

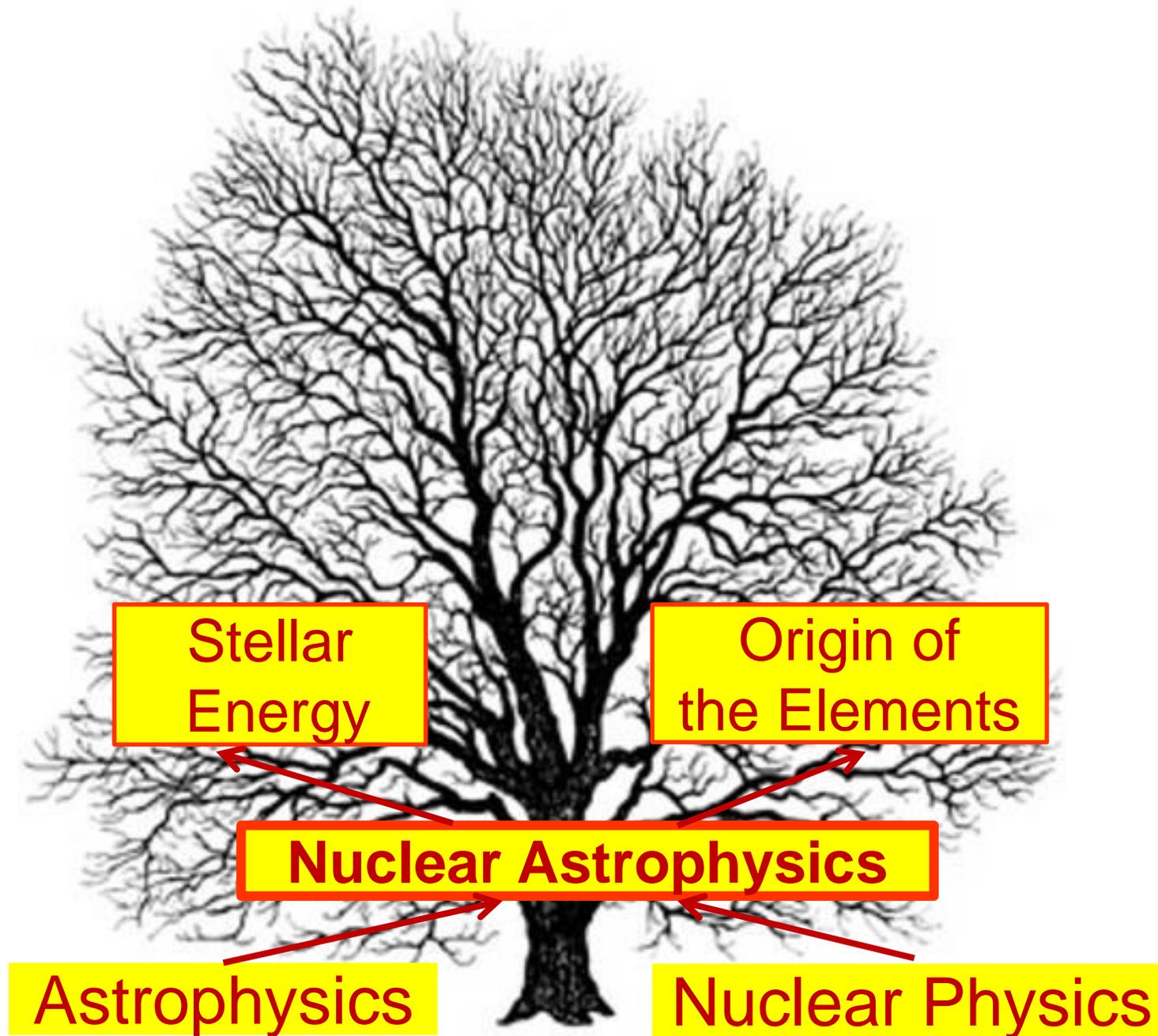
# **A BRIEF HISTORY OF NUCLEAR ASTROPHYSICS**

## **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



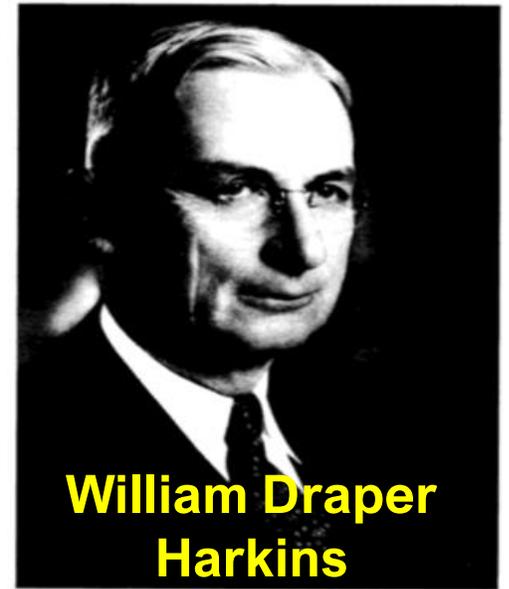
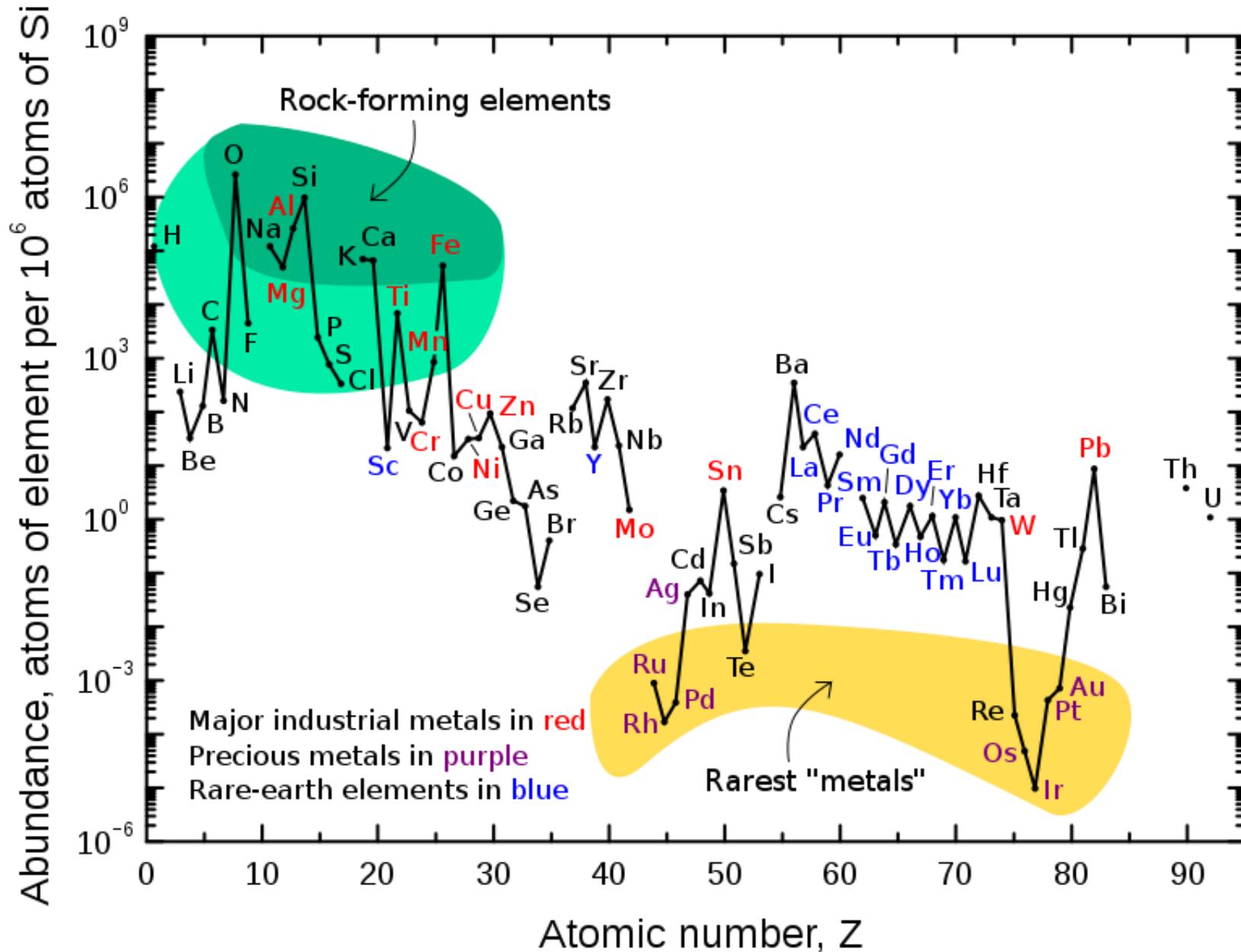
# Periodic table of the elements

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

lanthanoid series 6	58 <b>Ce</b>	59 <b>Pr</b>	60 <b>Nd</b>	61 <b>Pm</b>	62 <b>Sm</b>	63 <b>Eu</b>	64 <b>Gd</b>	65 <b>Tb</b>	66 <b>Dy</b>	67 <b>Ho</b>	68 <b>Er</b>	69 <b>Tm</b>	70 <b>Yb</b>	71 <b>Lu</b>
actinoid series 7	90 <b>Th</b>	91 <b>Pa</b>	92 <b>U</b>	93 <b>Np</b>	94 <b>Pu</b>	95 <b>Am</b>	96 <b>Cm</b>	97 <b>Bk</b>	98 <b>Cf</b>	99 <b>Es</b>	100 <b>Fm</b>	101 <b>Md</b>	102 <b>No</b>	103 <b>Lr</b>

\*Numbering system adopted by the International Union of Pure and Applied Chemistry (IUPAC). © Encyclopædia Britannica, Inc.

