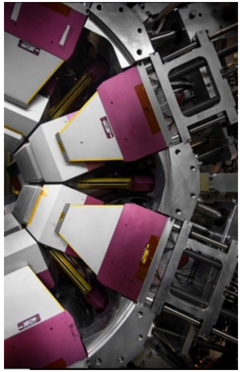
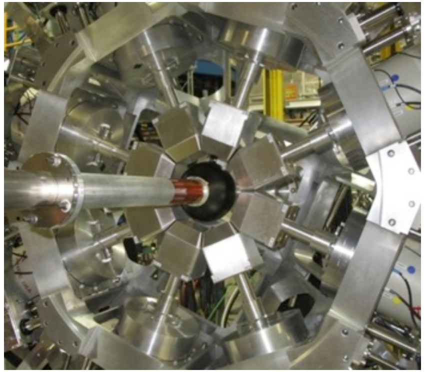
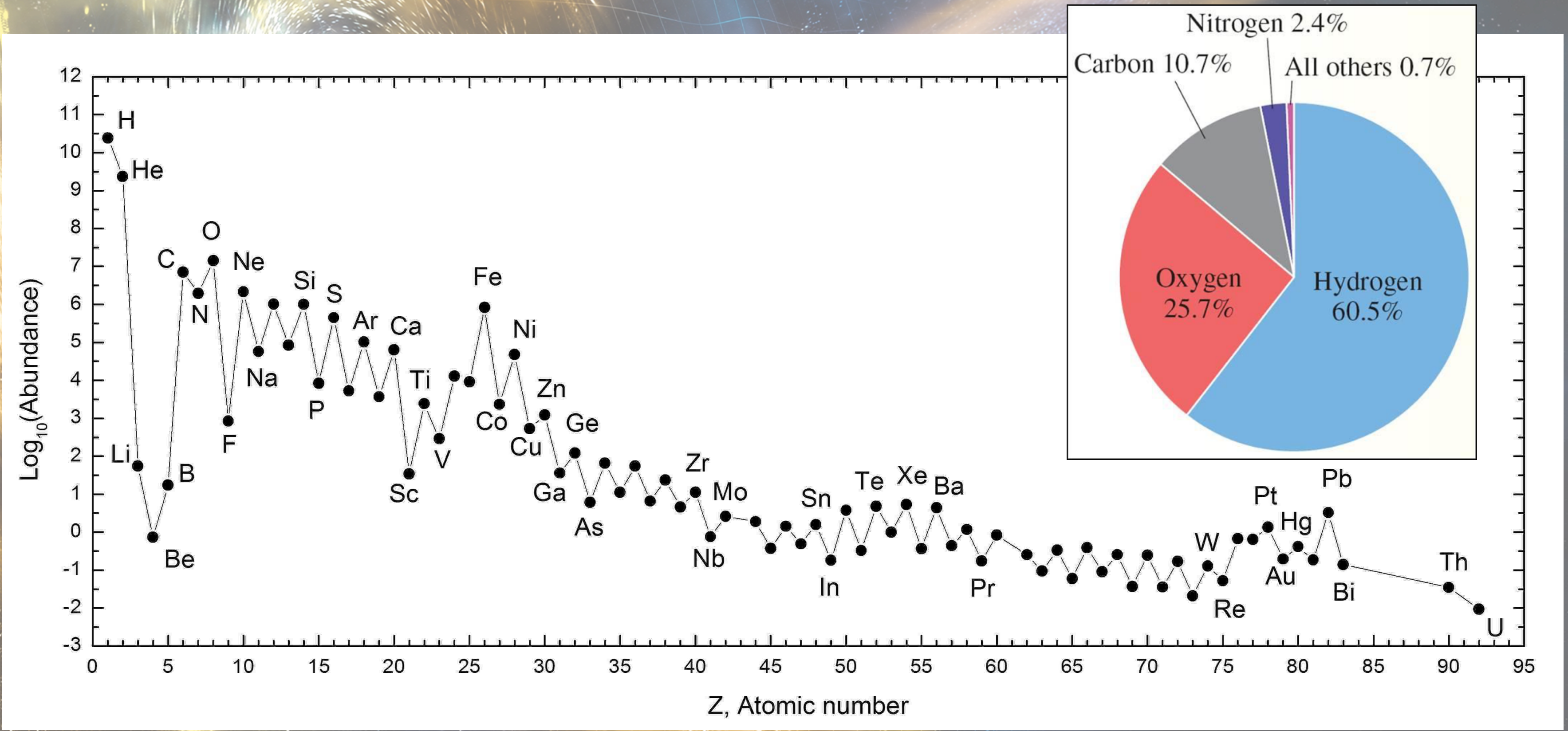
New experimental approaches for constraining neutron capture cross sections in exotic nuclei

Dennis Mücher
University of Guelph + TRIUMF

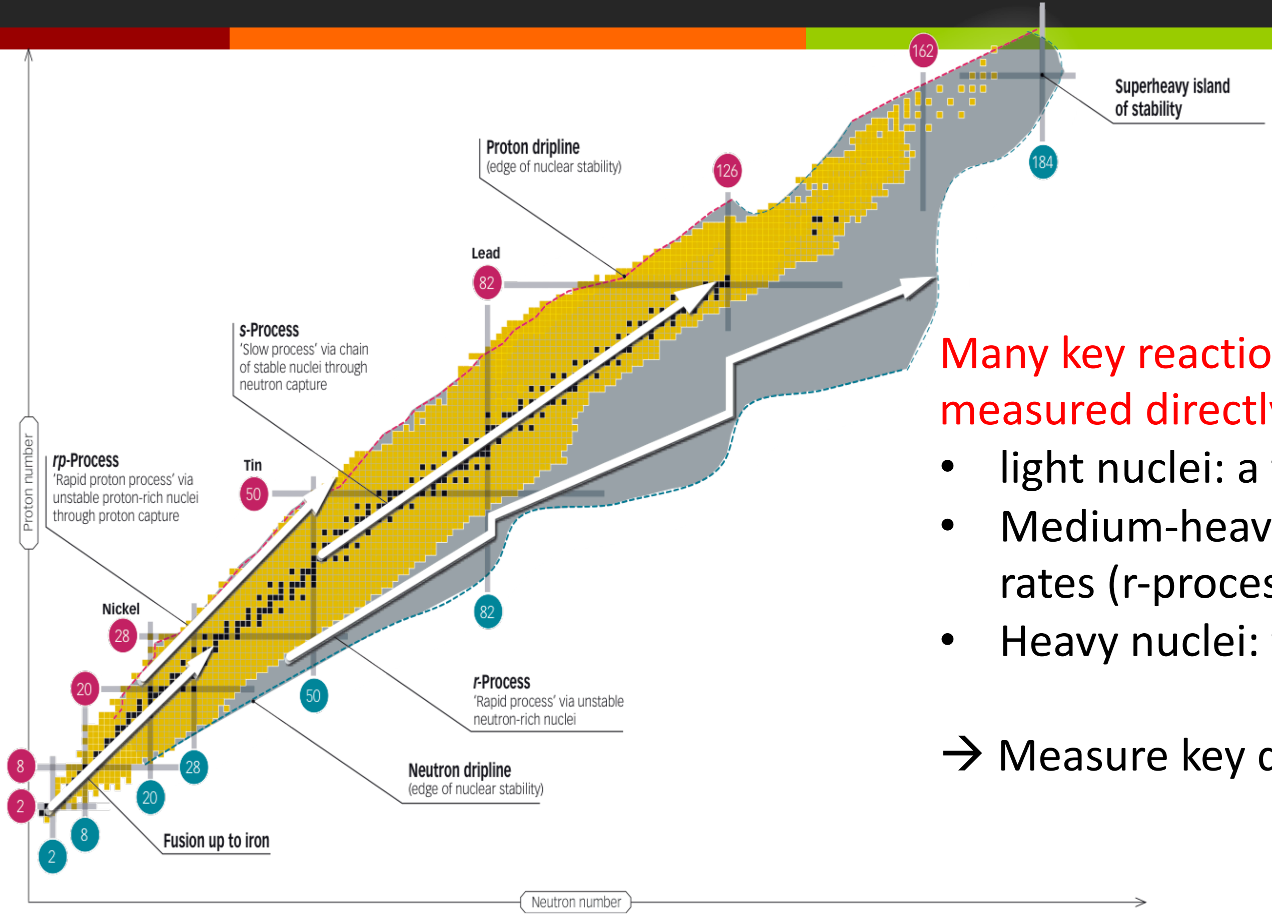


Abundance distribution in the Solar System



Overview: Nucleosynthesis

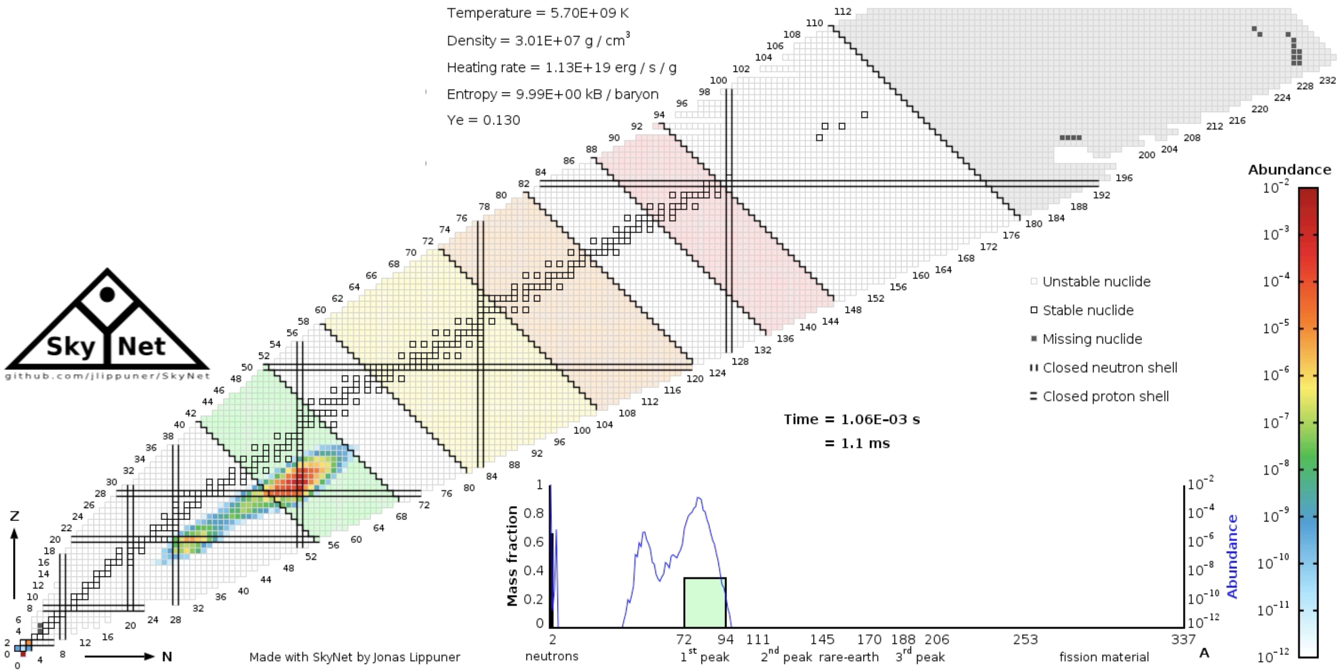


Many key reaction rates cannot be measured directly

- light nuclei: a few key resonances
- Medium-heavy nuclei: neutron capture rates (r-process)
- Heavy nuclei: fission along r-process

