

# Cosmic Fission: the Synthesis of the Heavy Elements and the role of Fission

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**Trial lecture**  
**29<sup>th</sup> March 2017**

Special: New Learning Series on Genetics, page 70

Complexity—the Science of Surprise | Your Inner Savant

# Discover

FEBRUARY 2002

DISCOVER.COM



The  
**11**  
Greatest  
Unanswered  
Questions  
of Physics

No.  
**9**  
What Is  
Gravity?



Research Council made a list over  
Unanswered Questions of Physics

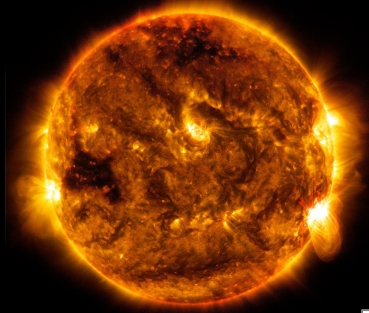
## Question 3

How were the heavy elements from iron to uranium made?

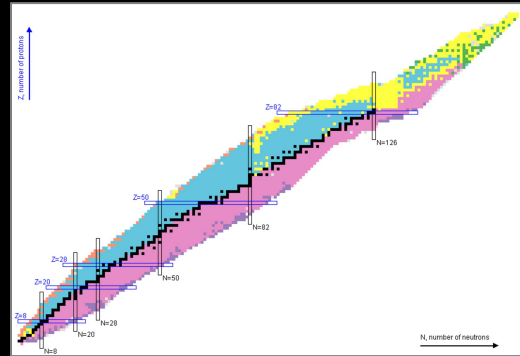


# This talk focuses on production of elements, particularly those heavier than iron, and the role of fission in this process

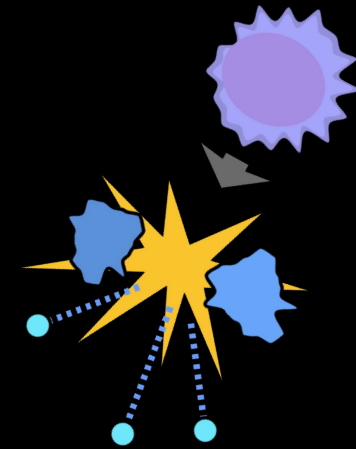
light elements are produced in stars by fusion



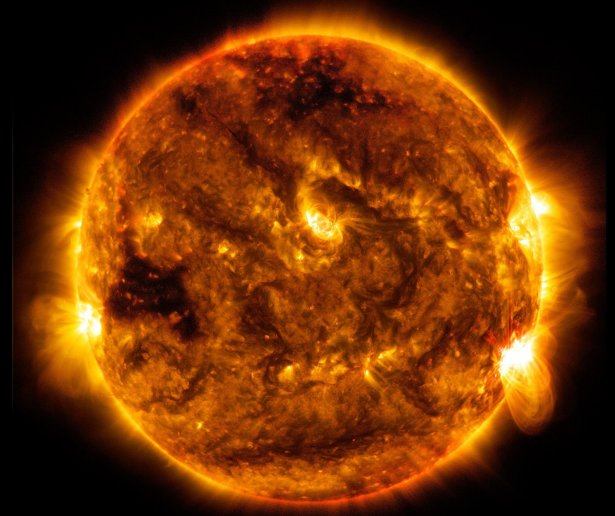
a guided tour of the chart of nuclides, by slow and rapid neutron capture



what happens when nuclei become too heavy? they fission...



# THE LIGHT ELEMENTS



# The periodic table of elements gives us an overview of all known elements

hydrogen and helium (nuclei) were created just after big bang (3 min)

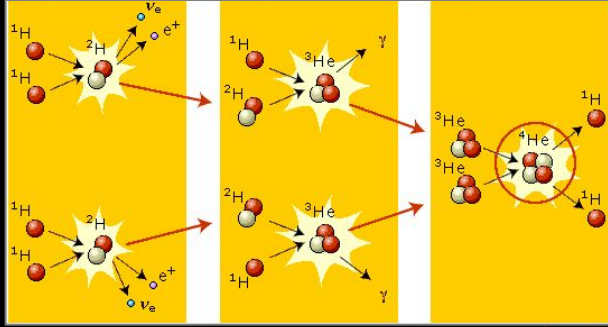
**Periodic Table of the Elements**

Atomic Number										Symbol										Name										Atomic Mass									
1 IA <b>H</b> Hydrogen 1.008	2 IIA 2A <b>Be</b> Beryllium 9.012											3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 IIIA 3A <b>B</b> Boron 10.811	14 IVA 4A <b>C</b> Carbon 12.011	15 VA 5A <b>N</b> Nitrogen 14.007	16 VIA 6A <b>O</b> Oxygen 15.999	17 VIIA 7A <b>F</b> Fluorine 18.998	18 VIIIA 8A <b>Ne</b> Neon 20.180												
11 <b>Na</b> Sodium 22.990	12 <b>Mg</b> Magnesium 24.305											13 <b>Al</b> Aluminum 26.982	14 <b>Si</b> Silicon 28.086	15 <b>P</b> Phosphorus 30.974	16 <b>S</b> Sulfur 32.066	17 <b>Cl</b> Chlorine 35.453	18 <b>Ar</b> Argon 39.948																						
19 <b>K</b> Potassium 39.098	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.956	22 <b>Ti</b> Titanium 47.867	23 <b>V</b> Vanadium 50.942	24 <b>Cr</b> Chromium 51.996	25 <b>Mn</b> Manganese 54.938	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933	28 <b>Ni</b> Nickel 58.693	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.38	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.631	33 <b>As</b> Arsenic 74.922	34 <b>Se</b> Selenium 78.971	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 84.798																						
37 <b>Rb</b> Rubidium 84.468	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.906	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.906	42 <b>Mo</b> Molybdenum 95.95	43 <b>Tc</b> Technetium 98.907	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.906	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.868	48 <b>Cd</b> Cadmium 112.414	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.711	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.6	53 <b>I</b> Iodine 126.904	54 <b>Xe</b> Xenon 131.294																						
55 <b>Cs</b> Cesium 132.905	56 <b>Ba</b> Barium 137.328	57-71 Lanthanide Series	72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.948	74 <b>W</b> Tungsten 183.84	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.217	78 <b>Pt</b> Platinum 195.085	79 <b>Au</b> Gold 196.967	80 <b>Hg</b> Mercury 200.592	81 <b>Tl</b> Thallium 204.383	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.980	84 <b>Po</b> Polonium [208.982]	85 <b>At</b> Astatine 209.987	86 <b>Rn</b> Radon 222.016																						
87 <b>Fr</b> Francium 223.020	88 <b>Ra</b> Radium 226.025	89-103 Actinide Series	104 <b>Rf</b> Rutherfordium [261]	105 <b>Db</b> Dubnium [262]	106 <b>Sg</b> Seaborgium [266]	107 <b>Bh</b> Bohrium [264]	108 <b>Hs</b> Hassium [269]	109 <b>Mt</b> Meitnerium [268]	110 <b>Ds</b> Darmstadtium [269]	111 <b>Rg</b> Roentgenium [272]	112 <b>Cn</b> Copernicium [277]	113 <b>Uut</b> Ununtrium unknown	114 <b>Fl</b> Flerovium [289]	115 <b>Uup</b> Ununpentium unknown	116 <b>Lv</b> Livermorium [298]	117 <b>Uus</b> Ununseptium unknown	118 <b>Uuo</b> Ununoctium unknown																						
		57 <b>La</b> Lanthanum 138.905	58 <b>Ce</b> Cerium 140.12	59 <b>Pr</b> Praseodymium 140.908	60 <b>Nd</b> Neodymium 144.24	61 <b>Pm</b> Promethium 144.913	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.925	66 <b>Dy</b> Dysprosium 162.500	67 <b>Ho</b> Holmium 164.930	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.934	70 <b>Yb</b> Ytterbium 173.055	71 <b>Lu</b> Lutetium 174.967																							
		89 <b>Ac</b> Actinium 227.028	90 <b>Th</b> Thorium 232.038	91 <b>Pa</b> Protactinium 231.036	92 <b>U</b> Uranium 238.029	93 <b>Np</b> Neptunium 237.048	94 <b>Pu</b> Plutonium 244.064	95 <b>Am</b> Americium 243.061	96 <b>Cm</b> Curium 247.070	97 <b>Bk</b> Berkelium 247.070	98 <b>Cf</b> Californium 251.080	99 <b>Es</b> Einsteinium [254]	100 <b>Fm</b> Fermium 257.095	101 <b>Md</b> Mendelevium 258.1	102 <b>No</b> Nobelium 259.101	103 <b>Lr</b> Lawrencium [262]																							

uranium and thorium are the heaviest elements found in nature

elements with a number higher than 92 are man-made

# The *light* elements are made in stars by fusion processes



the sun “burns” by fusing light nuclei, starting with hydrogen

fusion in stars will take us all the way up to iron

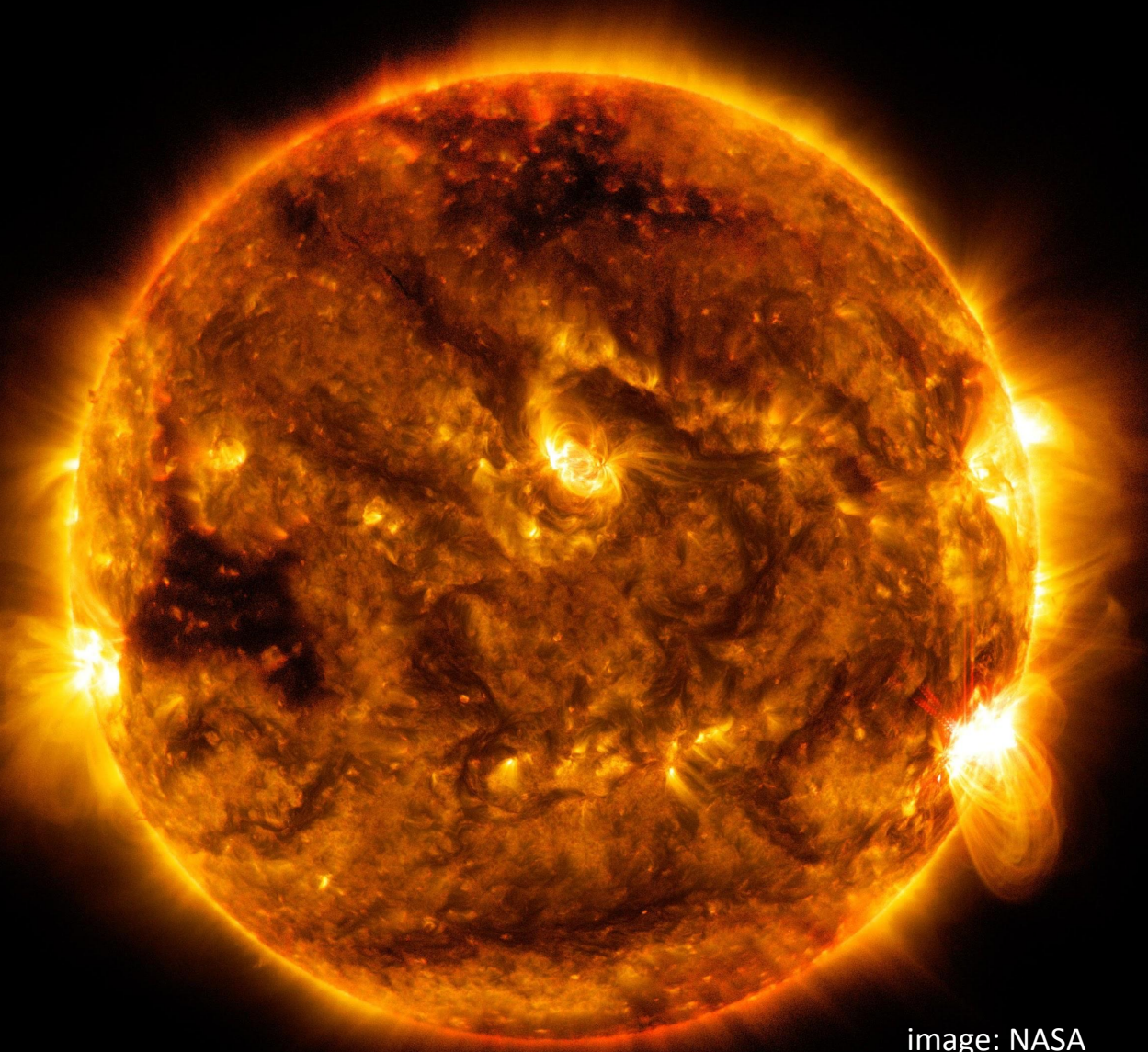
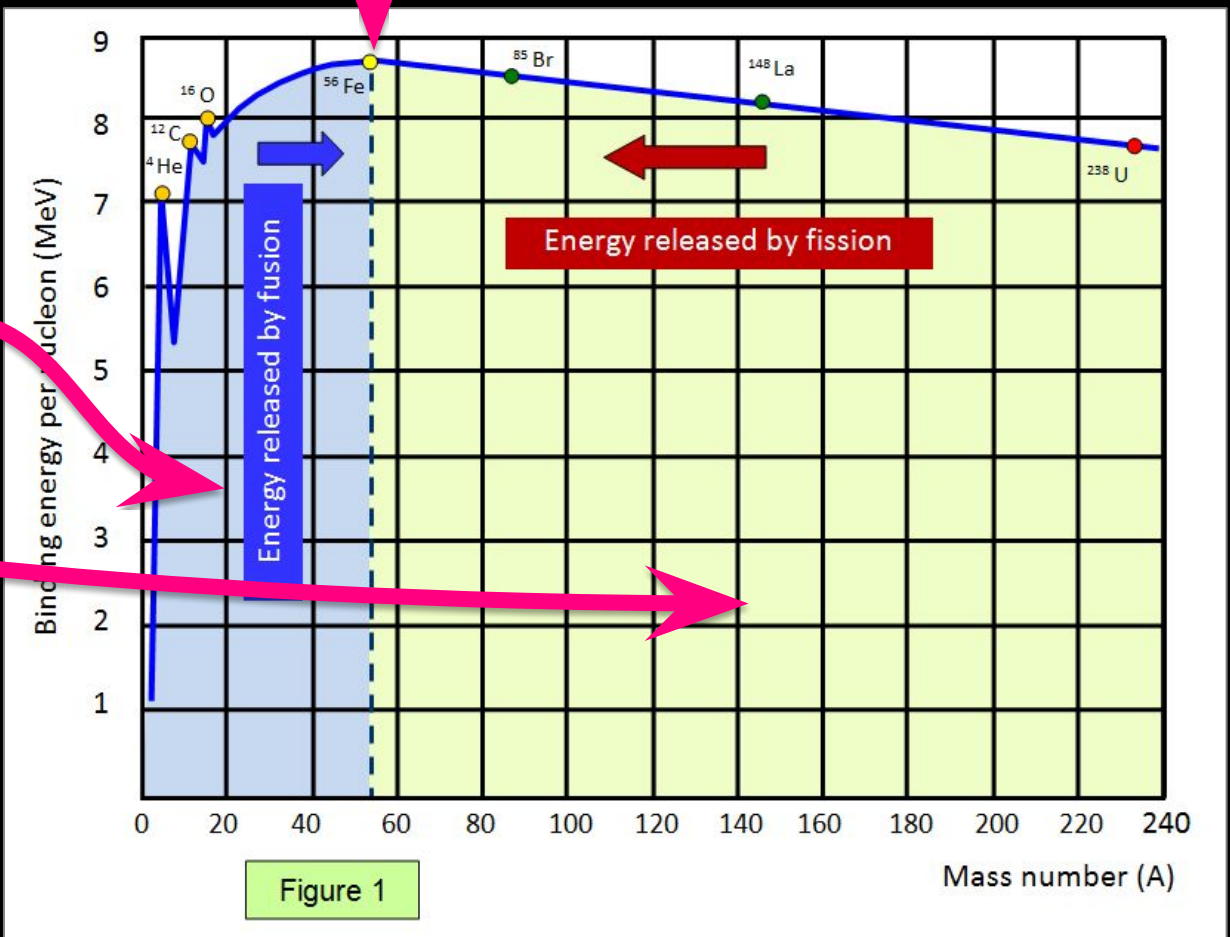


