Nuclear reactions at heavy-ion storage rings

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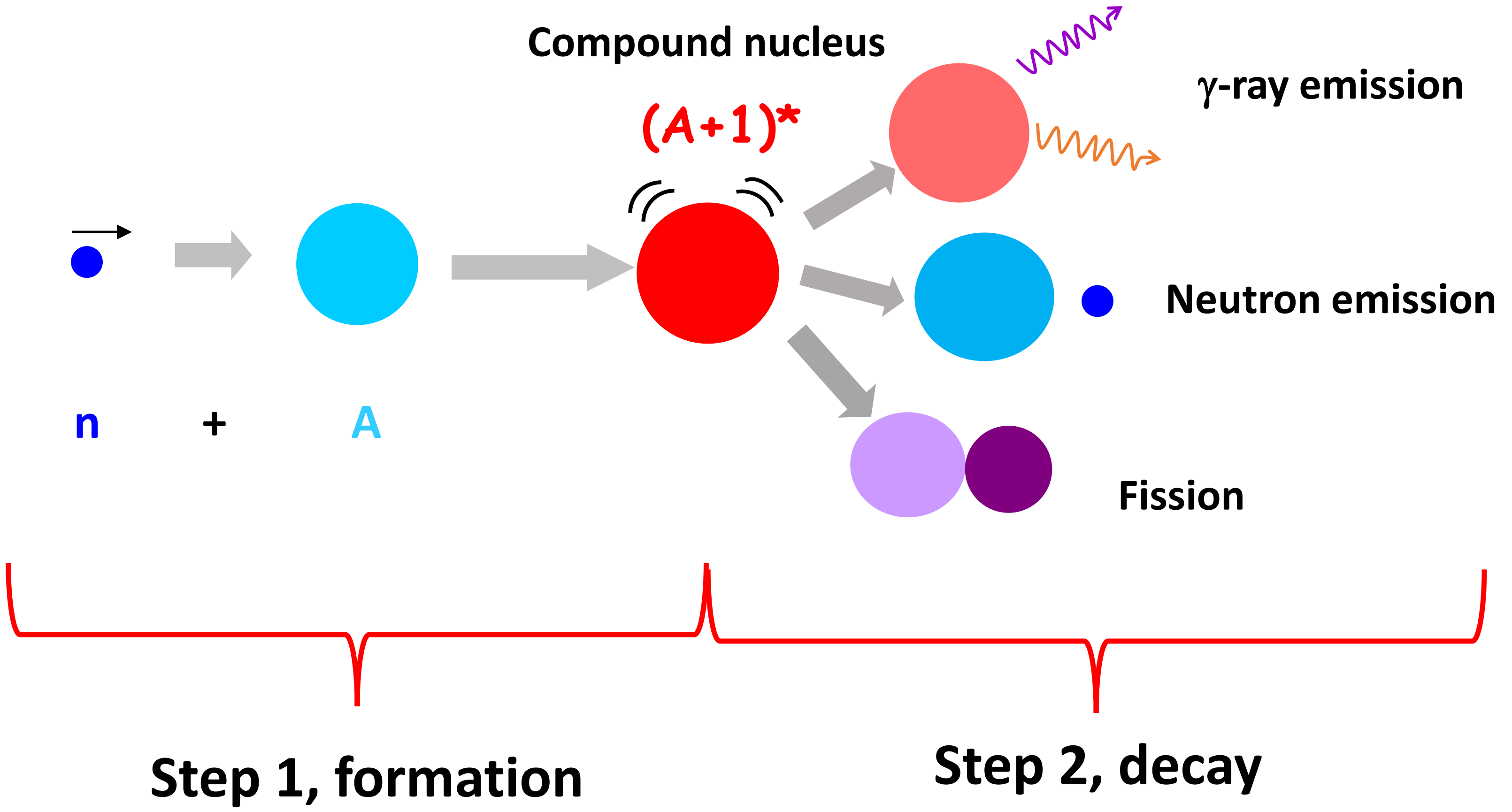
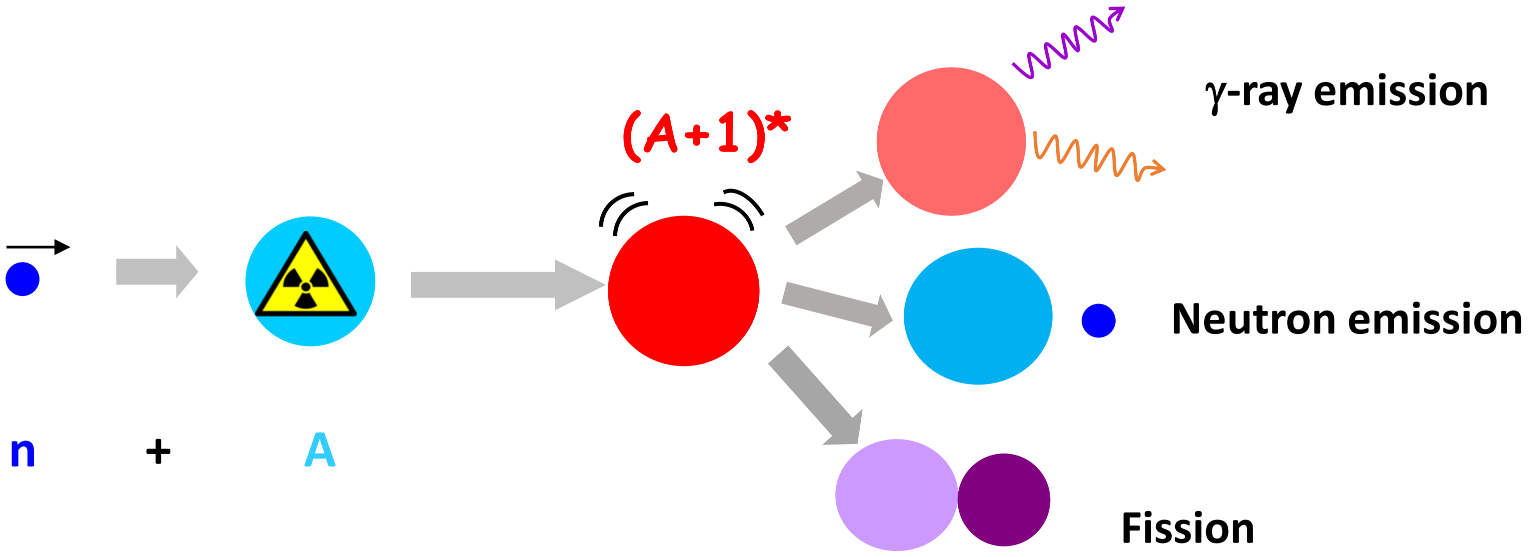
Introduction:

Neutron-induced reactions at energies below few MeV:



Motivation:

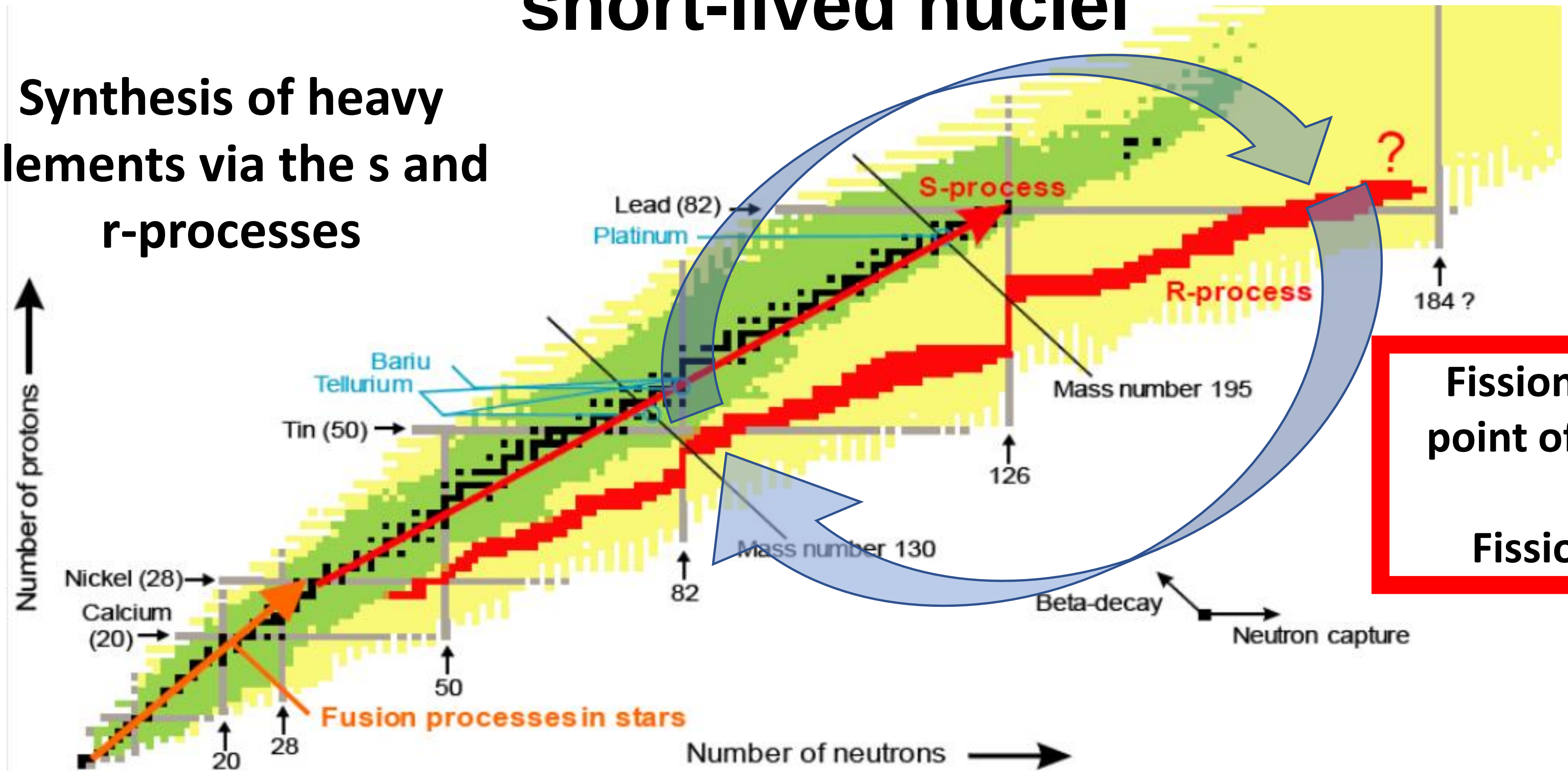
Need for neutron-induced reaction cross sections of radioactive nuclei



