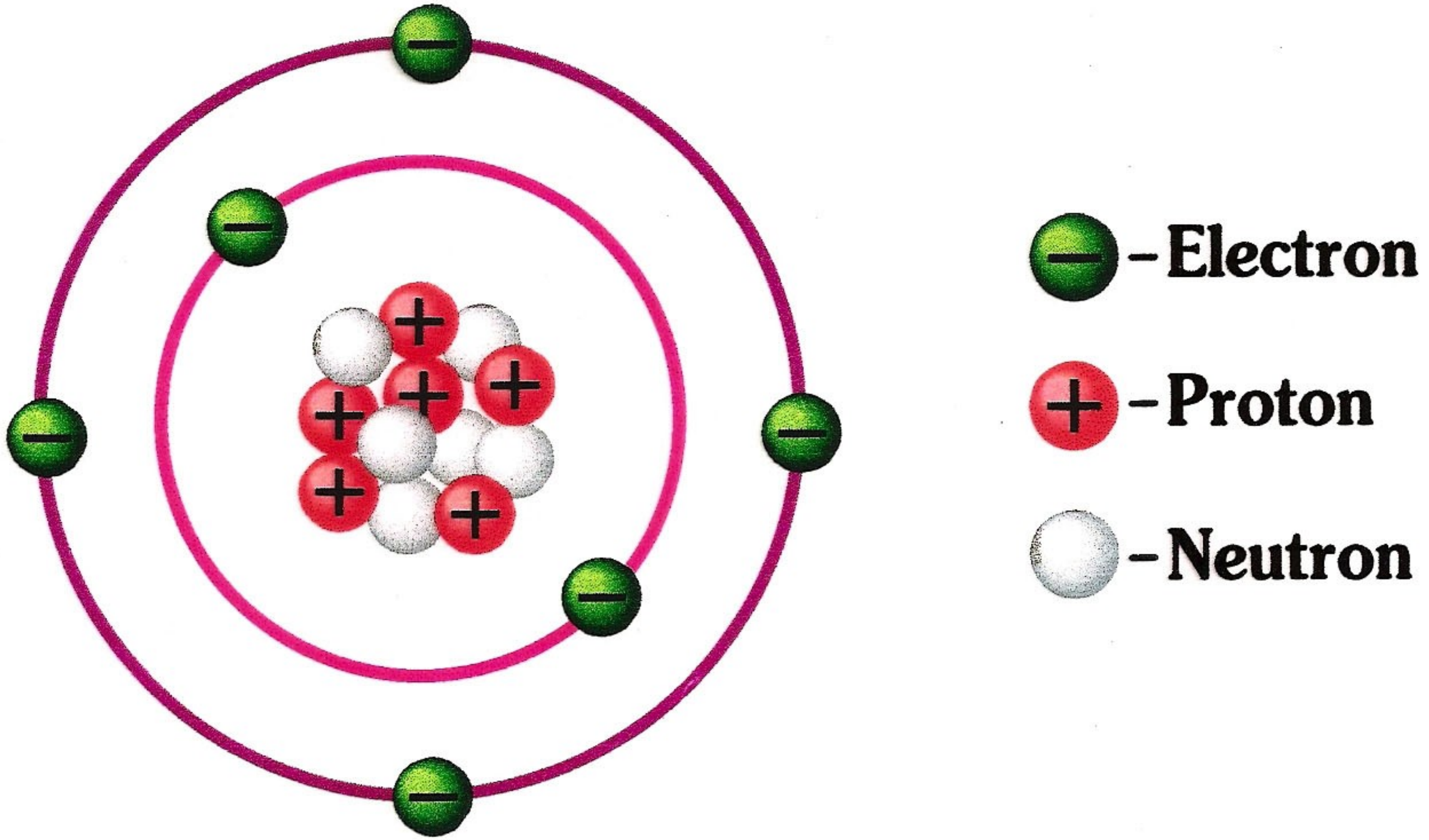
Physics of exotic nuclei

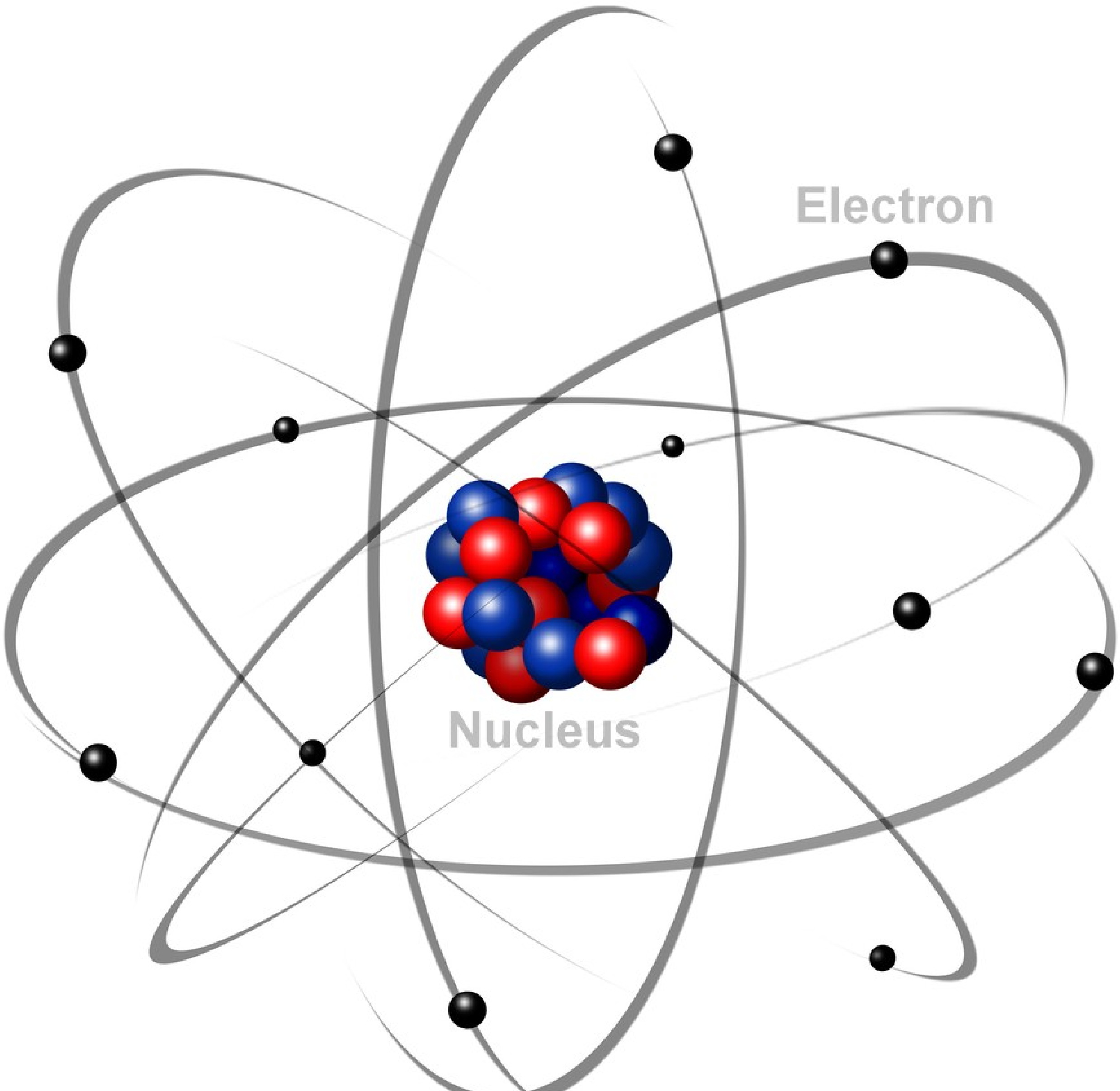
Vratislav Chudoba

FLNR JINR

Atom



Atom



Nucleus

- **ensemble of protons and neutrons**
- **mass ~ 10^{-27} – 10^{-26} kg (tens of GeV)**
- **size of atom:**
  ~ 10^{-10} m
- **size of nucleus:**
  ~ 10^{-15} m

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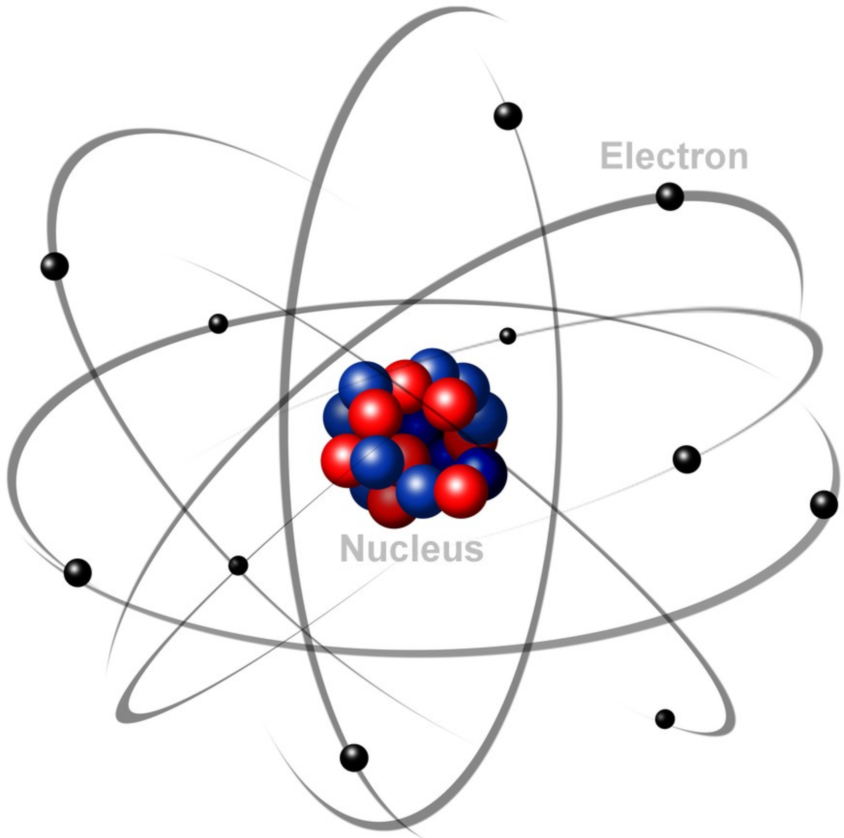

Nucleus

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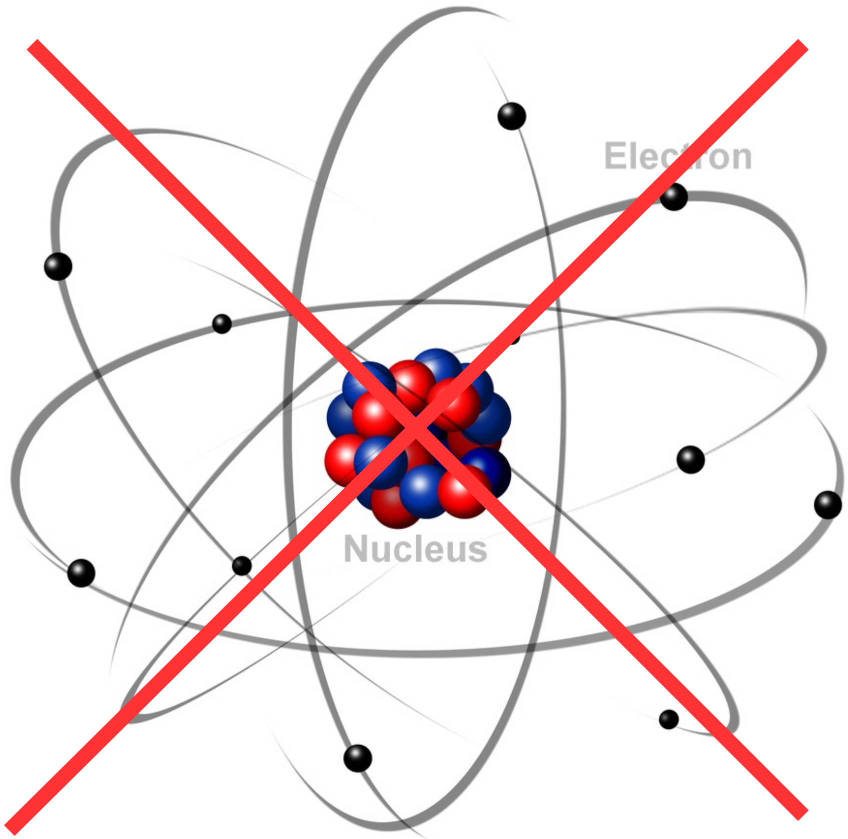
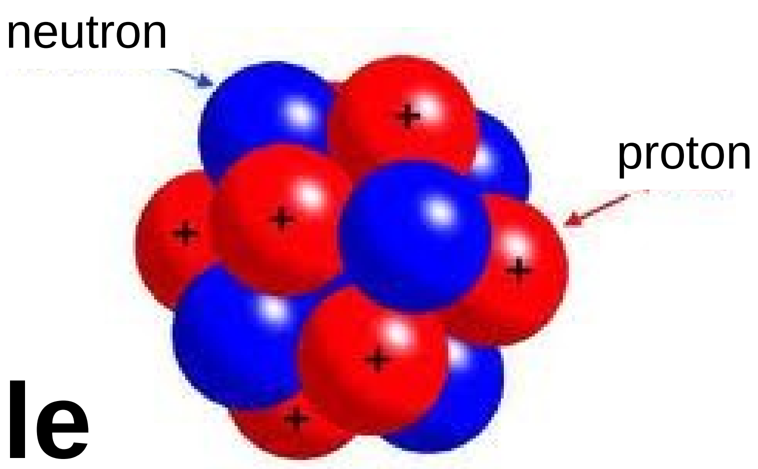


Why exotic?



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

too heavy **or** **strange in other way**

Периодическая таблица элементов Д.И. Менделеева

D.I. Mendeleev's Periodic Table of Elements

период	ряд	группы элементов: а I б	а II б	а III б	а IV б	а V б	а VI б	а VII б	а VIII б		
1	I	Водород H 1 $1s^1$ 1,00794 Hydrogen							Гелий He 2 $1s^2$ 4,0026 Helium		
2	II	Литий Li 3 $2s^1$ 6,941 Lithium	Бериллий Be 4 $2s^2$ 9,012182 Beryllium	Бор B 5 $2p^1$ 10,811 Boron	Углерод C 6 $2p^2$ 12,011 Carbon	Азот N 7 $2p^3$ 14,00674 Nitrogen	Кислород O 8 $2p^4$ 15,9994 Oxygen	Фтор F 9 $2p^5$ 18,9984032 Fluorine	Неон Ne 10 $2p^6$ 20,1797 Neon		
3	III	Натрий Na 11 $3s^1$ 22,989768 Sodium	Магний Mg 12 $3s^2$ 24,3050 Magnesium	Алюминий Al 13 $3p^1$ 26,981539 Aluminum	Кремний Si 14 $3p^2$ 28,0855 Silicon	Фосфор P 15 $3p^3$ 30,973762 Phosphorus	Сера S 16 $3p^4$ 32,066 Sulfur	Хлор Cl 17 $3p^5$ 35,4527 Chlorine	Аргон Ar 18 $3p^6$ 39,948 Argon		
4	IV	Калий K 19 $4s^1$ 39,0983 Potassium	Кальций Ca 20 $4s^2$ 40,078 Calcium	21 $3d^14s^2$ Скандий Sc 44,955910 Scandium	22 $3d^24s^2$ Титан Ti 47,88 Titanium	23 $3d^34s^2$ Ванадий V 50,9415 Vanadium	24 $3d^54s^1$ Хром Cr 51,9961 Chromium	25 $3d^54s^2$ Марганец Mn 54,93805 Manganese	26 $3d^64s^2$ Железо Fe 55,847 Iron	27 $3d^74s^2$ Кобальт Co 58,93320 Cobalt	28 $3d^84s^2$ Никель Ni 58,6934 Nickel
	V	29 $3d^{10}4s^1$ Медь Cu 63,546 Copper	30 $3d^{10}4s^2$ Цинк Zn 65,39 Zinc	Галлий Ga 31 $4p^1$ 69,723 Gallium	Германий Ge 32 $4p^2$ 72,61 Germanium	Мышьяк As 33 $4p^3$ 74,92159 Arsenic	Селен Se 34 9,75238 $4p^4$ 78,96 Selenium	Бром Br 35 $4p^5$ 79,904 Bromine	Криптон Kr 36 $4p^6$ 83,80 Krypton		
5	VI	Рубидий Rb 37 $5s^1$ 85,4678 Rubidium	Стронций Sr 38 $5s^2$ 87,62 Strontium	39 $4d^15s^2$ Иттрий Y 88,90585 Yttrium	40 $4d^25s^2$ Цирконий Zr 91,224 Zirconium	41 $4d^45s^1$ Ниобий Nb 92,90638 Niobium	42 $4d^55s^1$ Молибден Mo 95,94 Molybdenum	43 $4d^55s^2$ Технеций Tc [98] Technetium	44 $4d^75s^1$ Рутений Ru 101,07 Ruthenium	45 $4d^85s^1$ Родий Rh 102,90550 Rhodium	46 $4d^{10}$ Палладий Pd 106,42 Palladium
	VII	47 $4d^{10}5s^1$ Серебро Ag 107,8682 Silver	48 $4d^{10}5s^2$ Кадмий Cd 112,411 Cadmium	Индий In 49 $5p^1$ 114,818 Indium	Олово Sn 50 $5p^2$ 118,710 Tin	Сурьма Sb 51 $5p^3$ 121,757 Antimony	Теллур Te 52 $5p^4$ 127,60 Tellurium	Иод I 53 $5p^5$ 126,90447 Iodine	Ксенон Xe 54 $5p^6$ 131,29 Xenon		
6	VIII	Цезий Cs 55 $6s^1$ 132,90543 Cesium	Барий Ba 56 $6s^2$ 137,327 Barium	57 $5d^16s^2$ Лантан La 138,9055 Lanthanum	72 $5d^26s^2$ Гафний Hf 178,49 Hafnium	73 $5d^36s^2$ Тантал Ta 180,9479 Tantalum	74 $5d^46s^2$ Вольфрам W 183,84 Tungsten	75 $5d^56s^2$ Рений Re 186,207 Rhenium	76 $5d^66s^2$ Осмий Os 190,23 Osmium	77 $5d^76s^2$ Иридий Ir 192,22 Iridium	78 $5d^96s^1$ Платина Pt 195,08 Platinum
	IX	79 $5d^{10}6s^1$ Золото Au 196,96654 Gold	80 $5d^{10}6s^2$ Ртуть Hg 200,59 Mercury	Таллий Tl 81 $6p^1$ 204,3833 Thallium	Свинец Pb 82 $6p^2$ 207,2 Lead	Висмут Bi 83 $6p^3$ 208,98037 Bismuth	Полоний Po 84 $6p^4$ [209] Polonium	Астат At 85 $6p^5$ [210] Astatine	Радон Rn 86 $6p^6$ [222] Radon		
7	X	Франций Fr 87 4,073 $7s^1$ [223] Francium	Радий Ra 88 $7s^2$ 226,025 Radium	89 $6d^17s^2$ Актиний Ac [227] Actinium	104 Резерфордий Rf [261] Rutherfordium	105 Дубний Db [262] Dubnium	106 Сиборгий Sg [266] Seaborgium	107 Борий Bh [267] Bohrium	108 Хассий Hs [269] Hassium	109 Мейтнерий Mt [268] Meitnerium	110 Дармштадтий Ds [269] Darmstadtium
	XI	111 Рентгений Rg [272] Roentgenium	112 Коперникий Cn [285] Copernicium	113	Флеровий Fl 114 Flerovium	115	Ливерморий Lv 116 Livermorium	117	118		

Водород H 1 $1s^1$ 1,00794 Hydrogen

символ / symbol

электронная конфигурация / electronic configuration

атомная масса / atomic mass

S-ЭЛЕМЕНТЫ/ELEMENTS

p-элементы

d-элементы

f-элементы

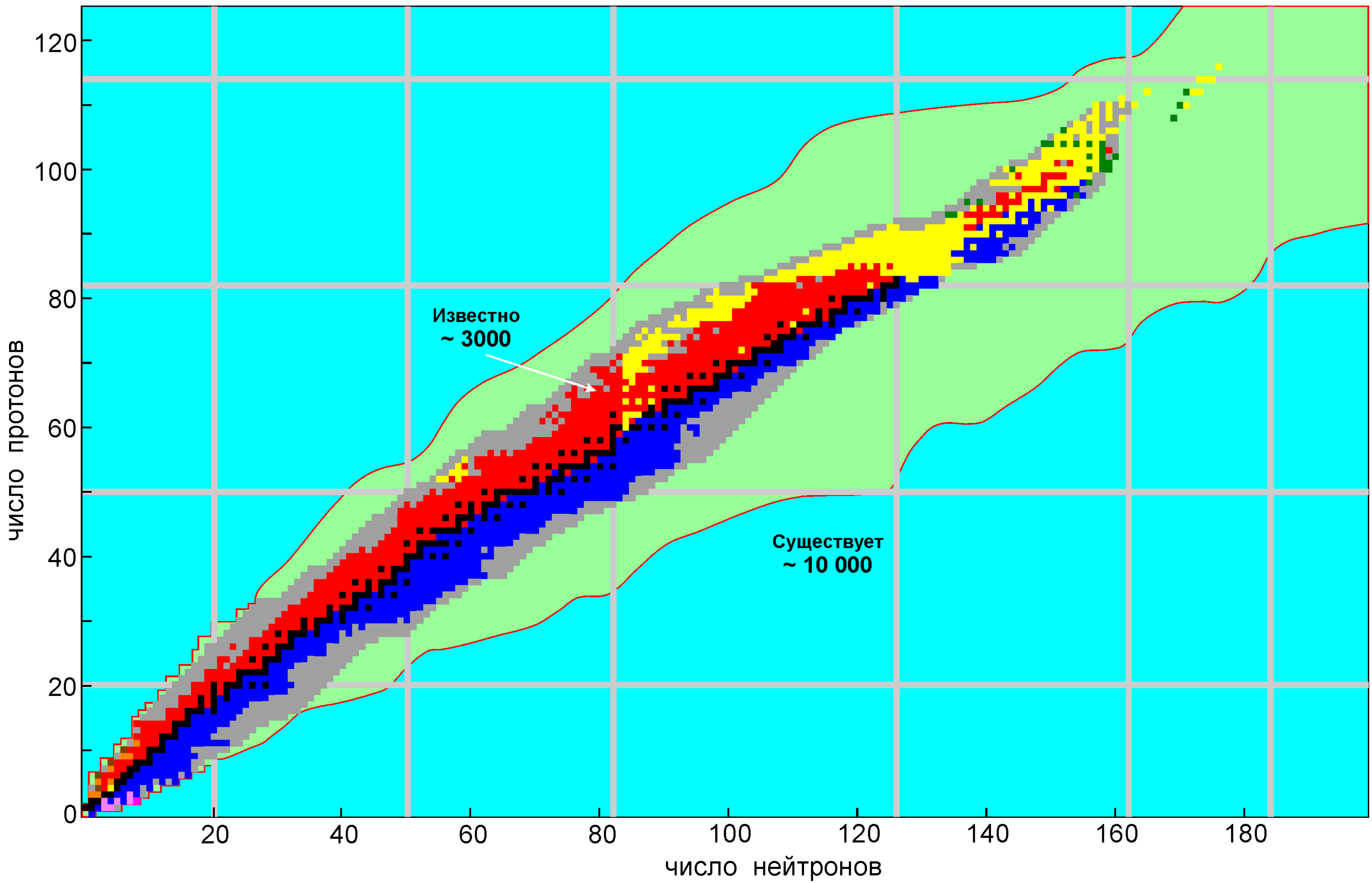
Лантаноиды Lanthanides

Церий Ce $4f^15d^1$ 140,115 Cerium	Празеодим Pr $4f^3$ 140,90765 Praseodymium	Неодим Nd $4f^4$ 144,24 Neodymium	Прометий Pm $4f^5$ [145] Promethium	Самарий Sm $4f^6$ 150,36 Samarium	Европий Eu $4f^7$ 151,965 Europium	Гадолиний Gd $4f^75d^1$ 157,25 Gadolinium	Тербий Tb $4f^9$ 158,92534 Terbium	Диспрозий Dy $4f^{10}$ 162,50 Dysprosium	Гольмий Ho $4f^{11}$ 164,93032 Holmium	Эрбий Er $4f^{12}$ 167,26 Erbium	Тулий Tm $4f^{13}$ 168,93421 Thulium	Иттербий Yb $4f^{14}$ 173,04 Ytterbium	Лютеций Lu $4f^{14}5d^1$ 174,967 Lutetium

