Double alpha decay

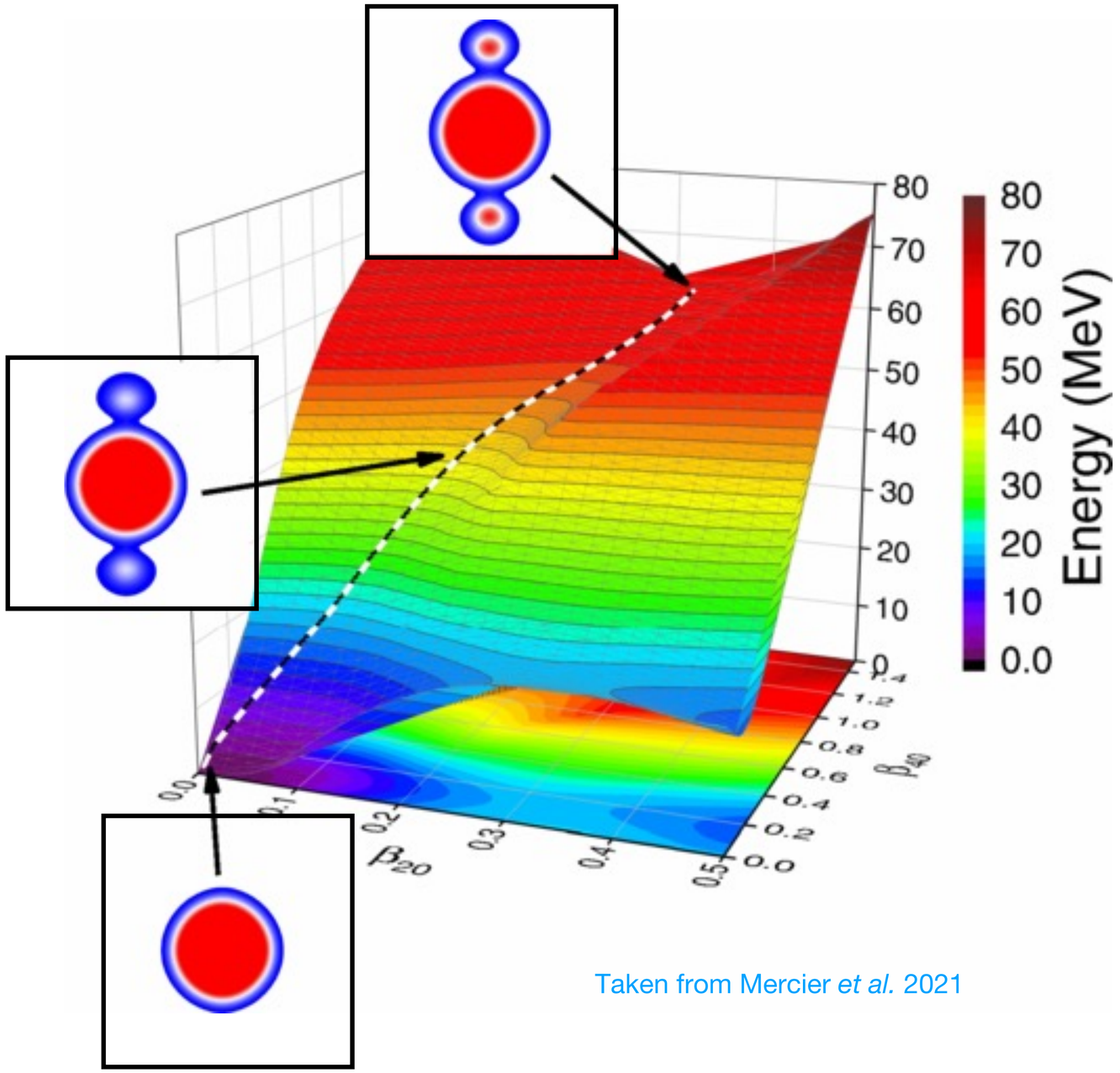
PHENIICS Fest 2023

L. Heitz

Henri Cartier-Bresson
Naples, 1960

Outline

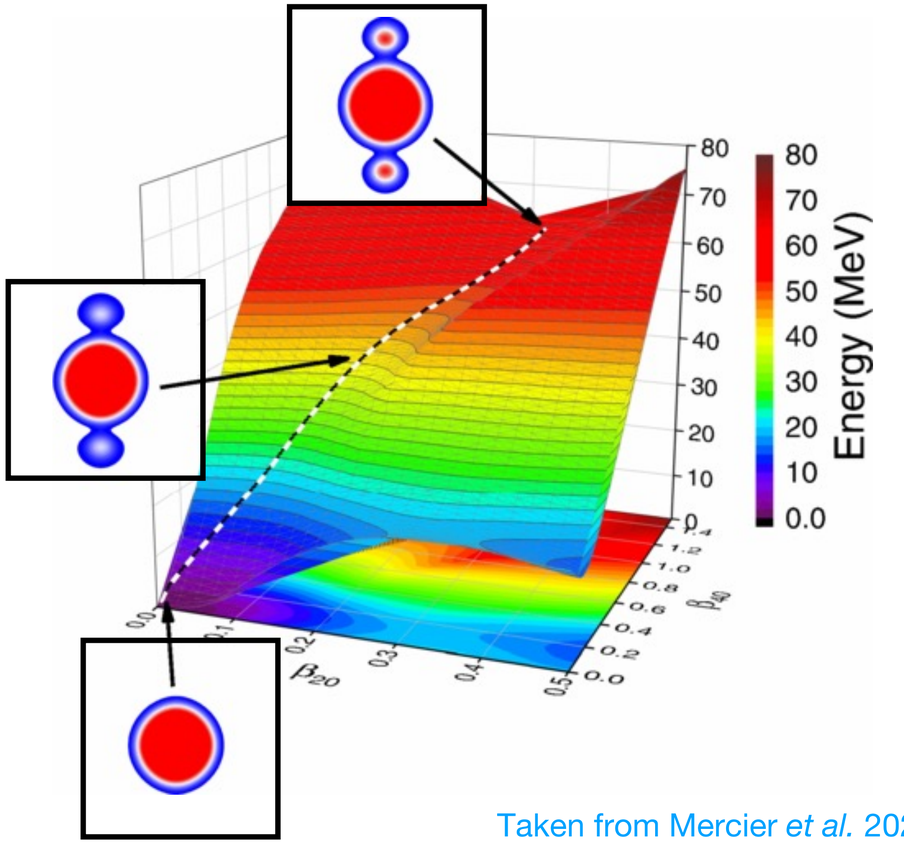
- Theoretical framework
- Experimental search for 2α
  - FRS Ion Catcher / GSI
  - Isolde, CERN / Saclay



Taken from Mercier *et al.* 2021

Theoretical framework

Microscopic description of radioactivity



Taken from Mercier *et al.* 2021

2021

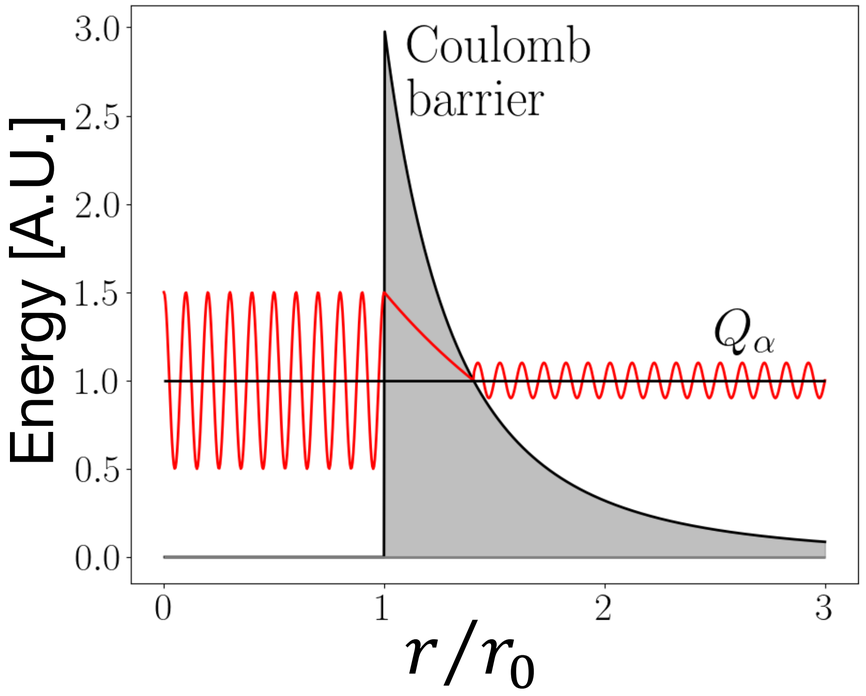
Theoretical framework

Alpha & double alpha radioactivities

Theoretical framework

Alpha & double alpha radioactivities

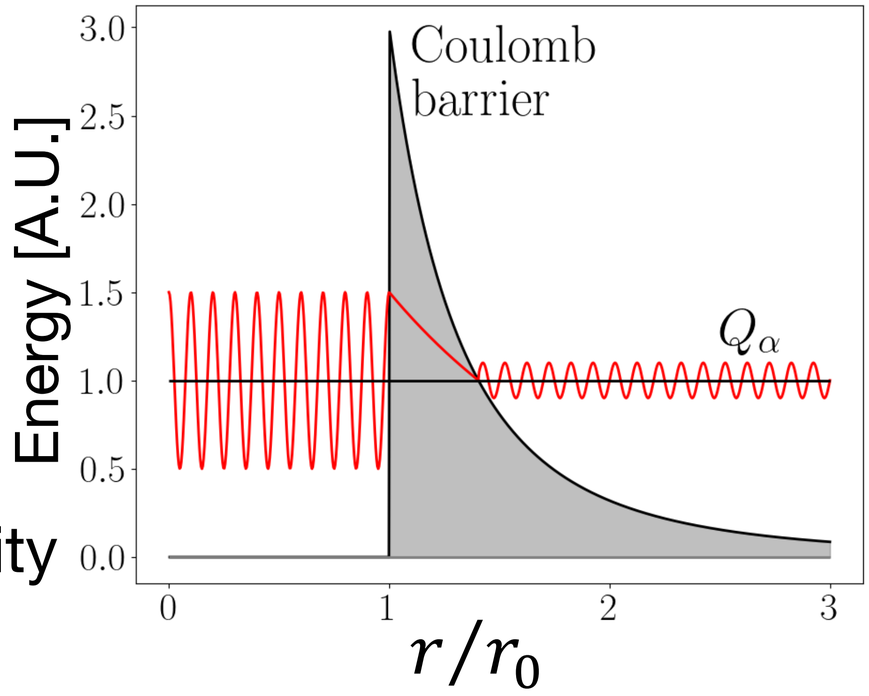
- **First model** for α decay : Gamow 1928 (tunneling)



Theoretical framework

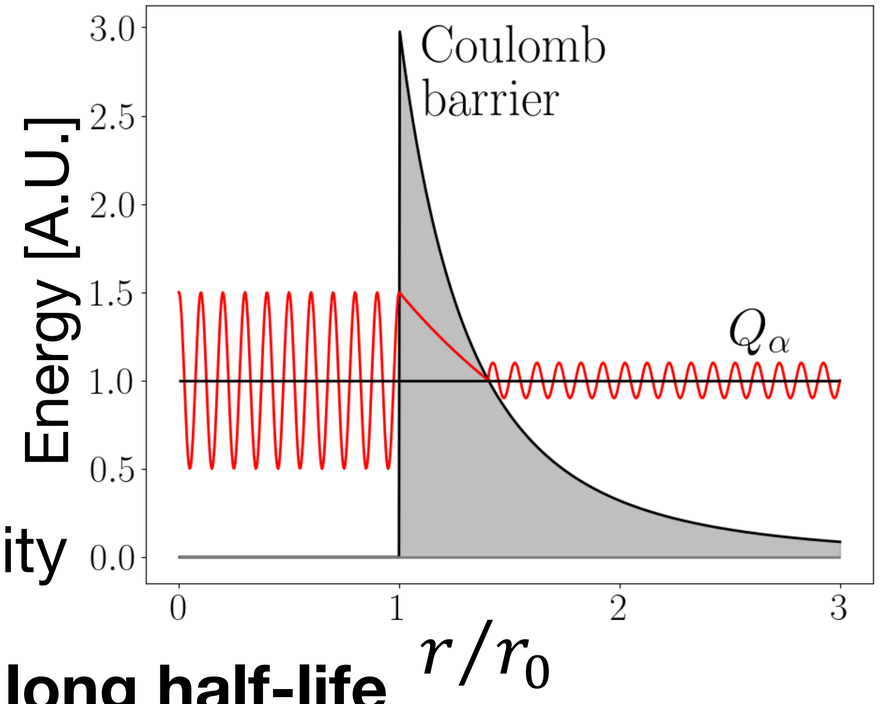
Alpha & double alpha radioactivities

- **First model** for α decay : Gamow 1928 (tunneling)
- **Phenomenological** models for alpha/cluster radioactivity

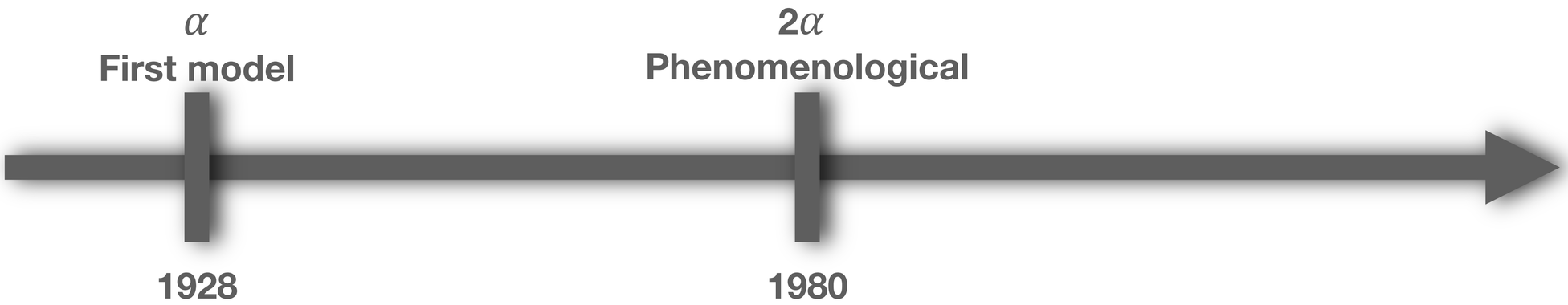


Theoretical framework

Alpha & double alpha radioactivities

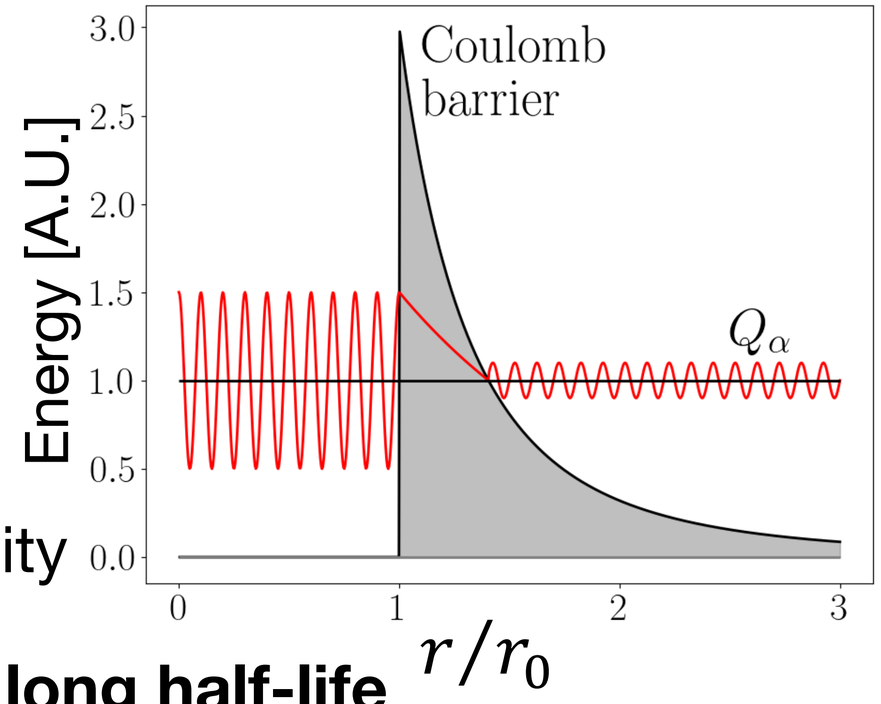


- **First model** for α decay : Gamow 1928 (tunneling)
- **Phenomenological** models for alpha/cluster radioactivity
- **First prediction for 2α :** Poenaru 1980 , ^{8}Be-like, **very long half-life**

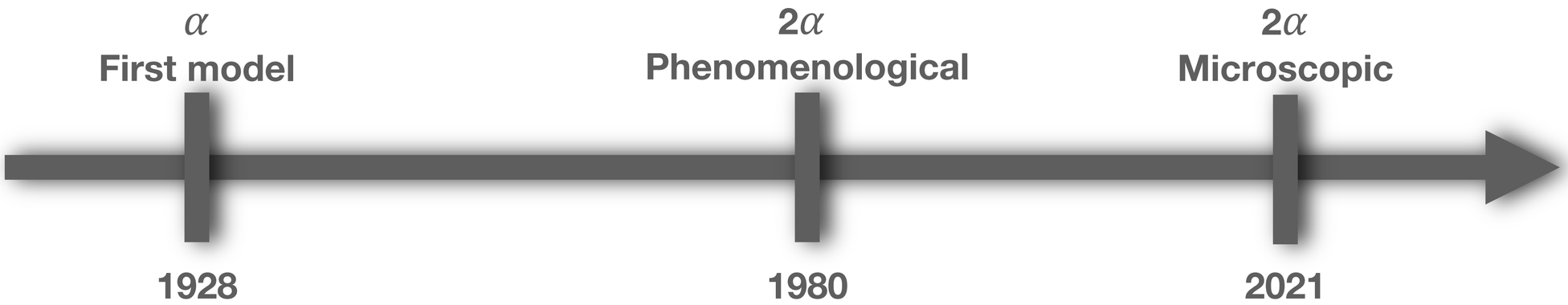


Theoretical framework

Alpha & double alpha radioactivities

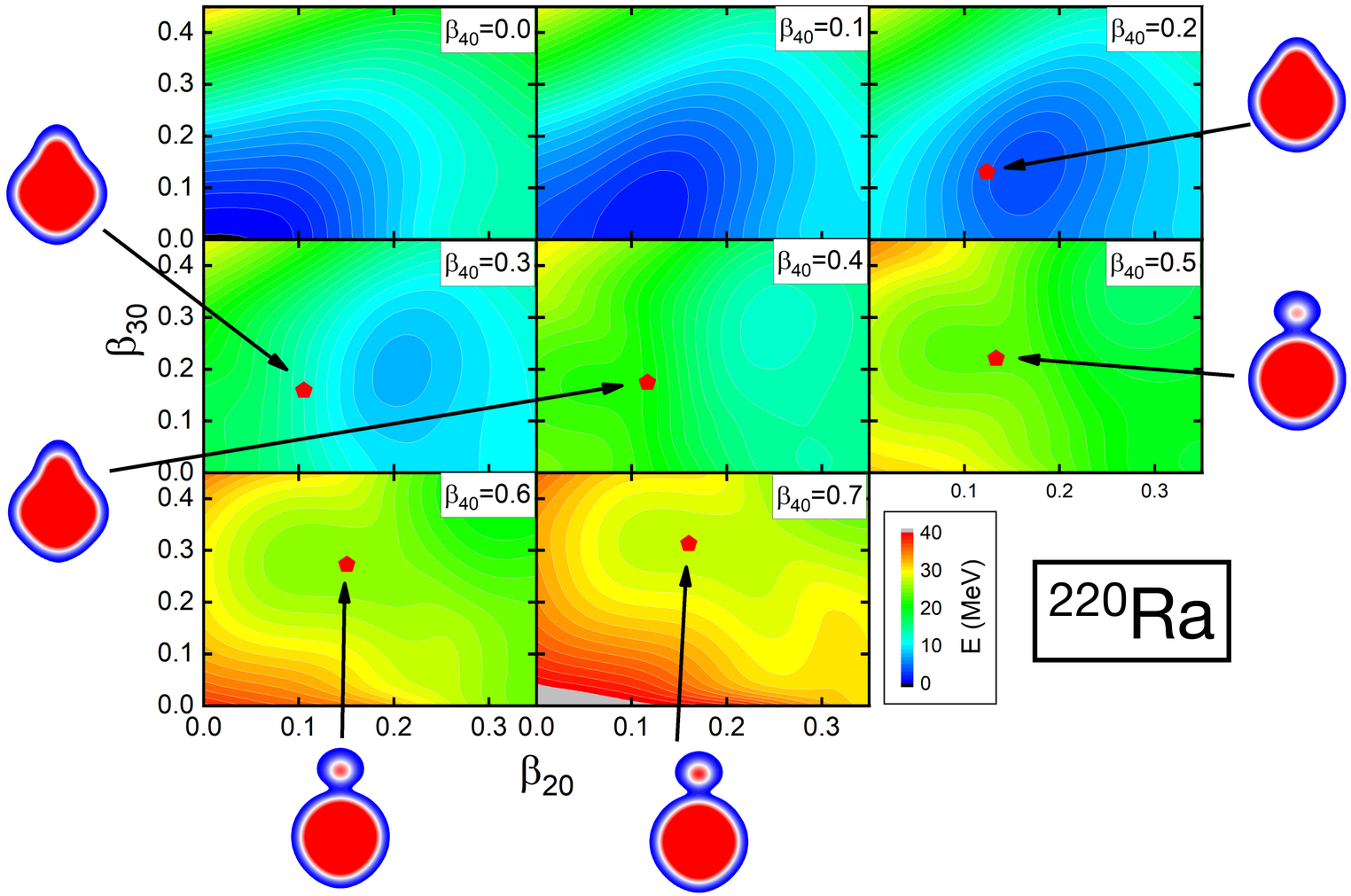


- **First model** for α decay : Gamow 1928 (tunneling)
- **Phenomenological** models for alpha/cluster radioactivity
- **First prediction for 2α :** Poenaru 1980 , ^{8}Be-like, **very long half-life**
- **Microscopic** description : Mercier 2021, Zhao 2023, of **α, 2α decays** (& cluster)



Theoretical framework

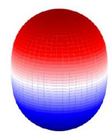
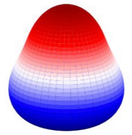
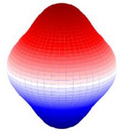
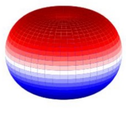
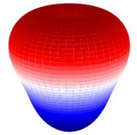
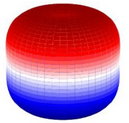
Single alpha decay

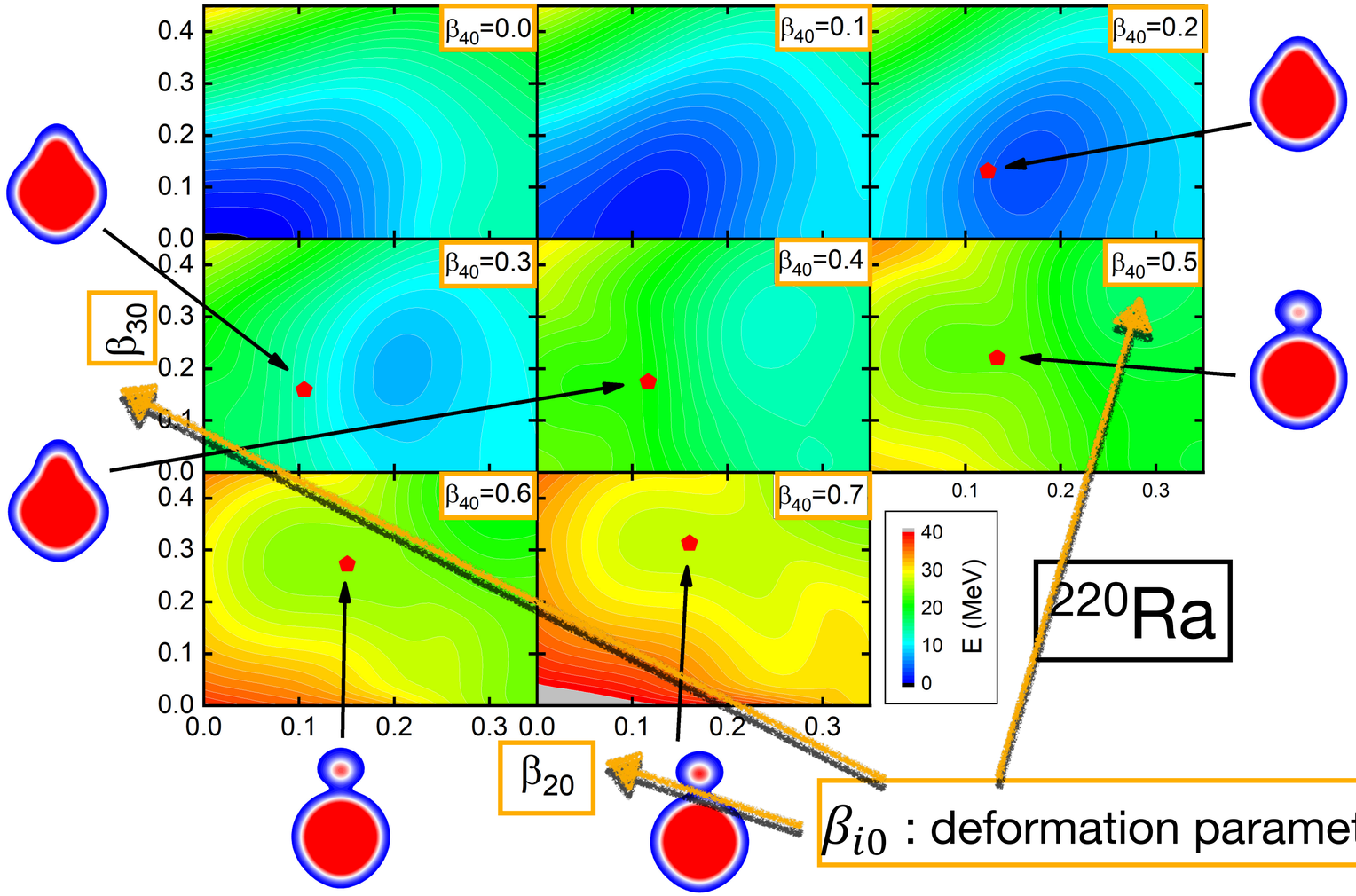


Theoretical framework

Single alpha decay

Taken from
Mercier PhD thesis

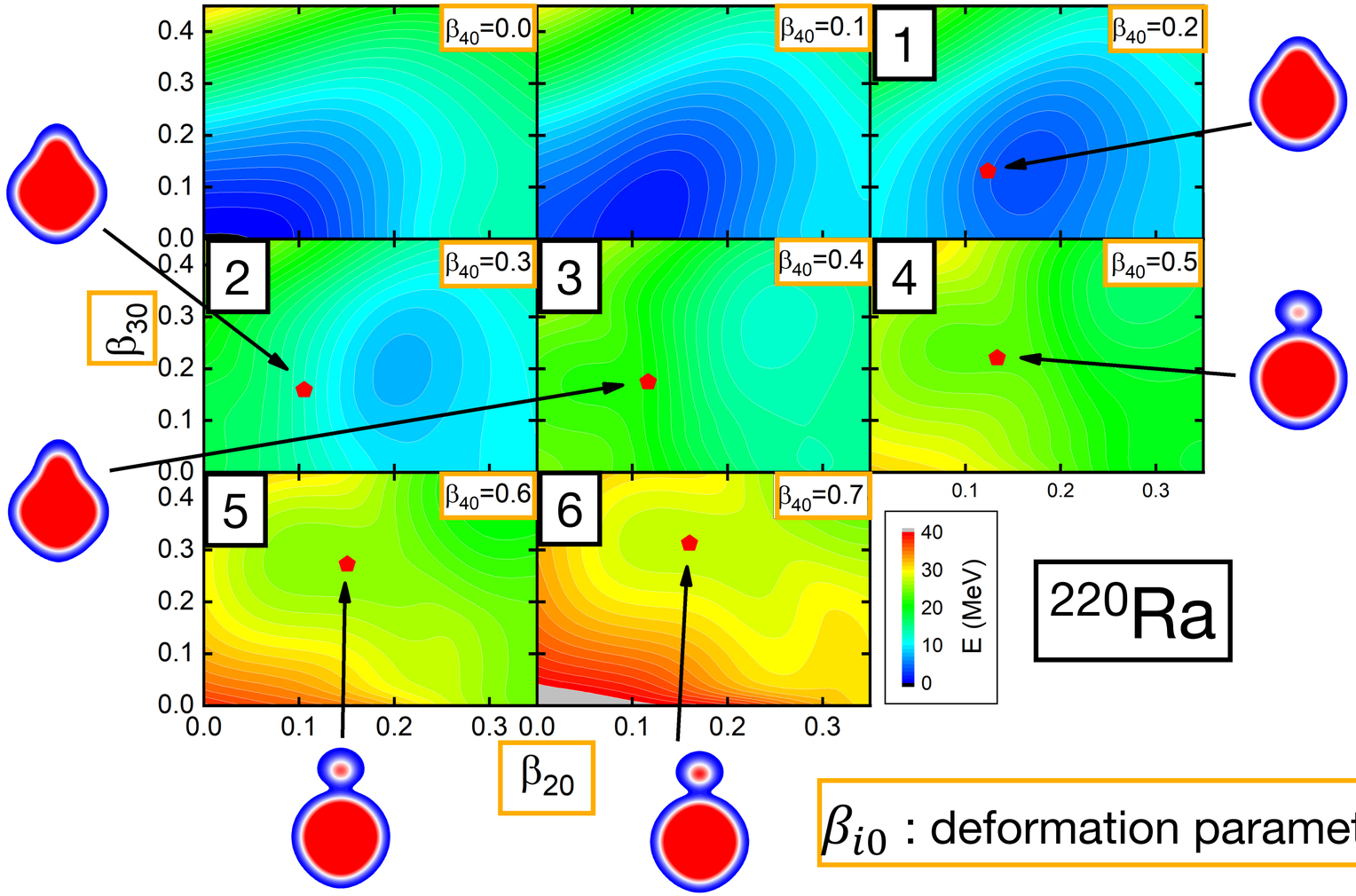
	β_{20}	β_{30}	β_{40}
$\beta_i > 0$			
$\beta_i < 0$			



Theoretical framework

Single alpha decay

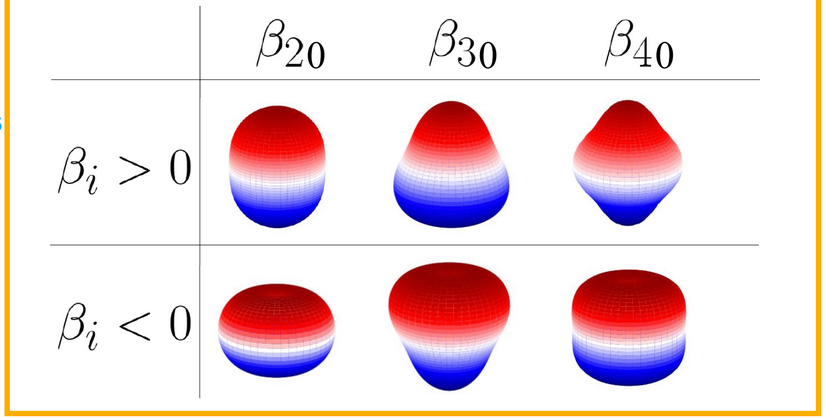
Points along dynamical path



^{220}Ra

β_{i0} : deformation parameters

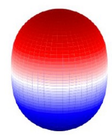
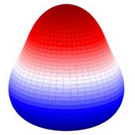
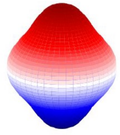
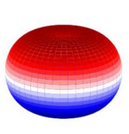
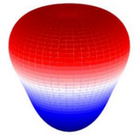
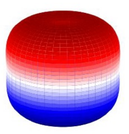
Taken from Mercier PhD thesis



