James Webb Telescope
December 2023

Ani Aprahamian

University of Notre Dame
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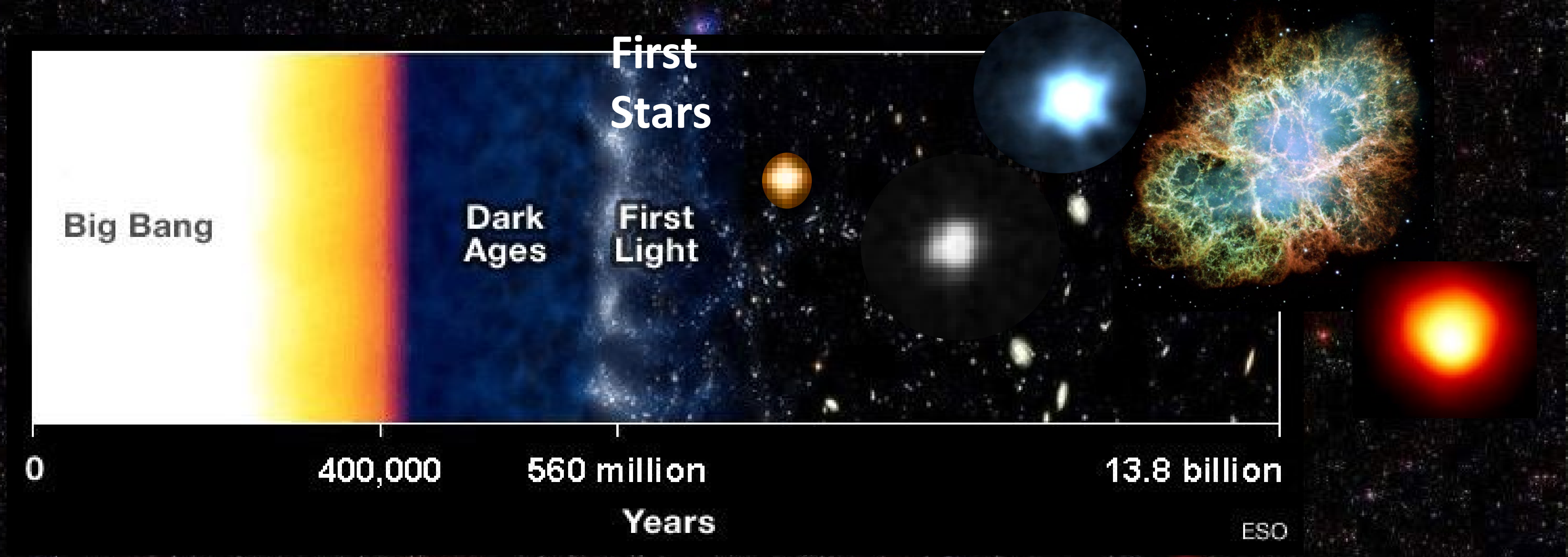
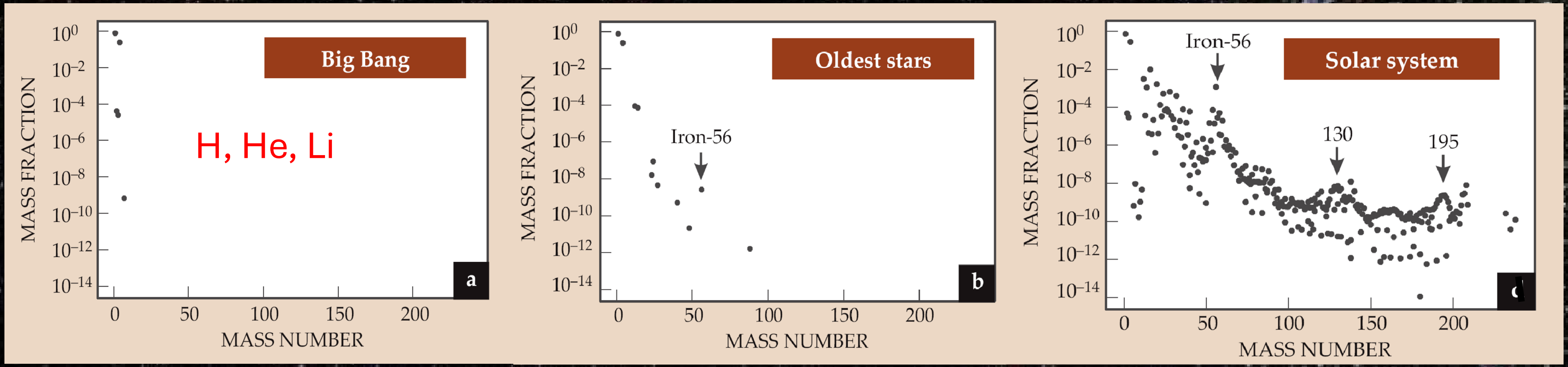
Nuclear Astrophysics 3:
The Death of Stars, the Heavy and Superheavy elements

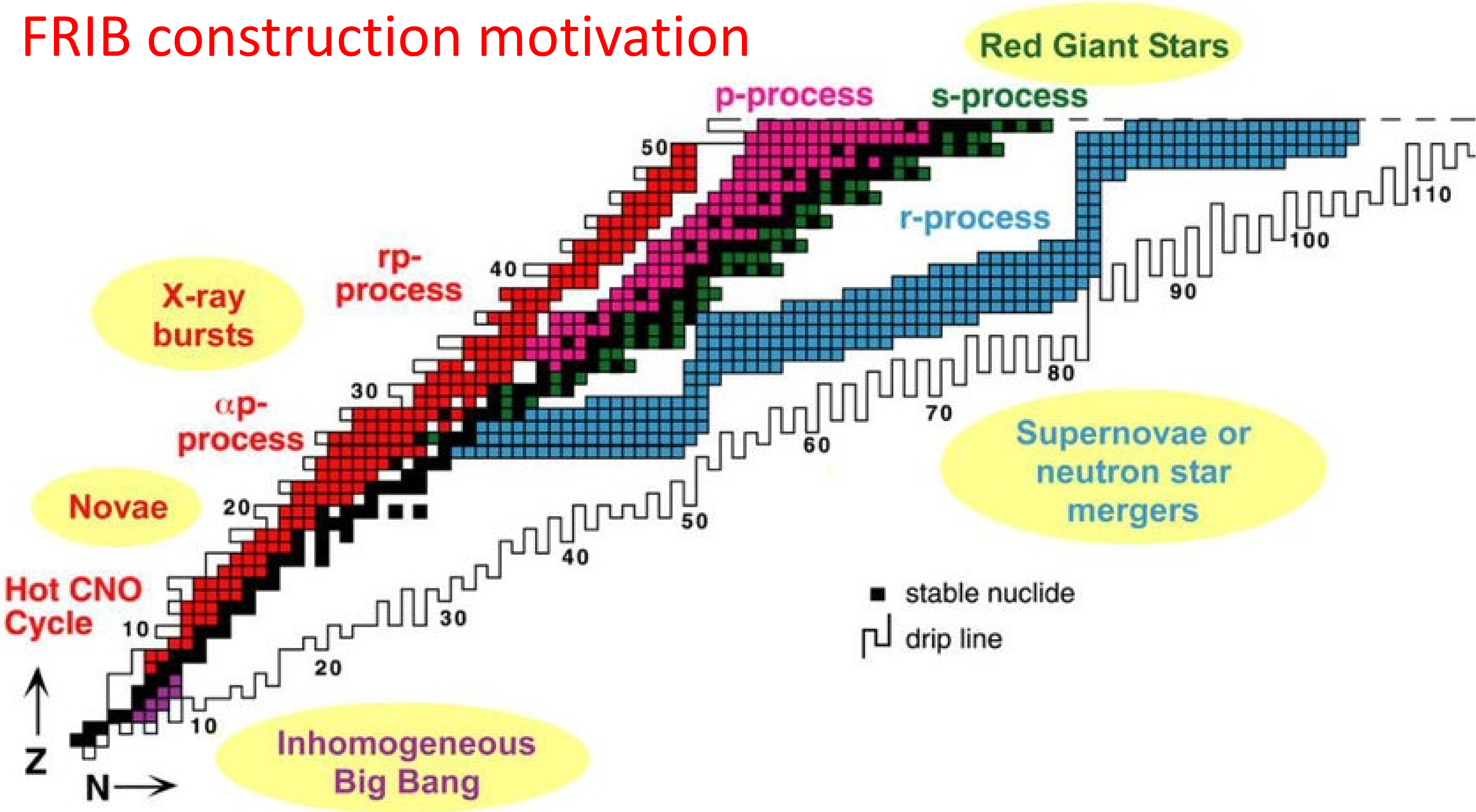
Neutron Sources in Stars

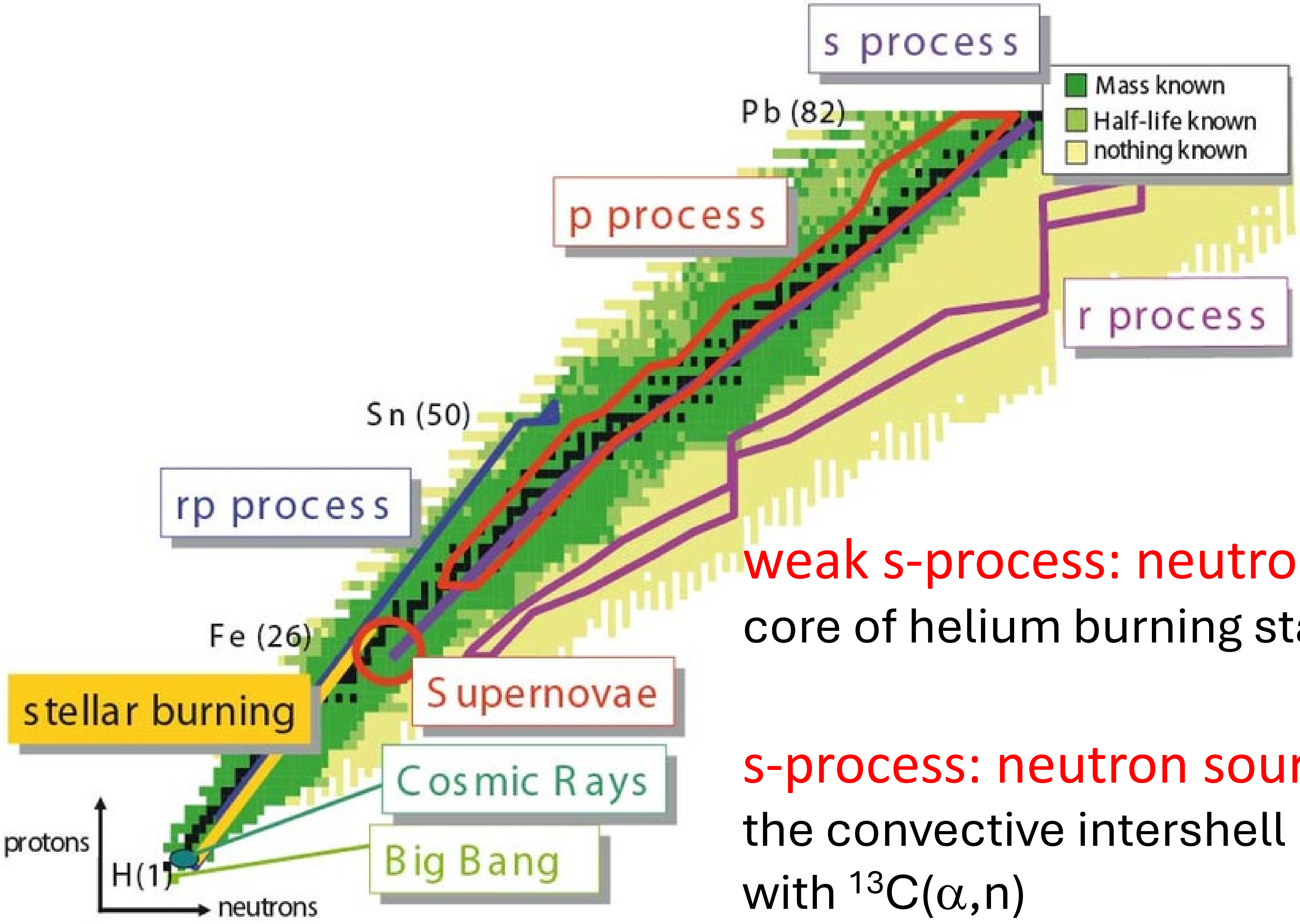
Galactic Chemical Evolution





FRIB construction motivation





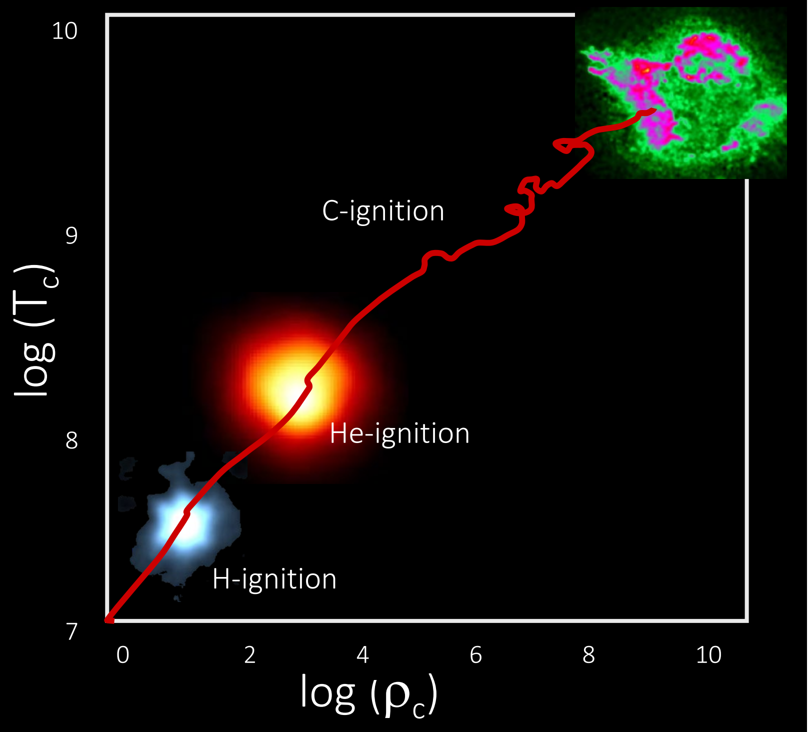
weak s-process: neutron source

core of helium burning stars with $^{22}Ne(\alpha,n)$

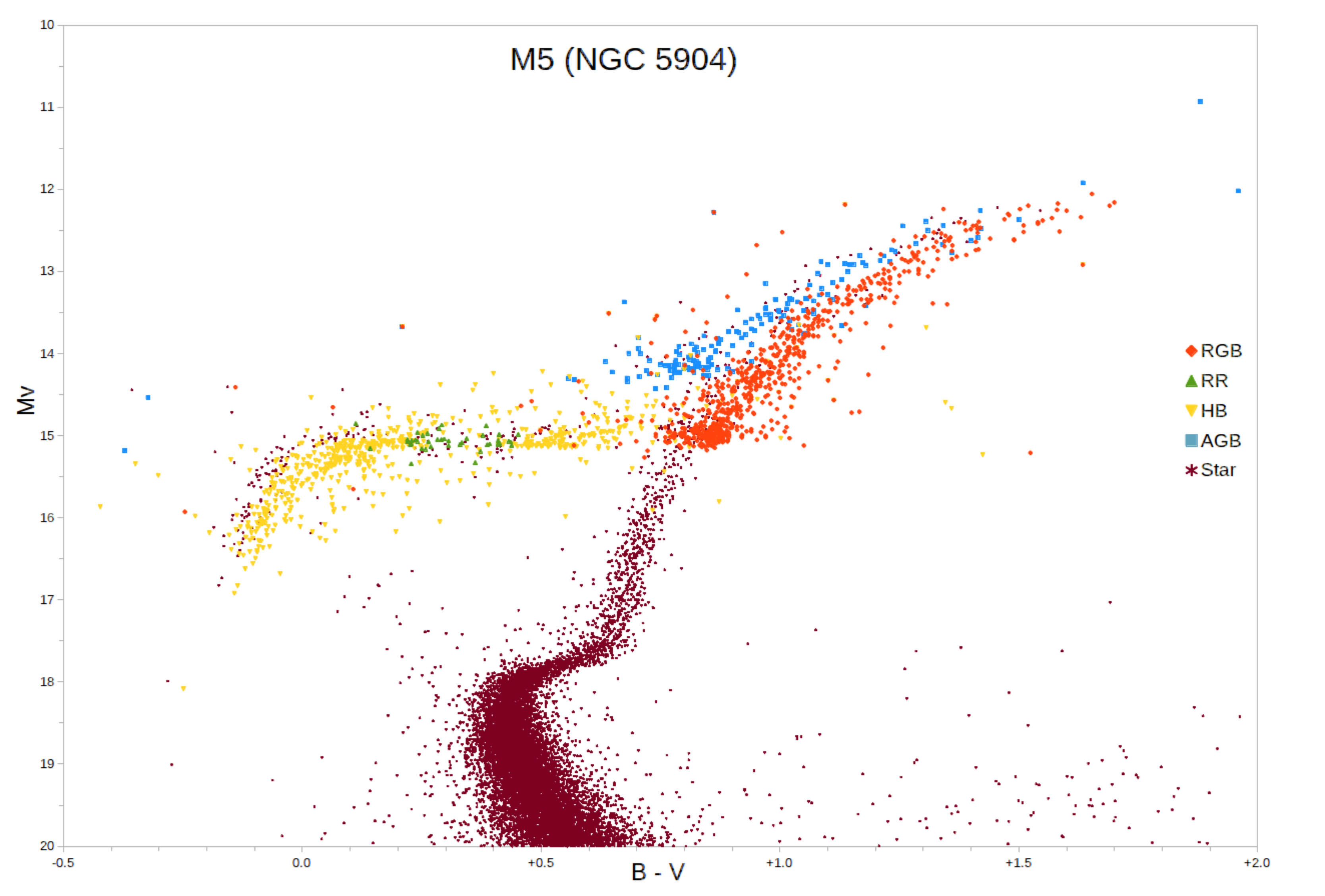
s-process: neutron source

the convective intershell range of AGB stars with $^{13}C(\alpha,n)$

AGB stars

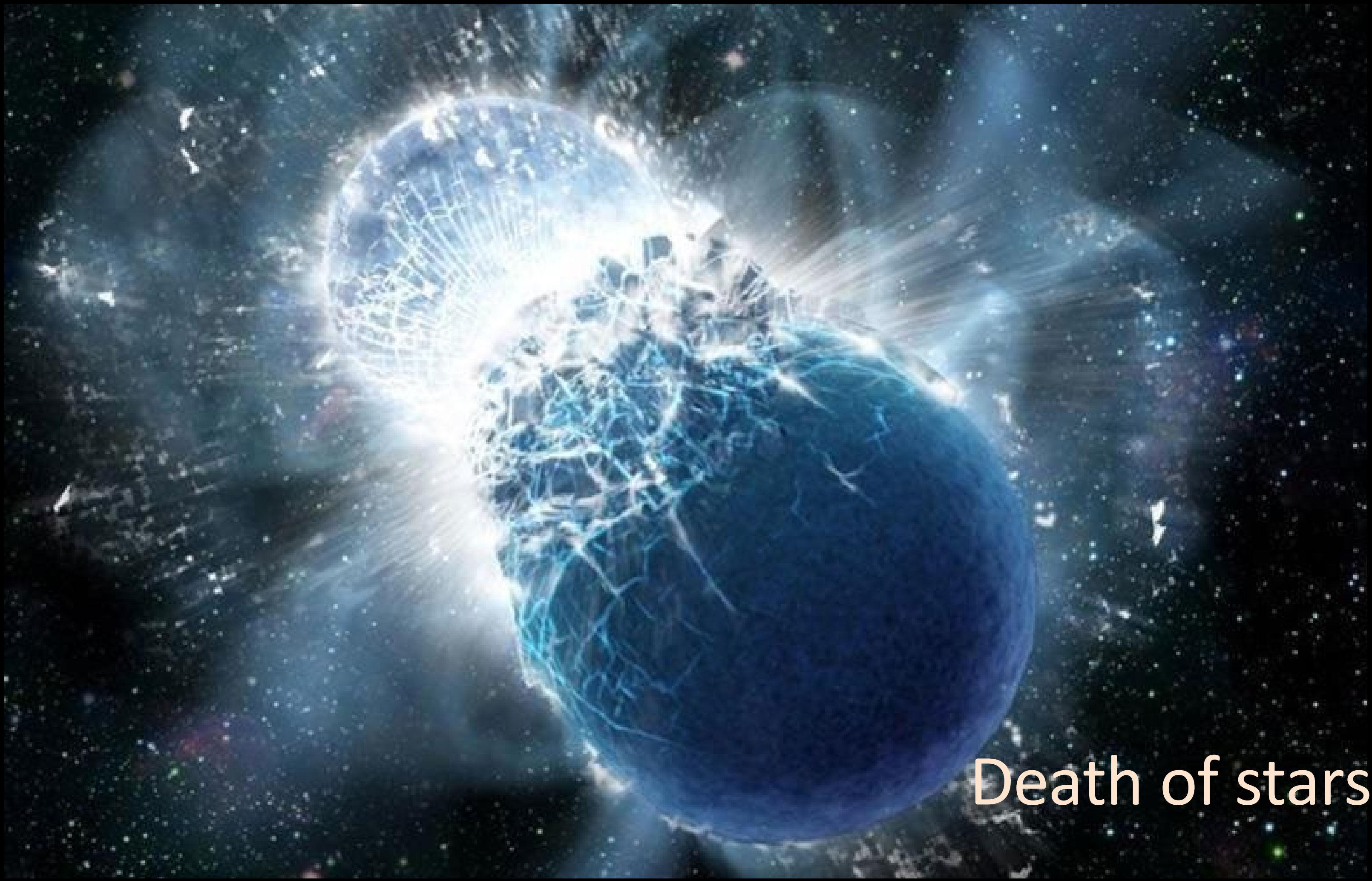


10
9
8
7
log (T_c)
C-ignition
He-ignition
H-ignition
0
2
4
6
8
10
log (ρ_c)

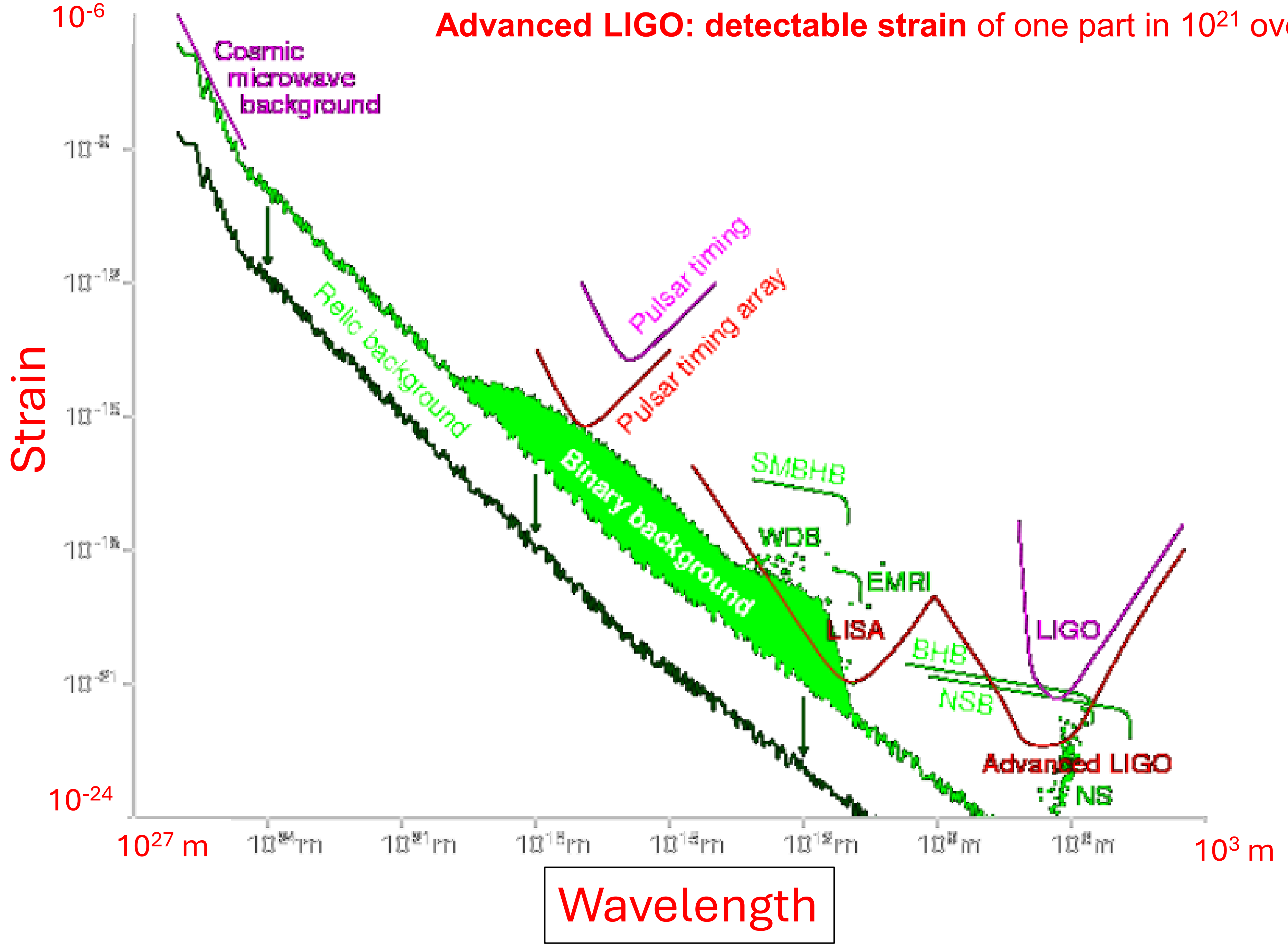


M5 (NGC 5904)
Mv
B - V
RGB
RR
HB
AGB
Star
10
11
12
13
14
15
16
17
18
19
20
-0.5
0.0
+0.5
+1.0
+1.5
+2.0

Dissociation of elements at high temperature and density conditions?