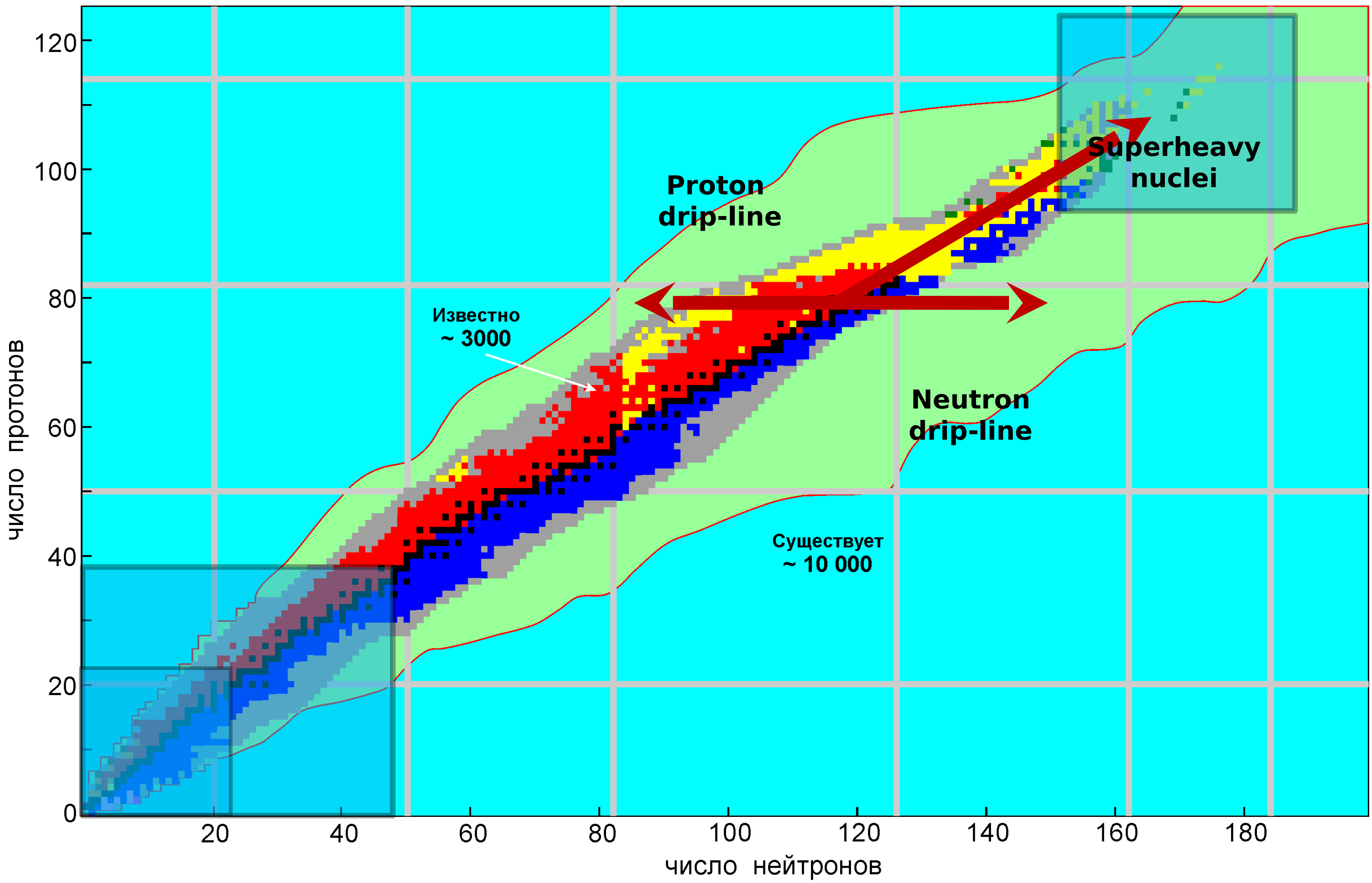
Актиноиды Actinides

Торий Th $7s^26d^2$ 232,0381 Thorium	Протактиний Pa $5f^26d^1$ 231,03588 Protactinium	Уран U $5f^36d^1$ 238,0289 Uranium	Нептуний Np $5f^46d^1$ [237] Neptunium	Плутоний Pu $5f^6$ [244] Plutonium	Америций Am $5f^7$ [243] Americium	Кюрий Cm $5f^76d^1$ [247] Curium	Берклий Bk $5f^9$ [247] Berkelium	Калифорний Cf $5f^{10}$ [251] Californium	Эйнштейний Es $5f^{11}$ [252] Einsteinium	Фермий Fm $5f^{12}$ [257] Fermium	Менделевий Md $5f^{13}$ [258] Mendelevium	Нобелий No $5f^{14}$ [259] Nobelium	Лоуренсий Lr $5f^{14}6d^1$ [262] Lawrencium

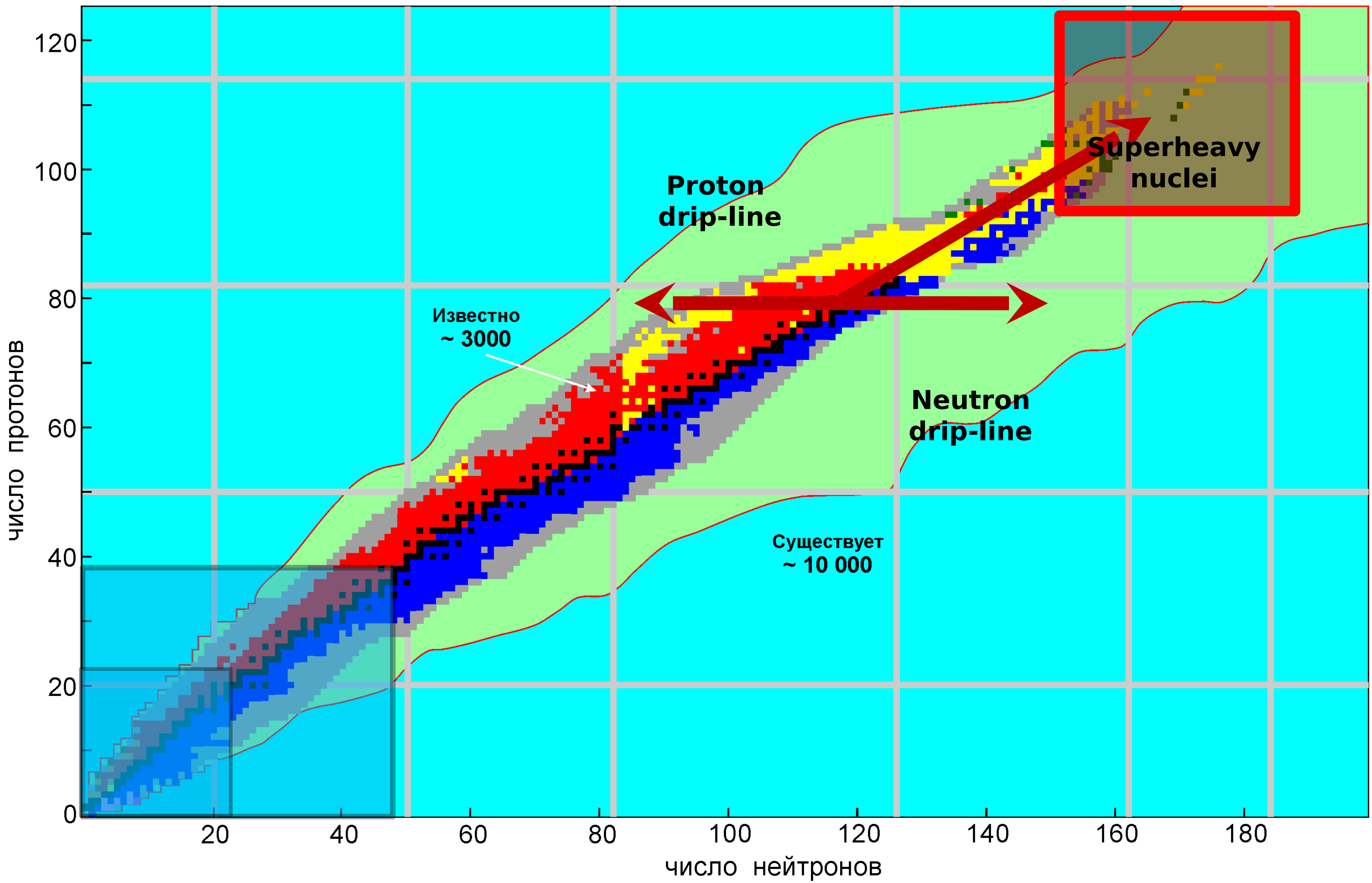
The same Periodic table of elements



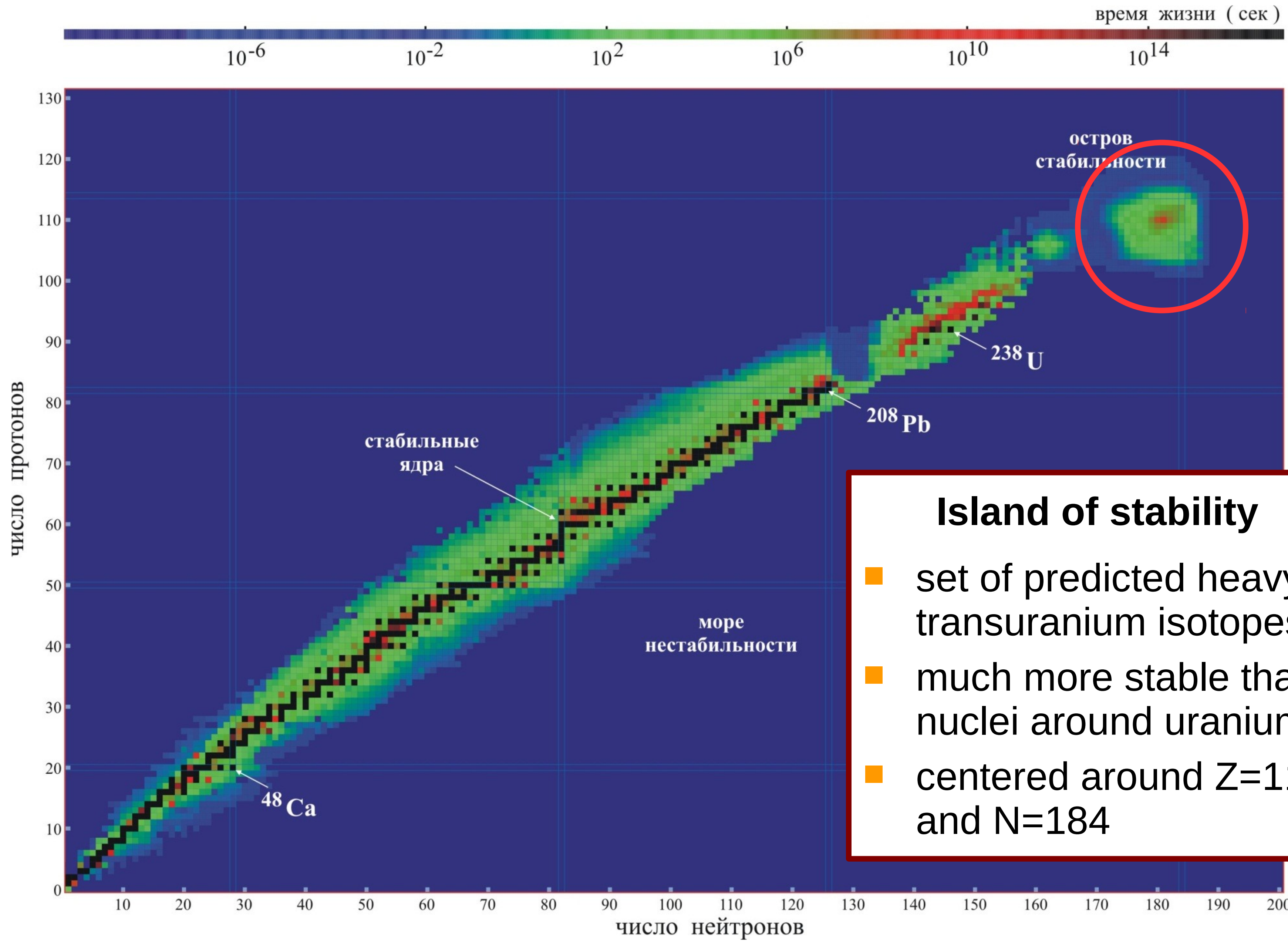
Fields of interest



Superheavy elements



Island of stability…



Island of stability

- set of predicted heavy transuranium isotopes
- much more stable than nuclei around uranium
- centered around Z=114 and N=184

...and to the Island of Stability

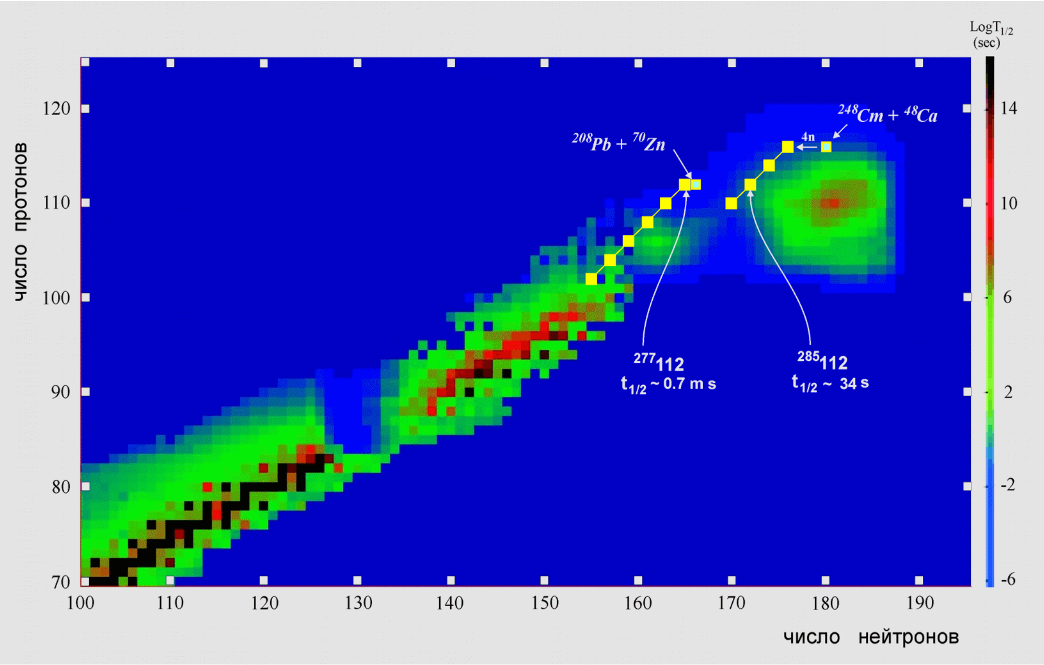
synthesis of superheavies

$$Z_1 + Z_2 = Z$$

$$N_1 + N_2 = N + (2 - 4)\mathrm{n}$$

“cold” fusion: Pb + heavy ion

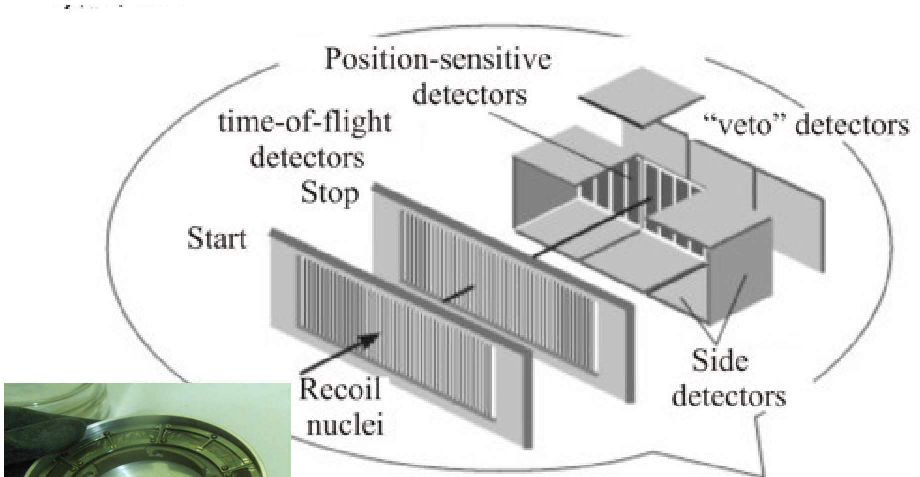
“hot” fusion: light beam + heavy target

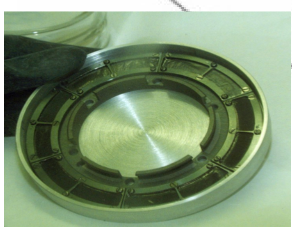


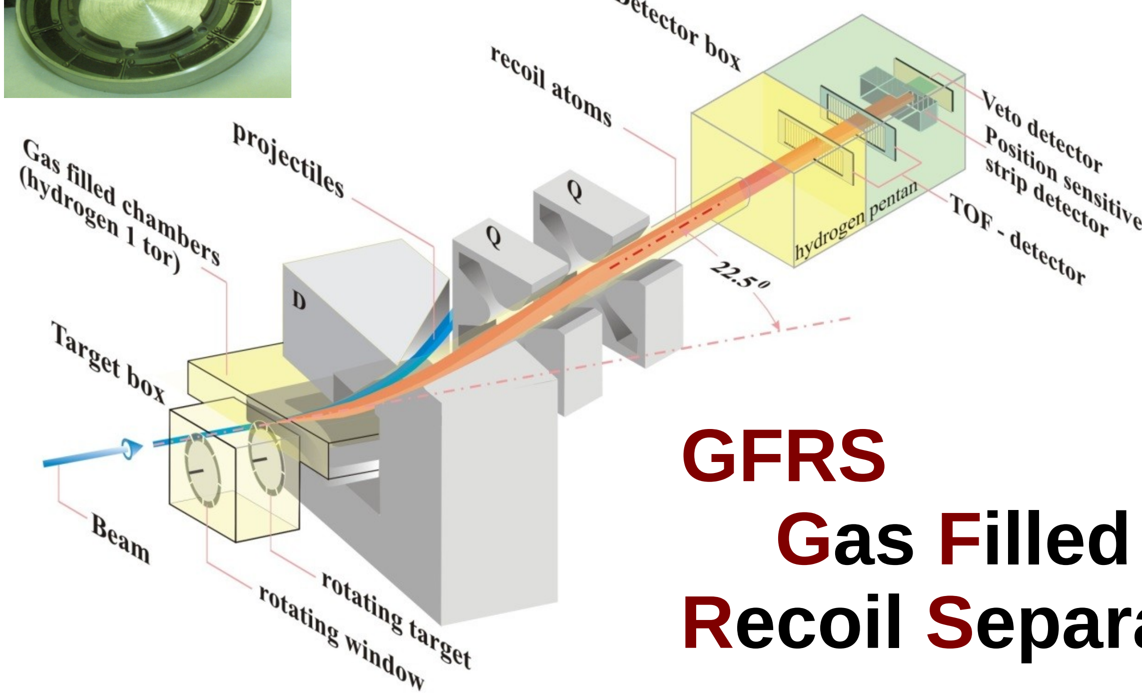
- low-energy physics
- compound nucleus
- combination of light and heavy nuclei gives higher cross sections

Synthesis of superheavies

collaboration of ORNL (USA) and JINR



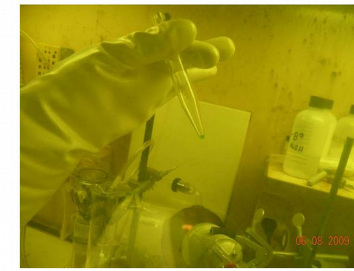




beams

^{48}Ca, ^{50}Ti, ^{64}Ni

254 MeV; 10^{11} pps



$Bk(NO_3)_3$Product

targets

^{249}Bk (117), ^{251}Cf (118)

