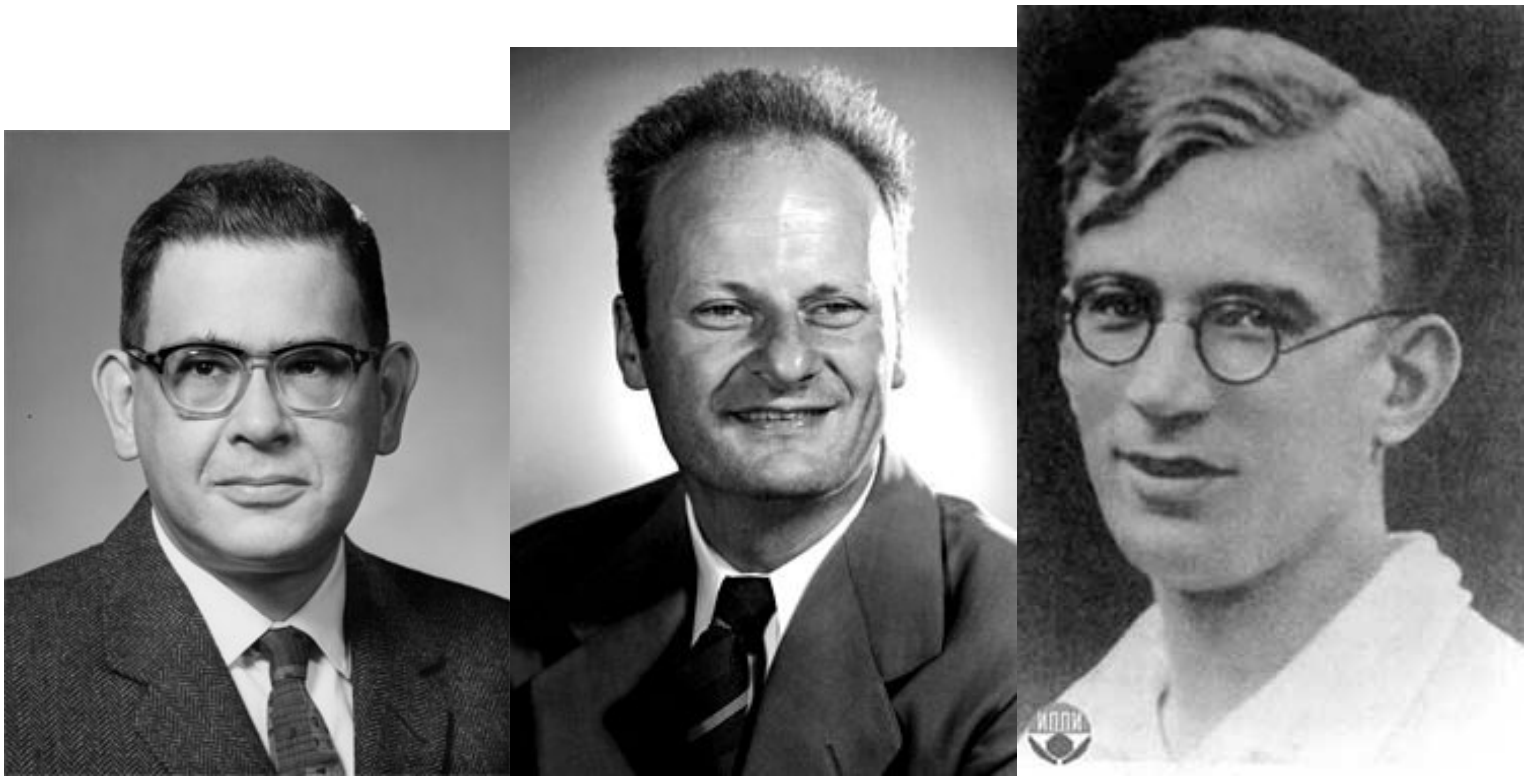
Where did you come from?

Jeremy Heyl

23 October 2018

Big-Bang Nucleosynthesis



Big-Bang Nucleosynthesis

- Alpher, Bethe and Gamov (1948) argued that all of the elements were produced in the early Universe,
- The nuclei built up through neutron capture in the "overheated neutral nuclear fluid."
- The neutrons started to stick to each other about 20 seconds after the start of time.

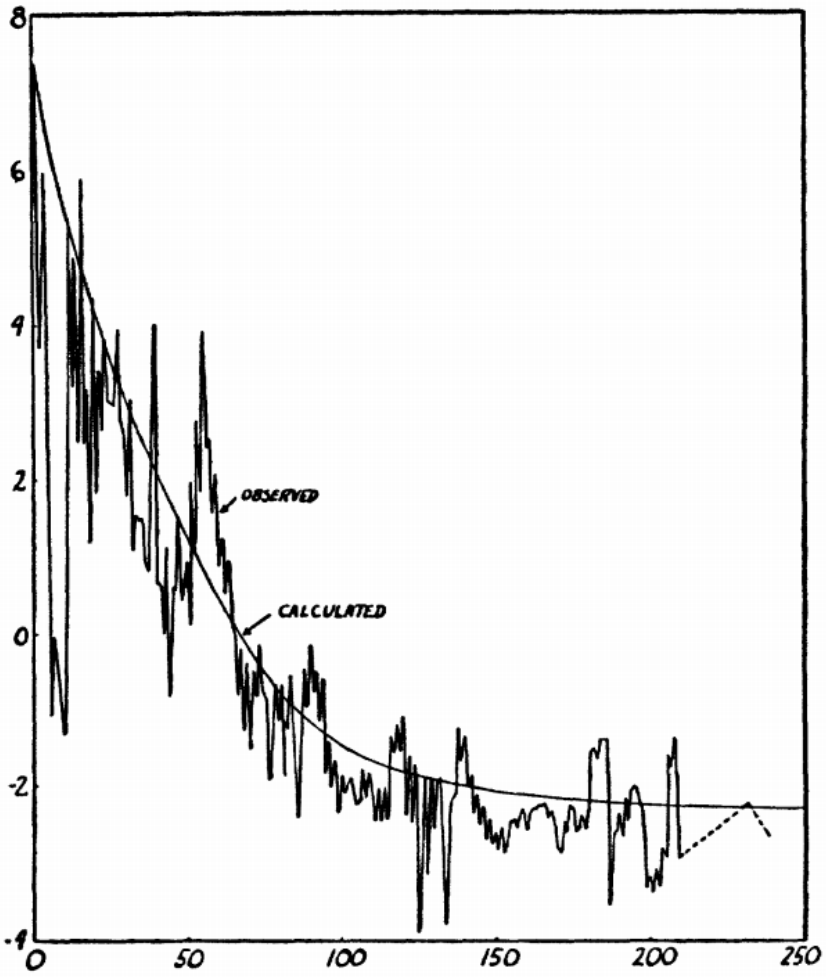


FIG. 1.

Log of relative abundance

Atomic weight

Big-Bang Nucleosynthesis

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- At 10 seconds, past the Big Bang, there are six protons for every neutron.

Big-Bang Nucleosynthesis

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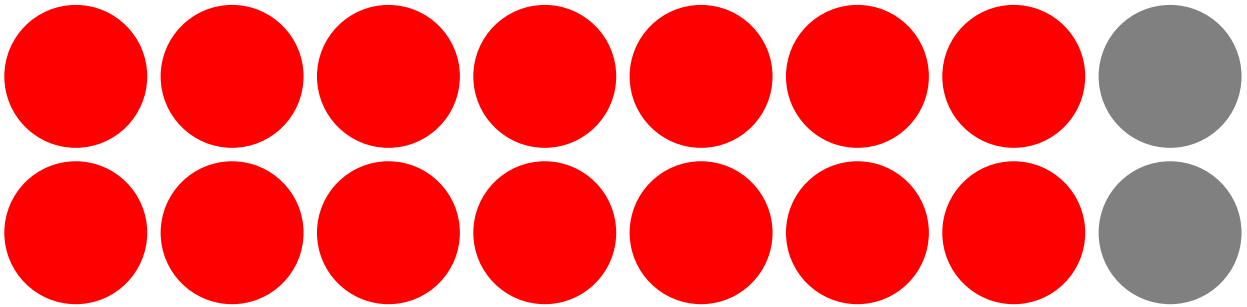
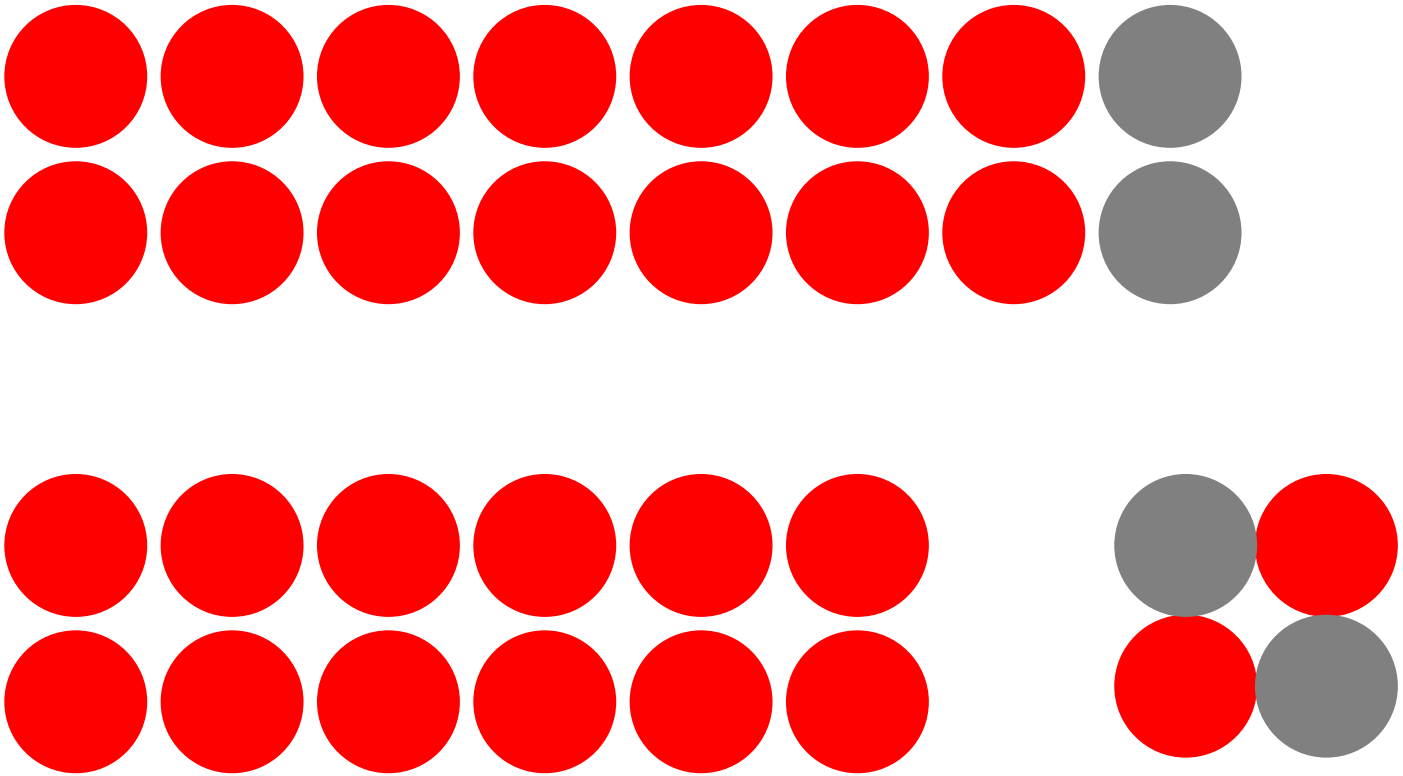
- From 10 seconds to 20 minutes after the Big Bang, it is hot enough nuclear reactions but not too hot so things remain stuck together.
- At 10 seconds, past the Big Bang, there are six protons for every neutron.
- But over the next 20 minutes, some neutrons decay, so on average there are seven protons for every neutron.

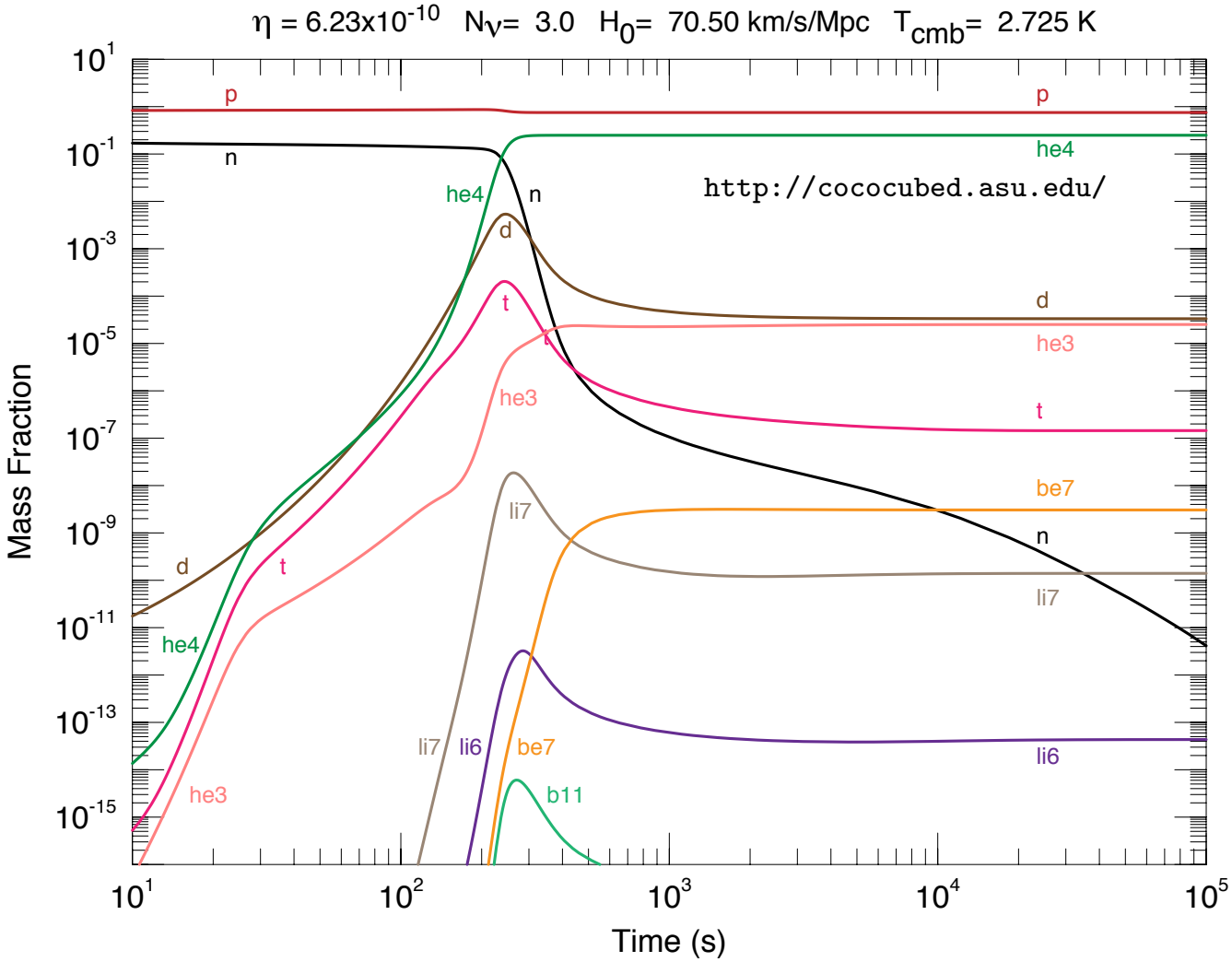
Big-Bang Nucleosynthesis



Big-Bang Nucleosynthesis

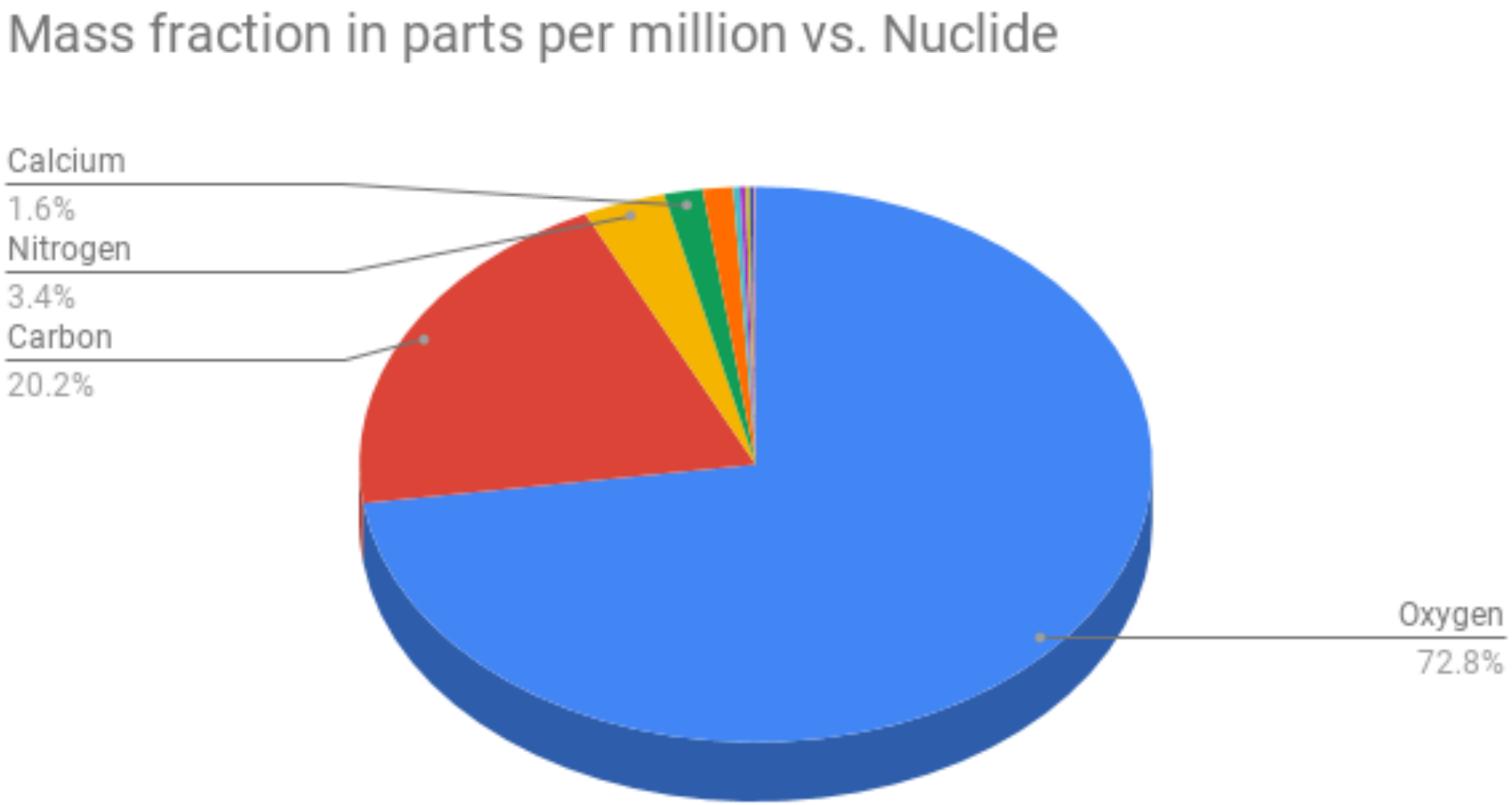


Big-Bang Nucleosynthesis



Alpher, Bethe and Gamov were wrong!