Advanced LIGO: detectable strain of one part in 10^{21} over a 100 Hz bandwidth

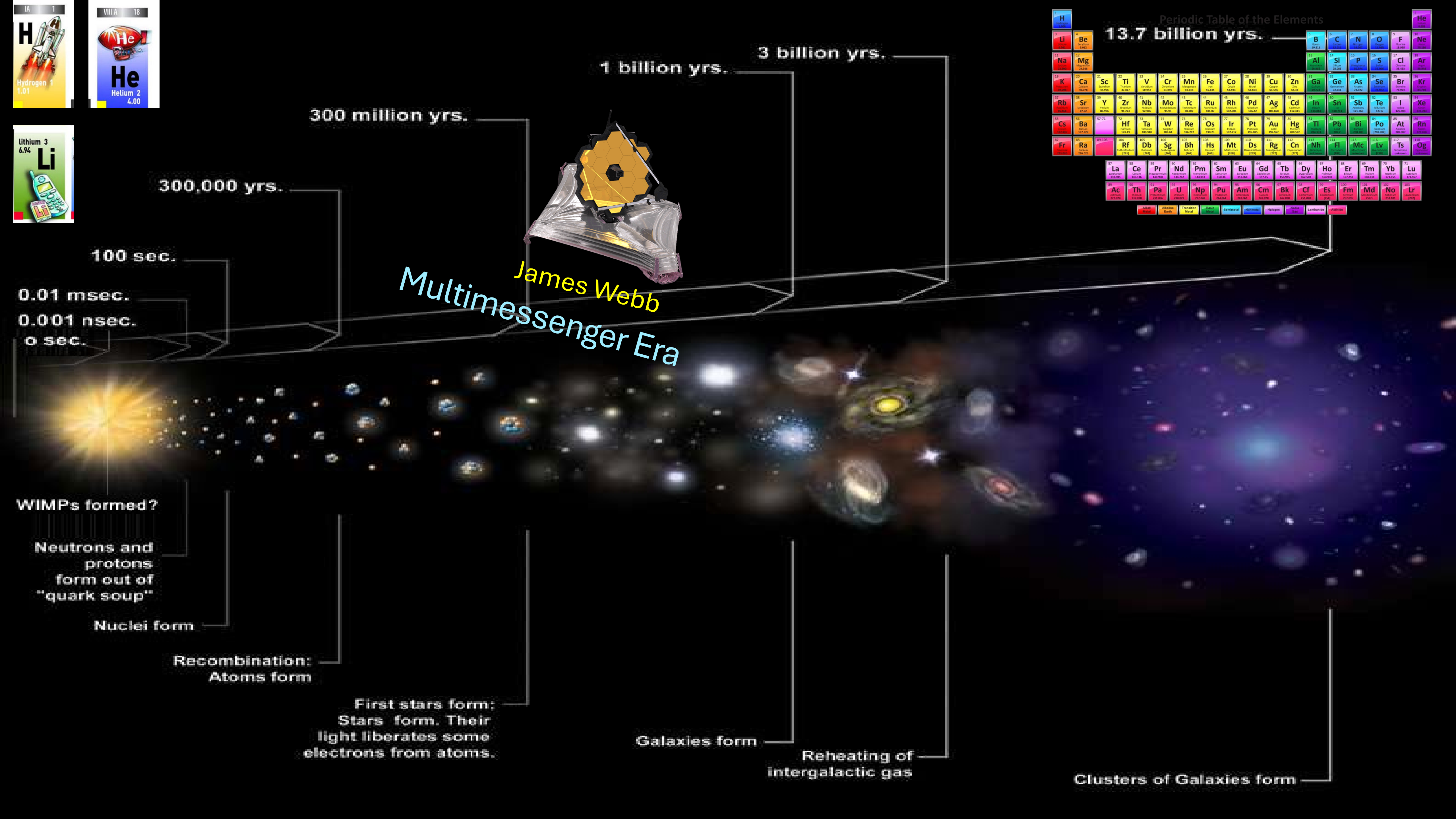


Gravitational Waves, The Heavy Elements, & Superheavy Nuclei

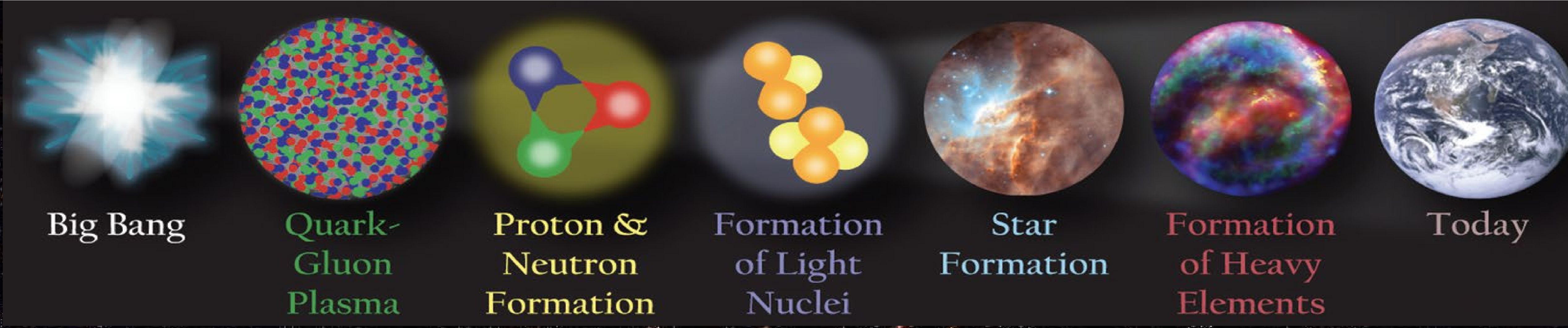
Where are the heavy elements made?

Were Superheavies made in the r-process?

Were the Heavy and Superheavy elements made in nature?

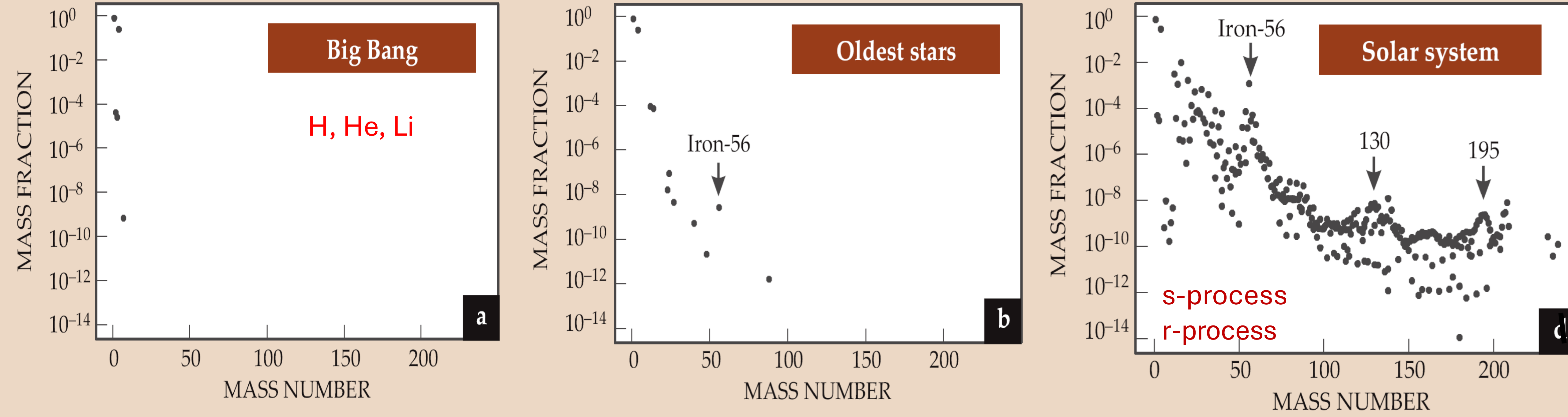


IA 1
H
Hydrogen 1
1.01
VIII A 18
He
Helium 2
4.00
lithium 3
6.94
Li
Periodic Table of the Elements
13.7 billion yrs.
3 billion yrs.
1 billion yrs.
300 million yrs.
300,000 yrs.
100 sec.
0.01 msec.
0.001 nsec.
0 sec.
James Webb
Multimessenger Era
WIMPs formed?
Neutrons and protons form out of "quark soup"
Nuclei form
Recombination: Atoms form
First stars form: Stars form. Their light liberates some electrons from atoms.
Galaxies form
Reheating of intergalactic gas
Clusters of Galaxies form

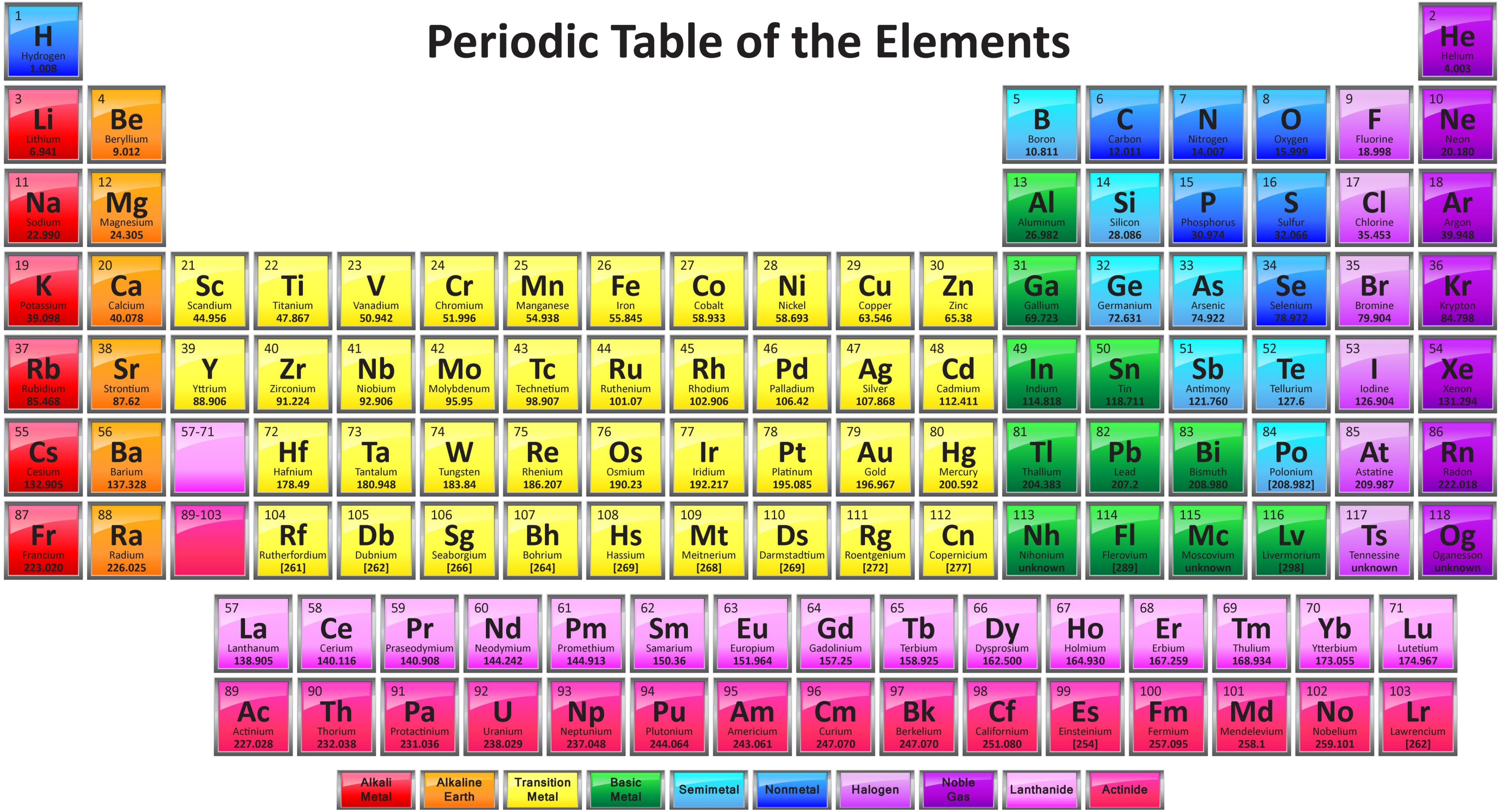


- How were elements Fe to U made?

Wiescher
Schatz



Periodic Table of the Elements

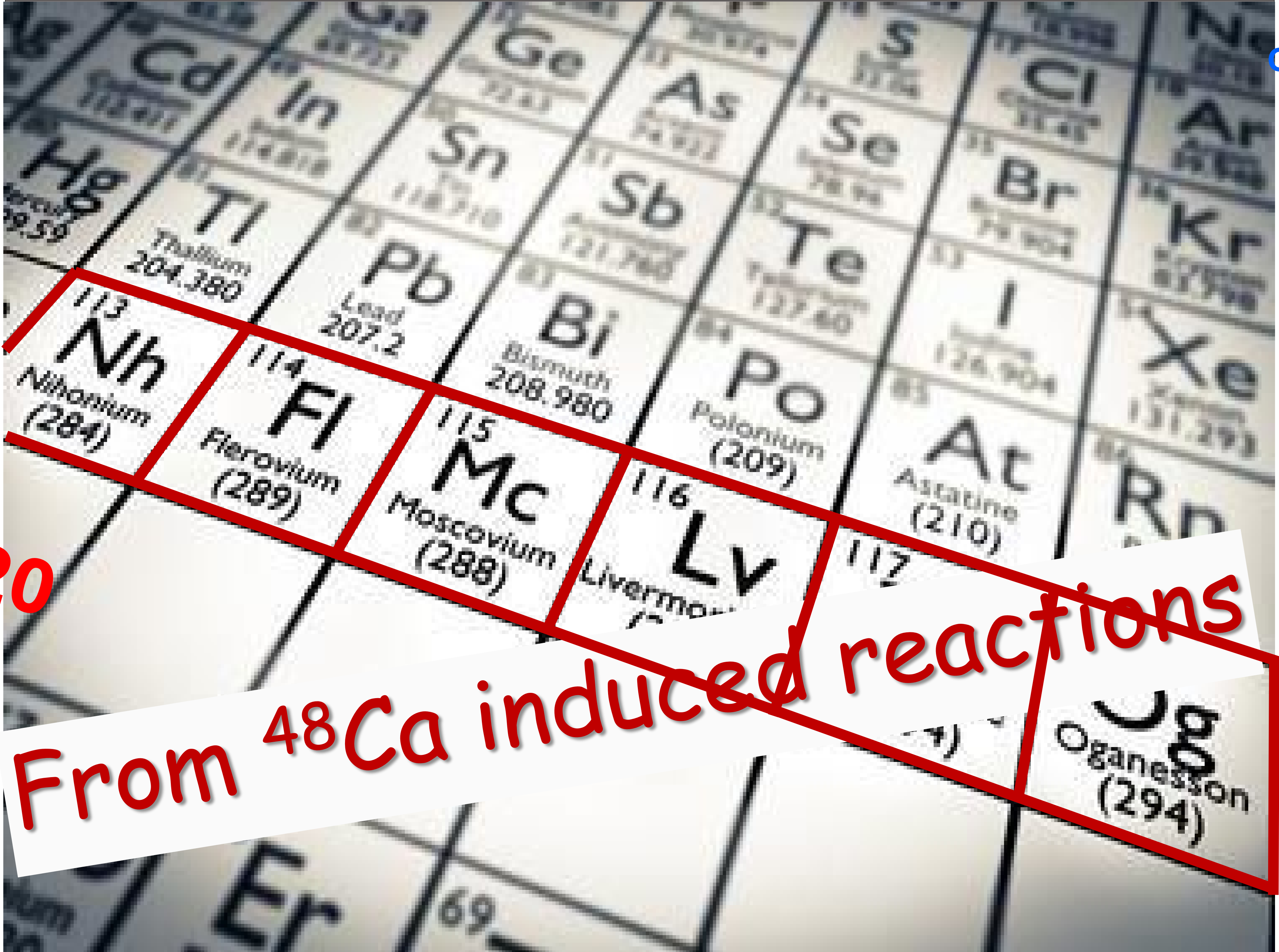


Are there more elements?

104	105	106
Rf	**Db**	**Sg**
Rutherfordium	Dubnium	Seaborgium
1964	**1970**	**1974**
Target ^{242}Pu, ^{249}Cf	Target ^{249}Bk, $^{249,250}Cf$	Target ^{249}Cf

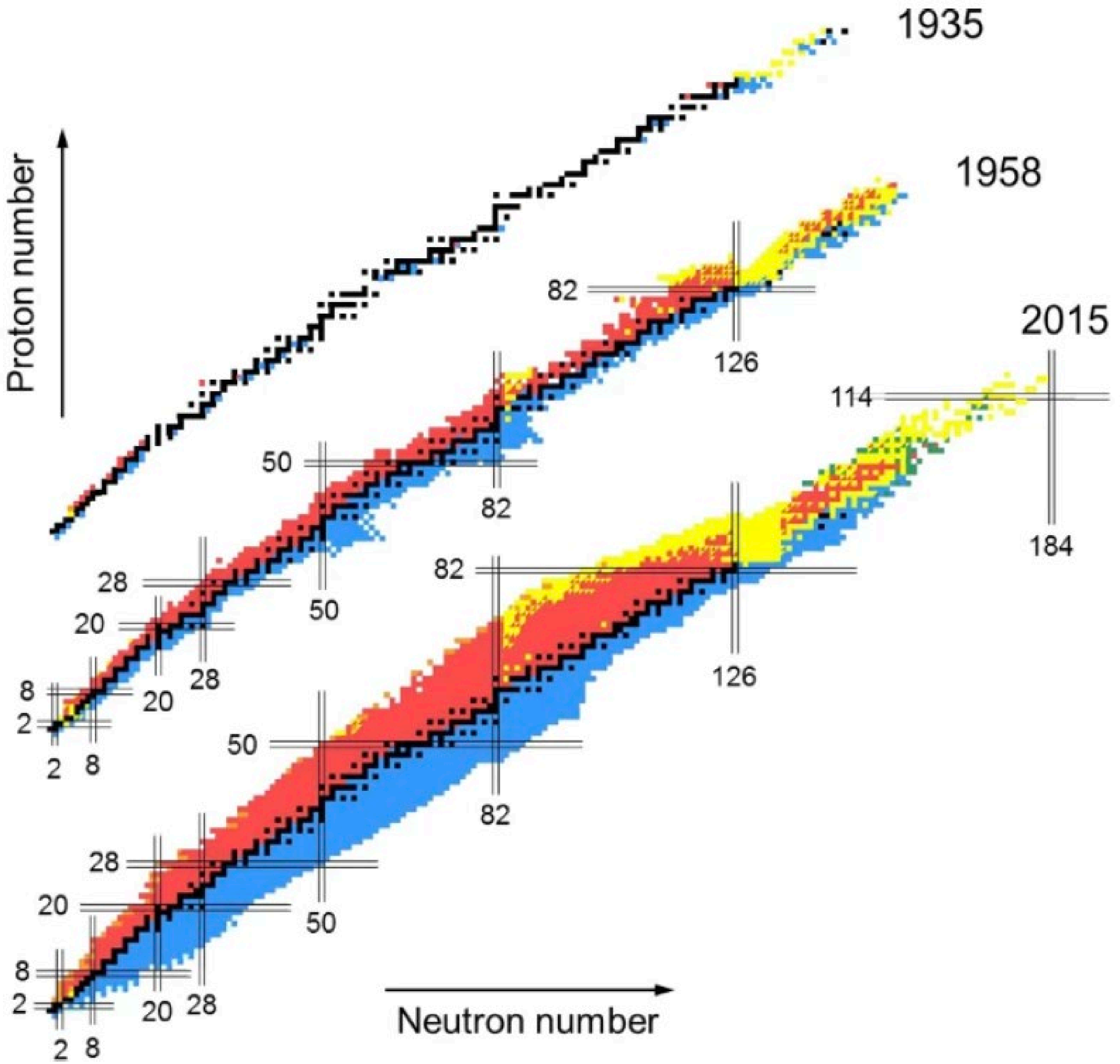
113	114	115	116	117	118
Nh	**Fl**	**Mc**	**Lv**	**Ts**	**Og**
Nihonium	Flerovium	Moscovium	Livermorium	Tennessine	Oganesson
2004	**2000**	**2004**	**2005**	**2010**	**2006**
Target ^{243}Am (decay from 115)	Target ^{244}Pu	Target ^{243}Am	Target $^{245,248}Cm$	Target ^{249}Bk	Target ^{249}Cf

Collaboration
LLNL
JINR
ORNL

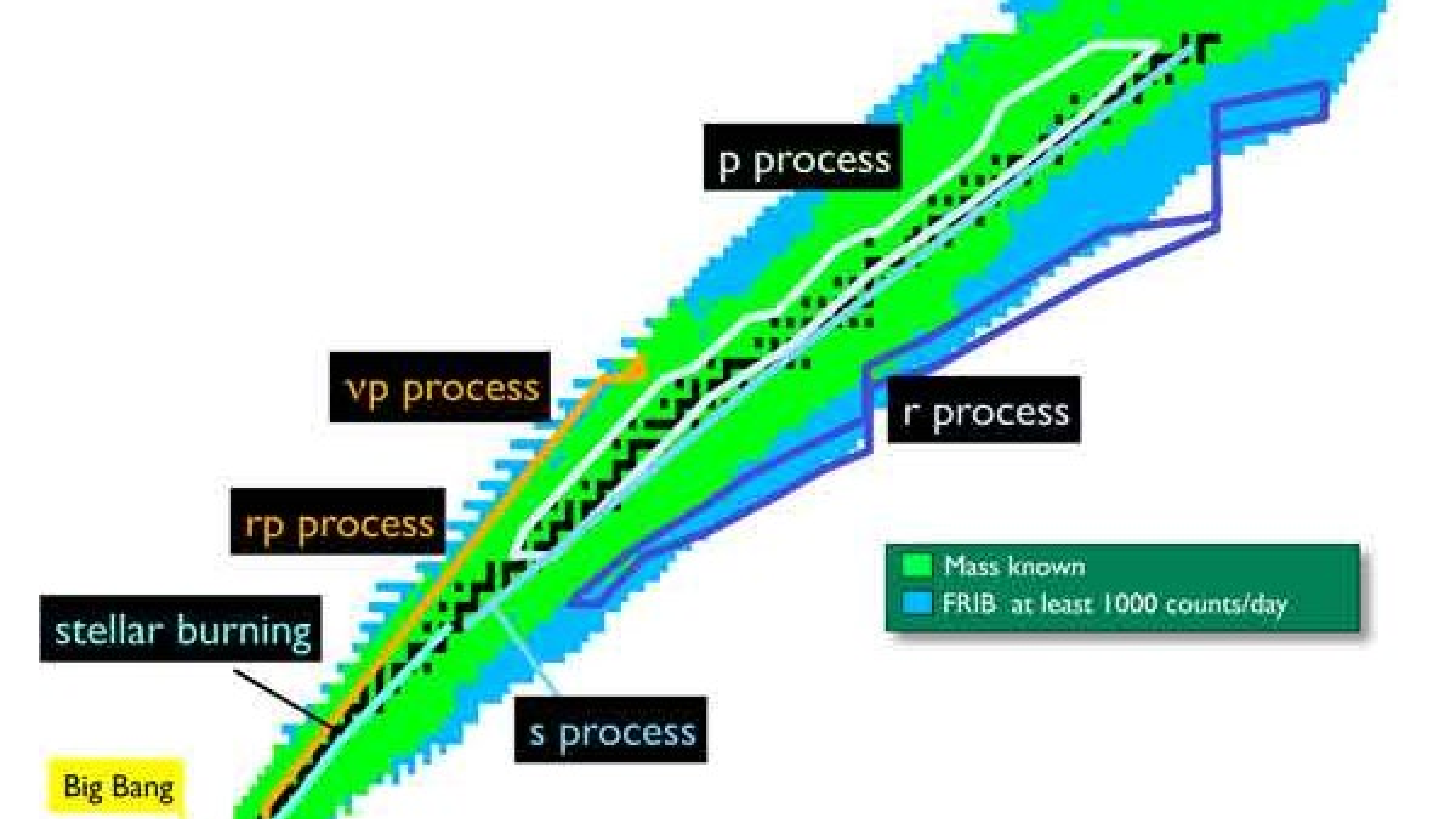


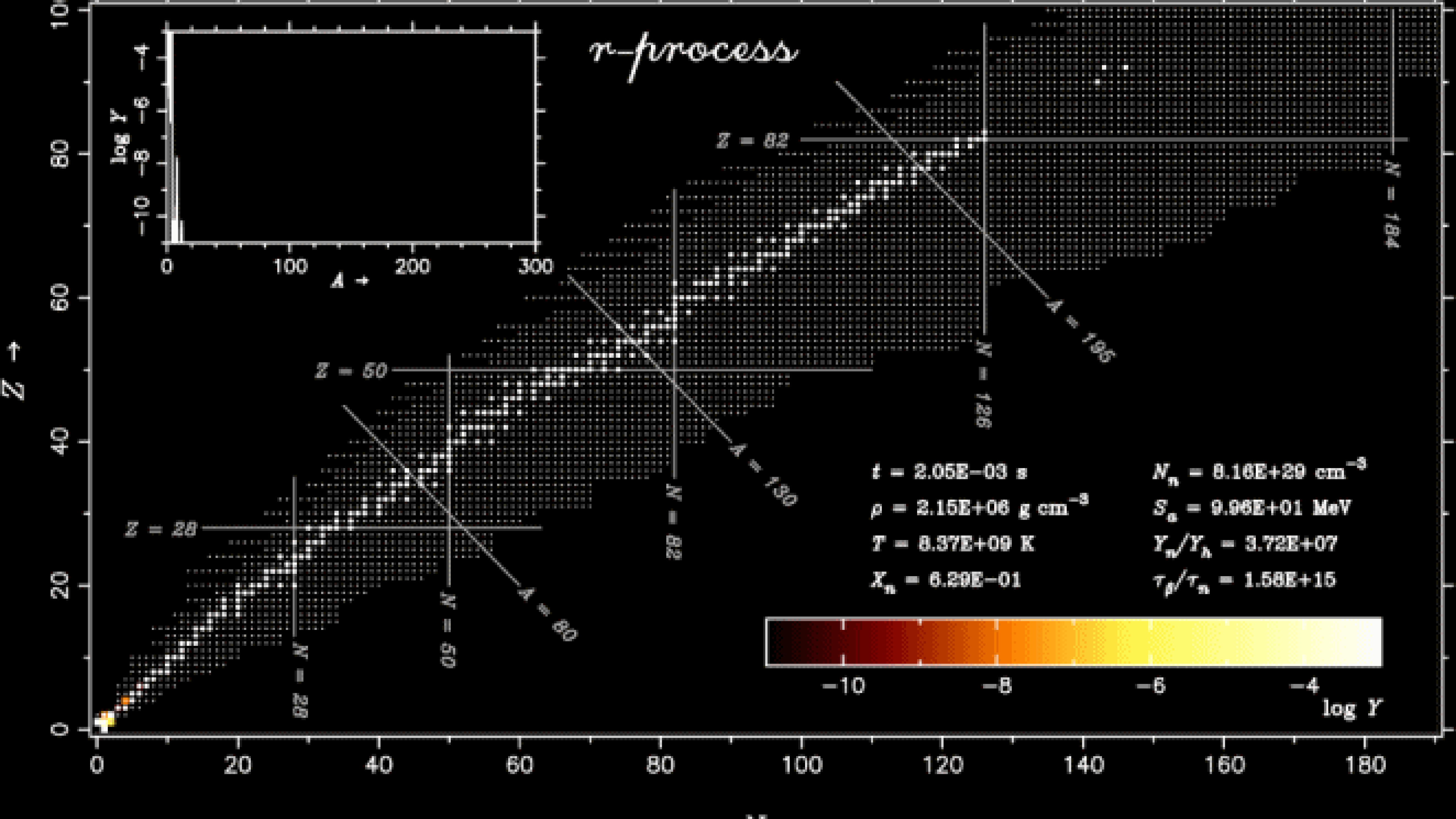
Z=120

Z=174



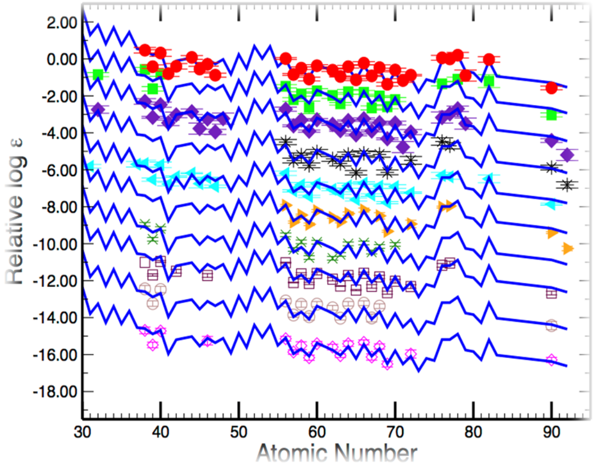
1935
1958
2015
Proton number
Neutron number
82
126
114
184
50
82
28
20
8
2
50
82
126
28
20
8
2
50
20
28
2
8
2
8
20
28
50


p process
vp process
r process
rp process
Mass known
FRIB at least 1000 counts/day
stellar burning
s process
Big Bang


r-process
Z = 82
Z = 50
Z = 28
N = 28
N = 50
N = 82
N = 126
N = 184
A = 80
A = 130
A = 195
t = 2.05E−03 s
ρ = 2.15E+06 g cm−3
T = 8.37E+09 K
Xn = 6.29E−01
Nn = 8.16E+29 cm−3
Se = 9.96E+01 MeV
Yn/Yh = 3.72E+07
τβ/τn = 1.58E+15
log Y
A →
Z →

