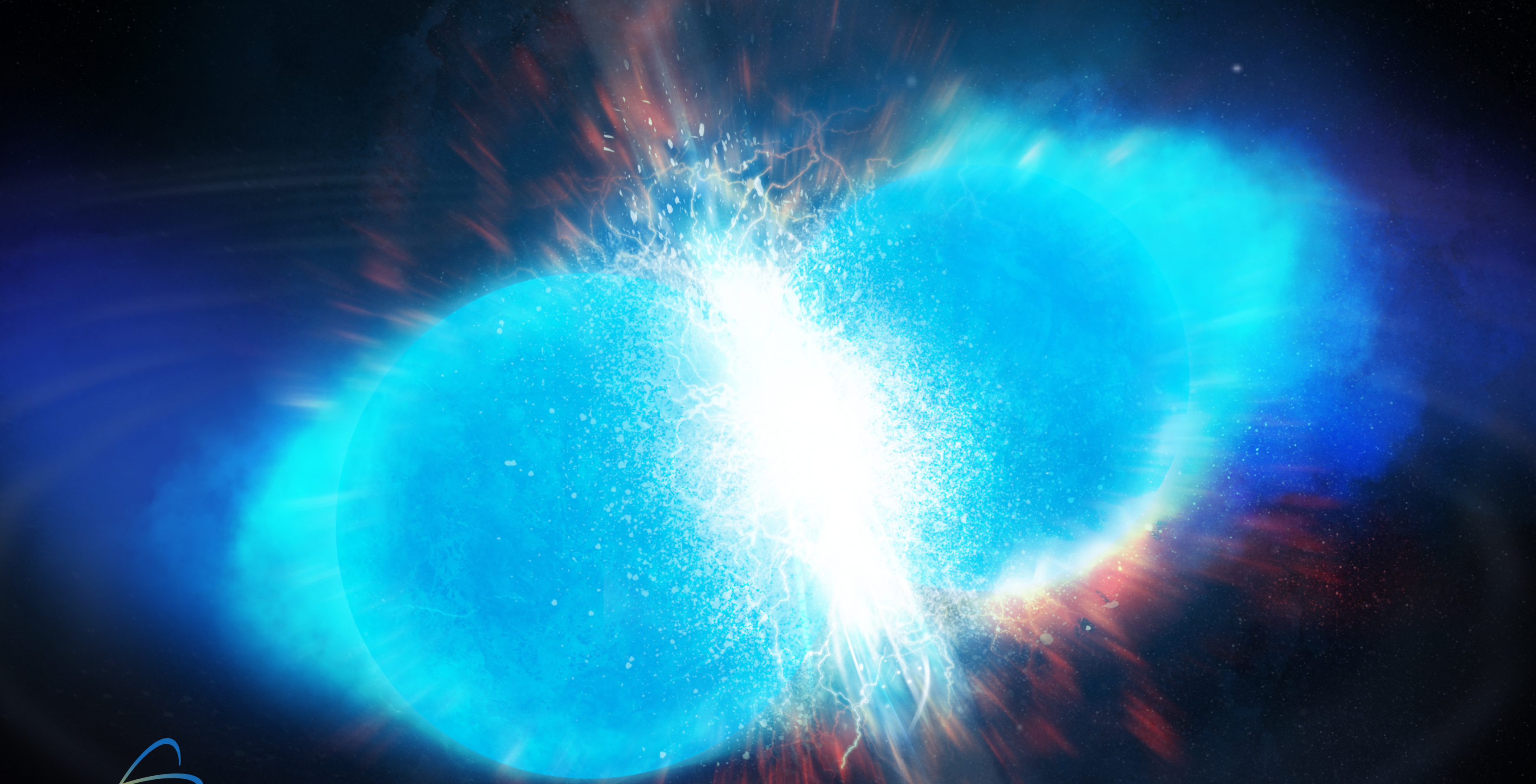
NUCLEOSYNTHESIS: CONNECTING NUCLEAR PHYSICS TO ASTROPHYSICS



Los Alamos NATIONAL LABORATORY EST. 1943

MATTHEW MUMPOWER

CTA Center for Theoretical ASTROPHYSICS

LA-UR-19-24624

Frontiers Summer School

Thursday May 16^{th} 2019

OUTLINE

History lesson

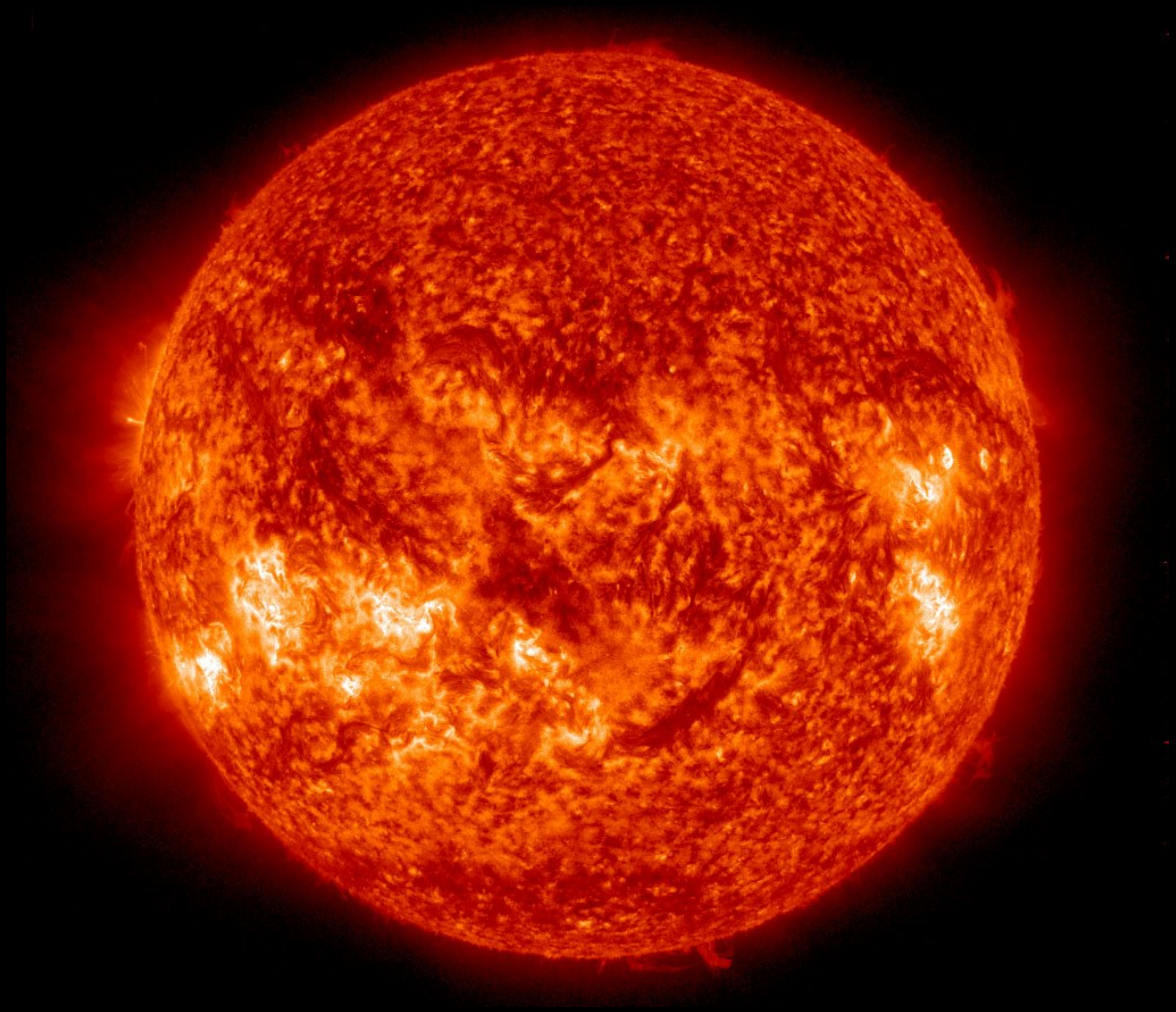
Nucleosynthesis

Where nuclear physics comes in

Heavy element nucleosynthesis

Concluding remarks

OBSERVATION: STARS SEEM TO SHINE FOR A LONG TIME...



How can we reconcile this observation with what we know?

WHAT COULD BE POWERING STARS?

Gravitational contraction: first proposed by Mayer, Helmholtz and lord Kelvin

Involves converting gravitational potential energy into heat

This was the leading postulate in the 1800's

Question: How long would the sun radiate under this assumption?

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LIFETIME $\sim$ (ENERGY) / (HEAT OUTPUT) = E / Q

LET'S TACKLE Q FIRST...

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Let's assume the heat from the sun is radiation dominated

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$$Q \sim 5.67 \times 10^{-8} \times 5800^4 \times 6.09 \times 10^{12} \times 1000^2 \sim 3.9 \times 10^{26} \text{ Watts}$$

GRAVITATIONAL ENERGY?

Considering gravitational potential energy

$$E = \frac{3}{5}\frac{GM^2}{R}$$

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Who came up with the idea of using nuclear physics?

EDDINGTON'S GREAT INSIGHT

Nuclear reactions release energy that power stars

"The internal constitution of the stars" (1920)

$$E = mc^2$$

A little bit of mass can create a lot of energy

Question: What percentage of mass will generate enough energy for the sun to last billions of years?

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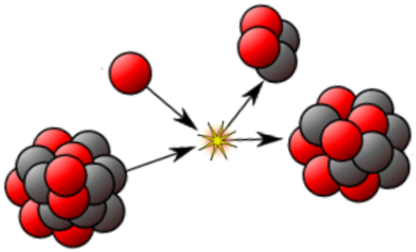
Question: How long would the sun last if it ran on fossil fuels?

NUCLEOSYNTHESIS

nu·cle·o·syn·the·sis The formation of new atomic nuclei by nuclear reactions, thought to occur in the interiors of stars and in the early stages of development of the universe.



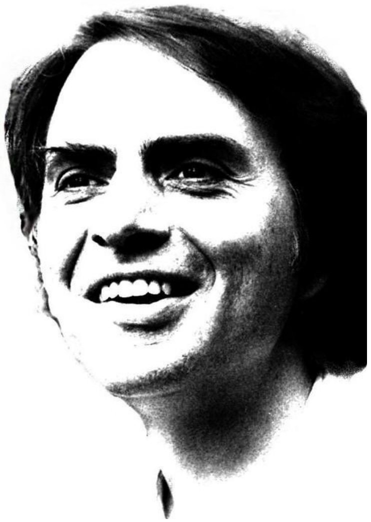
Nuclear Physics

+

Astrophysics

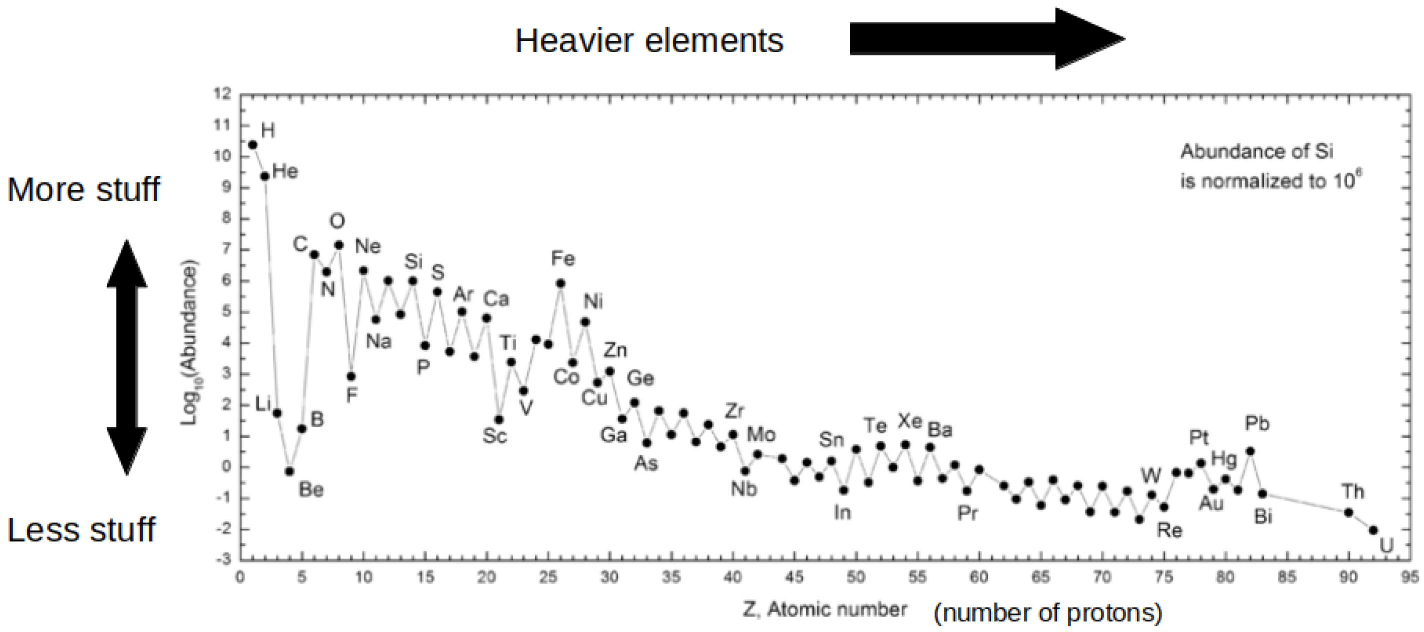
"We are all made of star stuff"

— Carl Sagan



STUFF IN THE SOLAR SYSTEM

Abundance is a quantity denoting how much stuff



Question: Where do we get this observational information?

