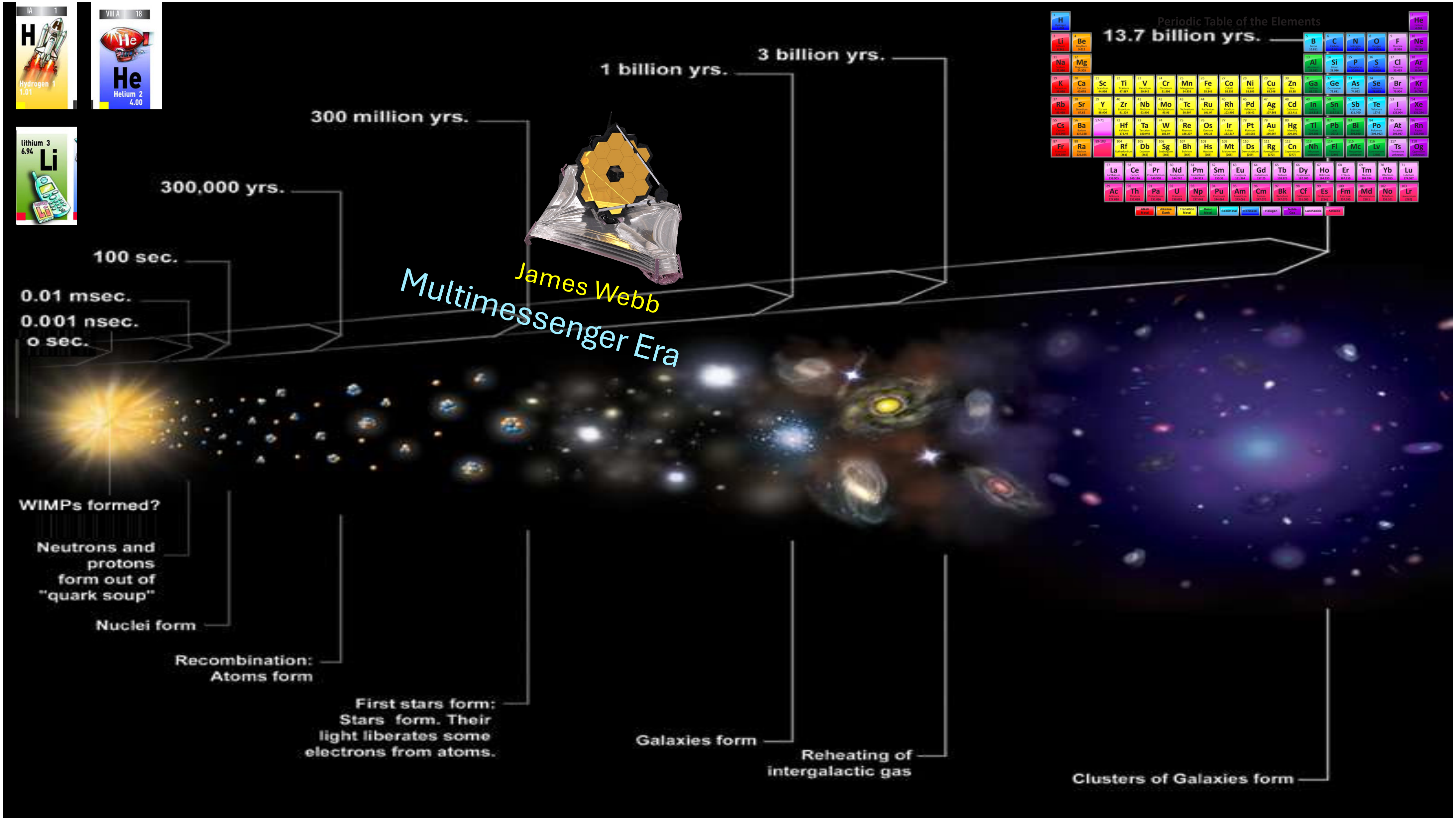
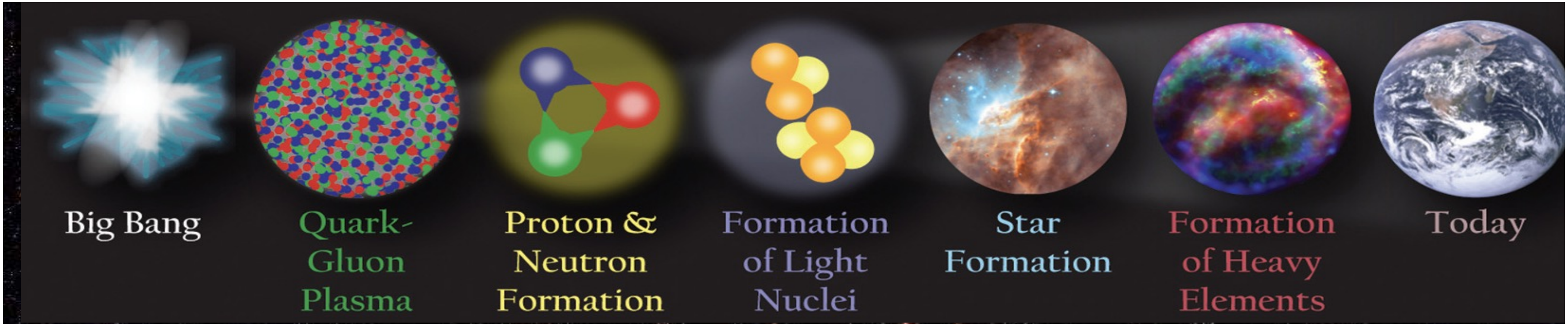
Were The Superheavy Elements made in Space?

Ani Aprahamian
University of Notre Dame
January 28, 2025

JINA-CEE

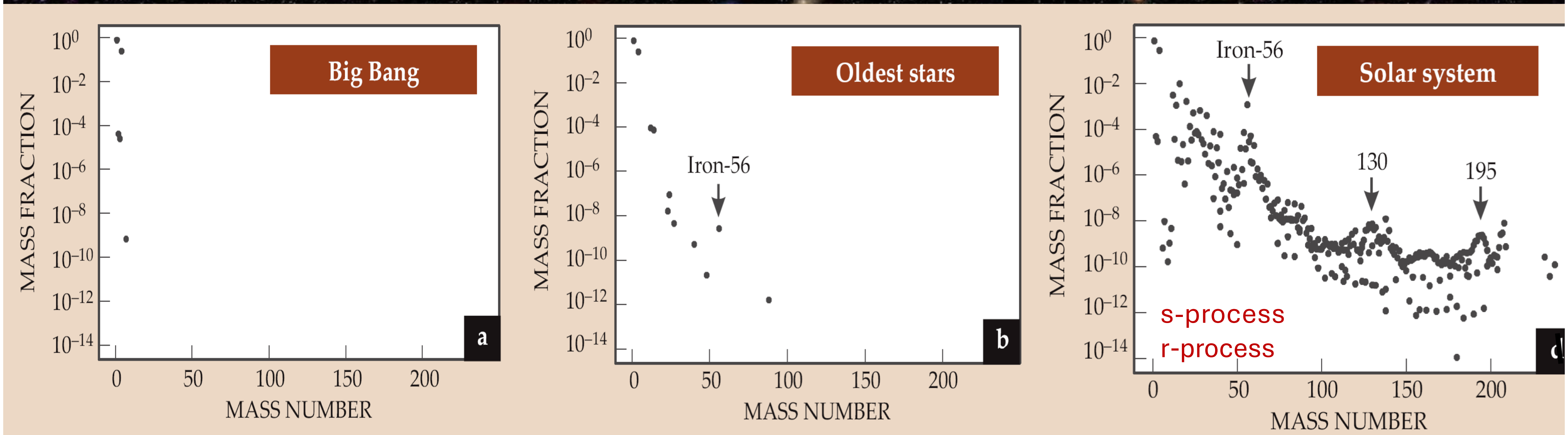


H
Hydrogen 1
1.01
He
Helium 2
4.00
Lithium 3
6.94
Li
13.7 billion yrs.
3 billion yrs.
1 billion yrs.
300 million yrs.
300,000 yrs.
100 sec.
0.01 msec.
0.001 nsec.
o sec.
James Webb
Multimessenger Era
WIMPs formed?
Neutrons and protons form out of "quark soup"
Nuclei form
Recombination: Atoms form
First 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



How were elements Fe to U made?

How did the basic building blocks of the universe originate?

How expansive is the material world?

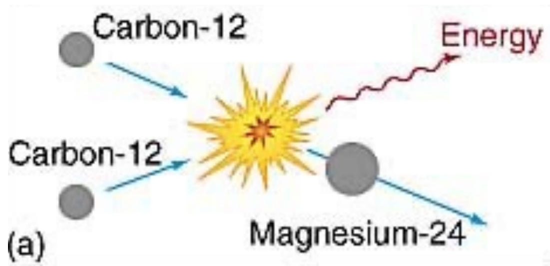
Where are the boundaries?

How do we determine the limits

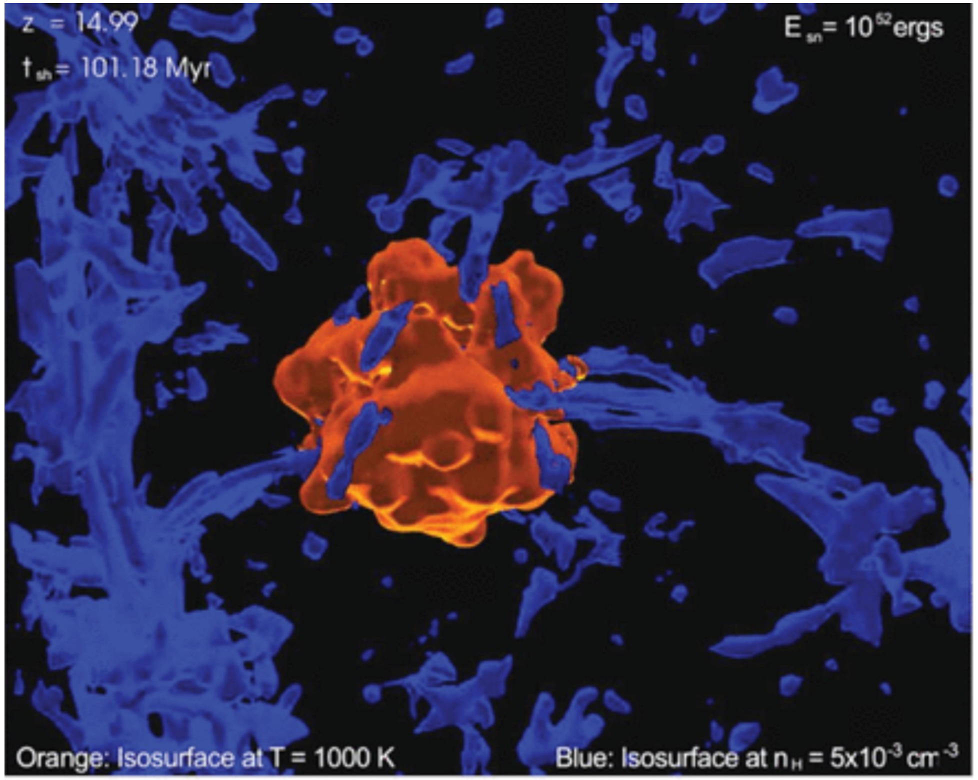
Fusion Reactions in Stars

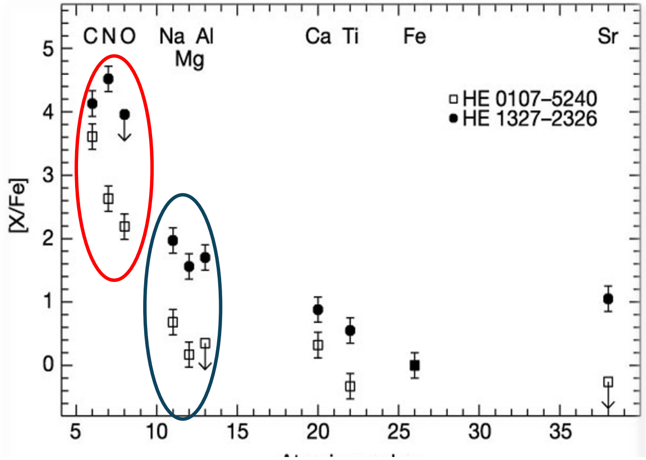
- First stars: fusion for mid-mass elements

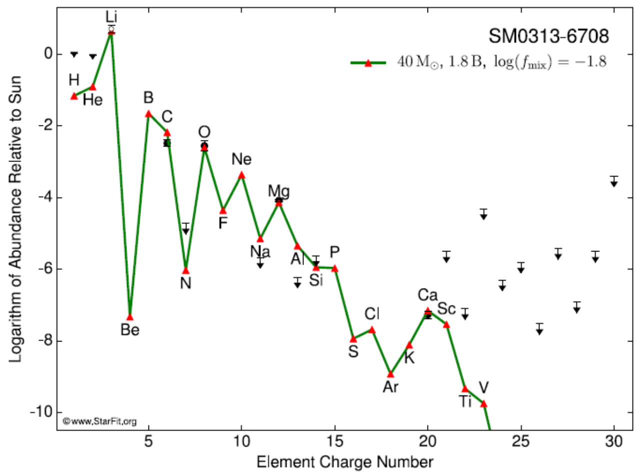
- Late stars: post-red-giant stellar evolution, carbon and oxygen burning
- Ignition of type Ia supernovae
- Ignition of superbursts



The first supernova







The first supernovae explode, ejecting carbon, nitrogen, oxygen, magnesium, silicon, and iron as seed for the next star generation.

