19th Russbach School on Nuclear Astrophysics
March 6, 2024

Superheavy elements, Fission, R-process

Ani Aprahamian
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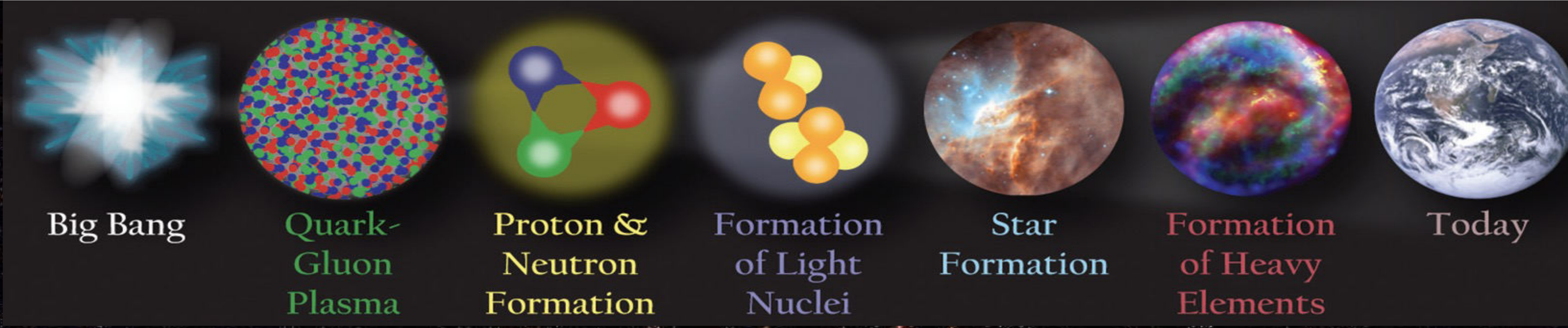
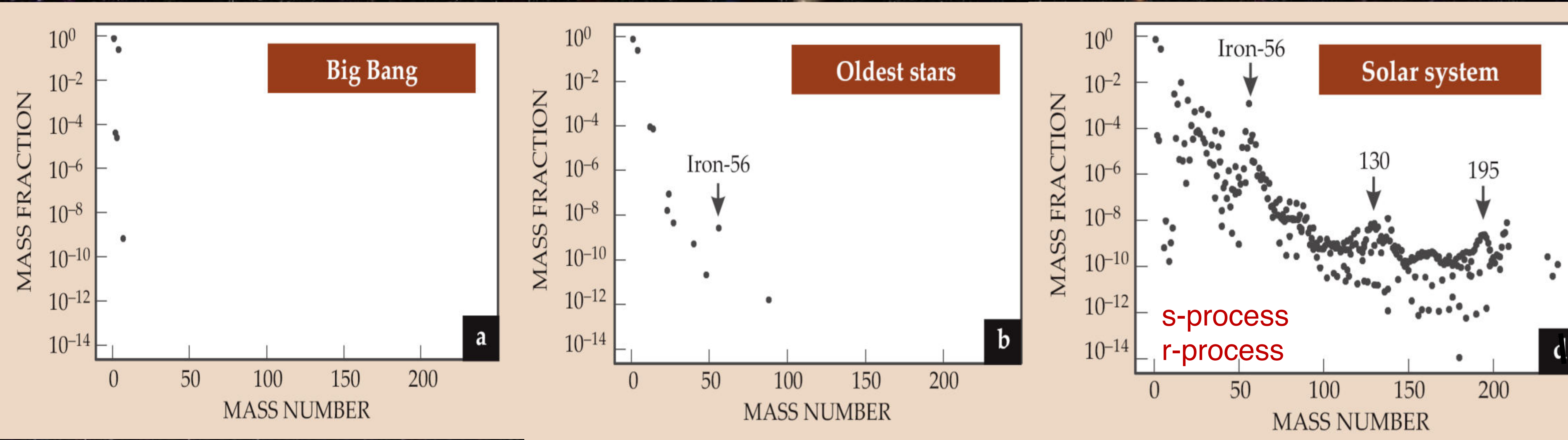
Notre Dame, IN (USA)

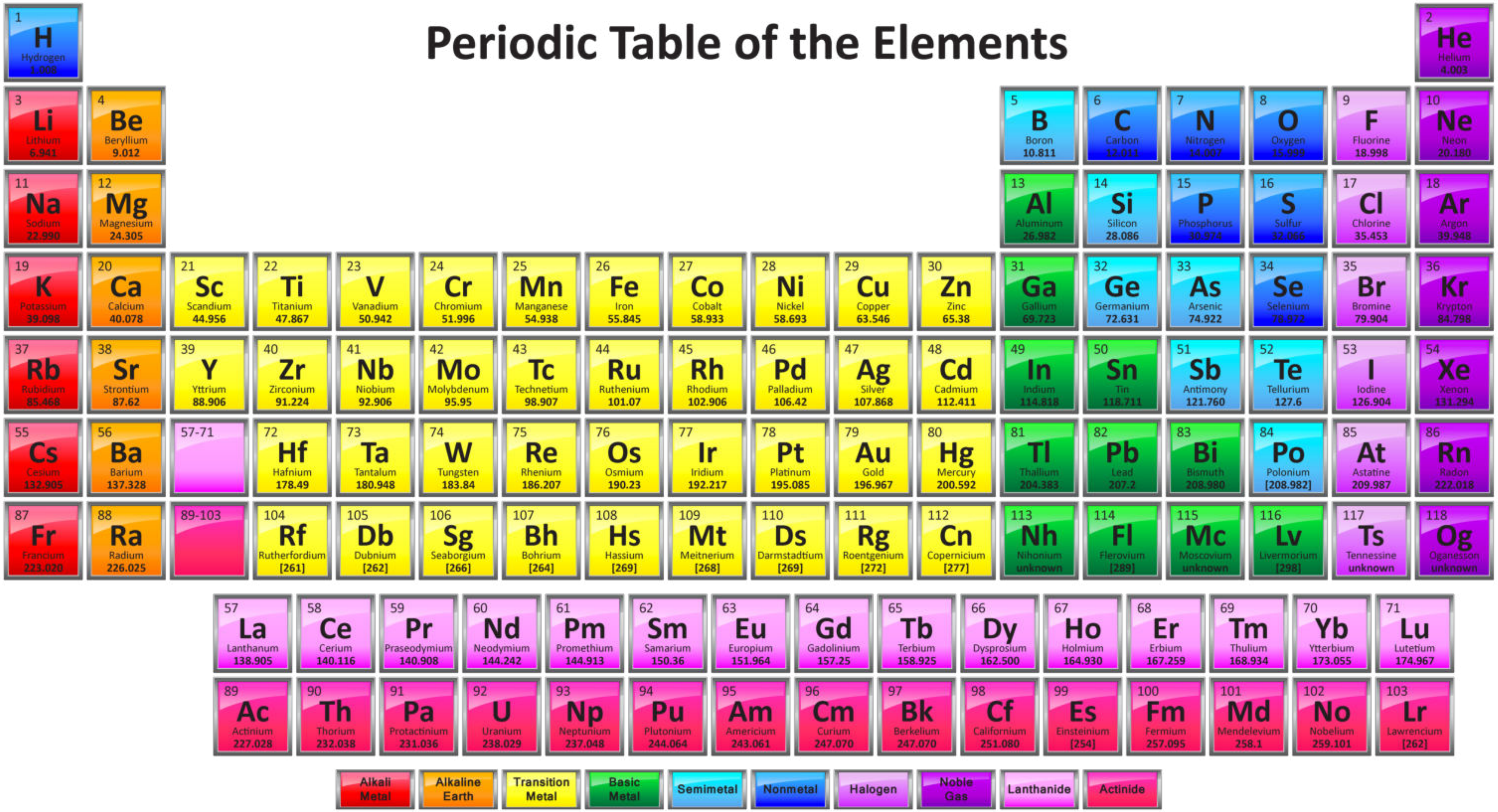
JINA-CEE



- How were elements Fe to U made?

Wiescher
Schatz



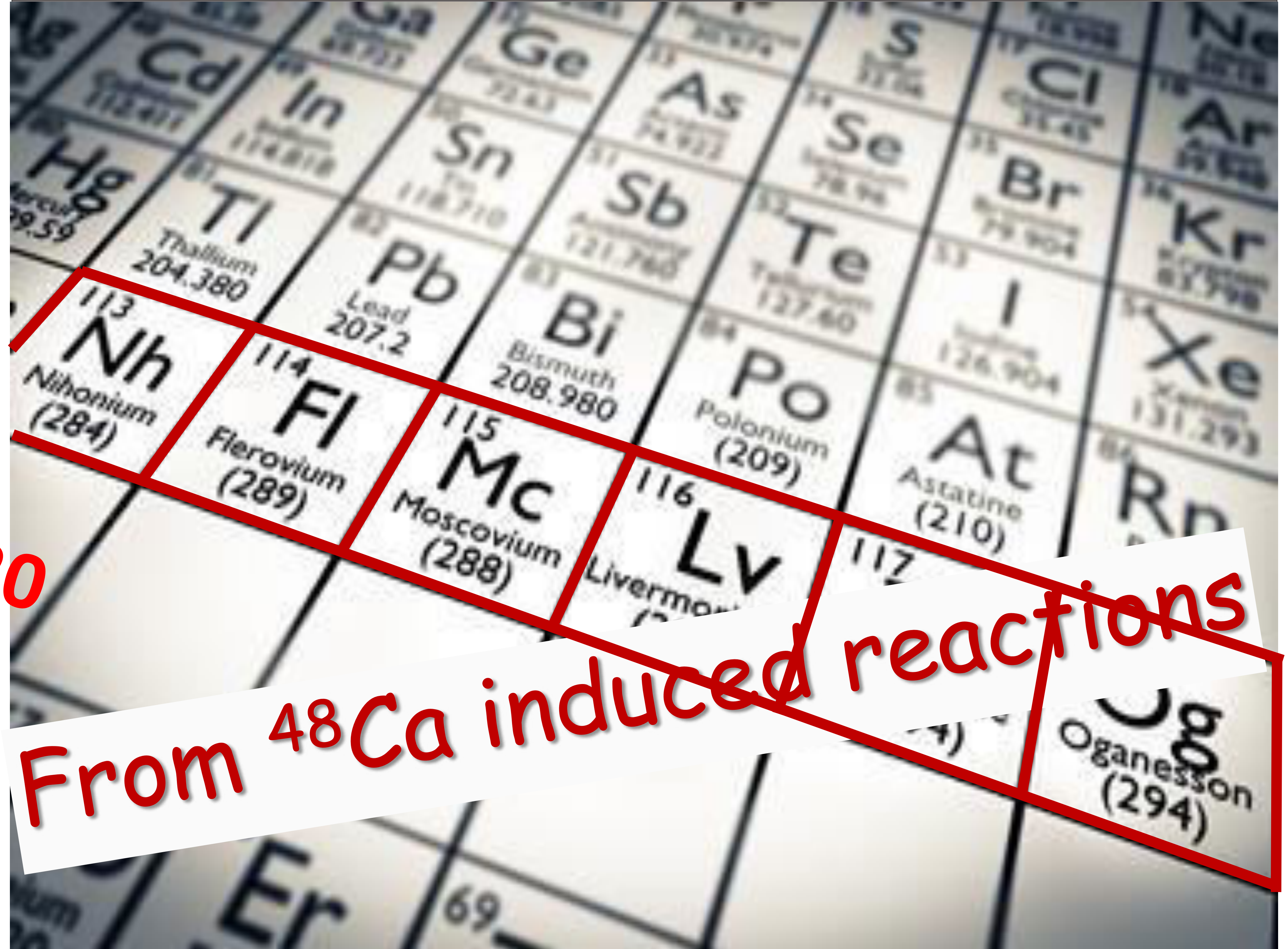


What are the heaviest elements made?

Are there more elements?


104
Rf
105
Db
106
Sg
Rutherfordium
1964
Target Pu, Cf
Dubnium
1970
Target Bk, Cf
Seaborgium
1974
Target Cf
113
Nh
114
Fl
115
Mc
116
Lv
117
Ts
118
Og
Nihonium
2004
Target Am
(decay from 115)
Flerovium
2000
Target Pu
Moscovium
2004
Target Am
Livermorium
2005
Target Cm
Tennessine
2010
Target Bk
Oganesson
2006
Target Cf
Kit
Chapman
SUPERHEAVY
Making and Breaking the Periodic Table
BLOOMSBURY