# Composition of Earth's crust



**William Draper Harkins**

*W. D. Harkins*

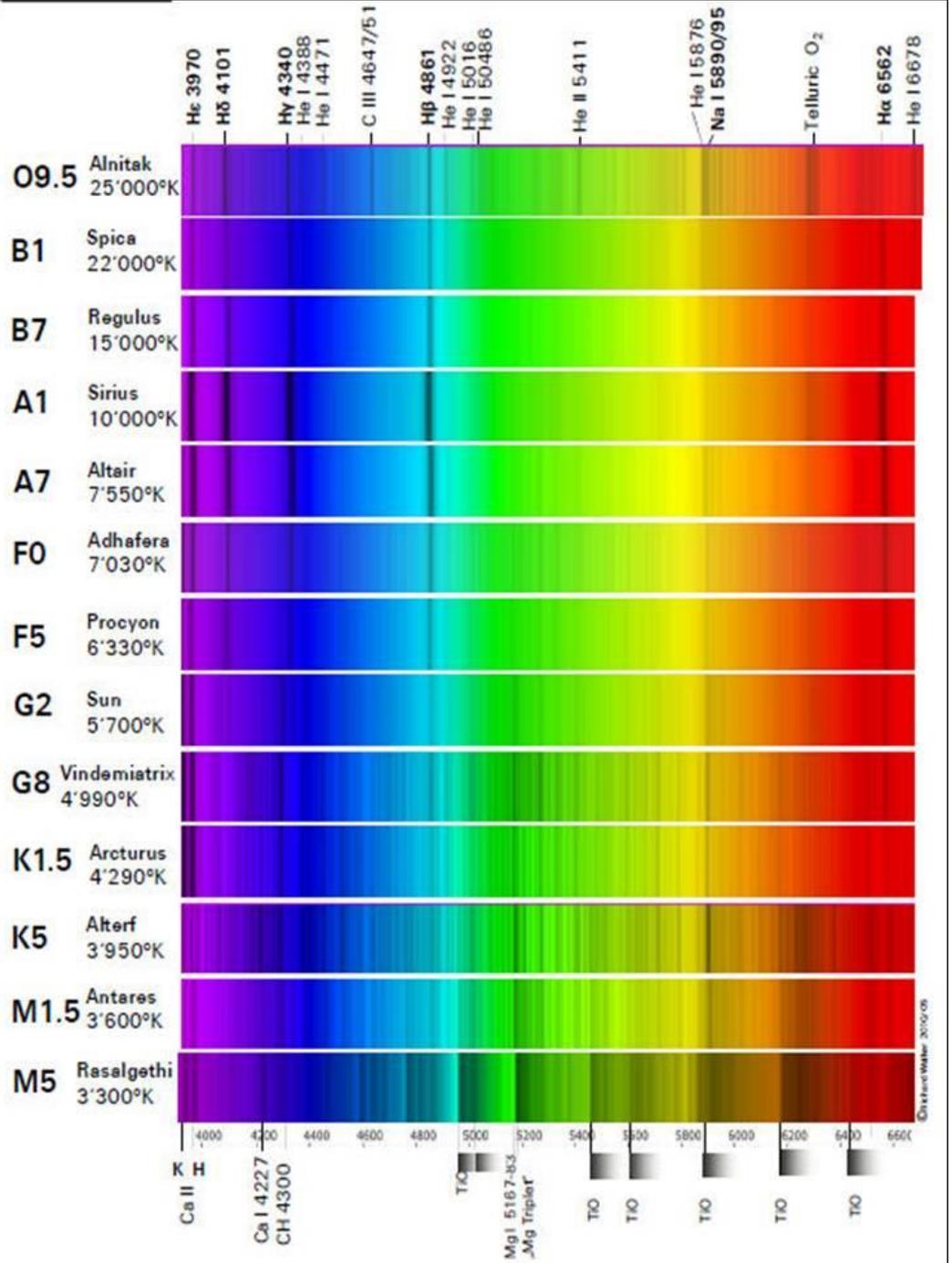
*Harkins rule (1915)*  
elements with specific properties  
are more abundant than other:  
**even vs odd charge**

It should be related  
**to the structure of their nuclei,**  
and not to their position in the  
Periodic Table

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

Determination of abundances requires models of stellar atmospheres

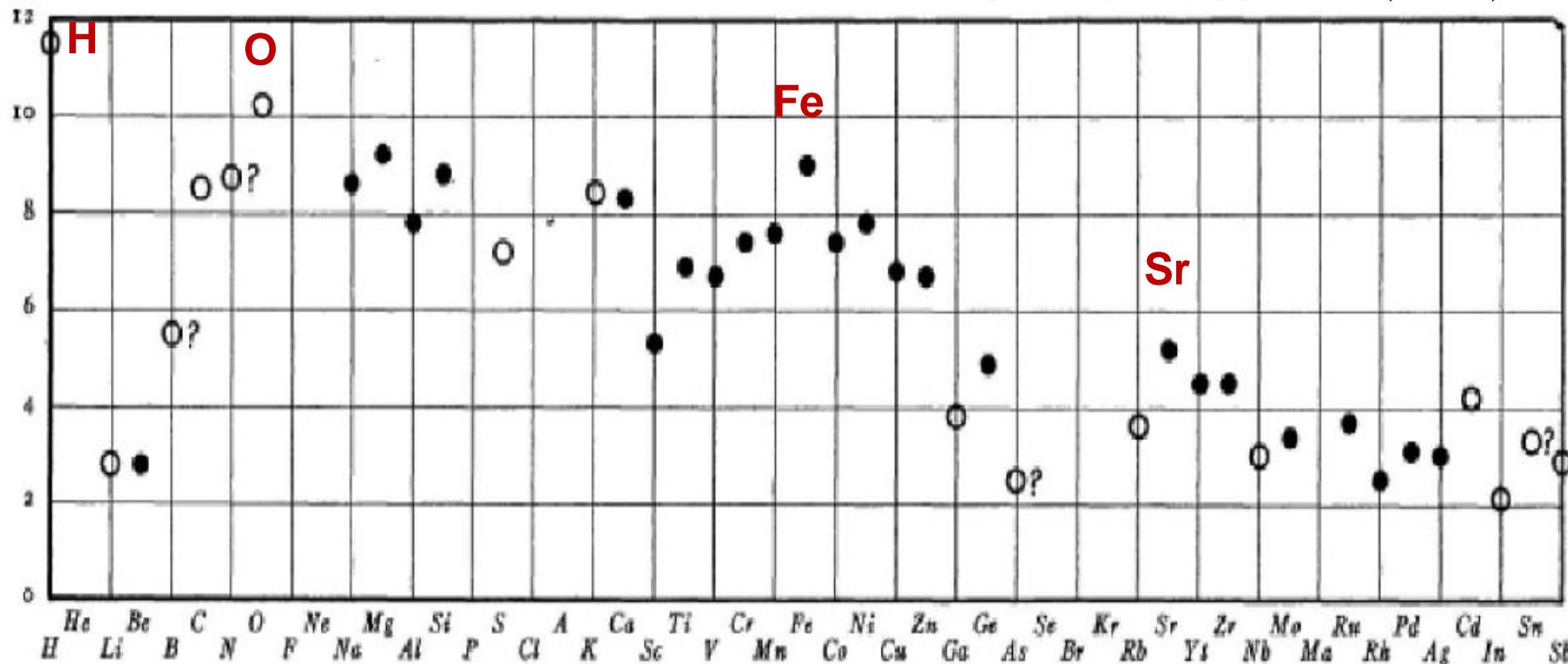
**1925: Cecilia Payne  
H and He are  
the most abundant  
elements  
in stellar atmospheres**



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<sup>2</sup> (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**

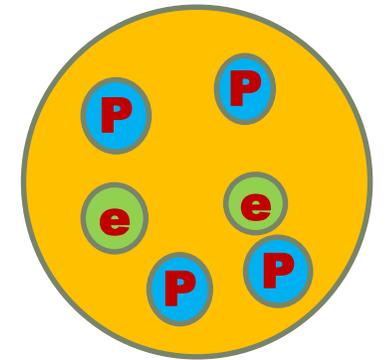
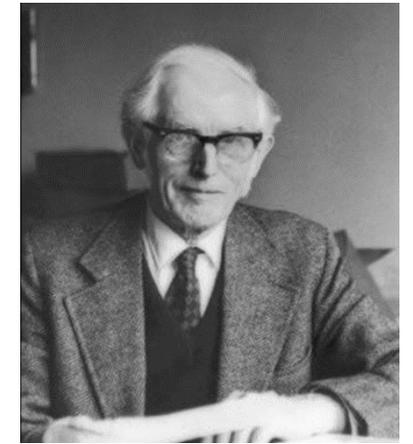
# ATOMIC SYNTHESIS AND STELLAR ENERGY. II

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



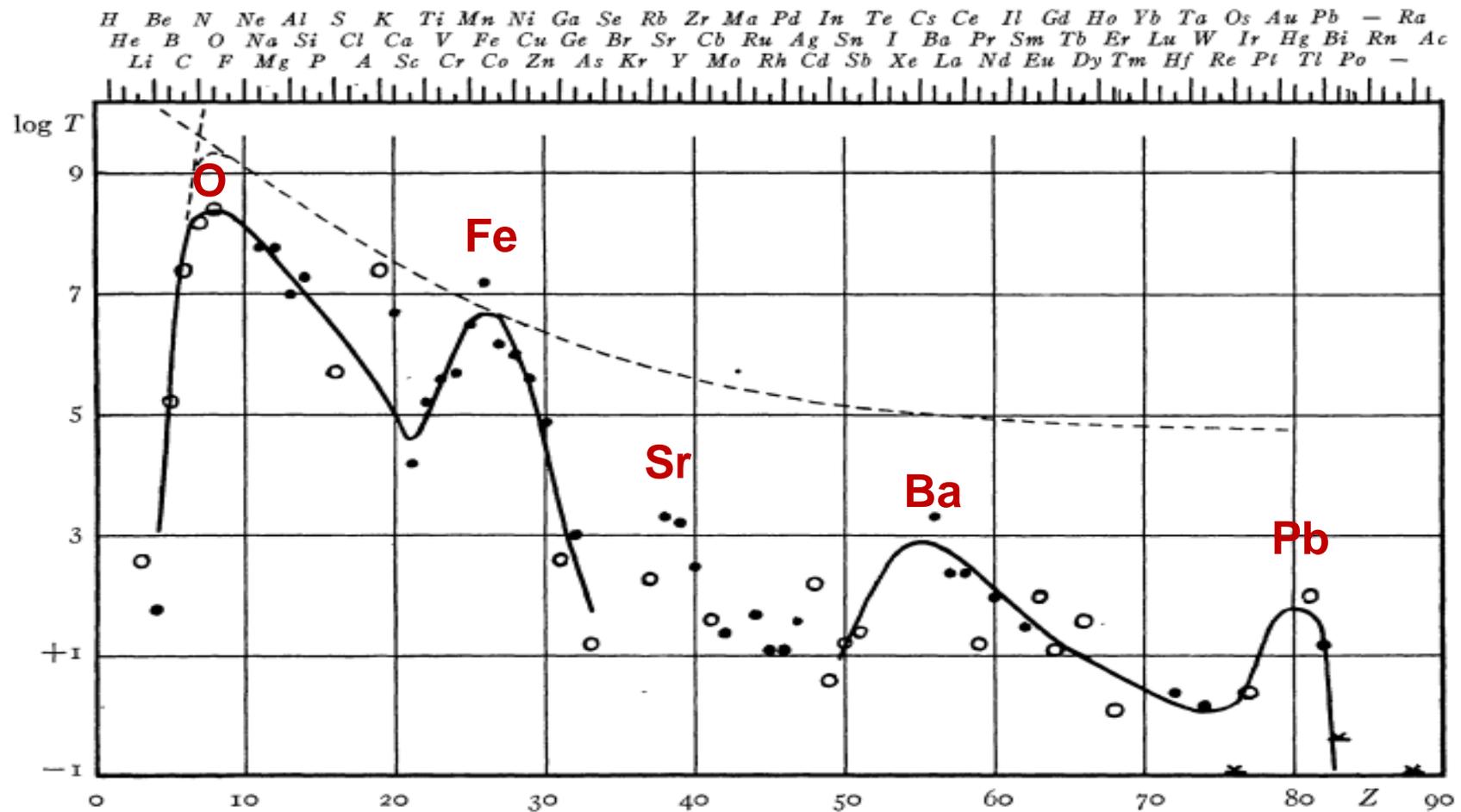


FIG. 2.—Amount of the elements in the sun's atmosphere. (After Russell; ordinates at odd  $Z$  values increased by 0.6.) ---- Equilibrium amounts; • First class determinations; ○ Second class determinations.

