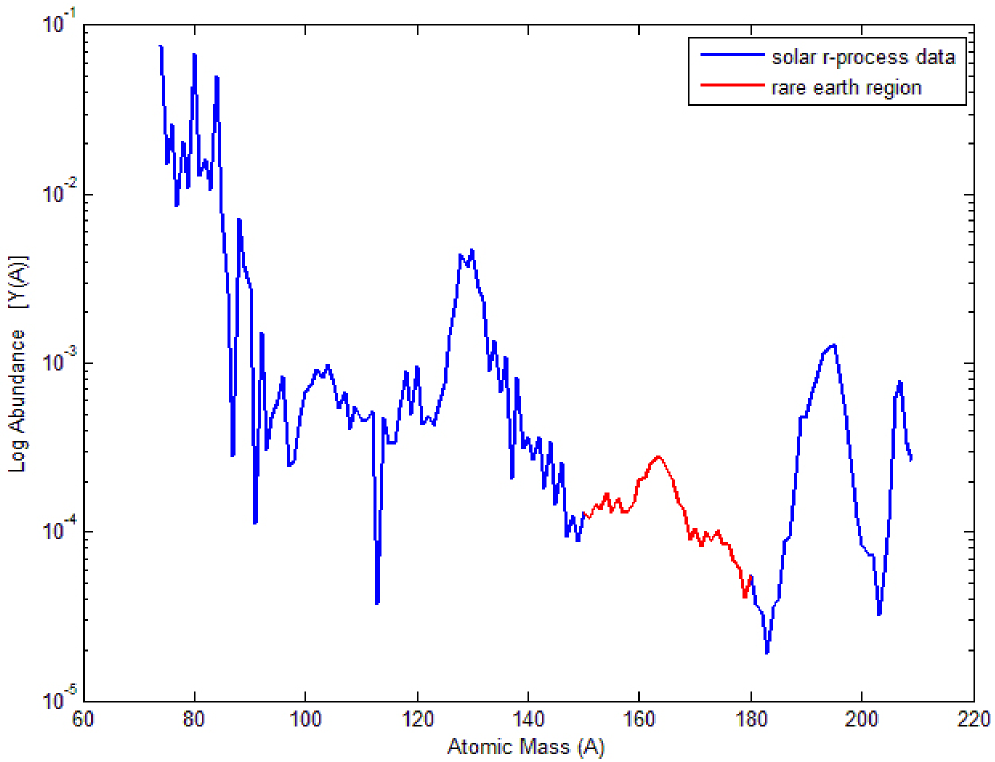
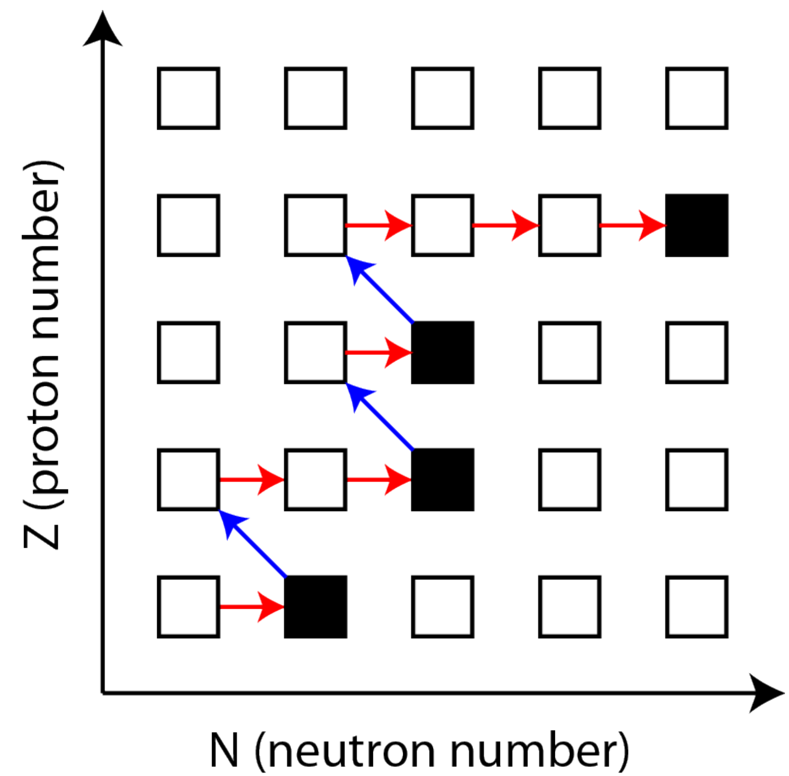
A Primer on r-process Nucleosynthesis





Matthew Mumpower

University of Notre Dame

Saturday Sept. 27th 2014

FAIRNESS Workshop

UNIVERSITY OF NOTRE DAME

JINA

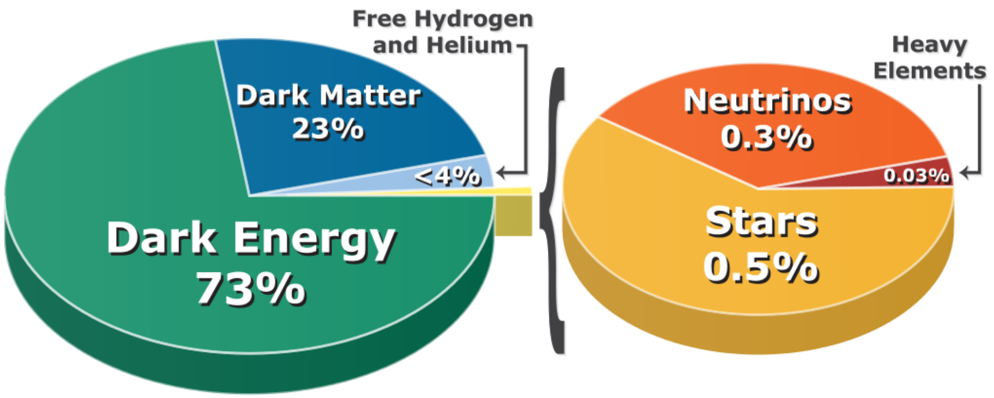
Where I Work

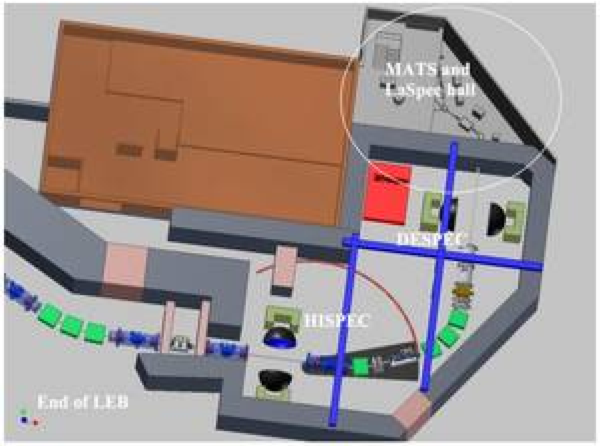
The middle of nowhere: South Bend, Indiana...

The Closest Thing To Italy In South Bend...

A Primer on r-process Nucleosynthesis

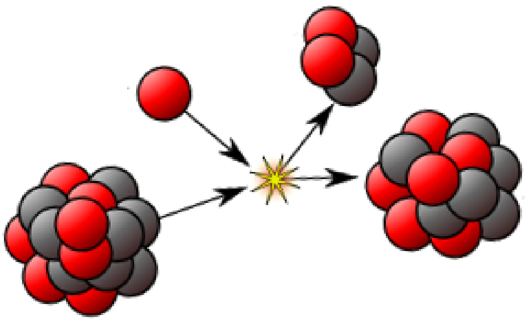
1. Short overview of nucleosynthesis
2. The r-process
   - Candidate sites
   - Astrophysical conditions
   - Observables & data
   - Example calculation
3. Connection to FAIR
   - Nuclear physics inputs
   - Some results
4. Summary & Outlook





Nucleosynthesis

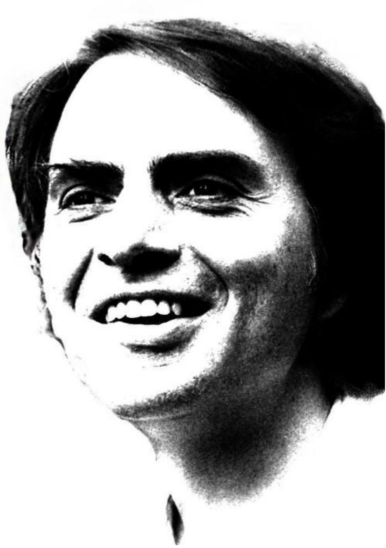
nu·cle·o·syn·the·sis The formation of new atomic nuclei by nuclear reactions, thought to occur in the interiors of stars and in the early stages of development of the universe.



Nuclear Physics

+

Astrophysics



"We are all made of star stuff..."

— ***Carl Sagan***

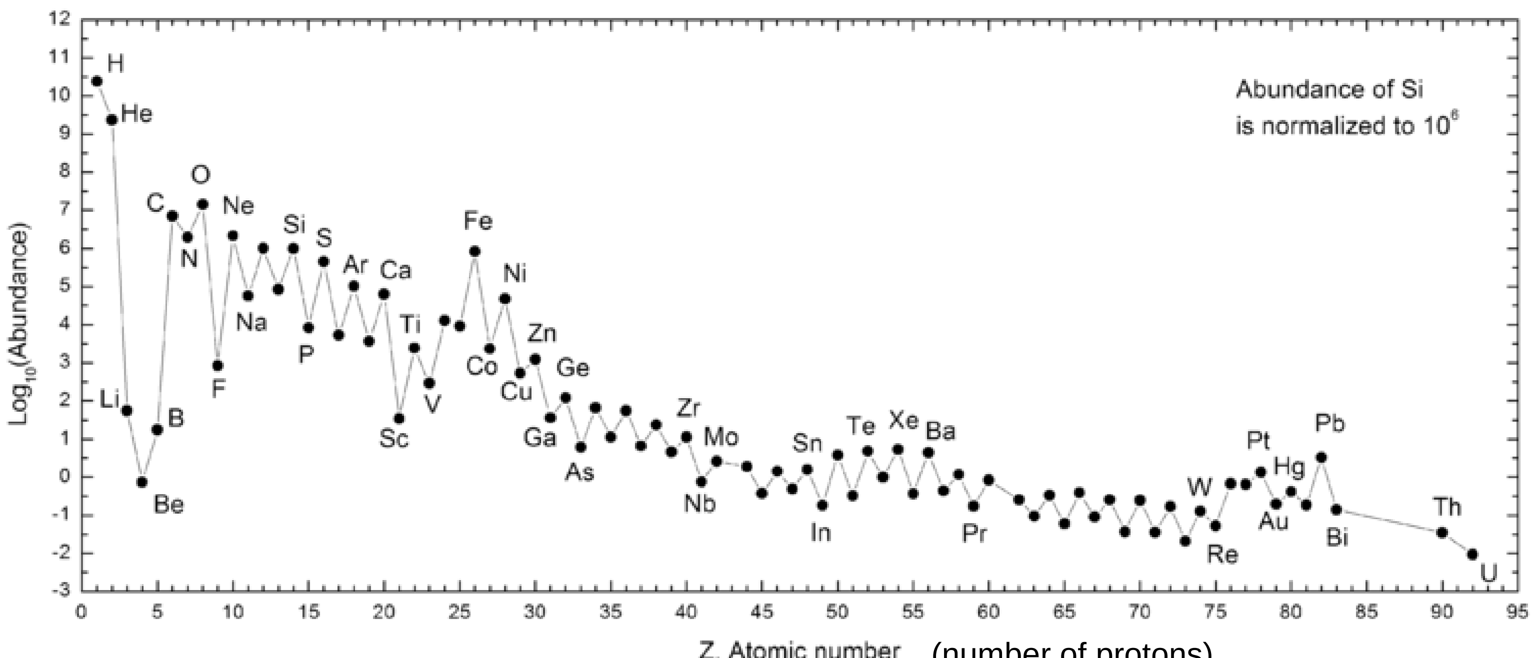
“Stuff” In the Solar System

Abundance is a quantity denoting how much stuff

Heavier elements

More stuff

Less stuff



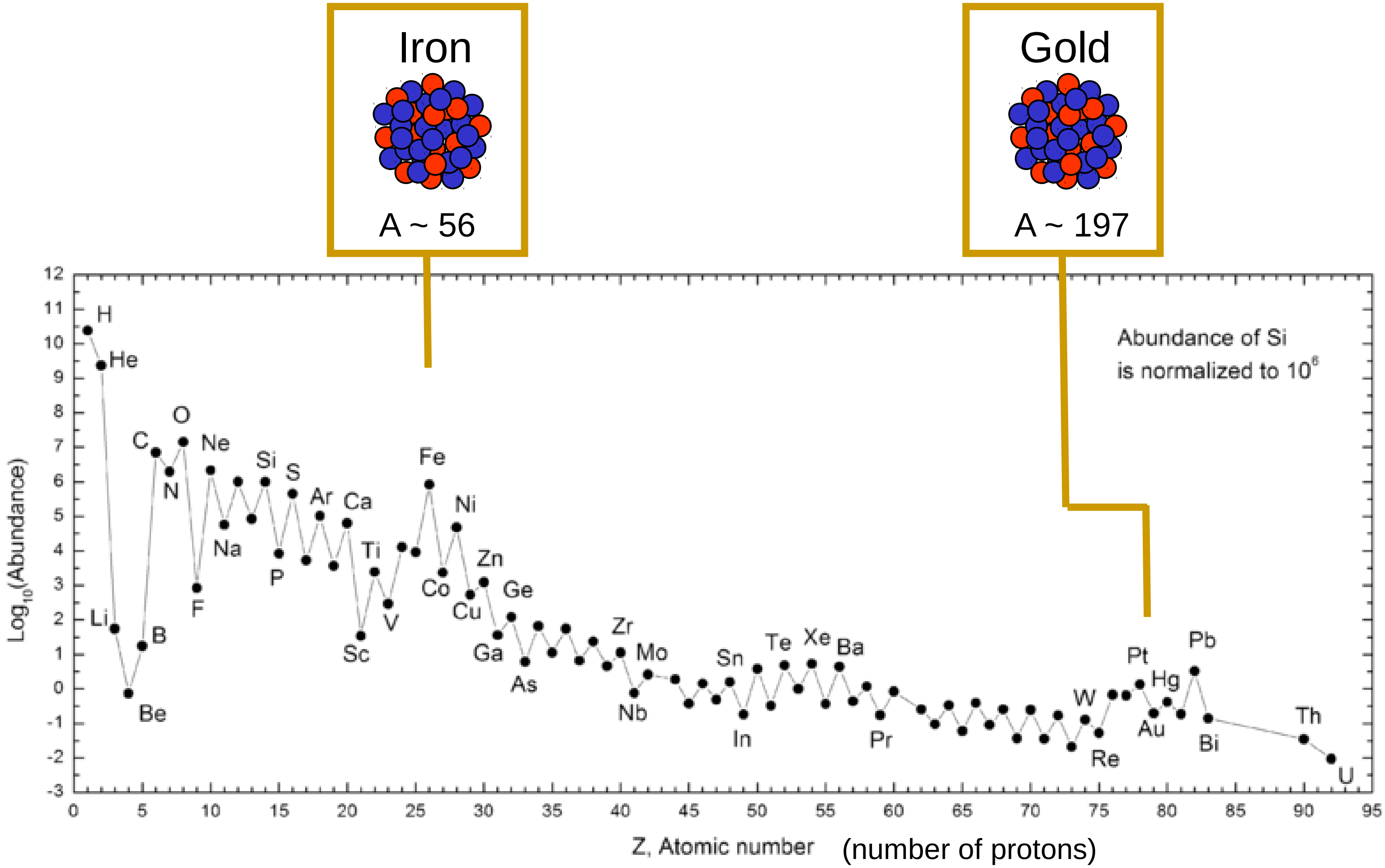
(number of protons)

We know the amount of stuff in the Solar System because we have data from meteorites and the sun's photosphere (outer shell). The sun has 99% of the mass of the solar system – so it is important to understand its composition.

