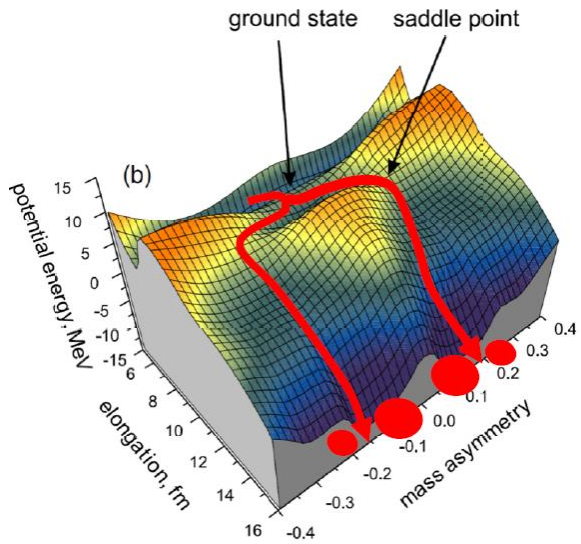
Fission studies in inverse kinematics : opportunities and perspectives

A. Lemasson
GANIL

IRL – NPA Kick Off Meeting 11th-13th December 2023

Fission Process



Key Open Questions :

Dynamical evolution of complex quantum system

At the crossroad of many research topics of nuclear physics with essential **interplay between structural and dynamical properties of nuclei.**

Fully microscopic description of the whole fission process (fissioning system, fission dynamics and fission fragment distributions and properties) is not yet available

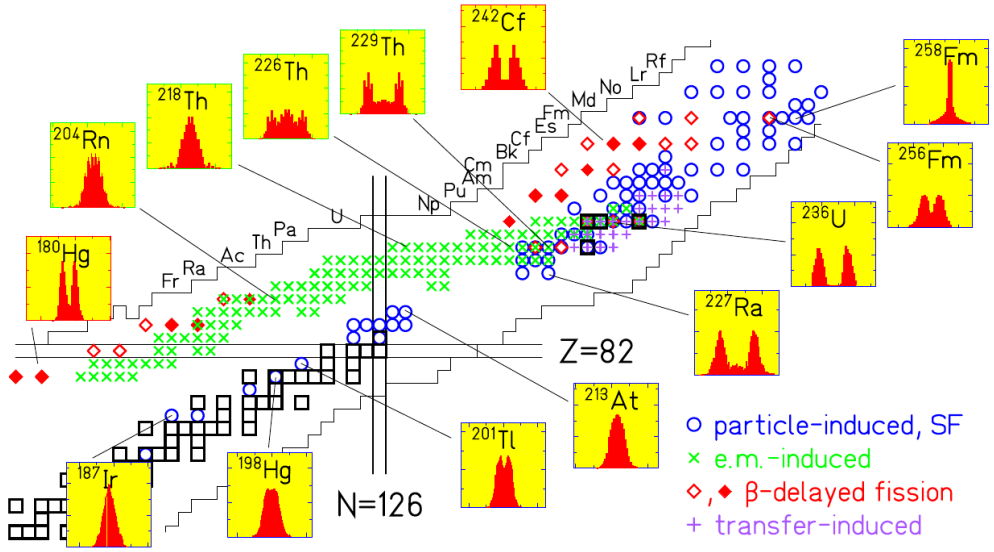
Relevant observables

- **Direct isotopic (A,Z) fission fragments data**
- **Complete fission yields**
  => Probing the role of shell effect in fission and dissipation
- **Kinetic energies and excitation energies of the fission fragments**
  => Probing the scission configurations (A, Z, Energy sharing)
- **Fission Barriers (evolution as function of excitation energy):**

=> Probing the potential energy surface as function of E*

=> Exploring the fission paths (different modes of fission)

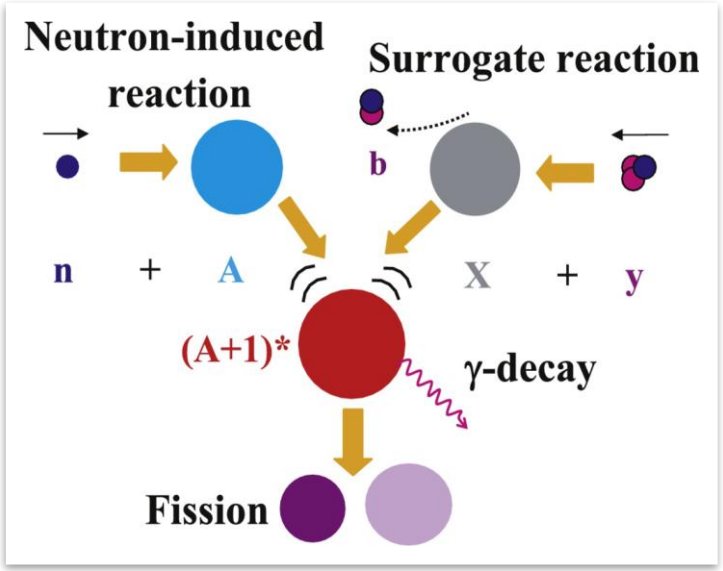
Changing N and Z content of fissioning systems



New experimental opportunities have revived the field of nuclear fission

New experimental techniques to measure Isotopic Fission (A,Z) Fragments yields
(compared to spontaneous or neutron-induced fission)

- Heavy ion reaction induced fission
  (fusion, transfer, inelastic excitation, …)



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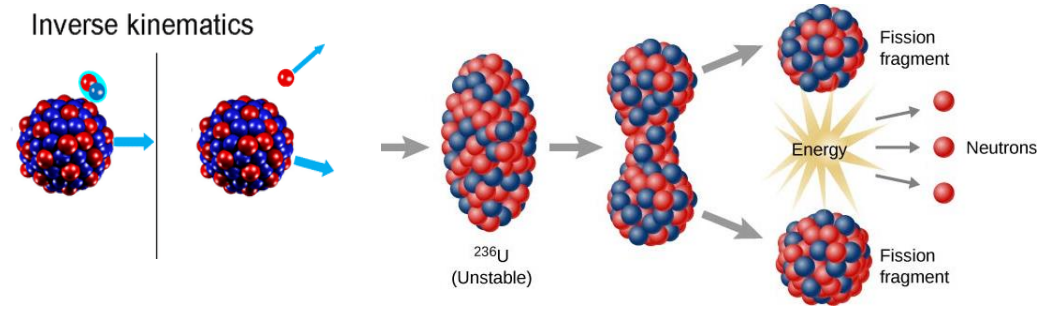
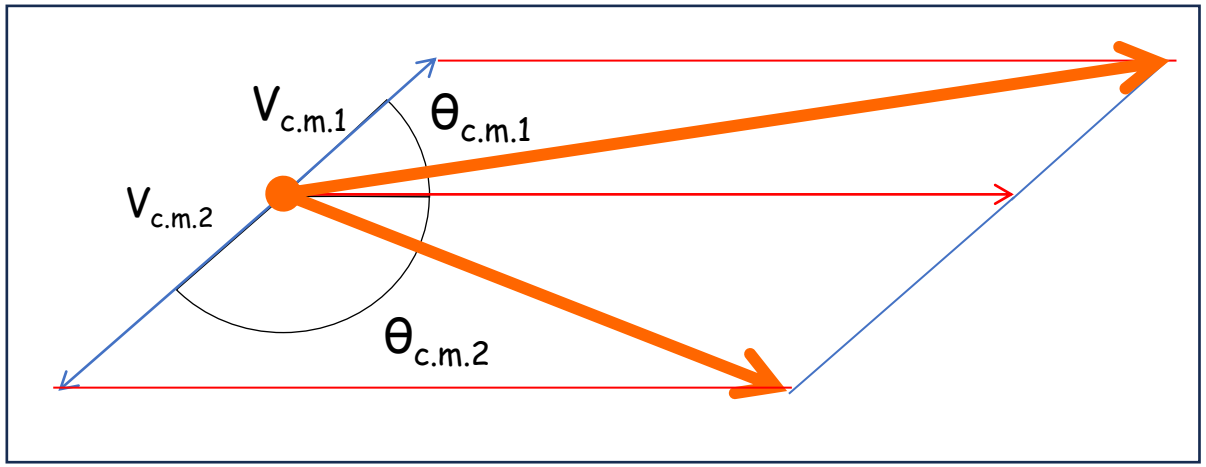
Inverse kinematics fission
Heavy beams + light target → Fission in motion / flight