Dissociation of elements at high temperature and density conditions?

Periodic Table of the Elements

1 H Hydrogen 1.008																	2 He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180
11 Na Sodium 22.990	12 Mg Magnesium 24.305											13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.867	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.845	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.38	31 Ga Gallium 69.723	32 Ge Germanium 72.631	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.798
37 Rb Rubidium 85.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.711	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.294
55 Cs Cesium 132.905	56 Ba Barium 137.328	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.84	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.217	78 Pt Platinum 195.085	79 Au Gold 196.967	80 Hg Mercury 200.592	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Nh Nihonium unknown	114 Fl Flerovium [289]	115 Mc Moscovium unknown	116 Lv Livermorium [298]	117 Ts Tennessine unknown	118 Og Oganesson unknown

57 La Lanthanum 138.905	58 Ce Cerium 140.116	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.242	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.964	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.500	67 Ho Holmium 164.930	68 Er Erbium 167.259	69 Tm Thulium 168.934	70 Yb Ytterbium 173.055	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

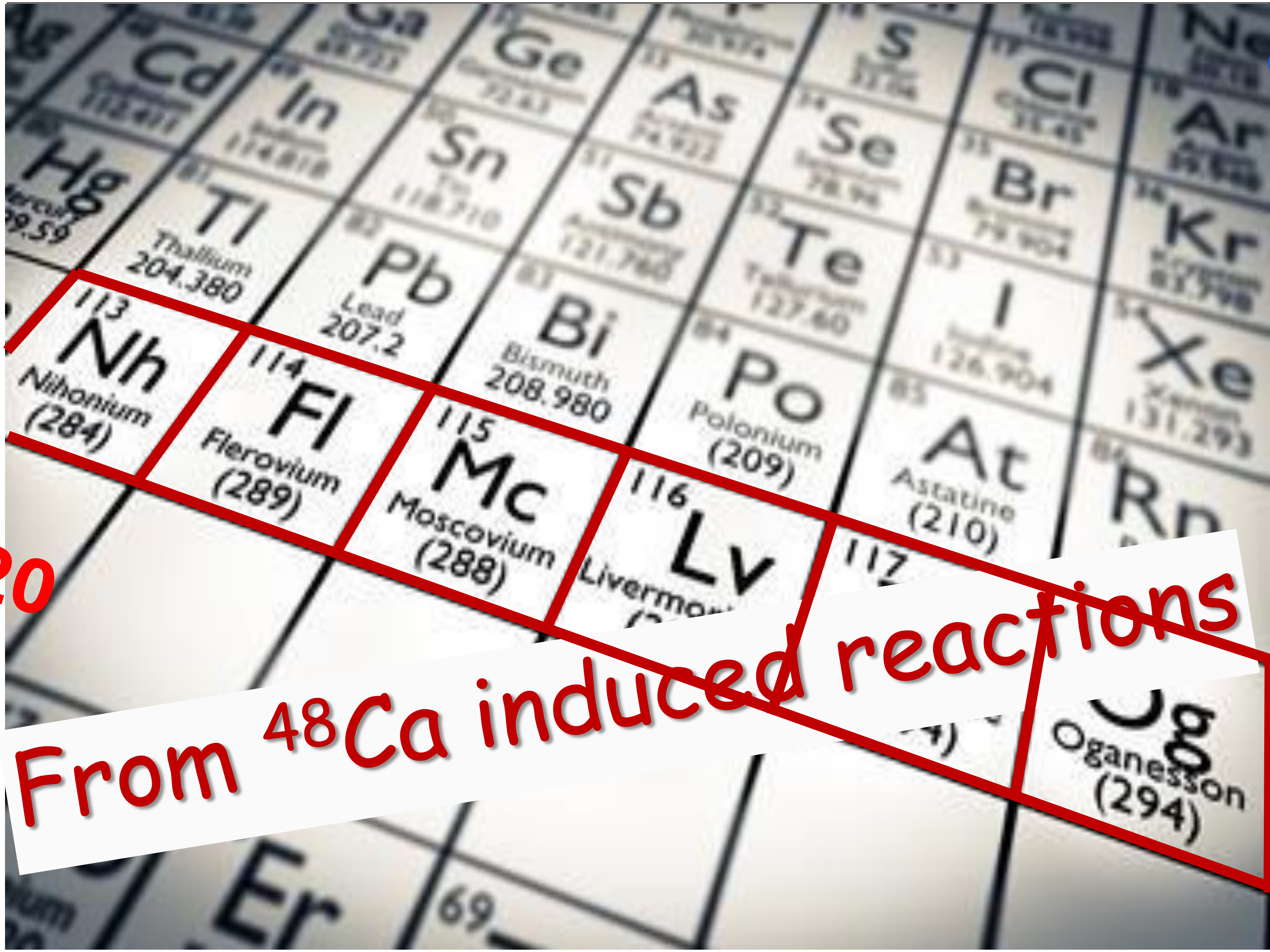
Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetal	Nonmetal	Halogen	Noble Gas	Lanthanide	Actinide

Are there more elements?

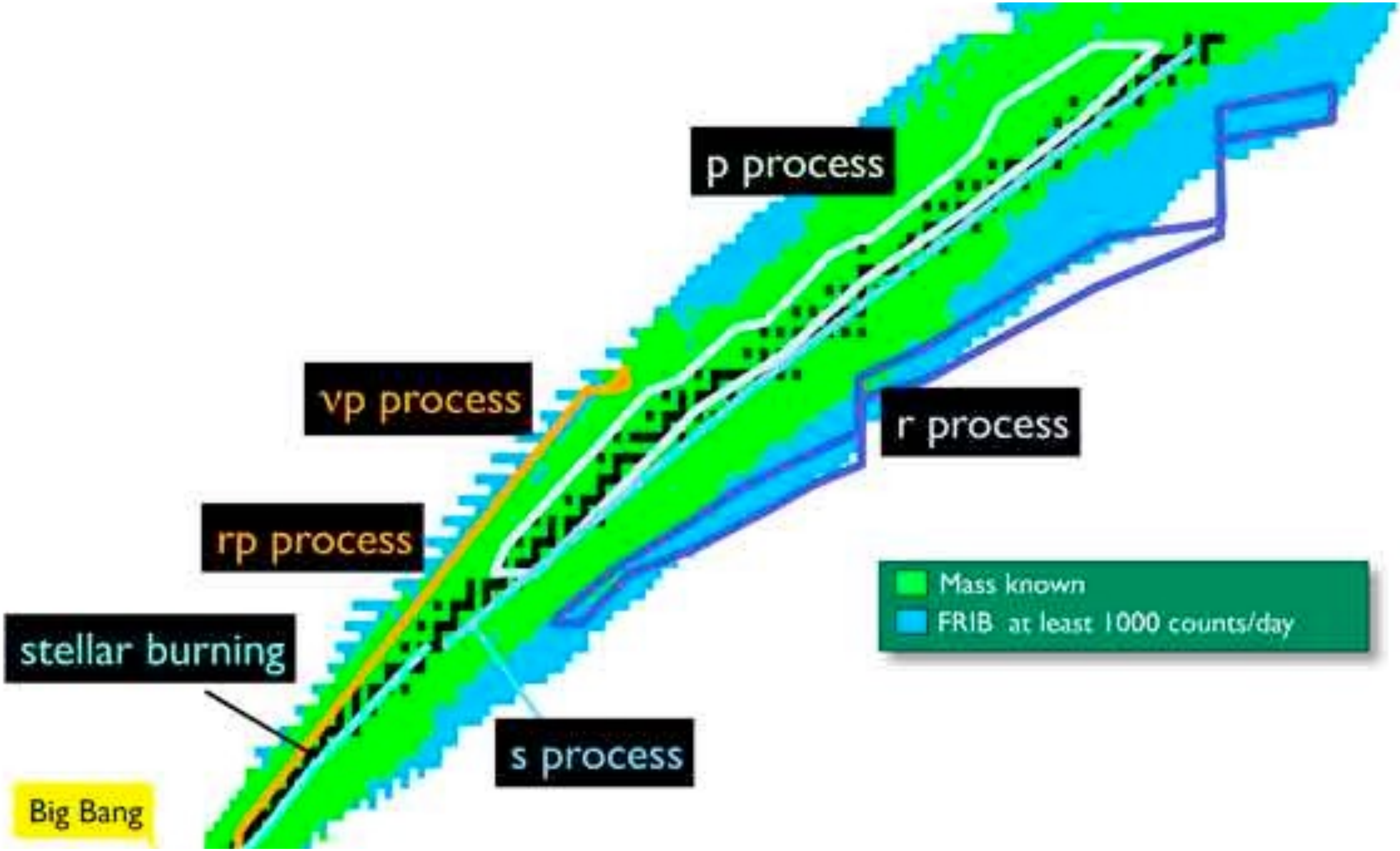
104 Rf
Rutherfordium
1964
Target ^{242}Pu, ^{249}Cf
105 Db
Dubnium
1970
Target ^{249}Bk, ^{249,250}Cf
106 Sg
Seaborgium
1974
Target ^{249}Cf
113 Nh
Nihonium
2004
Target ^{243}Am
(decay from 115)
114 Fl
Flerovium
2000
Target ^{244}Pu
115 Mc
Moscovium
2004
Target ^{243}Am
116 Lv
Livermorium
2005
Target ^{245,248}Cm
117 Ts
Tennessine
2010
Target ^{249}Bk
118 Og
Oganesson
2006
Target ^{249}Cf
Kit Chapman
SUPERHEAVY
Making and Breaking the Periodic Table
BLOOMSBURY

