

# **Experimental research with exotic nuclei**

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# Periodic table

период	ряд	группы элементов																						
		a	I	б	a	II	б	a	III	б	a	IV	б	a	V	б	a	VI	б	a	VII	б	a	VIII
1	I	Водород <b>H</b> 1,00794 Hydrogen	<b>1</b> 1s <sup>1</sup>																				Гелий <b>He</b> 4,0026 Helium	<b>2</b> 1s <sup>2</sup>
2	II	Литий <b>Li</b> 6,941 Lithium	<b>3</b> 2s <sup>1</sup>	Бериллий <b>Be</b> 9,012182 Beryllium	<b>4</b> 2s <sup>2</sup>	Бор <b>B</b> 10,811 Boron	<b>5</b> 2p <sup>1</sup>	Углерод <b>C</b> 12,011 Carbon	<b>6</b> 2p <sup>2</sup>	Азот <b>N</b> 14,00674 Nitrogen	<b>7</b> 2p <sup>3</sup>	Кислород <b>O</b> 15,9994 Oxygen	<b>8</b> 2p <sup>4</sup>	Фтор <b>F</b> 18,9984032 Fluorine	<b>9</b> 2p <sup>5</sup>	Неон <b>Ne</b> 20,1797 Neon	<b>10</b> 2p <sup>6</sup>							
3	III	Натрий <b>Na</b> 22,989768 Sodium	<b>11</b> 3s <sup>1</sup>	Магний <b>Mg</b> 24,3050 Magnesium	<b>12</b> 3s <sup>2</sup>	Алюминий <b>Al</b> 26,981539 Aluminum	<b>13</b> 3p <sup>1</sup>	Кремний <b>Si</b> 28,0855 Silicon	<b>14</b> 3p <sup>2</sup>	Фосфор <b>P</b> 30,973762 Phosphorus	<b>15</b> 3p <sup>3</sup>	Сера <b>S</b> 32,066 Sulfur	<b>16</b> 3p <sup>4</sup>	Хлор <b>Cl</b> 35,4527 Chlorine	<b>17</b> 3p <sup>5</sup>	Аргон <b>Ar</b> 39,948 Argon	<b>18</b> 3p <sup>6</sup>							
4	IV	Калий <b>K</b> 39,0983 Potassium	<b>19</b> 4s <sup>1</sup>	Кальций <b>Ca</b> 40,078 Calcium	<b>20</b> 4s <sup>2</sup>		<b>21</b> Скандий <b>Sc</b> 44,955910 Scandium	<b>22</b> Титан <b>Ti</b> 47,88 Titanium	<b>23</b> Ванадий <b>V</b> 50,9415 Vanadium	<b>24</b> Хром <b>Cr</b> 51,9961 Chromium	<b>25</b> Марганец <b>Mn</b> 54,93805 Manganese	<b>26</b> Железо <b>Fe</b> 55,847 Iron	<b>27</b> Кобальт <b>Co</b> 58,93320 Cobalt	<b>28</b> Никель <b>Ni</b> 58,6934 Nickel										
	V		<b>29</b> Медь <b>Cu</b> 63,546 Copper		<b>30</b> Цинк <b>Zn</b> 65,39 Zinc	Галлий <b>Ga</b> 69,723 Gallium	<b>31</b> 4p <sup>1</sup>	Германий <b>Ge</b> 72,61 Germanium	<b>32</b> 4p <sup>2</sup>	Арсен <b>As</b> 74,92159 Arsenic	<b>33</b> 4p <sup>3</sup>	Селен <b>Se</b> 78,96 Selenium	<b>34</b> 9,75238 <b>Br</b> 79,904 Bromine	<b>35</b> 4p <sup>5</sup>	Криптон <b>Kr</b> 83,80 Krypton	<b>36</b> 4p <sup>6</sup>								
5	VI	Рубидий <b>Rb</b> 85,4678 Rubidium	<b>37</b> 5s <sup>1</sup>	Стронций <b>Sr</b> 87,62 Strontium	<b>38</b> 5s <sup>2</sup>		<b>39</b> Иттрий <b>Y</b> 88,90585 Yttrium	<b>40</b> Цирконий <b>Zr</b> 91,224 Zirconium	<b>41</b> Ниобий <b>Nb</b> 92,90638 Niobium	<b>42</b> Молибден <b>Mo</b> 95,94 Molybdenum	<b>43</b> Технеций <b>Tc</b> [98] Technetium	<b>44</b> Рутений <b>Ru</b> 101,07 Ruthenium	<b>45</b> Родий <b>Rh</b> 102,90550 Rhodium	<b>46</b> Палладий <b>Pd</b> 106,42 Palladium										
	VII		<b>47</b> Серебро <b>Ag</b> 107,8682 Silver		<b>48</b> Кадмий <b>Cd</b> 112,411 Cadmium	Индий <b>In</b> 114,818 Indium	<b>49</b> 5p <sup>1</sup>	Олово <b>Sn</b> 118,710 Tin	<b>50</b> 5p <sup>2</sup>	Сурьма <b>Sb</b> 121,757 Antimony	<b>51</b> 5p <sup>3</sup>	Теллур <b>Te</b> 127,60 Tellurium	<b>52</b> 5p <sup>4</sup>	Иод <b>I</b> 126,90447 Iodine	<b>53</b> 5p <sup>5</sup>	Ксенон <b>Xe</b> 131,29 Xenon	<b>54</b> 5p <sup>6</sup>							
6	VIII	Цезий <b>Cs</b> 132,90543 Cesium	<b>55</b> 6s <sup>1</sup>	Барий <b>Ba</b> 137,327 Barium	<b>56</b> 6s <sup>2</sup>		<b>57</b> Лантан <b>La</b> 138,9055 Lanthanum	<b>58</b> Церий <b>Ce</b> 140,90765 Cerium	<b>59</b> Празмий <b>Pr</b> 140,90765 Praseodymium	<b>60</b> Неодим <b>Nd</b> 144,24 Neodymium	<b>61</b> Прометий <b>Pm</b> [145] Promethium	<b>62</b> Самарий <b>Sm</b> 150,36 Samarium	<b>63</b> Европий <b>Eu</b> 151,965 Europium	<b>64</b> Гадолиний <b>Gd</b> 157,25 Gadolinium	<b>65</b> Тербий <b>Tb</b> 158,92534 Terbium	<b>66</b> Диспрозий <b>Dy</b> 162,50 Dysprosium	<b>67</b> Гольмий <b>Ho</b> 164,93032 Holmium	<b>68</b> Эрбий <b>Er</b> 167,26 Erbium	<b>69</b> Тулий <b>Tm</b> 168,93421 Thulium	<b>70</b> Иттербий <b>Yb</b> 173,04 Ytterbium	<b>71</b> Лютеций <b>Lu</b> 174,967 Lutetium			
	IX		<b>79</b> Золото <b>Au</b> 196,96654 Gold		<b>80</b> Ртуть <b>Hg</b> 200,59 Mercury	Таллий <b>Tl</b> 204,3833 Thallium	<b>81</b> 6p <sup>1</sup>	Свинец <b>Pb</b> 207,2 Lead	<b>82</b> 6p <sup>2</sup>	Висмут <b>Bi</b> 208,98037 Bismuth	<b>83</b> 6p <sup>3</sup>	Полоний <b>Po</b> [209] Polonium	<b>84</b> 6p <sup>4</sup>	Астат <b>At</b> [210] Astatine	<b>85</b> 6p <sup>5</sup>	Радон <b>Rn</b> [222] Radon	<b>86</b> 6p <sup>6</sup>							
7	X	Франций <b>Fr</b> [223] Francium	<b>87</b> 4,073 7s <sup>1</sup>	Радий <b>Ra</b> 226,025 Radium	<b>88</b> 7s <sup>2</sup>		<b>89</b> Актиний <b>Ac</b> [227] Actinium	<b>104</b> Резерфордий <b>Rf</b> [261] Rutherfordium	<b>105</b> Дубний <b>Db</b> [262] Dubnium	<b>106</b> Сиборгий <b>Sg</b> [266] Seaborgium	<b>107</b> Борий <b>Bh</b> [267] Bohrium	<b>108</b> Хассий <b>Hs</b> [269] Hassium	<b>109</b> Мейтнерий <b>Mt</b> [268] Meitnerium	<b>110</b> Дармштадтий <b>Ds</b> [269] Darmstadtium										
	XI		<b>111</b> Рентгений <b>Rg</b> [272] Roentgenium		<b>112</b> Коперниций <b>Cn</b> [285] Copernicium		<b>113</b>	Флеровий <b>Fl</b> [244] Flerovium	<b>114</b>	<b>115</b>	Ливерморий <b>Lv</b> [243] Livermorium	<b>116</b>	<b>117</b>	<b>118</b>										



■ s-ЭЛЕМЕНТЫ/ELEMENTS

■ p-ЭЛЕМЕНТЫ

■ d-ЭЛЕМЕНТЫ

■ f-ЭЛЕМЕНТЫ

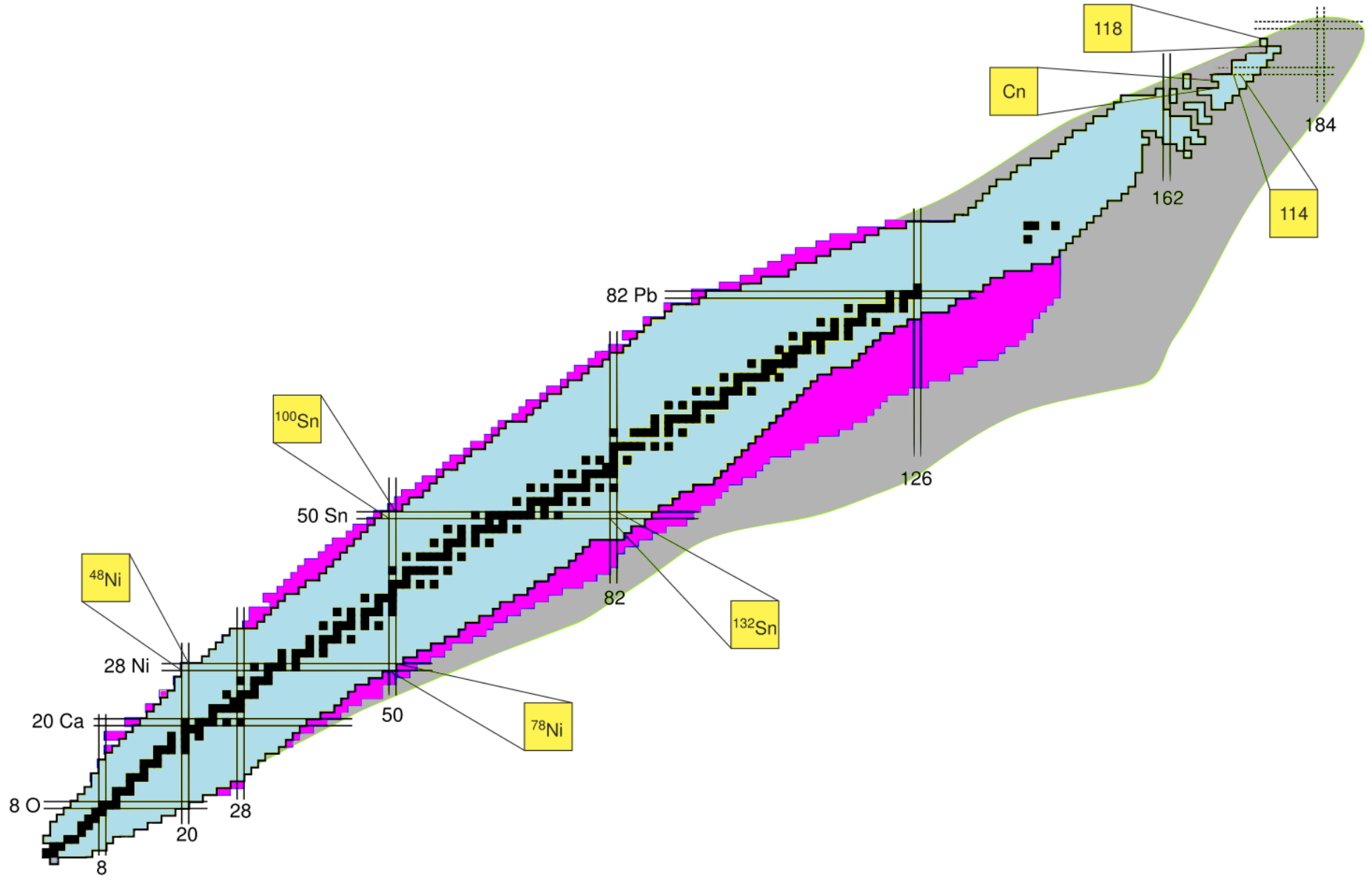
## Лантаноиды Lanthanides

Церий <b>Ce</b> 4f <sup>5d</sup> 140,115 Cerium	Прозермий <b>Pr</b> 4f <sup>6</sup> 140,90765 Praseodymium	Неодим <b>Nd</b> 4f <sup>6</sup> 144,24 Neodymium	Прометий <b>Pm</b> 4f <sup>6</sup> [145] Promethium	Самарий <b>Sm</b> 4f <sup>6</sup> 150,36 Samarium	Европий <b>Eu</b> 4f <sup>7</sup> 151,965 Europium	Гадолиний <b>Gd</b> 4f <sup>7</sup> 5d <sup>1</sup> 157,25 Gadolinium	Тербий <b>Tb</b> 4f <sup>7</sup> 158,92534 Terbium	Диспрозий <b>Dy</b> 4f <sup>9</sup> 162,50 Dysprosium	Гольмий <b>Ho</b> 4f <sup>11</sup> 164,93032 Holmium	Эрбий <b>Er</b> 4f <sup>12</sup> 167,26 Erbium	Тулий <b>Tm</b> 4f <sup>13</sup> 168,93421 Thulium	Иттербий <b>Yb</b> 4f <sup>14</sup> 173,04 Ytterbium	Лютеций <b>Lu</b> 4f <sup>14</sup> 5d <sup>1</sup> 174,967 Lutetium
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## Актиноиды Actinides

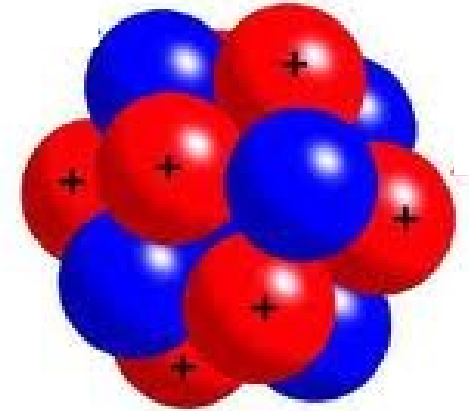
Торий <b>Th</b> 7s <sup>6d</sup> 232,0381 Thorium	Протактиний <b>Pa</b> 5f <sup>6d</sup> 231,03888 Protactinium	Уран <b>U</b> 5f <sup>6d</sup> 238,0289 Uranium	Нептуний <b>Np</b> 5f <sup>6d</sup> [237] Neptunium	Плутоний <b>Pu</b> 5f <sup>6</sup> [244] Plutonium	Америций <b>Am</b> 5f <sup>6</sup> [243] Americium	Кюрий <b>Cm</b> 5f <sup>6d</sup> [247] Curium	Берклий <b>Bk</b> 5f <sup>7</sup> [247] Berkelium	Калифорний <b>Cf</b> 5f <sup>9</sup> [251] Californium	Эйнштейний <b>Es</b> 5f <sup>11</sup> [252] Einsteinium	Фермий <b>Fm</b> 5f <sup>12</sup> [257] Fermium	Менделевий <b>Md</b> 5f <sup>13</sup> [258] Mendelevium	Нобелий <b>No</b> 5f <sup>14</sup> [259] Nobelium	Лоуренсий <b>Lr</b> 5f <sup>14</sup> 6d <sup>1</sup> [262] Lawrencium
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# Nuclear landscape



# Why exotic?

- **far from stable nuclei**
- **complicatedly available**



**too  
heavy**

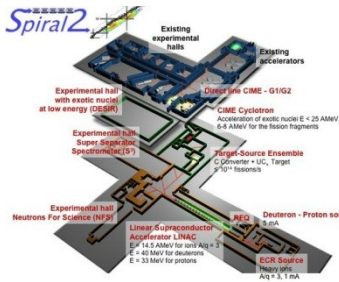
**or**

**strange  
in other  
way**

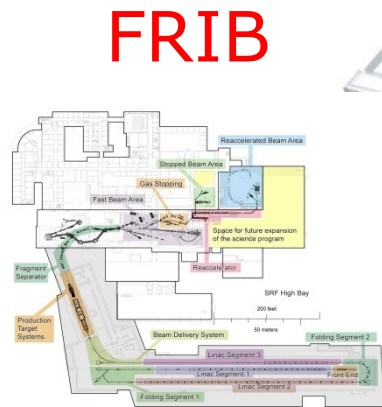
**What's  
going on?**

# Modest vs. big, bigger, the biggest

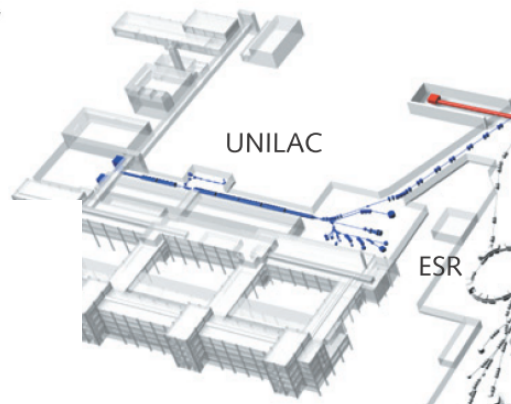
Huge increase in the scale of modern RIB facilities



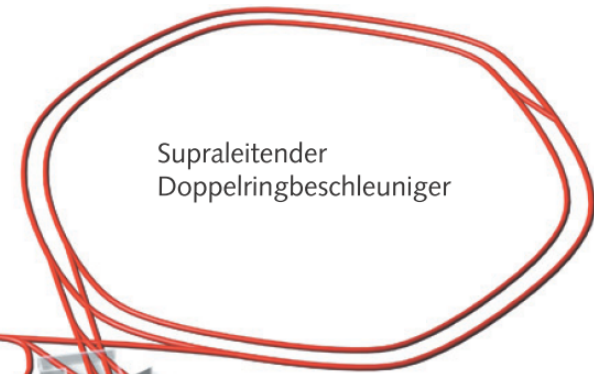
**SPIRAL 2**



**FRIB**

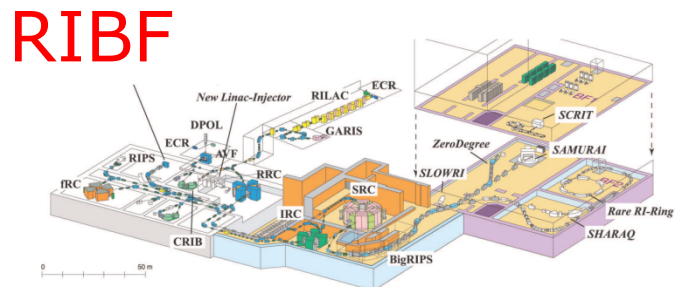


**FAIR**



**U400M hall**

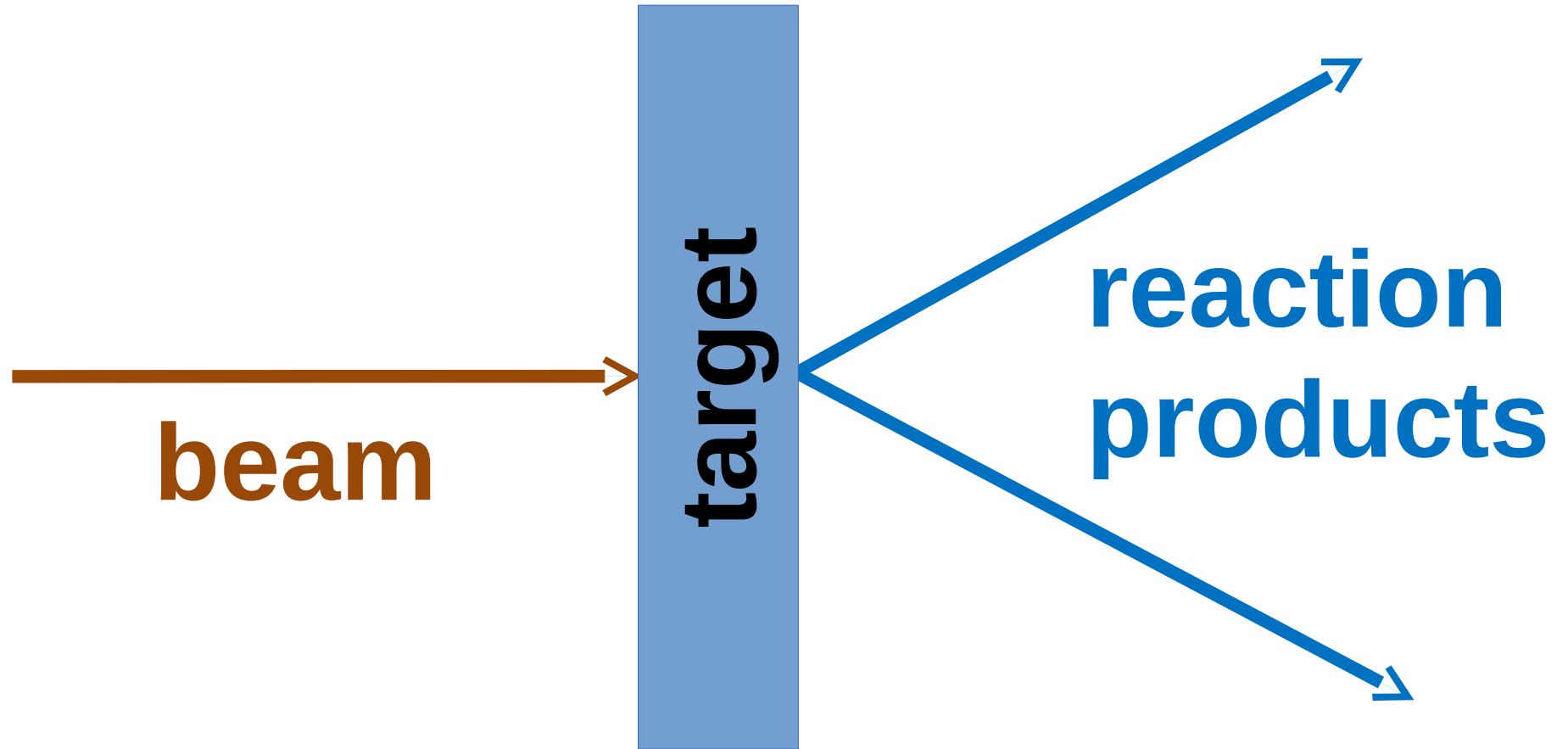
Antiprotonenring



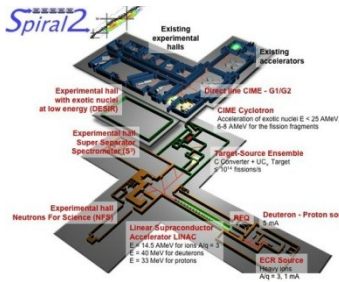
**RIBF**

Experimentier- und Speicherringe





# Modest vs. big, bigger, the biggest

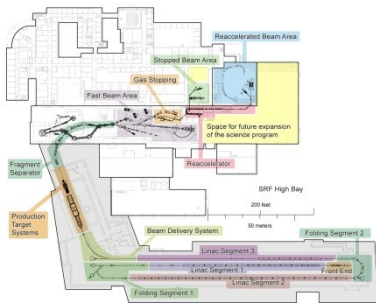


SPIRAL2

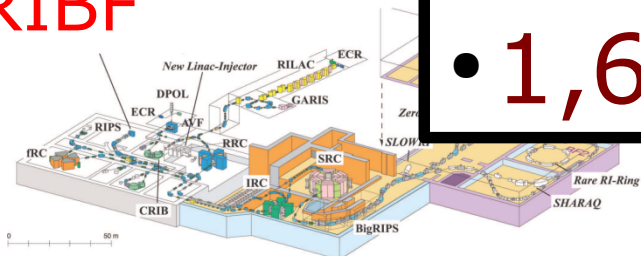
## Facility for Antiproton and Ion Research:

- 10 member states
- scientists from more than 50 countries
- 20 years of construction
- 1,6 billions euro

FRIB



RIBF



Experimentier- und Speicherringe

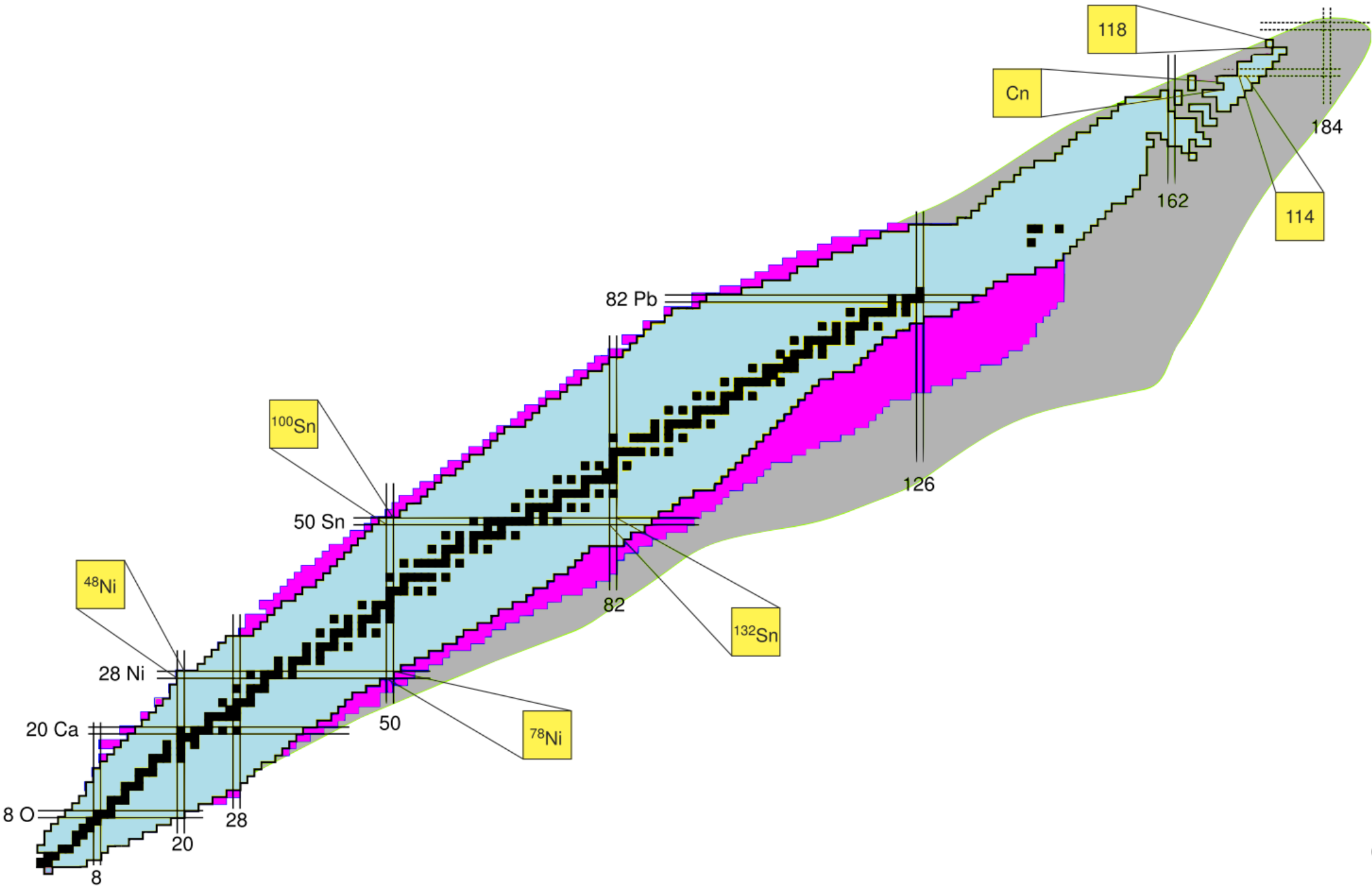
100m



# Radioactive ion beams

acceleration of a primary beam ( $I \sim 10^{12}$  pps)

# Radioactive ion beams



# Radioactive ion beams

acceleration of a primary beam ( $I \sim 10^{12}$  pps)

## ISOL technique

- reactions in a thick production target:  
(**fast** production – **slow** release)
- reaction products to be extracted, ionized and reaccelerated
- **secondary beam:** ( $I < 10^8$  pps)

# Radioactive ion beams

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reactions on a physical target

# Radioactive ion beams

acceleration of a primary beam ( $I \sim 10^{12}$  pps)

## ISOL technique

- reactions in a thick production target: (**fast** production – **slow** release)
- reaction products to be extracted, ionized and reaccelerated
- **secondary beam: ( $I < 10^8$  pps)**

## In-Flight Production

- reactions on a thin production target
- **secondary beam: fragment-separator ( $I < 10^6$  pps)**

reactions on a physical target

# Examples of RIB facilities

- In flight
  - GANIL (France), RIKEN (Japan), GSI (Germany), MSU (USA)
- ISOL
  - REX-ISOLDE (CERN), SPIRAL (France), TRIUMF (Canada)
- Other
  - Sao Paulo (Brazil), Orsay (France), Catania (Italy), Oak Ridge (USA), Jyvaskyla (Finland), Dubna

# FLNR itself



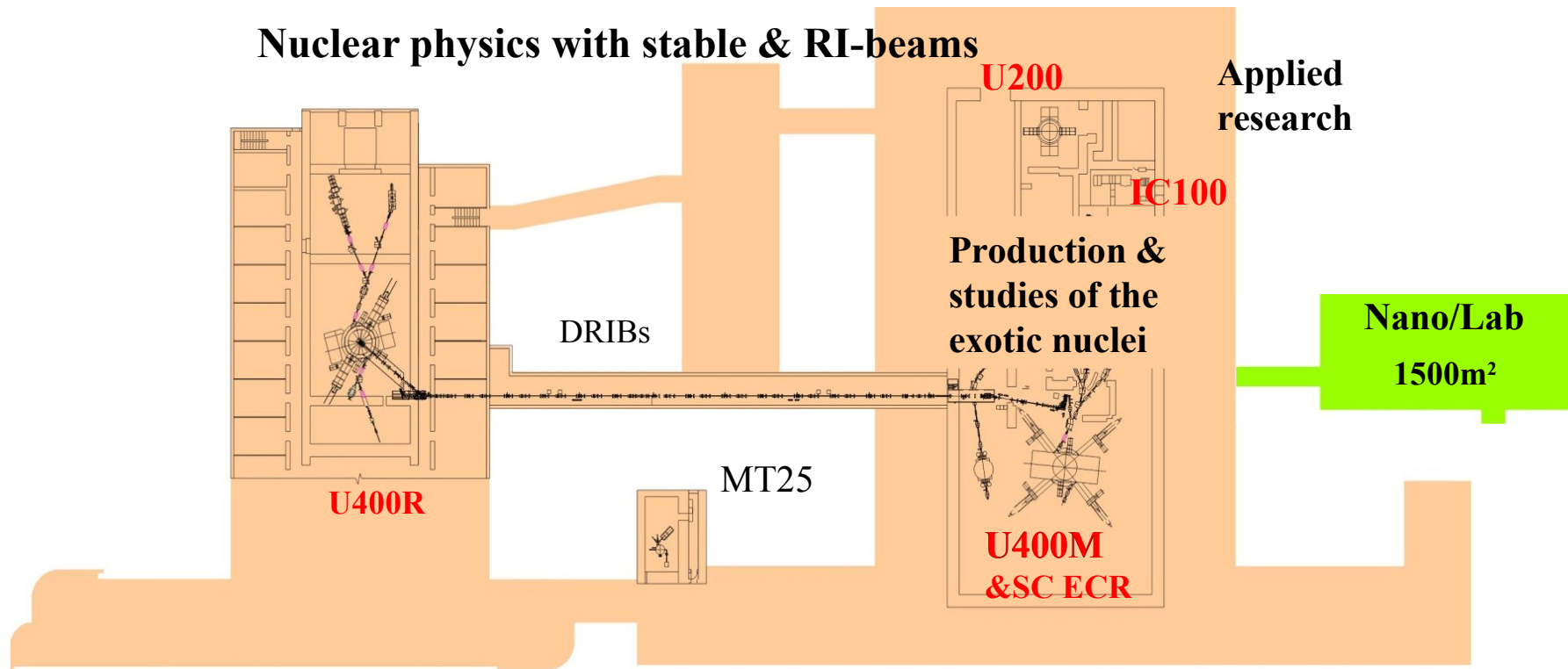
# Nuclear physics in FLNR

- **Heavy and superheavy elements**
  - synthesis of superheavy nuclei
  - nuclear spectroscopy
  - mass spectrometry
- **Light exotic nuclei**
  - properties and structure of light exotic nuclei
  - reactions with exotic nuclei



# FLNR accelerator complex

## Current state of FLNR

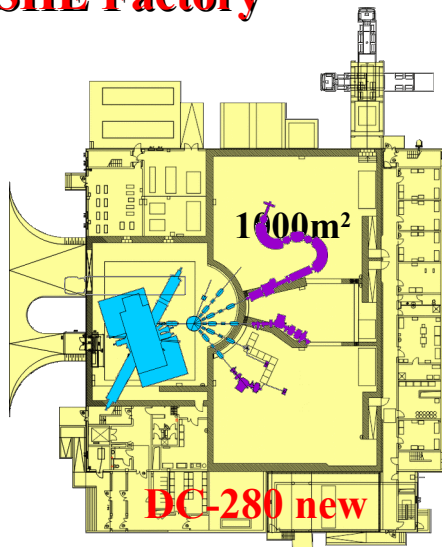


# FLNR accelerator complex

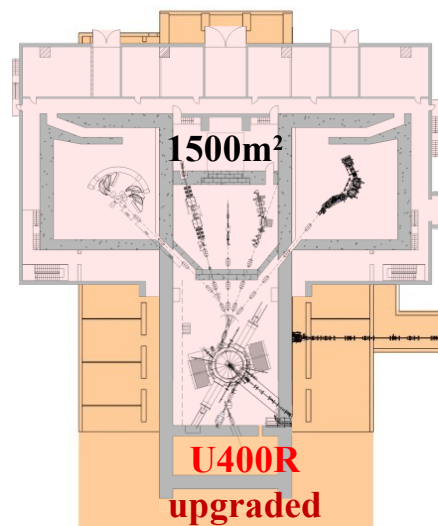
## Full-scale realization of the DRIBs-III

Dubna Radioactive Beams

**SHE Factory**



**Nuclear physics with stable & RI-beams**



DRIBs

MT25

**U200**

**IC100**

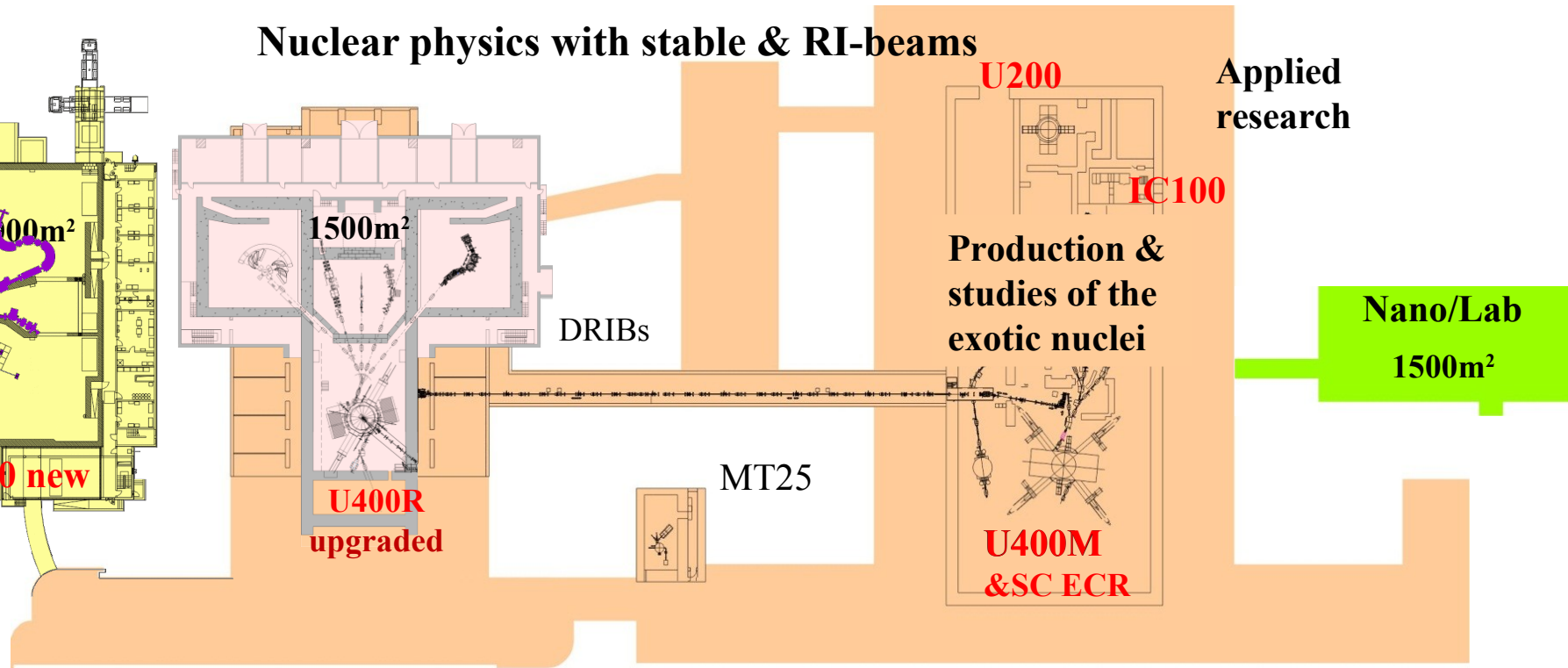
**Production & studies of the exotic nuclei**

