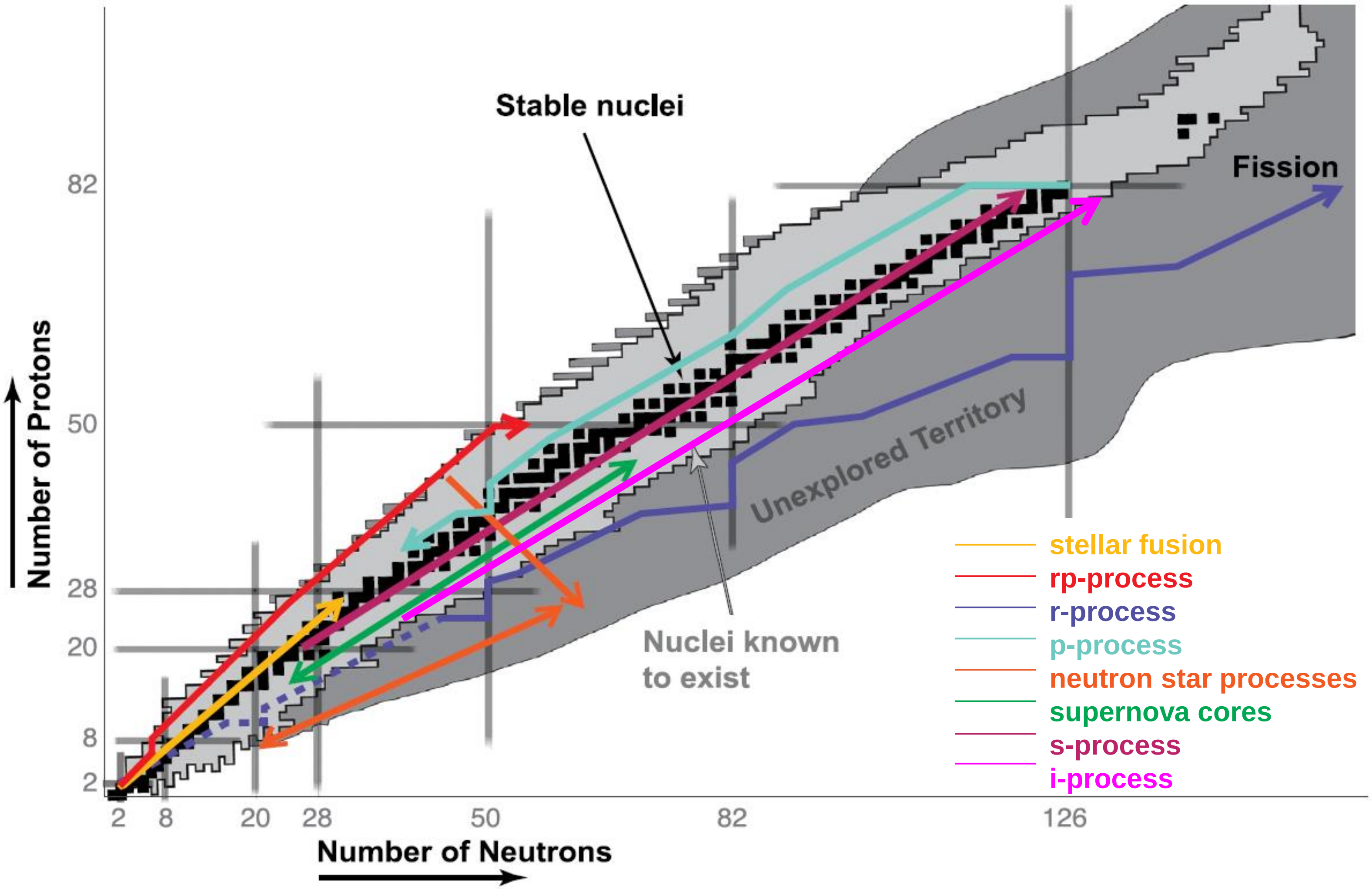
Neutron-capture reaction rates for astrophysical applications

S.N. Liddick

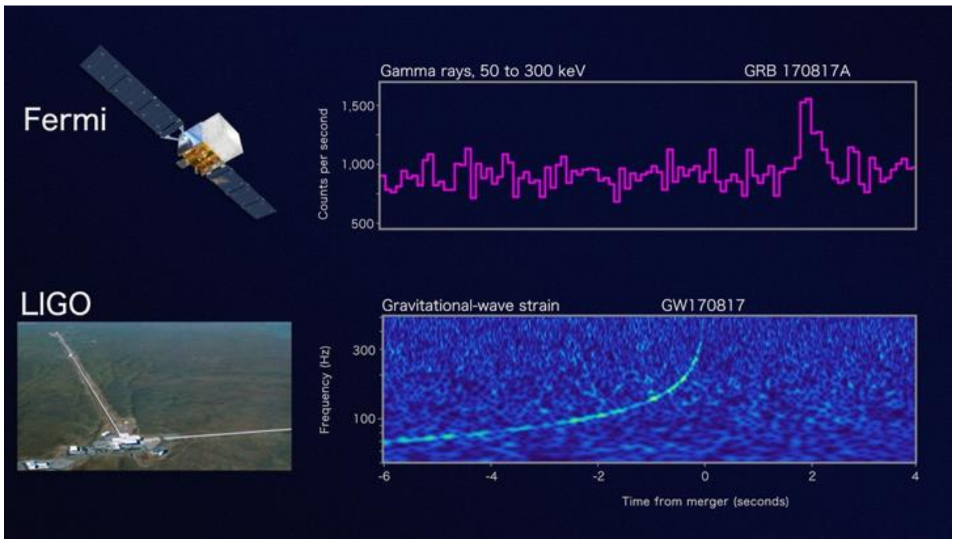
COMEX6

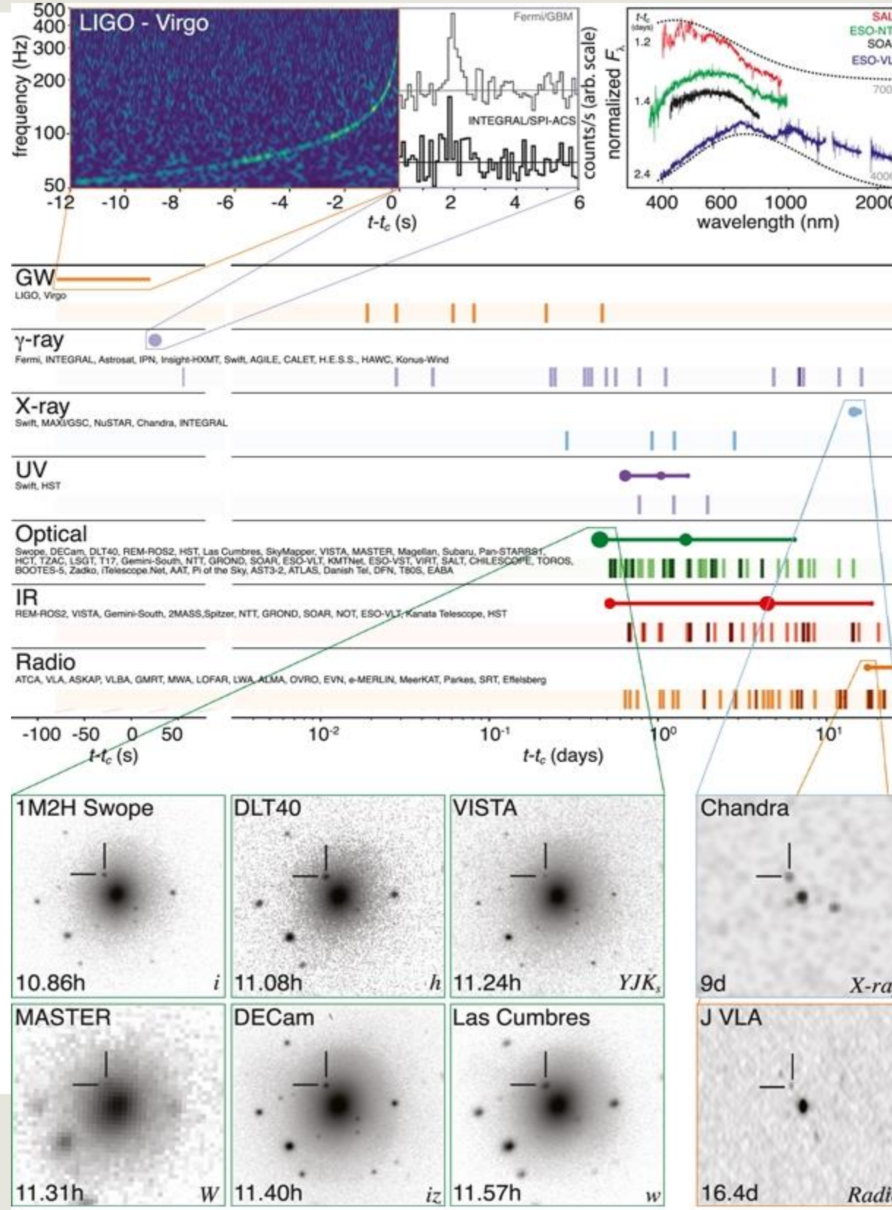
Nucleosynthesis across the nuclear chart