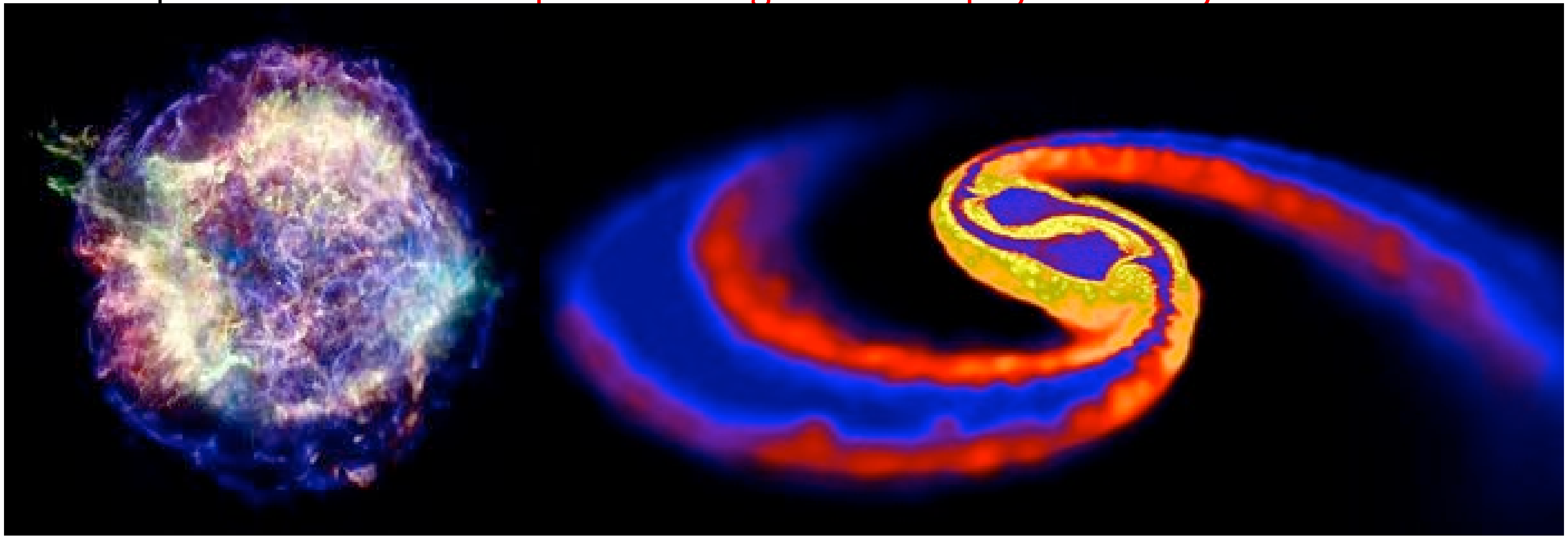
Explosive

r-process



Origin of more than 50% of all the elements beyond iron

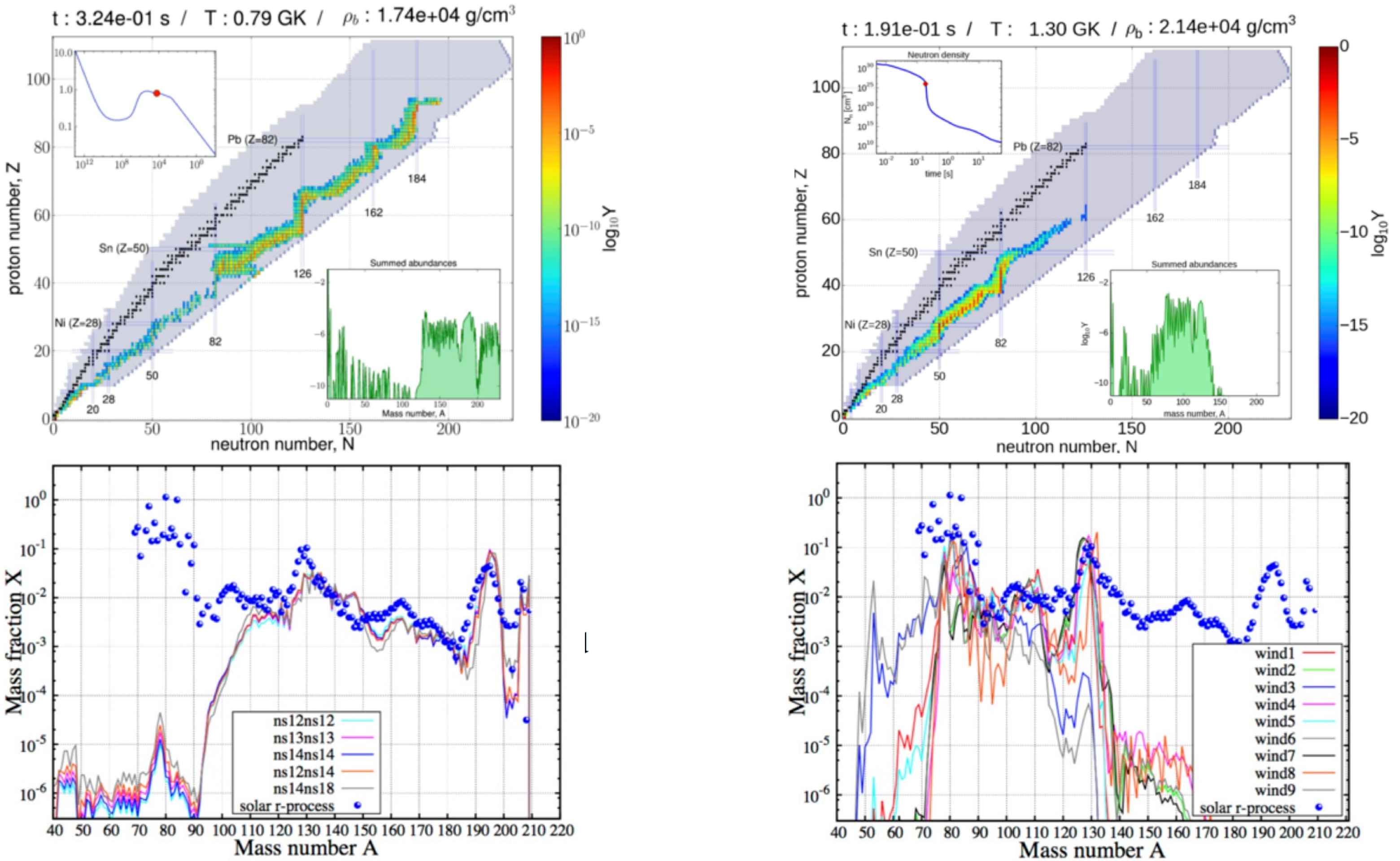
Site of r-process is still one of open challenges in all of physics today



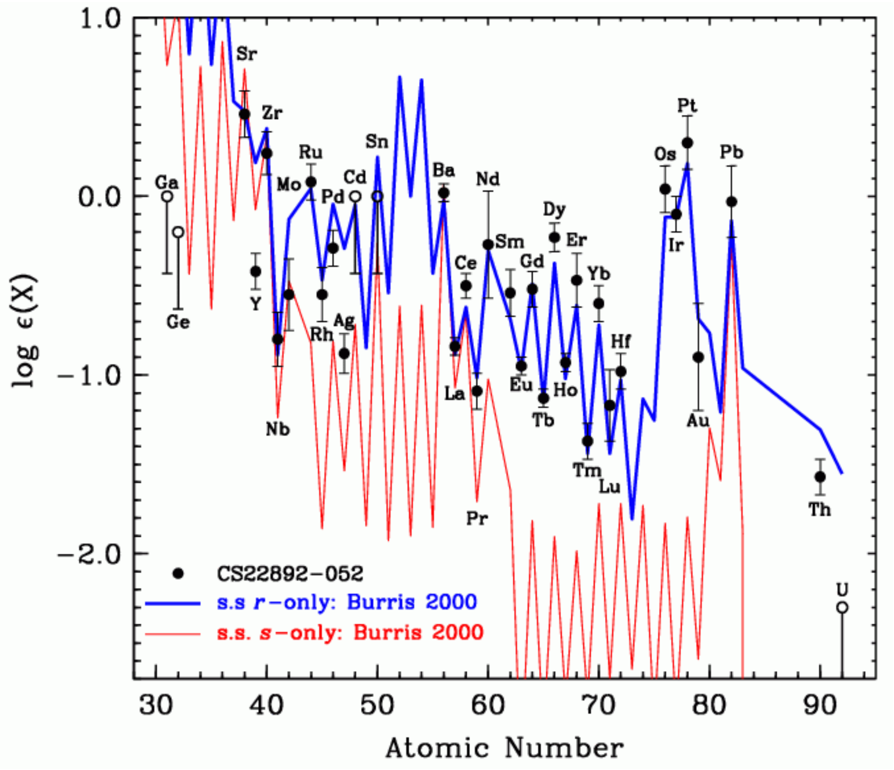
Temperature, density as a function of time, initial compositions,

where is the site of the r-process?

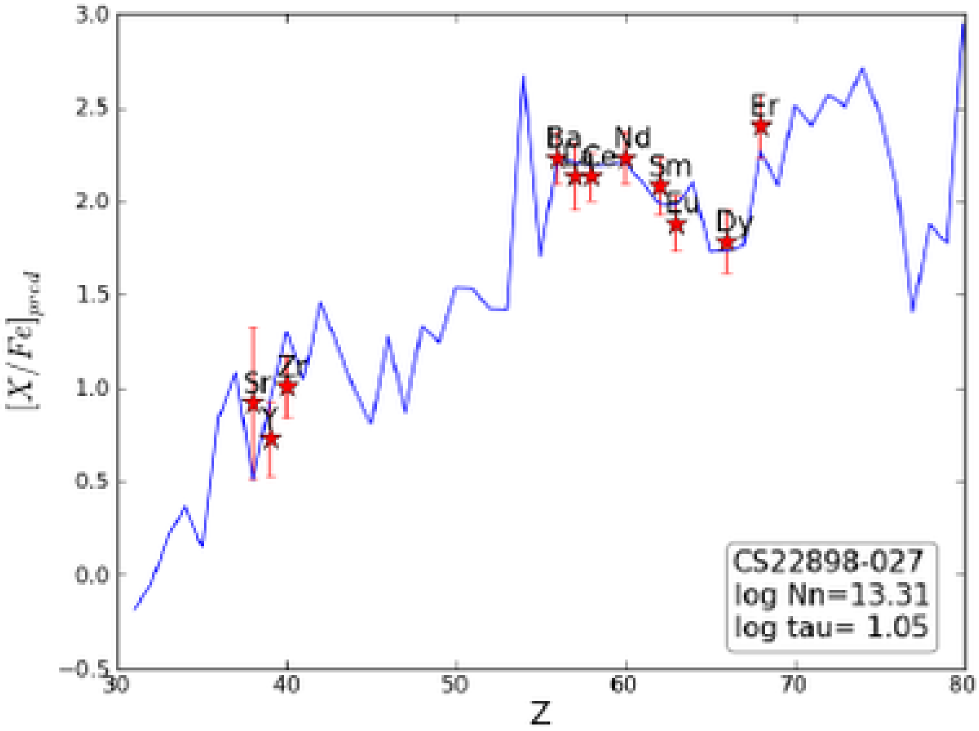
Merging neutron stars versus core collapse supernovae, gravitational wave detection identified neutron star mergers as a source of the very heavy elements!



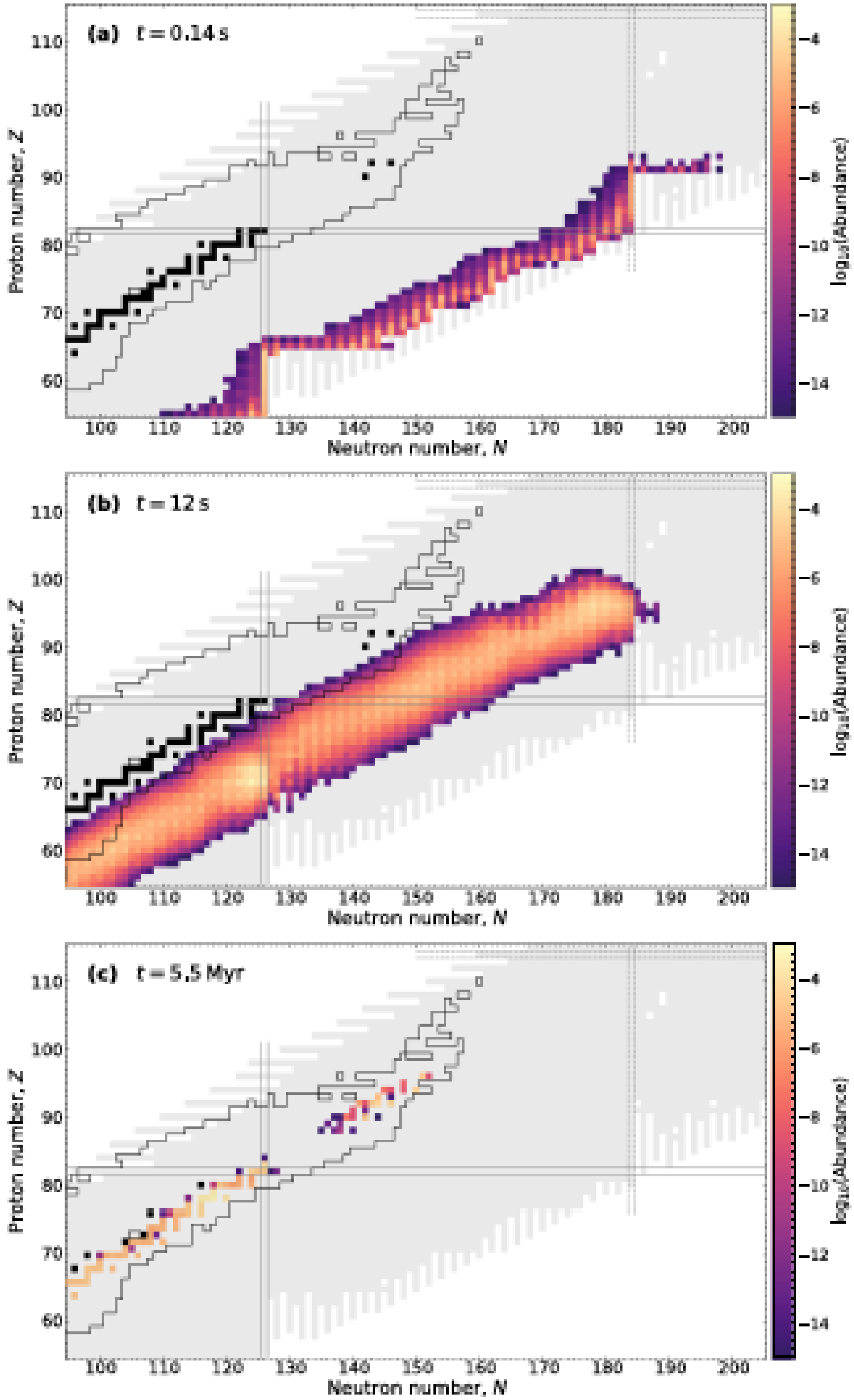
Abundances from other neutron induced nucleosynthesis processes



The s-process in comparison to the r-process.The scaling depends on the strength of the s-process neutron source



The i-process in CEMP stars, again the scale depends on the strength of neutron source



Eur. Phys. J. A (2023) 59:28
https://doi.org/10.1140/epja/s10050-023-00927-7

THE EUROPEAN PHYSICAL JOURNAL A

Review

Nucleosynthesis and observation of the heaviest elements

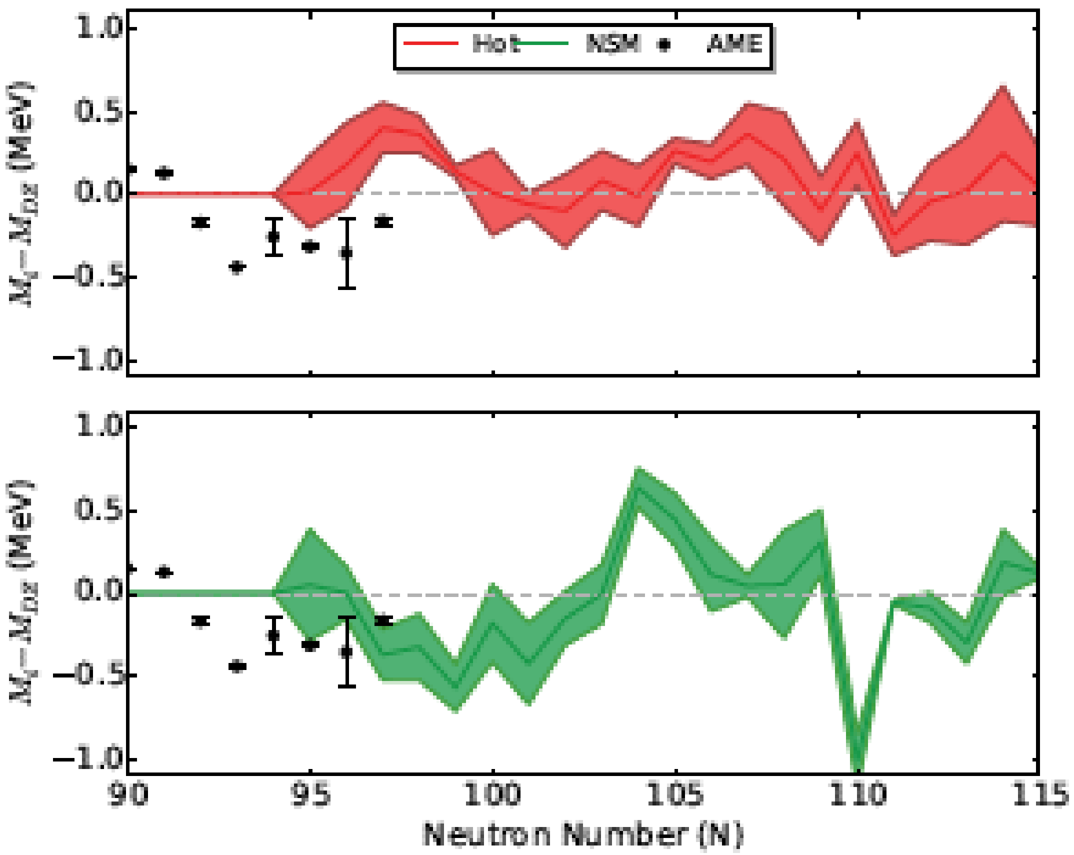
E. M. Holmbeck[1,a], T. M. Sprouse[2,3,b], M. R. Mumpower[2,3,c]

[1] The Observatories of the Carnegie Institution for Science, Pasadena, CA 91101, USA
[2] Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA
[3] Center for Theoretical Astrophysics, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

Snapshots of Simulations

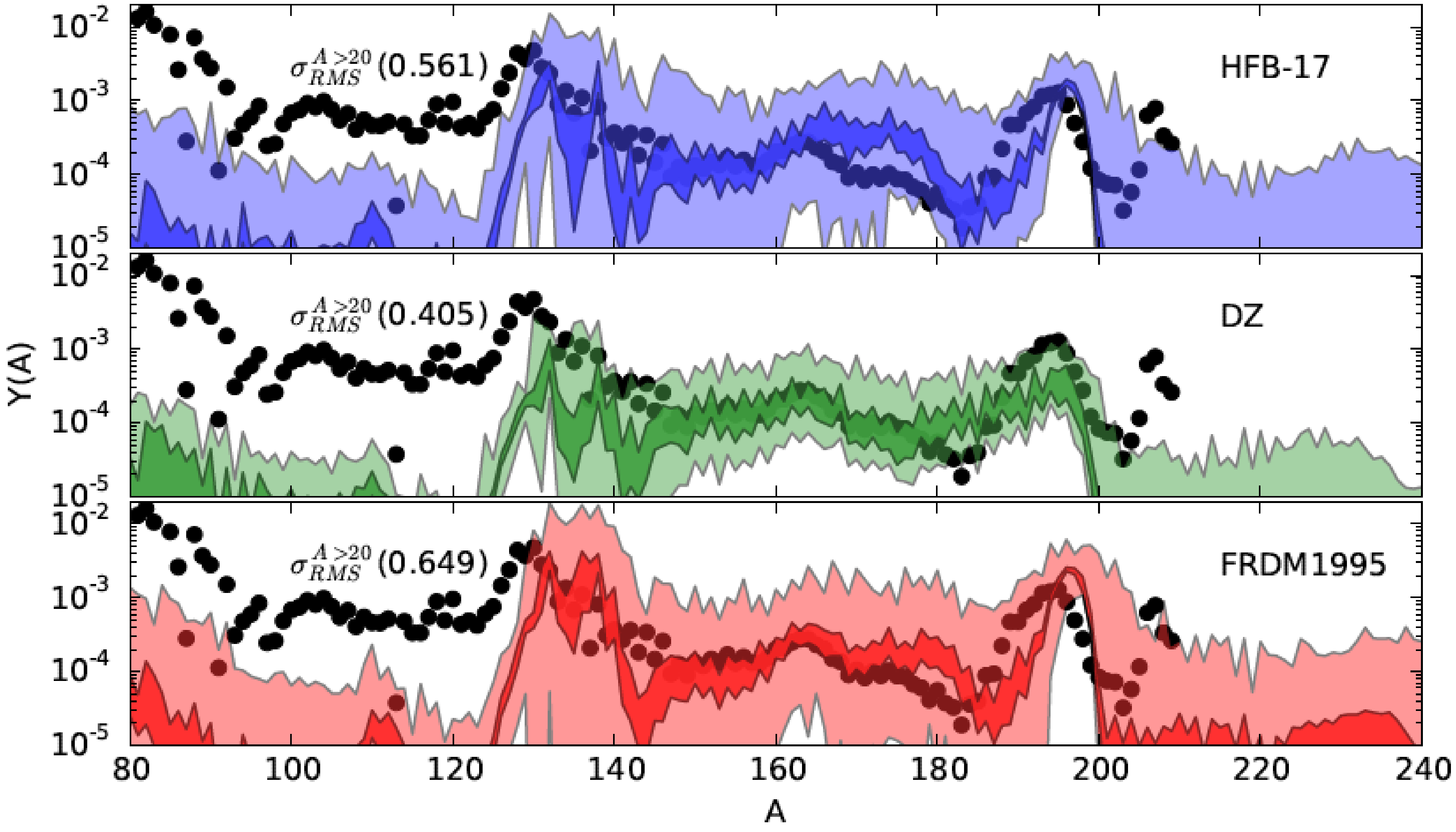
Input is **limited** to what we know

Mumpower, McLaughlin, Surman, and Steiner, Ap. J. 2016



Neutron Number (N)

Hot r-process trajectory



Uncorrelated nuclear mass uncertainties and r-process abundance predictions

Orford et al., Phys. Rev. Lett. 120, 262702 (2018)

Observed r-process elemental distributions

Merger accretion disk wind scenario

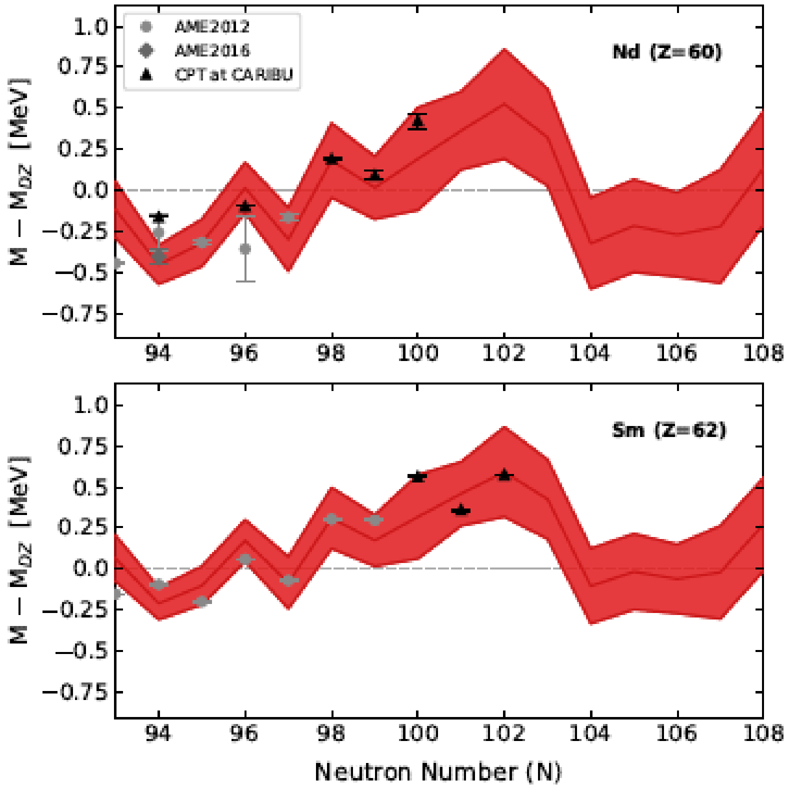


FIG. 2. (Color online) Comparison between experimental values and theoretical predictions (red band) of the nuclear masses relative to the Duflo-Zuker mass model for neodymium and samarium isotopes in a merger accretion disk wind scenario ($s/k_B = 30$, $\tau = 70\,\mathrm{ms}$, and $Y_e = 0.2$).

