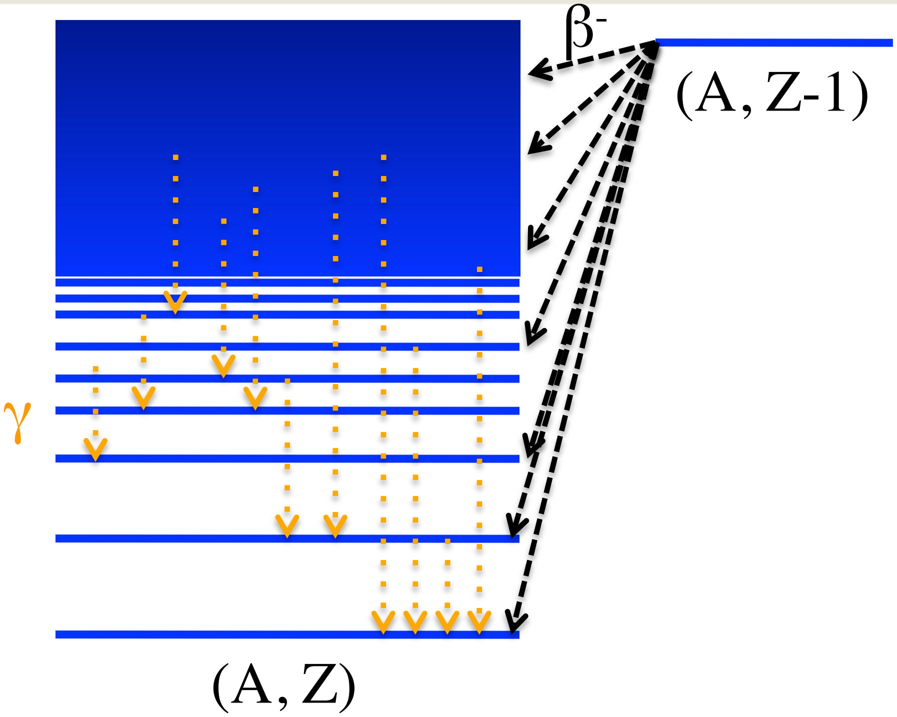
- Nuclear structure information
  - ➢ $T_{1/2}$ sensitive to nuclear shape
  - ➢ Can get same $T_{1/2}$ for different shapes
  - ➢ Sensitivity to the nuclear shape



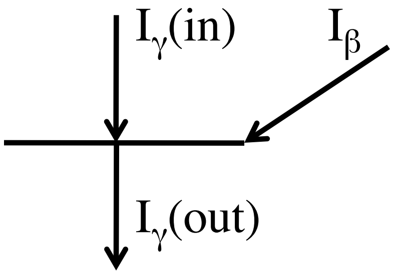
E. Nacher, *et al.*, *Phys. Rev. Lett.* 92 (2004) 232501.

The pandemonium effect

John Milton's "Paradise Lost



Small size – low efficiency detector

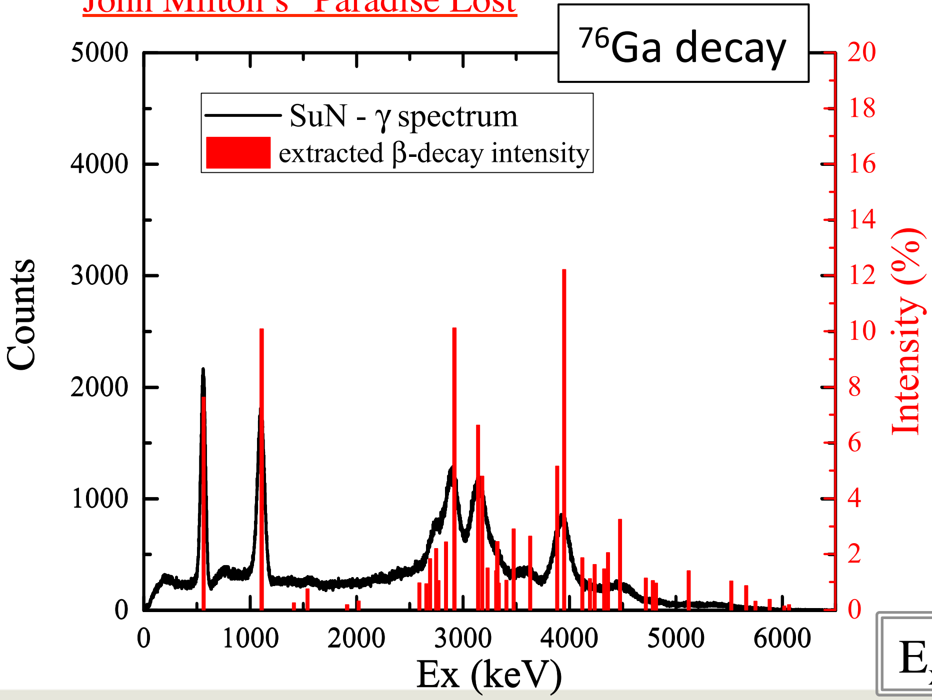


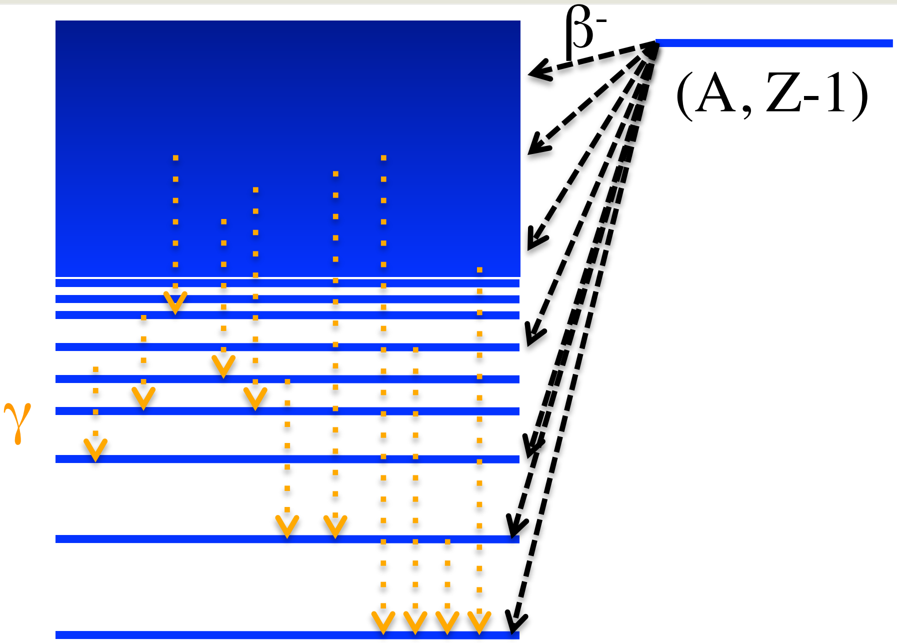
$$I_\beta = I_\gamma(\text{out}) - I_\gamma(\text{in})$$

