Indirect measurements of neutron-induced reaction cross-sections at storage rings

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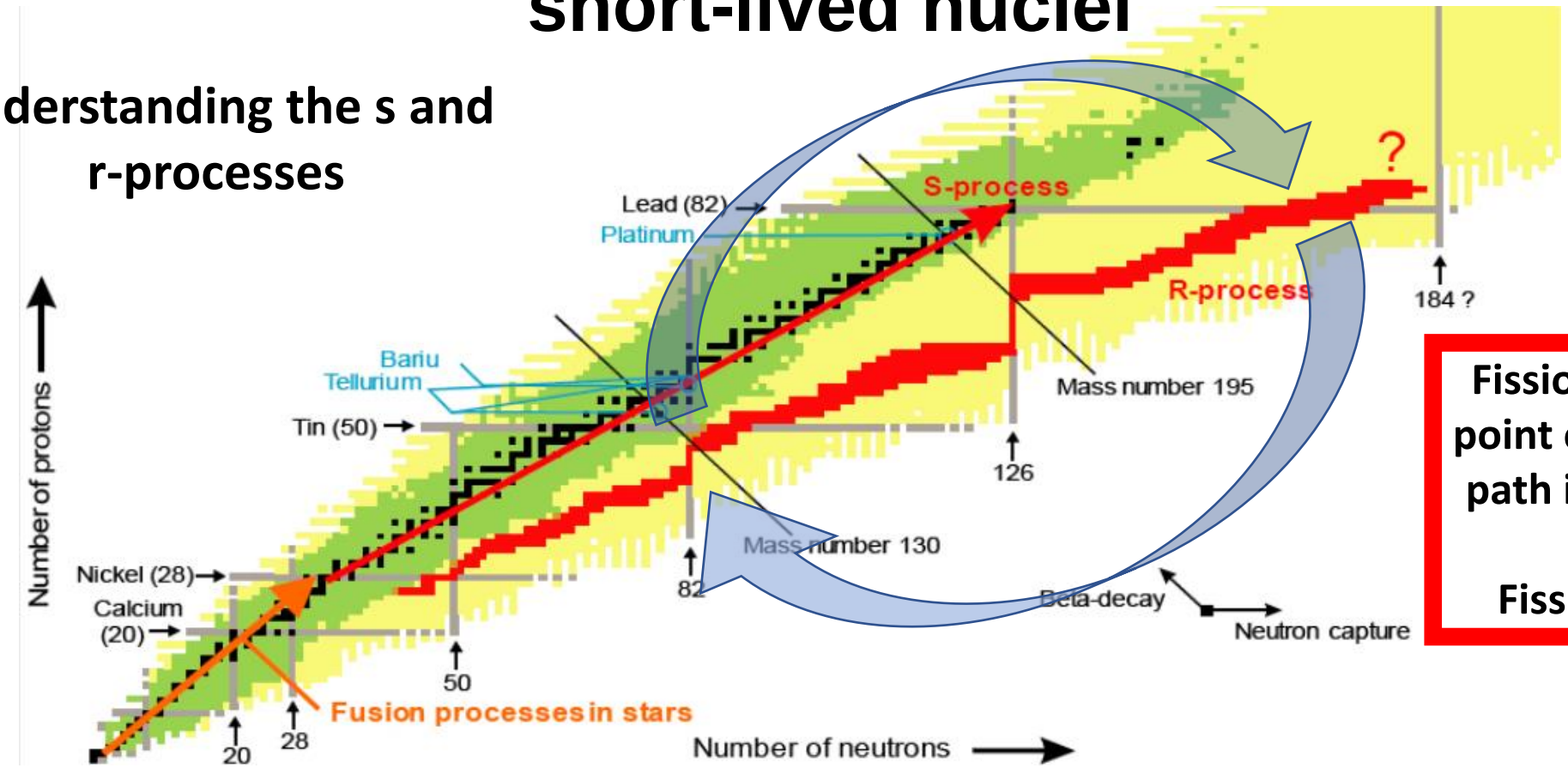
Need for neutron-induced reaction cross sections of short-lived nuclei

