Nuclear reactions at heavy-ion storage rings

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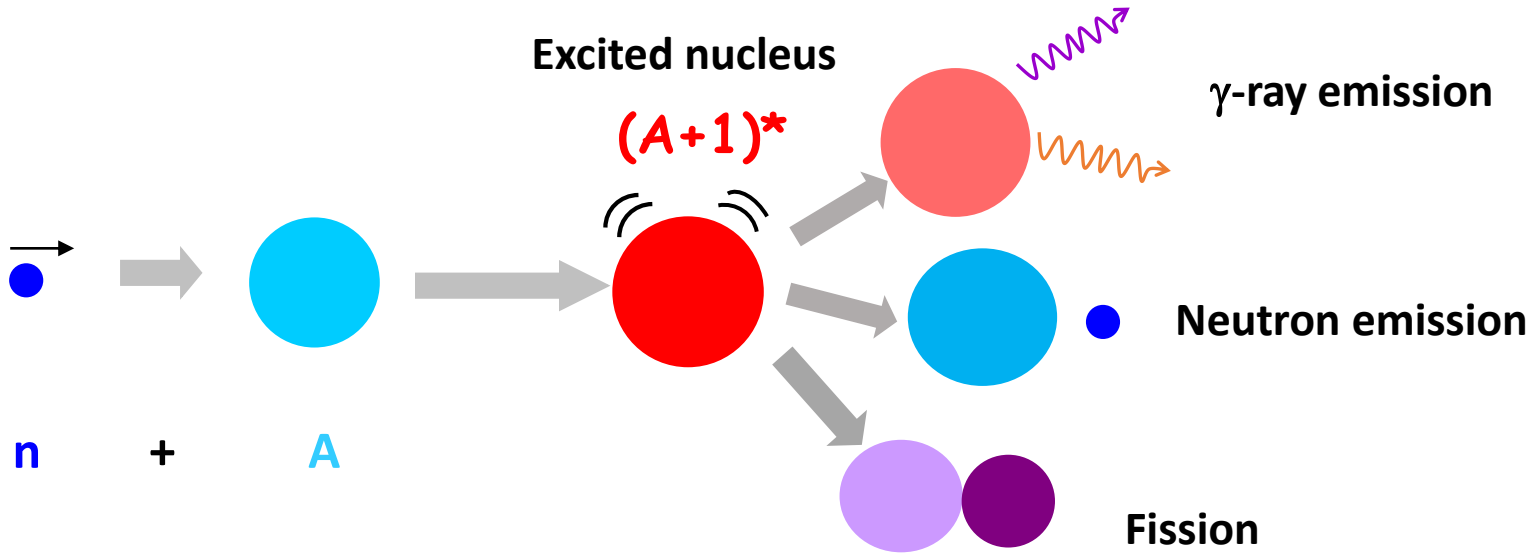
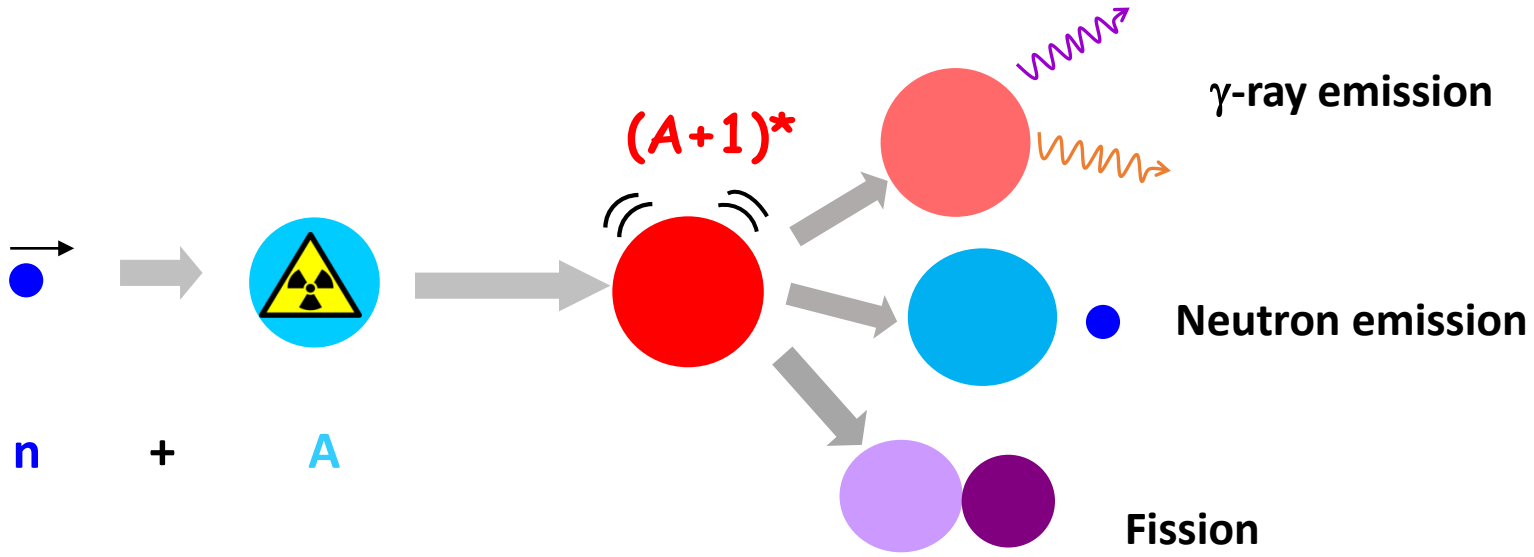
Introduction:

Neutron-induced reactions at energies below few MeV:



Motivation:

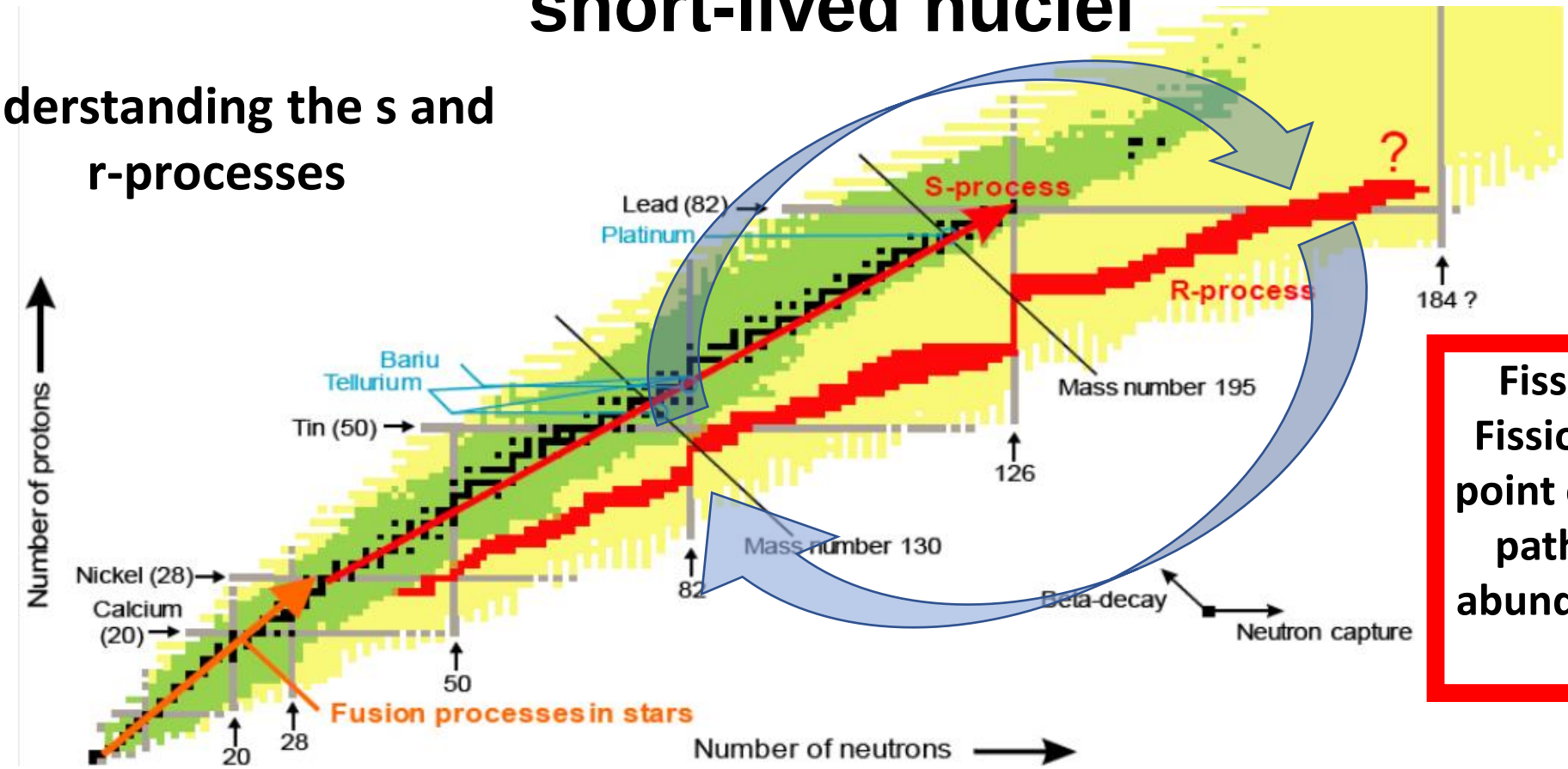
Need for neutron-induced reaction cross sections of radioactive nuclei