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

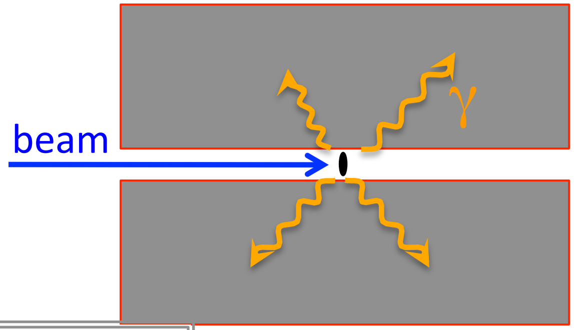
The pandemonium effect: solution

John Milton's "Paradise Lost





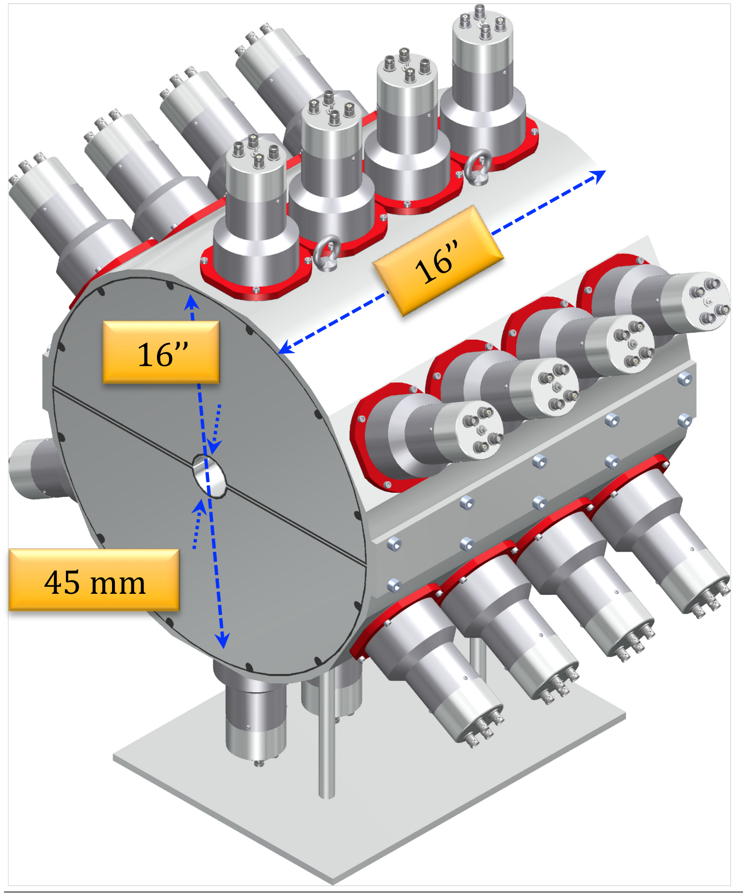
Large size - high efficiency detector

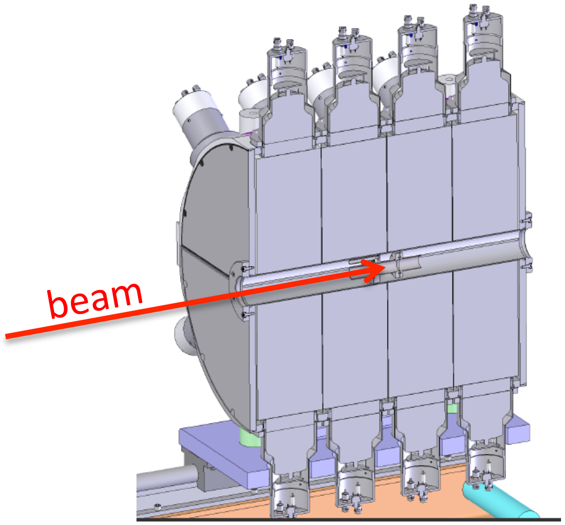


$$E_x = E_{\gamma1} + E_{\gamma2} + E_{\gamma3} + E_{\gamma4} + \dots$$

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

Summing NaI - SuN

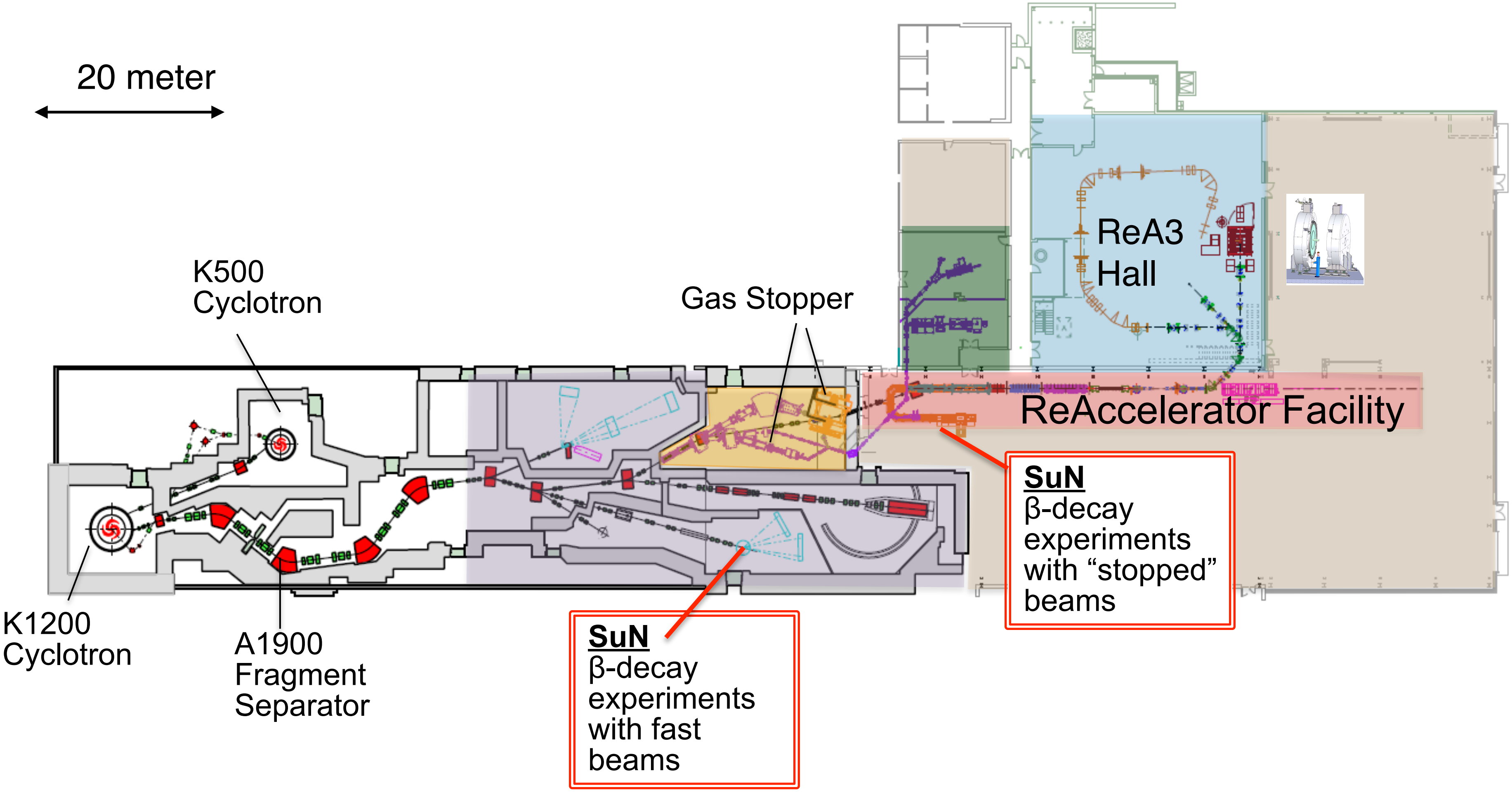




- ✓16x16 inch
- ✓45 mm borehole
- ✓2 pieces
- ✓8 segments
- ✓24 PMTs
- ✓ Efficiency > 85% for 1 MeV