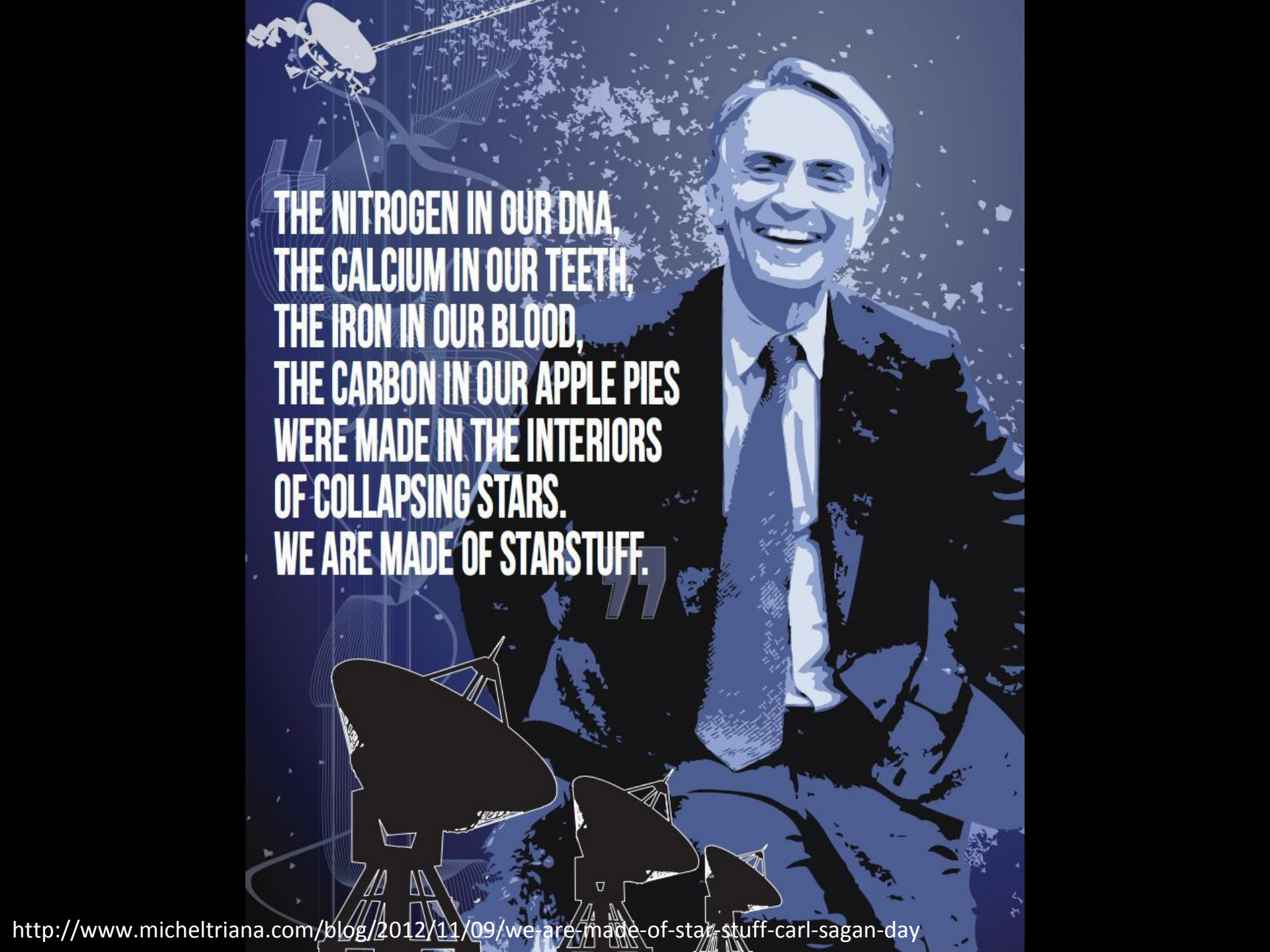
image: NASA

# For elements heavier than iron, the nuclear fusion process does not generate energy

more precisely, we'll get to  $^{56}\text{Fe}$ , where more fusion will "cost" energy

mass is transformed to energy,  $E = mc^2$ , by **fission** or **fusion**





**THE NITROGEN IN OUR DNA,  
THE CALCIUM IN OUR TEETH,  
THE IRON IN OUR BLOOD,  
THE CARBON IN OUR APPLE PIES  
WERE MADE IN THE INTERIORS  
OF COLLAPSING STARS.  
WE ARE MADE OF STARSTUFF.**



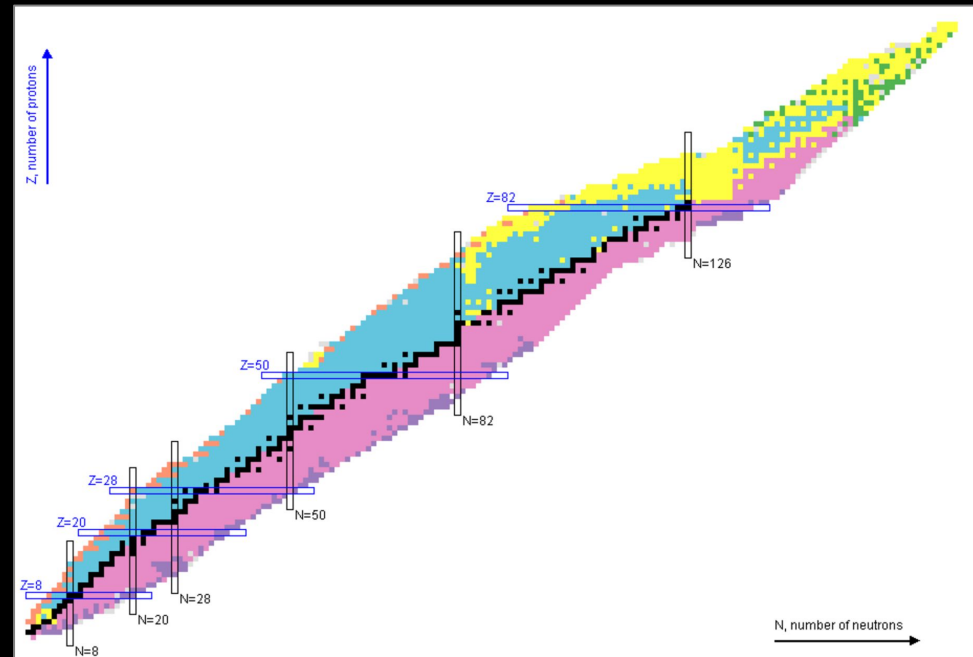


# To understand how elements heavier than iron are produced, we need to know beta decay, and the chart of nuclides

First I'll explain how beta decay transforms nuclei

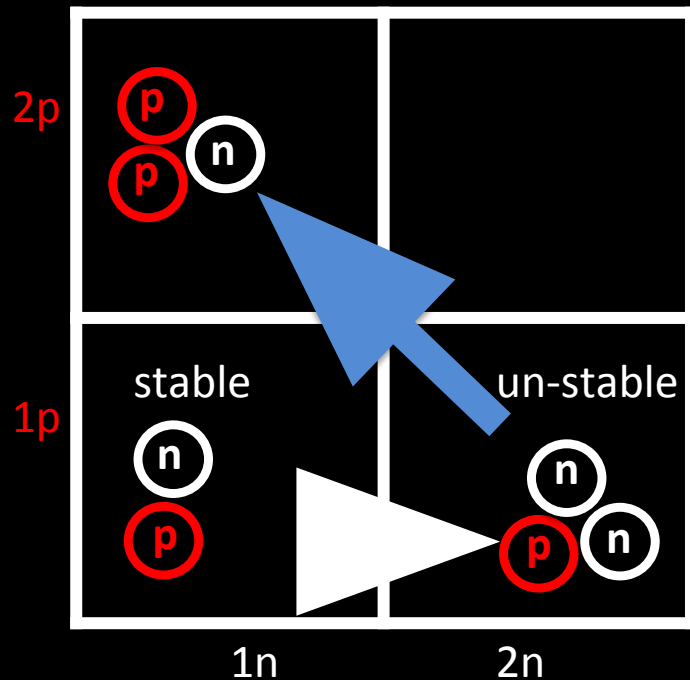
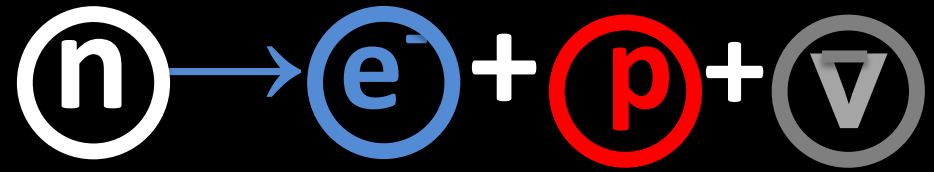
Then we'll see how nuclear information is organized in the chart of nuclides

And finally we can look at the processes by which heavy elements are produced



# An important nuclear reaction is neutron induced beta decay which changes a nucleus from one to another

a **neutron** can be transformed into a **proton** in the beta minus decay process