Understanding the s and r-processes

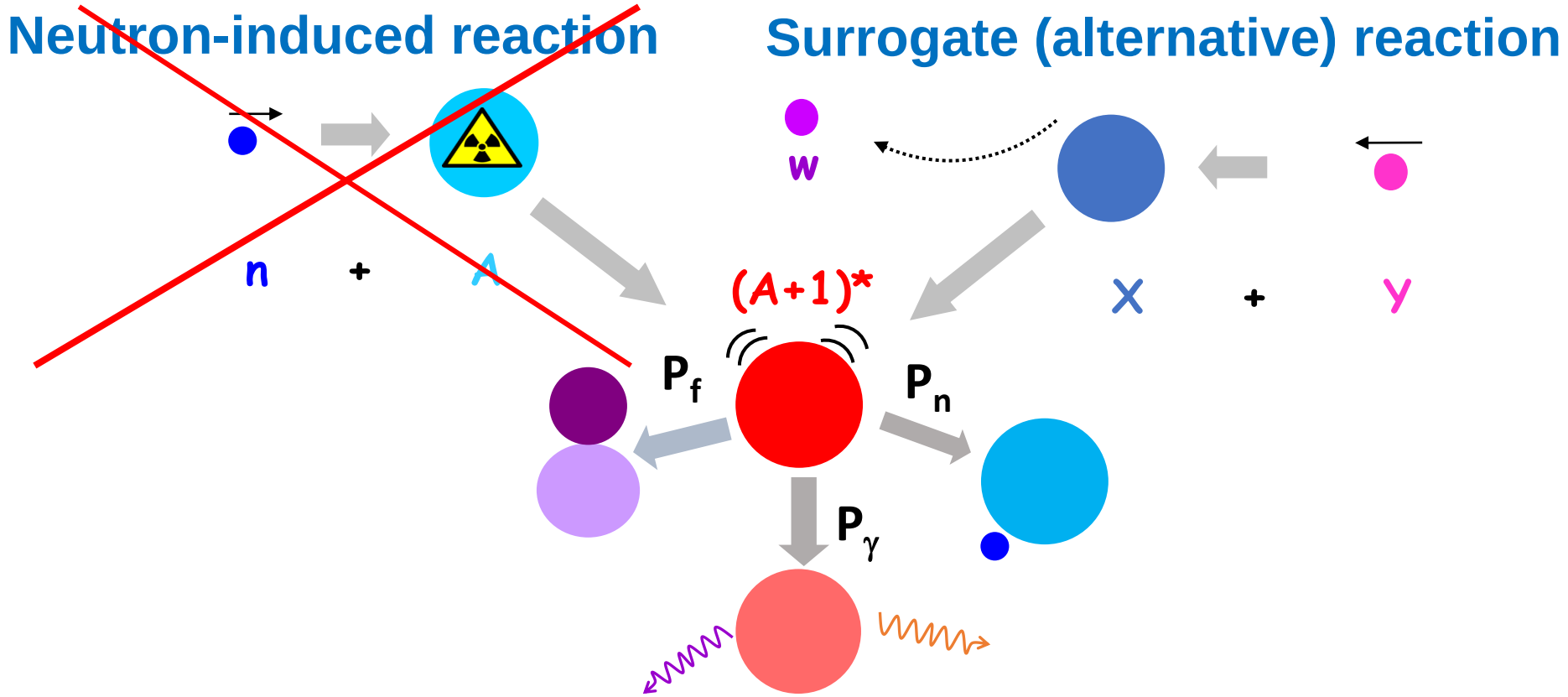


Fission sets the end point of the r-process path in neutron-star mergers.
Fission recycling.

→Very difficult or even impossible to measure with standard techniques because of the radioactivity of the targets.

→Complicated to calculate due to the difficulty to describe the de-excitation process. Calculations can be wrong by several orders of magnitude!

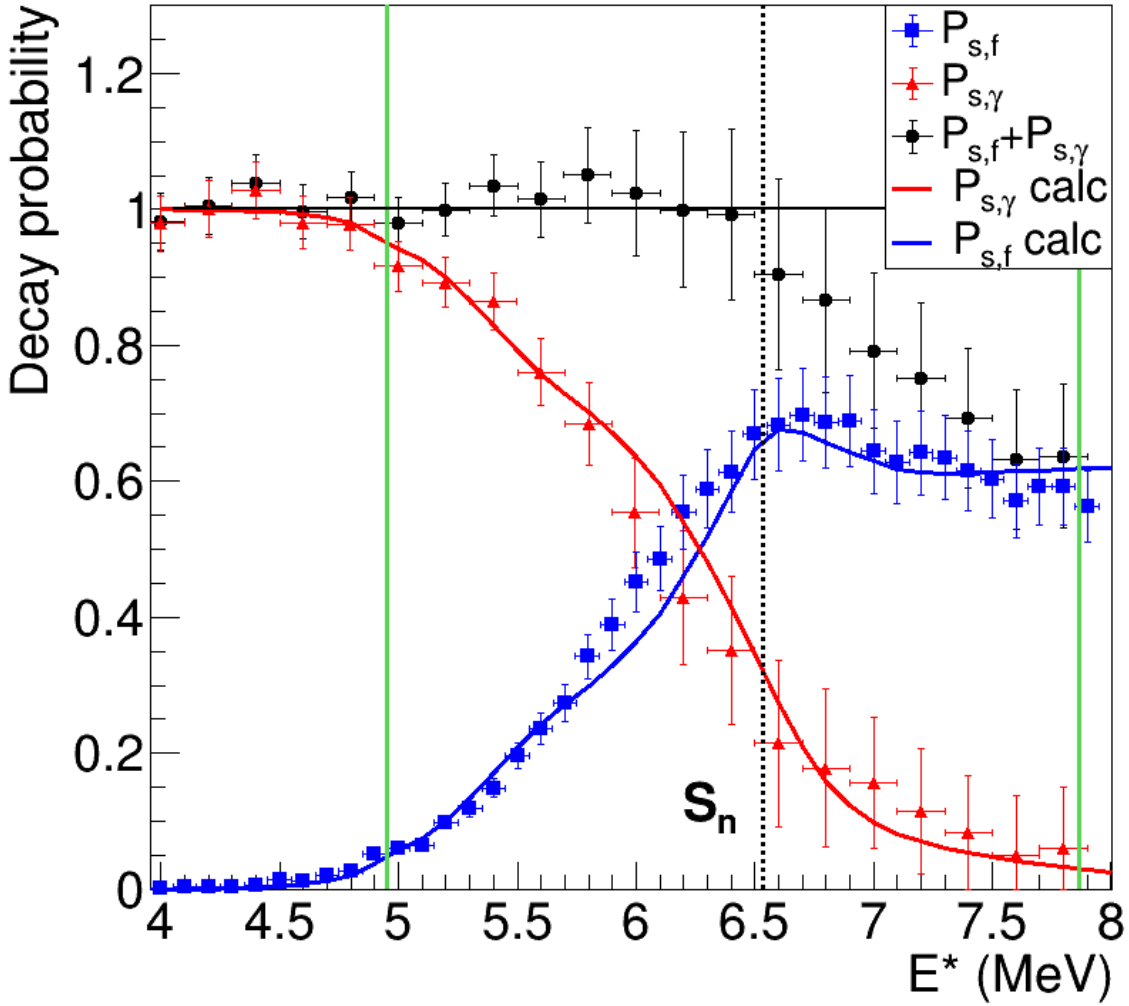
Surrogate-reaction method



Decay probabilities as a function of excitation energy are precious observables to constrain model parameters (fission barriers, level densities…) and provide much more accurate predictions for neutron-induced cross-sections of nuclei far from stability.

Benchmark:

4He+240Pu→4He'+240Pu*⇔n+239Pu→240Pu*



First simultaneous measurement of P_f and P_γ!