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

Experimental techniques



20 meter

K500 Cyclotron

Gas Stopper

ReA3 Hall

ReAccelerator Facility

K1200 Cyclotron

A1900 Fragment Separator

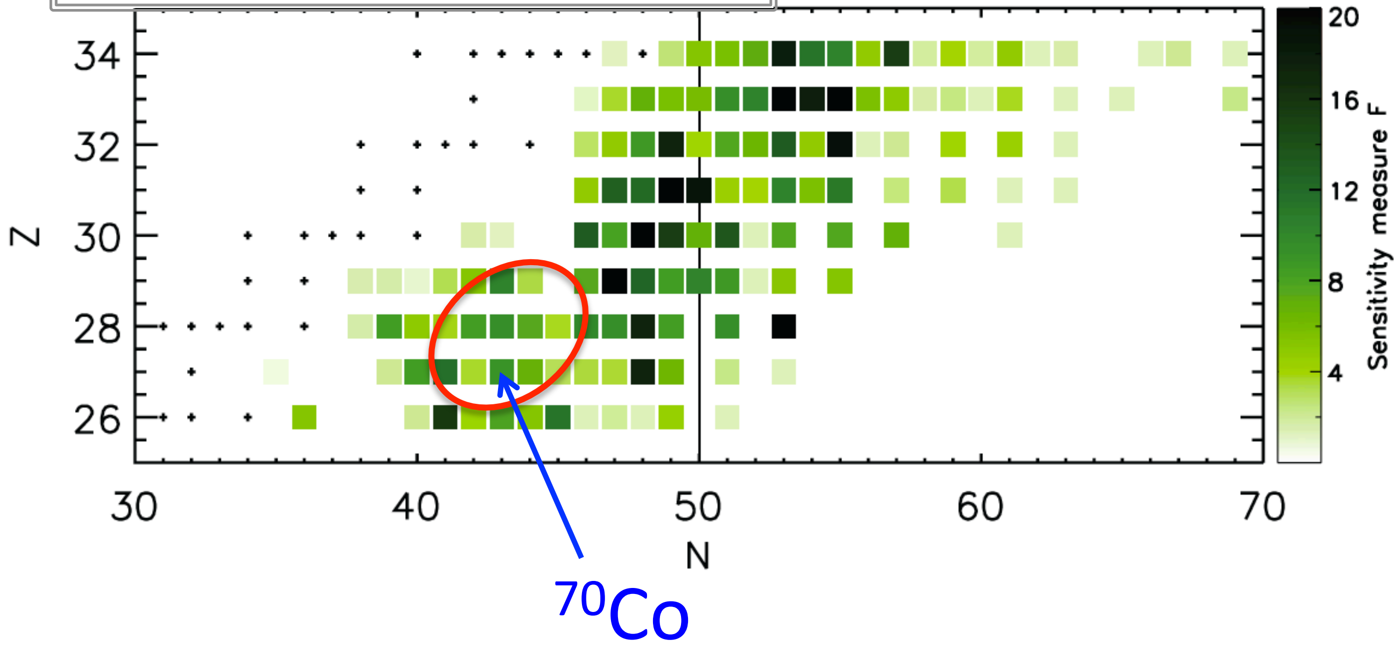
SuN
β-decay experiments with fast beams

SuN
β-decay experiments with "stopped" beams

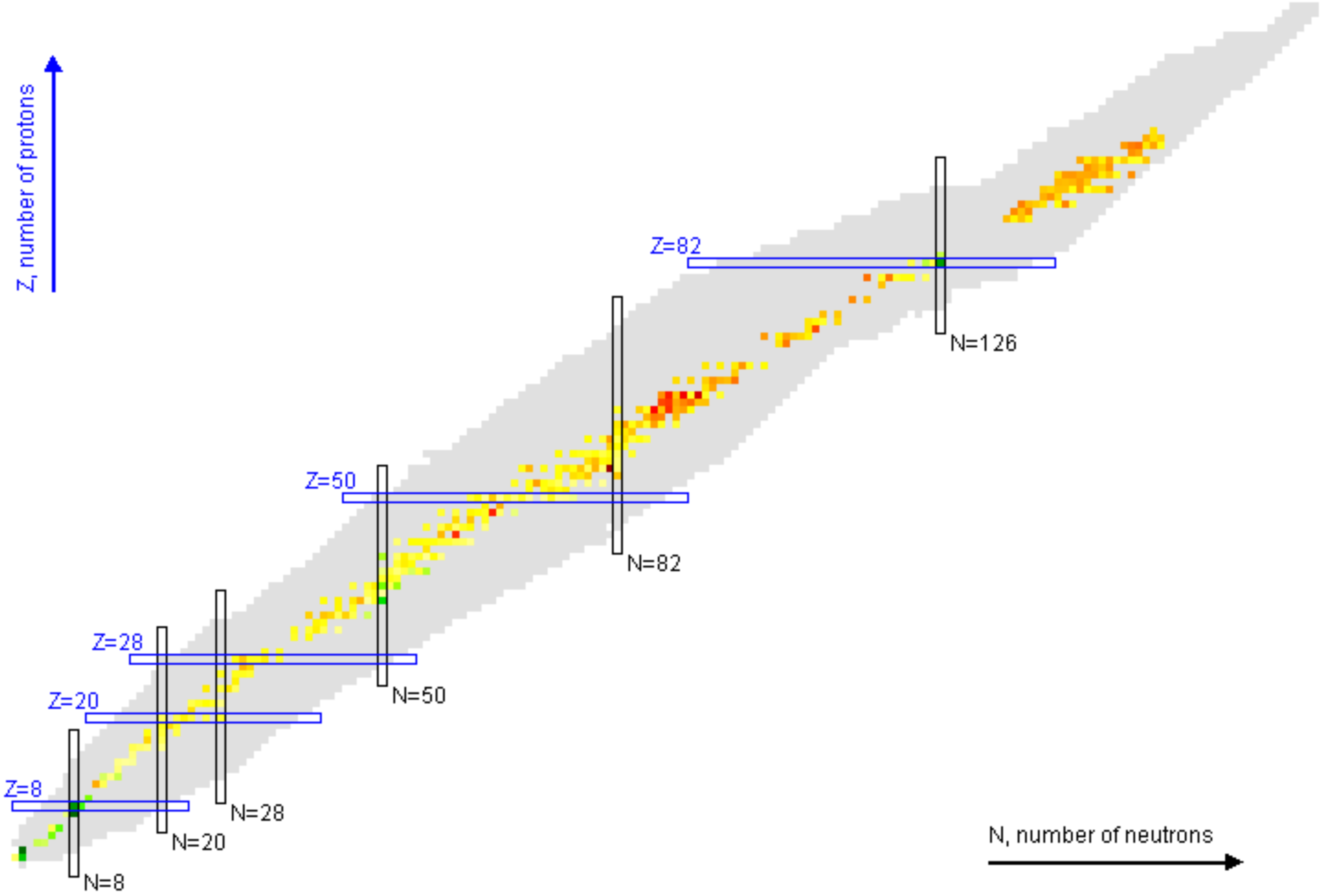
Fast Beams | Gas Stopper | Stopped beams | Reaccelerated Beams

Weak r-process sensitivity

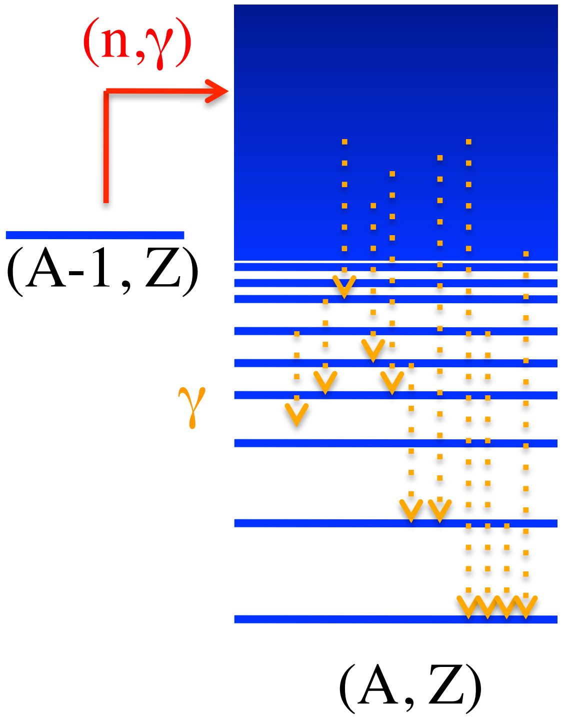
R. Surman, *et al.*, , AIP Advances 4, 041008 (2014)



Current (n,γ) measurements



Neutron Capture – Uncertainties



Hauser – Feshbach

- Nuclear Level Density

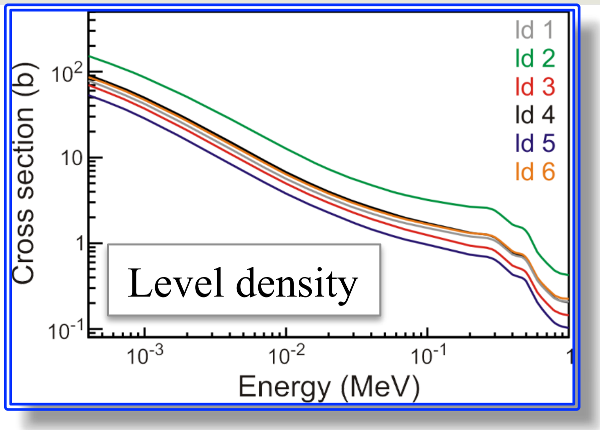
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

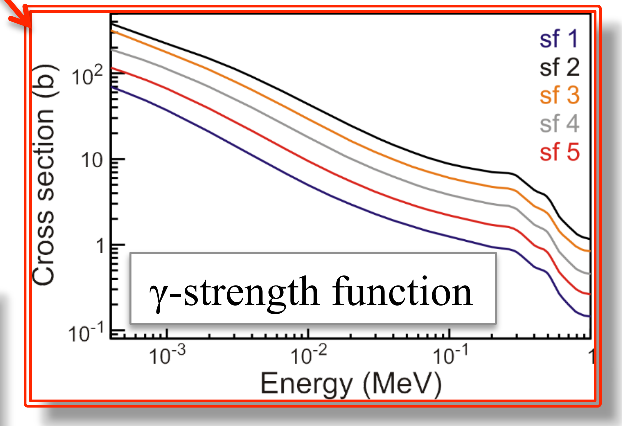
- γ-ray strength function

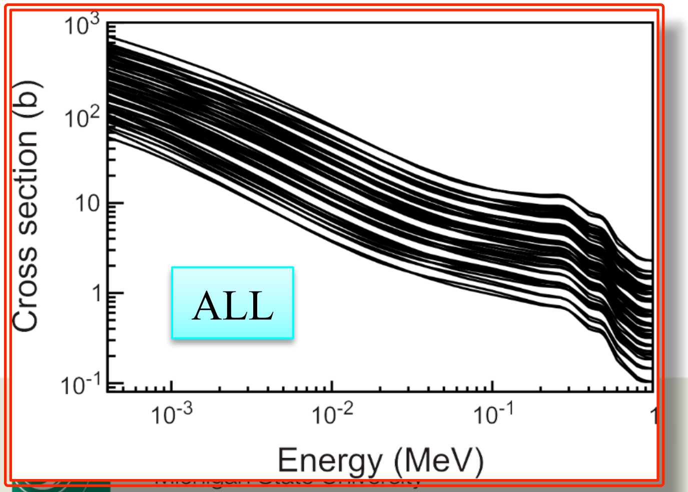
Generalized Lorentzian, Brink-Axel, various tables