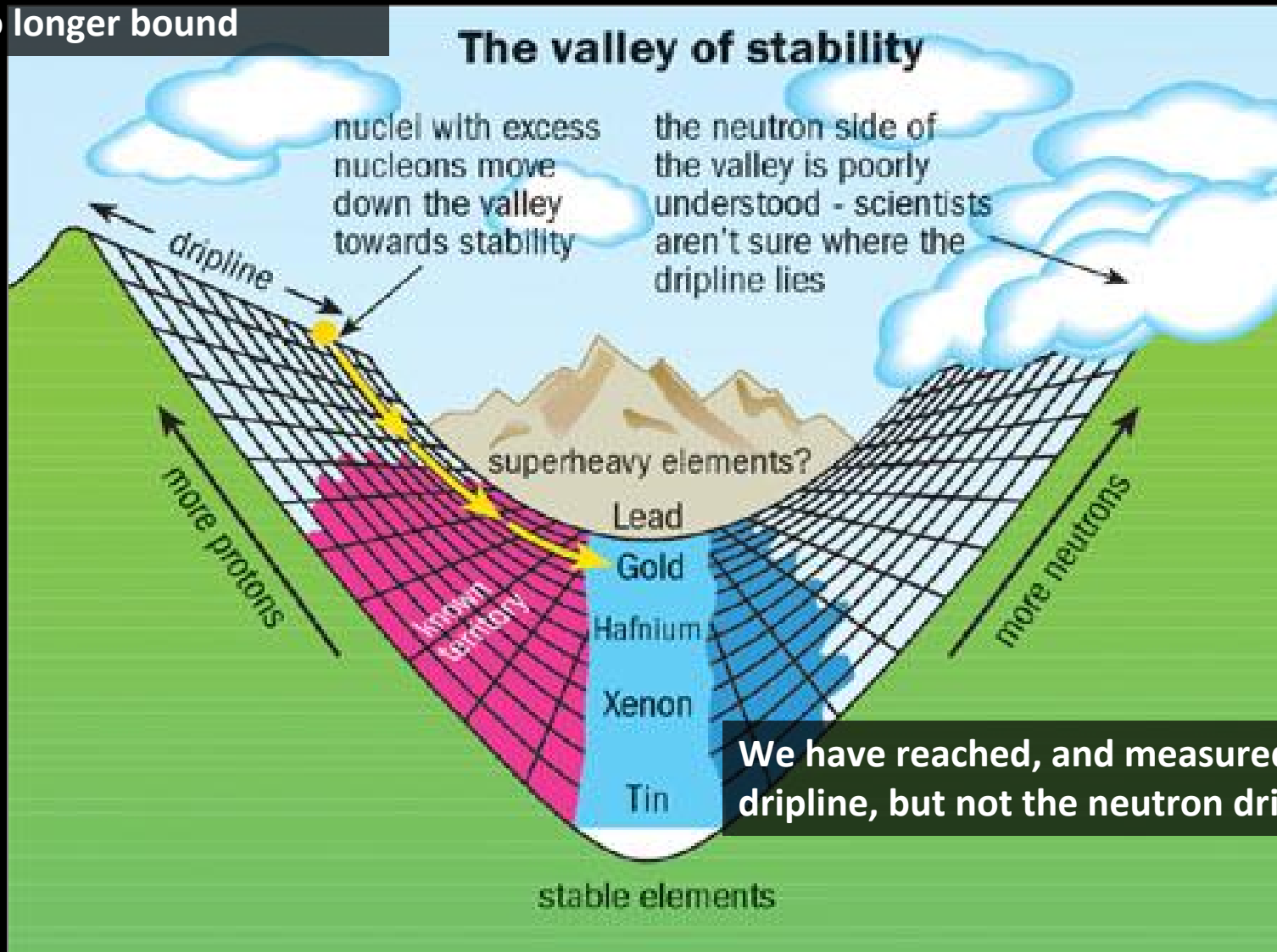


**neutron capture** can make a (stable) nucleus unstable to beta decay

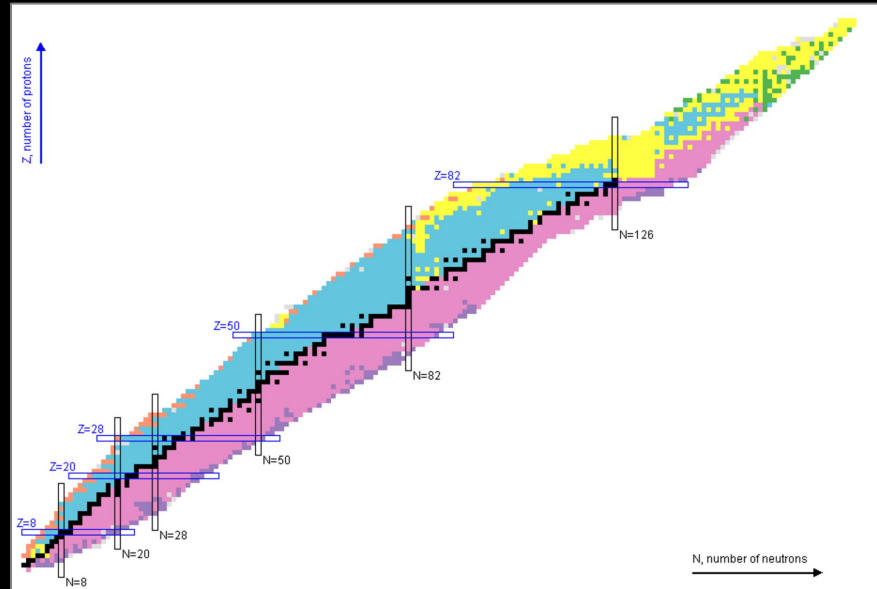


# Nuclei will always “fall down” into the valley of stability

At the dripline, nucleons are no longer bound

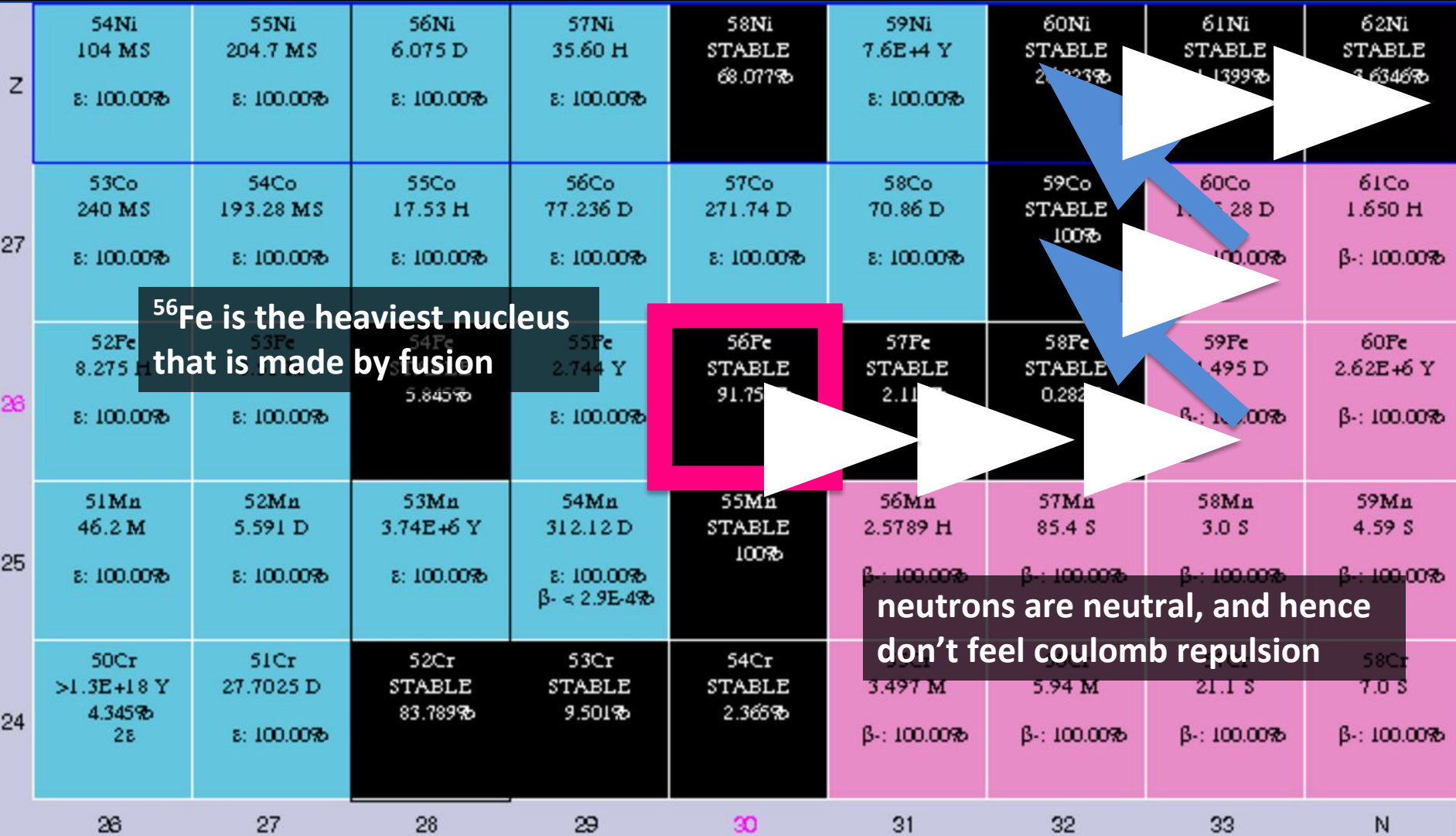


synthesis of heavy elements:



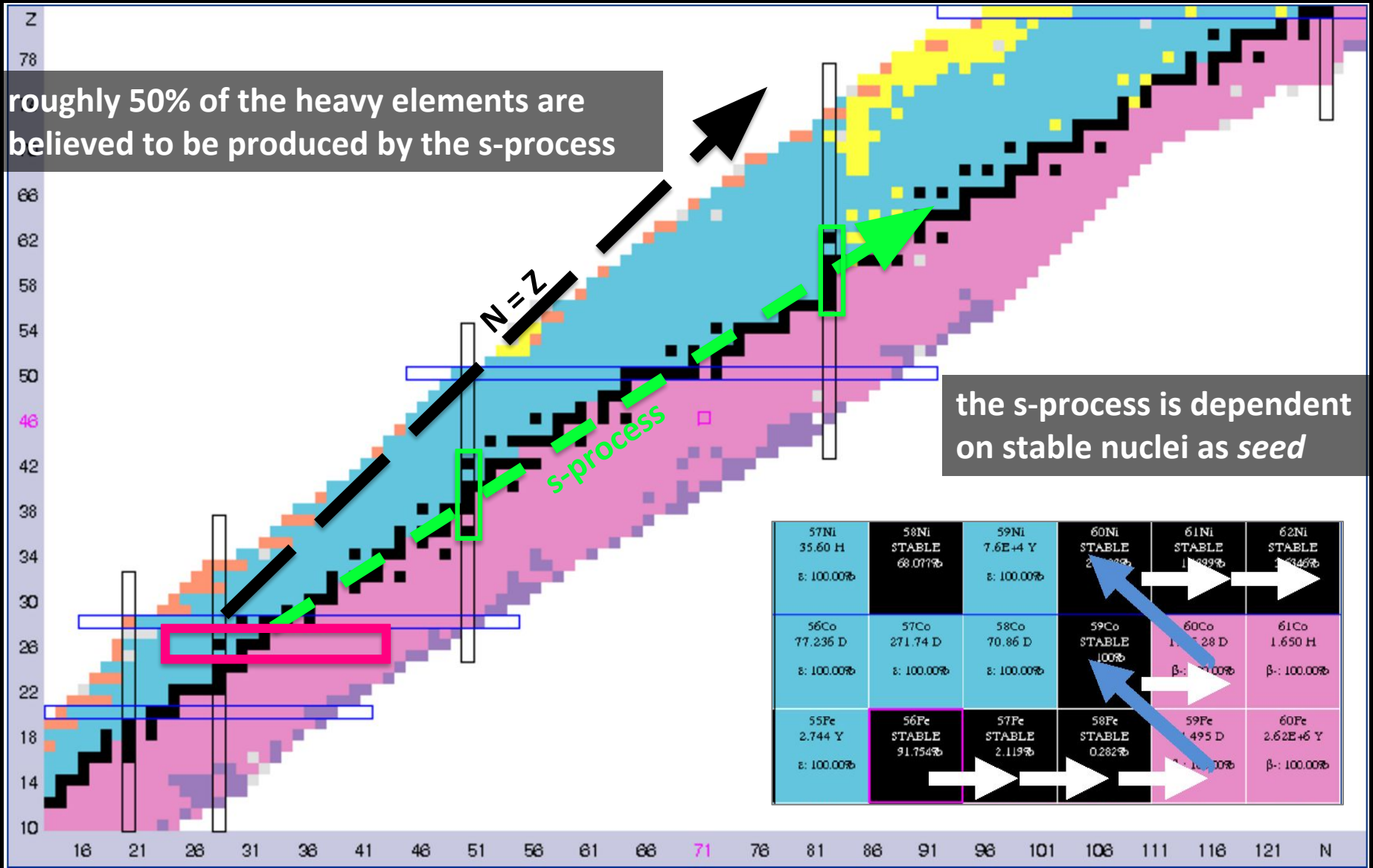
# SLOW NEUTRON CAPTURE PROCESS

# The s-process is the process where stable nuclei capture neutrons at a slow pace to produce heavier elements



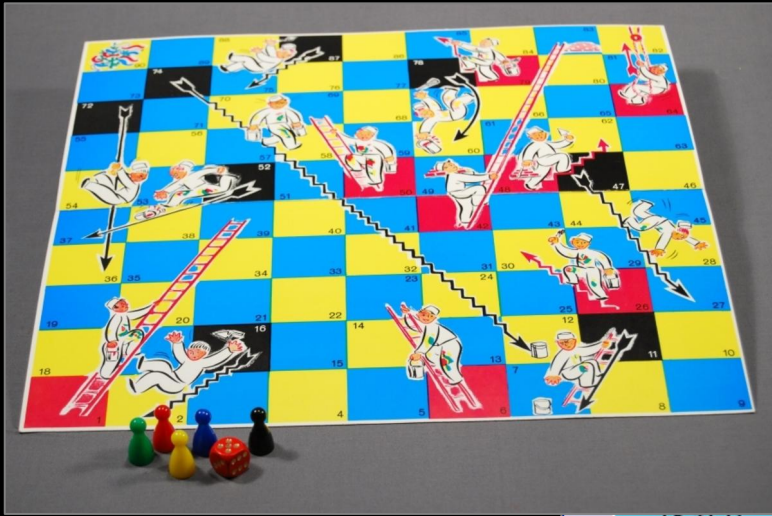
s-process is "easy": seeds are stable, need capture cross-sections we can easily measure, and a neutron density we can imagine