Varying thermodynamics has little effect

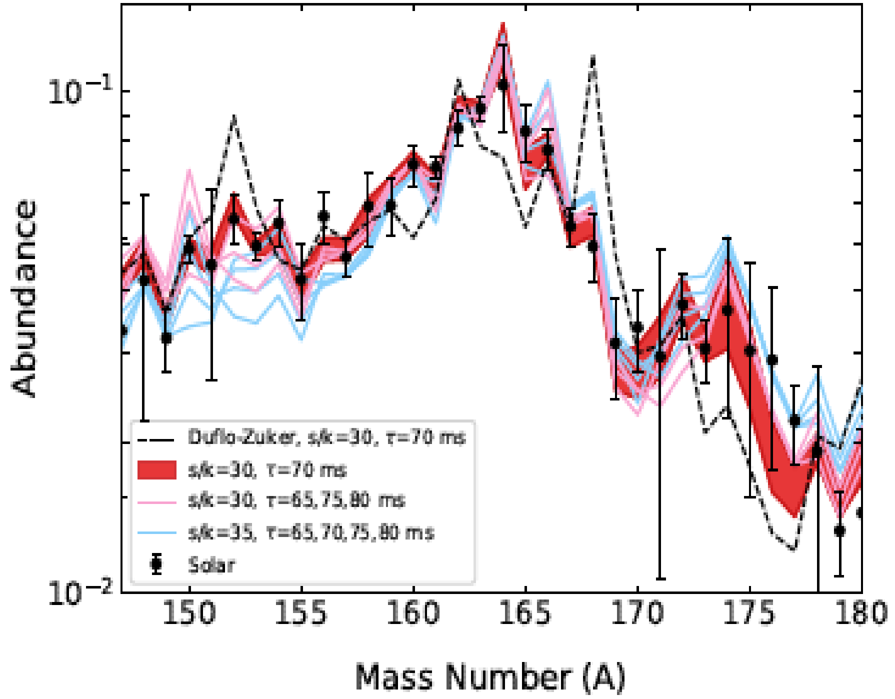
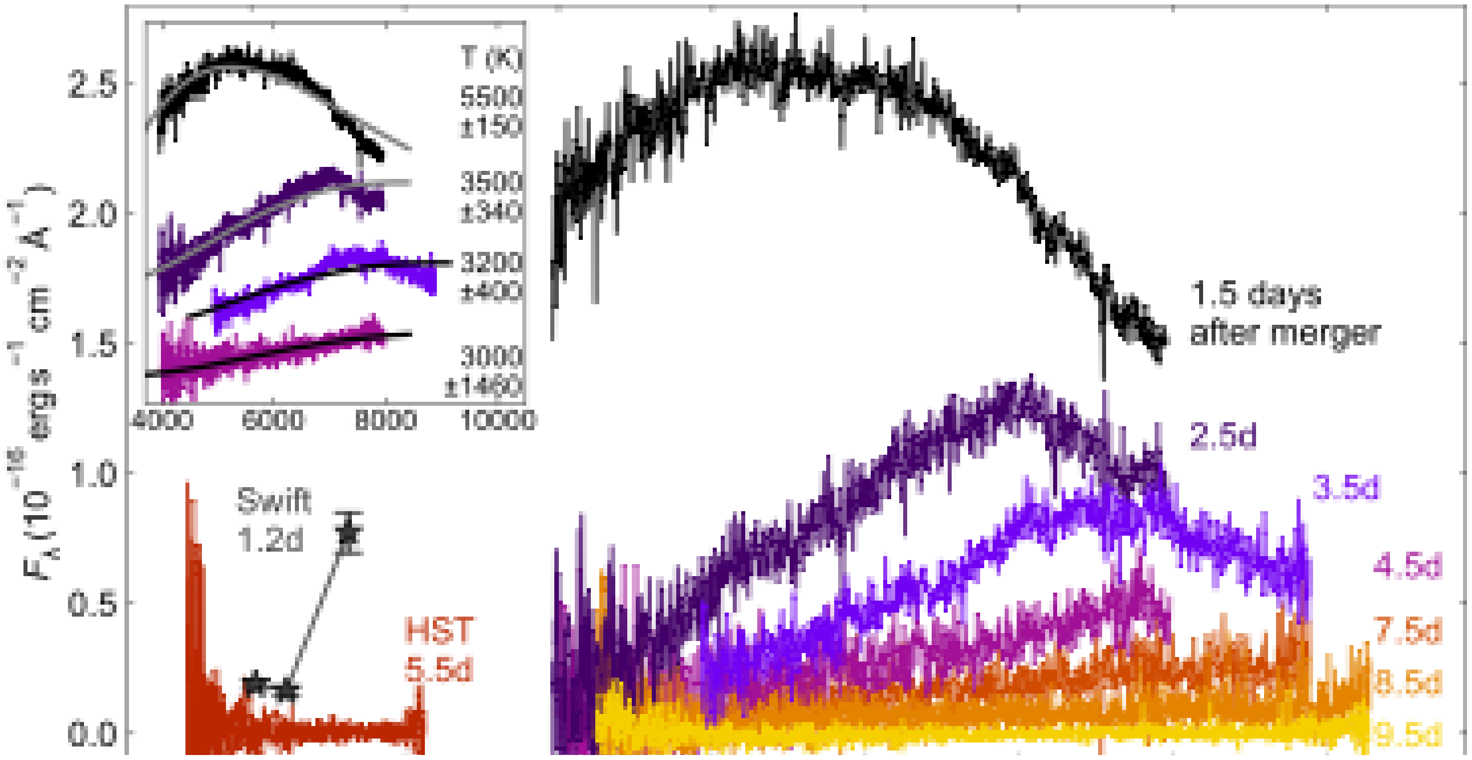


FIG. 3. (Color online) Rare-earth peak abundances using Dulfo-Zuker masses (black dashed) as compared to the result for this same astrophysical trajectory after the algorithm finds the mass predictions of Fig. 2 (solid red band). Pink and blue curves serve to show the change in the abundance pattern obtained from using other disk wind parameters but with the same mass surface.

GW170817 + 70 Electromagnetic transients



THE ASTROPHYSICAL JOURNAL LETTERS, 848:L18 (8pp), 2017 October 20

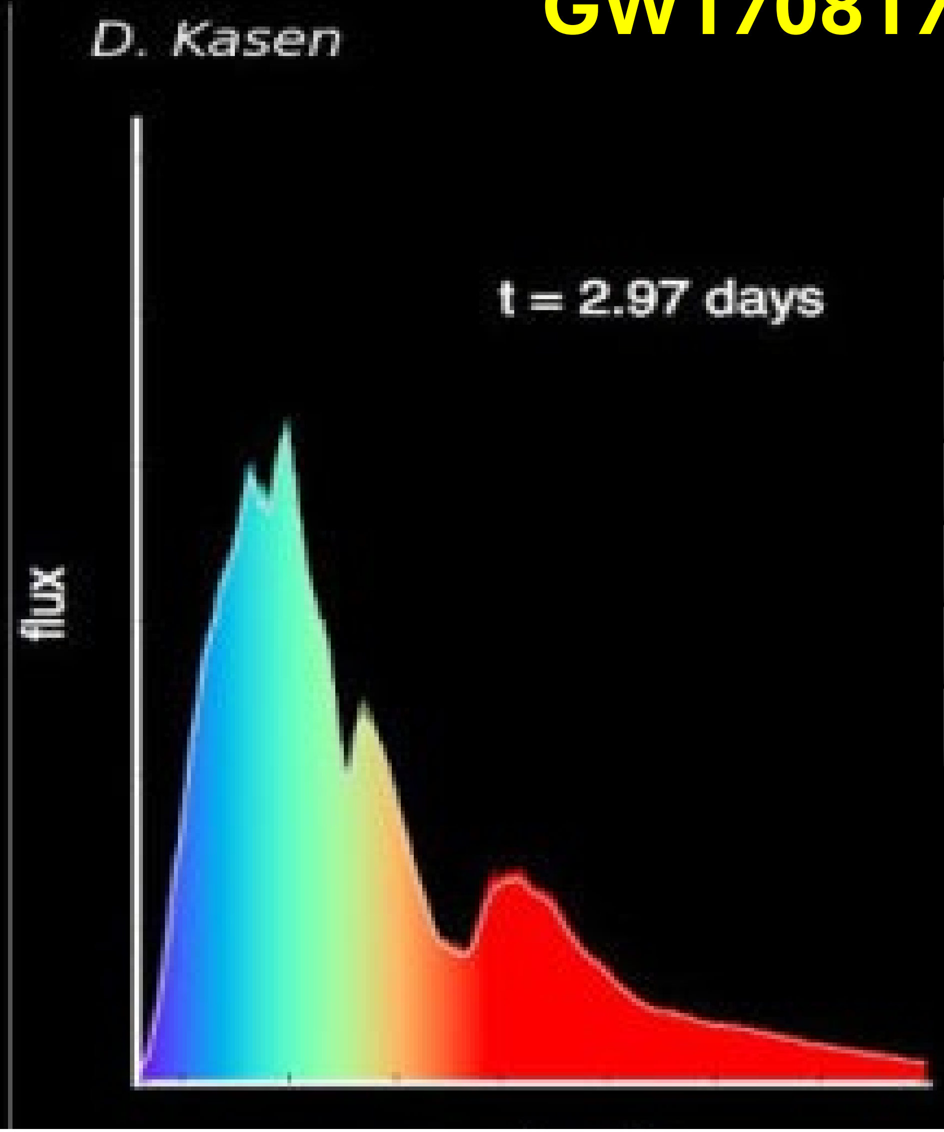
Lu visible signatures go into the IR

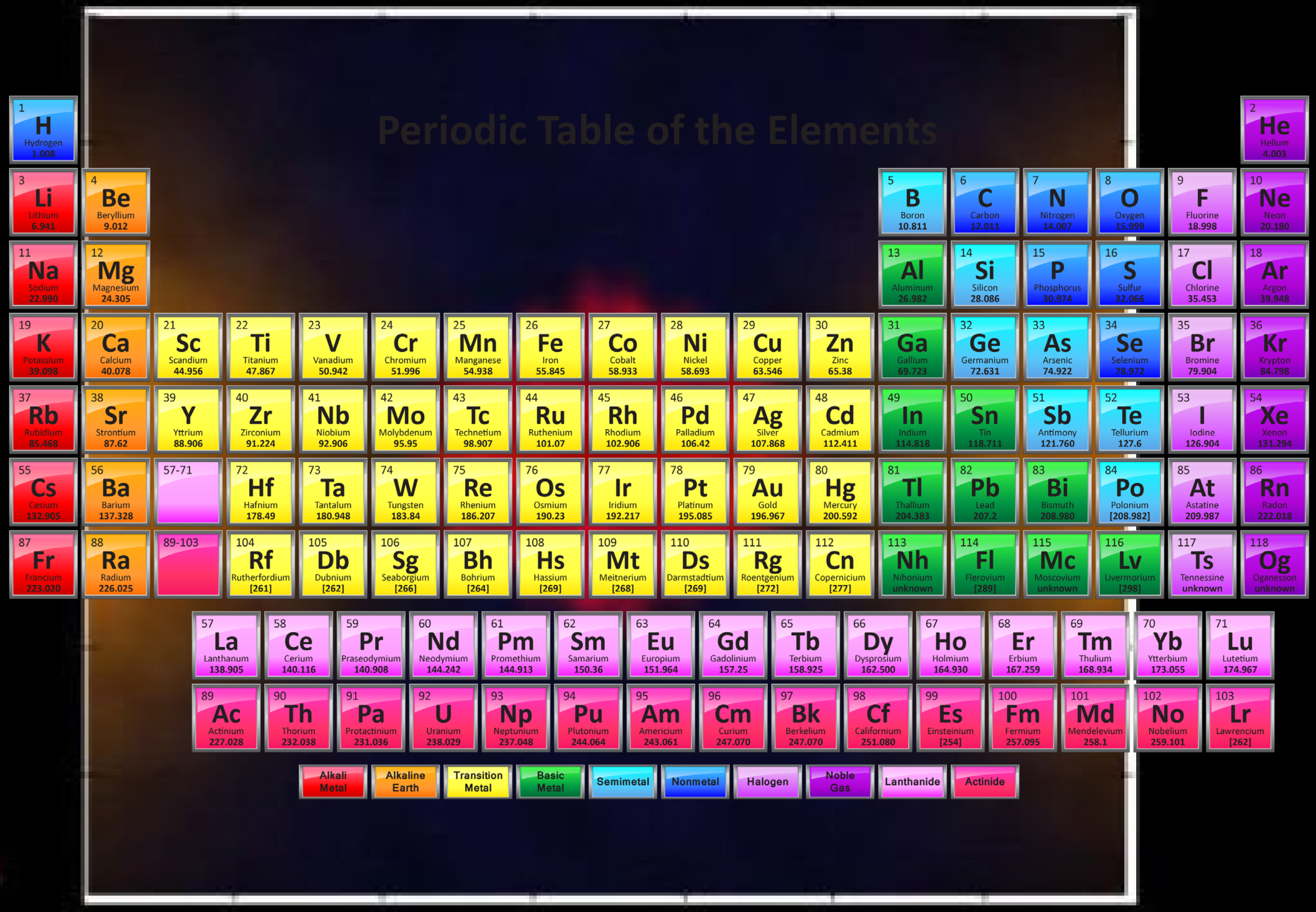
James Webb

Does the r-process make the actinides?

Big Question: Fission

GW170817 + 70 Electromagnetic Transients





The Astrophysical Journal Letters, 848:L18 (8pp), 2017 October 20

Implications for nuclear physics

LIGO, VIRGO, GAGRA began new observation run on May 24, 2023

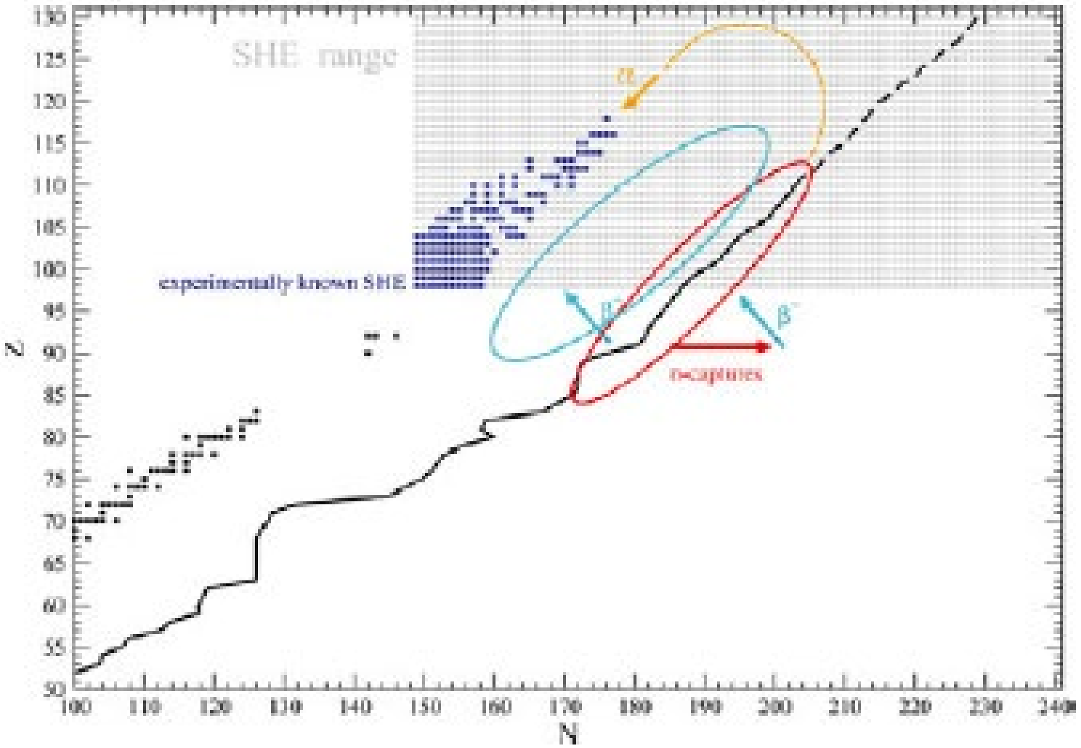
Eur. Phys. J. A (2012) **48**: 122
DOI 10.1140/epja/i2012-12122-6

THE EUROPEAN
PHYSICAL JOURNAL A

Regular Article – Theoretical Physics

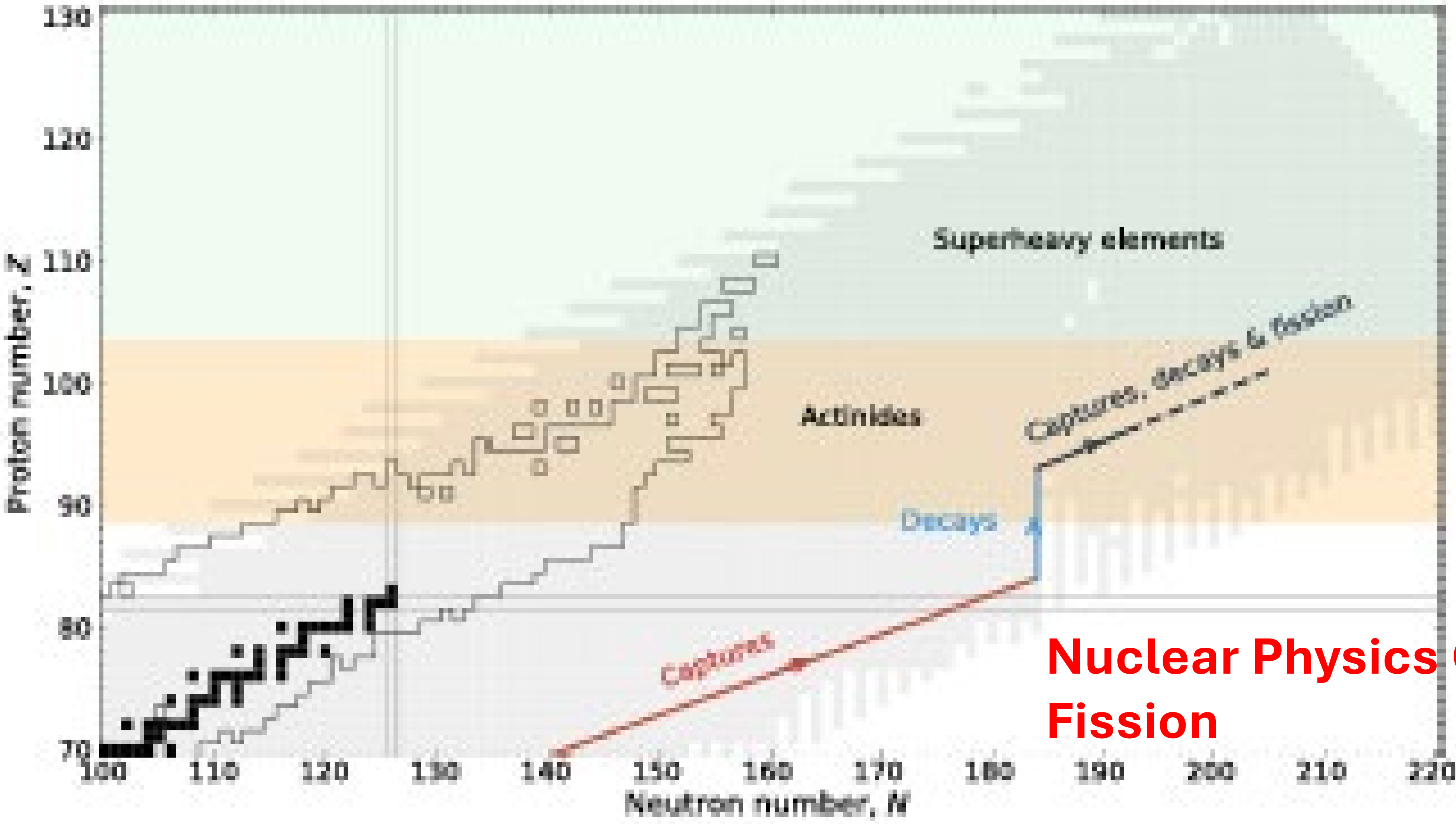
Have superheavy elements been produced in nature?

I. Petermann[1], K. Langanke[2,3,4], G. Martínez-Pinedo[2,3,a], I.V. Panov[5,6], P.-G. Reinhard[7], and F.-K. Thielemann[5]

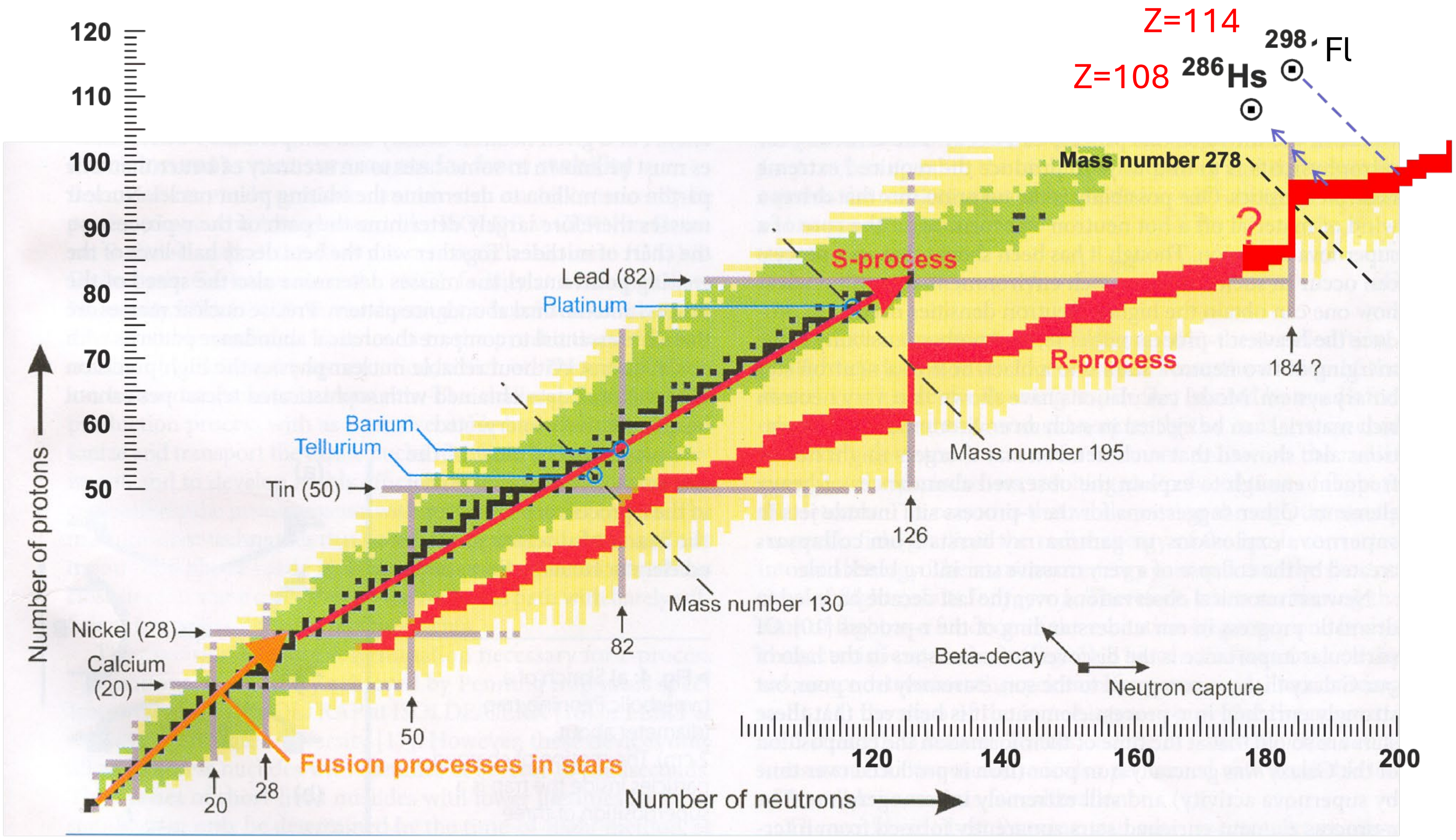


Are superheavy elements produced in the r-process?