**U400M & SC ECR**

**Applied research**

**Nano/Lab**

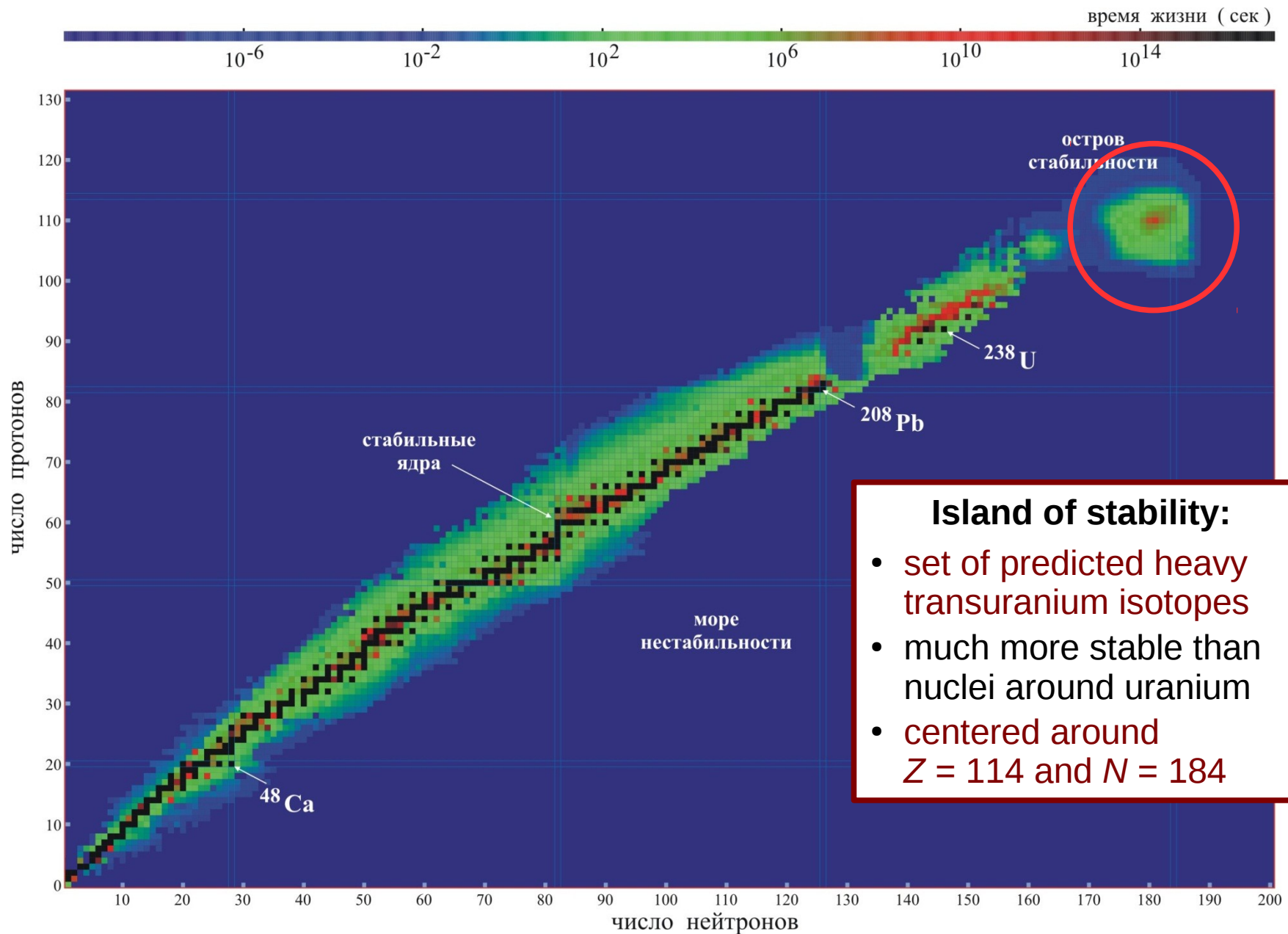
**1500m<sup>2</sup>**



# Superheavy elements factory



# SHE: Island of stability



# SHE: to the Island of Stability

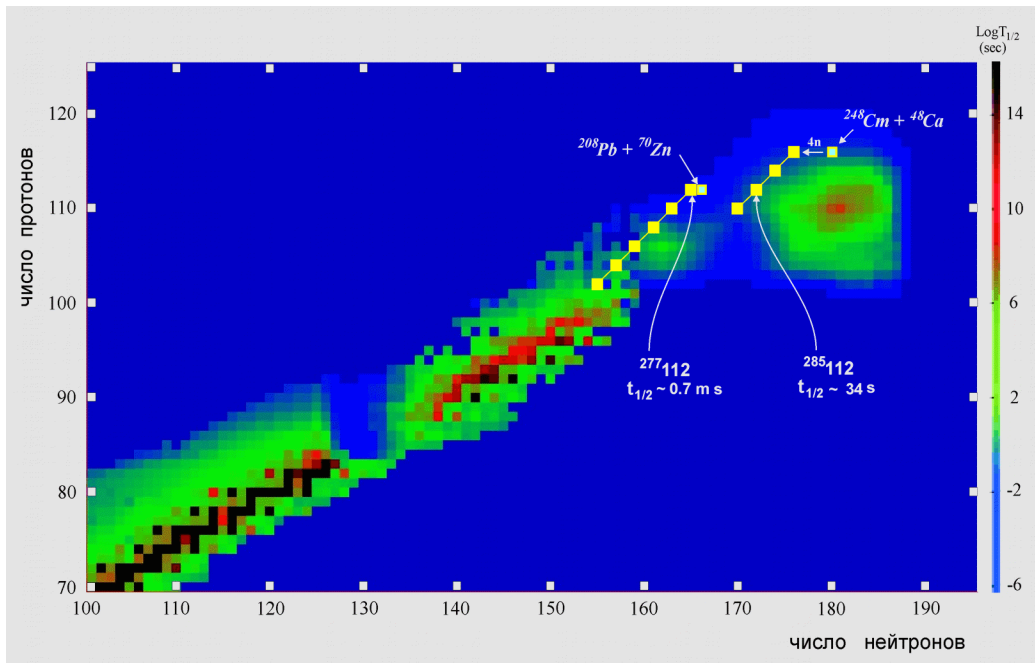
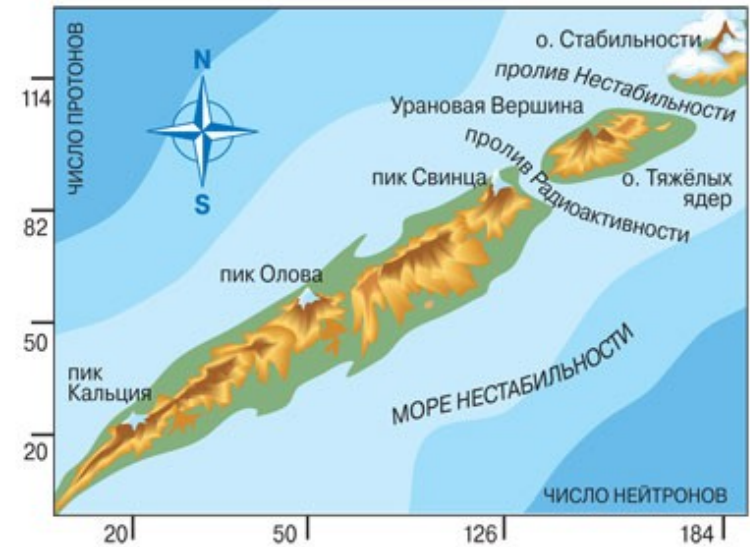
## synthesis of superheavies

$$Z_1 + Z_2 = Z$$

$$N_1 + N_2 = N + (2 - 4)n$$

“cold” fusion: Pb + heavy ion

“hot” fusion: light beam + heavy target



- low-energy physics
- compound nucleus
- combination of light and heavy nuclei gives higher cross sections

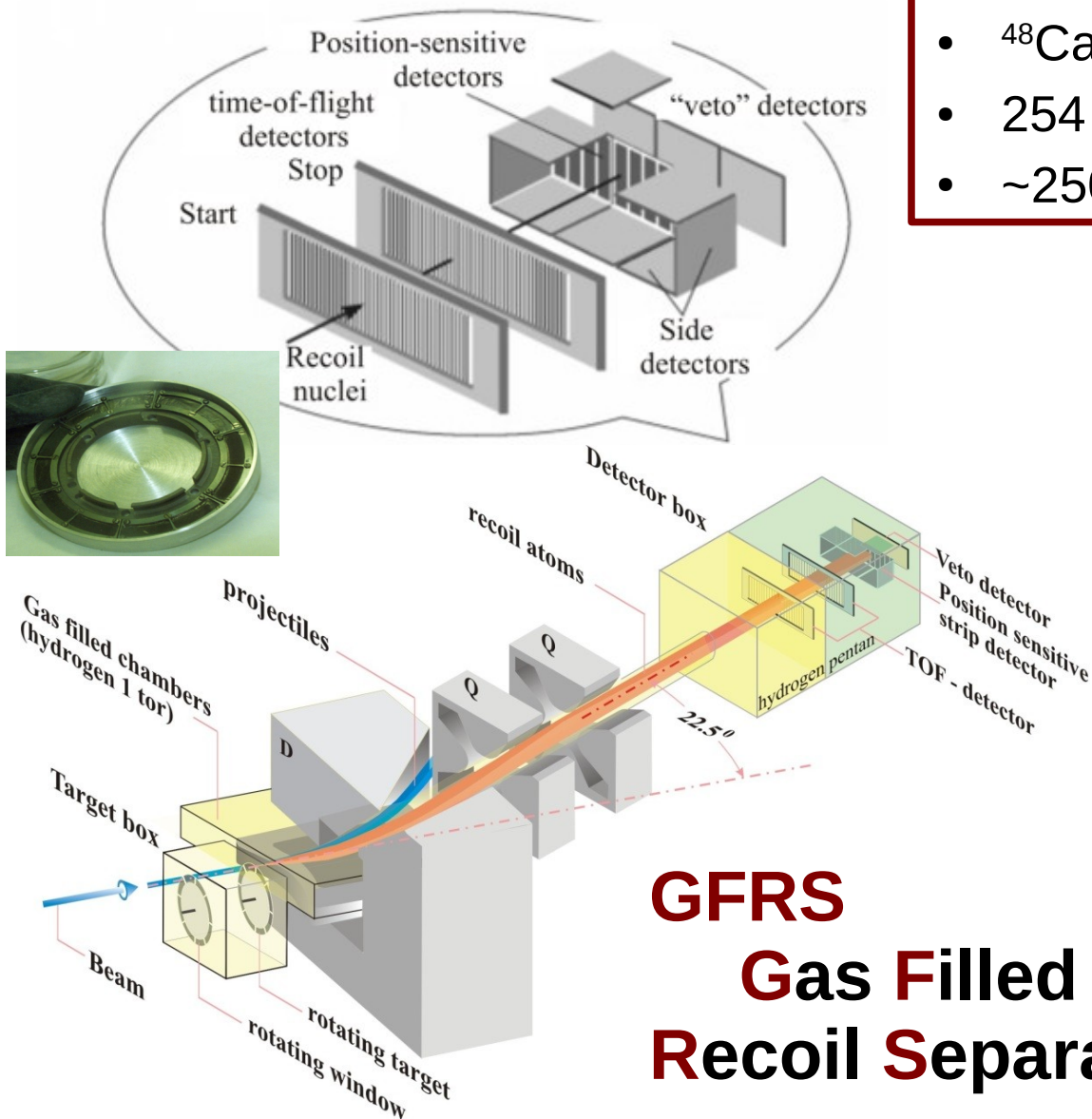
# SHE: synthesis of superheavies

in collaboration with LLNL (USA)

- beam**
- $^{48}\text{Ca}$
  - 254 MeV;  $10^{11}$  pps
  - ~250 000 USD/g



Bk(NO<sub>3</sub>)<sub>3</sub>Product



## GFRS Gas Filled Recoil Separator

- targets**
- $^{249}\text{Bk}$  (117),  $^{251}\text{Cf}$  (118)
  - $T_{1/2} = 330$  d, 900 y
  - much more expensive than beam
  - delivered by LLNL

- recently synthesized
- 2002: 118th element
  - 2010: 117th element

# Periodic table (~150 years ago)

Порядок элементов  
 основанных на химическом строении,  
 Д. Менделѣевъ.

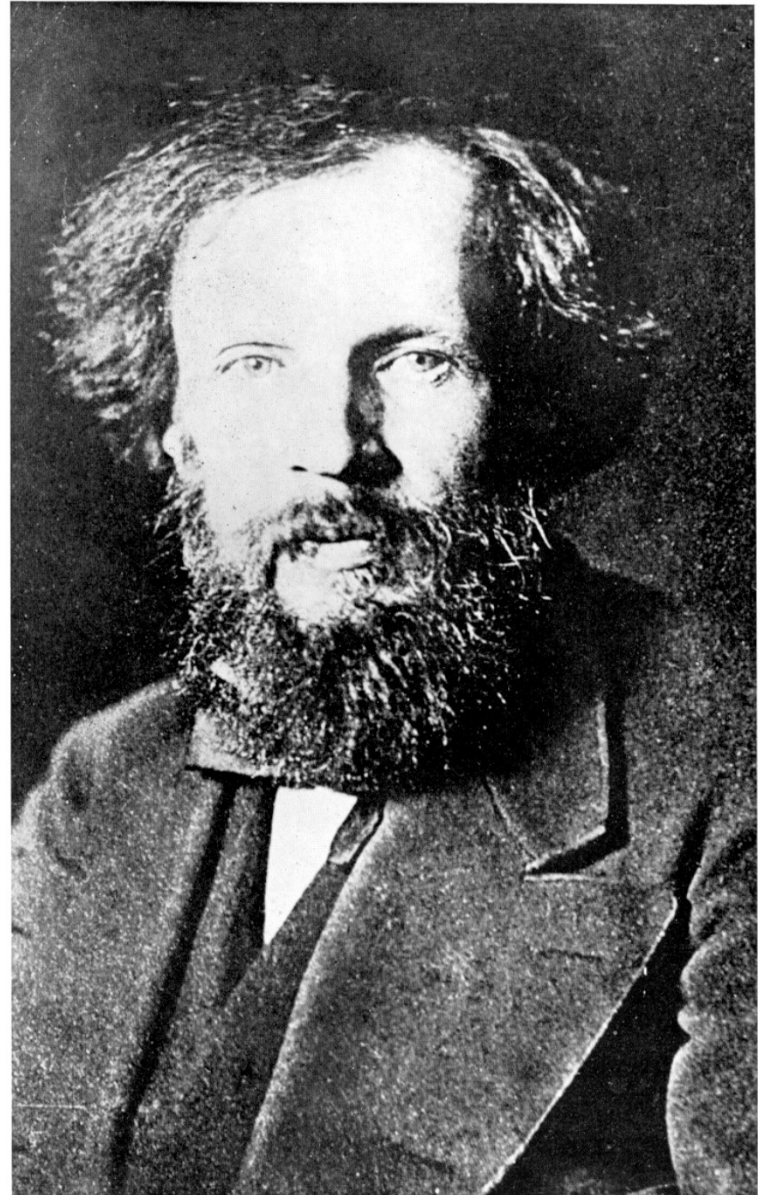
Мысль о периодичности  
 свойств элементов

	Li=7	Be=9	B=10	C=12	N=14	O=16	F=19	Ne=20	Na=23	Mg=24	Al=27	Si=28	P=31	S=32	Cl=35.5	Ar=36	K=39	Ca=40	Sc=45	Ti=48	V=51	Cr=52	Mn=55	Fe=56	Ni=58.7	Cu=63.5	Zn=65.4	Ga=70	Ge=72	As=75	Se=79	Br=80	Kr=84	Rb=85.5	Sr=87.6	Y=89	Zr=91.3	Nb=92.9	Mo=95.9	Tc=98	Xe=131.3	I=127	Ba=137.3	La=138.9	Ce=140.1	Pr=140.9	Nd=144.2	Pm=145	Sm=150.4	Eu=151.9	Gd=157.3	Tb=158.9	Dy=162.5	Ho=164.9	Er=167.3	Tm=168.9	Yb=173.0	Lu=175.0	Hf=178.5	Ta=182.0	W=183.8	Re=186.2	Os=190	Ir=192.2	Pt=195.1	Au=197	Hg=200.6	Tl=204	Pb=207.2	Bi=208	Po=209	At=210	Rn=222
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Essai d'une système des éléments d'après leurs poids atomiques et fonctions chimiques par D. Mendelѣeff

18 <sup>II</sup>/<sub>17</sub> 69.

Мысль о периодичности  
 свойств элементов



# Periodic table today



ЛАБОРАТОРИЯ ЯДЕРНЫХ РЕАКЦИЙ



## Периодическая таблица элементов Д.И. Менделеева

### D.I. Mendeleev's Periodic Table of Elements

1												13	14	15	16	17	18	
<b>Водород</b> 1 <b>H</b> 1.00794 Hydrogen												<b>Бор</b> 5 <b>B</b> 10.811 Boron	<b>Углерод</b> 6 <b>C</b> 12.011 Carbon	<b>Азот</b> 7 <b>N</b> 14.0067 Nitrogen	<b>Кислород</b> 8 <b>O</b> 15.9994 Oxygen	<b>Фтор</b> 9 <b>F</b> 18.9984 Fluorine	<b>Неон</b> 10 <b>Ne</b> 20.1797 Neon	
<b>Литий</b> 3 <b>Li</b> 6.941 Lithium	<b>Бериллий</b> 4 <b>Be</b> 9.01218 Beryllium												<b>Алюминий</b> 13 <b>Al</b> 26.981539 Aluminium	<b>Кремний</b> 14 <b>Si</b> 28.0855 Silicon	<b>Фосфор</b> 15 <b>P</b> 30.97376 Phosphorus	<b>Сера</b> 16 <b>S</b> 32.066 Sulfur	<b>Хлор</b> 17 <b>Cl</b> 35.4527 Chlorine	<b>Аргон</b> 18 <b>Ar</b> 39.948 Argon
<b>Натрий</b> 11 <b>Na</b> 22.989768 Sodium	<b>Магний</b> 12 <b>Mg</b> 24.3050 Magnesium	3	4	5	6	7	8	9	10	11	12	<b>Галлий</b> 31 <b>Ga</b> 69.723 Gallium	<b>Германий</b> 32 <b>Ge</b> 72.61 Germanium	<b>Мышьяк</b> 33 <b>As</b> 74.92159 Arsenic	<b>Селен</b> 34 <b>Se</b> 78.96 Selenium	<b>Бром</b> 35 <b>Br</b> 79.904 Bromine	<b>Криптон</b> 36 <b>Kr</b> 83.80 Krypton	
<b>Калий</b> 19 <b>K</b> 39.0983 Potassium	<b>Кальций</b> 20 <b>Ca</b> 40.078 Calcium	<b>Скандий</b> 21 <b>Sc</b> 44.95591 Scandium	<b>Титан</b> 22 <b>Ti</b> 47.88 Titanium	<b>Ванадий</b> 23 <b>V</b> 50.9415 Vanadium	<b>Хром</b> 24 <b>Cr</b> 51.9961 Chromium	<b>Марганец</b> 25 <b>Mn</b> 54.93805 Manganese	<b>Железо</b> 26 <b>Fe</b> 55.847 Iron	<b>Кобальт</b> 27 <b>Co</b> 58.93320 Cobalt	<b>Никель</b> 28 <b>Ni</b> 58.6934 Nickel	<b>Медь</b> 29 <b>Cu</b> 63.546 Copper	<b>Цинк</b> 30 <b>Zn</b> 65.39 Zinc	<b>Индий</b> 49 <b>In</b> 114.818 Indium	<b>Кадмий</b> 48 <b>Cd</b> 112.411 Cadmium	<b>Теллур</b> 52 <b>Te</b> 127.60 Tellurium	<b>Йод</b> 53 <b>I</b> 126.90447 Iodine	<b>Кселон</b> 54 <b>Xe</b> 131.29 Xenon		
<b>Рубидий</b> 37 <b>Rb</b> 85.4678 Rubidium	<b>Стронций</b> 38 <b>Sr</b> 87.62 Strontium	<b>Иттрий</b> 39 <b>Y</b> 88.90585 Yttrium	<b>Цирконий</b> 40 <b>Zr</b> 91.224 Zirconium	<b>Нобий</b> 41 <b>Nb</b> 92.90638 Niobium	<b>Молибден</b> 42 <b>Mo</b> 95.94 Molybdenum	<b>Технеций</b> 43 <b>Tc</b> [98] Technetium	<b>Рутений</b> 44 <b>Ru</b> 101.07 Ruthenium	<b>Родий</b> 45 <b>Rh</b> 102.90550 Rhodium	<b>Палладий</b> 46 <b>Pd</b> 106.42 Palladium	<b>Серебро</b> 47 <b>Ag</b> 107.8682 Silver	<b>Кадмий</b> 48 <b>Cd</b> 112.411 Cadmium	<b>Индий</b> 49 <b>In</b> 114.818 Indium	<b>Кадмий</b> 48 <b>Cd</b> 112.411 Cadmium	<b>Теллур</b> 52 <b>Te</b> 127.60 Tellurium	<b>Йод</b> 53 <b>I</b> 126.90447 Iodine	<b>Кселон</b> 54 <b>Xe</b> 131.29 Xenon		
<b>Цезий</b> 55 <b>Cs</b> 132.90543 Cesium	<b>Барий</b> 56 <b>Ba</b> 137.327 Barium	<b>Лантан</b> 57 <b>La</b> 138.9055 Lanthanum	<b>Гафний</b> 72 <b>Hf</b> 178.49 Hafnium	<b>Тантал</b> 73 <b>Ta</b> 183.84 Tantalum	<b>Вольфрам</b> 74 <b>W</b> 183.84 Tungsten	<b>Рений</b> 75 <b>Re</b> 186.207 Rhenium	<b>Осмий</b> 76 <b>Os</b> 190.23 Osmium	<b>Иридий</b> 77 <b>Ir</b> 192.22 Iridium	<b>Платина</b> 78 <b>Pt</b> 195.08 Platinum	<b>Золото</b> 79 <b>Au</b> 196.96654 Gold	<b>Ртуть</b> 80 <b>Hg</b> 200.59 Mercury	<b>Таллий</b> 81 <b>Tl</b> 204.3833 Thallium	<b>Свинец</b> 82 <b>Pb</b> 207.2 Lead	<b>Висмут</b> 83 <b>Bi</b> 208.98037 Bismuth	<b>Полоний</b> 84 <b>Po</b> [209] Polonium	<b>Астат</b> 85 <b>At</b> [210] Astatine	<b>Радон</b> 86 <b>Rn</b> [222] Radon	
<b>Франций</b> 87 <b>Fr</b> [223] Francium	<b>Радий</b> 88 <b>Ra</b> 226.025 Radium	<b>Актиний</b> 89 <b>Ac</b> [227] Actinium	<b>Резерфордий</b> 104 <b>Rf</b> [261] Rutherfordium	<b>Дубний</b> 105 <b>Db</b> [262] Dubnium	<b>Сибергий</b> 106 <b>Sg</b> [266] Seaborgium	<b>Борий</b> 107 <b>Bh</b> [267] Bohrium	<b>Хассий</b> 108 <b>Hs</b> [268] Hassium	<b>Мейтнерий</b> 109 <b>Mt</b> [269] Meitnerium	<b>Дармштадт</b> 110 <b>Ds</b> [271] Darmstadtium	<b>Рентгений</b> 111 <b>Rg</b> [272] Roentgenium	<b>Коперниций</b> 112 <b>Cn</b> [285] Copernicium	<b>Нихоний</b> 113 <b>Nh</b> [286] Nihonium	<b>Флеровий</b> 114 <b>Fl</b> [289] Flerovium	<b>Московий</b> 115 <b>Mc</b> [290] Moscovium	<b>Ливерморий</b> 116 <b>Lv</b> [293] Livermorium	<b>Теннесси</b> 117 <b>Ts</b> [294] Tennessine	<b>Оганессон</b> 118 <b>Og</b> [294] Oganesson	

#### Лантаноиды Lanthanoides

<b>Церий</b> 58 <b>Ce</b> 140.115 Cerium	<b>Прометий</b> 59 <b>Pr</b> 140.90765 Promethium	<b>Неодим</b> 60 <b>Nd</b> 144.24 Neodymium	<b>Прометий</b> 61 <b>Pm</b> [145] Promethium	<b>Самарий</b> 62 <b>Sm</b> 150.36 Samarium	<b>Европий</b> 63 <b>Eu</b> 151.965 Europium	<b>Гадолиний</b> 64 <b>Gd</b> 157.25 Gadolinium	<b>Тербий</b> 65 <b>Tb</b> 158.92534 Terbium	<b>Диспрозий</b> 66 <b>Dy</b> 162.59 Dysprosium	<b>Гольмий</b> 67 <b>Ho</b> 164.93032 Holmium	<b>Эрбий</b> 68 <b>Er</b> 167.26 Erbium	<b>Тулий</b> 69 <b>Tm</b> 168.93421 Thulium	<b>Иттербий</b> 70 <b>Yb</b> 173.04 Ytterbium	<b>Лютеций</b> 71 <b>Lu</b> 174.967 Lutetium
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<b>Водород</b> 1 <b>H</b> 1.00794 Hydrogen
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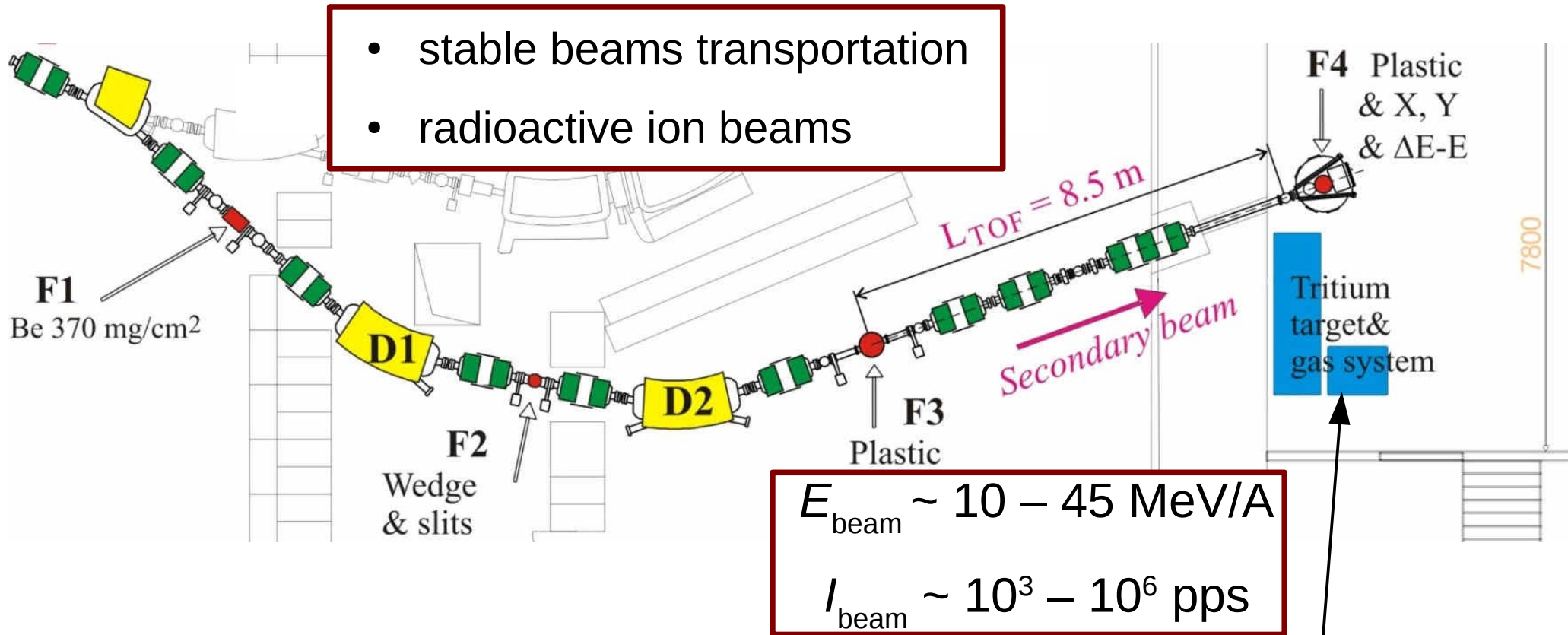
#### Актиноиды Actinoides

<b>Торий</b> 90 <b>Th</b> 232.0381 Thorium	<b>Протактиний</b> 91 <b>Pa</b> 231.03688 Protactinium	<b>Уран</b> 92 <b>U</b> 238.02891 Uranium	<b>Нептуний</b> 93 <b>Np</b> [237] Neptunium	<b>Плутоний</b> 94 <b>Pu</b> [244] Plutonium	<b>Америций</b> 95 <b>Am</b> [243] Americium	<b>Кюрий</b> 96 <b>Cm</b> [247] Curium	<b>Берклий</b> 97 <b>Bk</b> [247] Berkelium	<b>Калифорний</b> 98 <b>Cf</b> [251] Californium	<b>Эйнштейний</b> 99 <b>Es</b> [252] Einsteinium	<b>Фермий</b> 100 <b>Fm</b> [257] Fermium	<b>Менделеевий</b> 101 <b>Md</b> [258] Mendelevium	<b>Нобелий</b> 102 <b>No</b> [259] Nobelium	<b>Лавренций</b> 103 <b>Lr</b> [262] Lawrencium
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H - символ / symbol  
1.00794 - атомная масса / atomic mass  
1s<sup>1</sup> - электронная конфигурация / electron configuration  
13.59644 - 1-я потенциальная ионизация, эВ / 1st ionization potential, eV  
0.0899 - плотность, кг/м<sup>3</sup> / density, kg/m<sup>3</sup>  
-259.34 - температура плавления, °C / melting temperature, °C  
-252.87 - температура кипения, °C / boiling temperature, °C



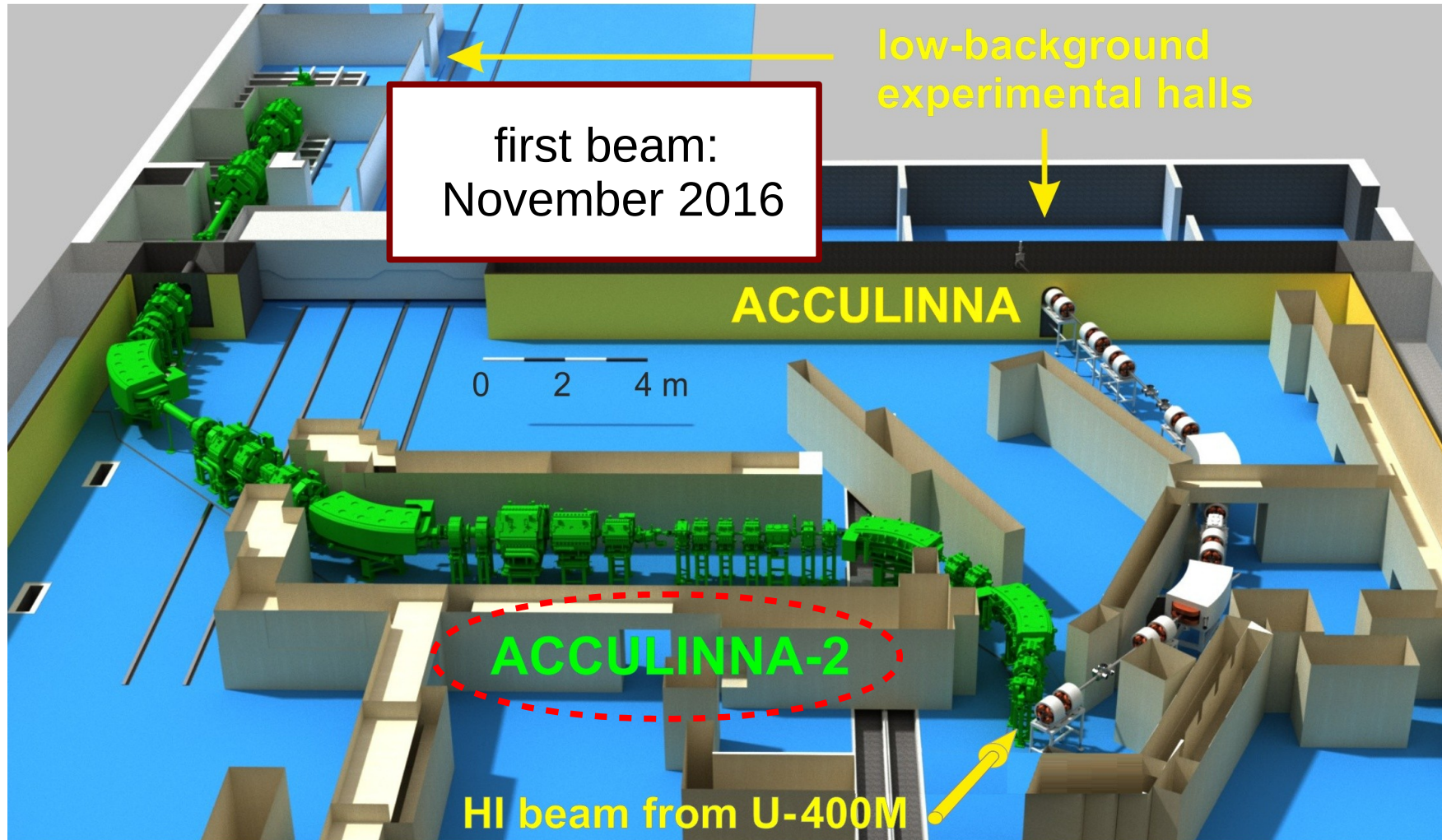
# ACCULINNA



- the only working RIB facility in JINR
- **in-flight technique**
- beams up to <sup>26</sup>S

unique combination of tritium beam and target

# ACCULINNA-2



- energy range 6 – 60 MeV/A
- beam intensities higher in 2 orders
- $Z_{\text{RIB}} \sim 1 - 36$



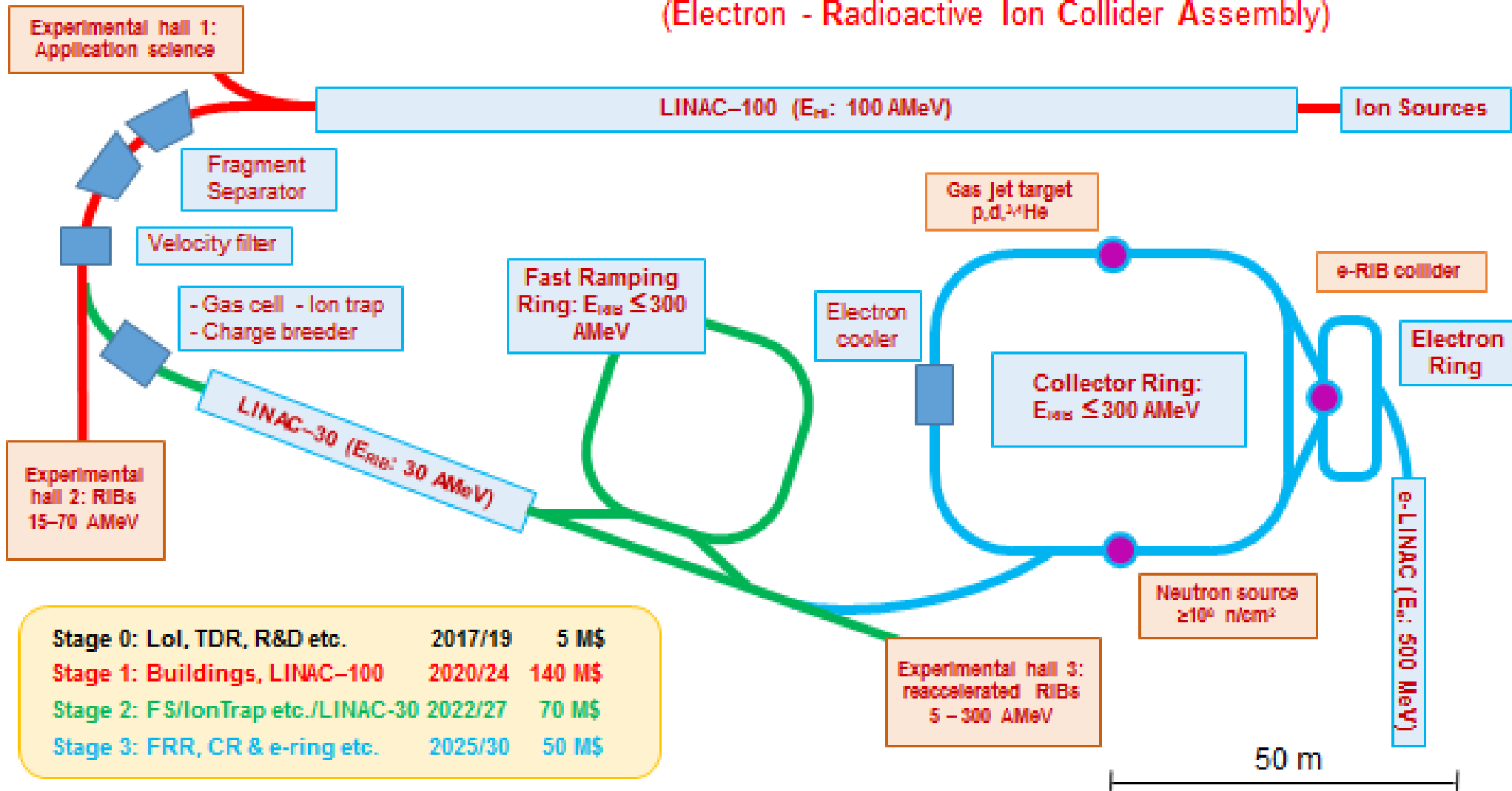
# New megascience project



# New megascience project

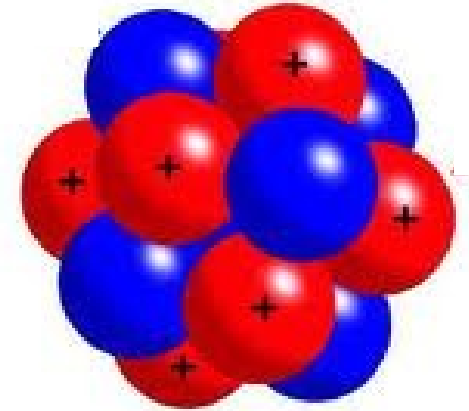
## Concept of ERICA complex

(Electron - Radioactive Ion Collider Assembly)



Stage 0: Lol, TDR, R&D etc.	2017/19	5 M\$
Stage 1: Buildings, LINAC-100	2020/24	140 M\$
Stage 2: FS/IonTrap etc./LINAC-30	2022/27	70 M\$
Stage 3: FRR, CR & e-ring etc.	2025/30	50 M\$

