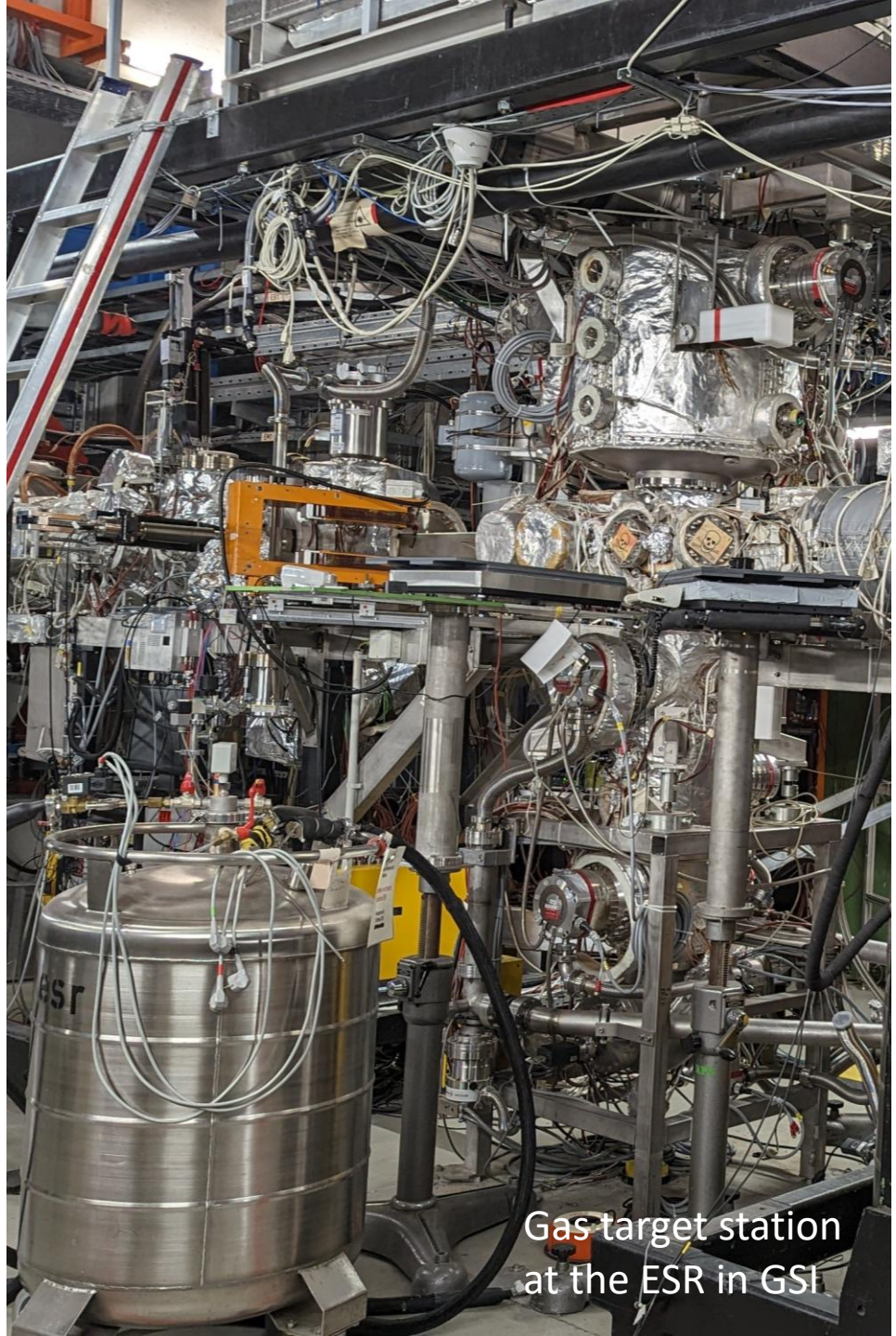
Surrogate reactions at the ESR:
the power of inverse kinematics in a storage ring

Guy Leckenby
Postdoc, LP2i Bordeaux

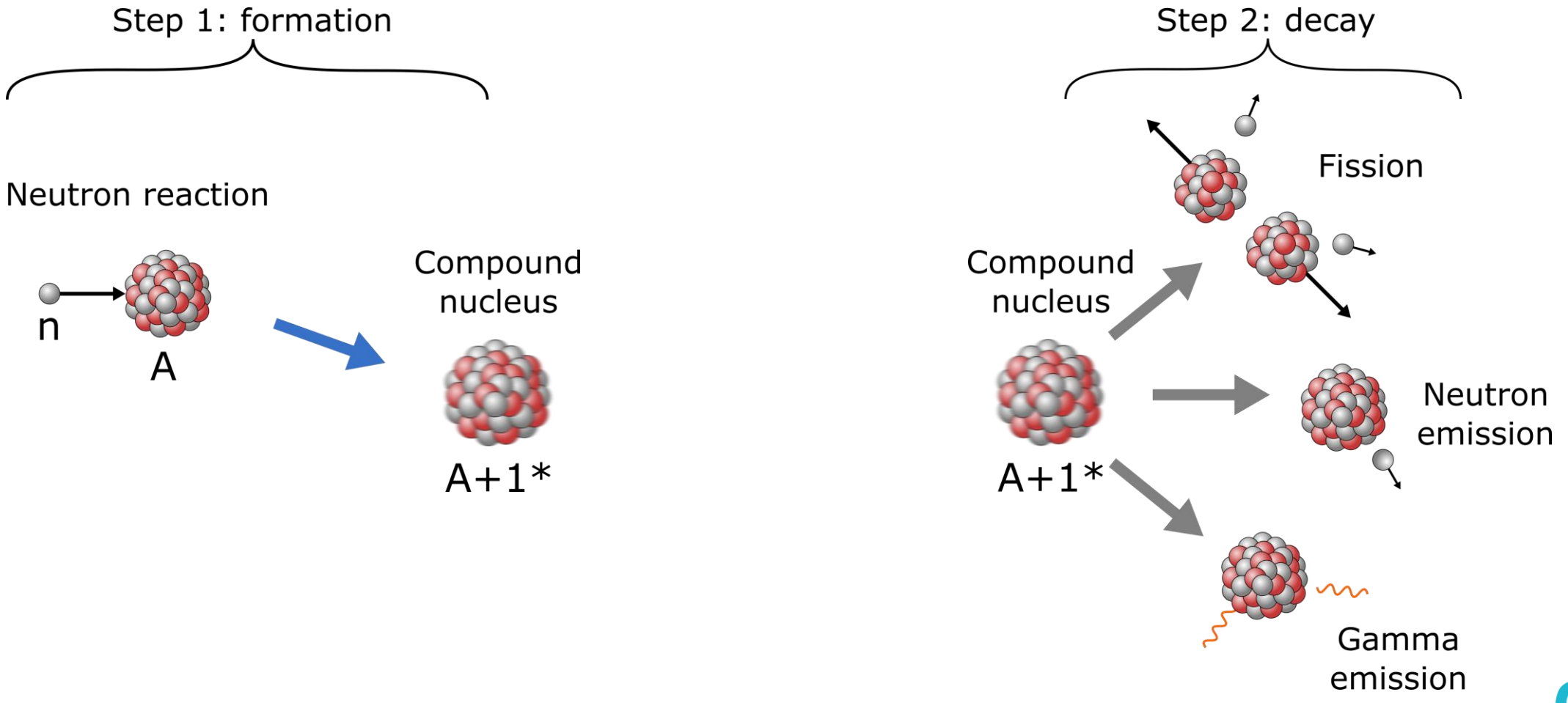
FRIB-TA Statistical Nuclear Properties Workshop
July 8th, 2026



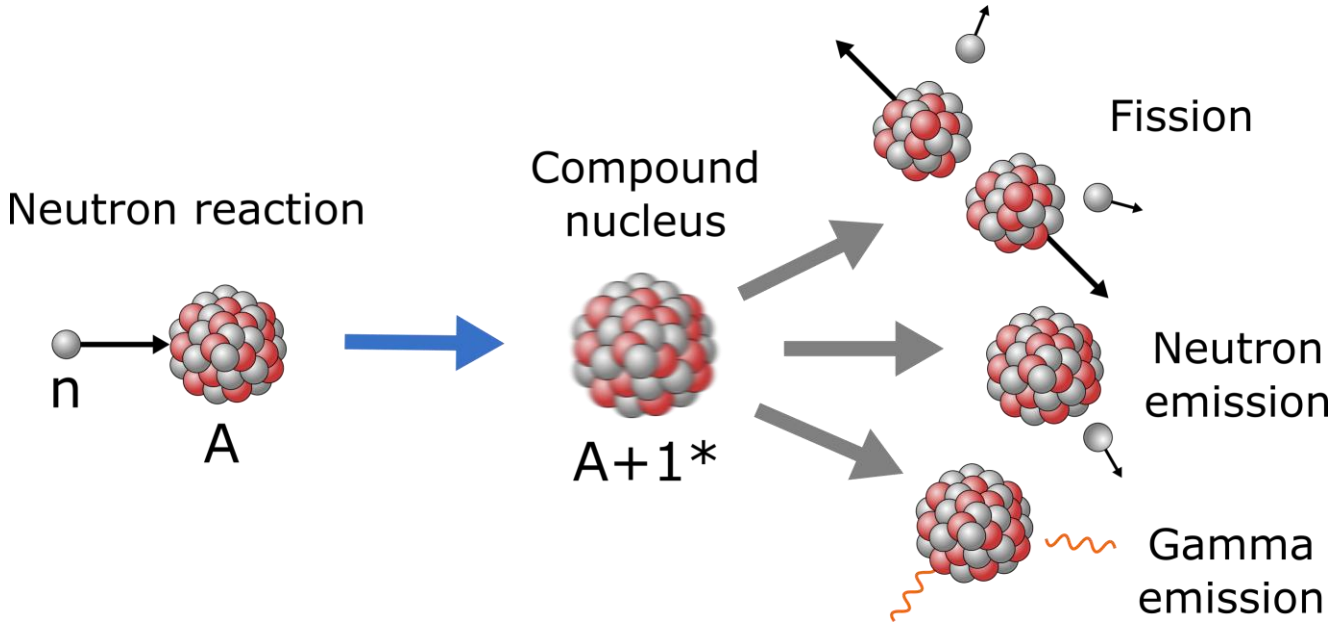
Gas target station at the ESR in GSI

State of (n, γ) theory

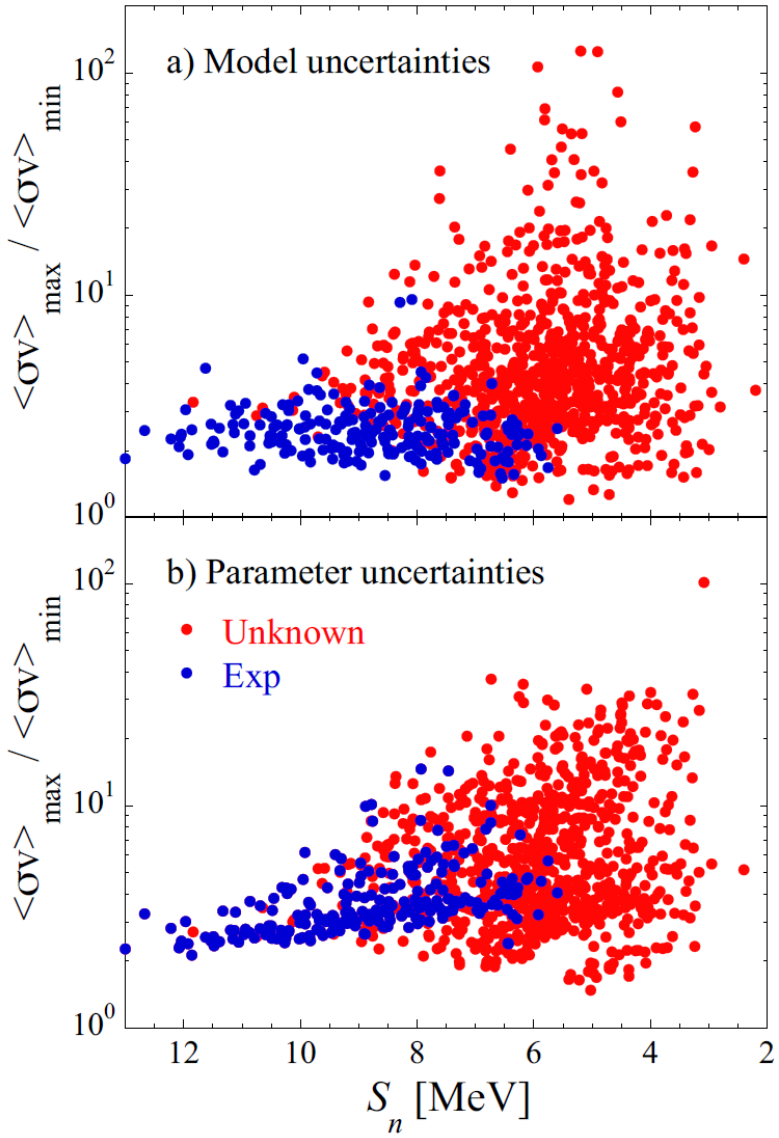
- For heavy nuclei, **Hauser-Feshbach theory** is a good approximation