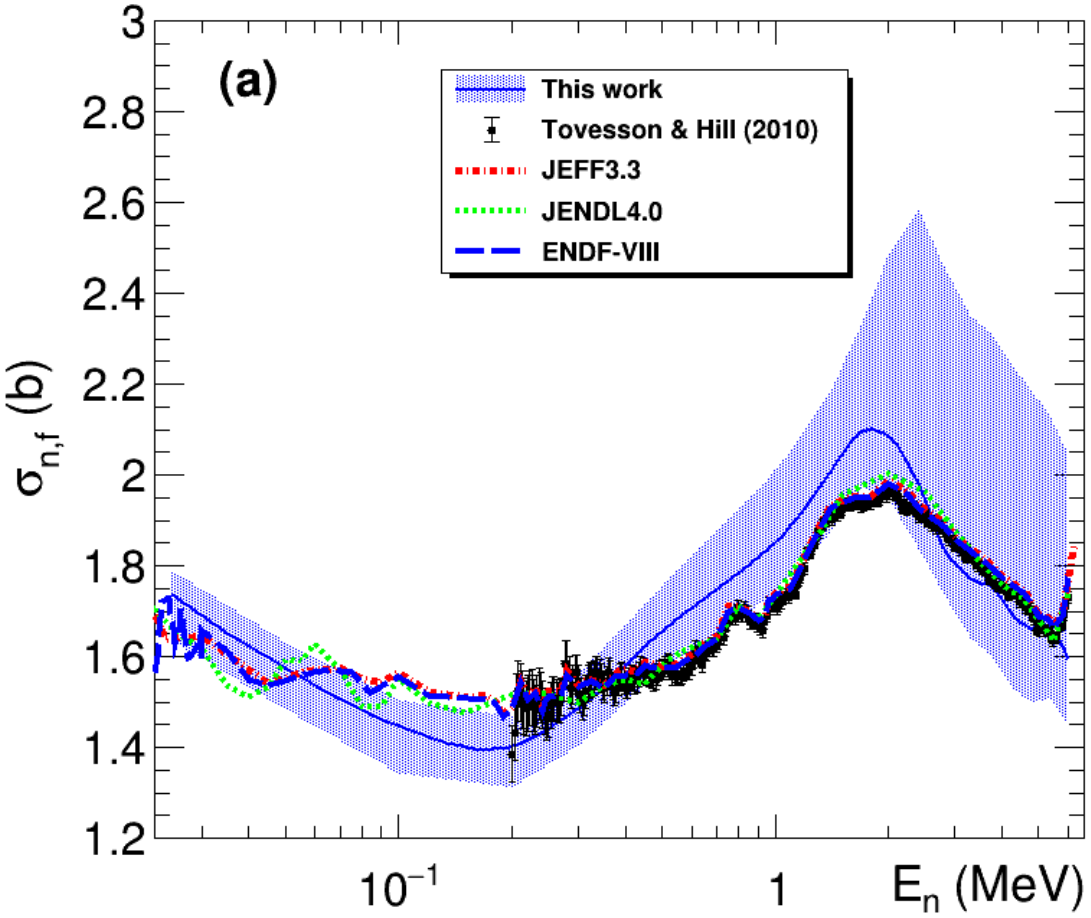
Stringent test of experimental method!

Accurate determination of model parameters!

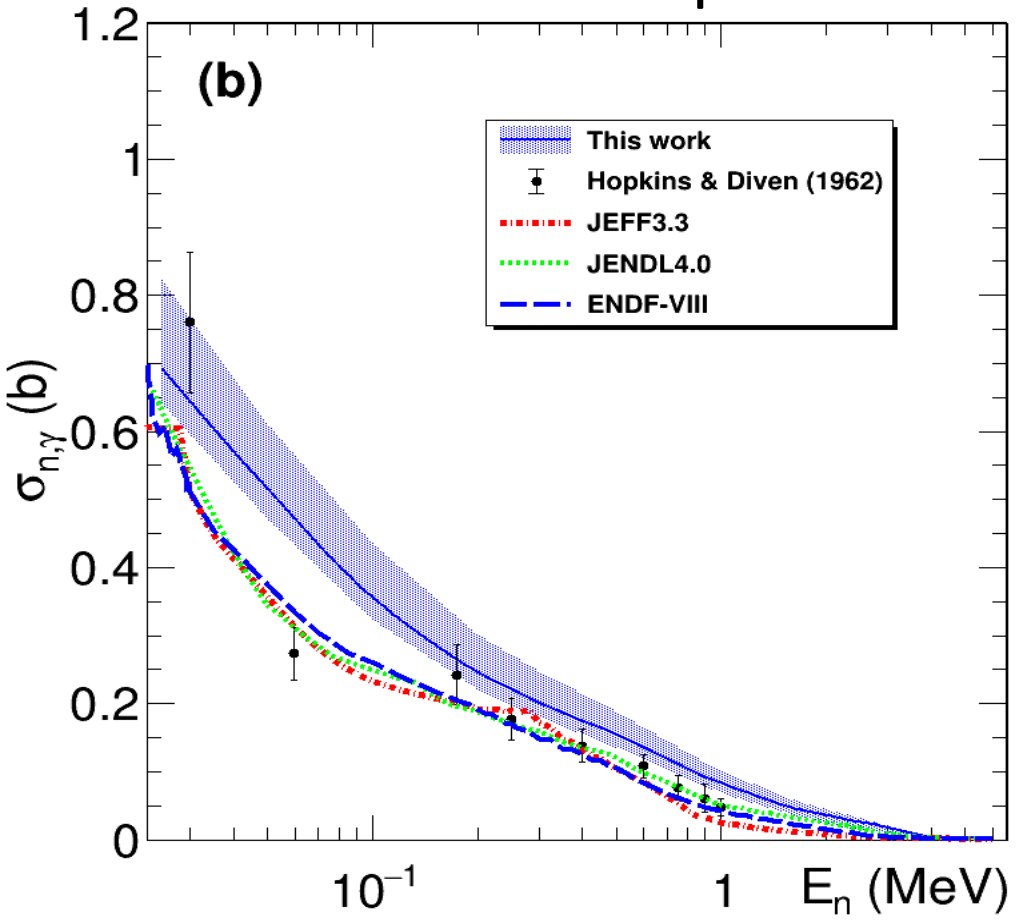
R. Perez Sanchez, BJ et al., Phys. Rev .Lett. 125 (2020) 122502