# Why exotic?



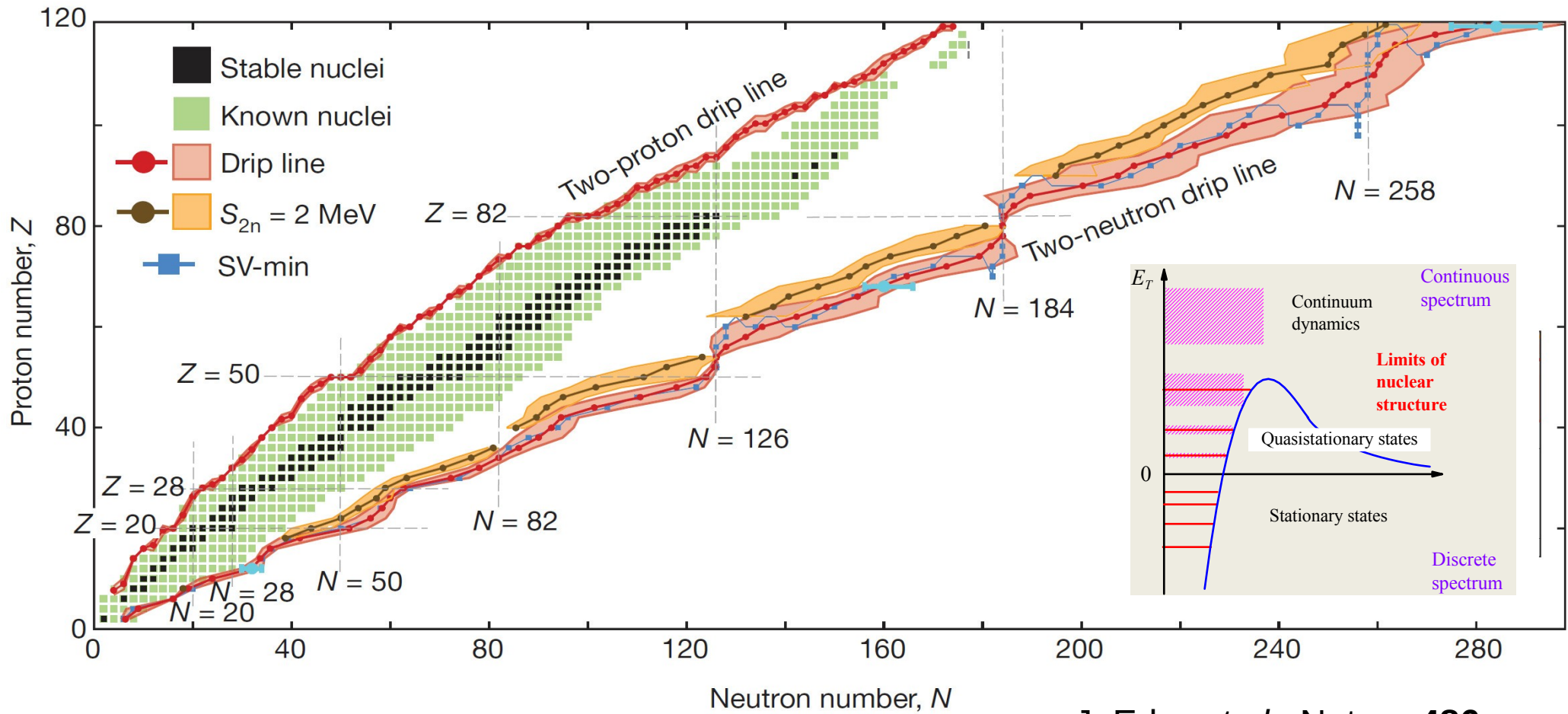
- **far from stable nuclei**
- **complicatedly available**

**too  
heavy**

**or**

**strange  
in other  
way**

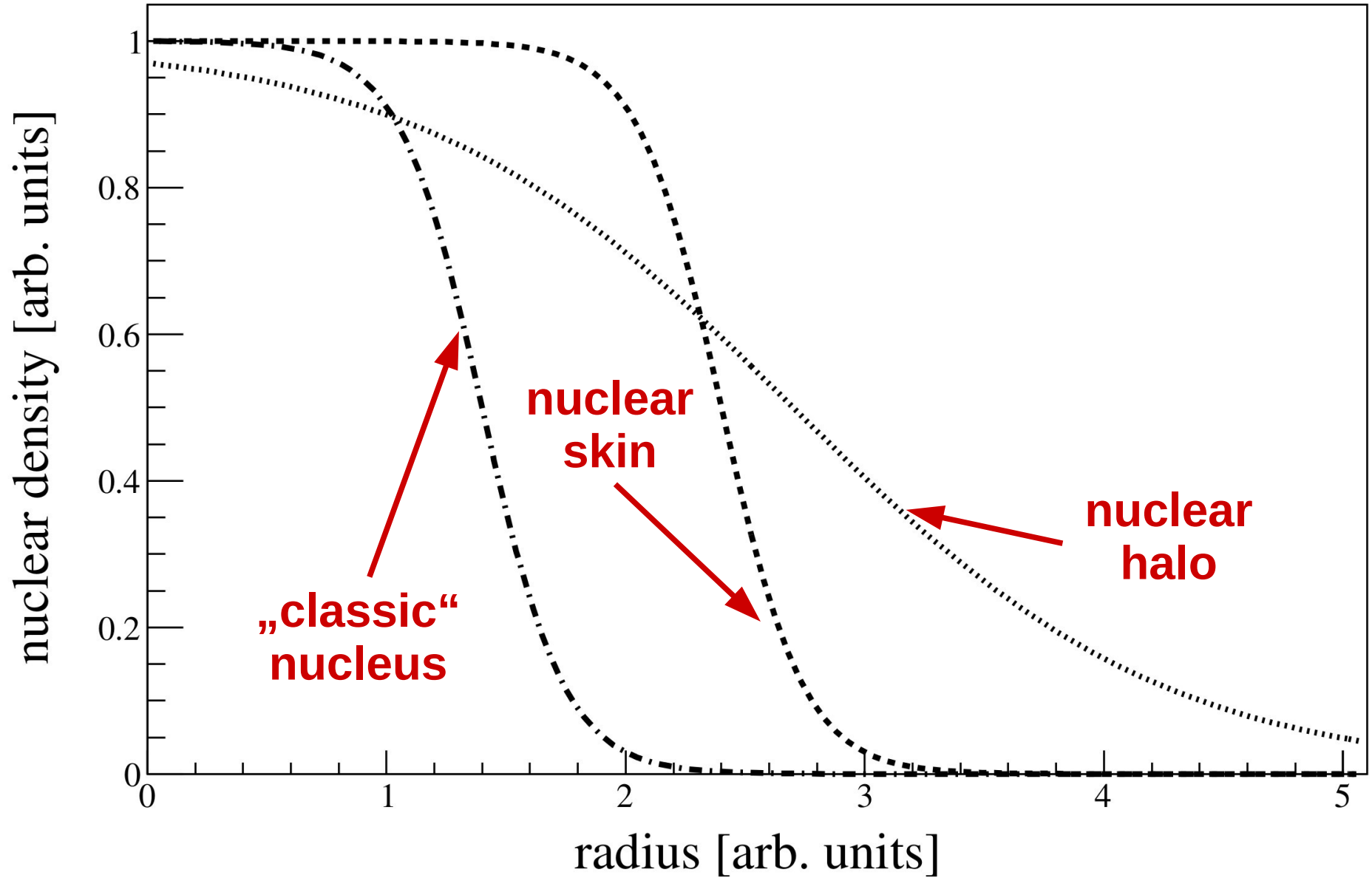
# Drip-line



J. Erler *et al.*, Nature **486**  
(2012) 509

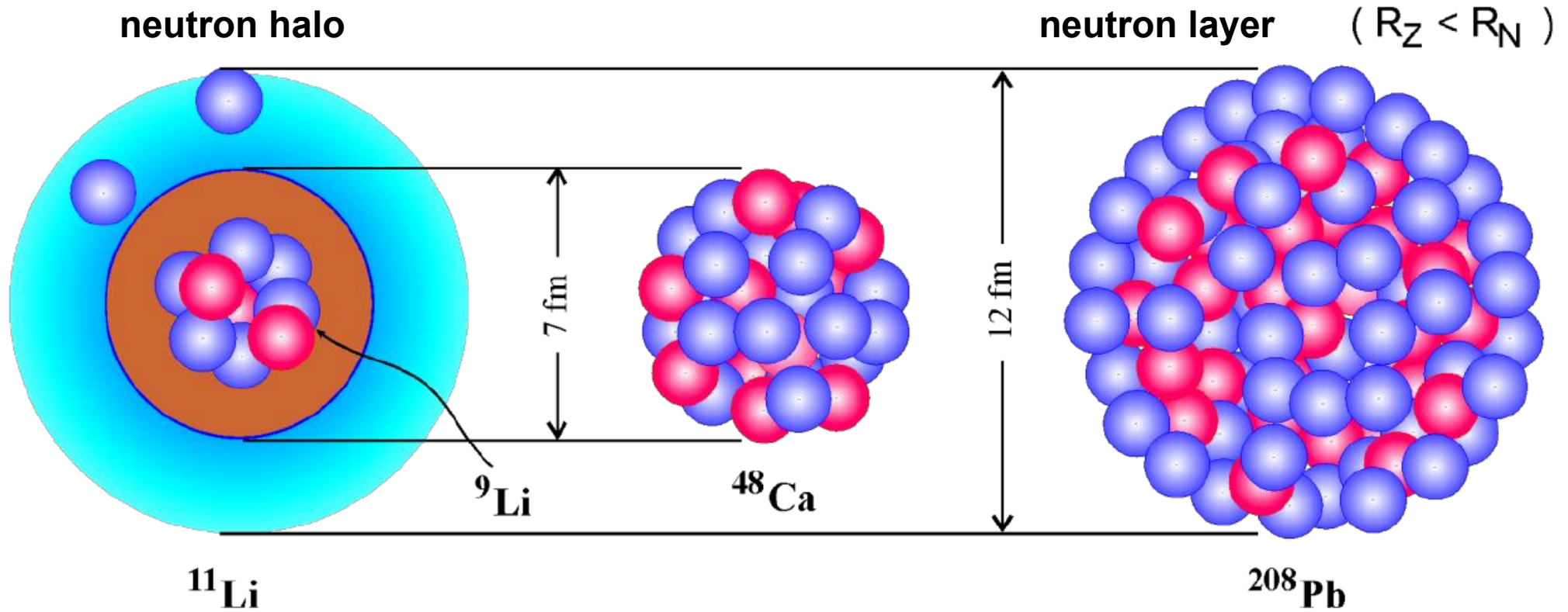
moving away from the nuclear stability →  
 transition from discrete spectrum to continuum  
 → immediate emission of nucleon

# Nuclear halo





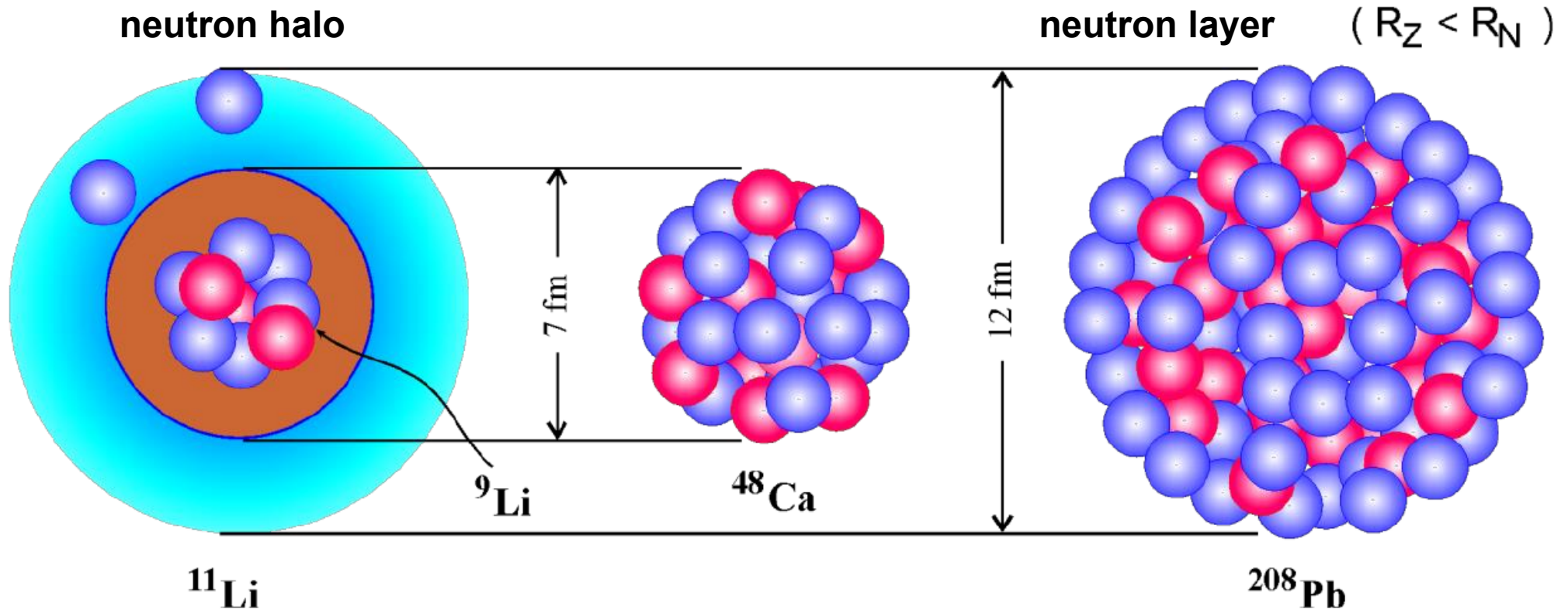
# Nuclear halo



- tunneling to the forbidden regions
- **extended size of nucleus**

B. Jonson P.G. Hansen. The Neutron Halo of Extremely Neutron-Rich Nuclei. Europhys. Lett., 4(4):409–414, **1987**

# Nuclear halo



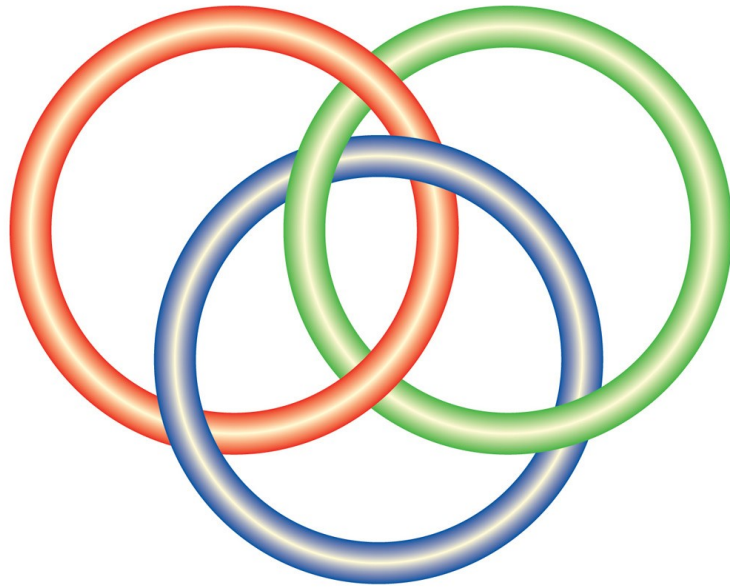
## First observation of $^6\text{He}$

T. Bjerge. Radio-Helium.  
NATURE, 137, 865,  
138:400–400, **1936!!!**

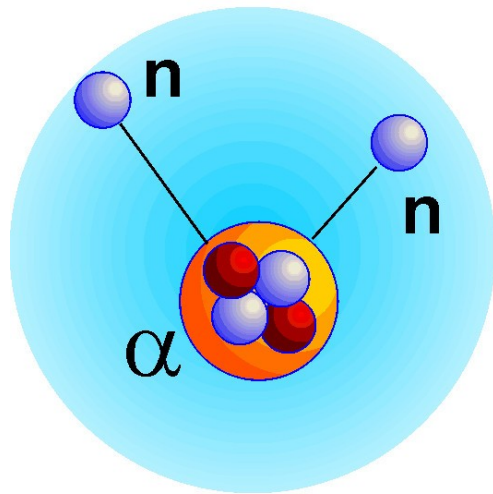
## Observation of large $^6\text{He}$ radius

I. Tanihata et al., Physics  
Letters B, 160(6):380–  
384, 1985.

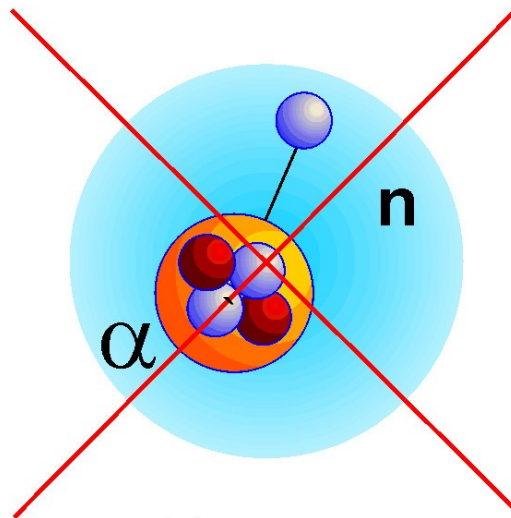
# Borromean nuclei



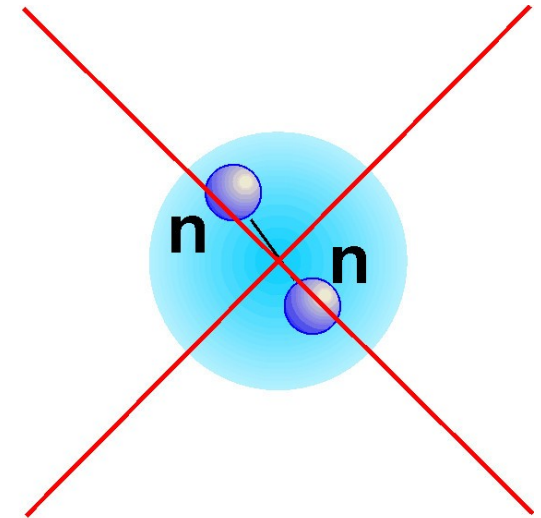
M.V. Zhukov et al., Bound state properties of Borromean halo nuclei:  ${}^6\text{He}$  and  ${}^{11}\text{Li}$ . Physics Reports, 231(4):151–199, 1993



${}^6\text{He}$

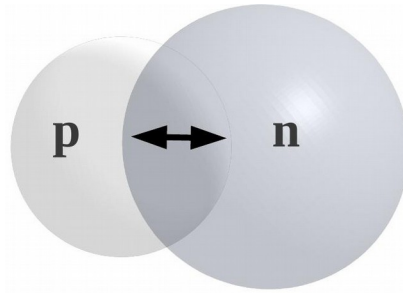


${}^5\text{He}$



$2n$

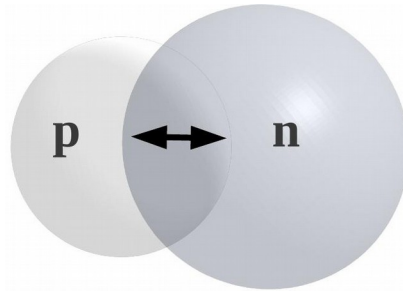
# Soft dipole mode (SDM) of Giant dipole resonance (GDR)



## **GDR**

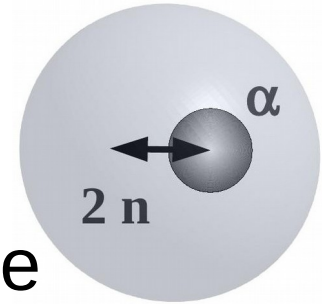
- protons vs. neutrons
- $E_{\text{GDR}} \sim 14 - 24 \text{ MeV}$
- induced by EM excitation

# Soft dipole mode (SDM) of Giant dipole resonance (GDR)



## GDR

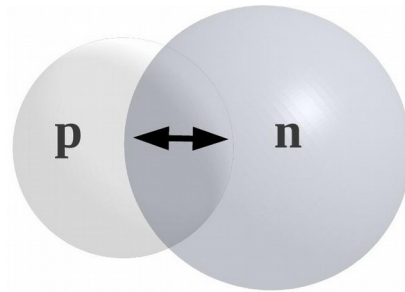
- protons vs. neutrons
- $E_{\text{GDR}} \sim 14 - 24 \text{ MeV}$
- induced by EM excitation



## SDM

- halo vs. core
- $E_{\text{SDM}}$  lower than  $E_{\text{GDR}}$
- induced by EM excitation and charge-exchange reaction

# Soft dipole mode (SDM) of Giant dipole resonance (GDR)

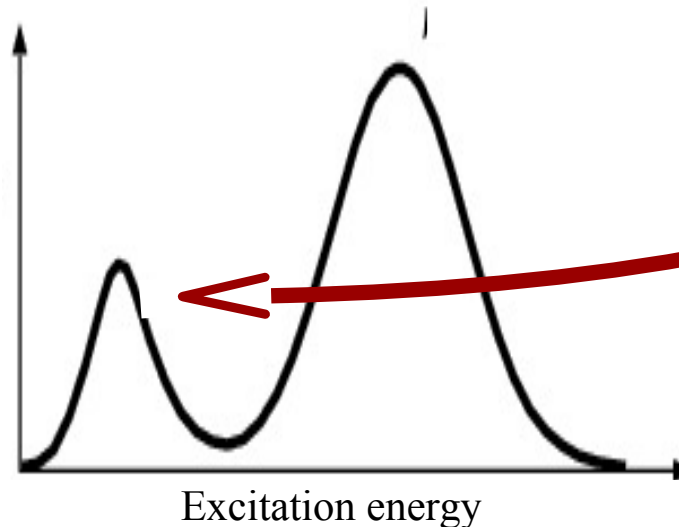
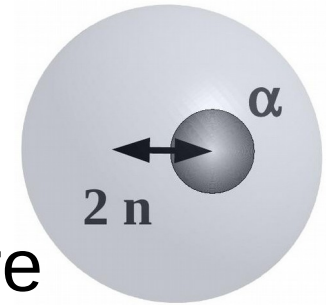


## GDR

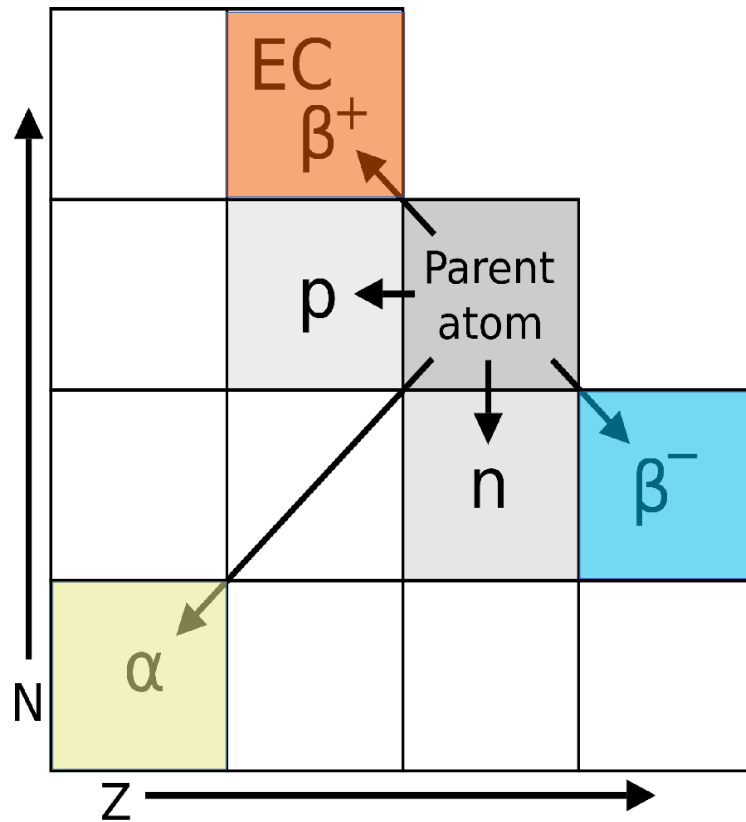
- protons vs. neutrons
- $E_{\text{GDR}} \sim 14 - 24 \text{ MeV}$
- induced by EM excitation

## SDM

- halo vs. core
- $E_{\text{SDM}}$  lower than  $E_{\text{GDR}}$
- induced by EM excitation and charge-exchange reaction



# Radioactivity and decays



**$\alpha$  decay**  
E. Rutherford, 1899

**$\beta^-$  decay**  
H. Becquerel, 1886

**$\beta^+$  decay**  
F. and I. Joliot-Curie,  
1932

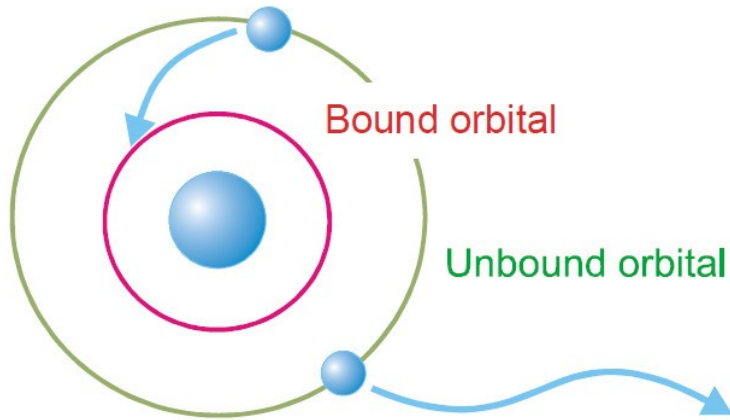
**p rad.**  
S. Hoffman,  
1982

**2p rad.**  
M. Pfützner,  
B. Blank,  
2002

**cluster  
emission**  
H. Rose,  
1984

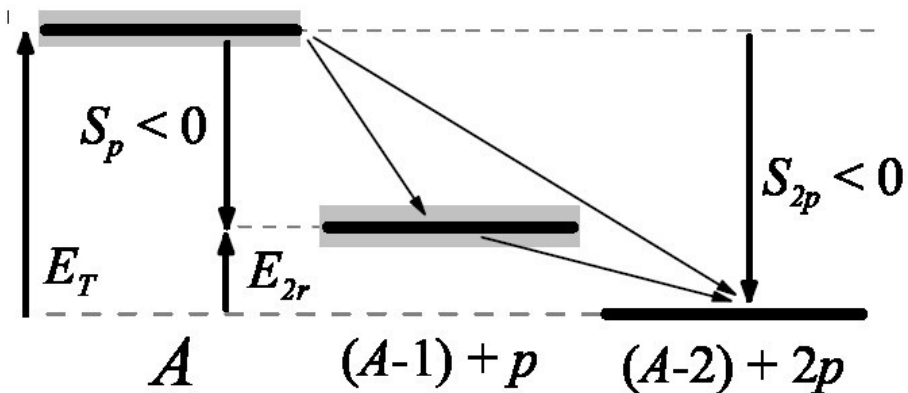
**(multi)-n  
radioactivity**  
still waiting

# Proton radioactivity



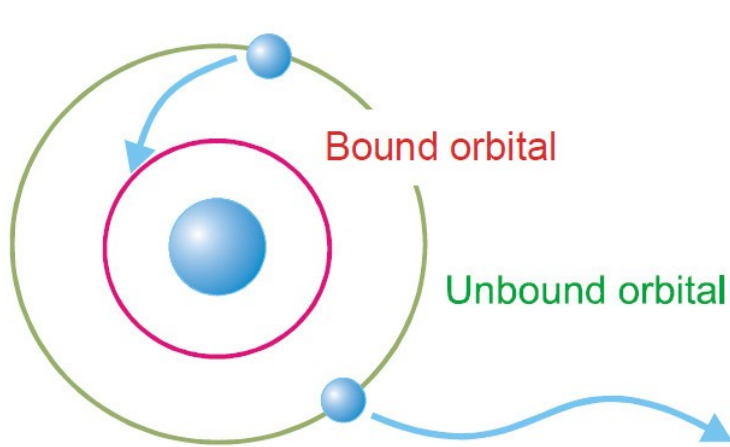
## p-radioactivity

natural generalization  
of  $\alpha$ -radioactivity



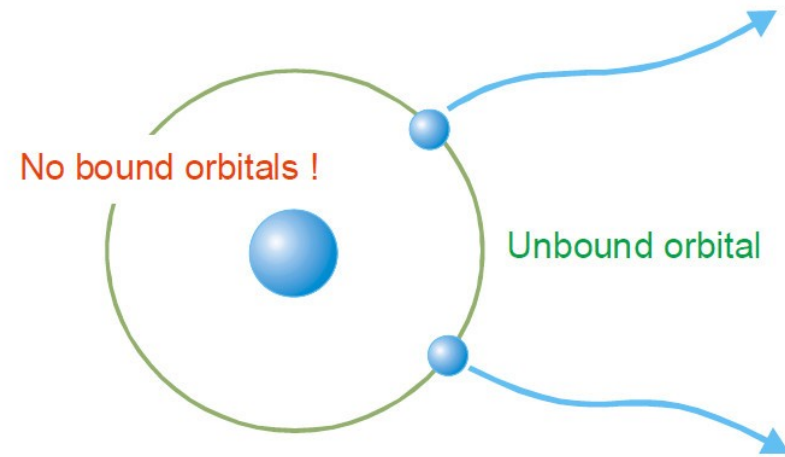


# Proton radioactivity



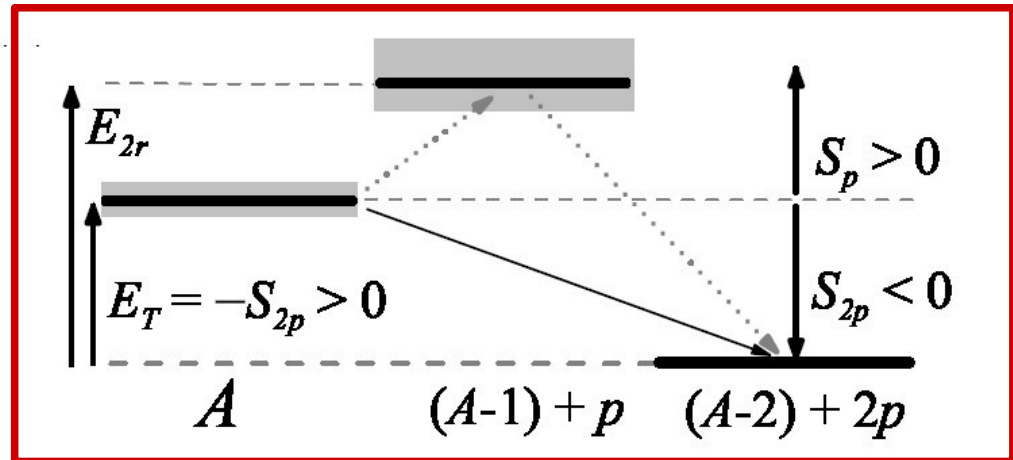
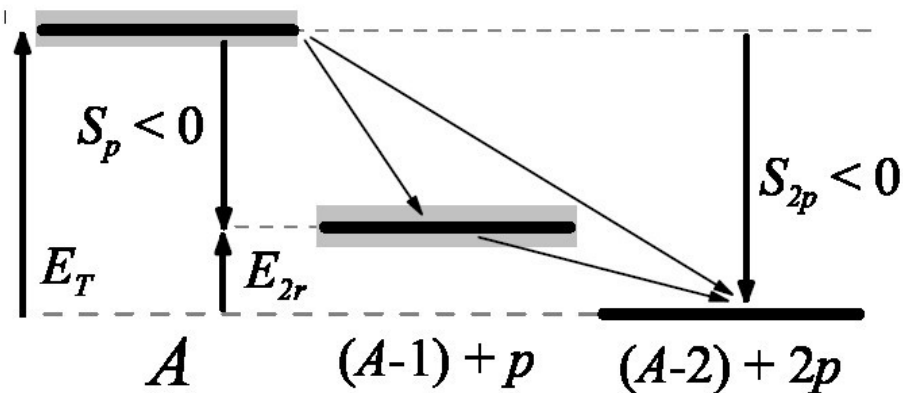
## p-radioactivity

natural generalization  
of  $\alpha$ -radioactivity

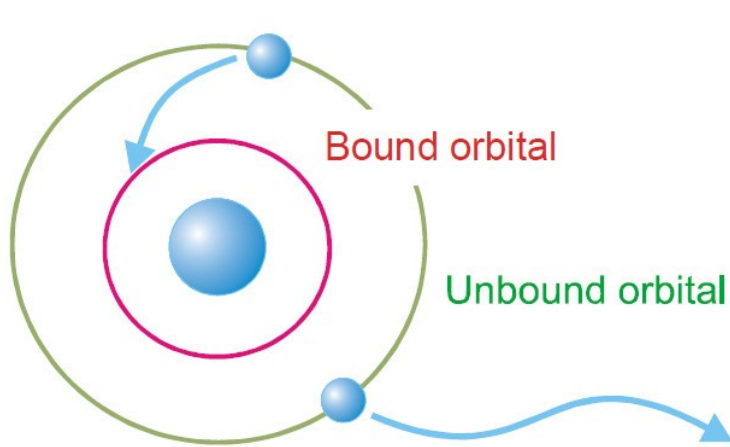


## 2p-radioactivity

no analogue in  
classical mechanics

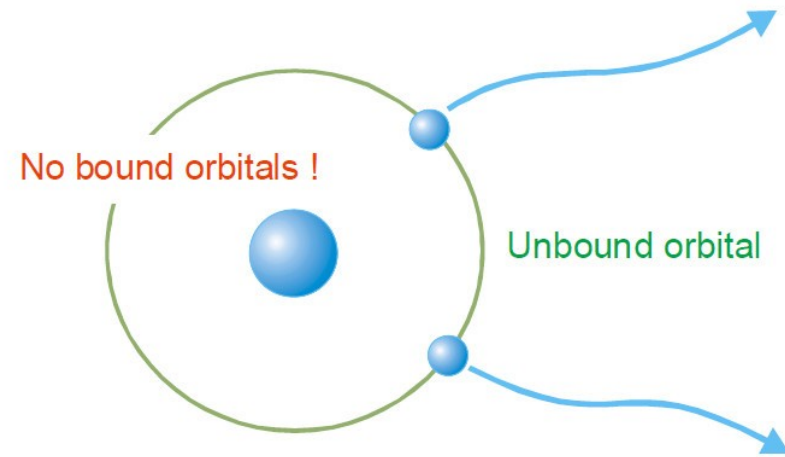


# Proton radioactivity



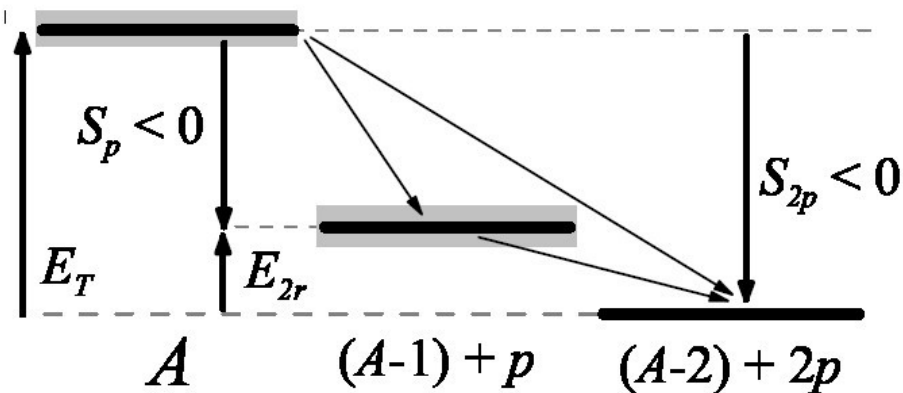
## p-radioactivity

natural generalization  
of  $\alpha$ -radioactivity



## 2p-radioactivity

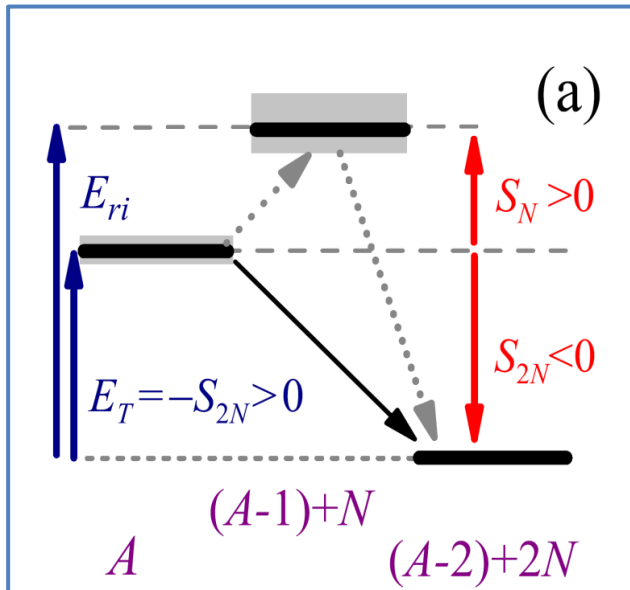
no analogue in  
classical mechanics



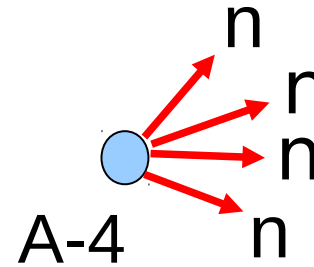
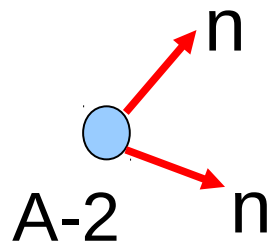
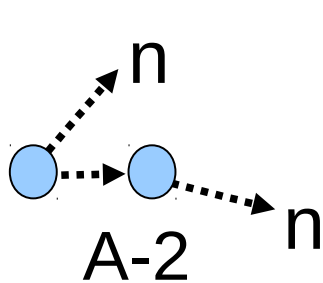
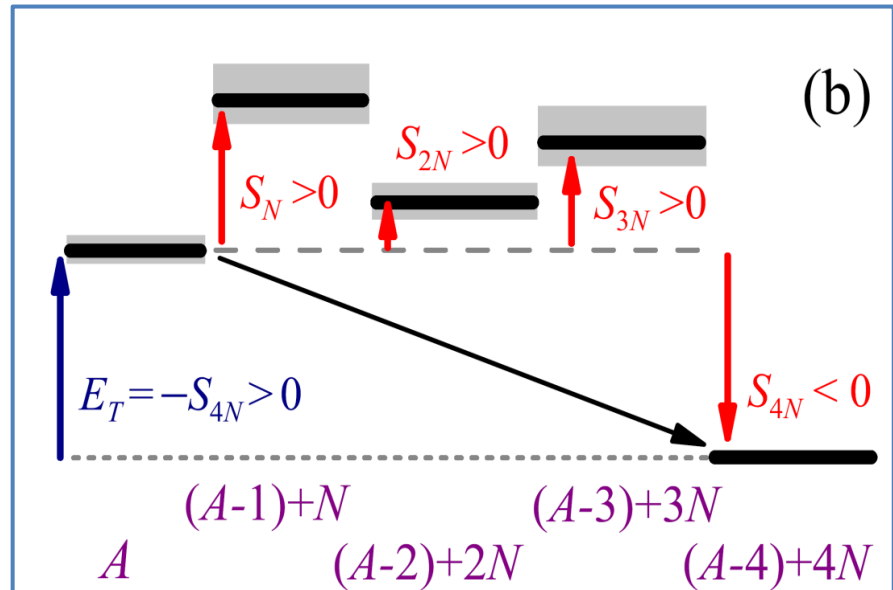
$^{45}\text{Fe}$ ,  $^{19}\text{Mg}$ ,  $^{54}\text{Zn}$ ,  
 $^{48}\text{Ni}$ ,  $^{67}\text{Kr}$ ,  $^{94m}\text{Ag}$

