Surrogate reactions at the Experimental Storage Ring

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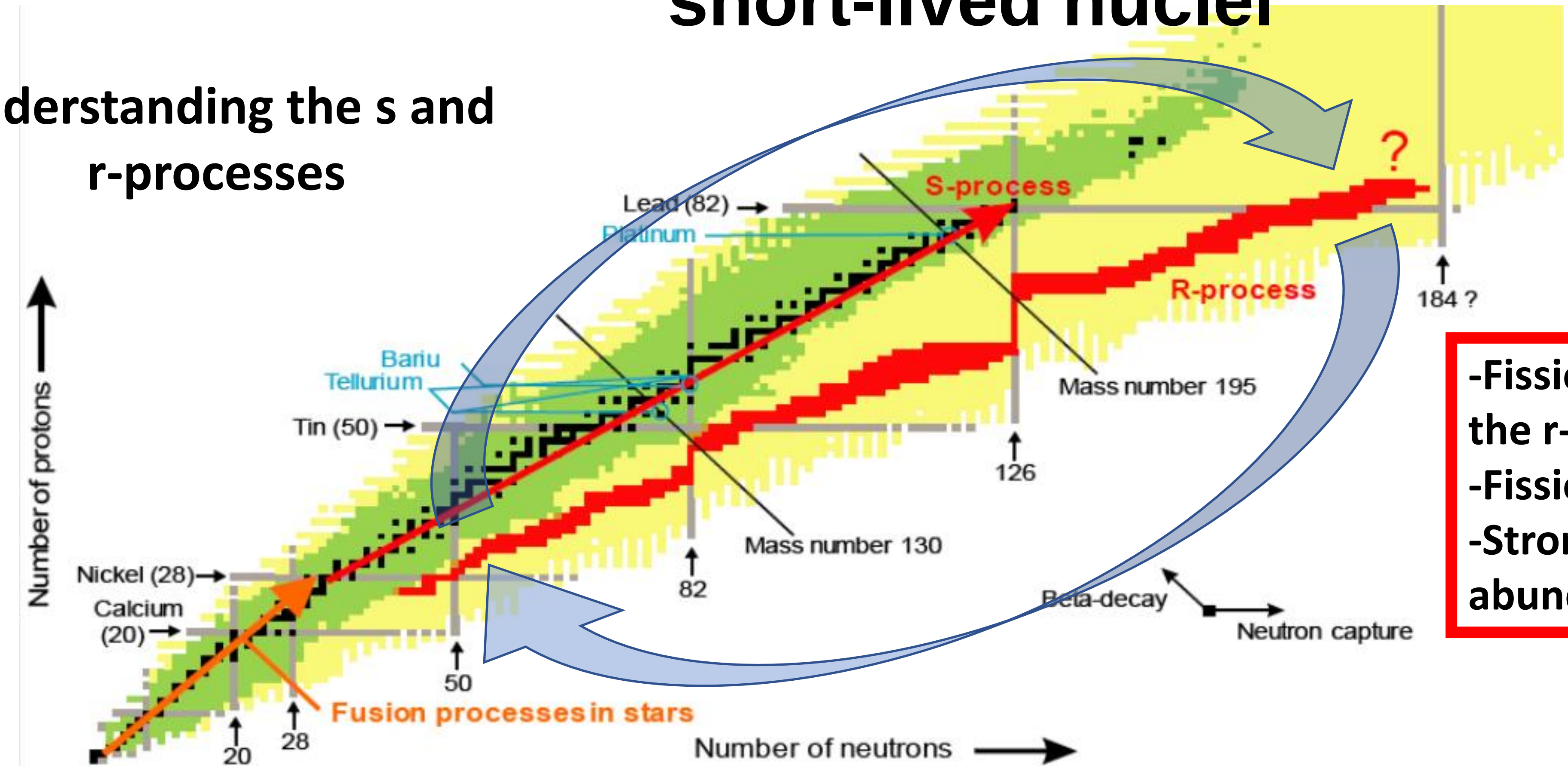
Need for neutron-induced reaction cross sections of short-lived nuclei

Understanding the s and r-processes

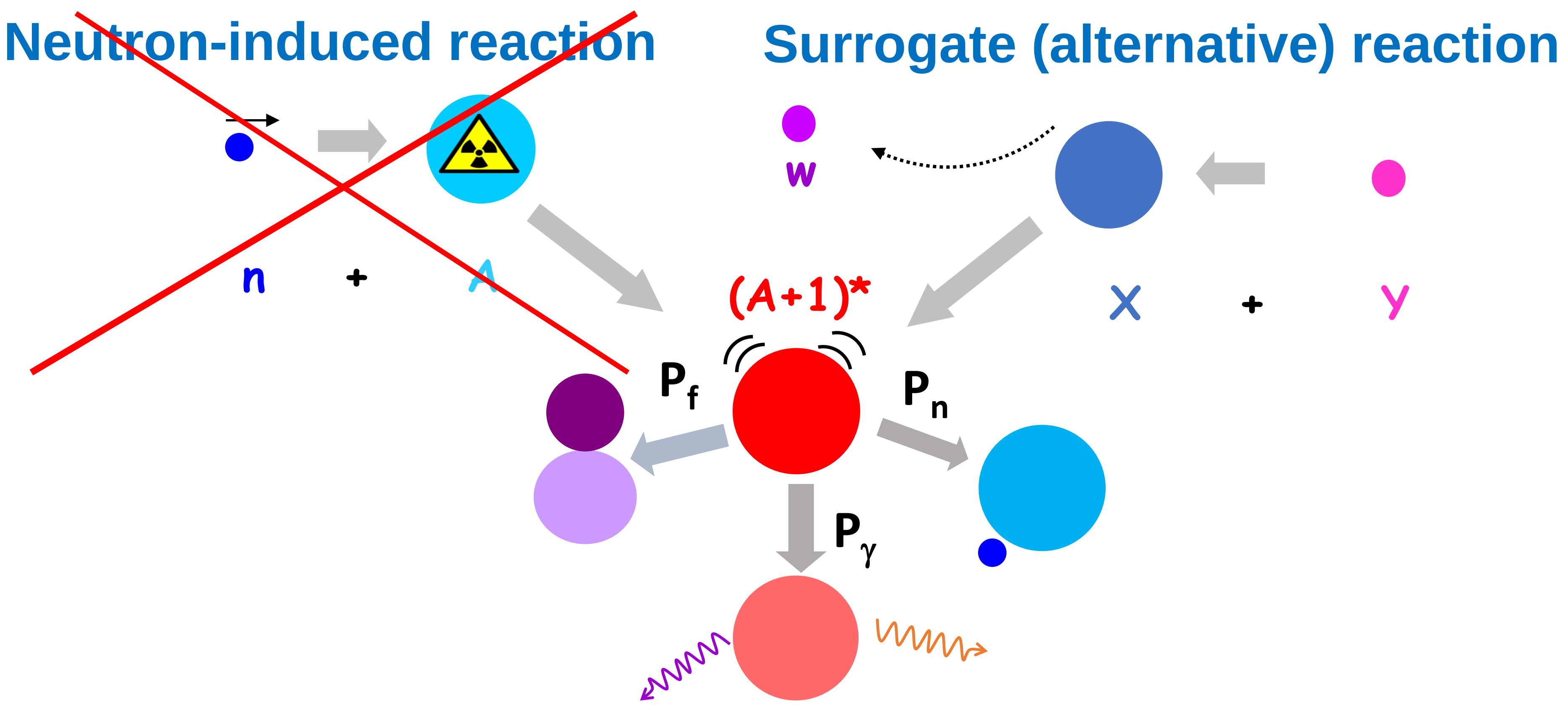


-Fission sets the end point of the r-process path.
-Fission recycling.
-Strong impact on abundances and light curves.