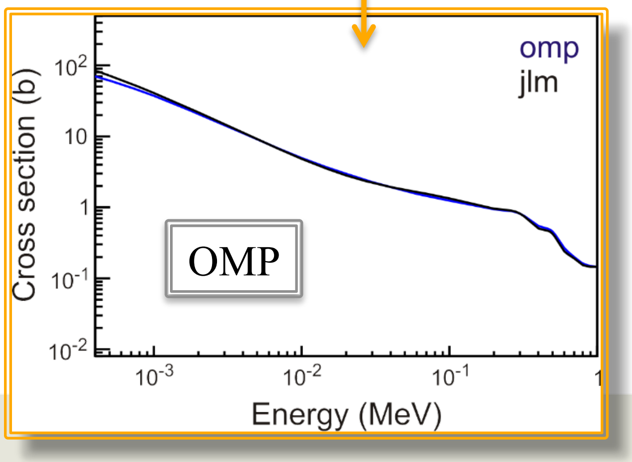
- Optical model potential

Phenomenological, Semi-microscopic





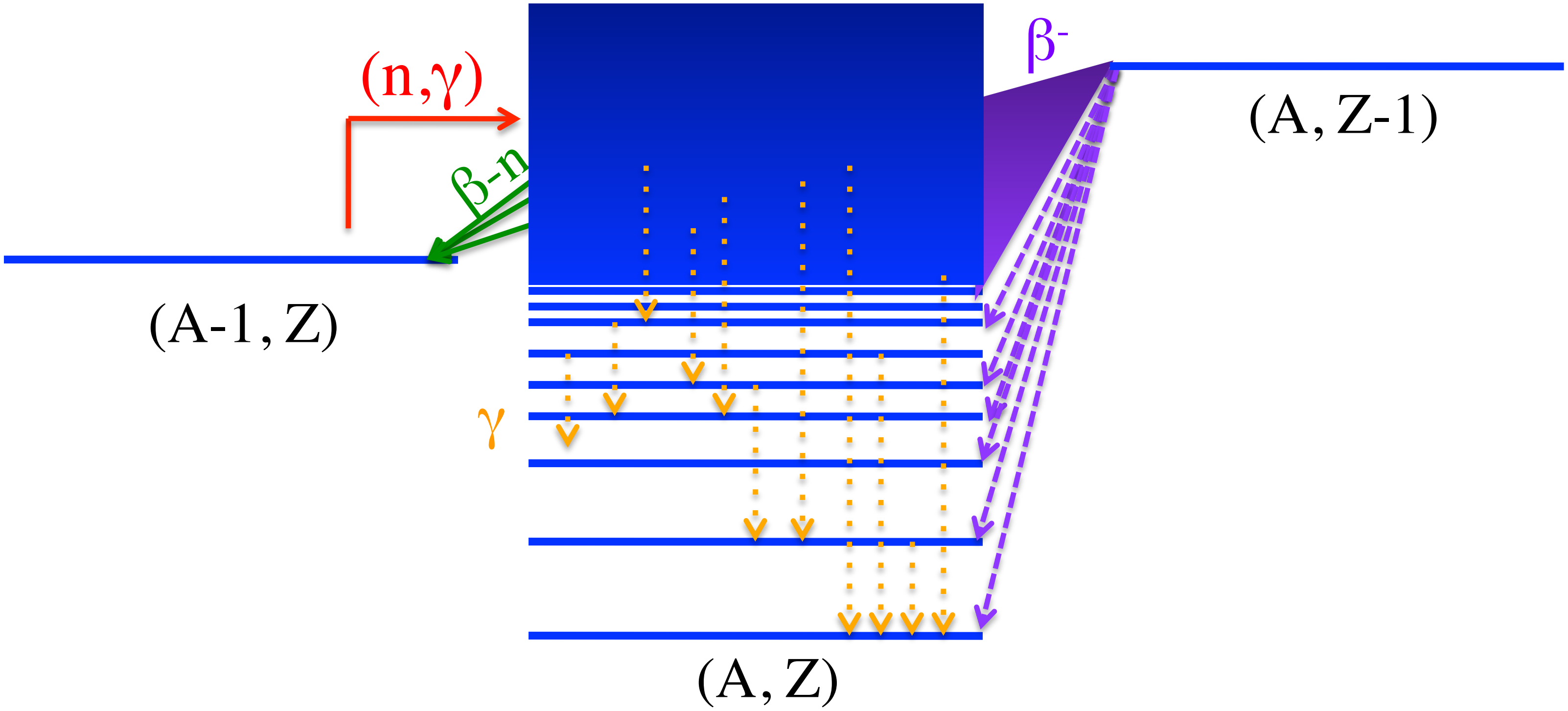




^{95}Sr(n,γ)^{96}Sr

TALYS

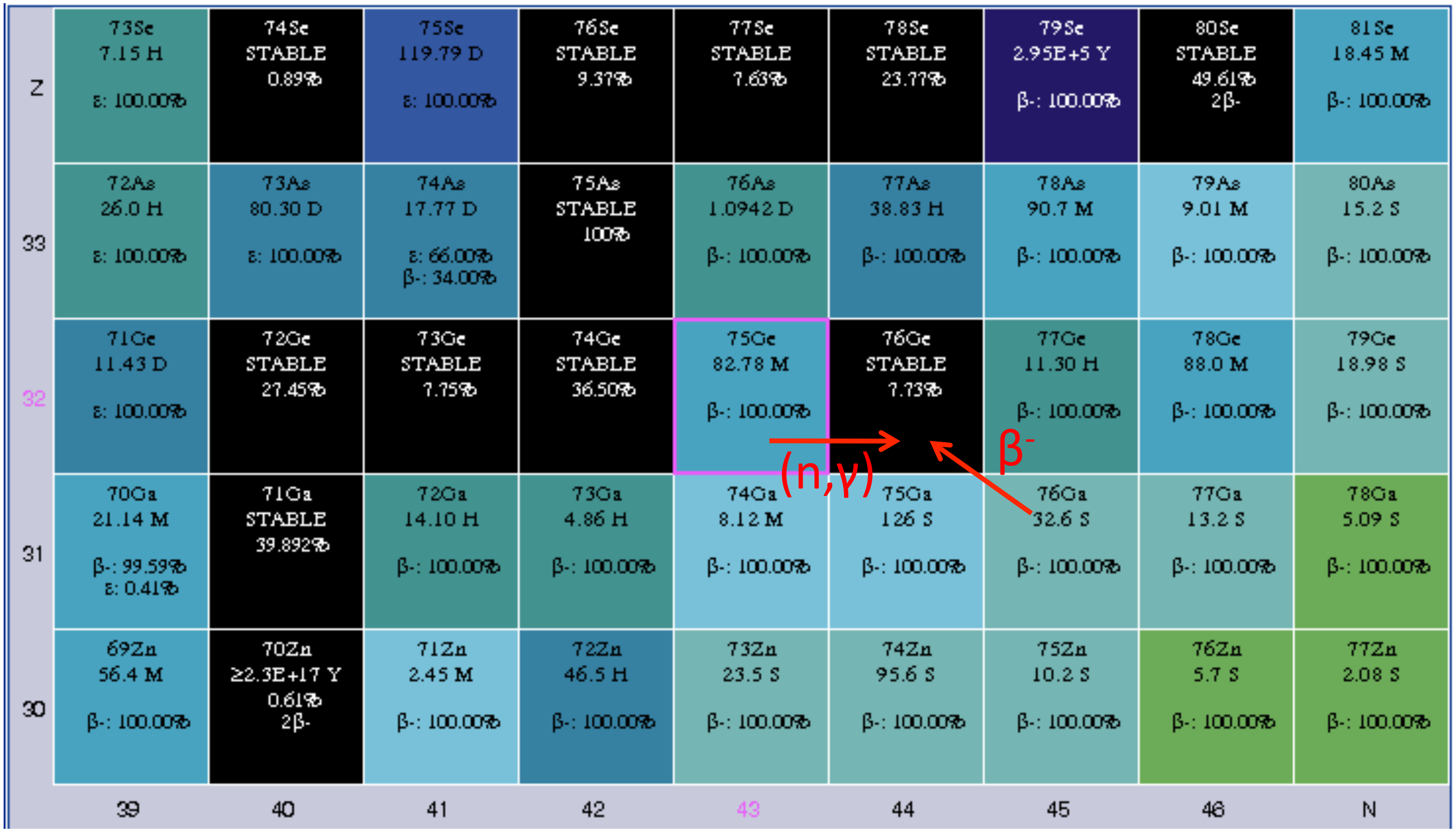
Neutron Capture – β-Oslo



- 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.

