Isomeric yield ratio measurements of Th(α,f) at 32 MeV

S. Cannarozzo[1], S. Pomp[1], A. Solders[1], Z. Gao[1], A. Al-Adili[1], M. Lantz[1] and the IGISOL group [2]

[1] Uppsala University, [2] University of Jyväskylä

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ARIEL - H2020 Final Workshop 17/19-01-24 - IJCLab

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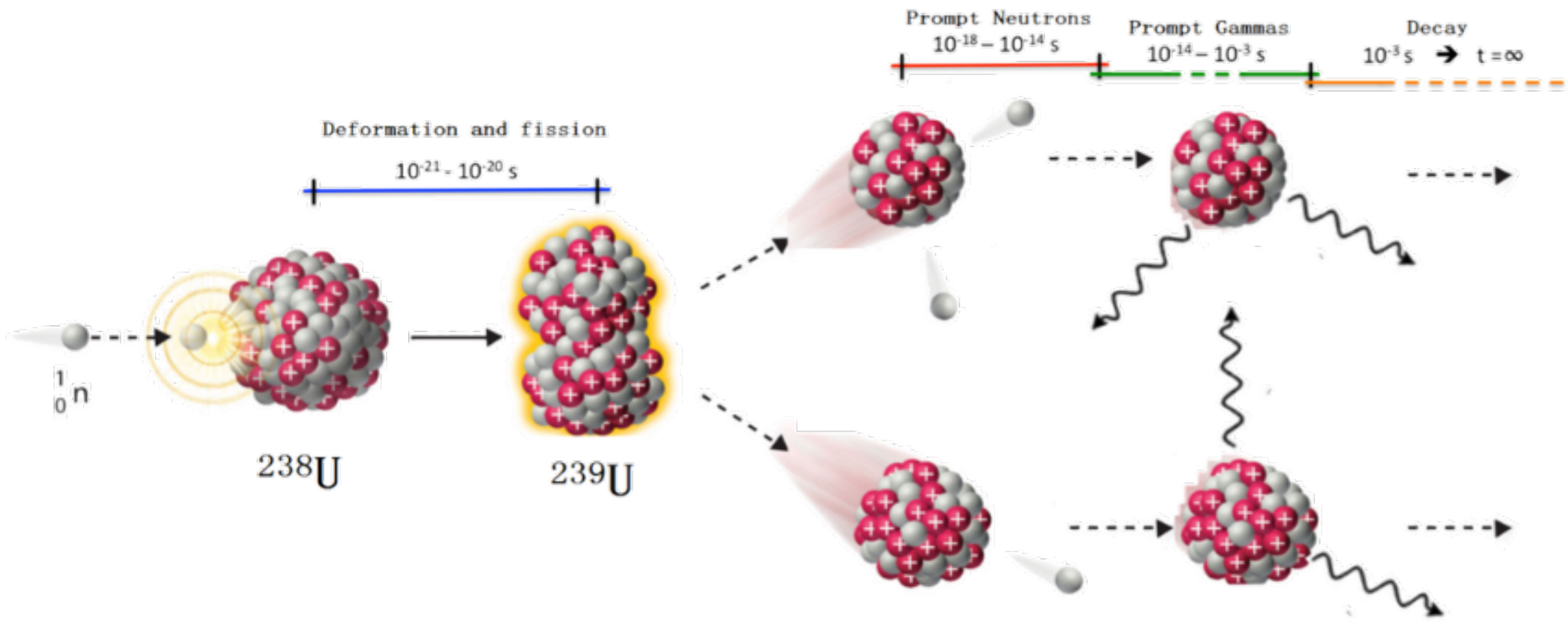
Introduction: from scission to isomers



Fundamental question: where does angular momentum of fission fragments come from?

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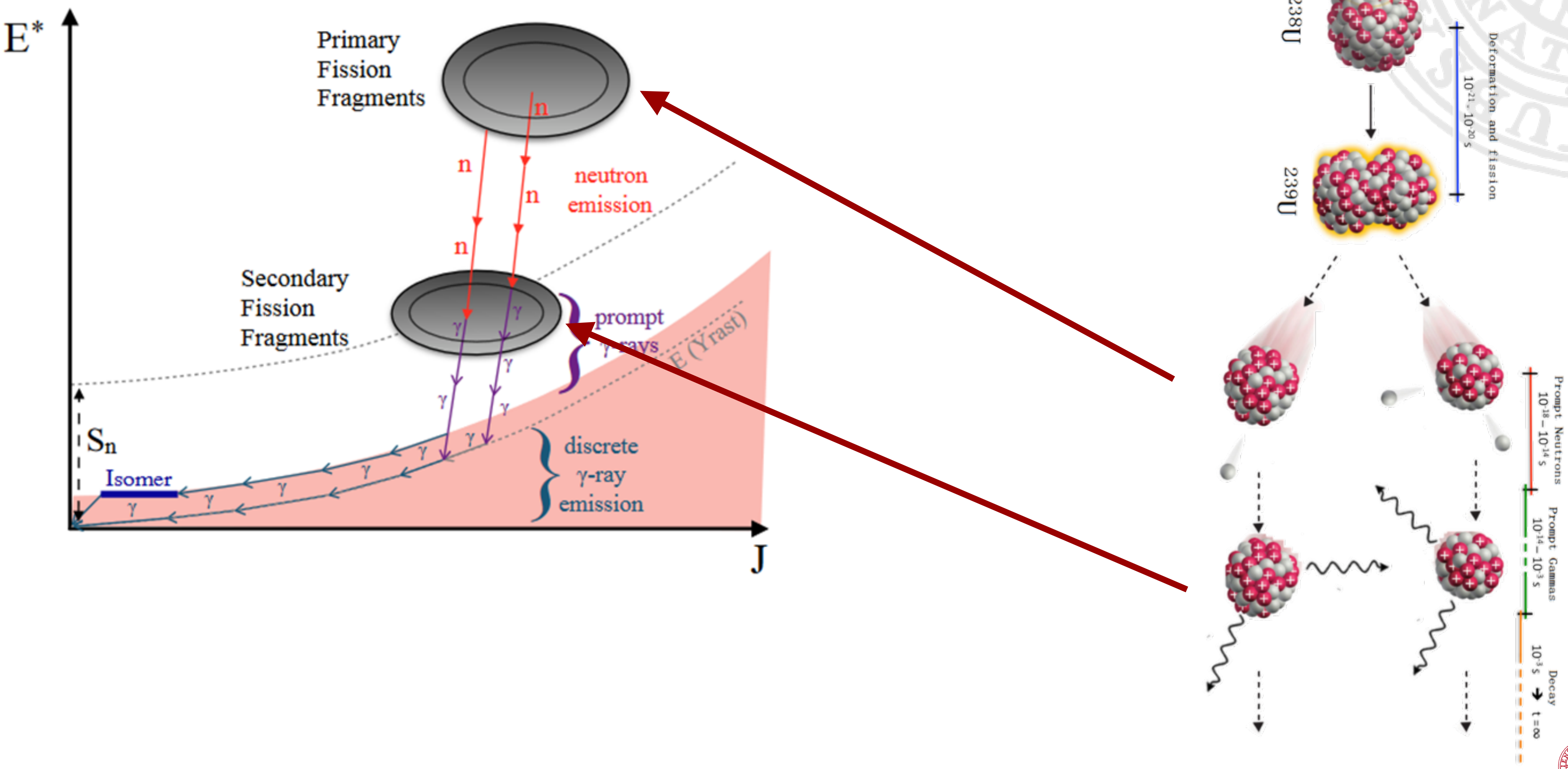

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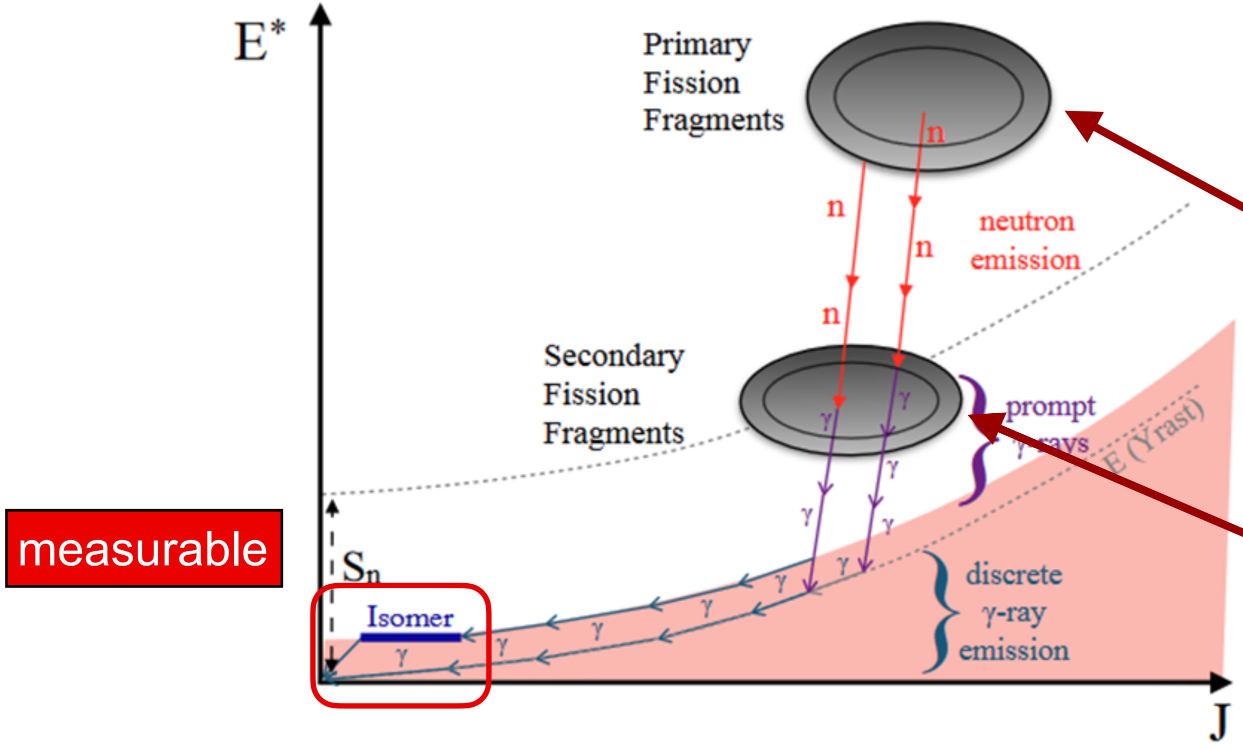

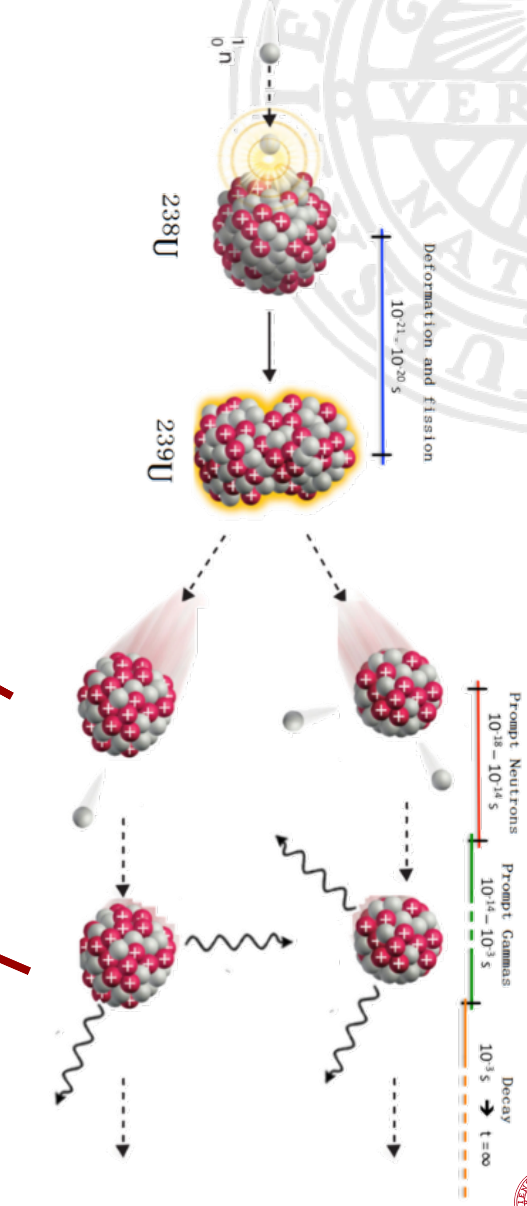

Isomers are excited **meta-stable states** of a nucleus

Yields depend on angular momentum and can be calculated

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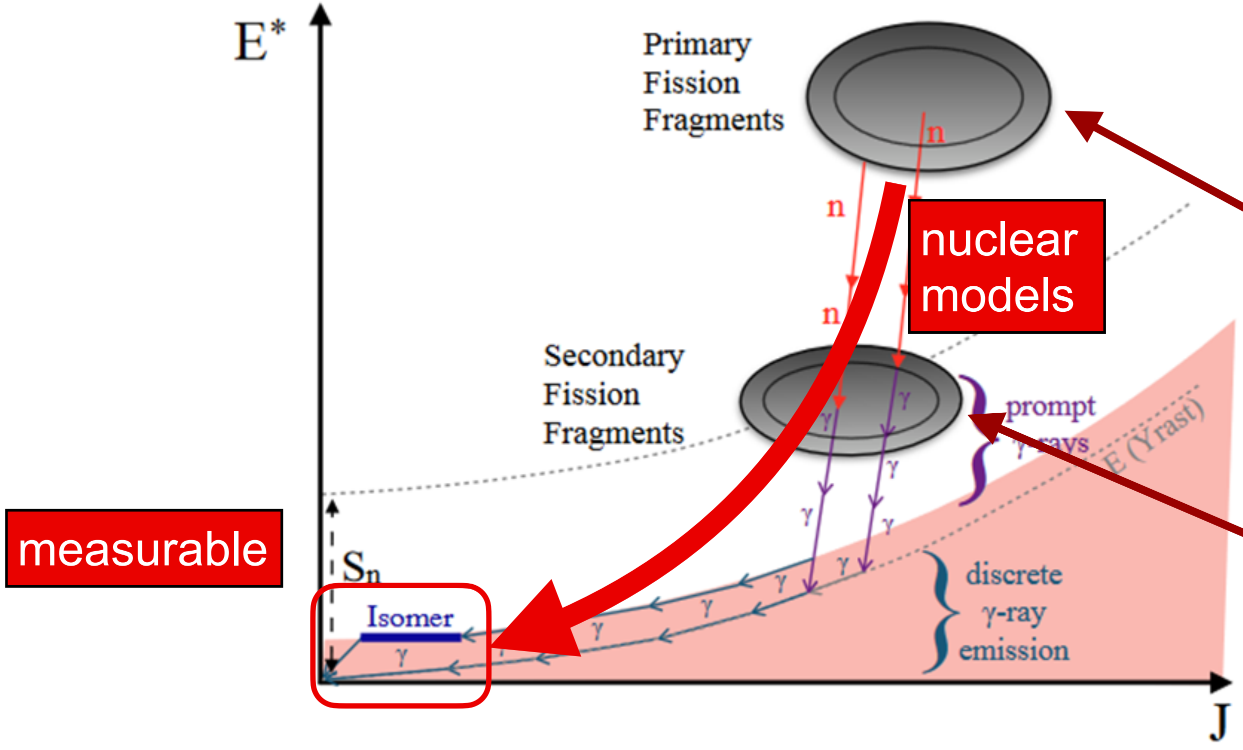

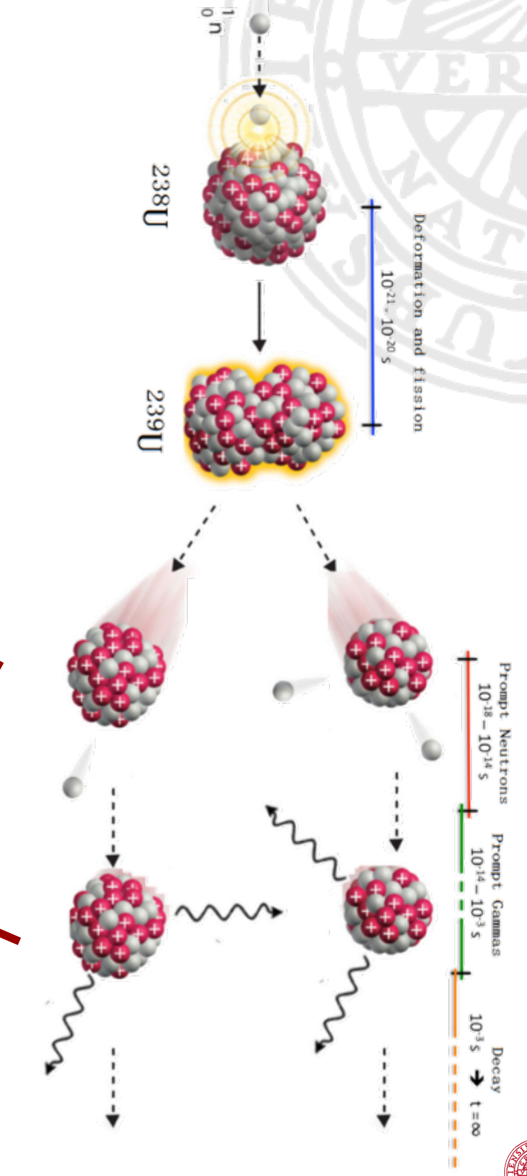

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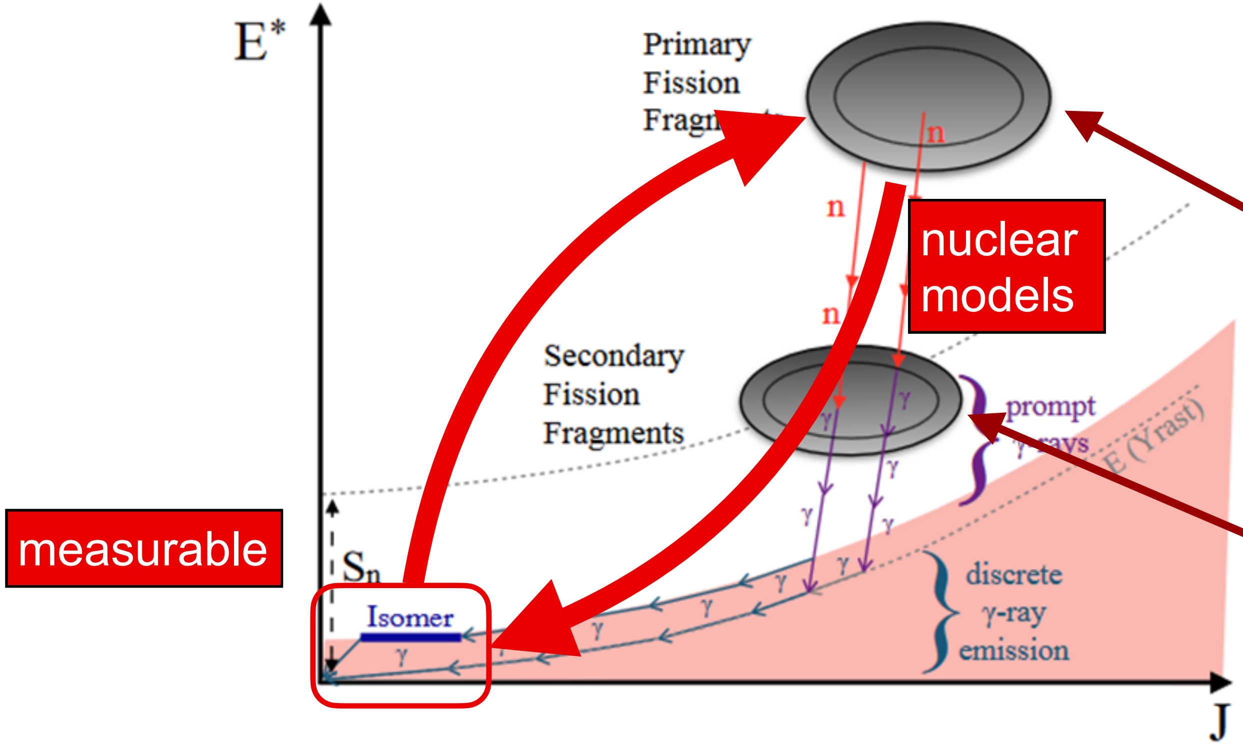

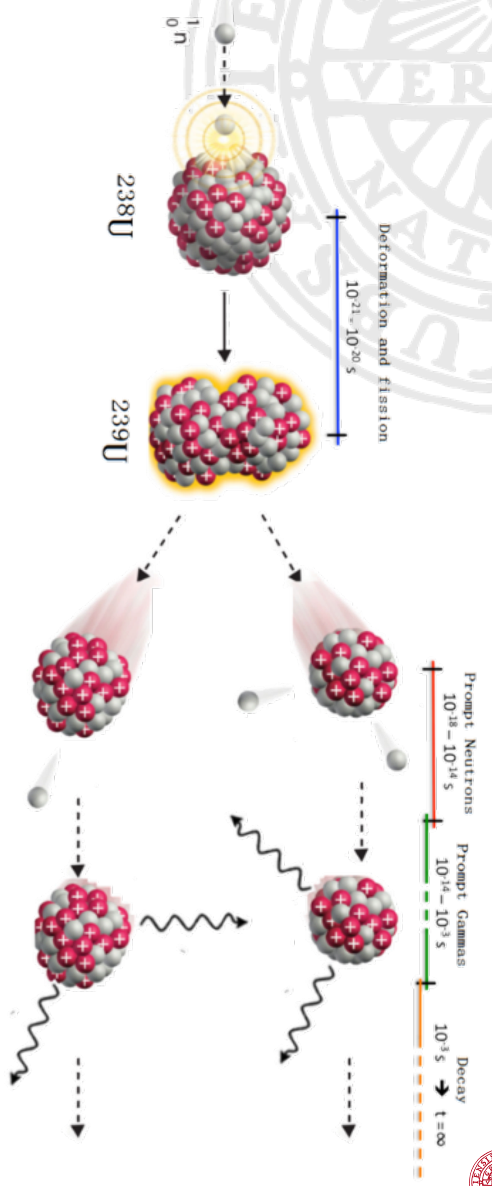

Isomers are excited **meta-stable states** of a nucleus

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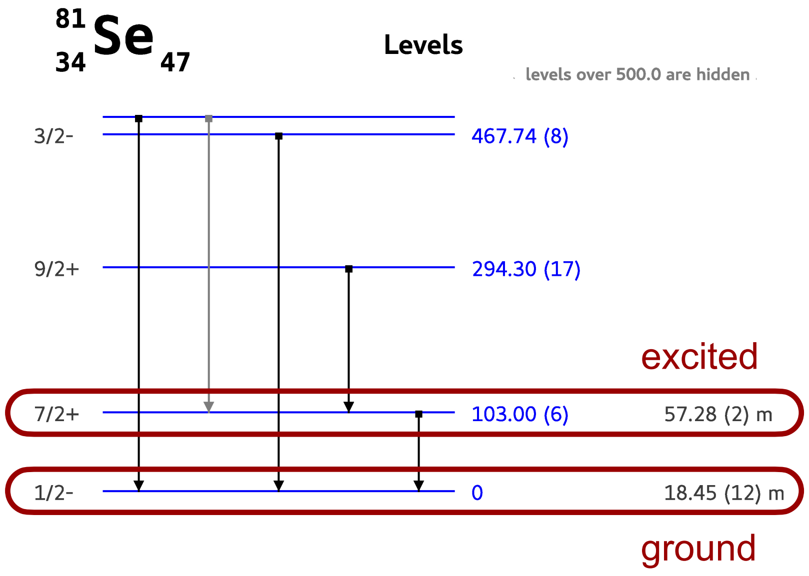
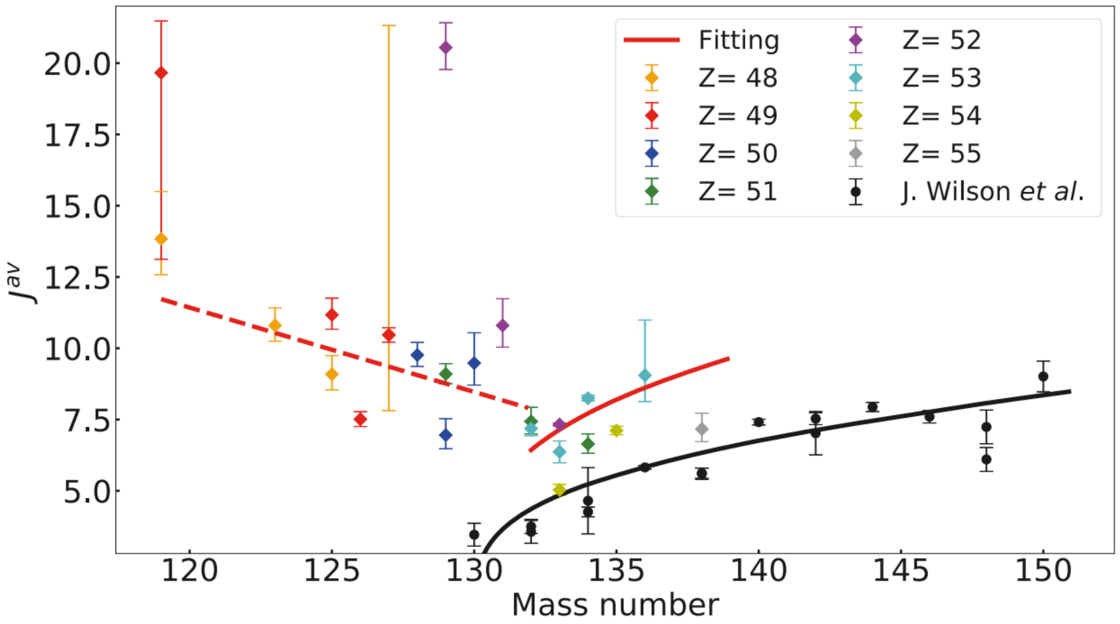
Introduction: isomers and isomeric yield ratio (IYR)

Isomeric yield ratio: ratio between yields of two isomers

$$IYR = \frac{Y_{high\ spin}}{Y_{high\ spin} + Y_{low\ spin}}$$



Gao Z., “Isomeric yield ratios in nuclear fission”, PhD thesis (2023)



IYR can be used to calculate the **angular momentum** of fission fragments [1-5]

Also useful to test nuclear models

We need experiments to measure IYRs!