# By the *s*-process, we climb the nuclear chart following the valley of stability – but how far can we go?





# The s-process terminates at $^{209}\text{Bi}$ , when there are no more stable "seed nuclei" to capture neutrons

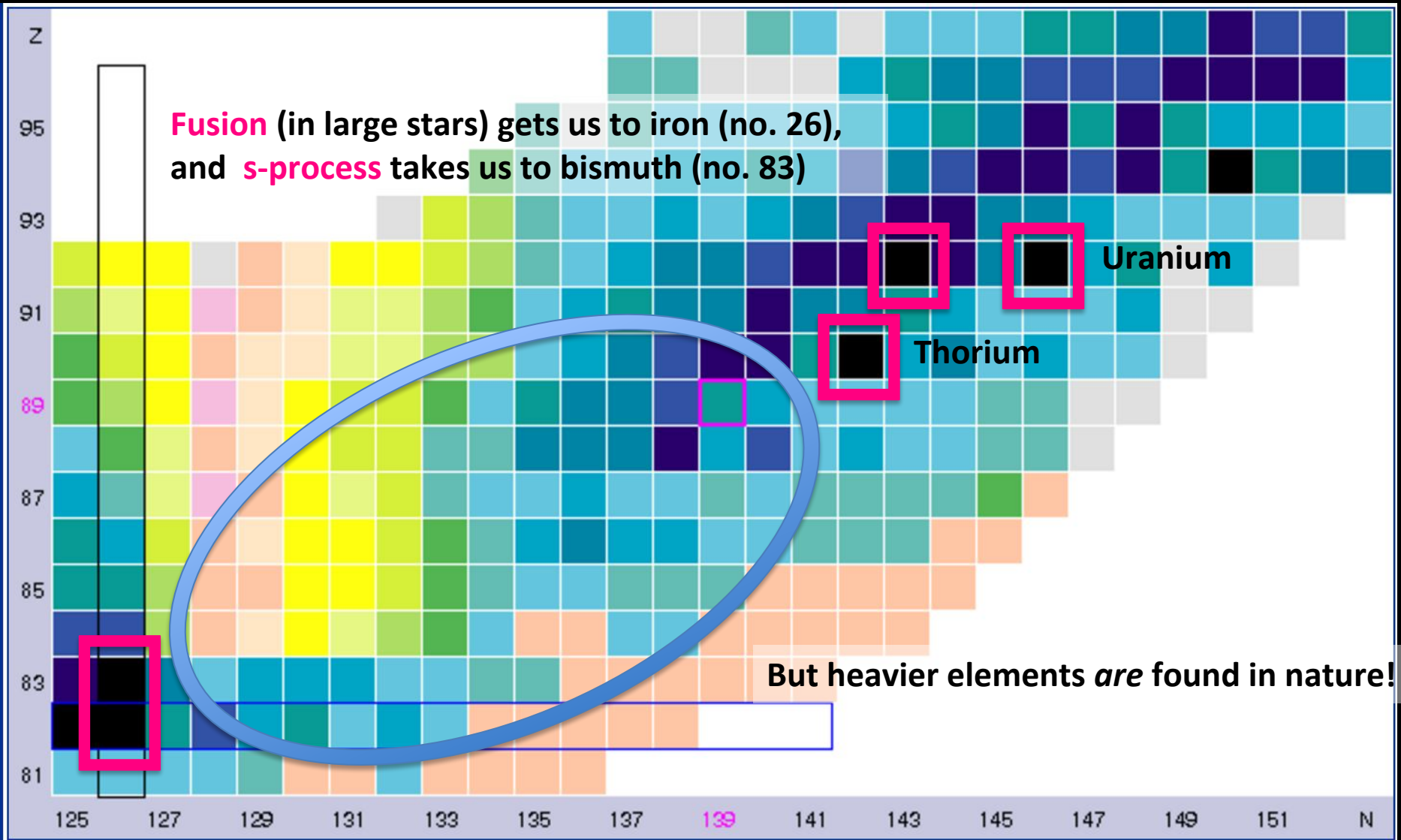


	208At 1.63 H ε: 99.45% α: 0.55%	209At 5.41 H ε: 95.90% α: 4.10%	210At 8.1 H ε: 99.82% α: 0.18%	211At 7.214 H ε: 58.20% α: 41.80%	212At 0.314 S α: 100.00% ε < 0.03%	213At 125 NS α: 100.00%	
	207Po 5.80 H ε: 99.98% α: 0.02%	208Po 2.898 Y α: 100.00% ε: 4.0E-3%	209Po 102 Y α: 99.52% ε: 0.48%	210Po 138.376 D α: 100.00%	211Po 0.516 S α: 100.00%	212Po 0.299 μS α: 100.00%	
	206Bi 15.51 D ε: 100.00%	207Bi 6.243 D ε: 100.00%	208Bi 31.55 Y ε: 100.00%	209Bi STABLE 100%	210Bi 5.012 D β-: 100.00% α: 1.3E-4%	211Bi 2.14 M α: 99.72% β-: 0.28%	
83	204Pb 2.4E+11 Y α: 100.00%	205Pb 1.5E+7 Y ε: 100.00%	206Pb STABLE 24.1%	207Pb STABLE 22.1%	208Pb STABLE 52.4%	209Pb 3.253 H β-: 100.00%	210Pb 22.20 Y β-: 100.00% α: 1.9E-6%
82	204Tl 3.783 Y β-: 99.08% ε: 2.92%	205Tl STABLE 70.48%	206Tl 4.202 M β-: 100.00%	207Tl 4.77 M β-: 100.00%	208Tl 3.053 M β-: 100.00%	209Tl 2.161 M β-: 100.00%	
81	204Tl STABLE 29.524%	205Tl STABLE 70.48%	206Tl 4.202 M β-: 100.00%	207Tl 4.77 M β-: 100.00%	208Tl 3.053 M β-: 100.00%	209Tl 2.161 M β-: 100.00%	
	122	123	124	125	126	127	128

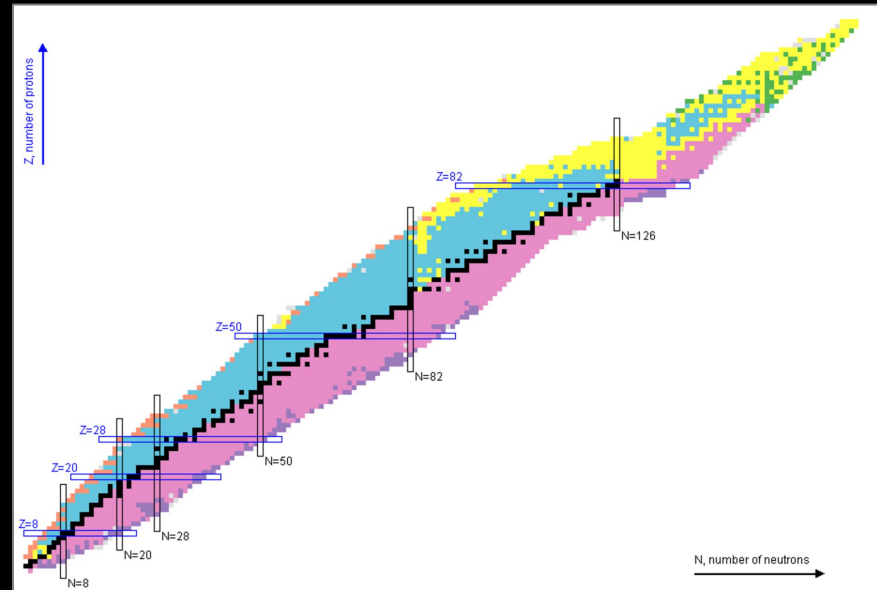
$^{209}\text{Bi}(n,\gamma)^{210}\text{Bi}(\beta^-)^{210}\text{Po}(\alpha)^{206}\text{Pb}$  chain leads to recycling of material in this mass region

the s-process has been observed in red giant stars

# The s-process terminates at $^{209}\text{Bi}$ , when there are no more stable “seed nuclei” to capture neutrons



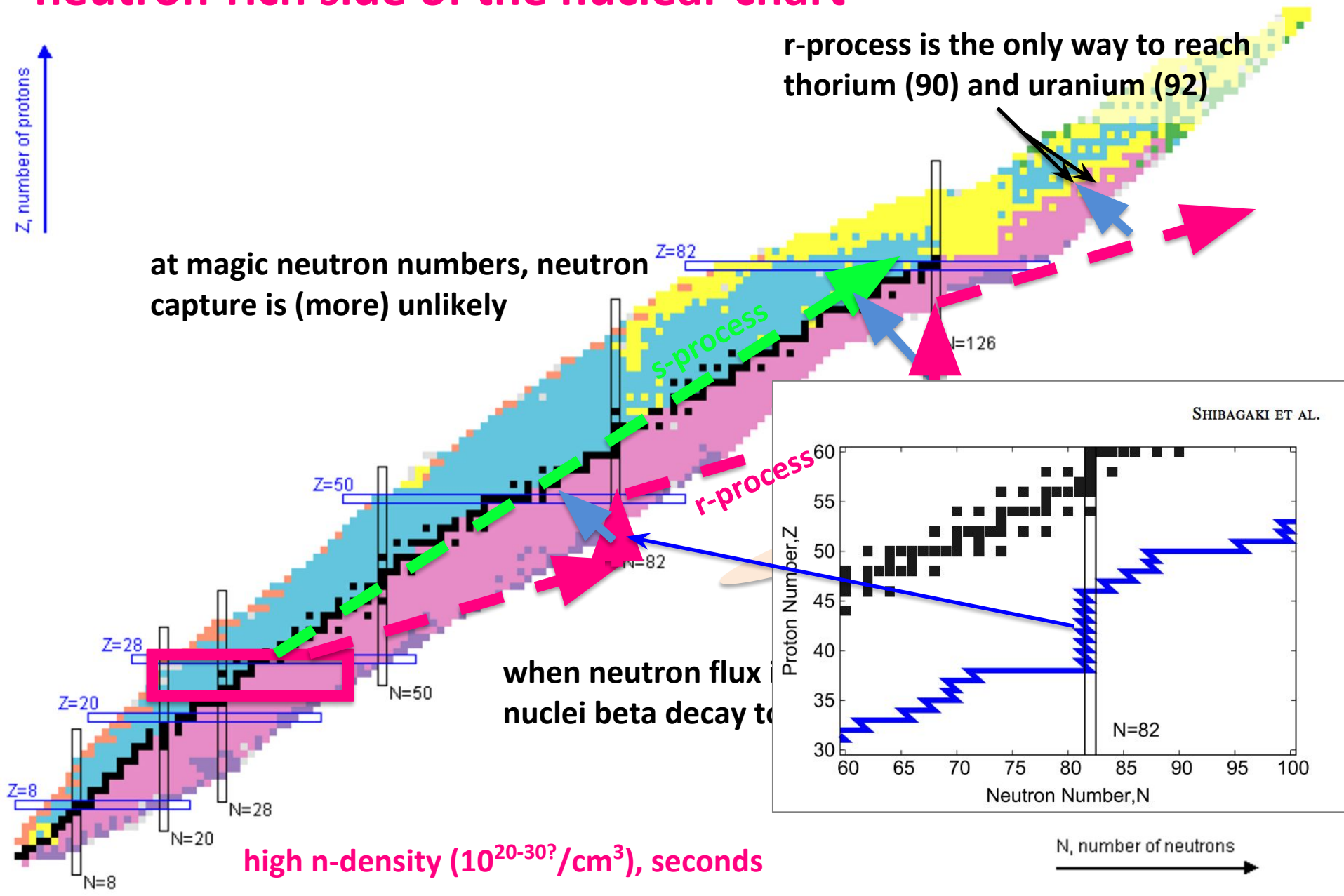
synthesis of heavy elements:



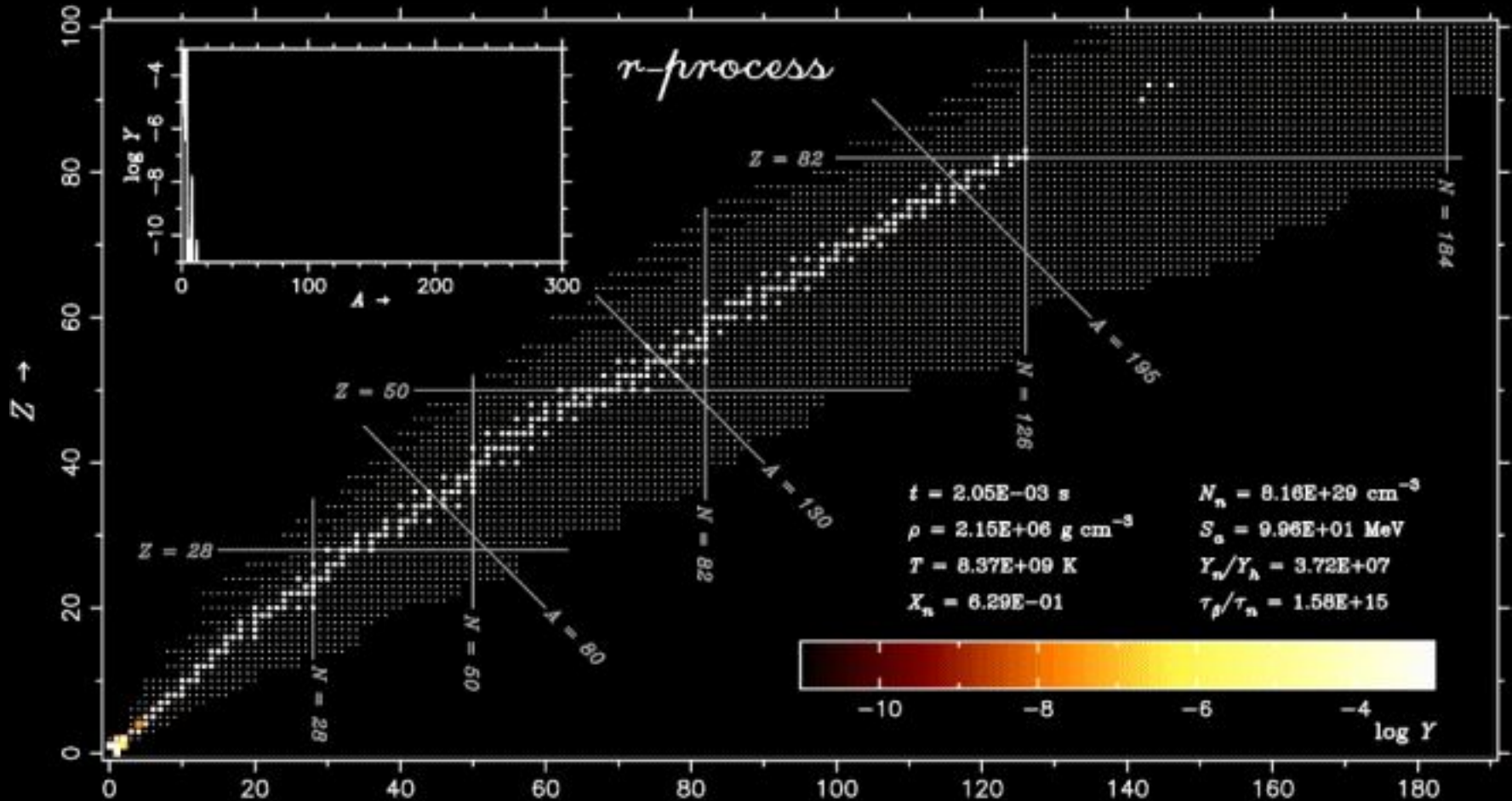
# RAPID NEUTRON CAPTURE PROCESS



# The r-process moves far from stability, at the extreme neutron-rich side of the nuclear chart



what goes into the animation are cross-sections, lifetimes, and fluxes

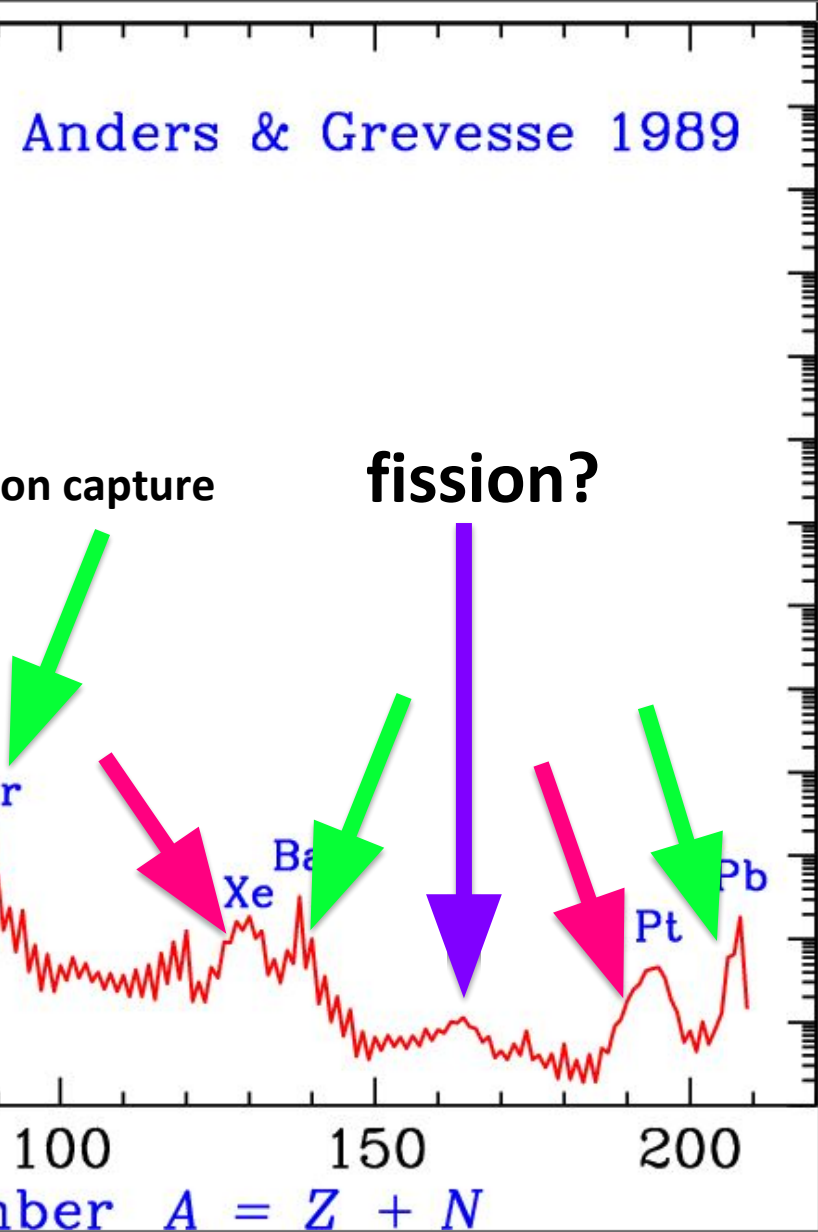
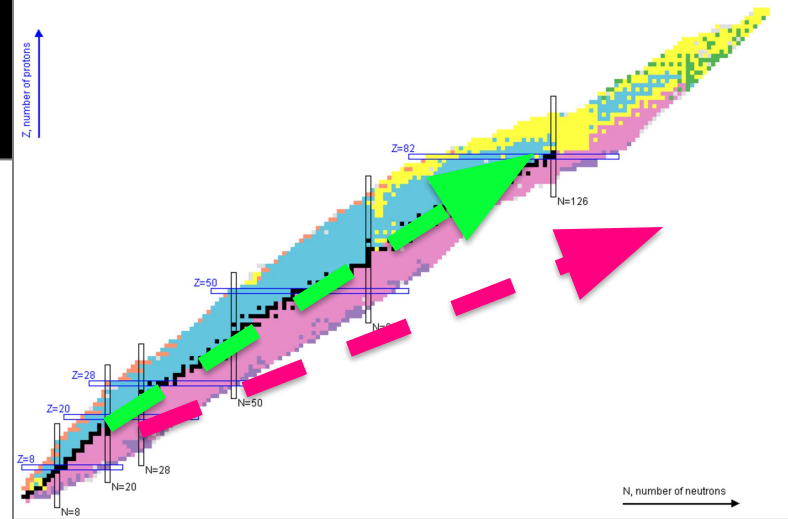


the elemental abundance a simulation gives must be compared to the experimental one

$N \rightarrow$   
 [Fabio:] available online on  
<http://www.ph.sophia.ac.jp/%7Eshinya/research/research.html>

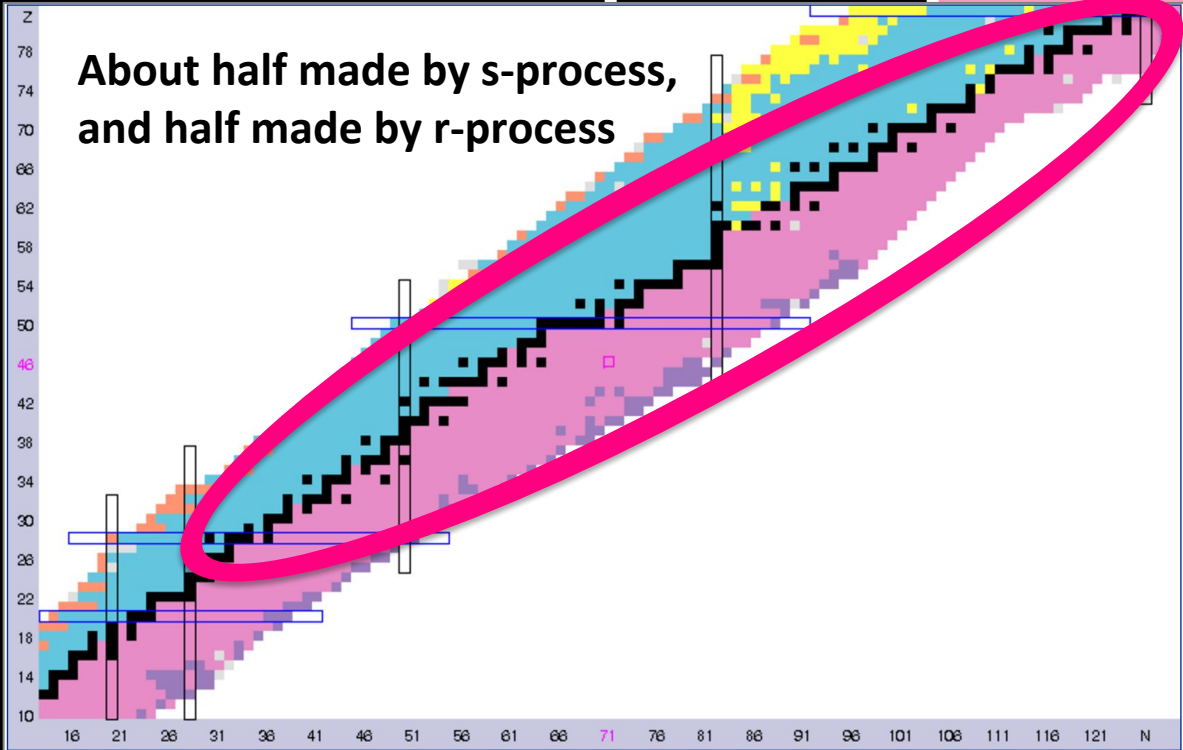
The solar abundance is the "solution", and our models must reproduce/explain this pattern

solar abundance ( $^{28}\text{Si} = 10^6$ )



Anders & Grevesse 1989

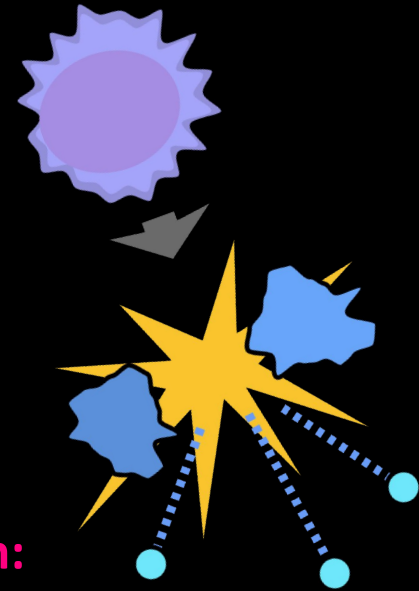
# The r-process is needed to explain abundance of certain isotopes close to the valley of stability



decay by beta minus

Some isotopes can't be reached neither by s- nor r-process

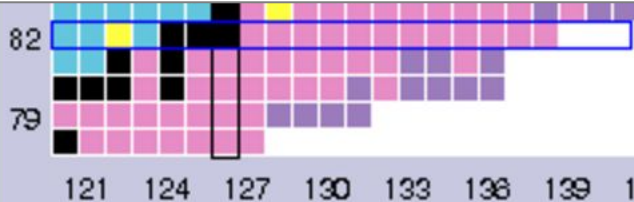
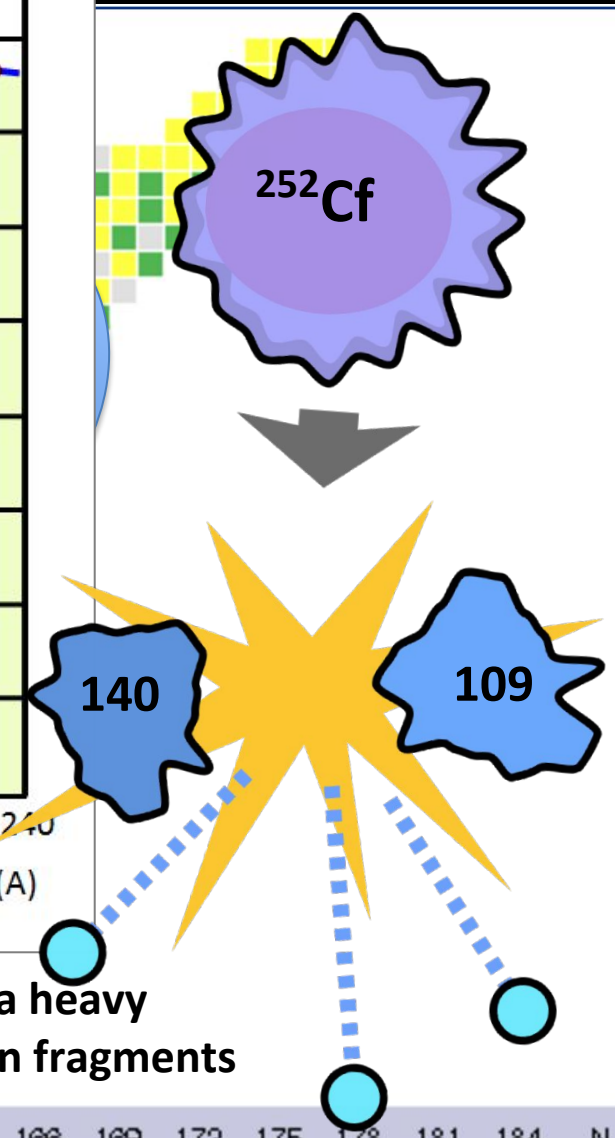
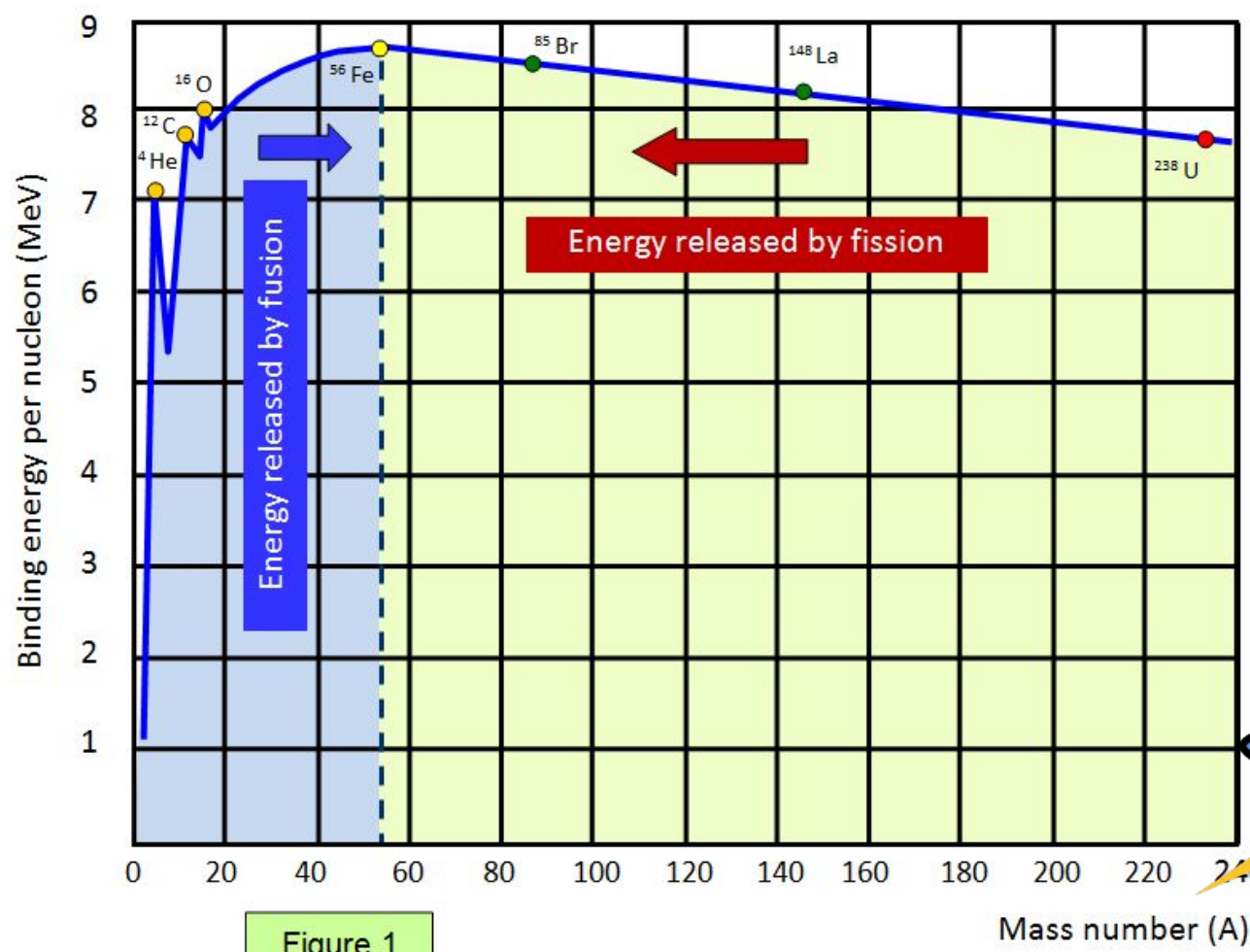