State of (n, γ) theory



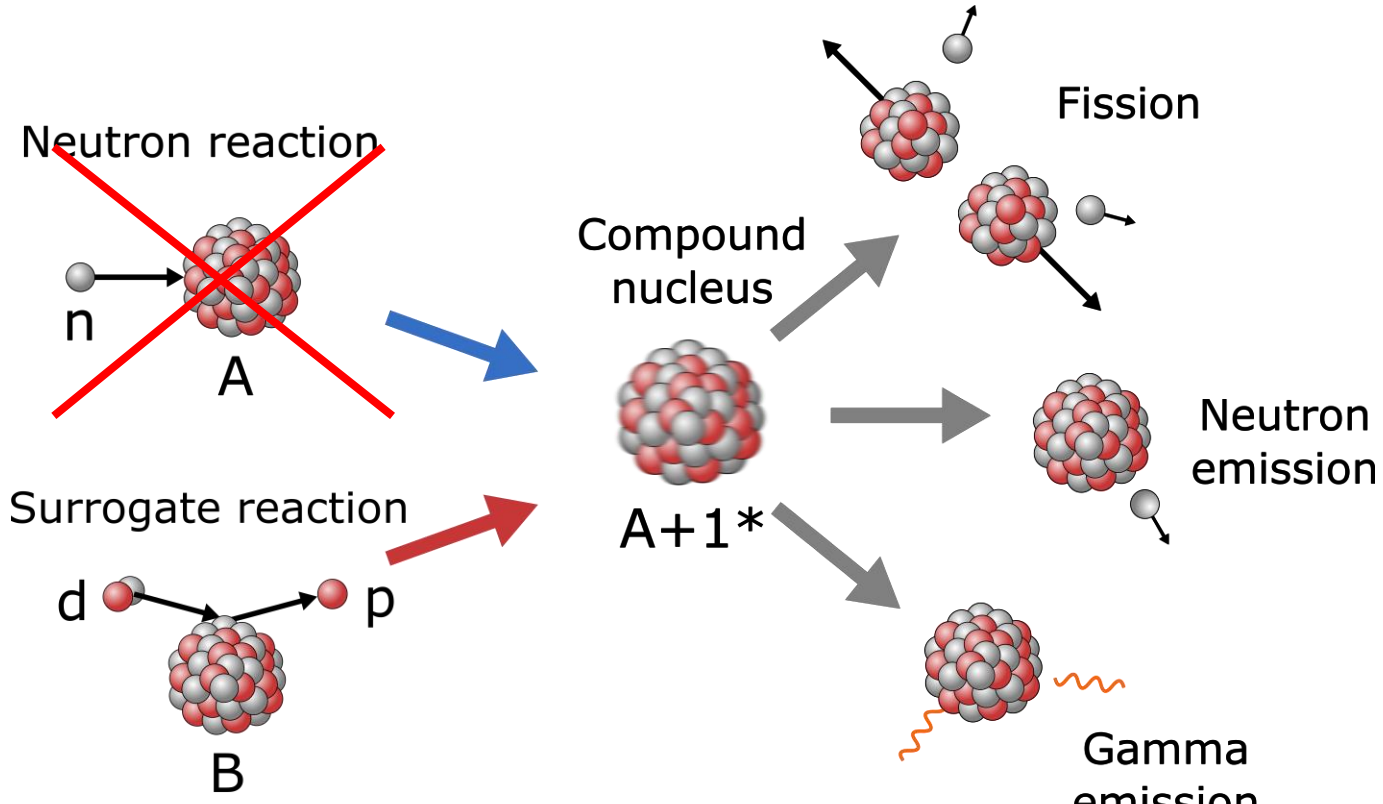
- Achieve factor ~2 around stability
- Uncertainties increase to factor ~100 as we go neutron rich



Martinet *et al.* (2024) Astr. & Astr. 684:A8

Indirect methods target the same compound nucleus

- Surrogate reaction is two-body
- CN probabilities as a function of E*

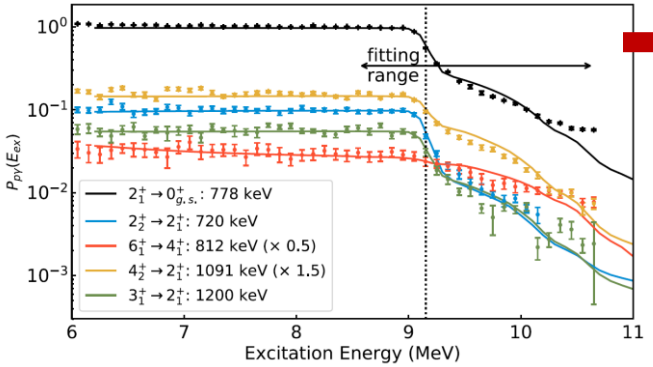


$$\sigma_{(n,\chi)} = \sigma_{\text{form}}^{CN}(E^*)\, P_\chi^n(E^*) \quad \overset{?}{\leftarrow} \quad P_\chi^{\text{sur}}(E^*)$$

The modern surrogate reaction method

- Even if $P_n(E^*) \neq P_{\mathrm{sur}}(E^*)$, measuring $P_{\mathrm{sur}}(E^*)$ is still useful

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

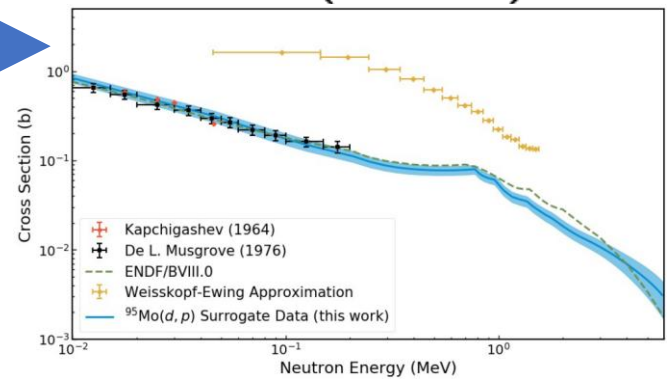




Hauser-Feshbach Code:

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

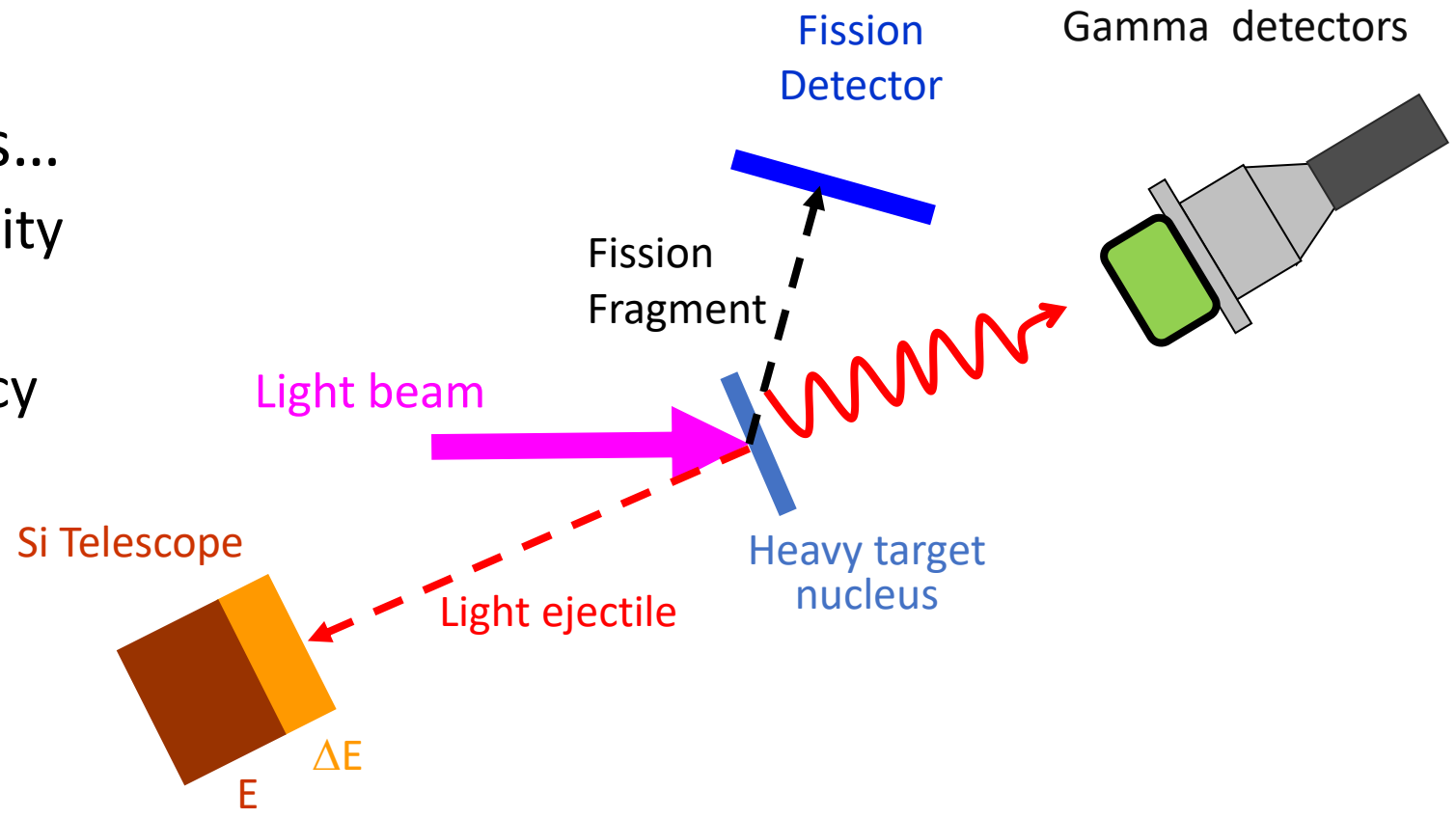
$P_n(E^*)$



- Method developed by Andrew Ratkiewicz, Jutta Escher and Richard Hughes at LLNL

Surrogates in Direct Kinematics

- Great E* resolution!
- Many target difficulties…
  - Availability / radioactivity
  - Target contaminants
  - Low detection efficiency

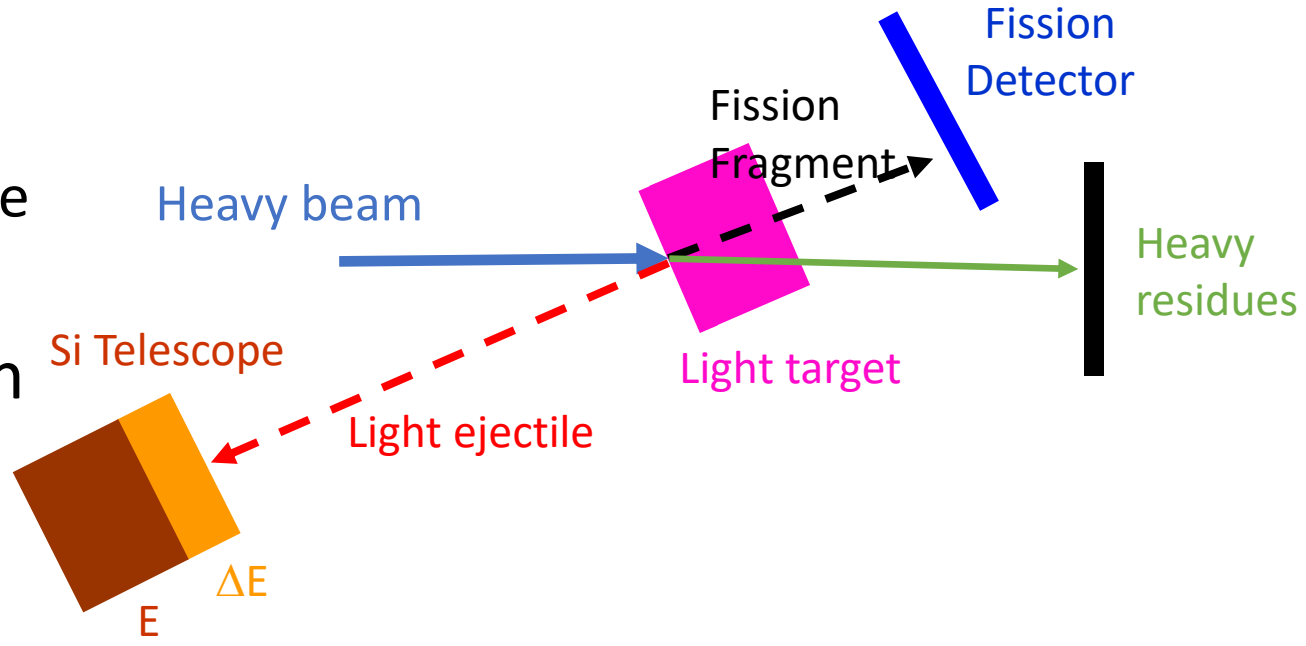


Surrogates in Inverse Kinematics

- Inverse kinematics solves target difficulties!
- Enables heavy residue detectors:
  - E.g. “gamma-less” surrogate
- But kinematic compression