Essential for astrophysics, energy production and medicine!

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

Understanding the s and r-processes

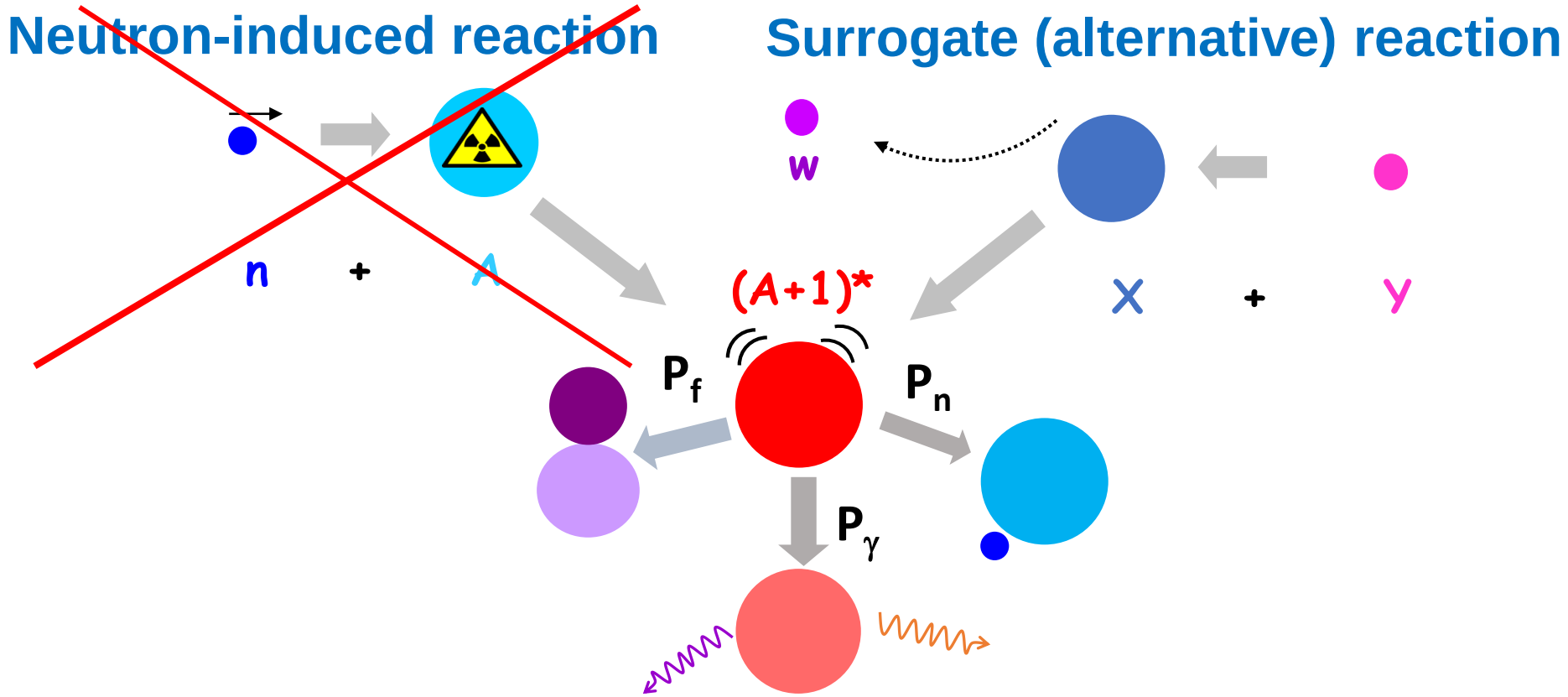


Fission recycling! Fission sets the end point of the r-process path and impacts abundances and light curves.

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

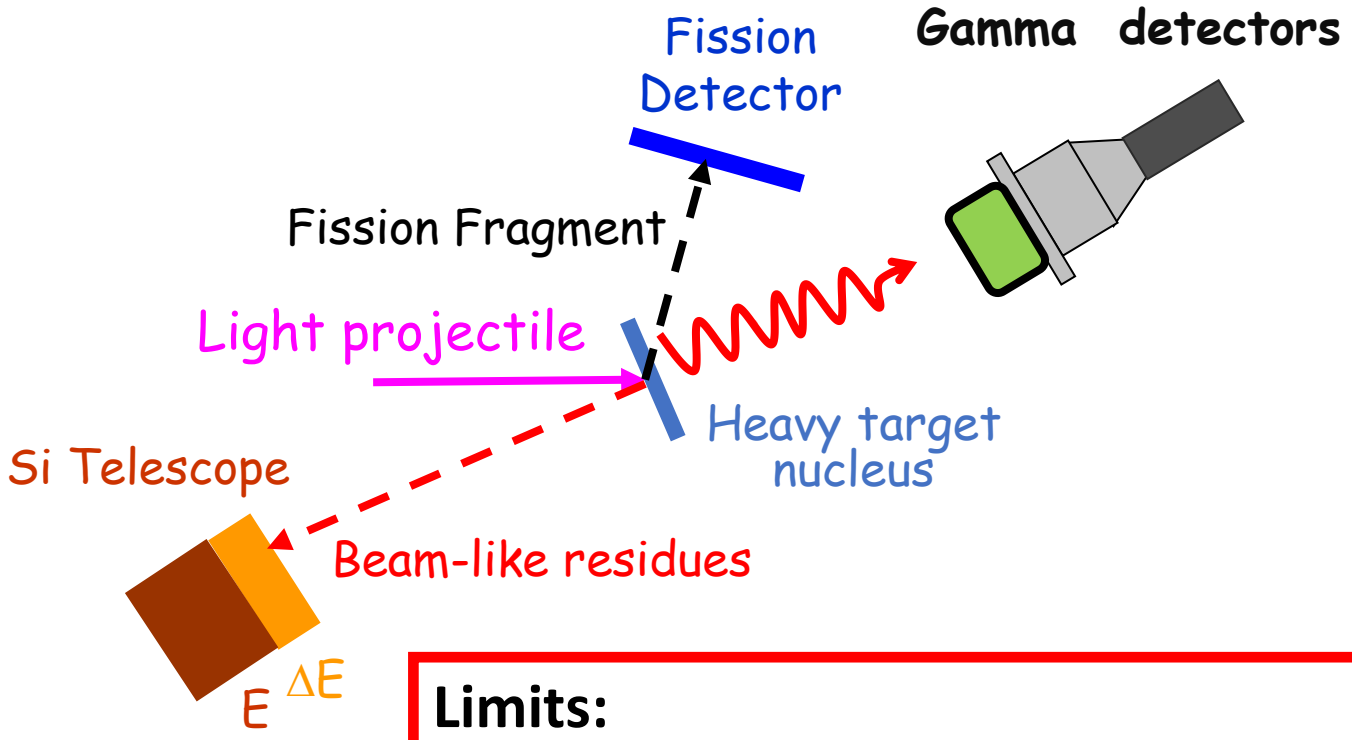
→Complicated to calculate due to the difficulty to describe the de-excitation process (level densities, γ-ray strength functions, fission barriers…). Calculations can be wrong by several orders of magnitude!