# Neutron radioactivity

2n decays



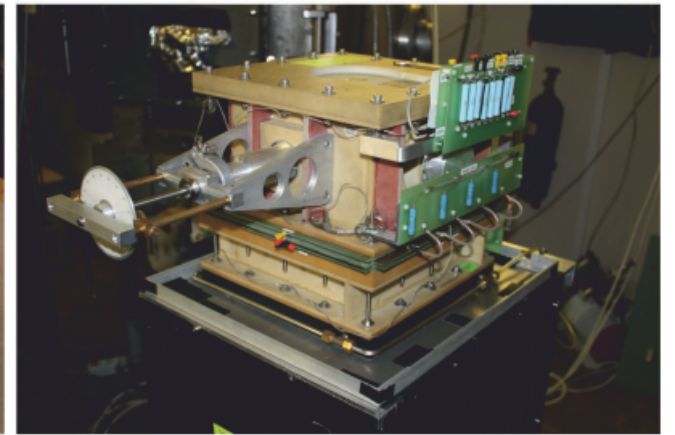
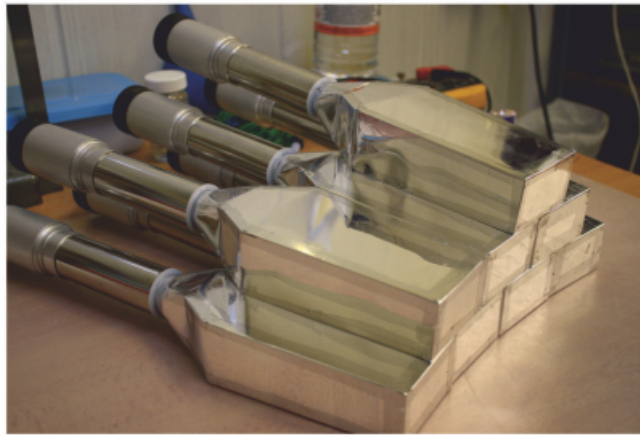
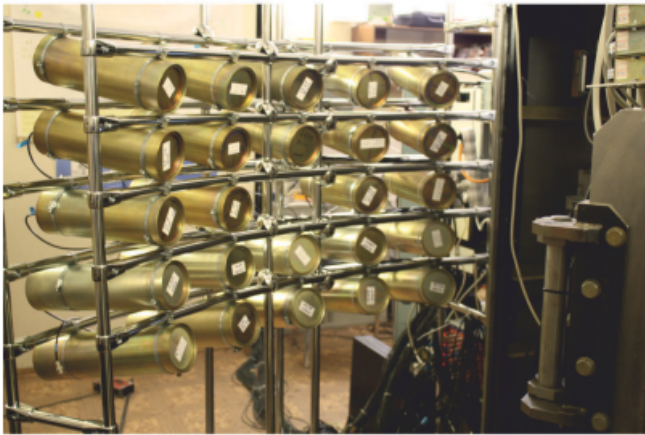
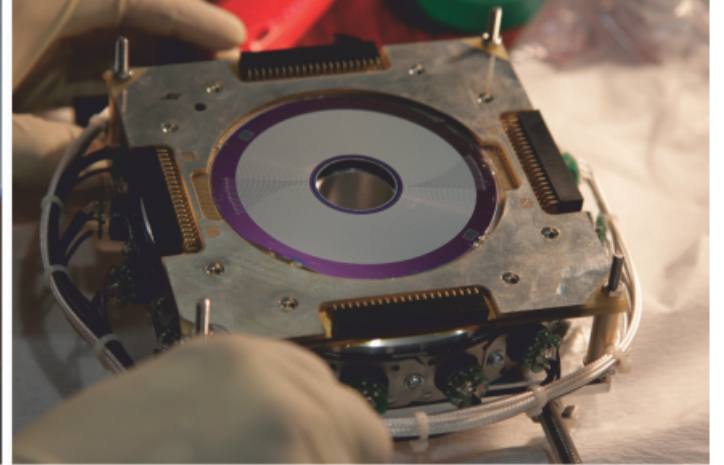
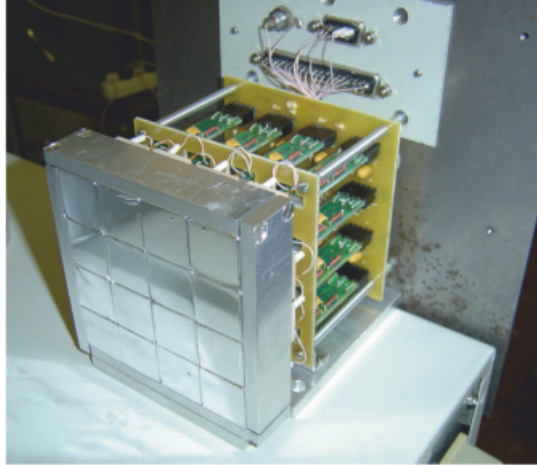
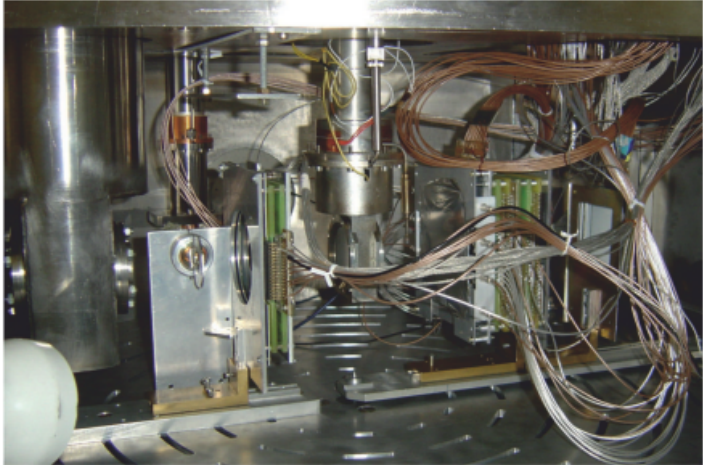
4n decays



${}^5\text{H}$ ,  ${}^{10}\text{He}$ ,  ${}^{26}\text{O}$ , ...

${}^7\text{H}$ ,  ${}^{18}\text{Be}$ ,  ${}^{28}\text{O}$ , ...

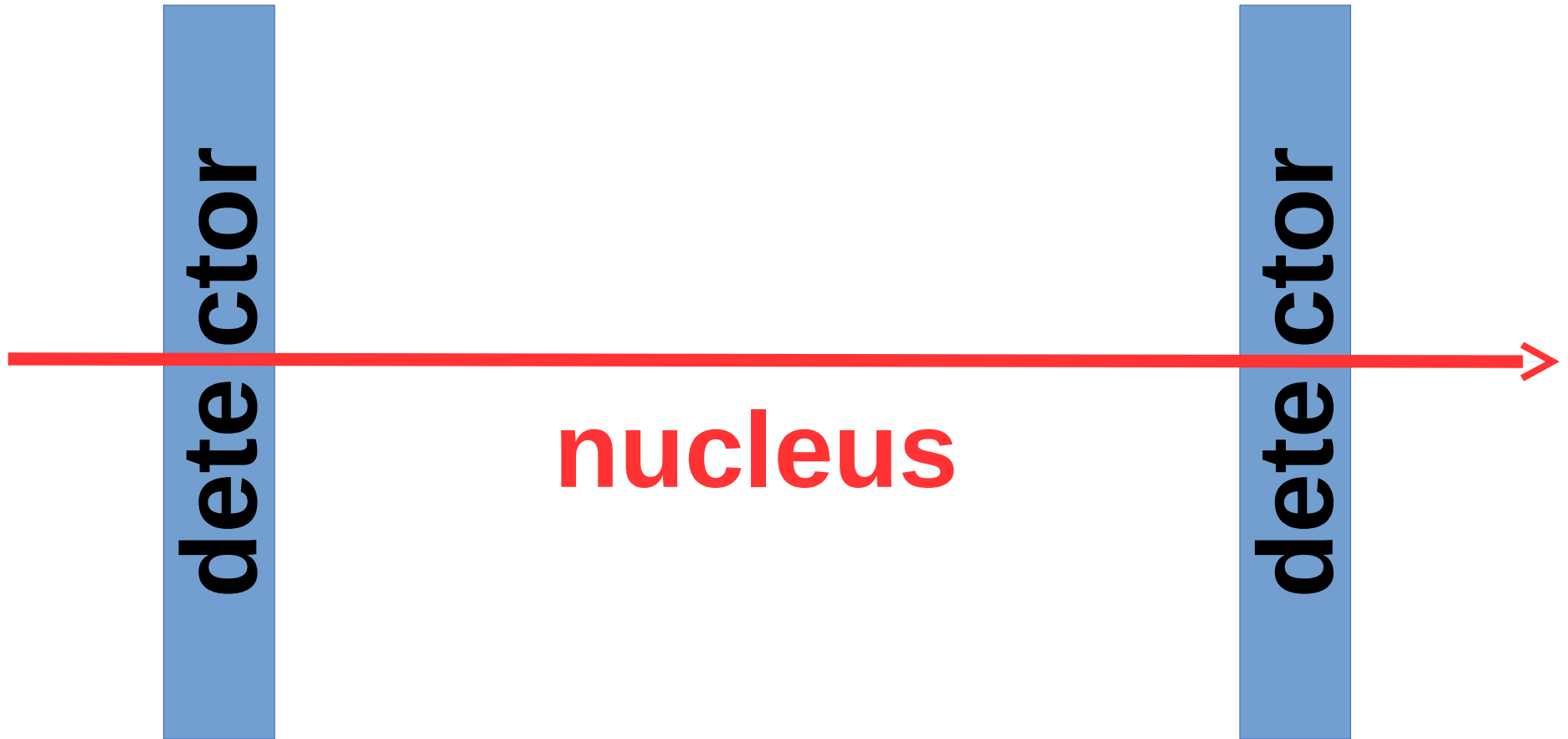




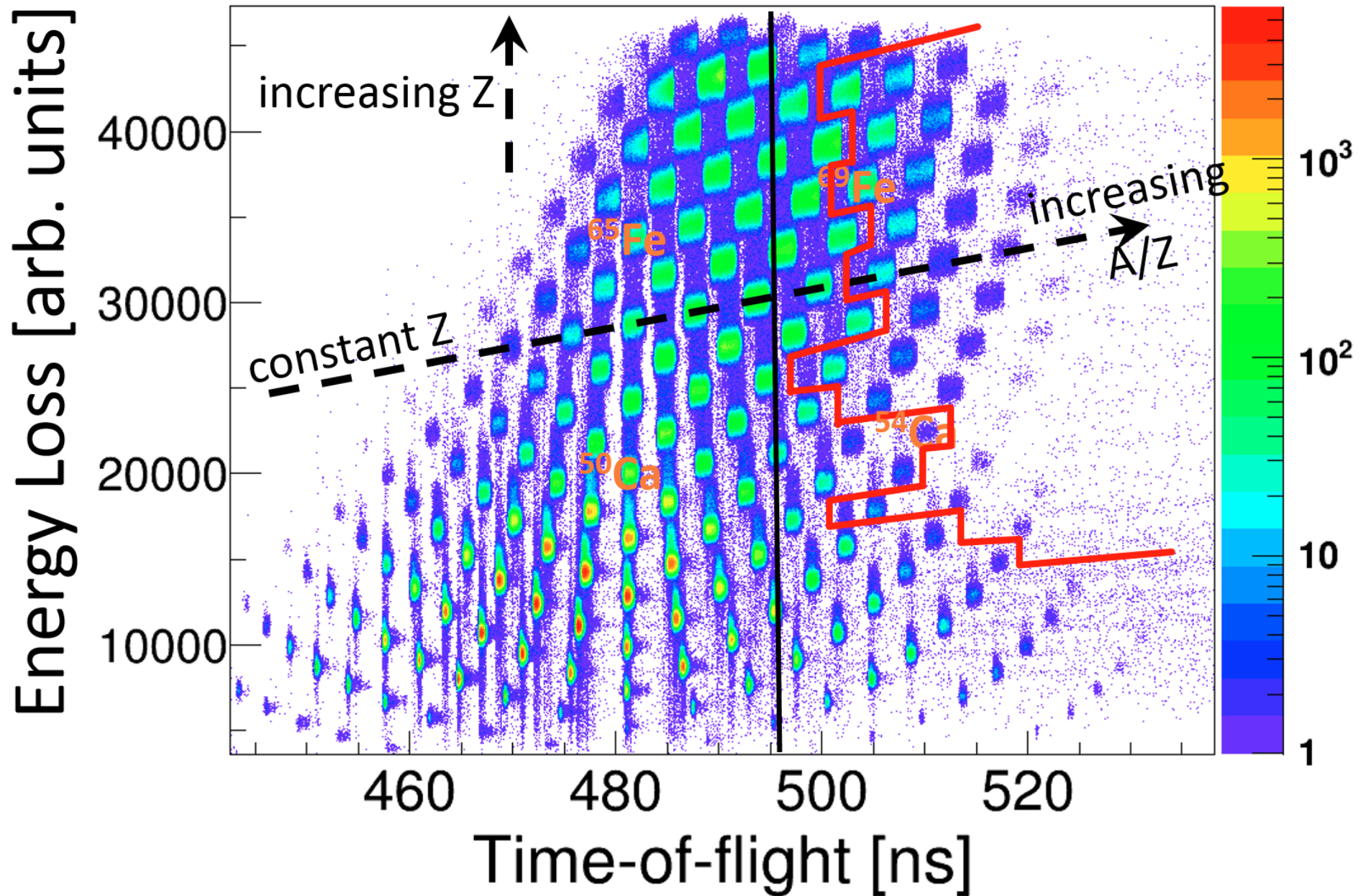
# General tasks

- 1) existence of the isotope
- 2) mass of the isotope
- 3) decays
- 4) eventually  $J^\pi$  identification

# Ion identification



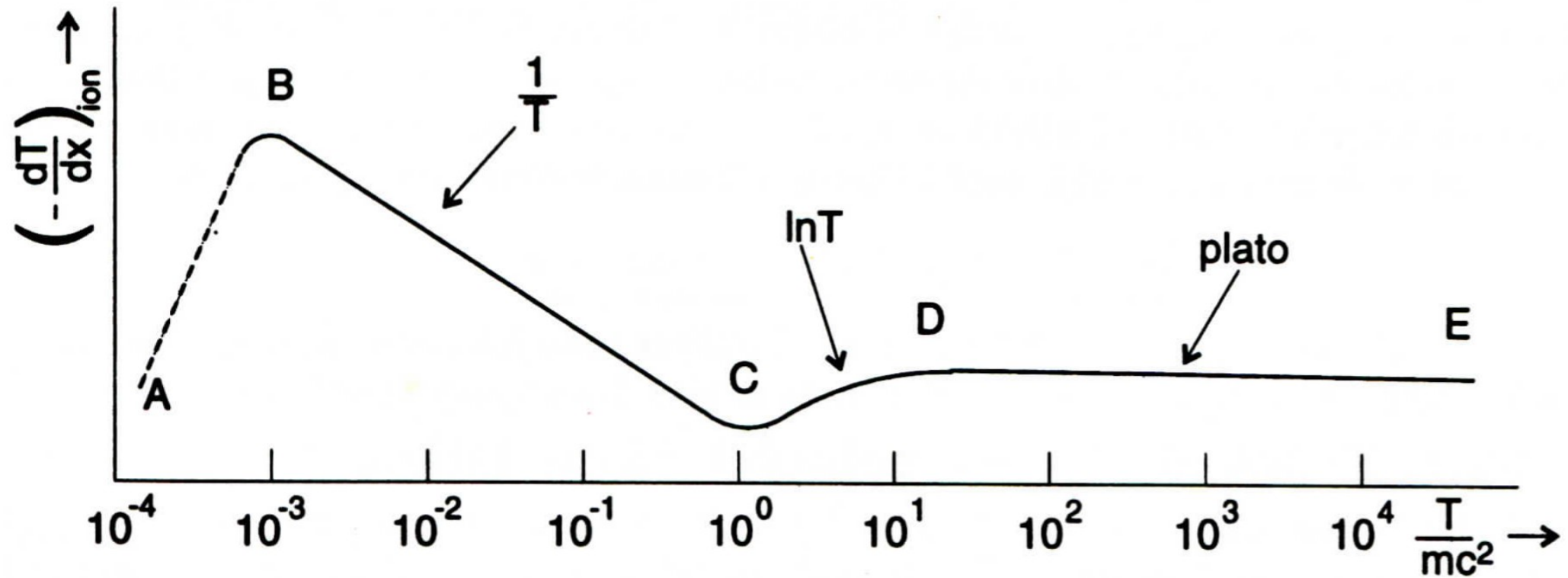
# Ion identification



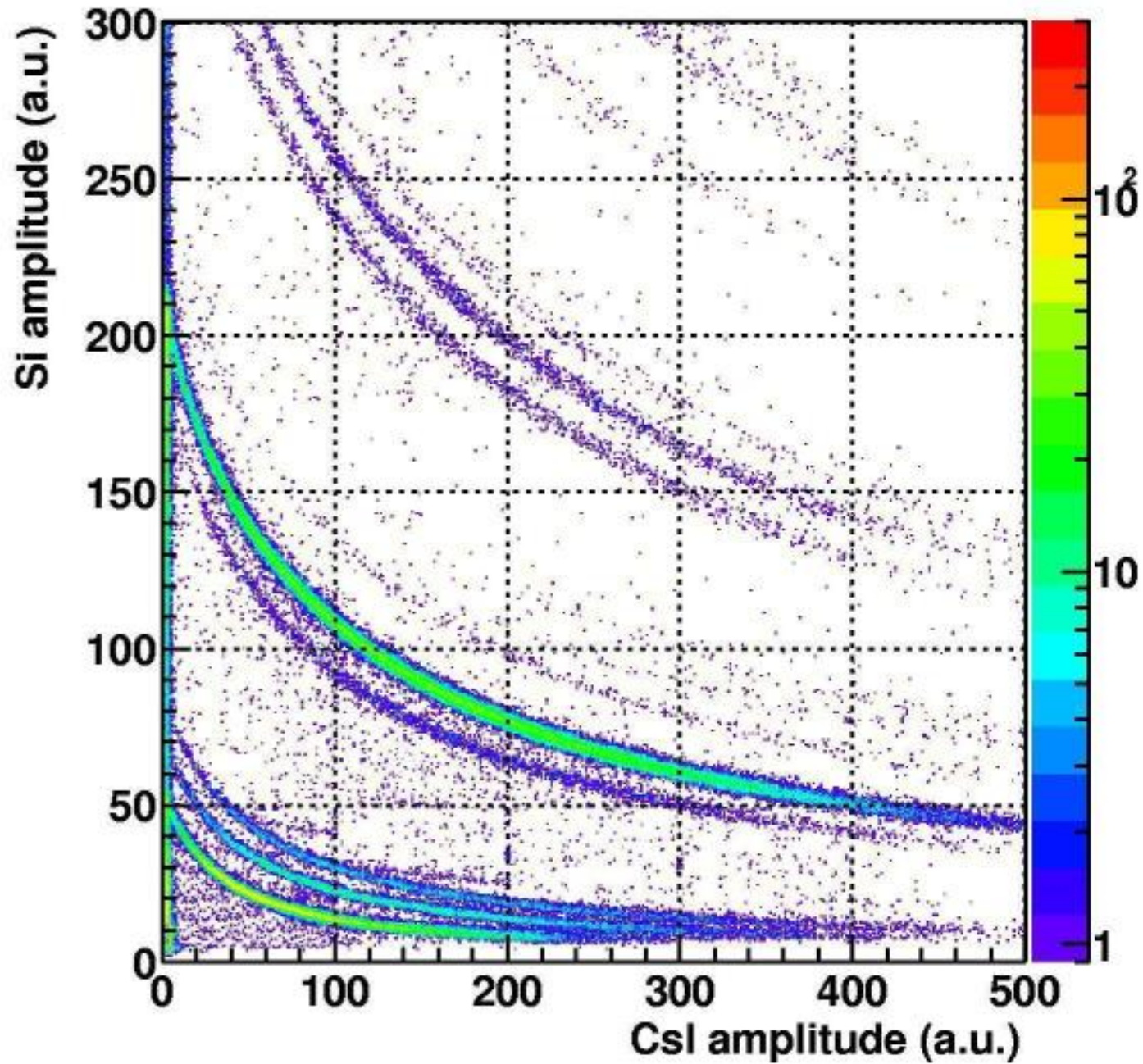


# Ion identification

## mean energy loss



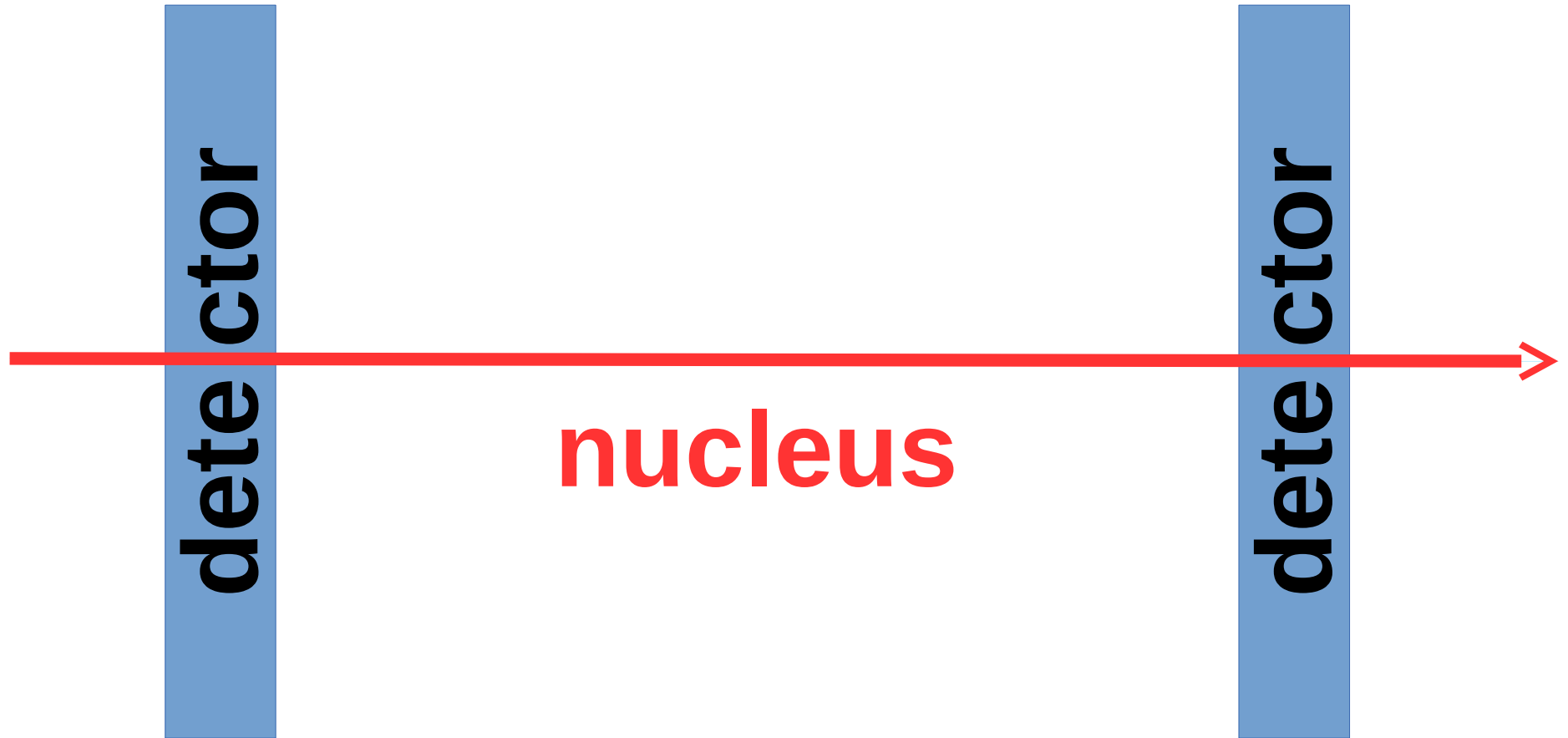
# Ion identification



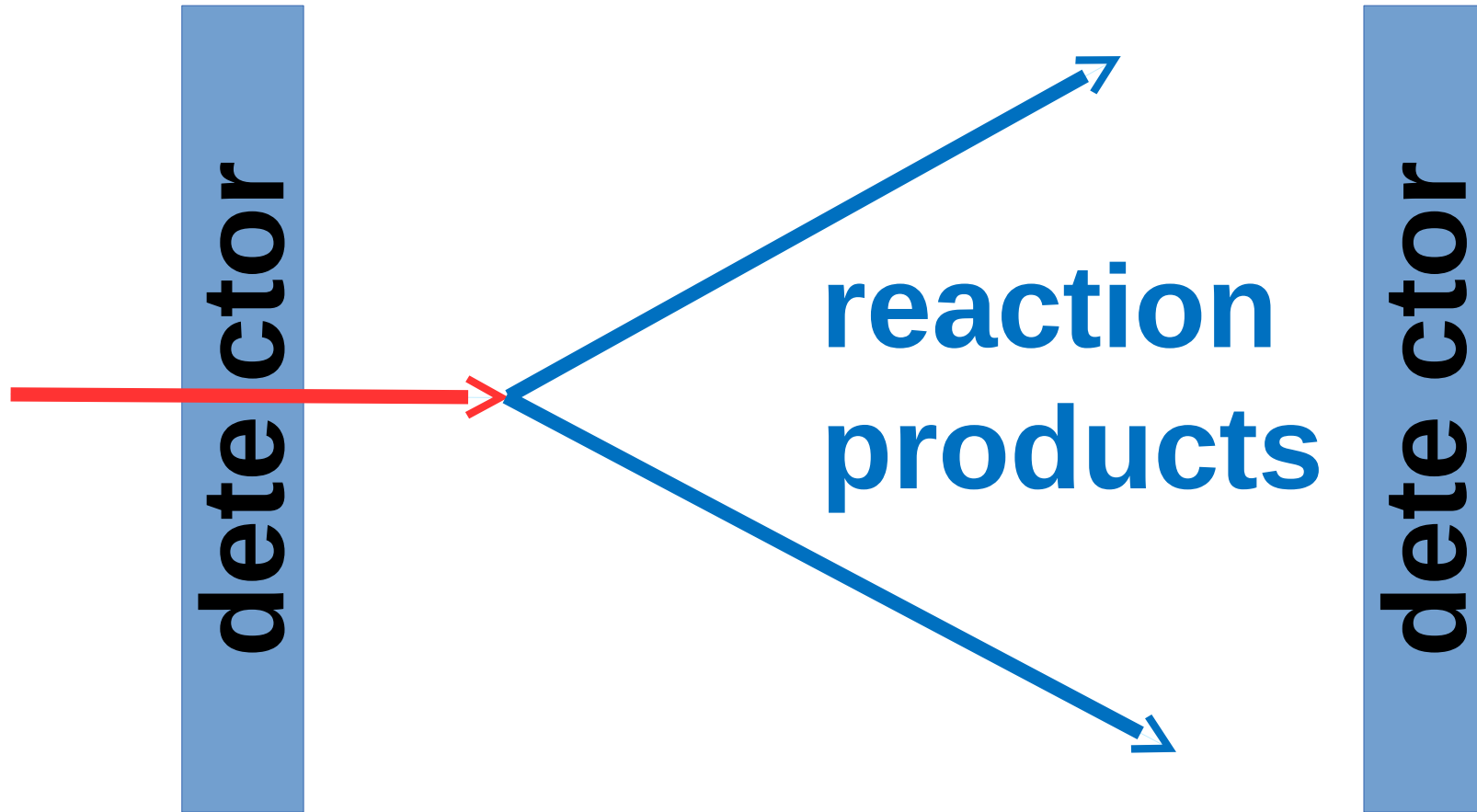
# Mass measurement

- **mass spectrometers**
- calculations from decay kinematics

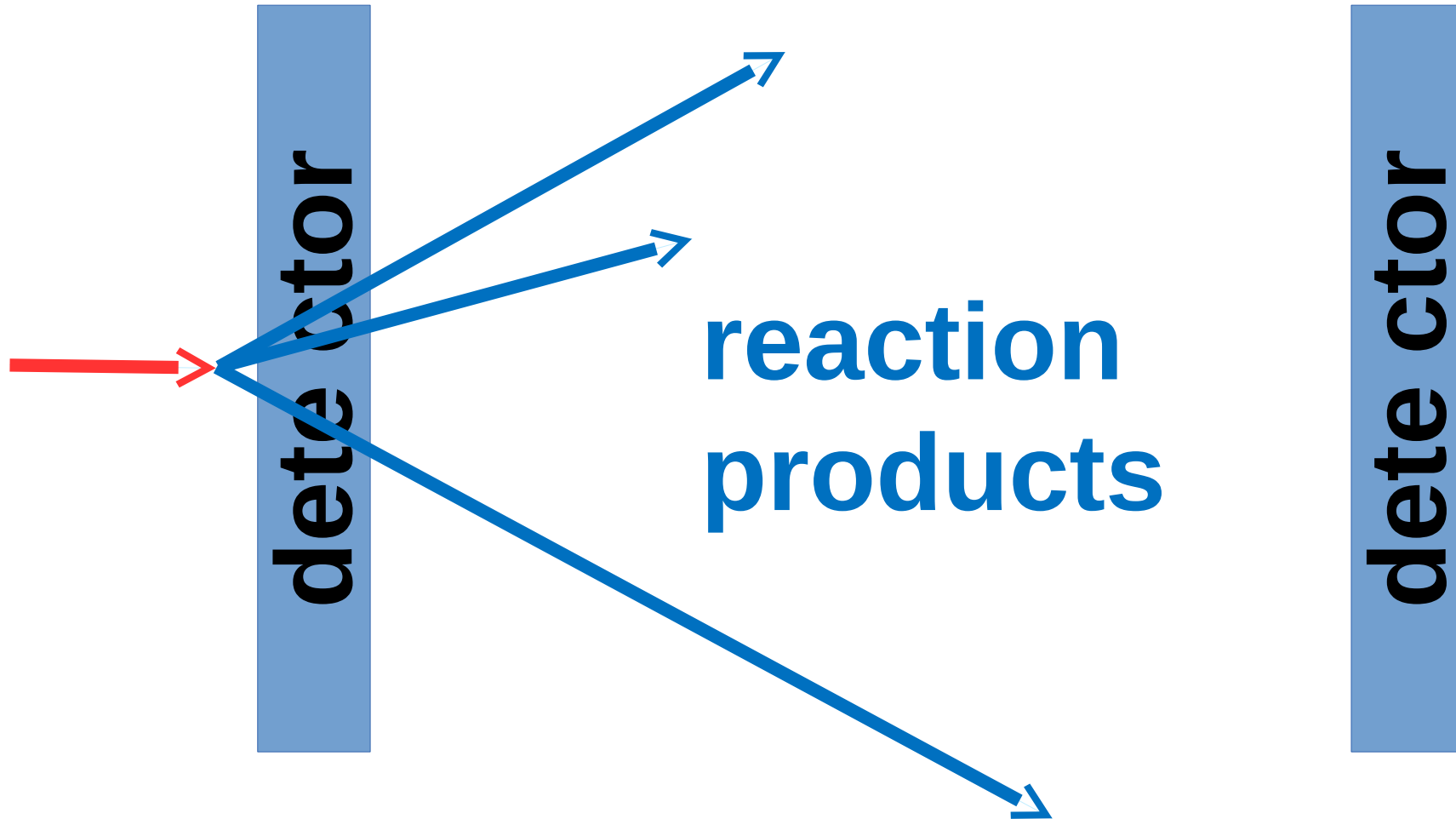
# Decays



# Decays



# Decays

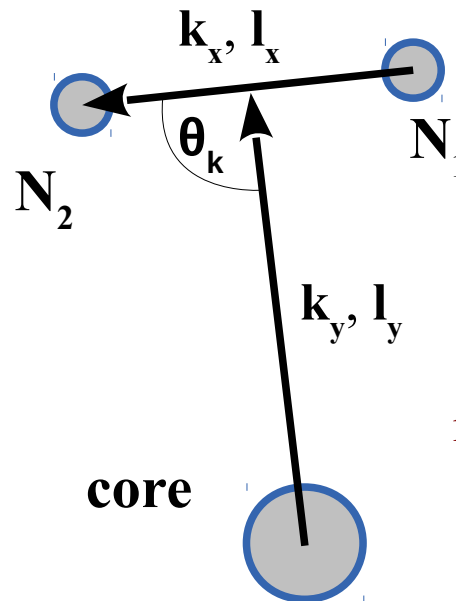


# 3-body decays

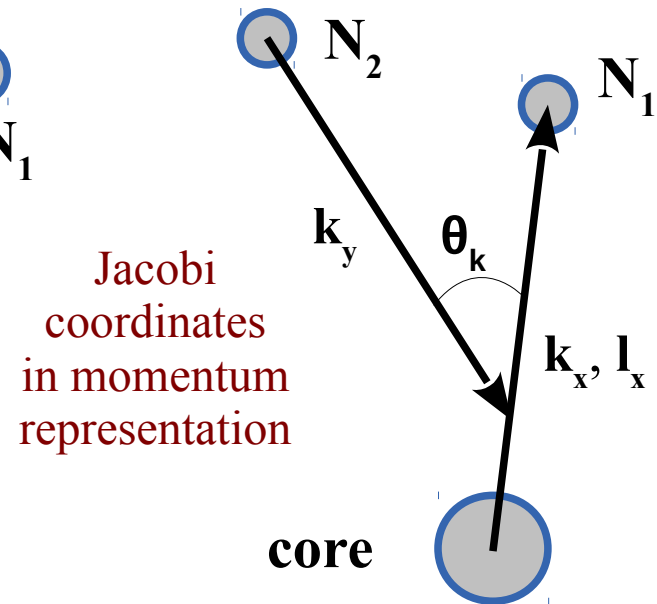
## 2-body vs. 3-body decay

- 2 parameters for 2-body decay ( $E, \Gamma$ )
- 5 additional parameters at given energy for 3-body decay