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

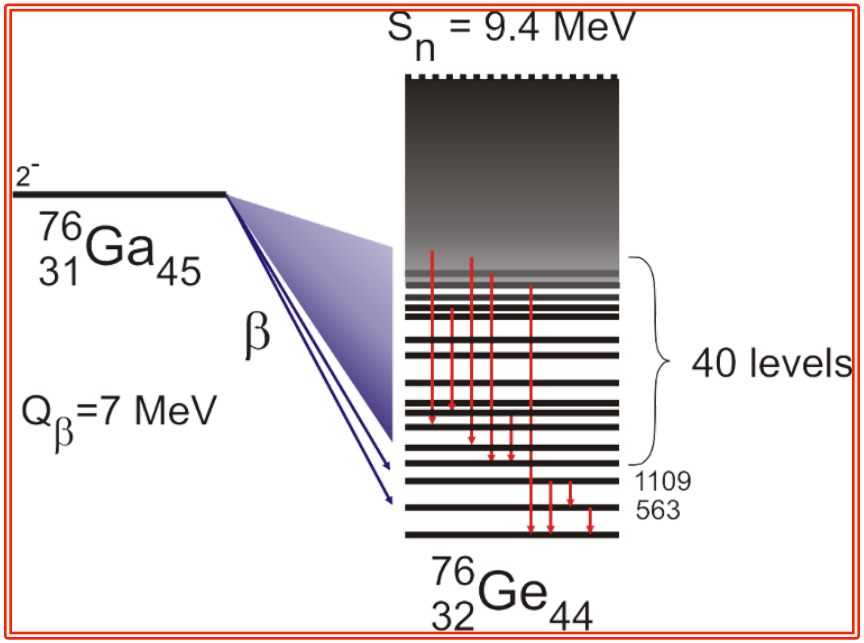
Proof-of-principle: $^{75}Ge(n,\gamma)^{76}Ge$

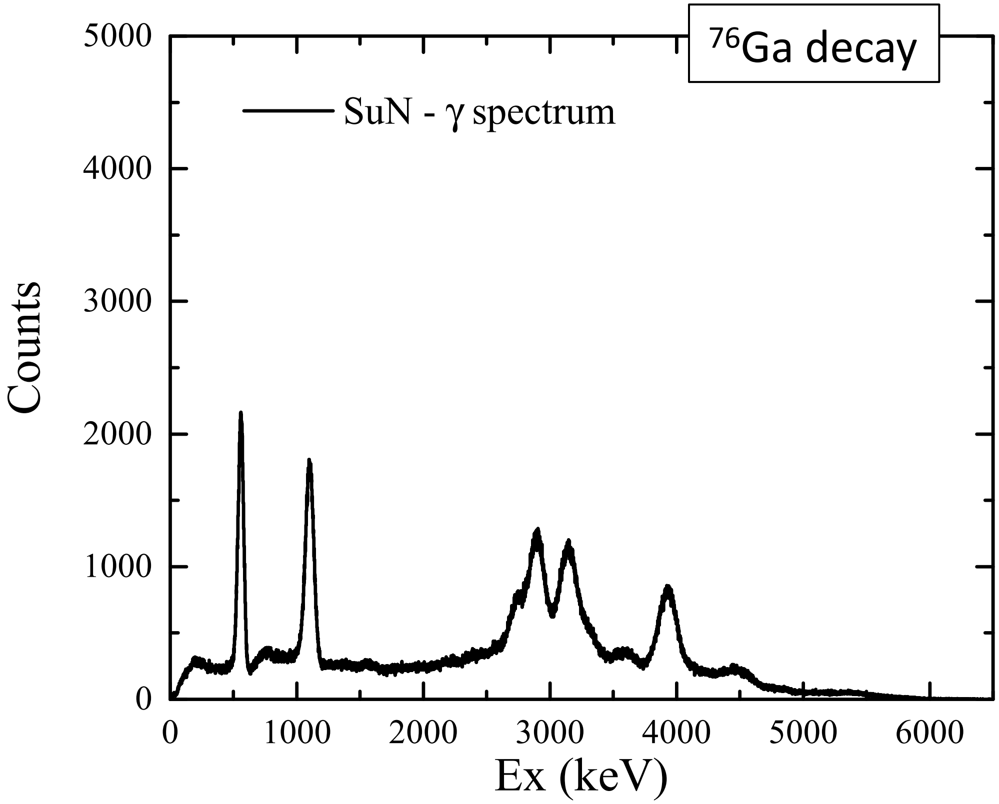


Z	73Se 7.15 H ε: 100.00%	74Se STABLE 0.89%	75Se 119.79 D ε: 100.00%	76Se STABLE 9.37%	77Se STABLE 7.63%	78Se STABLE 23.77%	79Se 2.95E+5 Y β-: 100.00%	80Se STABLE 49.61% 2β-	81Se 18.45 M β-: 100.00%
33	72As 26.0 H ε: 100.00%	73As 80.30 D ε: 100.00%	74As 17.77 D ε: 66.00% β-: 34.00%	75As STABLE 100%	76As 1.0942 D β-: 100.00%	77As 38.83 H β-: 100.00%	78As 90.7 M β-: 100.00%	79As 9.01 M β-: 100.00%	80As 15.2 S β-: 100.00%
32	71Ge 11.43 D ε: 100.00%	72Ge STABLE 27.45%	73Ge STABLE 7.75%	74Ge STABLE 36.50%	75Ge 82.78 M β-: 100.00%	76Ge STABLE 7.73%	77Ge 11.30 H β-: 100.00%	78Ge 88.0 M β-: 100.00%	79Ge 18.98 S β-: 100.00%
31	70Ga 21.14 M β-: 99.59% ε: 0.41%	71Ga STABLE 39.892%	72Ga 14.10 H β-: 100.00%	73Ga 4.86 H β-: 100.00%	74Ga 8.12 M β-: 100.00%	75Ga 126 S β-: 100.00%	76Ga 32.6 S β-: 100.00%	77Ga 13.2 S β-: 100.00%	78Ga 5.09 S β-: 100.00%
30	69Zn 56.4 M β-: 100.00%	70Zn ≥2.3E+17 Y 0.61% 2β-	71Zn 2.45 M β-: 100.00%	72Zn 46.5 H β-: 100.00%	73Zn 23.5 S β-: 100.00%	74Zn 95.6 S β-: 100.00%	75Zn 10.2 S β-: 100.00%	76Zn 5.7 S β-: 100.00%	77Zn 2.08 S β-: 100.00%
	39	40	41	42	43	44	45	46	N