Surrogate-reaction method



Decay probabilities as a function of excitation energy are precious observables to constrain models (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



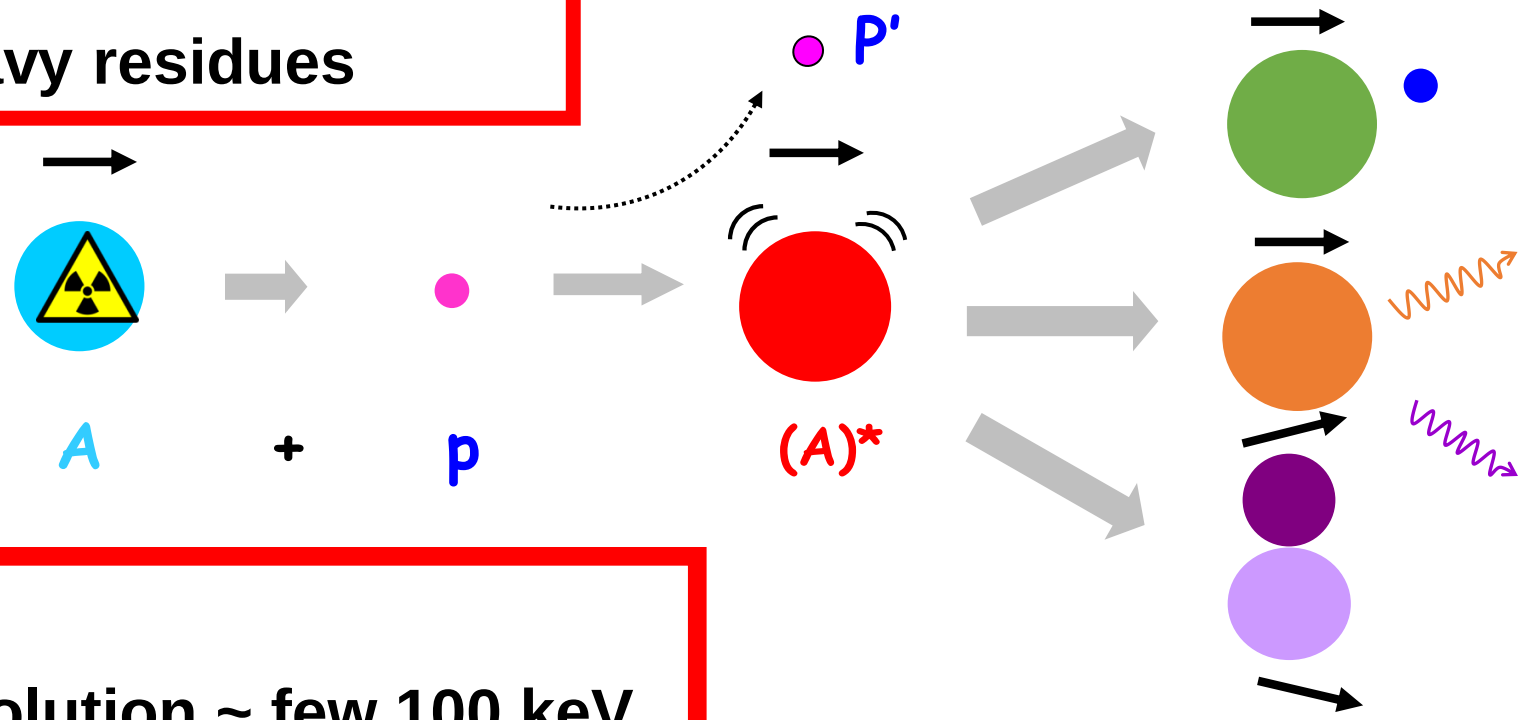
Limits:

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

Advantages of Inverse kinematics:

-Access to very short-lived nuclei

-Detection of heavy residues



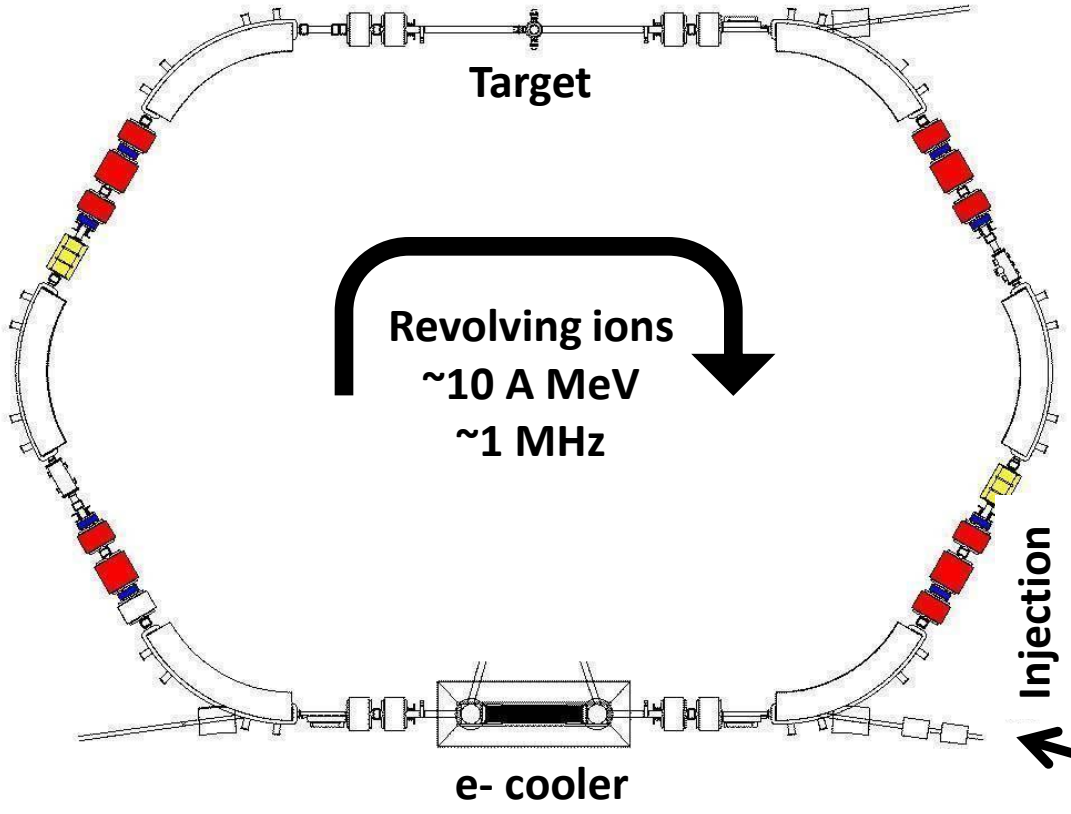
BUT!