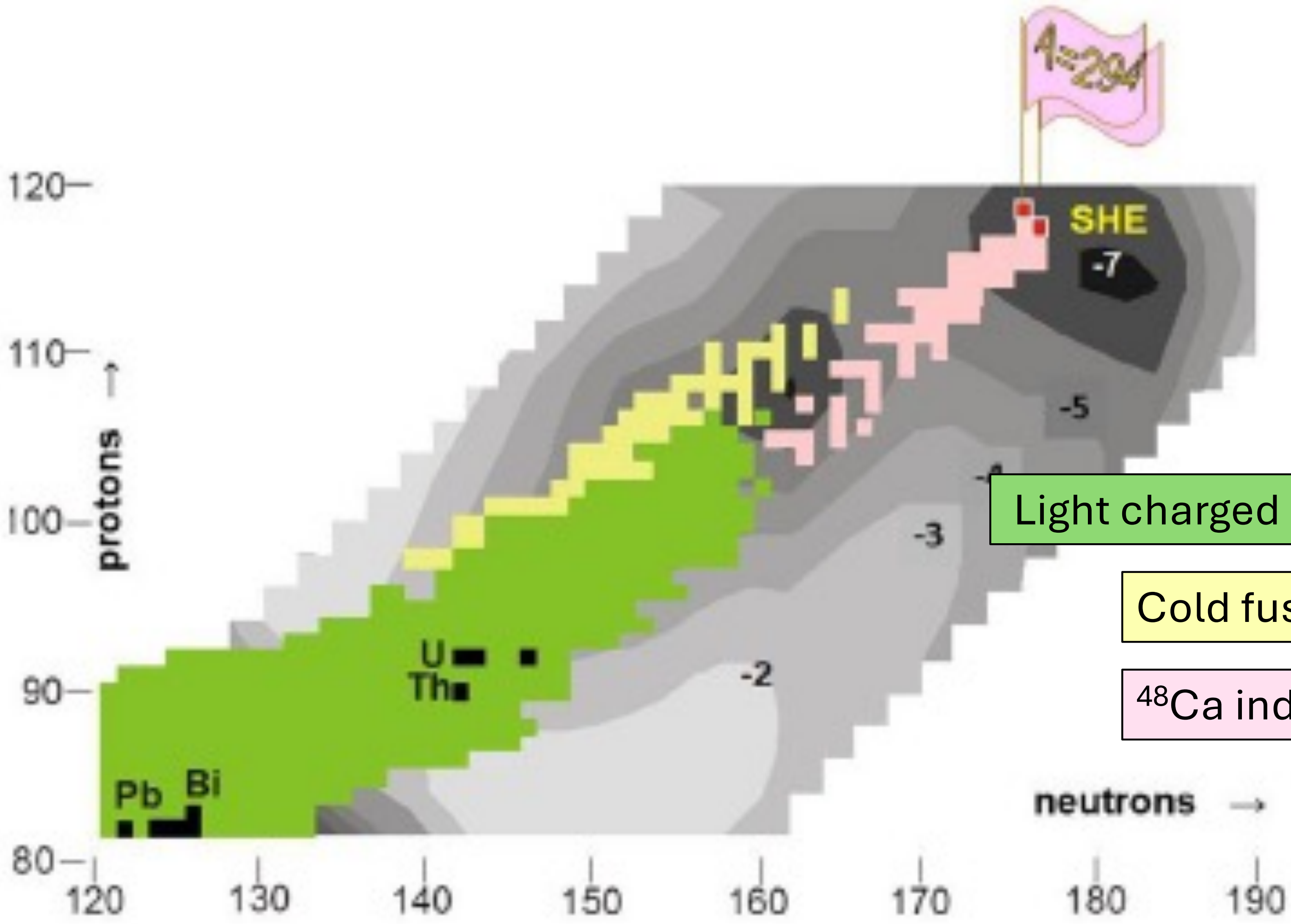
Collaboration
LLNL
JINR
ORNL

Z=120



Z=174


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



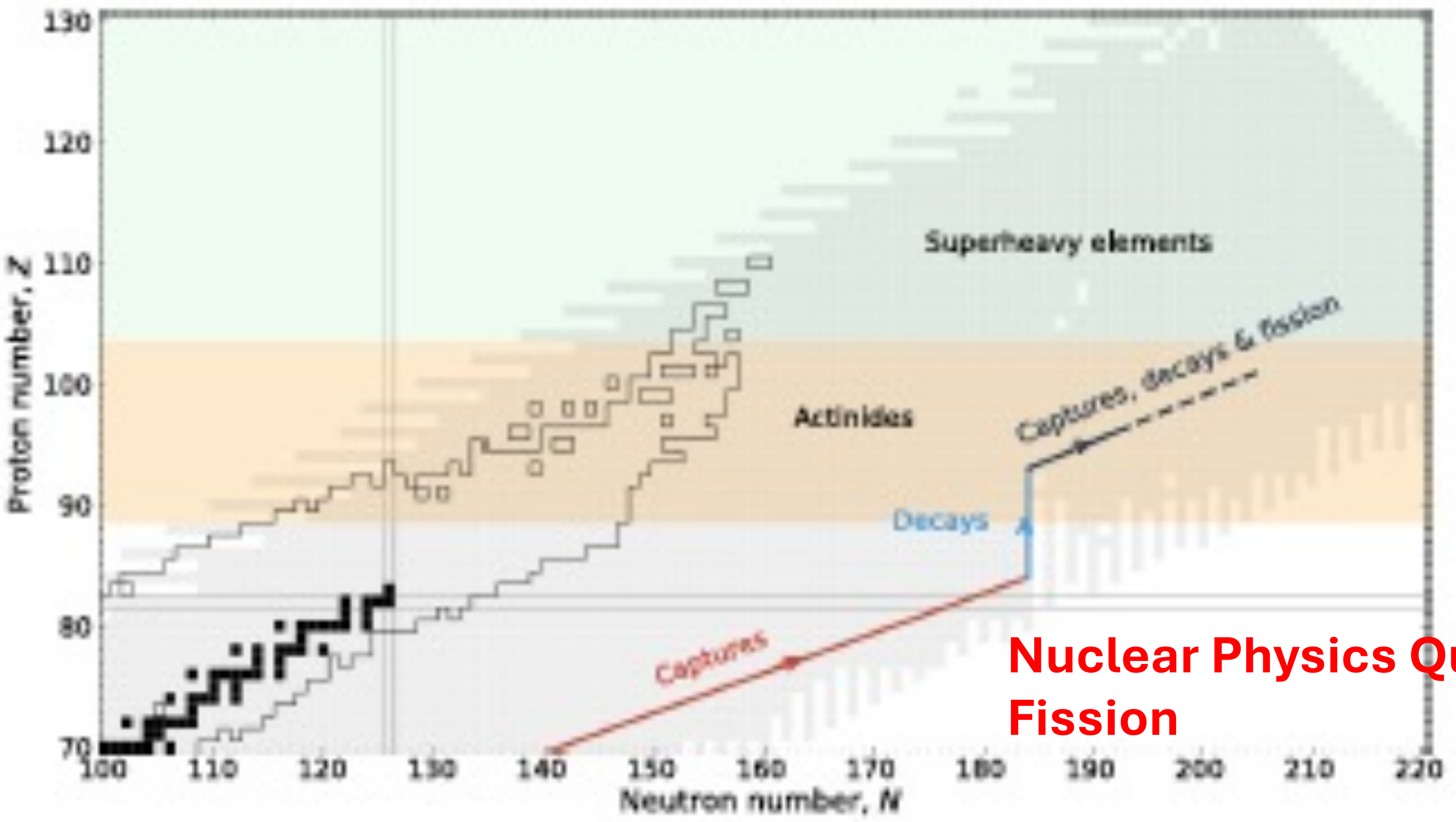
Light charged particles and neutrons

Cold fusion reactions

^{48}Ca induced reactions

Oganessian, Eur. Journal of Physics A, 60:227 (2024)

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



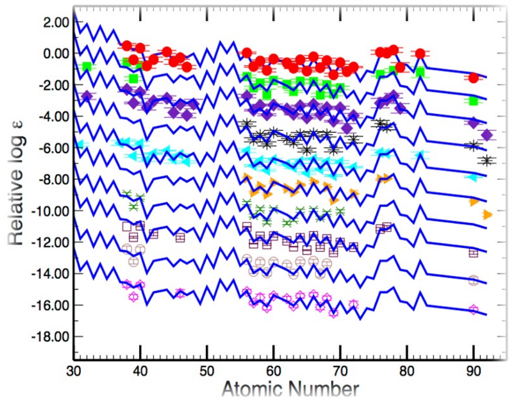
Nuclear Physics Question: Fission

Were Superheavies made in the r-process?