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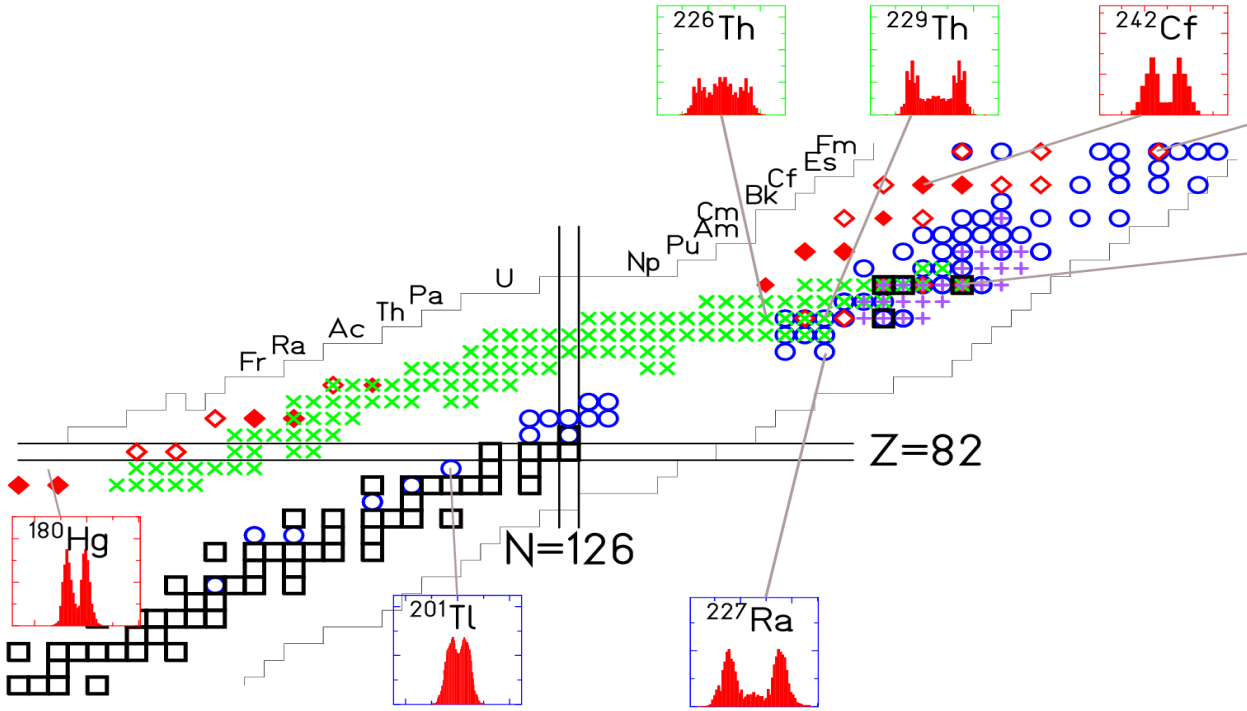
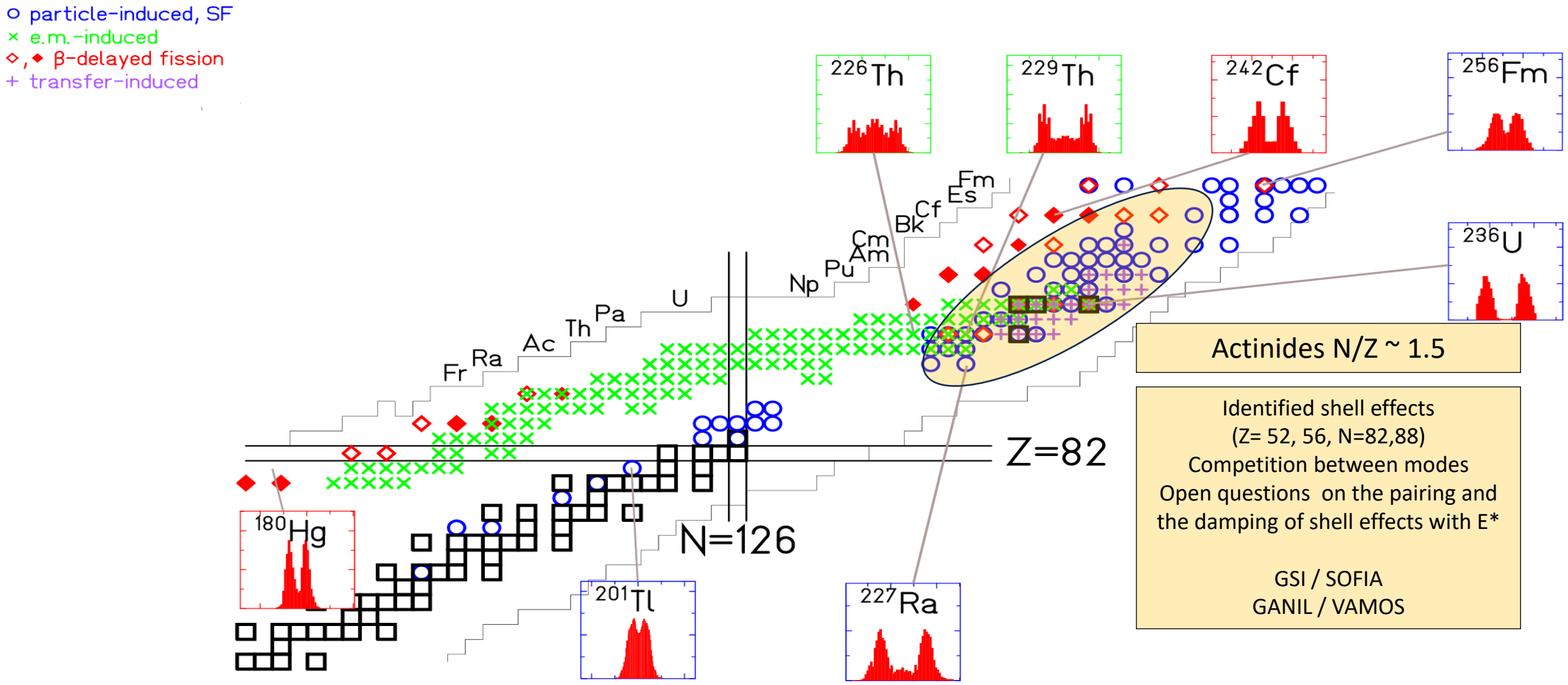
=> New Opportunities

- Range of fissioning systems (A, Z, Excitation Energy domain)
- Isotopic Identification of fission Fragments **(A_{ff}, Z_{ff}, q_{ff})**
- Complete kinematics (2v methods)



Exploring the fission landscape



Actinides N/Z ~ 1.5

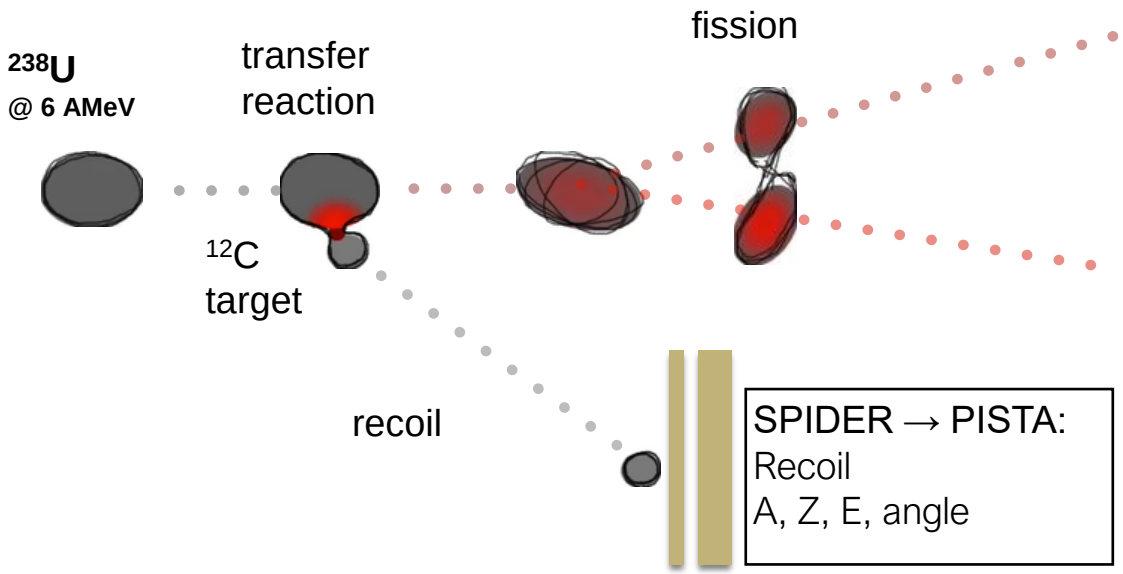
Identified shell effects
(Z= 52, 56, N=82,88)
Competition between modes
Open questions on the pairing and the damping of shell effects with E*

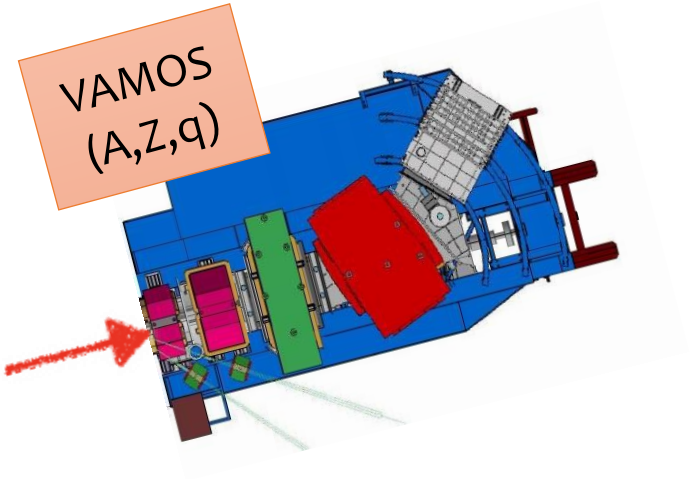
GSI / SOFIA
GANIL / VAMOS

Fission in inverse kinematics at VAMOS/GANIL

Inverse Kinematic using beams of ^{238}U around Coulomb Barrier

⇒ Access to « exotic » fissionning systems heavier than ^{238}U





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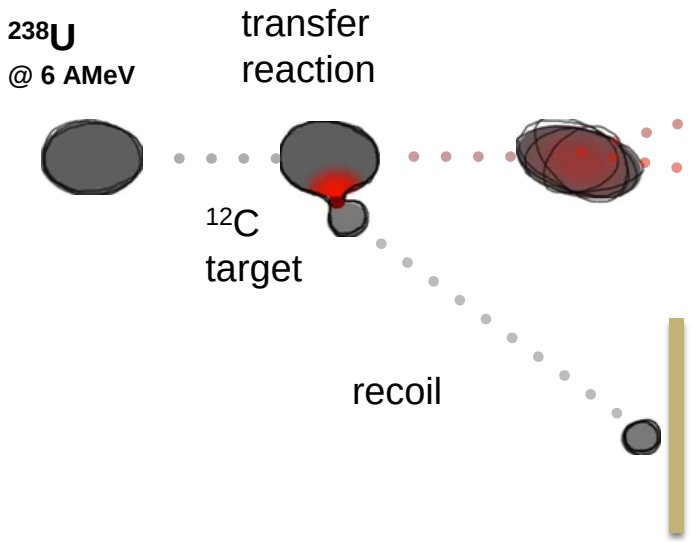
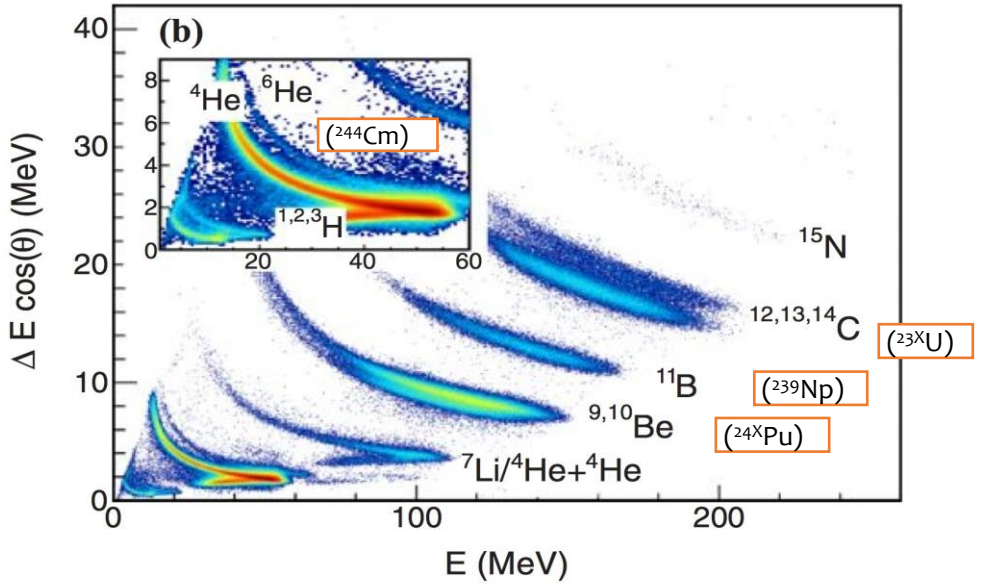