The Abundance of the Elements



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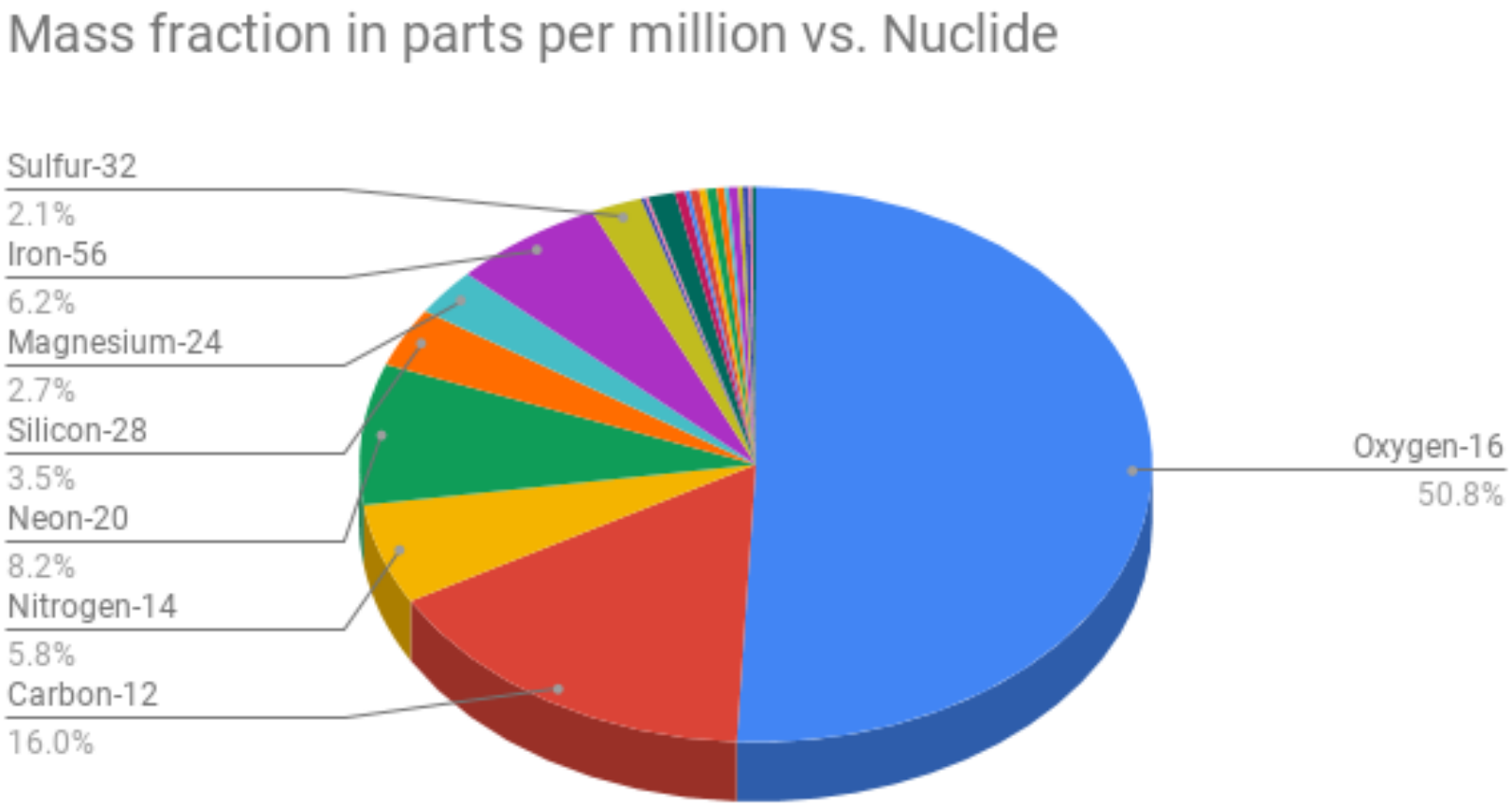

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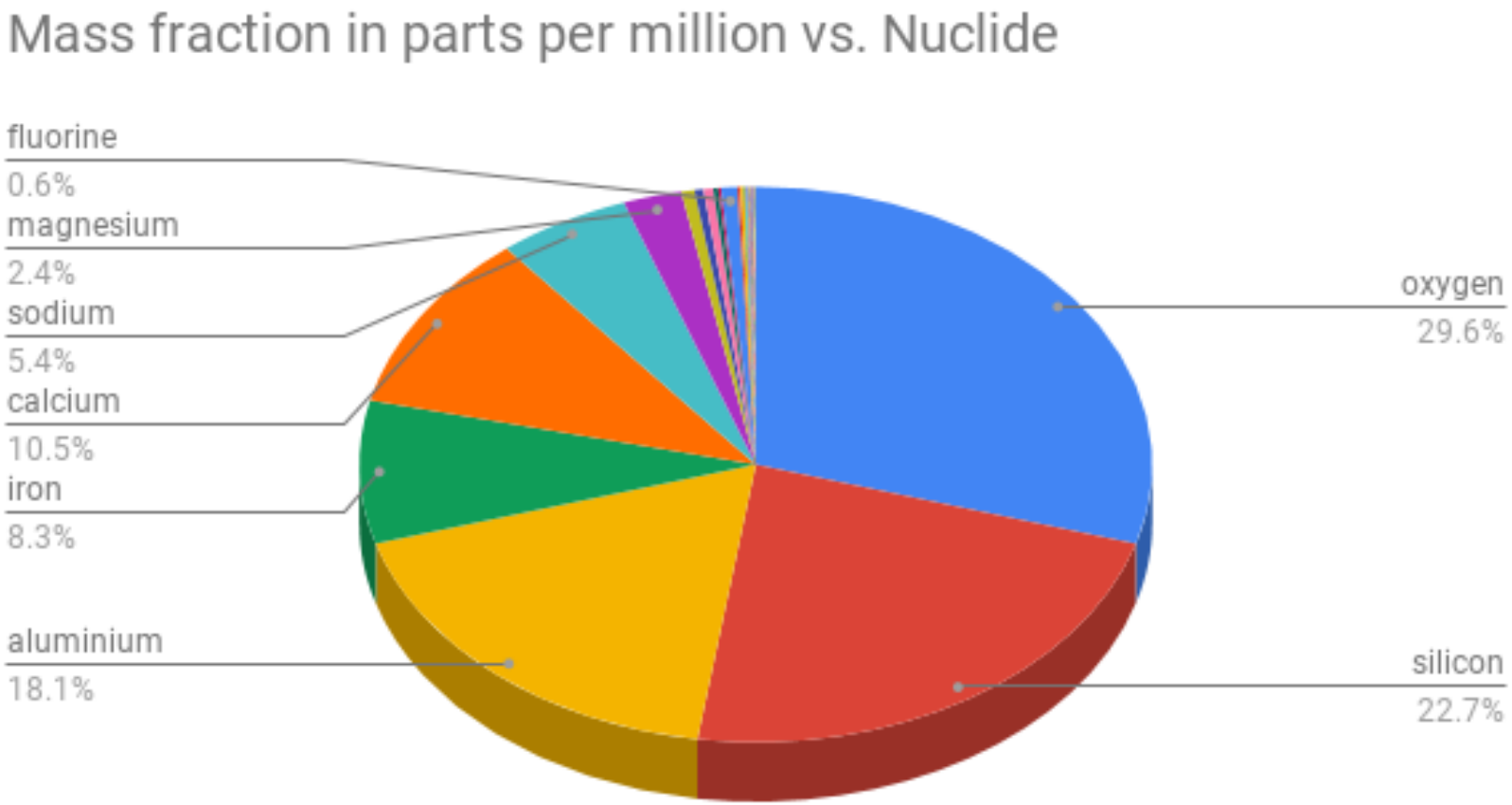

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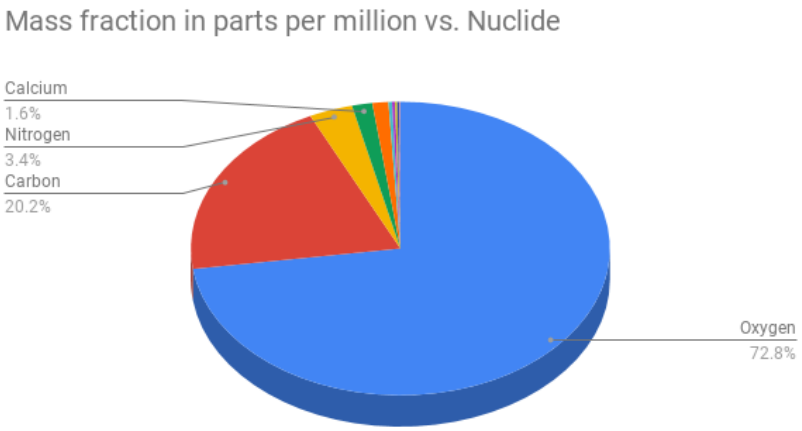

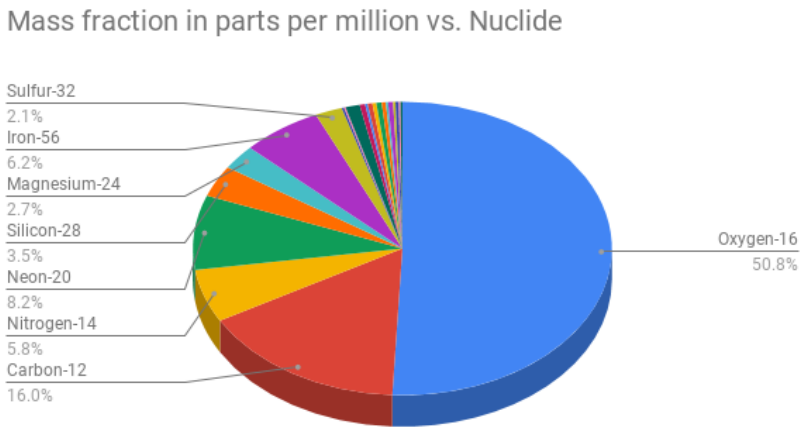

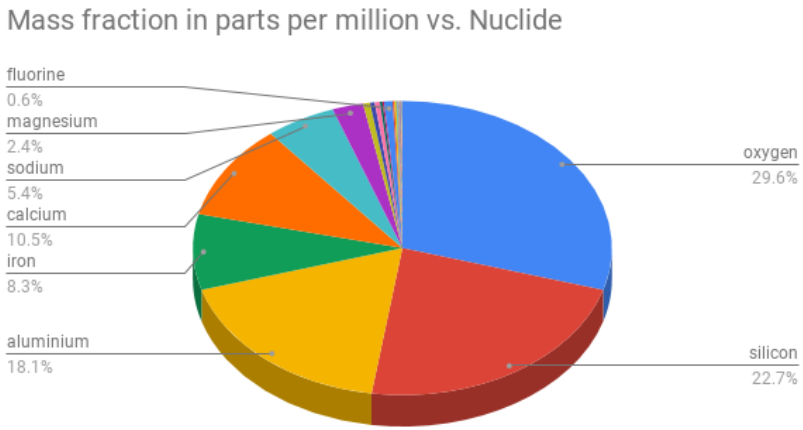

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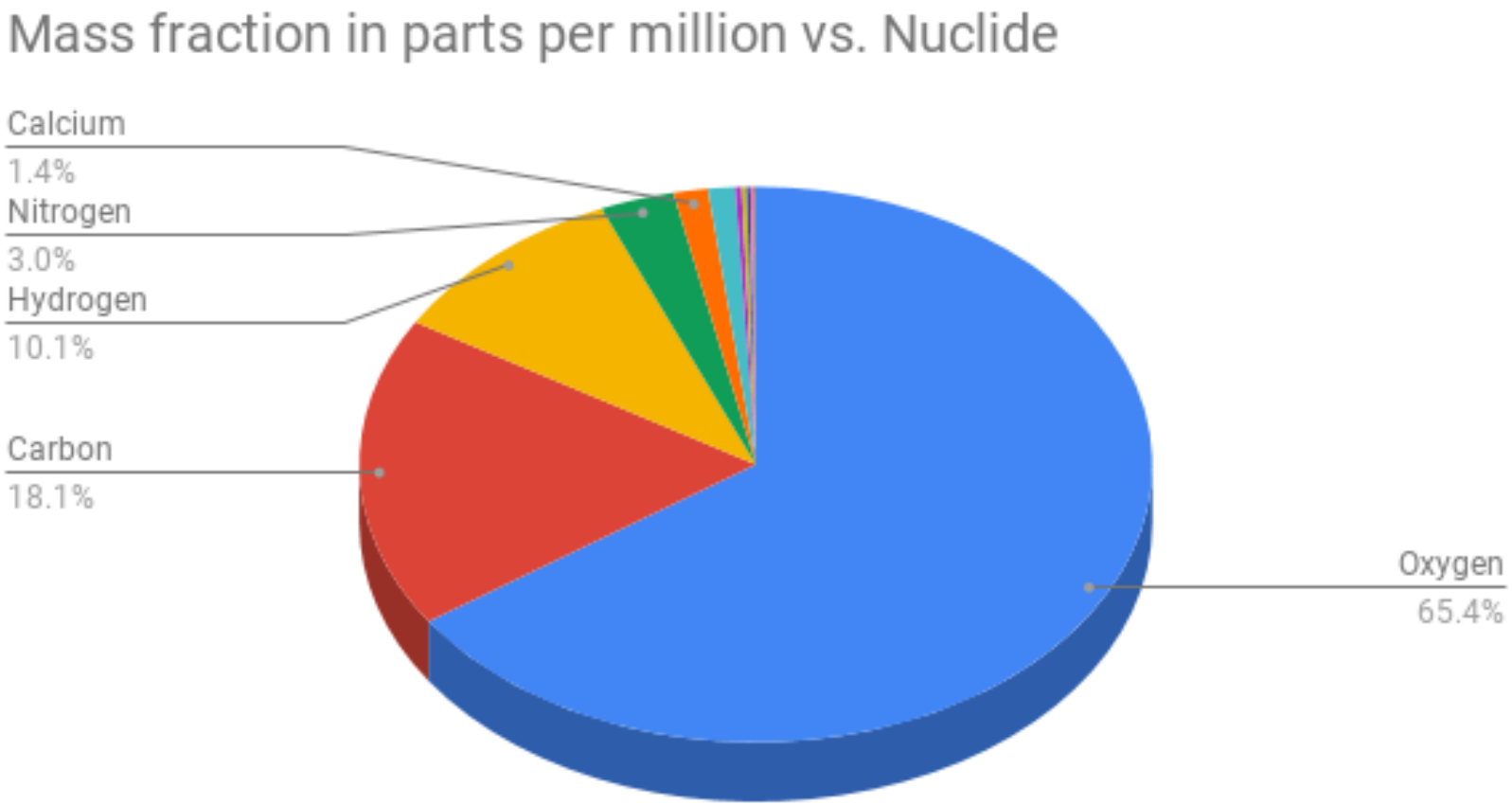

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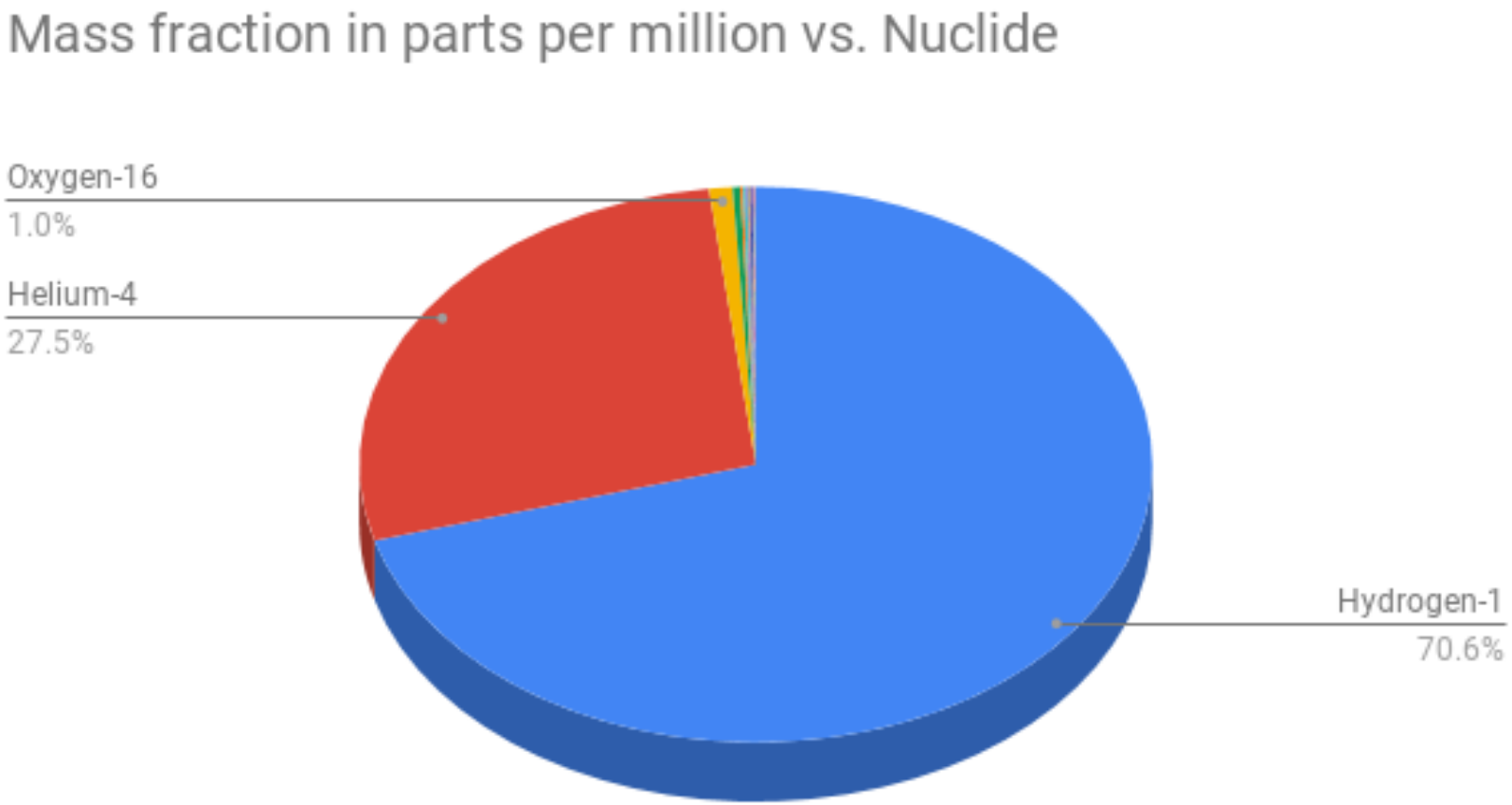

