Constraining (n,γ) reaction cross sections for astrophysical applications

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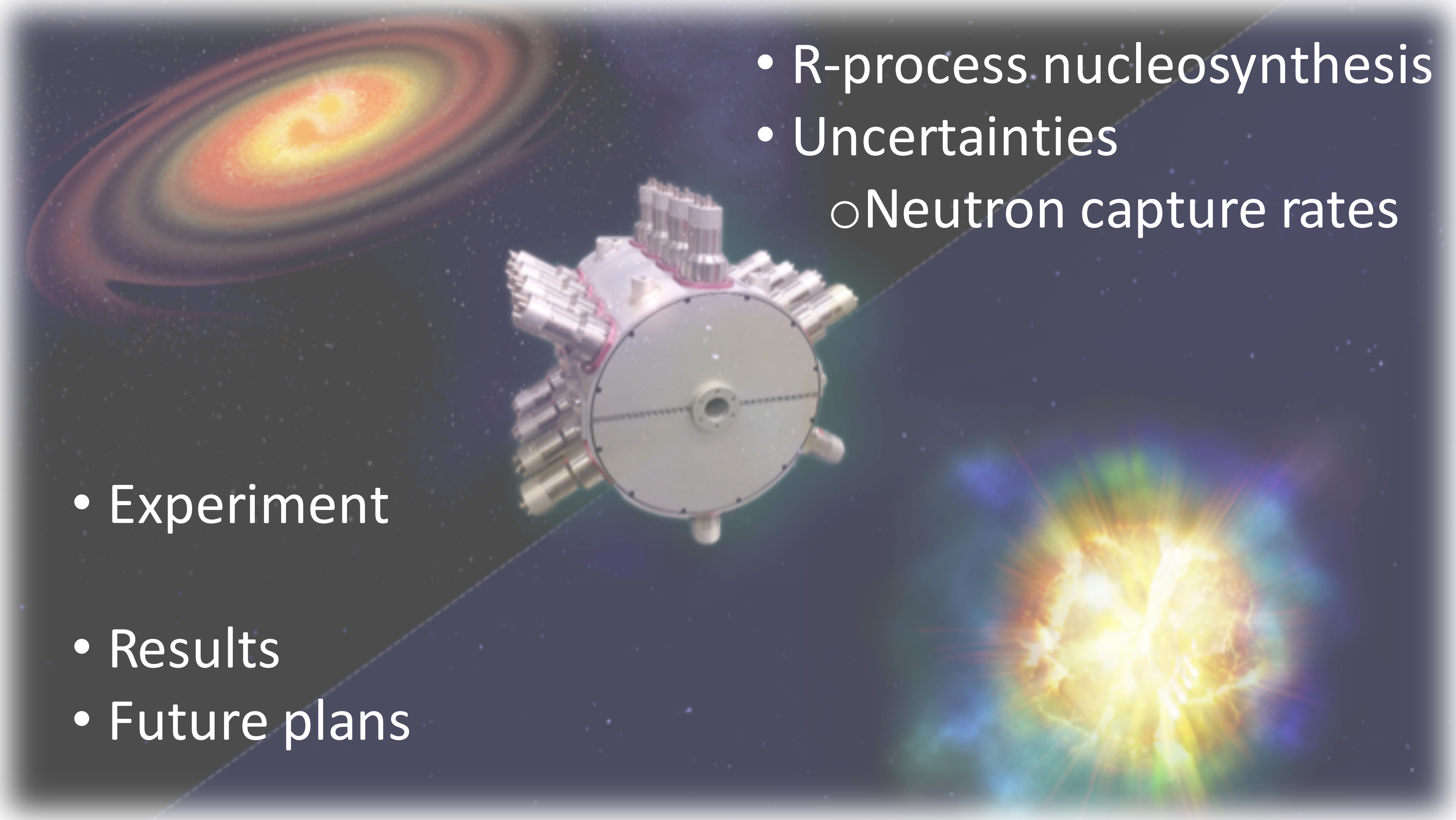
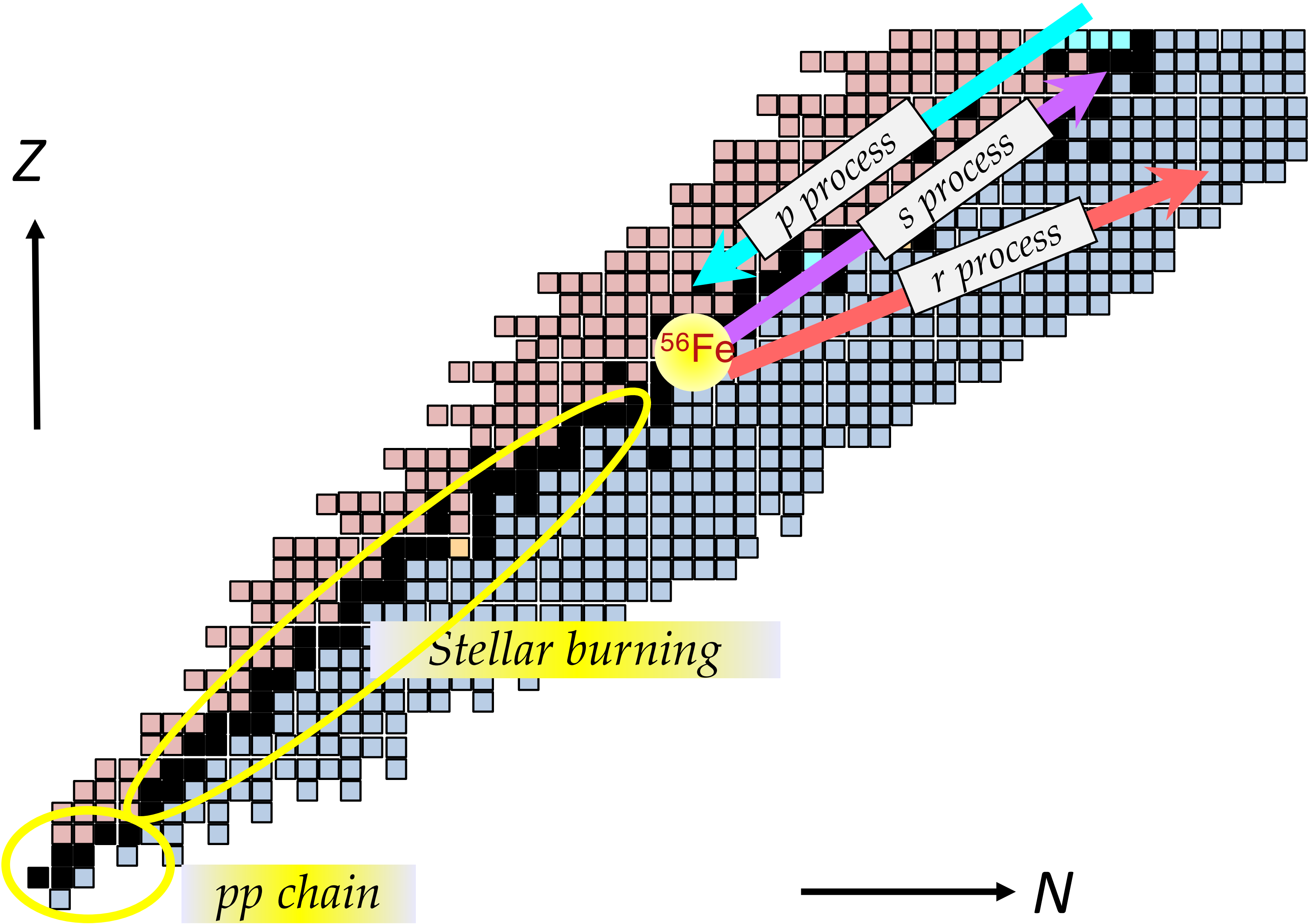
NSCL

Overview



- R-process nucleosynthesis
- Uncertainties
  - Neutron capture rates
- Experiment
- Results
- Future plans

