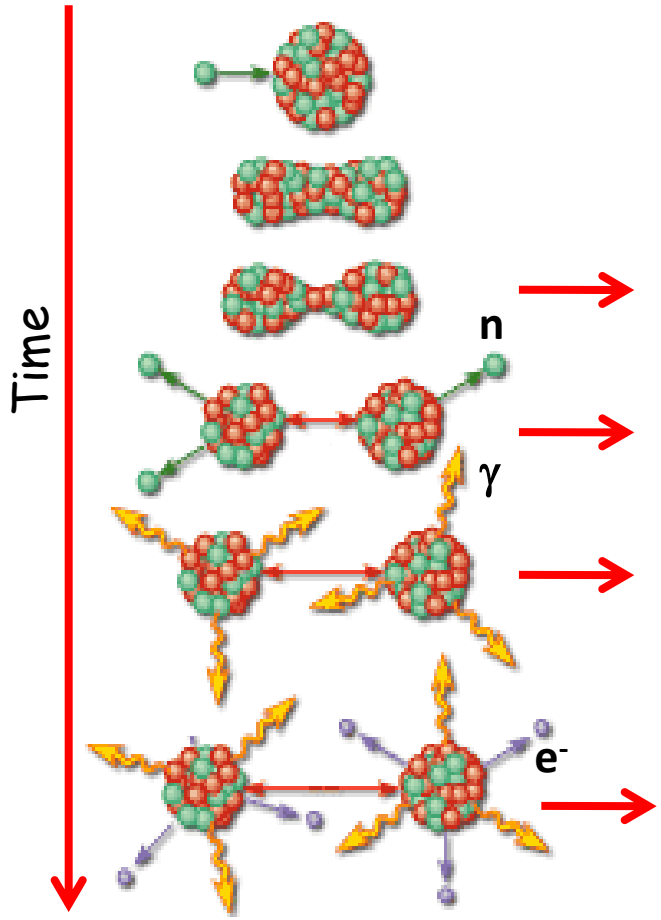
Nuclear fission and surrogate reactions at storage rings

Beatriz Jurado, LP2I, Bordeaux, France

The fission process



Before scission, deformed nuclei in contact through the neck

Fragments recover smaller deformation
E* release by prompt neutron emission

E* release by prompt gamma-ray emission

β decay

The fission barrier

The first fission model, based on the liquid-drop model

SEPTEMBER 1, 1939 PHYSICAL REVIEW VOLUME 56

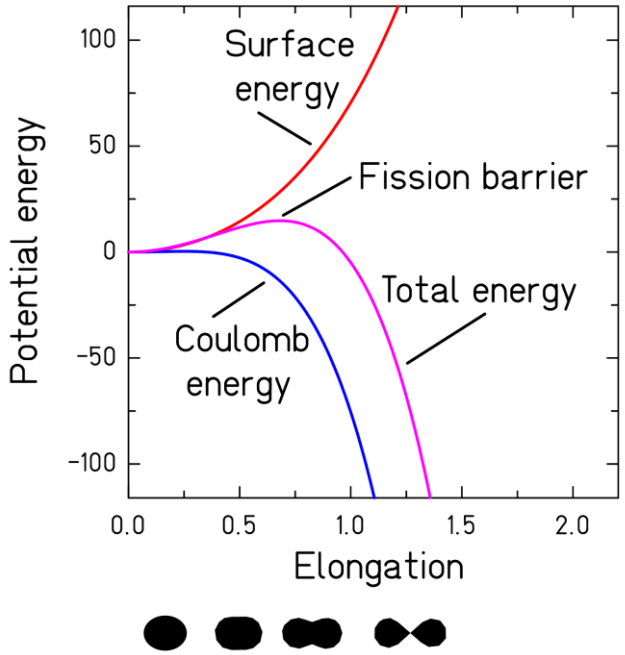
The Mechanism of Nuclear Fission

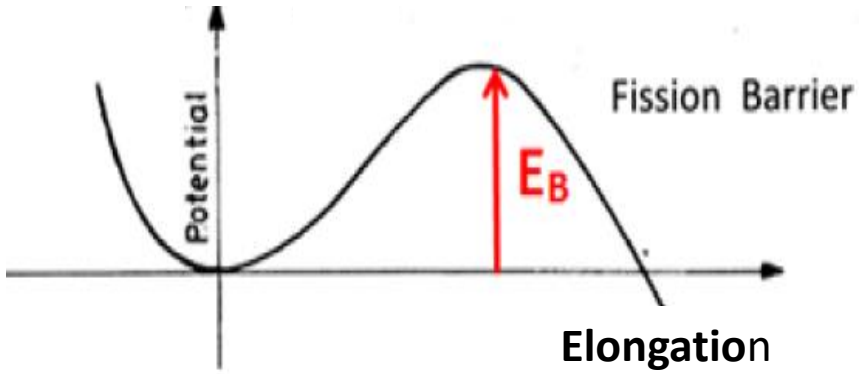
NIELS BOHR
University of Copenhagen, Copenhagen, Denmark, and The Institute for Advanced Study, Princeton, New Jersey

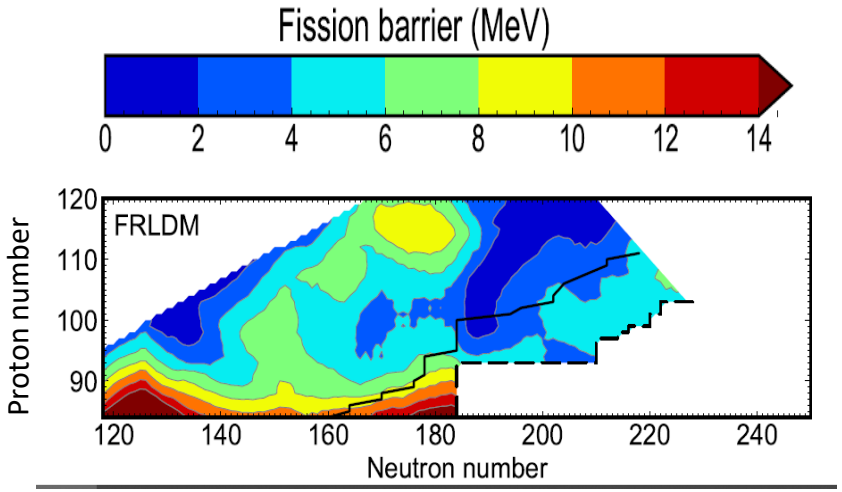
AND

JOHN ARCHIBALD WHEELER
Princeton University, Princeton, New Jersey

(Received June 28, 1939)

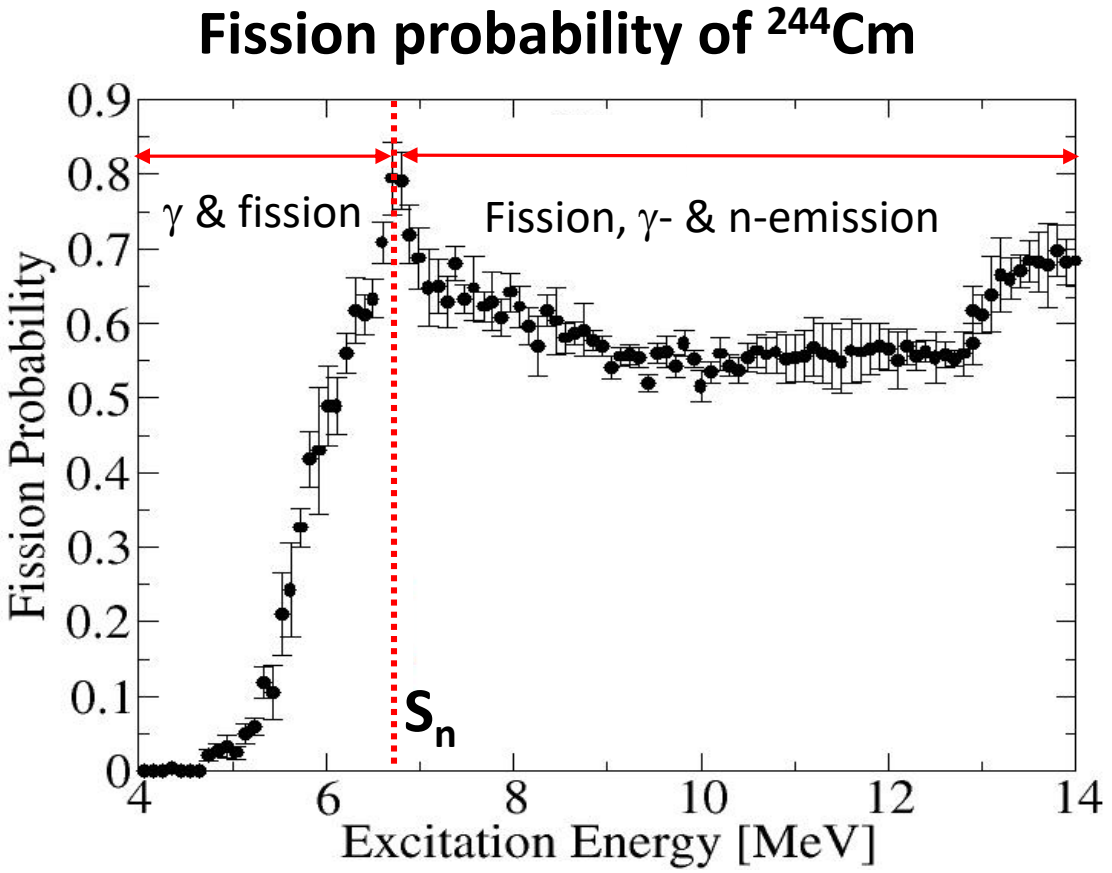


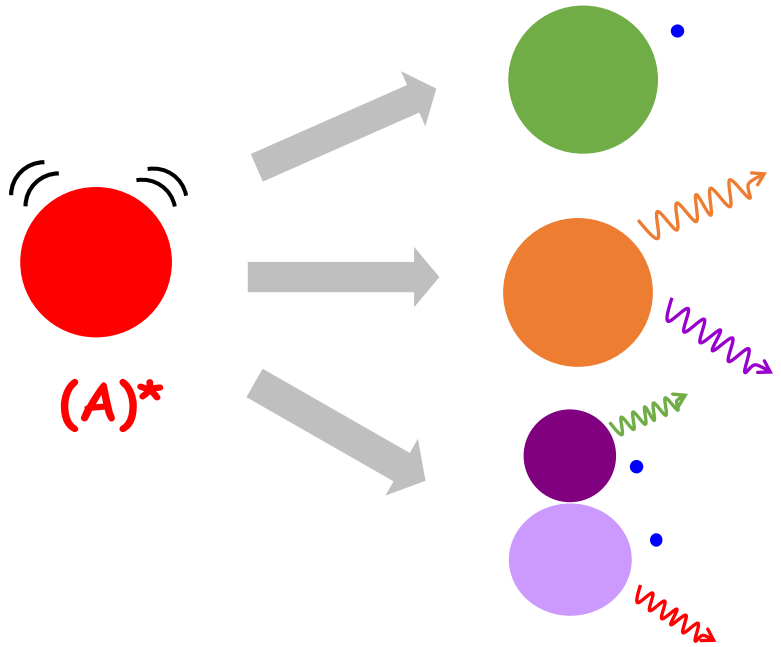




S. A. Giuliani et al., PRC 97 (2018) 034323

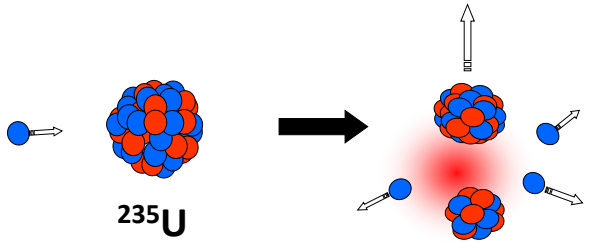
Fission probability, most direct observable for the fission barrier





Barrier parameters obtained from calculations based on statistical model
Need to consider the competing decay modes and also measure their probabilities

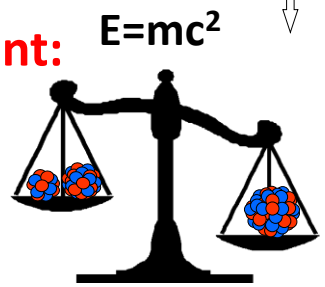
The importance of fission



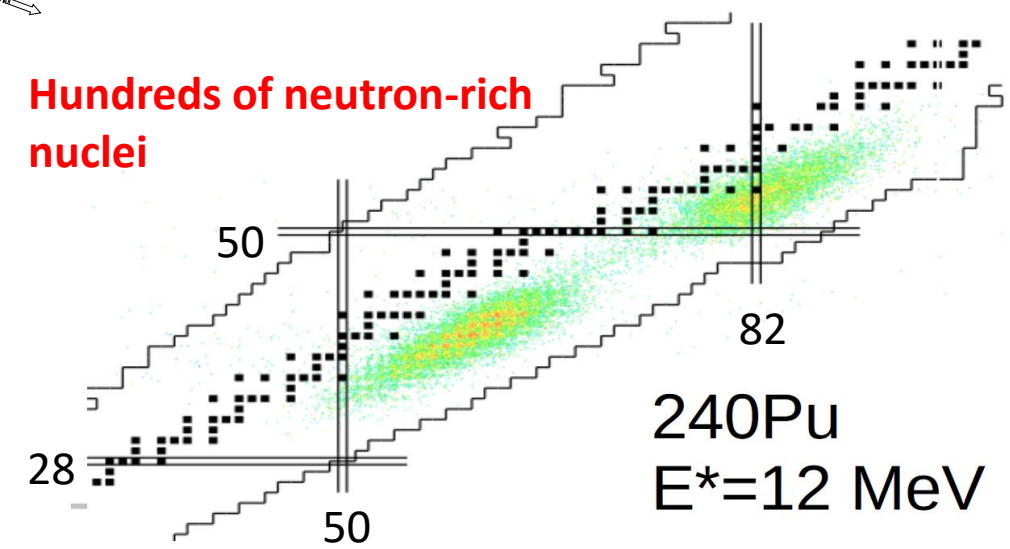
Huge amount of energy released per fission event: ~ 200 MeV!