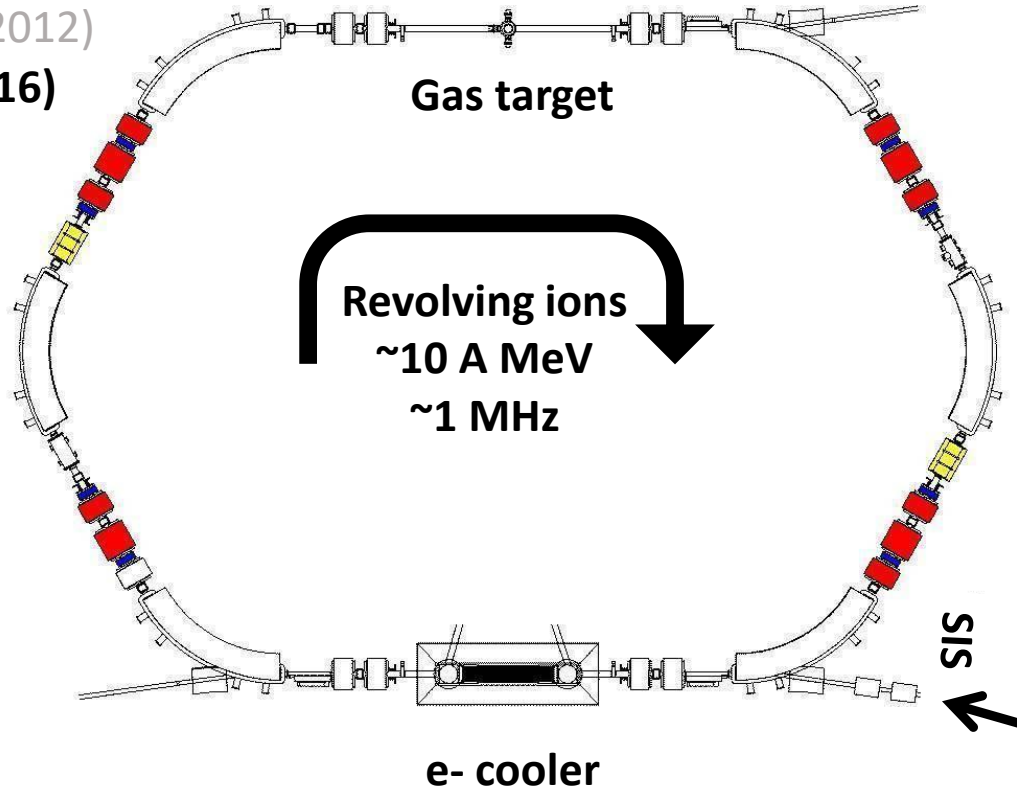
  + thick target

  = bad E* resolution



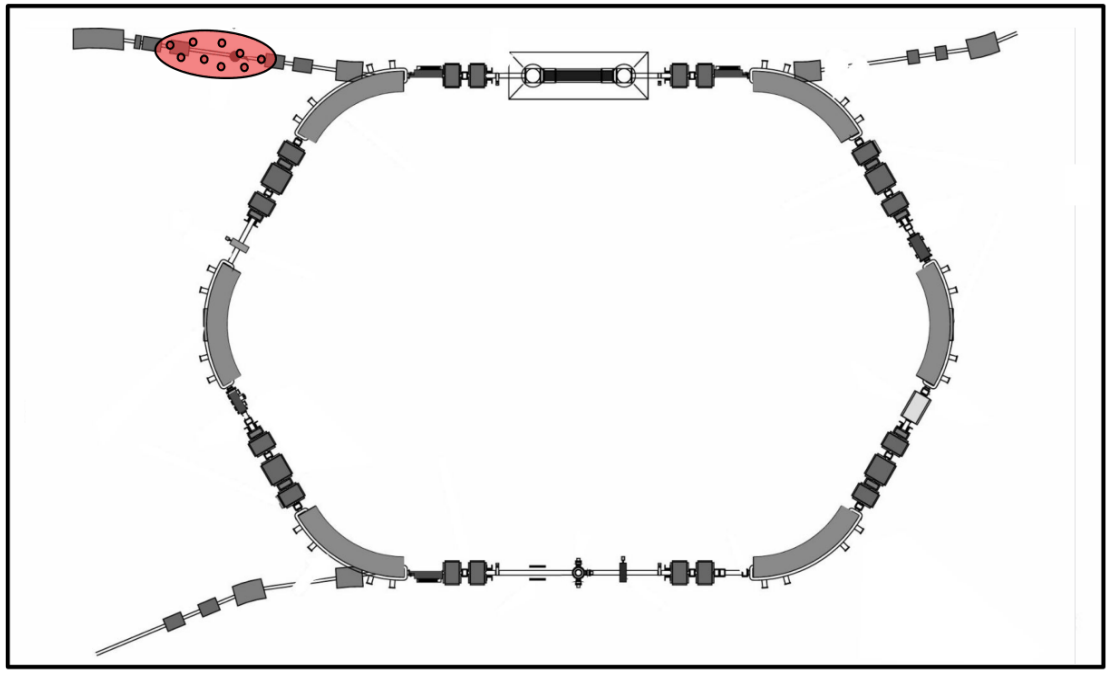
Nuclear reactions in the storage ring!

- Ions are bent into a circular orbit
- Only 5 rings in the world:
  1. **Experimental Storage Ring (ESR) at GSI Darmstadt (since 1990)**
  2. Cooler-Storage Ring (CSRe) at HIRF Lanzhou (since 2010)
  3. Rare RI Ring (R3) at RIKEN Nishina Center (since 2012)
  4. **CRYRING at GSI Darmstadt (1992-2014, since 2016)**
  5. Spectrometer Ring at HIAF in Huizhou (2025)
- But more may be on the way:
  1. FAIR storage rings (CR & HESR, >203x)
  2. Proposal for an ISOLDE Storage Ring
  3. Design study funded for TRIUMF Storage Ring
  4. Rumours of an ATLAS Storage Ring??
  5. LANL Storage Ring with free neutron target??



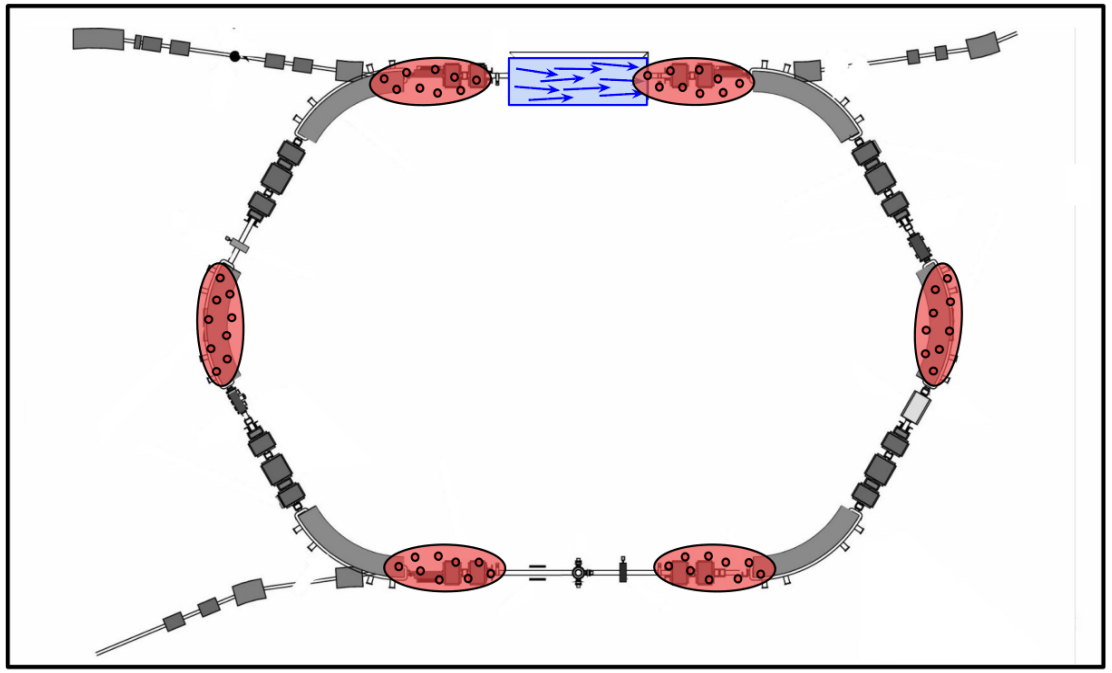
Storage rings provide unique reaction environment

- Stores fully-stripped heavy ion beams from 400 MeV/u → 7 MeV/u



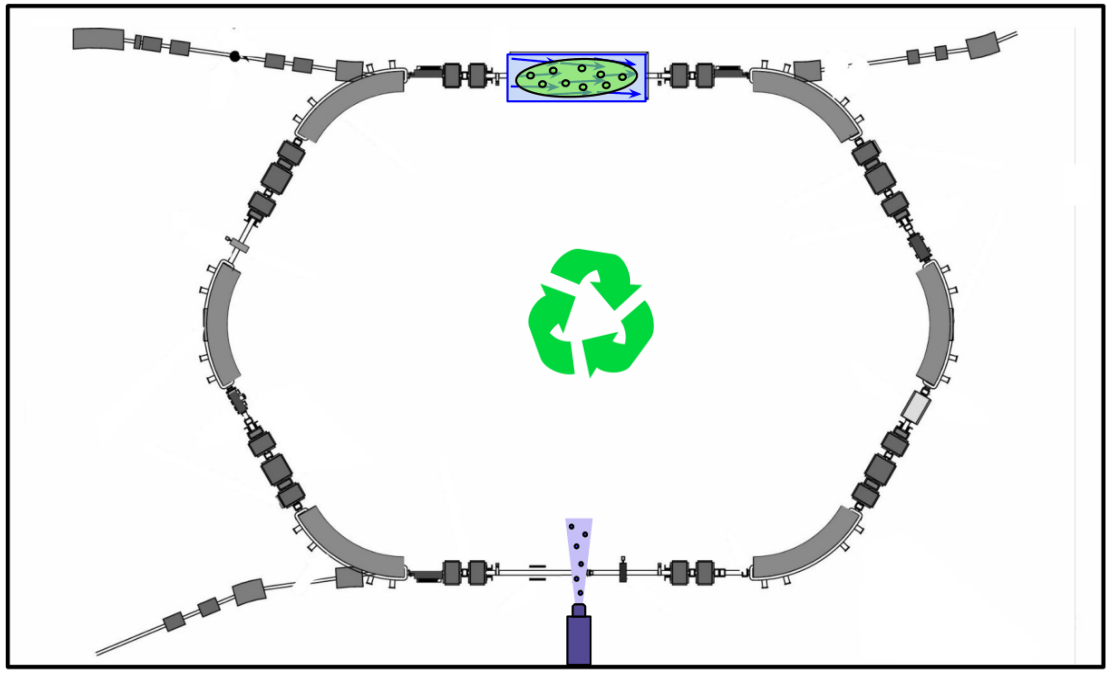
Storage rings provide unique reaction environment

- Stores fully-stripped heavy ion beams from 400 MeV/u → 7 MeV/u
- Stochastic + electron cooling gives high-quality beams: $\Delta p/p = 10^{-4}$
  - Even for secondary, radioactive beams!