E. M. Holmbeck, European Physical Journal A, 59:28 (2023)



Nuclear Physics Question: Fission



Z=114
298 Fl
Z=108
286 Hs
Mass number 278
S-process
R-process
Lead (82)
Platinum
Barium
Tellurium
Tin (50)
Nickel (28)
Calcium (20)
Mass number 195
Mass number 130
184 ?
126
82
50
28
20
Beta-decay
Neutron capture
Fusion processes in stars
Number of protons
Number of neutrons
120
110
100
90
80
70
60
50
120
140
160
180
200

r-process idea from weapons tests: B^2FH

Reviews of Modern Physics 29(4), 547 (1957)

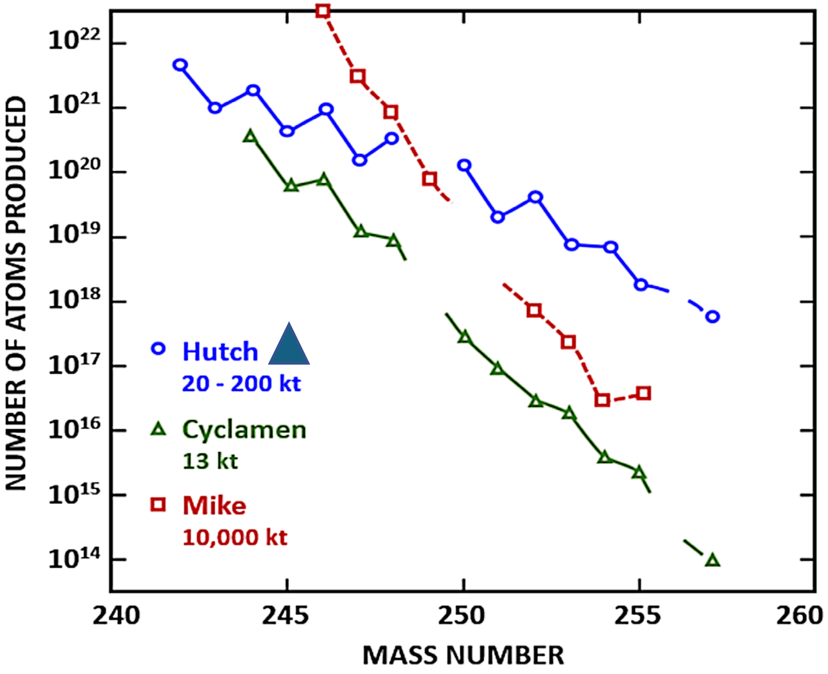
Lawrence Livermore Laboratory

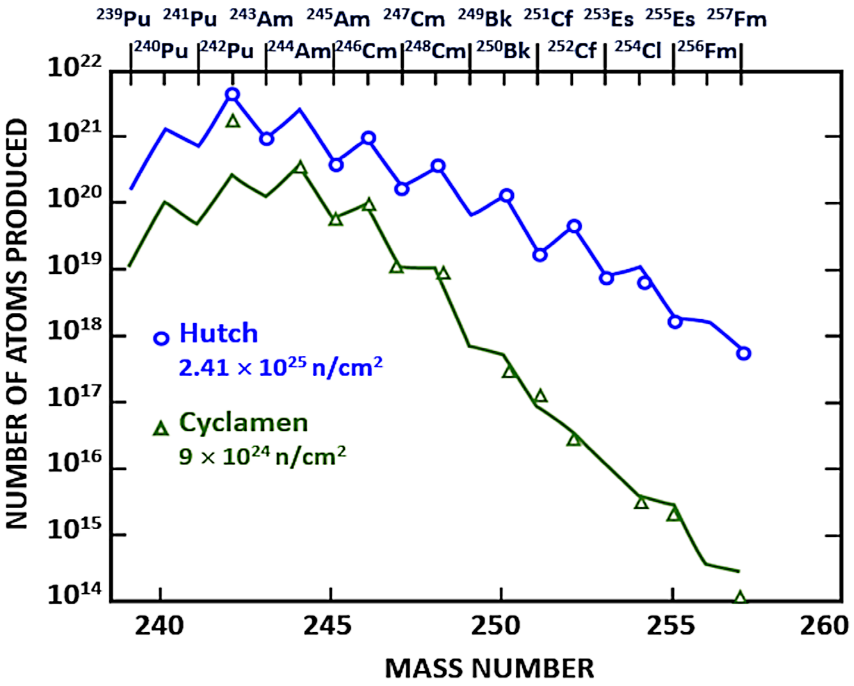
PRODUCTION OF EINSTEINIUM AND FERMIUM IN NUCLEAR EXPLOSIONS

R. Hoff, August 21, 1978

Z=99 Es

Z=100 Fm





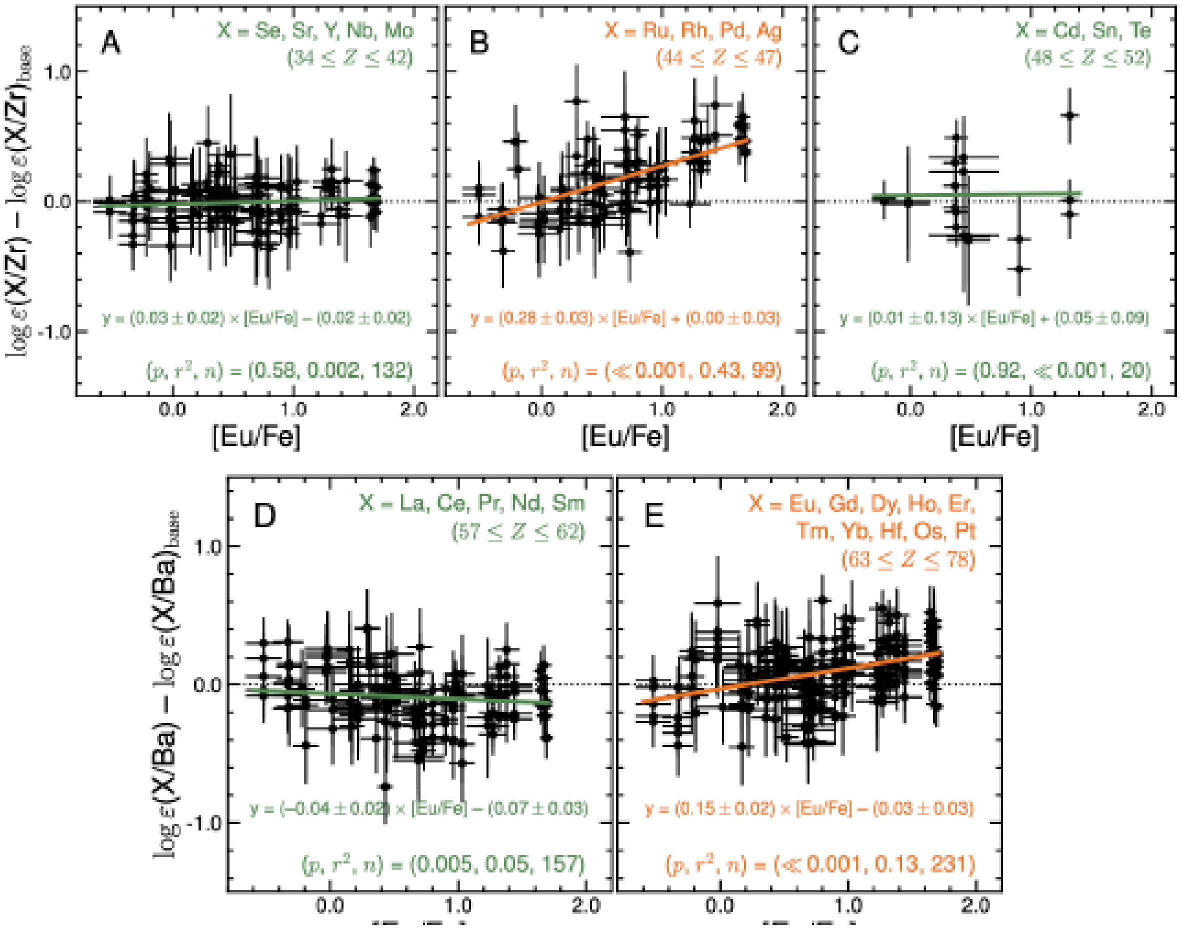
Neutron star: 10^{43} or 10^{41} neutrons/cm^2

Recent observations of r-process enhanced stars

Science 382, No.6675, Dec. 2023

Ru, Rh, Pd, Ag

Eu, Gd, Dy, Ho, Er,
Tm, Yb, Hf, Os, Pt



Fission recycling!

Title: Observational signatures of transuranic fission fragments in stars

Authors: Ian U. Roederer[1,2]*, Nicole Vassh[3], Erika M. Holmbeck[4,5,2], Matthew R. Mumpower[6,7,2], Rebecca Surman[8,2], John J. Cowan[9], Timothy C. Beers[8,2], Rana Ezzeddine[10,2], Anna Frebel[11,2], Terese T. Hansen[12], Vinicius M. Placco[13], Charli M. Sakari[14]

A>260 (110+ 150) were made in the r-process

Open Challenges to Nuclear Physics resulting from the neutron star merger

A. Aprahamian
NuPECC in Sept. 2021

Fission

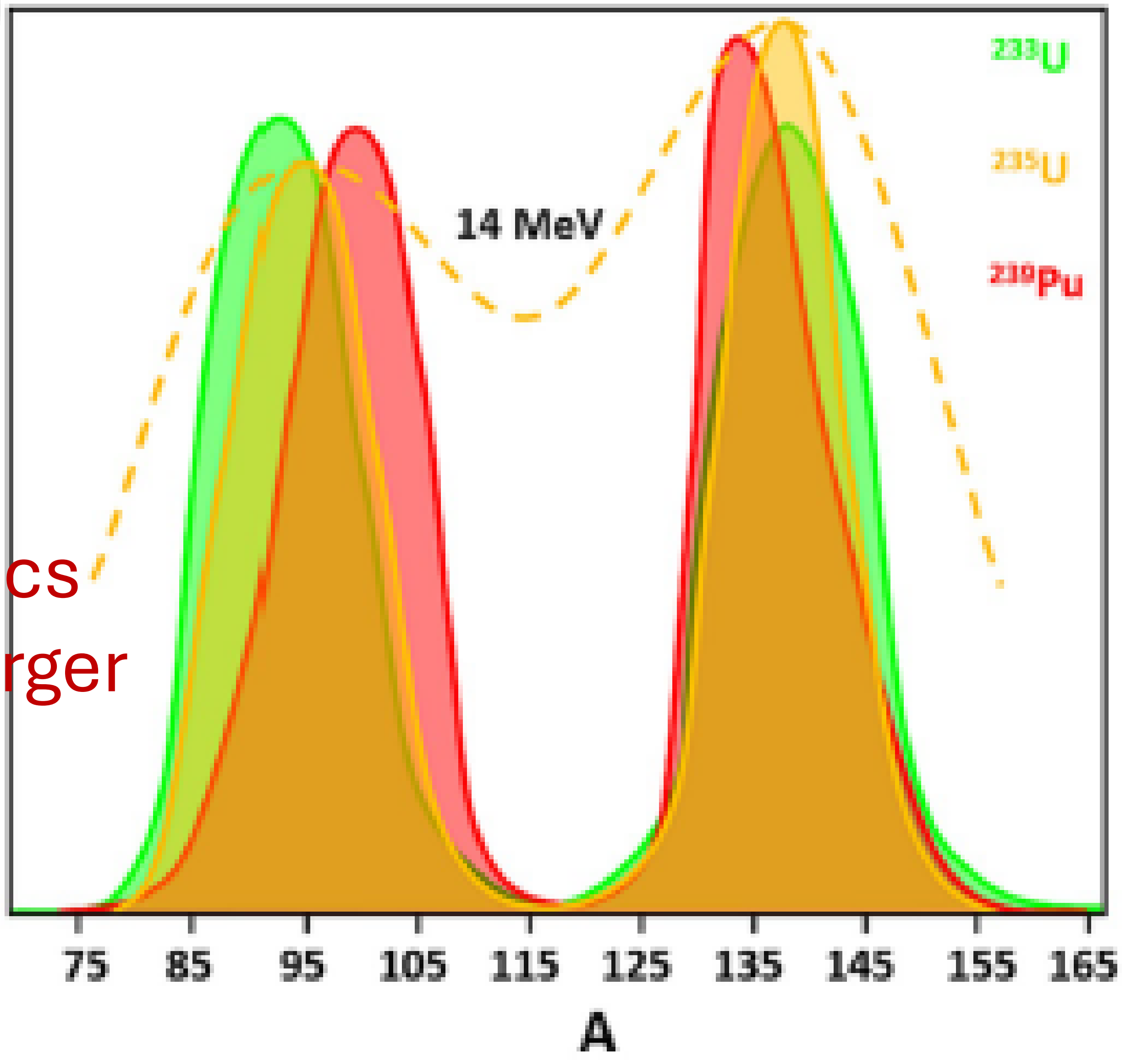
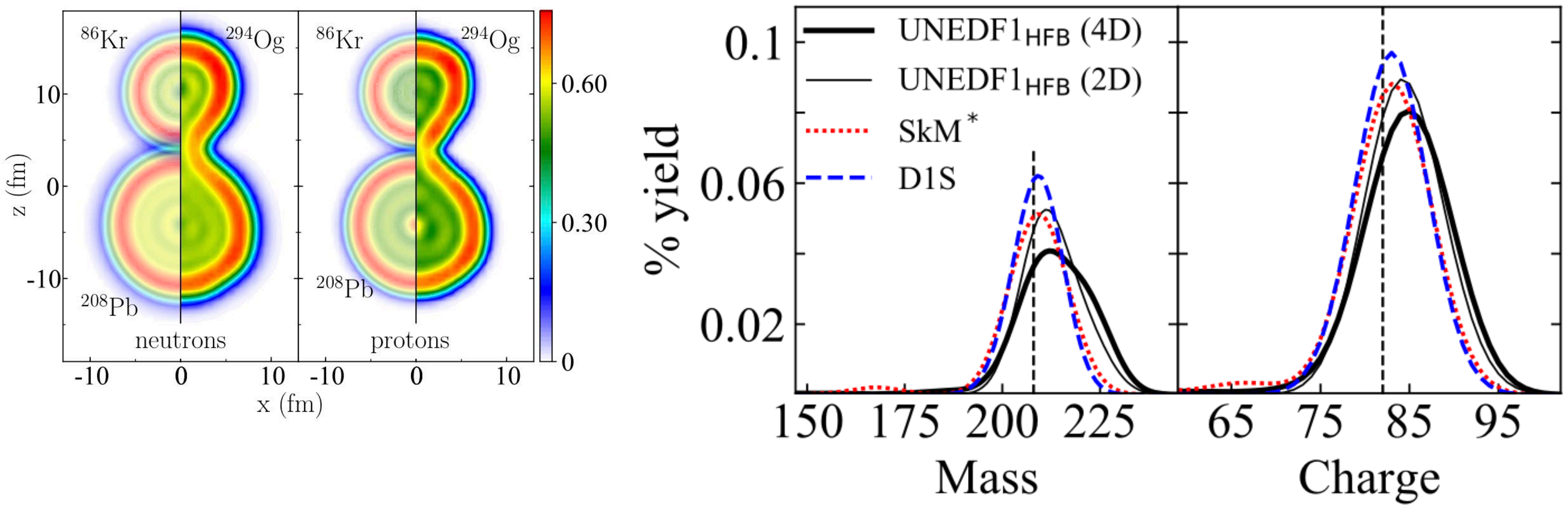


Figure 4. *Low-energy (thermal) neutron-induced fission fragment distributions with $^{233,235}U$ and ^{238}Pu. The dotted line indicates the fission of ^{235}U with 14 MeV neutrons.*

Cluster decay becomes the main fission mode

Z. Matheson et al., Phys. Rev. C 99, 041304(R) (2019)

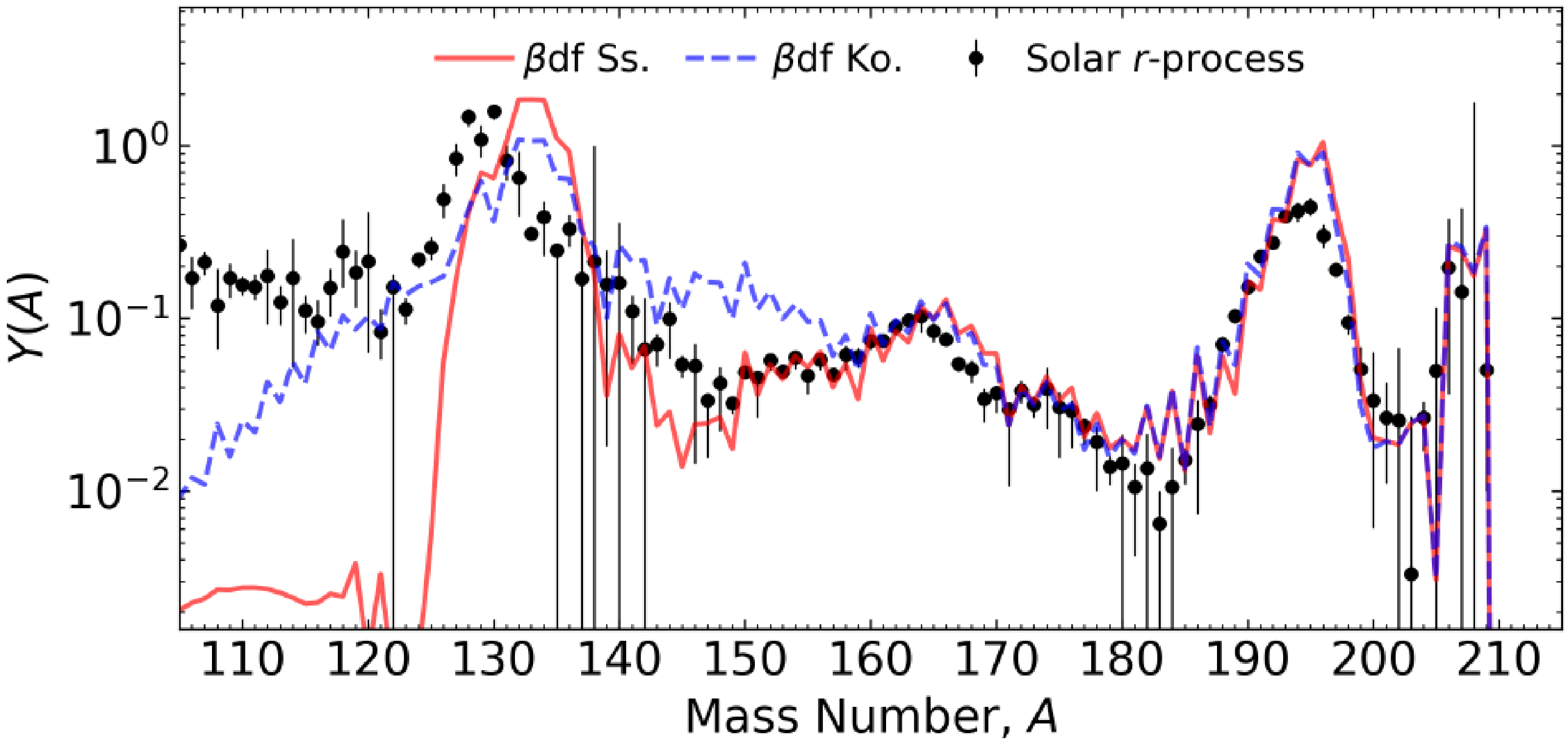


Robust prediction: extremely asymmetric fission

$^{294}Og \rightarrow {}^{208}Pb + {}^{86}Kr_{50}$

Courtesy of W. Nazarewicz

FISSION CAN IMPACT FINAL ABUNDANCES



Network calculation of tidal ejecta from a neutron star merger (FRDM2012)

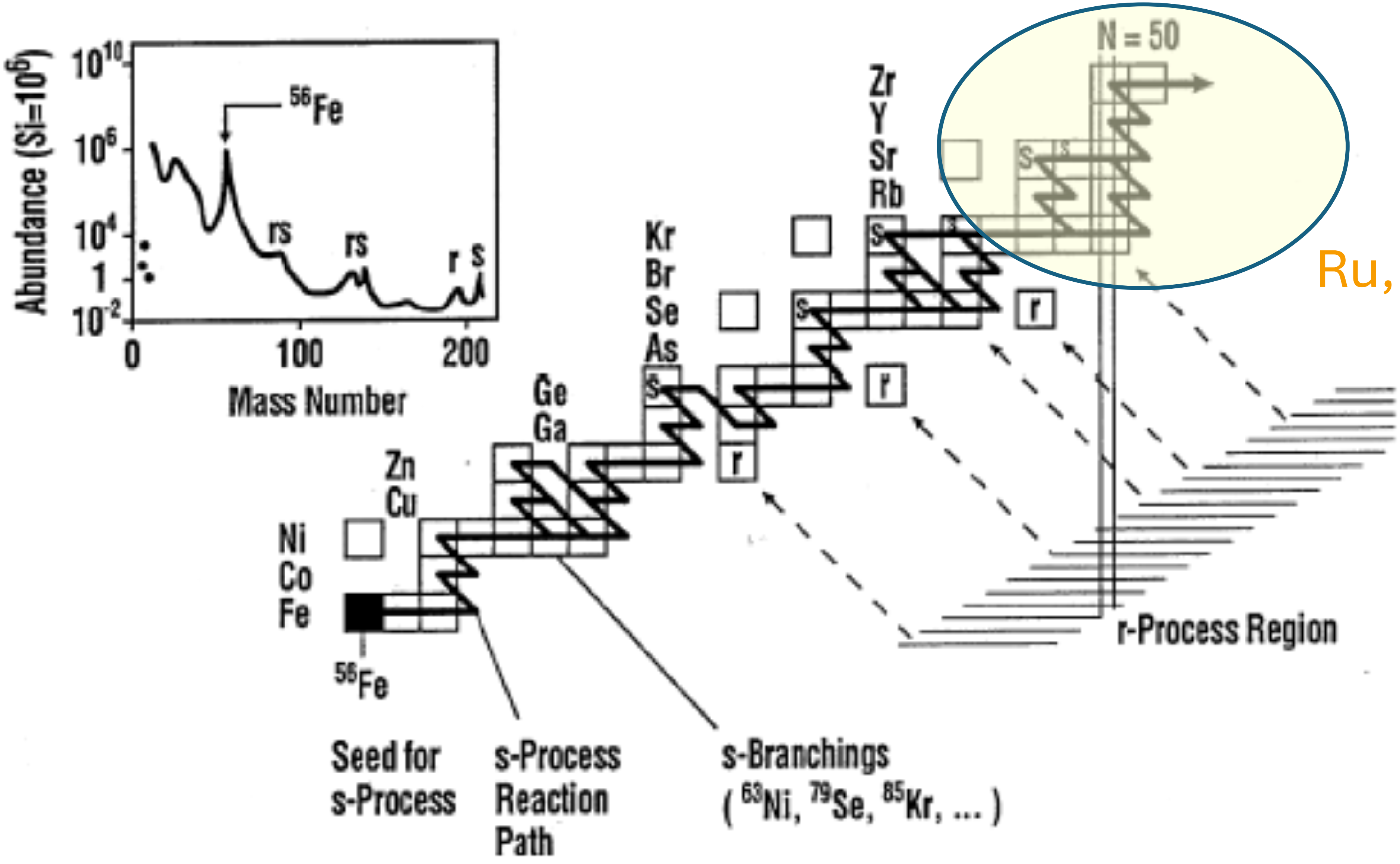
βdf can shape the final pattern near the $A = 130$ peak

This is because of a relatively long fission timescale

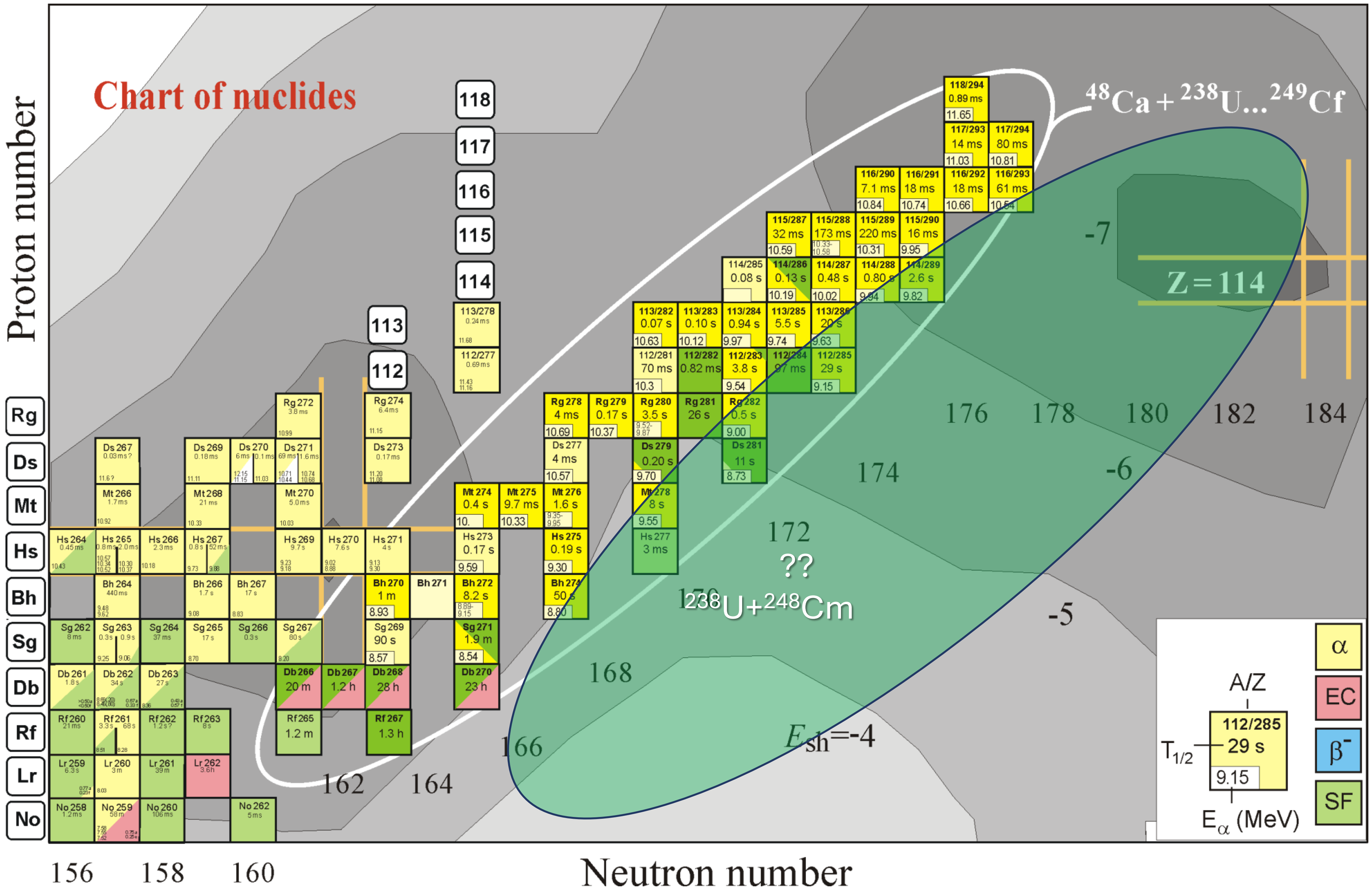
Conclusion $\Rightarrow$ we need a good description of fission yields to understand abundances near $A \sim 130$.