Essential for astrophysics, energy production and medicine!

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

Synthesis of heavy elements via the s and r-processes

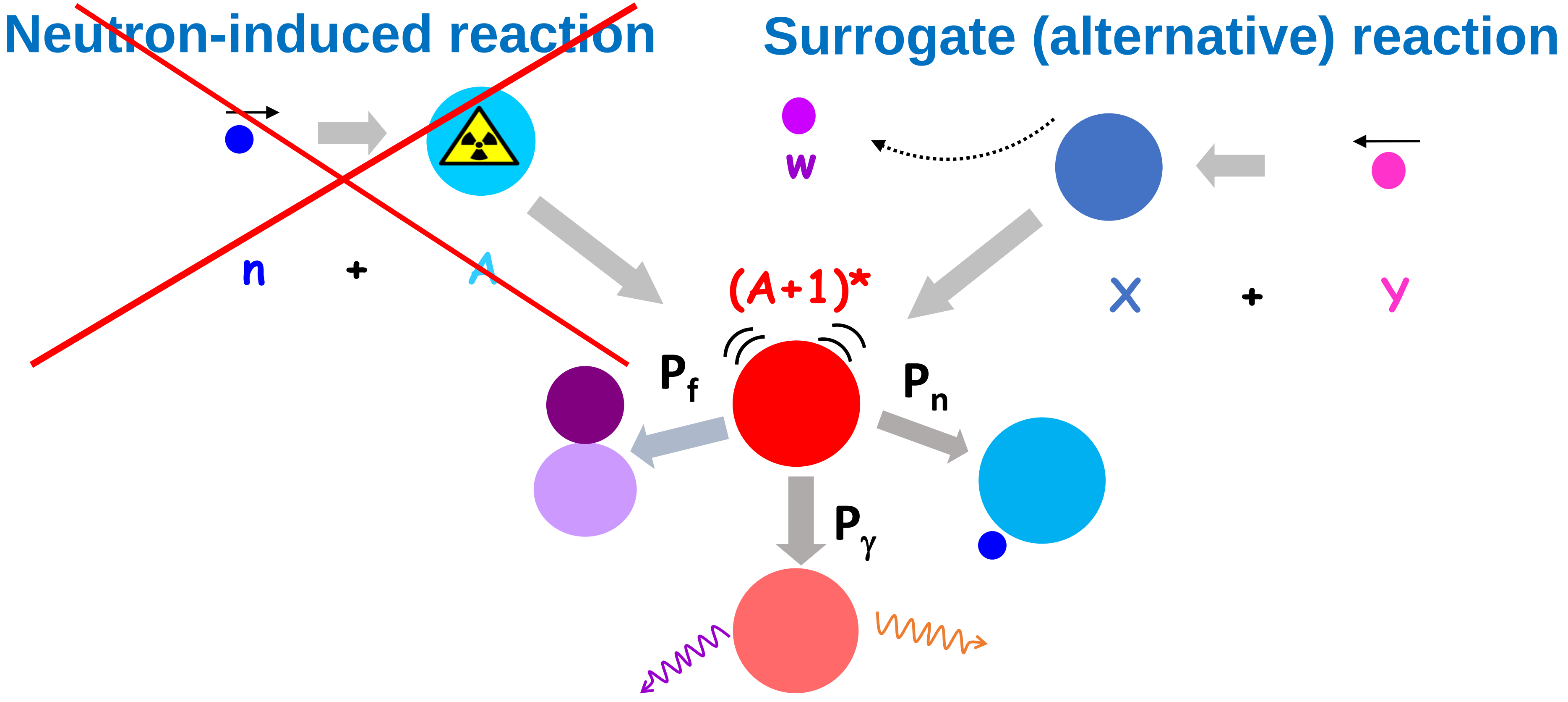


Fission sets the end point of the r-process path.
Fission recycling.

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

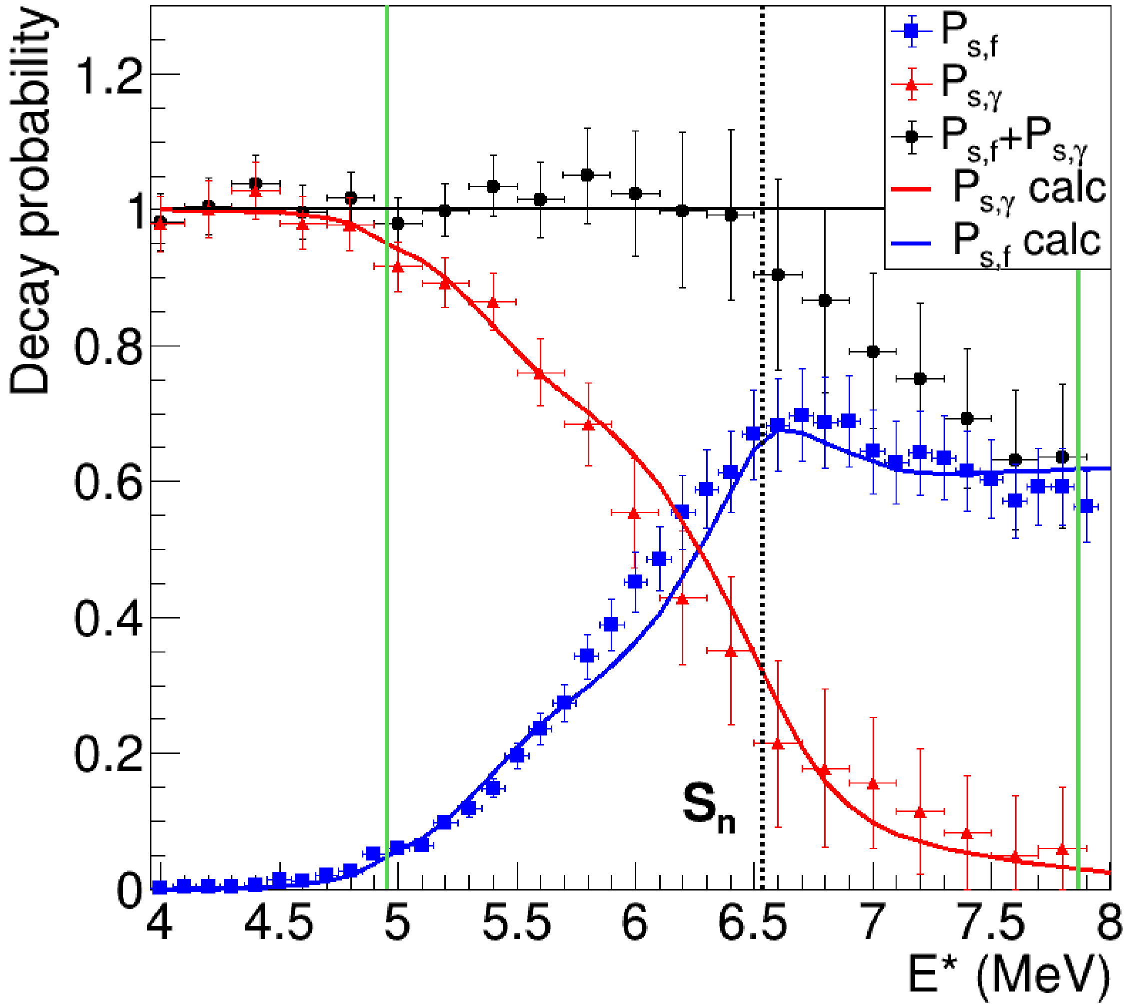
→Complicated to calculate due to the difficulty to describe the de-excitation process. Calculations can be wrong by several orders of magnitude!