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.



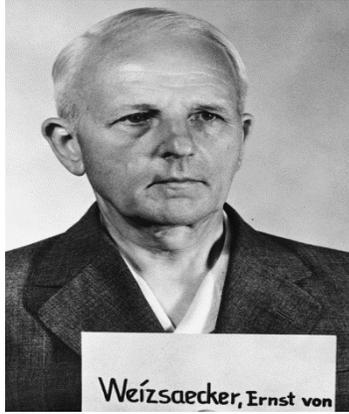
## On Elementary Transmutations in the Interior of Stars: Paper II (1937)

Carl Friedrich von Weizsäcker  
(1912 - 2007)

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

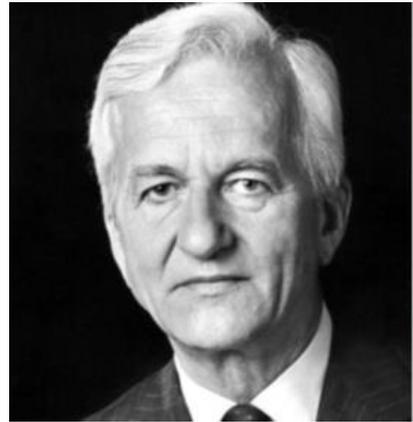
nuclear reactions exert two different influences at the same time: They change the physical state of the matter by releasing energy and its chemical composition by transmuting the elements. The generation of energy is the unproblematic part of the theory to consider: Nuclear reactions or effects of similar 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



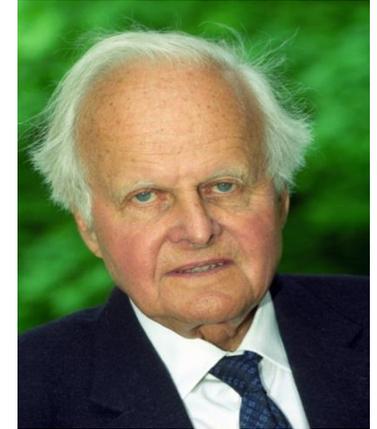
Ernst Heinrich von W.

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. If we had wanted Germany to win the war we would have succeeded!"*

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."*

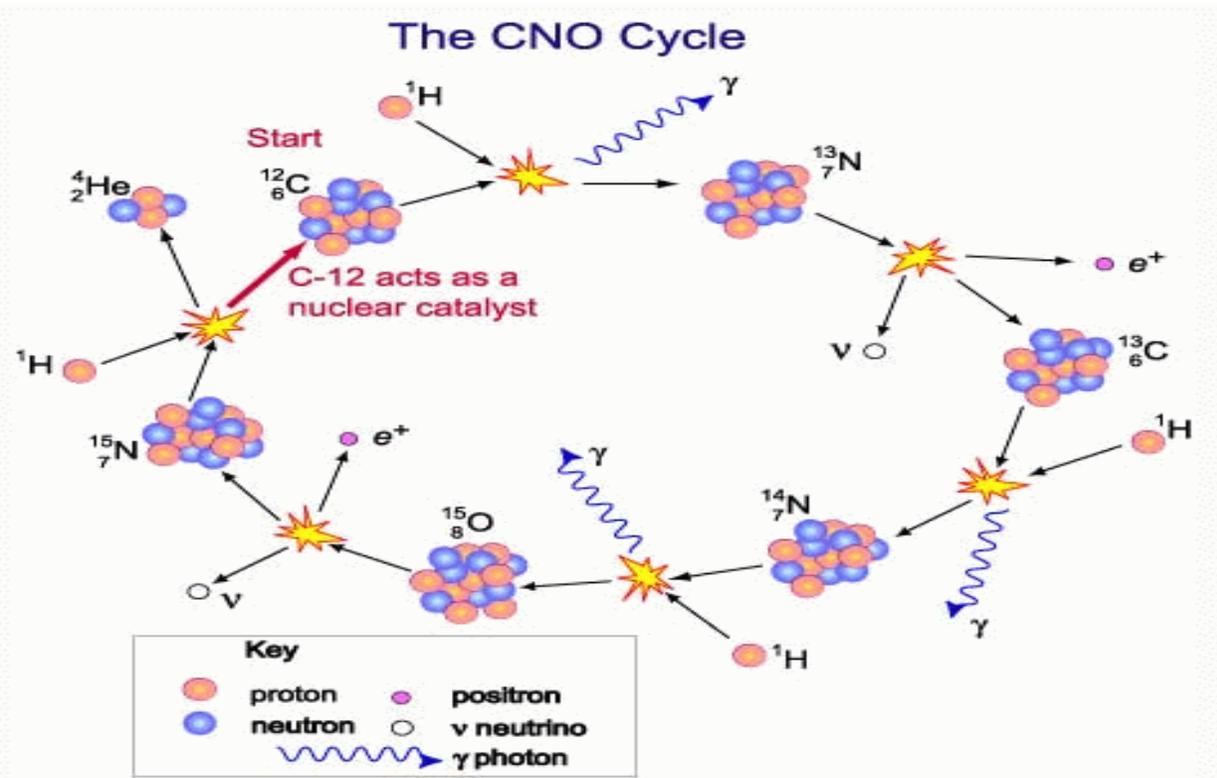
Max von Laue called this agreement "*die Lesart*" (the Version) : *"The leader in all these discussions was Weizsäcker. I did not hear any mention of any ethical point of view."*



# Energy Production in Stars\*

H. A. BETHE

*Cornell University, Ithaca, New York*



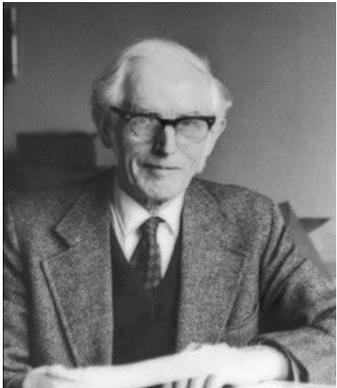
It is shown further (§5–6) that *no elements heavier than  $\text{He}^4$  can be built up in ordinary stars.* This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment ( $\alpha$ -emission!) rather than built up (by radiative capture). *The instability of  $\text{Be}^8$  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)



**1925: Cecilia Payne**

Stars are made mostly of Hydrogen



**1931: Robert Atkinson**

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



**1939: Hans Bethe**

Normal stars cannot built in their interiors elements heavier than Helium.

**1915: William Harkins**

Even elements on Earth's crust are more abundant than odd ones due to the structure of their nuclei



