Surrogate reactions in inverse kinematics at the Experimental Storage Ring

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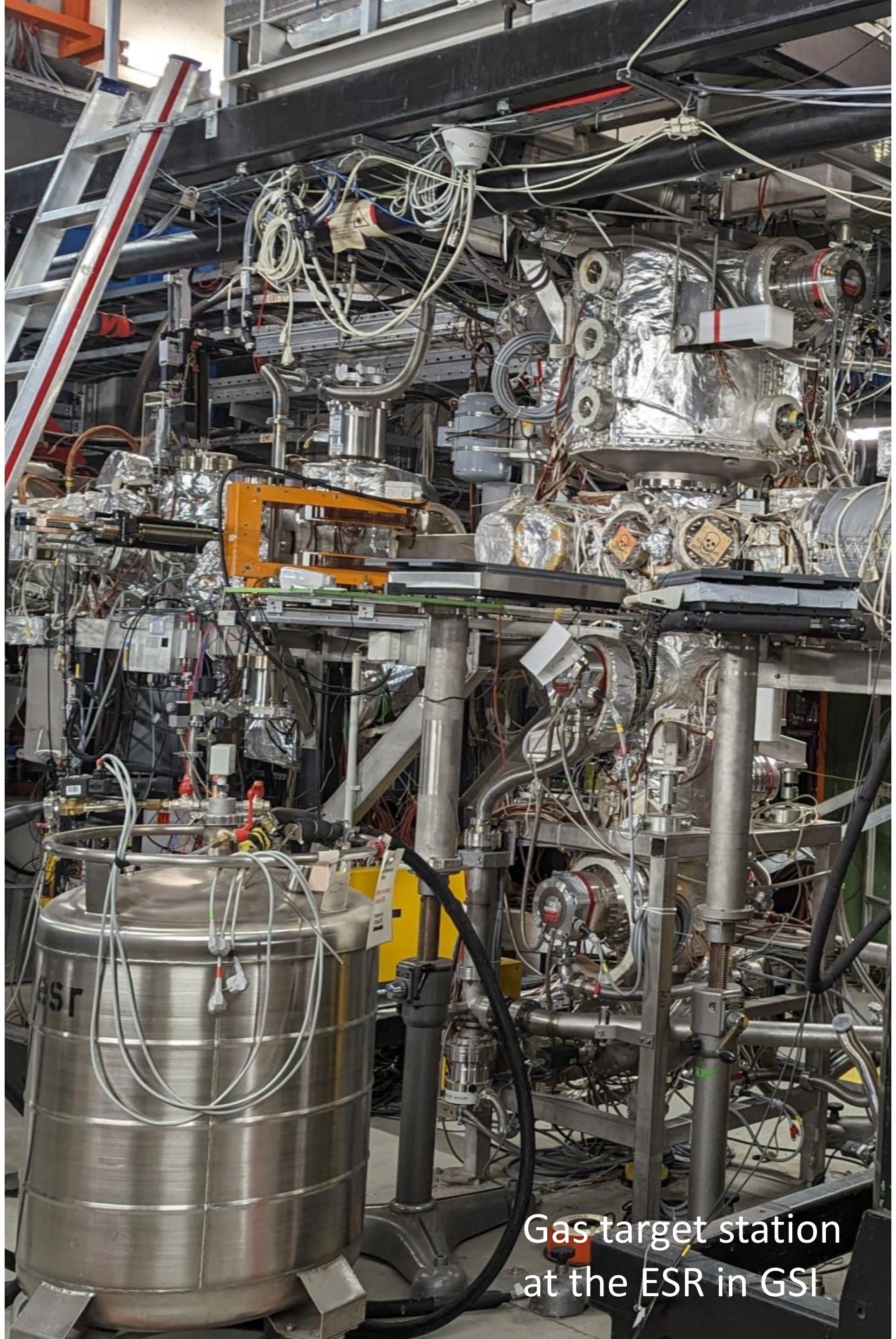
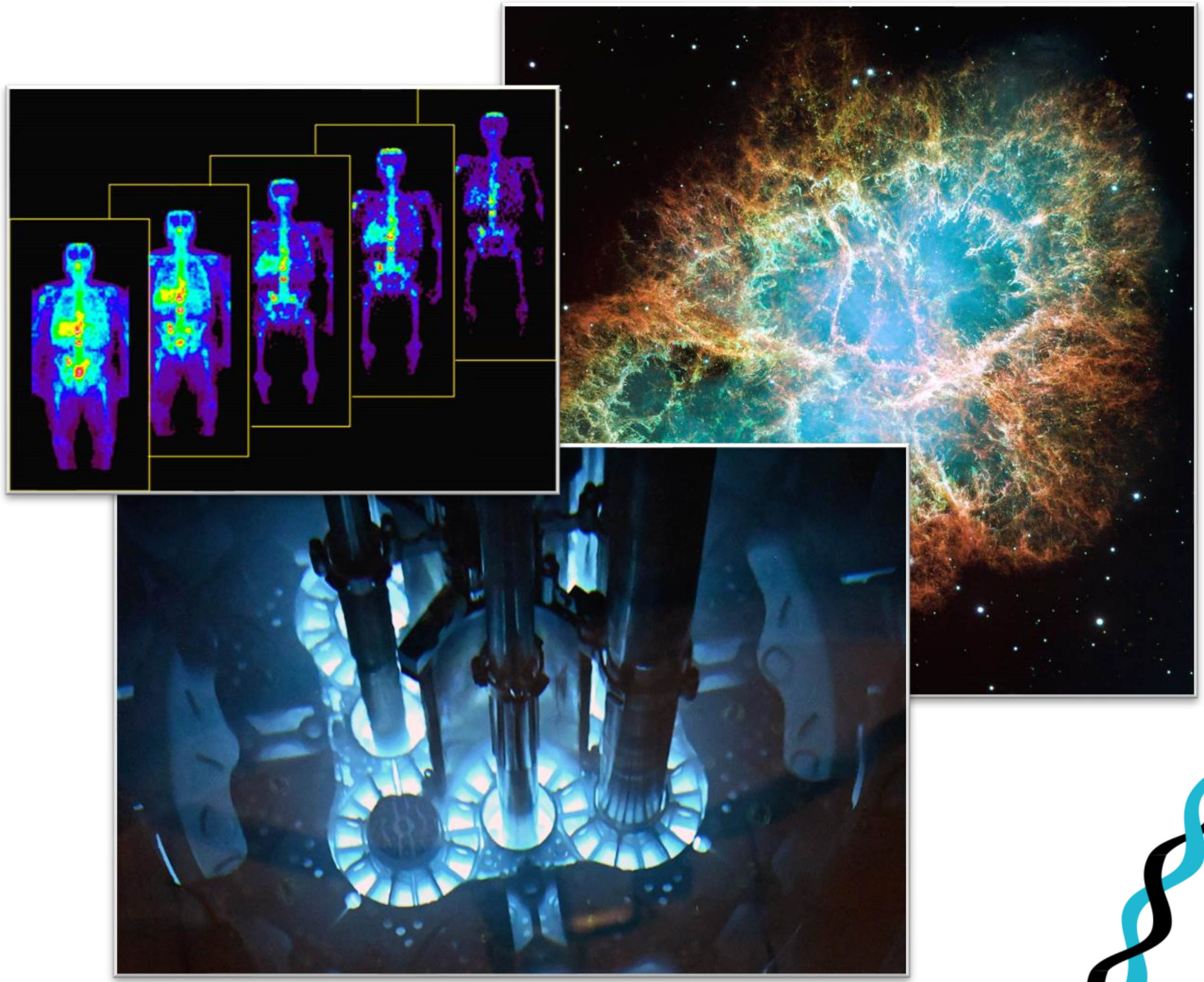


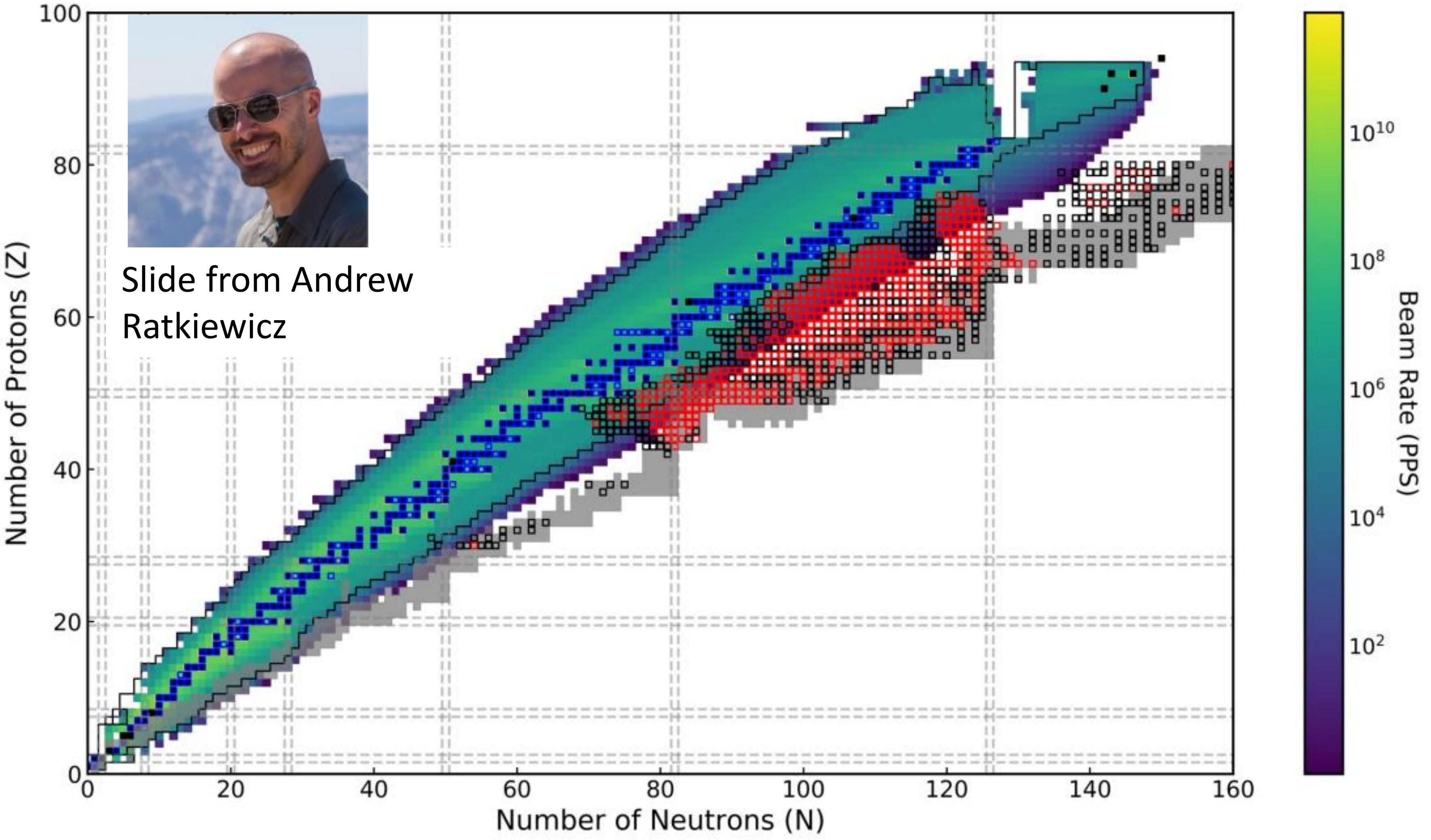
Gas target station at the ESR in GSI

Neutron-induced cross sections are interesting!

- Heavy element production in astrophysics
- Reactor cycles and waste management
- Medical isotope production



Neutron-induced cross sections are difficult

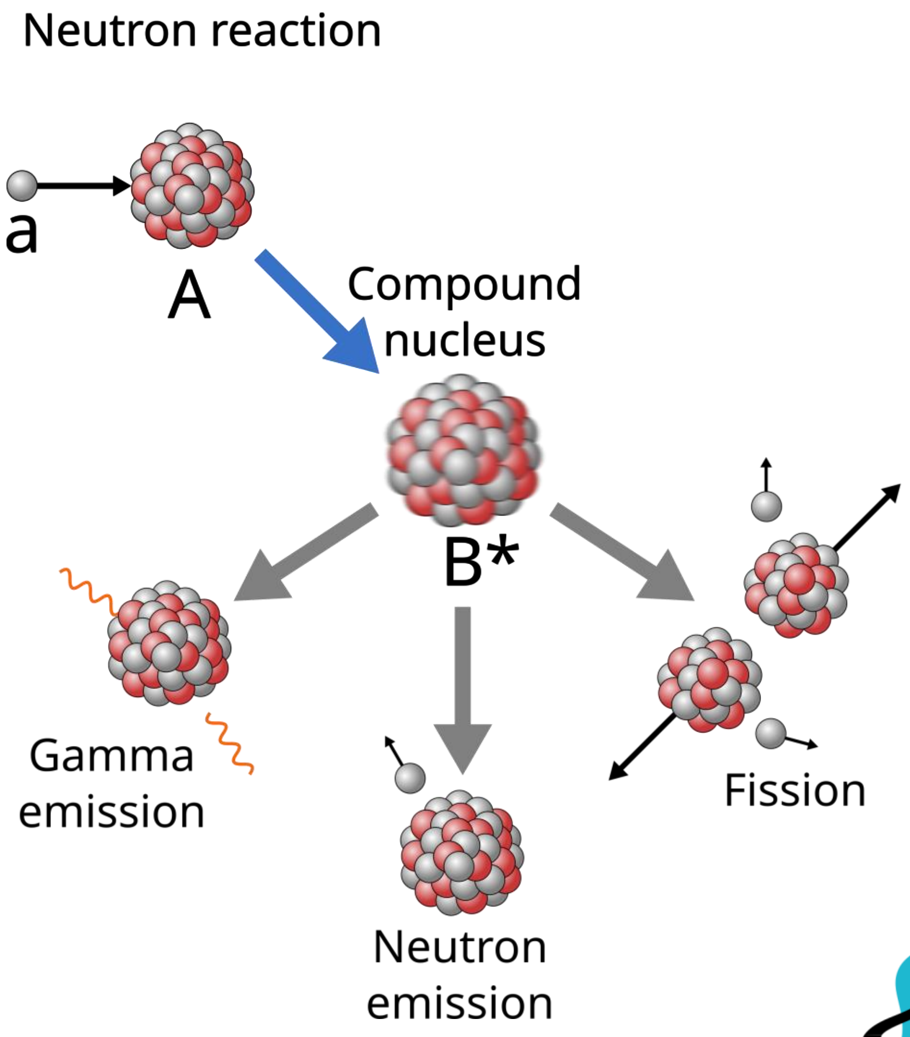


Slide from Andrew Ratkiewicz

- ❑ FRIB beam rates from LISE++ (Oleg Tarasov)
- ❑ (n,γ) rates from KADoNiS v0.3
- ❑ Cold *r*-process path from Lippuner & Roberts ApJ 815:2 (2015)
- ❑ *r*-process sensitivities from Mumpower *et al.* PPNP 86:86-126 (2016)