- **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

The ESR at GSI/FAIR, Darmstadt, Germany



Circunference of ~ 108 m

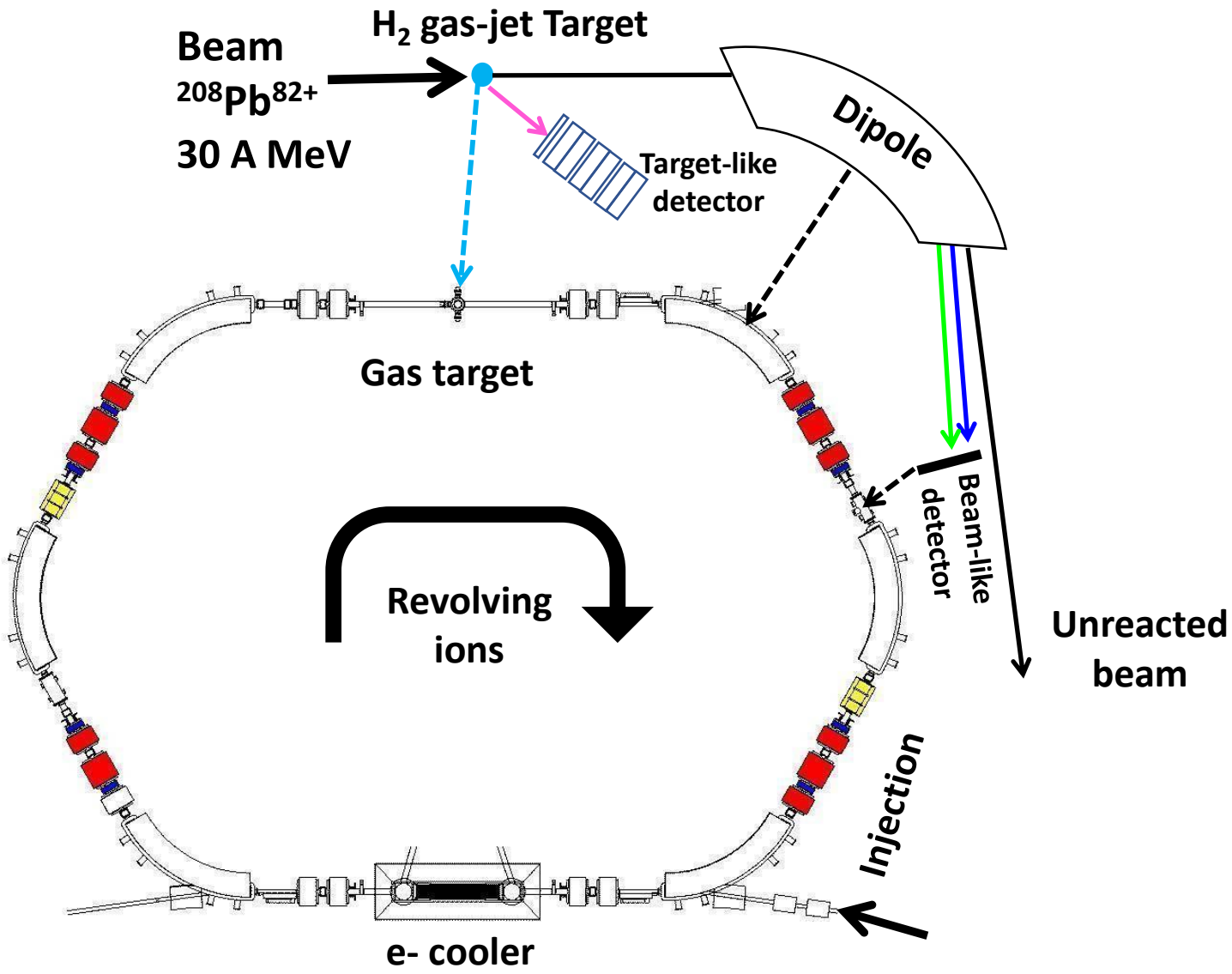
- **Beam cooling → Excellent energy and position resolution of the beam, maintained after each passage through the target, negligible, E-loss & straggling effects**
- **Use of ultra-low density in-ring gas-jet targets ~10^{13}/cm^2.**

  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!**

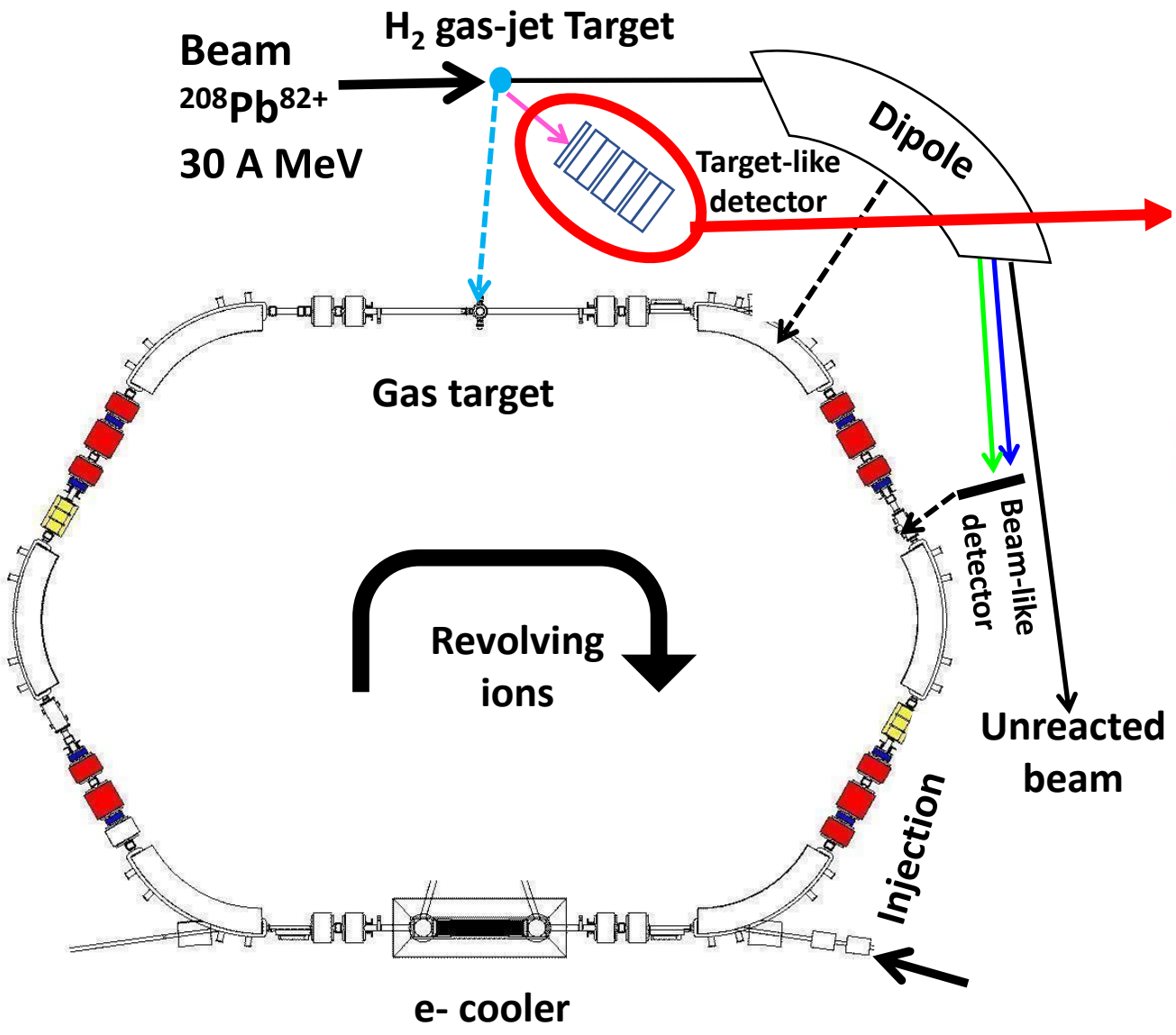
Challenge: Detectors in Ultra-High Vacuum (10^{-10}-10^{-11} mbar)!