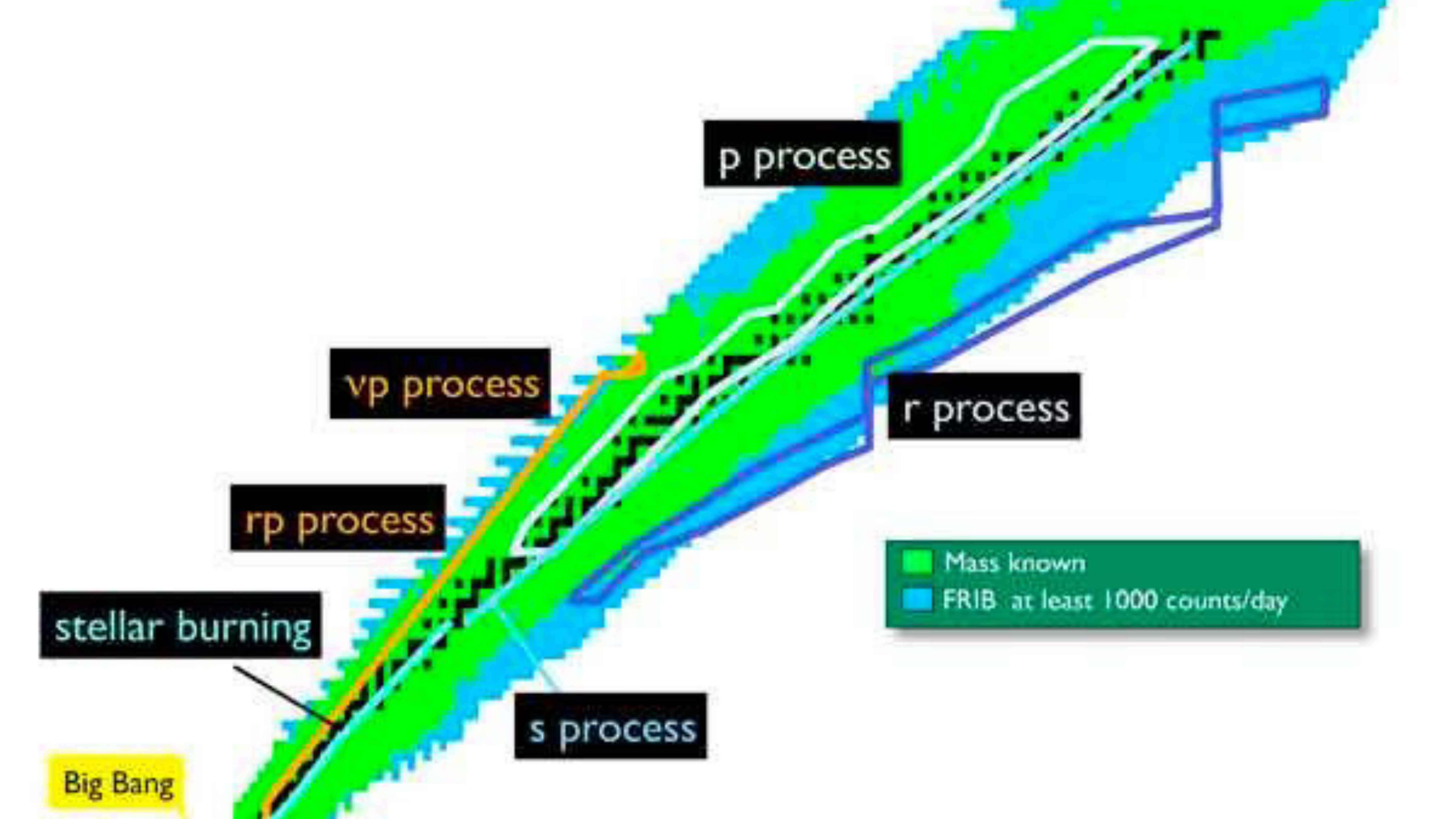
Collaboration
LLNL
JINR
ORNL



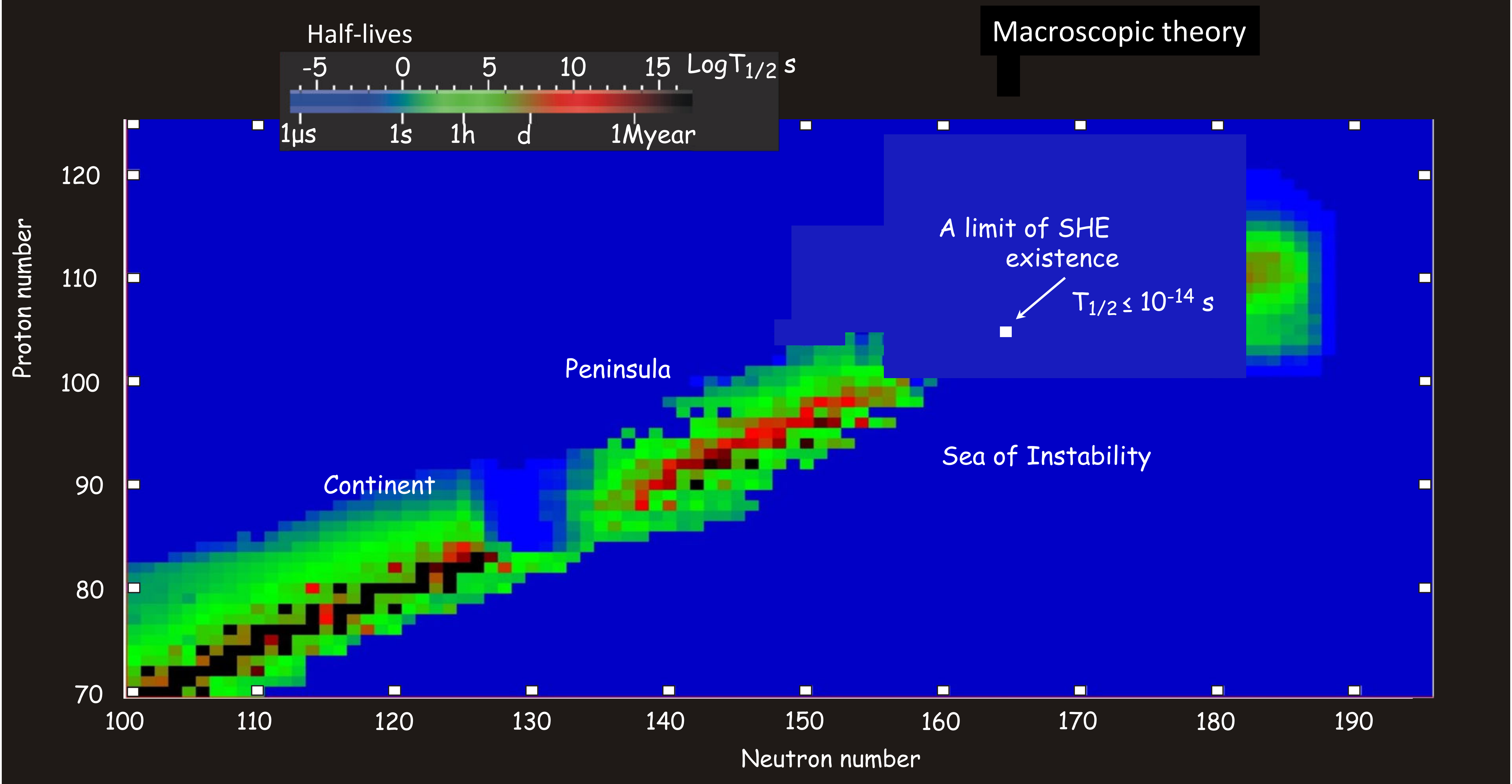
Z=120

From ^{48}Ca induced reactions

Z=174



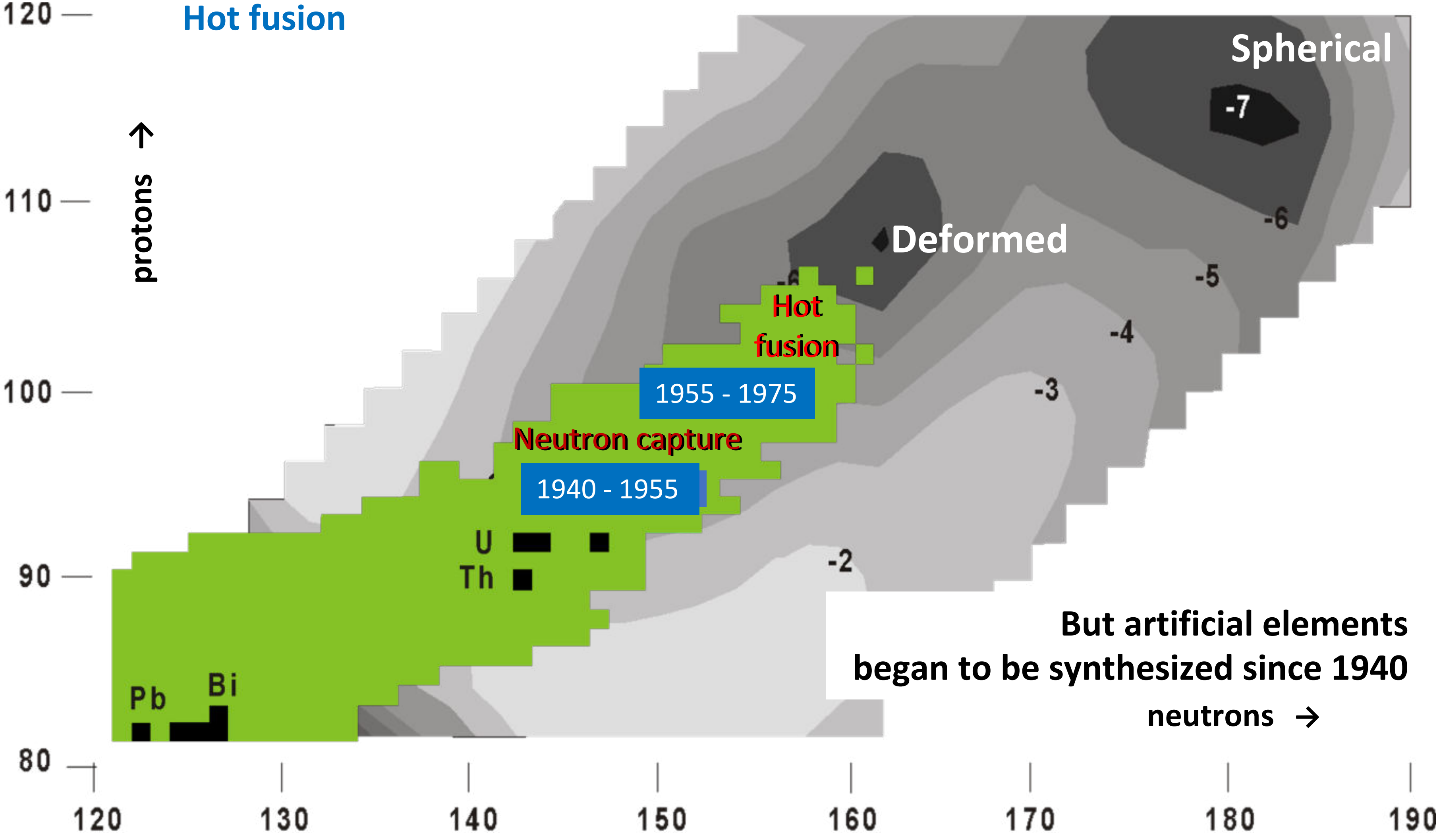
p process
νp process
r process
rp process
stellar burning
s process
Big Bang
Mass known
FRIB at least 1000 counts/day



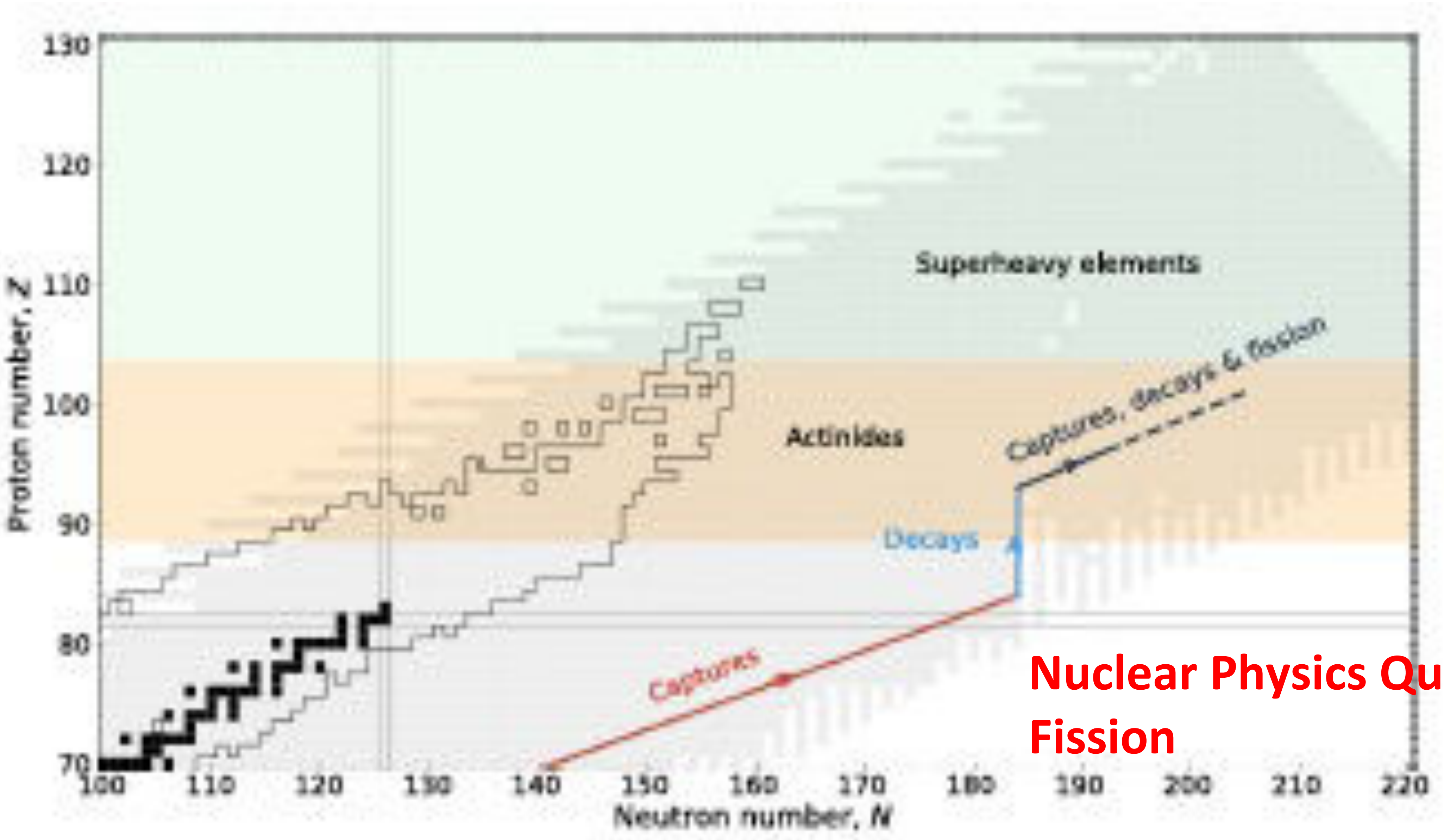
Macroscopic theory
Half-lives
-5 0 5 10 15 LogT1/2 s
1μs 1s 1h d 1Myear
A limit of SHE existence
T1/2 ≤ 10-14 s
Peninsula
Continent
Sea of Instability
Proton number
Neutron number
120
110
100
90
80
70
100 110 120 130 140 150 160 170 180 190

Reactions of Synthesis:
Hot fusion

This picture was created in 1966



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



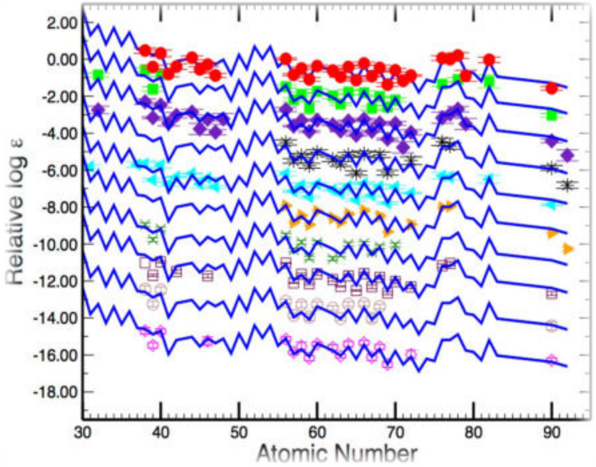
Nuclear Physics Question: Fission

Were the Superheavy elements made in the r-process?

Cowan et al. 2011

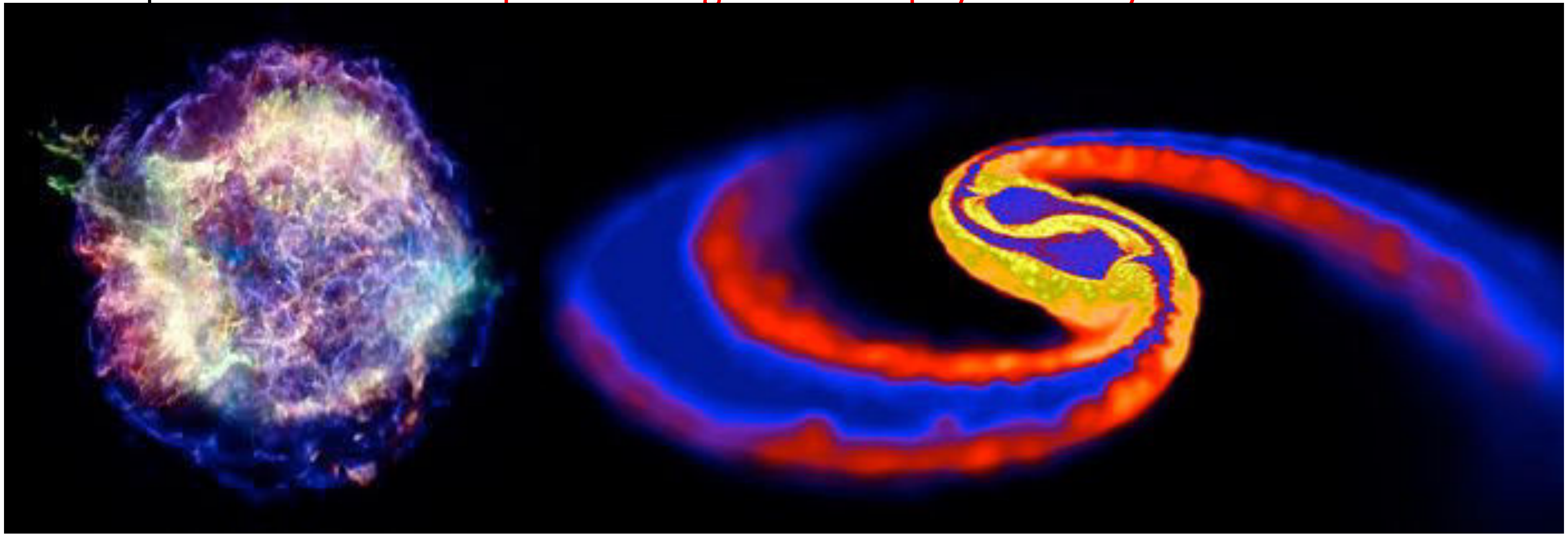
Explosive

r-process

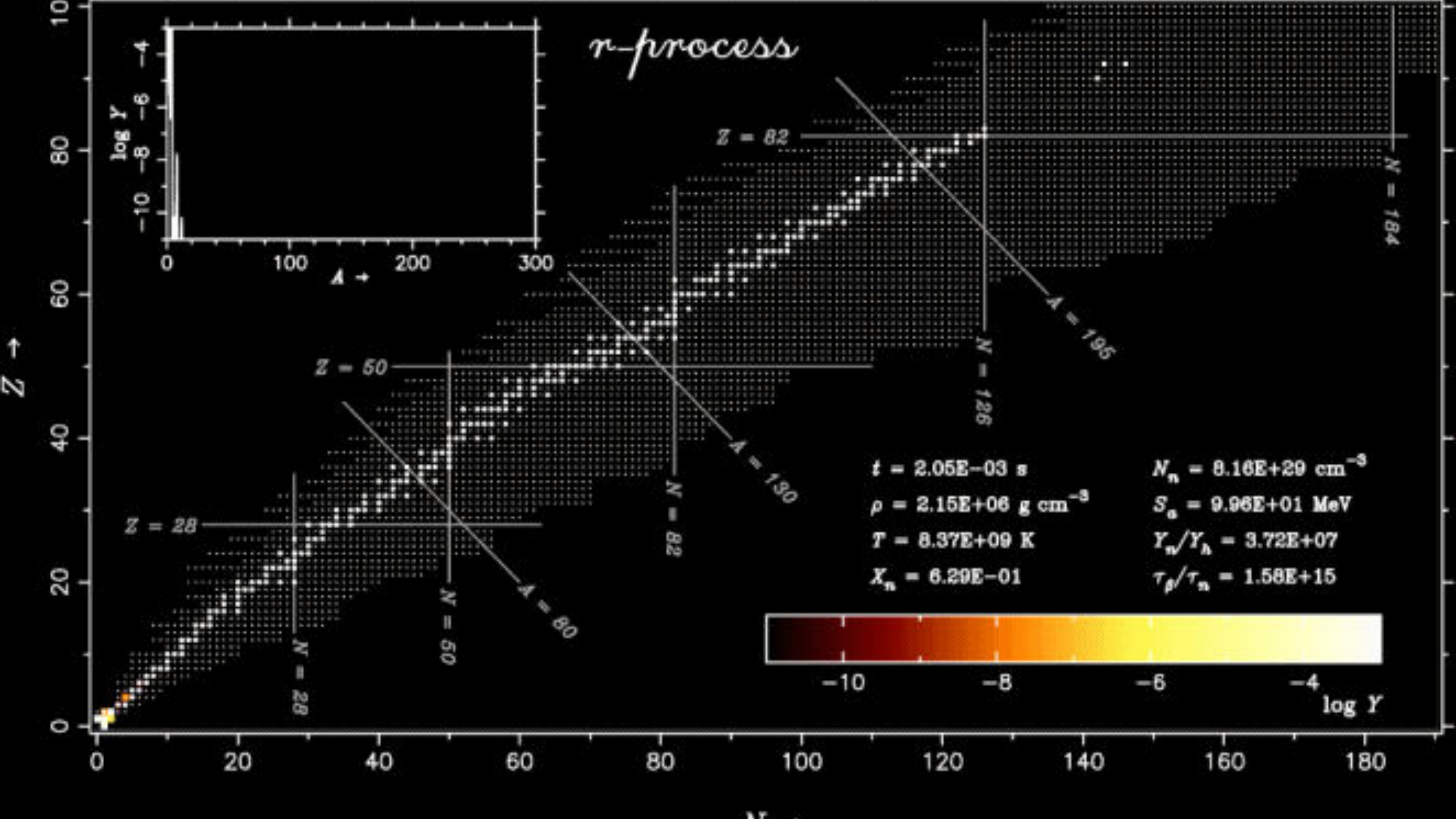


Origin of more than 50% of all the elements beyond iron

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

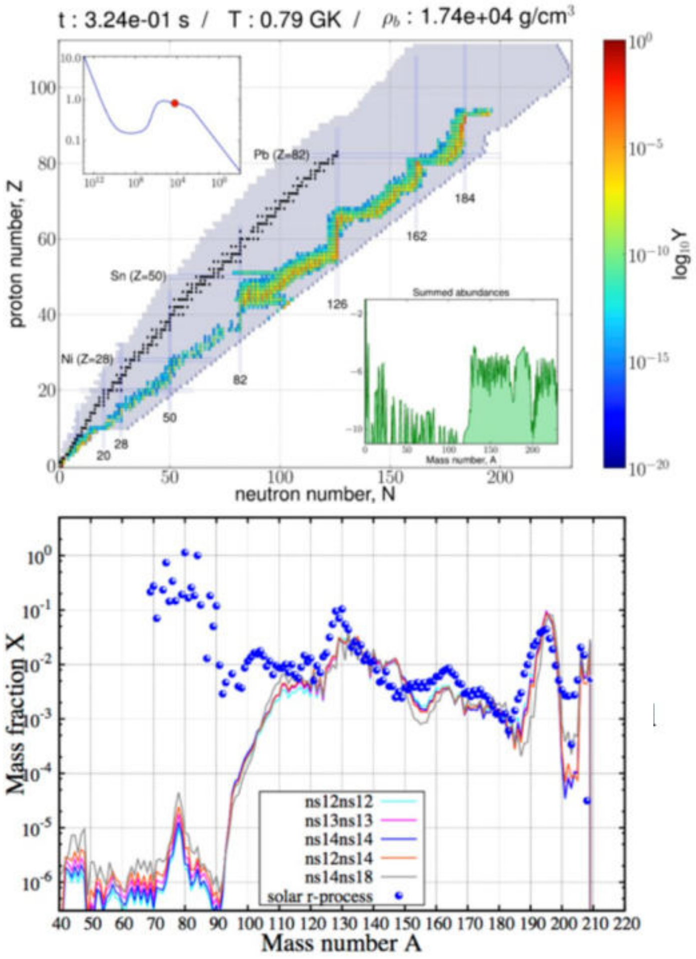


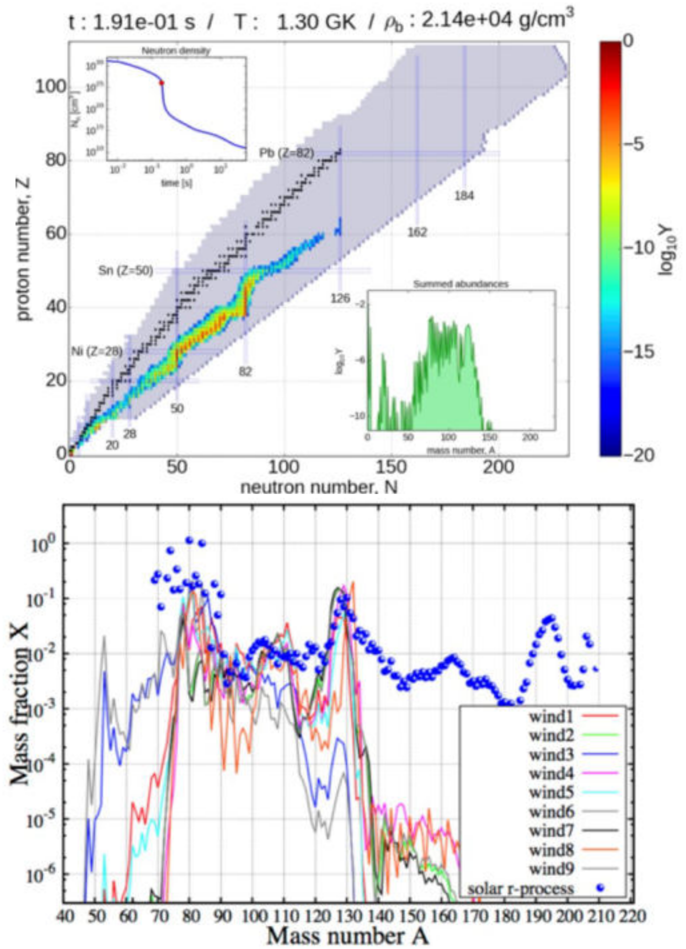
Temperature, density as a function of time, initial compositions, neutrons


r-process
Z = 82
Z = 50
Z = 28
N = 184
N = 126
N = 82
N = 50
N = 28
A = 195
A = 130
A = 80
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
Sa = 9.96E+01 MeV
Yn/Yh = 3.72E+07
τβ/τn = 1.58E+15
log Y
log Y
A →
Z →
N →

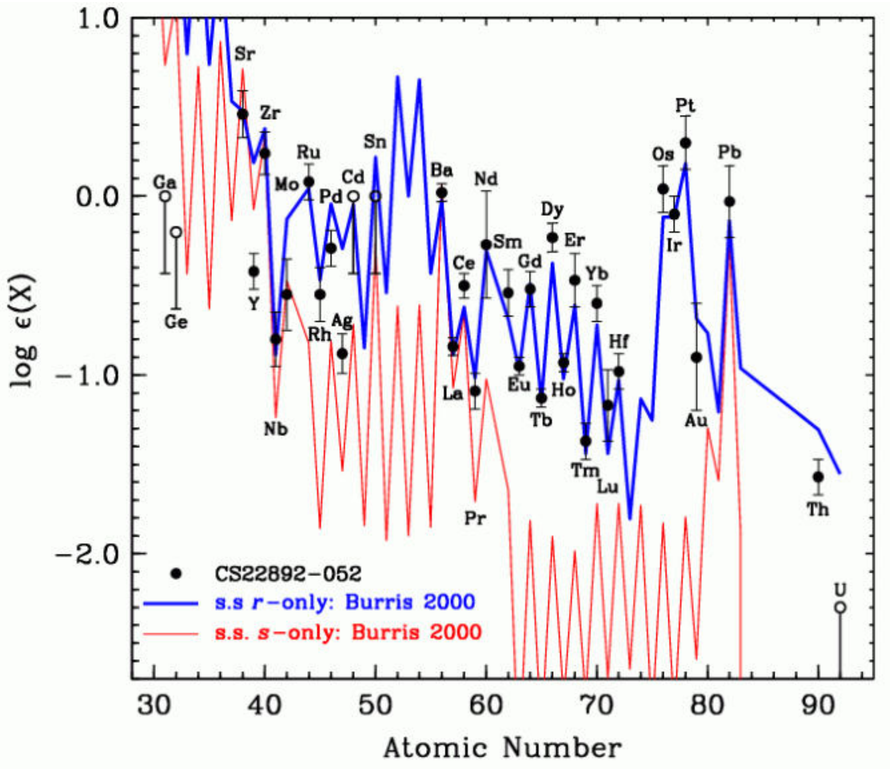
where is the site of the r-process?