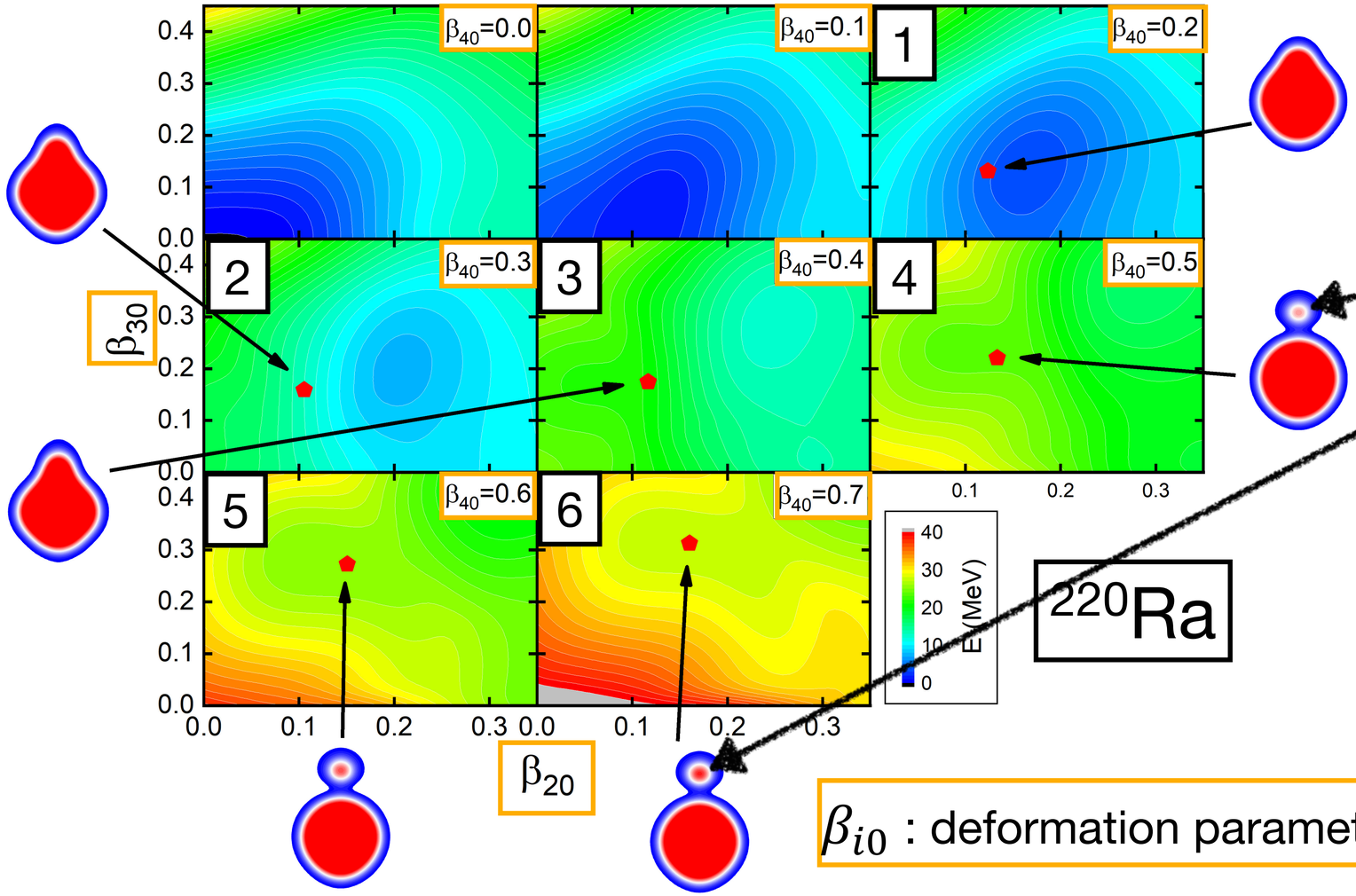
Theoretical framework

Single alpha decay

Taken from Mercier PhD thesis

	β_{20}	β_{30}	β_{40}
$\beta_i > 0$			
$\beta_i < 0$			

Points along dynamical path



Dynamical evolution:

formation of an α particle

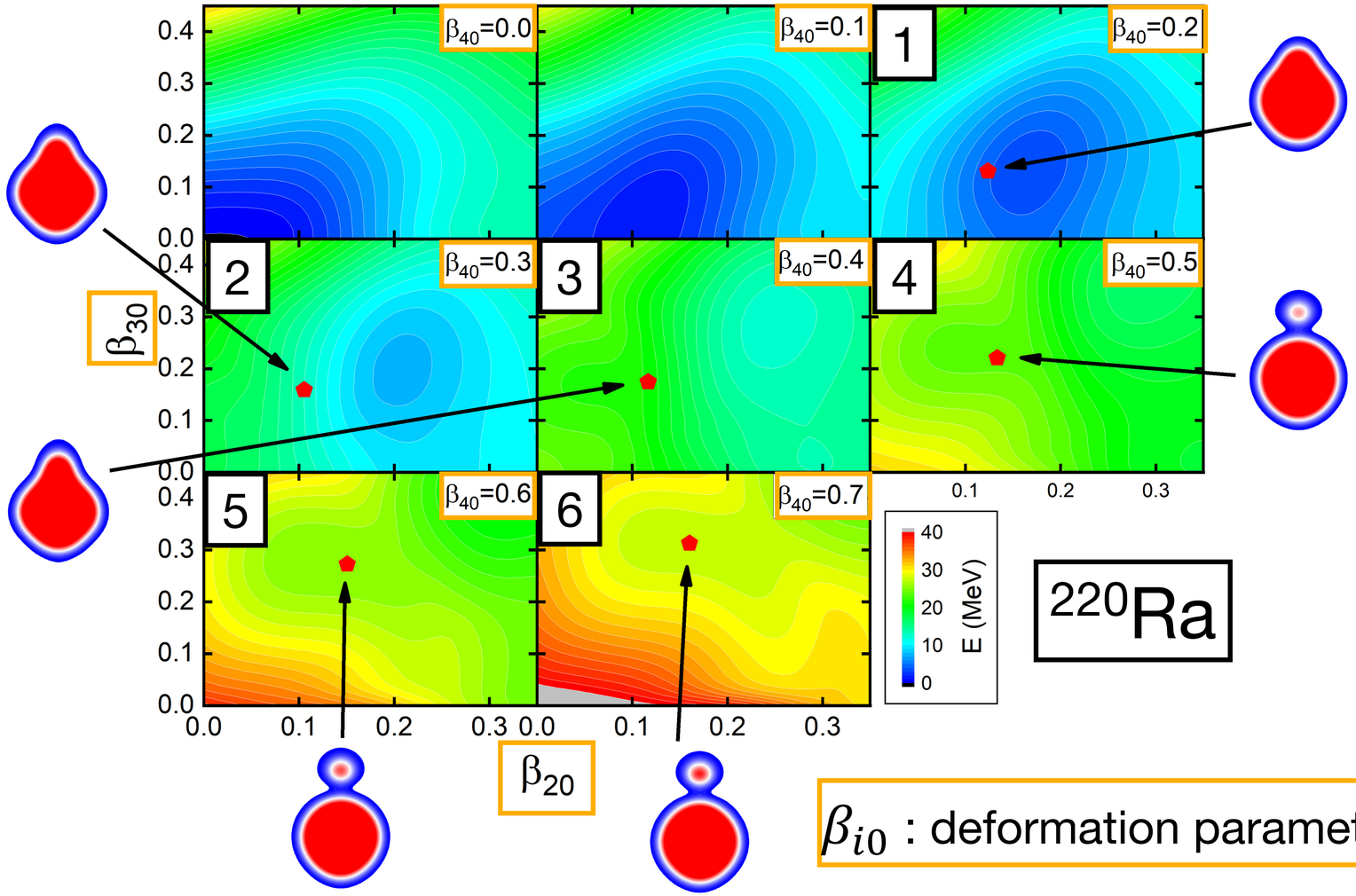
^{220}Ra

β_{i0} : deformation parameters

Theoretical framework

Single alpha decay

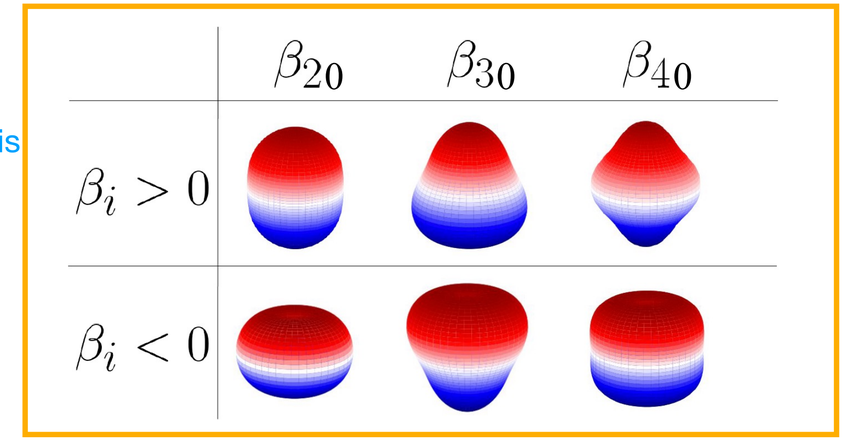
Points along dynamical path



^{220}Ra

β_{i0} : deformation parameters

Taken from Mercier PhD thesis



Dynamical evolution:
formation of an α particle

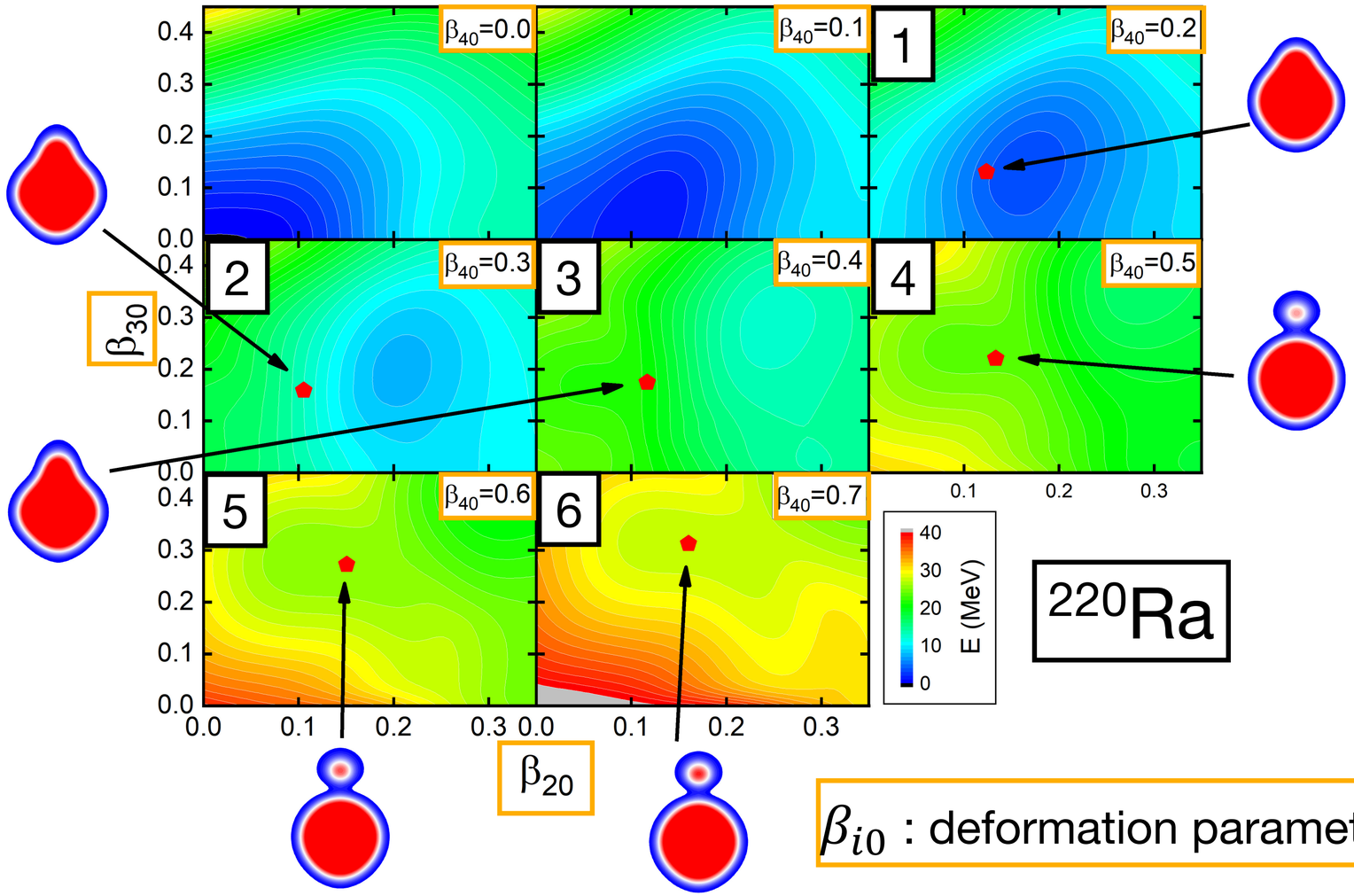
$$\tau_{\mathrm{exp}} = 18\ \mathrm{ms}$$

$$\tau_{\mathrm{th}} = 60\ \mathrm{ms}$$

Theoretical framework

Single alpha decay

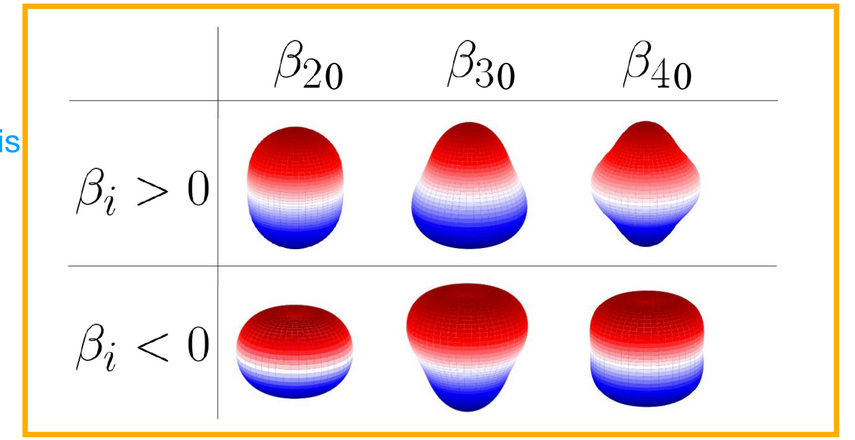
Points along dynamical path



^{220}Ra

β_{i0} : deformation parameters

Taken from Mercier PhD thesis



Dynamical evolution:
formation of an α particle

$$\tau_{\mathrm{exp}} = 18 \text{ ms}$$

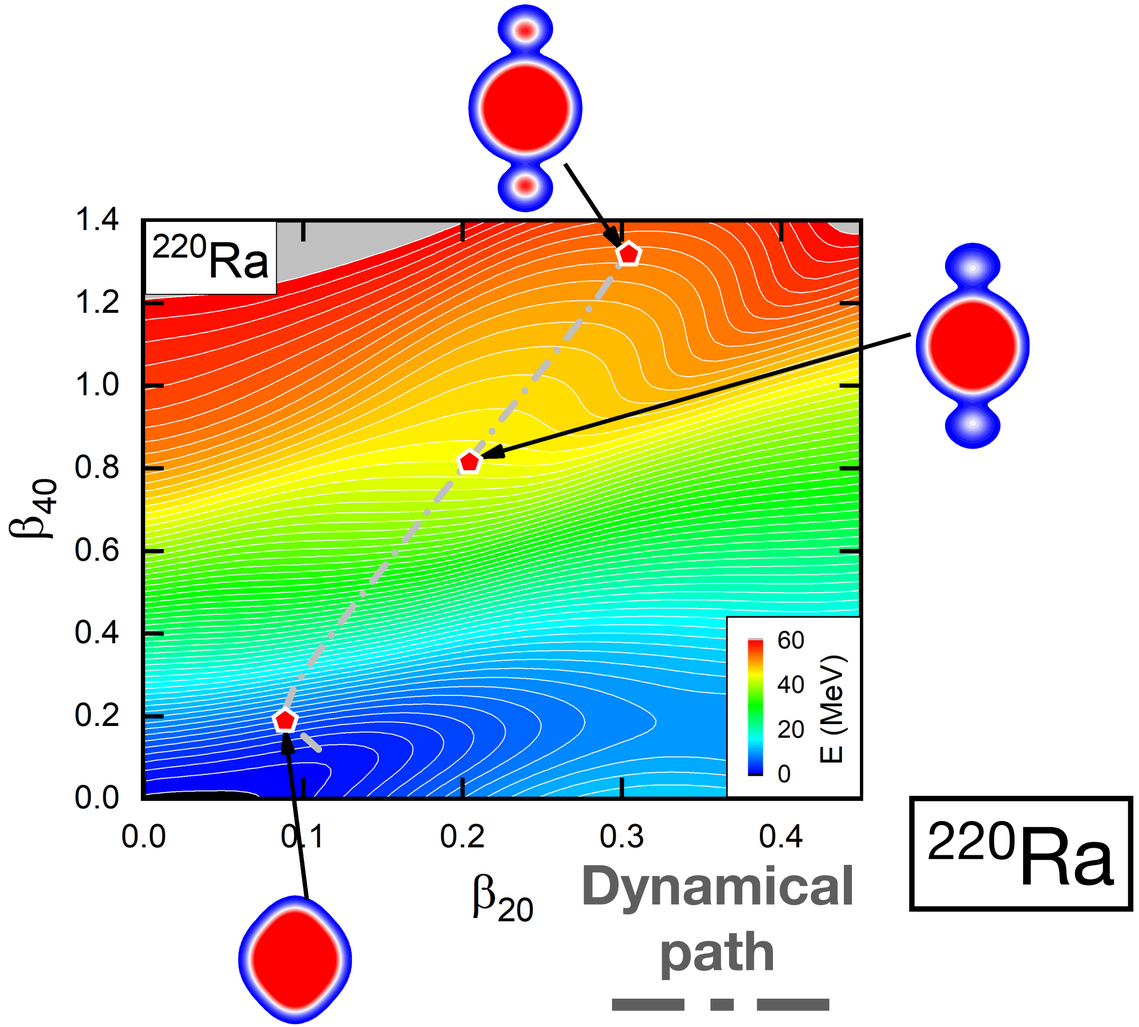
$$\tau_{\mathrm{th}} = 60 \text{ ms}$$

Quantity computed : $\log\tau$

→ **Very good agreement !**

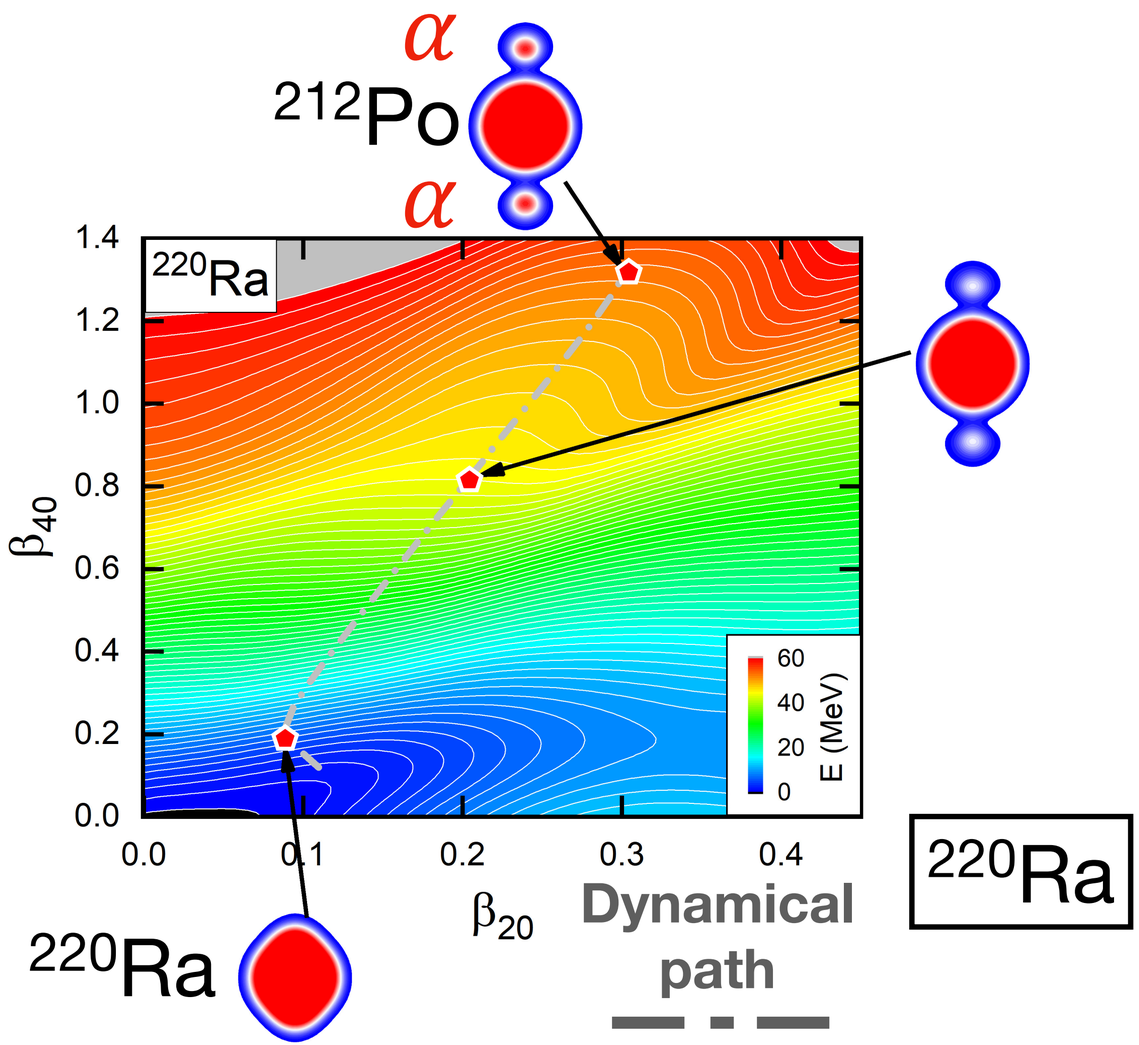
Theoretical framework

Double alpha decay



Theoretical framework

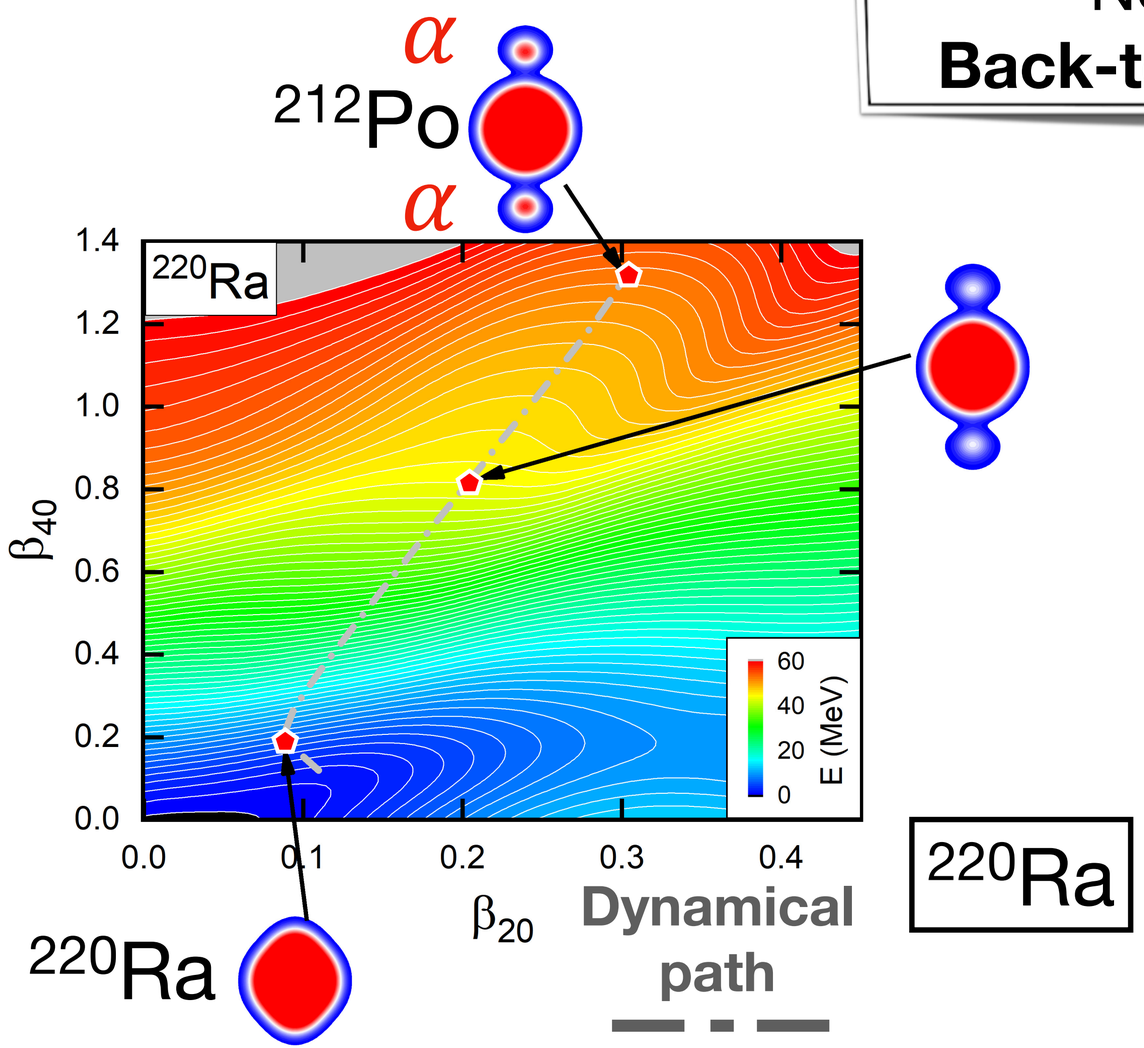
Double alpha decay



Theoretical framework

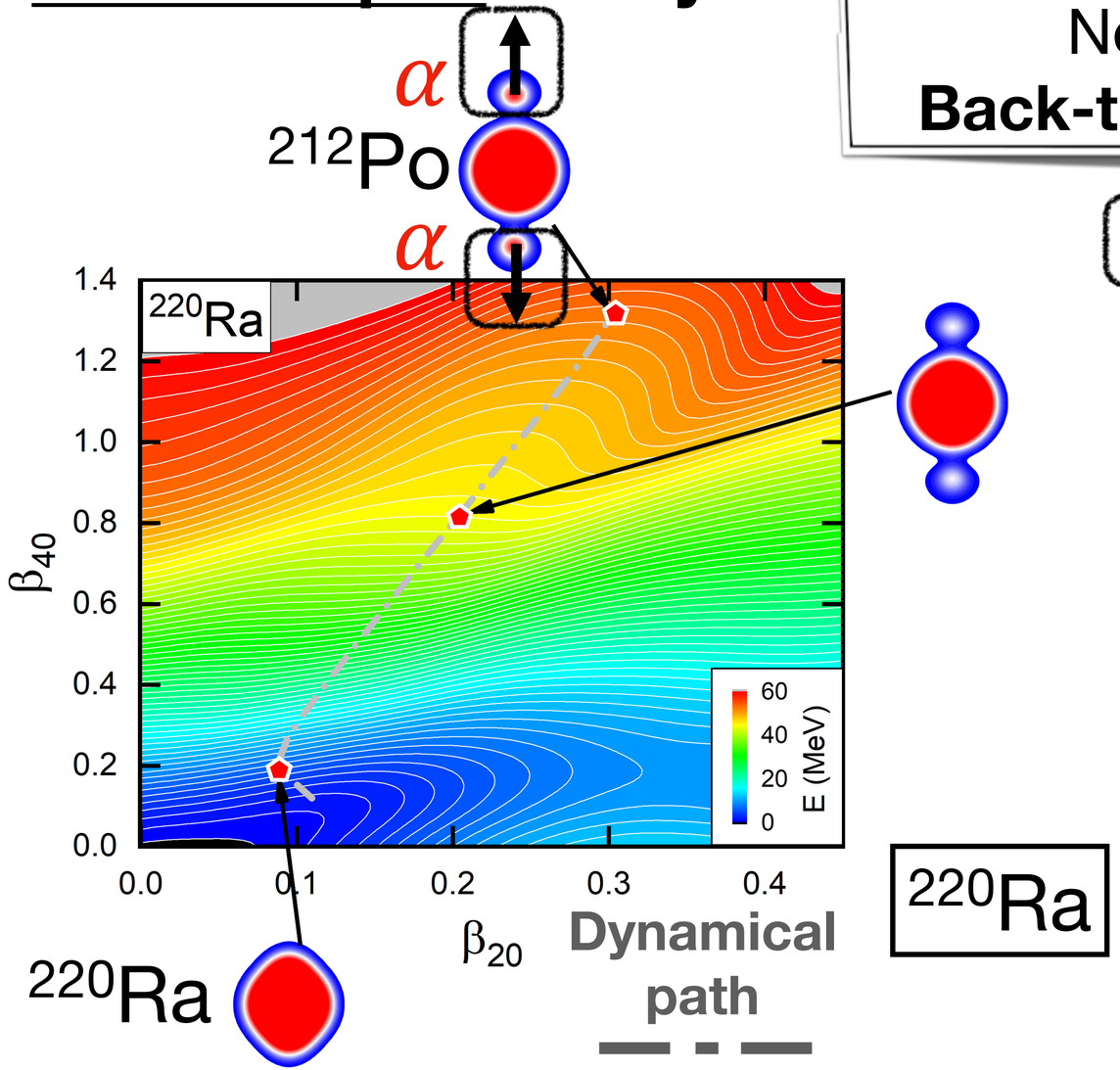
Double alpha decay

New type of radioactivity :
Back-to-back double alpha decay !



Theoretical framework

Double alpha decay

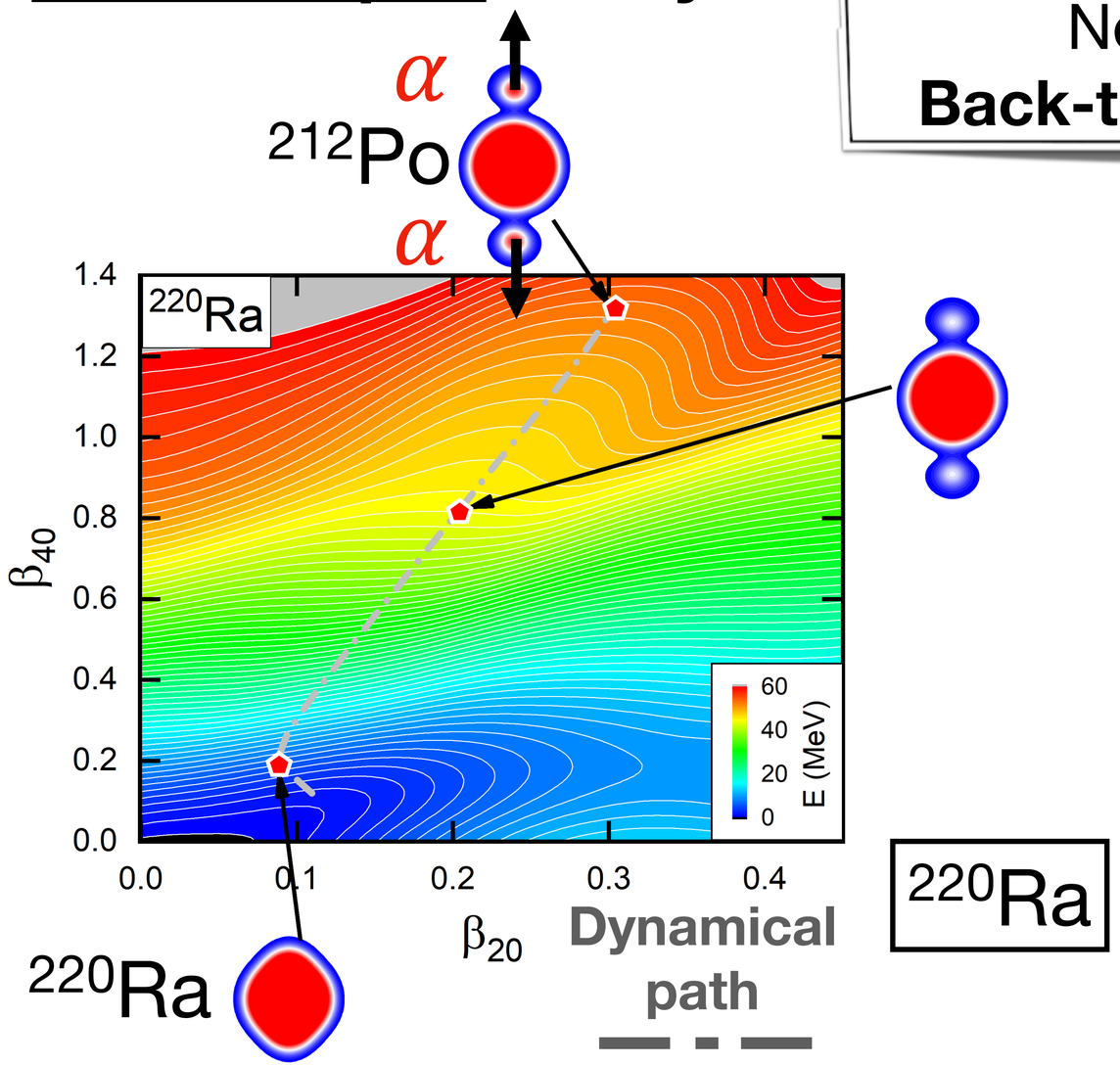


New type of radioactivity :
Back-to-back double alpha decay !

Back-to-back emission of 2 α particles

Theoretical framework

Double alpha decay



New type of radioactivity :
Back-to-back double alpha decay !

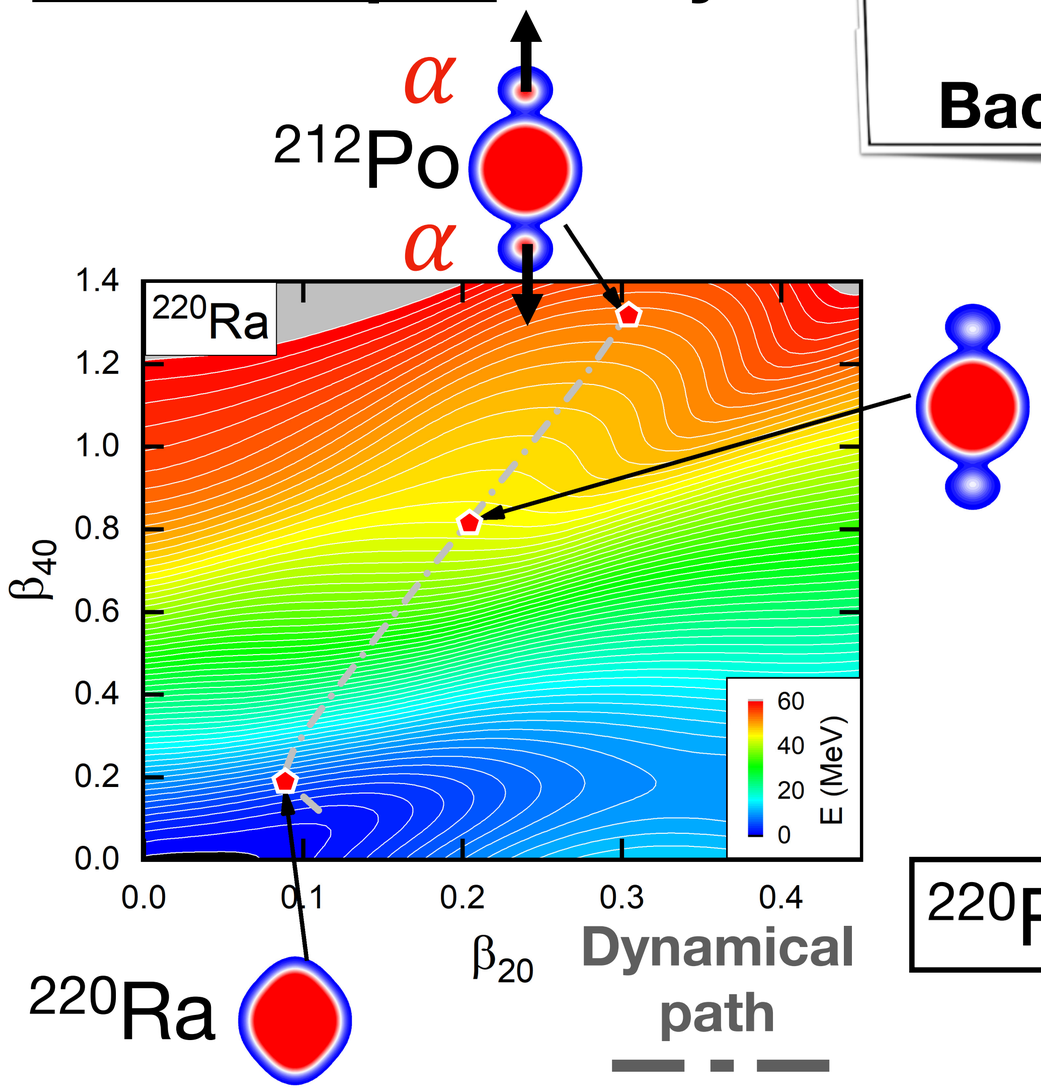
Back-to-back emission of 2 α particles

$$\log_{10}\tau_{\mathrm{th}}[\mathrm{s}] = 6.1$$

$$\log_{10}\tau_{\mathrm{exp}}[\mathrm{s}] = ??$$

Theoretical framework

Double alpha decay



New type of radioactivity :
Back-to-back double alpha decay !

Back-to-back emission of 2 α particles

$$\log_{10}\tau_{\mathrm{th}}[\mathrm{s}] = 6.1$$

$$\log_{10}\tau_{\mathrm{exp}}[\mathrm{s}] = ??$$

Branching Ratio (BR) :

$$\mathrm{BR} = \frac{\tau_{2\alpha}}{\tau_{\alpha}} \sim 10^{-7.3}$$

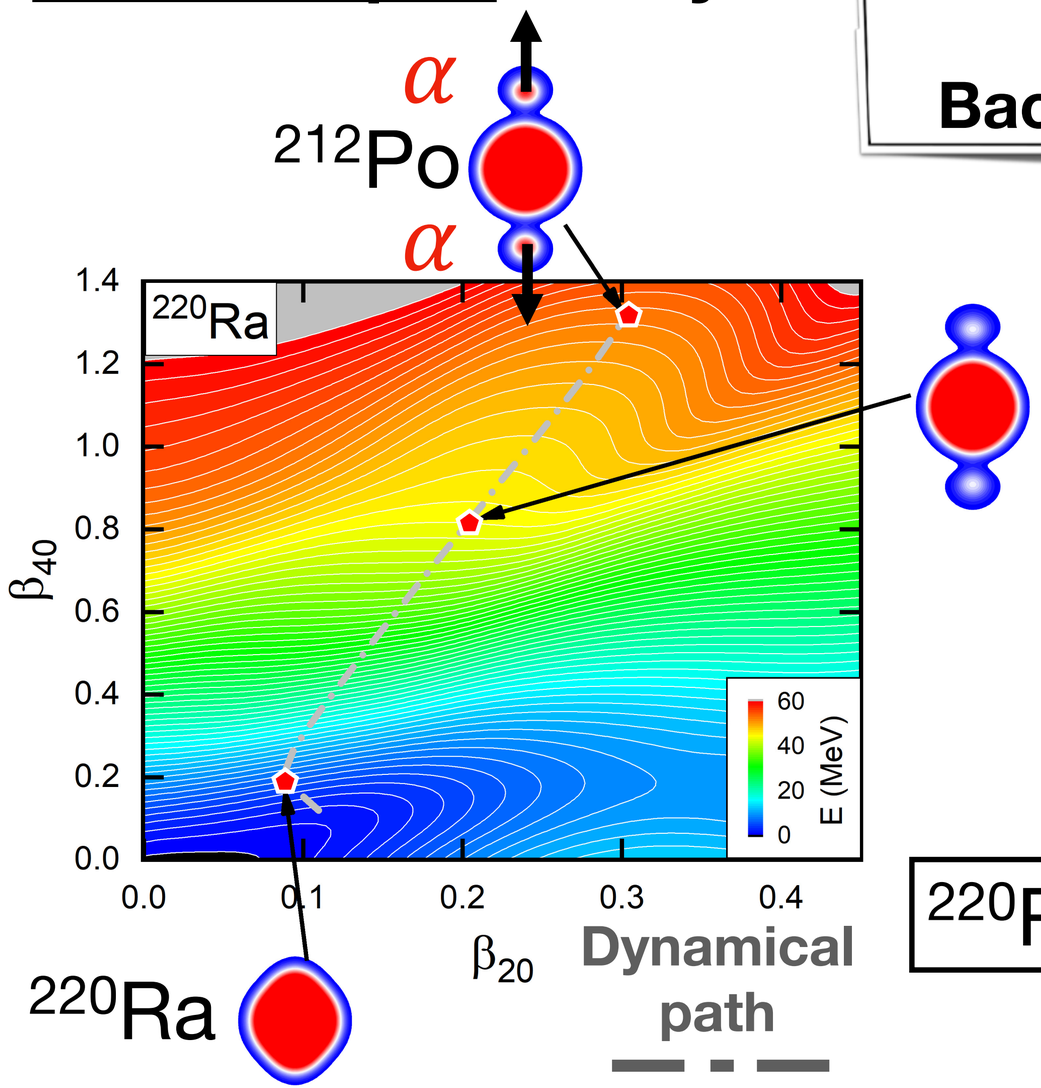
Theoretical framework

$$\mathrm{BR}_{\mathrm{cluster}} \sim 10^{-10}$$

Already observed

Double alpha decay

New type of radioactivity :
Back-to-back double alpha decay !