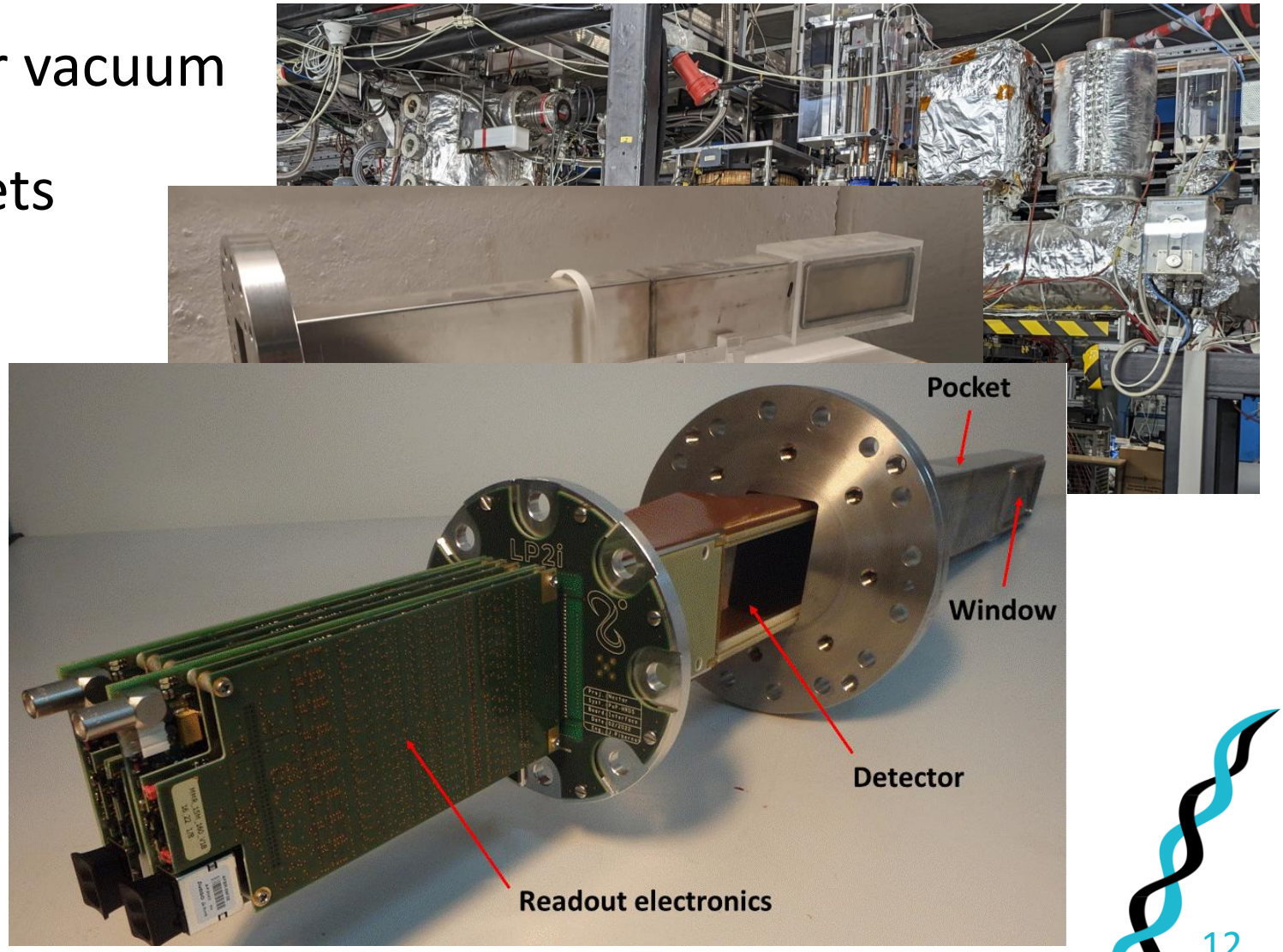
Storage rings provide unique reaction environment

- Stores fully-stripped heavy ion beams from 400 MeV/u → 7 MeV/u
- Stochastic + electron cooling gives high-quality beams: $\Delta p/p = 10^{-4}$
  - Even for secondary, radioactive beams!
- Gas-jet = pure, windowless, ultra-low density target ($\sim 10^{13}$ atoms/cm^3)
- Beam is recycled at ~1 MHz, boosting luminosity to solid target levels!



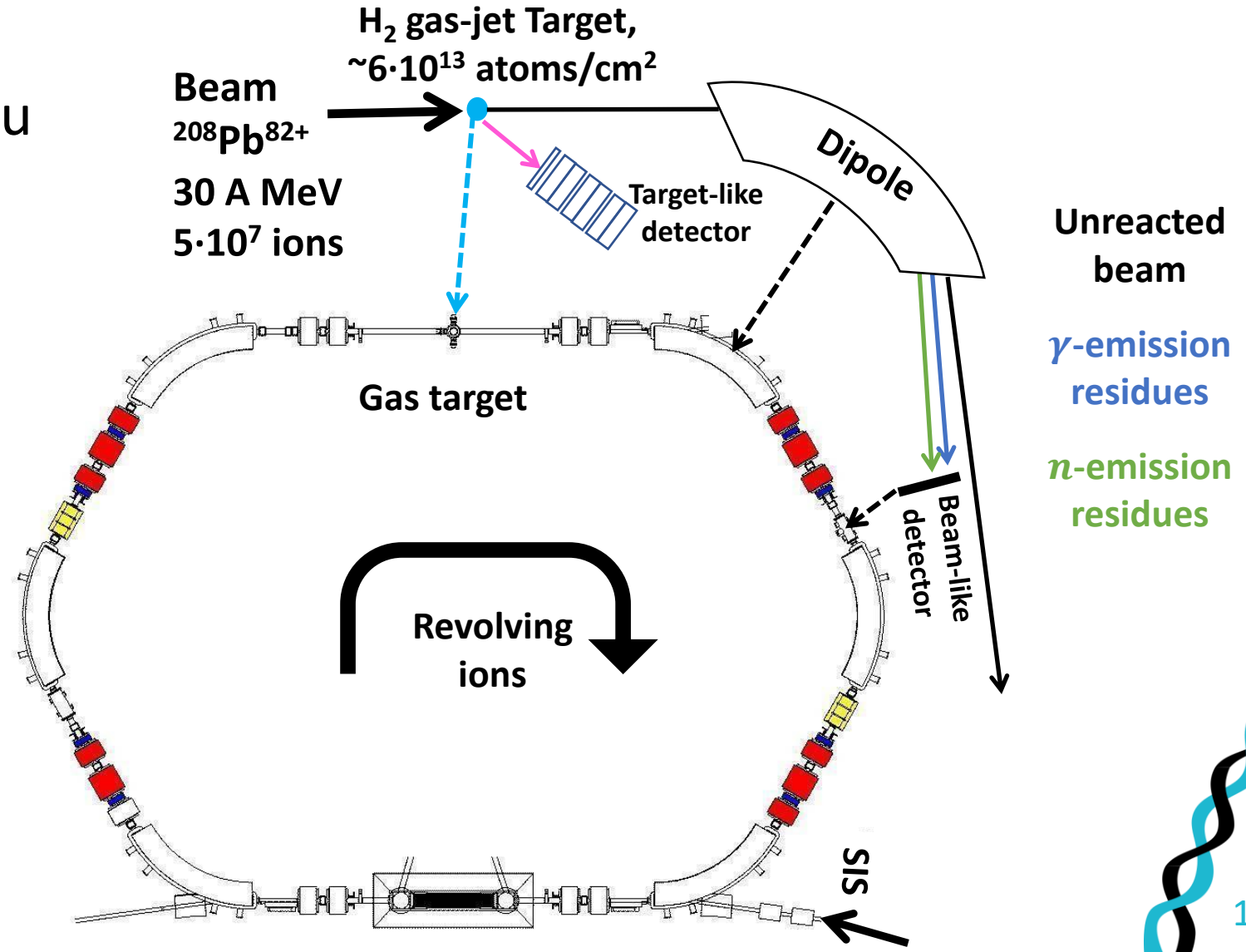
Challenges: ultra-high vacuum

- 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

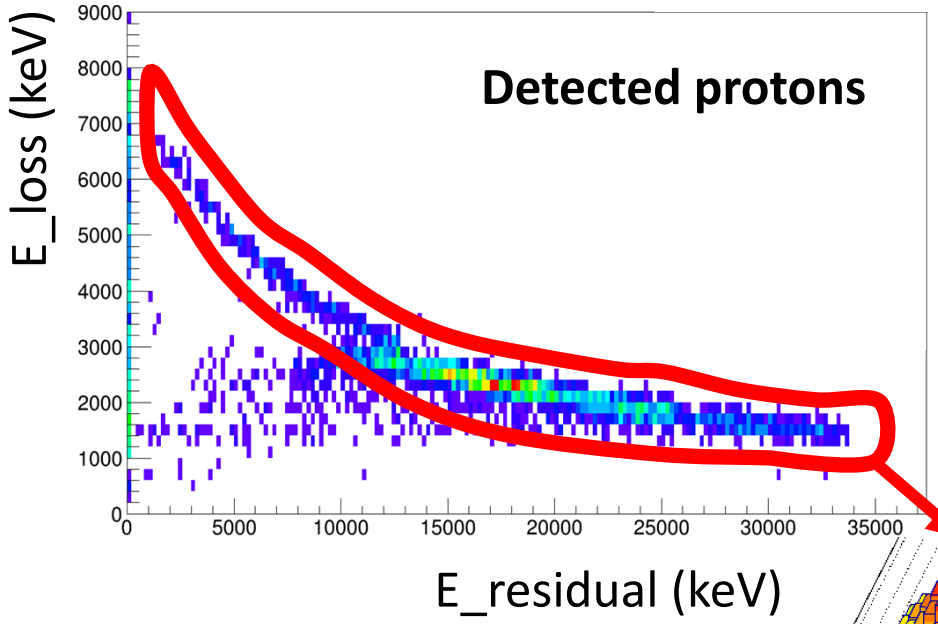
- First demonstration: ^{208}Pb(p, p') @ 30 MeV/u