*W. D. Harkins*

**1929: Henri Norris Russell**

Stellar abundances display specific regularities, similar to those on Earth

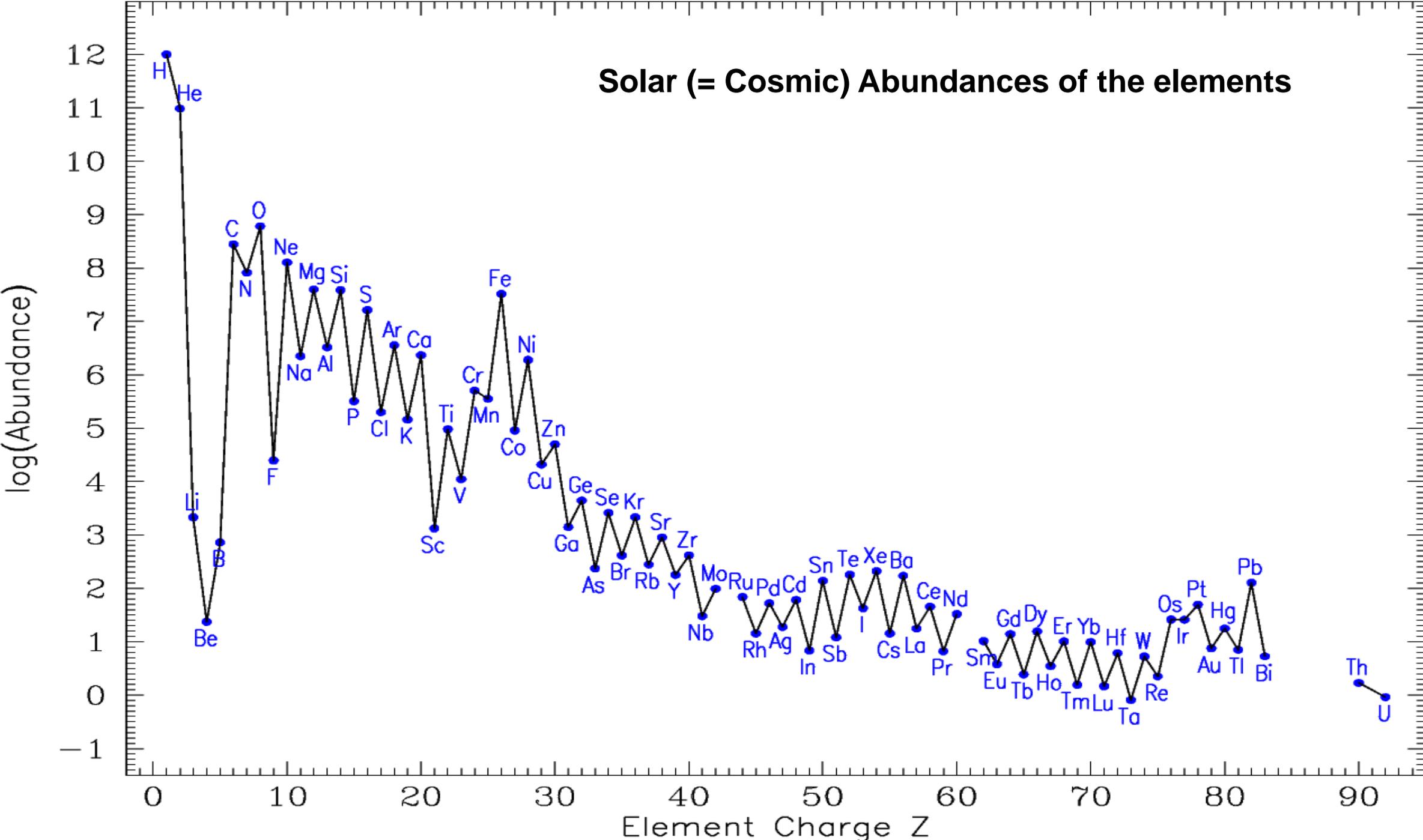


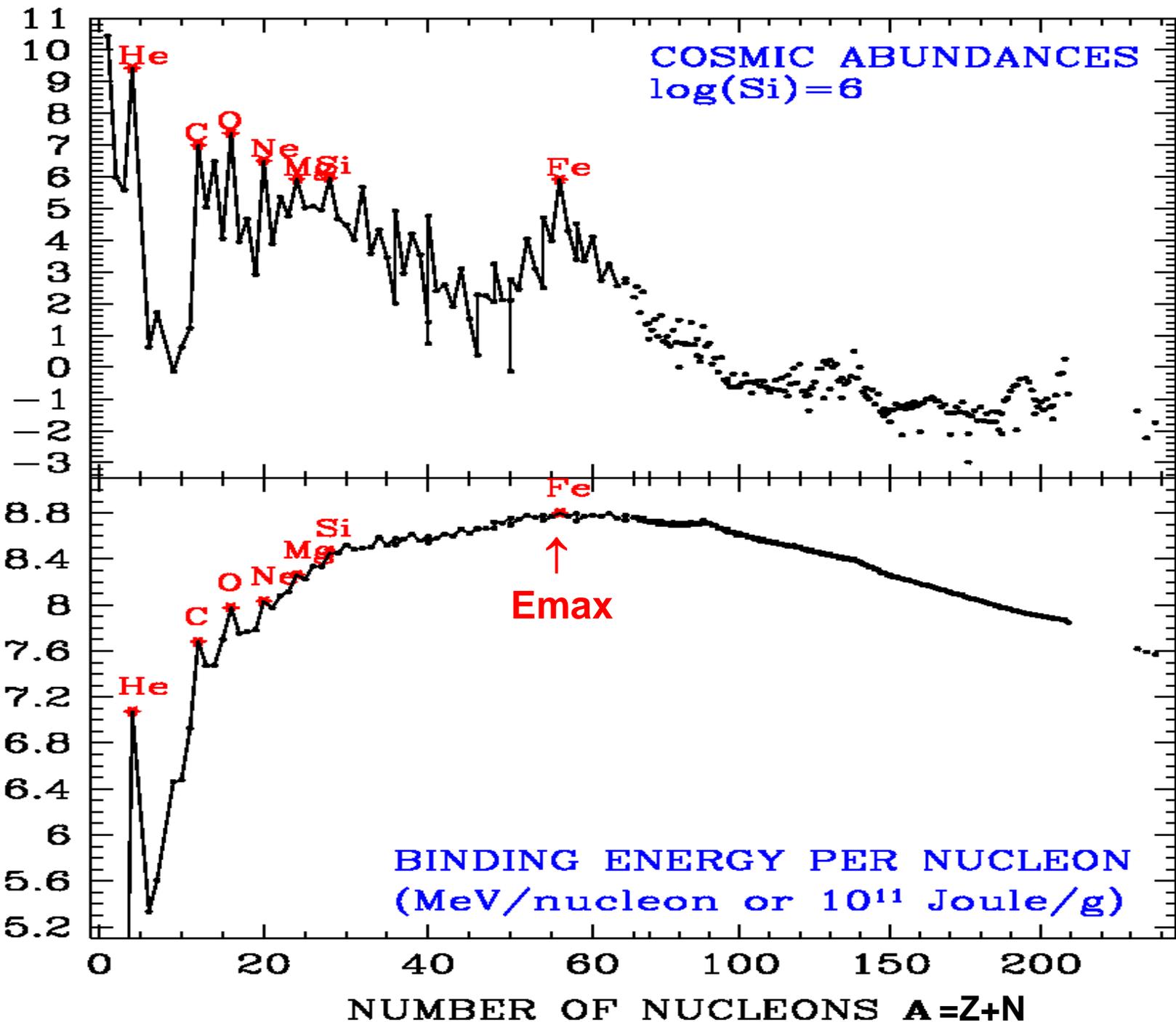
**1937: Carl F. von Weizsäcker**

may be; but perhaps the elements were made by another process, prior to their formation



# Solar (= Cosmic) Abundances of the elements





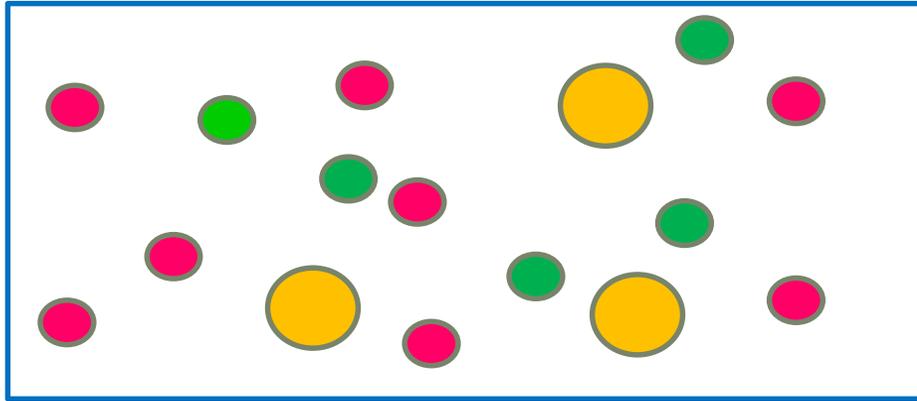
Cosmic abundances of nuclides are locally correlated with **nuclear stability** (*Binding energy per nucleon*):

alpha-nuclei ( $A = \text{multiple of } 4$ ),  
 “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  $\rho$  evolving for lapse of time  $L$

Nuclear reactions  $A + B \Rightarrow C + D$   
proceeding at rate  $R$

1.  $R \gg 1/L$  : All direct and inverse reactions proceed very fast :  $A + B \Leftrightarrow C + D$

**Nuclear  
statistical  
equilibrium**

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

Abundances of nuclei depend on  $T$ ,  $\rho$  and their binding energies  $B$

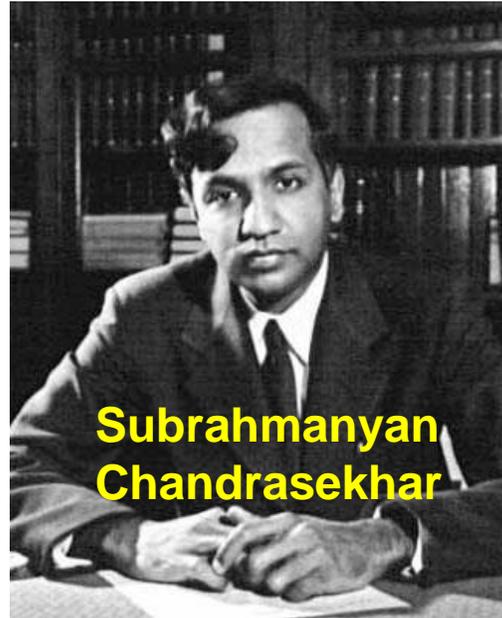
2.  $R \ll 1/L$  : Reactions proceed slowly :  $A + B \Rightarrow C + D$

Abundances of nuclei depend on reaction rates  $R(T, \rho)$   
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<sup>1</sup> 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

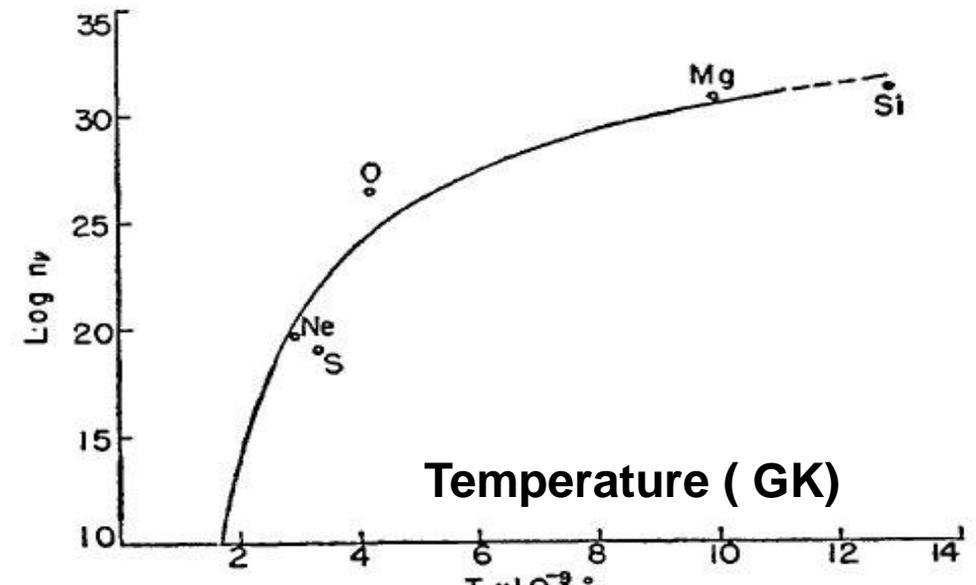
Starting at temperature  $T \sim 10$  GK ( $10^{10}$  K)  
and density  $\rho \sim 10^8$  g/cc built nuclei around Si

*In conditions of nuclear equilibrium*



then at lower  $T$  and  $\rho$  built lighter nuclei

But Fe and heavier nuclei NEVER produced

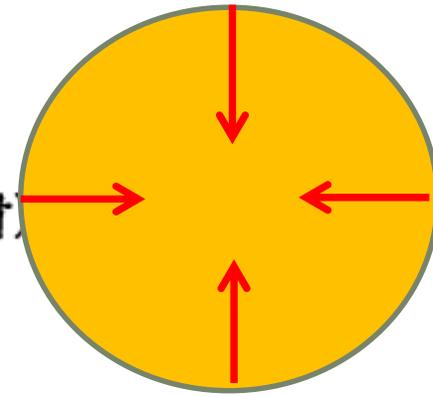


# THE SYNTHESIS OF THE ELEMENTS FROM HYDROGEN



*F. Hoyle*

(Received 1946 April 6)



*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.

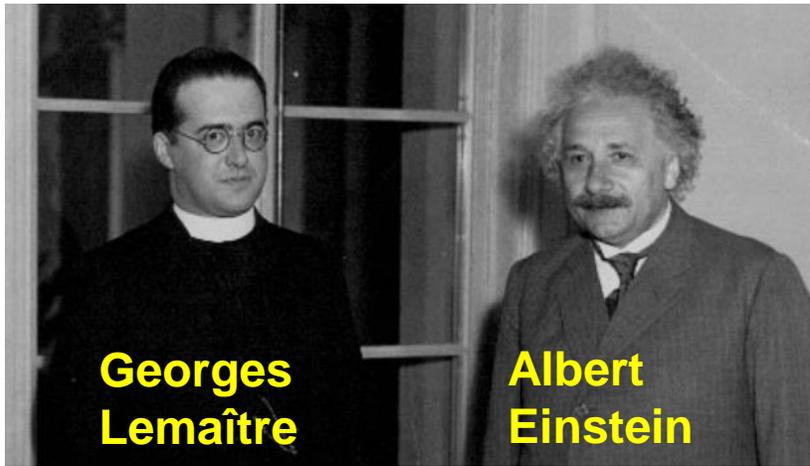
But  
HOW  
to get  
the material  
out of  
the star ?