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

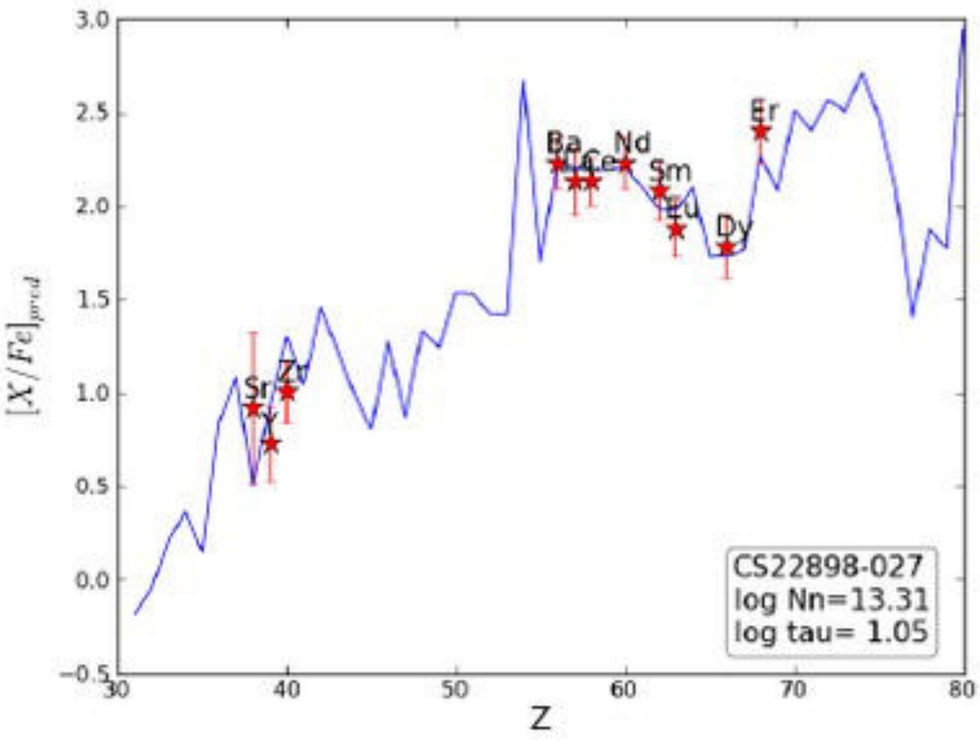




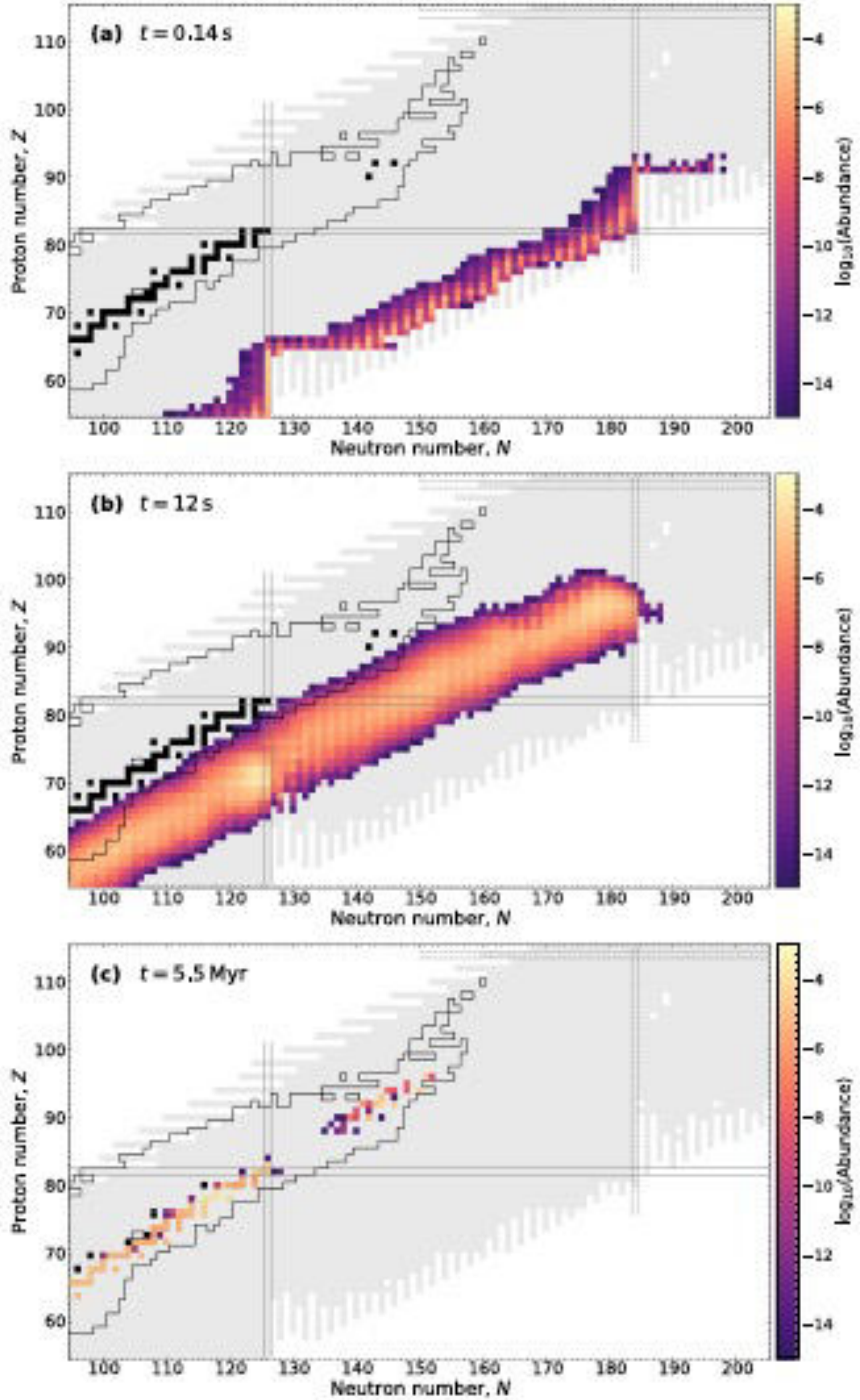
Abundances from other neutron induced nucleosynthesis processes



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

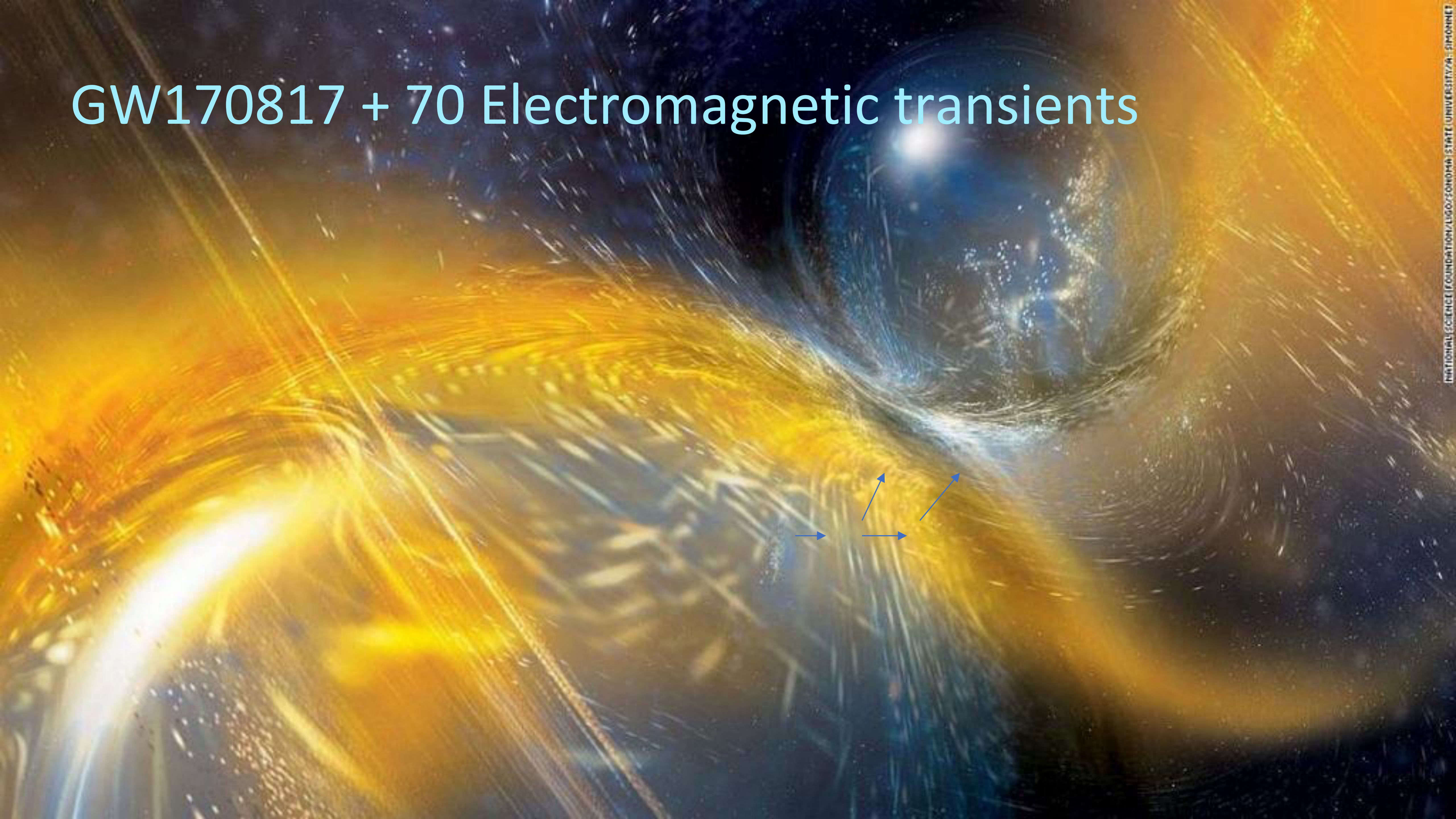
Review

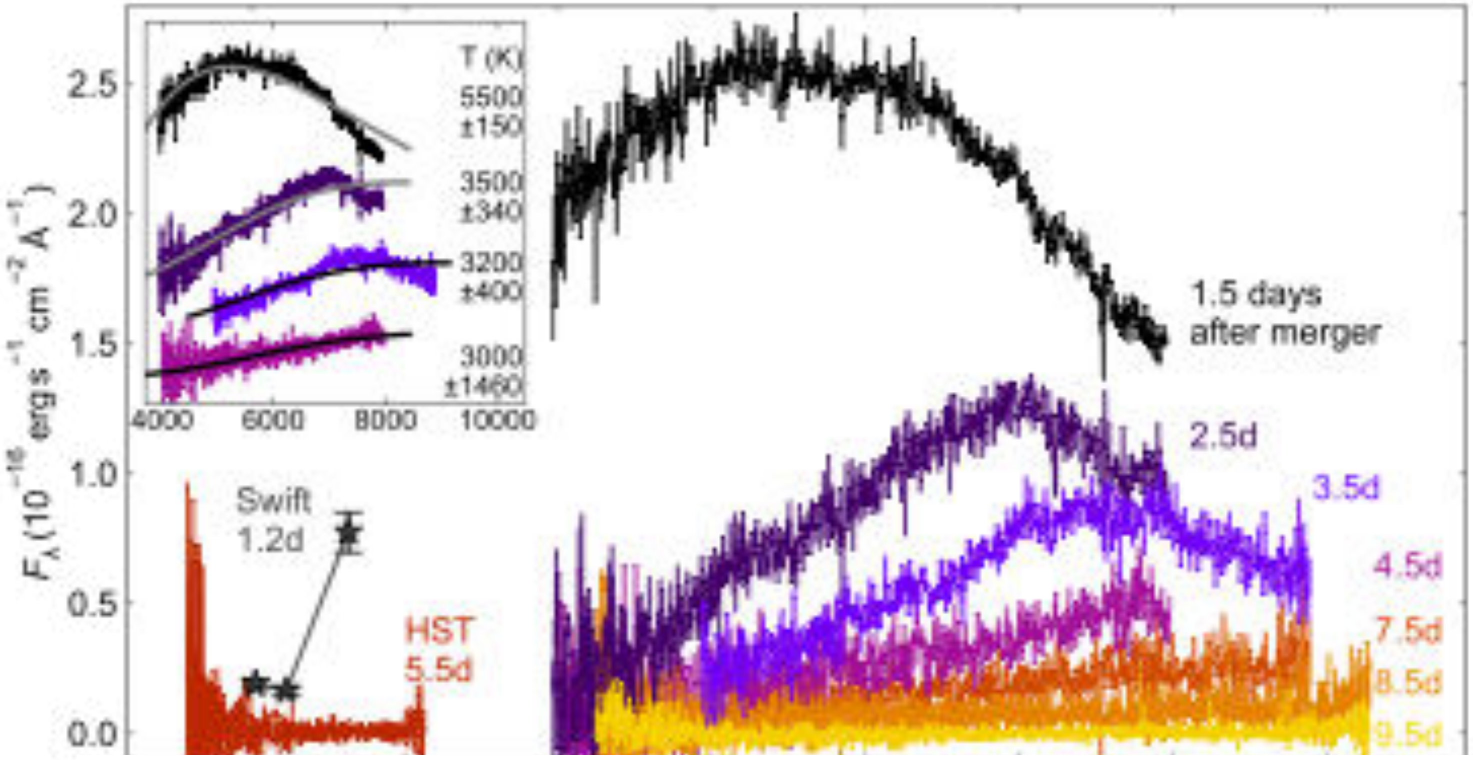
Nucleosynthesis and observation of the heaviest elements