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

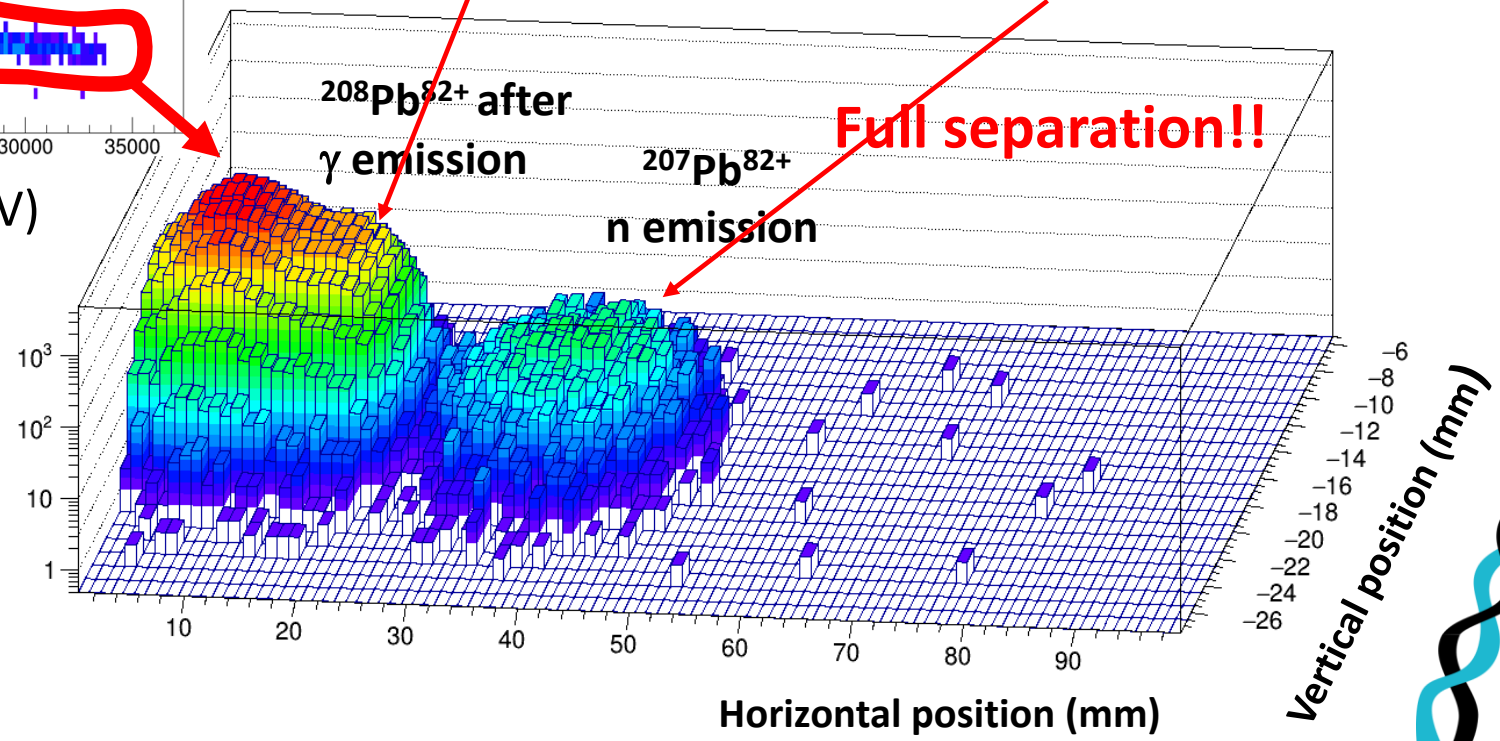
Analysis by Michele Sguazzin





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

Efficiency 100%!
0% in direct kinematics…

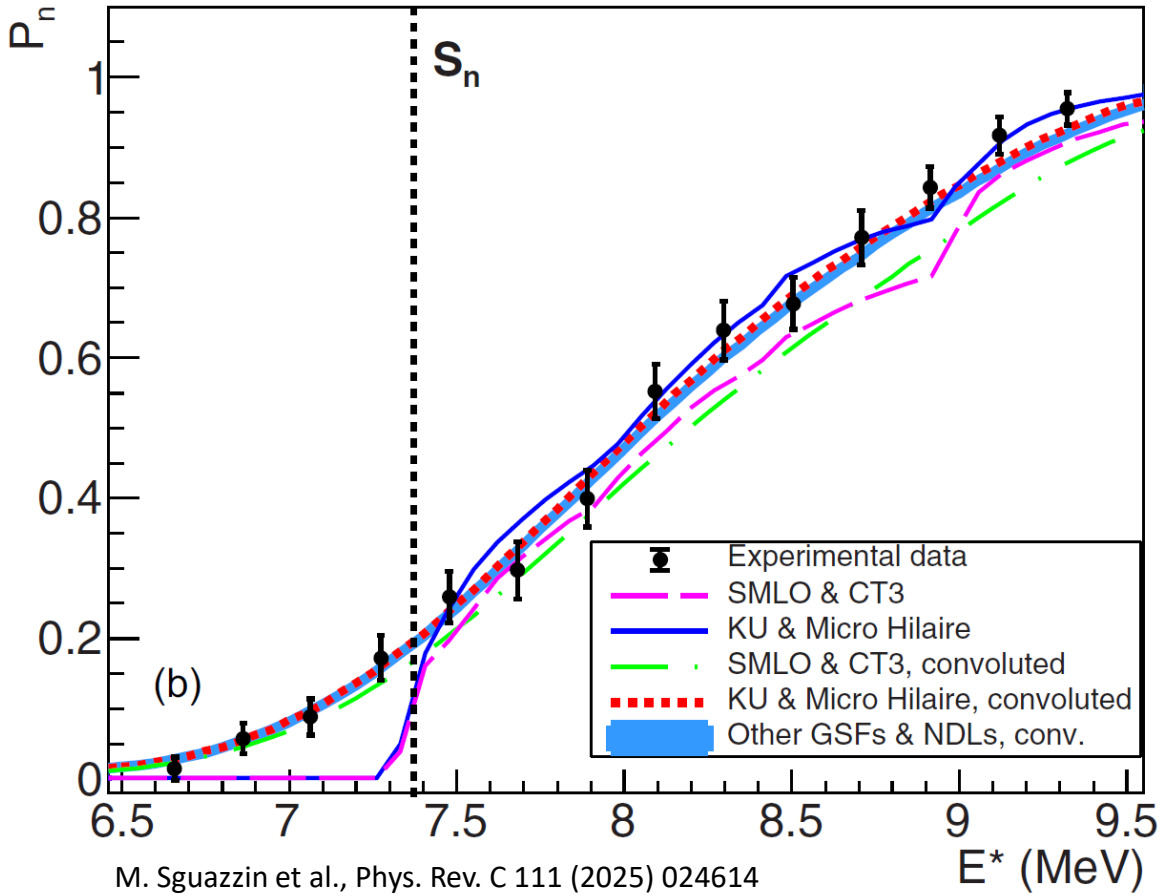


M. Sguazzin *et al.*, Phys. Rev. Lett. 134 (2025) 072501

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

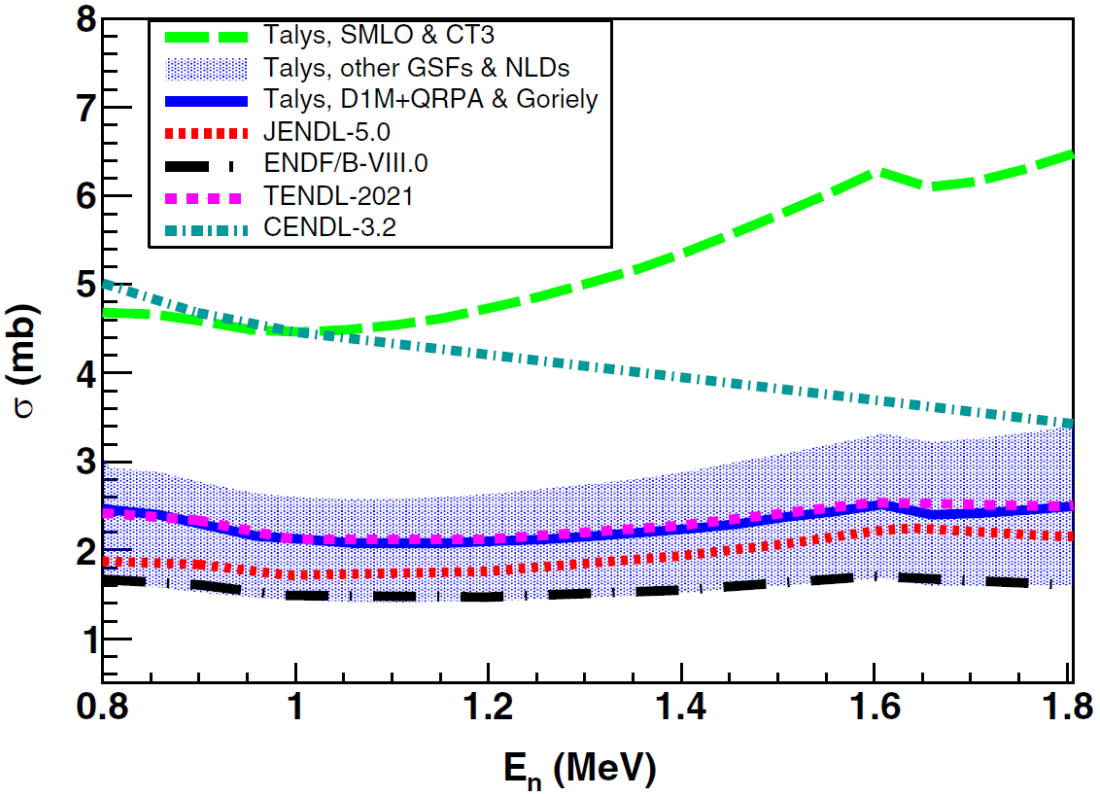
^{208}Pb(p, p') Results: TALYS Comparisons

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

^{238}U(d,p) at the ESR

Analysis by



Camille Berthelot & Boguslav Wloch

Formation and decay of compound nucleus (~10^{-20} s)

Fission fragments detector

$^{238}U^{92+}$

17 MeV/n

Gamma and neutron emission residue move together with unreacted beam

B

Dipole magnet separate nuclei with different rigidity

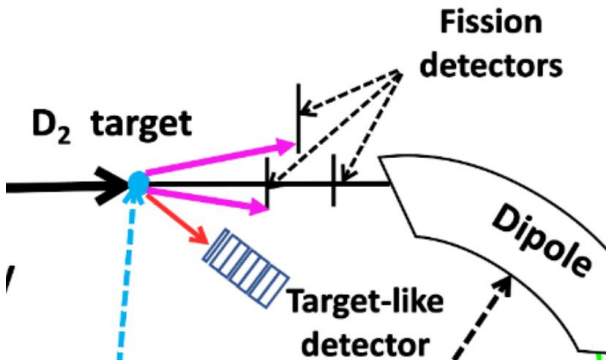
Target-like Telescope

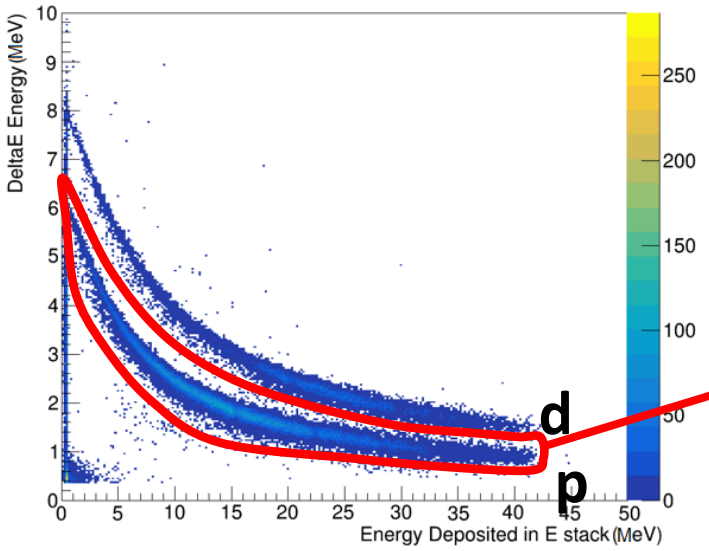
Decay residues are deflected more and hit heavy residue detector

Unreacted beam stays in the ring

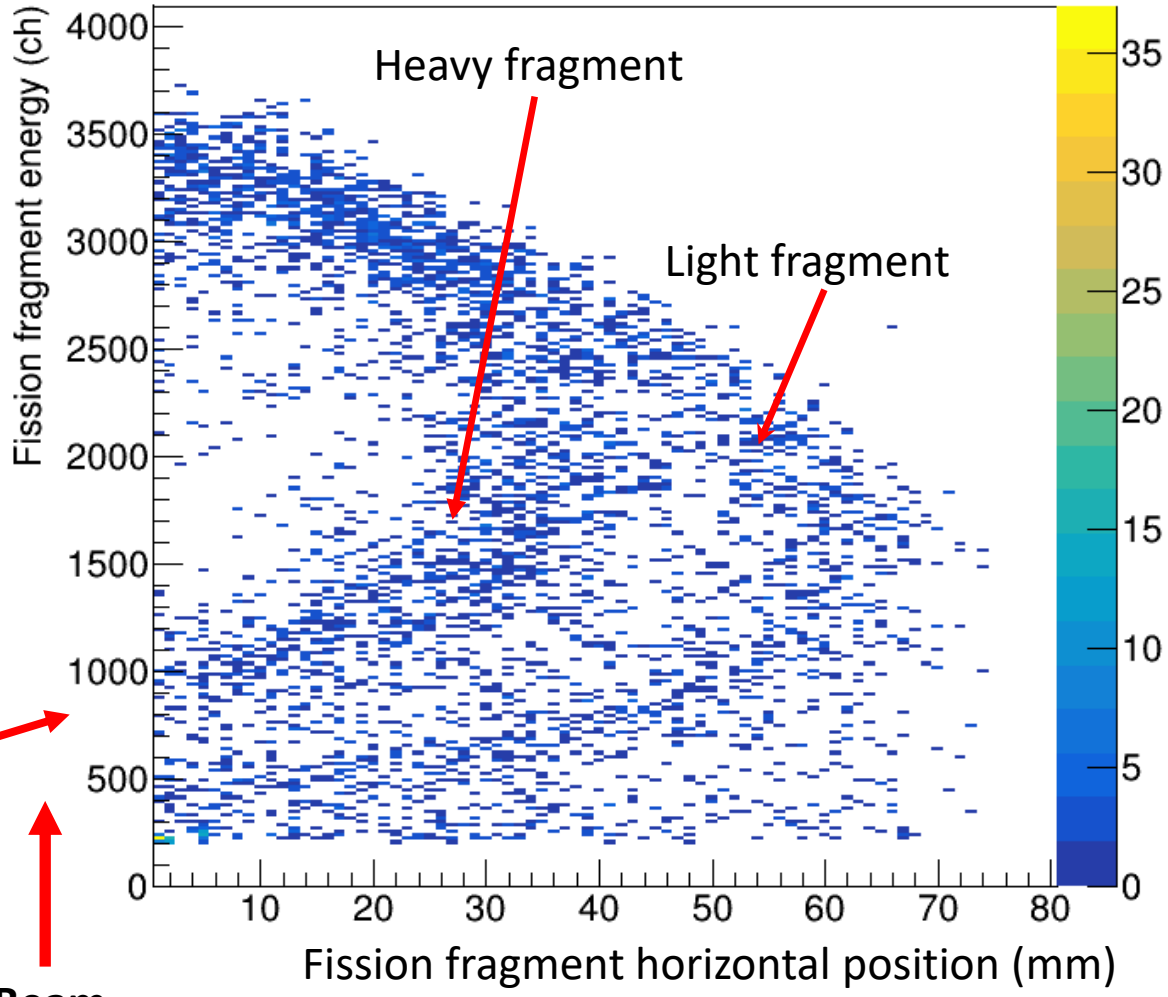
Beam-like residue detector

First time fission is studied in a storage ring!