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

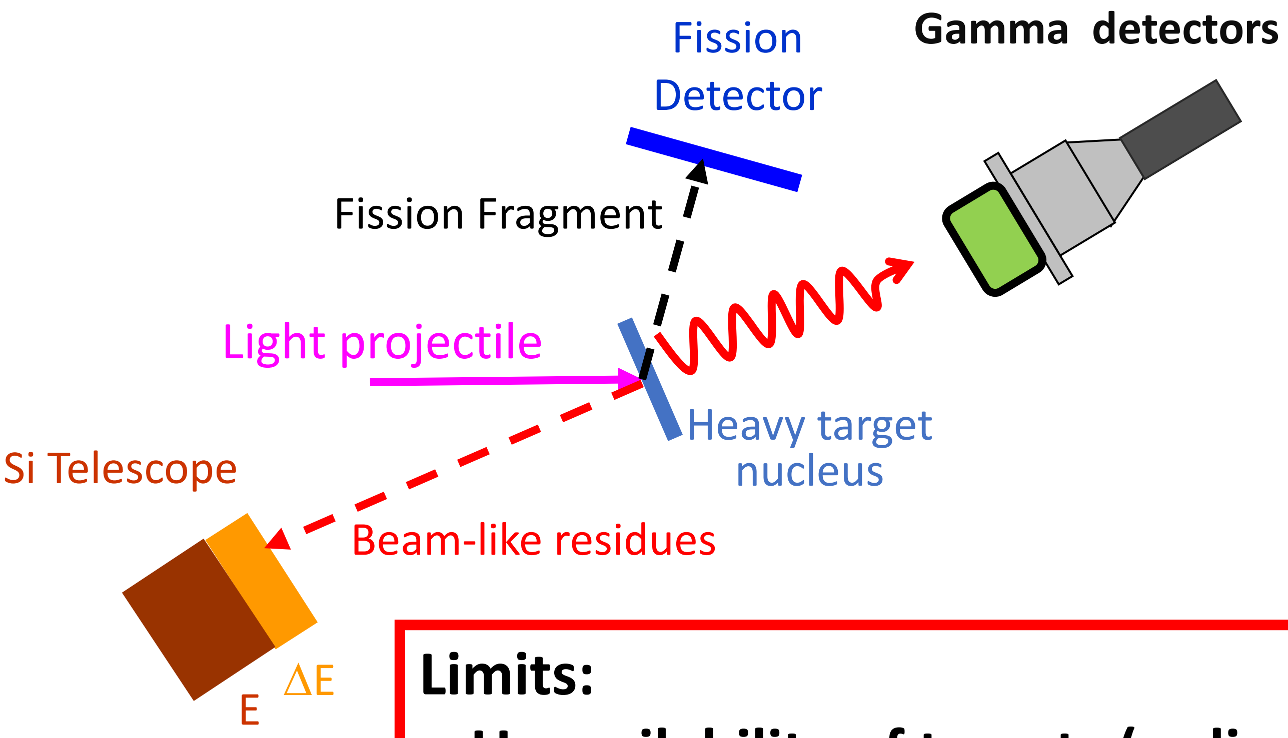
→**Complicated to calculate due to the difficulty to describe the de-excitation process. Calculations can be wrong by several orders of magnitude!**

Surrogate-reaction method



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

Setup for the study of surrogate reactions in direct kinematics



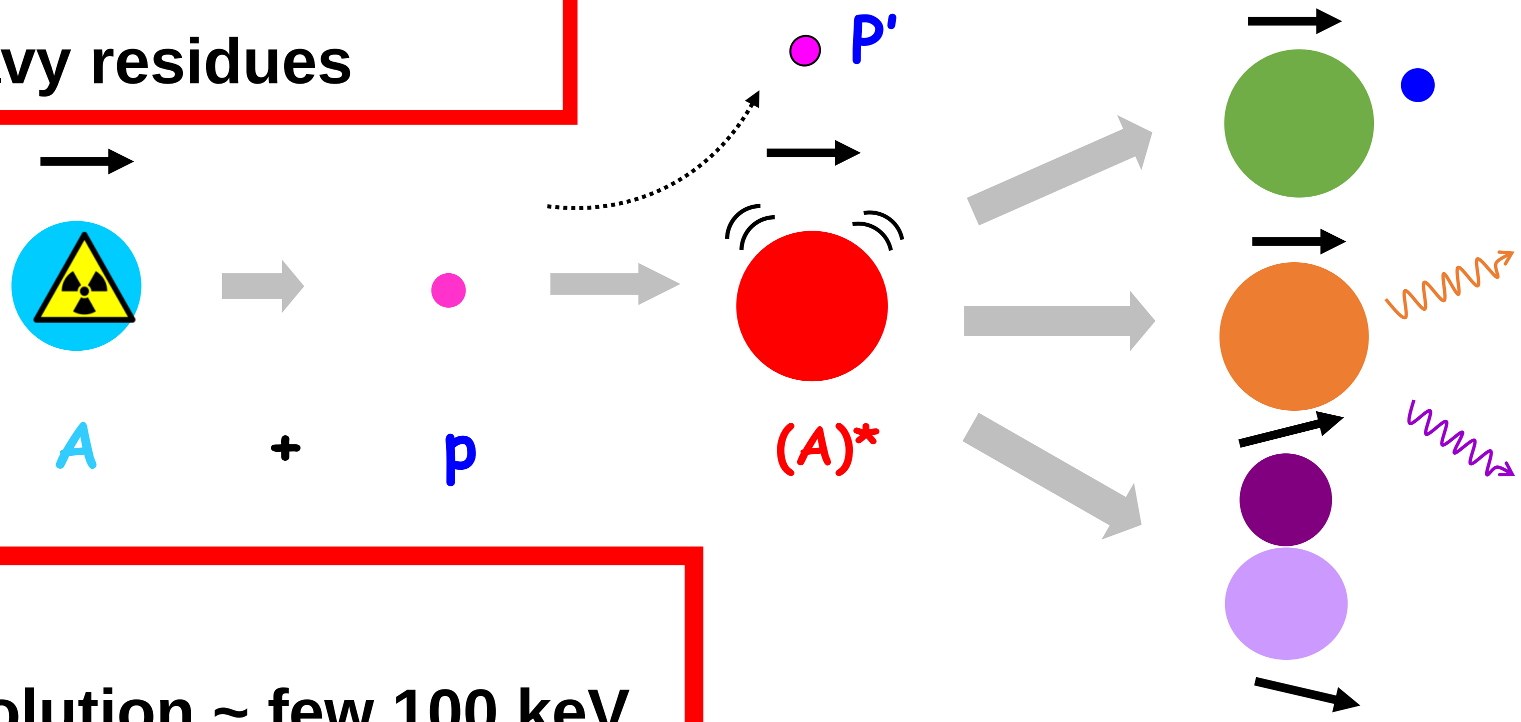
Limits:

- **Unavailability of targets (radioactive samples)**
- **Target contaminants and target support**
- **P_γ : rather low detection efficiency, background**
- **P_n: measurement of low-energy neutrons and neutron efficiency, background, never measured!**

Advantages of Inverse kinematics:

-Access to very short-lived nuclei

-Detection of heavy residues



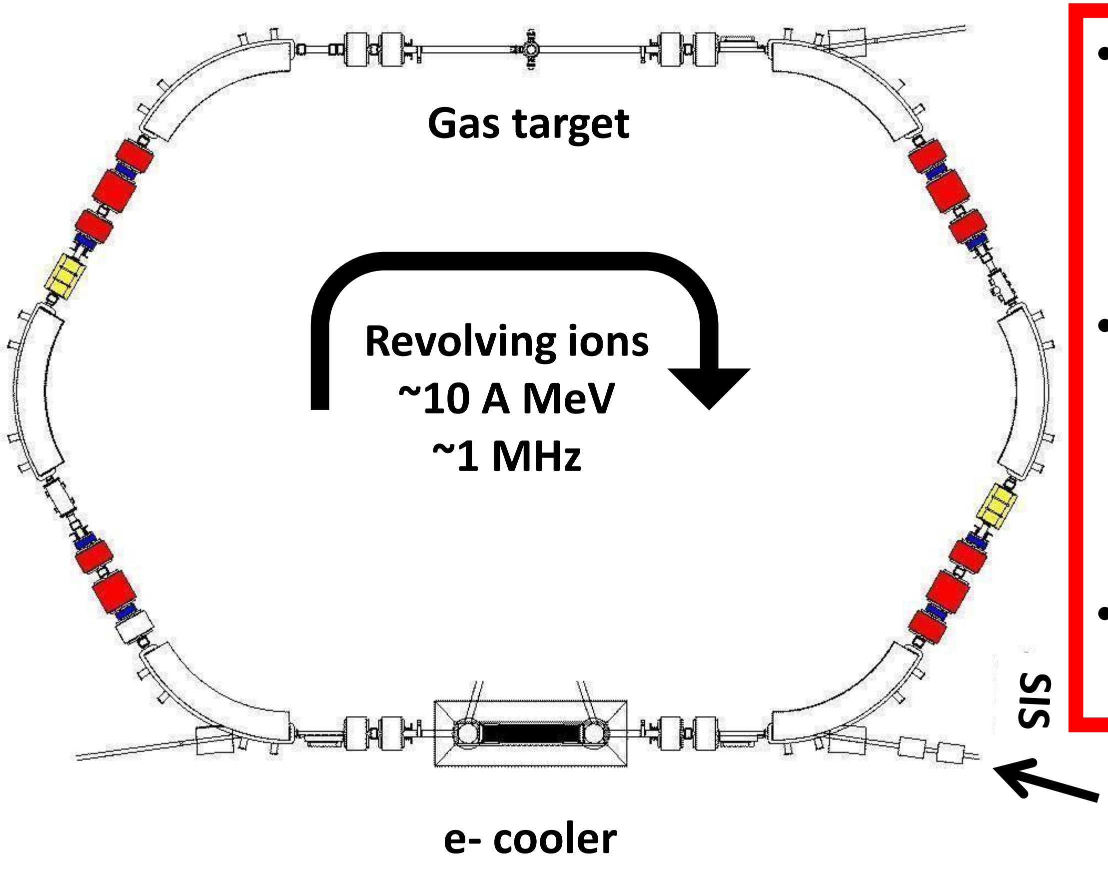
BUT!