Kodama & Takahashi (1975) • Shibagaki *et al.* ApJ (2016) • **Mumpower** *et al.* ApJ 869 1 (2018) • Vassh ***et al.*** J. Phys. G (2019)

What are the uncertainties? r- and s- process branchings

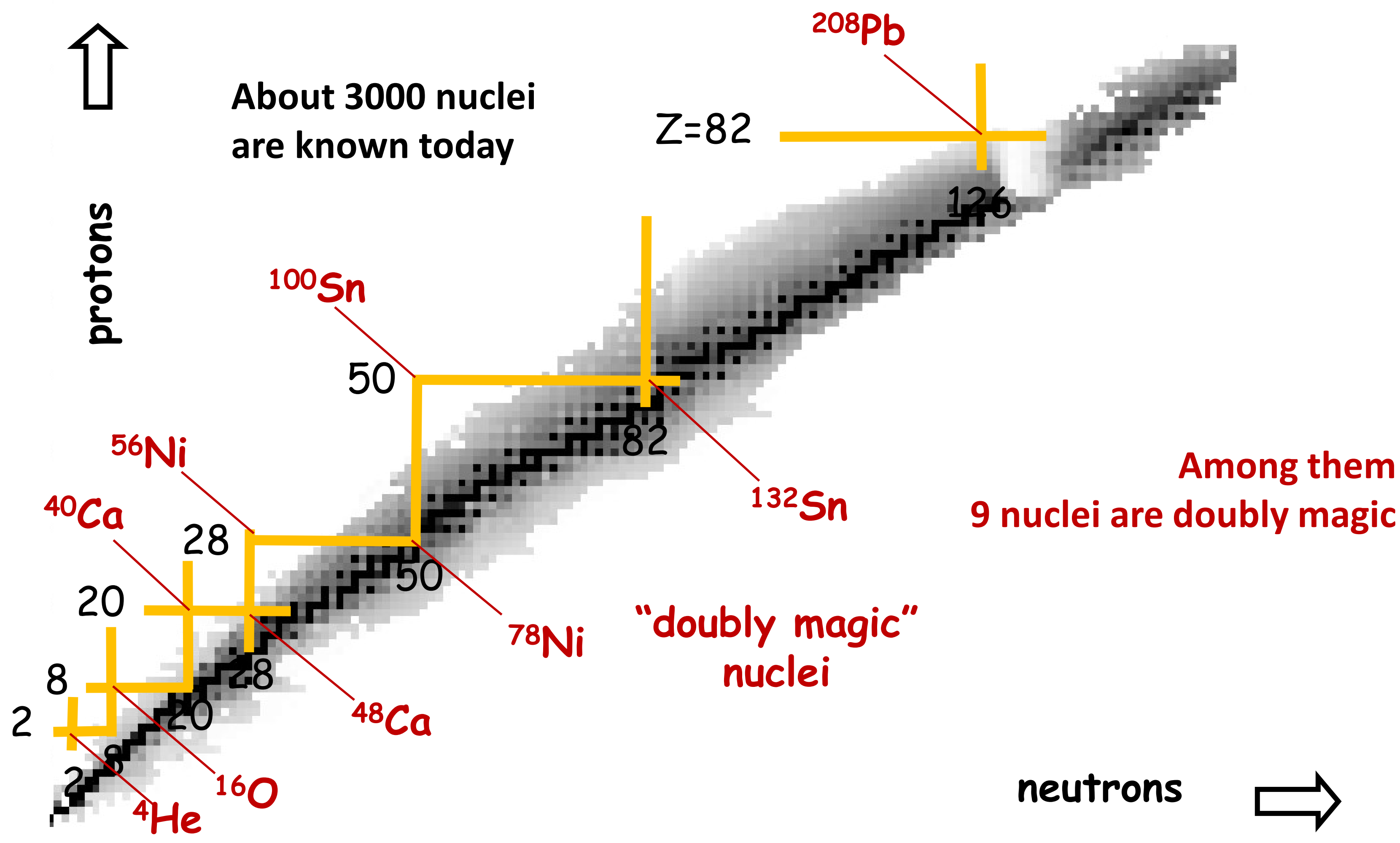


Ru, Rh, Pd, Ag

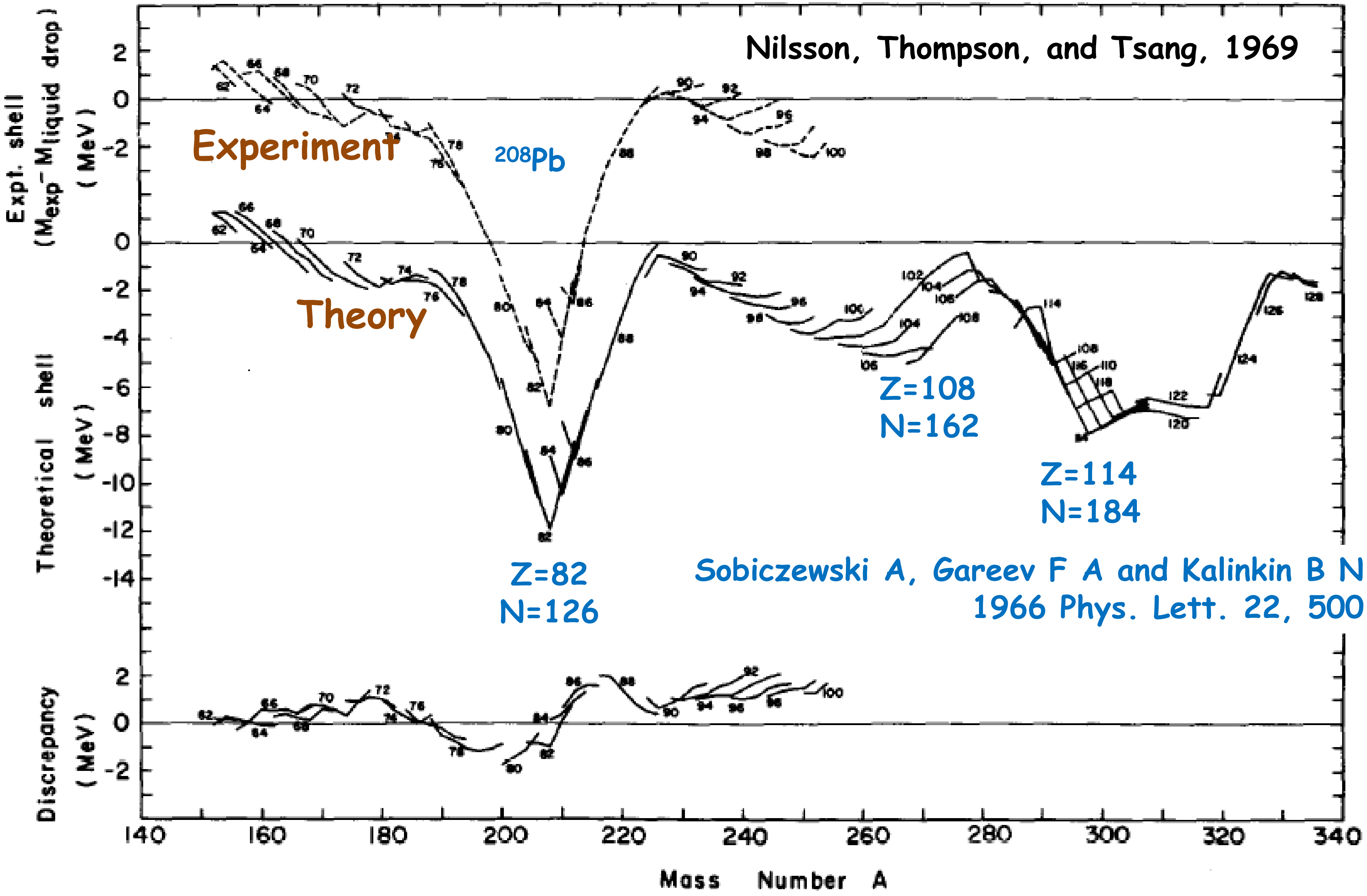


Courtesy of A. Karpov

Nuclear shells and the "magic numbers"



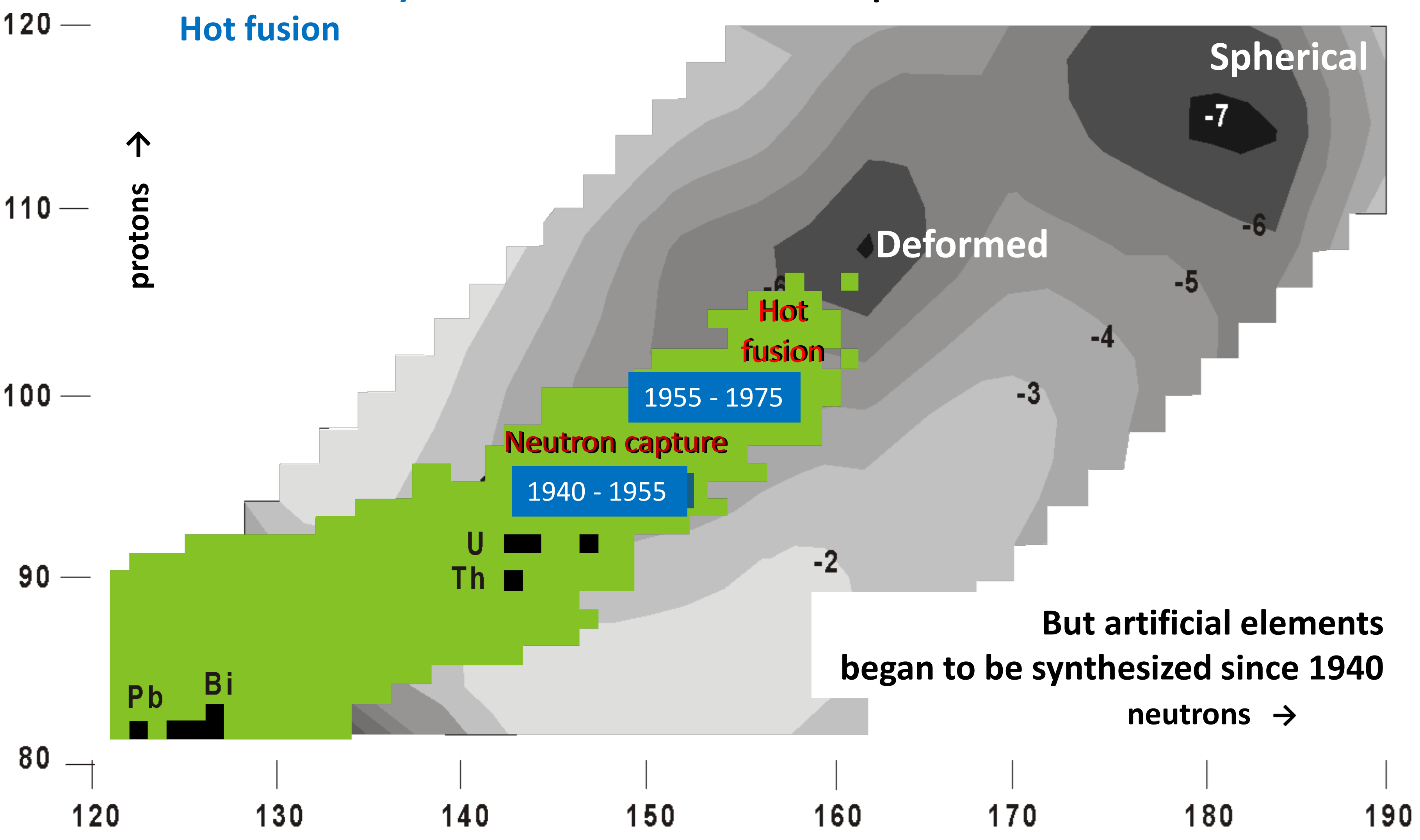
Macro-microscopic theory (Liquid Drop energy + Shell effect)



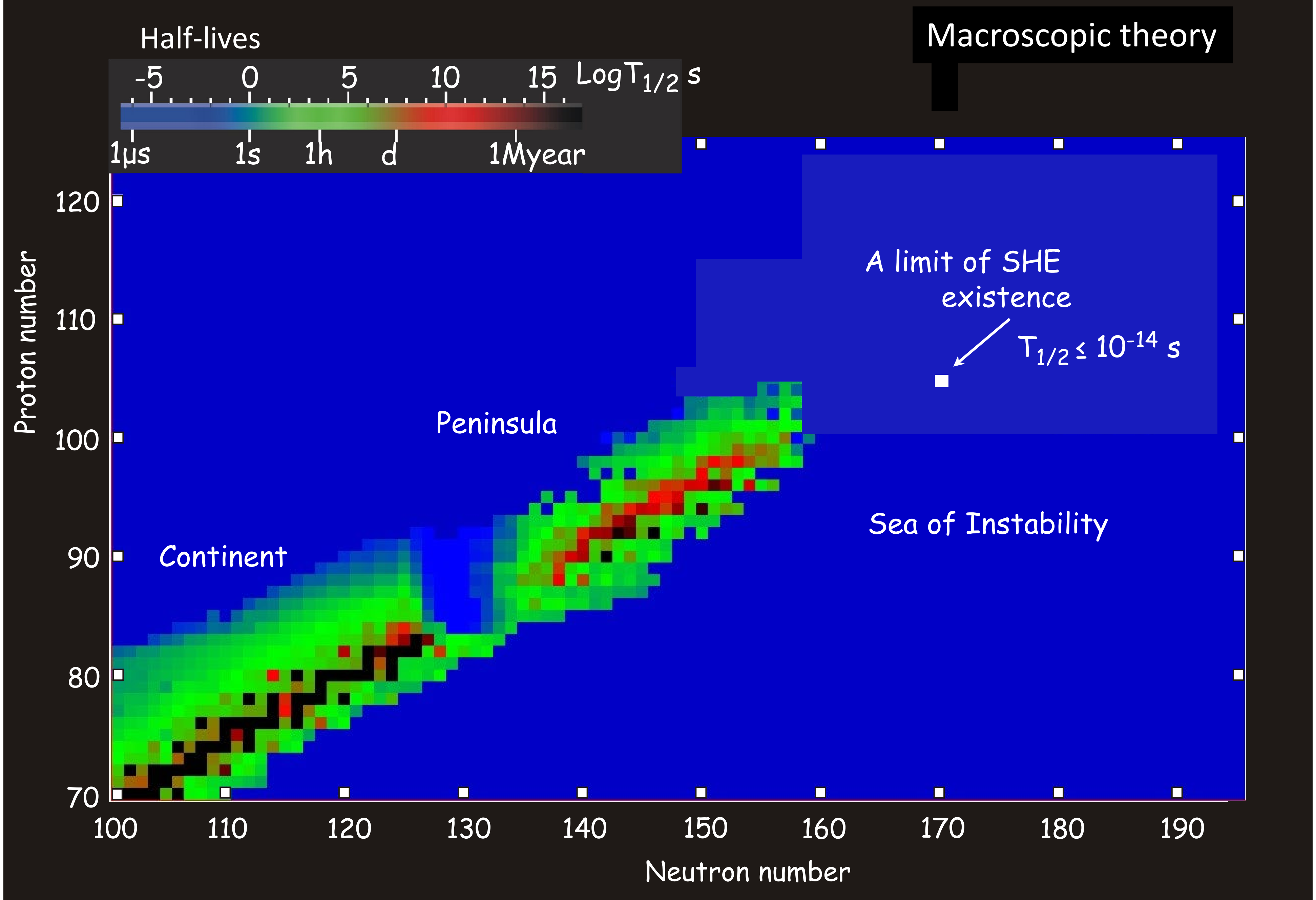
Sobiczewski A, Gareev F A and Kalinkin B N
1966 Phys. Lett. 22, 500

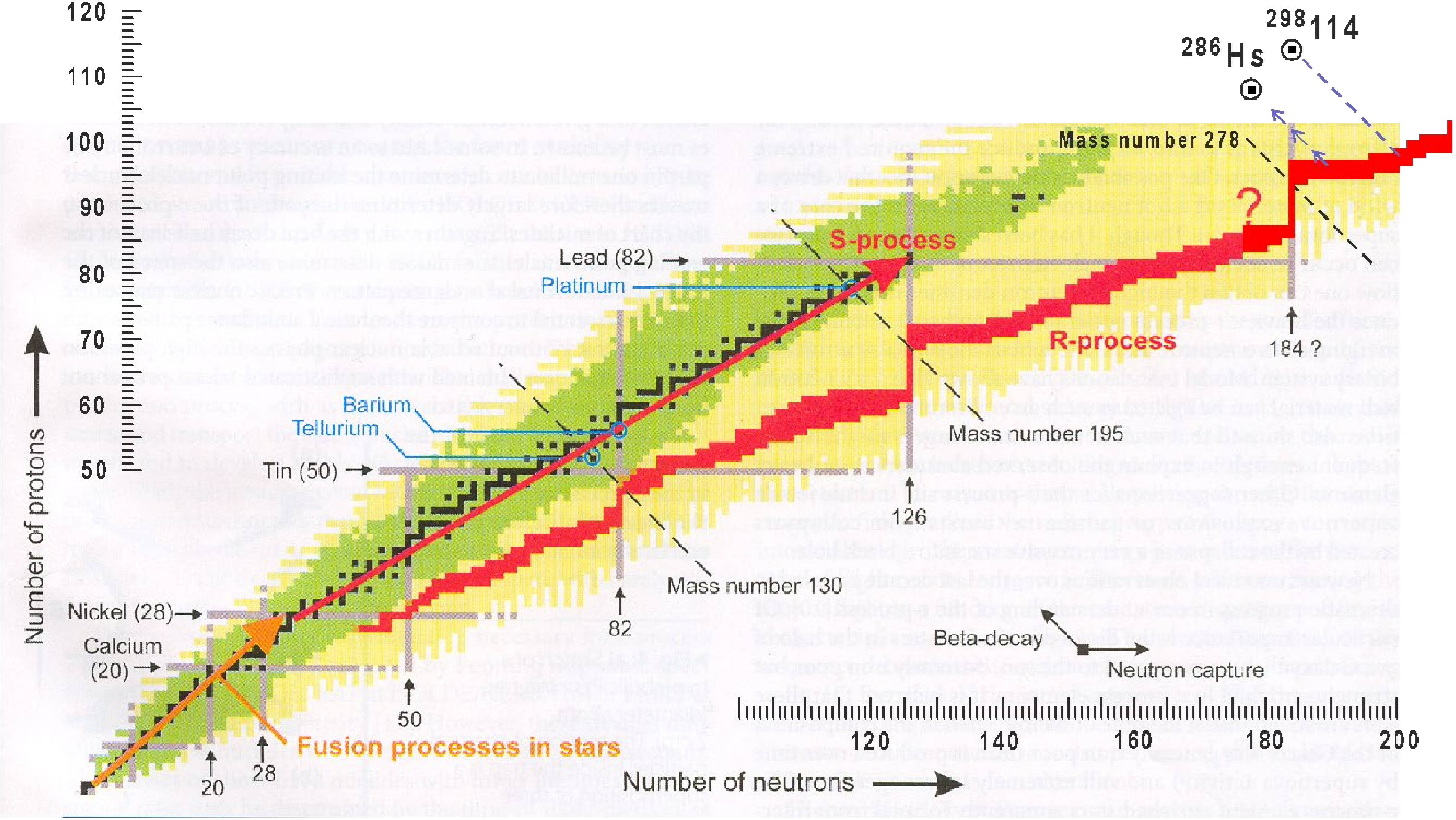
Reactions of Synthesis:
Hot fusion

This picture was created in 1966



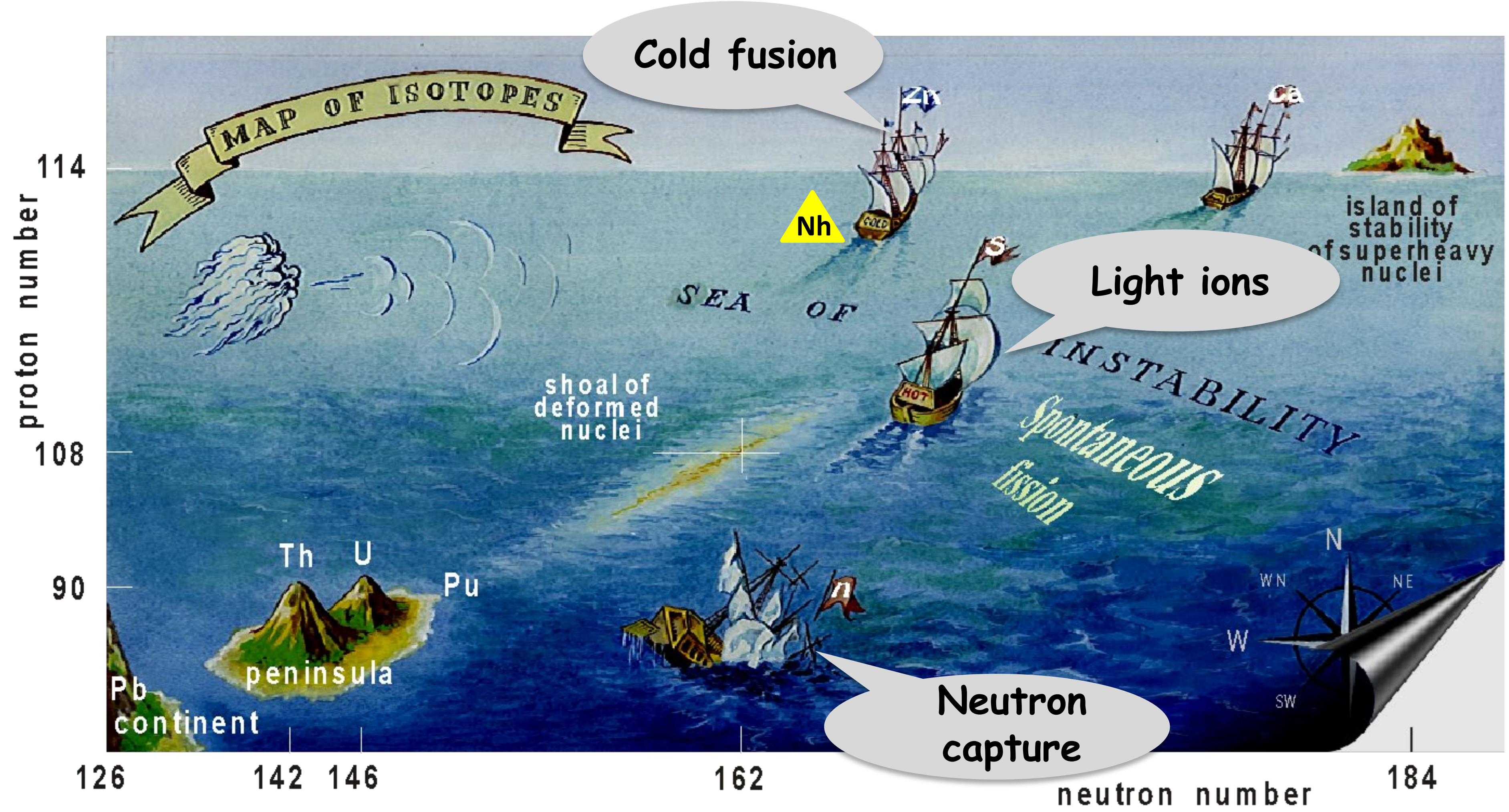
But artificial elements began to be synthesized since 1940


Macroscopic theory
Half-lives
-5 0 5 10 15 LogT1/2 s
1μs 1s 1h d 1Myear
A limit of SHE existence
T1/2 ≤ 10-14 s
Peninsula
Sea of Instability
Continent
Proton number
120
110
100
90
80
70
100 110 120 130 140 150 160 170 180 190
Neutron number

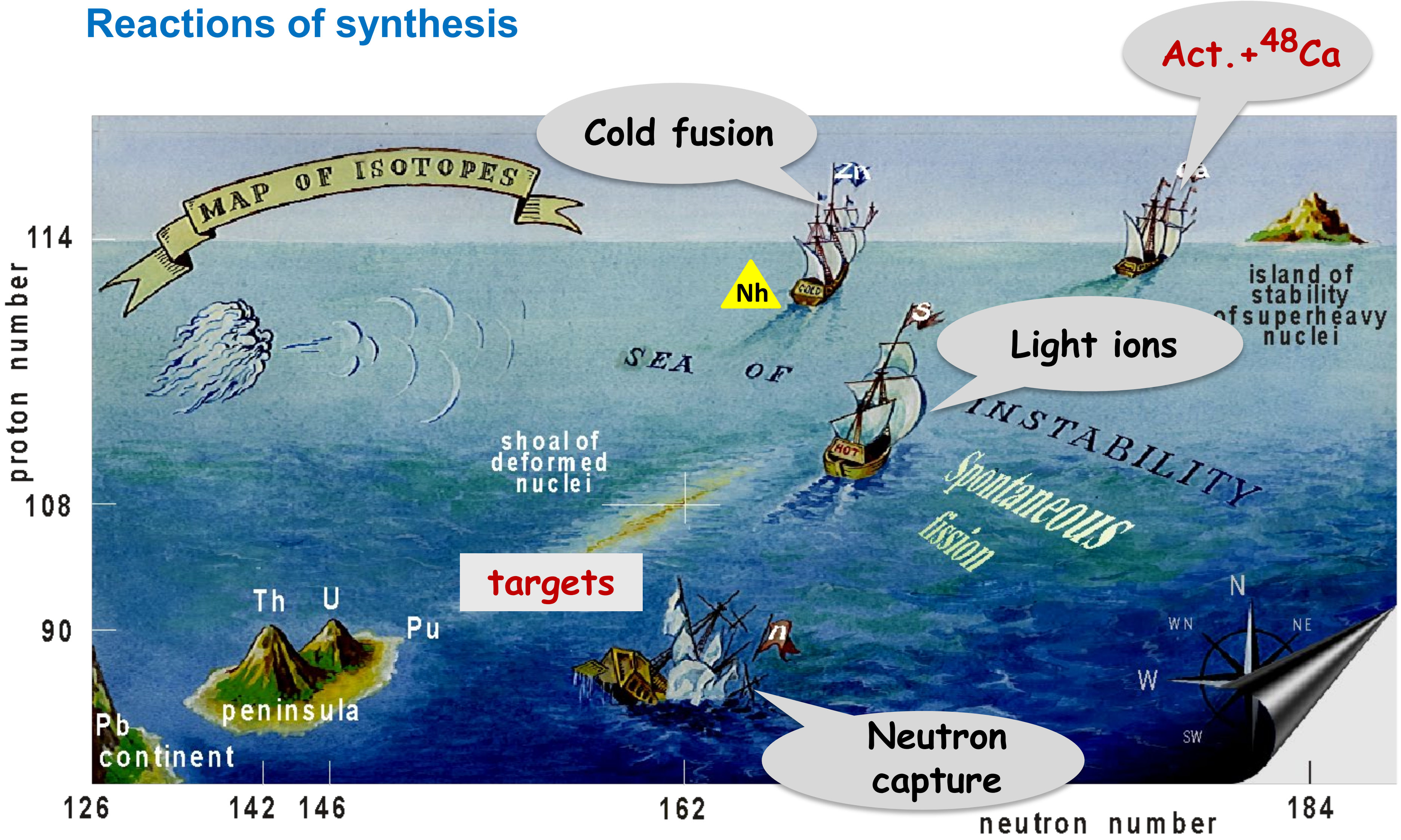


Yuri Oganessian. International Conference “Heaviest Nuclei and Atoms” Apr.25-30, 2023, Yerevan