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

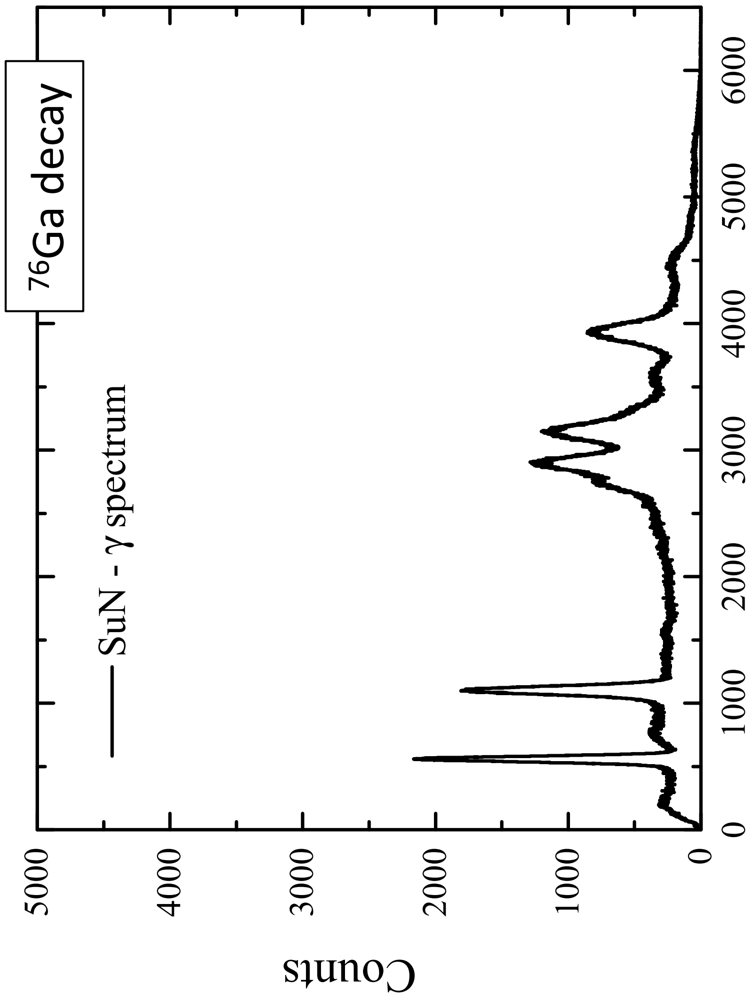
Proof-of-principle: ^{75}Ge(n,γ)^{76}Ge

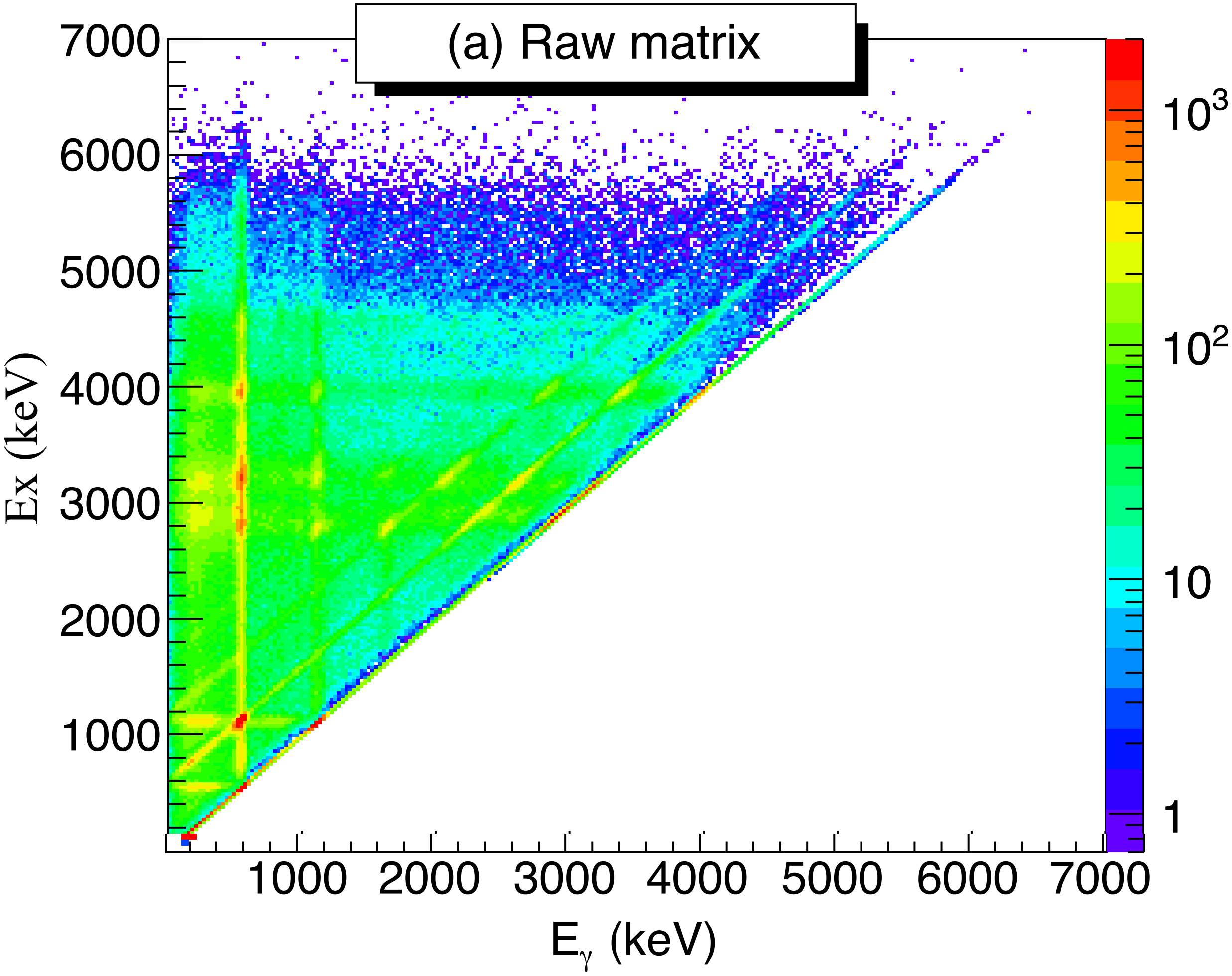




Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

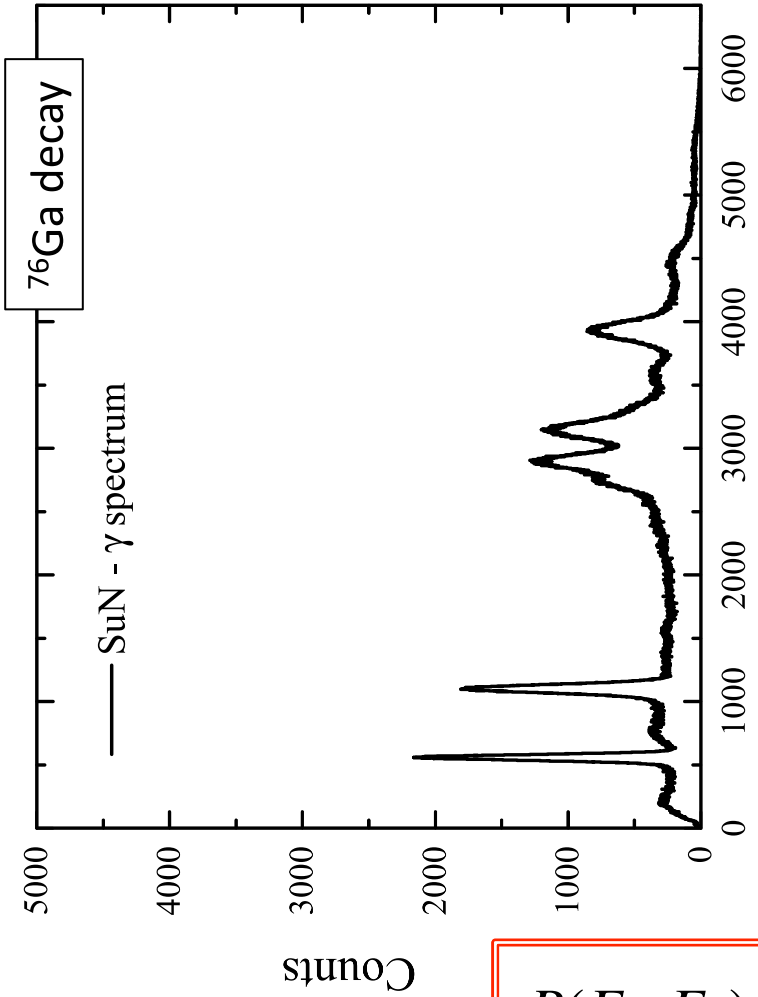
Proof-of-principle: ^{75}Ge(n,γ)^{76}Ge

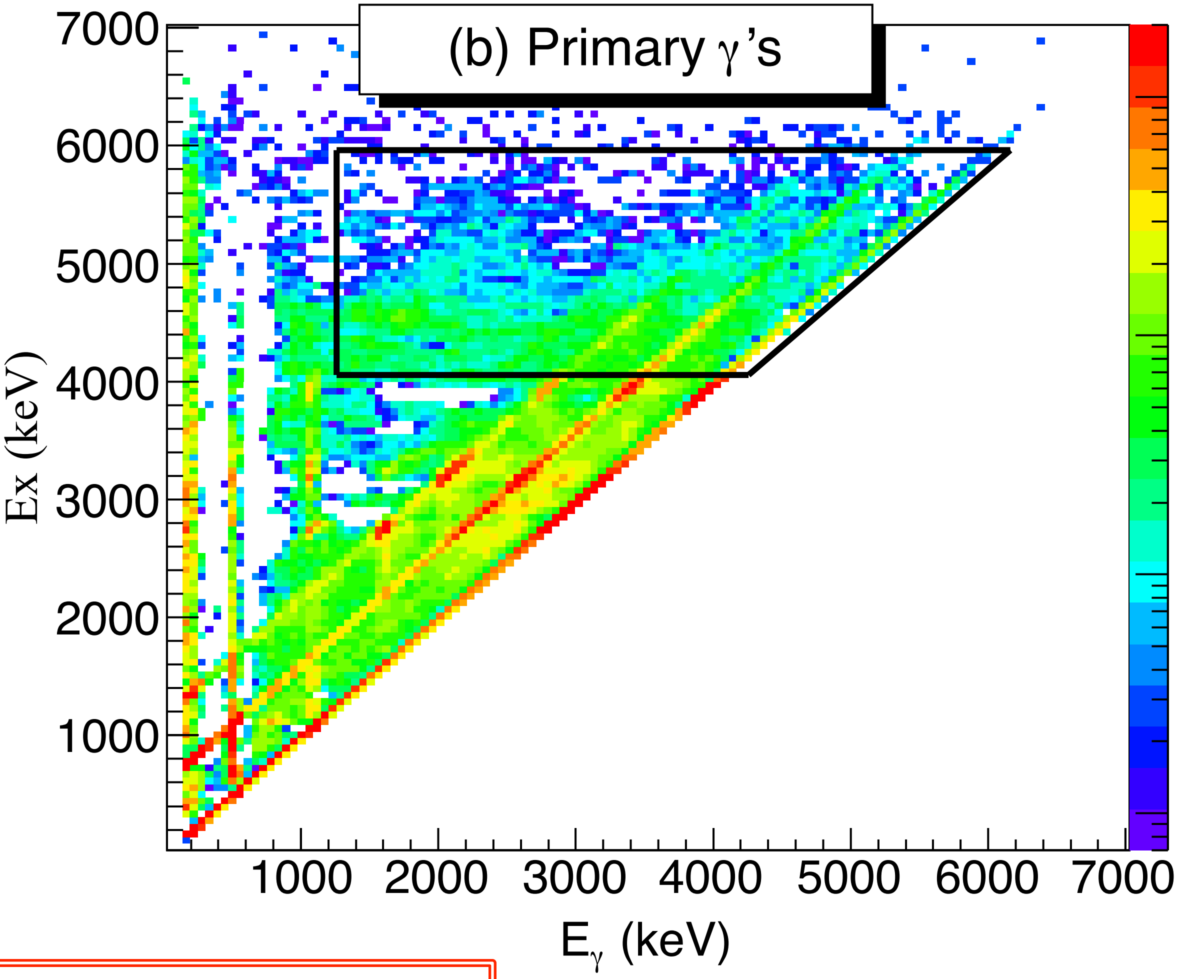




Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

Proof-of-principle: ^{75}Ge(n,γ)^{76}Ge



