The level density and γ-ray strength function of ^{67}Ni

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NorCC Workshop 2022

The Research Council of Norway

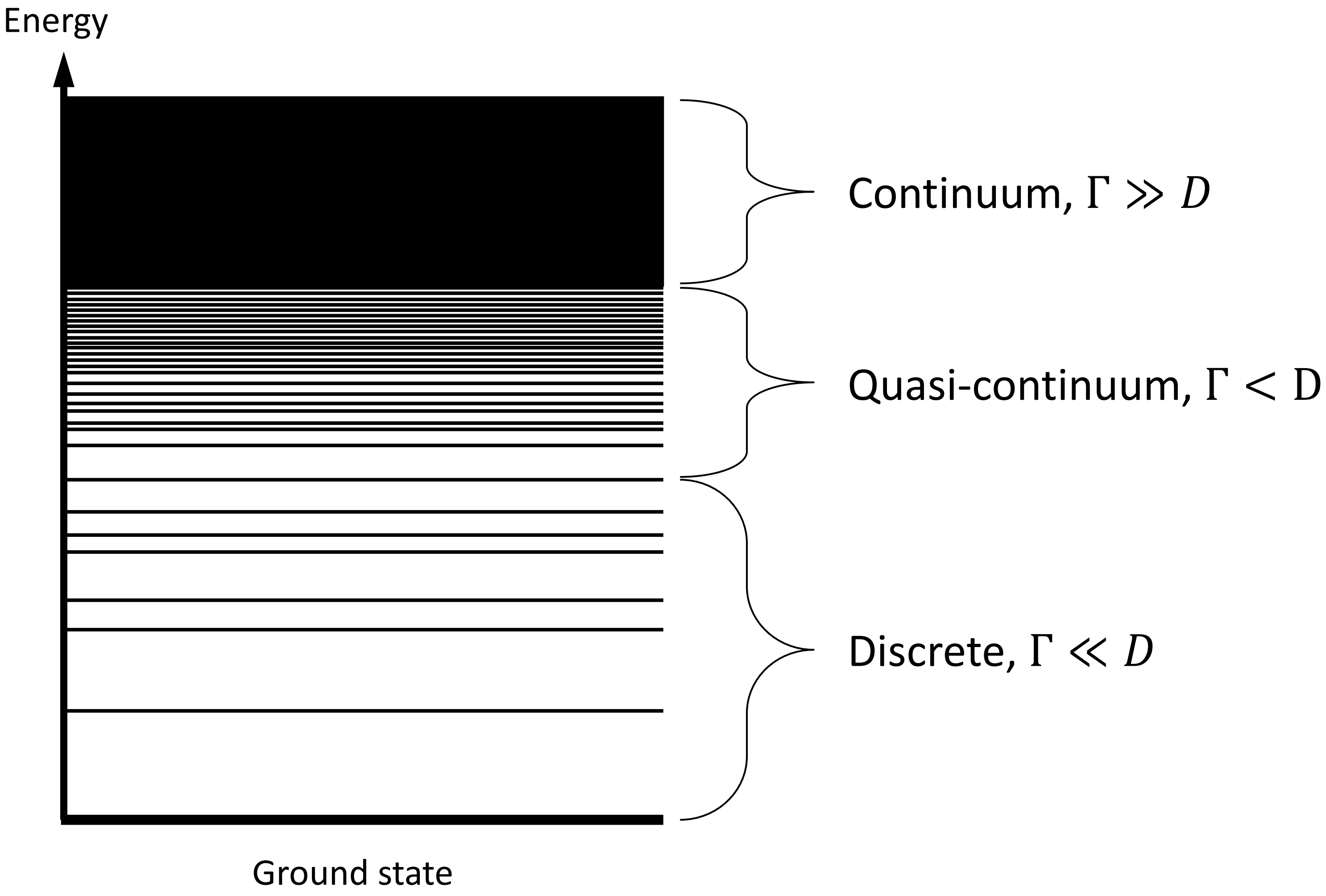
UNIVERSITY OF OSLO

CERN

Outline

- What are nuclear level densities (NLD) and γ-ray strength functions (γSF)?
- Nuclear astrophysics
- How can we measure these (the Oslo Method)?
- Experiment at ISOLDE
- Results

