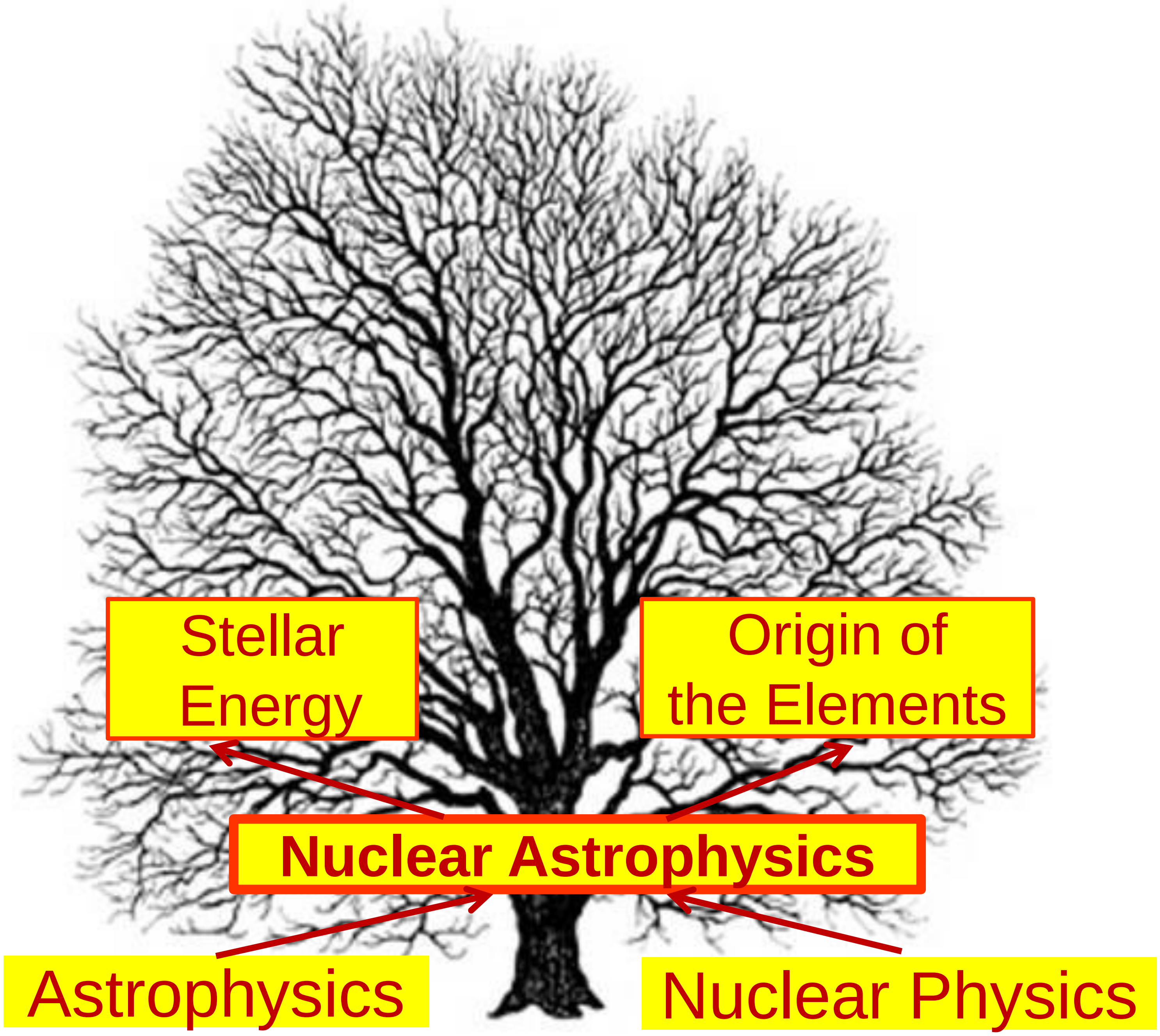
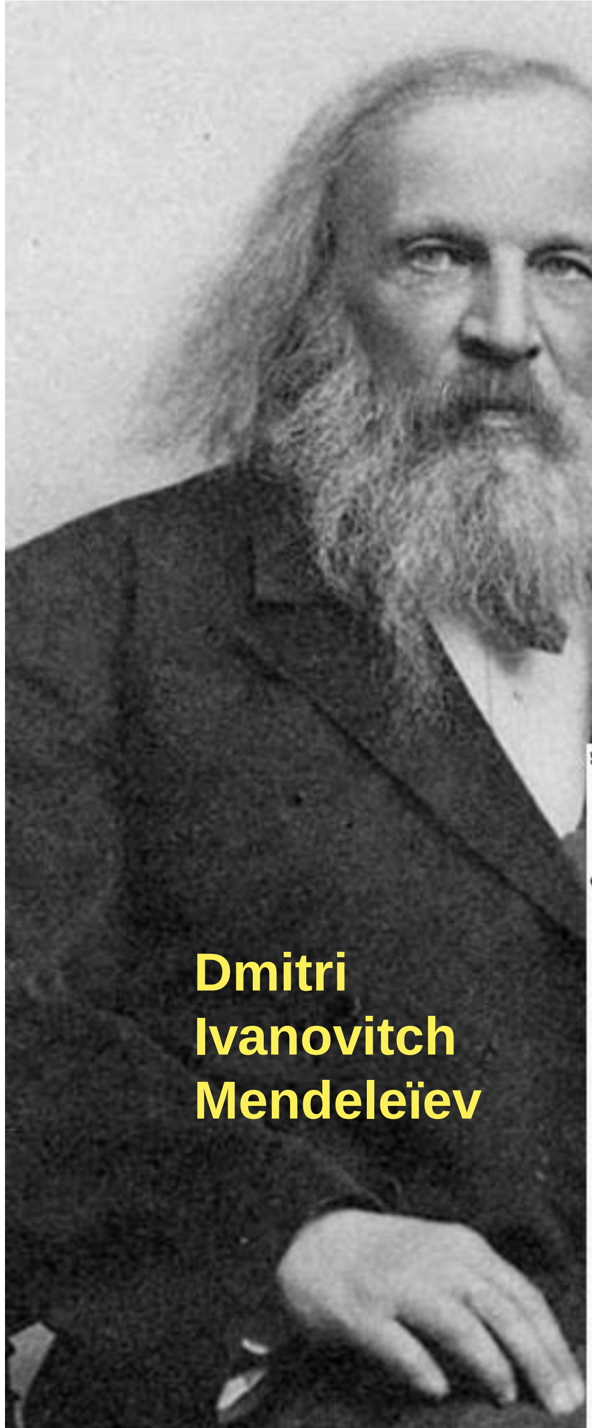
A BRIEF HISTORY OF NUCLEAR ASTROPHYSICS

PART II
THE ORIGIN OF THE ELEMENTS

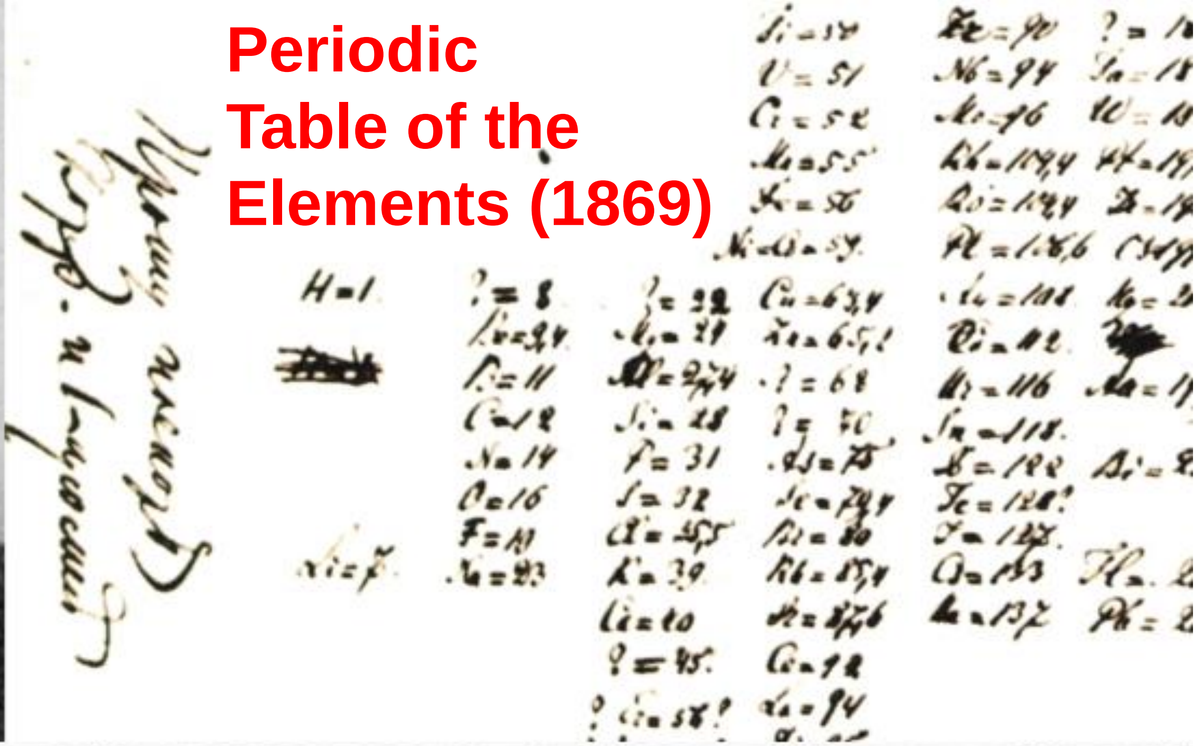
Nikos Prantzos Institut d’Astrophysique de Paris


Stellar Energy
Origin of the Elements
Nuclear Astrophysics
Astrophysics
Nuclear Physics

Periodic Table of the Elements (1869)

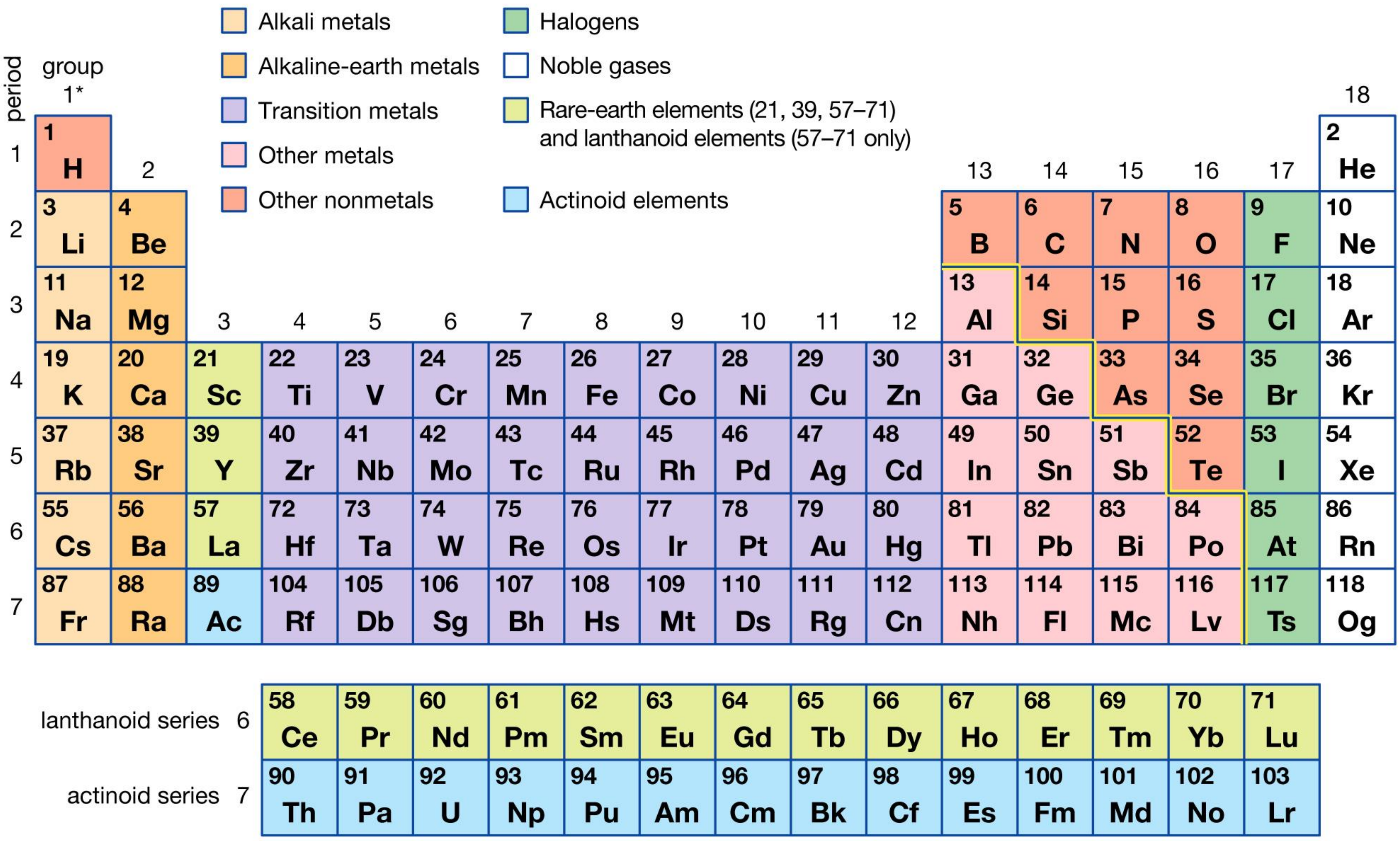


Dmitri Ivanovitch Mendeleïev



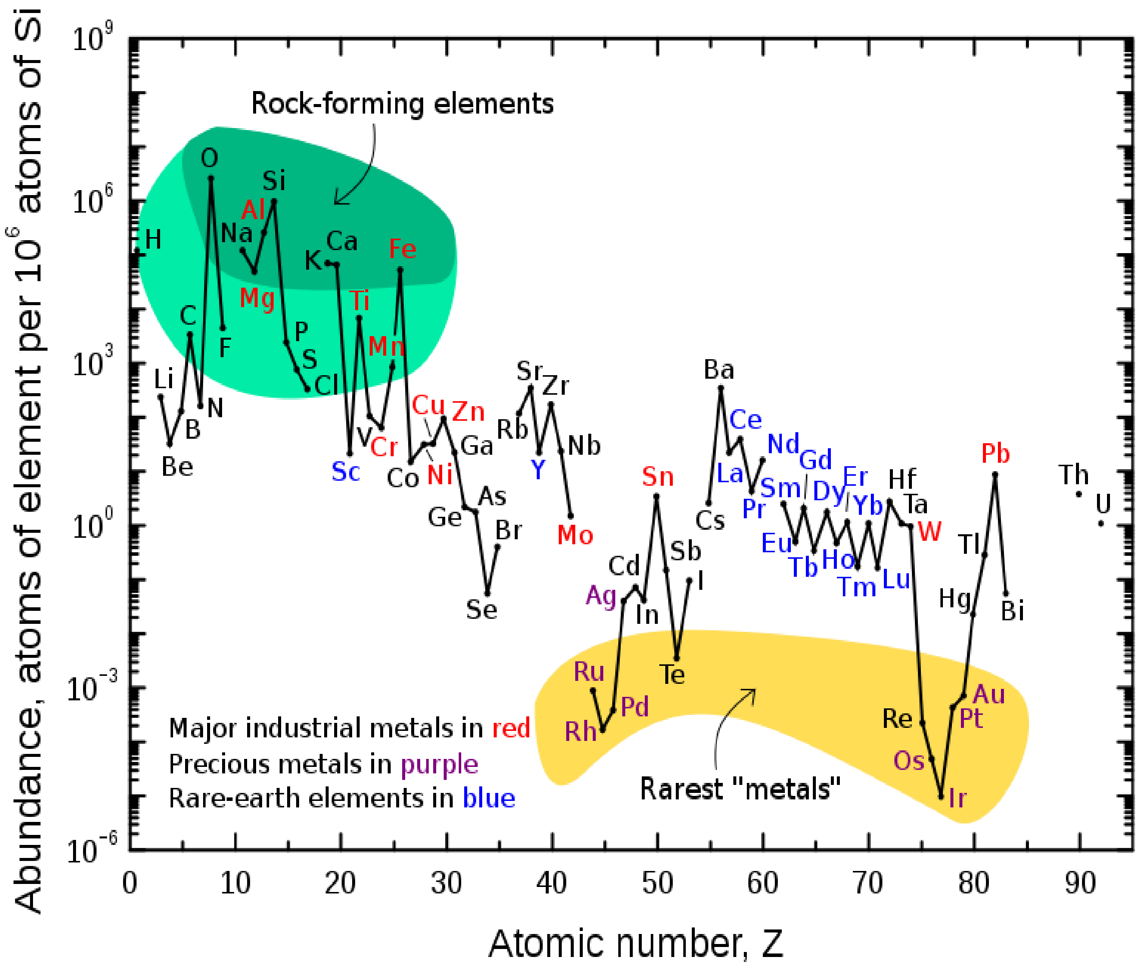
Reihen	Gruppo I. — R^2O	Gruppo II. — RO	Gruppo III. — R^2O^3	Gruppo IV. RH^4 RO^2	Gruppo V. RH^3 R^2O^5	Gruppo VI. RH^2 RO^3	Gruppo VII. RH R^2O^7	Gruppo VIII. — RO^4
1	H=1							
2	Li=7	Be=9,4	B=11	C=12	N=14	O=16	F=19	
3	Na=23	Mg=24	Al=27,3	Si=28	P=31	S=32	Cl=35,5	
4	K=39	Ca=40	—=44	Ti=48	V=51	Cr=52	Mn=55	Fe=56, Co=59, Ni=59, Cu=63.
5	(Cu=63)	Zn=65	—=68	—=72	As=75	Se=78	Br=80	
6	Rb=85	Sr=87	?Yt=88	Zr=90	Nb=94	Mo=96	—=100	Ru=104, Rh=104, Pd=106, Ag=108.
7	(Ag=108)	Cd=112	In=113	Sn=118	Sb=122	Te=125	J=127	
8	Cs=133	Ba=137	?Di=138	?Ce=140	—	—	—	— — — —
9	(—)	—	—	—	—	—	—	
10	—	—	?Er=178	?La=180	Ta=182	W=184	—	Os=195, Ir=197, Pt=198, Au=199.
11	(Au=199)	Hg=200	Tl=204	Pb=207	Bi=208	—	—	
12	—	—	—	Th=231	—	U=240	—	— — — —

Periodic table of the elements

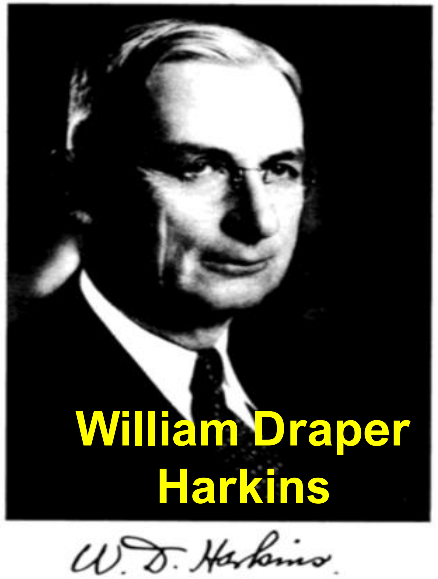


*Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC).