A. Arcones *et al.*, PPNP **94**, 67 (2017) and adapted from Frank Timmes

Neutron-star merger confirmed as a site of the r-process



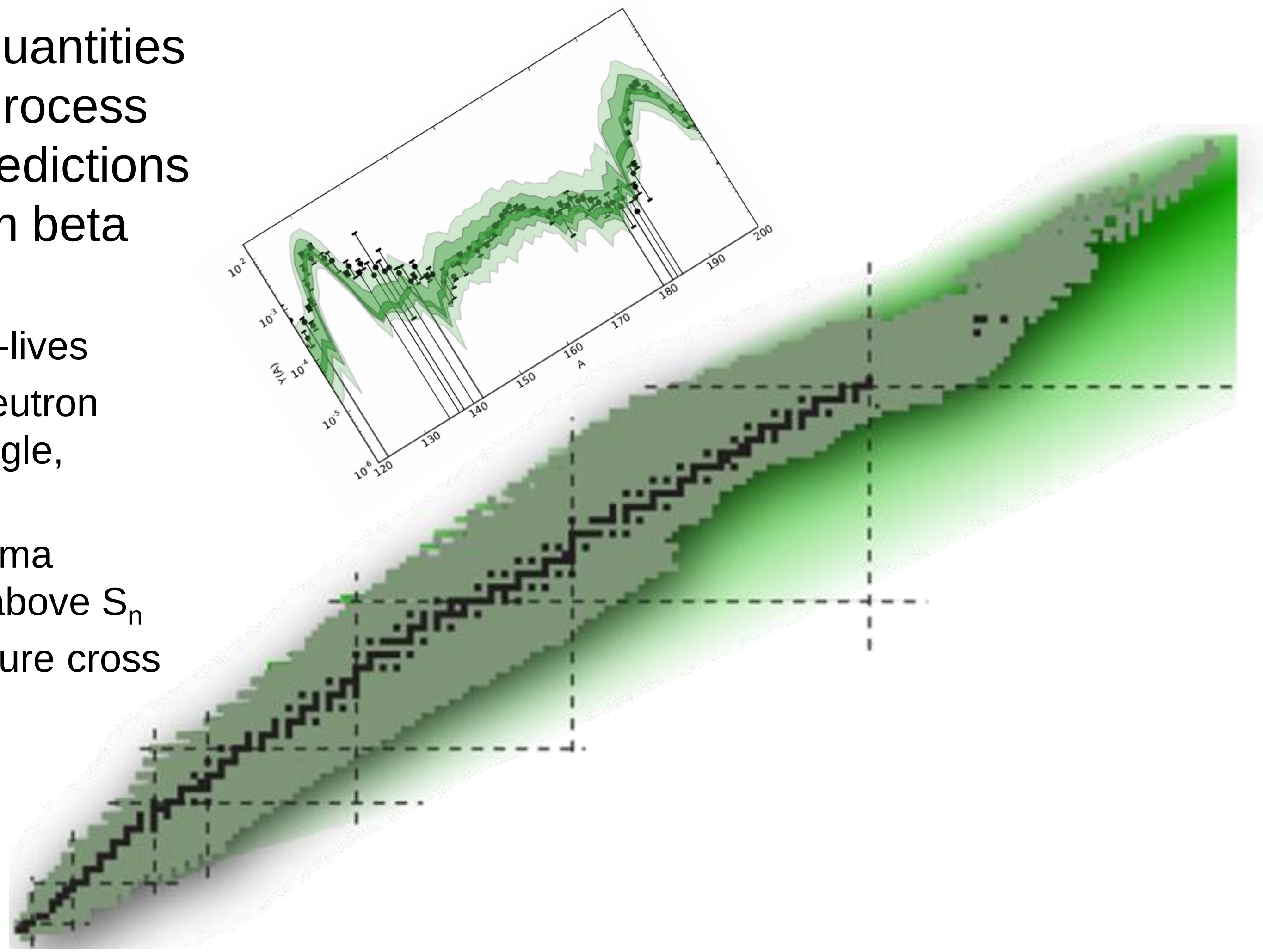


National Science Foundation
Michigan State University

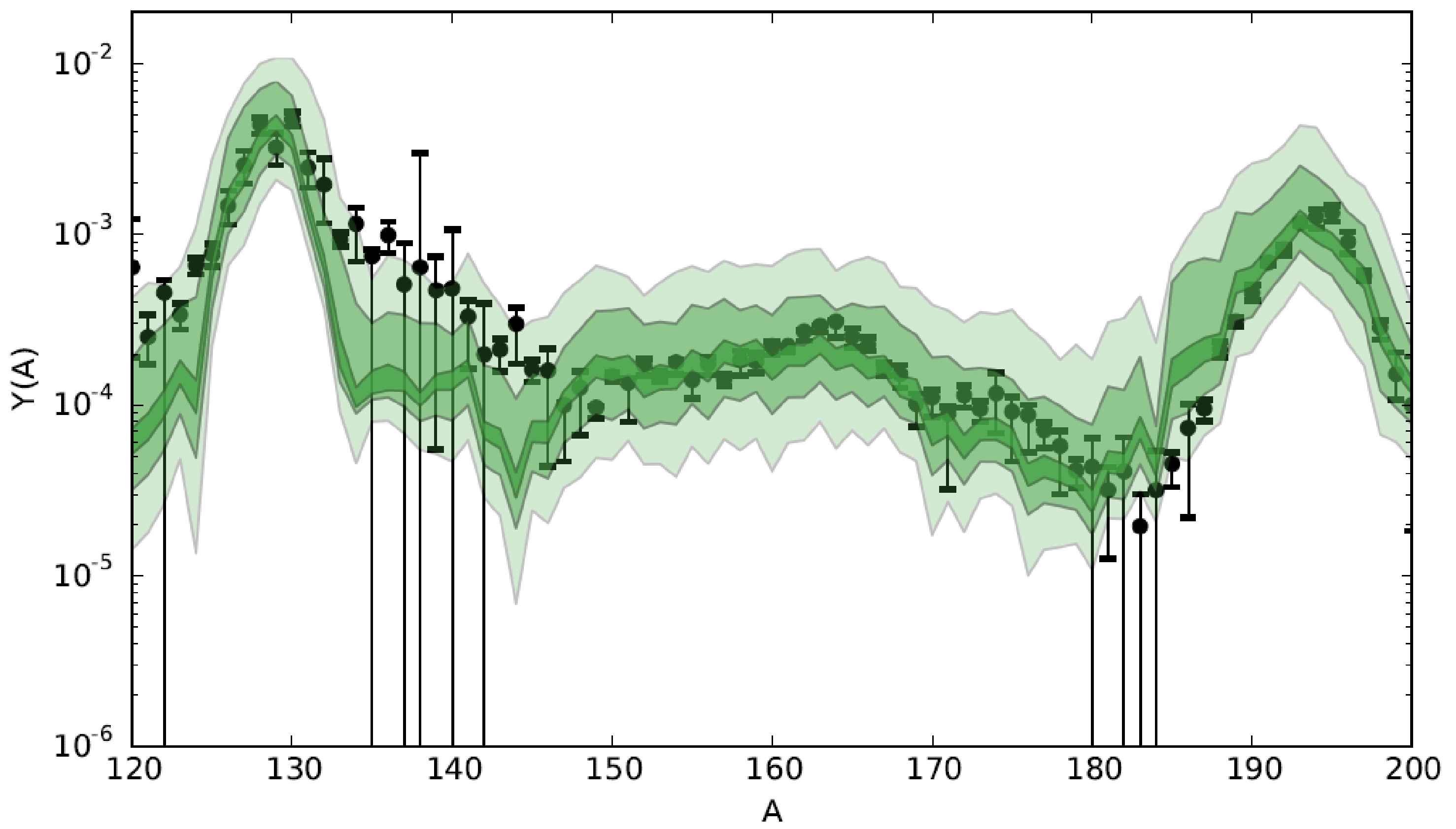
NASA's Goddard Space Flight Center, Caltech/MIT/LIGO Lab
B. P. Abbott et al. 2017 ApJL 848 L12

Nuclear Input for r-process Abundance Calculations

- A number of quantities needed for r-process abundance predictions can come from beta decay.
  - β-decay half-lives
  - β-delayed neutron emission (single, multiple, …)
  - Neutron/gamma competition above S_n
  - Neutron-capture cross sections
  - Structure



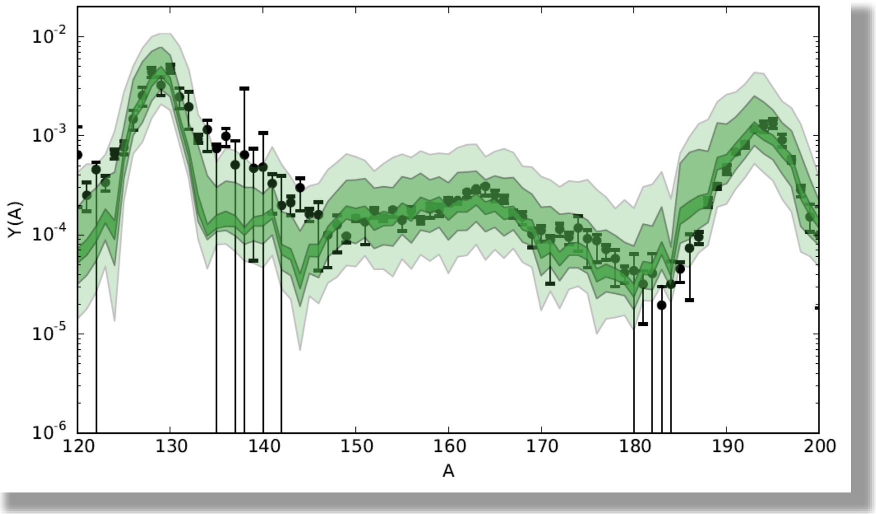
(n,γ) uncertainties impact the rapid-neutron capture process for heavy element creation



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

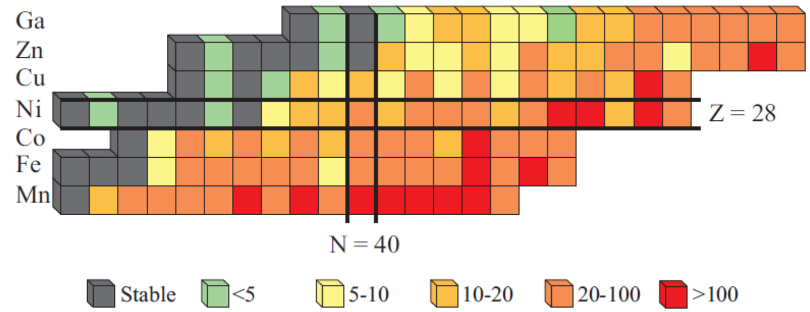
S.N. Liddick, A. Spyrou, *et al.*, Phys. Rev. Lett. **116**, 242502 (2016)
R. Surman and J. Engel, Phys. Rev. C, **64**, 035801 (2001)

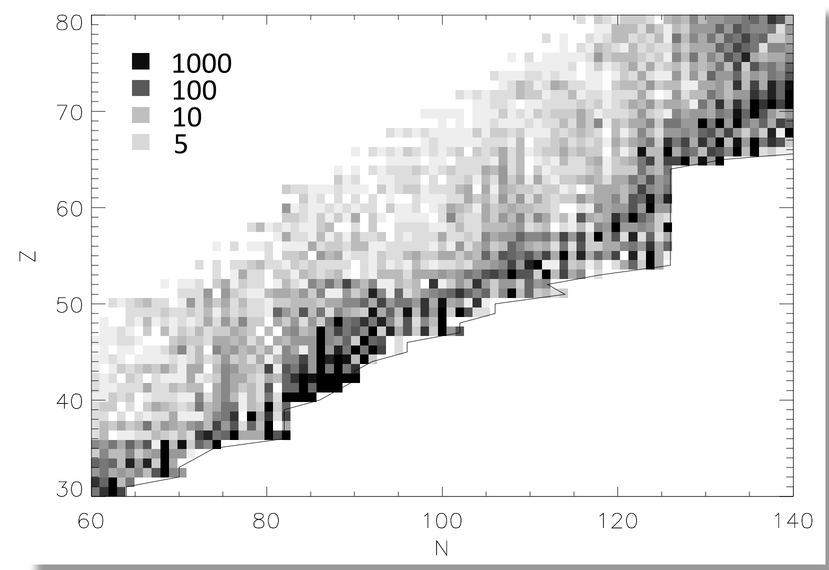
(n,γ) uncertainties impact the rapid-neutron capture process for heavy element creation



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

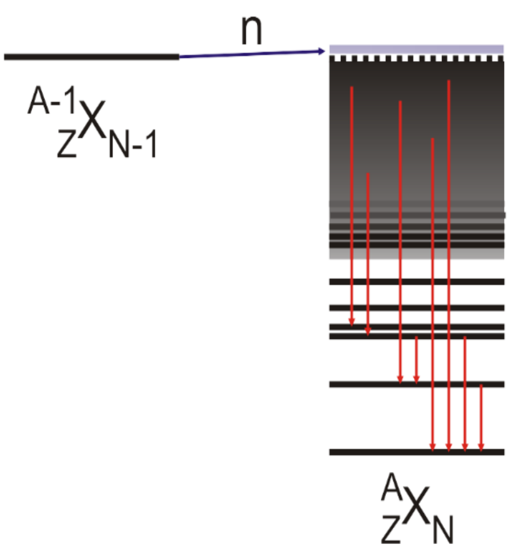
(n,γ) uncertainties





S.N. Liddick, A. Spyrou, *et al.*, Phys. Rev. Lett. **116**, 242502 (2016)
R. Surman and J. Engel, Phys. Rev. C, **64**, 035801 (2001)

Nuclear level densities and γ-ray strength functions are the dominate uncertainties in (n,γ) calculations