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

GW170817 + 70 Electromagnetic transients





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

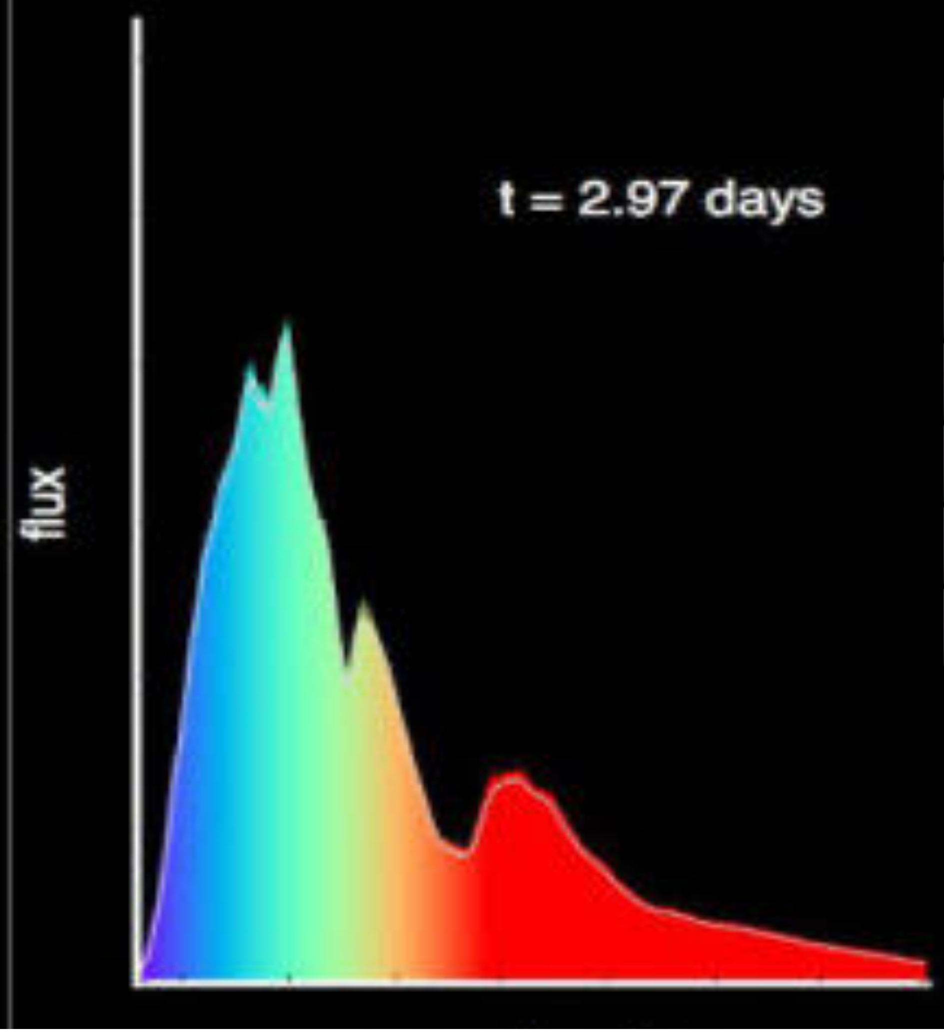
Lu visible signatures go into the IR

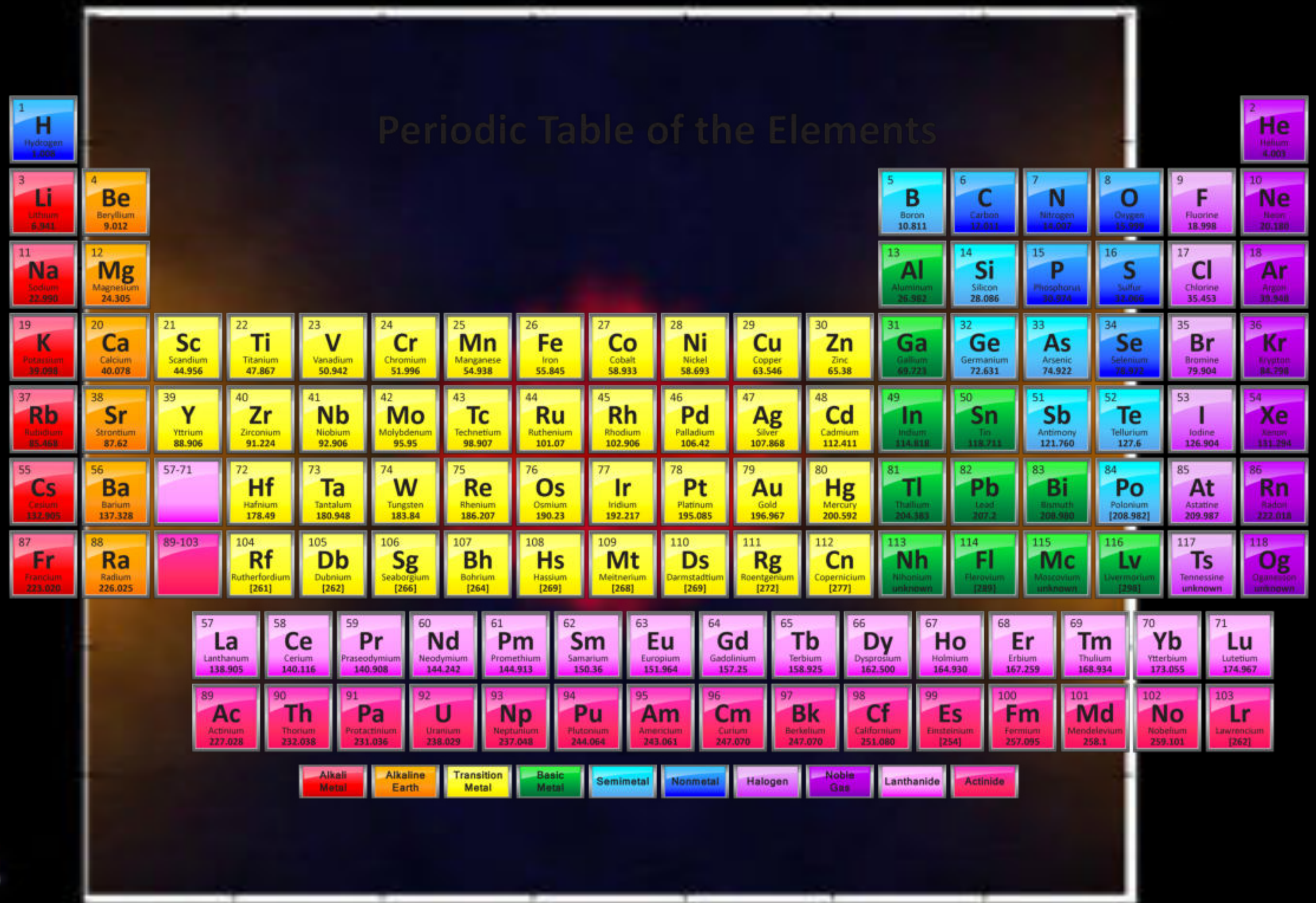
James Webb

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

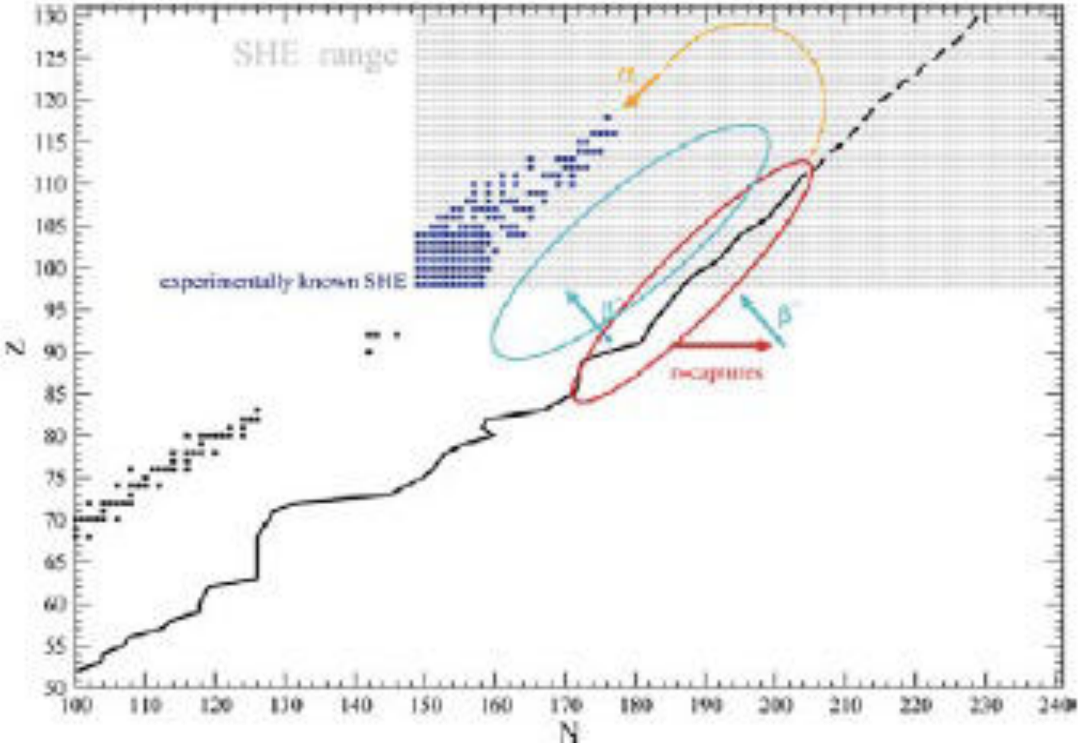
Eur. Phys. J. A (2012) **48**: 122
DOI 10.1140/epja/i2012-12122-6

THE EUROPEAN
PHYSICAL JOURNAL A

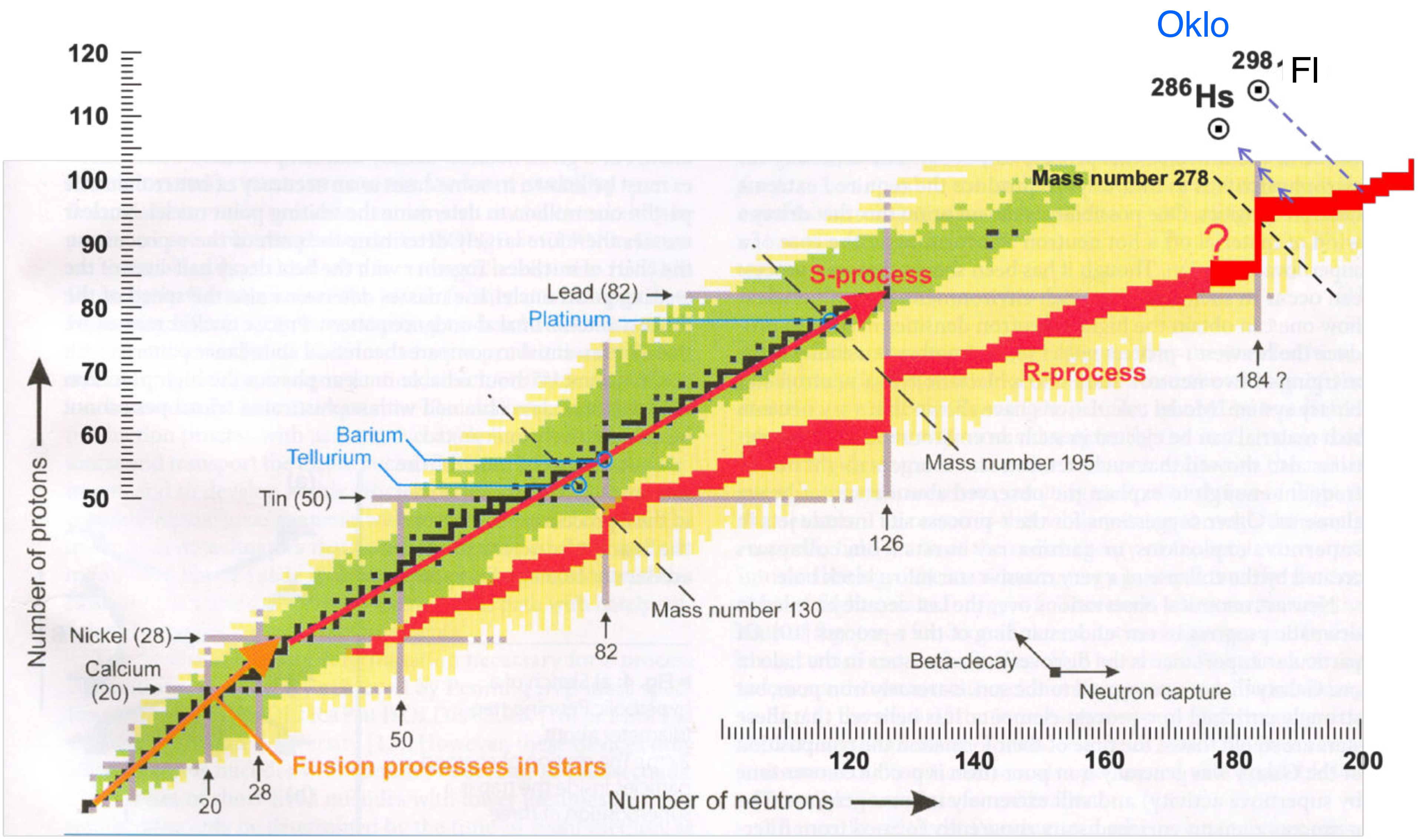
Regular Article – Theoretical Physics

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]

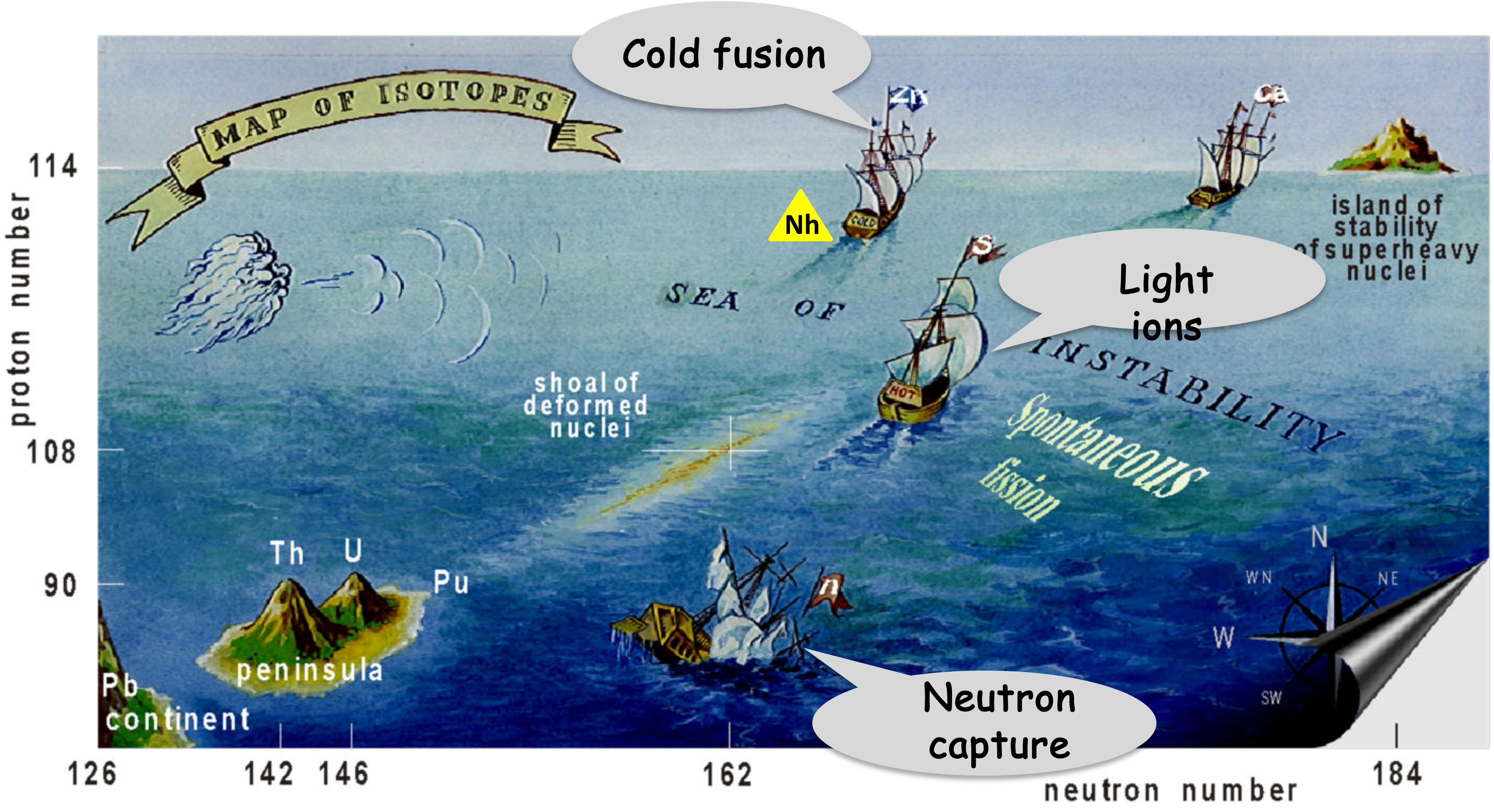


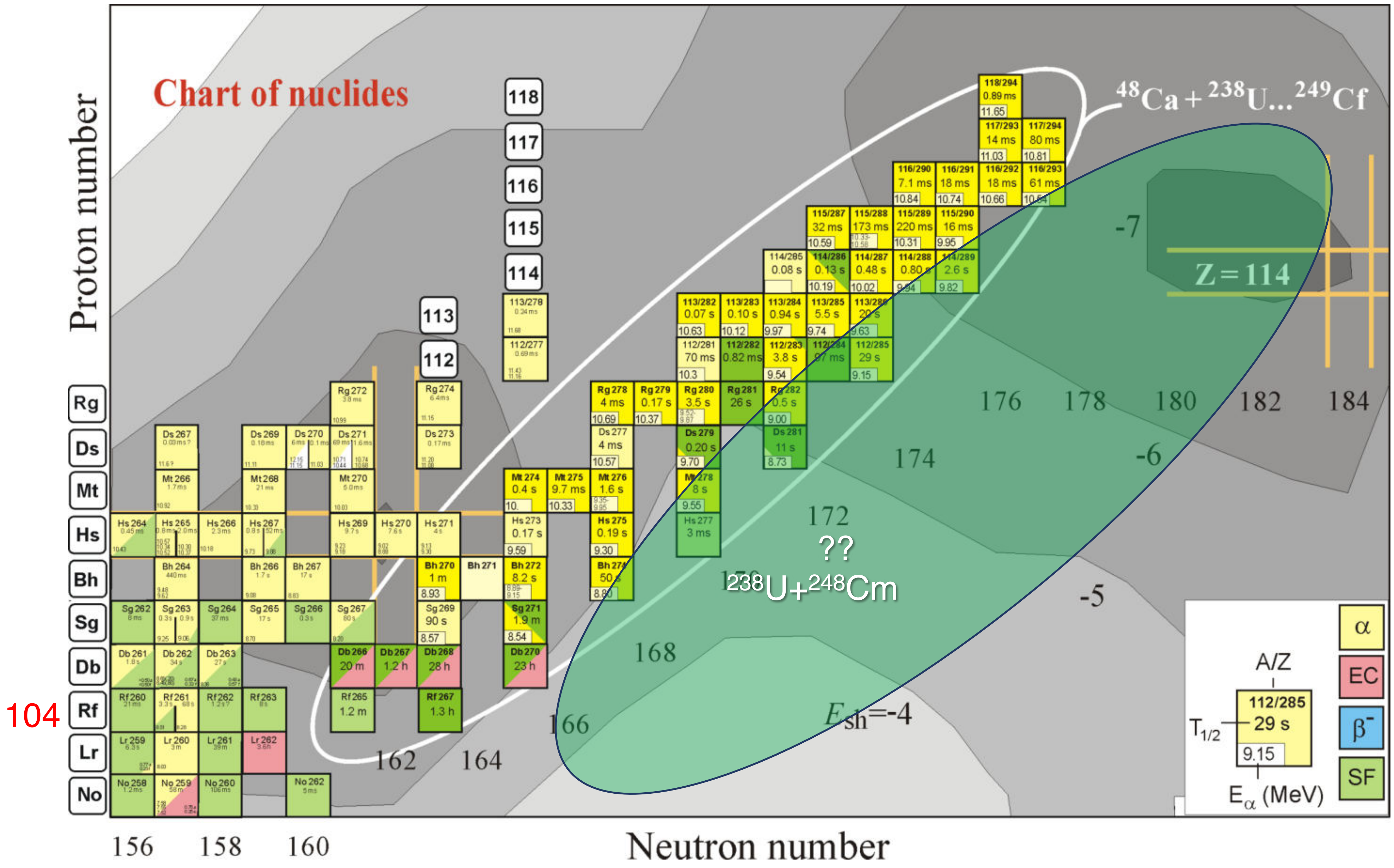
Are superheavy elements produced in the r-process?



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

Reactions of synthesis





Courtesy of A. Karpov

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

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

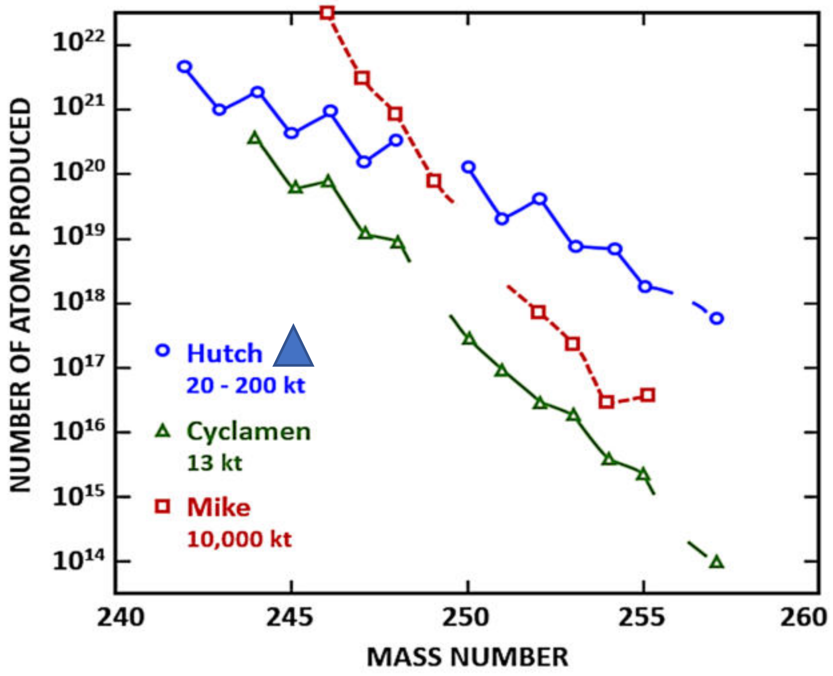
Lawrence Livermore Laboratory

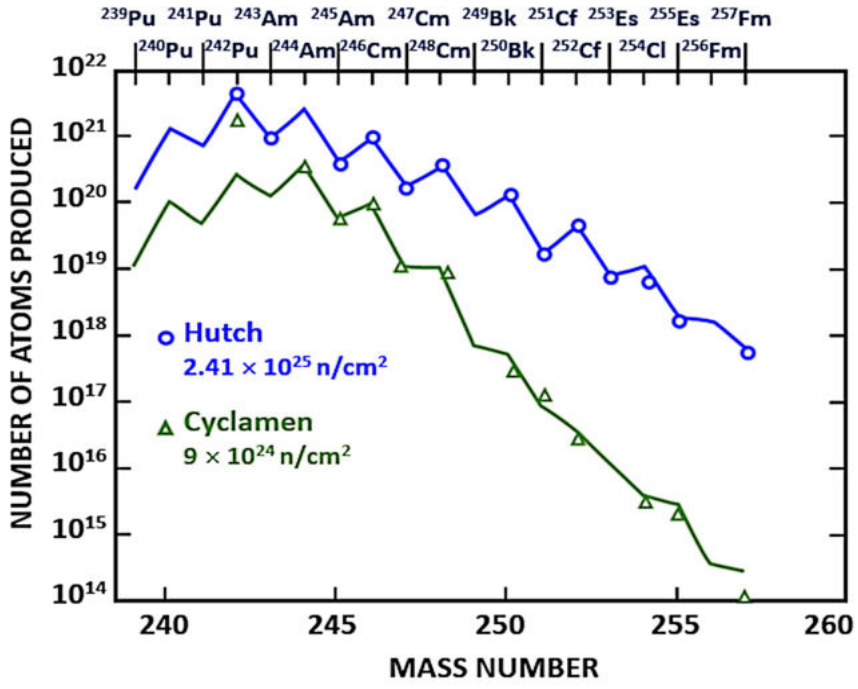
PRODUCTION OF EINSTEINIUM AND FERMIUM IN NUCLEAR EXPLOSIONS

R. Hoff, August 21, 1978

Z=99 Es

Z=100 Fm





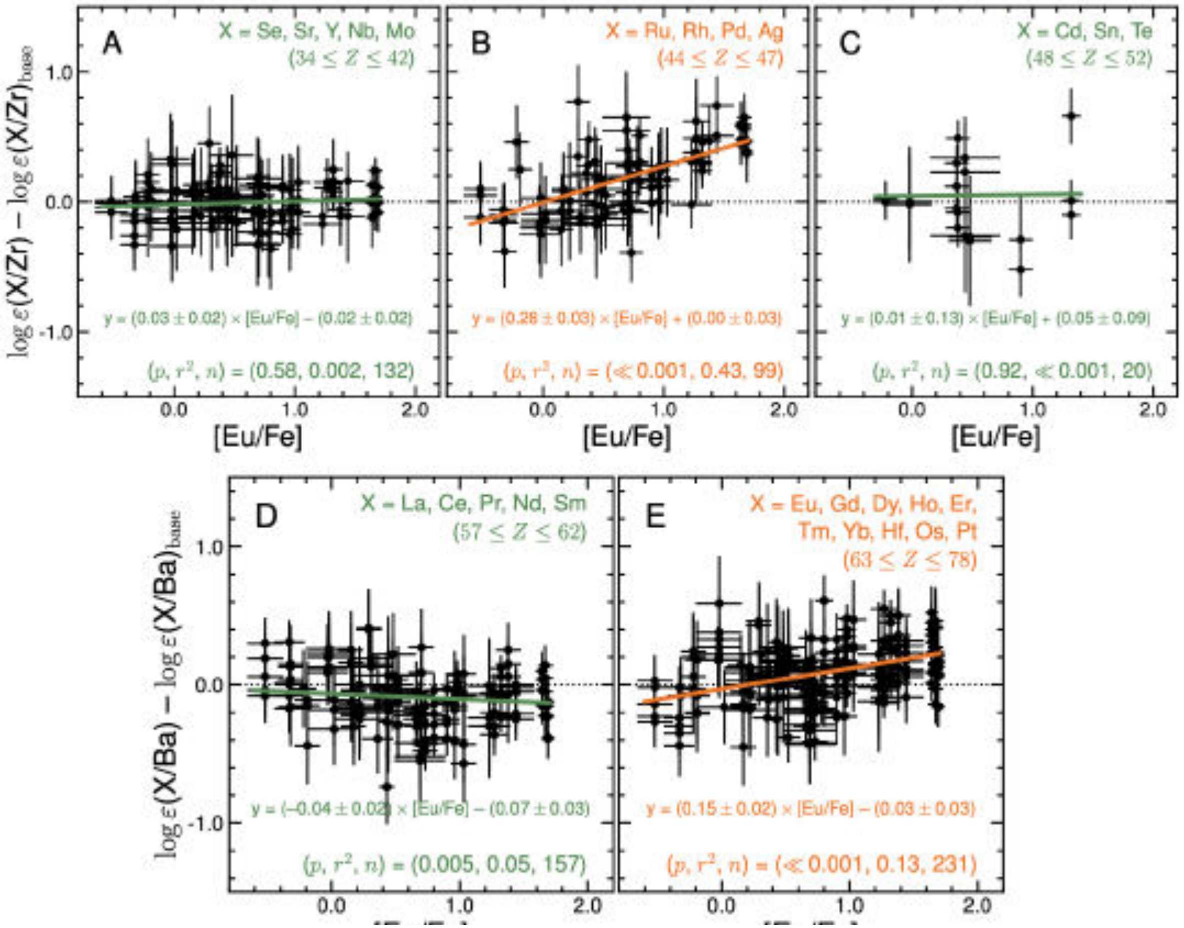
Neutron star: 10^{43} or 10^{41} neutrons/cm^2

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!