Composition of Earth' crust



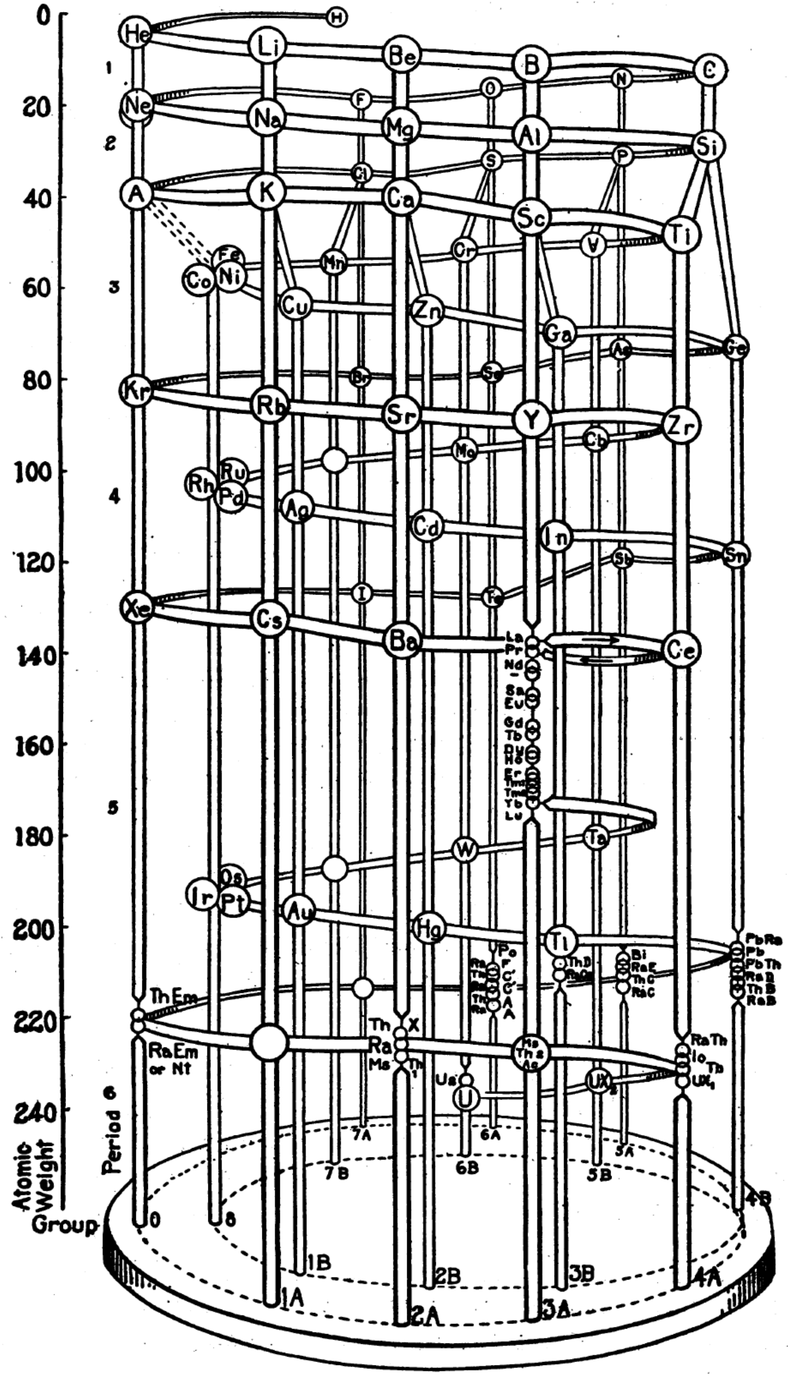
and of meteorites



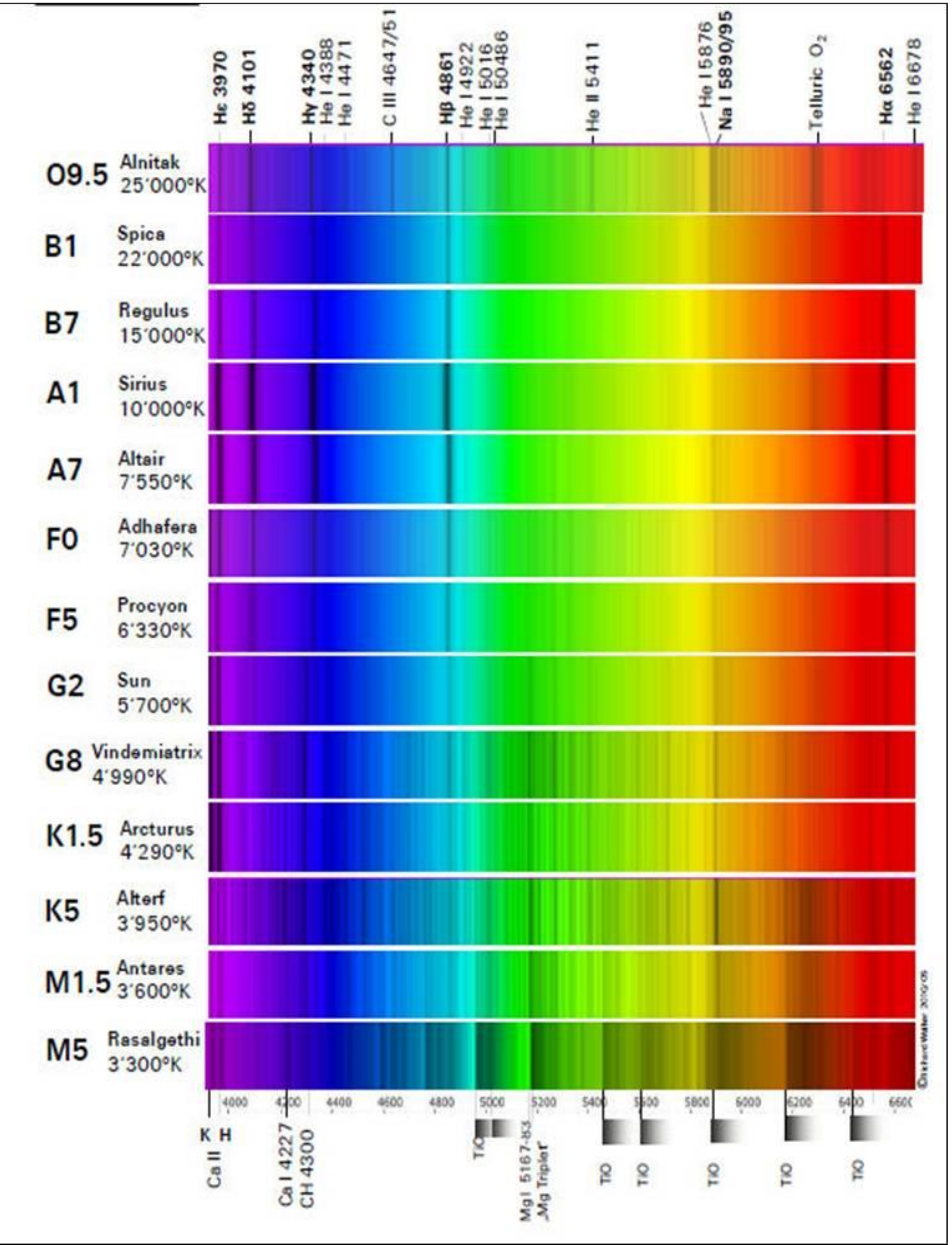
Harkins rule (1915)

« Elements with **even** atomic number are more abundant than their neighbors with **odd** number »

Related to the **structure of nuclei** (proton parity), not to position in Periodic Table



Periodic Table by W.D.Harkins



Stellar spectroscopy reveals the presence of chemical elements in stellar surfaces.

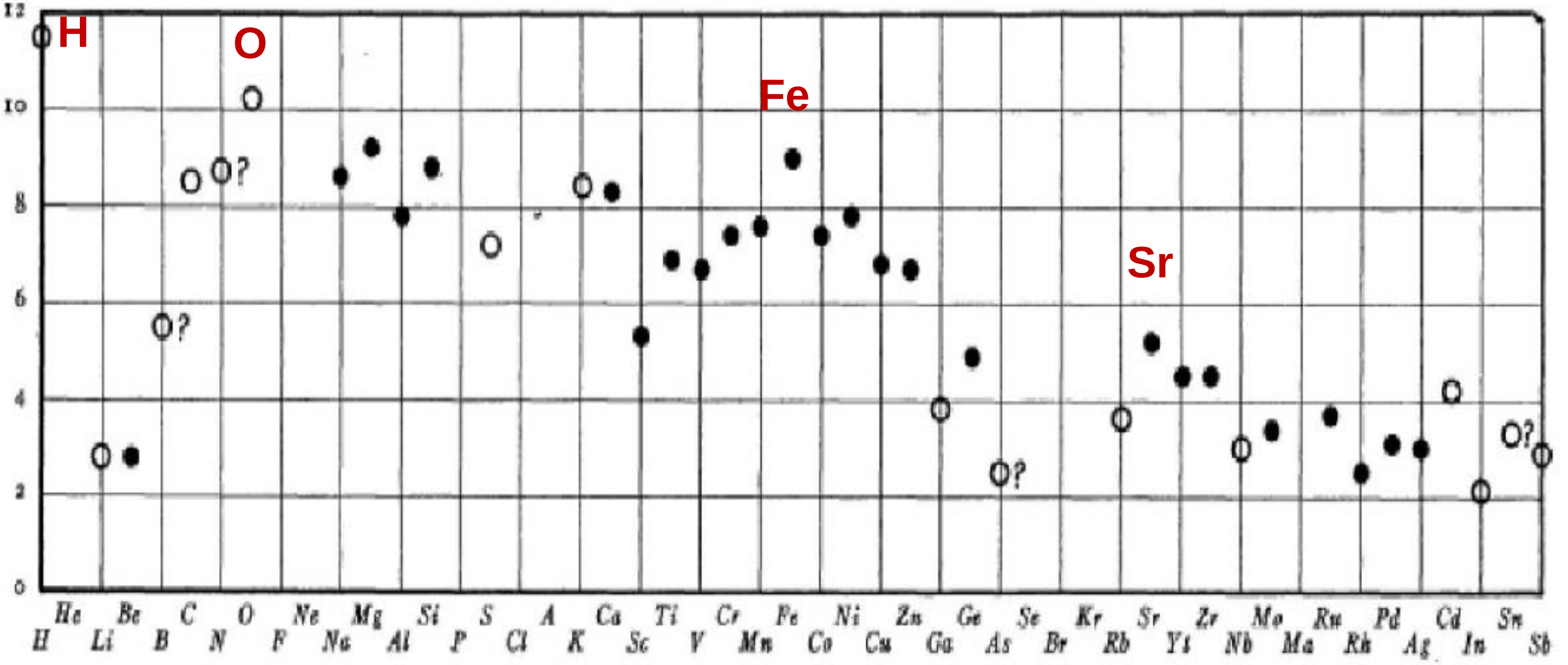
Determination of abundances requires models of stellar atmospheres *(quantum mechanical Saha equation)*

1925: Cecilia Payne
H and He are the most abundant elements in stellar atmospheres

The outstanding discrepancies between the astrophysical and terrestrial abundances are displayed for hydrogen and helium. The enormous abundance derived for these elements in the stellar atmosphere is almost certainly not real. Probably the result may be considered, for hydrogen, as another aspect of its abnormal behavior, already alluded to; and helium, which has some features of astrophysical behavior in common with hydrogen, possibly deviates for similar reasons. [...] The observations on abundances refer merely to the stellar

ON THE COMPOSITION OF THE SUN'S ATMOSPHERE

By HENRY NORRIS RUSSELL[2] (1929)



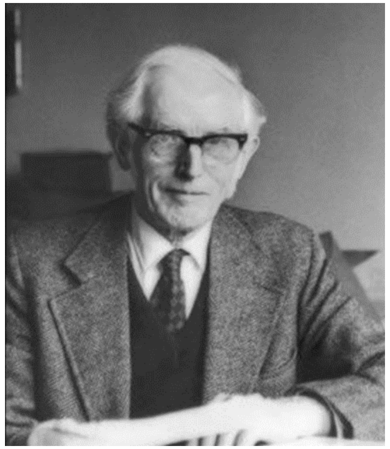
solar atmosphere contains 60 parts of hydrogen (by volume), 2 of helium, 2 of oxygen, 1 of metallic vapors, and 0.8 of free electrons, practically all of which come from ionization of the metals. This great abundance of hydrogen helps to explain a number of previously puzzling astrophysical facts. The temperature of the reversing layer is finally estimated

Harkins rule (1915)
elements with specific properties are more abundant than others:

even vs odd charge

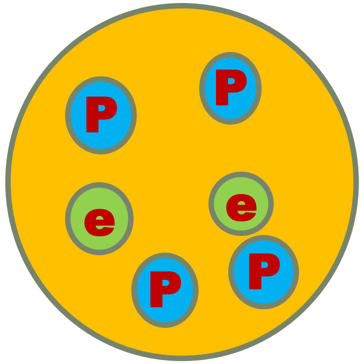
ATOMIC SYNTHESIS AND STELLAR ENERGY. II

ROBERT D'ESCOURT ATKINSON (1931)



ABSTRACT

A *synthesis theory of stellar energy and of the origin of the elements* is developed, in which the various chemical elements are built up step by step from lighter ones in stellar interiors, by the successive incorporation of protons and electrons one at a time. The essential feature is that *helium*, which cannot well be formed in this way, is supposed to be *produced entirely indirectly*, by the spontaneous *disintegration* of unstable nuclei which must first themselves be formed.



Russell has recently shown that the percentage of hydrogen in stars is probably very much greater even at the present time than had generally been supposed; in the sun's atmosphere, for example, sixty out of every sixty-five atoms are hydrogen. Since in addition the hydrogen nucleus is probably much simpler than any other, it seems very reasonable to assume that in its initial state any star, or indeed the entire universe, was composed solely of hydrogen; the

$4\ p^{+} + 2\ e^{-} \Rightarrow$ He-4

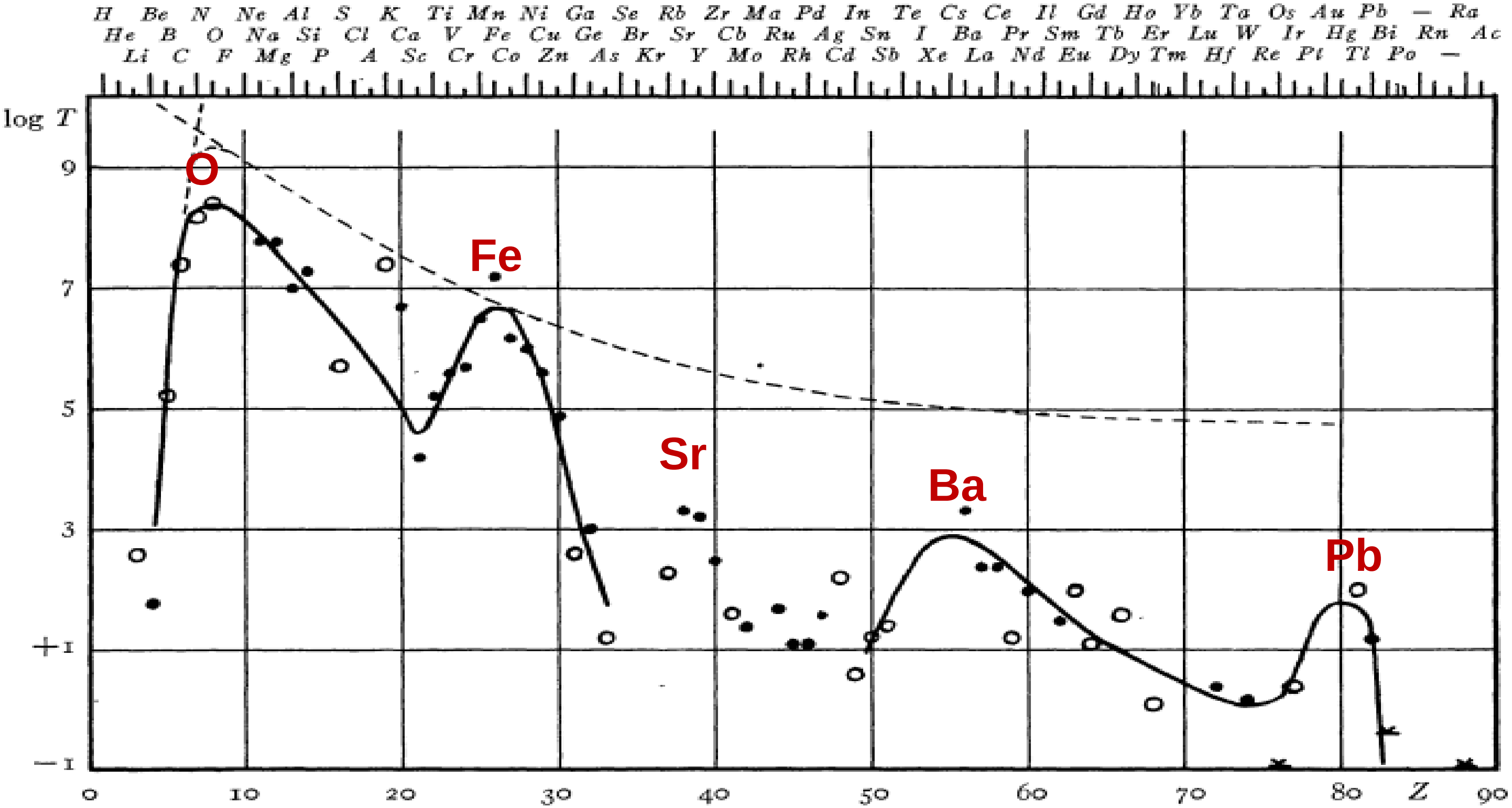
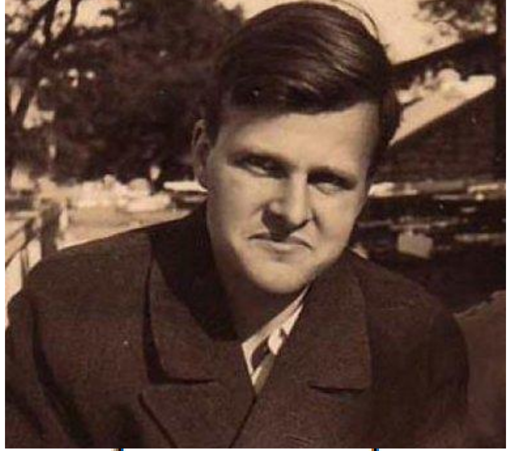


FIG. 2.—Amount of the elements in the sun's atmosphere. (After Russell; ordinates at odd Z values in-

The elements
are made by
nuclear reactions
inside the stars
where they are
observed,
starting by H and He

The *relative proportions of the elements* in stars of the main sequence follow from the theory, in *excellent qualitative agreement* with Russell's figures for the sun. The scarcity of the lightest elements, the principal maximum at a fairly early point, a minimum before the iron group, a maximum in it, a scarcity of all elements above it, and minor maxima in the barium and lead regions all follow (Fig. 2) without any special assumptions, from Gamow's theory of nuclear stability, owing to the peculiarities of the Aston mass-defect curve.



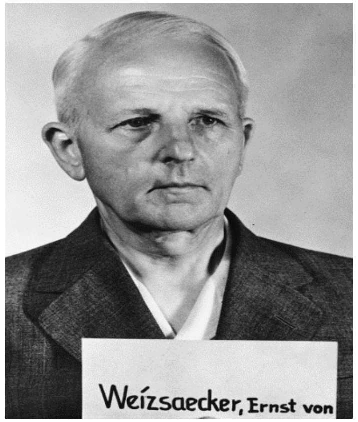
On Elementary Transmutations in the Interior of Stars: Paper II (1937)

Carl Friedrich von Weizsäcker (1912 - 2007)

Are stars making their own elements or is it something else preceding them?

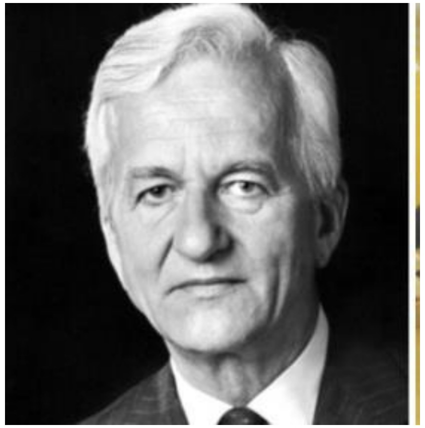
nuclear reactions exert two different influences at the same time: They change the physical state of the matter by releasing energy and its chemical composition by transmuting the elements. The generation of energy is the unproblematic part of the theory to consider: Nuclear reactions or effects of similar energy yield are necessary to explain stellar radiation; and the build-up hypothesis is equivalent to the assumption that the nuclear processes sufficed for that on their own as well. Transmutation of the elements, however, is to a certain extent a side-effect of the nuclear reactions, yet nothing is known about its importance in the history of stellar lifetimes. The empirical frequency distribution of the chemical elements exhibits characteristic regularities apparently quite uniformly valid throughout the entire cosmos, which compel us to attempt to explain it by assuming a uniform formation process. It would suggest itself to look for this process in the element transmutations necessarily connected with the generation of energy in the stars. Yet we cannot exclude at the outset the possibility that the chemical elements were formed by another process prior to the formation of the stars as we know them

The Weizsäcker family



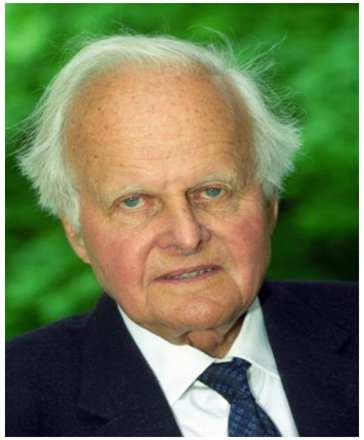
Ernst Heinrich von W.

diplomat, politician
War criminal
after Nuremberg II trial



Richard Karl von W.

Politician
President of German republic
(1984-1993)



Carl Friedrich von W.