"Stuff" In the Solar System

More stuff

Less stuff



(number of protons)

Creation of the elements did not occur all at the same time nor same place

This requires some detective work...

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

Lightest Elements: Big Bang

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

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■ Big Bang

Big Bang Nucleosynthesis

Created most of the Hydrogen and Helium 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!

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

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

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

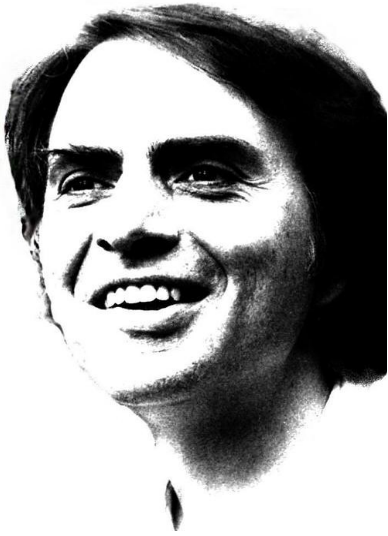
$$ {}^3_1\mathrm{T} + {}^4_2\mathrm{He} \longrightarrow {}^7_3\mathrm{Li} + \gamma \qquad {}^3_2\mathrm{He} + n^0 \longrightarrow {}^3_1\mathrm{T} + p^+$$

$$ {}^3_2\mathrm{He} + {}^2_1\mathrm{D} \longrightarrow {}^4_2\mathrm{He} + p^+ \qquad {}^3_2\mathrm{He} + {}^4_2\mathrm{He} \longrightarrow {}^7_4\mathrm{Be} + \gamma$$

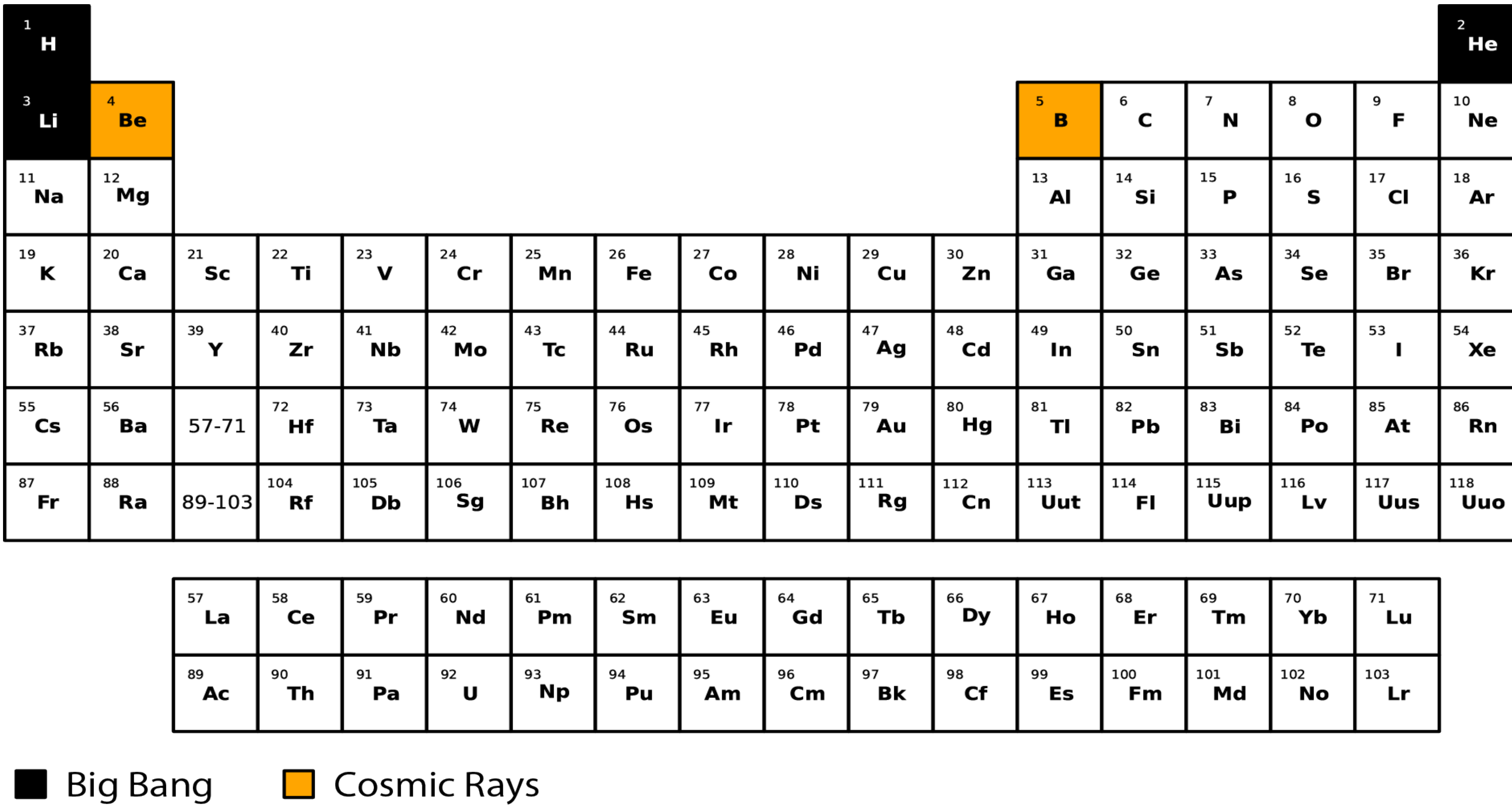
$$ {}^7_3\mathrm{Li} + p^+ \longrightarrow {}^4_2\mathrm{He} + {}^4_2\mathrm{He} \qquad {}^7_4\mathrm{Be} + n^0 \longrightarrow {}^7_3\mathrm{Li} + p^+$$

"If you wish to make an apple pie from scratch, you must first invent the universe. "

— Carl Sagan



Cosmic Rays


1 H
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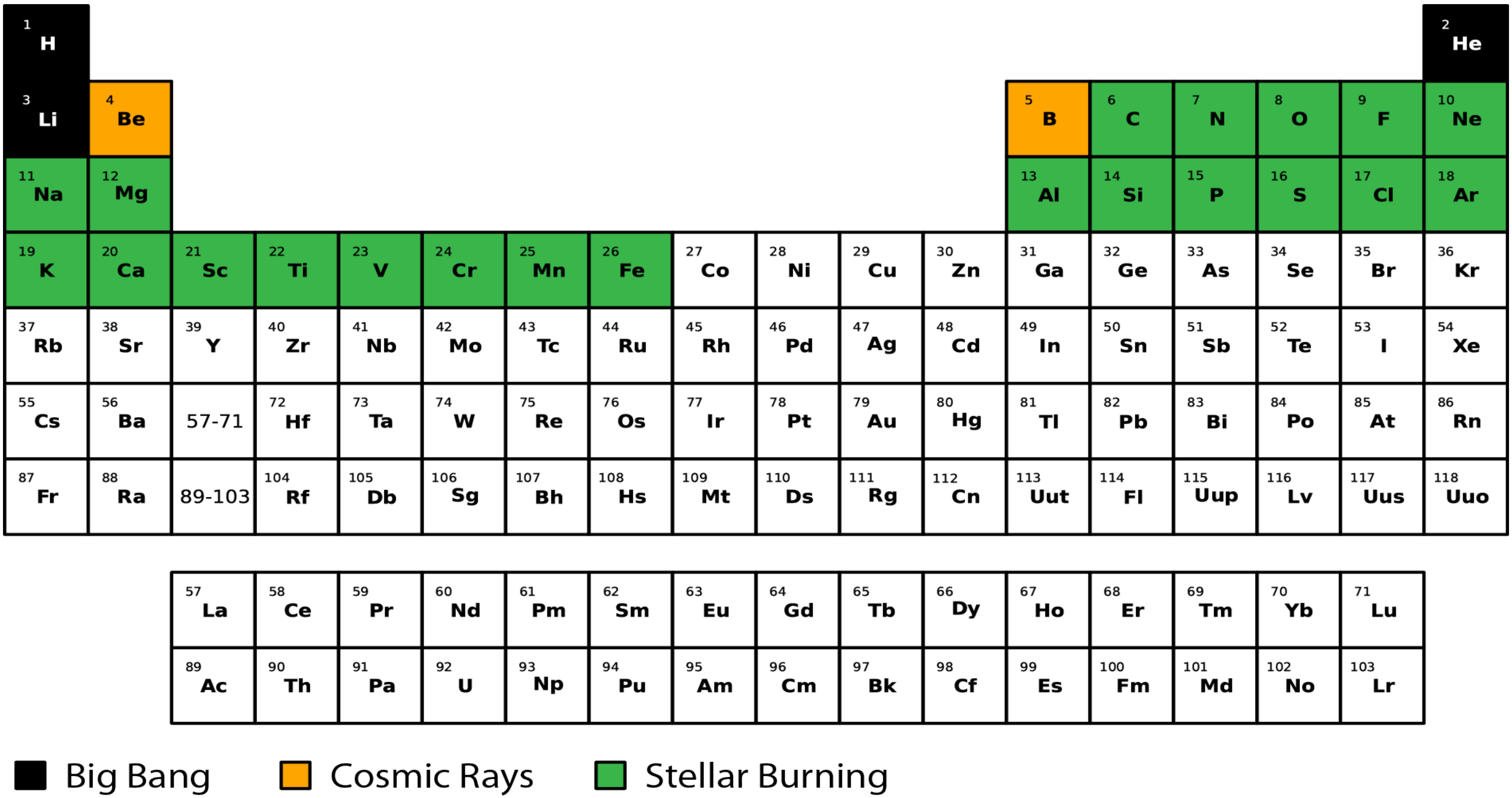
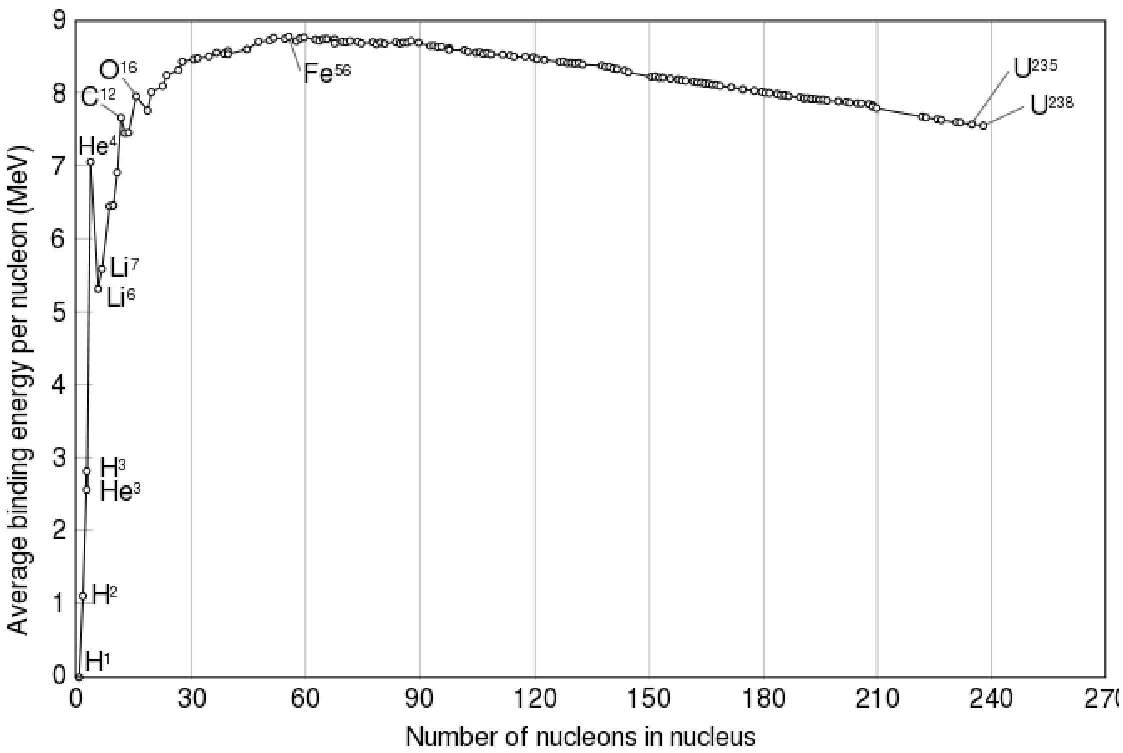
20 Ca
21 Sc
22 Ti
23 V
24 Cr
25 Mn
26 Fe
27 Co
28 Ni
29 Cu
30 Zn
31 Ga
32 Ge
33 As
34 Se
35 Br
36 Kr
37 Rb
38 Sr
39 Y
40 Zr
41 Nb
42 Mo
43 Tc
44 Ru
45 Rh
46 Pd
47 Ag
48 Cd
49 In
50 Sn
51 Sb
52 Te
53 I
54 Xe
55 Cs
56 Ba
57-71
72 Hf
73 Ta
74 W
75 Re
76 Os
77 Ir
78 Pt
79 Au
80 Hg
81 Tl
82 Pb
83 Bi
84 Po
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
Big Bang
Cosmic Rays