Nucleosynthesis paths



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

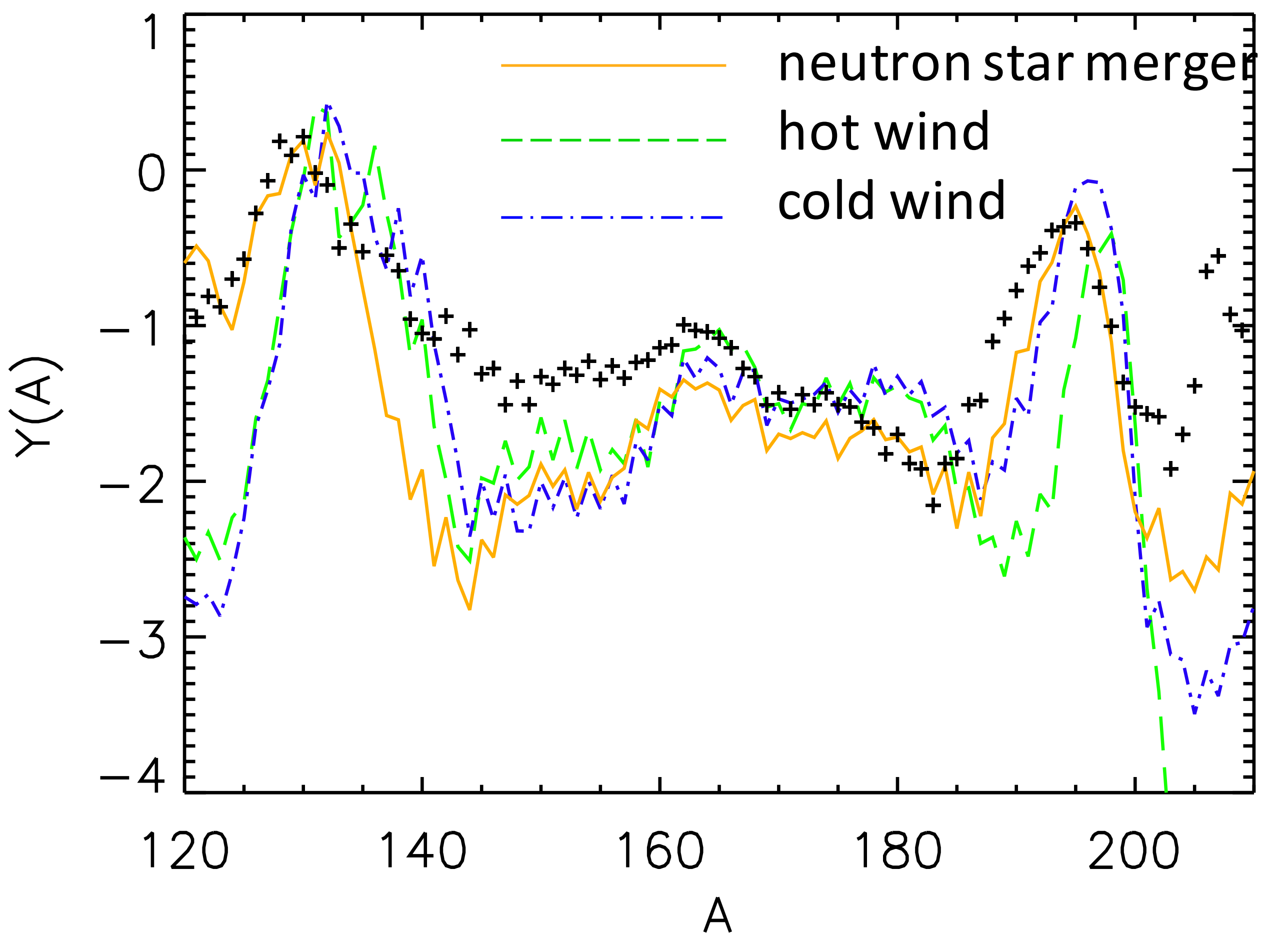
Credit: Erin O'Donnell, MSU

Core Collapse Supernova?

Neutron Star Merger?

Credit: NASA Goddard

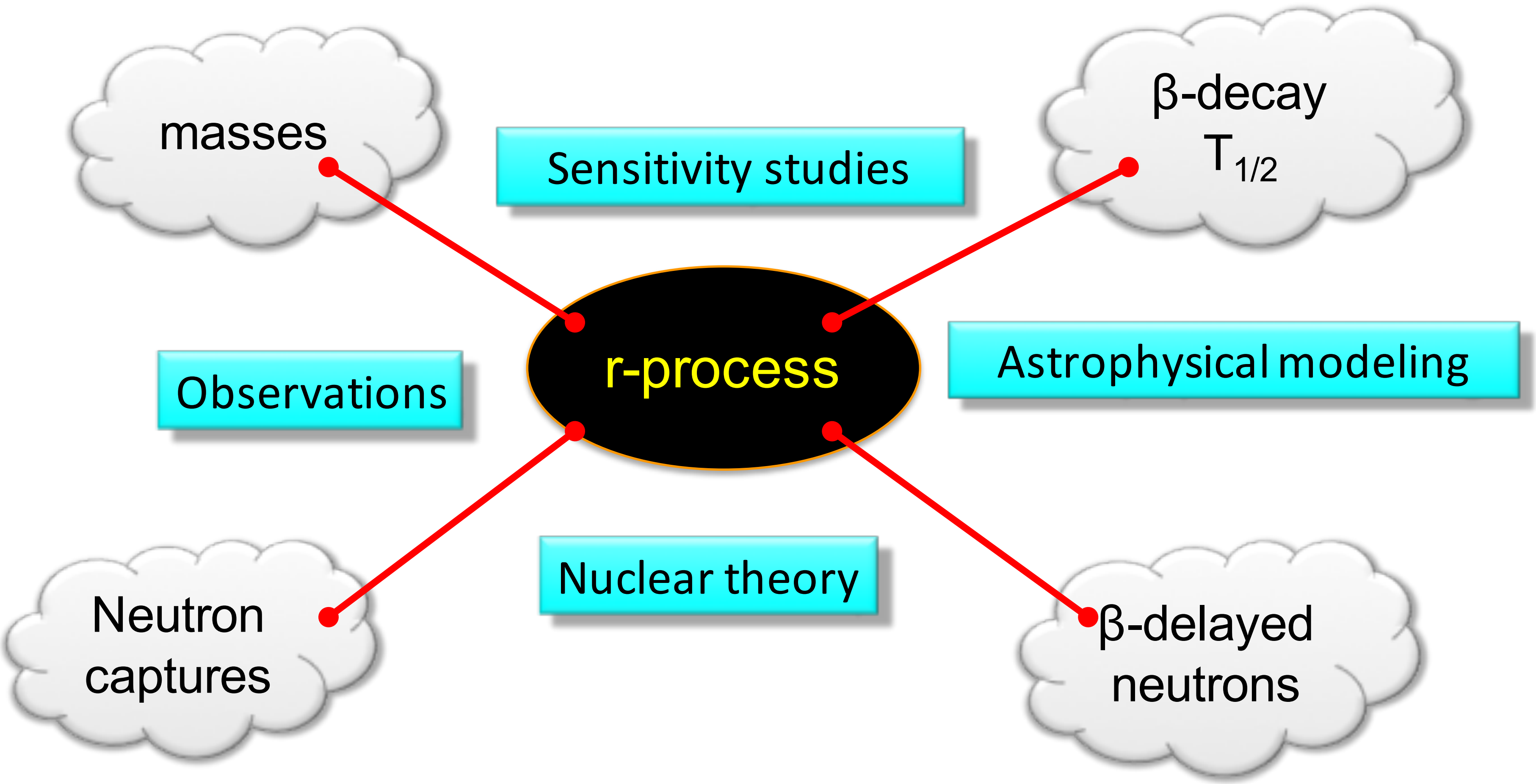
r-process calculations



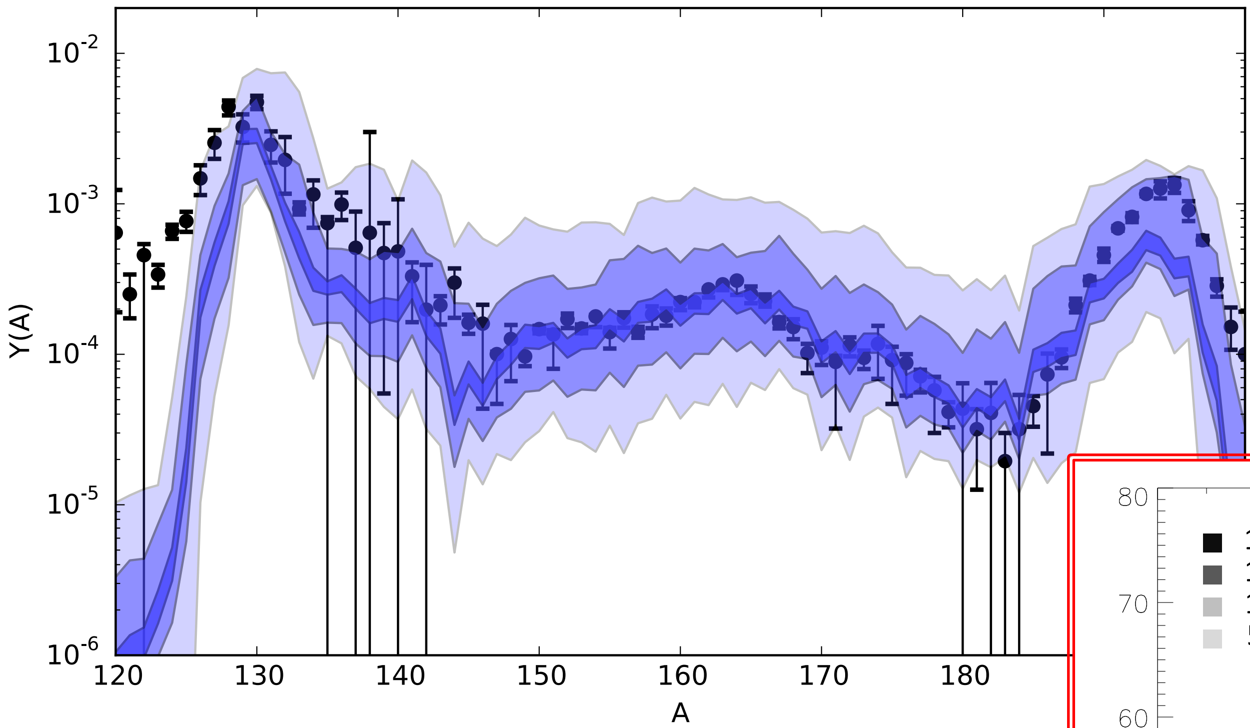
- Abundance pattern is different for the different astrophysical scenarios.
- Does one of them reproduce the observed abundances best?
- Why can't we tell?