$T_{1/2}$ = 330 d, 900 y

Prices per 1 mg

^{197}Au ≈ 0.05 $

^{239}Pu ≈ 4 $

^{48}Ca ≈ 80 $

^{249}Cf ≈ 60,000 $

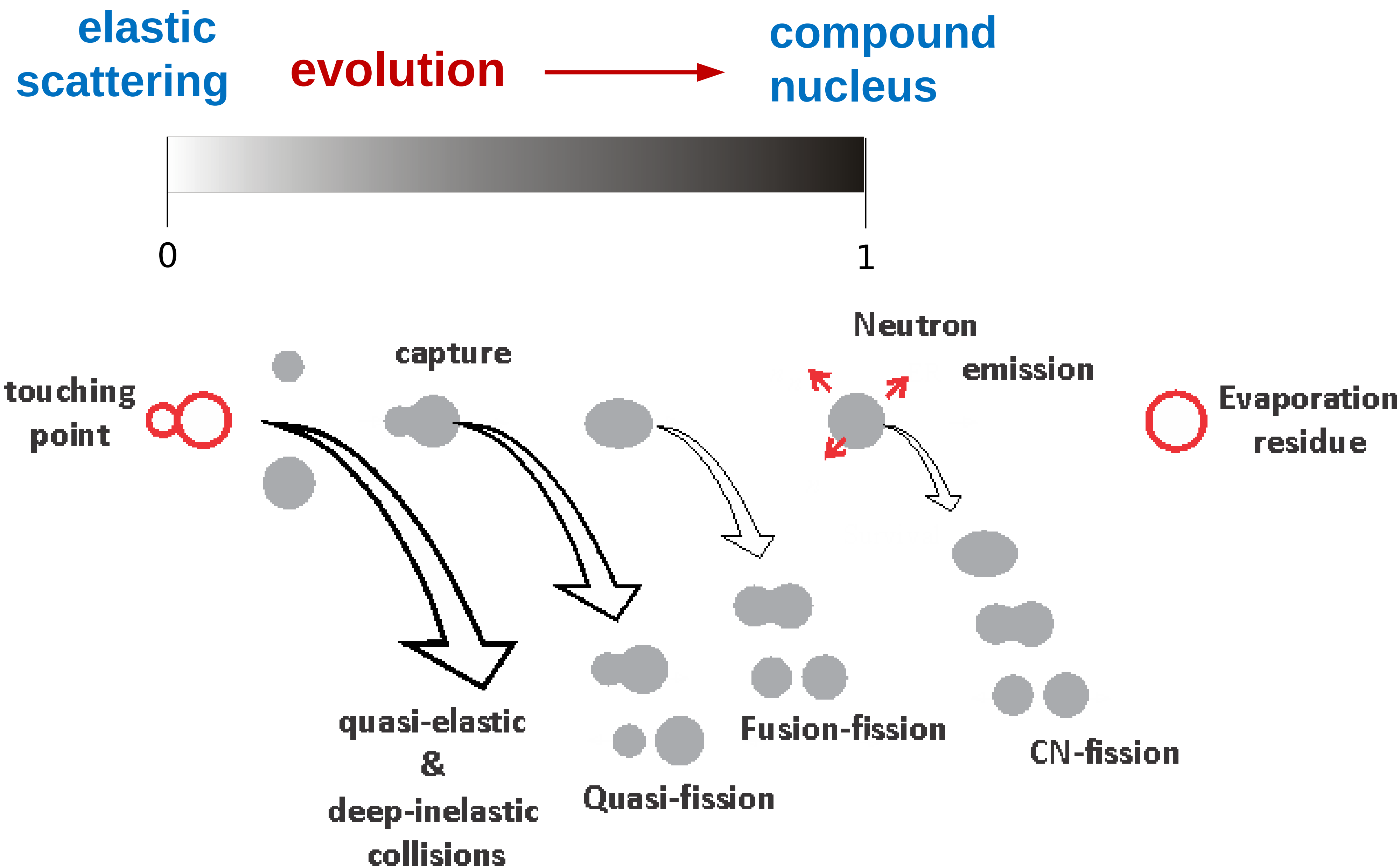
GFRS

Gas Filled Recoil Separator

recently synthesized

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

Scale of inelasticity



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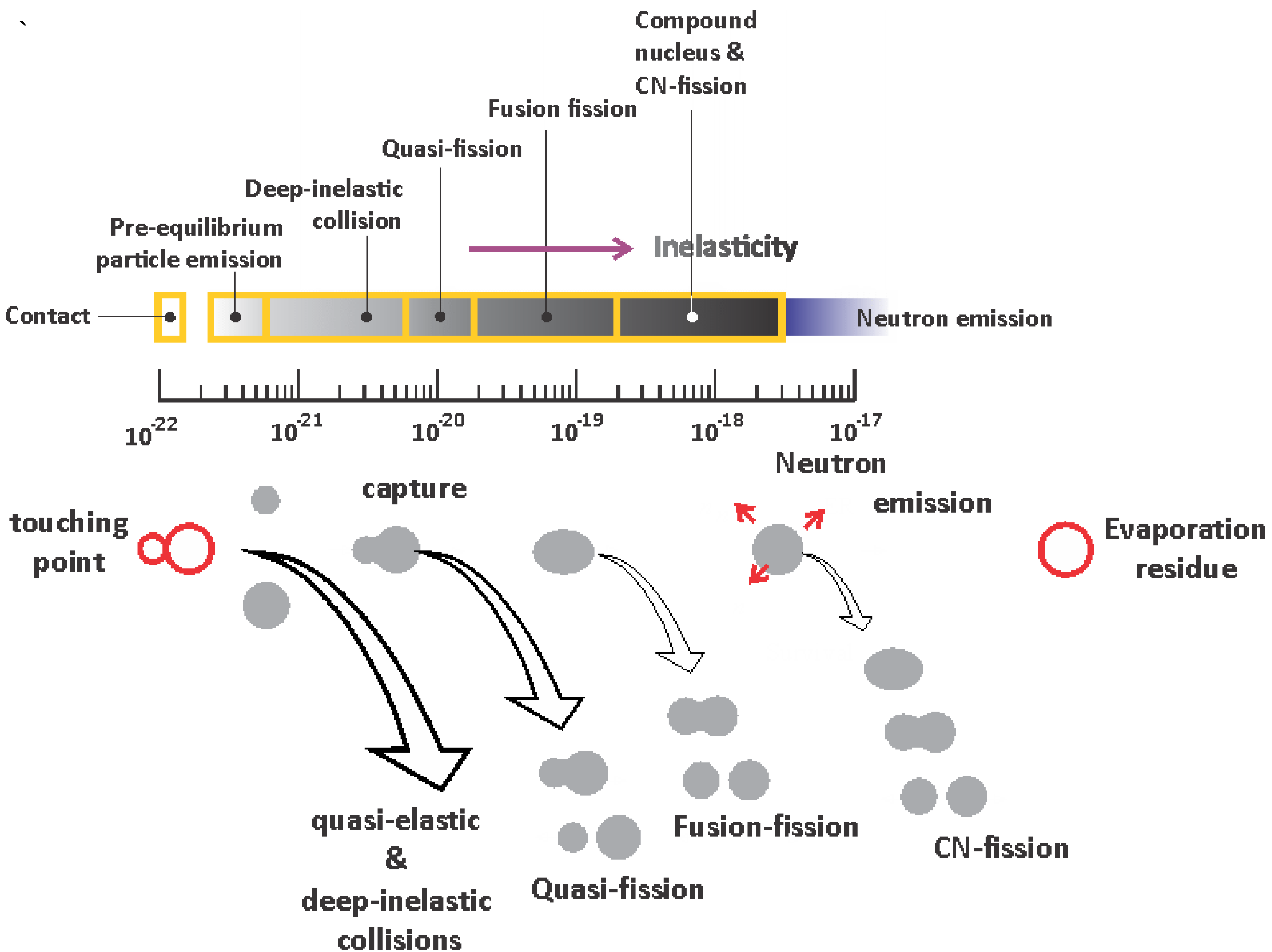
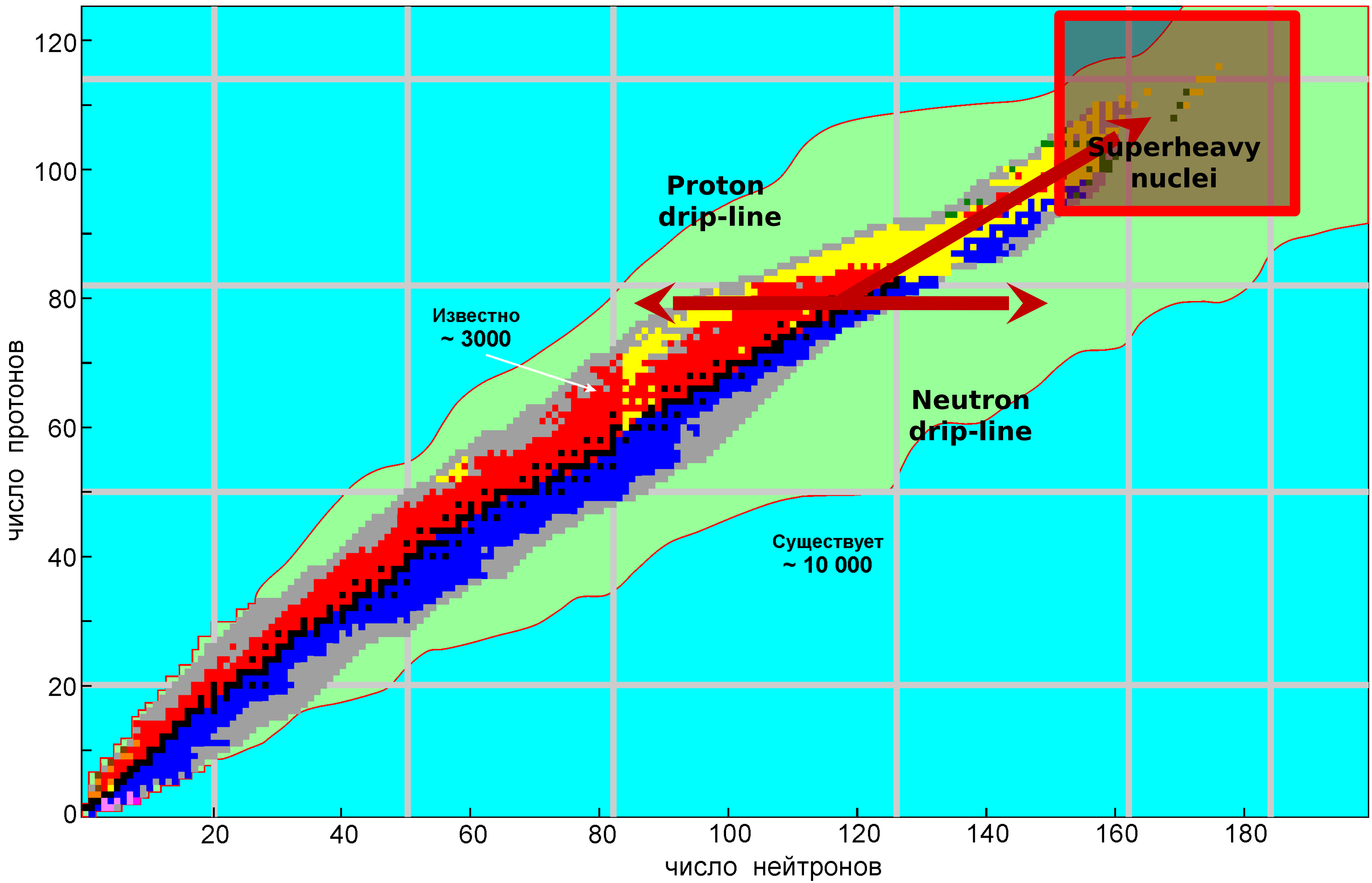
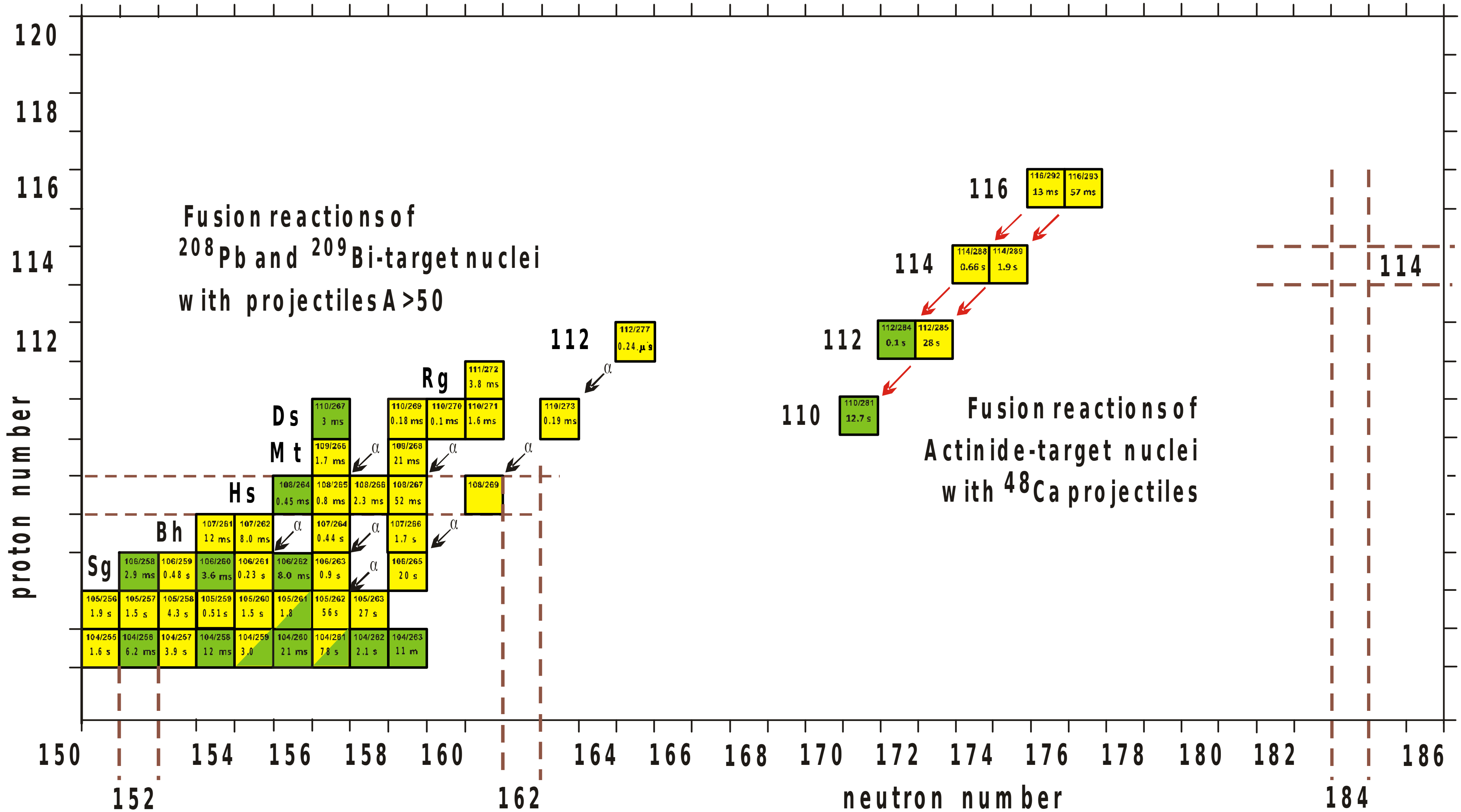


Compound nucleus & CN-fission
Fusion fission
Quasi-fission
Deep-inelastic collision
Pre-equilibrium particle emission
Inelasticity
Contact
Neutron emission
10^{-22}
10^{-21}
10^{-20}
10^{-19}
10^{-18}
10^{-17}
Neutron emission
capture
touching point
Evaporation residue
quasi-elastic & deep-inelastic collisions
Quasi-fission
Fusion-fission
CN-fission

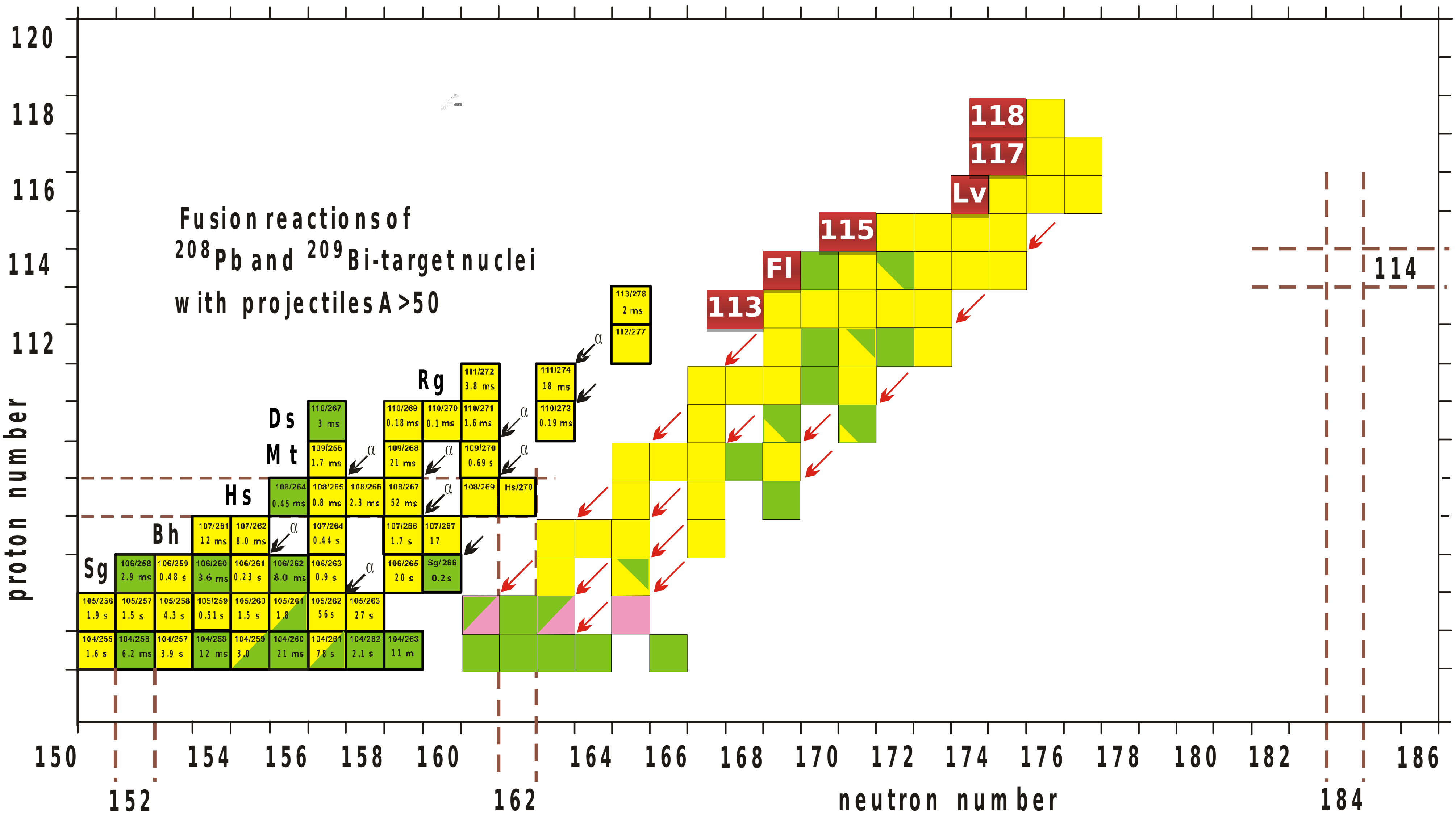
Superheavy elements



Superheavies in 2000

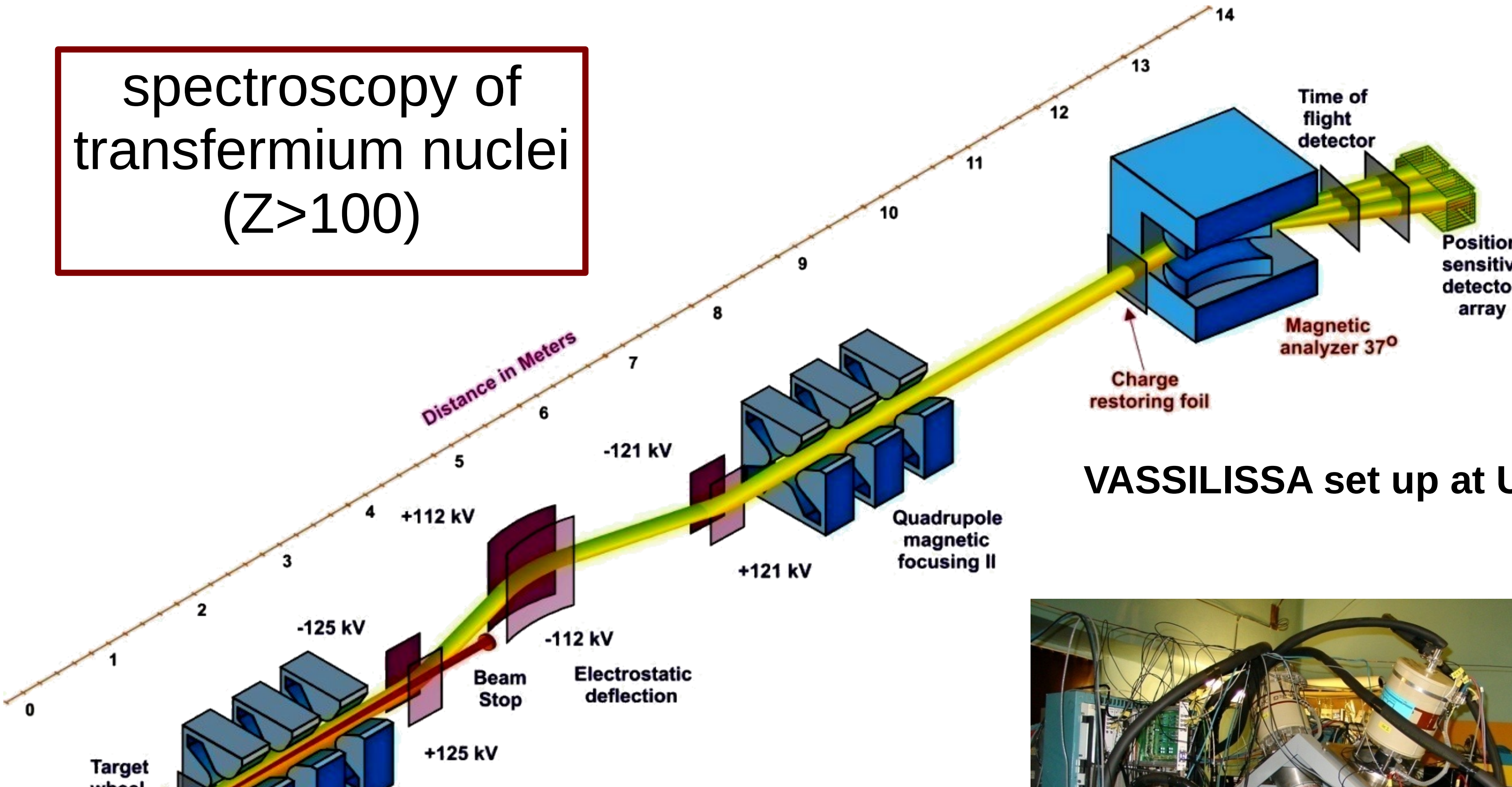


Superheavies in 2015

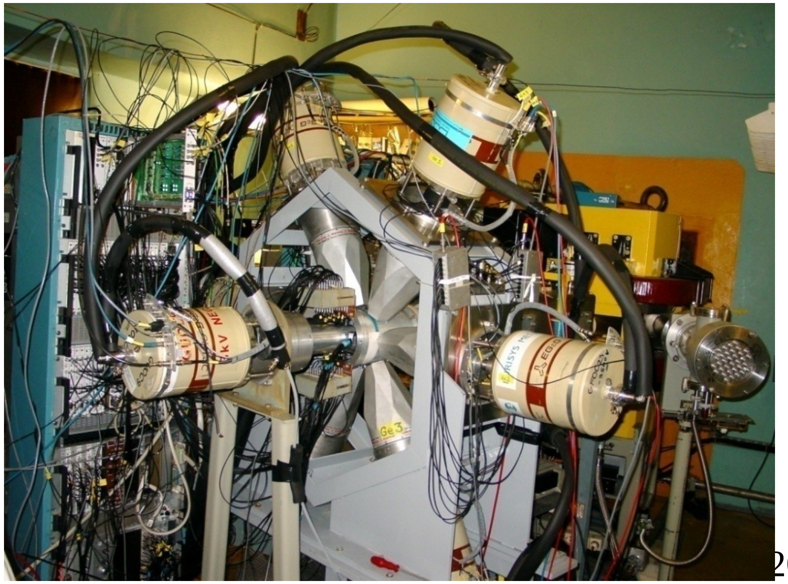


Spectroscopy of superheavies

spectroscopy of transfermium nuclei (Z>100)