Describing neutron-induced reactions

- For neutron induced reactions in heavy nuclei, **Hauser-Feshbach theory** is a good approximation
- 2 step process:
  1. Formation of **compound nucleus (CN)**
     - Theoretically doable
  2. CN **decays** through competing channels
     - Theoretically very challenging

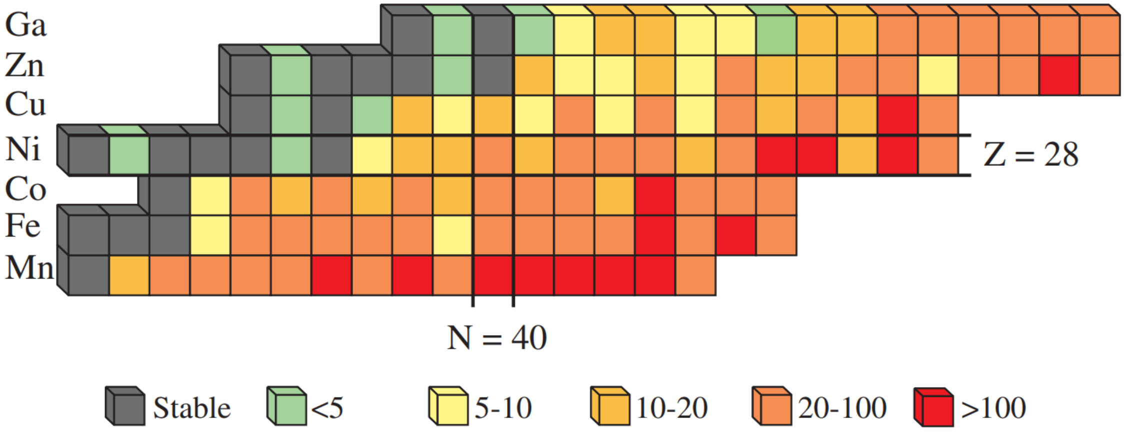


Why is Compound-Nucleus decay hard?

- Requires knowledge of complex nuclear properties:

  1. **Nuclear Level Density (NLD)**
  2. **γ-ray Strength Function (γSF)**
  3. **Fission barrier height**

- Order-of-magnitude uncertainties in cross sections



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

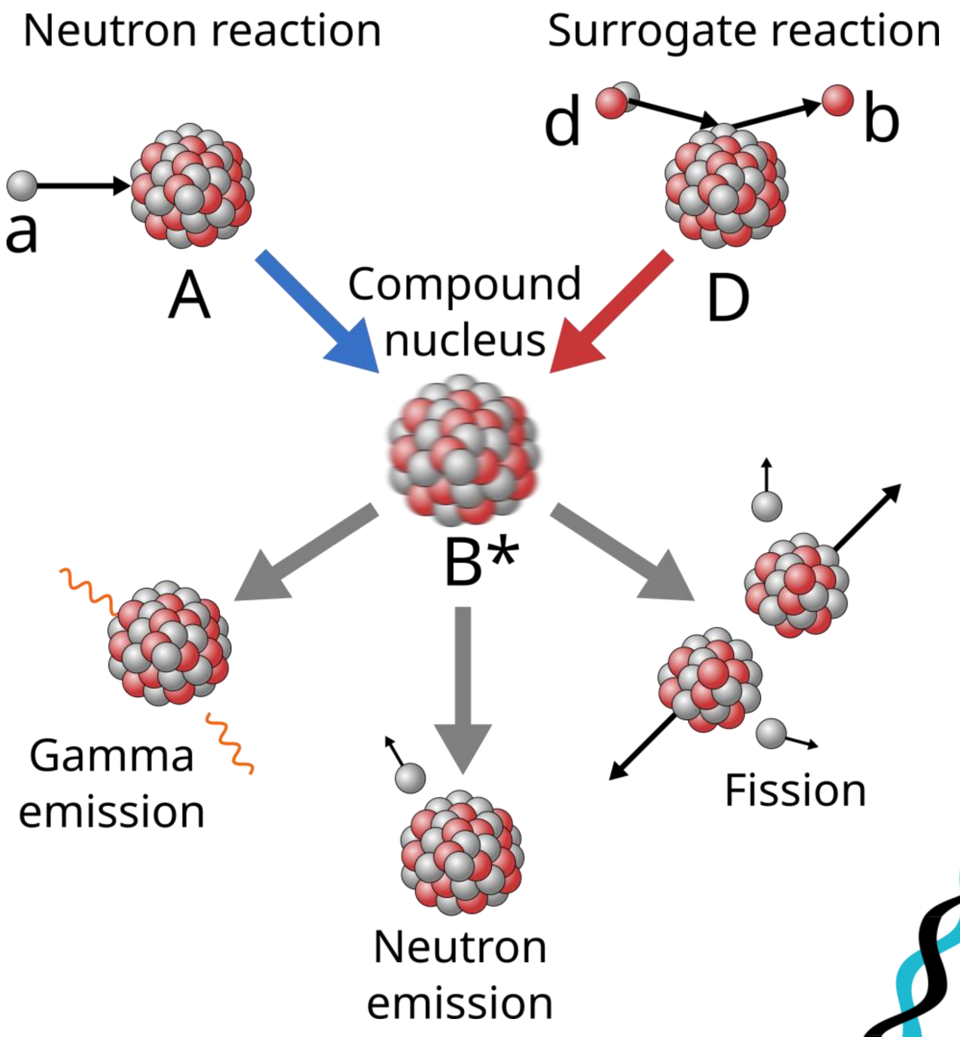
Simple surrogate reactions

- CN formation is erased by **statistical equilibrium**

$$\sigma_{(n,\chi)} = \sigma^{CN}_{\text{form}}(E^*)\, P^n_\chi(E^*)$$

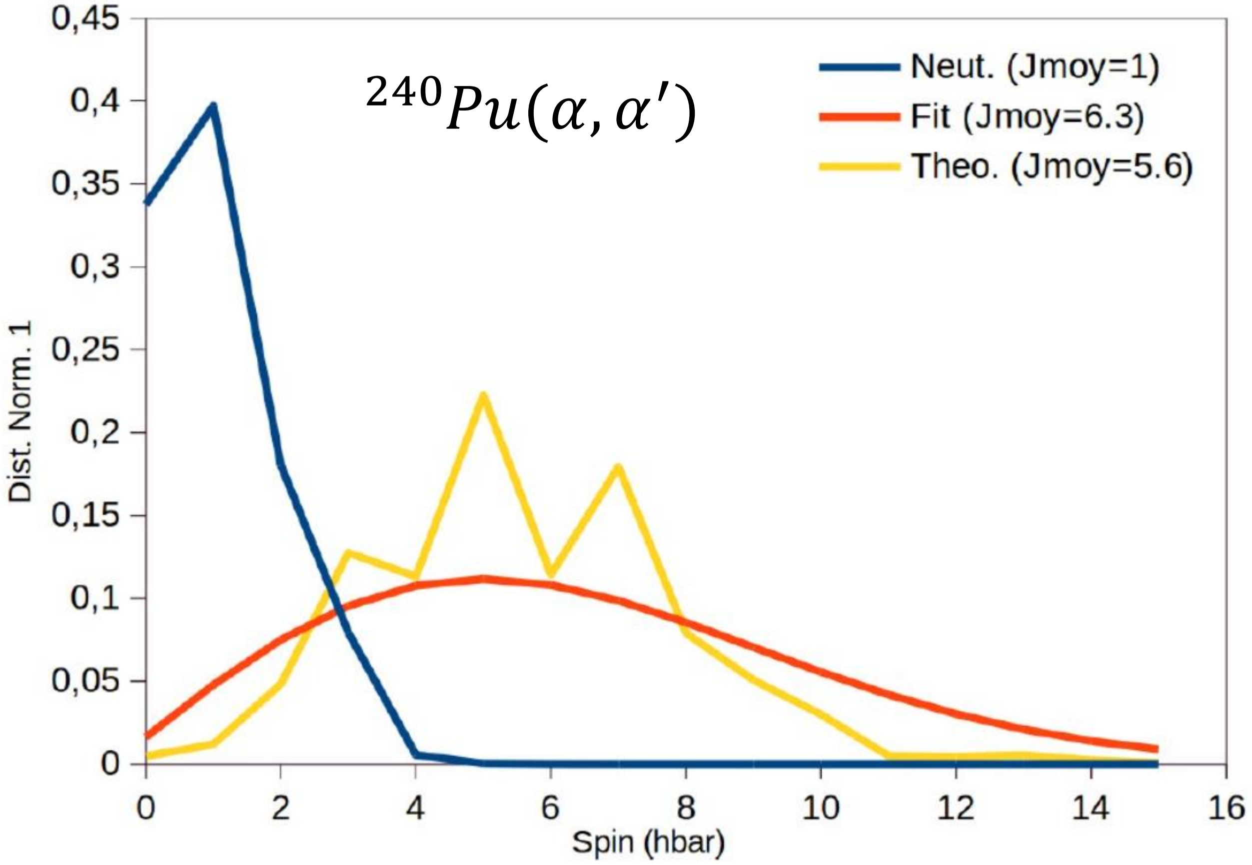
$\updownarrow$?

$$P^{\text{sur}}_\chi(E^*)$$



Spin-parity dependence

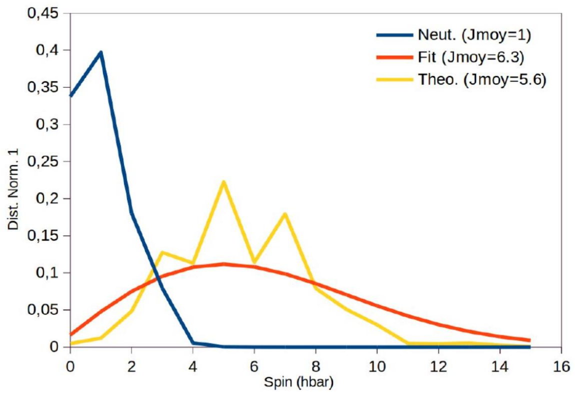
- Surrogate reactions populate higher spins

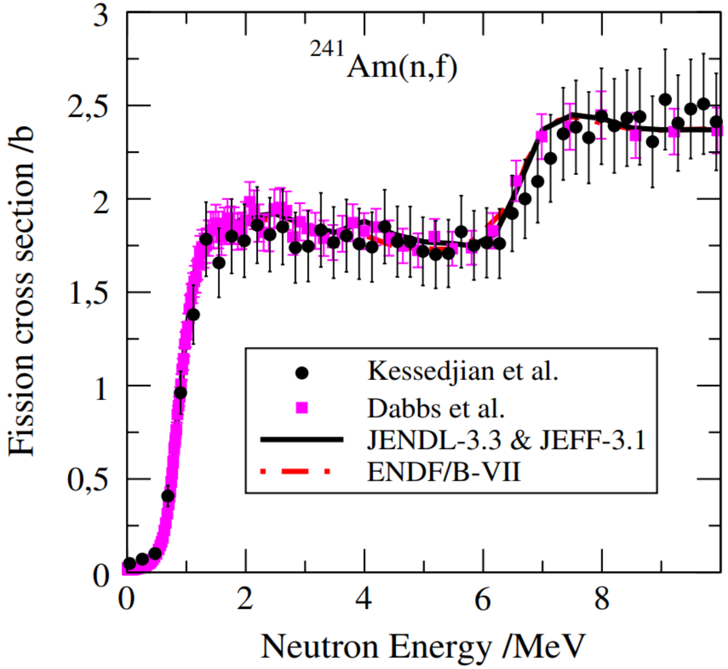


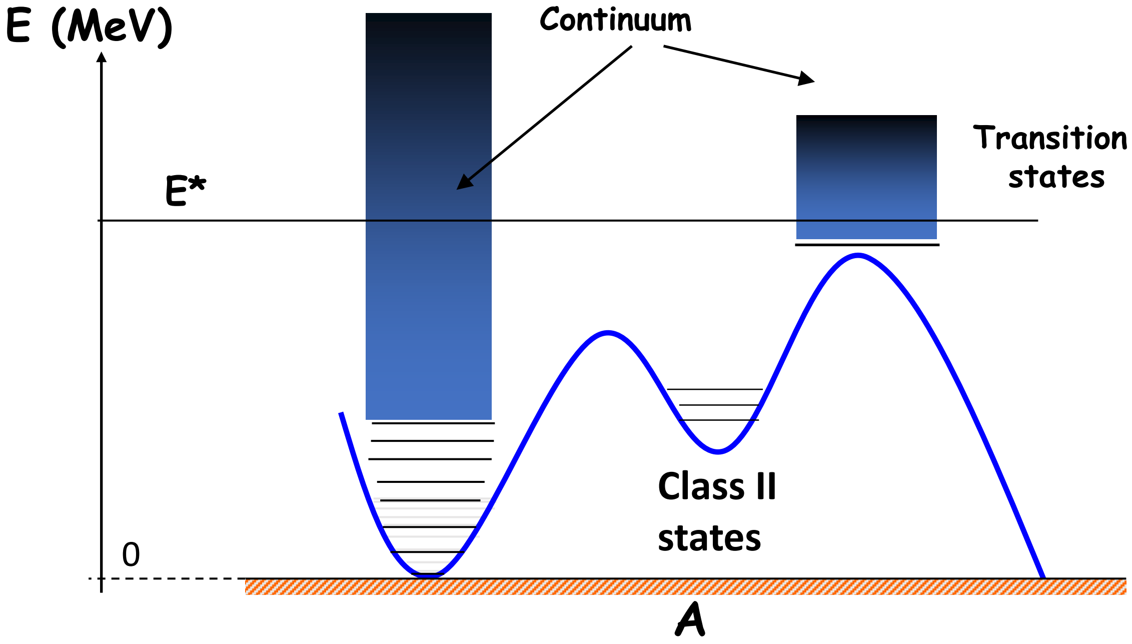
R. Perez Sanchez, (2019) PhD Thesis, U. Bordeaux

Spin-parity dependence

- Surrogate reactions populate higher spins
- Comparisons show it works for fission!