80% of the energy released in form of kinetic energy of fission products: 8000 km/s

Few eV for combustion of a molecule of coal, gas or oil…

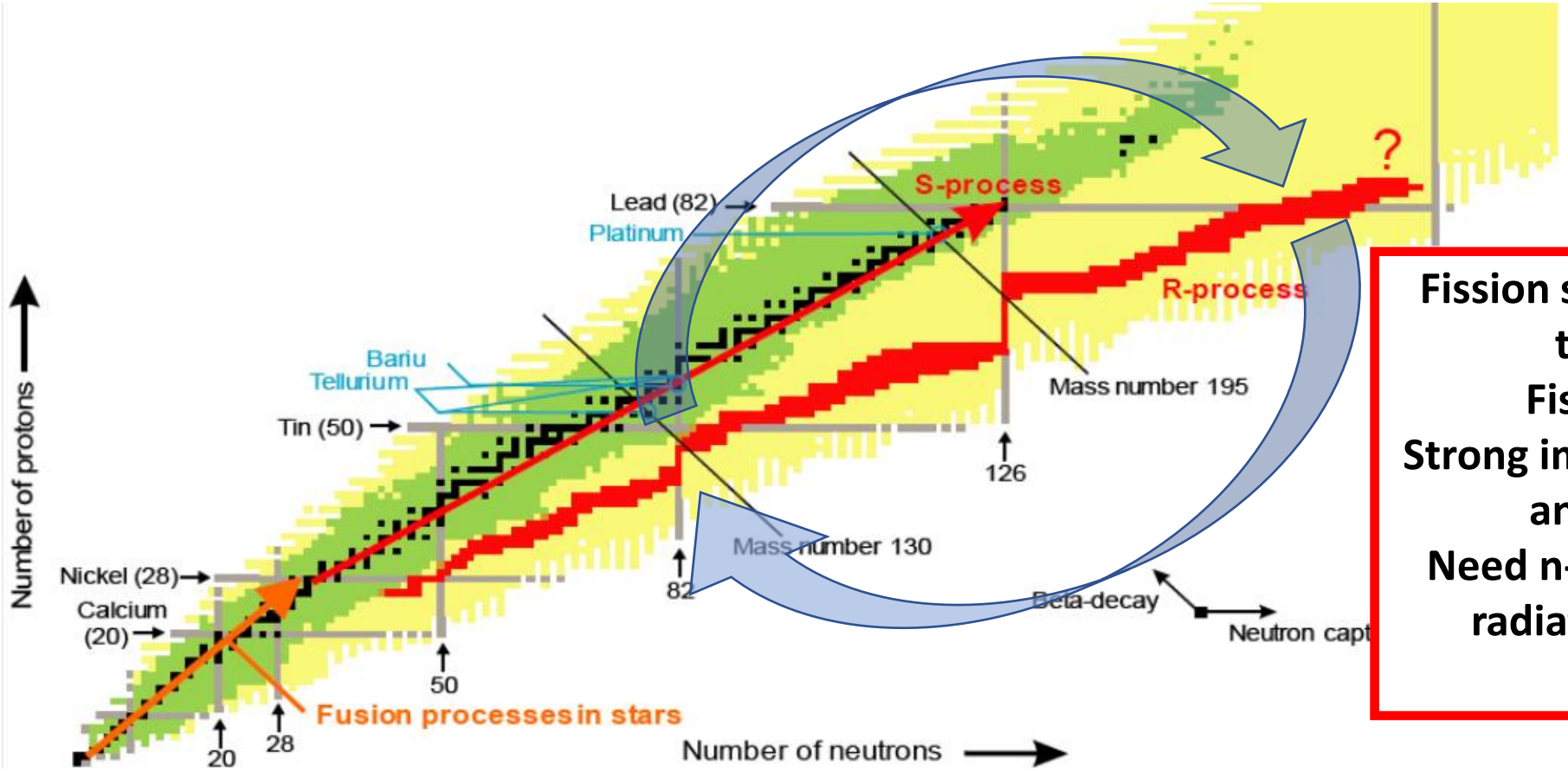


Hundreds of neutron-rich nuclei



- **Production of electricity in nuclear reactors (France ~ 70 %)**
- **Production of radio-isotopes for nuclear medicine: 99Mo, 131I, …**
- **Production of radioactive ion beams in research facilities**
- **Neutrino factory**

Fission and nucleosynthesis of heavy elements

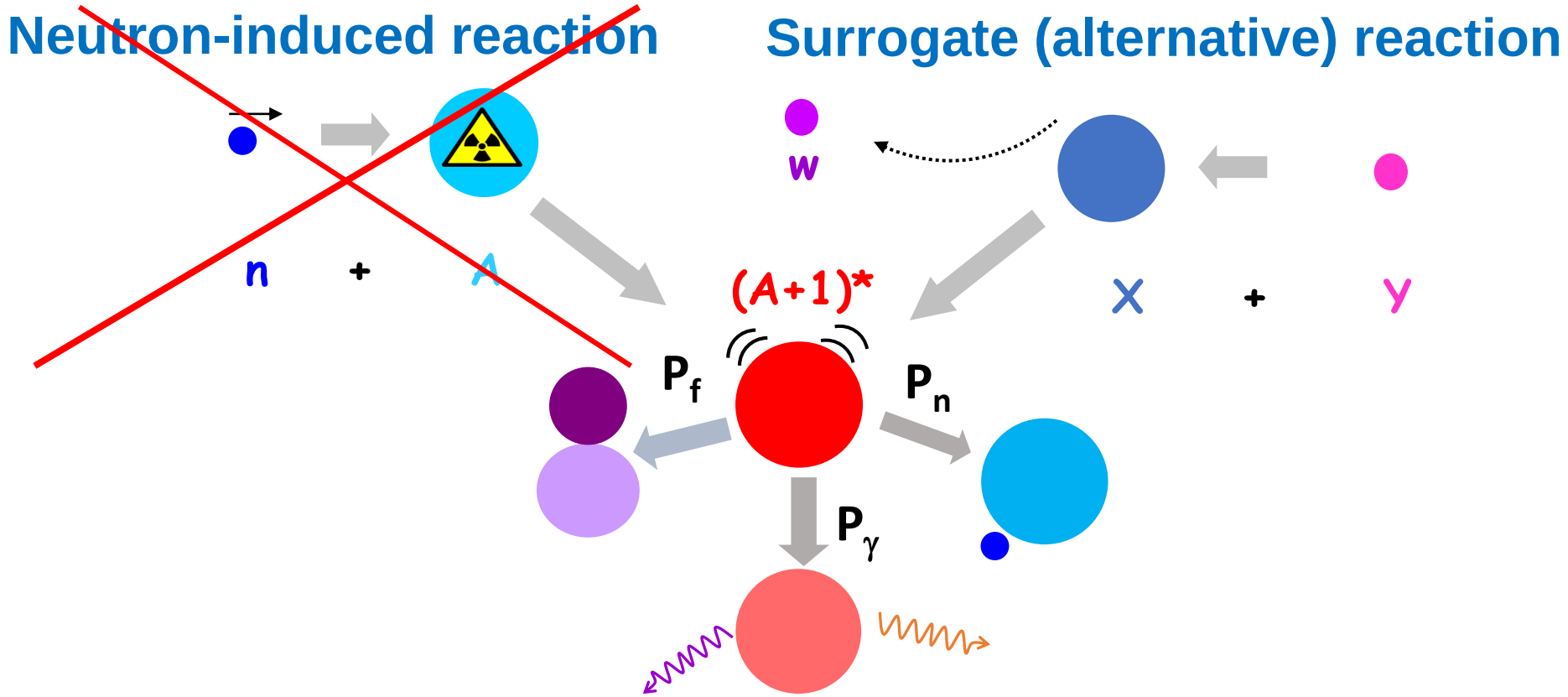


Fission sets the end point of the r-process!
Fission recycling!
Strong impact on abundances and light curves!
Need n-induced fission and radiative capture cross sections

→Very difficult or even impossible to measure these cross sections with standard techniques because targets are not available.

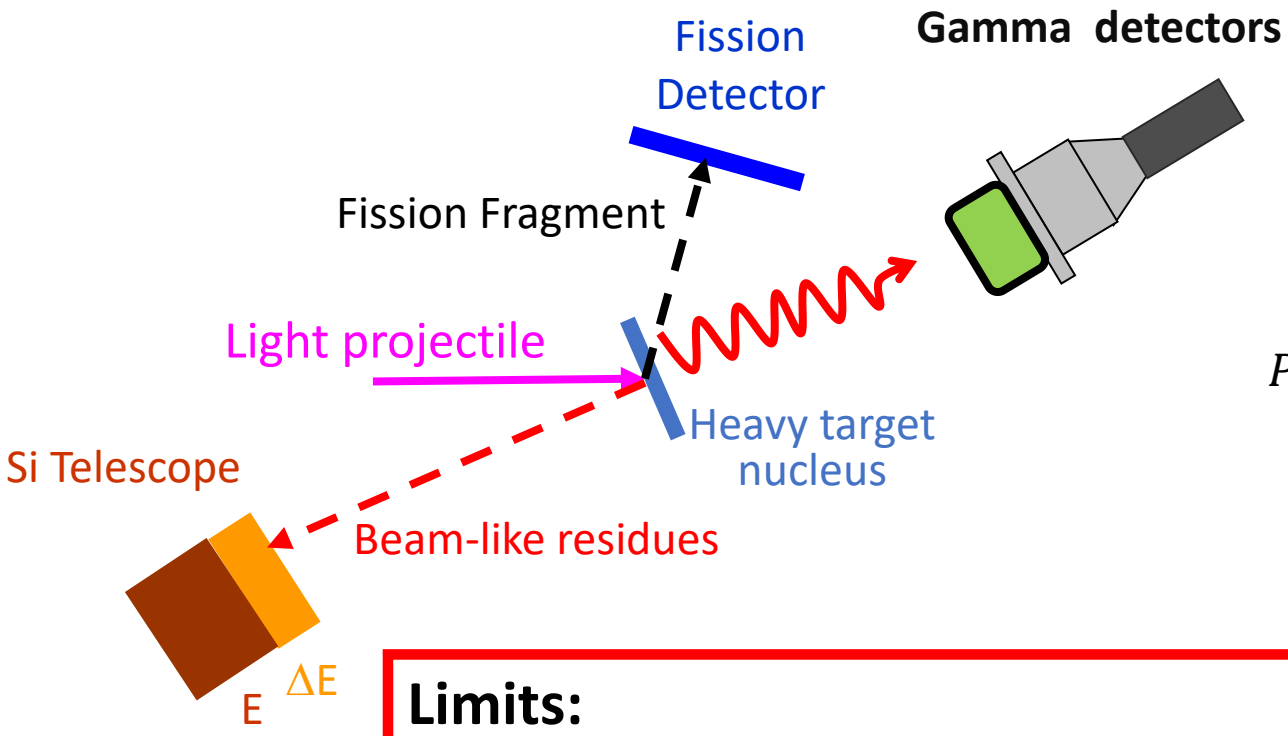
→Complicated to calculate due to the difficulty to describe the de-excitation process (fission barriers, level densities, γ-ray strength functions…). Calculations can be wrong by several orders of magnitude!