SPIDER → PISTA:
Recoil
A, Z, E, angle

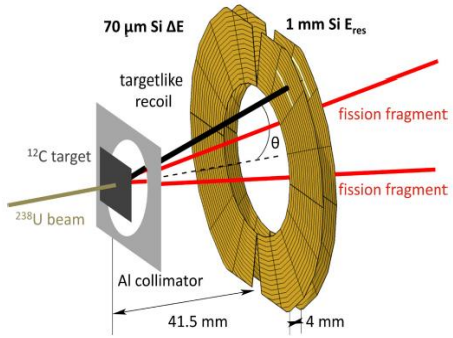


The reconstruction of the binary reaction gives kinematical information and the identification of the fissioning system

Surrogate reactions
(transfer induced fission)

⇒ Selection of the fissionning system

⇒ Measurement of the excitation energy



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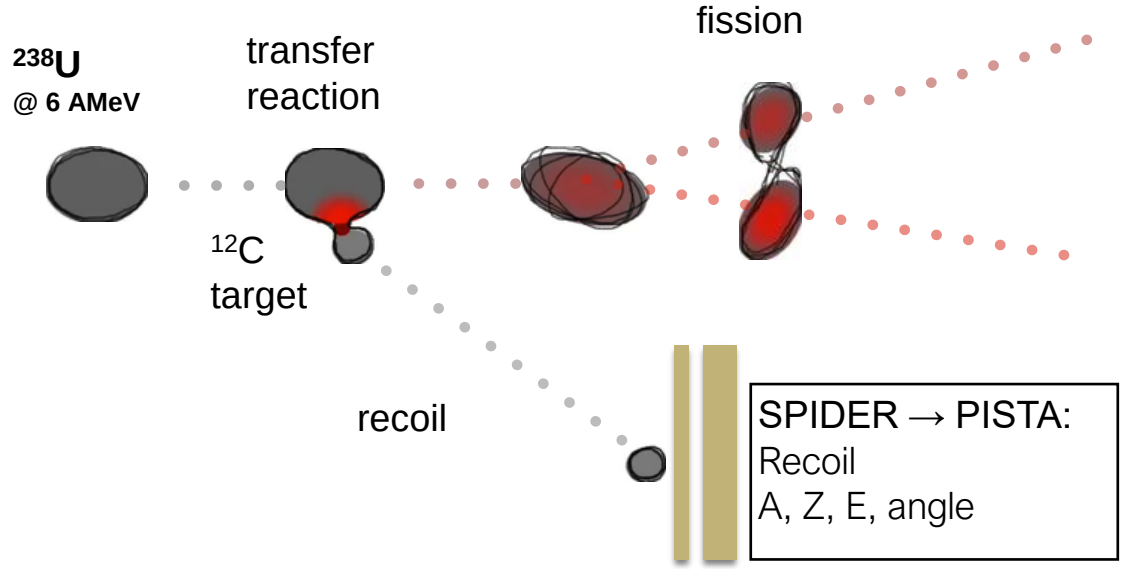

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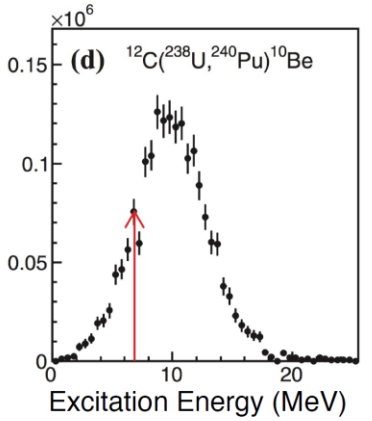
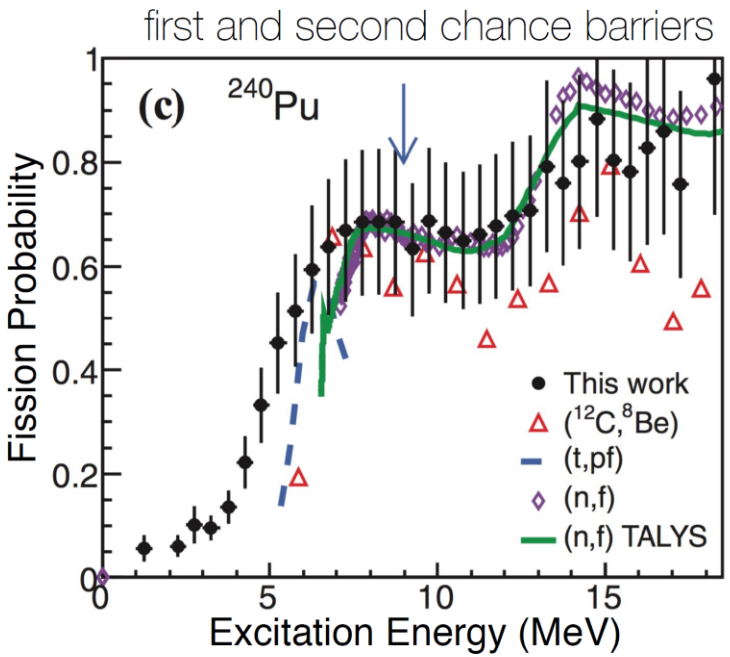


C. Rodríguez. Tajes et al., PRC 89 (2014) 024614

first and second chance barriers



The reconstruction of the binary reaction also provides information on the fission barrier

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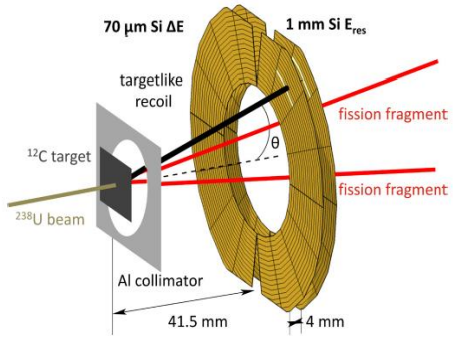

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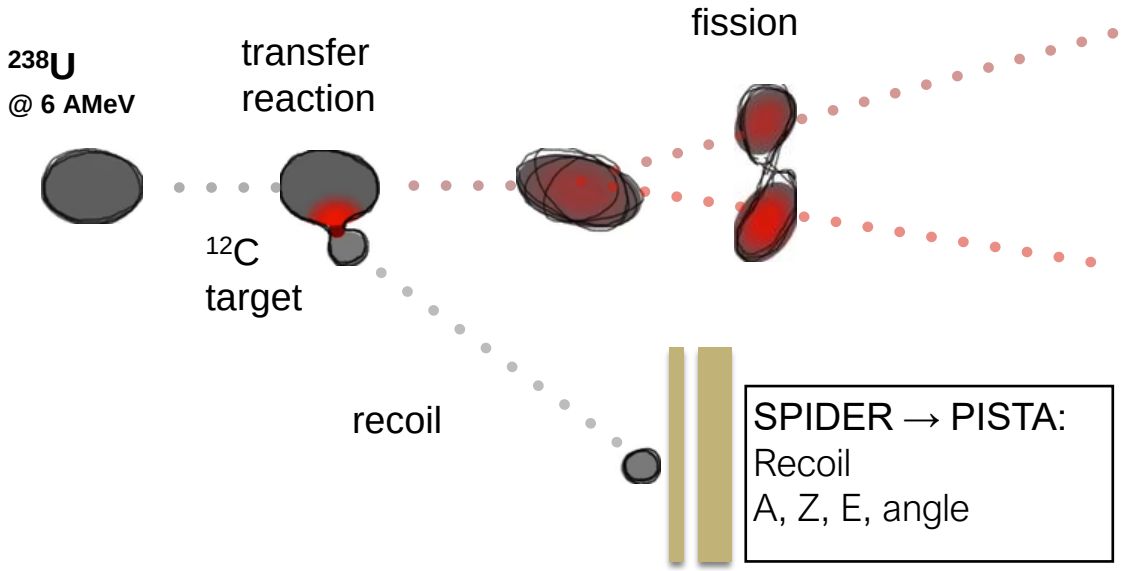

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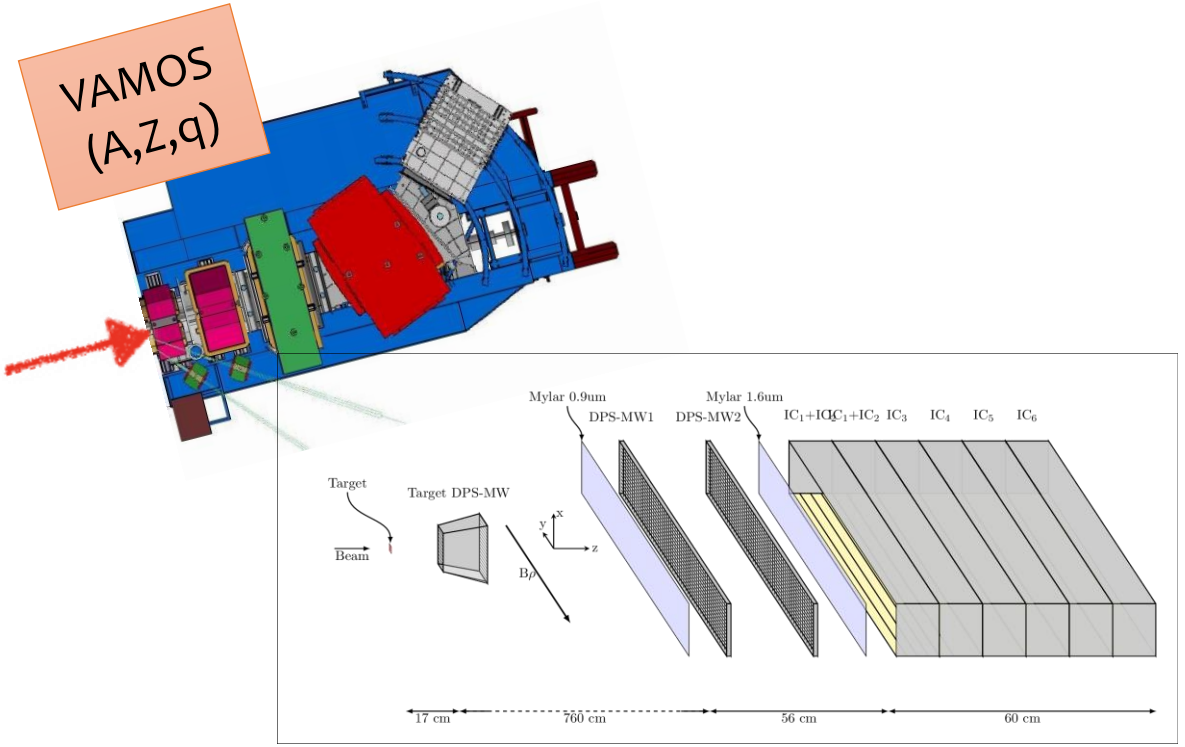