Back-to-back emission of 2 α particles

$$\log_{10}\tau_{\mathrm{th}}[\mathrm{s}] = 6.1$$

$$\log_{10}\tau_{\mathrm{exp}}[\mathrm{s}] = ??$$

Branching Ratio (BR) :

$$\mathrm{BR} = \frac{\tau_{2\alpha}}{\tau_{\alpha}} \sim 10^{-7.3}$$

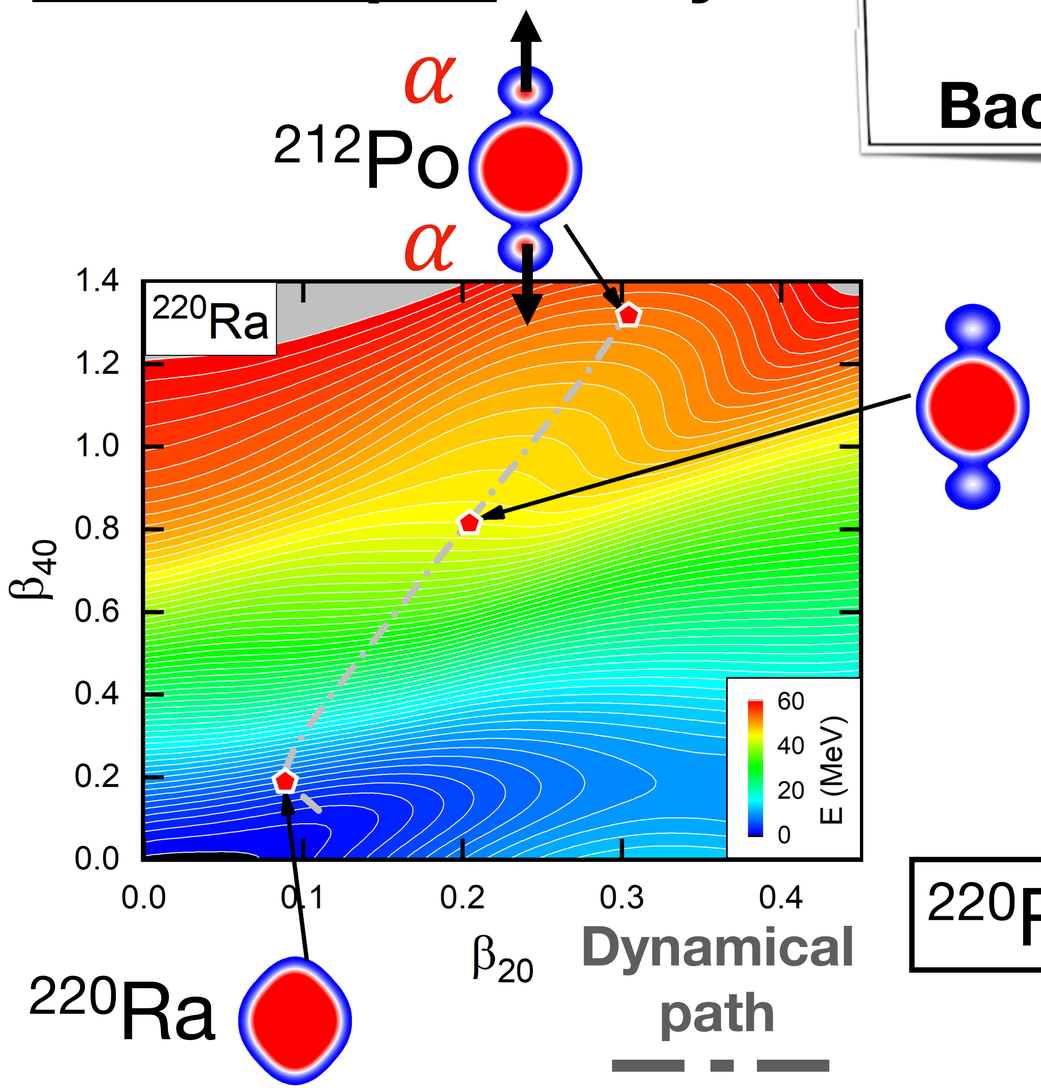
Theoretical framework

$$\mathrm{BR}_{\mathrm{cluster}} \sim 10^{-10}$$

Already observed

Double alpha decay

New type of radioactivity :
Back-to-back double alpha decay !



Back-to-back emission of 2 α particles

$$\log_{10}\tau_{\mathrm{th}}[\mathrm{s}] = 6.1$$

$$\log_{10}\tau_{\mathrm{exp}}[\mathrm{s}] = ??$$

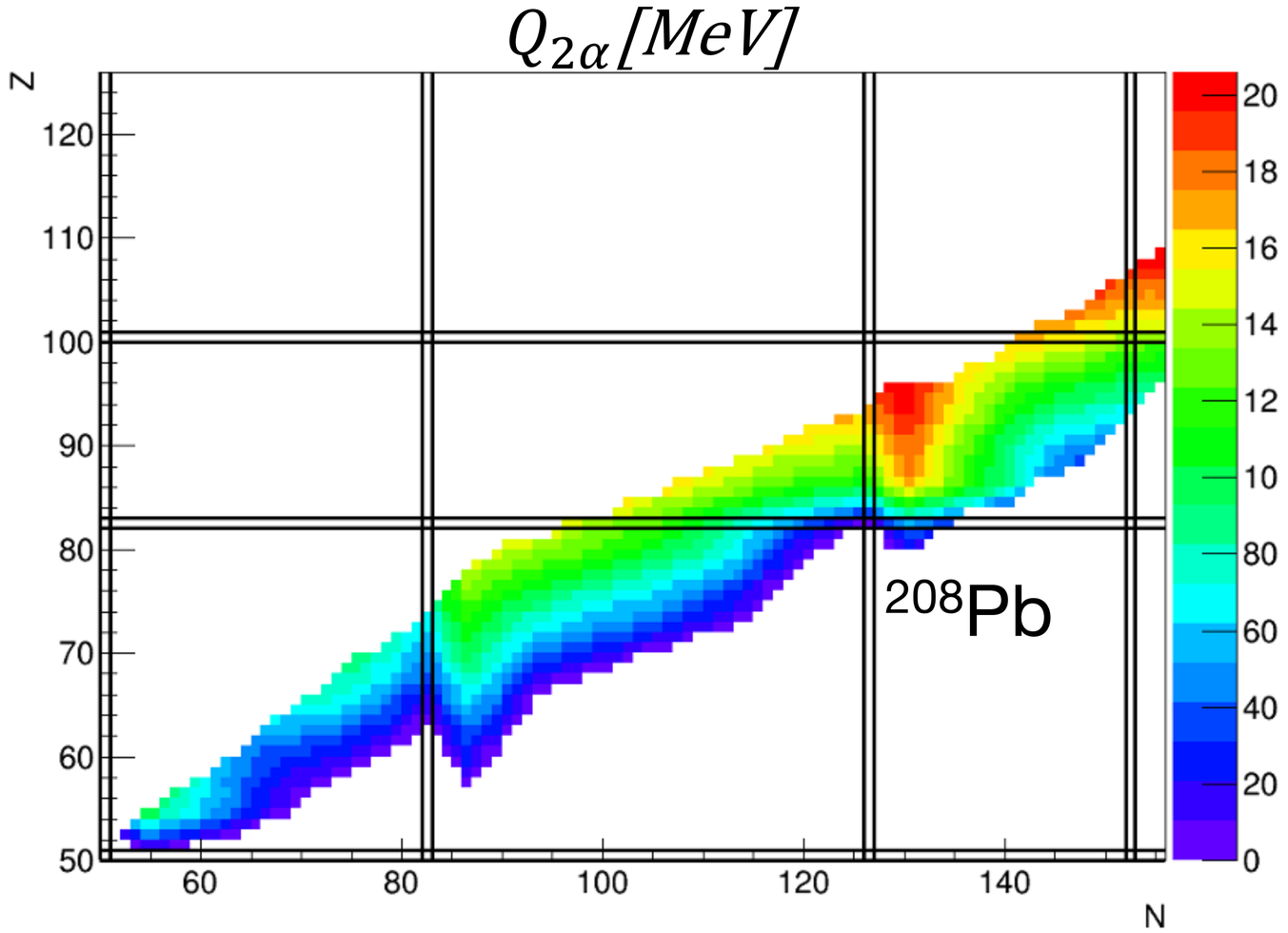
Branching Ratio (BR) :

$$\mathrm{BR} = \frac{\tau_{2\alpha}}{\tau_{\alpha}} \sim 10^{-7.3}$$

Experimentally Interesting !

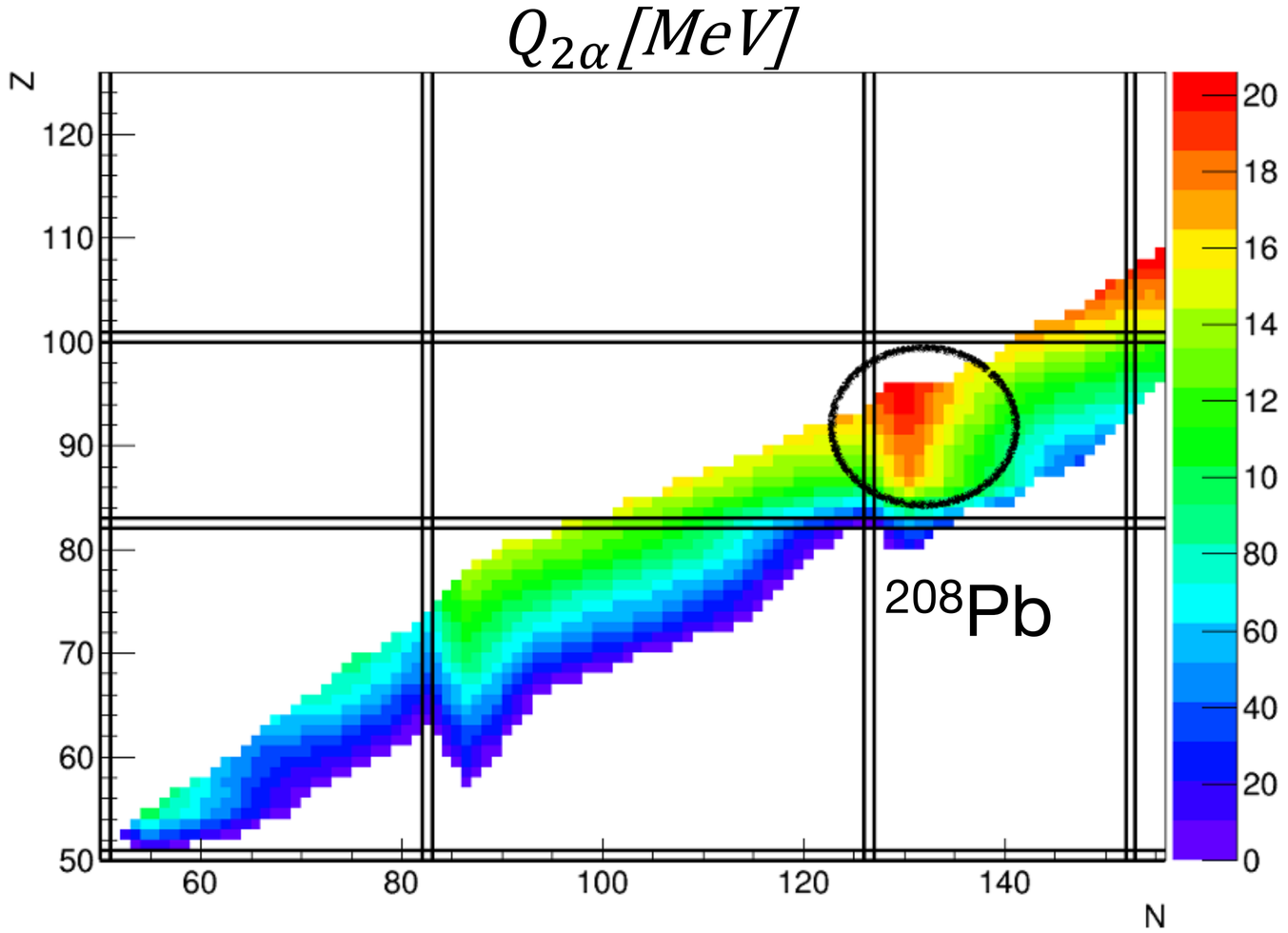
Theoretical framework

Double alpha candidates



Theoretical framework

Double alpha candidates

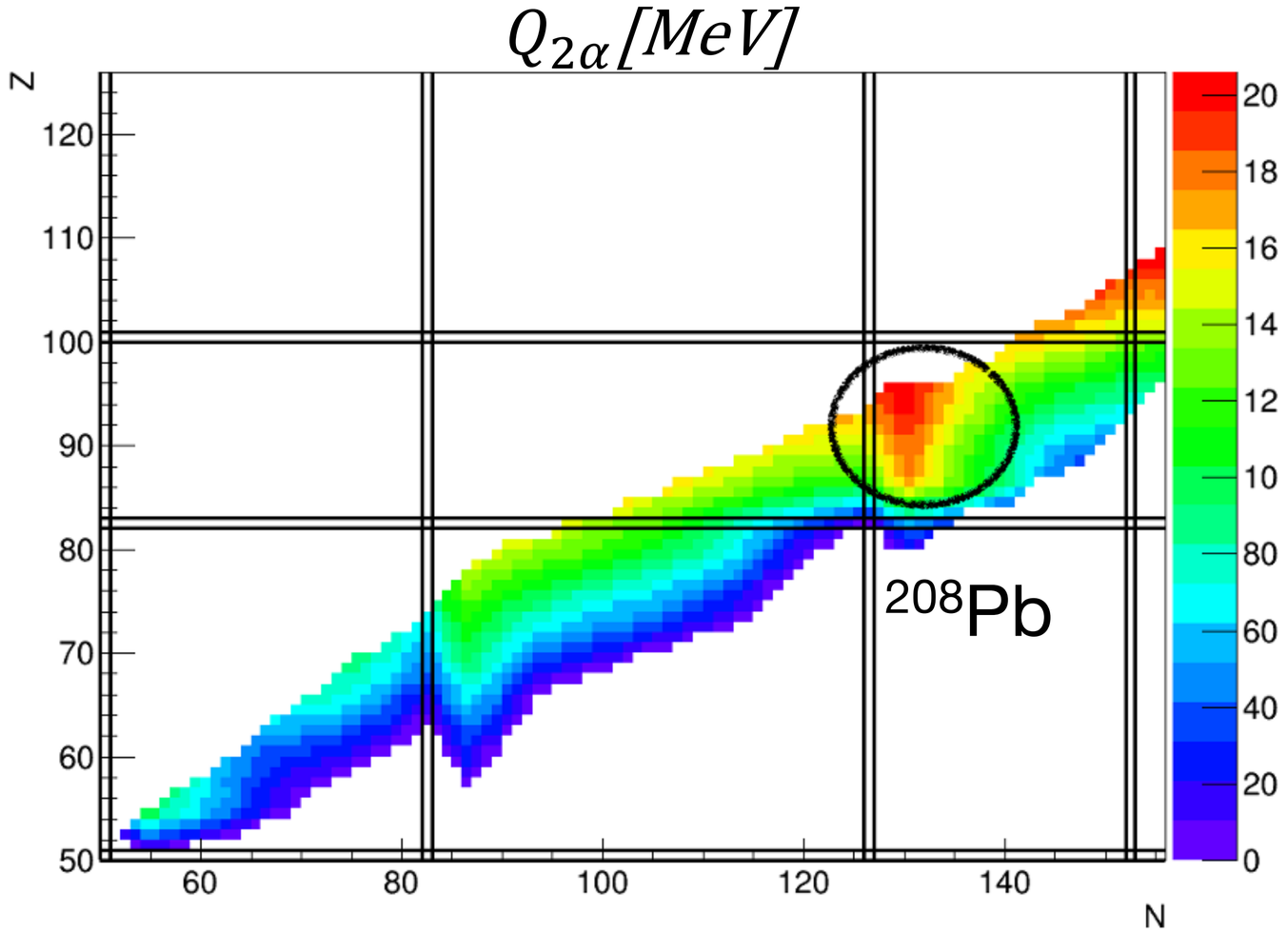


Region of interest : large $Q_{2\alpha}$ value

$\equiv$ expected smaller τ (~Geiger-Nuttall)

Theoretical framework

Double alpha candidates



Region of interest : large $Q_{2\alpha}$ value

$\equiv$ expected smaller τ (~Geiger-Nuttall)

^{208}Pb+2α $\equiv$ **^{216}Rn**

Other candidates :

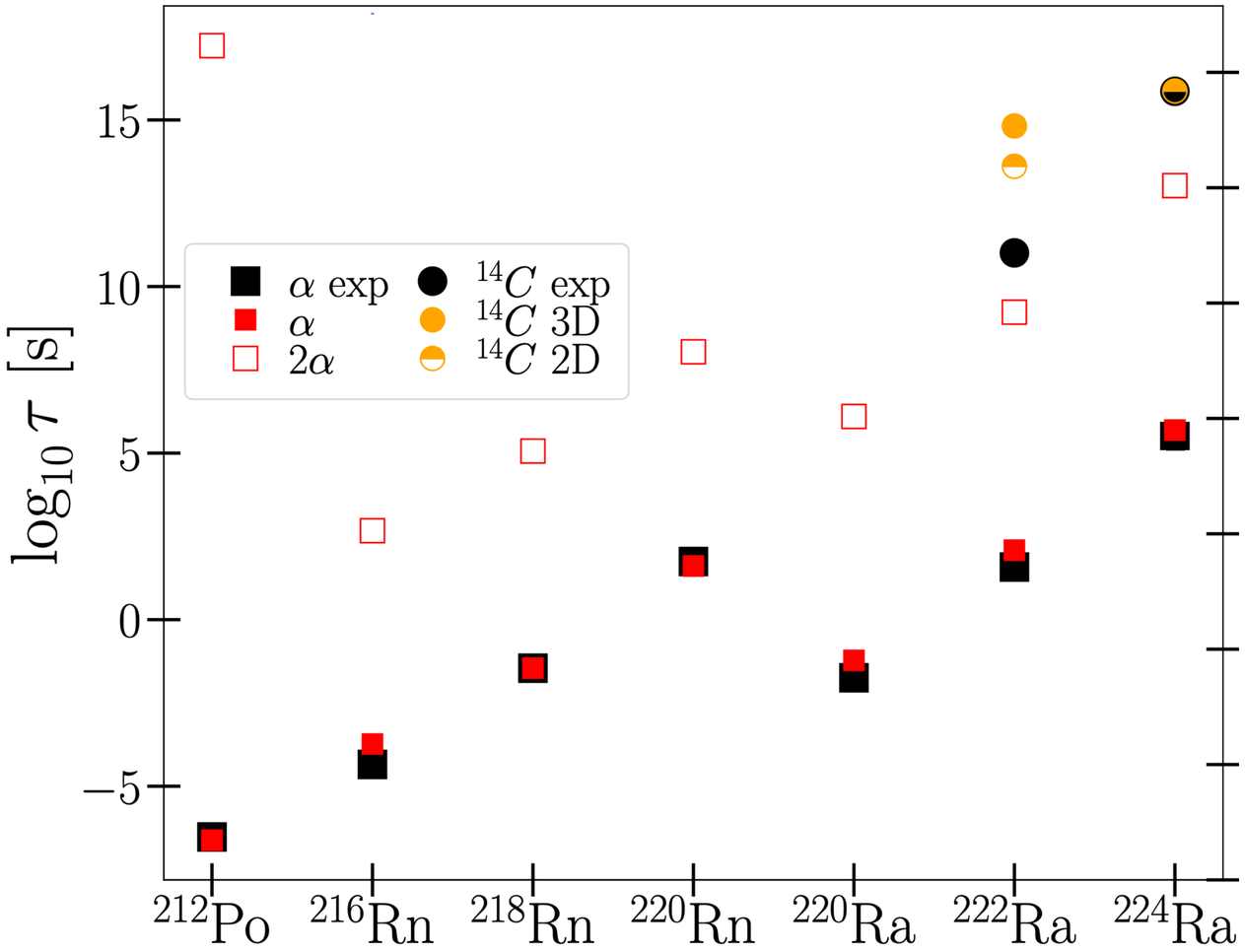
^{218,220}Rn **$^{220\text{-}224}$Ra**

Zhao, Ebran, Heitz, Khan, Mercier, Nikšic, Vretenar 2023

Theoretical framework

Summary

Black = exp **Color = theory**

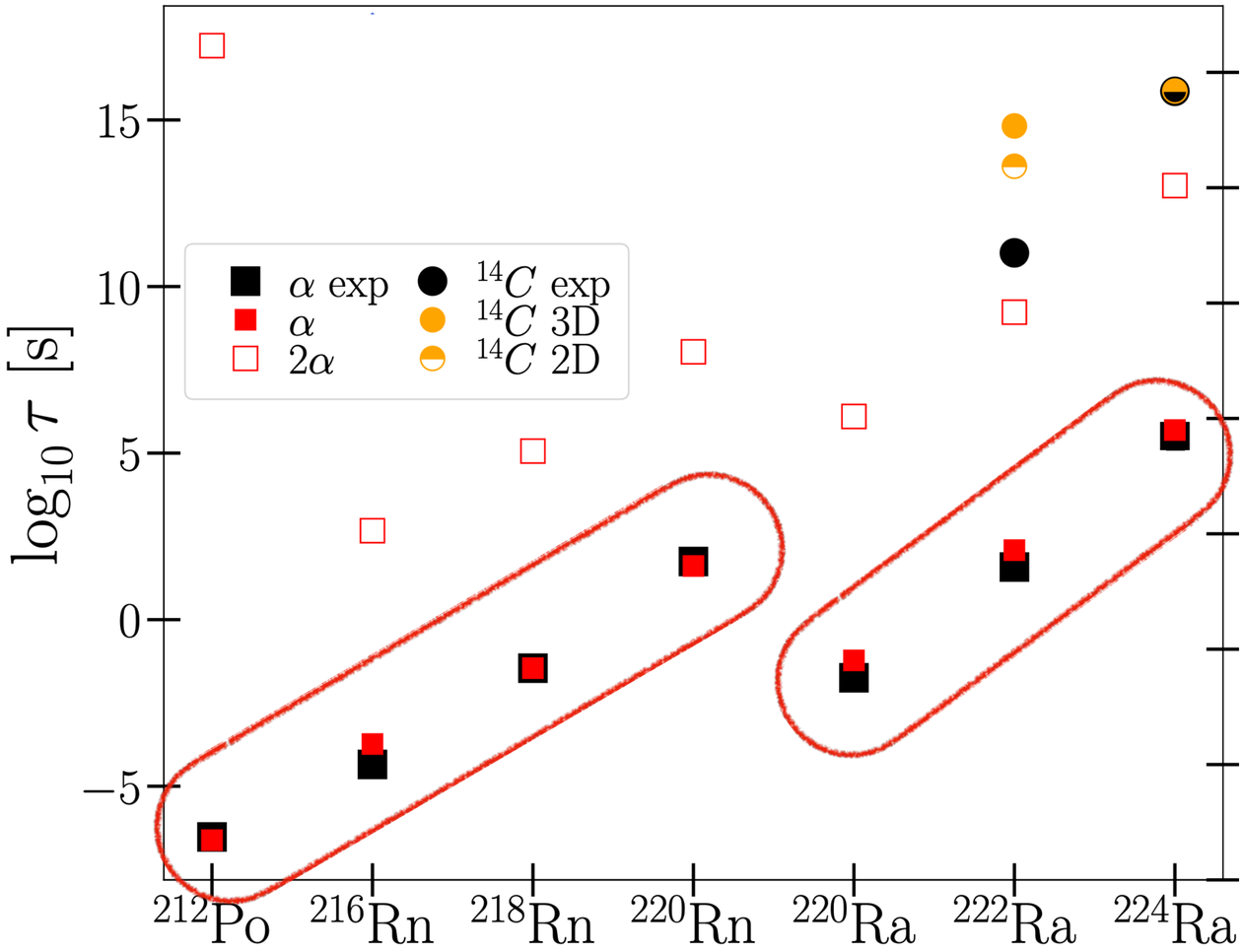


Zhao, Ebran, Heitz, Khan, Mercier, Nikšic, Vretenar 2023

Theoretical framework

Summary

Black = exp **Color = theory**



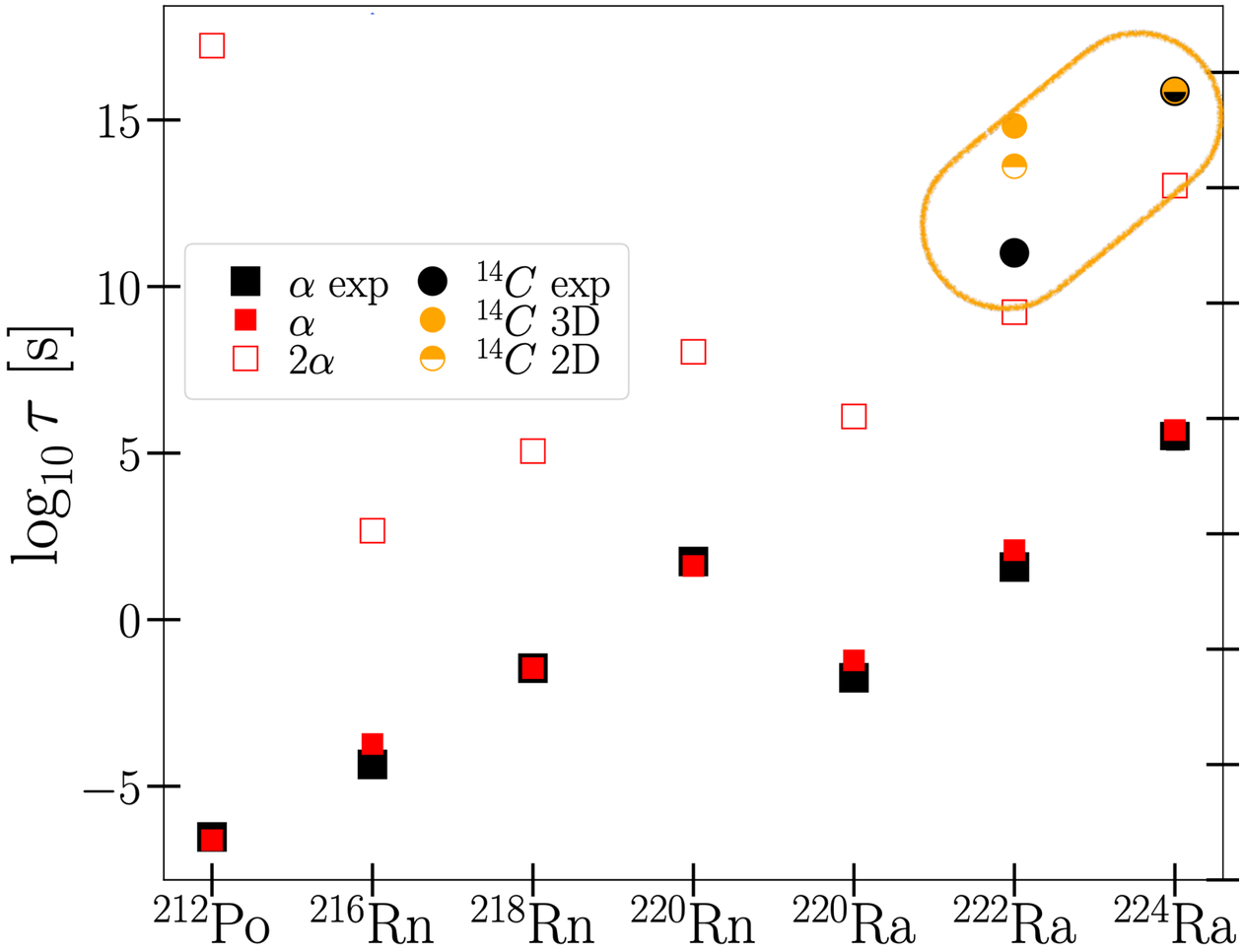
Single alpha : Excellent agreement

Zhao, Ebran, Heitz, Khan, Mercier, Nikšic, Vretenar 2023

Theoretical framework

Summary

Black = exp **Color = theory**



Single alpha : Excellent agreement

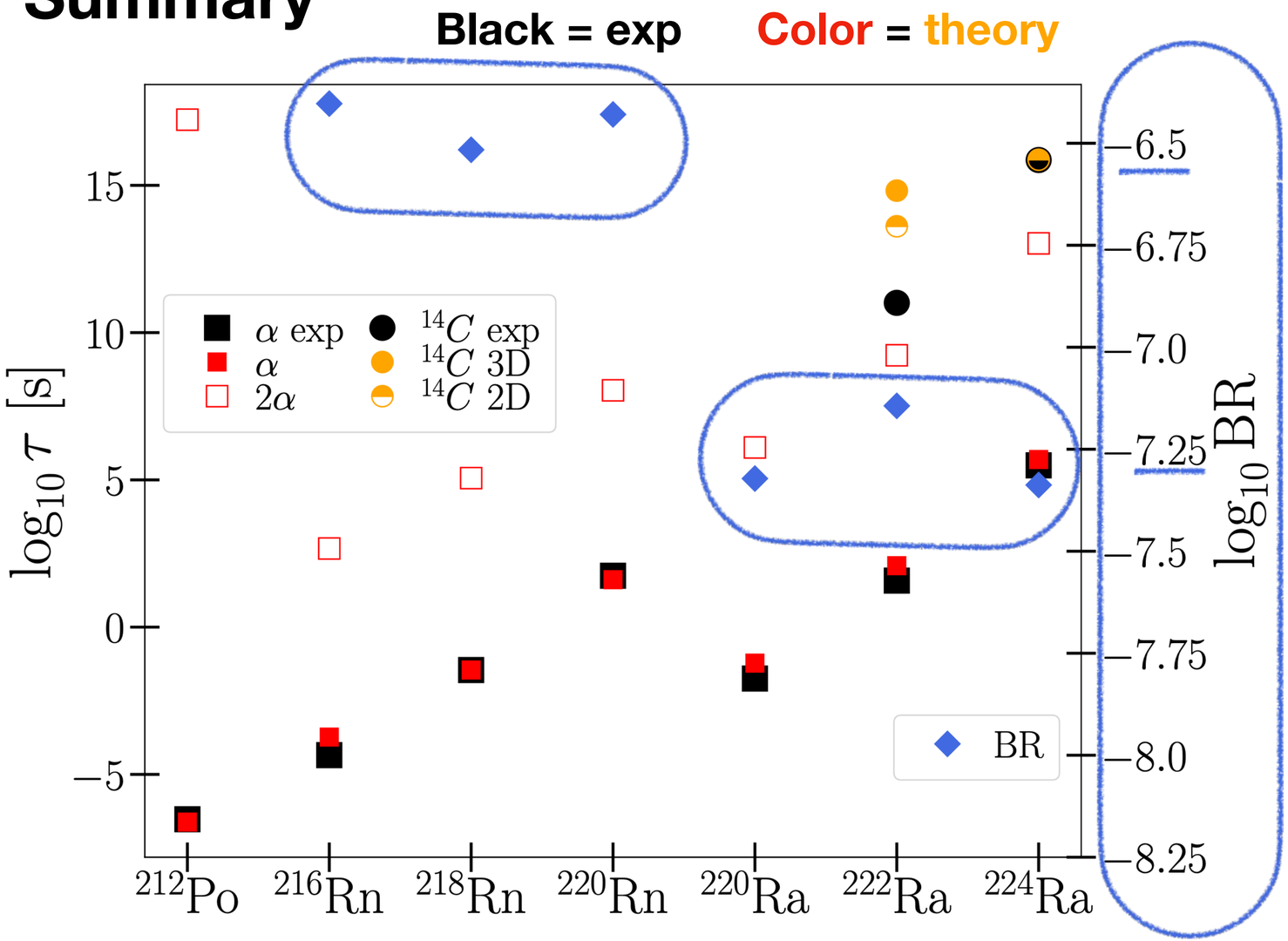
Cluster : good description

Further investigation needed

Zhao, Ebran, Heitz, Khan, Mercier, Nikšic, Vretenar 2023

Theoretical framework

Summary



Single alpha : Excellent agreement

Cluster : good description

Further investigation needed

Double alpha : interesting BR

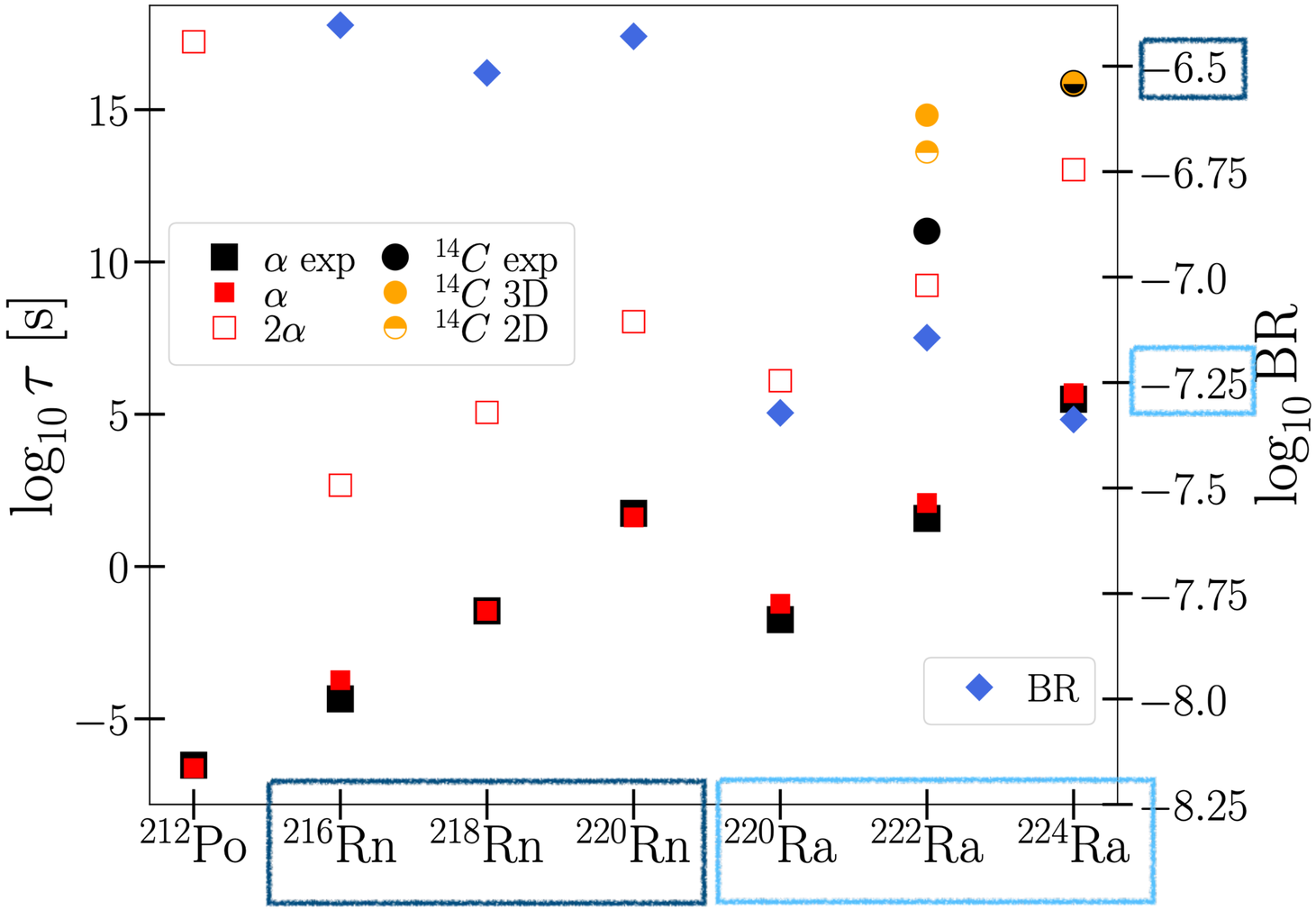
$$\mathrm{BR} = \frac{\tau_{2\alpha}}{\tau_{\alpha}}$$