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

r-process

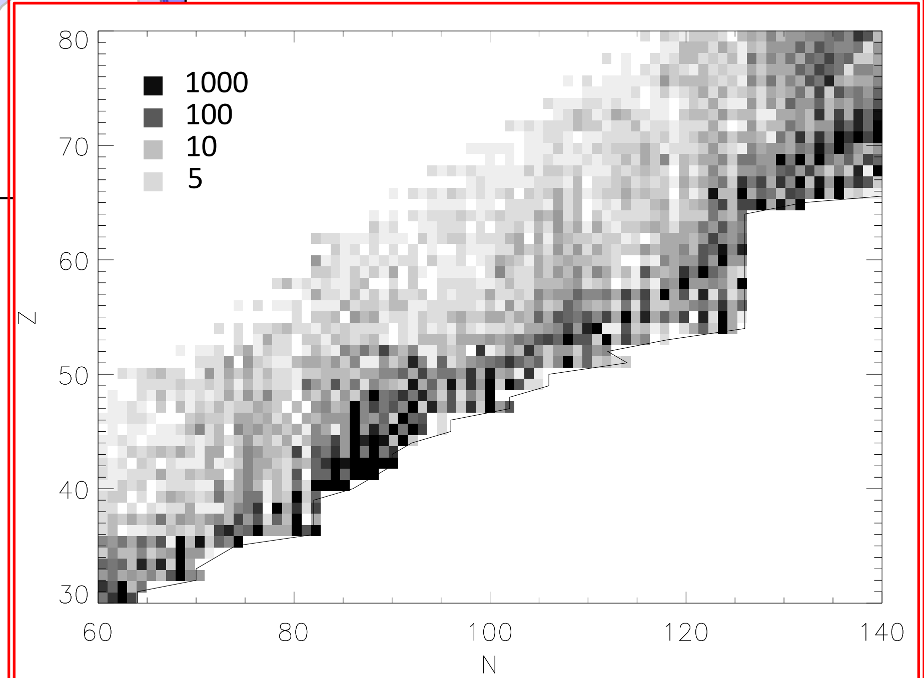

masses
Sensitivity studies
β-decay
T1/2
Observations
r-process
Astrophysical modeling
Neutron
captures
Nuclear theory
β-delayed
neutrons

Nuclear Physics Uncertainties: (n,γ)



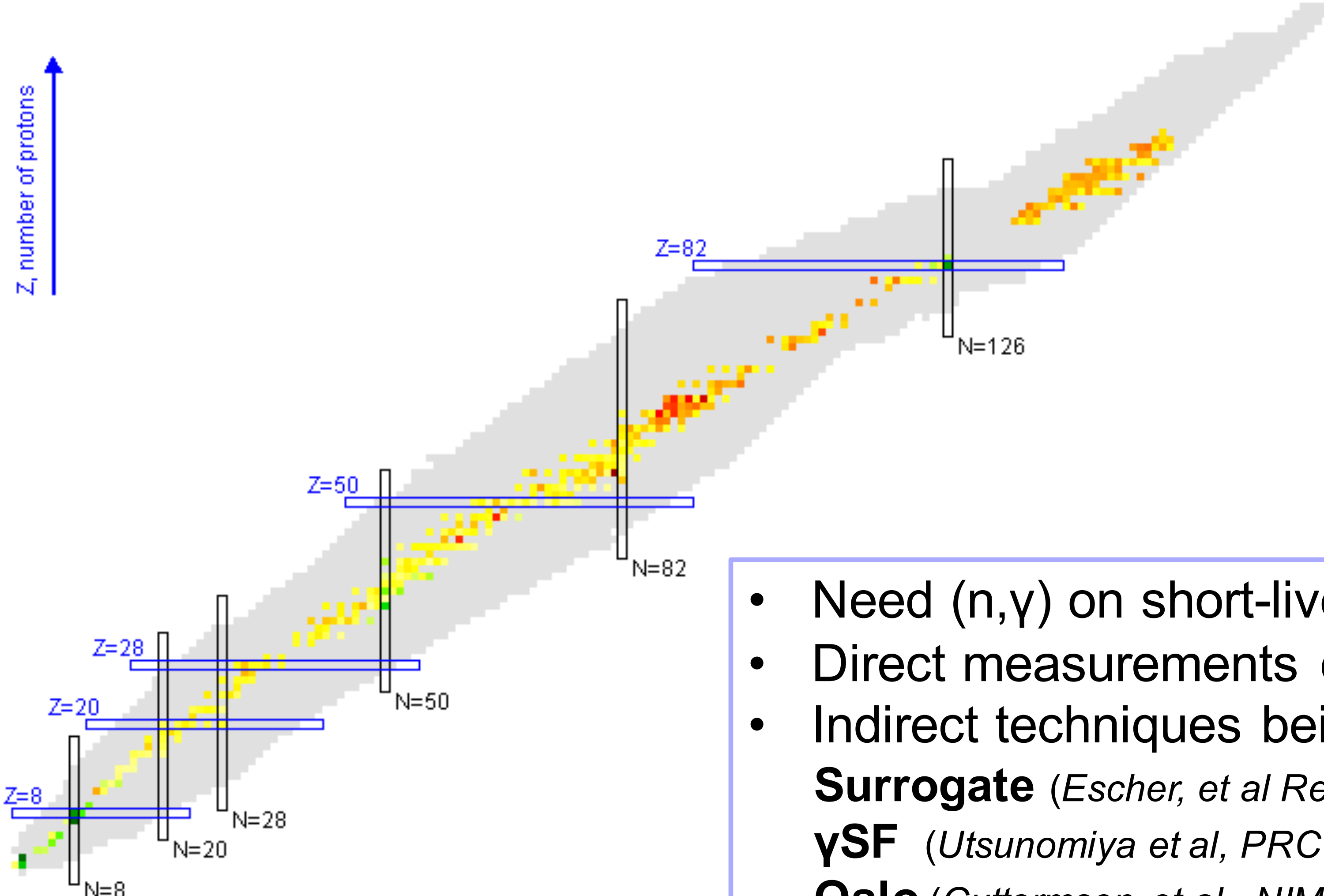
Monte-Carlo variations of (n,γ) rates within a factor 100 – 10 – 2 (light – darker – dark bands)

(n,γ) uncertainties



Surman and Engel PRC (2001)

Current (n,γ) measurements



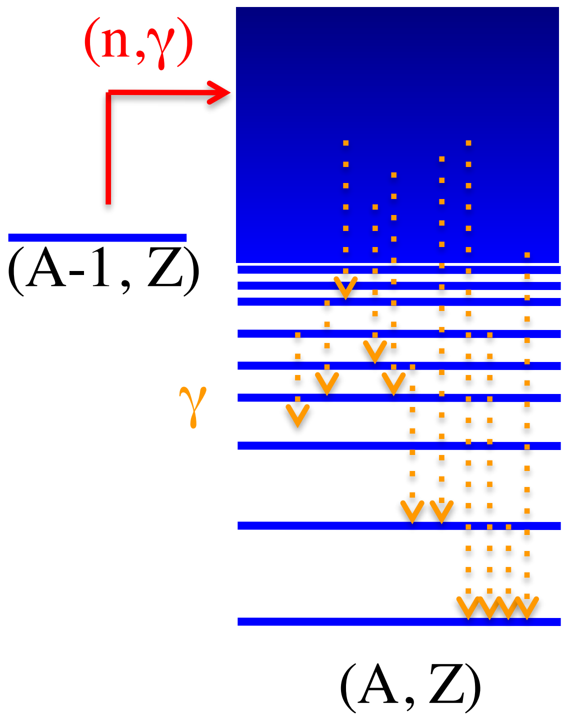
- Need (n,γ) on short-lived nuclei
- Direct measurements challenging
- Indirect techniques being developed:

  Surrogate (*Escher, et al Rev. Mod. Phys. 2012*)

  γSF (*Utsunomiya et al, PRC 2010*)

  Oslo (*Guttormsen et al., NIMA 1987*)

Neutron Capture – Uncertainties



Hauser – Feshbach

- Nuclear Level Density

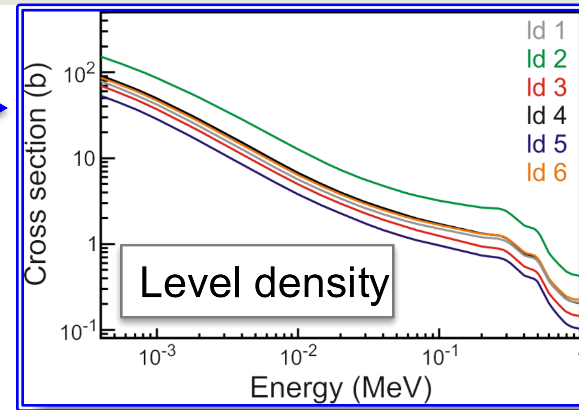
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