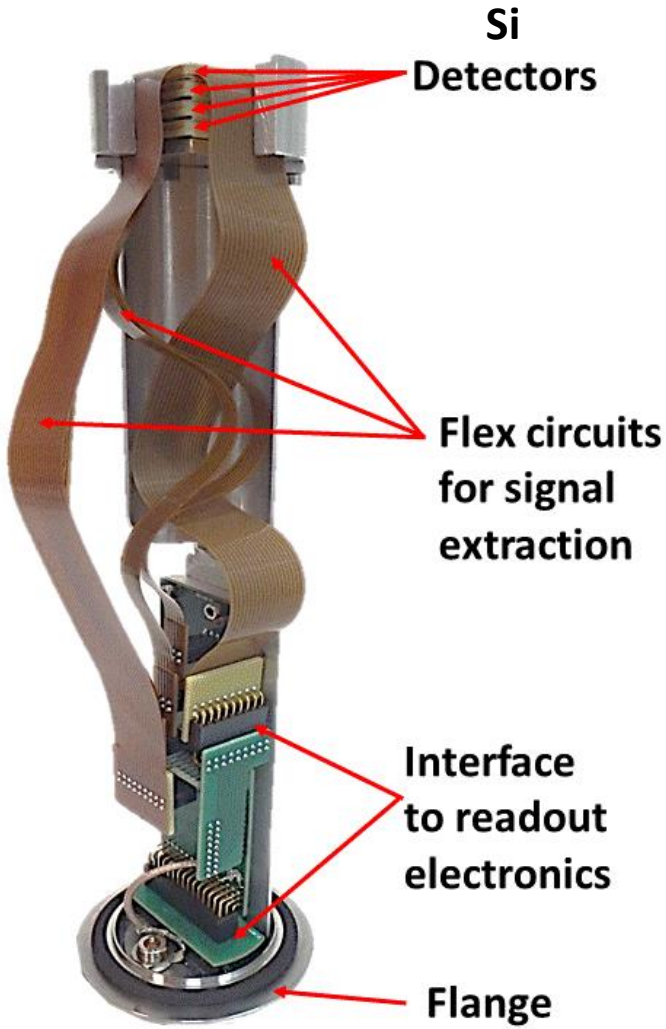
First surrogate reaction experiment at the ESR, 20-27 June 2022

208Pb+p→208Pb*+p' ↔ n + 207Pb → 208Pb*

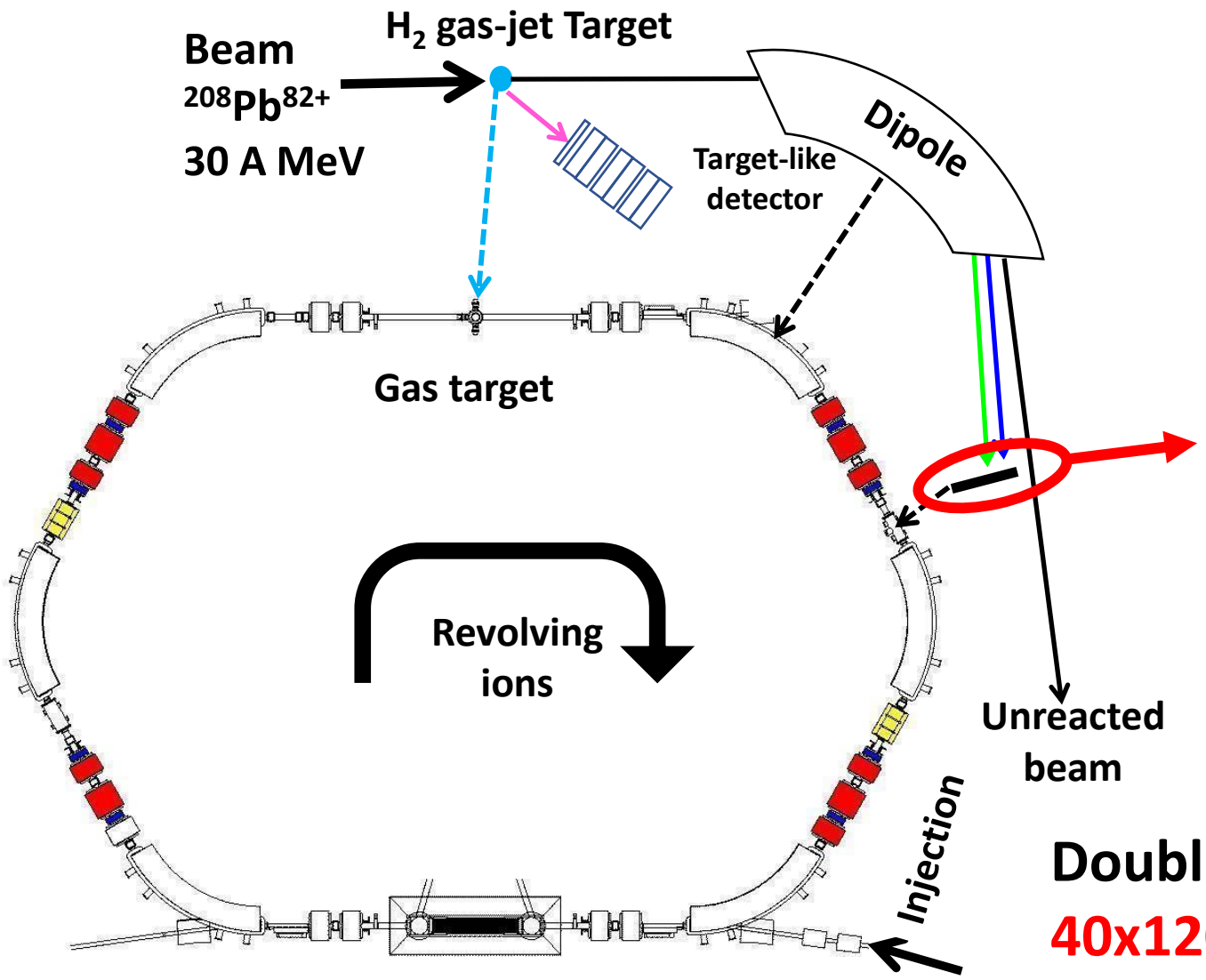


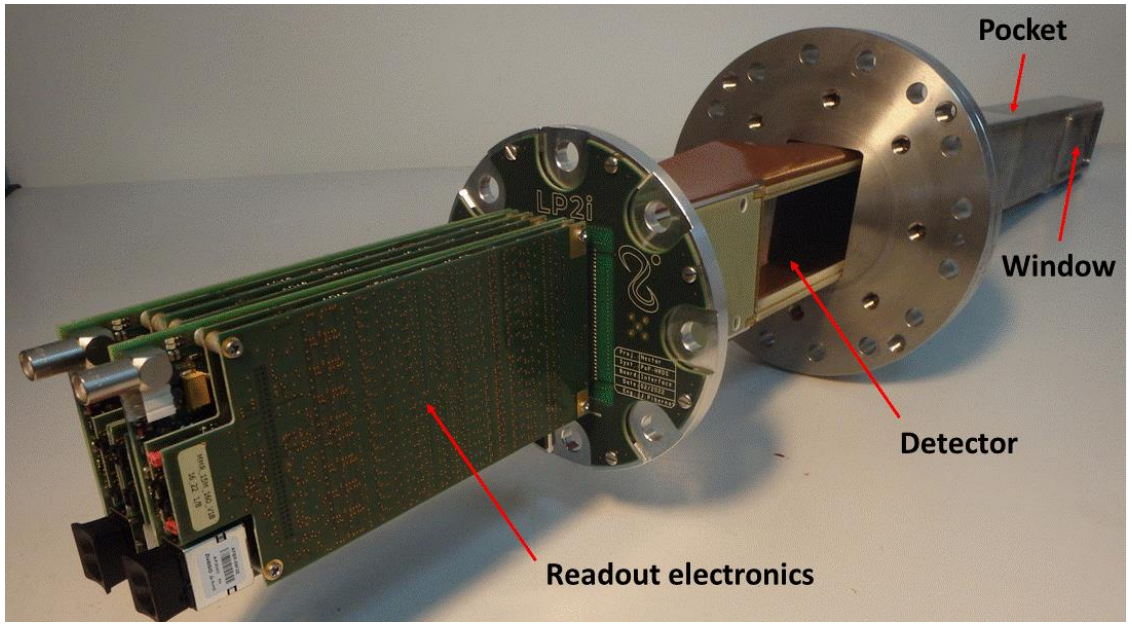
First surrogate reaction experiment at the ESR, target-residue detector system