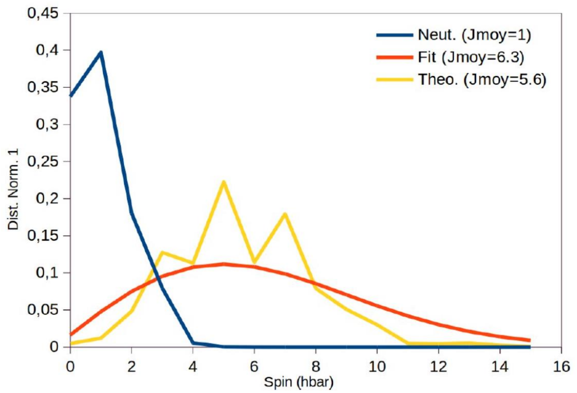


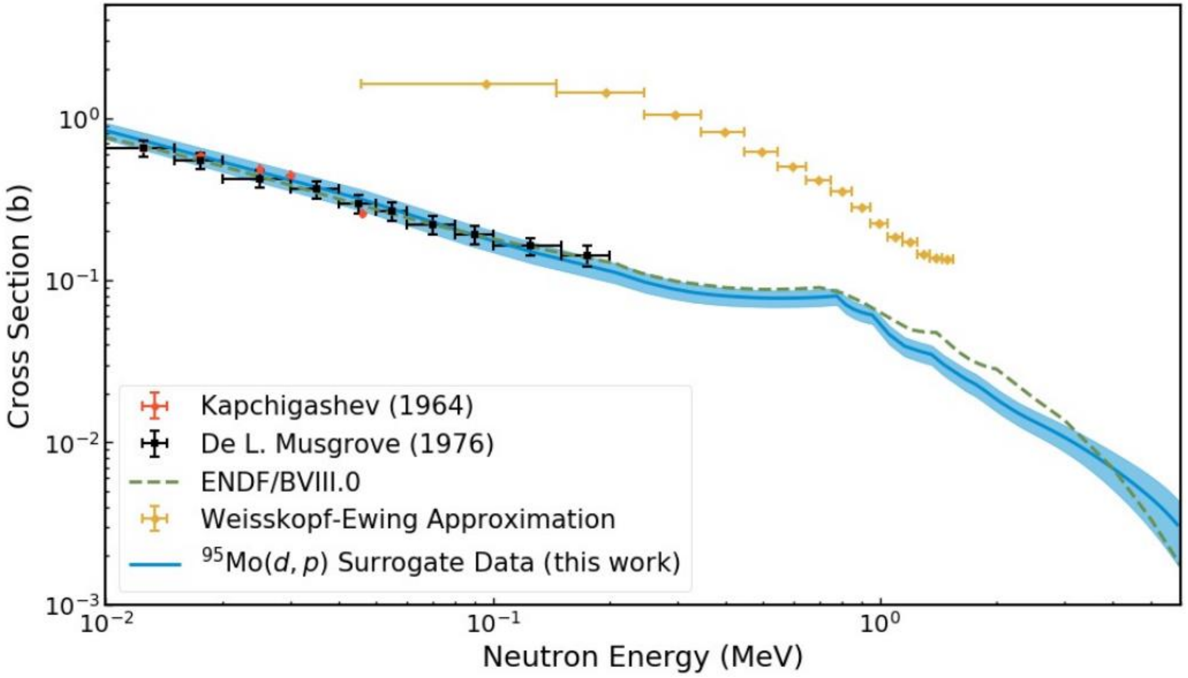


G. Kessedjian, *et al.* (2010) Phys. Lett. B 692:297-301

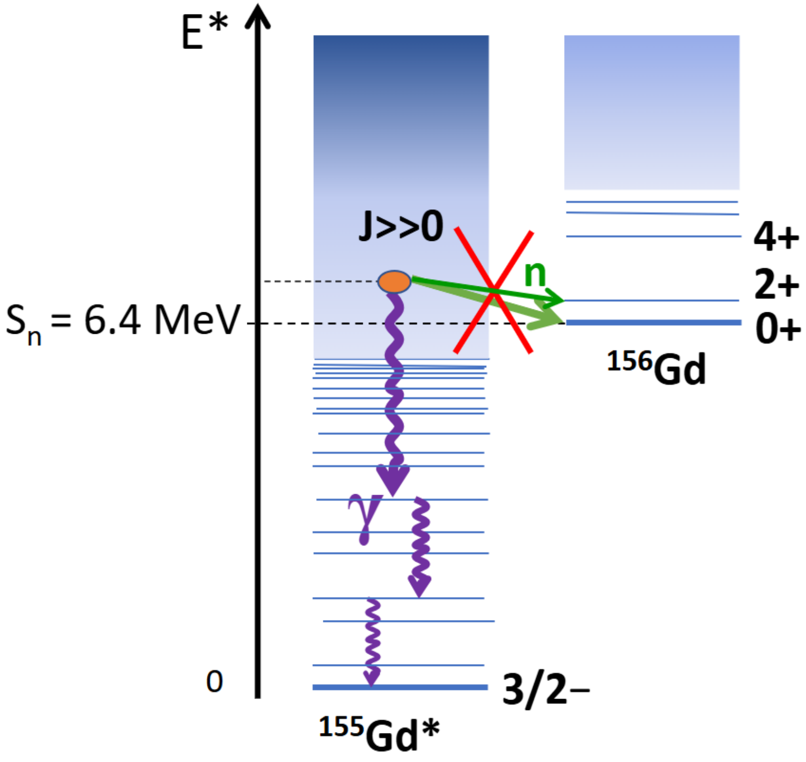
Spin-parity dependence

- Surrogate reactions populate higher spins
- Not so much for neutron capture...





Ratkiewicz, *et al.* (2019) Phys. Rev. Lett. 122:052502

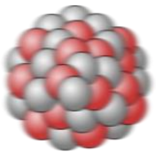


The modern surrogate reaction method

- Even if $P_n(E^*) \neq P_{\text{sur}}(E^*)$, measuring $P_{\text{sur}}(E^*)$ is still useful
- Method developed by Andrew Ratkiewicz, Jutta Escher and Richard Hughes at LLNL

$$P_{\text{sur}}(E^*)$$

Compound nucleus

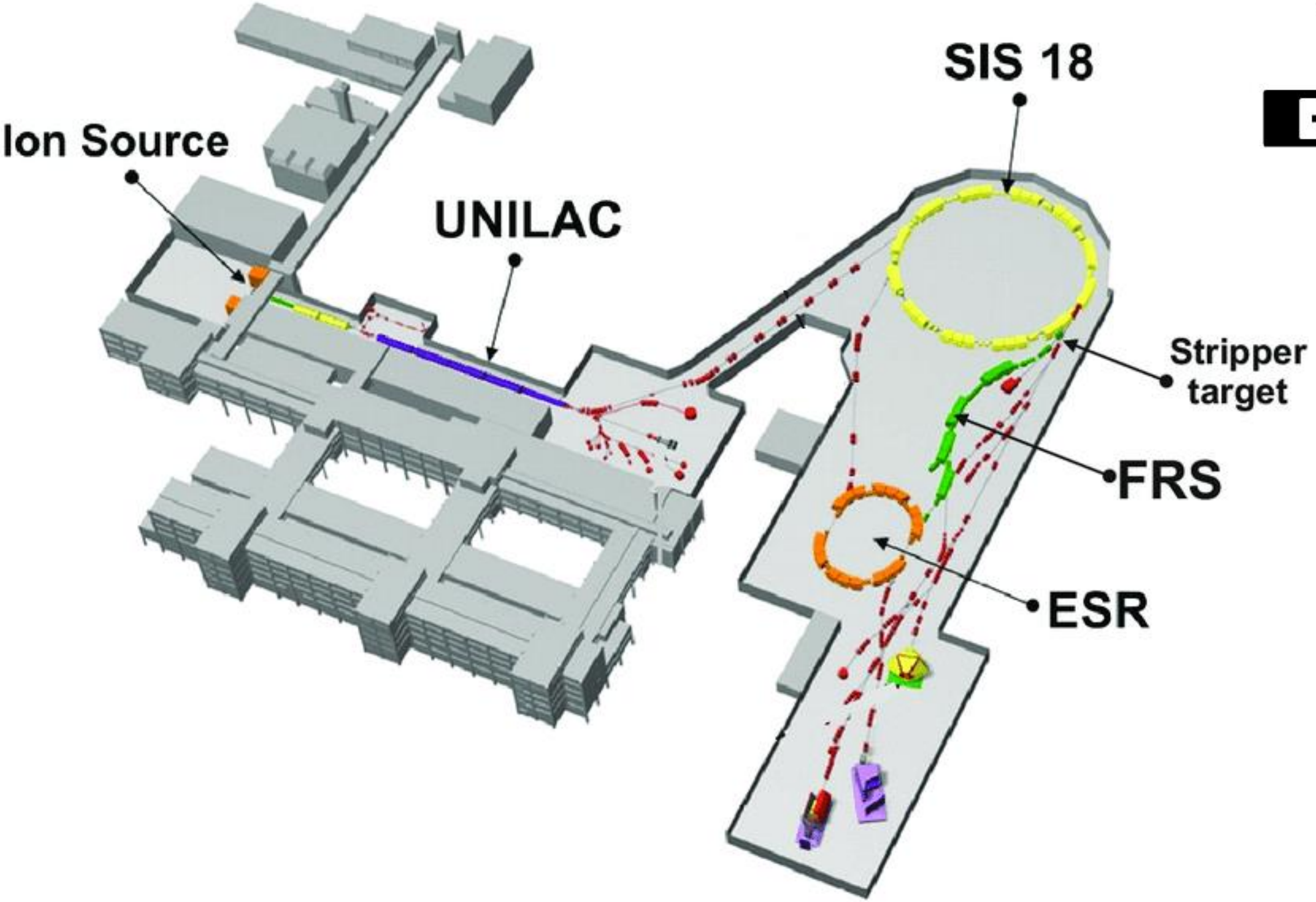


TALYS:

- Nuclear Level Density
- γ-ray Strength Function
- Fission Barriers

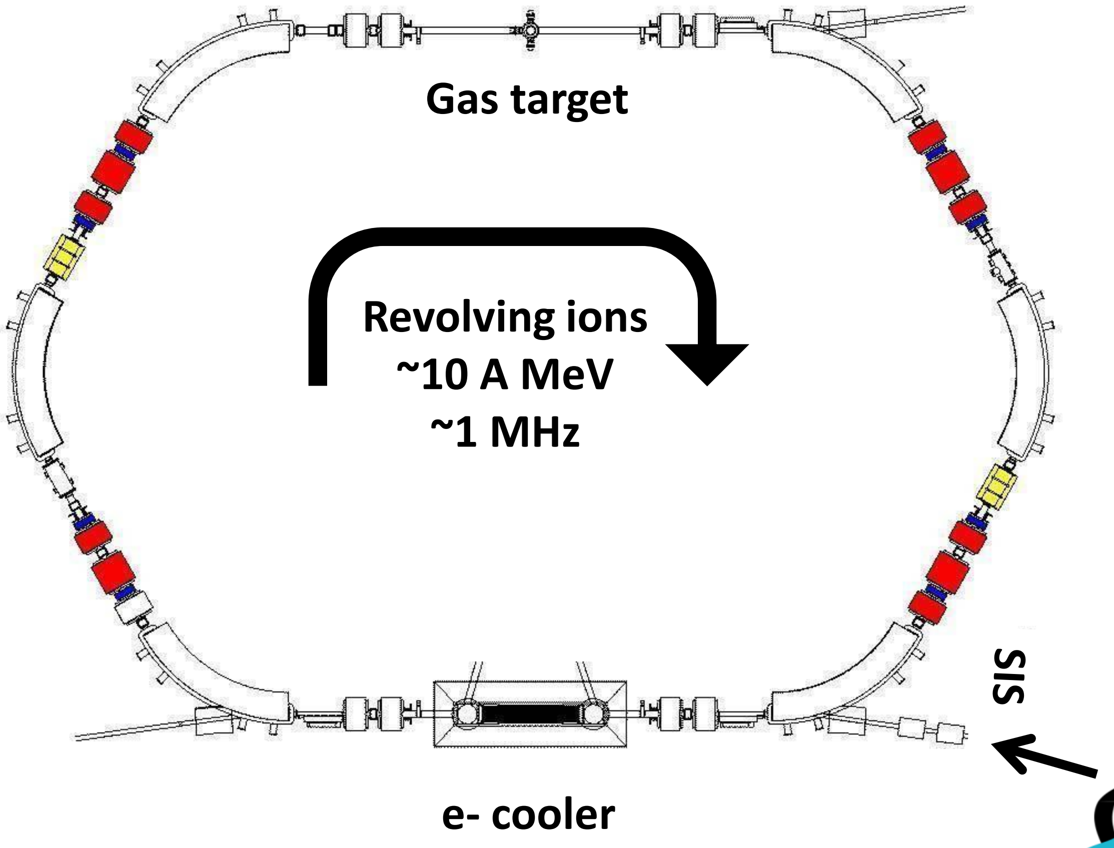
$$P_n(E^*)$$

Reactions in the ESR at GSI



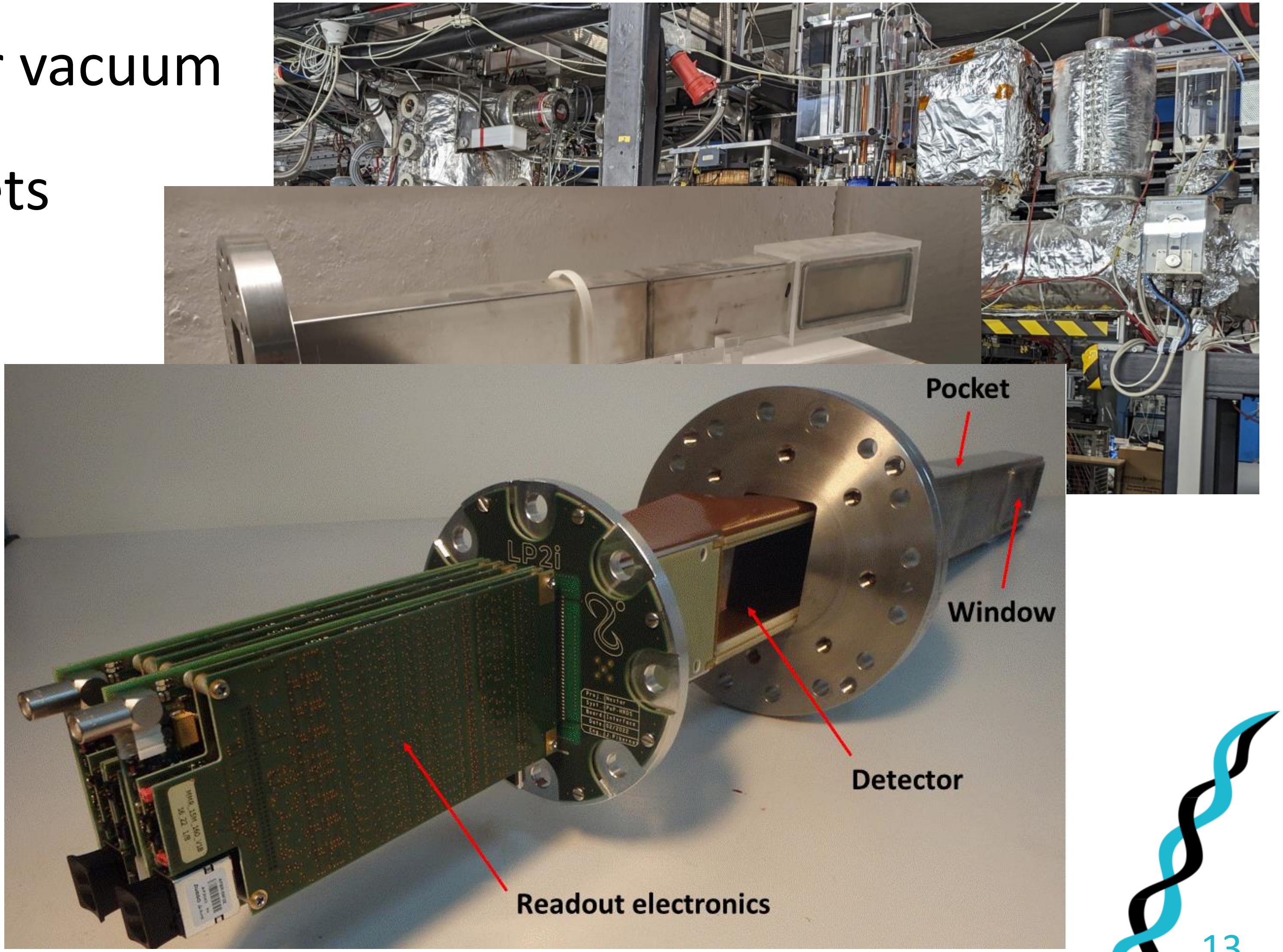
Many advantages to the storage ring

- Beam cooling maintains precise energy + position
  - even after multiple passages through target!
- Windowless, pure gas target
  - Low density of 10^{13} atoms/cm^3
  - Luminosity boosted by MHz revolution frequency
  - No background!
- Up to 100% detection efficiency



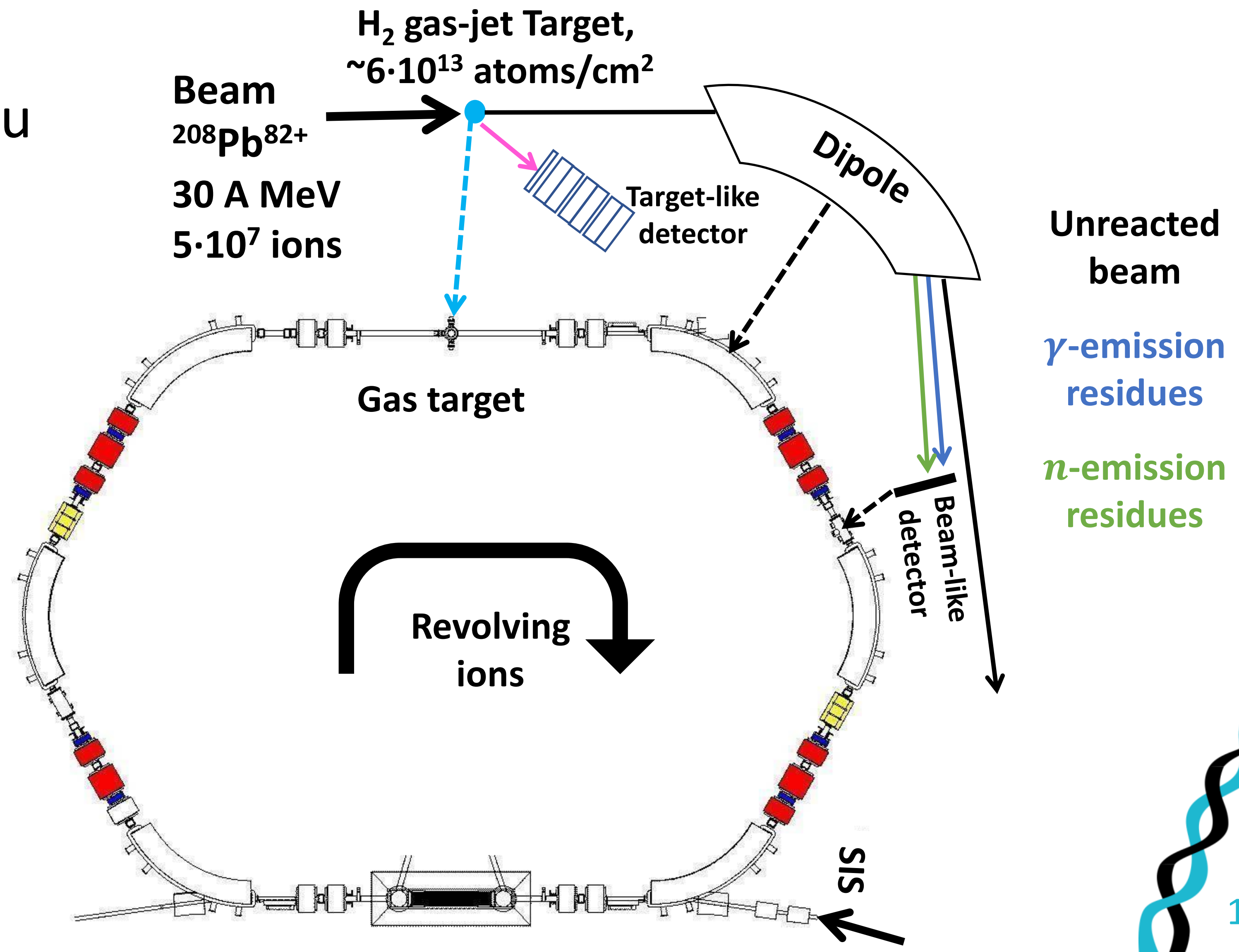
Challenges: ultra-high vacuum

- Ring maintains ~10^{-11} mbar vacuum
- Detectors inserted in pockets with 25 µm steel windows
- Severe space constraints, limited angular coverage