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!

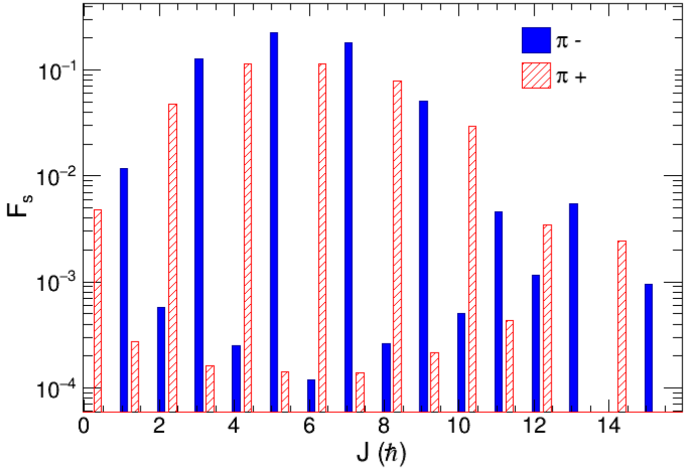
Only way to access the fission threshold of fissile nuclei!

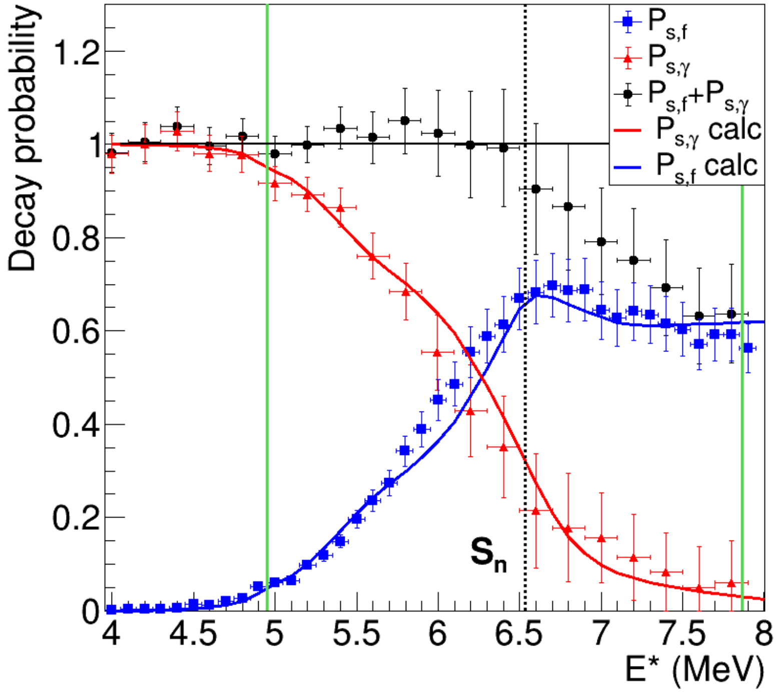
R. Perez Sanchez, BJ et al., Phys. Rev .Lett. 125 (2020) 122502

Determination of model parameters

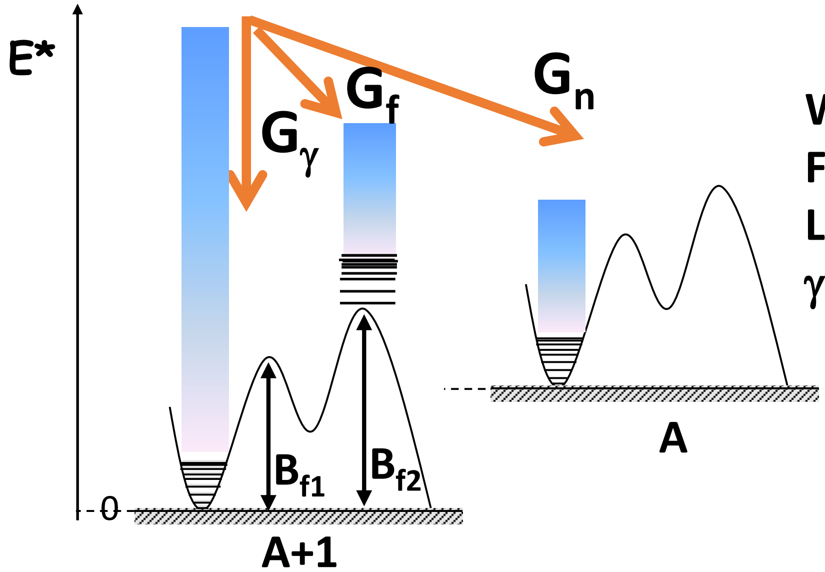
$$P_{s,decay}(E^*) = \sum_{J^\pi} F_s(E^*, J^\pi) G_{decay}(E^*, J^\pi)$$

Calculation of F_s populated in
4He+240Pu→4He'+240Pu
Marc Dupuis (CEA-DAM)





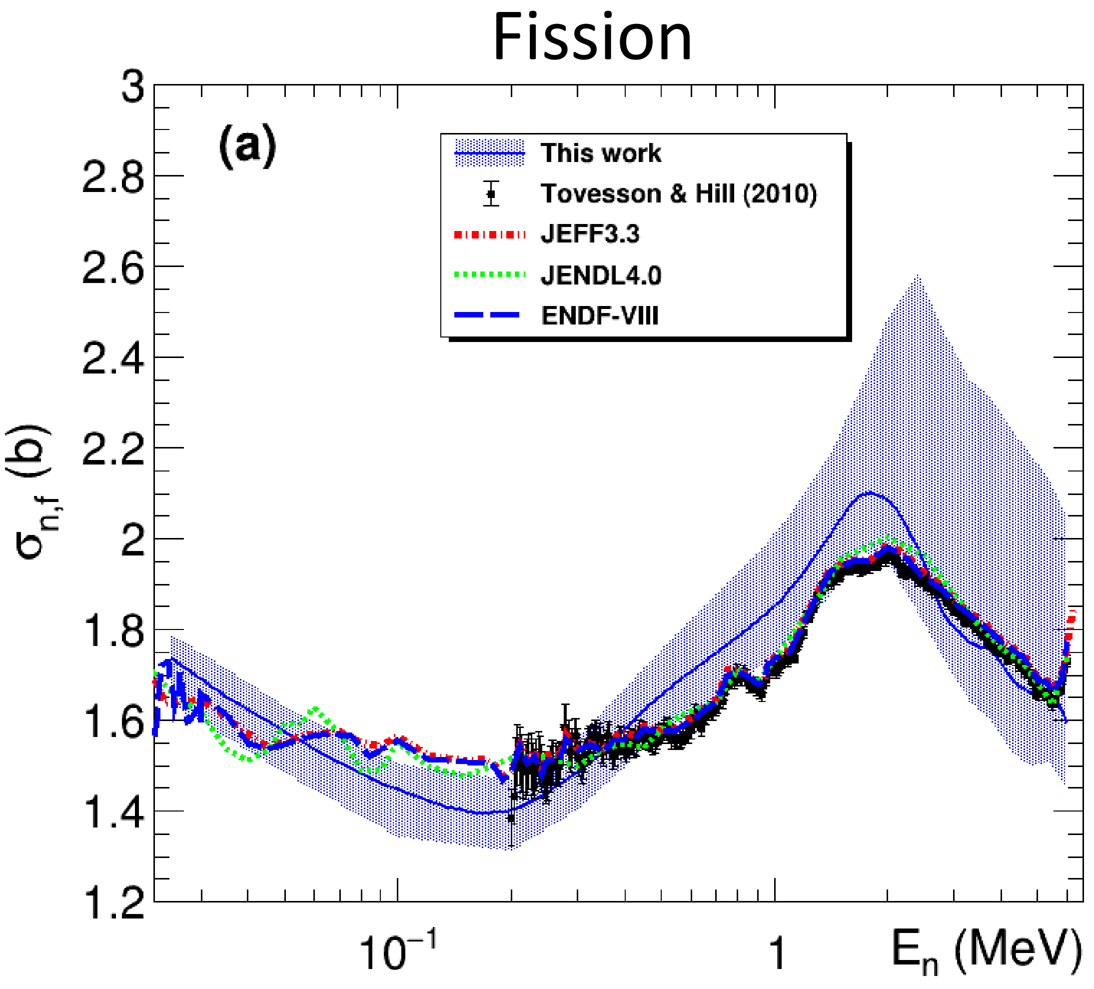
Statistical-model for de-excitation process (TALYS):