- **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

The ESR at GSI/FAIR

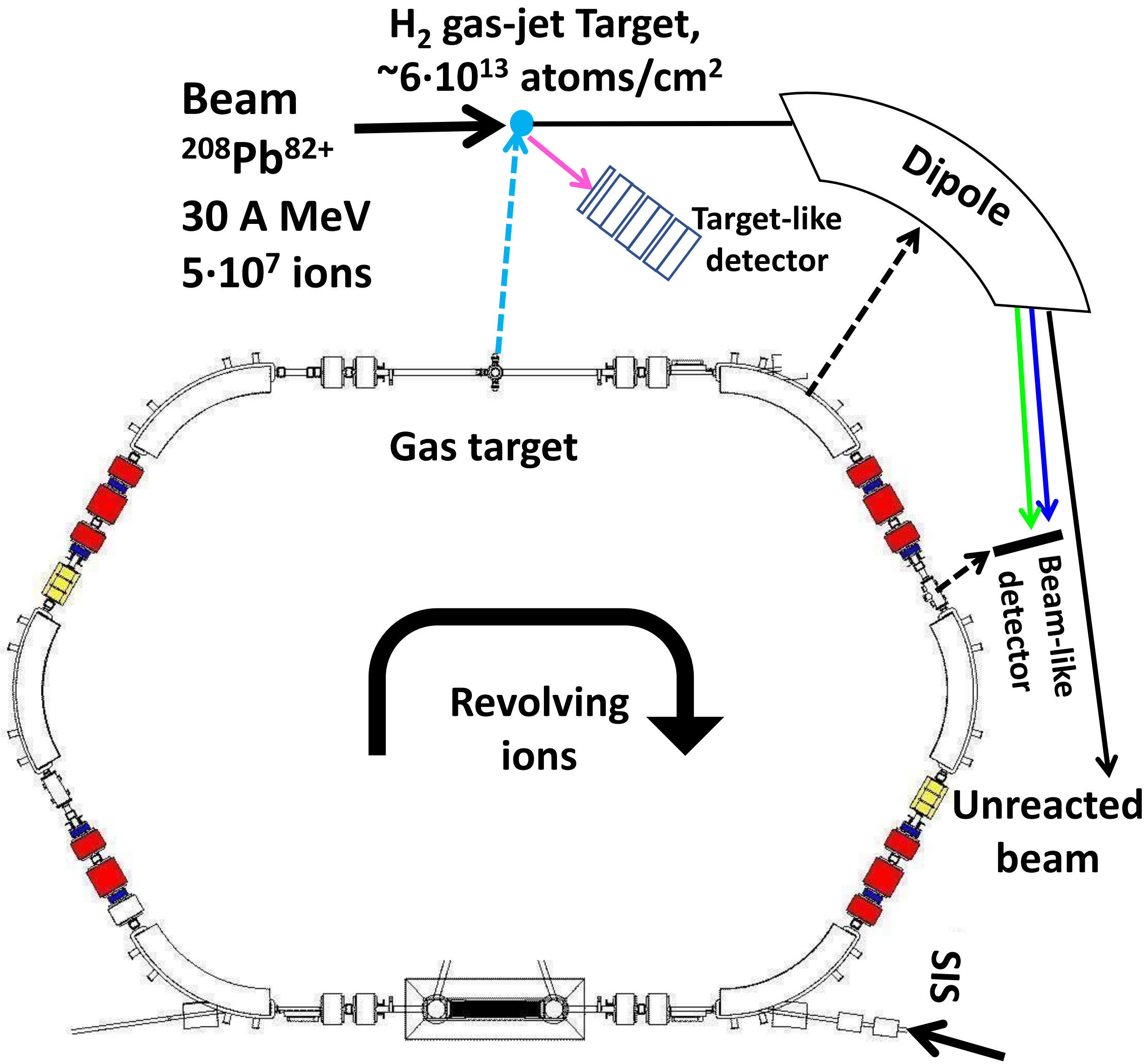


- Beam cooling → Excellent energy and position resolution of the beam, maintained after each passage through the target, negligible, E-loss & straggling effects
- Use of ultra-low density in-ring gas-jet targets ~$10^{13}/cm^2$.

  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!

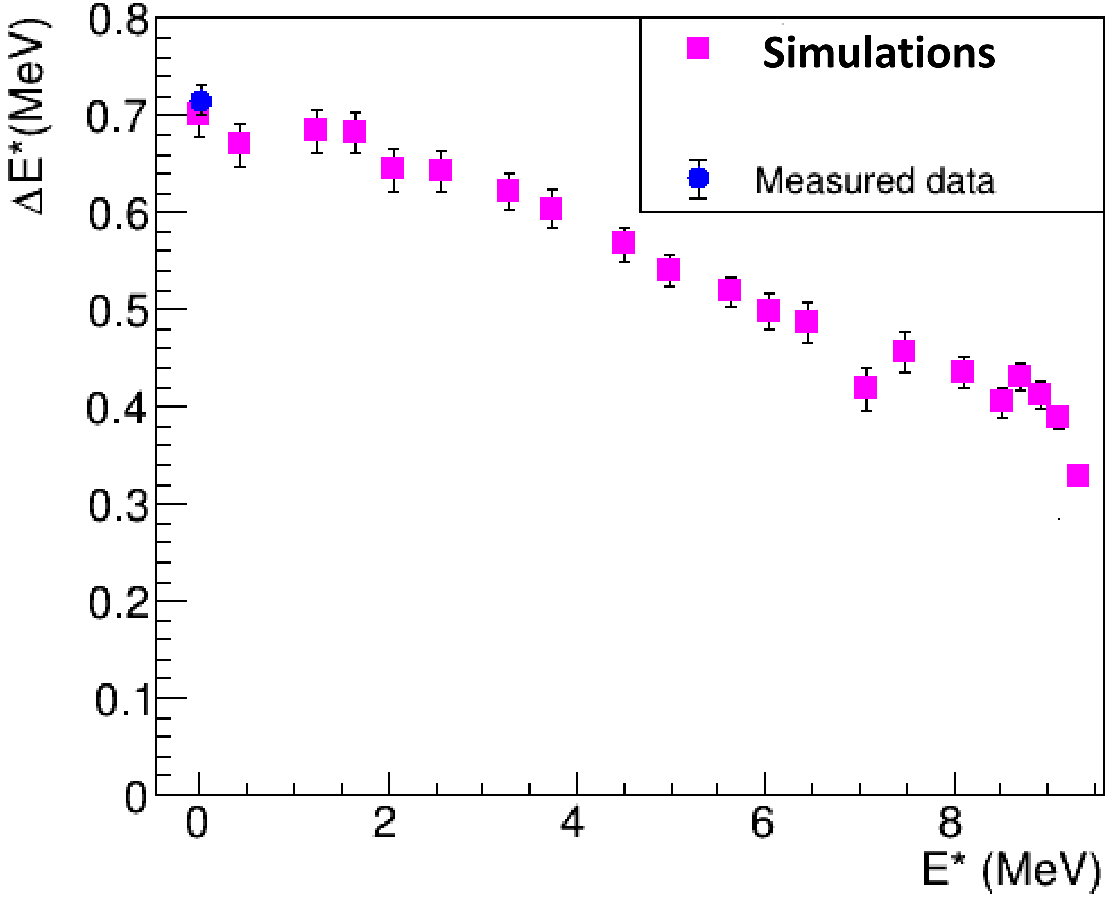
Challenge: Detectors in Ultra-High Vacuum (10^{-11}-10^{-12} mbar)!