VASSILISSA set up at U400



GABRIELA: Gamma Alpha Beta Recoil Investigation with the Electromagnetic Analyser

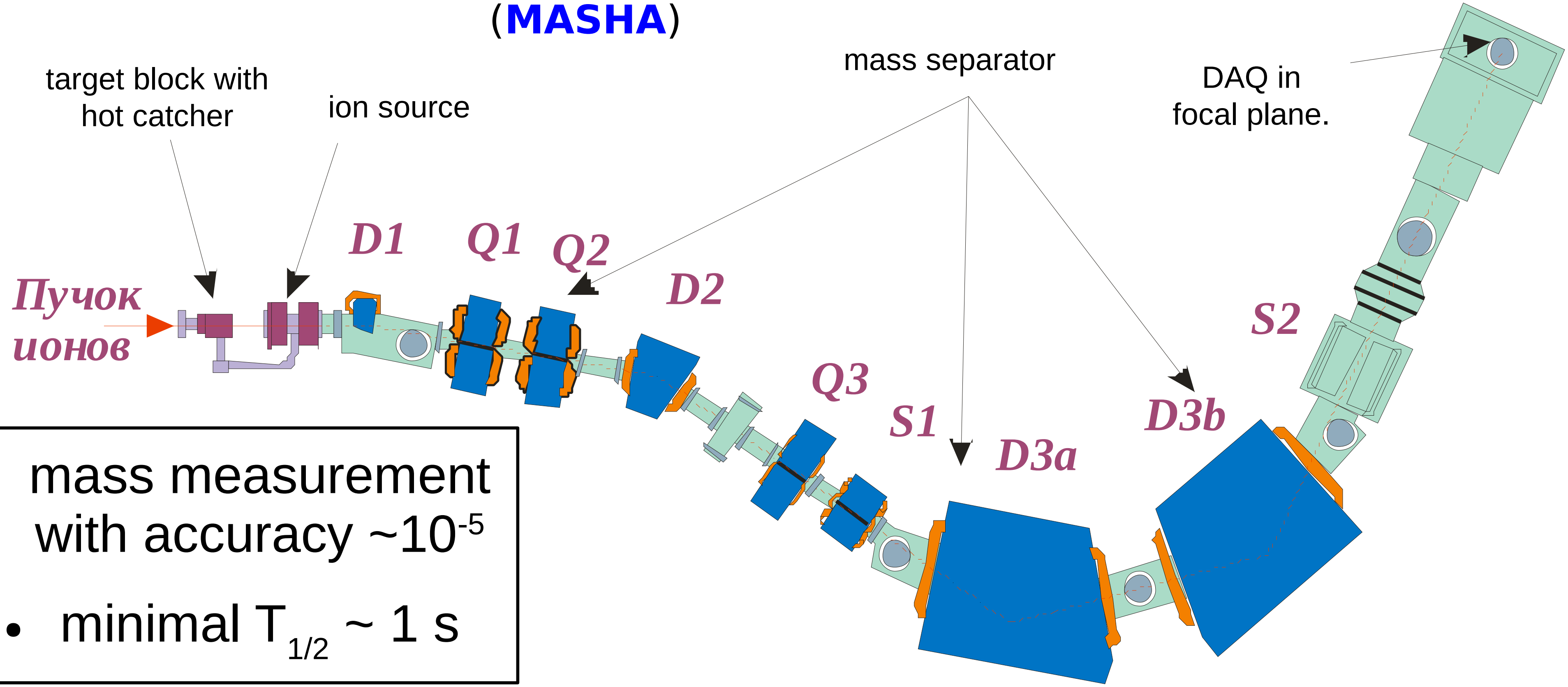
Mass spectrometry of superheavies

alpha-spectroscopy of transuranium elements

focal plane silicon multistrip detector

Mass **A**nalyzer of **S**uper **H**eavy **A**toms

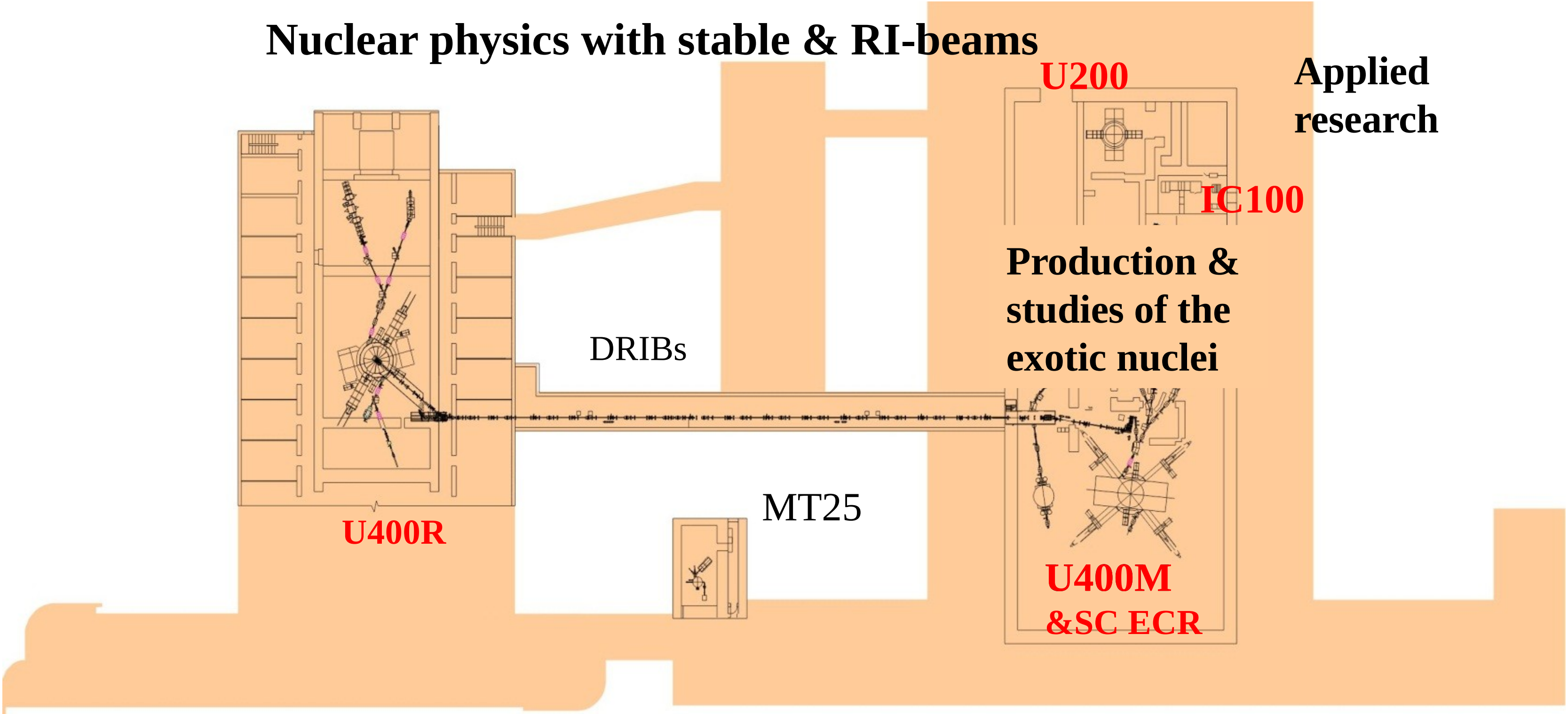
(**MASHA**)



- mass measurement with accuracy ~10^{-5}
- minimal $T_{1/2}$ ~ 1 s

Superheavy elements factory

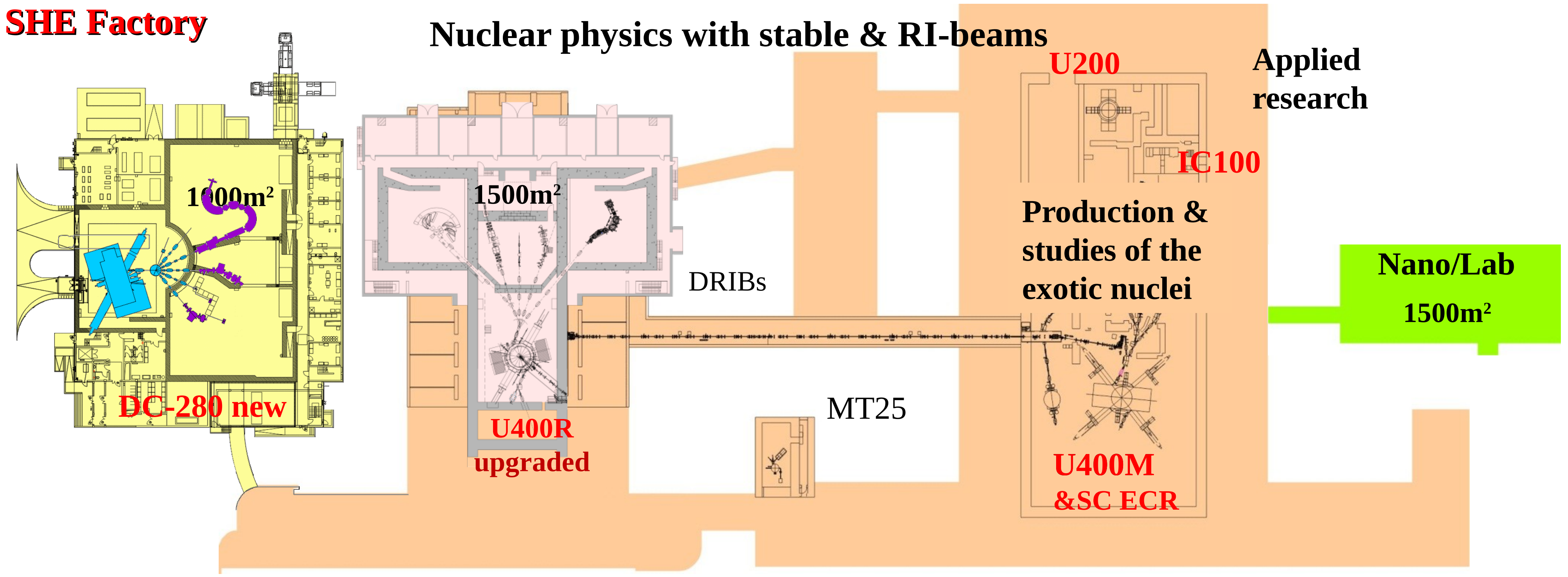
Current state of FLNR



Superheavy elements factory

Full-scale realization off the DRIBs-III

Dubna Radioactive Beams



targets

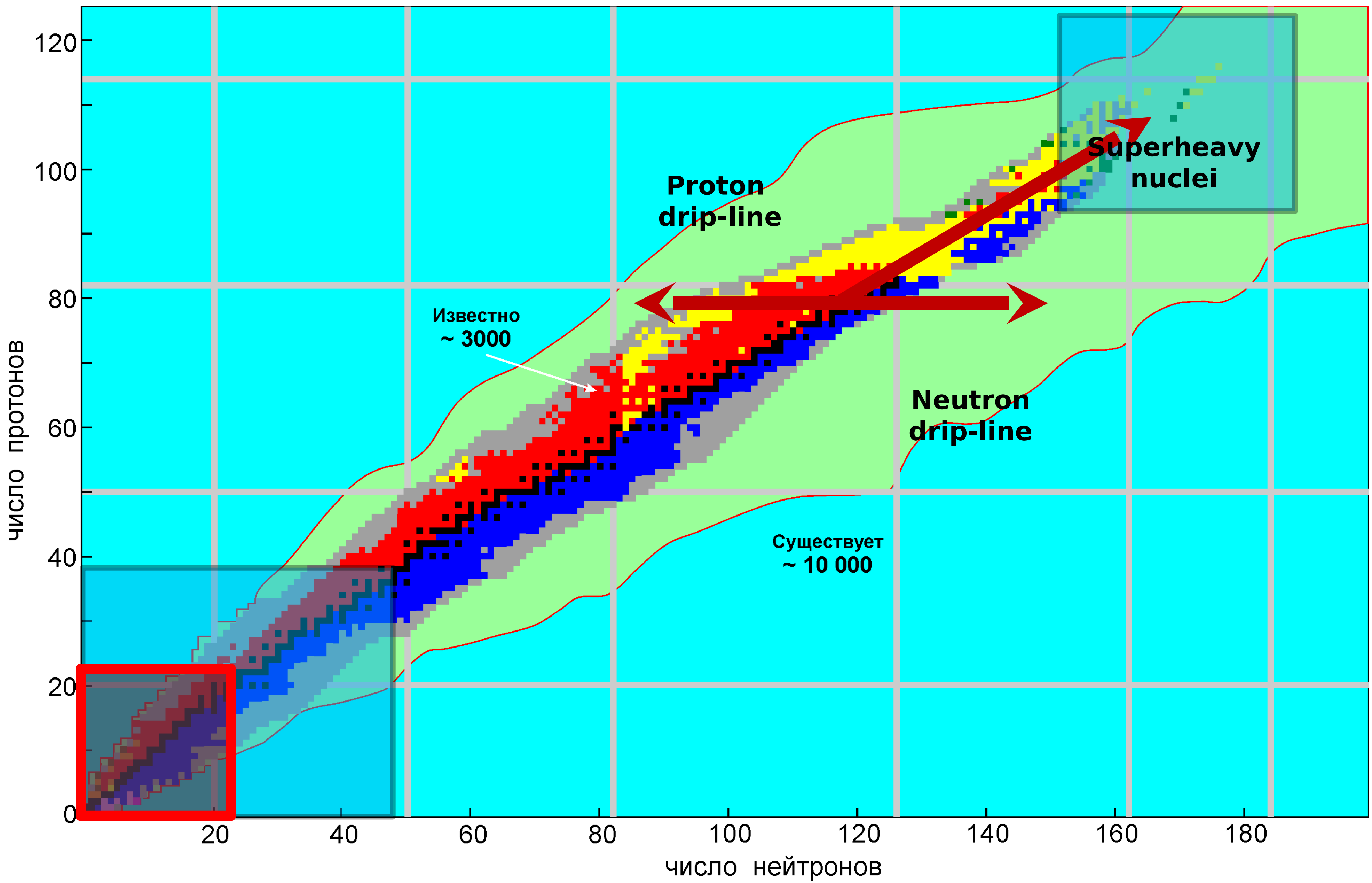
^{251}Cf, ^{254}Es, …?

beams

^{48}Ca; ^{50}Ti; ^{54}Cr; ^{58}Fe; ^{64}Ni

$I_{beam} > 10^{14}$ pps

Light exotic nuclei



Light exotic nuclei

- **light:** let's say Z = 1 – 20
- **exotic:** close to the „drip-lines“
- **large excess of protons or neutrons**
- **many interesting effects**