First simultaneous determination of neutron-induced fission and capture cross sections n+239Pu→240Pu*

Fission

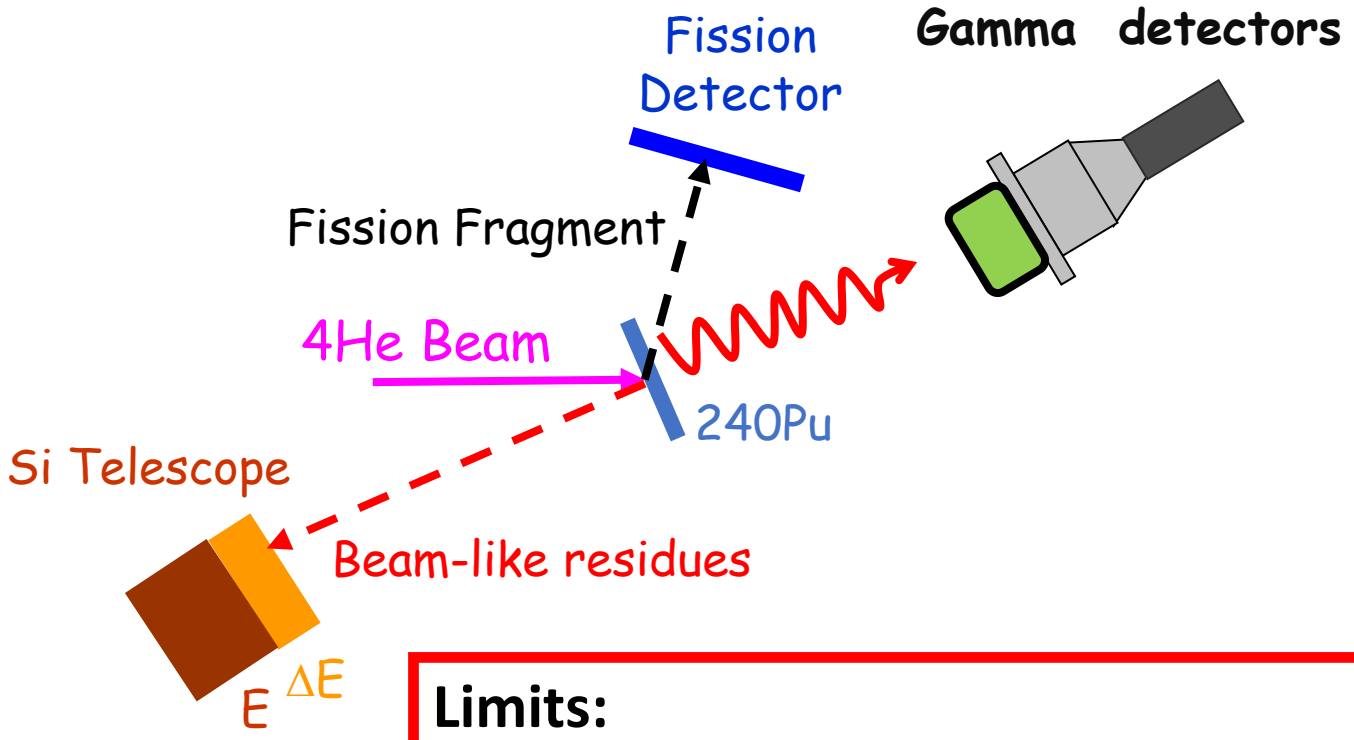


Radiative capture



R. Perez Sanchez, BJ et al., Phys. Rev .Lett. 125 (2020) 122502

Setup for the measurement of fission and gamma-emission probabilities in direct kinematics



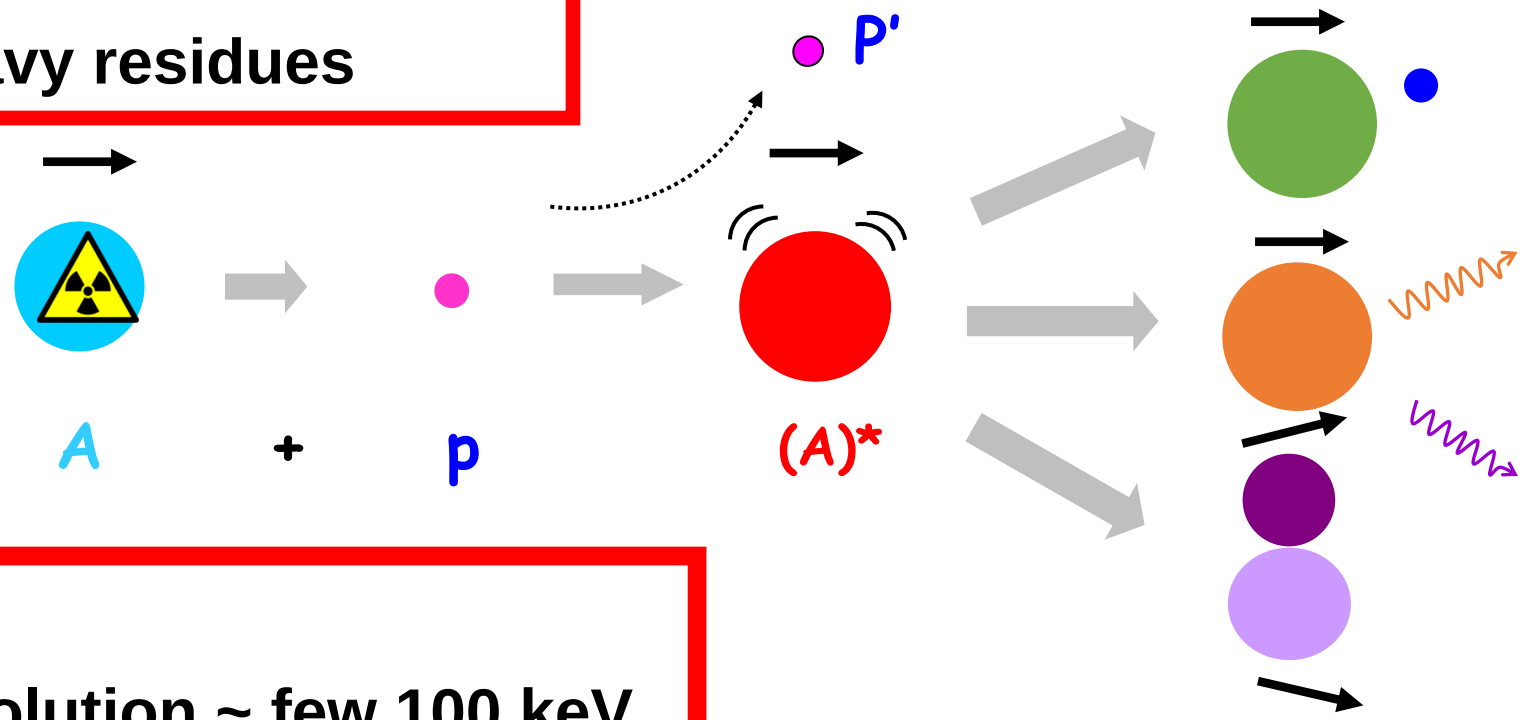
Limits:

- **Unavailability of targets (radioactive samples)**
- **Target contaminants and target support**
- **P_γ : rather low detection efficiency**
- **P_n: measurement of low-energy neutrons and neutron efficiency**

Advantages of Inverse kinematics:

-Access to very short-lived nuclei

-Detection of heavy residues

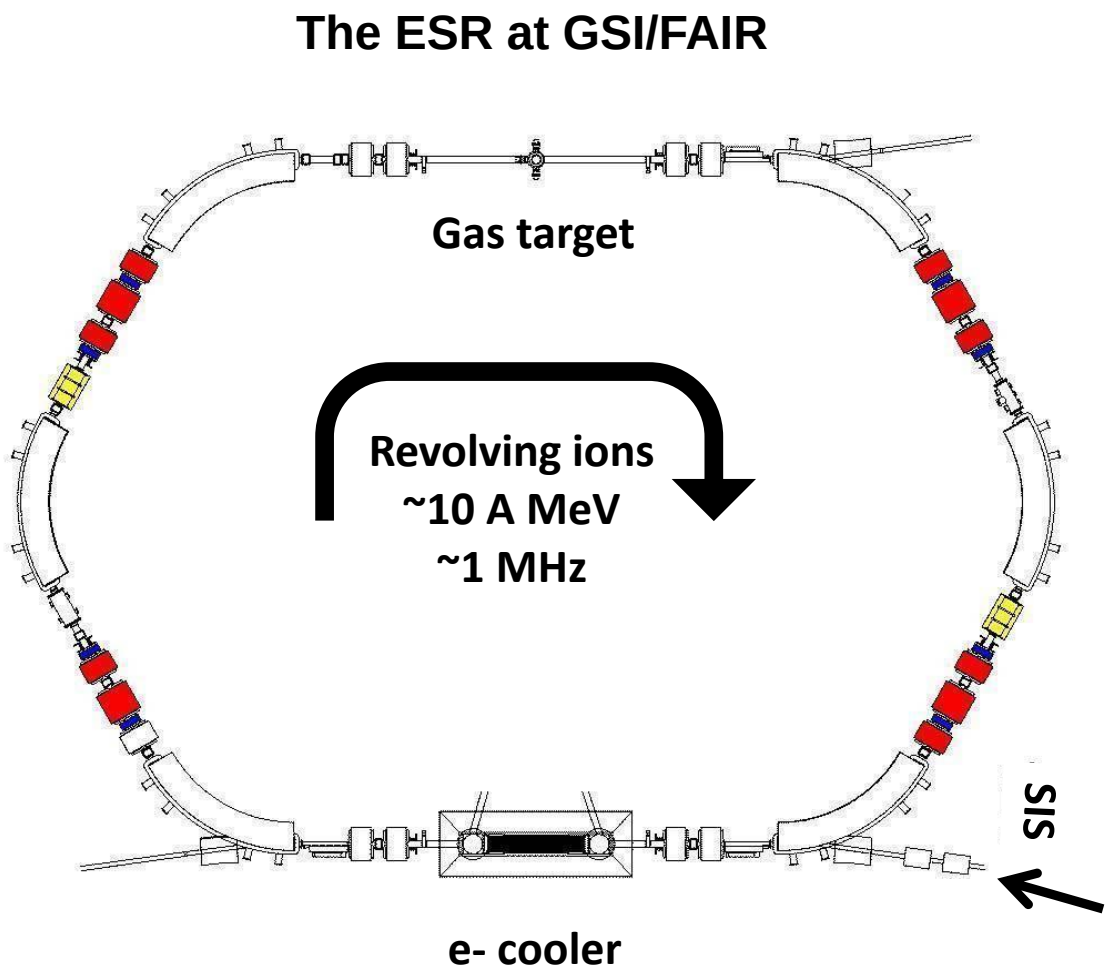


BUT!

- **Required E* resolution ~ few 100 keV, $E^*=f(E_{beam}, E_{target\_like}, \theta)$**
- **Target contaminants and target windows have to be avoided**

STORAGE RINGS!