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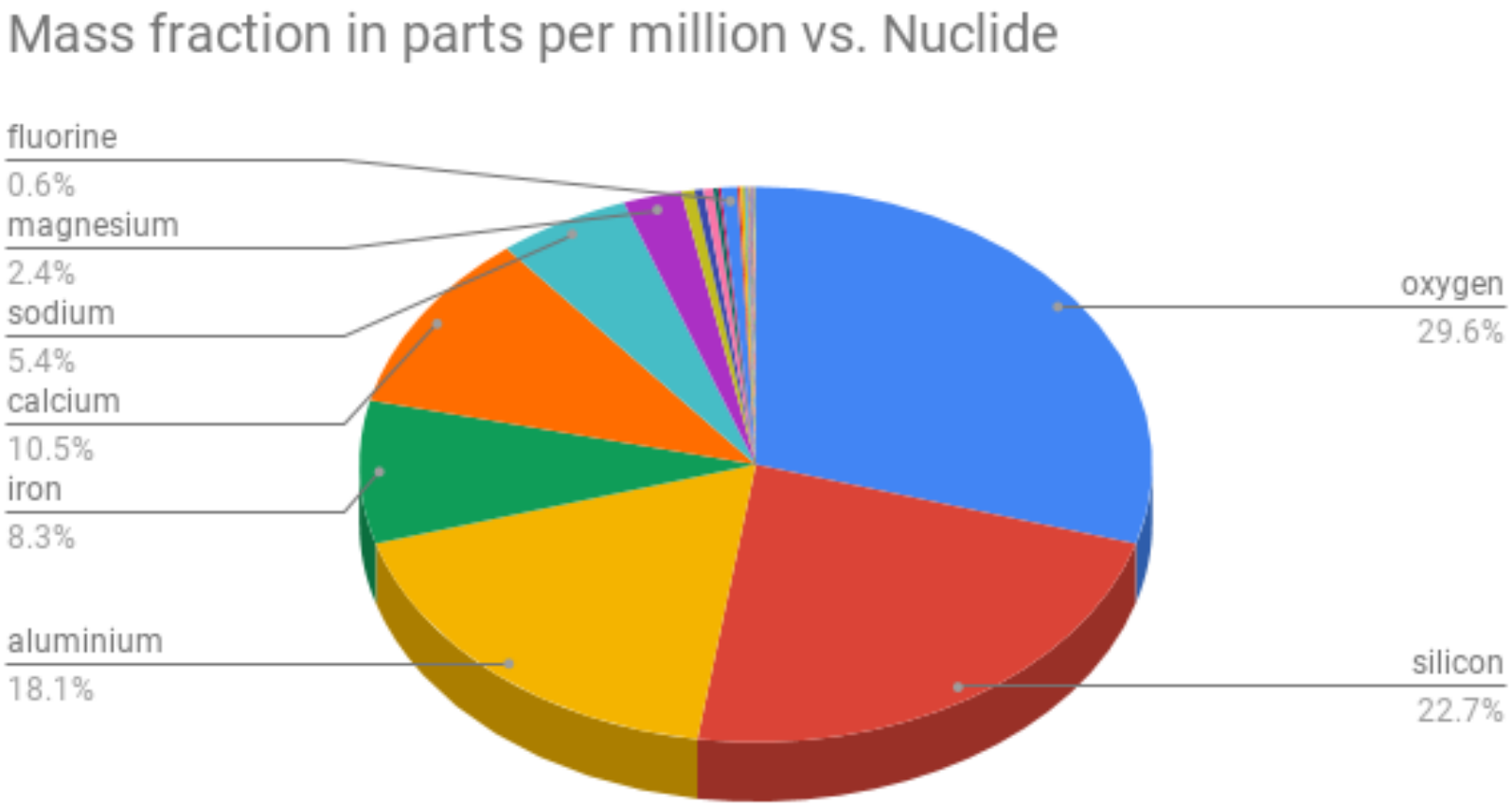

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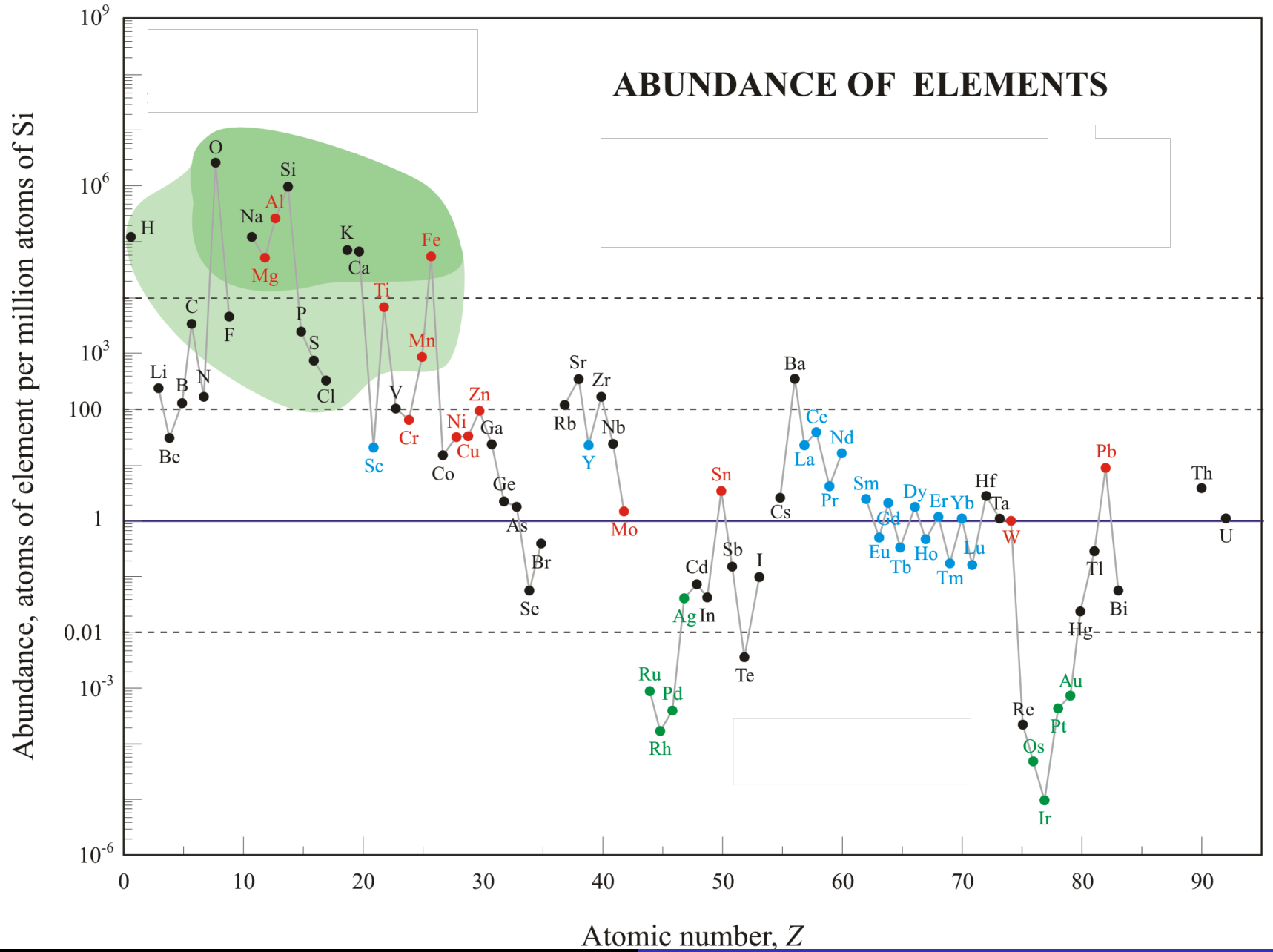

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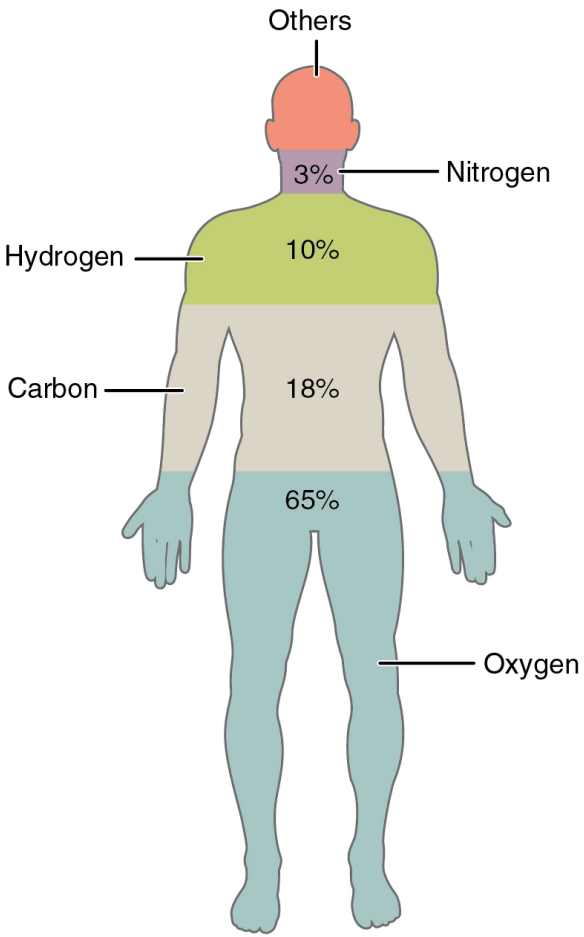
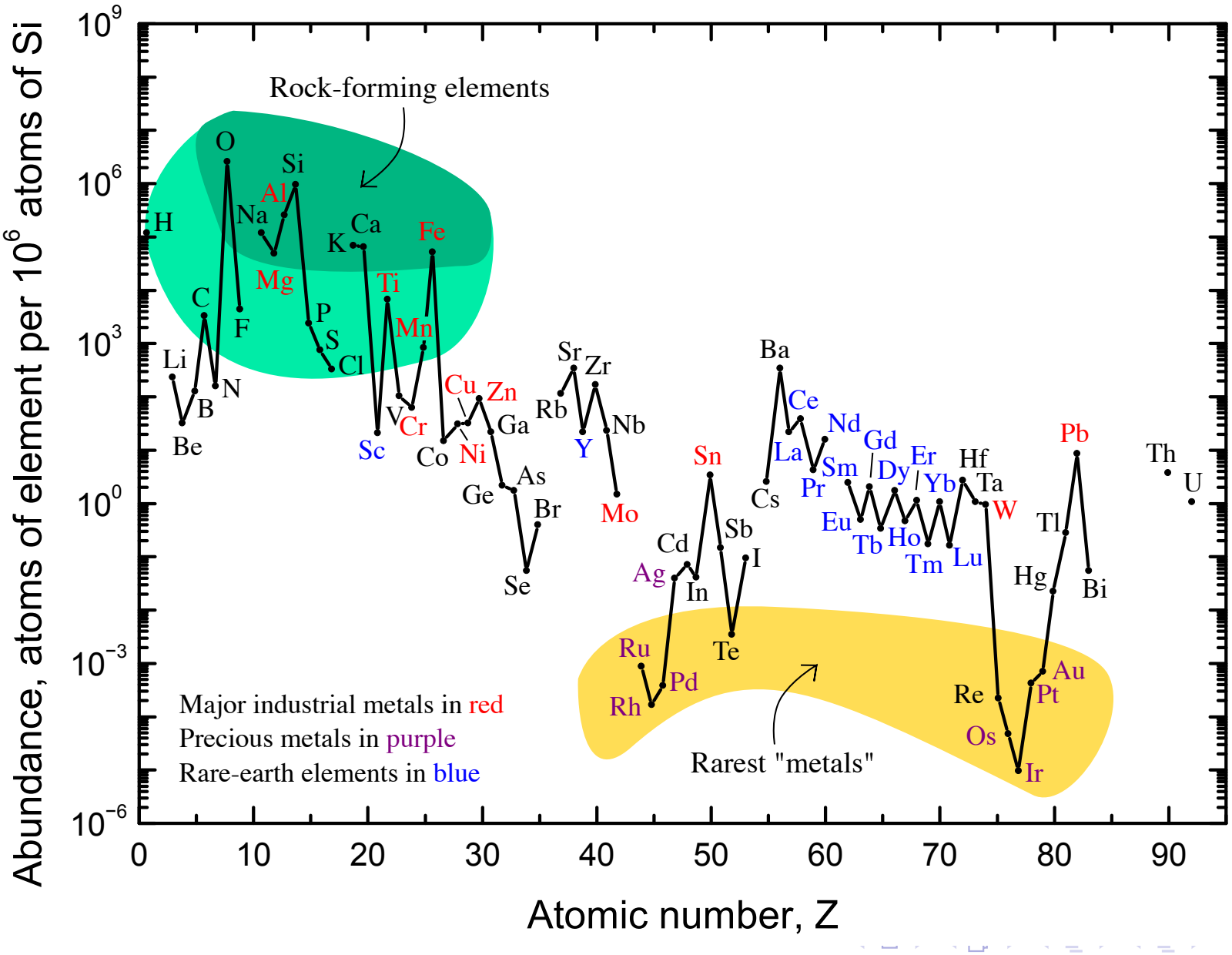
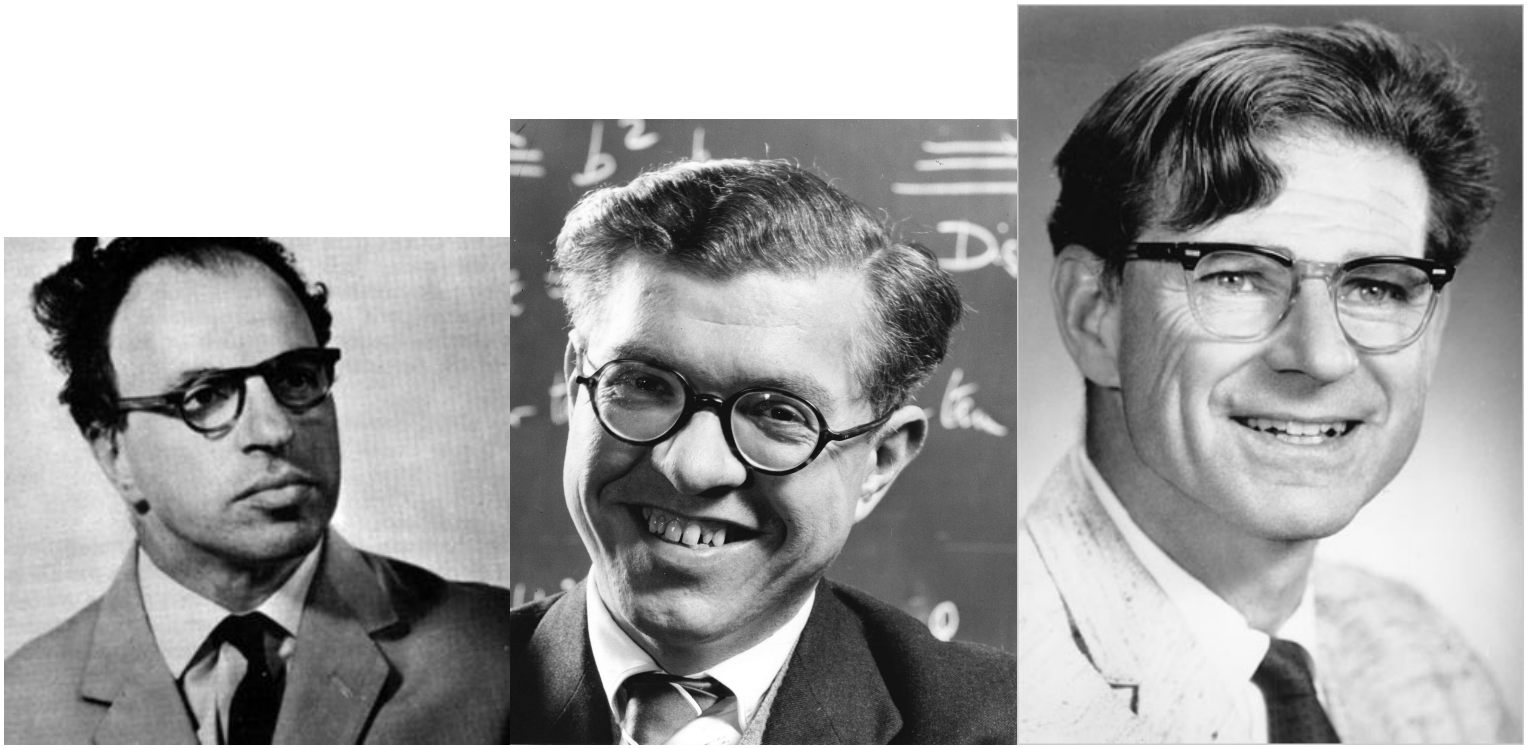


Element	Symbol	Percentage in Body
Oxygen	O	65.0
Carbon	C	18.5
Hydrogen	H	9.5
Nitrogen	N	3.2
Calcium	Ca	1.5
Phosphorus	P	1.0
Potassium	K	0.4
Sulfur	S	0.3
Sodium	Na	0.2
Chlorine	Cl	0.2
Magnesium	Mg	0.1
Trace elements include boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), and zinc (Zn).		less than 1.0

The Abundance of the Elements



Stars



Stars

According to Hoyle (1946)

1. Initially the only element present in the universe is hydrogen.
2. Helium is synthesized by thermonuclear reactions taking place in "normal" stars.
3. A further process occurs that synthesizes higher elements from hydrogen and helium. The elements produced are regarded as having a distribution similar to that found on the Earth.

According to Bondi and Salpeter (1952): After all of the helium is also used up, the star again contracts gravitationally. The central temperature increases, and heavier and heavier nuclei are built up . . . This may be identified with the observed spectacle of a supernova, and all the heavy elements in the universe may owe their origin to such processes.

Stars (Hoyle 1954 - up to Nickel)

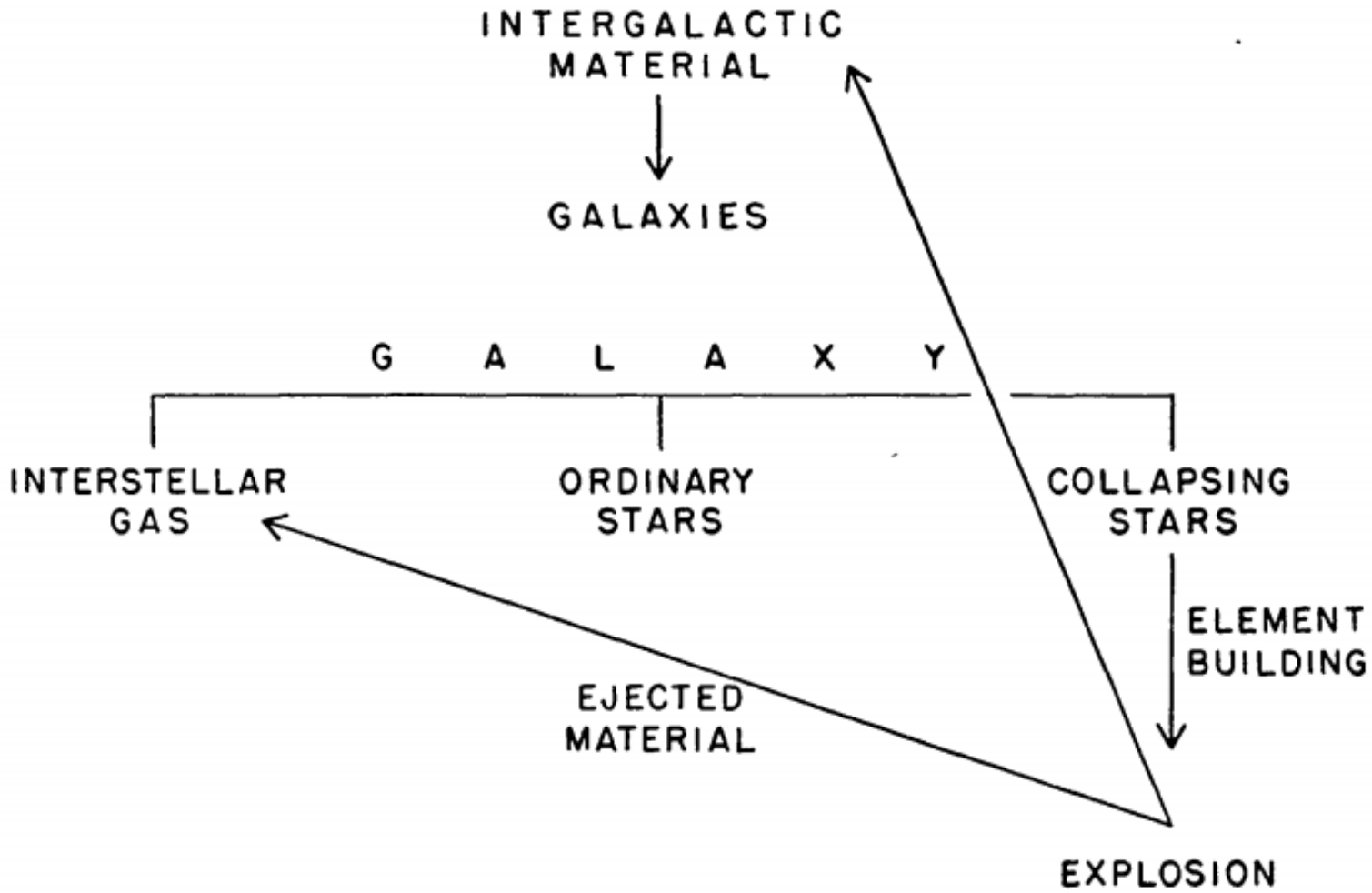


FIG. 1.—The general cosmological framework assumed for this discussion

How to get past nickel?