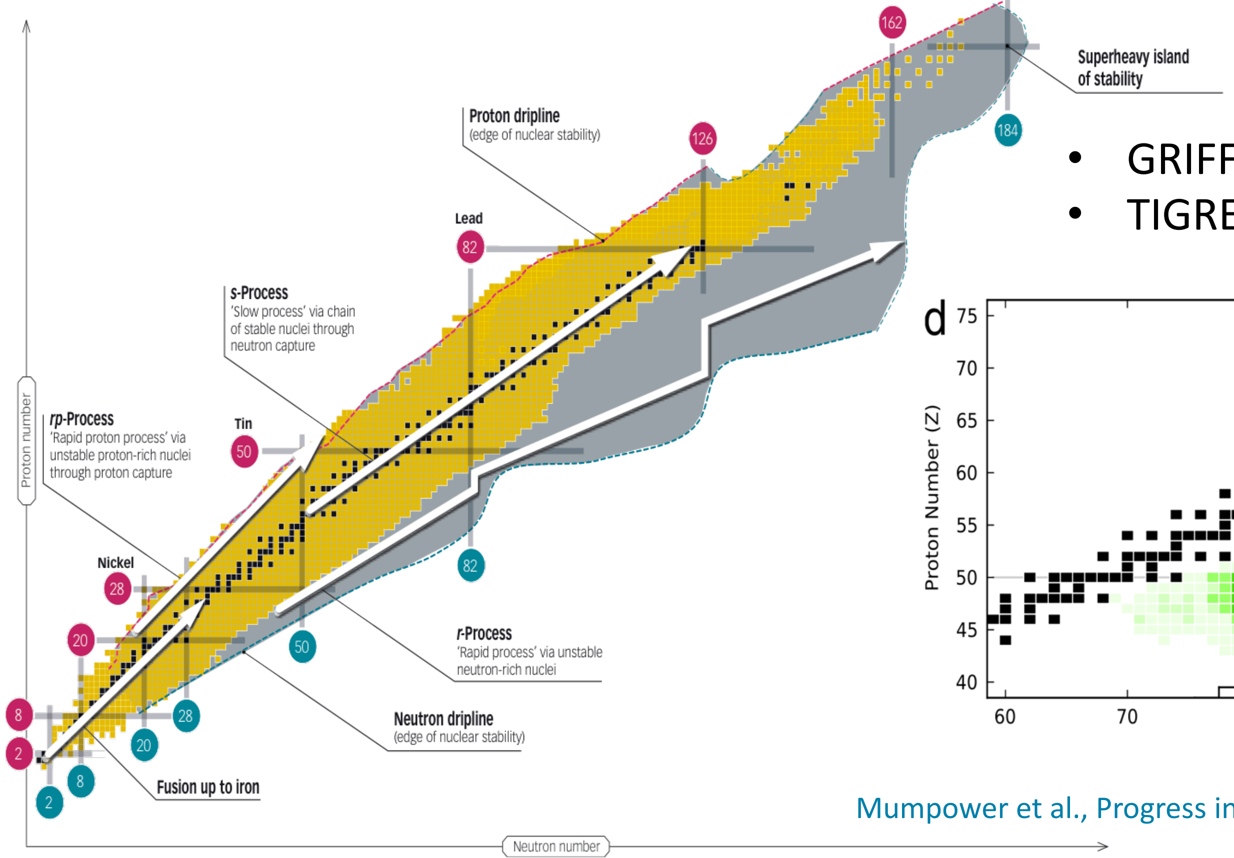
→ Measure key data + improve models

The r-process in action

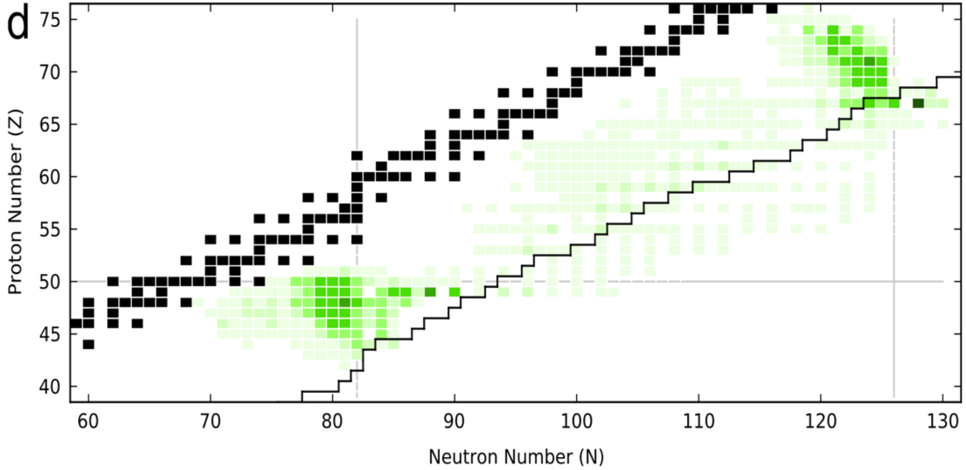


Made with SkyNet by Jonas Lippuner

Do we need to measure ALL of them?

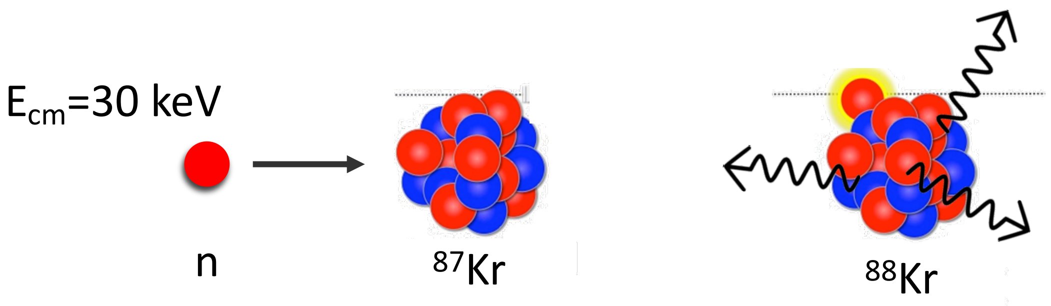


- GRIFFIN: $T_{1/2}$ and β-delayed neutrons
- TIGRESS: neutron capture rates



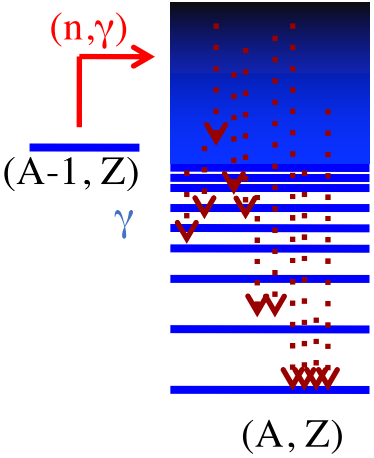
Mumpower et al., Progress in Particle and Nuclear Physics 86 (2016) 86–126

How to constrain neutron capture rates?



- Neutron capture rate measurements: (quasi)-stable nuclei, only!

Maybe we can calculate it?



Hauser – Feshbach

- Nuclear Level Density

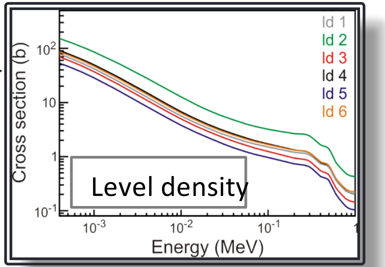
Constant T+Fermi gas, back-shifted Fermi gas, superfluid, semi-microscopic, …