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



$$P_{decay}(E^*) = \frac{N^{coin}(E^*)}{N^{sing}(E^*) \cdot \varepsilon_{decay}(E^*)}$$

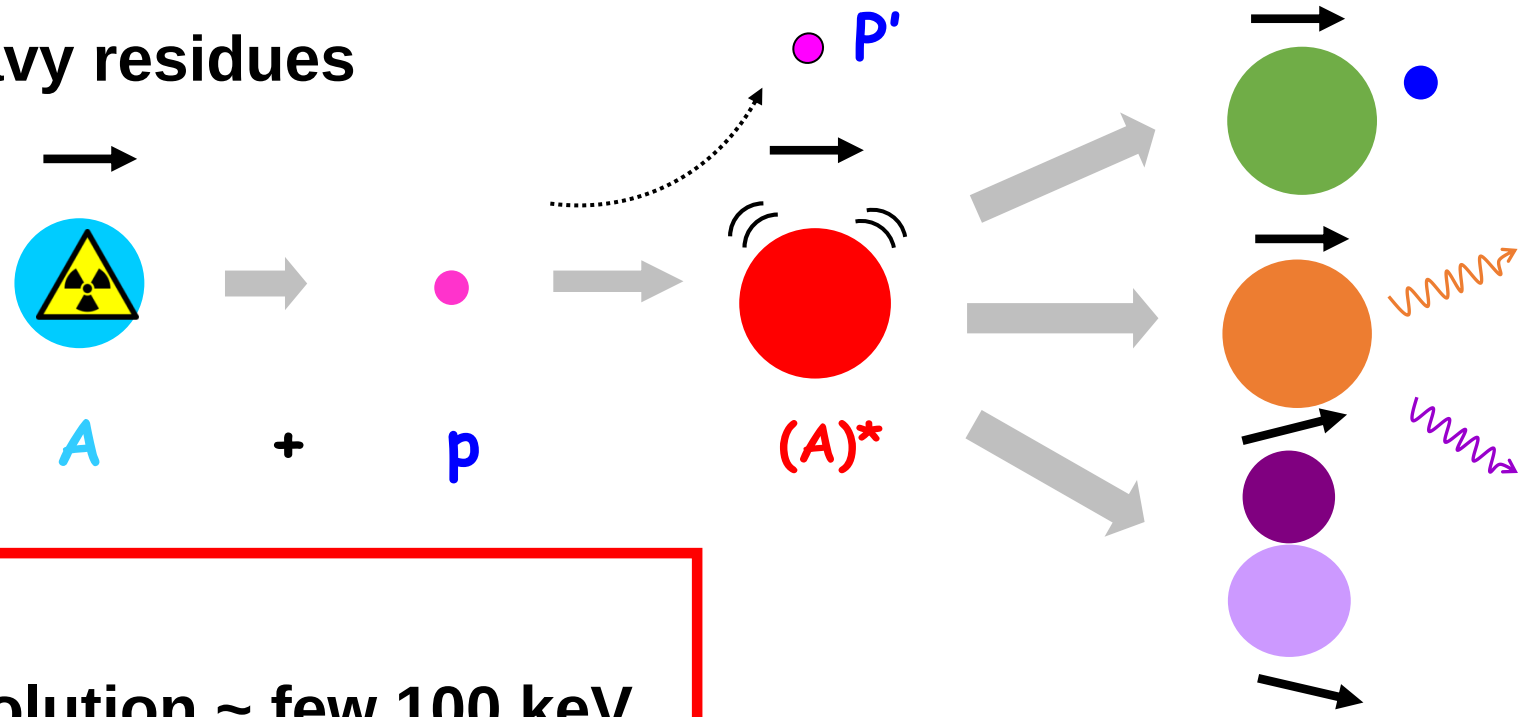
Limits:

- **Unavailability of targets (radioactive samples)**
- **Target contaminants and target support**
- **P_γ : rather low detection efficiency, background from FF**
- **P_n: very difficult, never measured before!**

Advantages of Inverse kinematics:

-Access to very short-lived nuclei

-Detection of heavy residues

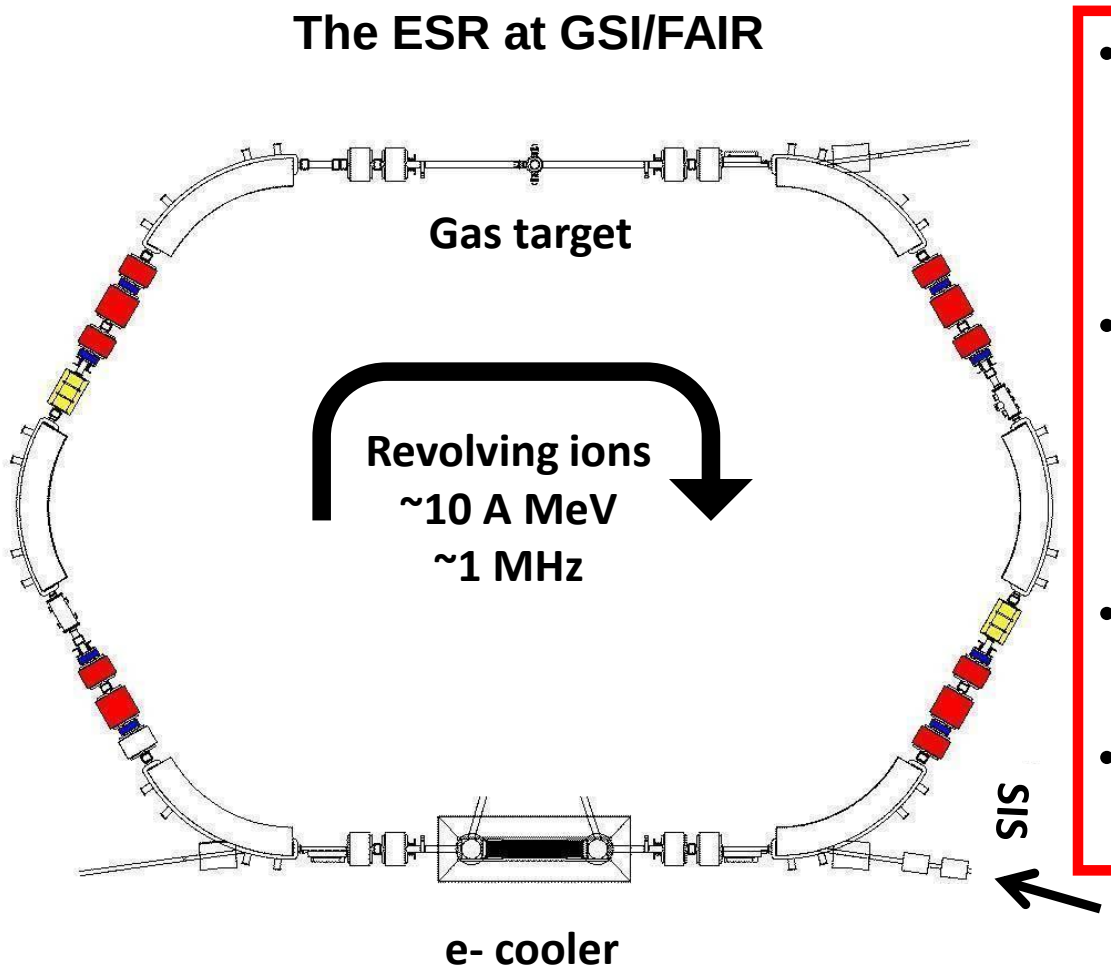


BUT!

- **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



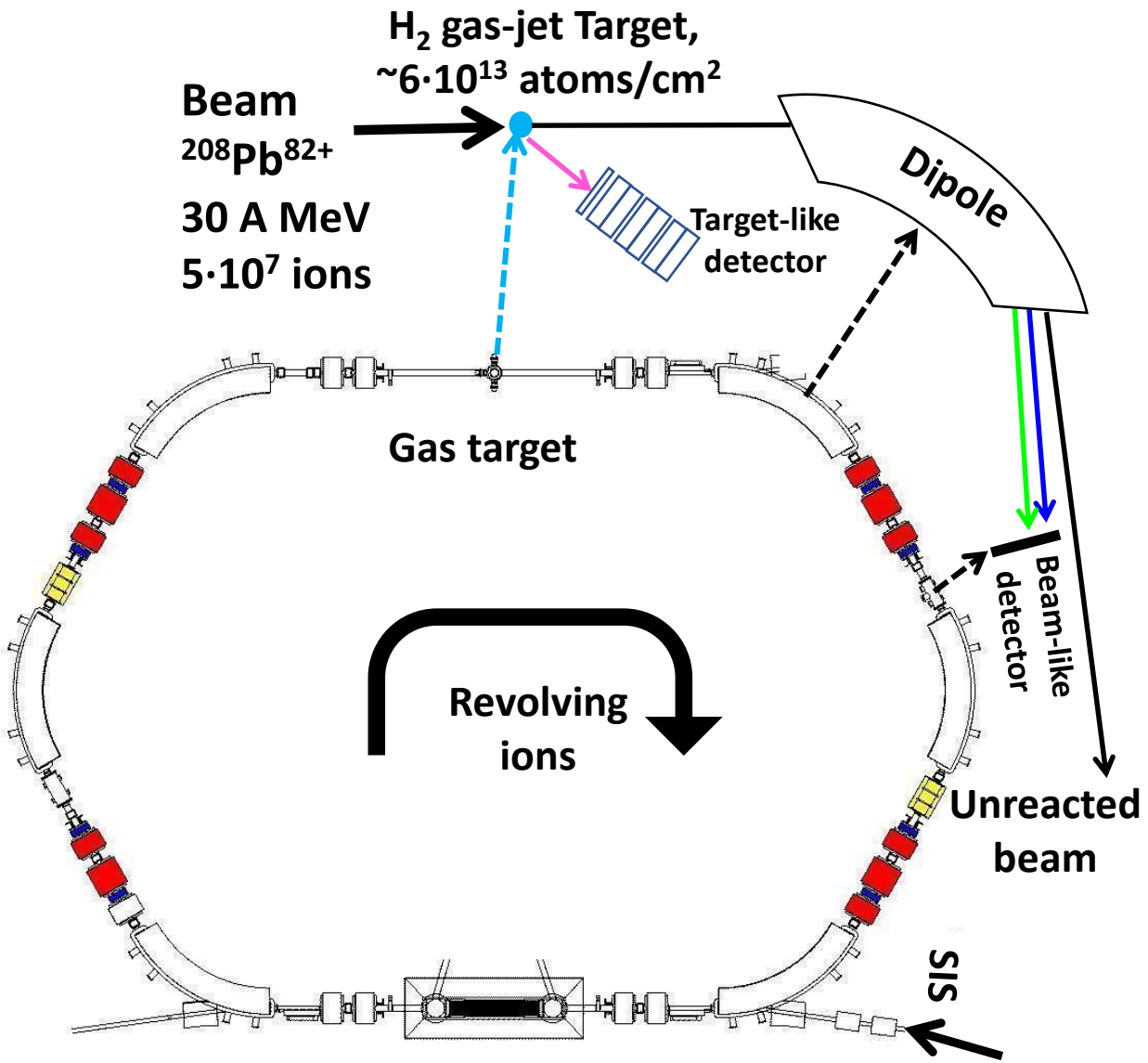
- Beam cooling → Excellent energy and position resolution of the beam, maintained after each passage through the target, negligible, E-loss & straggling effects
- Use of ultra-low density in-ring gas-jet targets ~10^{13}/cm^2.

  Effective target thickness increased by ~10^6 due to revolution frequency (at 10 A MeV).
- Probability for two consecutive reactions 10^{-20}, no charge state issues.
- High-quality, pure, fully-stripped beams and pure, ultra-low density, windowless targets→ unique!

