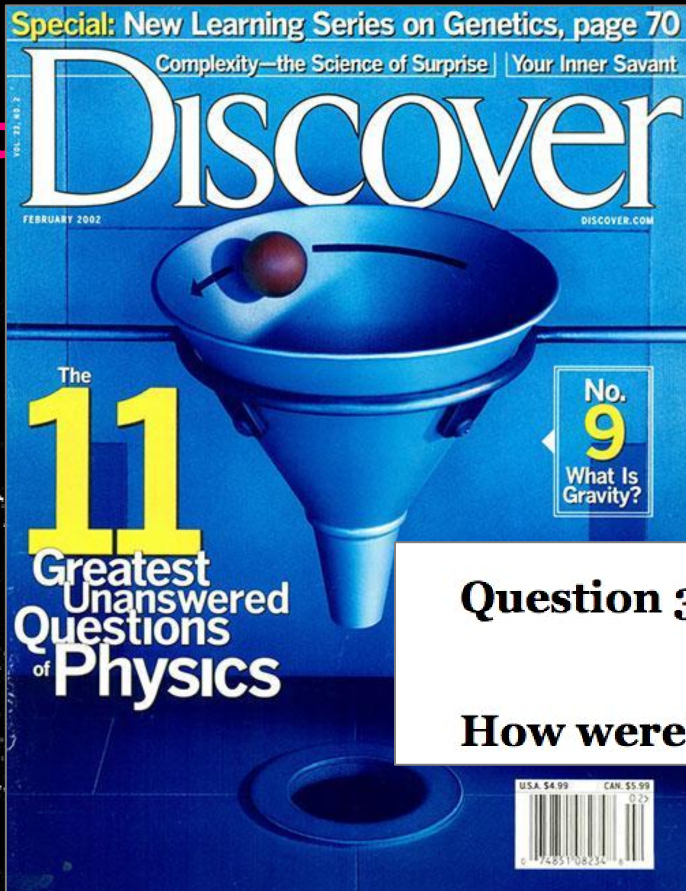
Cosmic Fission: the Synthesis of the Heavy Elements and the role of Fission

Sunniva Johanne Rose

Trial lecture
29th March 2017

I Research Council made a list over t wered Questions of Physics



Question 3

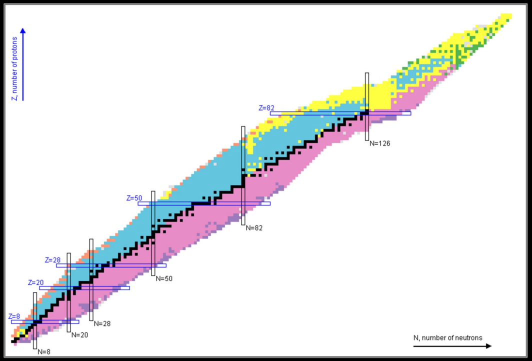
How were the heavy elements from iron to uranium made?

Image: https://www.flickr.com/photos/arnoldb/8537251229

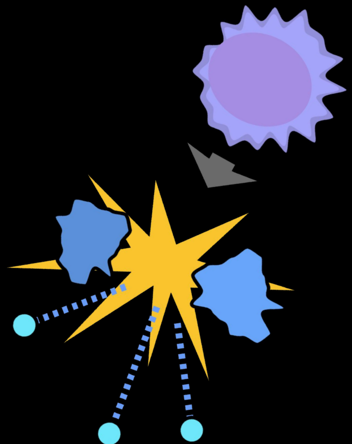
This talk focuses on production of elements, particularly those heavier than iron, and the role of fission in this process

light elements are produced in stars by fusion

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



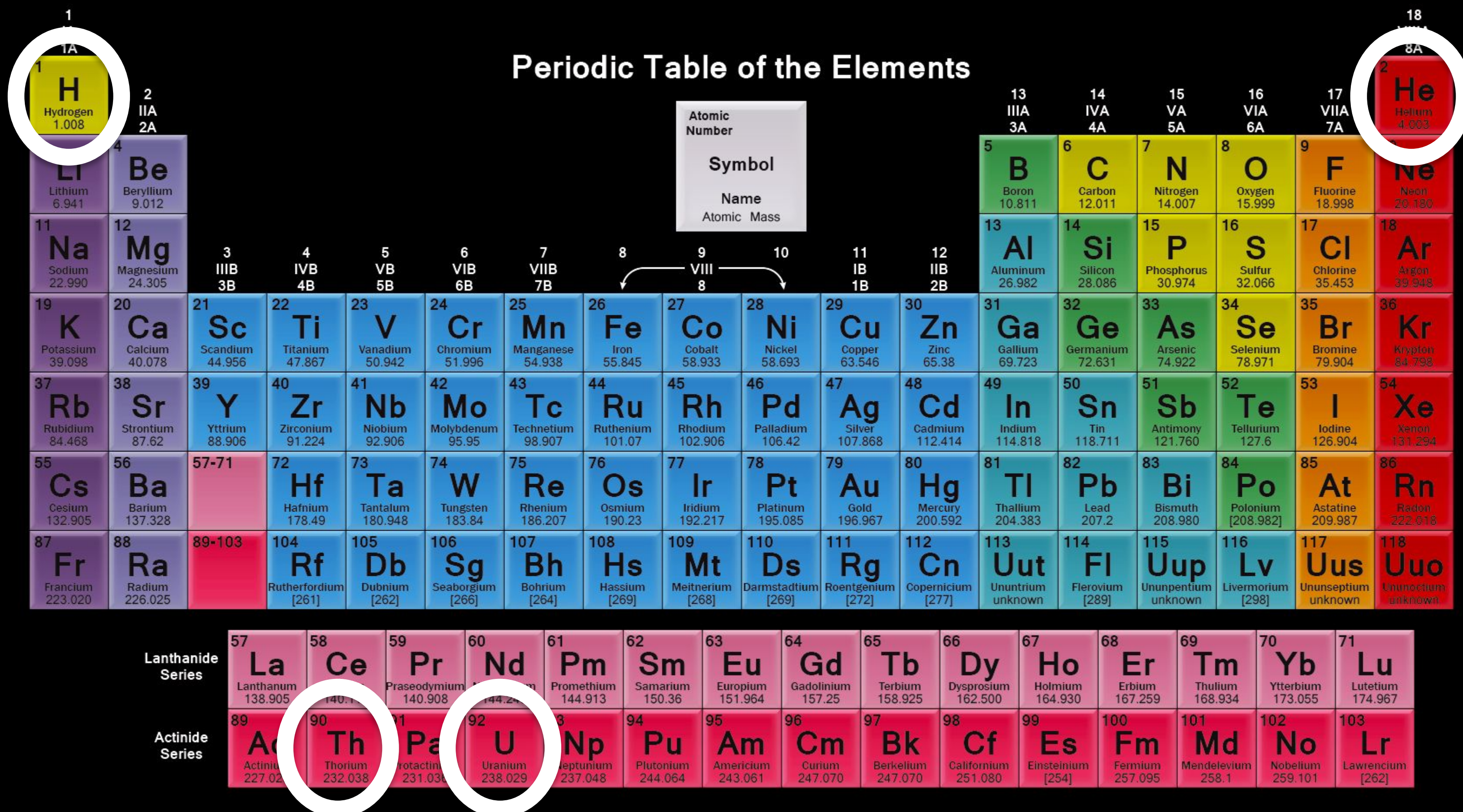
what happens when nuclei become too heavy? they fission…



THE LIGHT ELEMENTS

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

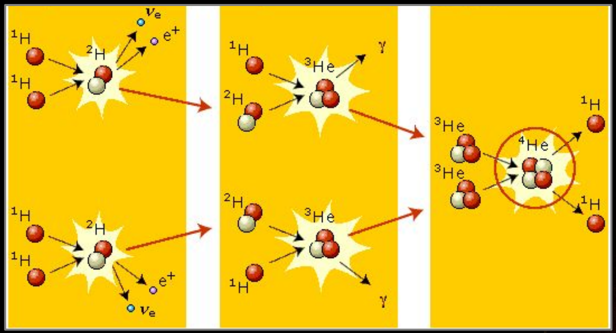
hydrogen and helium (nuclei) were created just after big bang (3 min)



uranium and thorium are the heaviest elements found in nature

elements with a number higher that 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