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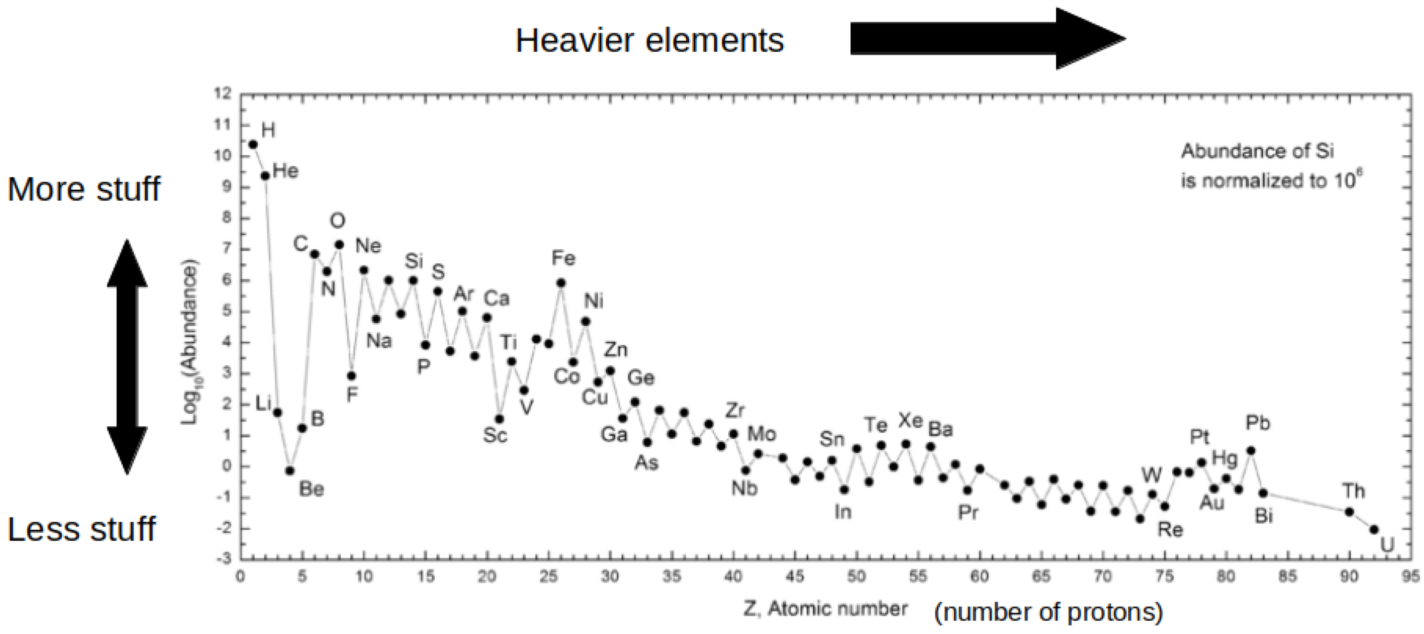
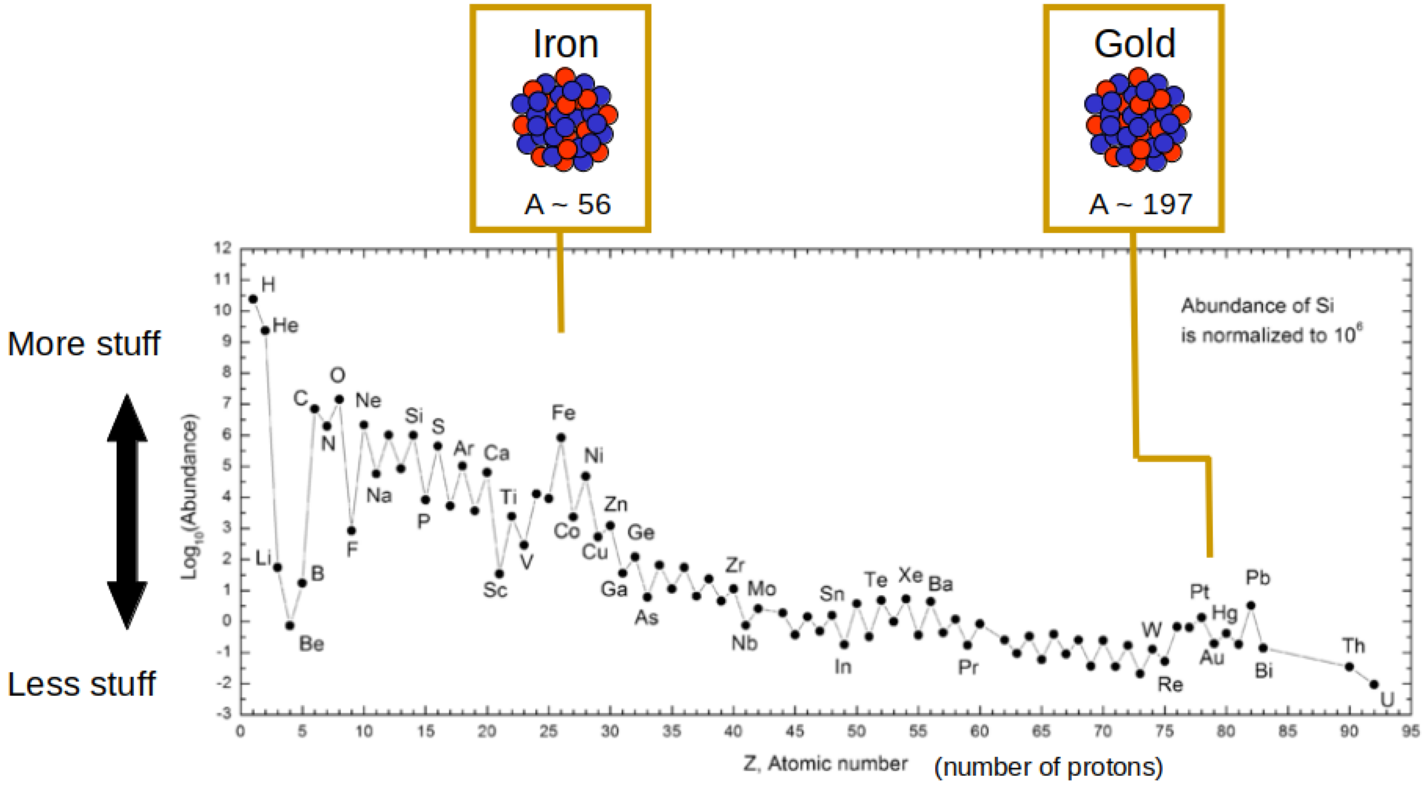


Question: Where do we get this observational information?

Hint: The sun has 99% of the mass of the solar system

STUFF IN THE SOLAR SYSTEM

(Answer: meteorites and photospheric observations)



The formation of the heavy elements didn't occur all at the same time nor the same place

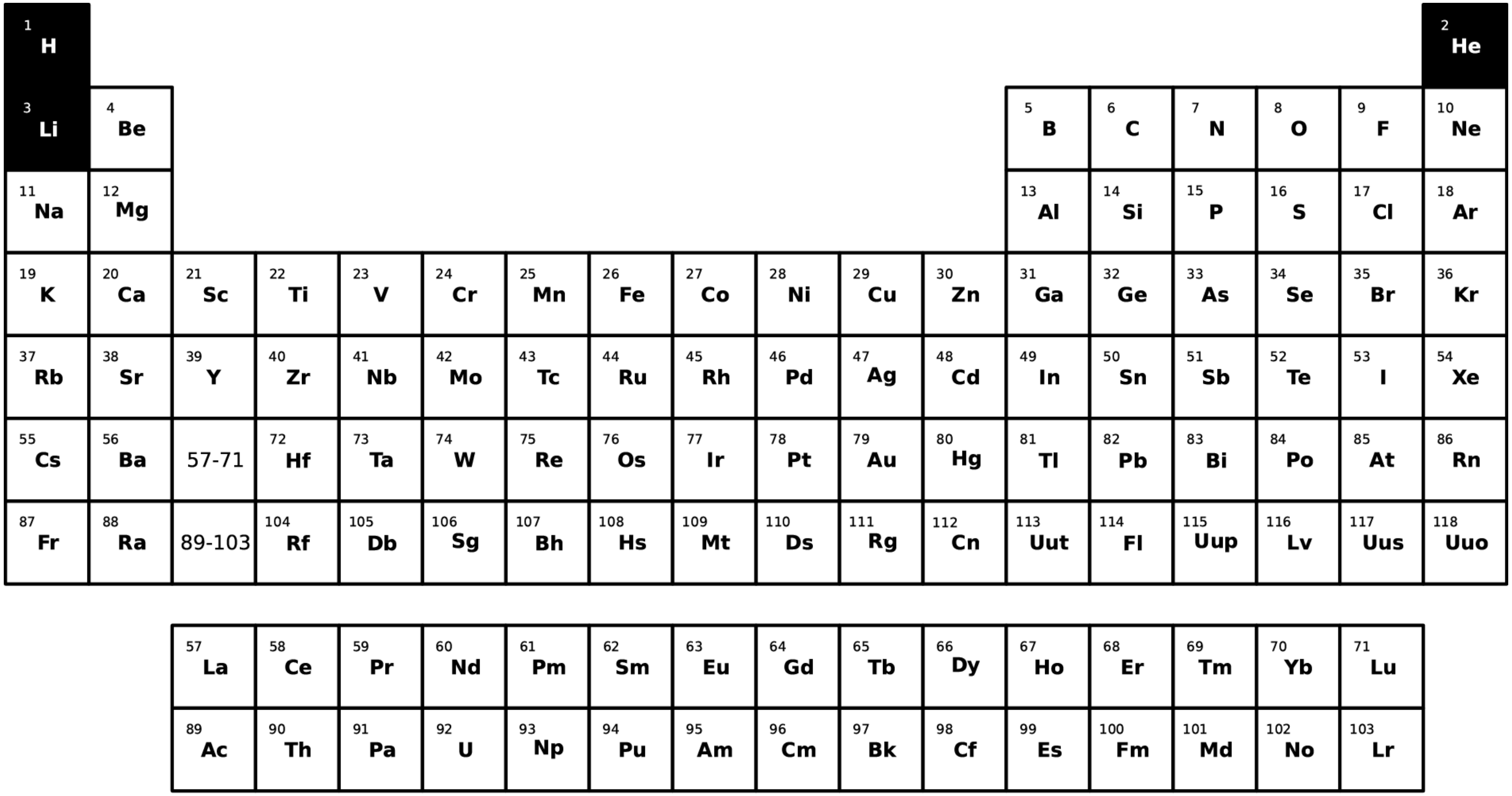
WHAT IS THE ORIGIN OF THE ELEMENTS?

1 **H**																	2 **He**
3 **Li**	4 **Be**											5 **B**	6 **C**	7 **N**	8 **O**	9 **F**	10 **Ne**
11 **Na**	12 **Mg**											13 **Al**	14 **Si**	15 **P**	16 **S**	17 **Cl**	18 **Ar**
19 **K**	20 **Ca**	21 **Sc**	22 **Ti**	23 **V**	24 **Cr**	25 **Mn**	26 **Fe**	27 **Co**	28 **Ni**	29 **Cu**	30 **Zn**	31 **Ga**	32 **Ge**	33 **As**	34 **Se**	35 **Br**	36 **Kr**
37 **Rb**	38 **Sr**	39 **Y**	40 **Zr**	41 **Nb**	42 **Mo**	43 **Tc**	44 **Ru**	45 **Rh**	46 **Pd**	47 **Ag**	48 **Cd**	49 **In**	50 **Sn**	51 **Sb**	52 **Te**	53 **I**	54 **Xe**
55 **Cs**	56 **Ba**	57-71	72 **Hf**	73 **Ta**	74 **W**	75 **Re**	76 **Os**	77 **Ir**	78 **Pt**	79 **Au**	80 **Hg**	81 **Tl**	82 **Pb**	83 **Bi**	84 **Po**	85 **At**	86 **Rn**
87 **Fr**	88 **Ra**	89-103	104 **Rf**	105 **Db**	106 **Sg**	107 **Bh**	108 **Hs**	109 **Mt**	110 **Ds**	111 **Rg**	112 **Cn**	113 **Uut**	114 **Fl**	115 **Uup**	116 **Lv**	117 **Uus**	118 **Uuo**

57 **La**	58 **Ce**	59 **Pr**	60 **Nd**	61 **Pm**	62 **Sm**	63 **Eu**	64 **Gd**	65 **Tb**	66 **Dy**	67 **Ho**	68 **Er**	69 **Tm**	70 **Yb**	71 **Lu**
89 **Ac**	90 **Th**	91 **Pa**	92 **U**	93 **Np**	94 **Pu**	95 **Am**	96 **Cm**	97 **Bk**	98 **Cf**	99 **Es**	100 **Fm**	101 **Md**	102 **No**	103 **Lr**

This requires a lot of detective work...

LIGHTEST ELEMENTS: BIG BANG



■ Big Bang

THE BIG BANG

Created most of the hydrogen (H) and helium (He) in the universe.

Started within the first 3 minutes of the beginning of the universe.

Ended within about 20 minutes due to expanding and cooling.