Hauser – Feshbach

- Nuclear Level Density

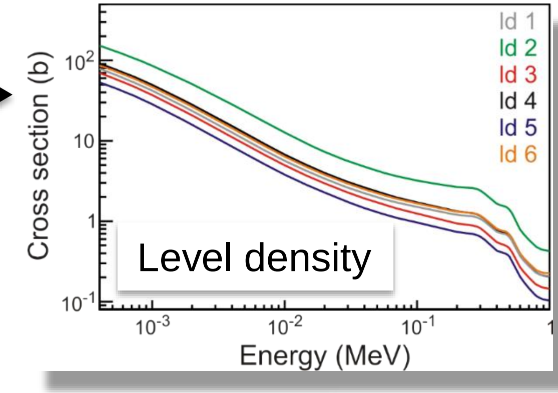
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, microscopic

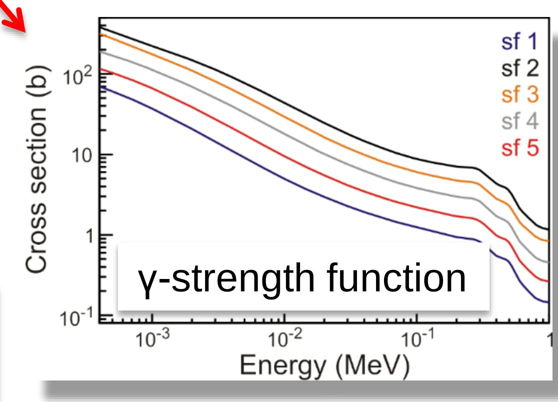
- γ-ray strength function

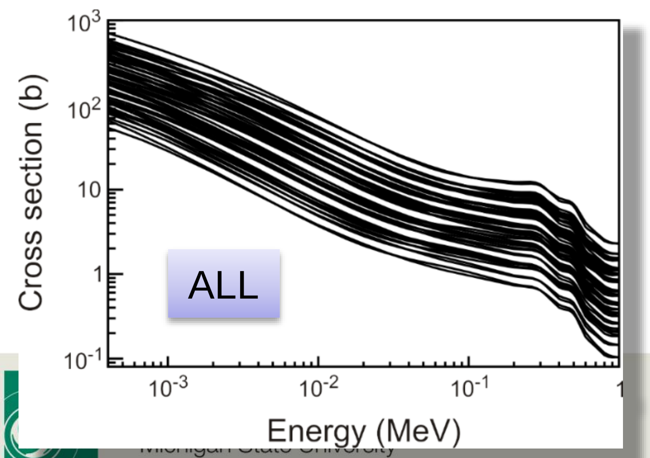
Generalized Lorentzian, Brink-Axel, various tables

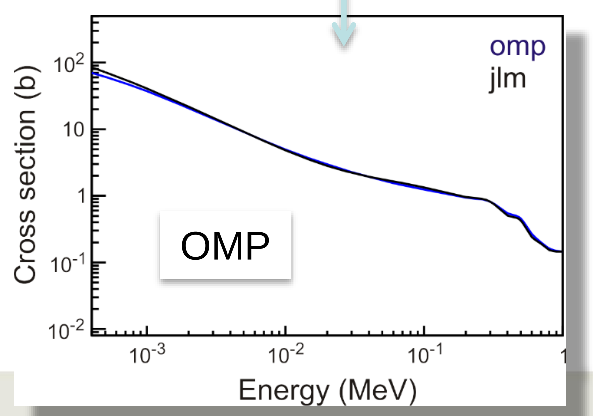
- Optical model potential

Phenomenological, Semi-microscopic









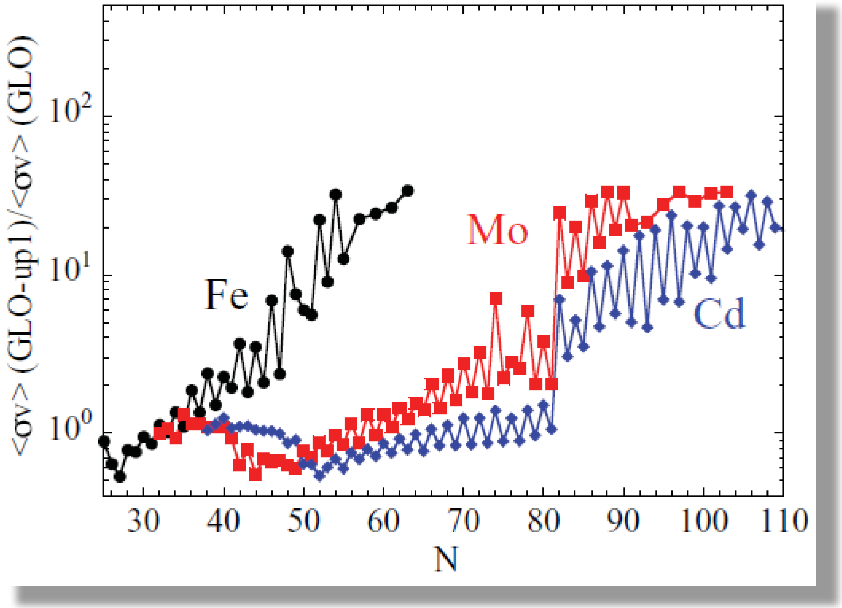
^{95}Sr(n,γ)^{96}Sr

TALYS

Extrapolation of nuclear level densities and γ-ray strength functions to exotic nuclei are uncertain

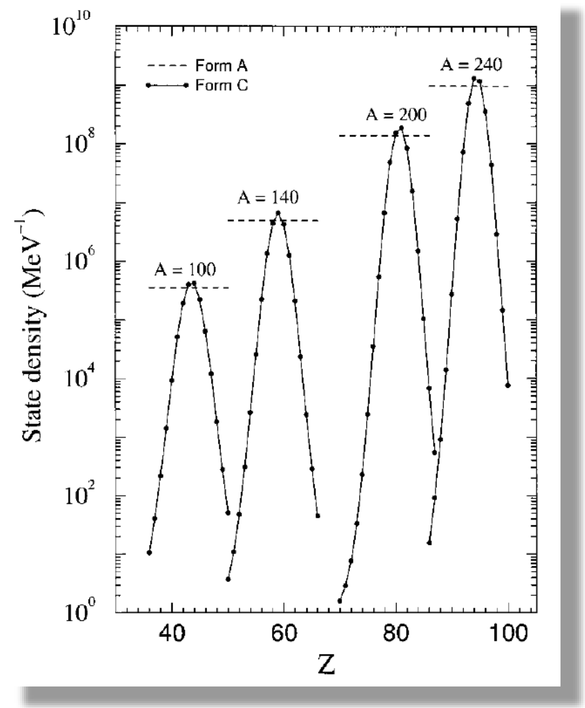
γ-ray strength functions

- Unexpected structural features.



Level densities

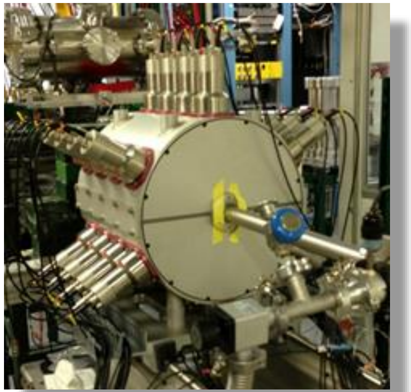
- What is N,Z dependence of a?

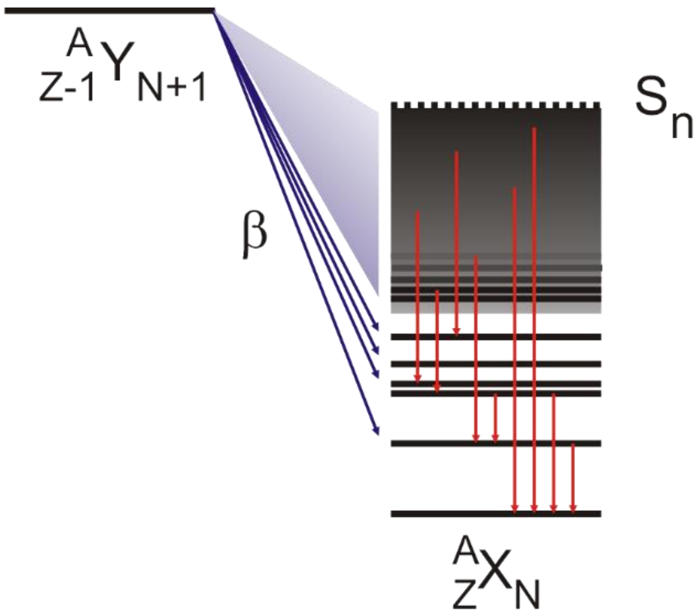


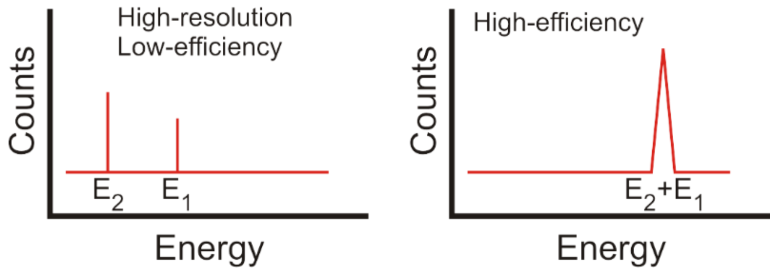
A.C. Larsen *et al.*, Phys. Rev. C, **82**, 014318 (2010)
Al-Quraishi *et al.*, Phys. Rev. C **63**, 065803 (2001)

Using beta decay total absorption spectroscopy to infer neutron capture cross sections

- Measure beta decay of nucleus.
  - Extract level densities and gamma-ray strength function
- Need total excitation energy of the daughter isotope.
  - Can’t use beta-decay electron (three body process)
- Instead, measure total emitted photon energy.

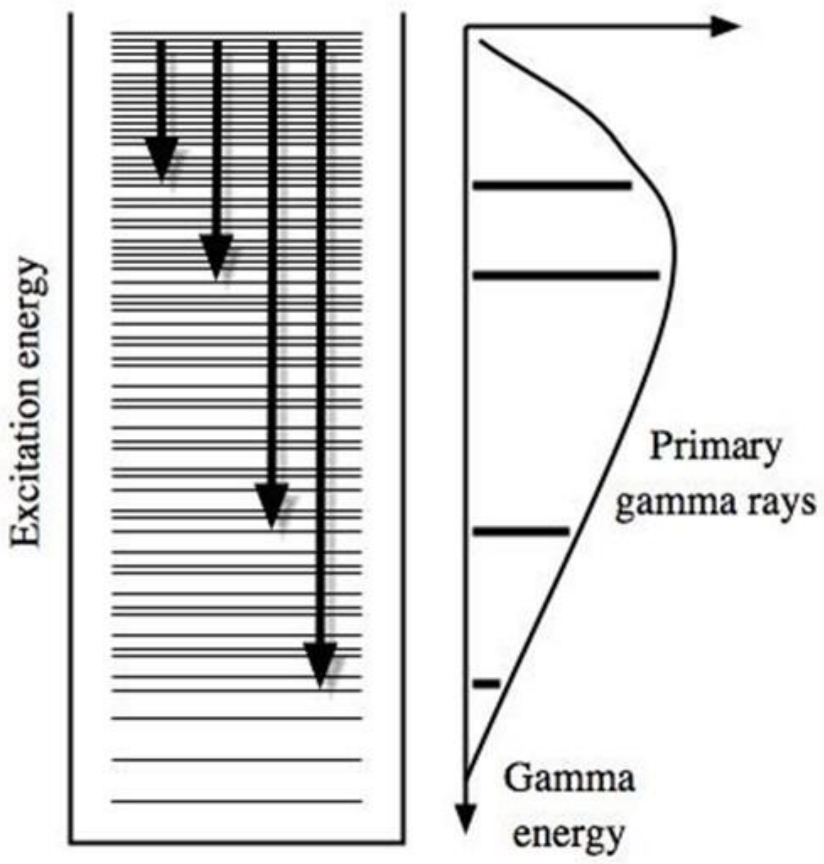






- Require high detection efficiency.
- Extract nuclear level density and γ-ray strength function.
- Insert both quantities into a statistical reaction model to constrain (n,γ) rate.