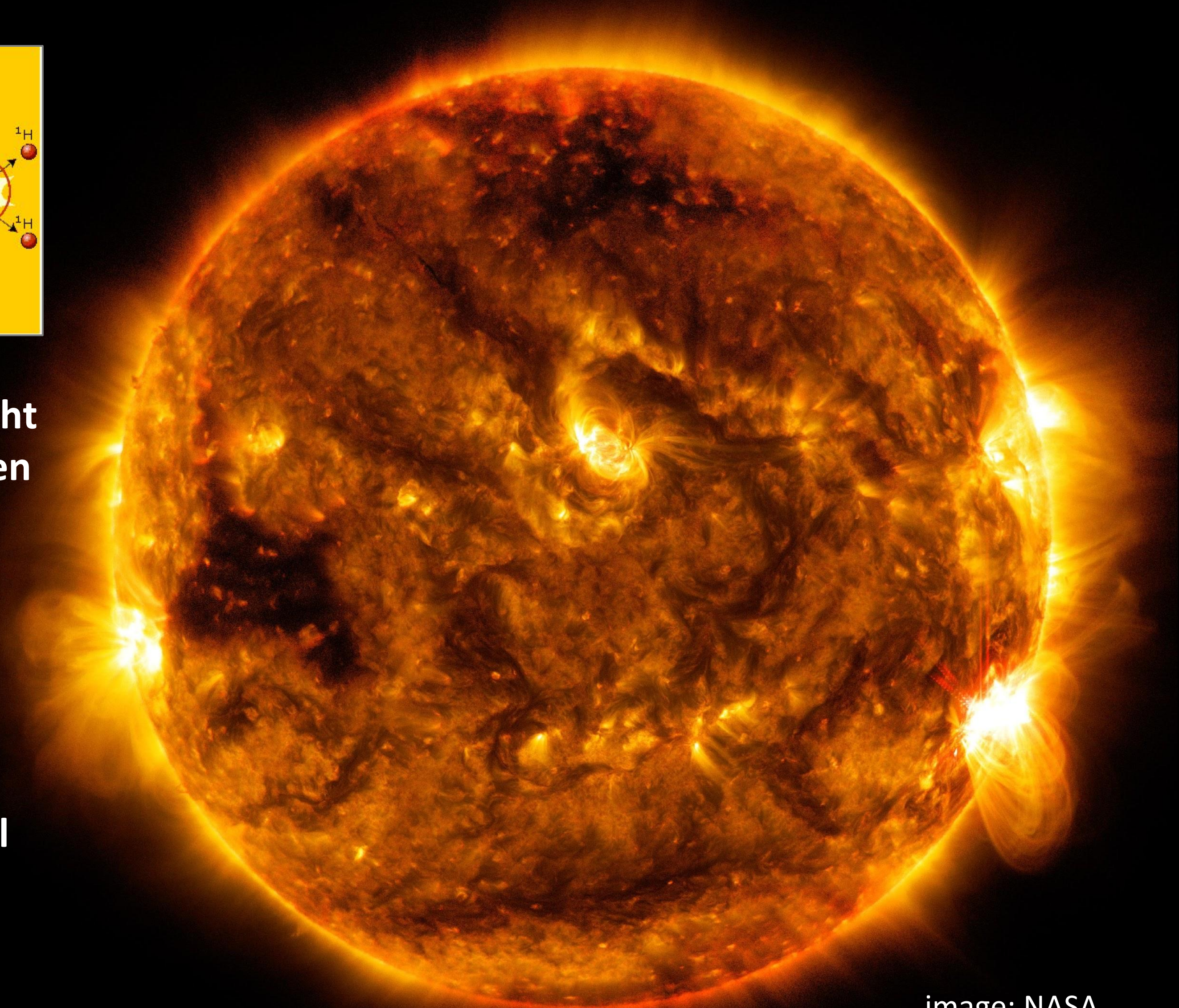


image: NASA

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

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

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

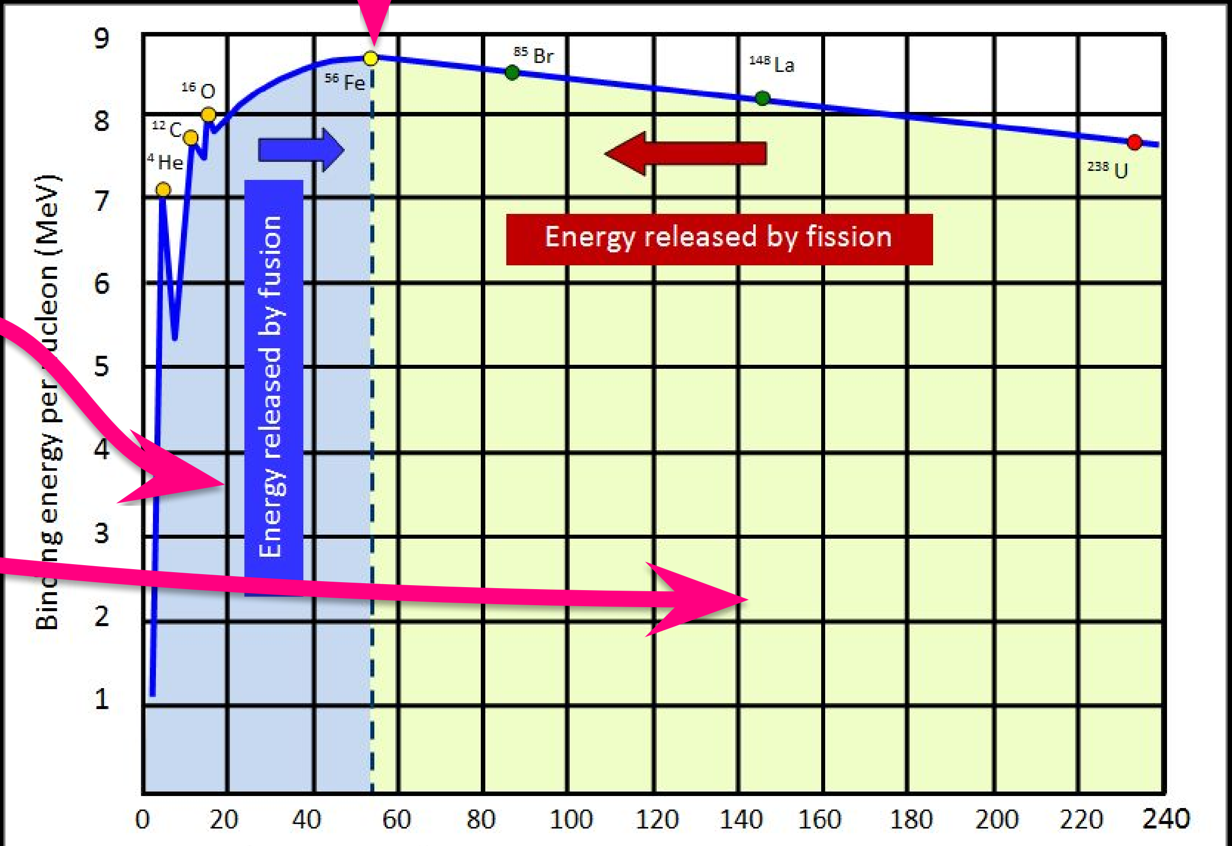
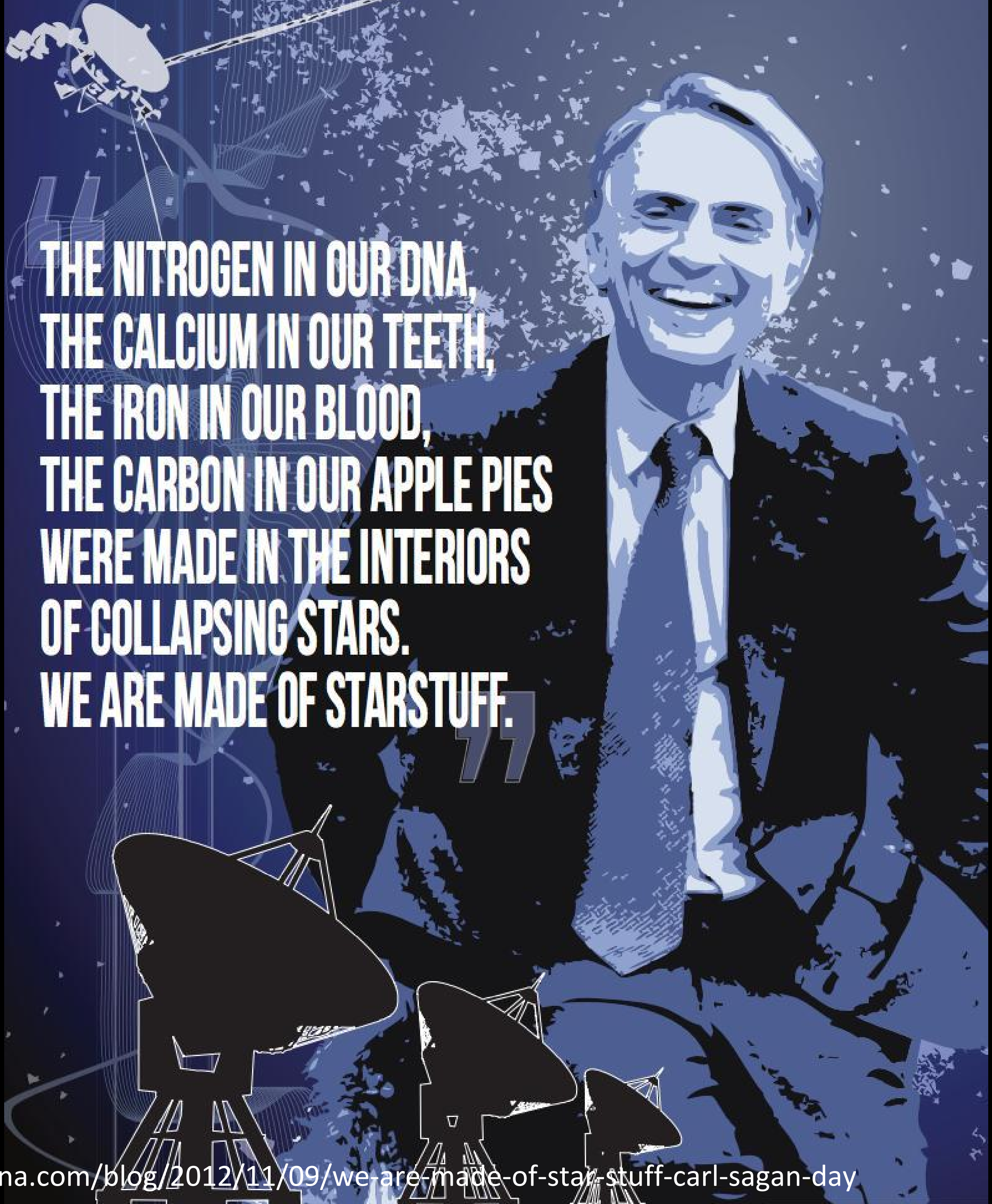
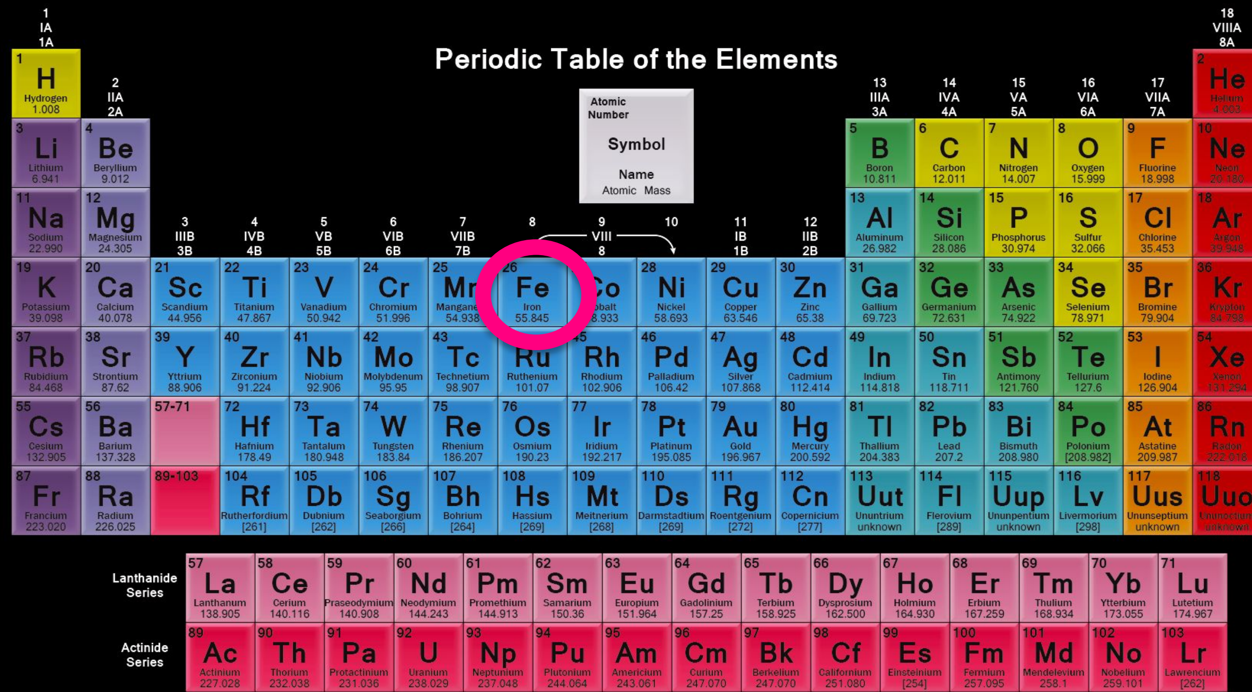


Figure 1



http://www.micheltriana.com/blog/2012/11/09/we-are-made-of-star-stuff-carl-sagan-day

So, we'll reach iron…but what now?



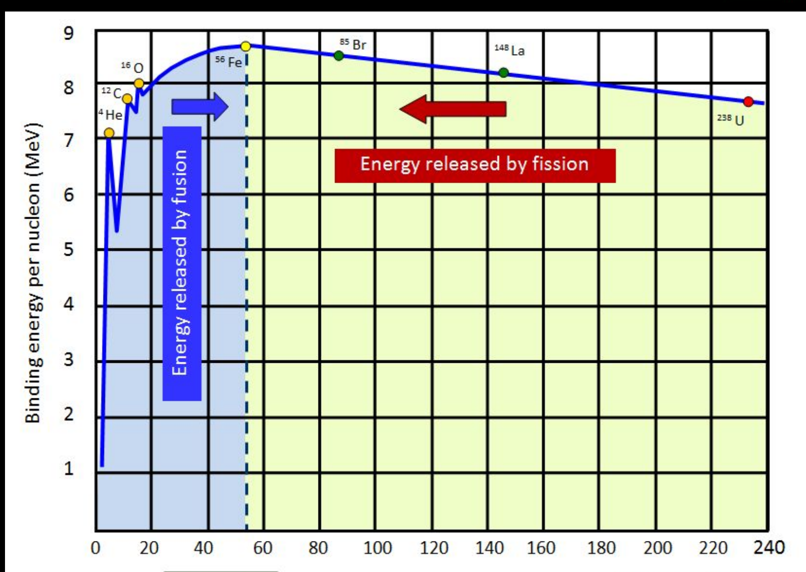


Figure 1

Iron has atomic number 26, but we know elements exist all the way up to 92 (118)

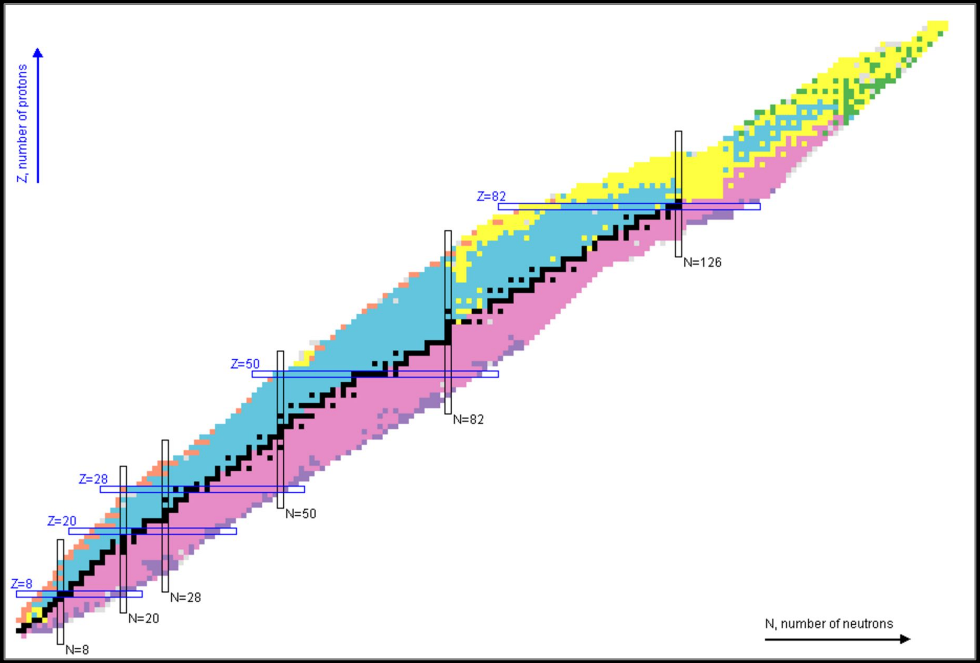
Elements heavier than iron can not be produced by fusion processes…

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

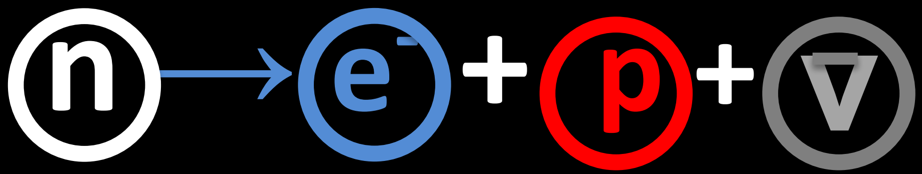
Then we'll see how nuclear information is organized in the chart of nuclides

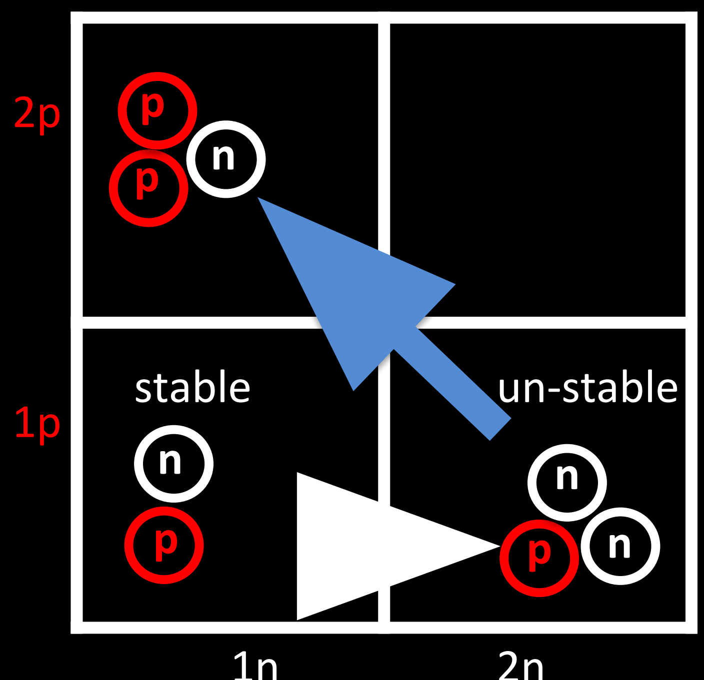
And finally we can look at the processes by which heavy elements are produced



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

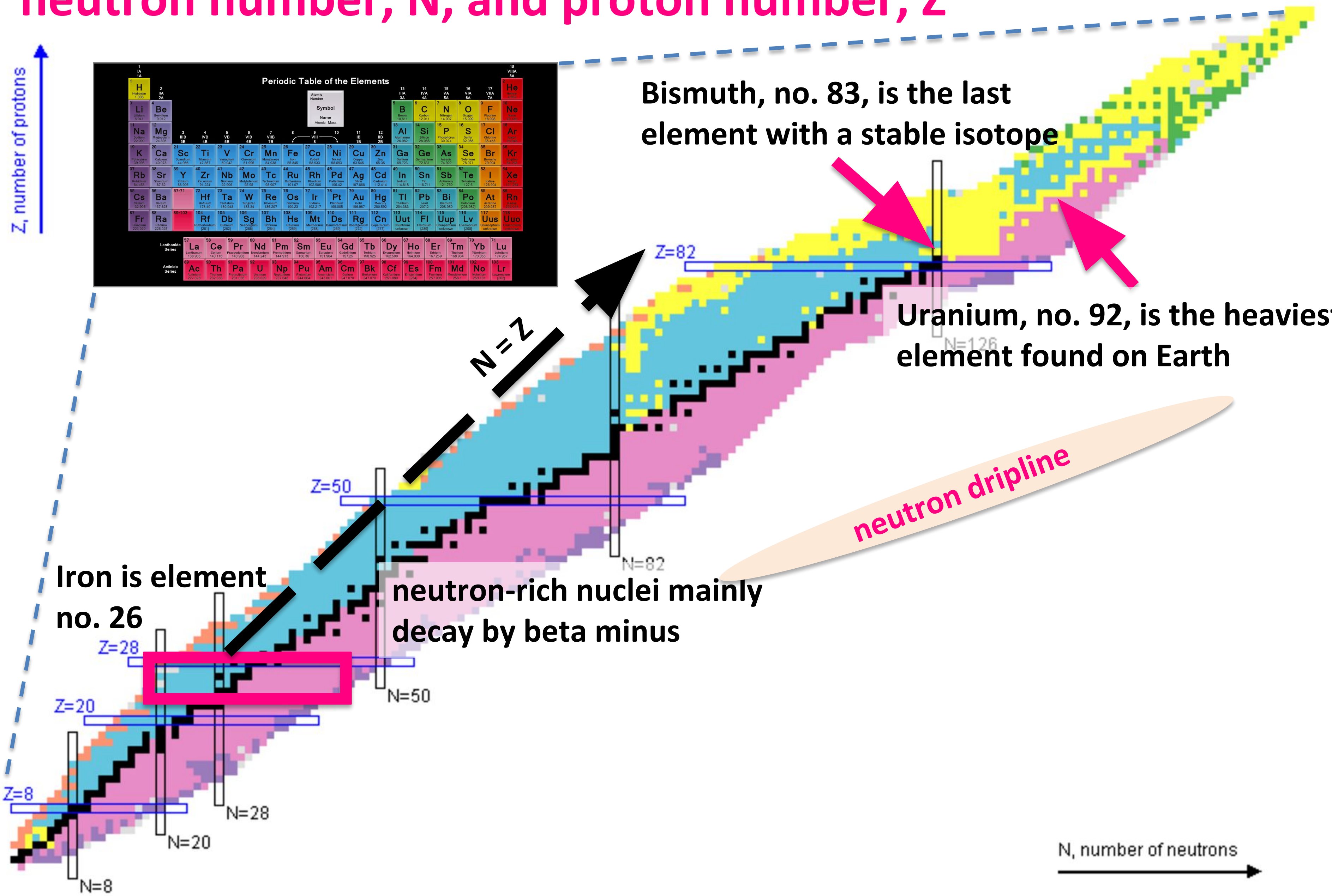
a **neutron** can be transformed into a **proton** in the beta minus decay process