Only 12 key reactions to take into account (easy!?)

$$\mathrm{n}^0 \longrightarrow \mathrm{p}^+ + \mathrm{e}^- + \bar{\nu}_e \qquad \mathrm{p}^+ + \mathrm{n}^0 \longrightarrow {}^2_1\mathrm{D} + \gamma$$

$${}^2_1\mathrm{D} + \mathrm{p}^+ \longrightarrow {}^3_2\mathrm{He} + \gamma \qquad {}^2_1\mathrm{D} + {}^2_1\mathrm{D} \longrightarrow {}^3_2\mathrm{He} + \mathrm{n}^0$$

$${}^2_1\mathrm{D} + {}^2_1\mathrm{D} \longrightarrow {}^3_1\mathrm{T} + \mathrm{p}^+ \qquad {}^3_1\mathrm{T} + {}^2_1\mathrm{D} \longrightarrow {}^4_2\mathrm{He} + \mathrm{n}^0$$

$${}^3_1\mathrm{T} + {}^4_2\mathrm{He} \longrightarrow {}^7_3\mathrm{Li} + \gamma \qquad {}^3_2\mathrm{He} + \mathrm{n}^0 \longrightarrow {}^3_1\mathrm{T} + \mathrm{p}^+$$

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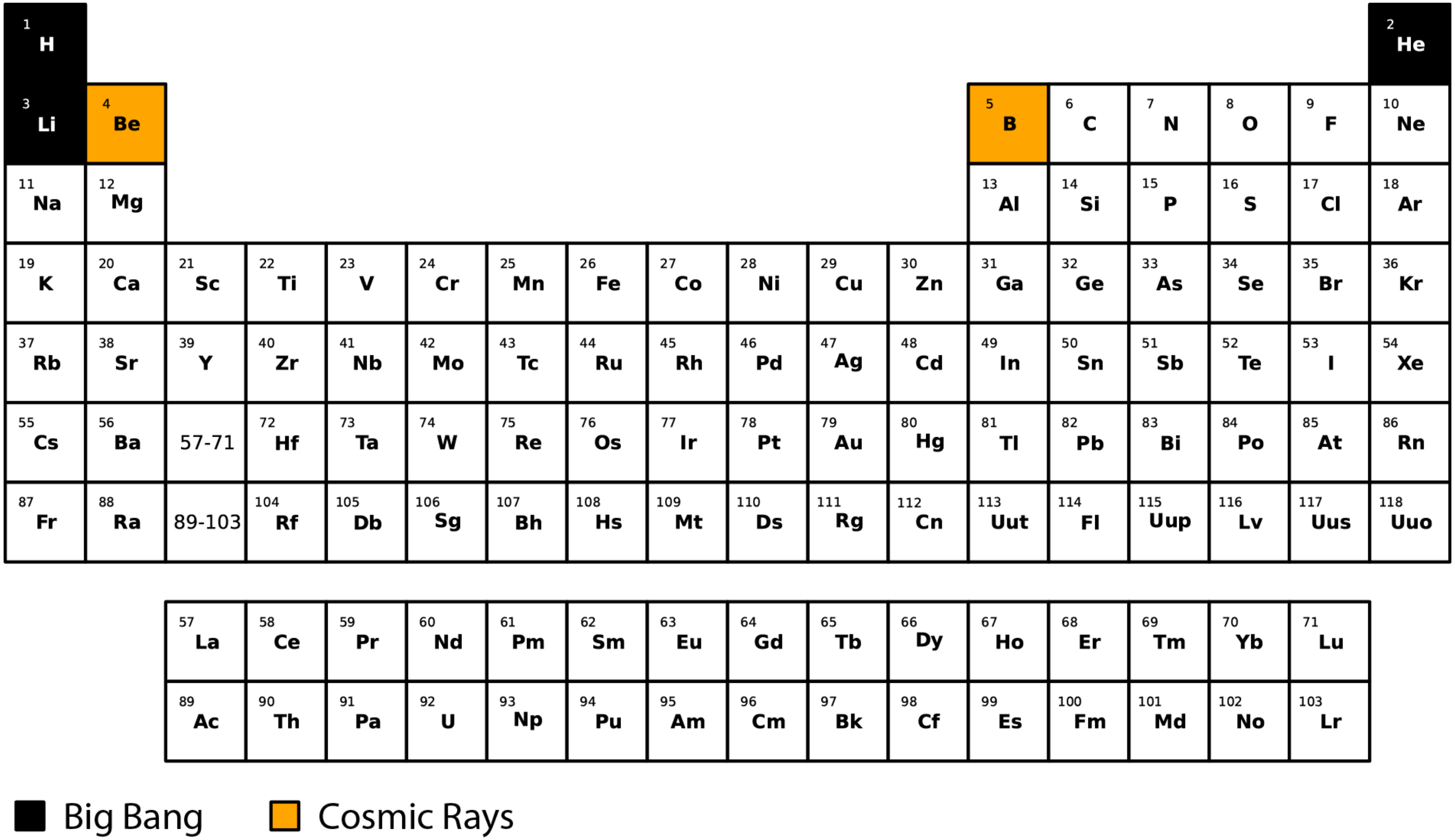
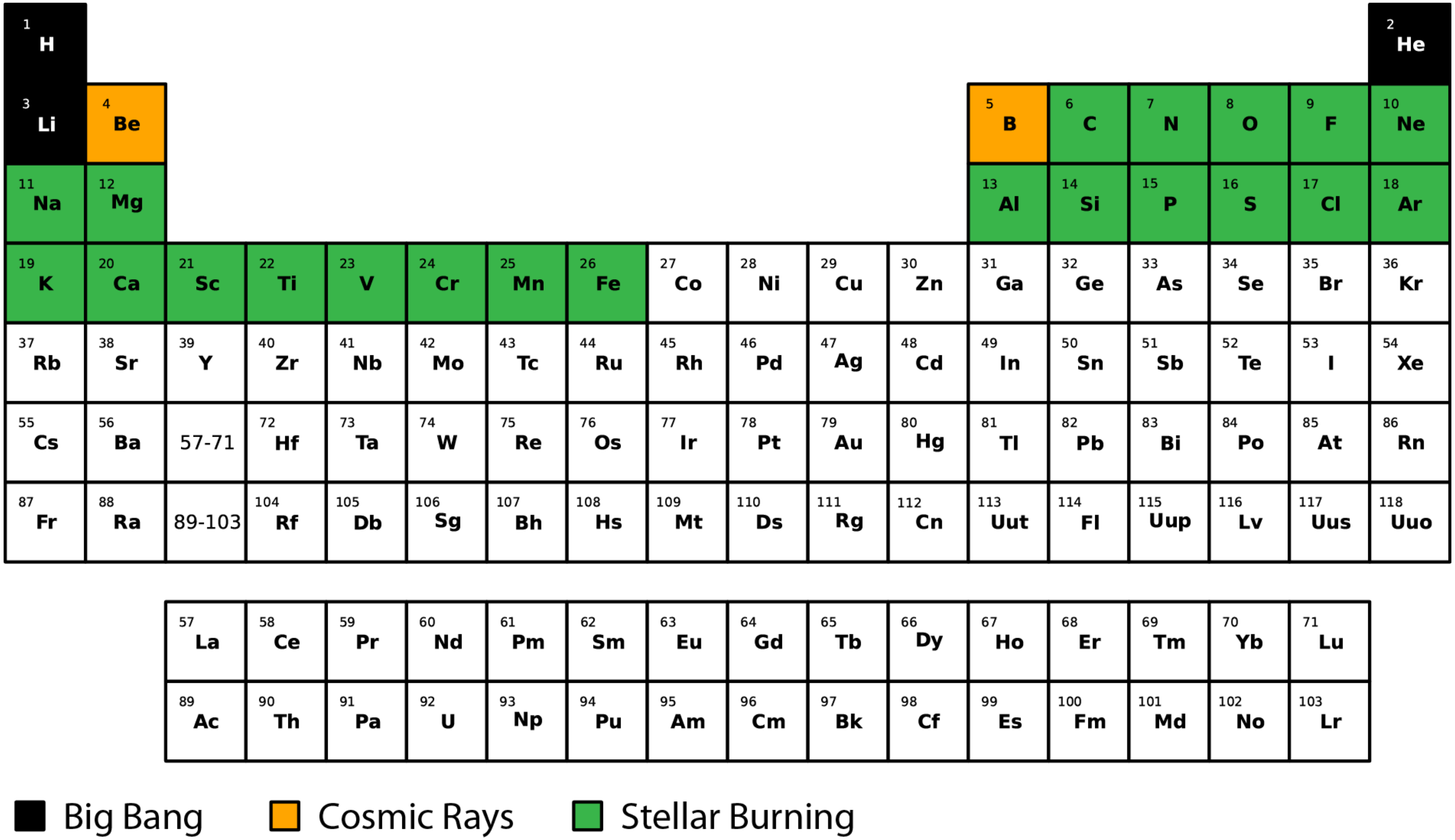
Google: cosmic lithium problem

SPALLATION BY COSMIC RAYS



Remember the dip in the solar abundances?

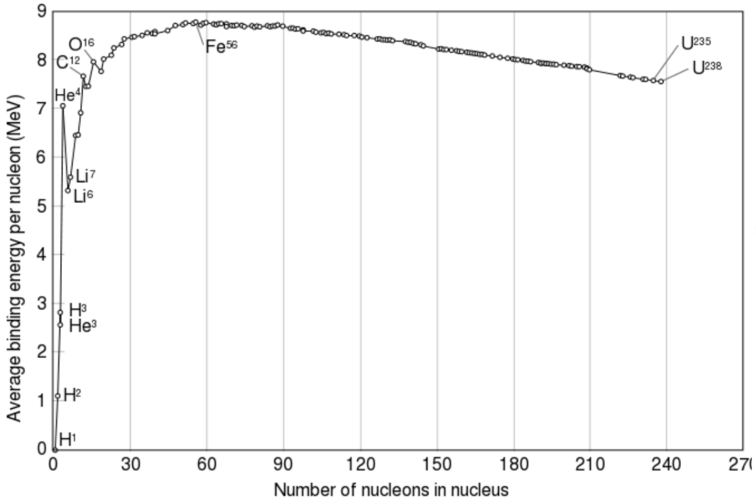
STELLAR BURNING

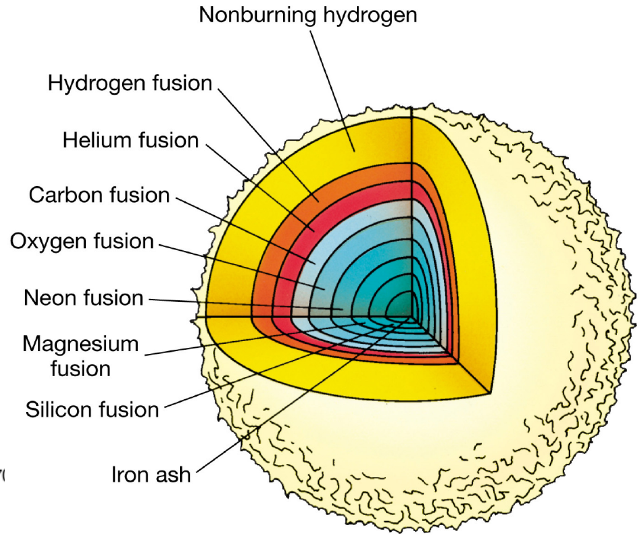


STELLAR BURNING

Nuclear fuel for the existence of stars

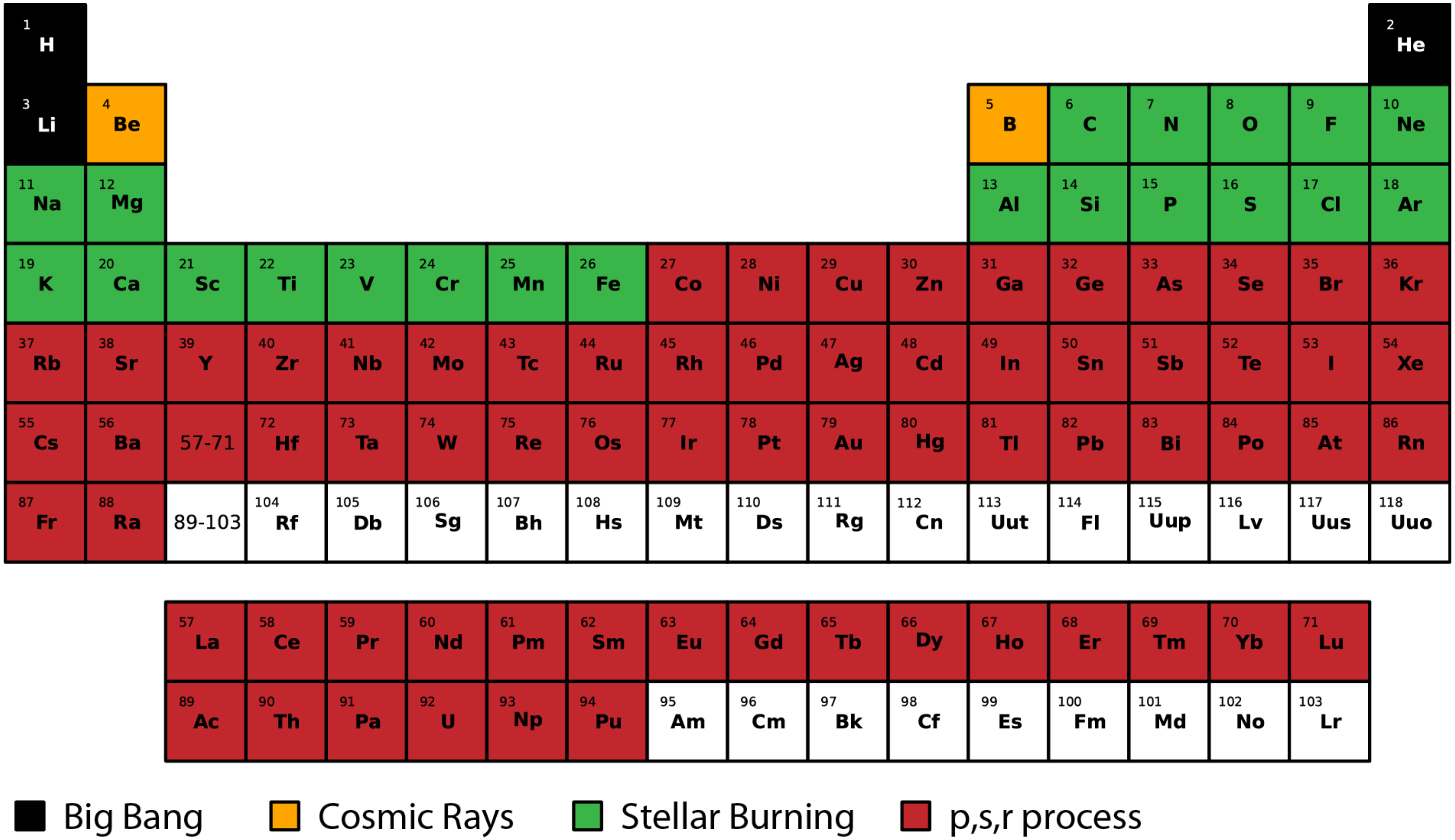
Nuclear Fuel	Main Products	T (10^9 K)	Duration (yr)
H	He	0.037	$8 * 10^6$
He	C, O	0.19	$1 * 10^6$
C	Ne, Mg	0.87	$1 * 10^3$
Ne	O, Mg	1.6	0.60
O	Si, S	2.0	0.25
Si	Fe	3.3	0.03