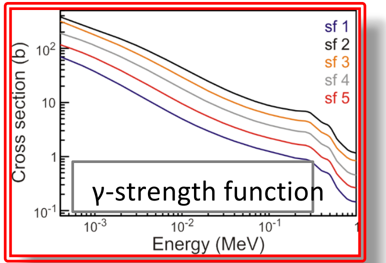
- γ-ray strength function

Generalized Lorentzian, Brink-Axel, …

- Optical model potential

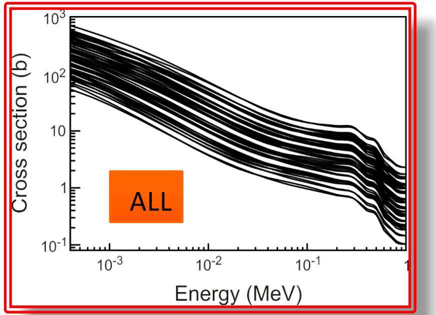
Phenomenological, Semi-microscopic

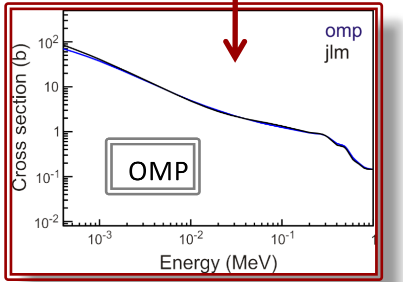




$^{95}Sr(n,\gamma)^{96}Sr$

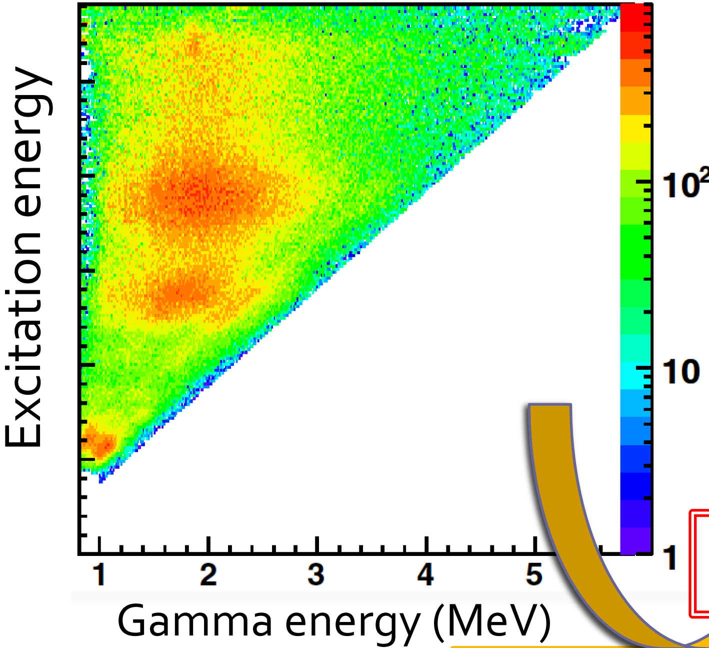
TALYS

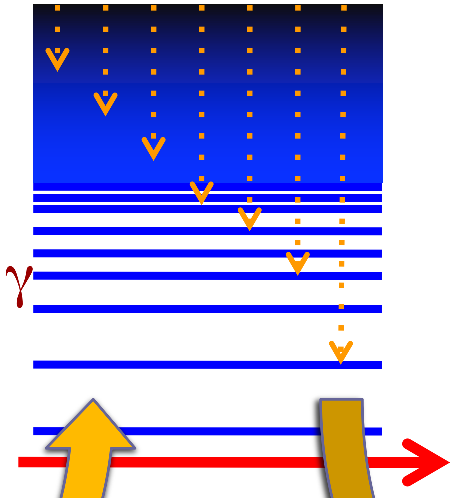




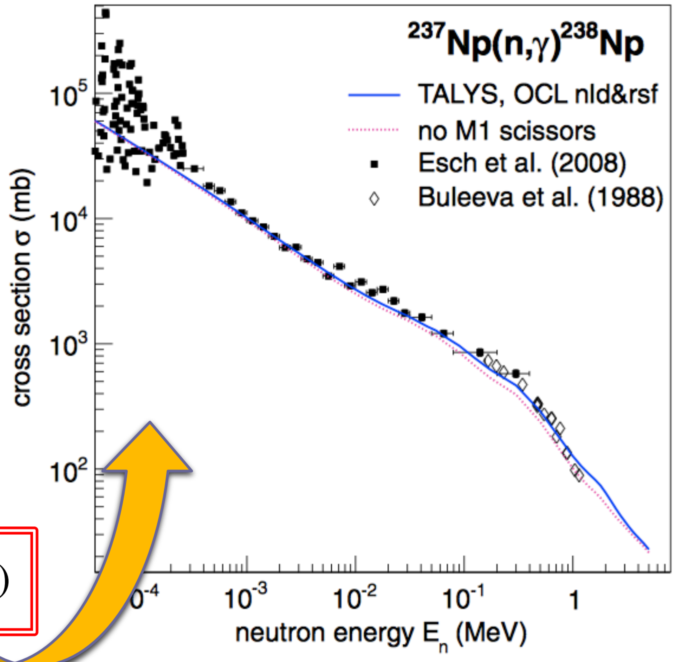
credit A. Spyrou, NSCL

The Oslo Method





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



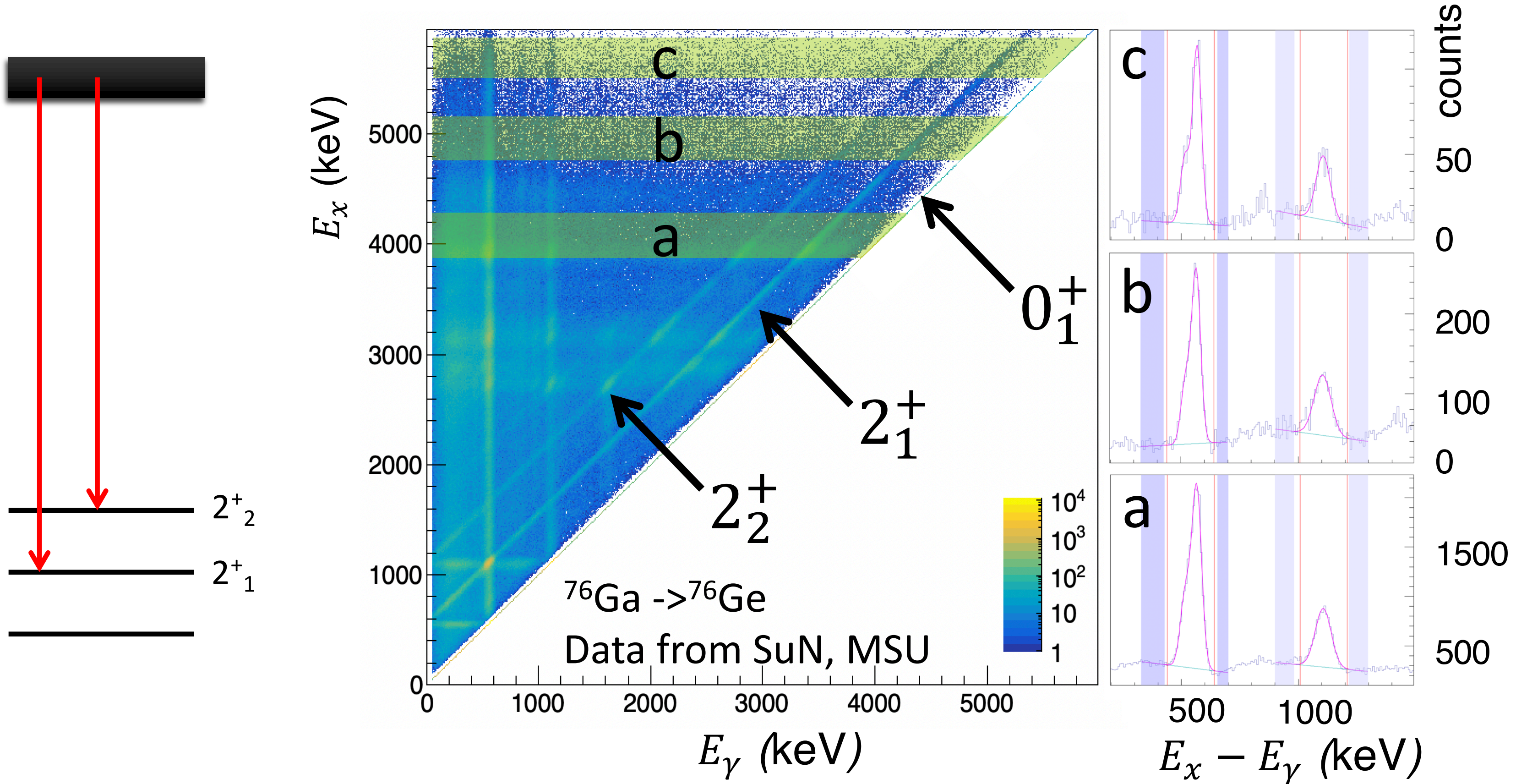
Unfolding
Iterative subtraction

Normalization

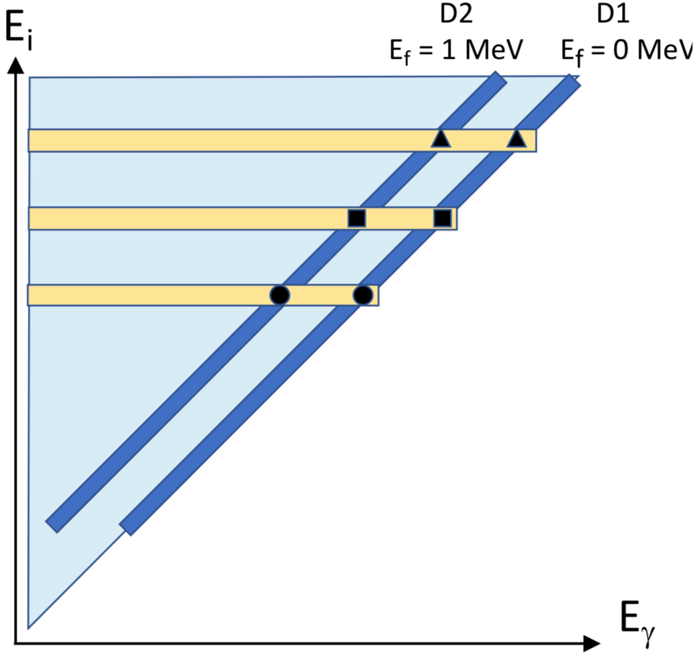
T.G. Tornyi, M. Guttormsen,et al., PRC2014

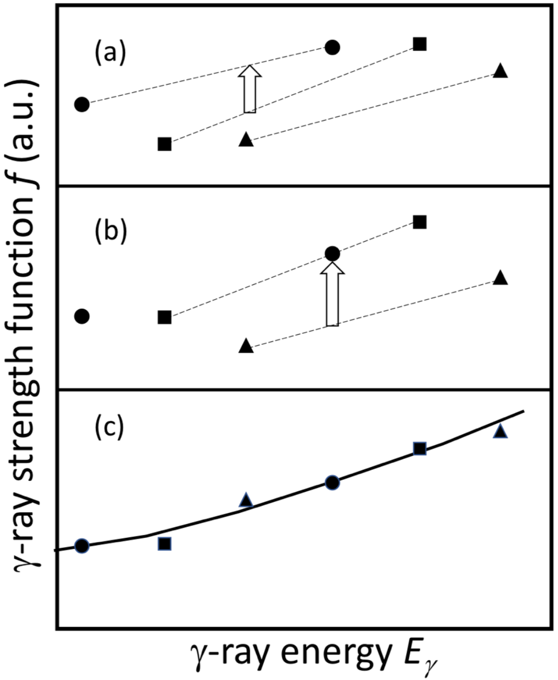
credit A. Spyrou, NSCL

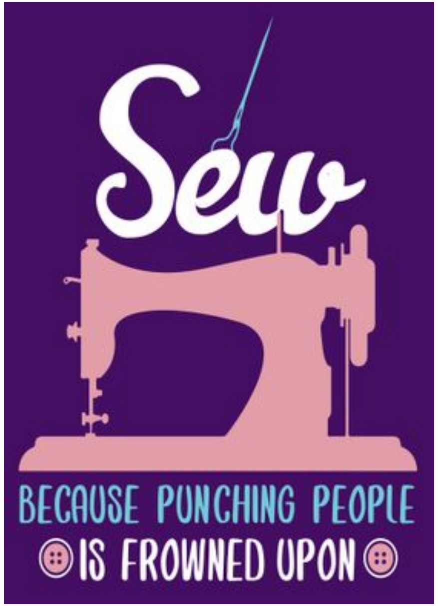
A model-independent approach to gSF



The “sewing” method

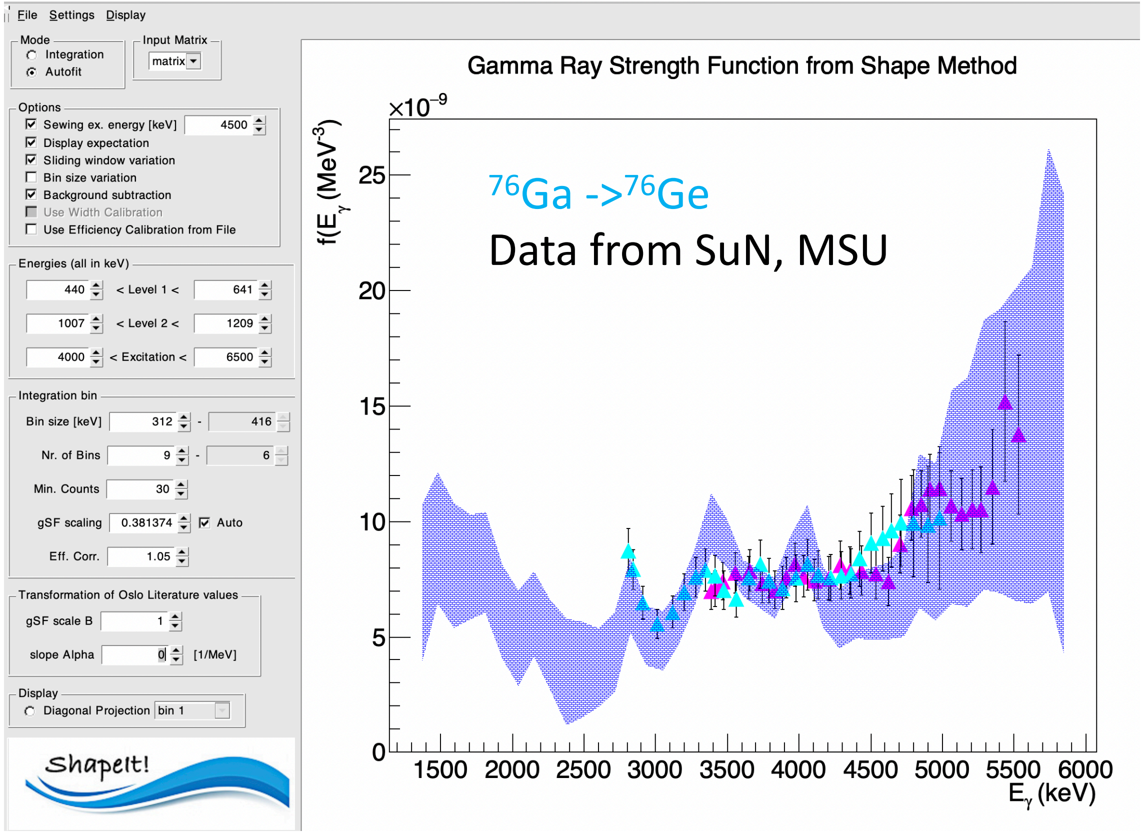




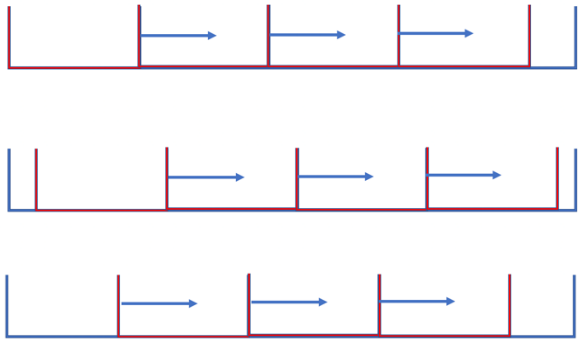


M. Wiedeking, M. Guttormsen et al, submitted to Phys. Rev. C (12/2020)
arXiv:2010.15696 (physics)

ShapeIt!



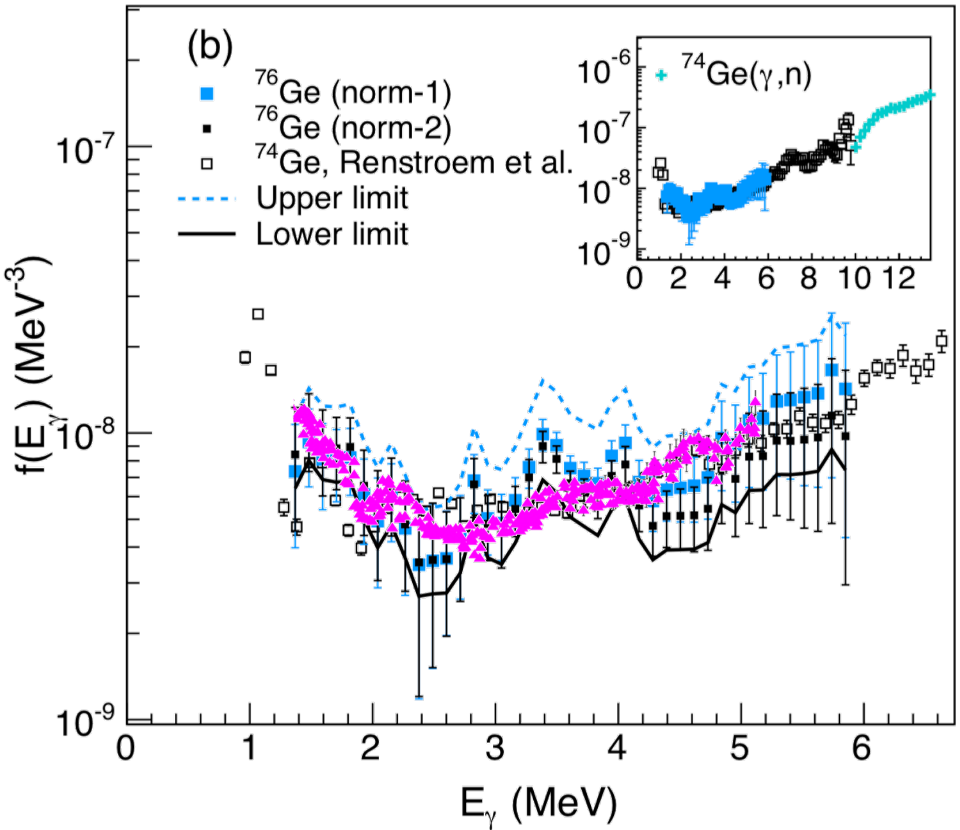
- Analysis Software “ShapeIt”:
- Sliding window variation



- Effect of integration bin size
- Peak fitting
- Chi2 minimization of “slope”

https://github.com/dennismuecher/ShapeIt

Did it work? Yes!