1. Huizenga and Vandenbosch, 1960
2. Rakopoulos, 2018
3. Rakopoulos, 2019
4. Al-Adili, 2019
5. Gao Z., 2023

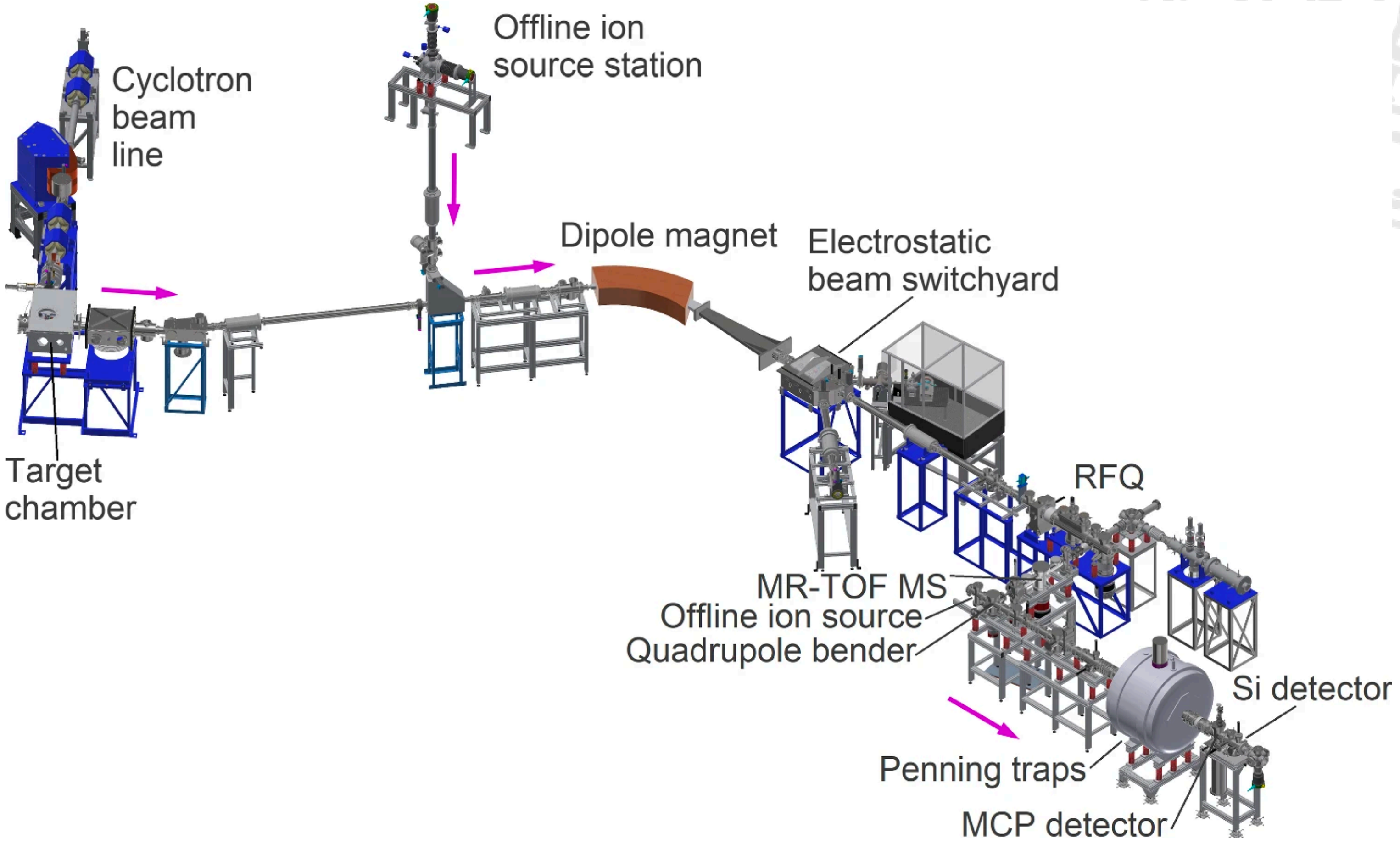
Introduction: experimental campaign (TAA_2_3)

$^{232}Th(\alpha, f)$ at 32 MeV at University of Jyväskylä (10/15.03.23)

- **Never measured system**: 11.7% of existing IYR ^{232}Th, never with α
- **Low energy of compound nucleus** (CN): $^{234}U^* \ @ \ 11.6 \ MeV$ (probability of 84%)
- Very similar CN of $^{233}U(n_{th}, f)$
- Investigate effect of high **momentum added** by α

Compare to data from other systems

Experimental: JYFLTRAP @ IGISOL



D.A. Nesterenko, “Study of radial motion phase advance during motion excitations in a Penning trap and accuracy of JYFLTRAP mass spectrometer” (2021)

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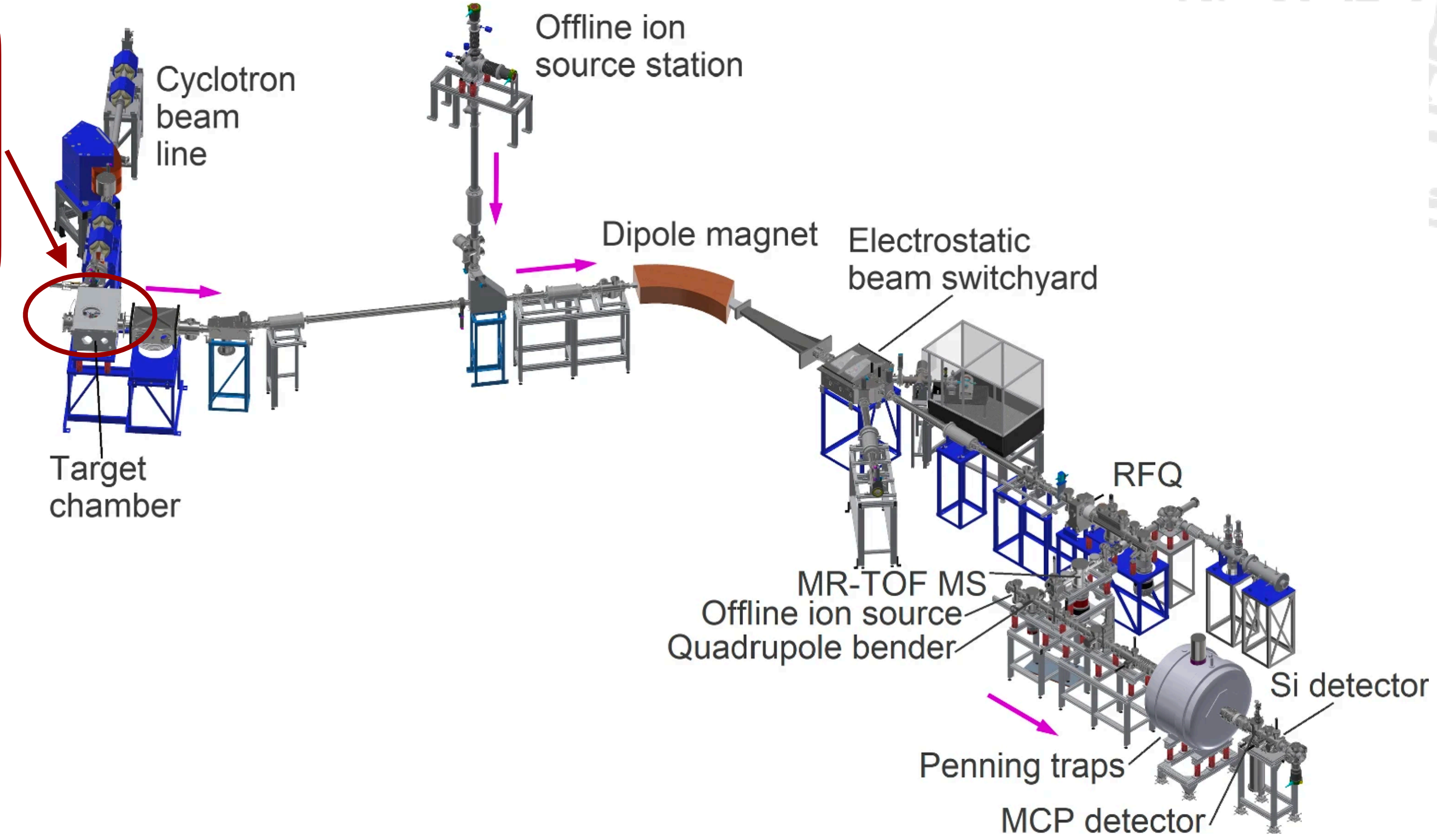

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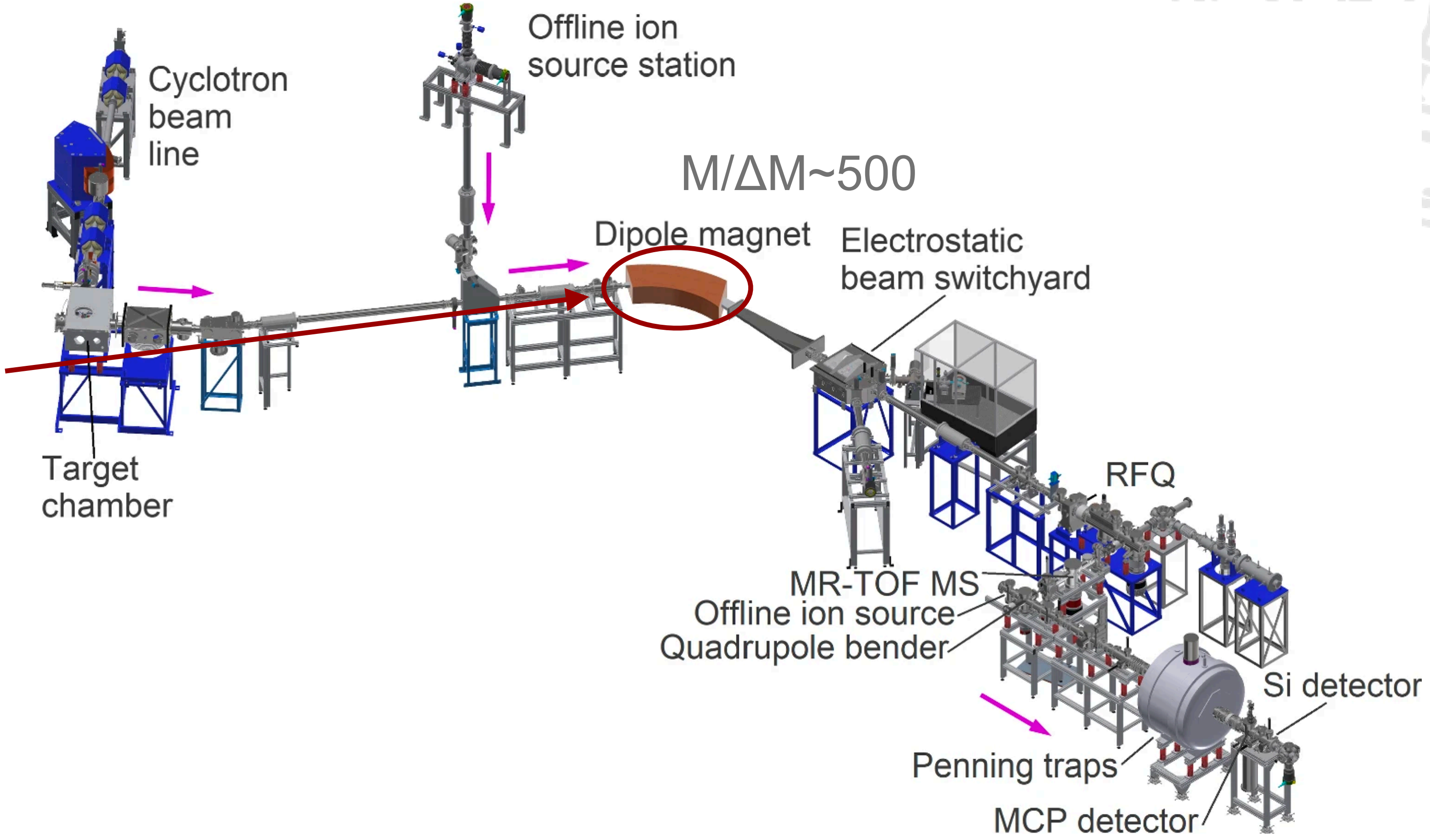

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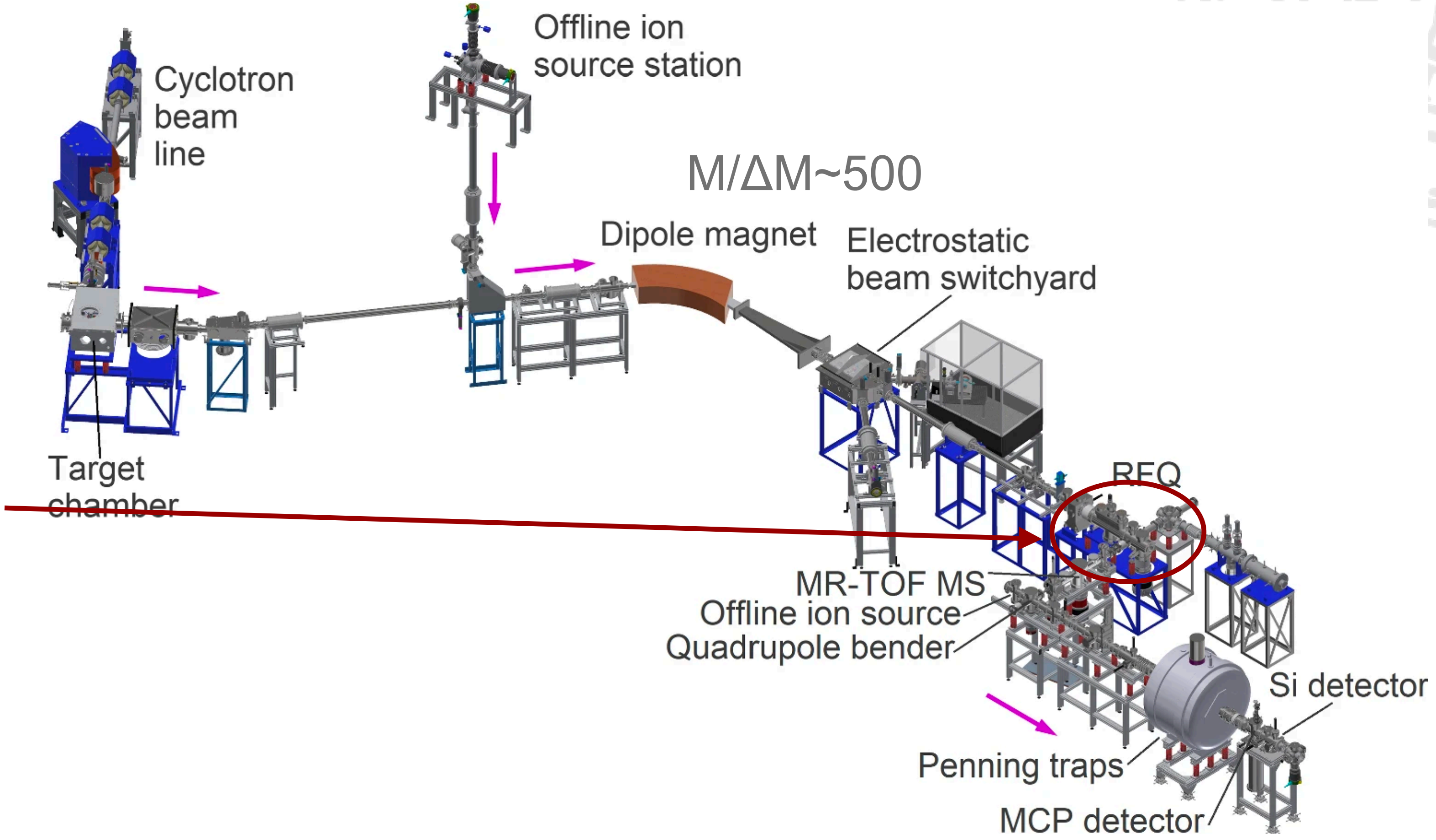

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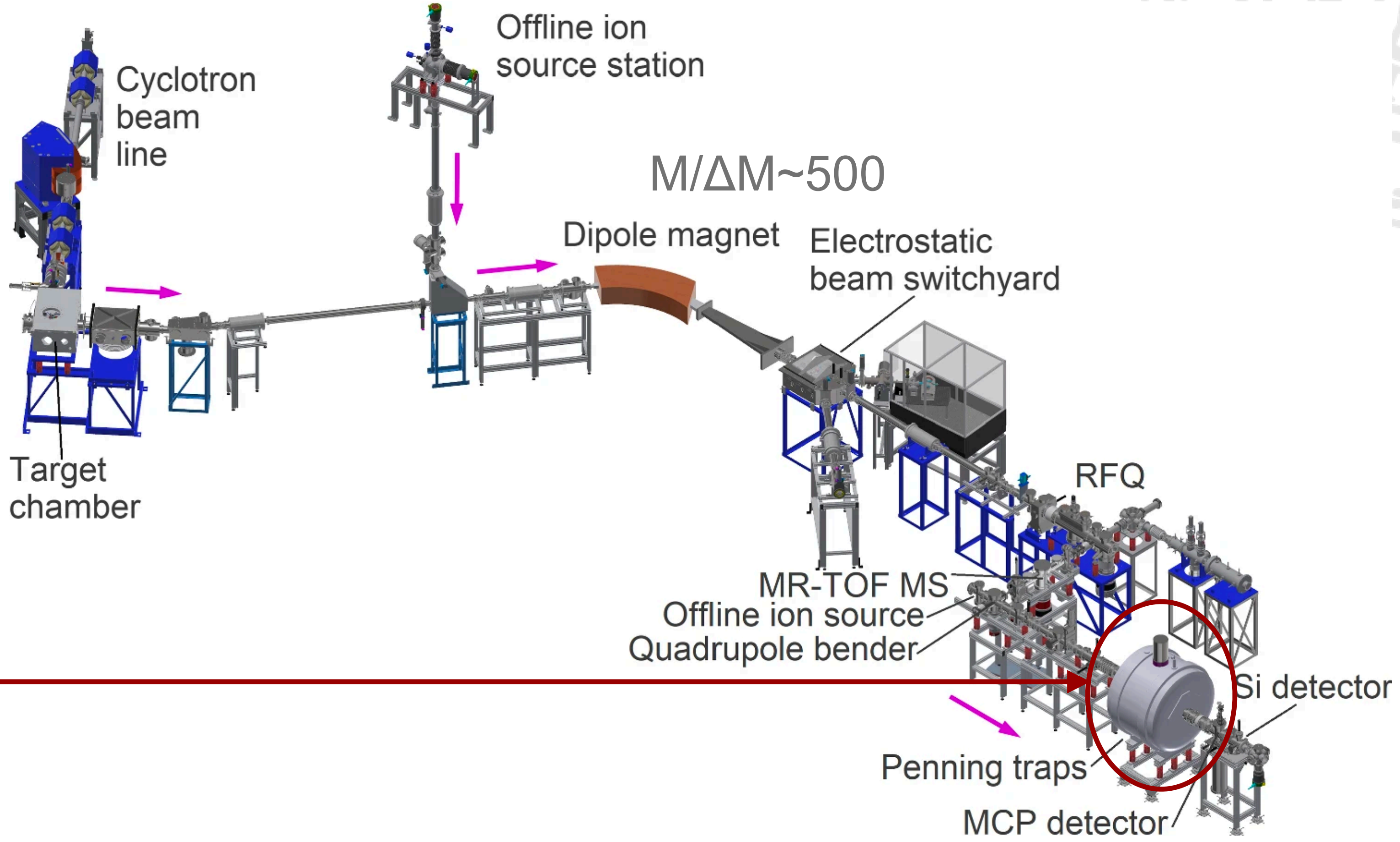
5. Isomer separation (Penning traps)



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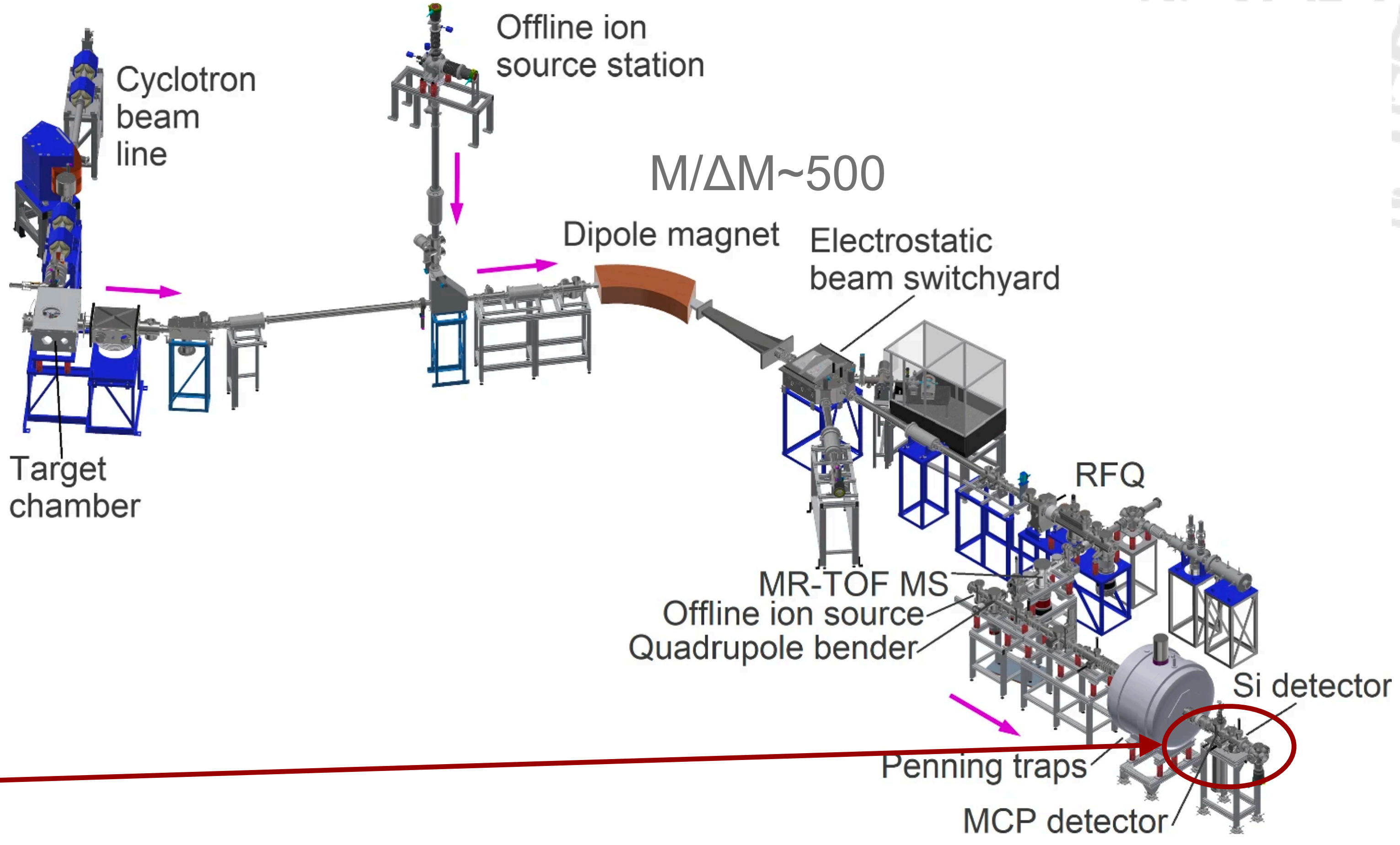
5. Isomer separation (Penning traps)
6. Position sensitive detection (MCP)



D.A. Nesterenko, "Study of radial motion phase advance during motion excitations in a Penning trap and accuracy of JYFLTRAP mass spectrometer" (2021)

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Experimental: motion in a Penning trap

Penning trap: device to store ions

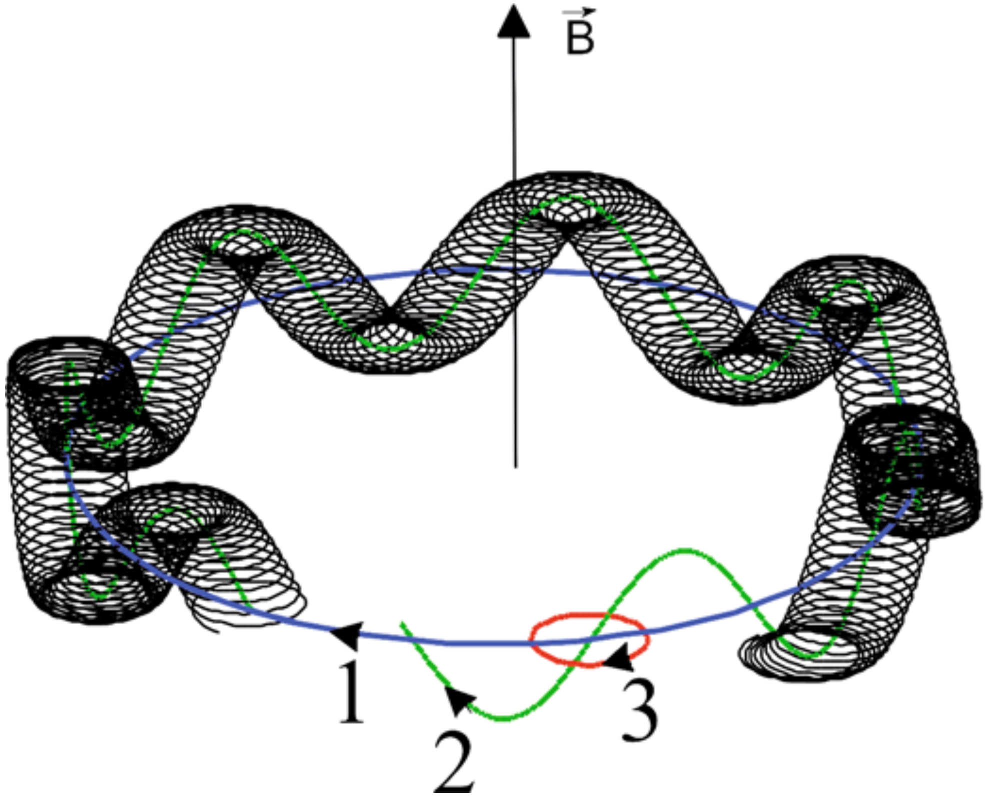
Superimposition of magnetic and quadrupolar electric field