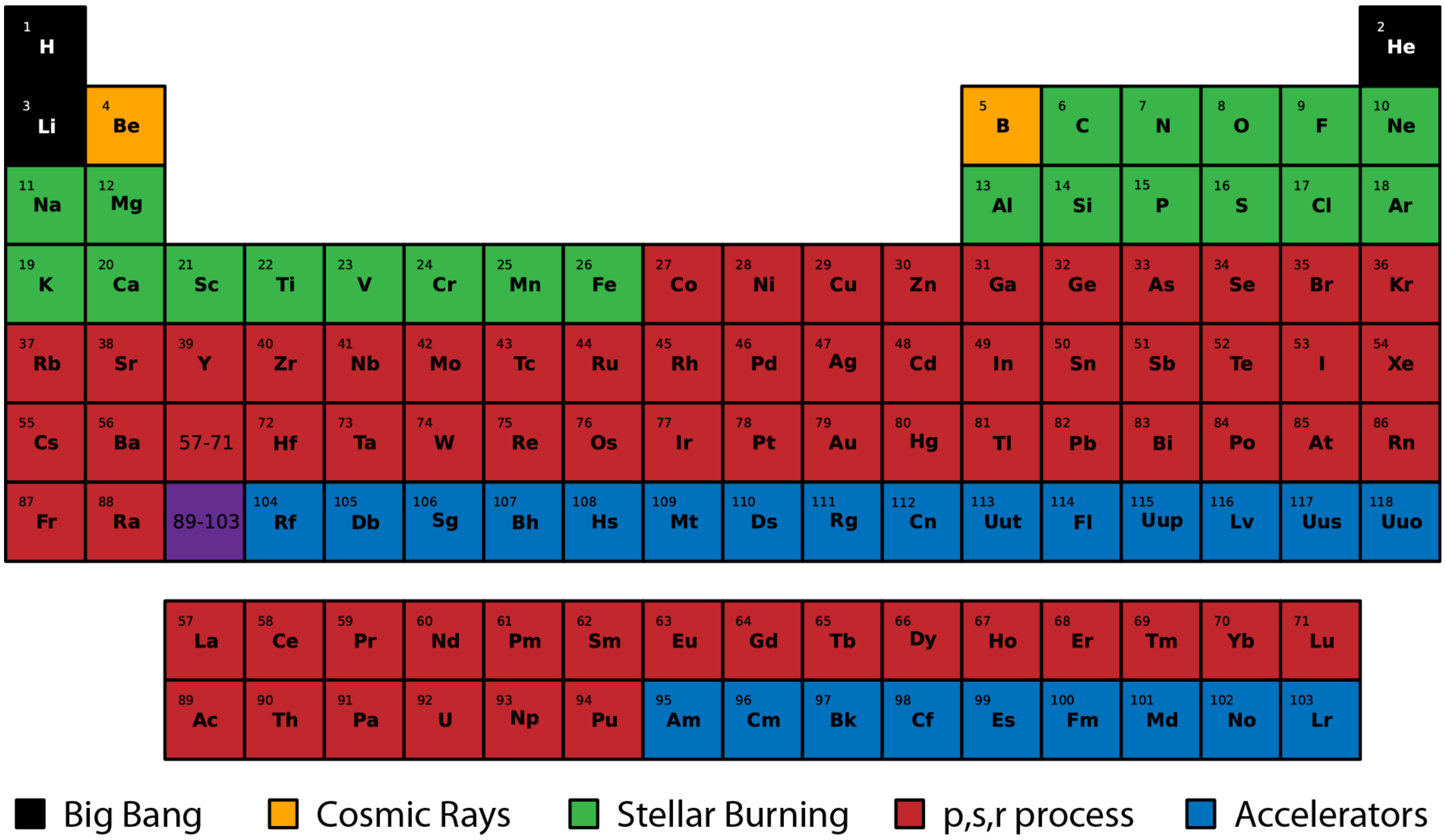
Google: onion model of stars

HEAVY ELEMENTS: DYING STARS, COMPACT OBJECTS



This is area is a hot topic of current research...

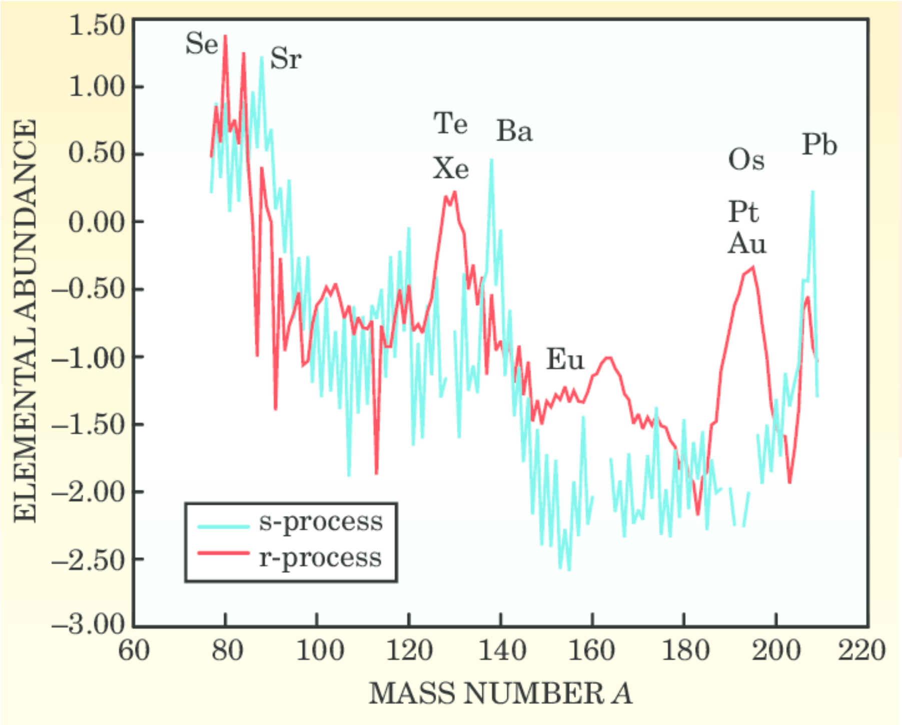
HEAVIEST ELEMENTS: MAN MADE



Google: what is the heaviest man made element?

FURTHER EVIDENCE

of nuclear physics in astrophysics



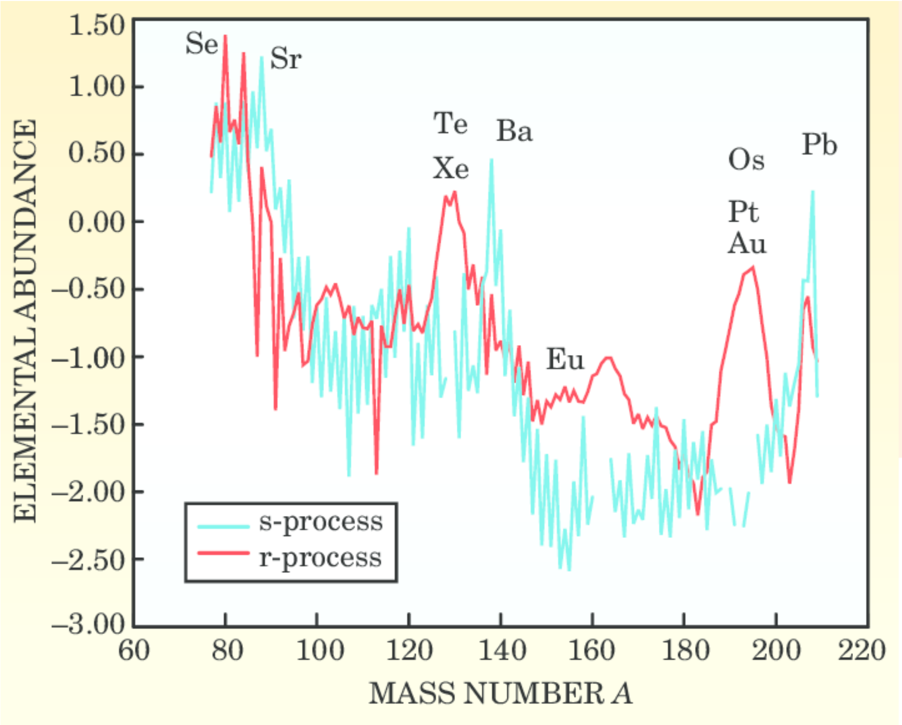
In the isotopic abundances there were two bumps

This implies two different processes are happening

Google: Suess & Urey abundance curve

FURTHER EVIDENCE

of nuclear physics in astrophysics



Question: What is causing the major bumps (peaks)?

Google: BBFH (Burbidge Burbidge Fowler and Hoyle)

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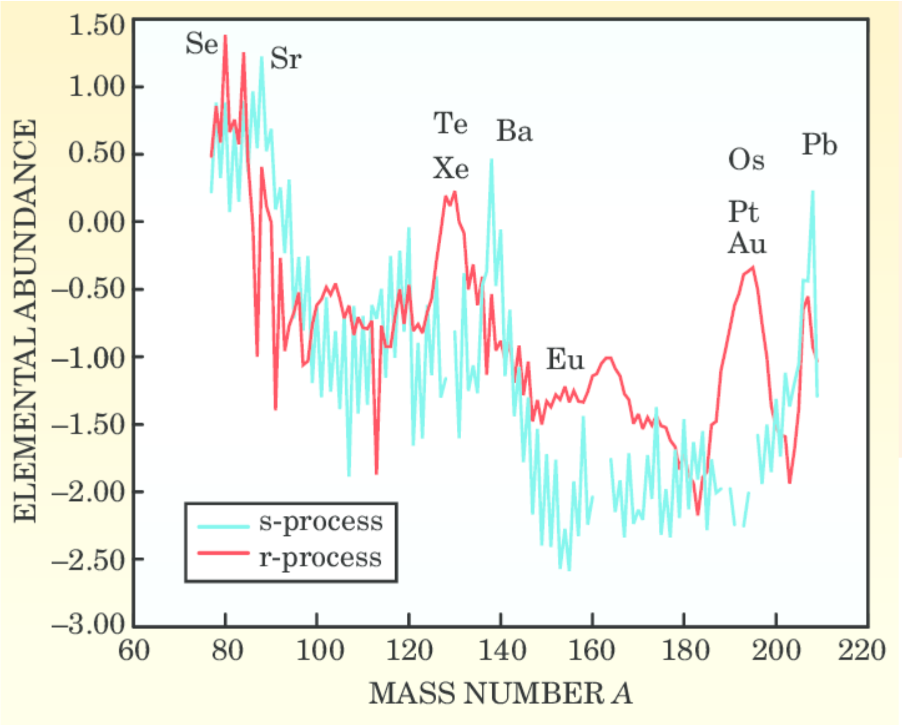


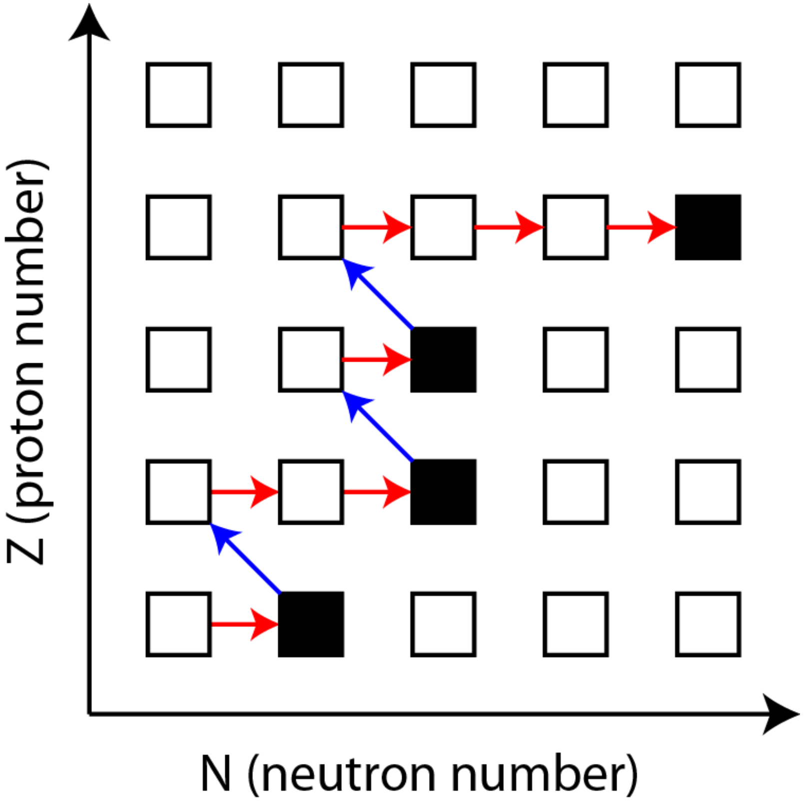
Question: What is causing the major bumps (peaks)?