Reactions of synthesis



Reactions of synthesis

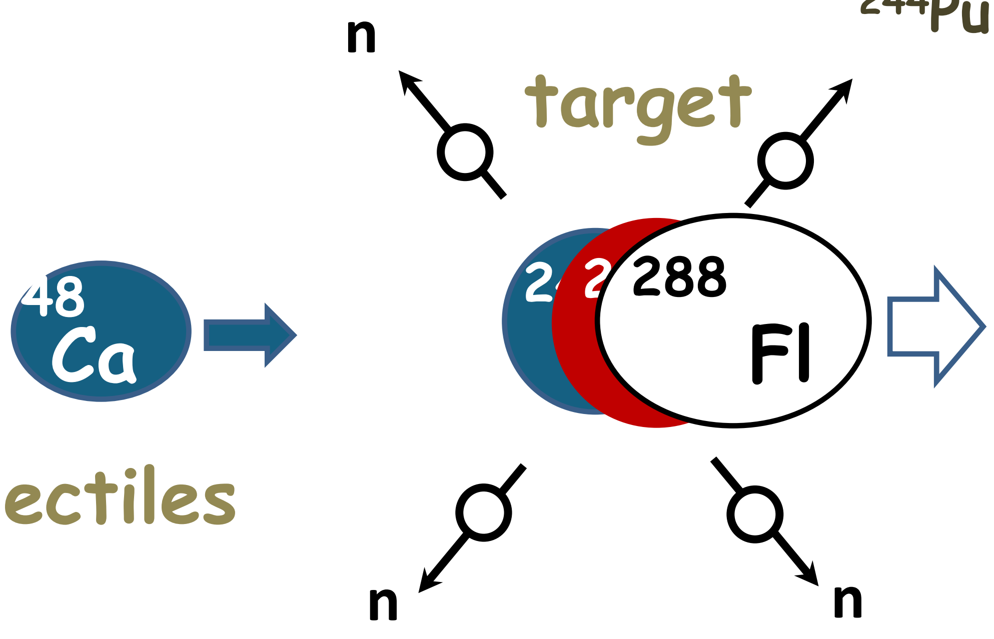


Reaction of synthesis

everything happens in a hydrogen medium at 1 torr

artificial element made in high flux nuclear reactor, ^{244}Pu, ^{248}Cm, ^{249}Bk ...

from accelerator

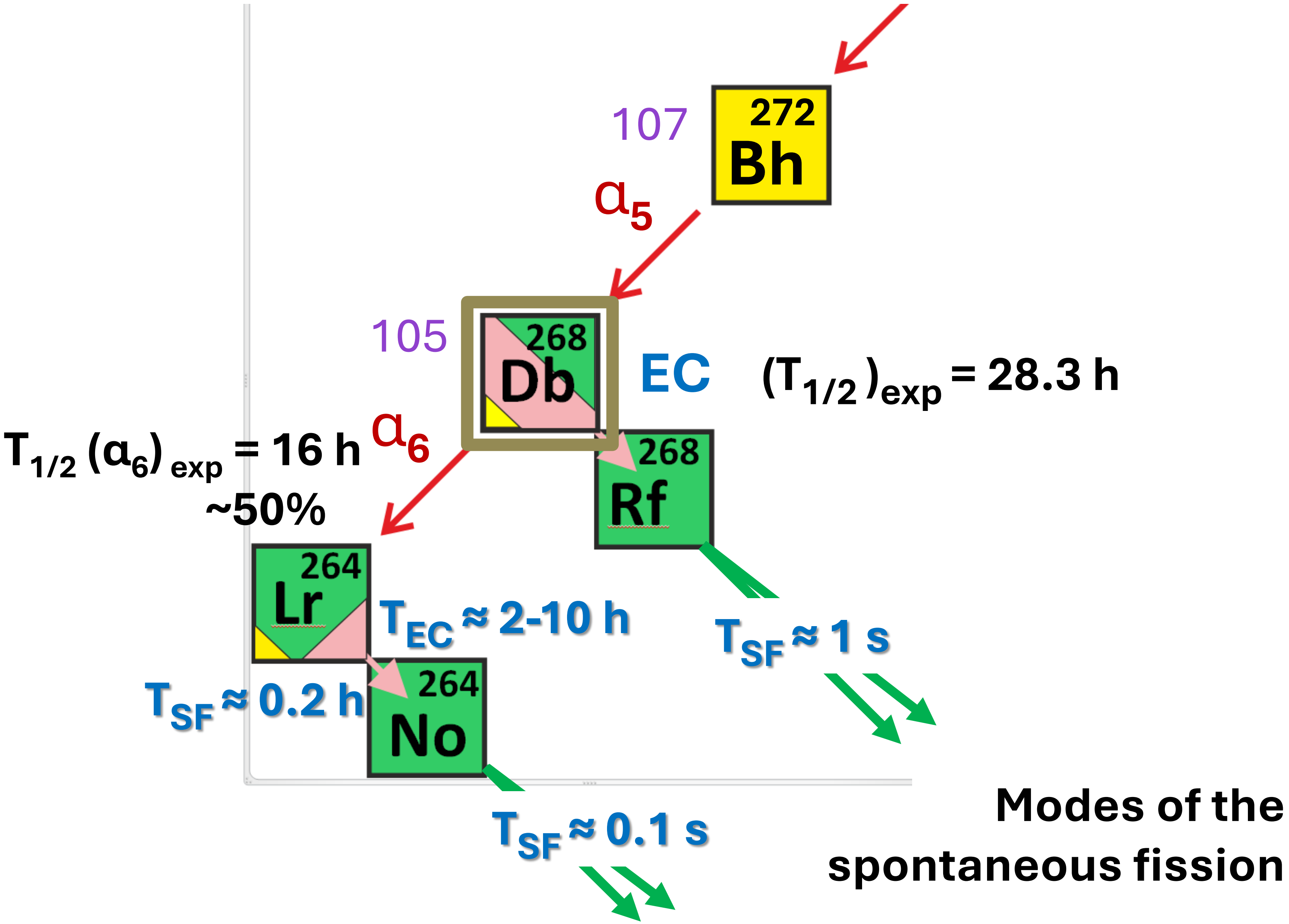


to separator

projectiles

rare and very expensive isotope of Ca

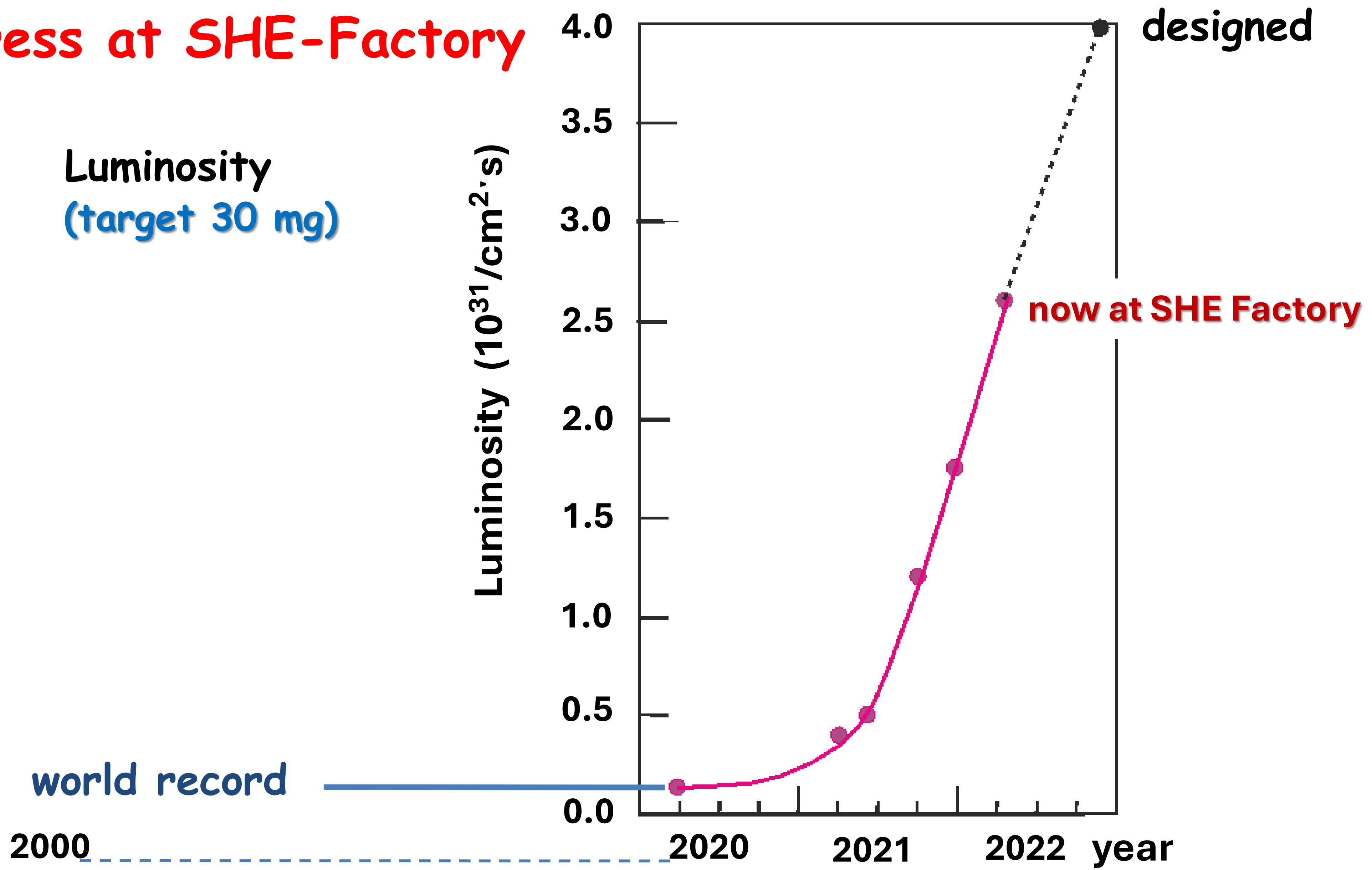
fusion & cooling



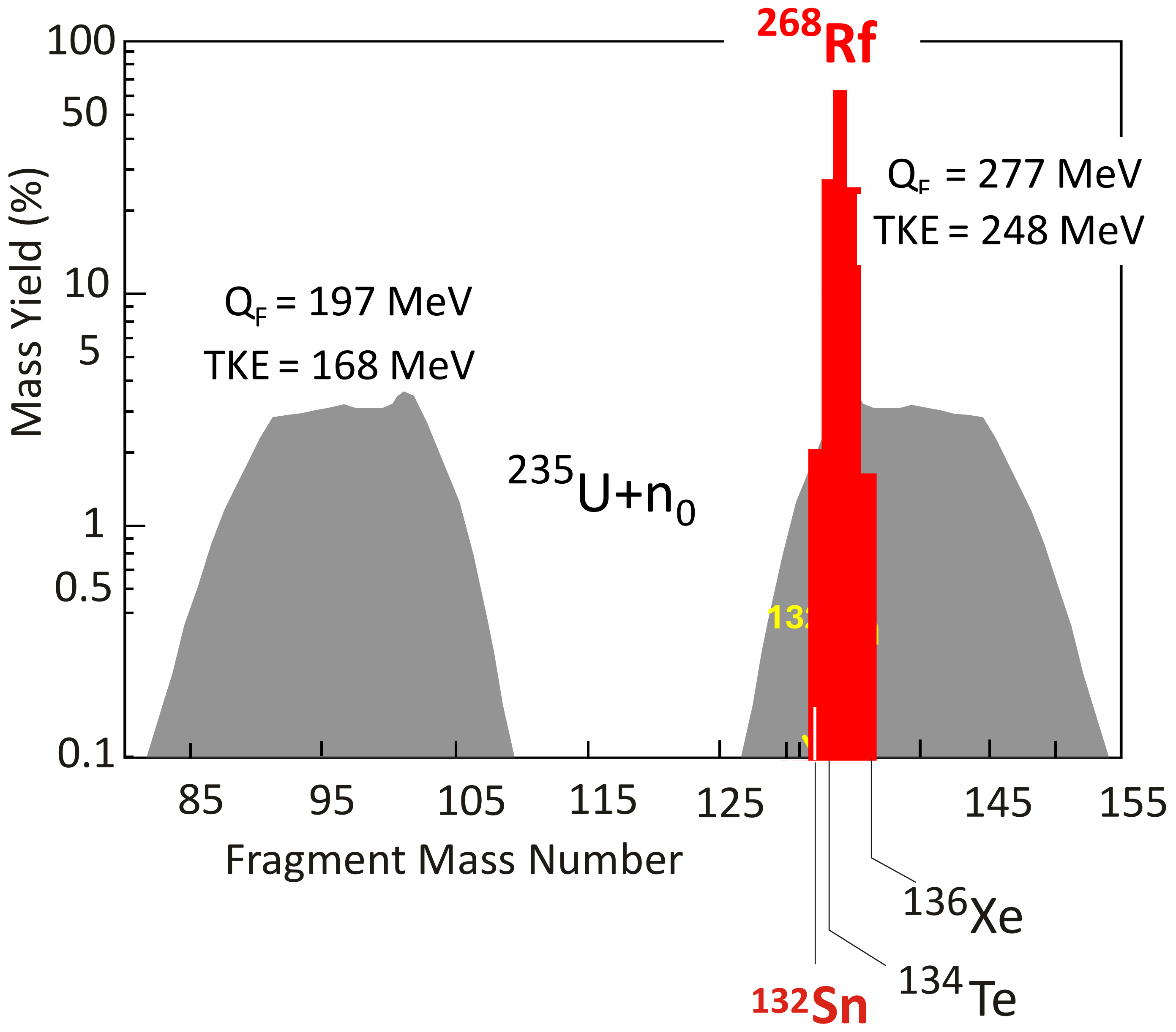
107
272
Bh
α5
105
268
Db
EC
(T1/2)exp = 28.3 h
T1/2 (α6) exp = 16 h
α6
~50%
268
Rf
264
Lr
TEC ≈ 2-10 h
TSF ≈ 1 s
TSF ≈ 0.2 h
264
No
TSF ≈ 0.1 s
Modes of the spontaneous fission

Progress at SHE-Factory

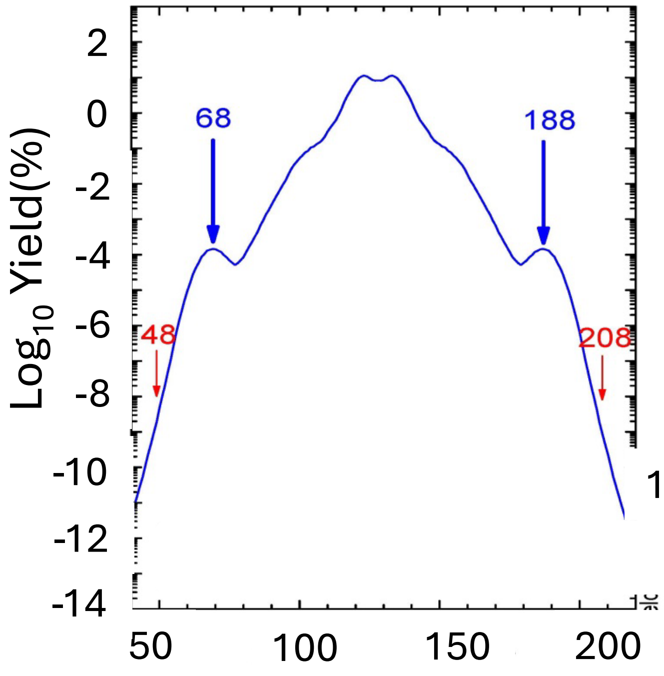
Luminosity
(target 30 mg)



Mass Distribution of the Fission Fragments

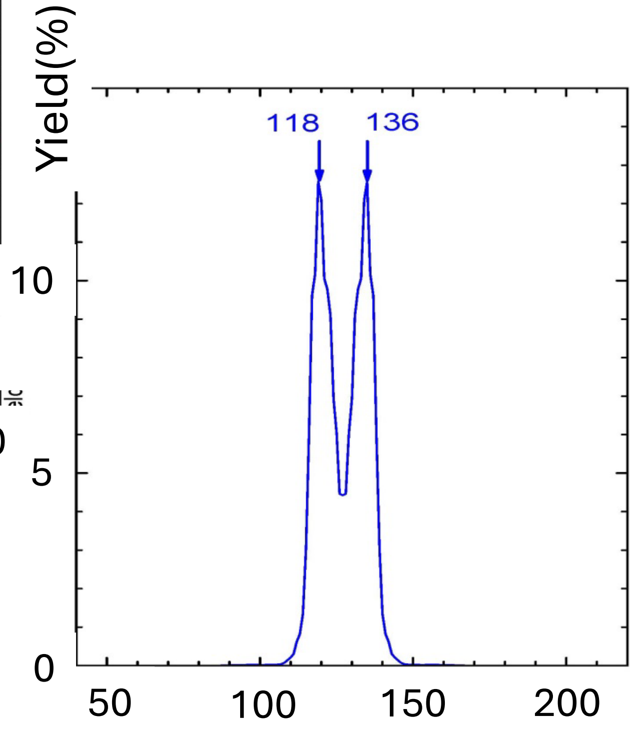


The three fission patterns of Nobelium predicted by the pre-scission model



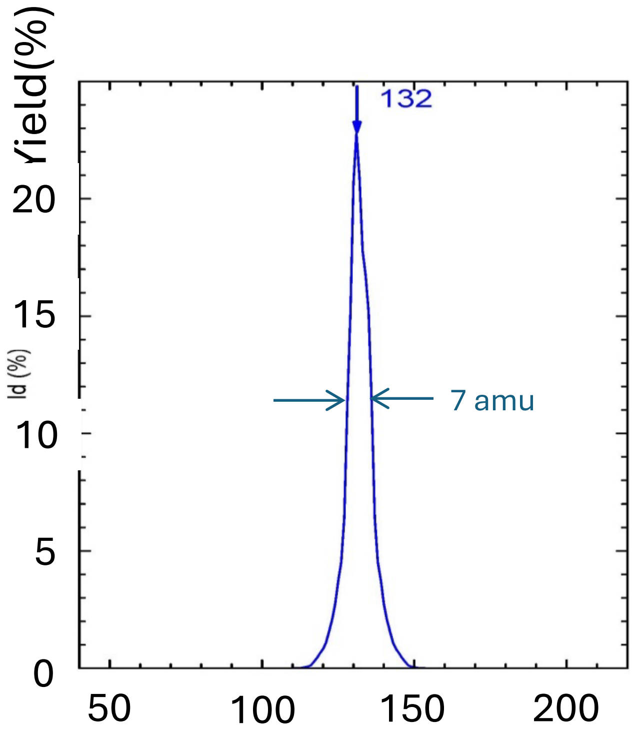
Fragment mass number

Super-asymmetric
^{256}No



Fragment mass number

Regular asymmetric
^{254}No



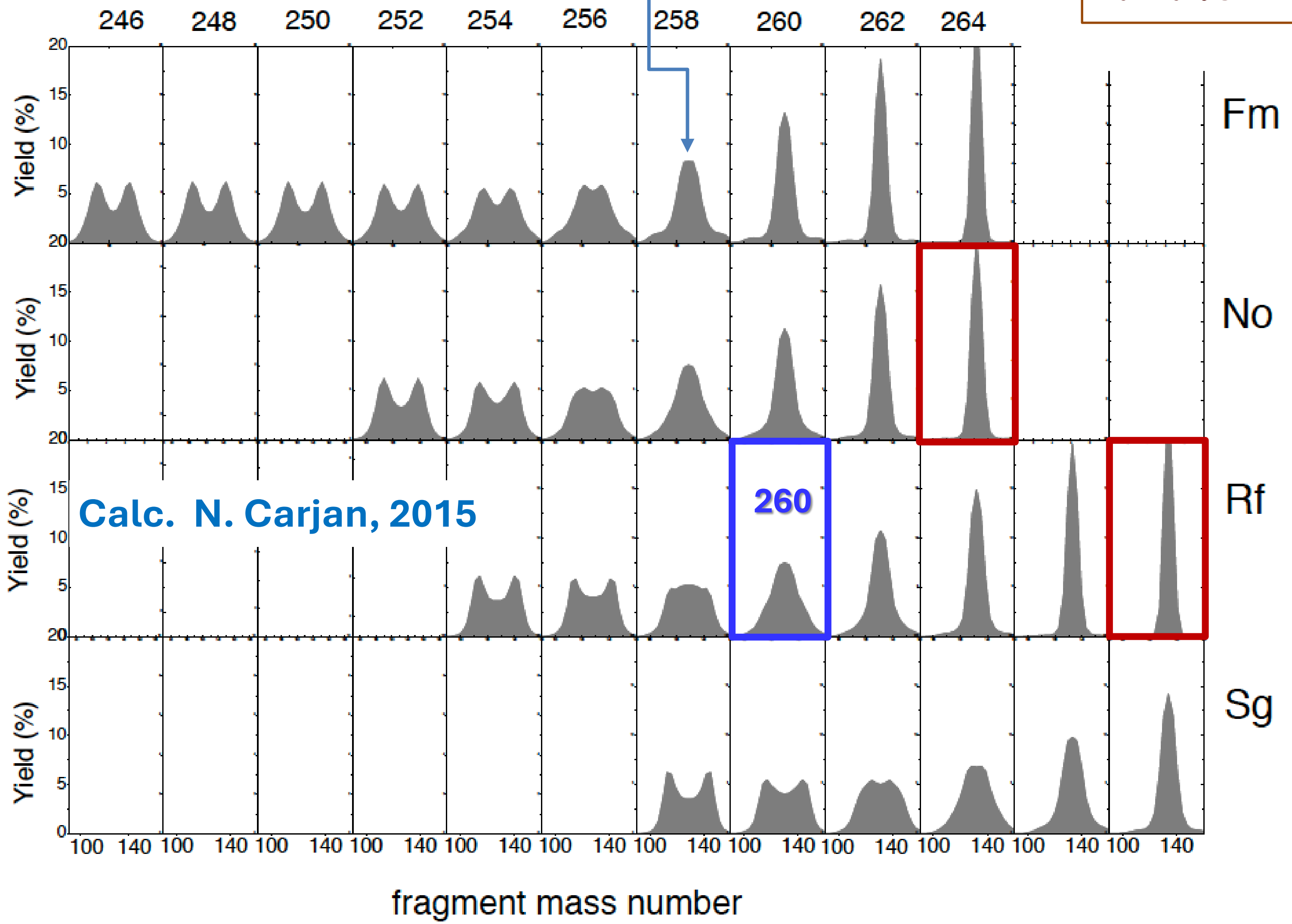
Fragment mass number

Super-symmetric
^{264}No

Discovery of mass-symmetric spontaneous fission of ^{258}Fm: Z=2x50 N=2x79

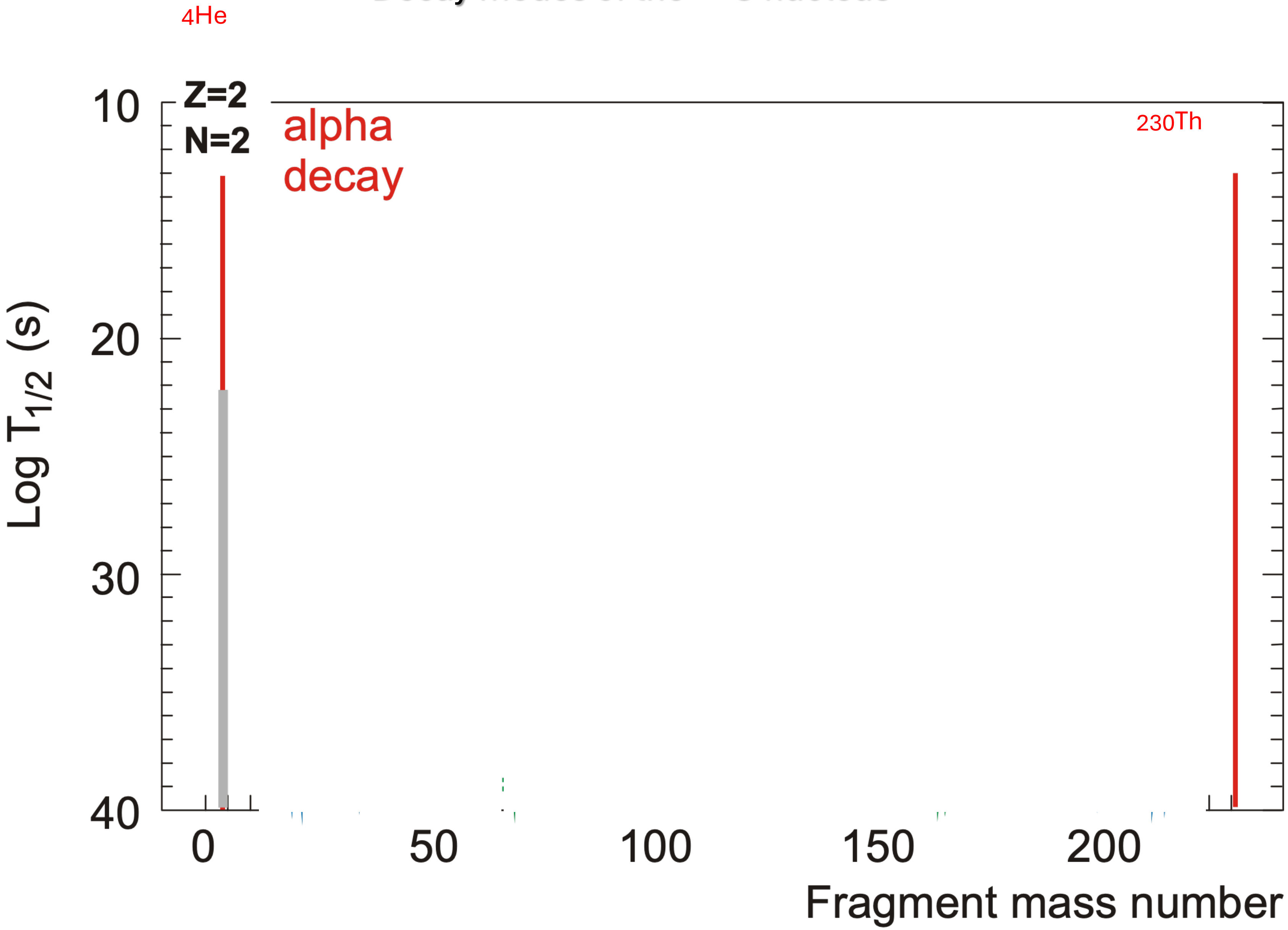
E. K. Hulet *et al.*, PRL **56**, 313 (1986)