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

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]

Open Challenges to Nuclear Physics resulting from the neutron star merger

A. Aprahamian
NuPECC in Sept. 2021

Fission

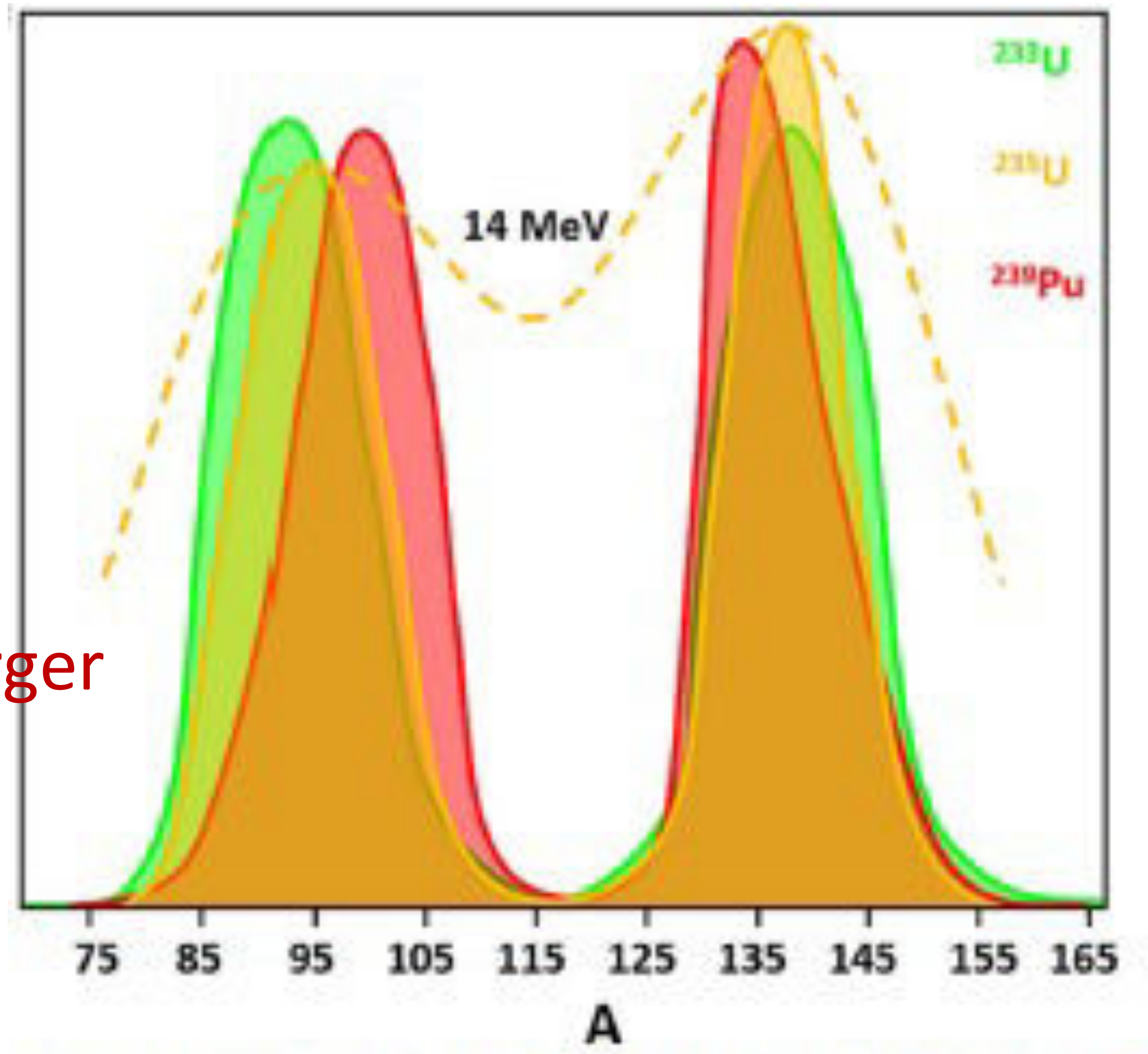
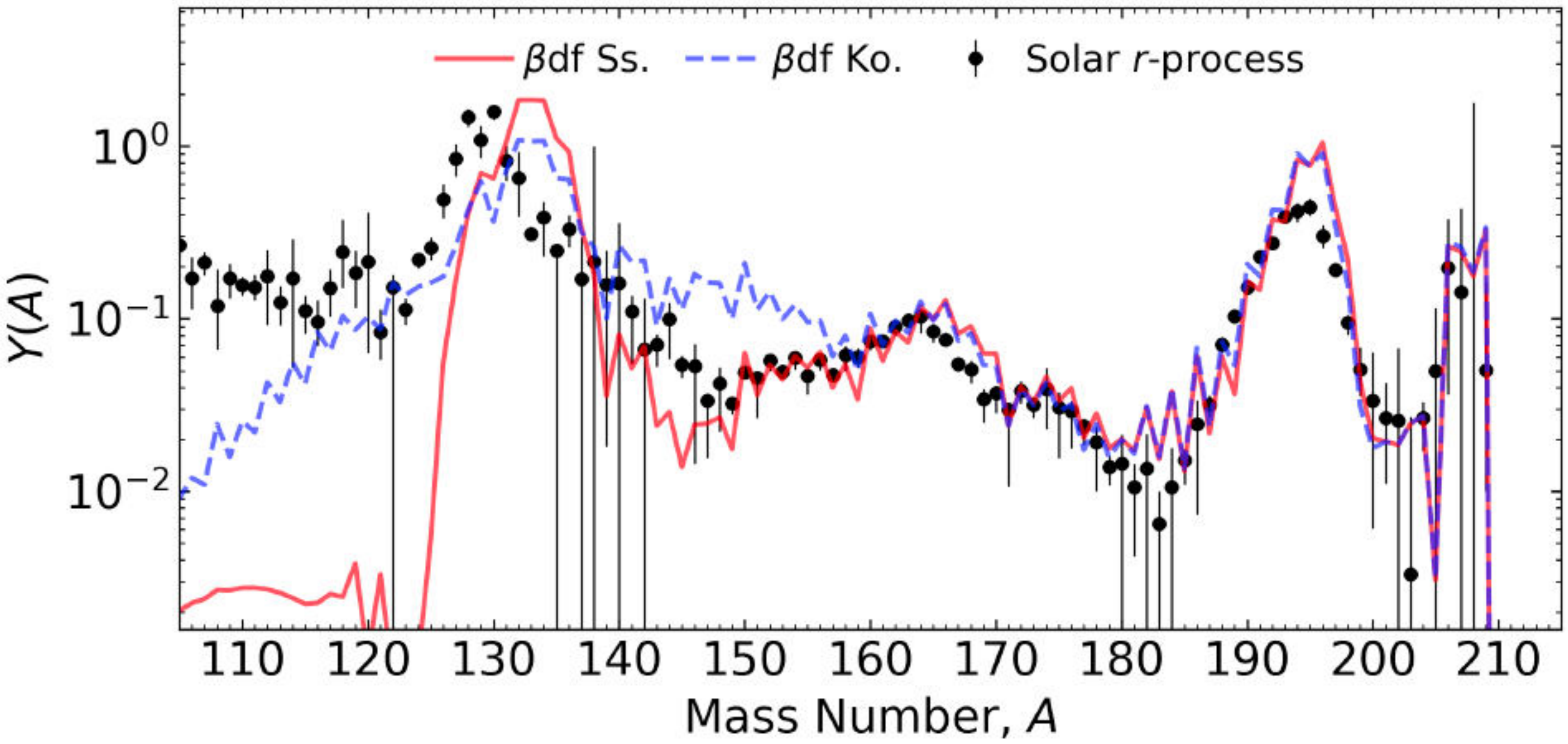


Figure 4. *Low-energy (thermal) neutron-induced fissio fragment distributions with ^{233,235}U and ^{238}Pu. The dotte line indicates the fission of ^{235}U with 14 MeV neutrons.*

FISSION CAN IMPACT FINAL ABUNDANCES

Figure by Mumpower



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

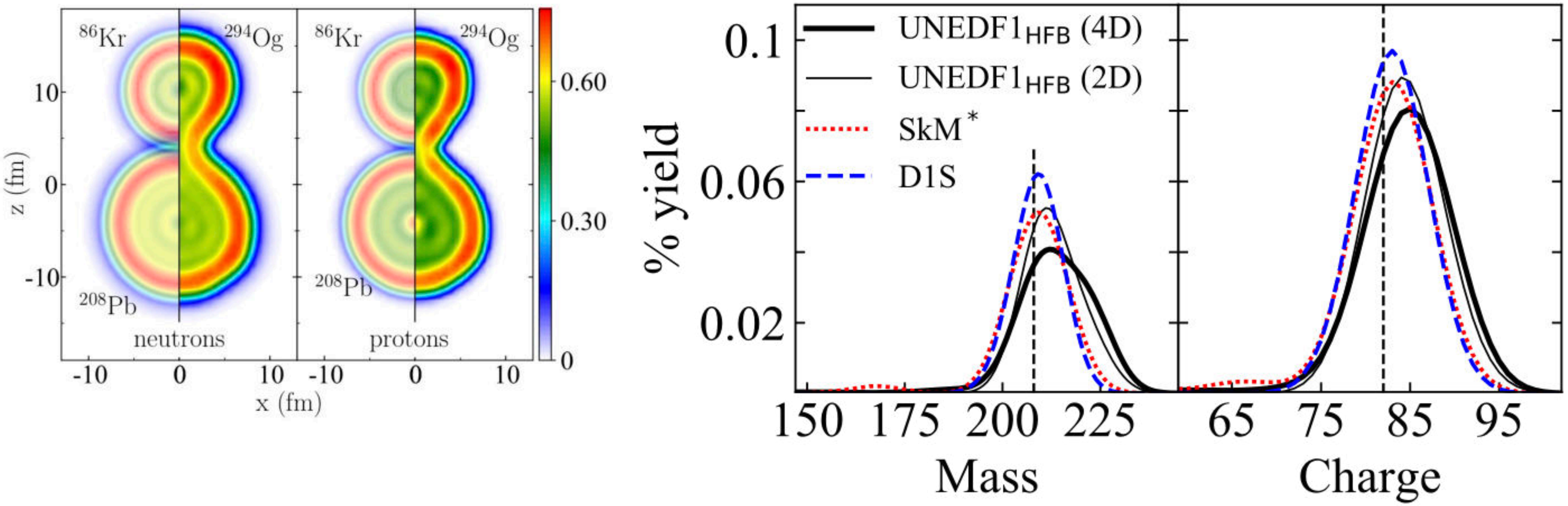
Conclusion $\Rightarrow$ we need a good description of fission yields to understand abundances near $A \sim 130$.

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

Cluster decay becomes the main fission mode

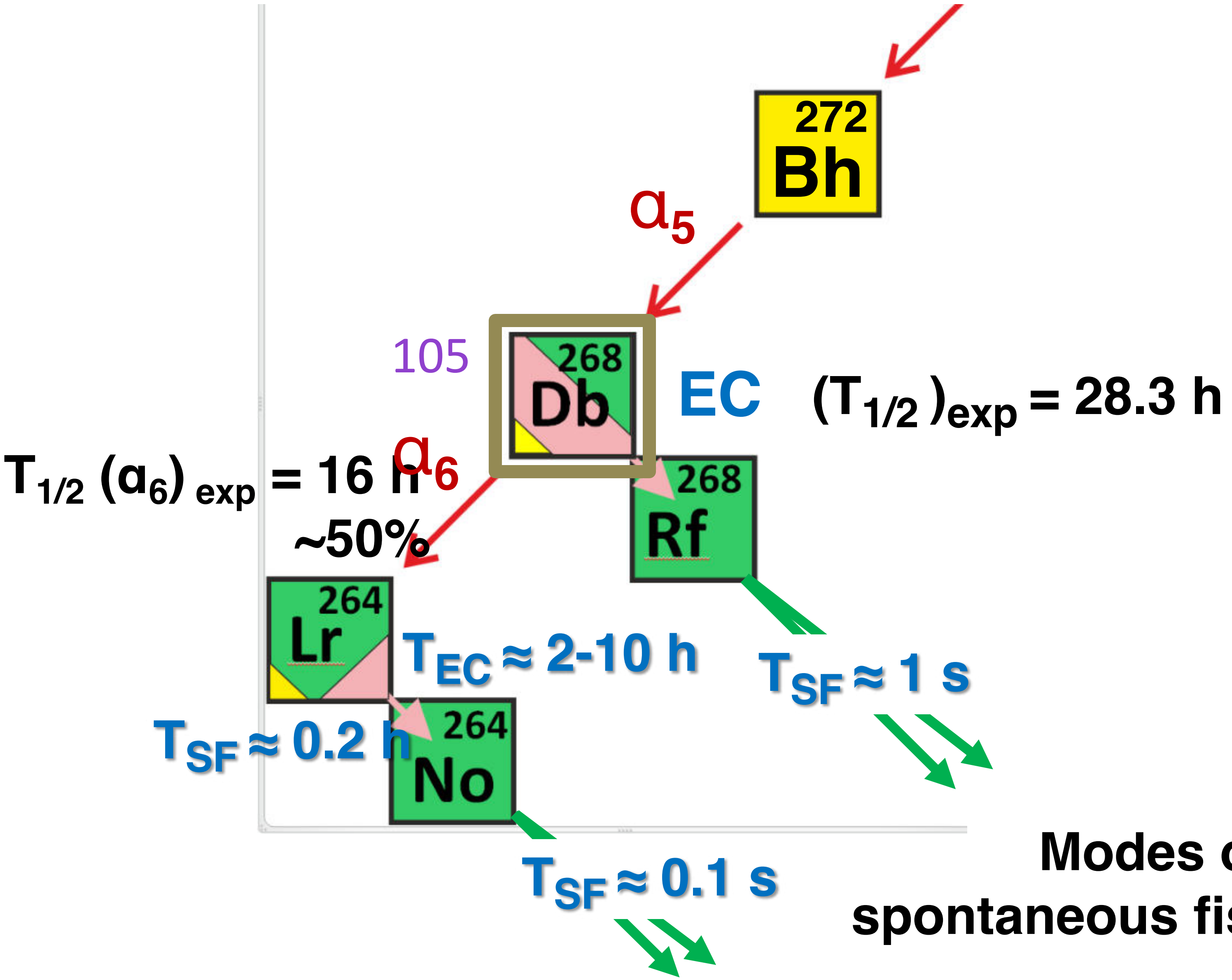
$^{294}Og \rightarrow \, ^{208}Pb + ^{86}Kr_{50}$

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



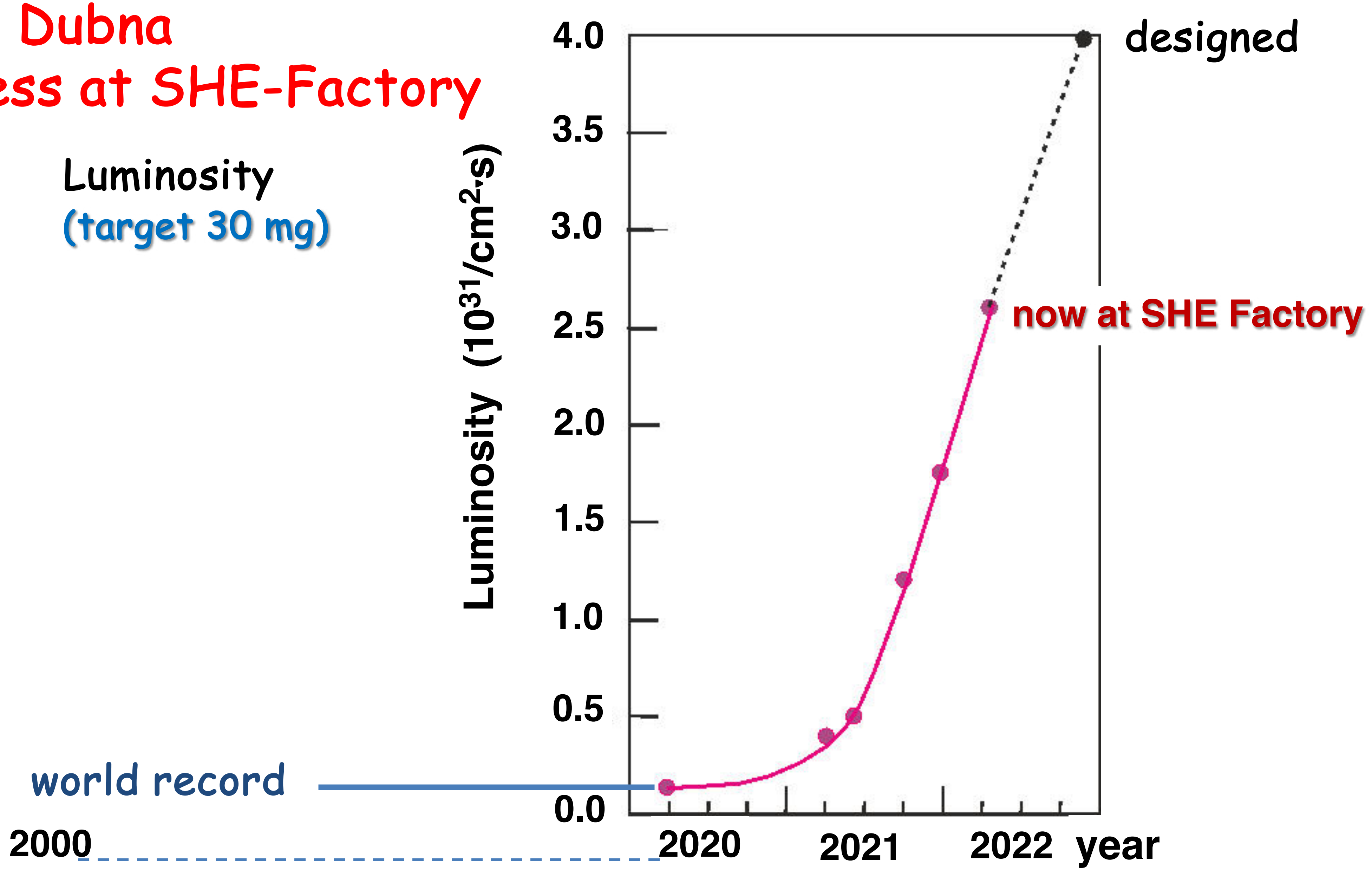
Robust prediction: extremely asymmetric fission