Advantages of heavy-ion storage rings

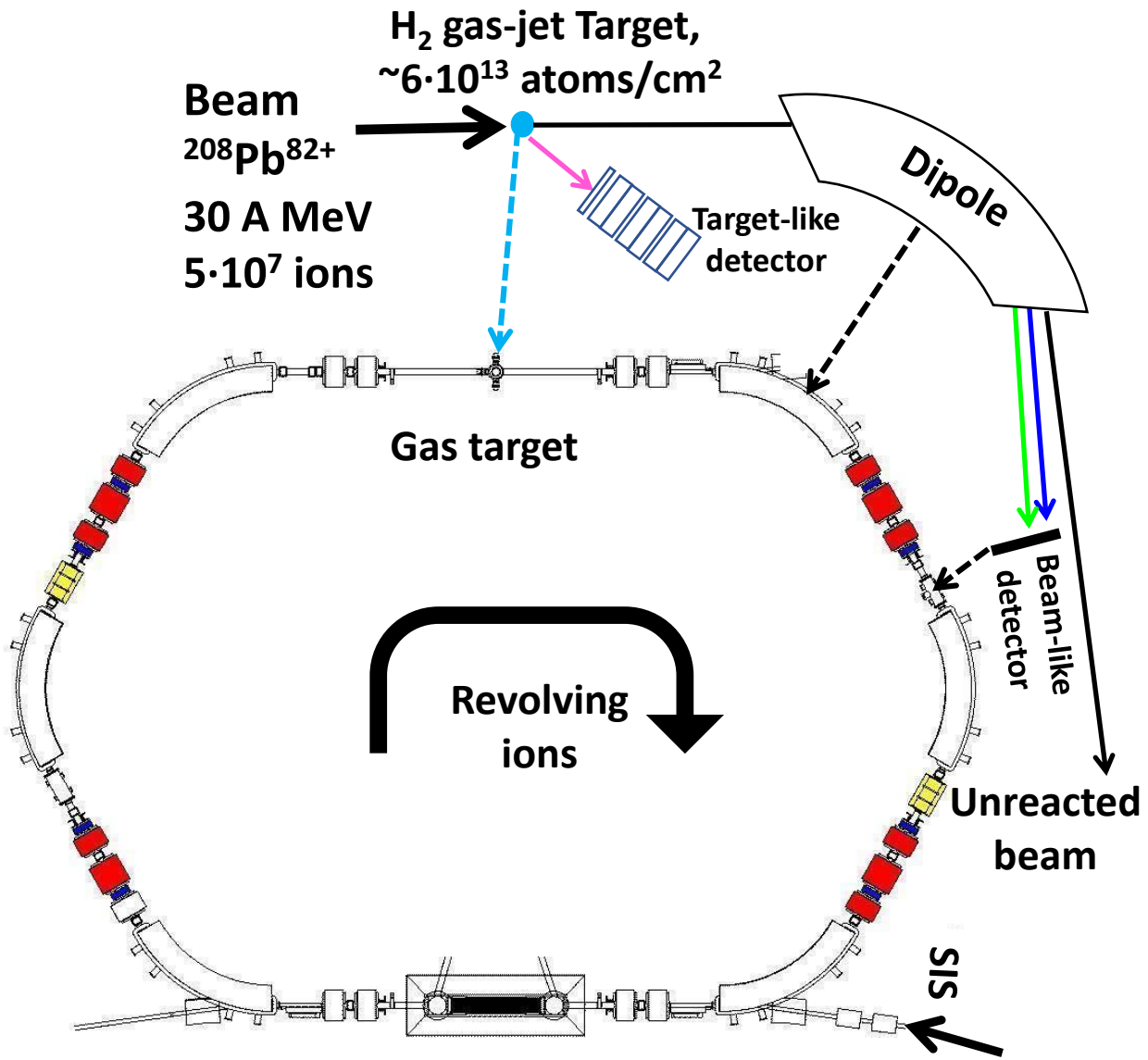


- Beam cooling → Excellent energy and position resolution of the beam, maintained after each passage through the target, negligible, E-loss & straggling effects
- Use of ultra-thin in-ring gas-jet targets ~10^{13}/cm^2. Effective target thickness increased by ~10^6 due to revolution frequency (at 10 A MeV)
- High-quality, pure, fully-stripped beams and pure, ultra-thin, windowless targets→ unique!

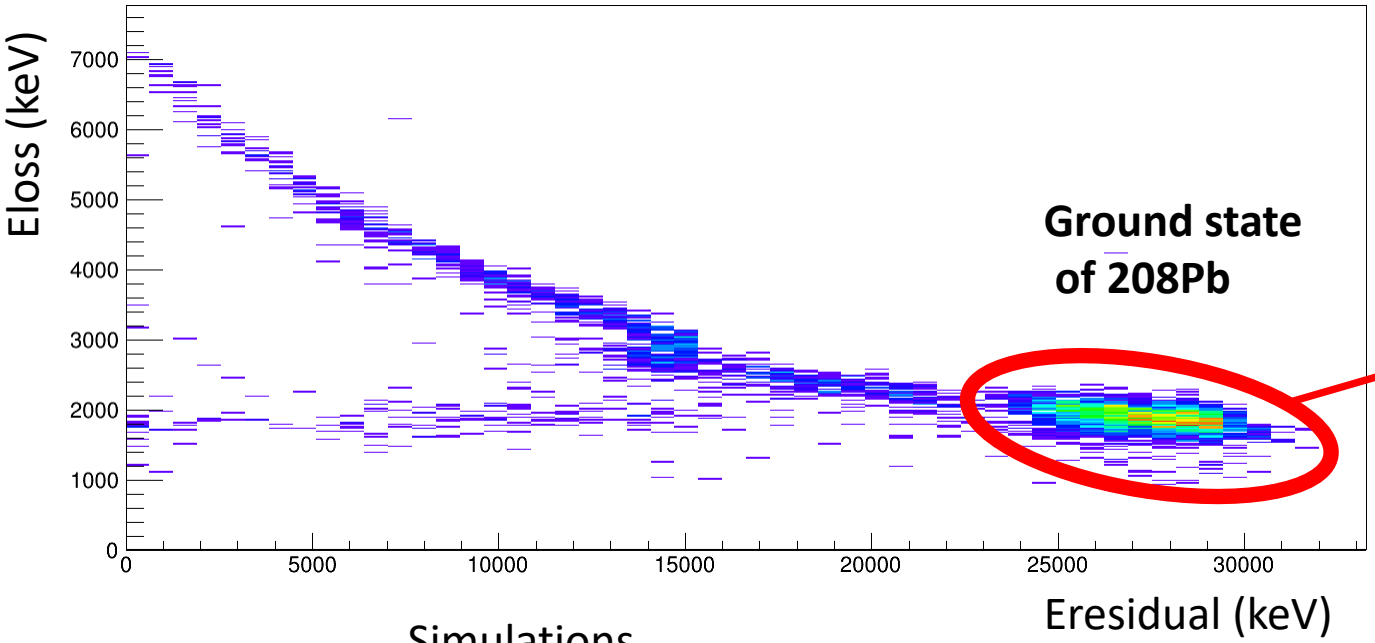
Challenge: Detectors in Ultra-High Vacuum (10^{-11}-10^{-12} mbar)!

