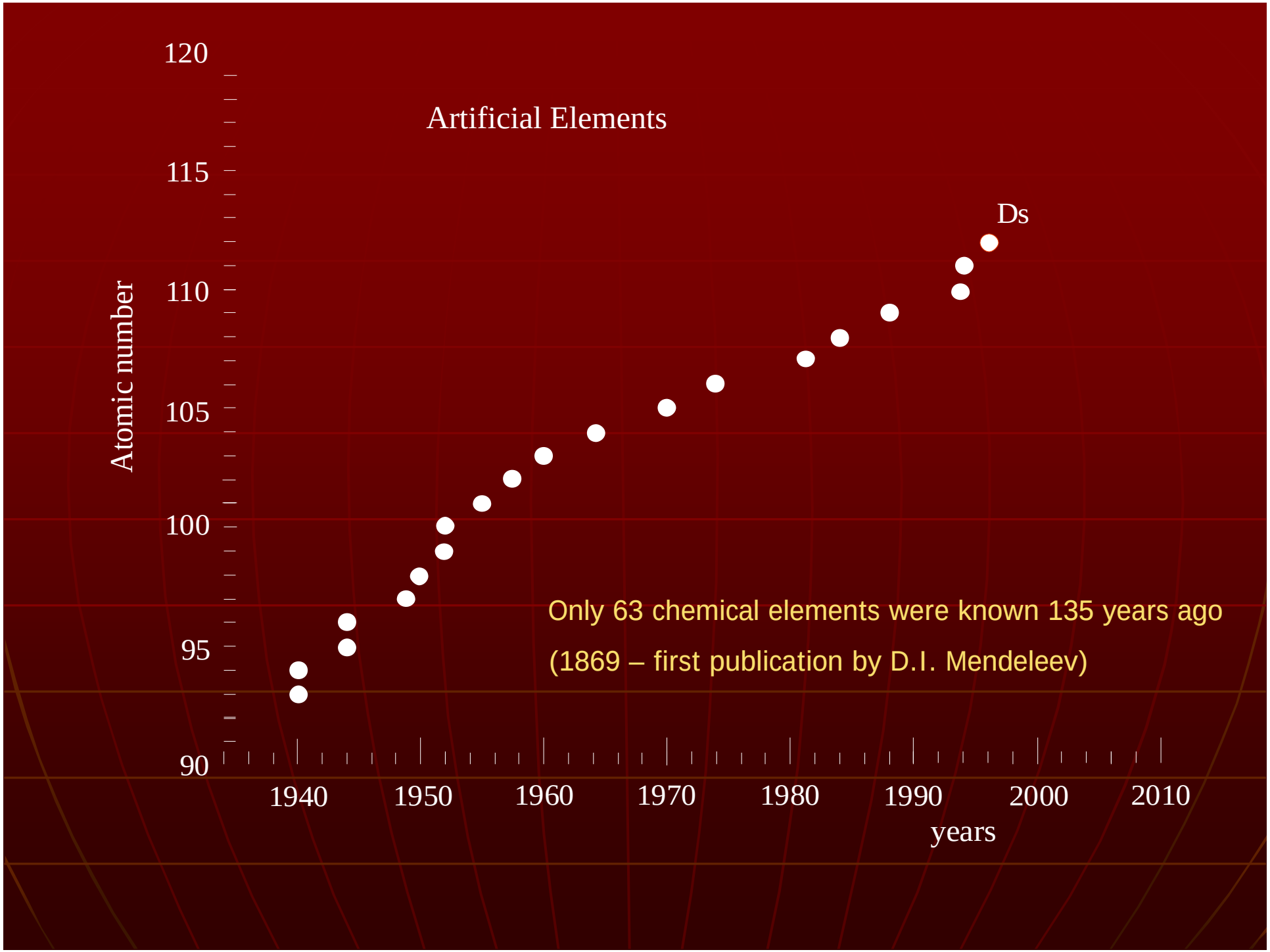
Superheavy Elements
current experiments and prospects

Yu. Ts. Oganessian

Flerov Laboratory of Nuclear Reactions
Joint Institute for Nuclear Research
Dubna

July 20, 2004 (Dubna)


Artificial Elements
Atomic number
120
115
110
105
100
95
90
Ds
Only 63 chemical elements were known 135 years ago
(1869 – first publication by D.I. Mendeleev)
1940
1950
1960
1970
1980
1990
2000
2010
years

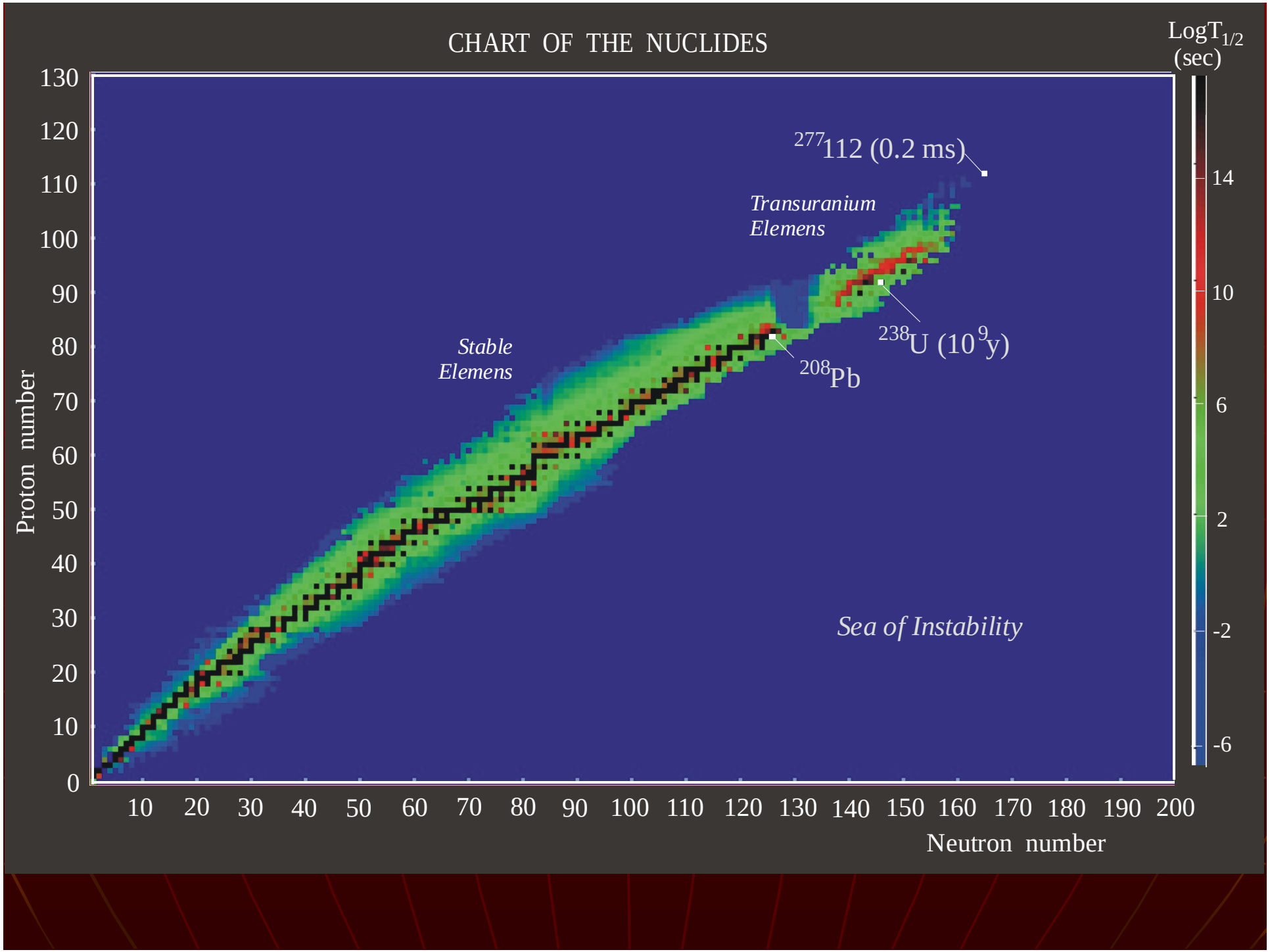
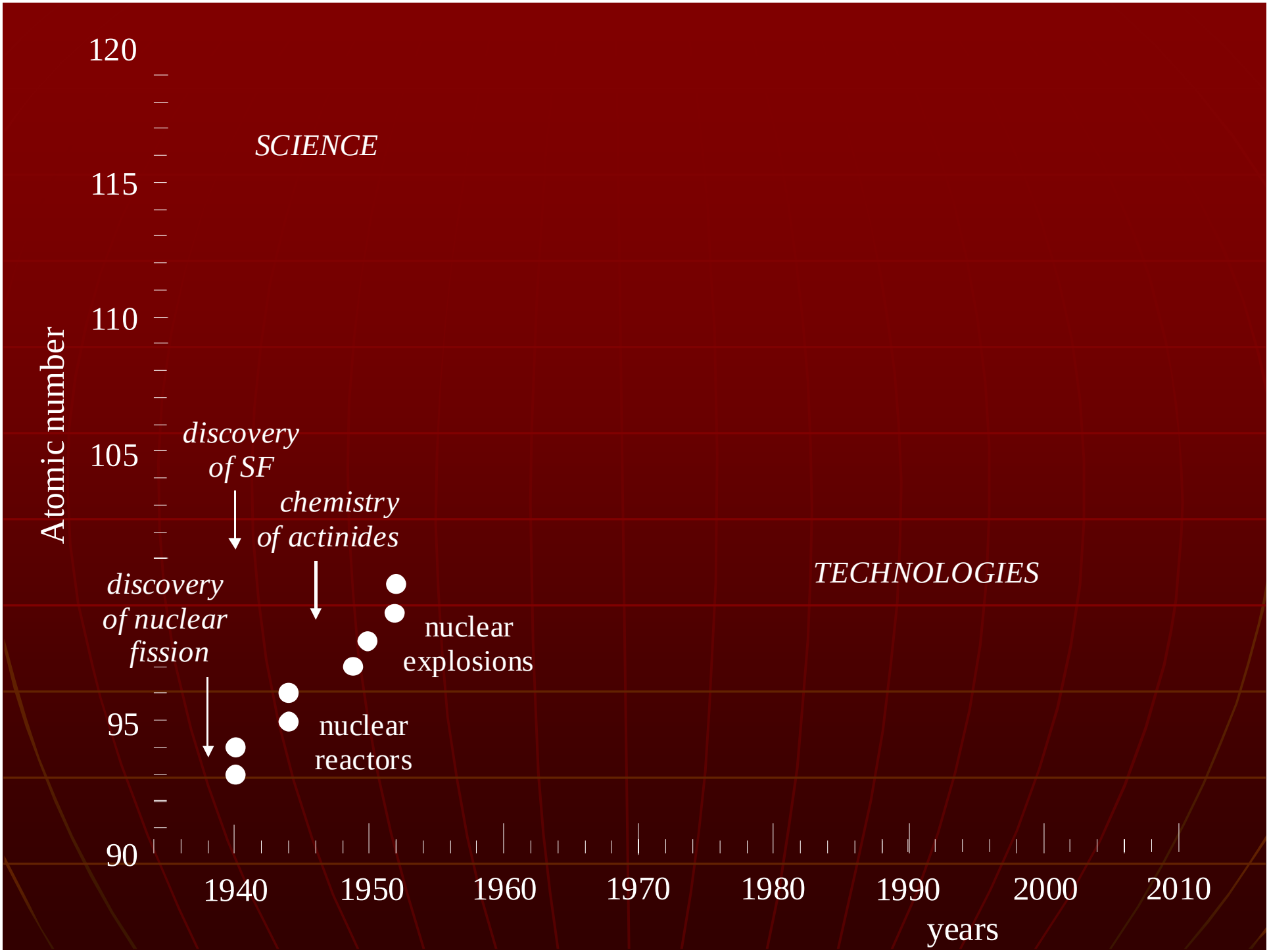
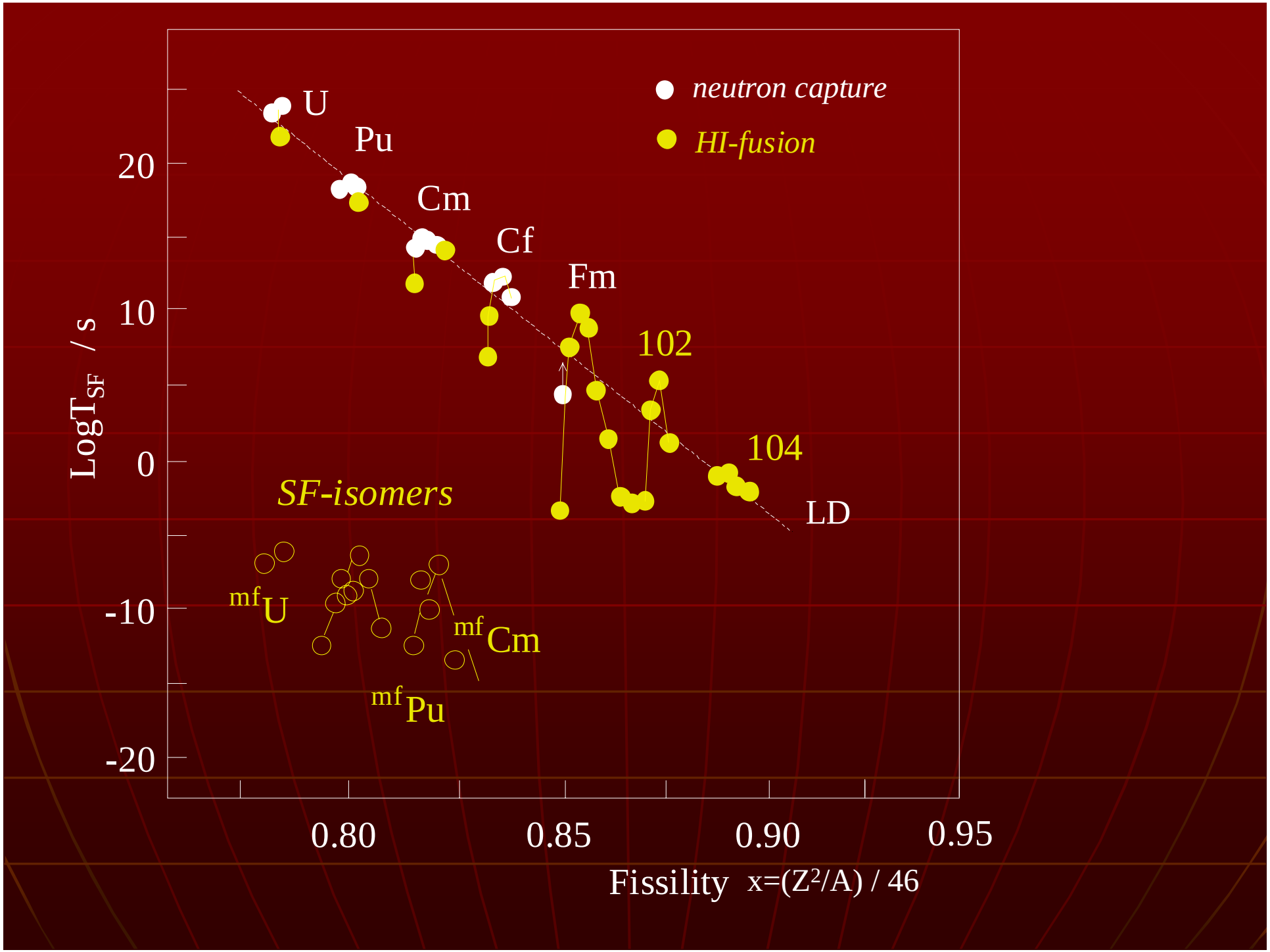


CHART OF THE NUCLIDES
LogT1/2 (sec)
14
10
6
2
-2
-6
277112 (0.2 ms)
Transuranium Elemens
238U (10 9y)
208Pb
Stable Elemens
Sea of Instability
Proton number
Neutron number
0
10
20
30
40
50
60
70
80
90
100
110
120
130
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200


120
115
110
105
95
90
Atomic number
SCIENCE
TECHNOLOGIES
discovery of SF
chemistry of actinides
discovery of nuclear fission
nuclear explosions
nuclear reactors
1940
1950
1960
1970
1980
1990
2000
2010
years


neutron capture
HI-fusion
U
Pu
Cm
Cf
Fm
102
104
LD
SF-isomers
mf U
mf Pu
mf Cm
20
10
0
-10
-20
LogT$_{SF}$ / s
0.80
0.85
0.90
0.95
Fissility x=(Z^2/A) / 46

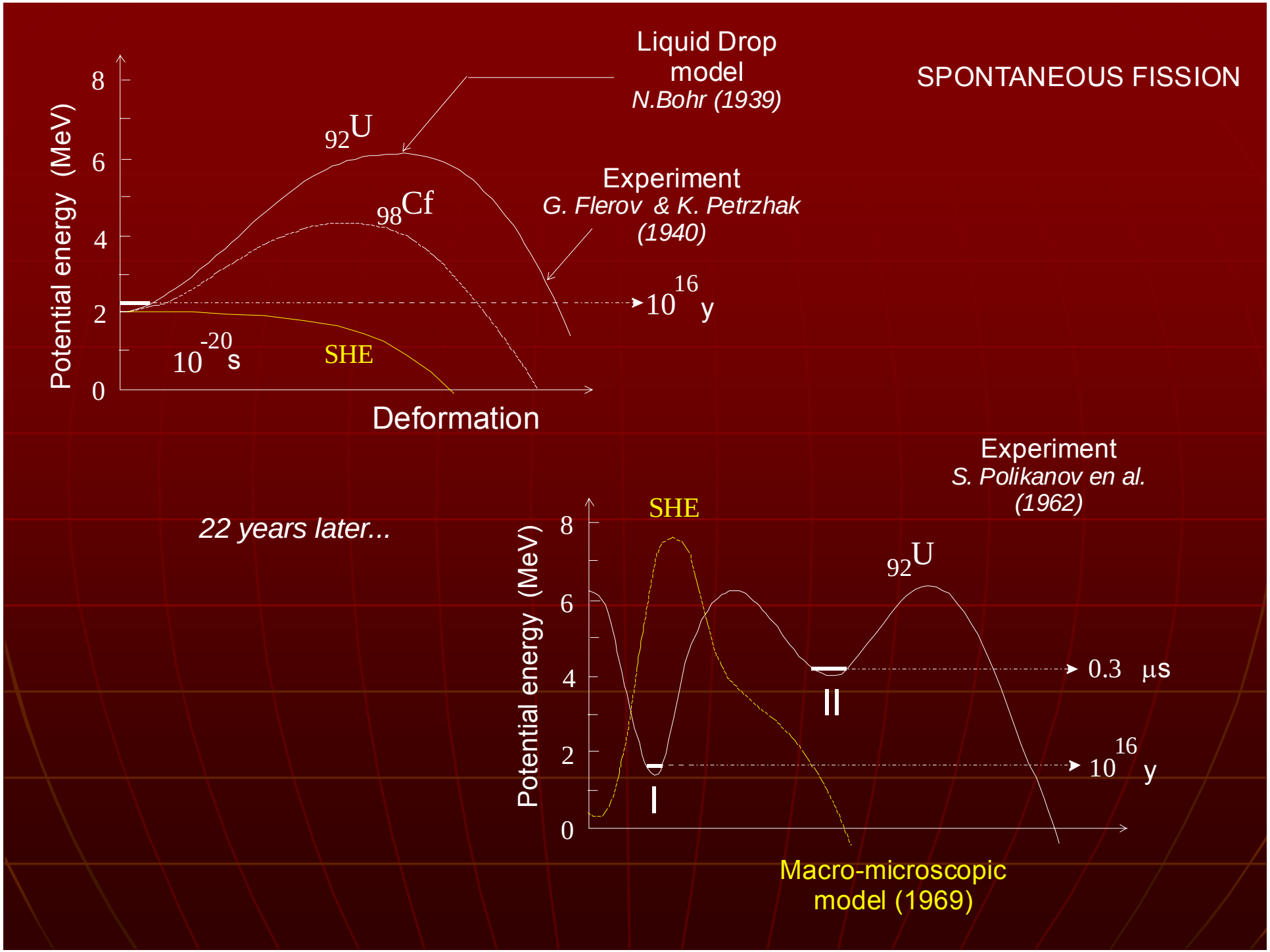
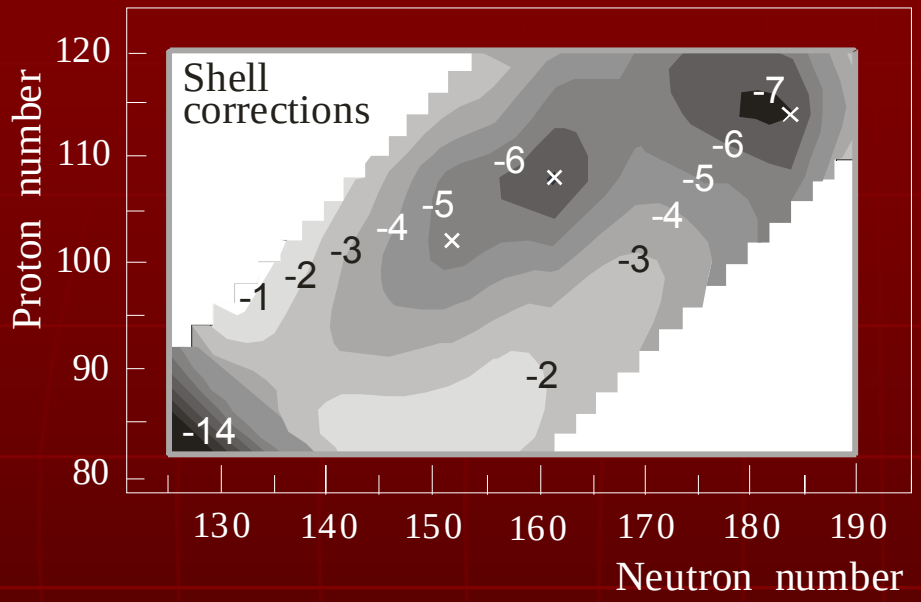
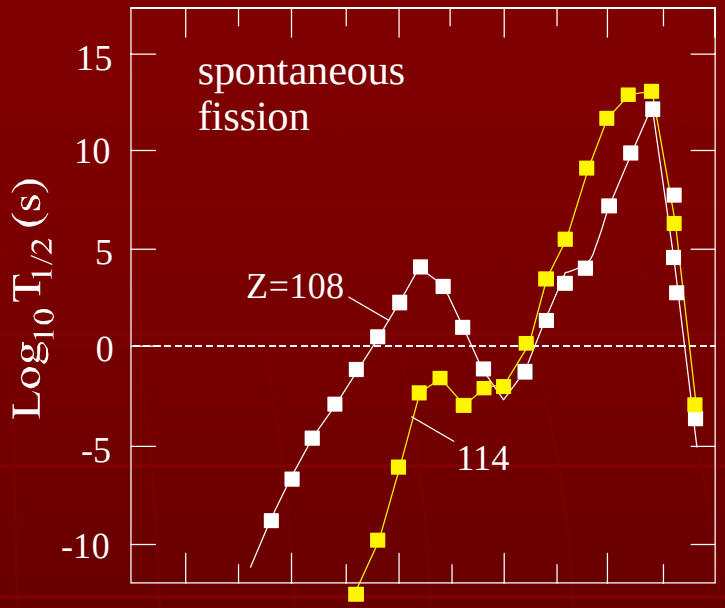
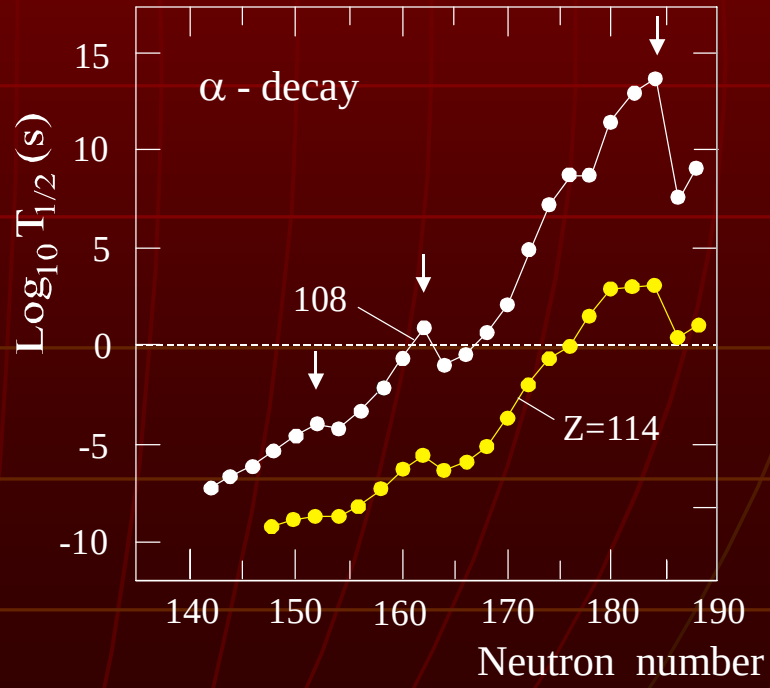