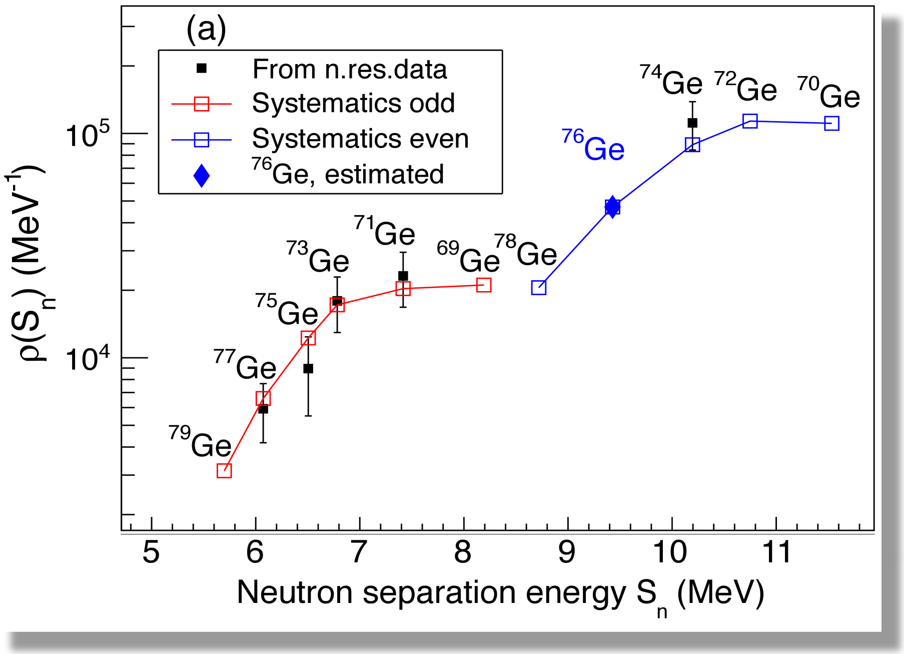


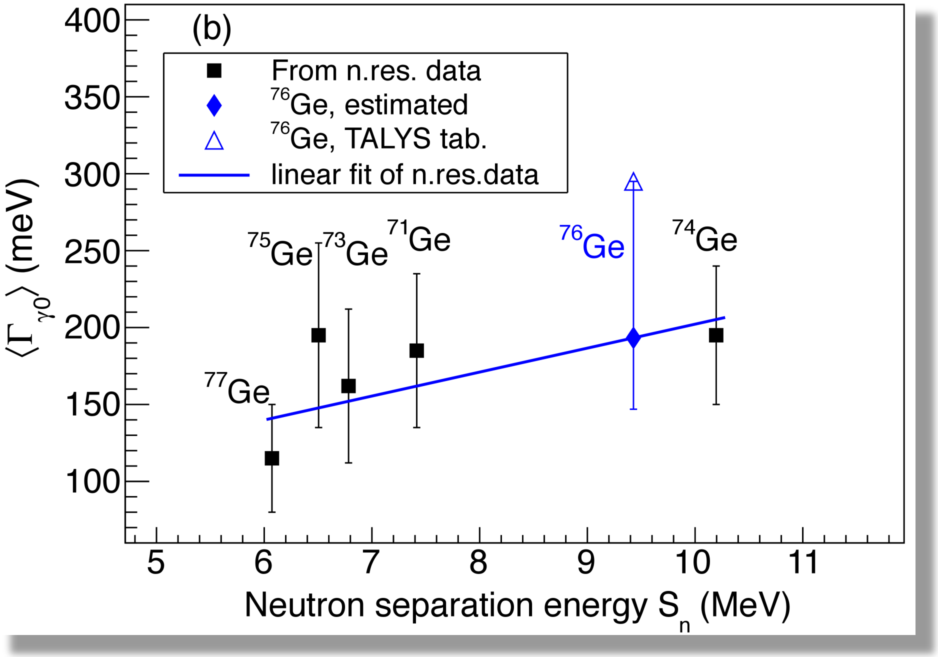
$$P(E_\gamma, E_x) = \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

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

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.

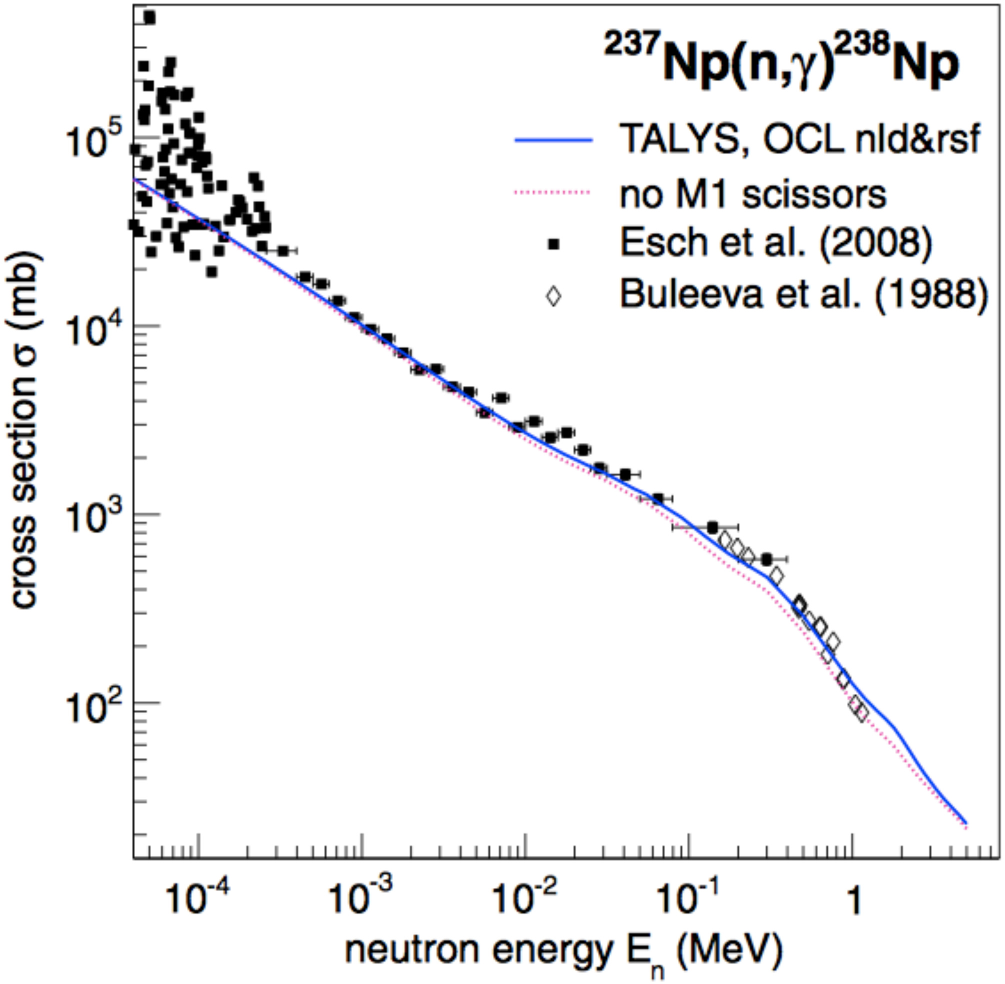




- $\rho(S_n)$ from
  - Systematics
  - Microscopic calculations
- $<\Gamma_\gamma>$ normalized from systematics