# Expanding Universe and the Origin of Elements

G. GAMOW

*The George Washington University, Washington, D. C.*

September 13, 1946



Georges  
Lemaître

Albert  
Einstein

**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

**I**T 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  $\beta$ -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-

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

$\alpha\beta\gamma$

R. A. ALPHER\*

*Applied Physics Laboratory, The Johns Hopkins University,  
Silver Spring, Maryland*

AND

H. BETHE

*Cornell University, Ithaca, New York*

AND

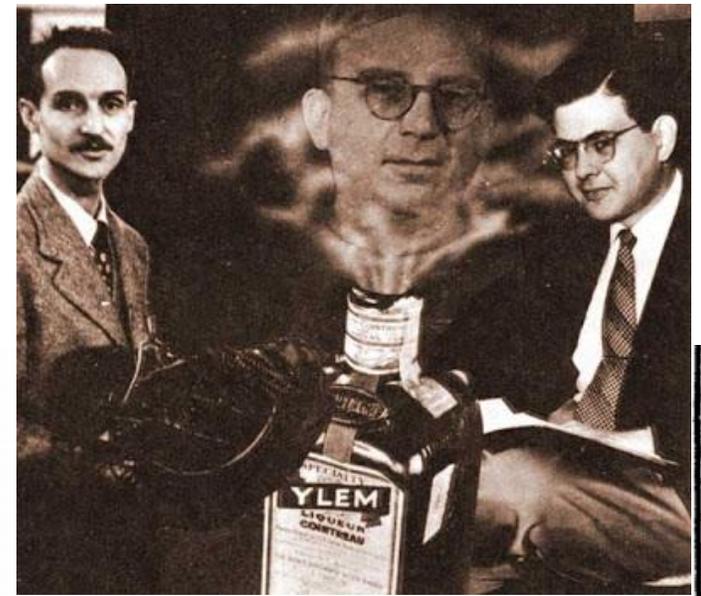
G. GAMOW

*The George Washington University, Washington, D. C.*

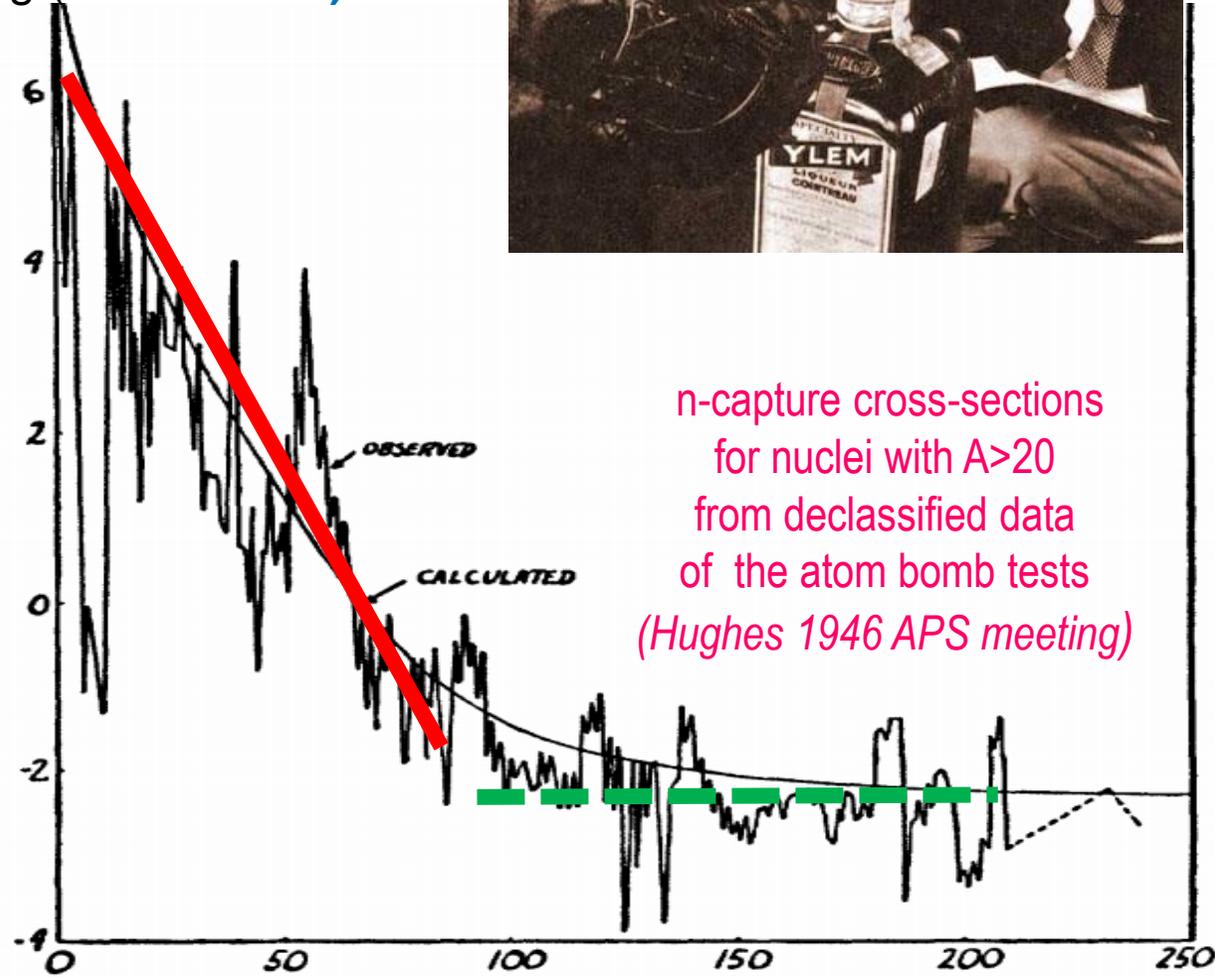
February 18, 1948

Phys.Rev., April 1st 1948

1 page, 1 equation, 1 figure



Log (Abundances)



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

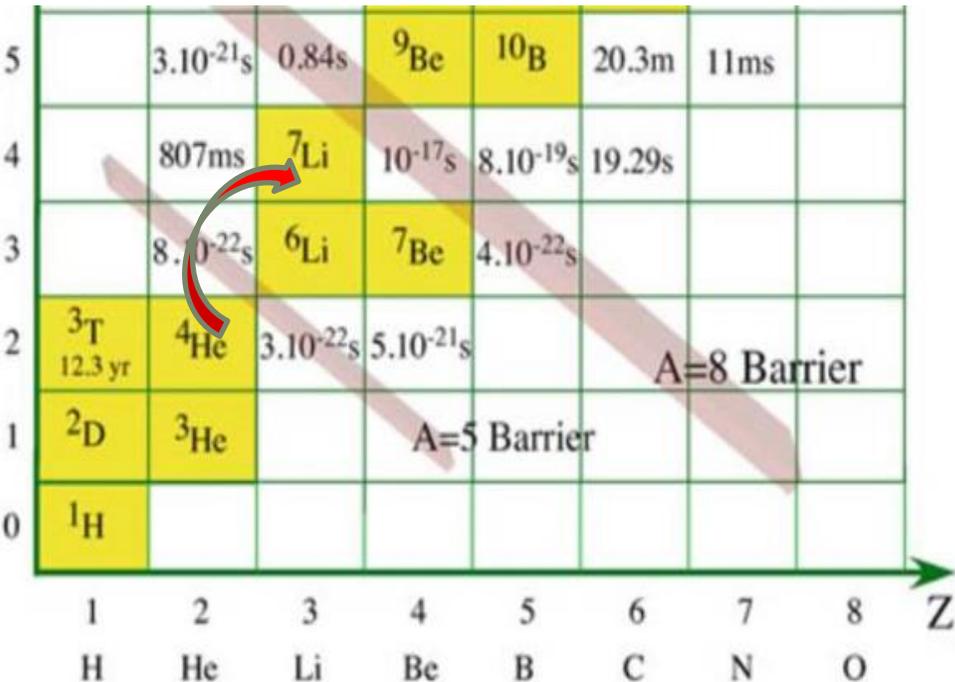
Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend ~~so~~ so much on their intrinsic stabilities (mass 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:

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

where  $n_i$  and  $\sigma_i$  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.

# *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 :  $n \rightleftharpoons p$  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

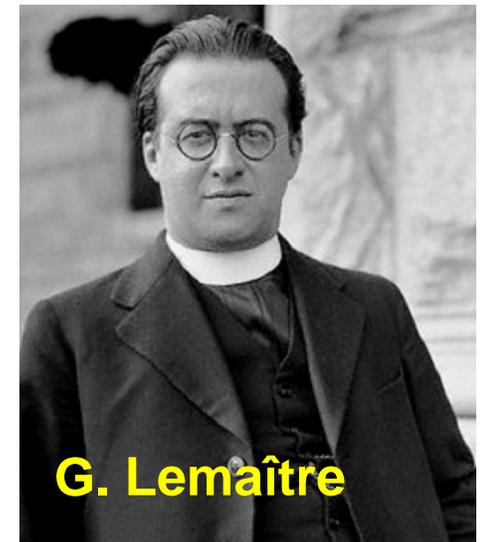
## Address to the Pontifical Academy of Sciences ( September 1951)

### 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

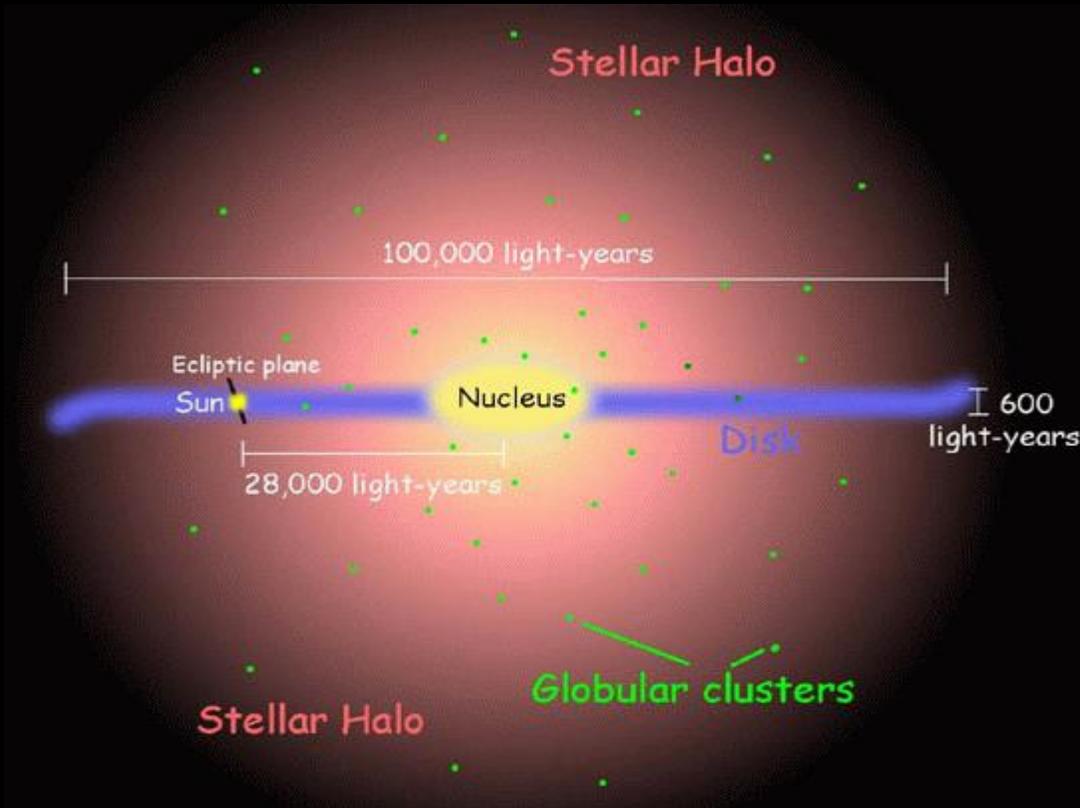




*G. Gamow*: all elements were produced in the hot primordial Universe (Big Bang) by successive neutron captures