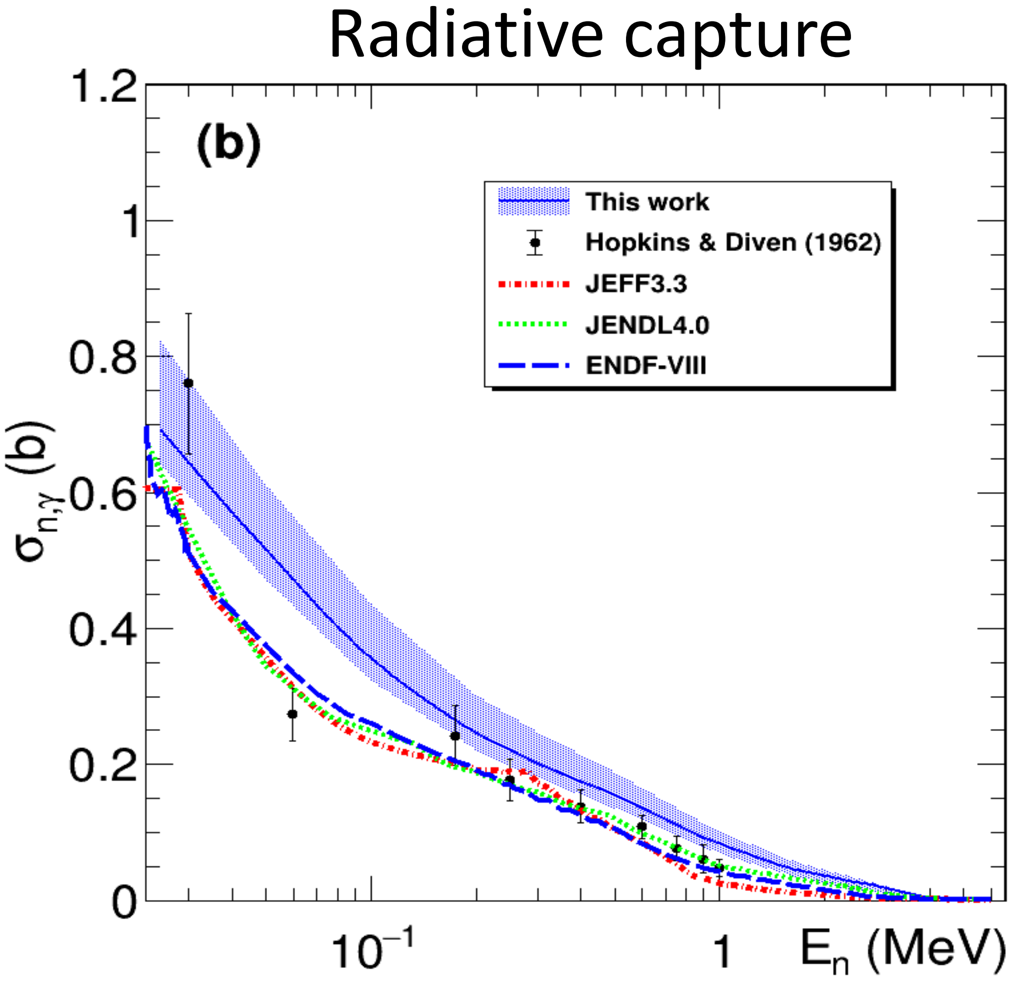


We need parameters for:
Fission barriers
Level densities
γ-ray strength functions!

Knowing both P_f and P_γ below Sn has allowed us to determine these parameters precisely!
B_f = 5.98 ± 0.02 MeV
(typical uncertainty for B_f is 200 keV!)

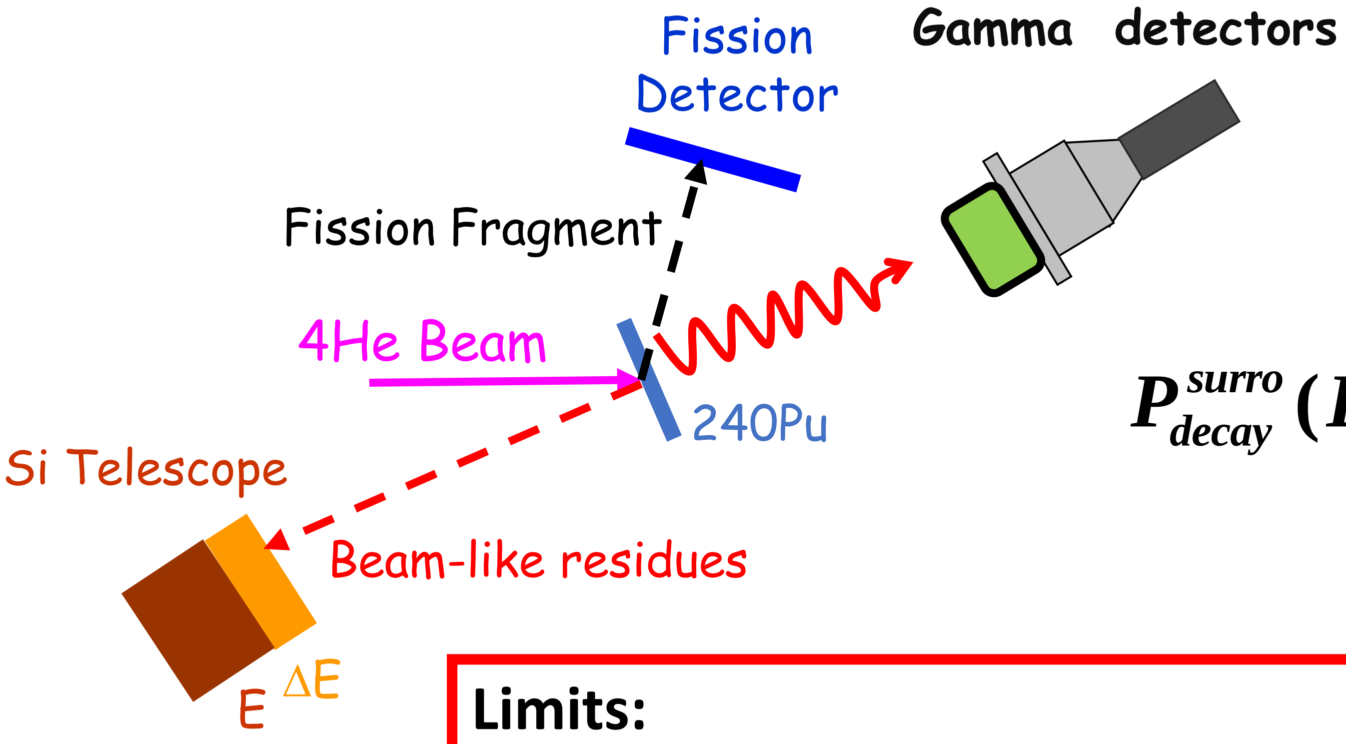
First simultaneous determination of neutron-induced fission and capture cross sections n+239Pu→240Pu*





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

Measurement of fission and gamma-emission probabilities in direct kinematics



$$P_{decay}^{surro}(E^*) = \frac{N_{beamlike-decay}^{coin}(E^*)}{N_{beamlike}^{sing}(E^*) \cdot \varepsilon_{decay}(E^*)}$$

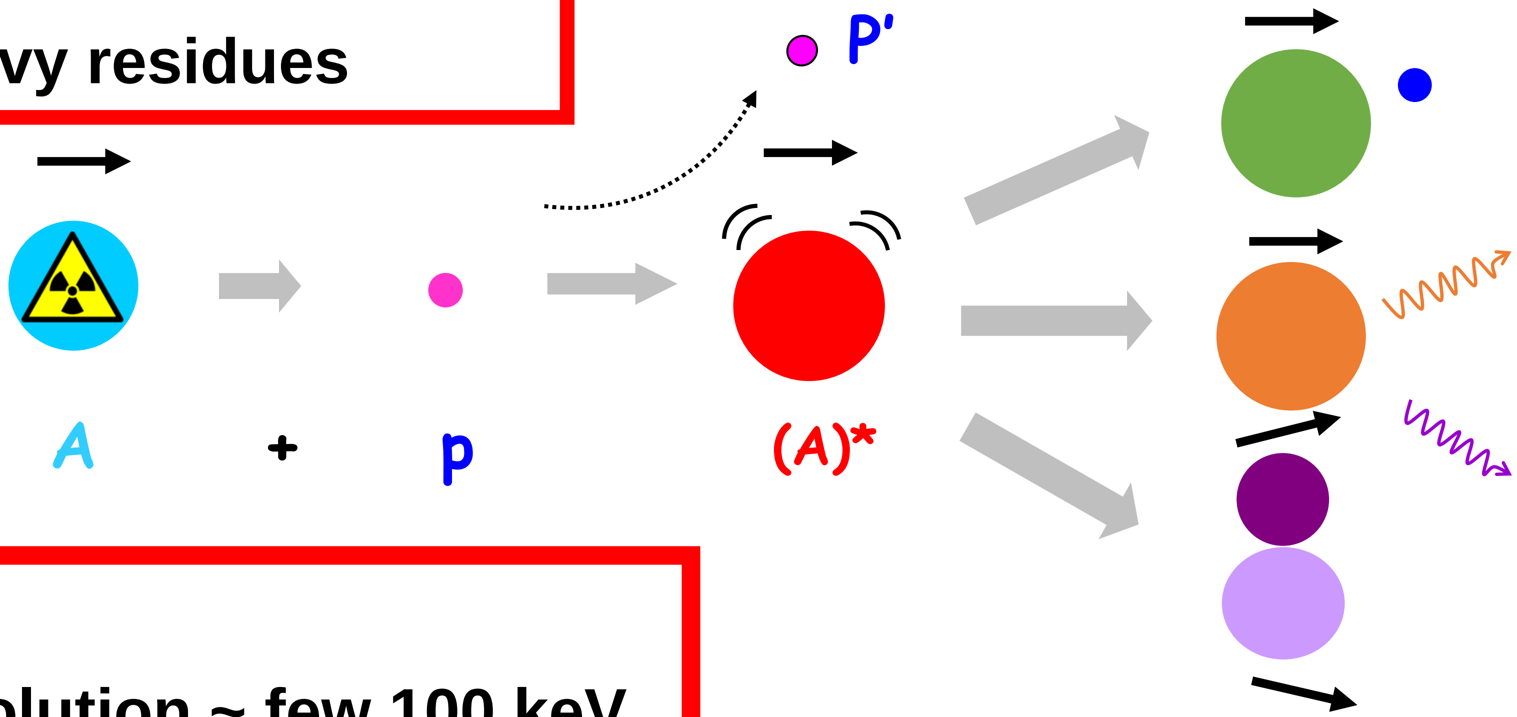
Limits:

- **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



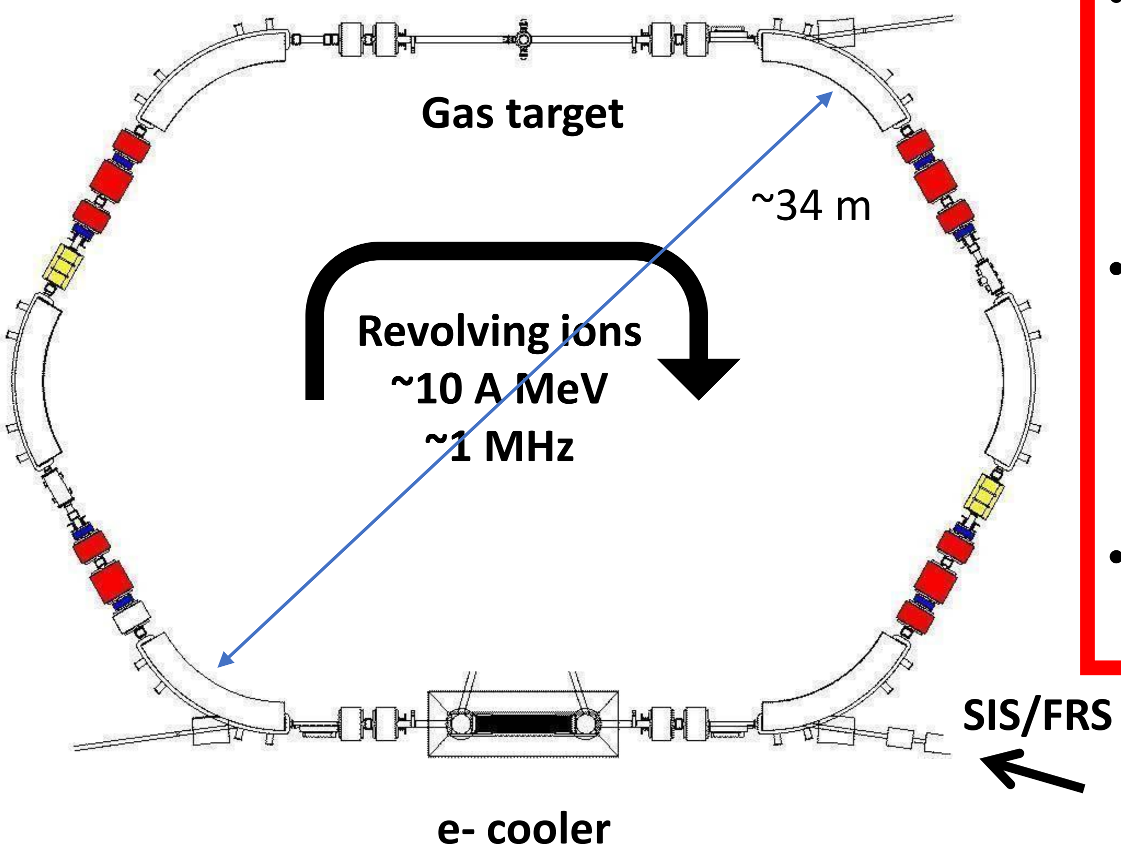
BUT!

- **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

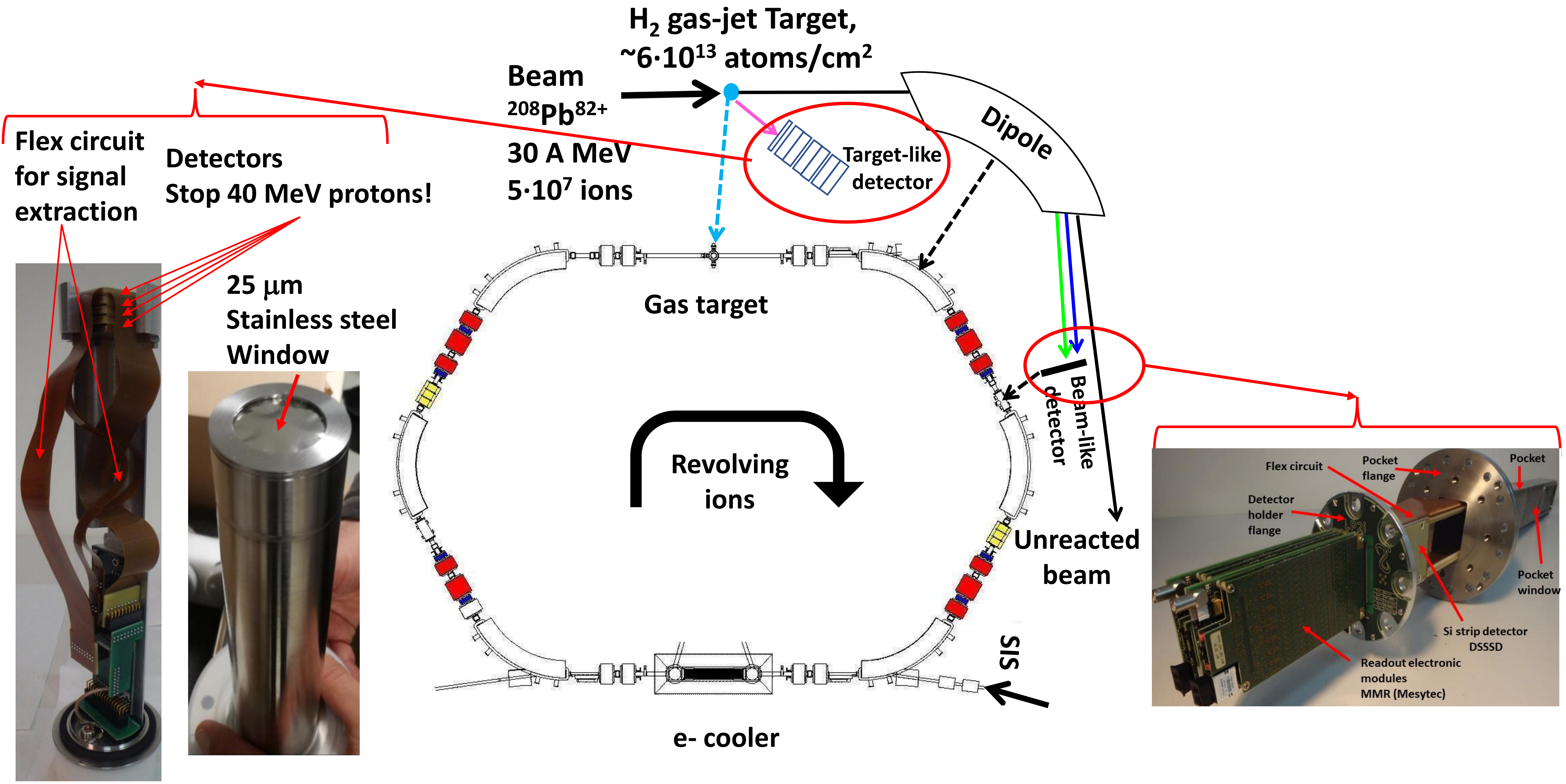


- Beam cooling → Excellent energy and position resolution of the beam, maintained after each passage through the target, negligible, E-loss & straggling effects
- Use of ultra-low density in-ring gas-jet targets $\sim 10^{13}/cm^2$.