Magic numbers Z=50 & N=82 in nuclear fission

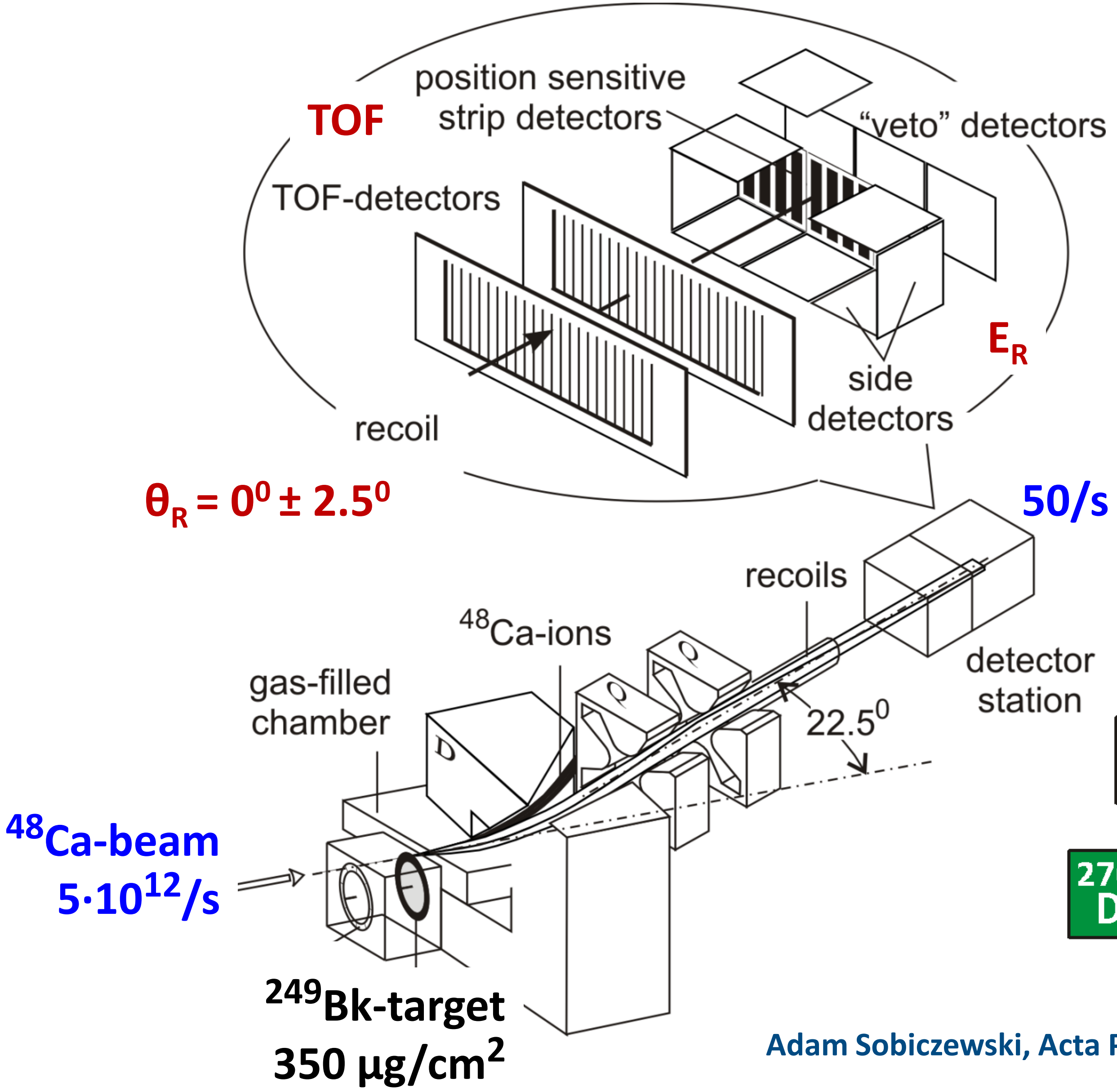


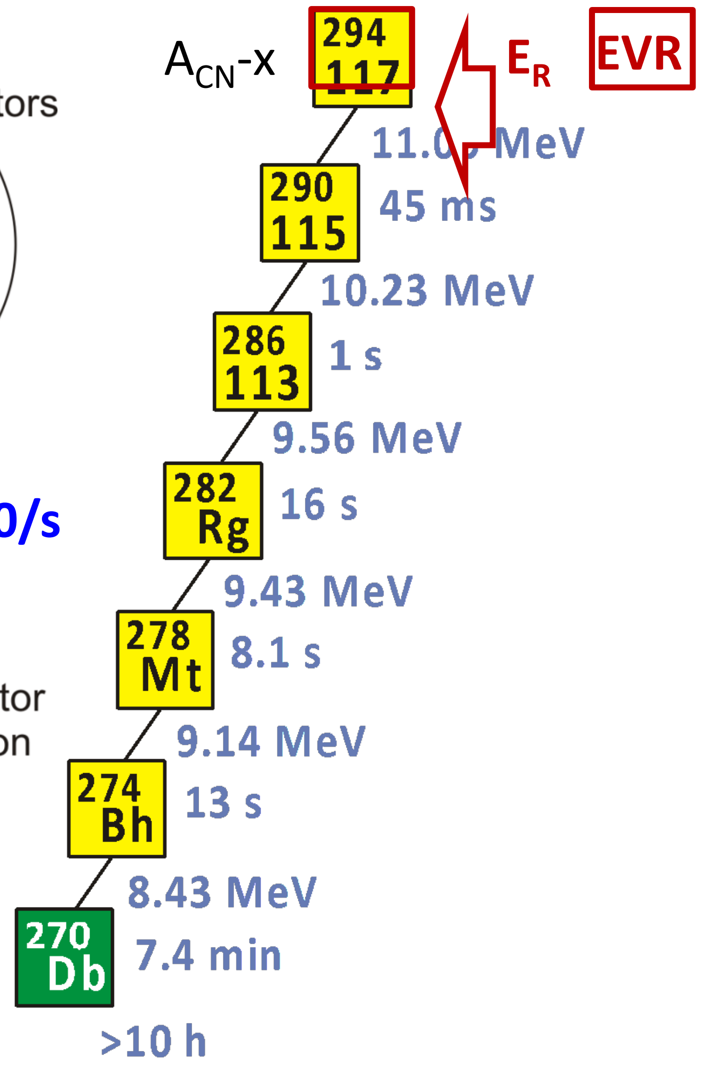
Yuri Oganessian. International Conference "Heaviest Nuclei and Atoms" Apr.25-30, 2023, Yerevan

Decay modes of the ^{234}U nucleus



Dubna Gas-Filled Recoil Separator



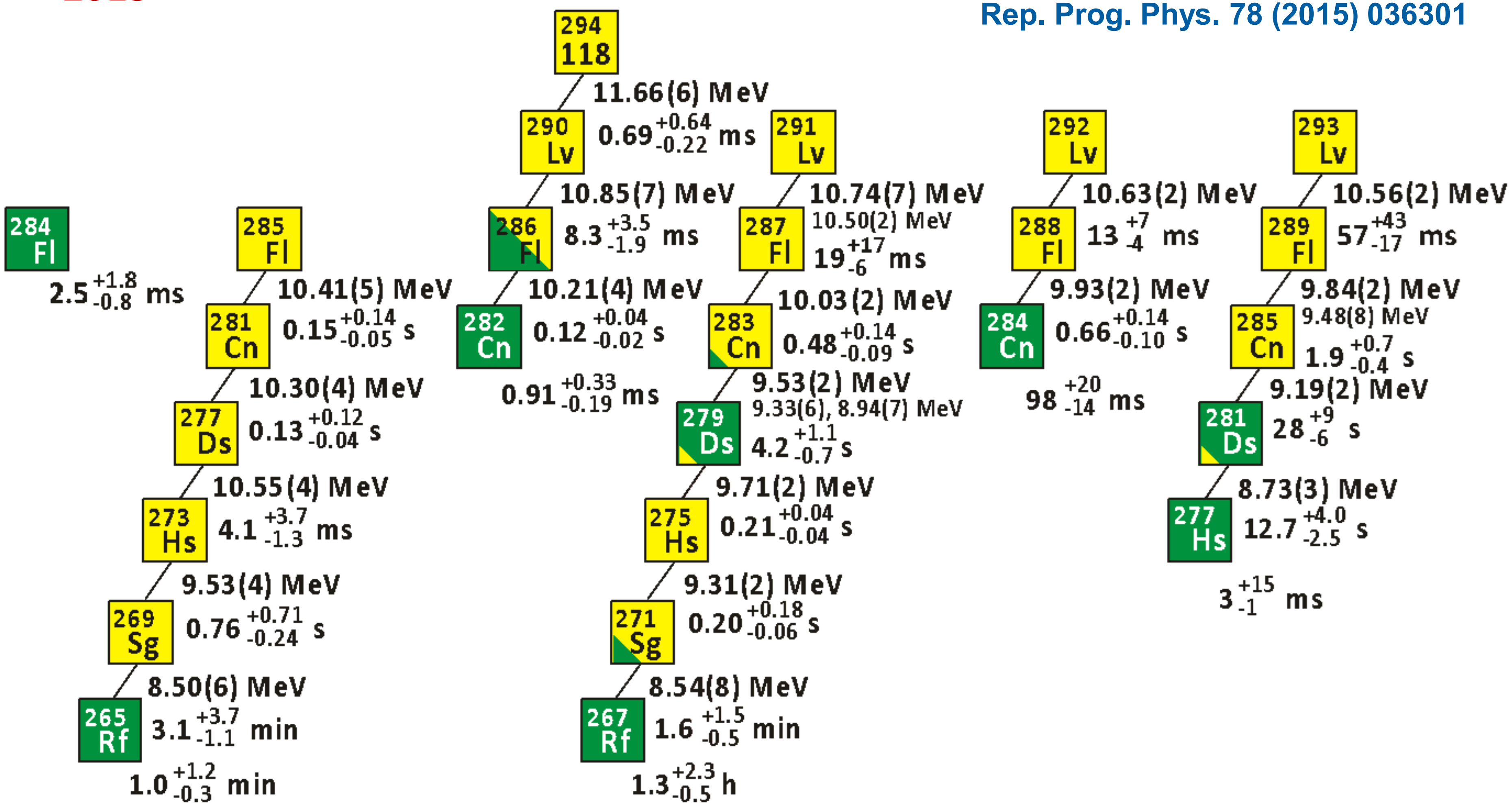


Adam Sobiczewski, Acta Phys. Pol. B 41, 157 (2010).

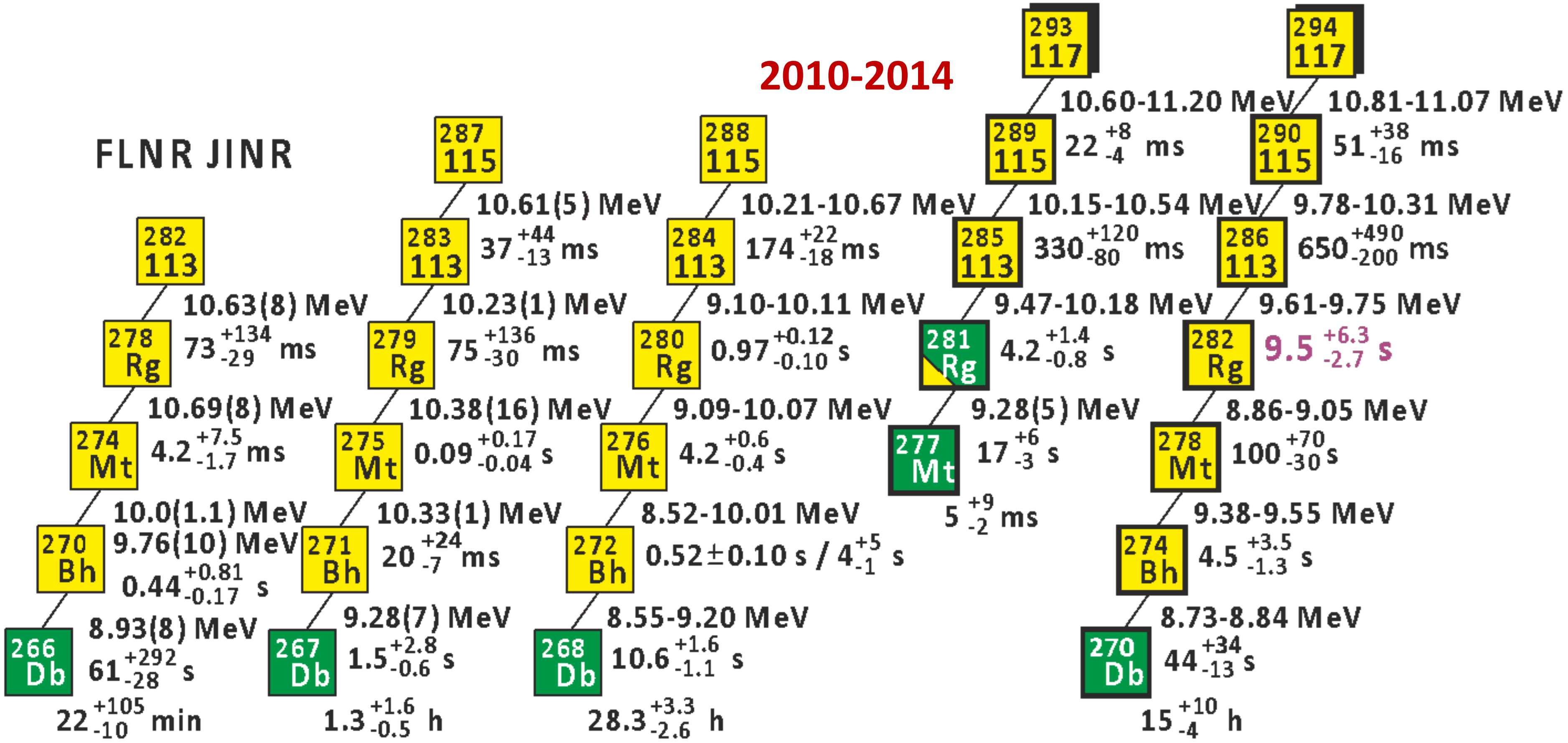
Summary decay properties of the Z-even isotopes observed in ^{238}U, ^{240,242,244}Pu, ^{245,248}Cm and ^{249}Cf + ^{48}Ca reactions

2015

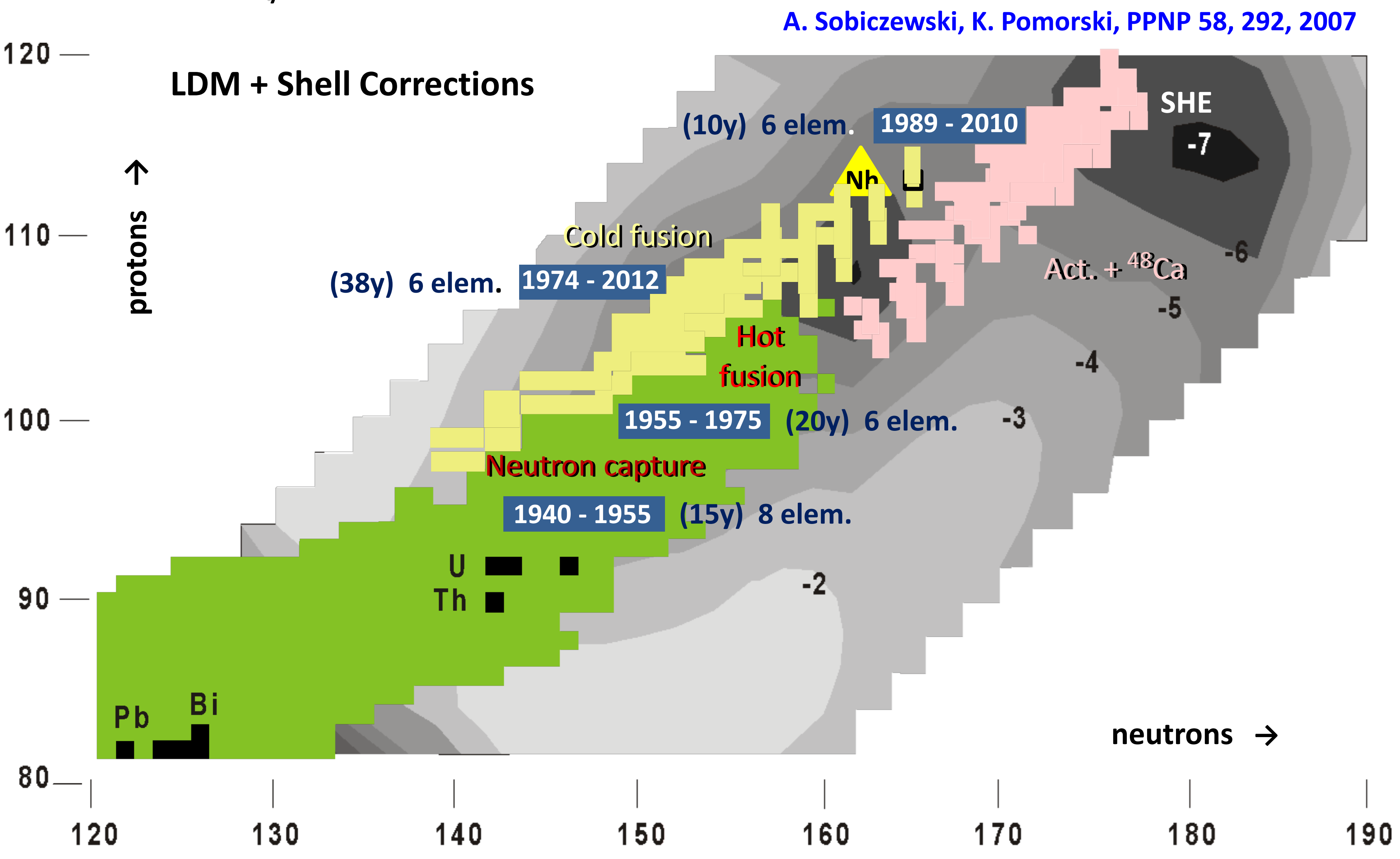
Yu Ts Oganessian and V K Utyonkov, Rep. Prog. Phys. 78 (2015) 036301

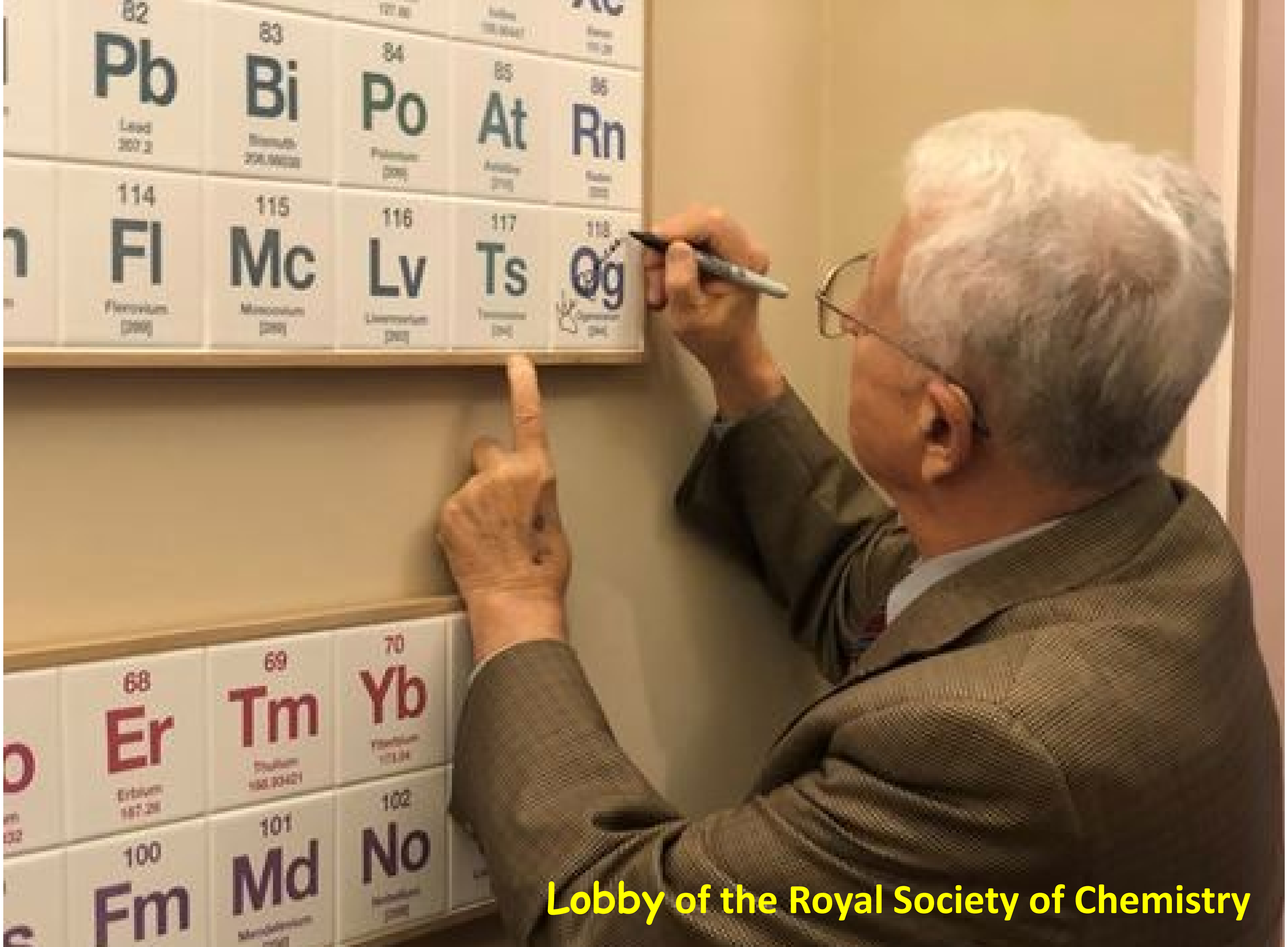


Summary decay properties of the isotopes of elements 113, 115, and 117 observed in ^{237}**Np**, ^{243}**Am** and ^{249}**Bk** + ^{48}**Ca** reactions



Reactions of Synthesis



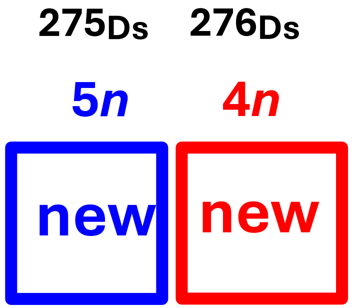


Lobby of the Royal Society of Chemistry

$^{232}Th + ^{48}Ca \rightarrow ^{280}Ds^*$

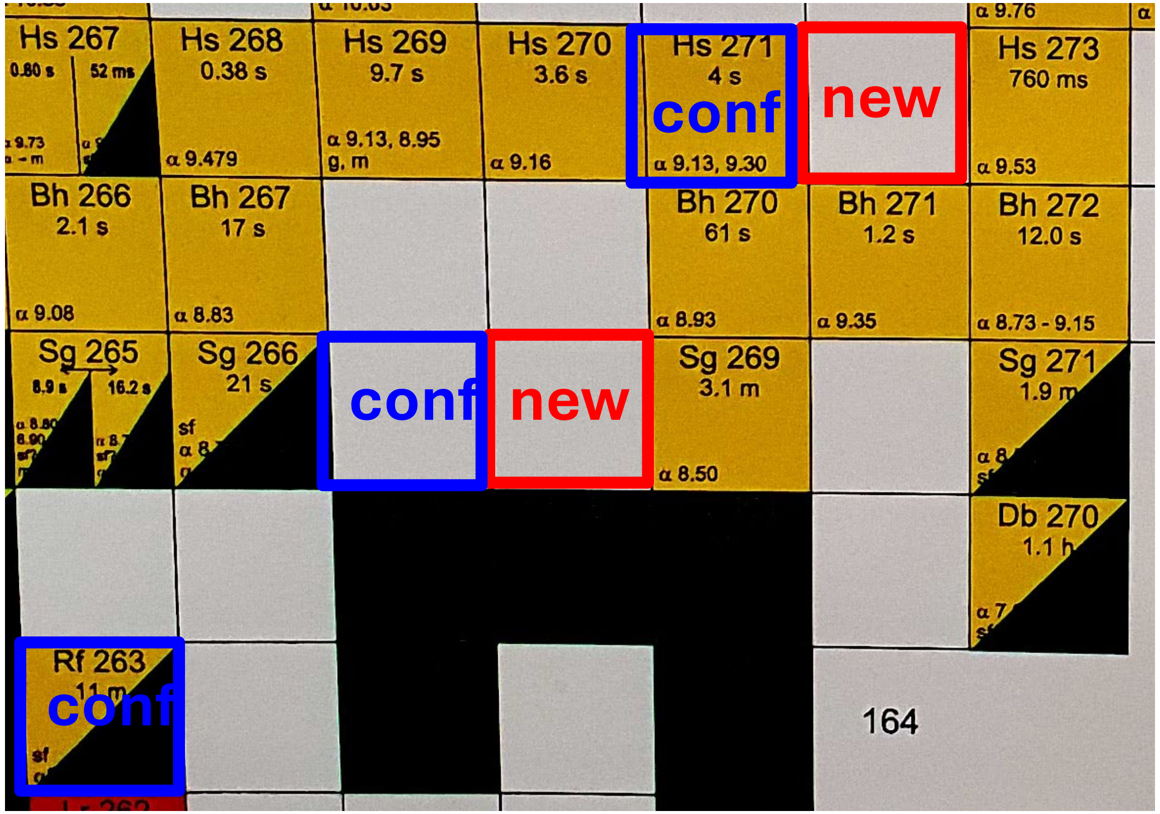
New nuclei ^{276}Ds, ^{272}Hs, ^{268}Sg

New isotope ^{275}Ds, confirmation for ^{271}Hs, ^{267}Sg, and ^{263}Rf



First observation of transition to the mainland

Yuri Oganessian. International Conference "Heaviest Nuclei and Atoms" Apr.25-30, 2023, Yerevan



125 new decay chains
New isotopes
Connect to mainland

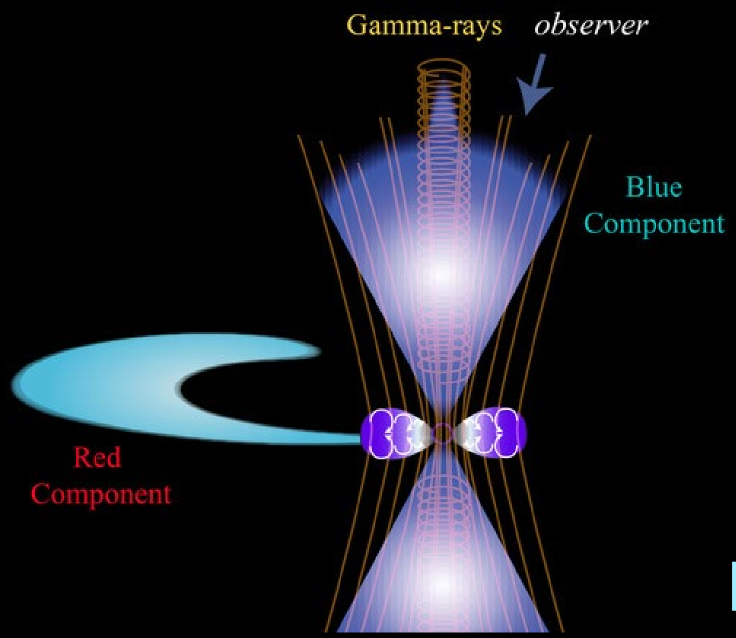
Bomb debris from environmental tests of nuclear weapons

Fission: LLNL – DUBNA – AANL

Ru, Rh, Pd, Ag

	Ranking of 10 longest-lived isotopes:	
	106Ru	374 days
	103Ru	39 days
	111Ag	7.45 d
	105Rh	
	112 Pd	
	109 Pd	
	113 Ag	
	105 Ru	
	112Ag	
	111Pd	
	107Rh	

Conclusion: Superheavies are probably made in the r-process!



Did the merger indeed make the actinides?
How far did the nucleosynthesis go?
What is the role of fission ?
What type of fission?

Fission (?): LLNL – ND- LBNL-JINR

Bomb debris from environmental tests of nuclear weapons
NIF experiments
LBL

Thank you for your attention!

UNIVERSITY OF NOTRE DAME