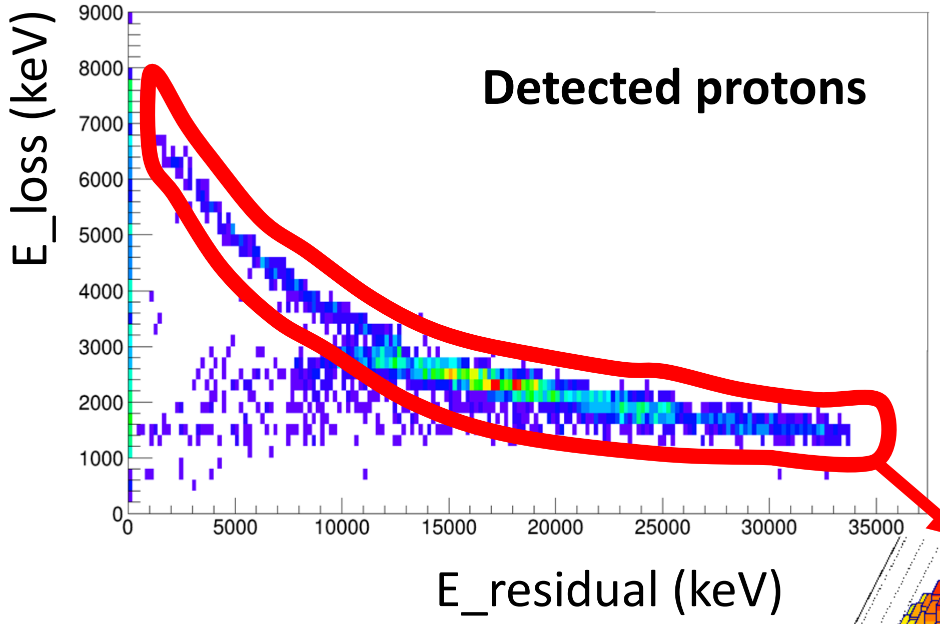
NECTAR: Surrogate reactions at the ESR

- First demonstration: ^{208}Pb(p, p') @ 30 MeV/u



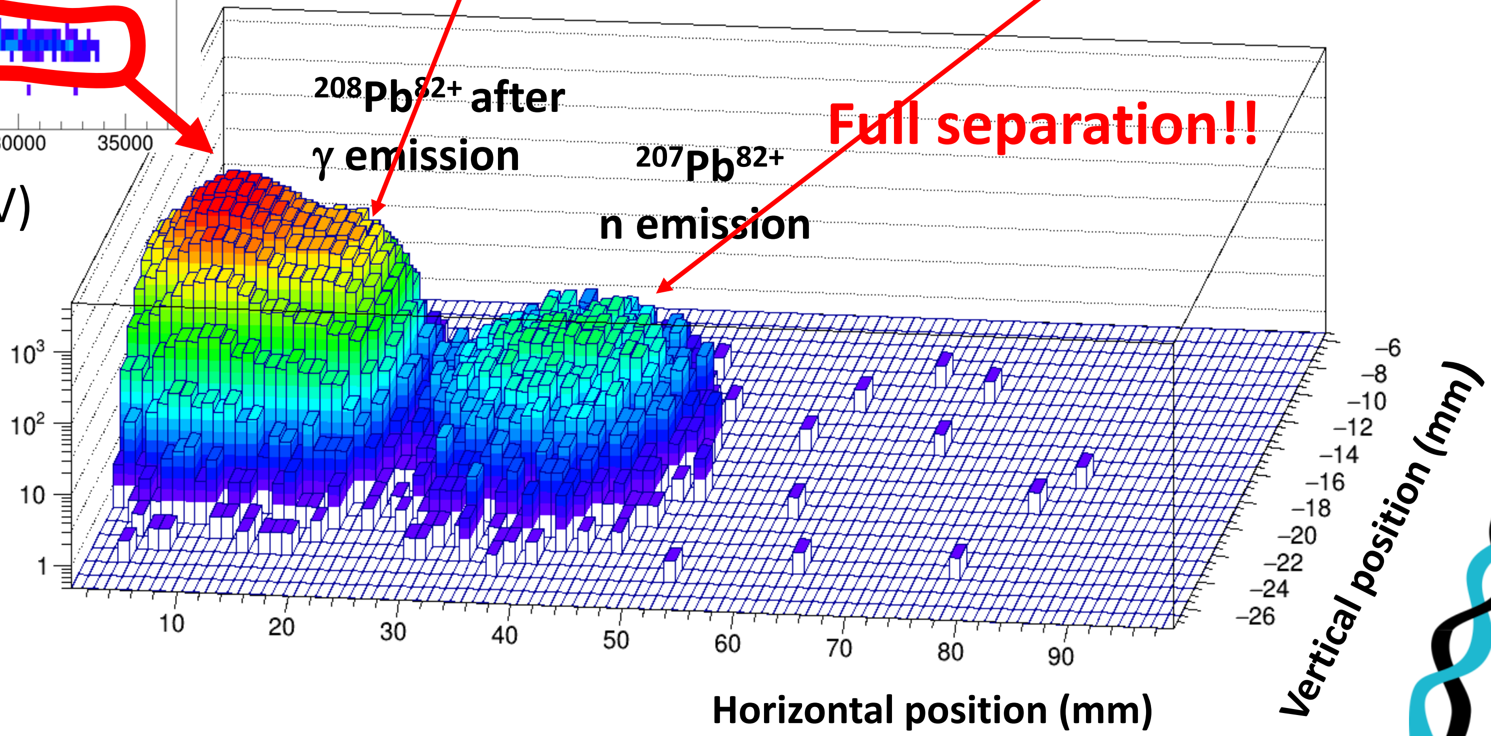
^{208}Pb(p, p') at the ESR

Analysis by Michele Sguazzin



Efficiency ~33-100%!
≈ Max 20 % in direct kinematics

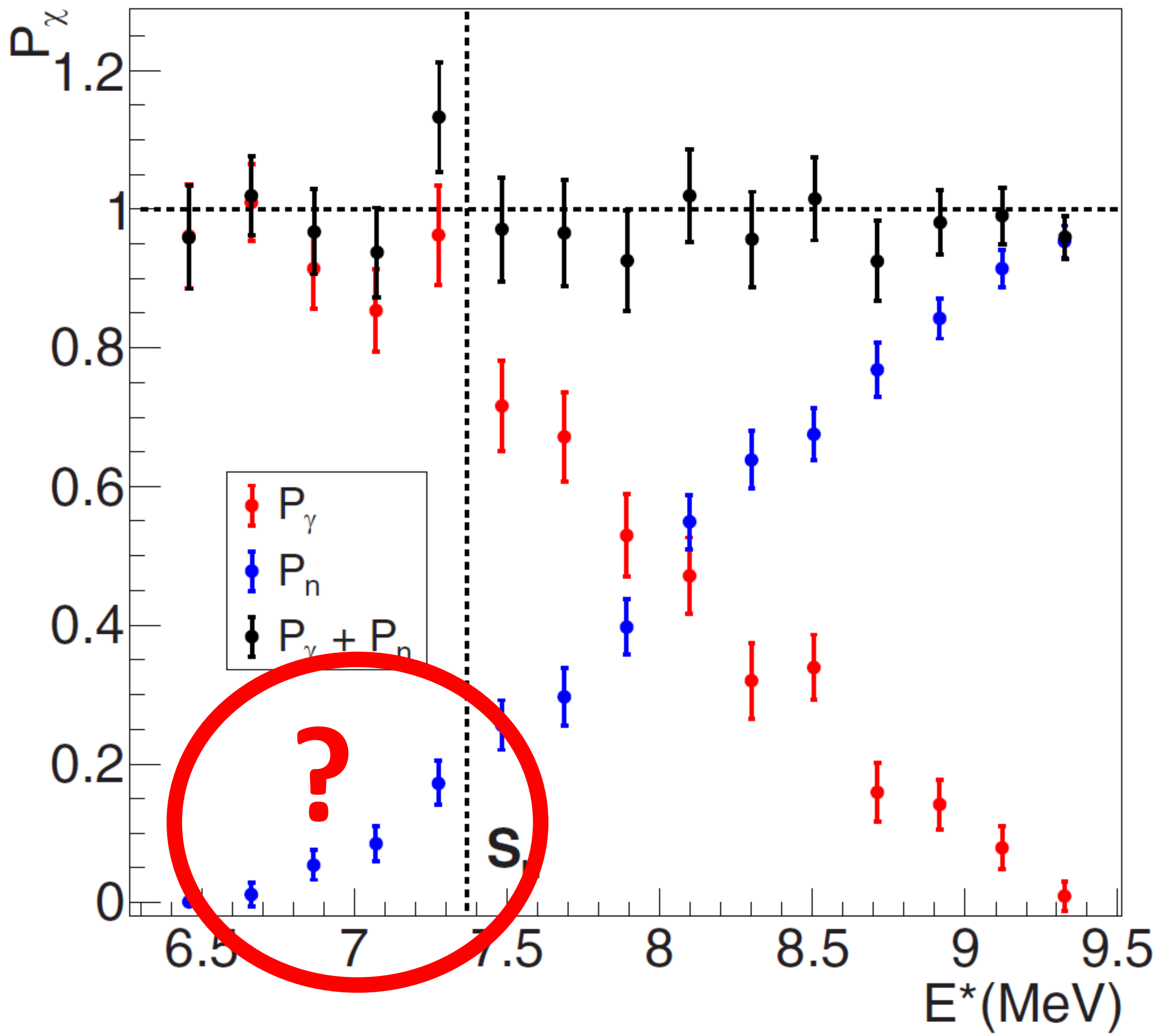
Efficiency 100%!
0% in direct kinematics…



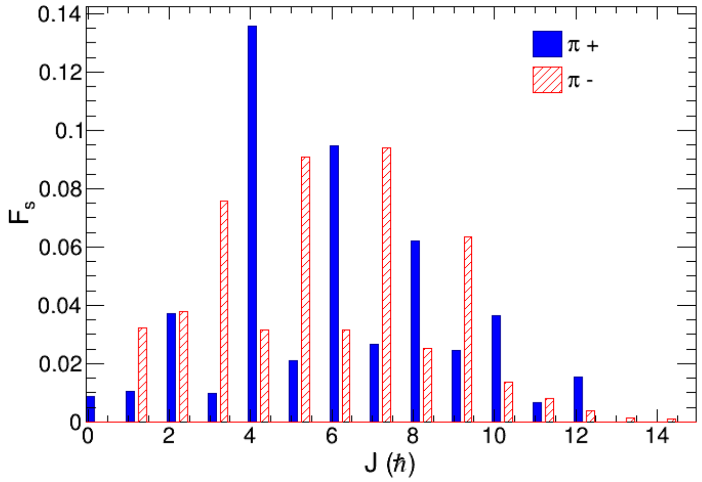
M. Sguazzin *et al.*, Phys. Rev. Lett. 134 (2025) 072501

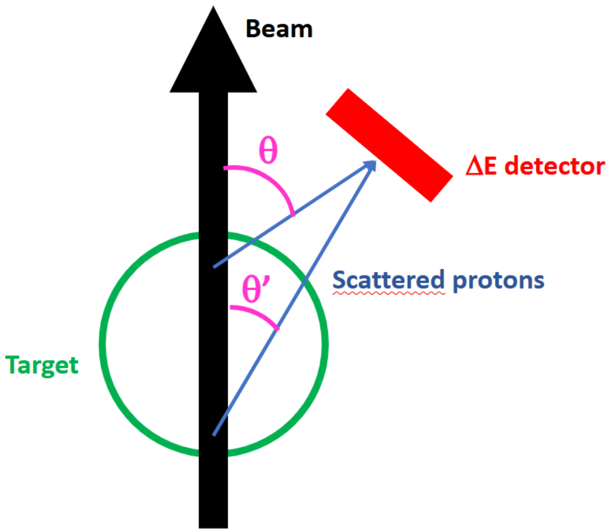
M. Sguazzin *et al.*, Phys. Rev. C 111 (2025) 024614

^{208}Pb(p, p') Results!



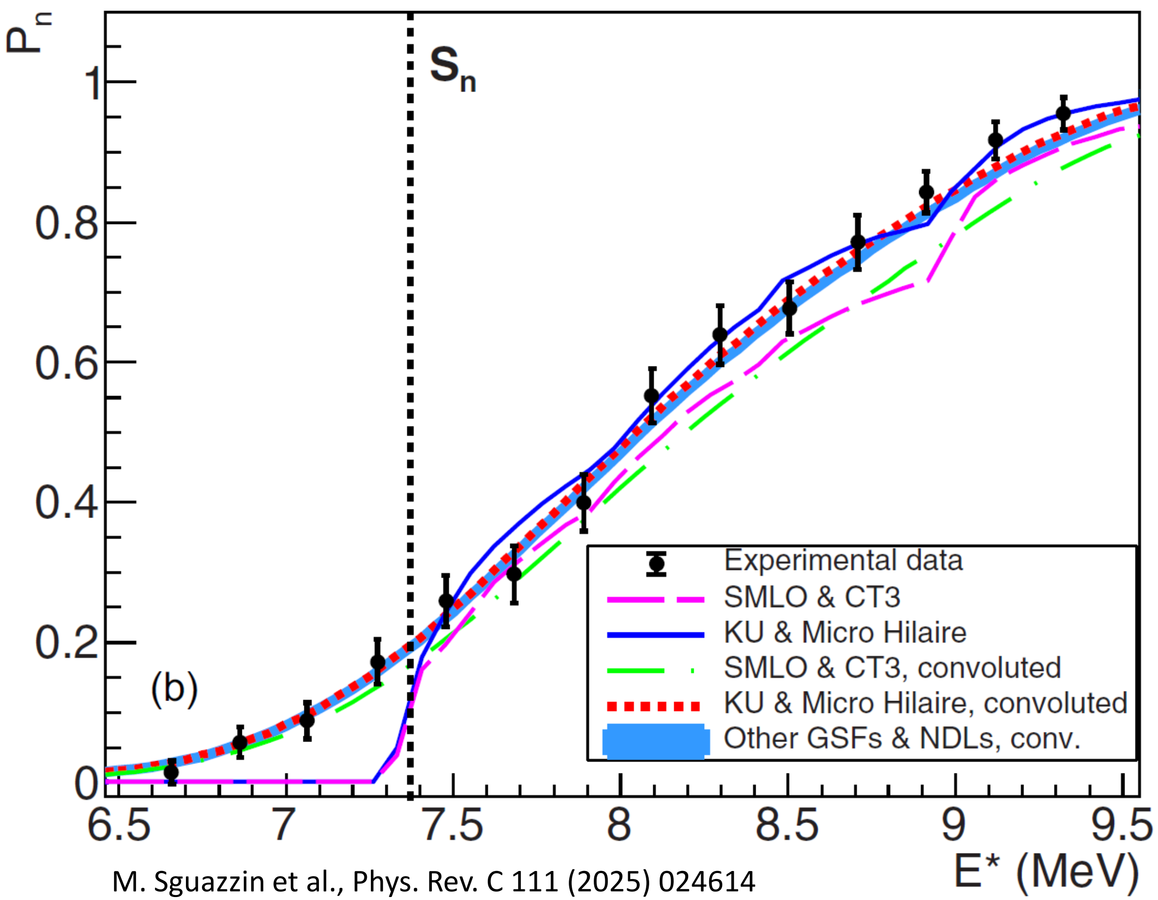
- Spin populations calculated by Marc Dupuis (CEA-DAM)





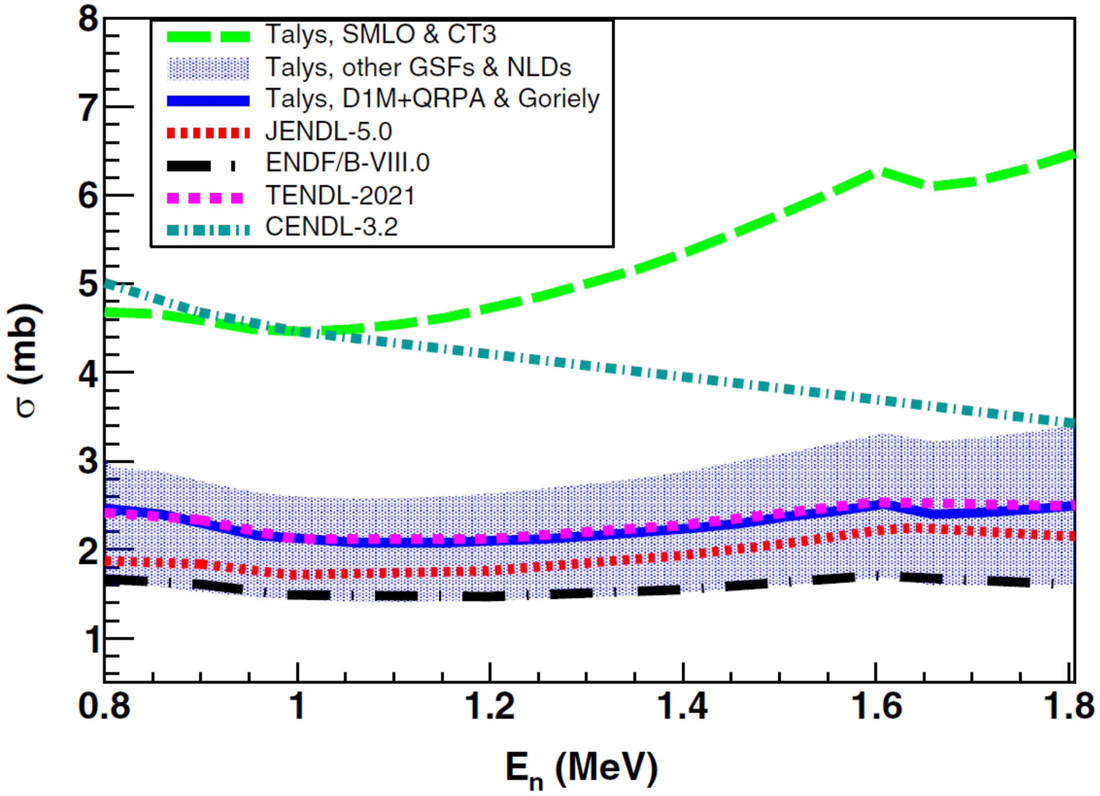
^{208}Pb(p, p') Results: TALYS Comparisons