synthesis of heavy elements and the role of fission:

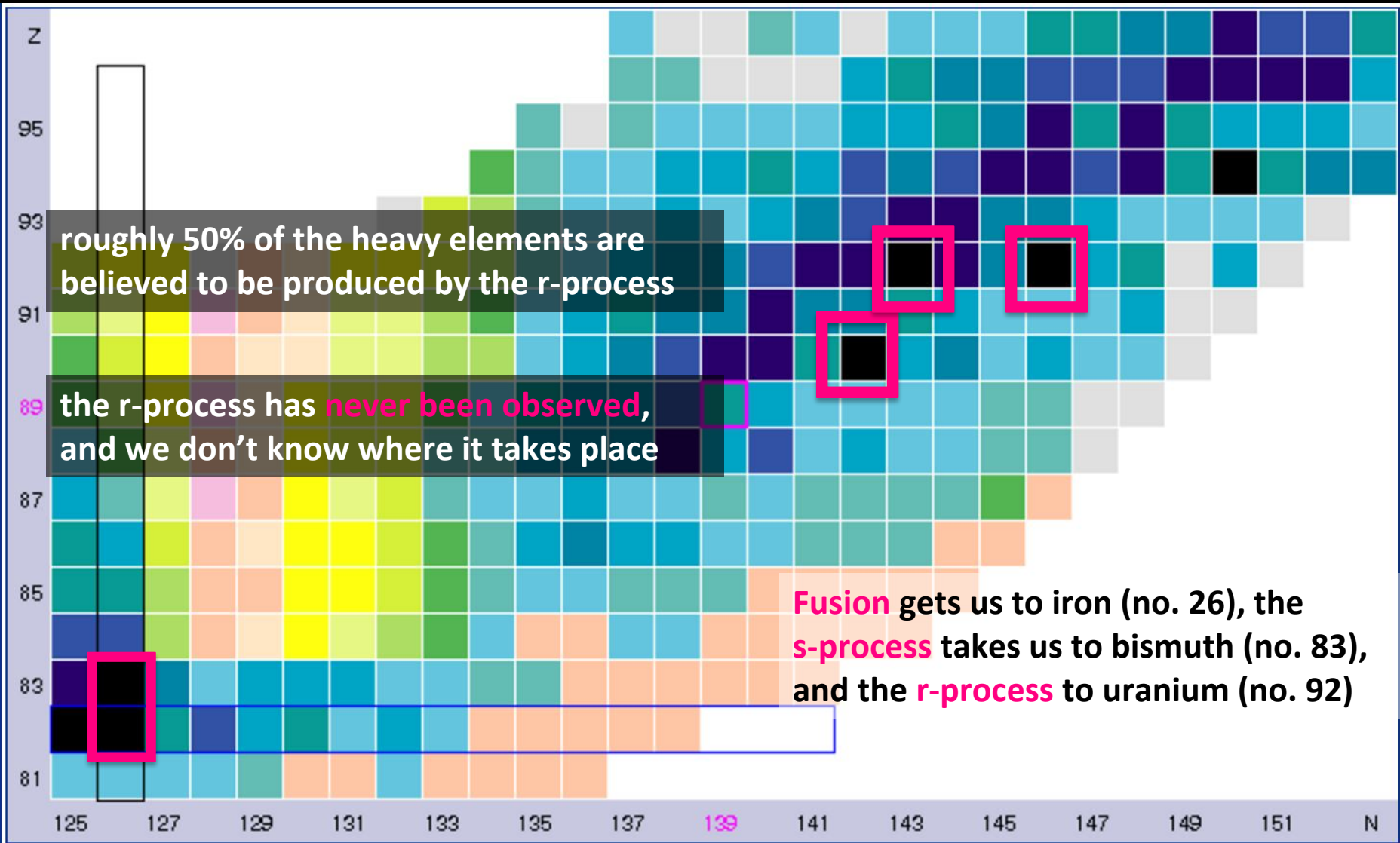
**HEAVY NUCLEI *WILL* EVENTUALLY  
FISSION**

# As number of protons increase, so does the fission probability (either spontaneously or induced)

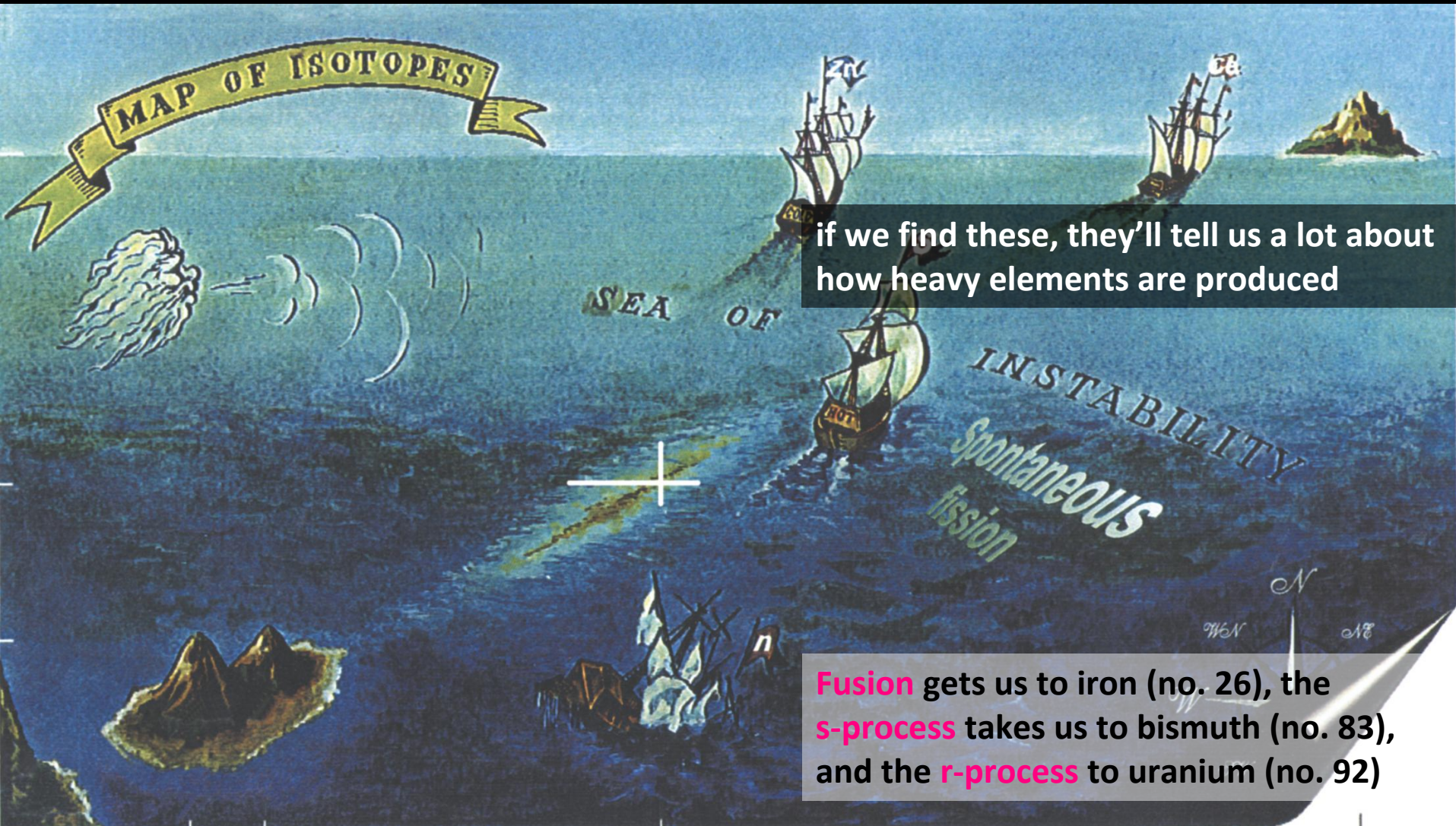


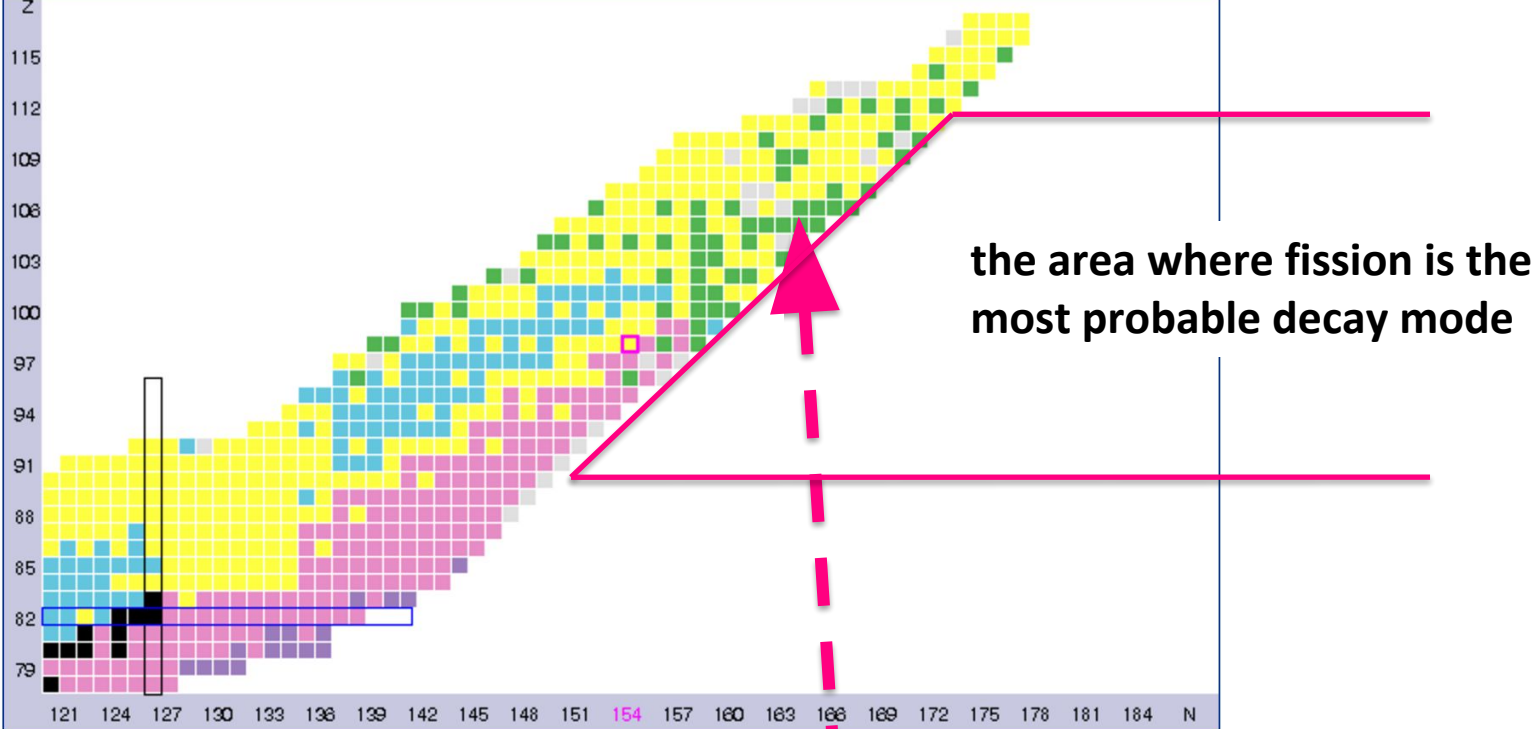
fission is the process where a heavy nucleus splits into two fission fragments