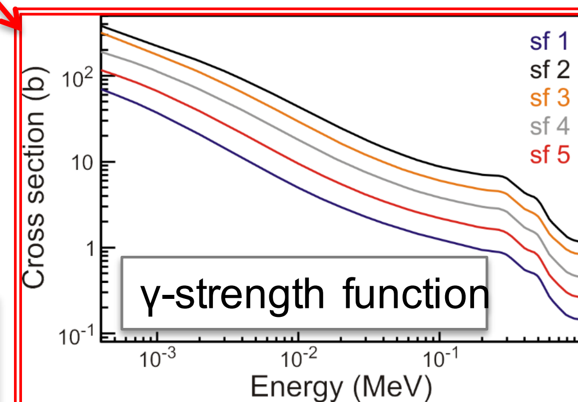
- γ-ray strength function

Generalized Lorentzian, Brink-Axel, various tables

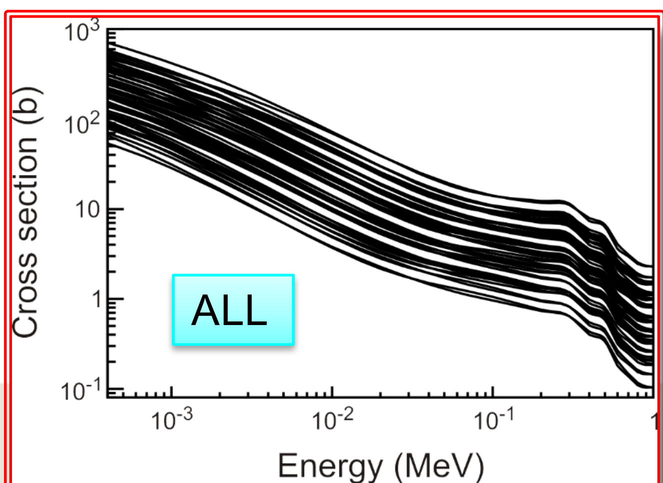
- Optical model potential

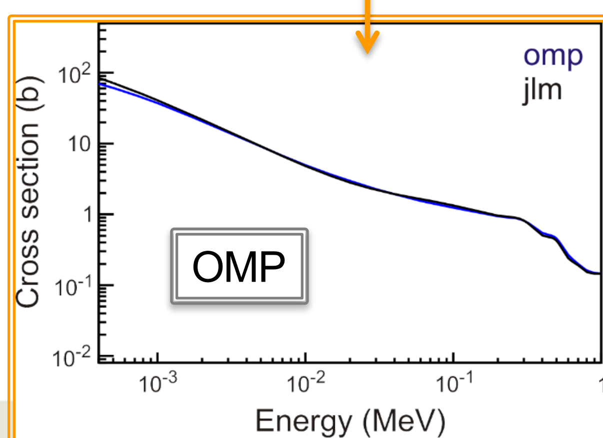
Phenomenological, Semi-microscopic





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

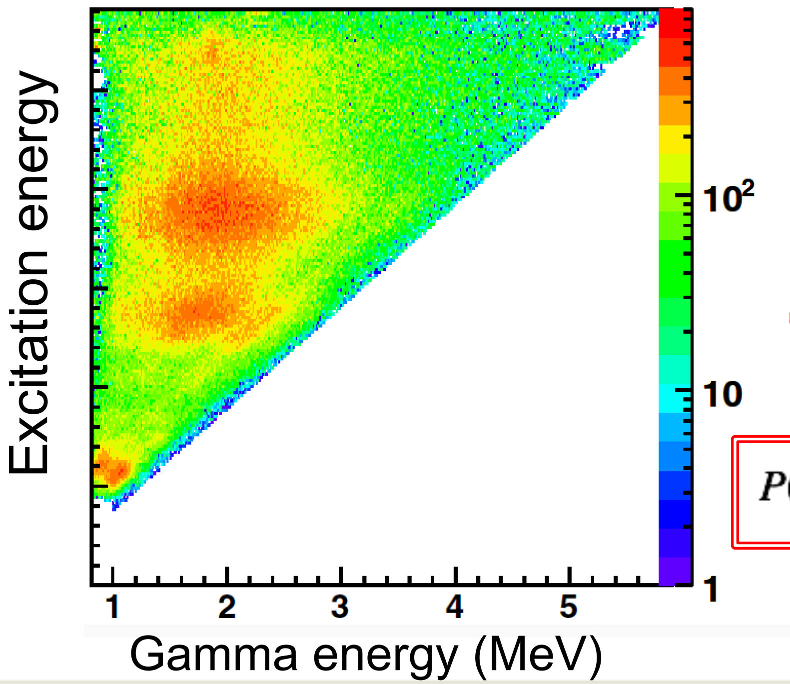




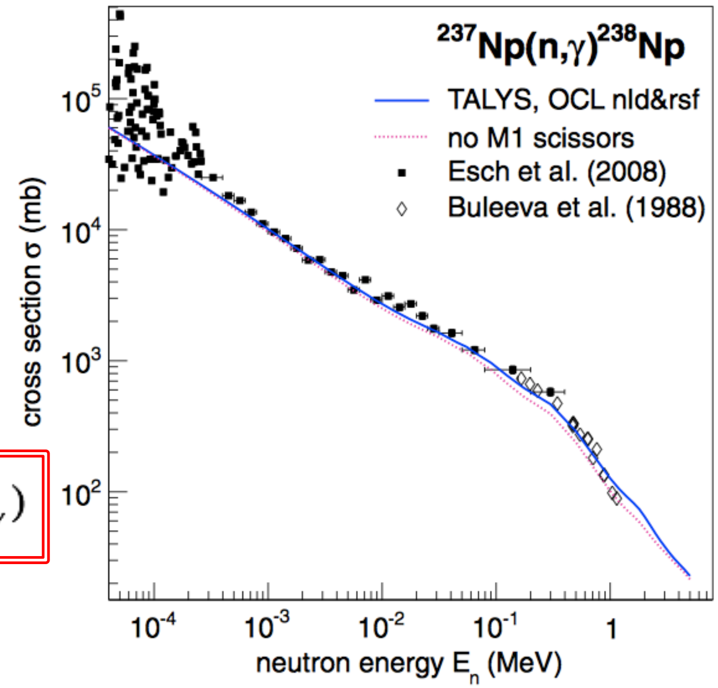
TALYS

Traditional Oslo method

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

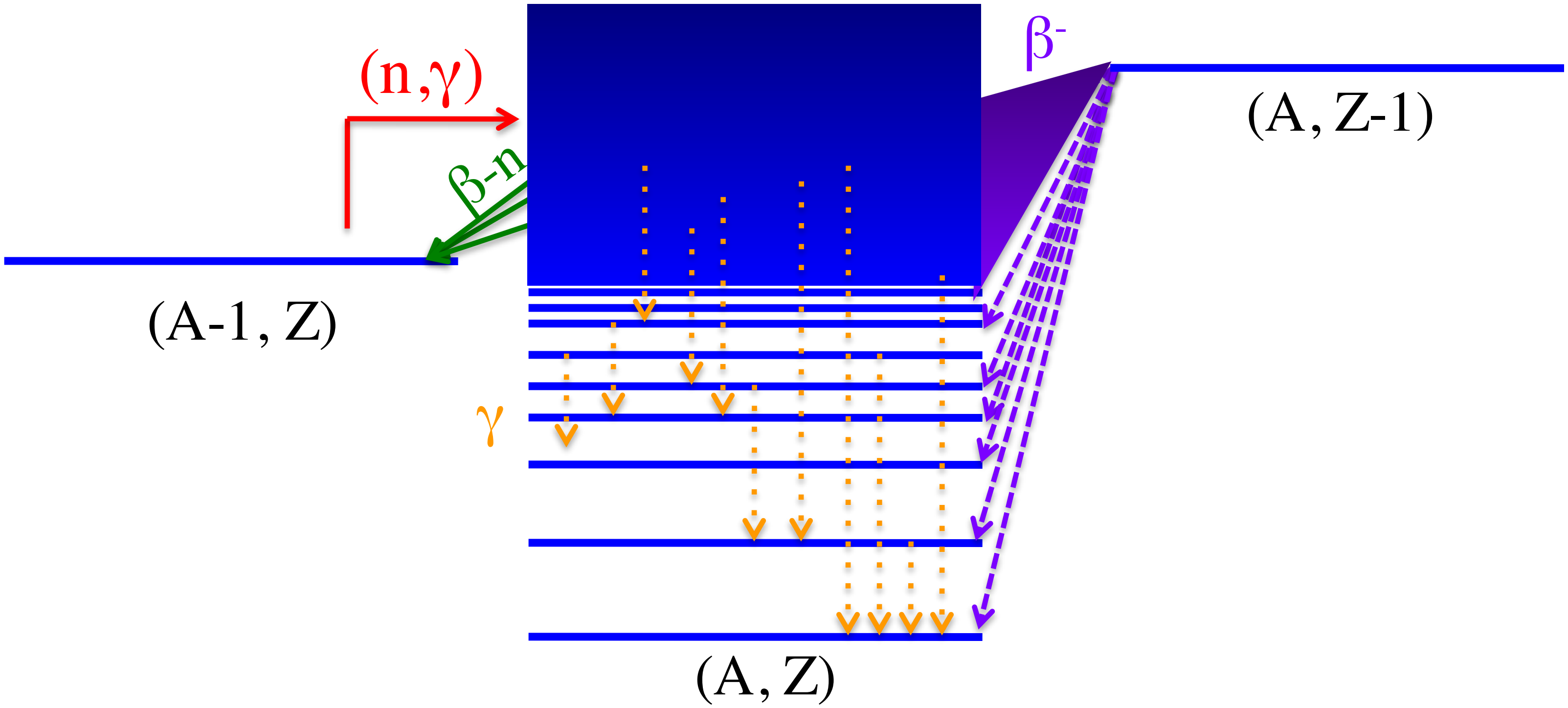