Motion has three components in a Penning trap:

1. Magnetron motion at ν_- ($\approx 1KHz$) (does not depend on the mass)
2. Axial motion at ν_z ($\approx 50KHz$)
3. Reduced cyclotron motion at ν_+ ($\approx 1MHz$)

1-3 are excited by RF signals

$$\nu_- + \nu_+ = \nu_c = \frac{1}{2\pi}\frac{q}{m}B$$



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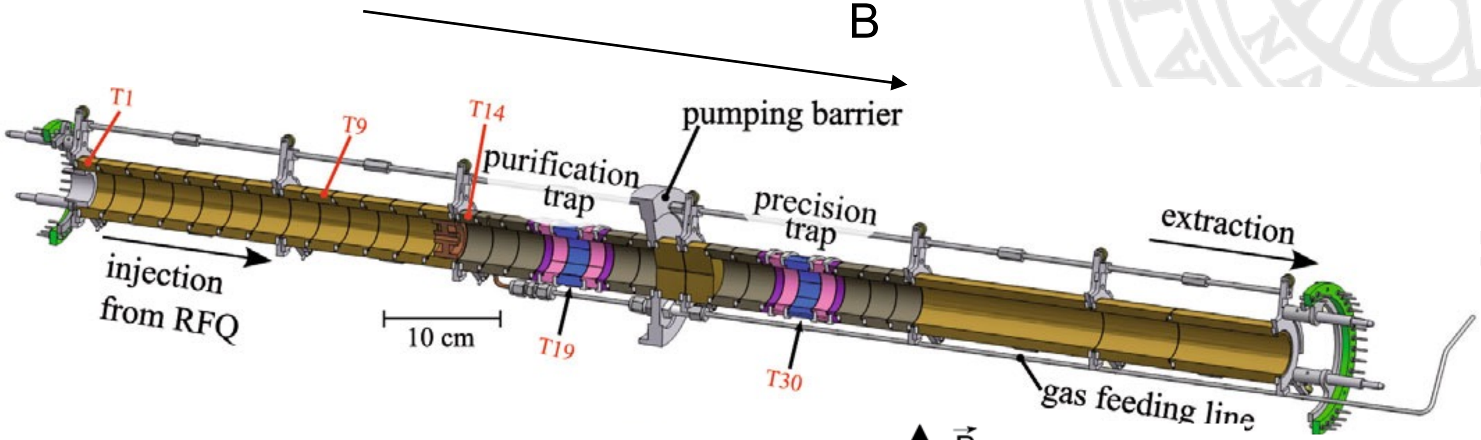
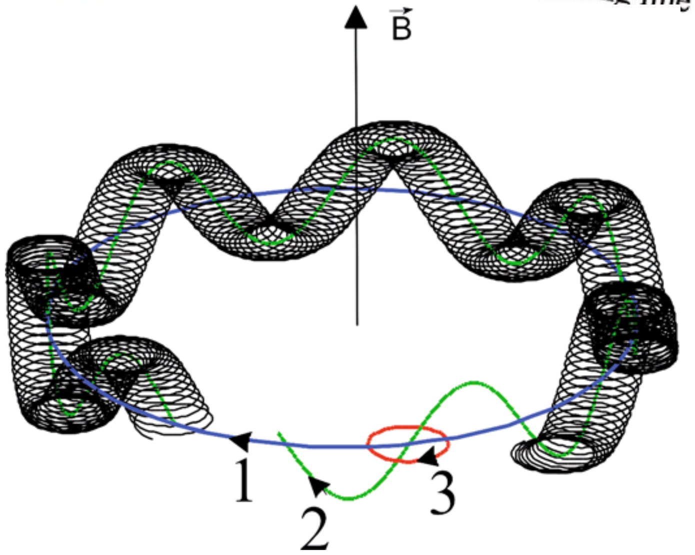
Experimental: purification trap (side-band cooling)

- The ion **bunch enters** purification trap
- Magnetron motion (1) excited: all ions on a **large radius**
- Cyclotron motion (2) of q/m excited: **ion of interest at higher ν**.
- Nuclei moving at higher frequency interact with gas and lose more energy: move **closer to axis**
- Only ions close to axis are extracted (small aperture)

This allows to select only a small mass window





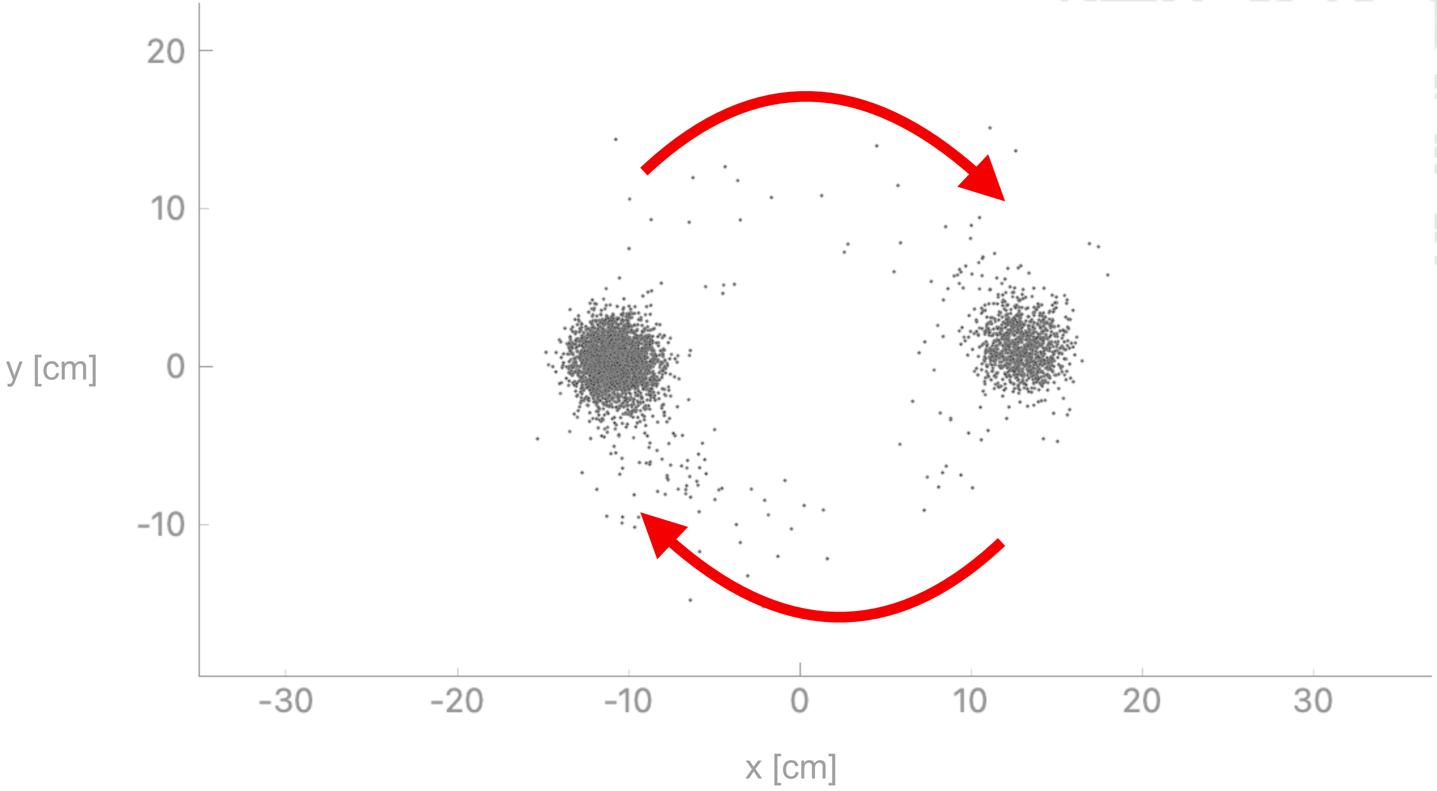
Eronen, "JYFLTRAP: a Penning trap for precision mass spectroscopy and isobaric purification" (2012)

Experimental: precision trap (Phase-Imaging Ion-Cyclotron-Resonance)

- Bunch enters precision trap
- Cyclotron motion excited; phase depends on frequency (mass) and time

$$\varphi_+ + 2\pi n_+ = 2\pi\nu_+ t$$

- Different masses (isomers) have different phases
- Ions projected on a microchannel plate detector (MCP)



This is a “picture” of ions moving

$$IYR = \frac{C_{high\ spin}}{C_{high\ spin} + C_{low\ spin}}$$

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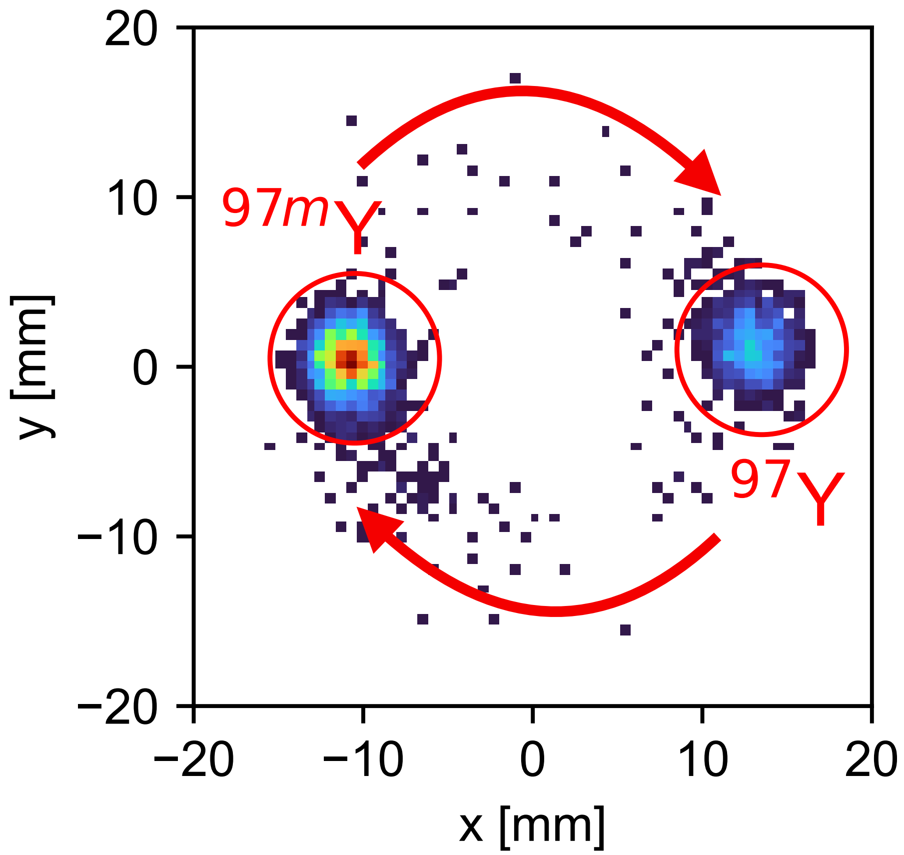

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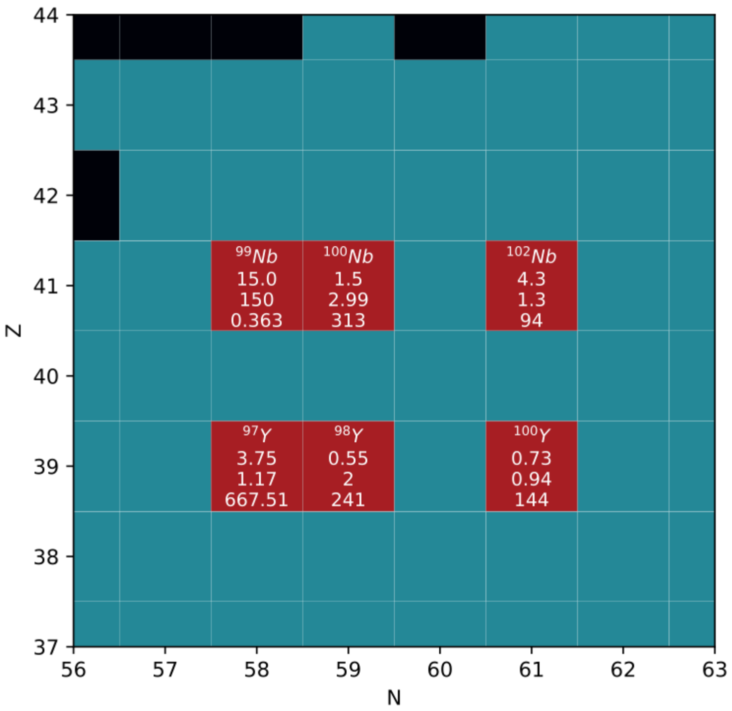
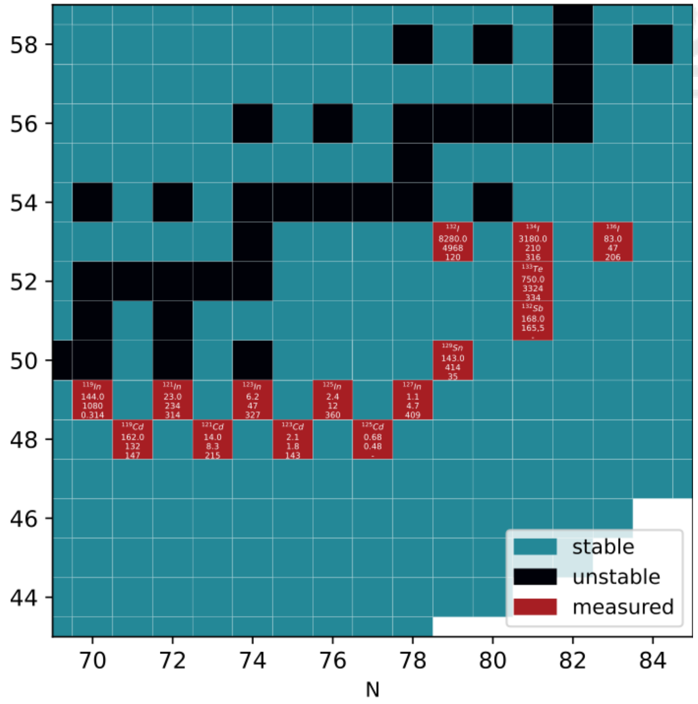
Experimental: measured nuclei overview

Nucleus	Ground State		Metastable state		
A	$T_{1/2}$ [s]	Spin	E_{ex} (keV)	$T_{1/2}$ [s]	Spin
97Y	3.75	1/2	667.51	1.17	9/2
98Y	0.55	0	241	2	4,5
100Y	0.73	1	144	0.94	4
99Nb	15	9/2	363	150	1/2
100Nb	1.5	1	313	2.99	5
102Nb	4.3	4	94	1.3	1
119Cd	162	1/2	147	132	11/2
121Cd	14	3/2	215	8.3	11/2
123Cd	2.1	3/2	143	1.8	11/2
125Cd	0.68	3/2	186	0.48	11/2
119In	144	9/2	311	1080	1/2
121In	23	9/2	314	234	1/2
123In	6.2	9/2	327	47	1/2
125In	2.4	9/2	360	12	1/2
127In	1.1	9/2	409	4.7	1/2
129Sn	143	3/2	35	414	11/2
132Sb	168	4	150	165,5	8
133Te	750	3/2	334	3324	11/2
132I	8280	4	120	4968	8
134I	3180	4	316	210	8
136I	83	1	206	47	6

21 isomers with $T_{1/2}$ down to 480 ms and E_{ex} of 35 keV (!)





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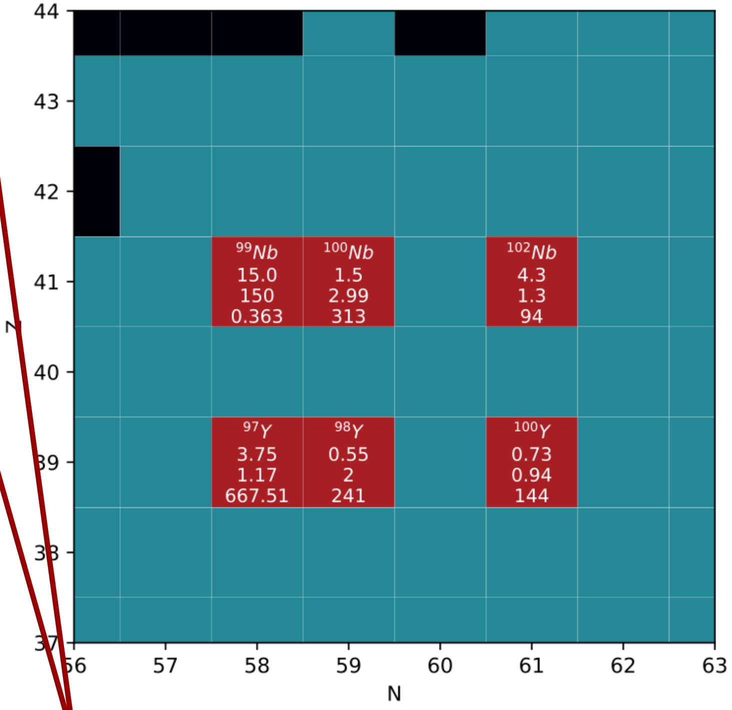

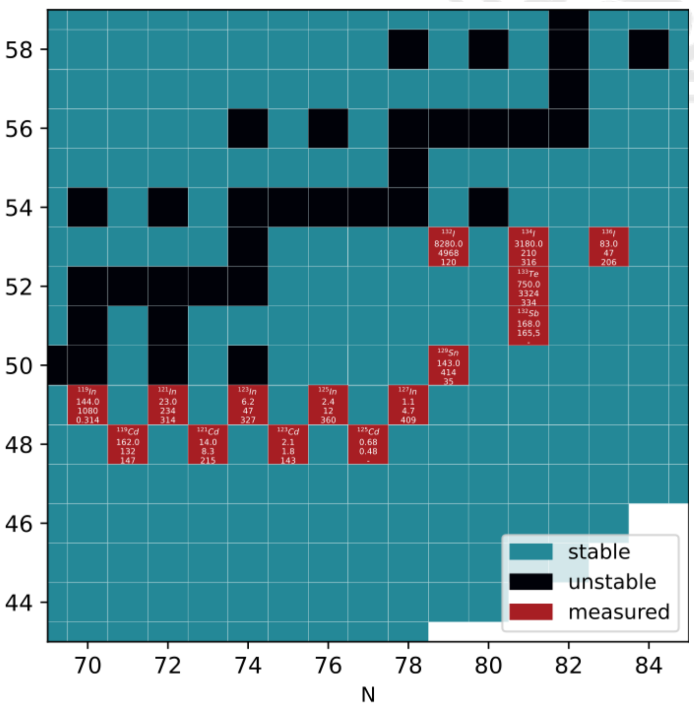

1st measurement!

very low energy!

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Analysis: important steps

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Three important steps to go from PI-ICR image to IYR value:

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- MCP efficiency correction → non-uniform sensitivity of MCP detector across its area

Analysis: important steps

Three important steps to go from PI-ICR image to IYR value:

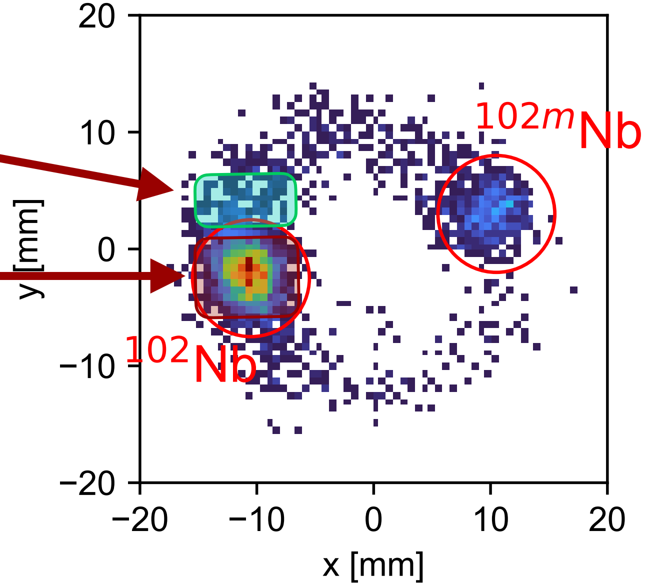
- MCP efficiency correction
- Identification method (to which state ions belong)

non-uniform sensitivity of MCP detector across its area

method to assign detected ions to a specific state

not so easy

easy



Analysis: important steps

Three important steps to go from PI-ICR image to IYR value:

- MCP efficiency correction
- Identification method (to which state ions belong)
- Decay correction

non-uniform sensitivity of MCP detector across its area

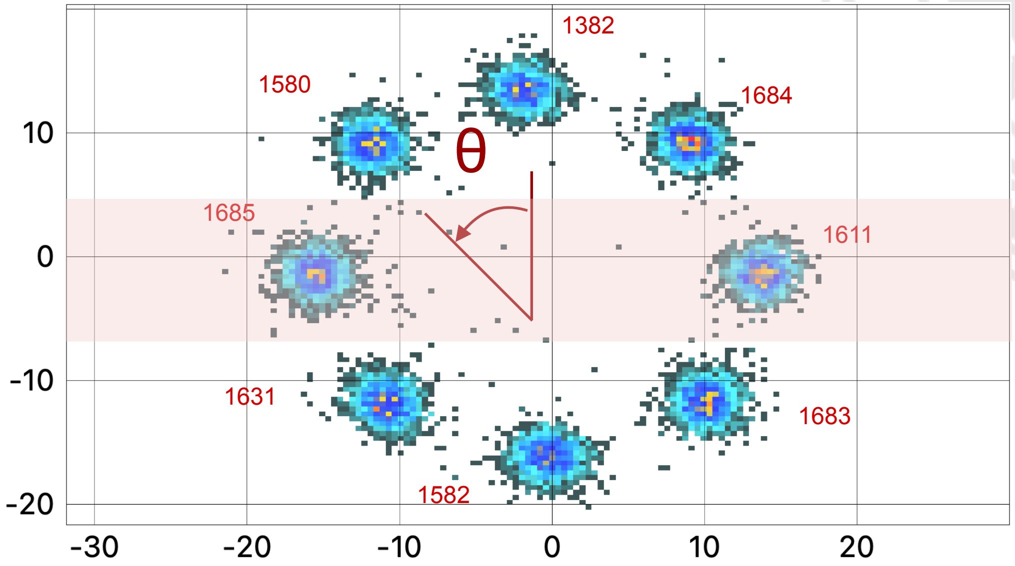
method to assign detected ions to a specific state

correct for the decay of ions during transport from target chamber to detection

100ms - 1s

Analysis: MCP efficiency correction - "calibration"

- Measurement of possible differences in sensitivity
  - Method (and positions spots) similar to real one
  - Internal ^{133}Cd source used
  - always used "equatorial" zone (90° and 270°)