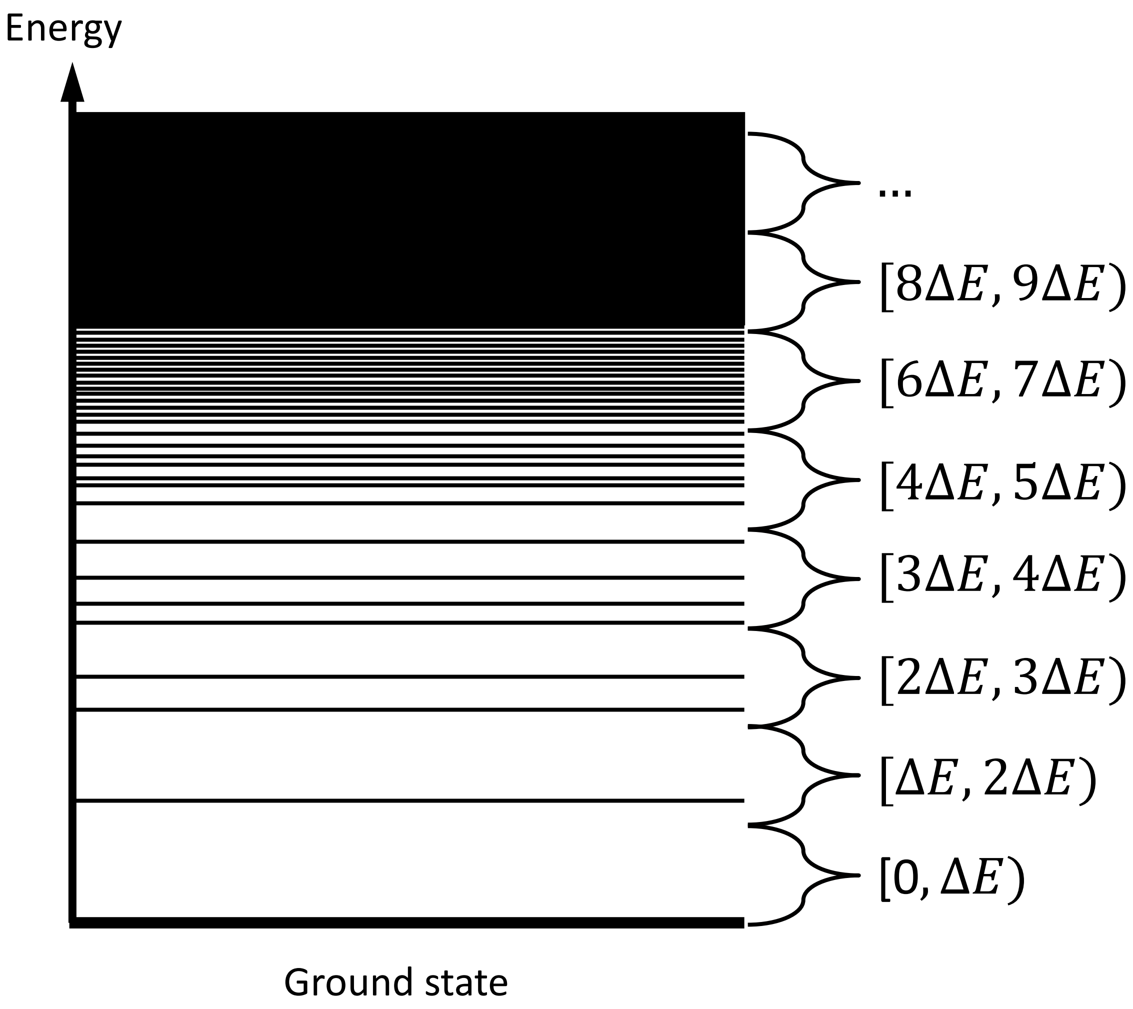
Statistical properties of nuclei



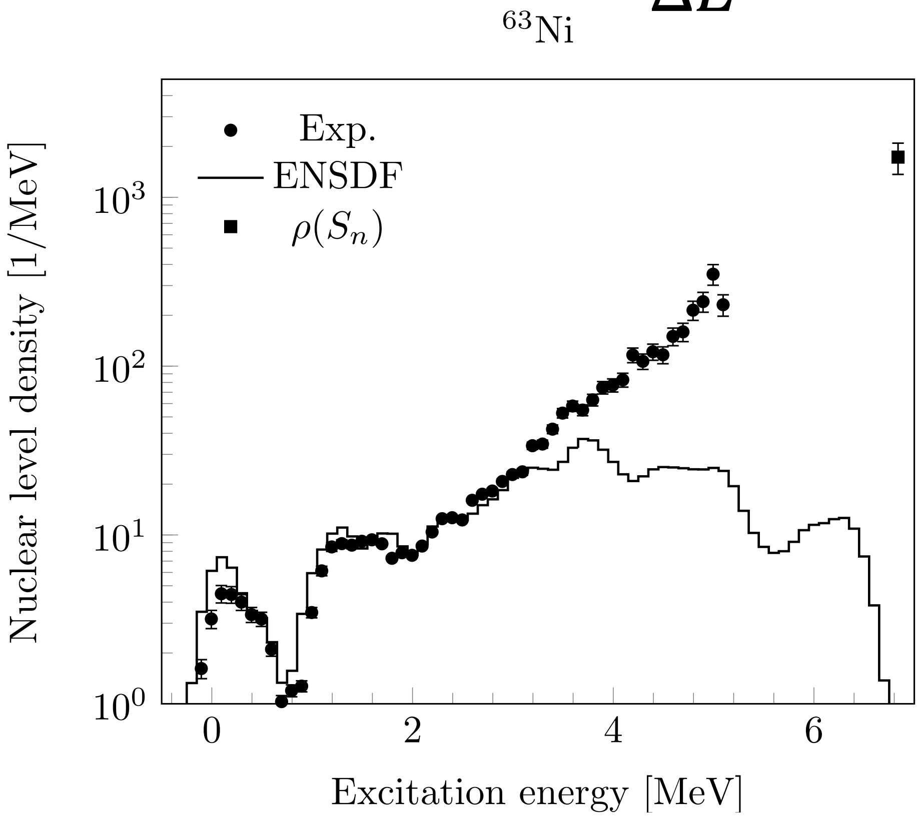
D: Average level spacing

Γ: Decay width, $\Gamma = \frac{\hbar}{\tau}$

Nuclear level density



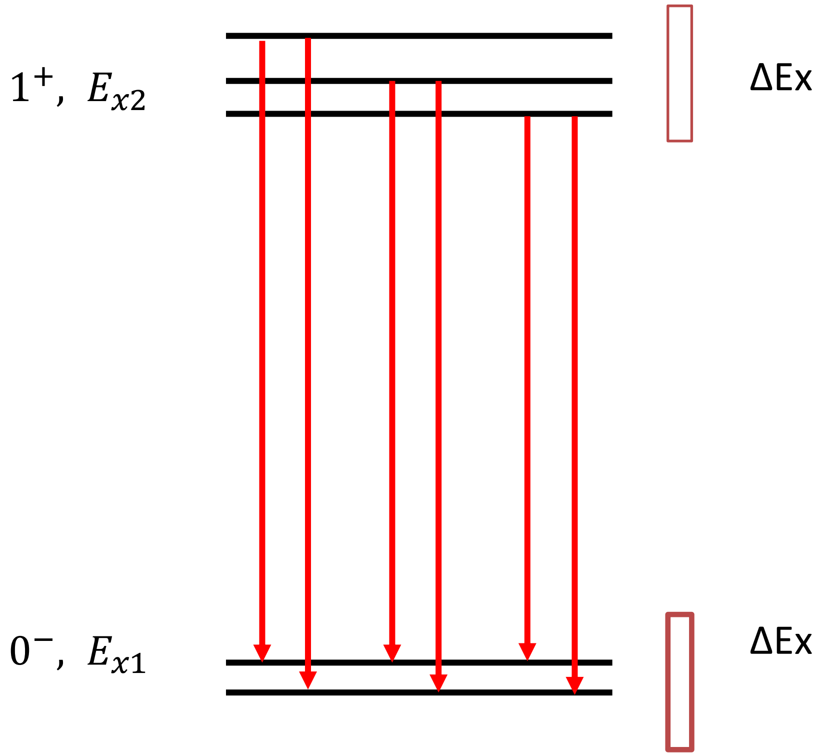
$$\rho(E,J,\pi) = \frac{N(E,J,\pi)}{\Delta E}$$



V. W. Ingeberg, Phys. Rev. C (in review)

ISOLDE

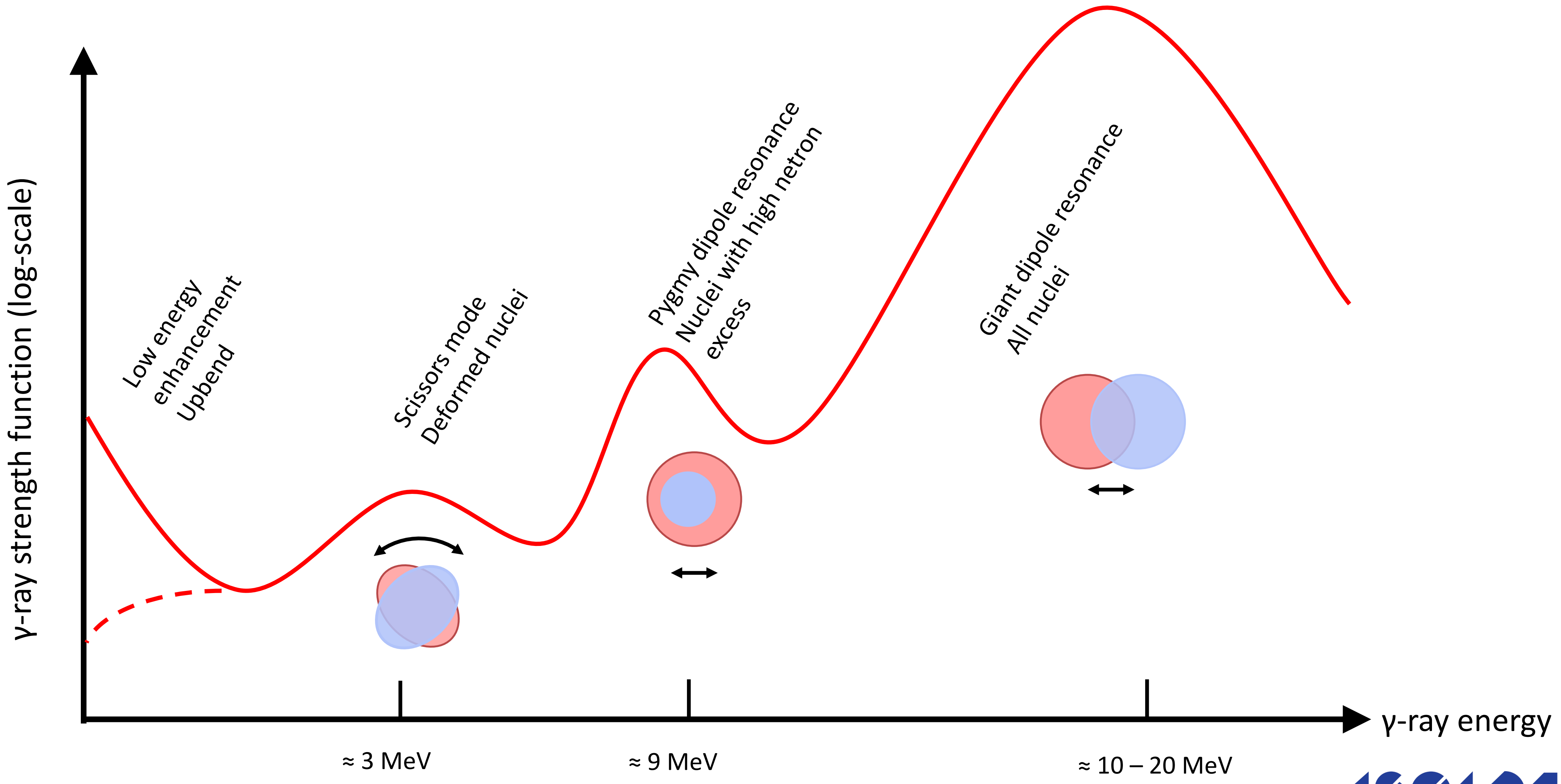
γ-ray strength function



$$f_{XL}(E_\gamma, E_i, J_i, \pi_i) = \frac{\langle\Gamma_\gamma^{XL}\rangle(E_\gamma, E_i, J_i, \pi_i)}{E_\gamma^{2L+1}}\rho(E_i, J_i, \pi_i)$$

- $\langle\Gamma_\gamma^{XL}\rangle(E_\gamma, E_i, J_i, \pi_i)$: Average decay width with γ-ray energy E_γ from excitation bin with energy E_i, spin J_i and parity π_i
- $\rho(E_i, J_i, \pi_i)$: Level density
- X=Electric or Magnetic
- Multipole L=1,2,3,etc.
- L=1, dipole will be dominating