First surrogate reaction experiment at the ESR, beam-like residue detector system

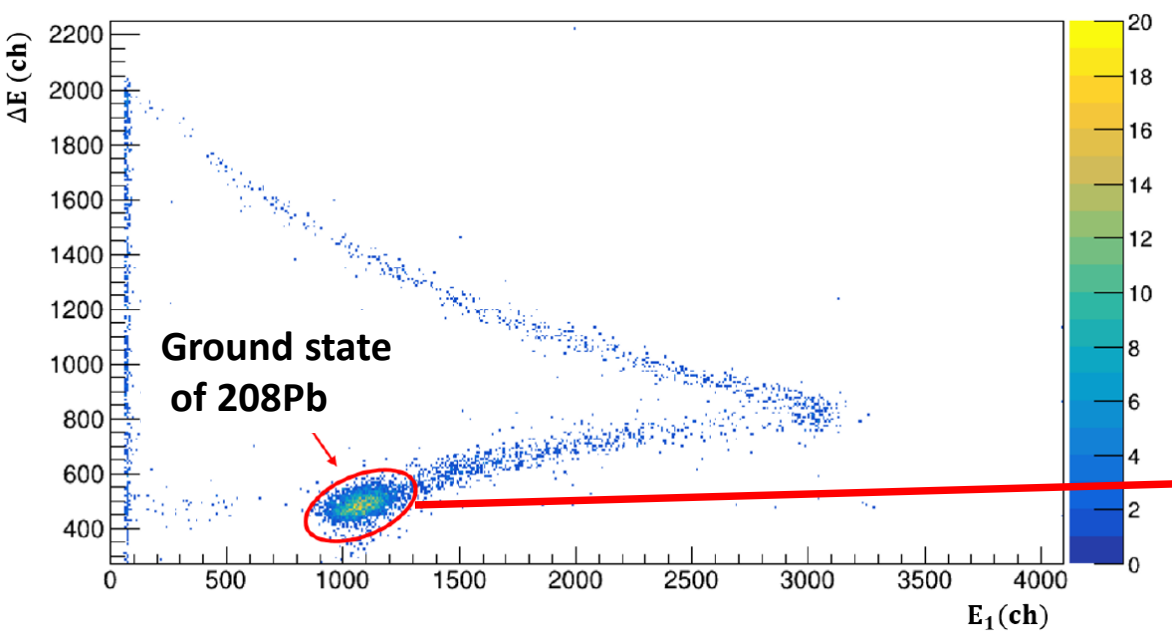


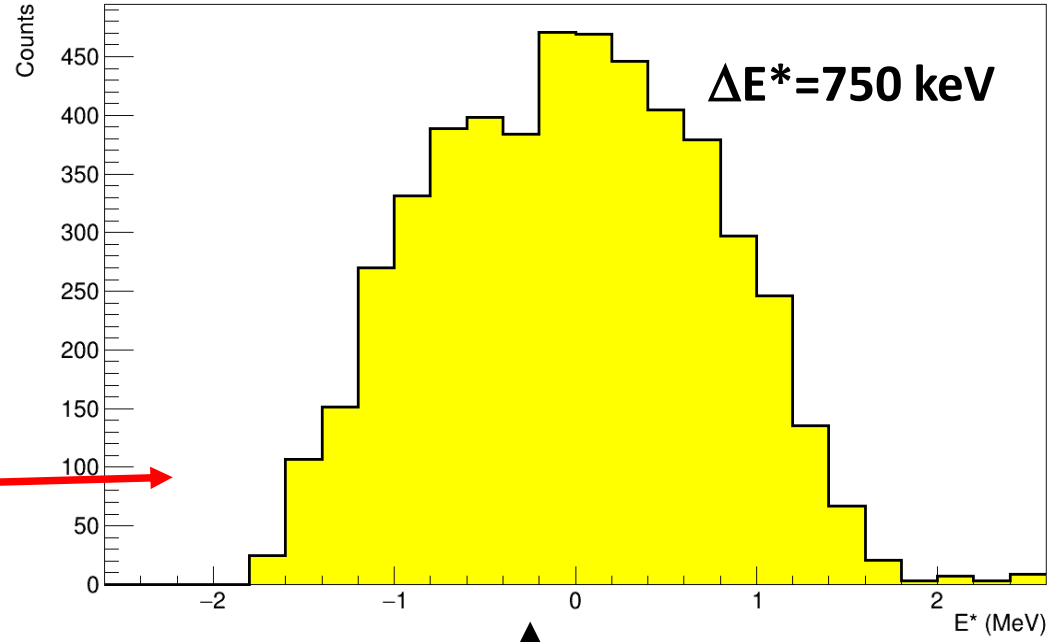


Double sided Si strip detector

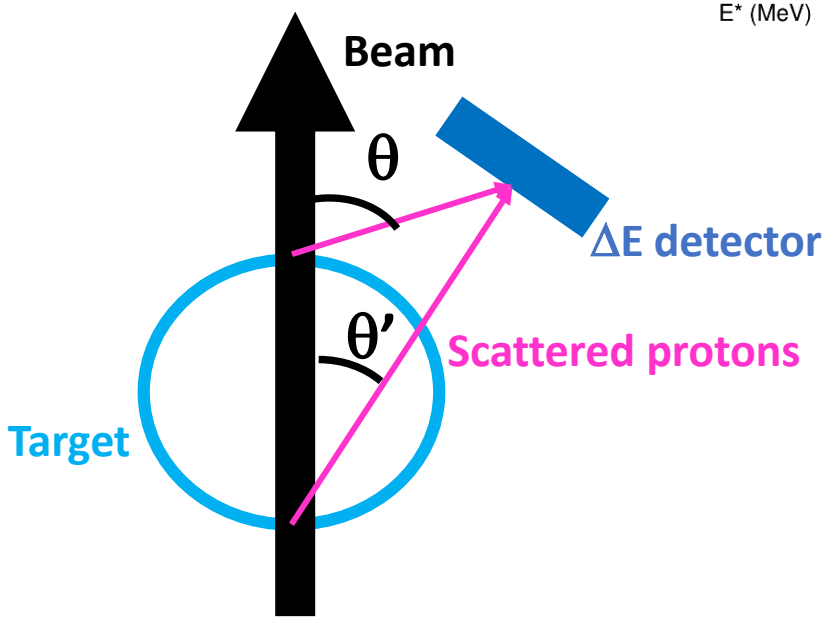
40x120 mm² stainless steel window of 25 μm!