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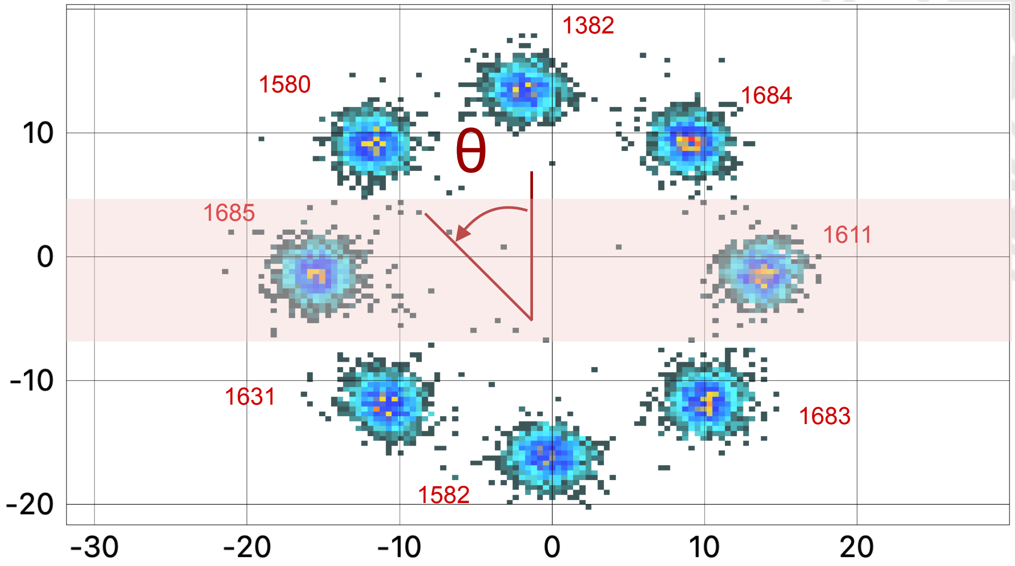
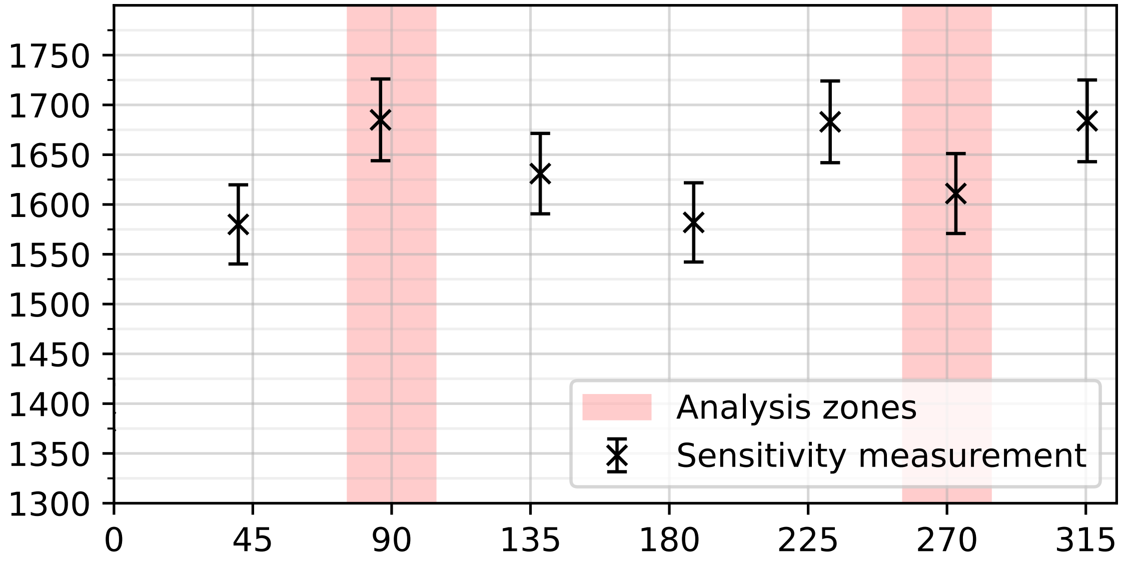




Observed possible **differences**

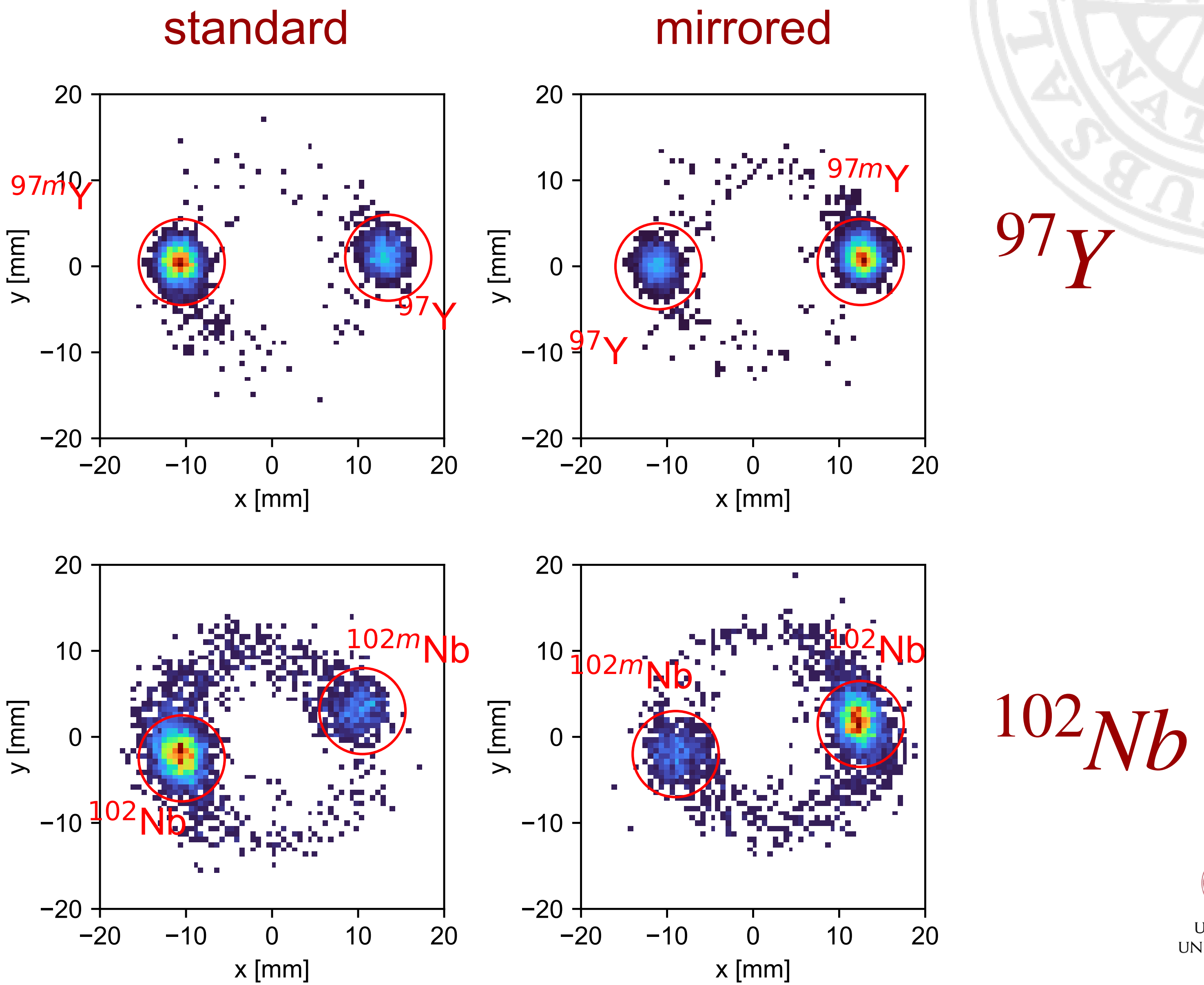
Solution: **two measurements** for each nucleus

Analysis: MCP efficiency correction - standard and mirrored

For each nucleus two data configurations measured:

- standard: high-spin state at 90°
- mirrored: high-spin state at 270°

Analysis of differences still in progress



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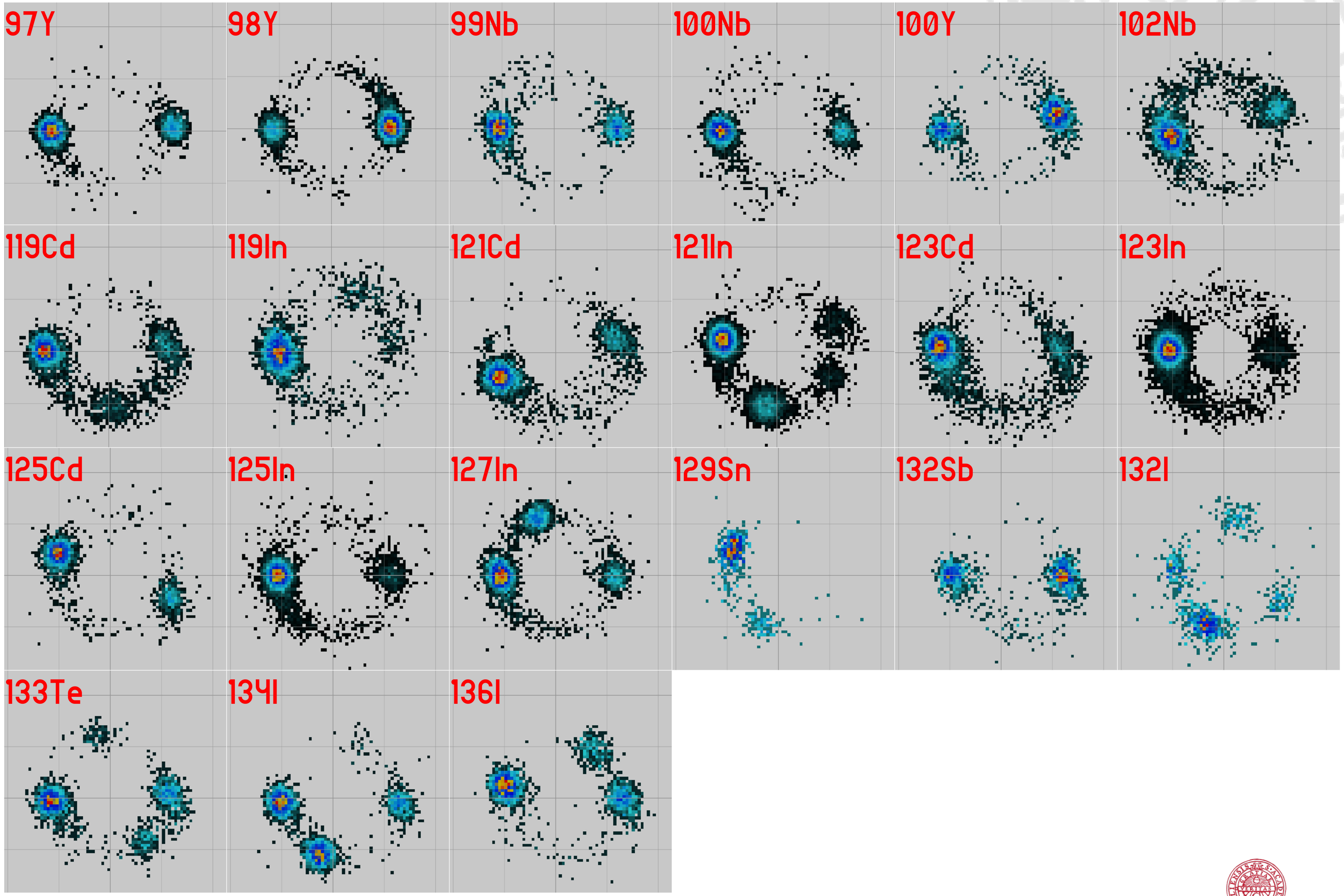
Analysis: identification method

- Method to identify to which state detected ions belong
- Strong **tails** are observed in a part of the cases
- **Unknown** origin
- **Different methods** for identification adopted to study the impact of including or not including them:
  - "**analogic**":
    - Angular cut
    - Angular cut with fixed sigma
  - **clustering**:
    - OPTICS



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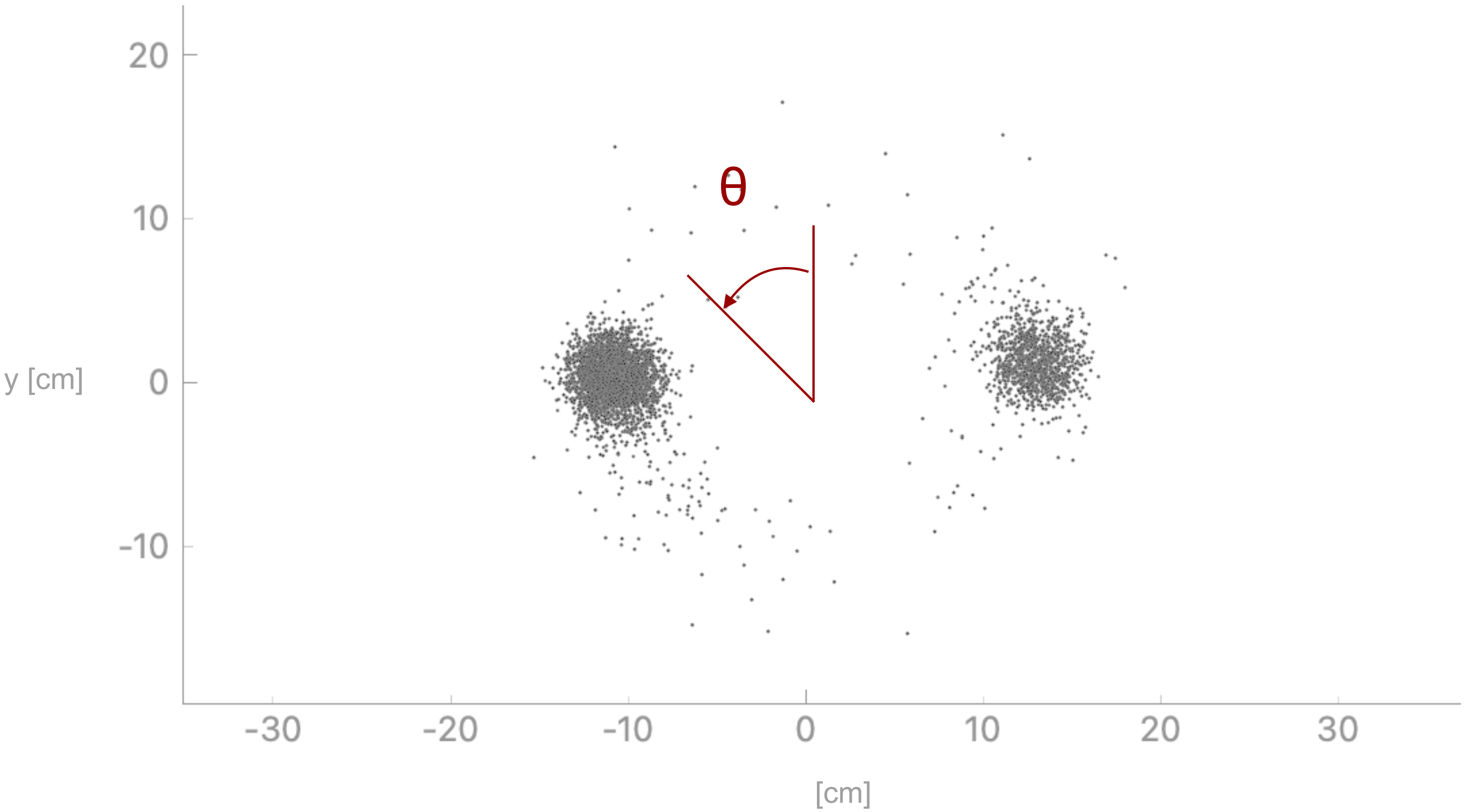
Analysis: identification method - angular cut



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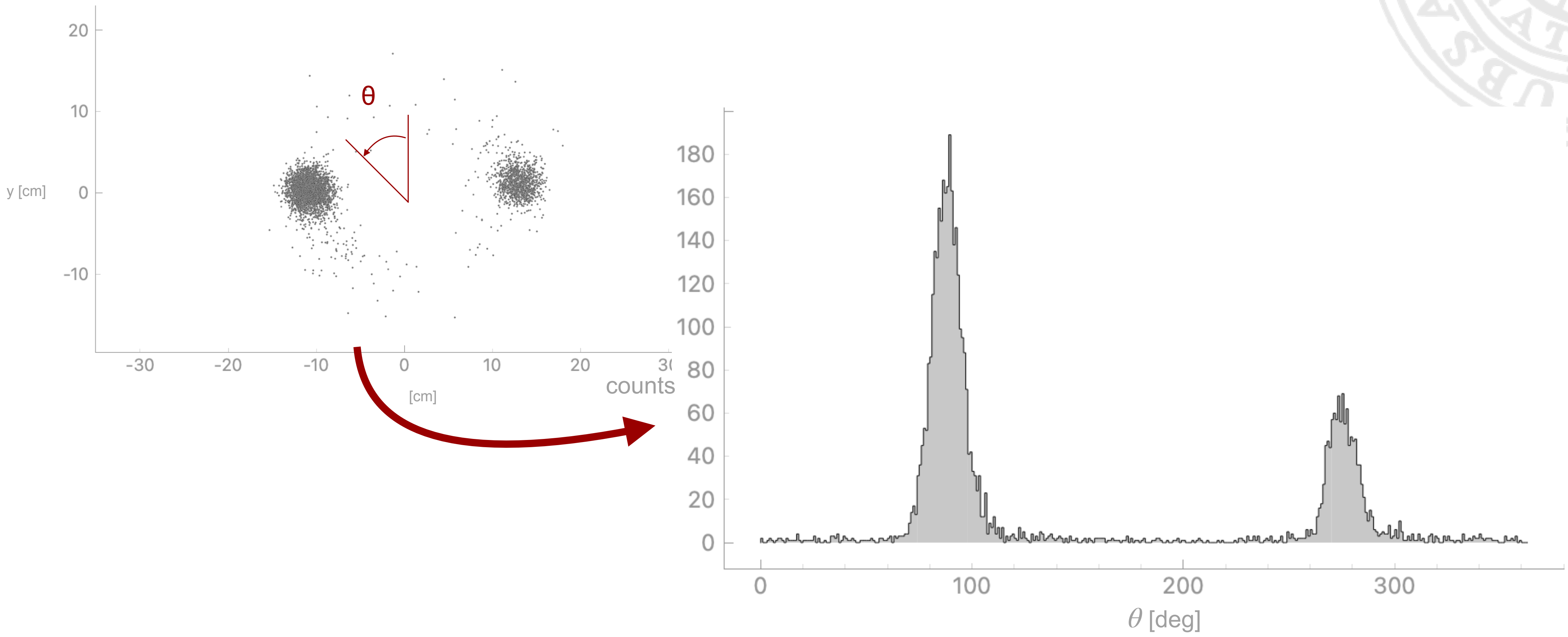

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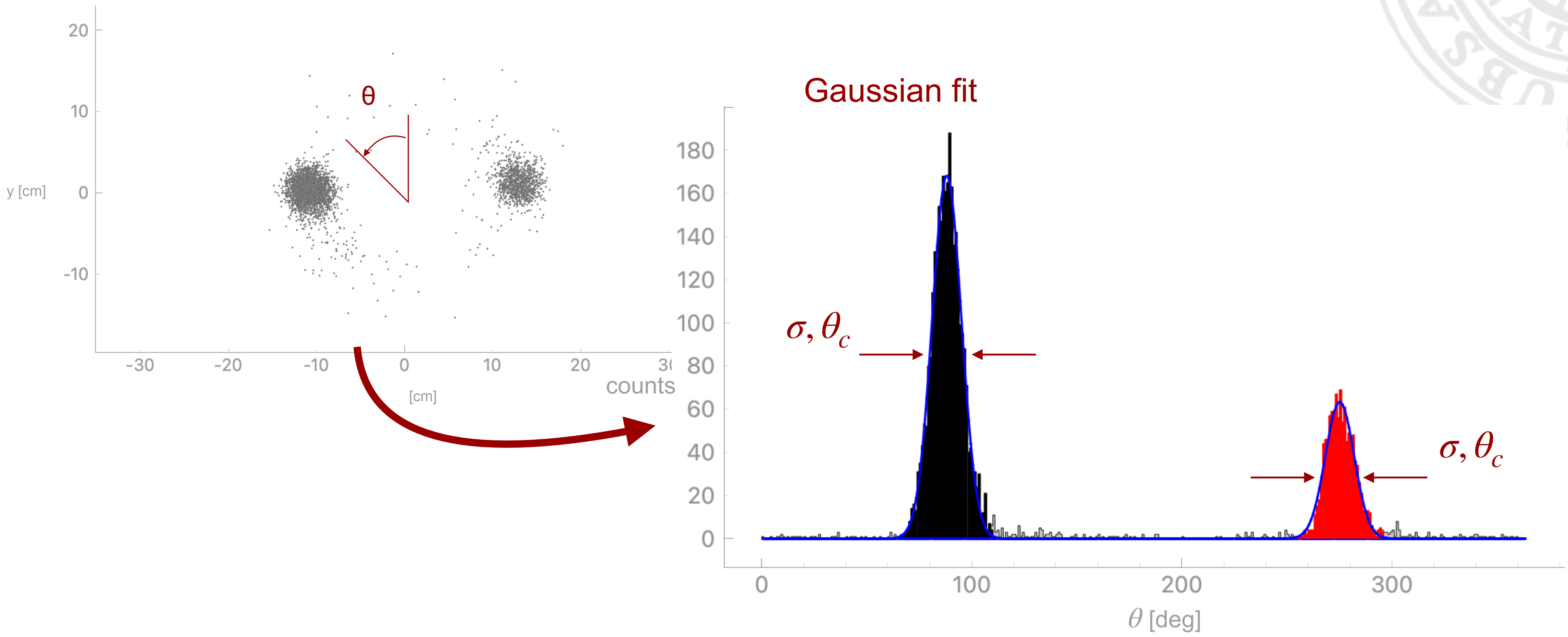
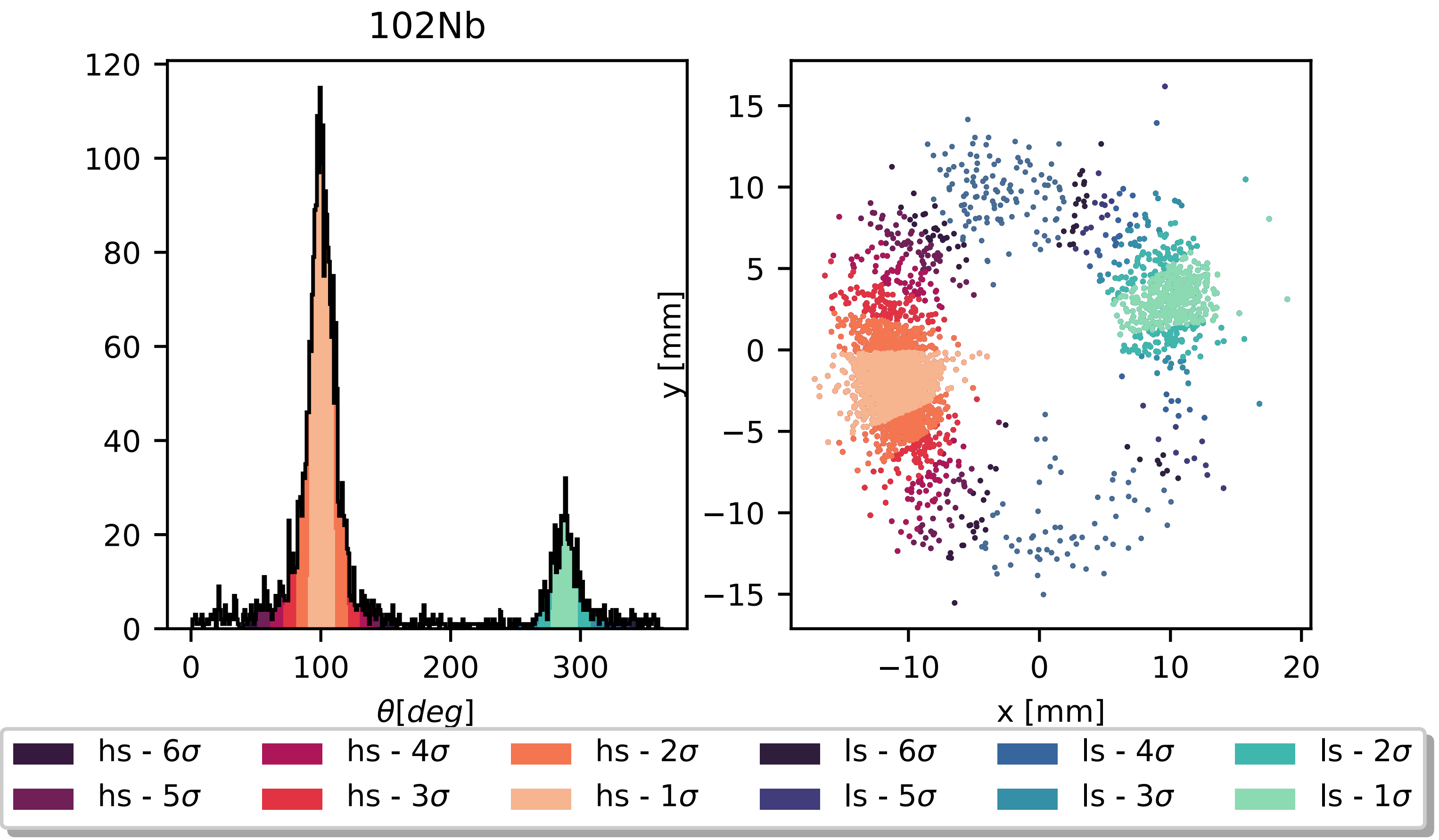


Analysis: identification method - angular cut

- For both spots, **gaussian** fit 1D distributions of **angular position** detected ions
- All counts in $[\theta_c - 3\sigma, \theta_c + 3\sigma]$ are summed