Surrogate probability



M. Sguazzin et al., Phys. Rev. C 111 (2025) 024614

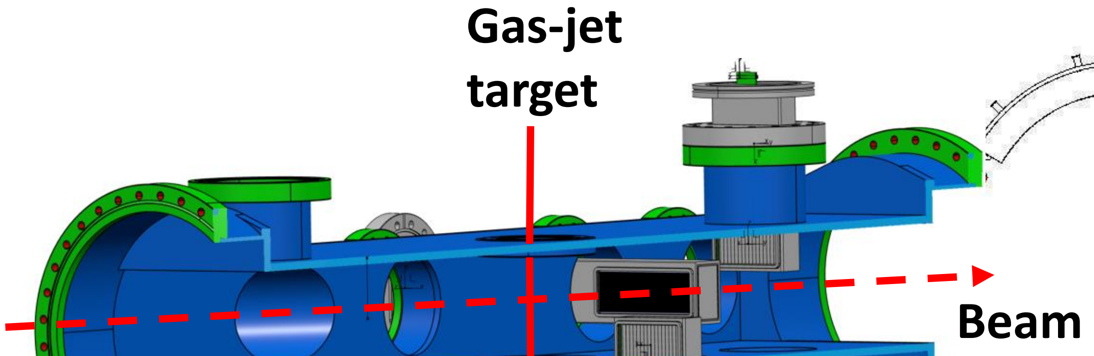
(n, γ) cross section

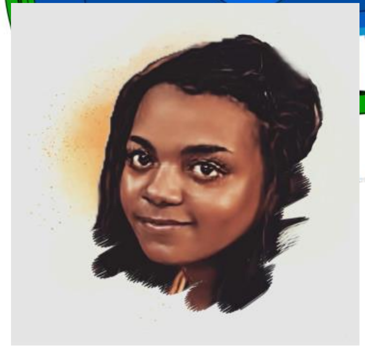


M. Sguazzin *et al.*, Phys. Rev. Lett. 134 (2025) 072501

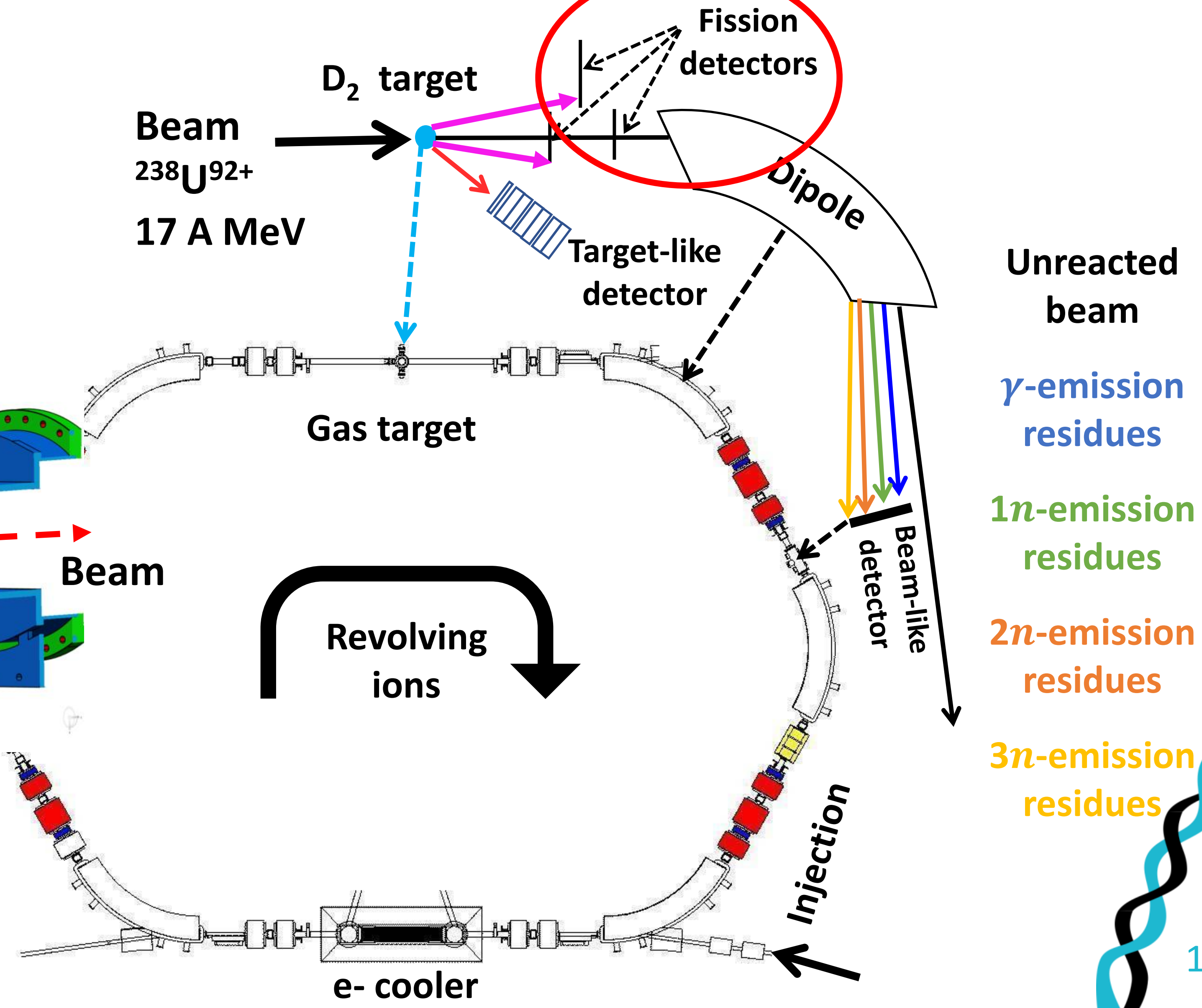
NECTAR: Surrogate reactions at the ESR

- Second demonstration: $^{238}U(d, p)$ & $^{238}U(d, d')$ @ 17 MeV/u

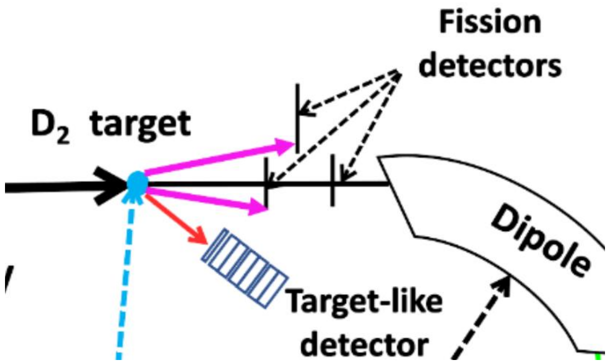


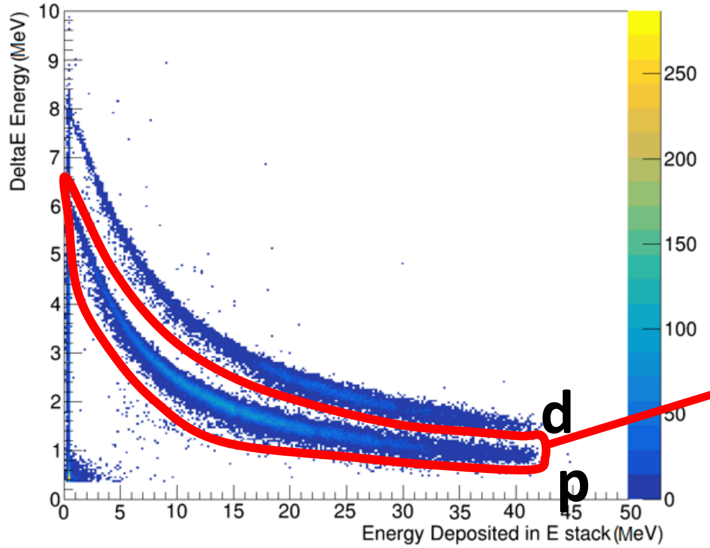


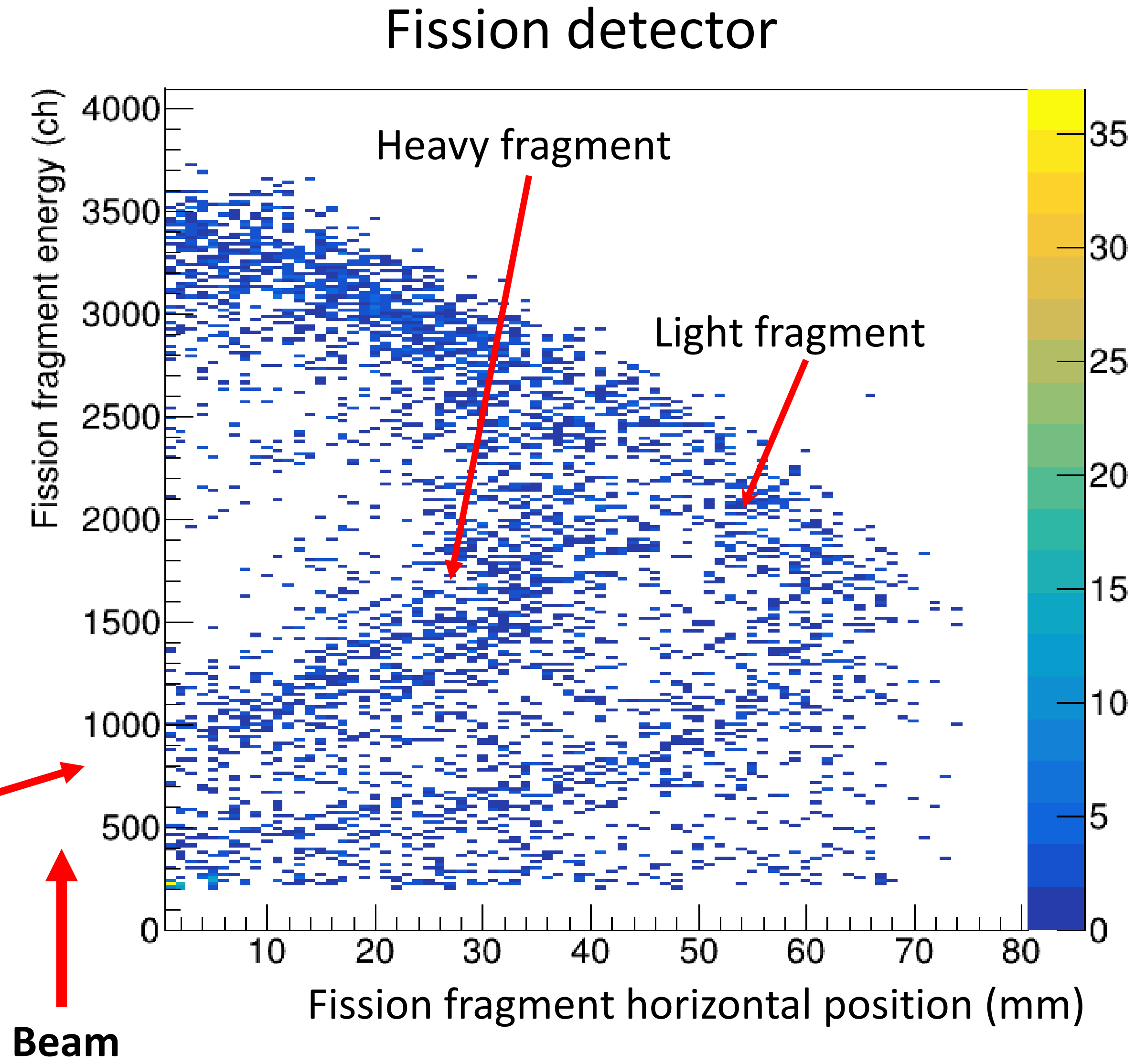
Analysis by Camille Berthelot & Boguslav Wloch



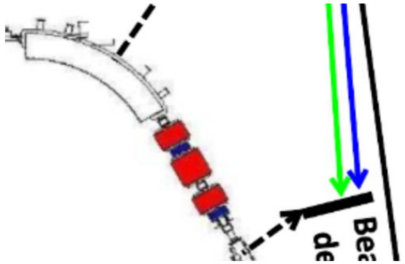
First time fission is studied in a storage ring!





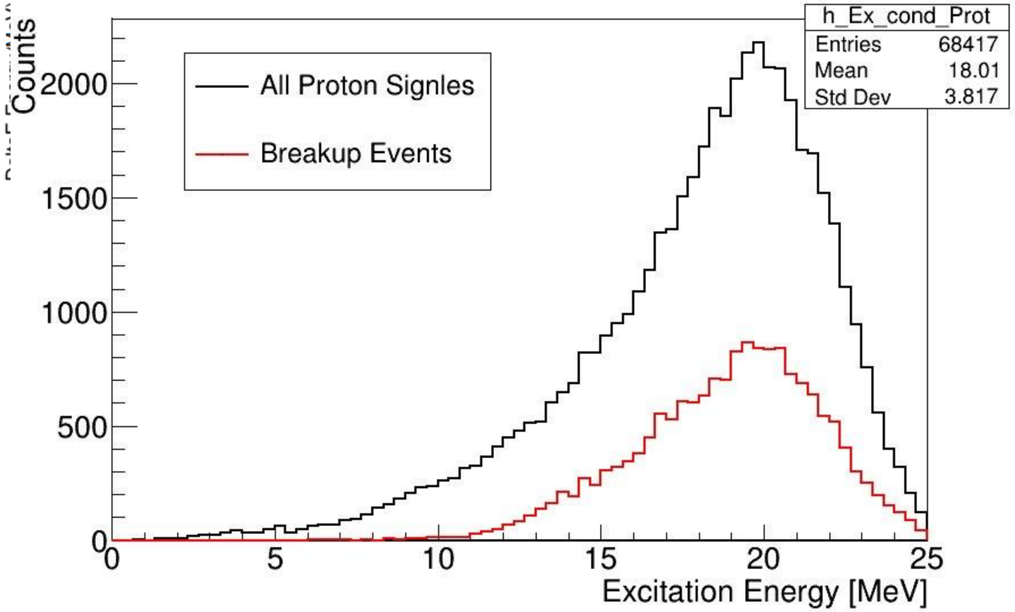


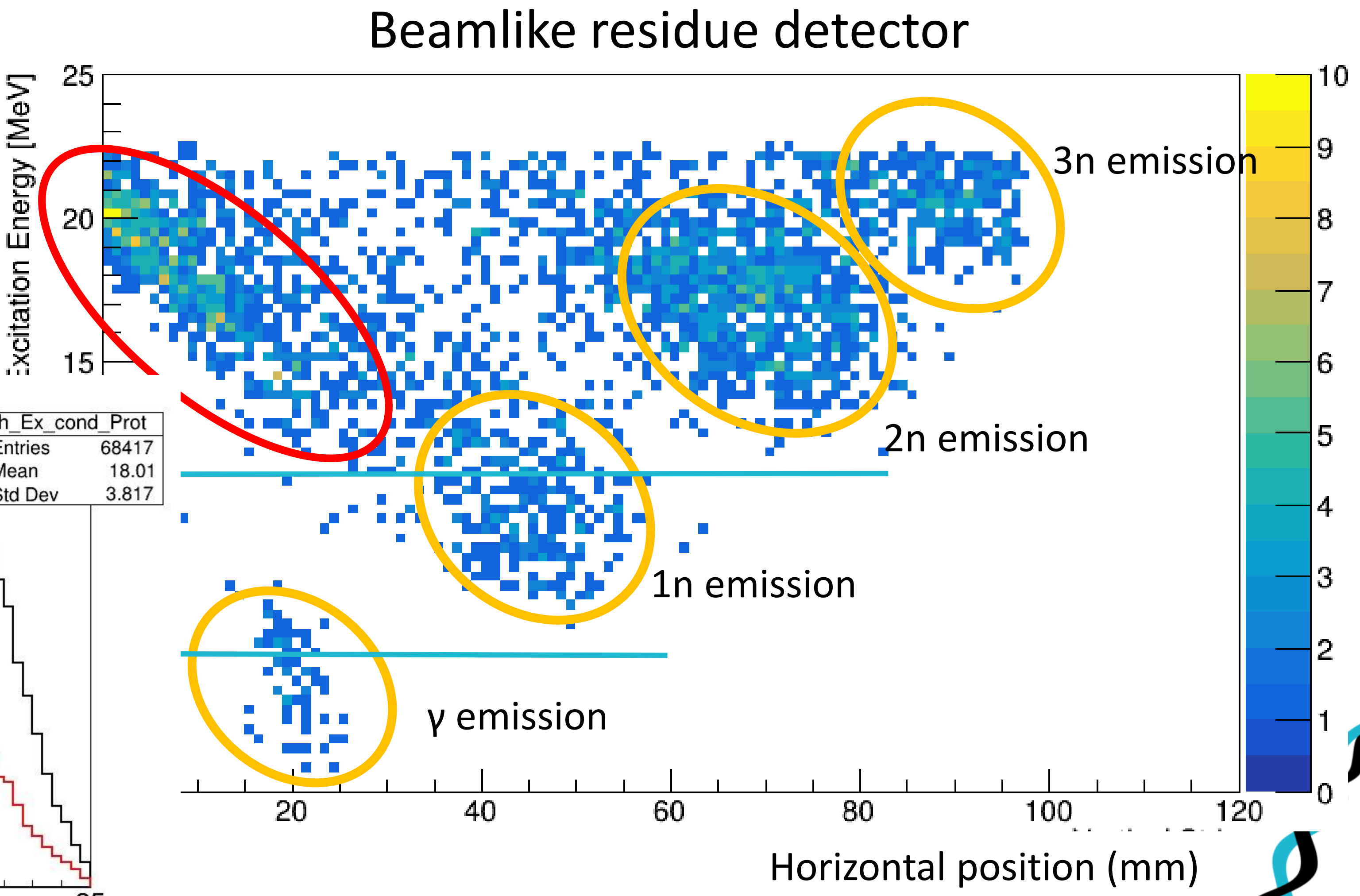
100% efficiency for γ and n emission!