Courtesy of W. Nazarewicz

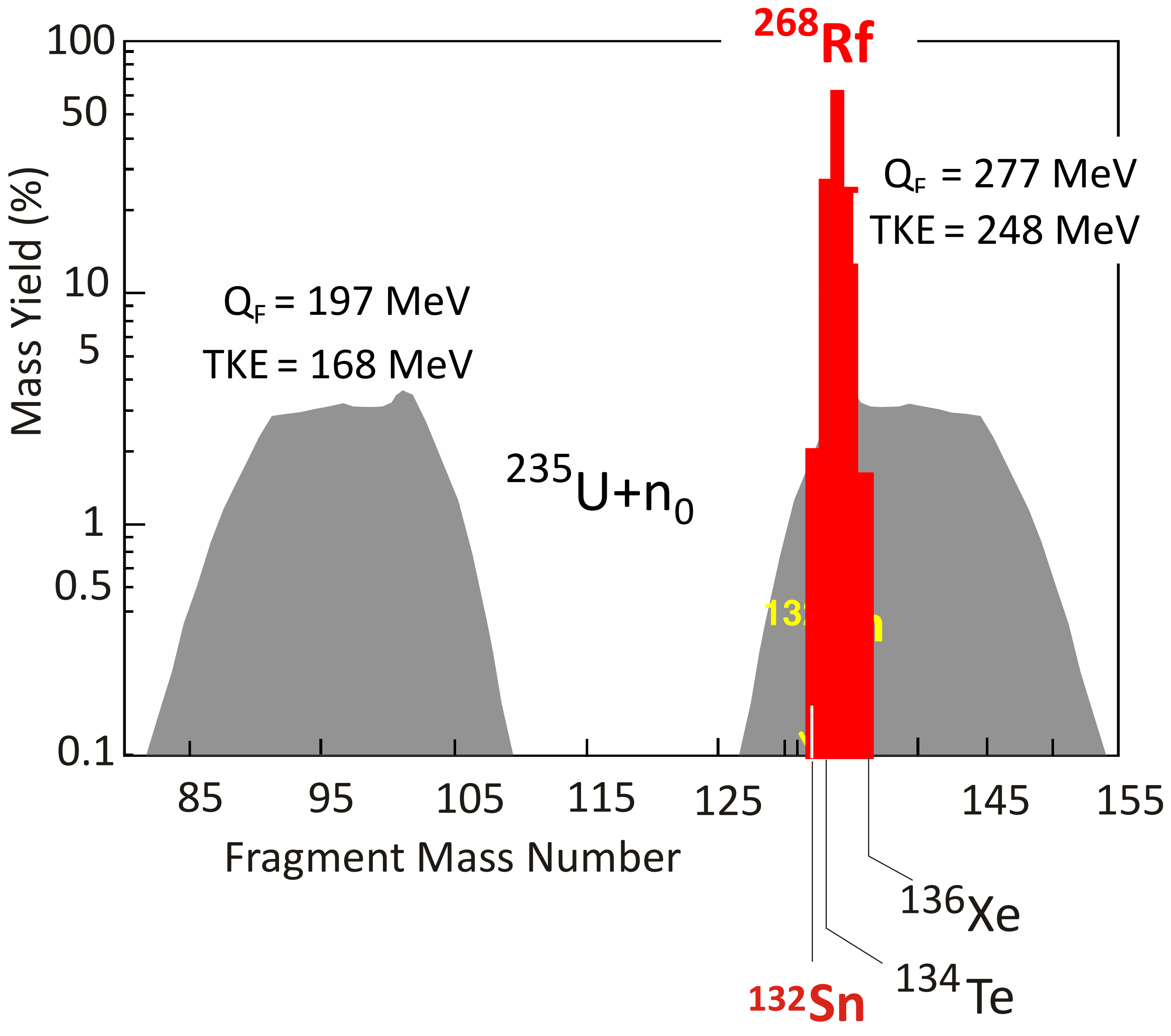


Modes of the spontaneous fission

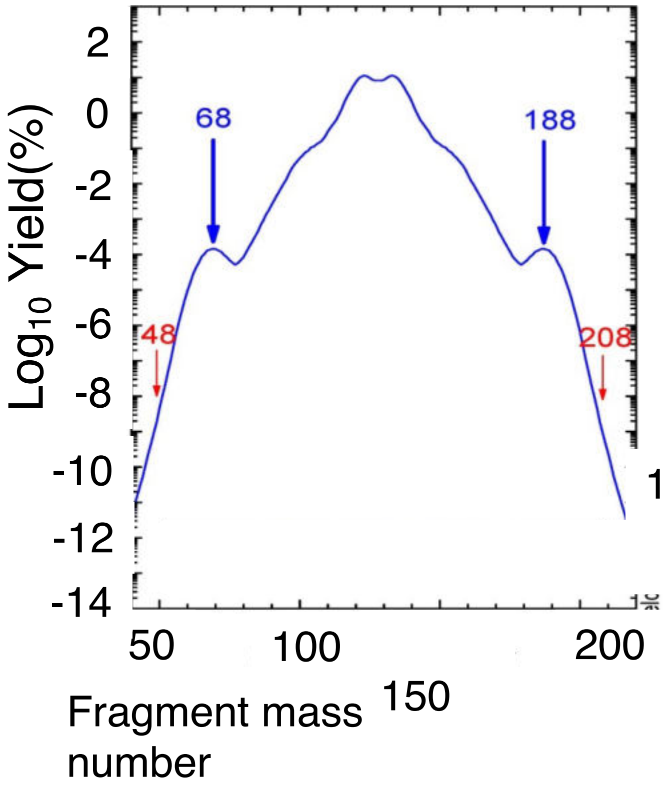
JINR: Dubna
Progress at SHE-Factory



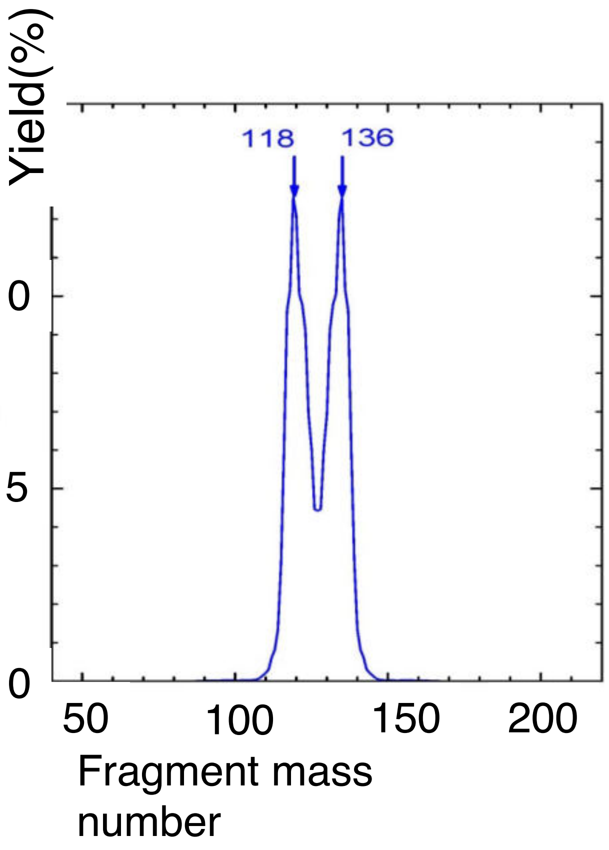
Mass Distribution of the Fission Fragments



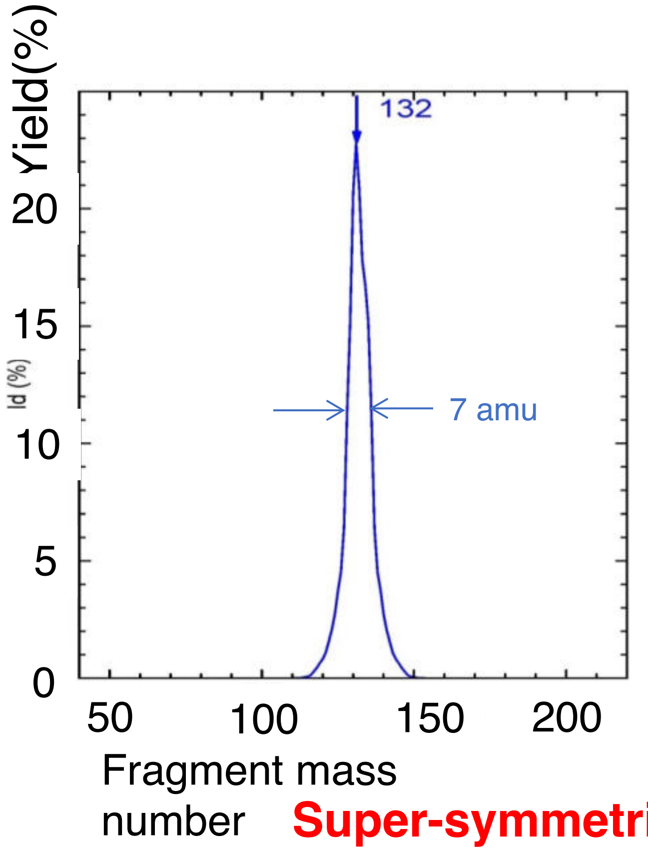
The three fission patterns of Nobelium predicted by the pre-scission model



Super-asymmetric
^{256}No



Regular asymmetric
^{254}No

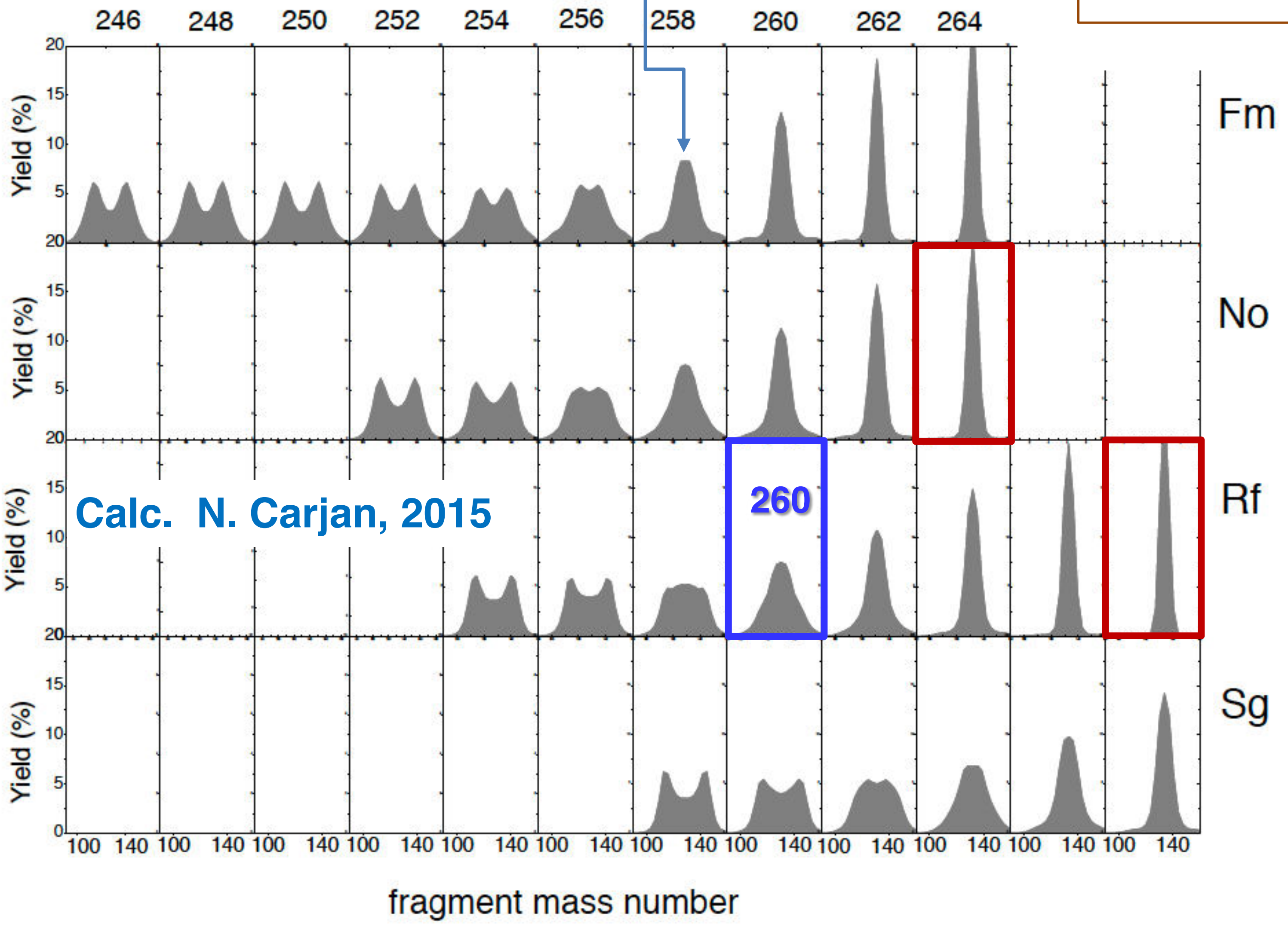


Super-symmetric
^{264}No

Discovery of mass-symmetric spontaneous fission of ^{258}Fm: $Z=2\times50$ $N=2\times79$

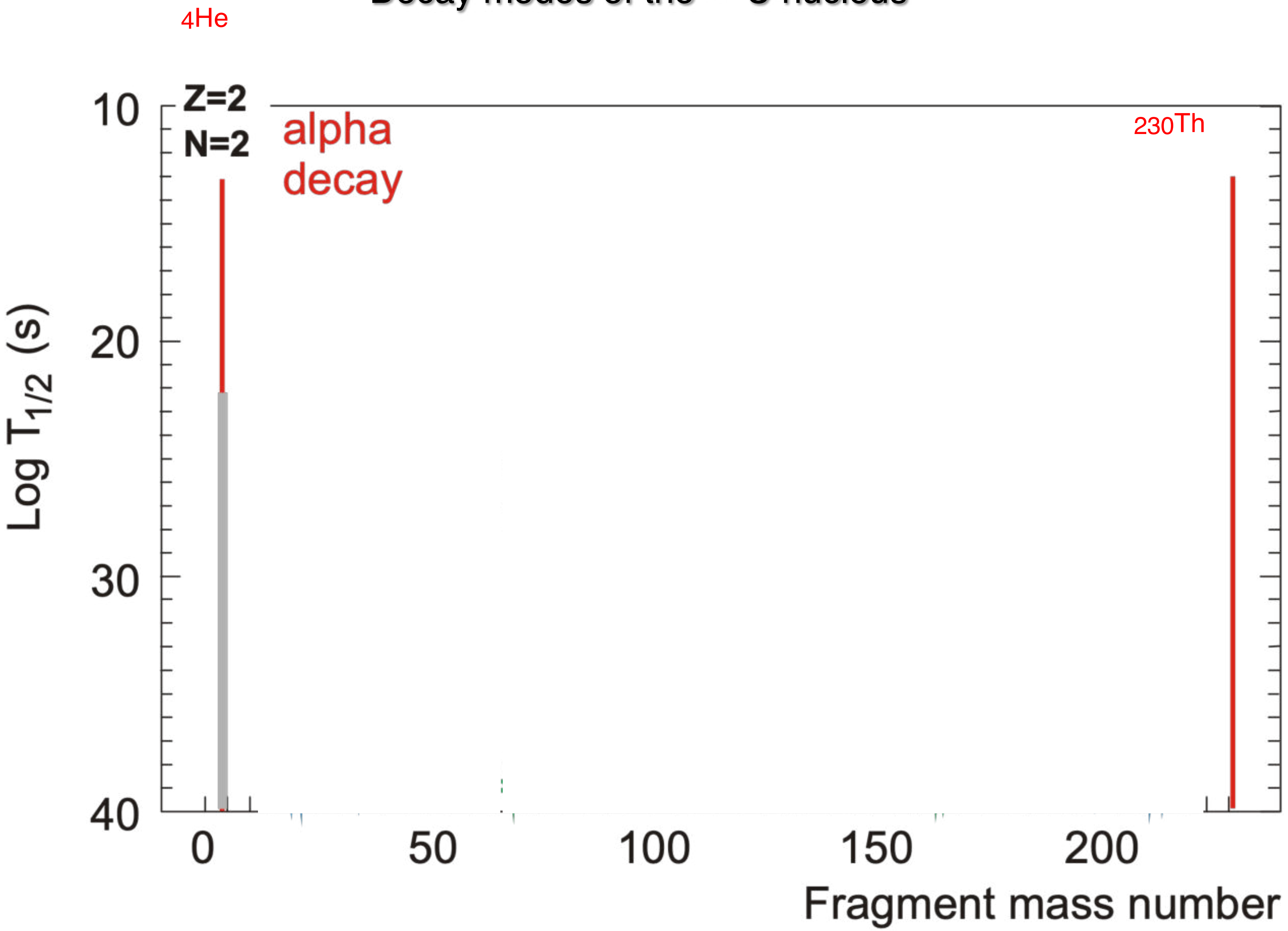
E. K. Hulet *et al.*, PRL **56**, 313 (1986)