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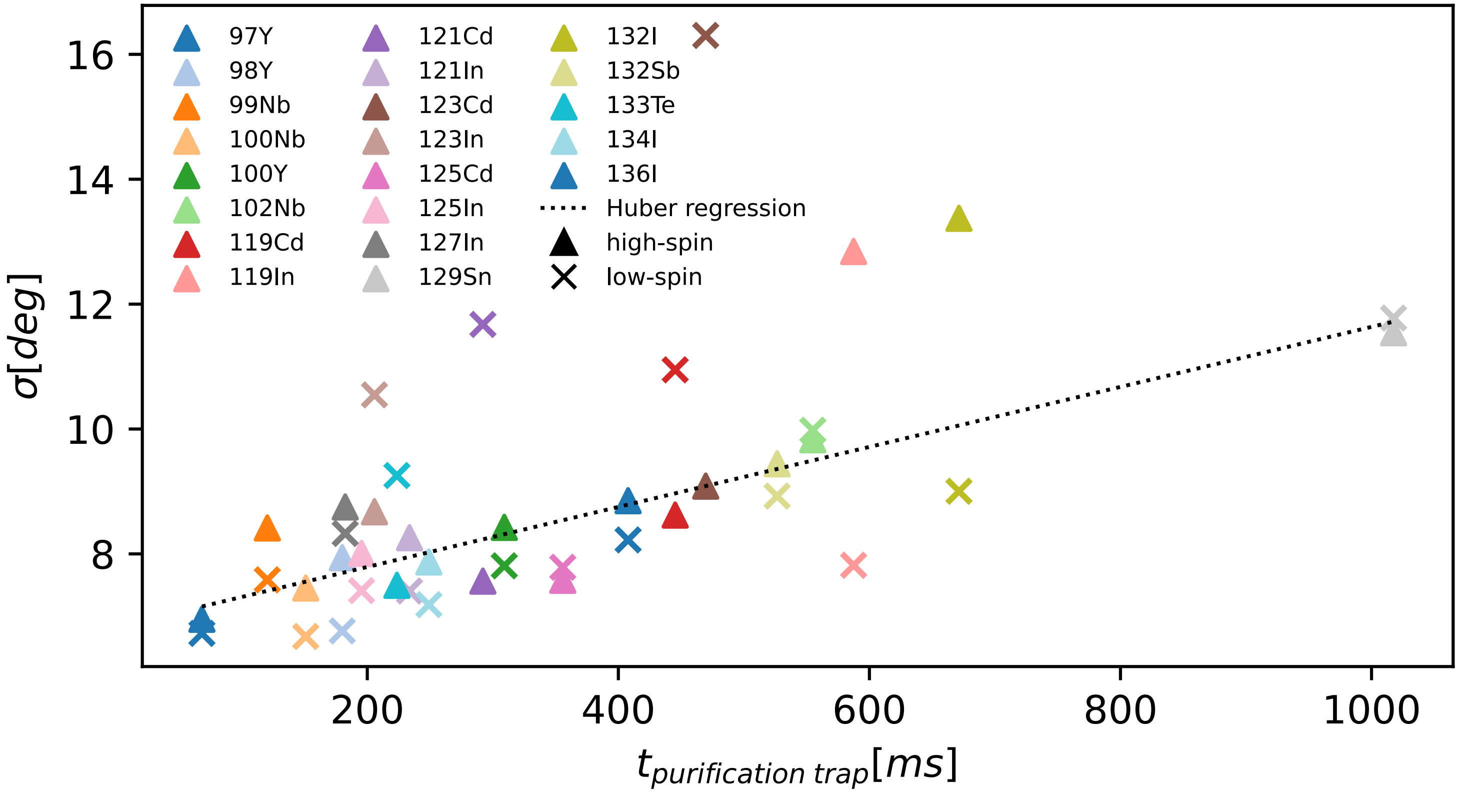
Analysis: identification method - spot size dependency

Spot size empirically depends on time spent in purification trap by ions

This dependency is fitted and used to calculate $\sigma(t_{T2})$



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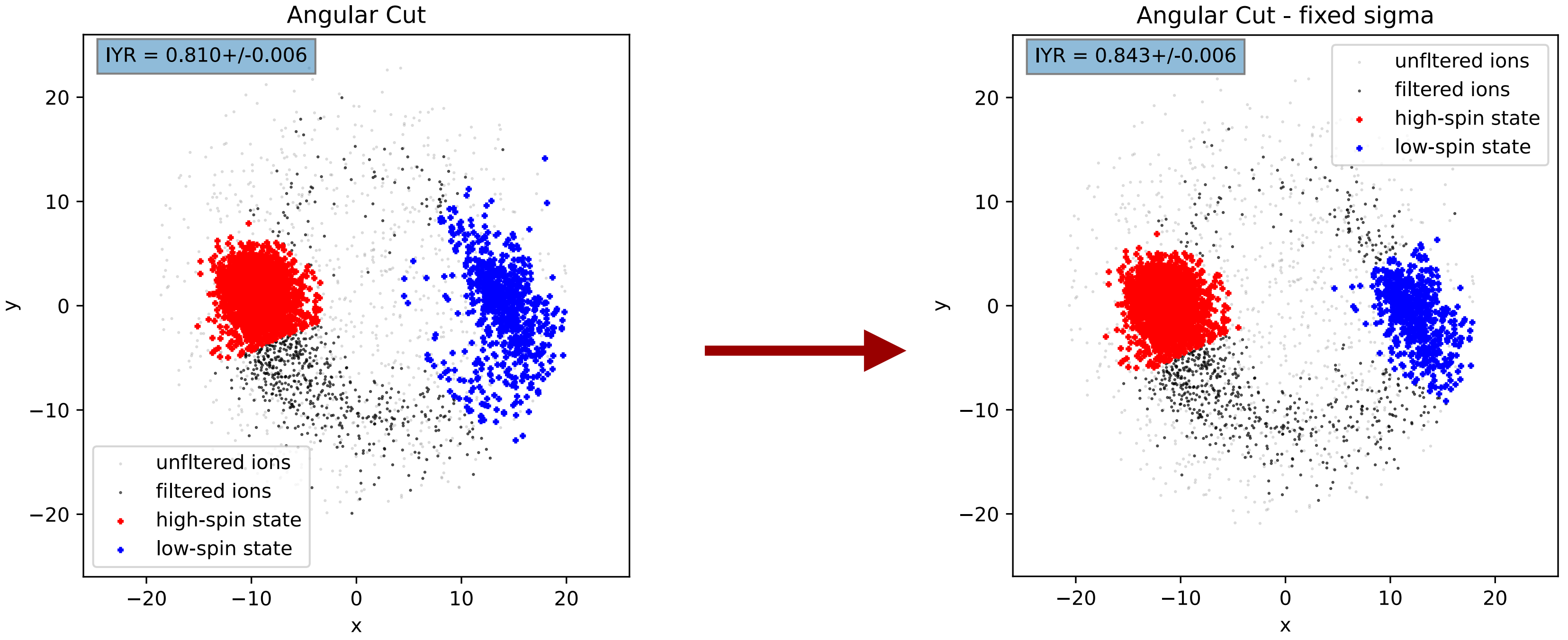
Analysis: identification method - angular cut & fixed sigma

- **Physics**: we expect comparable spot sizes
- Spot size used for counting is the one given by $\sigma(t_{T2})$
- Very similar but more **restrictive** approach

$$\sout{\theta_c - 3\sigma, \theta_c + 3\sigma}$$

$$\theta_c - 3\sigma(t_{T2}), \theta_c + 3\sigma(t_{T2})$$



^{123}Cd

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~~$\theta_c - 3\sigma, \theta_c + 3\sigma$~~

$$\theta_c - 3\sigma(t_{T2}), \theta_c + 3\sigma(t_{T2})$$

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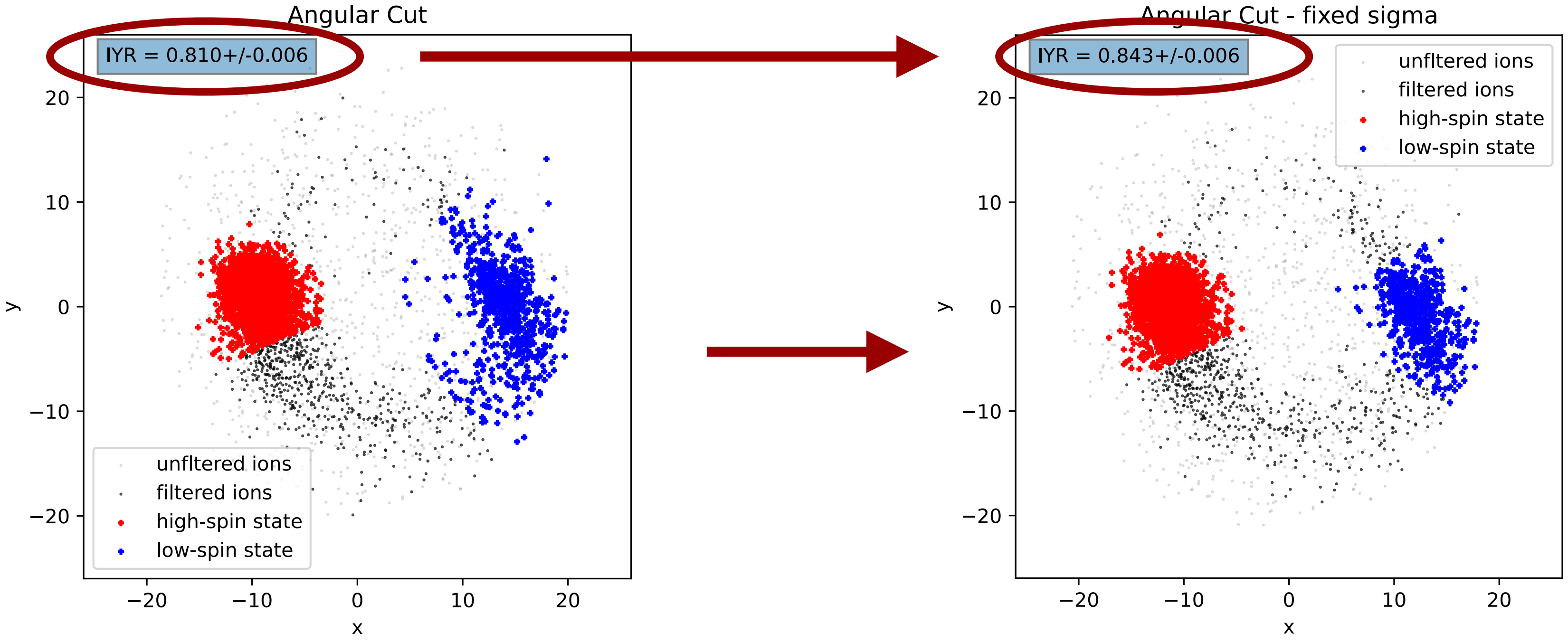
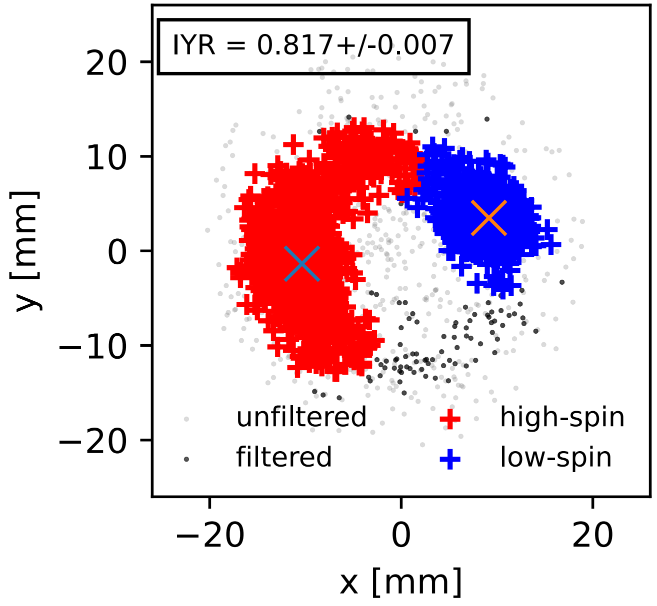


^{123}Cd

Analysis: identification method - OPTICS

- Clustering method based on distance (reachability) between spots
- External parameter to set: *eps* i.e. maximum reachability
- Two spots are assigned to same cluster if within distance lower than *eps*
- Usually tails are included

^{125}In



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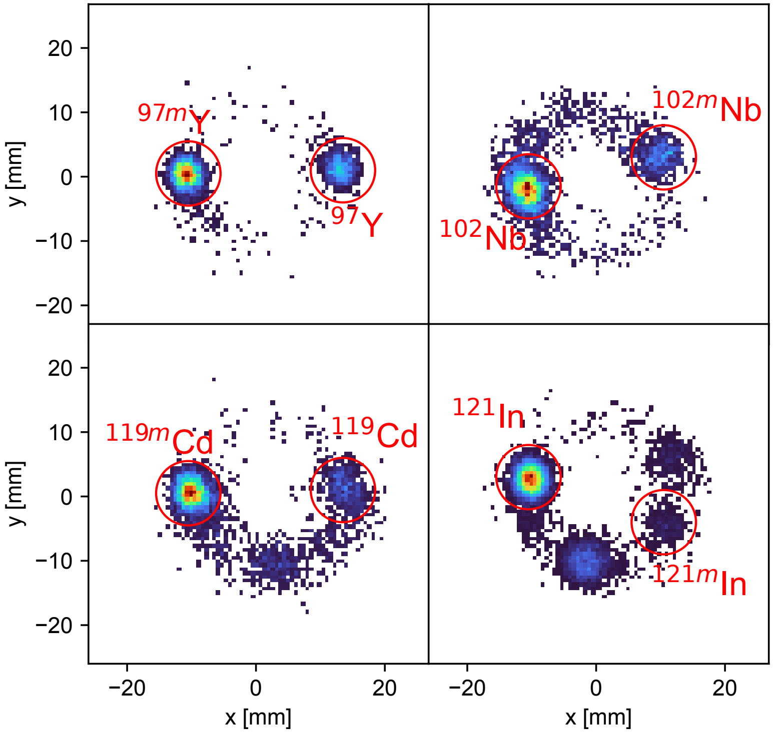
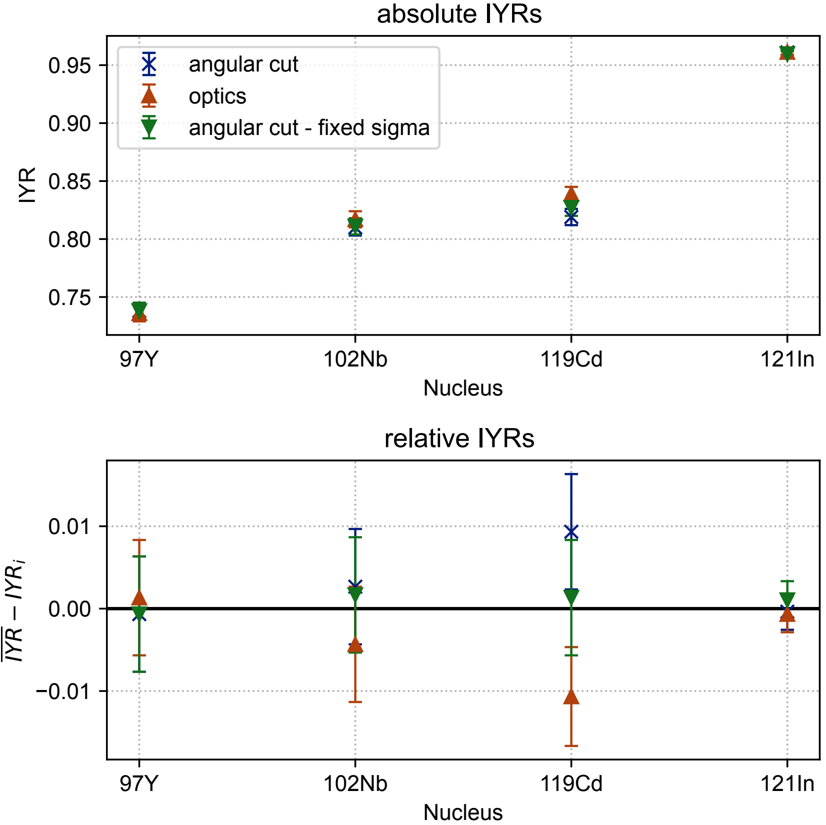
Analysis: identification method - identification methods compared





Very close results, except for ^{119}Cd, where anyway uncertainties overlap

Conclusion: tails are a relevant but **not critical factor** for IYR measurement

Analysis: decay correction

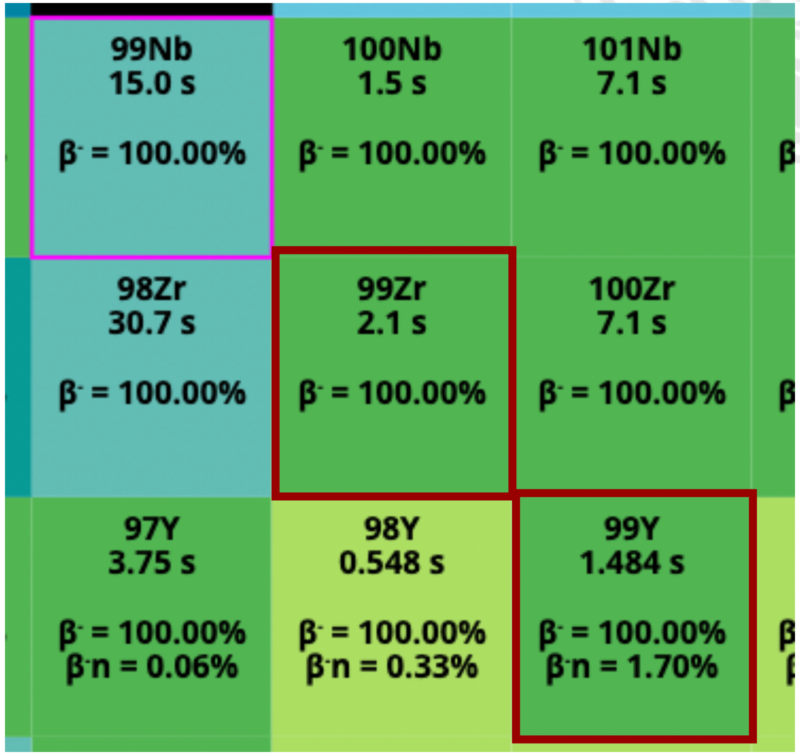
Takes a long time for ions to be extracted and to reach MCP (500-1000 ms)

So we need a **decay correction.** To consider:

- Decay of ground
- Influence of precursors

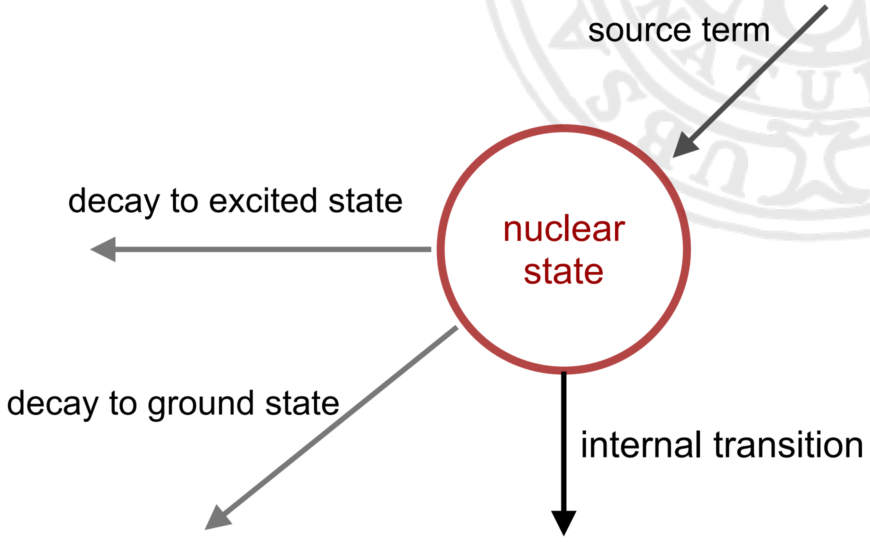
Ingredients we need:

- Half-lives → NUBASE2020 evaluation
- Fission yields → GEF using s.f. of $^{234}U^{*}$ @ $11.6\ MeV$
- Transition branching ratios → using NNDC decay schemes



Analysis: decay correction

- Simulation for the different stages (TC, RFQ, T1, T2)
- Dividing time in discrete intervals
- Calculating balance equation for ground and excited state:
  - **nucleus**
  - **first precursor**
  - **second precursor**



Initial IYR in target chamber **progressively changed** until simulated and experimental measured IYR match

Systematic uncertainty: calculation repeated 10^6 times resampling parameters (bootstrap)

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Analysis: decay correction - results

Result **can vary** significantly

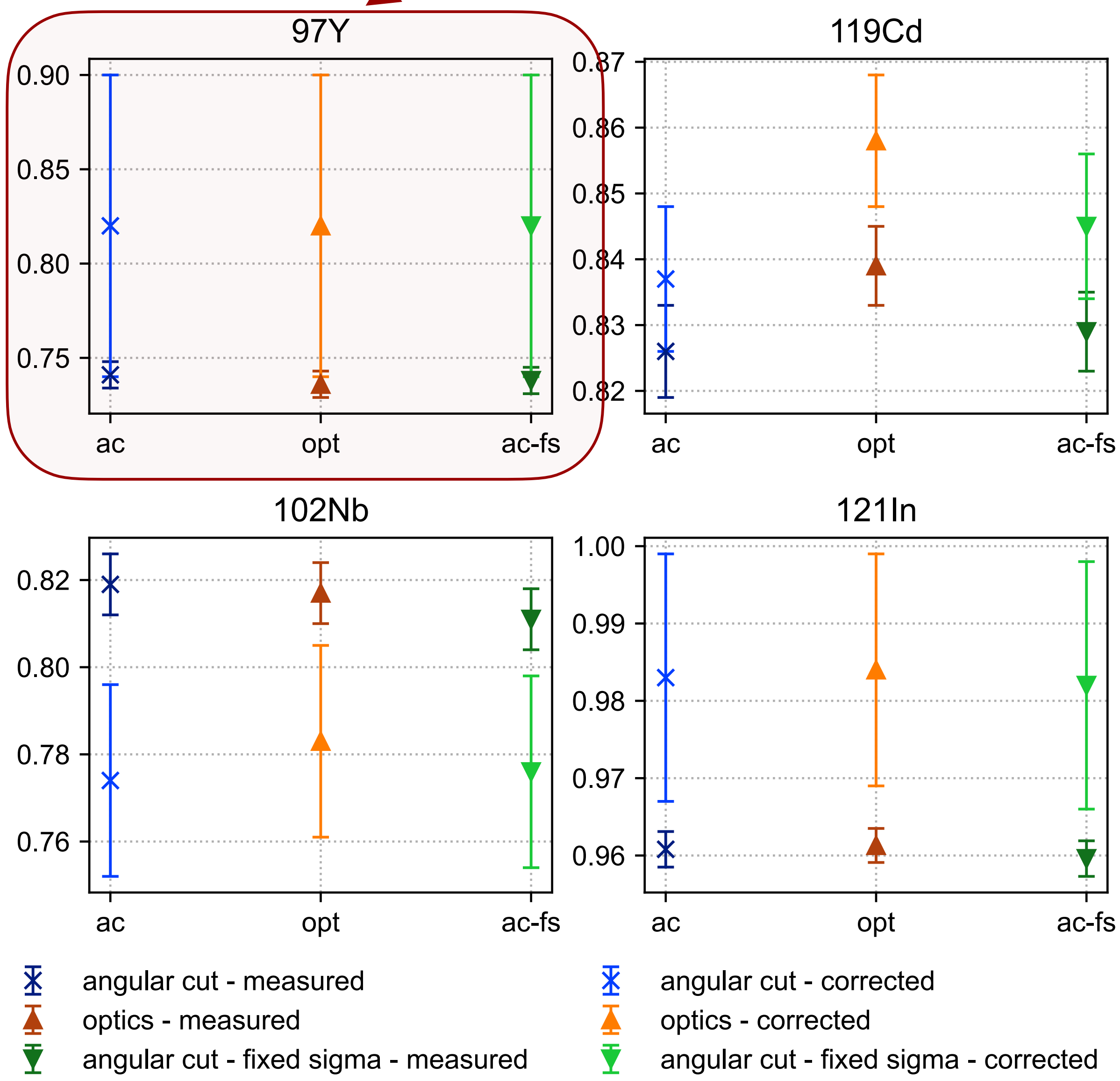
In some cases **large uncertainty** introduced due to **key parameter** not well known

Still work in progress, especially uncertainty calculation

precursor ^{97}Sr

$\lambda = 429 \pm 5$ ms

$FY_{rel} = 0.3$



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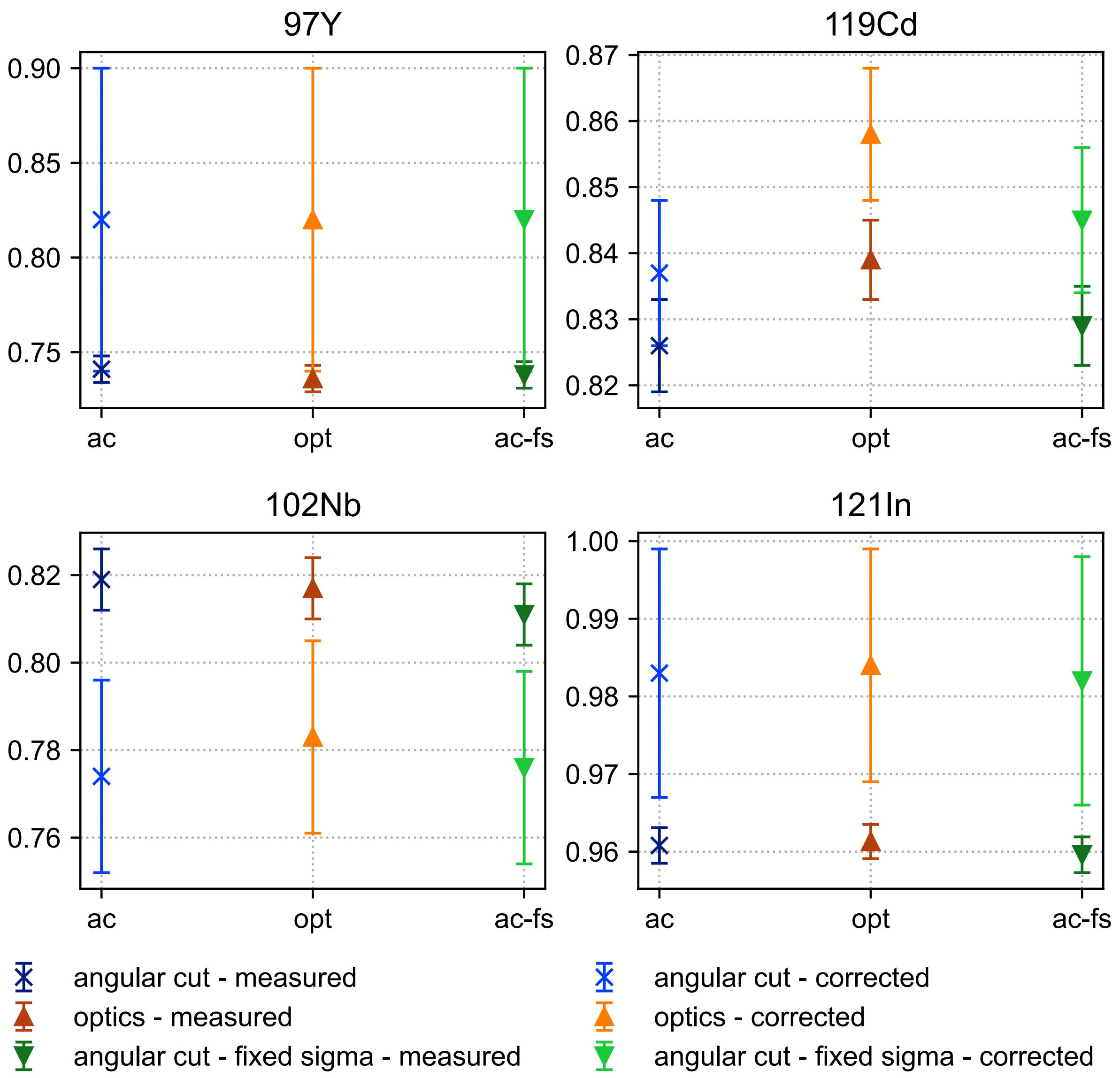