Nuclear structure!

Google: BBFH (Burbidge Burbidge Fowler and Hoyle)

THE SLOW NEUTRON CAPTURE PROCESS

s-process: neutron capture rates are slow relative to β-decay; $\tau_n \gg \tau_\beta$



$$(Z, N) + n \leftrightarrow (Z, N+1) + \gamma$$

$$(Z, N) \rightarrow (Z+1, N-1) + e^- + \bar{\nu}_e$$

HOW DO WE FORM THE PEAKS?

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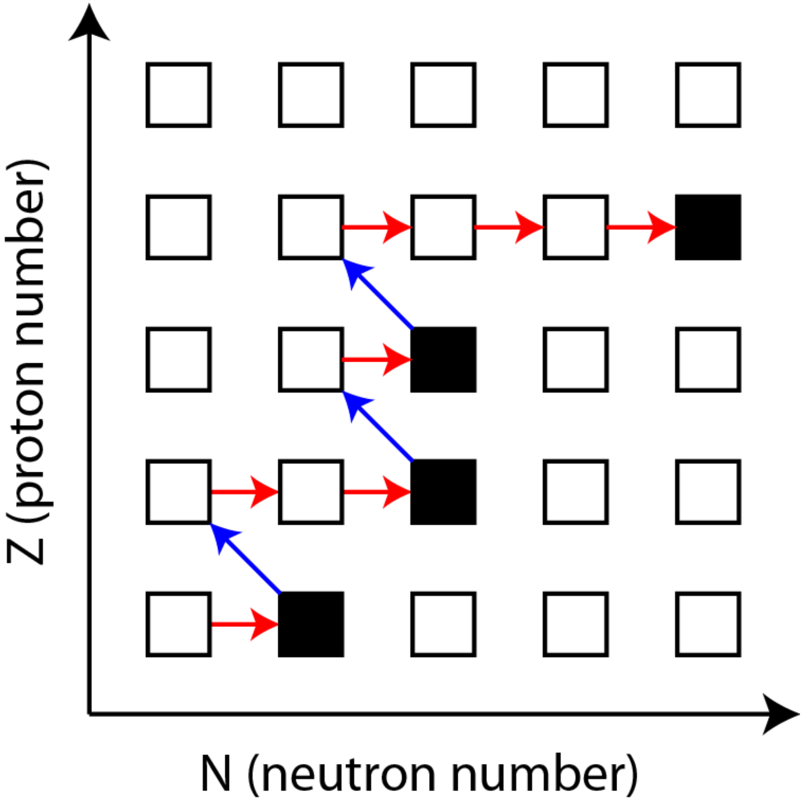
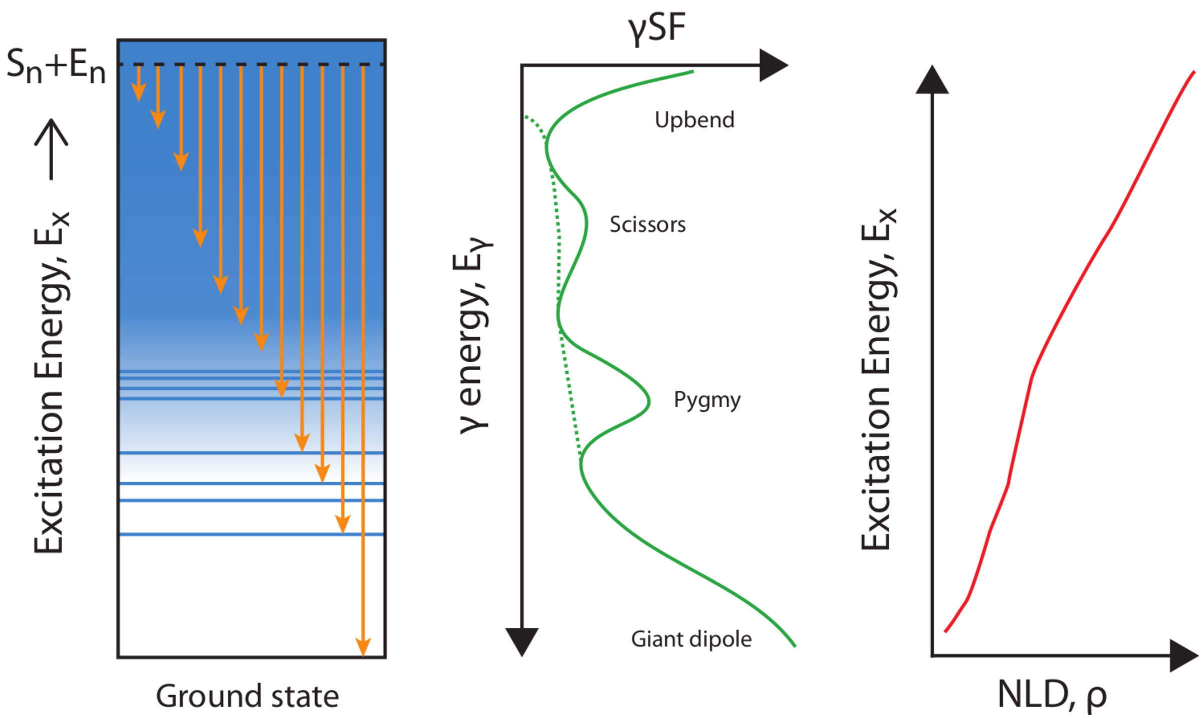


This process stays very close to the stable isotopes • most nuclear physics inputs are known

Primarily occurring in AGB stars

RADIATIVE NEUTRON CAPTURE

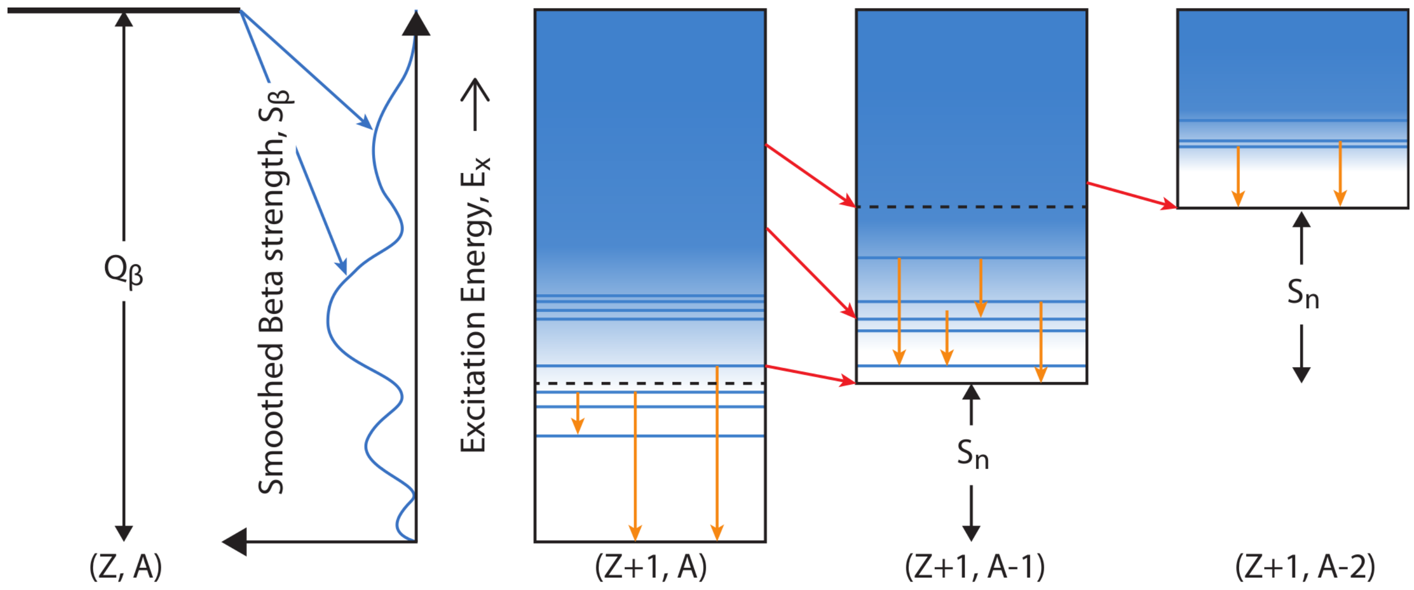


$$(Z, N) + n \leftrightarrow (Z, N+1) + \gamma$$

Key components: Optical potential • γ-ray strength function (γSF) • Nuclear Level Density (NLD)

Google: R-matrix theory • Hauser-Feshbach theory

NUCLEAR β^--DECAY



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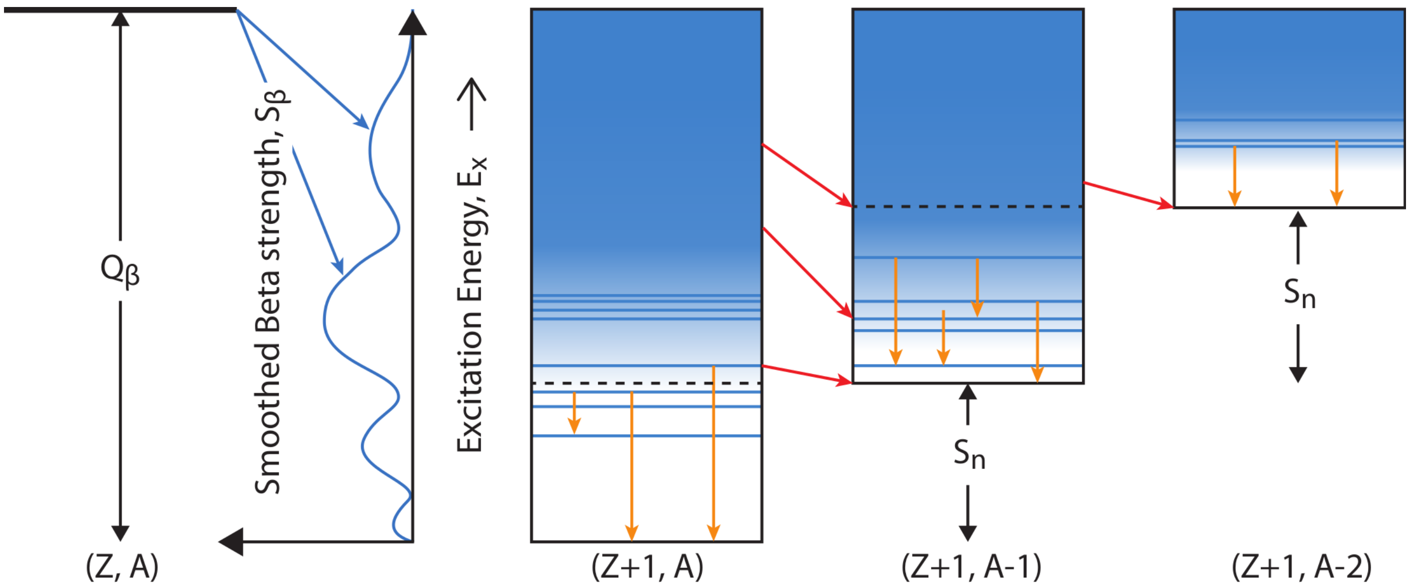
Key components: Fermi's Golden Rule • nuclear levels • binding energies • γSF / NLD

As we add neutrons: Q_{beta} ⇡ S_n ⇣ so what happens?

Google: Quasi-particle Random Phase Approximation (QRPA)