### T-system



### Y-system



Jacobi  
coordinates  
in momentum  
representation

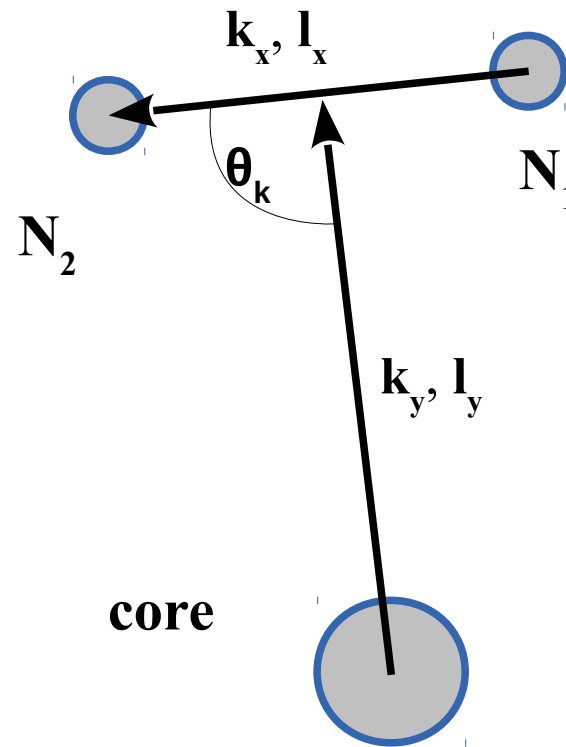
# Correlations

- full description of the internal correlations by parameters  $\varepsilon$  and  $\theta_k$

$$\varepsilon = \frac{E_x}{E_x + E_y}$$

$$\cos \theta_k = \frac{\mathbf{k}_x \cdot \mathbf{k}_y}{k_x k_y}$$

- external correlations:  
3-body system  
orientation



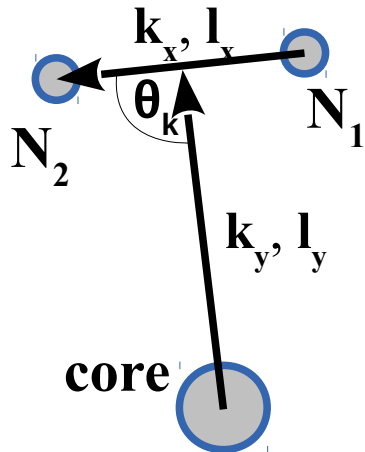


# Correlations

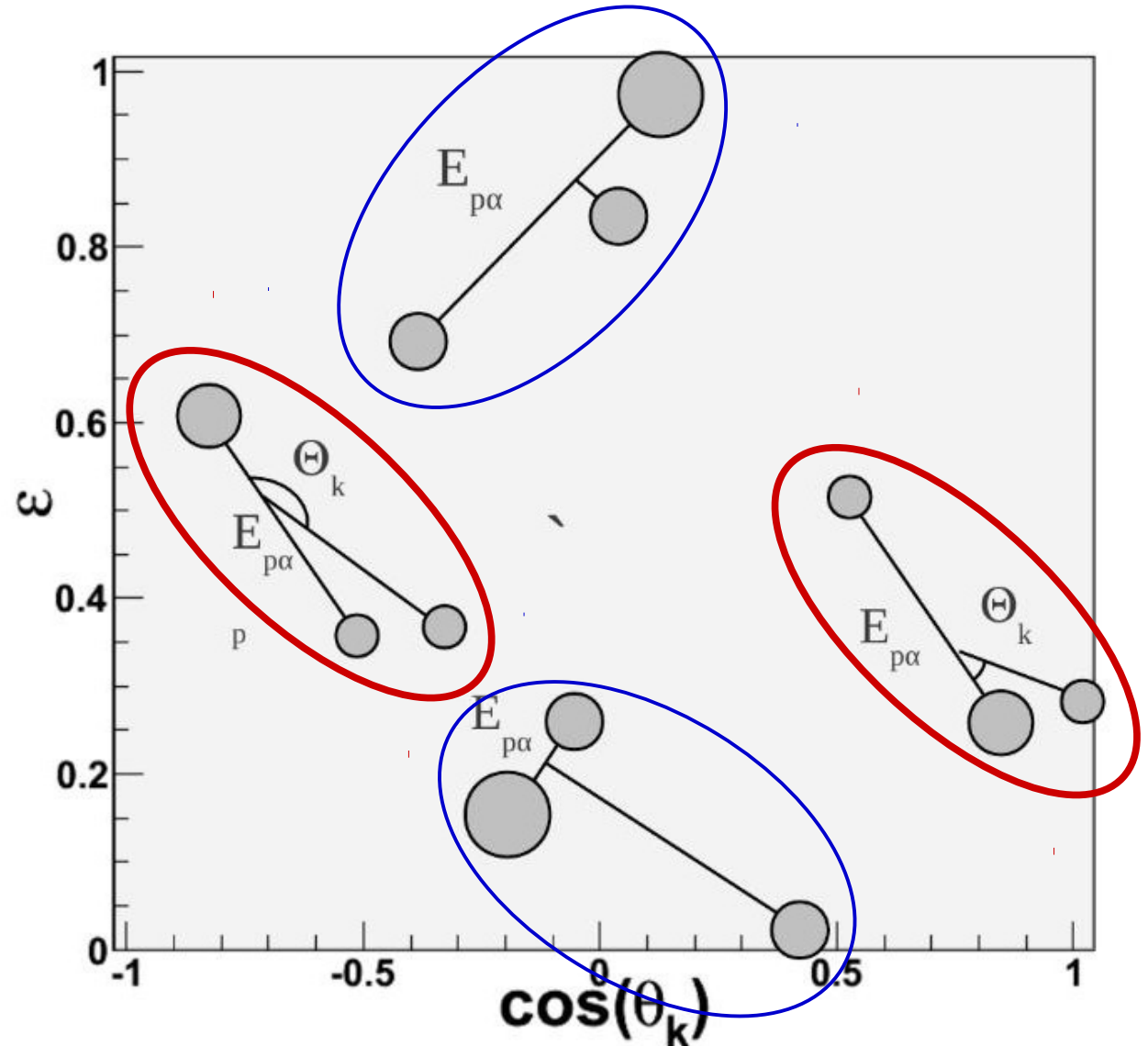
- full description of the internal correlations by parameters  $\varepsilon$  and  $\theta_k$

$$\varepsilon = \frac{E_x}{E_x + E_y}$$

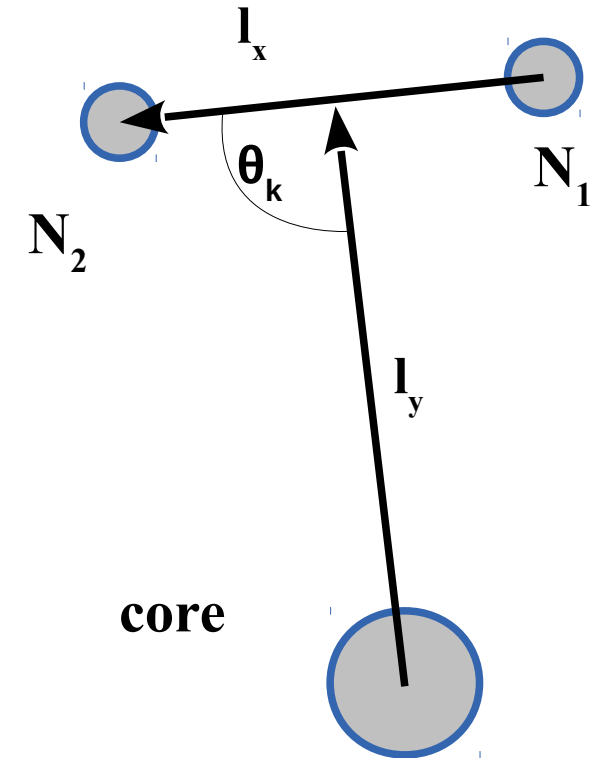
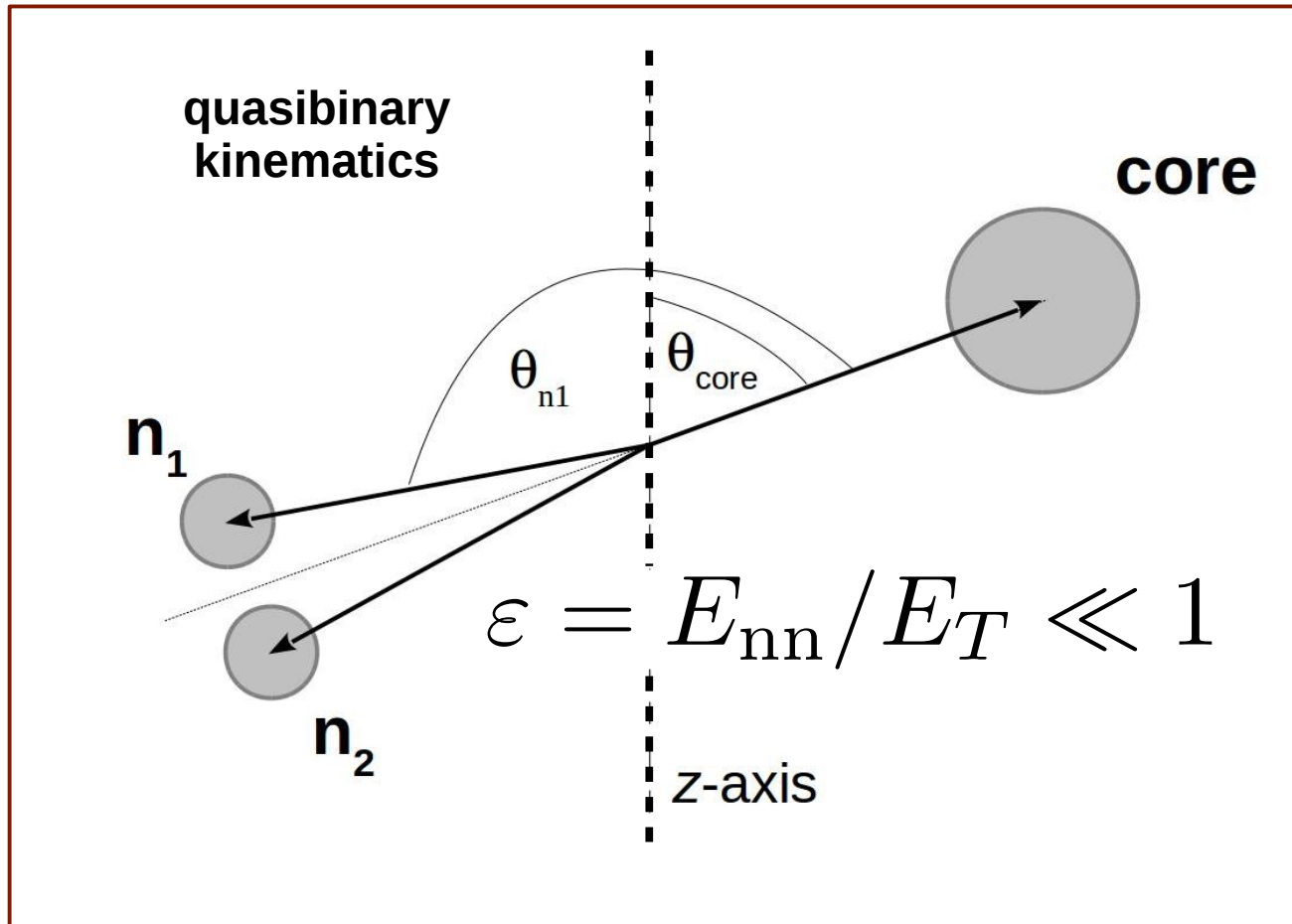
$$\cos \theta_k = \frac{\mathbf{k}_x \cdot \mathbf{k}_y}{k_x k_y}$$



- external correlations: 3-body system orientation



# External correlations



- useful when a few overlapping states present
- total angular momentum is determined by emission angle of the core

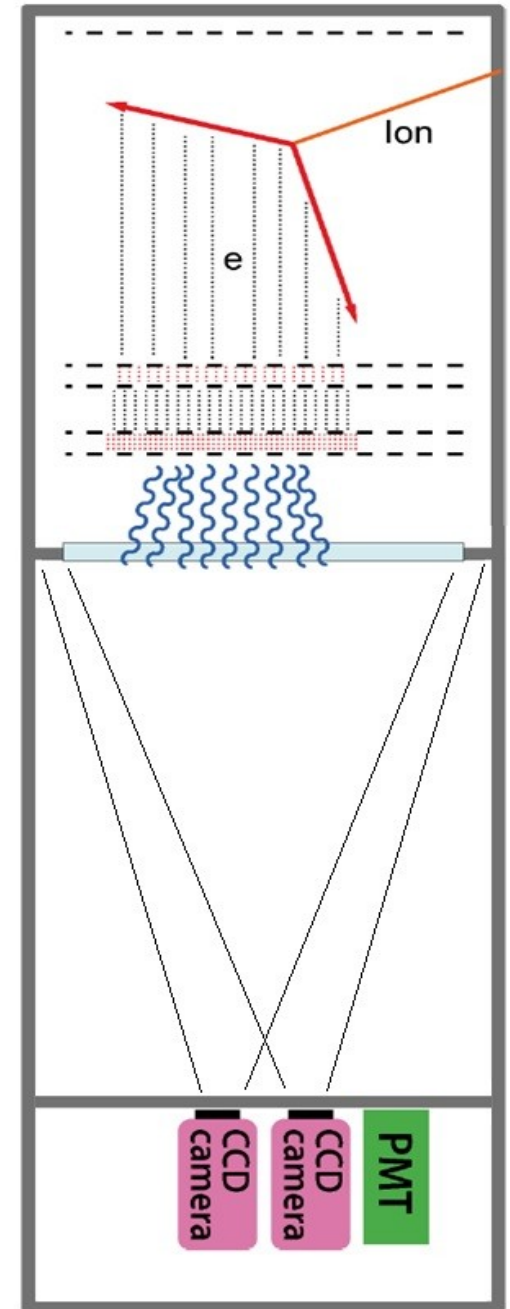
**Legendre  
polynomials  
can be visible**

# Available experimental methods

- ion-implantation method
- decay-in-flight by tracking technique
  - information on life-time accessible
  - identification of 2p-decay channels by correlations

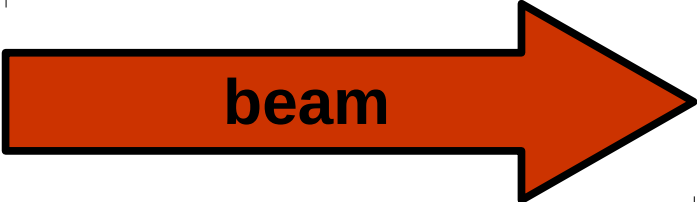
# Optical Time Projection Chamber

lifetime range:  
100 ns – 1 s

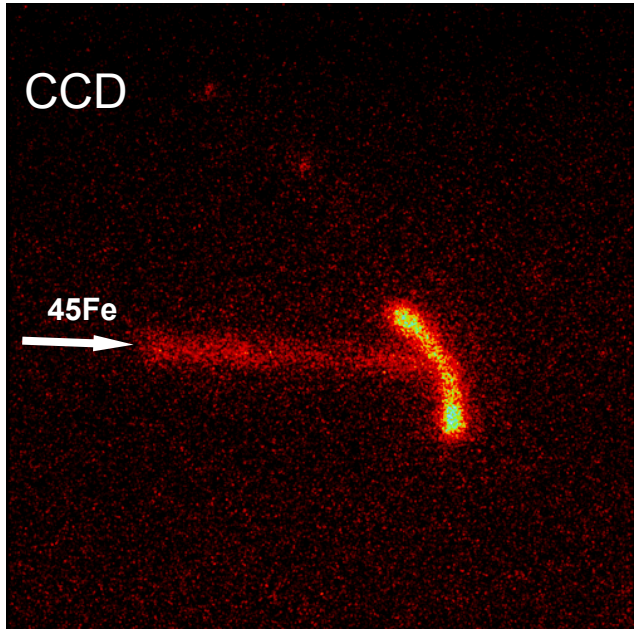


# Optical Time Projection Chamber

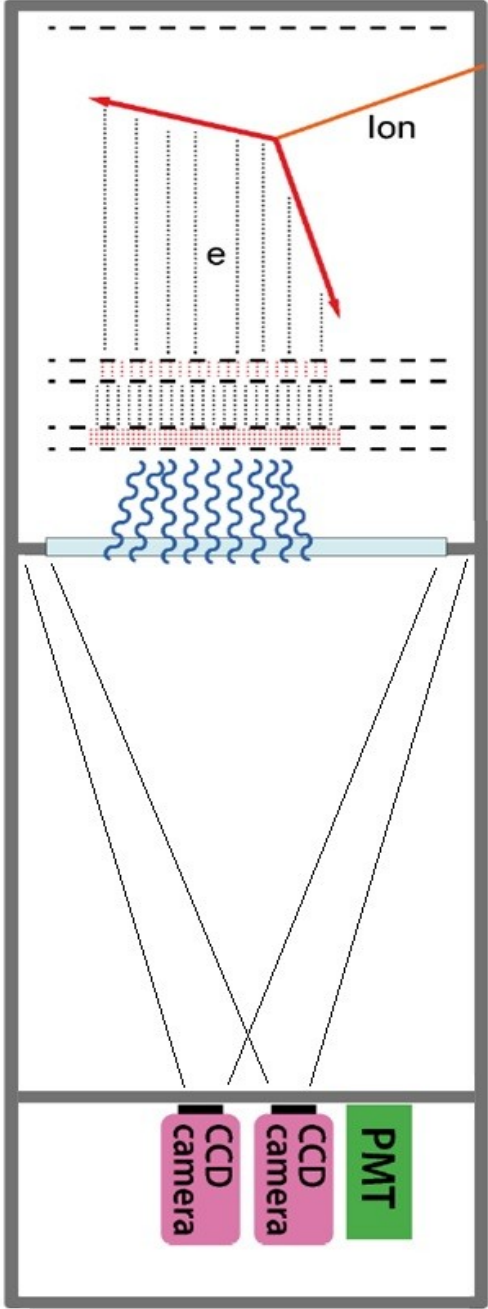
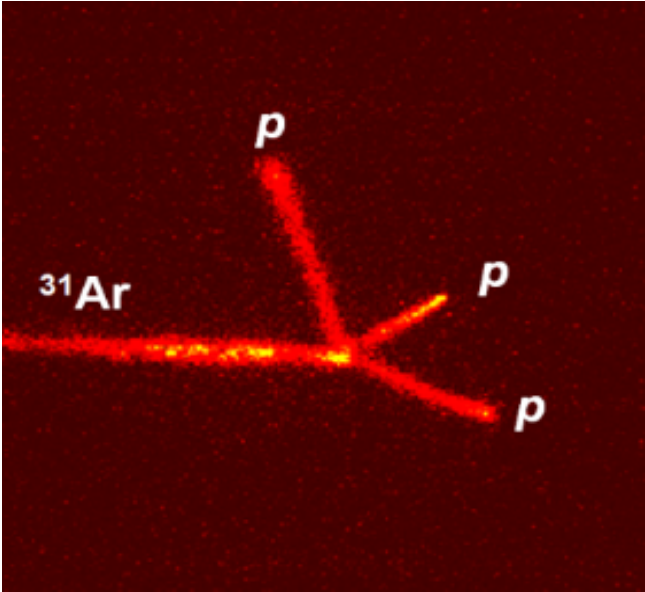
lifetime range:  
100 ns – 1 s



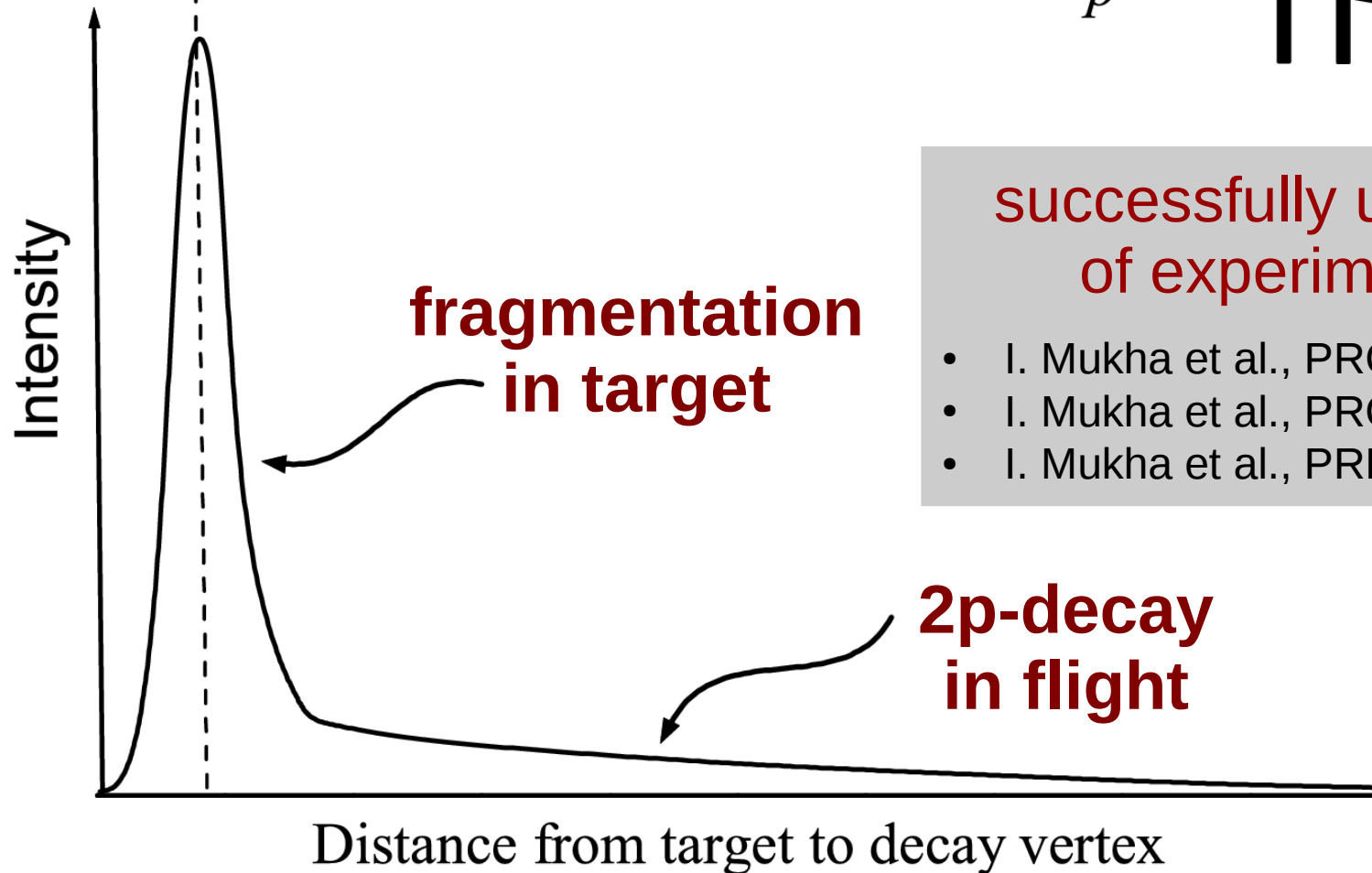
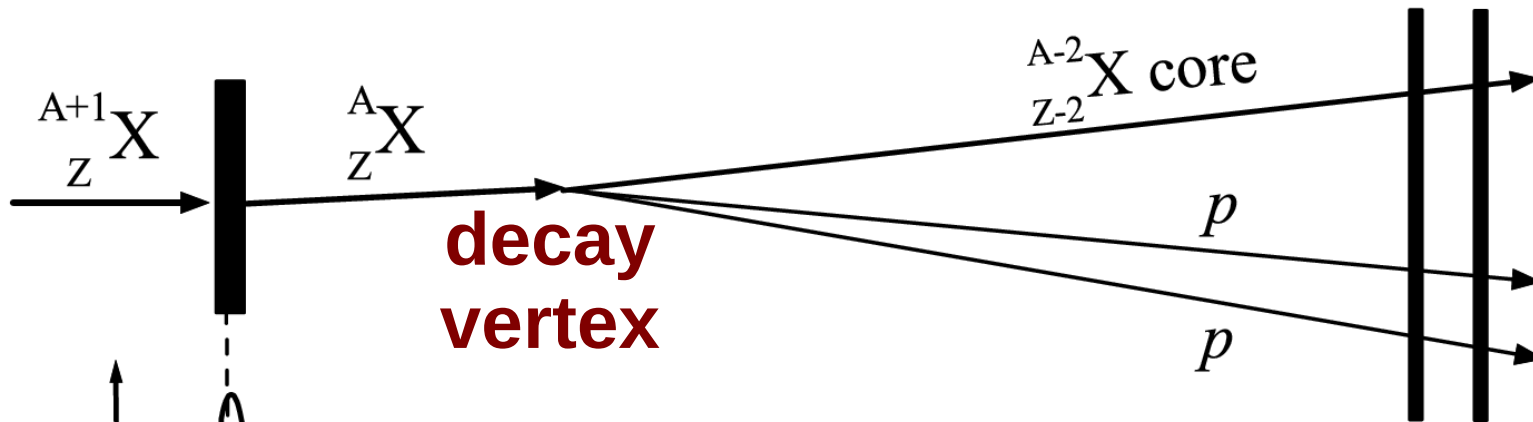
A.A. Lis et al., Phys. Rev. C91 (2015) 064309



M. Pfützner et al.,  
Eur.Phys.J. A, 14(3),  
2002



# Decay-in-flight by tracking

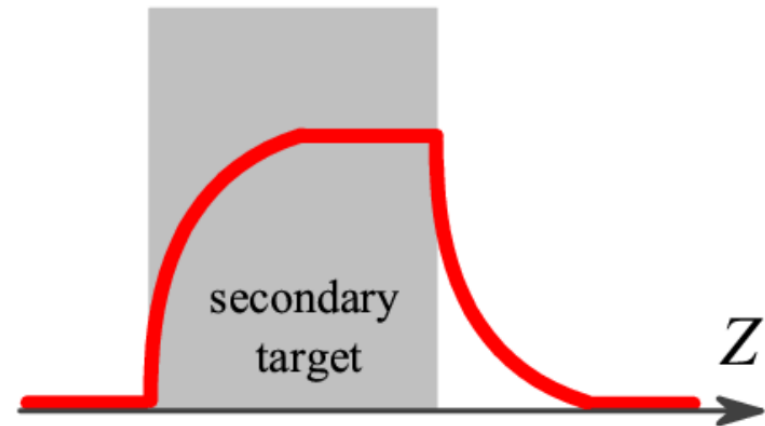
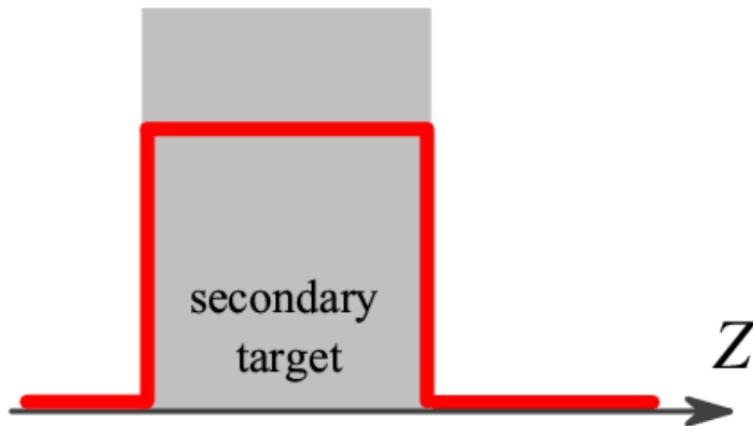
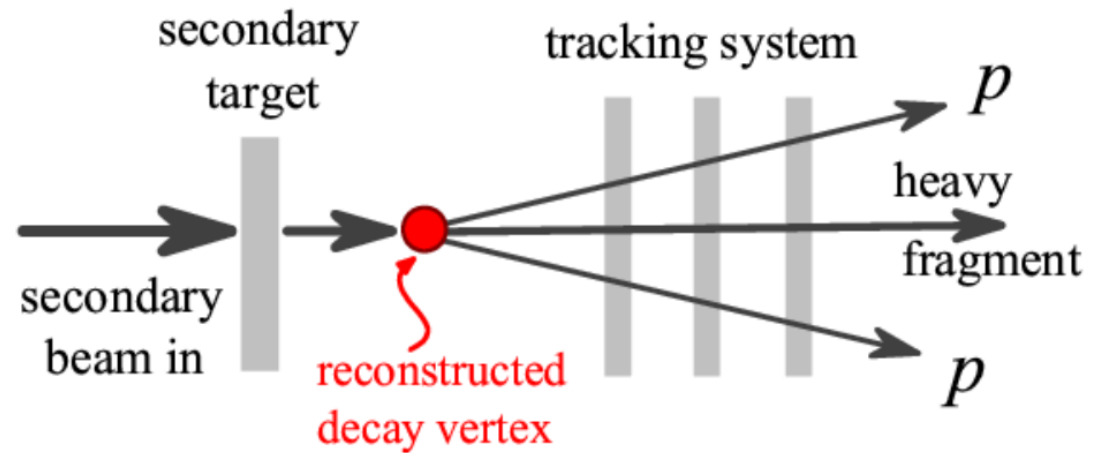


successfully used in series of experiments (e.g.)

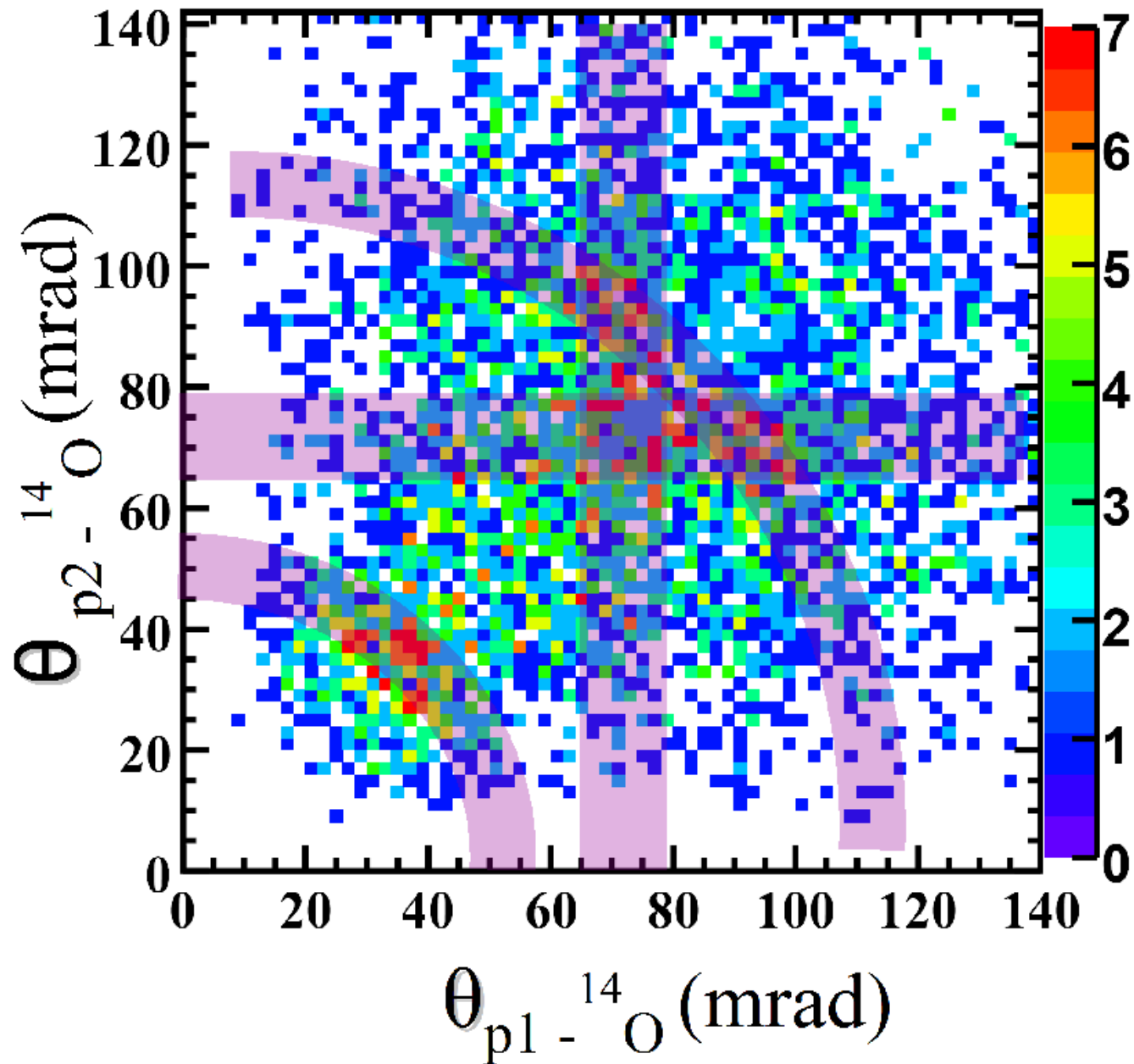
- I. Mukha et al., PRC 77 (2008) 061303
- I. Mukha et al., PRC 82 (2010) 054315
- I. Mukha et al., PRL 115 (2015) 202501

# Life-time measurement by tracking

- characteristic shape of vertices distribution
- suitable for lifetimes  $10^{-7} - 10^{-12}$  s

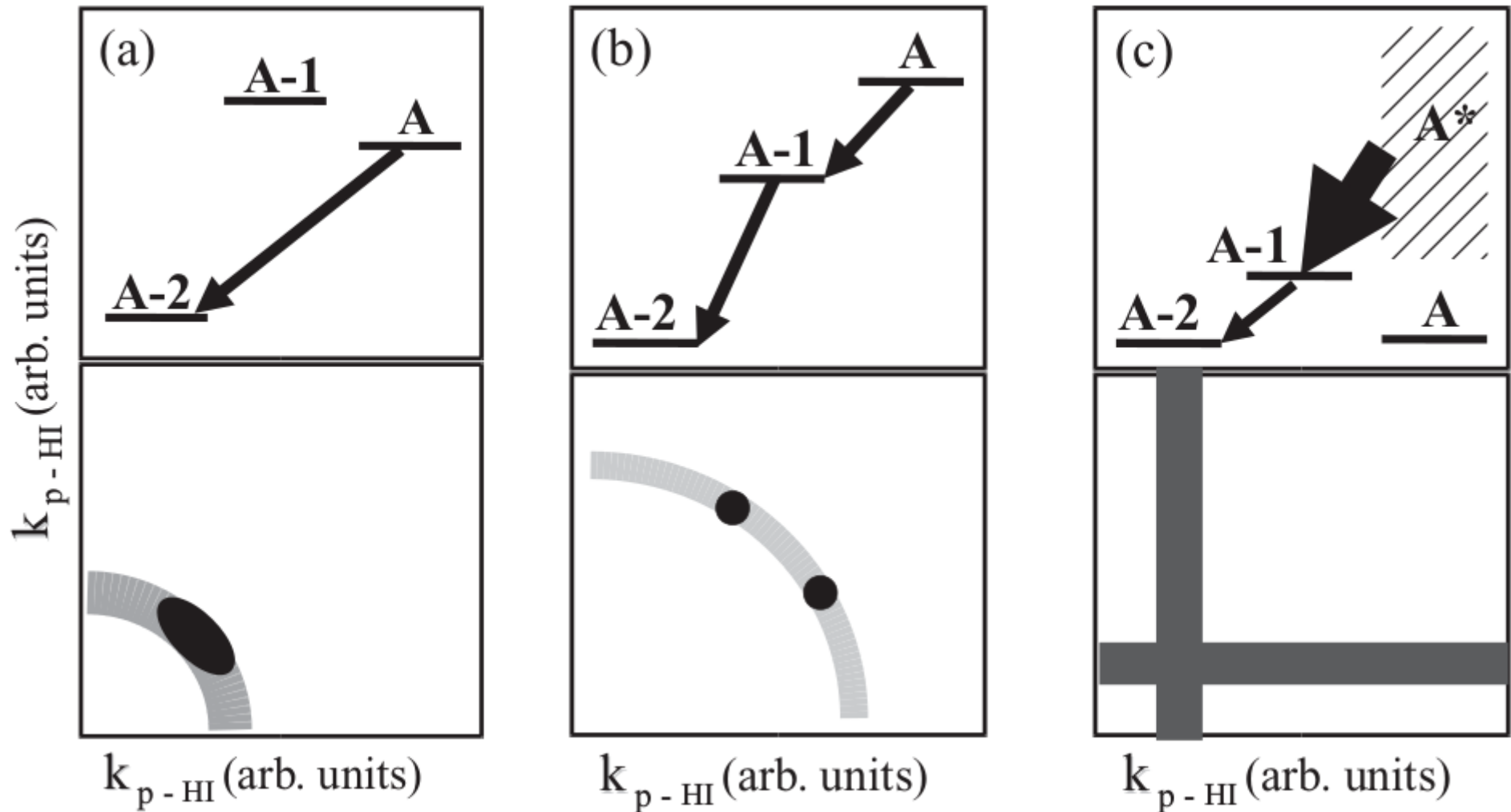


# Identification of 2p-decay channels





# Identification of 2p-decay channels

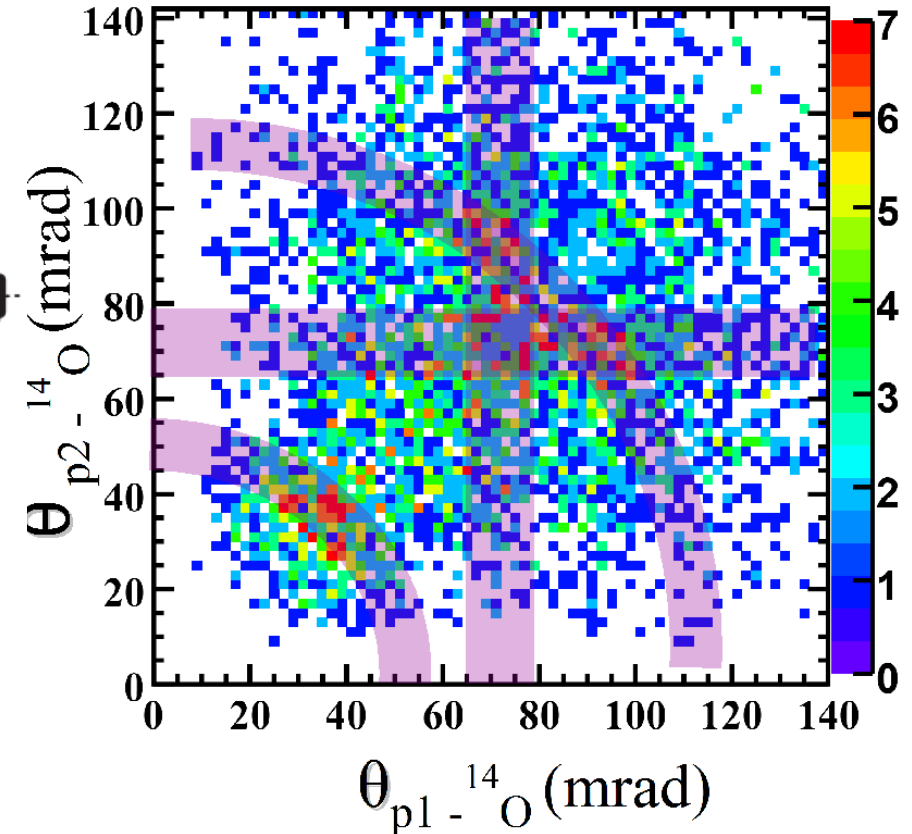
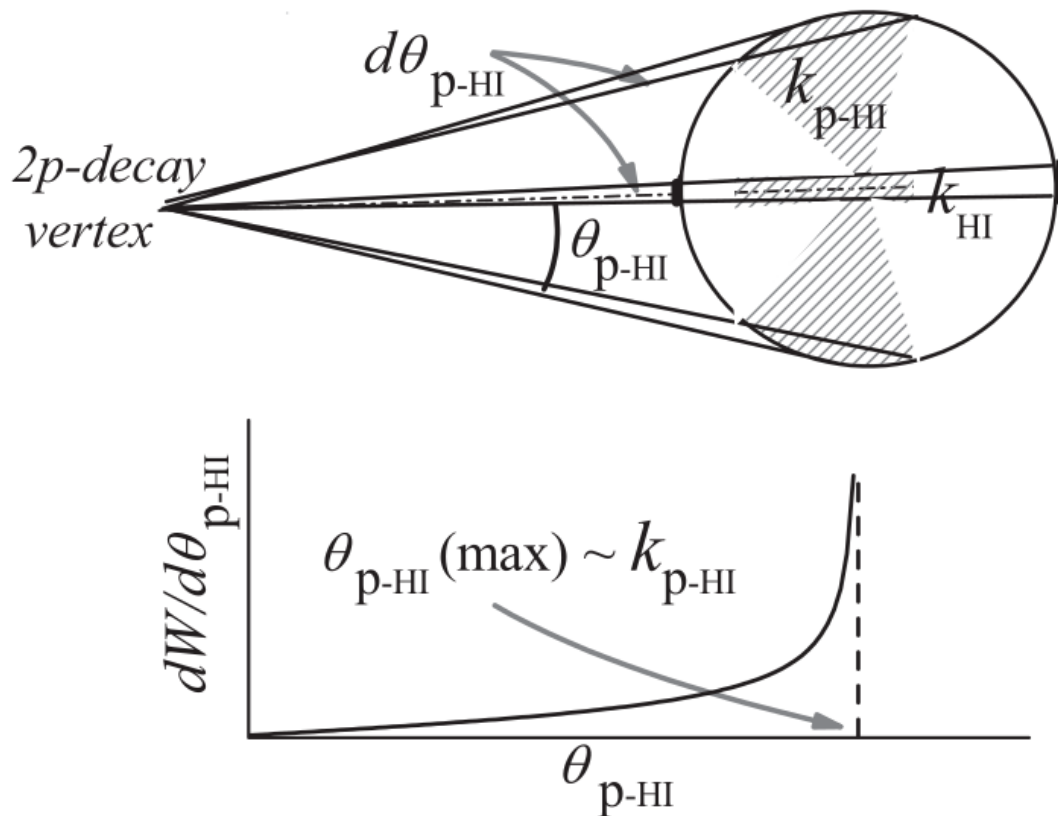