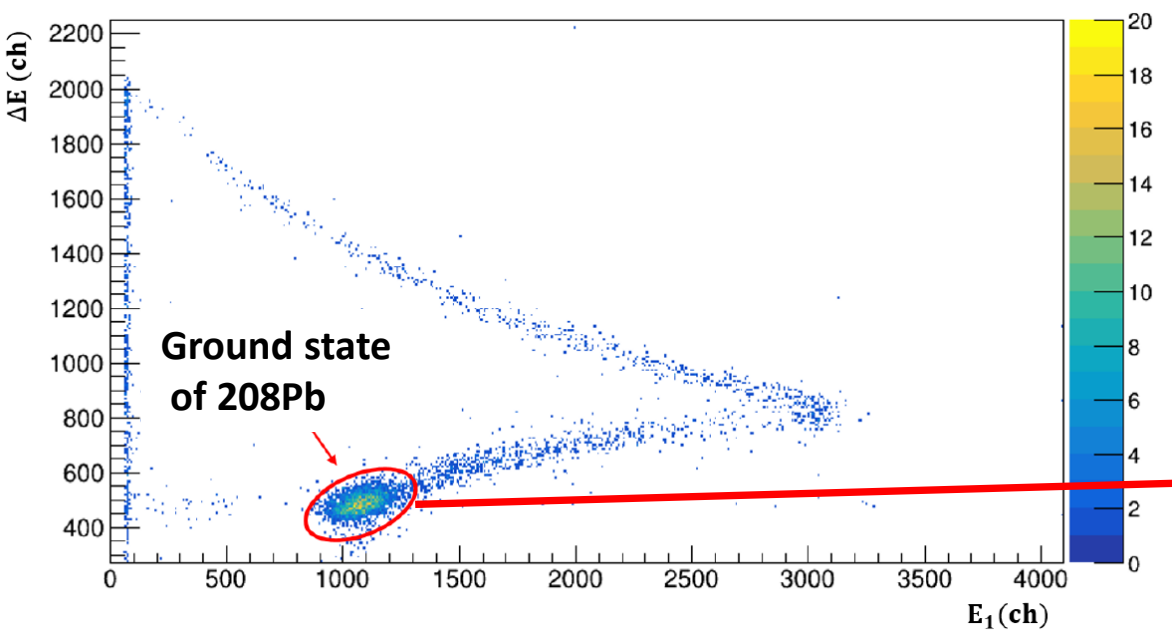
Challenge: Detectors in Ultra-High Vacuum (10^{-10}-10^{-11} mbar)!

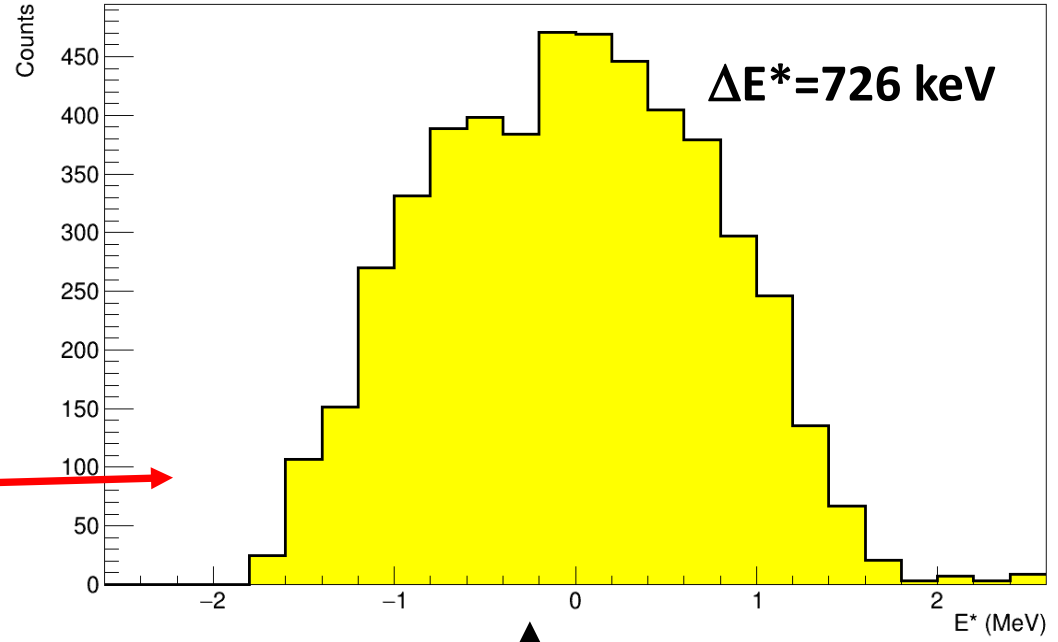
First surrogate reaction experiment at the ESR, 20-27 June 2022

208Pb+p→208Pb*+p' ←→ n+207Pb→208Pb*

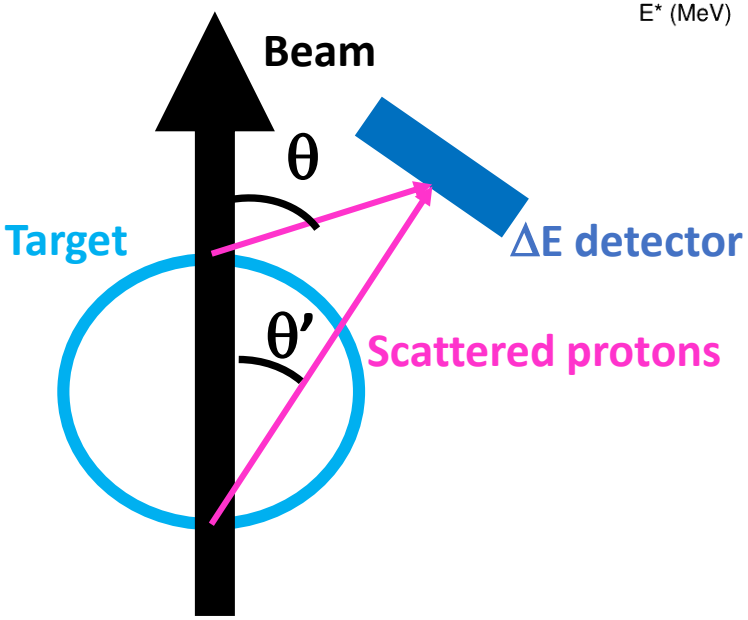


Excitation energy resolution

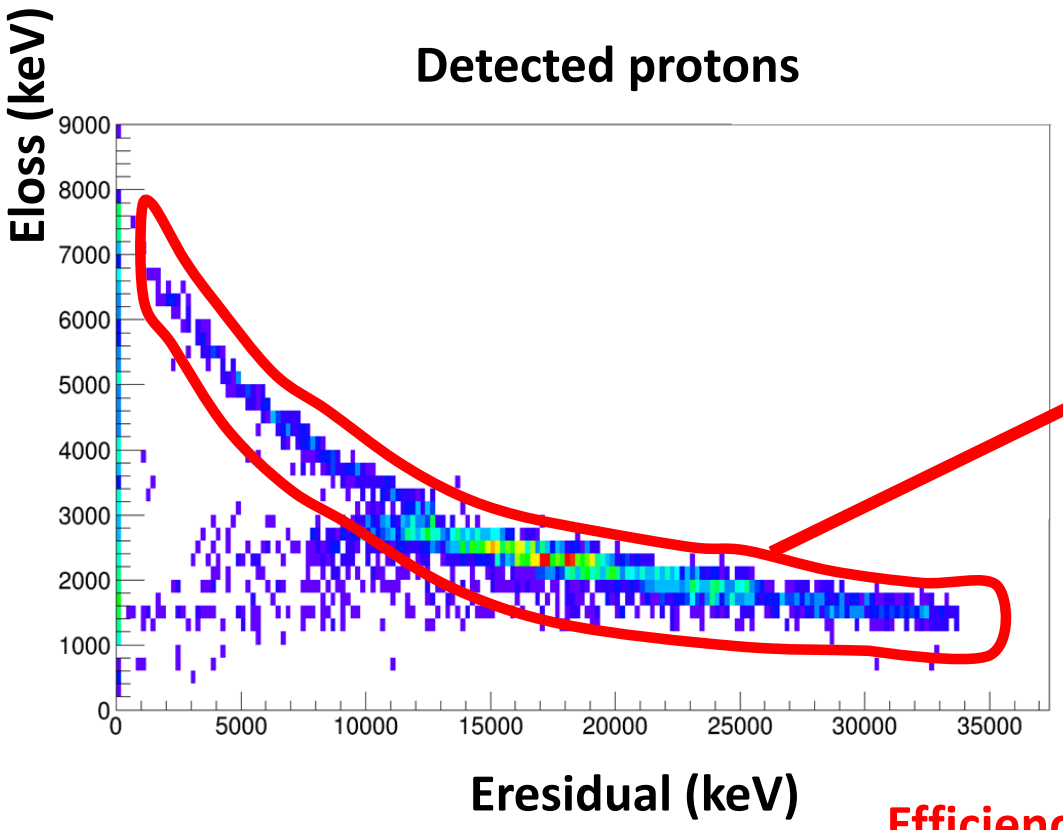


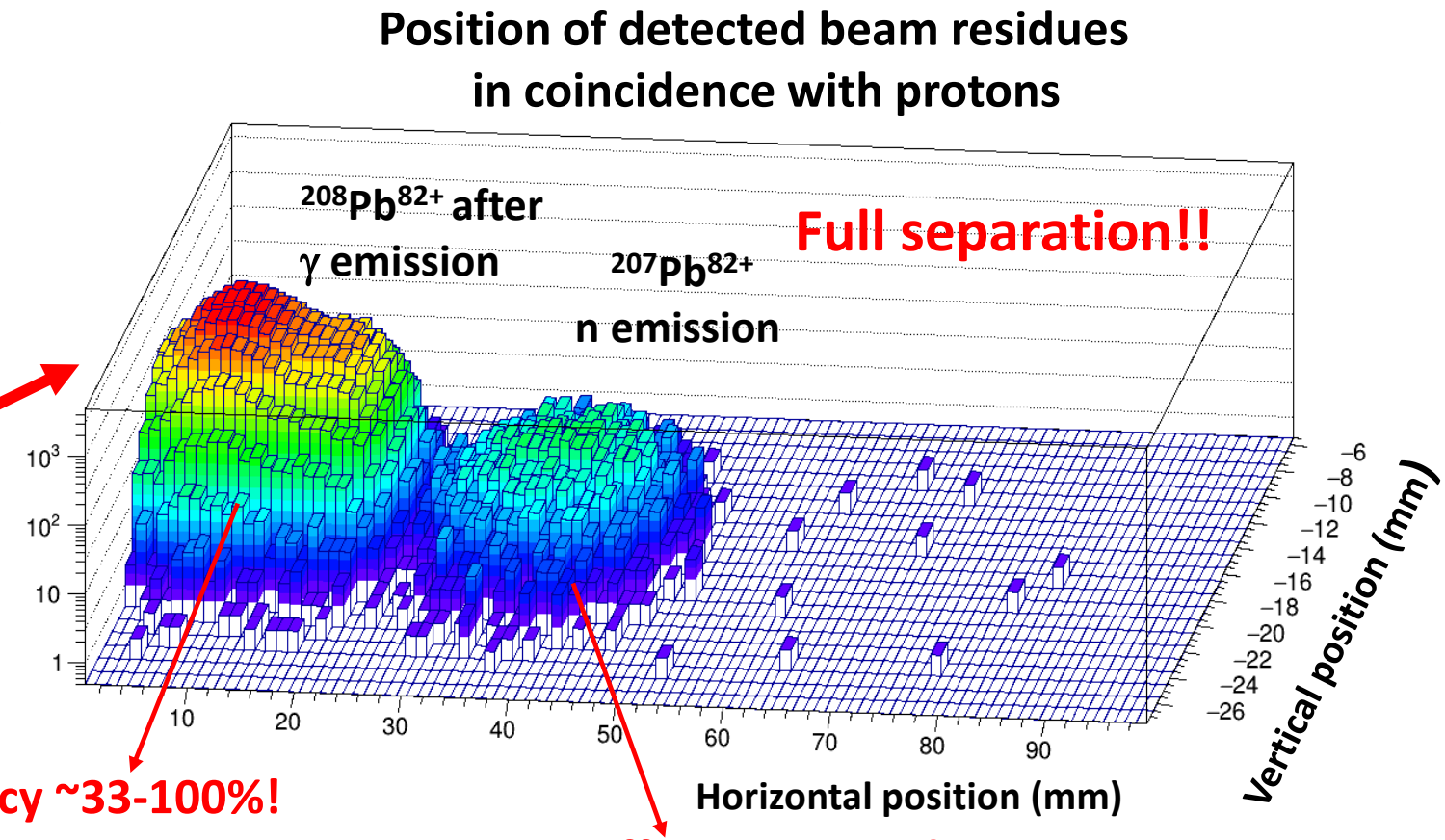


- ΔE*≈ 726 keV at E*= 0 MeV
- ΔE* improves to ~ 350 keV at E*= 9 MeV
- ΔE* dominated by the angular uncertainty due to target radius of ~2.5 mm.
- ΔE* ~ 350 keV to 120 keV with 0.5 mm target radius!