SPONTANEOUS FISSION
Liquid Drop model
N.Bohr (1939)
Experiment
G. Flerov & K. Petrzhak (1940)
92U
98Cf
10-20 s
SHE
10 16 y
Potential energy (MeV)
Deformation
22 years later...
Experiment
S. Polikanov en al. (1962)
SHE
92U
0.3 μs
10 16 y
I
II
Macro-microscopic model (1969)

Chart of shell corrections
to the LD-potential energy







Partial half lives with respect to a-decay and SF
of even-even isotopes with Z=108 and 114

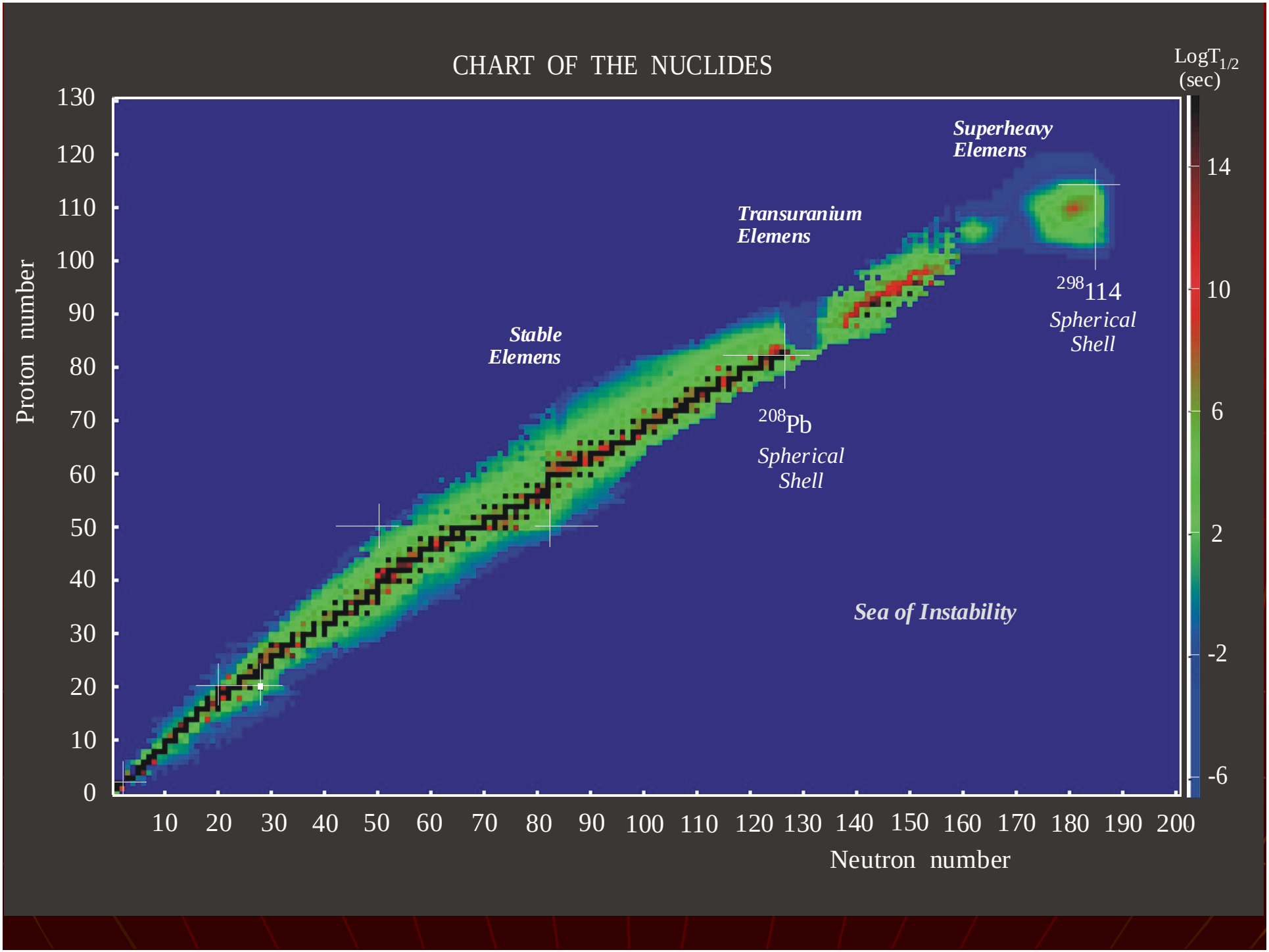
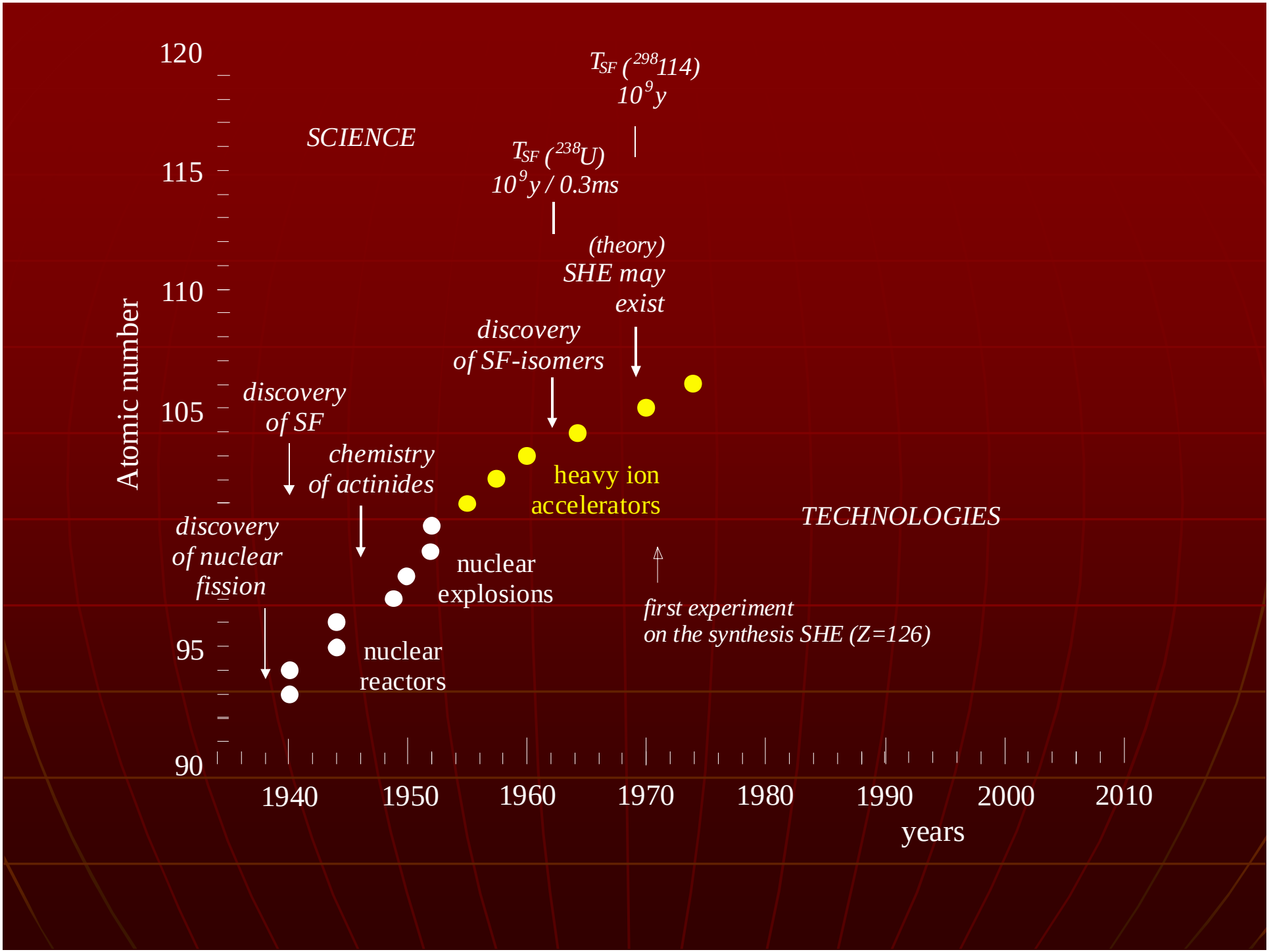
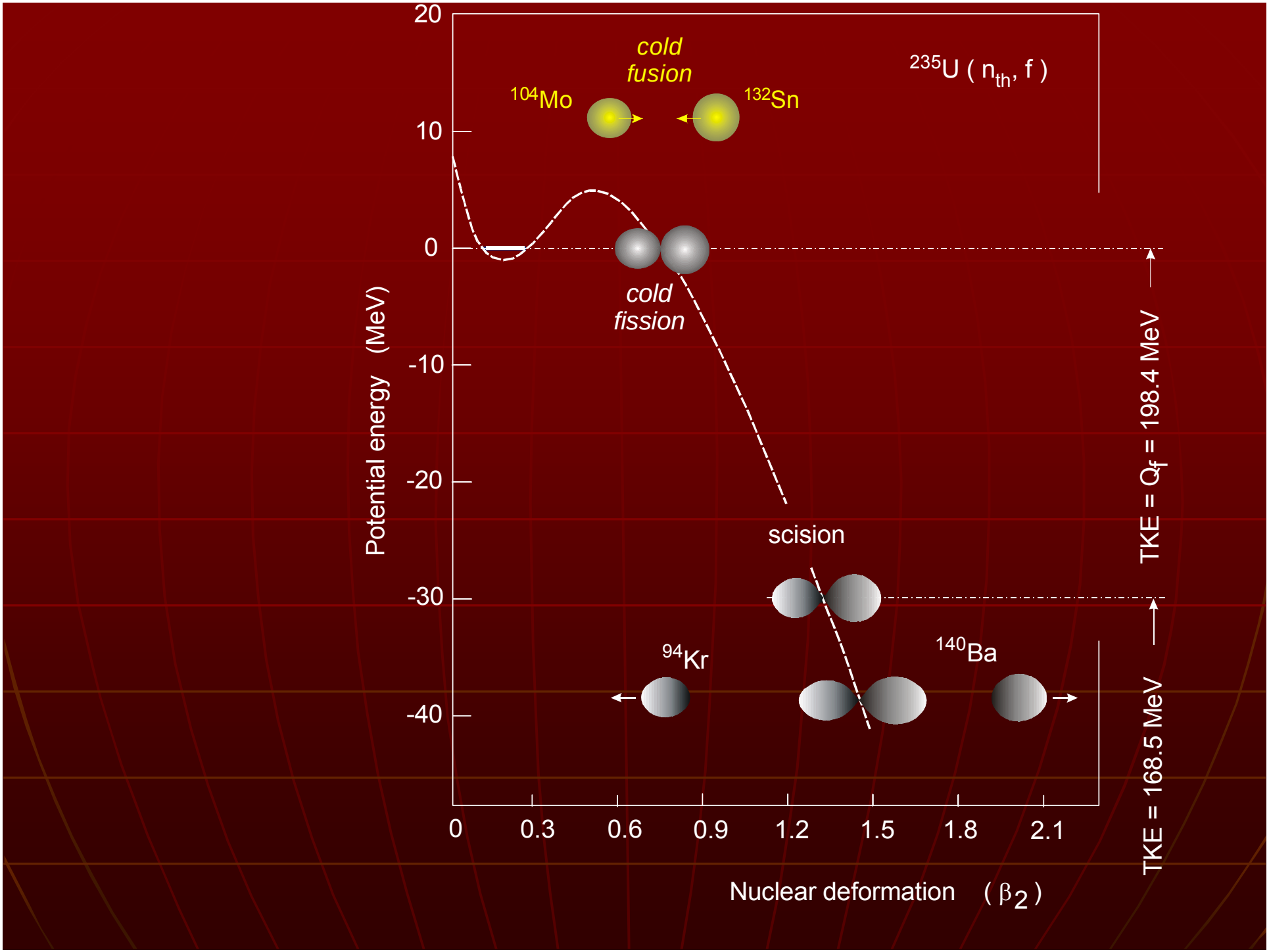
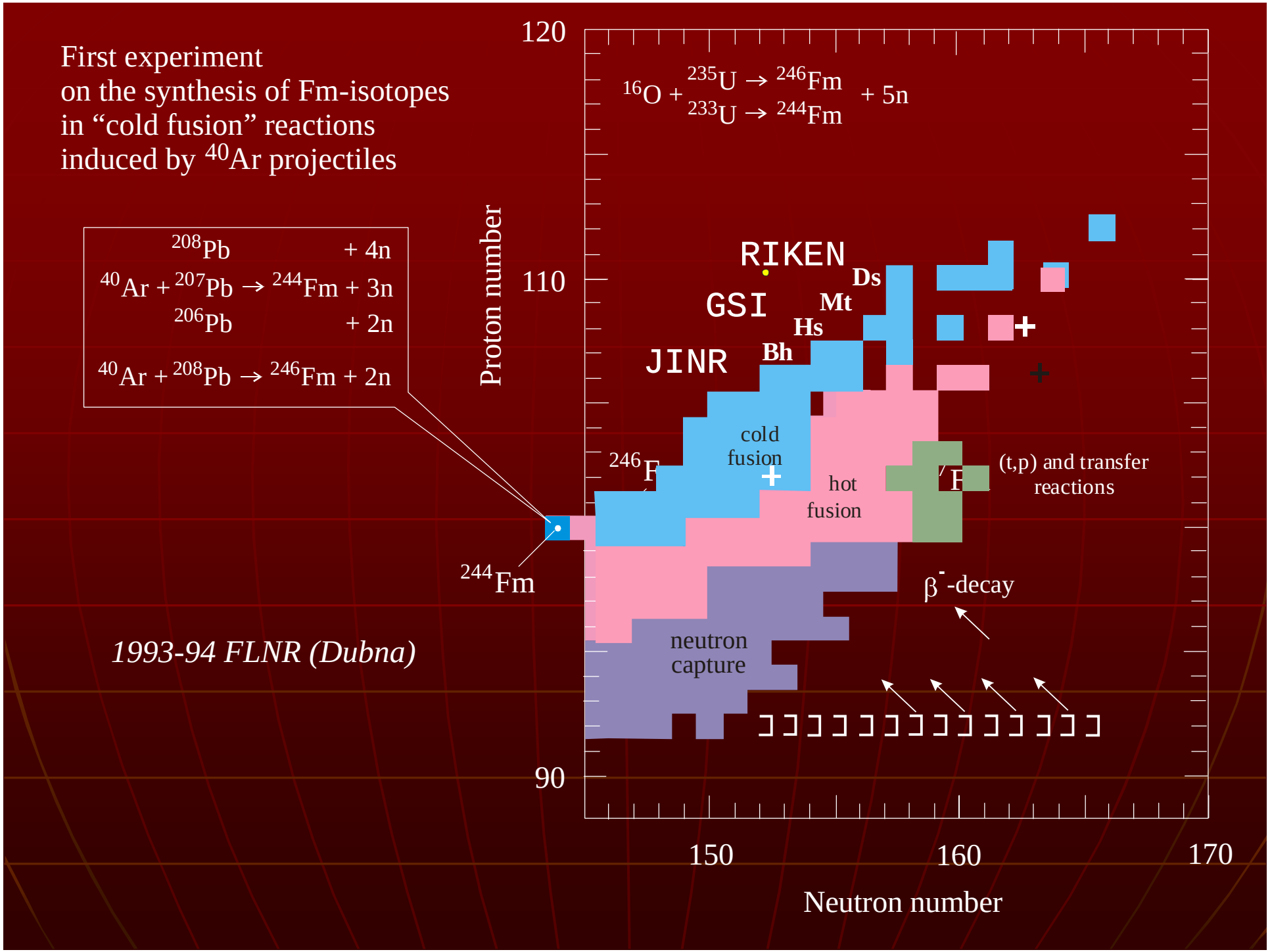


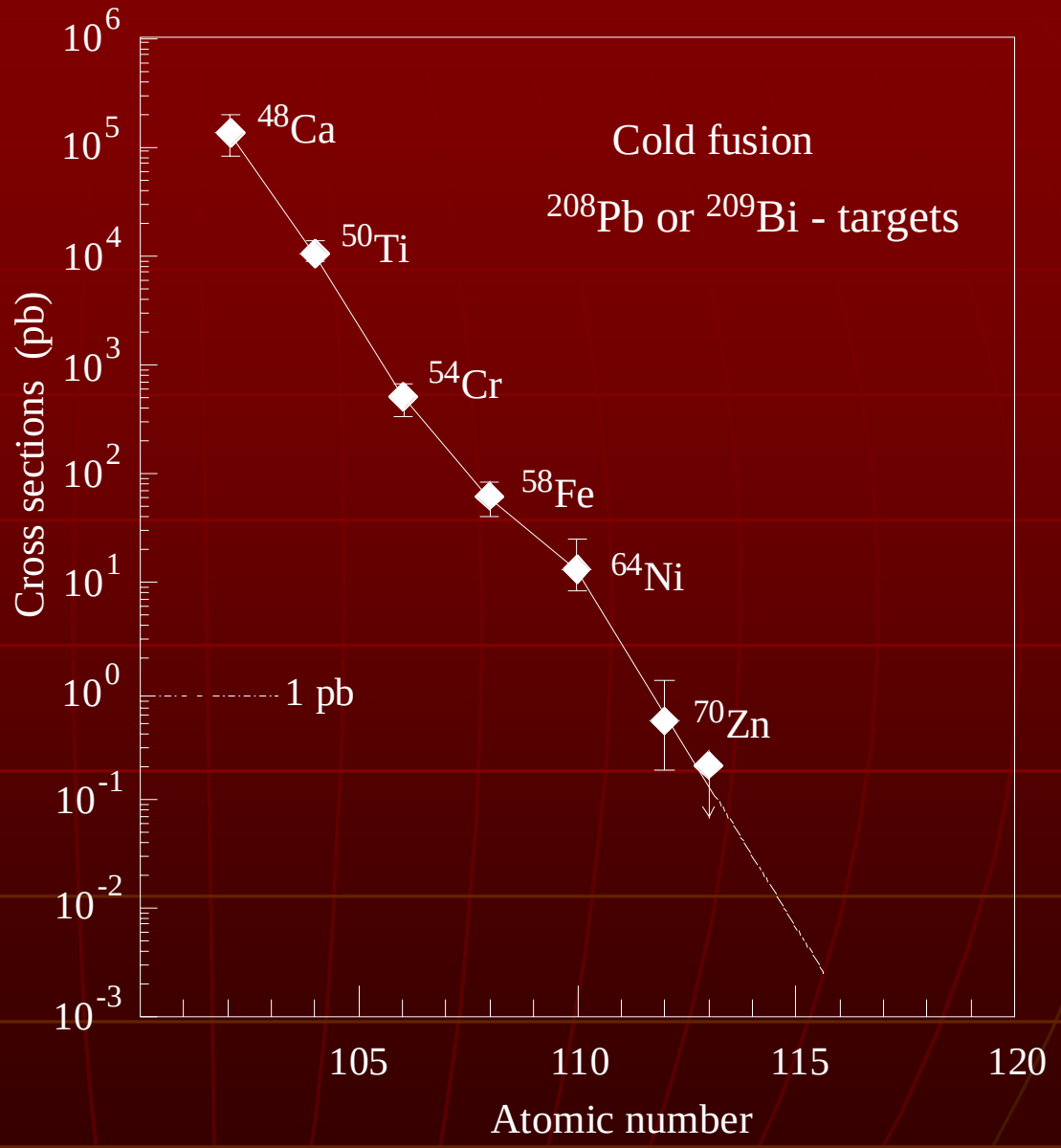
CHART OF THE NUCLIDES
LogT1/2 (sec)
14
10
6
2
-2
-6
Proton number
0
10
20
30
40
50
60
70
80
90
100
110
120
130
Neutron number
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
Superheavy Elemens
Transuranium Elemens
Stable Elemens
298114
Spherical Shell
208Pb
Spherical Shell
Sea of Instability

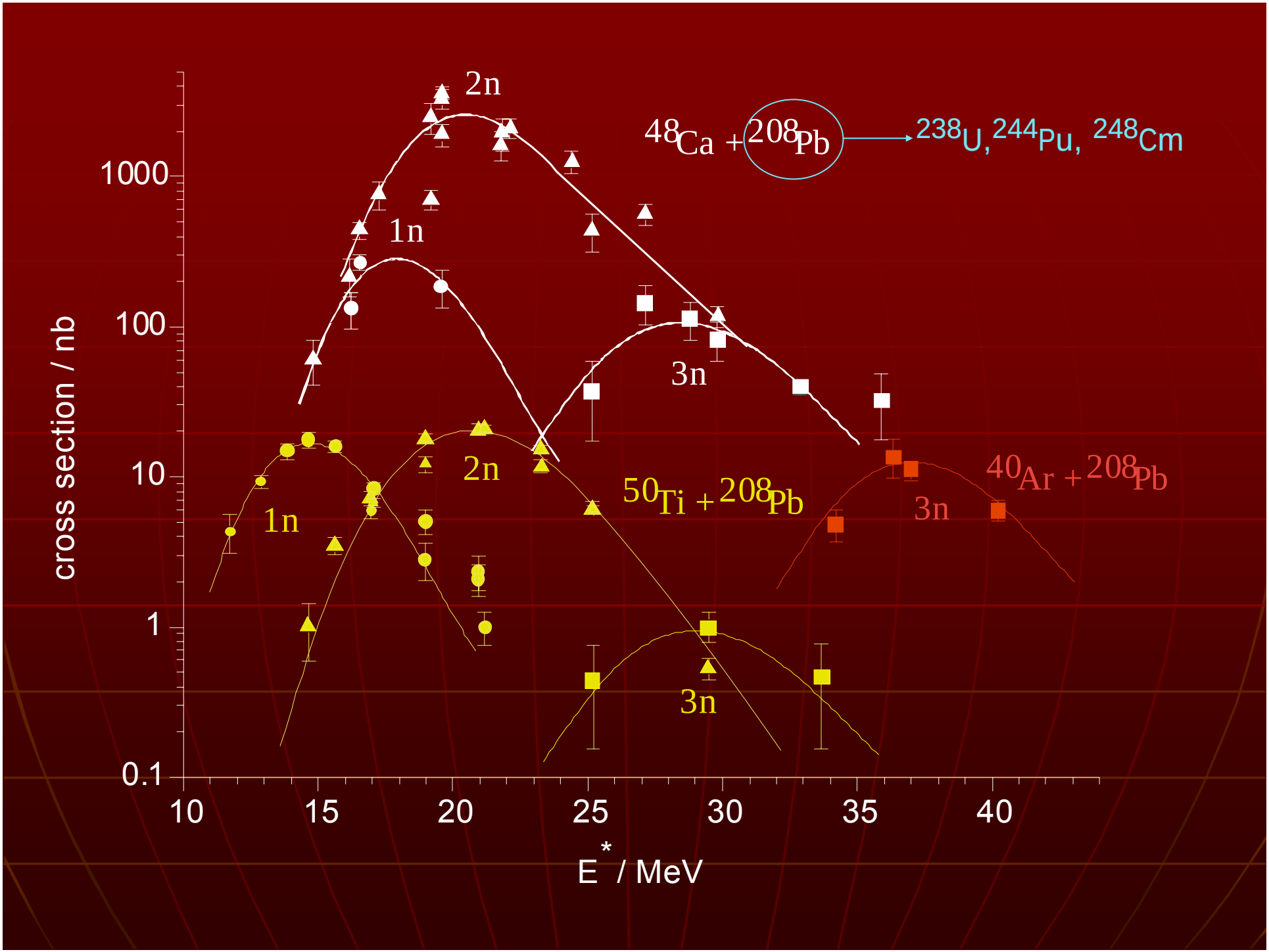

120
115
110
105
95
90
Atomic number
1940
1950
1960
1970
1980
1990
2000
2010
years
SCIENCE
TECHNOLOGIES
T_{SF} (^{298}114)
10^9y
T_{SF} (^{238}U)
10^9y / 0.3ms
(theory)
SHE may
exist
discovery
of SF-isomers
discovery
of SF
chemistry
of actinides
discovery
of nuclear
fission
heavy ion
accelerators
nuclear
explosions
nuclear
reactors
first experiment
on the synthesis SHE (Z=126)