### Early 1950ies

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

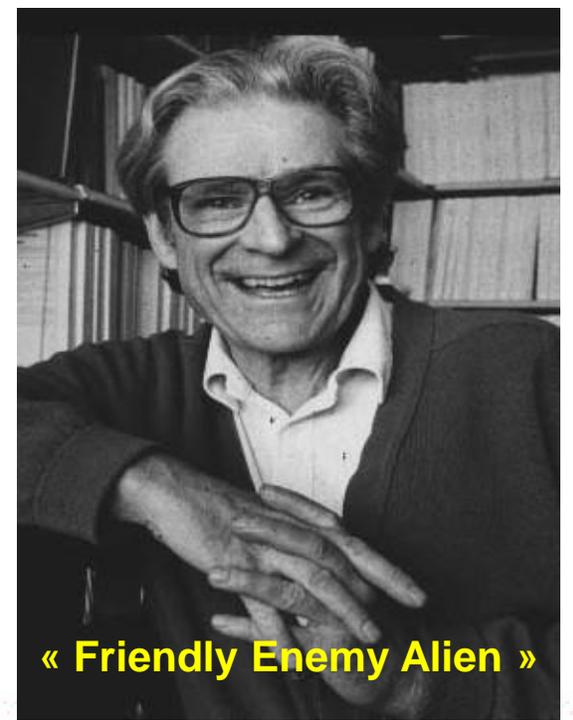


Old stars of galactic halo (Population II) contain less heavy elements (metals) than the younger stellar population (Population I) of the galactic disk  
*Chamberlain and Aller 1951*

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

# NUCLEAR REACTIONS IN STARS WITHOUT HYDROGEN\*

E. E. SALPETER

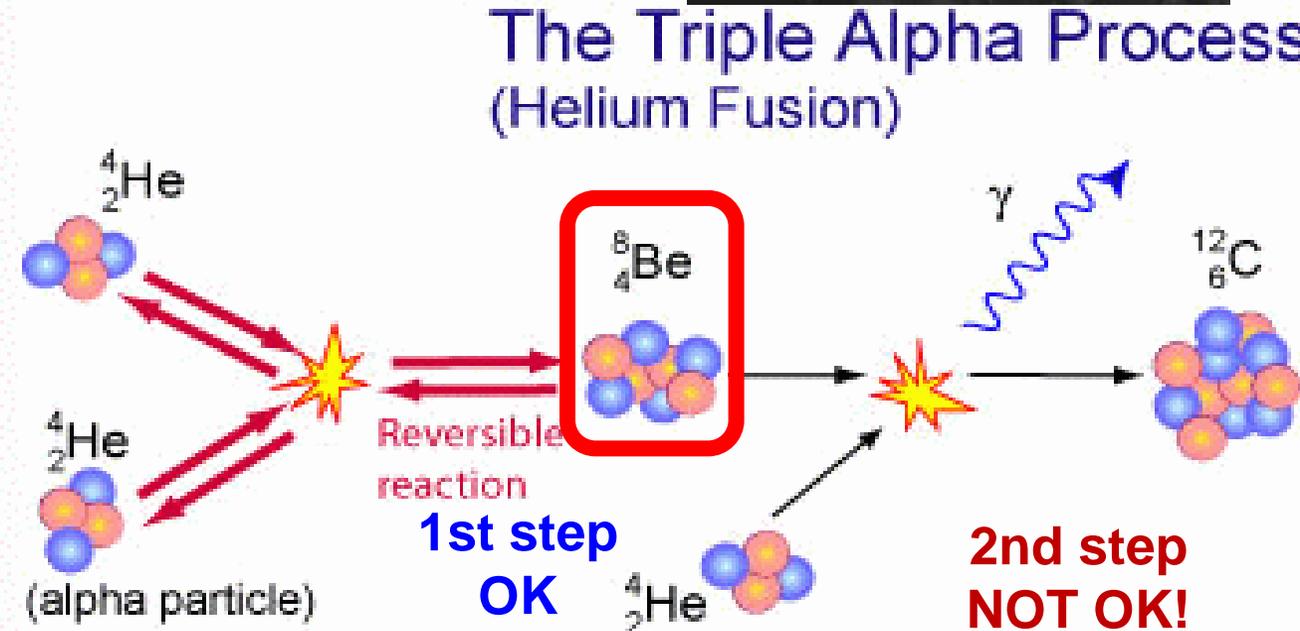


« Friendly Enemy Alien »

LABORATORY OF NUCLEAR STUDIES  
 CORNELL UNIVERSITY  
 October 2, 1951

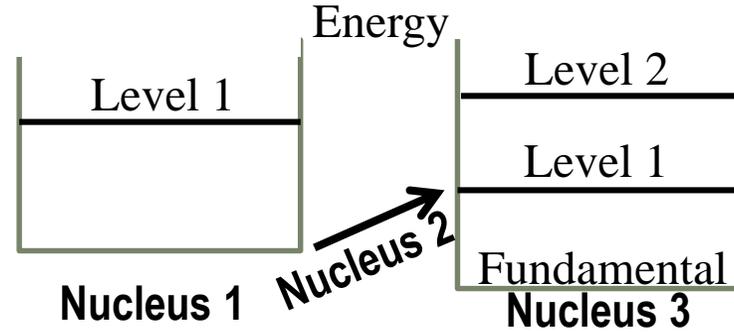
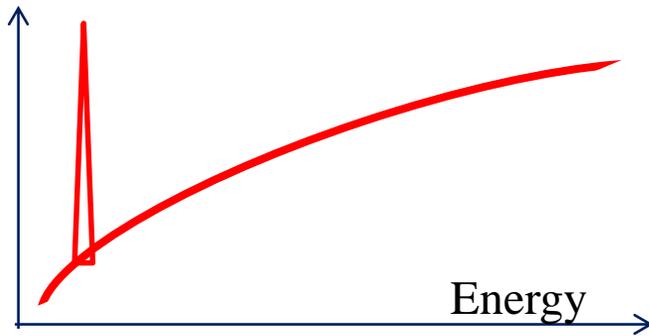
verted into helium by means of the carbon-nitrogen cycle. When the energy supply of the carbon-nitrogen cycle has been exhausted, the star undergoes gravitational contraction, and its temperature increases. Various nuclear processes<sup>1, 2, 3</sup> have been suggested for such a contracting star, all 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.

5		$3 \cdot 10^{-21}$ s	0.84s	${}^9\text{Be}$	${}^{10}\text{B}$	20.3m	11ms	
4		807ms	${}^7\text{Li}$	$10^{-17}$ s	$8 \cdot 10^{-19}$ s	19.29s		
3		$8 \cdot 10^{-22}$ s	${}^6\text{Li}$	${}^7\text{Be}$	$4 \cdot 10^{-22}$ s			
2	${}^3\text{T}$ 12.3 yr	${}^4\text{He}$	$3 \cdot 10^{-22}$ s	$5 \cdot 10^{-21}$ s				A=8 Barrier
1	${}^2\text{D}$	${}^3\text{He}$						A=5 Barrier
0	${}^1\text{H}$							
	1	2	3	4	5	6	7	8
	H	He	Li	Be	B	C	N	O

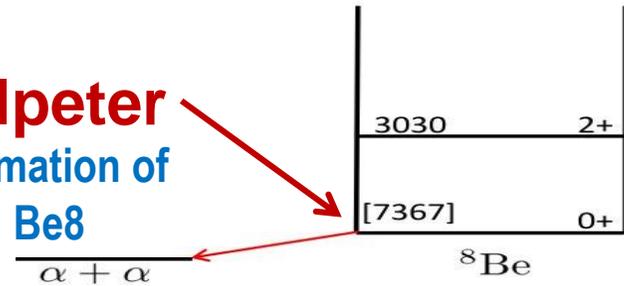


# Formation and survival of C-12 in He-burning

Probability of nuclear reaction  
**It becomes very high when the reaction is resonant**

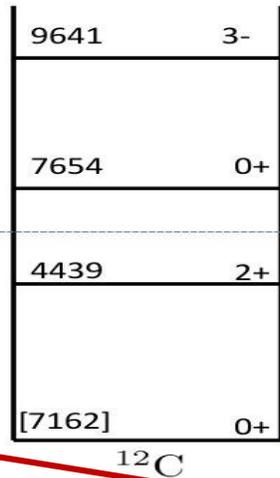


**Salpeter**  
 Formation of **Be8**

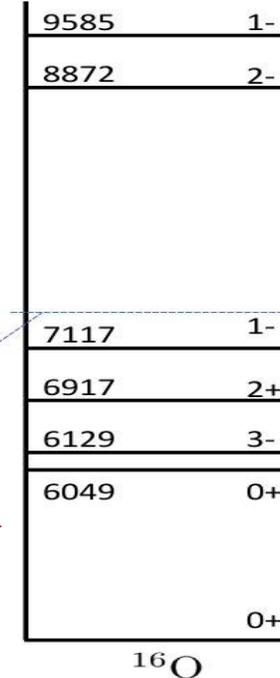


Fred Hoyle suggests that the reaction  $\text{Be8} + \alpha \Rightarrow \text{C12}$  is resonant because of the existence of a **nuclear energy level at 7.7 MeV (unknown at that time)** in C12

Formation of **C12**  
**Hoyle**



Survival of **C12**



The level is found in William Fowler's Kellogg 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<sup>12</sup>

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<sup>14</sup>(d,α)C<sup>12</sup> covering the excitation energy range from 4.4 to 9.2 Mev in C<sup>12</sup> shows a level at 7.68±0.03 Mev. At E<sub>d</sub>=620 kev, θ<sub>lab</sub>=90°, transitions to this state are only 6 percent of those to the level at 4.43 Mev.

SALPETER<sup>1</sup> and Öpic<sup>2</sup> have pointed out the importance of the Be<sup>8</sup>(α,γ)C<sup>12</sup> reaction in hot stars which have largely exhausted their central hydrogen.

Hoyle<sup>3</sup> explains the original formation of elements heavier than helium by this process and concludes from the observed cosmic abundance ratios of O<sup>16</sup>:C<sup>12</sup>:He<sup>4</sup>

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

<sup>1</sup> E. E. Salpeter, *Annual Review of Nuclear Science* (Annual Reviews, Inc., Stanford, 1953), Vol. 2, p. 41.

<sup>2</sup> E. J. Öpic, *Proc. Roy. Irish Acad.* **A54**, 49 (1952).

<sup>3</sup> F. Hoyle (private communication).