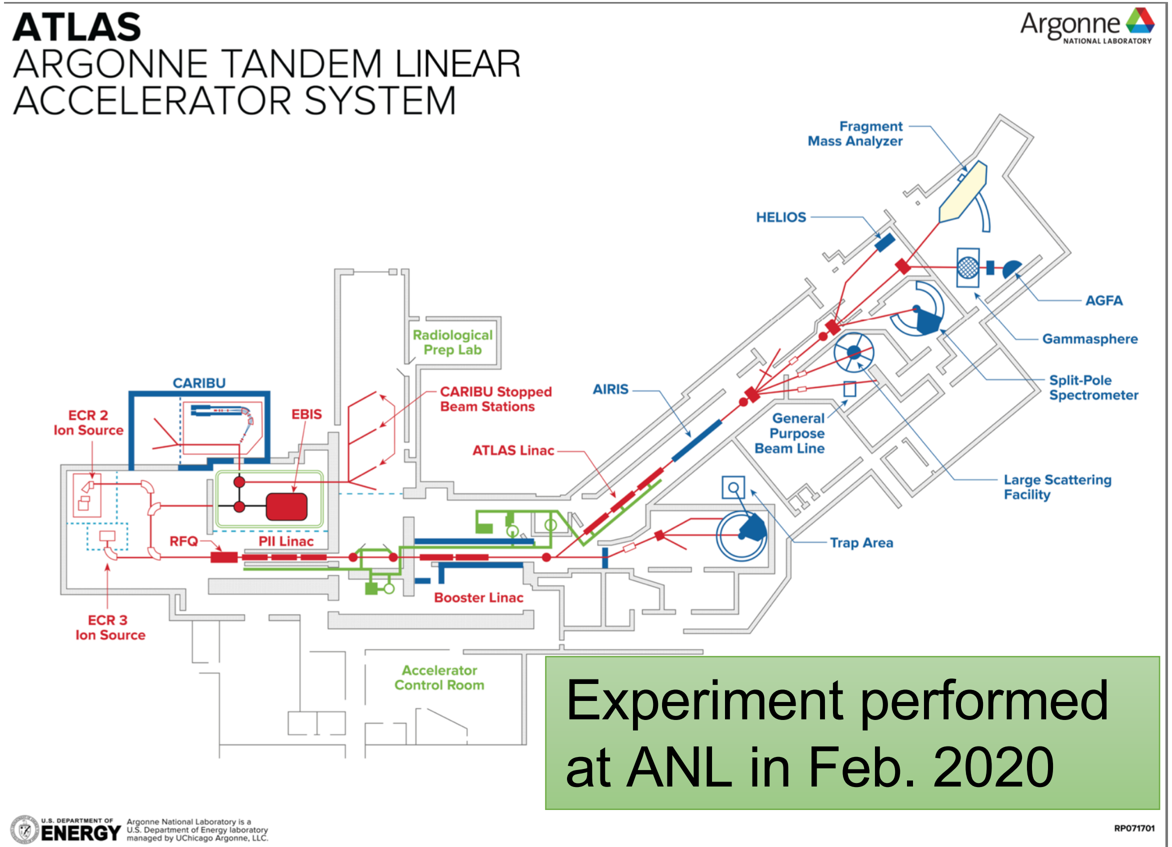


- Good match with previous results
- Model-independent "shape" of the gSF
- Absolute normalization still required

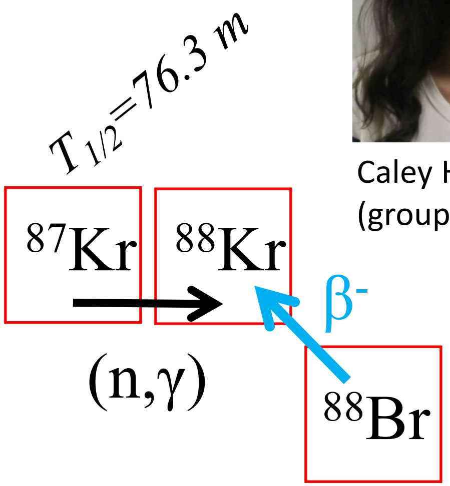
D.M, A. Spyrou et al,
submitted to Phys. Rev. Lett (12/20)

arXiv:2011.01071 (nucl-ex)

Decay into ^{88}Kr: CARIBU@ANL



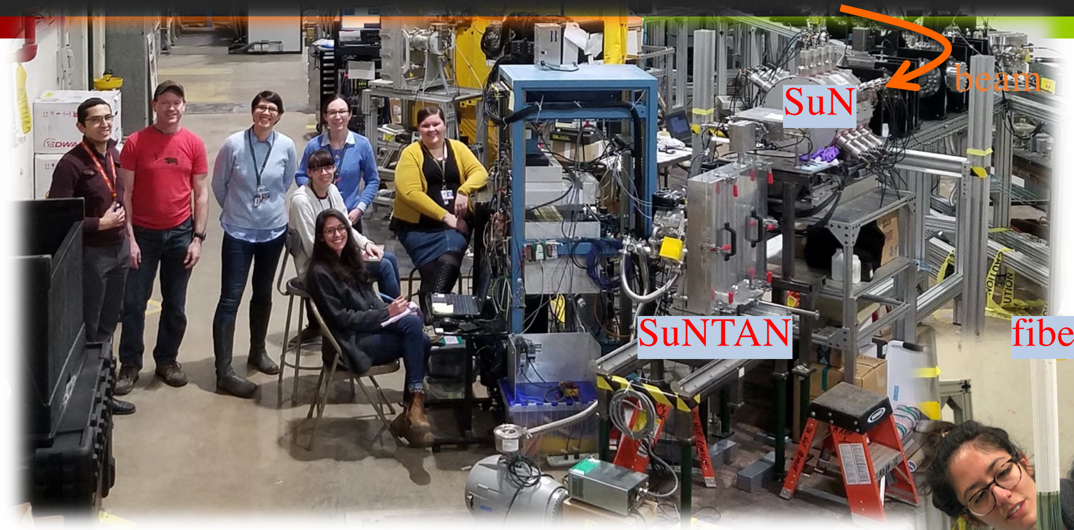
Experiment performed at ANL in Feb. 2020

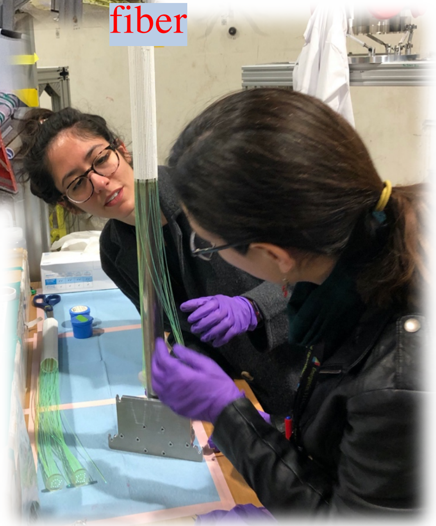


Caley Harris thesis (group A. Spyrou)

PI: Stephanie Lyons, PNNL

Setup: SuN@ANL





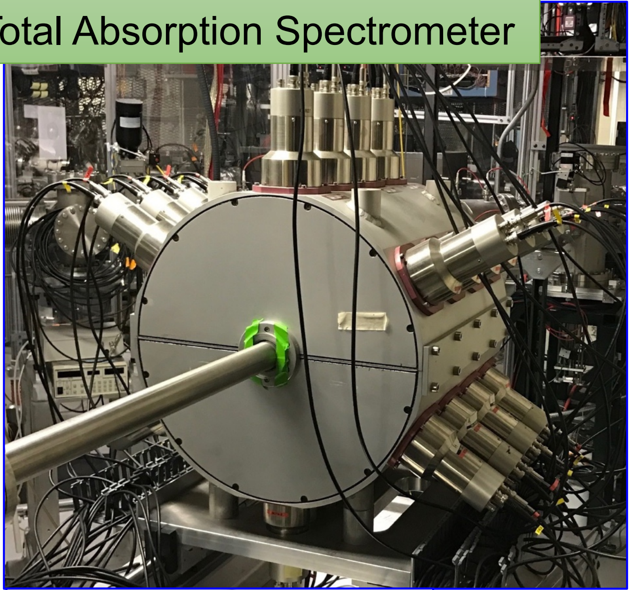
- Nov. 2019: SuN moved to ANL
- Feb. 2020: Commissioning
- Feb. 2020: First experiment

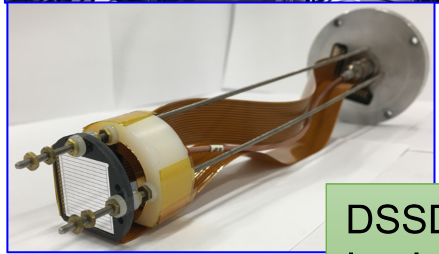
  $^{87\text{-}89}Kr(n,\gamma)^{88\text{-}90}Kr$

  PI: Stephanie Lyons, PNNL

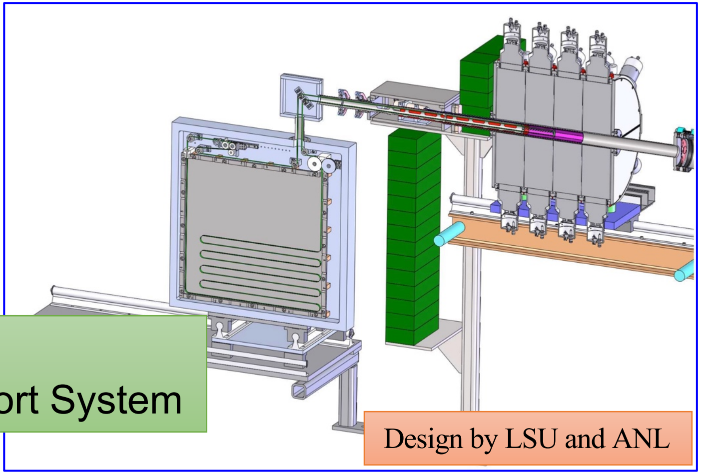
Beta-Oslo setup at NSCL (Slide by Artemis Spyrou)

SuN
γ-Total Absorption Spectrometer



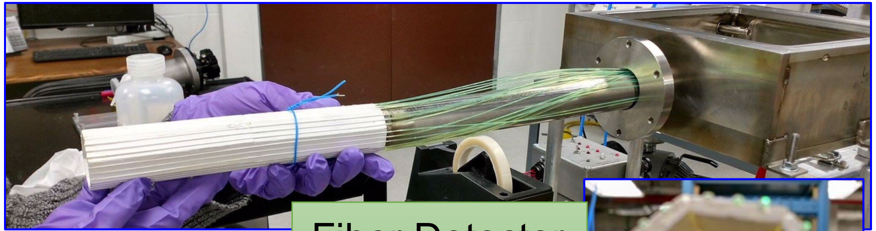


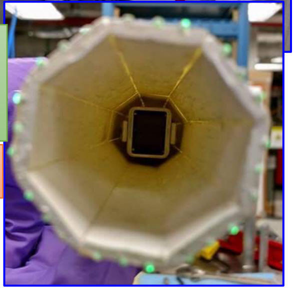
DSSD
Implantation-decay correlation



SuNTAN
Tape Transport System

Design by LSU and ANL

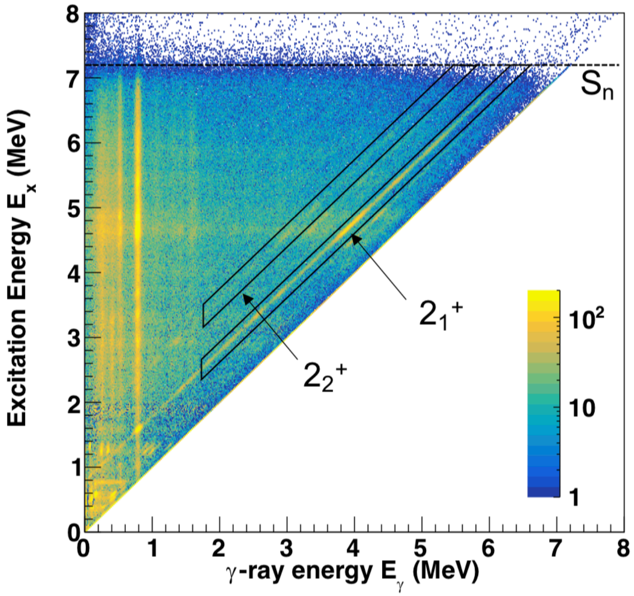


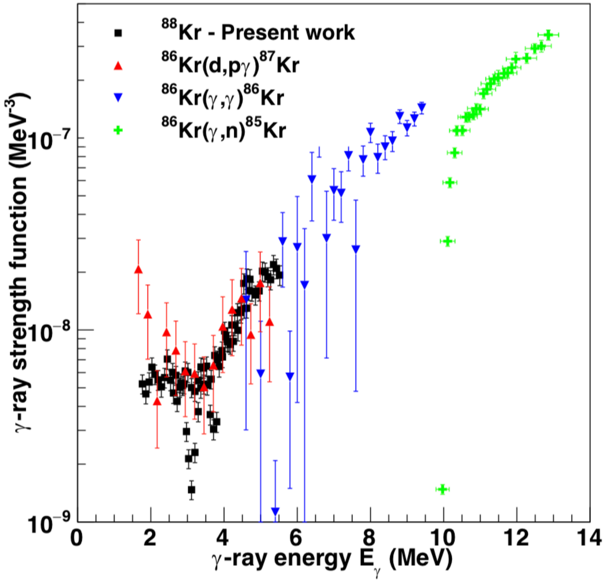


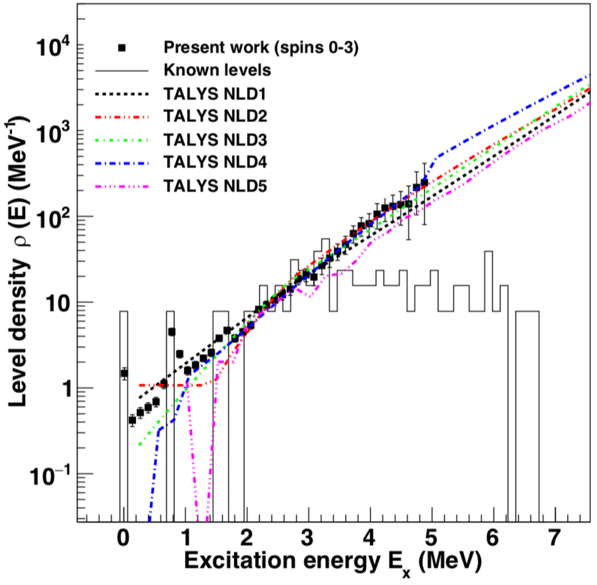
Fiber Detector
β-detection

Hope College

First case for an unstable nucleus!