Zhao, Ebran, Heitz, Khan, Mercier, Nikšic, Vretenar 2023

Theoretical framework

Summary

Black = exp **Color = theory**



Single alpha : Excellent agreement

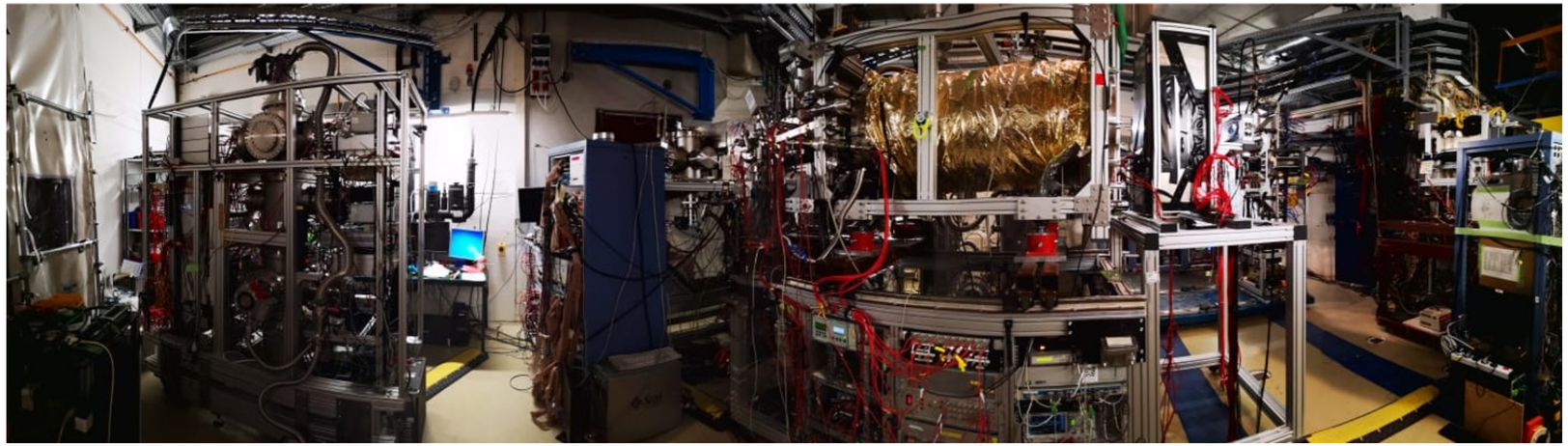
Cluster : good description

Further investigation needed

Double alpha : interesting BR

$$\mathrm{BR} = \frac{\tau_{2\alpha}}{\tau_{\alpha}}$$

Good potential candidates for experimental probe



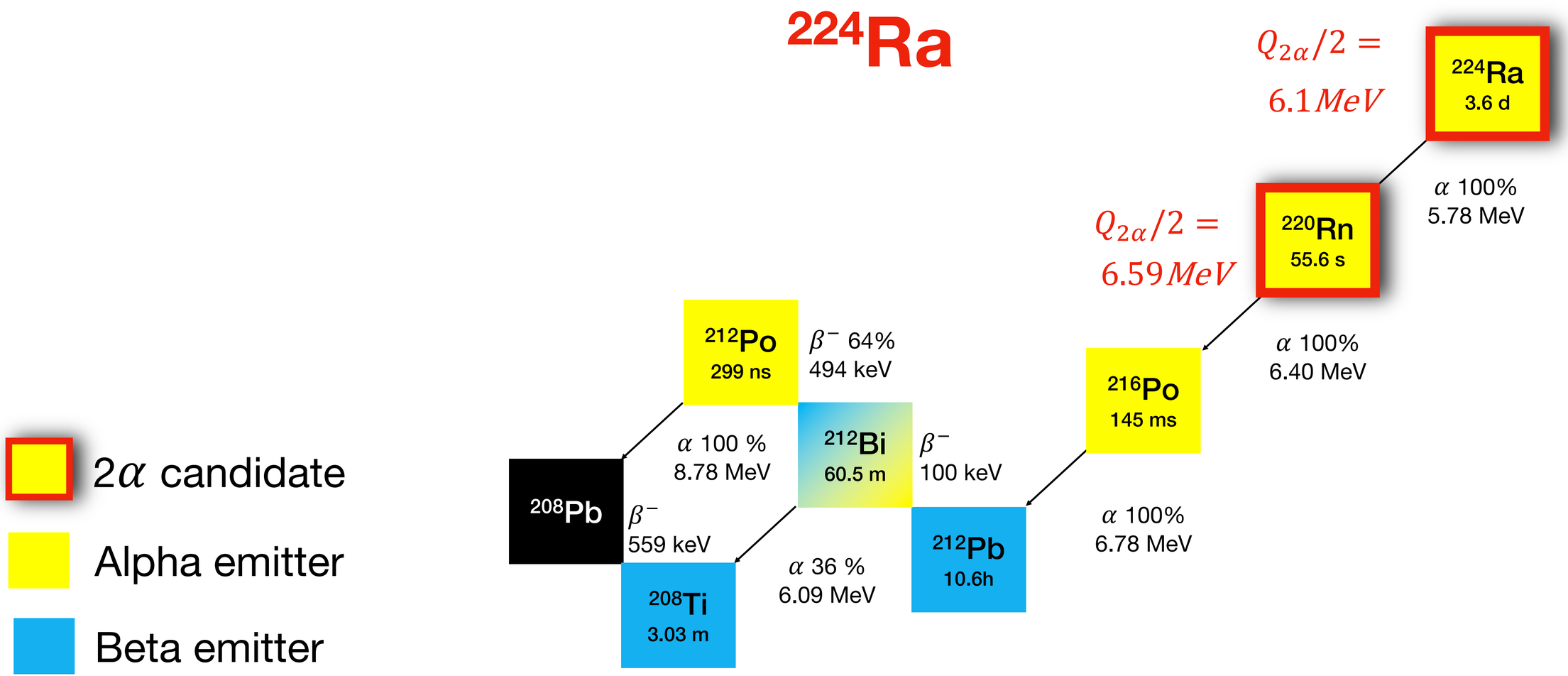
H. Wilsenach courtesy

Experimental search for 2α

FRS-Ion catcher GSI

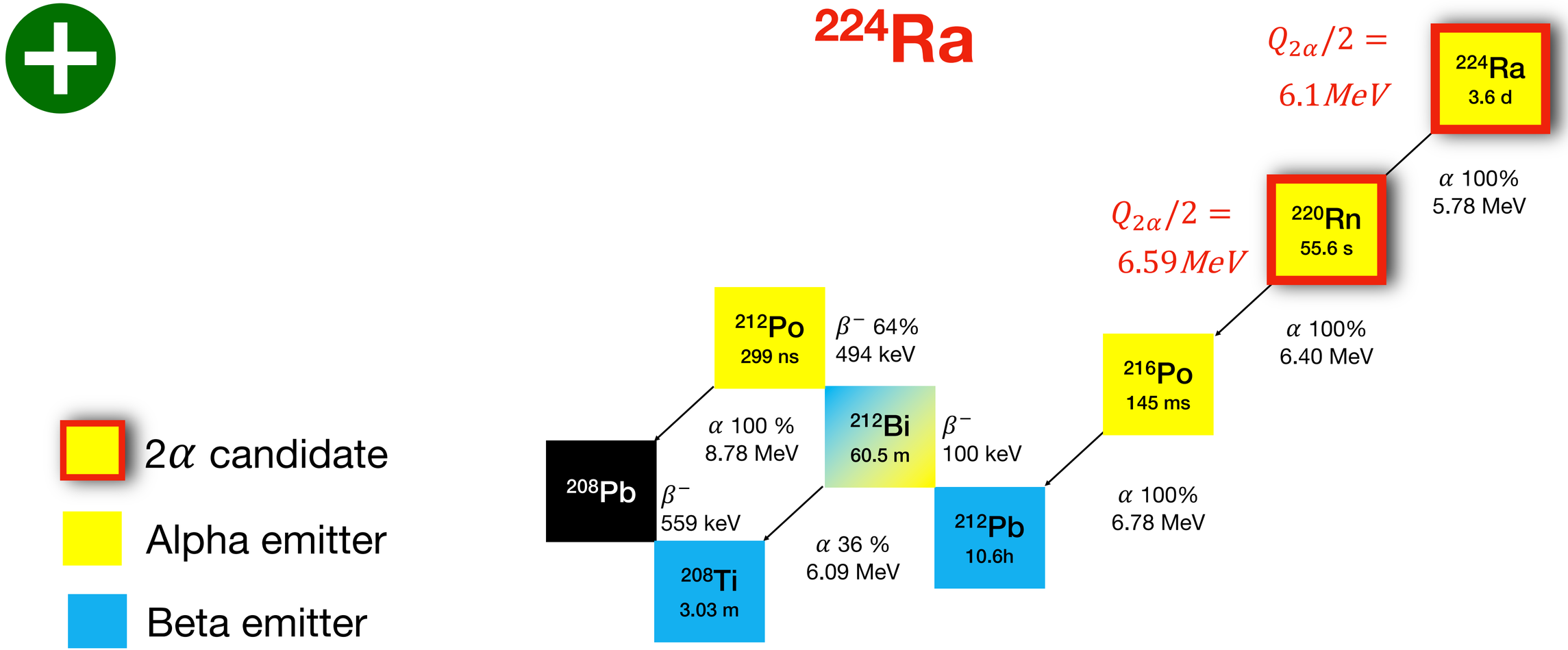
FRS Ion Catcher - GSI

Isotope choice - decay chain



FRS Ion Catcher - GSI

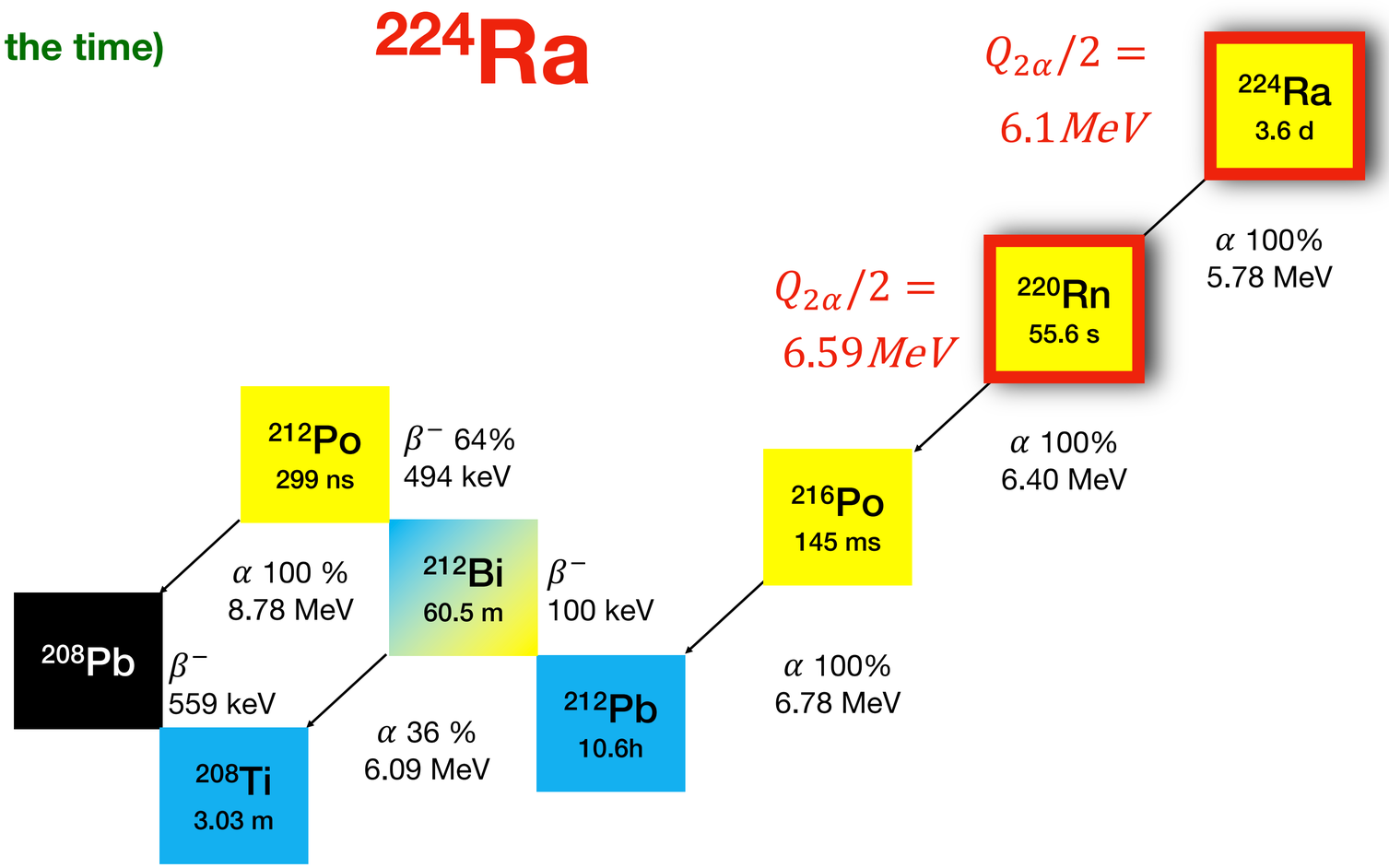
Isotope choice - decay chain



FRS Ion Catcher - GSI

Isotope choice - decay chain

(Only theoretical candidate at the time)



2α candidate

Alpha emitter

Beta emitter

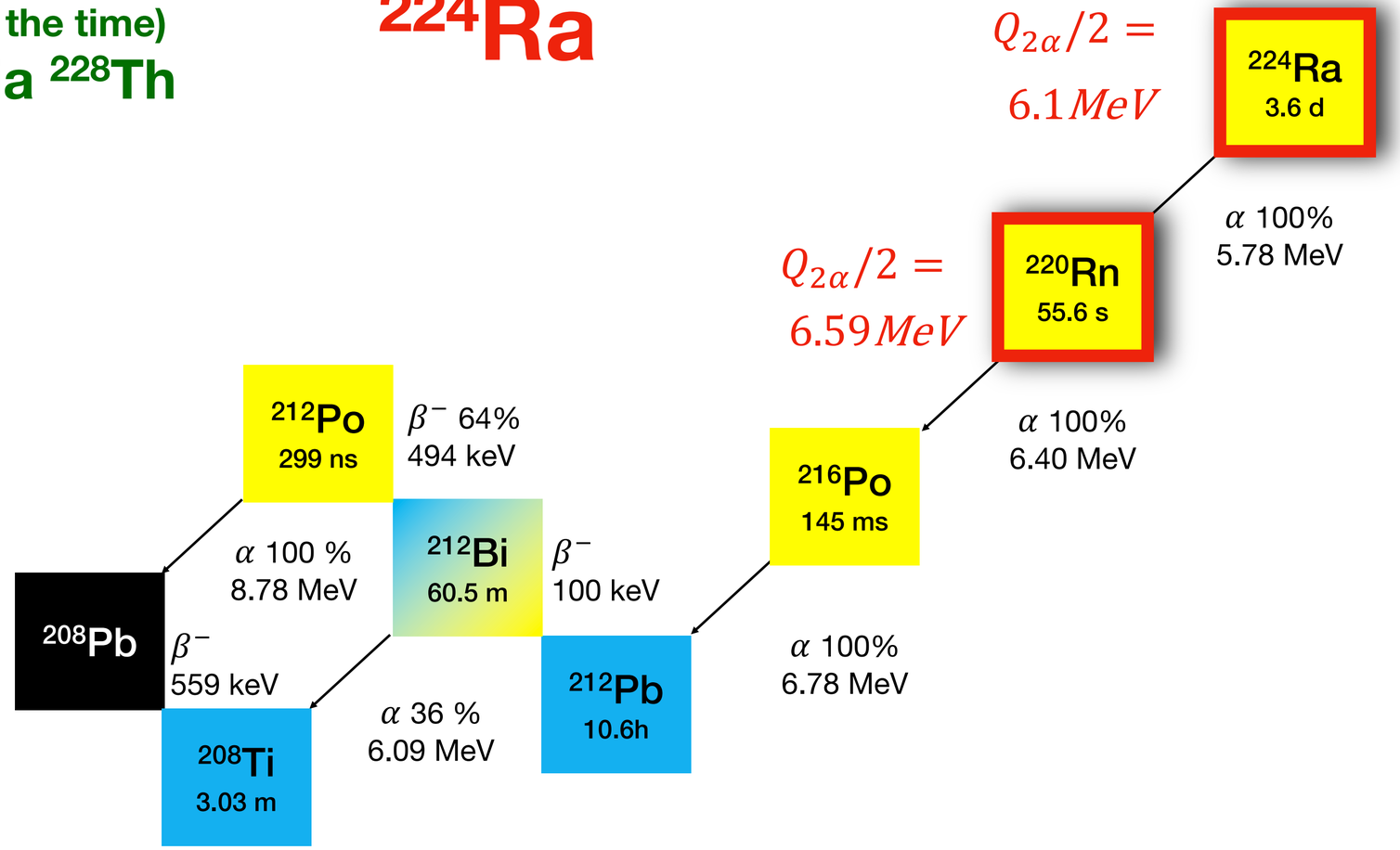
FRS Ion Catcher - GSI

Isotope choice - decay chain

(Only theoretical candidate at the time)

Source production via ^{228}Th

^{224}Ra



- 2α candidate
- Alpha emitter
- Beta emitter

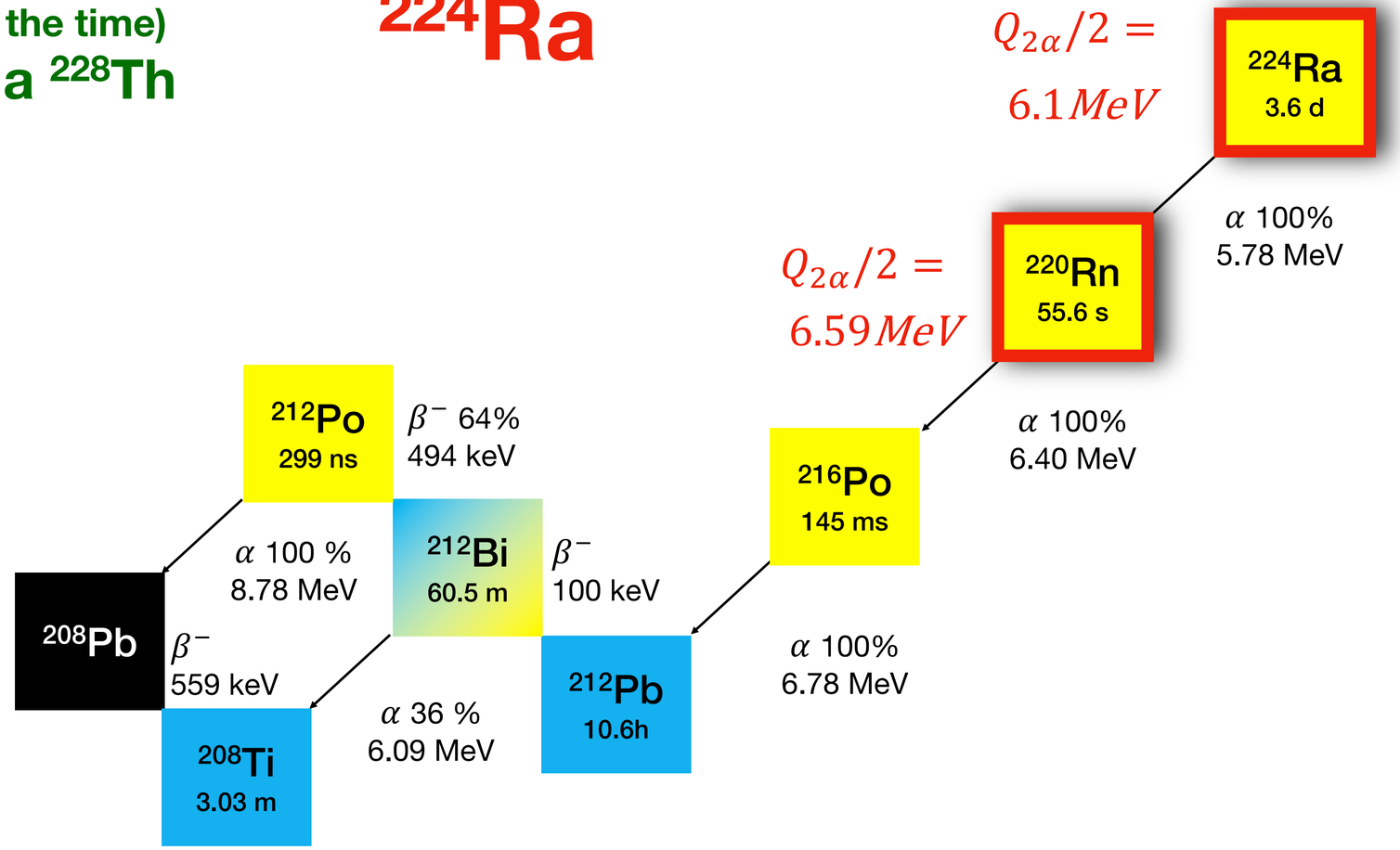
FRS Ion Catcher - GSI

Isotope choice - decay chain

(Only theoretical candidate at the time)

Source production via ^{228}Th

^{224}Ra



2α candidate

Alpha emitter

Beta emitter

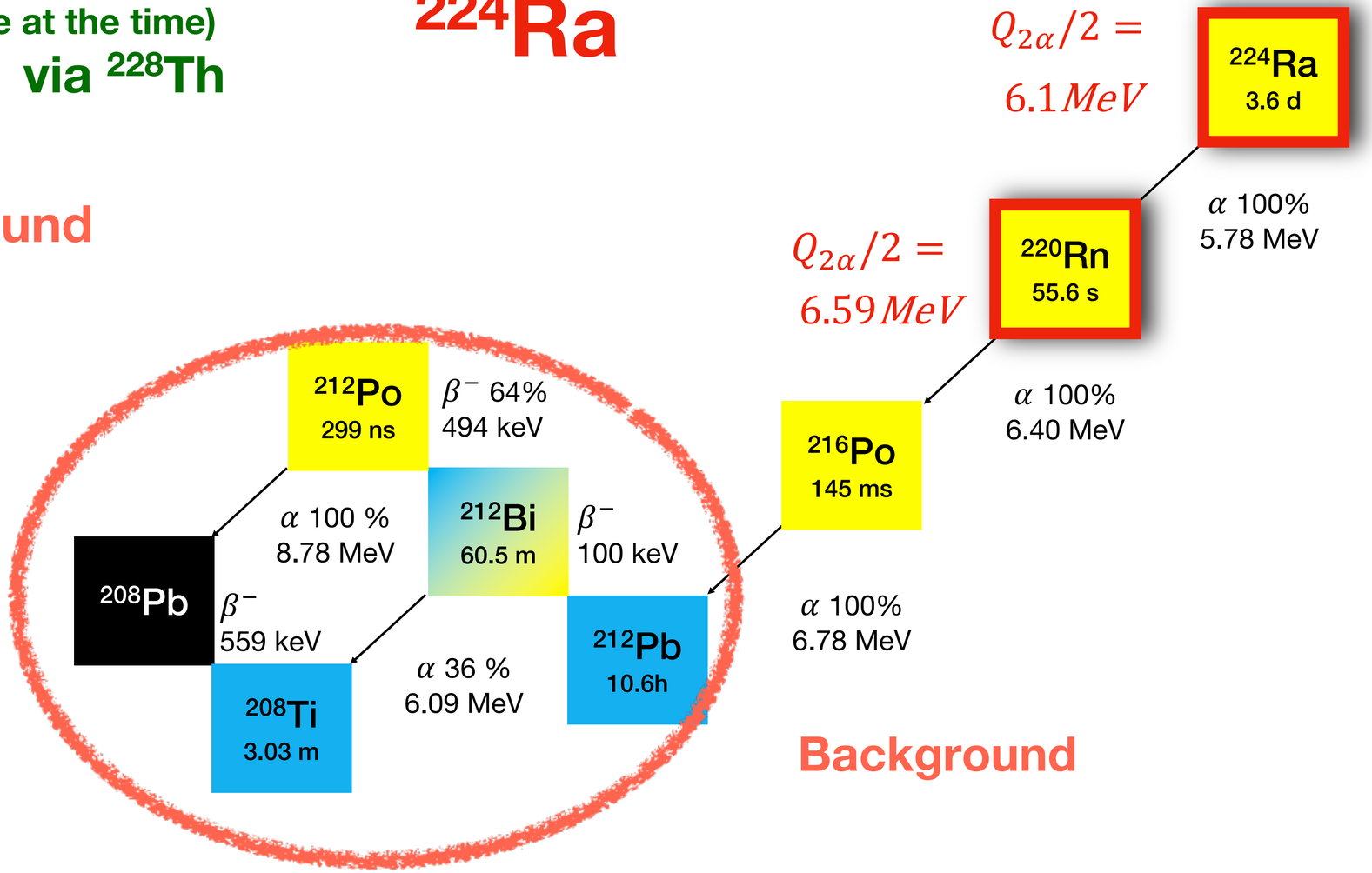
FRS Ion Catcher - GSI

Isotope choice - decay chain

(Only theoretical candidate at the time)
Source production via ^{228}Th

Beta background

^{224}Ra



- 2α candidate
- Alpha emitter
- Beta emitter

FRS Ion Catcher - GSI

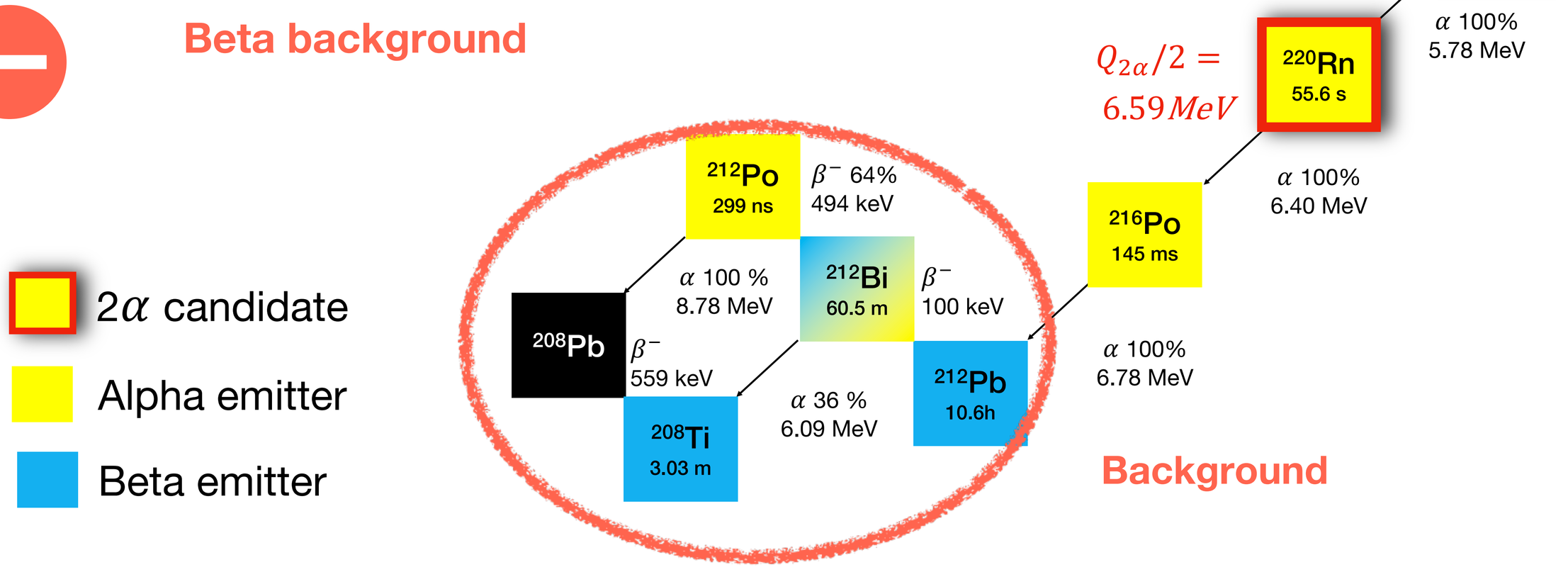
Isotope choice - decay chain

Spatial & Energy cuts
(180°) Back-to-back emission
$E_{\alpha 1} = E_{\alpha 2} = Q_{2\alpha}/2$

(Only theoretical candidate at the time)
Source production via ^{228}Th

^{224}Ra

Beta background



FRS Ion Catcher - GSI

Isotope choice - decay chain

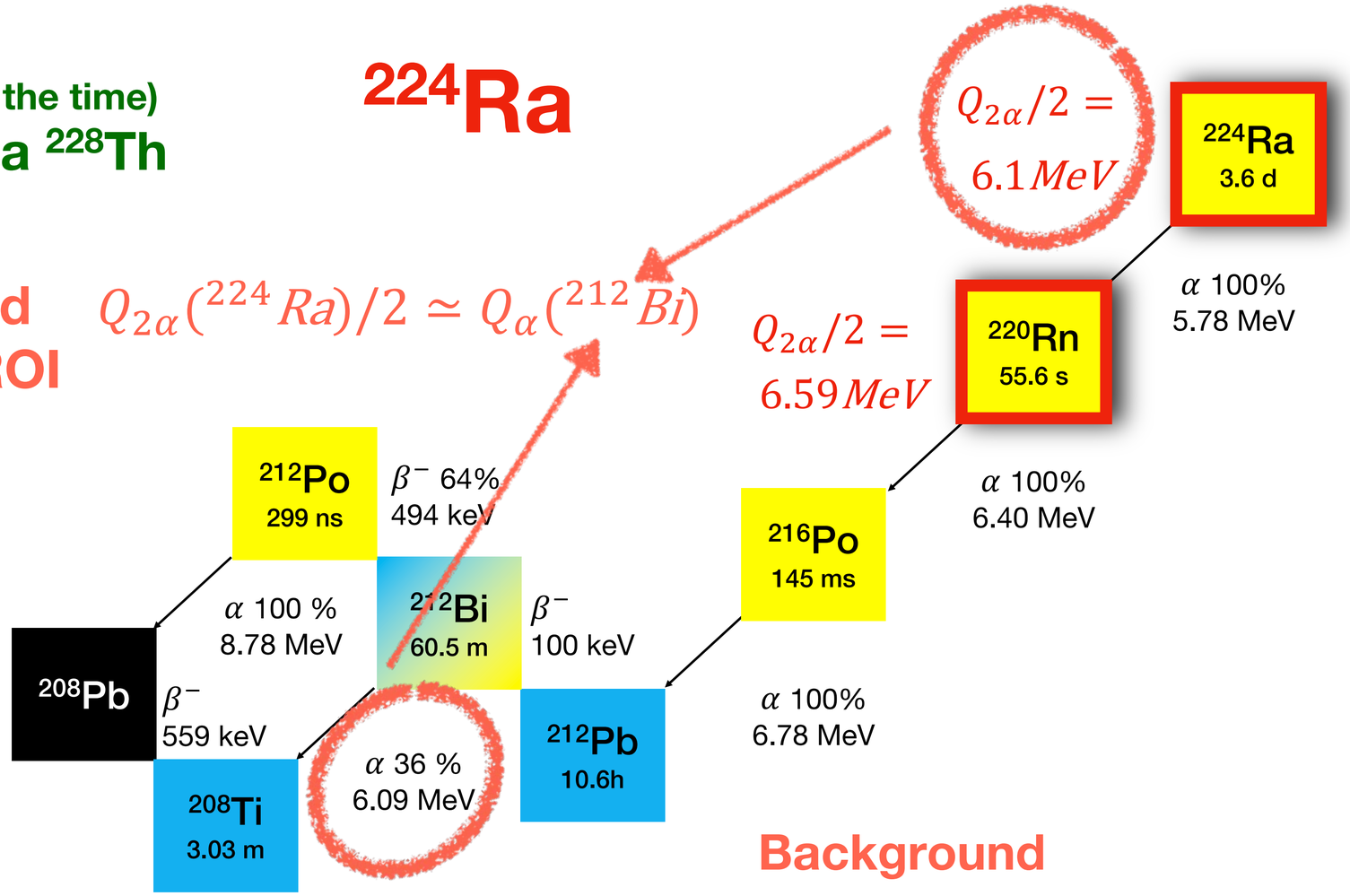
Spatial & Energy cuts
(180°) Back-to-back emission
$E_{\alpha 1} = E_{\alpha 2} = Q_{2\alpha}/2$