First surrogate reaction experiment at the ESR, June 2022
208Pb+p→208Pb*+p' <-> n+ 207Pb

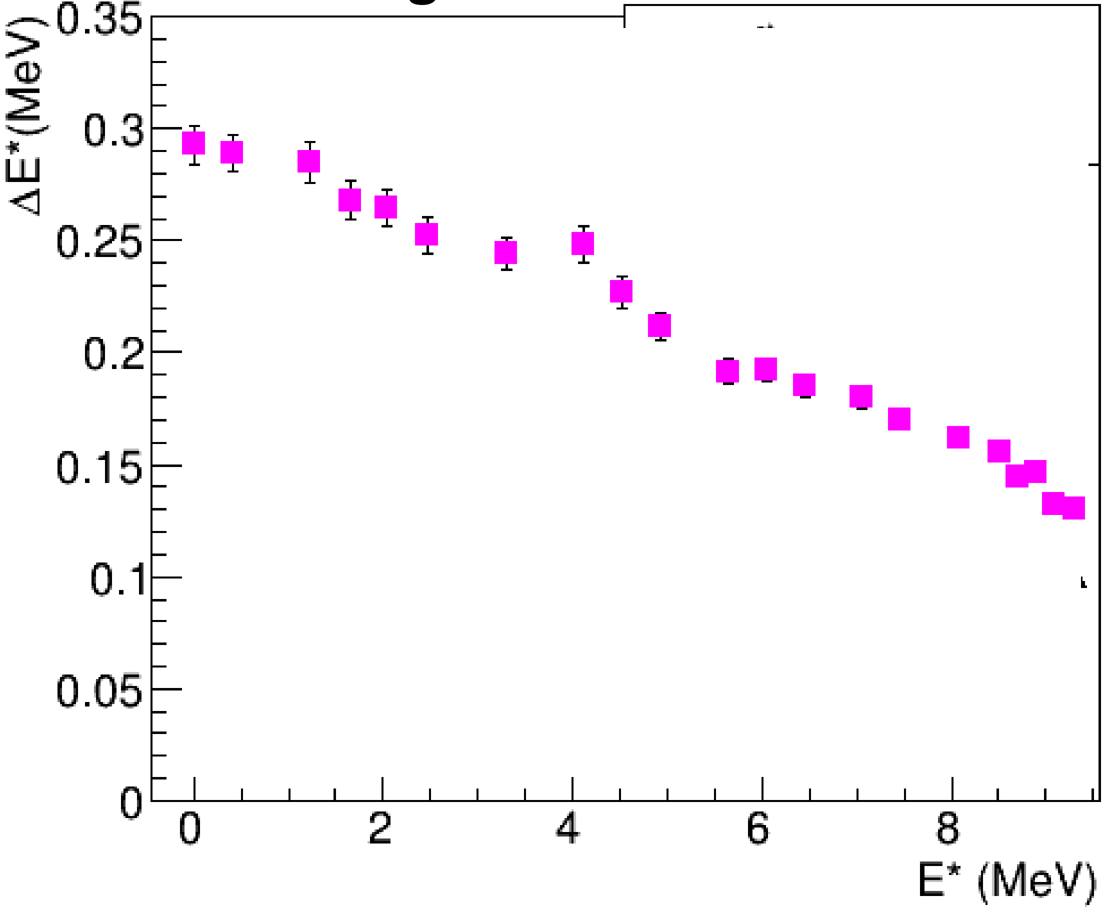


Excitation energy resolution

Target radius 2.5 mm



Target radius 0.5 mm



ΔE*dominated by the angular uncertainty due to target radius of ~2.5 mm.

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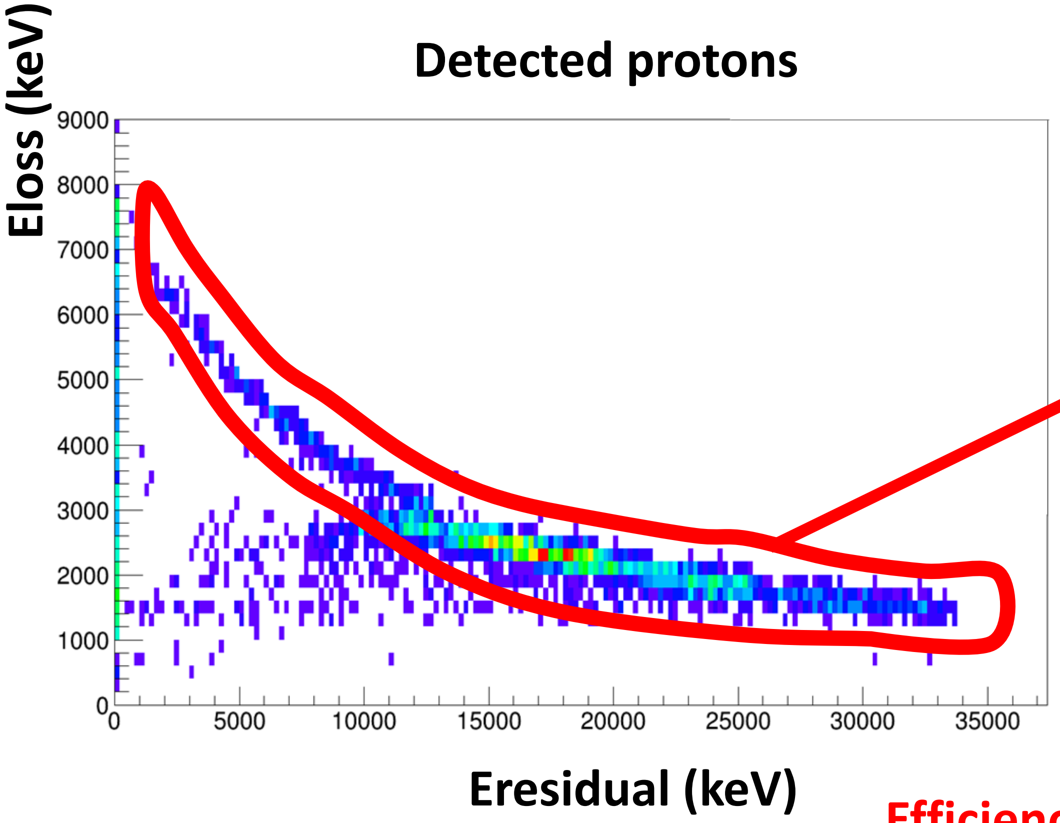
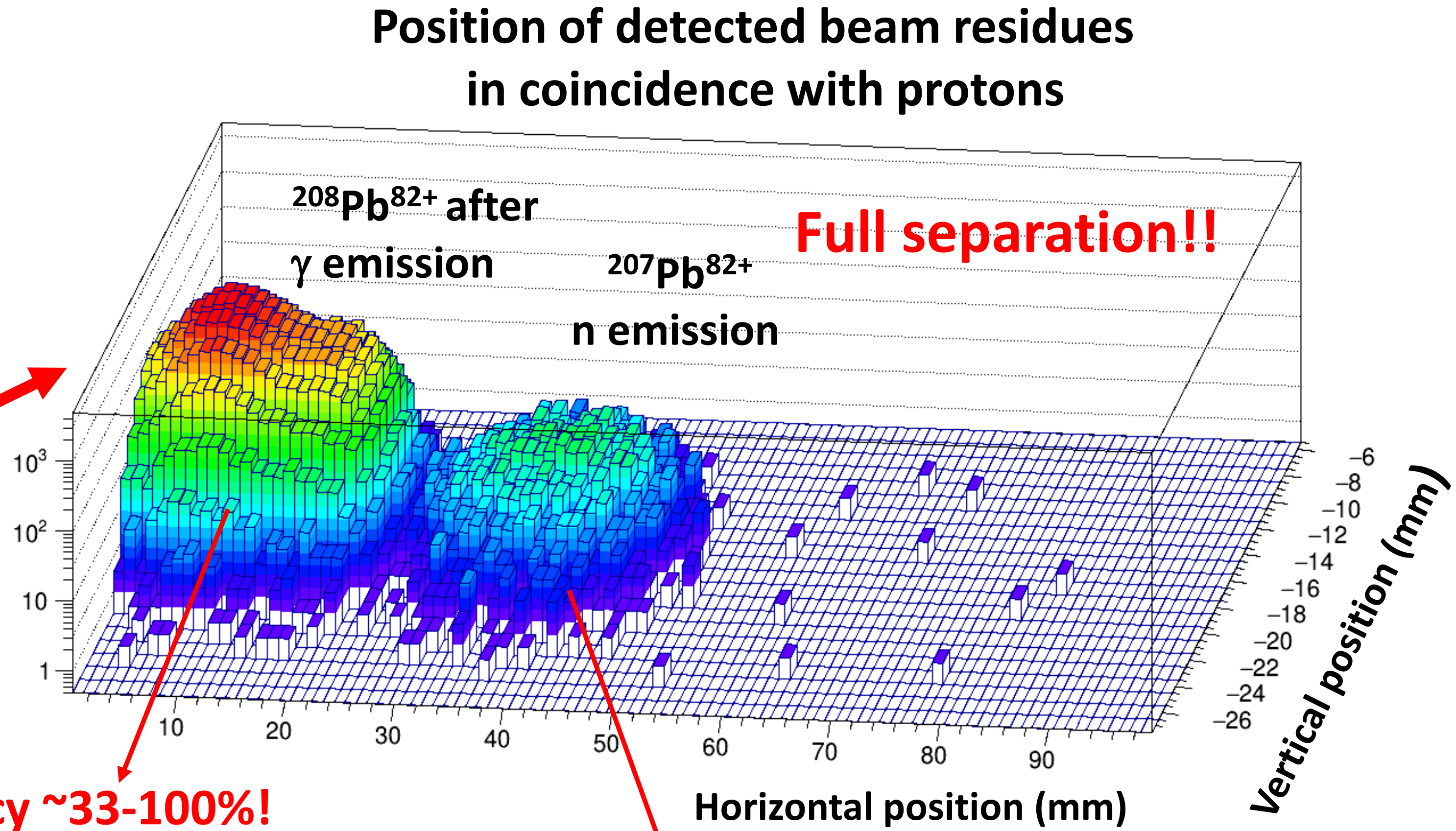
Detection of beam-like residues