VAMOS Magnetic Spectrometer

⇒ Direct and Complete isotopic fission fragment yields

Precise center-of-mass fission fragment velocities isotopically (due to Coulomb barrier energies)

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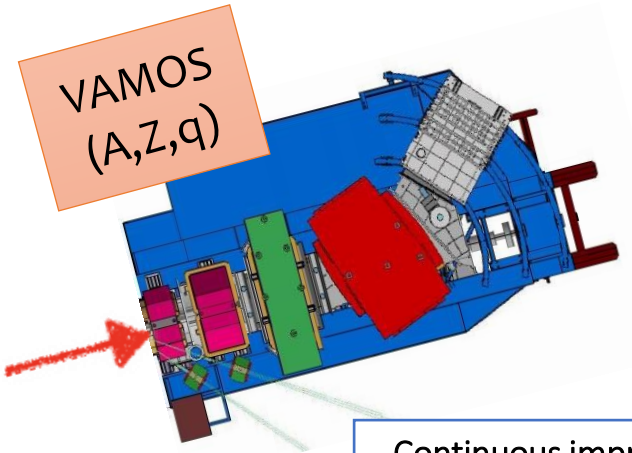
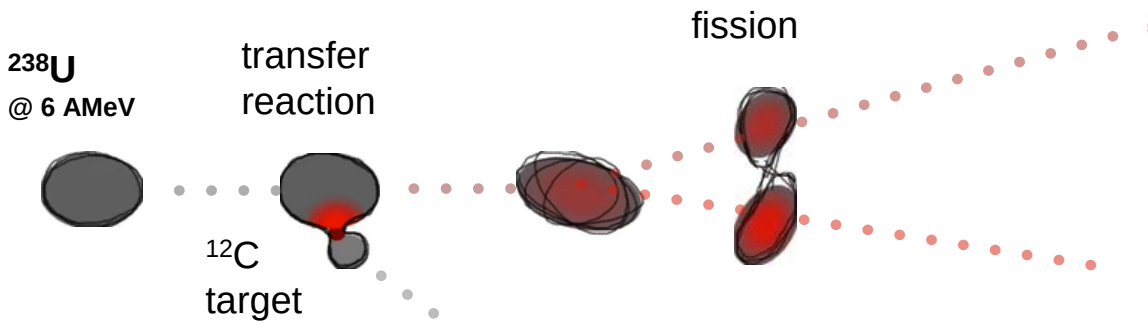
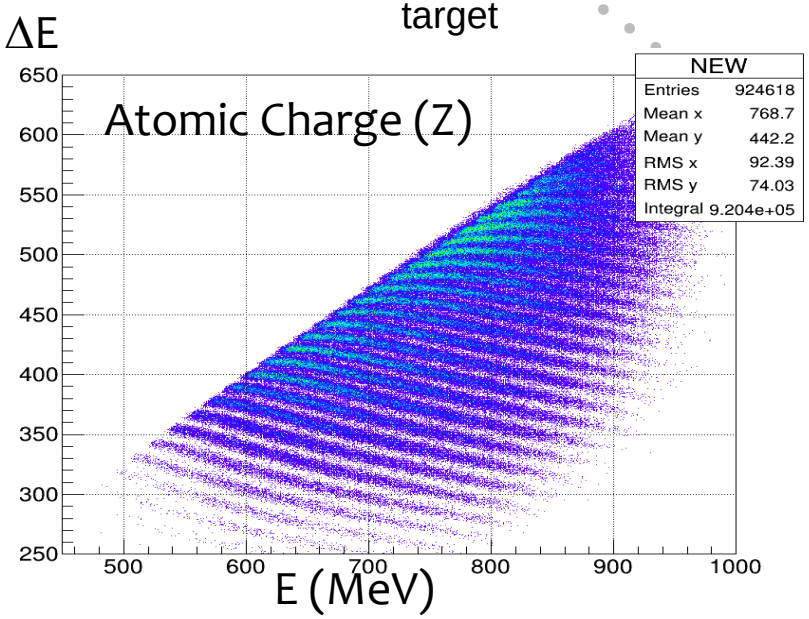
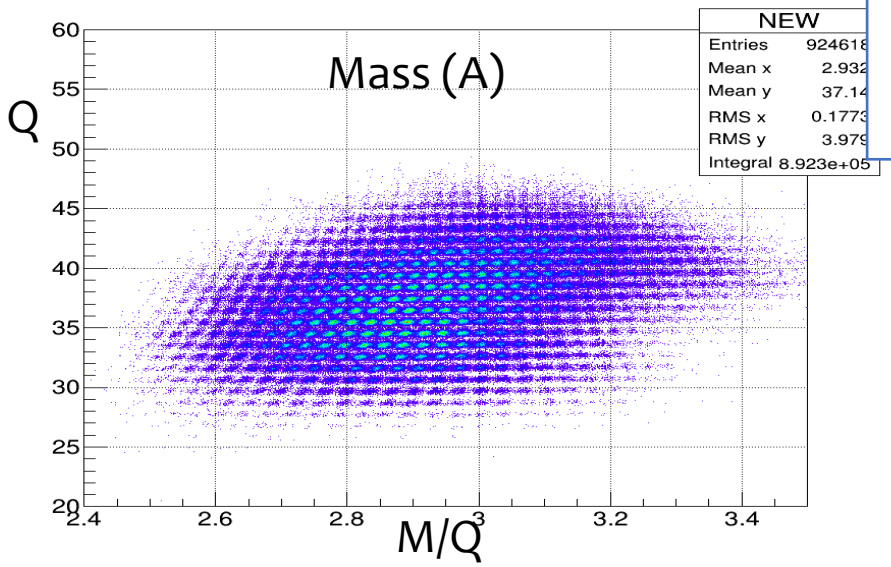




- Continuous improvement of detection/electronics
Rejmund et al. NIMA 2011,
Vandebrouck et al. NIMA 2016,
Kim et al. EPJA 2017
- Trajectory Reconstruction Methods
A. Lemasson, M. Rejmund NIM. A (2023)

ΔA/A ~ 5e-3
ΔE/E ~ 1,2%





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Sample of results from VAMOS@GANIL for actinides

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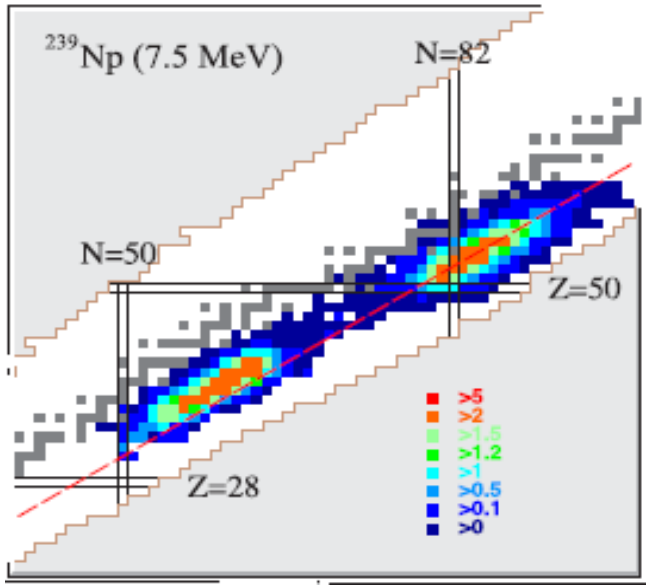

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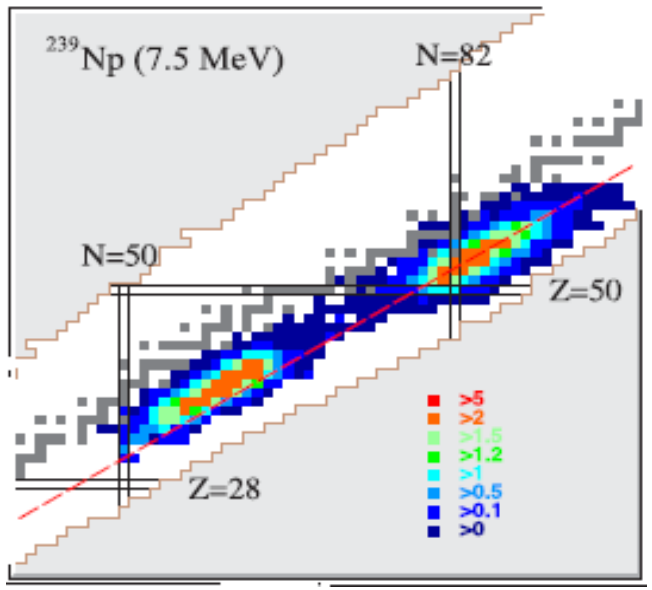