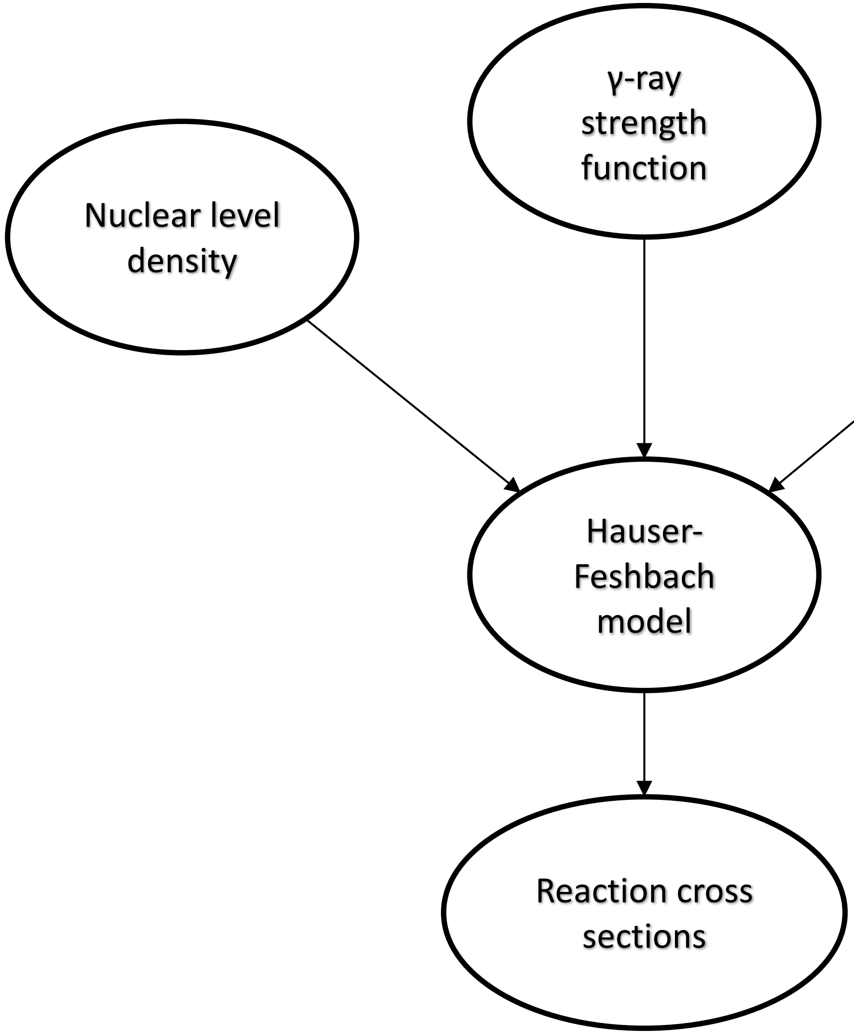
γ-ray strength function



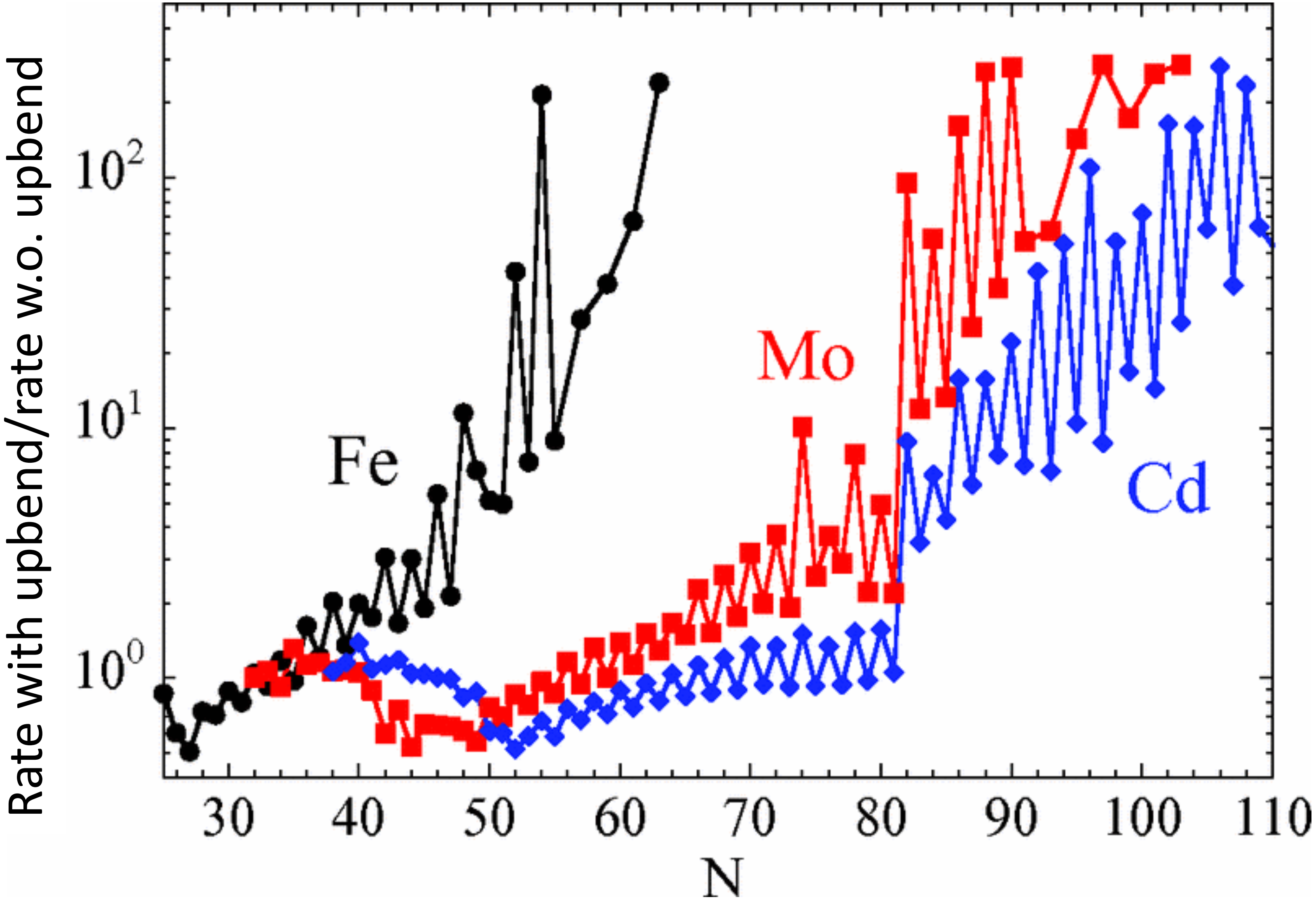
What does NLDs and γSFs tell us?

- The NLD and γSF provides important information on the nuclear structure

- Input parameters for Hauser-Feshbach model (reaction cross sections)



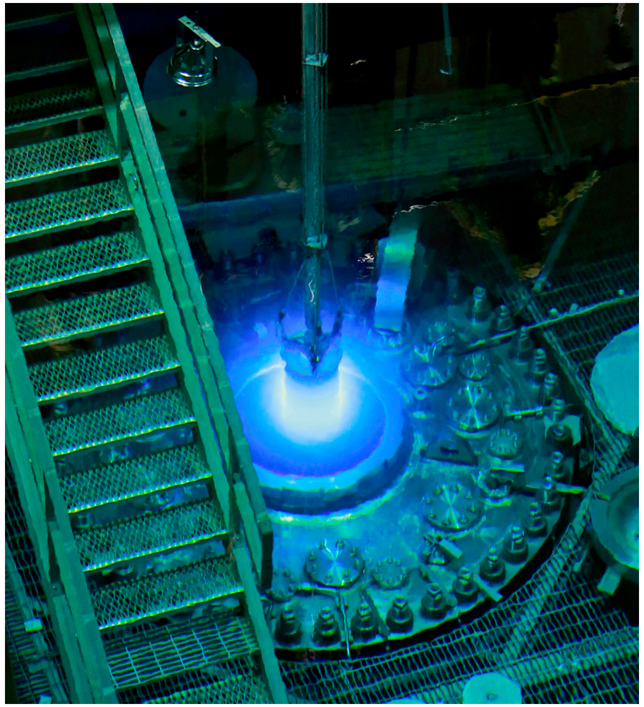
Impact of the low energy enhancement



A. C. Larsen and S. Goriely, Phys. Rev. C **82**, 014318 (2010)

Reaction cross sections

Reactor physics
Energy



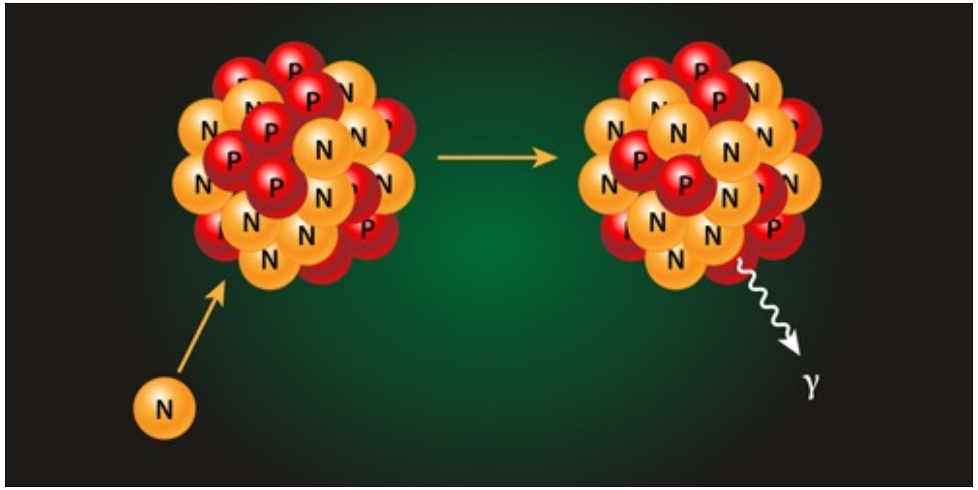
Isotope production
Nuclear medicine

Nuclear astrophysics
How are elements made?

Jason Richards/ORNL (CC),
ESO/L. Calçada/M. Kornmesser (CC)

How are the elements made?

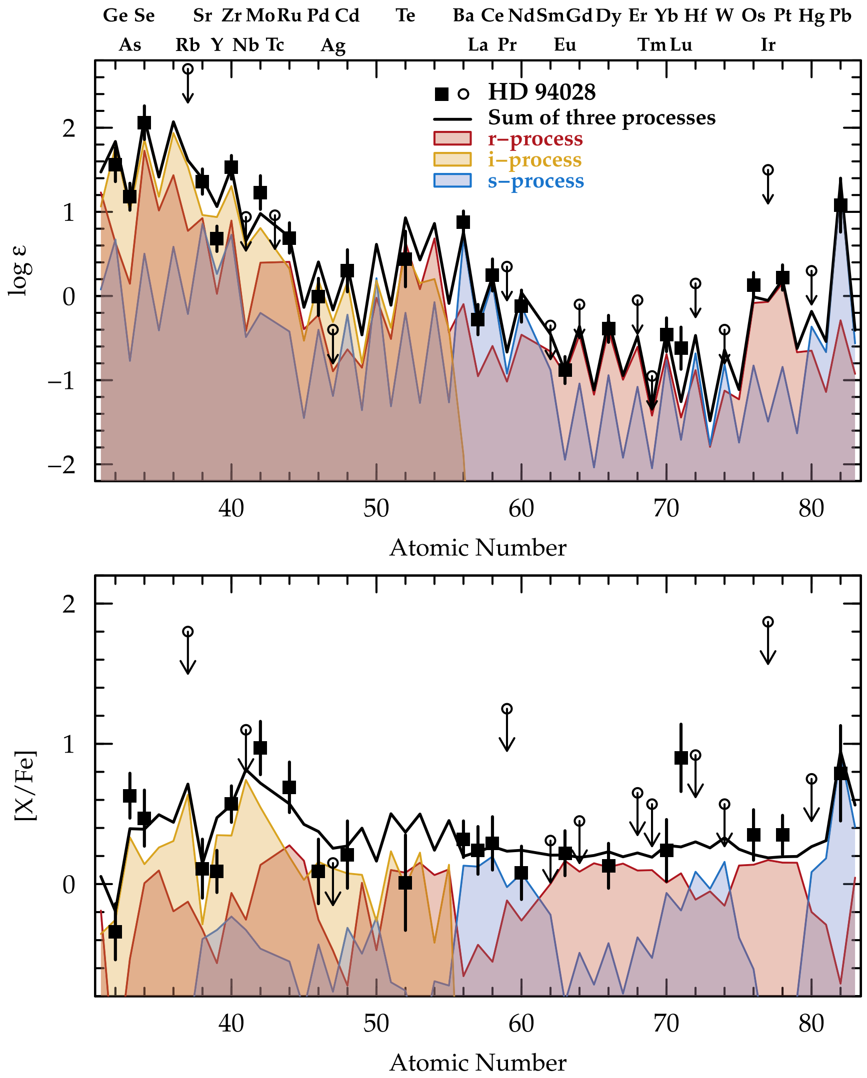
- Elements up to Fe/Ni – fusion reactions in stars
- Elements heavier than Fe/Ni – neutron capture processes
  - ➢ Slow neutron capture process (s-process) ≈ 50%
  - ➢ Rapid neutron capture process (r-process) ≈ 50%