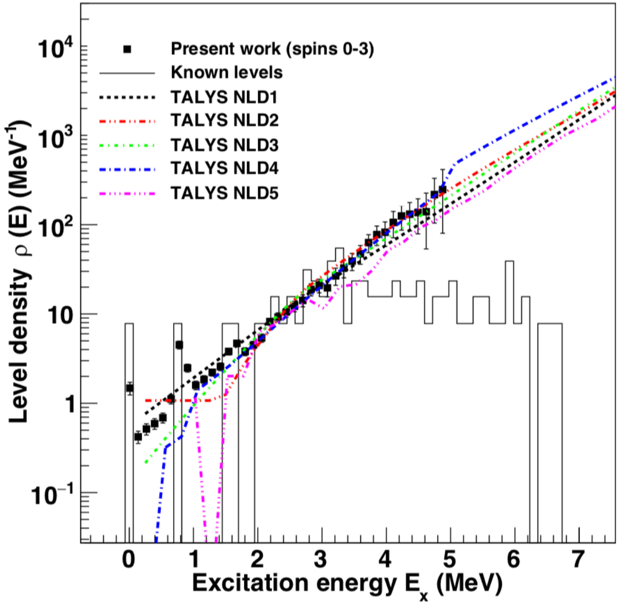
D.M, A. Spyrou et al,
submitted to Phys. Rev. Lett (12/20)
arXiv:2011.01071 (nucl-ex)

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

→ Absolute level density!

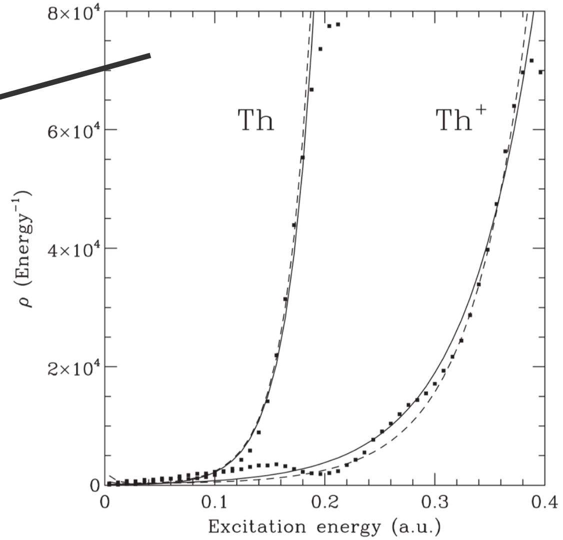
The absolute nuclear level density

"The nuclear level density is a key ingredient for understanding nuclear reactions in the laboratory, in technological applications, and in nucleosynthesis studies"
S. Karampagia, V. Zelevinsky: Int. J. Mod. Phys. E DOI: 10.1142/S0218301320300052



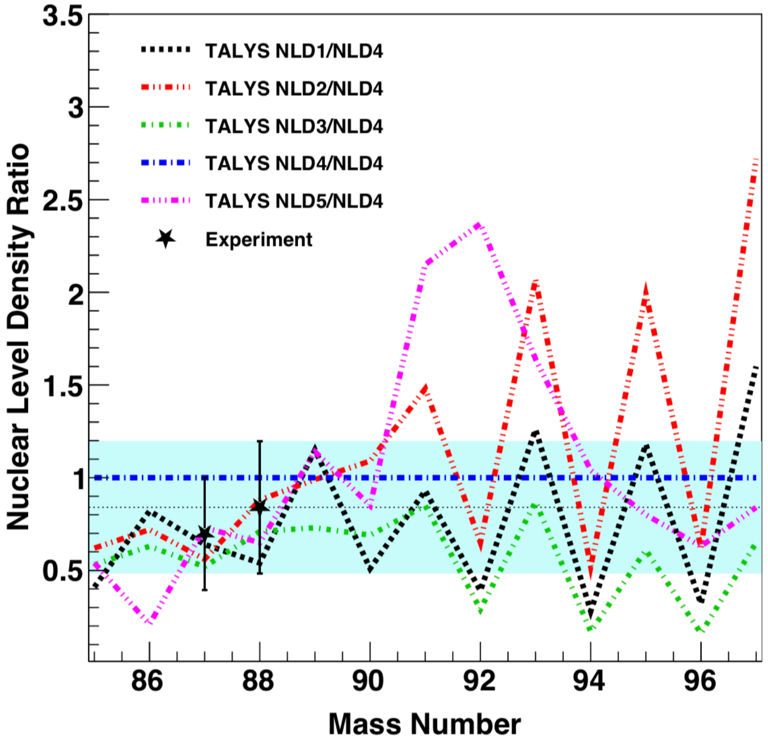
D.M, A. Spyrou et al, submitted to Phys. Rev. Lett (12/20)

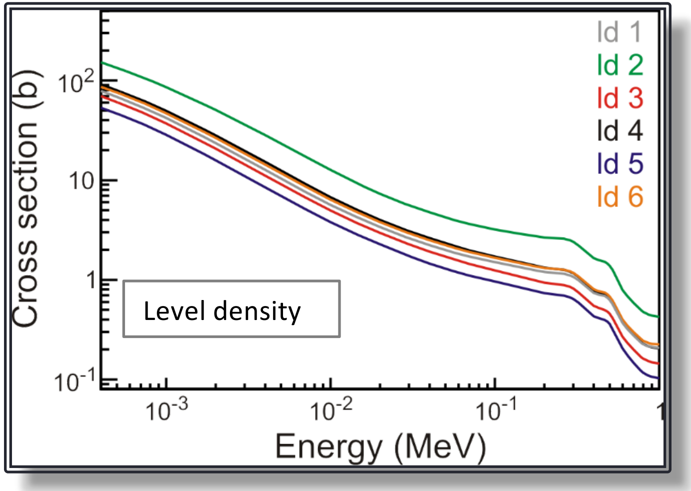
level density in Th atoms behaves statistical
→ important for nuclear clock



V. A. Dzuba and V. V. Flambaum
PRL 104, 213002 (2010)

Astrophysics: Are we sensitive enough?



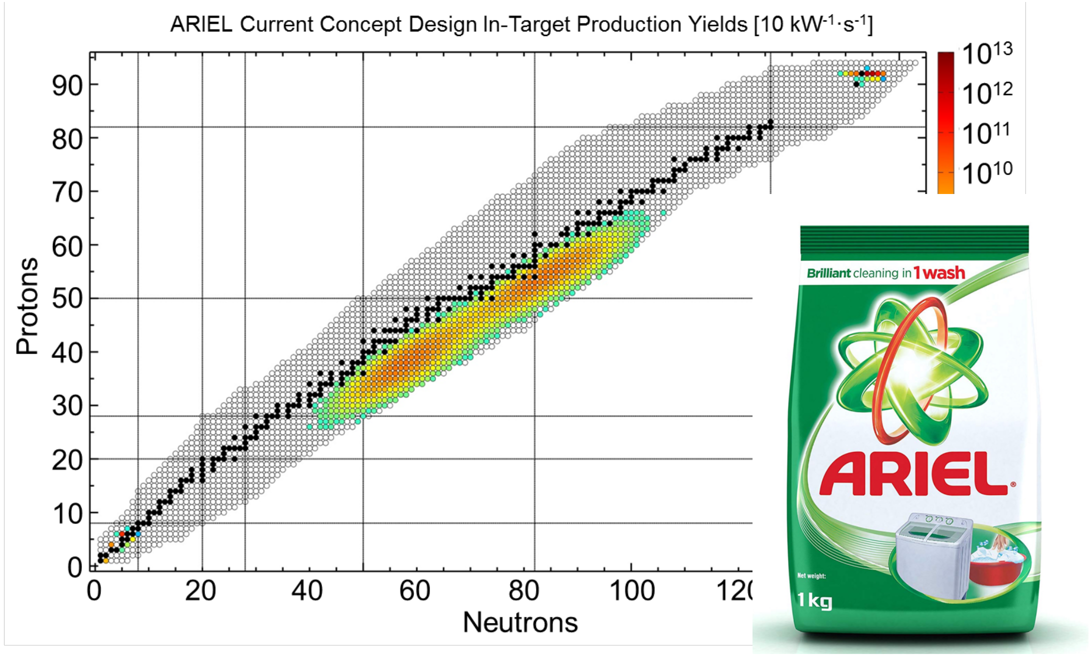


→ we can discriminate between different models used in nucleosynthesis simulations

D.M, A. Spyrou et al, submitted to Phys. Rev. Lett (12/20)

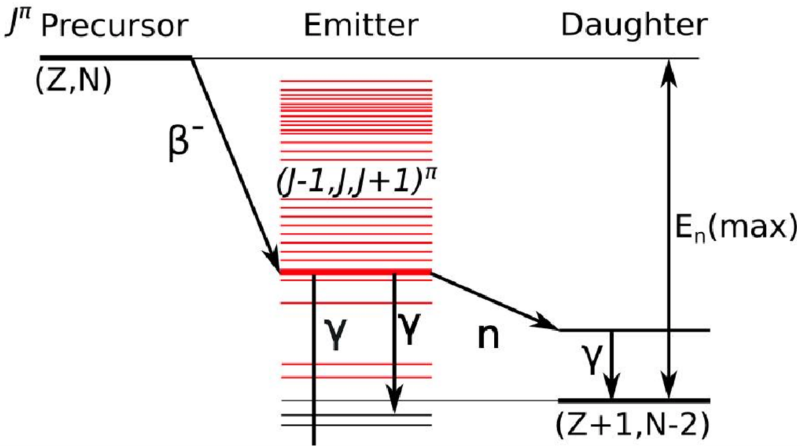
Future: ARIEL beams

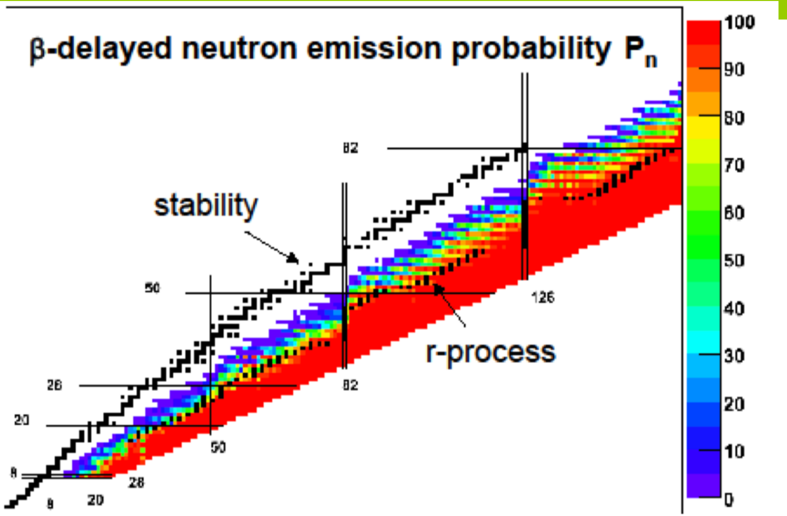
- Very competitive beam intensities expected around ^{132}Sn region
- ISAC-I: beta-decay
- ISAC-II: 6 MeV/u ideal for one-neutron-transfer
- High resolution gamma ray spectroscopy, specially compared to TAS



First significant improvement on its way: CANREB ion source

Experimental challenges





- Values for P_n presumably very large for almost all relevant r-process cases
- Current TAS instruments do not allow for event-by-event neutron-gamma discrimination
- MTAS (ORNL) can identify the presence of neutrons and are working on improvements towards better discrimination

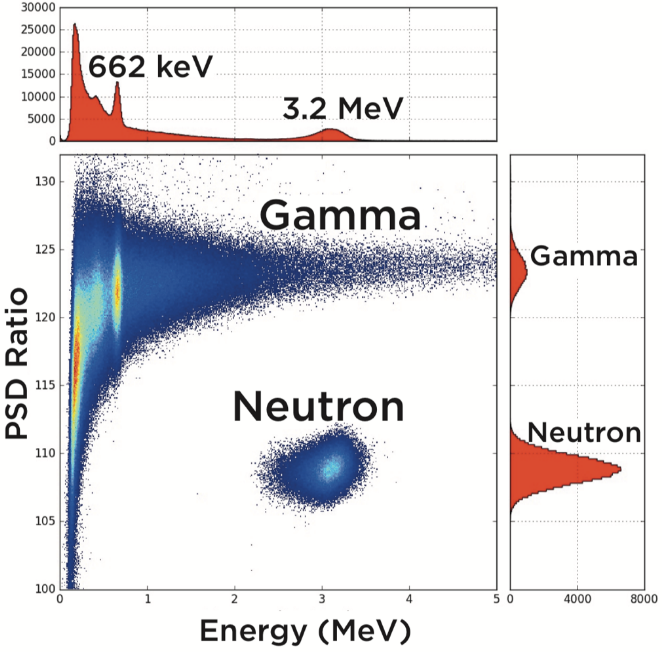
A Total Absorption Spectrometer for ISAC?