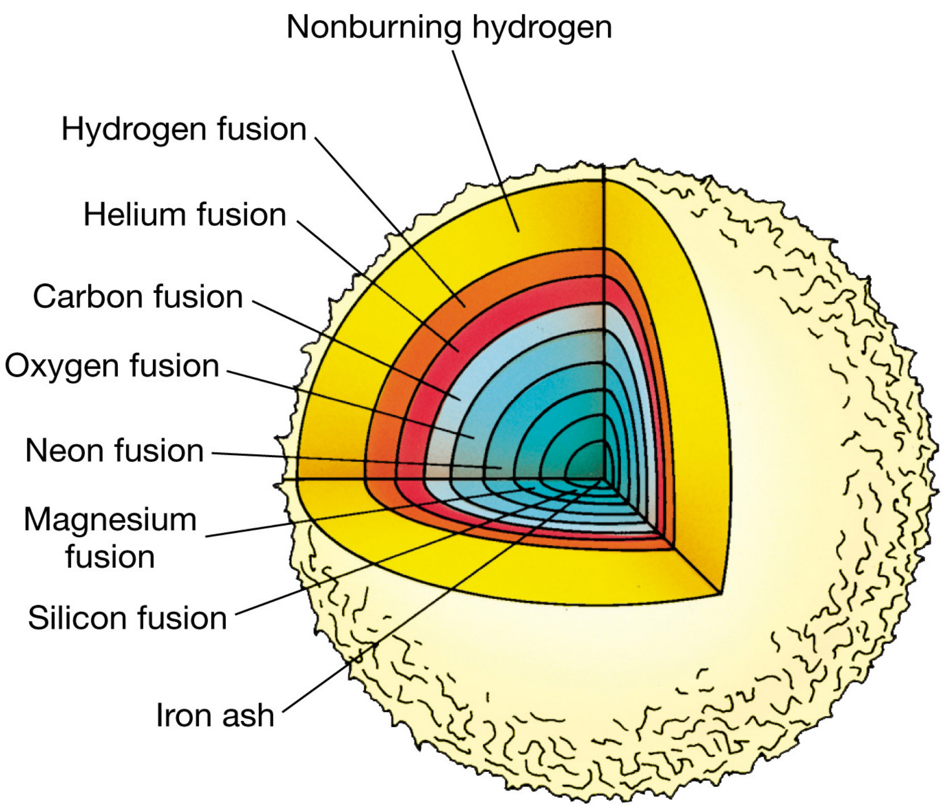
Stellar Burning Processes



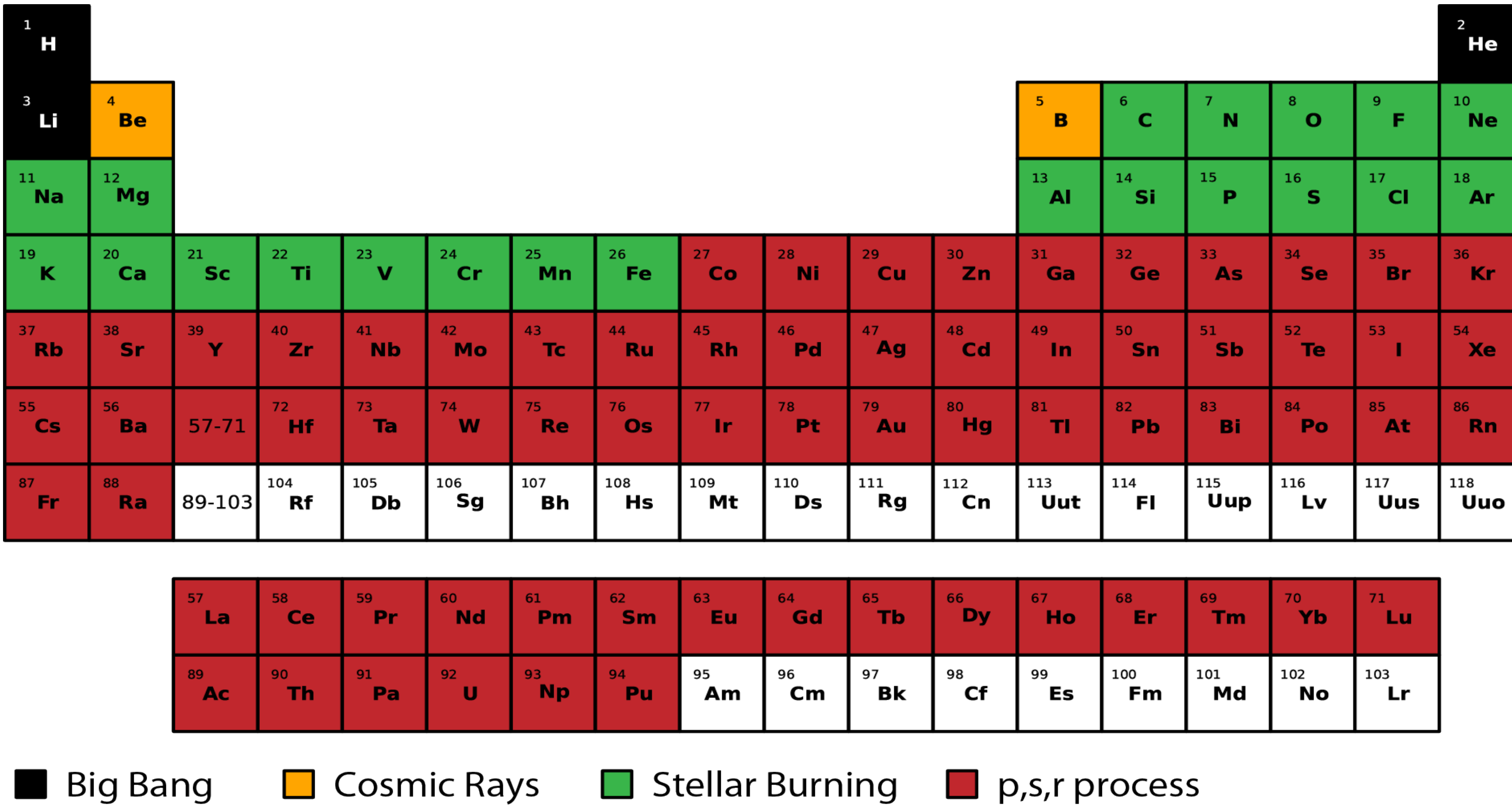
Stellar Burning Processes

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

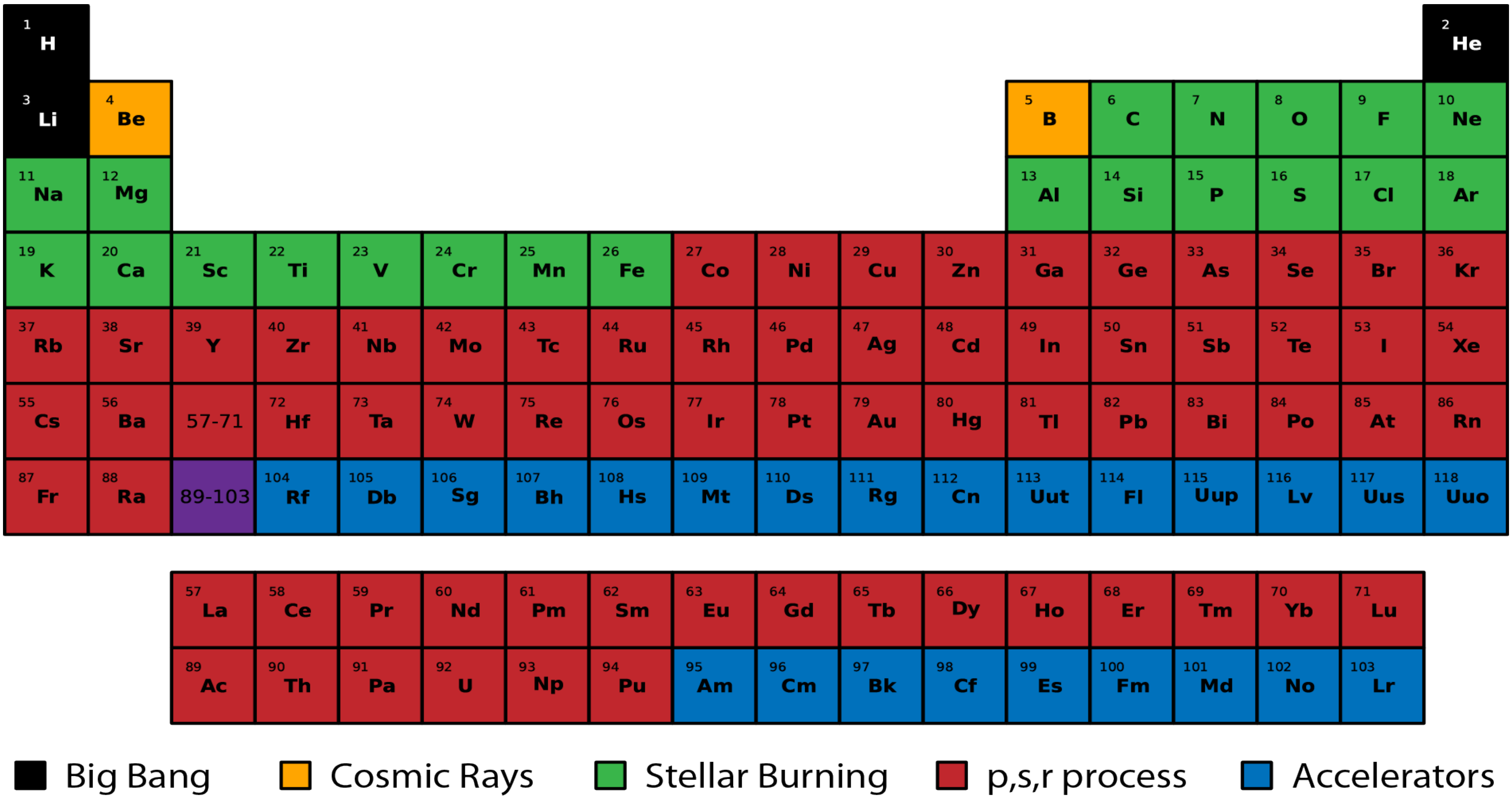




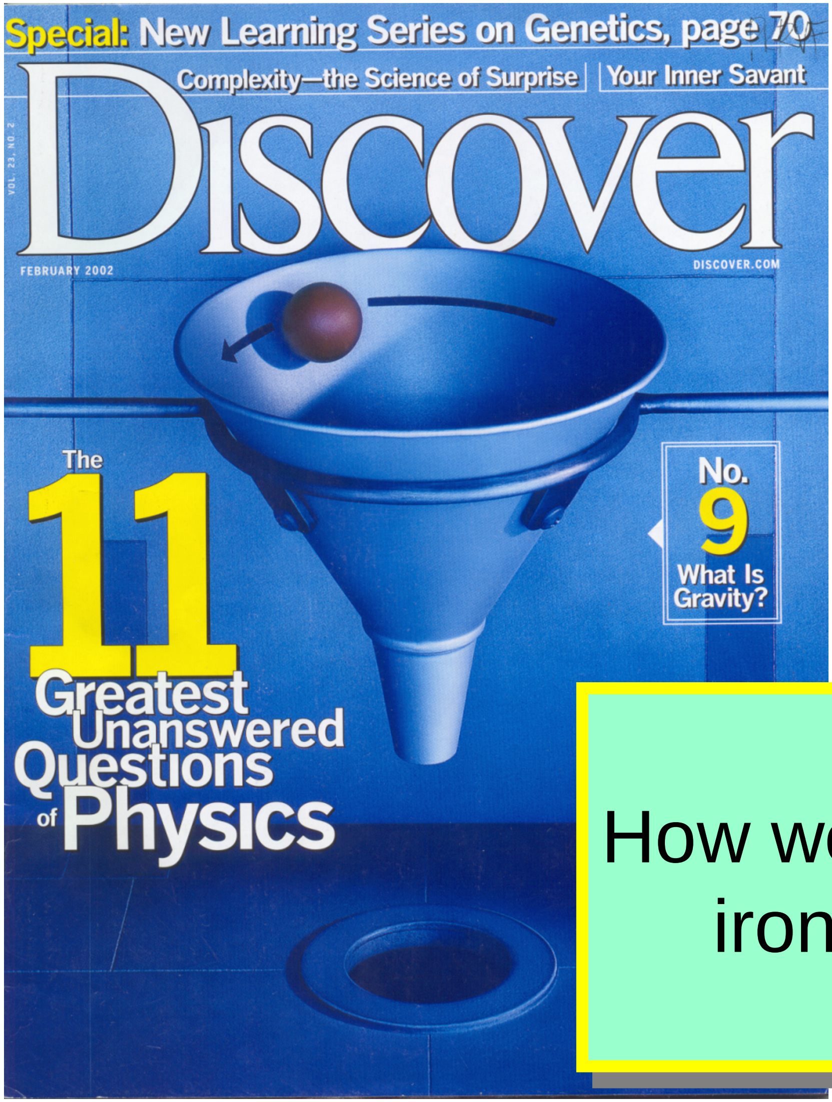
p,s,r Processes



Particle Accelerators



Synthesis Of The Heavy Elements



From the 2002 NRC report

Still many open problems...

•Where are these elements synthesized? (site?)

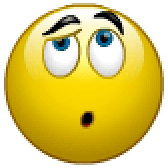
•Is there more than one site?

•What are the masses and half-lives of short-lived nuclei?

•Does fission of heavy elements play a role?

•What are the bounds of nuclear existence?

Question #3
How were the elements from iron to uranium made?



The r-Process

Capture neutrons very quickly - “rapid” compared to the time it takes to beta-decay.

So many neutrons are captured that we push the “path” far from the stable isotopes.

No information on nuclear properties of thousands of nuclei that participate in this process because they are too short-lived to be measured.

Further complicated because we don't know the location(s) where this process occurs.

The location must be able to provide a lot of neutrons!

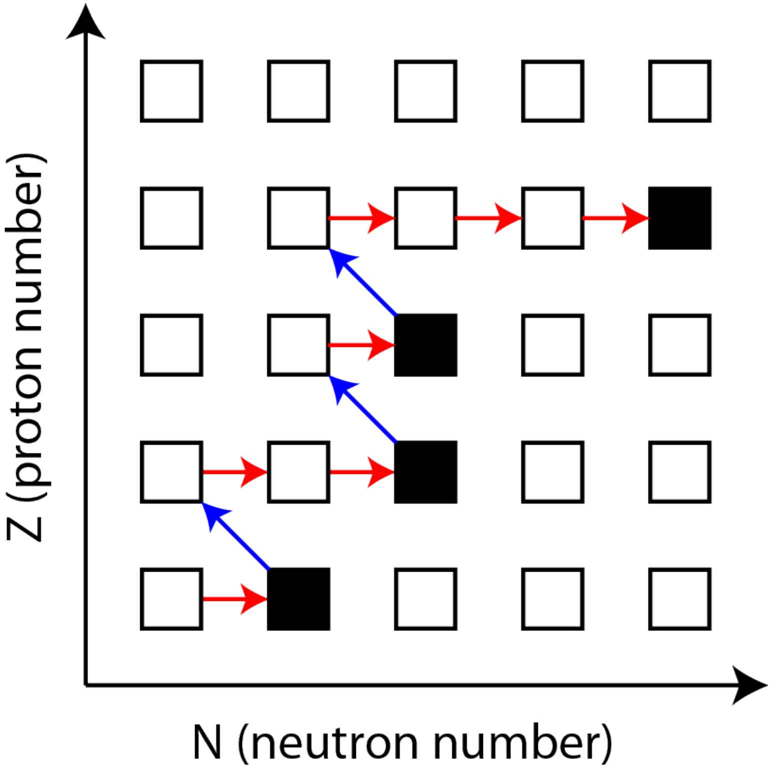
Event lasts ~10 seconds

Neutron Capture / Photo-dissociation

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

Beta Decay

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



One Possible r-Process Candidate Site

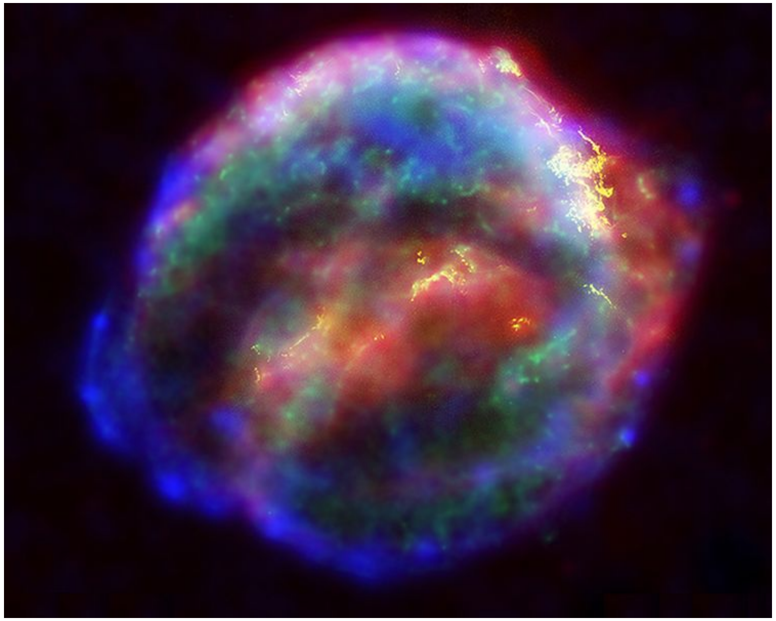
Supernova – End of the life of a massive star

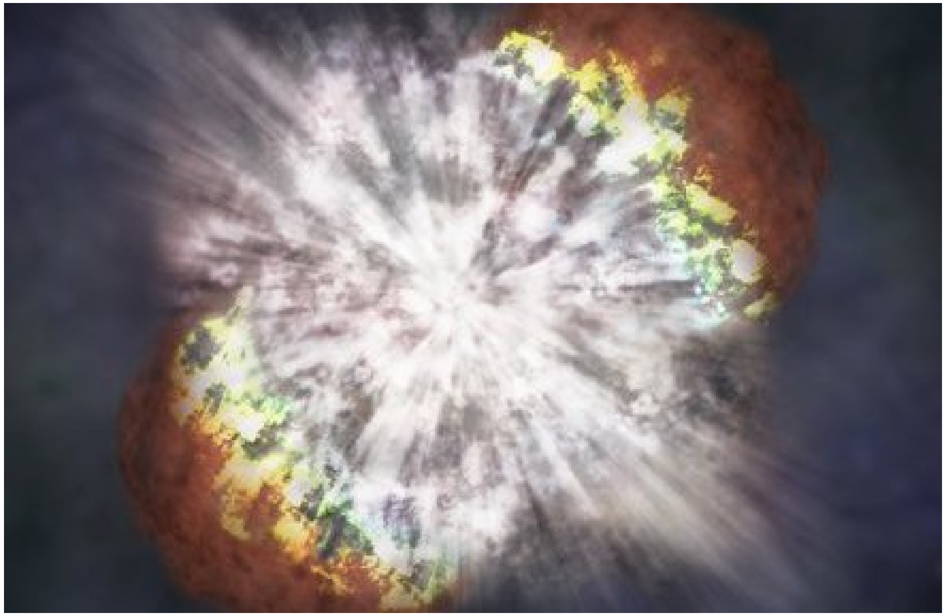
Extremely luminous - burst of radiation that can outshine host galaxy for several weeks expelling most of the star's material

During this short interval a supernova can radiate as much energy as the Sun is expected to emit over its entire life span.