(Only theoretical candidate at the time)
Source production via ^{228}Th

^{224}Ra

Beta background
Contaminant in ROI

$Q_{2\alpha}(^{224}Ra)/2 \simeq Q_{\alpha}(^{212}Bi)$

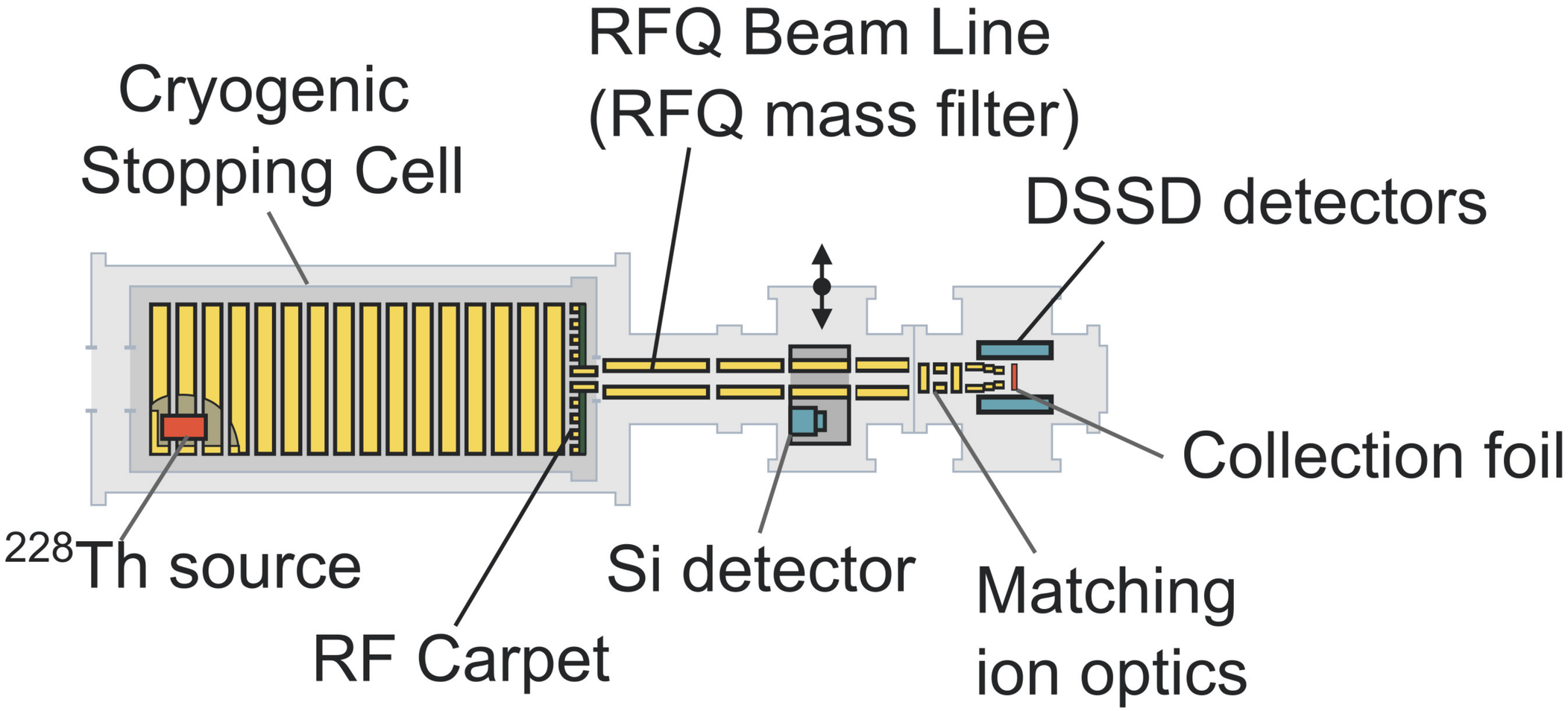


Background

- 2α candidate
- Alpha emitter
- Beta emitter

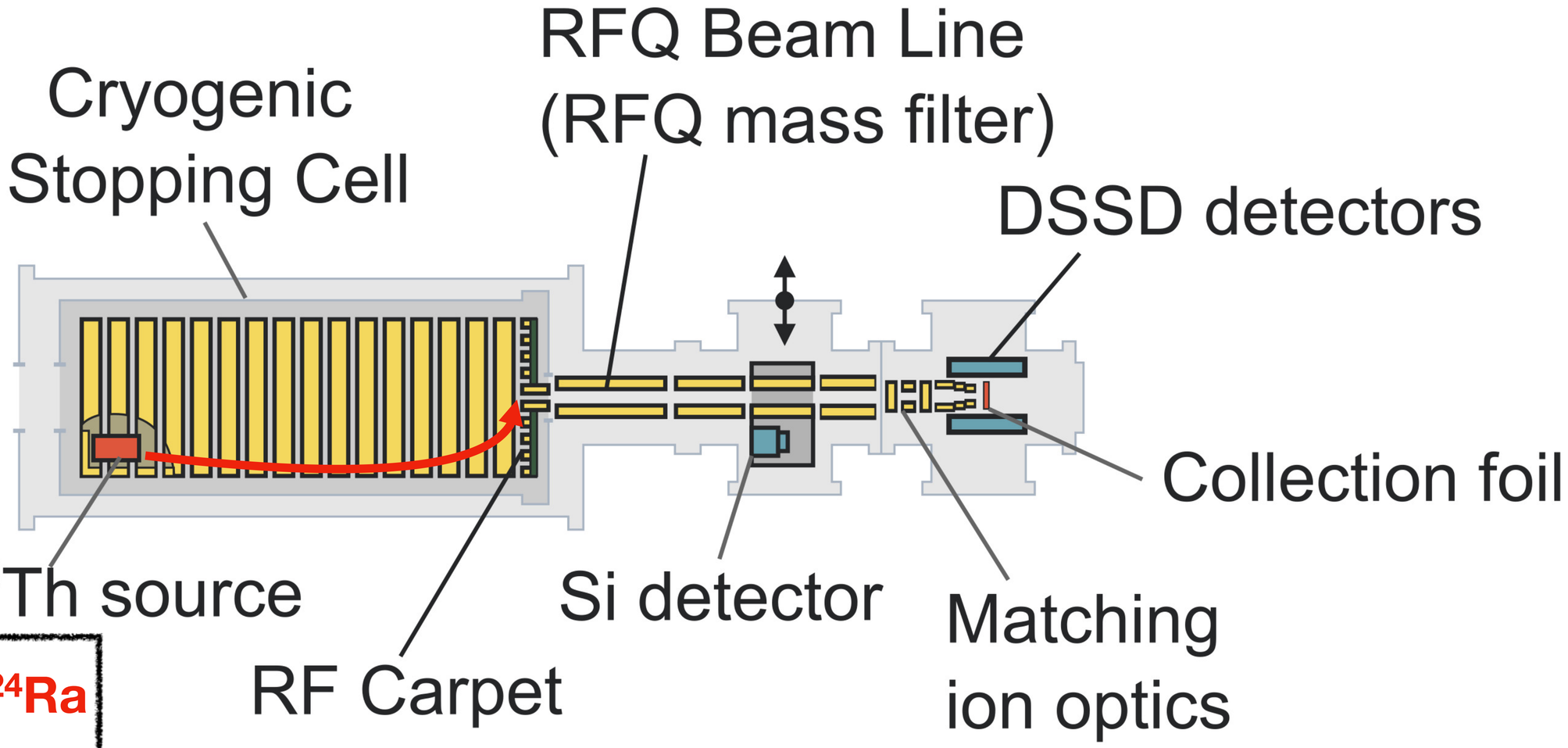
FRS Ion Catcher - GSI

Sketch of the setup



FRS Ion Catcher - GSI

Sketch of the setup

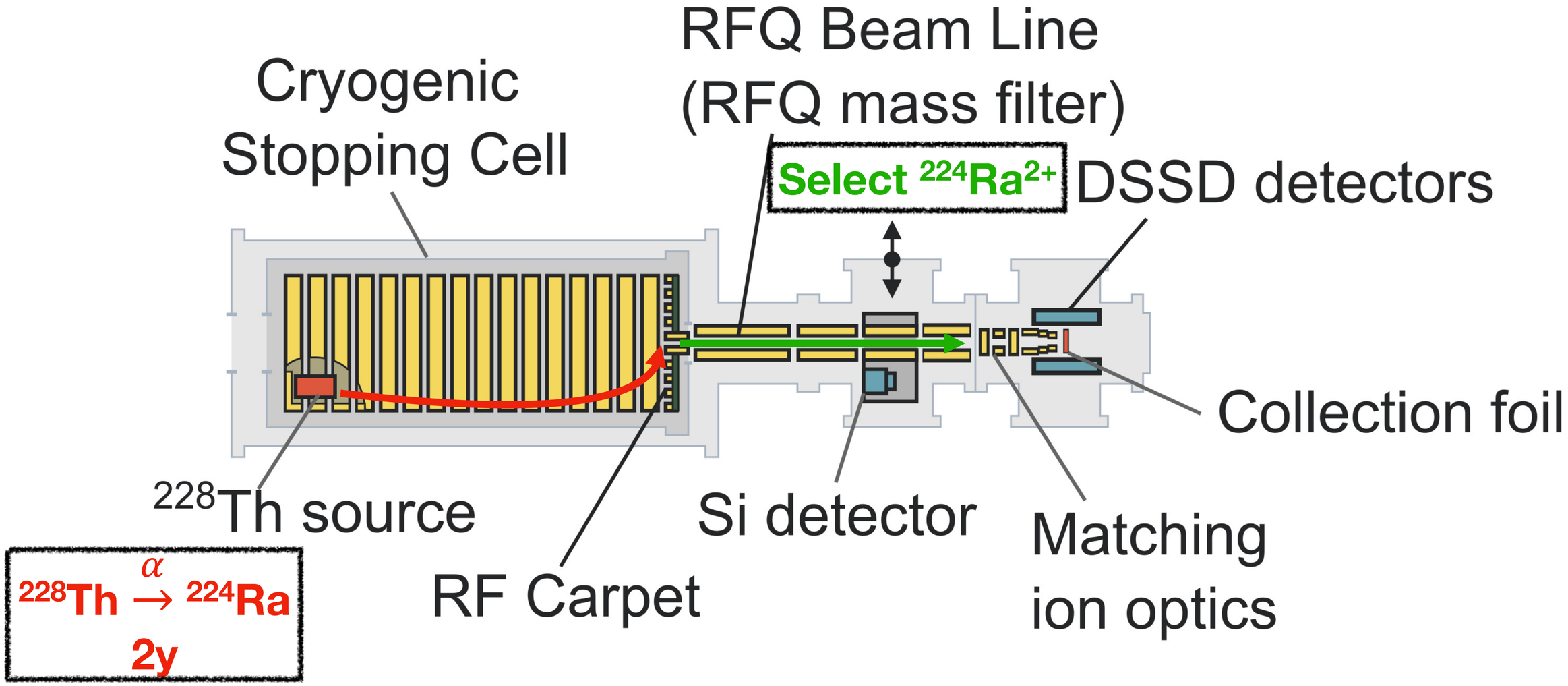


$^{228}Th \xrightarrow{\alpha} {}^{224}Ra$

2y

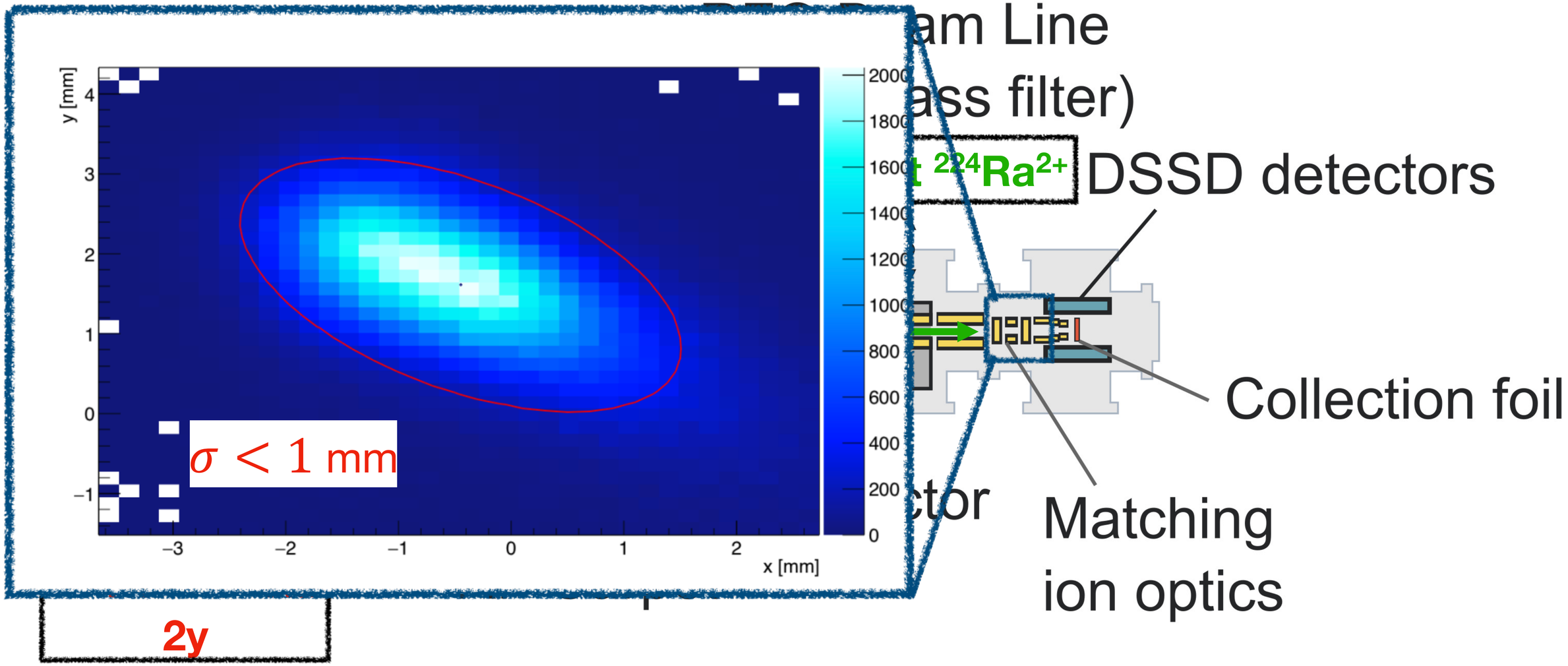
FRS Ion Catcher - GSI

Sketch of the setup



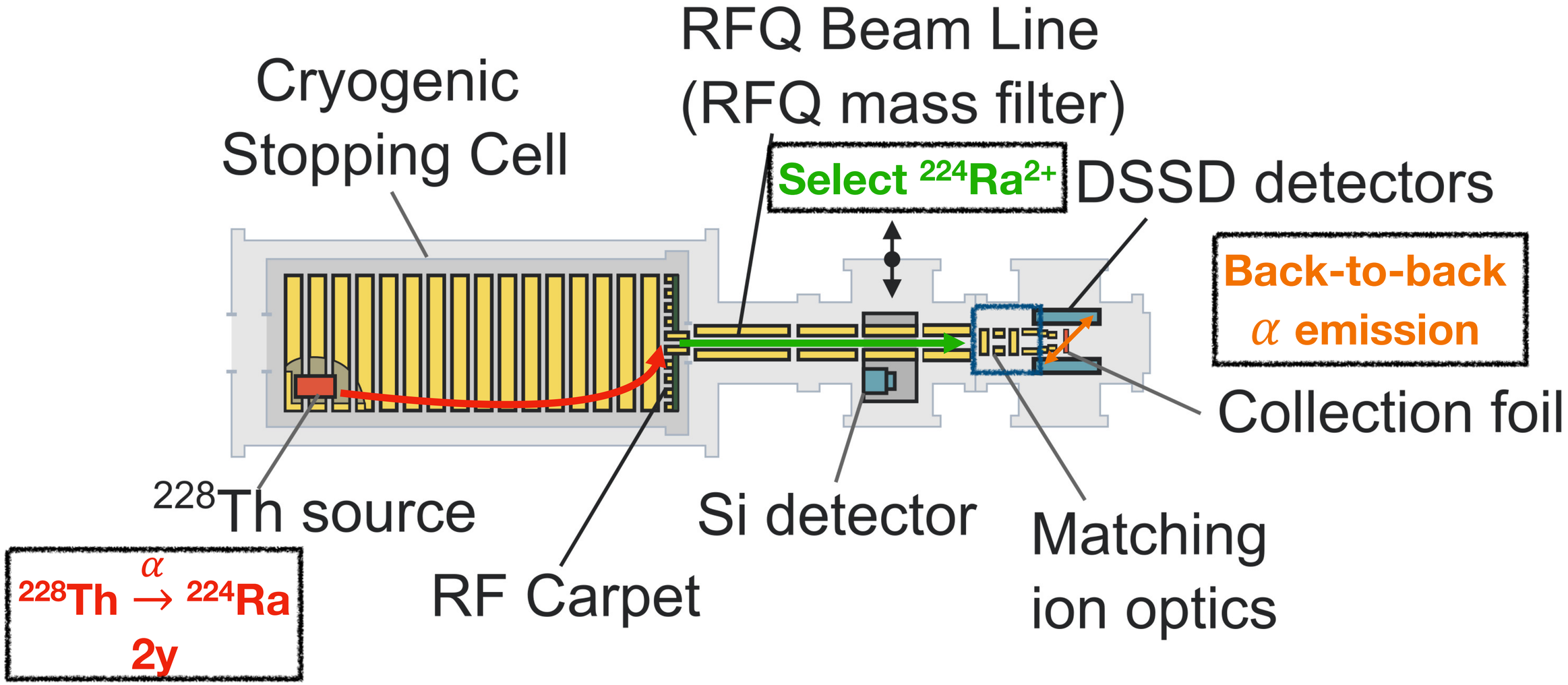
FRS Ion Catcher - GSI

Sketch of the setup



FRS Ion Catcher - GSI

Sketch of the setup

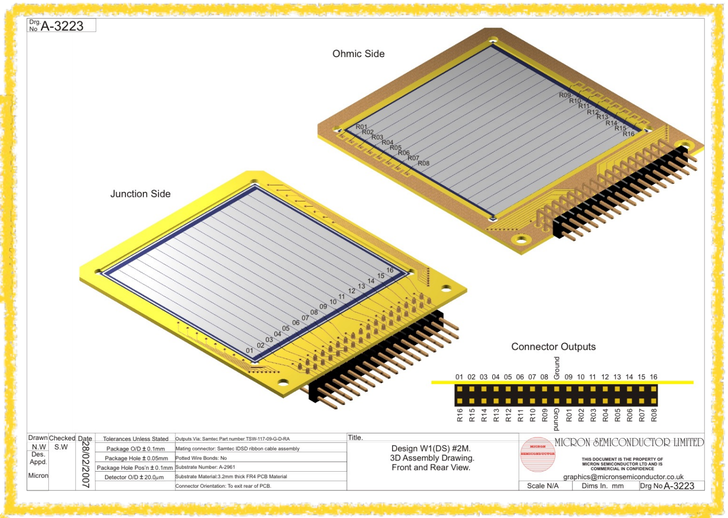


FRS Ion Catcher - GSI

Sketch of the setup

H. Wilsenach courtesy

50 x 50 mm^2
16 x 16 strips
Resolution ~ **25 keV**

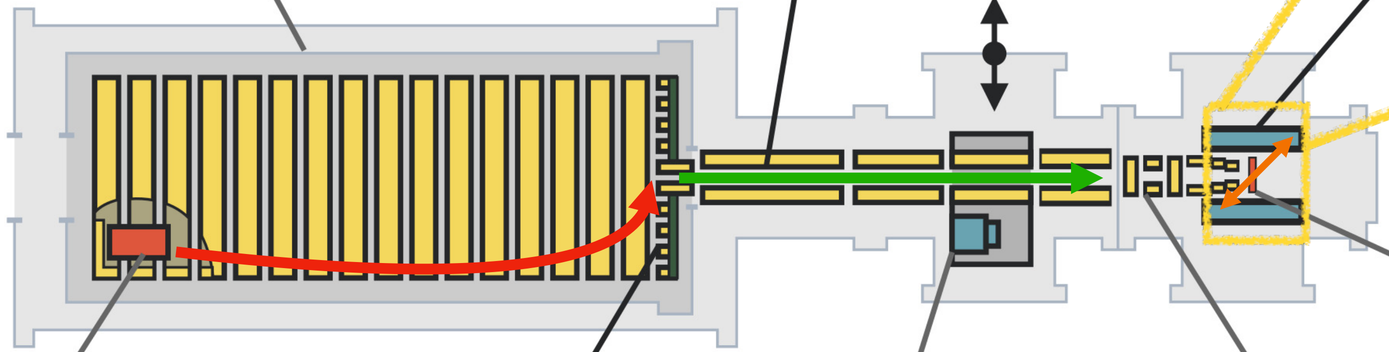


Cryogenic Stopping Cell

RFQ Beam Line (RFQ mass filter)

Select $^{224}Ra^{2+}$

DSSD detectors



Back-to-back α emission

Collection foil

^{228}Th source

RF Carpet

Si detector

Matching ion optics

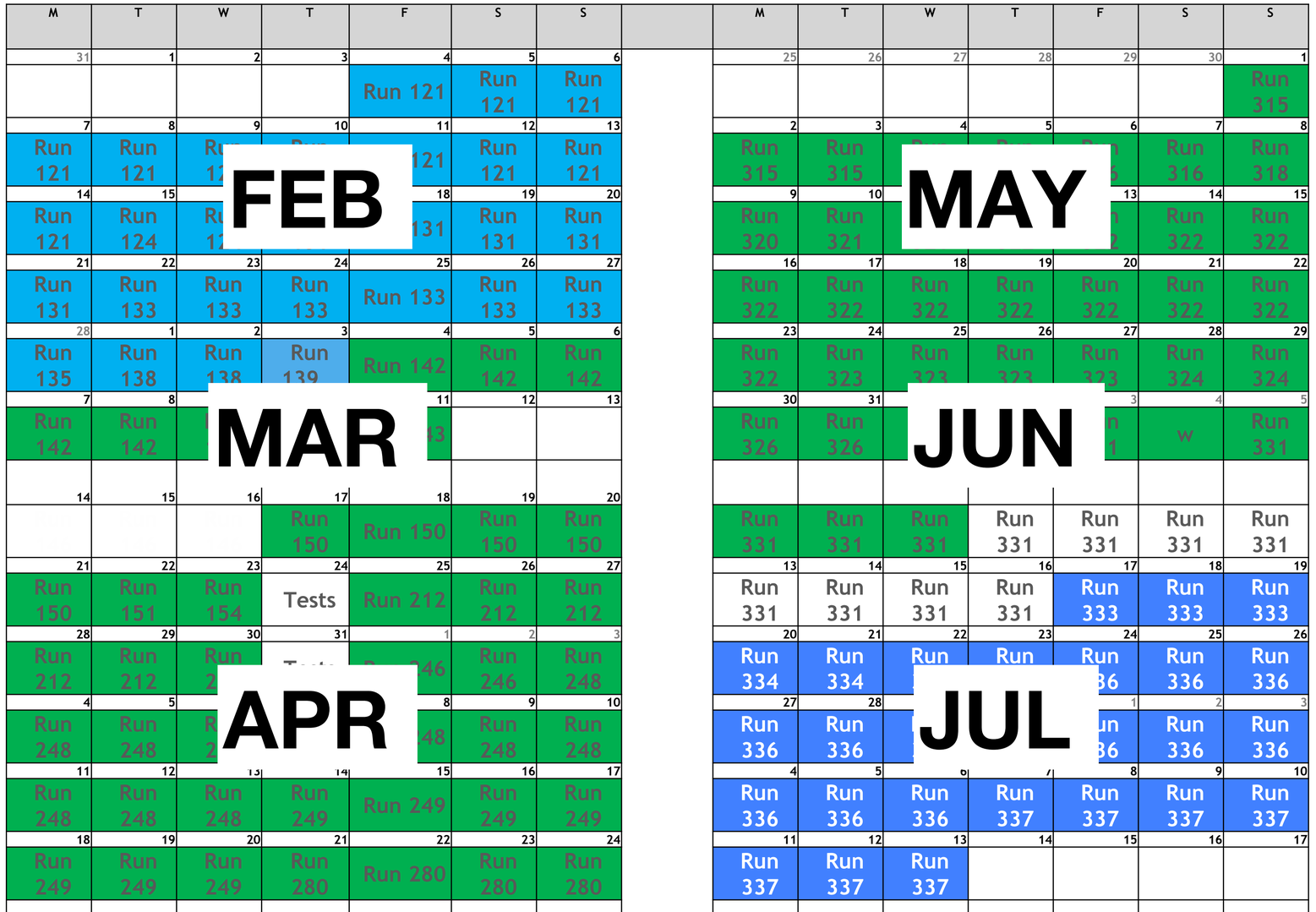
$^{228}Th \xrightarrow{\alpha} {}^{224}Ra$

2y

H. Wilsenach courtesy

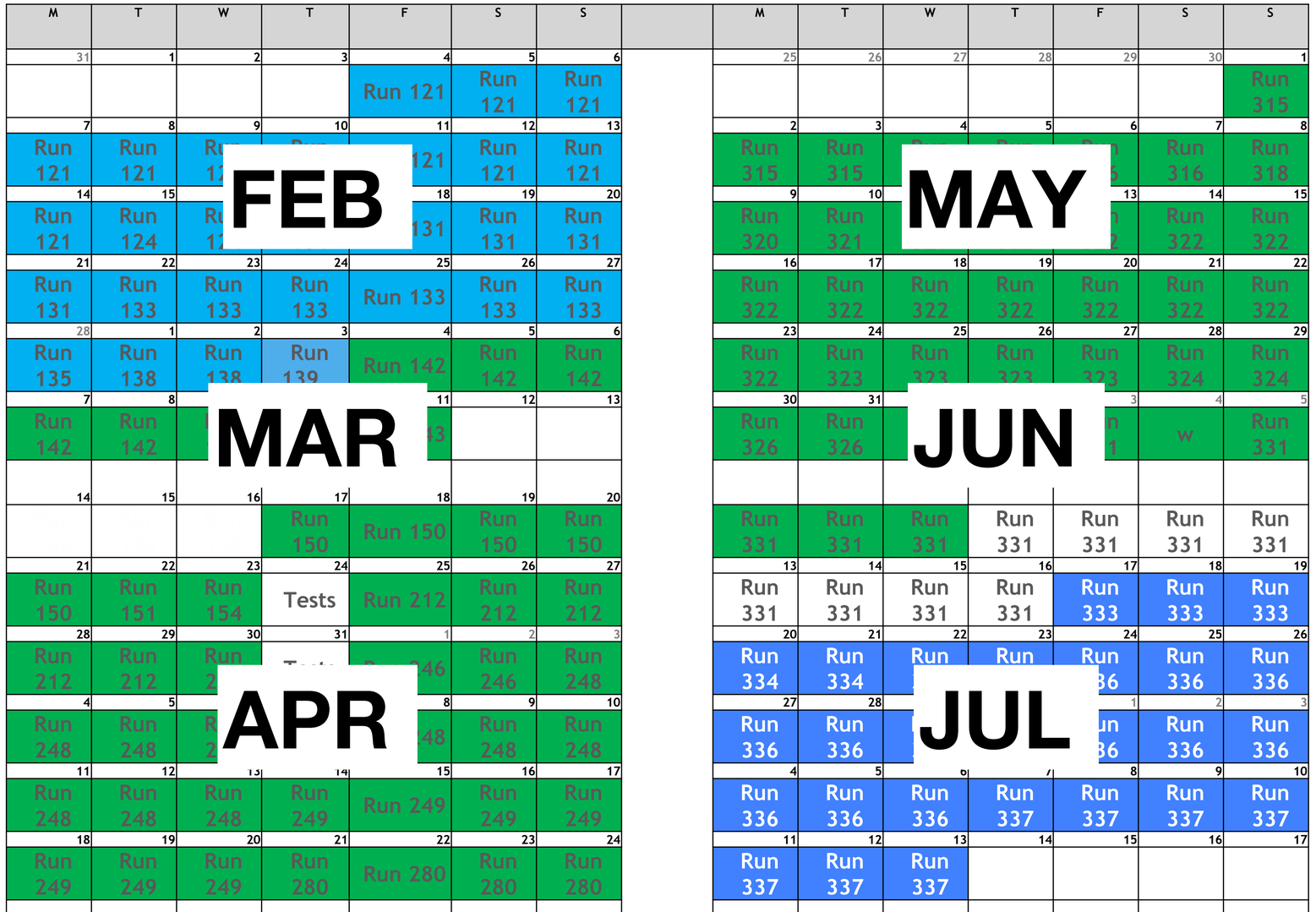
FRS Ion Catcher - GSI

Data Acquisition (2022)



FRS Ion Catcher - GSI

Data Acquisition (2022)

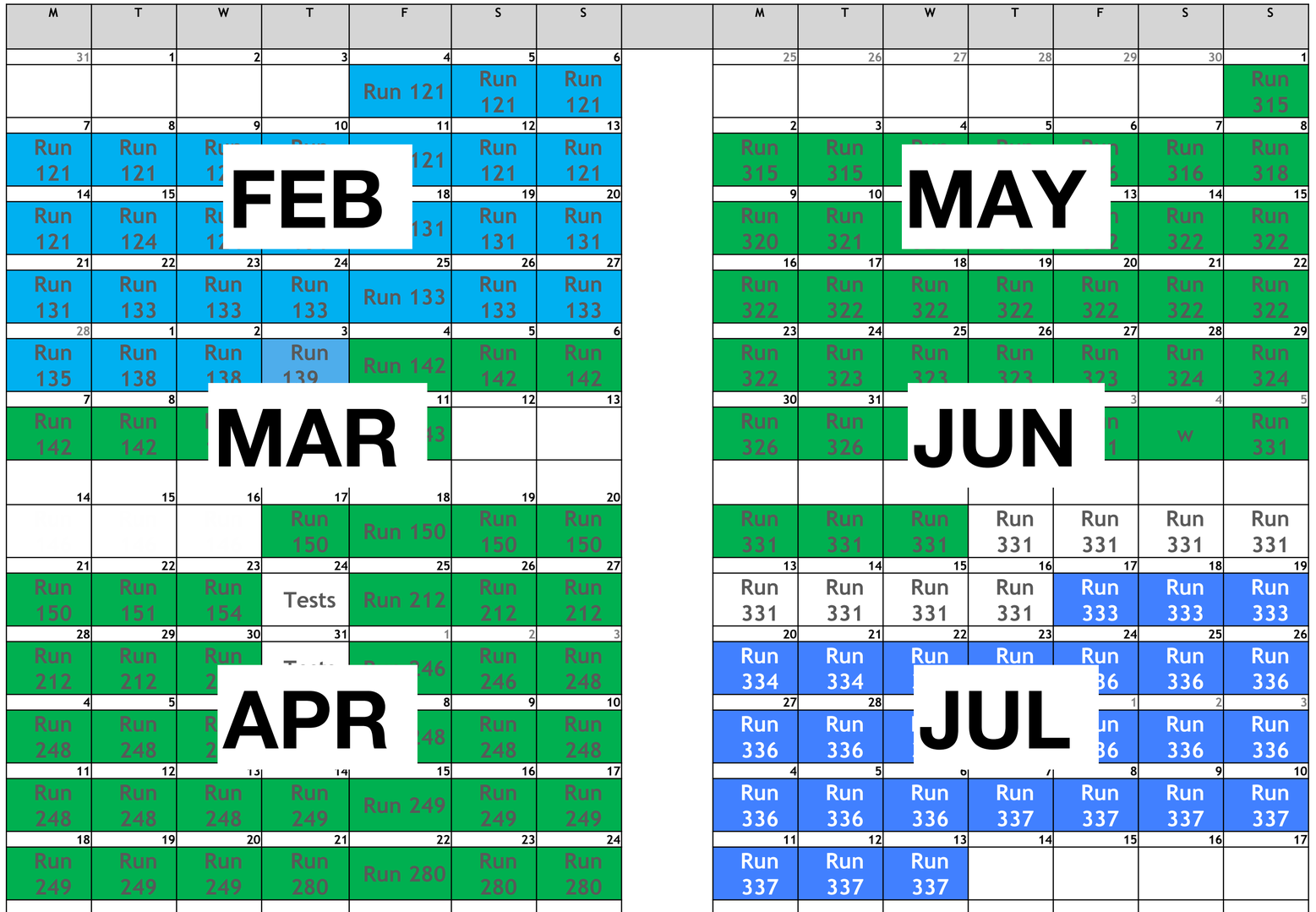


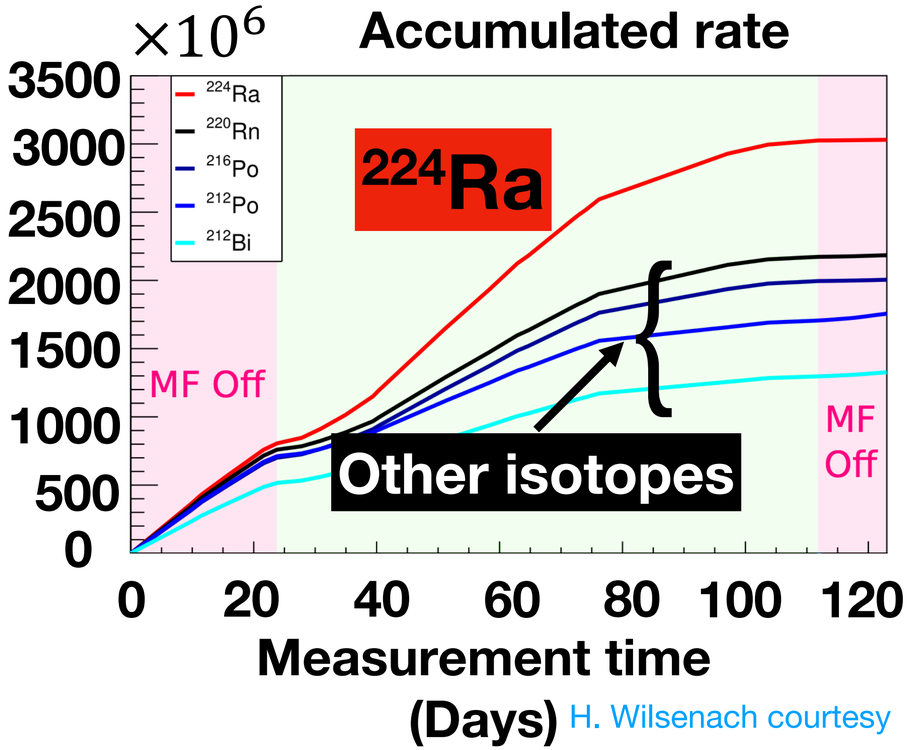
All ^{224}Ra BG

~**120** days of data

FRS Ion Catcher - GSI

Data Acquisition (2022)