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

Efficiency 100%!
0% in direct kinematics…

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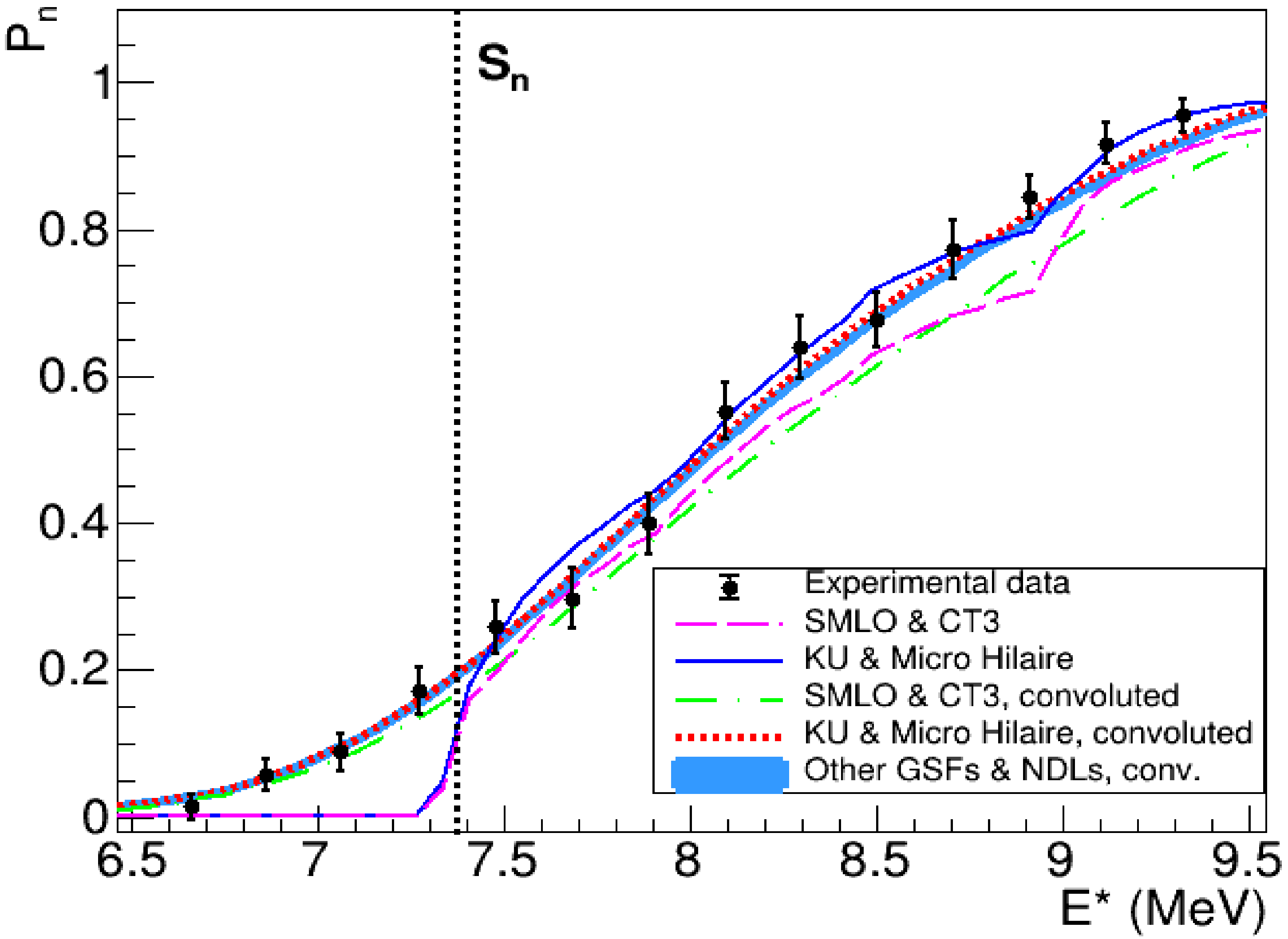
Comparison with TALYS calculations

Neutron emission probability of 208Pb



Effect of E* resolution at the neutron separation energy!

Largest level density description based on CT3 model is ruled out by our data!

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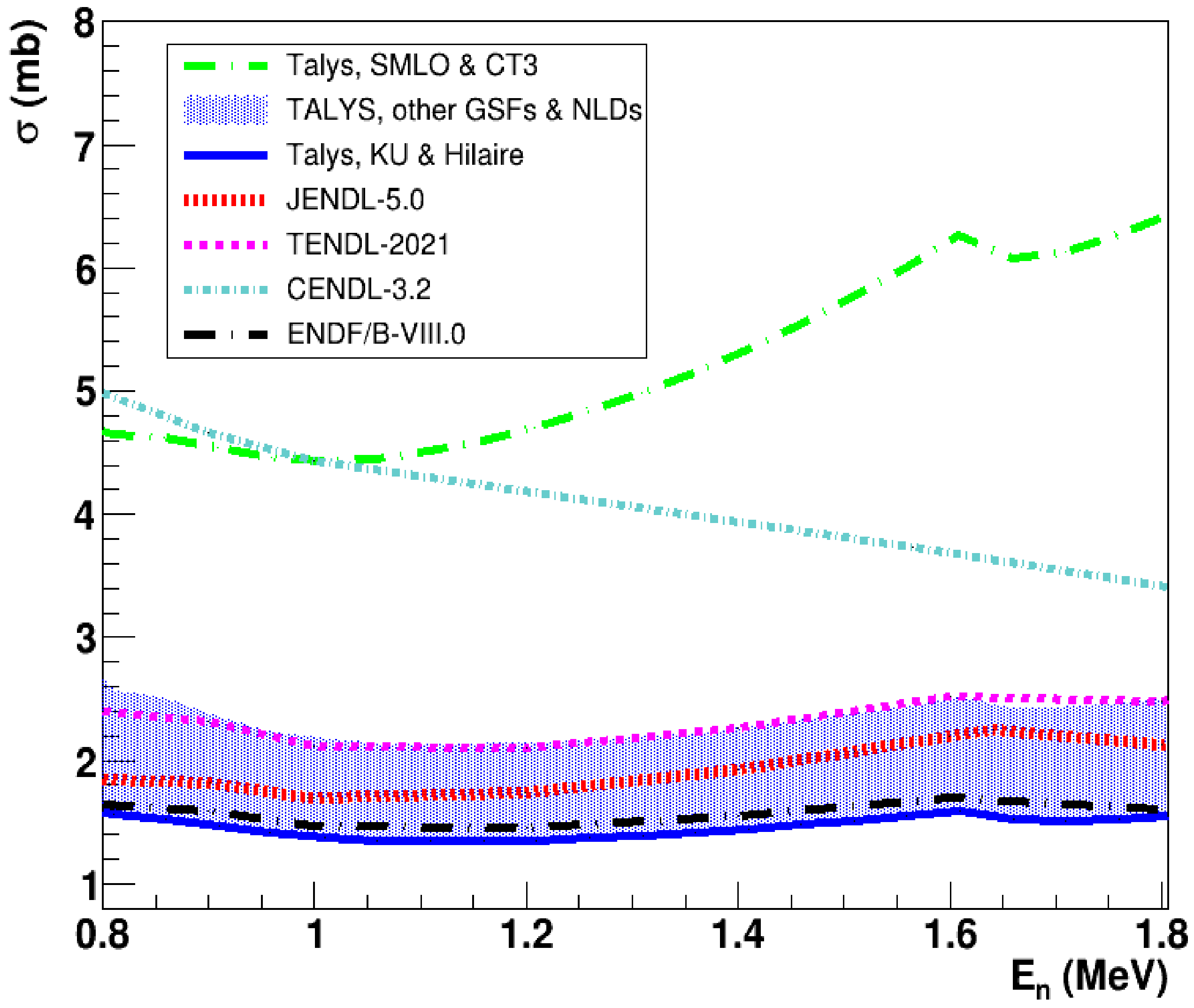
^{207}Pb(n, γ) cross section