Can it produce neutron-rich material?...

Require exascale computing to properly model...





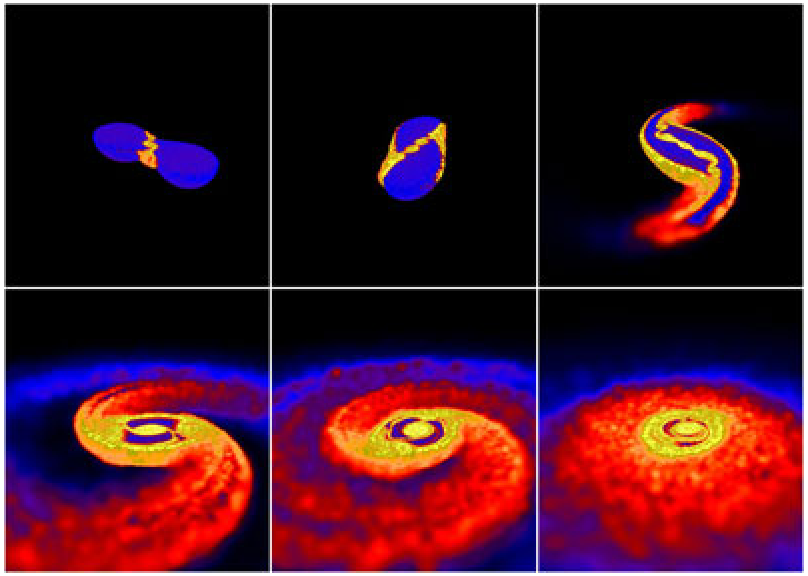
Another Possible r-Process Candidate Site

Neutron Star Mergers – Two neutron stars come together in a violent collision

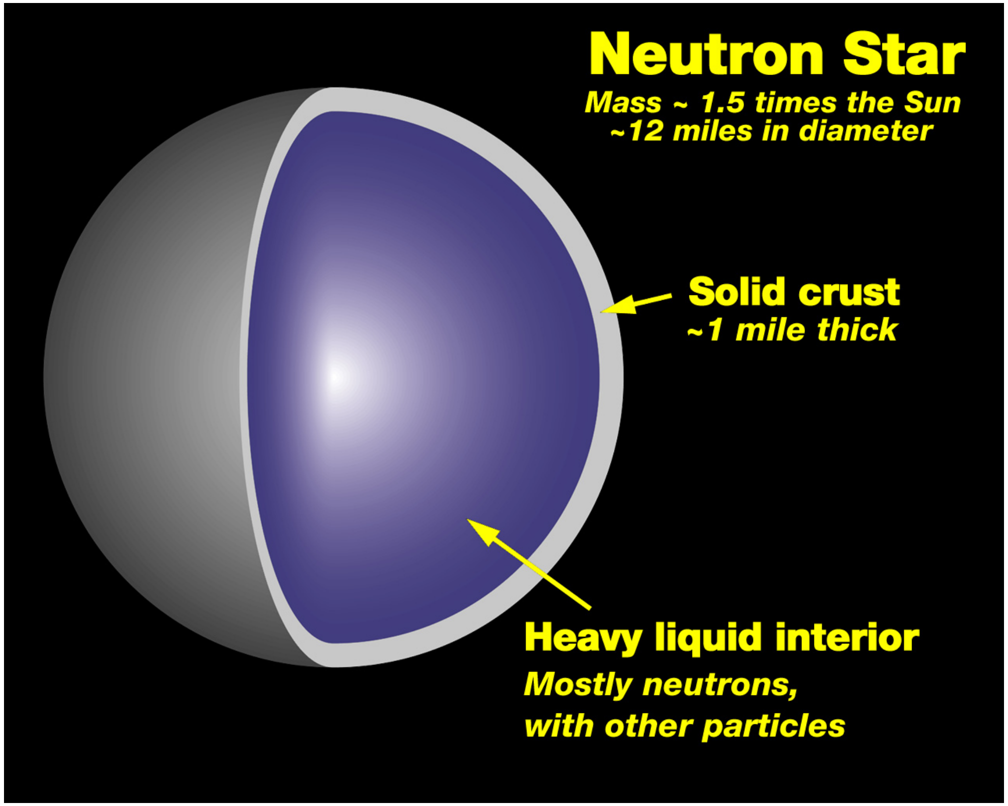
Extremely neutron rich – provides more than enough neutrons to produce the r-process

Must understand fission of heavy nuclei in order to accurately predict r-process abundances in this site

Gravitational waves?...



A simulation of two neutron stars merging and expelling material



Models Require An Immense Amount of Programming

What We Think r-Process Conditions Should Be...

High temperatures (T~1GK or T_9~1) and densities

Lots of free neutrons! Neutron number densities (N_n~$10^{23}cm^{-3}$)

Which yields sufficient neutron-to-seed ratio (R) for third peak (A=195) production

Eject enough material to enrich interstellar medium

Outflow timescale ~ 1ms to seconds

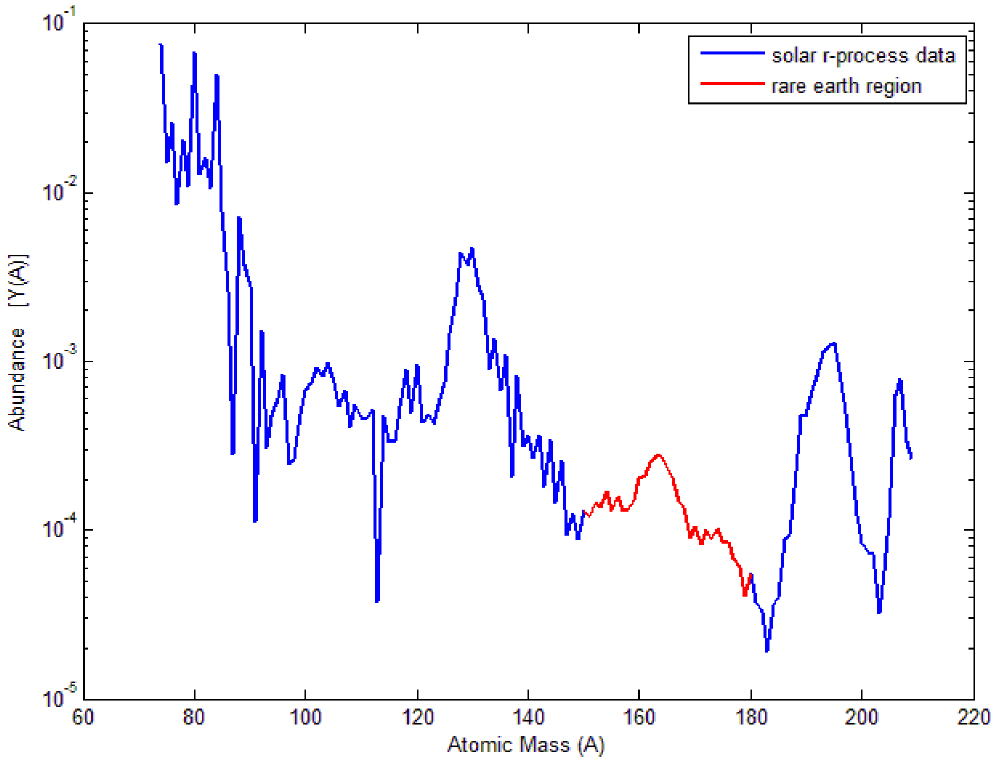
Entropy s ~ 50 to s ~ 400

Electron fraction Ye ~ .20 to Ye ~ .50

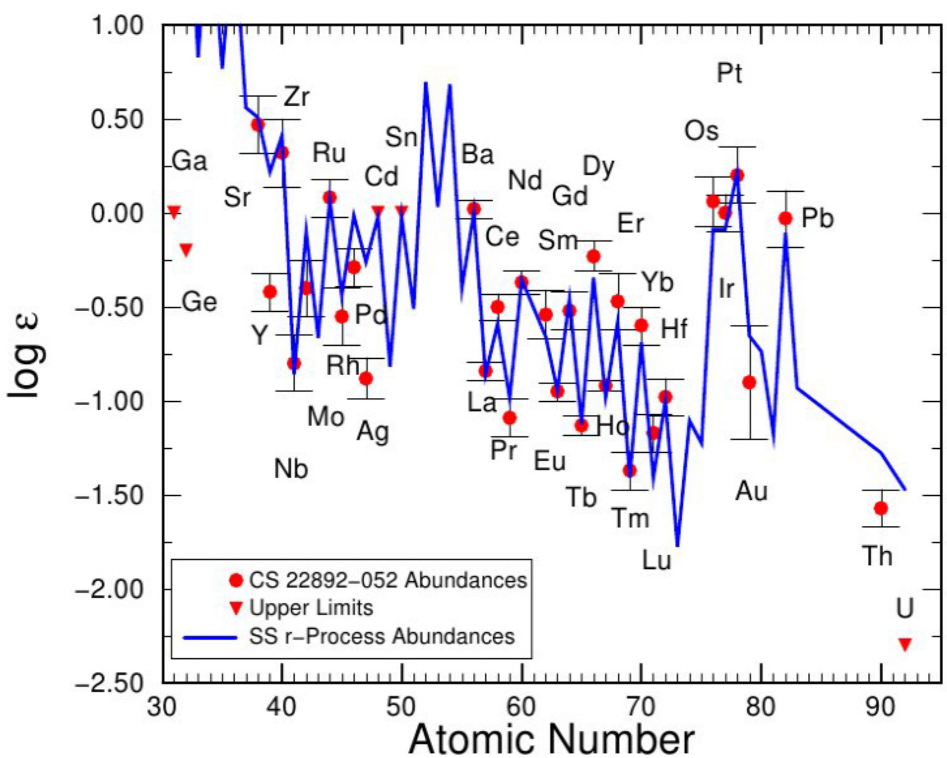
r-Process Data

Solar r-process residuals (meteoritic data)

Halo stars (observational data)



Isotopic abundances



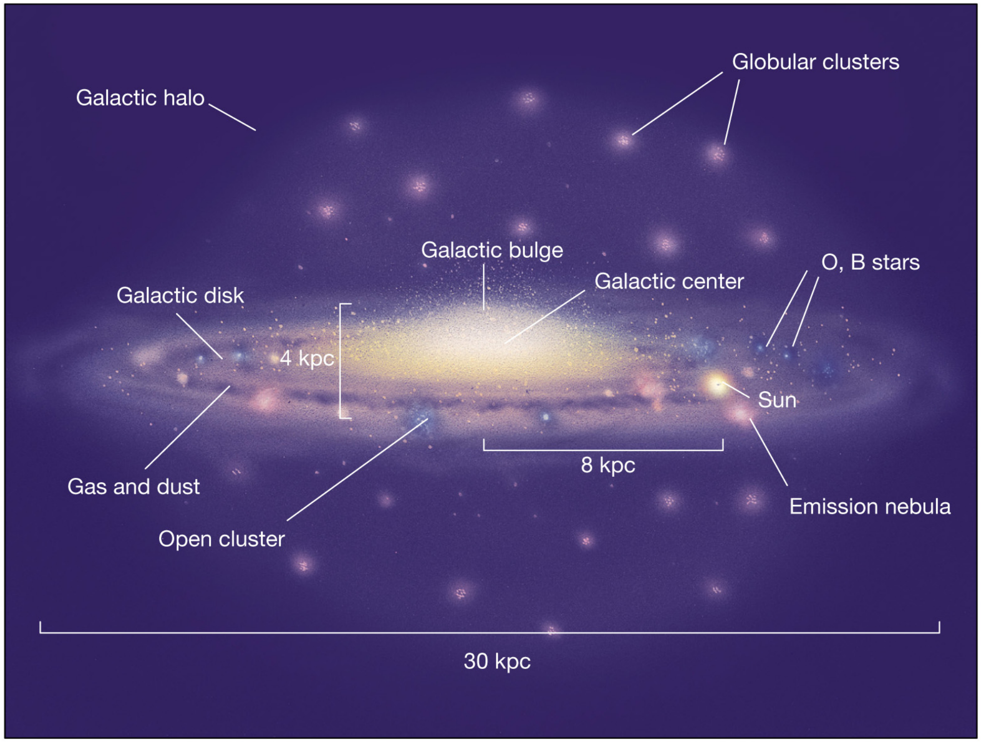
Elemental abundances

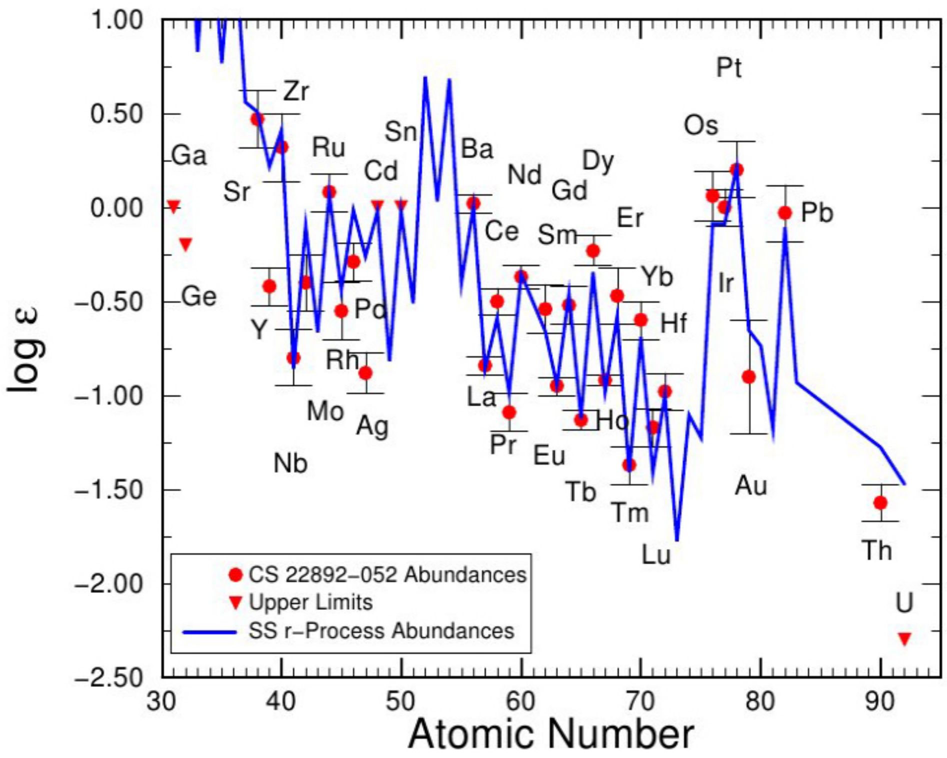
r-Process Data

We look to the galactic halo and analyze the abundances of very old “halo” stars.