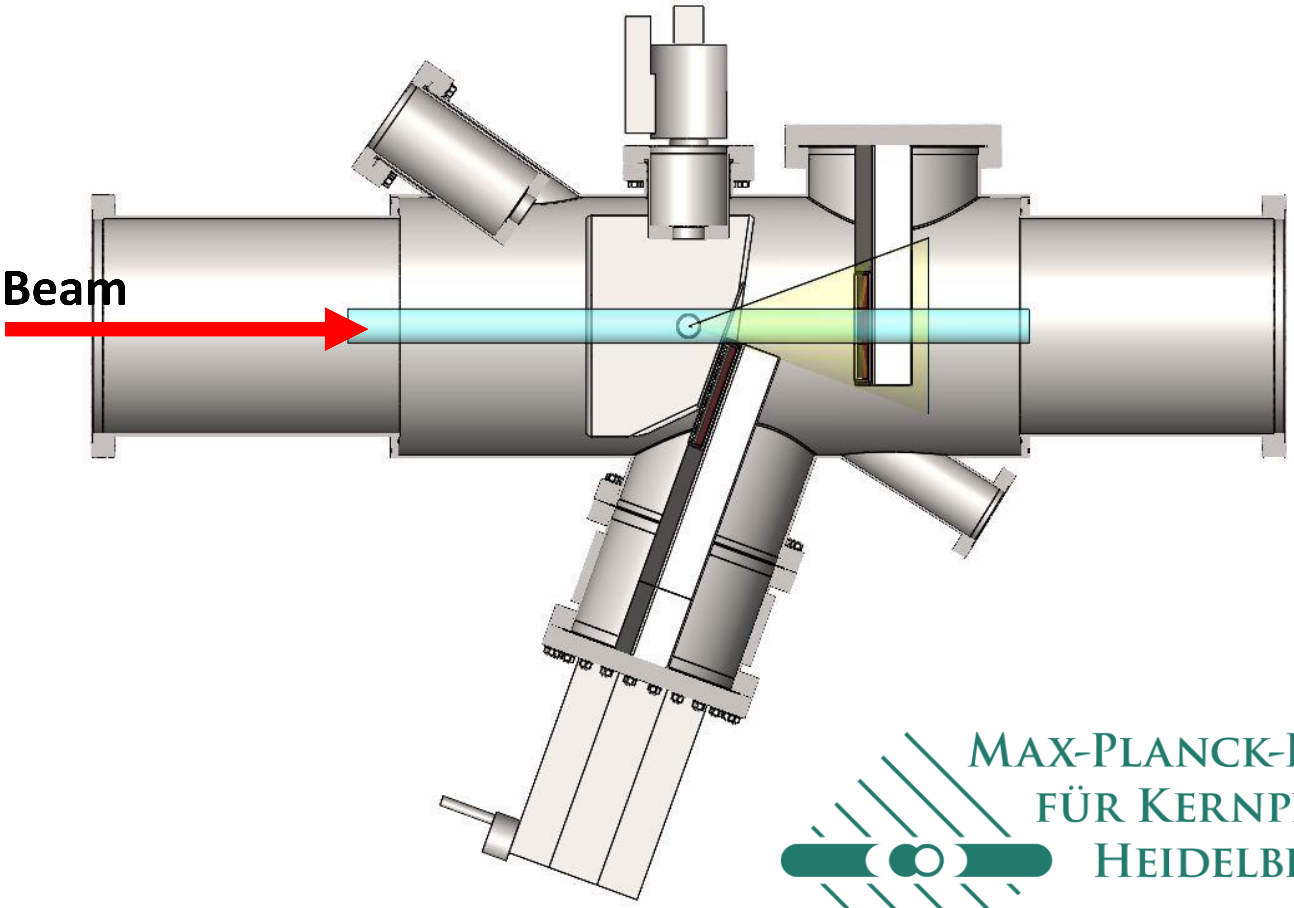
Deuteron breakup:

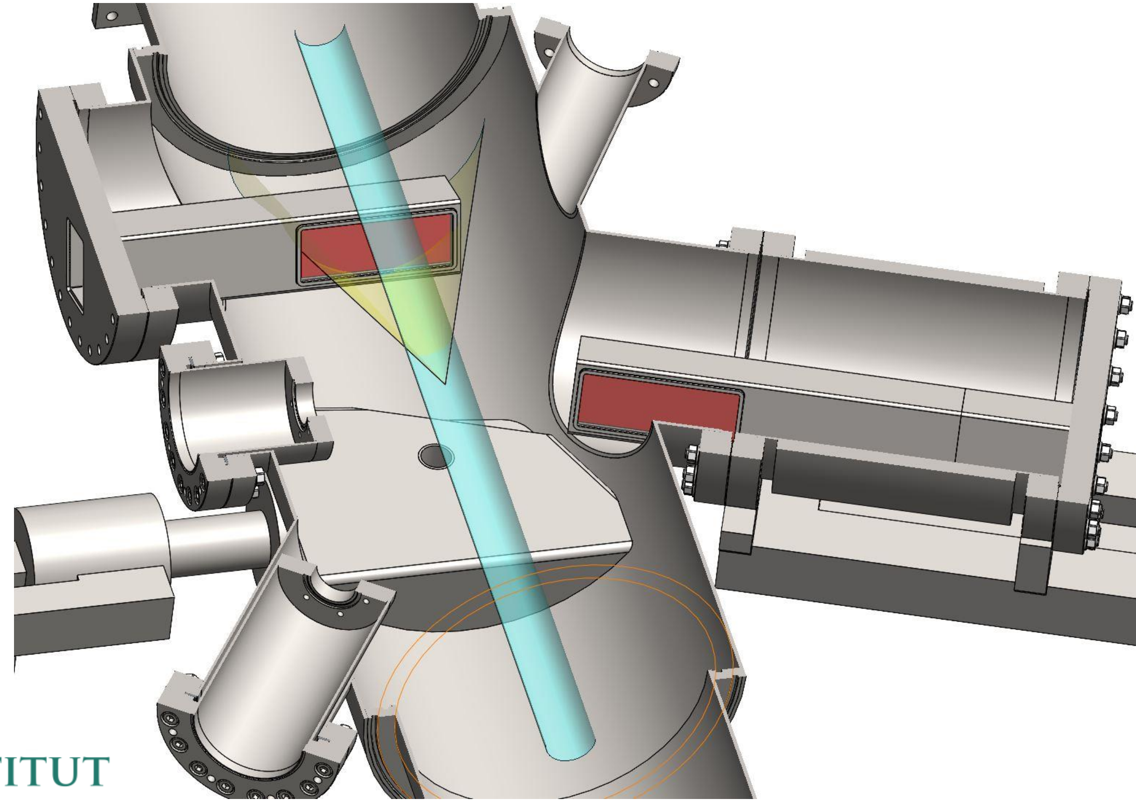
$^{238}U + d \rightarrow {}^{238}U + p + n$





Outlook: a new ESR reaction chamber





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Thank you, **Merci**

The NECTAR Team

European Research Council
Established by the European Commission

NECTAR
Nuclear rEaCTions At storage Rings

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11-GANIL, France
12-University of Osaka, Japan
13-FRIB, USA

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NECTAR: Nuclear rEaCTions At storage Rings

Accord de collaboration 19-80 GSI/IN2P3

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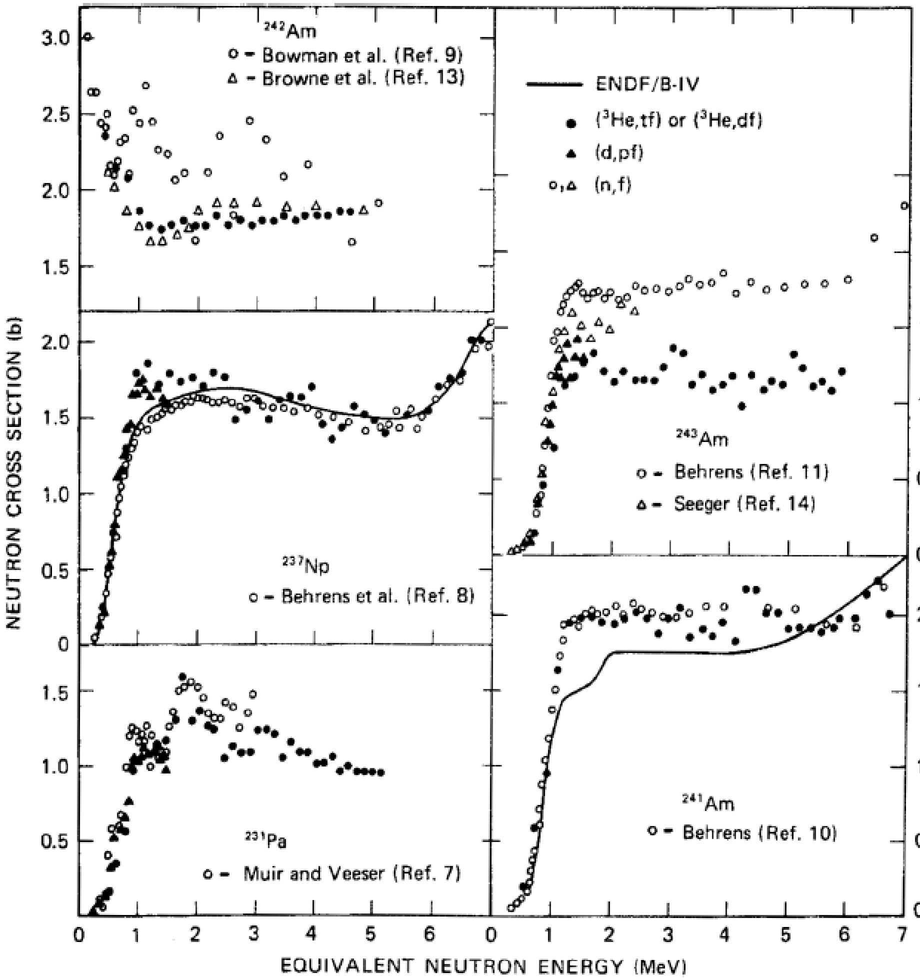
This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.

First surrogate reactions

- In 1970s, Cramer, Britt & Wilhelmy used surrogate reactions to investigate fission barrier at LANL

- Noticed that surrogate channel fission probabilities directly matched neutron-induced probabilities



Britt & Wilhelmy, 1979, Nucl. Sci. Eng. 72, 222.

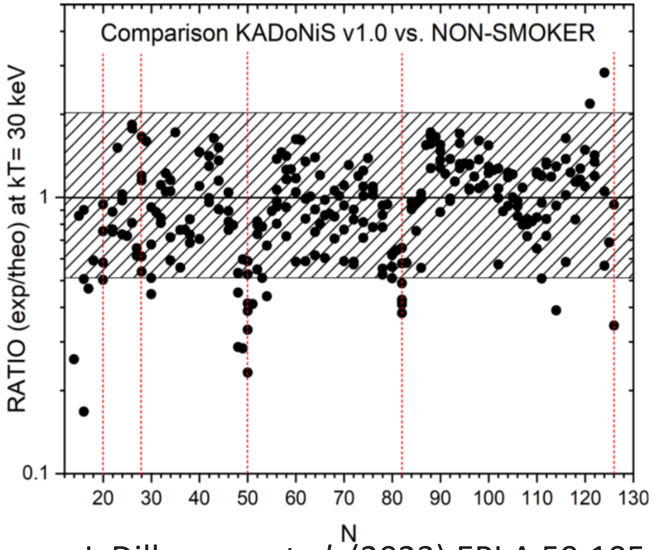
But surrogate reactions need theory?