20
10
0
-10
-20
-30
-40
Potential energy (MeV)
cold
fusion
^{104}Mo
^{132}Sn
^{235}U (n_{th}, f)
cold
fission
scision
^{94}Kr
^{140}Ba
TKE = Q_f = 198.4 MeV
TKE = 168.5 MeV
0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
Nuclear deformation (β_2)


First experiment
on the synthesis of Fm-isotopes
in “cold fusion” reactions
induced by ^{40}Ar projectiles
^{208}Pb + 4n
^{40}Ar + ^{207}Pb → ^{244}Fm + 3n
^{206}Pb + 2n
^{40}Ar + ^{208}Pb → ^{246}Fm + 2n
^{16}O + ^{235}U → ^{246}Fm + 5n
^{233}U → ^{244}Fm
120
110
90
Proton number
RIKEN
Ds
GSI
Mt
Hs
JINR
Bh
cold
fusion
hot
fusion
(t,p) and transfer
reactions
^{246}F
F
^{244}Fm
β⁻-decay
neutron
capture
150
160
170
Neutron number
1993-94 FLNR (Dubna)

Cross sections of the SHE production in the cold fusion reactions ^{208}Pb(HI, 1n)

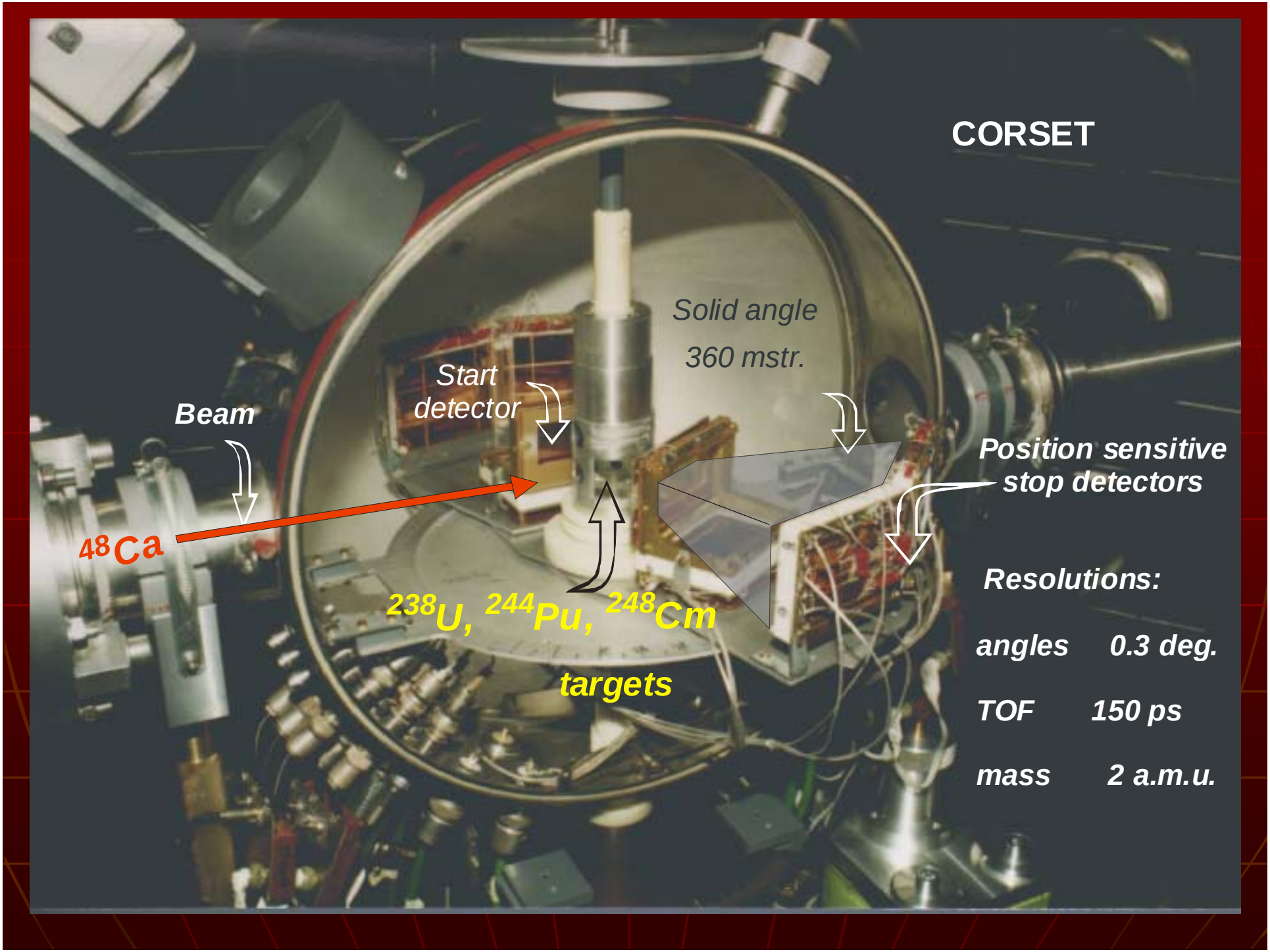


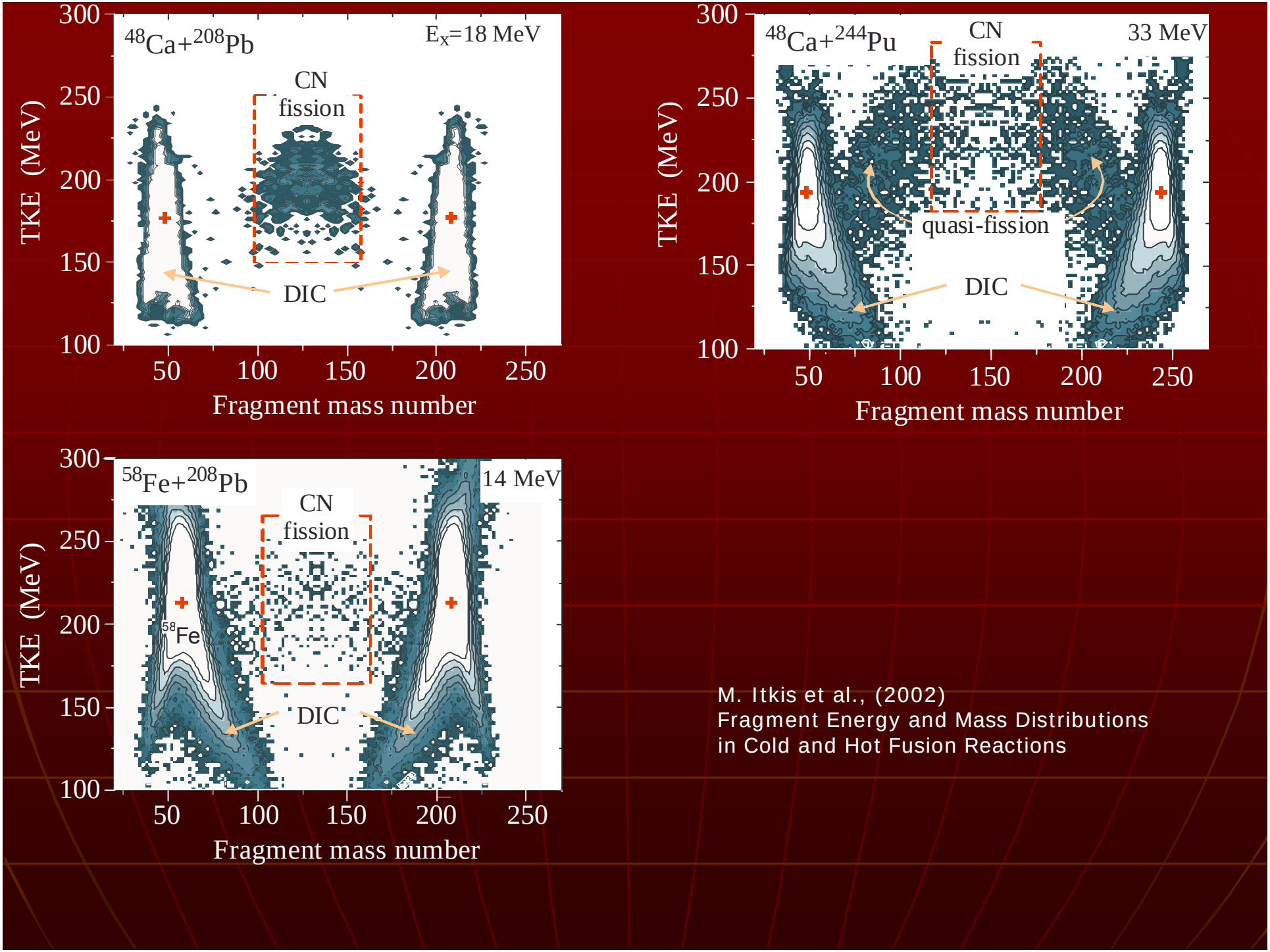

2n
1n
3n
$^{48}Ca + ^{208}Pb \rightarrow ^{238}U, ^{244}Pu, ^{248}Cm$
1000
100
10
1
0.1
cross section / nb
1n
2n
$^{50}Ti + ^{208}Pb$
3n
$^{40}Ar + ^{208}Pb$
3n
10
15
20
25
30
35
40
E^* / MeV

Here there are two questions:

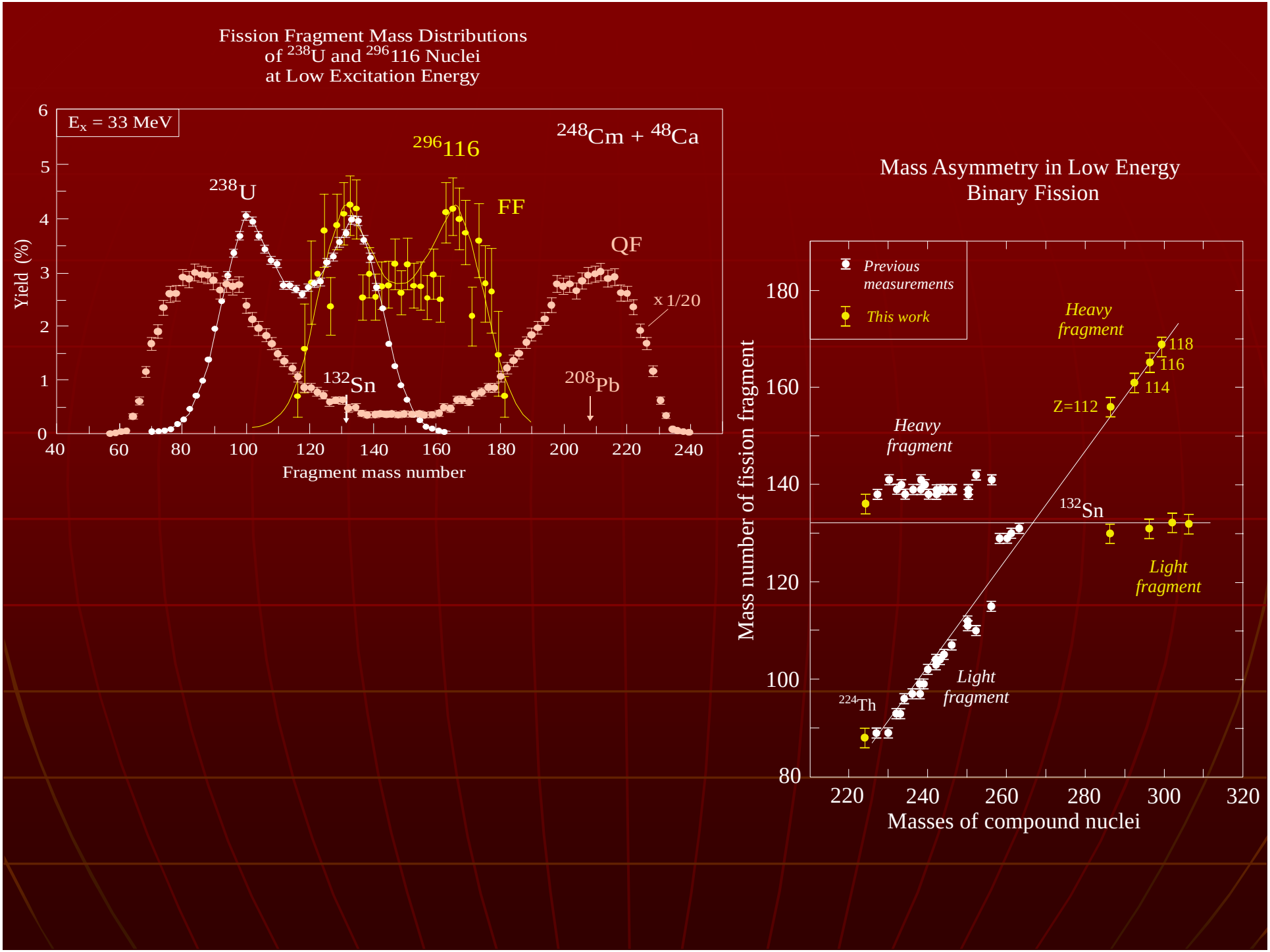
What is the fusion probability for ^{48}Ca and actinide nuclei?

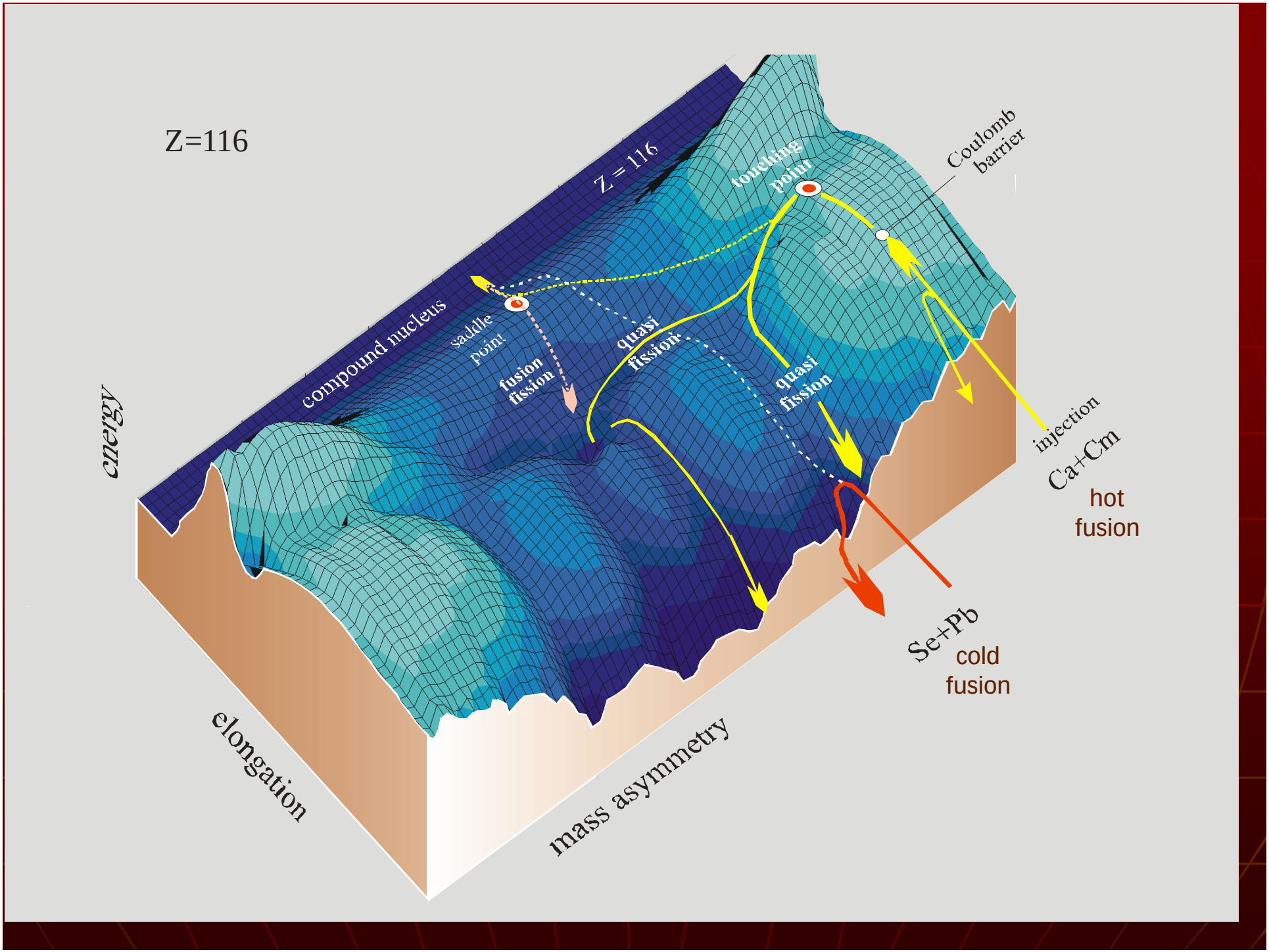
What is the survival probability of the compound nucleus with $Z=114\text{-}118$ at the excitation energy $E^{*} \geq 30$ MeV?

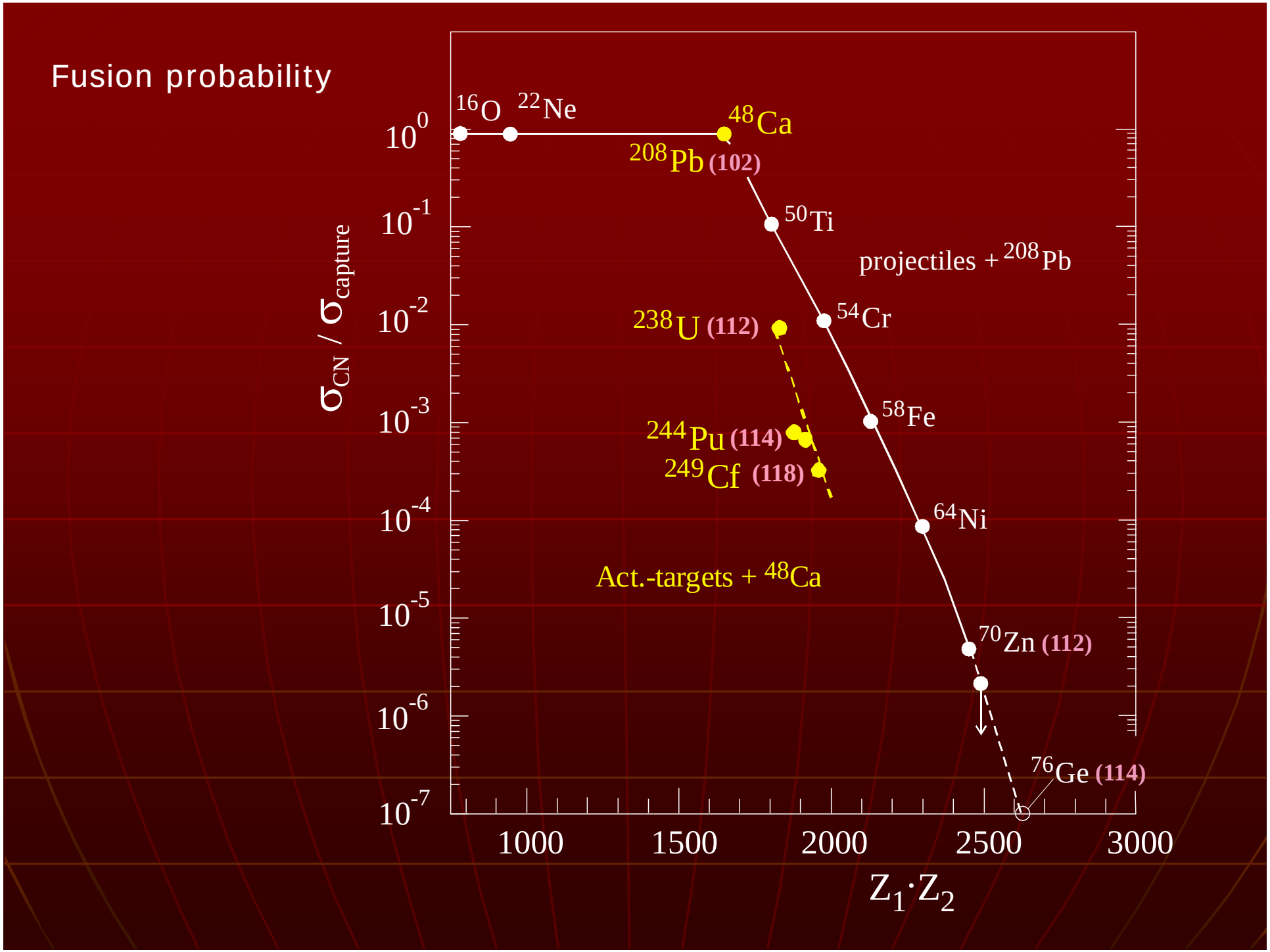

CORSET
Solid angle
360 mstr.
Start
detector
Beam
^{48}Ca
^{238}U, ^{244}Pu, ^{248}Cm
targets
Position sensitive
stop detectors
Resolutions:
angles 0.3 deg.
TOF 150 ps
mass 2 a.m.u.