Alan Stonebreaker/APS

i-process

- Elemental abundances in certain metal-poor stars cannot be explained by either s-process, r-process or a combination[1]
- An intermediate neutron capture process (i-process) can explain the discrepancy[1]
- Sensitivity study of the weak i-process suggests ^{66}Ni(n, γ) capture reaction as a major bottleneck affecting all abundances[2]
- ^{66}Ni(n, γ) rate is constrained by measuring the NLD and γSF of ^{67}Ni



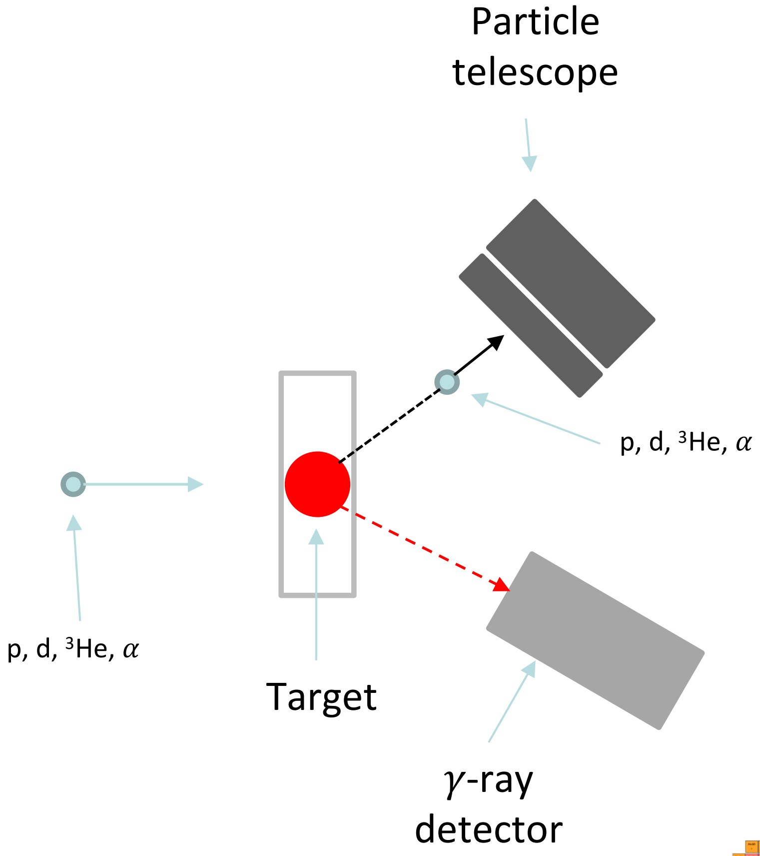
I. U. Roederer *et al.*, ApJ **821**, 37 (2016)

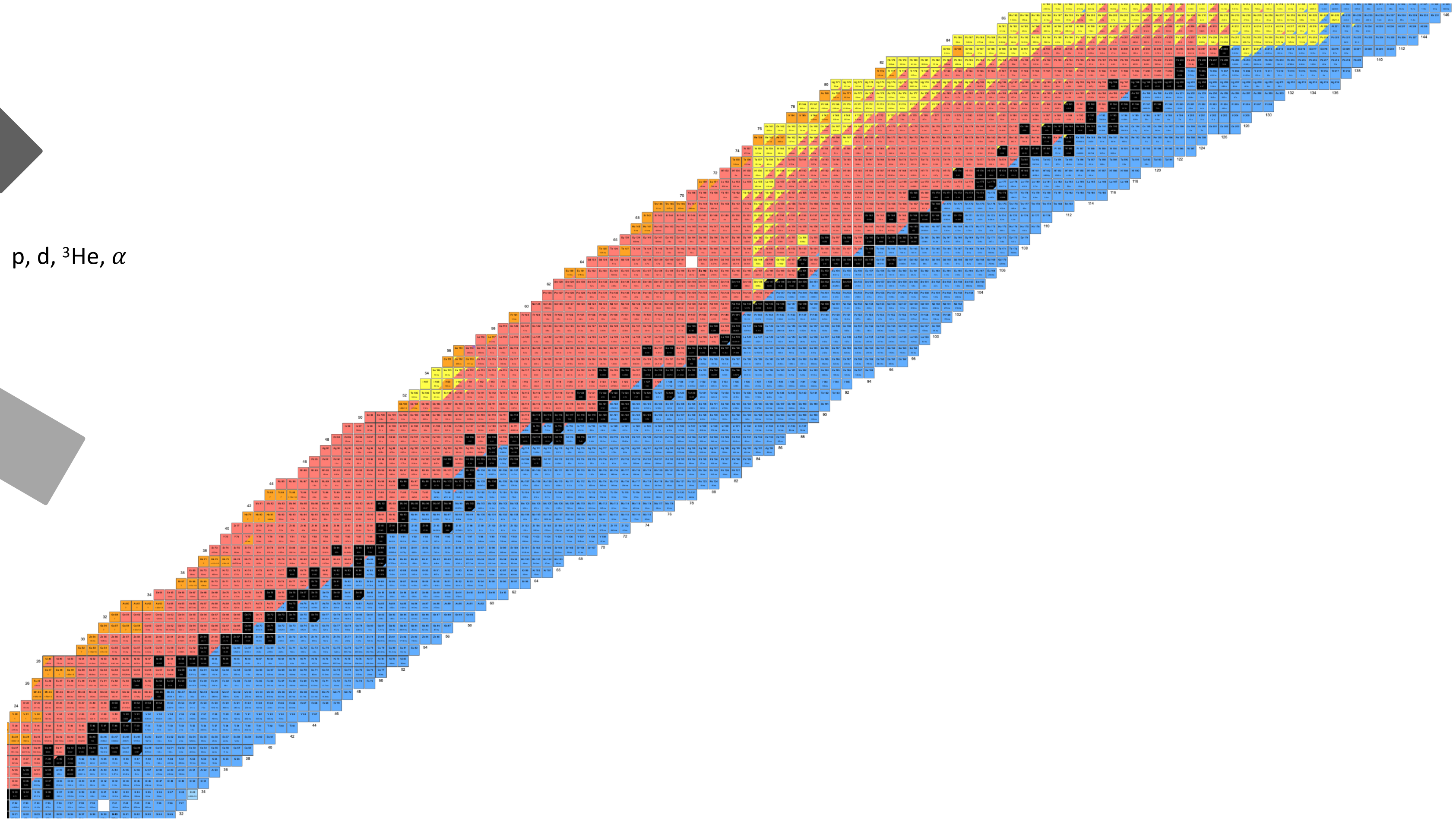
[1]I. U. Roederer *et al.*, ApJ **821**, 37 (2016)

[2]J. E. McKay *et al.*, MNRAS **491**, 5179 (2020)