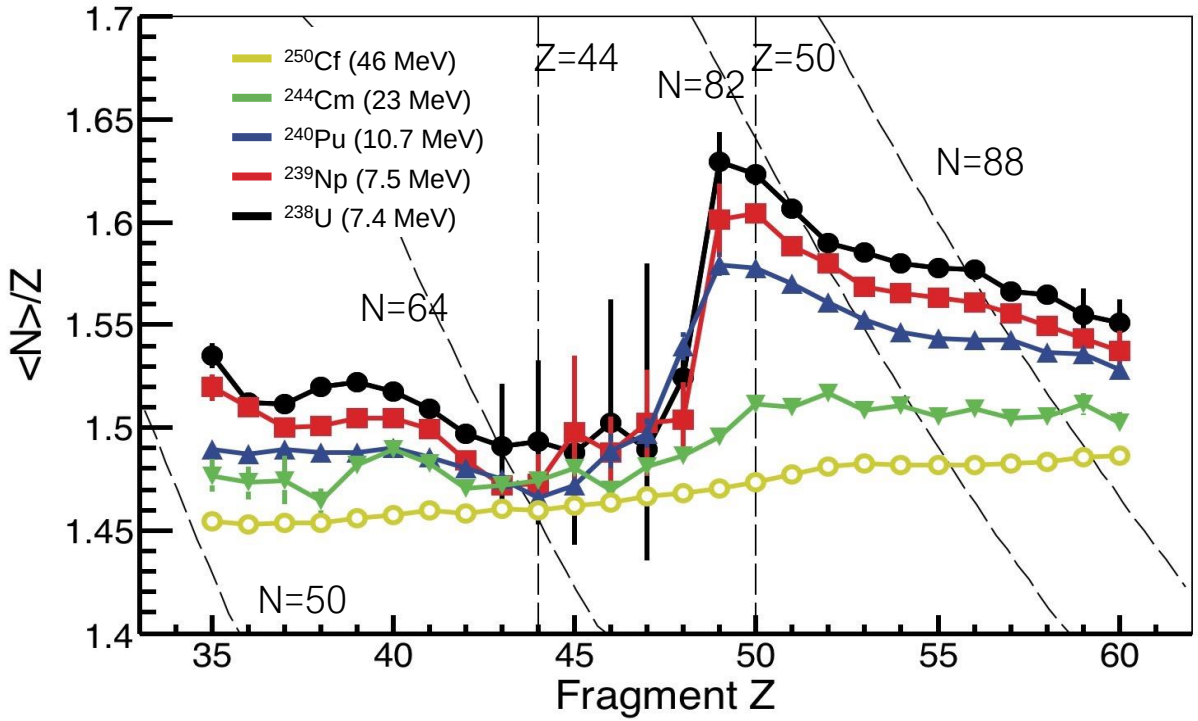

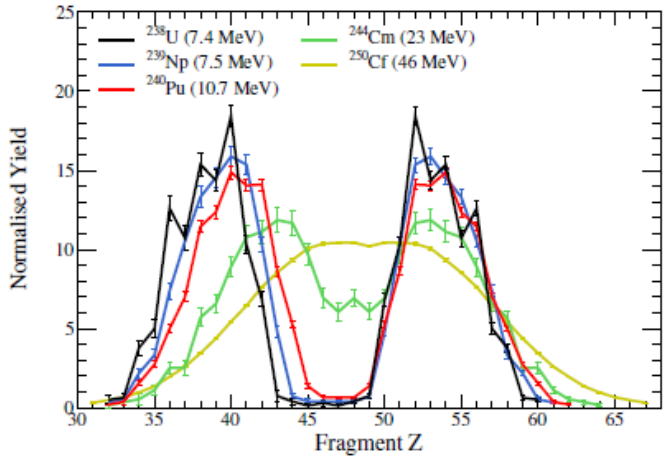

✓ Unique *Z* identification
→ **proton e-o staggering**
→ **pairing in fission**

✓ Same available for *N*

→ **Favored *N* or Z numbers?**
→ **Connection with known shells?**
→ **Washing out with E*?**

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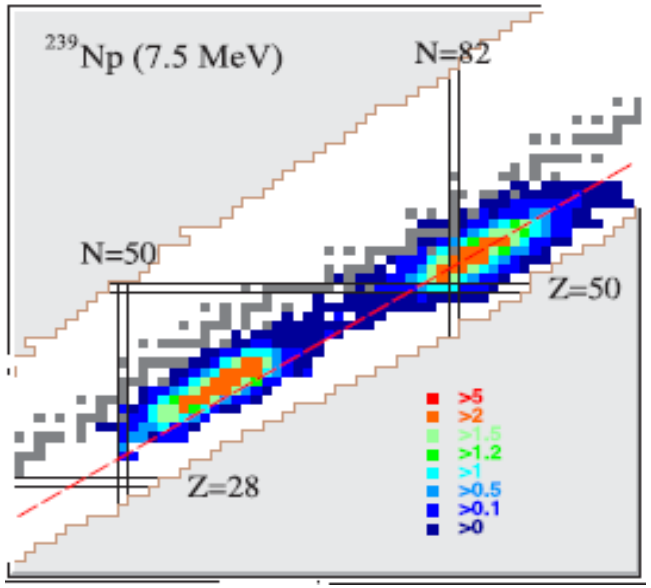
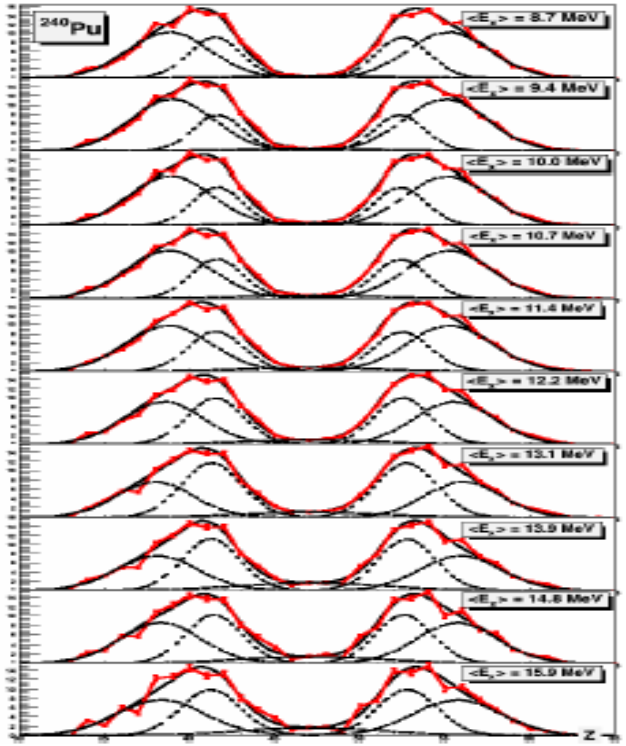
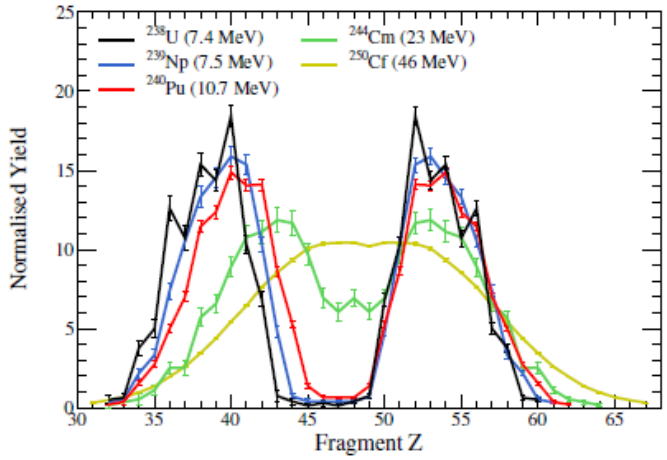


Fission mode dependence on E^* for a specific (A_{CN}, Z_{CN})





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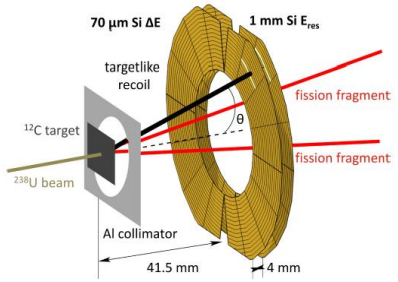
Much more in:

Camaano et al.,
PRC 88, 024605 (2013);
PRC 92, 034606 (2015),
Ramos et al.,
PRC 97, 054612 (2018);
PRC 99, 024615 (2019),
PRC 101, 034609(2020),
PRL 123, 092503(2020),
PRC 107, L021601 (2023)

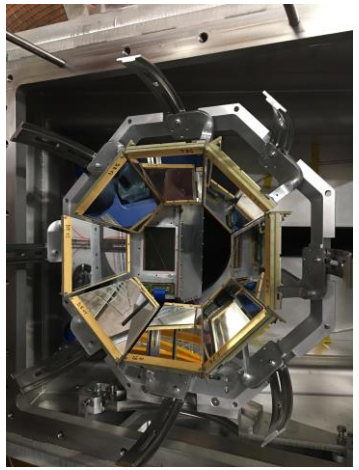
Also : **observable at scission, TKE, neutron evaporation, …**

Moving from SPIDER to PISTA

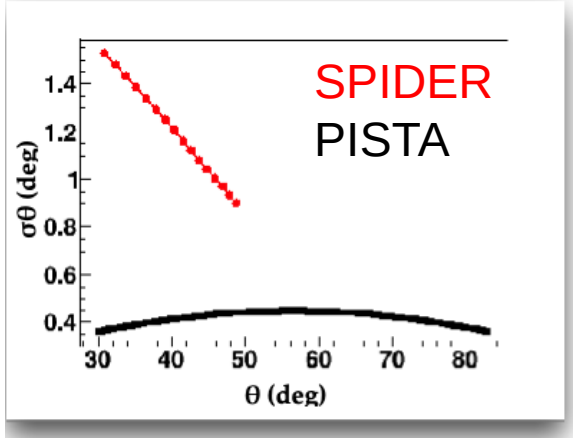
SPIDER



PISTA

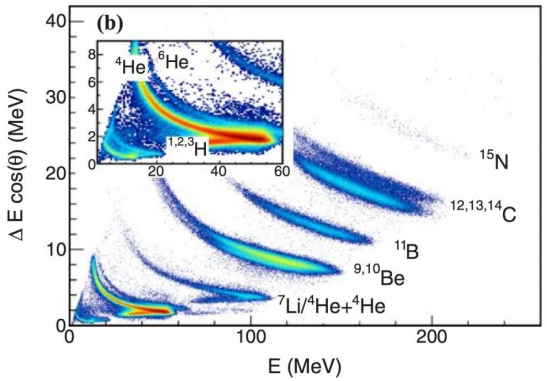


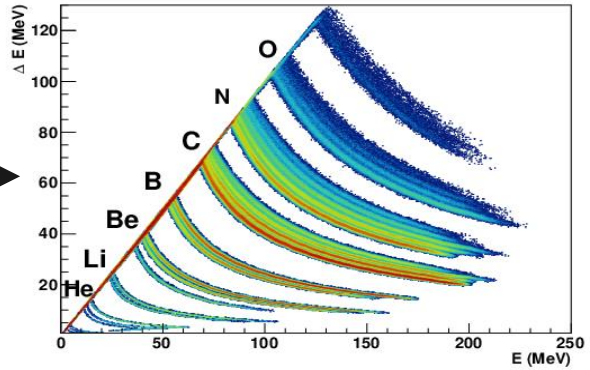
Higher Segmentation =>
Excitation Energy Resolution ~ 1 MeV

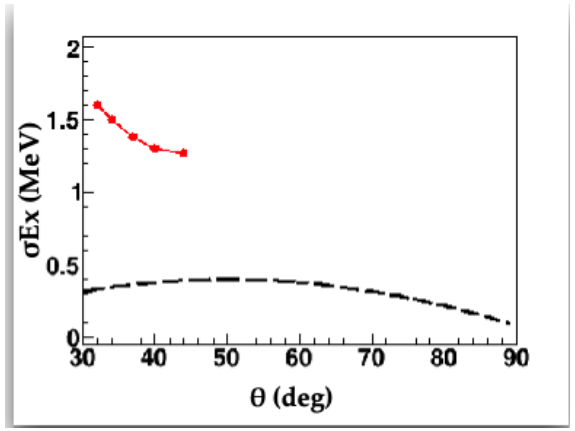


Particles Identification

SSD Silicon Detectors
ΔE => 100um /92 strips /(0,6mm)
E = > 1 mm /57 strips /(1,2 mm)