# Identification of 2p-decay channels

- transition  $k_{p\text{-HI}} \rightarrow \theta_{p\text{-HI}}$
- **without measurement of proton energies**

I. Mukha et al. Phys. Rev. C  
82 (2010) 054315

$^{16}\text{Ne}$

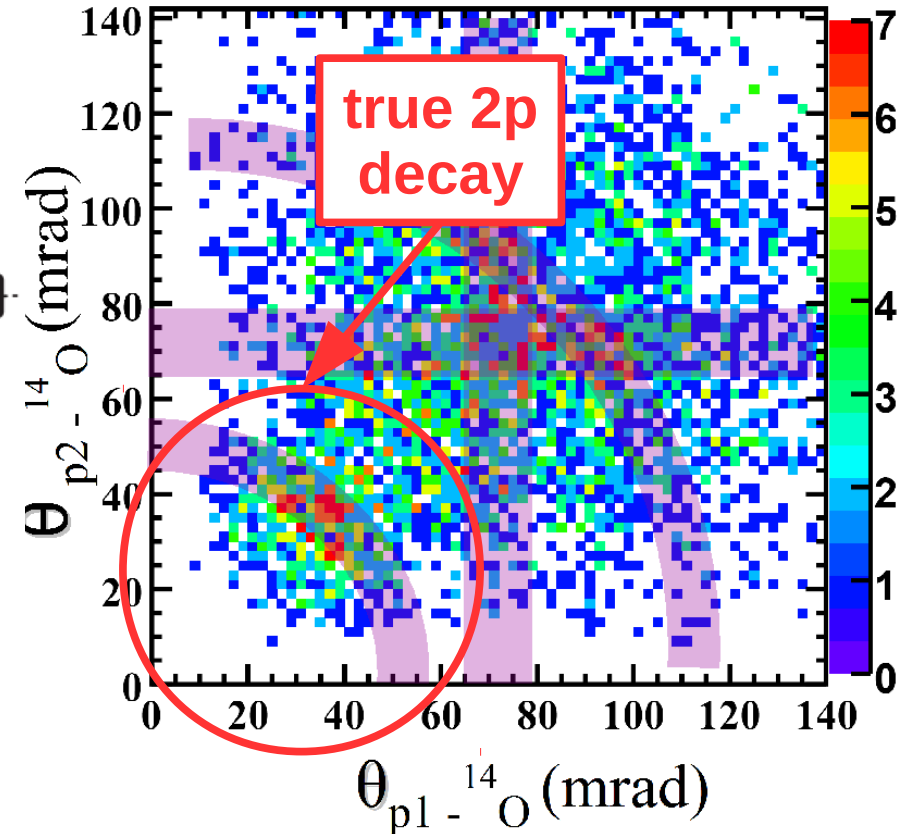
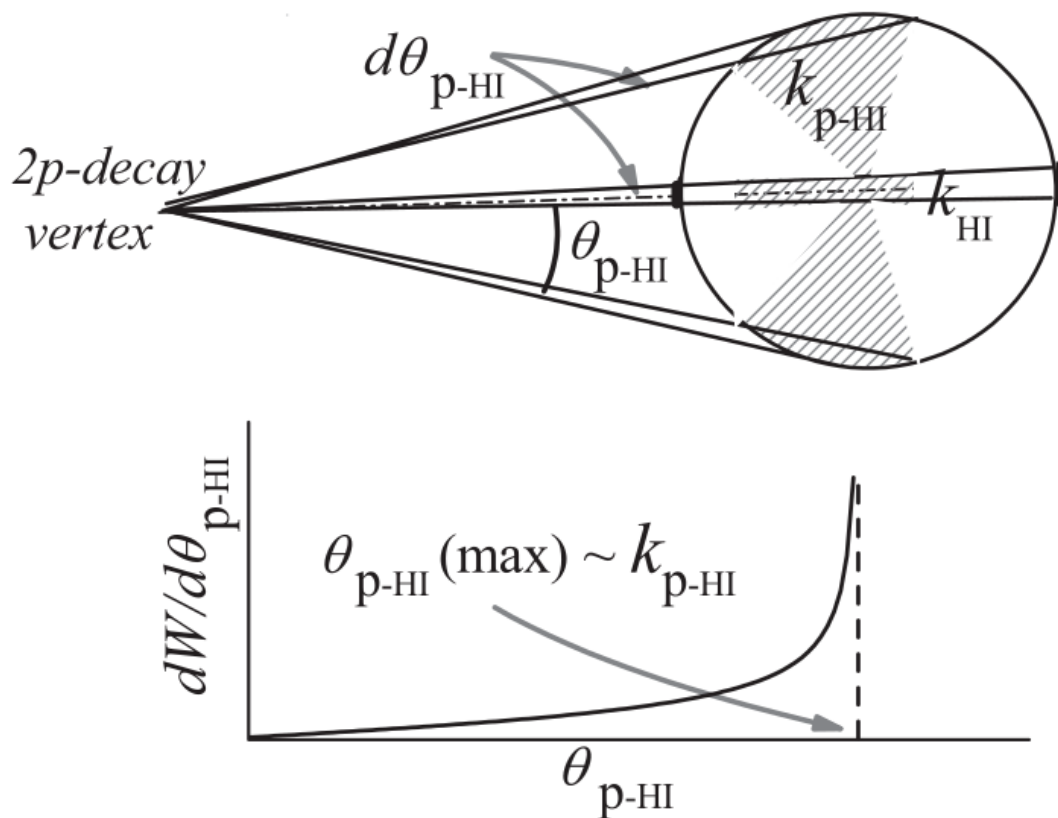


# Identification of 2p-decay channels

- transition  $k_{p\text{-HI}} \rightarrow \theta_{p\text{-HI}}$
- **without measurement of proton energies**

I. Mukha et al. Phys. Rev. C  
82 (2010) 054315

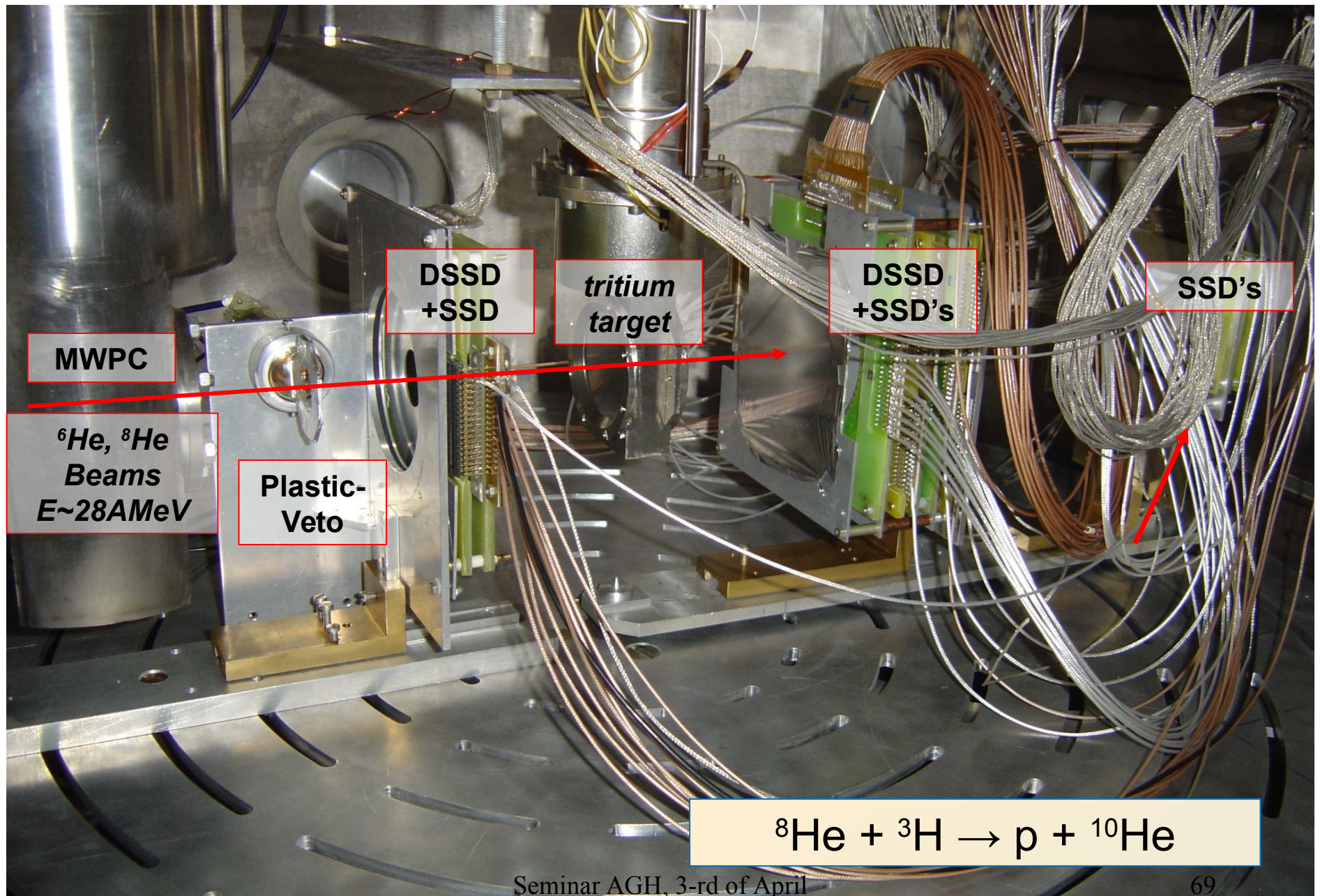
$^{16}\text{Ne}$



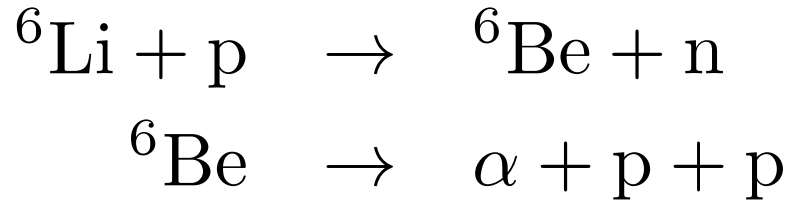
# ACCULINNA experiment



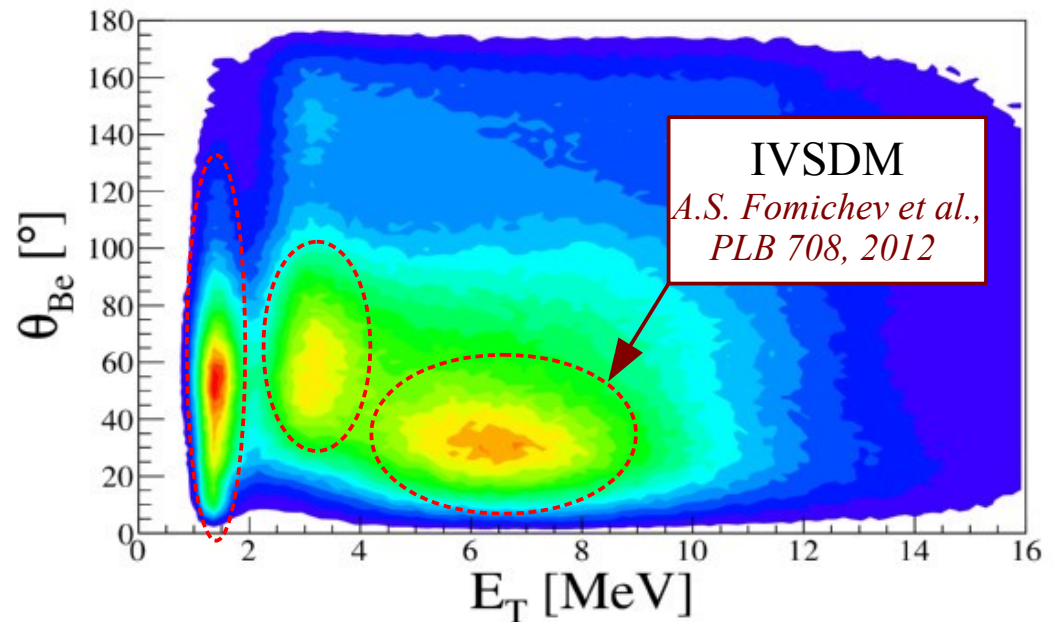
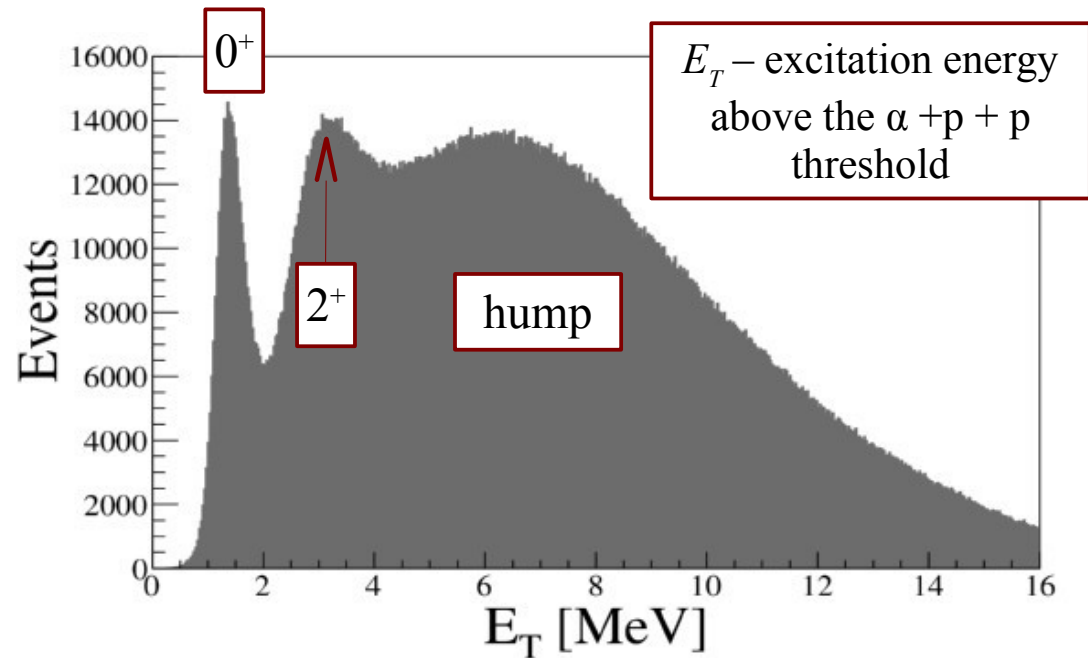
# ACCULINNA experiment



# ${}^6\text{Be}$ : Invariant mass spectrum

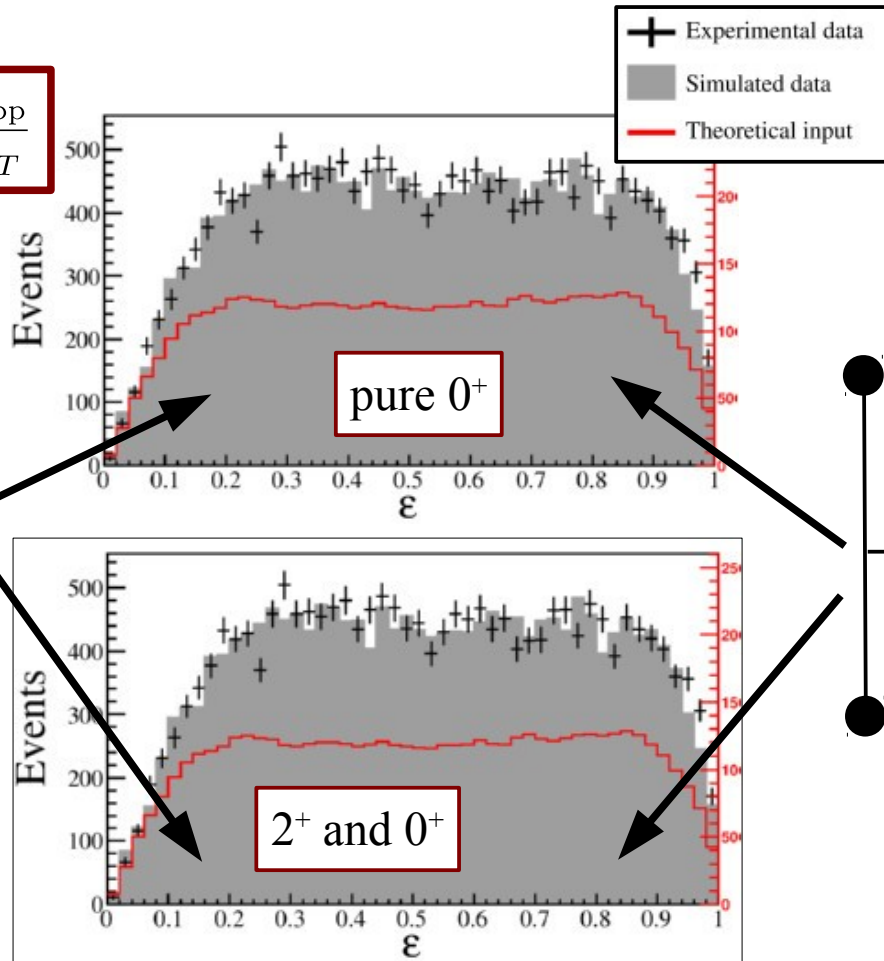


- $0^+$ ,  $2^+$  states
- broad hump at  $E_T > E_T(2^+)$



# ${}^6\text{Be}$ : Internal correlations

$$\varepsilon = \frac{E_{\text{pp}}}{E_T}$$



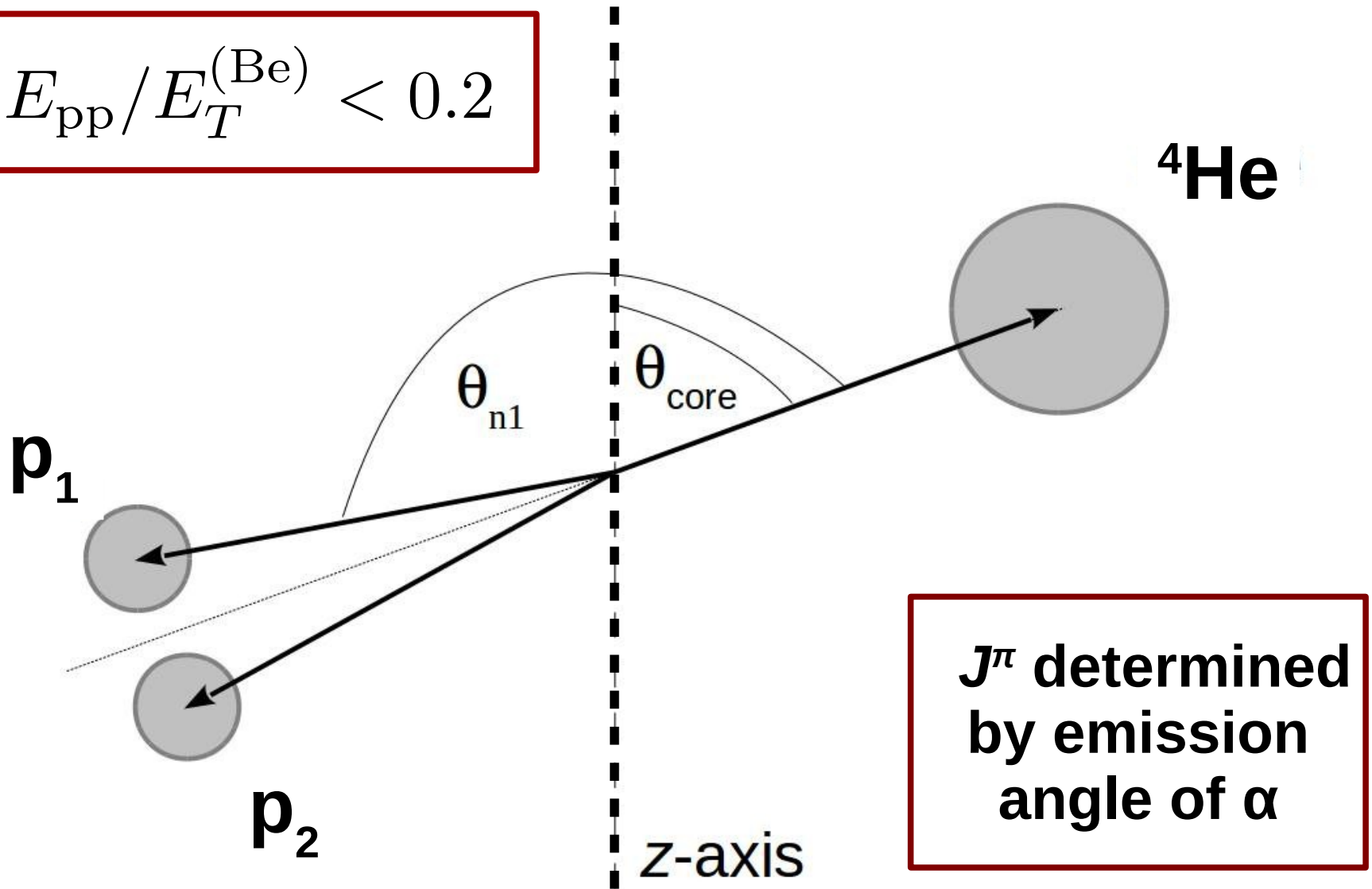
**Theoretical model**  
PWIA in combination with  
3-body model

- test on  $0^+$  ground state (no free parameters)
- overlapping states  $0^+$  and  $2^+$ 
  - $2^+$  alignment
  - Interference of  $0^+$  and  $2^+$

**low sensitivity of internal correlations to model parameters**

# ${}^6\text{Be}$ : Quasibinary kinematics

$$\varepsilon = E_{pp} / E_T^{(\text{Be})} < 0.2$$





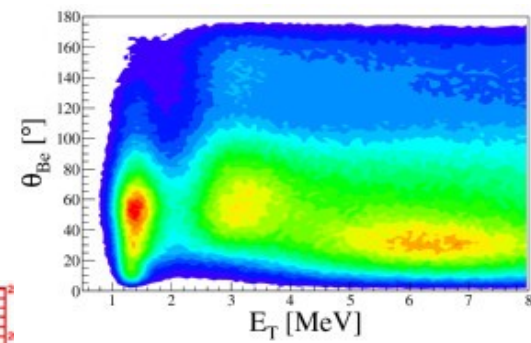
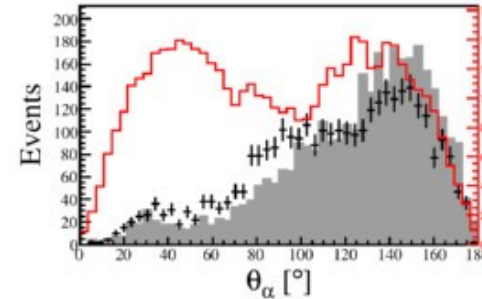
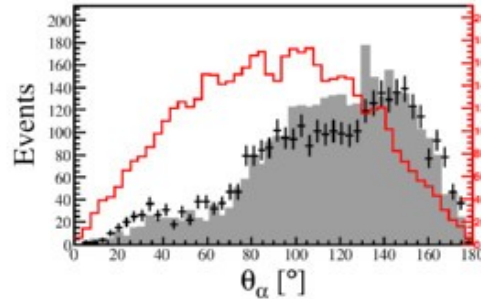
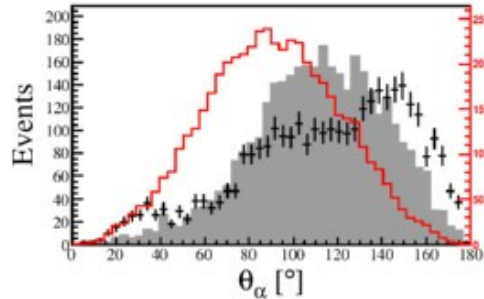
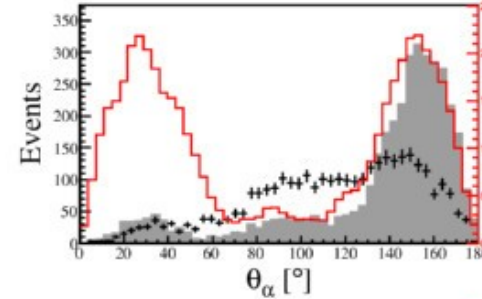
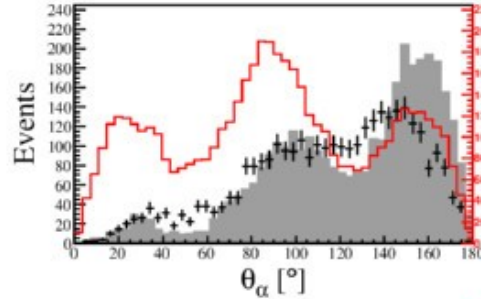
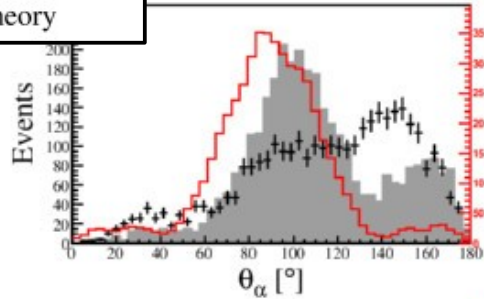
# ${}^6\text{Be}$ : External correlations

+ Experiment  
 ■ Simulation  
 — Theory

constructive

incoherent

destructive



← aligned

$E_T \in (1.9, 2.5)$  MeV

$\theta_{\text{Be}} \in (60, 75)^\circ$

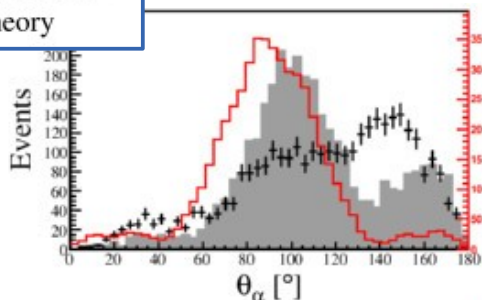
← nonaligned

- dramatic changes of the  $\theta_\alpha$  distributions depending on the model parameters
- level of alignment and interference angle is changing with  $E_T$  and  $\theta_{\text{Be}}$

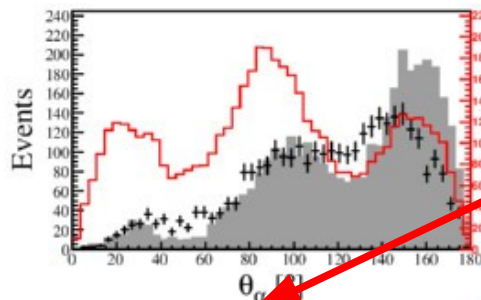
# ${}^6\text{Be}$ : External correlations

+ Experiment  
 ■ Simulation  
 — Theory

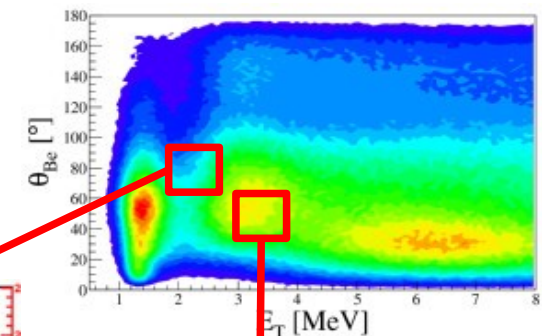
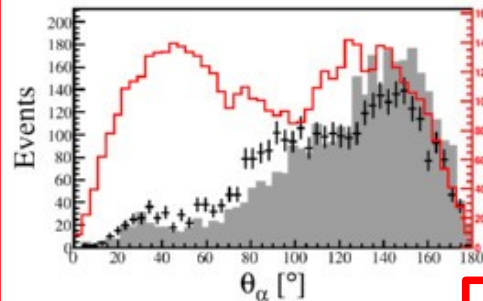
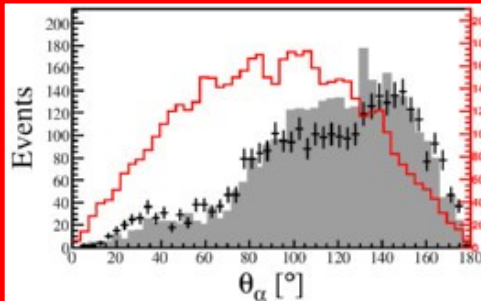
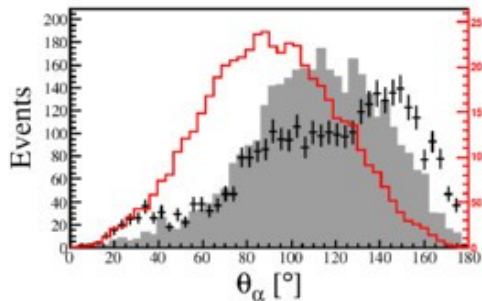
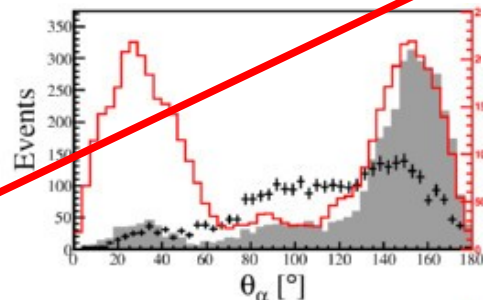
constructive interference



incoherent interference



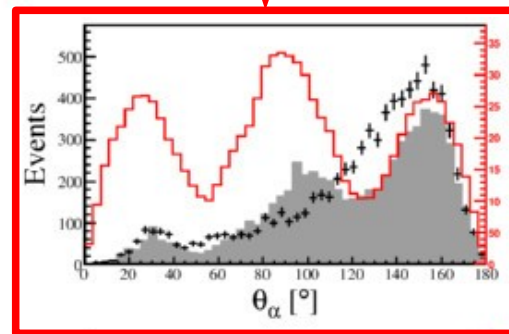
destructive interference



← aligned

$E_T \in (1.9, 2.5) \text{ MeV}$   
 $\theta_{\text{Be}} \in (60, 75)^\circ$

← nonaligned

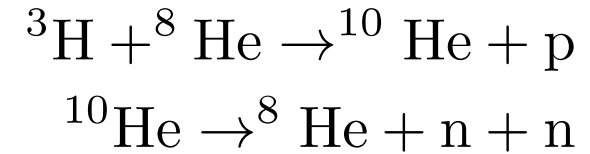
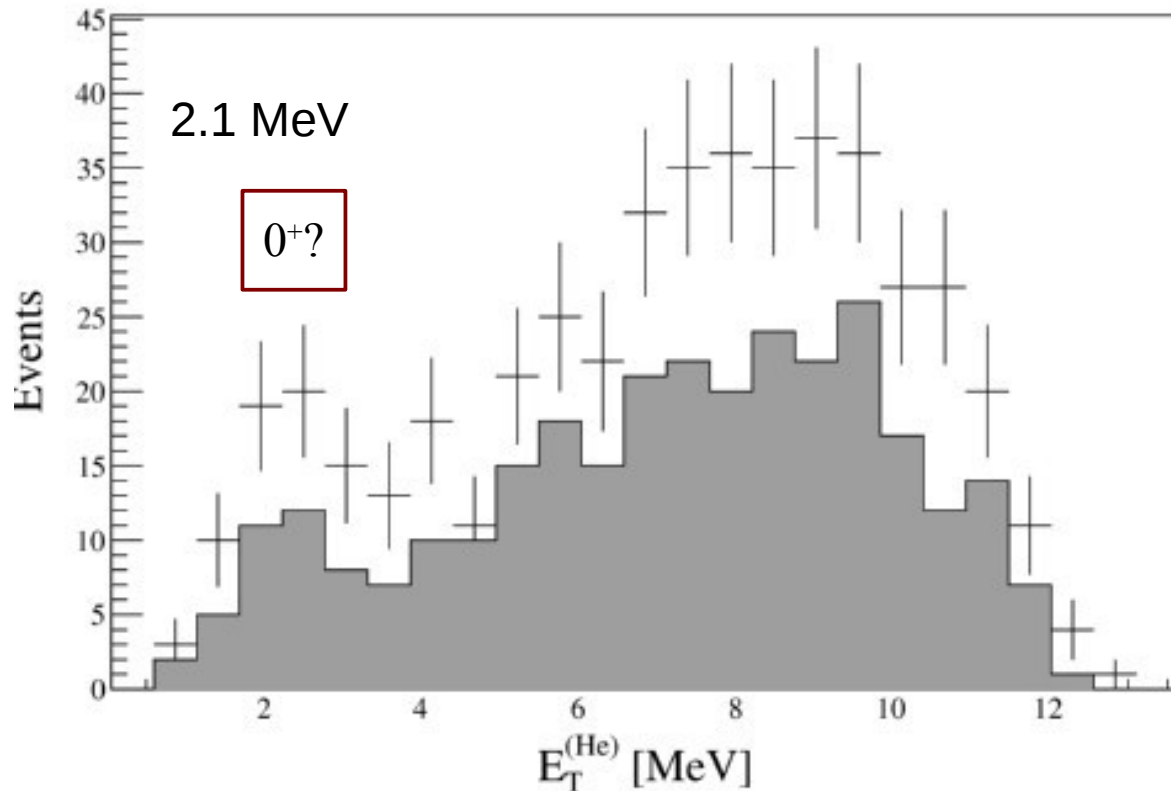


experimental sensibility to  $J^\pi$  orientation and interference between  $0^+$  and  $2^+$

- dramatic changes of the  $\theta_\alpha$  distributions depending on the model parameters
- level of alignment and interference angle is changing with  $E_T$  and  $\theta_{\text{Be}}$

**such detailed analysis was done for the first time**

# $^{10}\text{He}$ : Missing mass spectrum

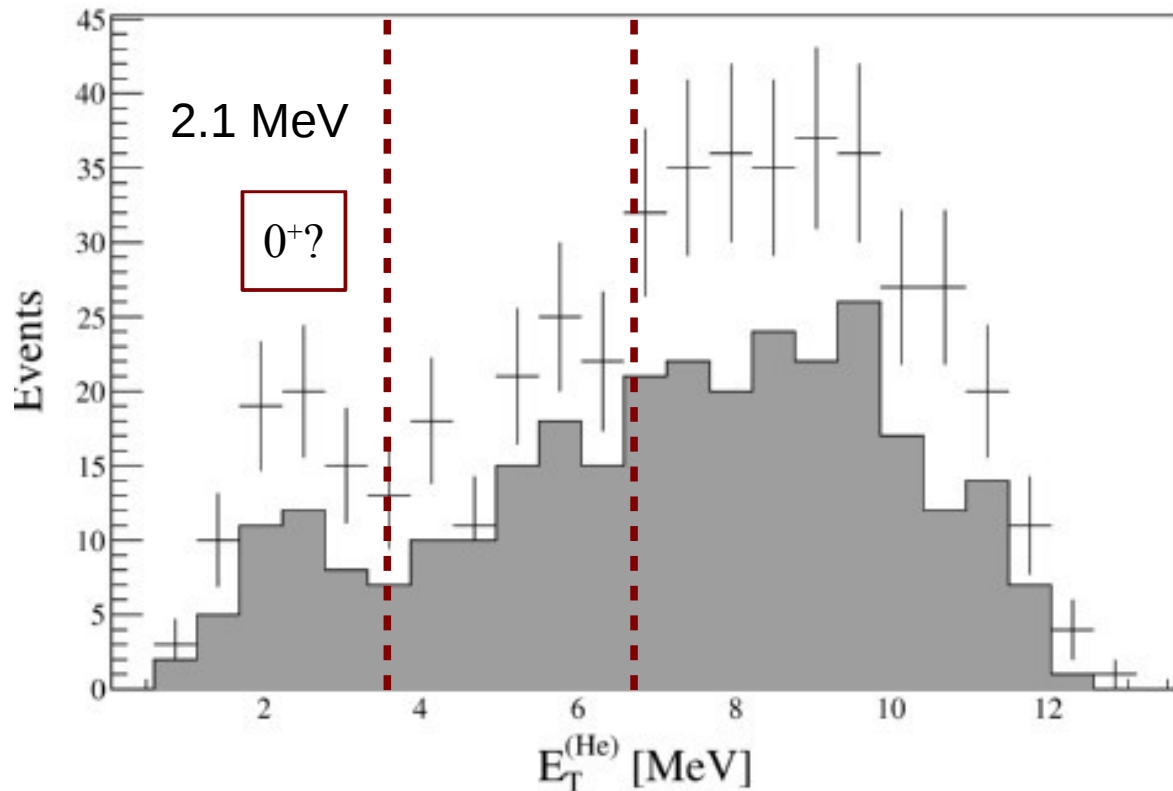


- missing mass spectrum from protons measured in coincidence with  ${}^8\text{He}$
- **479 events found**

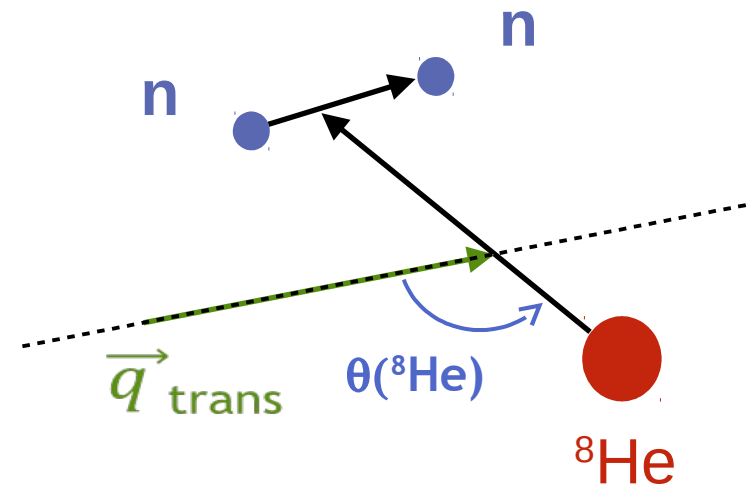
S.I. Sidorchuk et al.  
Phys. Rev. Lett. 108  
202502 (2012)

- population of  $0^+$  ground state with maximum at  $E_T \sim 2.1$  MeV
- **structureless spectrum for  $E_T > 4$  MeV**