$$P(E_\gamma, E_x) = \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$



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

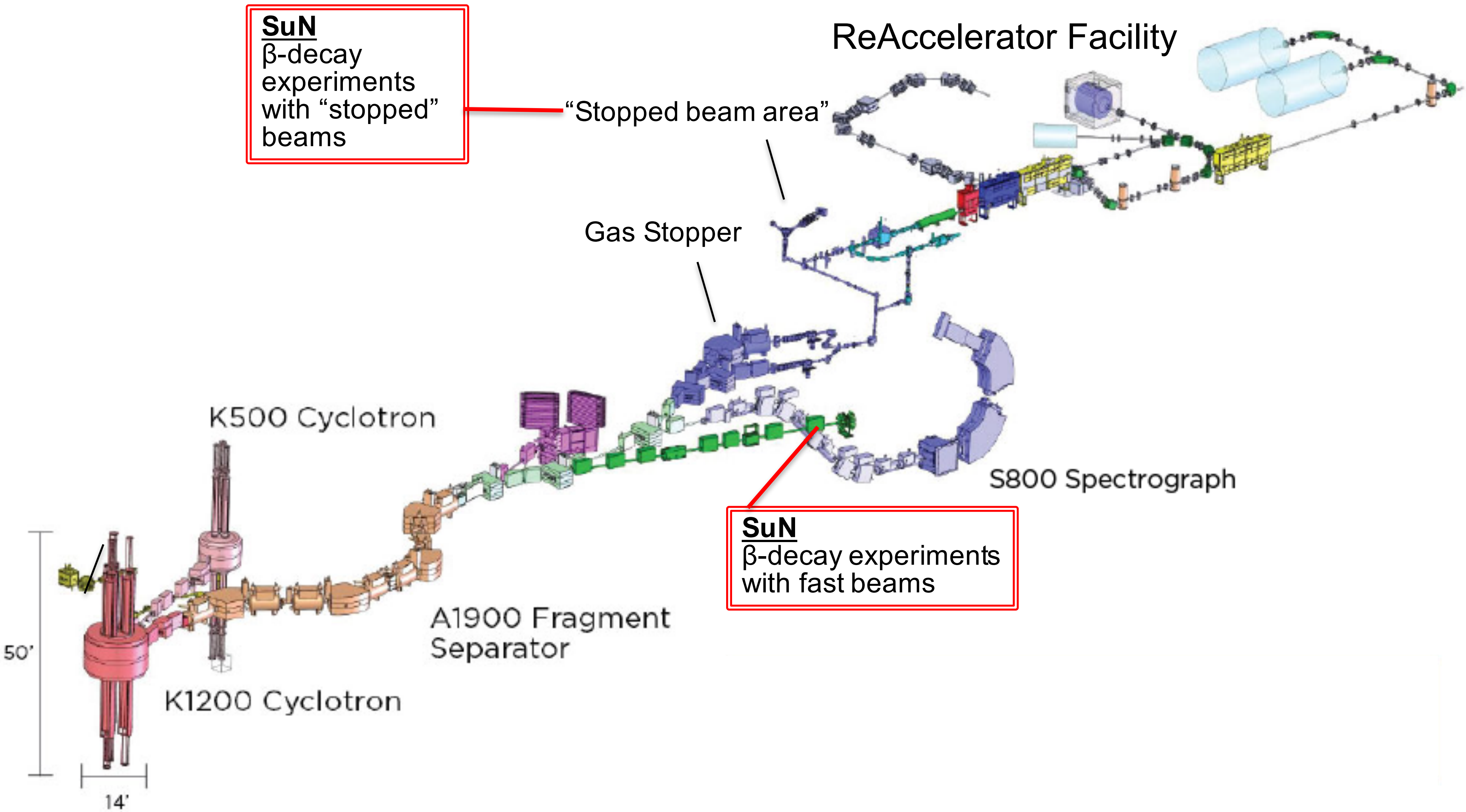
Neutron Capture – β-Oslo



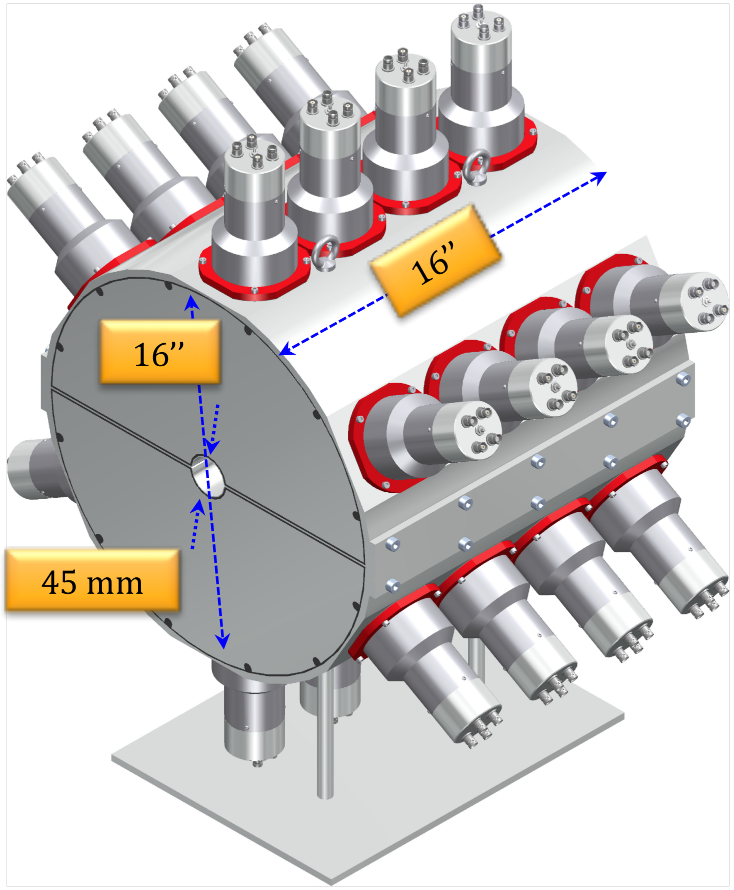
- Populate the compound nucleus via β-decay (large Q-value far from stability)
- Spin selectivity – correct for it
- Extract level density and γ-ray strength function
- Advantage: Can reach (n,γ) reactions where beam intensity is 1 pps.

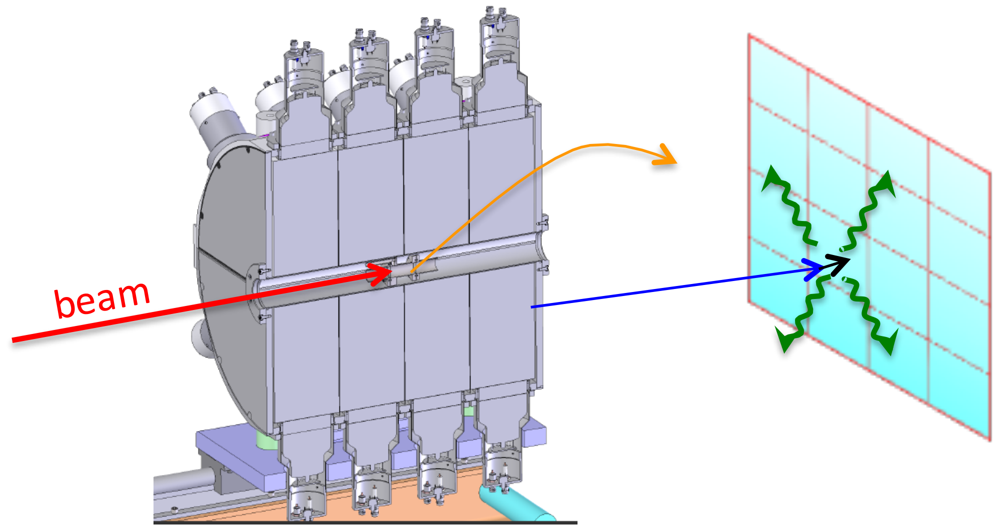
Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