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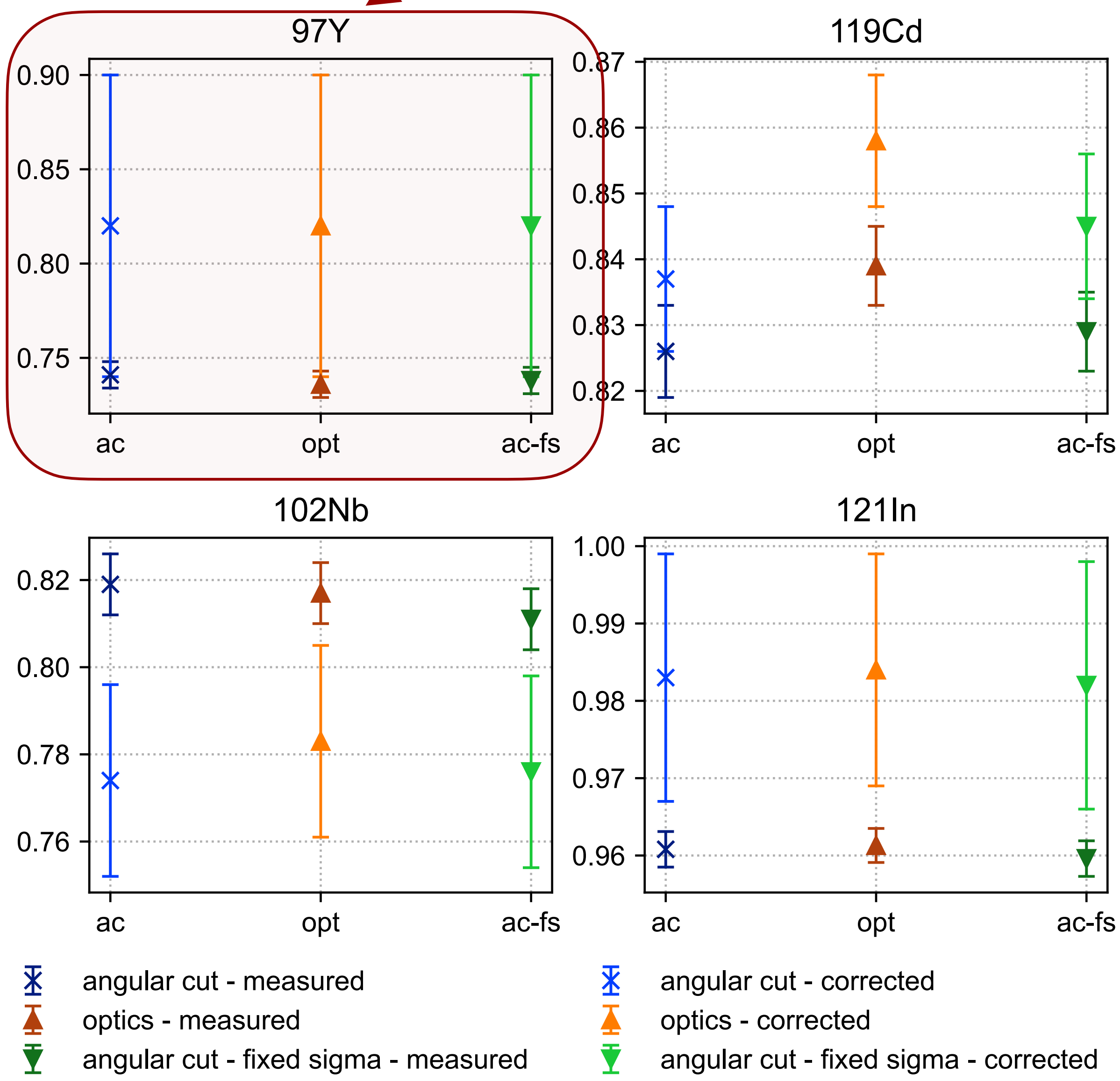

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Conclusions and future development

- Conclusions:
  - Close to final results
  - Interesting physics and results ahead
- Future development:
  - Complete analysis:
    - extend study to other nuclei
    - compare standard and mirrored results
  - Physical interpretation:
    - compare to other systems, especially $^{233}U(n_{th}, f)$
    - look for systematic behaviours and differences
  - Calculate angular momentum

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Thank you for the attention!

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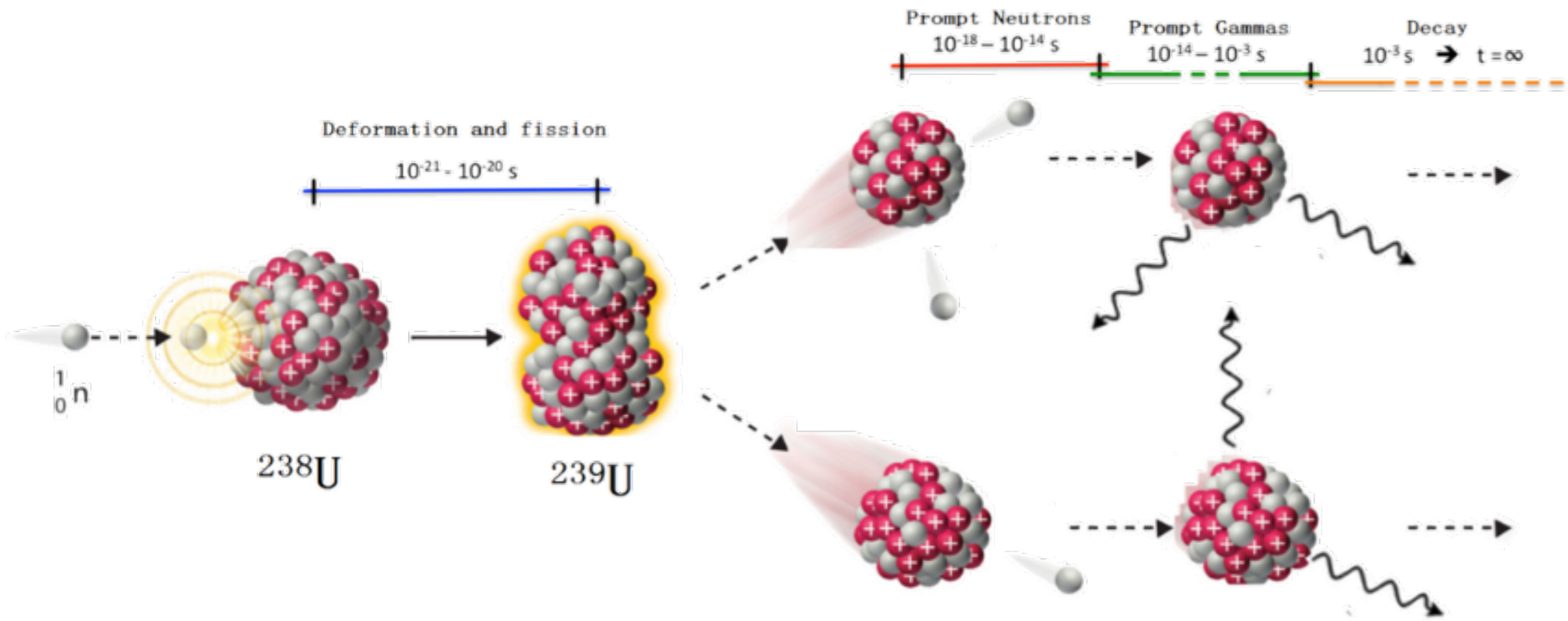
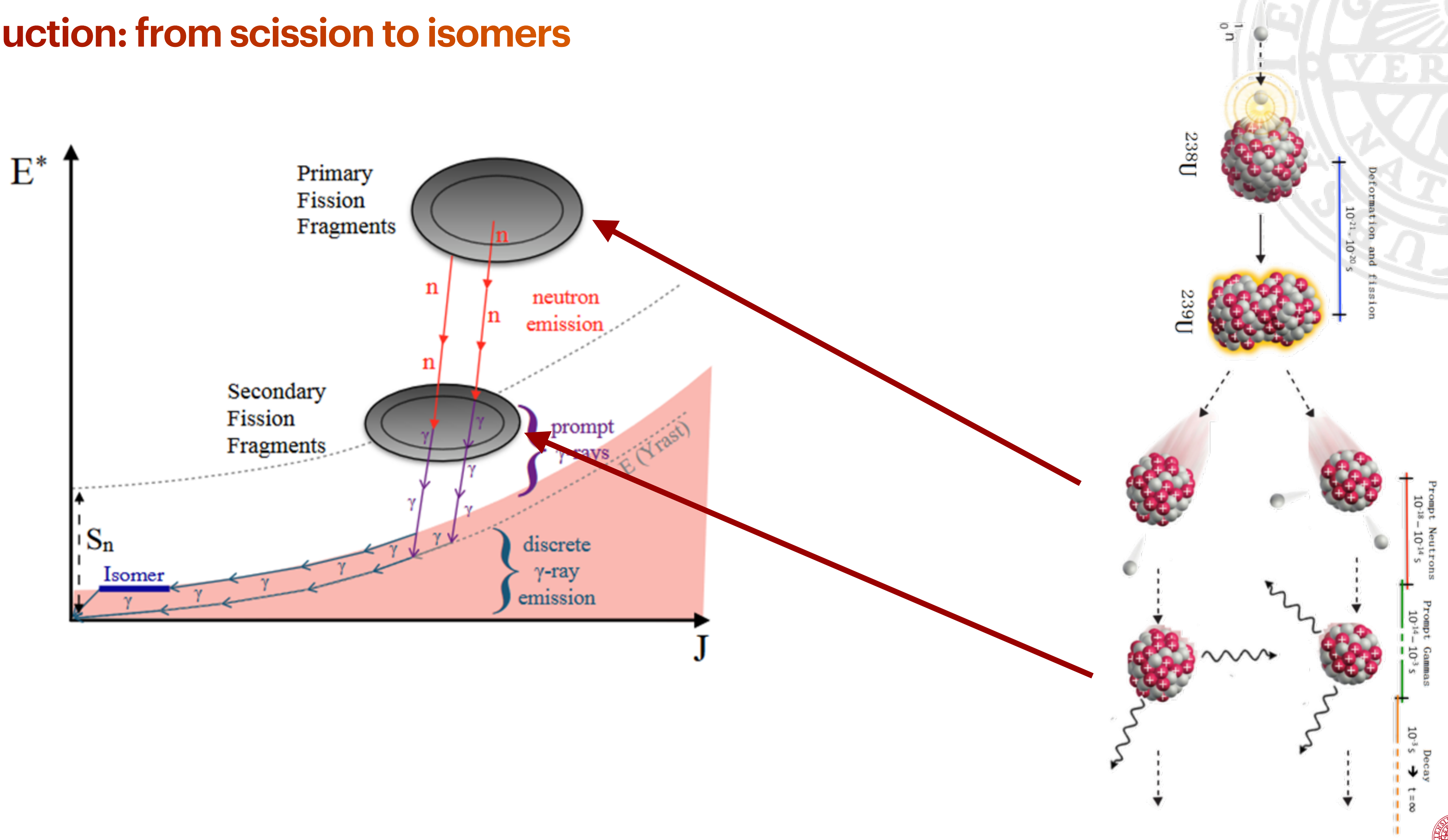
Introduction: from scission to isomers



Fundamental question: where does angular momentum of fission fragments come from?

Introduction: from scission to isomers



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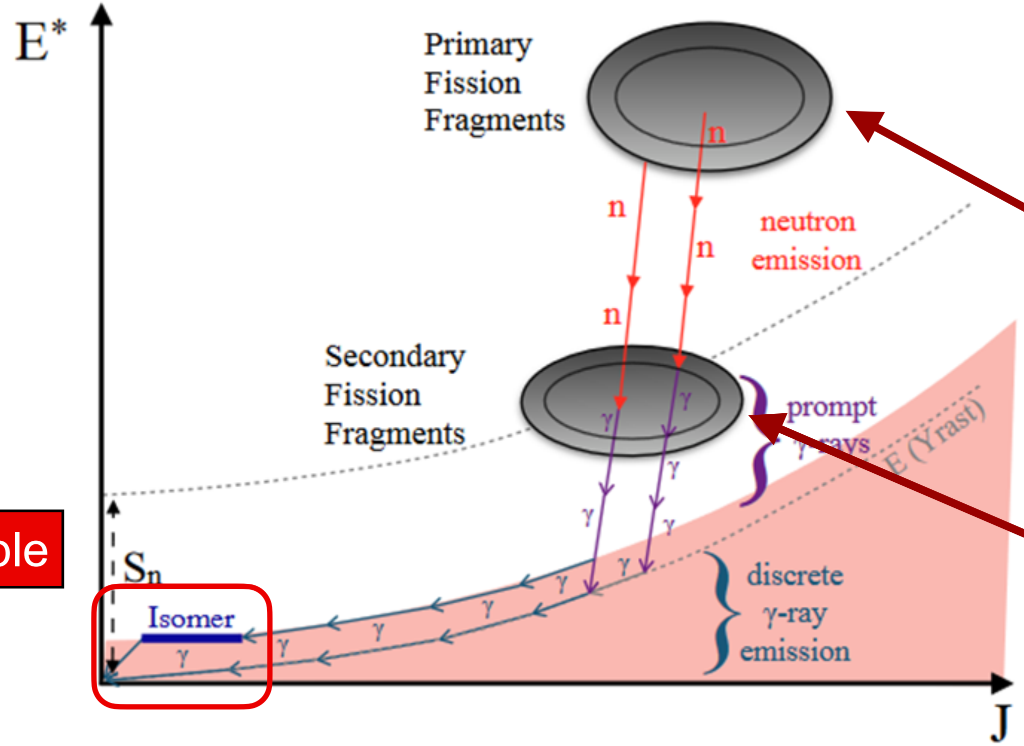
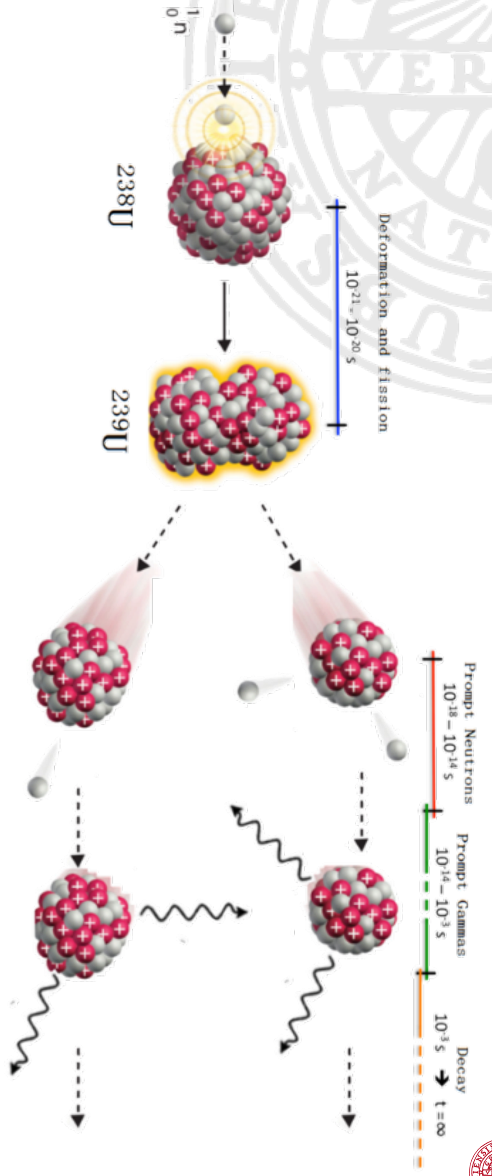


measurable



Isomers are excited **meta-stable states** of a nucleus

Yields depend on angular momentum and can be calculated

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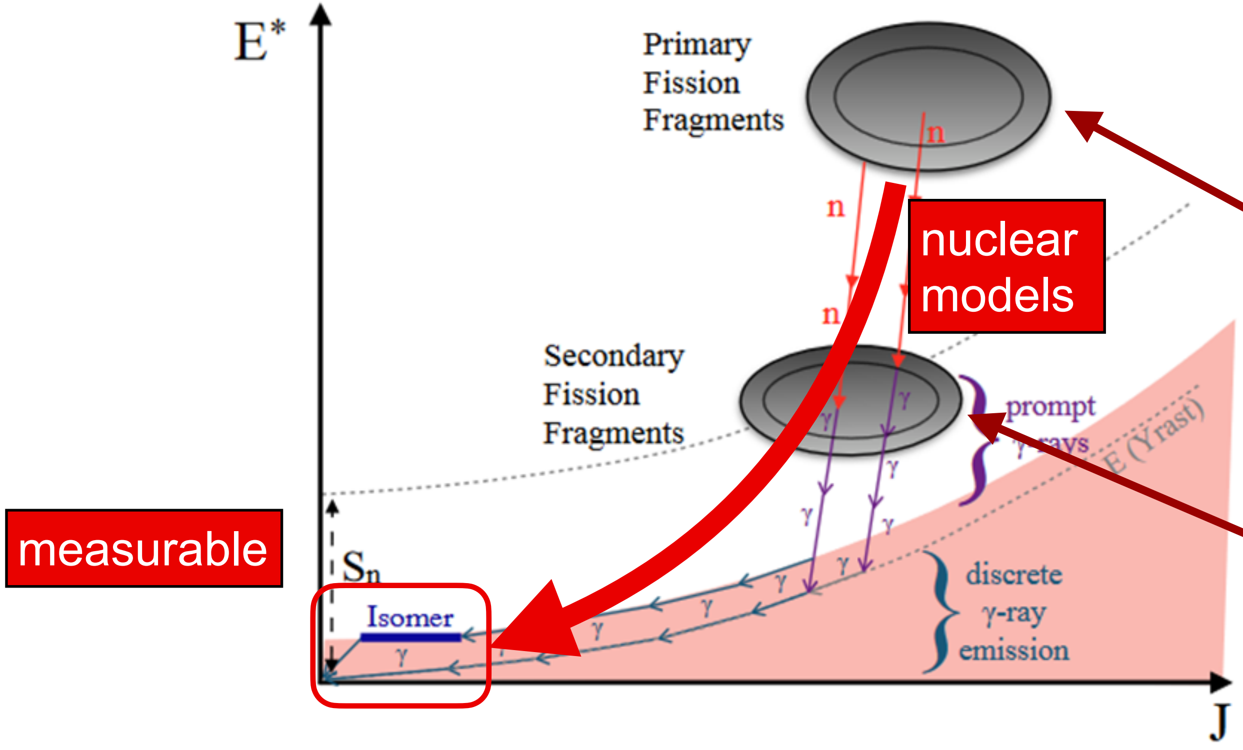
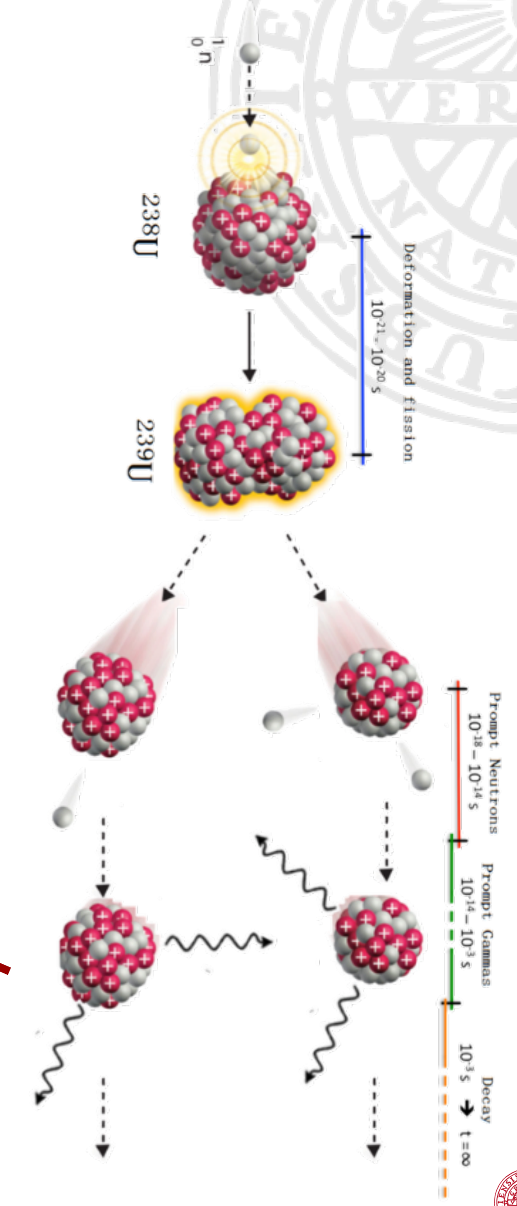
Introduction: from scission to isomers





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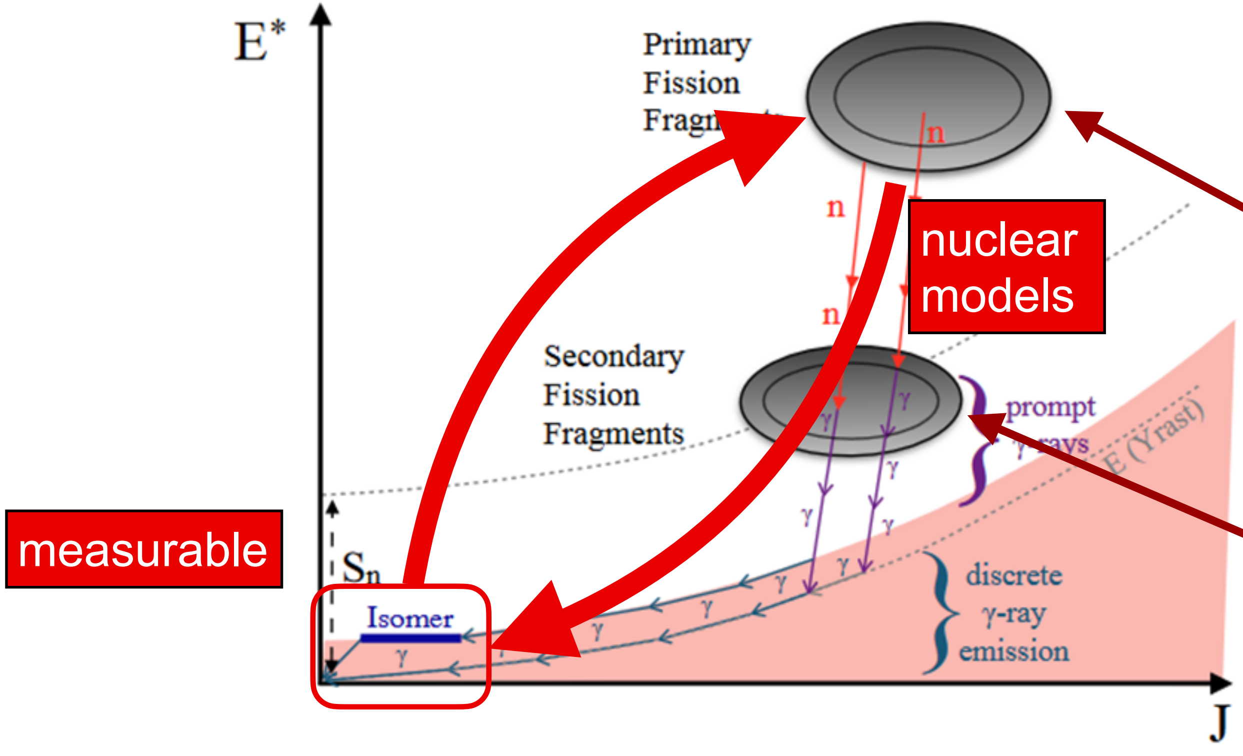