We find that the composition of these stars is similar to the Solar System.

This means that whatever processes are at work creating the heavy elements are fairly universal.



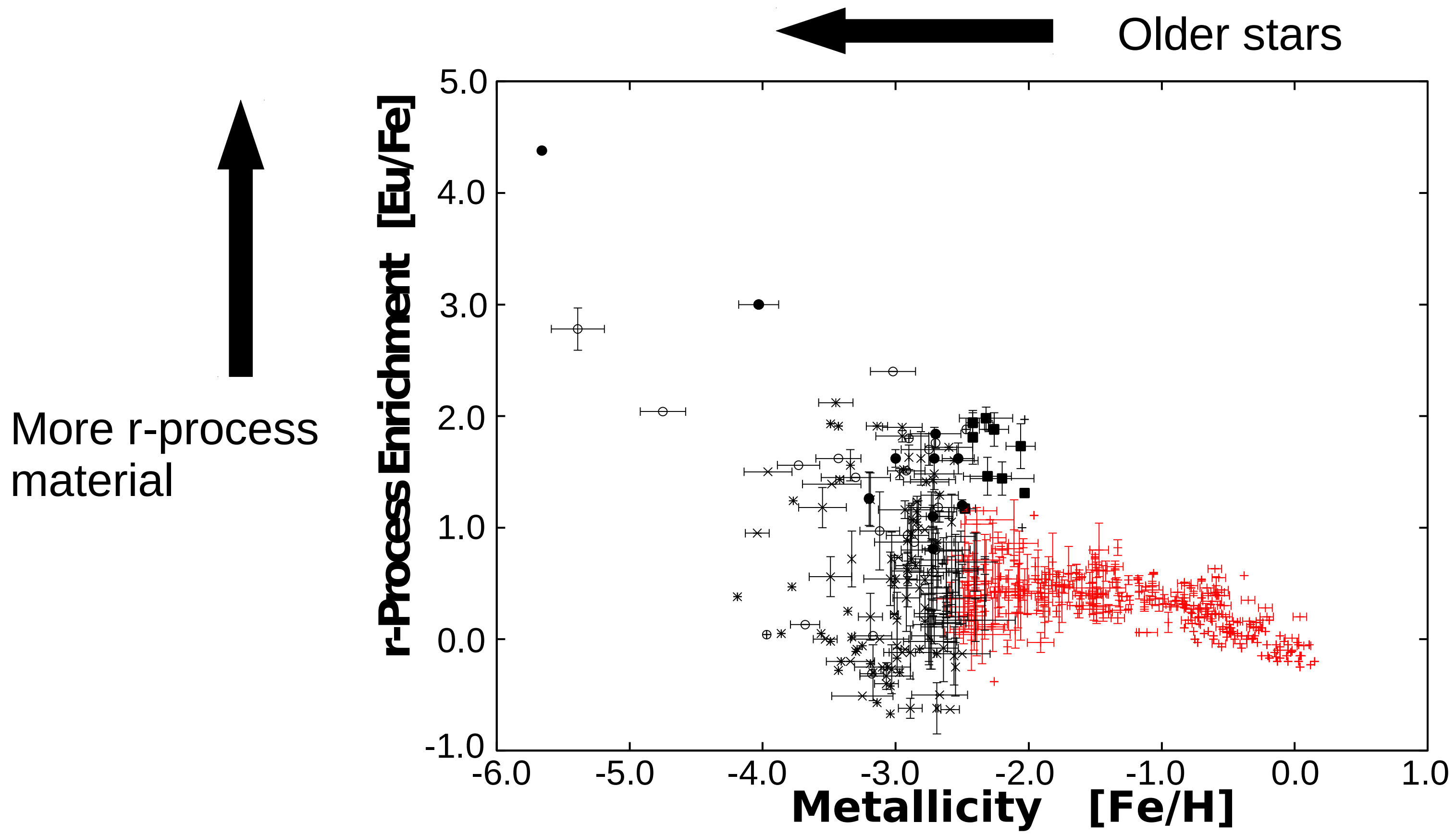


Maybe It's Both?

Could supernova and neutron star mergers both be responsible for the r-process?

Look at Europium (a known r-process element) in stars.

There seems to be two components.



Data from the Stellar Abundances for Galactic Archeology (SAGA) database

I Focus On...

Nuclear Data Needs for r-process calculations

- Neutron capture rates (n,γ) and inverse photo-dissociation (γ,n)

  Ground state properties, E1 strength, level densities, optical potential, reaction model: statistical vs direct capture

- β-decay rates and β-delayed neutron emission

  GT / Forbidden transitions, deformation, odd-nuclei, statistical γ-competition after neutron emission

- Fission (nif, sf, βdf) rates

- Fission fragment distributions

  Fission paths, calculation of saddle points, barrier heights

- Neutrino interactions (CC & NC) and ν-nucleus

  Opacities, oscillations, collective effects, in medium effects

A Simple r-Process Calculation

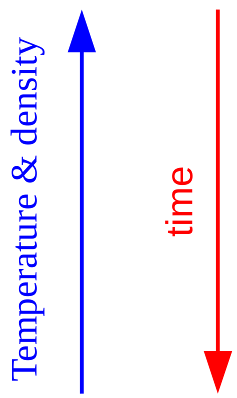
nuclear physics inputs

(Sn, β-rates, n-cap rates, …)

Environment conditions

(temperature, density, ...)

Stages of the r-Process



Nuclear Statistical Equilibrium (NSE)

Alpha recombination

$(n,\gamma) \leftrightarrow (\gamma,n)$ equilibrium & Quasi-equilibrium (QSE)

Freeze-out

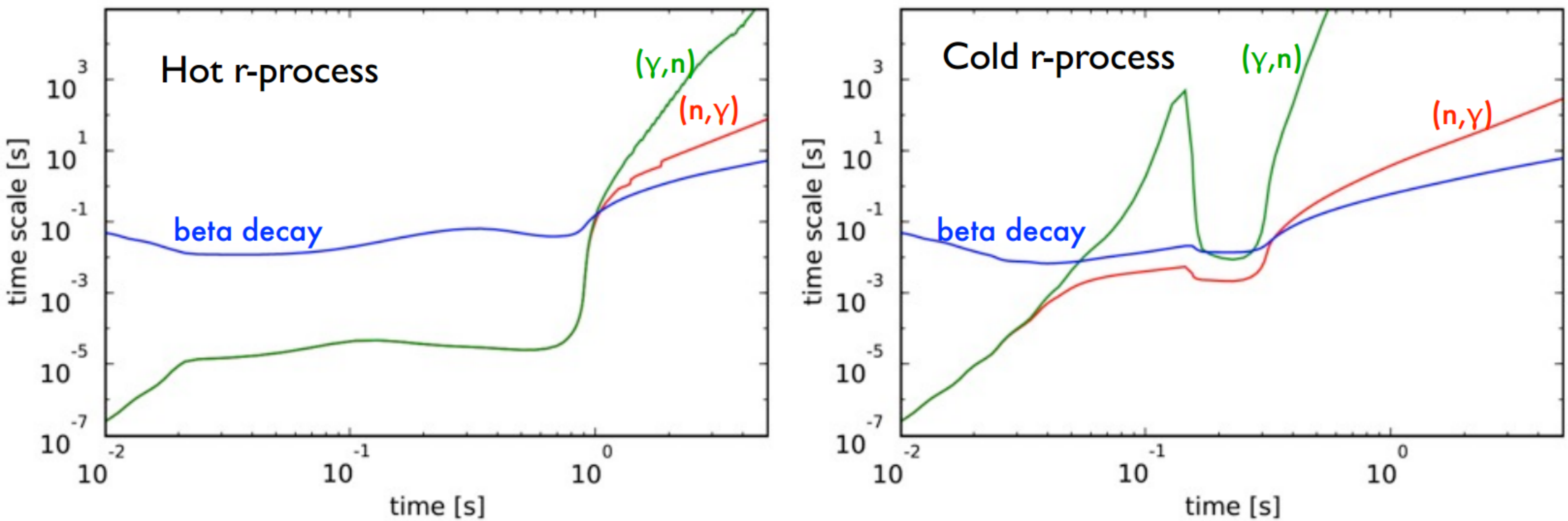
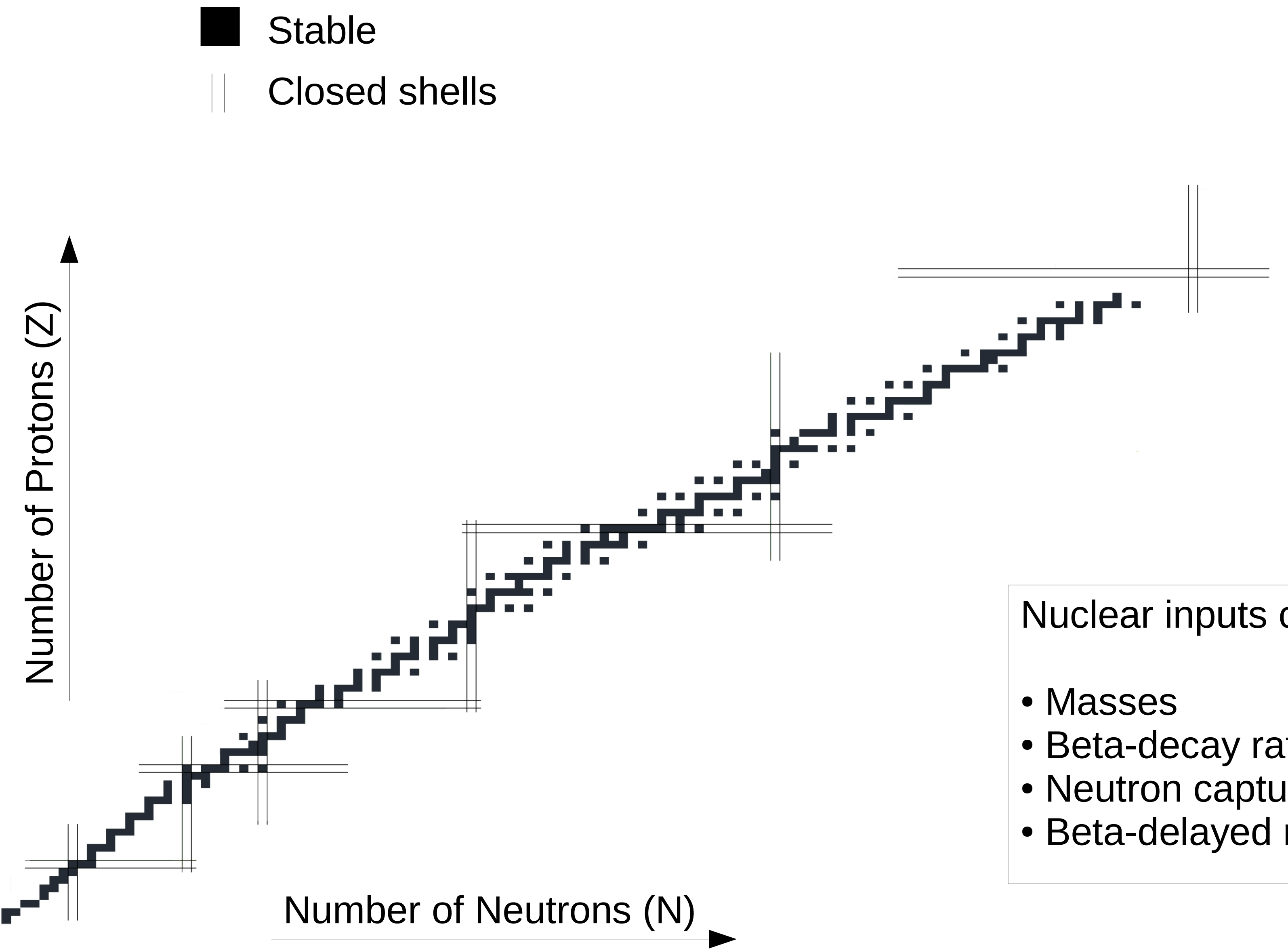


Figure from A. Arcones (2011)

Nuclear Data

The Nuclear Chart

Legend

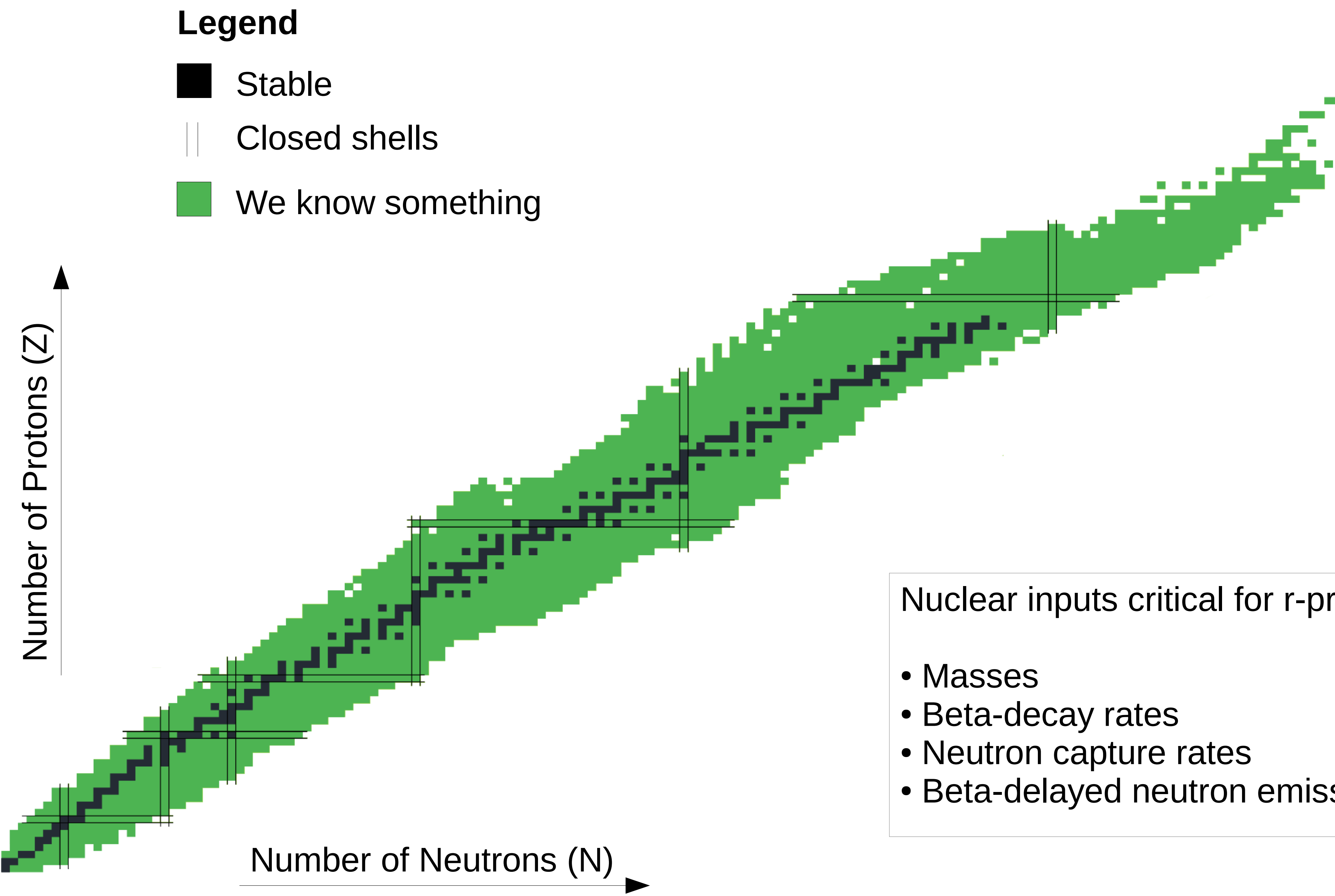


Nuclear inputs critical for r-process

- Masses
- Beta-decay rates
- Neutron capture rates
- Beta-delayed neutron emission

Nuclear Data

What Do We Know?