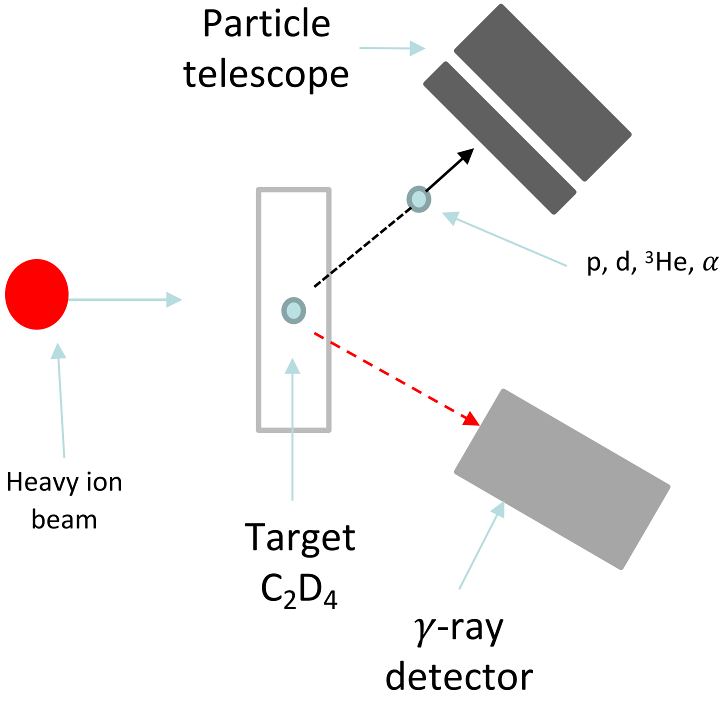
i-process

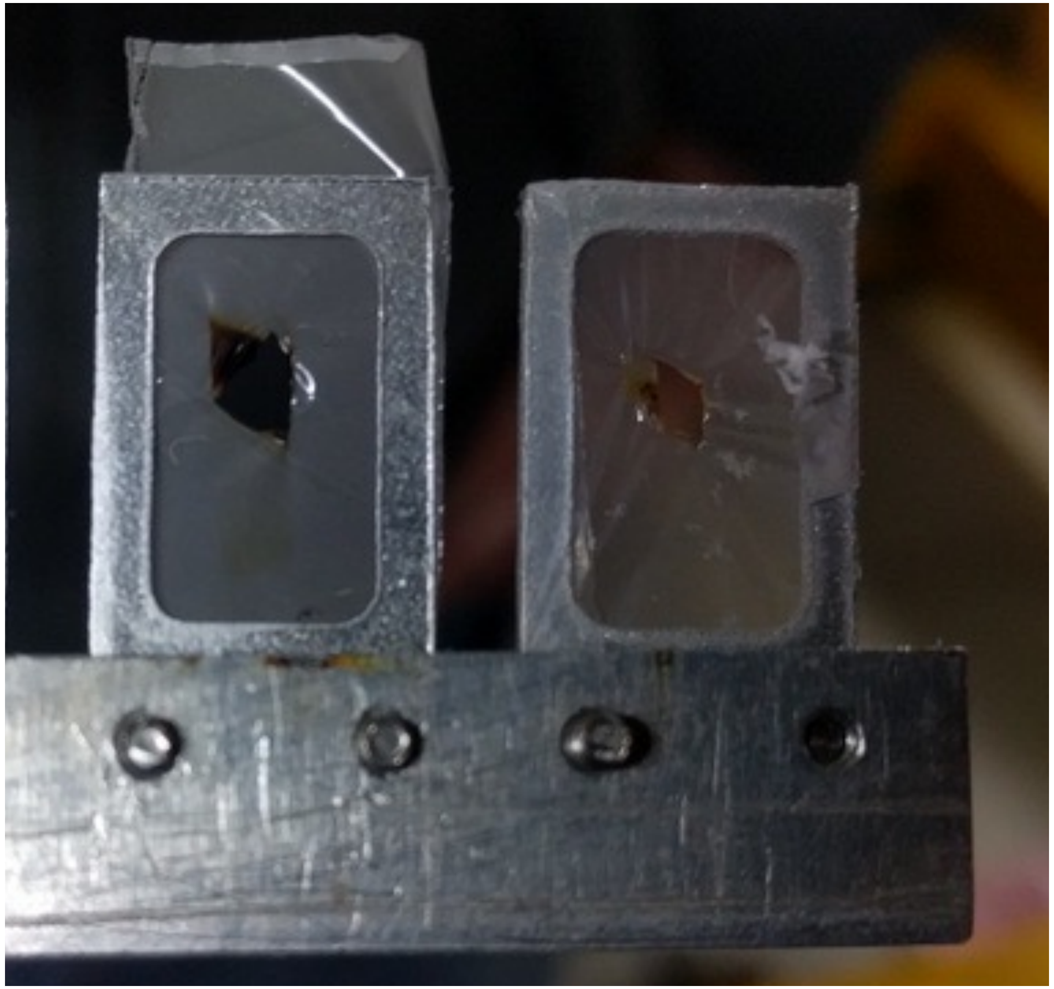
The Oslo Method



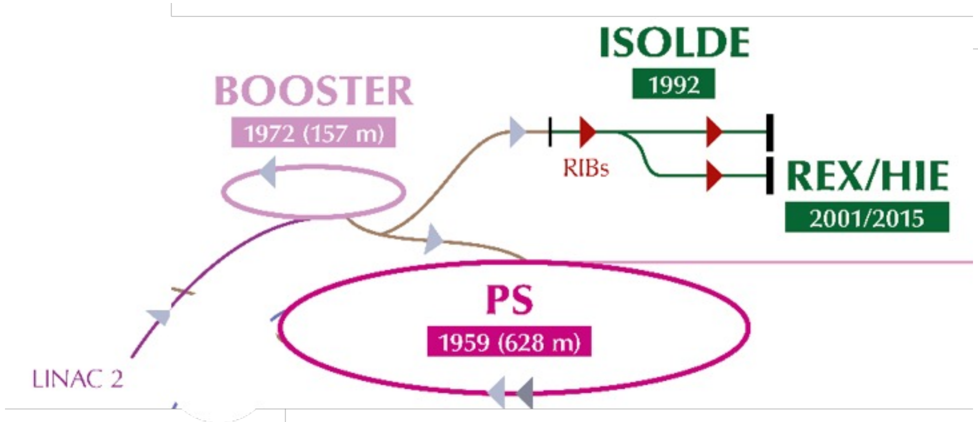


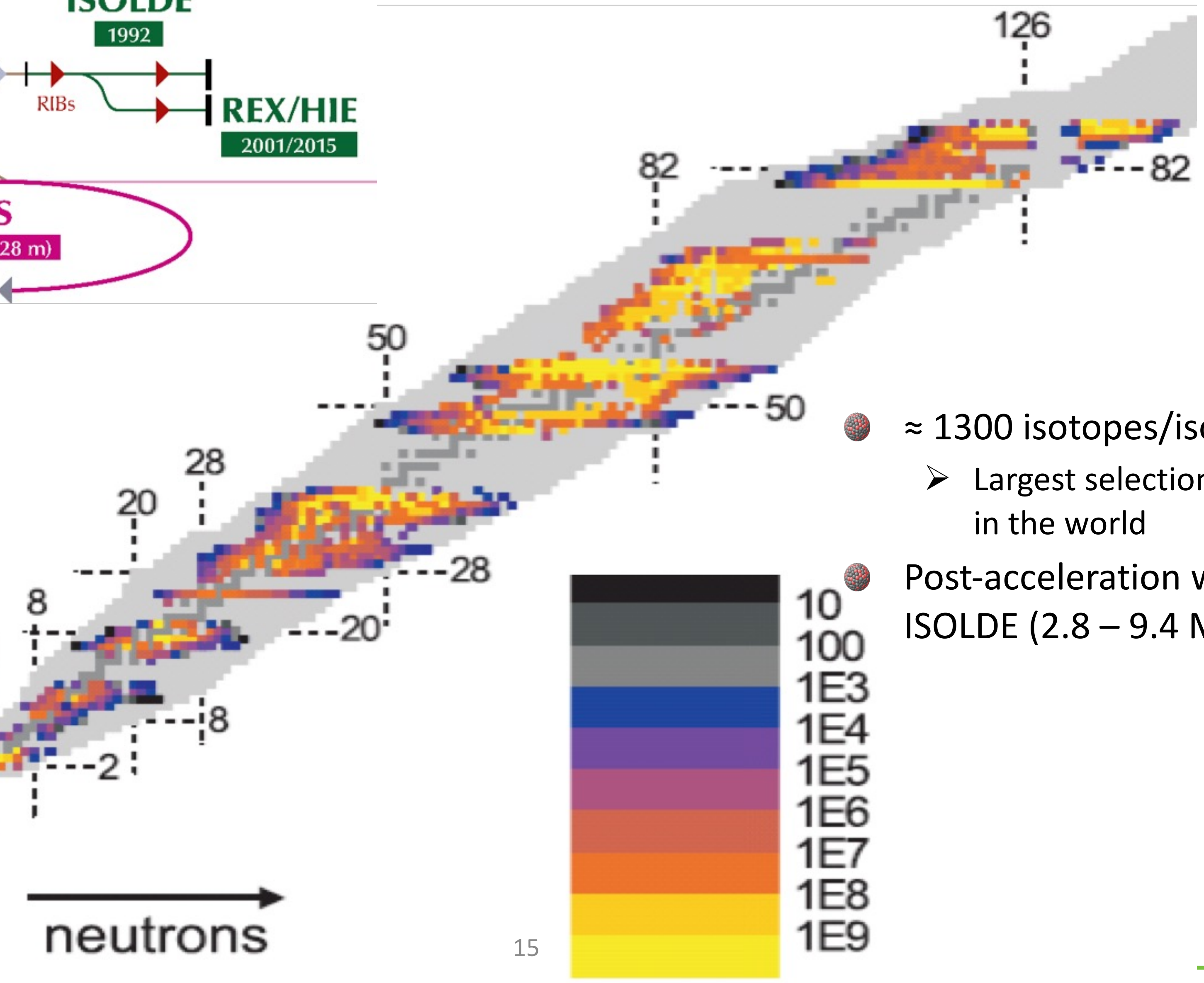
Inverse kinematics





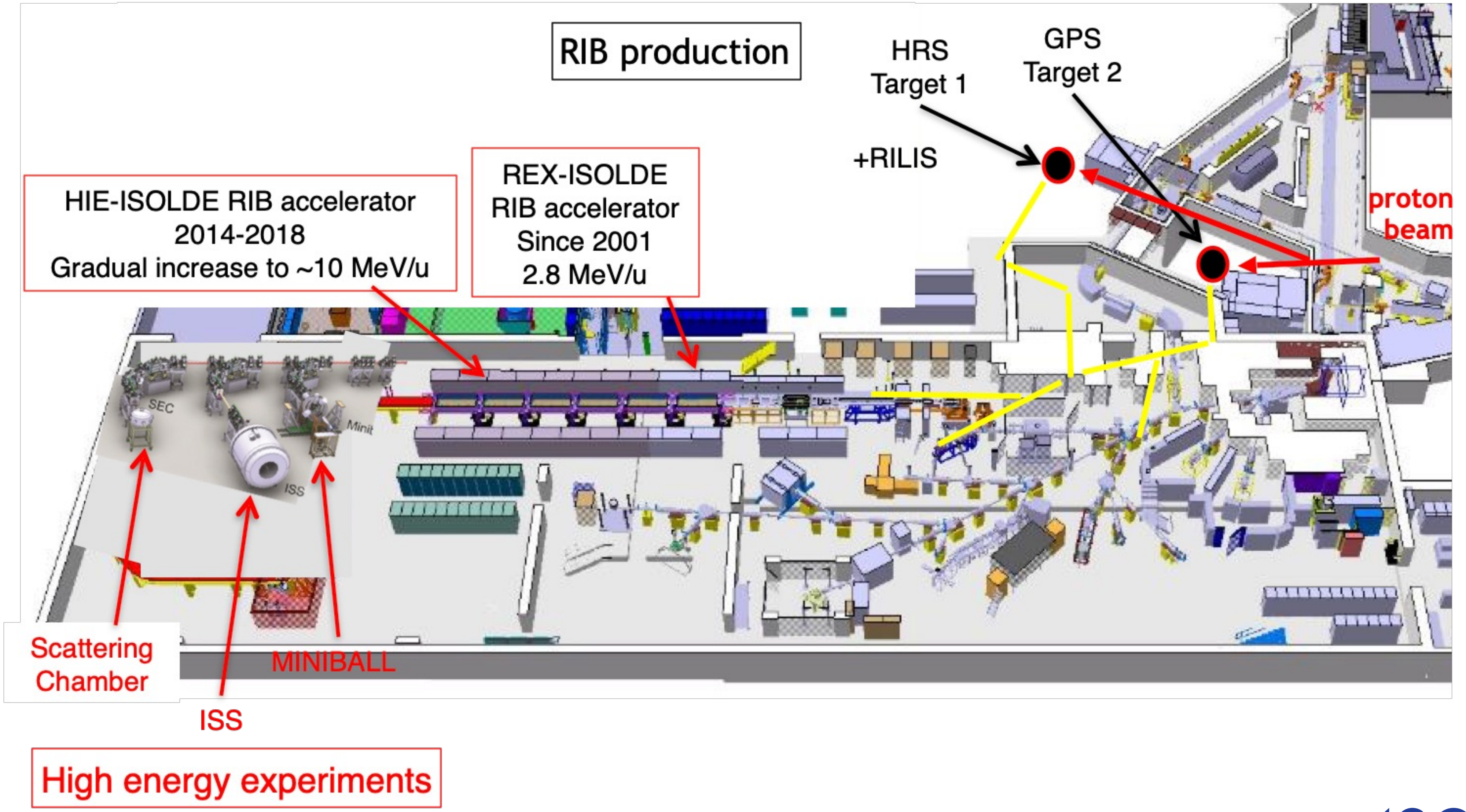
ISOLDE





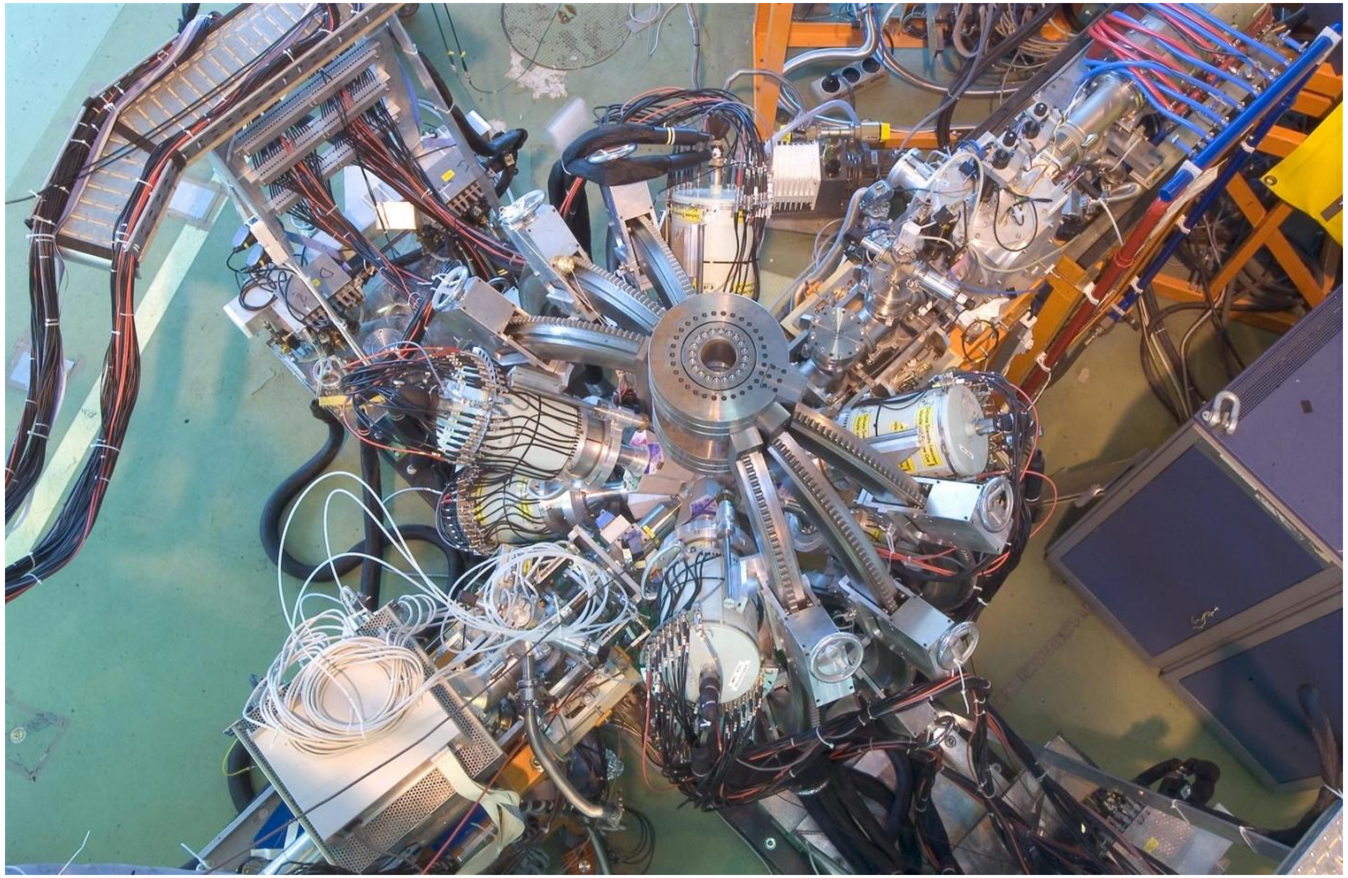
- ≈ 1300 isotopes/isomers available