Explosive

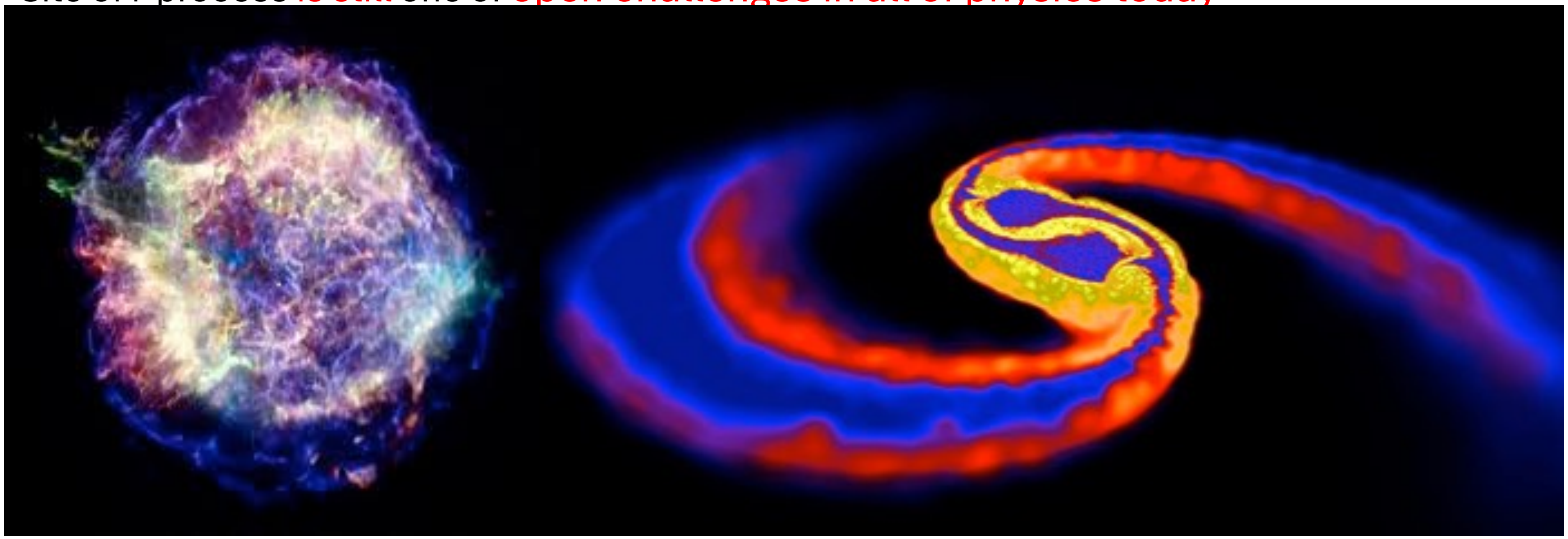
r-process

Cowan et al. 2011

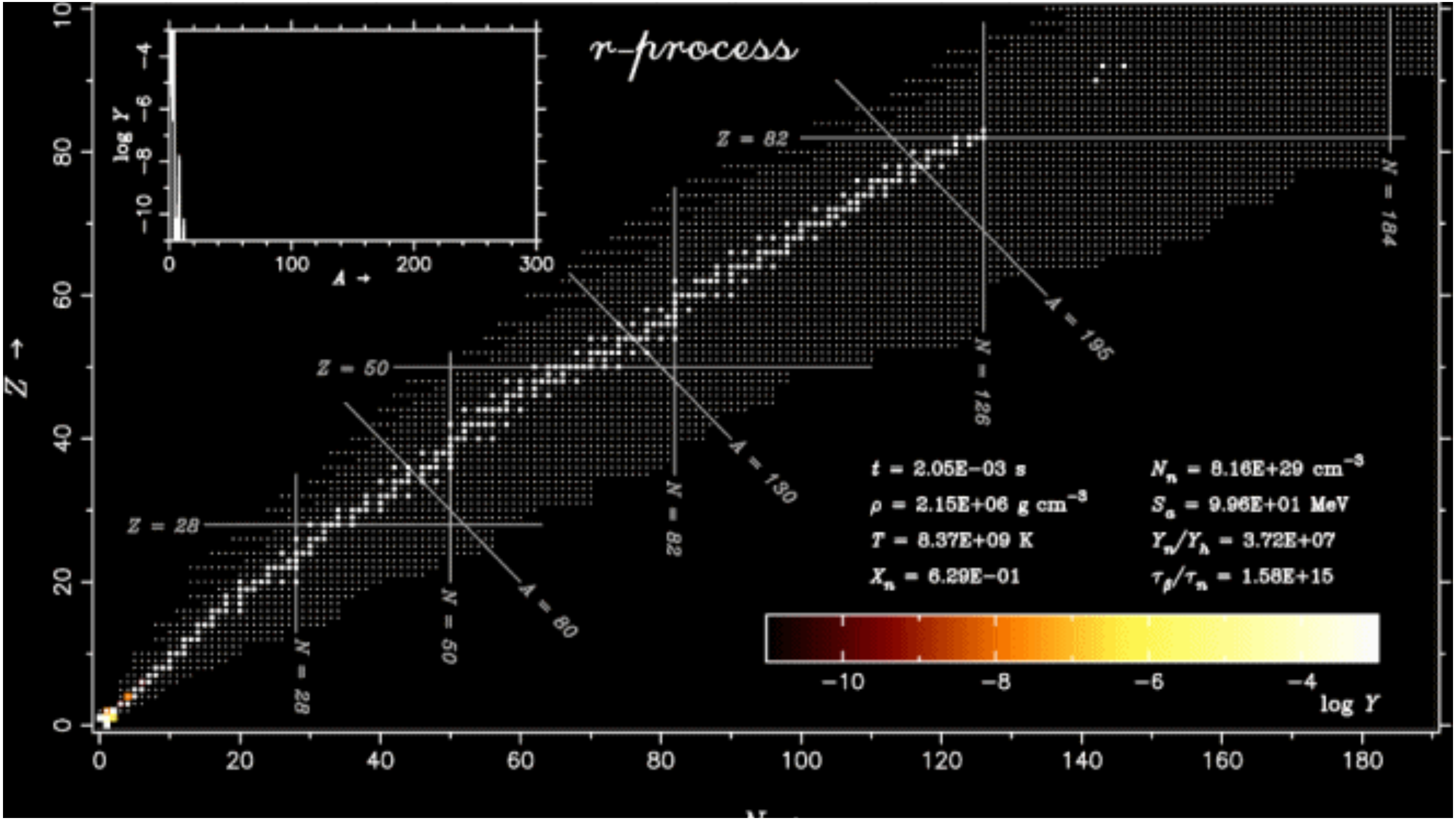


Origin of more than 50% of all the elements beyond iron

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

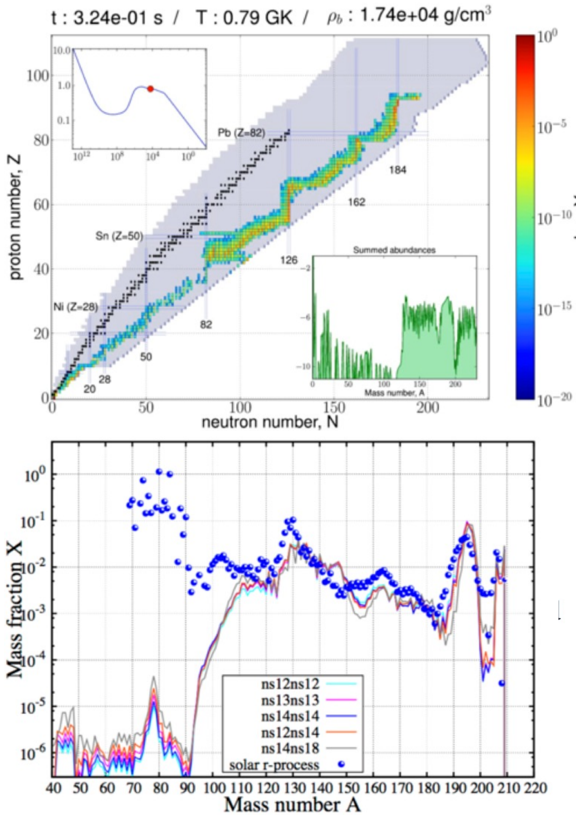


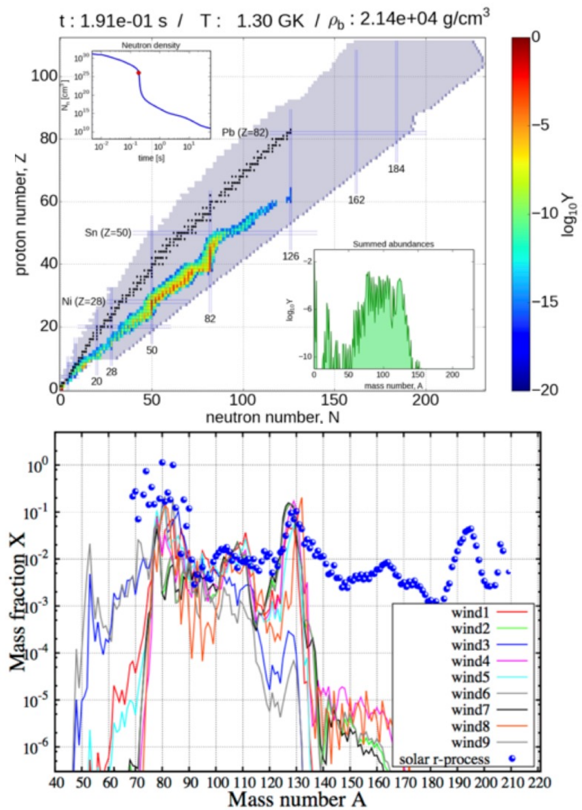
Temperature, density as a function of time, initial compositions, neutrons


r-process
log Y
A →
Z →
N →
Z = 28
Z = 50
Z = 82
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
Sn = 9.96E+01 MeV
Yn/Yh = 3.72E+07
τβ/τn = 1.58E+15

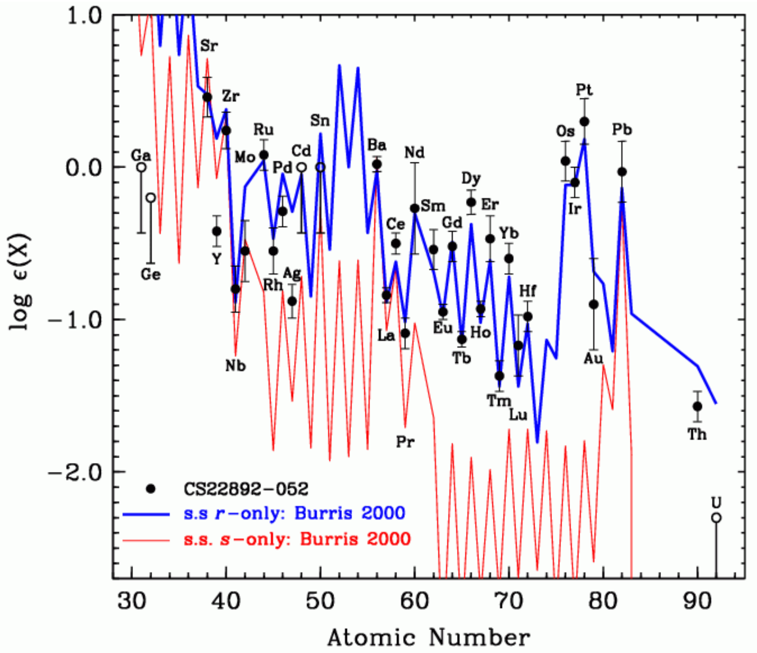
where is the site of the r-process?

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

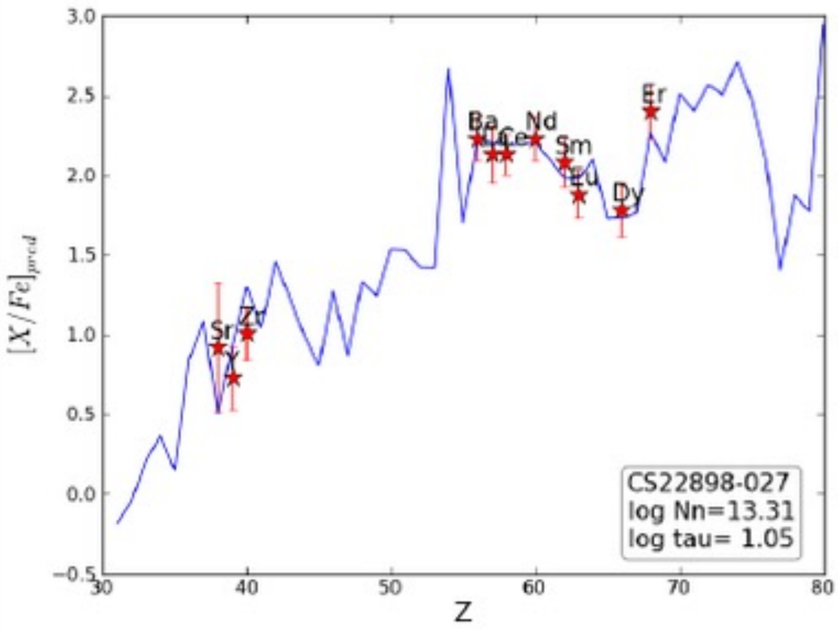




Abundances from other neutron induced nucleosynthesis processes



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

2004 Observation: R-process evidence in delayed MeV emission from SGR 1806-20 magnetar giant flare

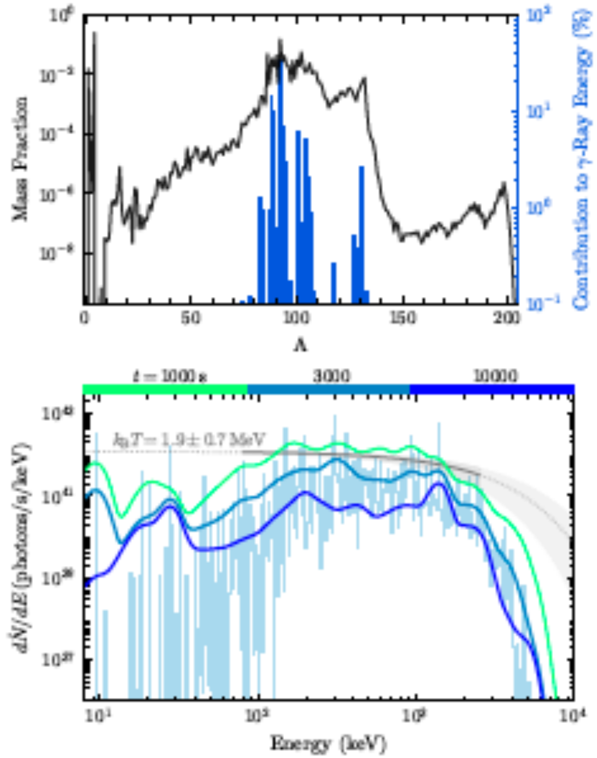
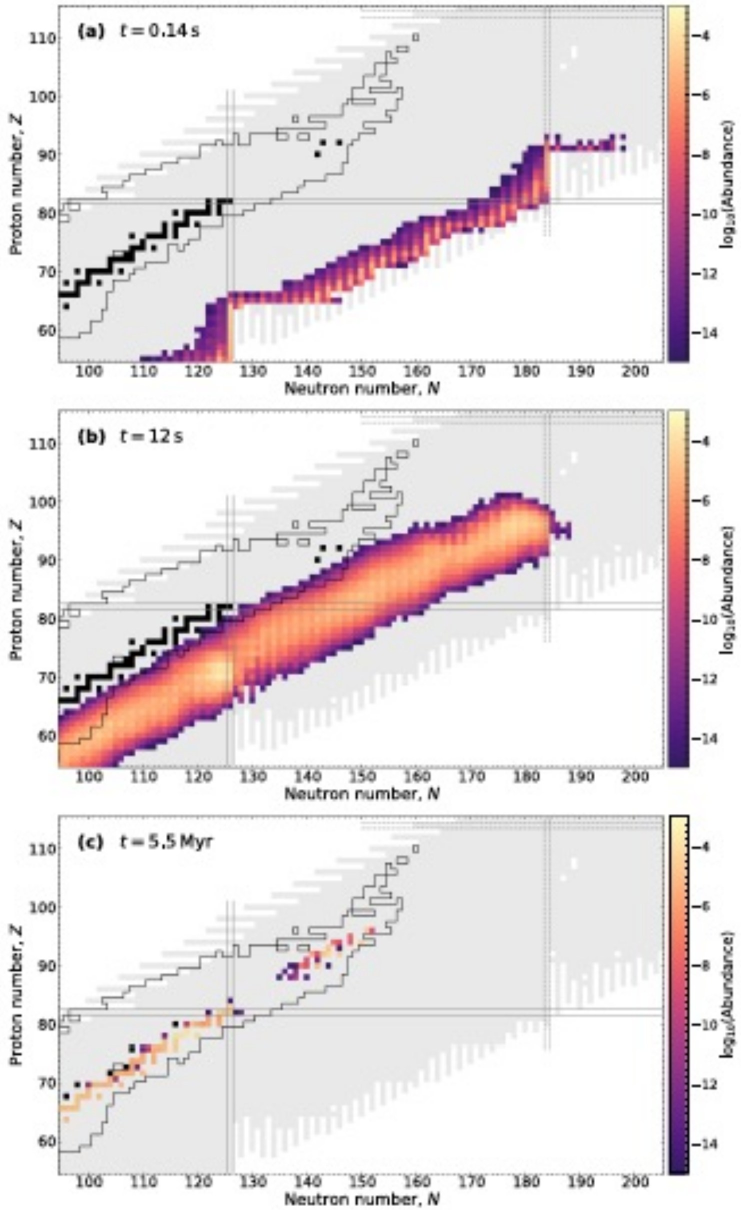


Figure 3. *Top panel:* Mass fraction of synthesized nuclei as a function of atomic mass A from our fiducial model which approximately reproduces the late-time gamma-ray emission light-curve from SGR 1806-20 (Fig. 2). Vertical blue bars (right axis) show the individual percentage contributions of radioactive nuclei to the total gamma-ray line luminosity in the time interval $t = 10^3$–10^4 s. *Bottom panel:* Synthetic gamma-ray spectra from the fiducial model at three snapshots, $t = 1000, 3000, 12000$ s, accounting for Doppler broadening due to the ejecta expansion but excluding extinction effects. For the spectrum at $t = 3000$ s we also show with lighter blue lines the intrinsic (i.e., non-broadened) decay lines which contribute to the total spectrum. A dark gray band shows the bremsstrahlung spectral fit made by Boggs

Table 1. Prominent Spectral Lines ($t \approx 10^3$–10^4 s)

Isotope	Daughter	$t_{1/2}$ (s)	Energy (keV)	Intensity[a]
^{88}Kr	^{88}Rb	10170	27.5	1.9
			196.3	26.0
^{89}Rb	^{89}Sr	919	657.8	10.8
			1031.9	62.9
			1248.1	45.9
			2195.9	14.5
			2570.2	10.7
^{90}Rb	^{90}Sr	158	831.7	39.9
			3383.2	6.7
			3534.2	4.0
			4135.5	6.7
			4365.9	8.0
			4646.5	2.3
			5187.4	1.2
^{92}Sr	^{92}Y	9396	1383.9	90.0
^{93}Sr	^{93}Y	445	168.5	18.4
			260.1	7.4
^{94}Y	^{94}Zr	1122	550.9	4.9
			918.7	56.0
			1138.9	6.0
^{101}Mo	^{101}Tc	877	9.3	2.1
			80.9	3.7
			191.9	18.2
^{101}Tc	^{101}Ru	852	306.8	88.7
^{104}Tc	^{104}Ru	1098	358.0	89.0
^{128}Sn	^{128}Sb	3544	32.1	4.0
			45.7	13.0
			75.1	27.7

[a] Absolute intensity, $b_i I_{ij}$ (Eq. (9)), per 100 counts.