Physicist, Philosopher
German research team on
*nuclear weapons in World War **II***

1945: Operation Alsos and the Farm Hall transcripts (released 1993)

Weizsäcker: "*I believe the reason we didn't do it was because all the physicists didn't want to do it, on principle. <u>If we had wanted Germany to win the war we would have succeeded!</u>*"

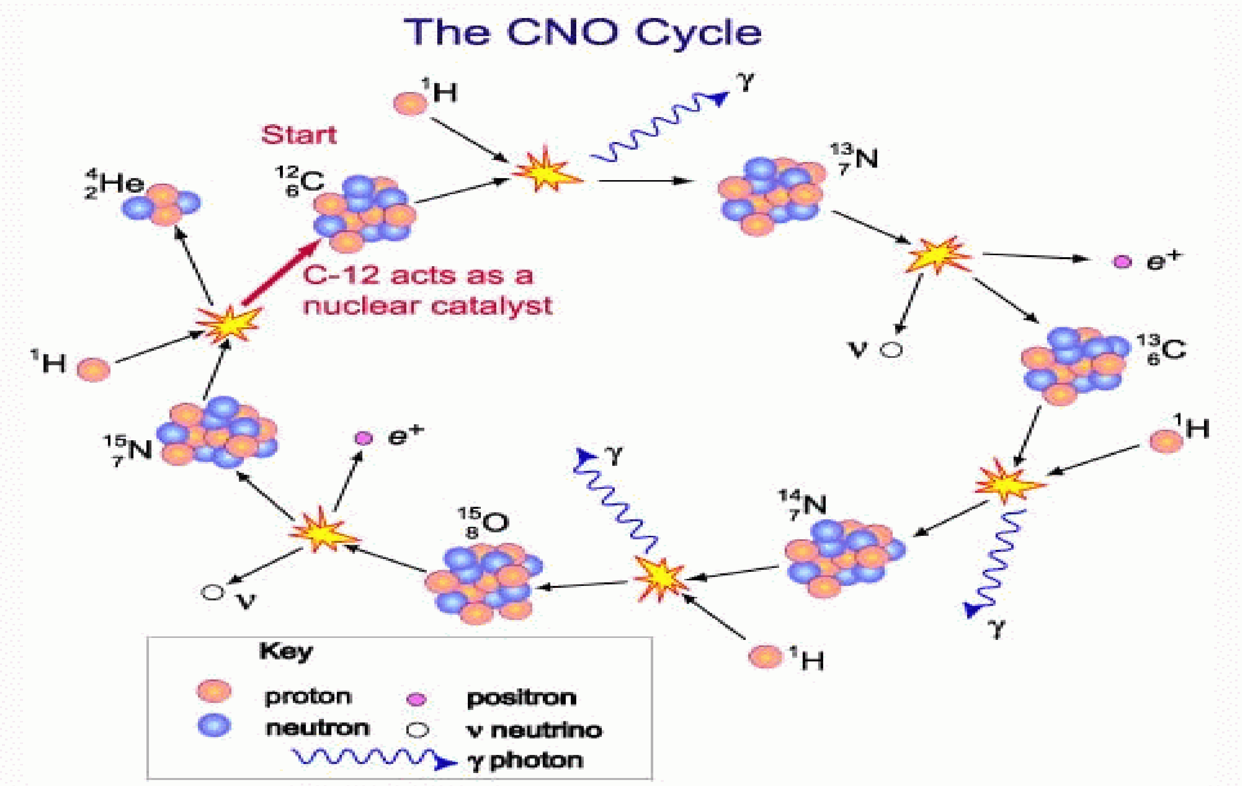
Heisenberg: "*Well, that's not quite right. I would say that I was absolutely convinced of the possibility of our making a uranium engine, but I never thought we would make a bomb and I am glad we did not.*"

Max von Laue called this agreement "*die Lesart*" (the Version) : "*The leader in all these discussions was Weizsäcker. I did not hear any mention of any ethical point of view.*"

Energy Production in Stars*

H. A. Bethe

Cornell University, Ithaca, New York



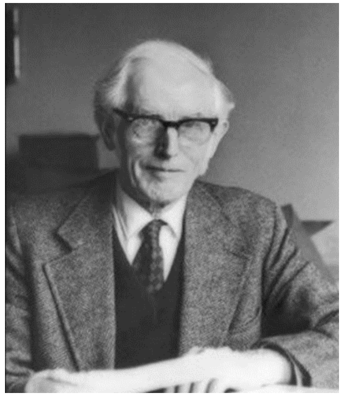
It is shown further (§5–6) that *no elements heavier than He^4 can be built up in ordinary stars.* This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Early studies and ideas about the origin of the elements (up to 1940)

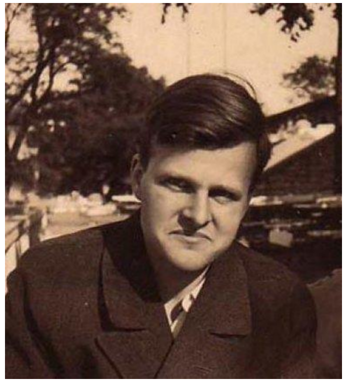
1915: William Harkins
Even elements on Earh's crust are more abundant than adjacent odd ones due to the structure of their nuclei

1925: Cecilia Payne
Stars are made mostly of Hydrogen

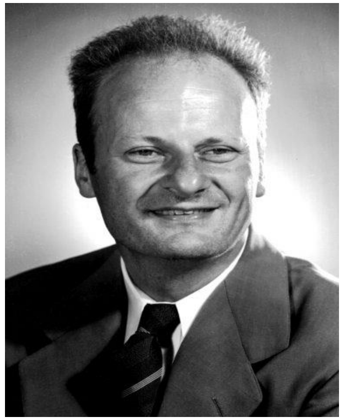
1929: Henri Norris Russell
Stellar abundances display specific regularities, similar to those on Earth



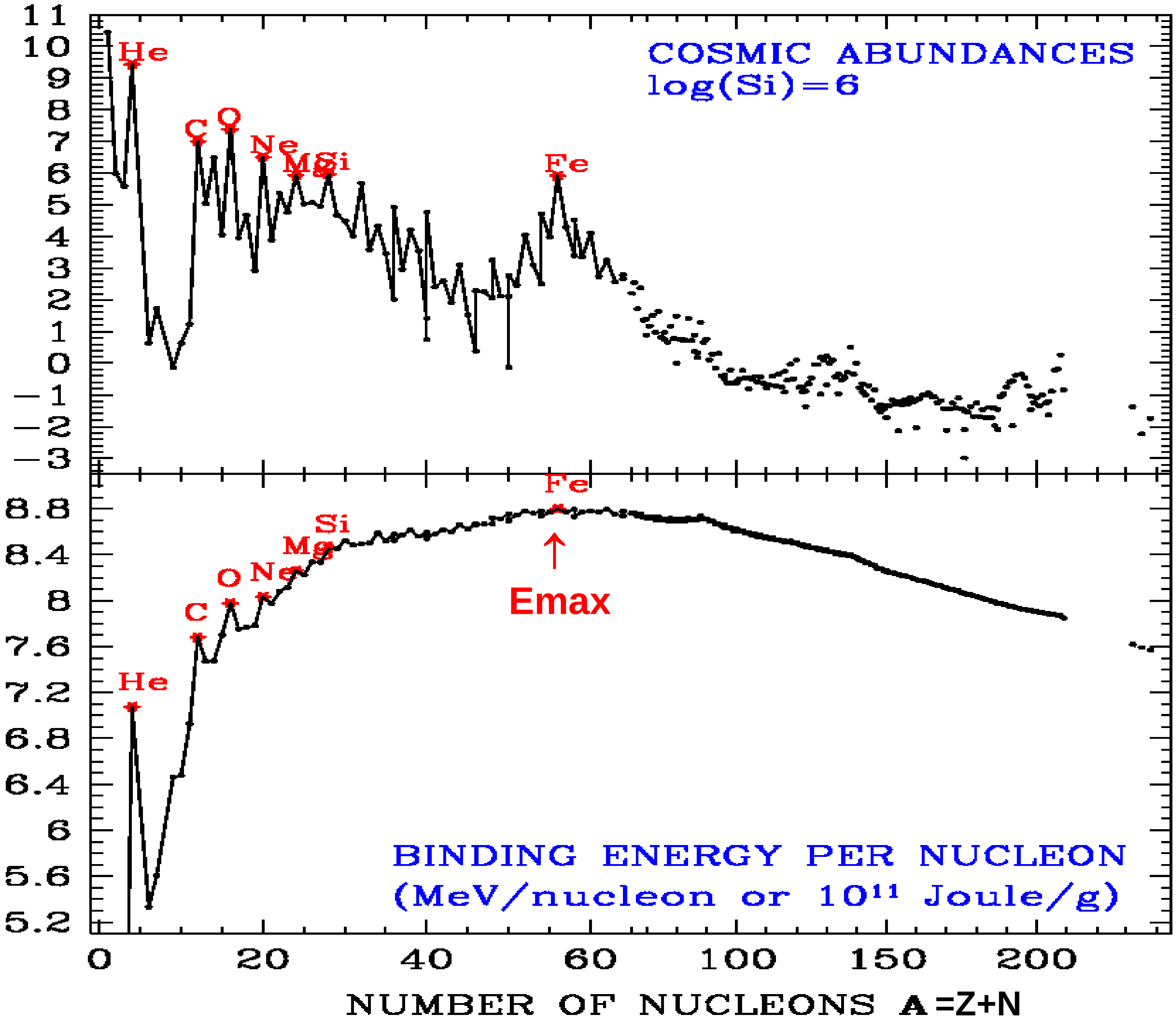
1931: Robert Atkinson
Stars build up their elements in their interiors by pre-existing Hydrogen (except for He !)



1937: Carl F. von Weizsäcker
perhaps the elements were made by another universal process, prior to their formation



1939: Hans Bethe
Normal stars cannot built in their interiors elements heavier than Helium.



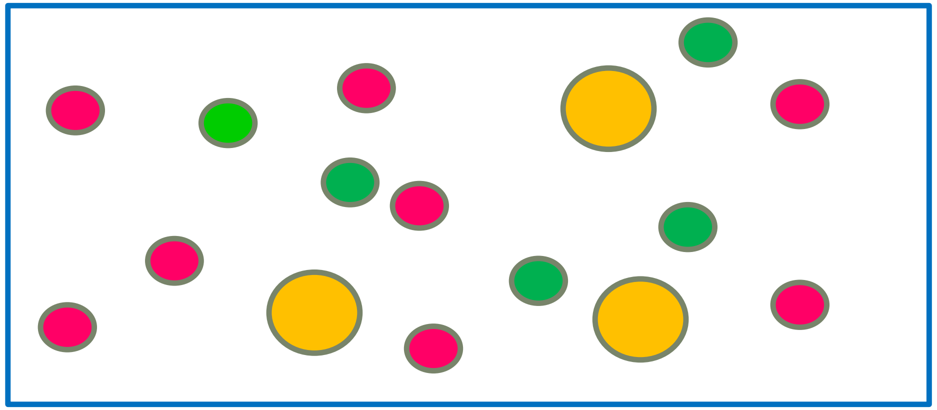
Cosmic abundances of nuclides are locally correlated with **nuclear stability** (*Binding energy per nucleon):*

alpha-nuclei (A=multiple of 4),
"magic" nuclei,
Fe peak nuclei or
nuclei with even A or Z
are more abundant than their neighbors

Nuclear processes have shaped the cosmic abundances of the chemical elements

WHERE ? HOW ?

Nuclear Reactions



System of interacting nuclei at temperature T and density ρ evolving for lapse of time L

Nuclear reactions A + B ⇒ C + D proceeding at rate R

1. R >> 1/L : All direct and inverse reactions proceed very fast : A + B ⇔ C + D

Nuclear statistical equilibrium

$$X_i(A_i, Z_i, T, \rho) = \frac{A}{N_A \rho}\omega(T)\left(\frac{2\pi kTM(A_i,Z_i)}{h^2}\right)^{3/2}\exp\left[\frac{\mu(A_i,Z_i)+\boxed{B(A_i,Z_i)}}{kT}\right]$$

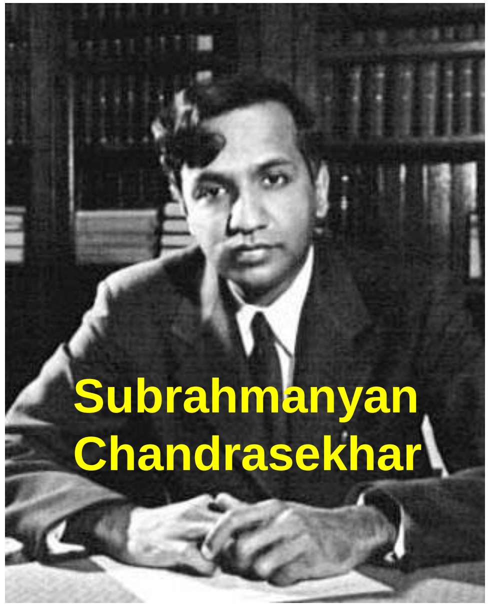
Abundances of nuclei depend on T, ρ and their binding energies B

2. R =< 1/L : Reactions proceed slowly : A + B ⇒ C + D

Abundances of nuclei depend on reaction rates R(T, ρ)
and are coupled to the abundances of all other nuclei of the system
Time-dependent treatment required

AN ATTEMPT TO INTERPRET THE RELATIVE ABUNDANCES OF THE ELEMENTS AND THEIR ISOTOPES

S. CHANDRASEKHAR AND LOUIS R. HENRICH 1942

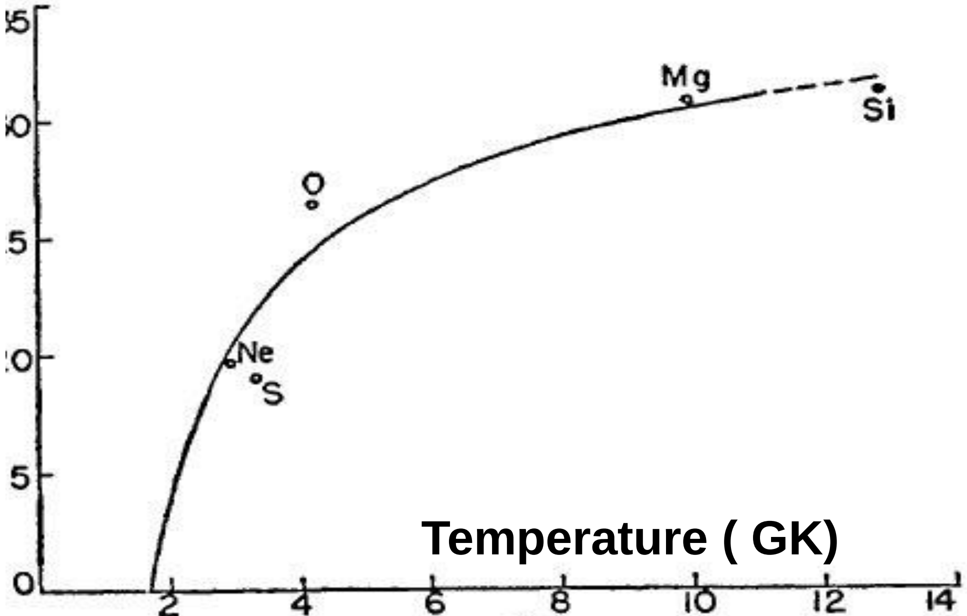


1. *Introduction.*—It is now generally agreed that the chemical elements cannot be synthesized under conditions now believed to exist in stellar interiors. Consequently, the question of the origin of the elements is left open. On the other hand, the striking regularities which the relative abundances of the elements and their isotopes reveal (e.g., Harkins' rule) require some explanation. It has therefore been suggested that the elements were formed at an earlier, *prestellar*, stage of the universe.

discussion of this problem by von Weizsäcker[1] has indicated that we should distinguish at least two distinct epochs in the prestellar state: an initial epoch of extreme density and temperature, when the heaviest elements, like gold and lead, were formed; and a later epoch of relatively "moderate" conditions, during which the present relative abundances of the lighter elements beyond oxygen (to at least sulphur, as we shall see in

Starting at temperature T~10 GK (10 10^9 K)
and density ρ~10^8 g/cc built nuclei around Si
In conditions of nuclear equilibrium
A + B $\Leftrightarrow$ *C +* D
then at lower T and ρ built lighter nuclei

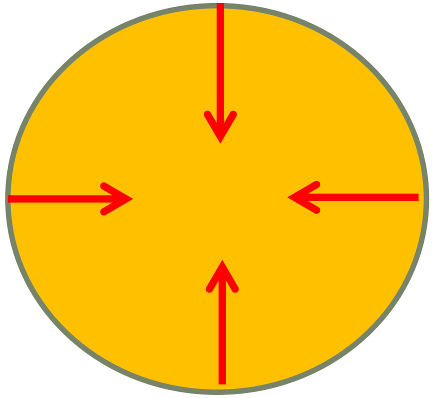
But Fe and heavier nuclei NEVER produced



THE SYNTHESIS OF THE ELEMENTS FROM HYDROGEN

F. Hoyle

(Received 1946 April 6 †)



Elements are made inside stars, but not inside those where they are observed !

Summary

Stars that have exhausted their supply of hydrogen in regions where thermonuclear reactions are important enter a collapsing phase. If the mass of the star exceeds Chandrasekhar's limit collapse will continue until rotational instability occurs. Rotational instability enables the star to throw material off to infinity. This process continues until the mass of the remaining stellar nucleus becomes of the order of, or less than Chandrasekhar's limit. The nucleus can then attain a white dwarf equilibrium state.

The temperature generated at the centre of a collapsing star is considered and it is shown that values sufficiently high for statistical equilibrium to exist between the elements must occur. The relative abundances of the elements can then be worked out from the equations of statistical mechanics. These equations are considered in detail and it is shown that a roughly uniform abundance of the elements over the whole of the periodic table can be obtained. The process of rotational instability enables the heavy elements built up in collapsing stars to be distributed in interstellar space.

They are first dispersed in interstellar space, to form new stars

But HOW the material gets out of the star ?

Expanding Universe and the Origin of Elements

G. Gamow

The George Washington University, Washington, D. C.

September 13, 1946

It is generally agreed at present that the relative abundances of various chemical elements were determined by physical conditions existing in the universe during the early stages of its expansion, when the temperature and density were sufficiently high to secure appreciable reaction-rates for the light as well as for the heavy nuclei.

Returning to our problem of the formation of elements, we see that *the conditions necessary for rapid nuclear reactions were existing only for a very short time*, so that it may be quite dangerous to speak about an equilibrium-state which must have been established during this period. It is also interesting to notice that the calculated time-period during which rapid nuclear transformations could have taken place is considerably shorter than the β-decay period of free neutrons which is presumably of the order of magnitude of one hour. Thus if free neutrons were present in large quantities in the beginning of the expan-

Lemaître 1927 :
Recession of galaxies explained as due to expansion of the Universe

Einstein to Lemaître:
Your calculations are correct, but your physics is atrocious"

1931:
Explosion of the Primeval Atom

NOT nuclear equilibrium

time-dependent treatment of nuclear reactions is necessary

little time available (less than the time for neutron decay ~1 h)

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland

AND

H. BETHE
Cornell University, Ithaca, New York

AND

G. GAMOW
The George Washington University, Washington, D. C.

February 18, 1948

αβγ

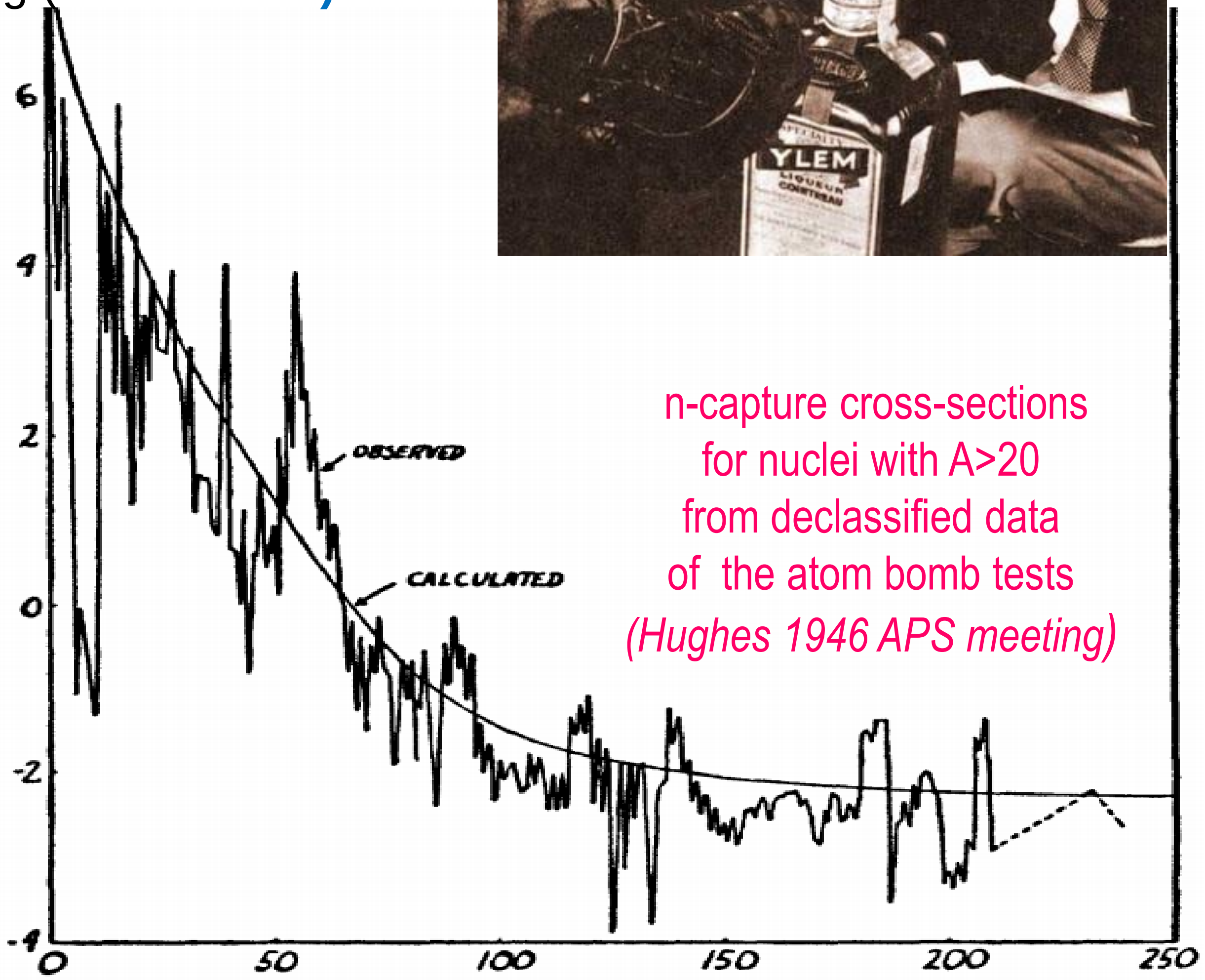
Phys.Rev., April 1st 1948

1 page, 1 equation, 1 figure

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt}=f(t)(\sigma_{i-1}n_{i-1}-\sigma_i n_i) \quad i=1,2,\cdots 238, \qquad (1)$$