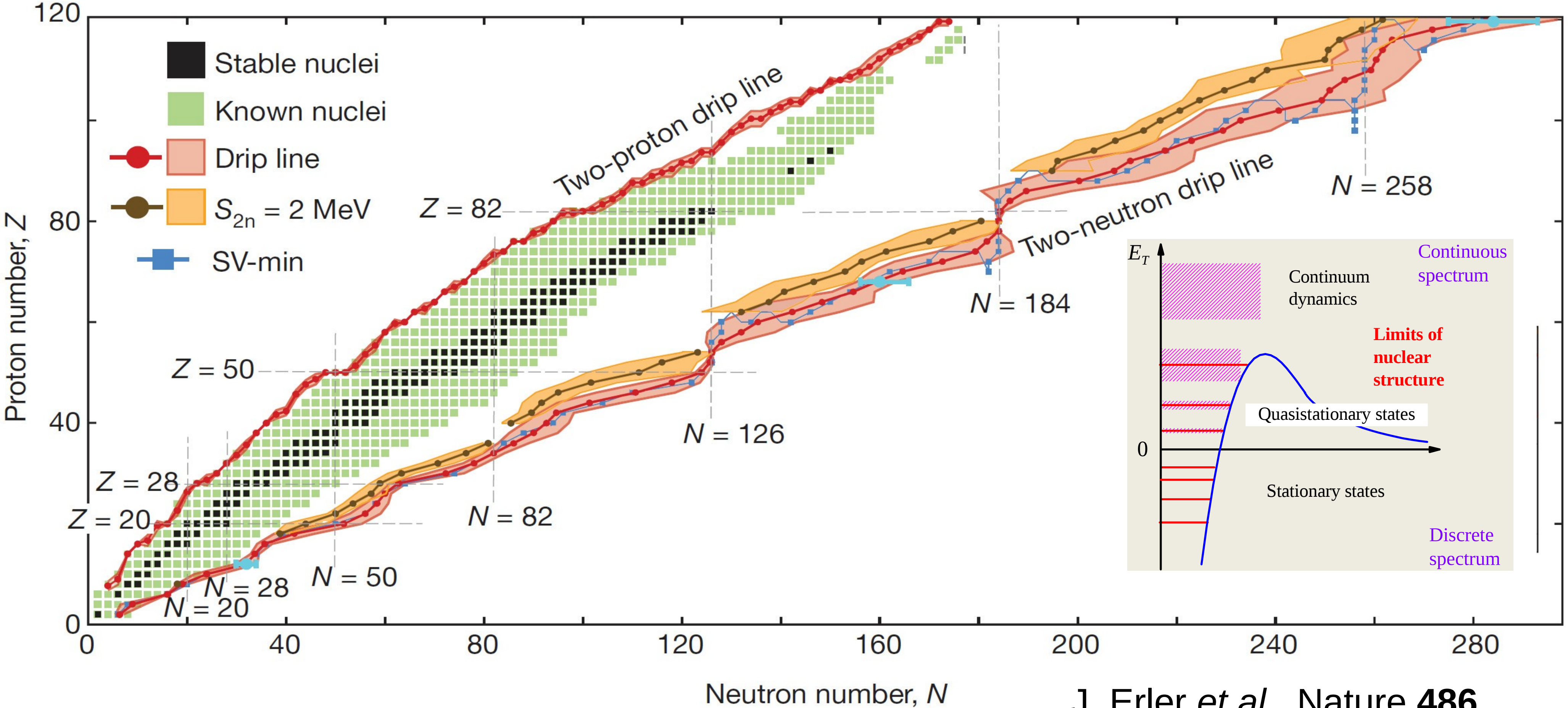
First observation of ^{6}He

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

Observation of large ^{6}He radius

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

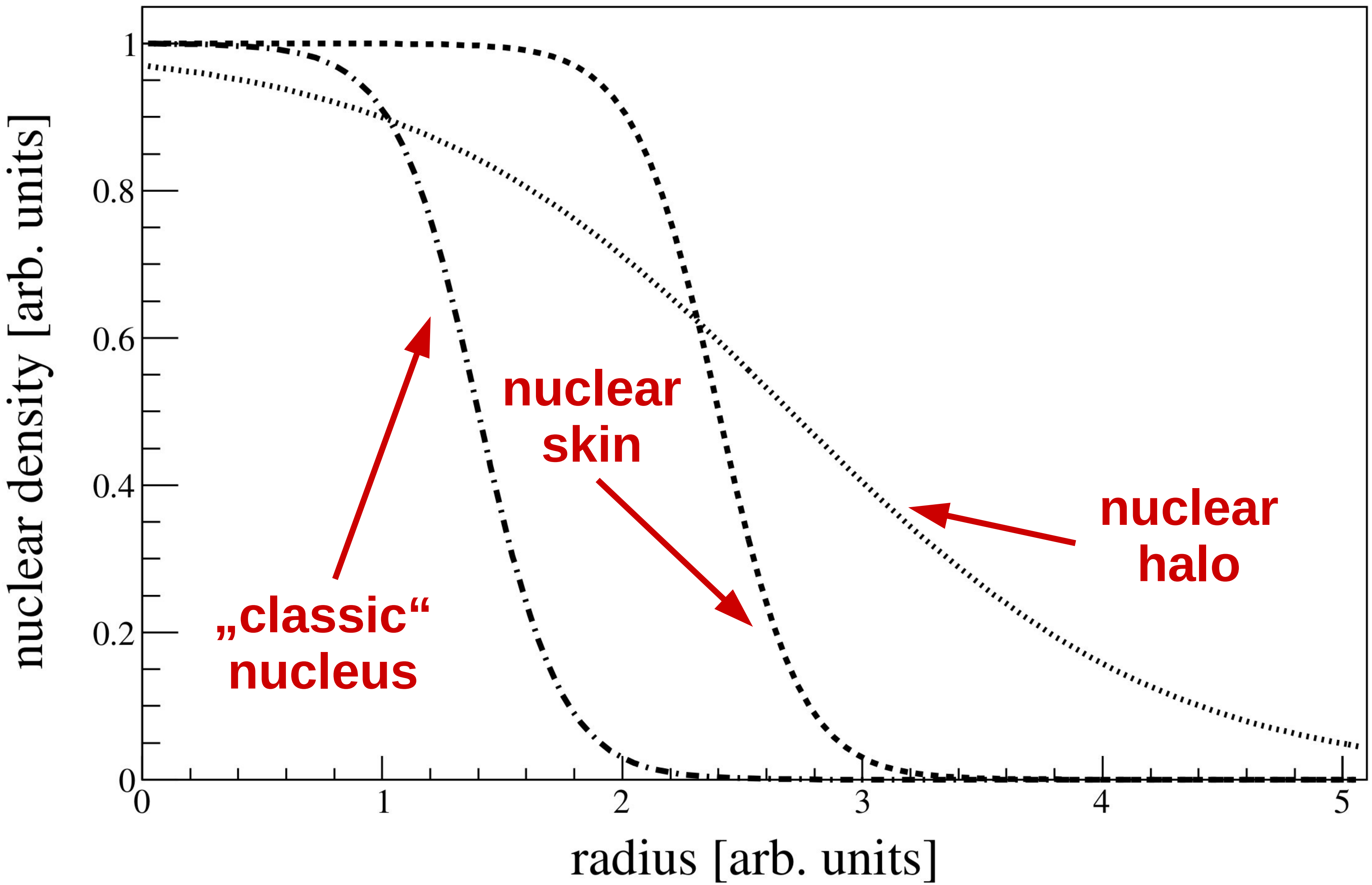
Drip-line



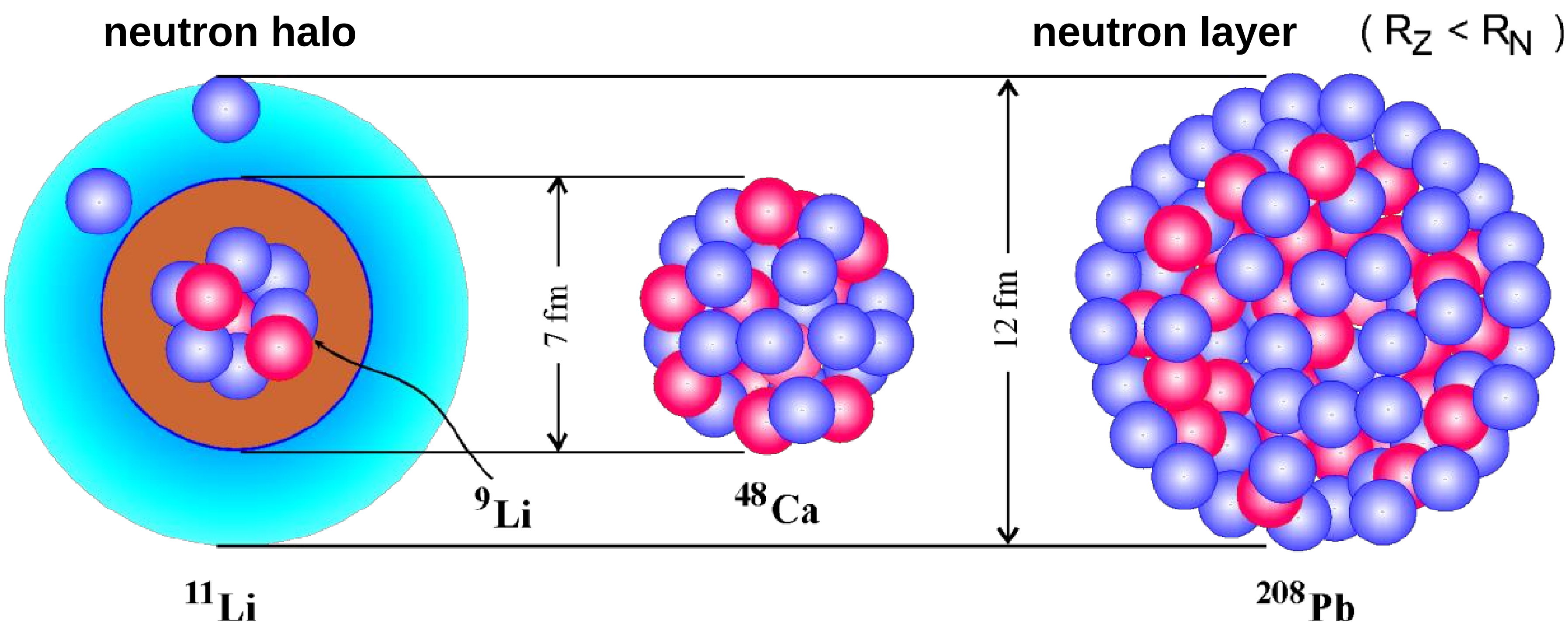
J. Erler *et al.*, Nature **486** (2012) 509

- **boundary of nuclear stability**
- **immediate emission of nucleon**

Nuclear halo



Nuclear halo



- **tunneling to the forbidden regions**
- **extended size of nucleus**
- **strange spatial distribution**

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

Nuclear halo

Stable nuclei

$$< r_n^2 >^{1/2} - < r_p^2 >^{1/2} \approx 0.1 fm$$

Exotic nuclei

$$< r_n^2 >^{1/2} - < r_p^2 >^{1/2} \gtrsim 1.5 fm$$

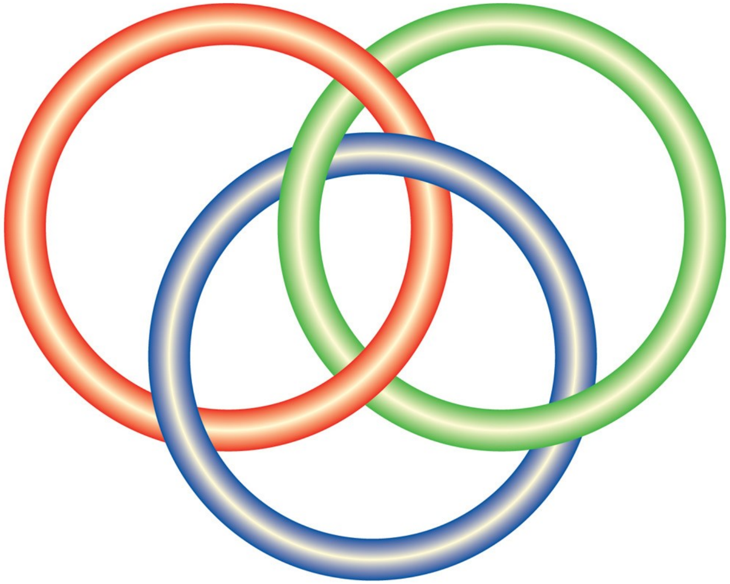
neutron halo

one neutron: ^{11}**Be**, ^{19}**C**
two neutron: ^{6}**He**, ^{11}**Li**, ^{17}**B**, ^{19}**B**, ^{22}**C**
neutron skin: ^{8}**He and** ^{14}**Be**

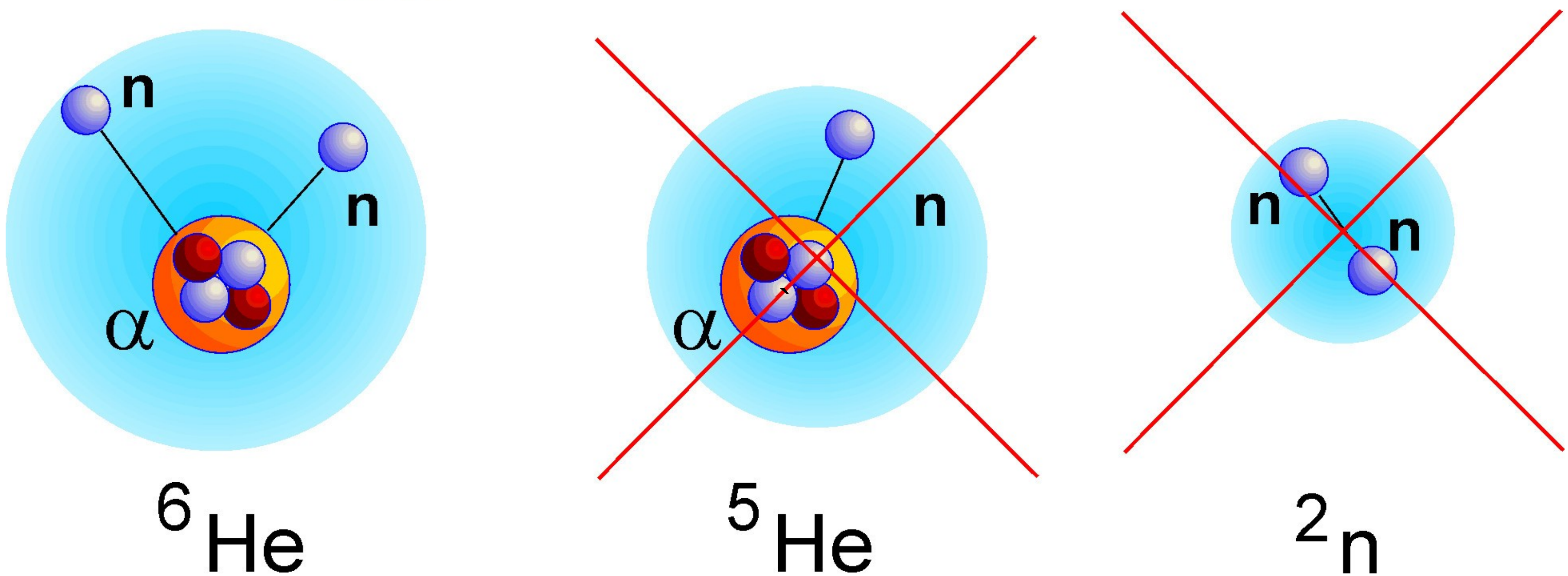
proton halo

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

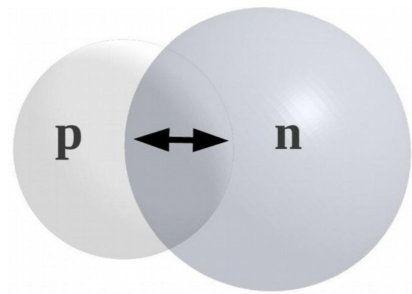
Borromean nuclei



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

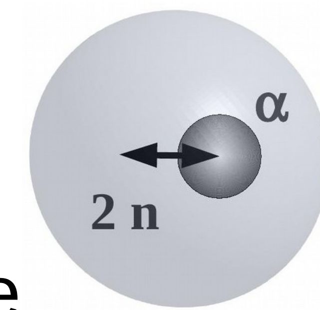


Soft dipole mode (SDM) of Giant dipole resonance (GDR)



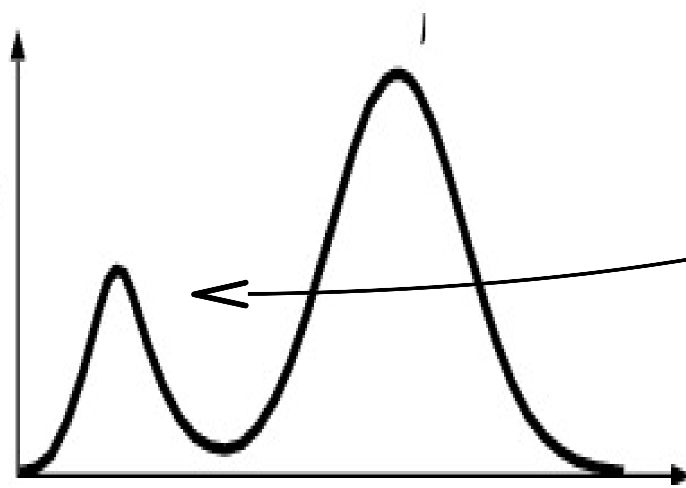
GDR

- protons vs. neutrons
- E_{GDR} ~ 14 – 24 MeV
- induced by EM excitation

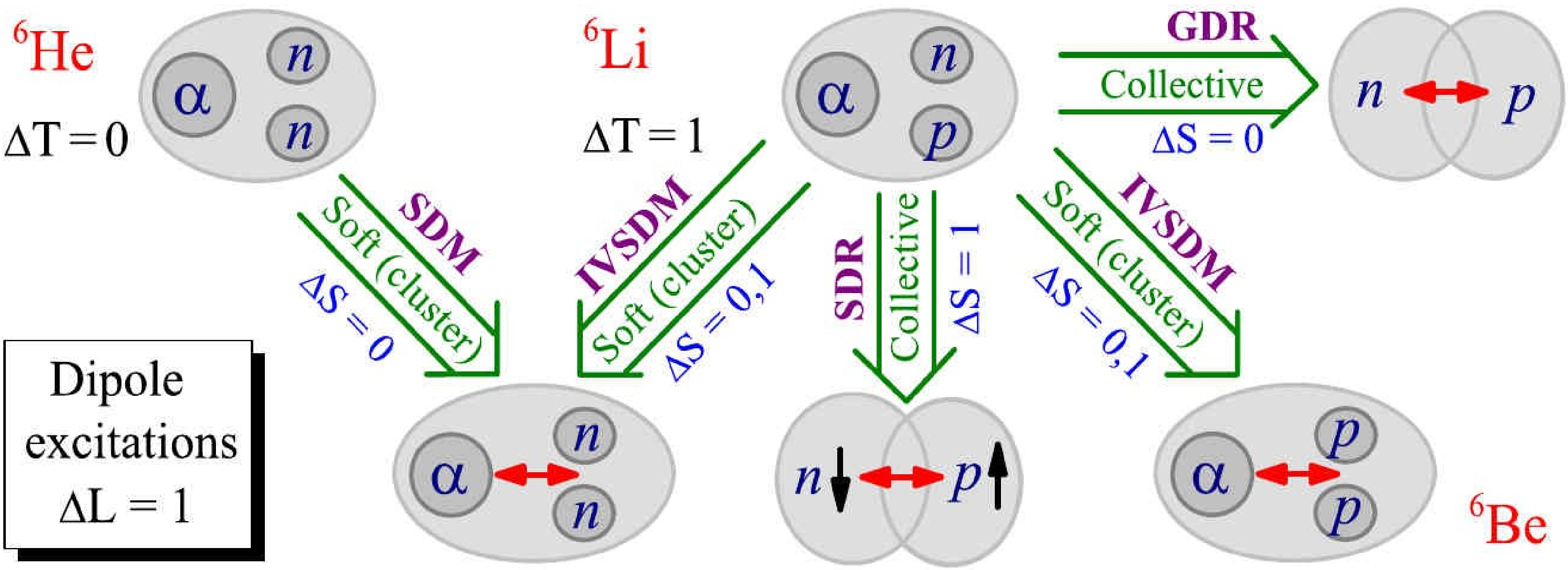


SDM

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



Dipole modes

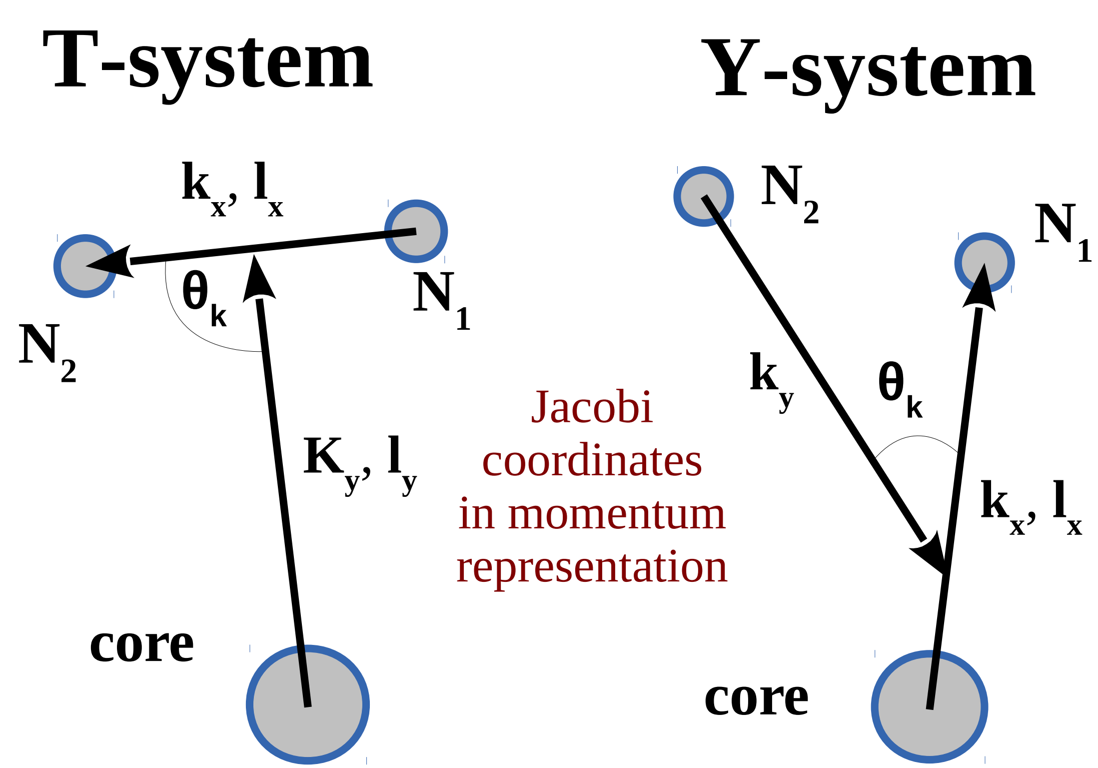


resonance	**vs.**	**mode**
• property of particular nucleus • its population does not depend on reaction mechanism		• characteristic for specific reaction • its population is given by reaction mechanism

3-body systems

2-body vs. 3-body decay

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



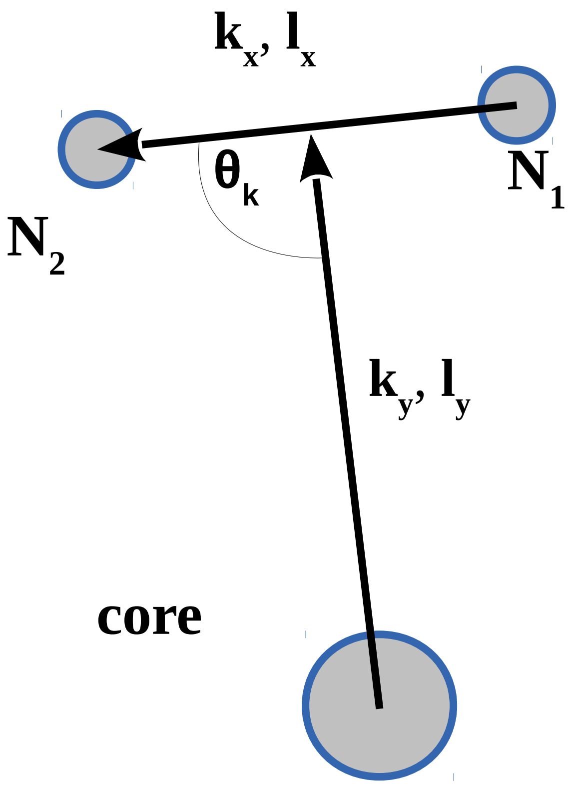
Correlations

- full description of the internal correlations by parameters ε and θ_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