Wishlist for a dedicated ISAC-TAS:

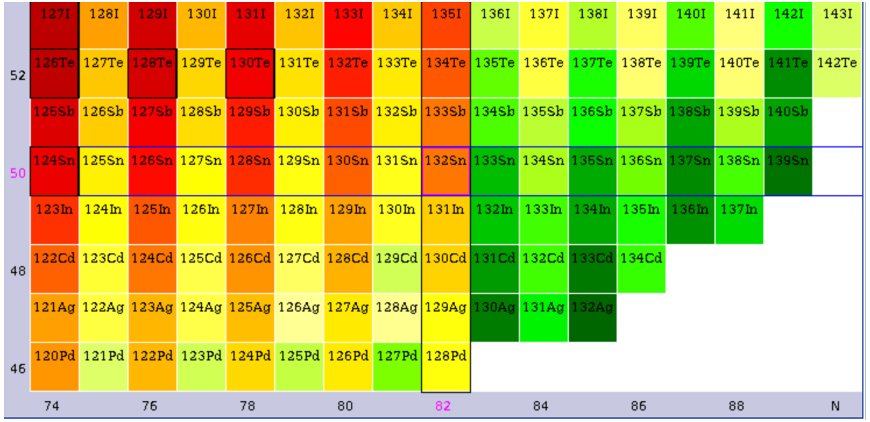
- Basic design like existing TAS devices (SuN, MTAS)
- Tape system critical (we have experience with this at TRIUMF)
- new: neutron identification, e.g. NaI(Tl+Li) crystals
- new: suppression of β-decay electrons:
    - Permanent magnetic inside the bore?
    - External magnetic field?
    - Extra, inner, detector layer?
- new: Phototubes → SiPMs

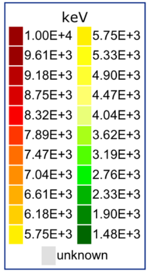
Next steps:

- Input from ISAC community: other potential uses for such a device?
- Level-0 design study, cost estimate ($2.5M?)
- Gate-0 review
- Do we have the manpower at TRIUMF and/or elsewhere?



Beta-decay has its limitations…

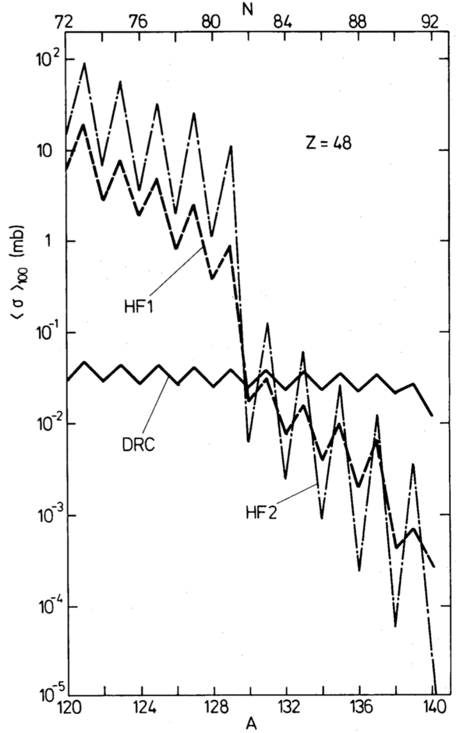




Nuclei "south-east" of ^{132}Sn are very weakly bound

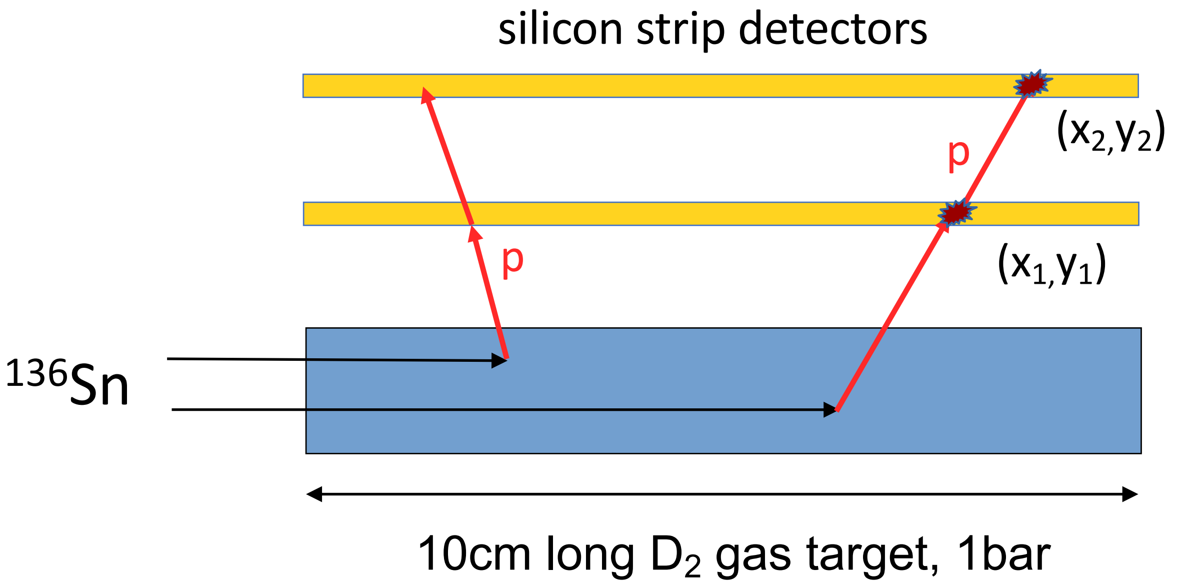
→ Low level density at S_n

→ Hauser Feshbach applicable?

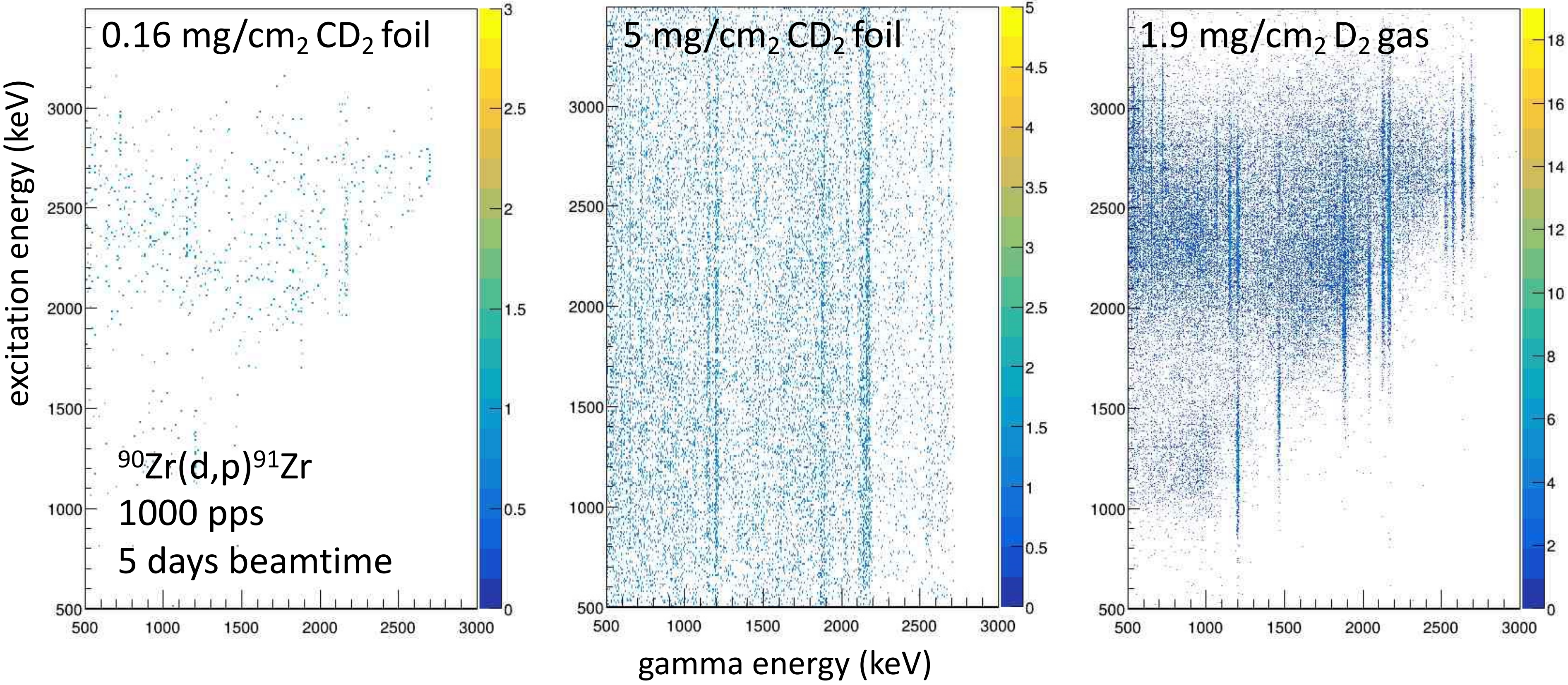


Mathews et al, Astrophysical Journal 270, 1983

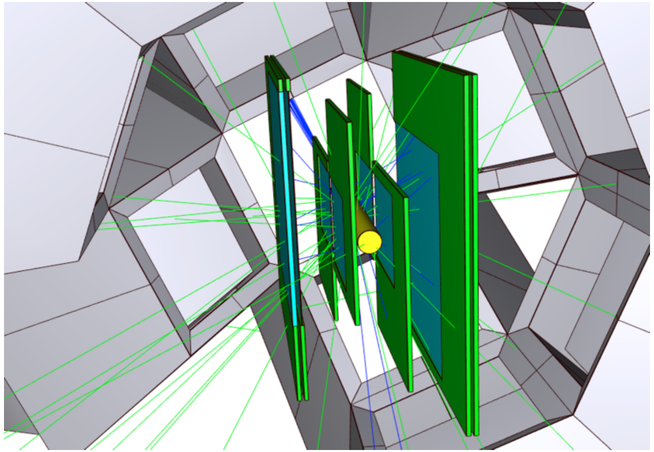
Idea:vertex tracking at ISOL energies using Si detectors



Oslo-method using TI-STAR and TIGRESS



Layout of TI-STAR

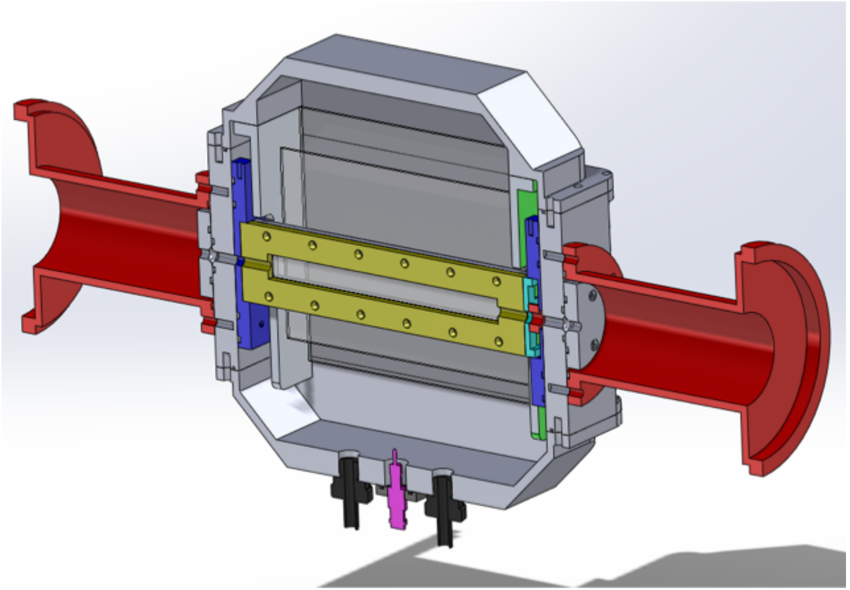


Geant4: TI-STAR + TIGRESS: Joseph Turko, UoG

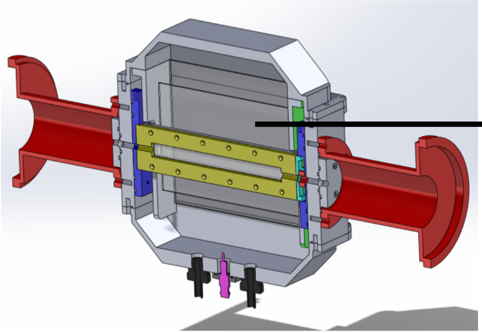
TI-STAR =
TIGRESS **S**ilicon **T**racker **AR**ray

Mechanical Design:

- Fred Sarazin (Colorado School of Mines)
- Robert Hendersson (TRIUMF)

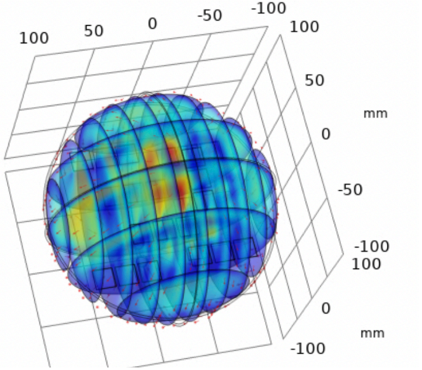


PCB Design SKIROC-2 ASICs



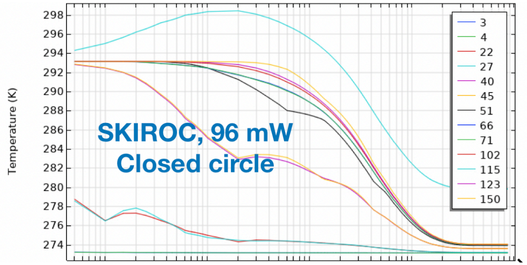
PCB Design: H. Behnamian, UoGuelph

- Fits into 20cm spherical scattering chamber
- ~3000 silicon channels
- SKIROC-2 delivers fully digital signal
- Custom-made FPGA board outside TI-STAR