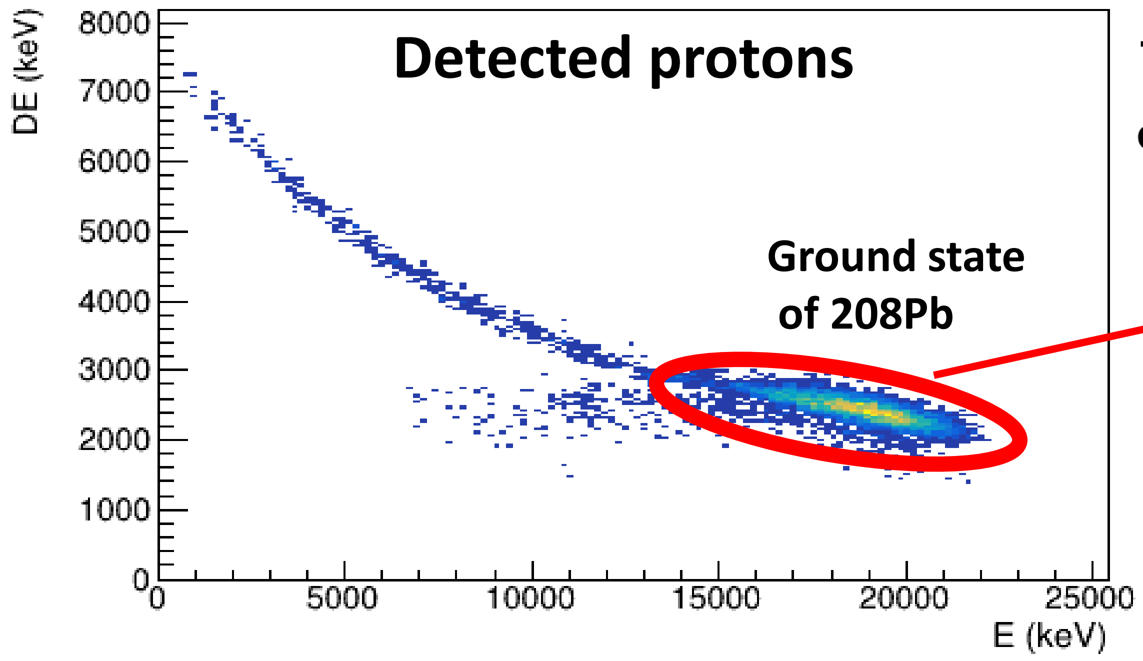
  Effective target thickness increased by $\sim 10^6$ due to revolution frequency (at 10 A MeV)
- High-quality, pure, fully-stripped beams and pure, ultra-thin, windowless targets→ unique!

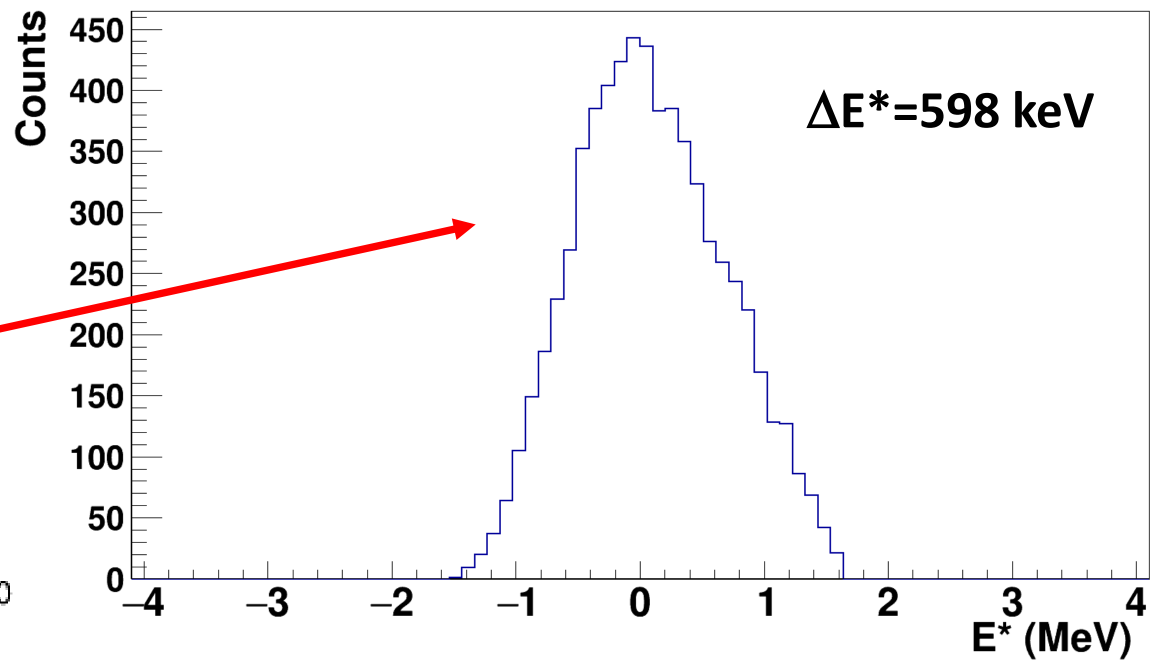
Challenge: Detectors in Ultra-High Vacuum (10^{-11}-10^{-12} mbar)!

First proof of principle experiment at the ESR, 208Pb(p,p'), 20-27 June 2022

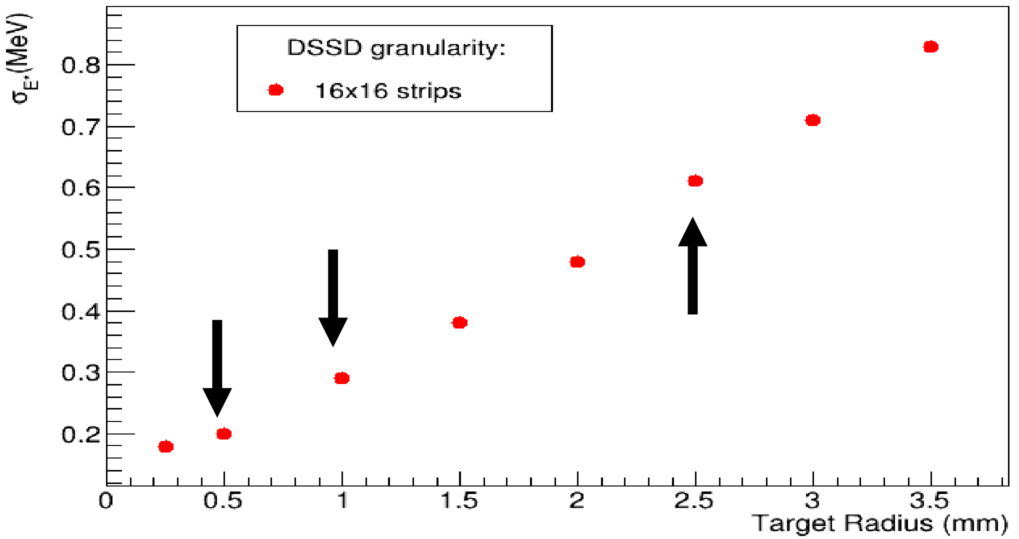


Preliminary results, excitation energy resolution





Simulations



ΔE*≈ 600 keV, dominated by the angular uncertainty due to target radius of 2.5 mm.

With target radius 0.5 -1.5 mm →ΔE*=200-300 keV!