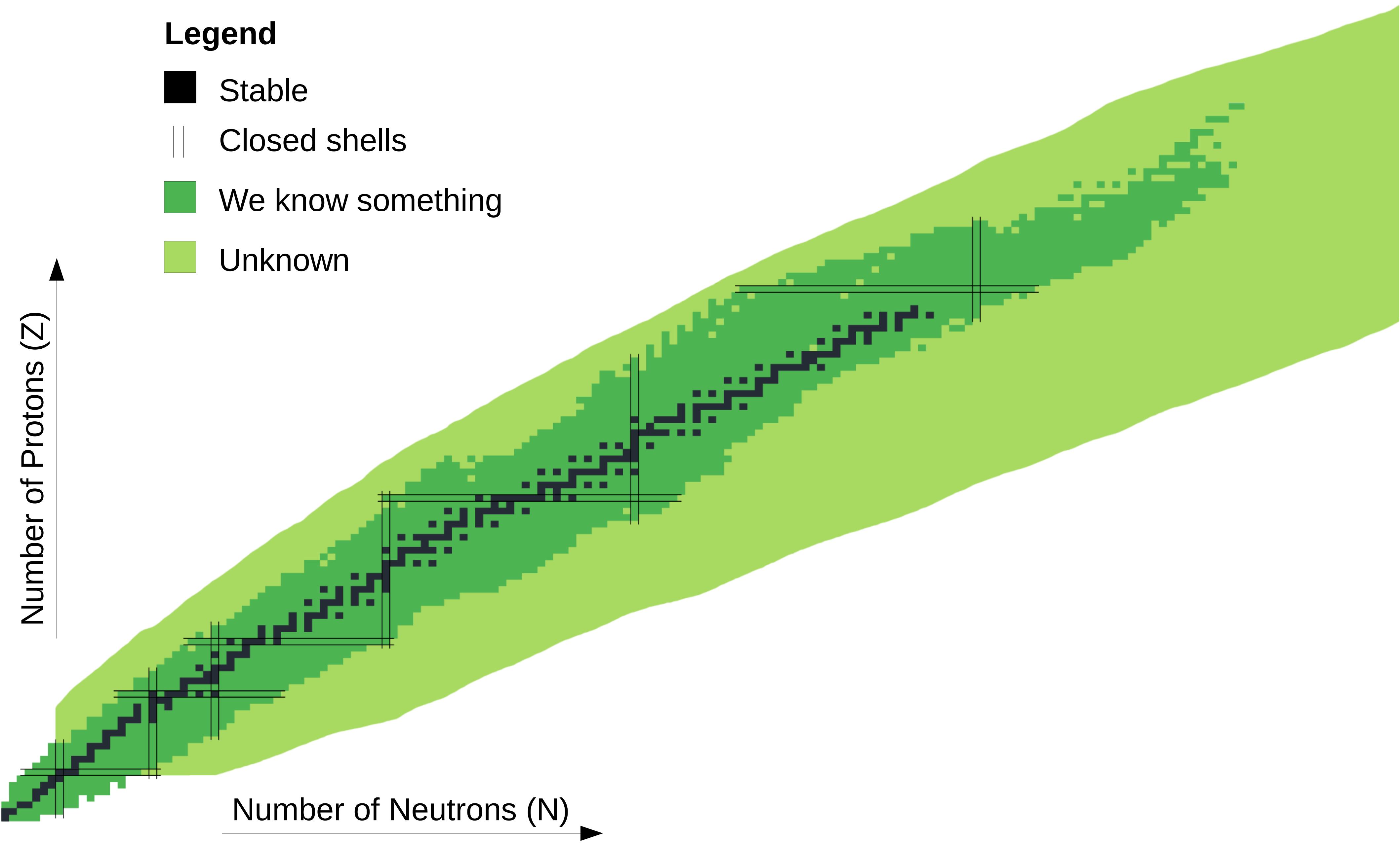


Nuclear inputs critical for r-process

- Masses
- Beta-decay rates
- Neutron capture rates
- Beta-delayed neutron emission

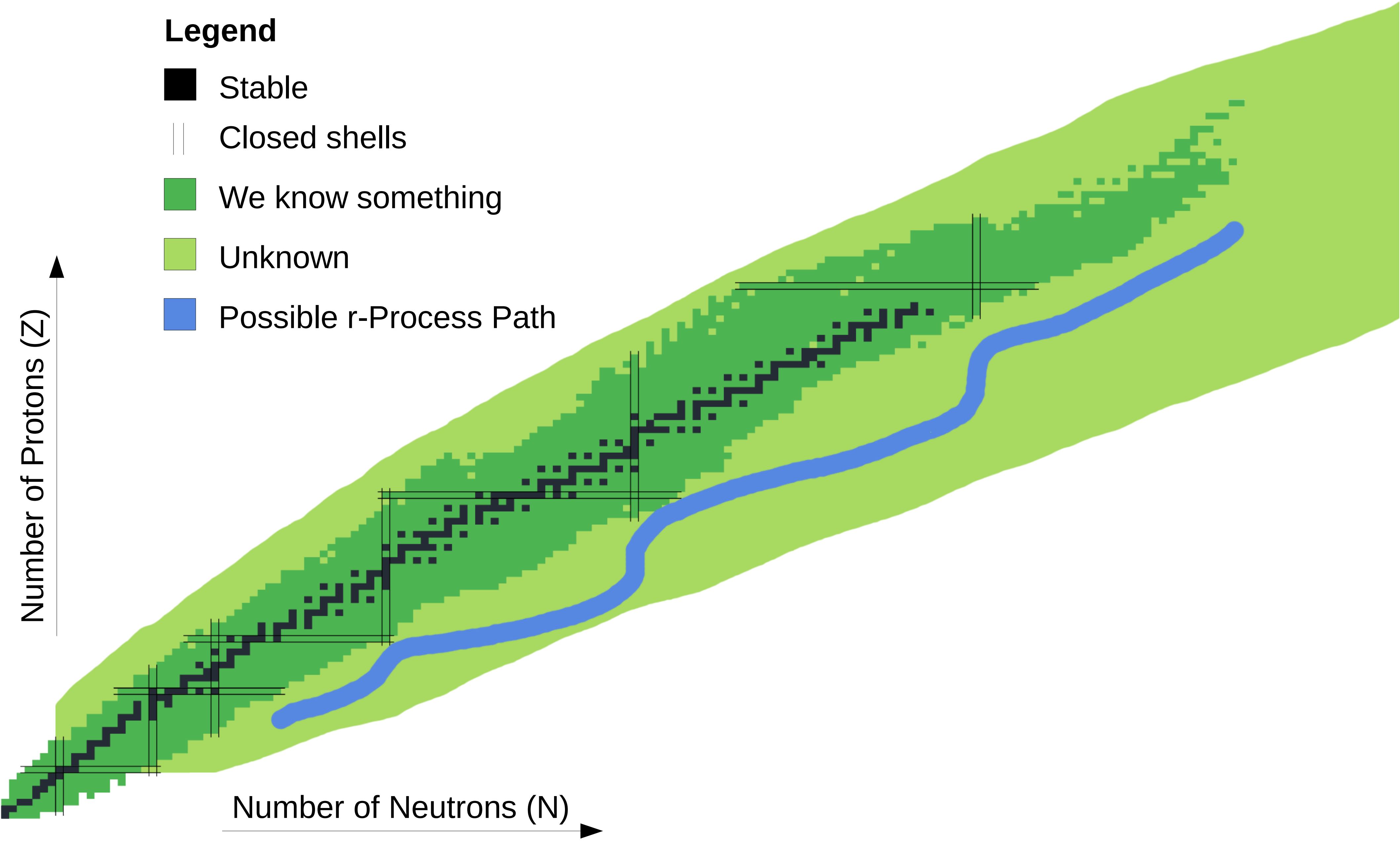
Nuclear Data

What We Don't Know



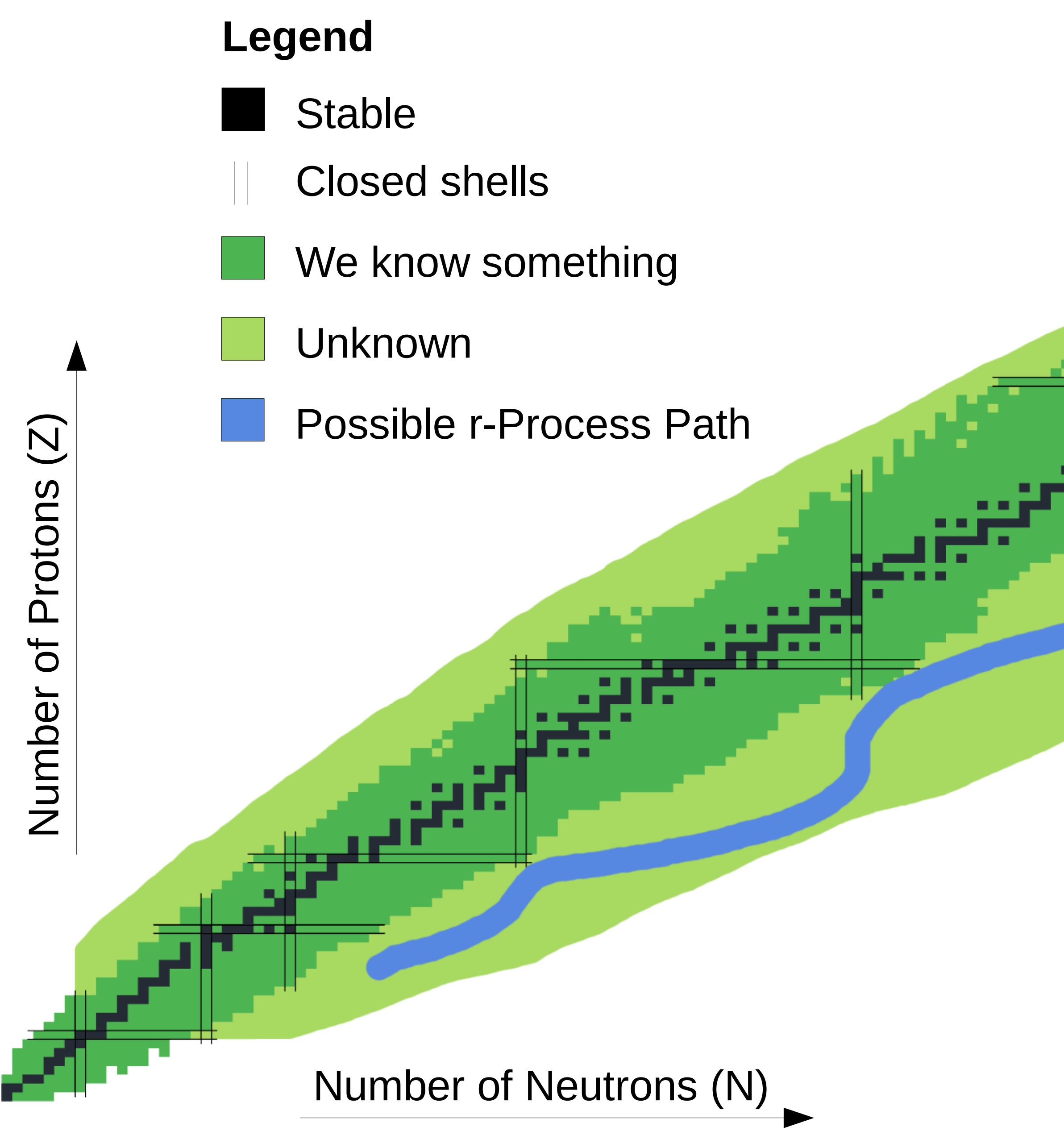
Nuclear Data

Possible r-Process Path



Nuclear Data

Possible r-Process Path



A few more points...

- We only have masses or ½-lives for dark green region

<u>We lack information about</u>

- Neutron capture
- Beta-delayed neutron emission
- Fission

<u>Open Questions</u>

- Shell evolution
- Deformation
- Location of neutron dripline

Connection with FAIR Physics

It is difficult to produce the nuclei that can participate in the r-process because these nuclei are short-lived.

However Recent Progress Has Been Made

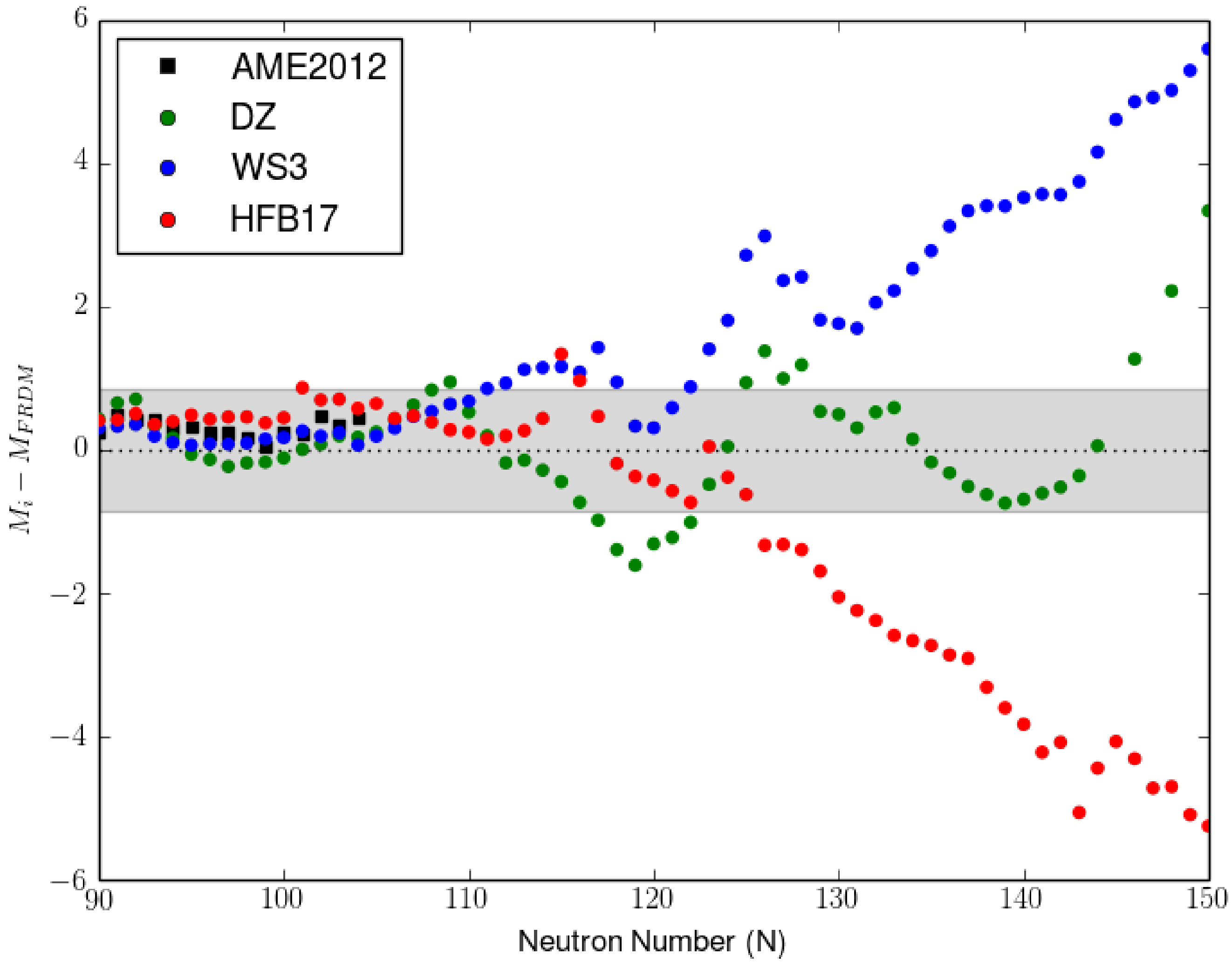
1. Radioactive ion-beams allow us to reach these short-lived nuclei using inverse kinematics.