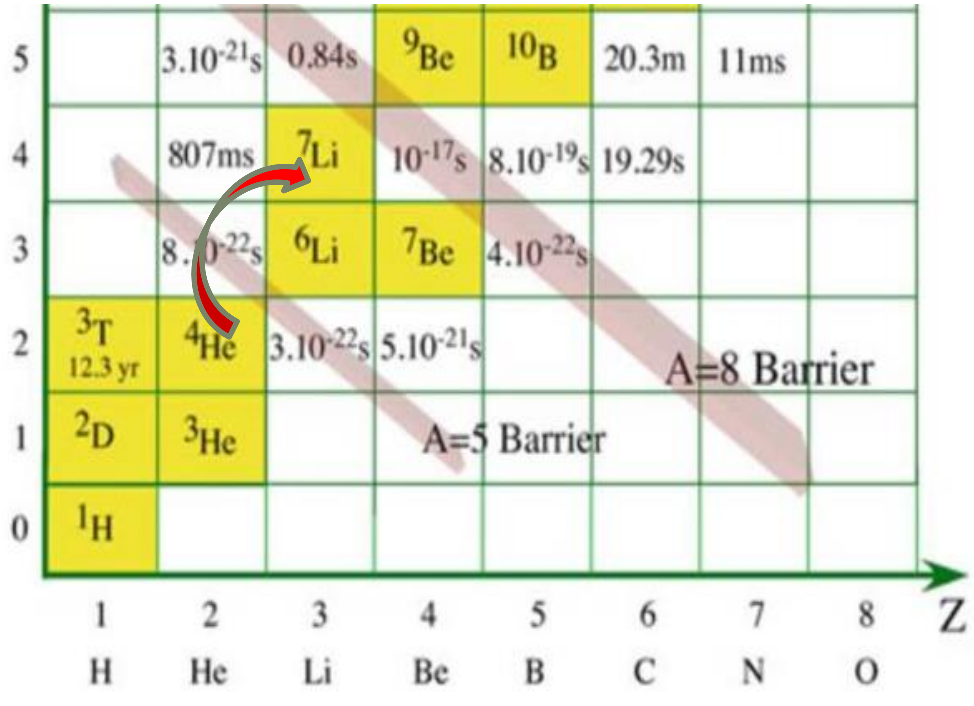
where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.



n-capture cross-sections for nuclei with A>20 from declassified data of the atom bomb tests *(Hughes 1946 APS meeting)*

The Washington Post, 16 April 1948 : "World Began in 5 Minutes, New Theory"

At the very beginning of everything, the universe had infinite density concentrated in a single zero point. Then just 300 seconds – five minutes – after the start of everything, there was a rapid expansion and cooling of the primordial matter. The neutrons – those are the particles that trigger the atomic bomb – started decaying into protons and building up the heavier chemical elements. … This act of creation of the chemical elements took the surprisingly short time of an hour. (The Bible story said something about six days for the act of creation)

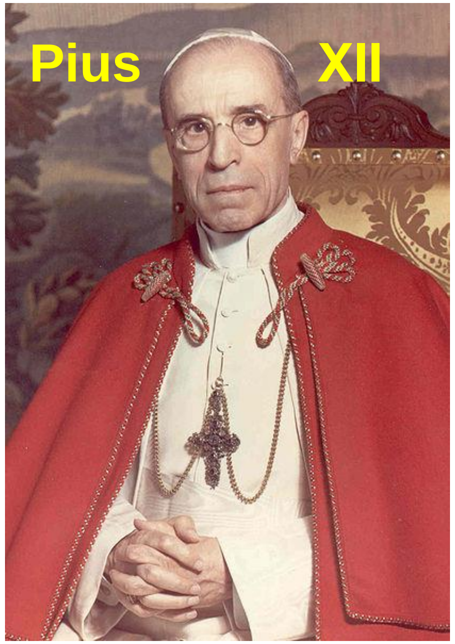


Fermi and Turkevich (1949, unpublished)
No elements beyond He, (Li) because of A=5 (8) gap

Hayashi (1950): At $T \sim 10^{10}$ K : n ⇔ p equilibrium

After the discovery of 3 K microwave background *(Penzias and Wilson 1965):*

Peebles (1966), Wagoner, Fowler and Hoyle (1967)
First calculations of « realistic » Big Bang nucleosynthesis



Address to the Pontifical Academy of Sciences (*September 1951*)

THE PROOFS FOR THE EXISTENCE OF GOD IN THE LIGHT OF MODERN NATURAL SCIENCE

Present-day science, with one sweeping step back across millions of centuries, has succeeded in bearing witness to that primordial *"Fiat lux"* uttered at the moment when, along with matter, there burst forth from nothing a sea of light and radiation, while the particles of chemical elements split and formed into millions of galaxies…

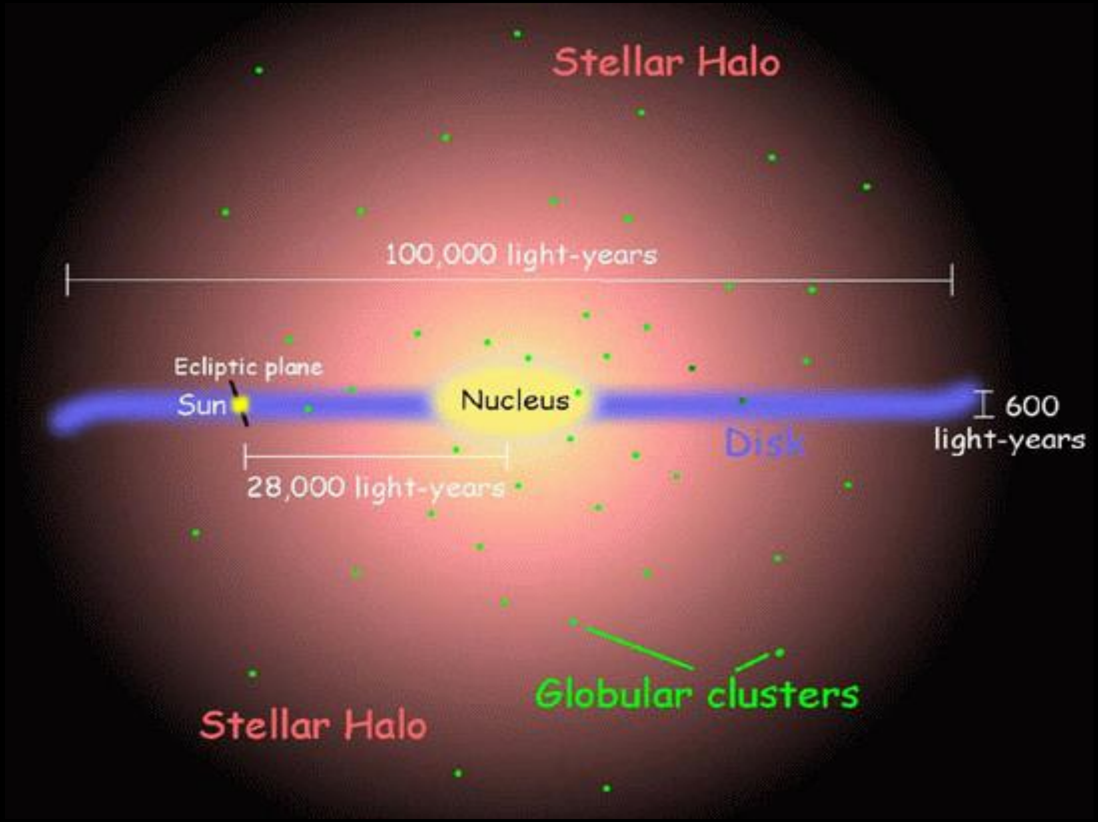
Hence, creation took place in time. Therefore, there is a Creator. Therefore, God exists! Although it is neither explicit nor complete, this is the reply we were awaiting from science, and which the present human generation is awaiting from it.

We may speak of this event as of a beginning. I do not say a creation. Physically it is a beginning in the sense that if something happened before, it has no observable influence on the behavior of our universe, as any feature of matter before this beginning has been completely lost by the extreme contraction at the theoretical zero. The question if it was really a beginning or rather a creation, something started from nothing, is a philosophical question which cannot be settled by physical or astronomical considerations

G. Gamow: all elements were produced
in the hot primordial Universe (Big Bang)
by successive neutron captures

Early 1950ies

F. Hoyle: all elements produced
Inside stars during their collapsing stage,
by thermonuclear reactions



Old stars of galactic halo (Population II)
contain less heavy elements (metals)
than the younger stellar population
(Population I) of the galactic disk
Chamberlain and Aller 1951

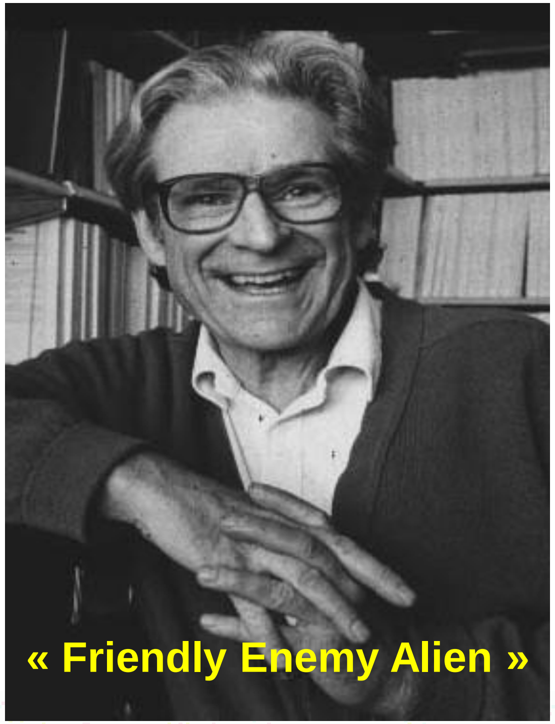
The chemical composition of the Milky Way
was substantially different in the past

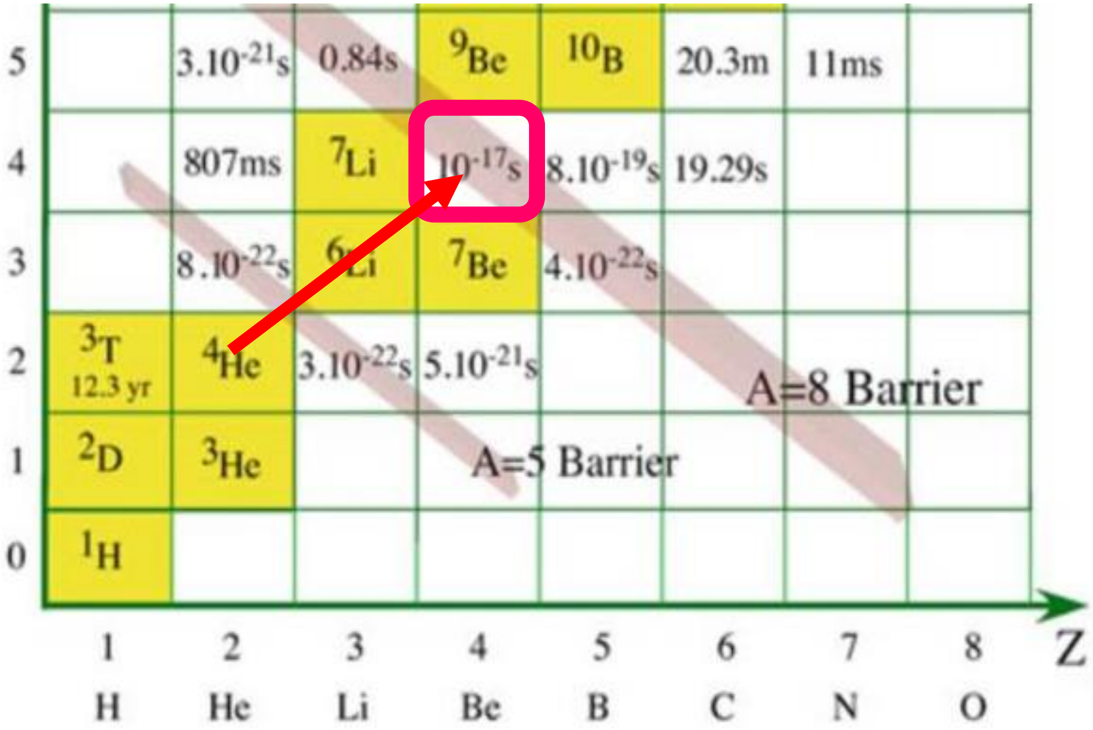
NUCLEAR REACTIONS IN STARS WITHOUT HYDROGEN*

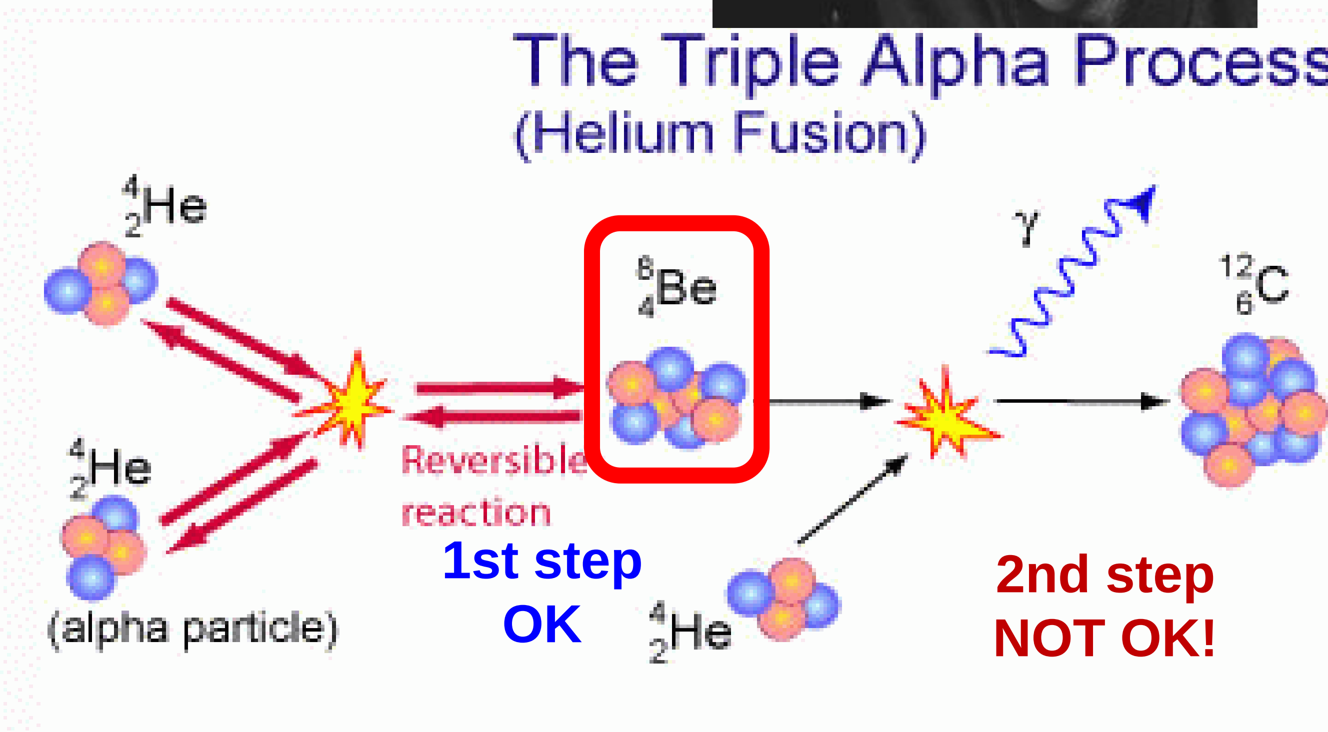
E. E. Salpeter

Laboratory of Nuclear Studies
Cornell University
October 2, 1951

verted into helium by means of the carbon-nitrogen cycle. When the energy supply of the carbon-nitrogen cycle has been exhausted, the star undergoes gravitational contraction, and its temperature increases. Various nuclear processes[1, 2, 3] have been suggested for such a contracting star, all of which require temperatures of well over $10^{9°}$ K. The main aim of this note is to point out that there is one nuclear process which takes place at a much lower temperature of about $2 \times 10^{8°}$ K, namely, the conversion of three helium nuclei into one carbon nucleus.



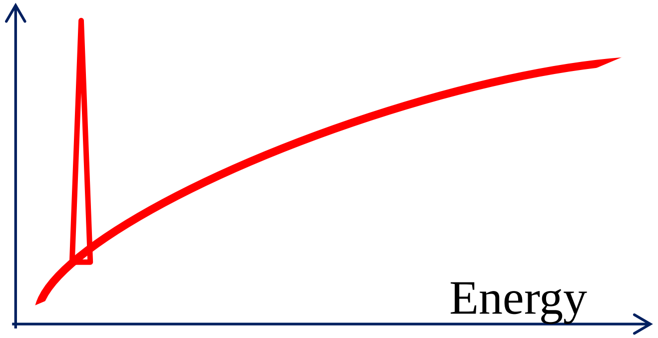


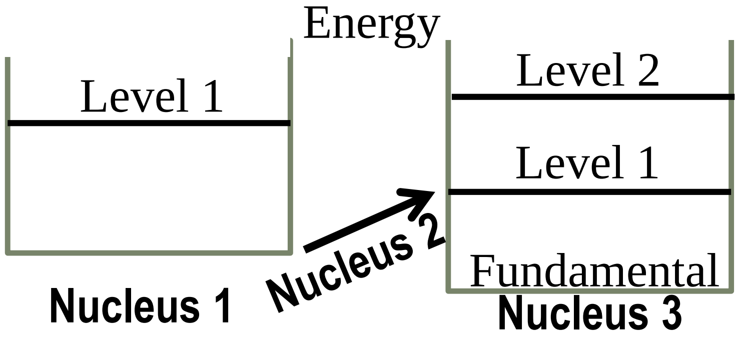


Formation and survival of C-12 in He-burning

Probability of nuclear reaction

It becomes very high when the reaction is resonant

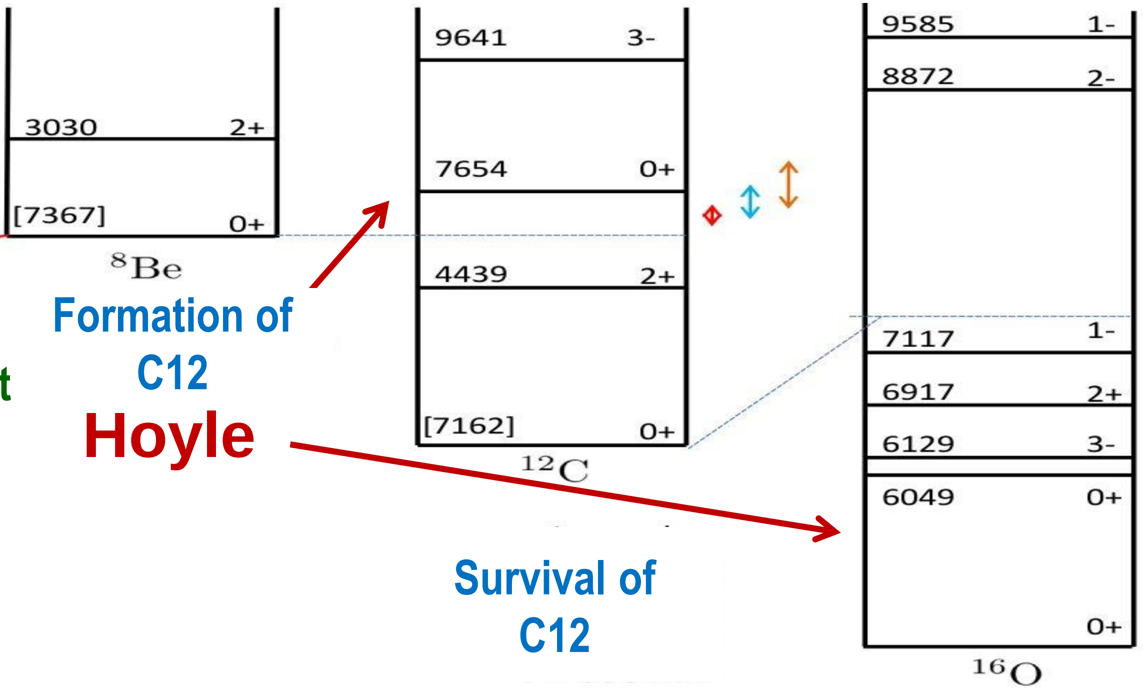




Salpeter

Formation of Be8

$\alpha + \alpha$



Formation of C12

Hoyle

Survival of C12

Fred Hoyle suggests that the reaction Be8 + α ⇒ C12 is resonant because of the existence of a *nuclear energy level at 7.7 MeV* *(unknown at that time)* in C12

The level is found in William Fowler's Kellog laboratory in 1953

First quantitative prediction of a microscopic property of matter (structure of C12 nucleus) from a macroscopic one (abundances of C12 and O16)

1st and only « prediction » of the Anthropic Principle ?

Formation of Carbon (C-12)

PHYSICAL REVIEW VOLUME 92, NUMBER 3 NOVEMBER 1, 1953

The 7.68-Mev State in C^{12}

D. N. F. Dunbar,* R. E. Pixley, W. A. Wenzel, and W. Whaling
Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California

(Received July 21, 1953)

Magnetic analysis of the alpha-particle spectrum from $N^{14}(d,\alpha)C^{12}$ covering the excitation energy range from 4.4 to 9.2 Mev in C^{12} shows a level at 7.68 ± 0.03 Mev. At $E_d=620$ kev, $\theta_{lab}=90°$, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

Salpeter[1] and Öpic[2] have pointed out the importance of the $Be^8(\alpha,\gamma)C^{12}$ reaction in hot stars which have largely exhausted their central hydrogen. Hoyle[3] explains the original formation of elements heavier than helium by this process and concludes from the observed cosmic abundance ratios of $O^{16}:C^{12}:He^4$ that this reaction should have a resonance at 0.31 Mev or at 7.68 Mev in C^{12}.

An early measurement of the range of the alpha particles from $N^{14}(d,\alpha)C^{12}$ indicated a level in C^{12} at 7.62 Mev.[4] However, a recent magnetic analysis of this reaction failed to detect a transition to any level in this region of excitation,[5] nor did the level show up in the neutron spectrum[6] from $B^{11}(d,n)C^{12}$. From the

* On leave from the University of Melbourne, Melbourne, Australia.

[1] E. E. Salpeter, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 41.