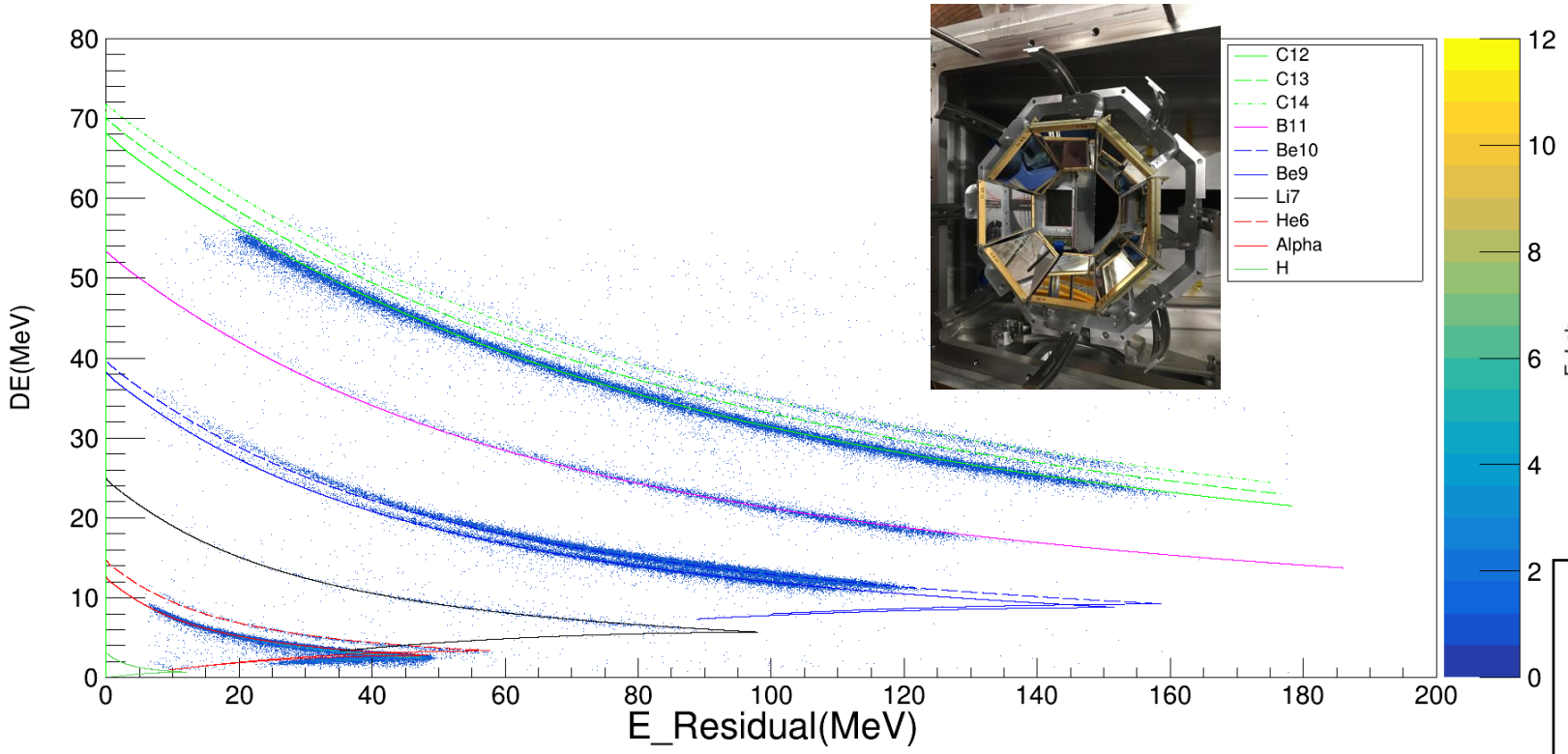


- Higher particle-identification capabilities
- Higher energy resolution (2.5 MeV → **0.7 MeV**)
- Larger angular coverage

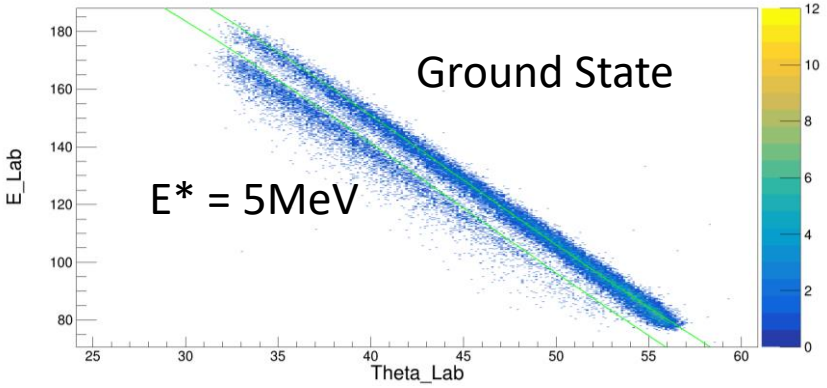
Experimental Campaign 2023-2024
$^{238}U+^{12}C, ^{232}Th+^{12}C$ - Collaboration GANIL/CEA-DAM

PISTA – June 2023 - Preliminary

^{238}U (5.9 MeV/U)+^{12}C
Collaboration PISTA GANIL/CEA-DAM



^{238}U(^{12}C,^{12}C')^{238}U'
Elastic + Inelastic Kinematics



Experimental Campaign
^{238}U + ^{12}C (2023-2024)
^{232}Th + ^{12}C (2024)

- Large variety of Fission Fragment Yields Y(A,Z,E*)
- Population of same nucleus under different entrance channel

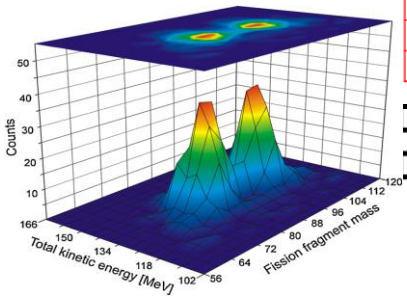
PhD Work of L. Begué Guillou (GANIL)

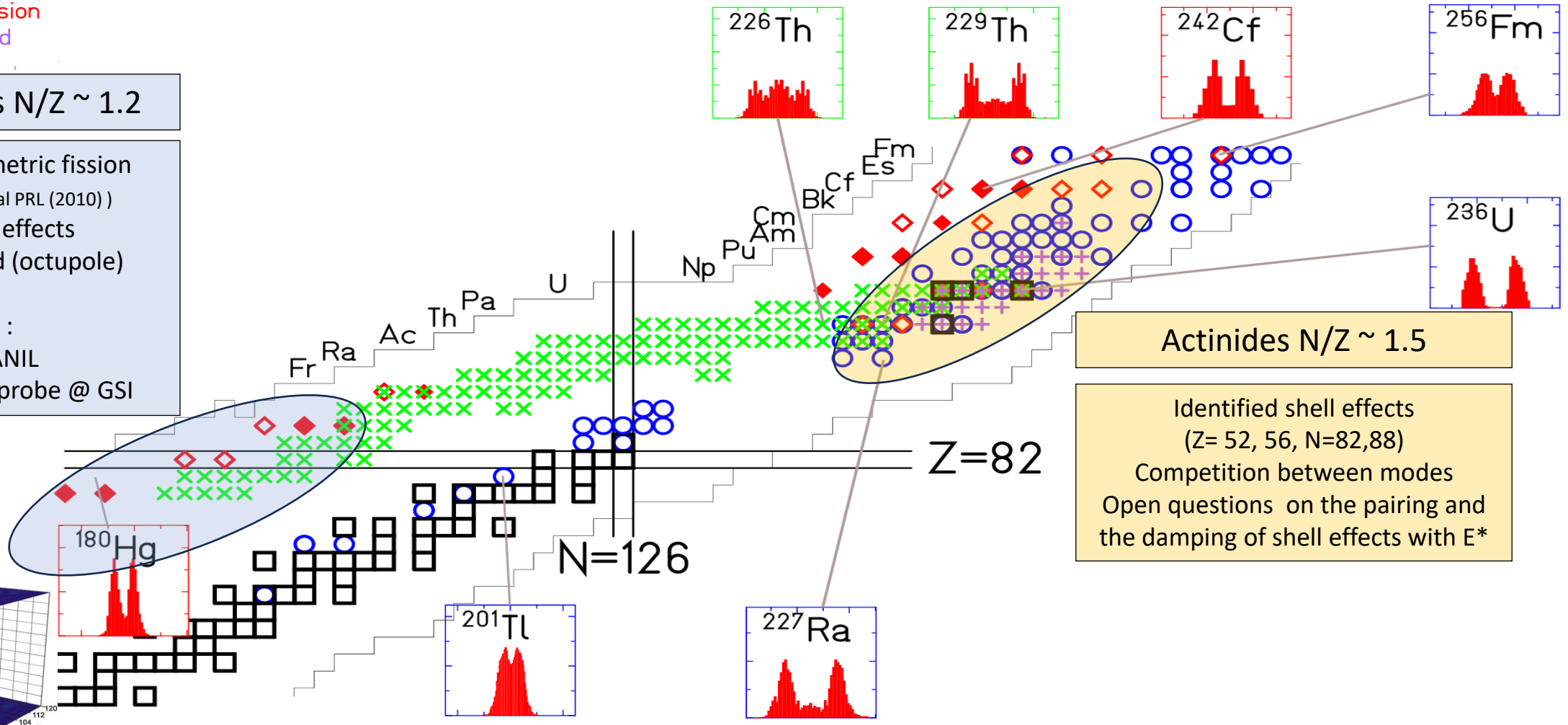
Exploring further the fission landscape

o particle-induced, SF
× e.m.-induced
◇,◆ β-delayed fission
+ transfer-induced

Pre-Actinides N/Z ~ 1.2

Unexpected Assymetric fission in ^{180}Hg (Andreiev et al PRL (2010))
=> New stabilizing effects at Z ~ 36 deformed (octupole) configuration
Ongoing programs :
- Fusion Fission GANIL
- Electromagnetic probe @ GSI