National Superconducting Cyclotron Lab



Summing NaI - SuN



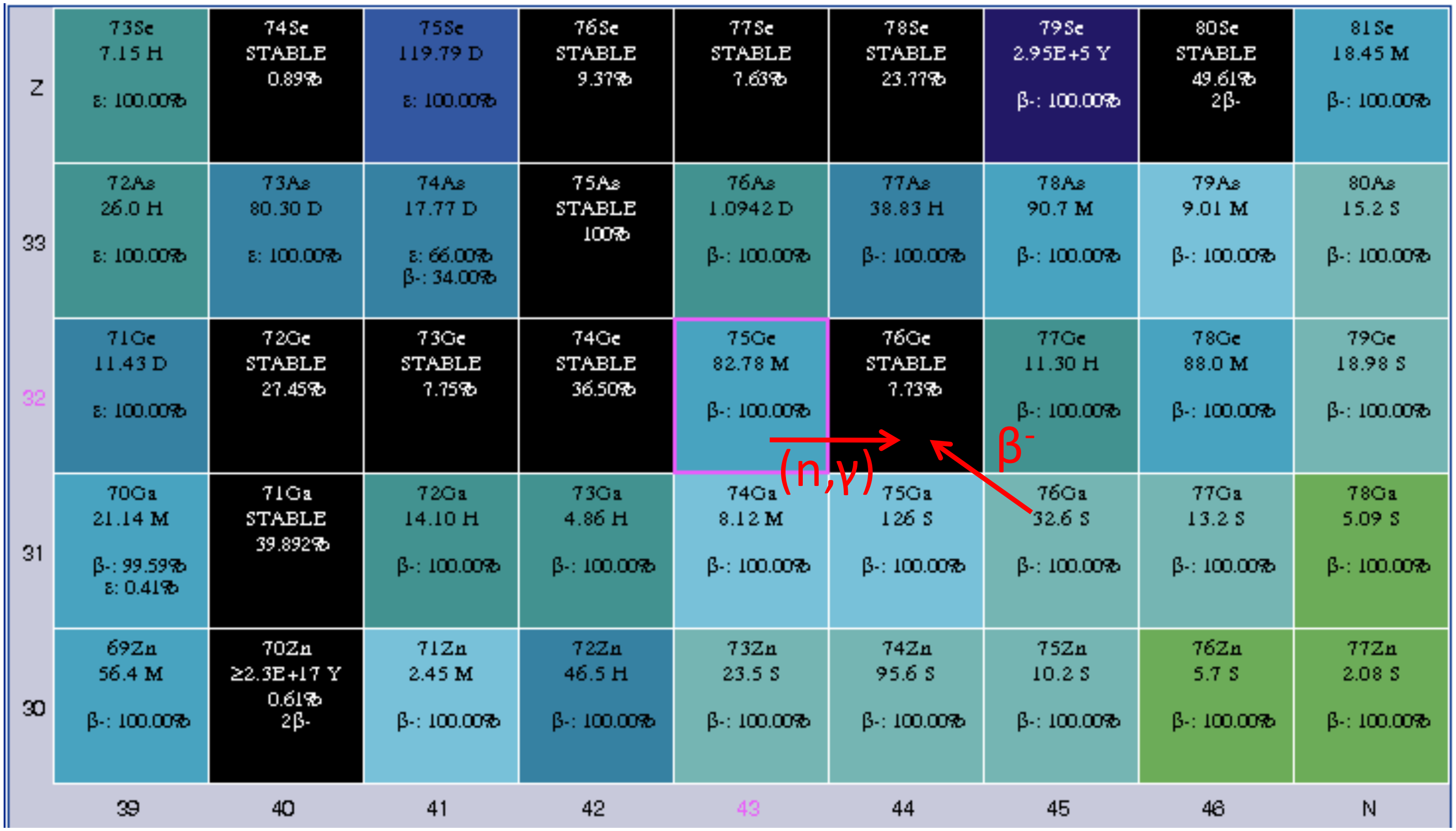


$$E_x = E_{\gamma 1} + E_{\gamma 2} + E_{\gamma 3} + E_{\gamma 4} + \ldots$$

- ✓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: $^{75}Ge(n,\gamma)^{76}Ge$

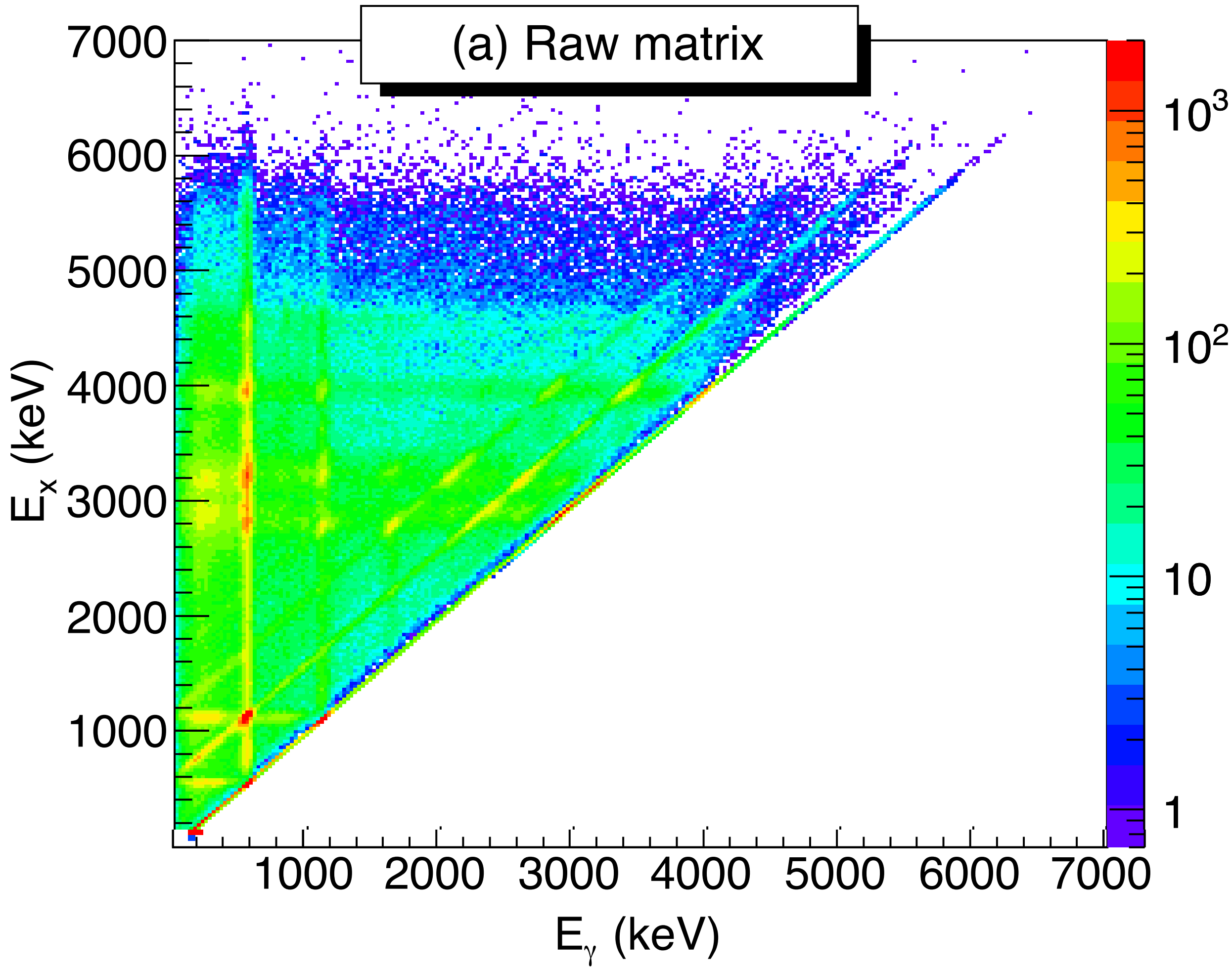


^{76}Ga: $T_{1/2} = 32.6$ s
$Q_{\beta-} = 7.0$ MeV
S_n (^{76}Ge) = 9.4 MeV

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

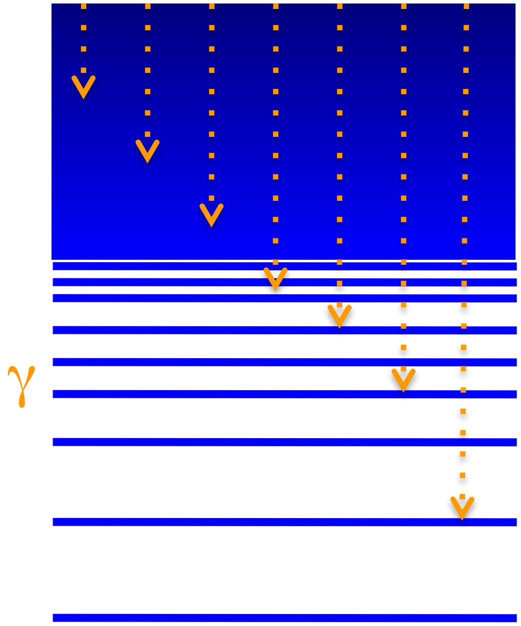
Proof-of-principle: $^{75}Ge(n,\gamma)^{76}Ge$