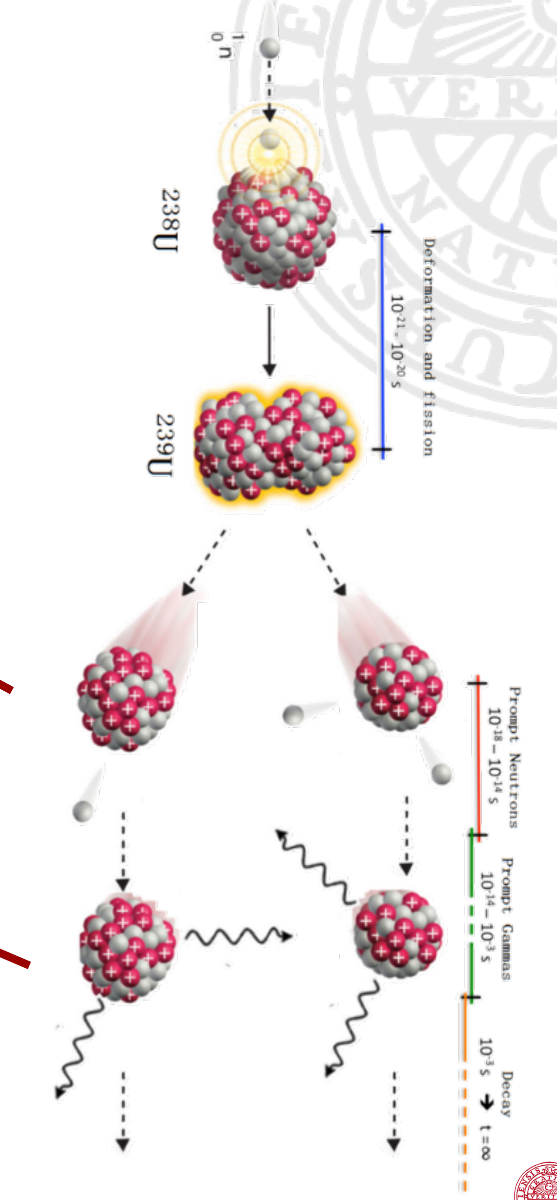

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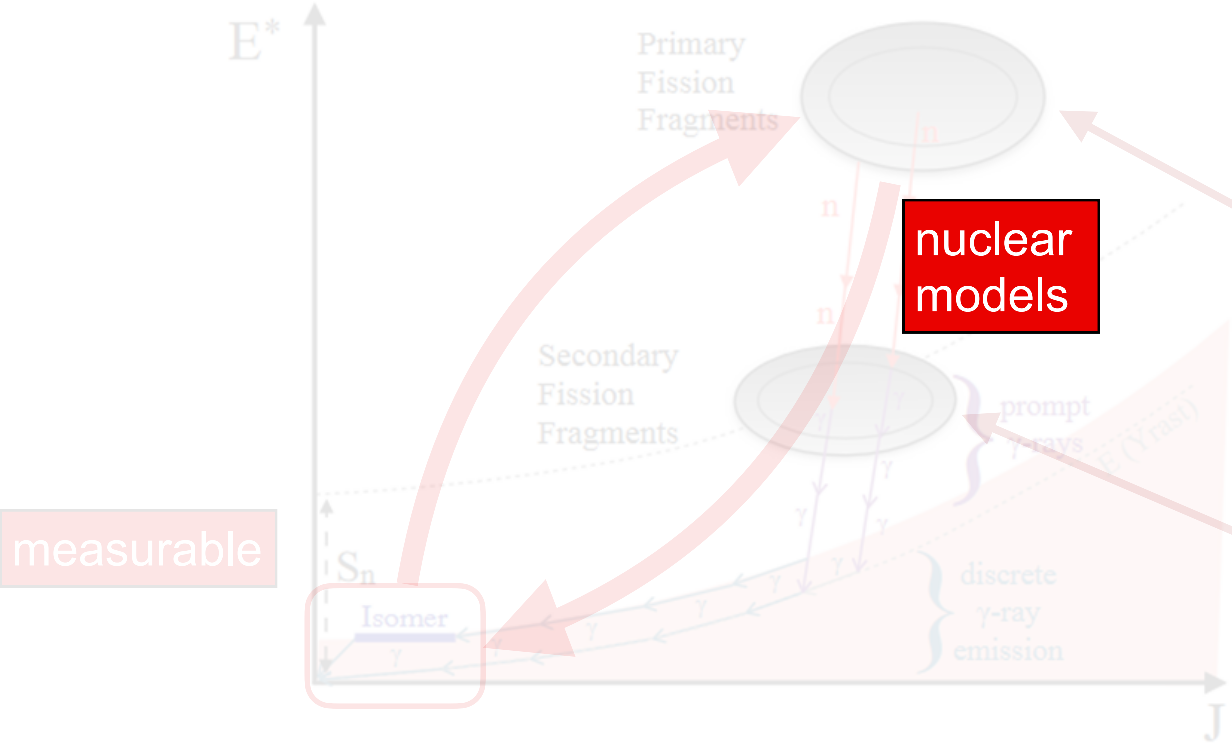


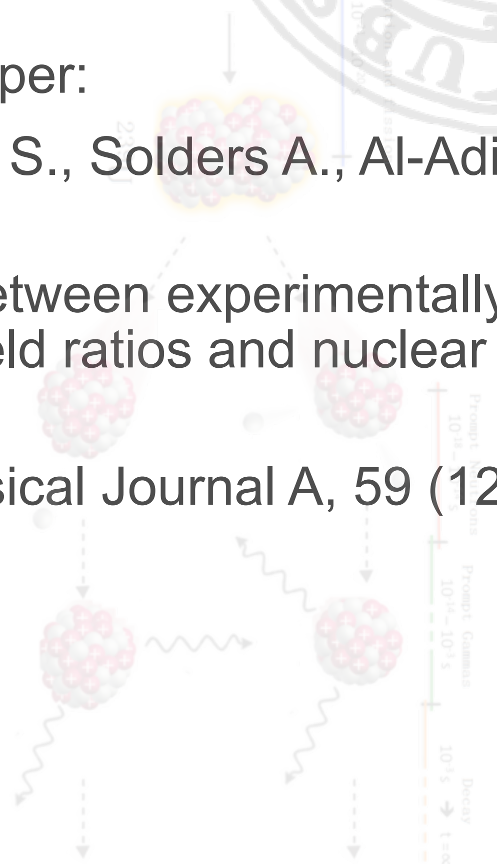
Current efforts on this

Recently published paper:

Cannarozzo S., Pomp S., Solders A., Al-Adili A., Göök A., Koning A.

“Global comparison between experimentally measured isomeric yield ratios and nuclear model calculations”

(2023) European Physical Journal A, 59 (12), art. no. 295



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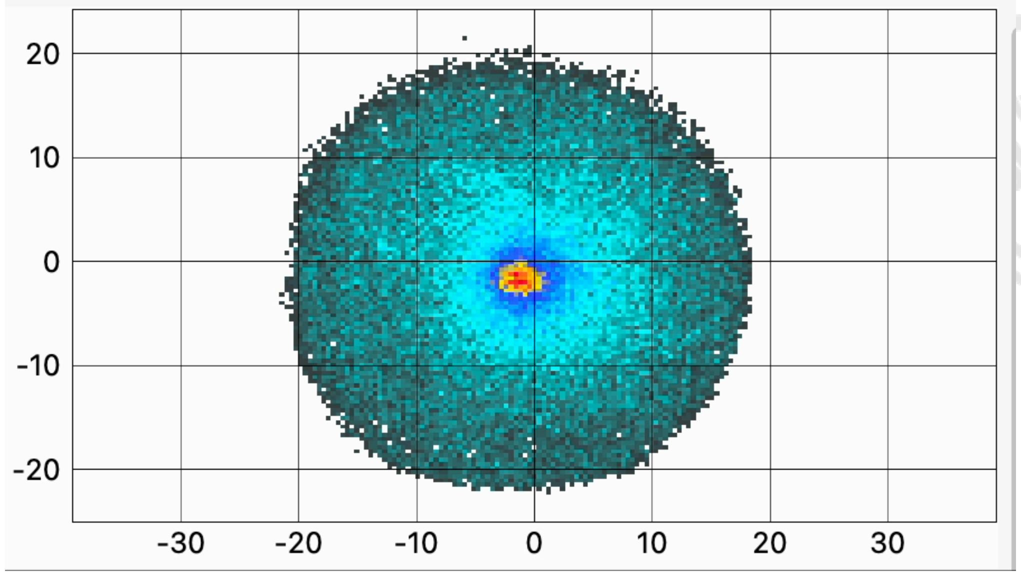
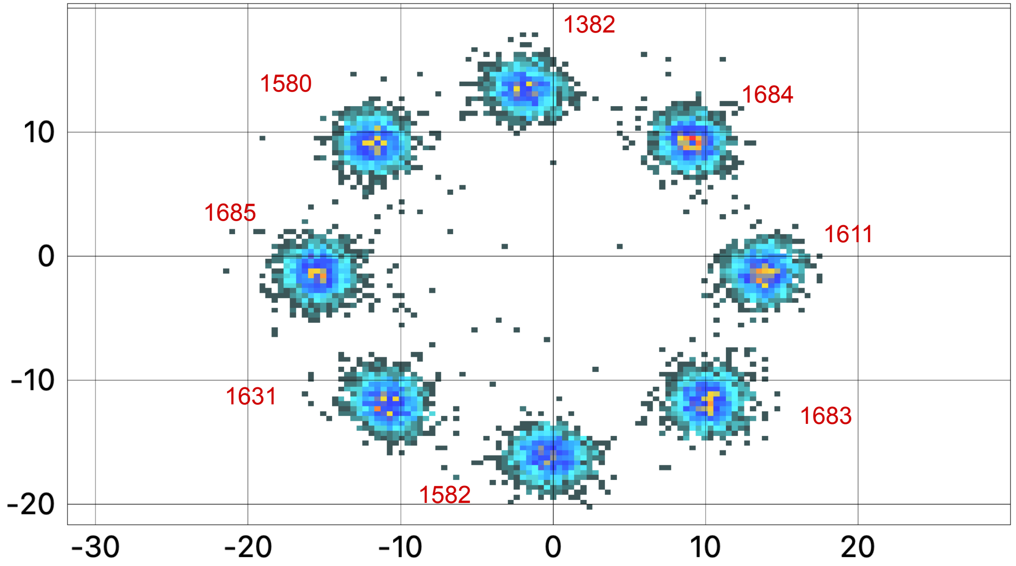
Yields depend on angular momentum and can be calculated

Experimental - MCP sensitivity

- Measurements of possible differences in sensitivity
- Two ways:
  - Circular:
    - Radius progressively changed (by changing extraction time)
    - Gives global info
    - Method different than one used for measurement
  - Spots:
    - Radius progressively changed (by changing accumulation time)
    - Gives more local info
    - Method (and positions spots) similar to real one





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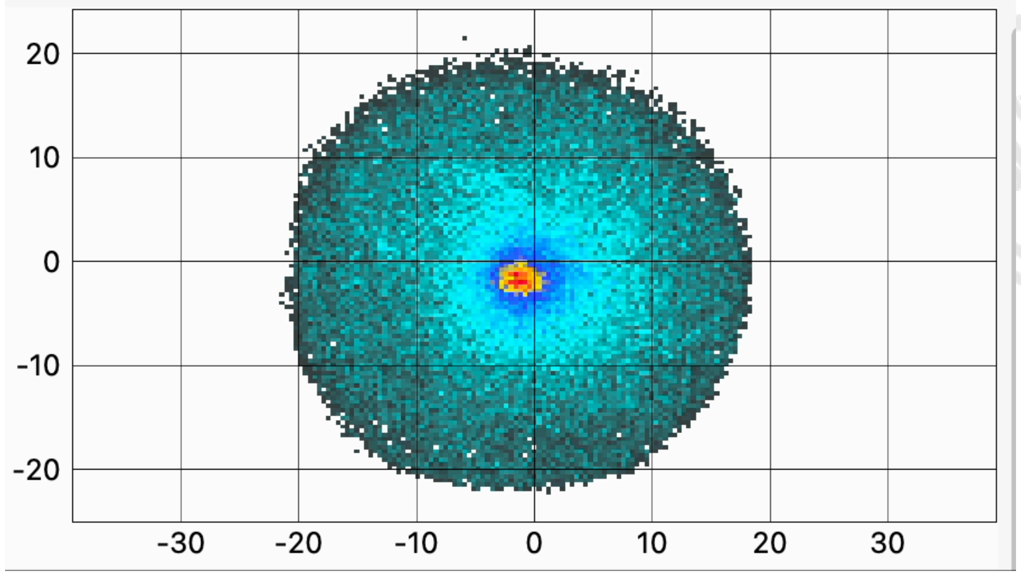

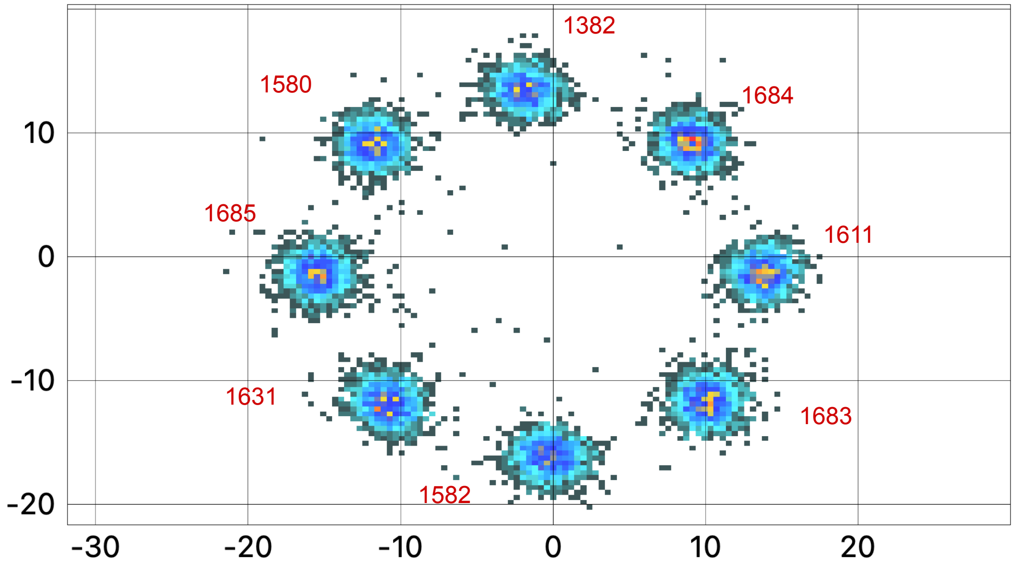

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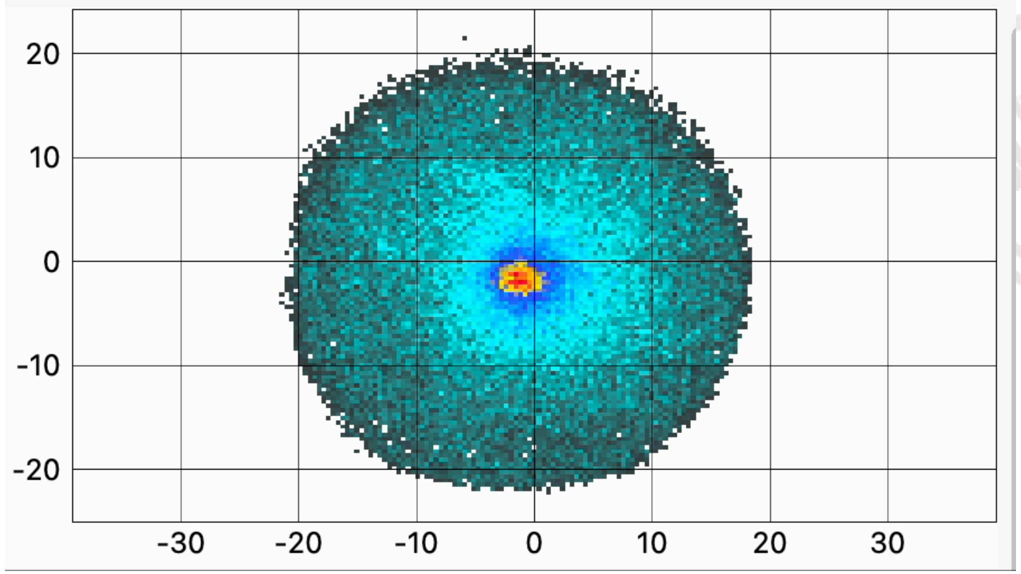

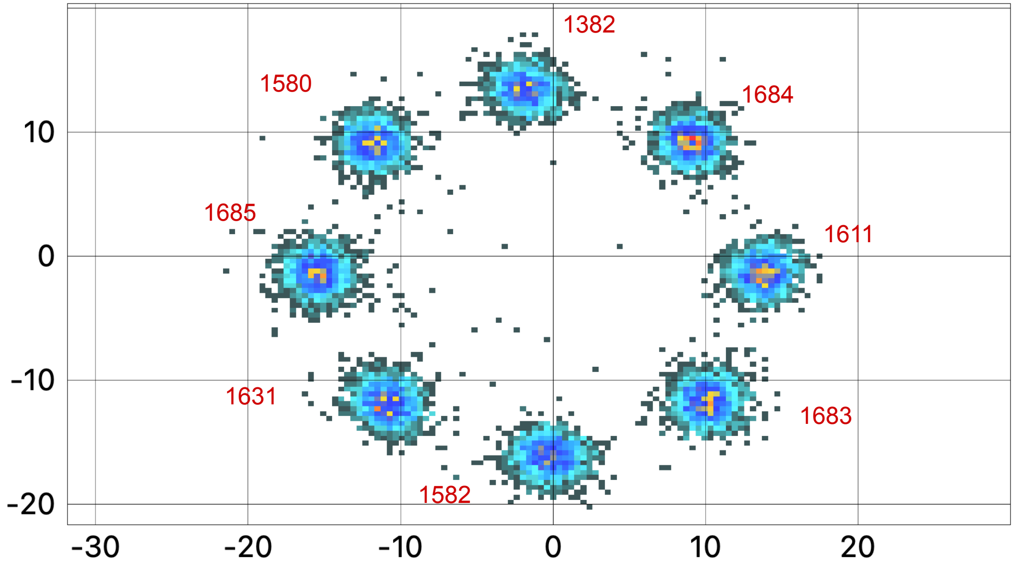

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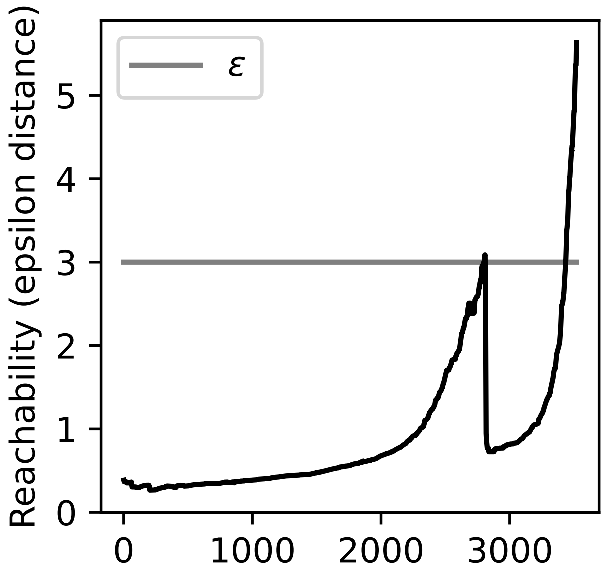
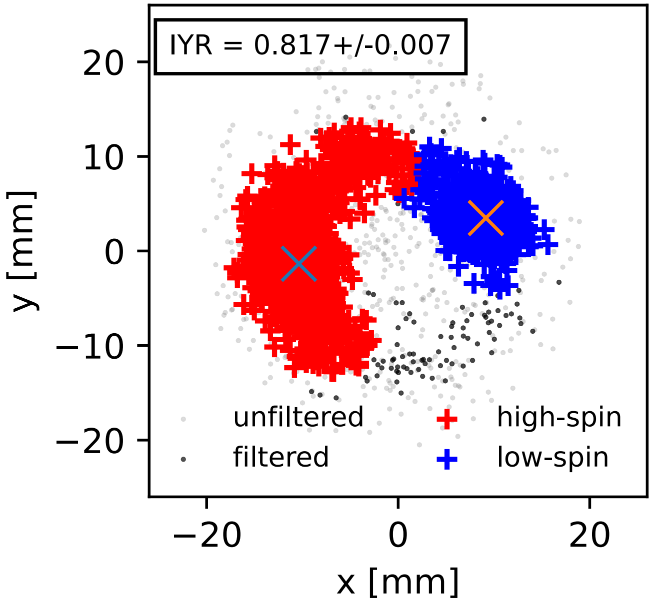
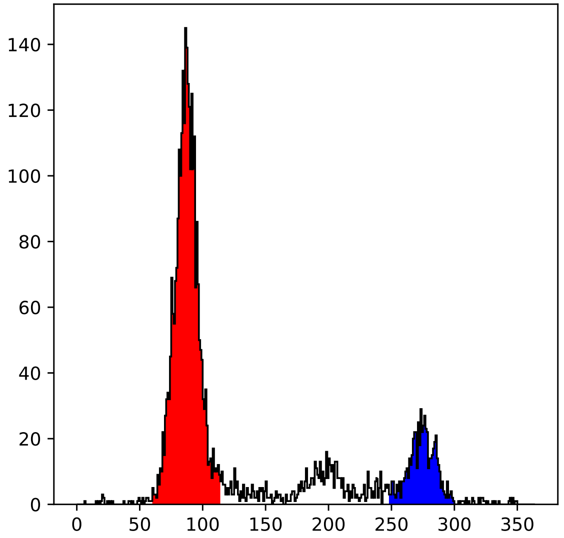


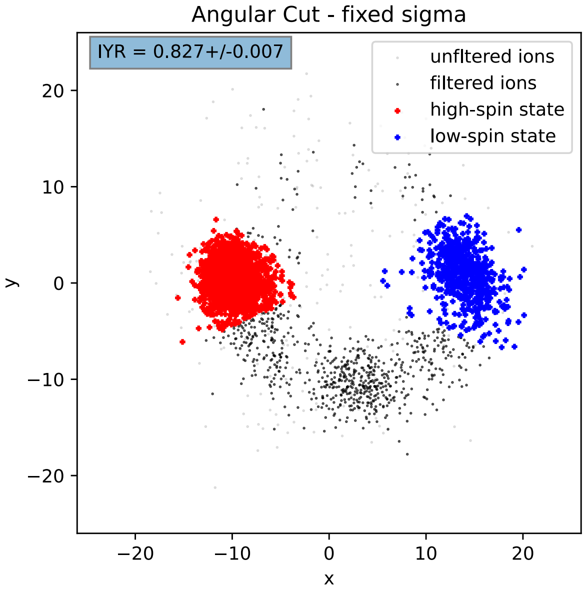
ε
Reachability (epsilon distance)
0
1
2
3
4
5
0
1000
2000
3000

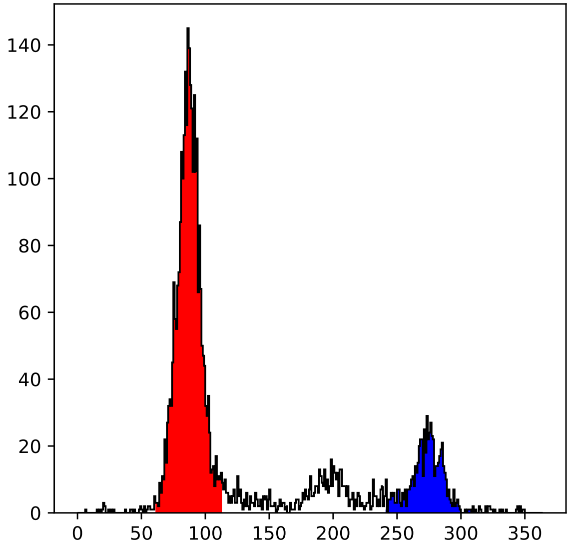


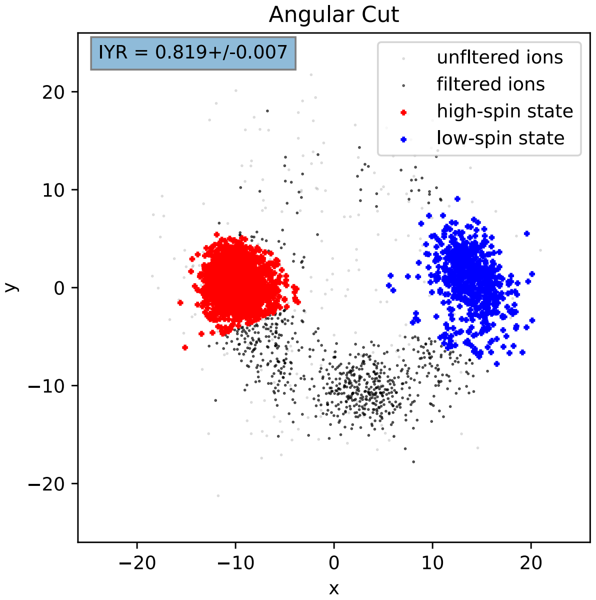
IYR = 0.817+/-0.007
y [mm]
x [mm]
20
10
0
−10
−20
unfiltered
filtered
high-spin
low-spin

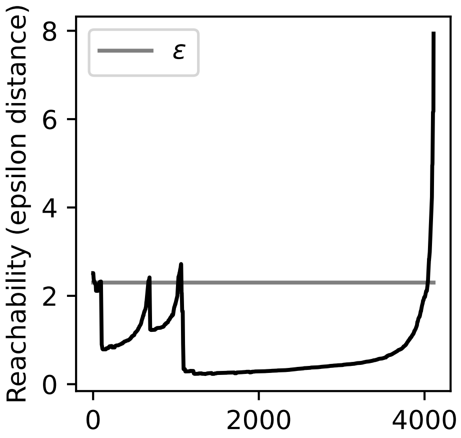
119Cd

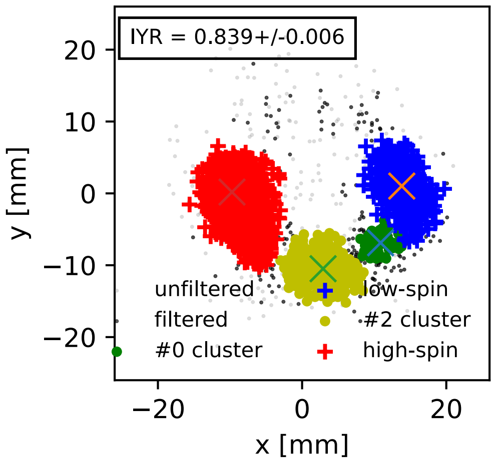

140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350


Angular Cut - fixed sigma
IYR = 0.827+/-0.007
unfltered ions
filtered ions
high-spin state
low-spin state
y
x