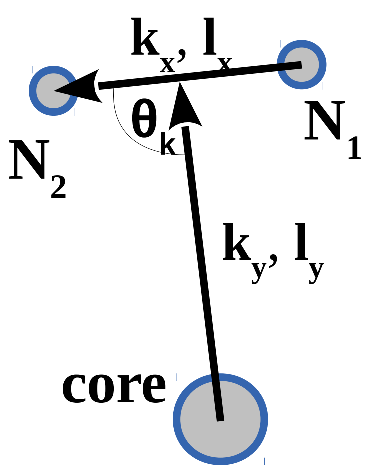


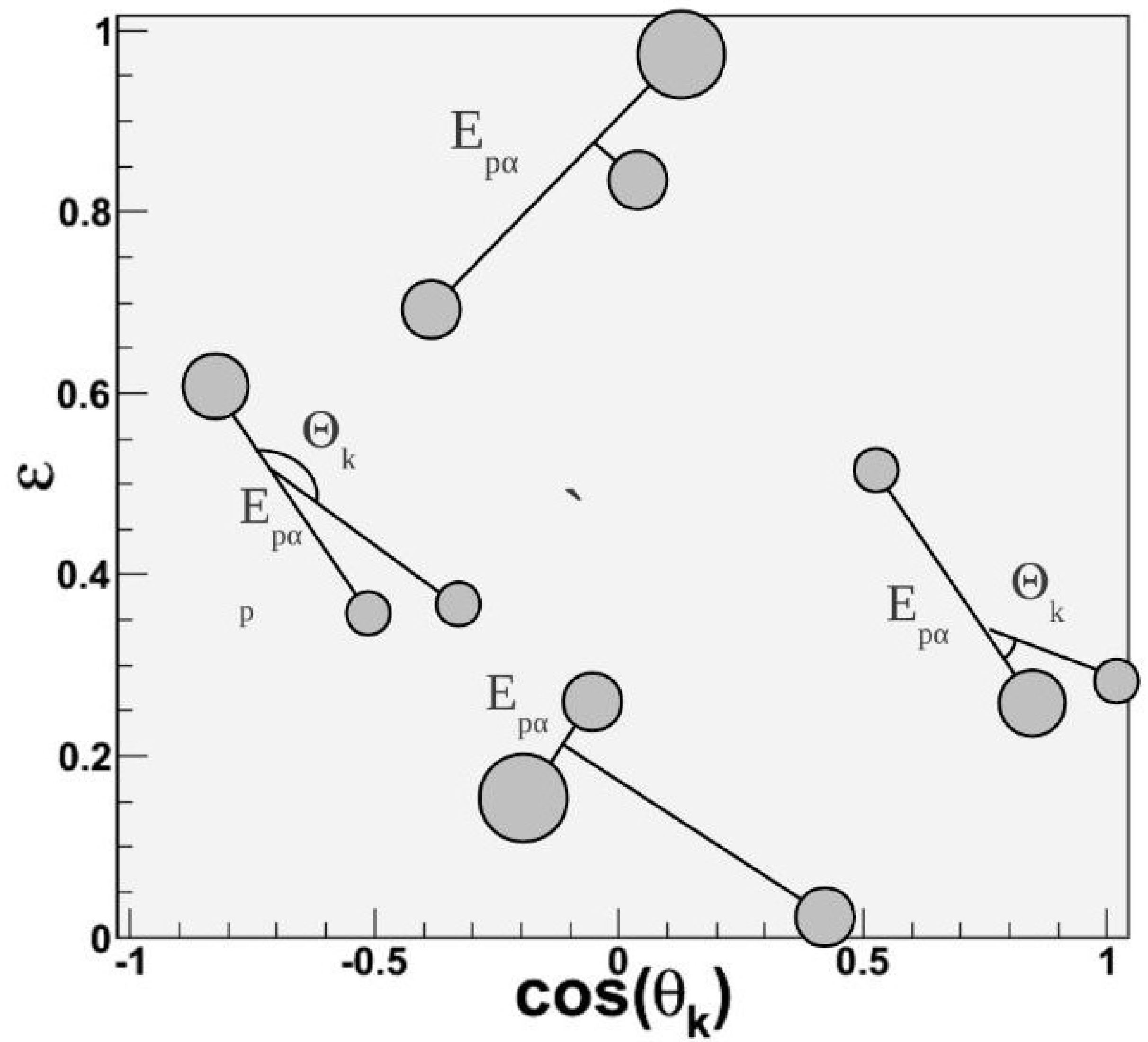
Correlations

- full description of the internal correlations by parameters ε and θ_k

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

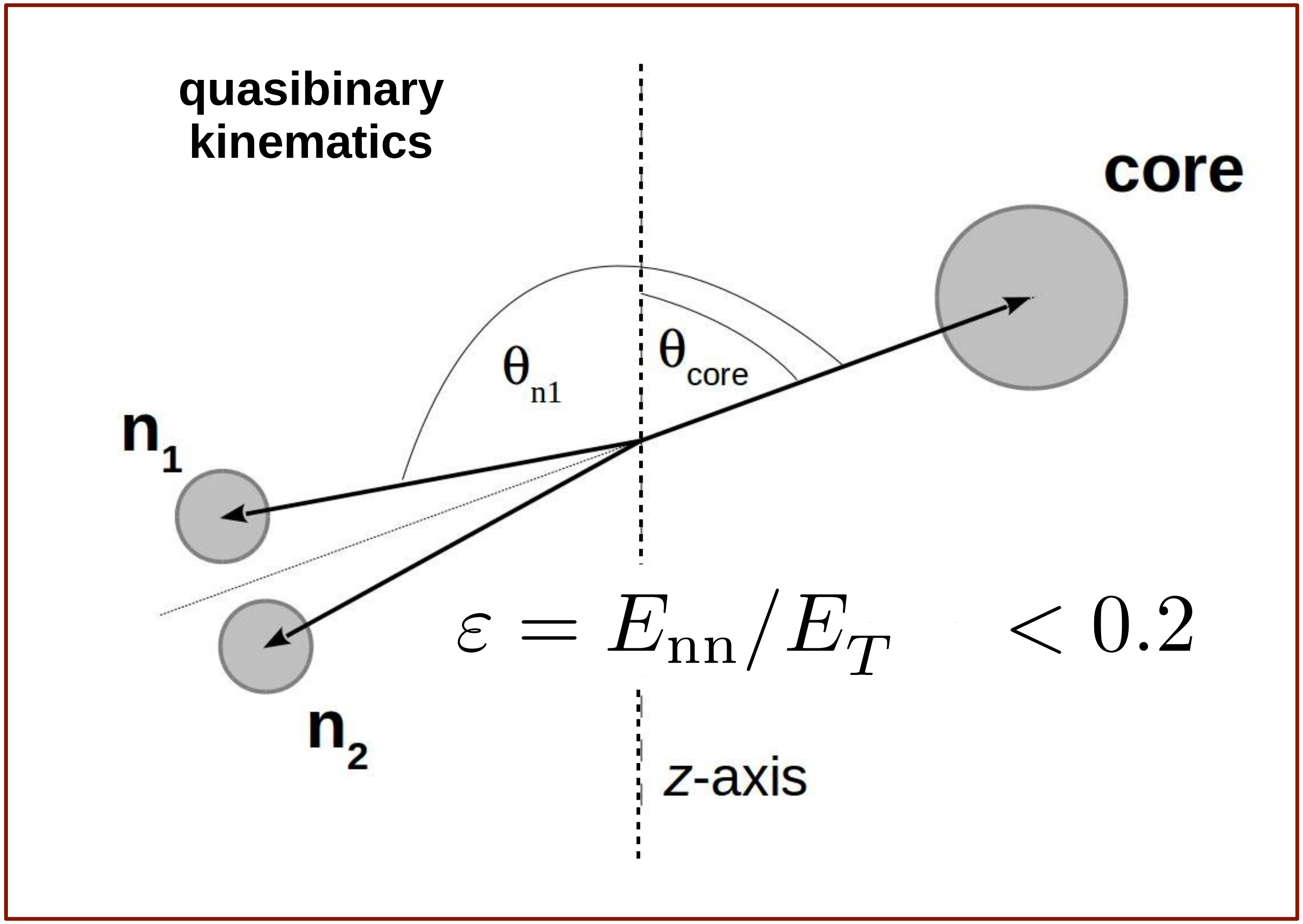
$$\cos\theta_k = \frac{\mathbf{k}_x \cdot \mathbf{k}_y}{k_x k_y}$$

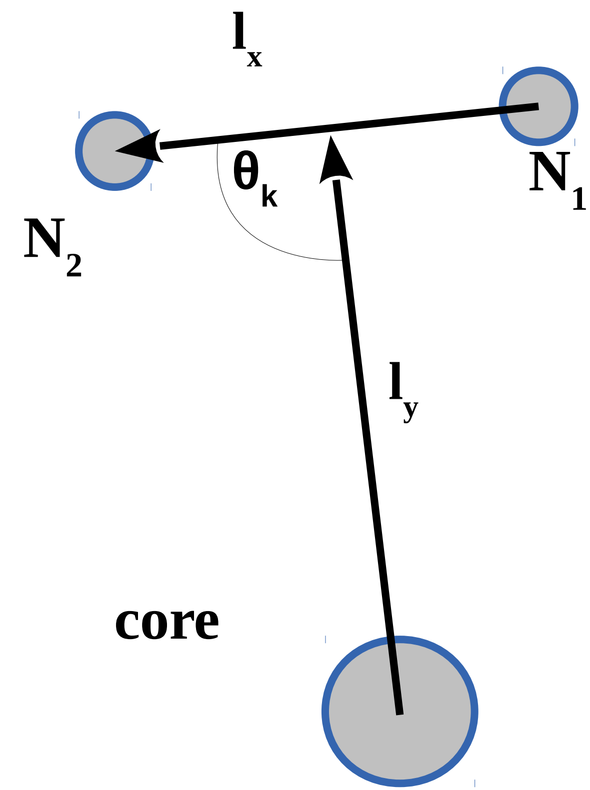




- external correlations: 3-body system orientation

External correlations



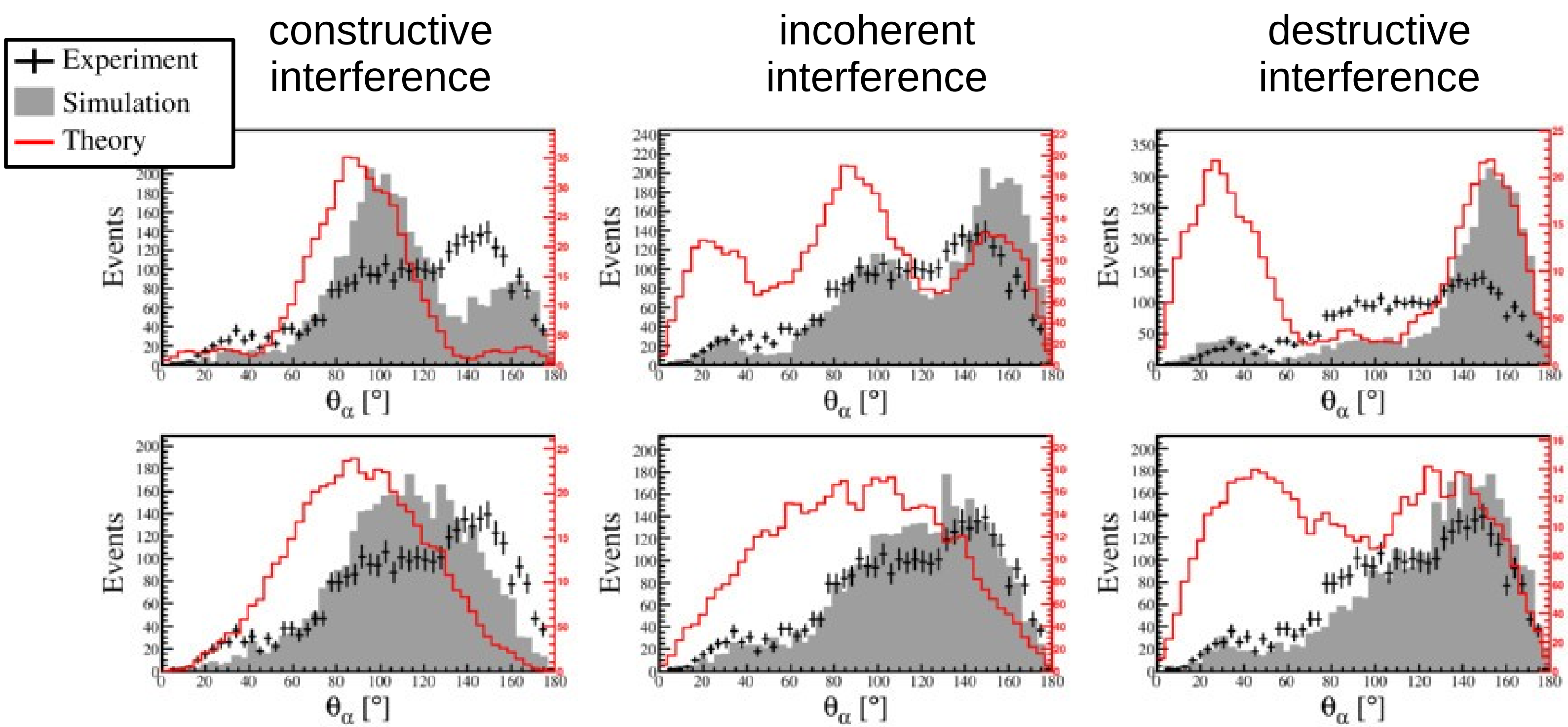


- useful when a few overlapping states present
- total angular momentum is determined by emission angle of the core

Legendre polynomials can be visible

Correlations: examples

^{6}Be
structure



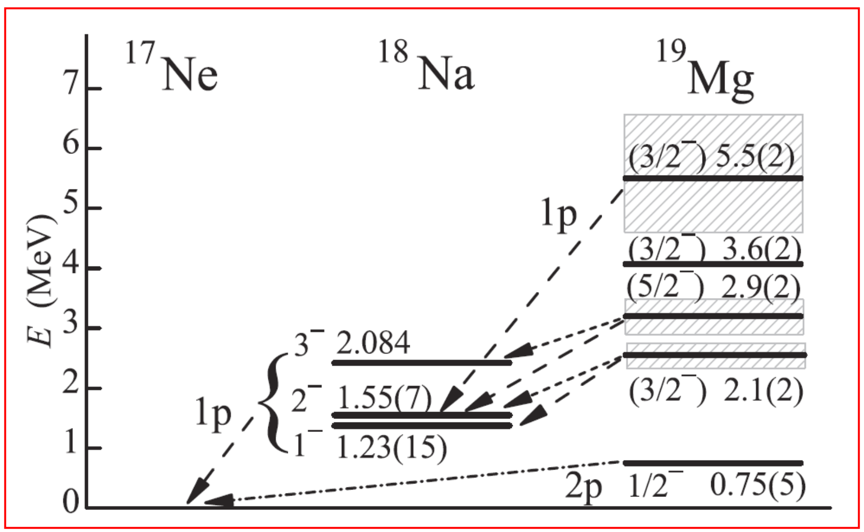
aligned

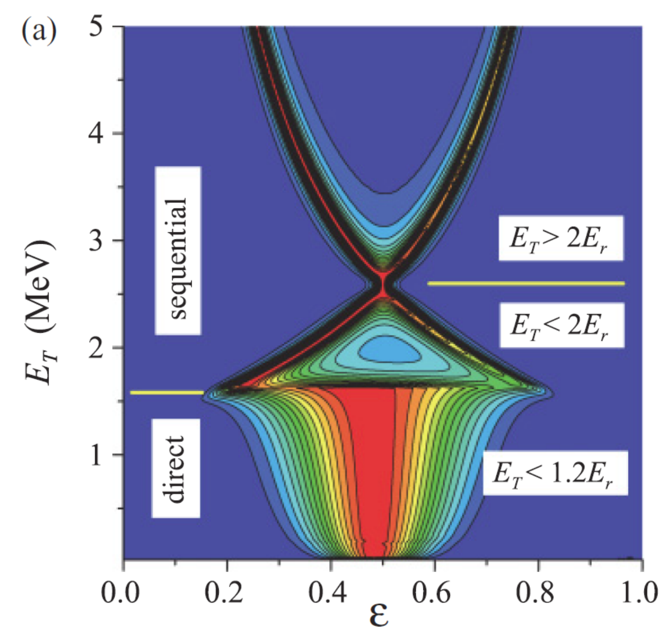
$E_T \in (1.9,2.5)$ MeV
$\theta_{Be} \in (60,75)°$

nonaligned

^{19}Mg
2p-decay

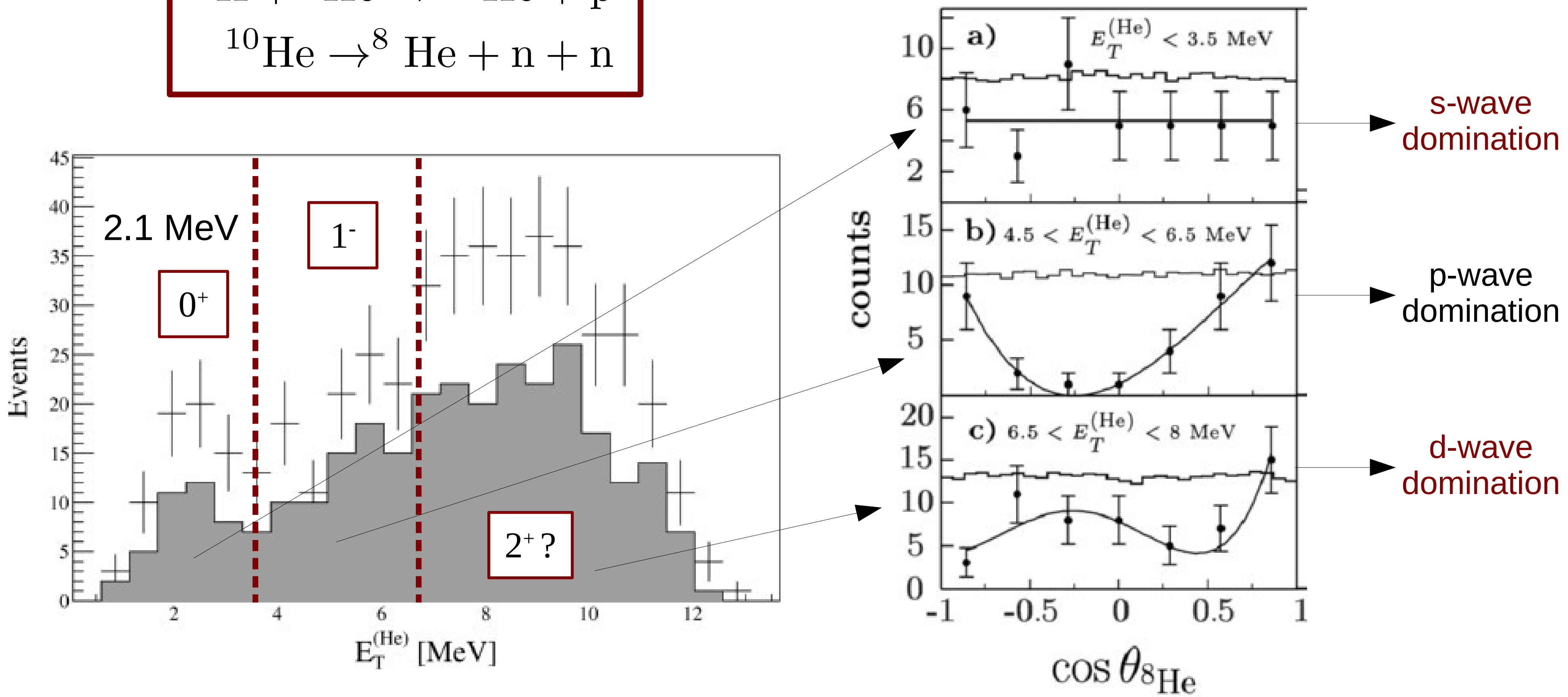
I.Mukha et al., Phys.Rev. C **85** (2012)





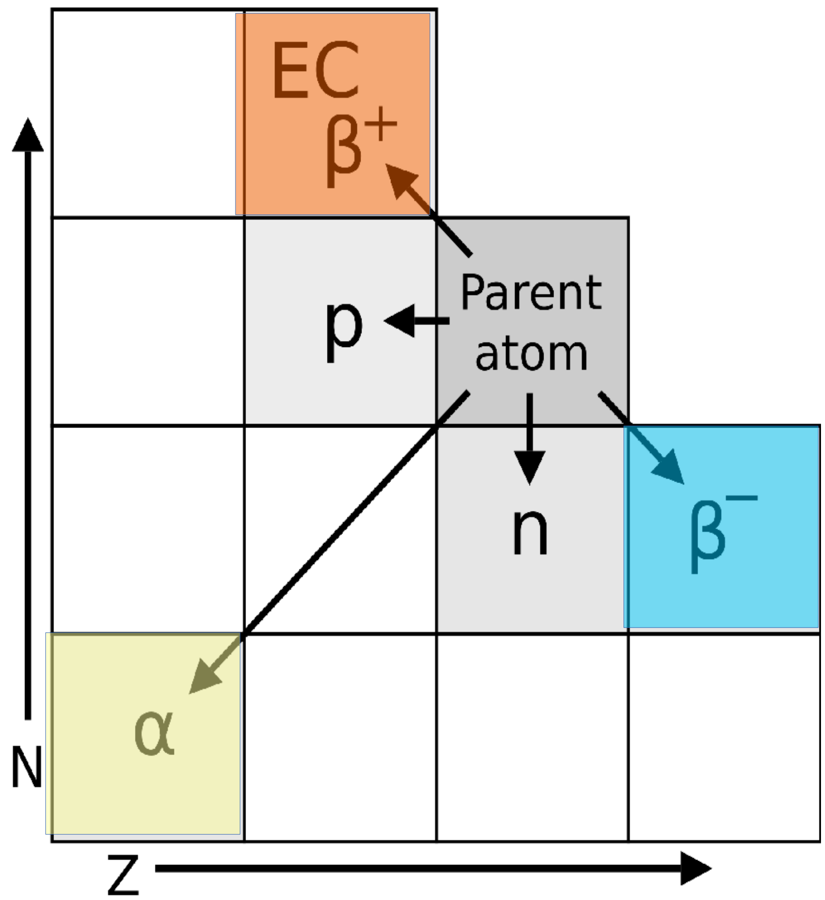
Correlation study of ^{10}He

$$^{3}\mathrm{H} + ^{8}\mathrm{He} \rightarrow ^{10}\mathrm{He} + \mathrm{p}$$
$$^{10}\mathrm{He} \rightarrow ^{8}\mathrm{He} + \mathrm{n} + \mathrm{n}$$