  - Largest selection of any ISOL facility in the world
- Post-acceleration with REX/HIE-ISOLDE (2.8 – 9.4 MeV/u)

ISOLDE

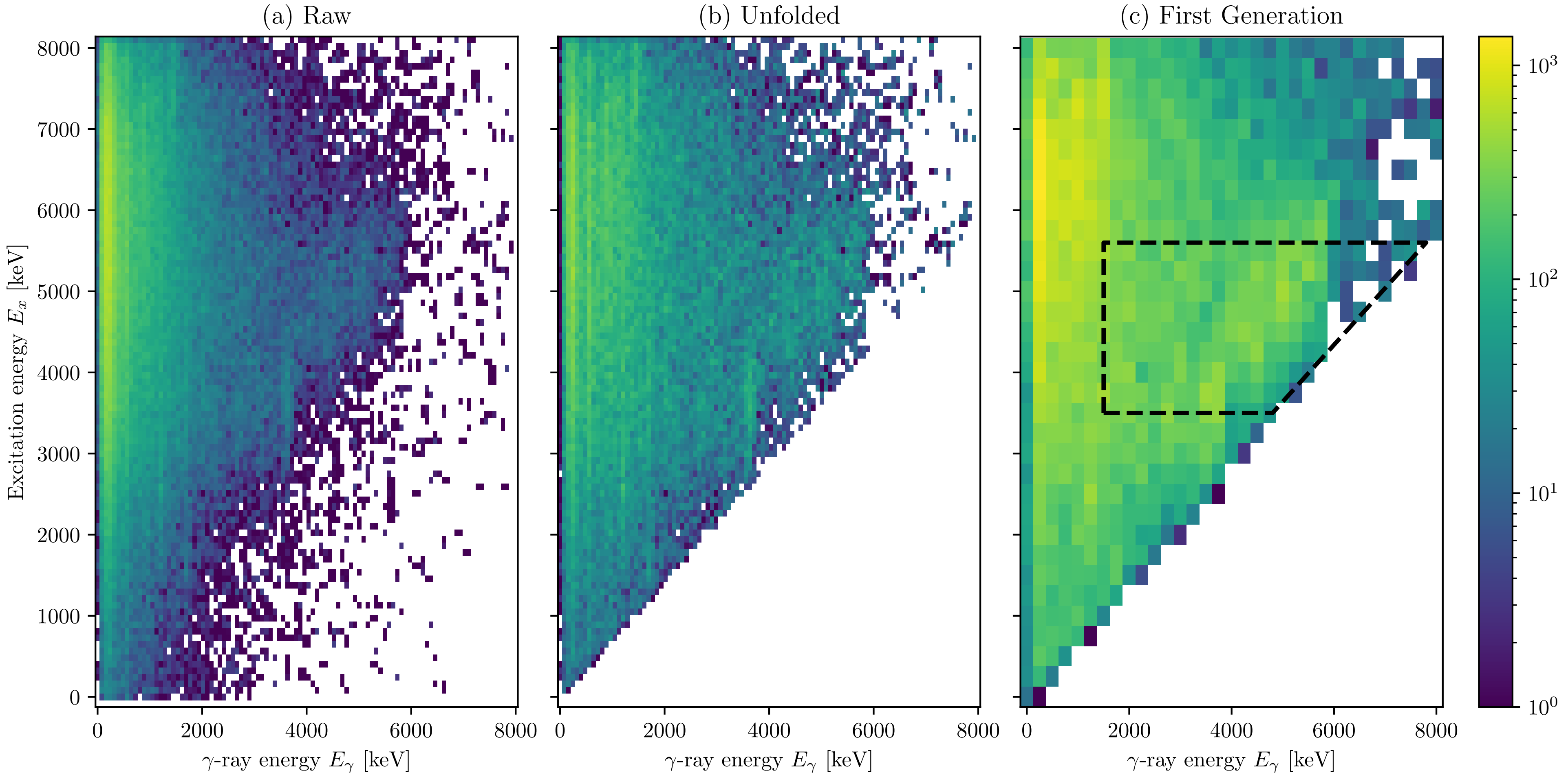

RIB production
HRS
Target 1
GPS
Target 2
+RILIS
proton
beam
HIE-ISOLDE RIB accelerator
2014-2018
Gradual increase to ~10 MeV/u
REX-ISOLDE
RIB accelerator
Since 2001
2.8 MeV/u
SEC
ISS
Scattering
Chamber
MINIBALL
ISS
High energy experiments