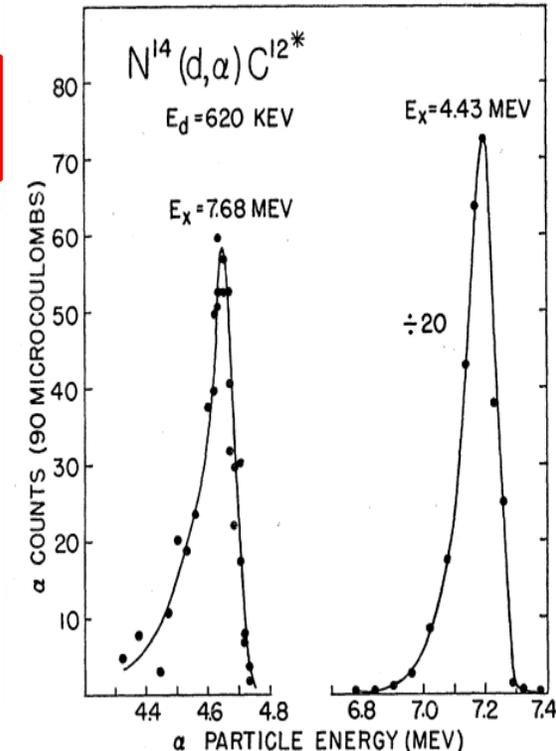
that this reaction should have a resonance at 0.31 Mev or at 7.68 Mev in C<sup>12</sup>.

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

<sup>4</sup> M. G. Holloway and B. L. Moore, *Phys. Rev.* **58**, 847 (1940).

<sup>5</sup> R. Malm and W. W. Buechner, *Phys. Rev.* **81**, 519 (1951).

<sup>6</sup> 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

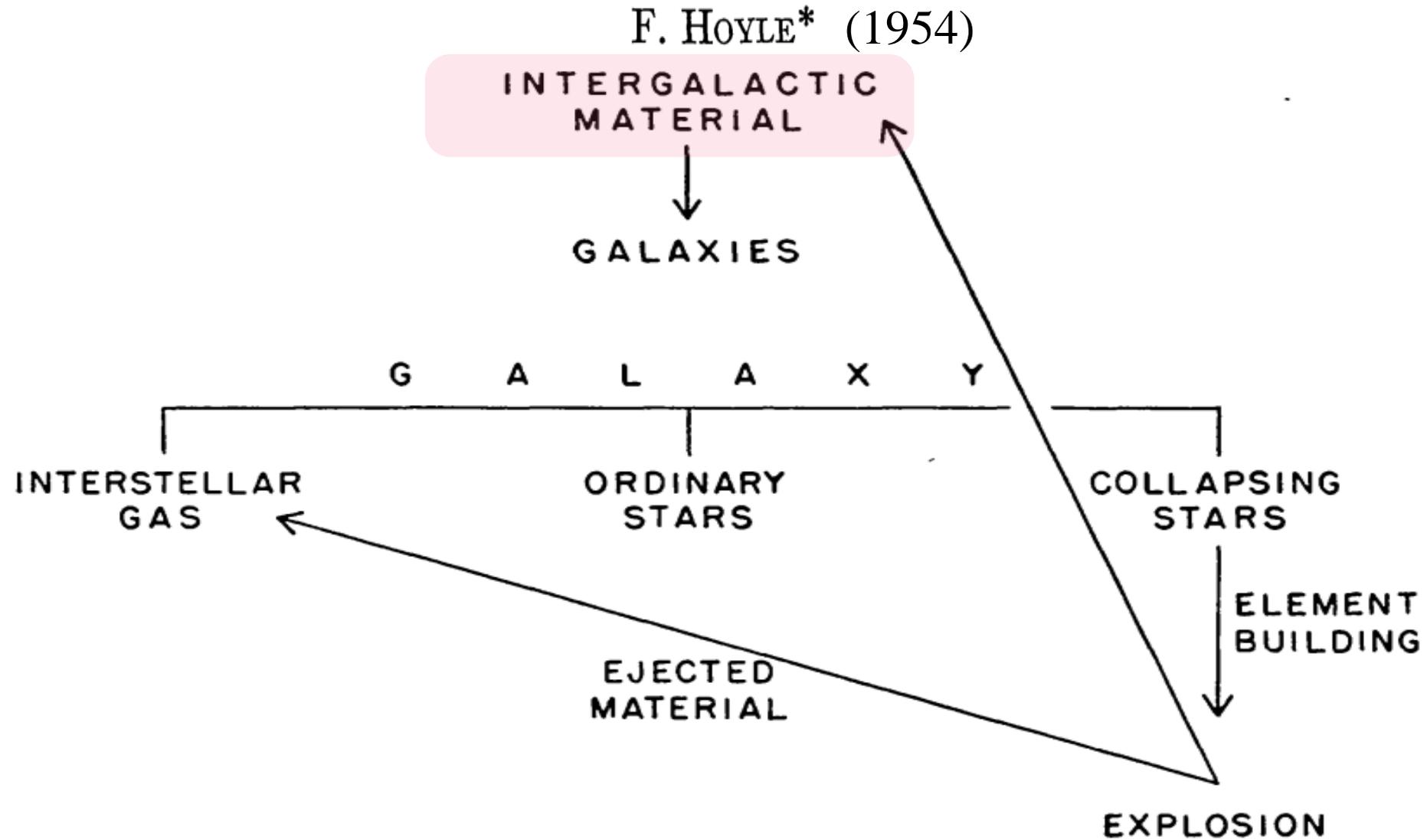
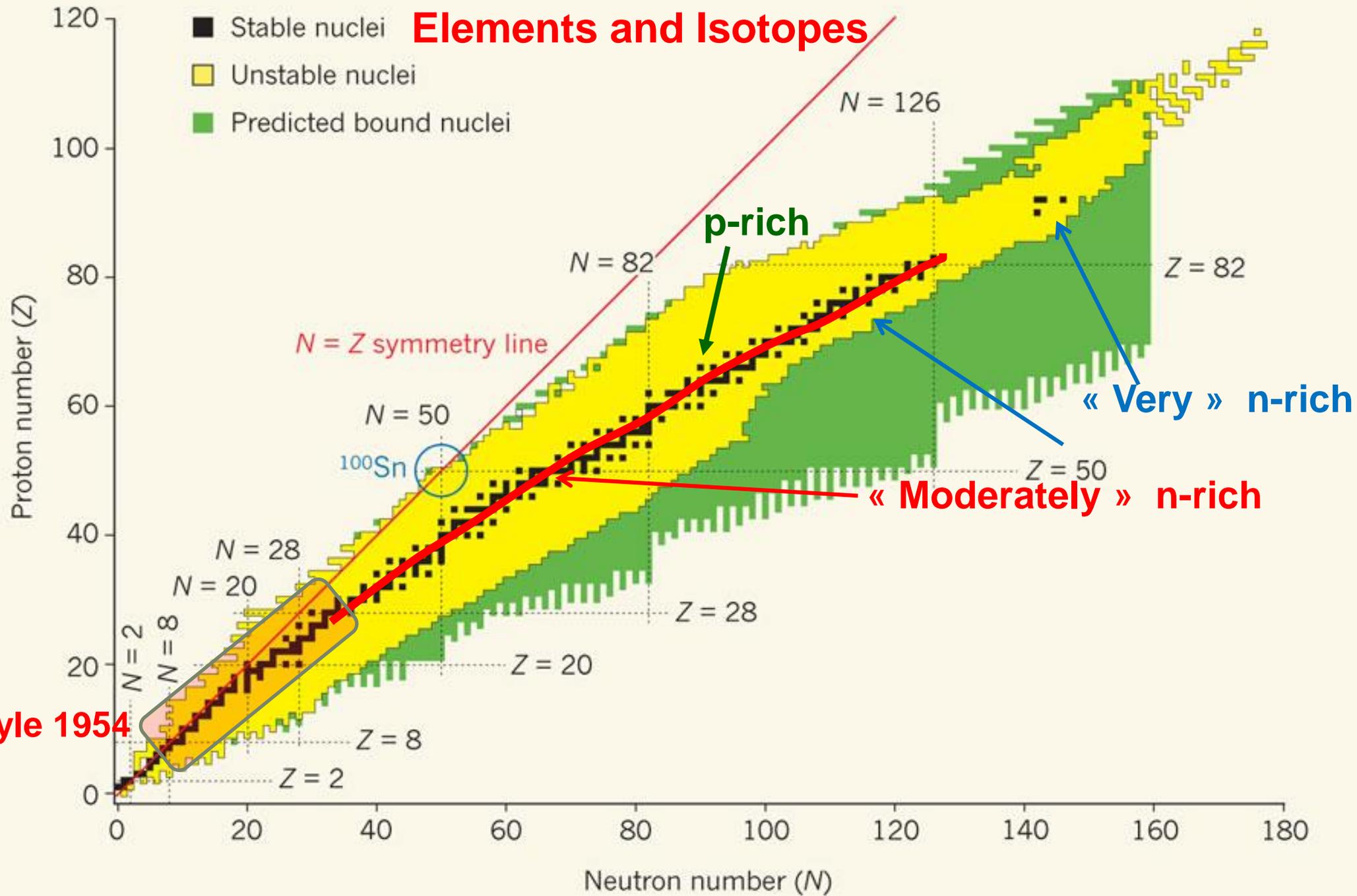