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Fission of pre-actinides

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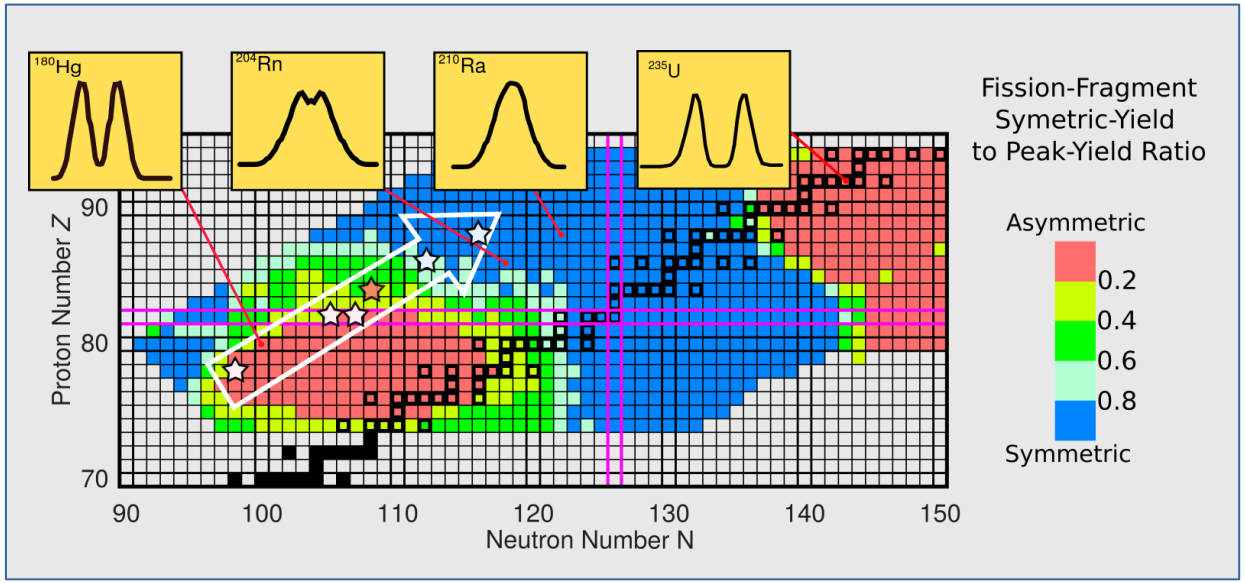
Island of Assymetric Fission and competition between assymetric and symmetric fission



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Experimental opportunities

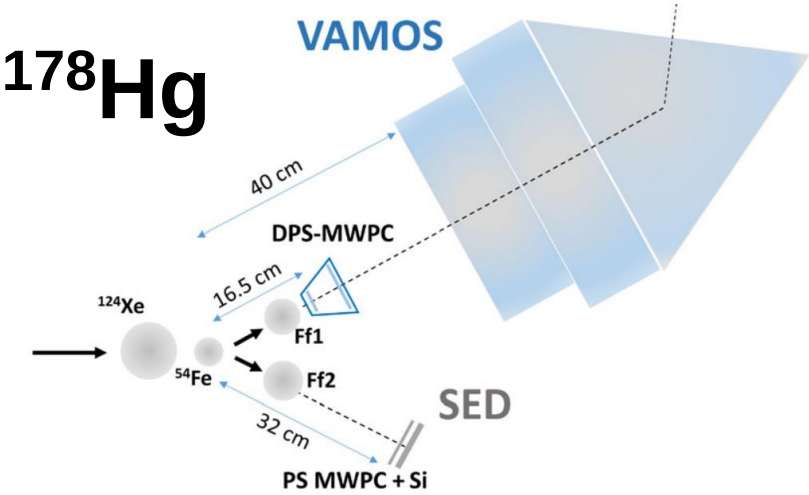
Isotopic identification in VAMOS Y(A,Z)

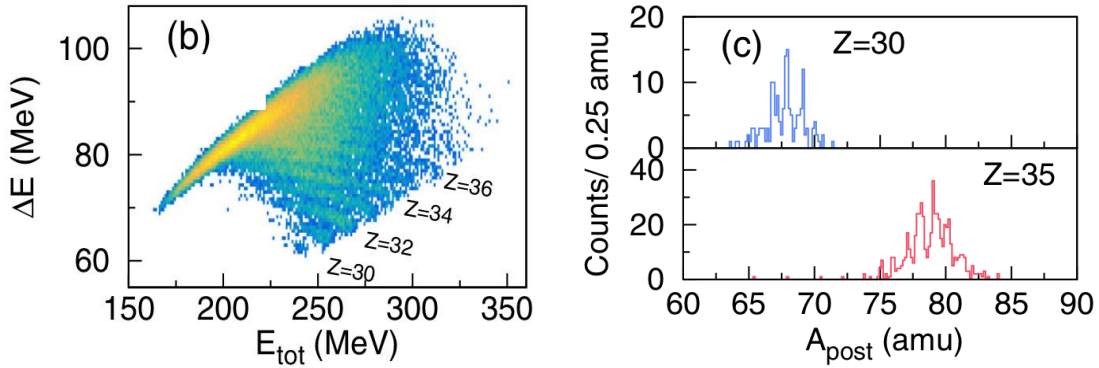
Very Different N/Z compared to actinides

Second Arm (2v method) : A_{pre}, Mn

Challenges : Low Energy of recoils, Low Cross sections

^{178}Hg





C. Schmitt et al. PRL 126, 132502 (2021)
A. Jinghan et al. PRC 2022

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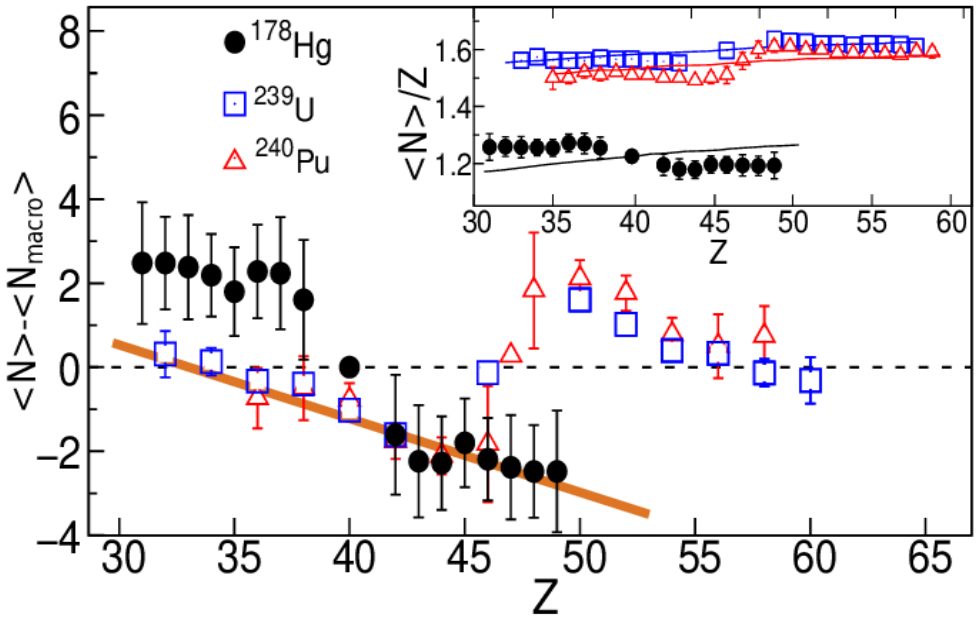

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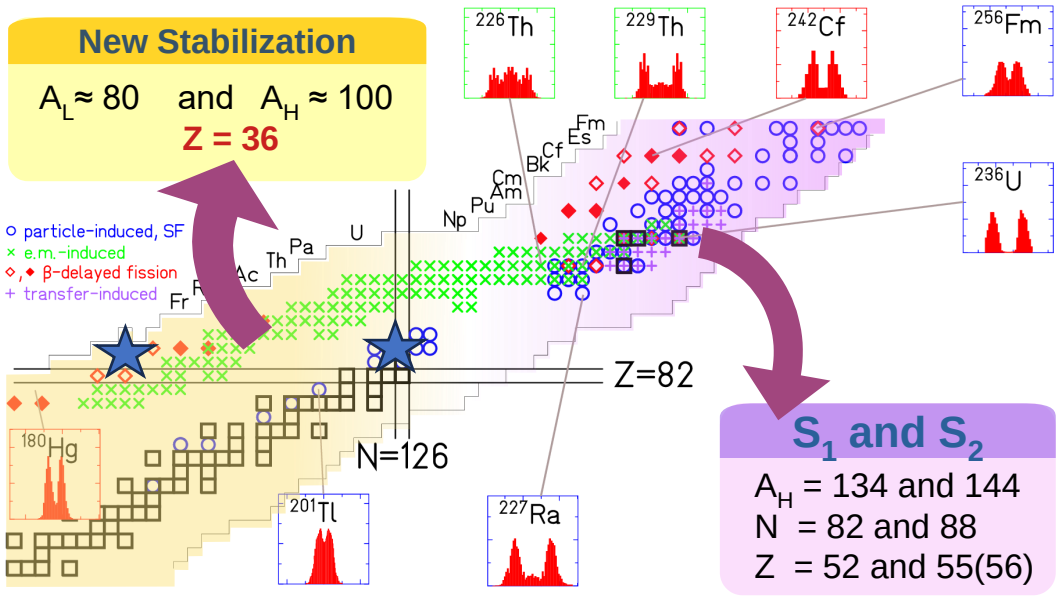
Low Cross sections

« Universal » driving effects of protons from pre-actinide to actinides ?

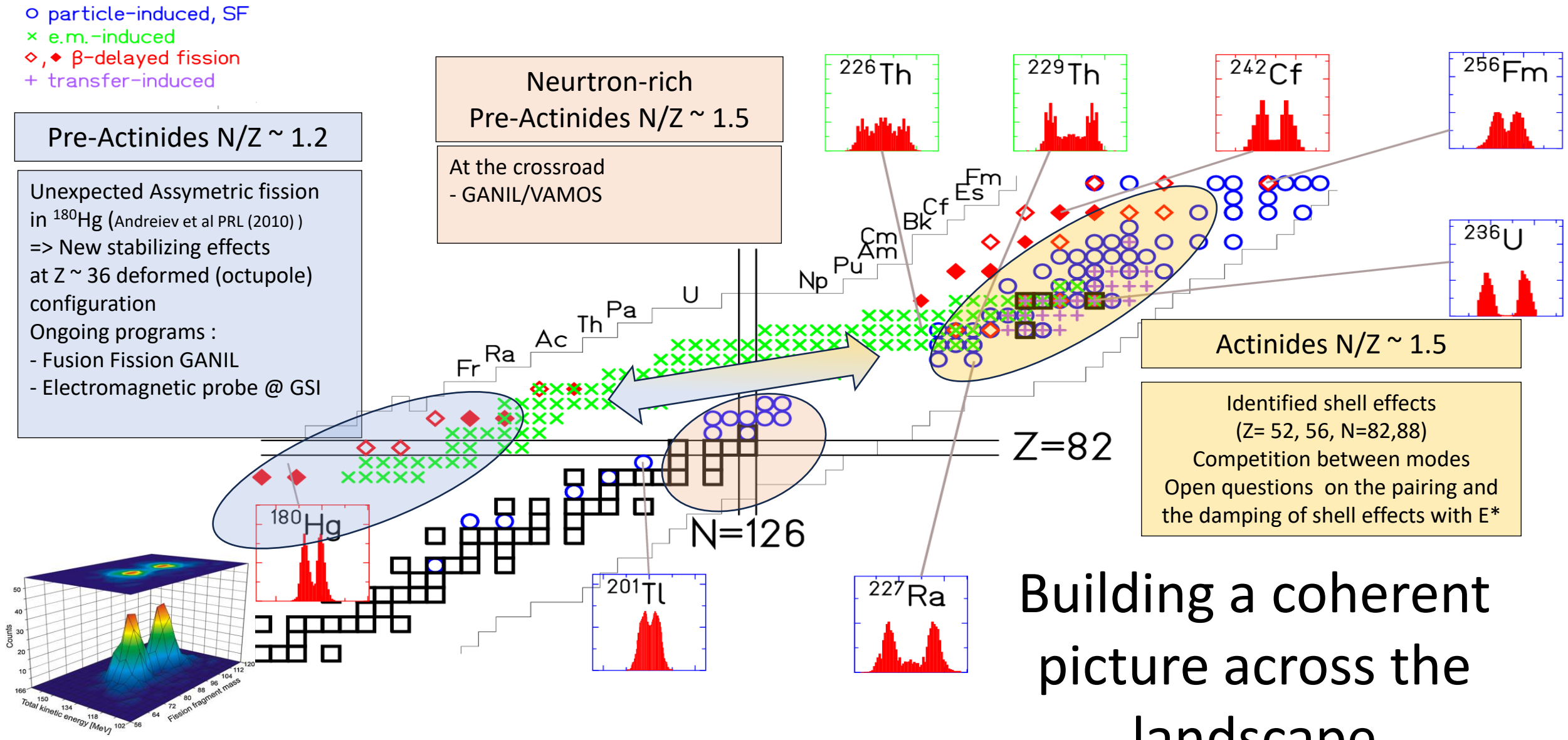


Experimental Program :