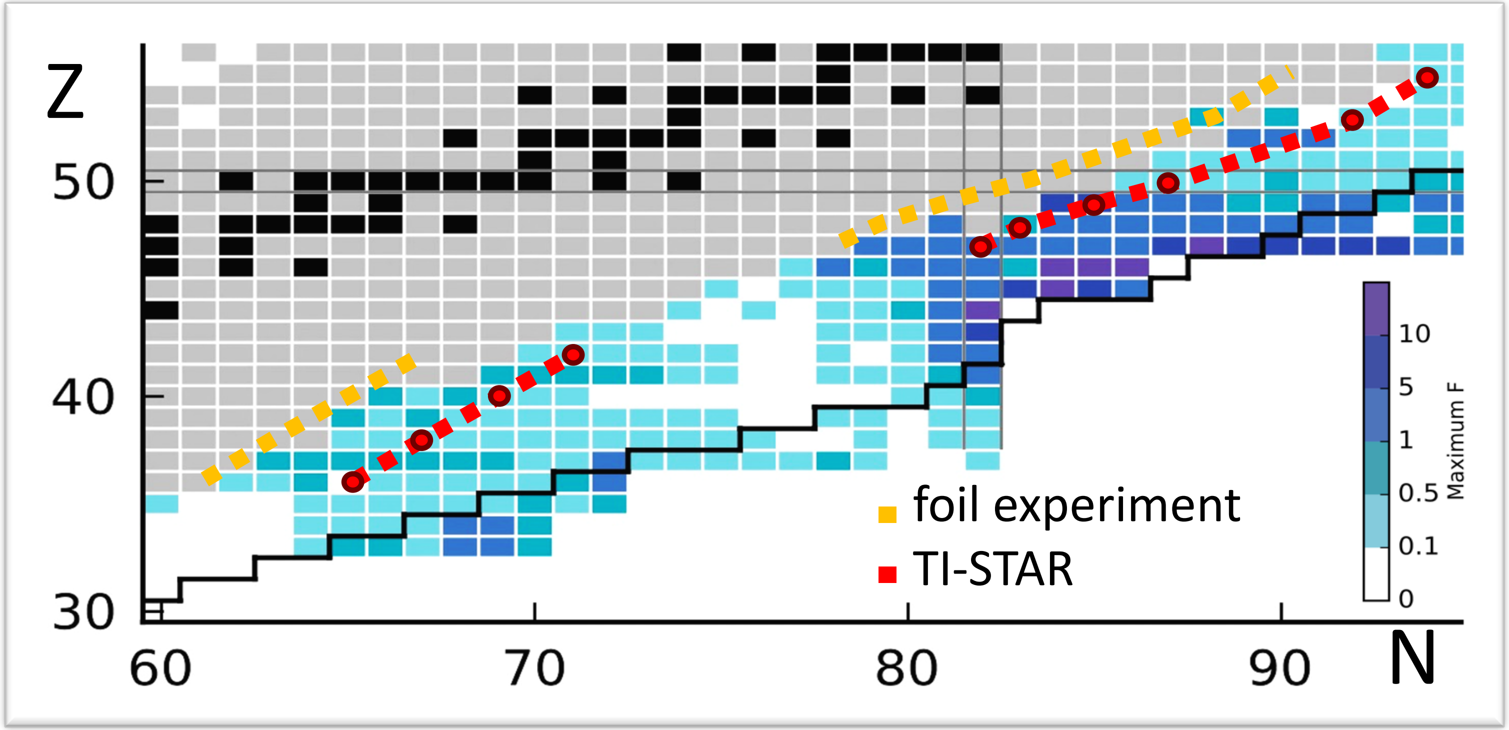


COMSOL

heat transfer simulation using 24 ASICs



Neutron capture rates accessible using ARIEL beams



adapted from Prog. Part Nucl Phys 86 (2016) 86-126

Summary+ Thank you to all the people

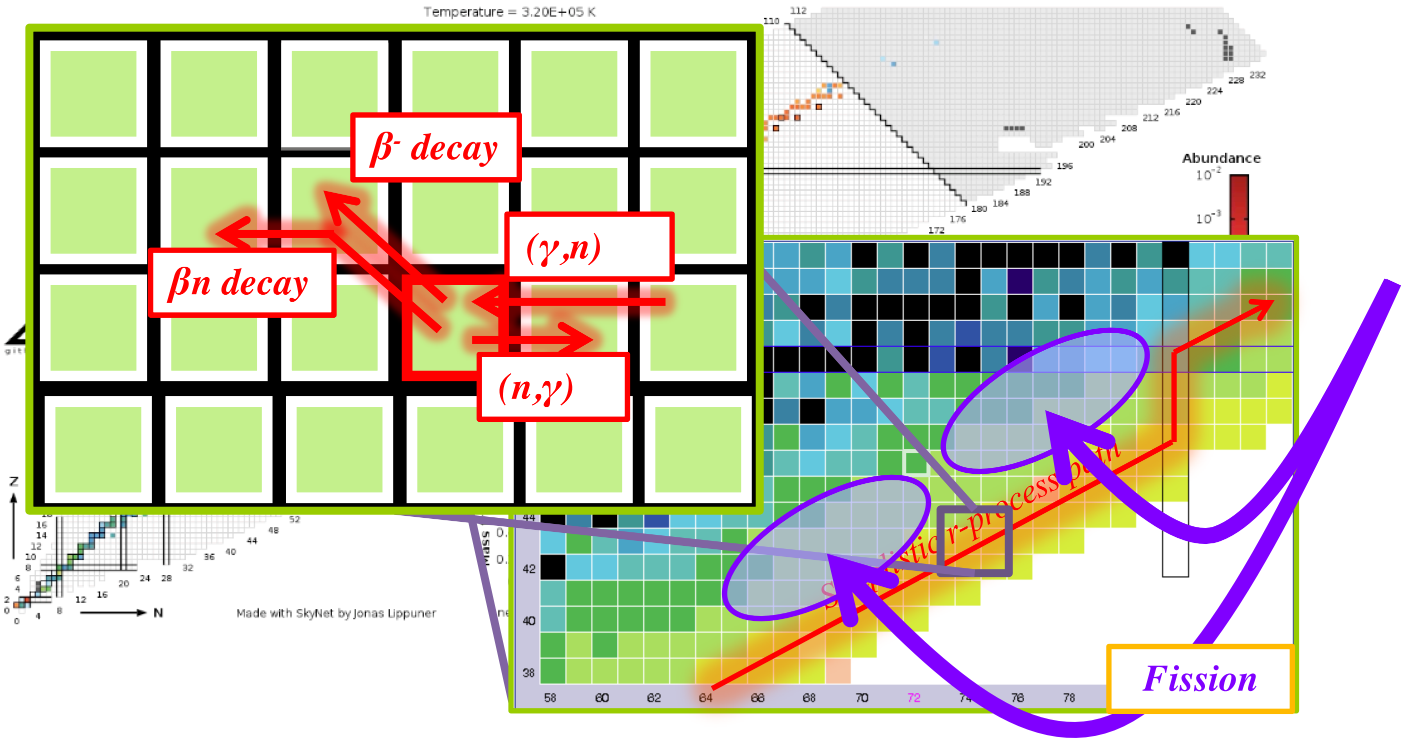
- Neutron capture rates are a critical input to pin down origin of r-process
- We are now able to constrain these rates far away from stability with reduced model dependence
- We also get access to the absolute nuclear level density

- Future experimental work:
  - TI-STAR @ ISAC-II (under construction)
  - TAS @ ISAC (early ideas)
  - Collaborations with ANL and FRIB

- Artemis Spyrou, NSCL
- SuN@ANL team
  - Stephanie Lyons (PI)
  - Caley Harris (PhD)
  - + all the group members
- CARIBU + ANL team: thank you!

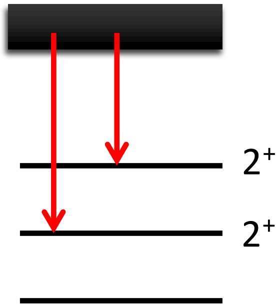
- TI-STAR team
  - Hadi Behnamian
  - Fred Sarazin
  - Vinzenz Bildstein
  - Beau Greaves

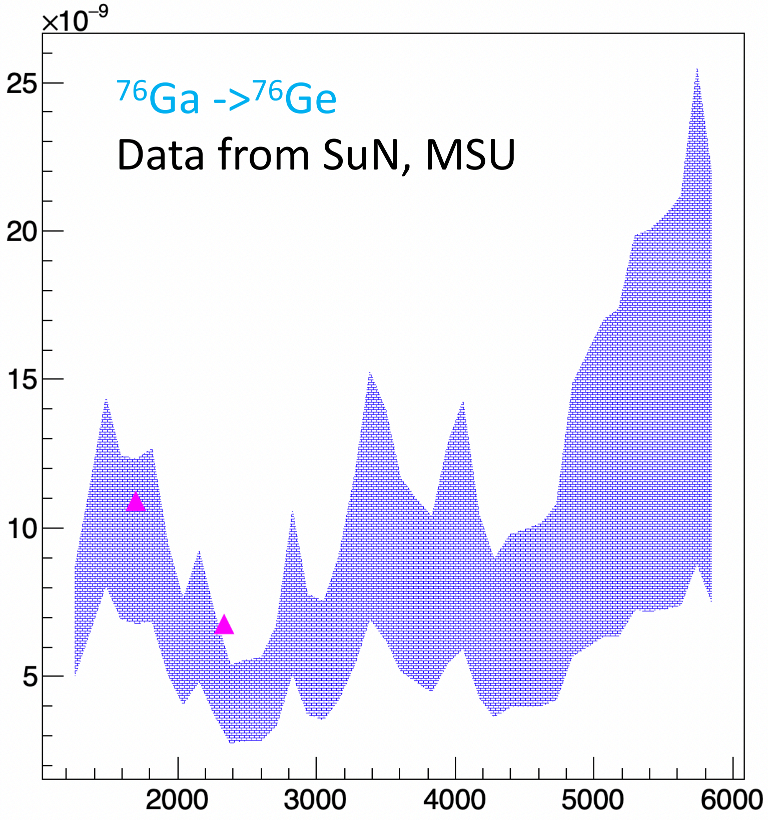
What is needed?