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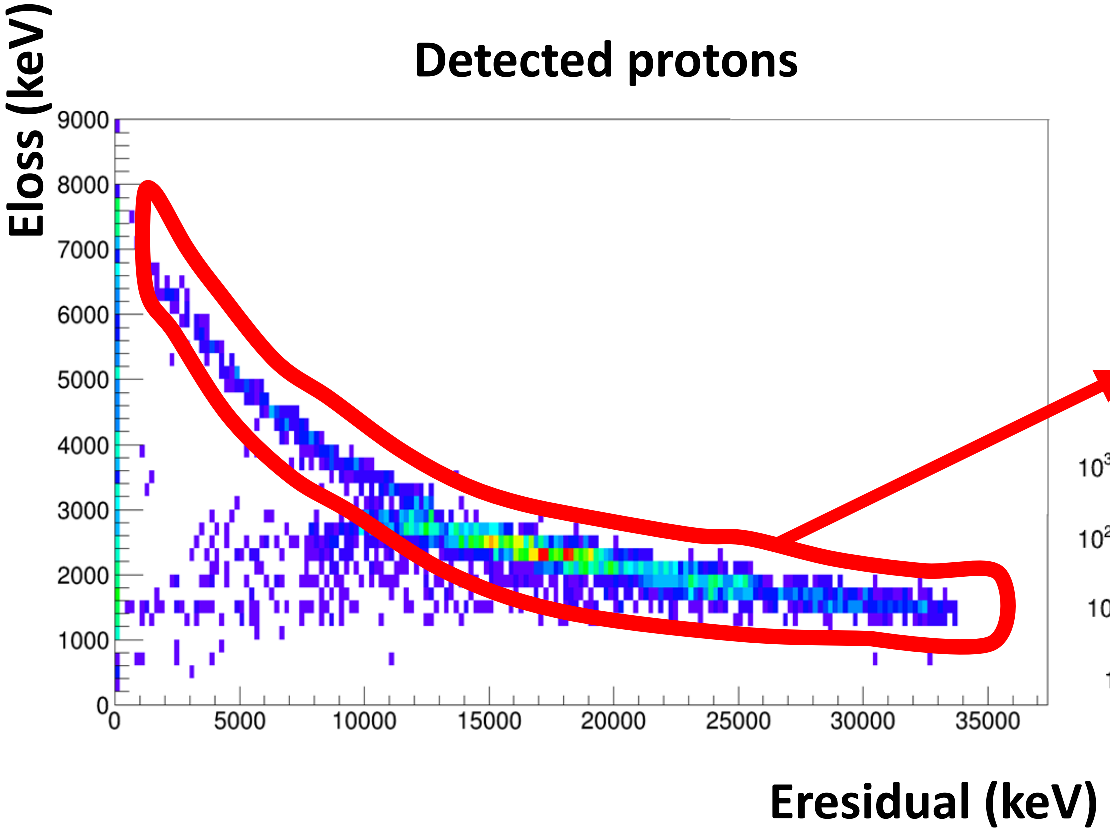
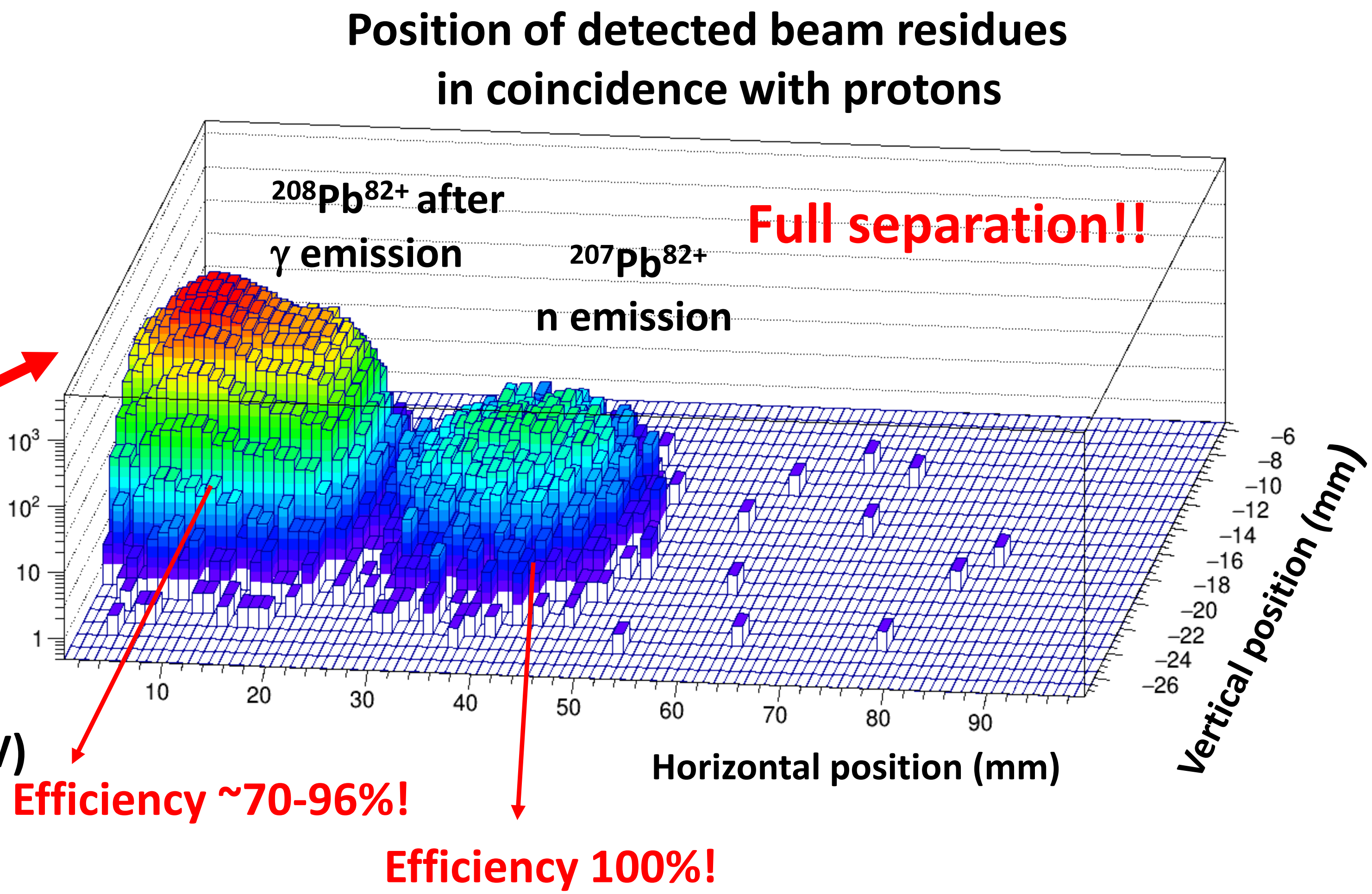
Preliminary results, detection of beam-like residues





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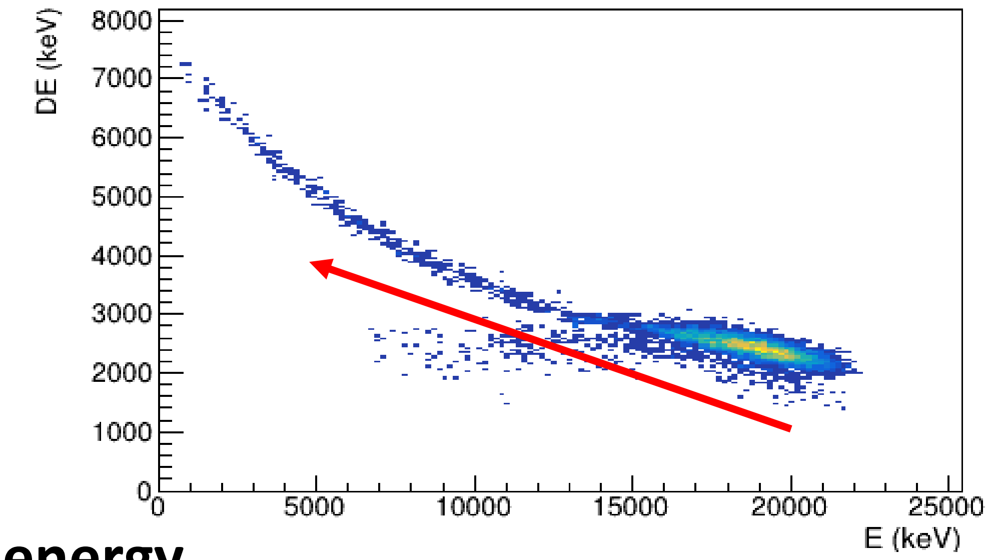
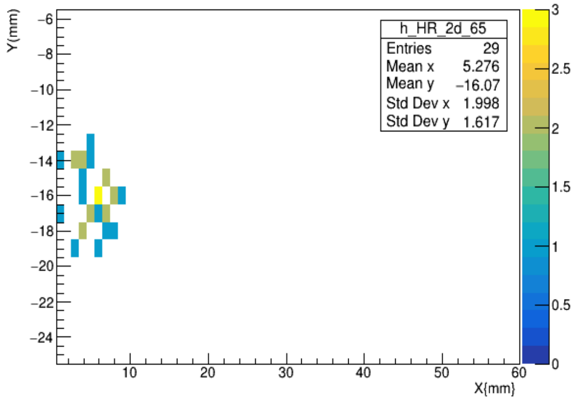
Preliminary results, detection of beam-like residues