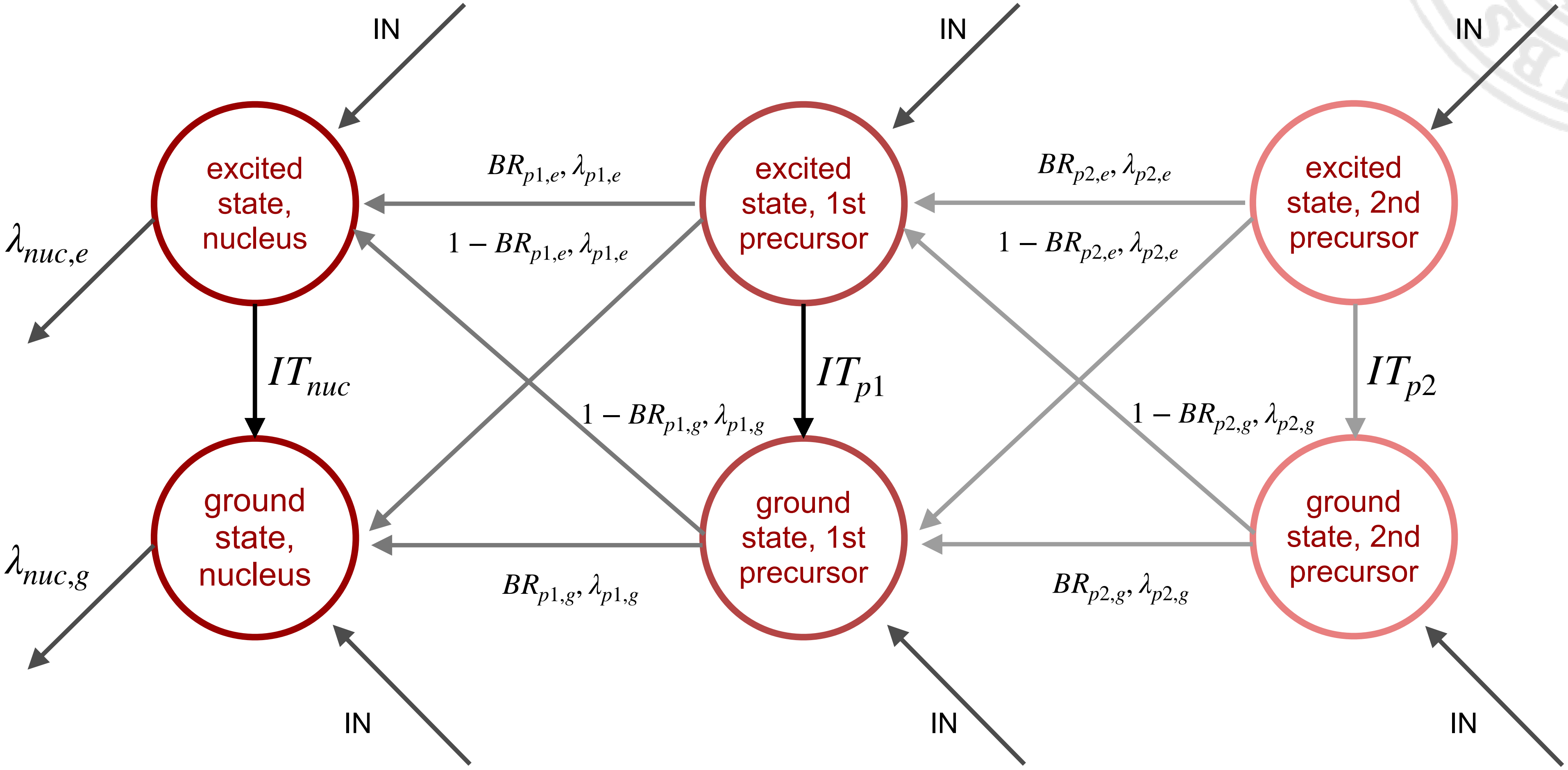

140
120
100
80
60
40
20
0
0
50
100
150
200
250
300
350


Angular Cut
IYR = 0.819+/-0.007
unfltered ions
filtered ions
high-spin state
low-spin state
y
x


Reachability (epsilon distance)
ε
0
2000
4000


IYR = 0.839+/-0.006
y [mm]
x [mm]
unfiltered
filtered
#0 cluster
low-spin
#2 cluster
high-spin

Decay correction: possible transitions



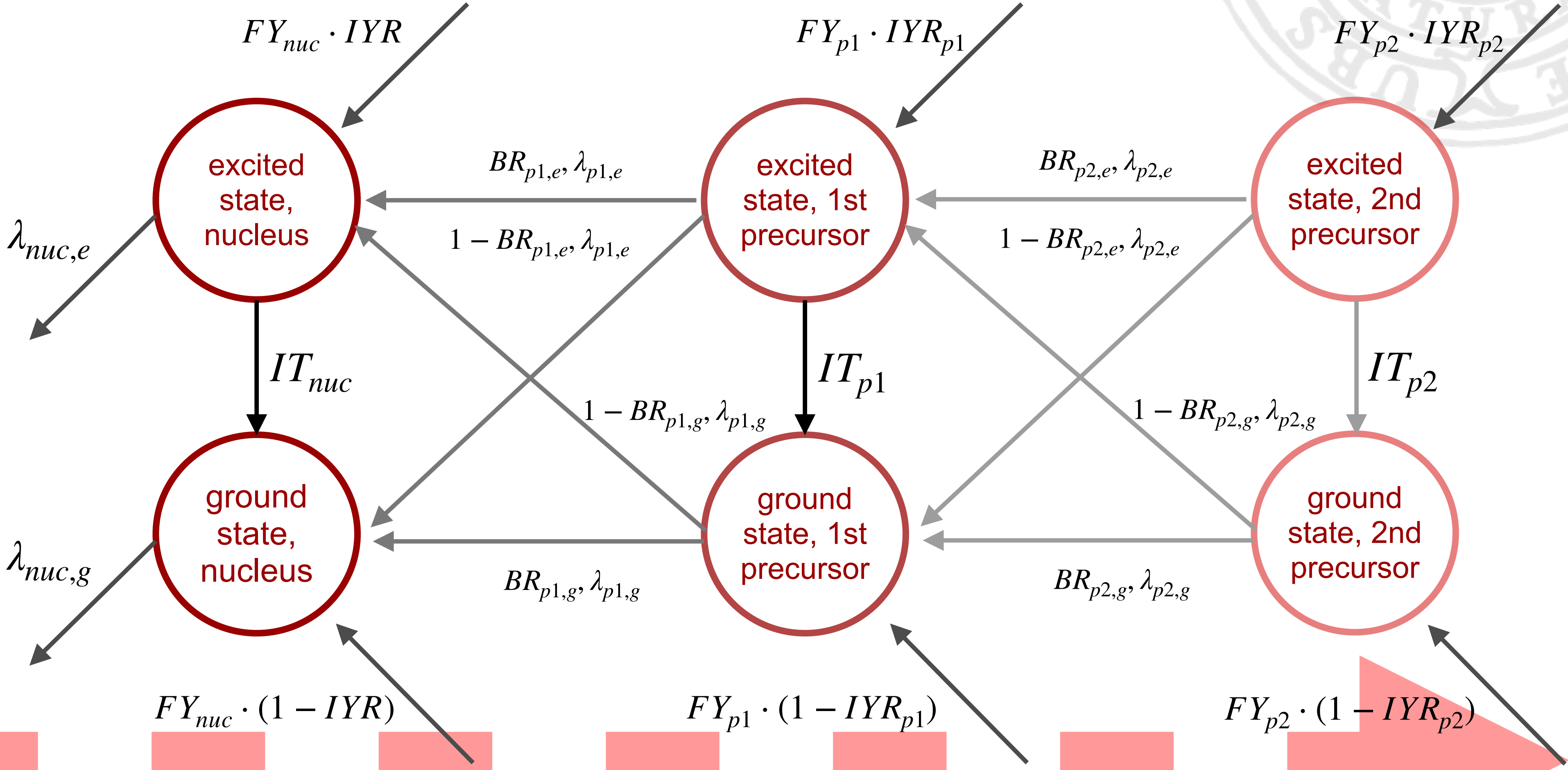
Decay correction: different steps

Gas Cell	RFQ - ion buncher	Purification trap	Precision trap
ions continuously produced in fission events	ions trapped, incoming beam from gas cell	ions trapped, no incoming beam, still precursors present	ions trapped, no incoming beam, no precursors present

Decay correction: different steps

Gas Cell

ions continuously produced in fission events

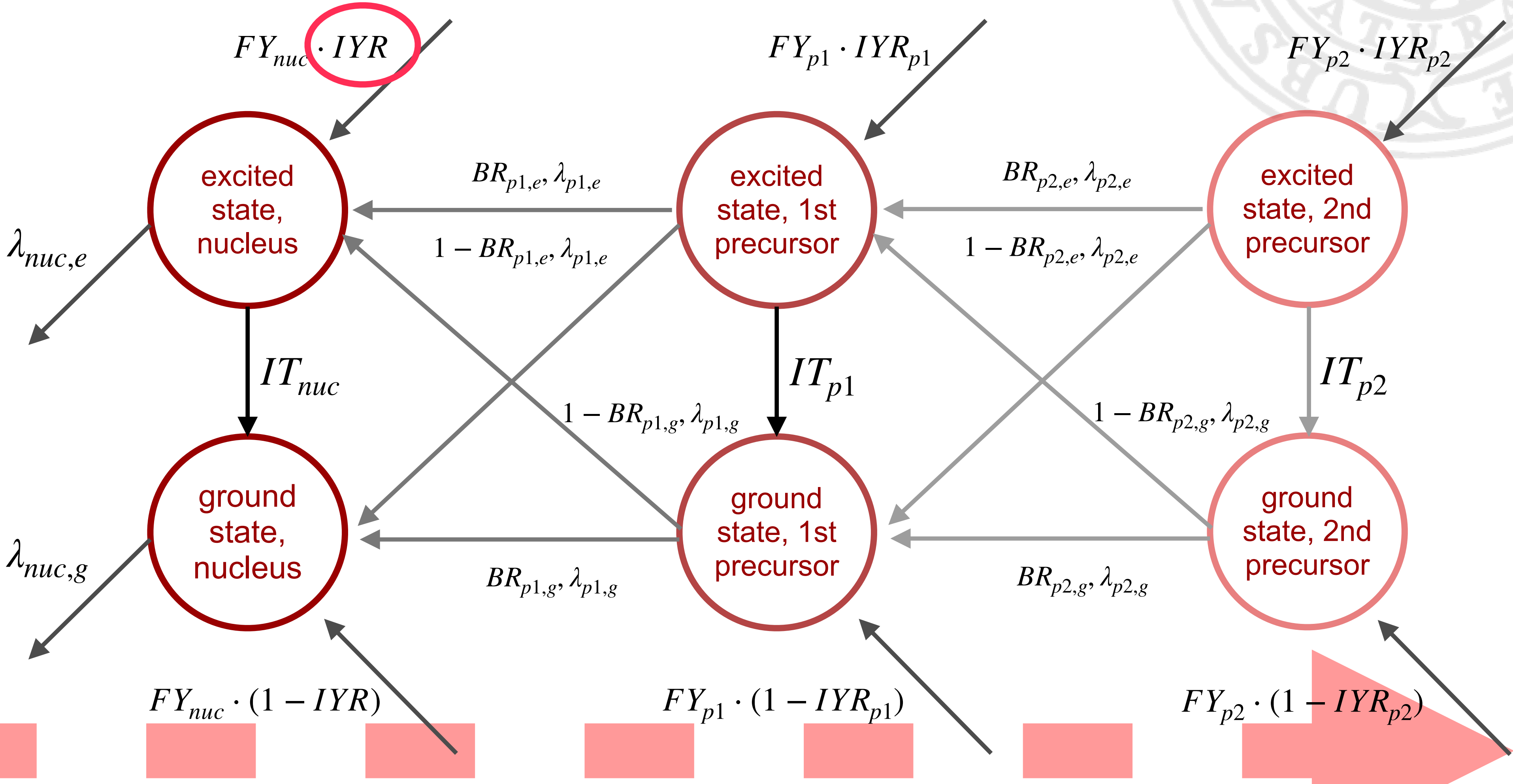


Decay correction: different steps

THIS IS WHAT WE LOOK FOR!

Gas Cell

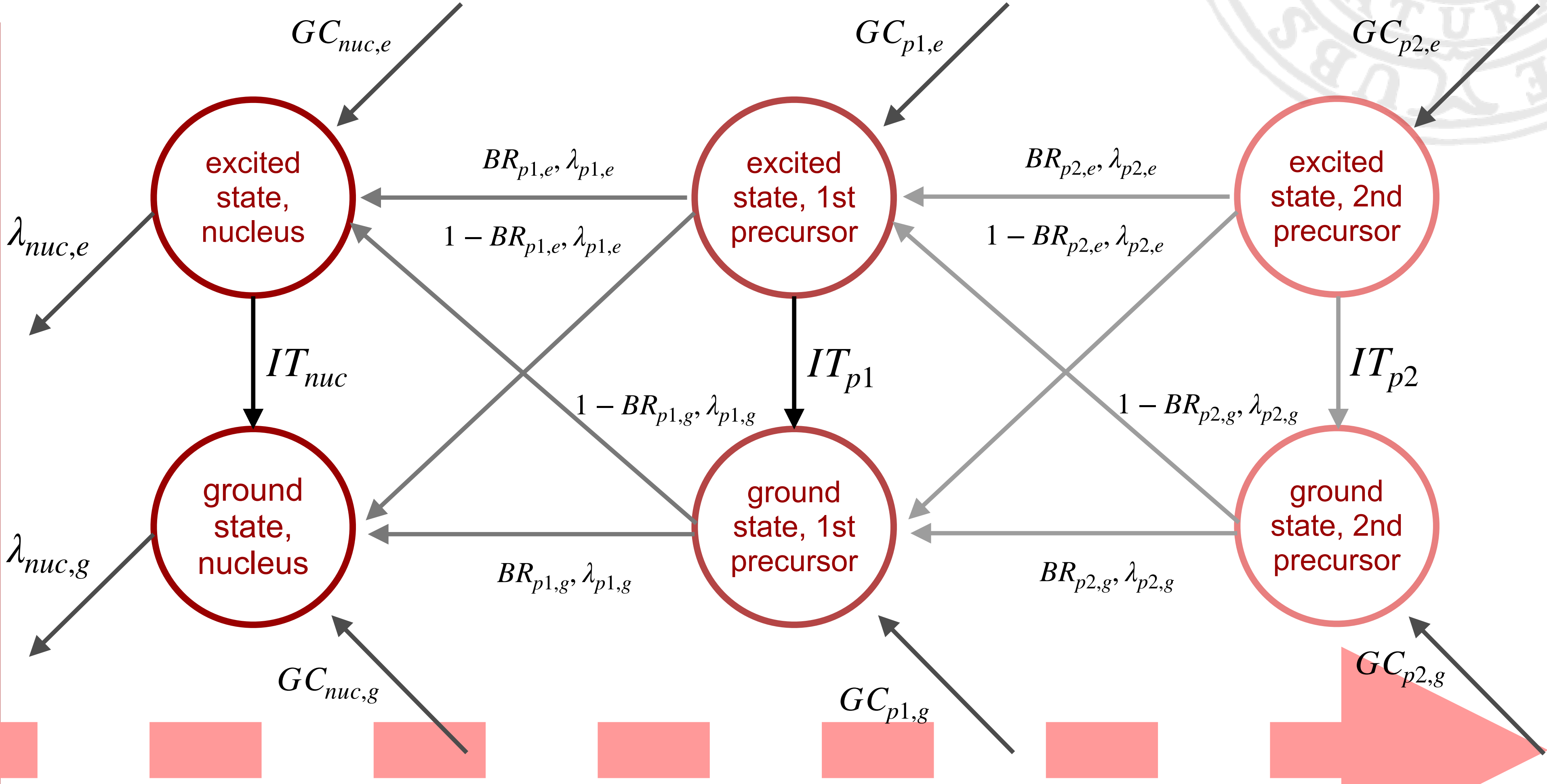
ions continuously produced in fission events



Decay correction: different steps

RFQ - ion buncher

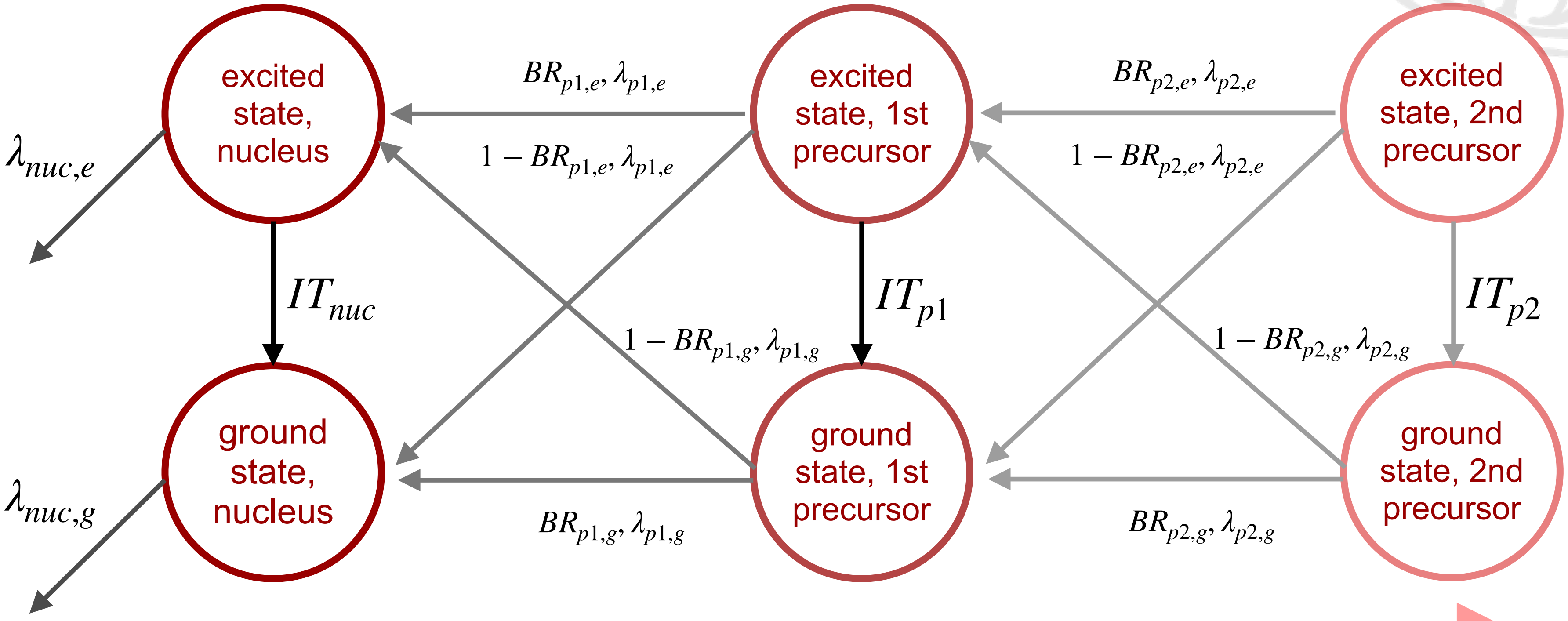
ions trapped, incoming beam from gas cell



Decay correction: different steps

Purification trap

ions trapped, no incoming beam, still precursors present



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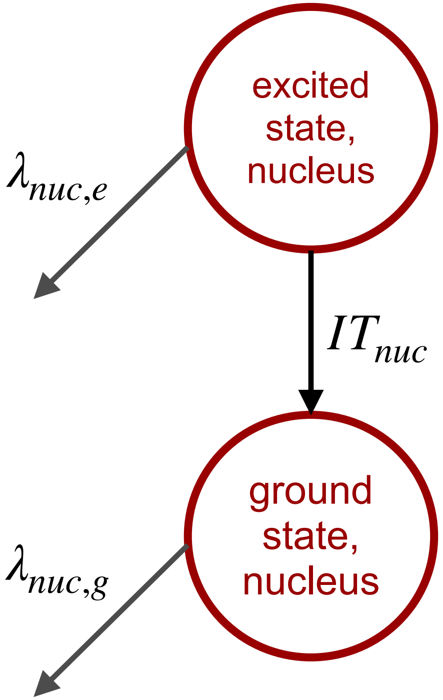
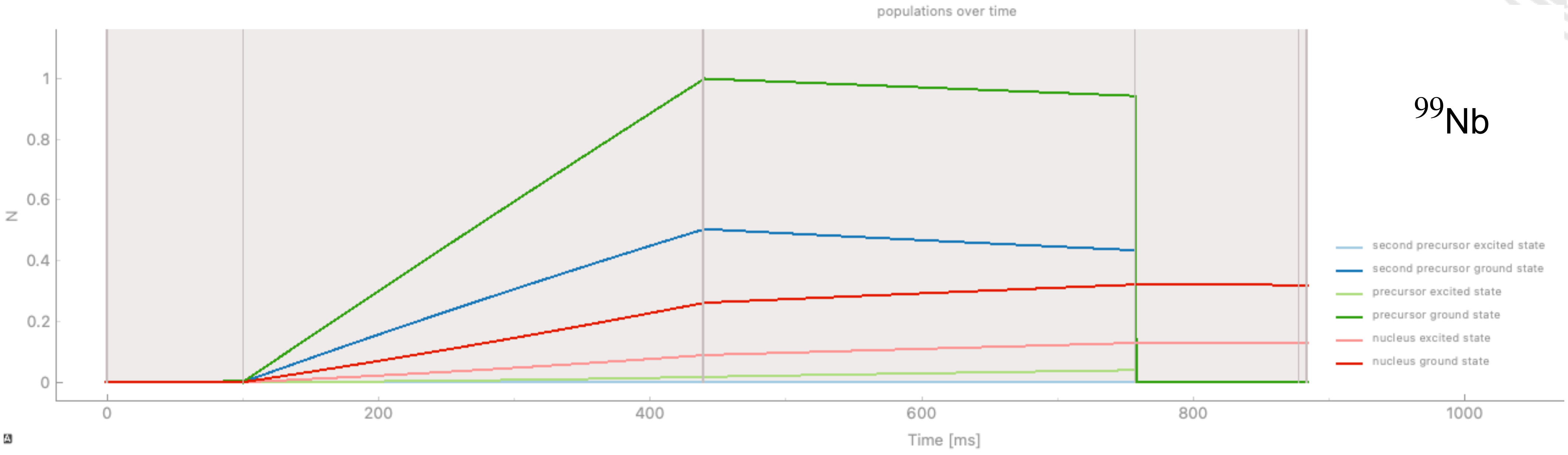
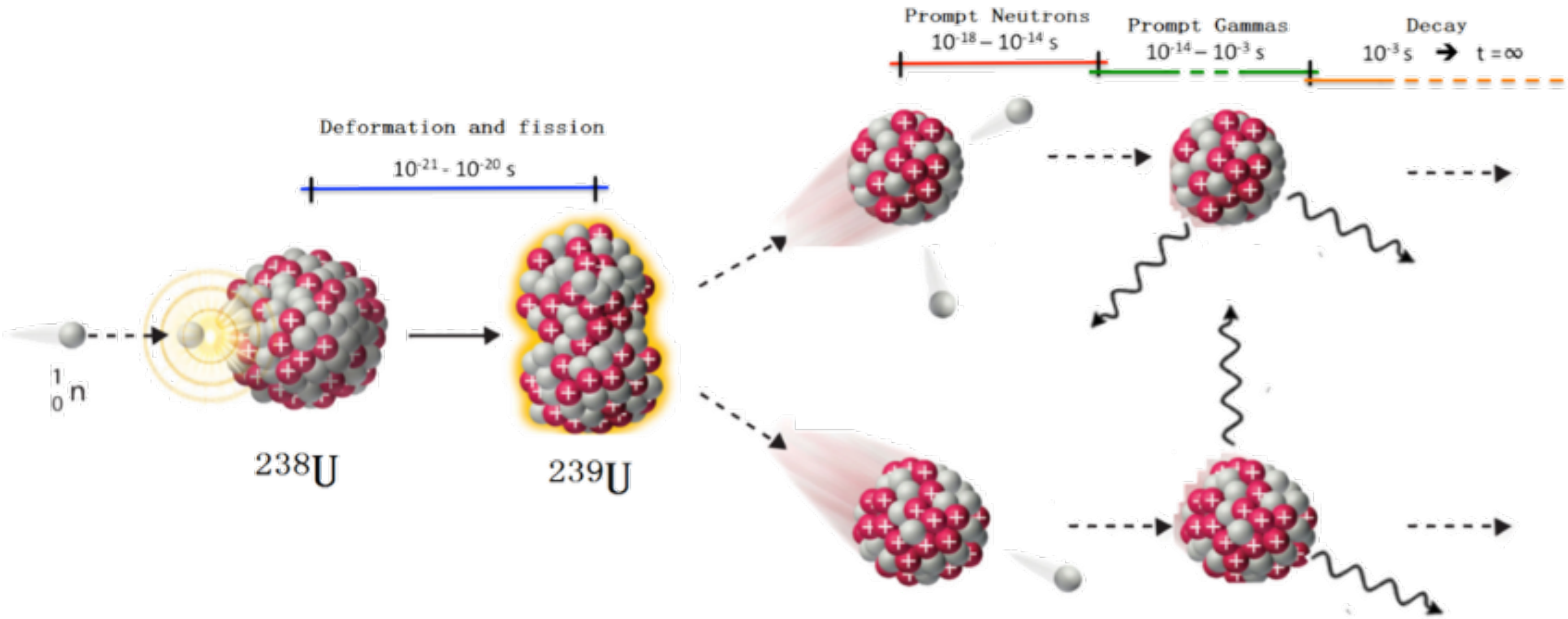



populations over time
N
Time [ms]
second precursor excited state
second precursor ground state
precursor excited state
precursor ground state
nucleus excited state
nucleus ground state

^{99}Nb

Introduction: fission



Fundamental question: where does angular momentum of fission fragments come from?