# The r-process is terminated by fission, and $^{238}\text{U}$ is the heaviest nucleus found in nature



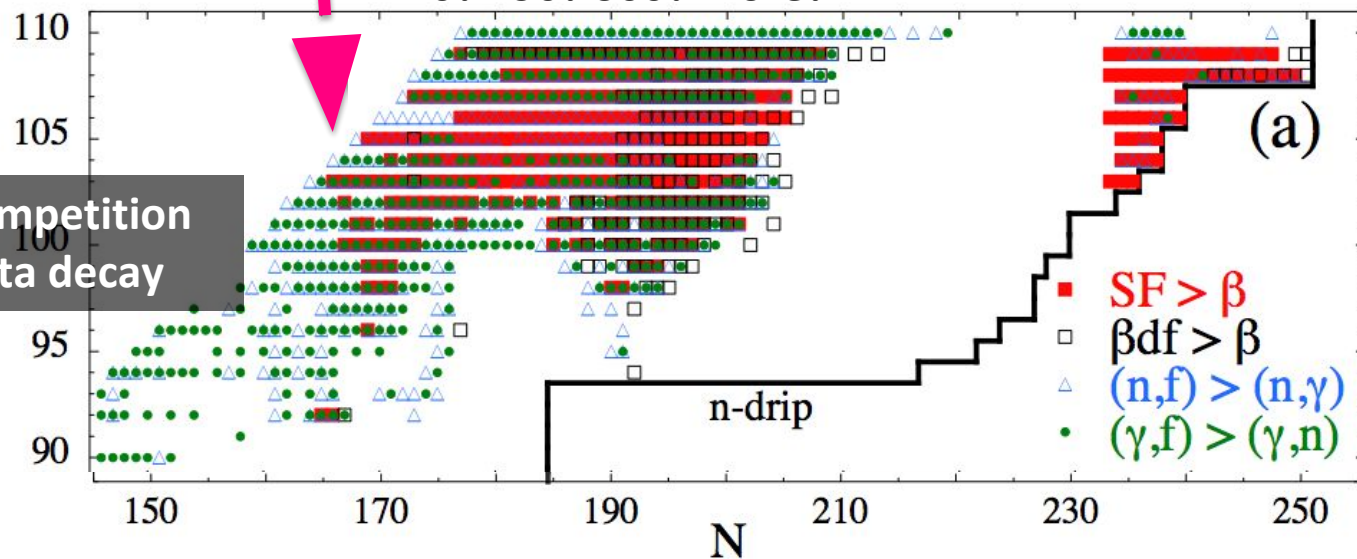
# Does the *island of stability* exist?





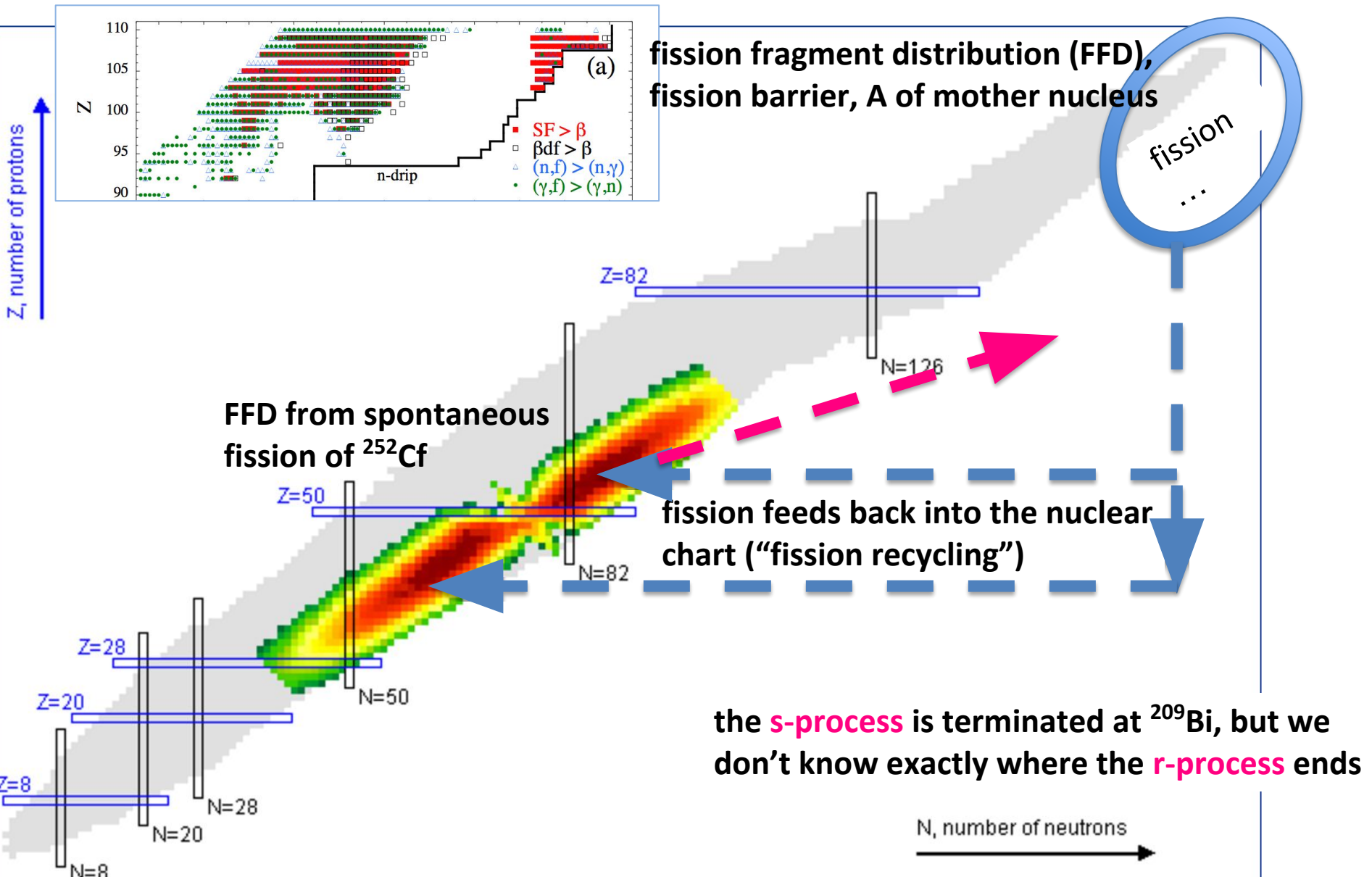
how far can we go?  
270? 290? 300? more?

Goriely et. al, PRL 2013



eventually there is a competition between fission and beta decay

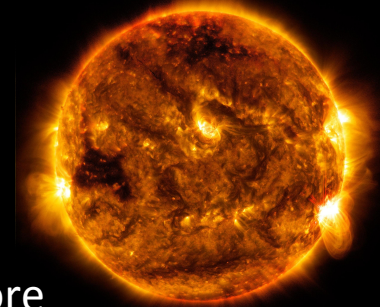
# When nuclei fission, they will “feed” back into the chart of nuclides, at A dependent on the size of the fissioning nucleus



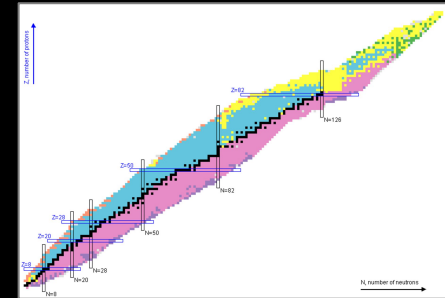
synthesis of heavy elements:

**NEUTRONS ARE KEY...**

# Close to 100% of the elements heavier than iron are made by neutron captures, so supply of neutrons is key



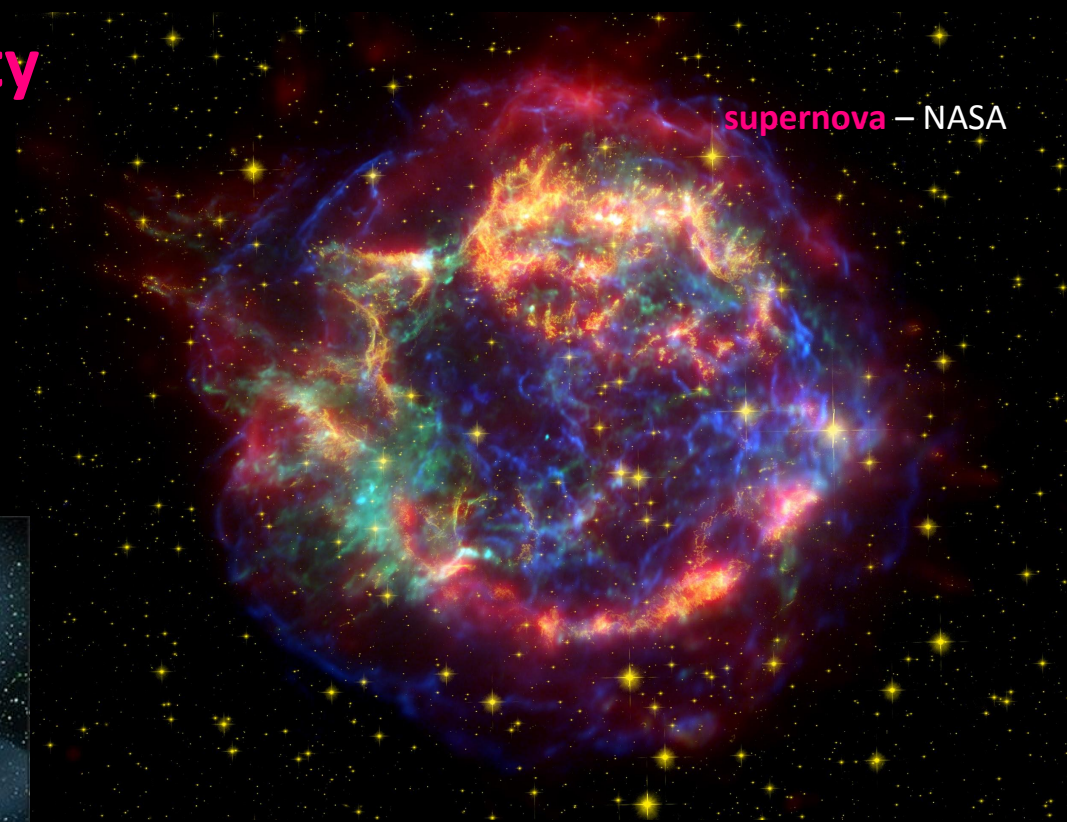
- fusion takes us to iron, where energy can not be “won” anymore
- s-process is responsible for ~50% of elemental abundance above iron
- r-process produces roughly the other half of the heavy nuclei
- the heaviest elements found in nature are thorium and uranium
- fission terminates the r-process/synthesis of heavy elements
- fission fragments feed into the nuclear chart, but how heavy/many neutrons do the fissioning nuclei have?
- the r-process has never been observed...
- **we need neutrons!**





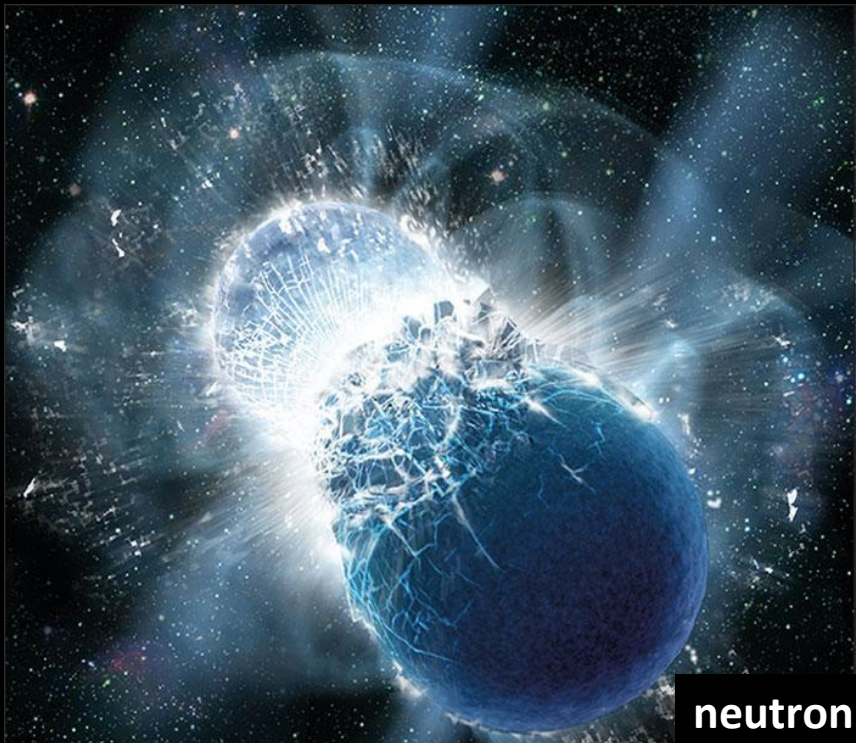
# The r-process must happen in an environment with a very high neutron density