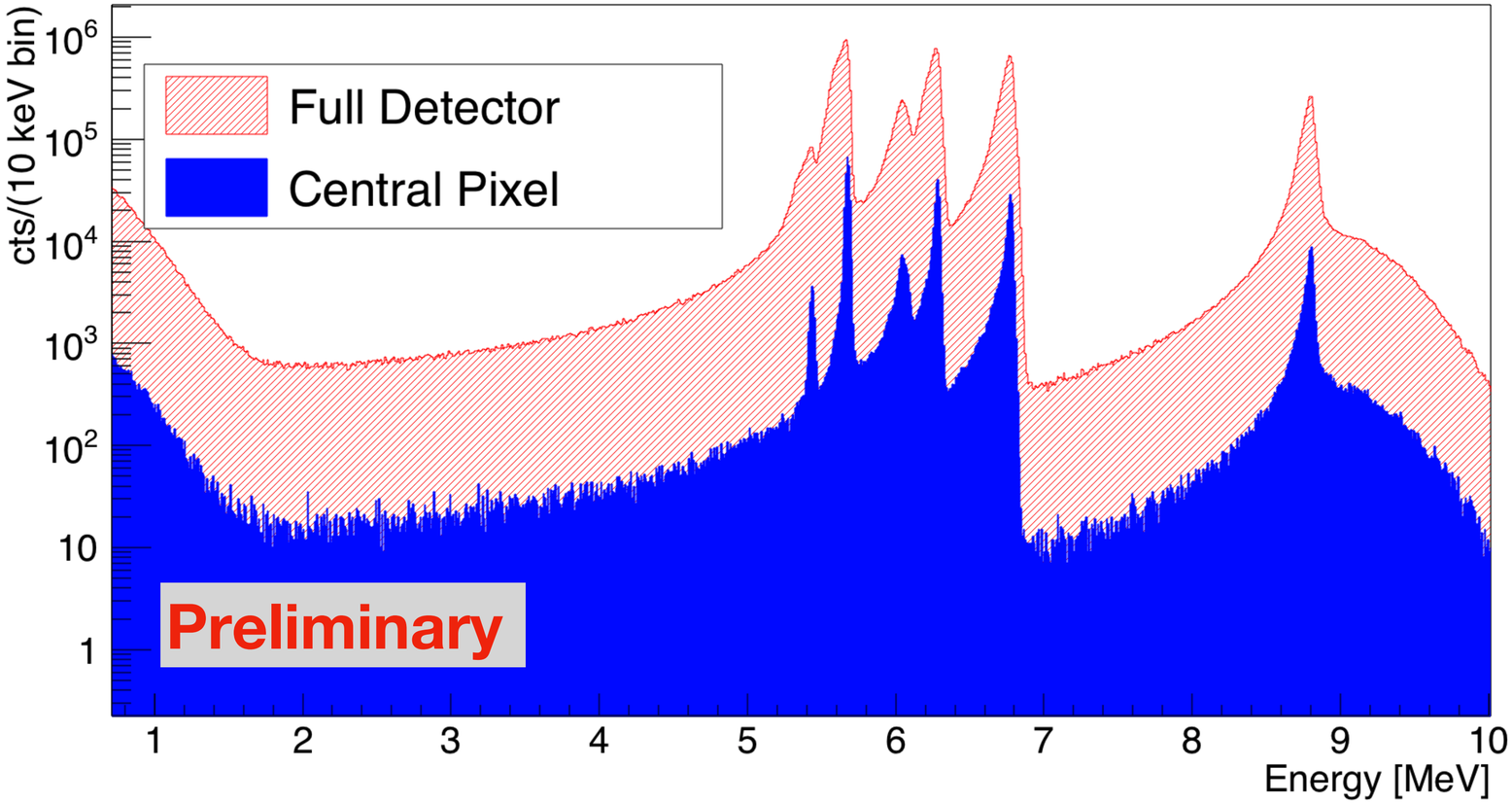
All ^{224}Ra BG

~120 days of data

~3×10^9 ^{224}Ra implanted

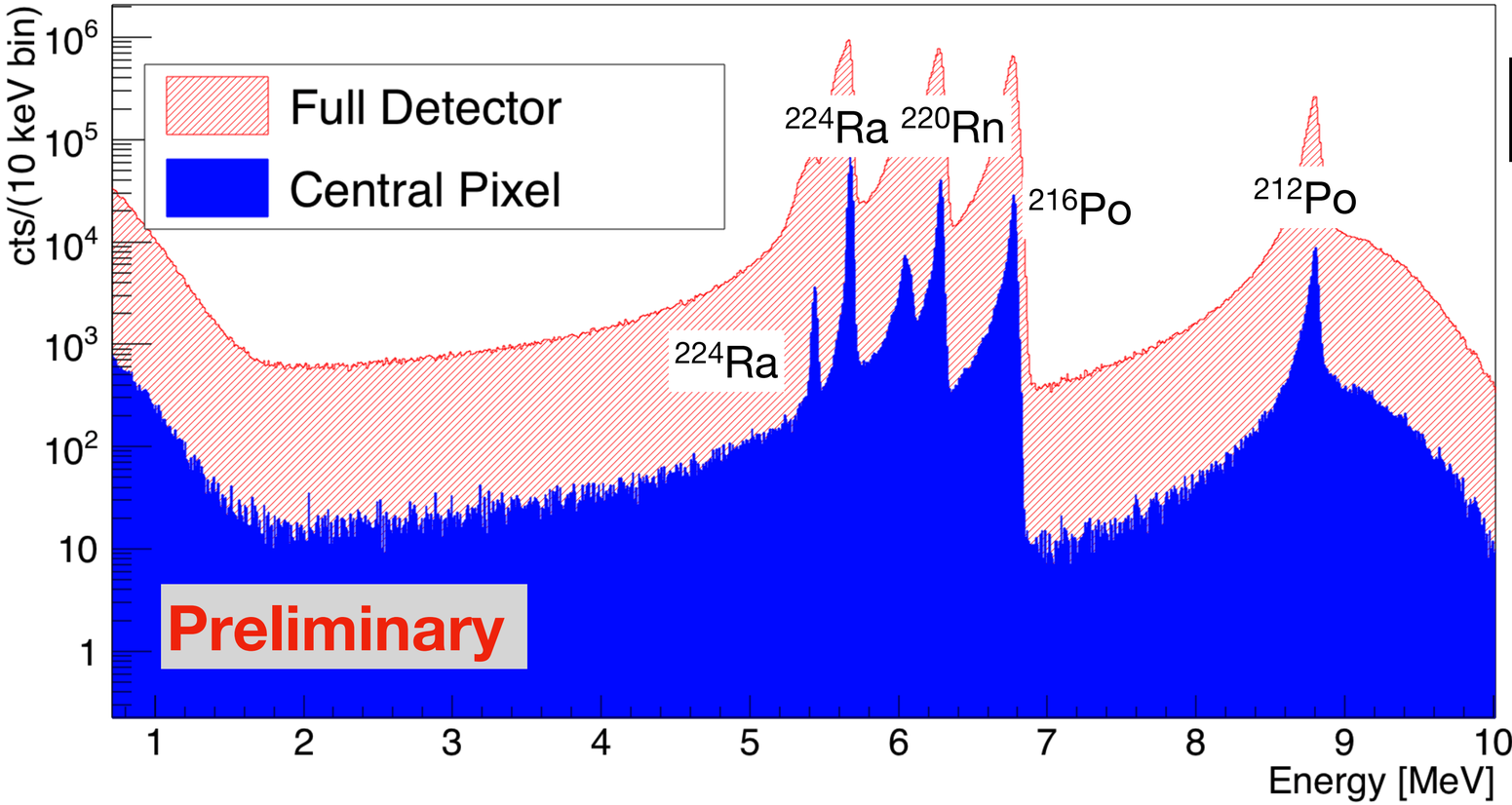
FRS Ion Catcher - GSI

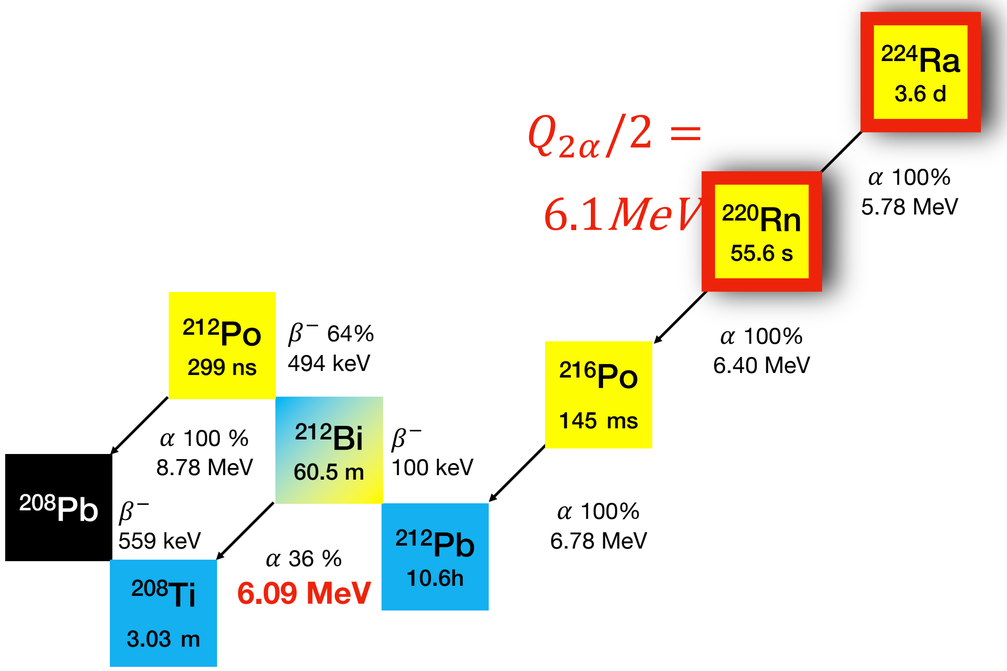
Data analysis



FRS Ion Catcher - GSI

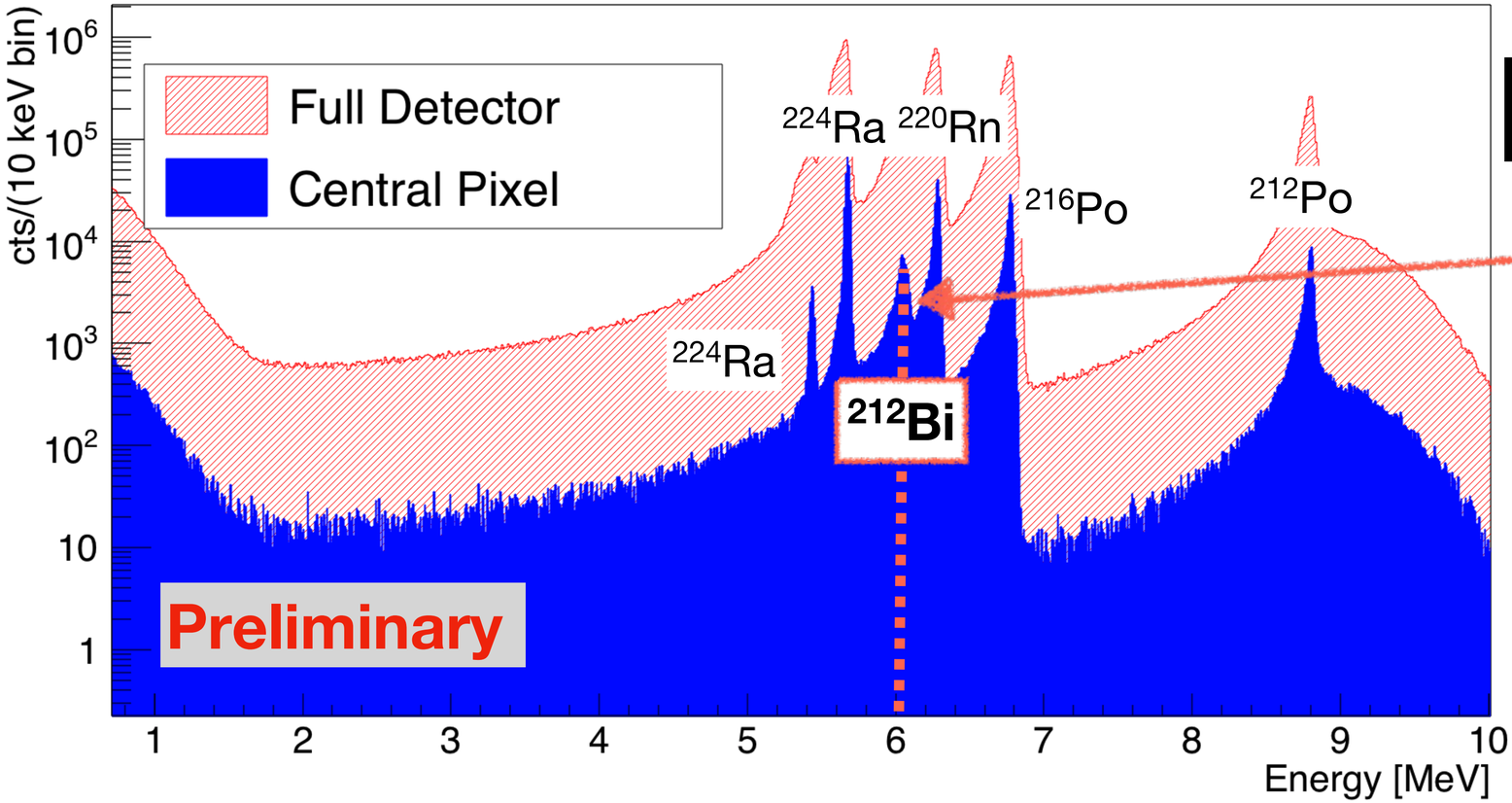
Data analysis

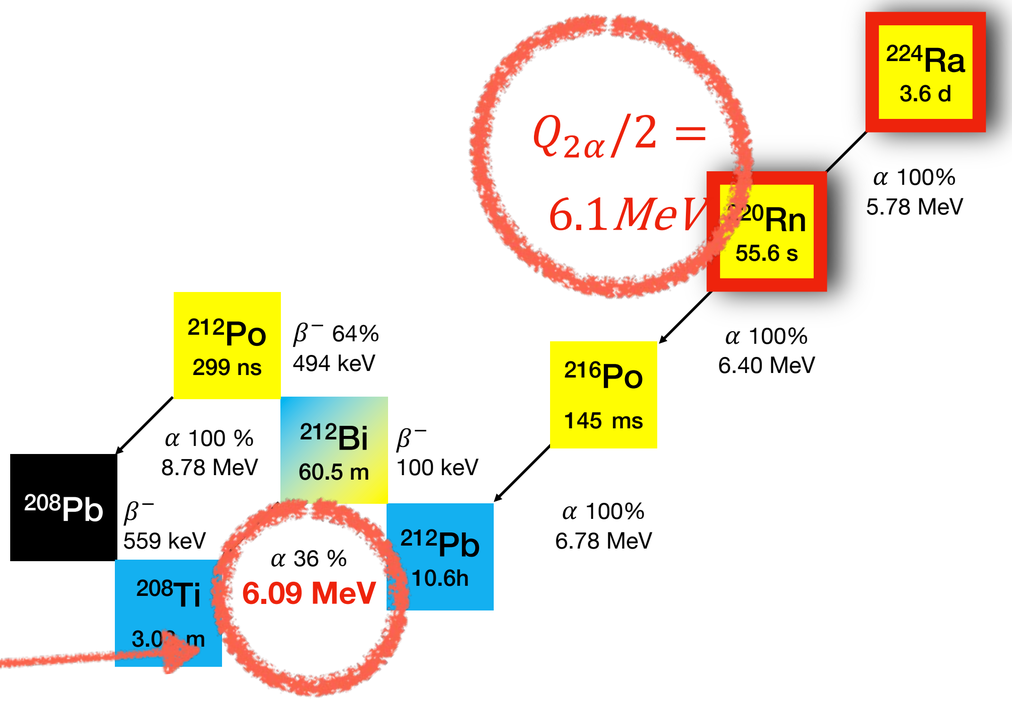




FRS Ion Catcher - GSI

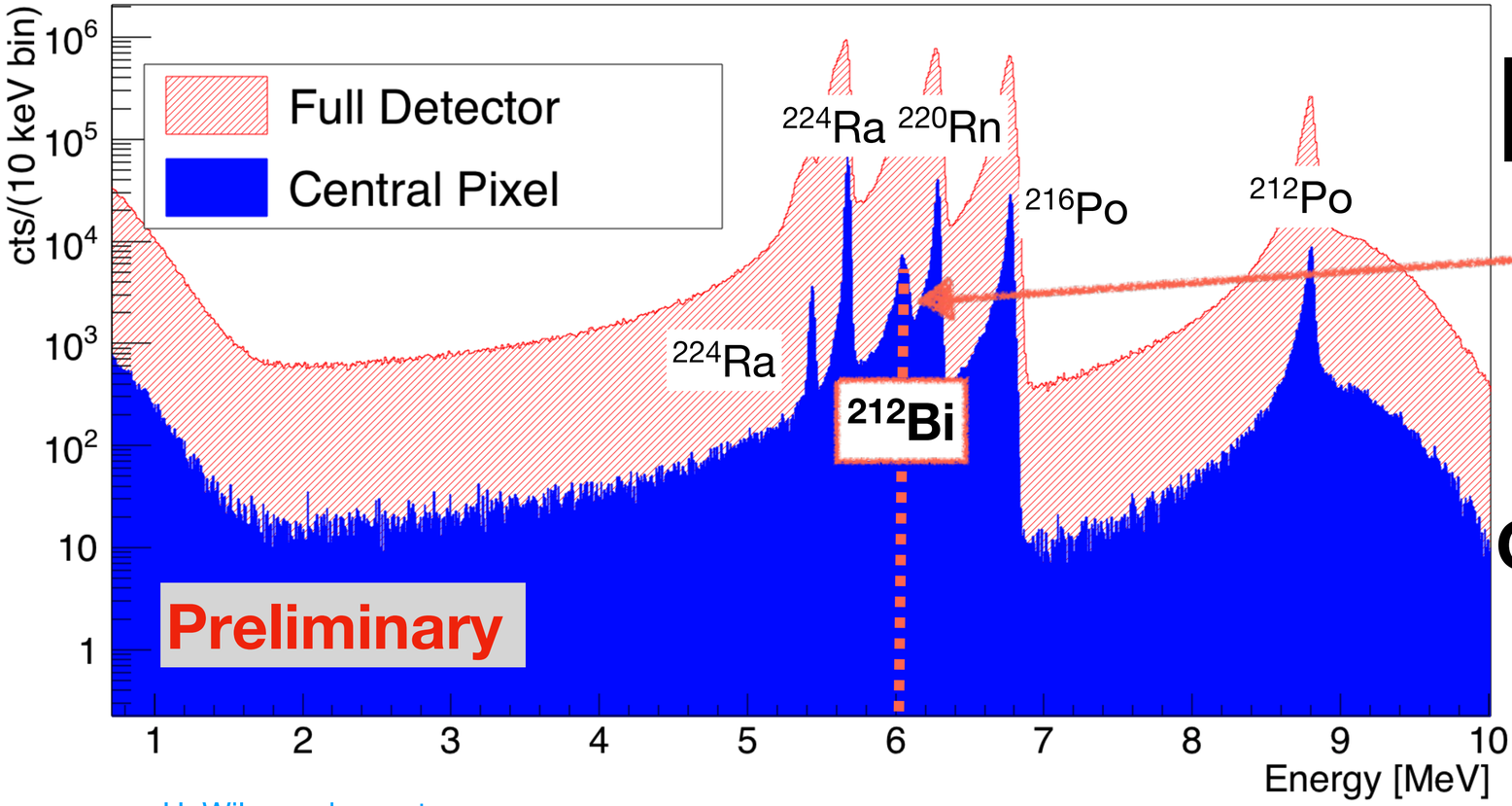
Data analysis



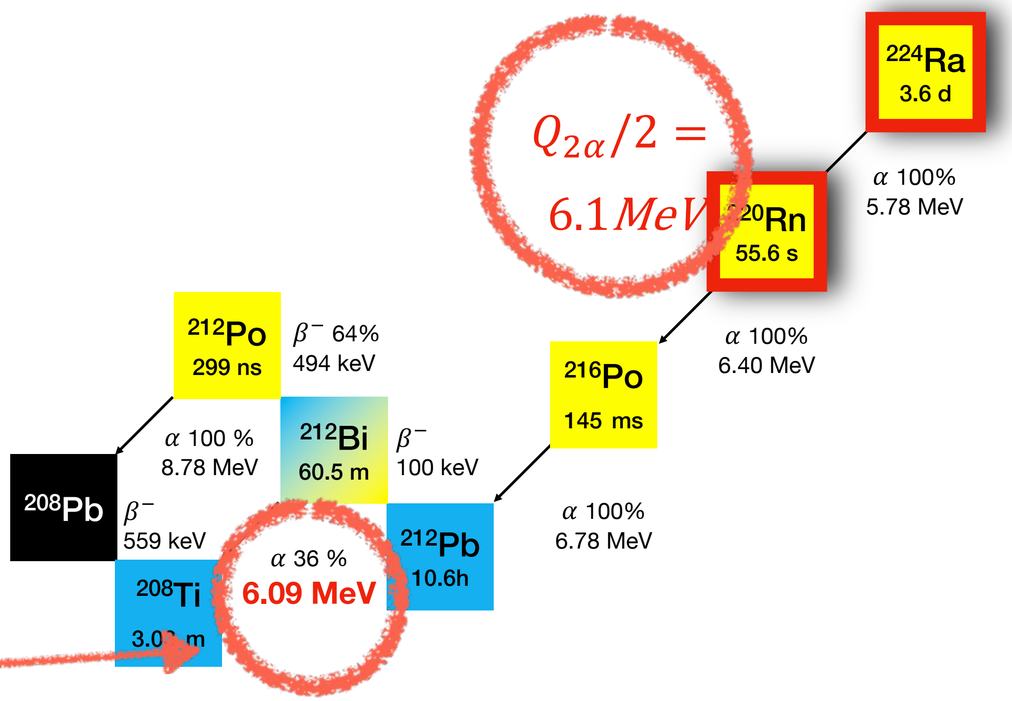


FRS Ion Catcher - GSI

Data analysis



H. Wilsenach courtesy

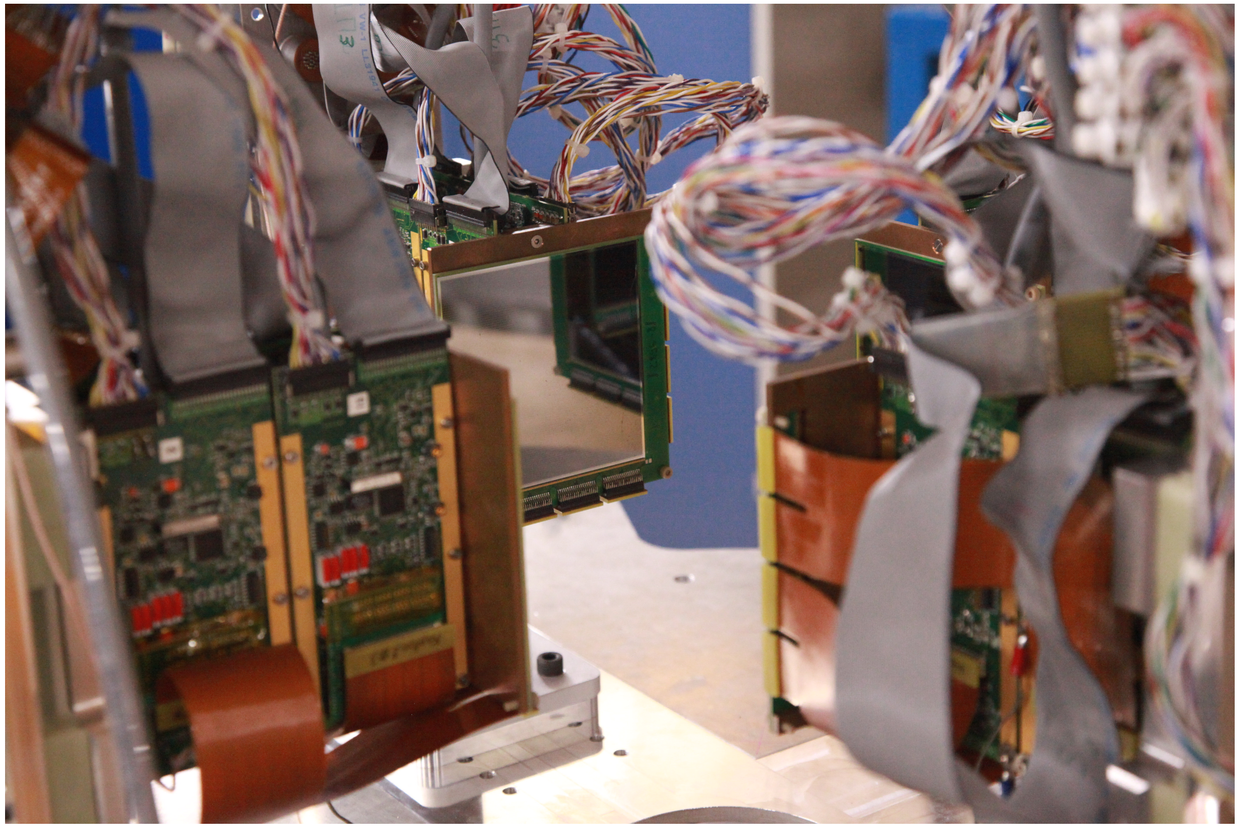


Contamination in ROI for ^{224}Ra

^{220}Rn better candidate ?