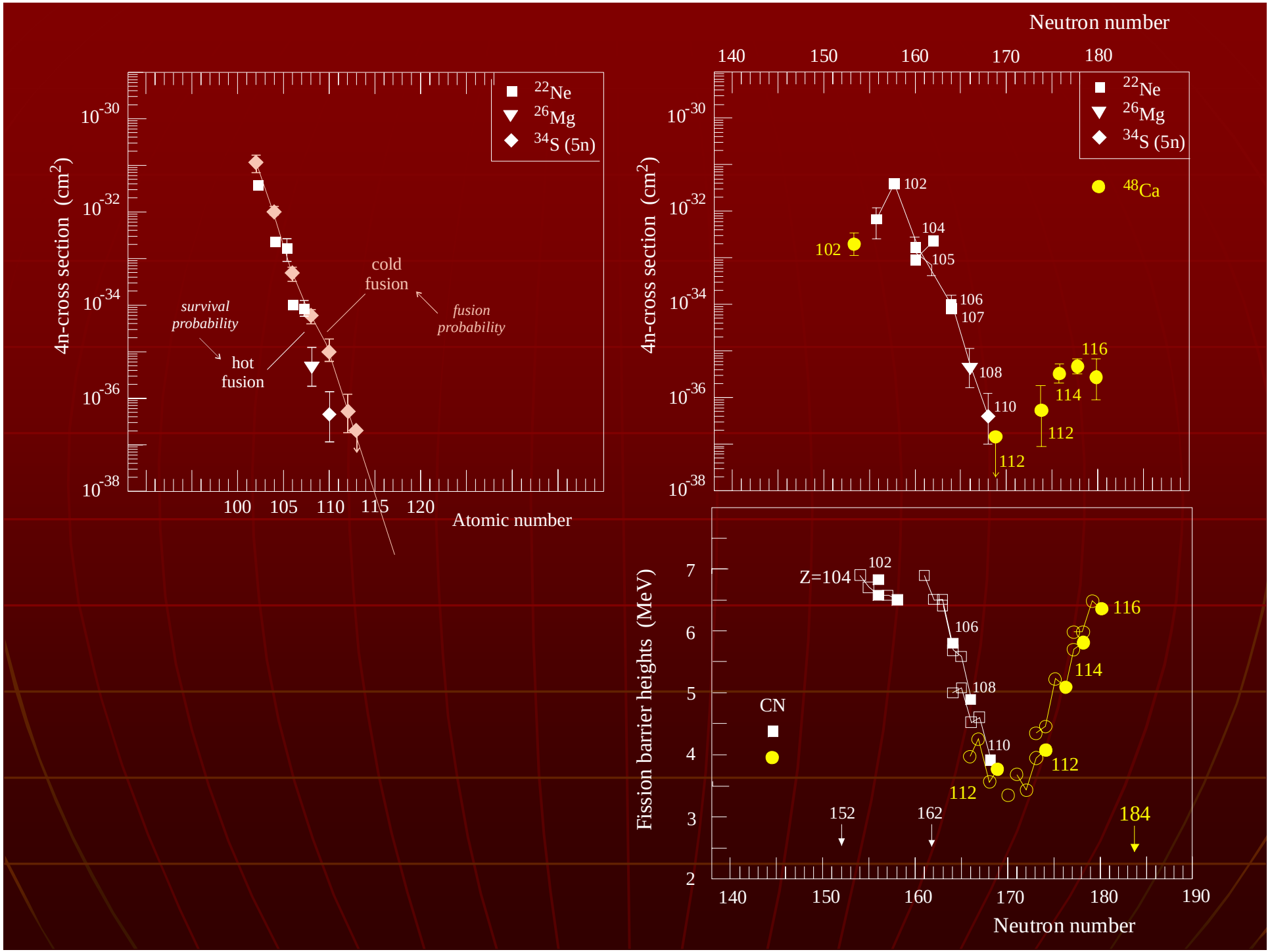


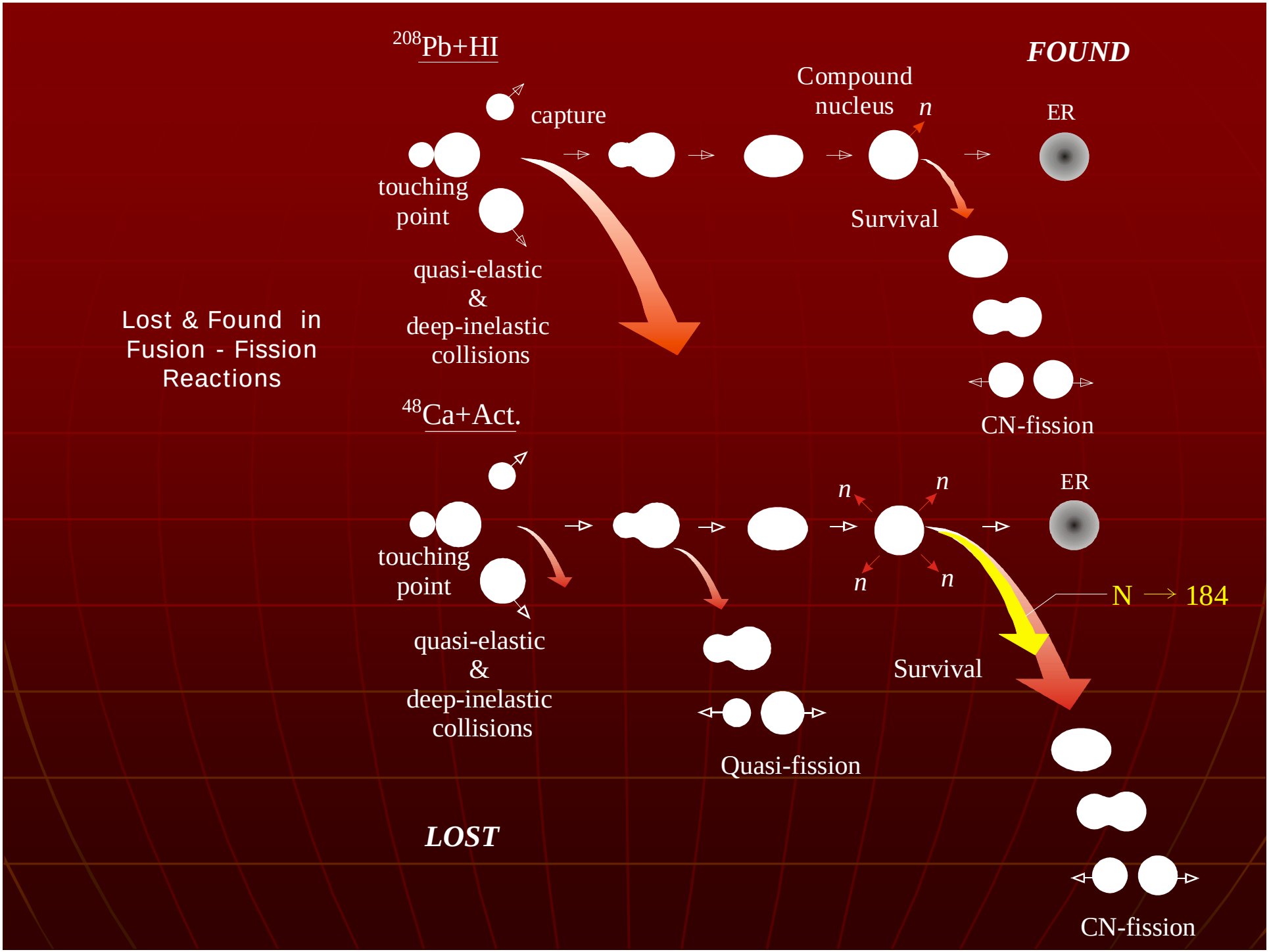
M. Itkis et al., (2002)
Fragment Energy and Mass Distributions
in Cold and Hot Fusion Reactions

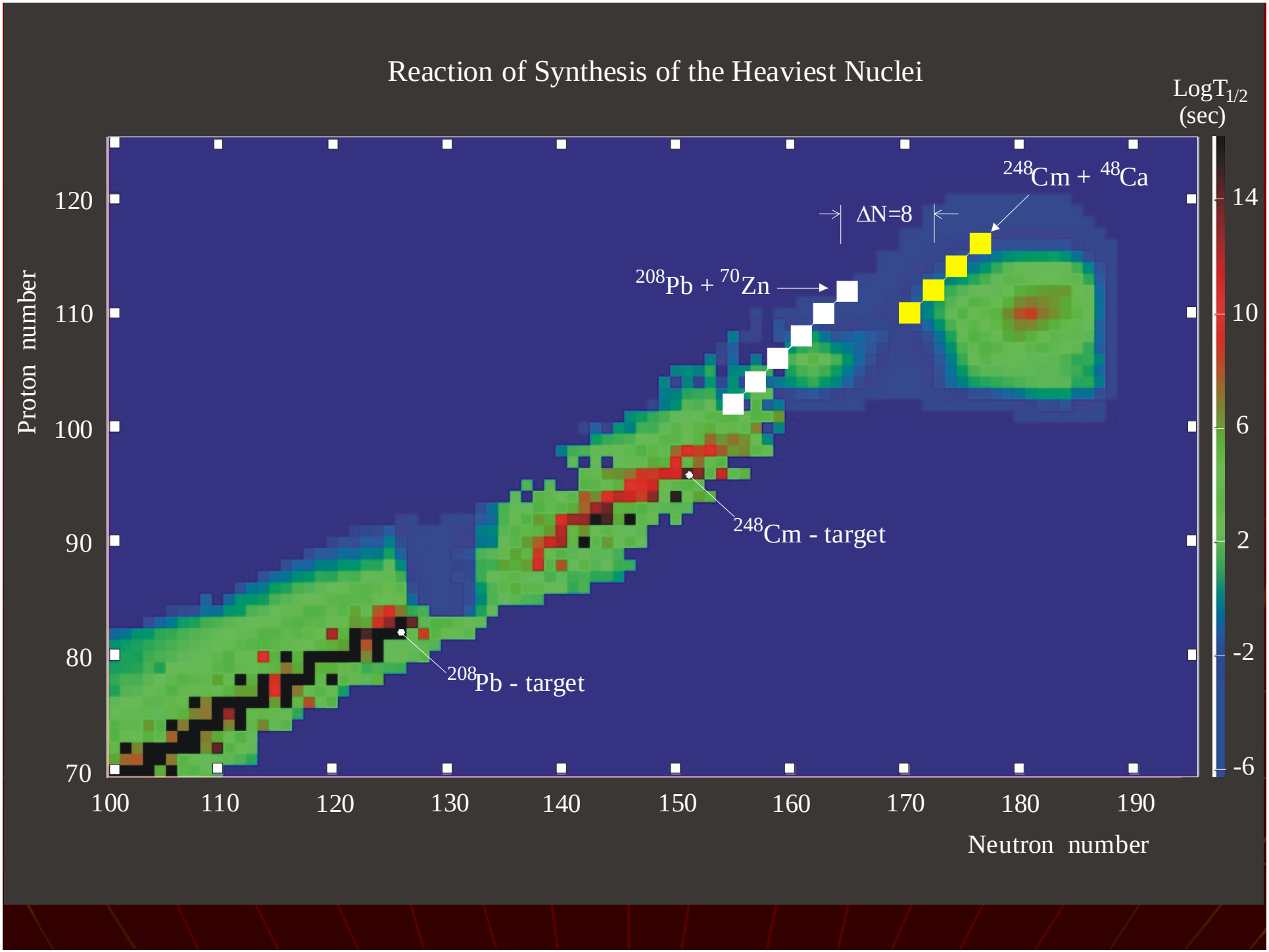

Fission Fragment Mass Distributions
of 238U and 296116 Nuclei
at Low Excitation Energy
Ex = 33 MeV
248Cm + 48Ca
296116
238U
FF
QF
x 1/20
132Sn
208Pb
Yield (%)
Fragment mass number
Mass Asymmetry in Low Energy
Binary Fission
Previous measurements
This work
Heavy fragment
Light fragment
Z=112
118
116
114
224Th
Mass number of fission fragment
Masses of compound nuclei

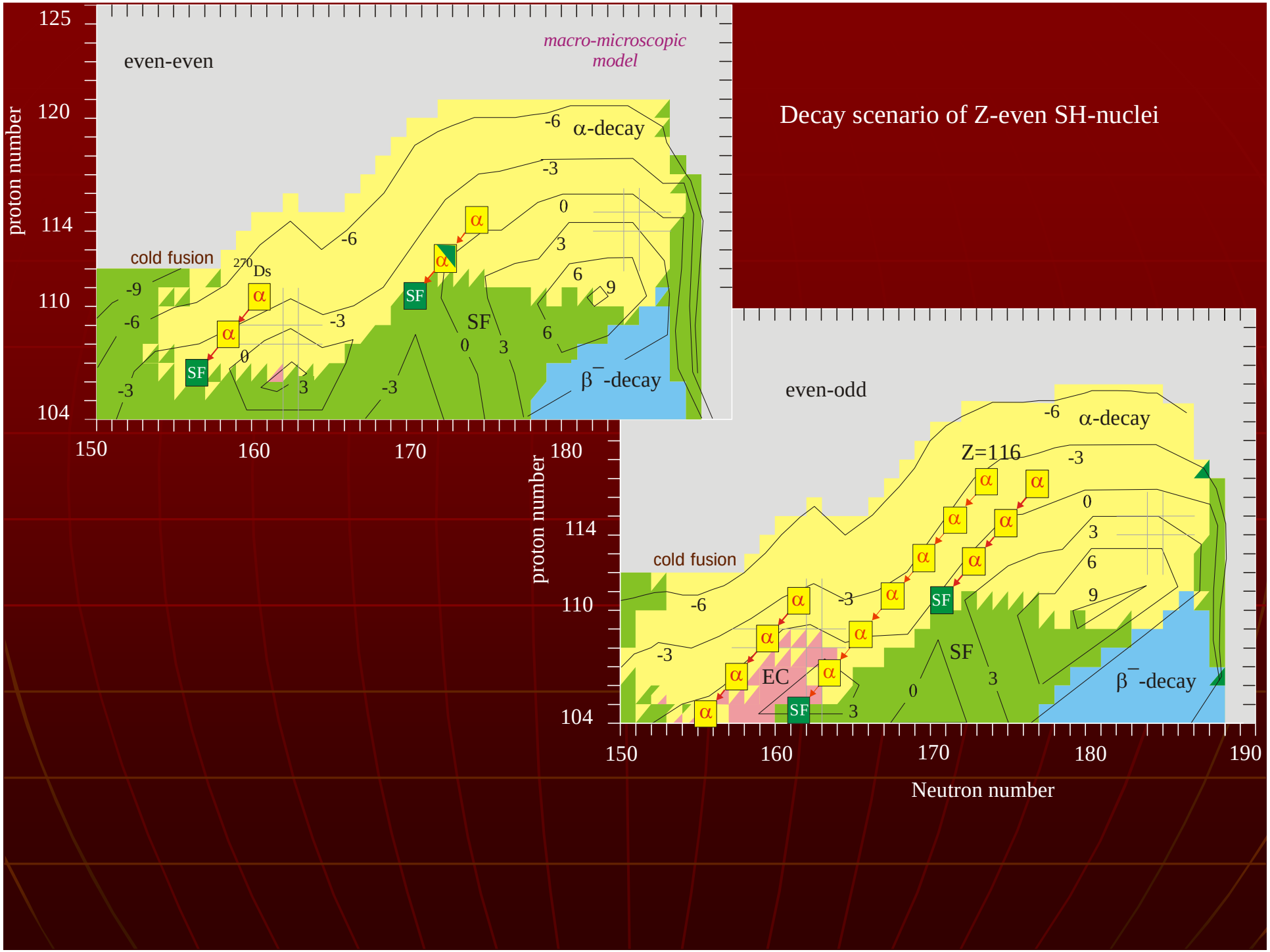

Z=116
Z = 116
compound nucleus
saddle point
fusion fission
quasi fission
quasi fission
touching point
Coulomb barrier
injection
Ca+Cm
hot fusion
Se+Pb
cold fusion
energy
elongation
mass asymmetry


Fusion probability
$\sigma_{CN} / \sigma_{capture}$
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
^{16}O
^{22}Ne
^{48}Ca
^{208}Pb (102)
^{50}Ti
^{54}Cr
^{58}Fe
^{64}Ni
^{70}Zn (112)
^{76}Ge (114)
projectiles + ^{208}Pb
^{238}U (112)
^{244}Pu (114)
^{249}Cf (118)
Act.-targets + ^{48}Ca
1000
1500
2000
2500
3000
$Z_1 \cdot Z_2$

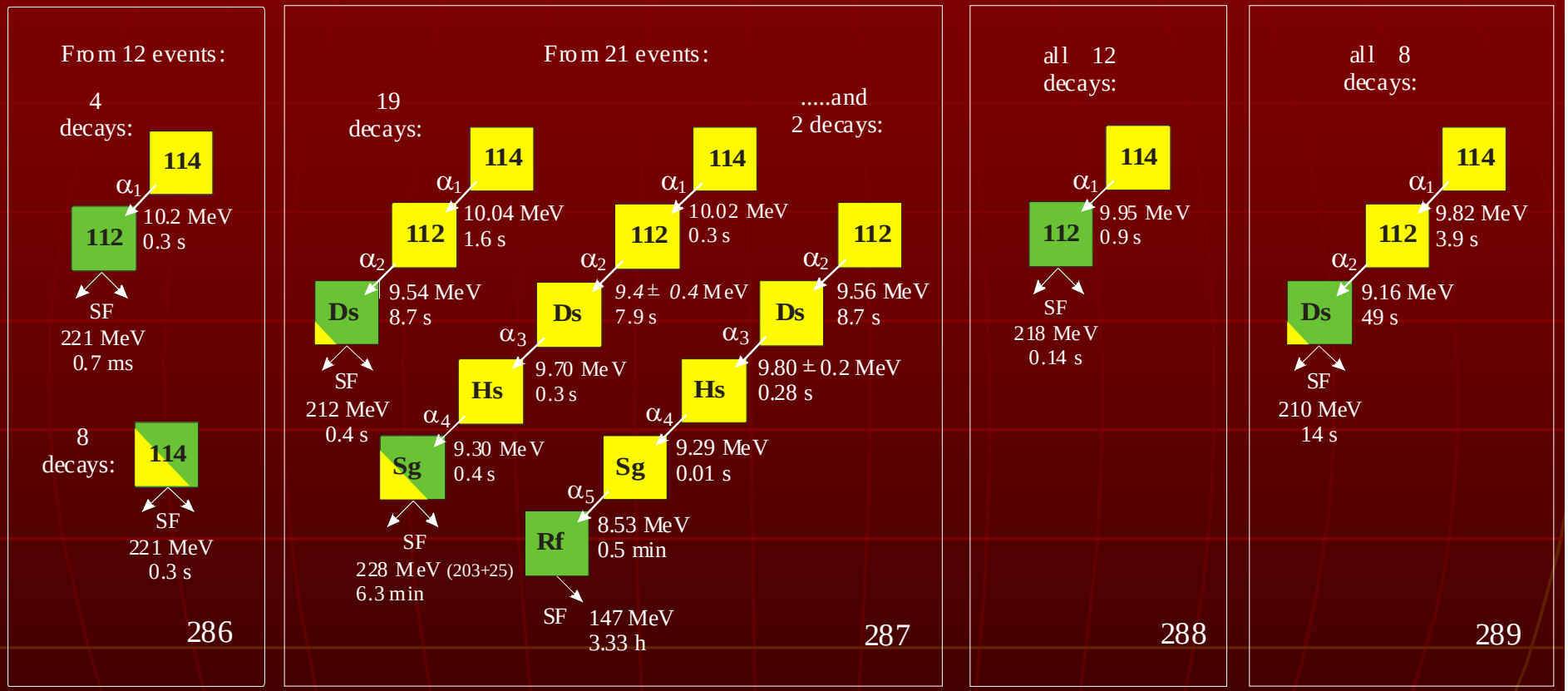

4n-cross section (cm^2)
10^{-30}
10^{-32}
10^{-34}
10^{-36}
10^{-38}
100 105 110 115 120
Atomic number
^{22}Ne
^{26}Mg
^{34}S (5n)
cold fusion
survival probability
fusion probability
hot fusion
Neutron number
140 150 160 170 180
^{48}Ca
102
104
105
106
107
108
110
112
114
116
Fission barrier heights (MeV)
2 3 4 5 6 7
Z=104
CN
152
162
184
190


Lost & Found in Fusion - Fission Reactions
^{208}Pb+HI
capture
touching point
quasi-elastic & deep-inelastic collisions
Compound nucleus
n
ER
FOUND
Survival
CN-fission
^{48}Ca+Act.
touching point
quasi-elastic & deep-inelastic collisions
n
n
n
n
ER
N → 184
Survival
Quasi-fission
LOST
CN-fission

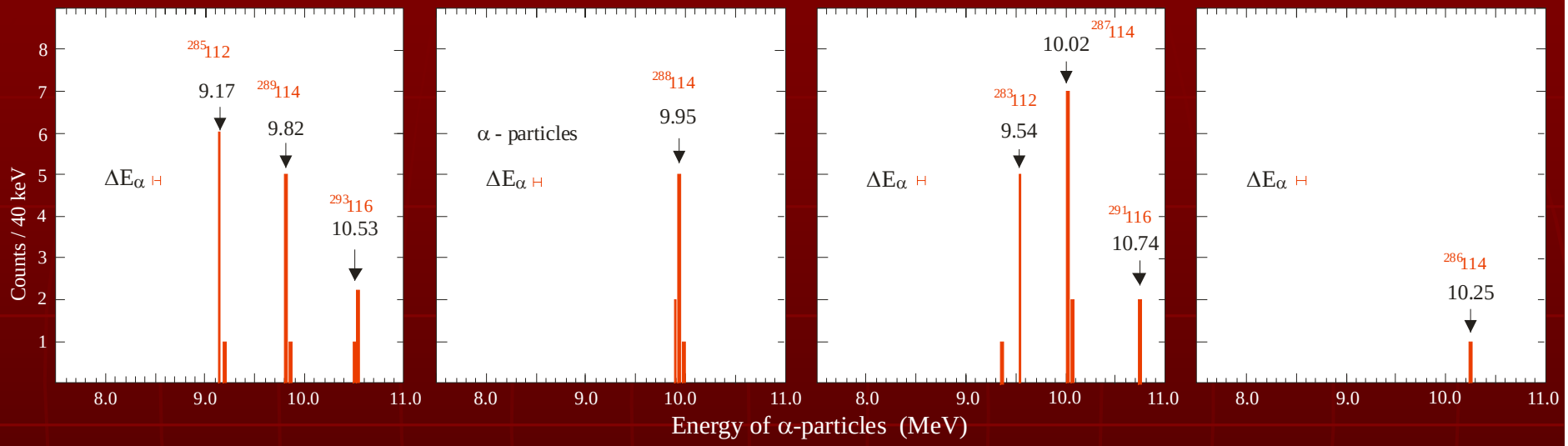

Reaction of Synthesis of the Heaviest Nuclei
LogT1/2 (sec)
14
10
6
2
-2
-6
248Cm + 48Ca
ΔN=8
208Pb + 70Zn
248Cm - target
208Pb - target
Proton number
120
110
100
90
80
70
100
110
120
130
140
150
160
170
180
190
Neutron number

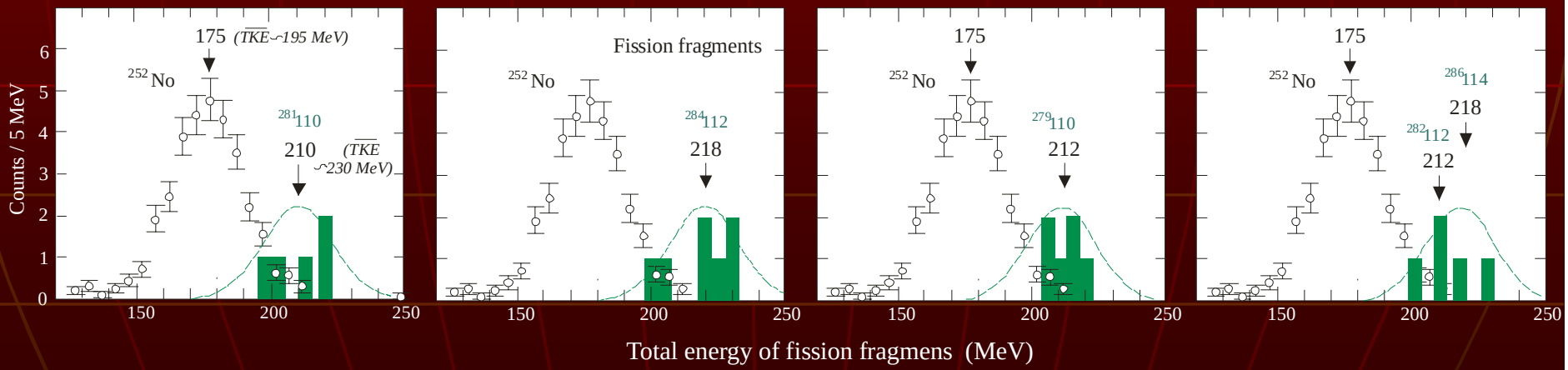

Decay scenario of Z-even SH-nuclei
even-even
macro-microscopic model
cold fusion
^{270}Ds
α-decay
SF
β⁻-decay
-6
-3
0
3
6
9
-9
proton number
125
120
114
110
104
150
160
170
even-odd
Z=116
EC
180
190
Neutron number

Decay Chains of the Isotopes with Z=114



Spectra of a-particles and sum kinetic energies of fission fragments from the decay chains of Z=110, 112, 114 and 116 isotopes observed in ^{48}Ca- induced reactions