Detection of beam-like residues

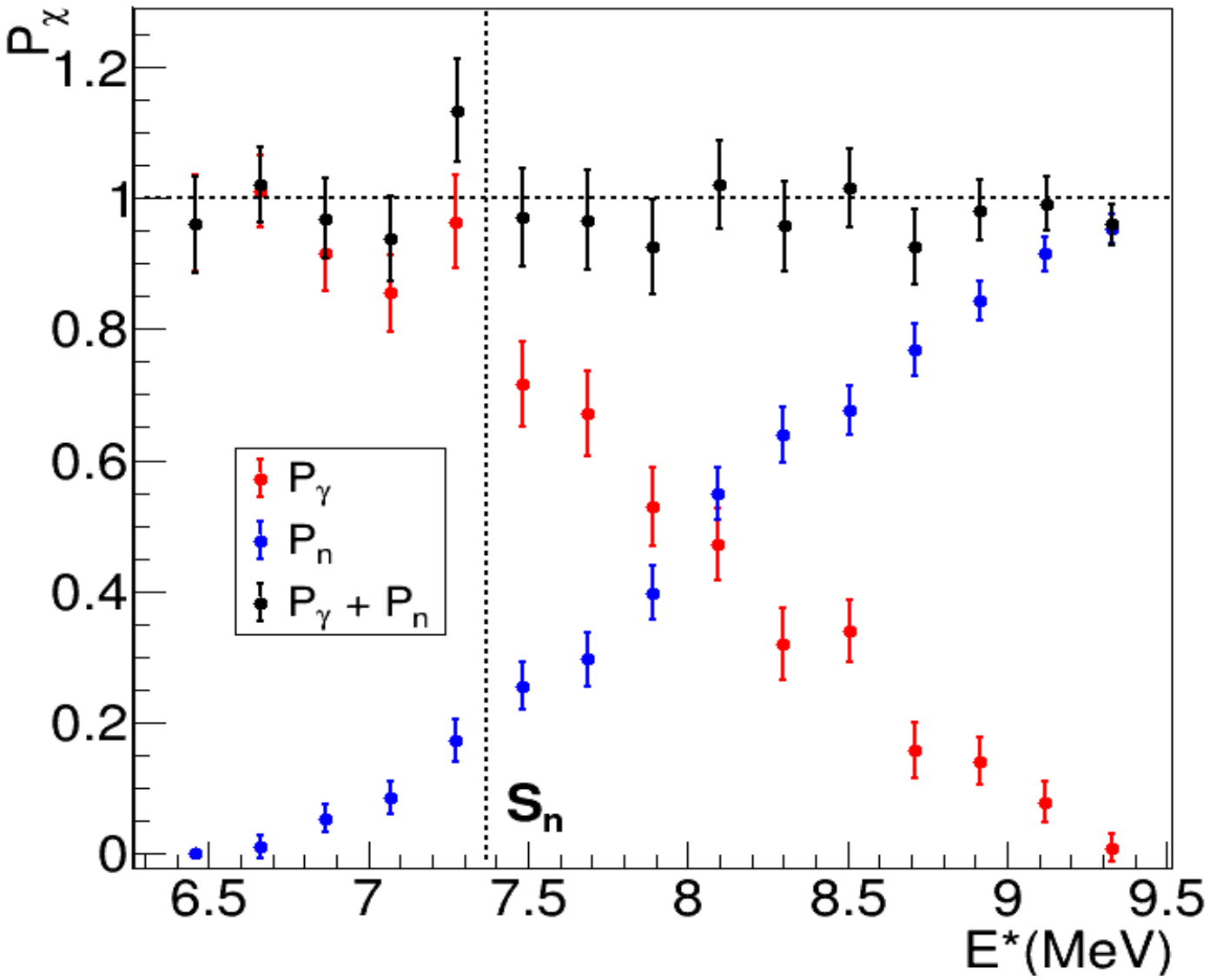




Efficiency ~33-100%!
≈ Max 20 % in direct kinematics

Efficiency 100%!
0% in direct kinematics…

Results

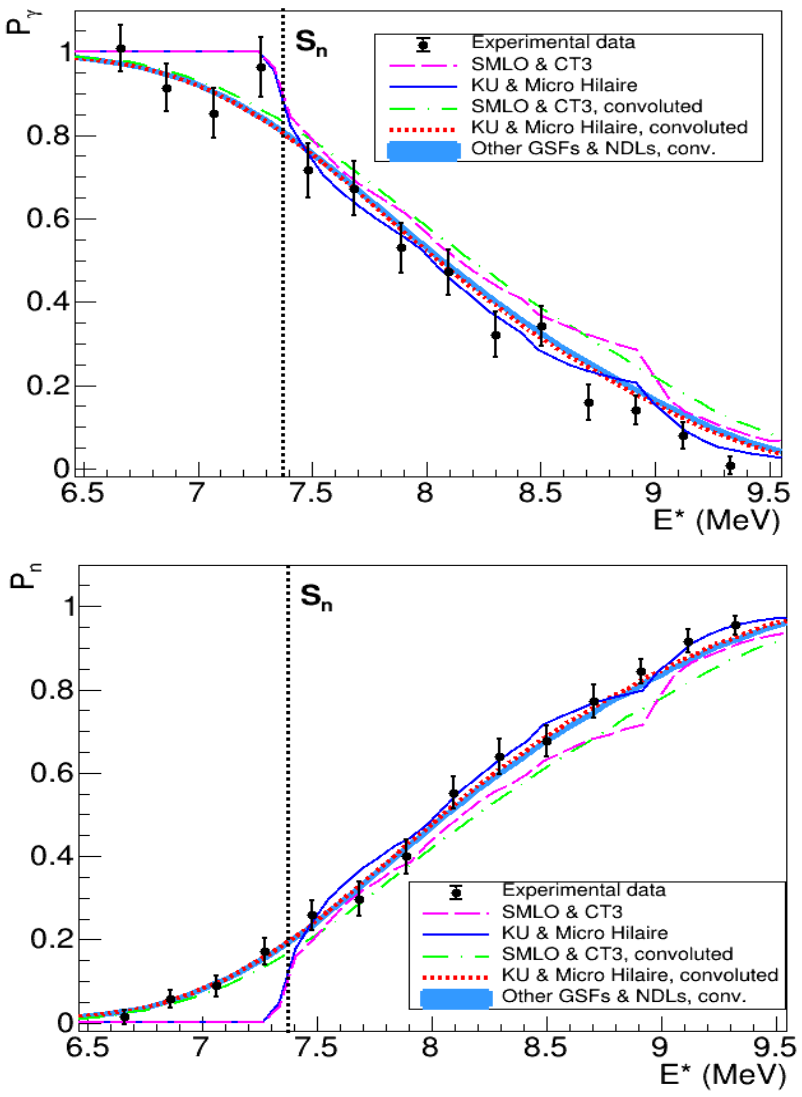


Pn+Pγ≈1!

Validation of experimental technique!

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

Comparison with calculations

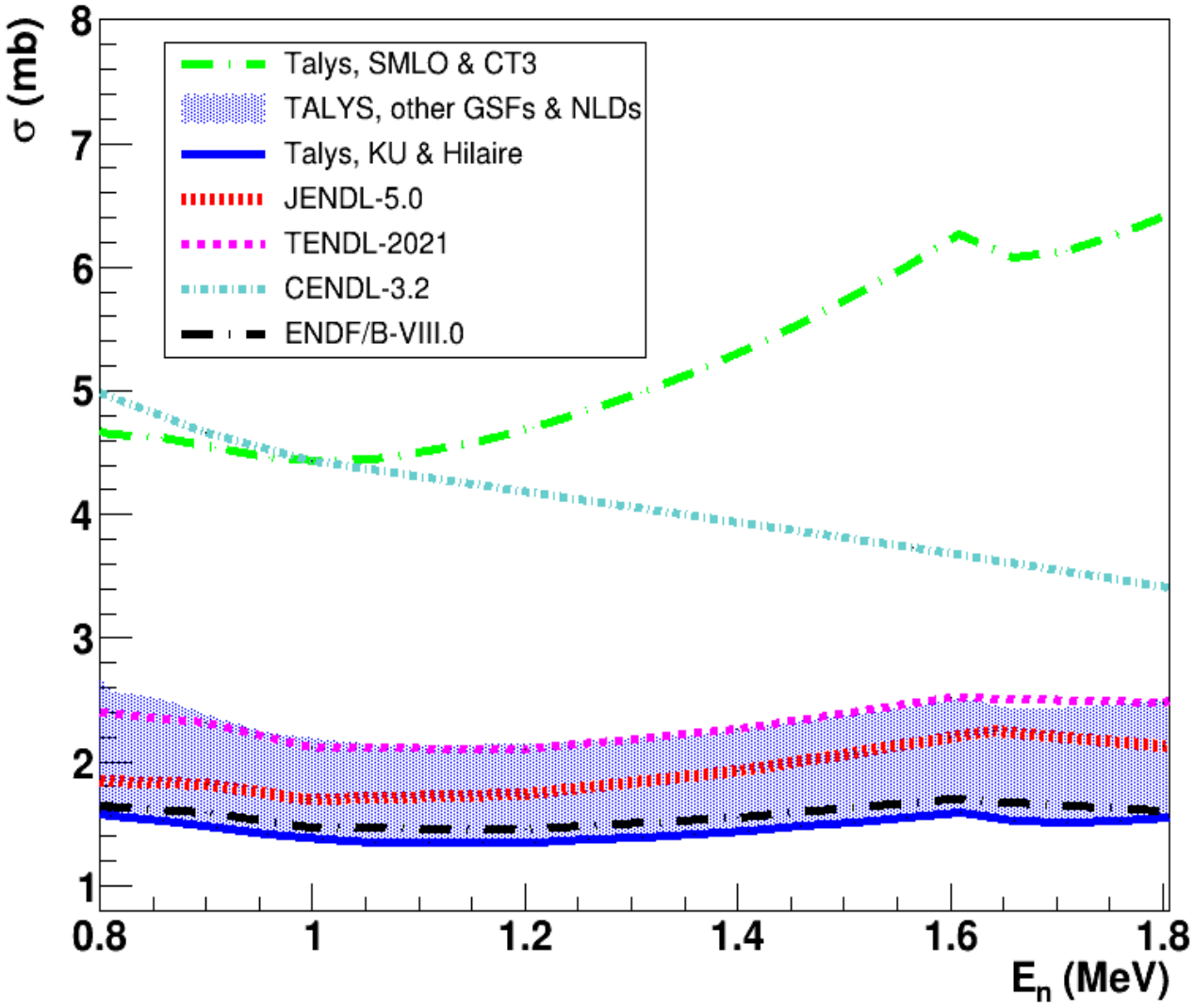


Effect of E* resolution at the neutron separation energy!