Artificial radioactivity
$^{27}\mathrm{Al}(\alpha, n)^{30}\mathrm{P}$

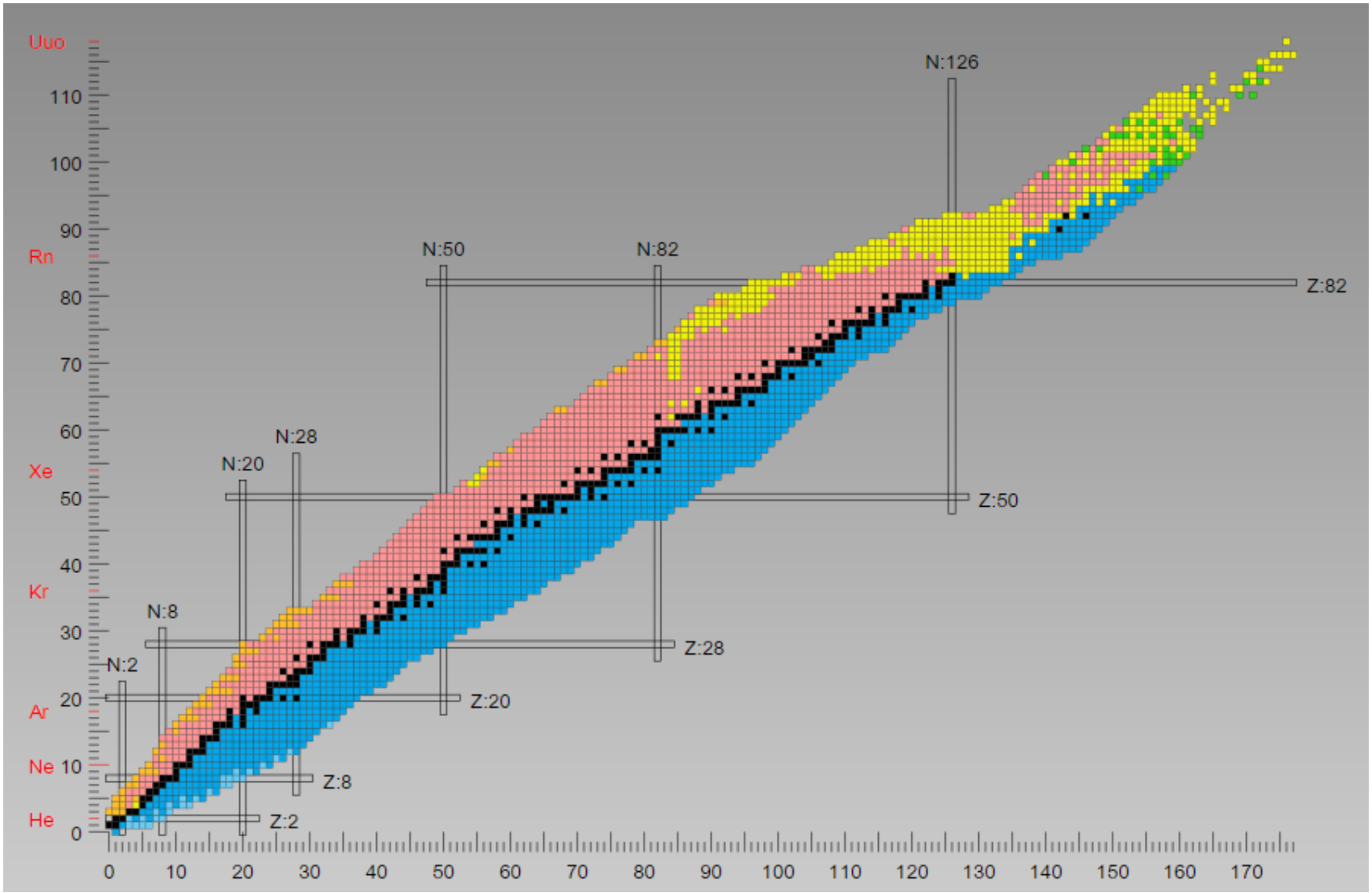
How to get past nickel?

How to get past nickel?

How to get past nickel?

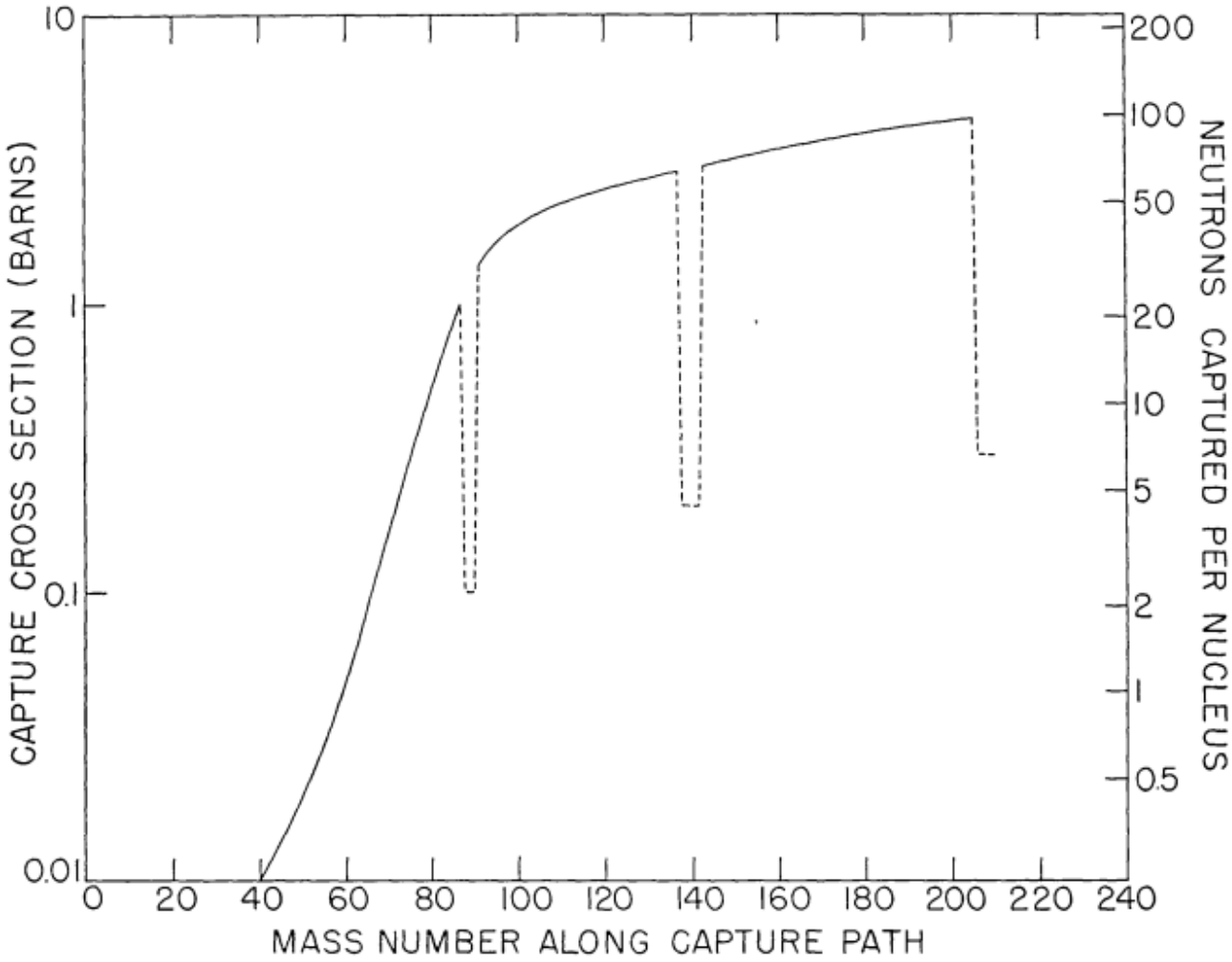
Making neutrons during helium burning:
$^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$

Adding Neutrons

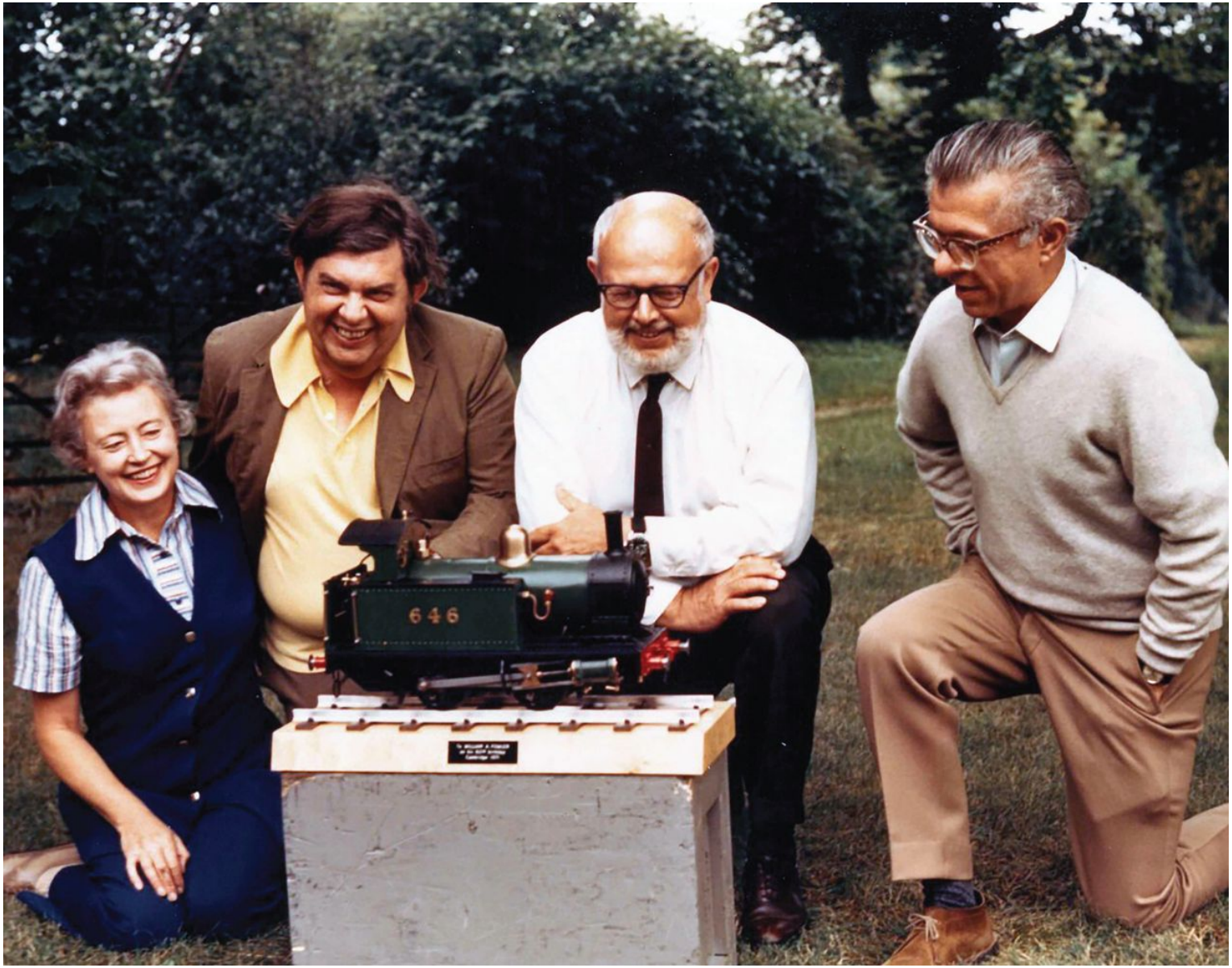


Stars (Cameron 1955)

The $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}$ reaction produces neutrons rapidly at a temperature of 10^8 K.

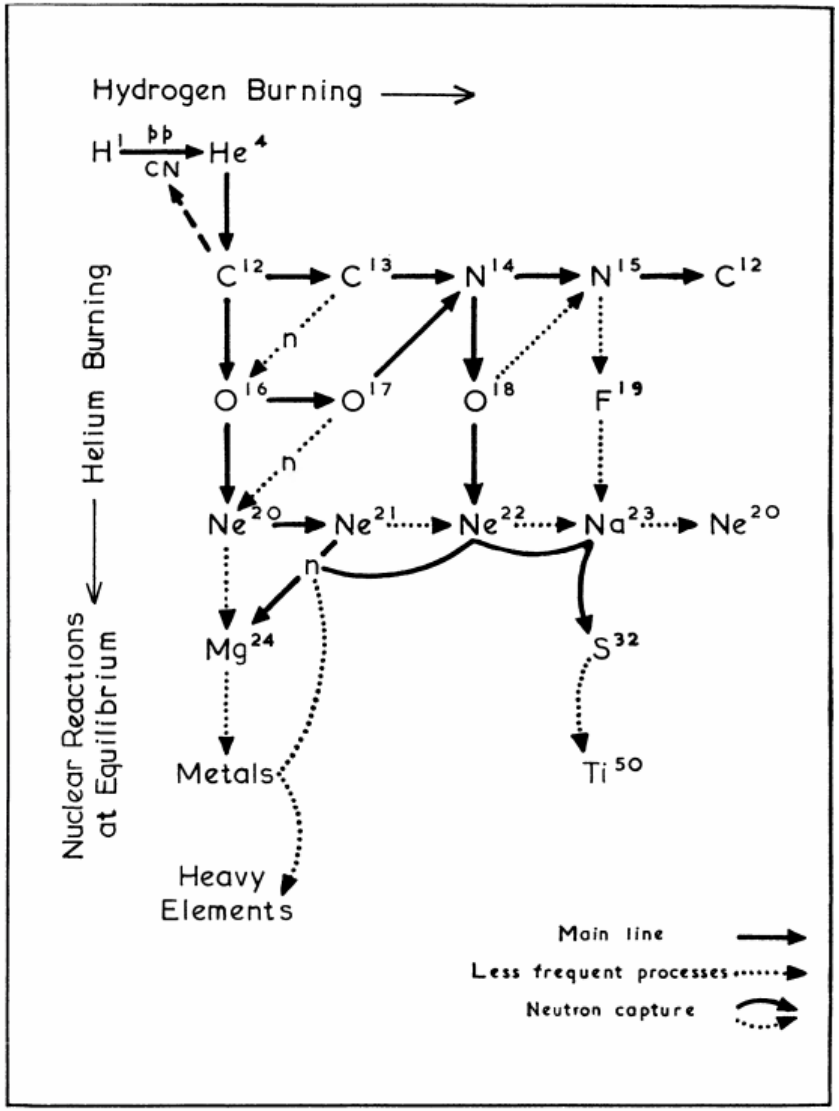


Burbidge, Burbidge, Fowler, Hoyle



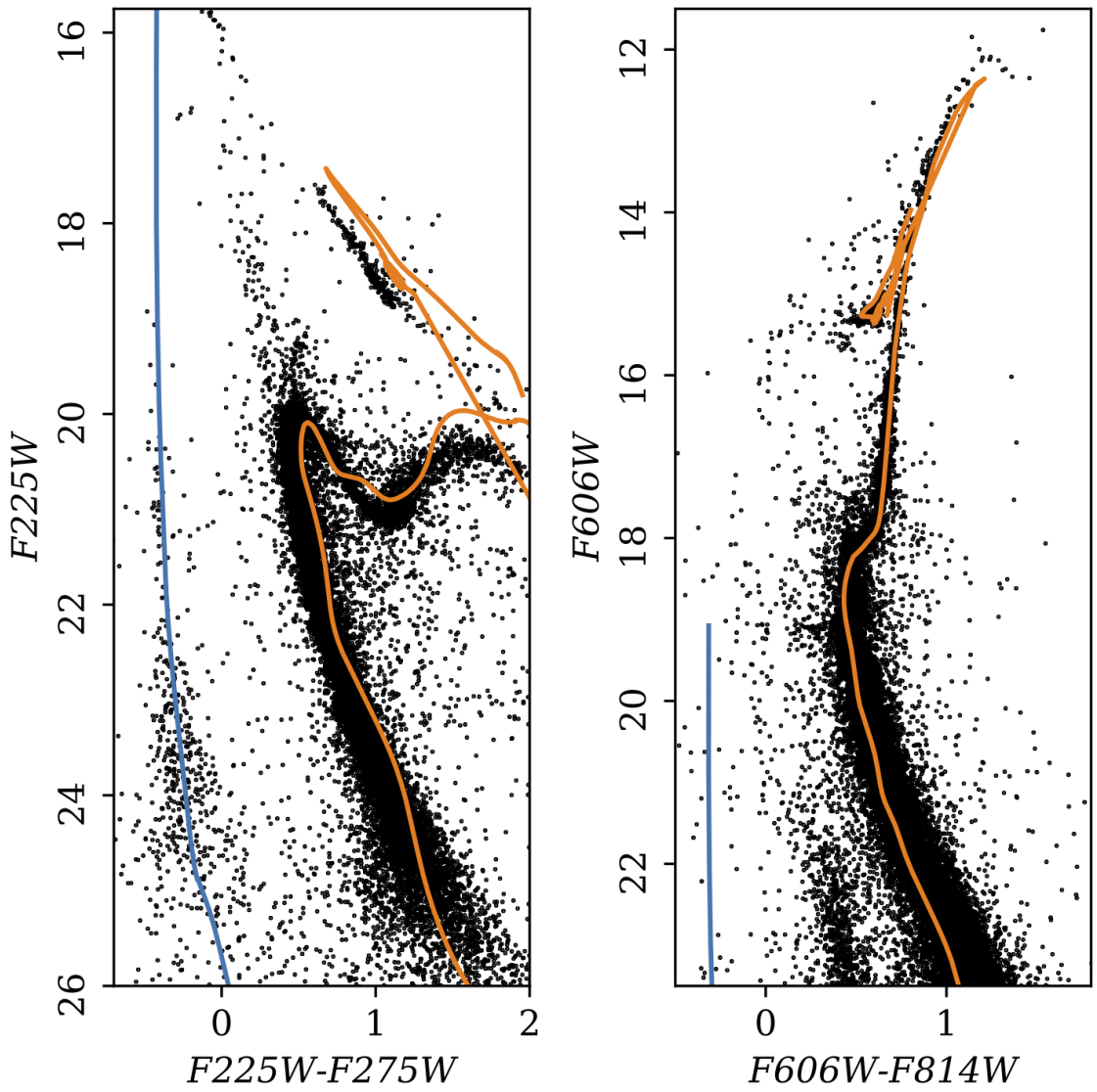
Stars (FB^2 1955a)

"Within the error due to the uncertainties in the quantities used in this estimate, it does appear, therefore, that synthesis of the heavy elements in the S-star stage alone could account for a considerable fraction of the heavy elements. A fraction of the same order would be obtained by supposing that the normal M giants were also synthesizing the heavy elements at a much slower rate."