Extracting NLD and γSF with the β-Oslo Method

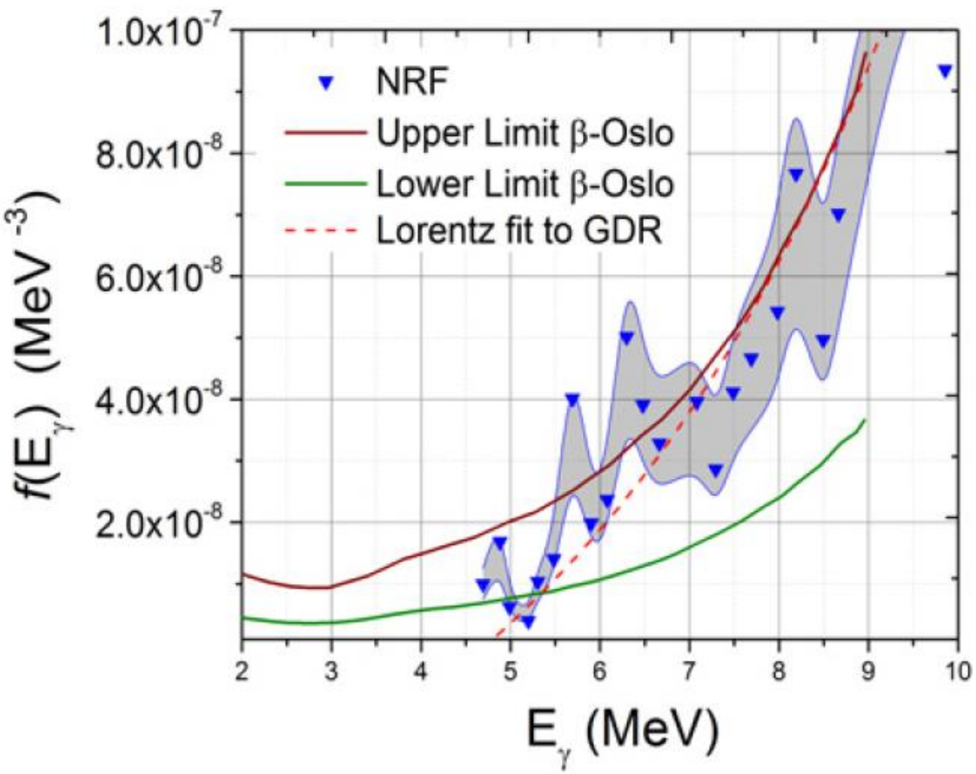


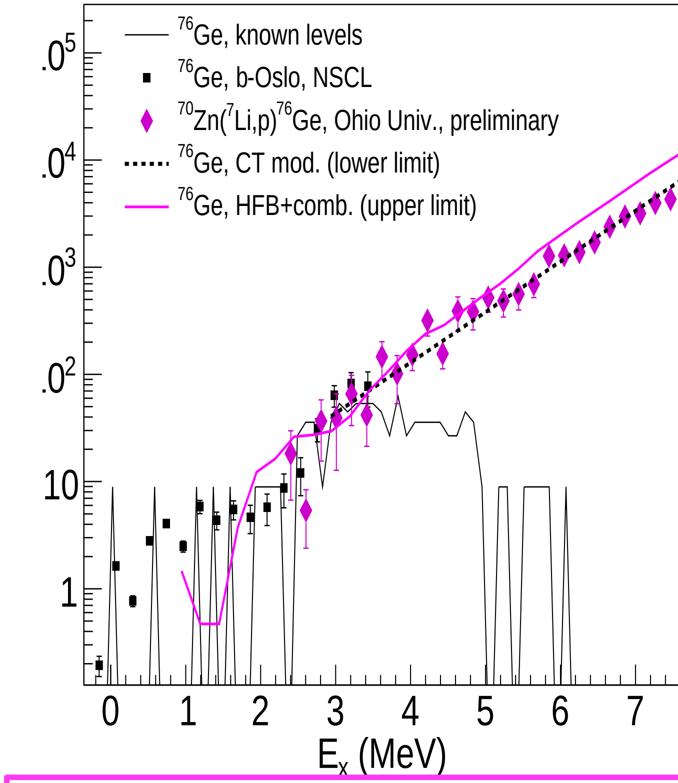
$$P(E_\gamma, E_x) \propto \rho(E_x - E_\gamma) \cdot T(E_\gamma)$$

$$\gamma SF(E_\gamma) = \frac{1}{2\pi} \frac{T(E_\gamma)}{E_\gamma^3}$$

M. Guttormsen *et al.*, Phys. Rev. Lett. **116**, 012502 (2016).

Validation of NLD and γSF – ^{76}Ge

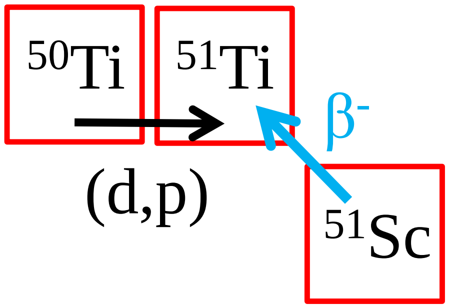




A. Tonchev, *et al. EPJ Web of Conf,* ***146****, 01013 (2017)*
Photoscattering exeriment – HIγS

A. Voinov, T. Renstrom, A.-C. Larsen, *et al.*
Preliminary Analysis - *^{70}Zn(^{7}Li,p)^{76}Ge reaction*
Experiment at Ohio University

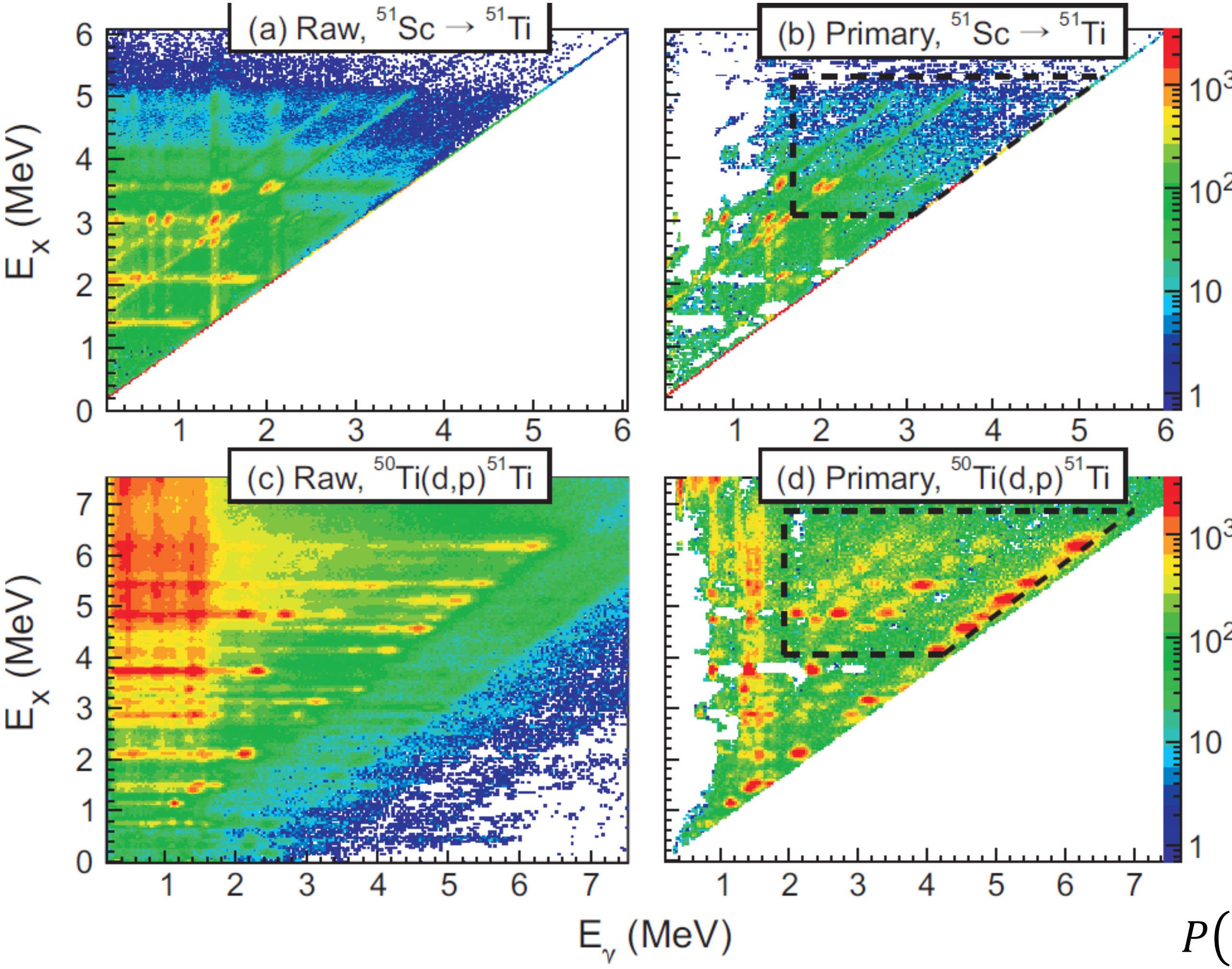
Comparison to a known neutron capture – ^{51}Ti



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

- ^{50}Ti(d,p)^{51}Ti performed at Oslo.
- ^{51}Sc beta decay performed at NSCL.
- NLD and γSF extracted from both experiments.