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

M. Sguazzin *et al.*, Phys. Rev. Lett. 134 (2025) 072501
M. Sguazzin *et al.*, Phys. Rev. C 111 (2025) 024614

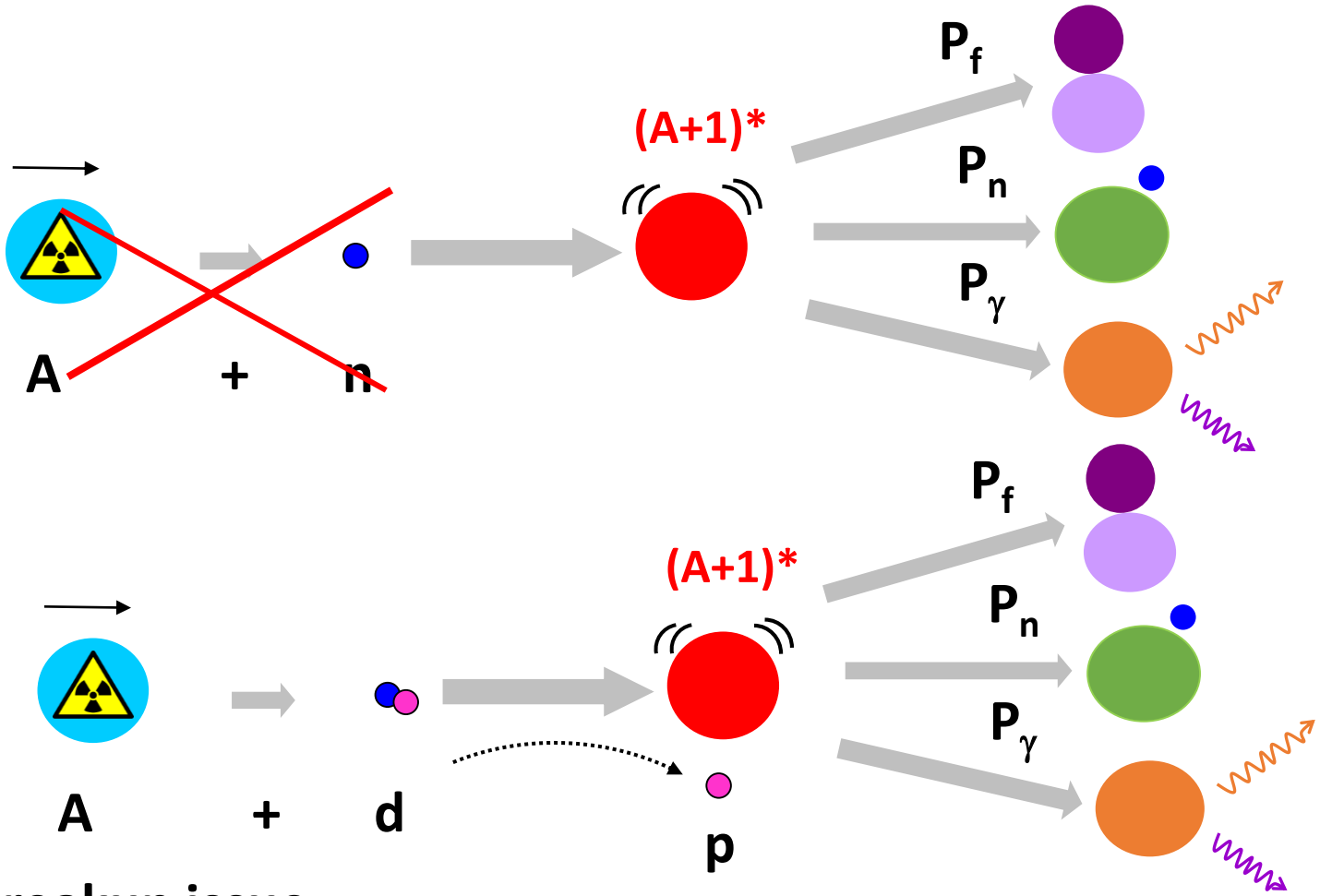
^{207}Pb(n, γ) cross section



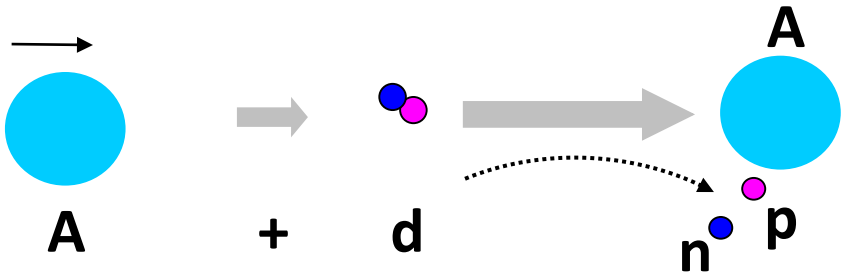
Good agreement with all evaluations except CENDL-3.2!