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

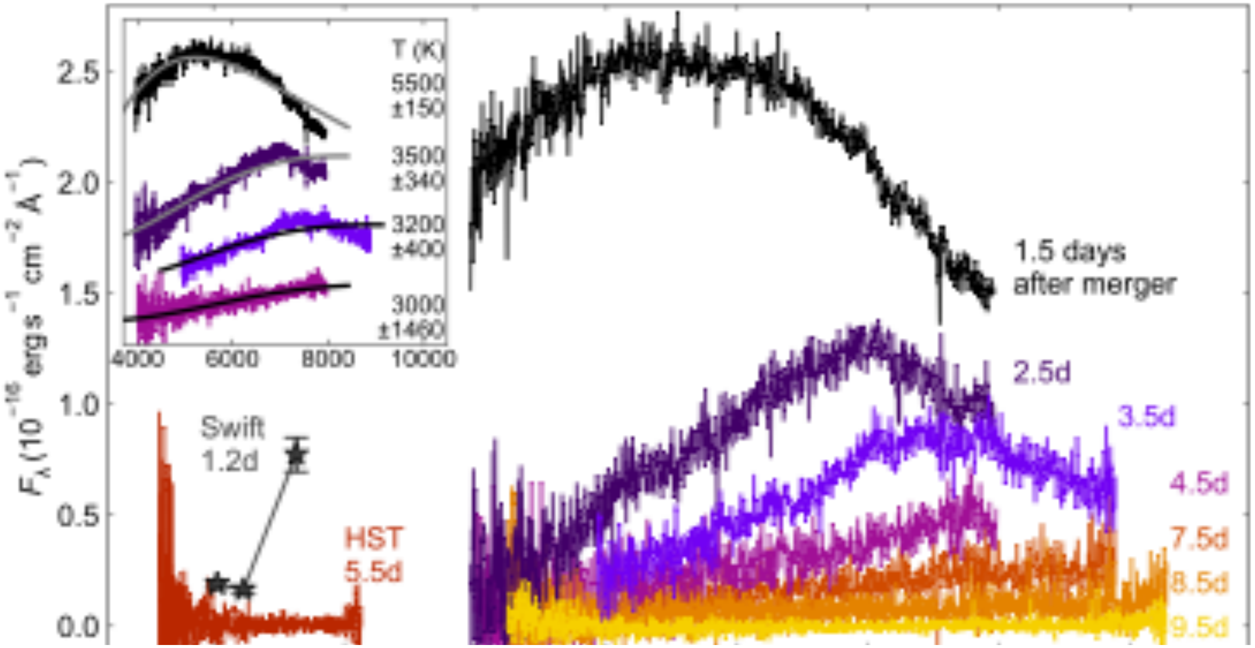
E. M. Holmbeck[1,a], **T. M. Sprouse**[2,3,b], **M. R. Mumpower**[2,3,c]

[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



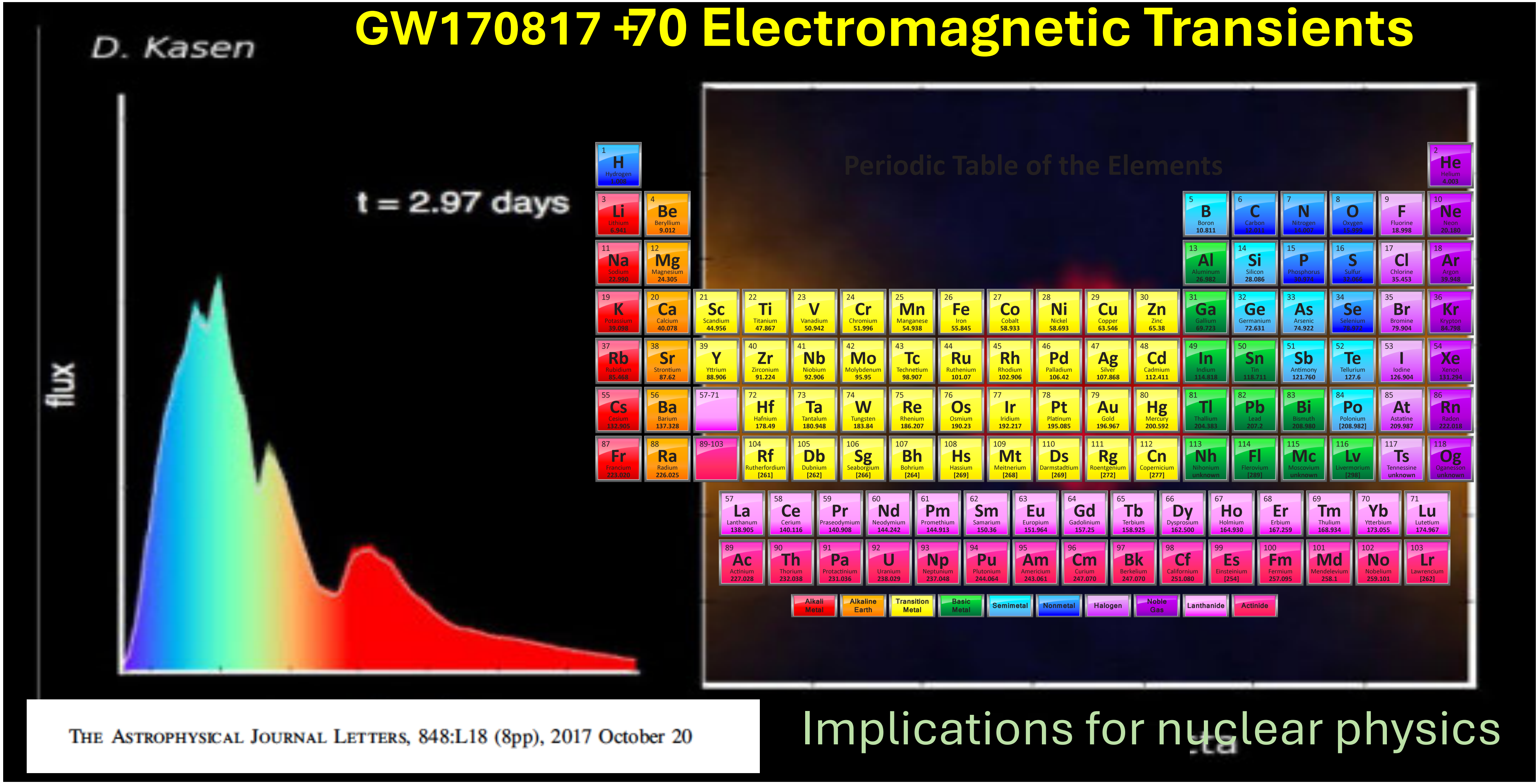
THE ASTROPHYSICAL JOURNAL LETTERS, 848:L18 (8pp), 2017 October 20

Lu visible signatures go into the IR

James Webb

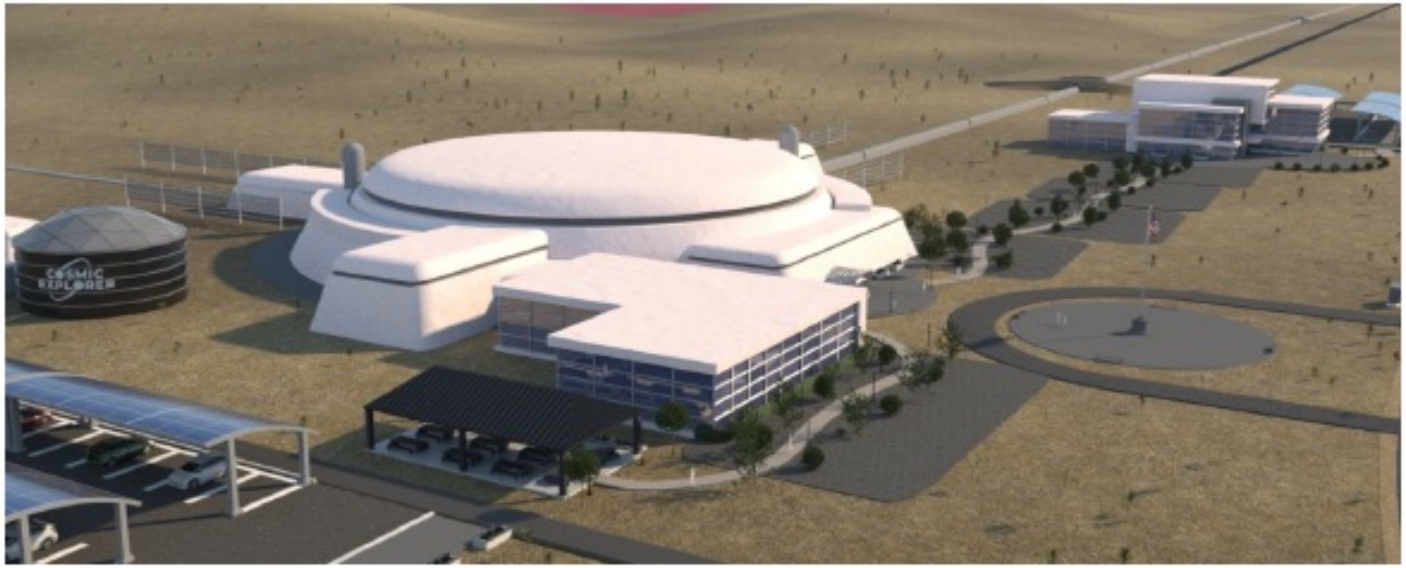
Does the r-process make the actinides?

Fission



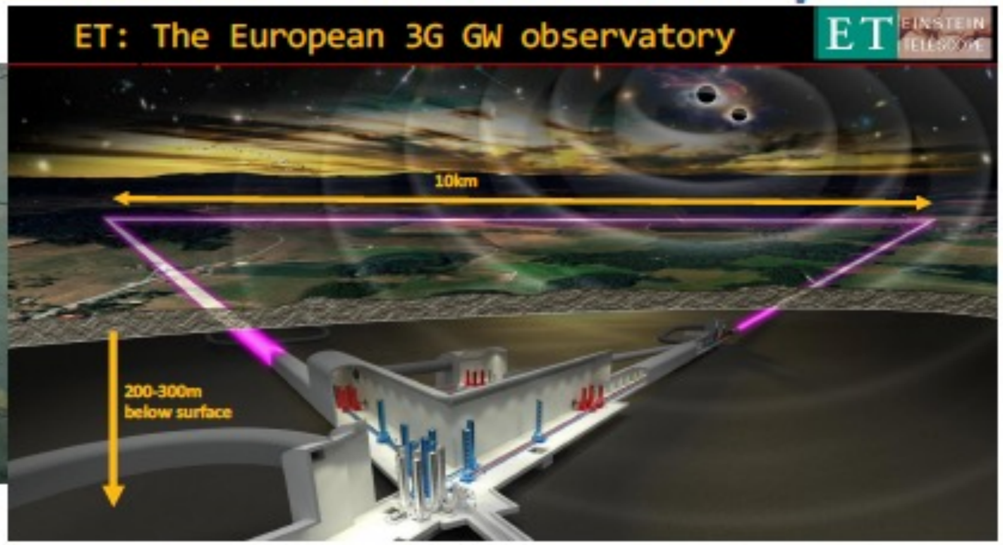
LIGO, VIRGO, GAGRA began new observation run on May 24, 2023

Next Generation considerations



Cosmic Explorer

Einstein Telescope



LIGO - India

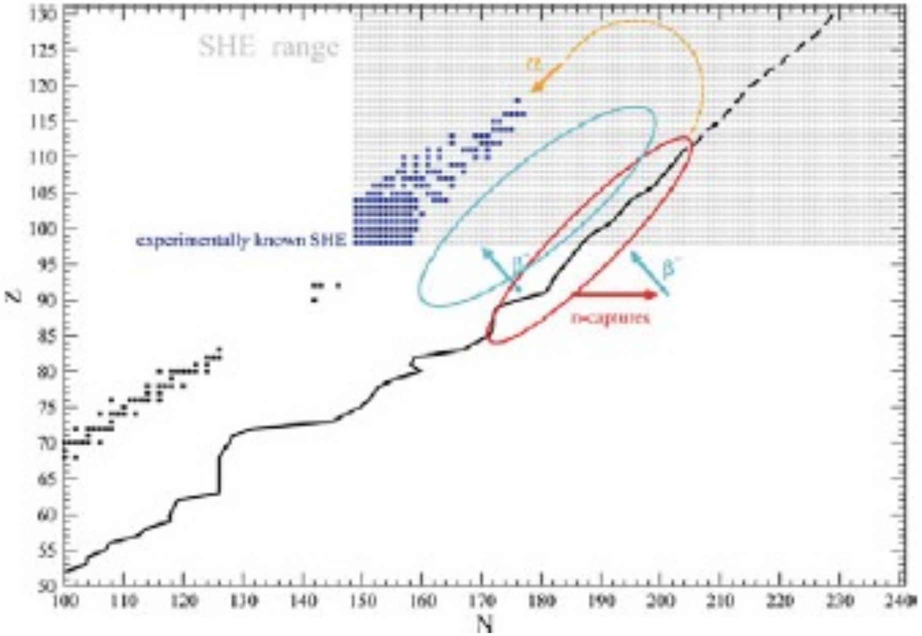
Eur. Phys. J. A (2012) **48**: 122
DOI 10.1140/epja/i2012-12122-6