Raw and primary matrices – ^{51}Ti



- ^{50}Ti(d,p)^{51}Ti performed at Oslo.
- ^{51}Sc beta decay performed at NSCL.
- NLD and γSF extracted from both experiments.

$$P(E_x, E_\gamma) \propto \rho(E_x - E_\gamma)\mathrm{T}(E_\gamma)$$

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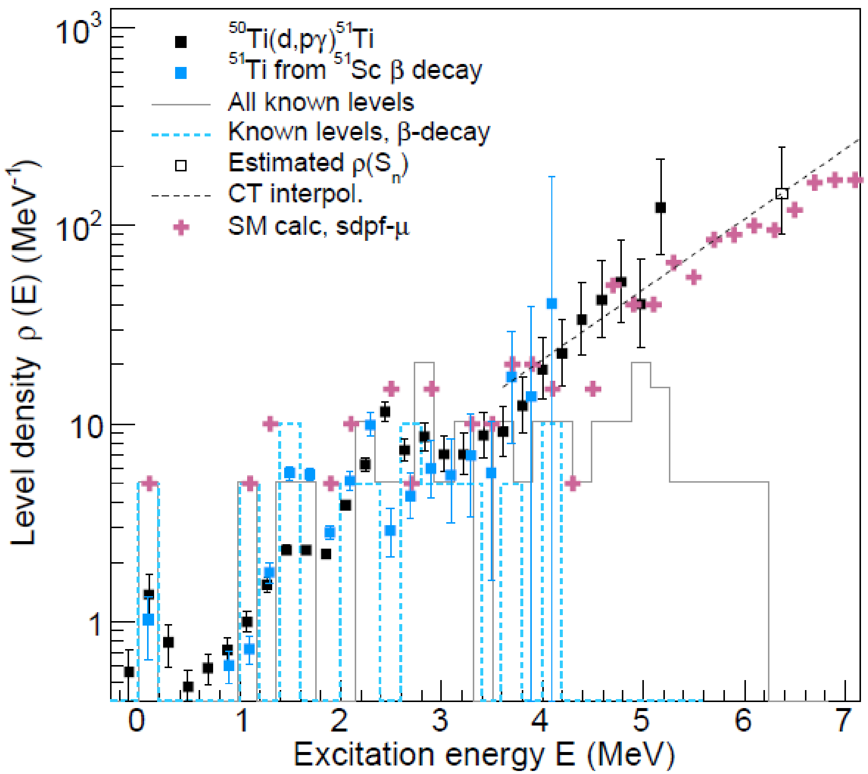
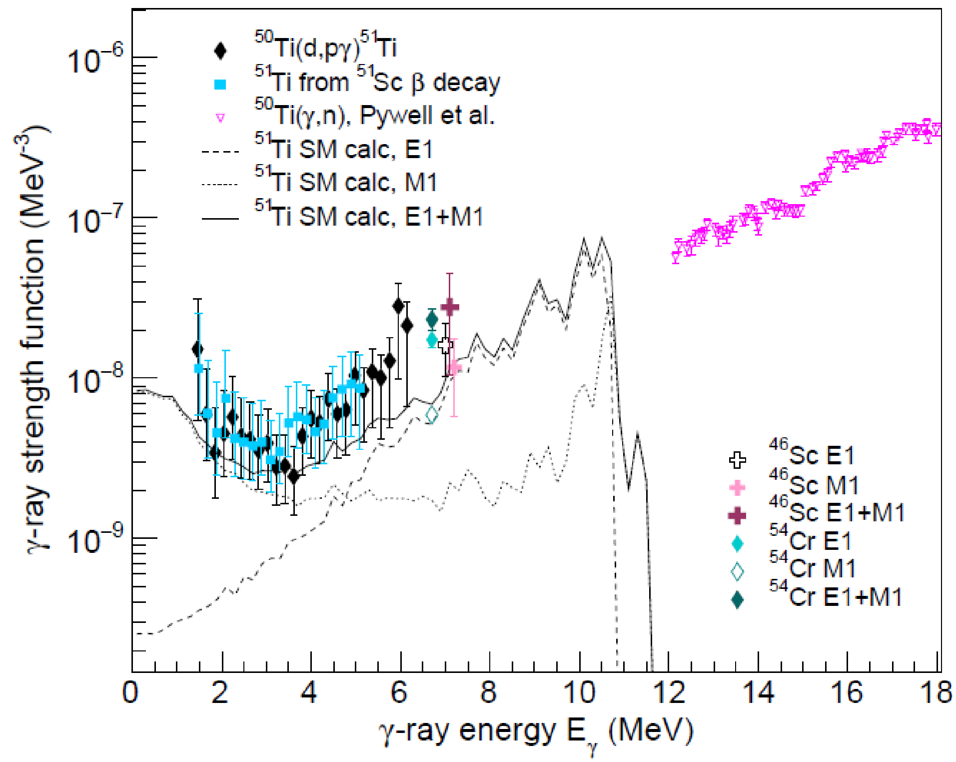
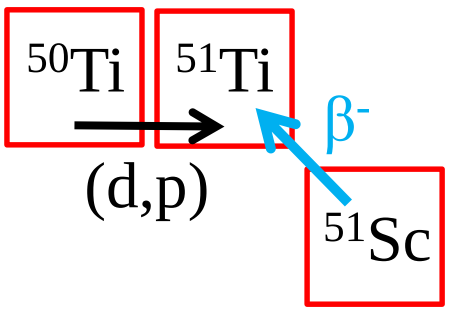
^{51}Ti level density and γ-strength function





Validation – ^{51}Ti



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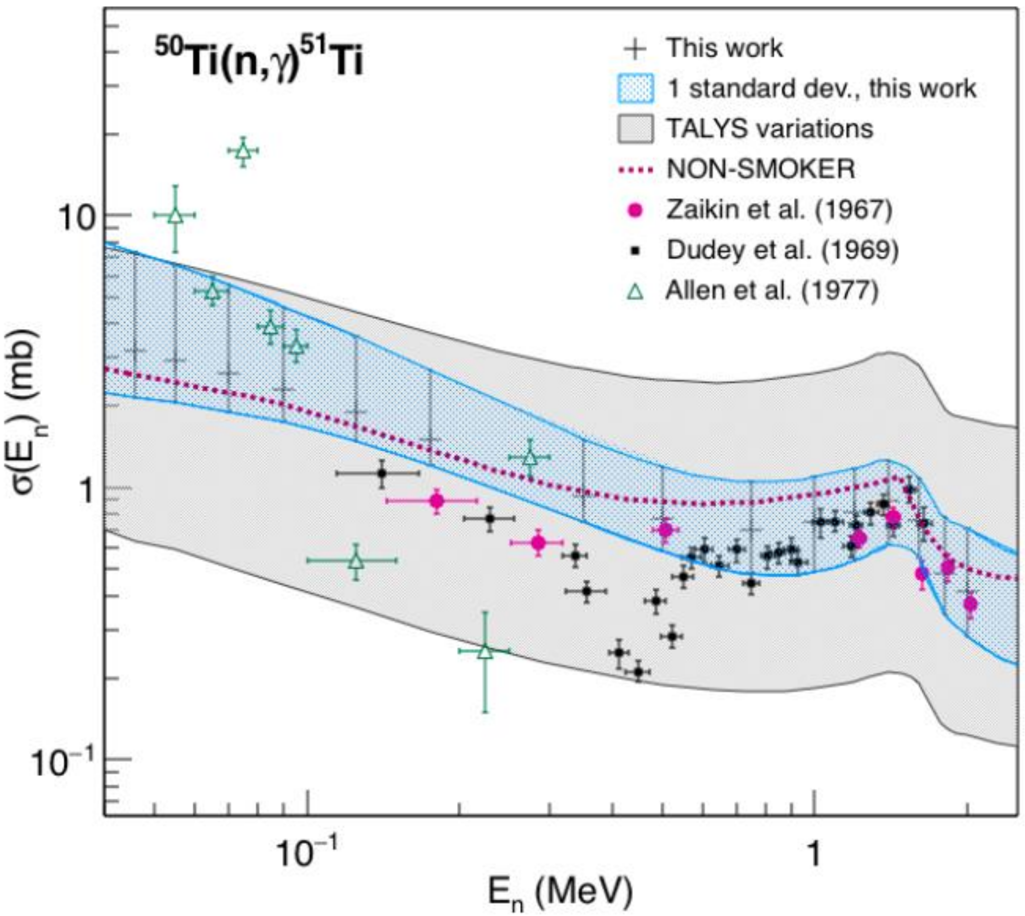
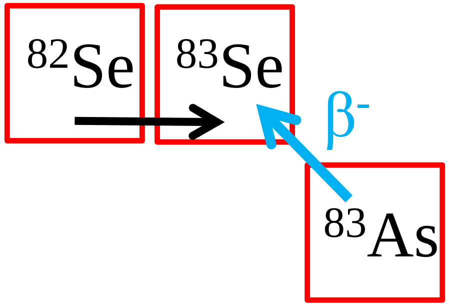
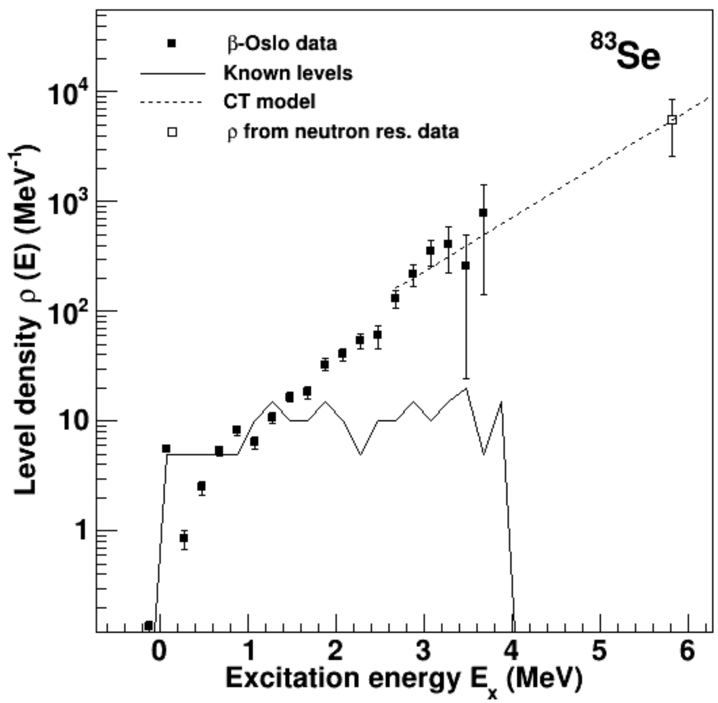
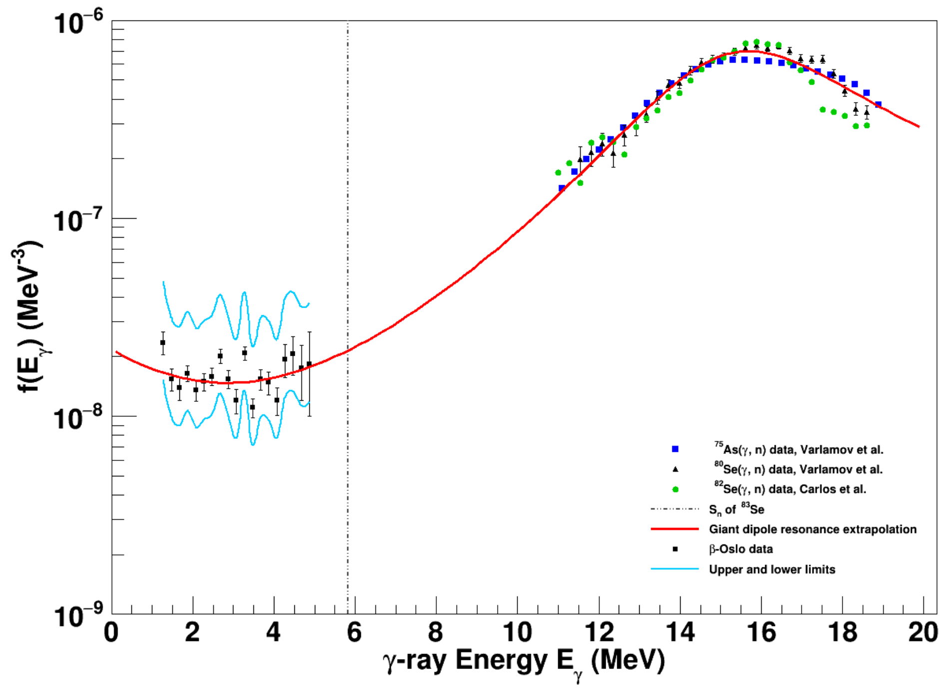