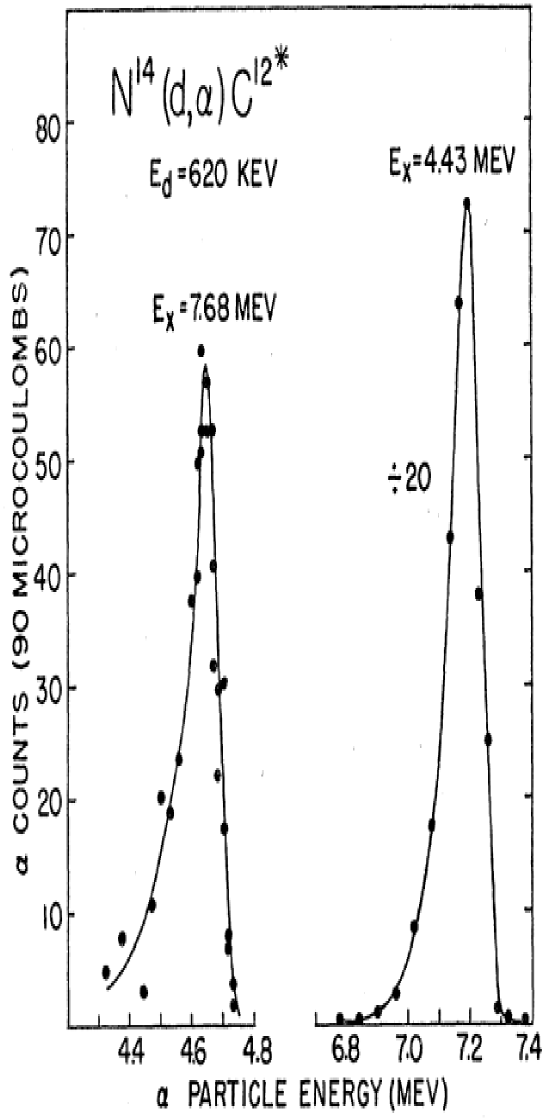
[2] E. J. Öpic, Proc. Roy. Irish Acad. **A54**, 49 (1952).

[3] F. Hoyle (private communication).

[4] M. G. Holloway and B. L. Moore, Phys. Rev. **58**, 847 (1940).

[5] R. Malm and W. W. Buechner, Phys. Rev. **81**, 519 (1951).

[6] W. M. Gibson, Proc. Phys. Soc. (London) **A62**, 586 (1949); V. R. Johnson, Phys. Rev. **86**, 302 (1952).



ON NUCLEAR REACTIONS OCCURRING IN VERY HOT STARS. I. THE SYNTHESIS OF ELEMENTS FROM CARBON TO NICKEL

F. Hoyle* (1954)

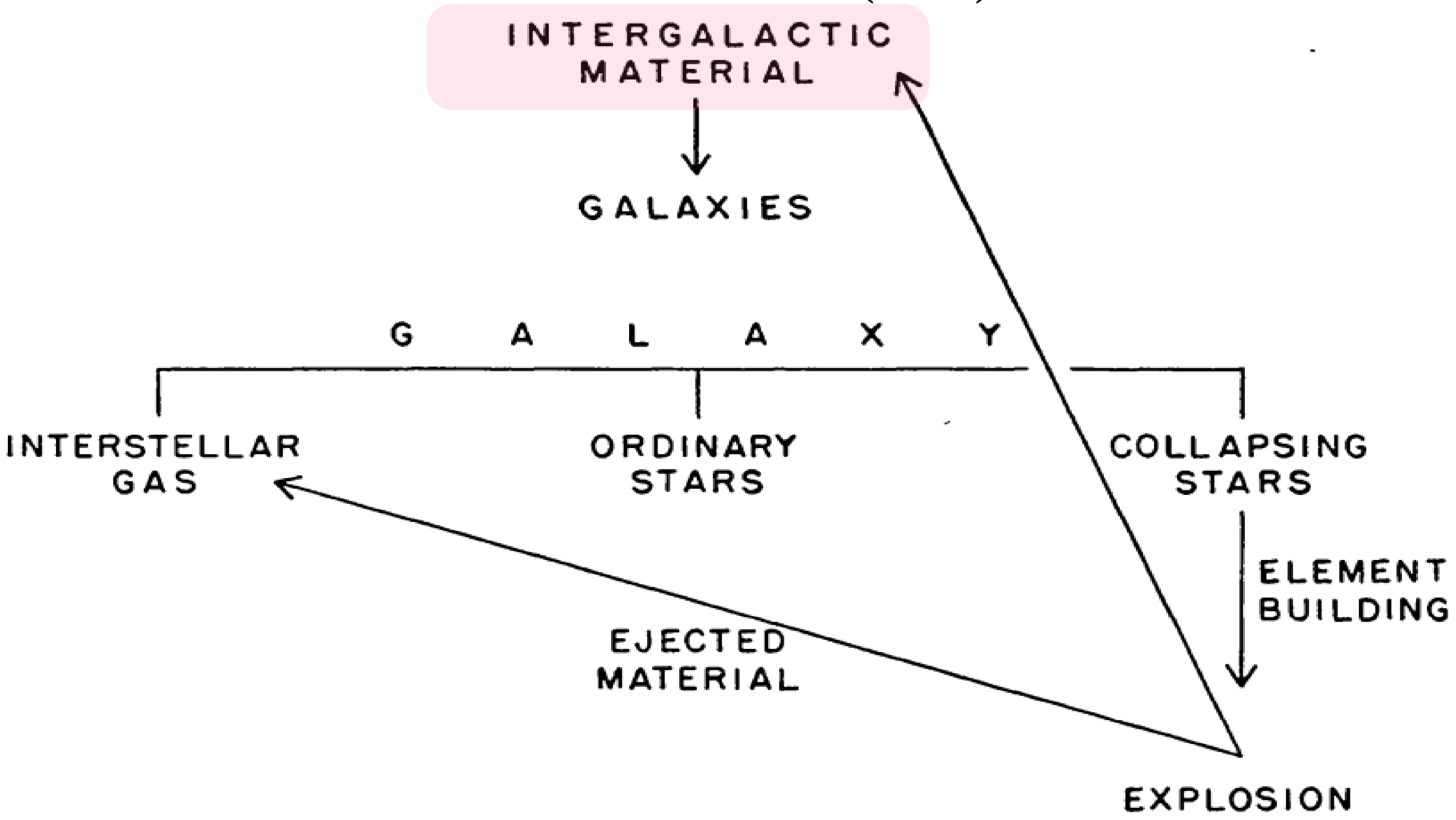
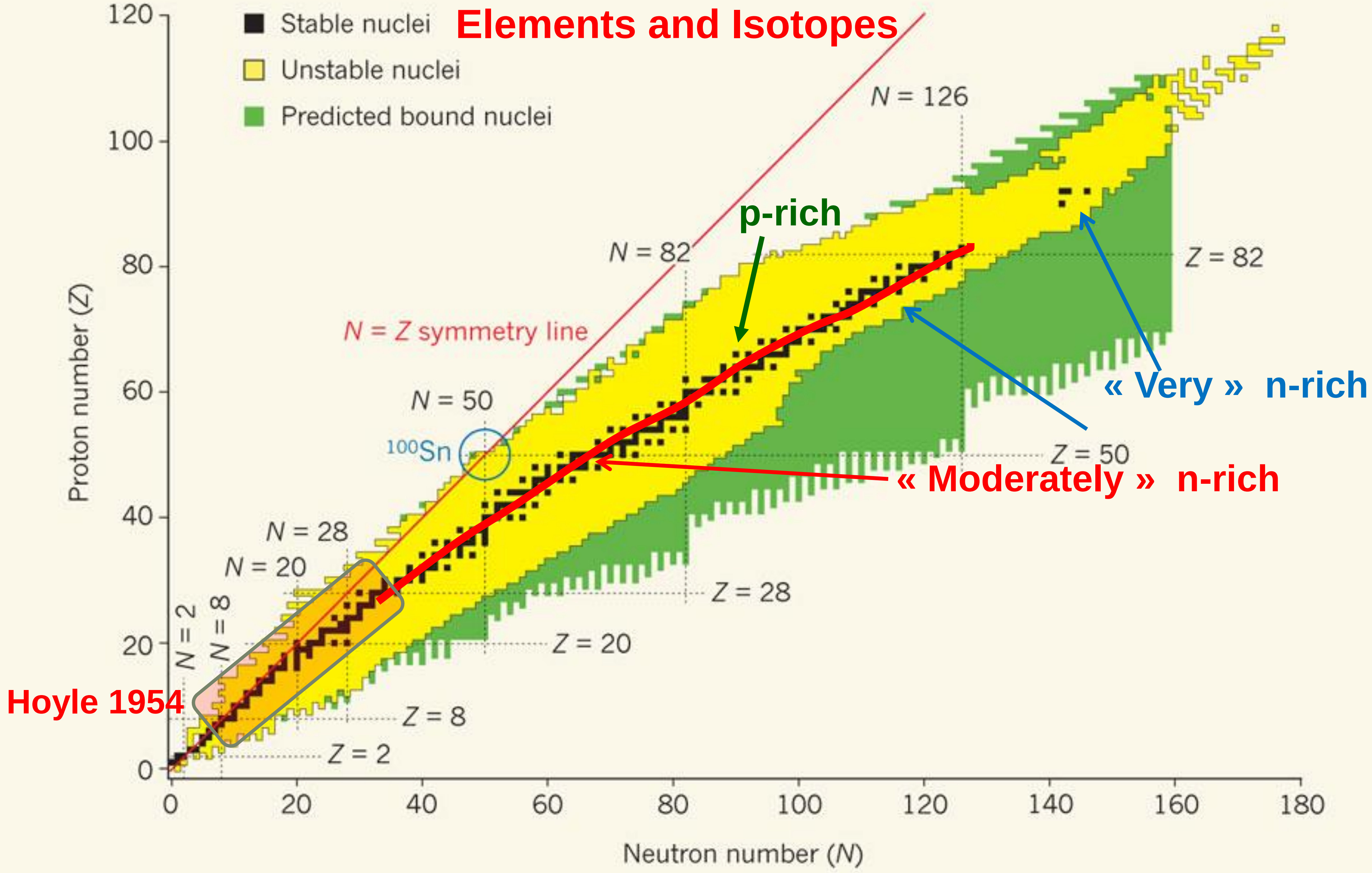


Fig. 1.—The general cosmological framework assumed for this discussion

Elements and Isotopes



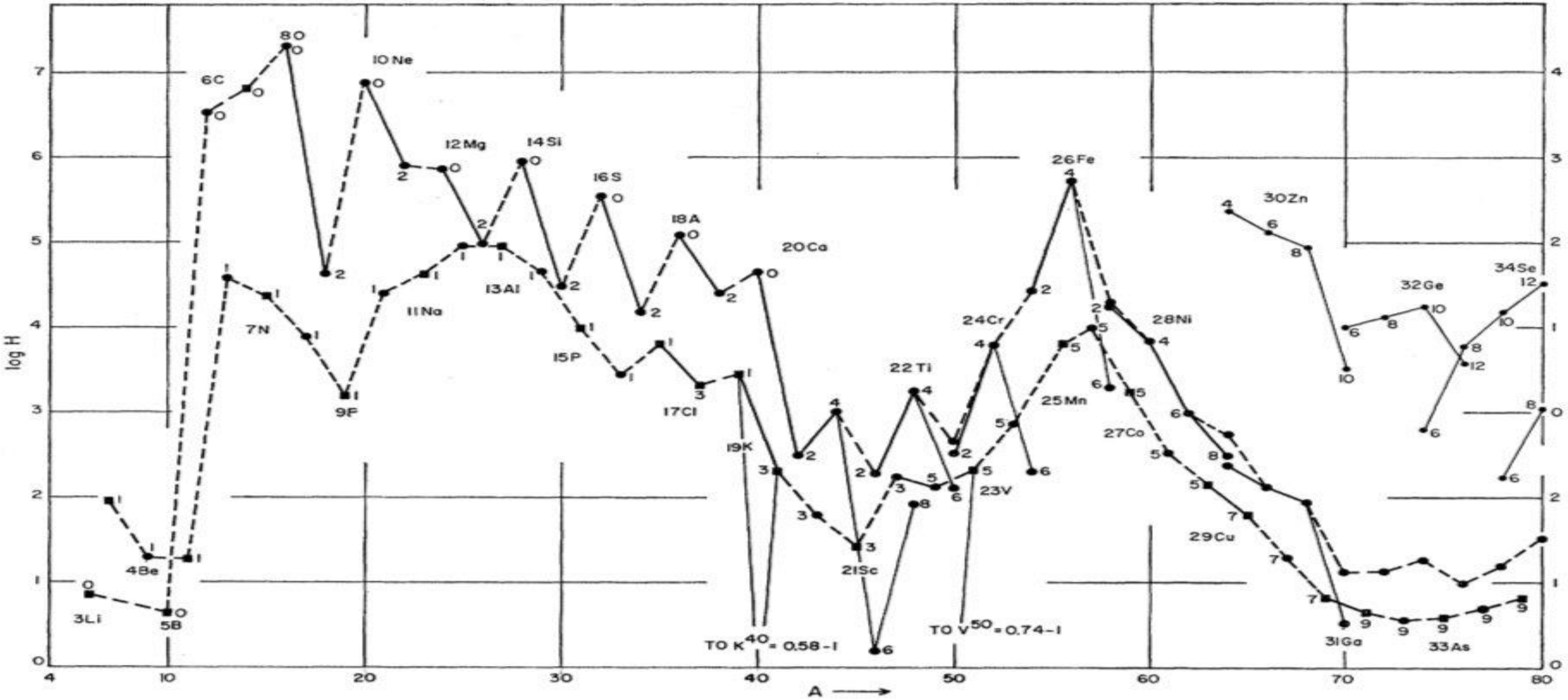
REVIEWS OF MODERN PHYSICS VOLUME 28, NUMBER 1 JANUARY, 1956

Abundances of the Elements*

HANS E. SUESS,† *U. S. Geological Survey, Washington, D. C.*

AND

HAROLD C. UREY, *Department of Chemistry and Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois*



Reviews of Modern Physics 1957

Synthesis of the Elements in Stars*

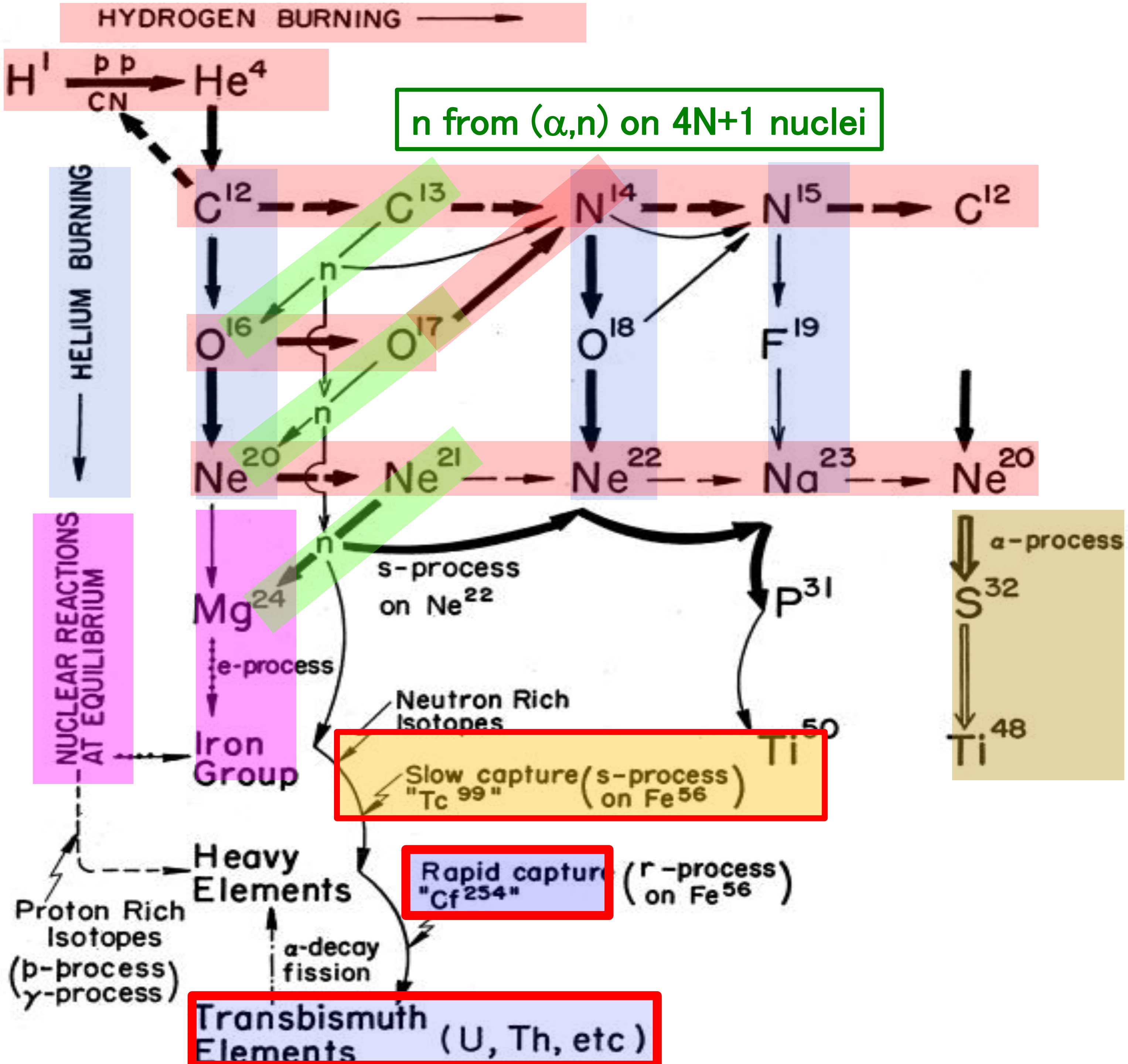
E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

Kellogg Radiation Laboratory, California Institute of Technology, and Mount Wilson and Palomar Observatories, Carnegie Institution of Washington, California Institute of Technology, Pasadena, California

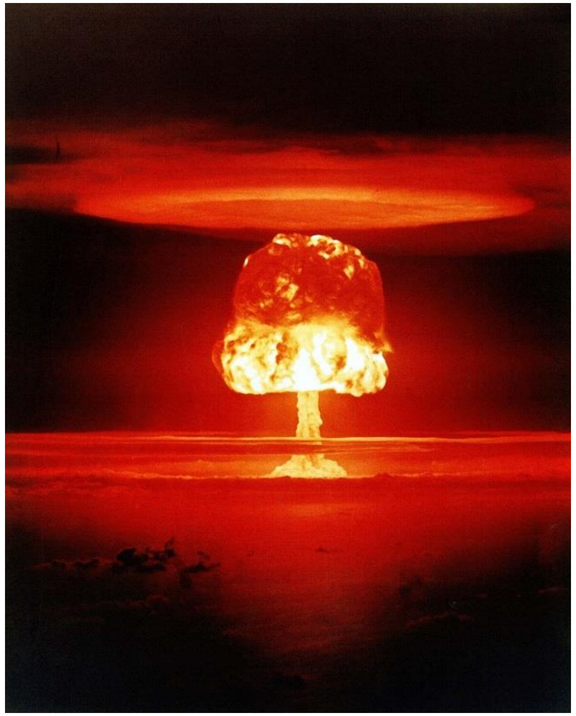
"It is the stars, The stars above us, govern our conditions";
(*King Lear*, Act IV, Scene 3)

but perhaps

"The fault, dear Brutus, is not in our stars, But in ourselves,"
(*Julius Caesar*, Act I, Scene 2)



Data on neutron capture cross-sections and yields from the first H-bomb test in Bikini island (1952)



1957 :
Alastair G. W. Cameron

Nuclear reactions in stars and nucleogenesis

(Chalk River report)

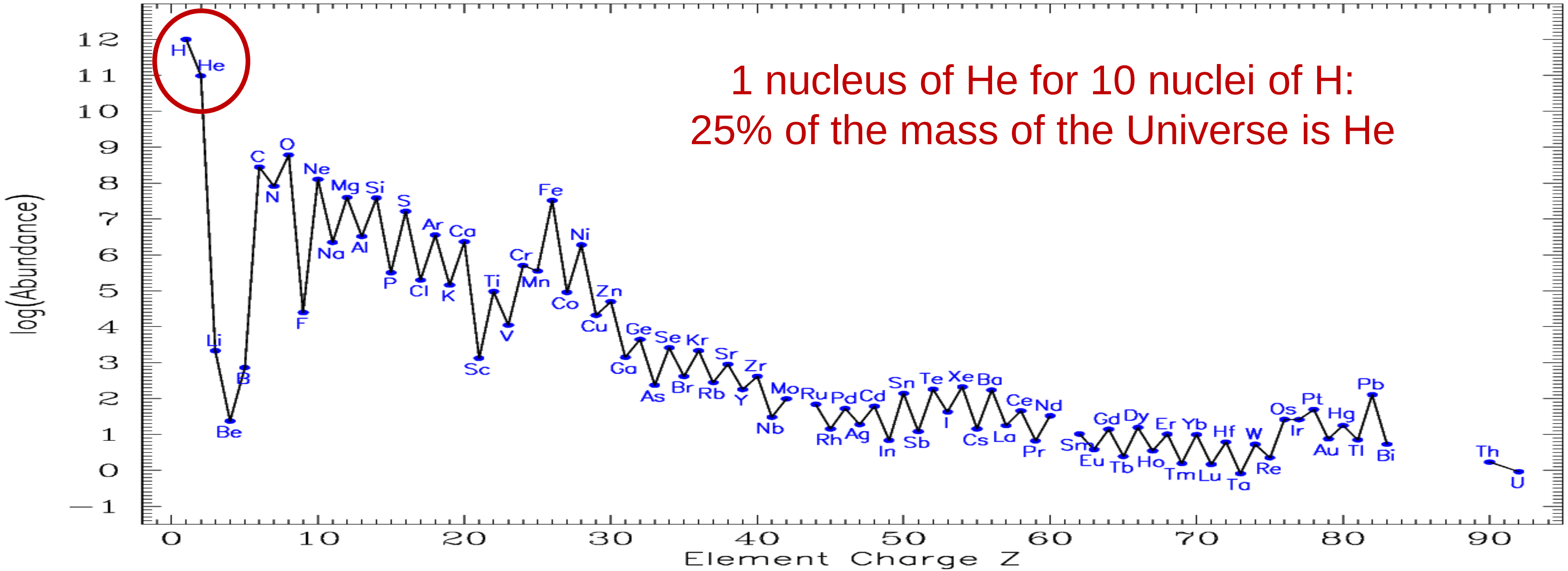
Elements	Method of Formation
D, Li, Be, B	Not formed in stellar interiors. Possibly made by nuclear reactions in stellar atmospheres
He, C, N, O, F, Ne	Hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors
Ne to Ca	1. Heavy-ion thermonuclear reactions in orderly evolution of stellar interiors 2. Neutron capture on slow time scale 3. Hydrogen and helium thermonuclear reactions in supernova explosions
Fe peak	Statistical equilibrium in pre-supernovae and in supernovae
Heavy elements :	
(*a*) Unshielded	Neutron capture on fast time scale in Type I supernovae
(*b*) Shielded	Neutron capture on slow time scale in orderly evolution of stellar interiors
(*c*) Excluded	1. Proton capture and photonuclear reactions in Type II supernovae 2. Photonuclear reactions on slow time scale in orderly evolution of stellar interiors
(*d*) Trans-bismuth	Neutron capture on fast time scale in Type I supernovae