Experimental search for 2α

CERN/Isolde - Saclay



Experimental search for 2 α

2α candidate

Alpha emitter

Beta emitter

Decay chains

^{220}Ra

^{222}Ra

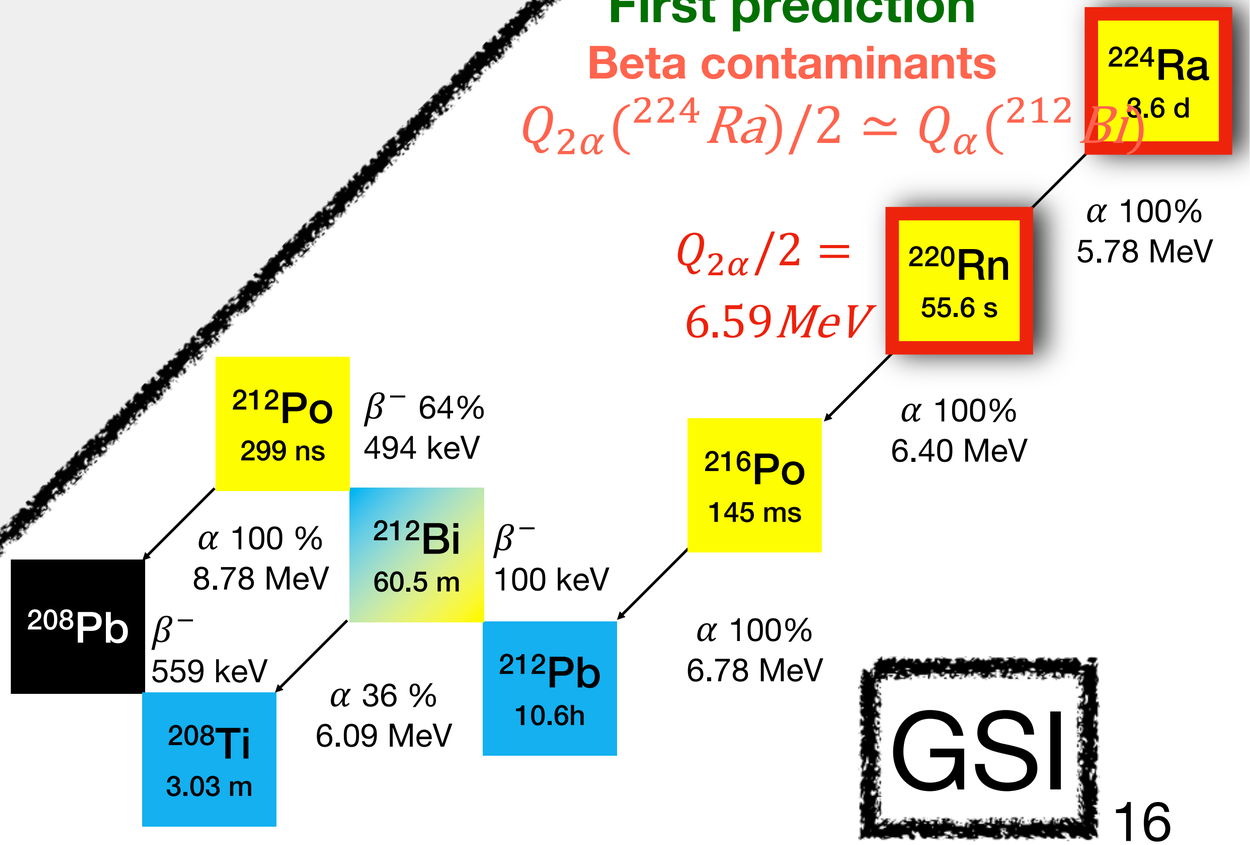
^{224}Ra

$Q_{2\alpha}/2 = 6.1 MeV$

First prediction

Beta contaminants

$Q_{2\alpha}(^{224}Ra)/2 \simeq Q_{\alpha}(^{212}Bi)$



CERN

GSI

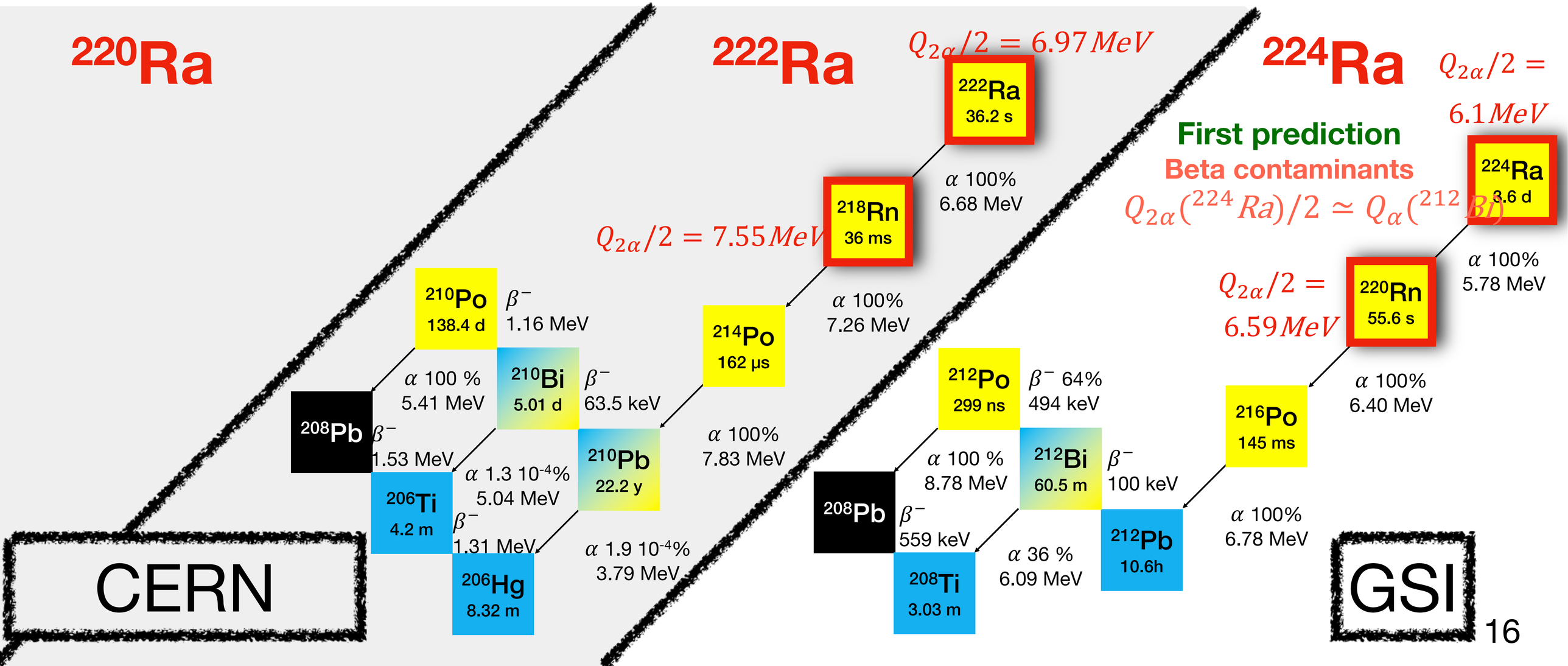
Experimental search for 2 α

2α candidate

Alpha emitter

Beta emitter

Decay chains



CERN

GSI

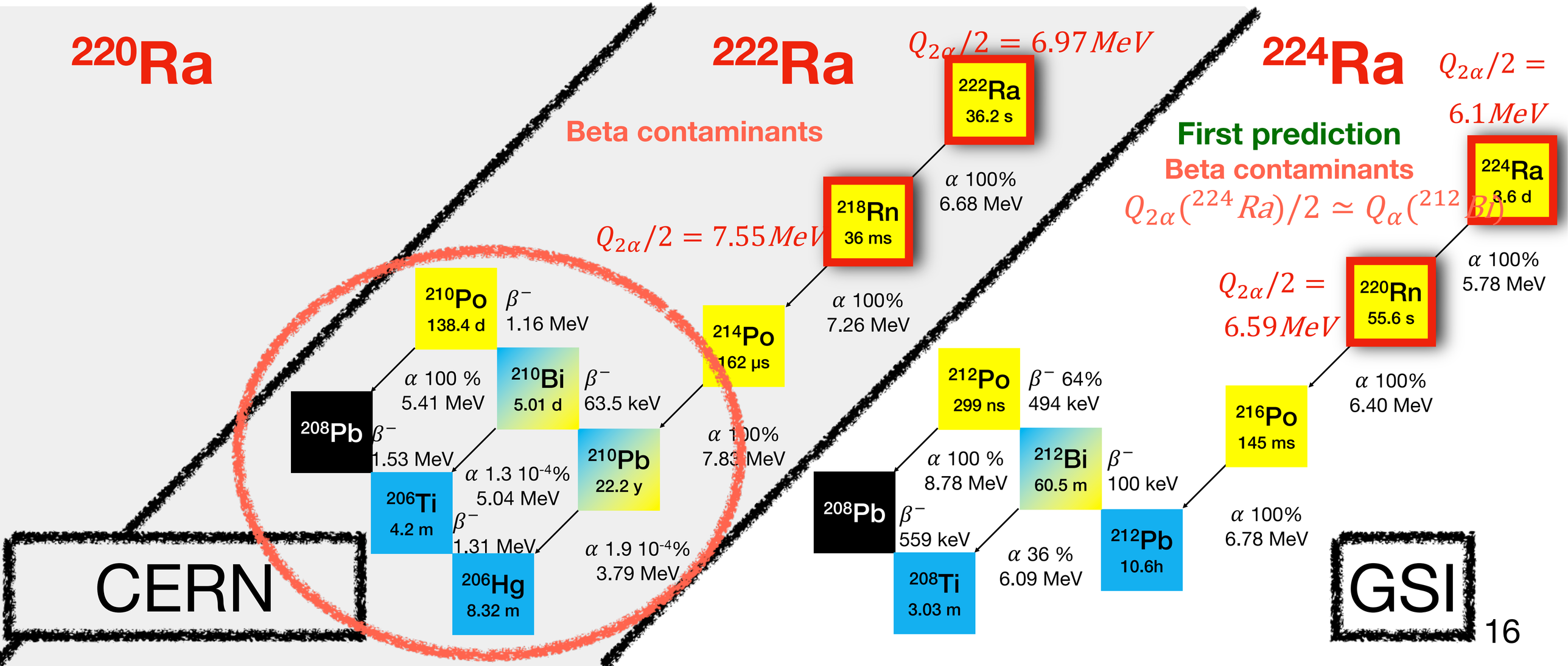
Experimental search for 2 α

2α candidate

Alpha emitter

Beta emitter

Decay chains



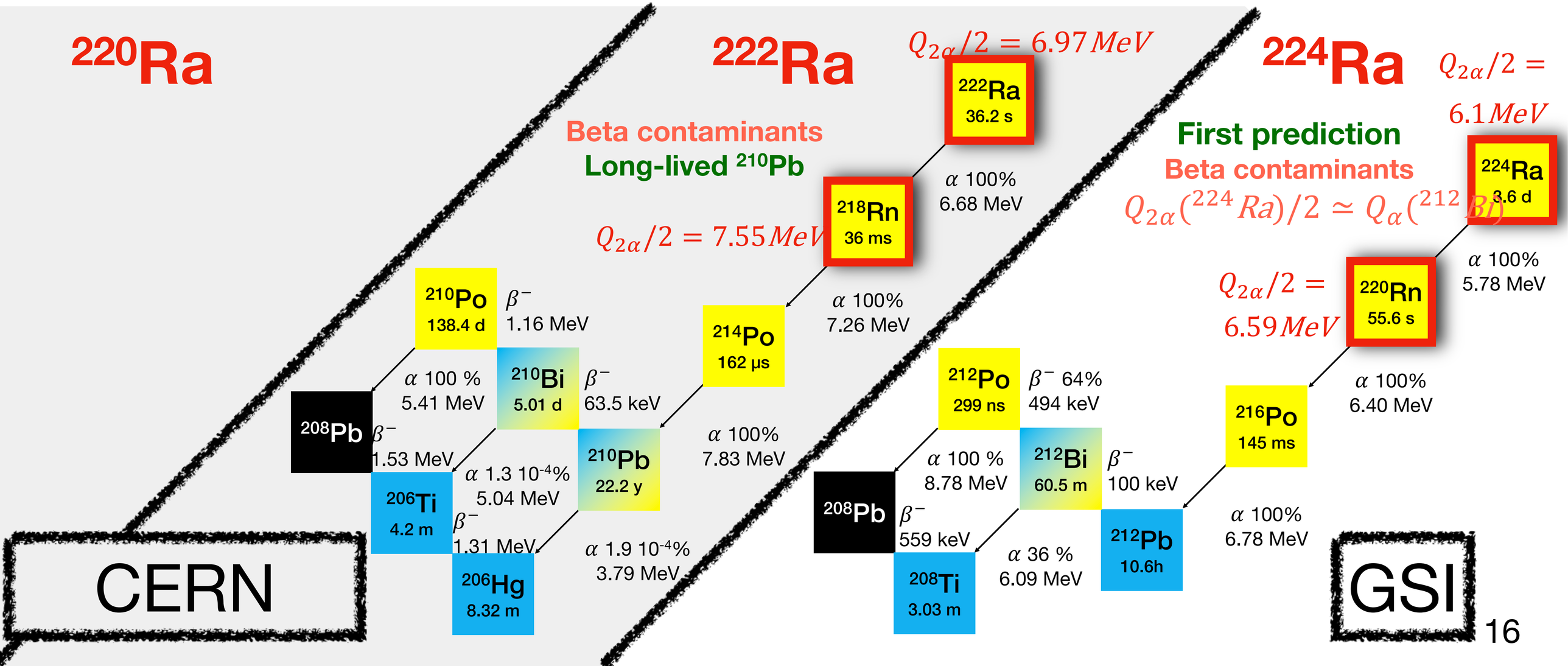
Experimental search for 2 α

2α candidate

Alpha emitter

Beta emitter

Decay chains



CERN

GSI

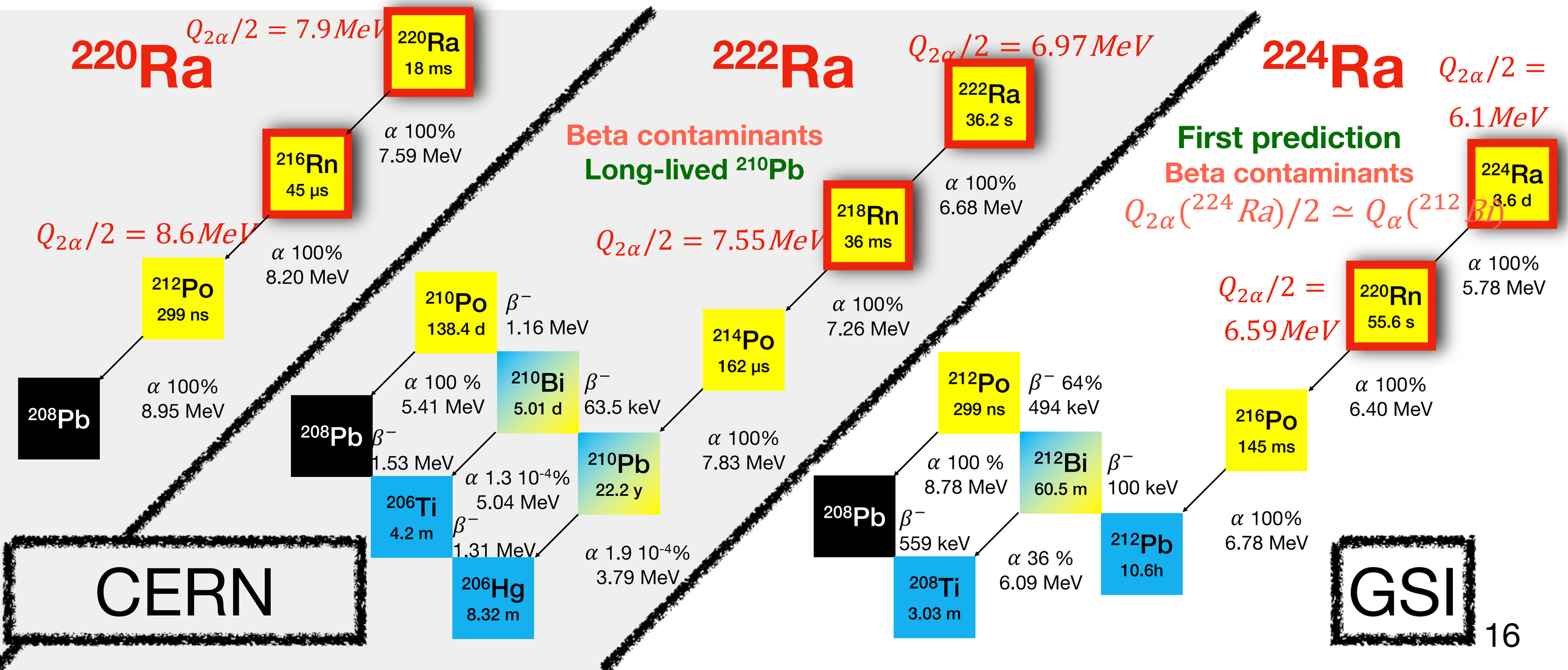
Experimental search for 2 α

2α candidate

Alpha emitter

Beta emitter

Decay chains



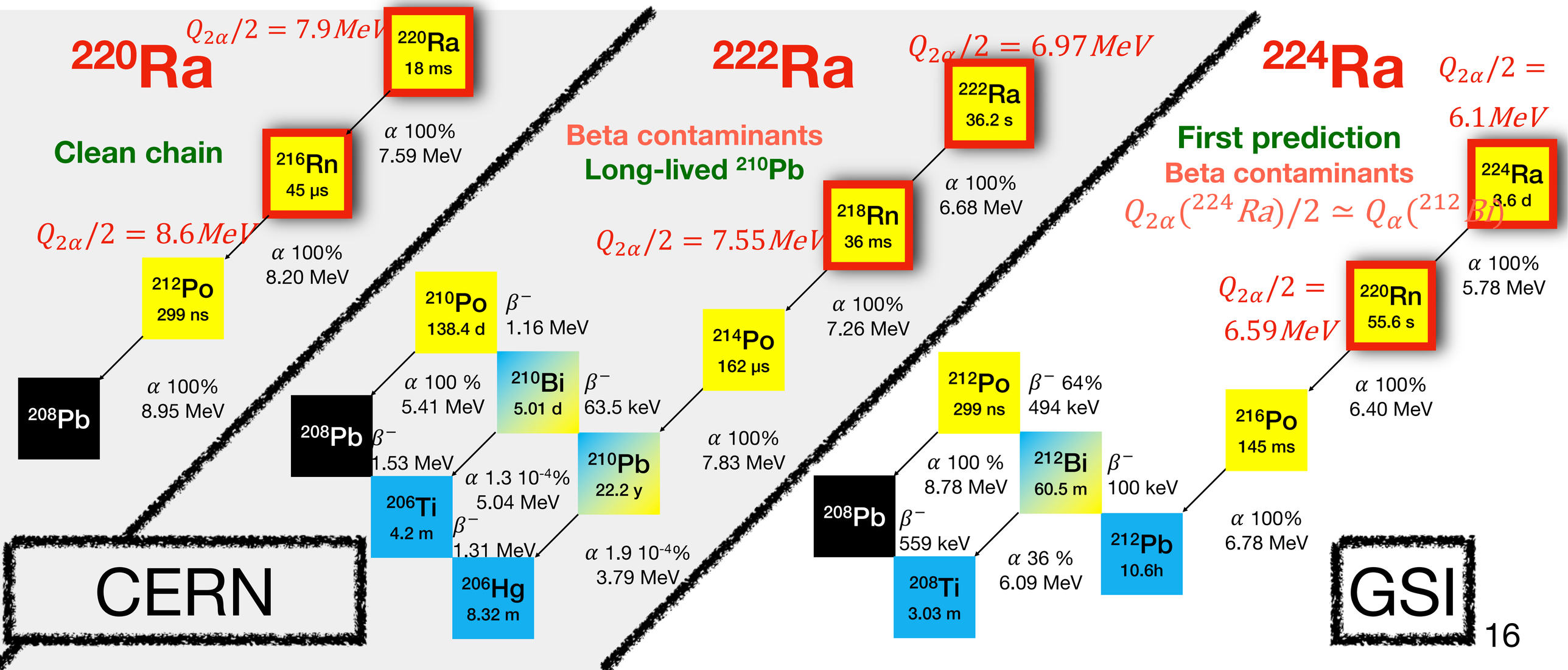
Experimental search for 2 α

2α candidate

Alpha emitter

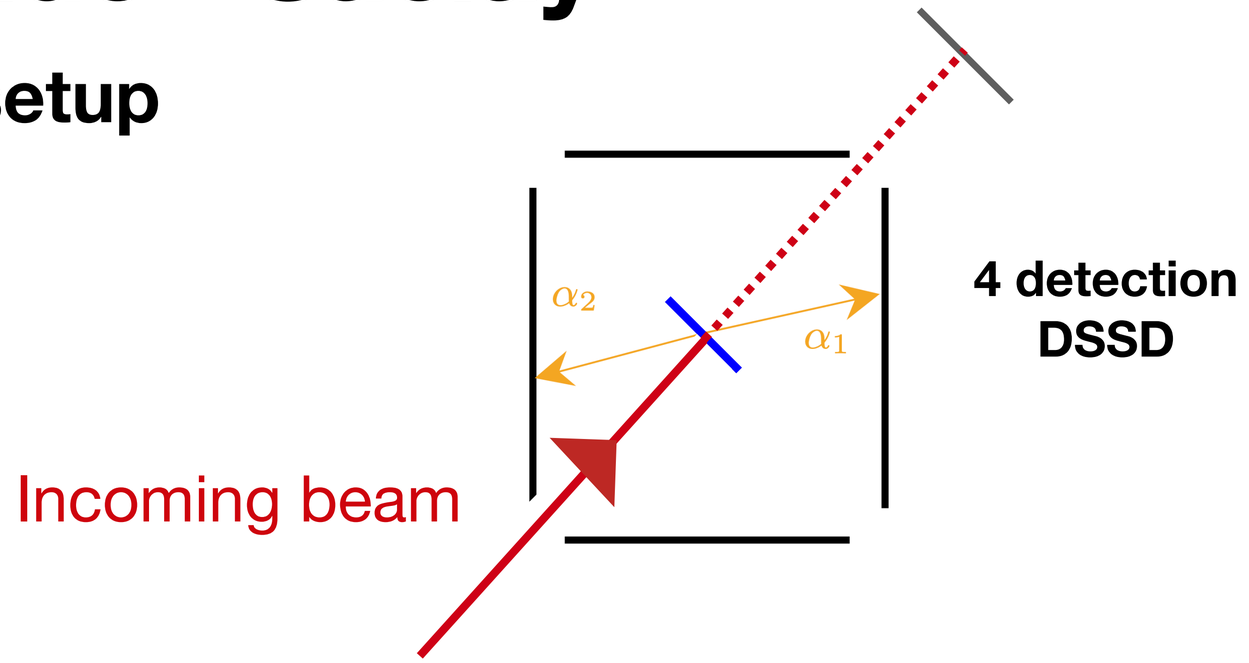
Beta emitter

Decay chains



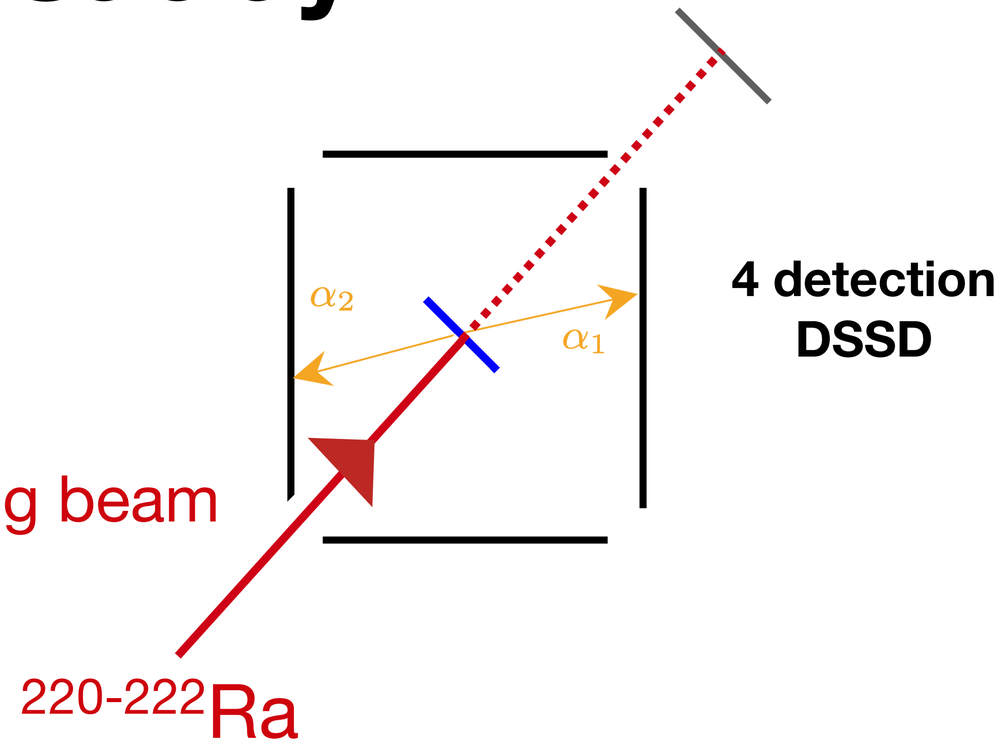
CERN/Isolde - Saclay

Sketch of the setup



CERN/Isolde - Saclay

Sketch of the setup



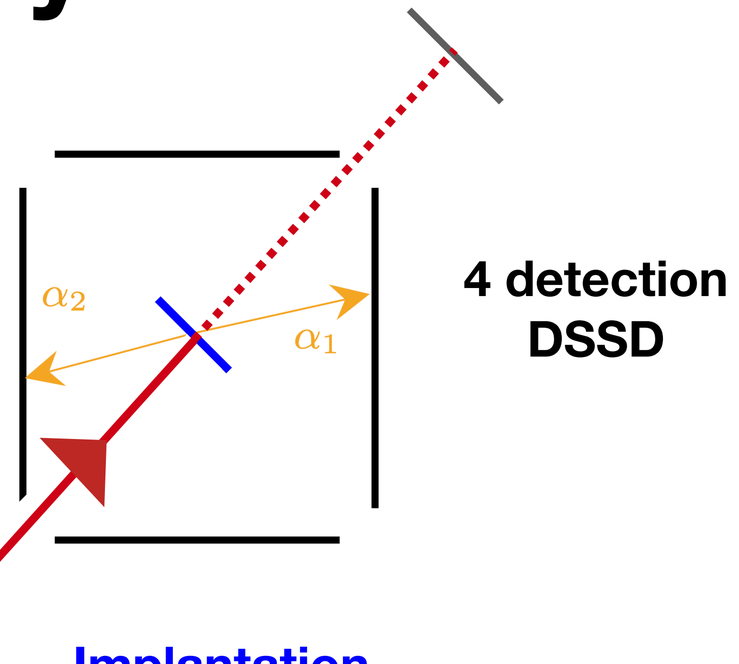
~2 10^4 pps
30 keV/A
1 week

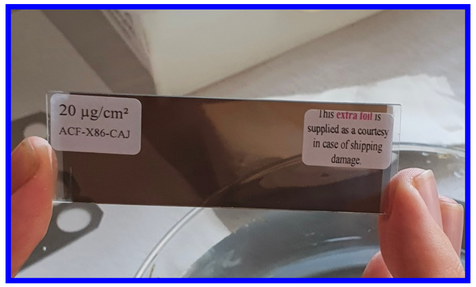
~tens of events
expected

CERN/Isolde - Saclay

Sketch of the setup

~2 10^4 pps
30 keV/A
1 week





~tens of events
expected

20 µg/cm² Carbon foil

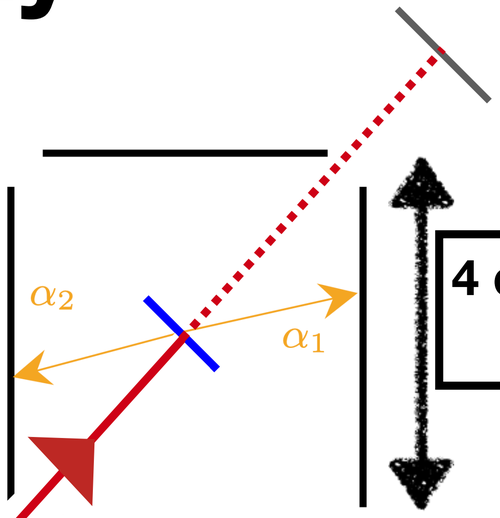
CERN/Isolde - Saclay

Sketch of the setup

~2 10^4 pps
30 keV/A
1 week

Incoming beam

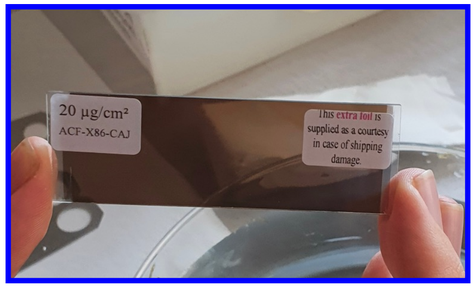
220-222Ra



4 detection DSSD

10 cm

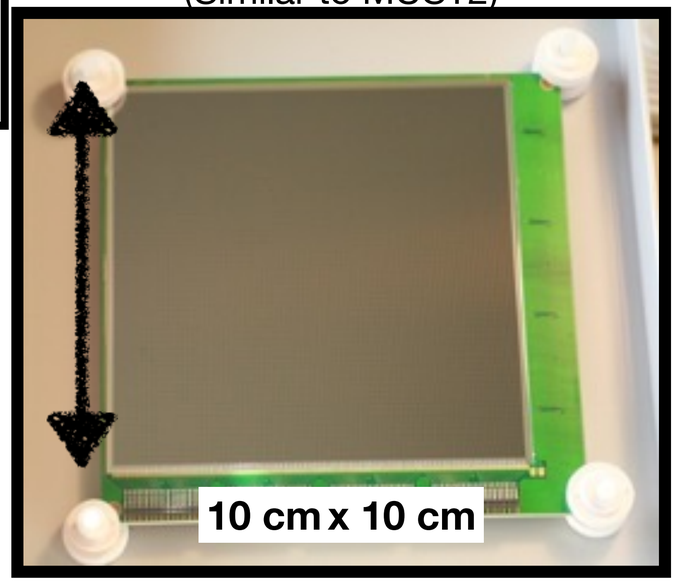
Implantation foil



20 µg/cm² Carbon foil

~tens of events expected

MUSETT setup
(Similar to MUST2)

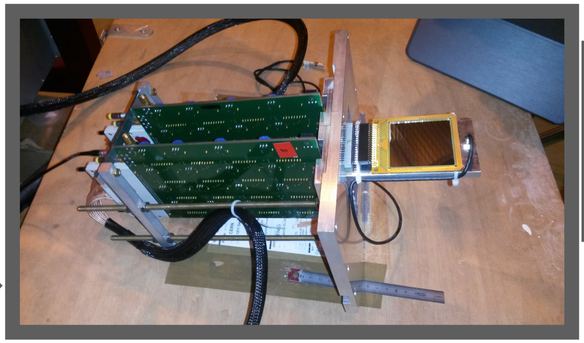


128 + 128 strips
Electronics & DAQ by GANIL & IJCLab

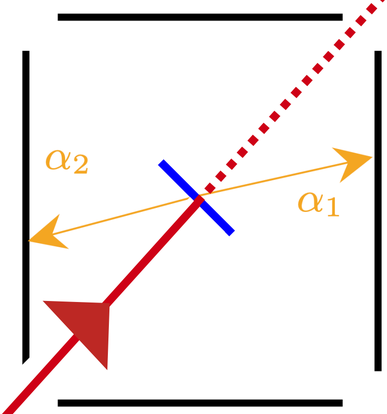
Back-to-back spatial coincidence

CERN/Isolde - Saclay

Sketch of the setup



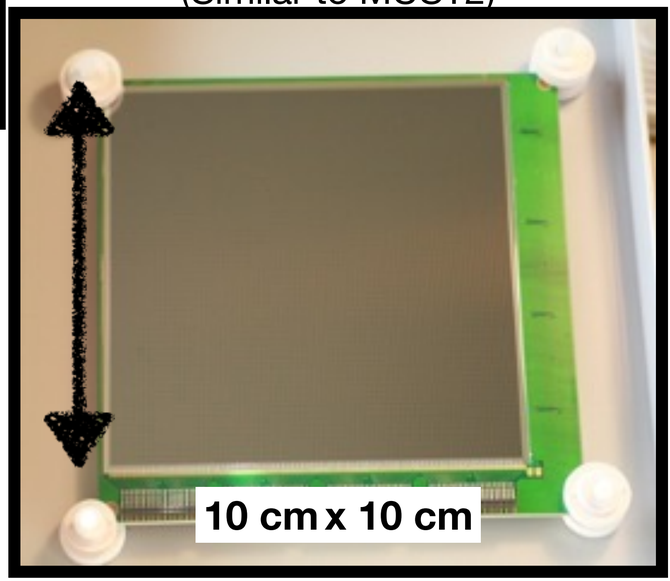
Beam inspection DSSD



4 detection DSSD

10 cm

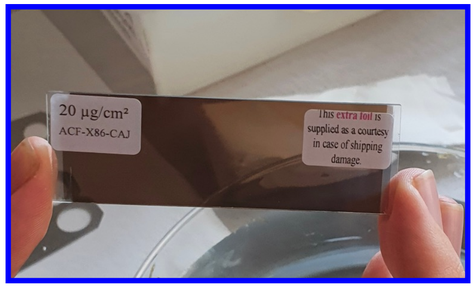
MUSETT setup
(Similar to MUST2)



Incoming beam

220-222Ra

Implantation foil



20 µg/cm² Carbon foil

128 + 128 strips
Electronics & DAQ by GANIL & IJCLab

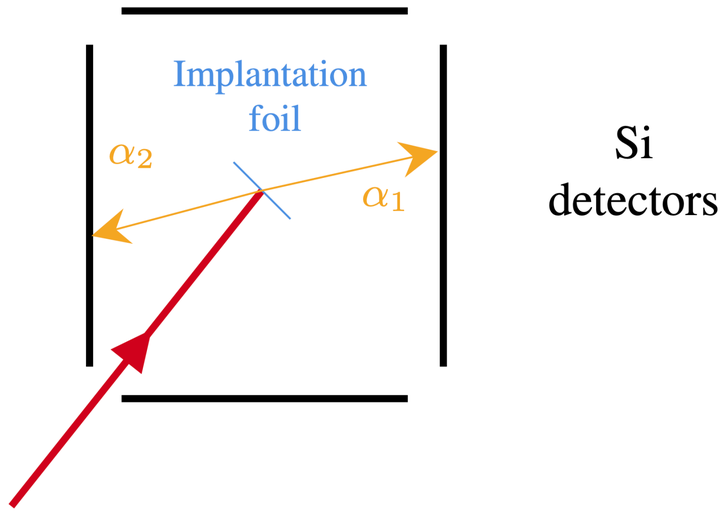
Back-to-back spatial coincidence

~2 10⁴ pps
30 keV/A
1 week

~tens of events
expected

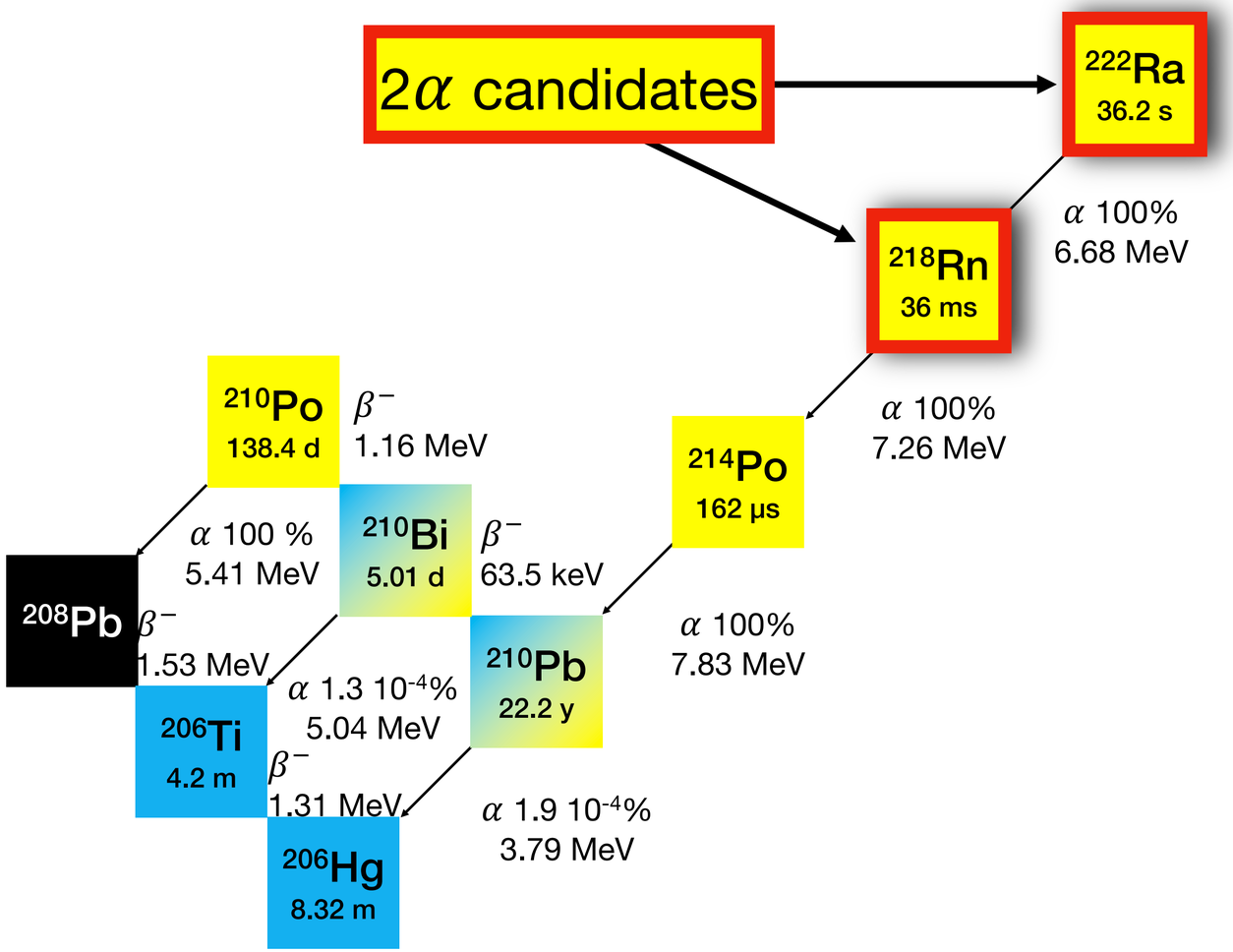
CERN/Isolde - Saclay

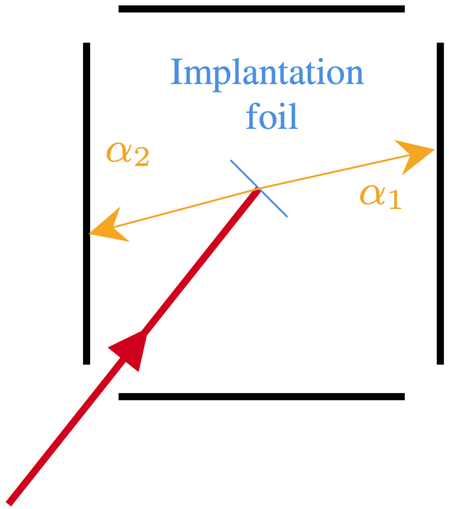
Simulation for background estimate- ^{222}Ra



CERN/Isolde - Saclay

Simulation for background estimate- ^{222}Ra



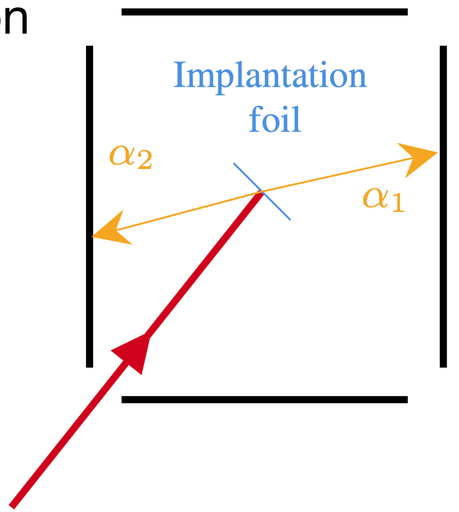


Incoming
^{222}Ra beam

Si
detectors

CERN/Isolde - Saclay

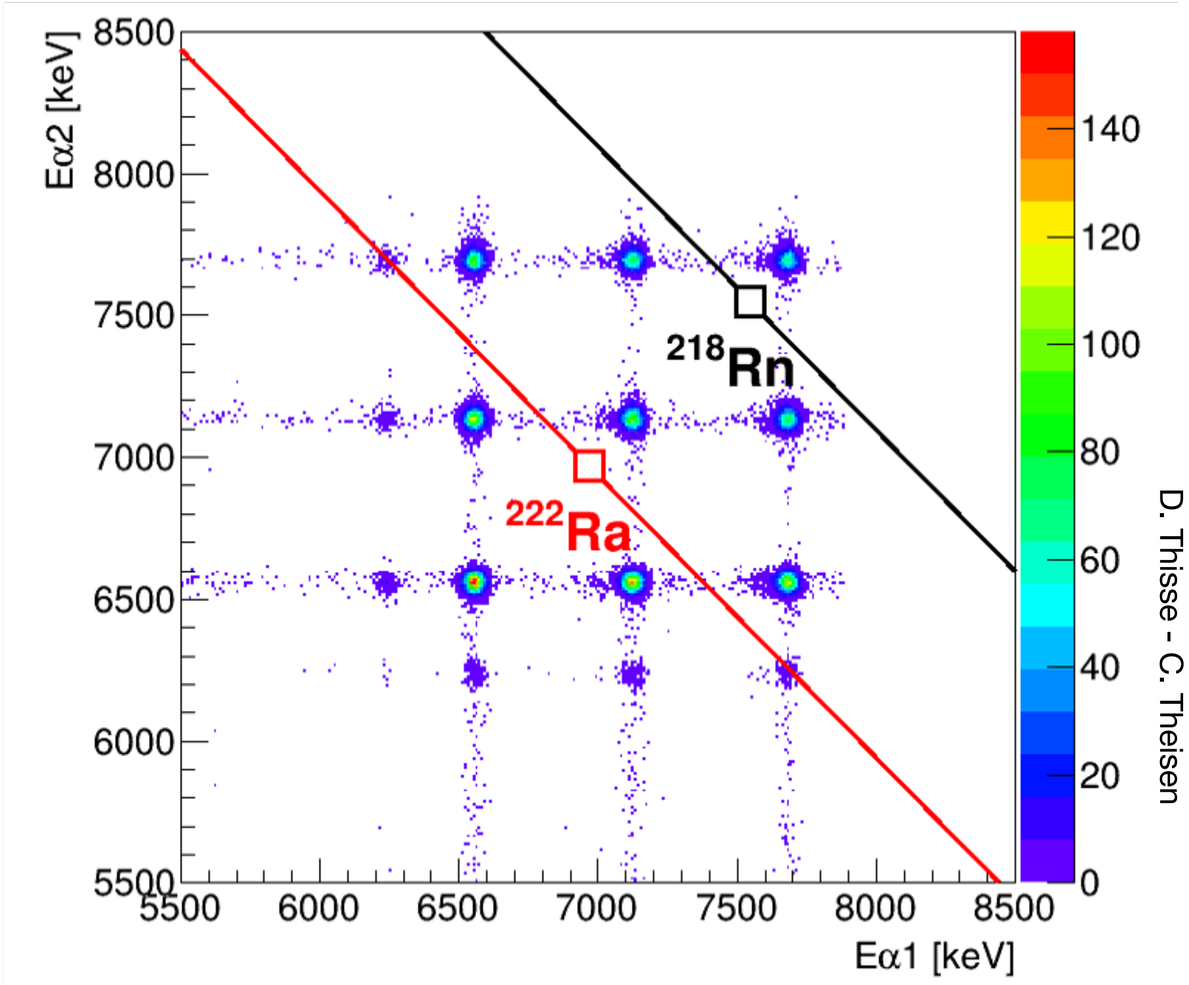
Spatial cut :
Back-to-Back emission
(+ time cuts)



Si
detectors

Simulation for background estimate- ^{222}Ra

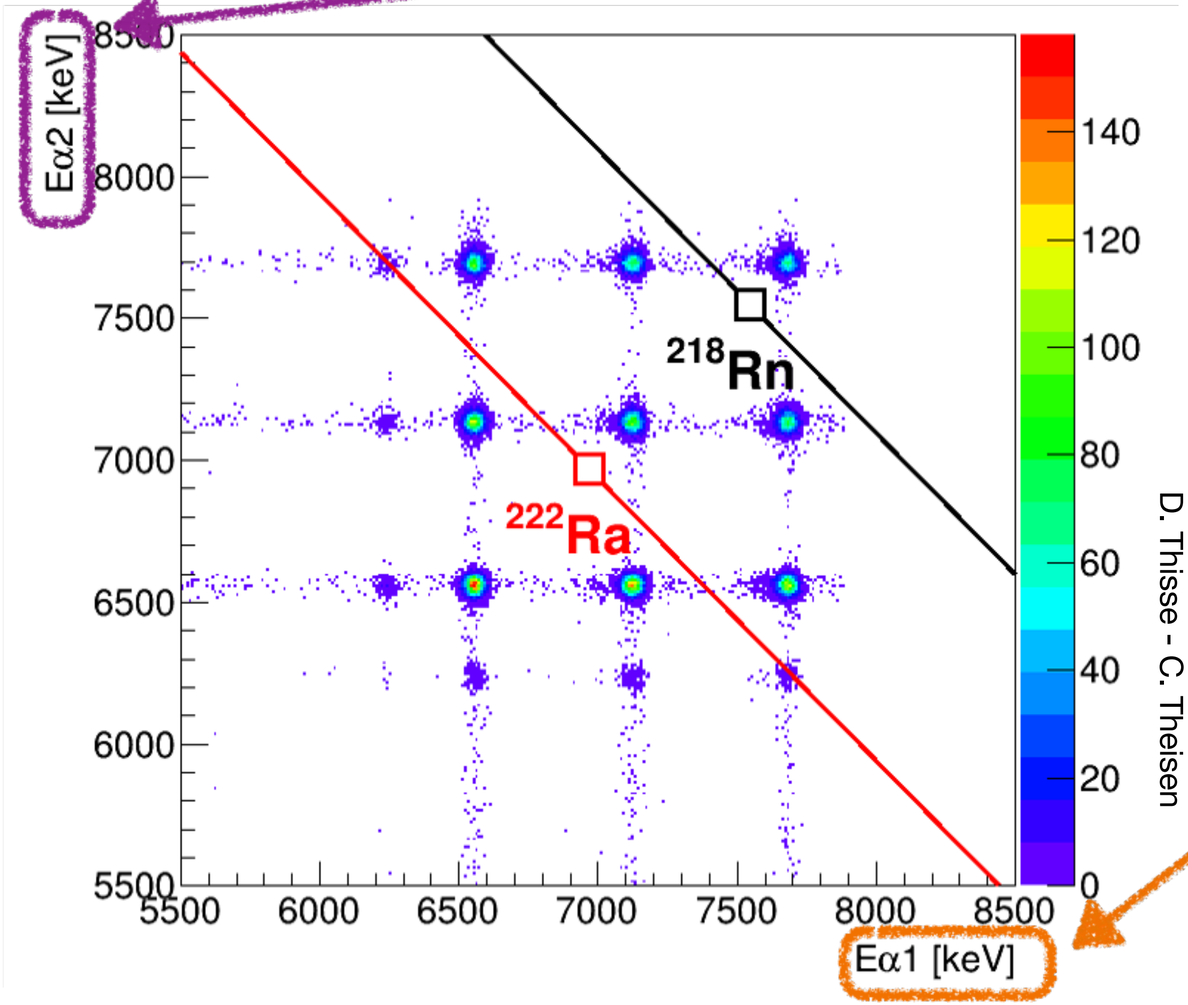
Incoming
^{222}Ra beam

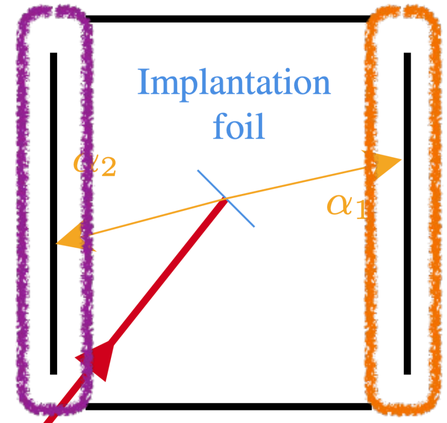


CERN/Isolde - Saclay

Spatial cut :
Back-to-Back emission
(+ time cuts)

Simulation for background estimate- ^{222}Ra





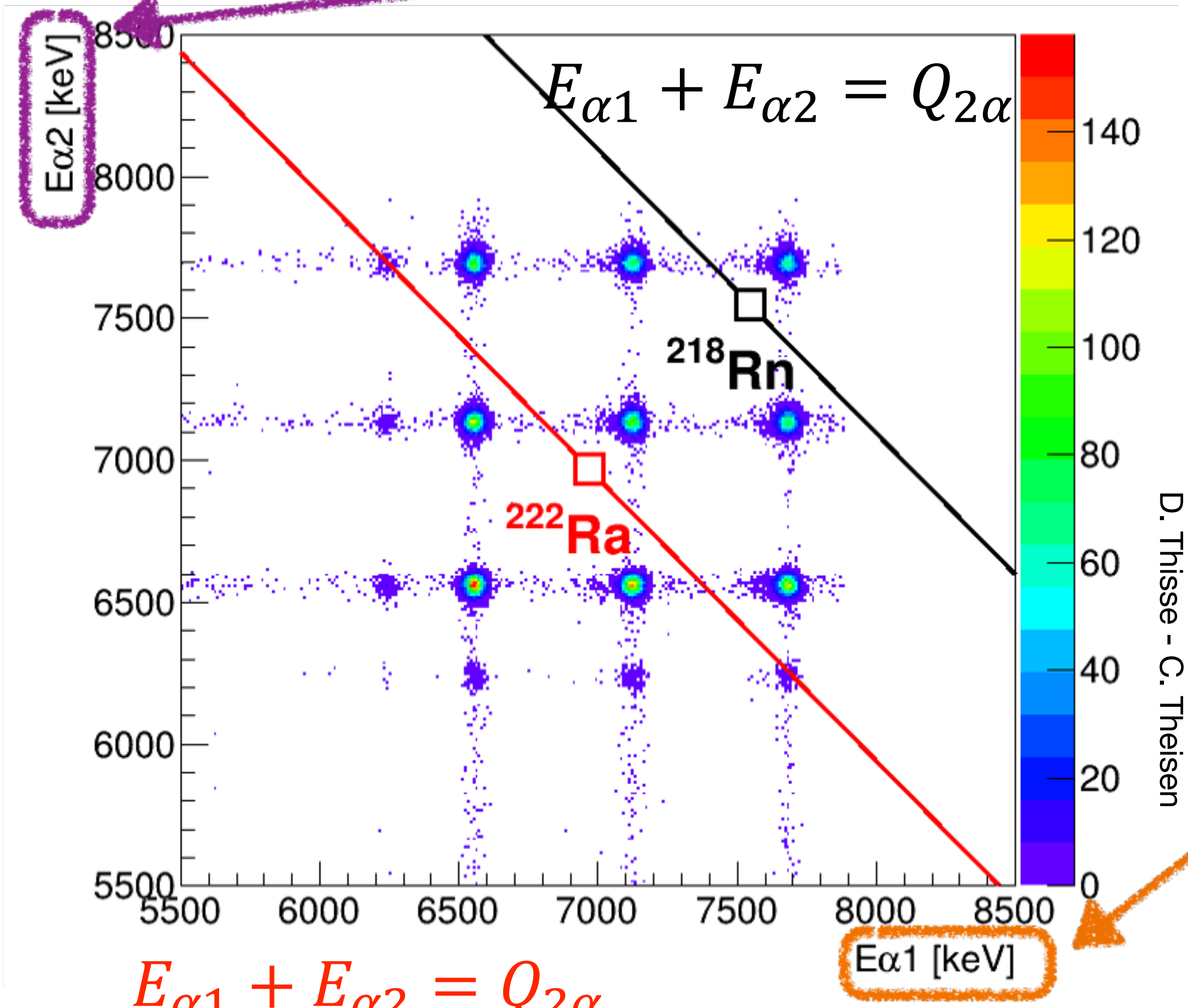
Incoming
^{222}Ra beam

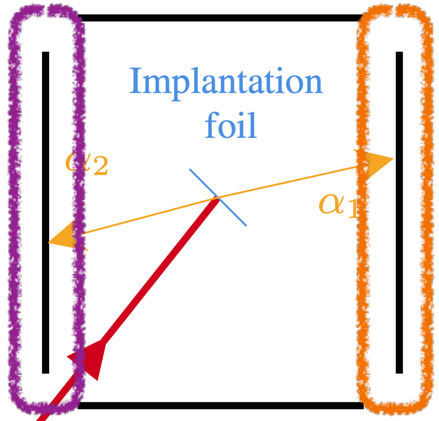
Si
detectors

CERN/Isolde - Saclay

Spatial cut :
Back-to-Back emission
(+ time cuts)

Simulation for background estimate- ^{222}Ra





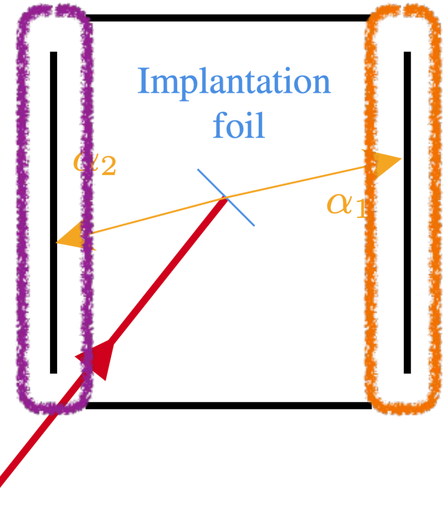
Incoming
^{222}Ra beam

Si
detectors

$E_{\alpha1} + E_{\alpha2} = Q_{2\alpha}$

CERN/Isolde - Saclay

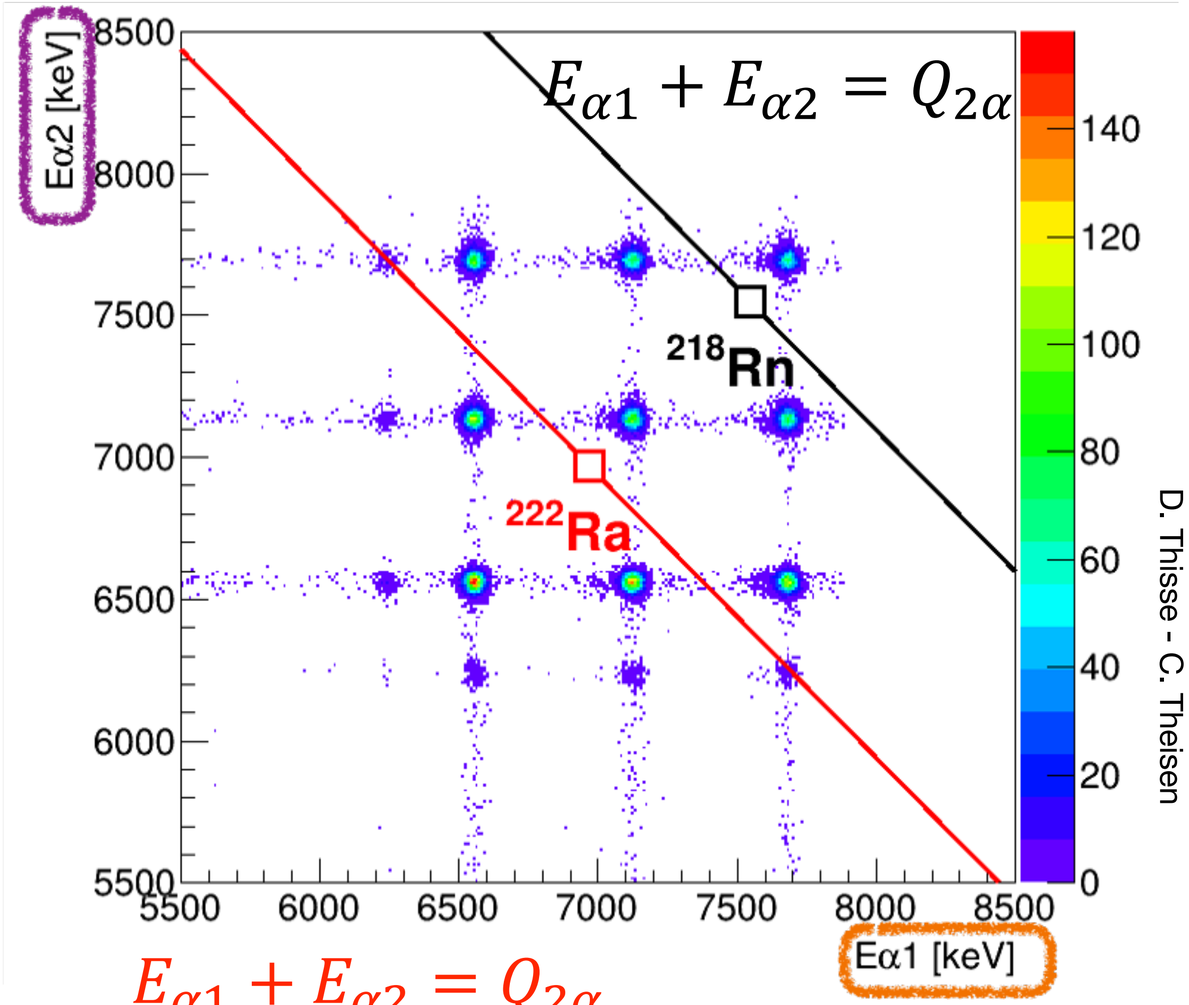
Spatial cut :
Back-to-Back emission
(+ time cuts)