Stars

Stars


F225W
16
18
20
22
24
26
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1
2
F225W-F275W
F606W
12
14
16
18
20
22
0
1
F606W-F814W

Stars (FB^2 1955b)

Facts about Carbon Stars:

1. Sr, Y, and Zr are overabundant by a factor of about 25.
2. La, Ce, Pr, Nd, Sm, Eu, Gd, and Dy have a mean excessive abundance ratio of the order of 600, while Ba is the only member of this group to have an apparently normal (solar) abundance.
3. Pb is probably overabundant by a factor of about 1500

Stars (FB^2 1955b)

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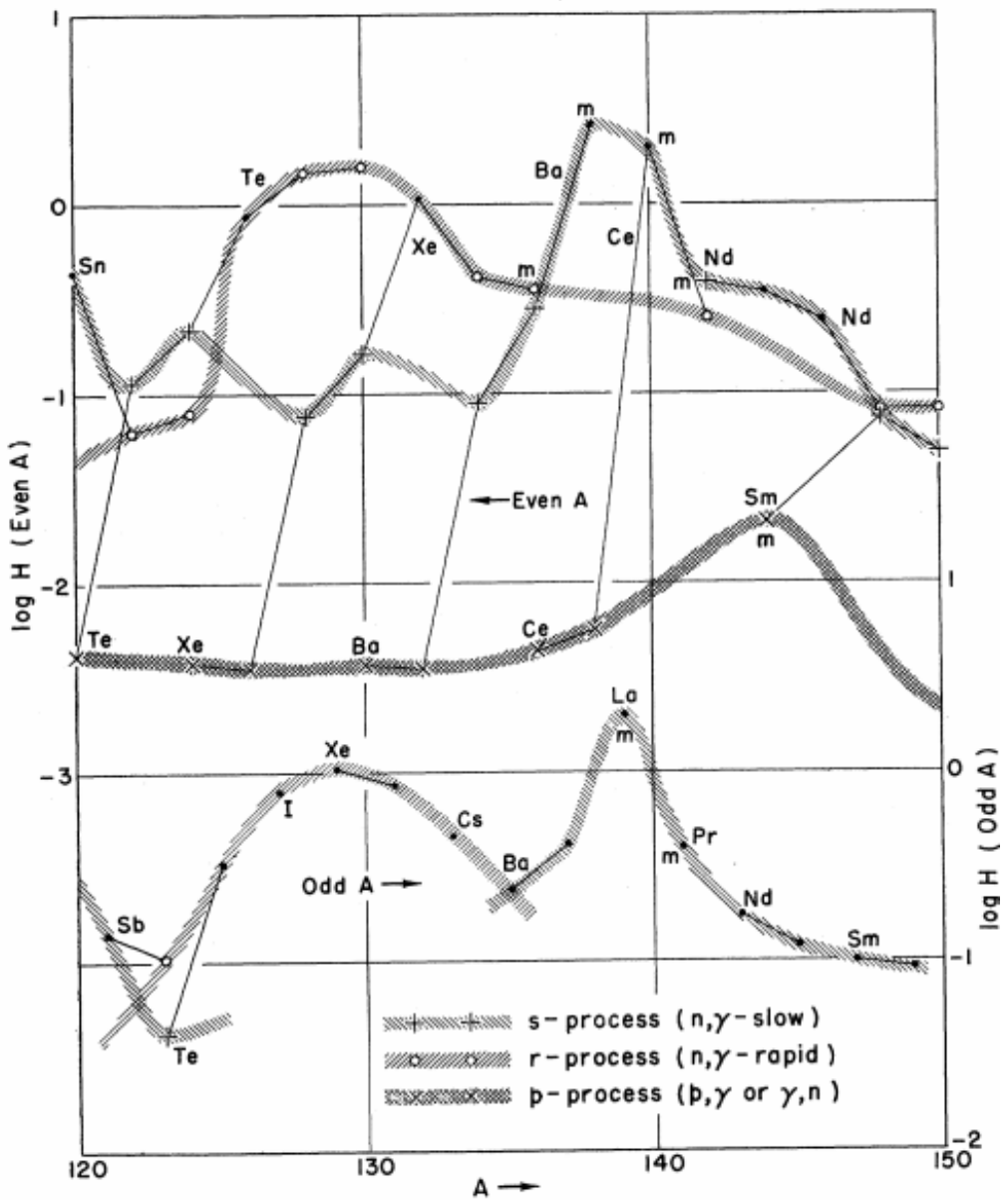
"The natural radioactive elements may be produced by collisions between metal nuclei and the stable, heavy nuclei, such as lead and bismuth."

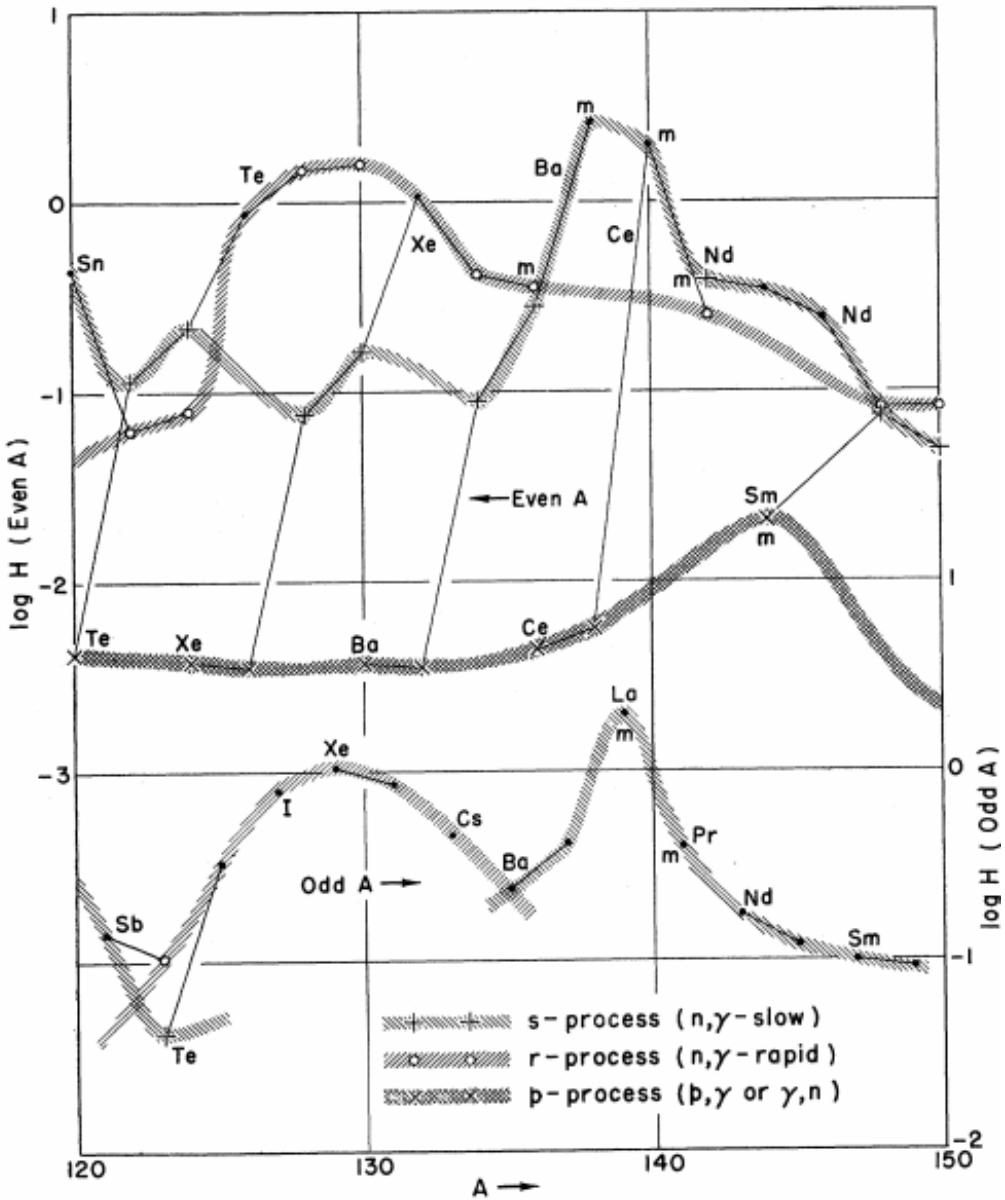
Ivy Mike (1952)

Stars (HFB^2 1956)

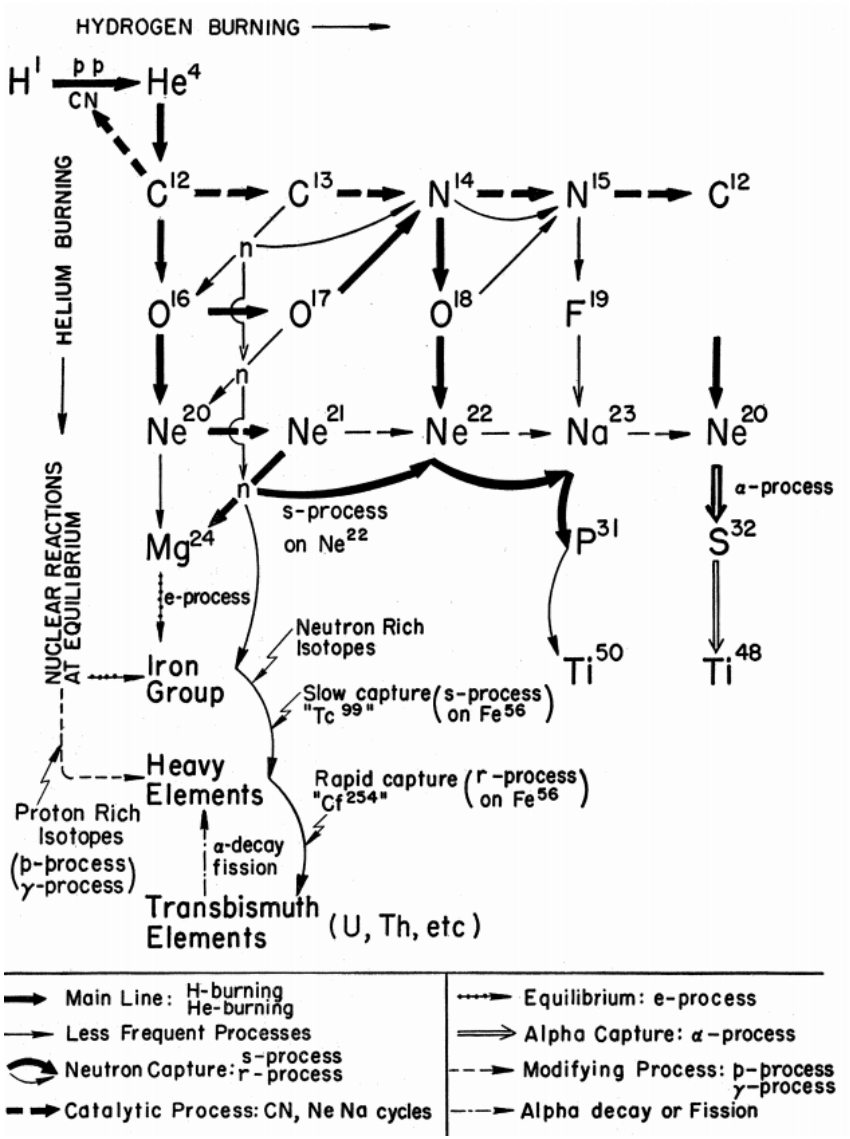


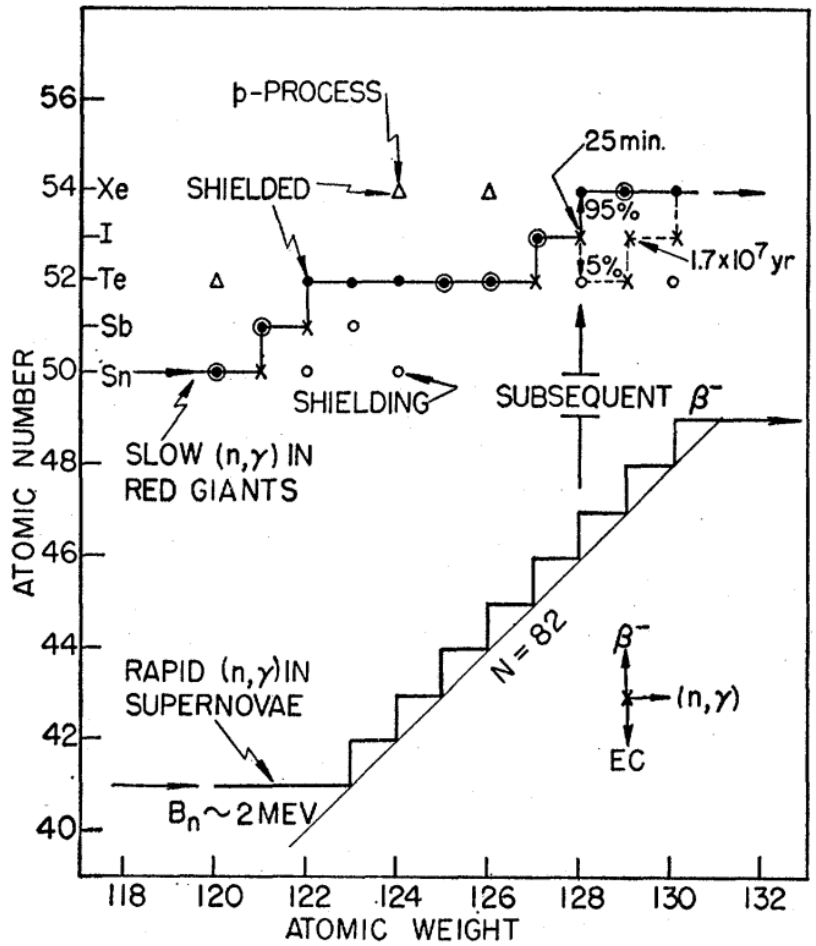
Stars (HFB^2 1956)

"The production of ^{254}Cf in the thermonuclear test at Bikini in November 1952 demonstrates that rapid neutron capture can surmount spontaneous radioactivity"

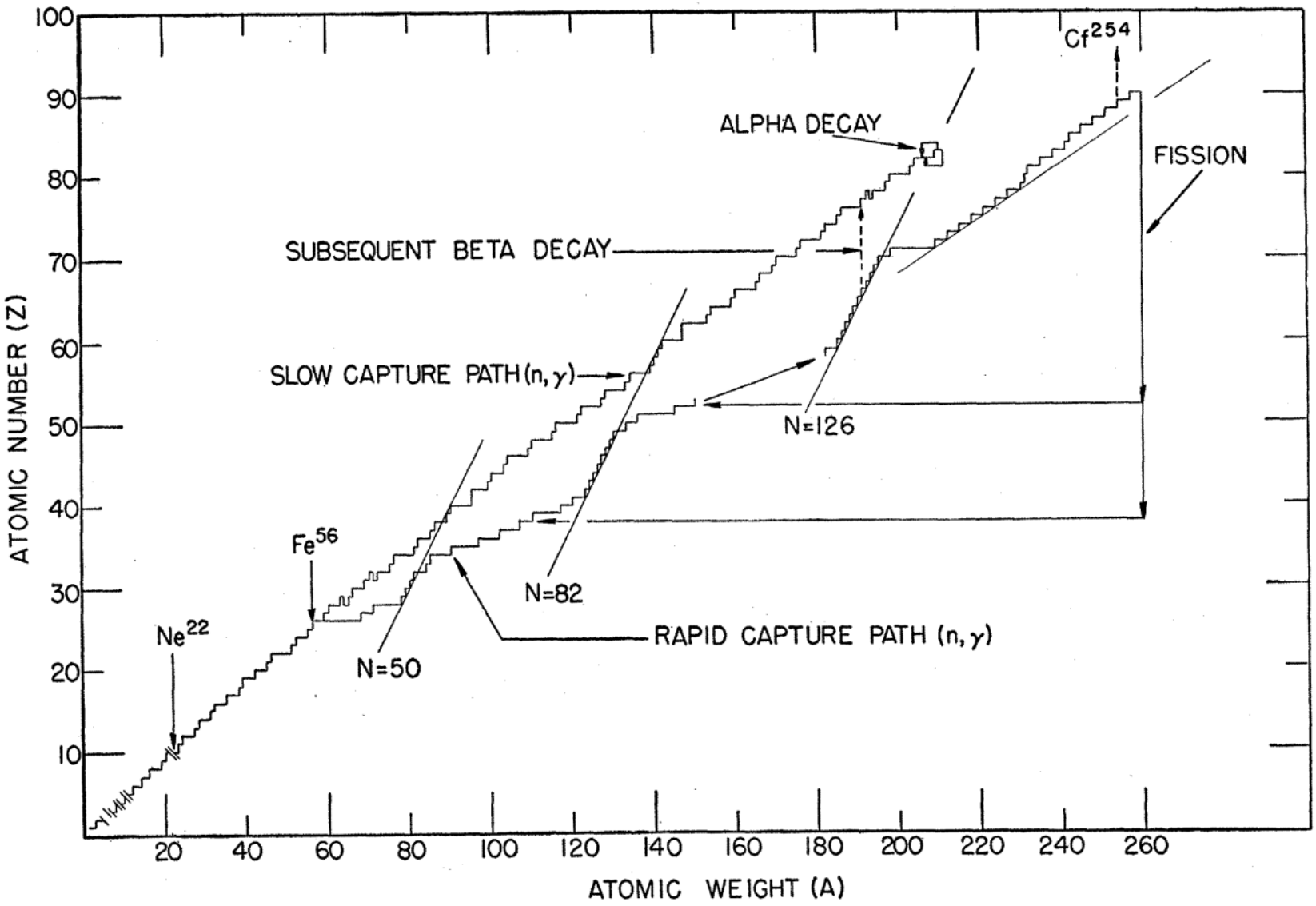


Stars (B^2FH 1957)





Stars (B^2FH 1957)



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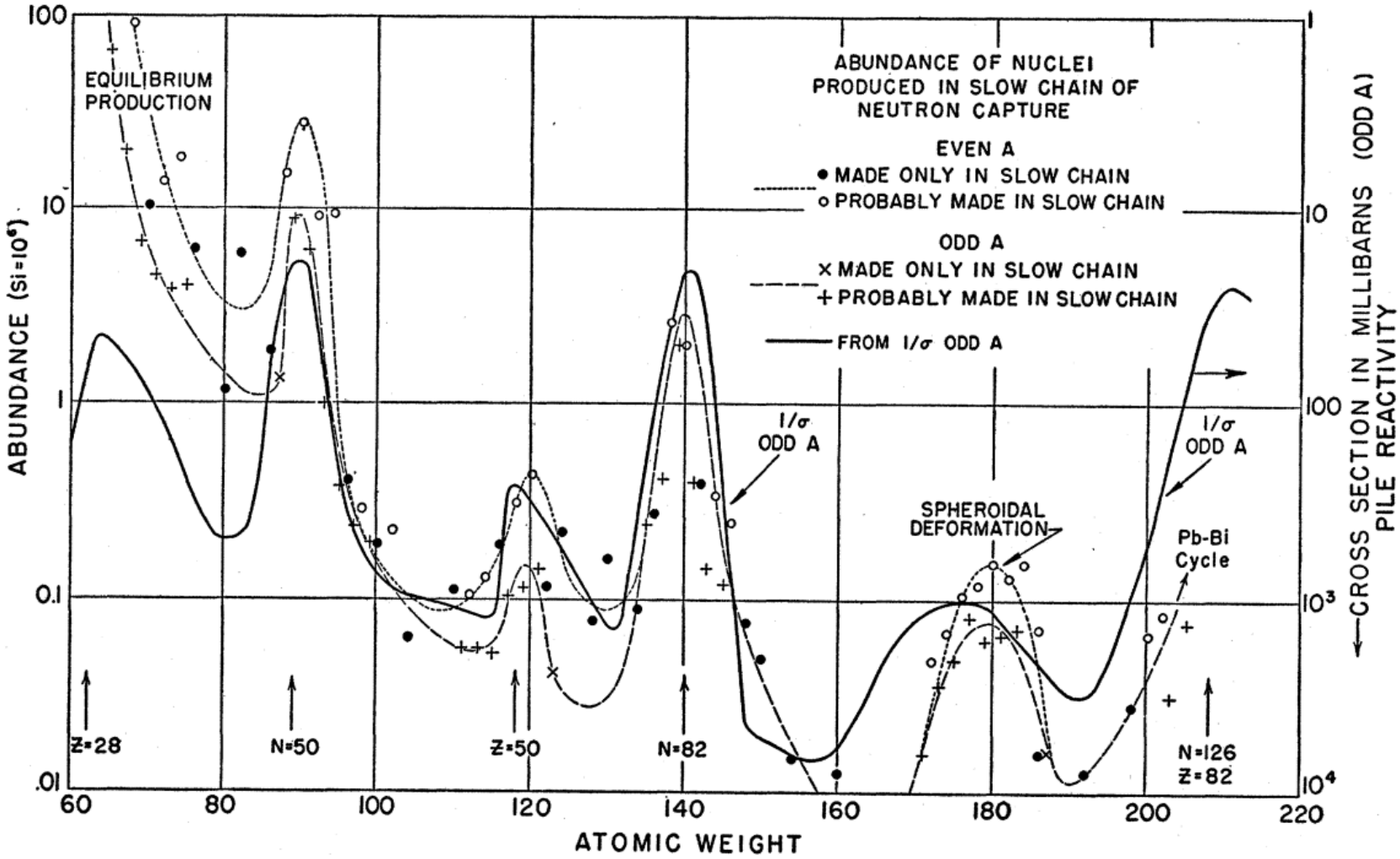