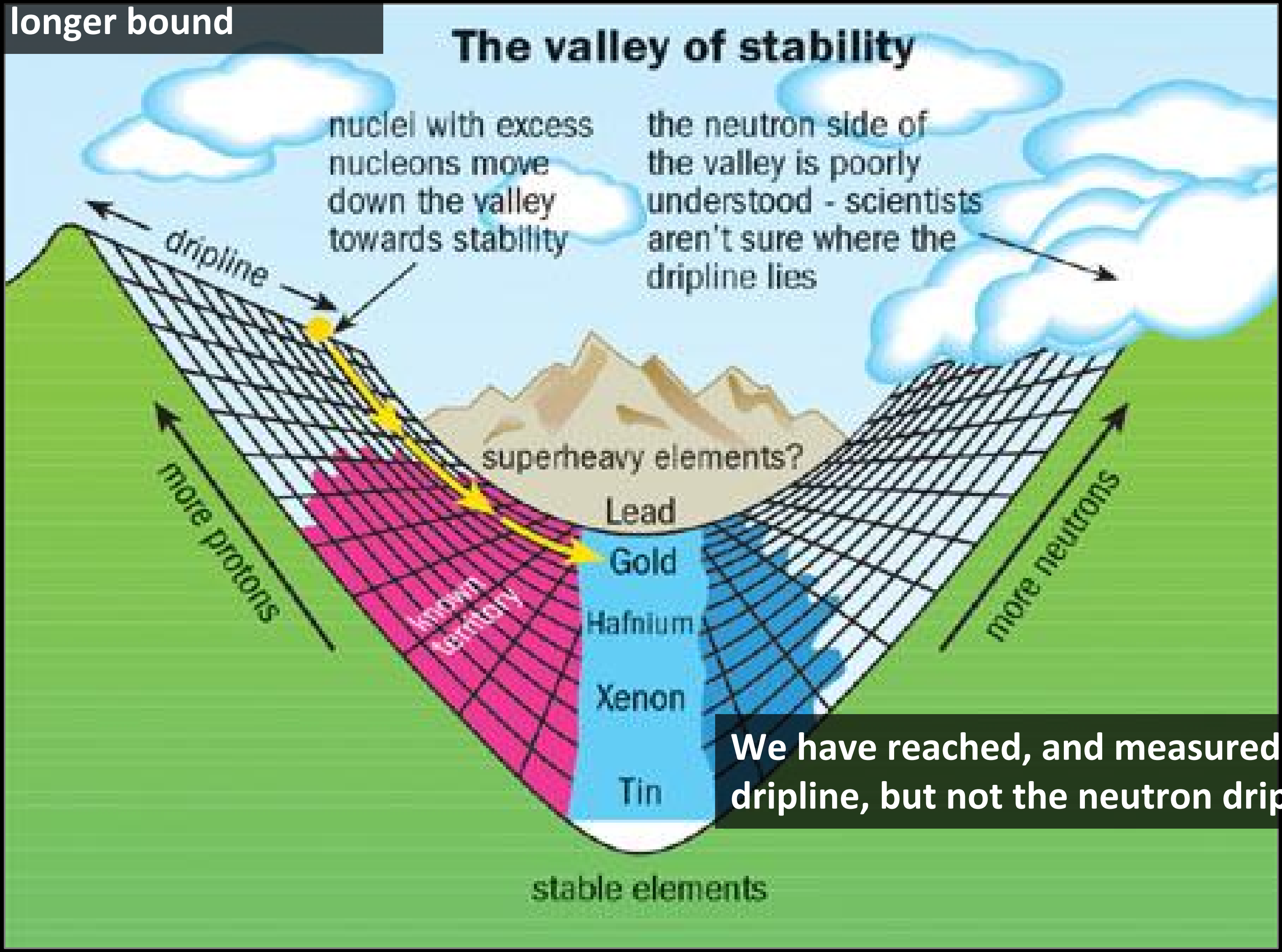
neutron capture can make a (stable) nucleus unstable to beta decay

The chart of nuclides plots all known nuclei as a function of neutron number, N, and proton number, Z



Nuclei will always "fall down" into the valley of stability

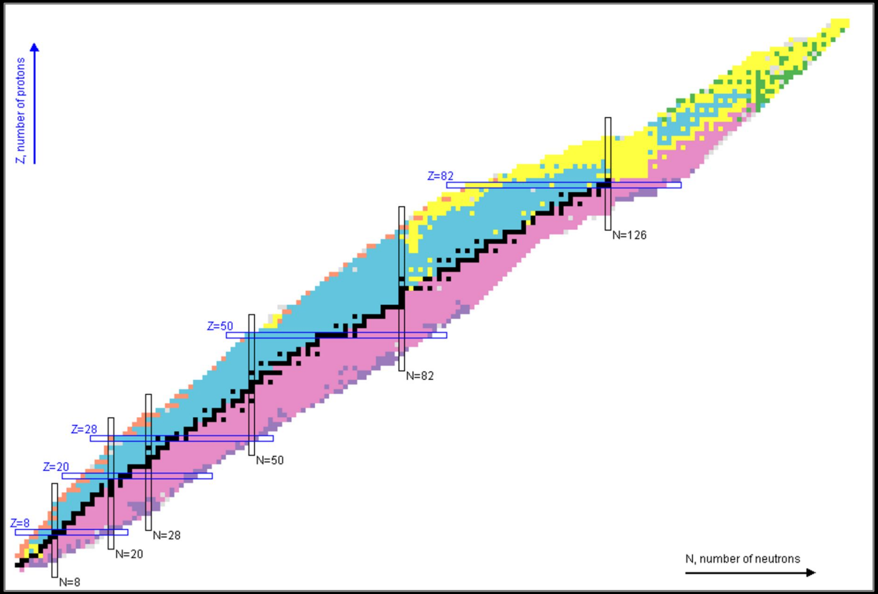
At the dripline, nucleons are no longer bound



We have reached, and measured the proton dripline, but not the neutron dripline

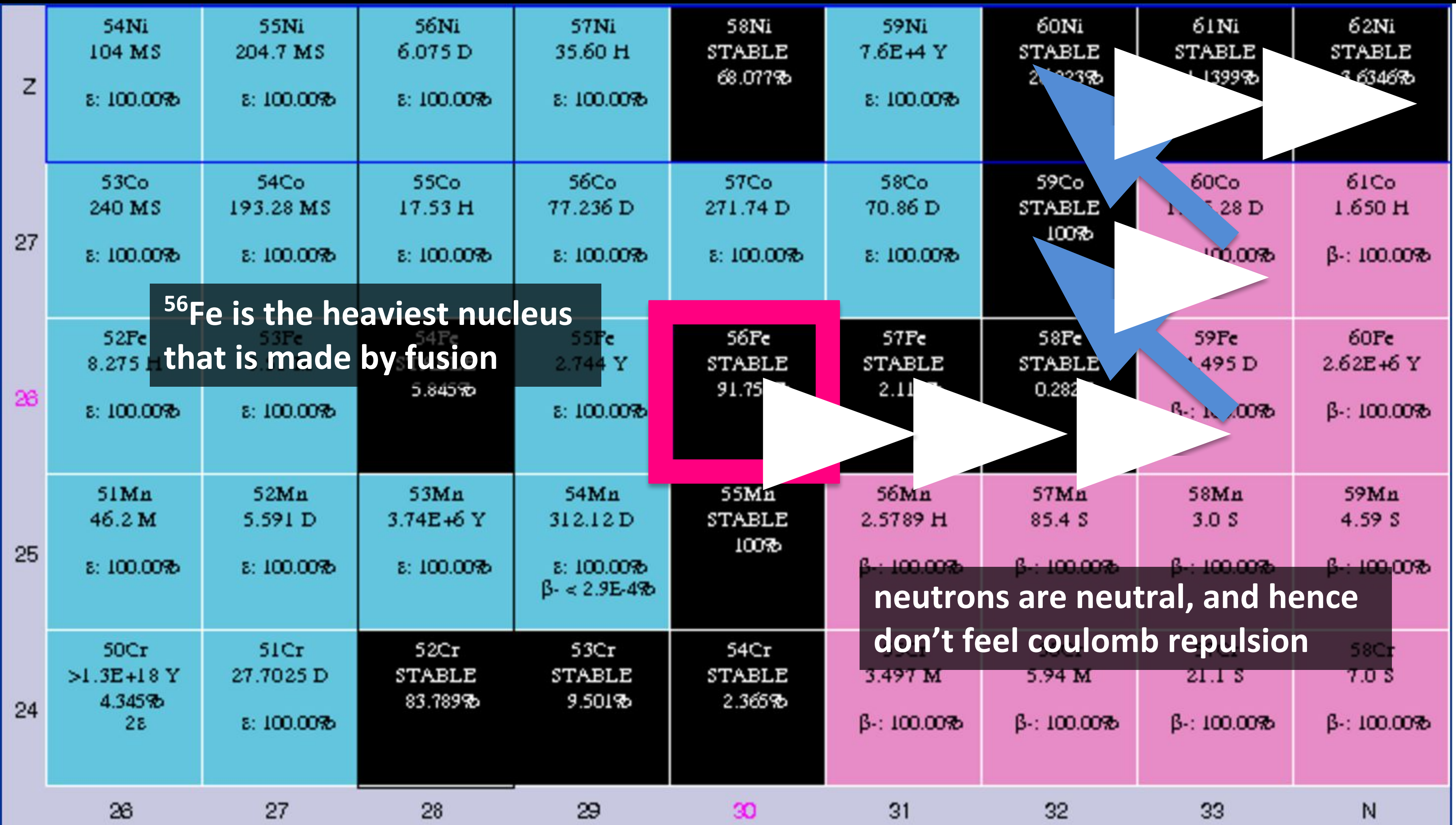
http://cerncourier.com/cws/article/cern/28587/1/cernria1_3-02

synthesis of heavy elements:



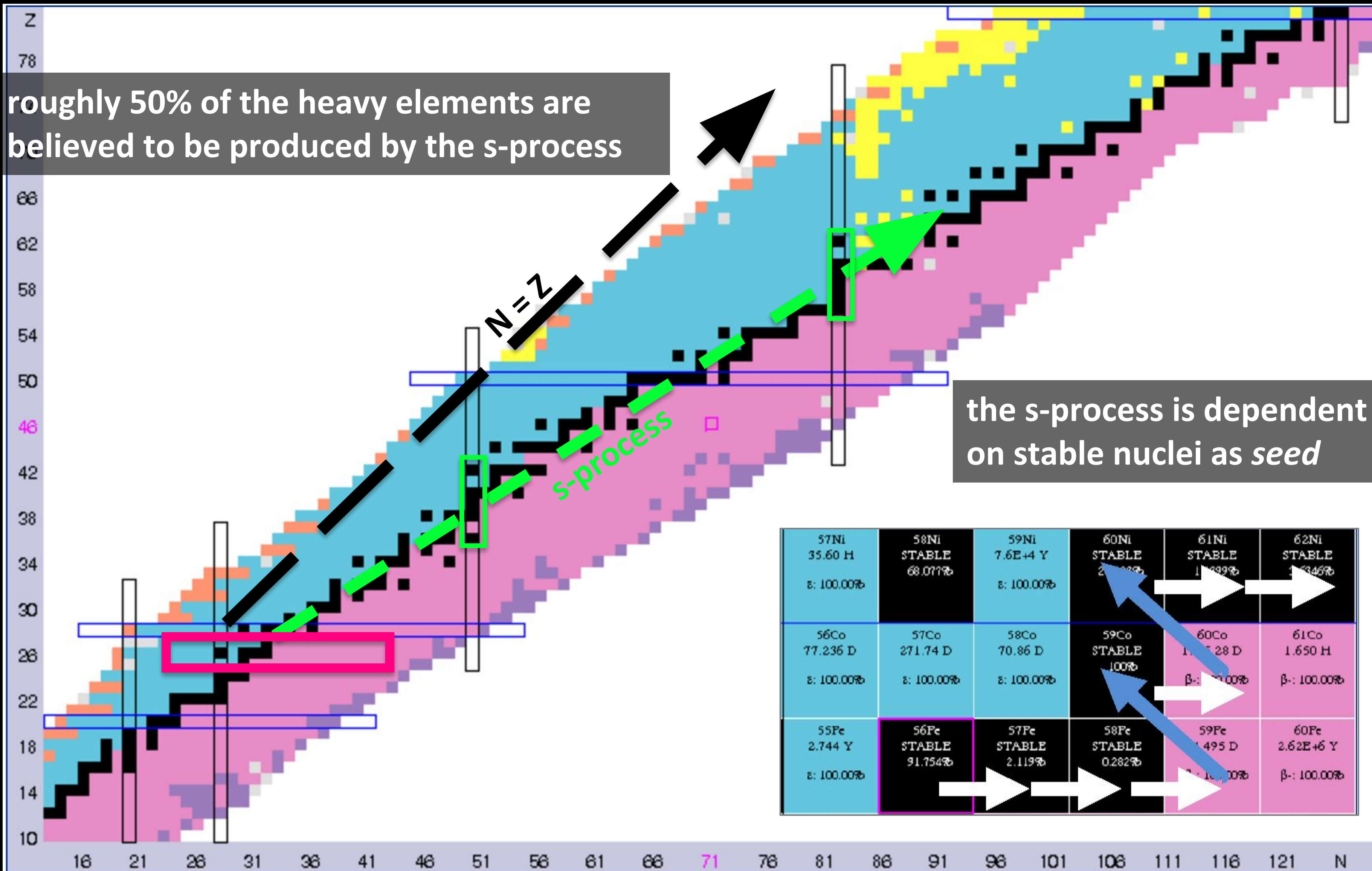
SLOW NEUTRON CAPTURE PROCESS

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

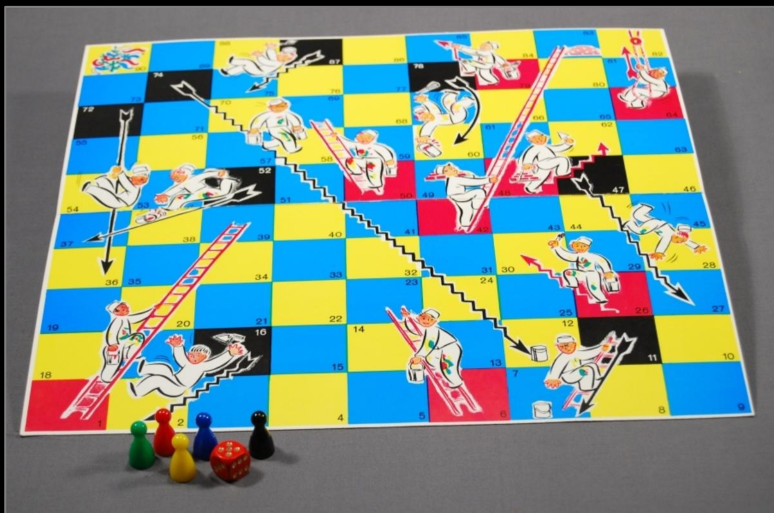
By the *s-process*, we climb the nuclear chart following the valley of stability – but how far can we go?