Good agreement with all evaluations except CENDL-3.2!

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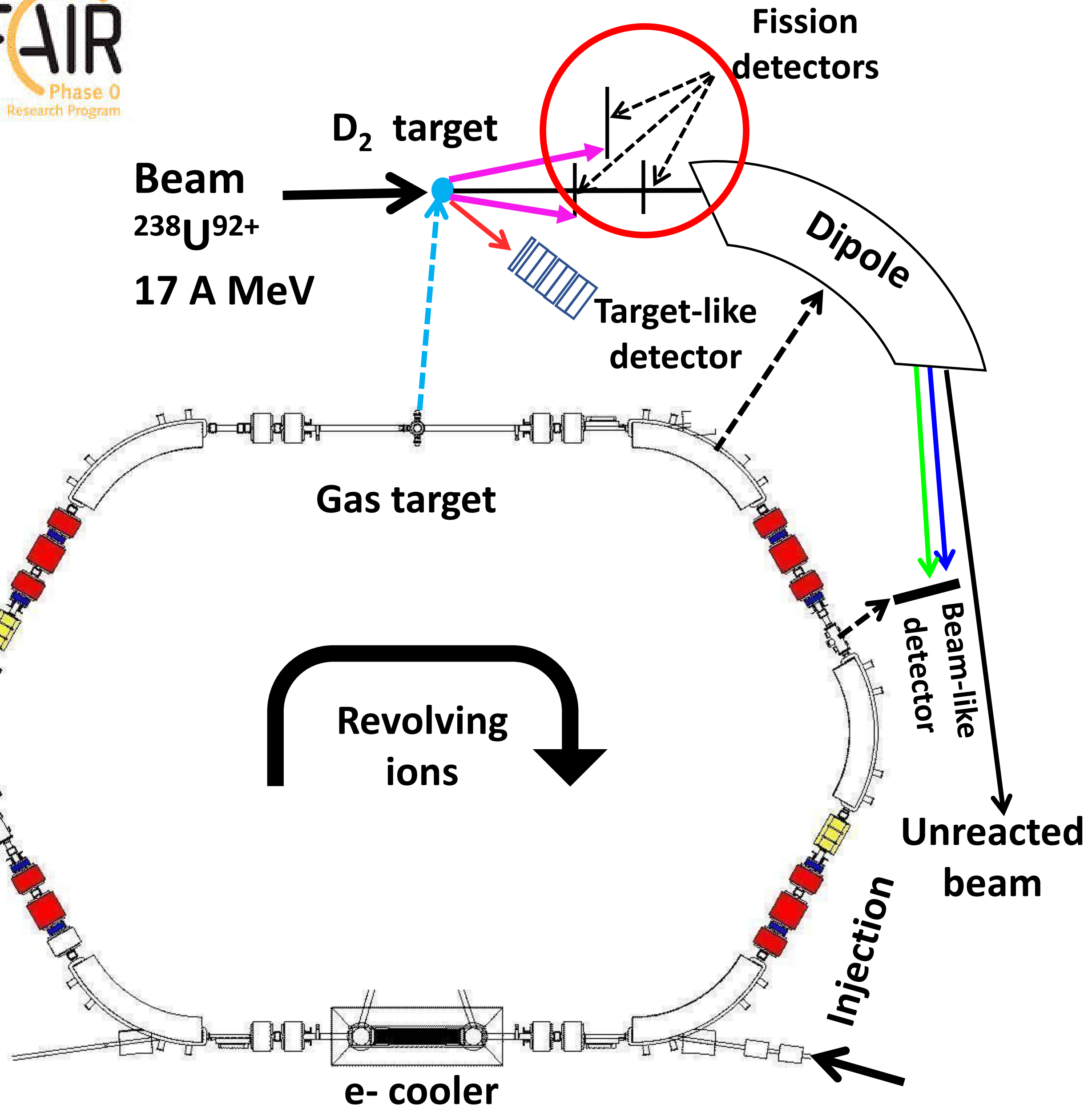
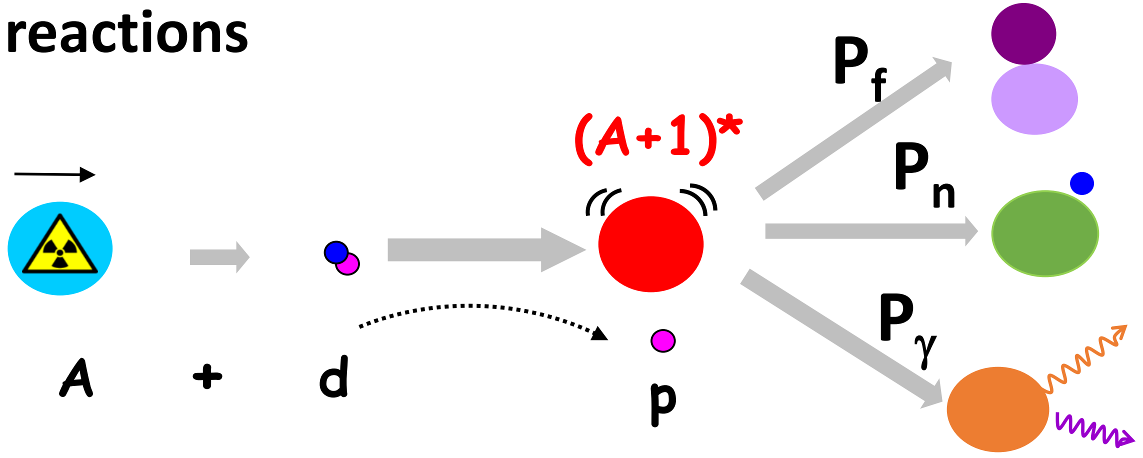
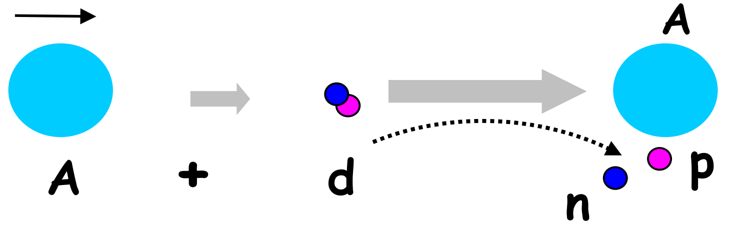
Second surrogate reaction experiment at the ESR, 20-27 June 2024