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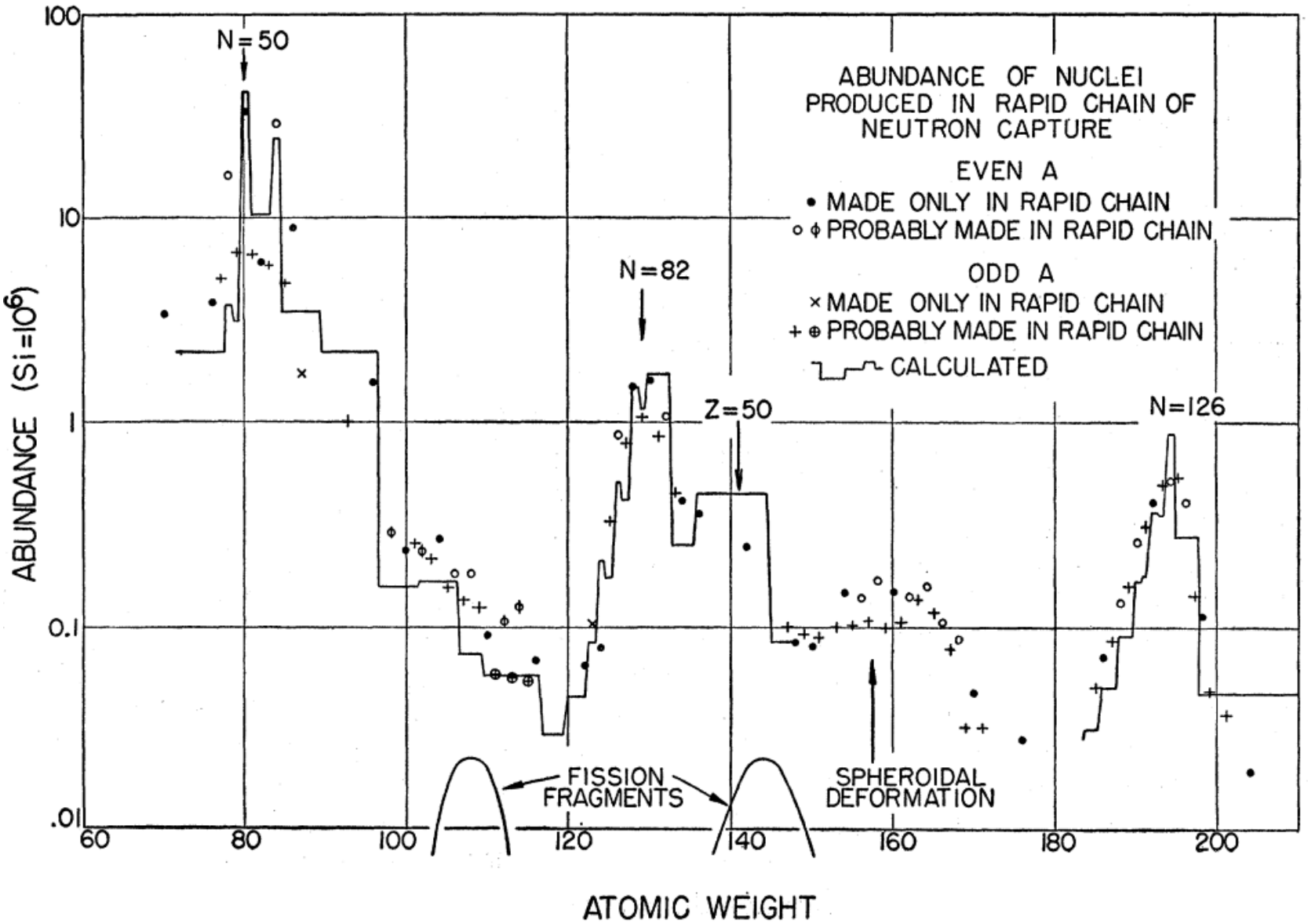
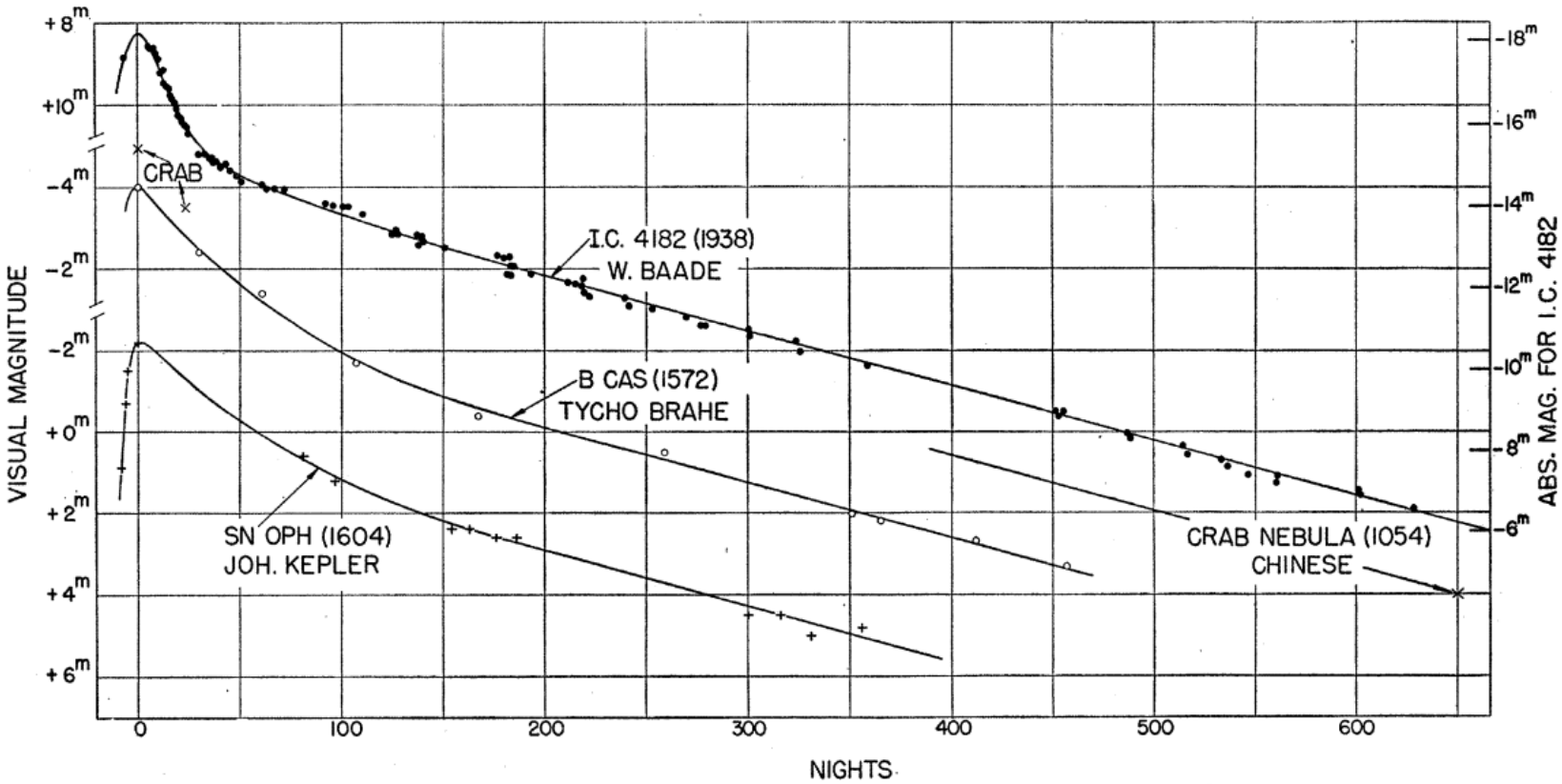
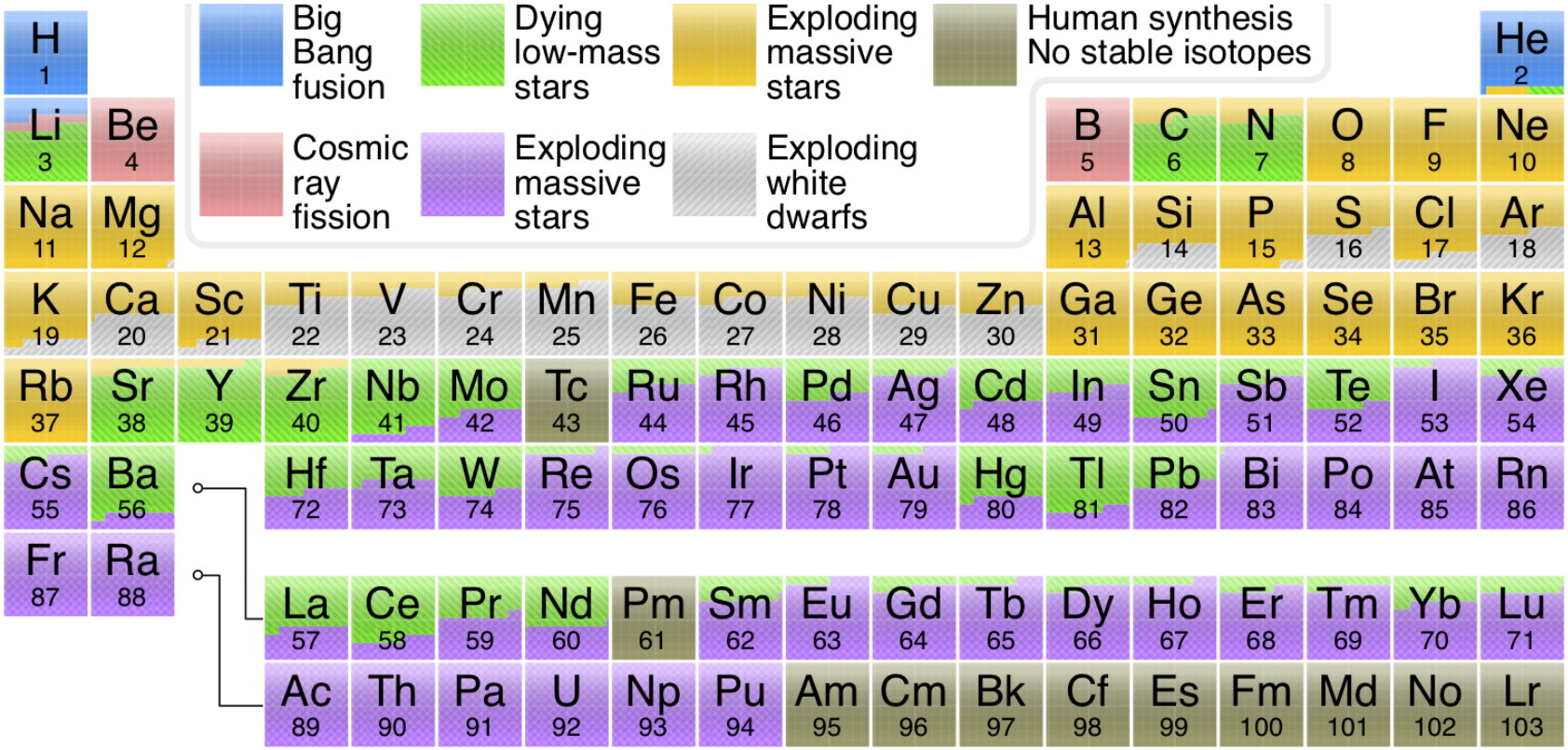


Stars (B^2FH 1957)