roughly 50% of the heavy elements are believed to be produced by the s-process

the s-process is dependent on stable nuclei as *seed*

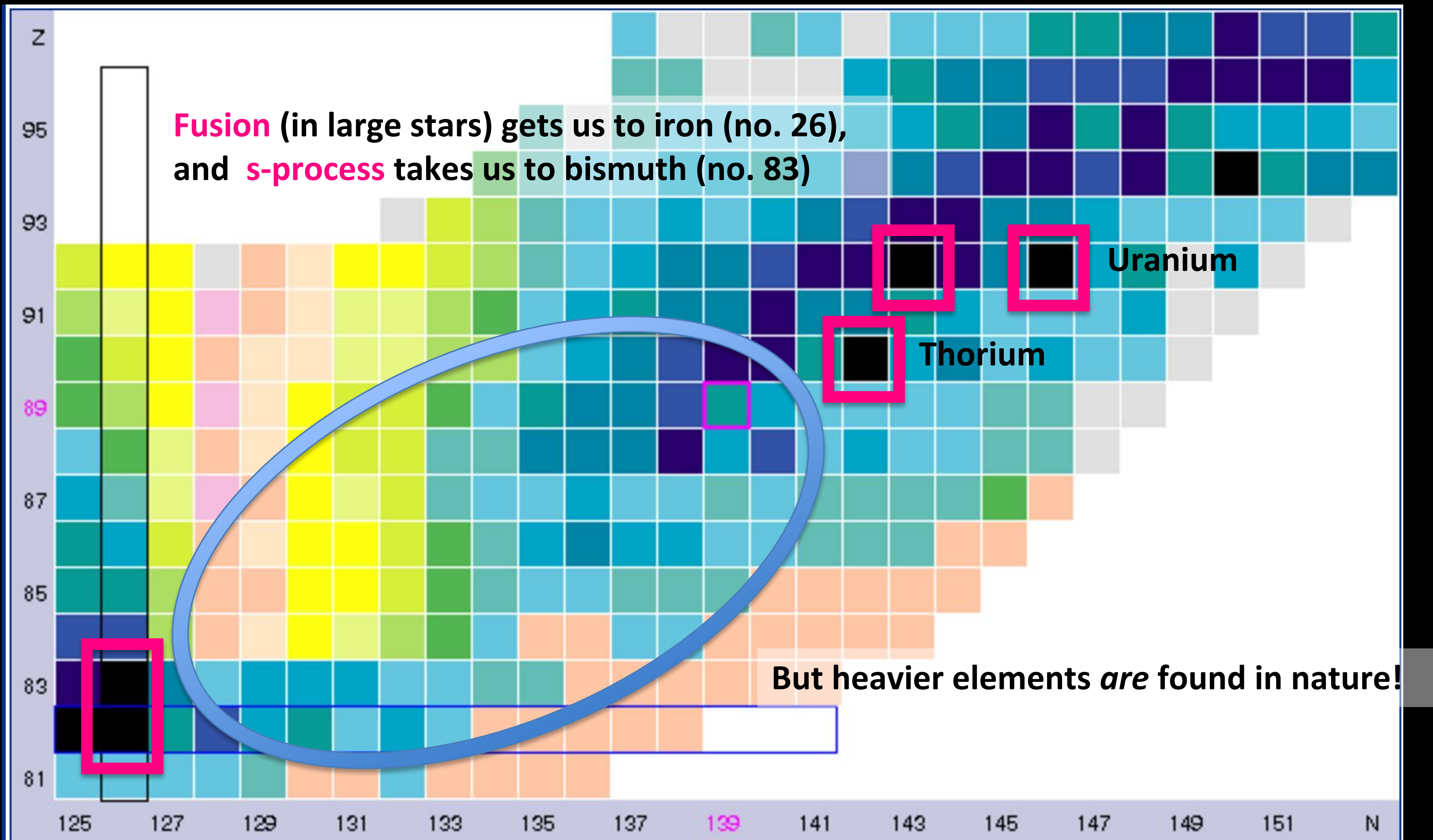
The s-process terminates at ^{209}Bi, when there are no more stable "seed nuclei" to capture neutrons



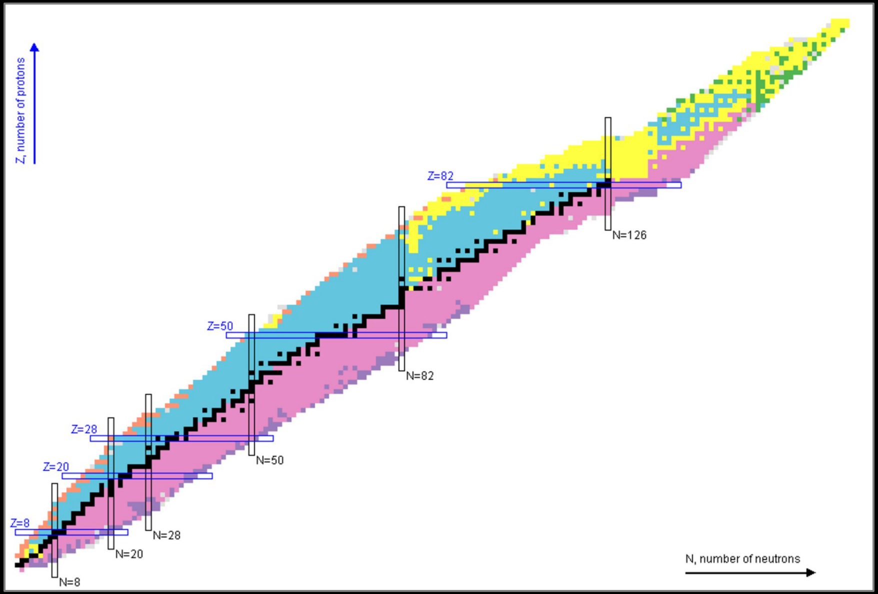
^{209}Bi(n,γ)^{210}Bi(β$^-$)^{210}Po(α)^{206}Pb chain leads to recycling of material in this mass region

the s-process has been observed in red giant stars

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

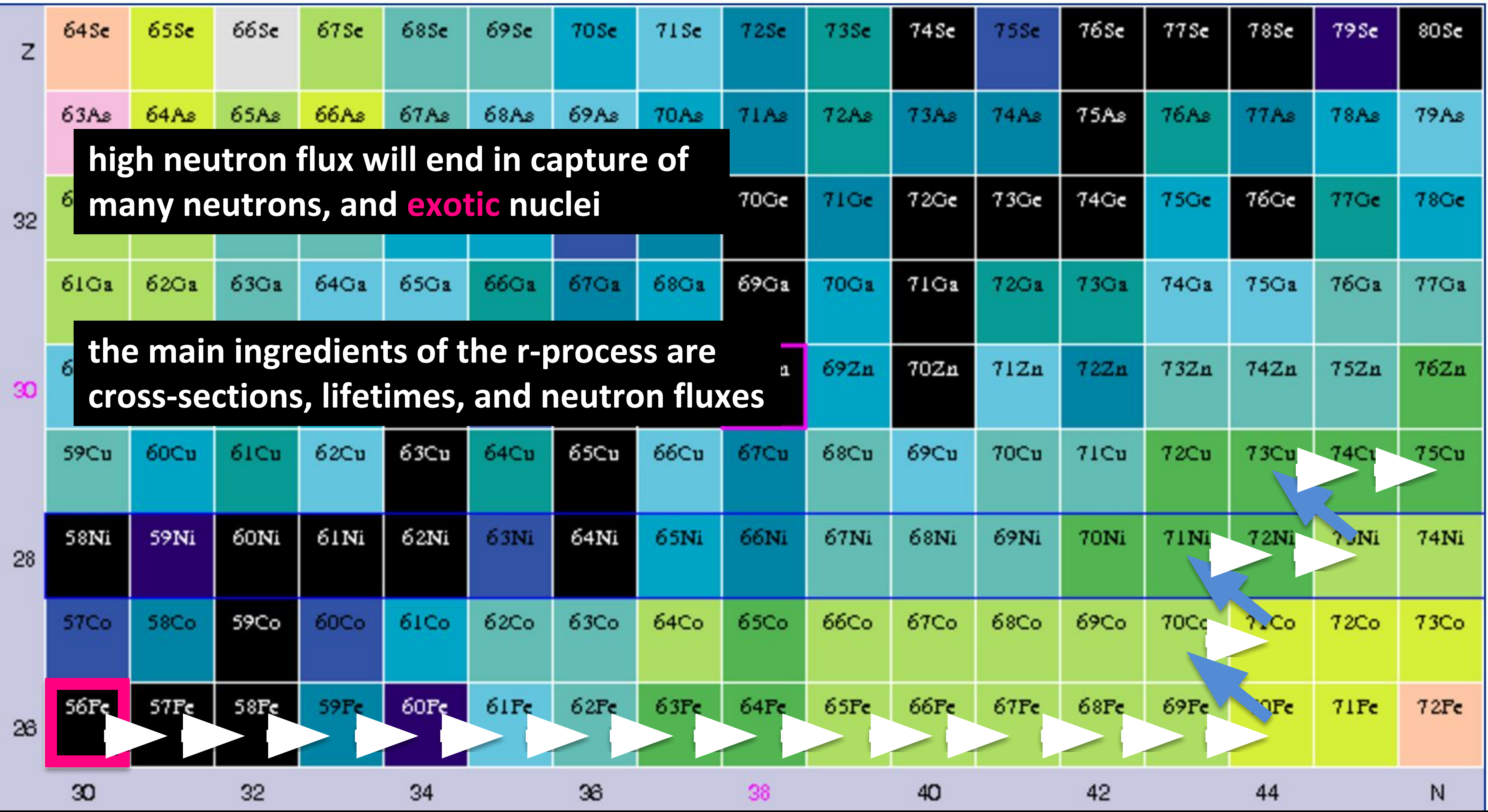


synthesis of heavy elements:

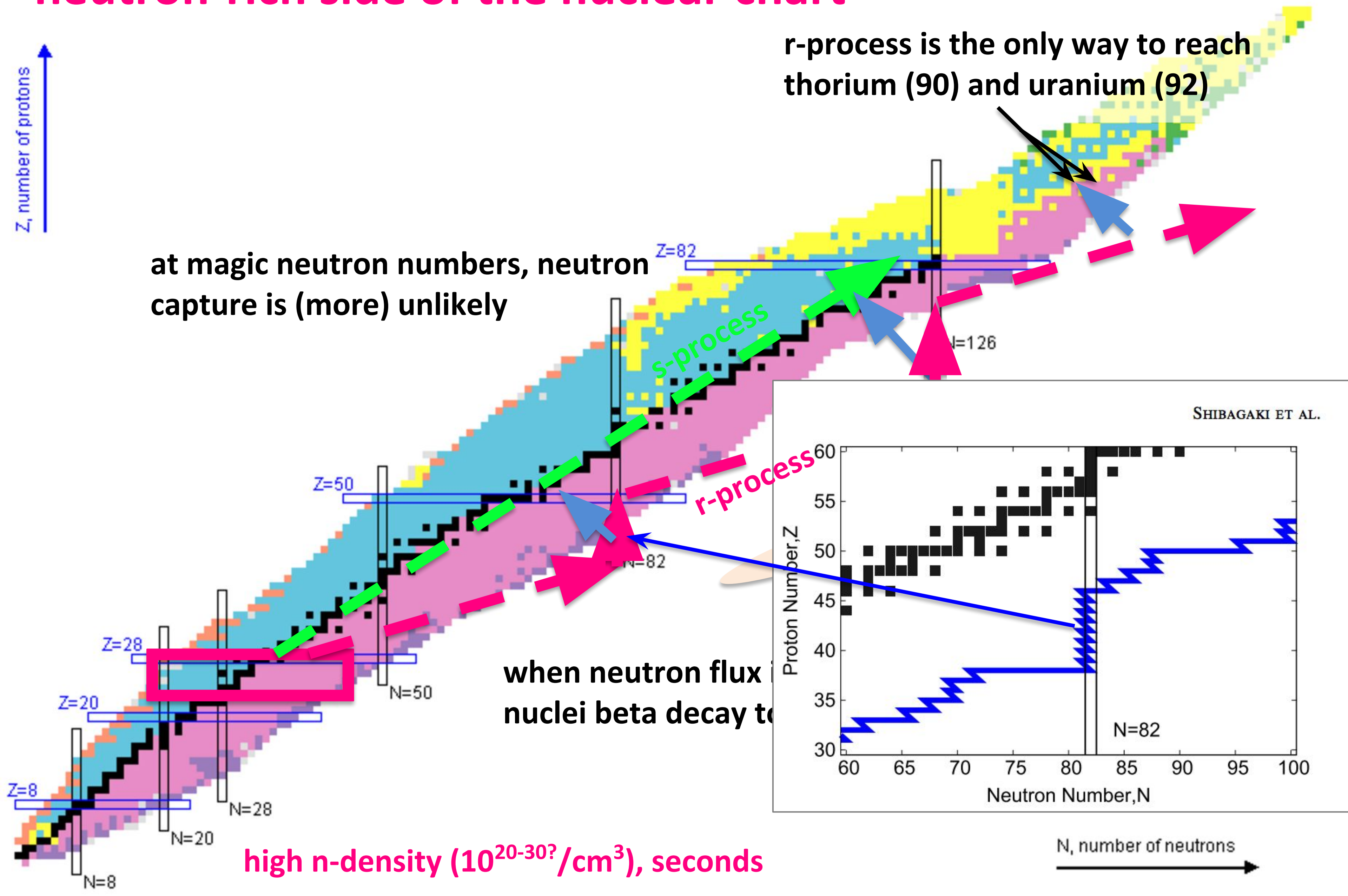


RAPID NEUTRON CAPTURE PROCESS

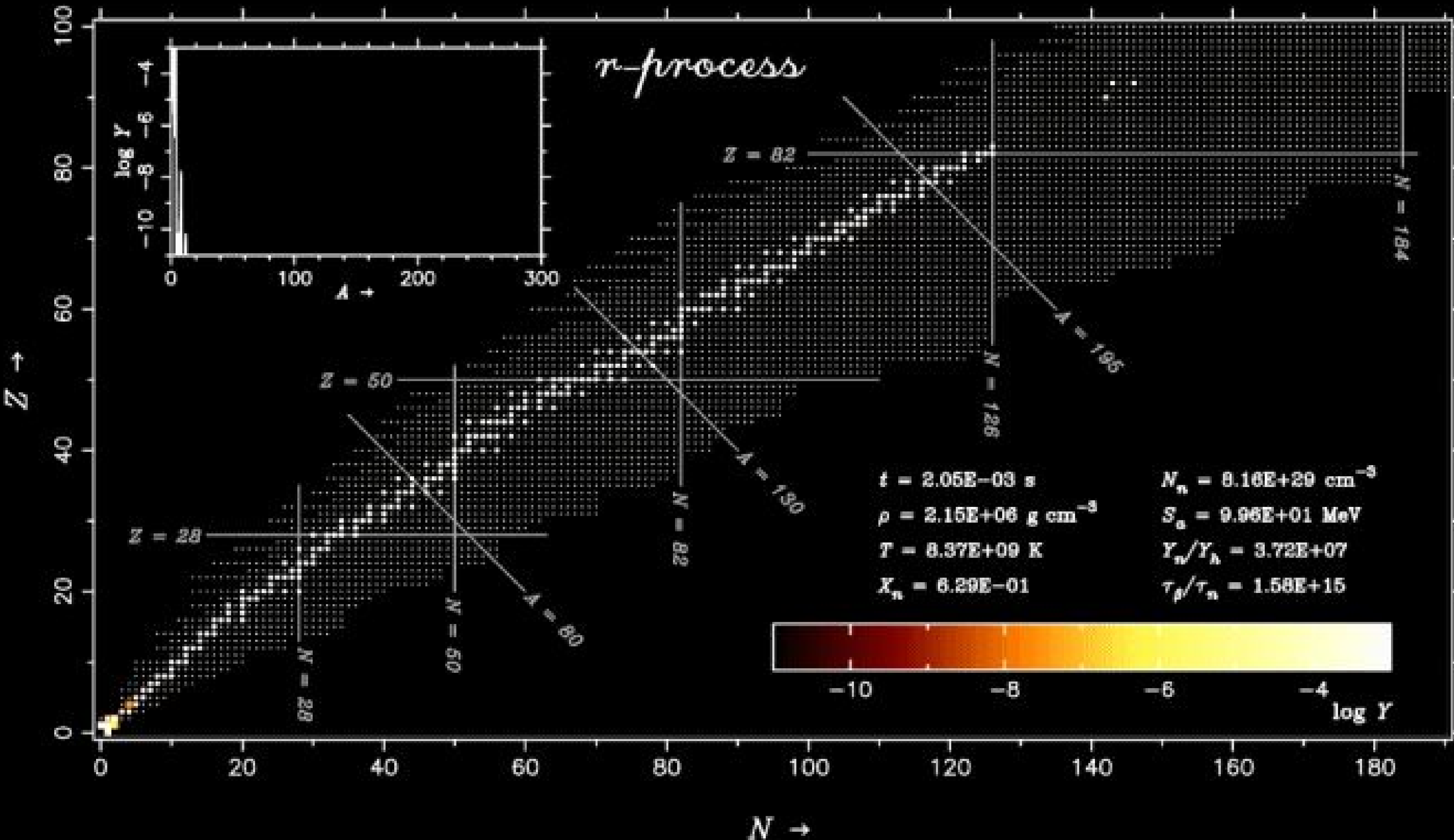
The *r-process* is the based on the idea that neutron density is high, and neutron captures are faster than beta decay