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

Decays



α decay
E. Rutherford, 1899

β⁻ decay
H. Becquerel, 1886

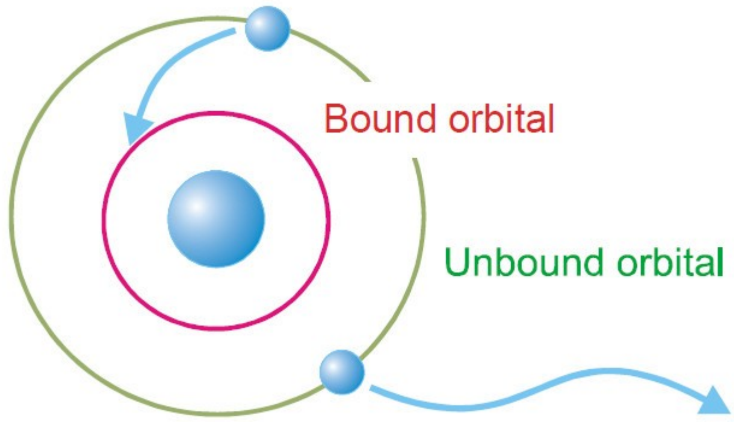
β⁺ decay
F. and I. Joliot-Curie, 1932

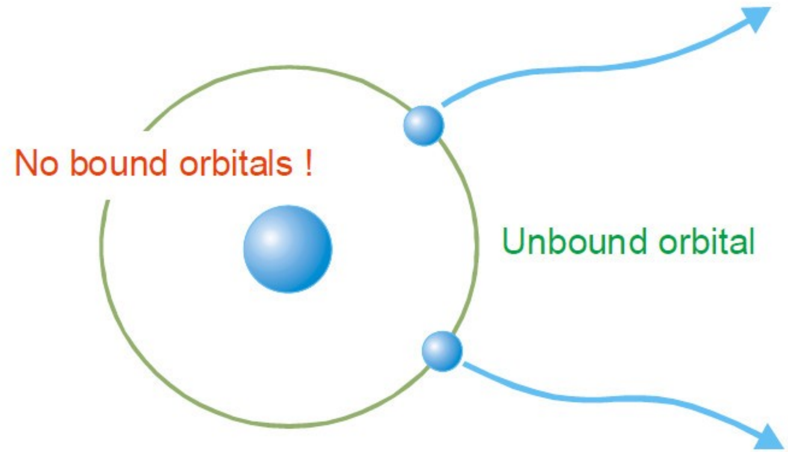
p radioactivity
S. Hoffman, 1982

2p radioactivity
M. Pfutzner, 2002

neutron radioactivity
still waiting

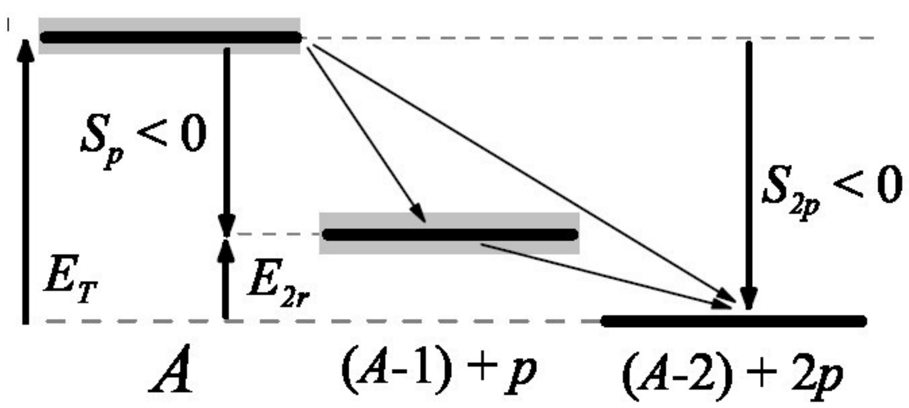
Proton radioactivity

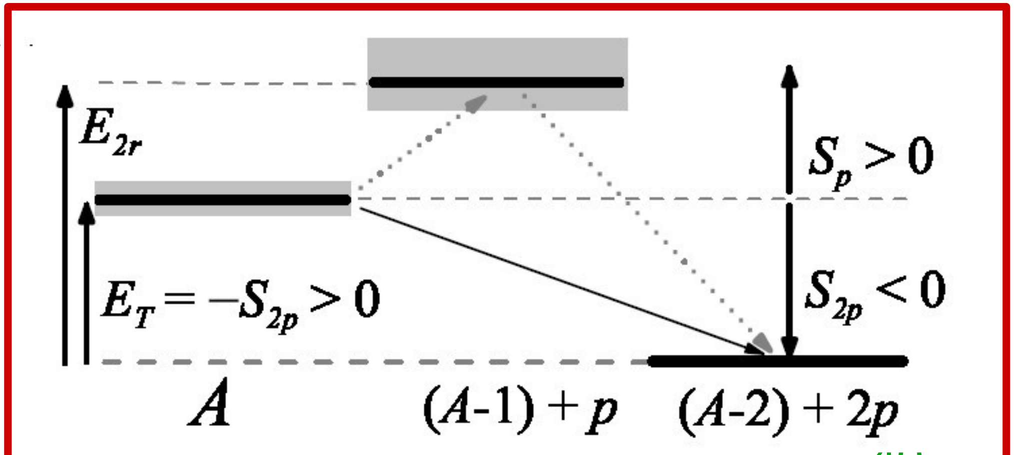




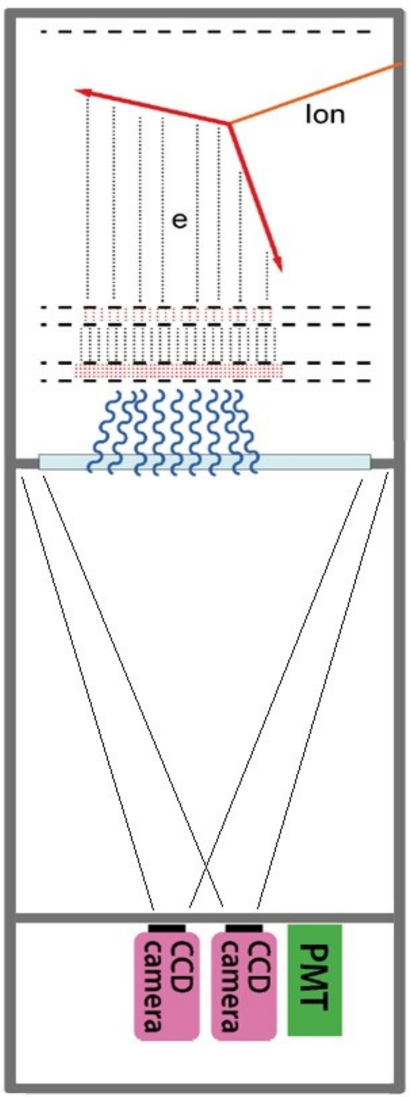
p-radioactivity
natural generalization of α-radiactivity

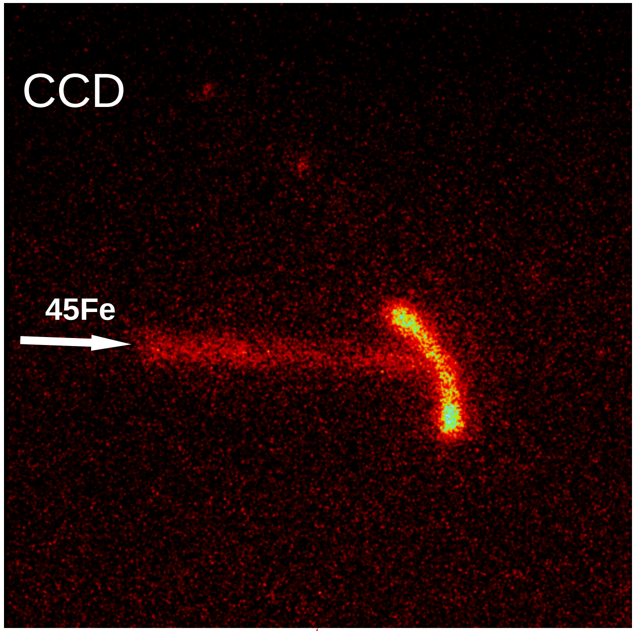
2p-radioactivity
genuine quantum mechanical phenomenon



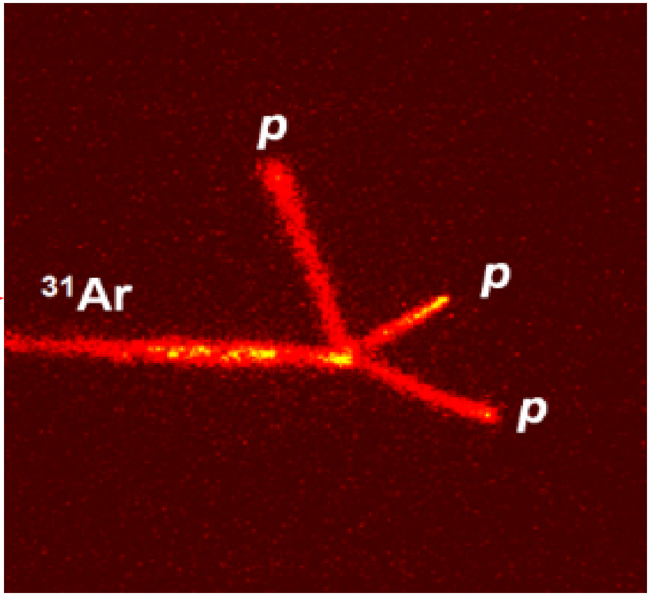


Proton radioactivity





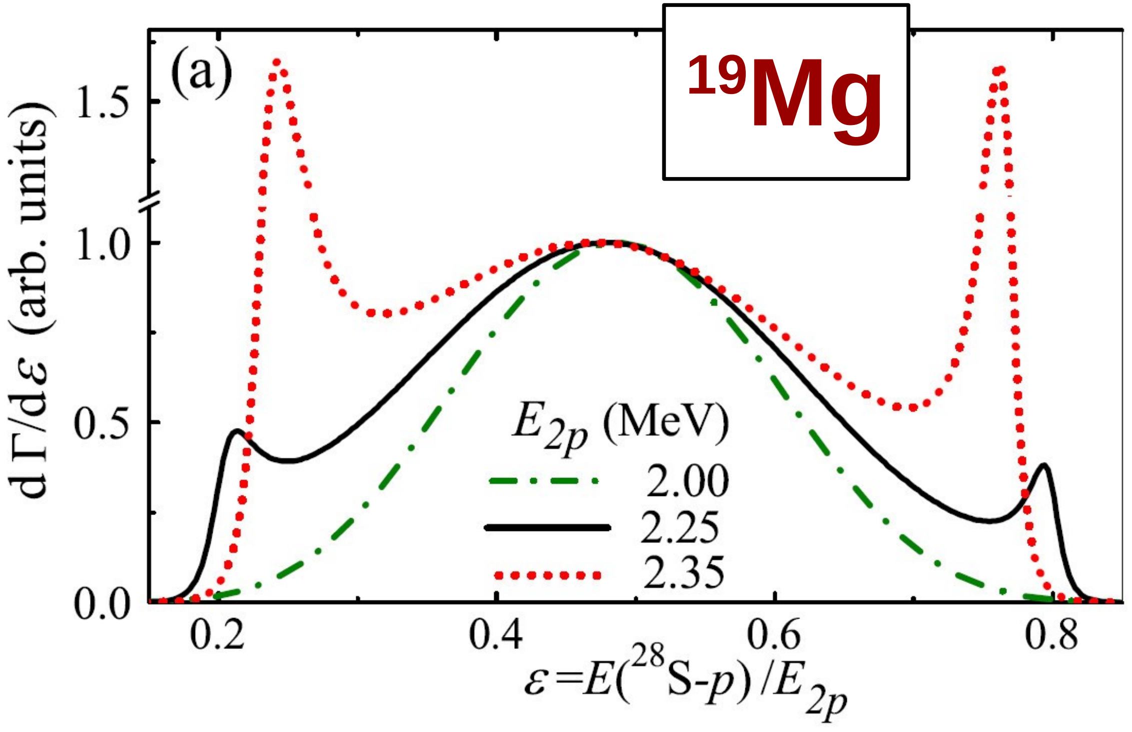
M. Pfützner et al., Eur.Phys.J. A, 14(3), 2002



A.A. Lis et al., Phys. Rev. C **91** (2015) 064309

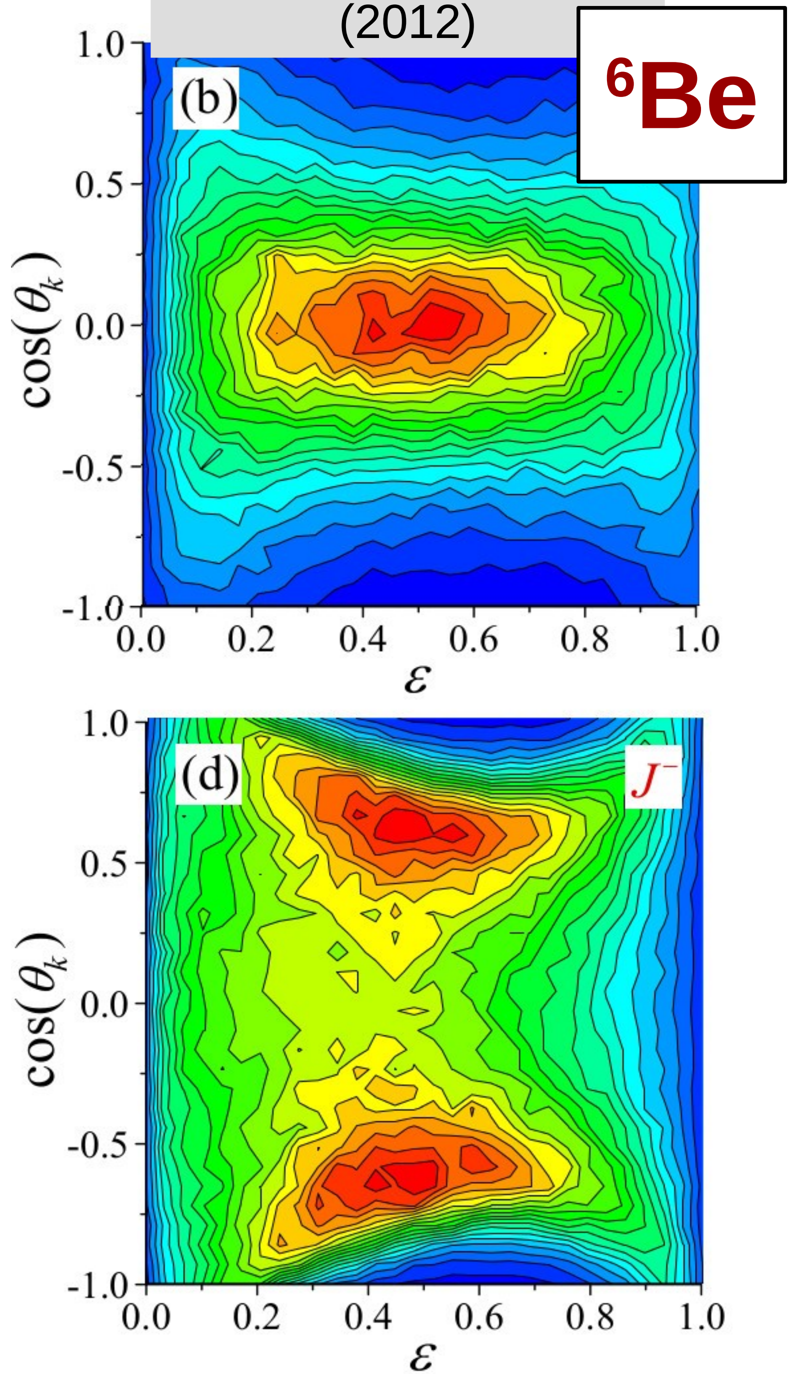
2p decay

Interplay between true 2p and sequential proton decay mechanisms



I. Mukha et al., Phys. Rev. Lett. 115 (2015) 2022501

A.S. Fomichev et al., Phys.Lett.B708 (2012)



Instrumentation

Radioactive ion beams

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

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)