1108 NATURE September 12, 1964 Vol. 203

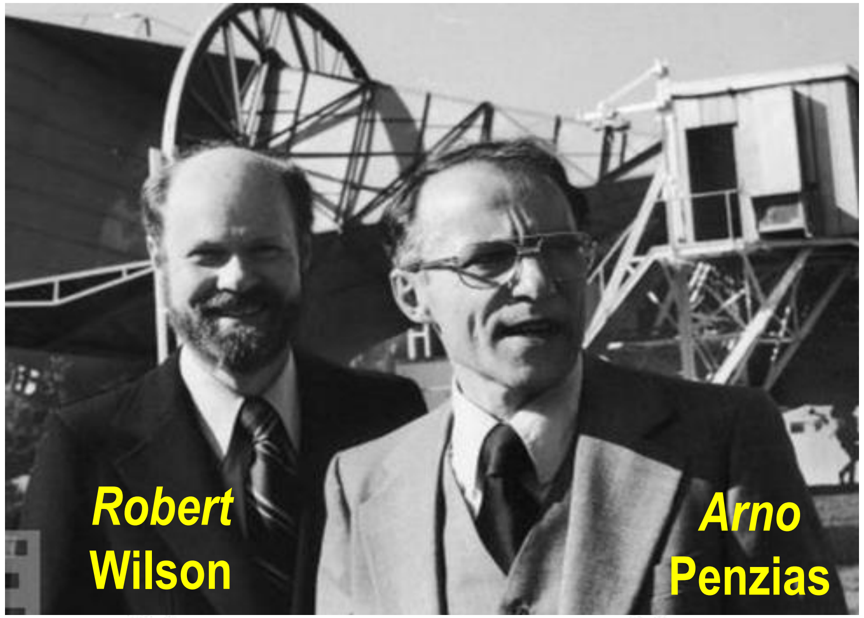
THE MYSTERY OF THE COSMIC HELIUM ABUNDANCE

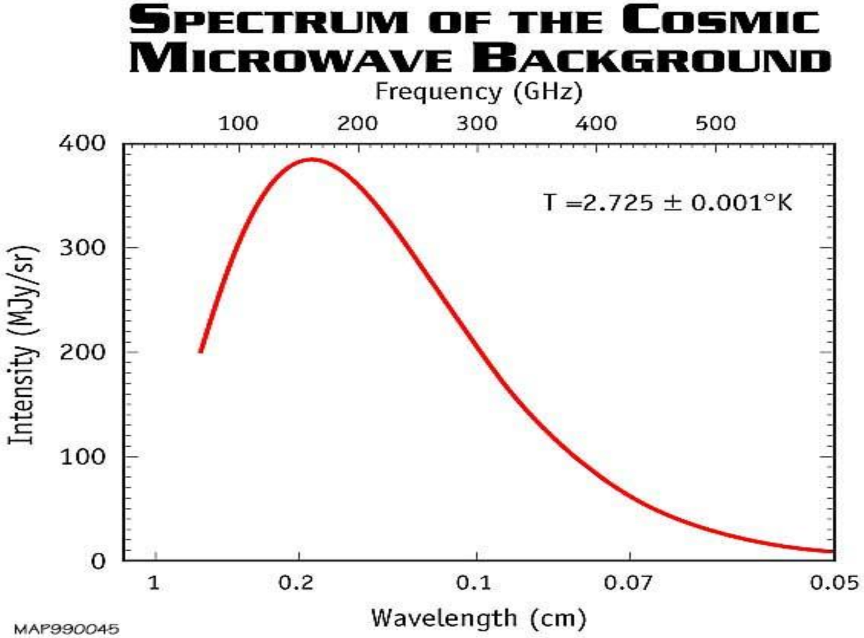
By Prof. F. HOYLE, F.R.S., and Dr. R. J. TAYLER
University of Cambridge

This brings us back to our opening remarks. There has always been difficulty in explaining the high helium content of cosmic material in terms of ordinary stellar processes. The mean luminosities of galaxies come out appreciably too high on such a hypothesis. The arguments presented here make it clear, we believe, that the helium was produced in a far more dramatic way. Either the Universe has had at least one high-temperature, high-density phase, or massive objects must play (or



1965 : discovery of the Cosmic Microwave Background





*This lecture was delivered December 8, 1978, on the occasion of the presentation of the 1978 Nobel Prizes in Physics.

The origin of the elements*

Arno A. Penzias

Communications Sciences Division, Bell Laboratories, 4E–605,

Throughout most of recorded history, matter was thought to be composed of various combinations of four basic elements; earth, air, fire, and water. Modern science has replaced this list with a considerably longer one; the known chemical elements now number well over one hundred. Most of these, the oxygen we breathe, the iron in our blood, the uranium in our reactors, were formed during the fiery lifetimes and explosive deaths of stars in the heavens around us. A few of the elements were formed before the stars even existed, during the birth of the universe itself.

ON THE SYNTHESIS OF ELEMENTS AT VERY HIGH TEMPERATURES*

ROBERT V. WAGONER, WILLIAM A. FOWLER, AND F. HOYLE
California Institute of Technology, Pasadena, California, and Cambridge University
Received September 1, 1966

ABSTRACT

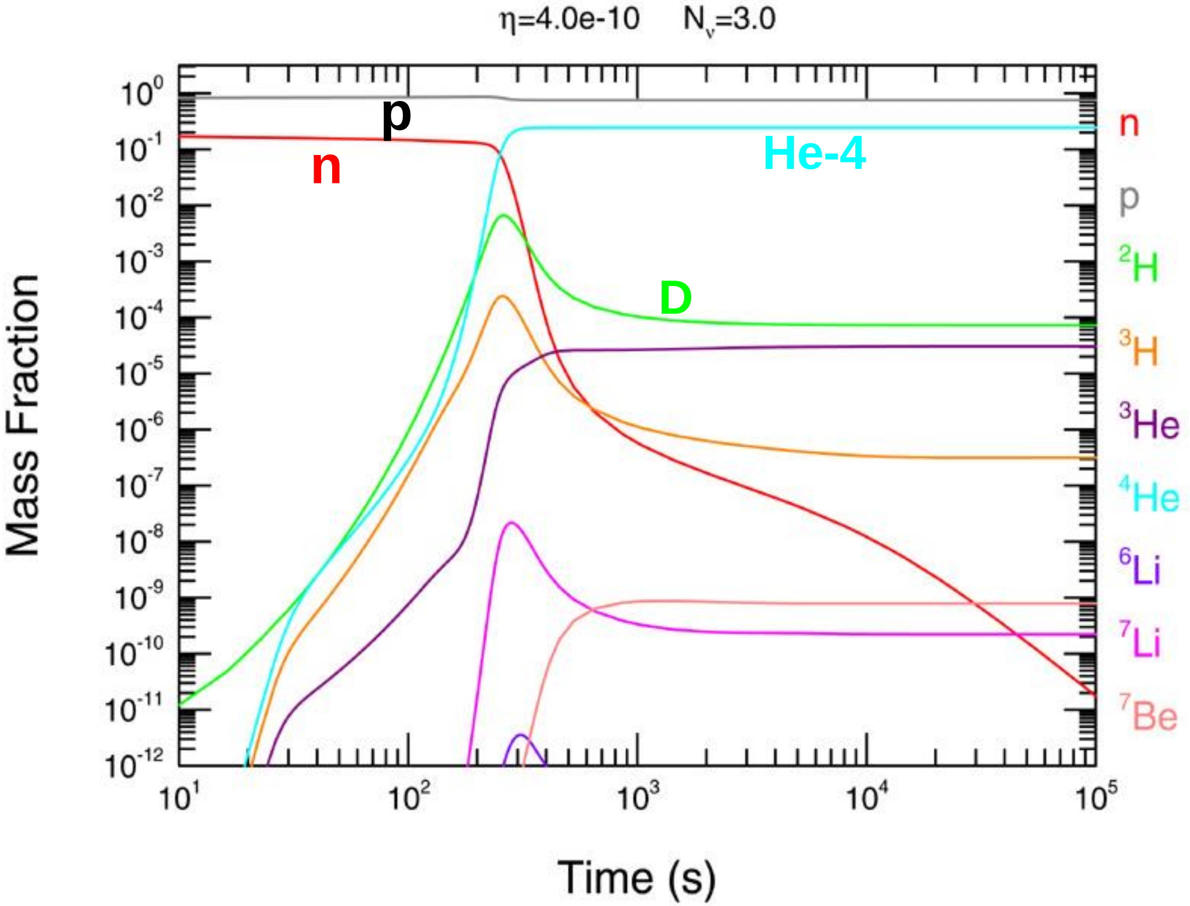
A detailed calculation of element production in the early stages of a homogeneous and isotropic expanding universe as well as within imploding-exploding supermassive stars has been made. If the recently measured microwave background radiation is due to primeval photons, then significant quantities of only D, He³, He⁴, and Li⁷ can be produced in the universal fireball. Reasonable agreement with solar-system abundances for these nuclei is obtained
density is $\sim 2 \times 10^{-31}$ gm cm³, corresponding

Hayashi (1950). n - p equilibrium

$X(n)/X(p) \sim 0.13$ at freeze-out
$X(\text{He-4}) \sim 2\, X(n) \sim 0.25$

-Only way to produce so much He4
- (25 % by mass)
-Only way to produce Deuterium
(destroyed in stellar interiors)

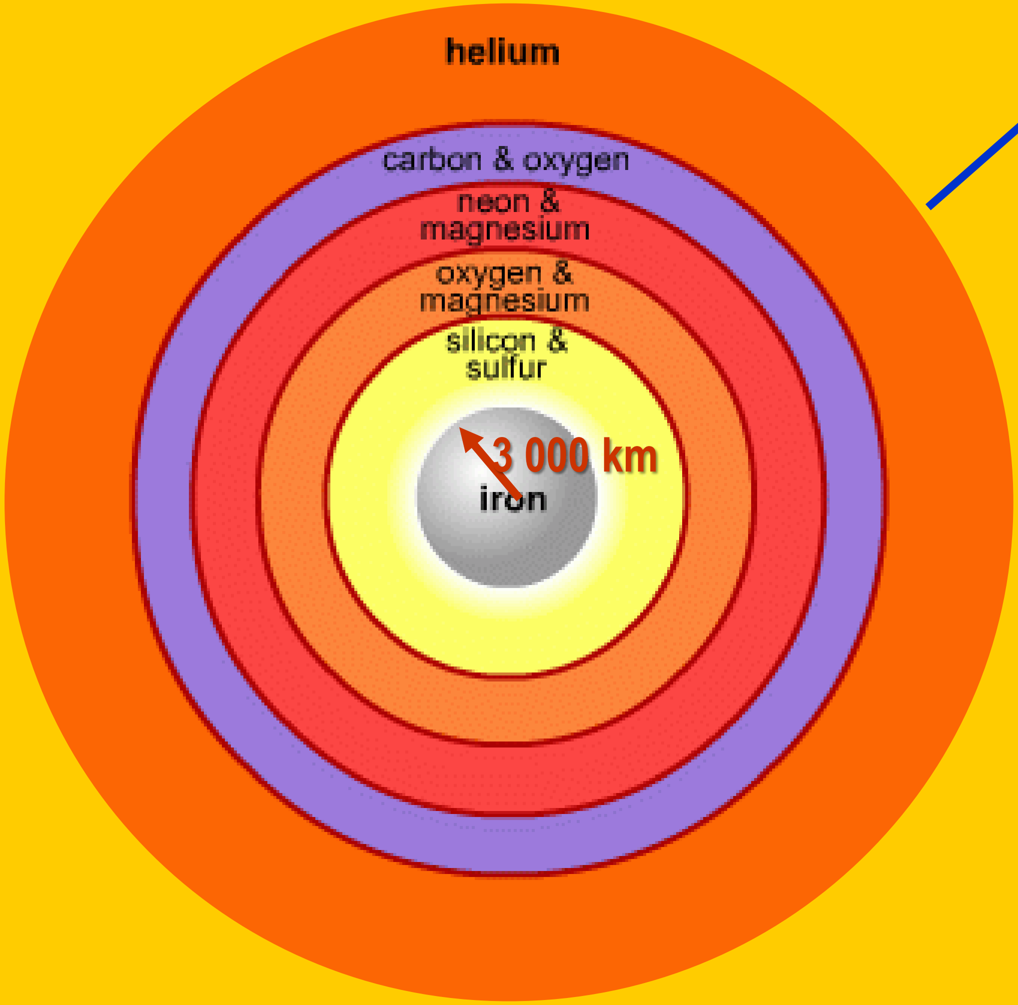
In excellent agreement with observations



Back to the stars

Hydrogen envelope

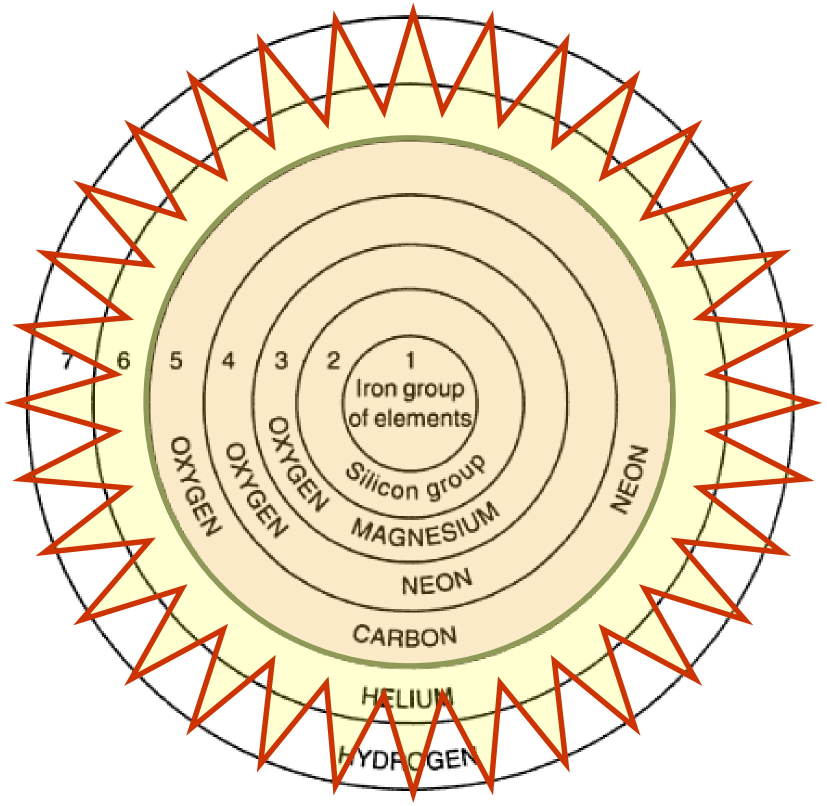
Radius:
700 000 000 km
$=1000\ R_{\odot}$



Massive stars "burn" heavier and heavier nuclei, until they turn their cores into iron Fe-56

Fe-56 is the most stable nucleus in nature
(its reactions are endothermic).
No nuclear energy source available in the core

Advanced evolution and nucleosynthesis phases in massive stars



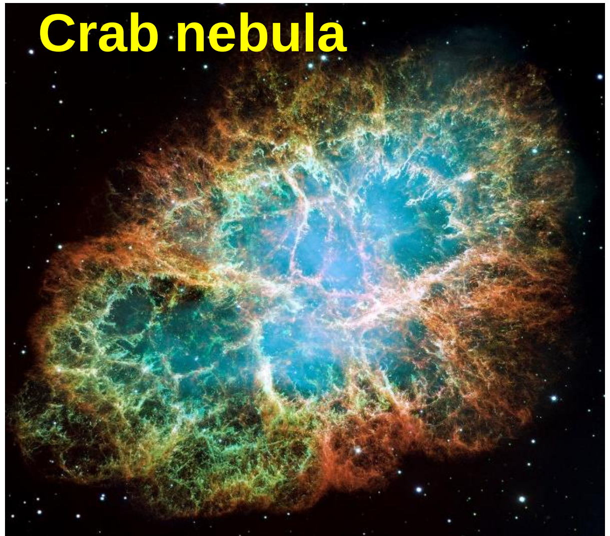
Because of the increased sensitivity of nuclear reactions to temperature heavier nuclei are produced closer to the centre of the star

The outer layers keep (partially) the products of previous phases of stellar nucleosynthesis

The « onion skin » model (Hoyle 1955)

The material synthesized in stellar interiors must come out through the final event of a supernova explosion : **which mechanism ?**

Explosive nucleosynthesis produces new elements, including radioactivities, powering the SN lightcurve **; which ones ?**



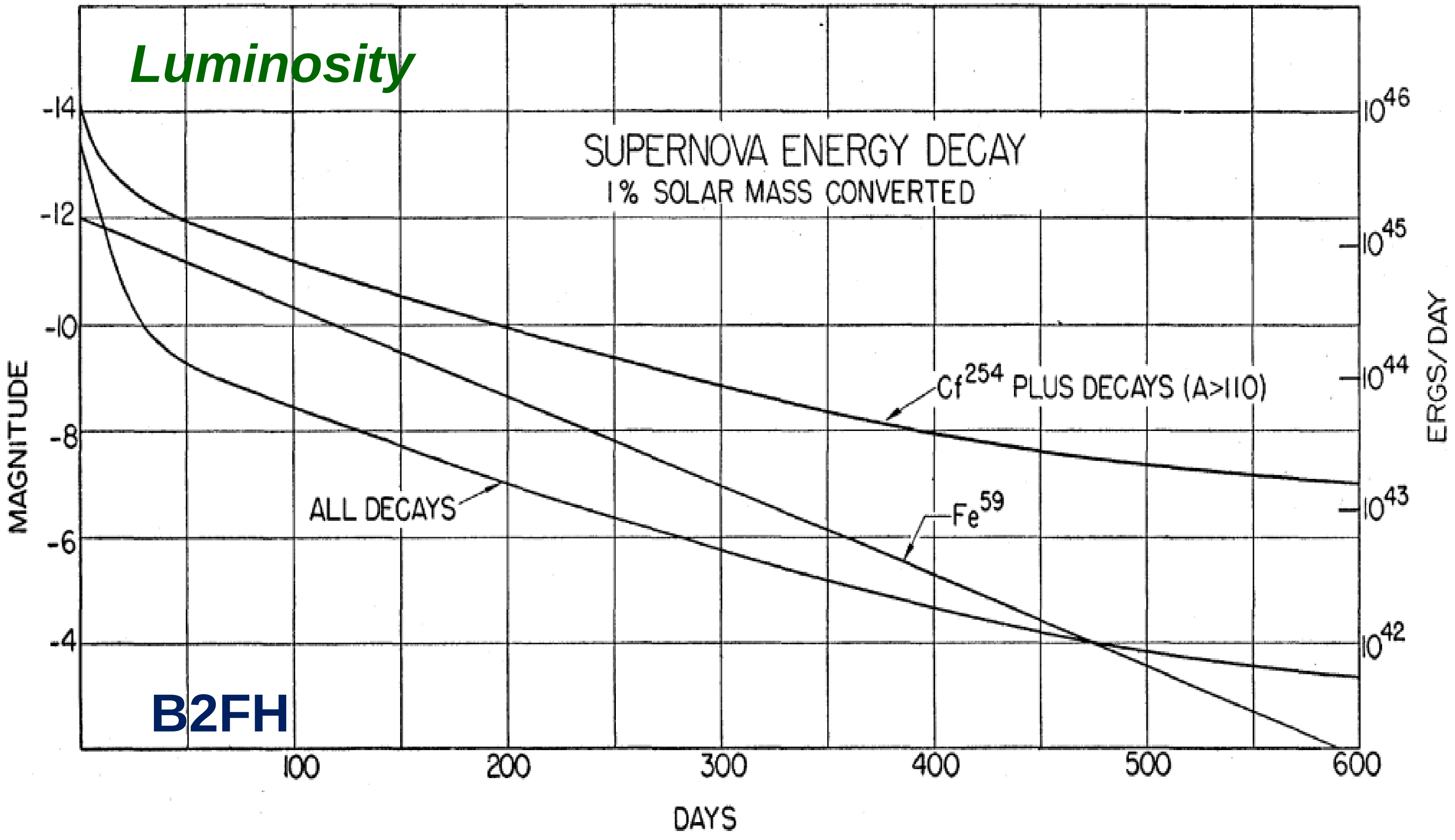
F. Hoyle & W. Fowler (1960) *« Nucleosynthesis in supernovae »*

Layers above the Fe core also fall inwards, they are heated and ignite their nuclear fuels

Thermonuclear explosion

Type II	Type I
Obs: Hydrogen	*Obs:*No Hydrogen
Massive stars	Small mass stars
Imploding core	Non imploding

What powers the exponentially decreasing lightcurves of supernovae ?