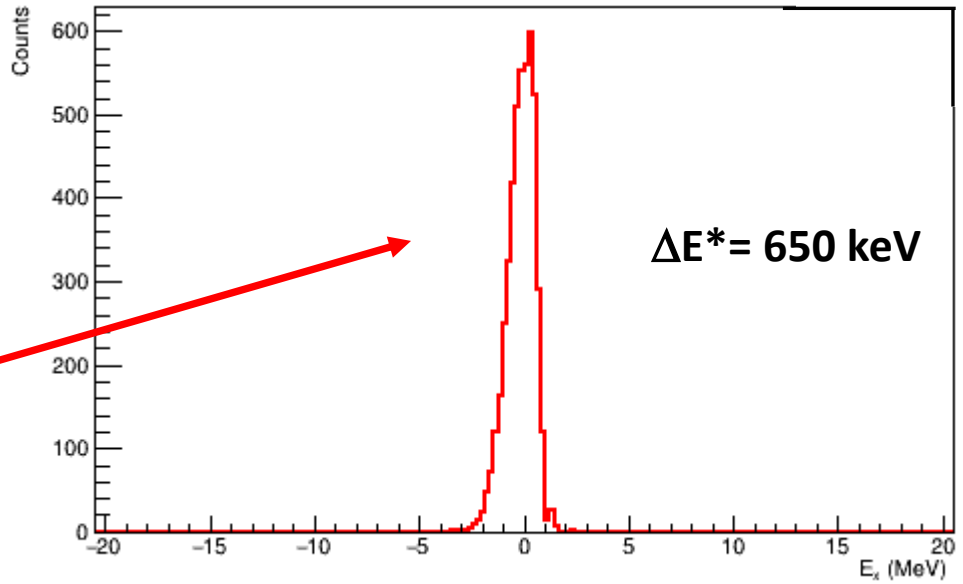
Proof-of-principle experiment at the ESR, 20-27 June 2022

208Pb+p→208Pb*+p'

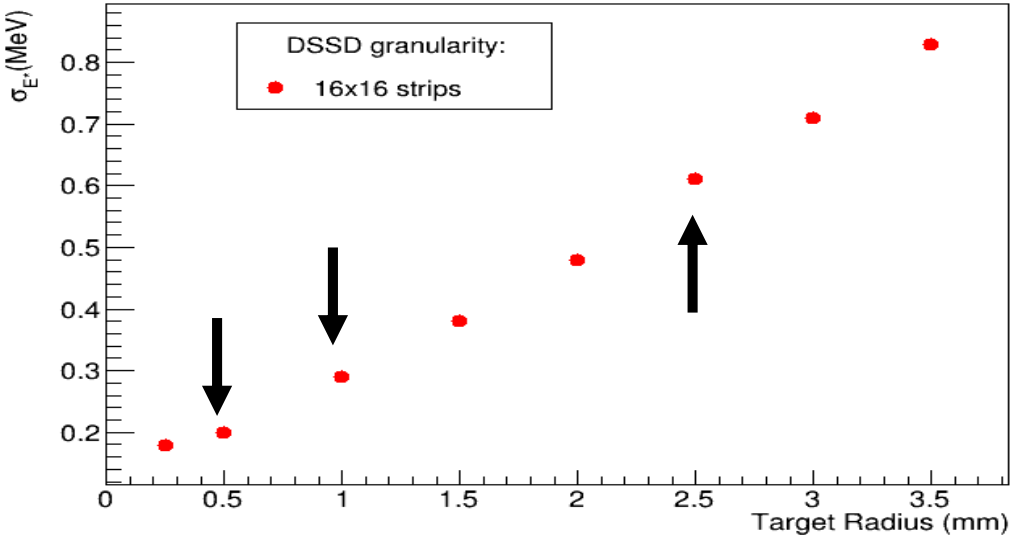


Preliminary results, excitation energy resolution





Simulations



ΔE*=650 keV, dominated by the angular uncertaintiy due to target radius of 2.5 mm.
With target radius 0.5 -1.5 mm →ΔE*=200-300 keV!