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

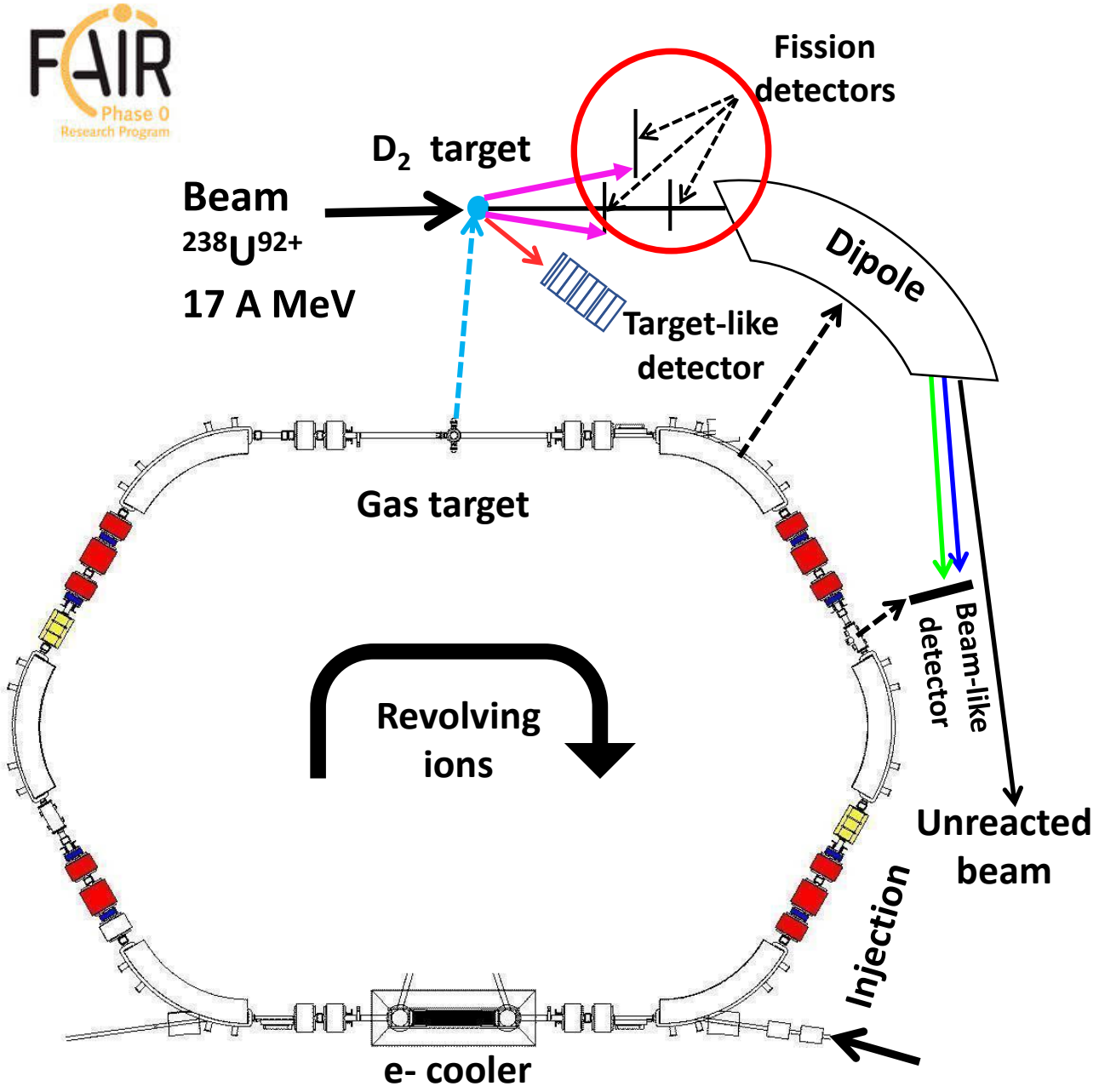
The (d,p) reaction



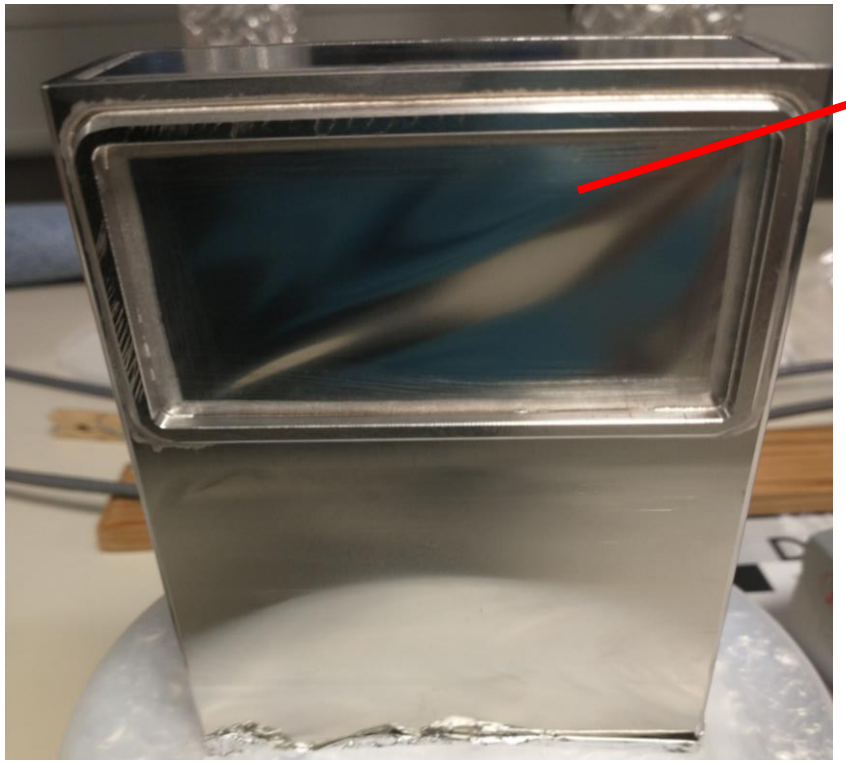
The deuteron breakup issue



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

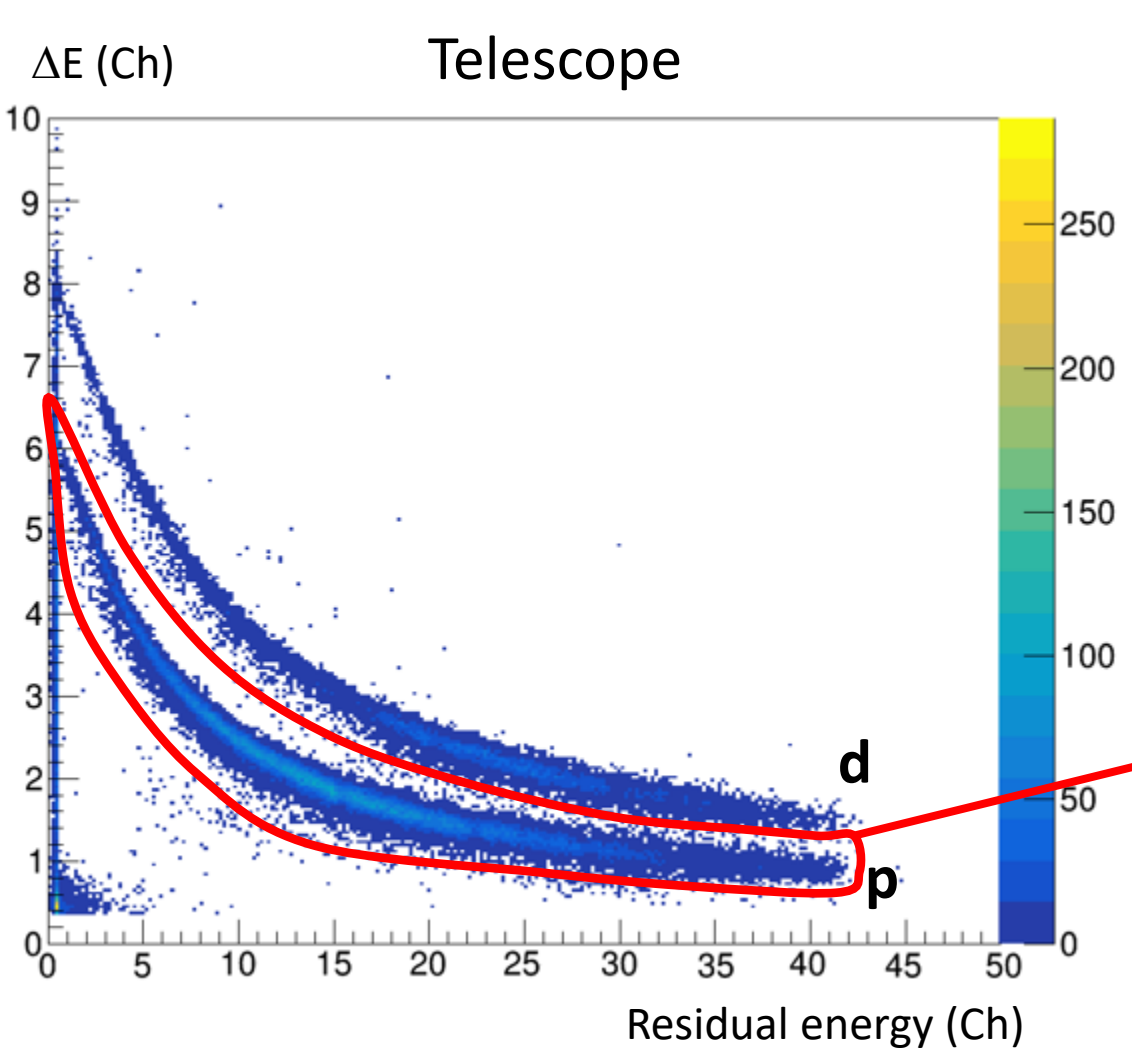


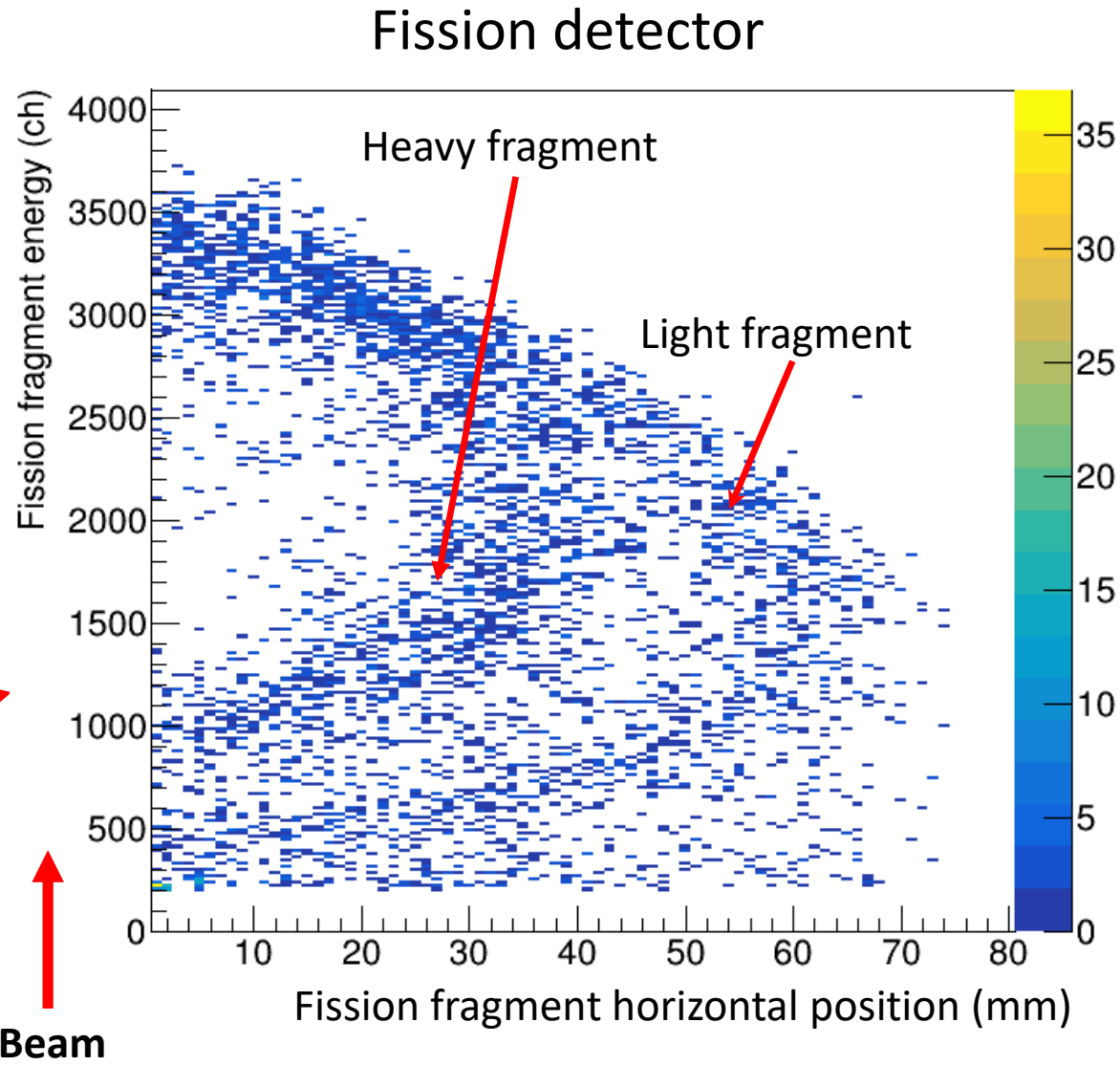
Pockets for fission detectors



Many failures until finding the appropriate procedure for soldering the window and making it vacuum tight!

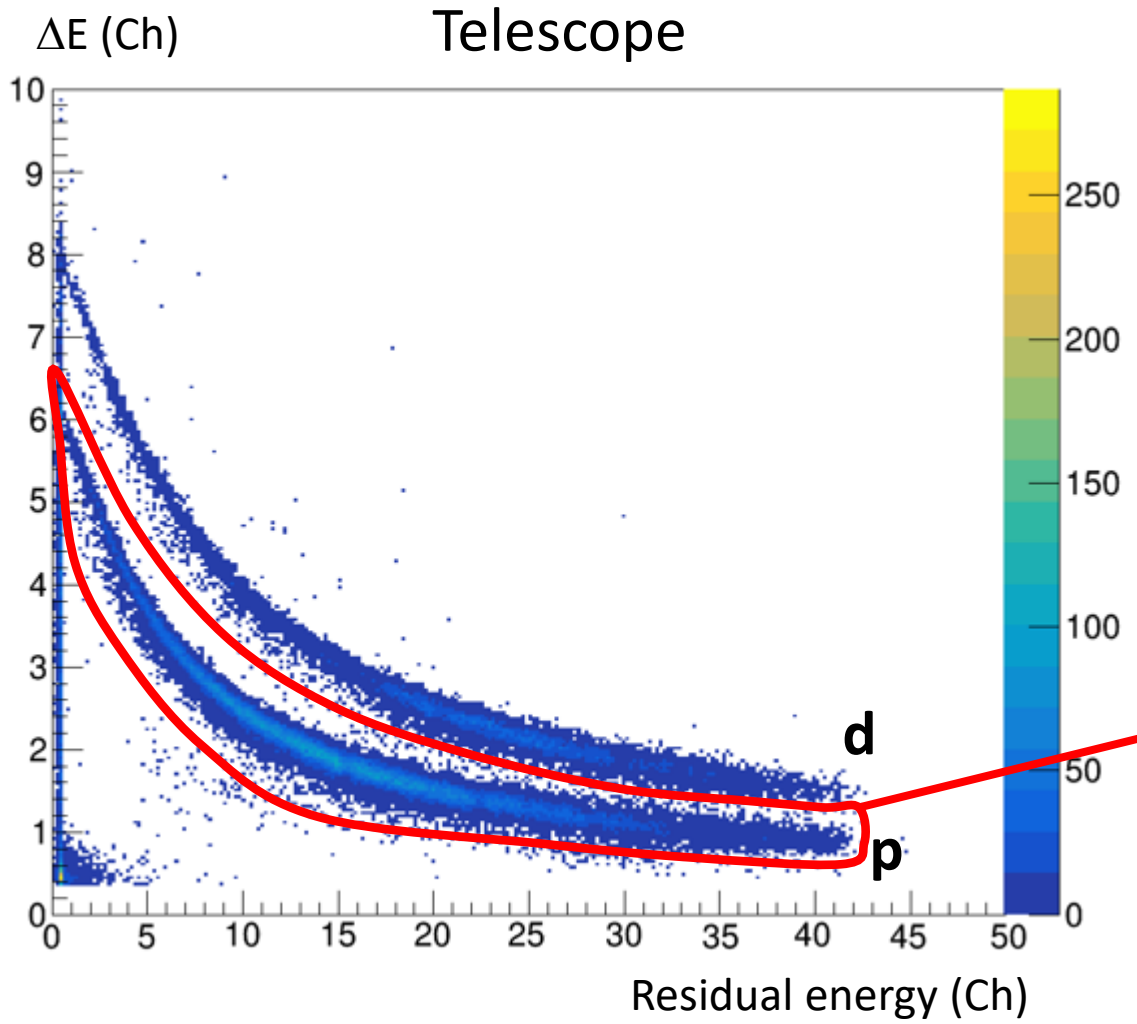
Preliminary results, 238U(d,p)

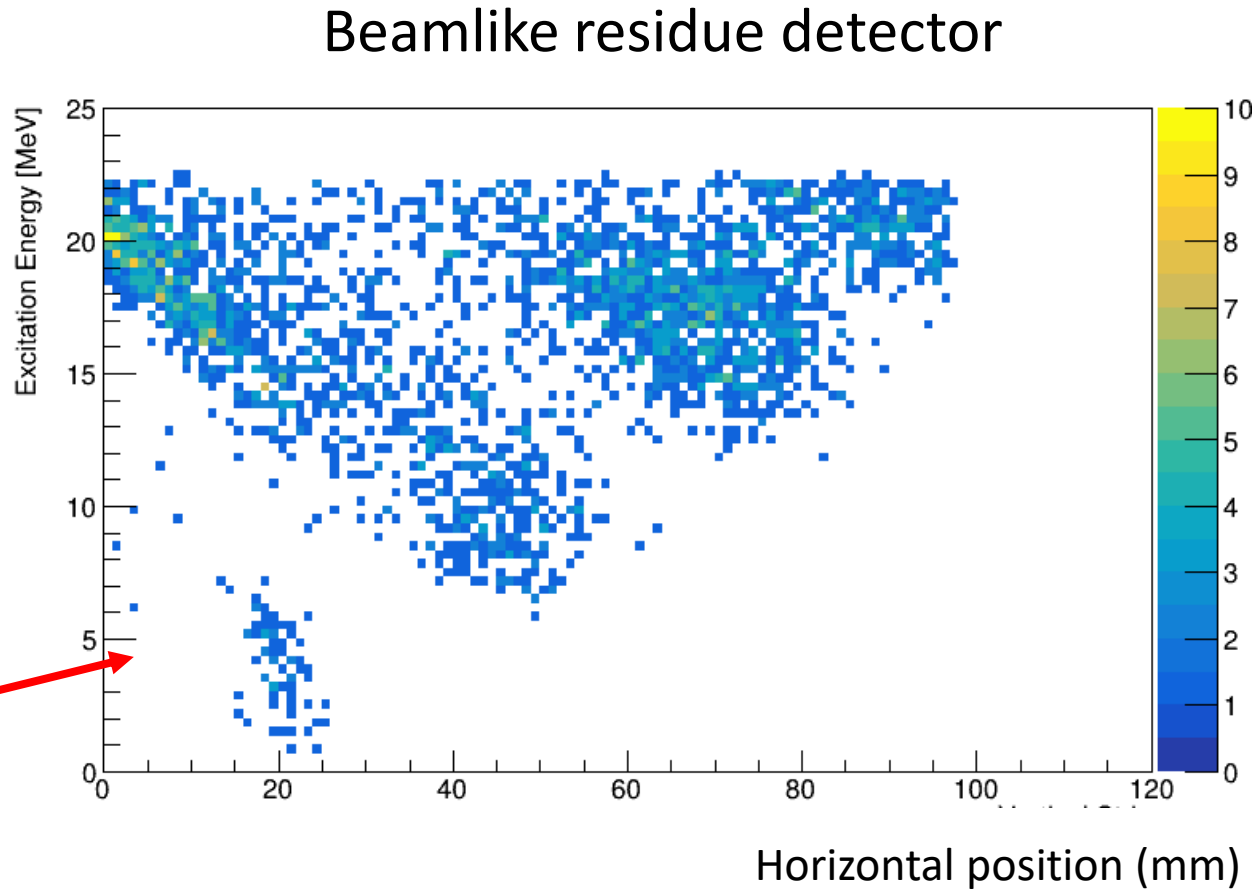




First time that fission is studied in a storage ring!