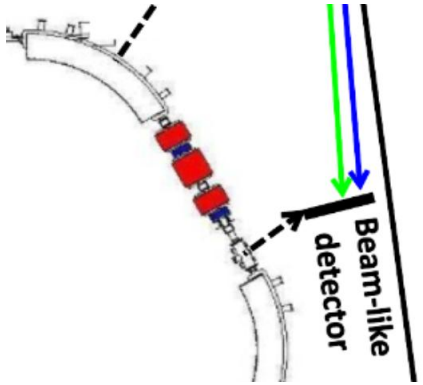


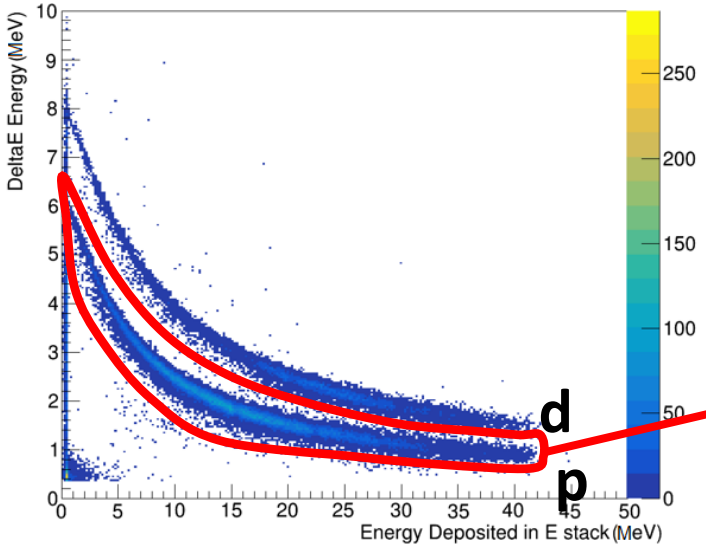


Fission detector

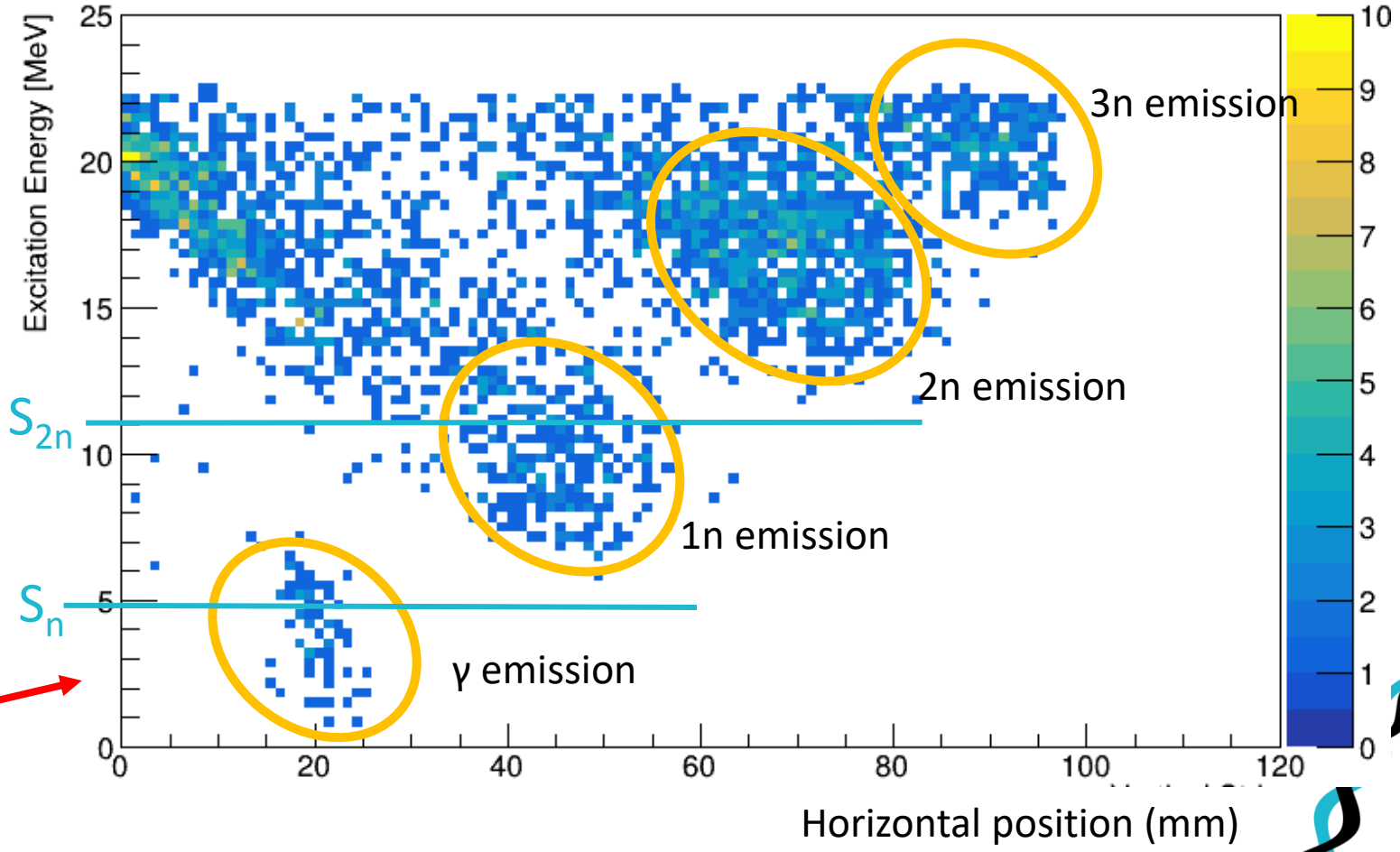


100% efficiency for γ and n emission!