- Yes, but we can also constrain
  1. the neutron-transmission coefficients with our probabilities
  2. The spin-parity distributions with angular cross sections

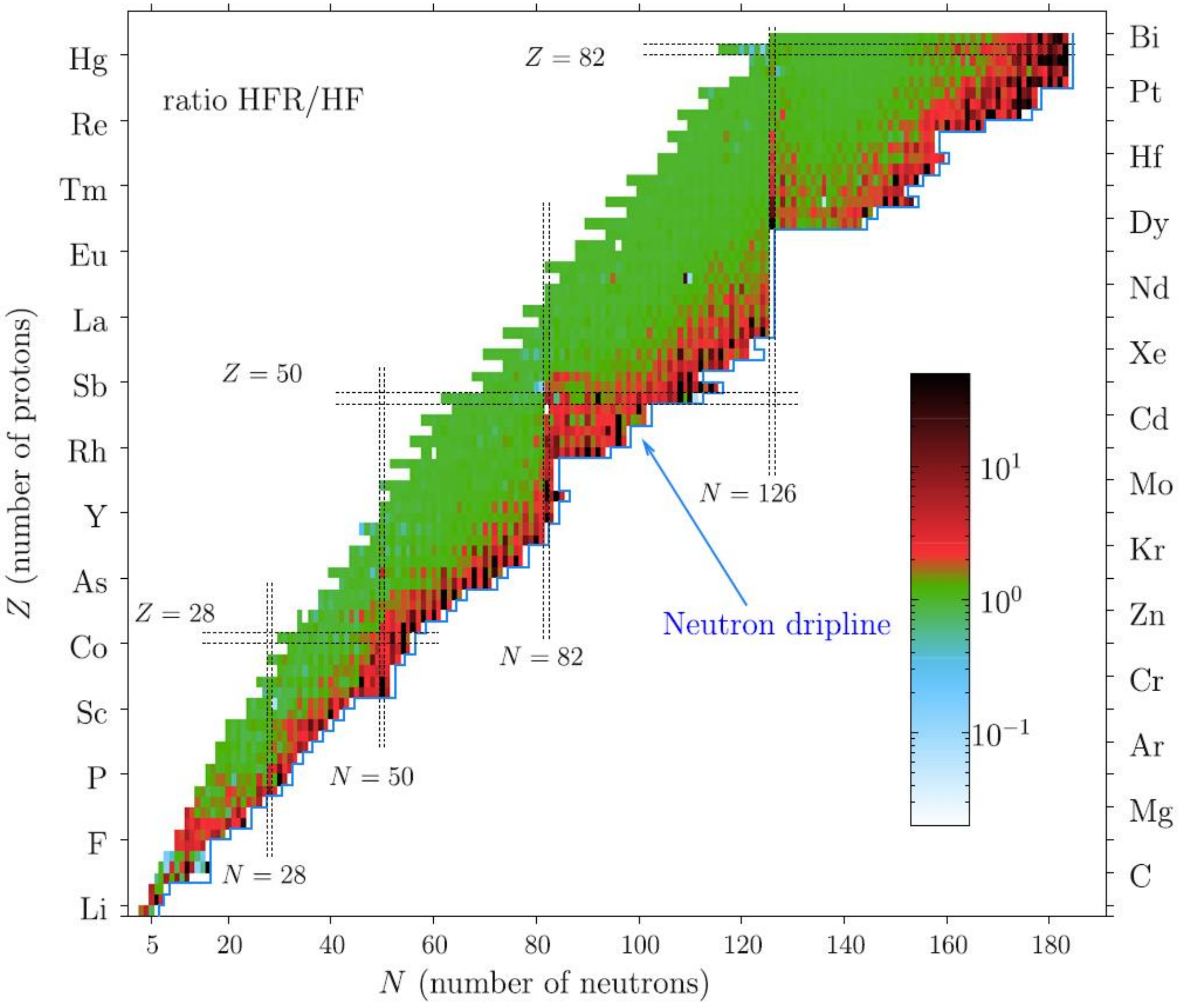
- We haven't yet studied such exotic nuclei, but the dream is to bootstrap the required theory

When does the Surrogate Method not work?

- Hauser-Feshbach assumes statistical equilibrium for CN
- Needs enough levels to be considered "statistical"
  - High neutron separation energy



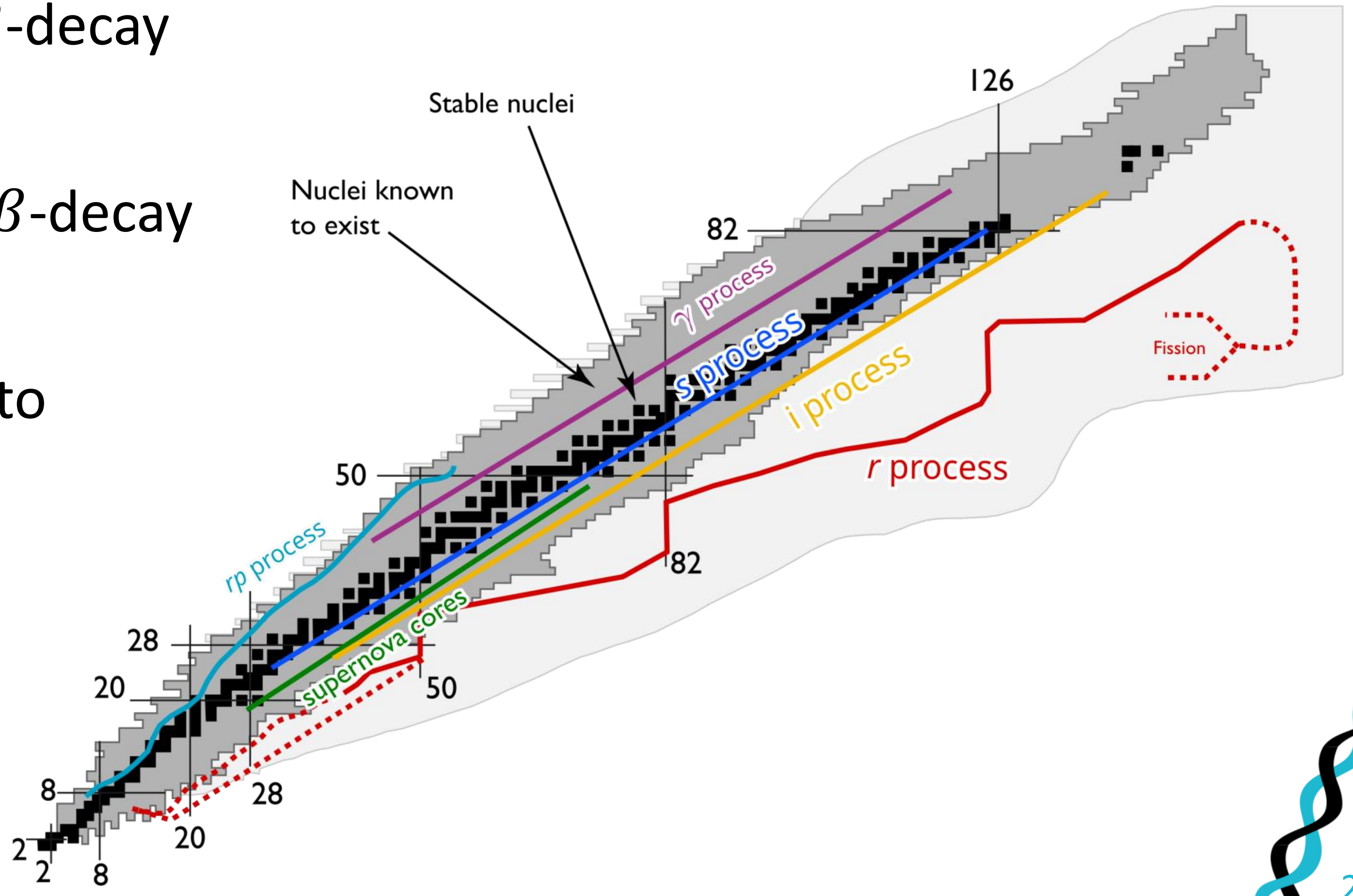
I. Dillmann, *et al.* (2023) EPJ A 59:105



D. Rochman, *et al.* (2017) Phys. Lett. B 764:109-113

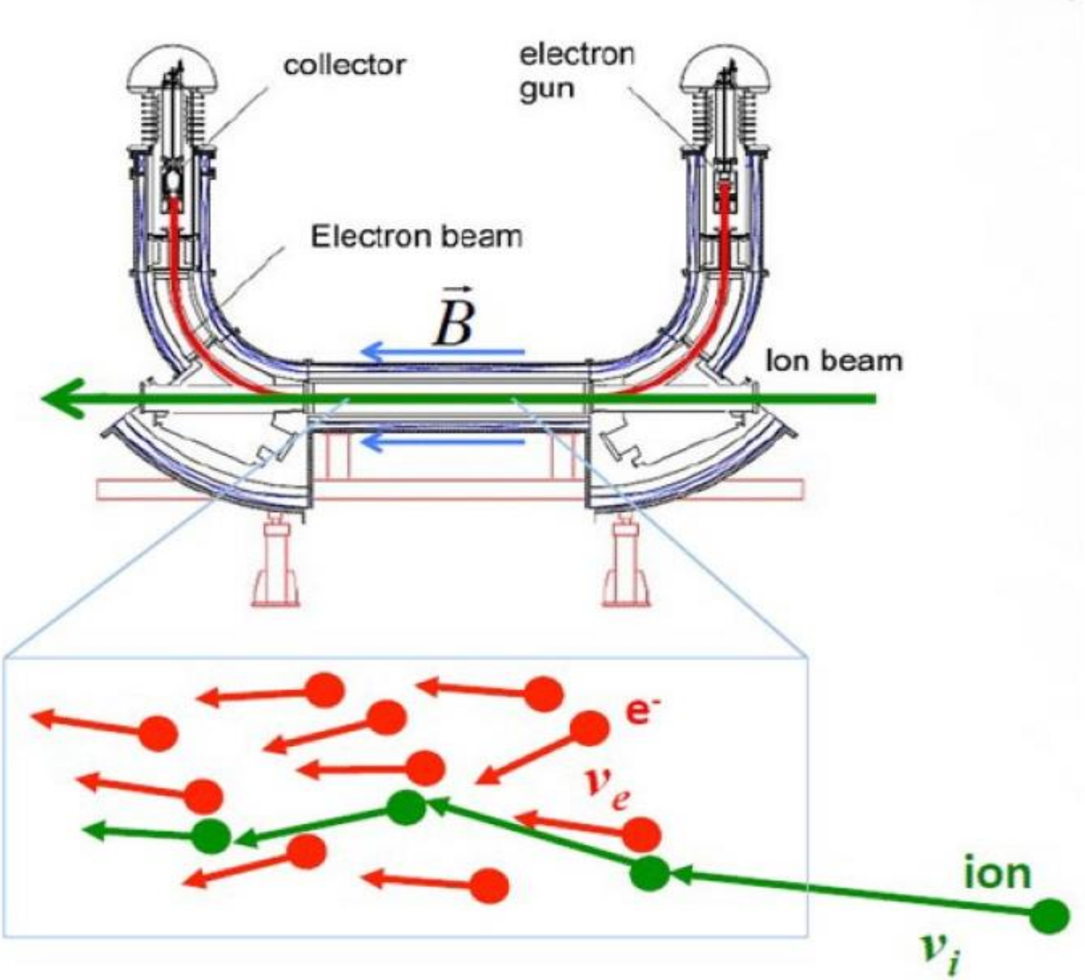
Neutron capture produces the heavy elements

- Slow compared to β-decay
  $\rightarrow$ *s* process
- Rapid compared to β-decay
  $\rightarrow$ *r* process
- Maybe an *i* process to explain early stars?



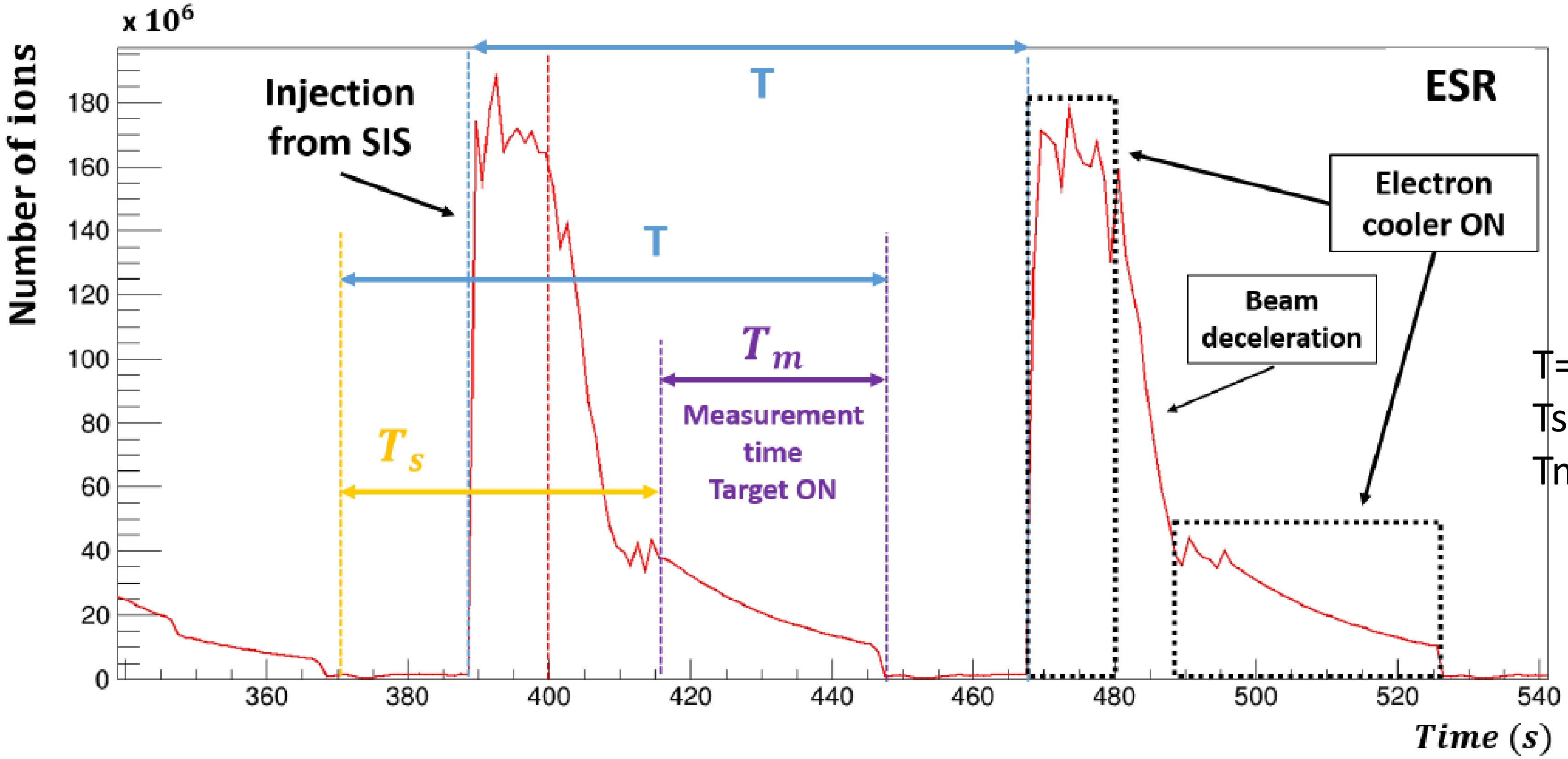
What is electron cooling?

- Newly injected beam is “hot” meaning it have large spread in position and momentum space
- “Cool” electron beam is merged in the same direction as the beam
- Velocity of the electron is made equal to the velocity of the beam
- Net heat transfer to lighter electrons
- Electrons are removed leaving original beam with lower momentum spread



Beam preparation in the ESR

- Radioactive isotopes: minimum preparation time 50 s



T= 80 s
Ts = 50 s Preparation time
Tm = 30 s Measurement time

TALYS Comparison for $^{208}Pb(p,p')$