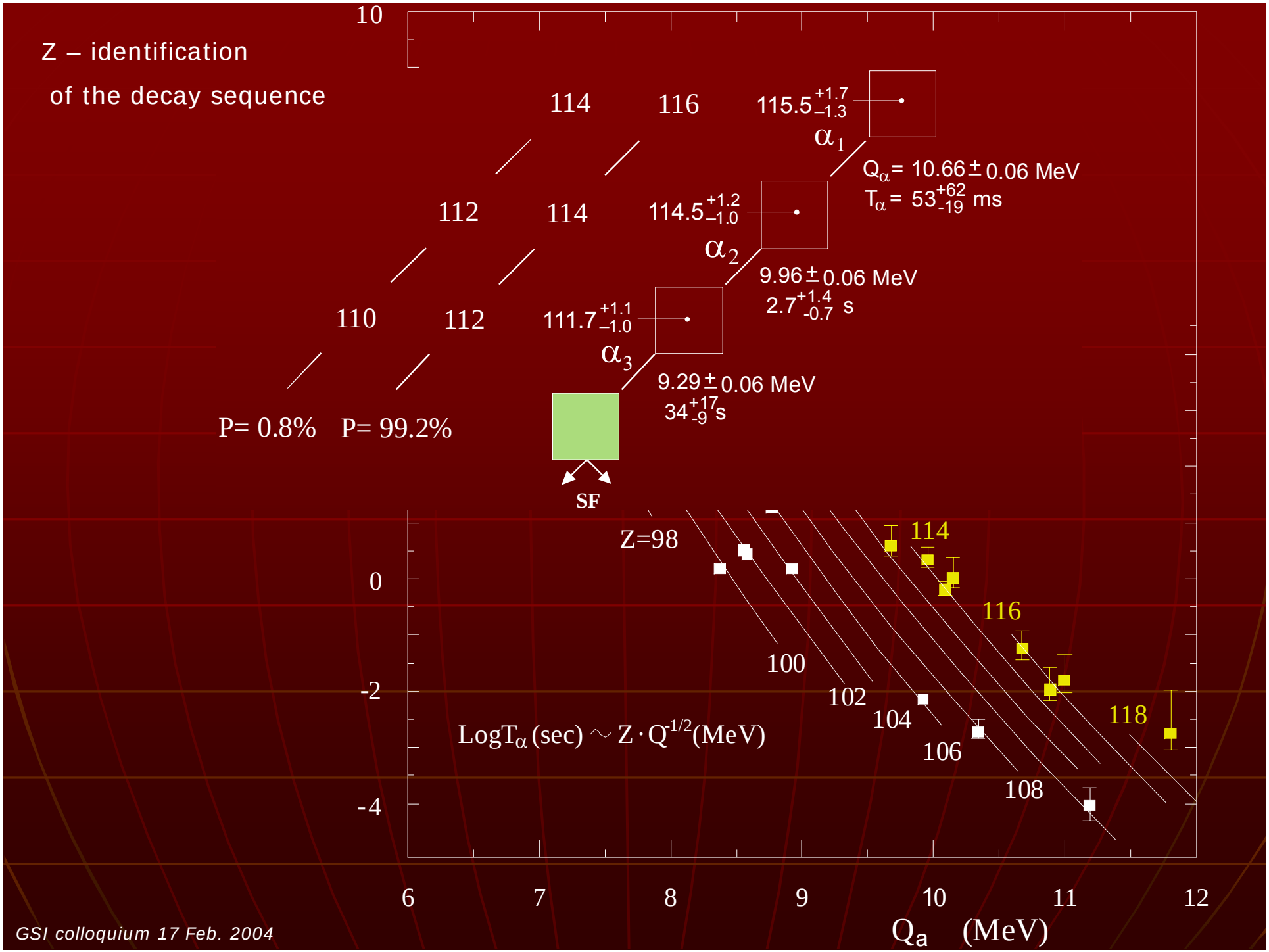


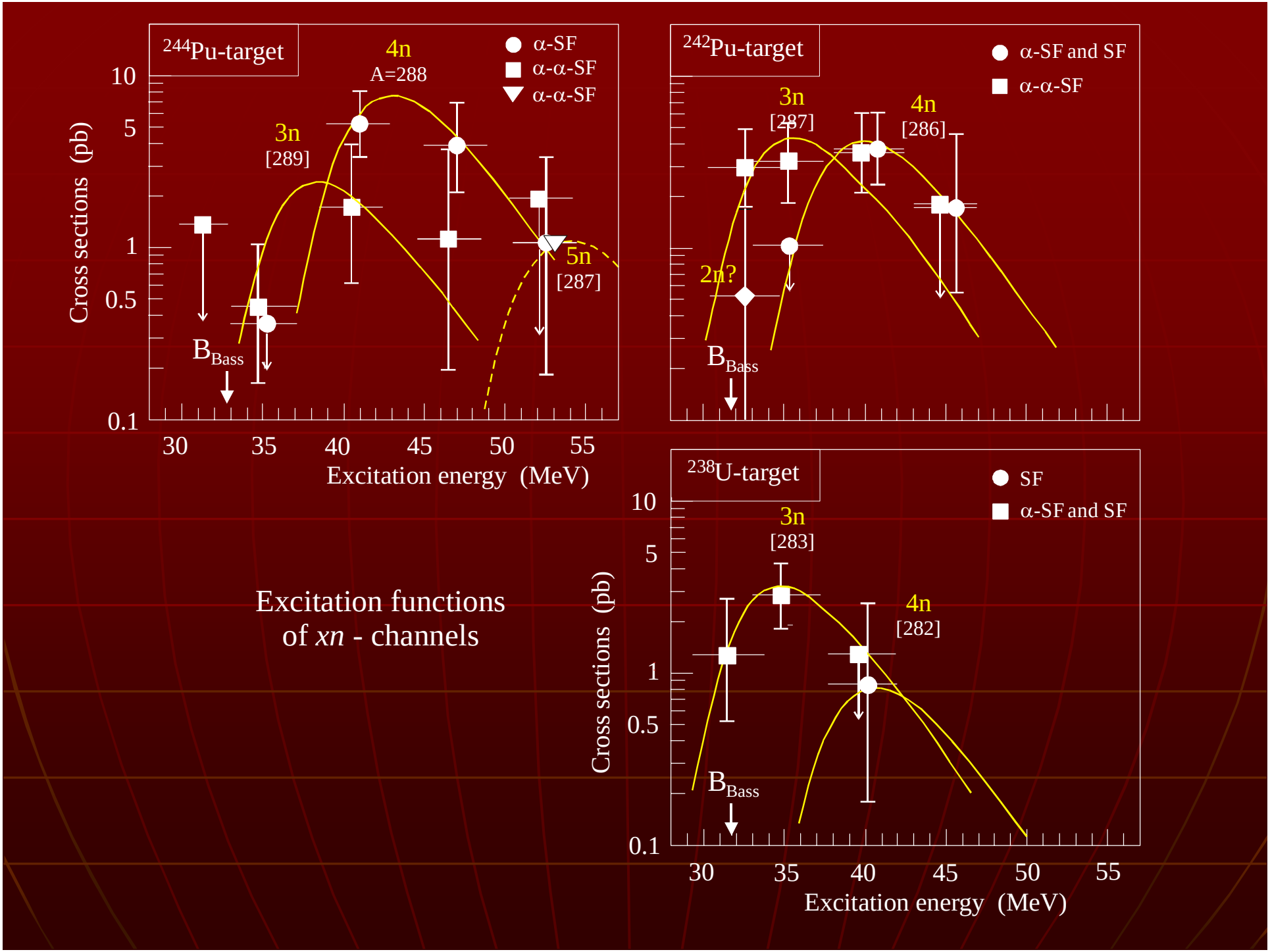


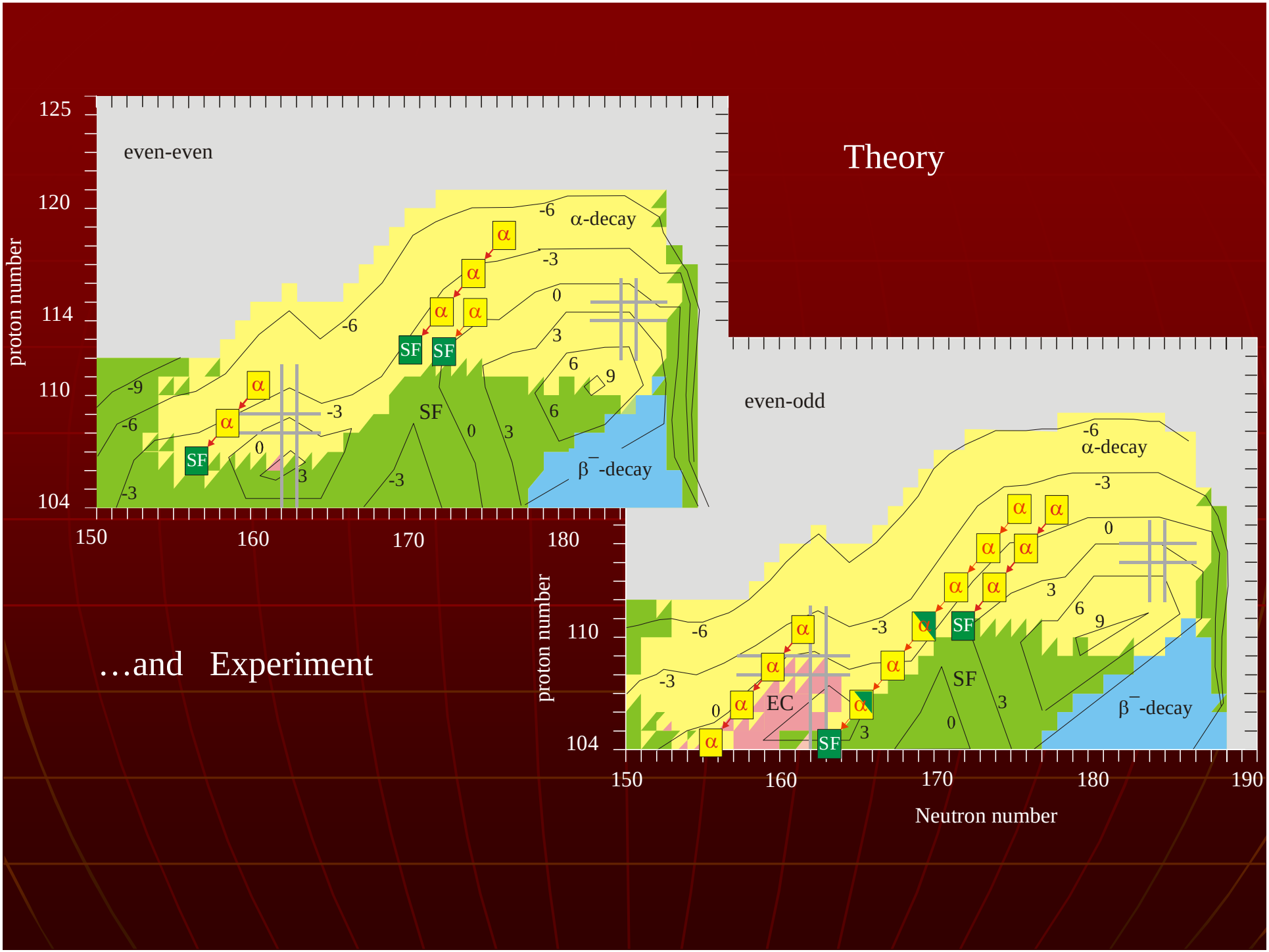
GSI colloquium 17 Feb. 2004

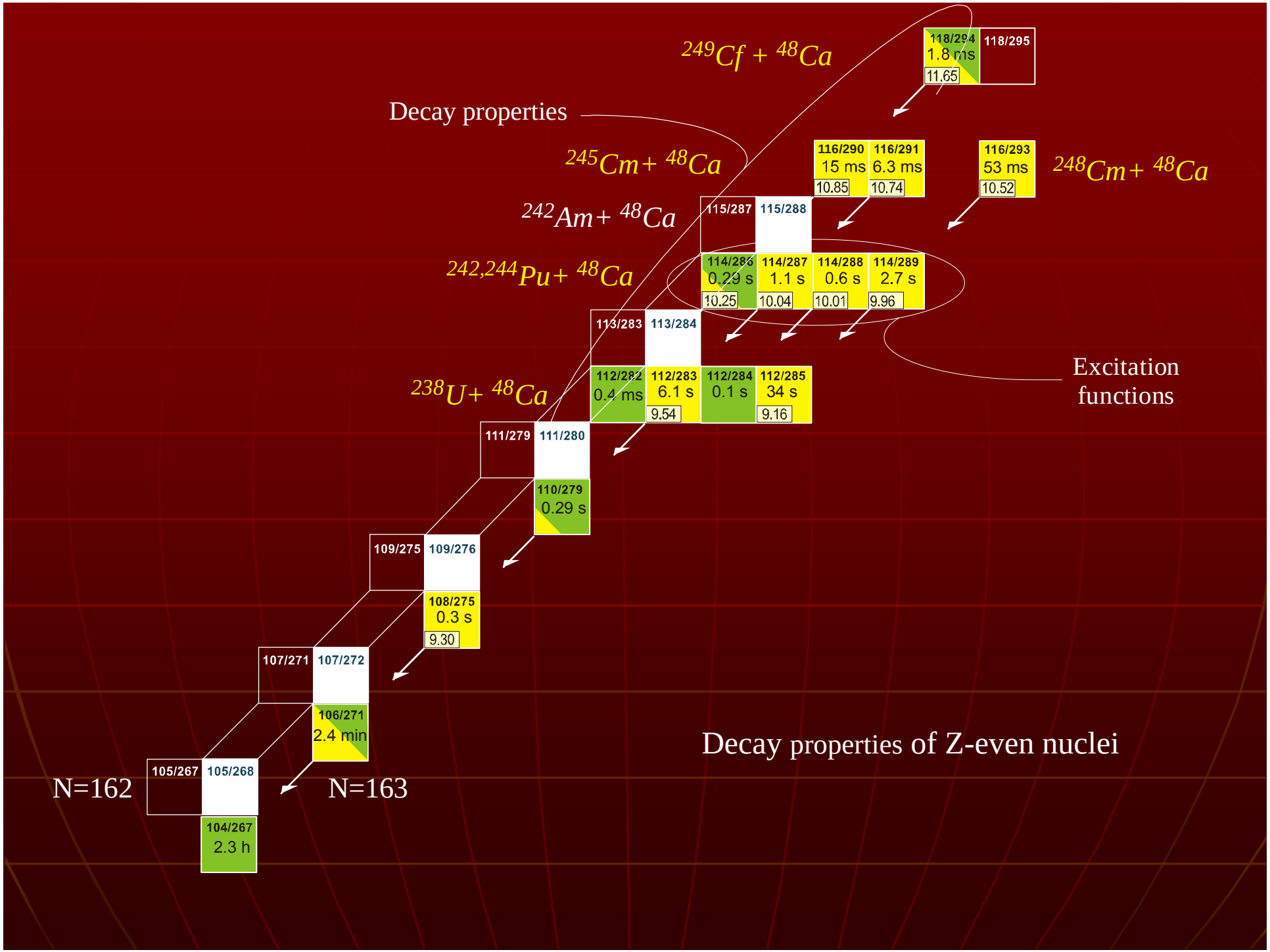
Z – identification

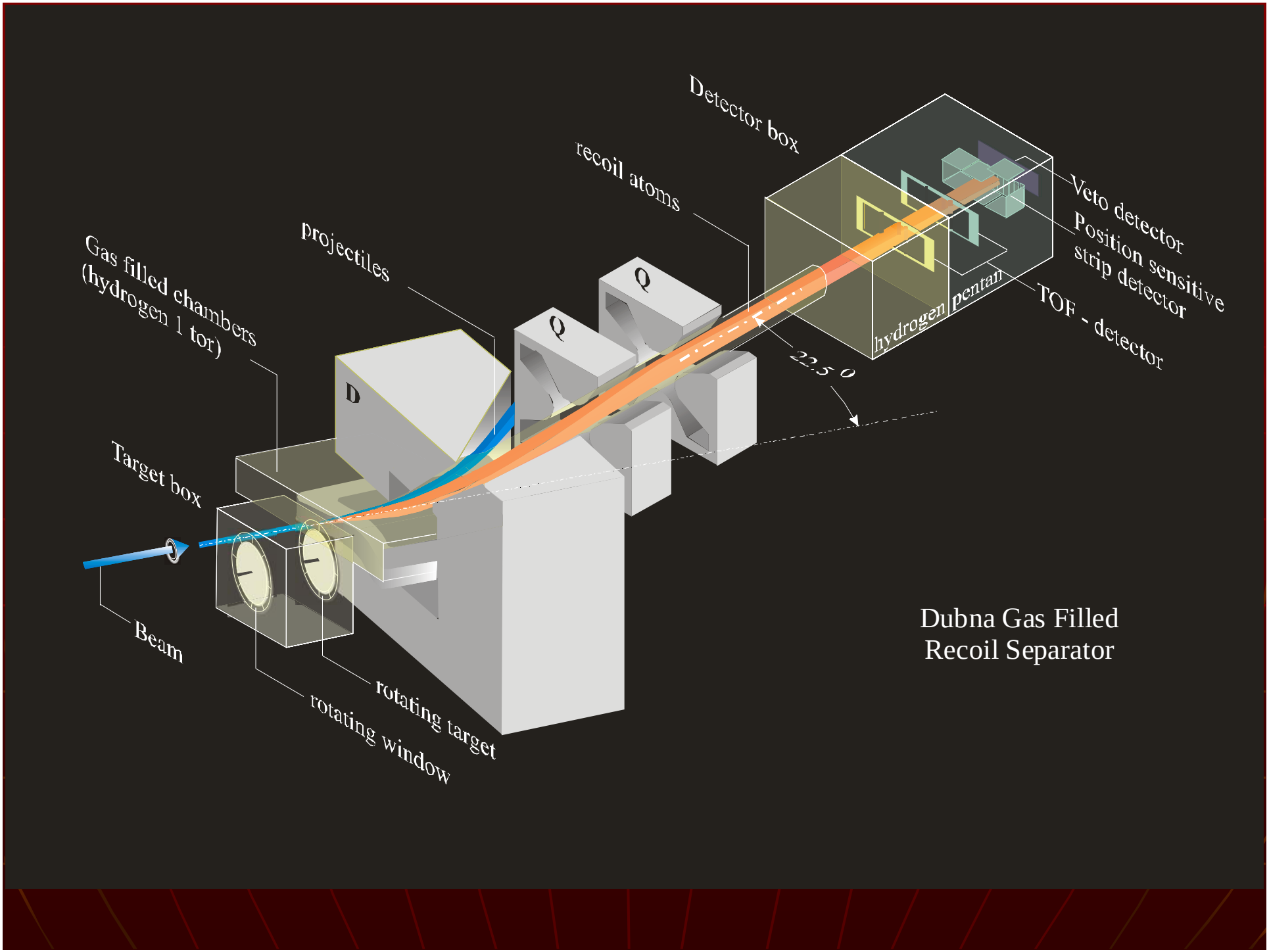
of the decay sequence

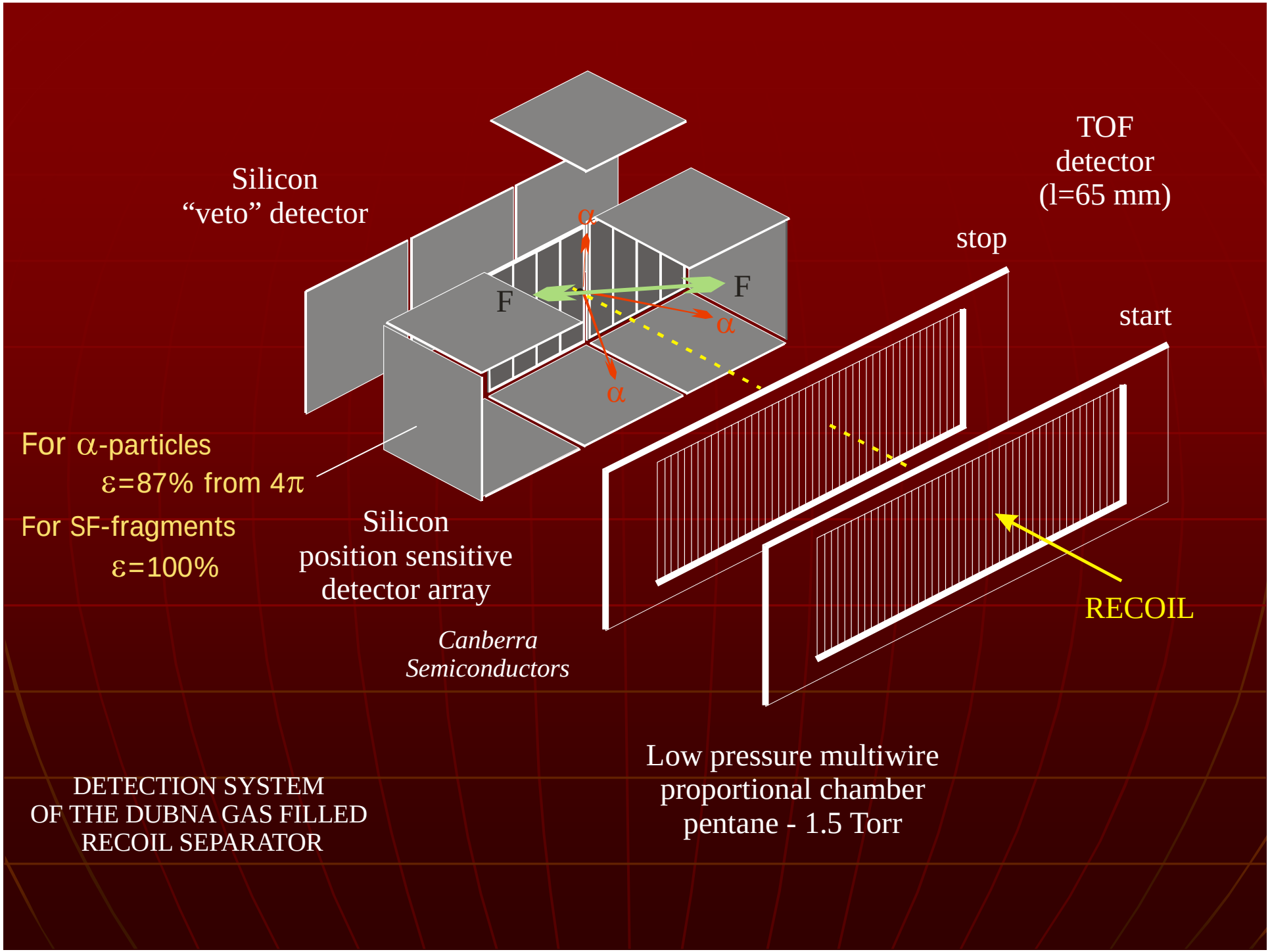



^{244}Pu-target
4n
A=288
3n
[289]
5n
[287]
α-SF
α-α-SF
α-α-SF
B_{Bass}
Cross sections (pb)
10
5
1
0.5
0.1
30
35
40
45
50
55
Excitation energy (MeV)
^{242}Pu-target
3n
[287]
4n
[286]
2n?
α-SF and SF
α-α-SF
B_{Bass}
Excitation functions
of *xn* - channels
^{238}U-target
3n
[283]
4n
[282]
SF
α-SF and SF
B_{Bass}
Cross sections (pb)
10
5
1
0.5
0.1
30
35
40
45
50
55
Excitation energy (MeV)

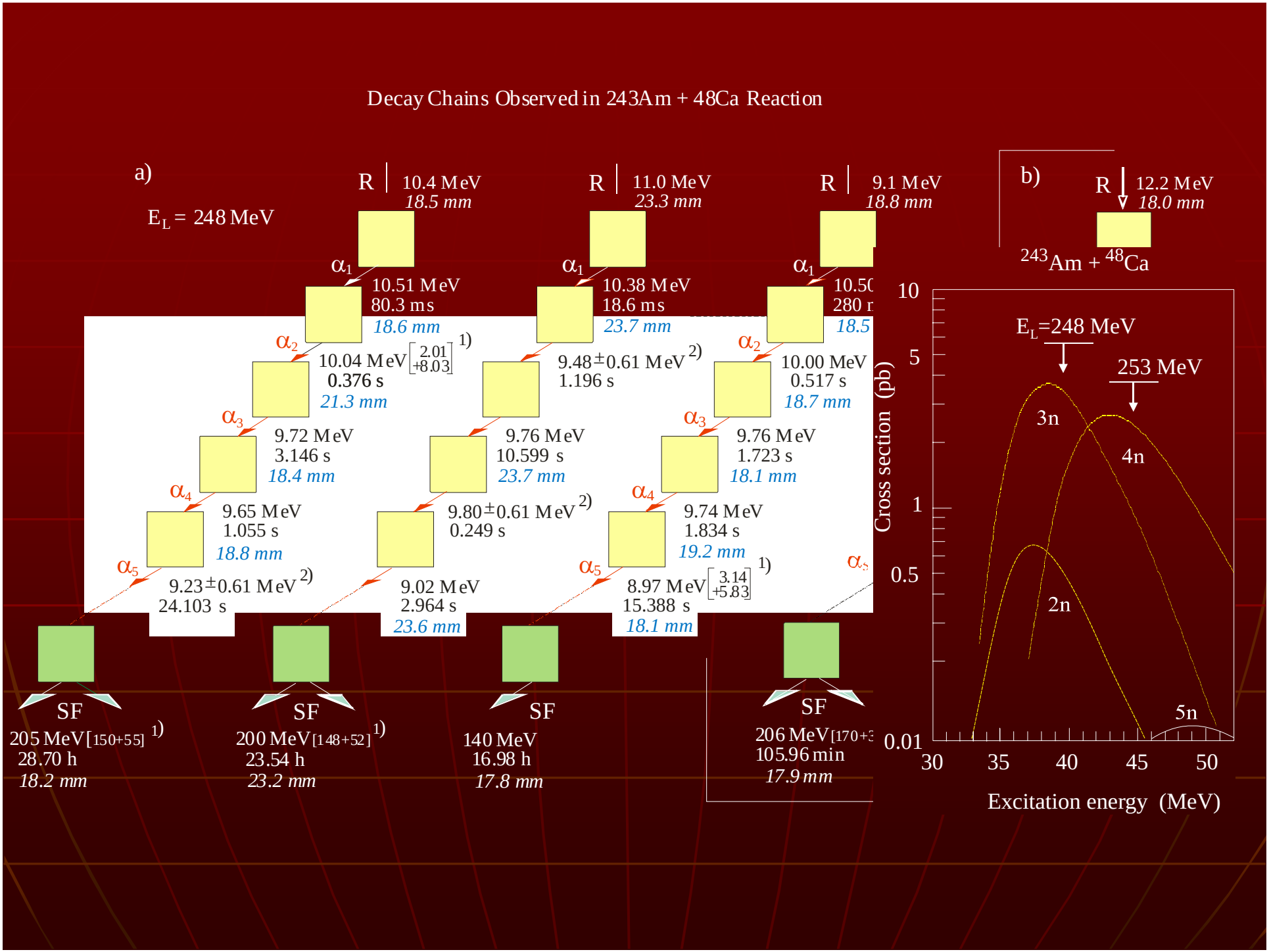

Theory
even-even
α-decay
SF
β⁻-decay
proton number
125
120
114
110
104
150
160
170
180
…and Experiment
even-odd
α-decay
SF
EC
β⁻-decay
proton number
110
104
150
160
170
180
190
Neutron number