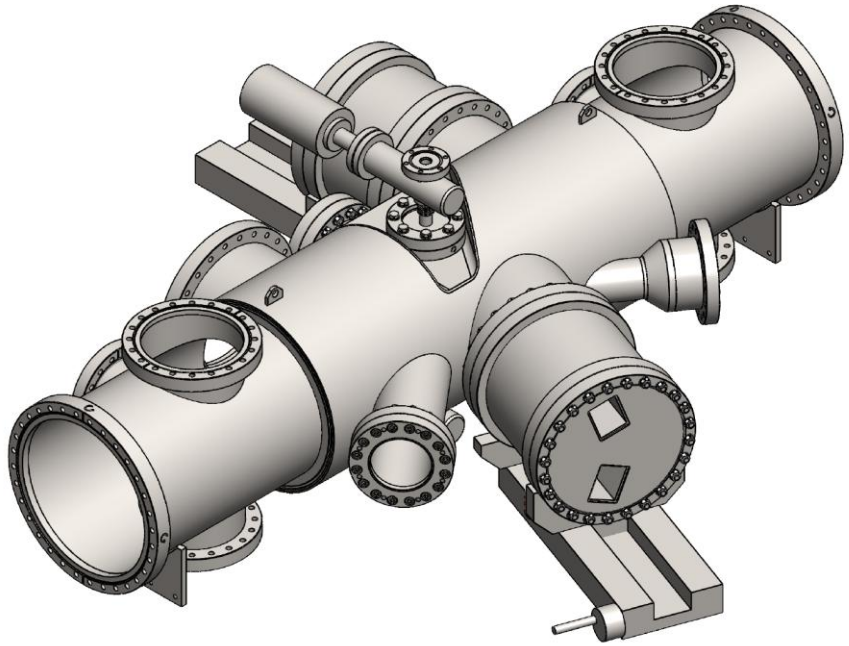


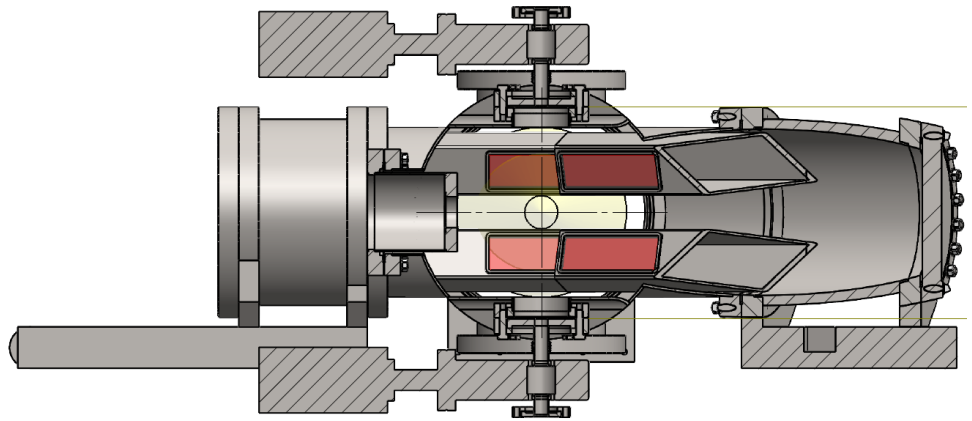


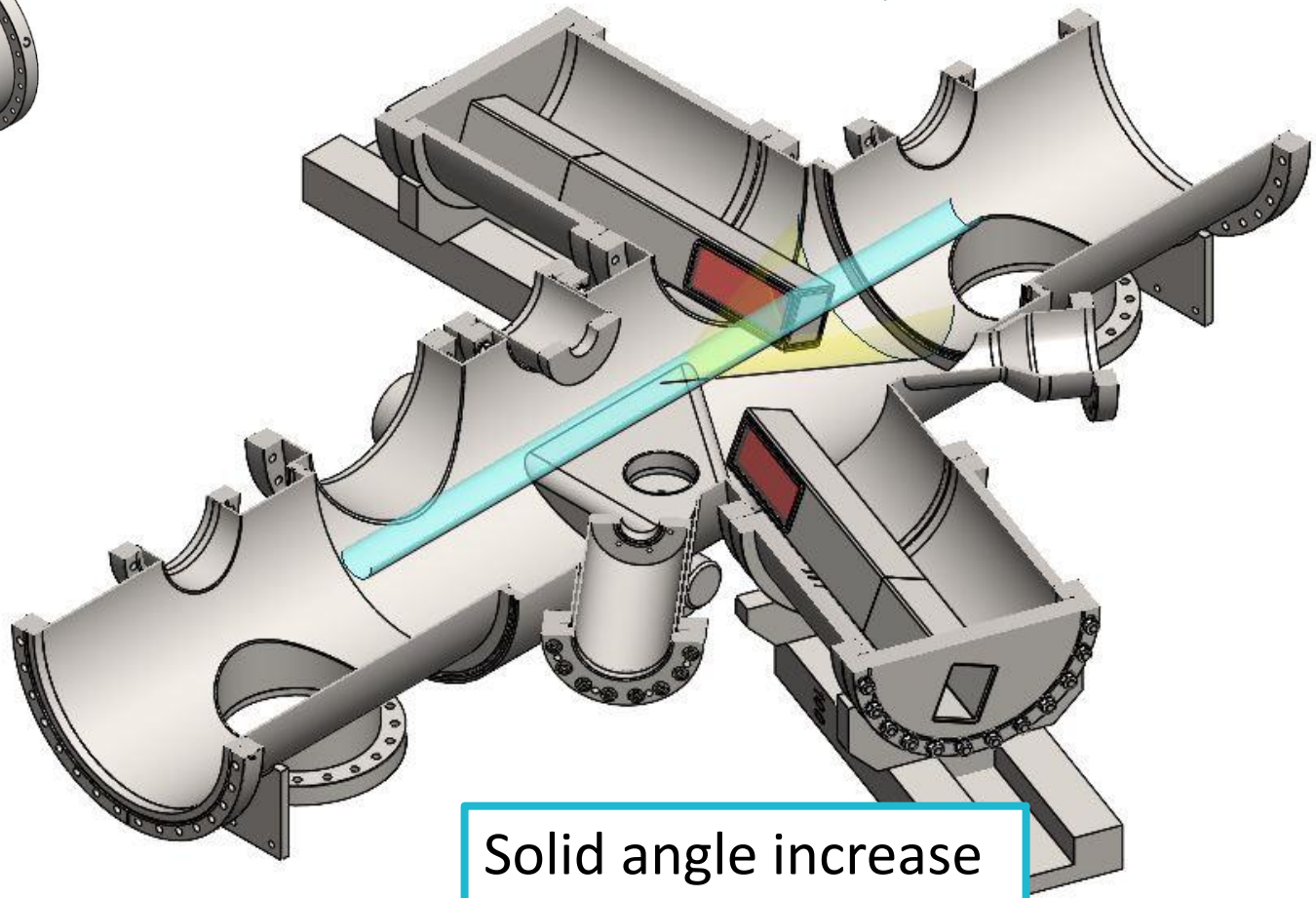
Beamlike residue detector



New reaction chamber at the ESR



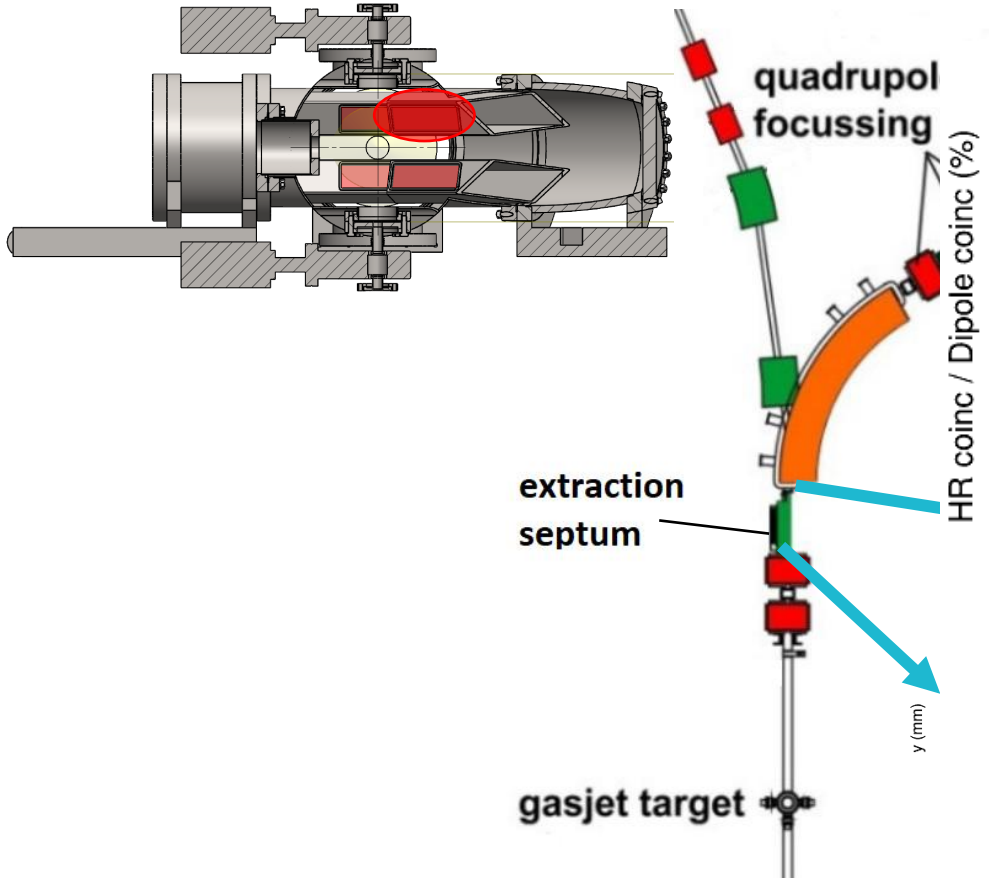


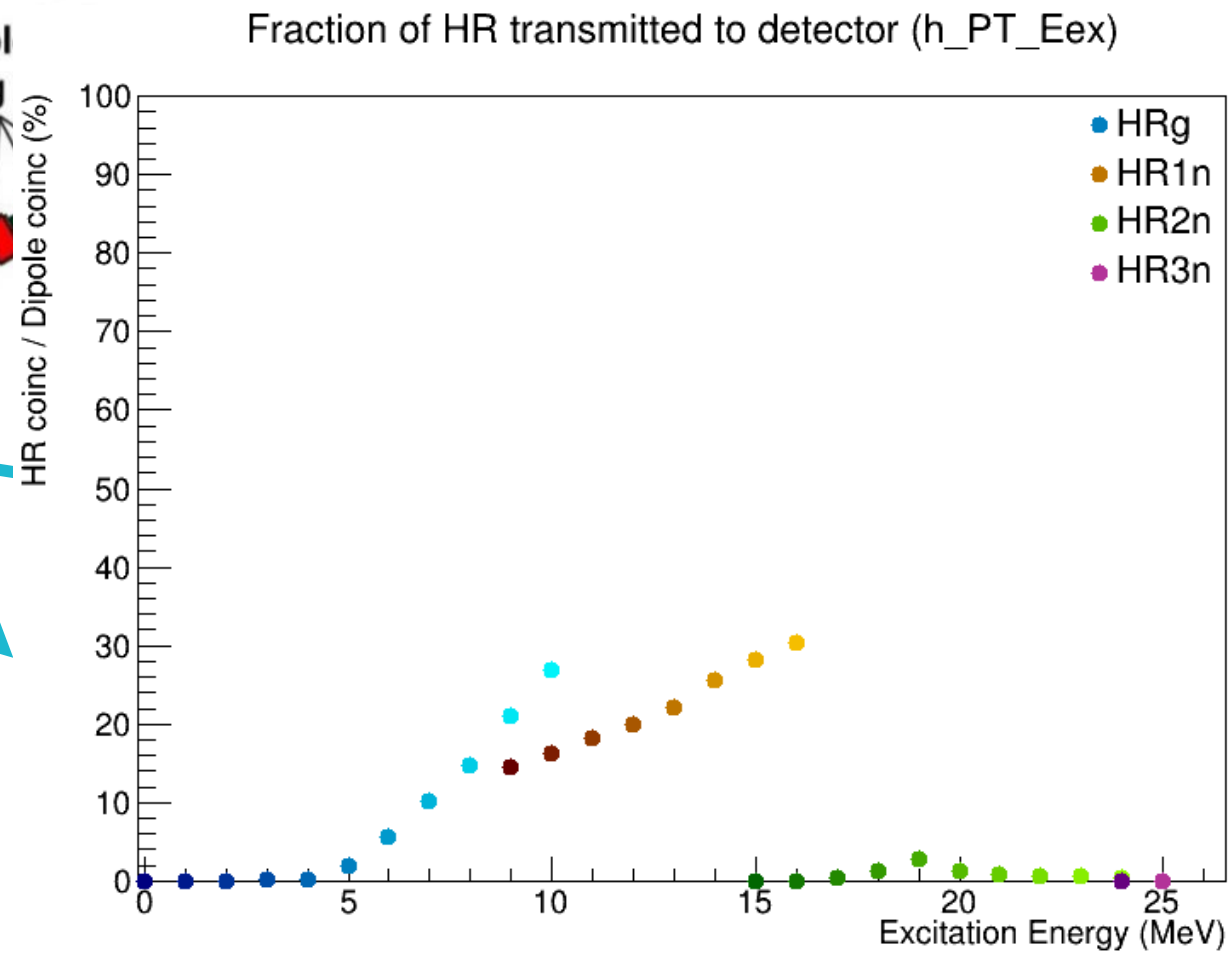


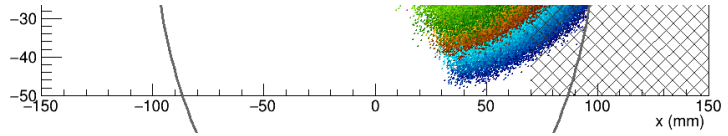
Solid angle increase by a factor of 230!!!

^{135}Xe(d,p) at forward lab angles = ☹

Gamma
1 neutron
2 neutron

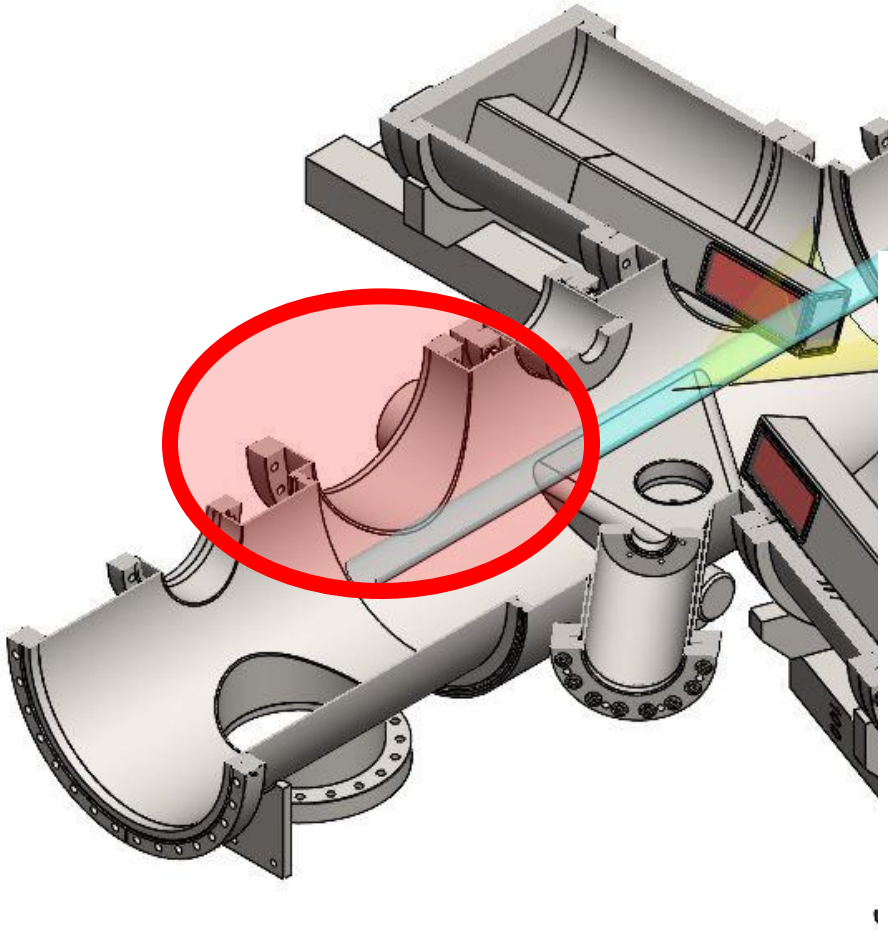


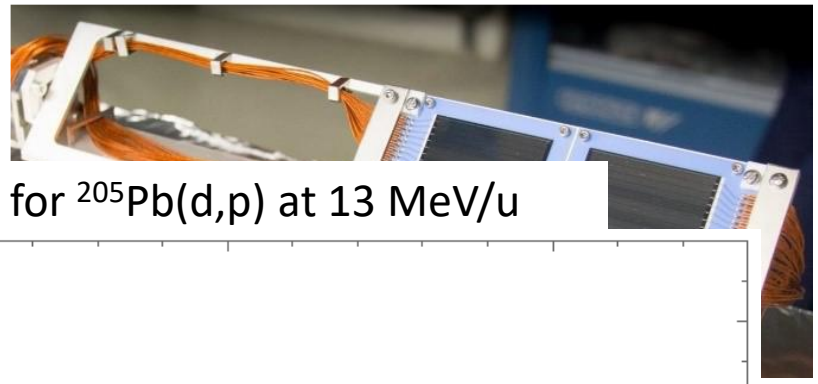




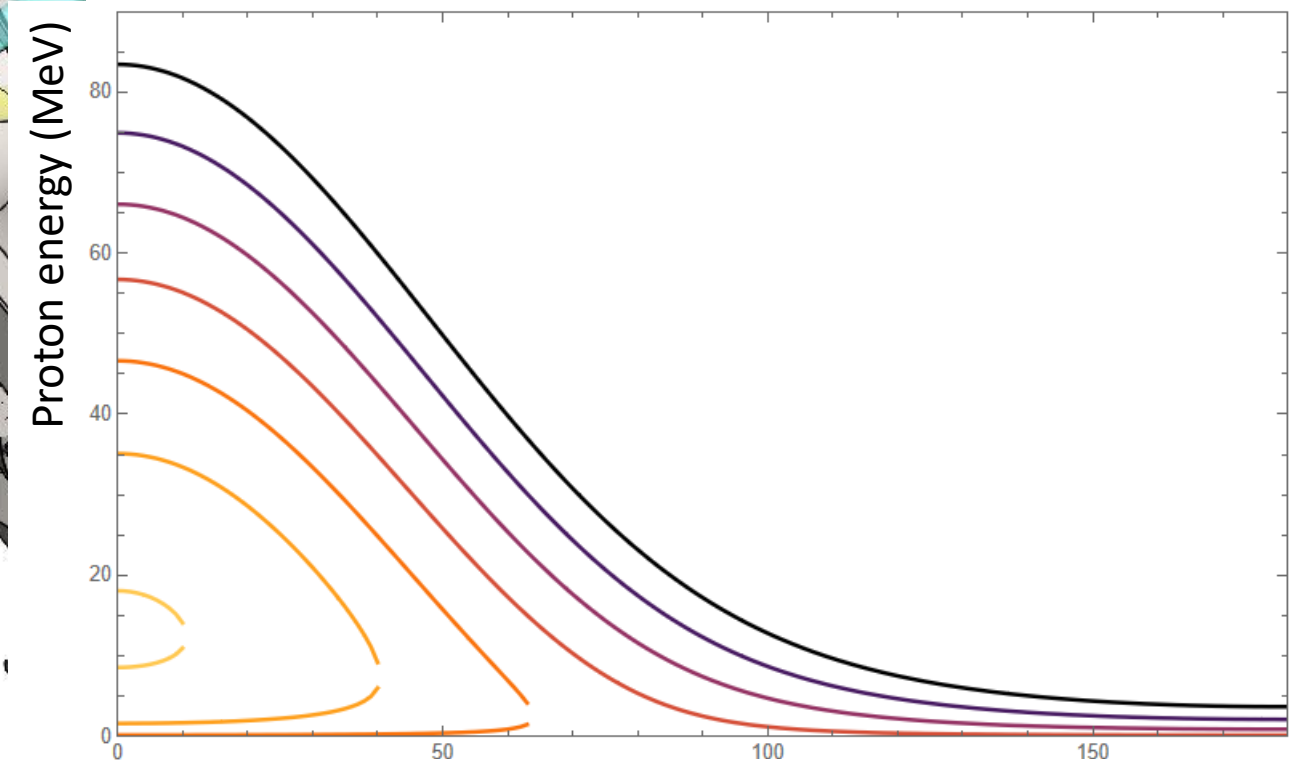
Our crazy idea: in-vacuum backward angles