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

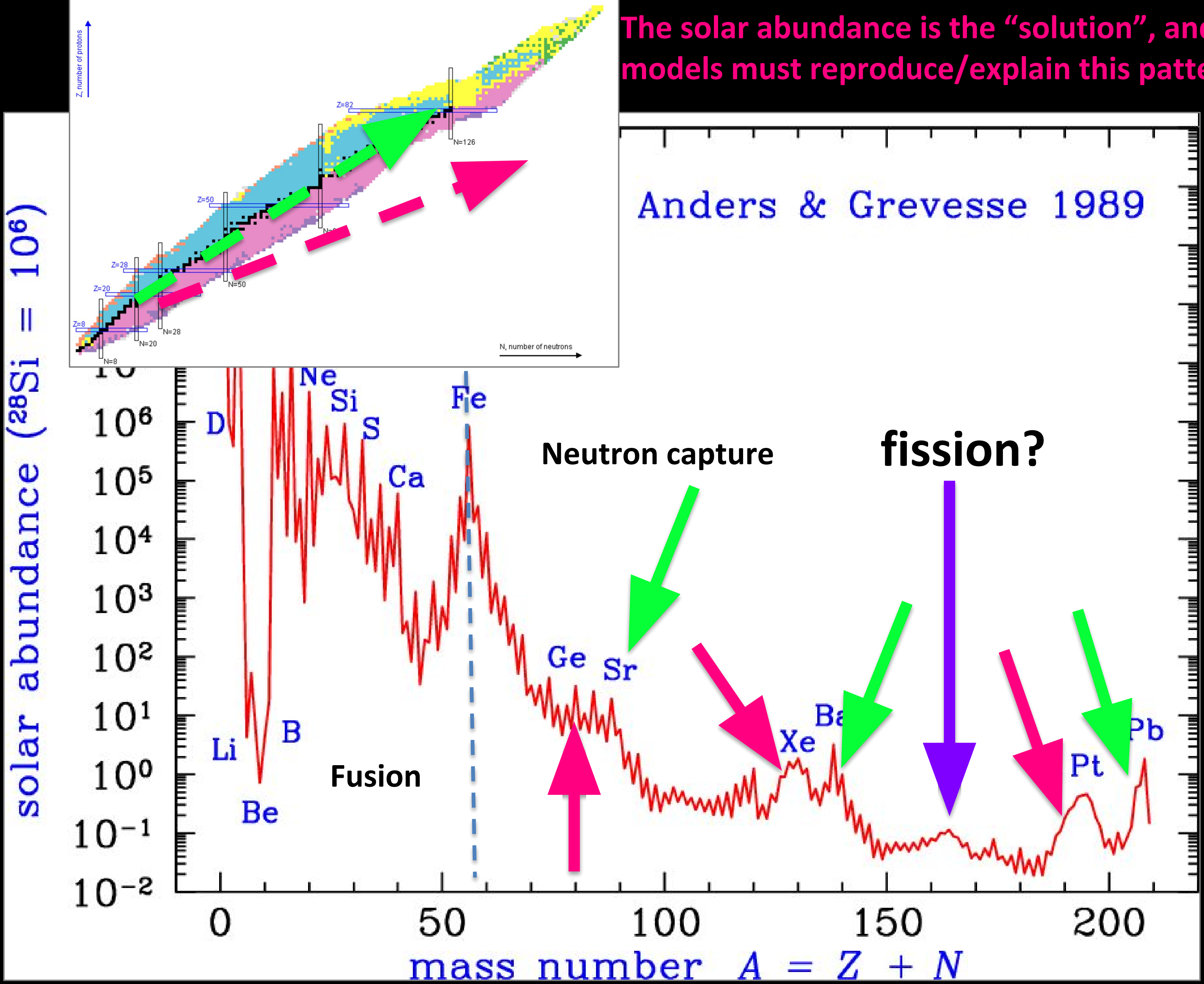


the elemental abundance a simulation gives must be compared to the experimental one

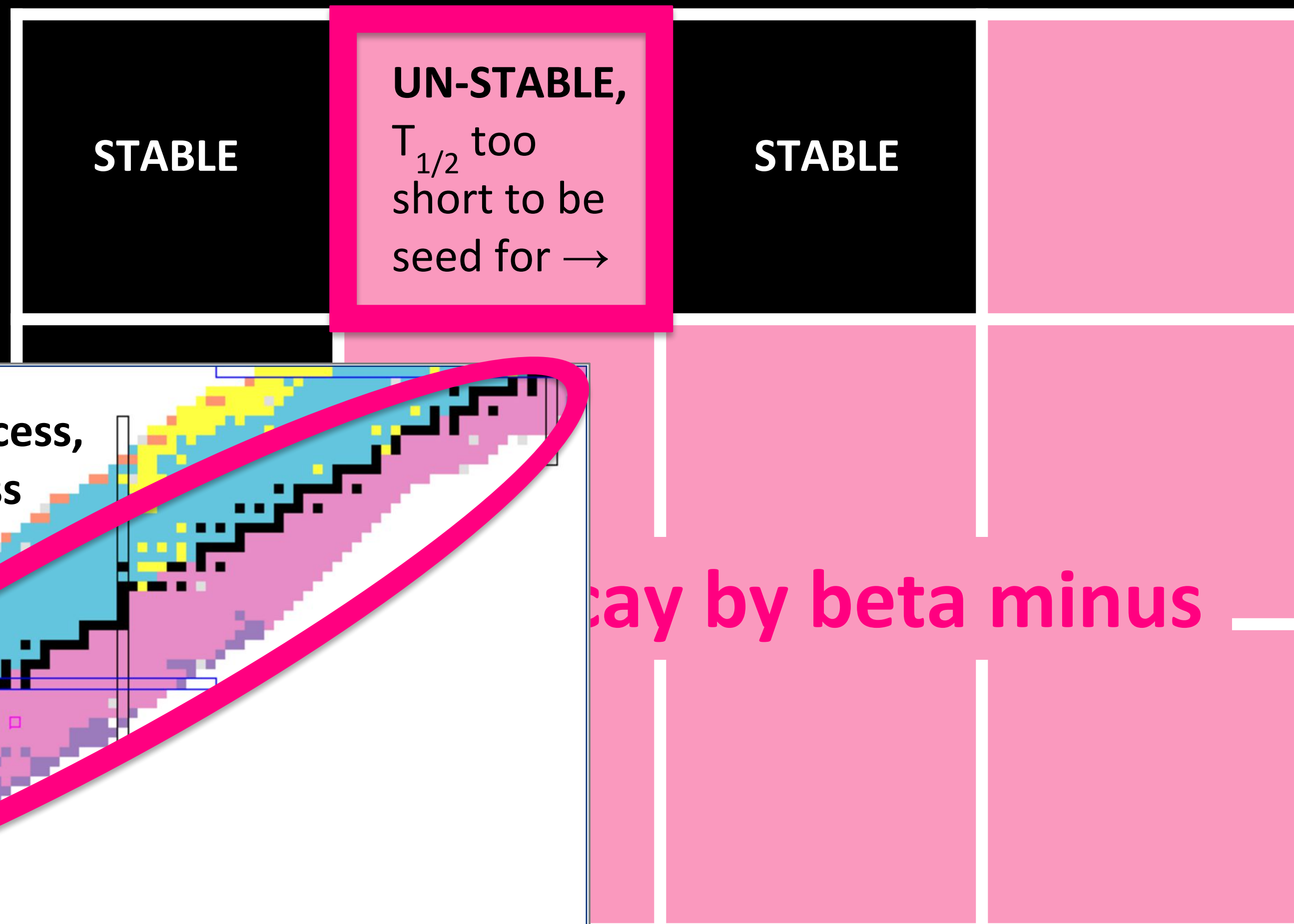
[Fabio:] available online on http://www.ph.sophia.ac.jp/%7Eshinya/research/research.html

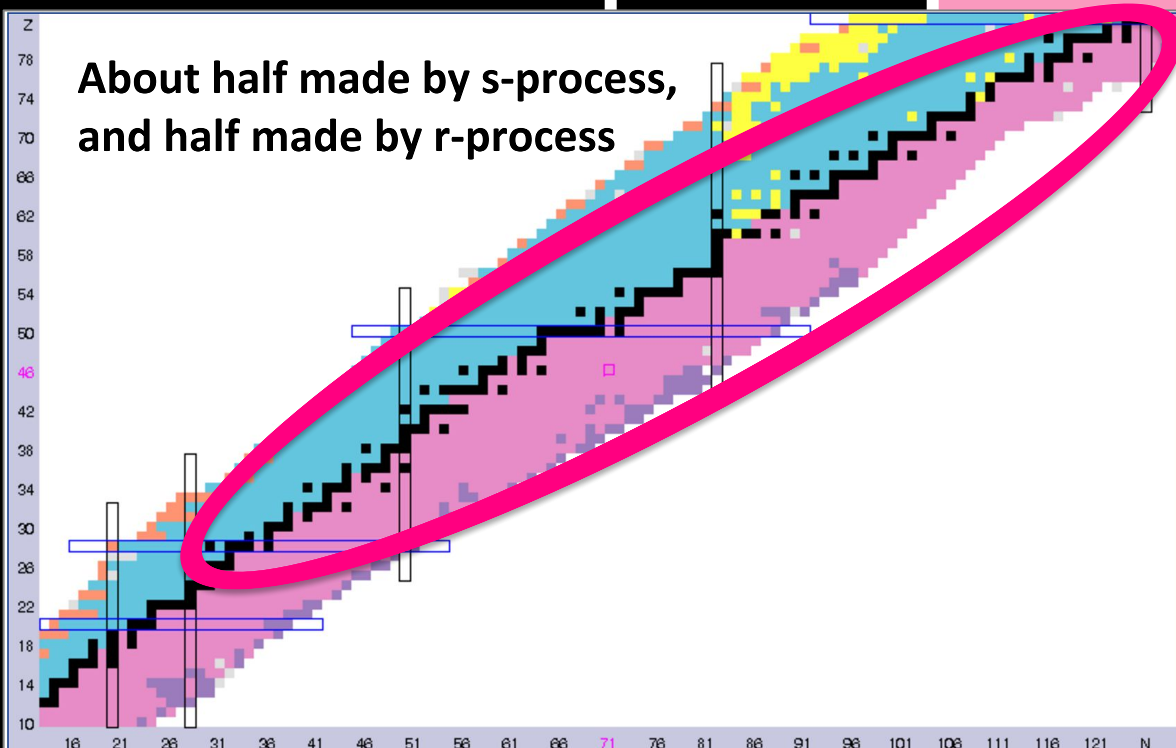
S. Wanajo et al Université de Tokyo

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



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





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)