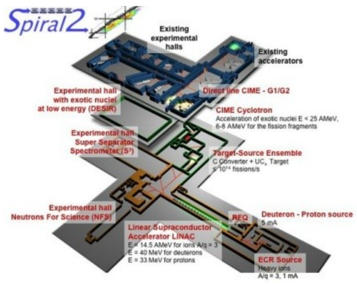
In-Flight Production

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

reactions on a physical target

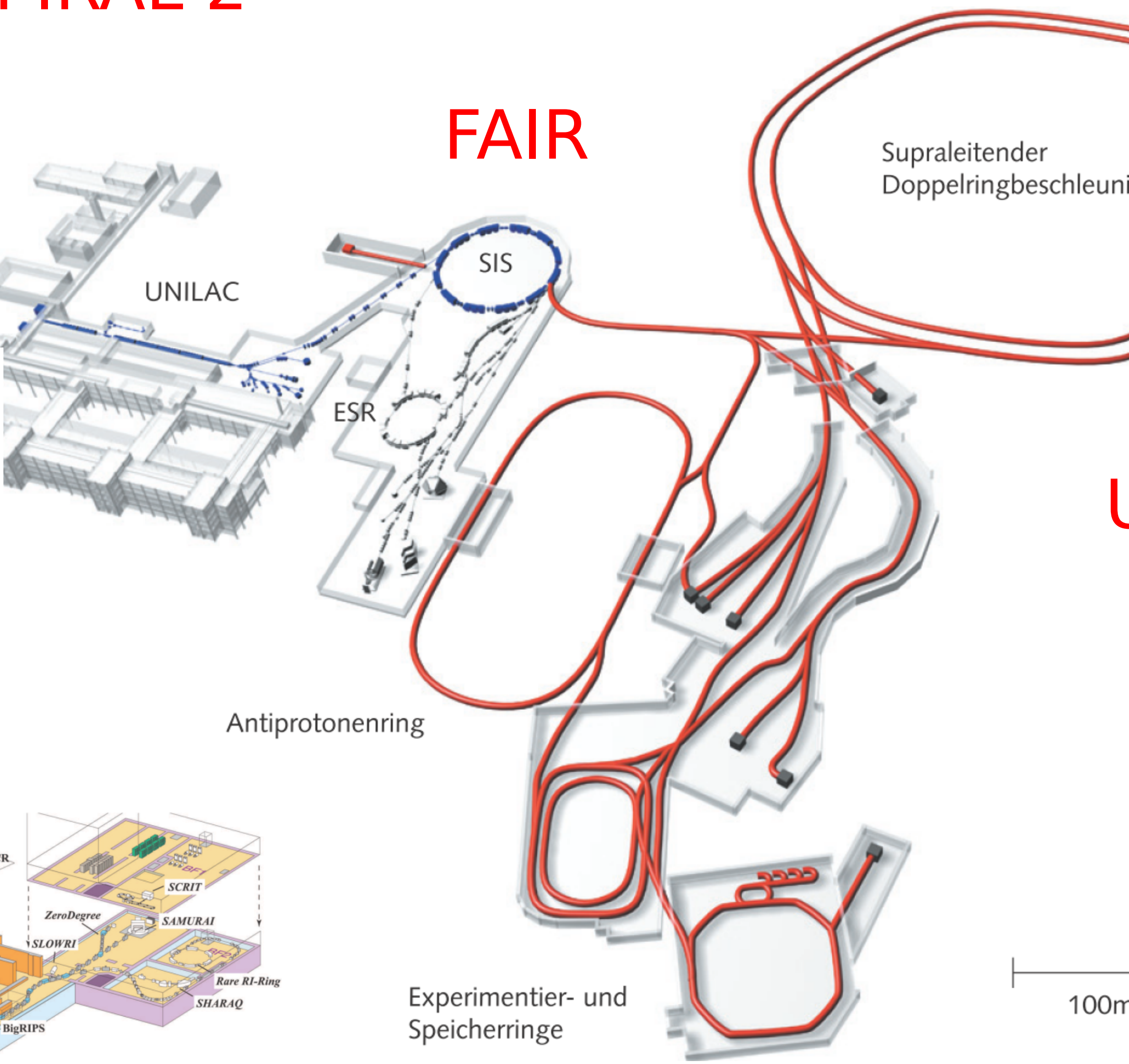
Modest vs. big, bigger, the biggest

Huge increase in the scale of modern RIB facilities

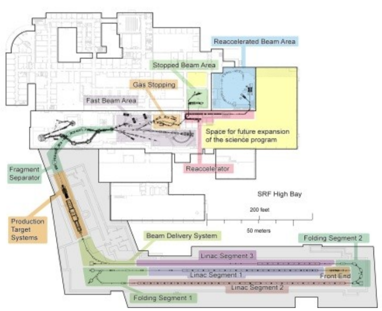


SPIRAL 2

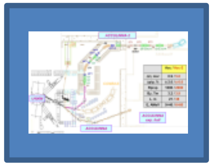
FAIR



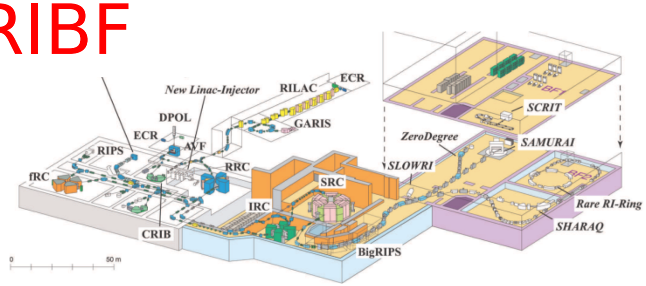
FRIB



U400M hall

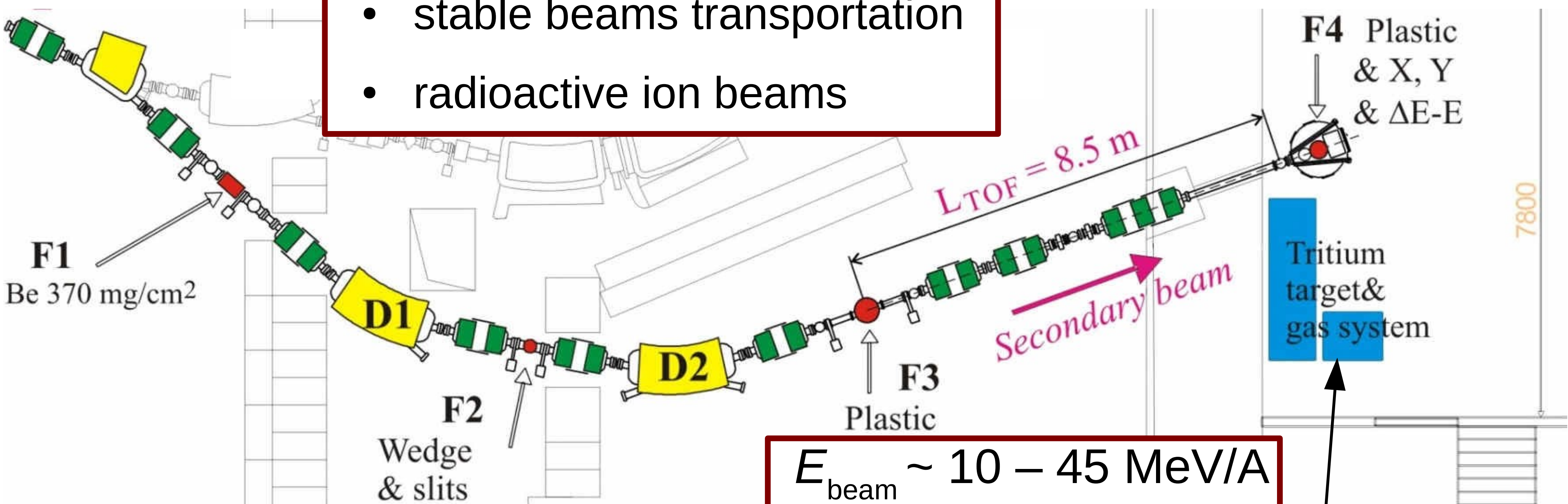


RIBF



ACCULINNA

- stable beams transportation
- radioactive ion beams



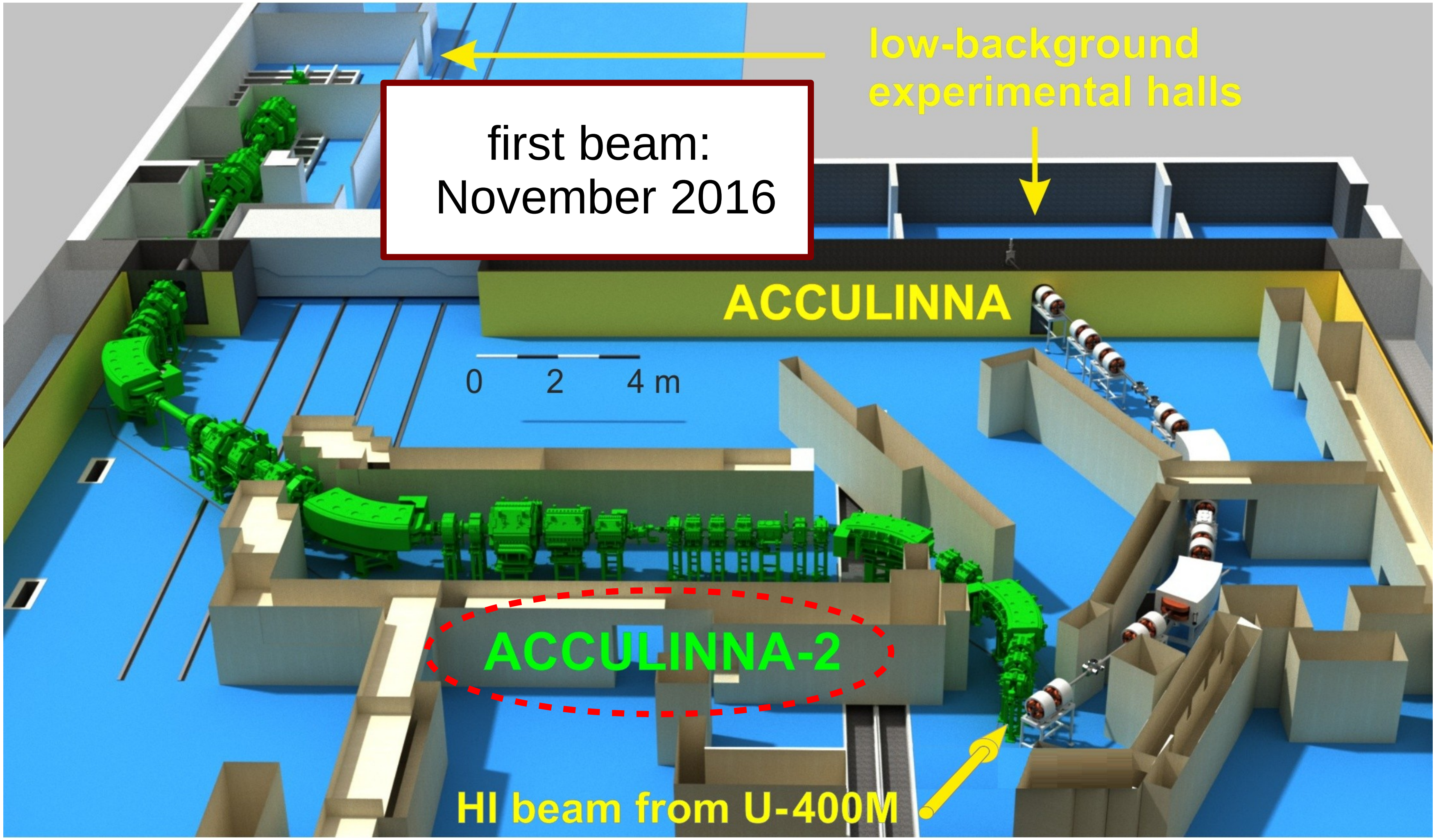
E_{beam} ~ 10 – 45 MeV/A

I_{beam} ~ 10^3 – 10^6 pps

- the only working RIB facility in JINR
- in-flight technique
- beams up to ^{26}S

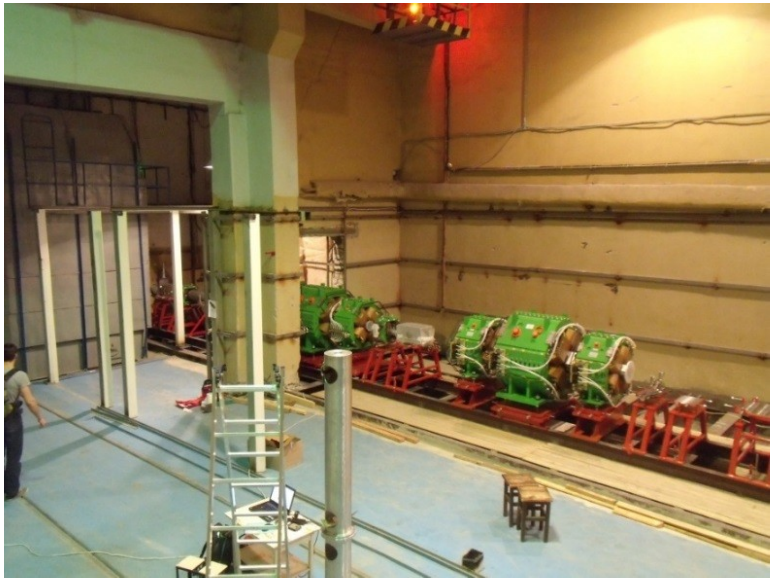
unique combination of tritium beam and target

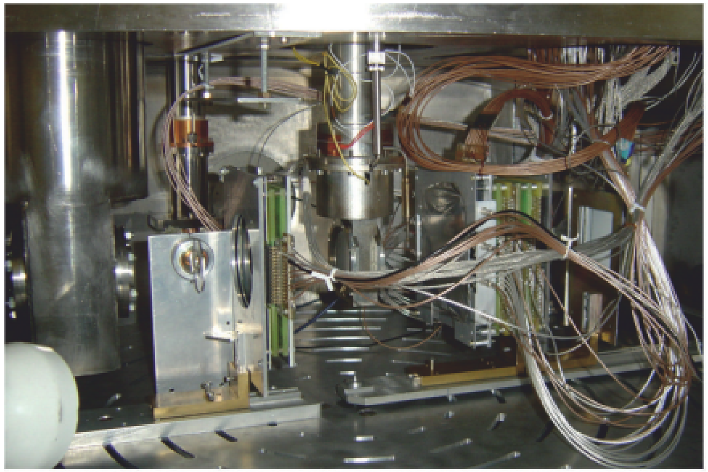
ACCULINNA-2

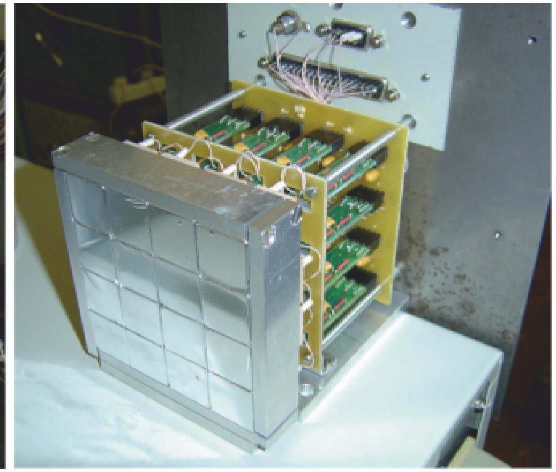


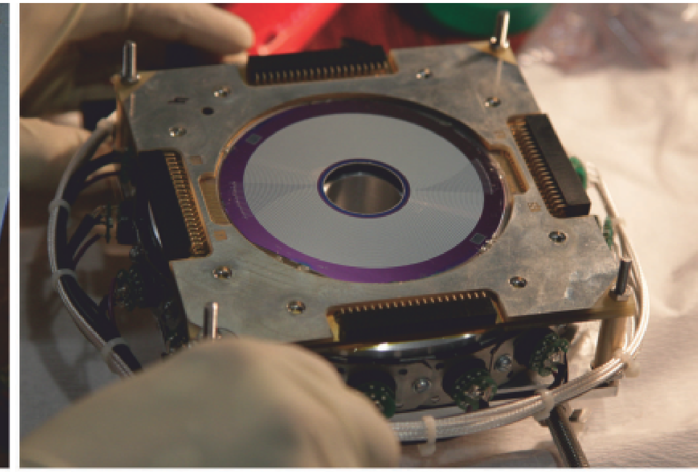
- energy range 6 – 60 MeV/A
- beam intensities higher in 2 orders
- $Z_{\mathrm{RIB}} \sim 1 – 36$

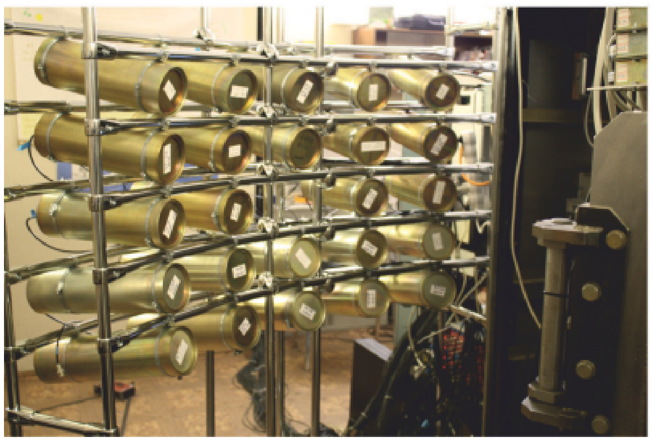

BQ4
BQ3

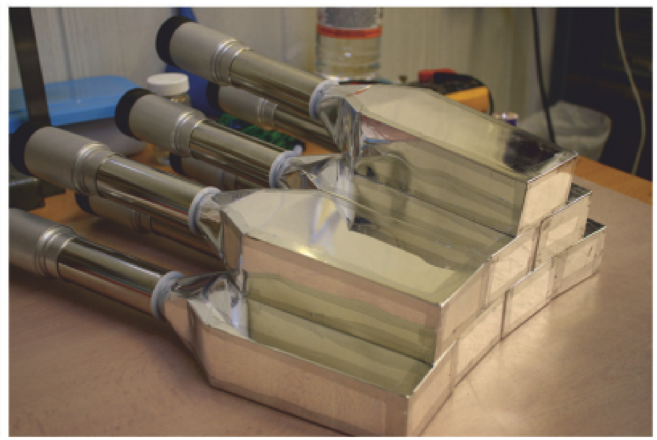


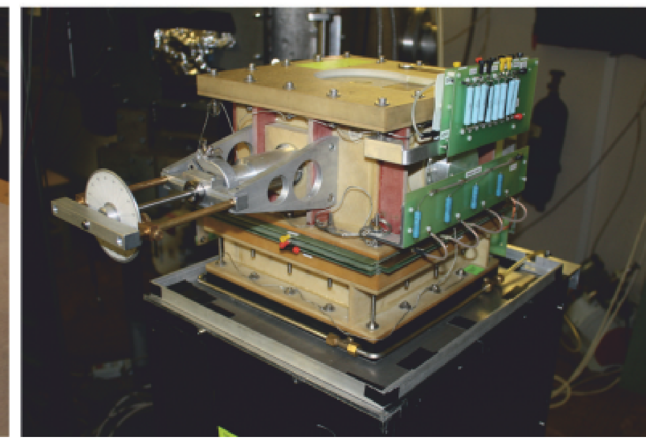


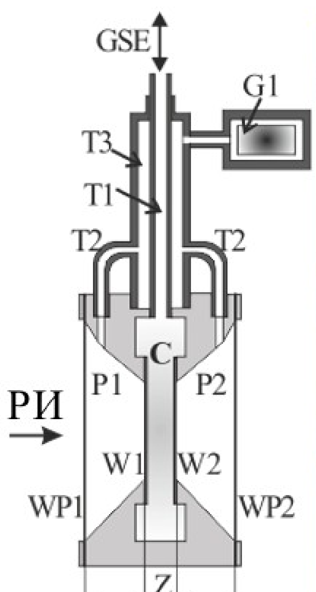




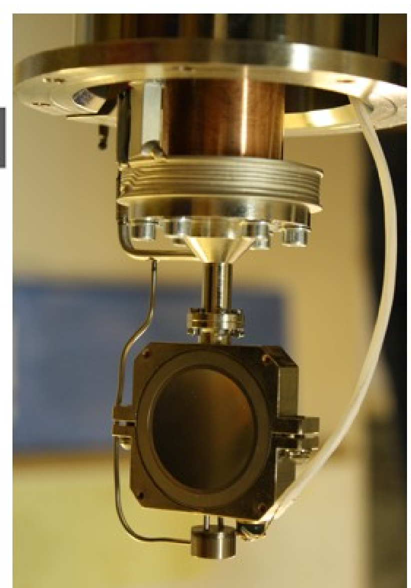








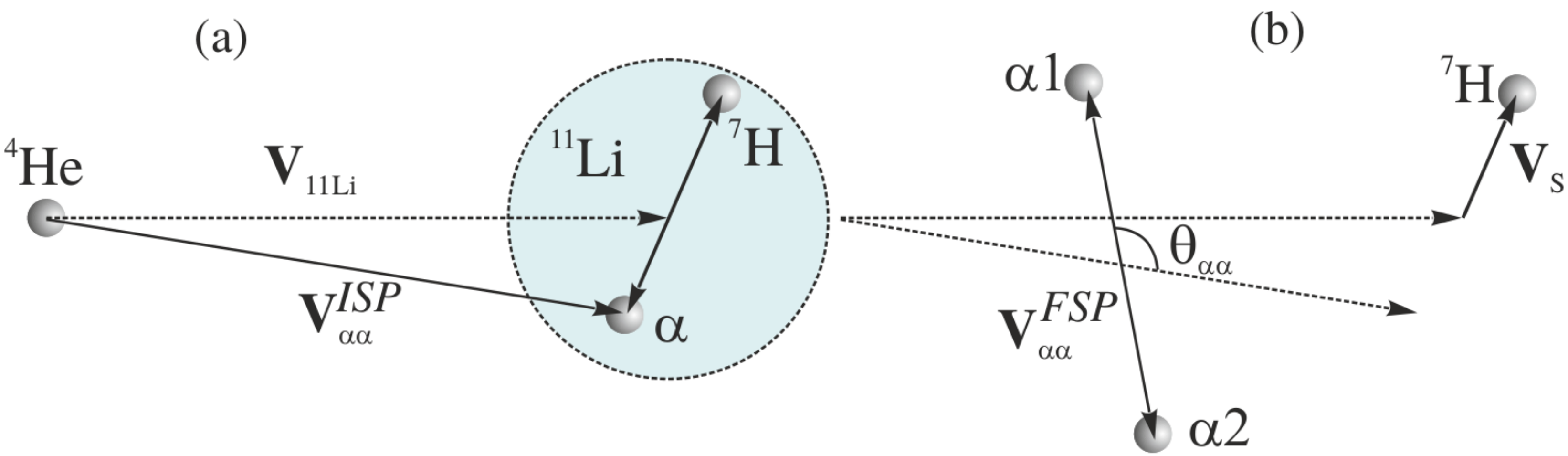
GSE
G1
T3
T1
T2
T2
C
P1
P2
РИ
W1
W2
WP1
WP2
Z



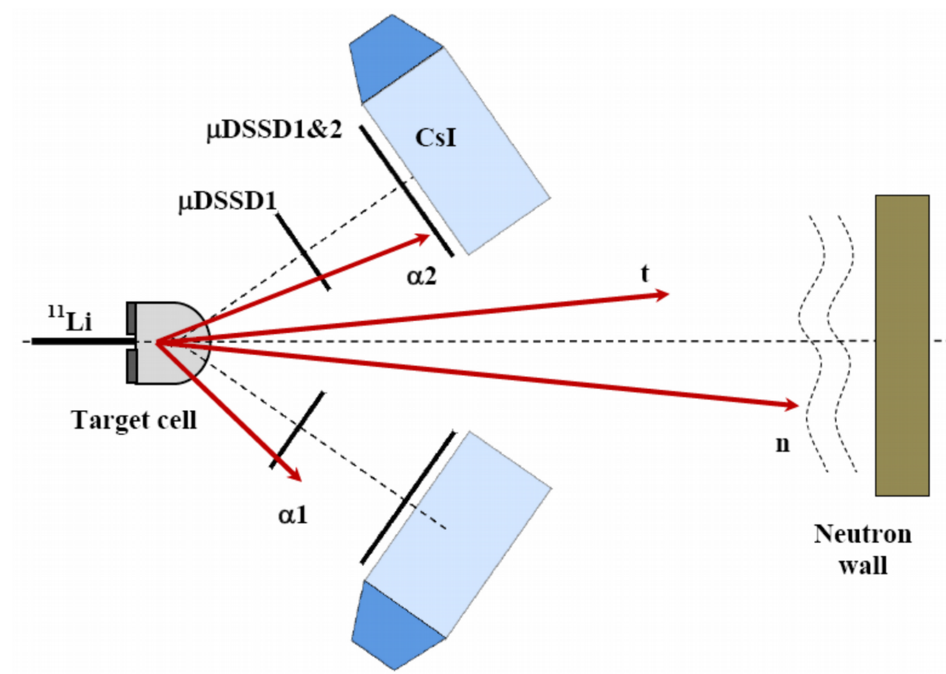
^{5}H and ^{7}H isotopes

$$^4\mathrm{He}(^9\mathrm{Li}, 2\alpha)^5\mathrm{H}$$
$$^4\mathrm{He}(^{11}\mathrm{Li}, 2\alpha)^7\mathrm{H}$$

quasifree scattering

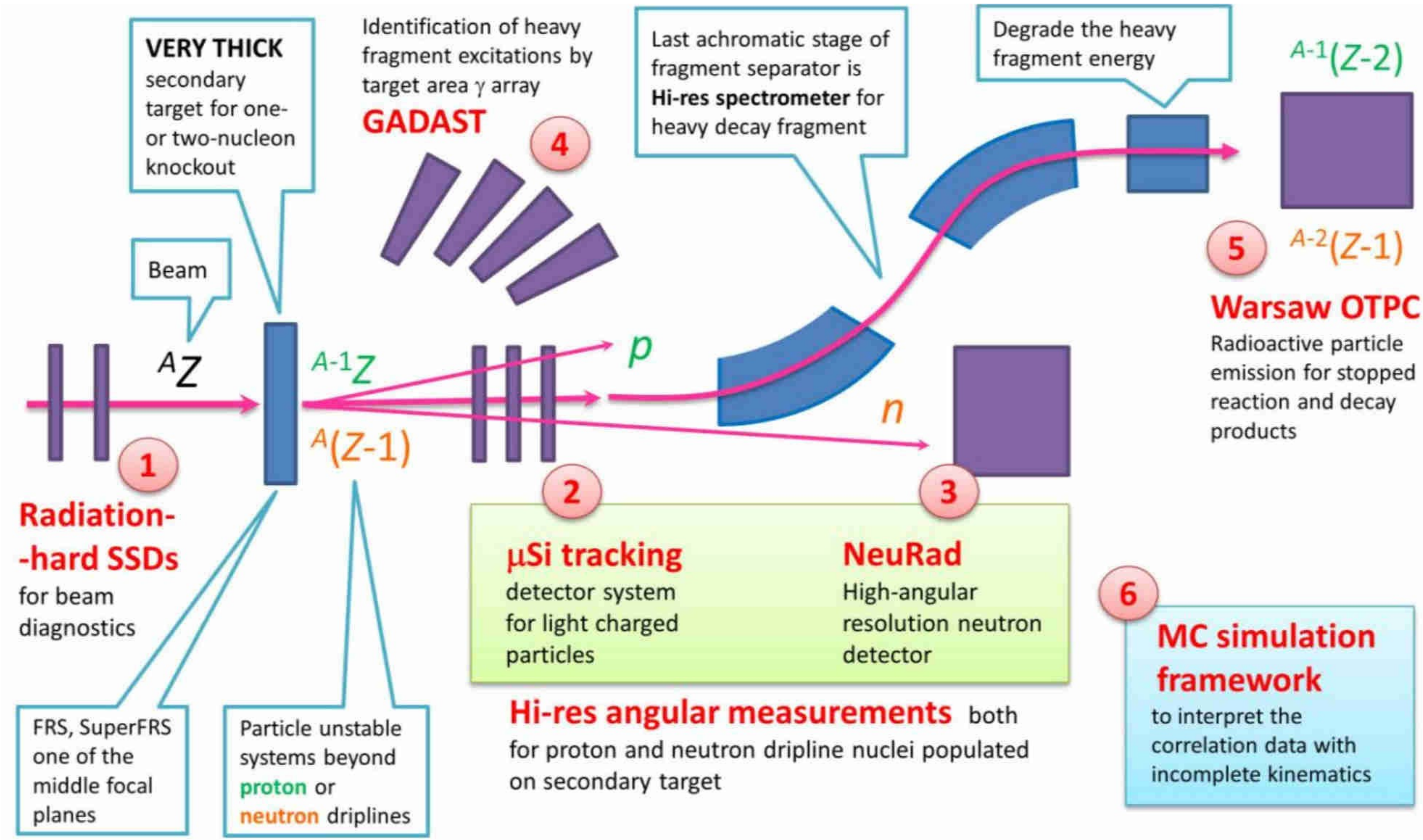


- largest proton-neutron asymmetry among known nuclei
- decay pattern
  - 3-body: t + 2n
  - 5-body: t + 5n !!!!!



Спасибо за внимание!

EXPERT@SuperFRS@FAIR



Appendix: SHE Spectroscopy

Presently Working Experimental Set Ups in the World

Dubna Gas Filled Separator (Russia)

SHIP (Darmstadt, Germany)

Berkeley Gas Filled Separator (USA)

GARIS (Saitama, Japan)

VASSILISSA (Dubna, Russia)

LISE3 (GANIL, France)

RITU (JYFL, Finland)

FMA (Argonne, USA)

JAERI-RMS (Tokai, Japan)

TASCA (Darmstadt, Germany)

★		Gas - filled	
★	✦	Vac. V filter	Focal plane
★		Gas - filled	
★		Gas - filled	
★	✦	Vac. E filter → Vac. V filter	Focal plane
★	✦	Vac. V filter	Focal plane
	✦	Gas - filled	RDT
	✦	Vac. RMS	RDT
★		Vac. RMS	
★	✦	Gas - filled	Focal plane

★ Heavy element research ✦ Spectroscopy studies