2. Penning traps allow for precise measurements of masses & decay studies (Recall the talks from Thursday).

3. Beta-Paul traps allow for measurements of delayed neutron emitters (current prototype @ ANL).

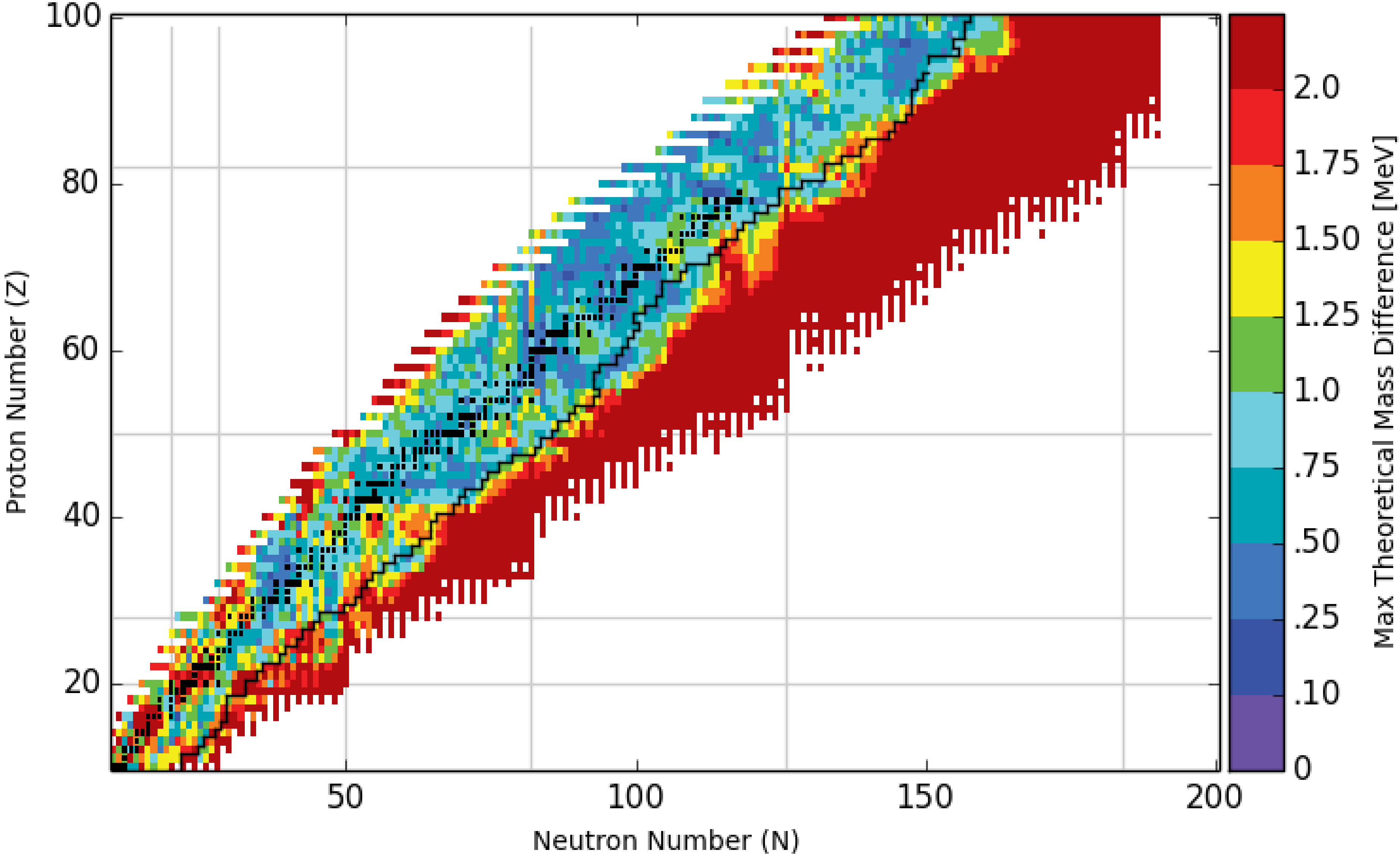
MATS (Precision **M**easurements of very short-lived nuclei using an **A**dvanced **T**rapping **S**ystem for highly-charged ions)

Which Nuclear Model Should We Use?

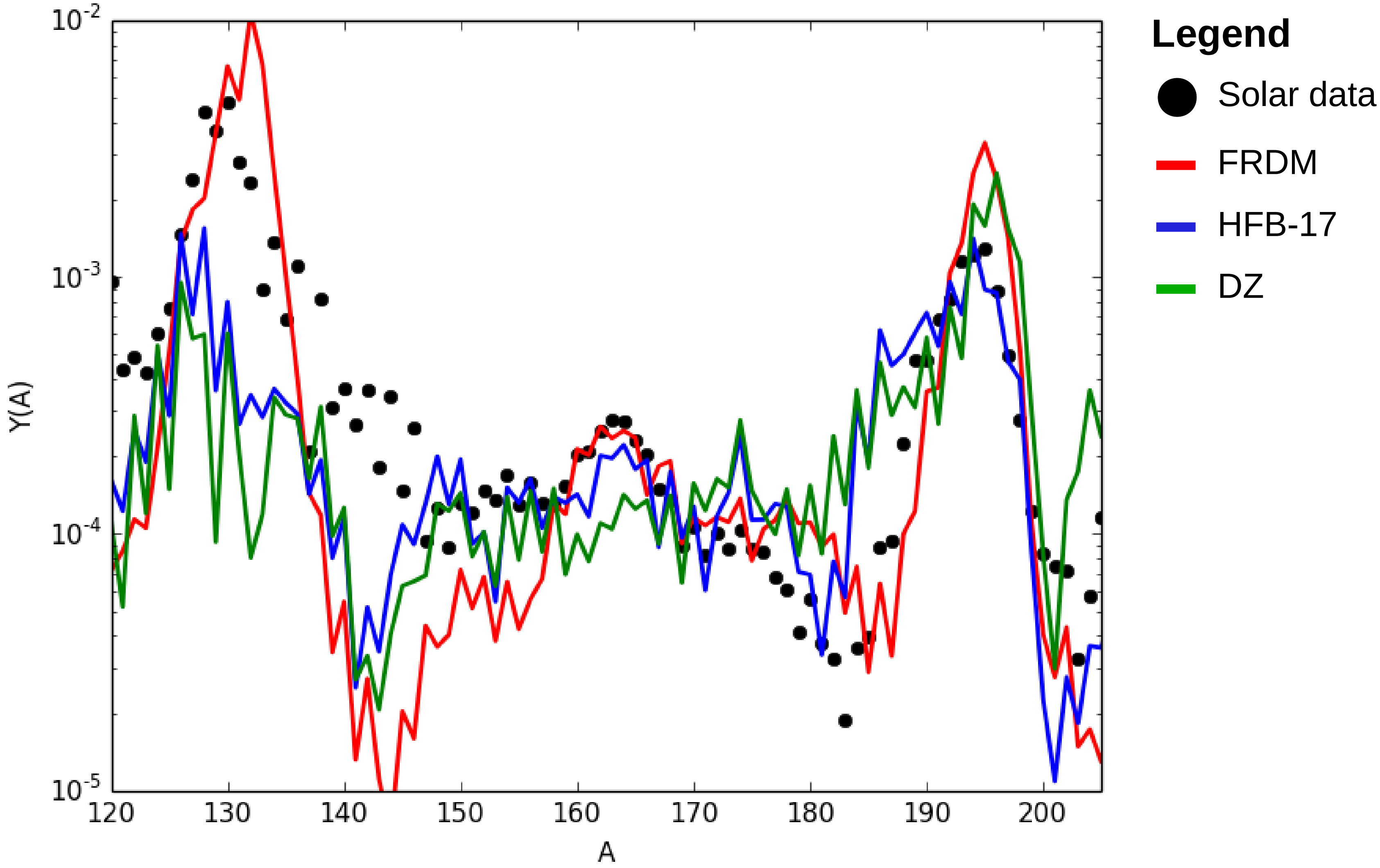


Differences in Mass Model Predictions

Across The Chart of Nuclides



Which Nuclear Model Should We Use?



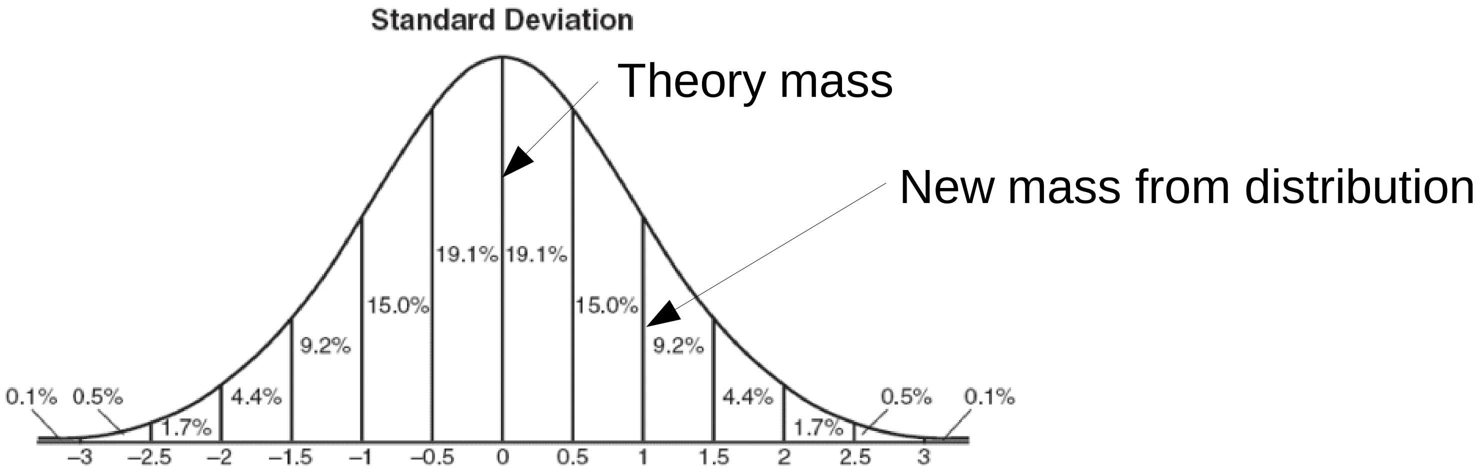
Simulations run with same astrophysical conditions

Global Mass Model Uncertainties

• Fix astrophysical environment.

• Perform Monte Carlo: vary every mass that enters into the network where we don't have measurements (most of the nuclei).

• Masses are Gaussian distributed with variance equal to the RMS value of the theoretical model.

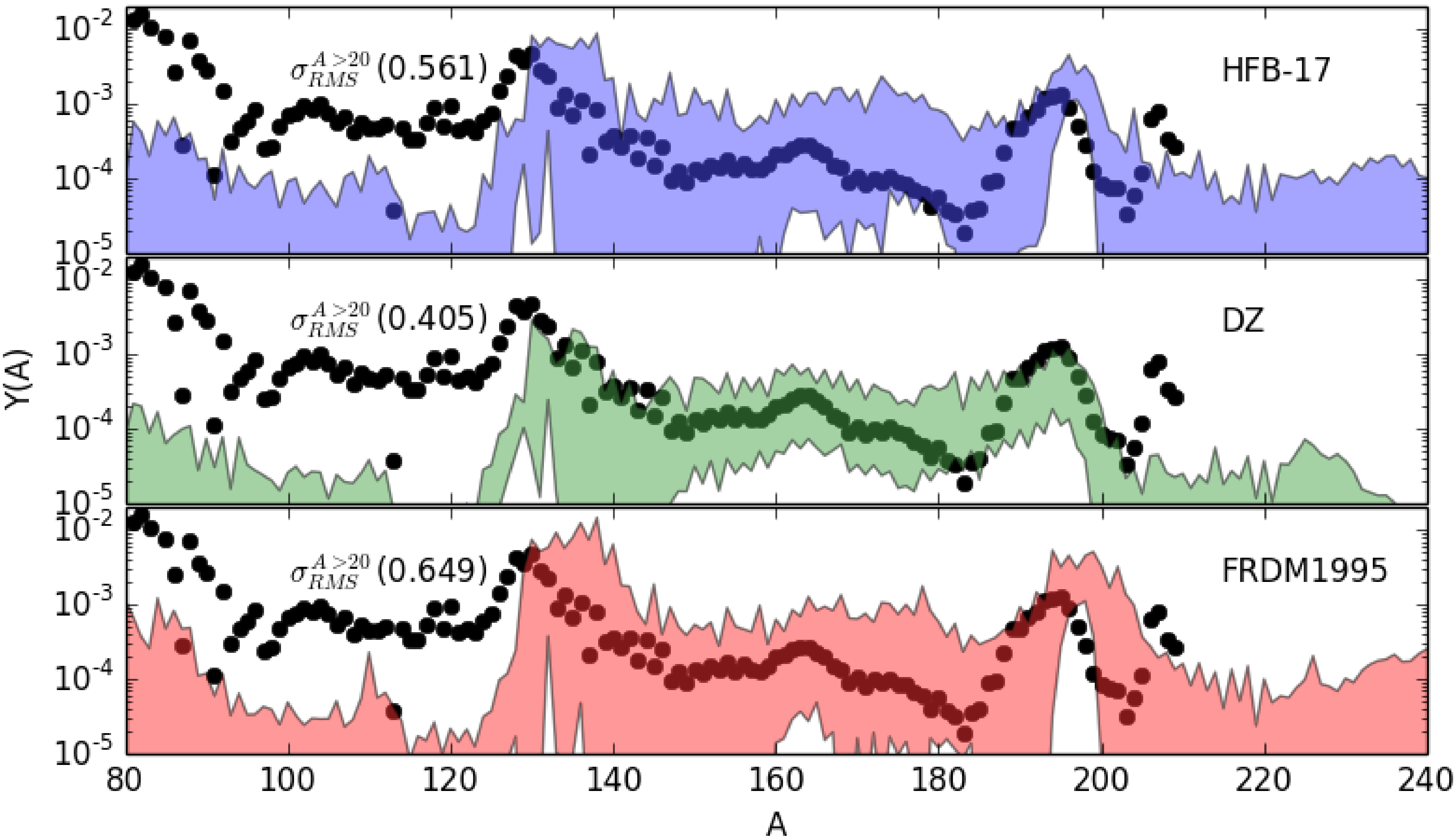


• Repeat procedure many times, each time producing an abundance pattern.