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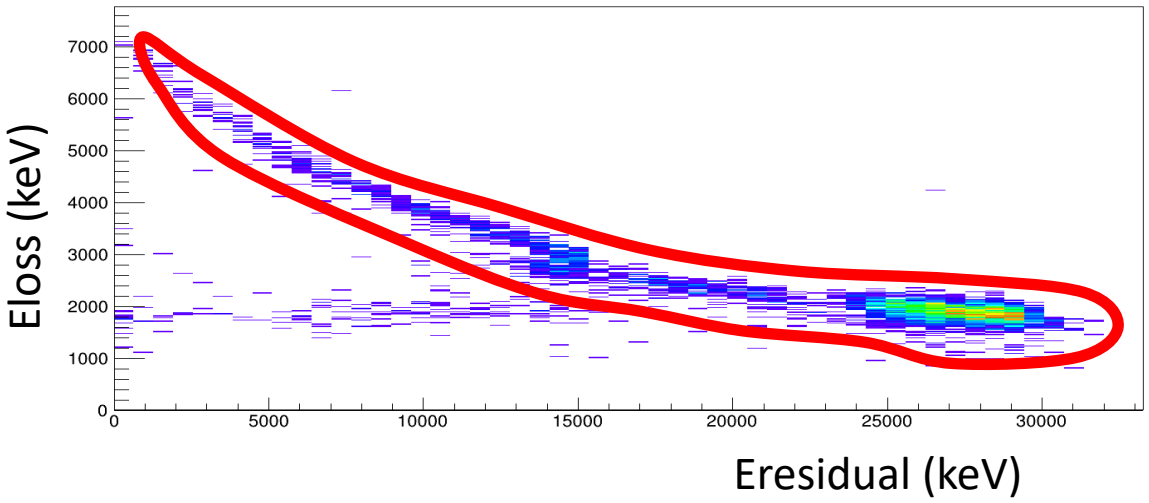
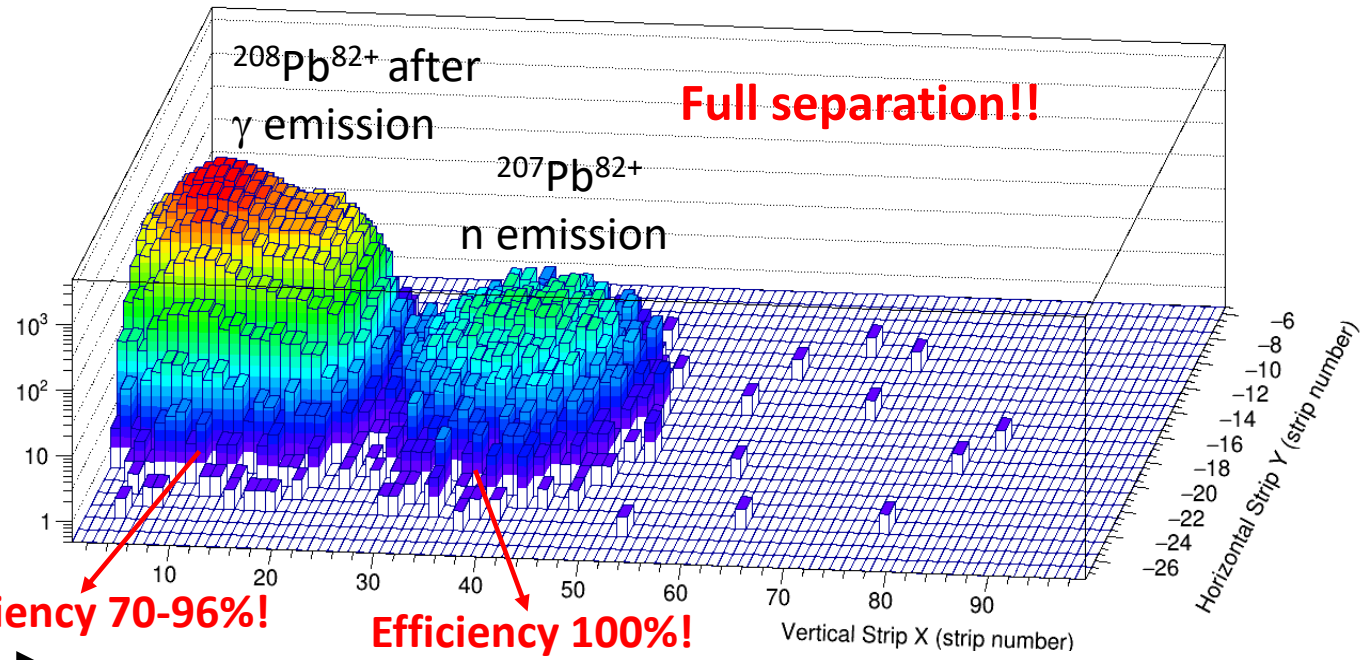
Preliminary results, detection of beam-like residues

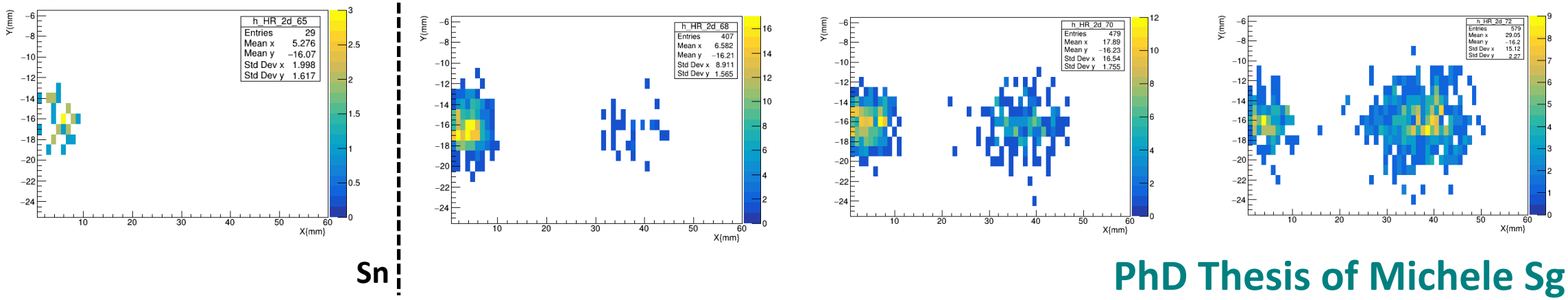
Detected protons



Position of detected beam residues in coincidence with protons



Excitation energy



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Conclusions…

-Storage rings offer the ideal conditions to investigate surrogate reactions!

-First proof of principle experiment succesfully conducted at the ESR in June 2022

→$\Delta E^* \approx 650$ keV in accordance with expectations

→ Full separation and 70-100% detection efficiency for beam-like residues

→Validation of new methodology for simultaneous measurement of P_γ and P_n

…Perspectives

-Pursue data analysis to infer P_γ and P_n and neutron-induced cross sections of 207Pb

-Add a fission detector to measure simultaneously P_γ, P_n and P_f of ^{238}U & target radius 0.5-1 mm.

-Measurements with radioactive beams!

Acknowledgements

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NECTAR: Nuclear rEaCTions At storage Rings

Prime 80 program from CNRS, PhD thesis of M. Sguazzin