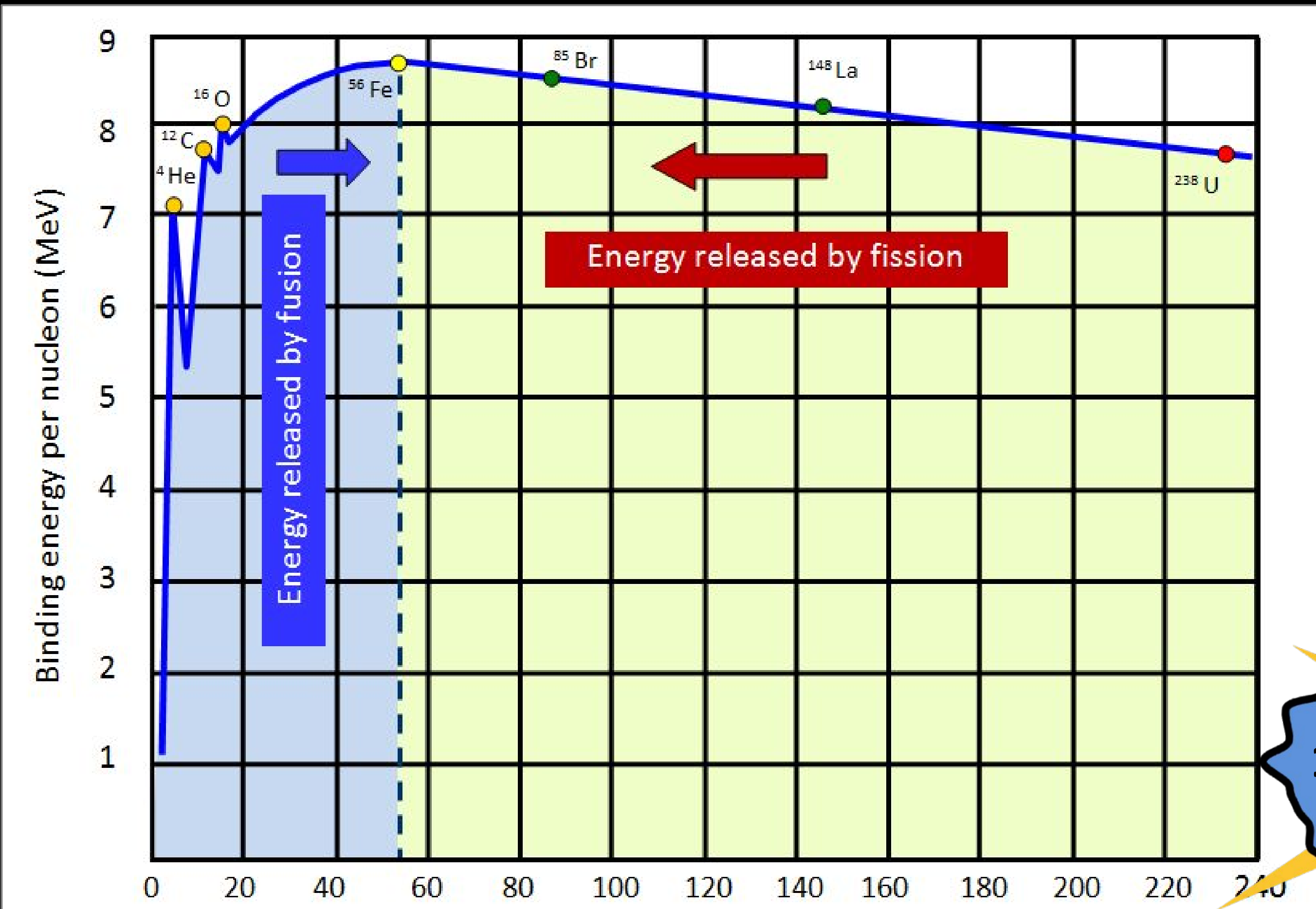
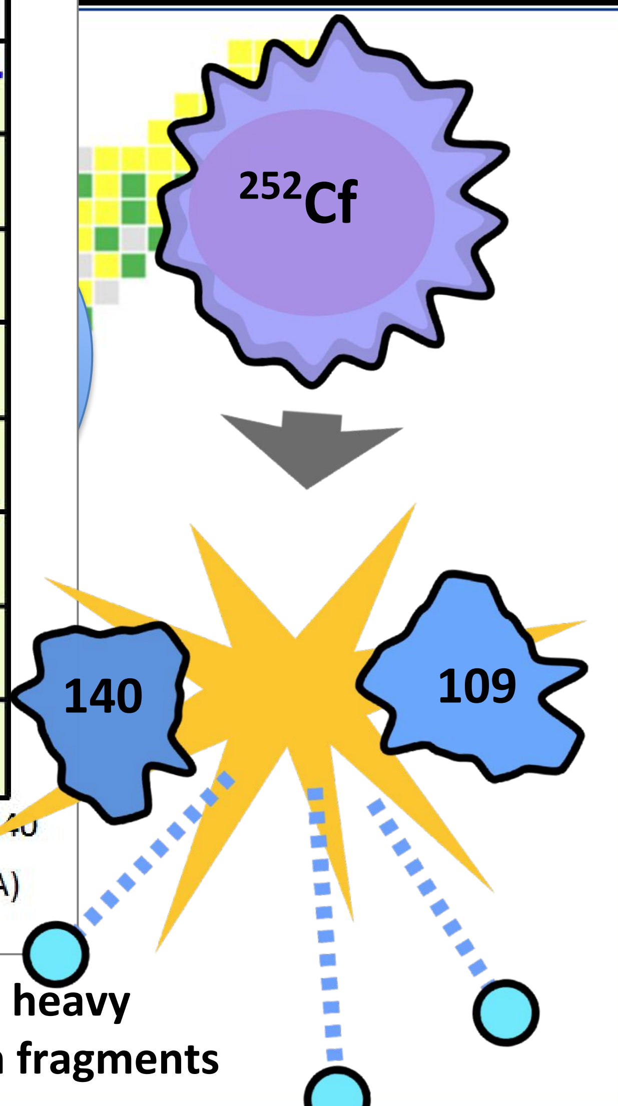
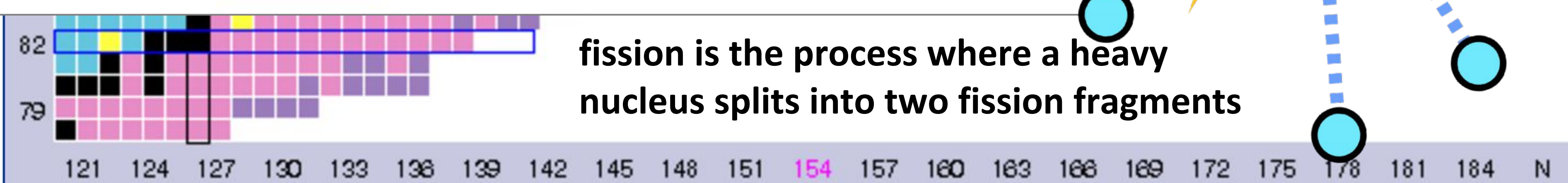


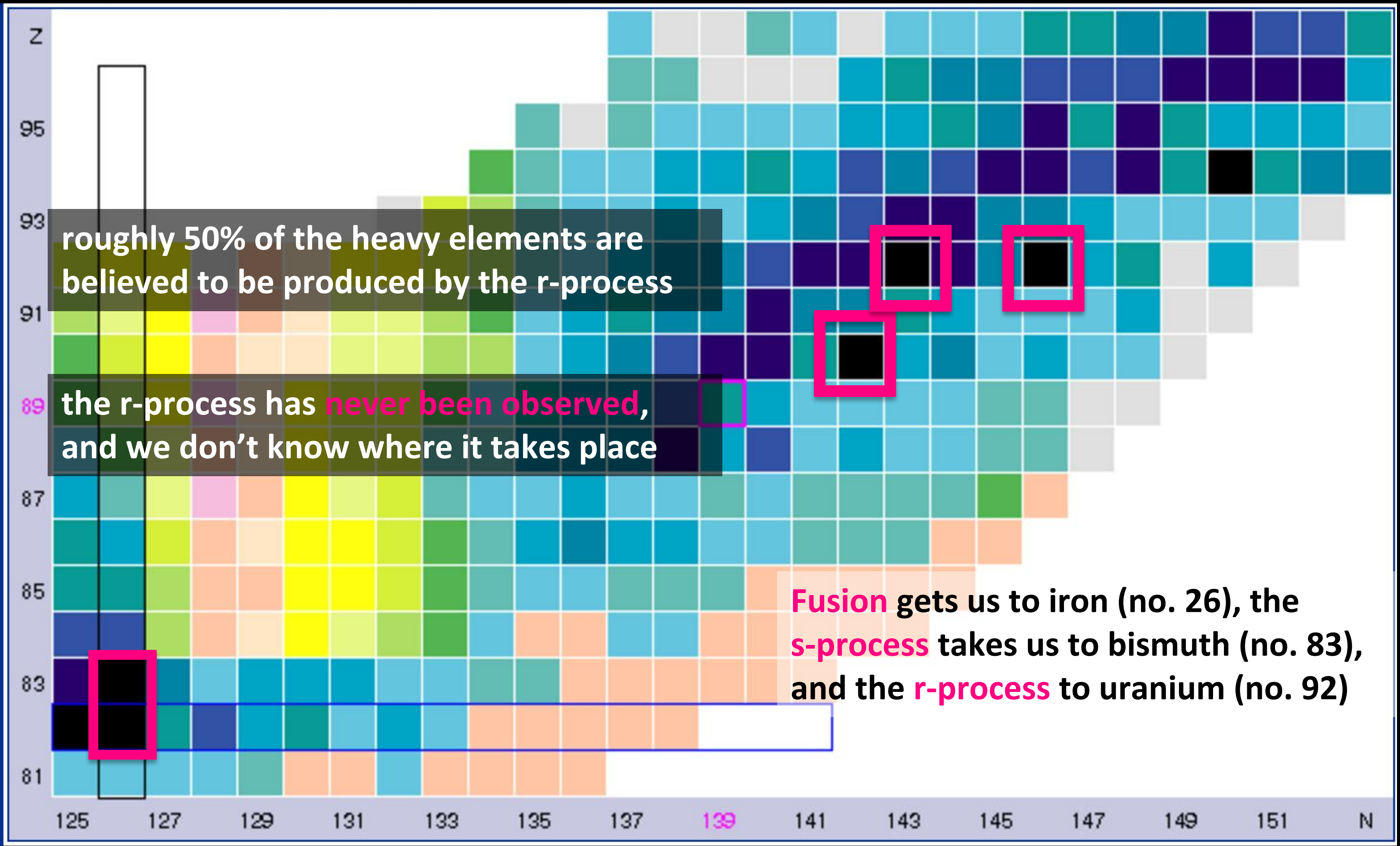
Figure 1





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

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

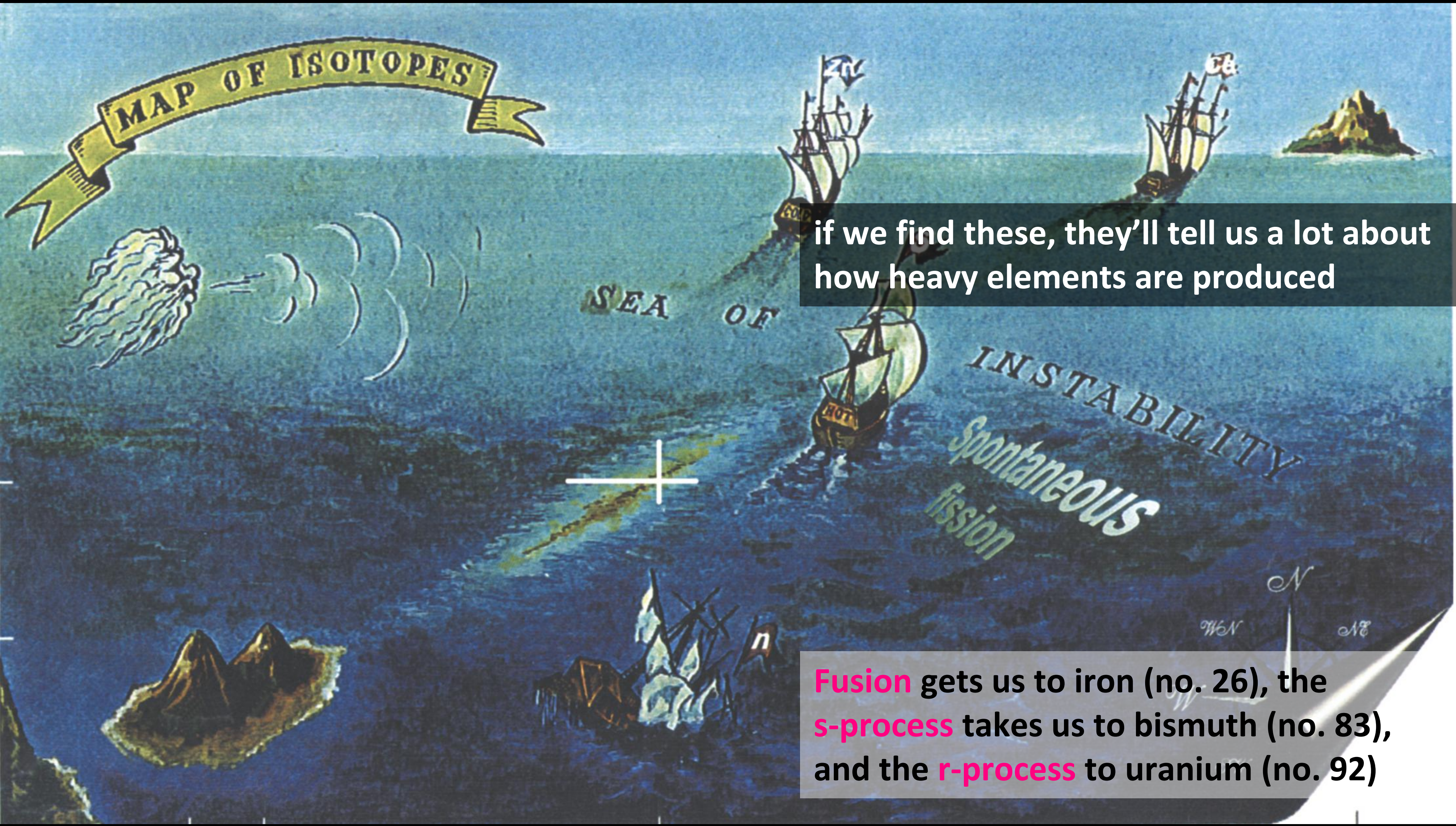


roughly 50% of the heavy elements are believed to be produced by the r-process

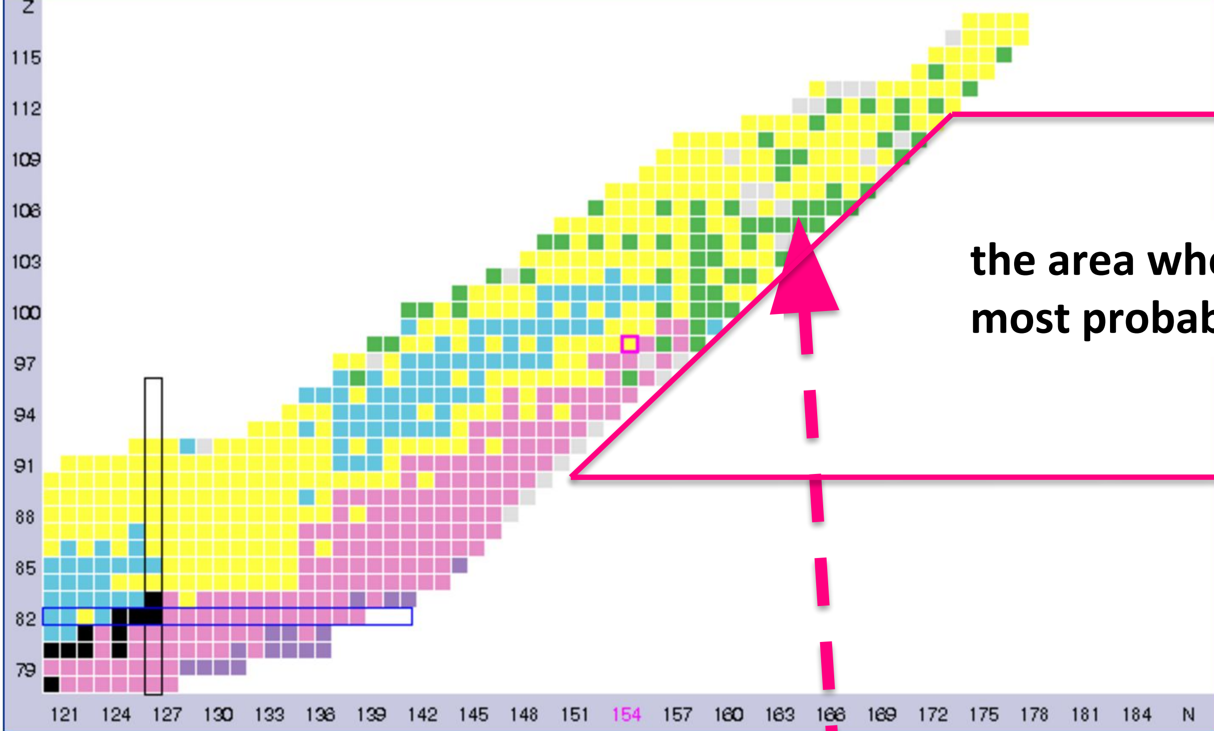
the r-process has never been observed, and we don't know where it takes place

Fusion gets us to iron (no. 26), the s-process takes us to bismuth (no. 83), and the r-process to uranium (no. 92)

Does the *island of stability* exist?