- ^{124}Xe+^{68}Zn → ^{192}Po (N/Z = 1.29) (2024)
- ^{206}Pb+^{4}He → ^{210}Po (N/Z = 1.5) (2025 ?)

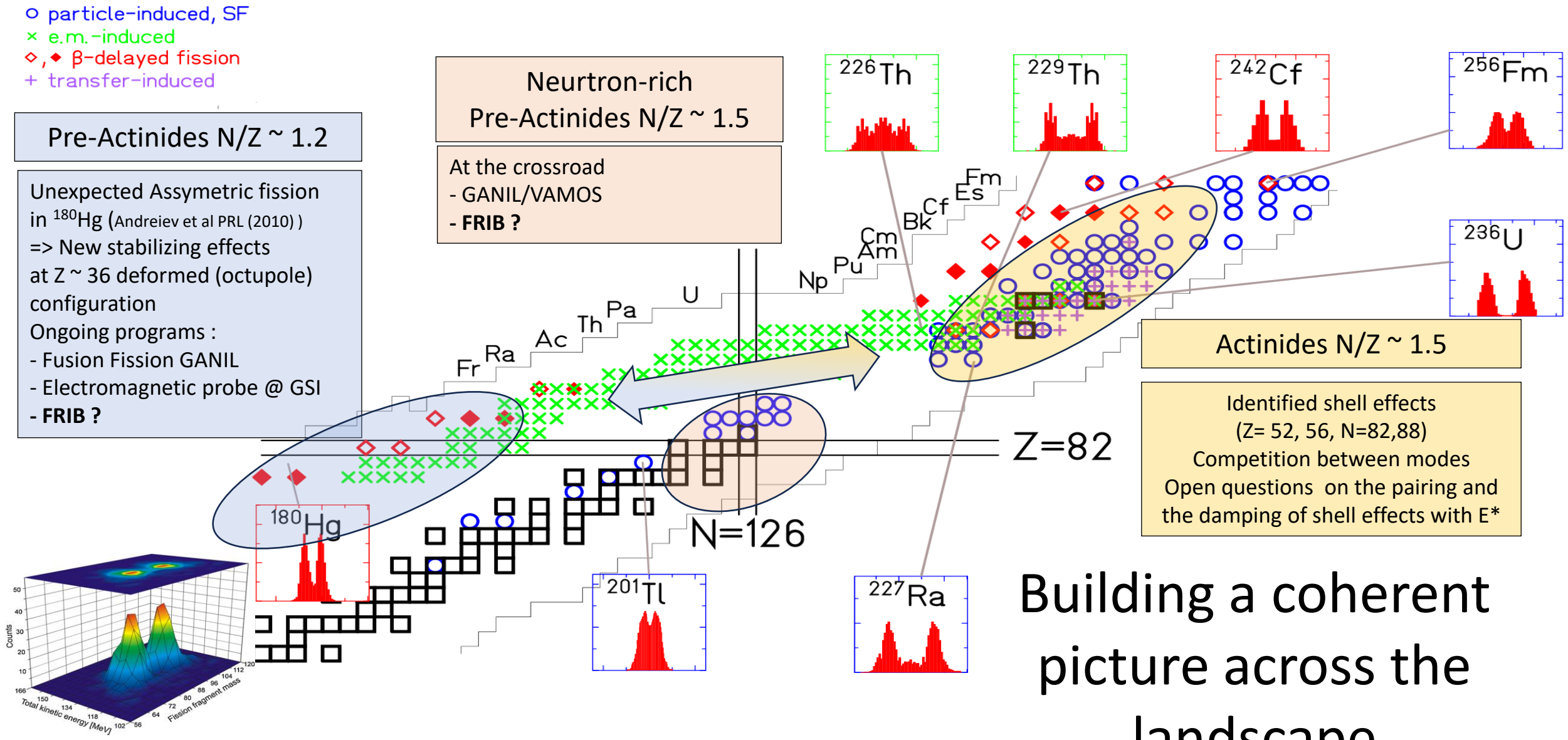
Gaz cell Target => Low E*, Inverse Kinematics+

Exploring further the fission landscape



Building a coherent picture across the landscape

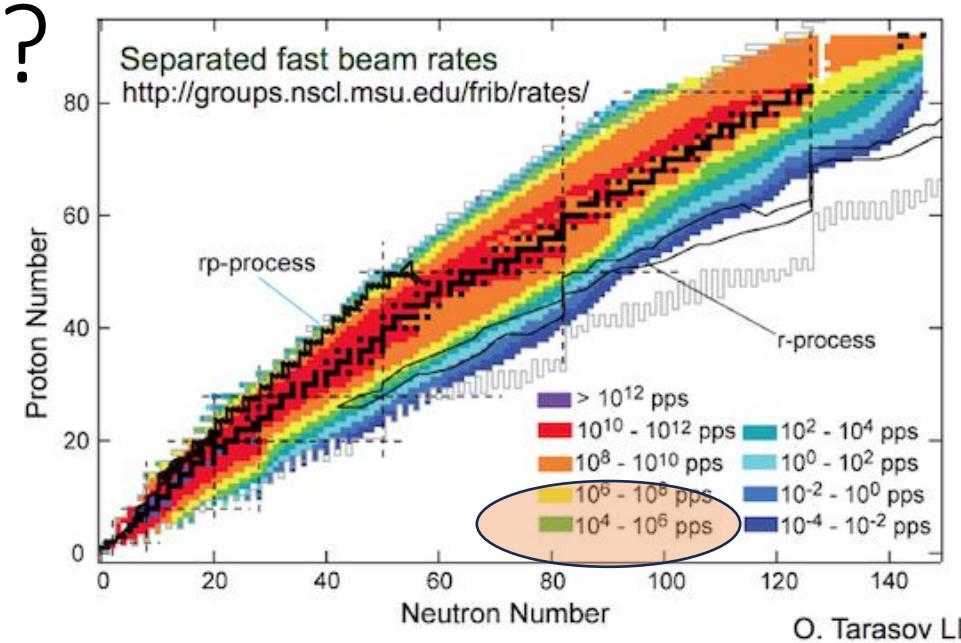
Exploring further the fission landscape



Building a coherent picture across the landscape

Fission studies with FRIB beams?

- $^{238}U/^{208}Pb$ fast fragmentation beams at FRIB
- (p,2p f) reactions
  - 1-10 mb cross sections
  - proton tracking
    => excitation energy measurement
- Fragments measurements
  (Large acceptance spectrometer (HRS ?), one fragment + second fragment velocity, neutrons ?)
  - Fission (A,Z) yields
  - Kinematical (de)-focussing to get 2v method for pre-evaporation yields
  - Neutron evaporation/TKE determination
    (2v Method) improved with respect to SOFIA/GSI
- Open question : which complementarity with present and future programs at GSI/FAIR (SOFIA/NECTAR) and RIKEN ?
- Theoretical/Experimental synergies



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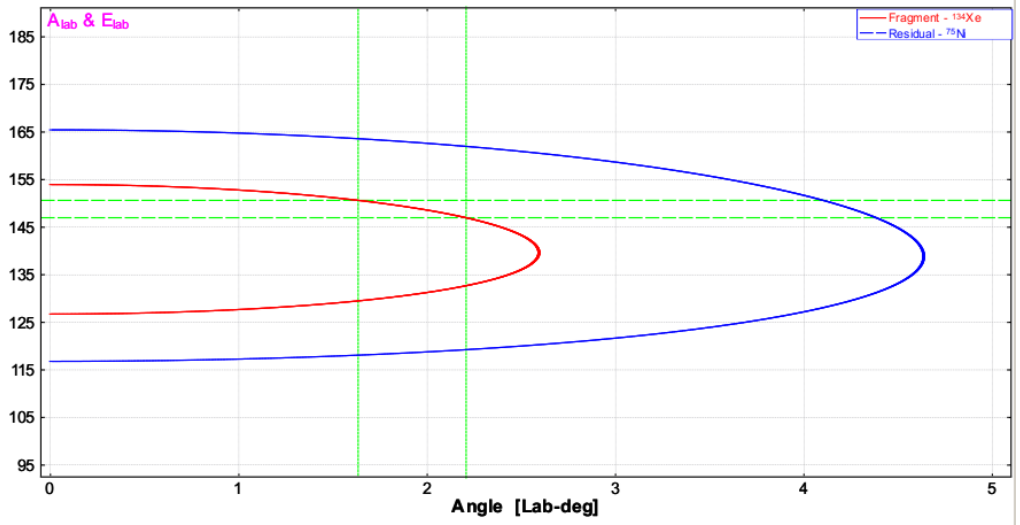

Summary and Outlook

- The field of nuclear fission was revitalized under the impulsion of new experimental methods (and theoretical devt.)
  - New experimental datasets (and new observables) on « exotic » fissioning systems at low E* have been released across the « fission landscape»
  - Expectation of new high precision experimental data in the coming years Ypost(E*,A,Z), Ypre(E*,A,Z), N/Z, ν(A,Z)
- Theoretical development and synergies with experimentalists are crucial to move further on the microscopic description of fission and get closer to a unified description across the fission landscape.
- Can exotic fissioning systems in the pre-actinide region (neutron rich and deficient) be addressed at FRIB using (p,2p) reactions ?

Thank you for your attention !