249Cf + 48Ca
Decay properties
245Cm+ 48Ca
242Am+ 48Ca
242,244Pu+ 48Ca
238U+ 48Ca
248Cm+ 48Ca
Excitation functions
118/294 1.8 ms 11.65
118/295
116/290 15 ms 10.85
116/291 6.3 ms 10.74
116/293 53 ms 10.52
115/287
115/288
114/286 0.29 s 10.25
114/287 1.1 s 10.04
114/288 0.6 s 10.01
114/289 2.7 s 9.96
113/283
113/284
112/282 0.4 ms
112/283 6.1 s 9.54
112/284 0.1 s
112/285 34 s 9.16
111/279
111/280
110/279 0.29 s
109/275
109/276
108/275 0.3 s 9.30
107/271
107/272
106/271 2.4 min
105/267
105/268
104/267 2.3 h
N=162
N=163
Decay properties of Z-even nuclei


Detector box
recoil atoms
Veto detector
Position sensitive
strip detector
TOF - detector
Gas filled chambers
(hydrogen 1 tor)
projectiles
Q
Q
D
hydrogen pentan
22.5 o
Target box
Beam
rotating window
rotating target
Dubna Gas Filled
Recoil Separator

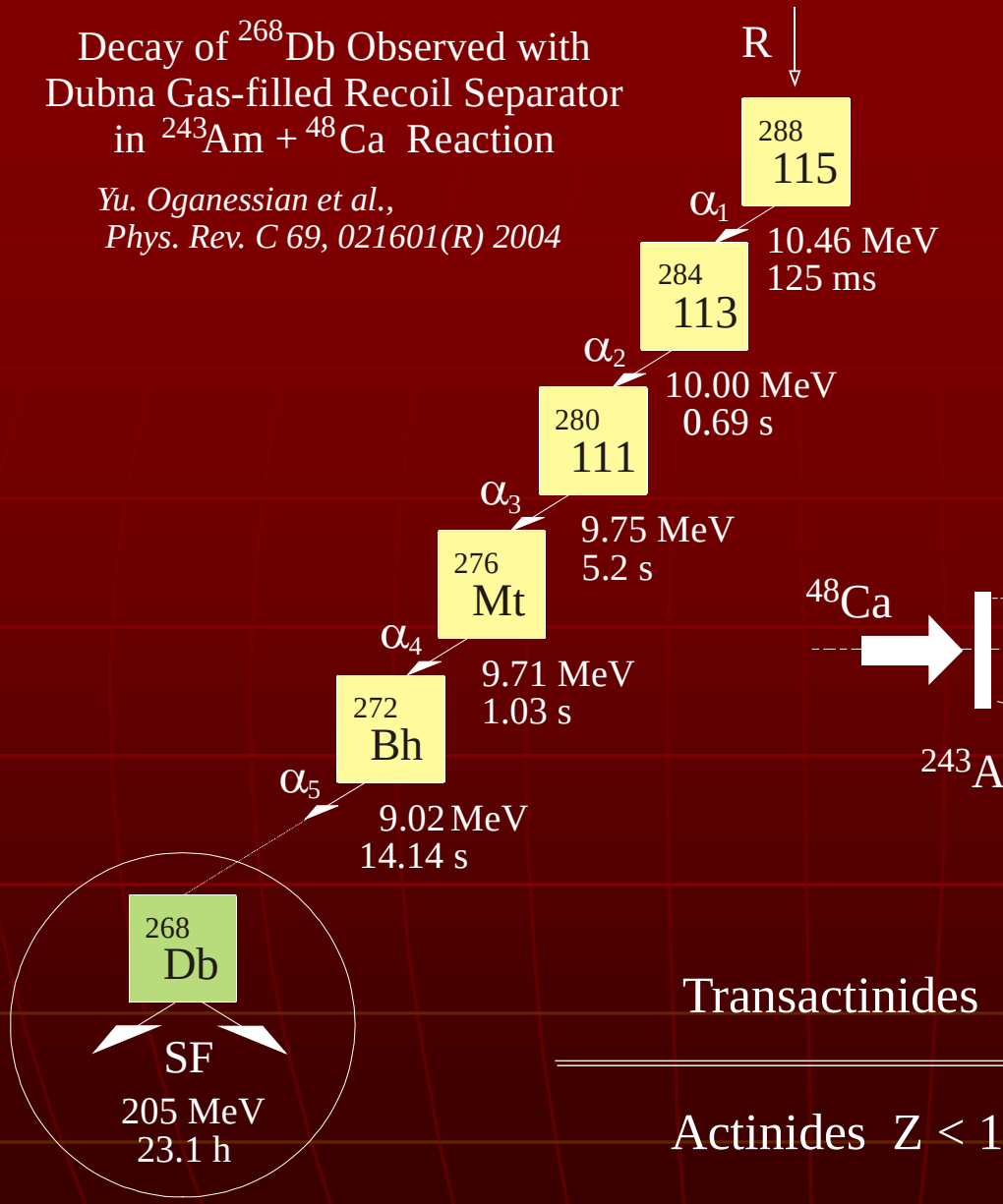


DETECTION SYSTEM
OF THE DUBNA GAS FILLED
RECOIL SEPARATOR

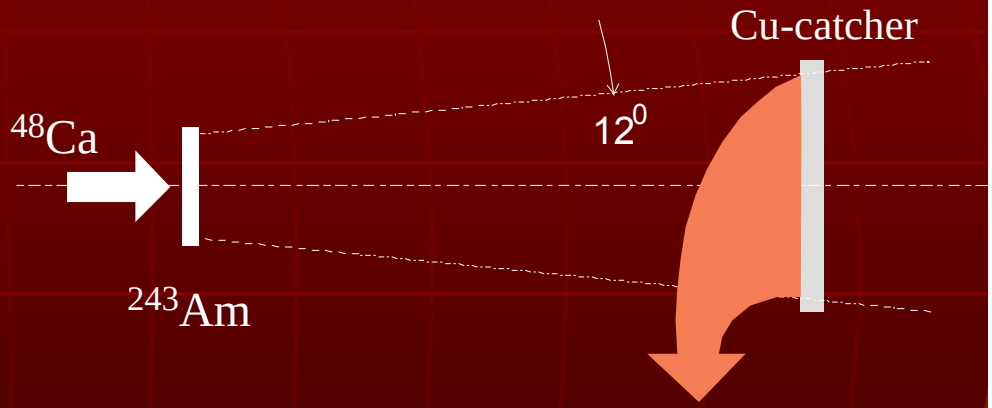

Decay Chains Observed in 243Am + 48Ca Reaction
a)
E_L = 248 MeV
R
10.4 MeV
18.5 mm
11.0 MeV
23.3 mm
9.1 MeV
18.8 mm
α1
10.51 MeV
80.3 ms
18.6 mm
10.38 MeV
18.6 ms
23.7 mm
α2
10.04 MeV [2.01 +8.03] 1)
0.376 s
21.3 mm
9.48±0.61 MeV 2)
1.196 s
10.00 MeV
0.517 s
18.7 mm
α3
9.72 MeV
3.146 s
18.4 mm
9.76 MeV
10.599 s
23.7 mm
9.76 MeV
1.723 s
18.1 mm
α4
9.65 MeV
1.055 s
18.8 mm
9.80±0.61 MeV 2)
0.249 s
9.74 MeV
1.834 s
19.2 mm
α5
9.23±0.61 MeV 2)
24.103 s
9.02 MeV
2.964 s
23.6 mm
8.97 MeV [3.14 +5.83] 1)
15.388 s
18.1 mm
SF
205 MeV [150+55] 1)
28.70 h
18.2 mm
200 MeV [148+52] 1)
23.54 h
23.2 mm
140 MeV
16.98 h
17.8 mm
206 MeV [170+
105.96 min
17.9 mm
b)
R
12.2 MeV
18.0 mm
243Am + 48Ca
E_L=248 MeV
253 MeV
3n
4n
2n
5n
Cross section (pb)
10
5
1
0.5
0.01
30
35
40
45
50
Excitation energy (MeV)

Decay of ^{268}Db Observed with Dubna Gas-filled Recoil Separator in ^{243}Am + ^{48}Ca Reaction

Yu. Oganessian et al., Phys. Rev. C 69, 021601(R) 2004



Chemical isolation of ^{268}Db

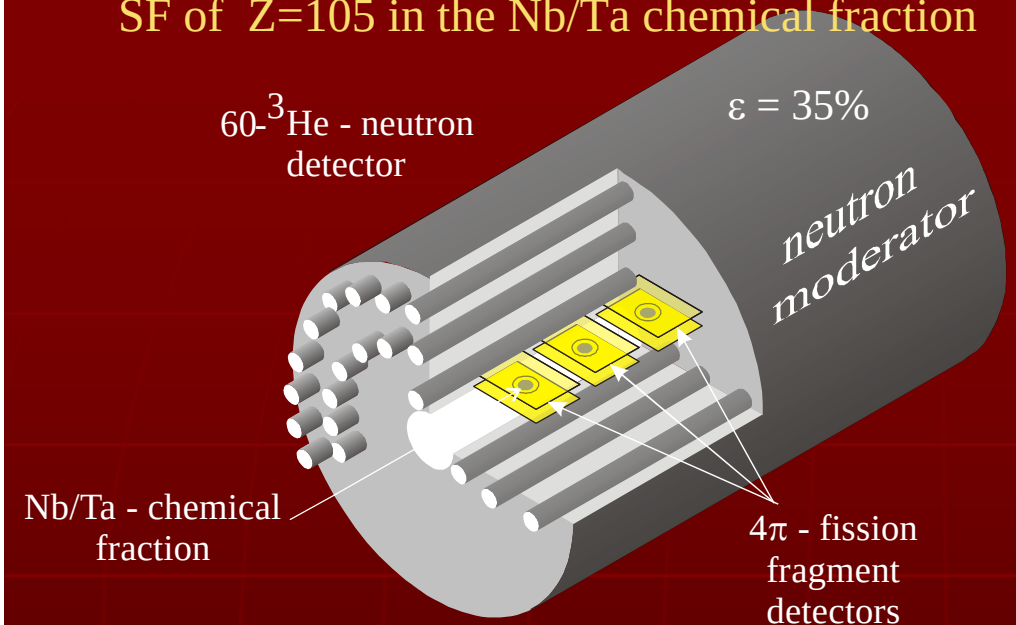


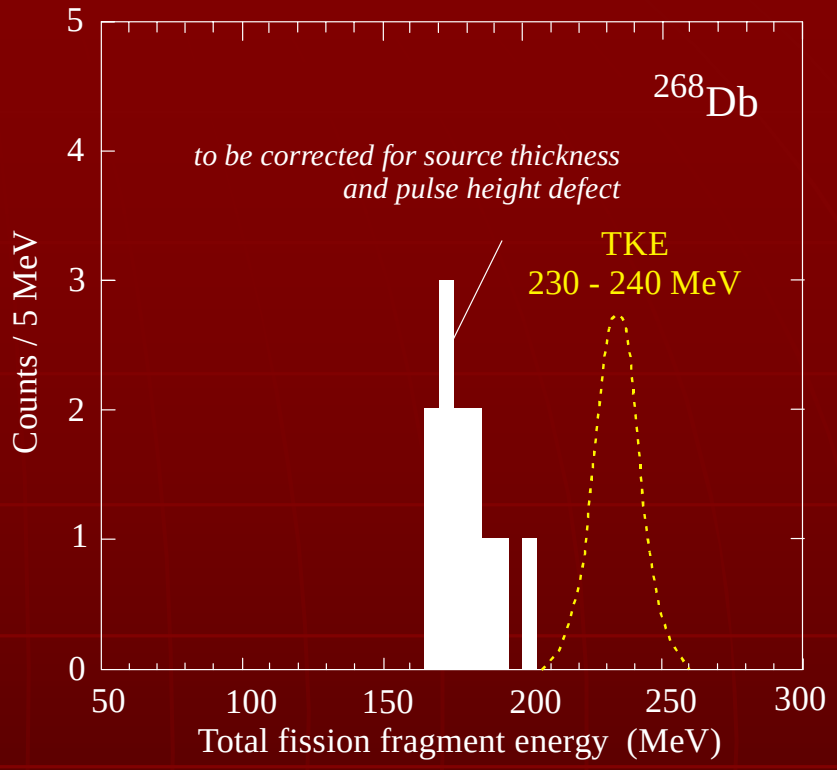
Nb / Ta / Db - fraction

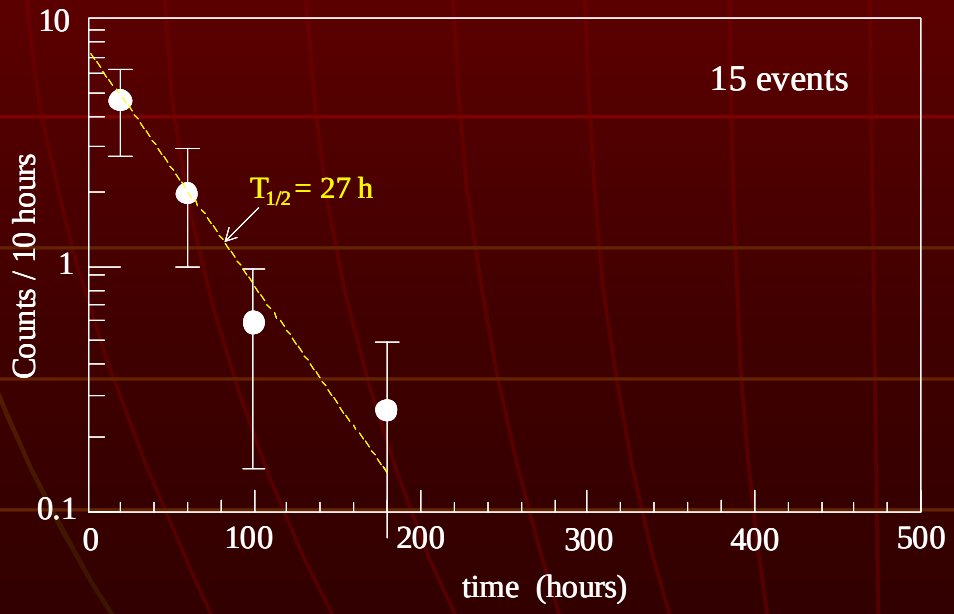
Transactinides Z ≥ 104

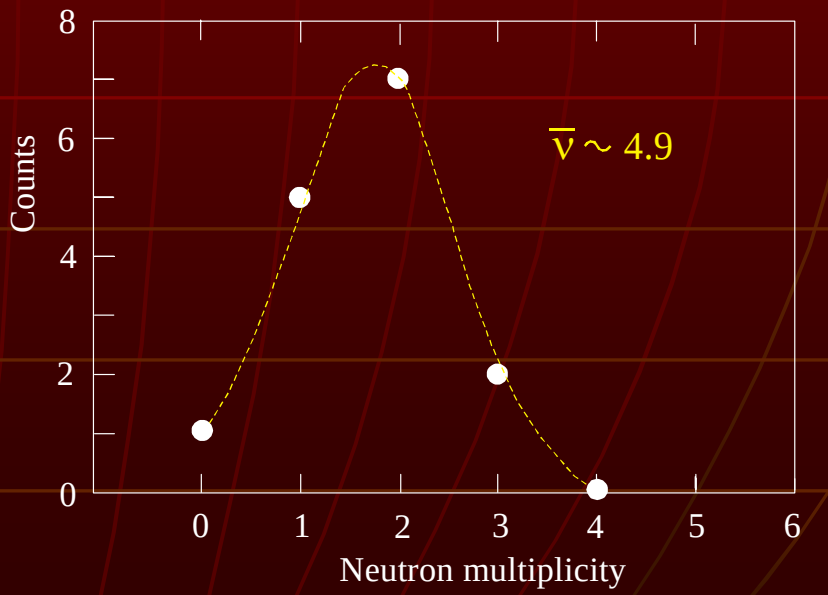
Actinides Z < 104

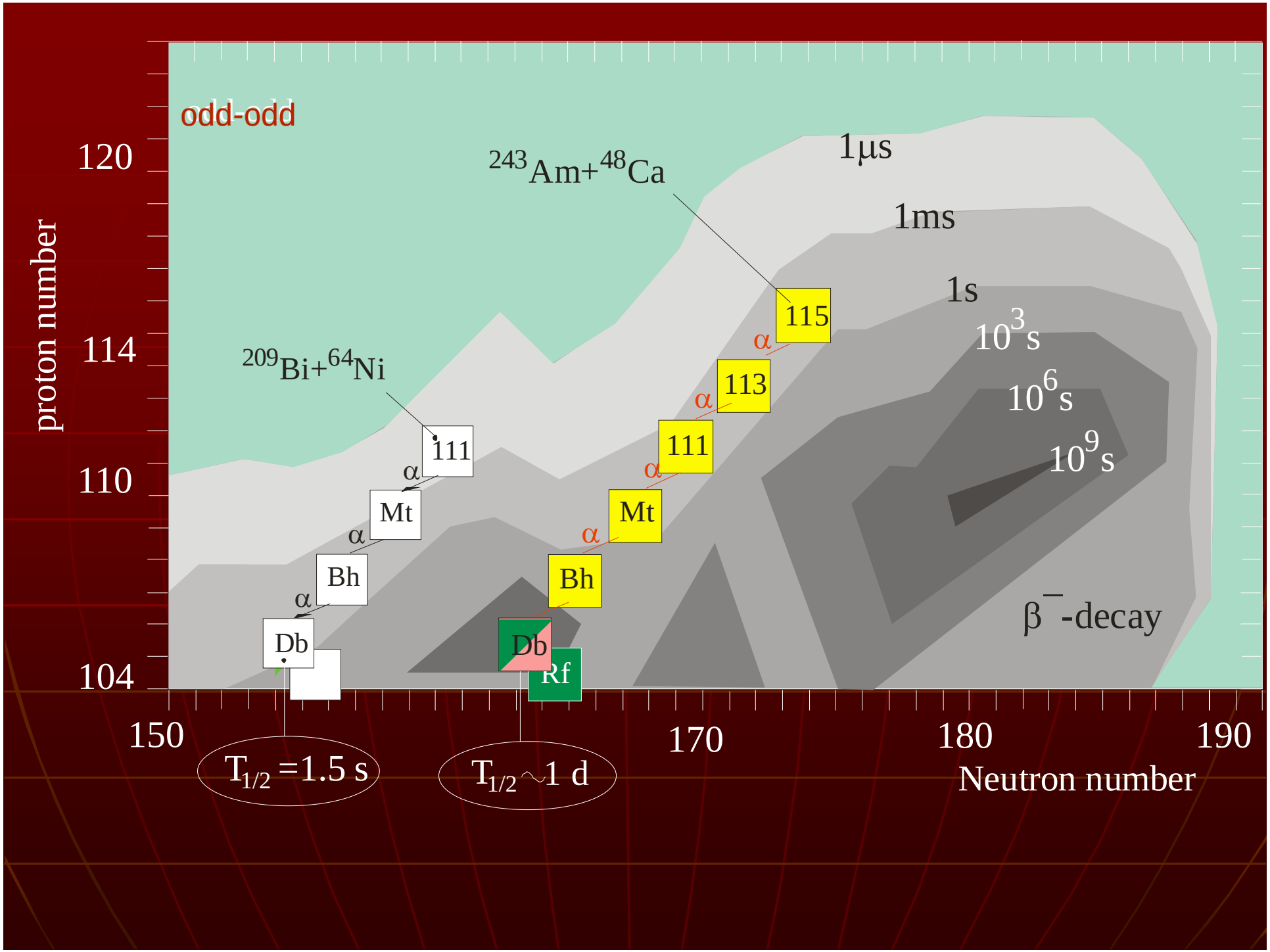
SF of Z=105 in the Nb/Ta chemical fraction










odd-odd
120
114
110
104
proton number
150
170
180
190
Neutron number
1μs
1ms
1s
10^3 s
10^6 s
10^9 s
β⁻-decay
243Am+48Ca
209Bi+64Ni
115
113
111
111
Mt
Mt
Bh
Bh
Db
Db
Rf
α
α
α
α
α
T1/2 =1.5 s
T1/2 ~1 d