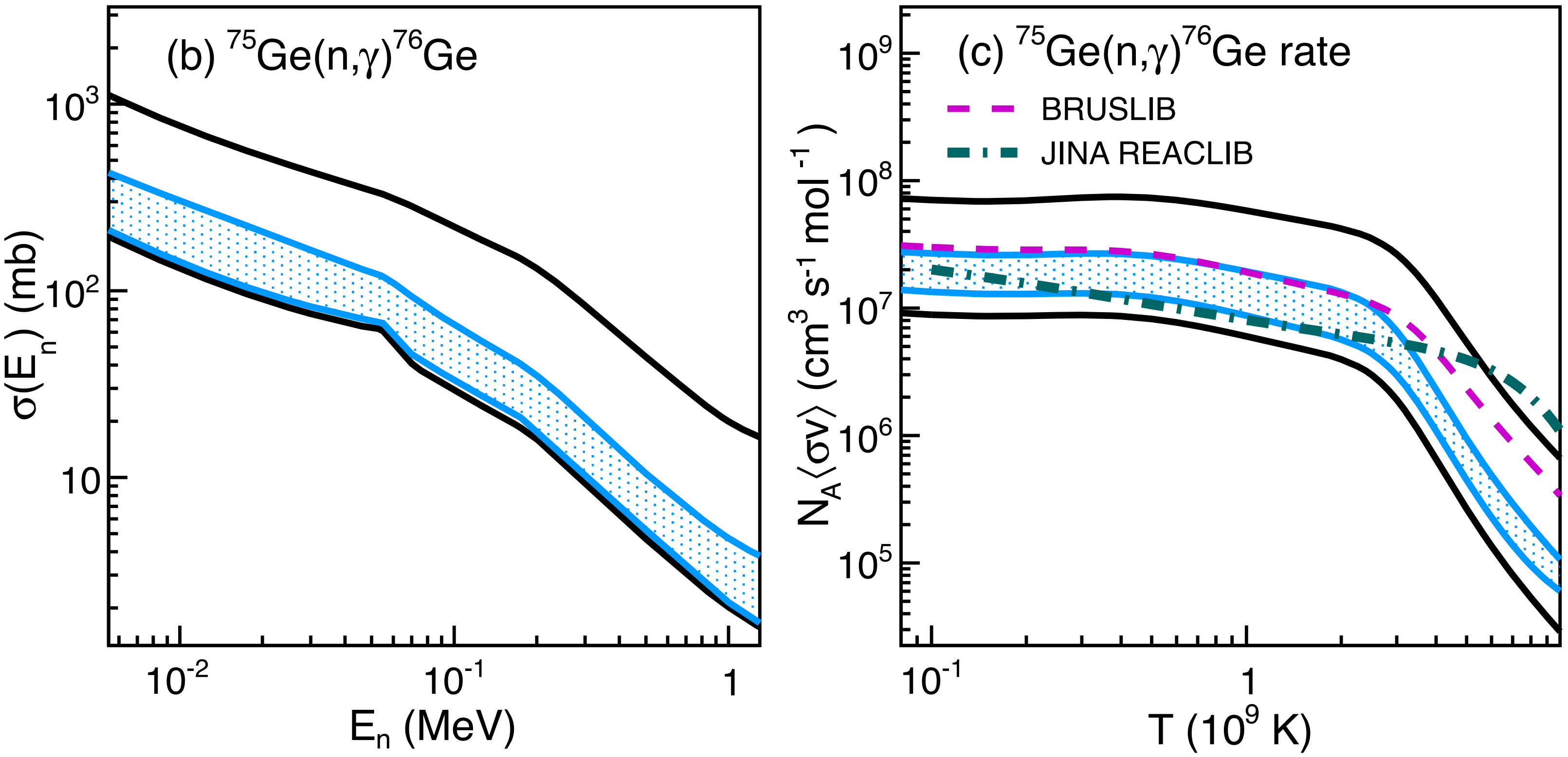
Traditional Oslo method

- 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

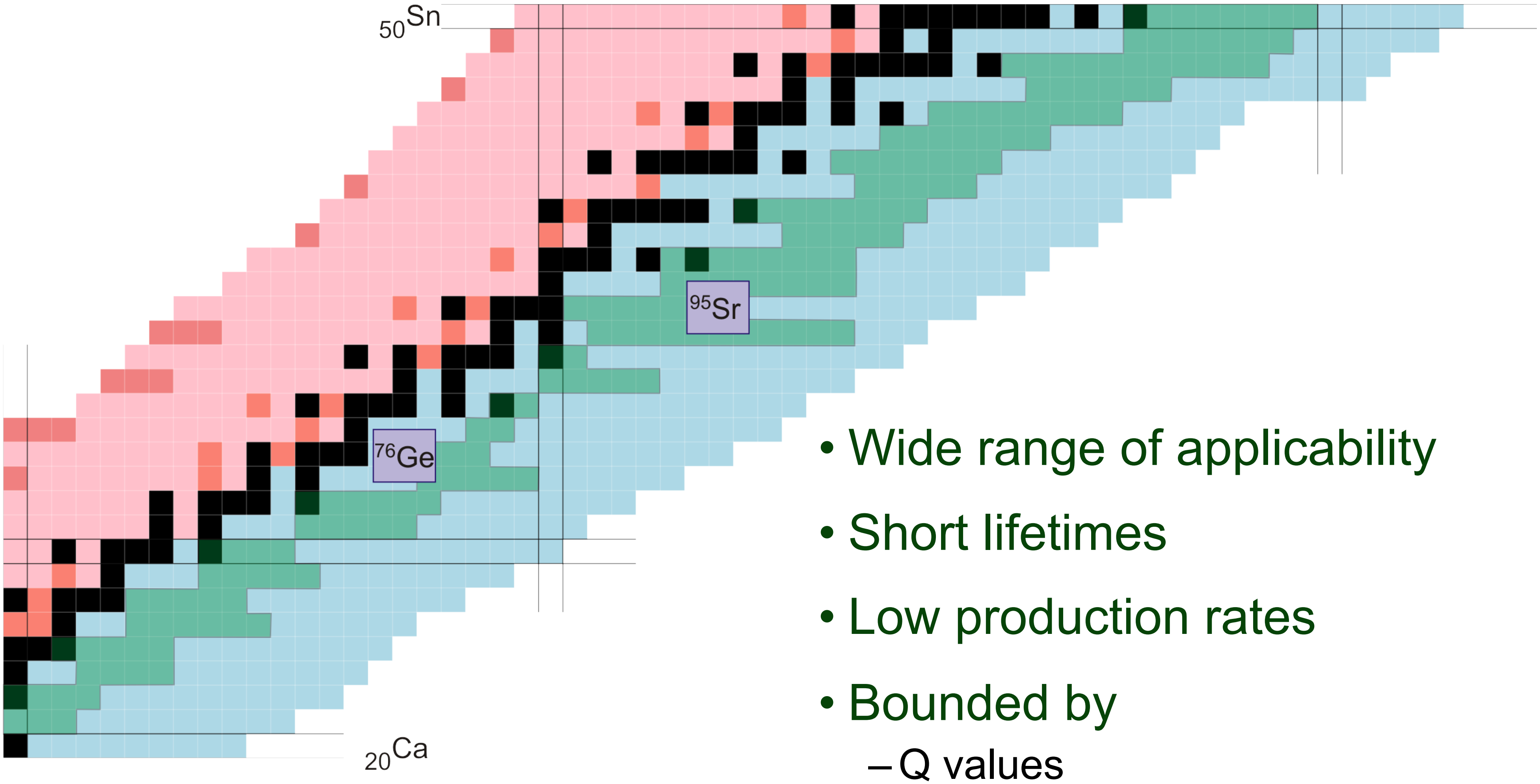


T.G. Tornyi, M. Guttormsen,et al., PRC2014

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



Applicability



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

Collaboration

Michigan State University

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

University of Oslo

- A.C. Larsen
- M. Guttormsen
- T. Renstrøm

Central Michigan University

- G. Perdikakis

Notre Dame

- A. Simon

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.