NUCLEAR Β¯-DECAY



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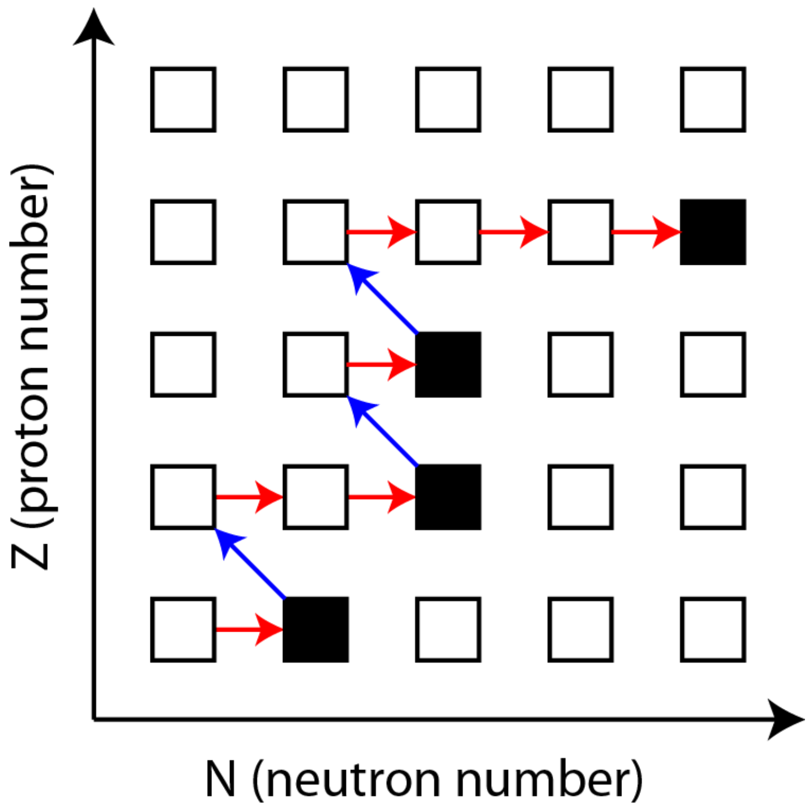
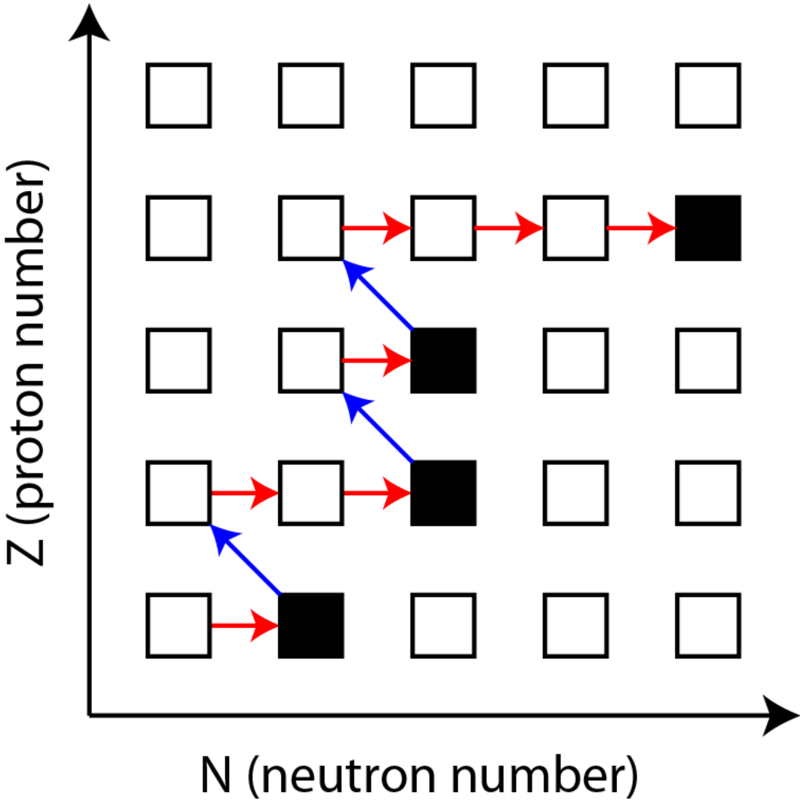
We release more neutrons!

Google: Quasi-particle Random Phase Approximation (QRPA)

WHAT HAPPENS WHEN $\tau_n \ll \tau_\beta$?



WHAT HAPPENS WHEN $T_N \ll T_B$?



We're going to go far from the stable isotopes (further to the right)!

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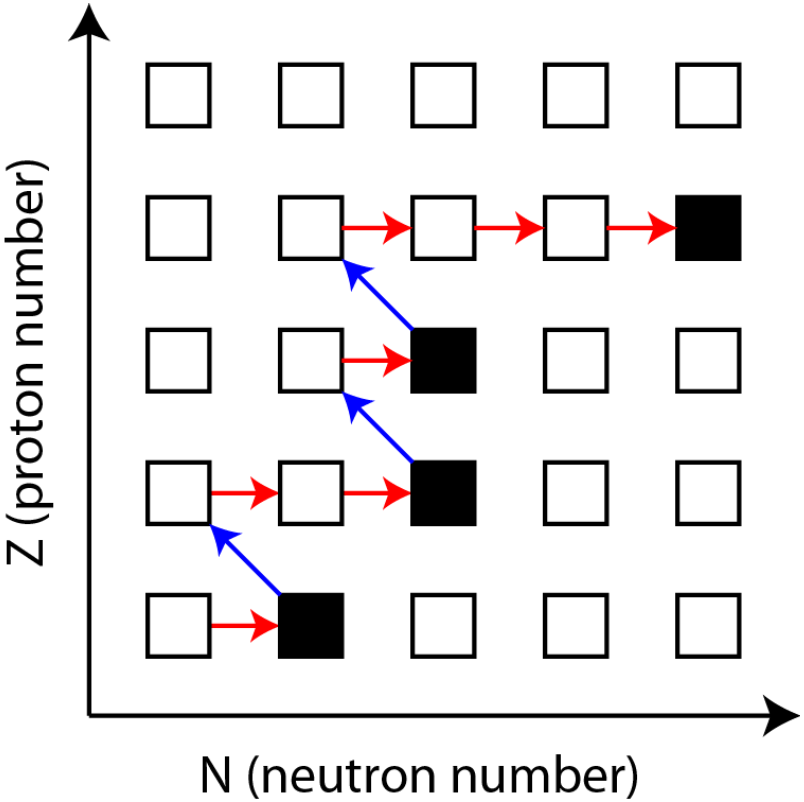

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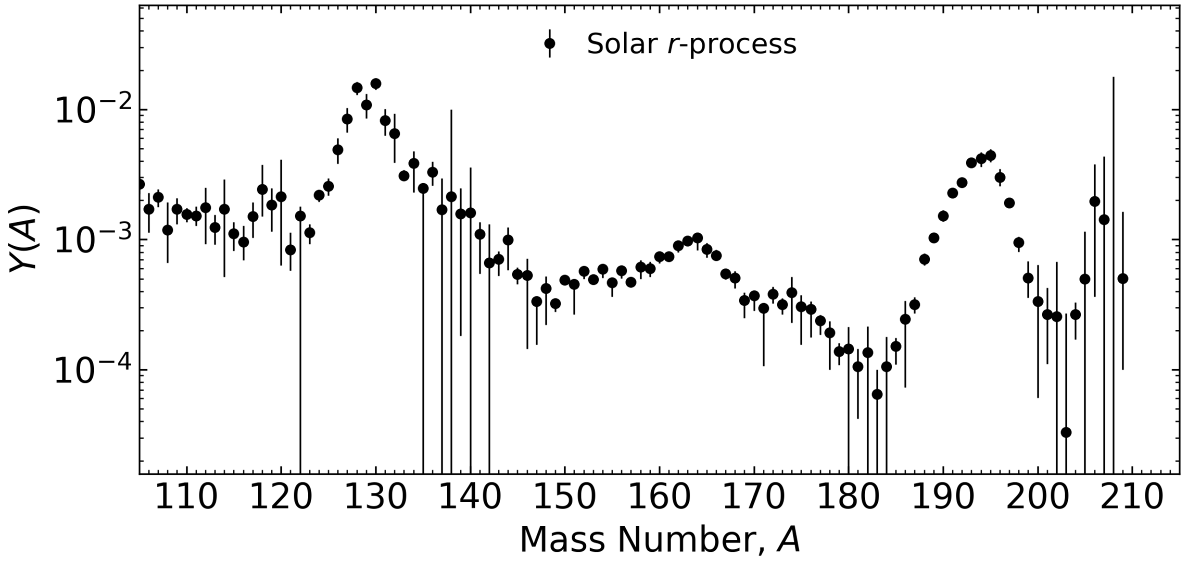
This is known as the rapid neutron capture process (r-process)

THE r-PROCESS



Believed to be responsible for roughly half the elements above iron

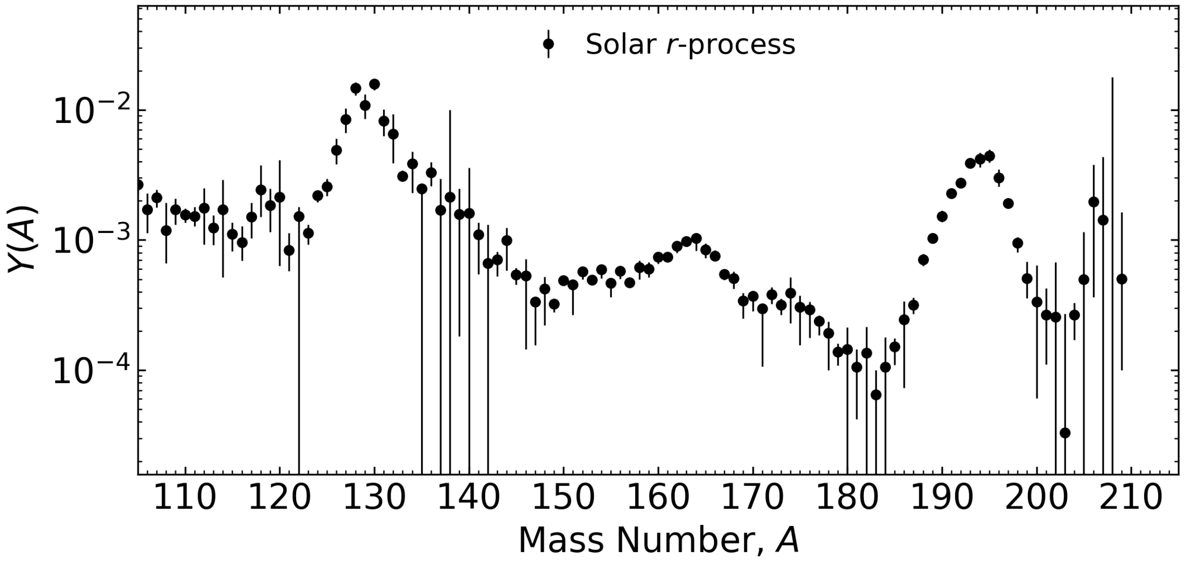
All of the actinides are produced by this nucleosynthesis process; many neutrons required

Major problem: We only have hints of where this process occurs in nature

Another major problem: we barely have any nuclear data in this region

Why?...

THE R-PROCESS



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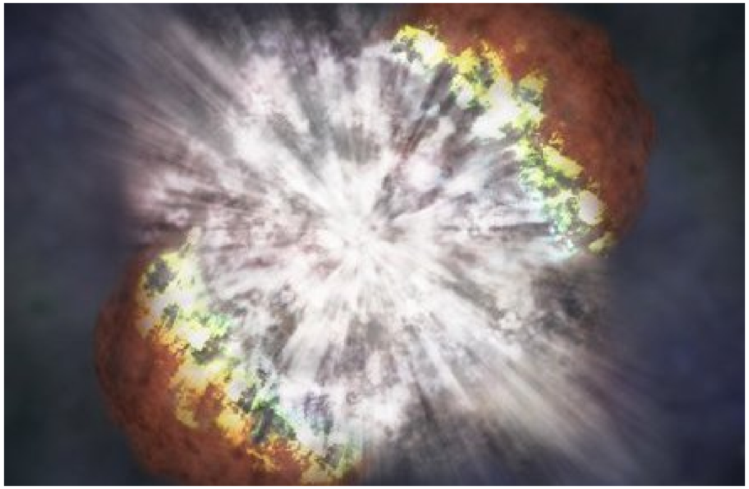
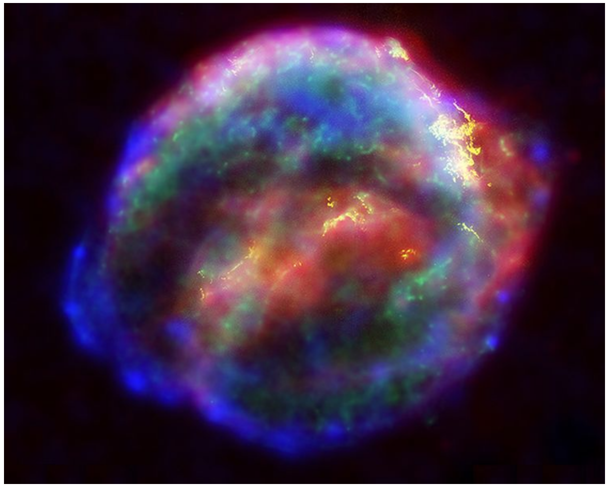
Why?... nuclei are *short-lived*

ONE POSSIBLE CANDIDATE SITE: SUPERNOVA

End of the life of a massive star





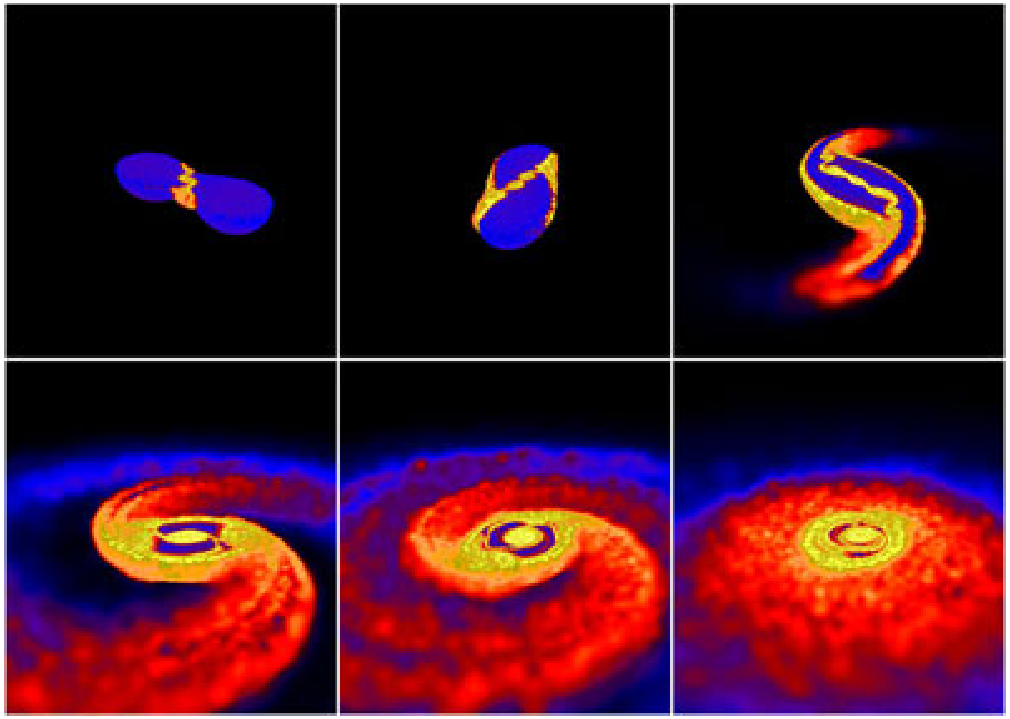
Extremely luminous - burst of radiation that can outshine host galaxy for several weeks expelling the star's material

Can it produce neutron-rich material? This is under debate... MHD jets?