R a d i o a c t i v i t y,
of lifetime ~2 months

Be-7 : *Borst 1950*
Cf-254: *Baade, B2FH 1956*

PANKEY, Jr., Titus, 1925–
POSSIBLE THERMONUCLEAR ACTIVITIES IN NATURAL TERRESTRIAL MINERALS.

Howard University, Ph.D., 1962
Physics, nuclear

Ni56 ⟶ Co56 ⟶ Fe56
7 days *2 months*

Hoyle and Fowler 1960: *Explosive nucleosynthesis*

sions. *The input of radioactive energy into the exploding debris of supernovae cannot be neglected.* Furthermore, the production of Cf^{254} within an interval of a few microseconds in the first hydrogen bomb test in 1952 must be taken as observational evidence for the *rapid process* of neutron capture, by which fissionable material is produced in supernova explosions. The heaviest nucleus in the bomb components was U^{238}. At least 16 neutrons were added in the short interval of the bomb explosion. It is not unreasonable to extrapolate by a factor of 10 or more in going to stellar explosions, where the iron-group elements serve as seed nuclei but the neutron fluxes are considerably enhanced.

Abundances of the Elements*

HANS E. SUESS,† U. S. Geological Survey, Washington, D. C.

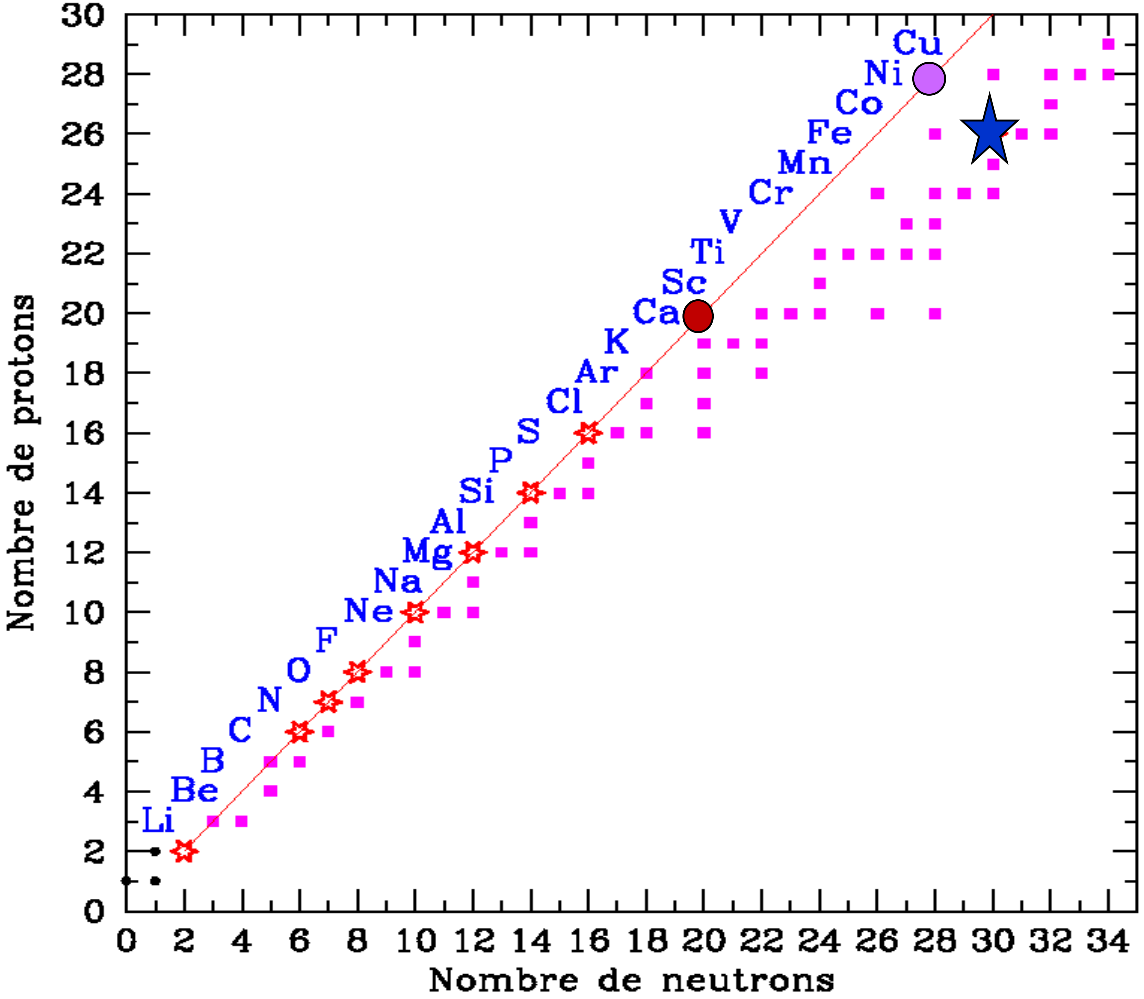
AND

HAROLD C. UREY, Department of Chemistry and Enrico Fermi Institute for Nuclear Studies, University of Chicago, Chicago, Illinois

The Iron Peak and the Lower Mass Region

The new value for the Fe to Si ratio, which is about one third of that previously assumed, still leaves the abundance of Fe^{56} larger than the sum of abundance of all other nuclear species with mass numbers greater than 40. No property of the Fe^{56} nucleus is known that could possibly explain its predominance in nature. Fe^{56}, however, is an isobar of the "double magic" unstable Ni^{56}, which contains 28 protons and 28 neutrons. The expectation of a correlation of abundances with nuclear properties leads inevitably to the conclusion that Ni^{56} was the primeval nucleus from which Fe^{56} has formed‖ and, hence, that the nuclei of this mass region had formed on the neutron deficient side of the energy valley. The half-life of Ni^{56}, which decays by K-capture into Co^{56} (80d) has recently been found to be 6.5 days [Sheline and Stoughton (1952) and Worthington (1952)]. Hence the process leading to the excessive abundance of mass 56 cannot have taken longer than a few days.

The way towards the Fe-peak: hydrostatic vs explosive



Ca40 is the last stable nucleus with N=Z
on the way of Si-melting
towards the Fe-peak

In the stellar core
weak interactions (p + e$^+$)
turn some protons into neutrons

and
Fe56 dominates the composition in
FULL nuclear statistical equilibrium

In **explosive nucleosynthesis**, weak (=slower) interactions have little time to operate
and the nuclear flow goes through N = Z up to **Ni56 (N=Z=28)**

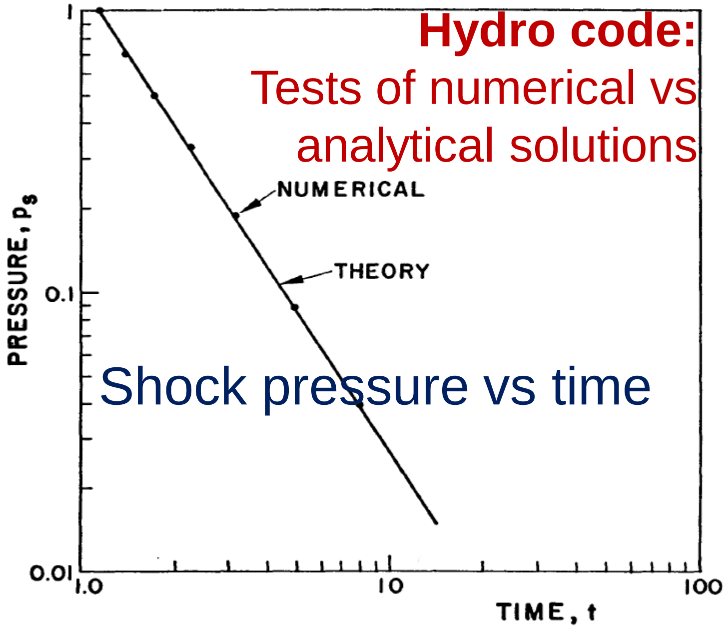
Hoyle's greatest regret : missing the origin of Fe56, the most stable nucleus in nature
It is produced as unstable Ni56 in supernova explosions

THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS*

ApJ 1966

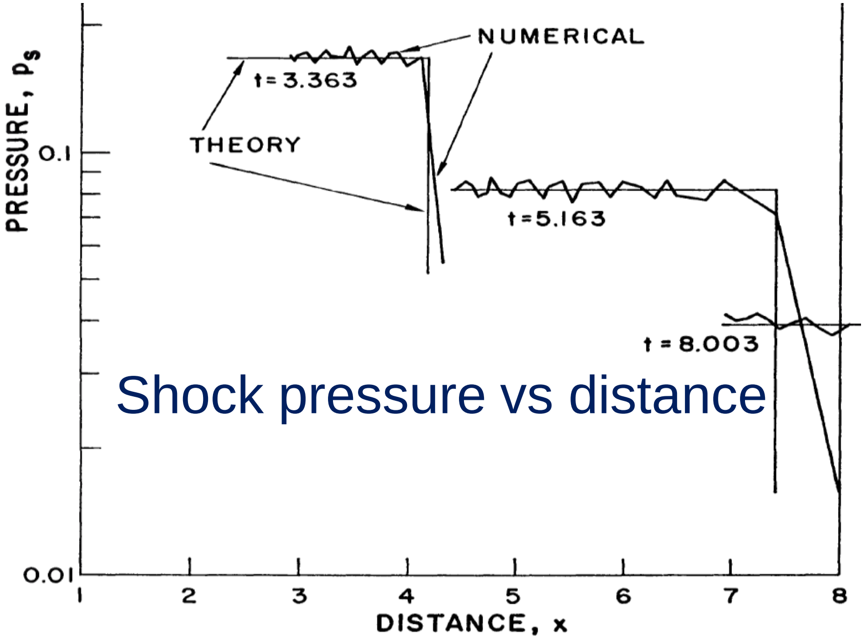
56 p. 106 eq. 45 fig.

Stirling A. Colgate and Richard H. White
Lawrence Radiation Laboratory, University of California, Livermore, California



Hydro code:
Tests of numerical vs analytical solutions

Shock pressure vs time



Shock pressure vs distance

Stirling Colgate

America's premier diagnostician of thermonuclear weapons in the 1950s

1954: Leader (*age 28*) of the largest USA thermonuclear weapon test (*Castle Bravo*, Bikini atoll, 15 Megatons)

"Although thermonuclear energy has been considered as the primary energy source for Type I supernova (Fowler and Hoyle 1964) and Type II supernova (Ohyama 1963), we find that the rarefaction left by the imploding core is always sufficient essentially to "swallow" the thermonuclear explosion, because the sound speed in the unstable, imploding core is higher than in the external thermonuclearly exploded material".

The **imploding Fe core** is

photo-disintegrated: (high T): **Fe ⇒ α ⇒ p,n**

neutronized *:* (high ρ) : $\mathbf{p + e^- \Rightarrow n + \nu}$

and it stabilizes within a few ms, when it reaches ***nuclear densities*** (~10^{15} g/cm3) and the pressure of the degenerate neutron gas supports the gravity of the core, heated to **T ~10^{11} K**

THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS*

STIRLING A. COLGATE AND RICHARD H. WHITE

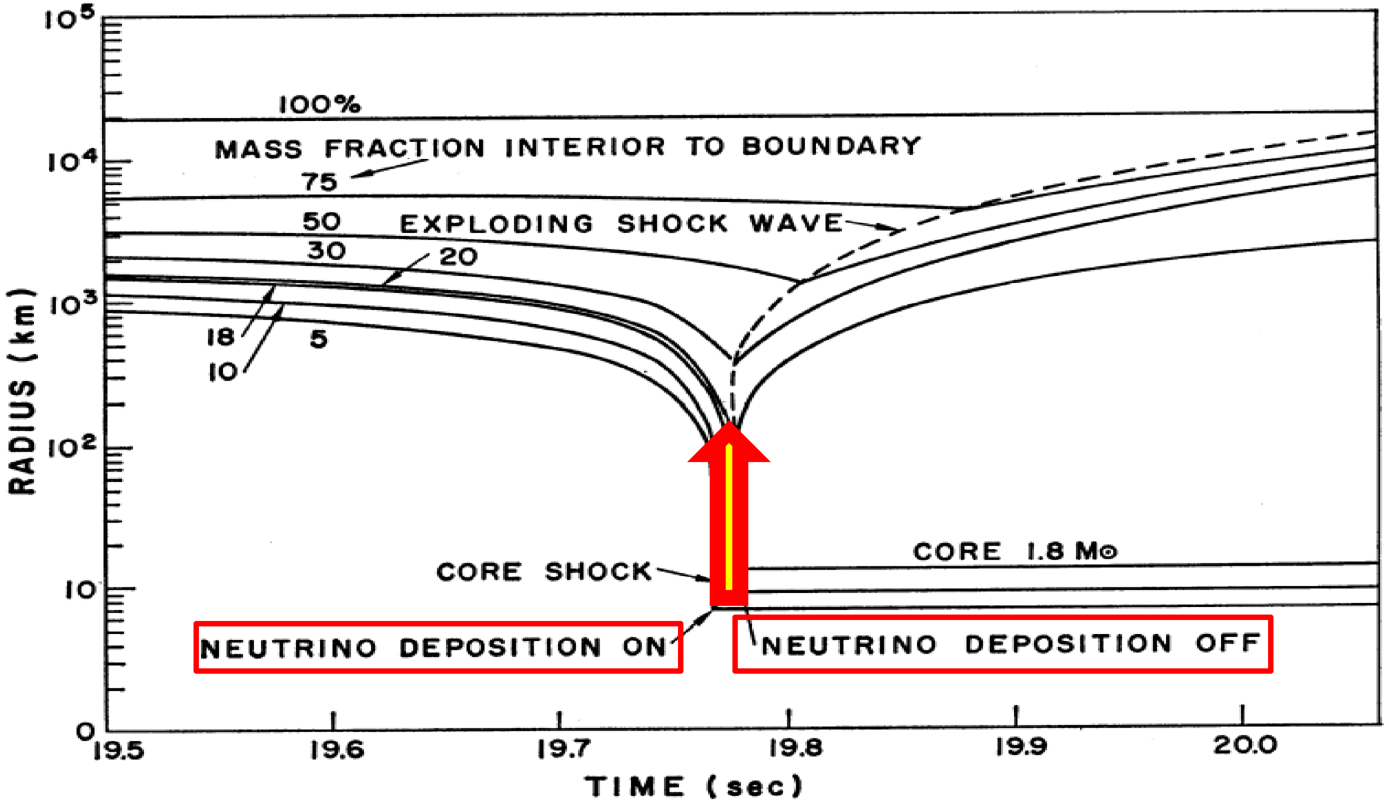
Abstract

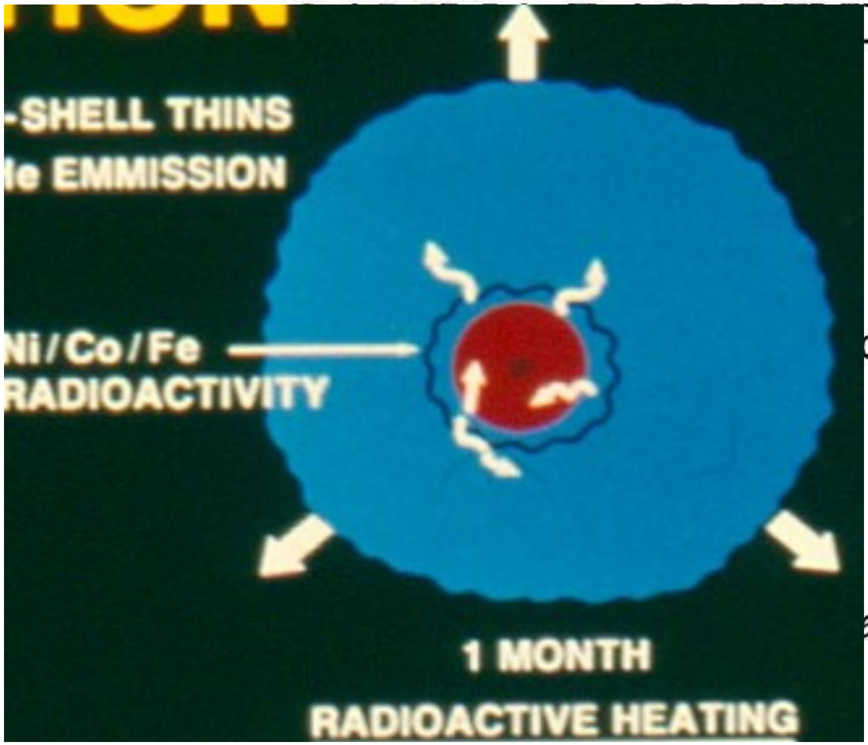
We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, and Hoyle, we find that the dynamical implosion is so violent that an energy many times greater than the available thermonuclear energy is released from the star's core and transferred to the star's mantle in a supernova explosion. The energy released corresponds to the change in gravitational potential of the unstable imploding core

Energy: **Gravitational,** not thermonuclear

Origin**: implosion of Fe core**
(M ~Msun, R~10 km)
$E_{GRAV} \sim G M^2 / R \sim 10^{53}$ ergs

In the neutronized core, at $T \sim 10^{11}$ K,
most (99%) of that energy
turns into neutrinos which escape;
some of them deposit part of that energy
to the stellar mantle
thus causing the explosion





ES FROM YOUNG SUPERN

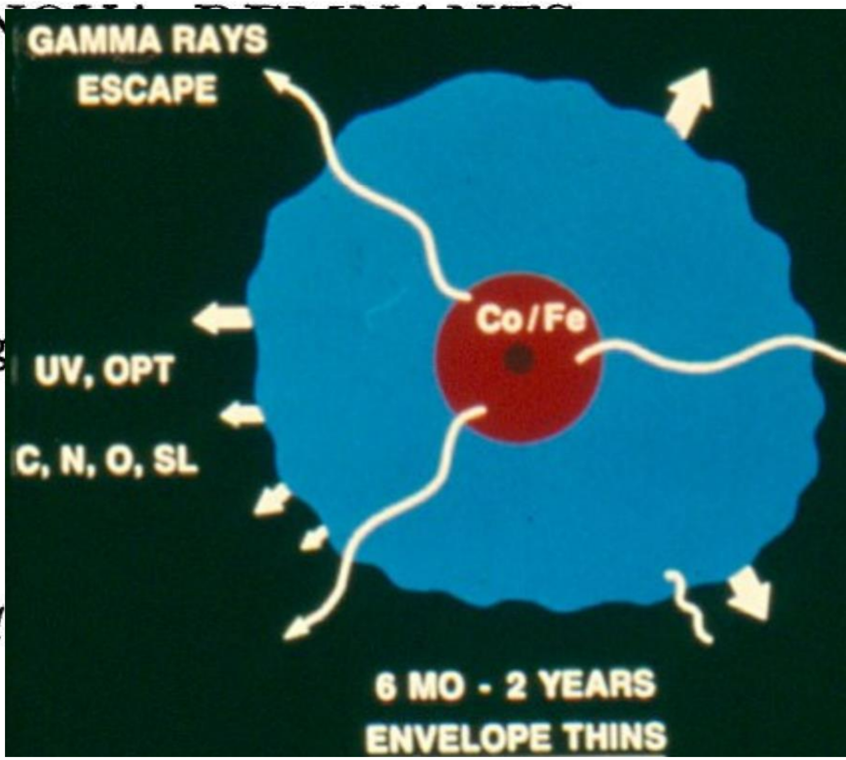
DONALD D. CLAYTON*
Rice University, Houston, Texas