THE EUROPEAN PHYSICAL JOURNAL A

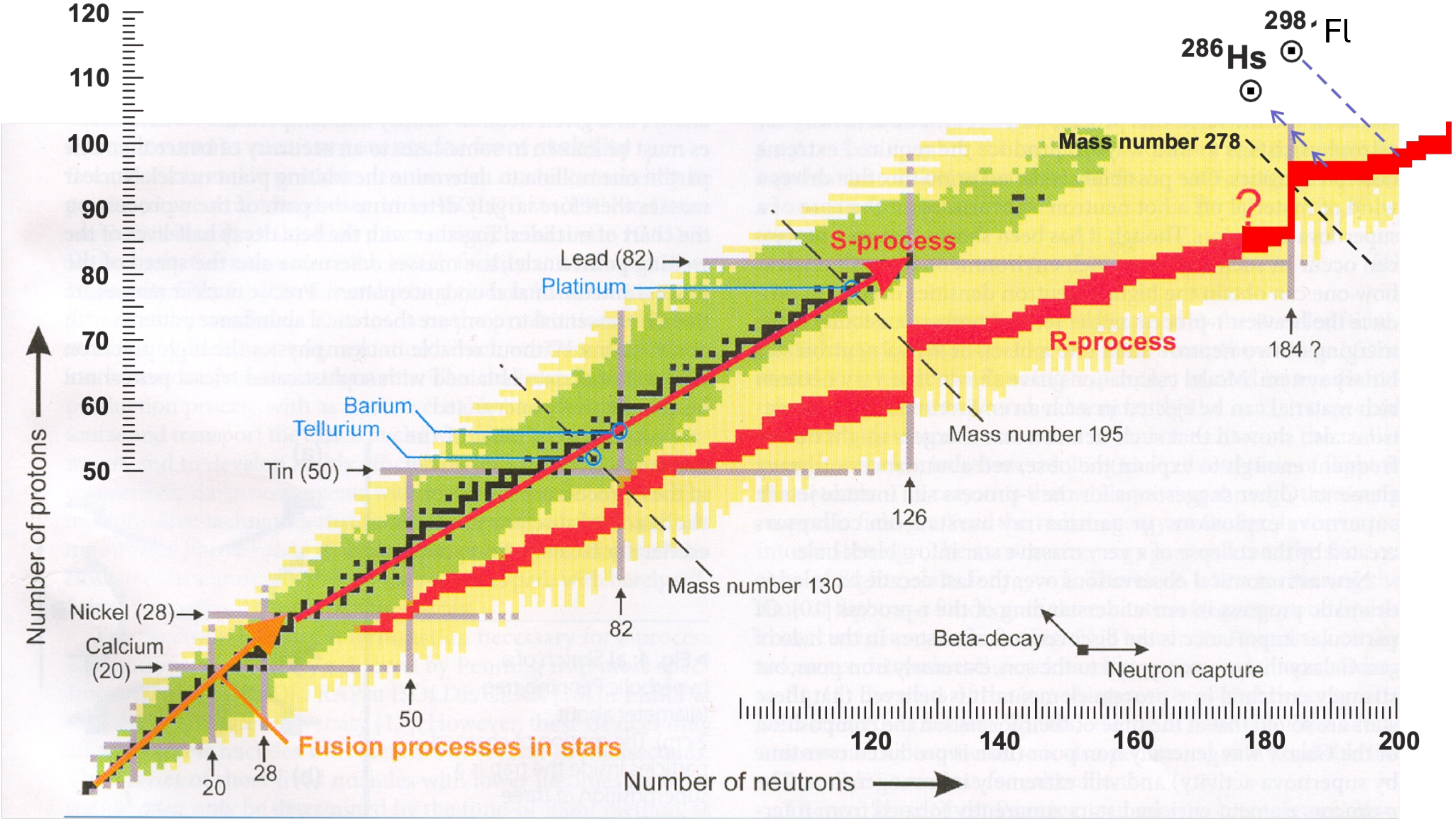
Regular Article – Theoretical Physics

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]

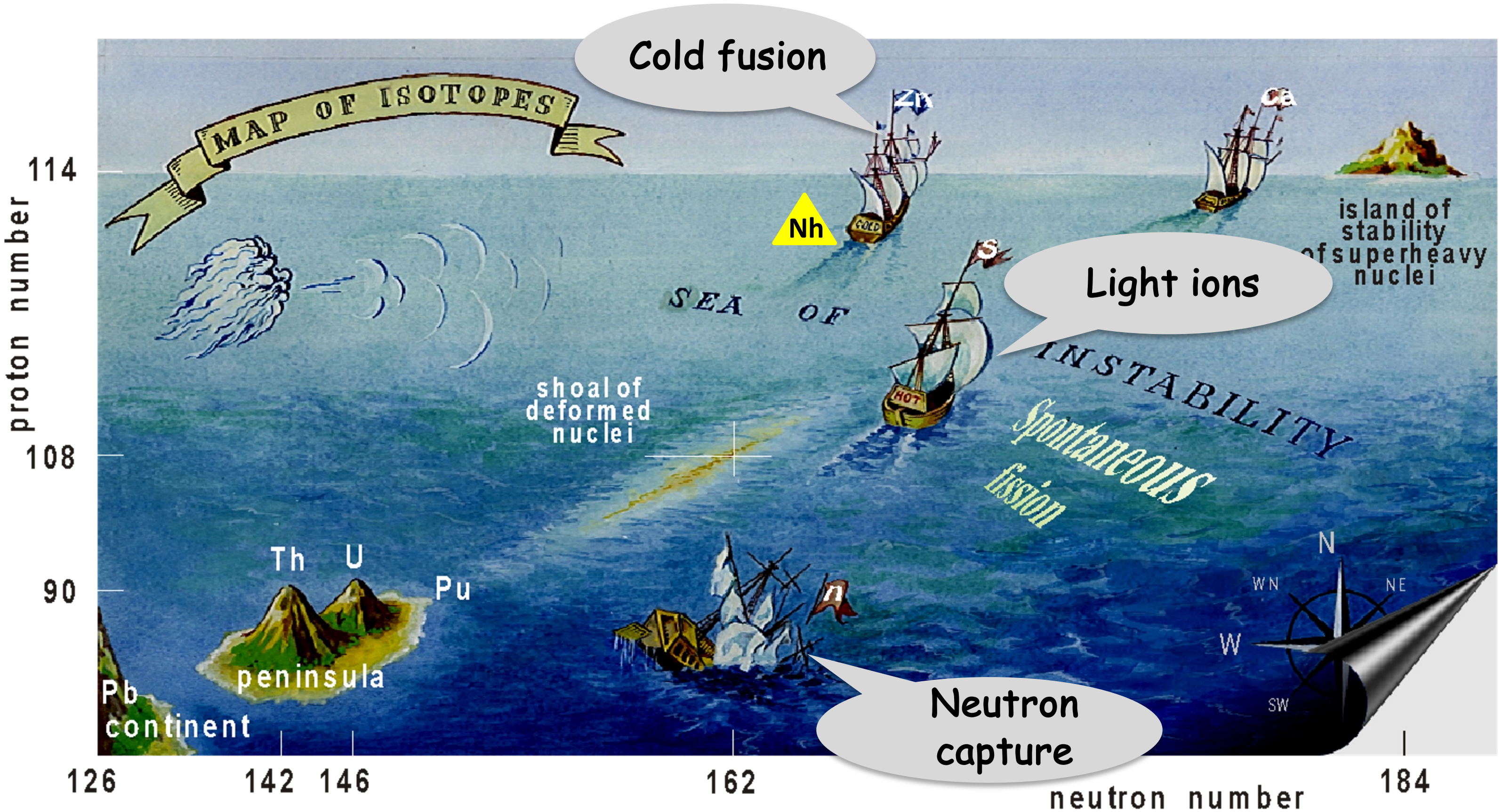


Are superheavy elements produced in the r-process?



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

Reactions of synthesis



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

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

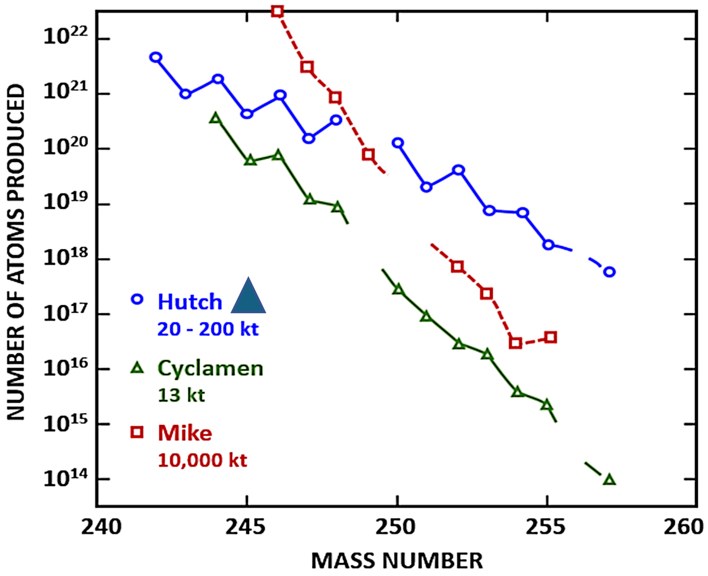
Lawrence Livermore Laboratory

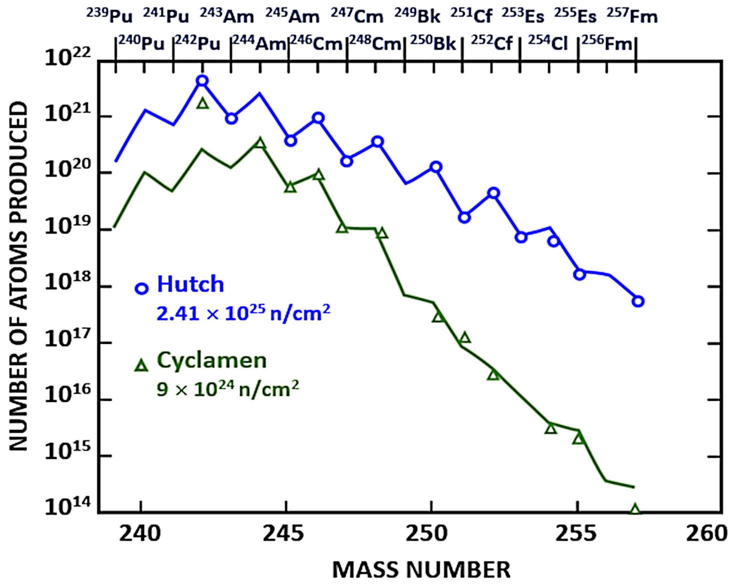
PRODUCTION OF EINSTEINIUM AND FERMIUM IN NUCLEAR EXPLOSIONS

R. Hoff, August 21, 1978

Z=99 Es

Z=100 Fm





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

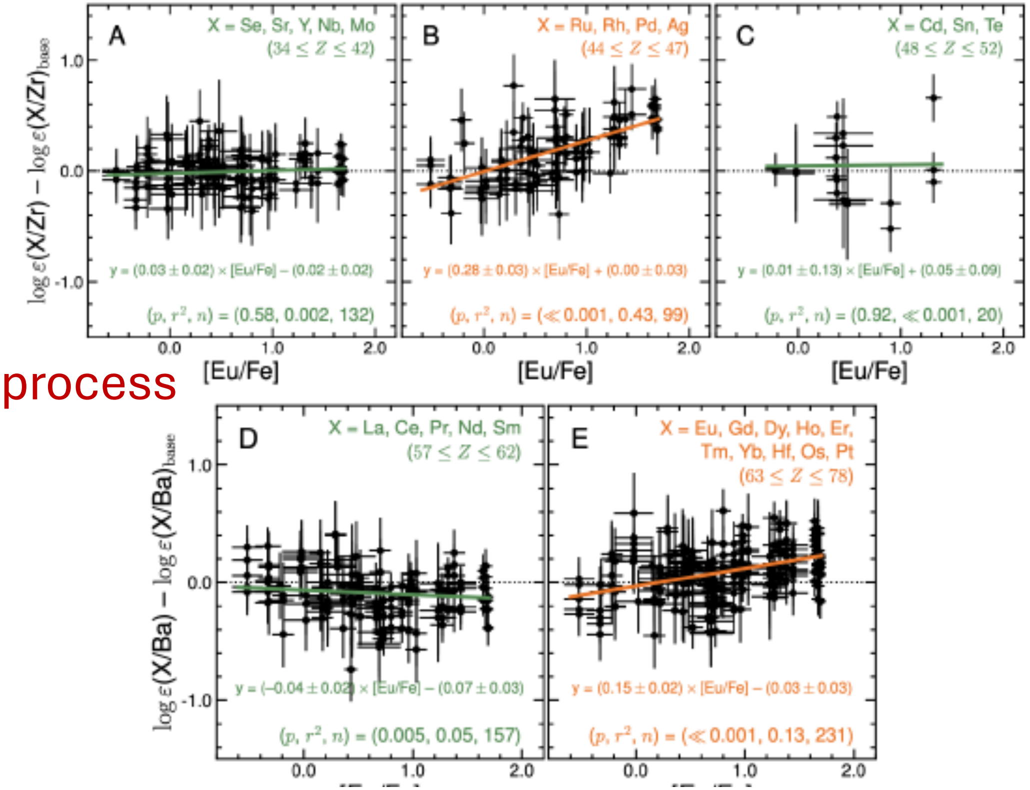
Recent observations of r-process enhanced stars

Science 382, No.6675, Dec. 2023

Ru, Rh, Pd, Ag

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

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]