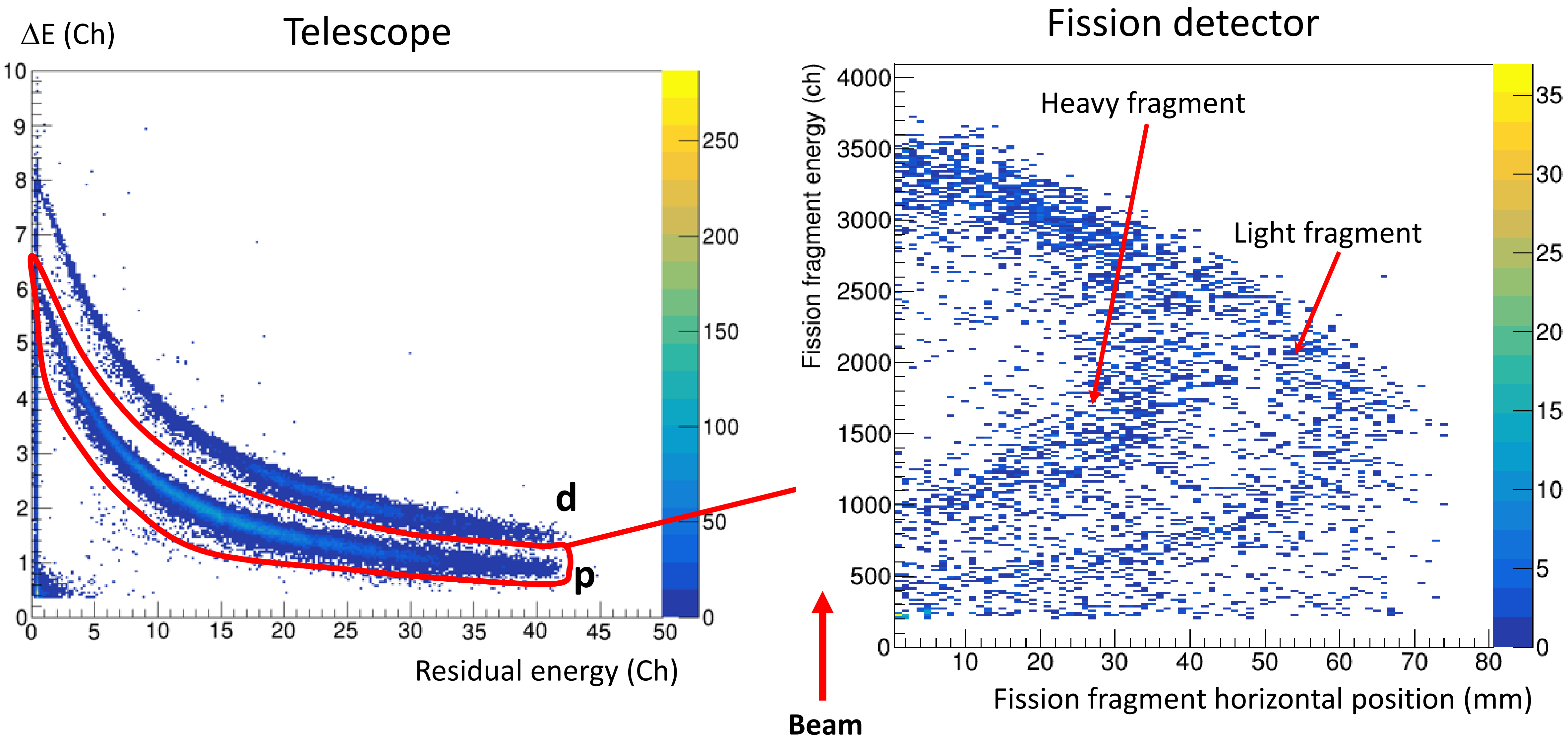
- Added fission detectors. **First time that fission is studied in a storage ring!**
- Studied 238U(d,d') and 238U(d,p) reactions



- Deuteron breakup issue

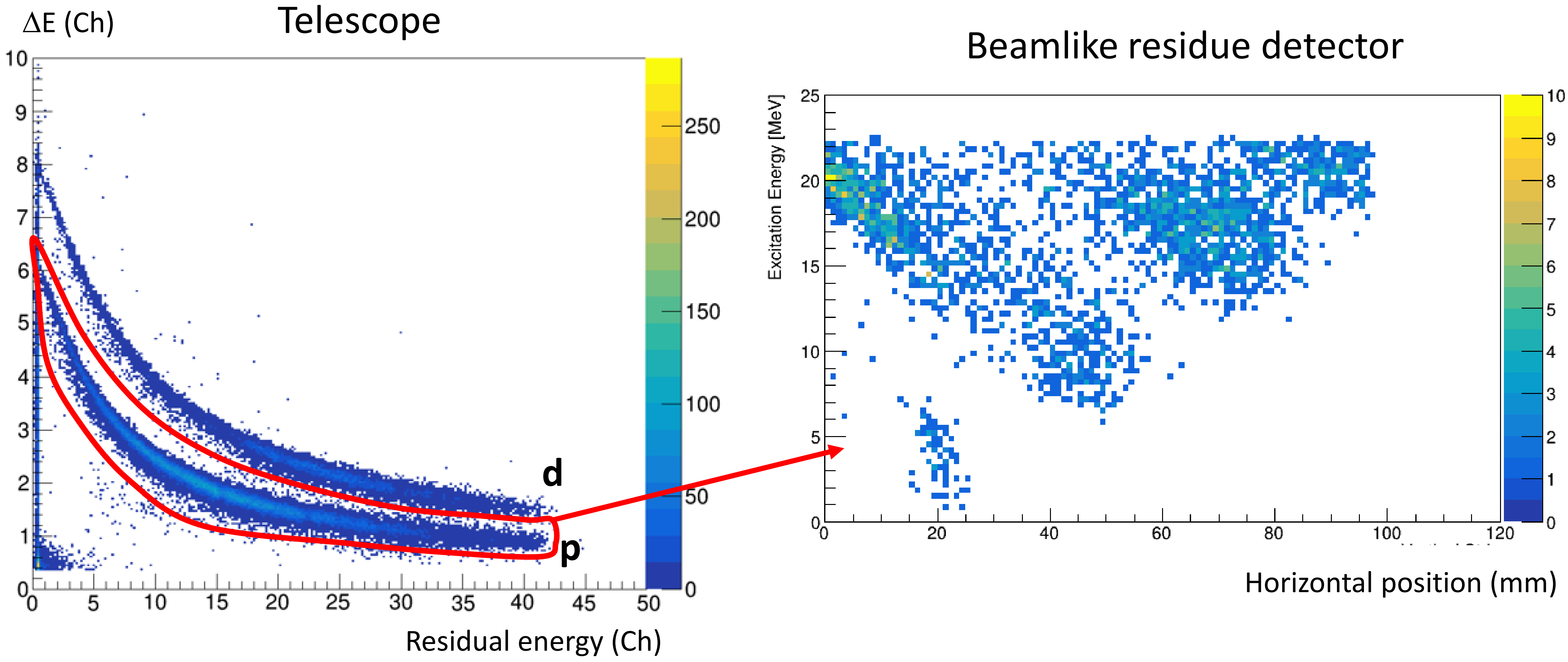


Preliminary results, 238U(d,p)



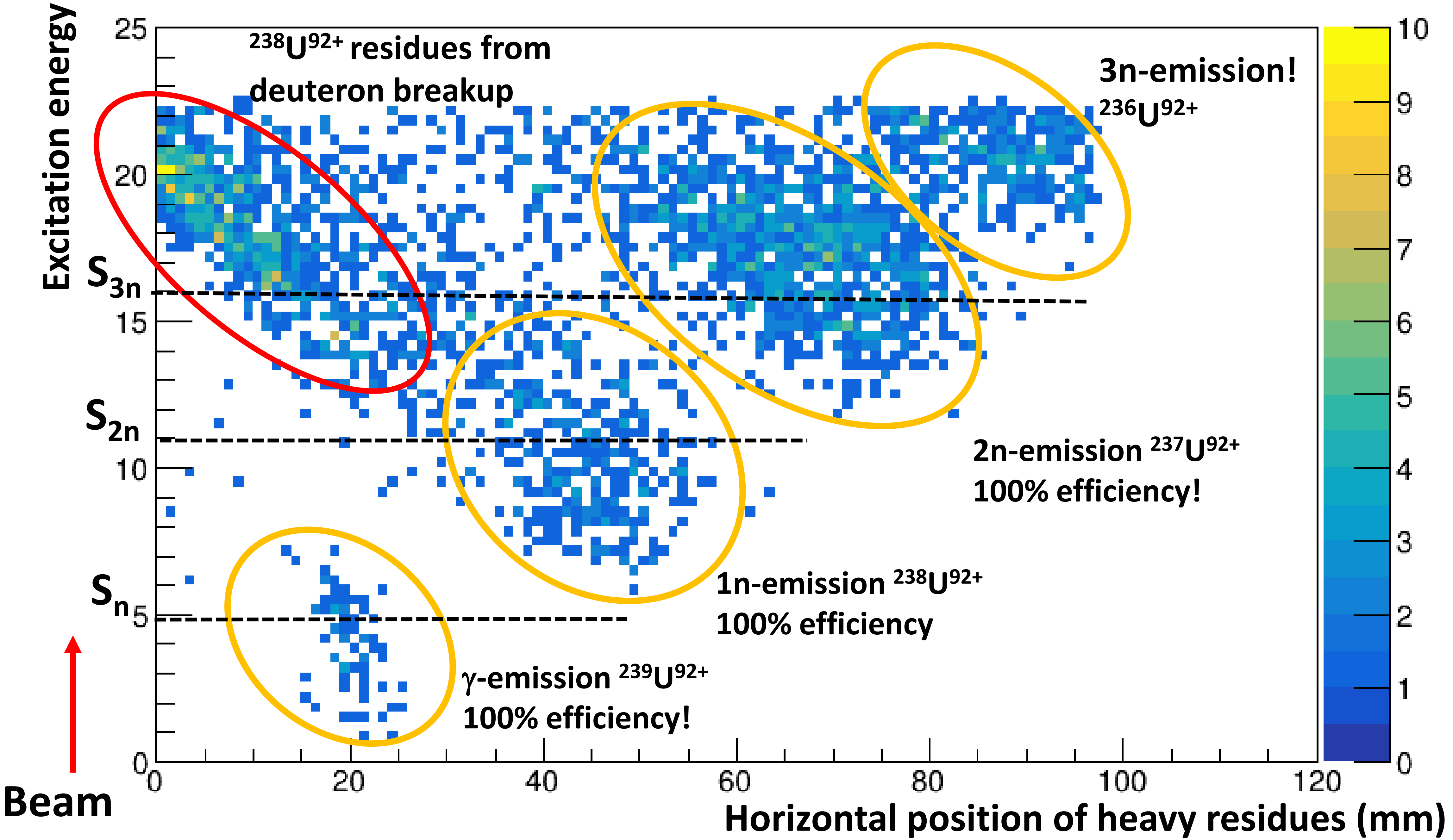
Analysis by Camille Berthelot & Boguslaw Wloch