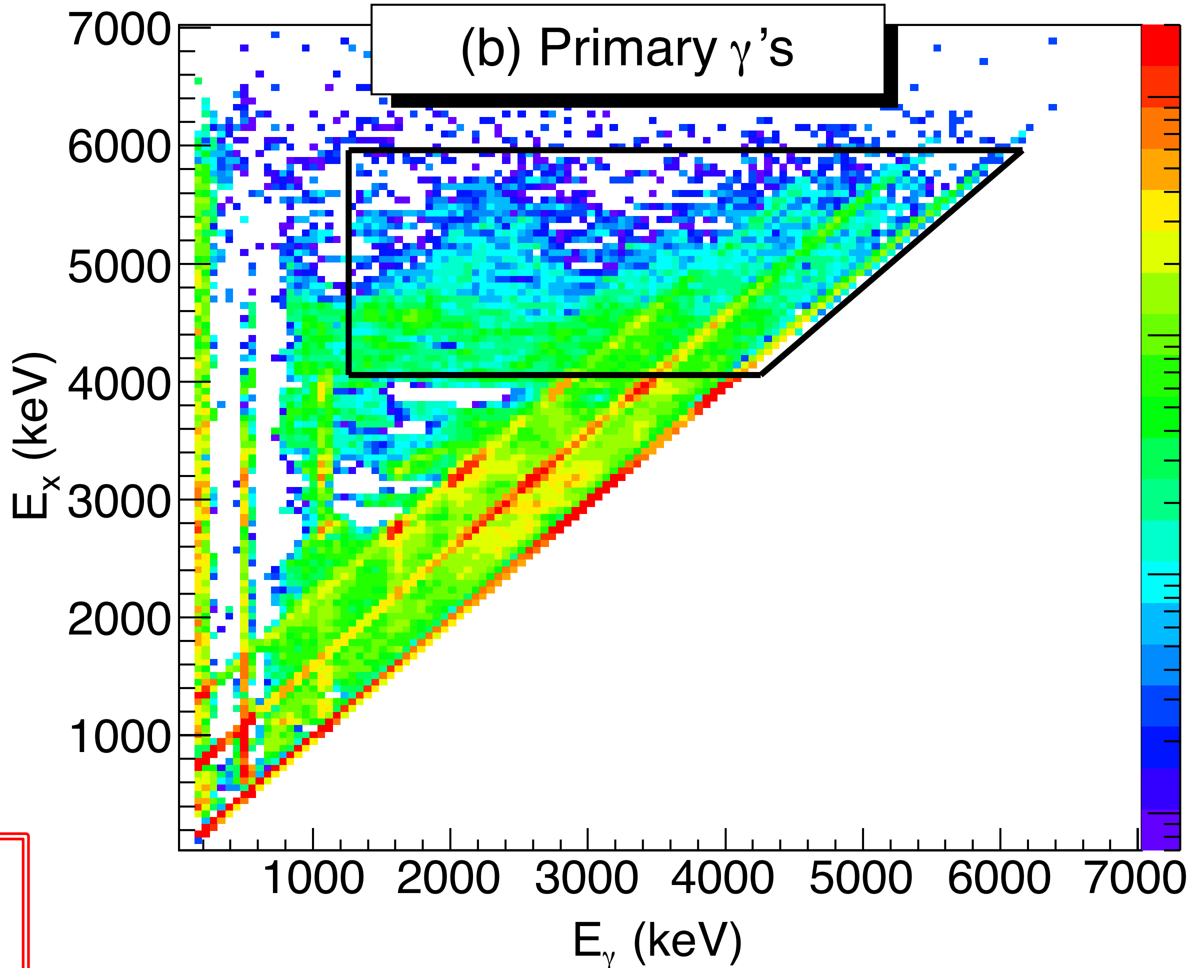
SuN – Total Absorption



SuN – Individual Segments

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

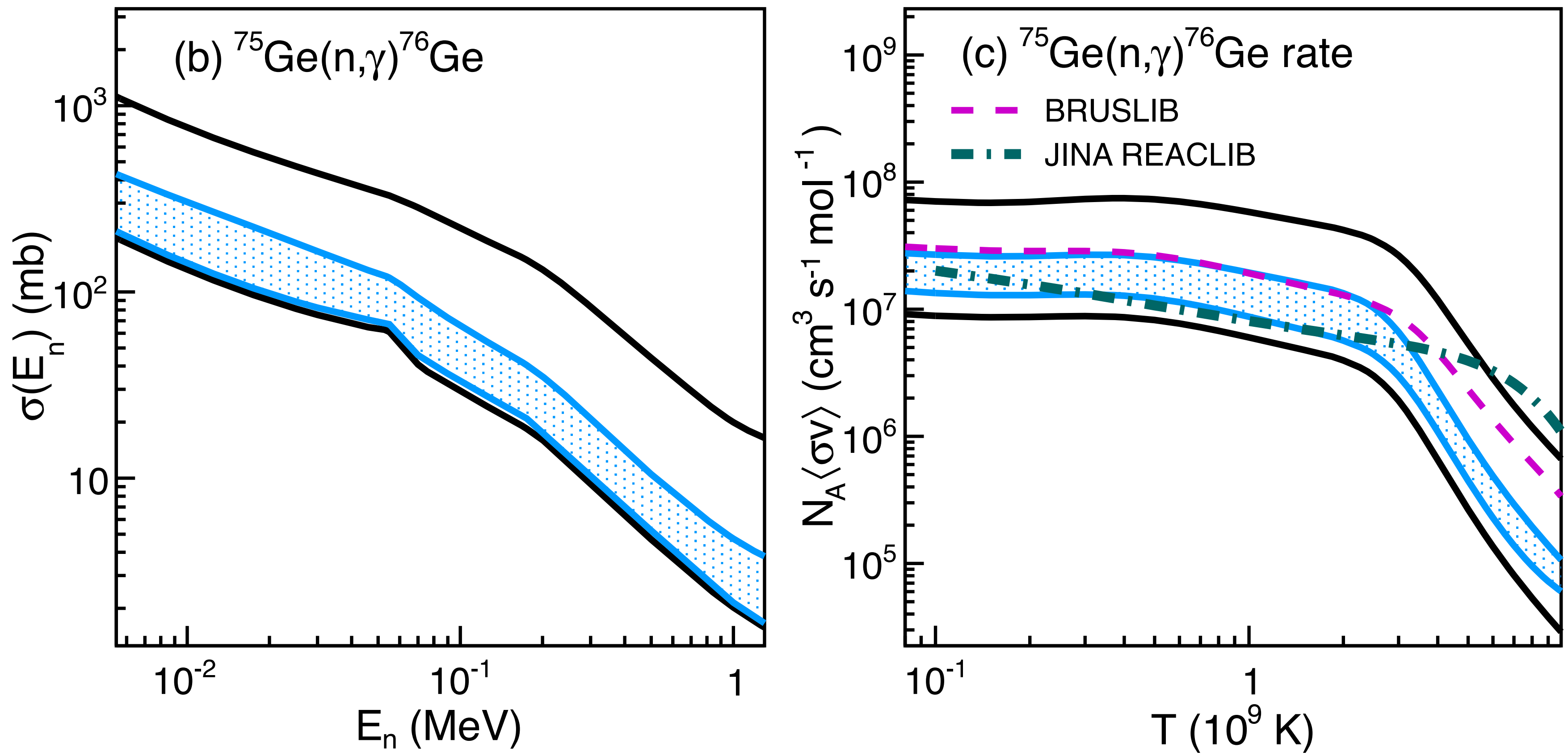




$$P(E_\gamma, E_x) = \rho(E_x - E_\gamma)\mathcal{T}(E_\gamma)$$

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

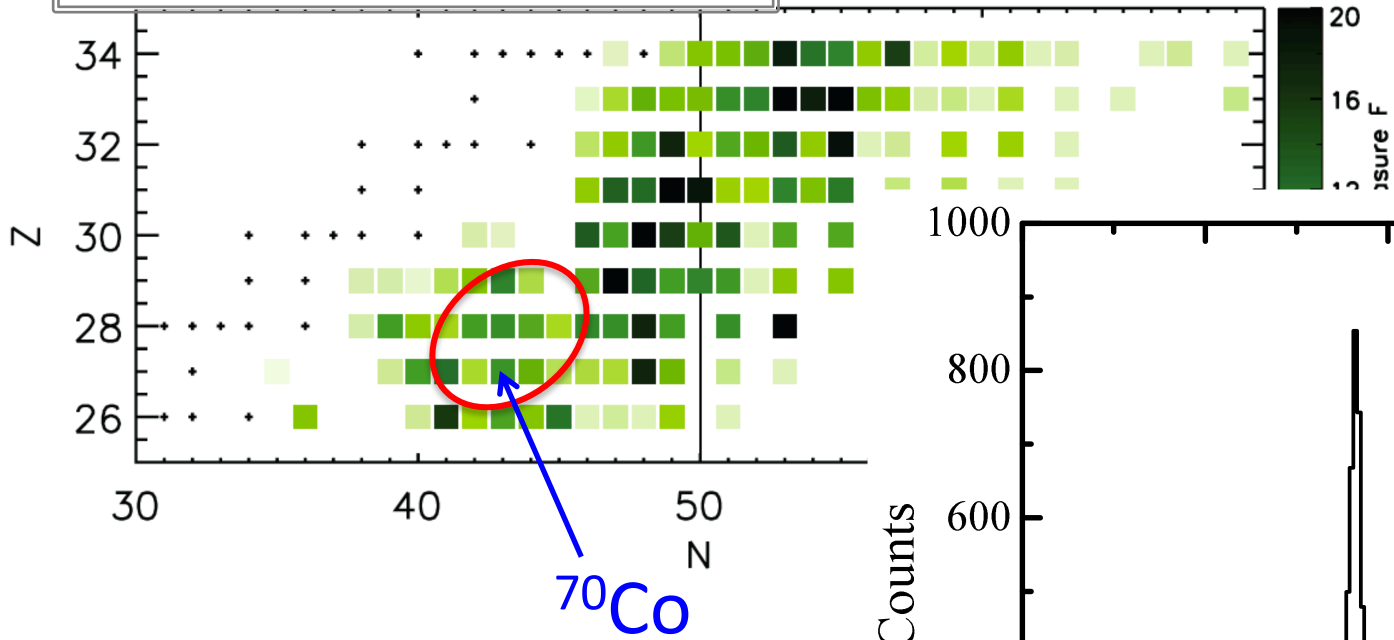
Results: $^{75}Ge(n,\gamma)^{76}Ge$

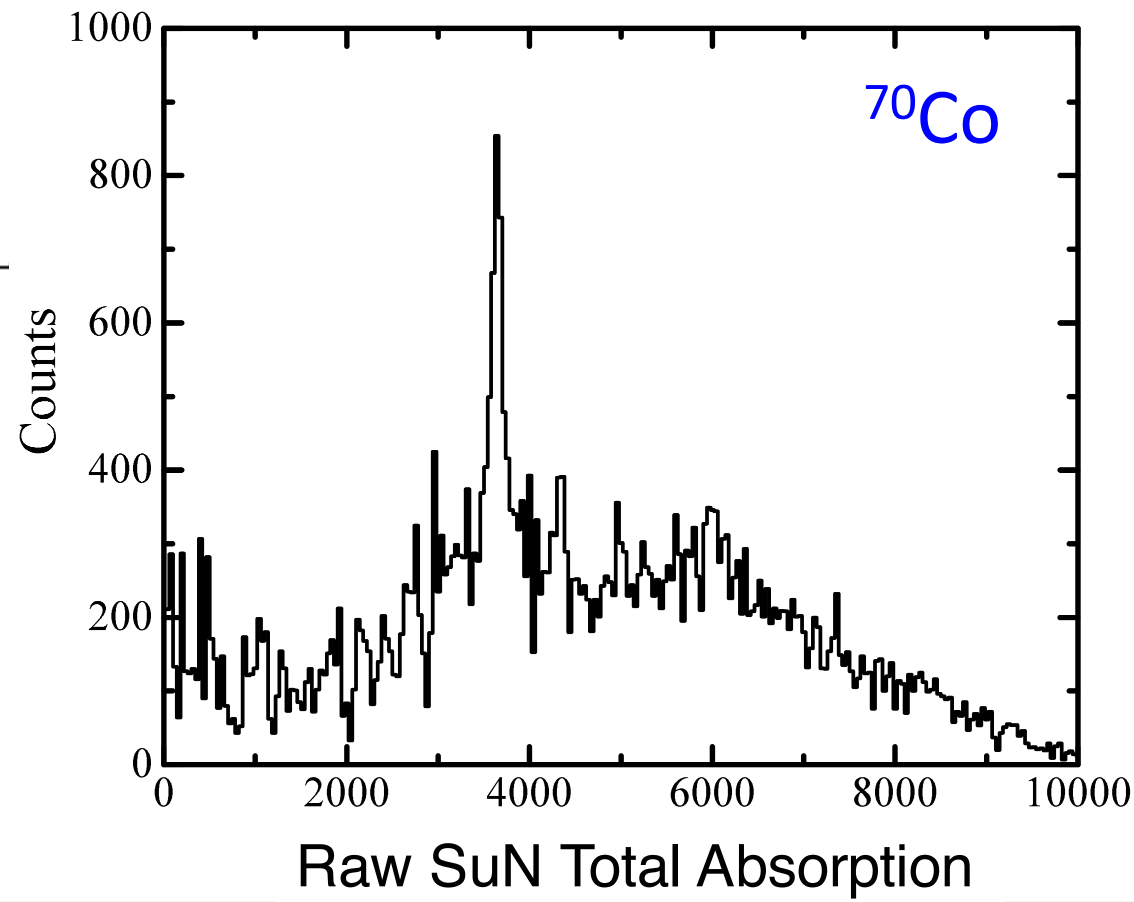


Spyrou, Liddick, Larsen, Guttormsen, et al, PRL2014

Weak r-process measurements

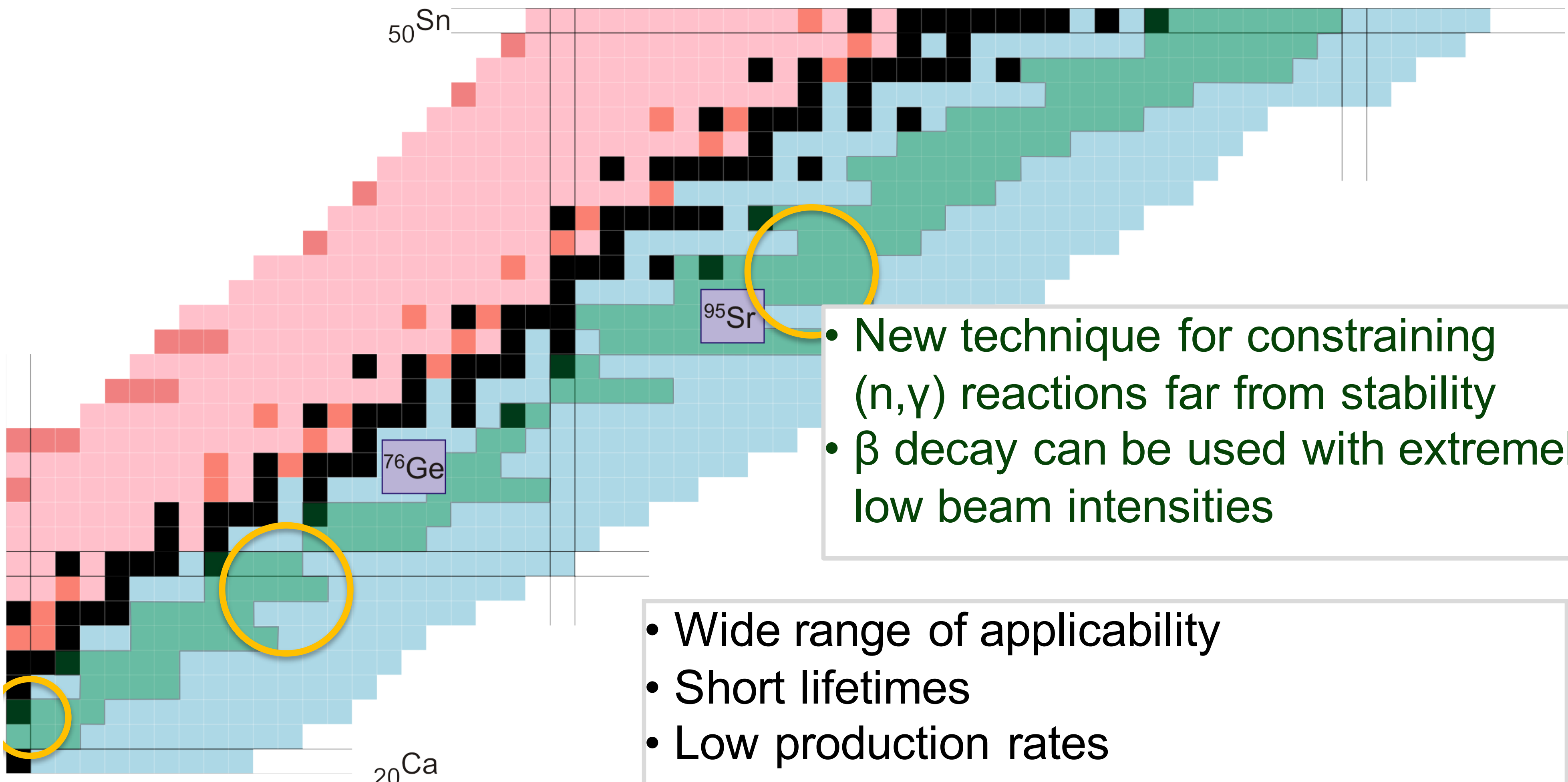
R. Surman, et al., , AIP Advances 4, 041008 (2014)





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

Summary and Applicability



- New technique for constraining (n,γ) reactions far from stability
- β decay can be used with extremely low beam intensities

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

Collaboration

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- R. Lewis
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- F. Naqvi
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- A. Rodriguez
- C.S. Sumithrarachchi
- R.G.T. Zegers

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- M. Guttormsen
- T. Renstrøm
- S. Siem
- L. Crespo-Campo

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- G. Perdikakis

<u>Notre Dame</u>

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<u>Los Alamos National Lab</u>

A. Couture

S. Mosby

<u>Lawrence Livermore National Lab</u>

D.L. Bleuel

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