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



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

^{275}Ds ^{276}Ds

5*n* 4*n*

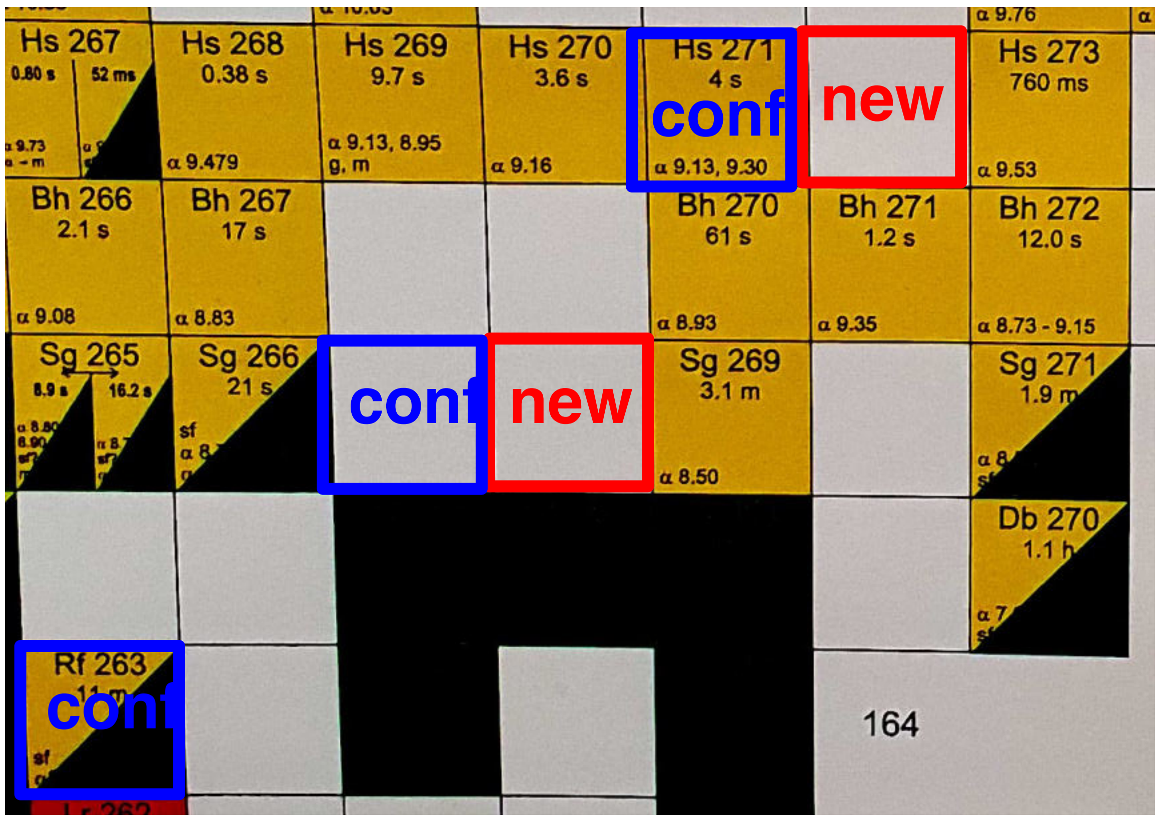
new new

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

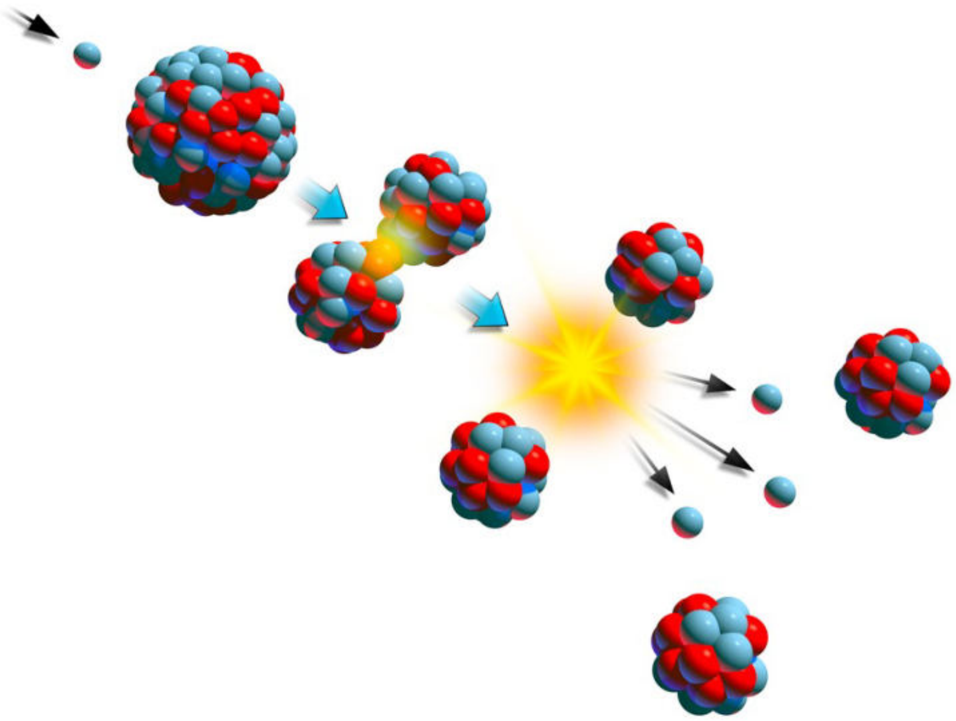
New isotopes

Connect to mainland

Bomb debris from environmental tests of nuclear weapons

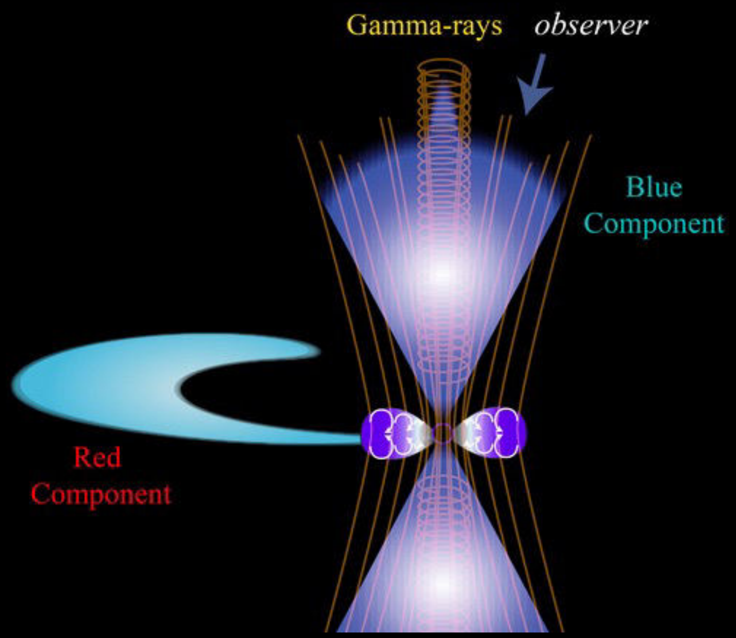
Fission: LLNL – DUBNA – AANL

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

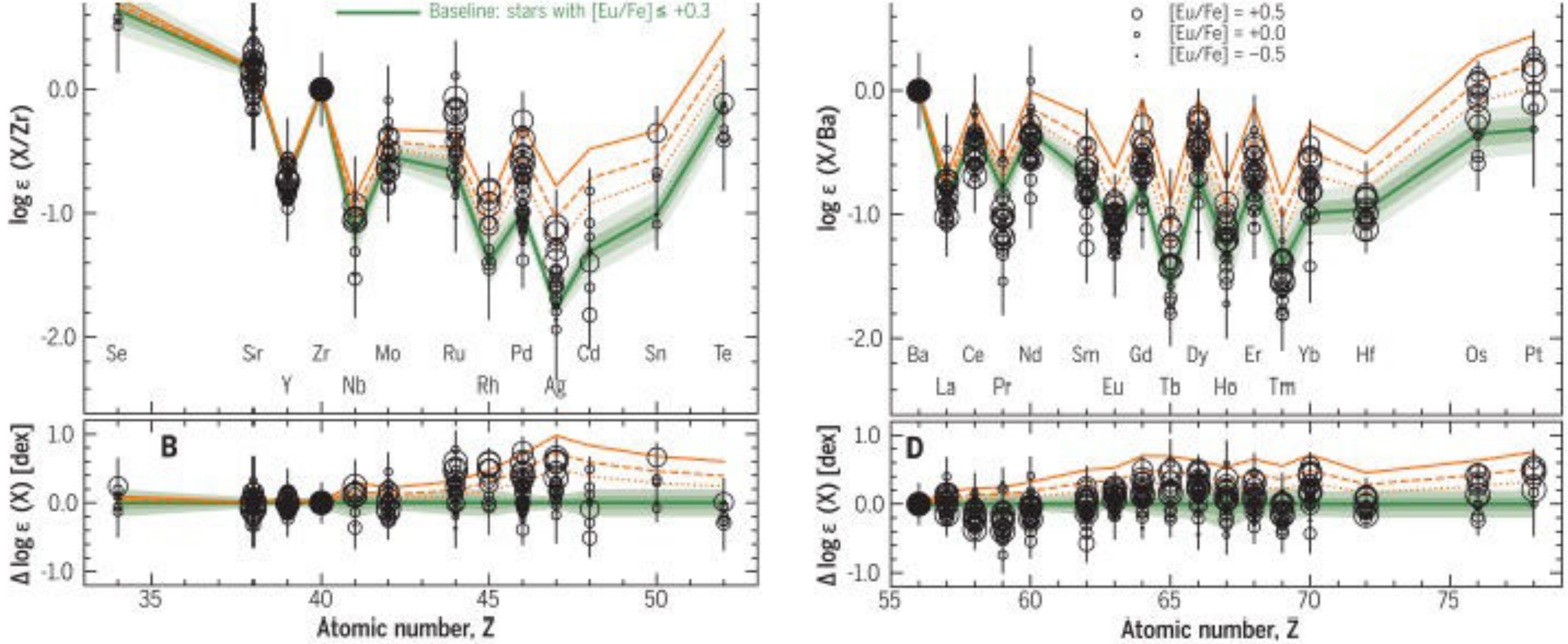
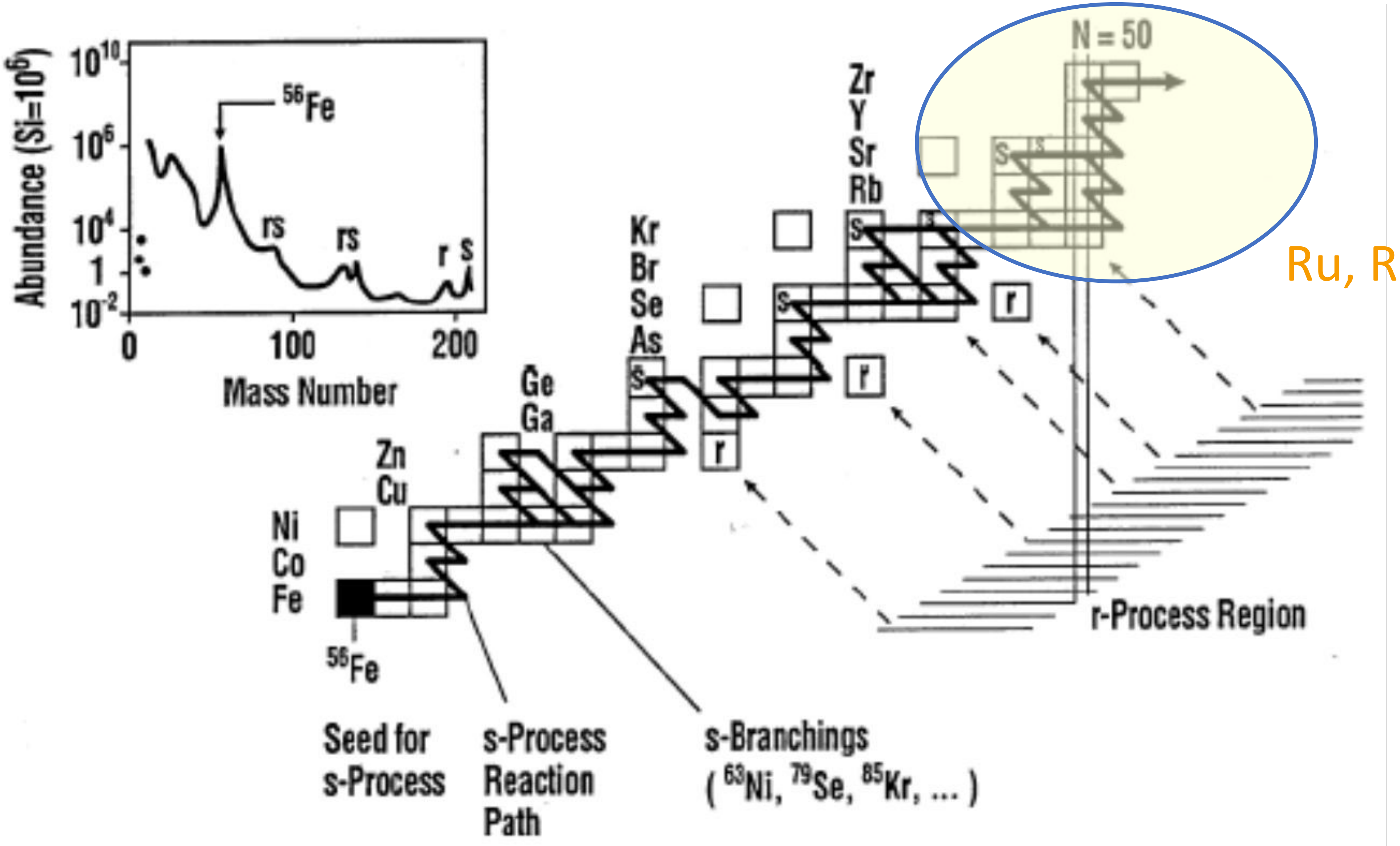


Fig. 1. Observed abundance patterns compared with fission model predictions.

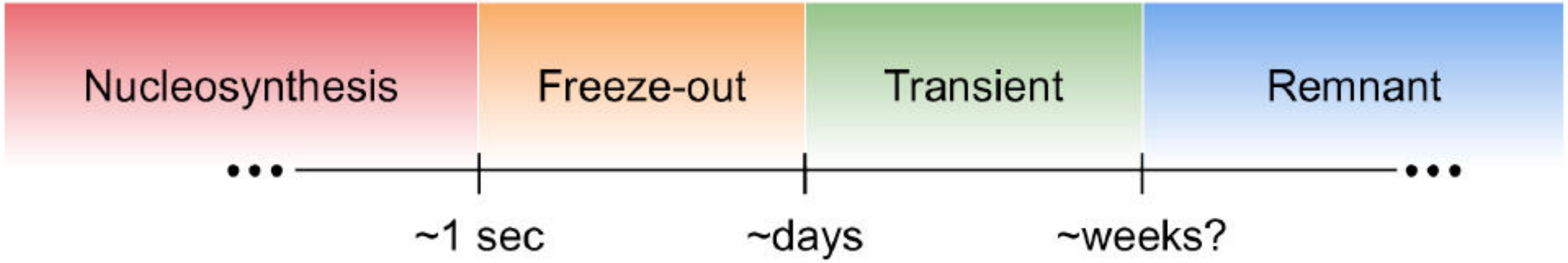
Shown are logarithmic abundances (open circles) measured for 30 *r*-process elements in the 42 stars of our sample, plotted as a function of atomic number. The symbol sizes are proportional to [Eu/Fe], and error bars indicate 1σ uncertainties. The green line is the empirical baseline pattern we defined as the mean abundance ratios for the subset of 13 stars with [Eu/Fe] ≤ +0.3. Light shading and dark green shading indicate ± 1 and ± 2 times the standard error in the baseline, respectively. The orange lines indicate models of fission fragments added to the baseline pattern; the dotted line has equal contributions from the baseline and the fission model, the dashed line has two parts fission fragments plus one part baseline pattern, and the solid line has four parts fission plus one part baseline. (**A**) Elements 34 < Z < 52, normalized to Zr (solid circle). Elements are labeled at bottom. (**B**) Residuals between the data and the baseline pattern in (A). (**C** and **D**) Same as (A) and (B), respectively, but for elements 56 < Z < 78, normalized to Ba (solid circle). Numerical values are provided in data S1.

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



Ru, Rh, Pd, Ag

RADIONUCLIDES IN THE r-PROCESS

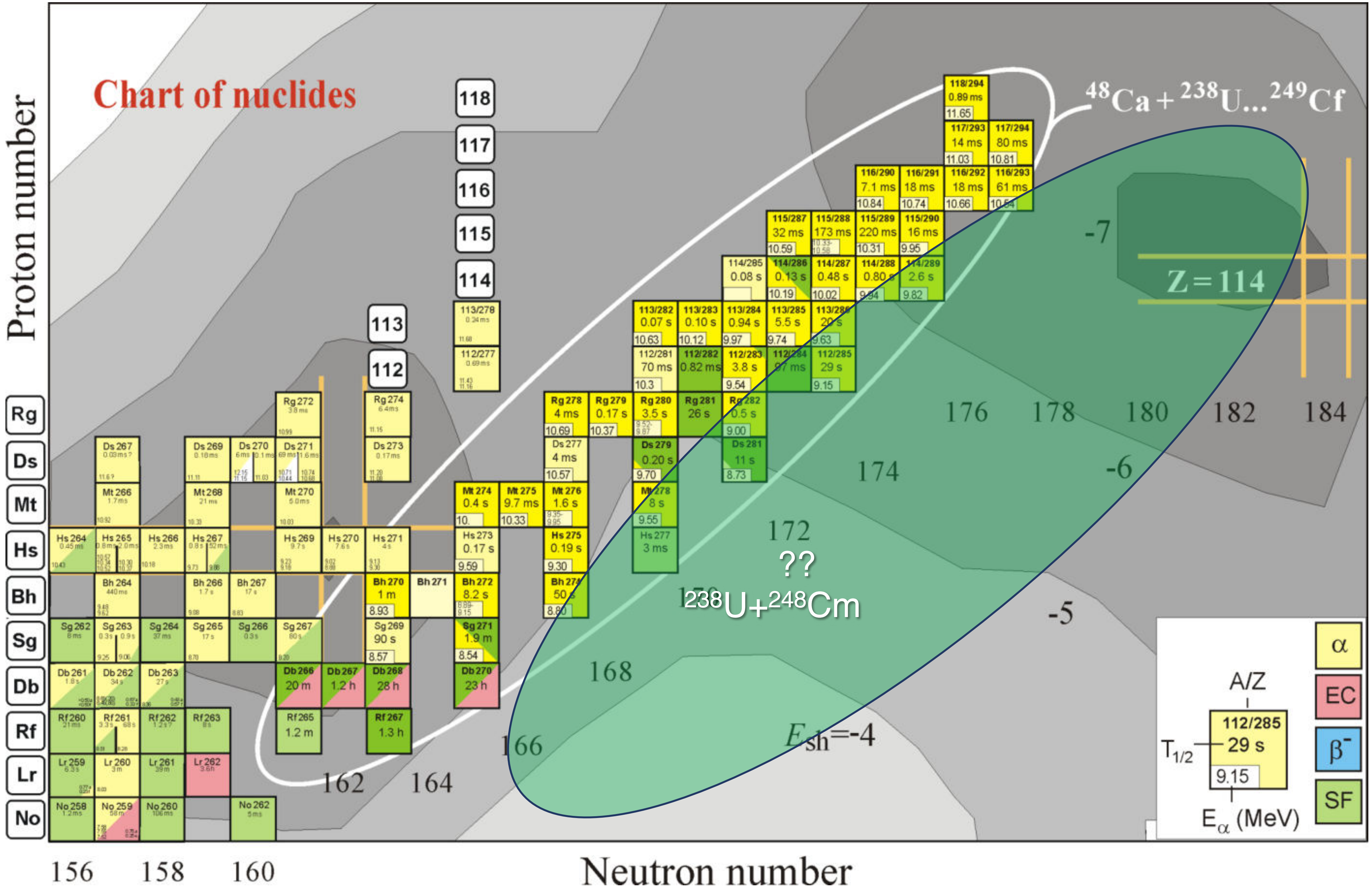


While the nucleosynthesis of the r-process is short-lived (~1 second)

The creation of radionuclides spans half-lives from microseconds to near-stable

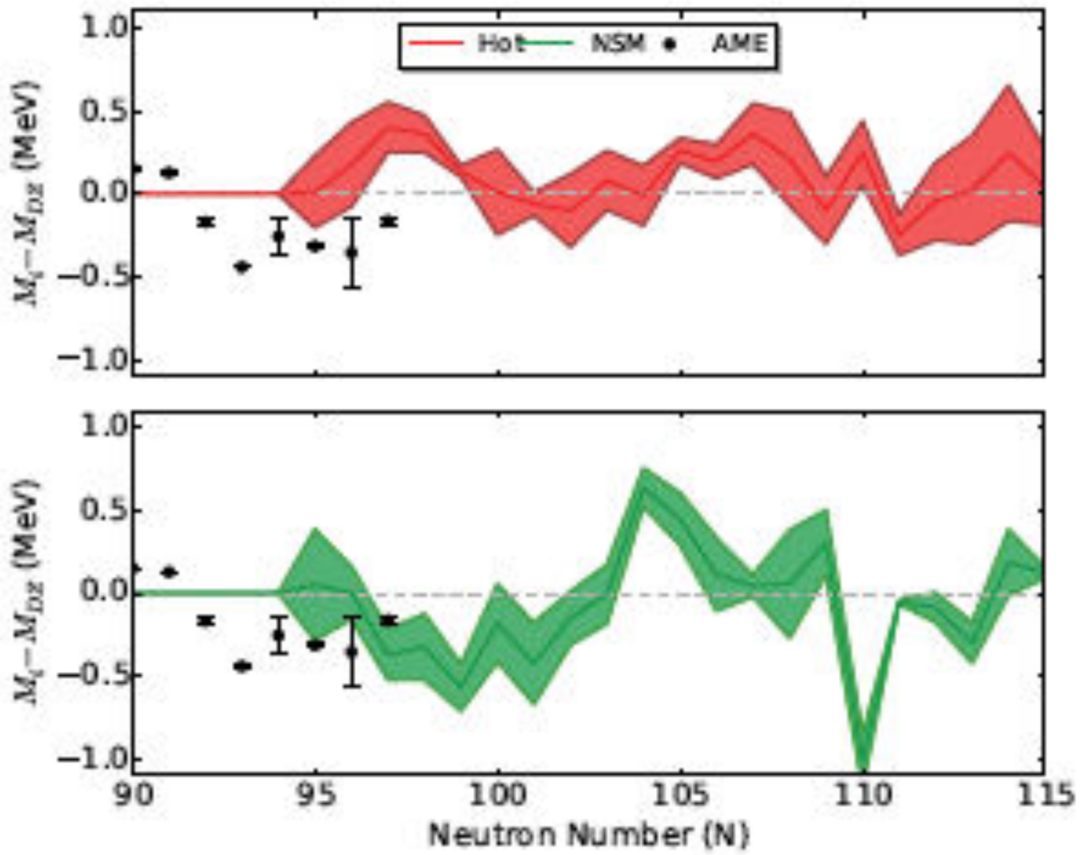
Different epocs have unique and interesting radioactive nuclei present along with associated signatures