Preliminary results for heavy-residue detection
238U(d,p)



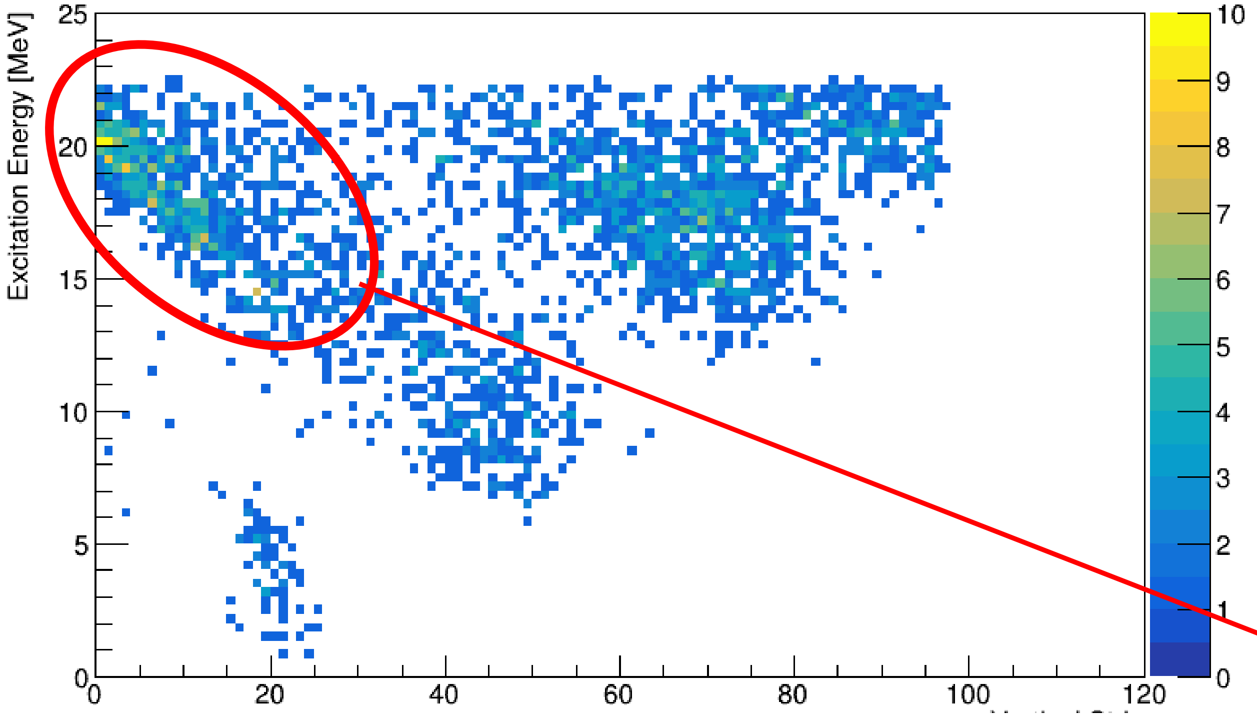
Analysis by Camille Berthelot & Boguslaw Wloch

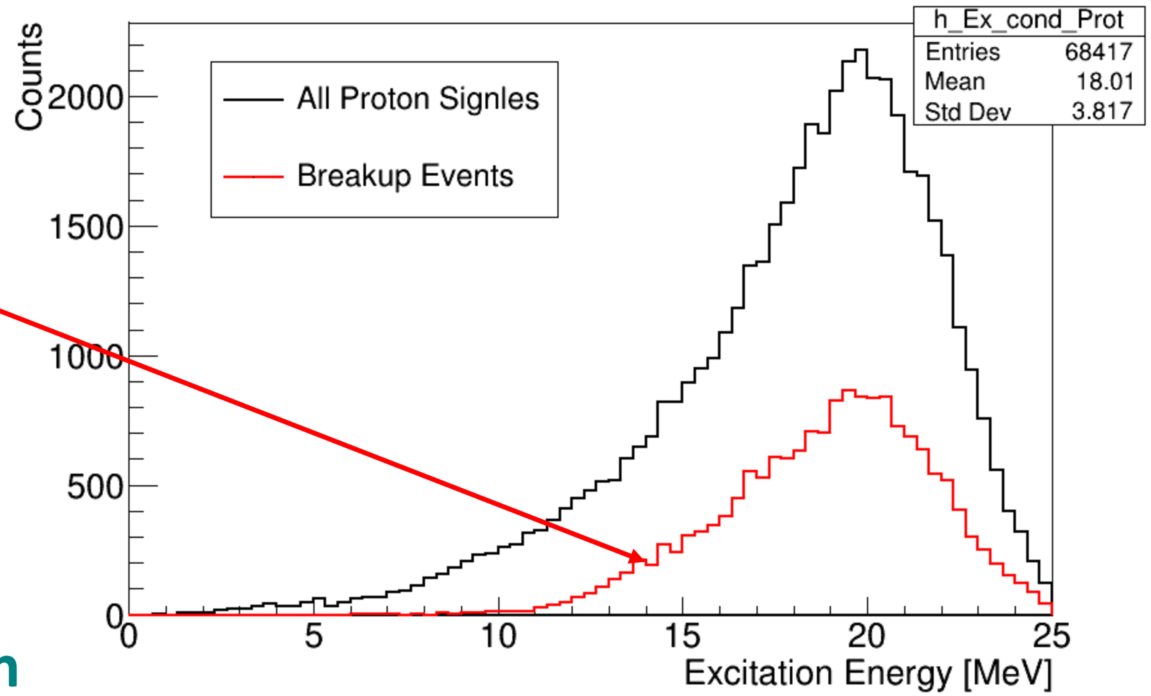
Preliminary results for heavy-residue detection



Correction of deuteron breakup events

$^{238}U^{92+}$ residues from deuteron breakup





Analysis by Camille Berthelot & Boguslaw Wloch

Conclusions

- **Storage rings offer the ideal conditions to investigate surrogate reactions and more largely, nuclear reactions!**
- **In the ESR, high-quality radioactive beams of bare ions at few 10 MeV/nucleon repeatedly interact with an ultra-low density, pure gas-jet targets enabling us to measure simultaneously for the first time the fission, gamma, one, two and three neutron-emission probabilities!**

Perspectives →See talk of G. Leckenby

- **Bayesian analysis, to extract 238U(n,g), (n,f), (n,n'), (n,2n) and (n,3n) cross sections**
- **Upgrade setup to make experiments with radioactive beams**
- **Next experiment, infer neutron-induced reaction cross sections of ^{205}Pb**

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NECTAR: Nuclear rEaCTions At storage Rings

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