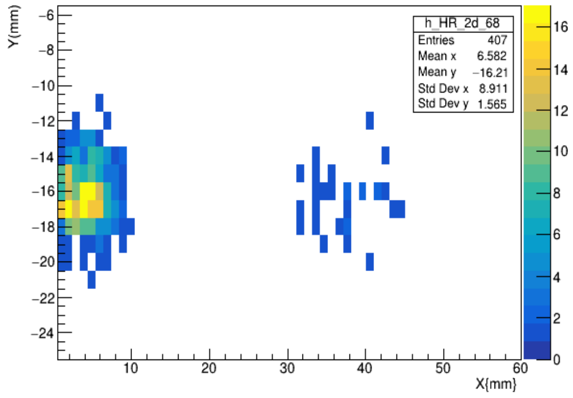
Excitation energy

5.7 < E* < 6.1 MeV

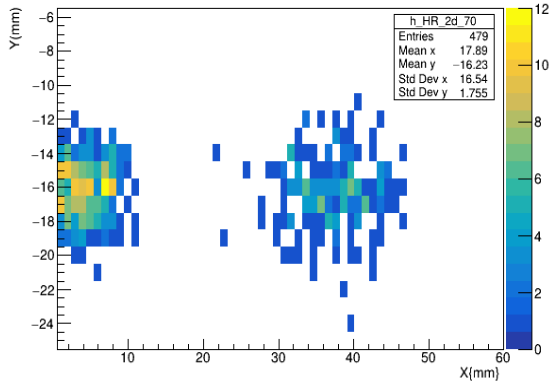


Sn

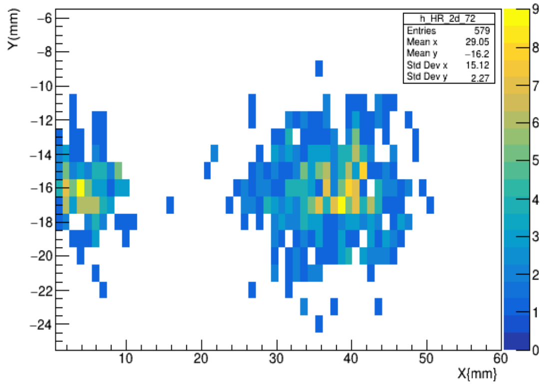
7.0 < E* < 7.4 MeV



7.8 < E* < 8.2 MeV



8.6 < E* < 9.0 MeV



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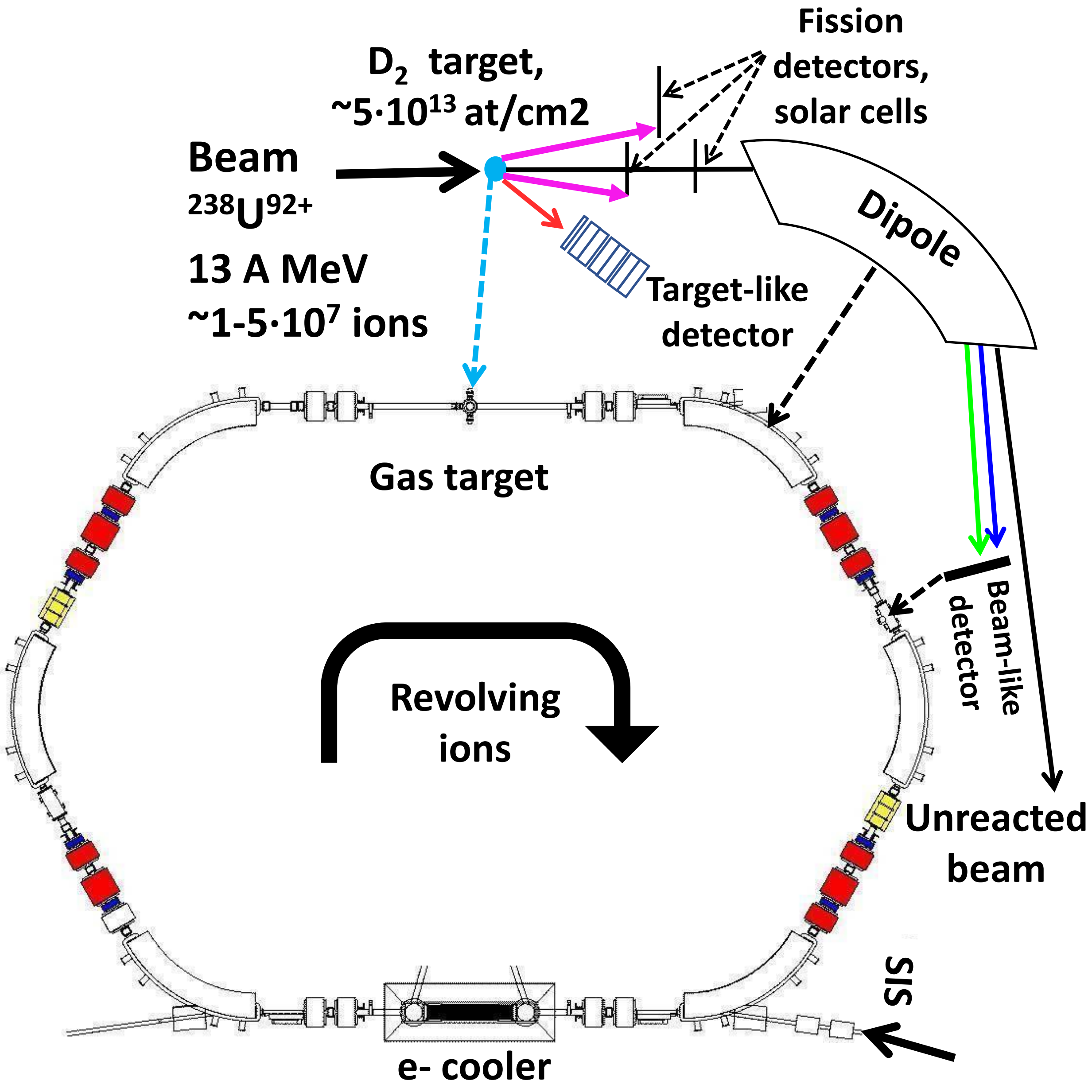
Perspectives: measure simultaneously fission, neutron and gamma-emission probabilities

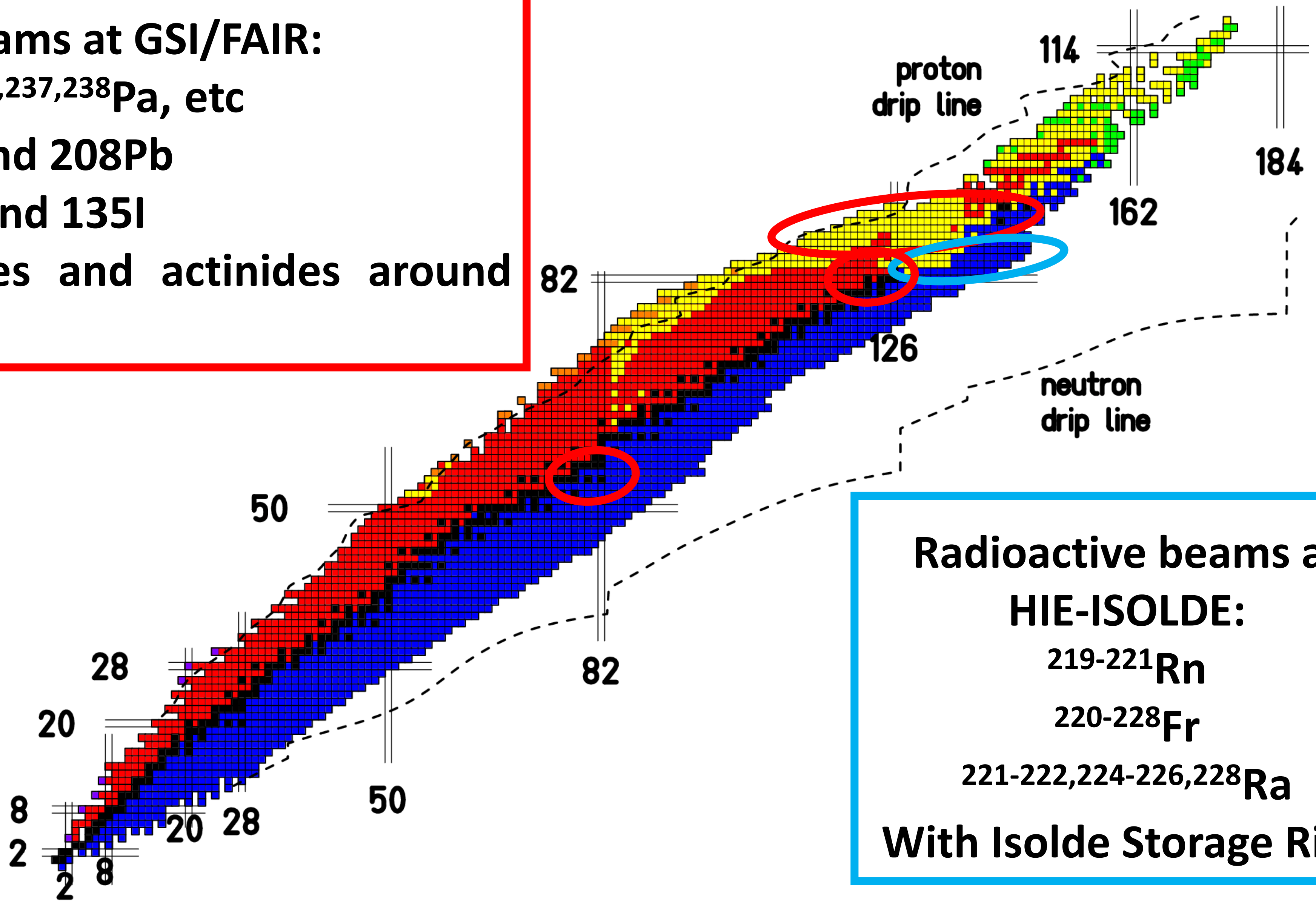


- Add fission detectors. First time that fission is studied in a storage ring!
- Demonstrate feasibility for measuring simultaneously P_f, P_γ and P_n!
- Experiment accepted, to be probably conducted in 2024!
- After, produce dedicated reaction chamber to increase target-residue and fission detection efficiencies!

Longer term perspectives: other stable & radioactive beams…

Stable and radioactive beams at GSI/FAIR:

- $^{235, 236, 237, 238,239}U$, $^{235,236,237,238}Pa$, etc
- Region around 209Bi and 208Pb
- Region around 136Xe and 135I
- Region of pre-actinides and actinides around shell N=126



Radioactive beams at HIE-ISOLDE:

$^{219-221}Rn$

$^{220-228}Fr$

$^{221-222,224-226,228}Ra$

With Isolde Storage Ring

Conclusions…

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

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

→$\Delta E^* \approx$ 600 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

-Use P_γ and P_n to determine the neutron-induced cross sections of 207Pb

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

-Build a dedicated reaction chamber to significantly increase efficiency for target residues and fission

-Measurements with radioactive beams!

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NECTAR: Nuclear rEaCTions At storage Rings

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The NECTAR core team

2+1 year post-doc position open in 2023!