free neutrons beta decay with an average lifetime of 15 minutes



supernova – NASA

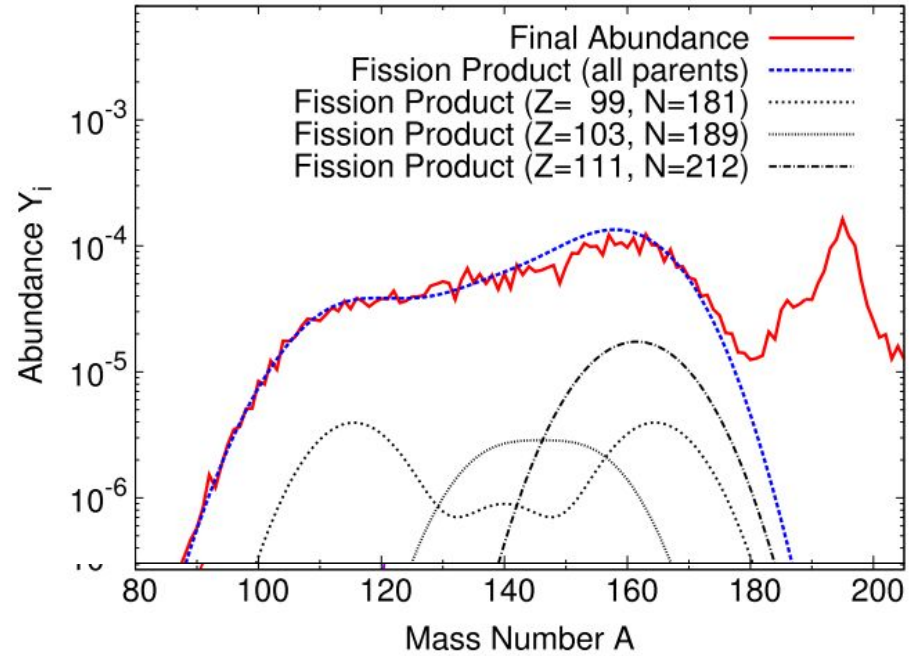
supernovae were thought to be the prime production site of the r-process



neutron star merger – CERN

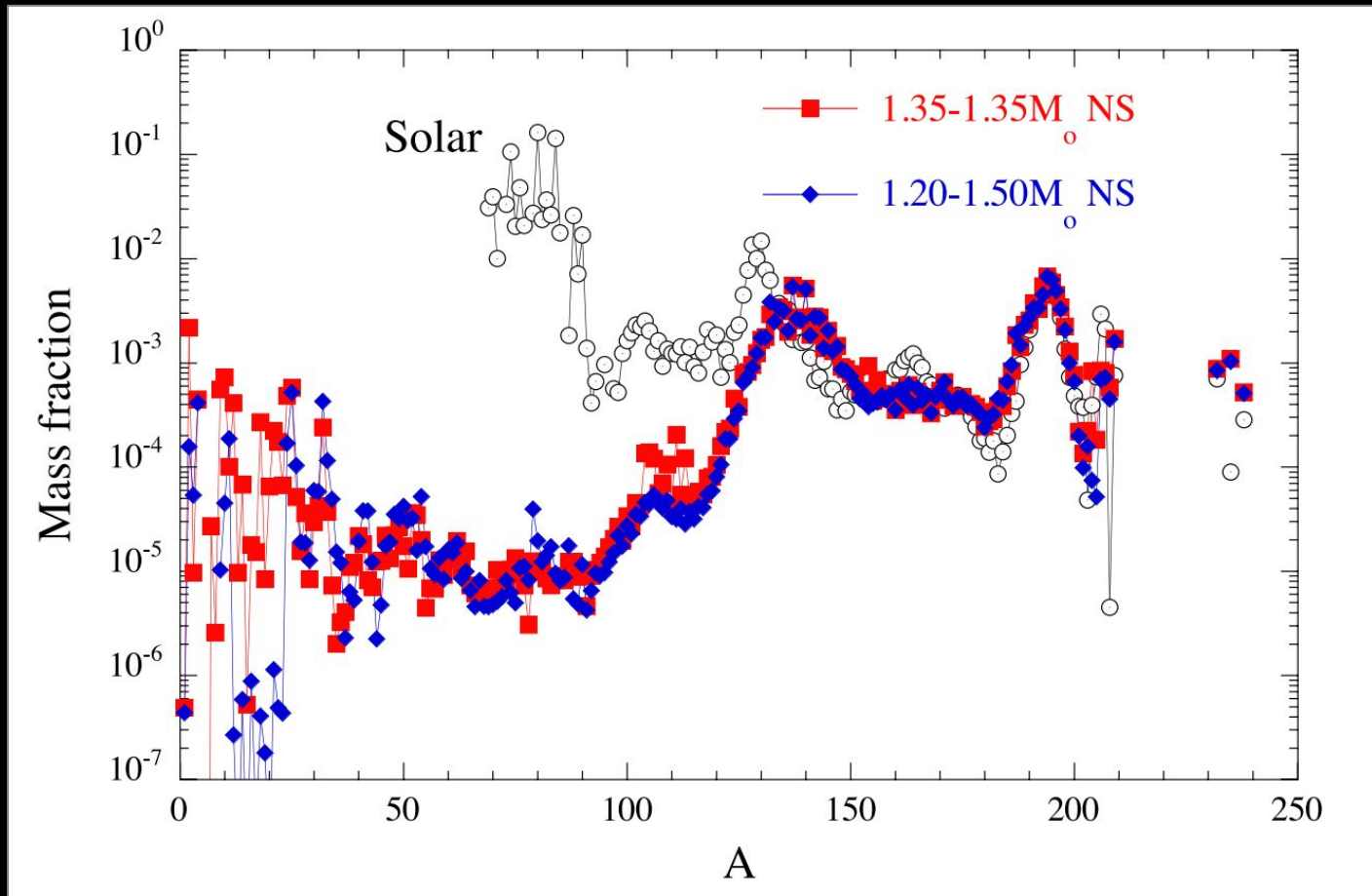
neutron star mergers have a higher neutron density

SHIBAGAKI ET AL.



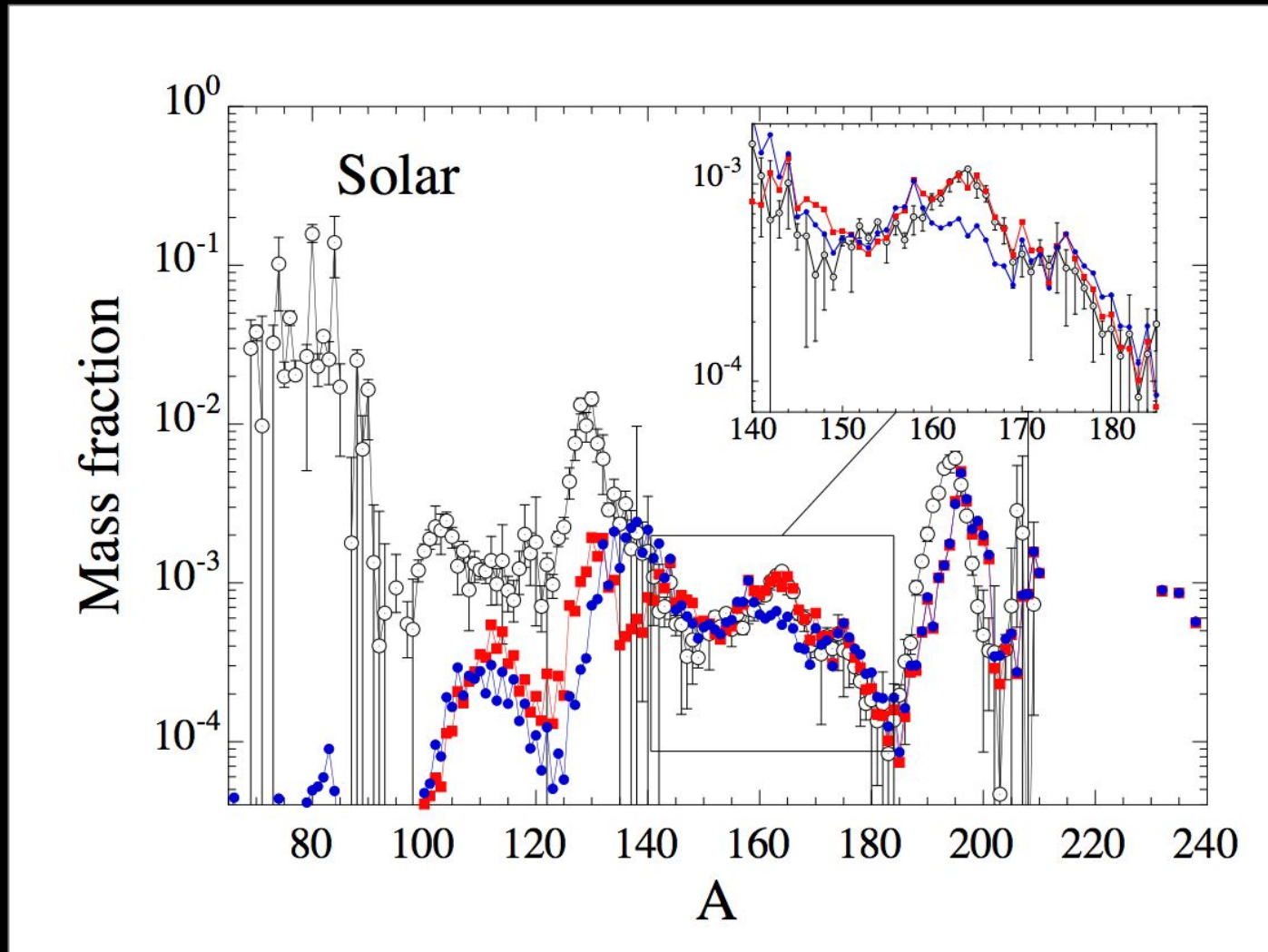
the effect of at what A the r-process  
is terminated (neutron flux)

“the peak around  $A=140$  originates exclusively from the fission recycling, which takes place in the  $A \sim 280-290$  region at the time all neutrons have been captured”

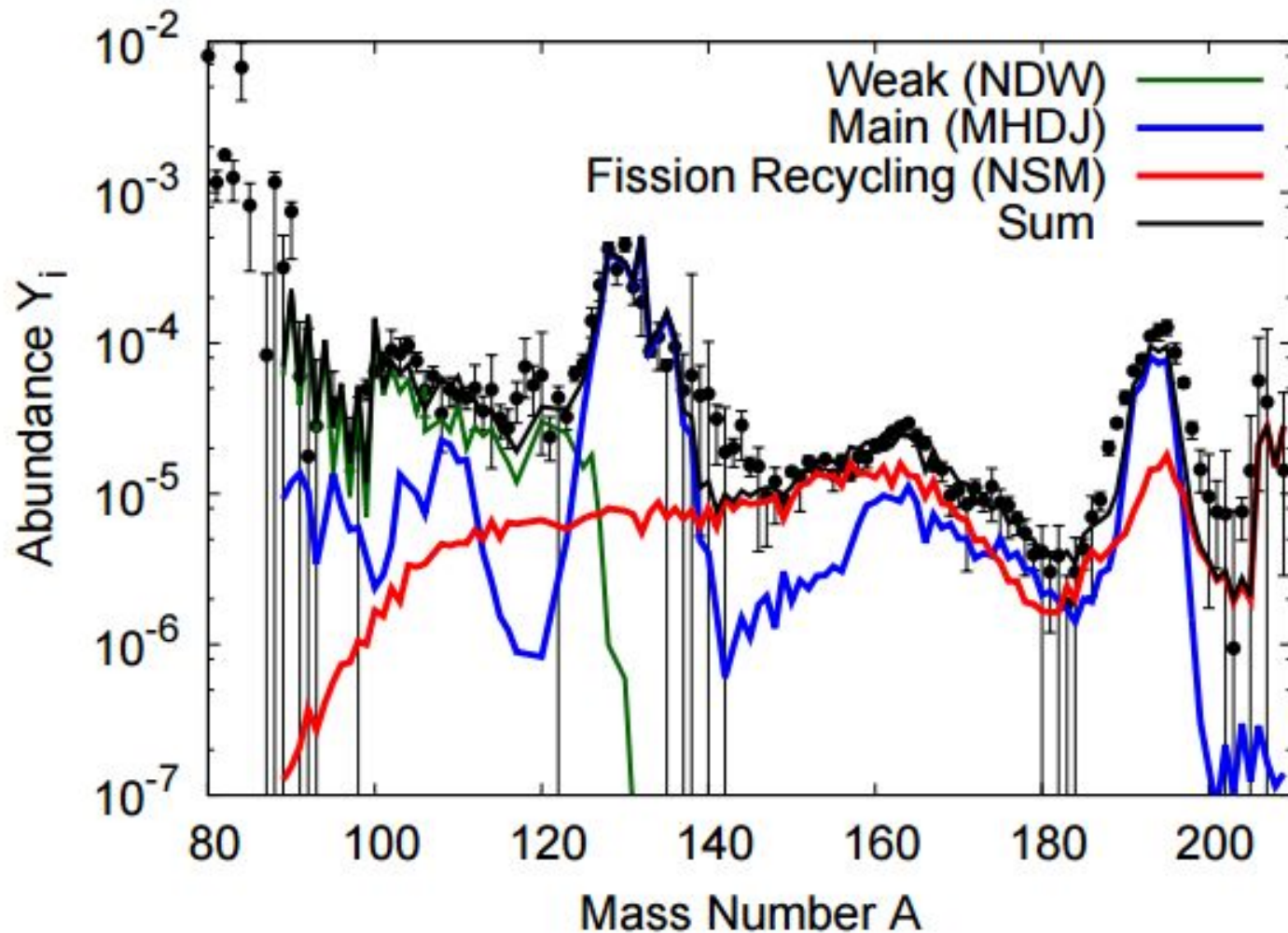


at which  $A$  the r-process terminates affects the abundance distributions

two years later, the same authors are more concerned with the peak at 165



**fission fragment distributions  
affects the abundance distributions**



propose a combination of supernova  
and neutron star mergers

fission recycling as a main contributor  
to the  $A \sim 165$  abundance peak

# In summary, the synthesis of heavy elements involves the s- and r-process, and it's terminated by (spontaneous) fission

need lots of nuclear and astro physics information to model the r-process properly

the fission barrier and FFD are key nuclear input parameters for termination of the r-process

neutron star mergers as site of the r-process  
*may* explain the  $A \sim 165$  abundance peak