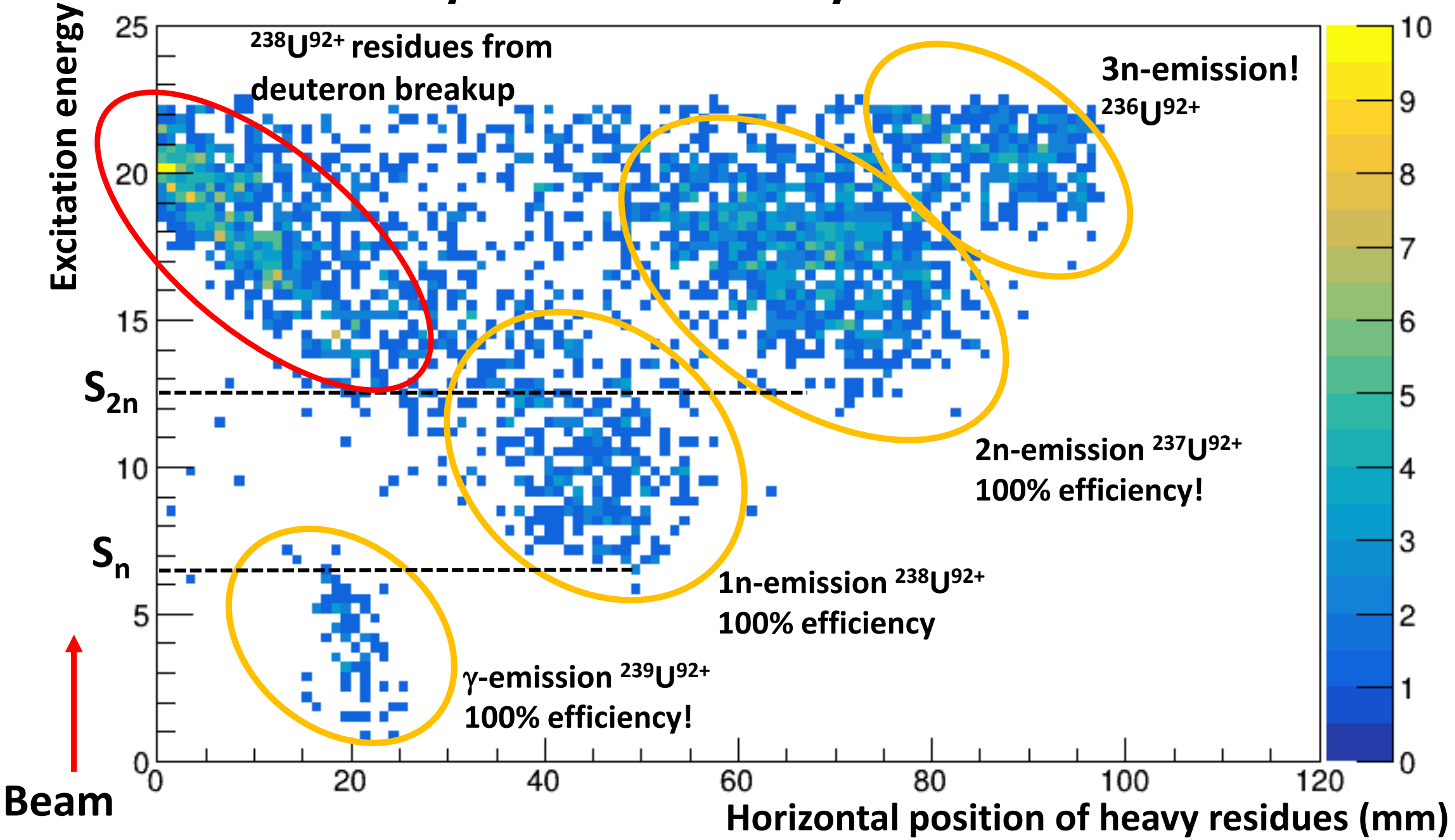
Preliminary results for heavy-residue detection 238U(d,p)





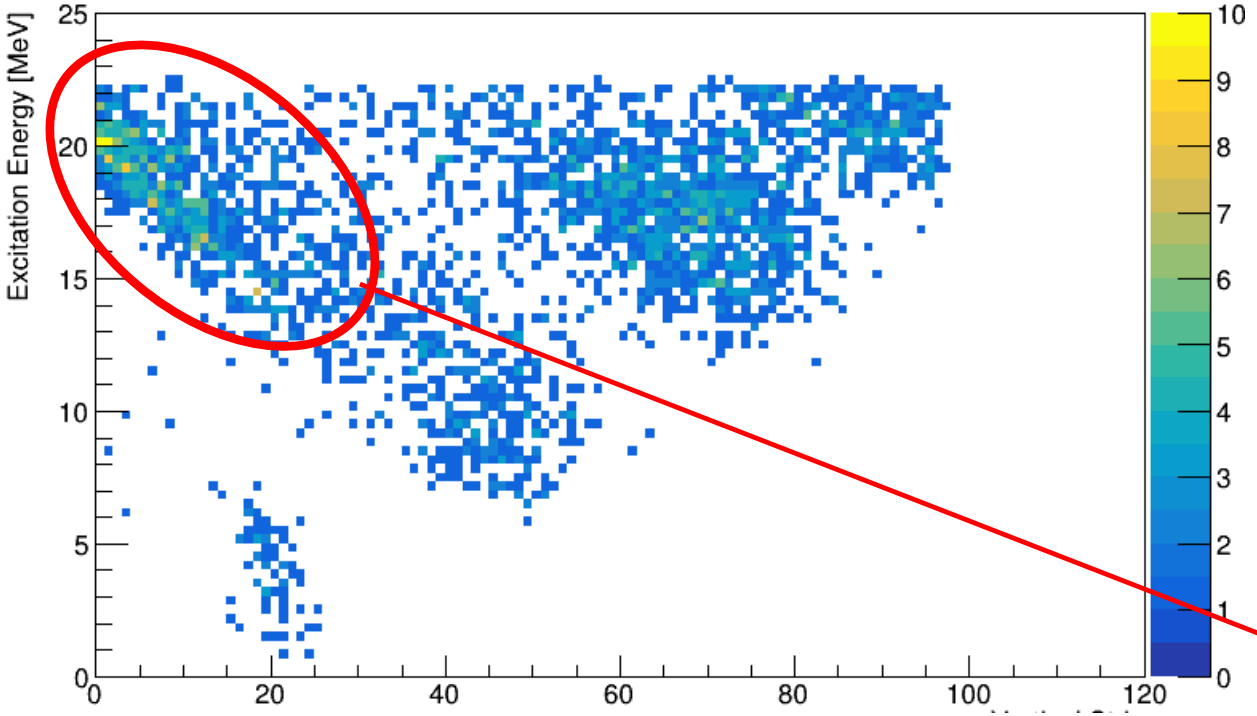
Analysis by Camille Berthelot & Boguslaw Wloch

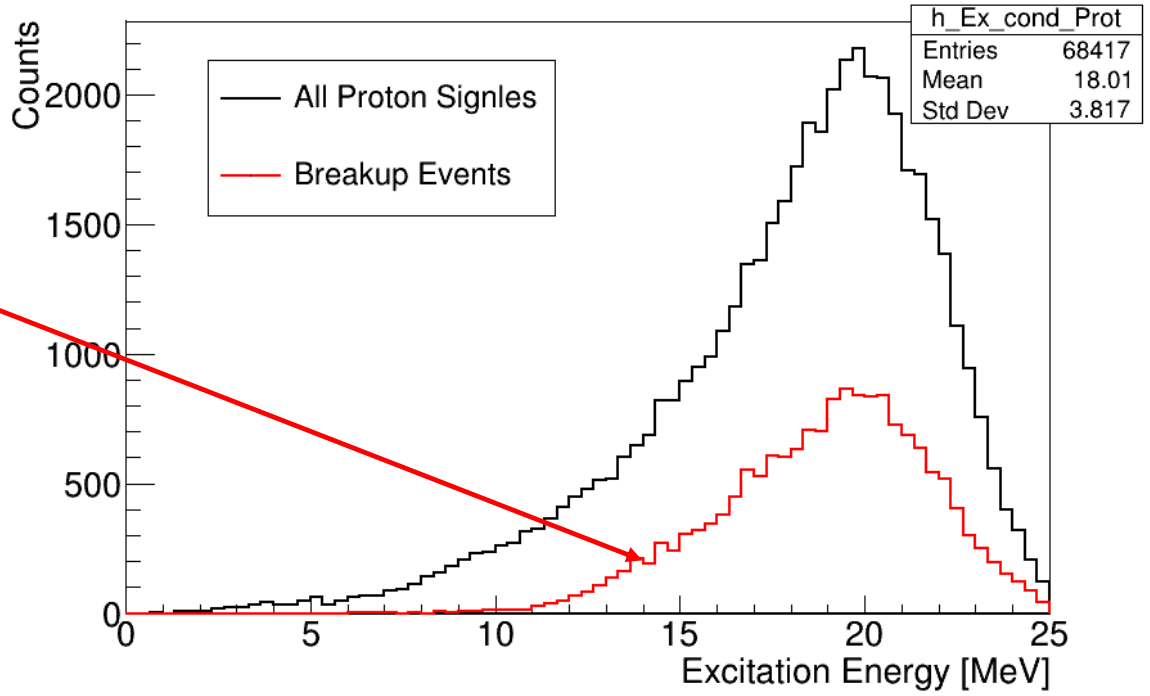
Preliminary results for heavy-residue detection



Correction of deuteron breakup events

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





Conclusions

- **Nuclear fission is important, many fissioning nuclei yet to be studied!**
- **Storage rings offer the ideal conditions to investigate the fission threshold, 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

- **Upgrade setup to make experiments with radioactive beams.**
- **Next experiment, infer n-induced reaction cross sections ^{205}Pb, see talk by Guy Leckenby!**

M. Sguazzin
PhD student,
Bordeaux

C. Berthelot
PhD student,
Bordeaux

G. Leckenby
Post-doc,
Bordeaux

B. Wloch
Post-doc,
Bordeaux

J. Pibernat
Engineer,
Bordeaux

M. Grieser
MPIK
Heidelberg

J. Glorius
GSI
Darmstadt

M. Sguazzin[1], C. Berthelot[1], B. Wloch[1], J. Pibernat[1], G. Leckenby[1], J. A. Swartz[1], M. Grieser[2], J. Glorius[3], Y. A. Litvinov[3], R. Reifarth[4], K. Blaum[2], P. Alfaurt[1], P. Ascher[1], L. Audouin[5], C. Berthelot[1], B. Blank[1], B. Bruckner[4], S. Dellmann[4], I. Dillmann[6], C. Domingo-Pardo[7], M. Dupuis[8], P. Erbacher[4], M. Flayol[1], O. Forstner[3], D. Freire-Fernandez[2], M. Gerbaux[1], J. Giovinazzo[1], S. Grévy[1], C. Griffin[6], A. Gumberidze[3], S. Heil[4], A. Heinz[9], D. Kurtulgil[4], S. Litvinov[3], B. Lorentz[3], V. Méot[8], J. Michaud[1], S. Perard[1], U. Popp[3], M. Roche[1], M.S. Sanjari[3], R.S. Sidhu[10], U. Spillmann[3], M. Steck[3], Th. Stöhlker[3], B. Thomas[1], L. Thulliez[8], M. Versteegen[1], L. Begue-Guillou[11], D. Ramos[11], A. Cobo[11], A. Francheteau[11], M. Fukutome[12], A. Henriques[13], I. Jangid[11], A. Kalinin[3], W. Korten[8], T. Yamaguchi[12]

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

Acknowledgements

This work is supported by the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (ERC-Advanced grant NECTAR, grant agreement No 884715).
NECTAR: Nuclear rEaCTions At storage Rings

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

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

This project has received funding from the European Union's Horizon Europe Research and Innovation programme under Grant Agreement No 101057511.