NLD and γSF for ^{83}Se



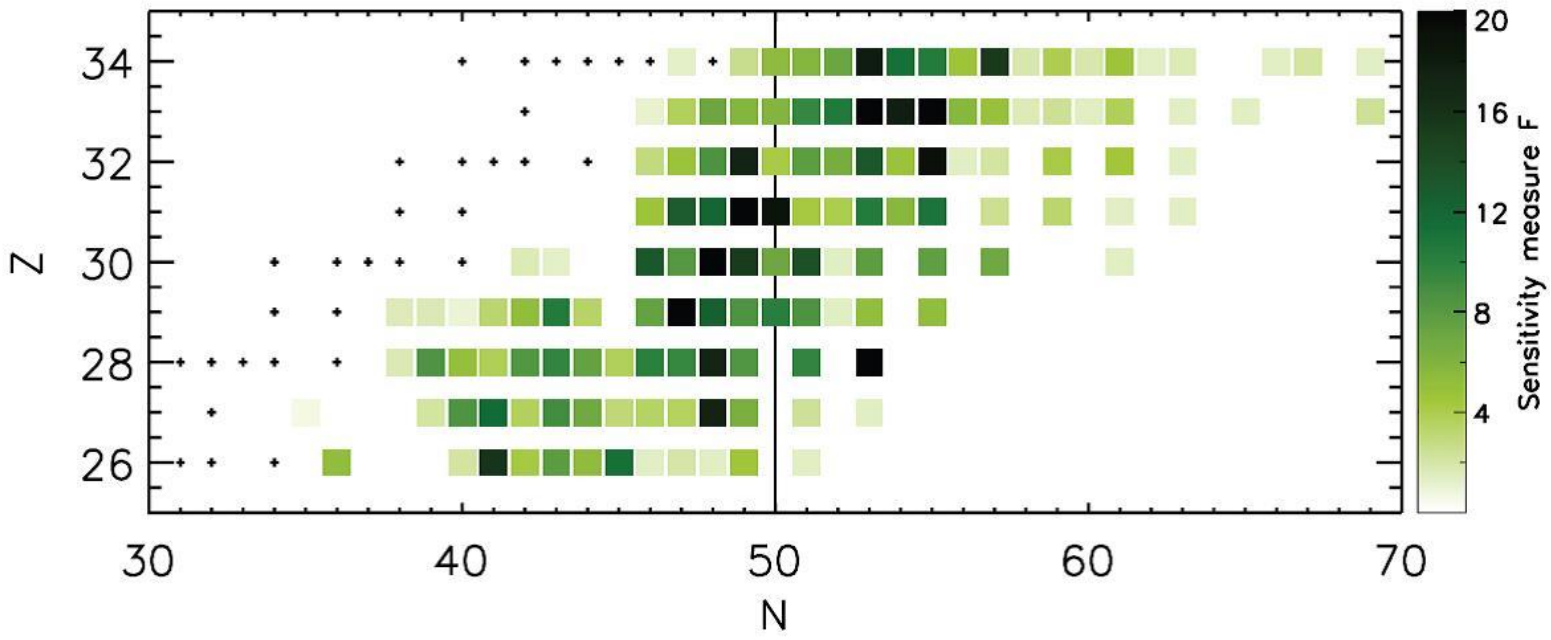
^{83}As: $T_{1/2}$ = 13.4 s
$Q_{\beta-}$ = 5.67 MeV
S_n (^{51}Ti) = 5.81 MeV





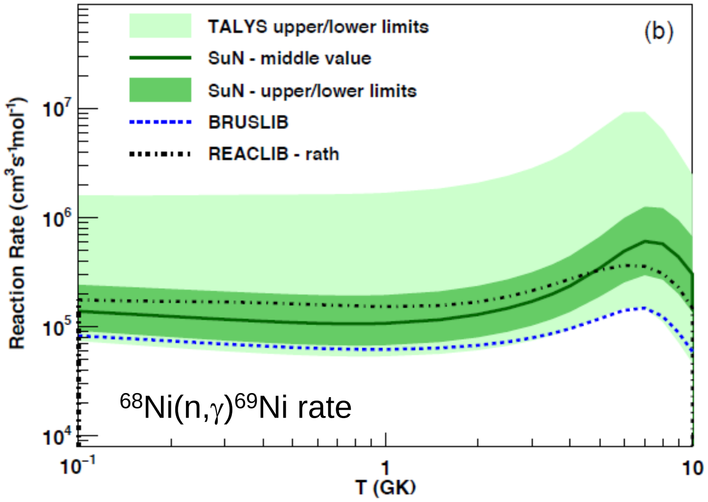
work of K. Childers

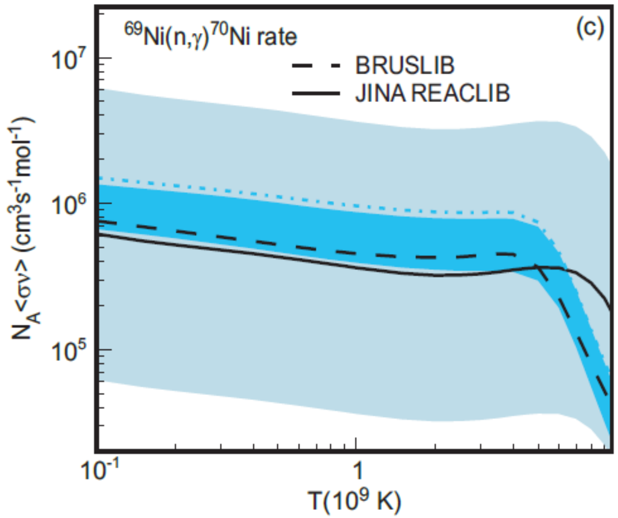
Importance of (n,γ) on short-lived nuclei

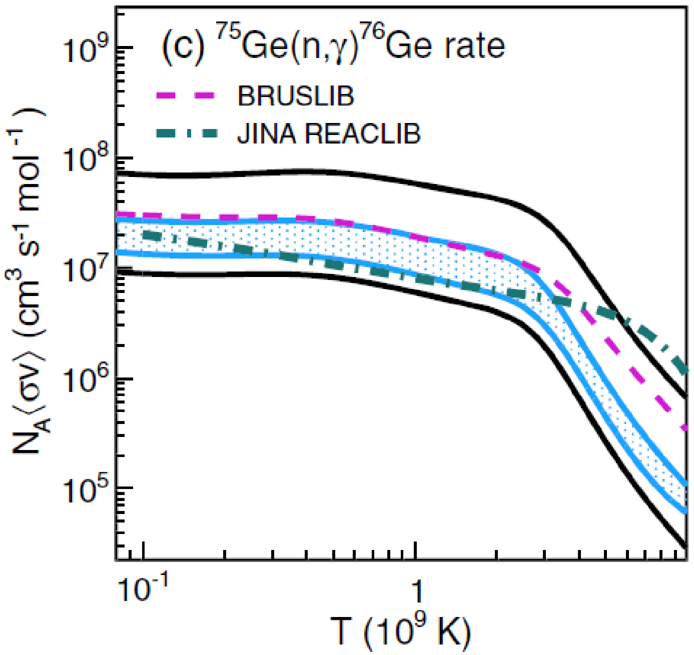


Surman et. al. AIP Adv. **4**, 041008 (2014)

Complete (n,γ) results



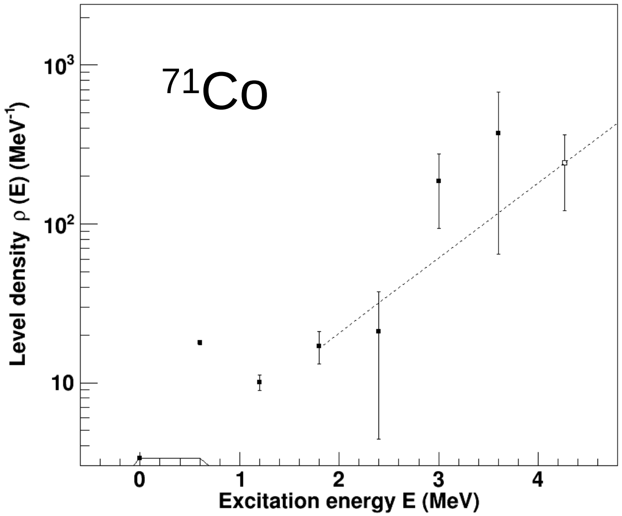


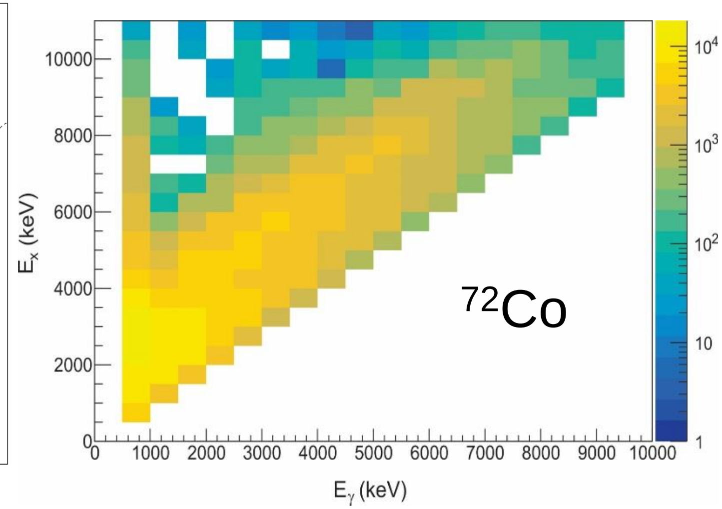


S.N. Liddick *et al.*, PRL **116**, 242502 (2016)

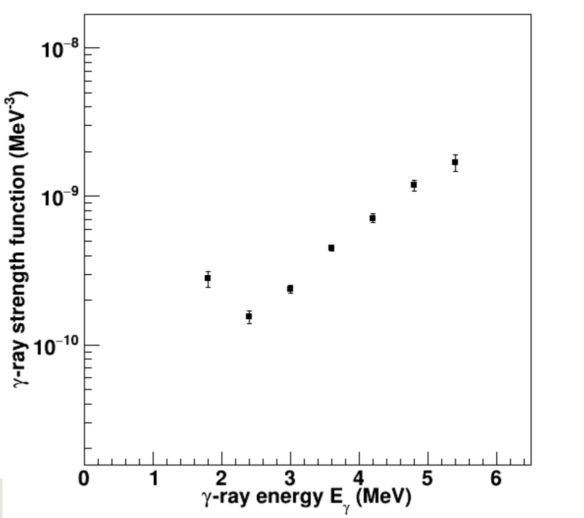
A. Spyrou *et al.*, JPG **44**, 044002 (2016)