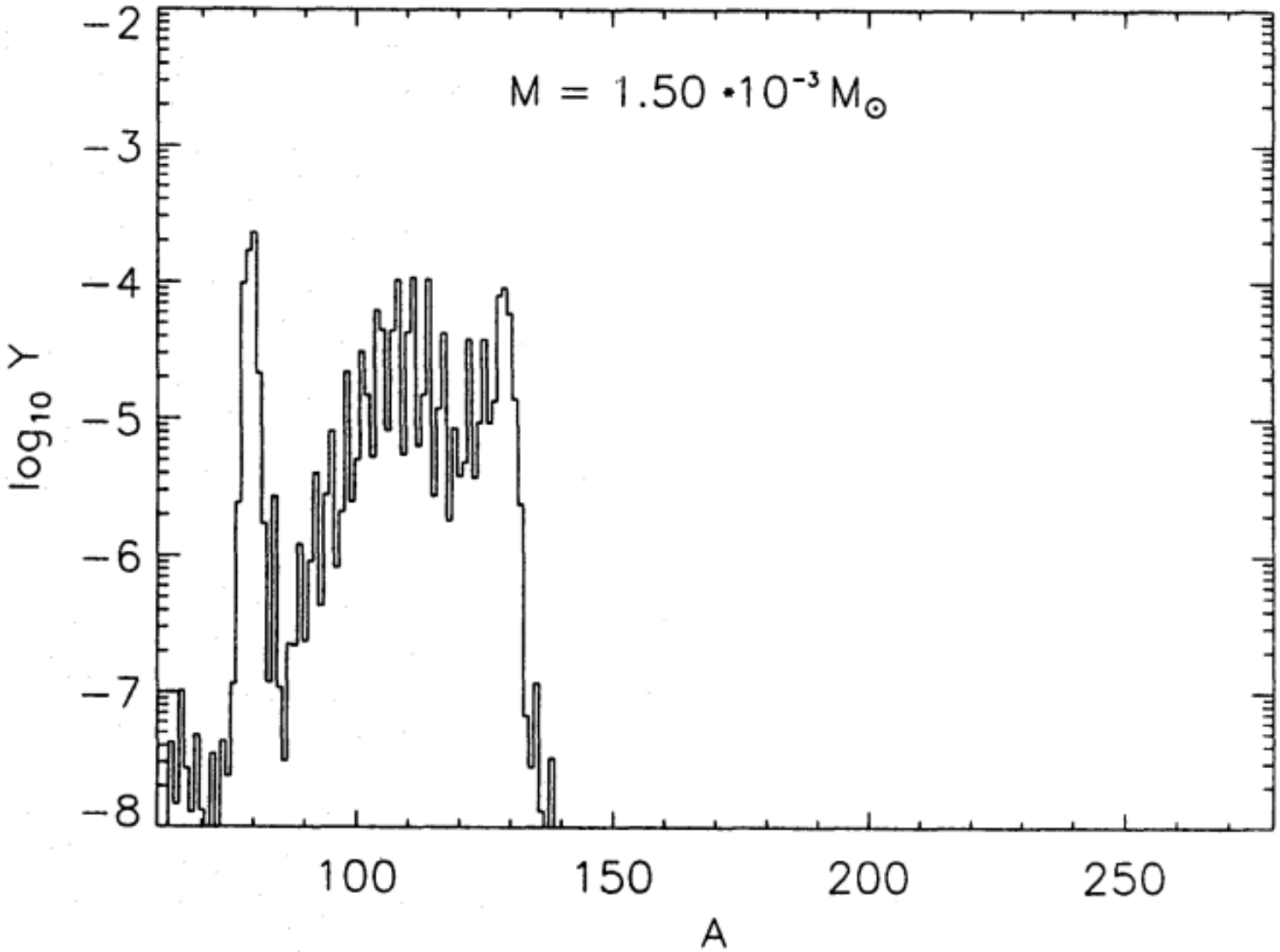


Nucleosynthesis



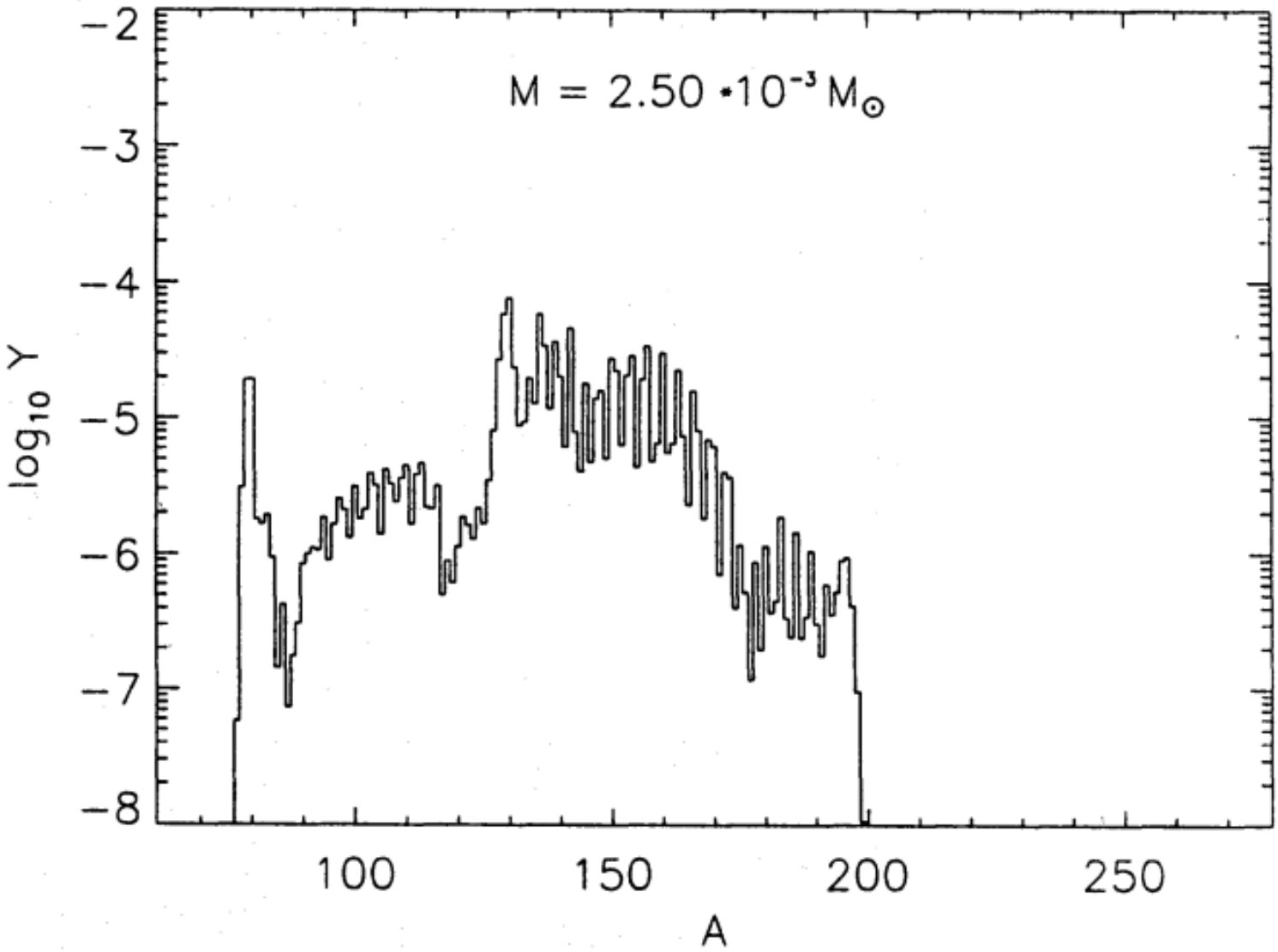
Jennifer Johnson

$r-$process in Core-Collapse SN to the limit



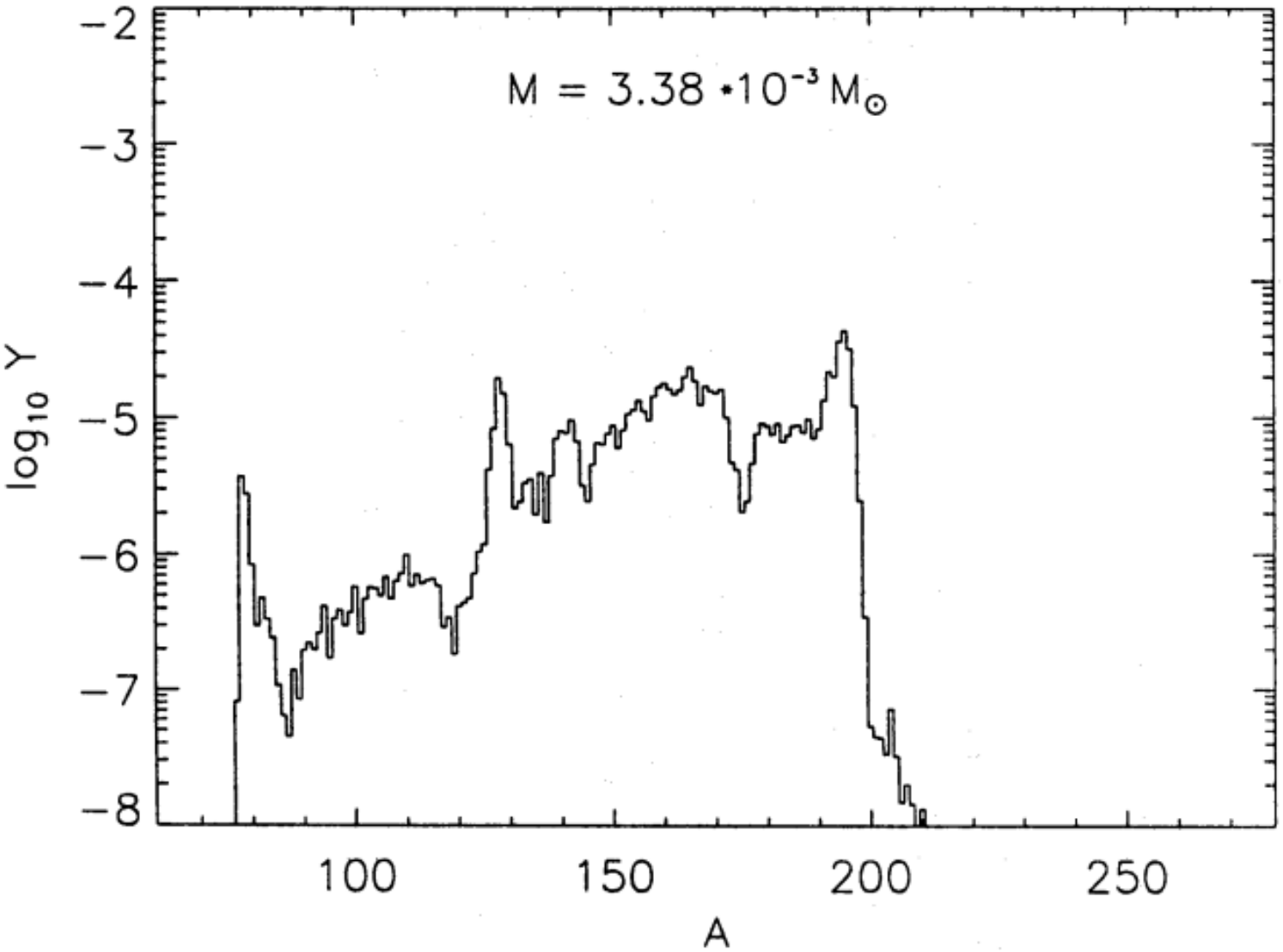
Takahashi, Witti & Janka 1994, $Y_n / Y_{\mathrm{seed}} = 19$

$r-$process in Core-Collapse SN to the limit



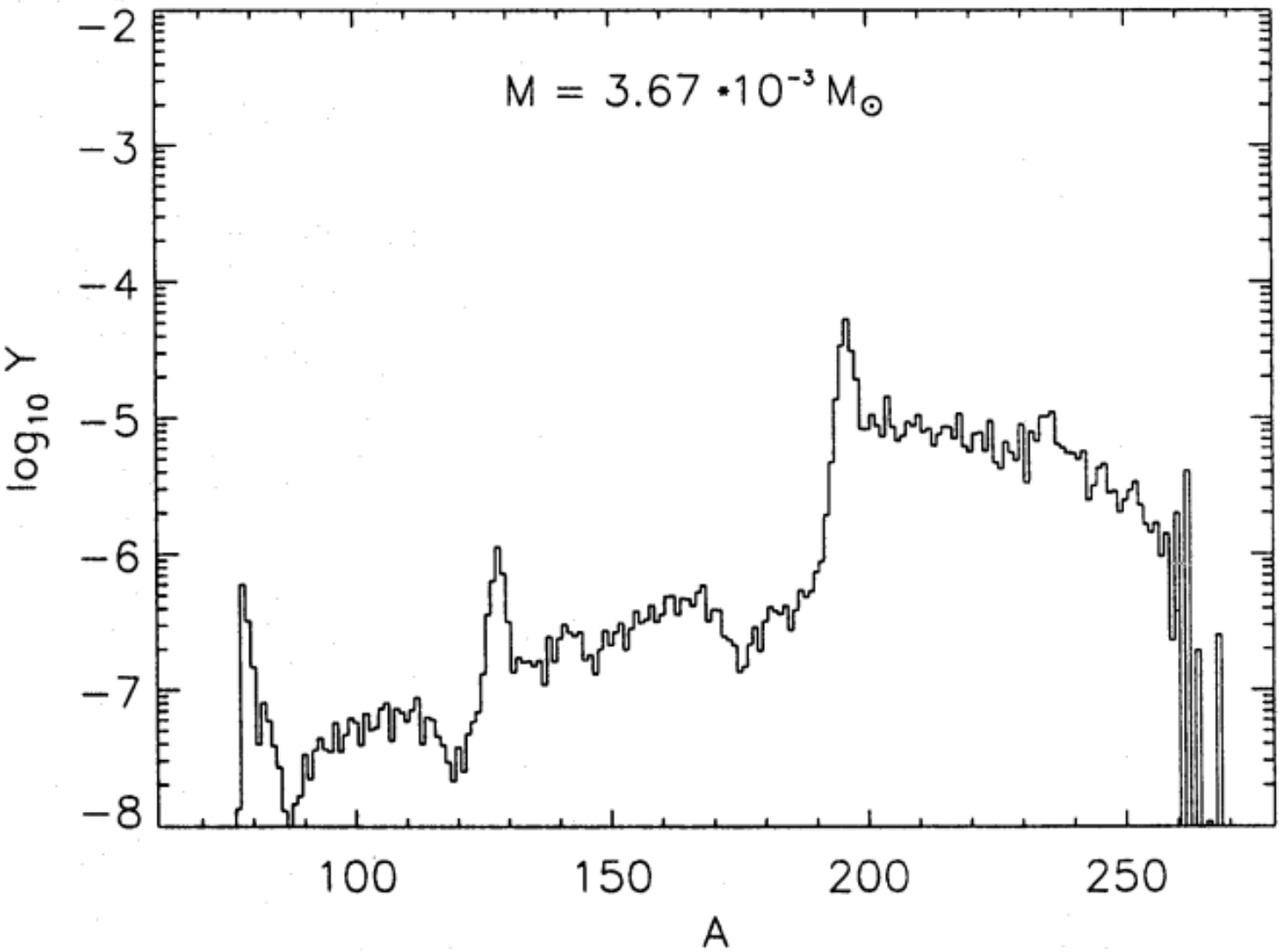
Takahashi, Witti & Janka 1994, $Y_n / Y_{\mathrm{seed}} = 51$

$r-$process in Core-Collapse SN to the limit



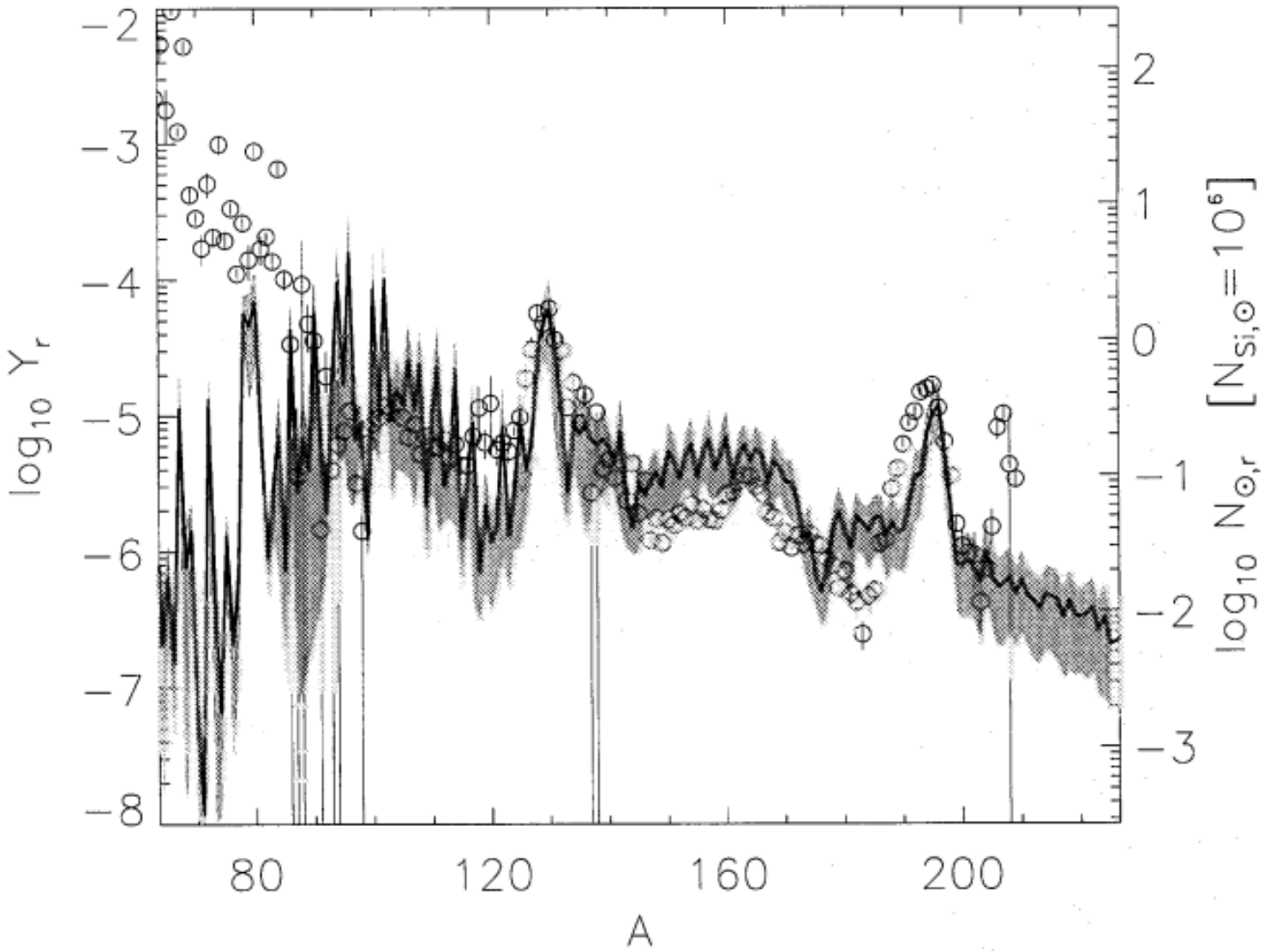
Takahashi, Witti & Janka 1994, $Y_n/Y_{\rm seed} = 75$

$r-$process in Core-Collapse SN to the limit



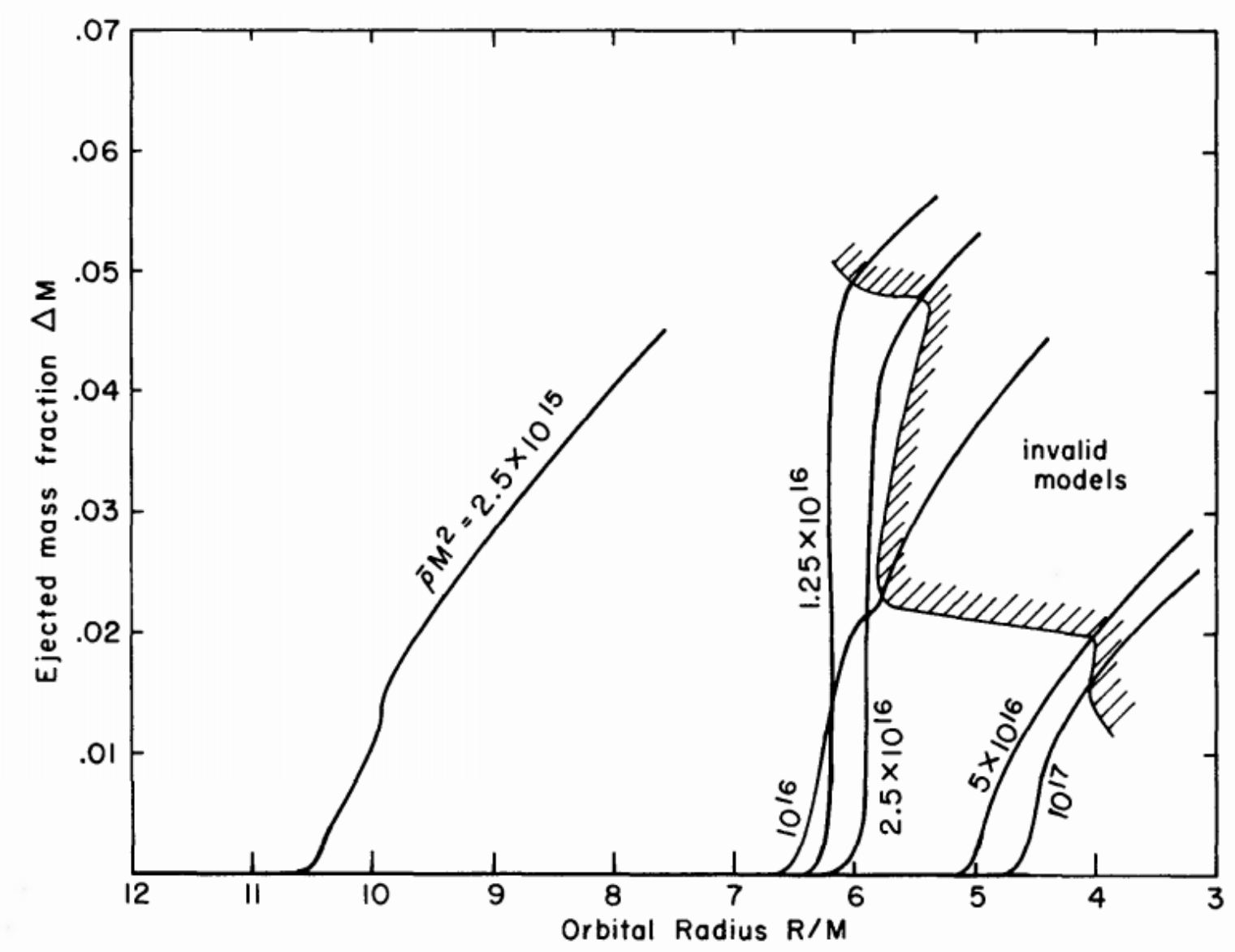
Takahashi, Witti & Janka 1994, $Y_n / Y_{\mathrm{seed}} = 125$