Requires exascale computing to properly model in full 3D

ANOTHER CANDIDATE SITE: COMPACT OBJECT MERGERS

Merger of two neutron stars • merger of neutron star with black hole



Very rare events • lots of neutrons! • different types of ejecta

Google: neutron star mergers

NUCLEAR PHYSICS DIFFICULTIES OF THE r-PROCESS

Every possible neutron-rich species that could exist in nature may be accessed (1000's)

Problem: we have some (incomplete) data for several hundred...

We need binding energies, decay rates, branching ratios, reaction rates, even fission information

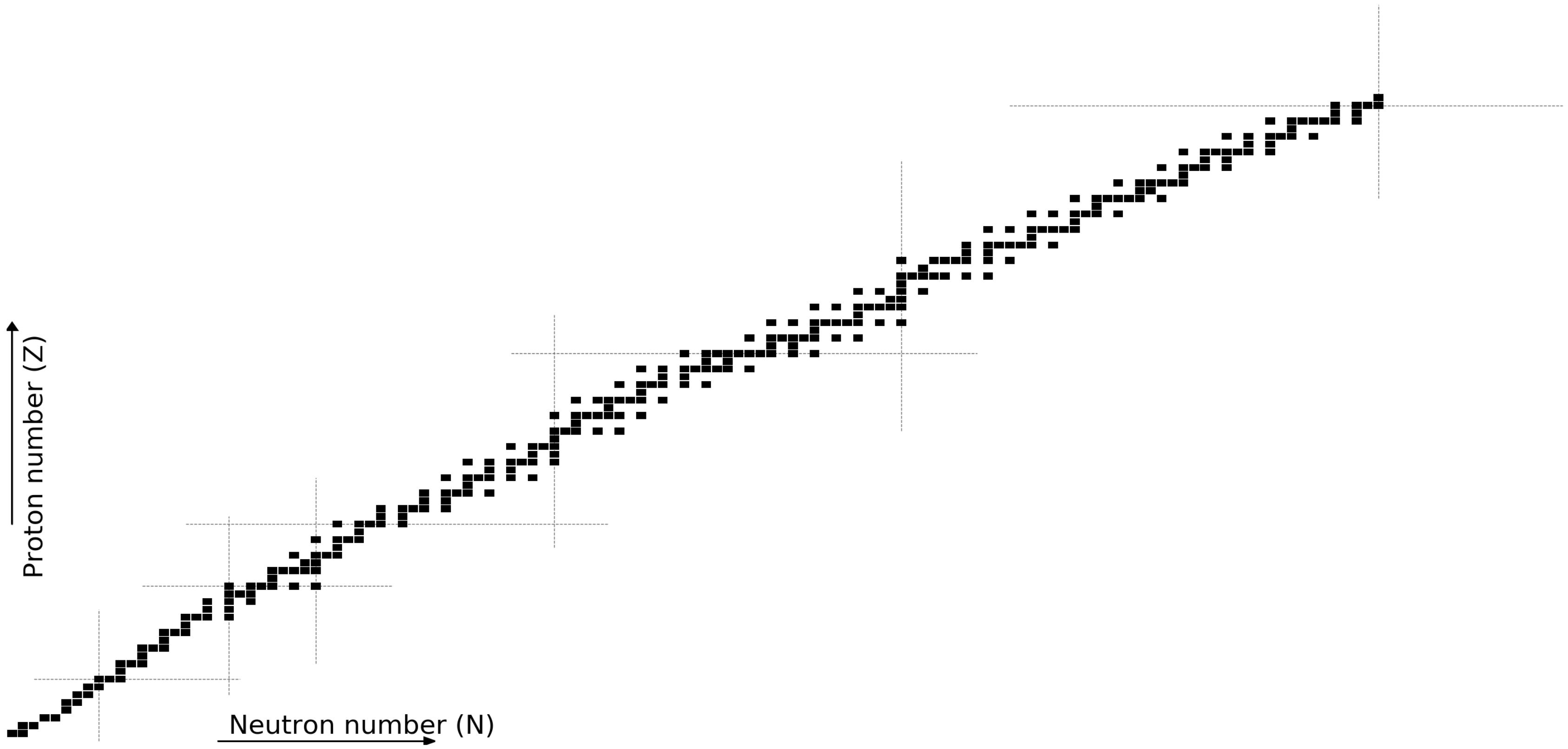
There's no way around this... we require nuclear theory

NUCLEAR PHYSICS AS THE LANGUAGE OF THE r-PROCESS

1st order: masses, β-decay rates, capture rates & fission

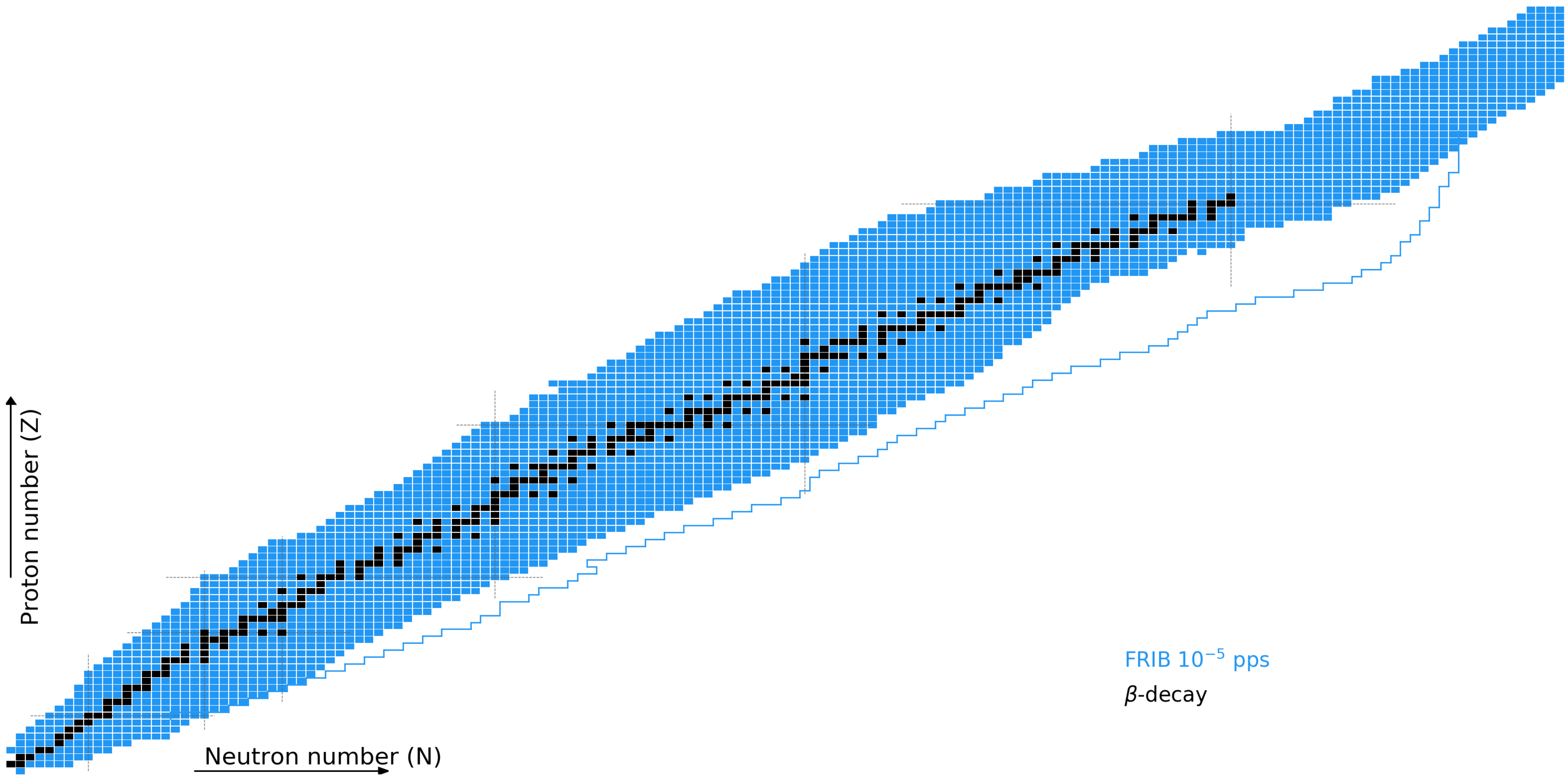
WHAT DO WE KNOW?

The chart of nuclides



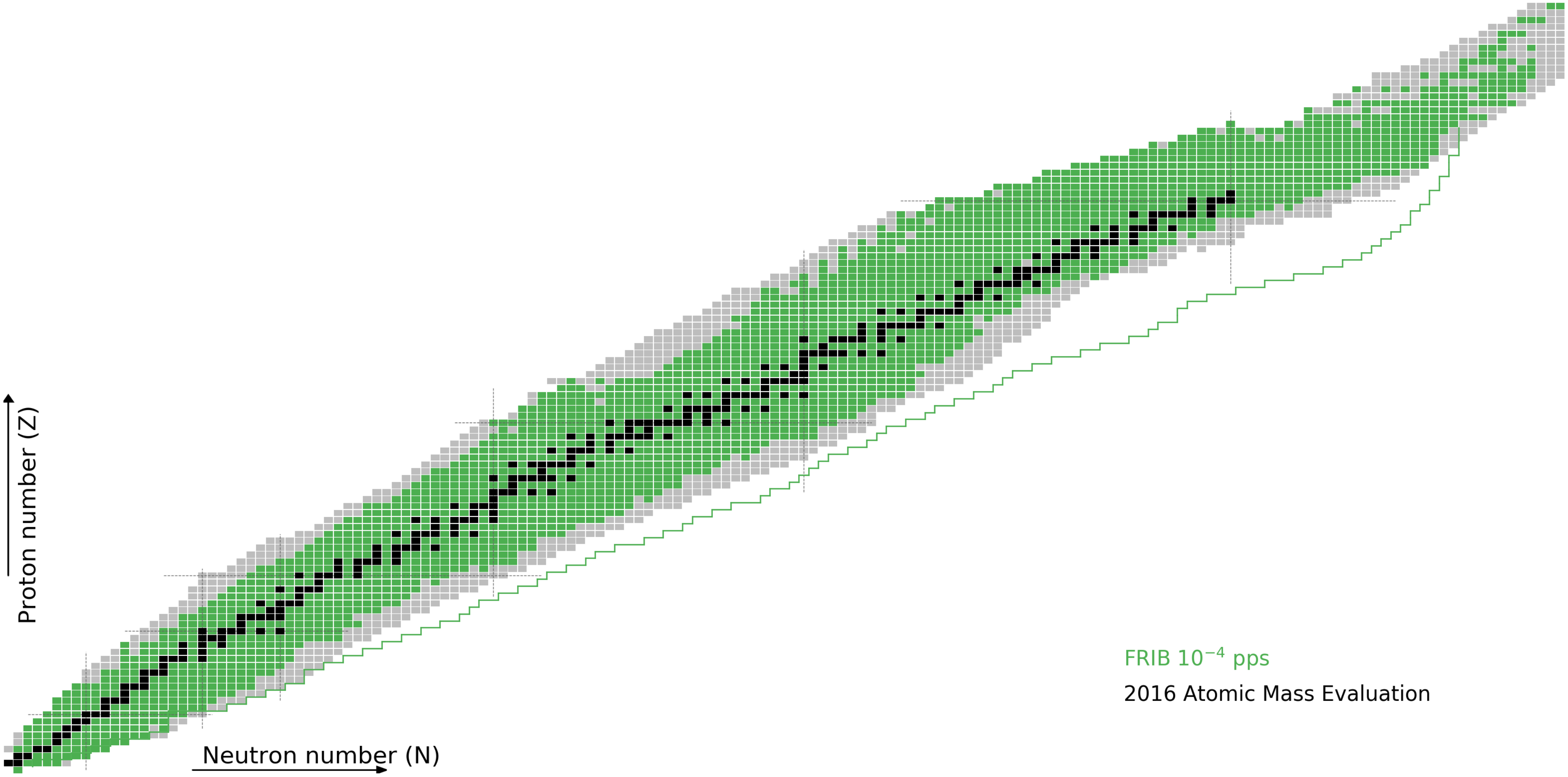
WHAT DO WE KNOW?