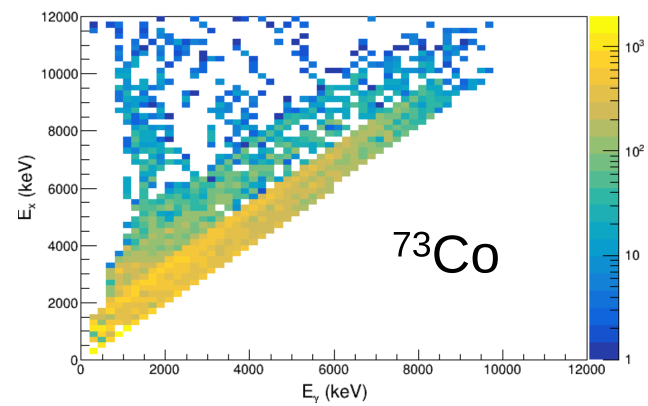
Upcoming (n,γ) Ni results - Preliminary





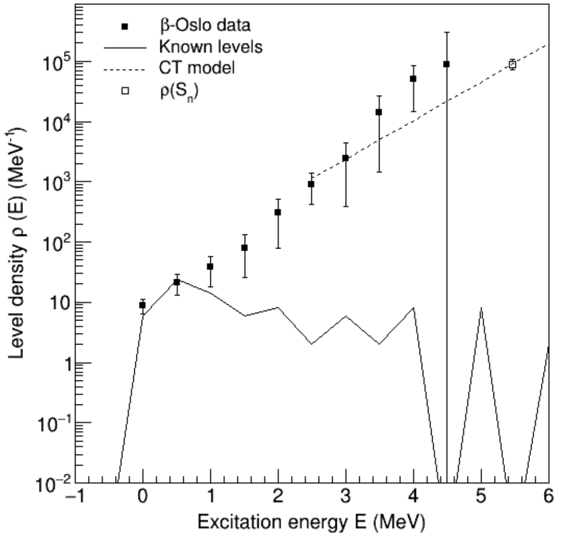
Primary



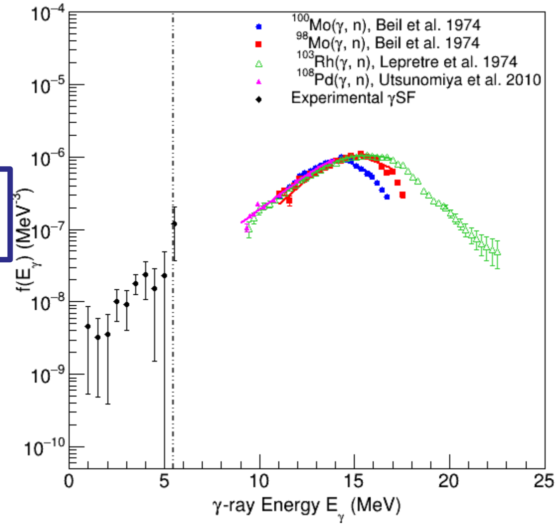


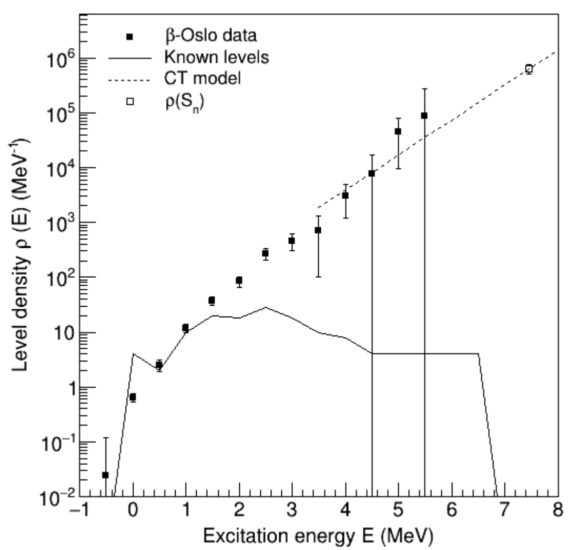
work of R. Lewis

Upcoming (n,γ) Mo results - Preliminary

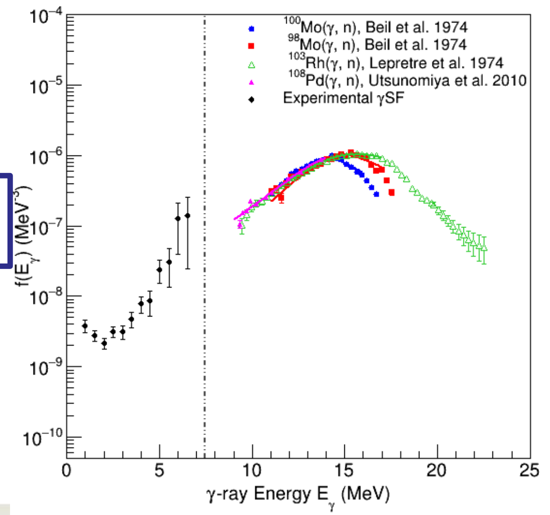


^{103}Mo



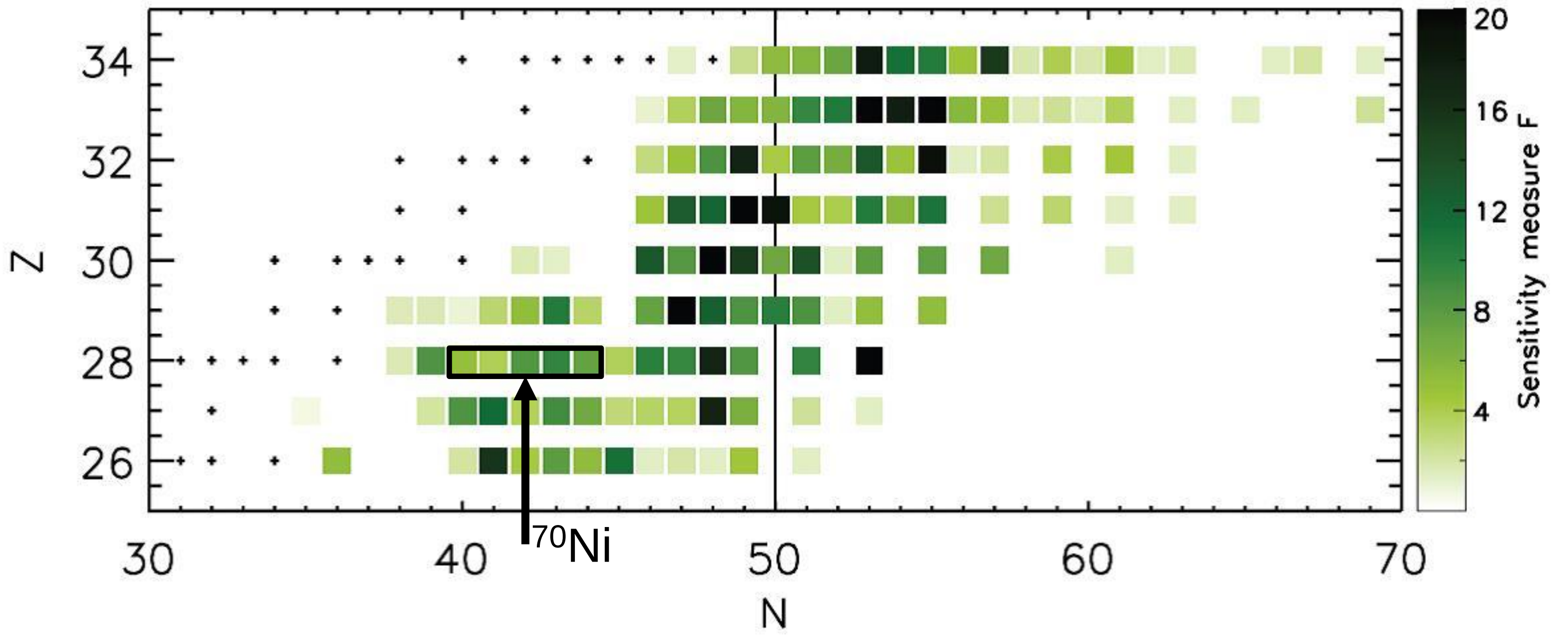


^{104}Mo



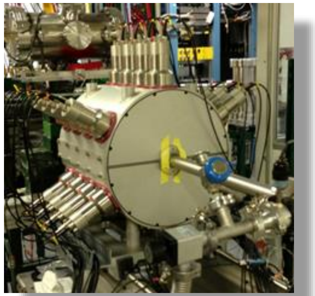
work of A. Richard

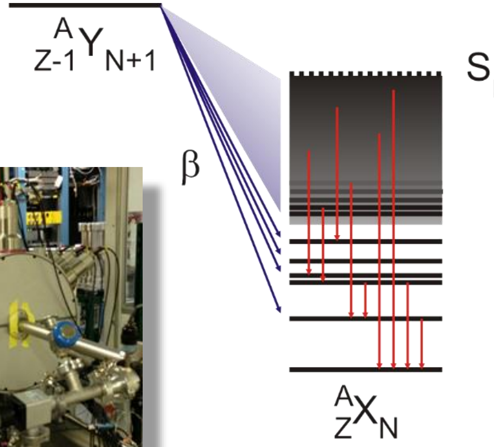
Systematic investigations along Ni isotopic chain are possible



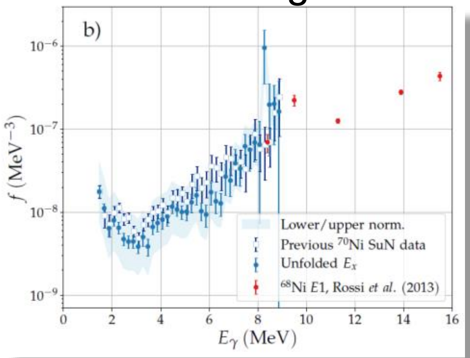
Much more can be extracted than just (n,g)

- Leading to the development an entirely new technique experimental technique …
  - β-Oslo technique developed for neutron-rich neutron capture
- And generating an abundance of nuclear science and nuclear data …
- Same experiment has multiple outcomes.