Preliminary results, excitation energy resolution



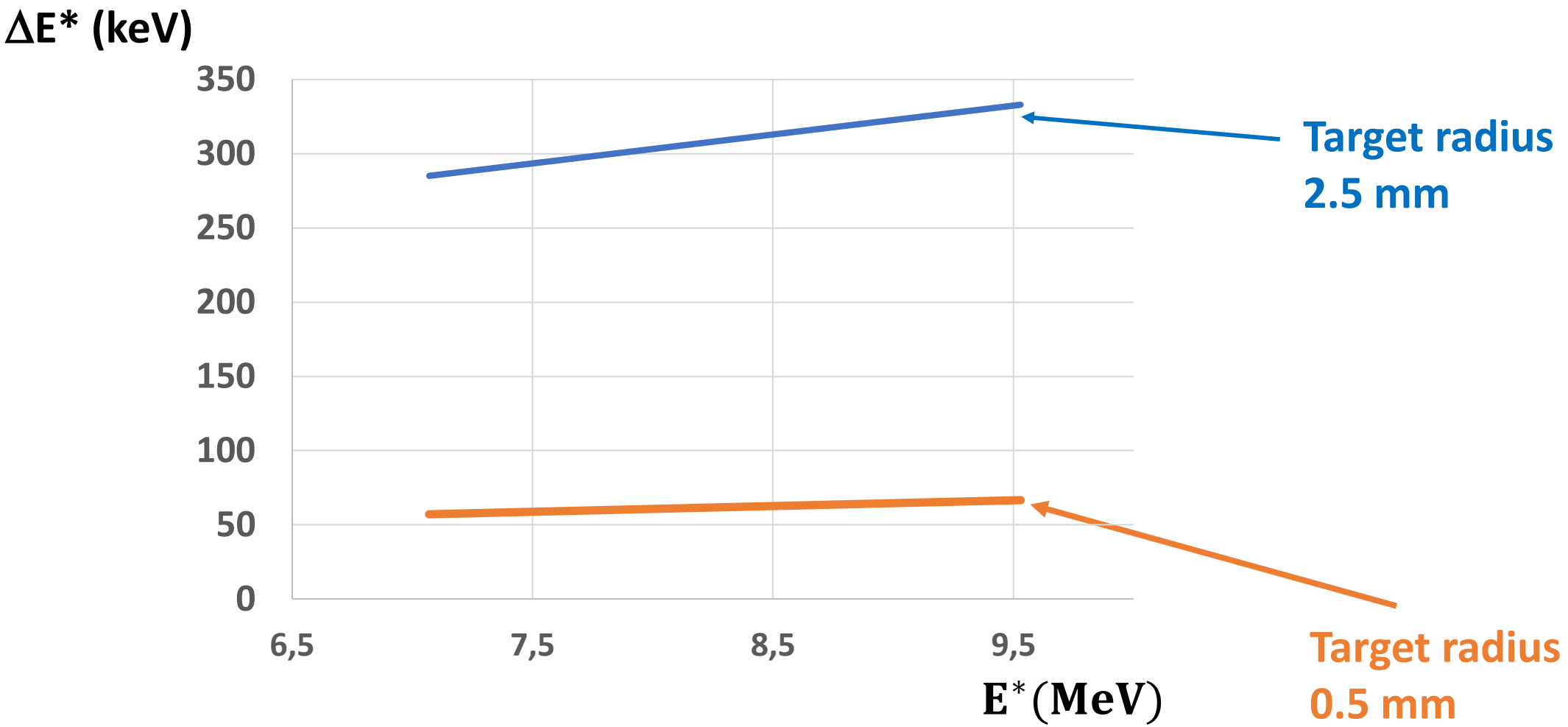


ΔE*≈ 750 keV at E*= 0 MeV, dominated by the angular uncertainty due to target radius of ~2.5-3 mm.



PhD Thesis of Michele Sguazzin

Simulations of excitation energy resolution



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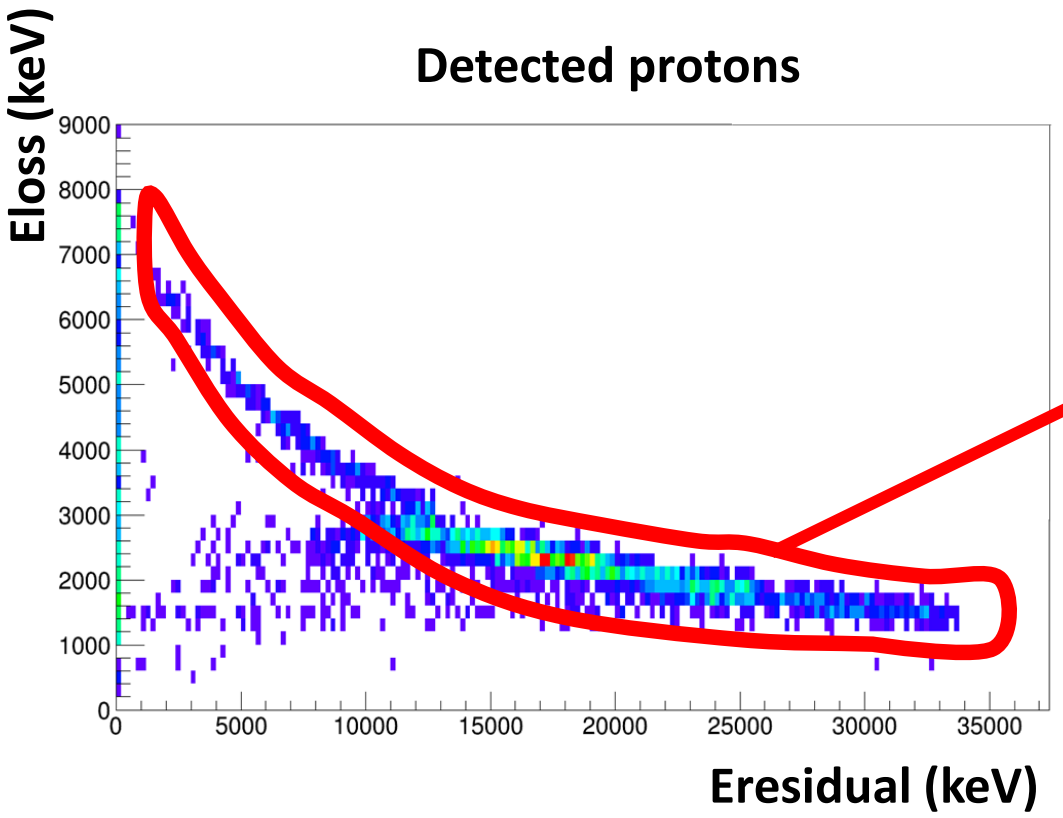
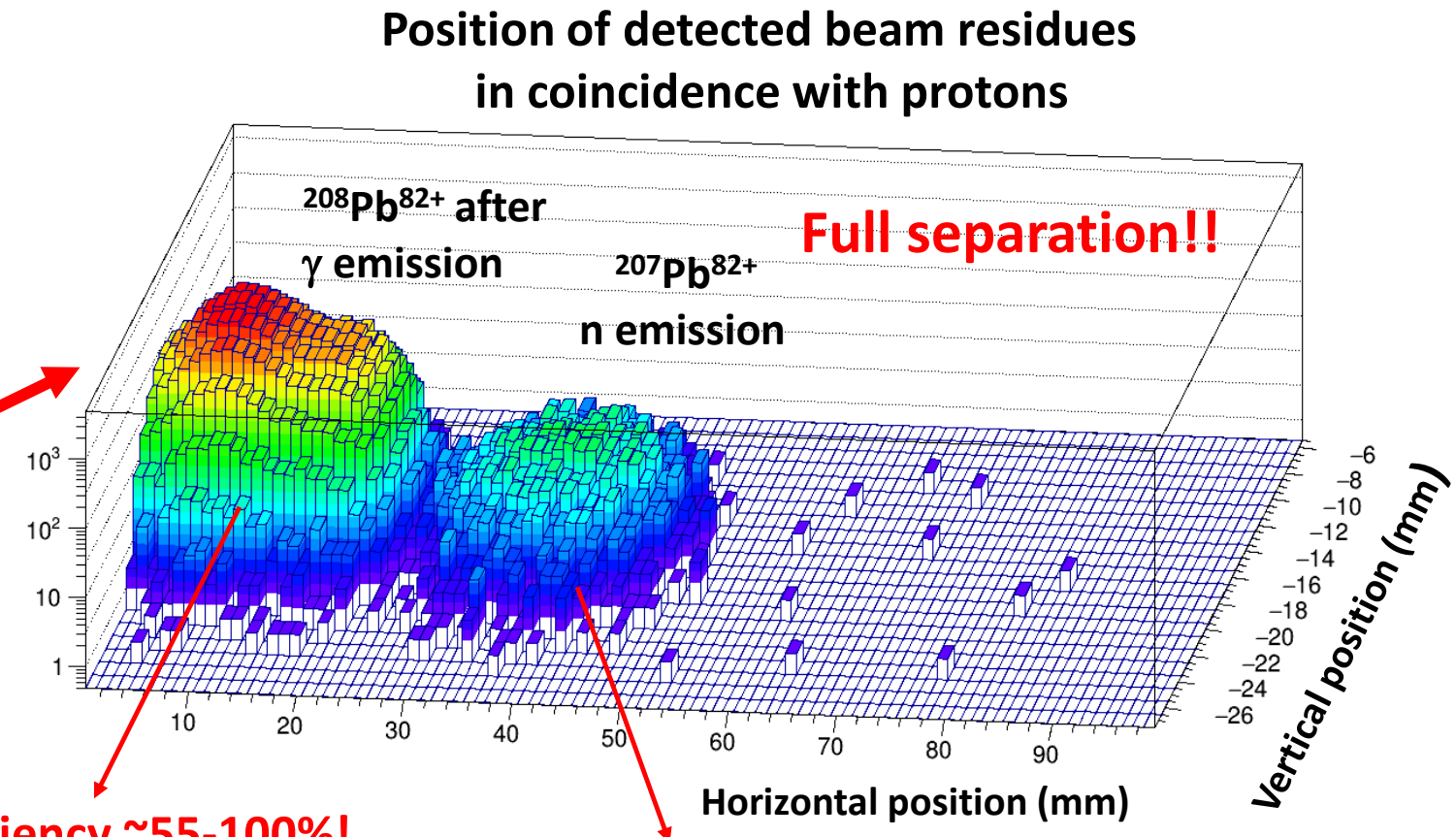
Preliminary results, detection of beam-like residues