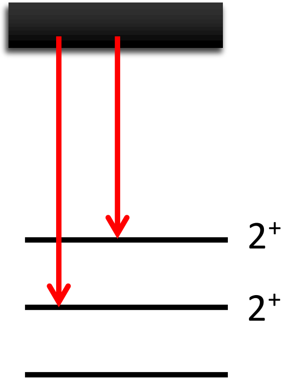
credit A. Spyrou, NSCL

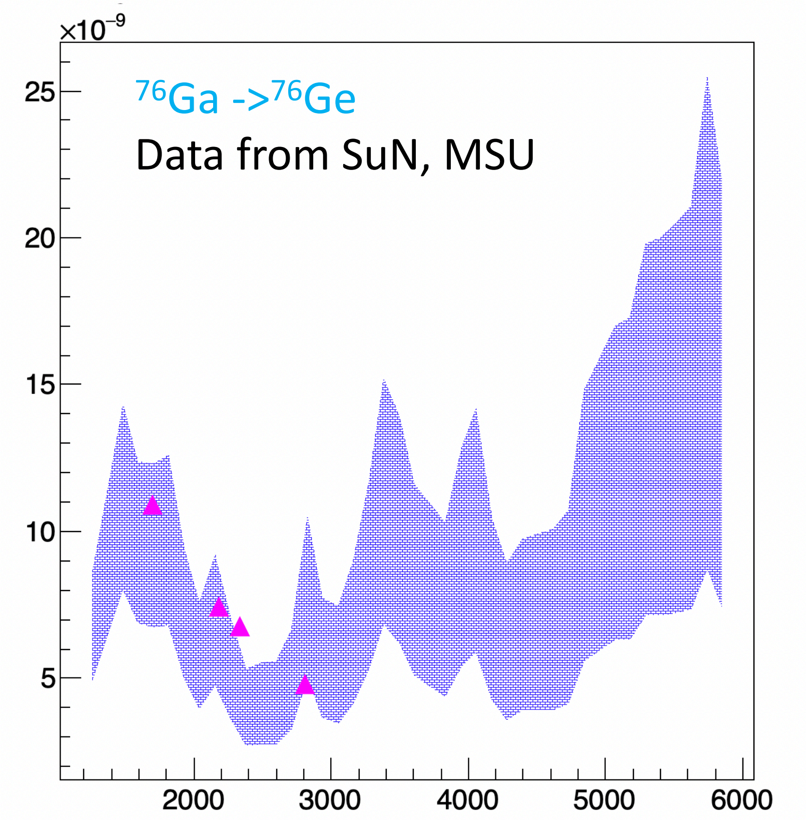
The "Shape method" for ^{76}Ge



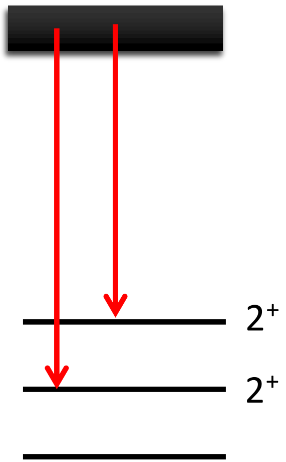


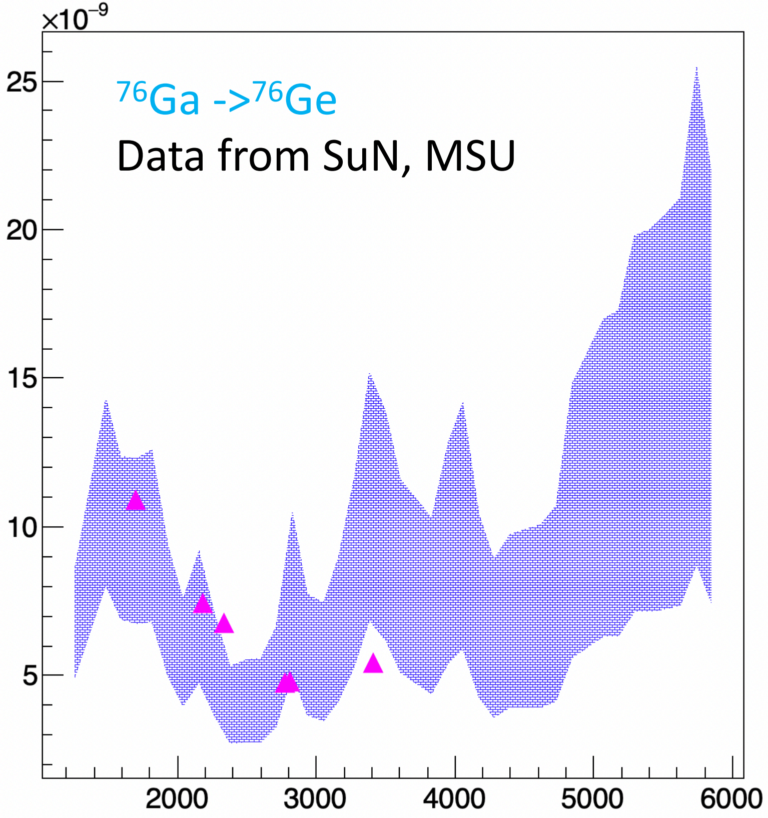
The "Shape method" for ^{76}Ge



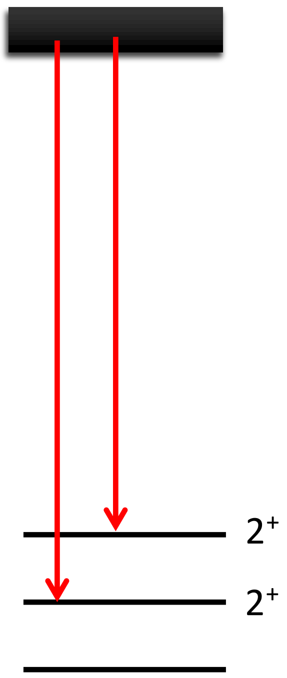


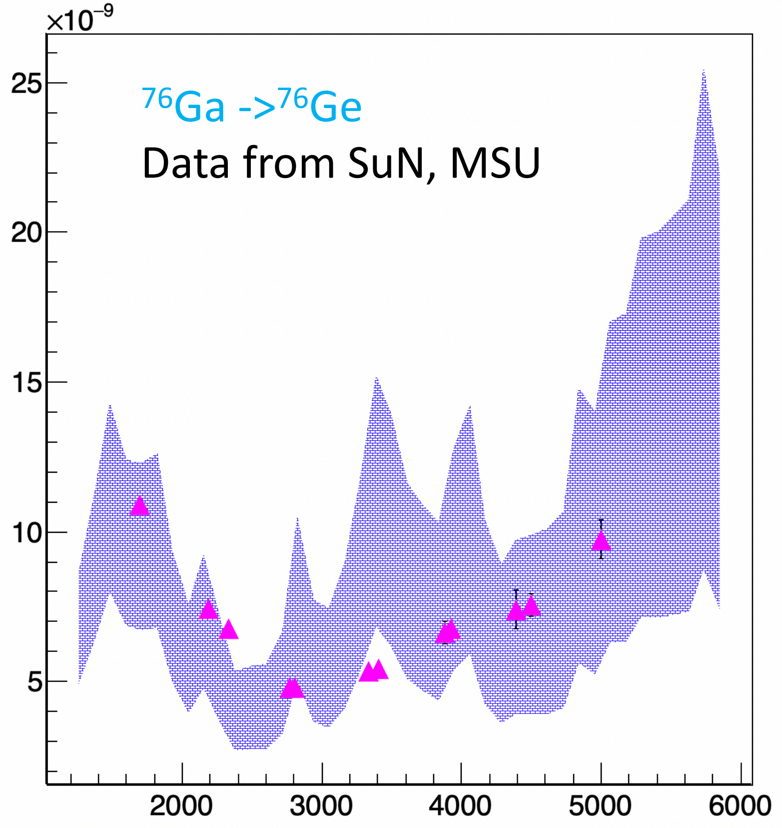
The "Shape method" for ^{76}Ge





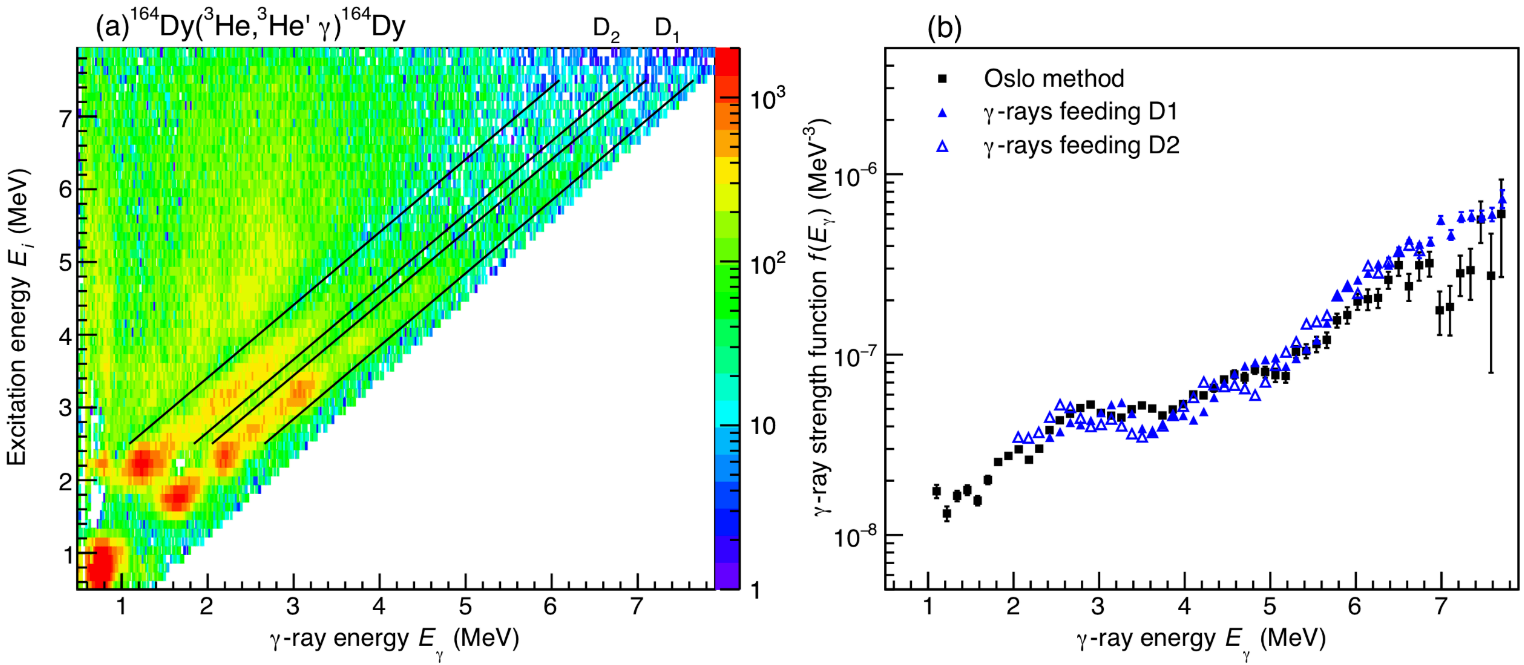
The "Shape method" for ^{76}Ge





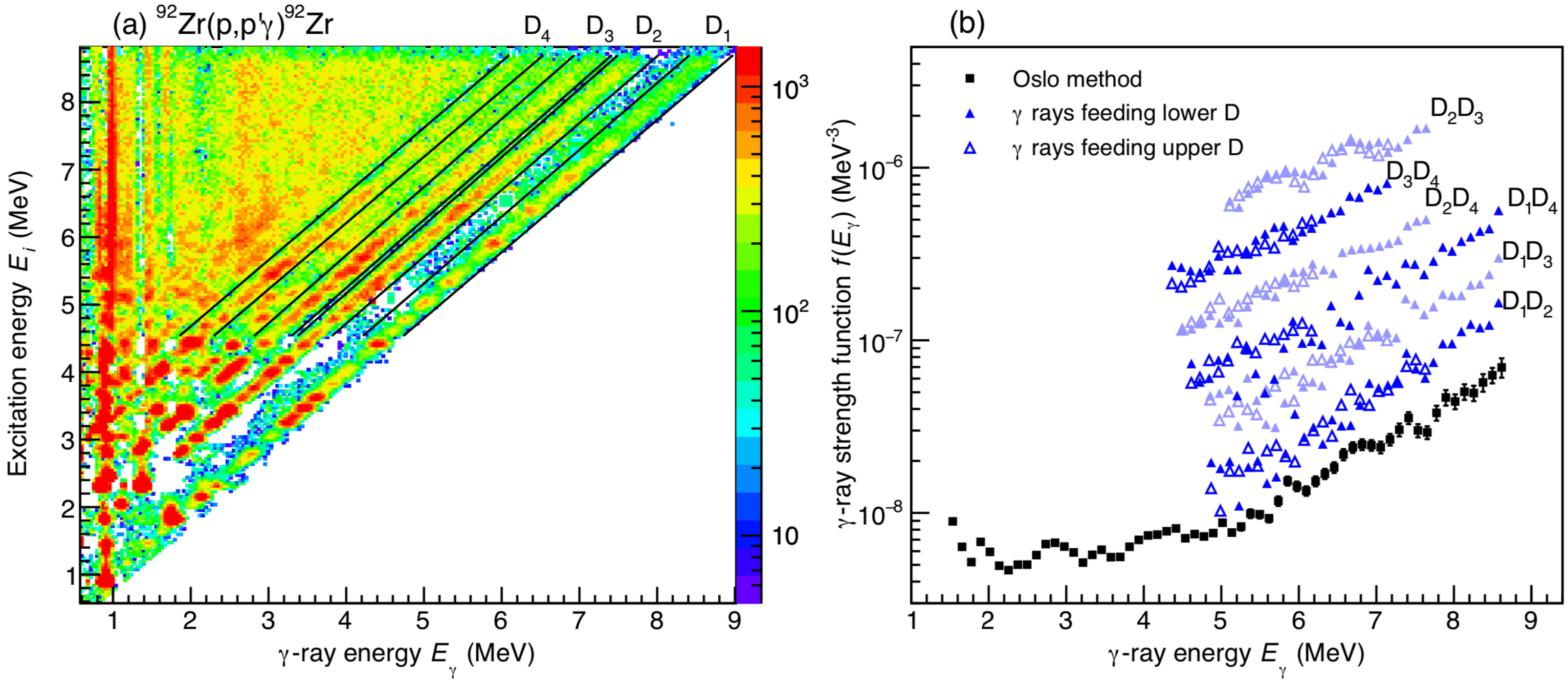
- Independent of D_0
- Does not require building "first generation" matrix
- Requires resolving two discrete low-lying states
- Two states with same spin and parity preferred

Maybe we just got lucky tough…



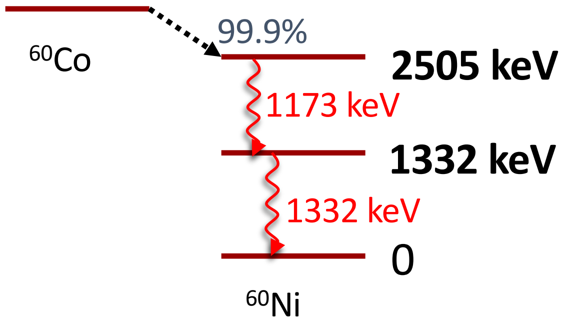
M. Wiedeking, M. Guttormsen et al, submitted to Phys. Rev. C (12/2020)
arXiv:2010.15696 (physics)

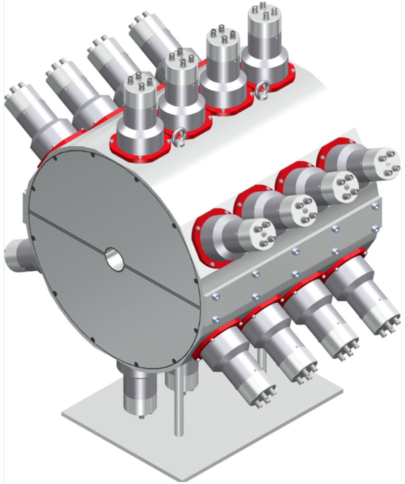
It works for multiple states! (it better…)



M. Wiedeking, M. Guttormsen et al, submitted to Phys. Rev. C (12/2020)
arXiv:2010.15696 (physics)

Total Absorption Spectrometry





SuN, NSCL