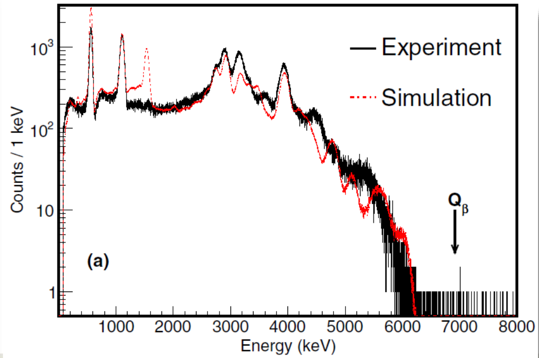




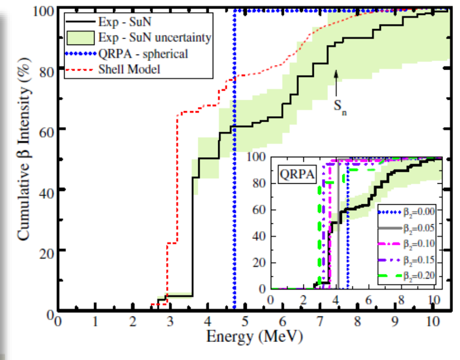
Nuclear structure: strength



Nuclear structure: levels

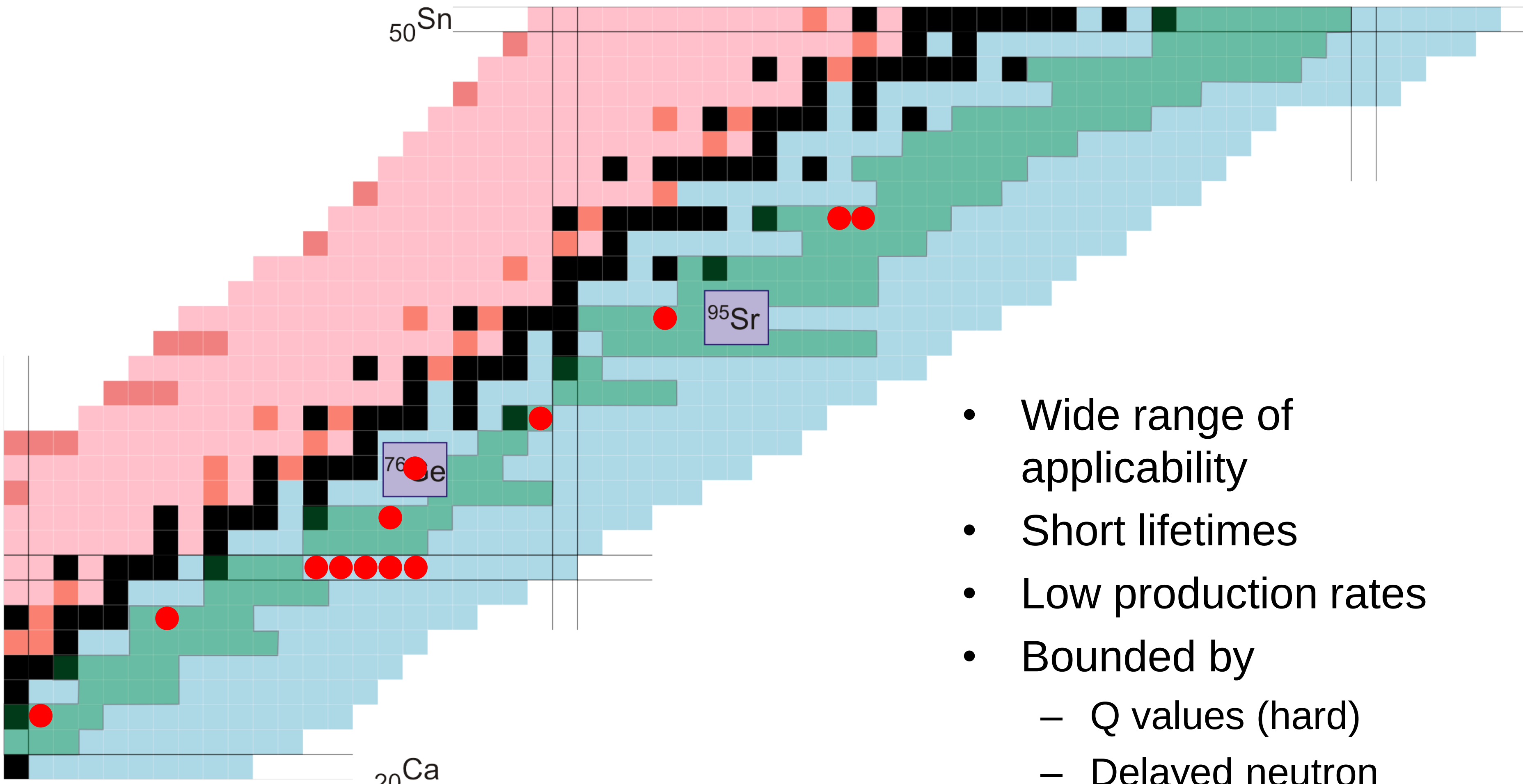


n,γ competition



A. Spyrou, S.N. Liddick *et al.*, Phys. Rev. Lett. 116, 061801 (2016)
A. Dombos, *et al.*, Phys. Rev. C, 93, 064317 (2016)
A.C. Larsen *et al.*, Phys. Rev. C (accepted)

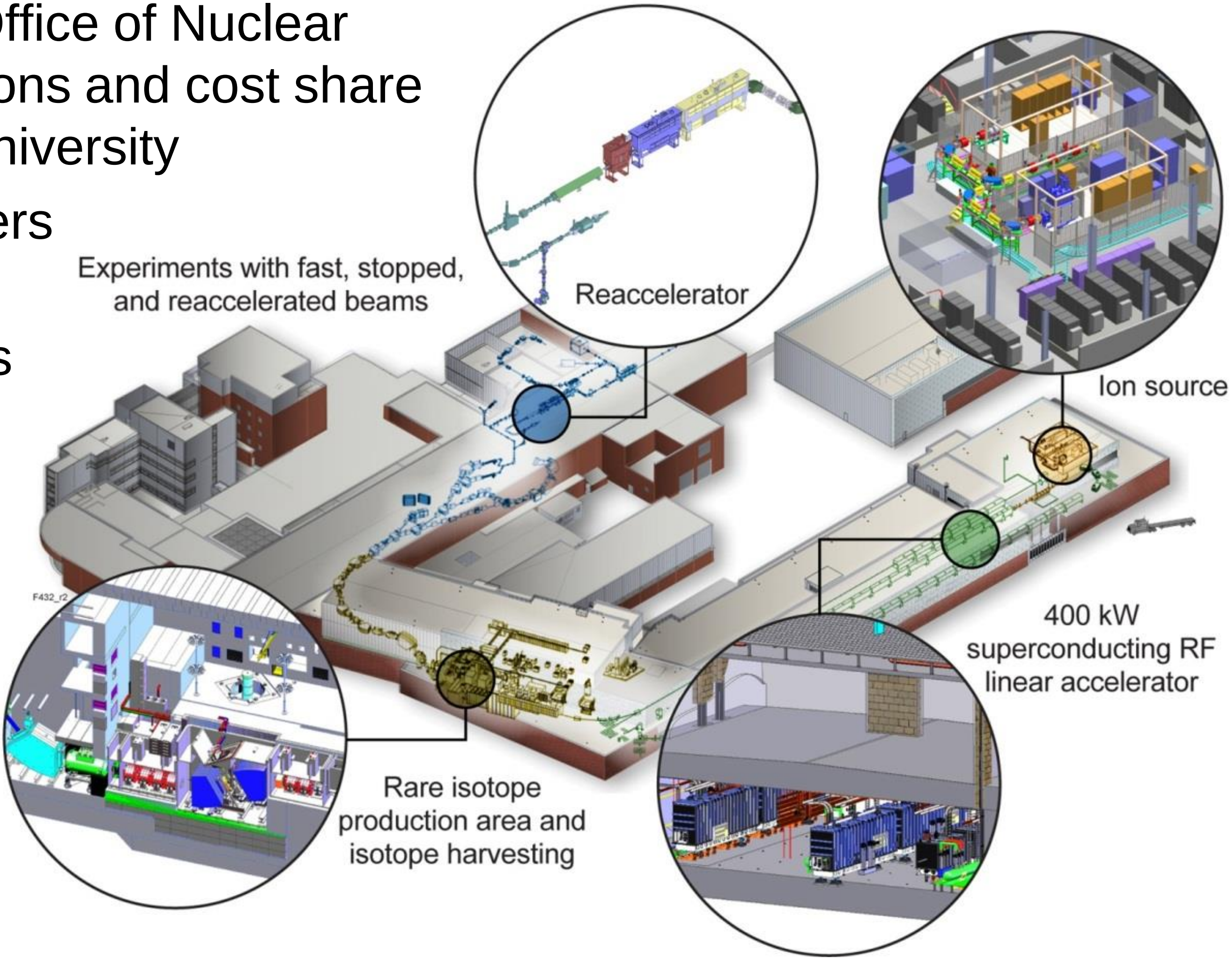
Range of Applicability



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

Facility for Rare Isotope Beams
A Future DOE-SC National User Facility

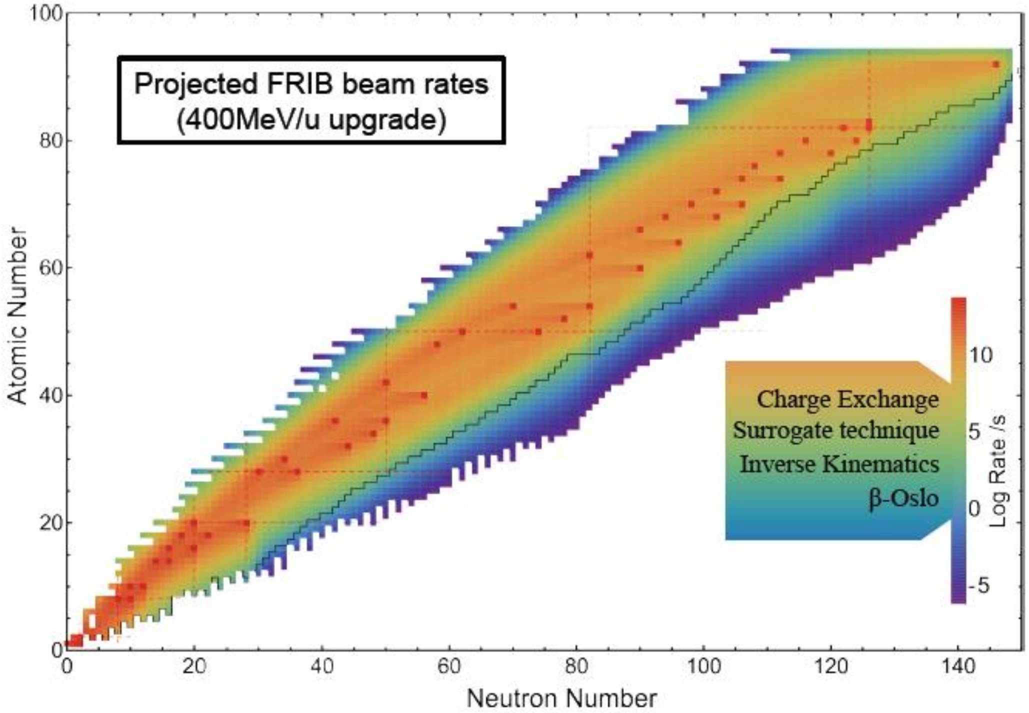
- Funded by DOE–SC Office of Nuclear Physics with contributions and cost share from Michigan State University
- Serving over 1,400 users
- Key feature is 400 kW beam power for all ions (e.g. 5×10^{13} ^{238}U/s)
- Separation of isotopes in-flight provides
  - Fast development time for any isotope
  - All elements and short half-lives
  - Fast, stopped, and reaccelerated beams

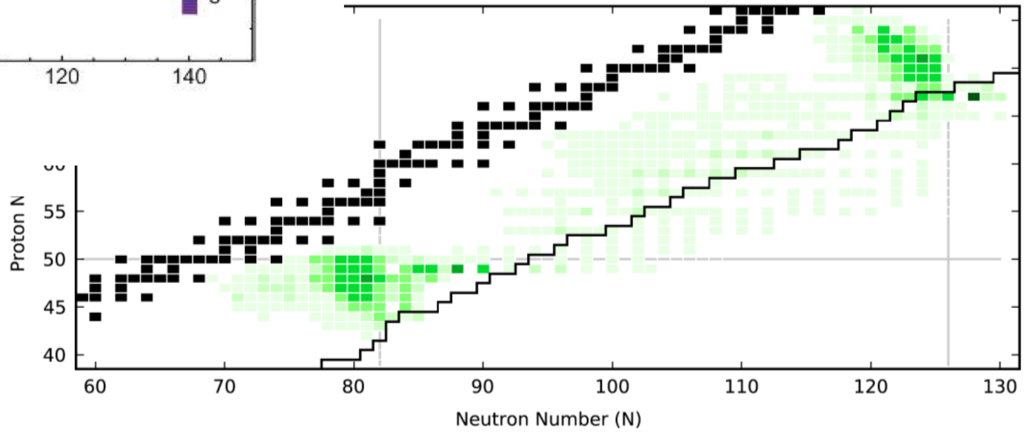


Civil Construction Reached Beneficial Occupancy in March 2017

Web cams at frib.msu.edu

FRIB





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

Summary

- β-Oslo technique can lead to NLD and γSF for nuclei far from stability.
- NLD and γSF from β-Oslo can be used to constrain the neutron capture cross section
- Constrained neutron capture cross section agrees with directly measured values
- Potential for systematic investigation of NLD, γSF, and (n, γ) rates as a function of neutron and proton number
- Possibility for explorations of spin dependences using beta decay.
- FRIB intestines allow for a coverage of a significant number of important (n, γ) rates.

Thanks

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

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- T. Renstrøm
- J. Mitbo

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- G. Perdikakis
- S. Nikas

Notre Dame

- A. Simon
- R. Surman

LLNL

- D.L. Bluel
- N. Scielzo

LANL

- A. Couture
- S. Mosby
- M. Mumpower

Questions?