# $^{10}\text{He}$ : Correlations



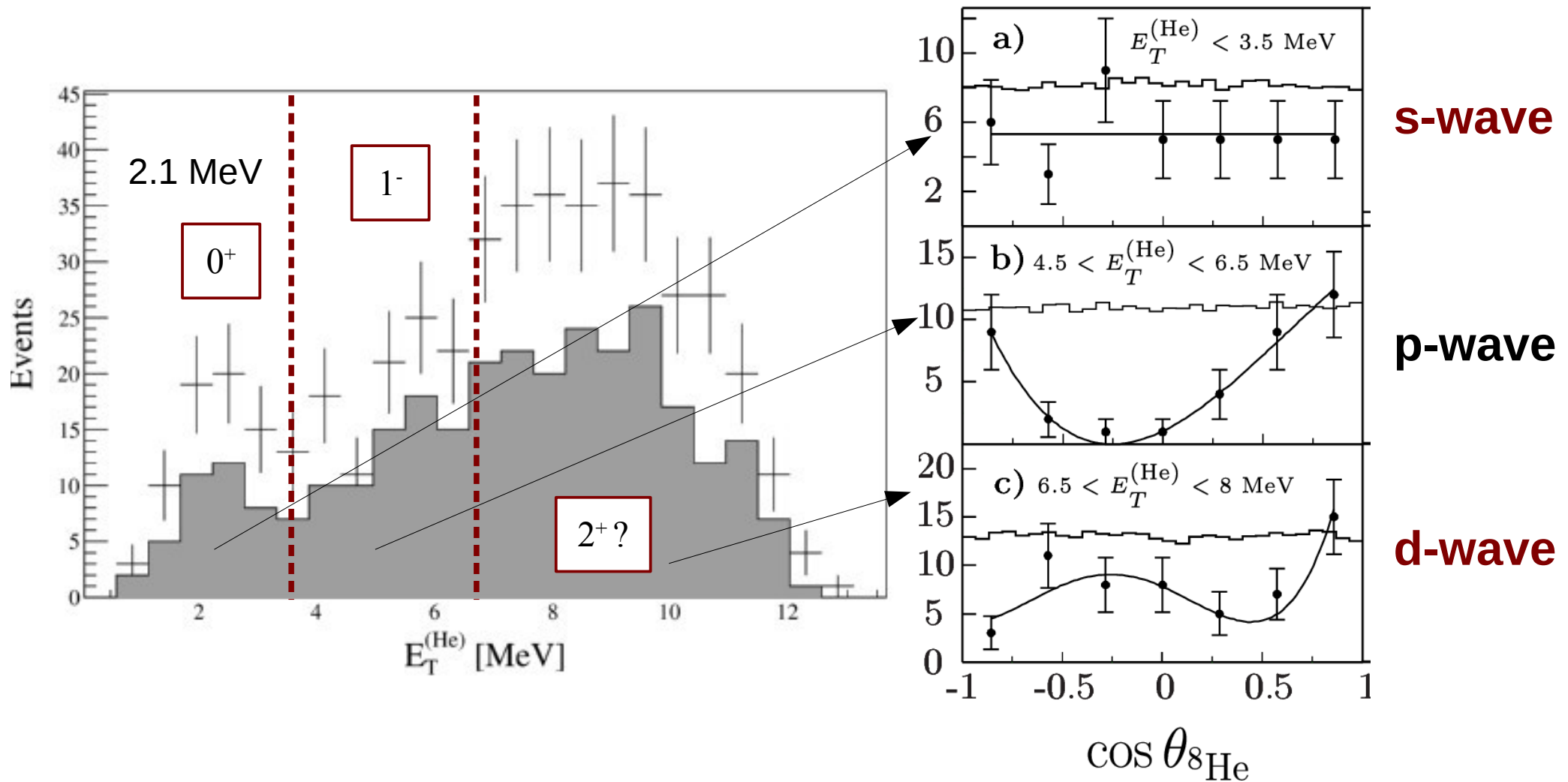
quasibinary  
kinematics



- $J^\pi$  is fully determined by L of  $^8\text{He}$

$$\varepsilon = E_{nn} / E_T^{(\text{He})} < 0.5$$

# $^{10}\text{He}$ : Correlations



- $J^\pi$  of the ground state confirmed by the experimental data analysis
- $J^\pi$  of the  $1^-$  states determined from experimental data for the first time

# Conclusion and outlook

- extensive field for pioneering research
- 3000 isotopes known, 3000 to be discovered
- new RIB factories constructed worldaround
- new facility in Dubna, new plans for the future (ERICA)
- new research methods

**Thank for  
attention**

**End**

# Spin-parity identification

## Standard methods:

- Elastic resonance scattering
- Direct reactions



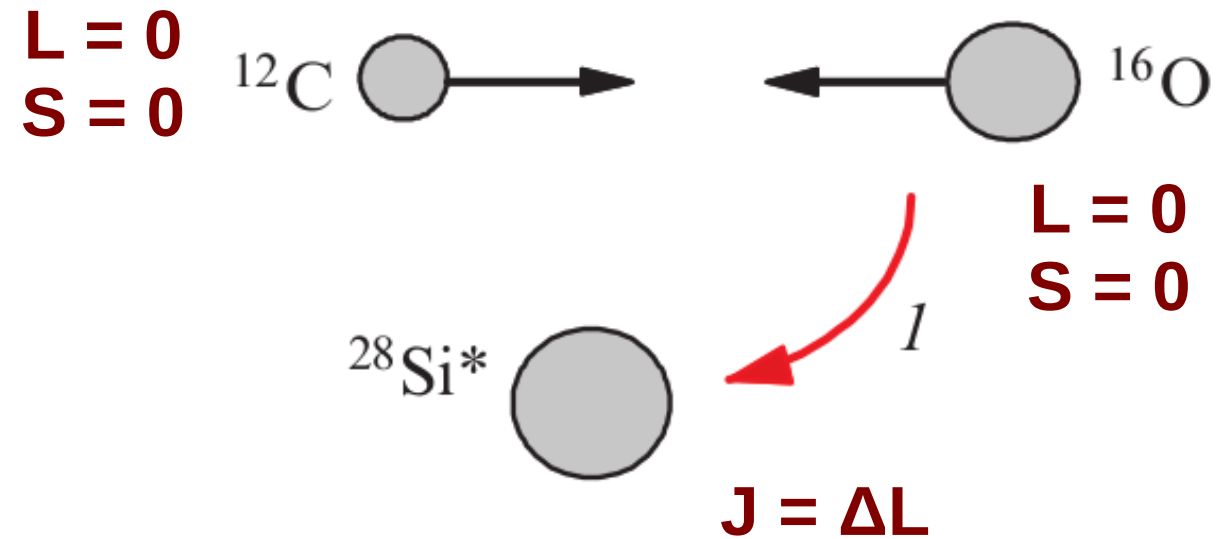
# Elastic resonance scattering

- fit to R-matrix
- unambiguous  $J^\pi$  identification
- constrains:
  - width of resonance
  - existing beams

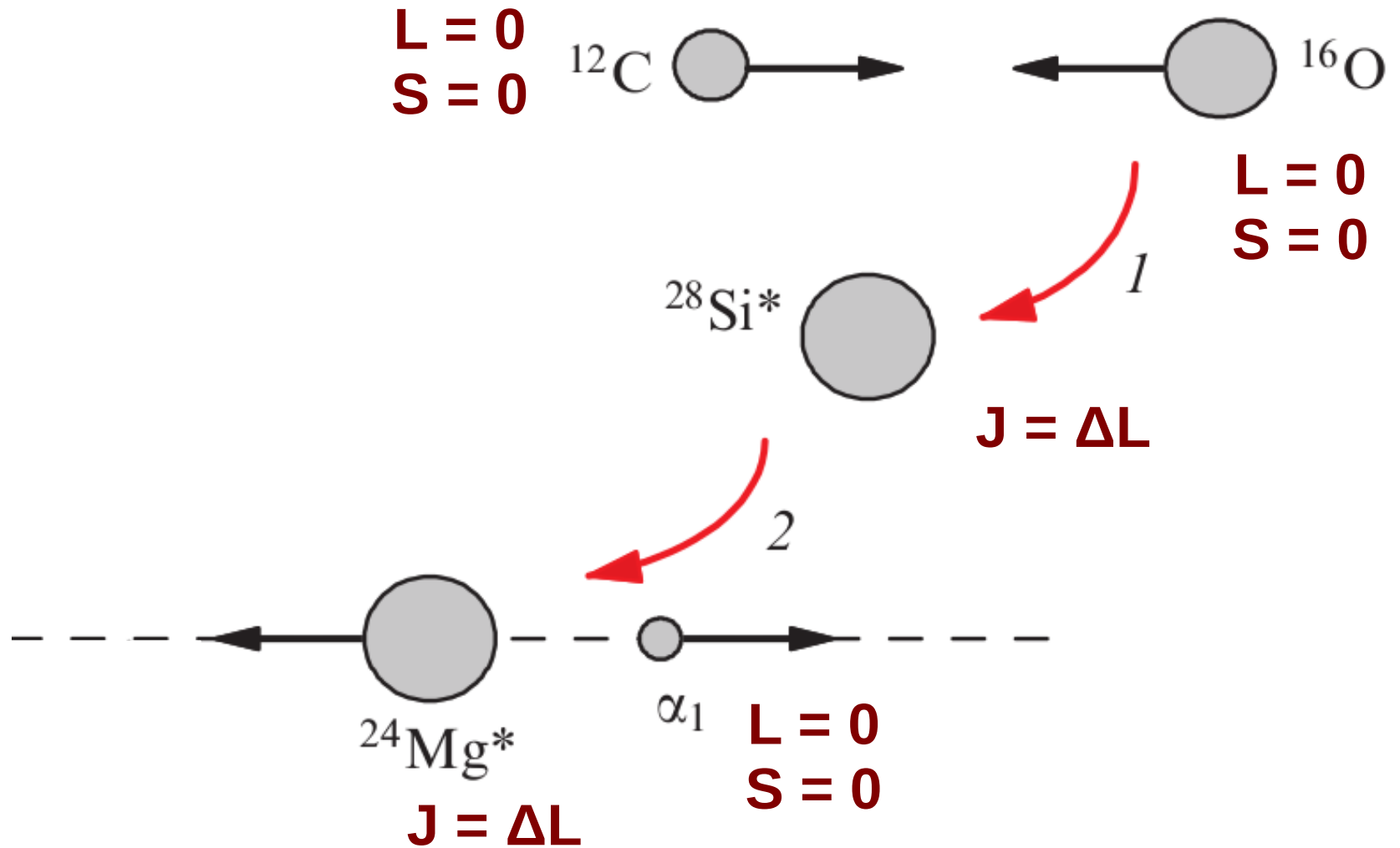
# Direct reactions

- angular distribution of products
  - using (*e.g.* DWBA)  $\Delta L$  may be determined
- “zero geometry” approach

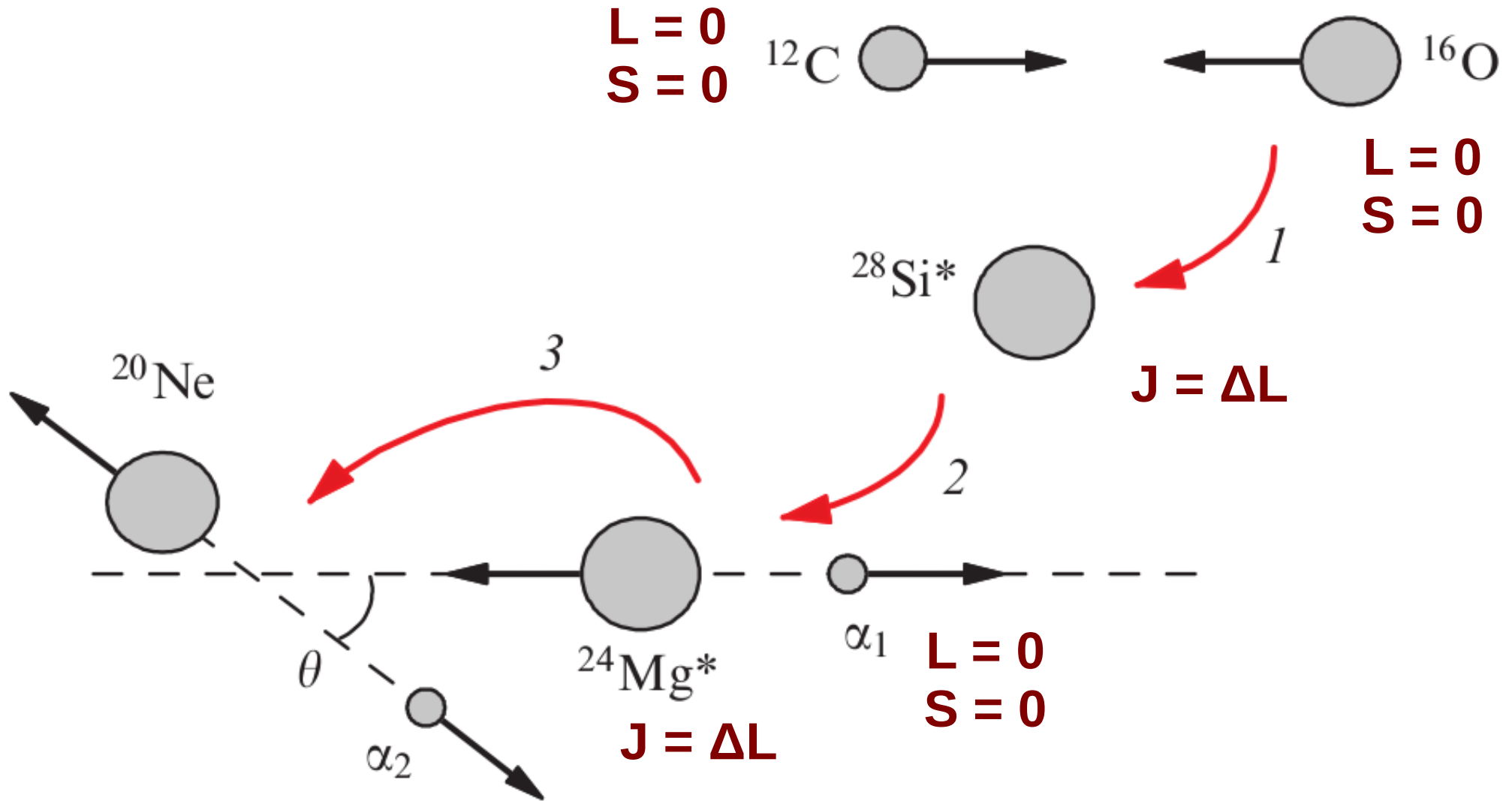
# Zero geometry approach



# Zero geometry approach



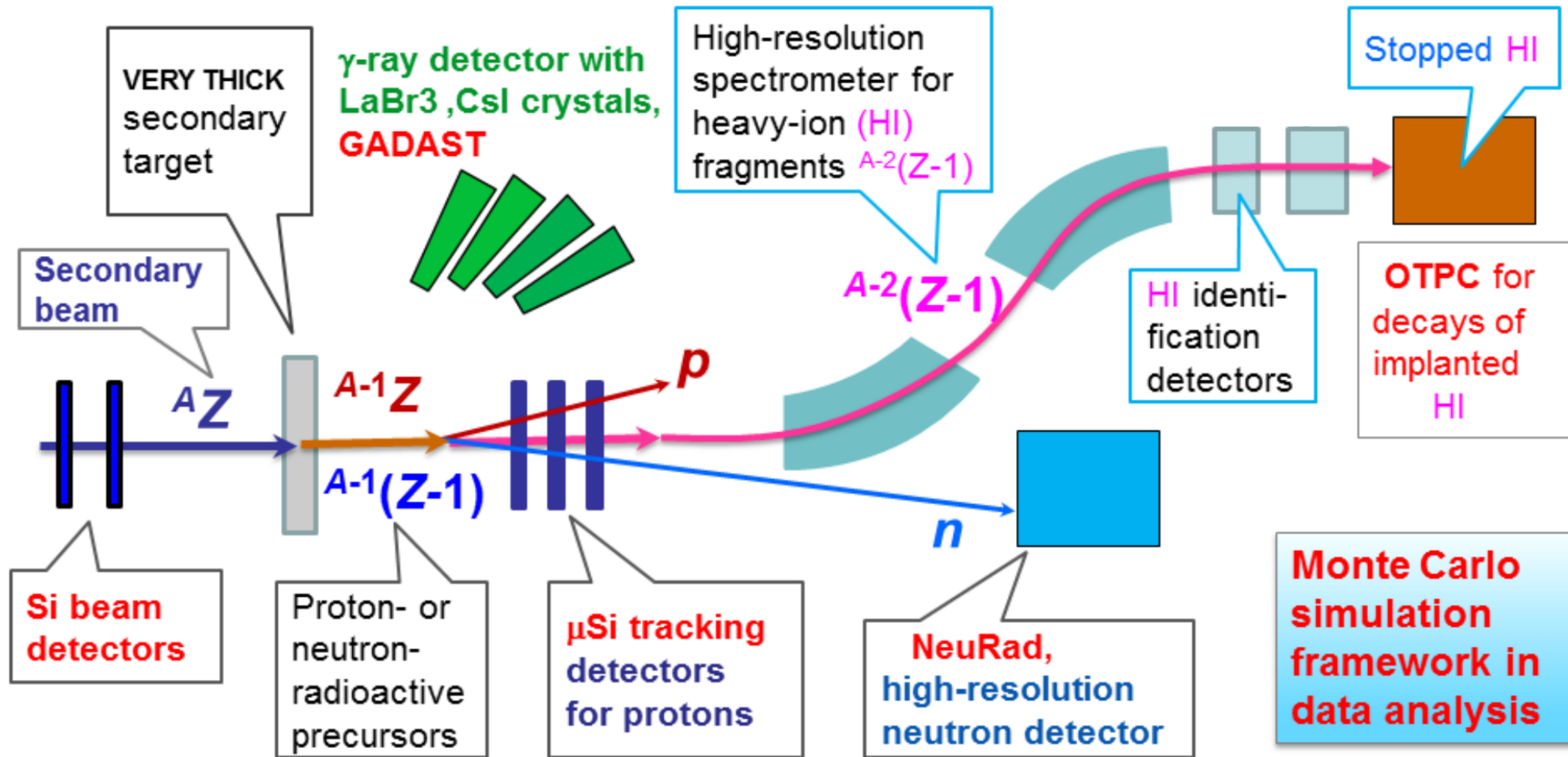
# Zero geometry approach



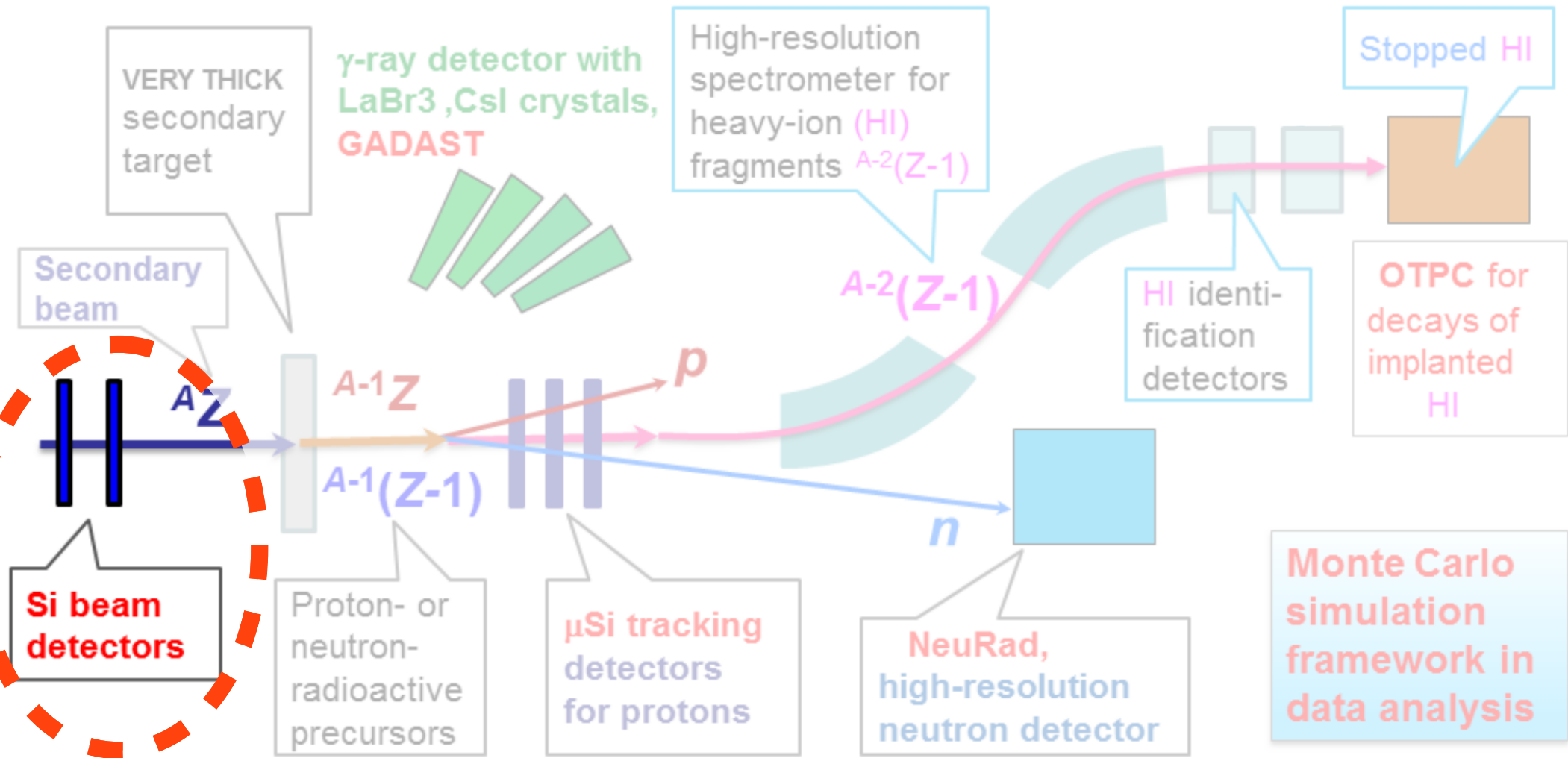
# Zero geometry approach

- **constrains:**
  - spinless reaction participants
  - high reaction cross section needed
- **it can be easily generalized**
  - **correlation patterns**

# EXPERT: Experimental setup

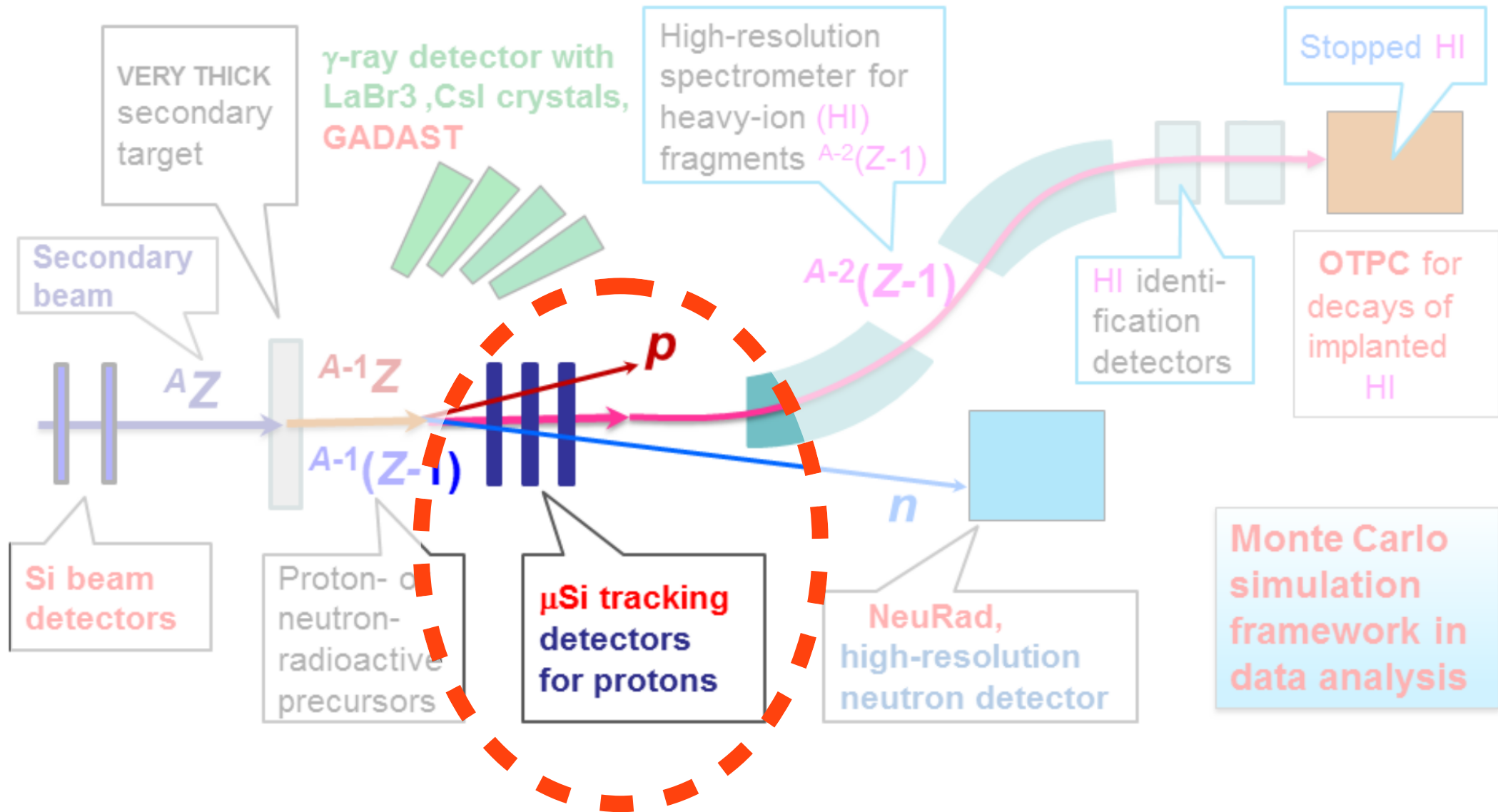


# EXPERT: Experimental setup

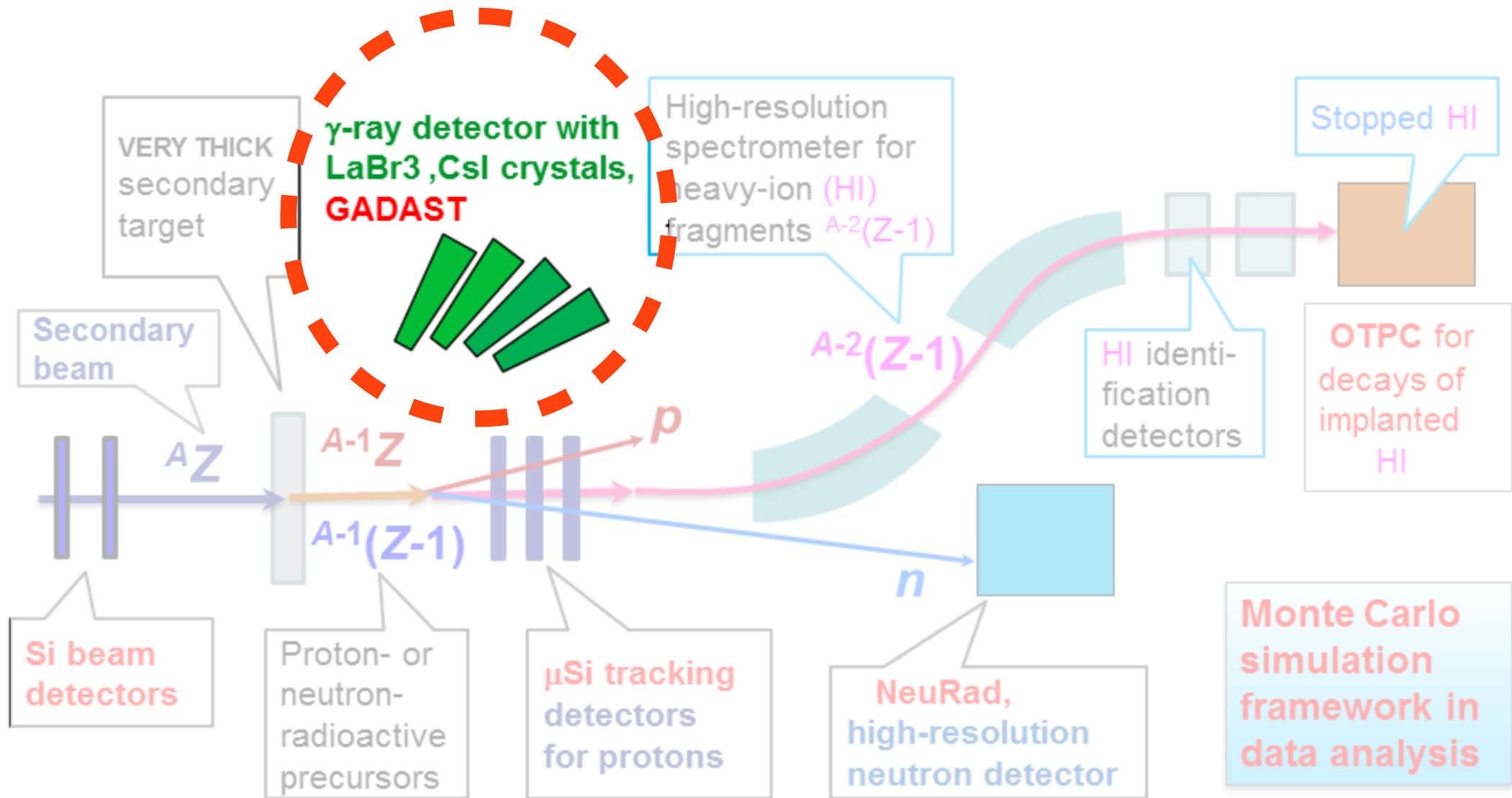




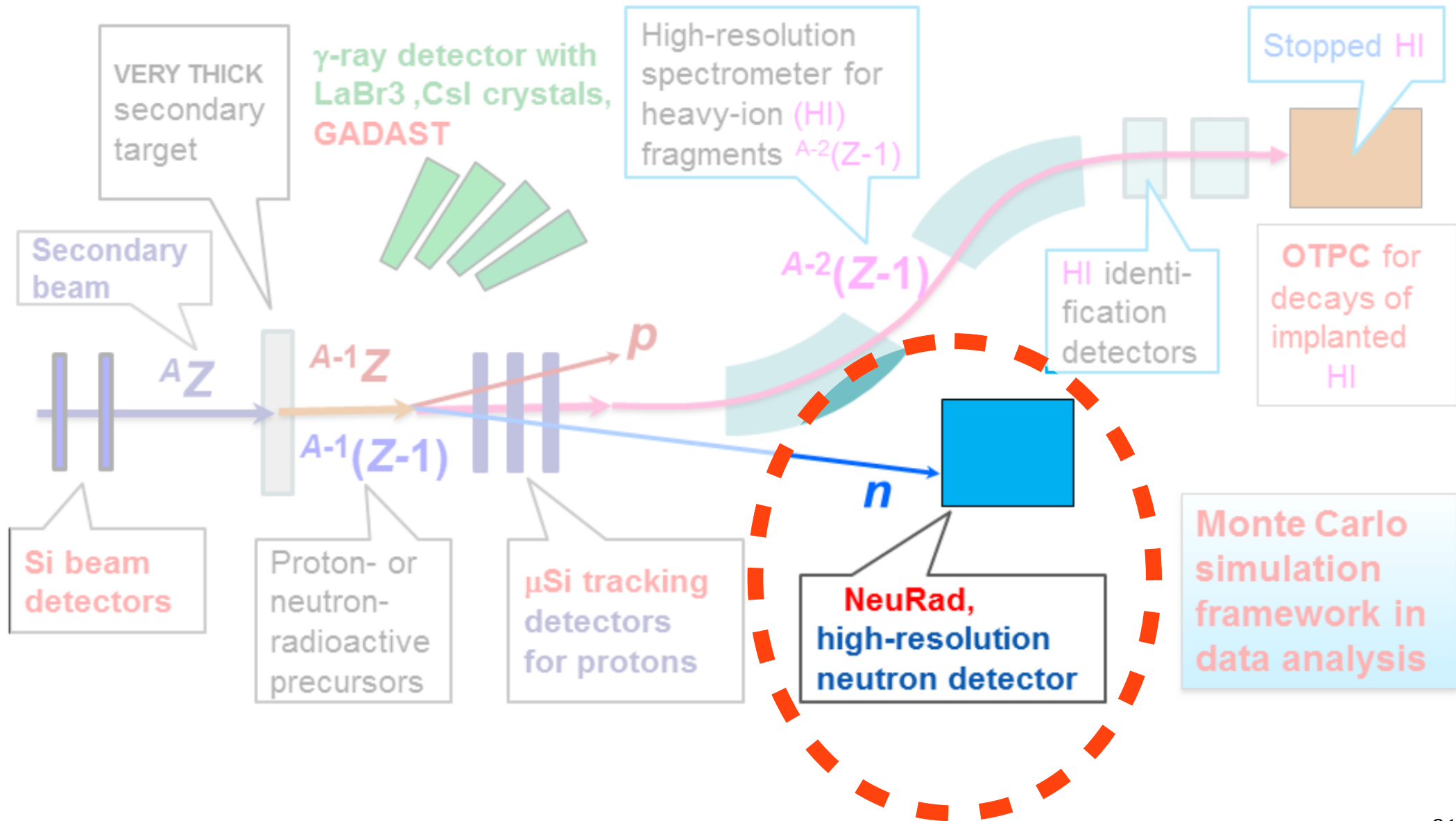
# EXPERT: Experimental setup



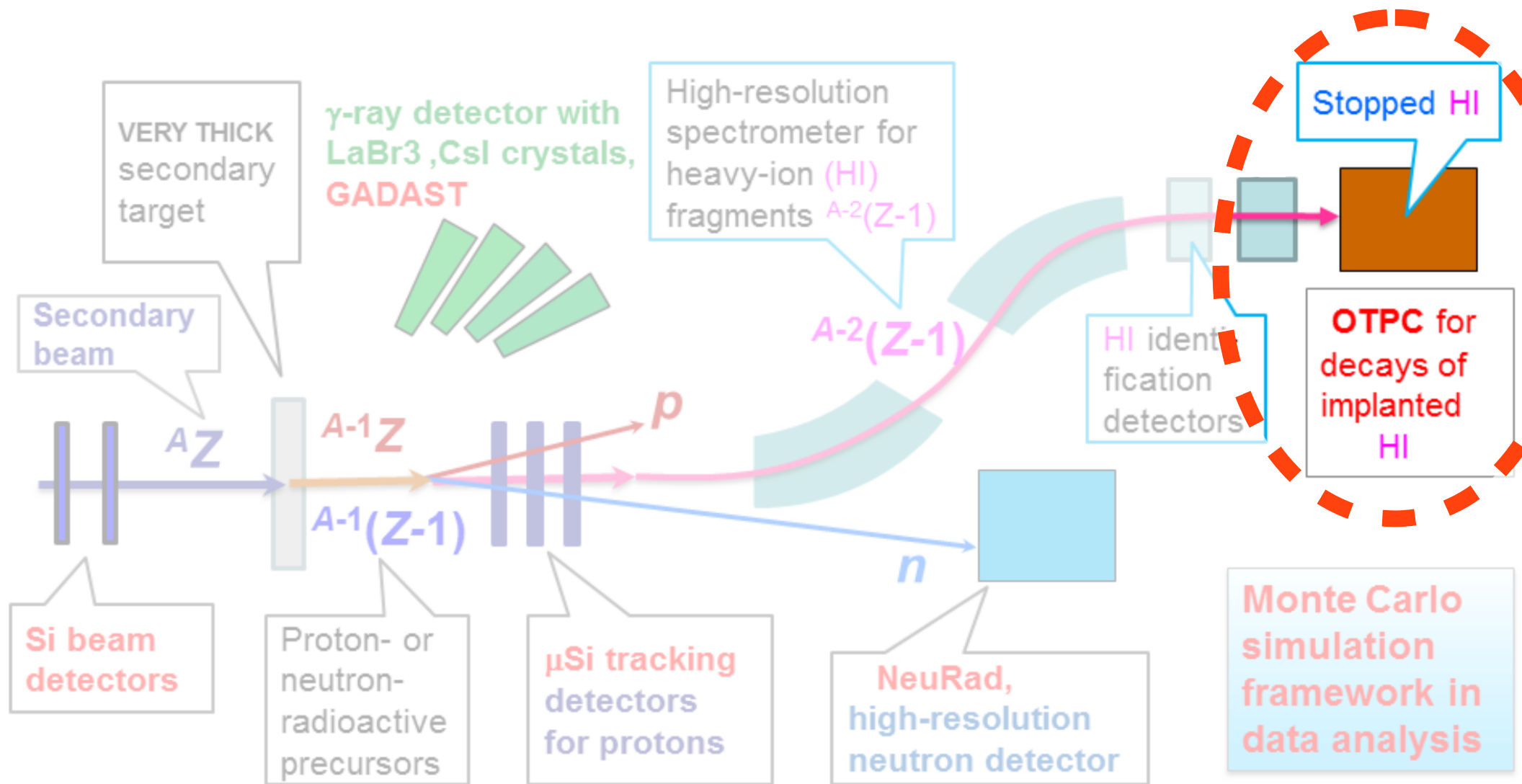
# EXPERT: Experimental setup



# EXPERT: Experimental setup



# EXPERT: Experimental setup

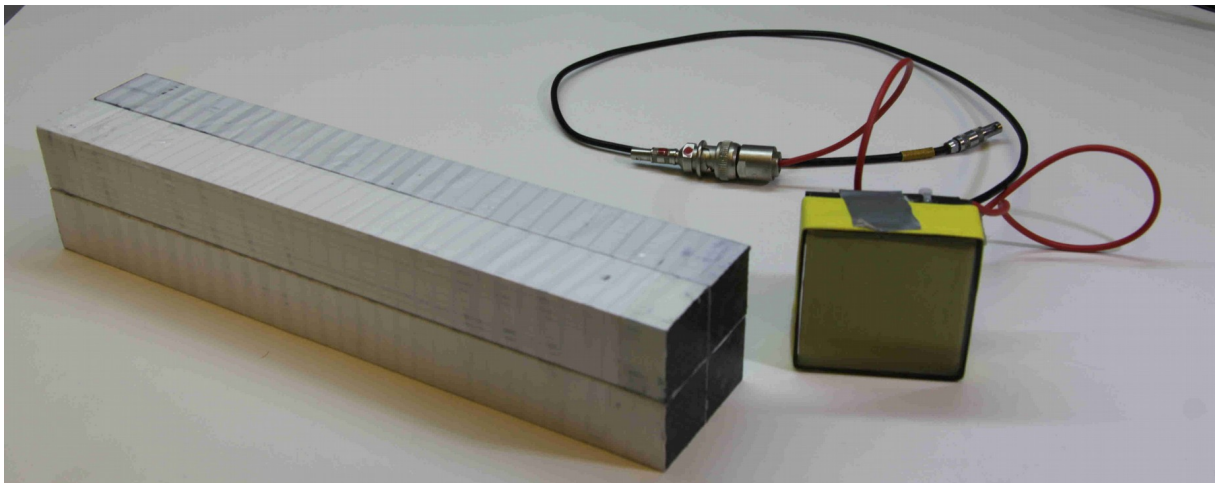
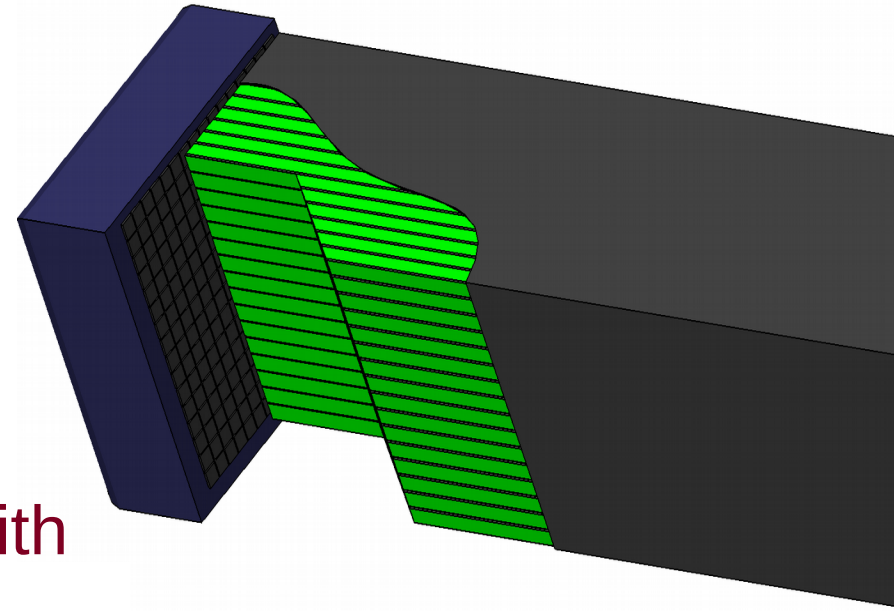