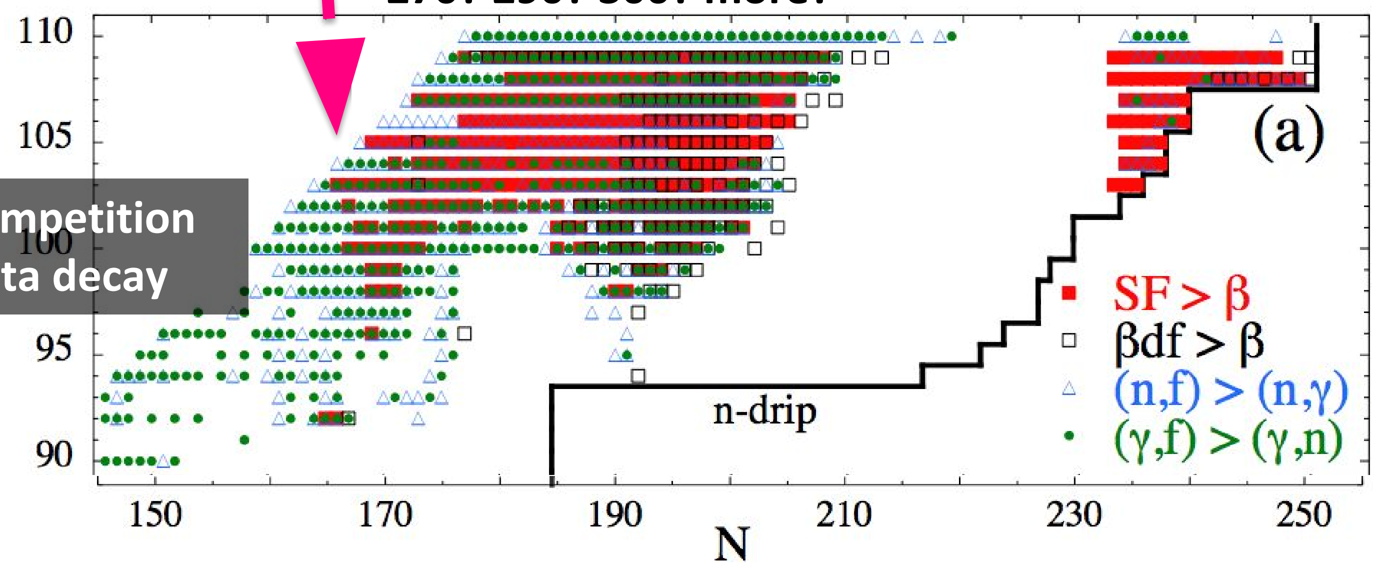
https://pls.llnl.gov/research-and-development/nuclear-science/project-highlights/livermorium/elements-113-and-115



the area where fission is the most probable decay mode

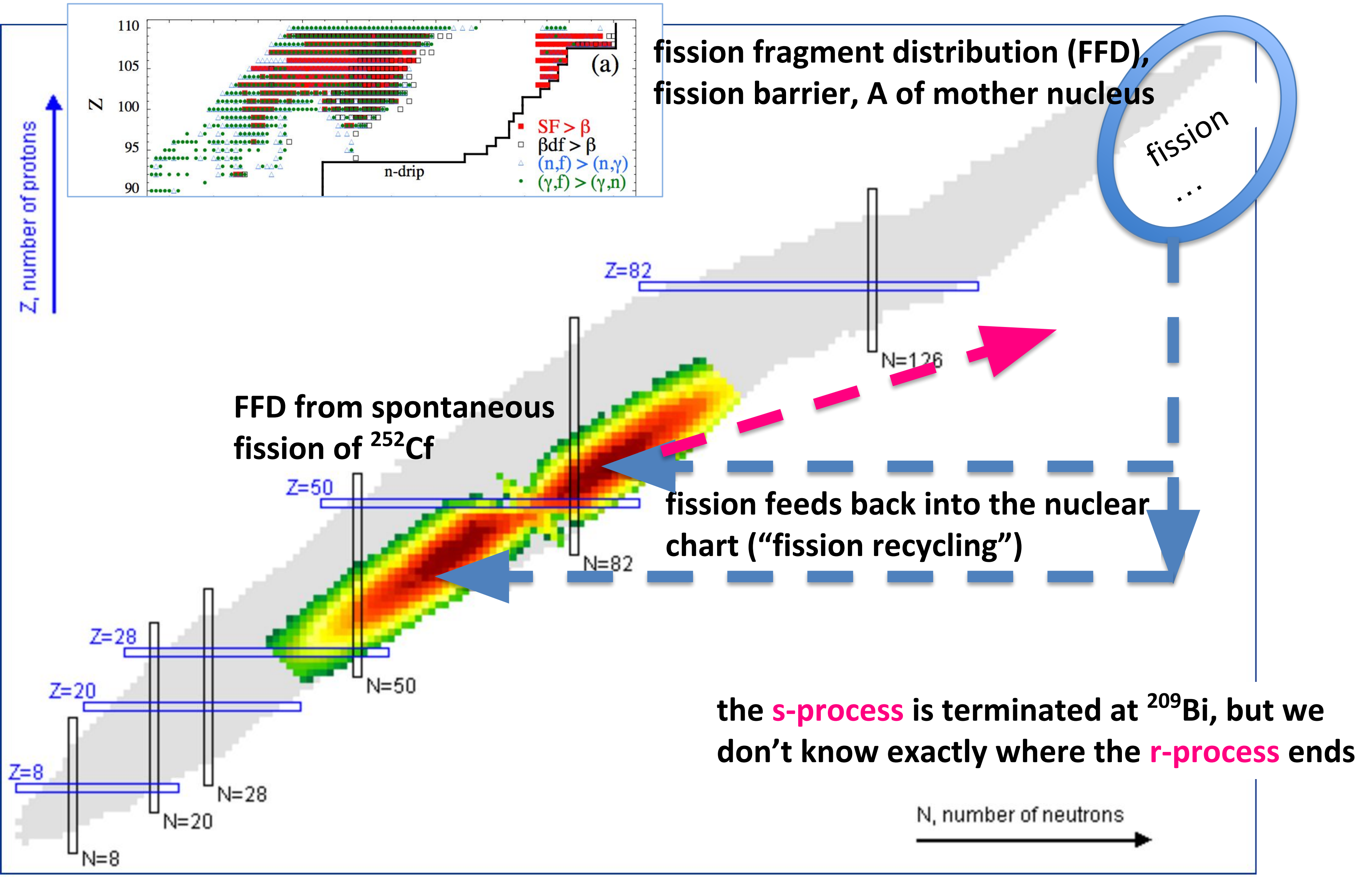
how far can we go?
270? 290? 300? more?

Goriely et. al, PRL 2013



eventually there is a competition between fission and beta decay

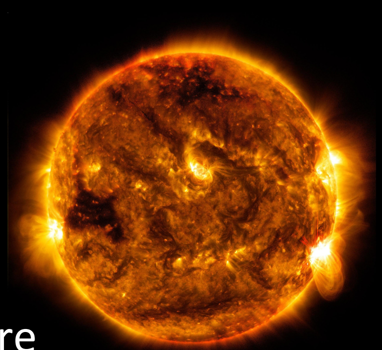
When nuclei fission, they will "feed" back into the chart of nuclides, at A dependent on the size of the fissioning nucleus



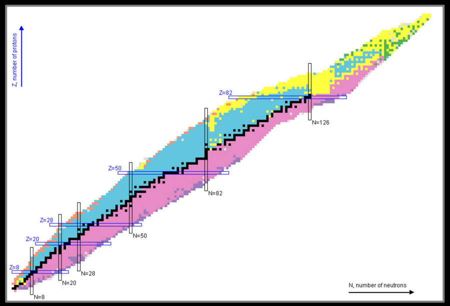
synthesis of heavy elements:

NEUTRONS ARE KEY…

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

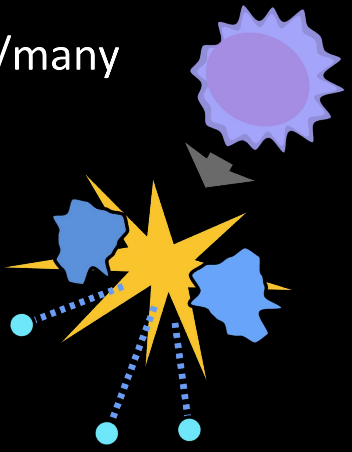


- fusion takes us to iron, where energy can not be “won” anymore



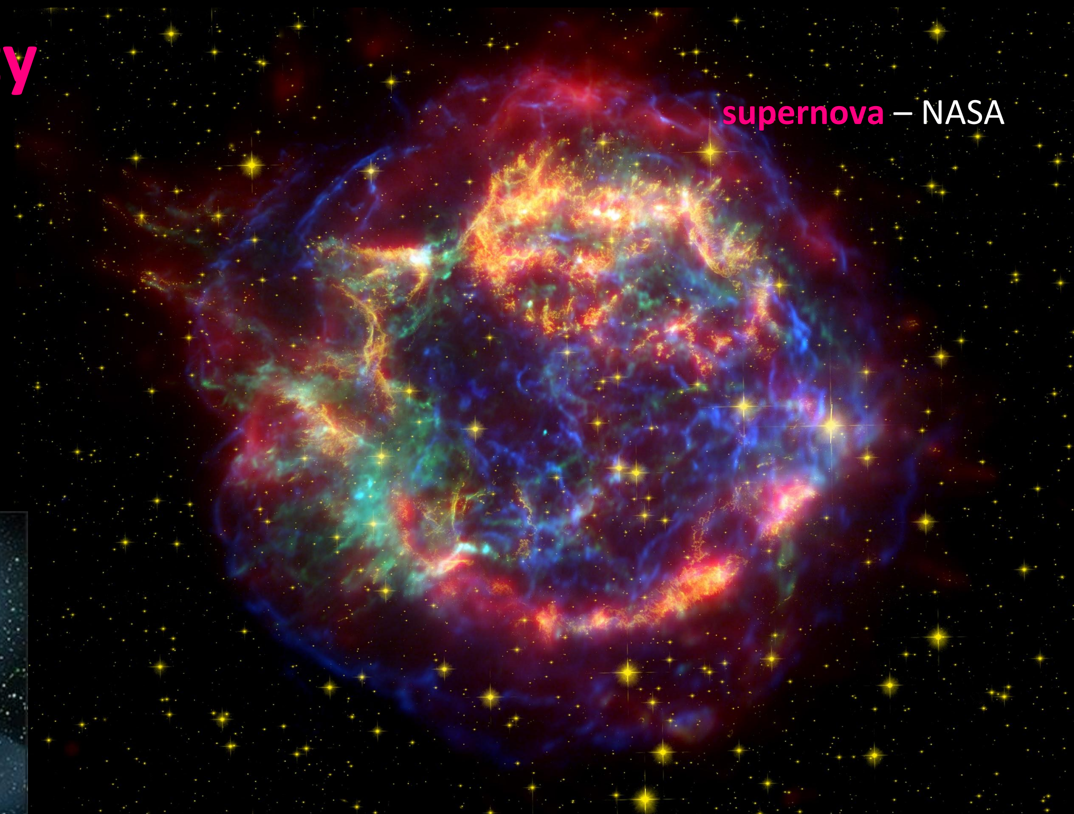
- s-process is responsible for ~50% of elemental abundance above iron
- r-process produces roughly the other half of the heavy nuclei
- the heaviest elements found in nature are thorium and uranium

- 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?



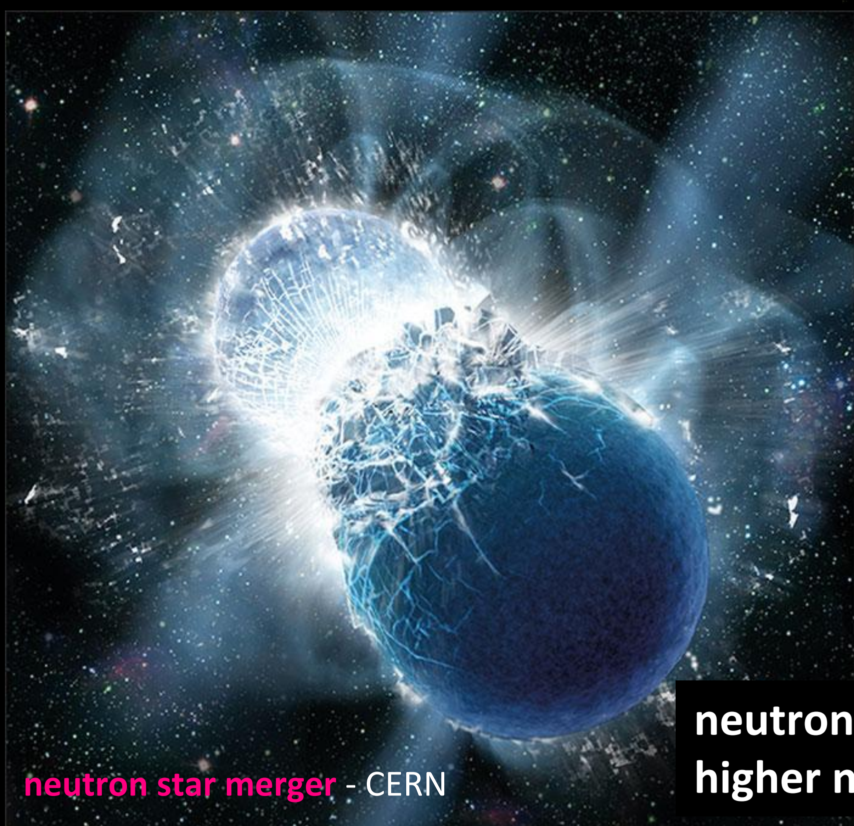
- the r-process has never been observed…
- **we need neutrons!**

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


supernova – NASA

free neutrons beta decay with an average lifetime of 15 minutes

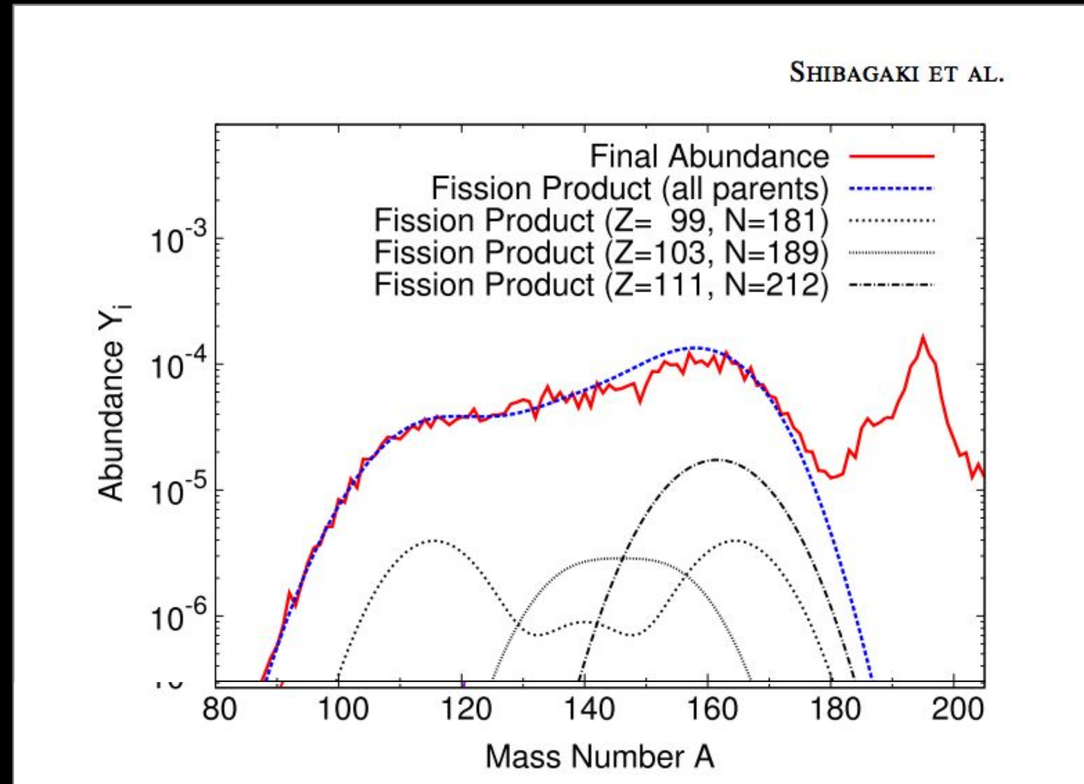
supernovae were thought to be the prime production site of the r-process