In-vacuum Si detectors for (p,γ) at the ESR



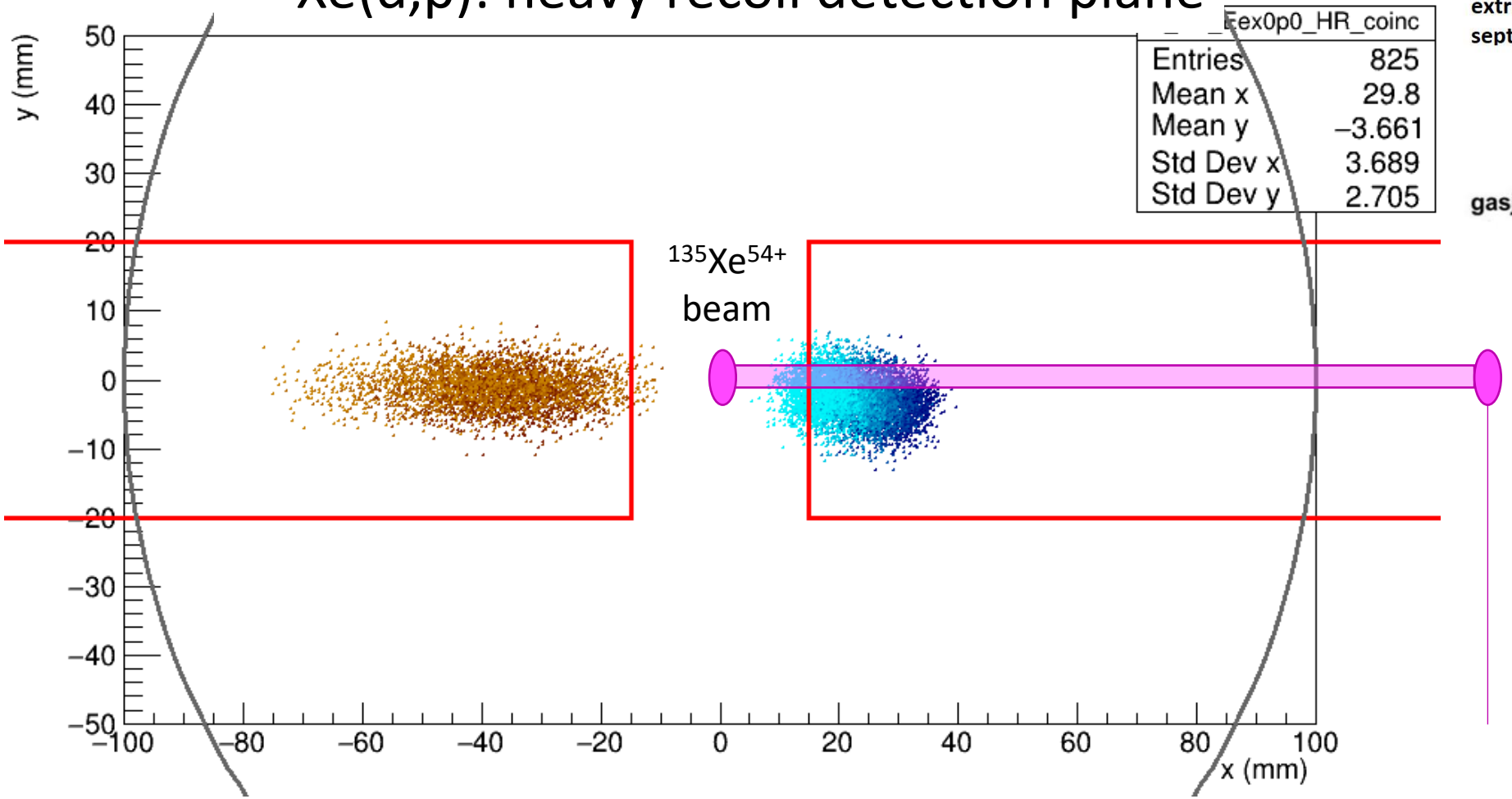


Kinematics for ^{205}Pb(d,p) at 13 MeV/u

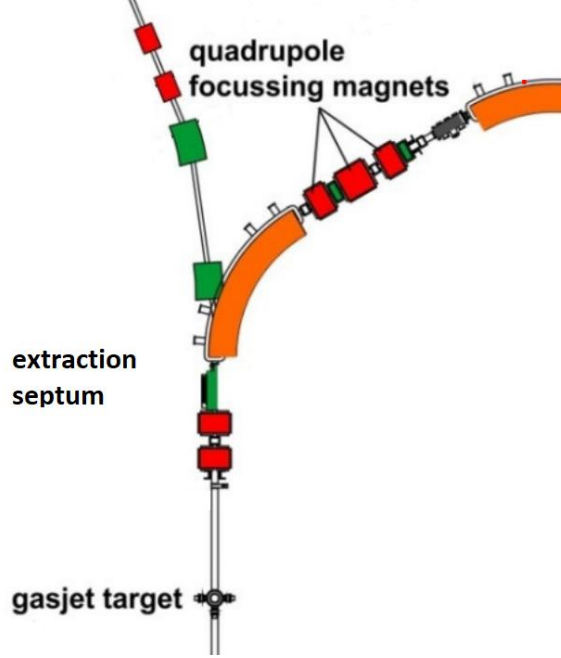


Transmission for backward angles

^{135}Xe(d,p): heavy recoil detection plane

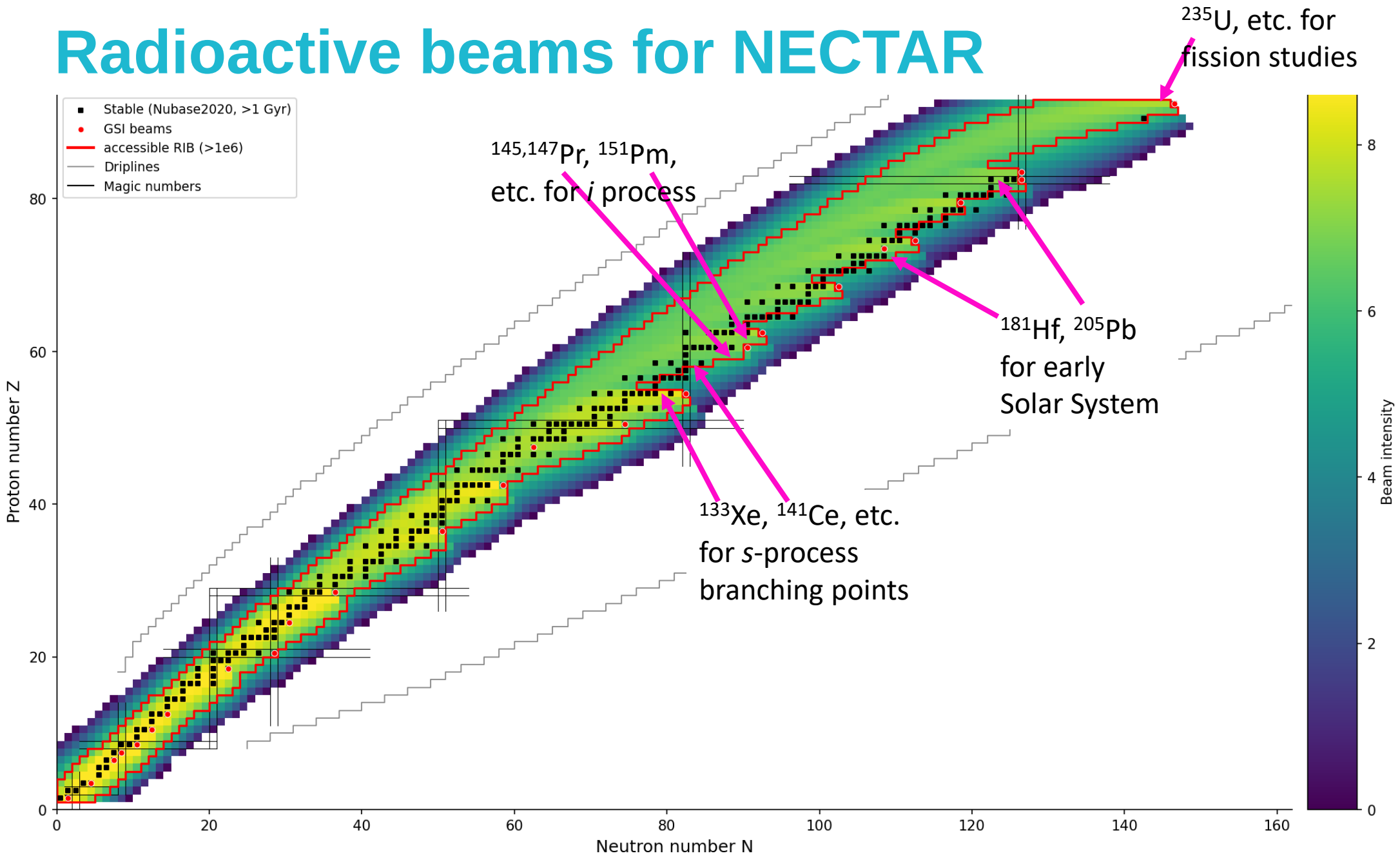


$^{135}Xe^{54+}$ beam



$^{135}Xe^{53+}$ outside of beam pipe

Radioactive beams for NECTAR



^{205}Pb in the early Solar System

- ^{205}Pb ($t_{1/2}$ = 17 Myr) has potential to be a unique cosmochronometer



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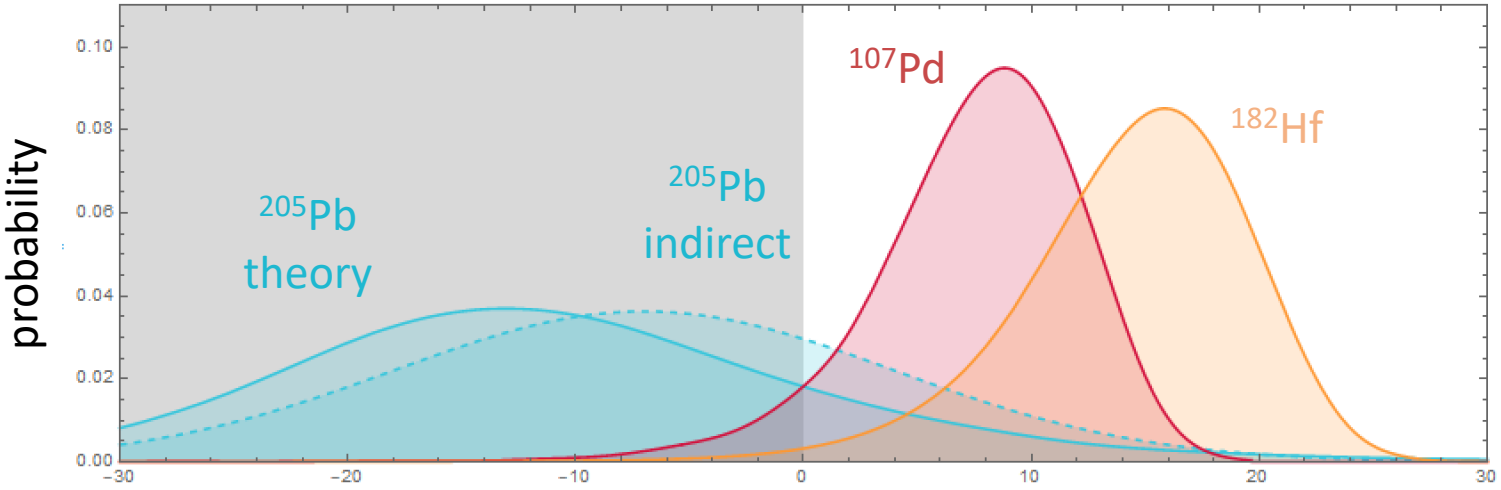
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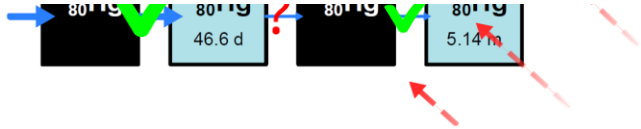
High-temperature ^{205}Tl decay clarifies ^{205}Pb dating in early Solar System

Guy Leckenby, Ragandeep Singh Sidhu, Rui Jiu Chen, Riccardo Mancino, Balázs Szányi, Mei Bai, Umberto Battino, Klaus Blaum, Carsten Brandau, Sergio Cristallo, Timo Dickel, Iris Dillmann, Dmytro Dmytriiev, Thomas Faestermann, Oliver Forstner, Bernhard Franczak, Hans Geissel, Roman Gernhäuser, Jan Glorius, Chris Griffin, Alexandre Gumberidze, Emma Haettner, Pierre-Michel Hillenbrand, Amanda Karakas, ... Jianwei Zhao + Show authors

Nature **635**, 321–326 (2024) | Cite this article

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Thank you, **Merci**

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1- LP2I (ex-CENBG), Bordeaux, France, 2- MPIK, Heidelberg, Germany 3-GSI, Darmstadt, Germany 4-University of Frankfurt, Germany 5-IJCLAB, Orsay, France 6-Triumf, Vancouver, Canada 7-IFIC, Valencia, Spain 8-CEA-DAM & CEA-IRFU, France 9-University of Chalmers, Sweden 10-University of Edinburgh, UK 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

The results presented here are based on the experiment E146, which was performed at the GSI Helmholtzzentrum fuer Schwerionenforschung, Darmstadt (Germany) in the context of FAIR Phase-0

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