All half-lives



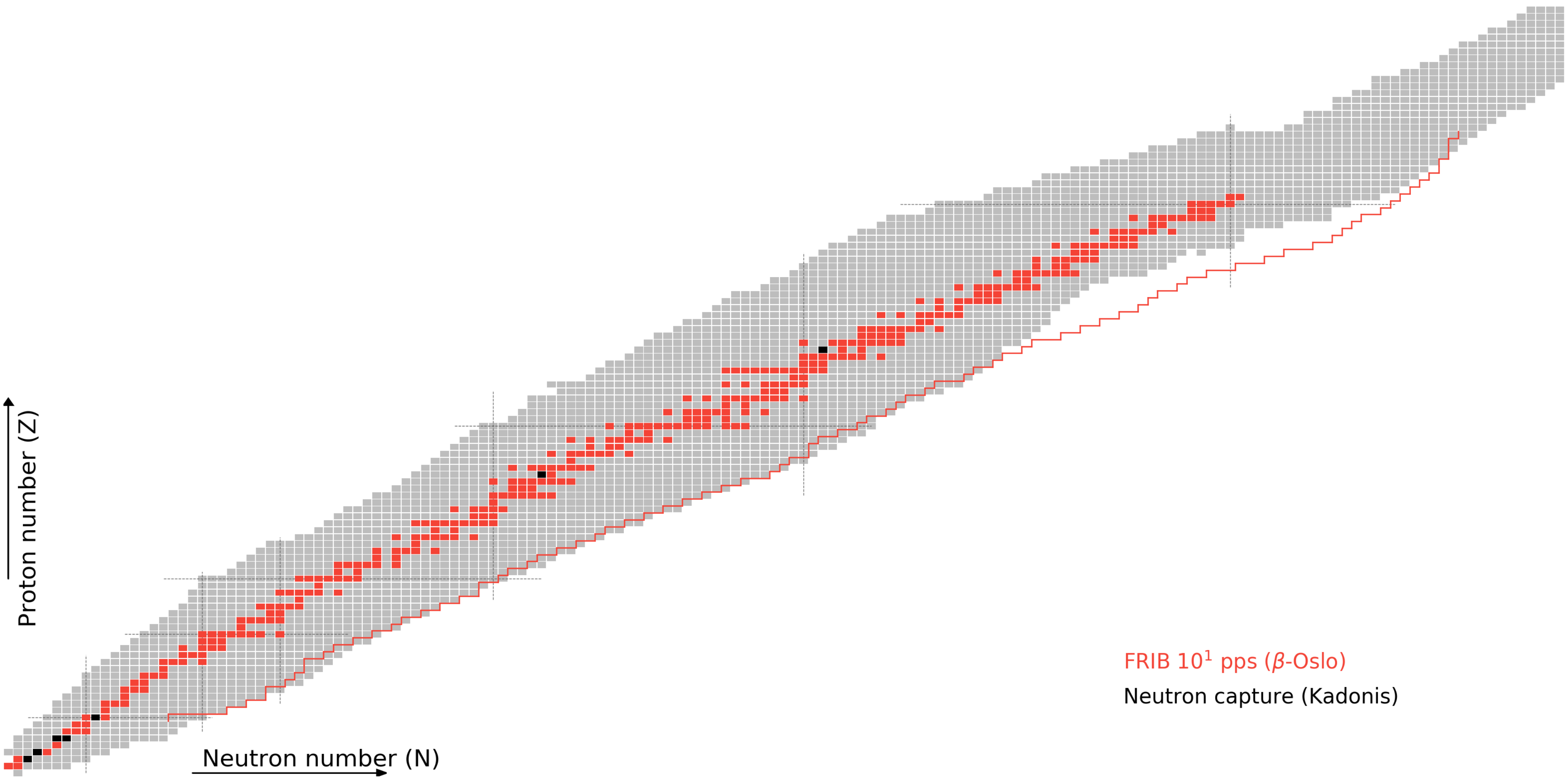
WHAT DO WE KNOW?

Nuclear masses



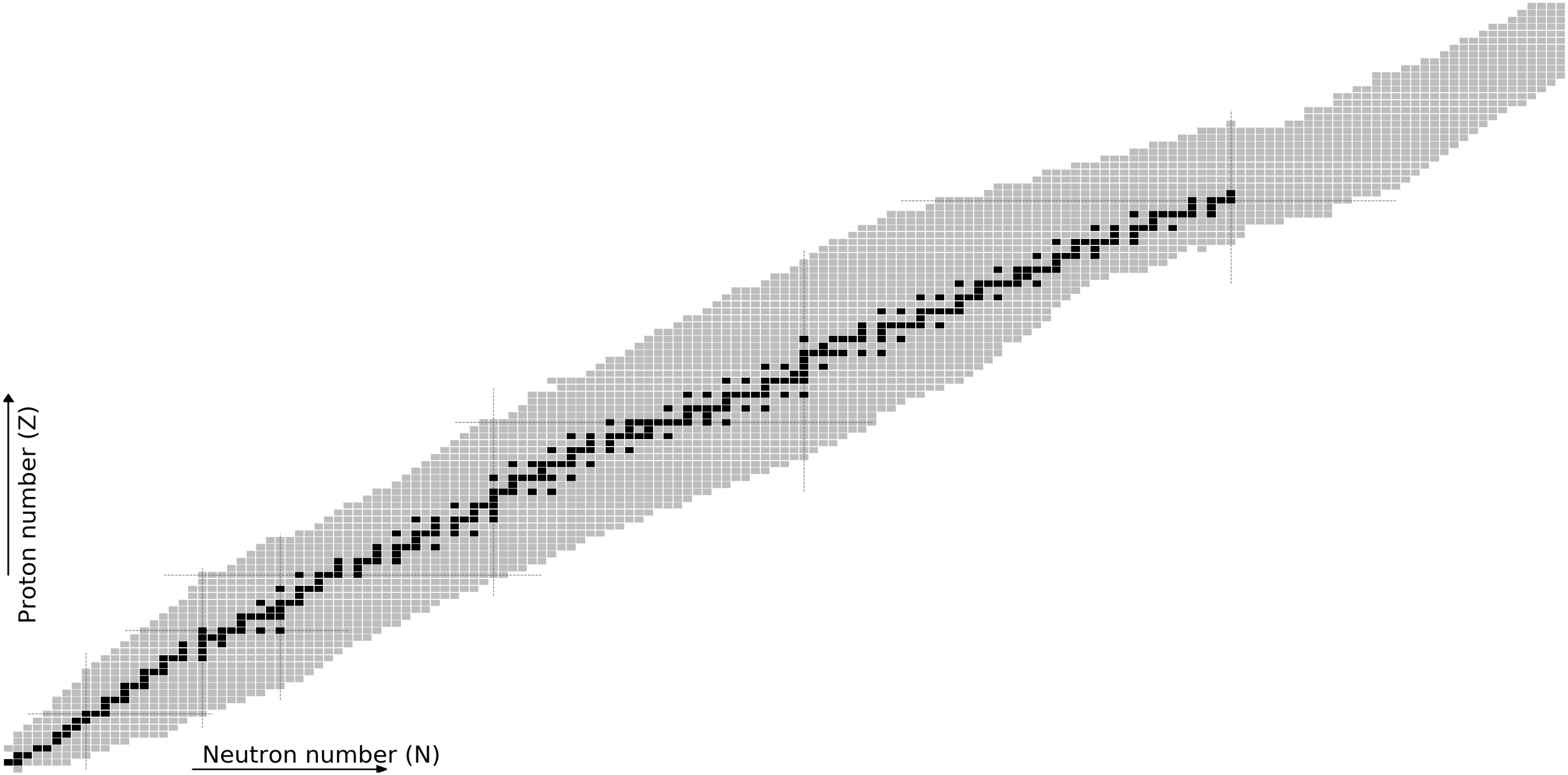
WHAT DO WE KNOW?

Neutron capture rates



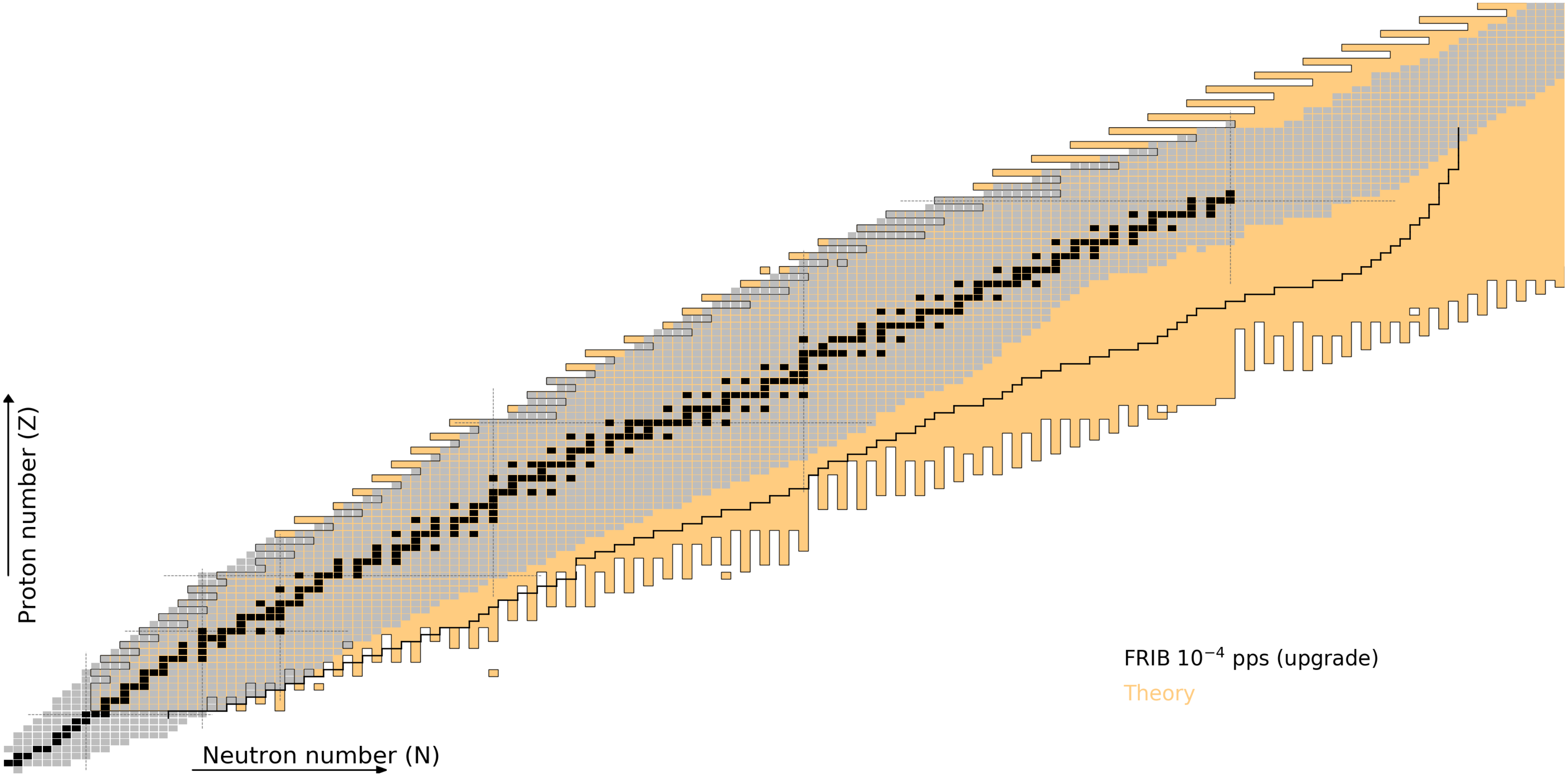
WHAT DO WE KNOW?

As of today, to varying degrees of accuracy

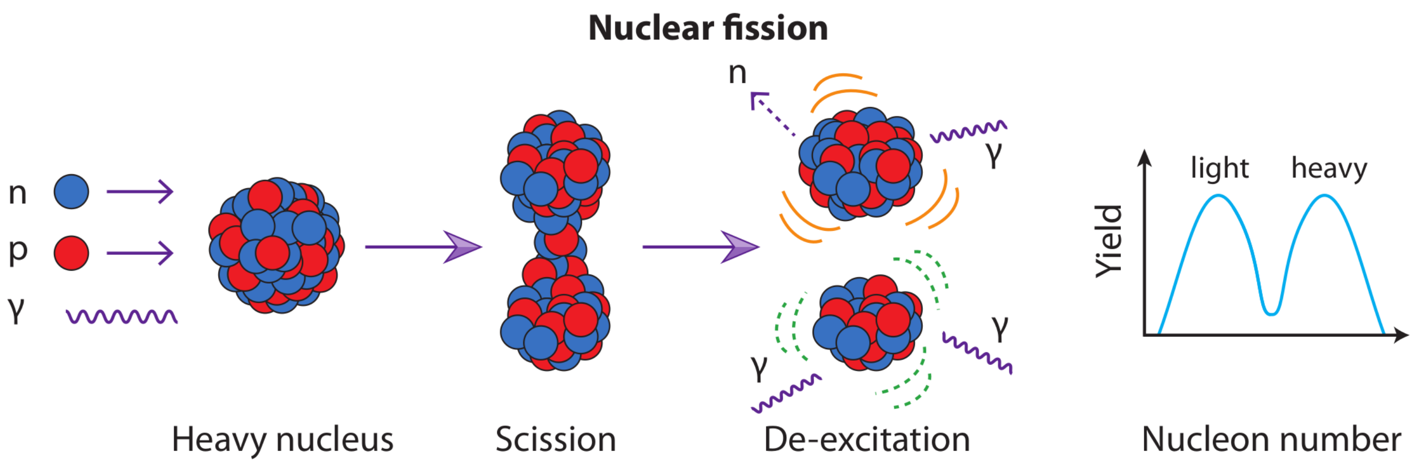


THE FUTURE

FRIB as the r-process machine



SCHEMATIC OF NUCLEAR FISSION



Heavy nucleus is unstable (naturally or via particle absorption) splitting into two lighter fragments

Breaking configuration is known as scission

Ensemble of events produces a fission yield

The high amount of energy released makes it interesting for observations

HOW DOES A NUCLEOSYNTHESIS CALCULATION WORK?

nuclear physics inputs
(Sn, β-rates, n-cap rates, …)

PRISM
reaction network

abundances

thermodynamic conditions

(temperature, density, ...)

combine nuclear physics inputs with astrophysical conditions

SUMMARY

Nuclear physics is intimately connected to astrophysics

Nucleosynthesis is one aspect of this connection

There are many different nucleosynthesis processes

Big Bang ▲ s-process ▲ r-process

The formation of the heaviest elements still remains an unsolved problem

FRIB and other facilities will help in this endeavor by constraining nuclear theories used in calculations

More information @ MatthewMumpower.com