neutron star merger - CERN

neutron star mergers have a higher neutron density

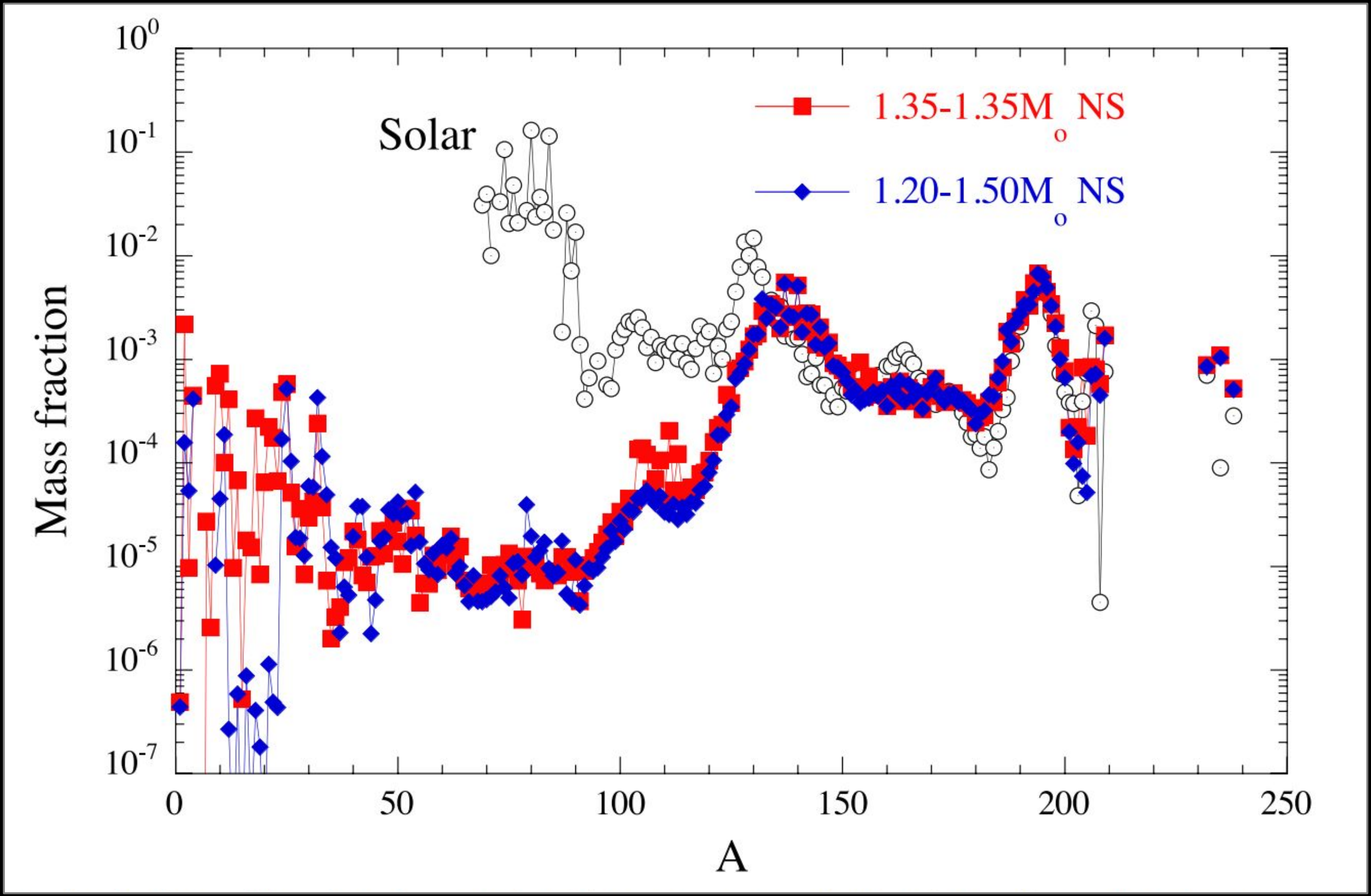
Shibagaki et. al, AJL, 2016

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



AJL 2011,Goriely, Bauswein, Jankal

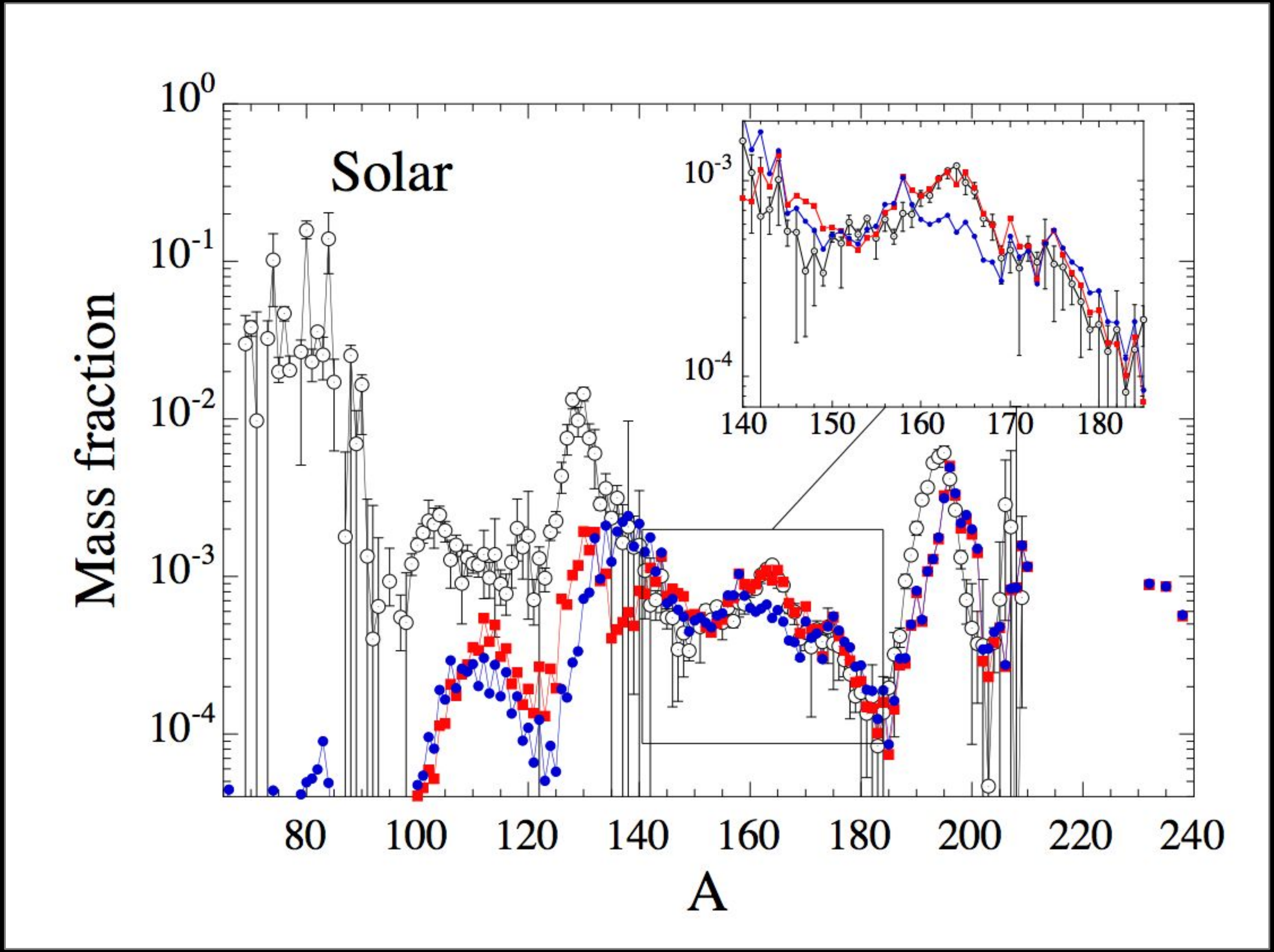
"the peak around A=140 originates exclusively from the fission recycling, which takes place in the A~280-290 region at the time all neutrons have been captured "



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

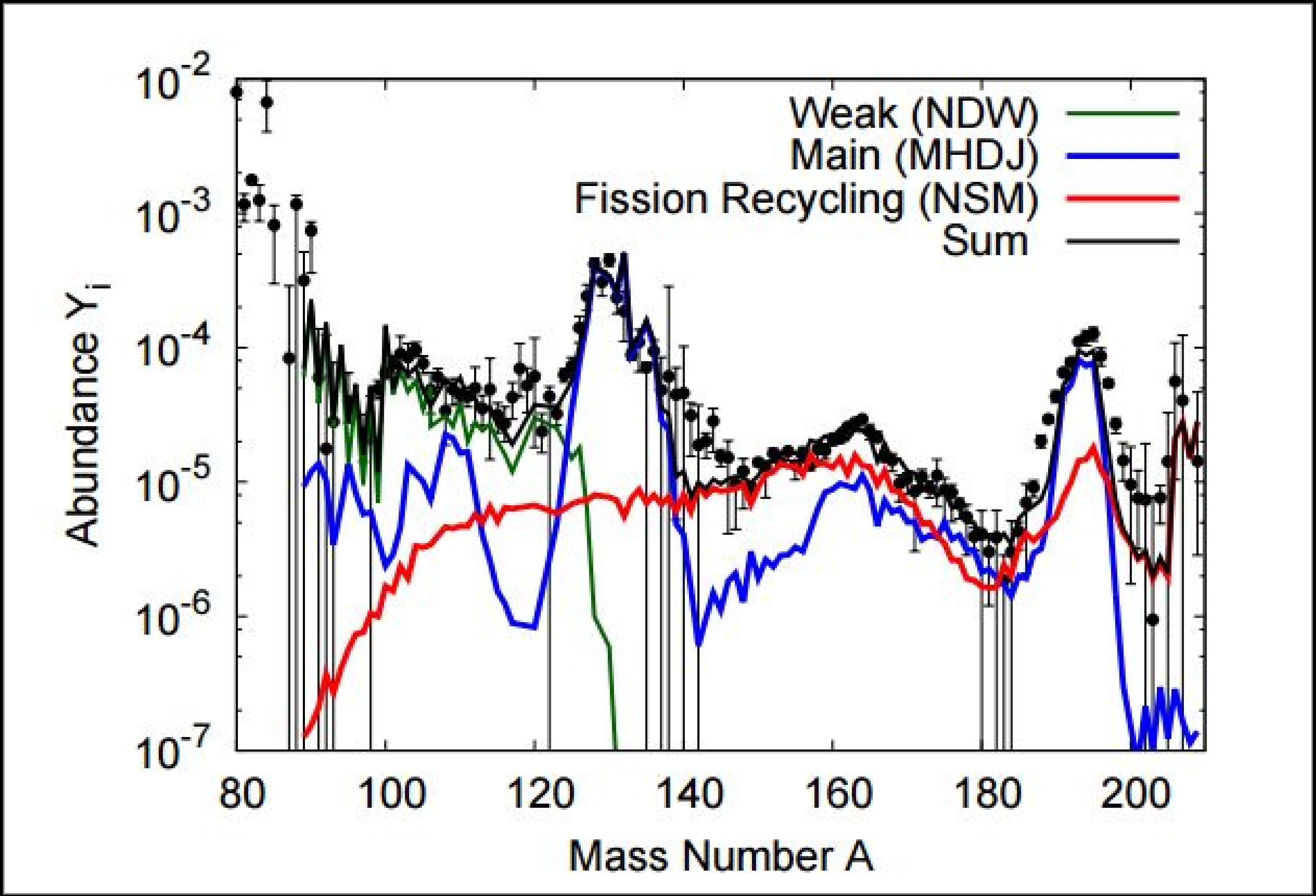
Gorieley, PRL 2013

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



fission fragment distributions affects the abundance distributions

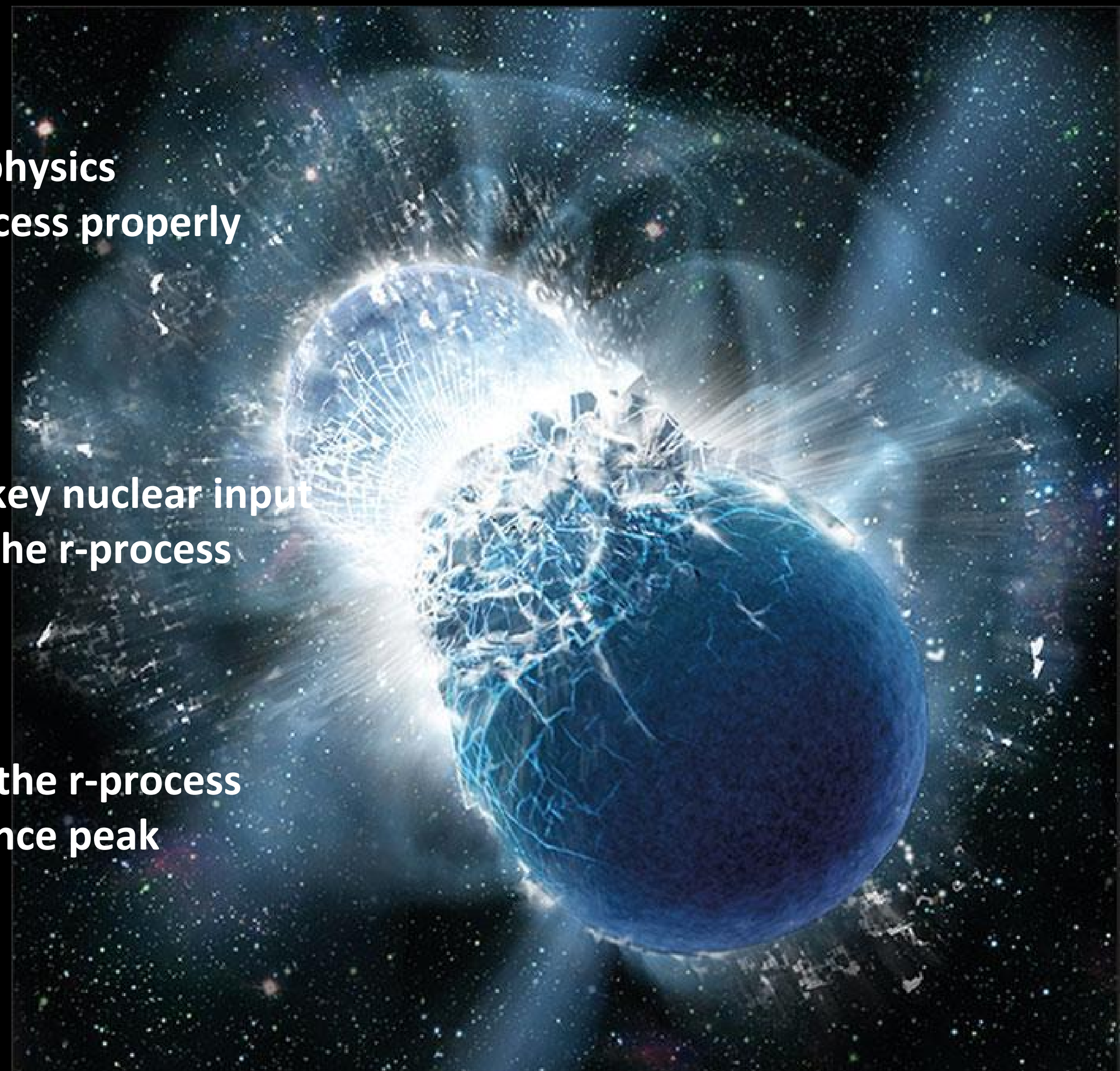
Shibagaki et. al, AJL, 2016



propose a combination of supernova and neutron star mergers

fission recycling as a main contributor to the A~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~165 abundance peak