STIRLING A. COLGATE
co Institute of Mining and Technolog

AND

GERALD J. FISHMAN
Rice University, Houston, Texas

eived May 20, 1968; revised June 24, 1

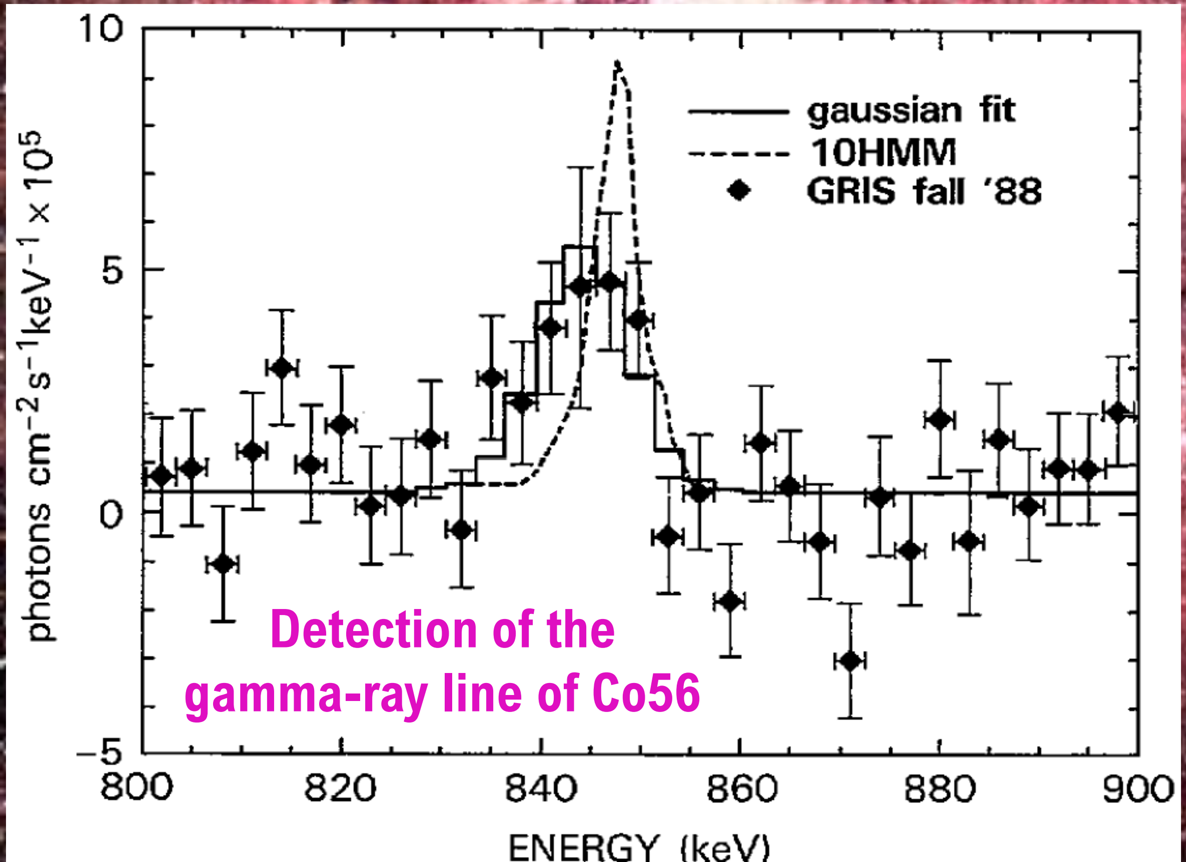


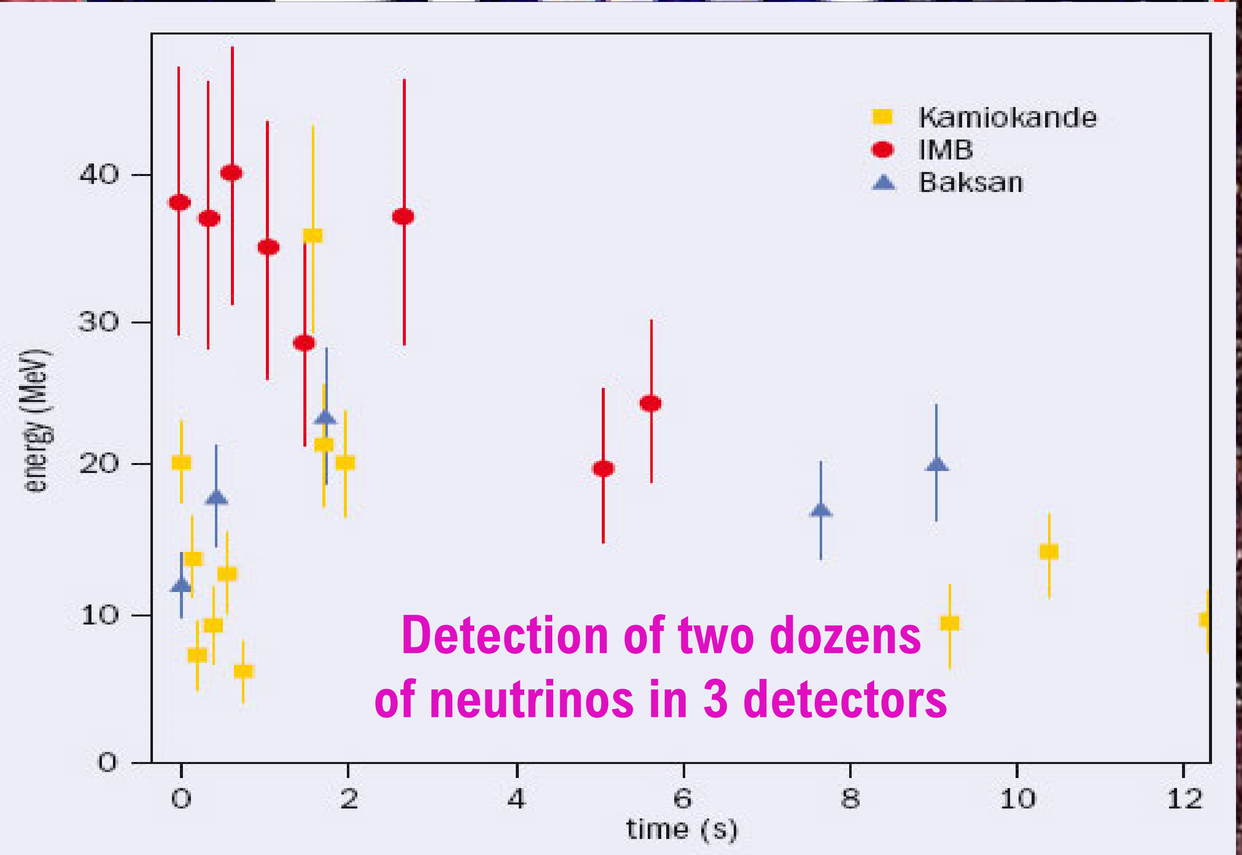
ABSTRACT

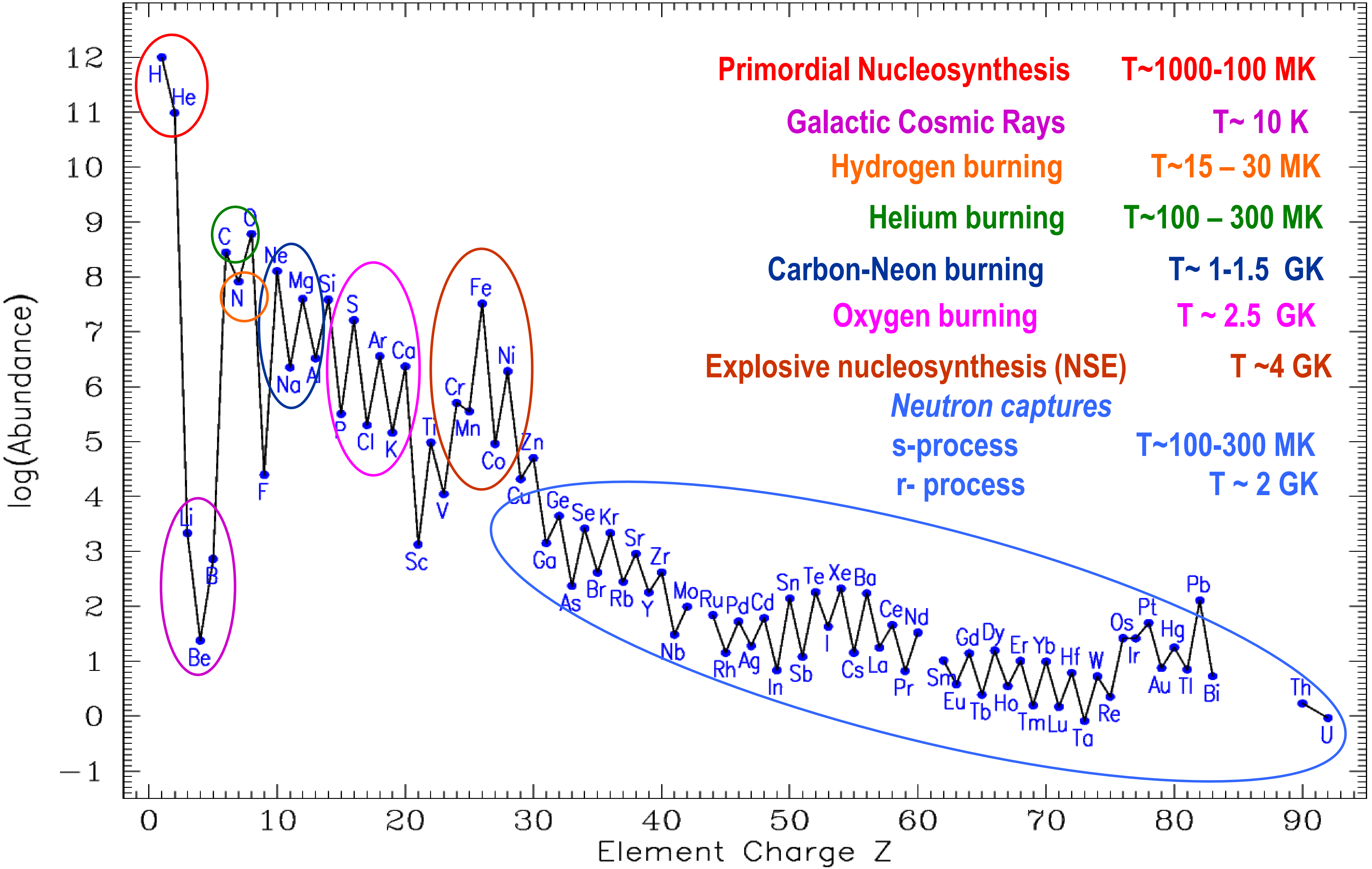
The gamma-ray luminosity of a typical type I supernova remnant has been calculated by assuming that the origin of the optical luminosity is due to the energy of the radioactive decay of Ni^{56}. It is expected that Ni^{56} is the most abundant nucleus resulting from silicon burning in the supernova shock conditions. The requisite mass of Ni^{56} ($0.14\ M_\odot$) gives rise to gamma-ray lines with energies near 1 MeV that should be detectable in young supernova remnants at distances up to a few Mpc. Future detectors aboard satellites should be able to detect events at the rate of about two observable events per year. A few supernova remnants in the Galaxy should be observable at all times in lines following the decay of Ti^{44}.

Thus, the observation of gamma-ray line emission from a young supernova seems very promising in the near future. This observation, or even a null observation at a low threshold, will have great significance in the fields of nuclear astrophysics and supernova theory. The scientific importance of a positive measurement would be analogous with and comparable to the importance of the successful detection of neutrinos from the Sun.

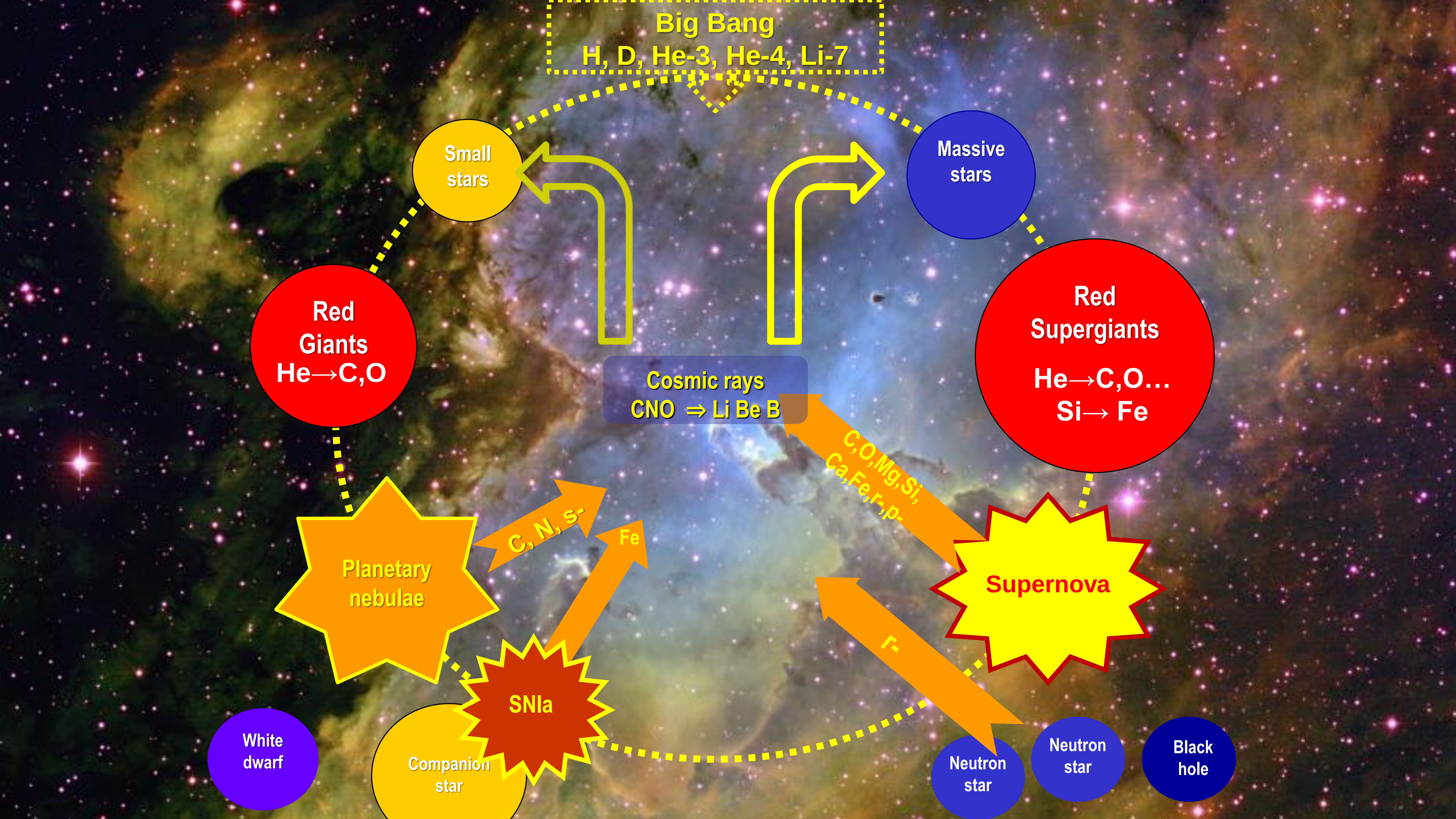
SN 1987A in the Large Magellanic Cloud
150 000 light years from Earth

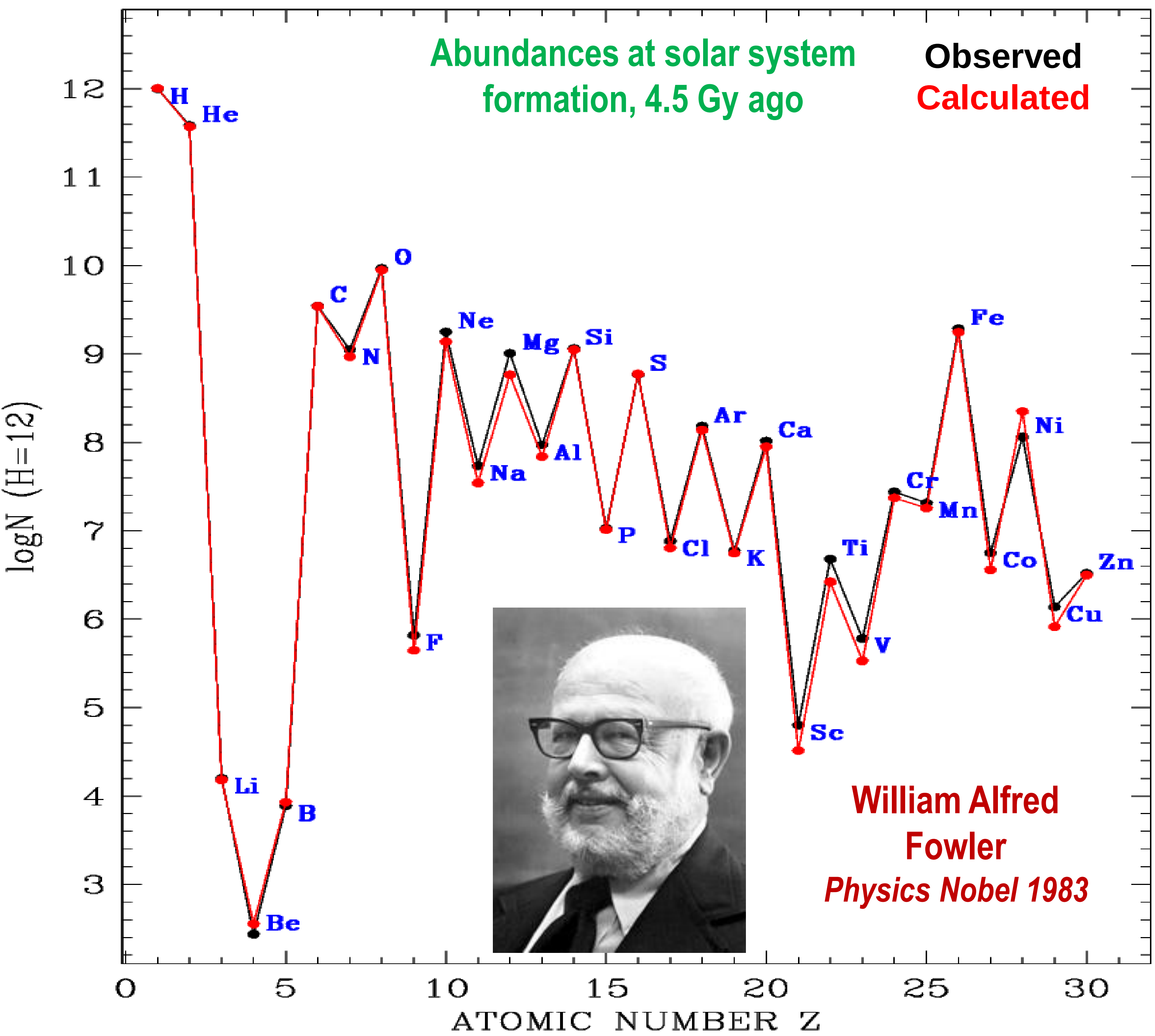


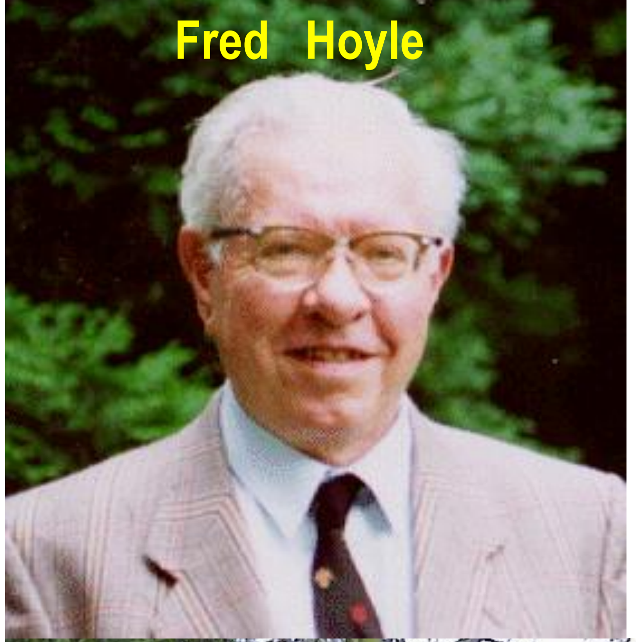




Primordial Nucleosynthesis T~1000-100 MK
Galactic Cosmic Rays T~ 10 K
Hydrogen burning T~15 – 30 MK
Helium burning T~100 – 300 MK
Carbon-Neon burning T~ 1-1.5 GK
Oxygen burning T ~ 2.5 GK
Explosive nucleosynthesis (NSE) T ~4 GK
Neutron captures
s-process T~100-300 MK
r- process T ~ 2 GK
log(Abundance)
Element Charge Z
H He Li Be B C N O F Ne Na Mg Al Si P S Cl Ar K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr Rb Sr Y Zr Nb Mo Ru Rh Pd Ag Cd In Sn Sb Te I Xe Cs Ba La Ce Pr Nd Sm Eu Gd Tb Dy Ho Er Tm Yb Lu Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Th U


Big Bang
H, D, He-3, He-4, Li-7
Small stars
Massive stars
Red Giants He→C,O
Cosmic rays
CNO ⇒ Li Be B
Red Supergiants
He→C,O…
Si→ Fe
C,O,Mg,Si,
Ca,Fe,r-,p-
C, N, s-
Fe
Planetary nebulae
Supernova
r-
SNIa
White dwarf
Companion star
Neutron star
Neutron star
Black hole


Abundances at solar system
formation, 4.5 Gy ago
Observed
Calculated
logN (H=12)
ATOMIC NUMBER Z
H
He
Li
Be
B
C
N
O
F
Ne
Na
Mg
Al
Si
P
S
Cl
Ar
K
Ca
Sc
Ti
V
Cr
Mn
Fe
Co
Ni
Cu
Zn
William Alfred
Fowler
Physics Nobel 1983


Fred Hoyle

Dust

Globular cluster composition

AGB, C-stars, s-stars, WR, …

Novae, X-bursts

Galactic Chemical evolution

Pre-solar grains

γ-ray astronomy

Nucleo cosmo chronology

LIM stars Massive stars

SN Types Lightcurves SN remnants

Stable nuclei

Radioactive

Convection, Mass loss Metallicity Rotation, …

Hydro 1-2-3D, GR, EOS, ν-transport, …

β-decays, ν-induced n-captures, fission Thermonuclear

GCR properties

Solar ν

Solar model

Advanced phases

Supernovae

Hydrostatic

Explosive

Nuclear properties: masses, decay rates, reaction cross-sections

Stellar Photometry

Stellar, ISM spectroscopy

3K MWB

GCR spectra

Stellar Physics

Cosmology

Cosmic ray physics

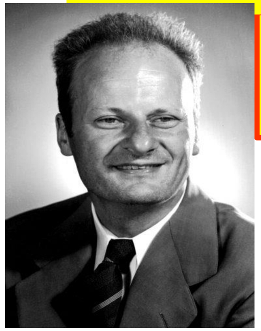
H-burn : Main Seq

3-α: Red giants

Stellar

Primordial

Spallogenic



Stellar Energy

Origin of Elements

Nuclear Astrophysics

Nuclear Physics

Astrophysics