Open Challenges to Nuclear Physics resulting from the neutron star merger

A. Aprahamian
NuPECC in Sept. 2021

Fission

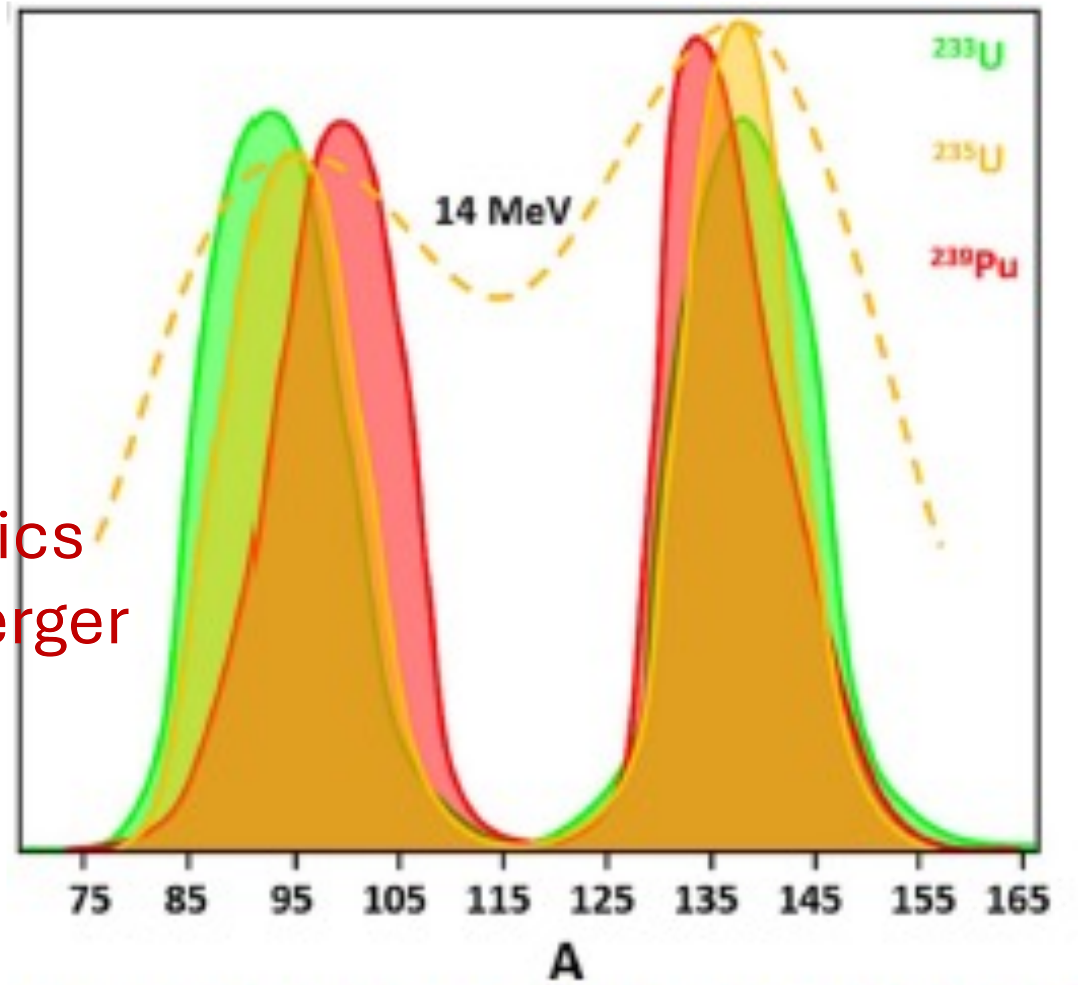
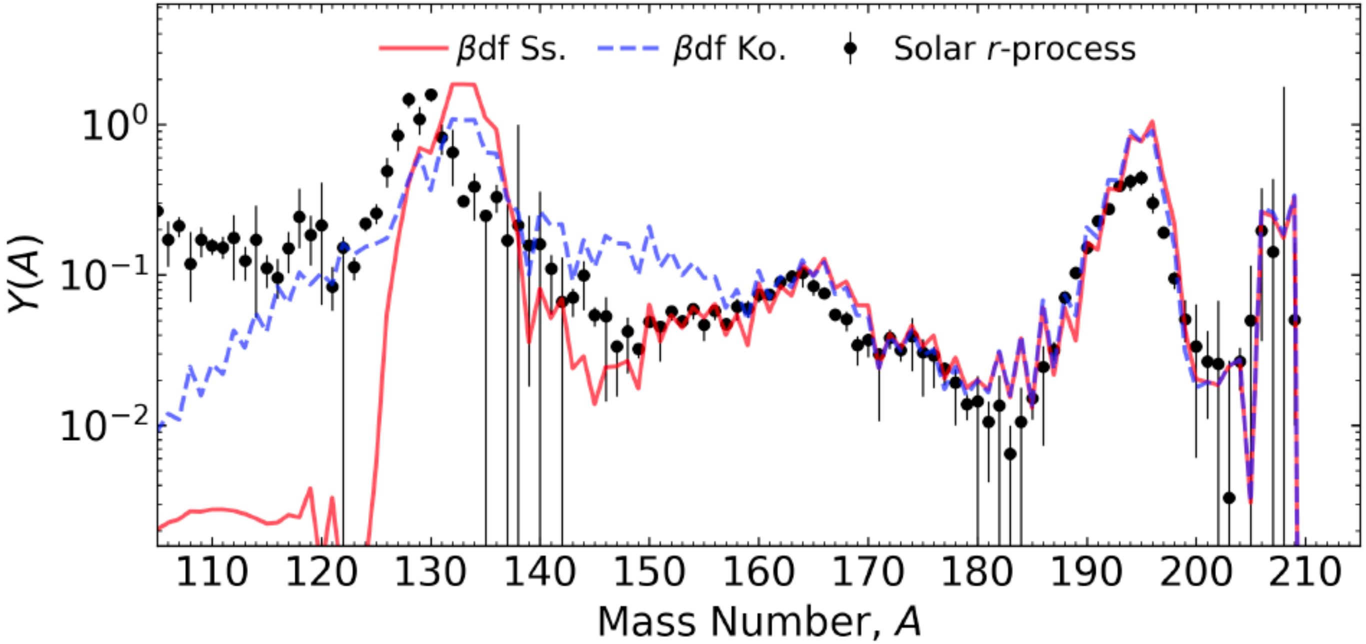


Figure 4. *Low-energy (thermal) neutron-induced fissio fragment distributions with $^{233,235}U$ and ^{238}Pu. The dotte line indicates the fission of ^{235}U with 14 MeV neutrons.*

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

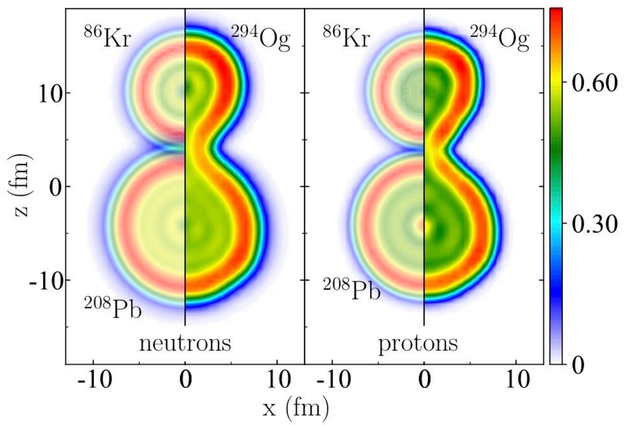
Conclusion $\Rightarrow$ we need a good description of fission yields to understand abundances near $A \sim 130$.

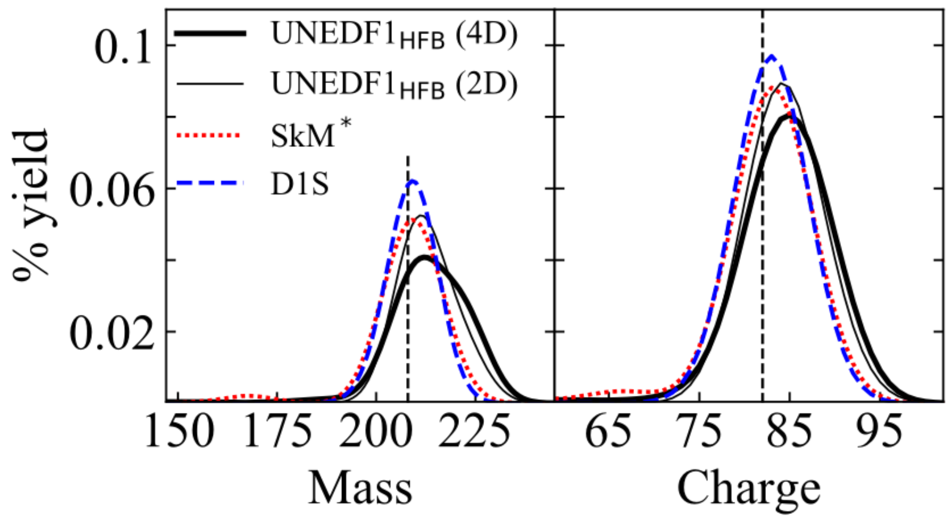
Kodama & Takahashi (1975) • Shibagaki *et al.* ApJ (2016) • **Mumpower** *et al.* ApJ 869 1 (2018) • Vassh ***et al.*** J. Phys. G (2019)

Cluster decay becomes the main fission mode

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

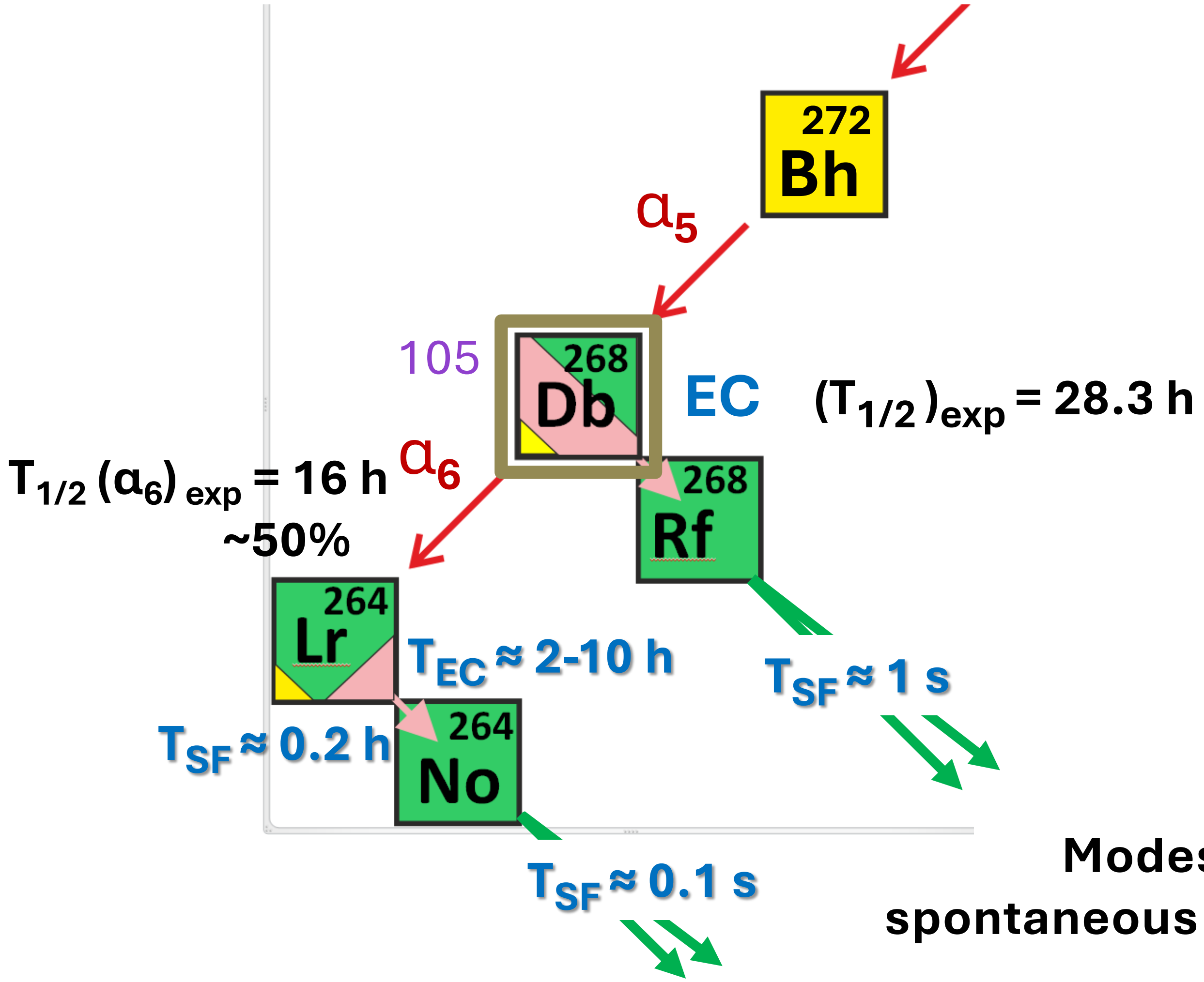
Z. Matheson et al., Phys. Rev. C 99, 041304(R) (2019)