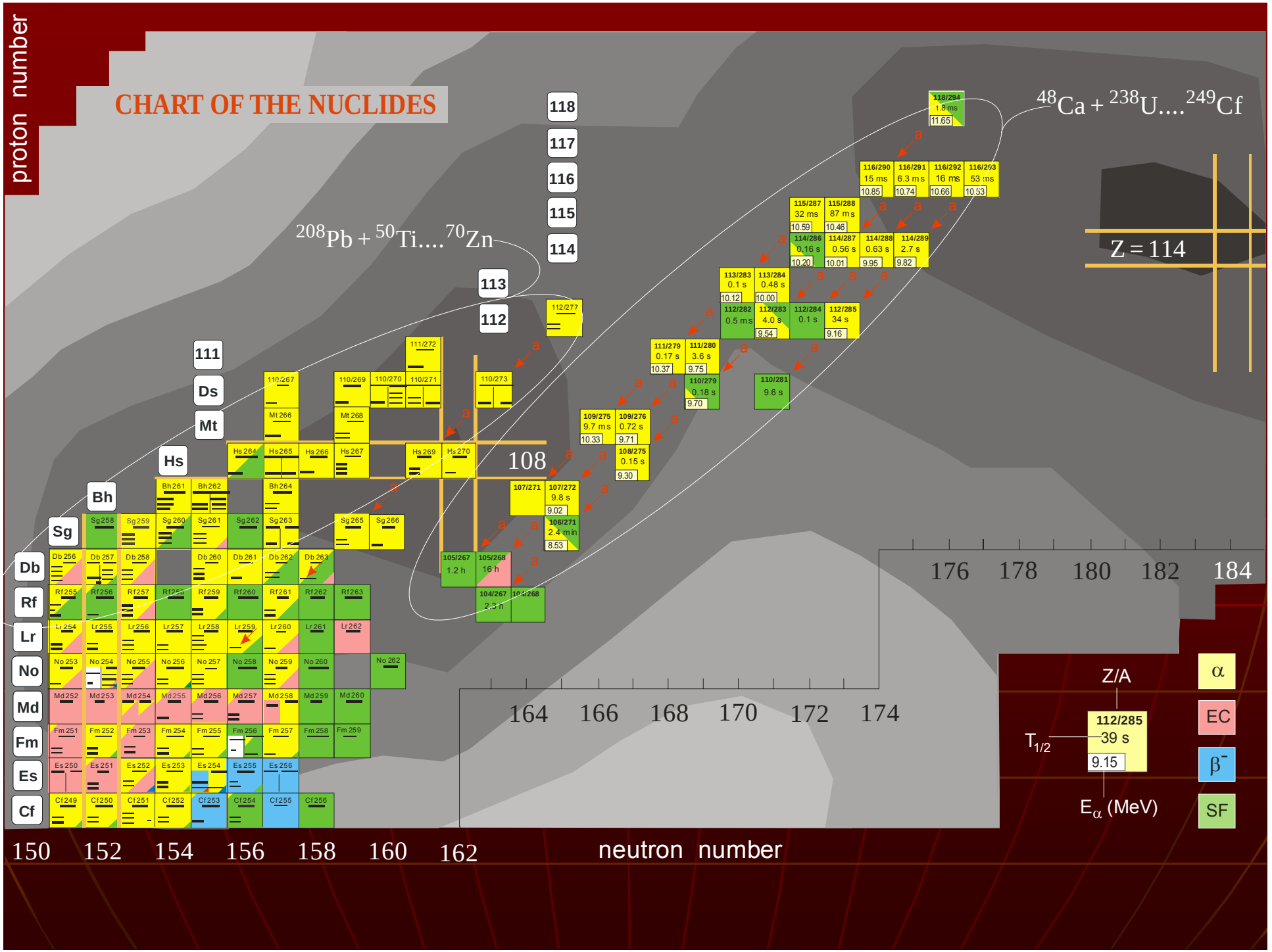
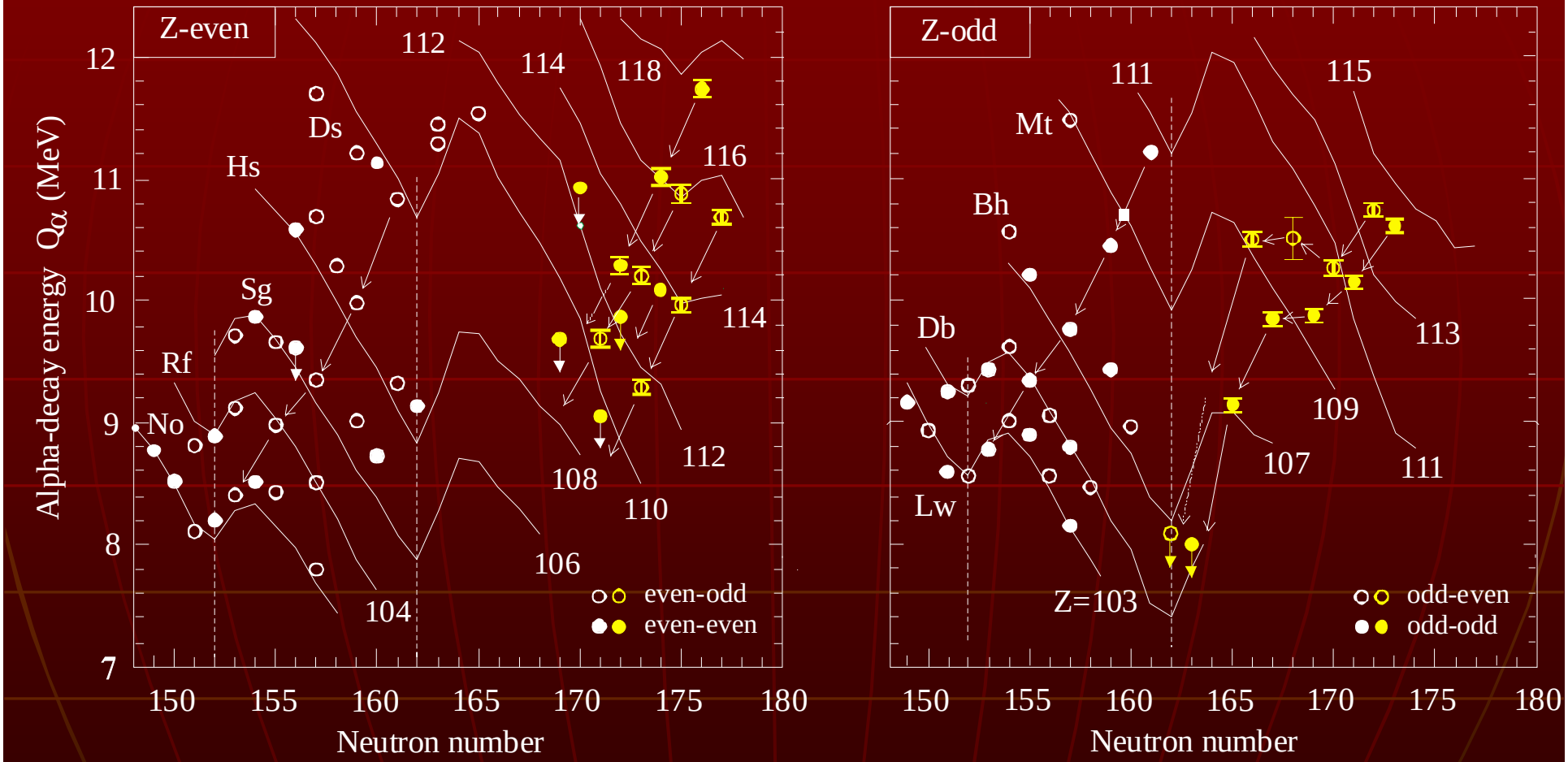
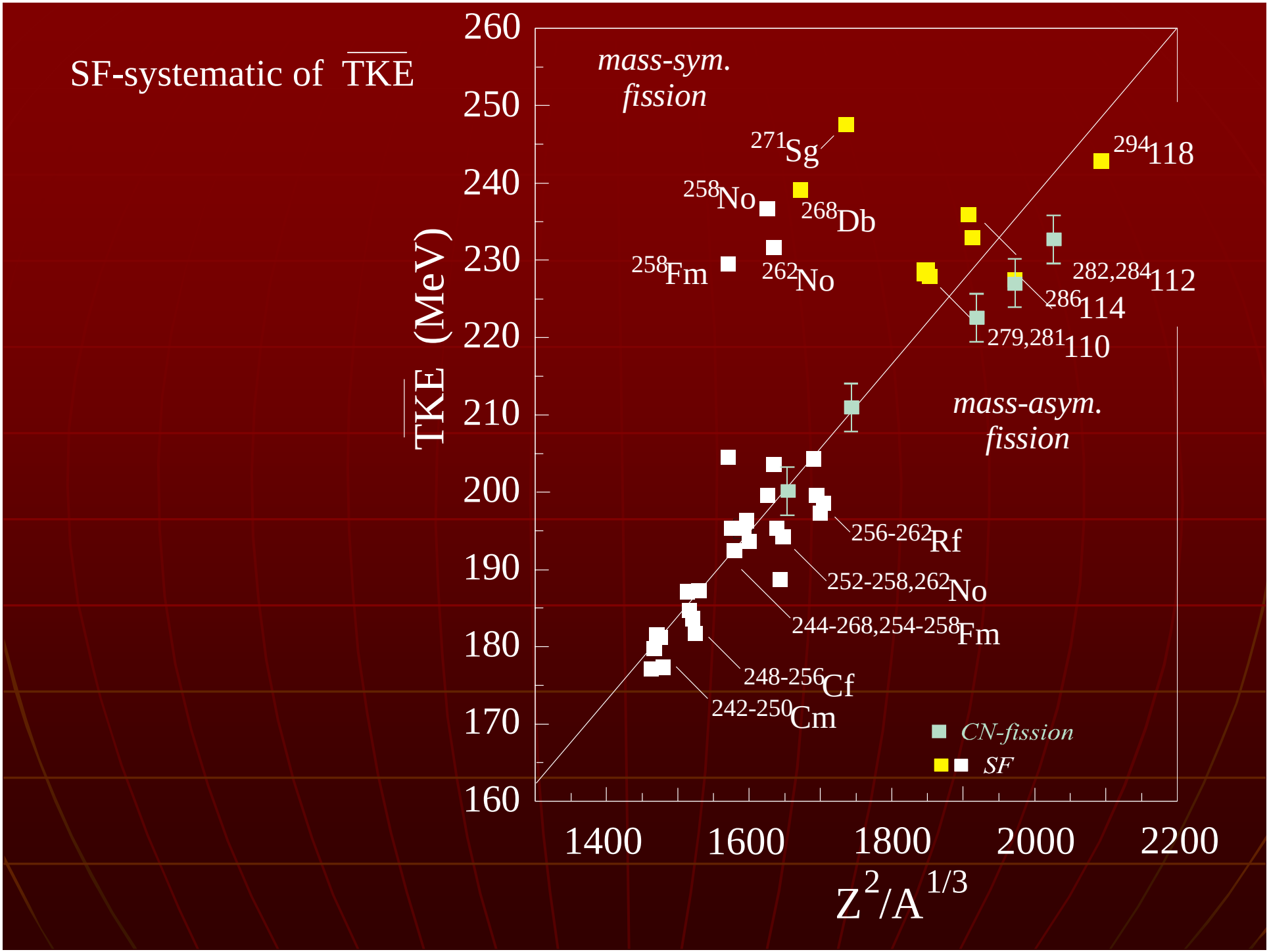


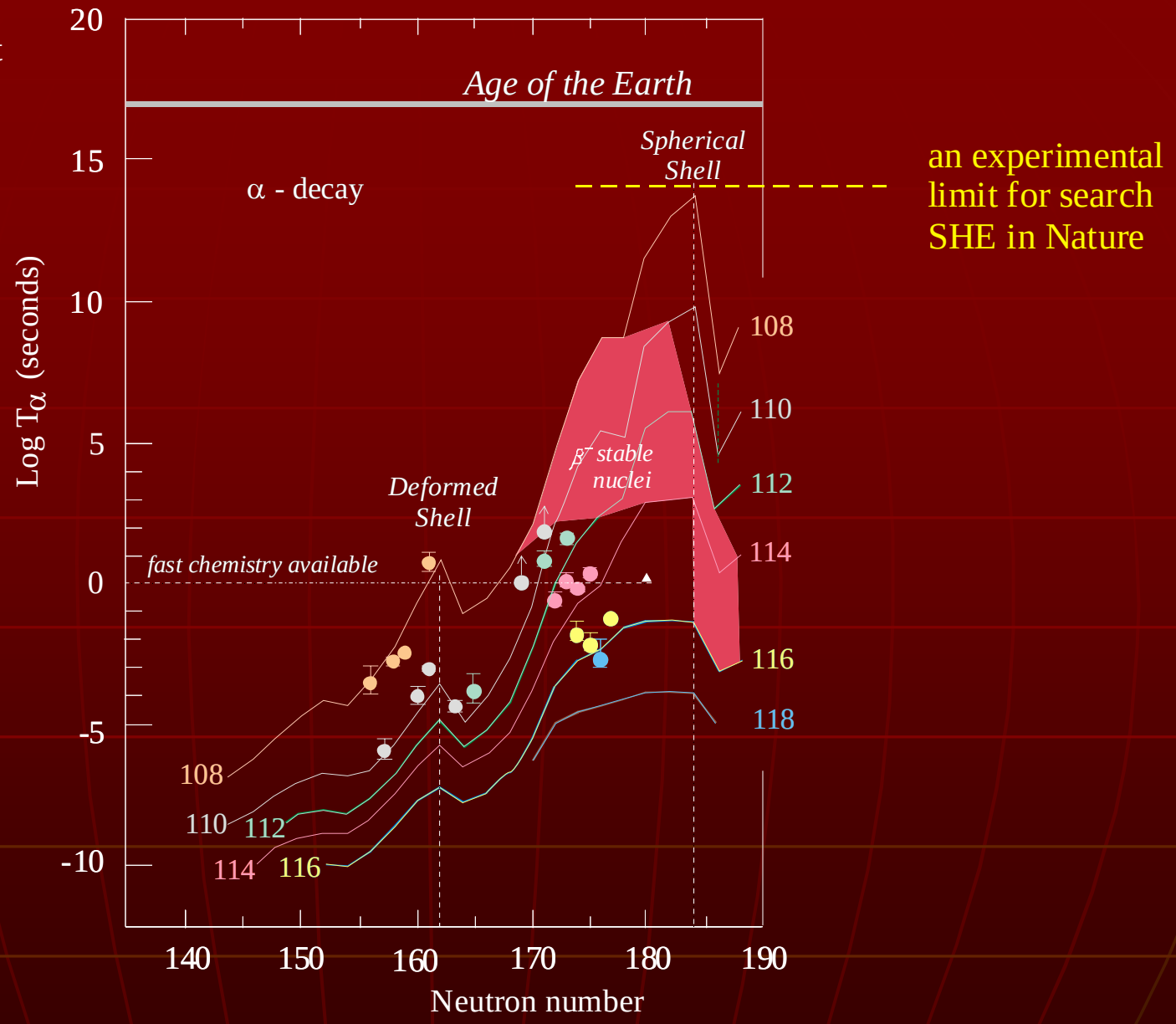
CHART OF THE NUCLIDES
proton number
neutron number
$^{208}Pb + ^{50}Ti....^{70}Zn$
$^{48}Ca + ^{238}U....^{249}Cf$
Z = 114
108
118
117
116
115
114
113
112
111
Ds
Mt
Hs
Bh
Sg
Db
Rf
Lr
No
Md
Fm
Es
Cf
150 152 154 156 158 160 162
164 166 168 170 172 174
176 178 180 182 184
Z/A
$T_{1/2}$
E_α (MeV)
112/285
39 s
9.15
α
EC
β^-
SF

Alpha-decay energy vs. neutron number for isotopes of elements Z > 102

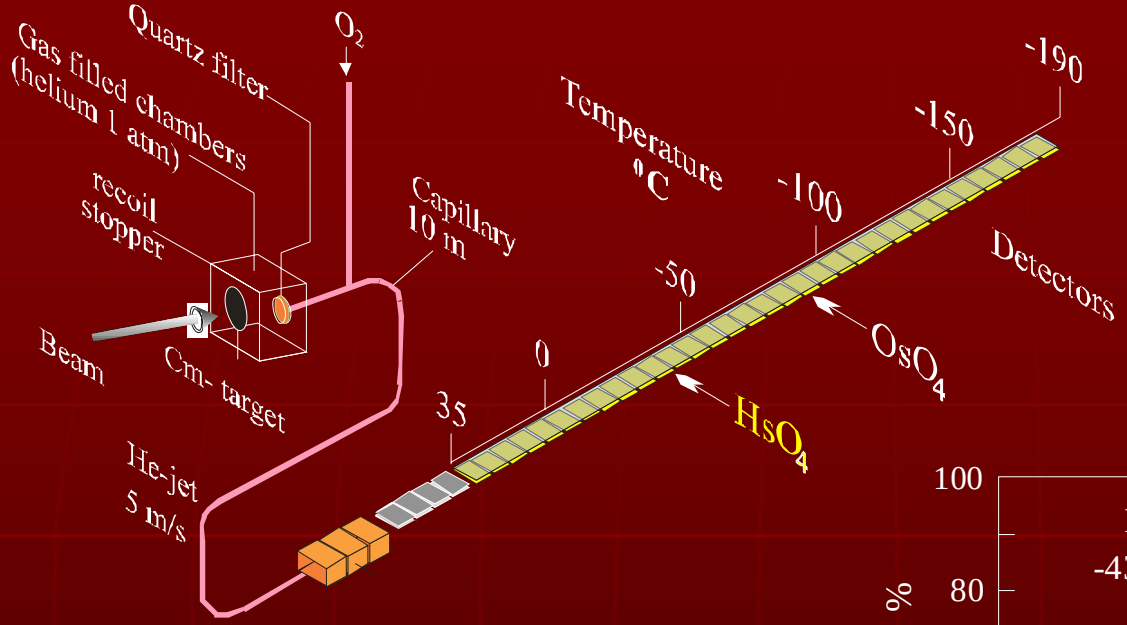



SF-systematic of $\overline{TKE}$
$\overline{TKE}$ (MeV)
260
250
240
230
220
210
200
190
180
170
160
1400
1600
1800
2000
2200
$Z^2/A^{1/3}$
mass-sym. fission
mass-asym. fission
^{271}Sg
^{294}118
^{258}No
^{268}Db
^{258}Fm
^{262}No
^{282,284}112
^{286}114
^{279,281}110
256-262Rf
252-258,262No
244-268,254-258Fm
248-256Cf
242-250Cm
CN-fission
SF

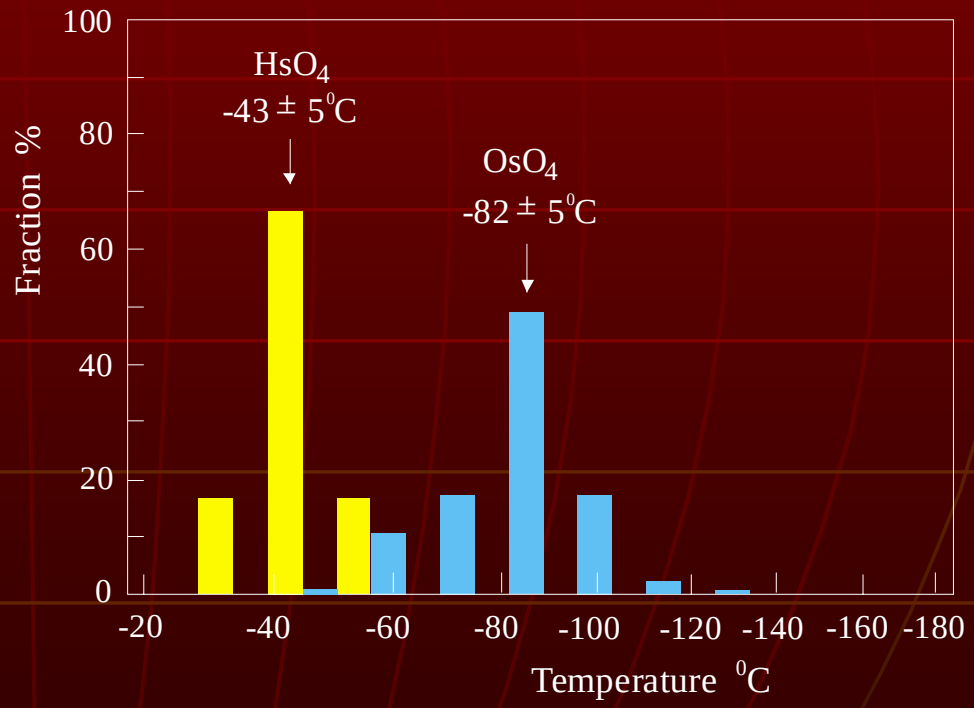
Theory and Experiment



an experimental limit for search SHE in Nature



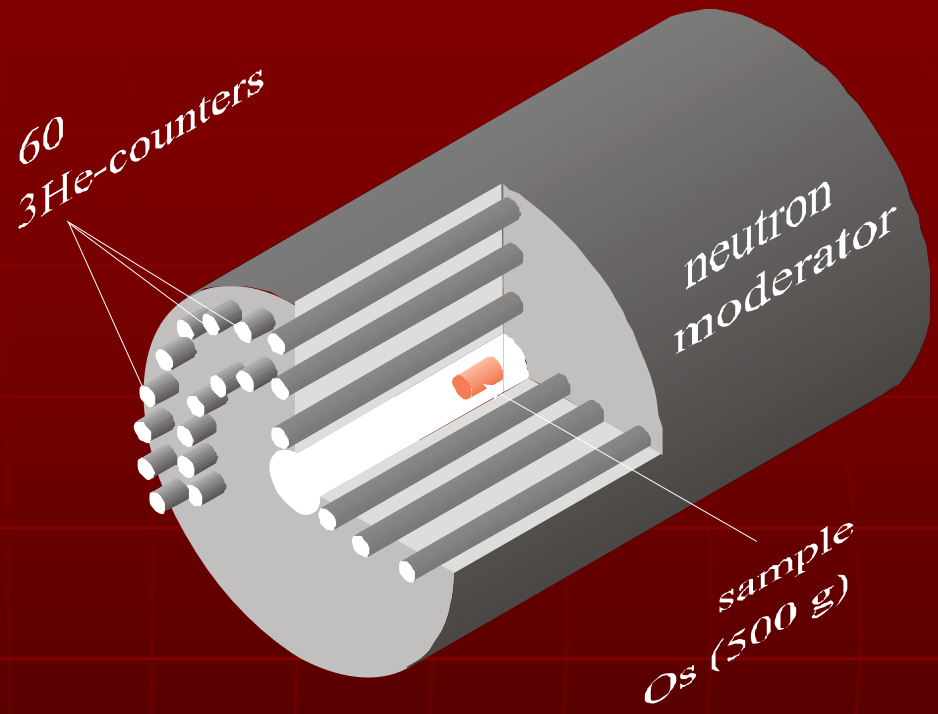
Chemistry of Hs (Z=108)



Reaction:

$^{248}Cm + {}^{26}Mg \rightarrow {}^{269}Hs(9s) + 5n$

Search for SF of naturel Eka Os
by detection of fission neutrons



Underground Laboratory
Modane (France)

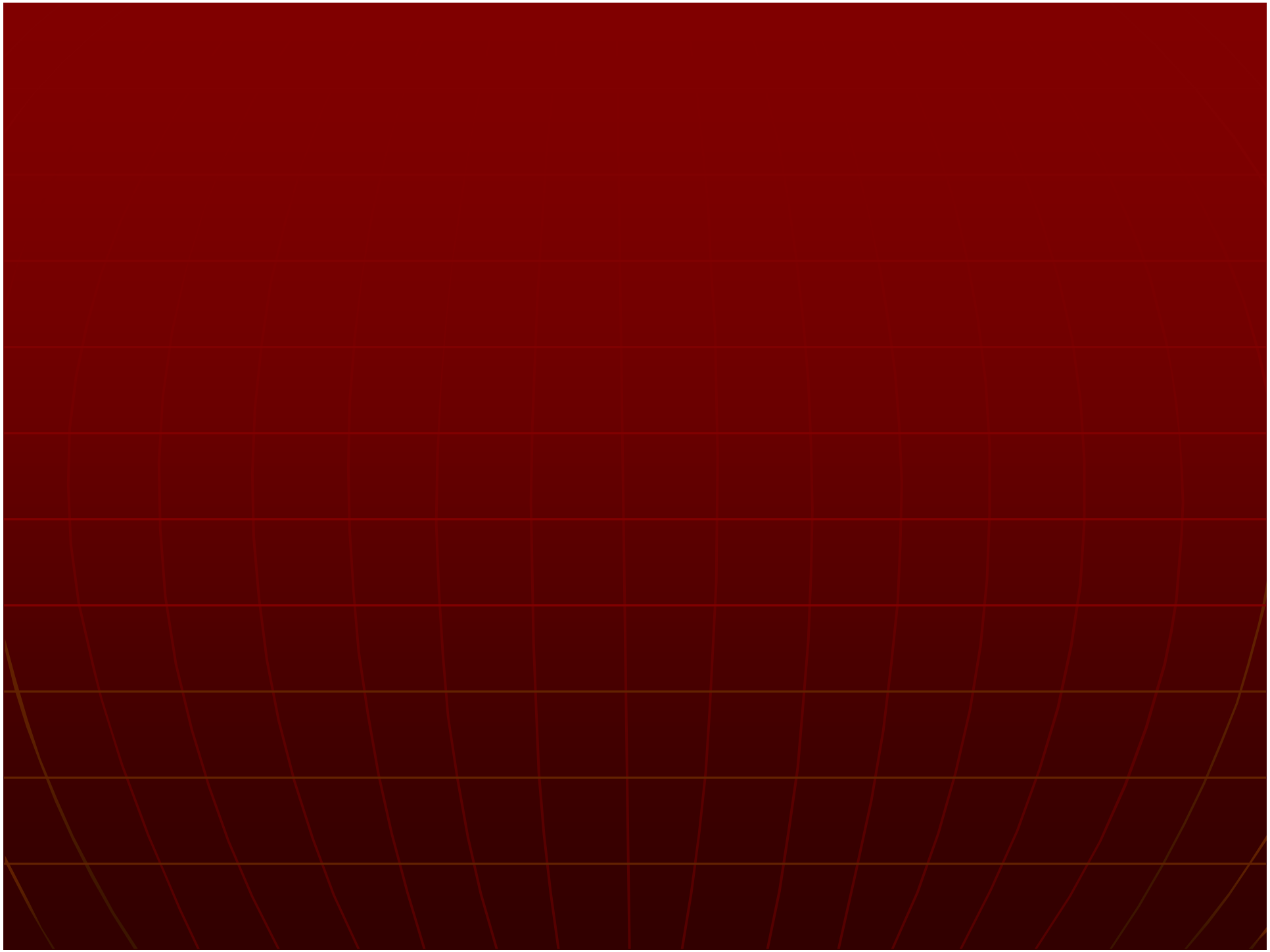
Depth: 4000 m (w. eq.)