ISOLDE/Miniball experiment

- Beam: ^{66}Ni@4.47(1) MeV/u
- Target: 670 ug/cm^2 deuterated polyethylene (C_2D_4)
- ≈ 140 hours of beam time
- ≈ 3.5×10^6 pps
- 6 MINIBALL clusters + 6 large volume $LaBr_3$:Ce detector from OSCAR
- C-REX particle array
- Approx. 320,000 particle- γ coincidences

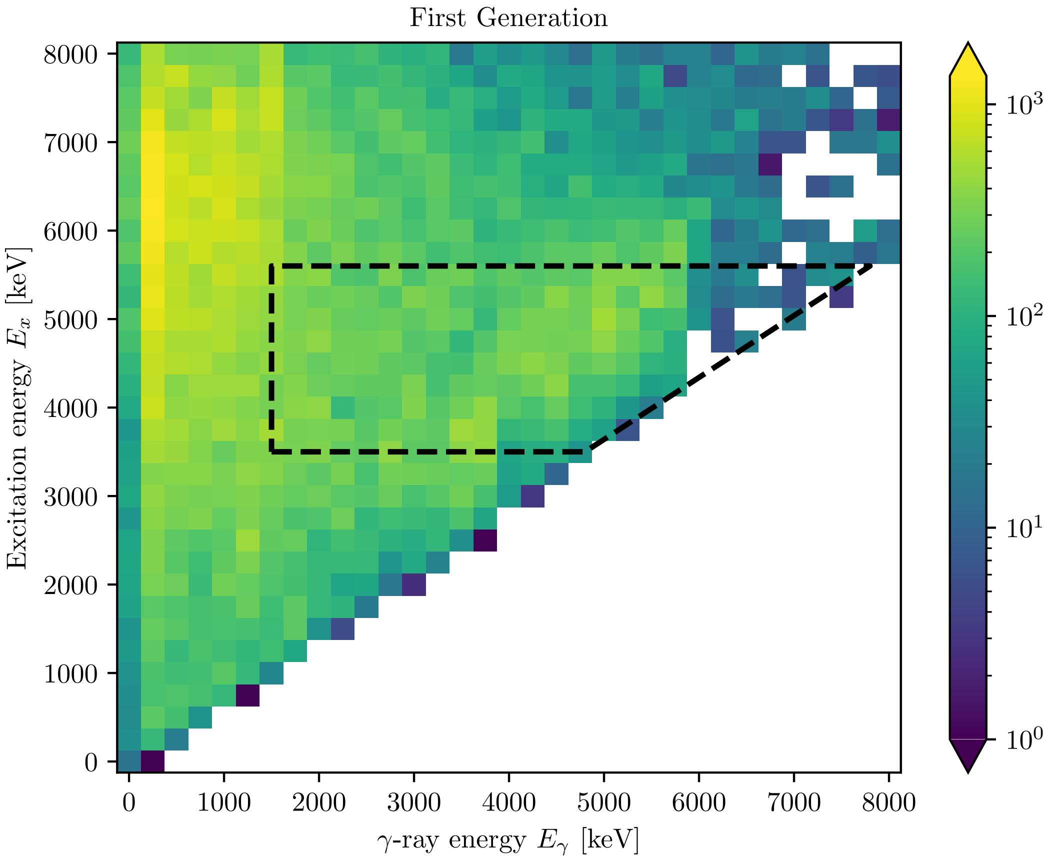


The Oslo Method



V. W. Ingeberg *et al.* (in preparation)

Extraction of NLD and γSF



- $P(E_x, E_\gamma) \propto E_\gamma^3 f(E_\gamma)\rho(E_x - E_\gamma)$

- NLD and gSF extracted by fitting theoretical FG:

$$P_{th}(E_x E_\gamma) = \frac{E_\gamma^3 f(E_\gamma)\rho(E_x - E_\gamma)}{\sum_{E_\gamma = E_\gamma^{min}}^{E_x} E_\gamma^3 f(E_\gamma)\rho(E_x - E_\gamma)}$$

- $f(E_\gamma)$ & $\rho(E_x - E_\gamma)$: Free parameters for each E_γ and $\mathrm{E_f} = \mathrm{E_x} - E_\gamma$

- Need to normalize extracted NLD and gSF since Pth is invariant under transformation

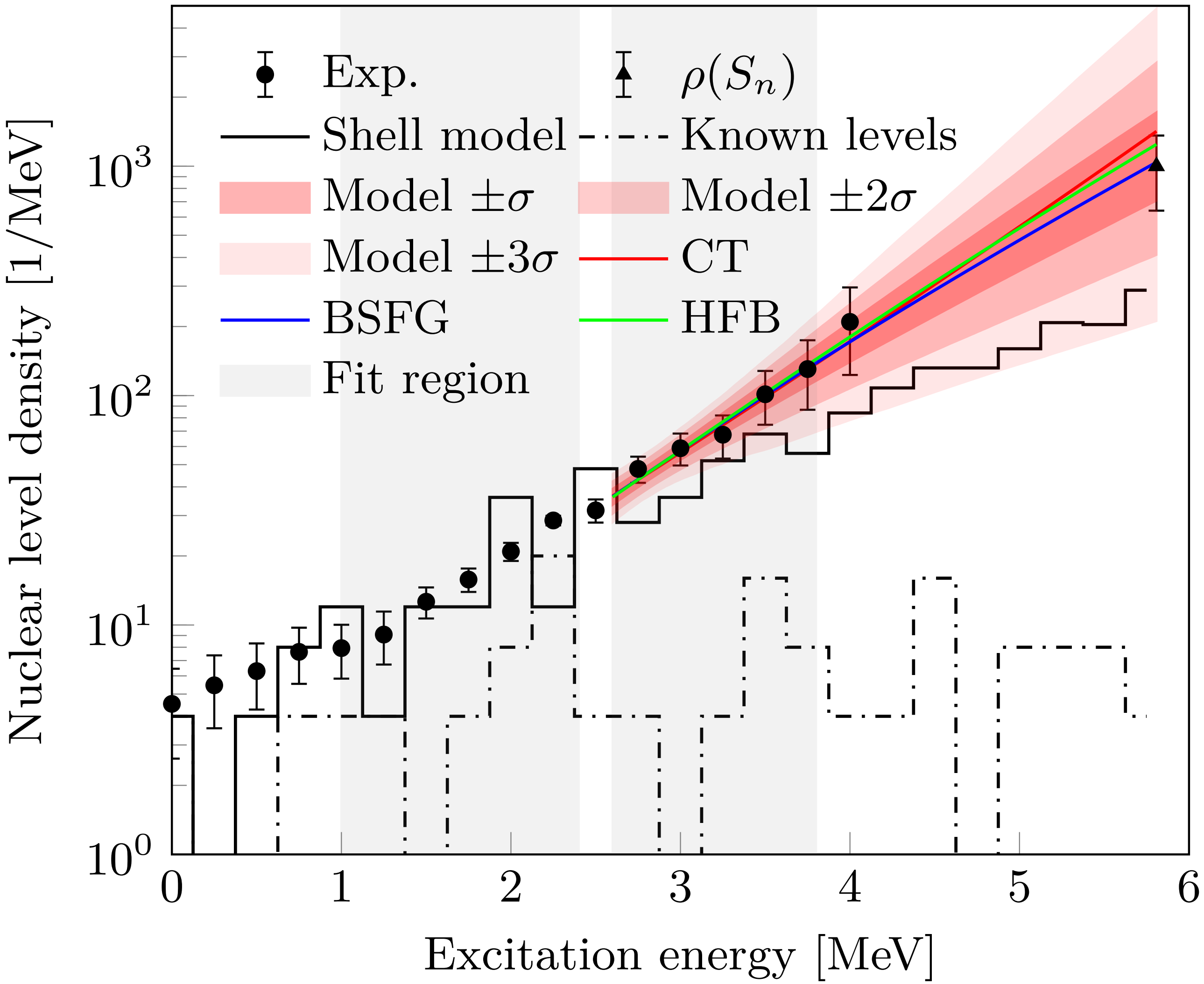
$$\tilde{\rho}(E_f) = A\rho(E_f)e^{\alpha E_f}$$
$$\tilde{f}(E_\gamma) = Bf(E_\gamma)e^{\alpha E_\gamma}$$

V. W. Ingeberg *et al.*, in preparation

Normalization of NLD

- Typically normalize to auxiliary nuclear data
- NLD from known levels
- NLD at neutron separation energy

- Level scheme of ^{67}Ni is (very) incomplete
- NLD of ^{67}Ni at neutron separation is unknown
- Solution: Normalize to large scale shell model calculations