Robust prediction: extremely asymmetric fission

Courtesy of W. Nazarewicz



Modes of the spontaneous fission

JINR: Dubna
Progress at SHE-Factory

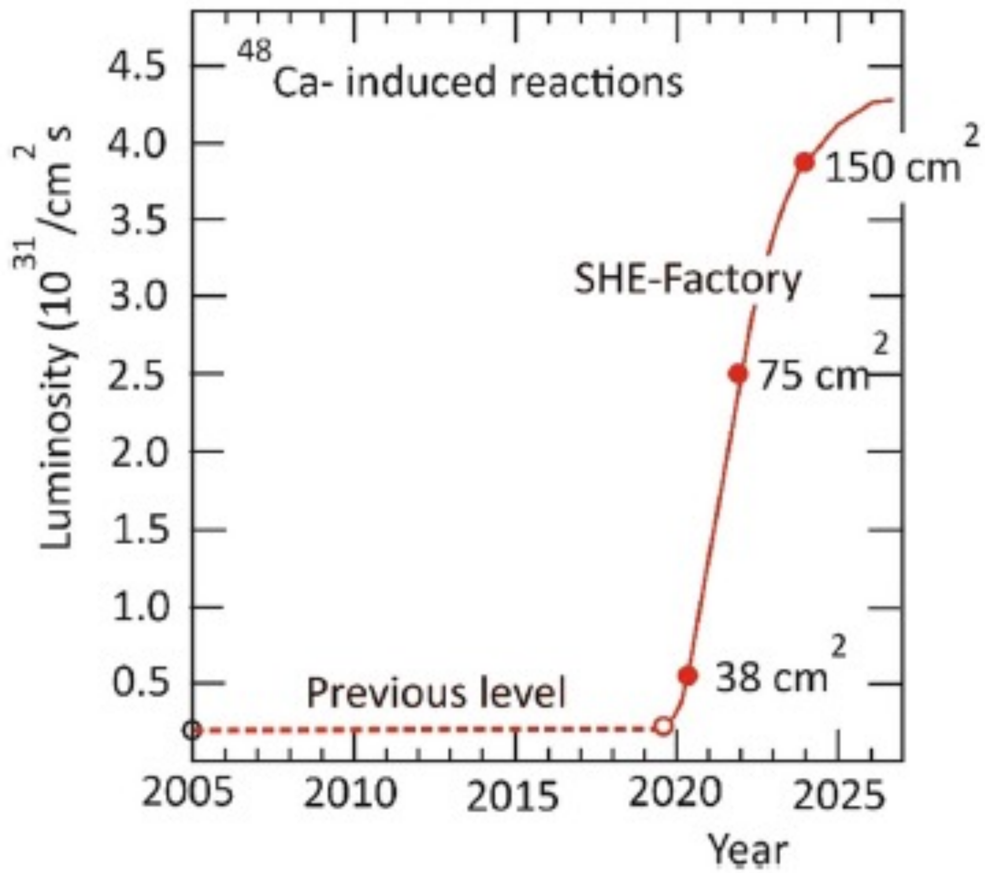
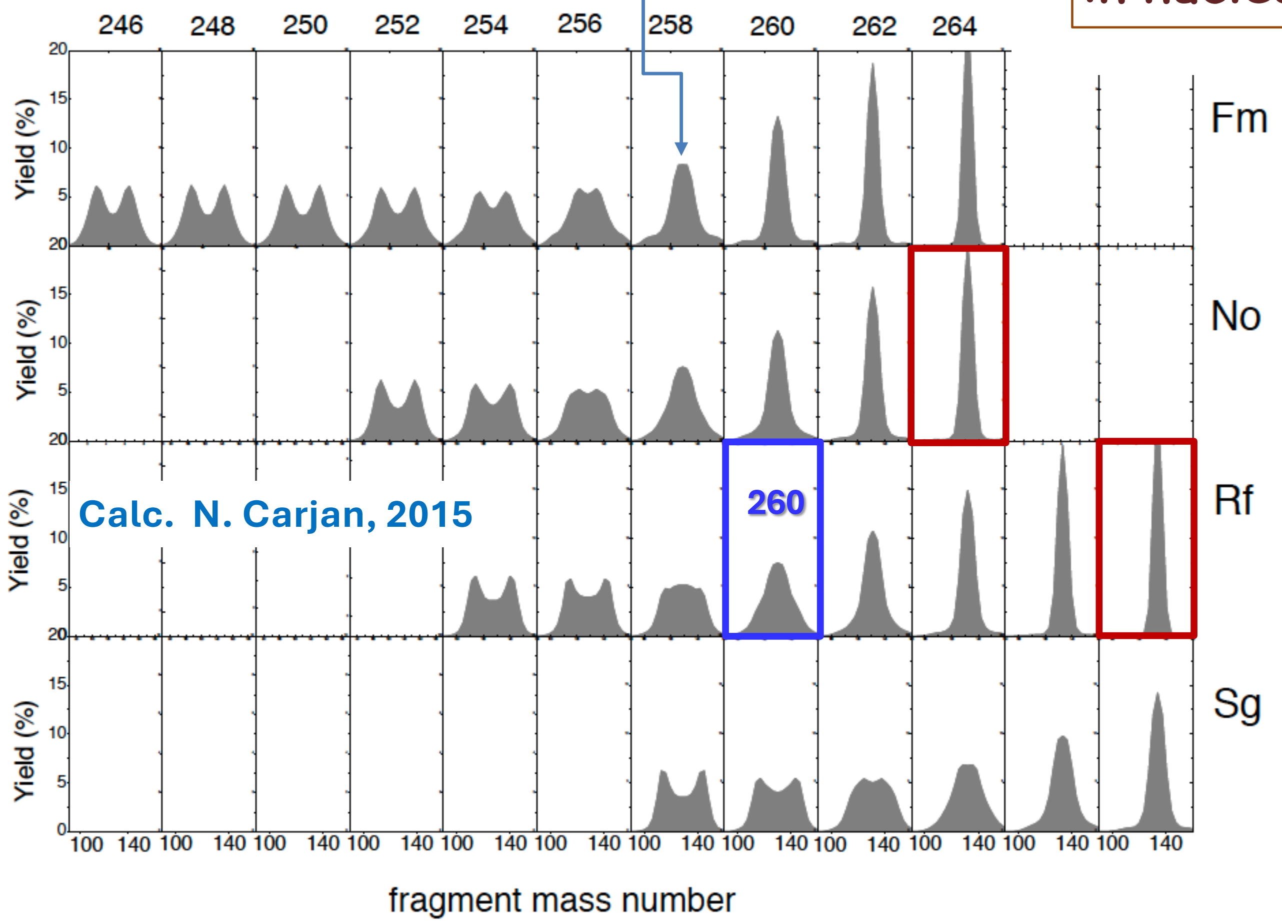


Fig. 5 Luminosity of experiments on synthesis SHE in ^{48}Ca-fusion. Before 2020, the studies were carried out at the accelerator complex U-400 + DGFRS-1 (dashed red line). With the start-up of the SHE Factory: DC-280 cyclotron + new gas field recoil separators, the luminosity increases (solid red line). Rotating targets of different area were used in the experiments (shown in the graph)

Discovery of mass-symmetric spontaneous fission of ^{258}Fm: $Z=2^{x}50$ $N=2^{x}79$

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

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

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

^{275}Ds | ^{276}Ds
5*n* | 4*n*
new | new

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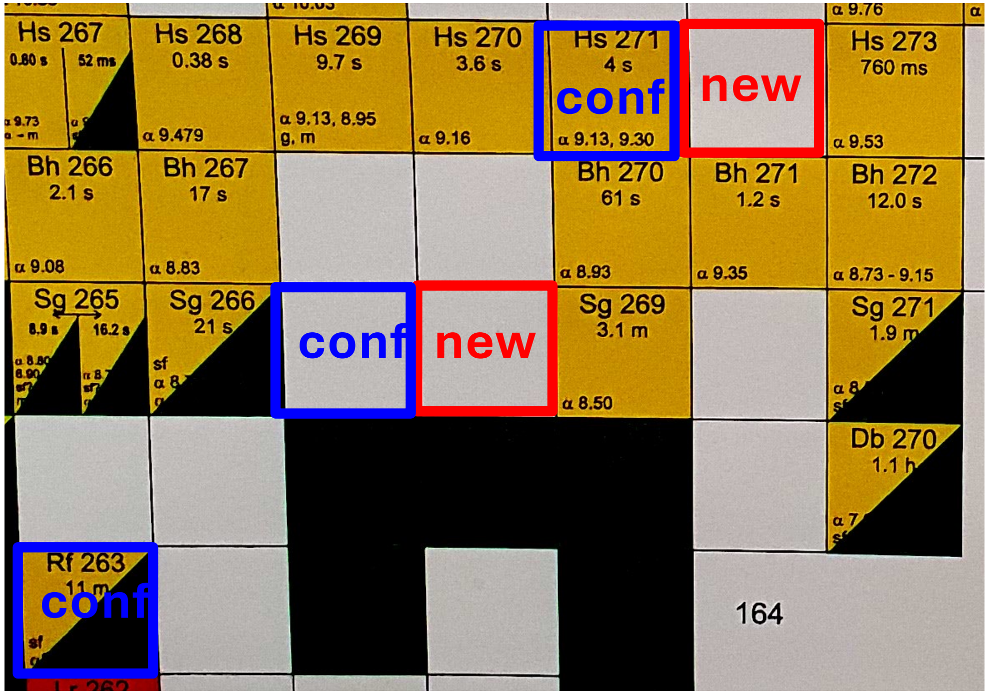
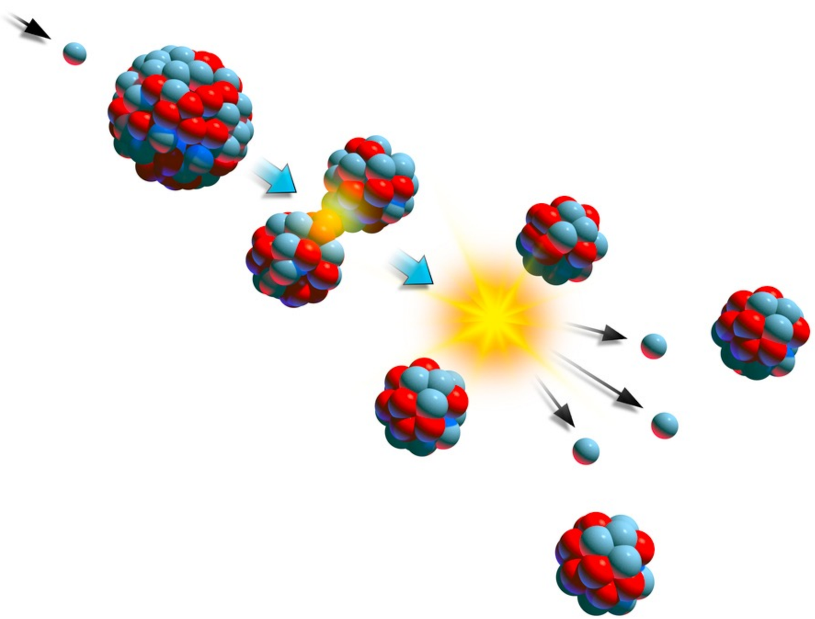


125 new decay chains
New isotopes
Connect to mainland

Bomb debris from environmental tests of nuclear weapons

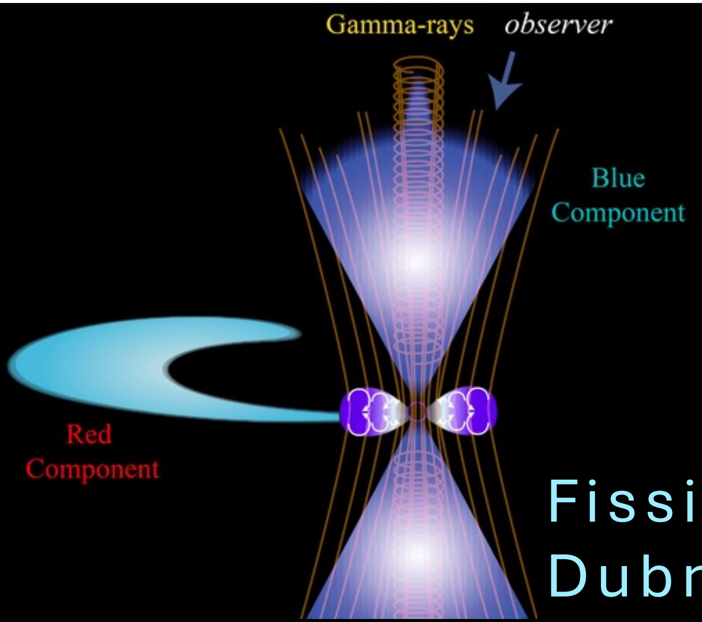
Fission: LLNL – DUBNA – AANL

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 Dubna

Bomb debris from environmental tests of nuclear weapons
NIF experiments
LBL

Thank you for your attention!