**OTPC**

# NeuRad

# NeuRad

- neutron radioactivity studies
- $E_n \sim 200 - 800$  MeV in LAB
- low transverse momenta  
0.1 – 100 keV
- precise information on angular correlations of decay neutrons with a charged fragment
- angular resolution  $\sim 0.1 - 0.2$  mrad



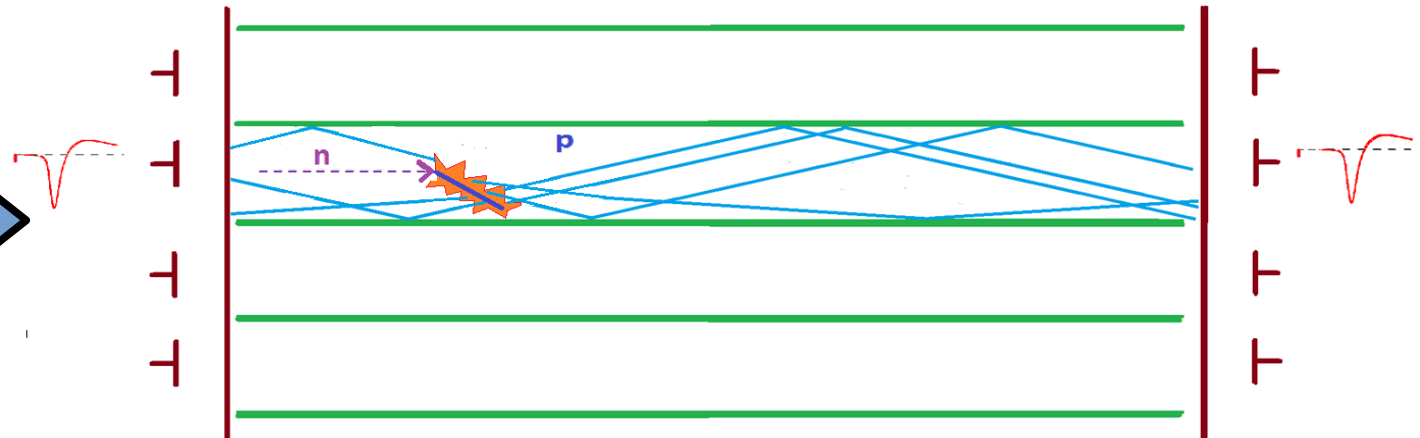
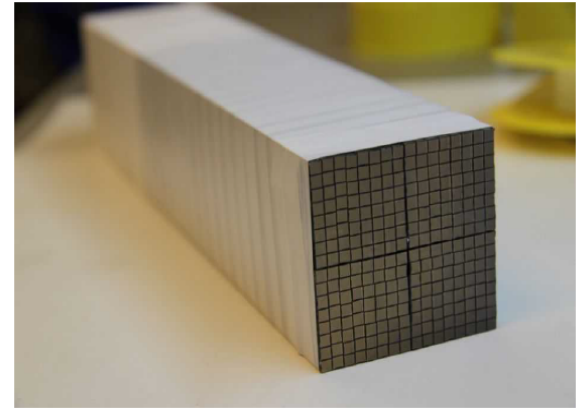
28 m from the target  
in FMF2

at least 36 modules  
 $30 \times 30 \times 100$  cm<sup>3</sup>

# NeuRad

## bundles

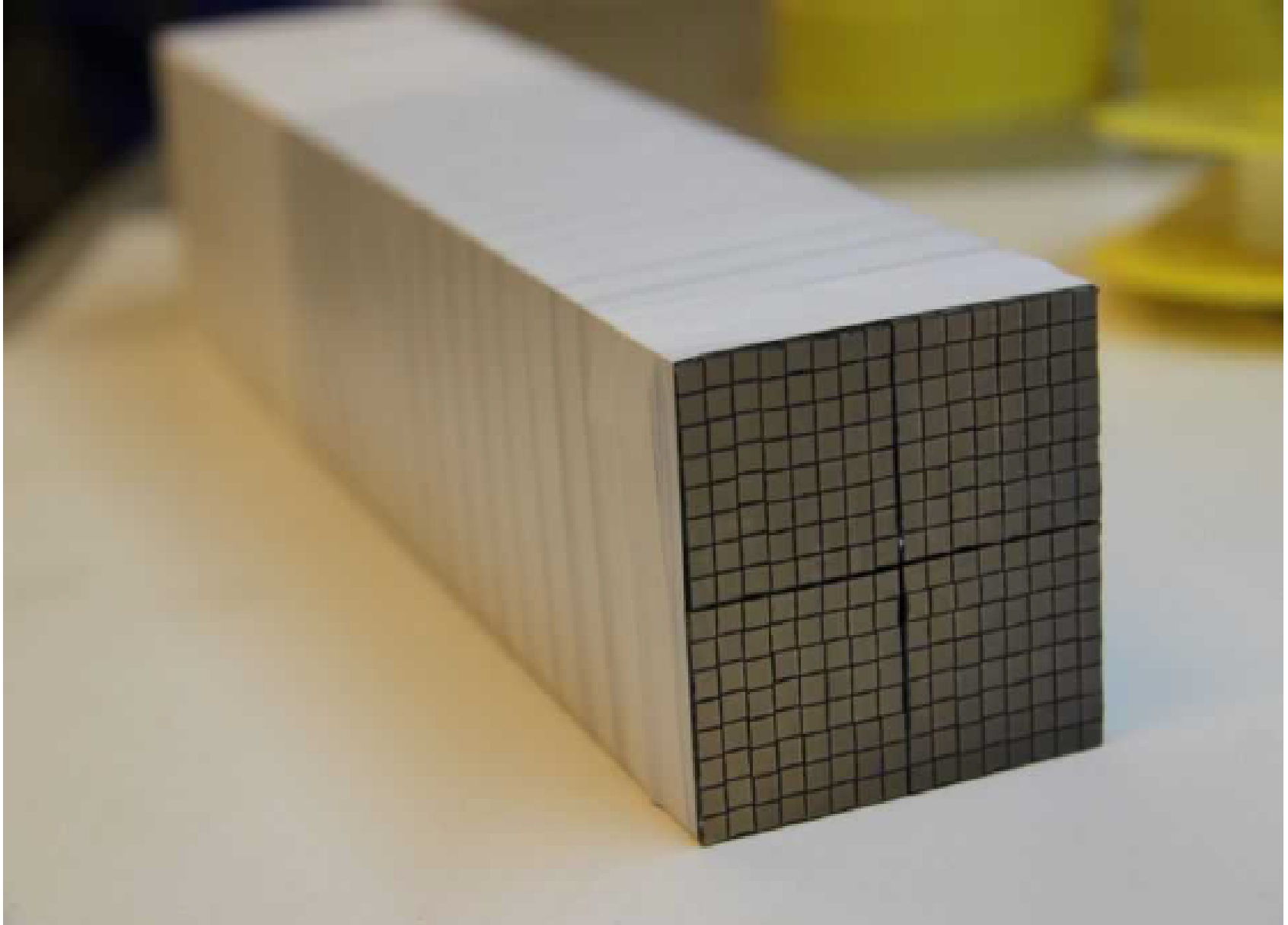
- 3 x 3 mm scintillation fibers BCF12
- 48 x 48 x 1000 mm
- 2 MAPMT from both sides



- **longitudinal coordinate** of the n interaction along the fiber
- **determination the very first hit**
- **avoid neutron cross-talk**



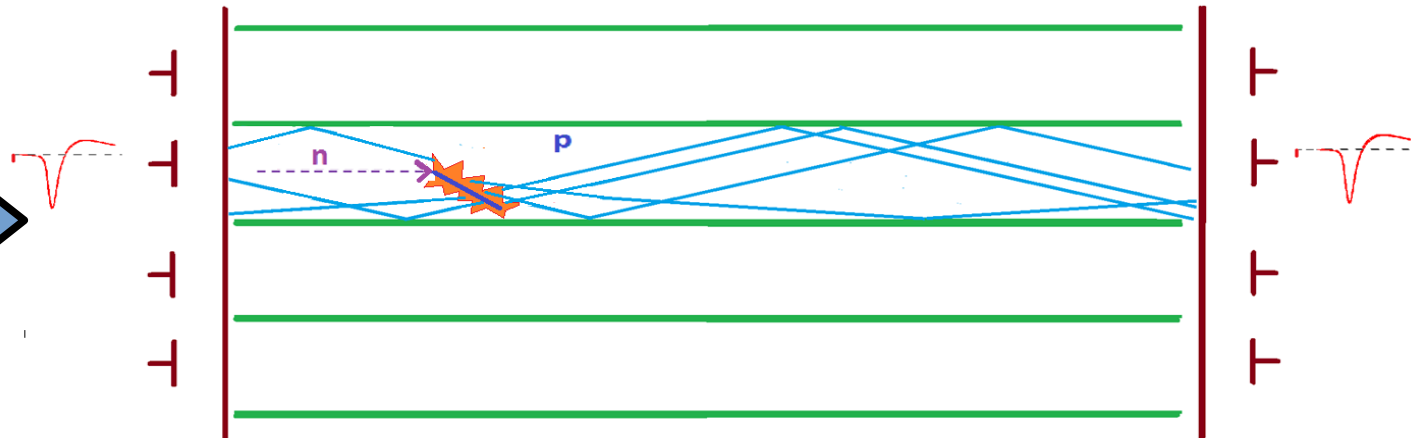
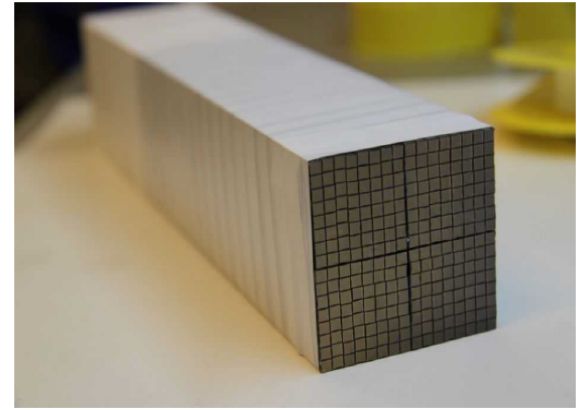
# NeuRad



# NeuRad

## bundles

- 3 x 3 mm scintillation fibers BCF12
- 48 x 48 x 1000 mm
- 2 MAPMT from both sides



- **longitudinal coordinate** of the n interaction along the fiber
- **determination the very first hit**
- **avoid neutron cross-talk**

# Appendix: Nuclear halo

## Stable nuclei

$$\langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} \approx 0.1 \text{ fm}$$

## Exotic nuclei

$$\langle r_n^2 \rangle^{1/2} - \langle r_p^2 \rangle^{1/2} \gtrsim 1.5 \text{ fm}$$

### neutron halo

*one neutron:*  $^{11}\text{Be}$ ,  $^{19}\text{C}$

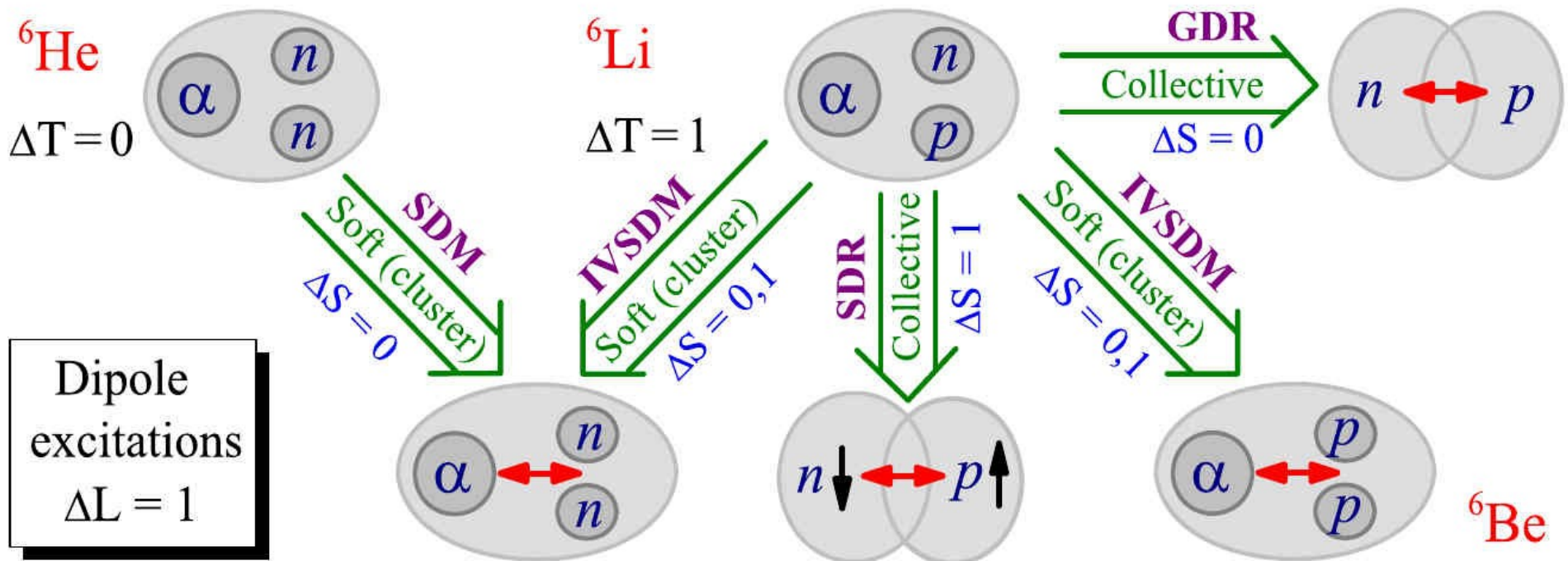
*two neutron:*  $^6\text{He}$ ,  $^{11}\text{Li}$ ,  $^{17}\text{B}$ ,  
 $^{19}\text{B}$ ,  $^{22}\text{C}$

*neutron skin:*  $^8\text{He}$  and  $^{14}\text{Be}$

### proton halo

*g.s. of*  $^8\text{B}$ ,  $^{13}\text{N}$ ,  $^{17}\text{Ne}$ ,  $^{26}\text{P}$ ,  $^{27}\text{S}$   
*the first e.s. of*  $^{17}\text{F}$

# Appendix: Dipole modes



## resonance

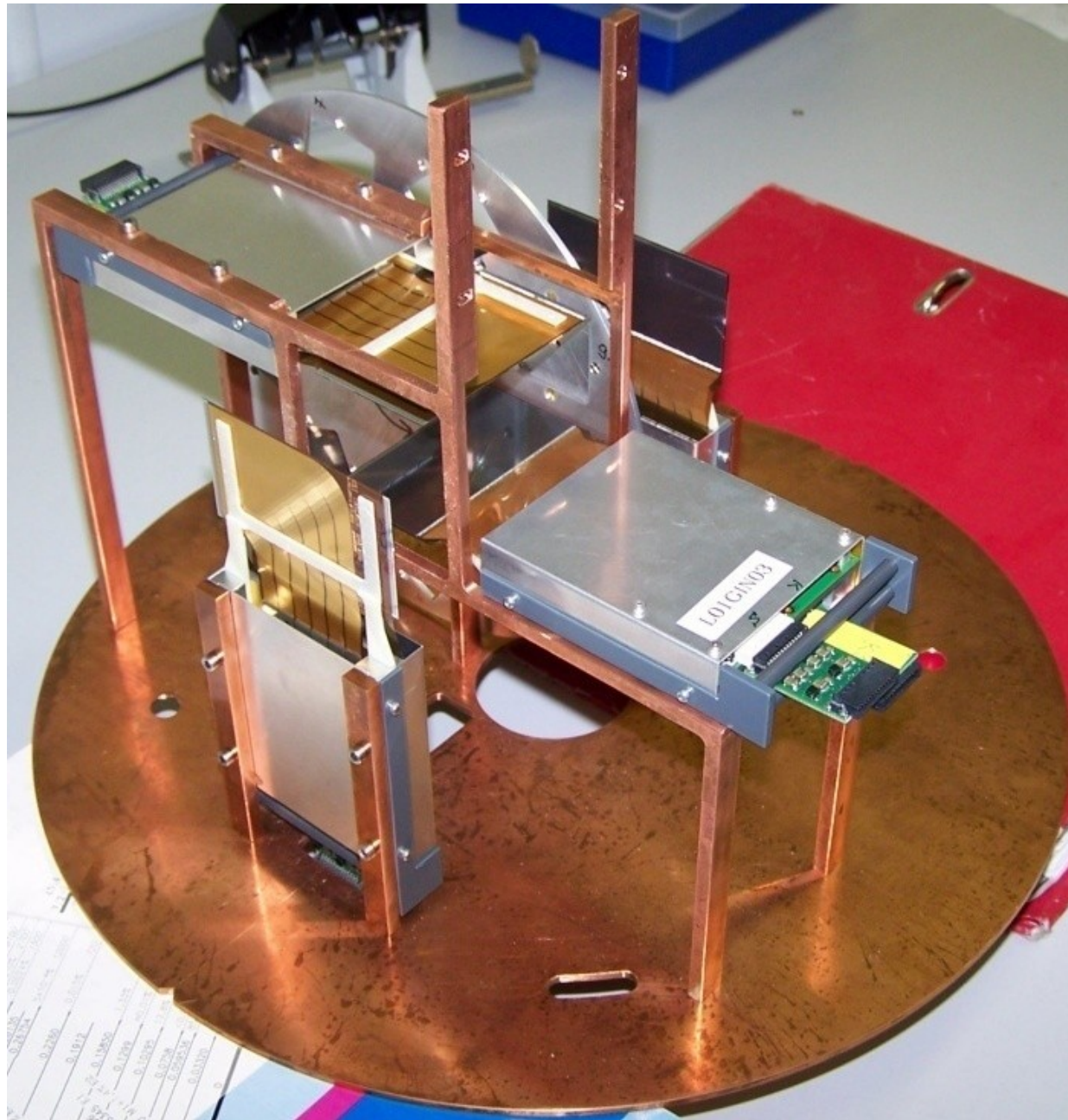
vs.

## mode

- property of particular nucleus
- its population does not depend on reaction mechanism

- characteristic for specific reaction
- its population is given by reaction mechanism

# Appendix: microStrip detectors

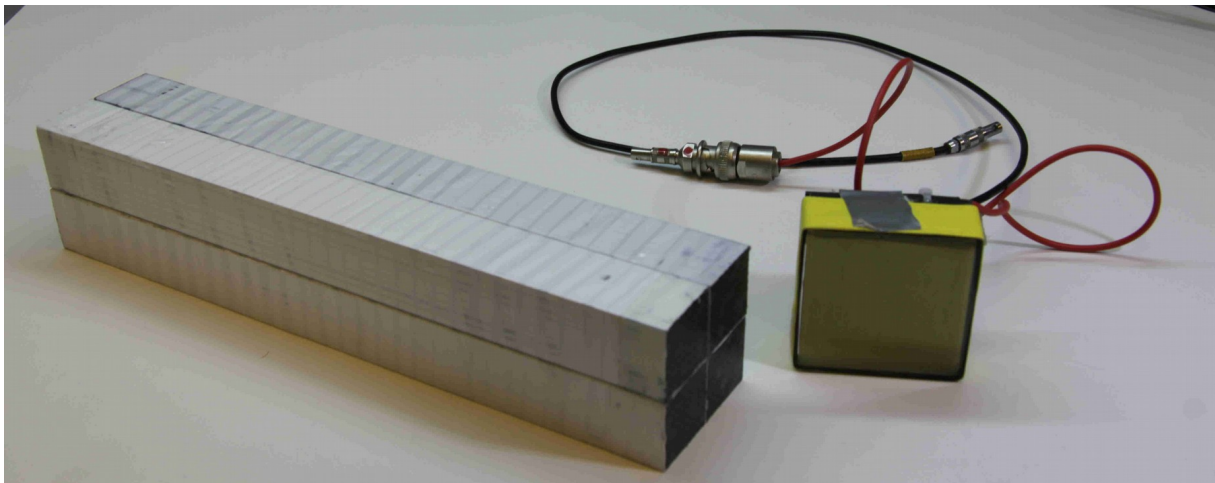
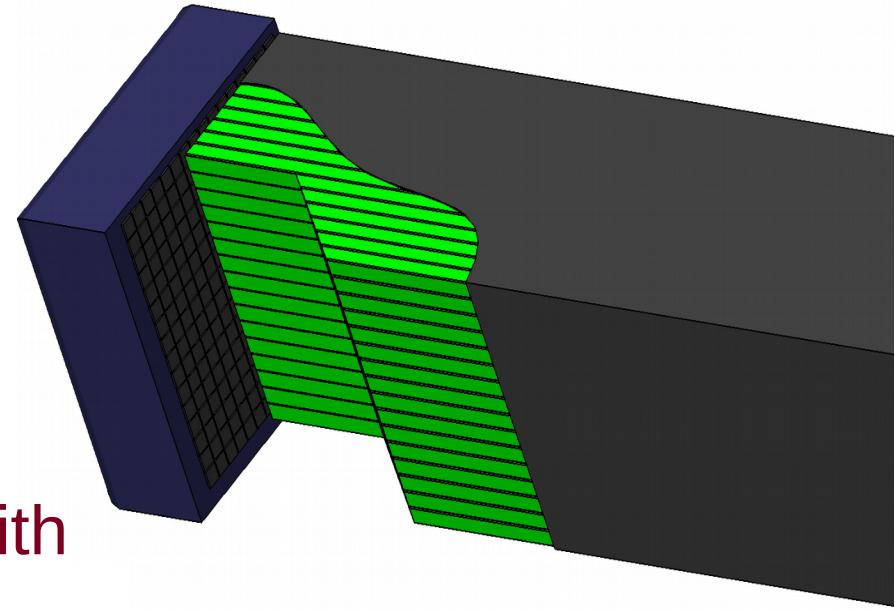


# Hardware

# NeuRad

# NeuRad

- neutron radioactivity studies
- $E_n \sim 200 - 800$  MeV in LAB
- low transverse momenta  
0.1 – 100 keV
- precise information on angular correlations of decay neutrons with a charged fragment
- angular resolution  $\sim 0.1 - 0.2$  mrad



28 m from the target  
in FMF2

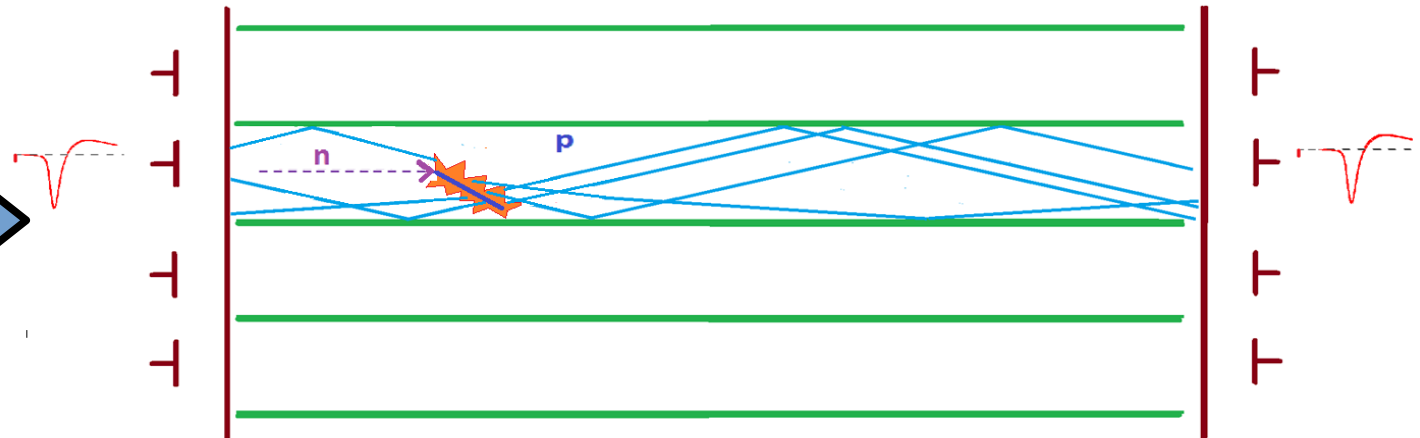
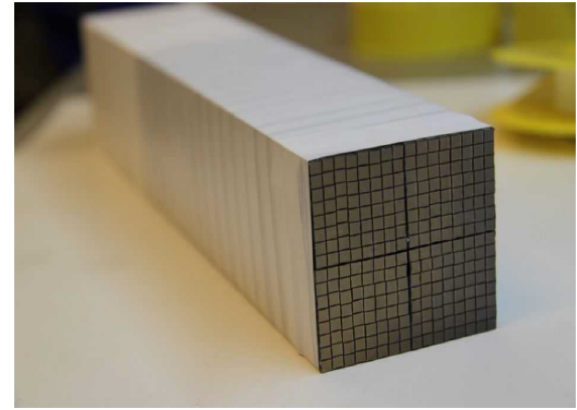
at least 36 modules  
 $30 \times 30 \times 100$  cm<sup>3</sup>



# NeuRad

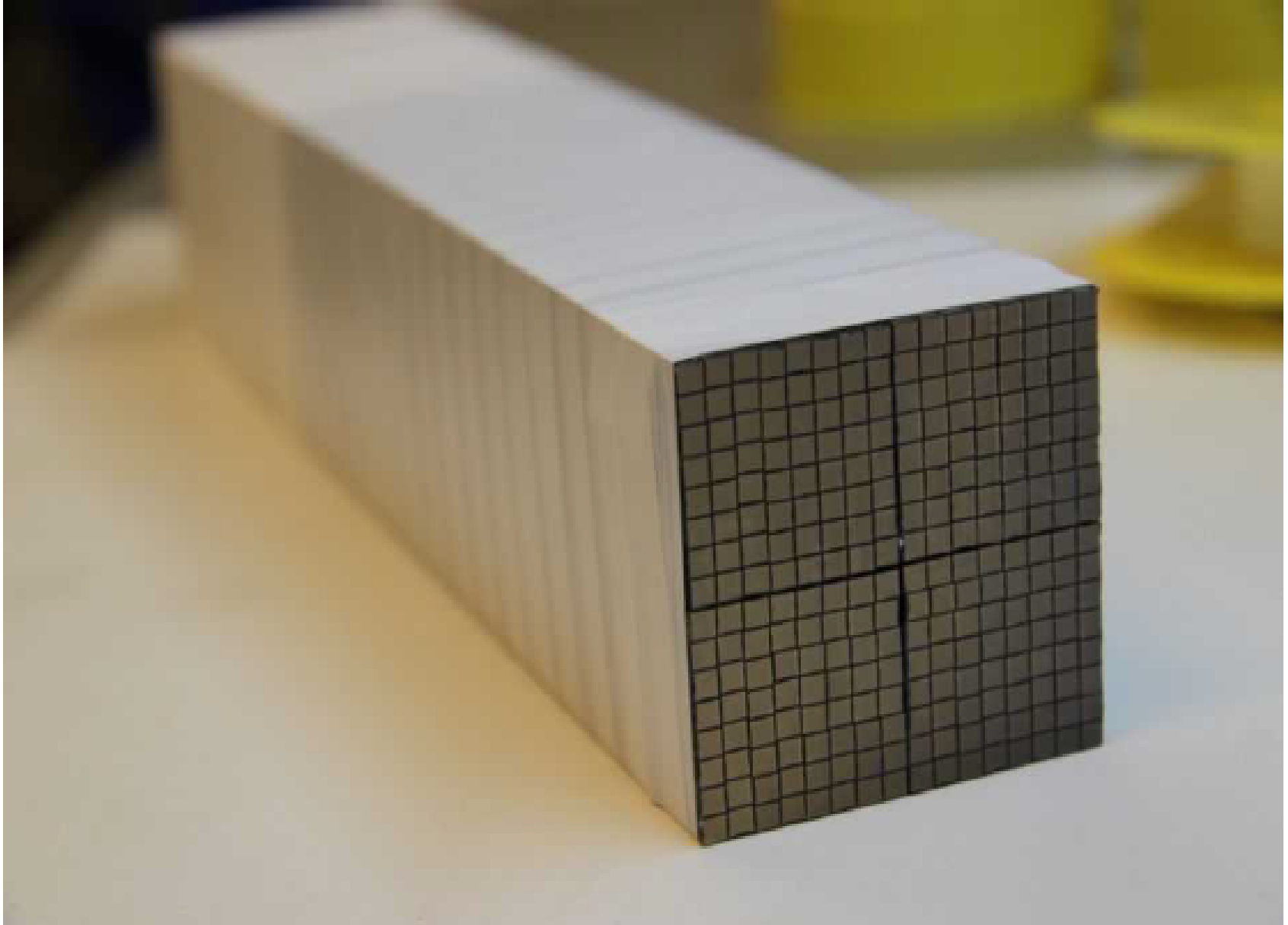
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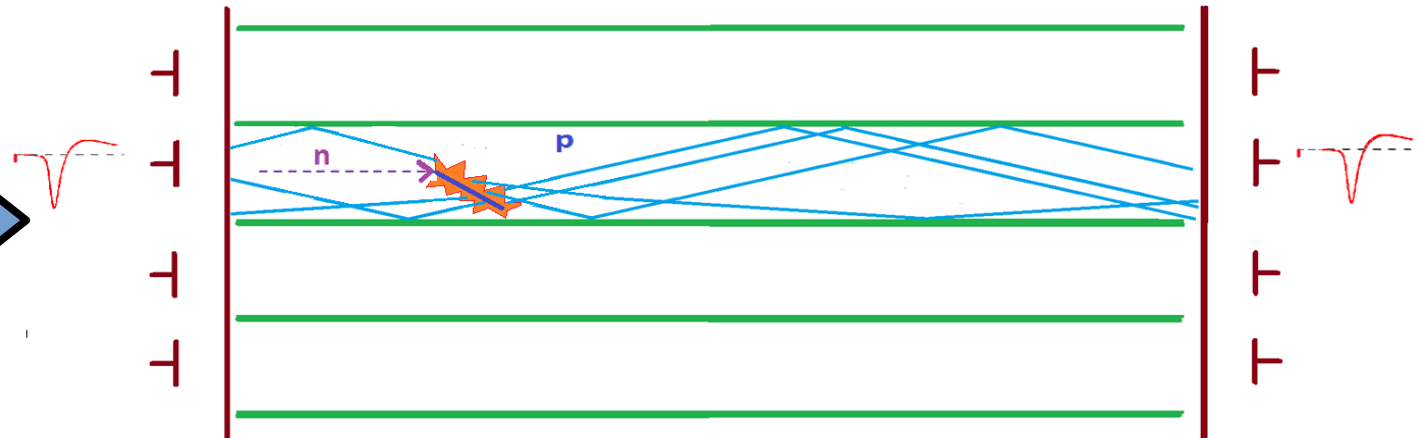
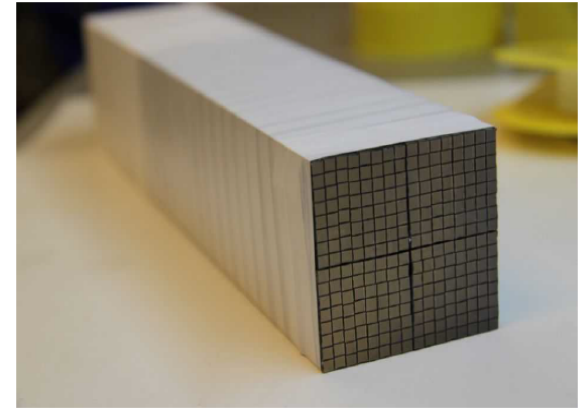
# NeuRad



# NeuRad

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# Appendix: Theoretical model

- PWIA in combination with 3-body problem
- task reduced to solving of Schroedinger equation with source

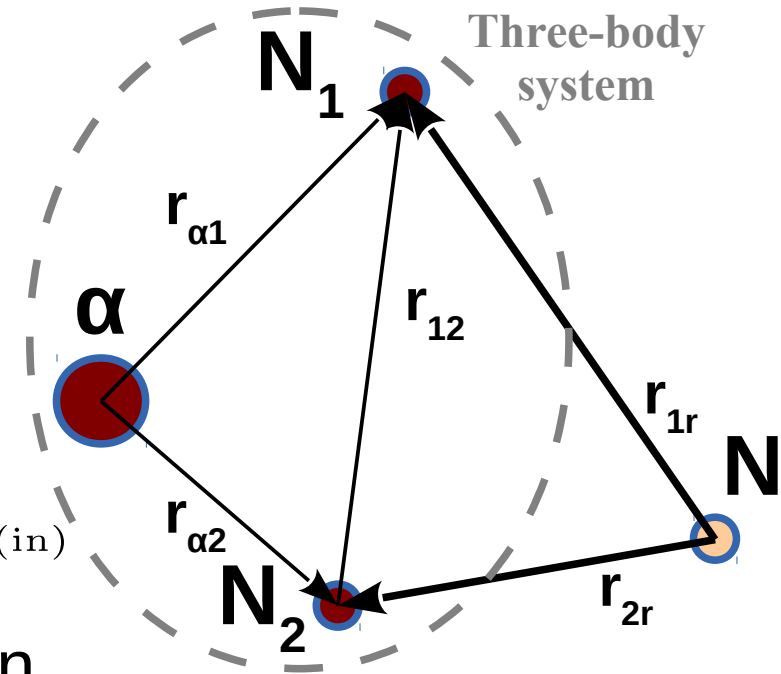
$$(\hat{H}_3 - E_T)\Psi_{6\text{Be}}^{JM(+)} = \hat{O}_{\mu'\mu}\Psi_{6\text{Li}}^{J^{(\text{in})}M^{(\text{in})}}$$

- transition operator contains information about population of  ${}^6\text{Be}$  from  ${}^6\text{Li}$

$$\hat{O}_{\mu'\mu} = \sum_{i=1,2} \sum_{lm} f_l(q, r_i) Y_{lm}(\hat{r}_i) Y_{lm}^*(\hat{q}) \tau_-^{(i)} \sum_{\nu} (-1)^{\nu} \sigma_{\nu}^{(i)} C_{\frac{1}{2}\mu 1\nu}^{\frac{1}{2}\mu'}$$

- Transition operator takes a “simple” analytical form thanks to the choice of the N-N potential used in PWIA

$$\hat{V}_{ir}(r_{ir}) = (\boldsymbol{\sigma}_i \cdot \boldsymbol{\sigma}_r)(\boldsymbol{\tau}_i \cdot \boldsymbol{\tau}_r) V_0 \exp \left[ -((\mathbf{r} + \mathbf{r}_i)^2 / r_0^2) \right]$$



# NUSTAR

## NUclear STructure, Astrophysics and Reactions



- HISPEC/DESPEC (High-Resolution Spectroscopy/Decay Spectroscopy)
- R3B (Reactions with Relativistic Radioactive Beams)
- MATS (Precision Measurements of very short-lived nuclei with Advanced Trapping System)
- LaSpec (Laser Spectroscopy)
- ILIMA (Isomeric Beams, Lifetimes and Masses)
- ELISe (Electron-Ion Scattering in a Storage Ring)
- EXL (Exotic nuclei studied in light-ion induced reactions at the NESR storage ring)
- **Super-FRS Experiments**
- SHE (Super-Heavy Element Research)

# SuperFRS Experiments

- **Mass and charge resolution**
  - Search for new isotopes and ground-state properties
  - Atomic collisions
- **Unique experiments at Super-FRS as high-energy high-resolution spectrometer**
  - Spectroscopy of meson-nucleus bound system
  - Exotic hypernuclei and their properties
  - Importance of tensor forces in nuclear structure
  - Delta resonances probing nuclear structure
- **Experiments taking advantages of multi-stages and high-resolution of the Super-FRS**
  - Nuclear radii and momentum distributions
  - EXPERT (**EX**otic **P**article **E**mission and **R**adioactivity by **T**racking)
  - Low-q experiments with an active target
  - Nuclear reaction studies and synthesis of isotopes with low-energy RIBs