Efficiency ~55-100%!
≈ 5% in direct kinematics…

Efficiency 100%!
0% in direct kinematics…

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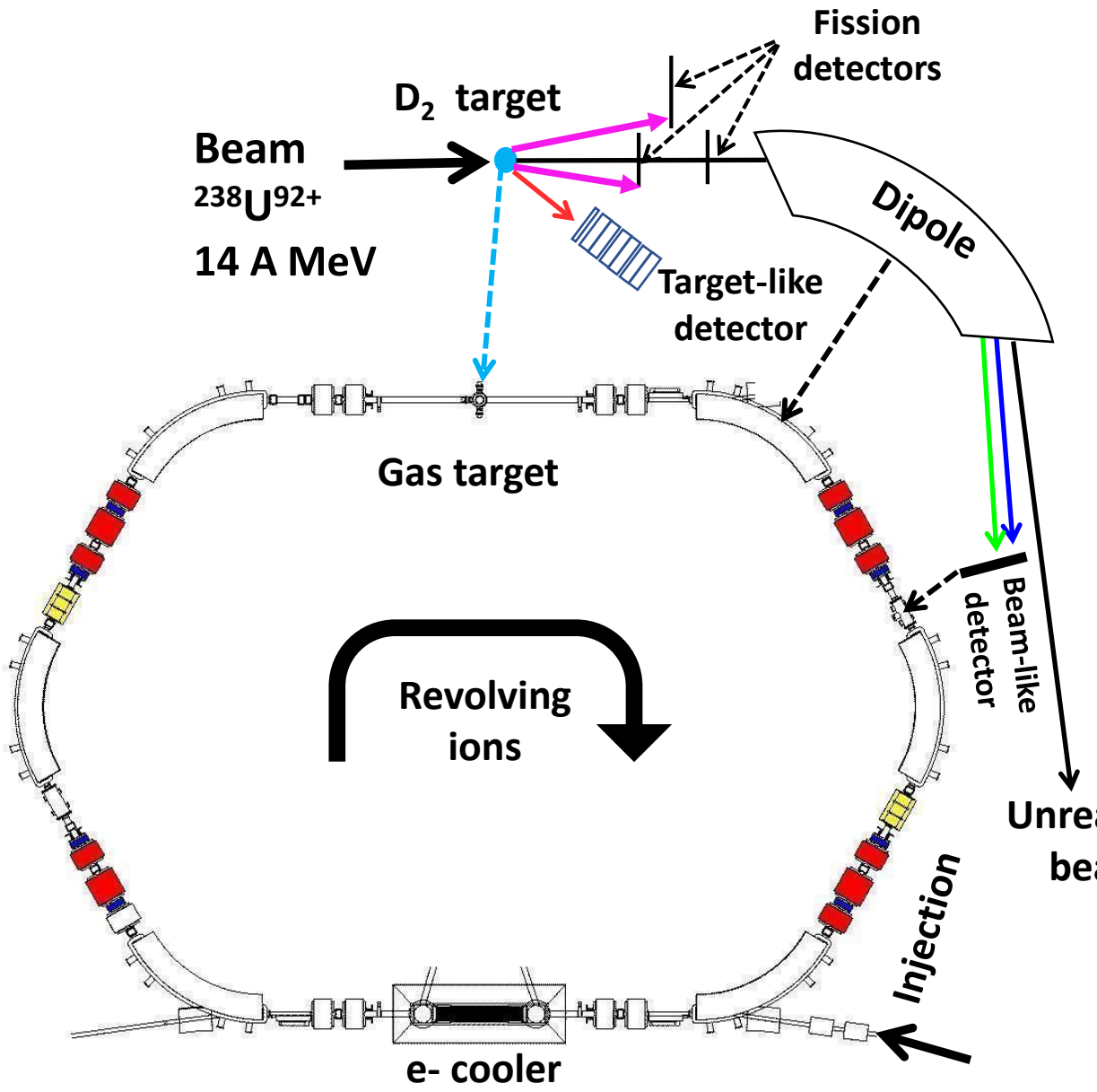
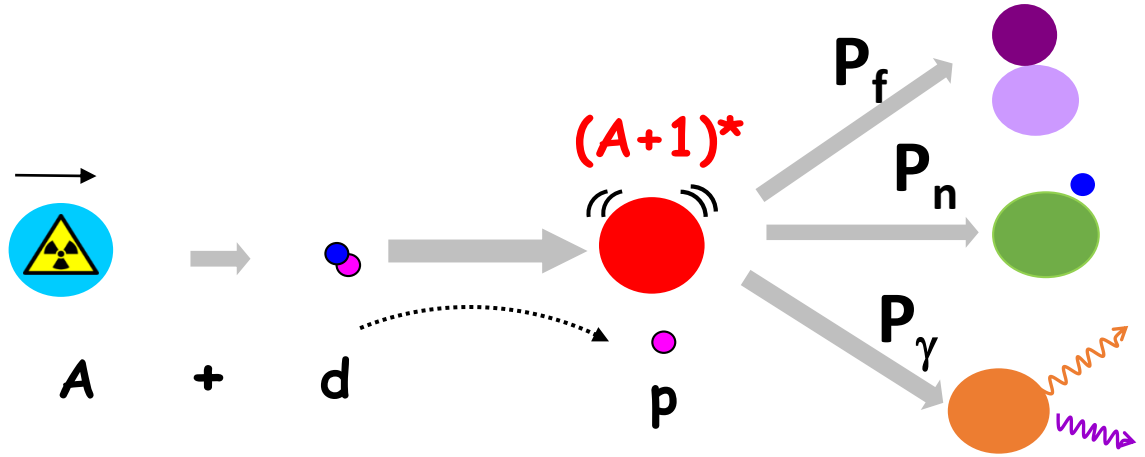
Perspectives: measure simultaneously fission, neutron and gamma-emission probabilities



- Add fission detectors. First time that fission is studied in a storage ring!
- Measure simultaneously P_f, P_γ and P_n with 238U(d,p) and 238U(d,d') reactions



Conclusions…

-Storage rings offer the ideal conditions to investigate surrogate reactions and more largely, nuclear reactions!

-First experiment succesfully conducted at the ESR in June 2022

→$\Delta E^* \approx$ 280-330 keV, expect < 100 keV with smaller target radius

→ Full separation and 55-100% detection efficiency for beam-like residues

→First ever measurement of P_n

→Our data on P_n allowed us to select level-density & γ-ray strength functions of 208Pb

→Predicted 207Pb(n,γ) cross section agrees with evaluations

-Adding fission detectors to measure simultaneously P_γ, P_n and P_f with ^{238}U at ESR, June 2024

…Perspectives

-Build dedicated reaction chamber to significantly increase efficiency for target residues and fission at ESR. Target radius 0.5-1 mm!

-Precision measurements of P_γ, P_n, P_f and P_{2n} with radioactive beams!

Acknowledgements

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NECTAR: Nuclear rEaCTions At storage Rings

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

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