$r-$process in Core-Collapse SN to the limit



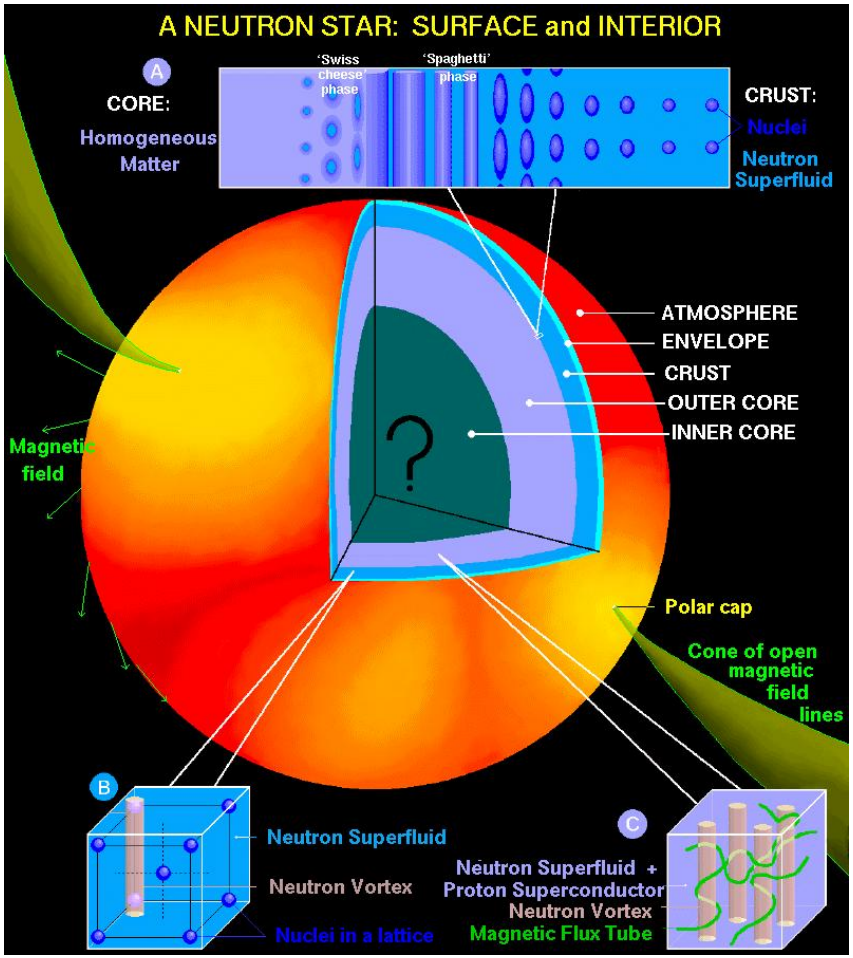
Takahashi, Witti & Janka 1994

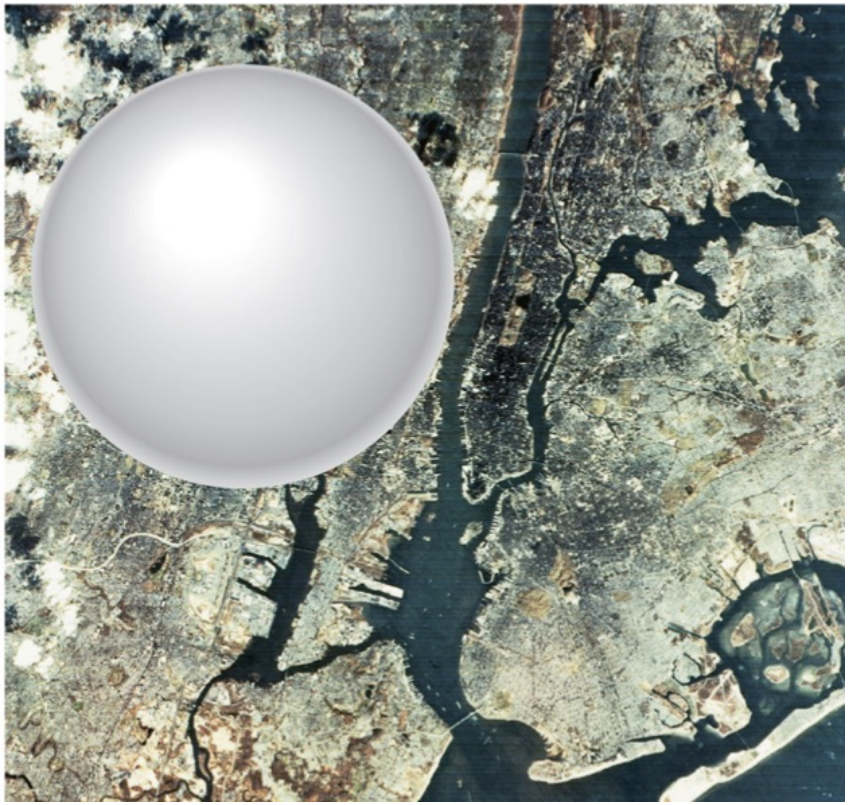
Another $r-$process



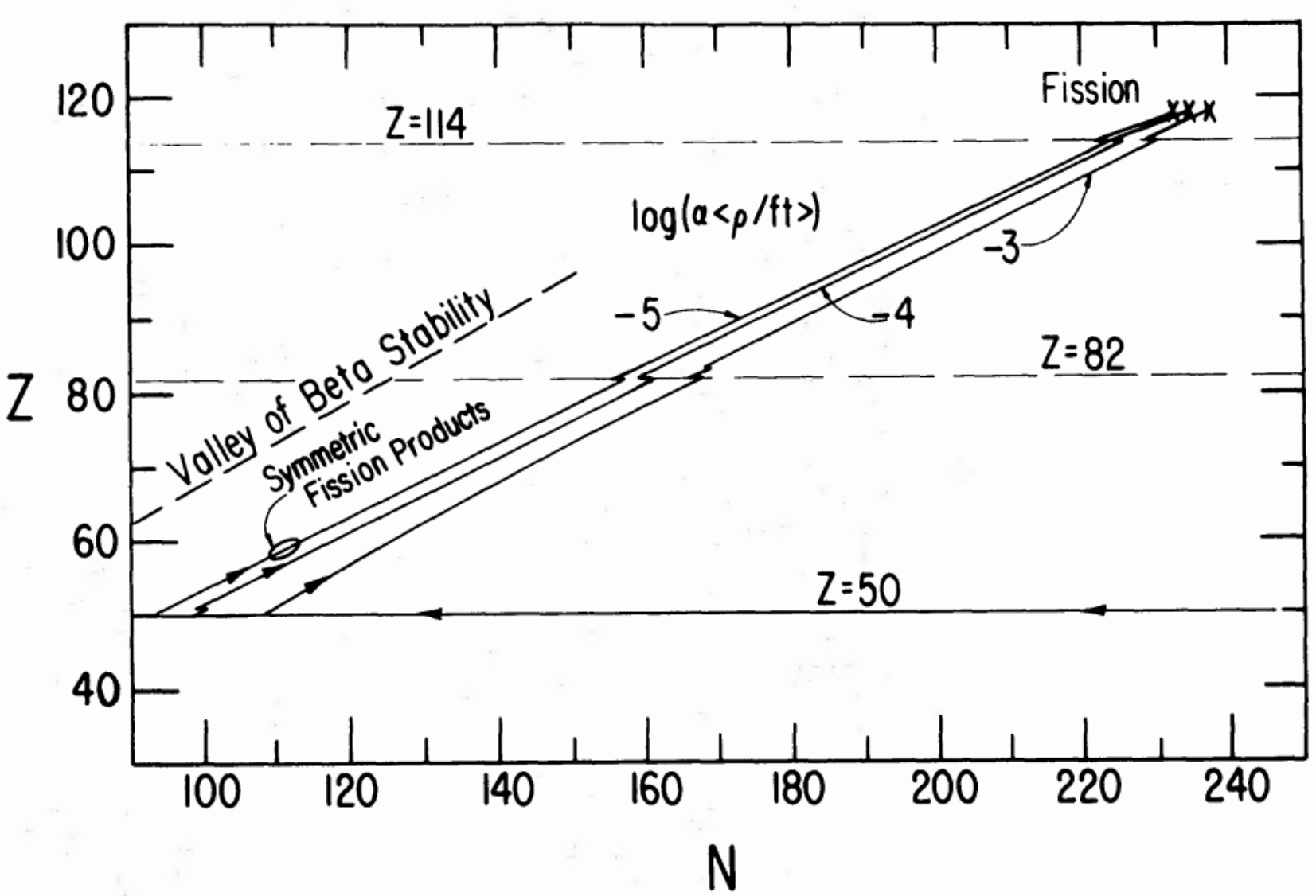
Lattimer & Schramm 1976

Neutron Stars





Another $r-$process



Lattimer *et al.* 1977

GRB 170817

Subject: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of a possible gravitational-wave counterpart
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Date: Thu, August 17, 2017 6:23 am
To: heyl@phas.ubc.ca
Priority: Normal
Create Filter: Automatically | From | To | Subject
Options: View Full Header | View Printable Version | Download this as a file | View Message Details

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TITLE:   GCN CIRCULAR
NUMBER:  21505
SUBJECT: Fermi GBM trigger 524666471/170817529: LIGO/Virgo Identification of a
possible  gravitational-wave counterpart
DATE:    17/08/17 13:21:42 GMT
FROM:    Reed Clasey Essick at MIT  <ressick@mit.edu>

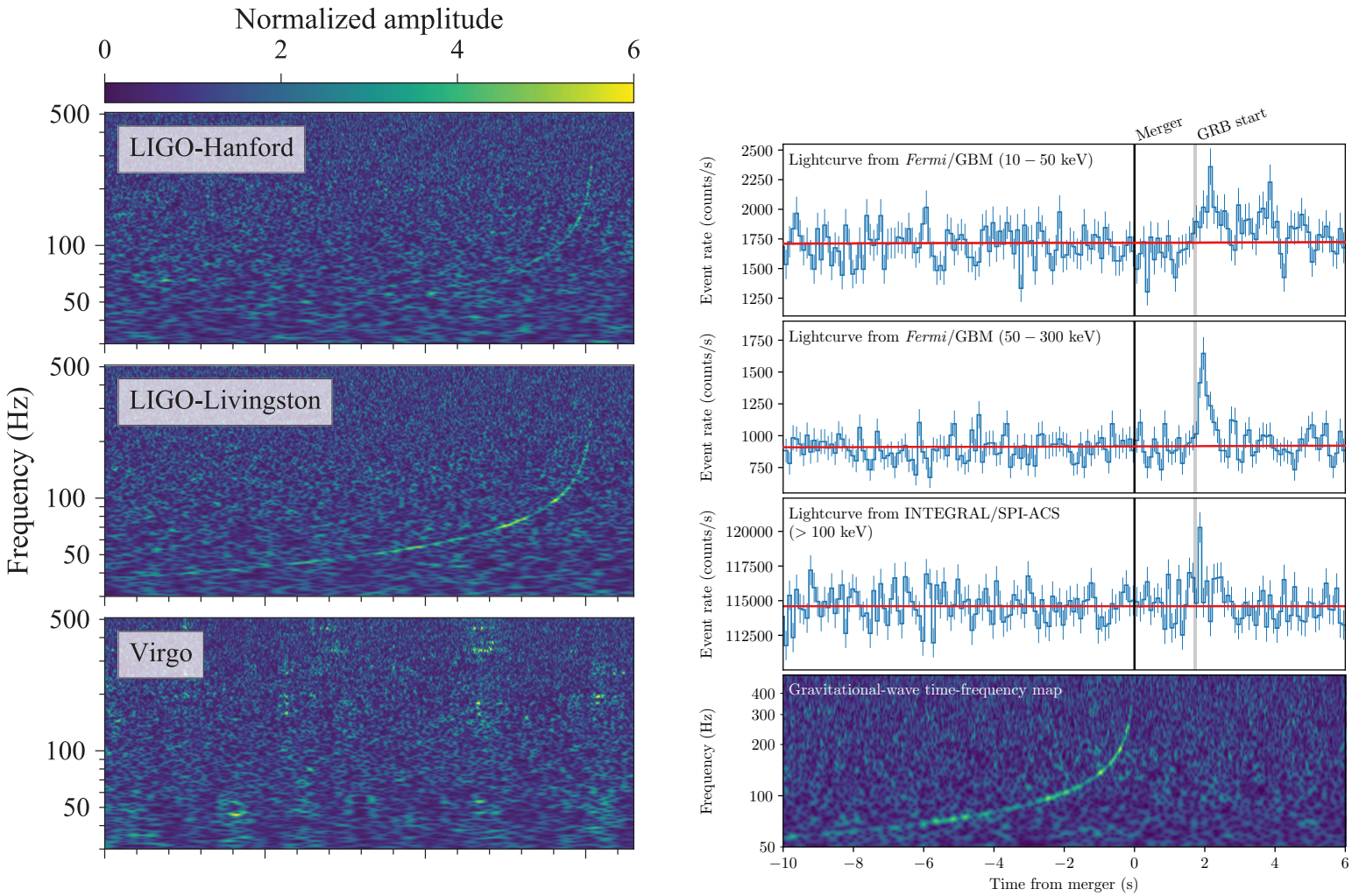
The LIGO Scientific Collaboration and the Virgo Collaboration report:

The online CBC pipeline (gstlal) has made a preliminary
identification of a GW candidate associated with the time of Fermi GBM trigger
524666471/170817529 at gps time 1187008884.47 (Thu Aug 17 12:41:06 GMT 2017) with
RA=186.62deg Dec=-48.84deg and an error radius of 17.45deg.

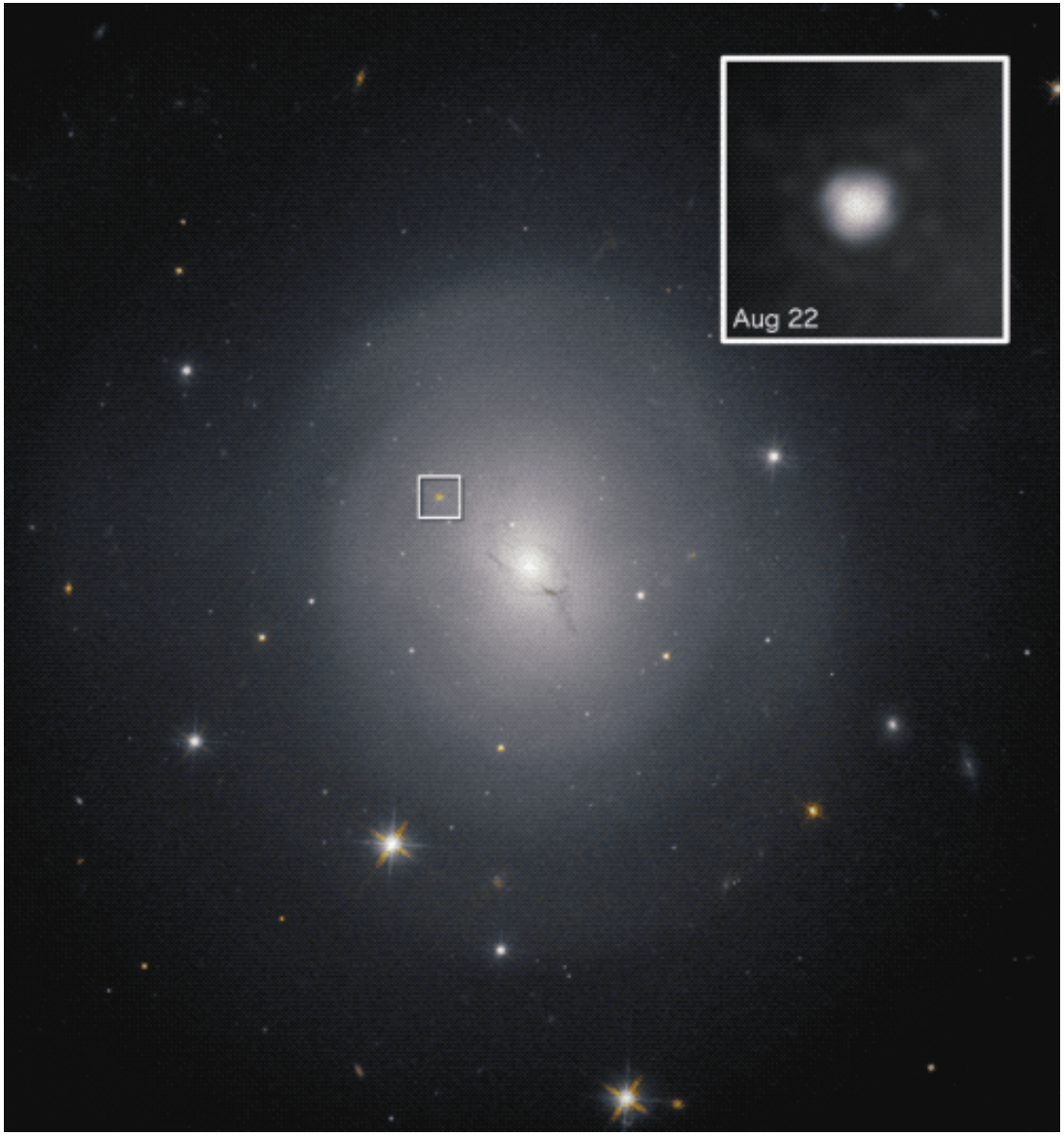
The candidate is consistent with a neutron star binary coalescence with
False Alarm Rate of ~1/10,000 years.

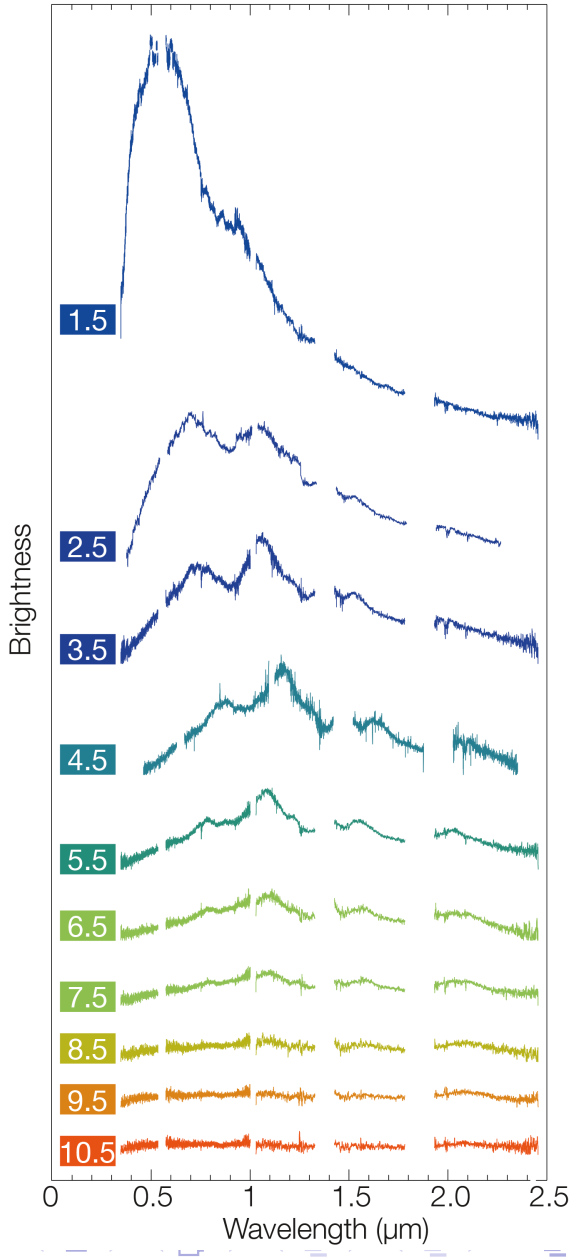
An offline analysis is ongoing. Any significant updates will be provided
by a new Circular.
```

GRB 170817

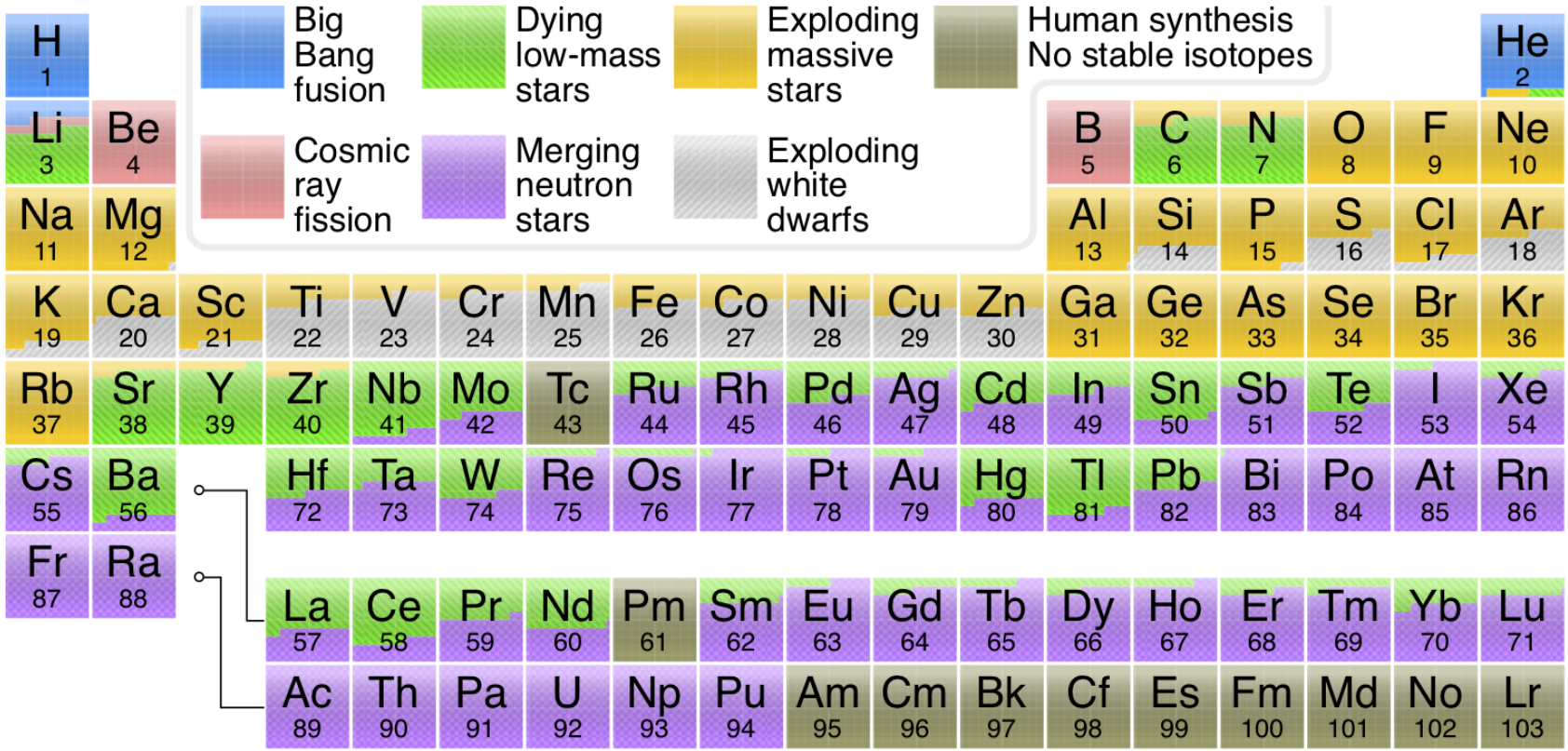

Normalized amplitude
0
2
4
6
LIGO-Hanford
LIGO-Livingston
Virgo
Frequency (Hz)
500
100
50
Merger
GRB start
Lightcurve from Fermi/GBM (10 − 50 keV)
Lightcurve from Fermi/GBM (50 − 300 keV)
Lightcurve from INTEGRAL/SPI-ACS
(> 100 keV)
Event rate (counts/s)
Gravitational-wave time-frequency map
Time from merger (s)

GRB 170817


Aug 22


Brightness
1.5
2.5
3.5
4.5
5.5
6.5
7.5
8.5
9.5
10.5
0
0.5
1
1.5
2.0
2.5
Wavelength (μm)

Nucleosynthesis



Jennifer Johnson

Full Circle

- Alpher, Bethe and Gamov (1948) argued that the nuclei built up through neutron capture in the expanding "overheated neutral nuclear fluid" after the Big Bang.
- Most of the $r-$process occurs through neutron capture in the expanding "cold neutral nuclear fluid" in neutron-star collisions.

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