Figure by Mumpower



Courtesy of A. Karpov

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



Neutron Number (N)

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

Observed r-process elemental distributions

Merger accretion disk wind scenario

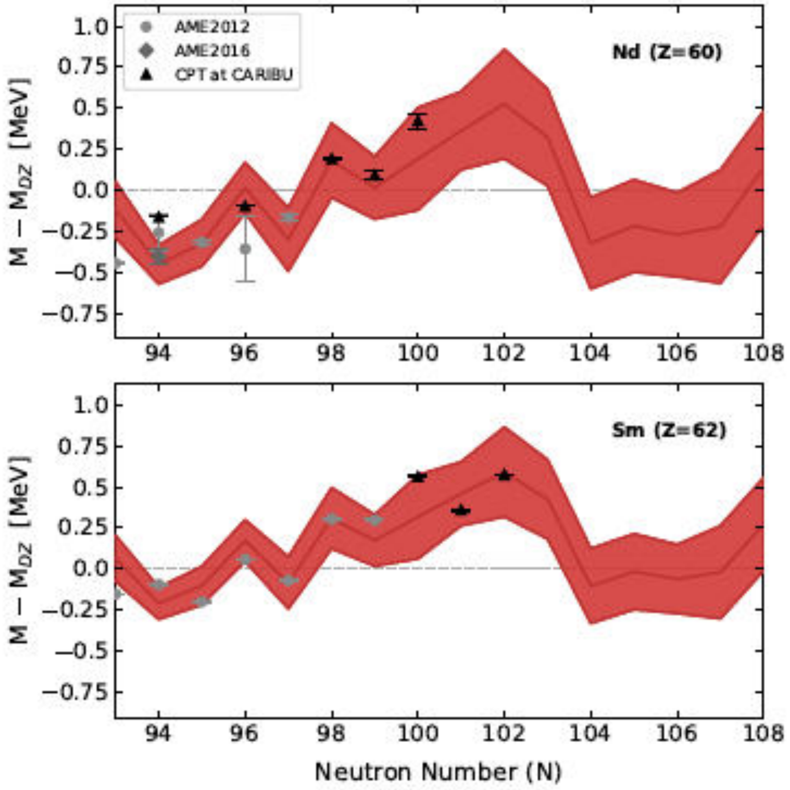


FIG. 2. (Color online) Comparison between experimental values and theoretical predictions (red band) of the nuclear masses relative to the Duflo-Zuker mass model for neodymium and samarium isotopes in a merger accretion disk wind scenario ($s/k_B = 30$, $\tau = 70\,\mathrm{ms}$, and $Y_e = 0.2$).

Varying thermodynamics has little effect

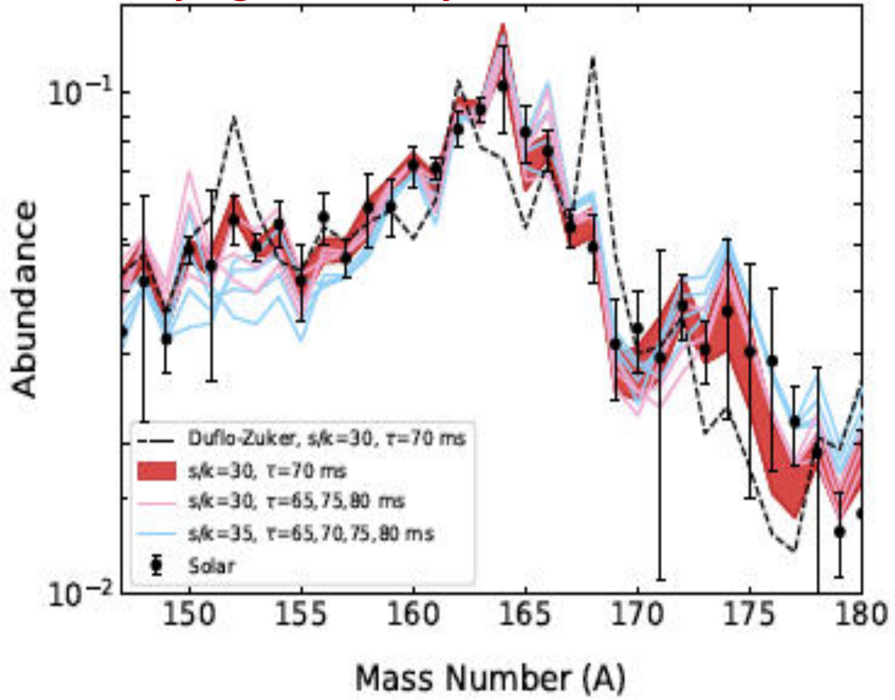
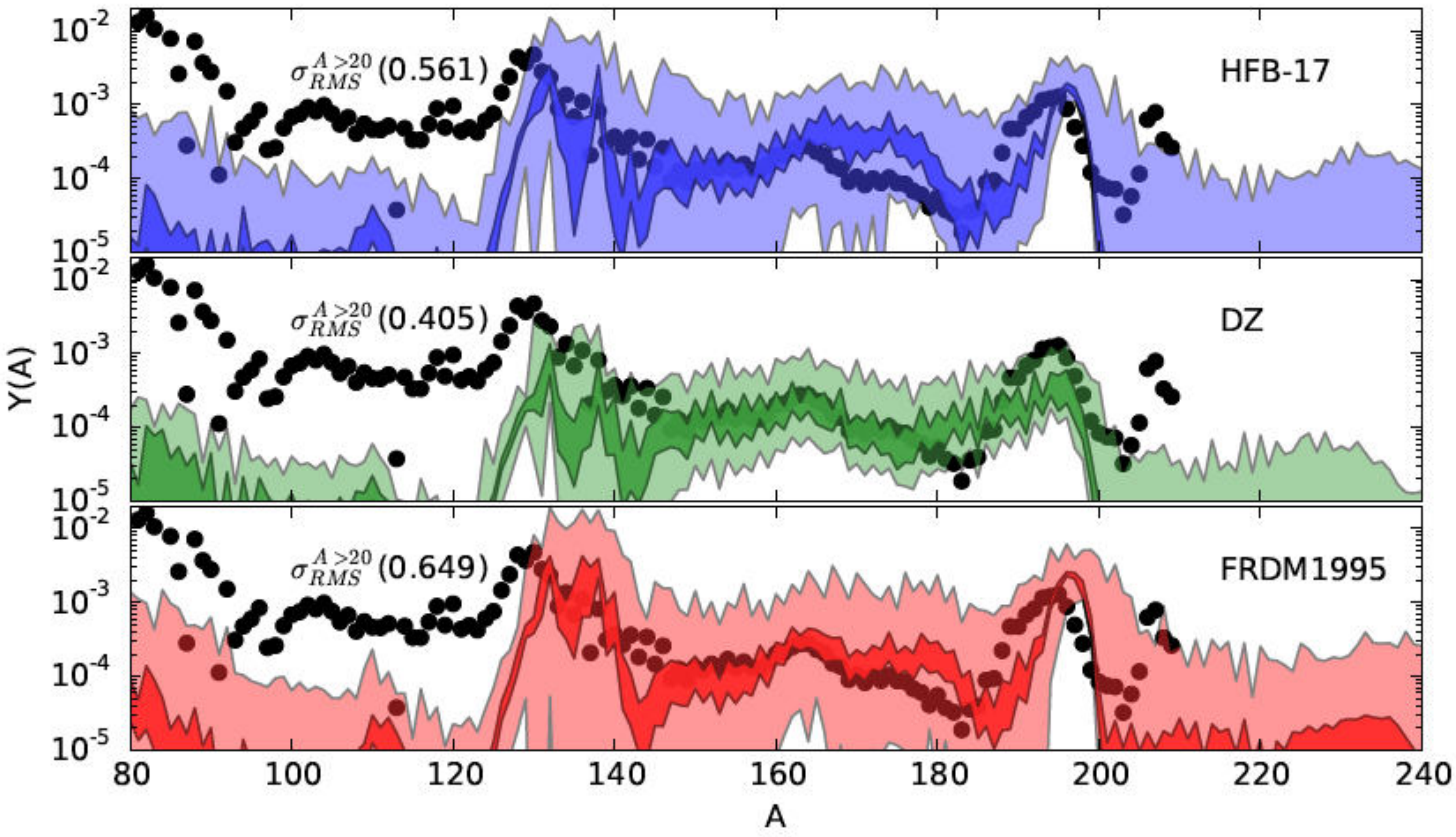


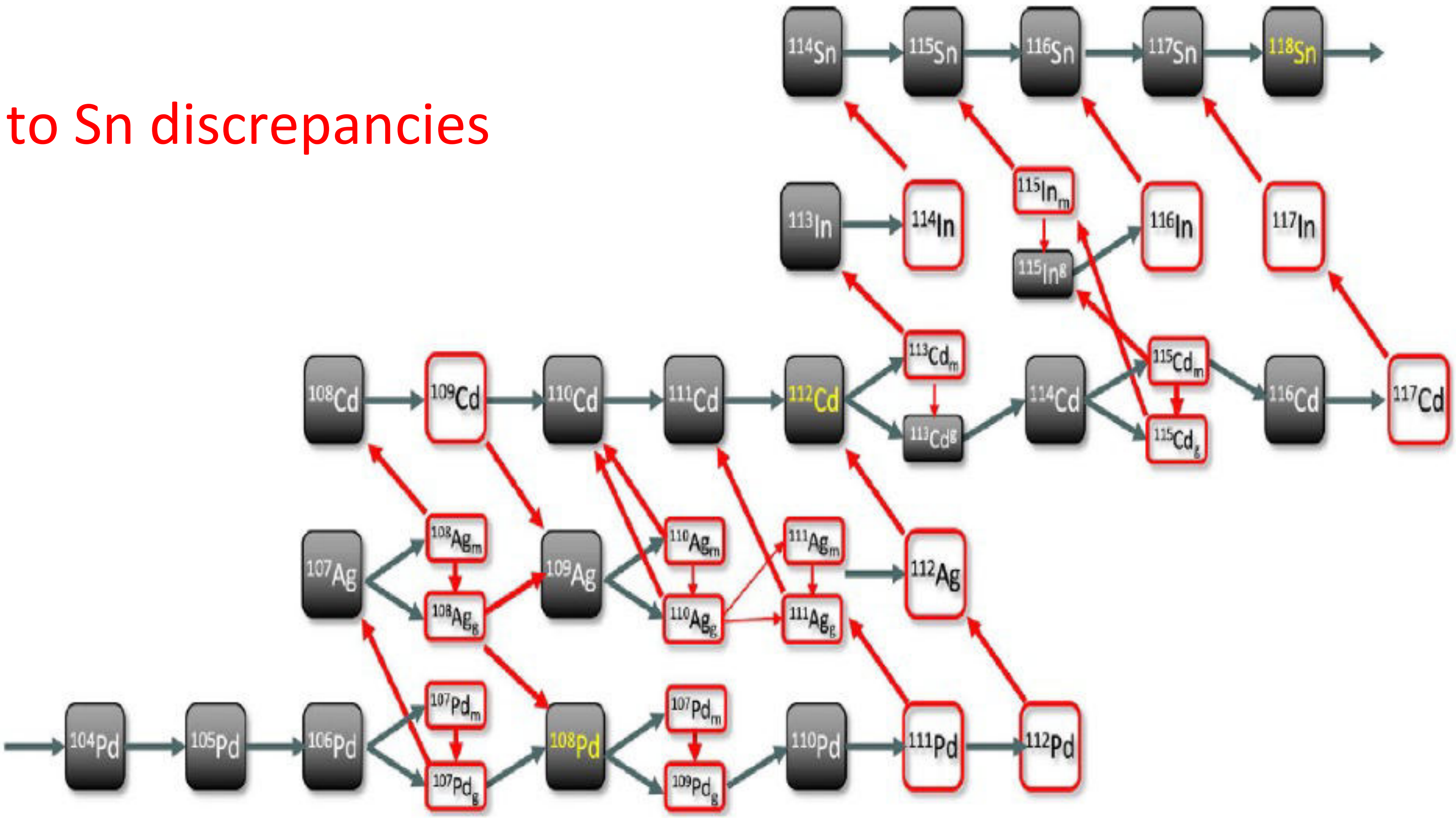
FIG. 3. (Color online) Rare-earth peak abundances using Dulfo-Zuker masses (black dashed) as compared to the result for this same astrophysical trajectory after the algorithm finds the mass predictions of Fig. 2 (solid red band). Pink and blue curves serve to show the change in the abundance pattern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

Hot r-process trajectory

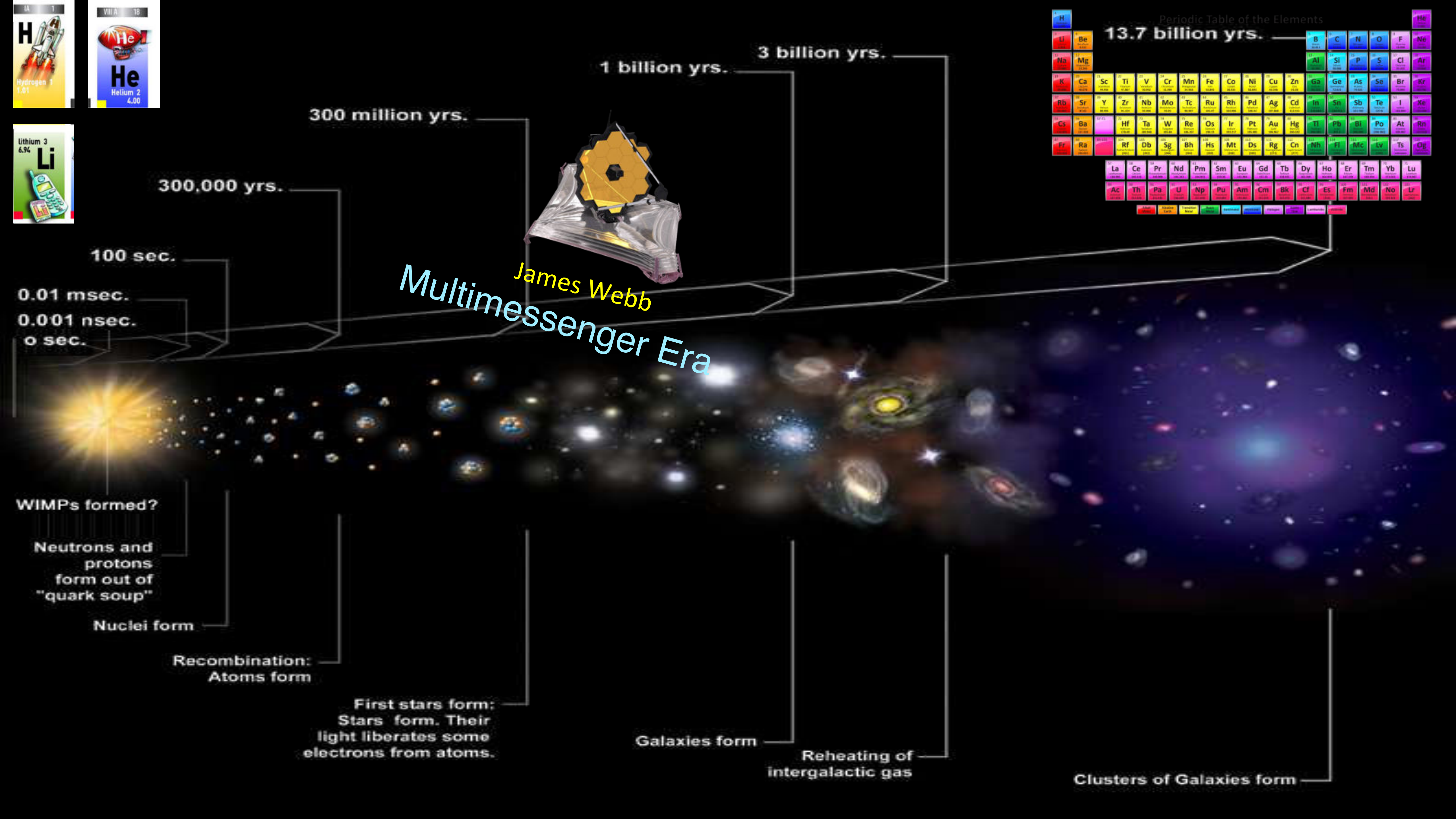


Uncorrelated nuclear mass uncertainties and r-process abundance predictions

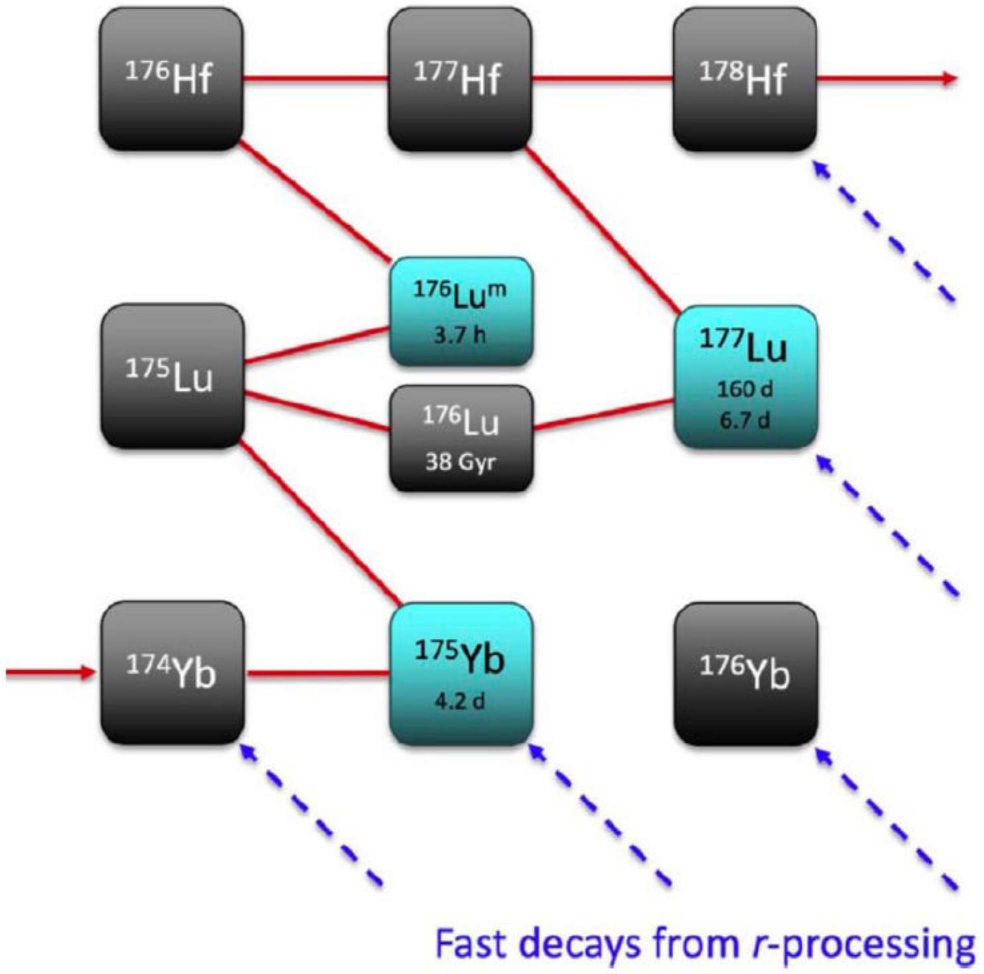
Pd to Sn discrepancies



A. Aprahamian, K. Lee, S. R. Lesher, Eur. Jour. Phys. To be published (2024)
M. M. Busso et al., Front. Astron. Space Sci. 9, 956633 (2022).



H
Hydrogen 1
1.01
He
Helium 2
4.00
Lithium 3
6.94
Li
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



176Hf
177Hf
178Hf
176Lum
3.7 h
175Lu
176Lu
38 Gyr
177Lu
160 d
6.7 d
174Yb
175Yb
4.2 d
176Yb
Fast decays from r-processing