• Compute the variance of this distribution of abundance patterns and compare to solar data.

Mumpower et al. (in prep)

Global Mass Model Uncertainties



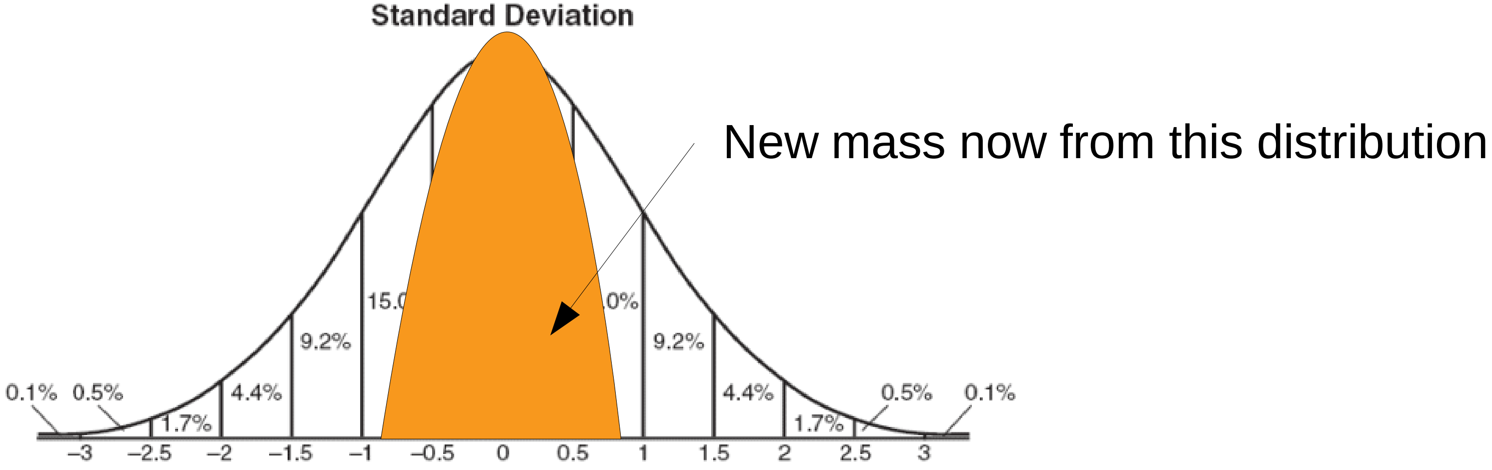
Mumpower et al. (in prep)

FAIR: Reduce Uncertainties In Nuclear Models

• Fix astrophysical environment.

• Perform Monte Carlo: vary every mass that enters into the network where we don't have measurements (most of the nuclei).

• Masses are Gaussian distributed with variance equal to the RMS value of the theoretical model.

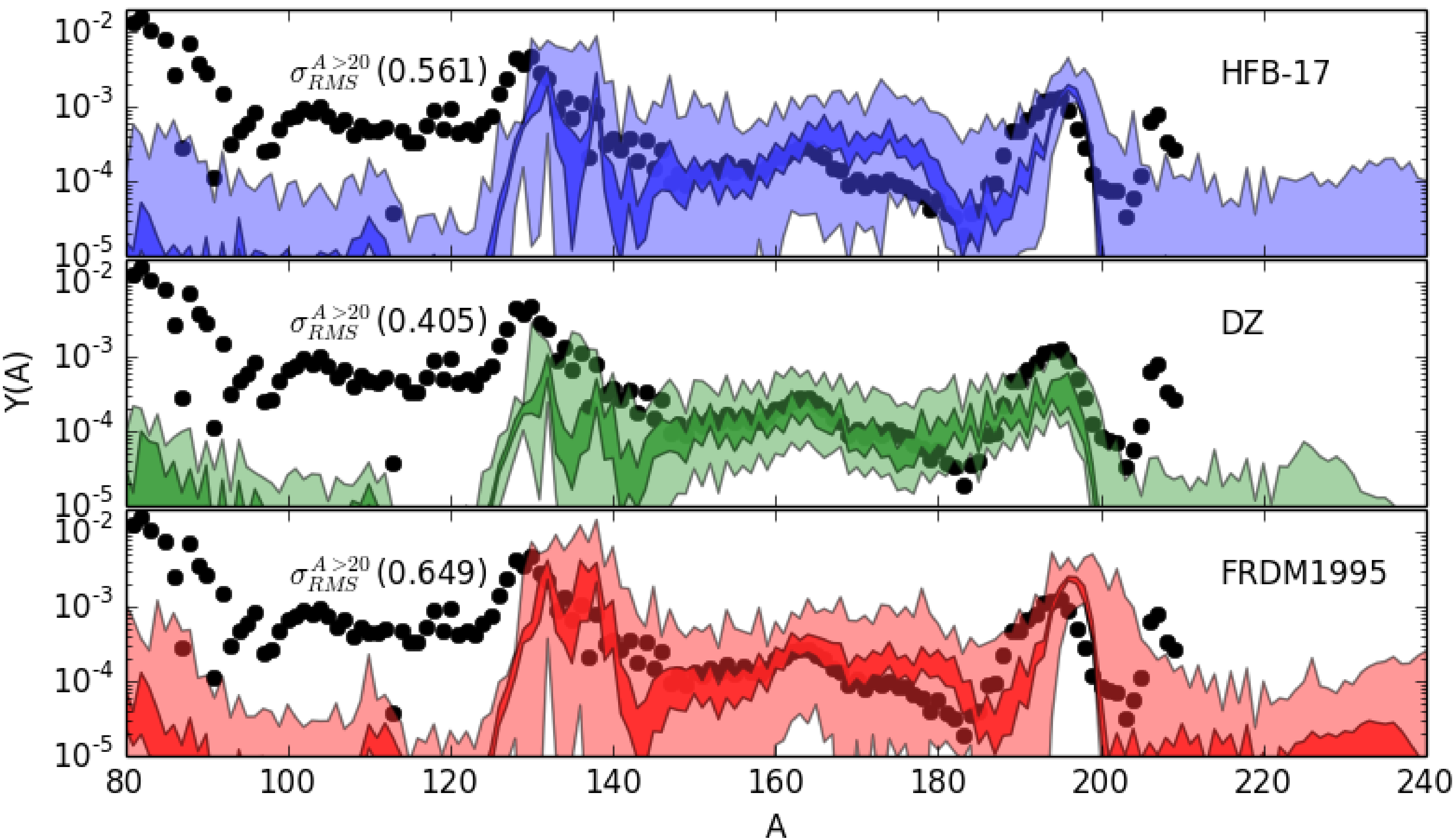


• Repeat procedure many times, each time producing an abundance pattern.

• Compute the variance of this distribution of abundance patterns and compare to solar data.

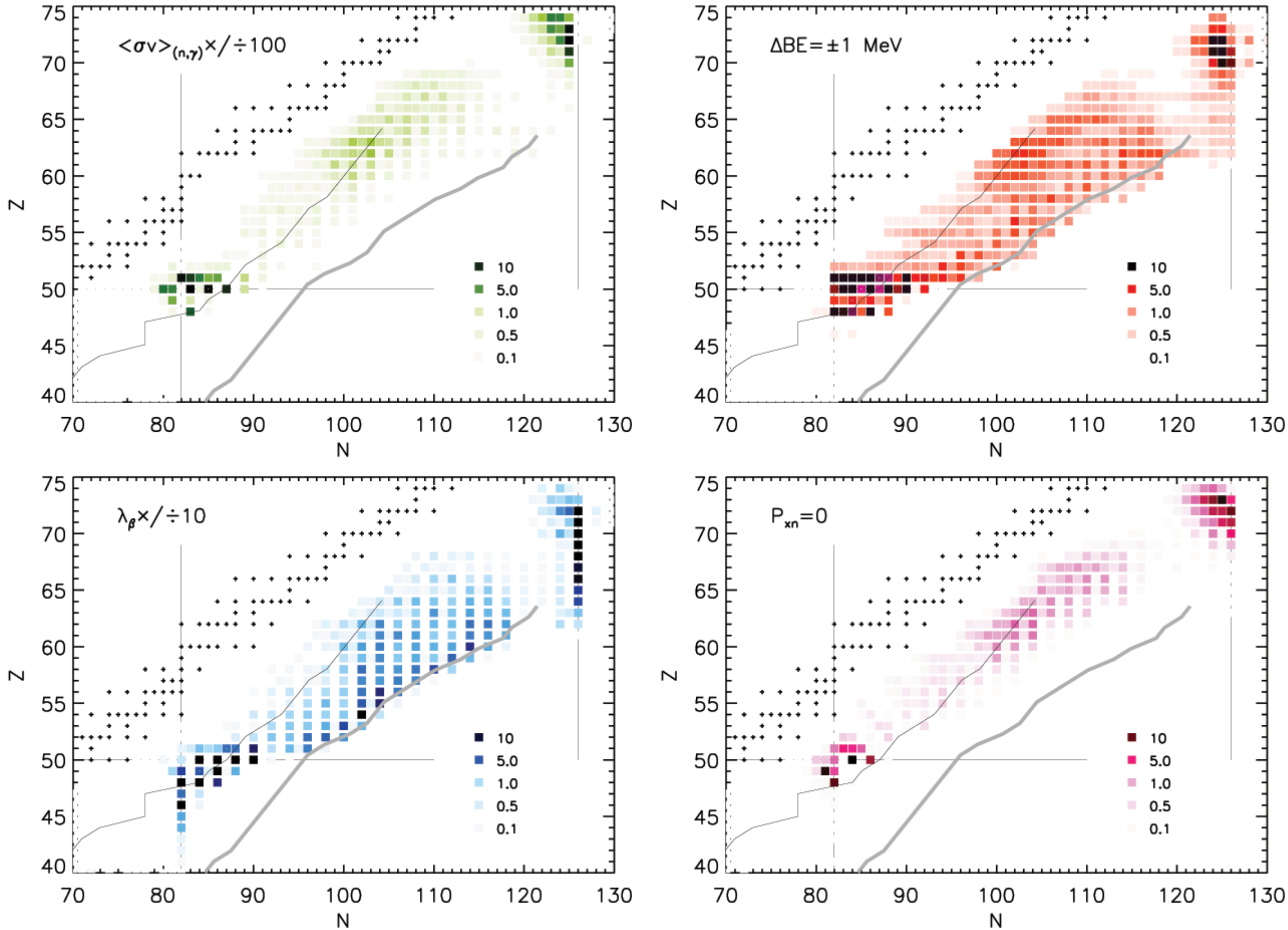
Mumpower et al. (in prep)

FAIR: Reduce Uncertainties In Nuclear Models



Mumpower et al. (in prep)

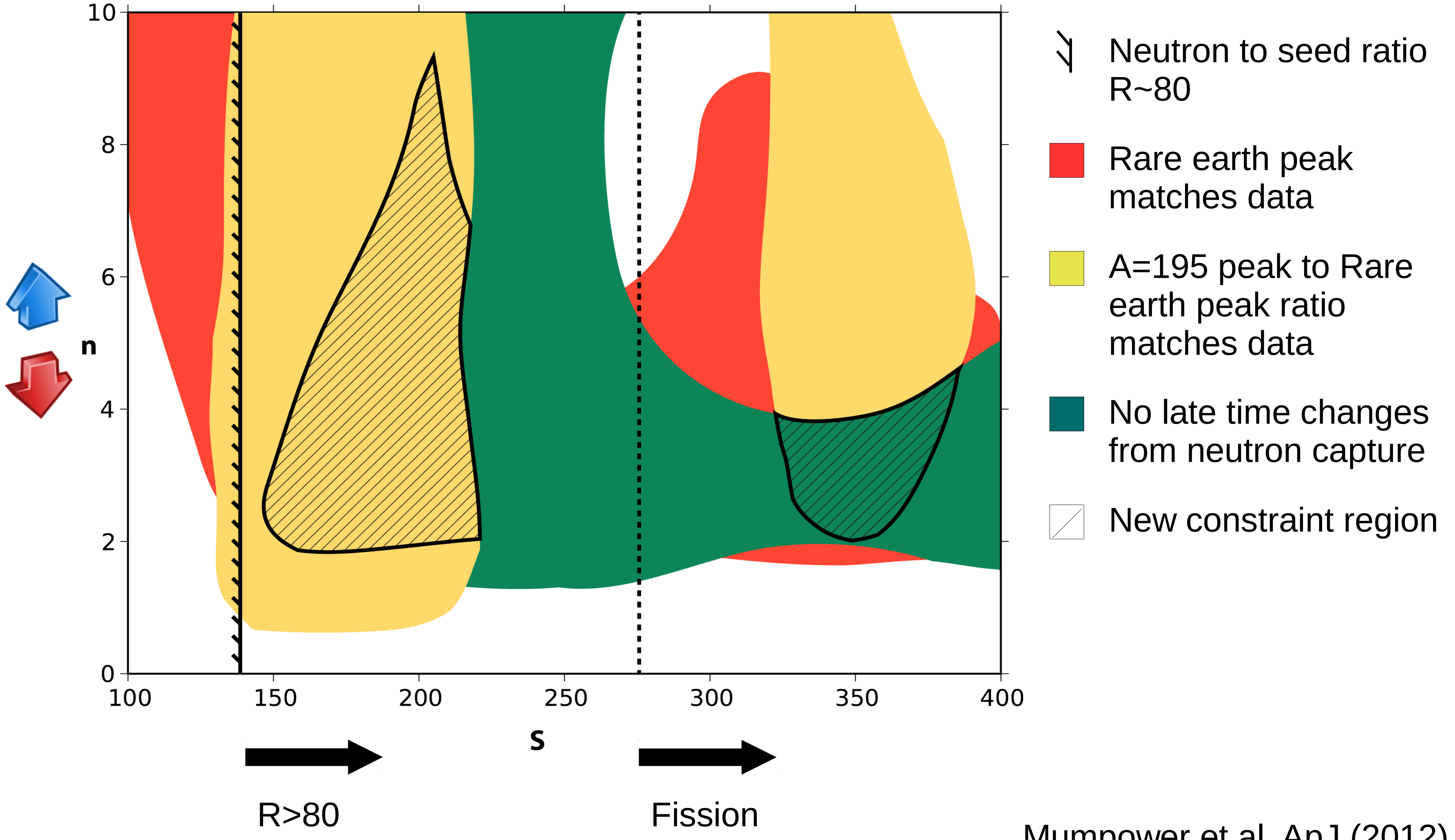
Laundry List Of Important Nuclei To Measure



Accessibility Limits — CARIBU — Predicted FRIB

Why Are New Measurements Important?

Can be used to constrain r-process site e.g. rare earth peak



Mumpower et al. ApJ (2012)

Summary & Outlook

- There are still many open problems in the field of r-process nucleosynthesis.
- New measurements @ FAIR and other facilities will help us to understand how trends (e.g. masses, half-lives, deformation) evolve with neutron excess.
- This in turn will help us to improve our nuclear models.
- Ultimately we can then use this knowledge to strengthen our understanding of the astrophysical conditions necessary for heavy element production.

Thanks For Listening!