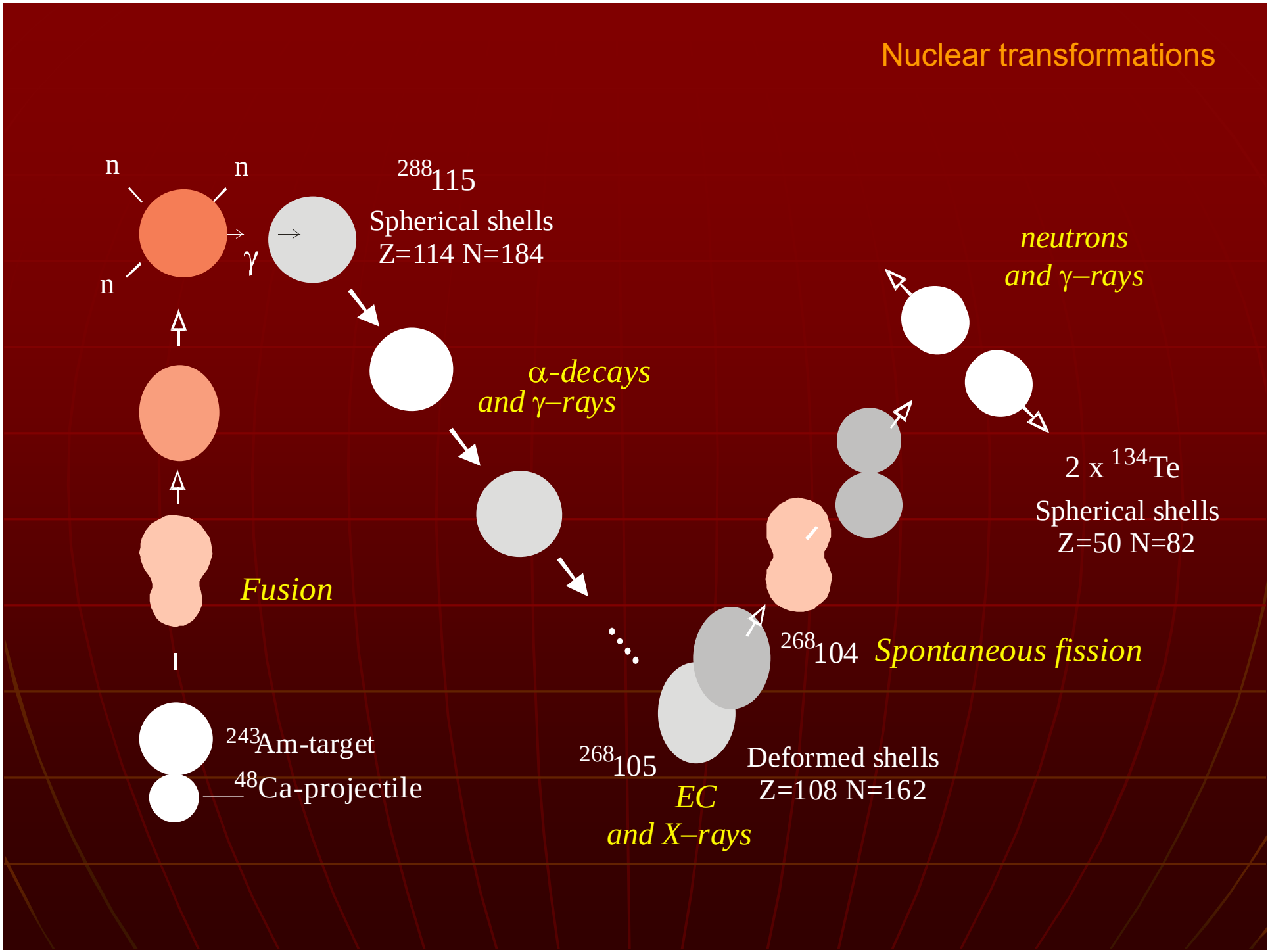
1 SF-event per year ($T_{1/2} = 10^{9}$ y)
corresponds to concentration:

EkaOs/Os = 5.10^{-15} g/g

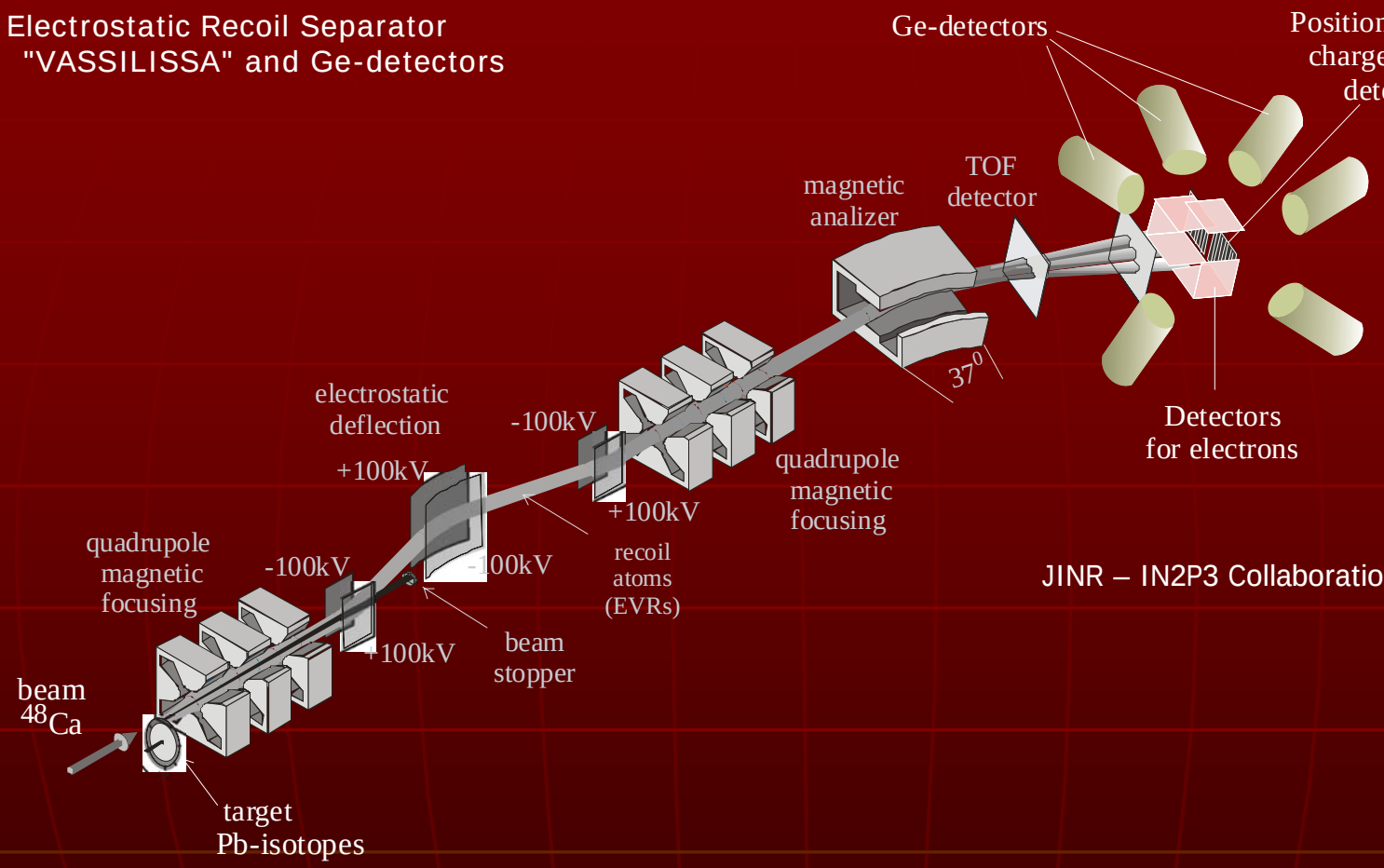
(or 10^{-22} g/g in the terrestrial matter, or 10^{-16} of U)


Dubna, February 2004
Flerov Laboratory for Nuclear Reactions
of the Joint Institute for Nuclear Research
Thanks for your attention

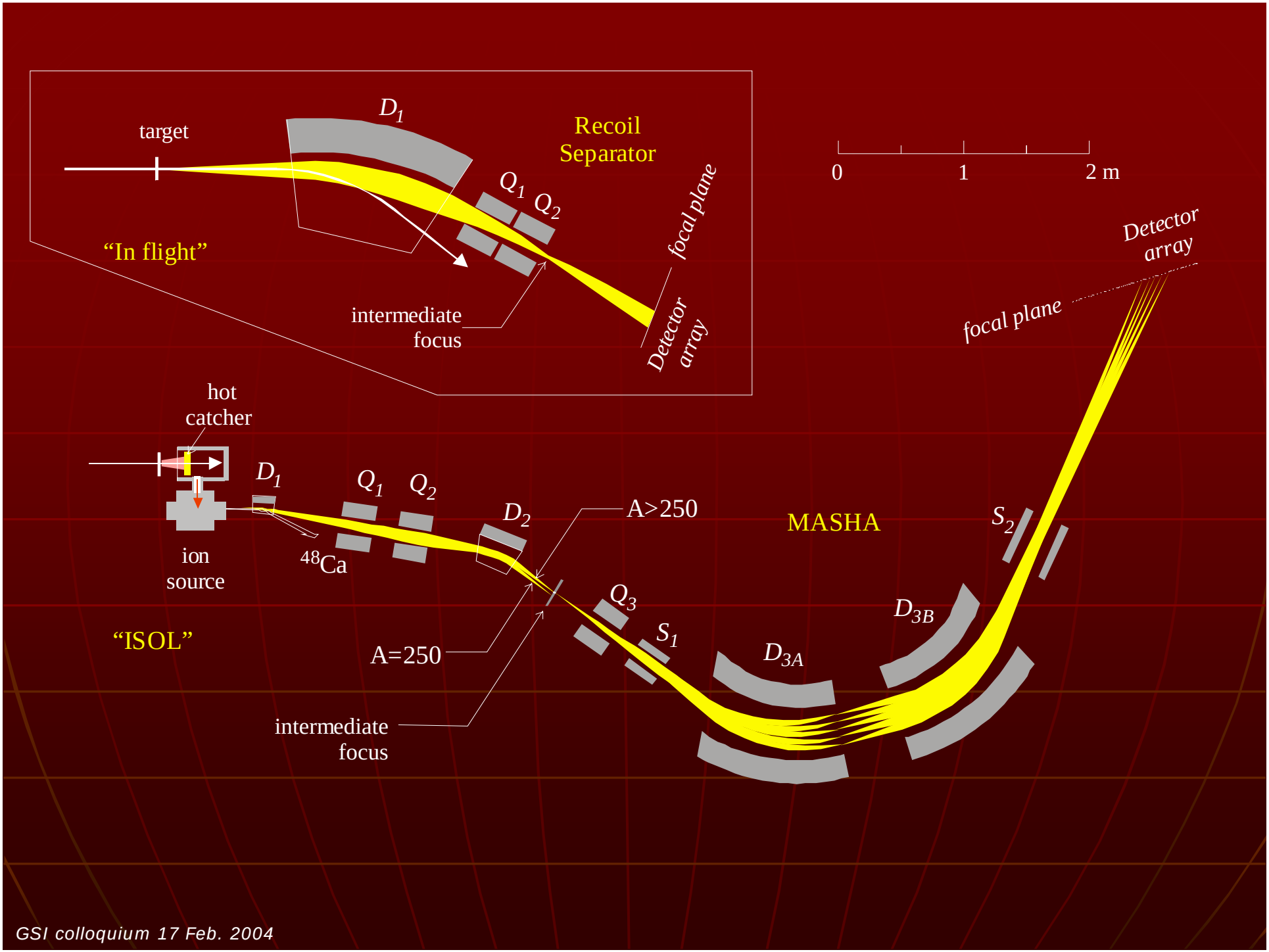



Nuclear transformations
n
n
n
γ
^{288}115
Spherical shells
Z=114 N=184
α-decays
and γ–rays
Fusion
^{243}Am-target
^{48}Ca-projectile
^{268}105
EC
and X–rays
^{268}104
Spontaneous fission
Deformed shells
Z=108 N=162
neutrons
and γ–rays
2 x ^{134}Te
Spherical shells
Z=50 N=82

Electrostatic Recoil Separator "VASSILISSA" and Ge-detectors

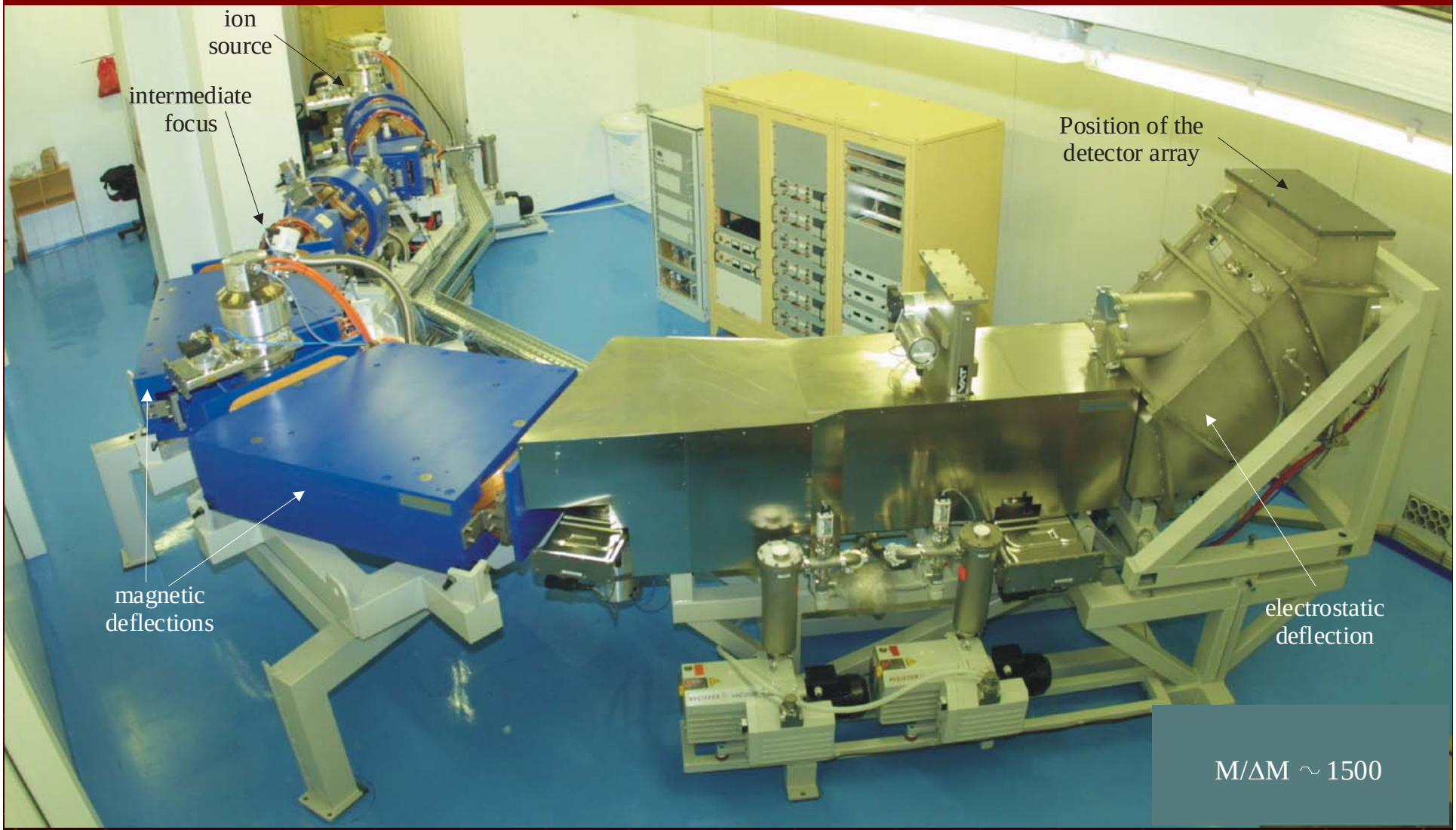


JINR – IN2P3 Collaboration

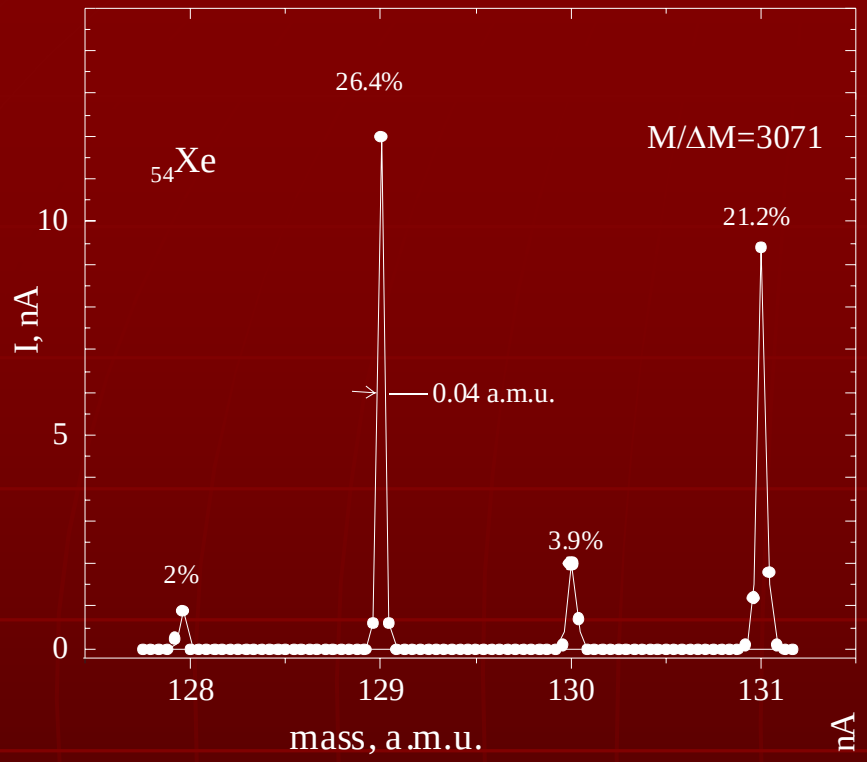

target
D_1
Recoil
Separator
Q_1
Q_2
focal plane
"In flight"
intermediate
focus
Detector
array
0
1
2 m
Detector
array
focal plane
hot
catcher
D_1
Q_1
Q_2
D_2
A>250
MASHA
S_2
ion
source
^{48}Ca
Q_3
D_{3B}
S_1
"ISOL"
A=250
D_{3A}
intermediate
focus

Mass Analyzer of Super Heavy Atoms

(MASHA)

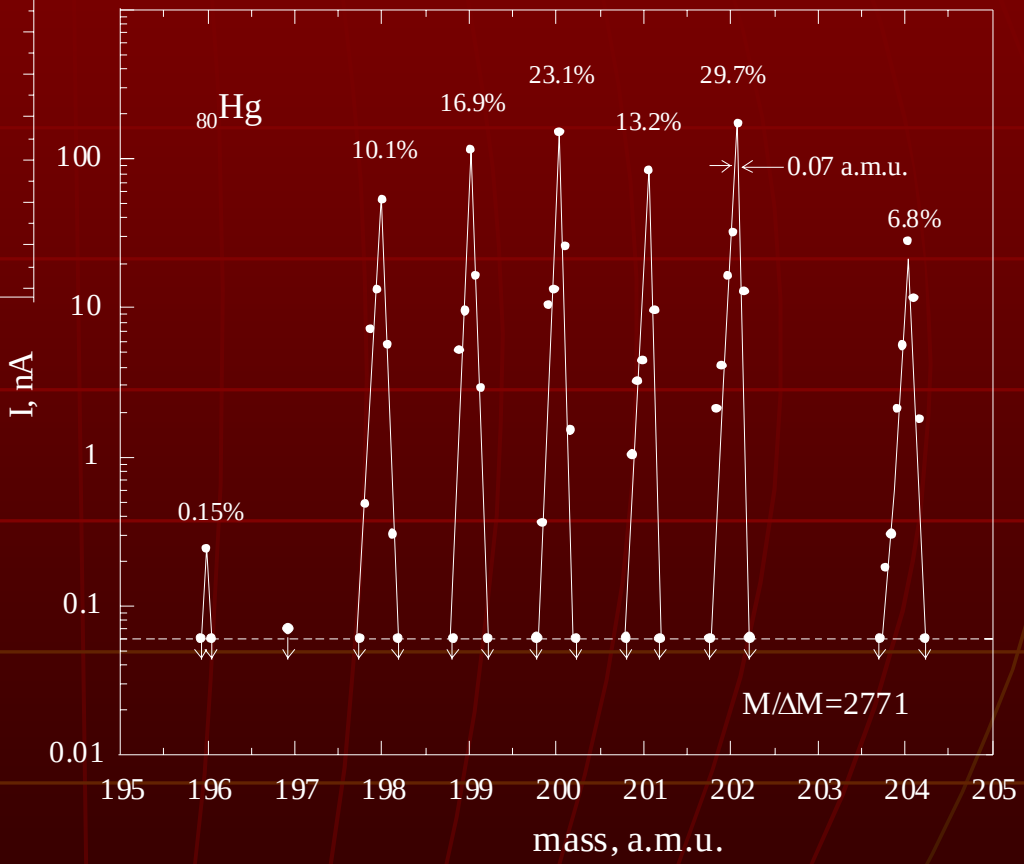


MASHA off-line test with stable isotopes



Plasma Ion Source, type FEBIAB

V_0 =30kV



Consumption
of ^{48}Ca (68%) - 0.5 mg/ [0.25mg/h]

beam
intensity - $5 \cdot 10^{12}$/s [$5 \cdot 10^{13}$/s]

beam time - 2000 h/y [6000h/y]

Isotopes:

U[238], Np[237], Pu[244], Cm[247] + ^{48}Ca[...^{64}Ni] → Z = 114 - 122

technology of the
target preparation - 0.3 mg/cm^2 [1.0 mg/cm^2]

isotope enrichment - 98-99% [99.9%]

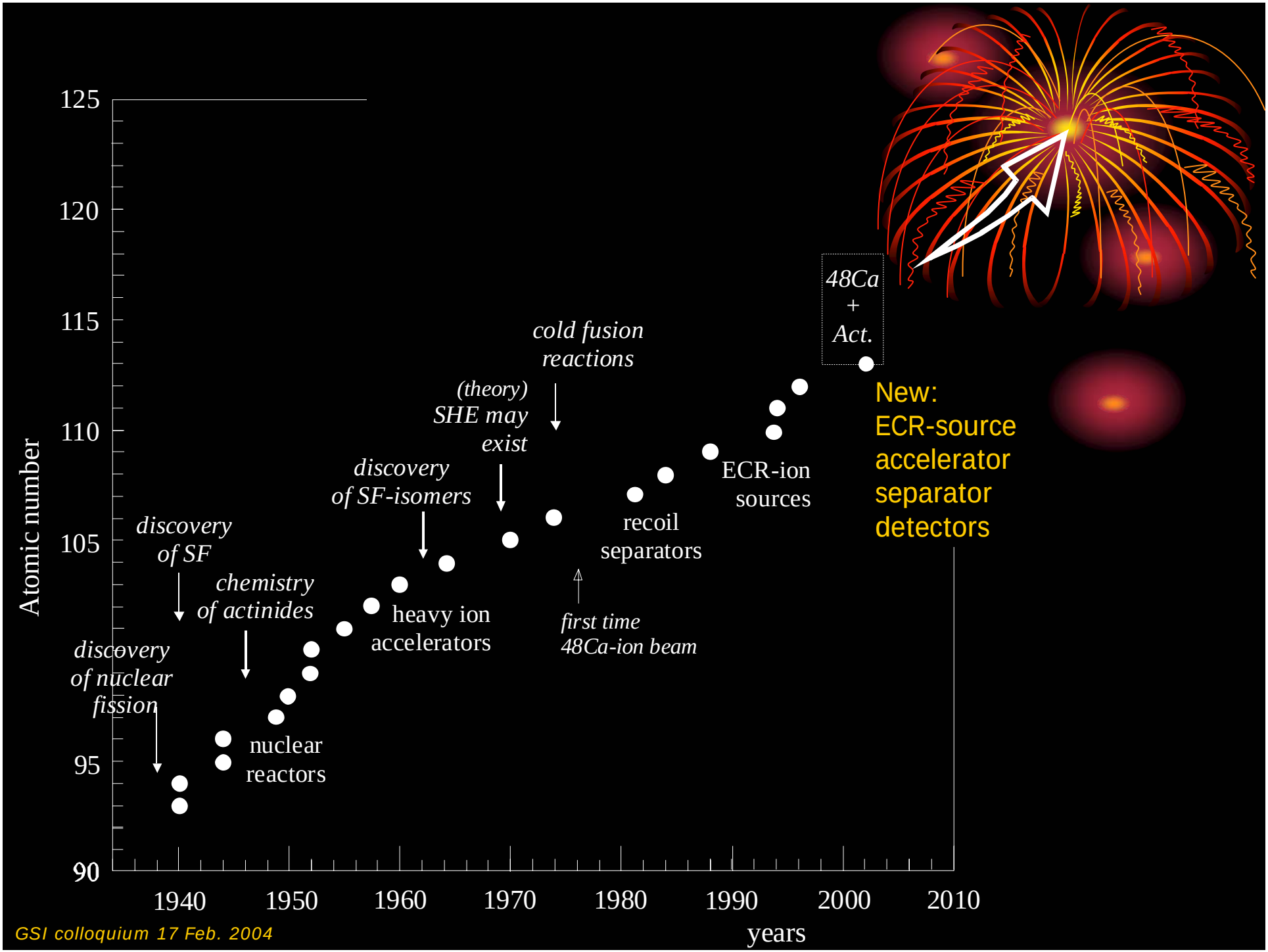
Separation of super heavy nuclei and
detection of their radioactive decay

now: SHIP, DGFRS, SAASY, GARIS,....

new facilities.....

such as MASHA but more fast!

+ neutron and γ-arrays: DEMON, EUROBALL,
AGATA,....


125
120
115
110
105
95
90
Atomic number
1940
1950
1960
1970
1980
1990
2000
2010
years
discovery of nuclear fission
discovery of SF
chemistry of actinides
nuclear reactors
heavy ion accelerators
discovery of SF-isomers
(theory) SHE may exist
cold fusion reactions
first time 48Ca-ion beam
recoil separators
ECR-ion sources
48Ca + Act.
New: ECR-source accelerator separator detectors
GSI colloquium 17 Feb. 2004