Si
detectors

Simulation for background estimate- ^{222}Ra

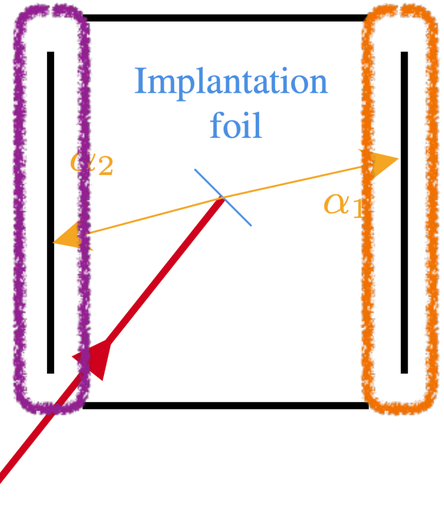
Incoming
^{222}Ra beam



$E_{\alpha1} + E_{\alpha2} = Q_{2\alpha}$

CERN/Isolde - Saclay

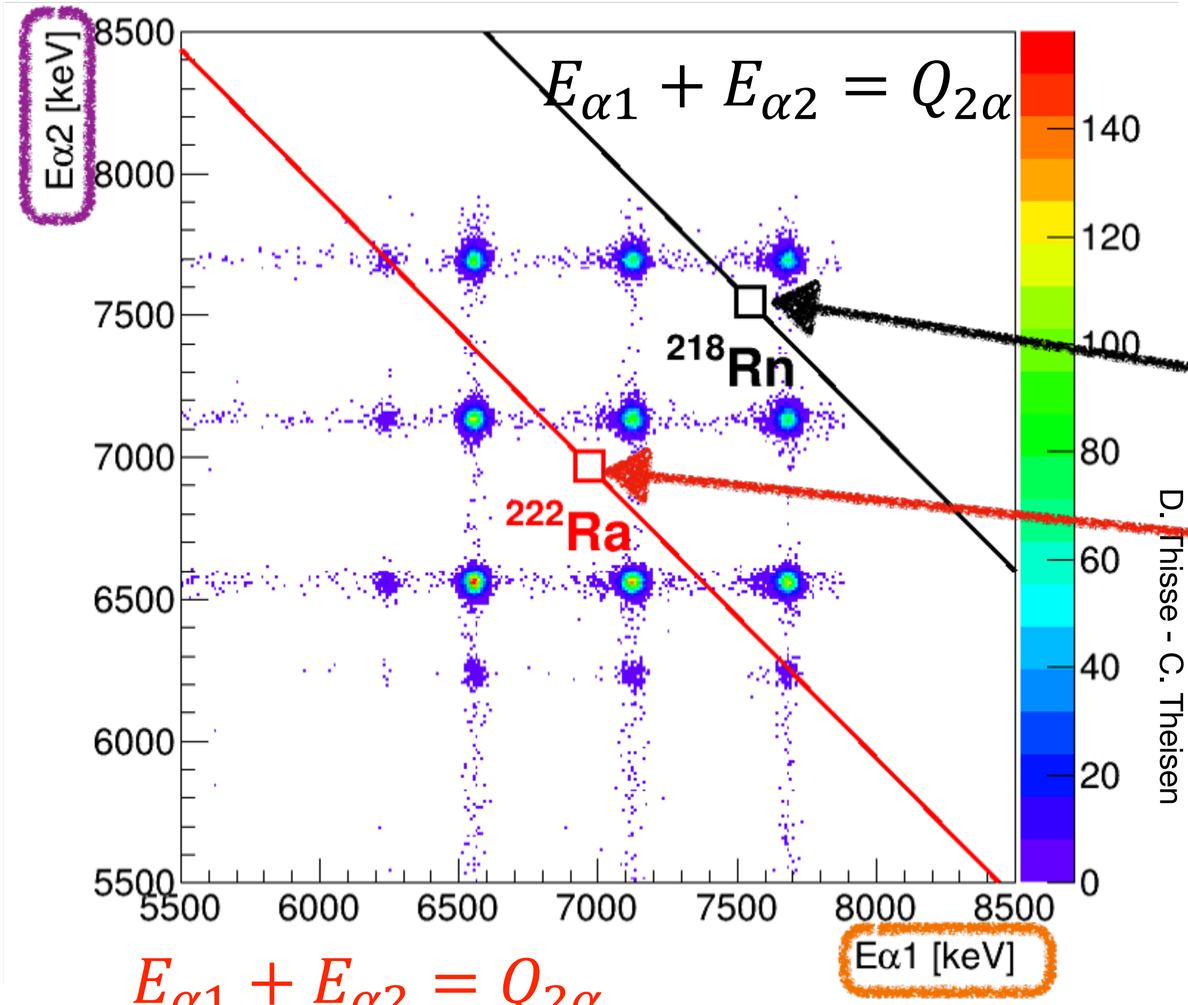
Spatial cut :
Back-to-Back emission
(+ time cuts)



Si
detectors

Simulation for background estimate- ^{222}Ra

Incoming
^{222}Ra beam



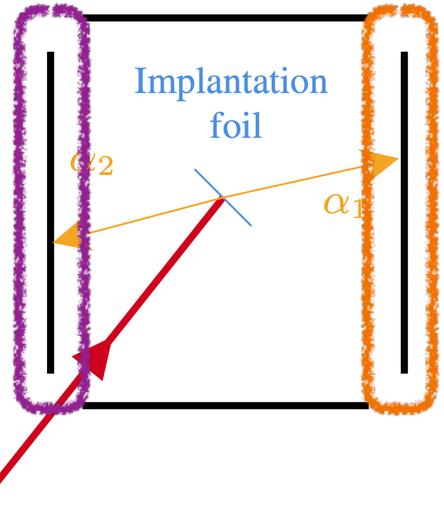
$$E_{\alpha1} = E_{\alpha2} = \frac{Q_{2\alpha}}{2}$$

$$E_{\alpha1} = E_{\alpha2} = \frac{Q_{2\alpha}}{2}$$

$$E_{\alpha1} + E_{\alpha2} = Q_{2\alpha}$$

CERN/Isolde - Saclay

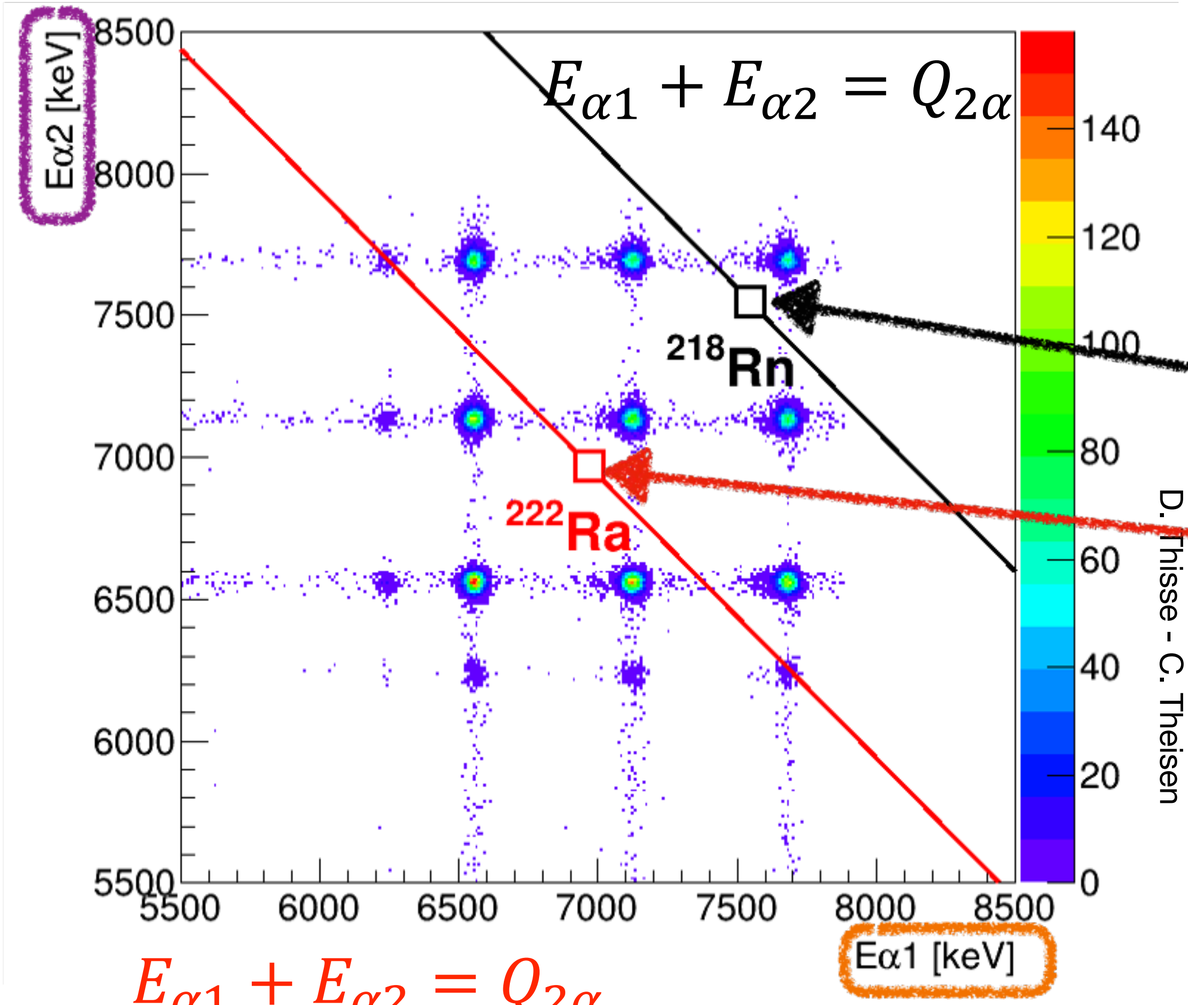
Spatial cut :
Back-to-Back emission
(+ time cuts)



Si
detectors

Incoming
^{222}Ra beam

Simulation for background estimate- ^{222}Ra



$E_{\alpha1} + E_{\alpha2} = Q_{2\alpha}$

$$E_{\alpha1} = E_{\alpha2} = \frac{Q_{2\alpha}}{2}$$

$$E_{\alpha1} = E_{\alpha2} = \frac{Q_{2\alpha}}{2}$$

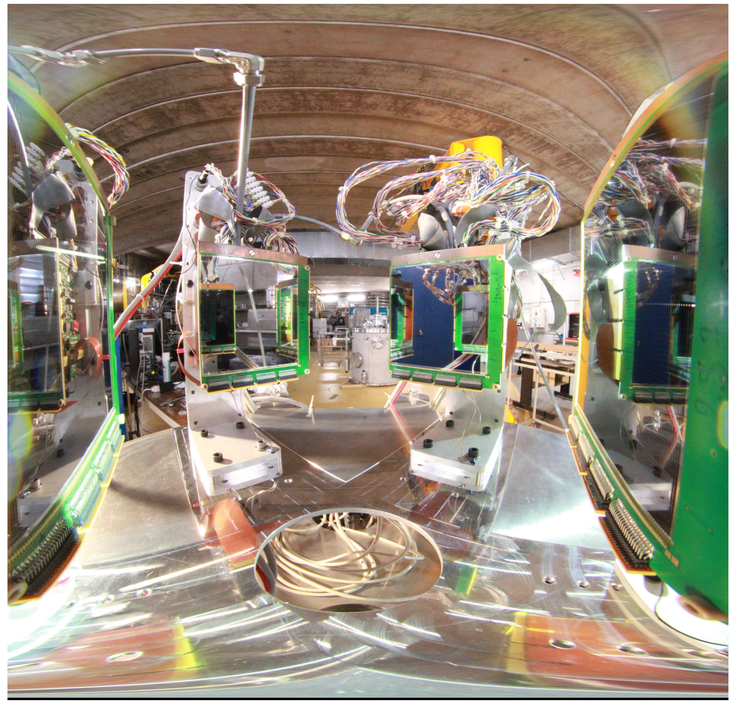
Free of contaminants !

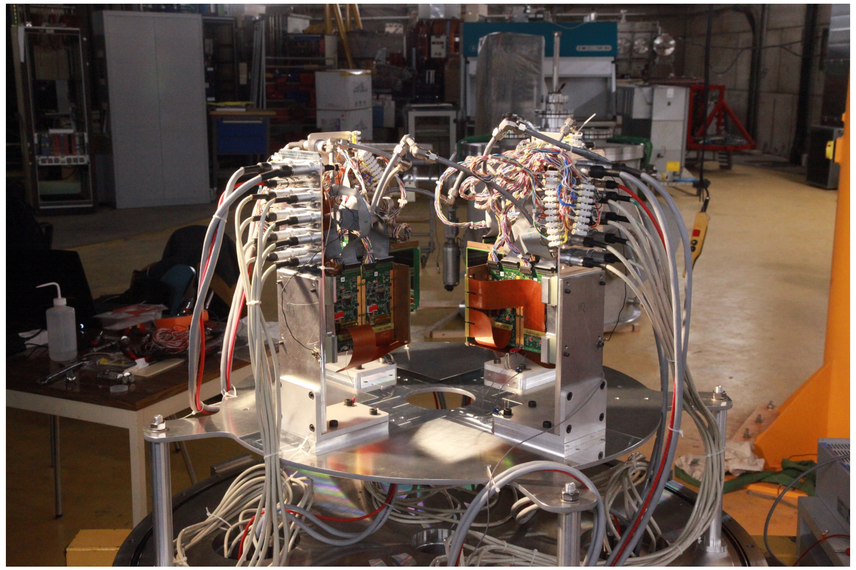
(Same conclusion for ^{220}Ra)

CERN/Isolde - Saclay

Current status

Detectors & electronics tested
Saclay/GANIL





Full setup ready
GANIL

Scheduled on June 20th

Experimental search for 2 α

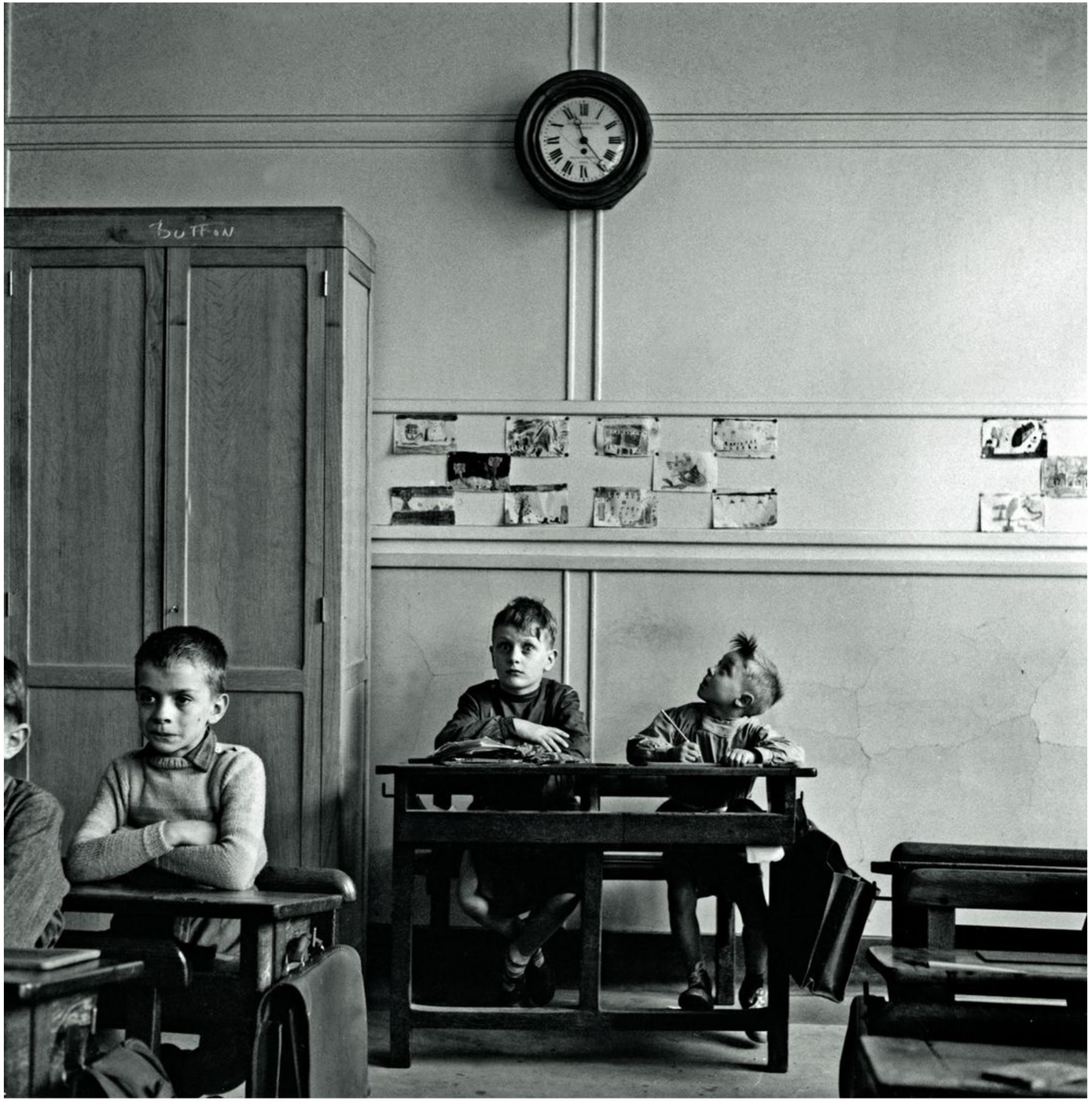
Experiment	GSI (FRS-Ion Catcher)	Saclay (CERN/Isolde)
Isotope production	Source	Beam
Experiment duration	~ 3 months	1 week
Double alpha candidates	^{224}Ra - ^{220}Rn	^{222}Ra - ^{218}Rn ^{220}Ra - ^{216}Rn
Current status	Data analysis	Final setup ready

Henri Cartier-Bresson
Le Mur de Berlin

Thank you for your attention !

H. Wilsenach, O. Hall, T. Dickel, PM. Reiter, D. Amanbayev, T. Davinson, L. Heitz, I.Pohjalainen, M. Simonov ,N. Tortorelli, L. Varga, J. Yu, J. Zhao, S. Ayet, S. Beck, Z. Ge, H. Geissel, C. Hornung, N. Kalantar-Nayestanaki, E. Khan, G. Kripko-Koncz, I. Mardor, D. Morrissey, M. Narang, W. Plaß, C. Scheidenberger, A. State, C. Theisen, M. Vandebrouck, P. Woods
and the FRS Ion Catcher Collaboration

C. Theisen, E. Khan, L. Heitz, T. Roger, T. Chaminade, B. Blank, J. Giovinazzo, M. Vandebrouck, B.Sulignano, D.Thisse, J.-P. Ebran, M. Zielinska, A. Drouart, L. Thuilliez, E. Clement, H. Wilsenach, T. Dickel, M. Simonov, M. Assié, D. Beaumel, Y. Blumenfeld, I. Moore, I. Pohjalainen, PM Reiter, P. Woods, T.Davinson, M. Kowalska
and the Double Alpha @CERN Collaboration



Robert Doisneau
L'horloge

Back-up

2 alpha predictions

	Approach	Comments	Best B.R.
Poenaru - 1985	Super Asymetric Fission	Large BR. Close to ^{8}Be	~10^{-13}
Tretyak - 2021	^{8}Be cluster	Very Large BR (T_{2alpha}>10^{33} yr)	…
Santhosh - 2021	Modified Liquid Drop Model	Large BR. Close to ^{8}Be, weird ^{209}Bi	Close to Poenaru
Mercier Zhao - 2021,2023	Time Dependant evolution, EDF	uncertainties hard to estimate	~$10^{-6.5}$
Denisov - 2022	Modification of Unified Model for Alpha Decay	Very small B.R.	~10^{-2}

Half-life computation

- Generic (phenomenological) formula for radioactive decays

$$\tau^{-1} = \nu \times S \times P_s$$

Half-life

Assault frequency
$(\sim 10^{20}\ s^{-1})$

Preformation factor
Hard to estimate

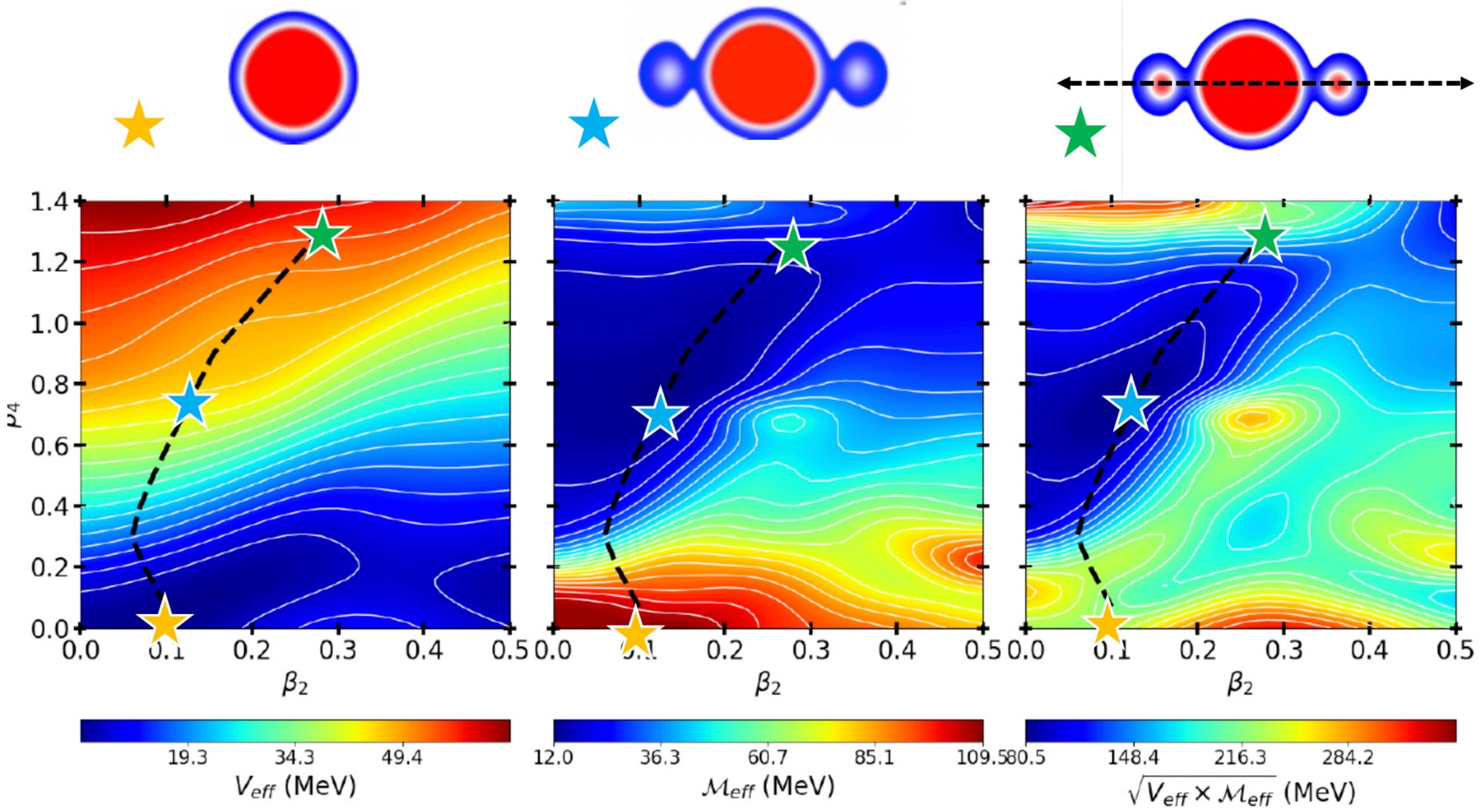
Barrier Penetration Probability

WKB-like expressions

$$\log P_s \propto -2\int dr \sqrt{2B(r)(E(r) - E_0)}$$

B ~ reduced mass
E ~energy of the system

- Different models : different S, P_s $(E\ and\ B)$



$$S(L) = \int_{s_{\text{in}}}^{s_{\text{out}}} \frac{1}{\hbar} \sqrt{2\mathcal{M}_{\text{eff}}(s)[V_{\text{eff}}(s) - E_0]}\, ds \qquad P = \frac{1}{1 + \exp[2S(L)]} \qquad T_{1/2} = \frac{\ln(2)}{nP}$$

Half-life computation

$$\tau^{-1} = \nu \frac{1}{1 + \exp 2S}$$

Half-life computation

$$\tau^{-1} = \nu \frac{1}{1 + \exp 2S}$$

Assault frequency

Half-life computation

$$\tau^{-1} = \nu \frac{1}{1 + \exp 2S}$$

Assault frequency

Minimised integral action

$$\delta S = 0$$

$$S = \int_{s_{in}}^{s_{out}} ds \sqrt{\mathcal{M}_{eff}(s)(V_{eff}(s) - E_0)}$$

Half-life computation

$$\tau^{-1} = \nu \frac{1}{1 + \exp 2S}$$

Assault frequency

Minimised integral action

$$\delta S = 0$$

$$S = \int_{s_{in}}^{s_{out}} ds \sqrt{\mathcal{M}_{eff}(s)(V_{eff}(s) - E_0)}$$

PES

Information about energy cost of a path

(Computed w/ RHB)

Half-life computation

$$\tau^{-1} = \nu \frac{1}{1 + \exp 2S}$$

Assault frequency

Minimised integral action

$$\delta S = 0$$

$$S = \int_{s_{in}}^{s_{out}} ds \sqrt{\mathcal{M}_{eff}(s)\left(V_{eff}(s) - E_0\right)}$$

$$\mathcal{M}_{\mathrm{eff}}(s) = \sum_{ij} \mathcal{M}_{ij} \frac{\mathrm{d}q_i}{\mathrm{d}s} \frac{\mathrm{d}q_j}{\mathrm{d}s}$$

$$\mathcal{M} = M_{(1)}^{-1} M_{(3)} M_{(1)}^{-1}$$

$$\left[M_{(k)}\right]_{ij} = \sum_{\mu\nu} \frac{\langle 0|\hat{q}_i|\mu\nu\rangle \langle \mu\nu|\hat{q}_j|0\rangle}{\left(E_\mu + E_\nu\right)^k}$$

Inertial effective mass

Information about energy needed to deform nucleus

(Computed w/ ATDHB & perturbed cranked approx)

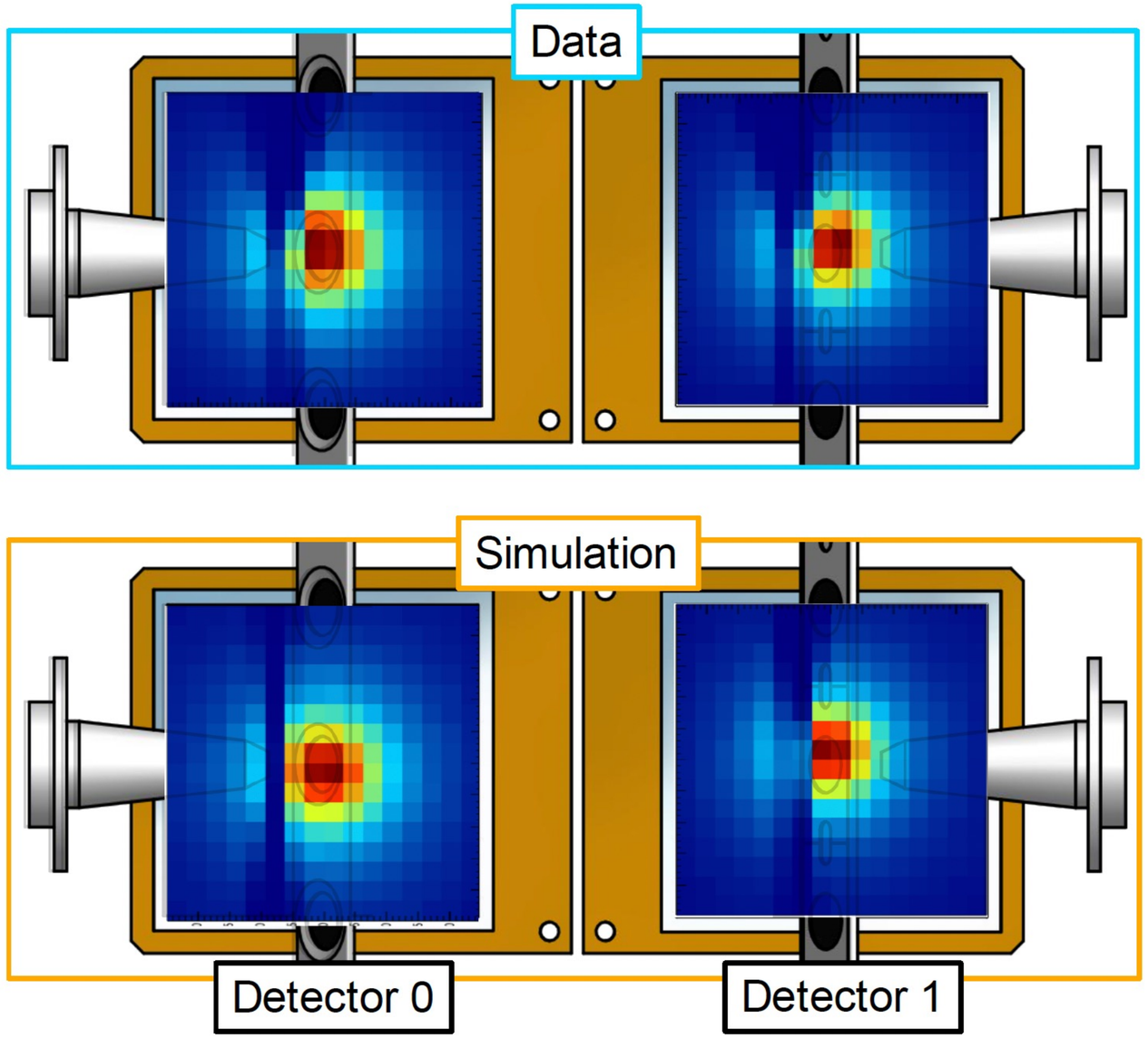
PES

Information about energy cost of a path

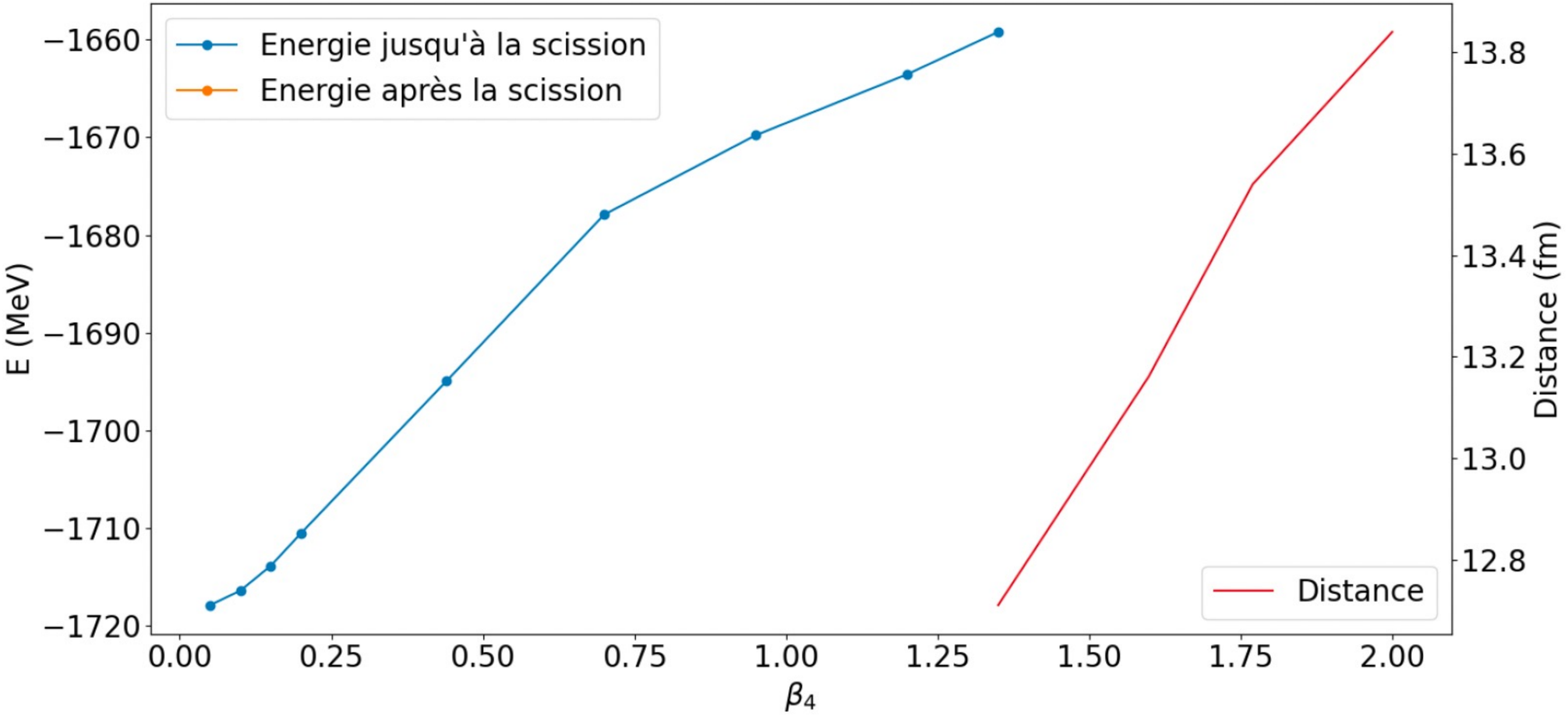
(Computed w/ RHB)

FRS Ion Catcher - GSI

Simulations



Barrier


Energie jusqu'à la scission
Energie après la scission
Distance
E (MeV)
Distance (fm)
β_4
−1660
−1670
−1680
−1690
−1700
−1710
−1720
13.8
13.6
13.4
13.2
13.0
12.8
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00

History of radioactivity

- 1895 Wilhelm Röntgen : **X-ray**
- 1896 Henri Becquerel : **radioactivity**
- 1898 Ernest Rutherford : **α and β rays**
- 1900 Paul Villard : **gamma rays**
- 1929 Maria Goeppert-Mayer : **double gamma prediction**
- 1934 Irène and Fréderic Joliot-Curie : **artificial radioactivity**
- 1935 Maria Goeppert-Mayer : **double beta prediction**
- 1937 Luis Alvarez : **electron capture**
- 1938 Otto Hahn, Fritz Strassmann, Lise Meitner : **fission**
- 1946 L.L. Green and D.L. Livesey, San-Tsiang Tsien et al. : **ternary fission**
- 1960 Vitalii I Goldansky : **proton and double proton prediction**
- 1970 K.P. Jackson et al. : **proton emission** (from an isomeric state)
- 1980 A. Sandulescu, D.N. Poenaru and W. Greiner : **cluster radioactivity prediction**
- 1984 H.J. Rose and G.A. Jones : **cluster radioactivity**
- 1987 S. R. Elliott, A. A. Hahn, and M. K. Moe : **double beta decay**
- 1985 Dorin Poenaru : **double, triple alpha prediction**
- 2002 Jérôme Giovinazzo et al., Marek Pfützner et al : **double proton**

Ch. Theisen courtesy