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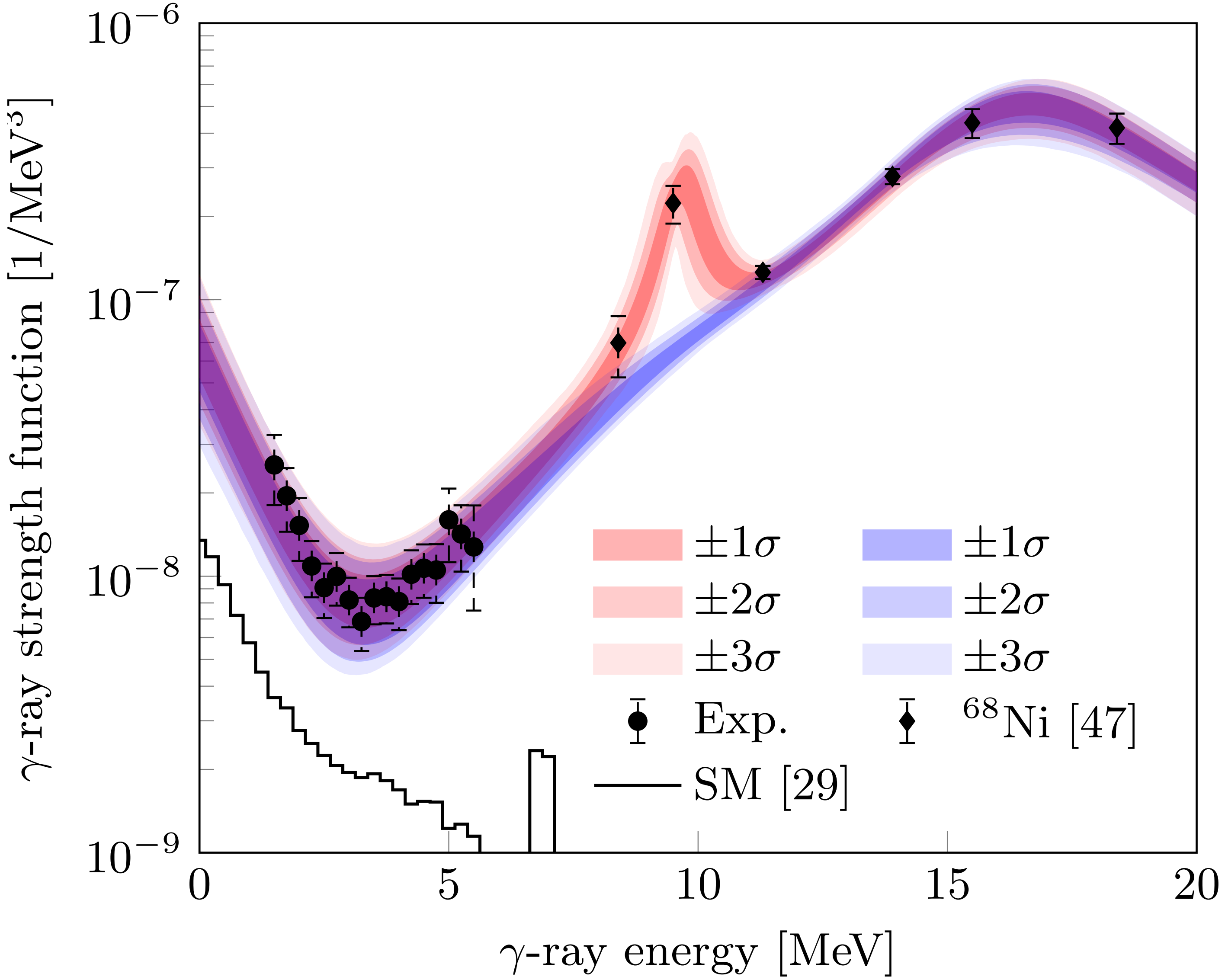
Normalization of γSF



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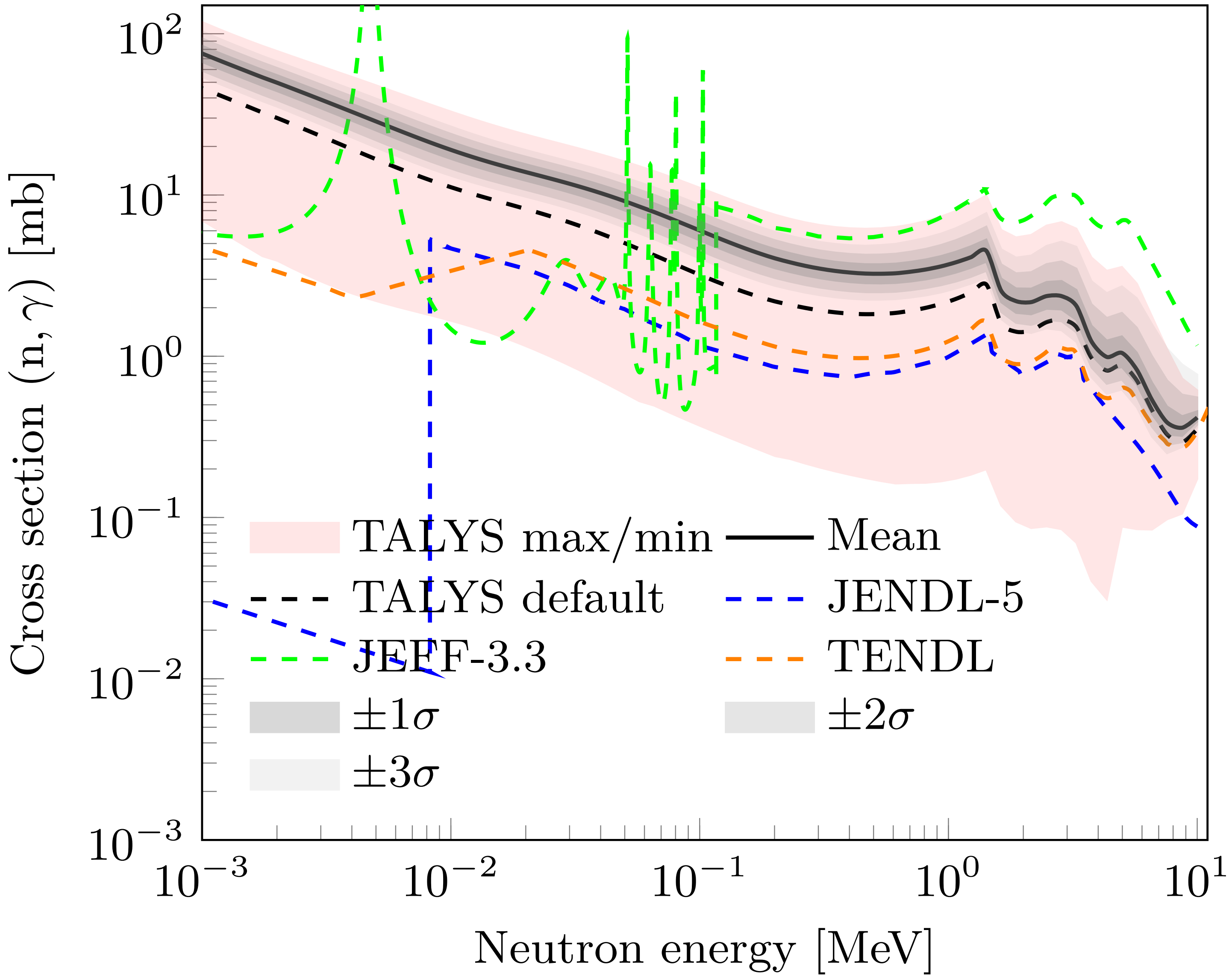
Neutron capture cross section



V. W. Ingeberg *et al.* (in preparation)

Summary

- We have measured the γSF and NLD of 67Ni
- First time the Oslo Method has been applied to an inverse kinematics experiment with radioactive beam
- Expect a rather quick i-process
- Soon to be submitted
- Paves the way for new Oslo Method experiments at ISOLDE

Future plans at ISOLDE

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Neutron single-particle states and neutron-capture cross sections towards ^{78}Ni: ^{79}Zn$(d,p)^{80}$Zn

January 6, 2021

E. Sahin[1], G. de Angelis[2] K.S. Beckmann[1], F. Bello[1], H.C. Berg[3] T.K. Eriksen[1], D. Gjestvang[1], A. Görgen[1], M. Guttormsen[1], K. Hadyńska-Klęk[4], V. W. Ingeberg[1], P. Jones[5], A.C.Larsen[1], K.L.Malatji[5], M. Markova[1], W. Paulsen[1], L.G. Pedersen[1], L.Pellegri[5], S. Siem[1], M. Wiedeking[5], F.Zeiser[1] and TREX and MINIBALL collaborations.

Bring OSCAR to ISOLDE?

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

Neutron-capture cross section for *i* process bottleneck ^{75}Ga: ^{75}Ga(d,pγ)^{76}Ga

December 20, 2021

F. Pogliano[1], R. Gernhaeuser[2], A. C. Larsen[1], K. S. Beckmann[1], F. Bello[1], H. C. Berg[4], T. K. Eriksen[1], D. Gjestvang[1], S. Golenev[2], A. Görgen[1], M. Guttormsen[1], A. Spyrou[4], S. Liddick[4], D. Mücher[7], K. Hadyńska-Klęk[5], V. W. Ingeberg[1], P. Jones[6], K. L. Malatji[6], M. Markova[1], W. Paulsen[1], L. G. Pedersen[1], L. Pellegri[6], E. Sahin[1], S. Siem[1], M. Wiedeking[6], F. Zeiser[1], P. Rieter[8], K. Arnswald[8], M. Droste[8], H. Hess[8], P.H. Kleis[8]

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