FIG. 1.—The general cosmological framework assumed for this discussion

# Elements and Isotopes



# 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

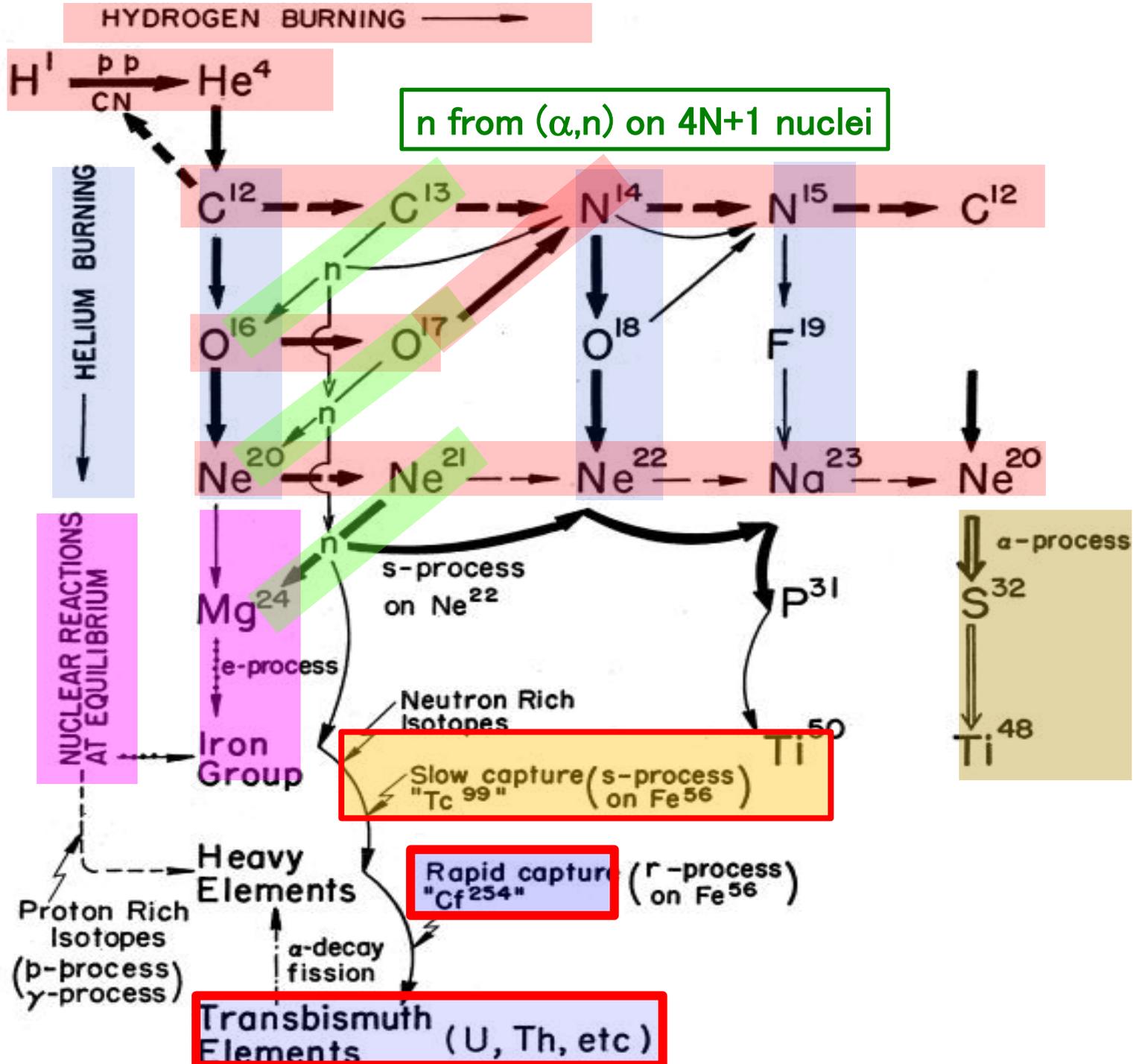
“The fault, dear Brutus, is not in our stars, But in ourselves,”  
(*Julius Caesar*, Act I, Scene 2)



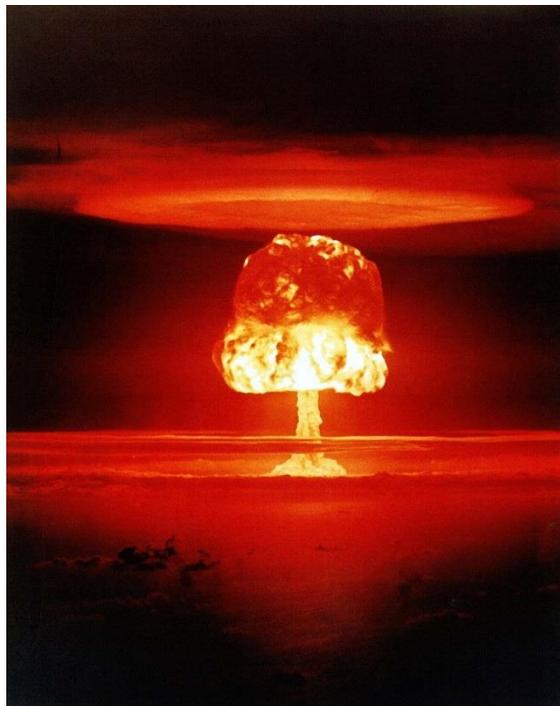
**Margaret Geoffrey  
Burbidge**

**William  
Fowler**

**Fred  
Hoyle**



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)



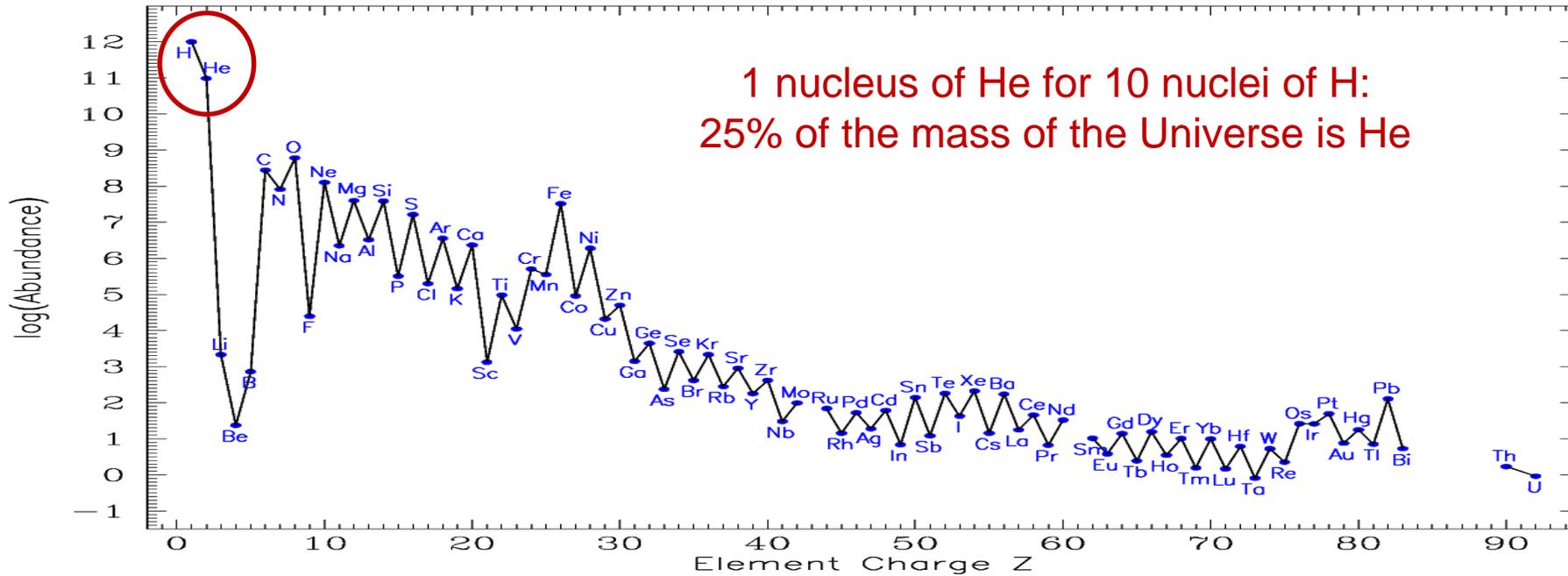
Elements	Method of Formation
D, Li, Be, B	Not formed in stellar interiors. Possibly made by nuclear reactions in stellar atmospheres
He, C, N, O, F, Ne	Hydrogen and helium thermonuclear reactions in orderly evolution of stellar interiors
Ne to Ca	<ol style="list-style-type: none"><li>1. Heavy-ion thermonuclear reactions in orderly evolution of stellar interiors</li><li>2. Neutron capture on slow time scale</li><li>3. Hydrogen and helium thermonuclear reactions in supernova explosions</li></ol>
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	<ol style="list-style-type: none"><li>1. Proton capture and photonuclear reactions in Type II supernovae</li><li>2. Photonuclear reactions on slow time scale in orderly evolution of stellar interiors</li></ol>
(d) Trans-bismuth	Neutron capture on fast time scale in Type I supernovae

# THE MYSTERY OF THE COSMIC HELIUM ABUNDANCE

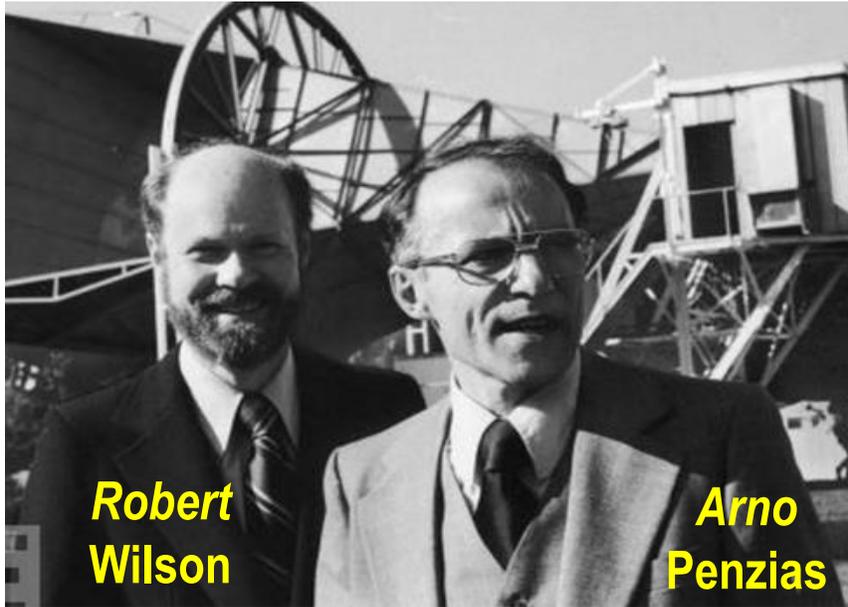
By PROF. F. HOYLE, F.R.S., and DR. R. J. TAYLER

University of Cambridge

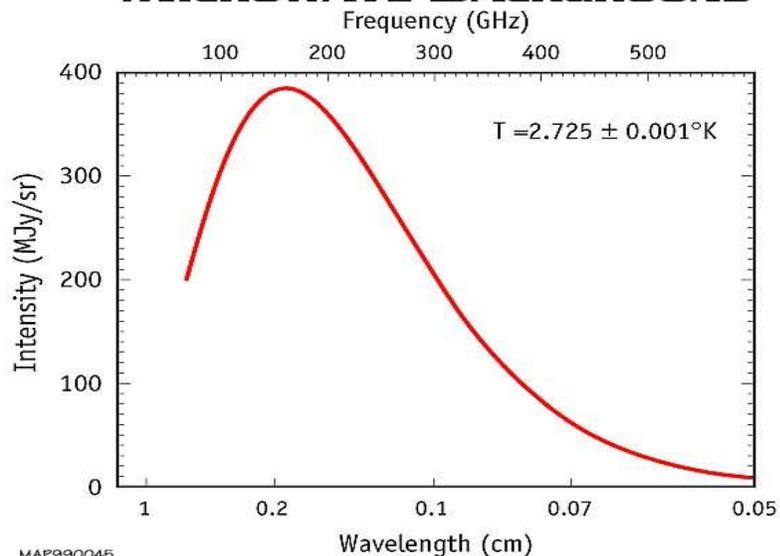
This brings us back to our opening remarks. There has always been difficulty in explaining the high helium content of cosmic material in terms of ordinary stellar processes. The mean luminosities of galaxies come out appreciably too high on such a hypothesis. The arguments presented here make it clear, 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



## SPECTRUM 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, He<sup>3</sup>, He<sup>4</sup>, and Li<sup>7</sup> can be produced in the universal fireball. Reasonable agreement with solar-system abundances for these nuclei is obtained if the density is  $\sim 2 \times 10^{-31}$  gm cm<sup>3</sup>, corresponding

Hayashi (1950). n - p equilibrium

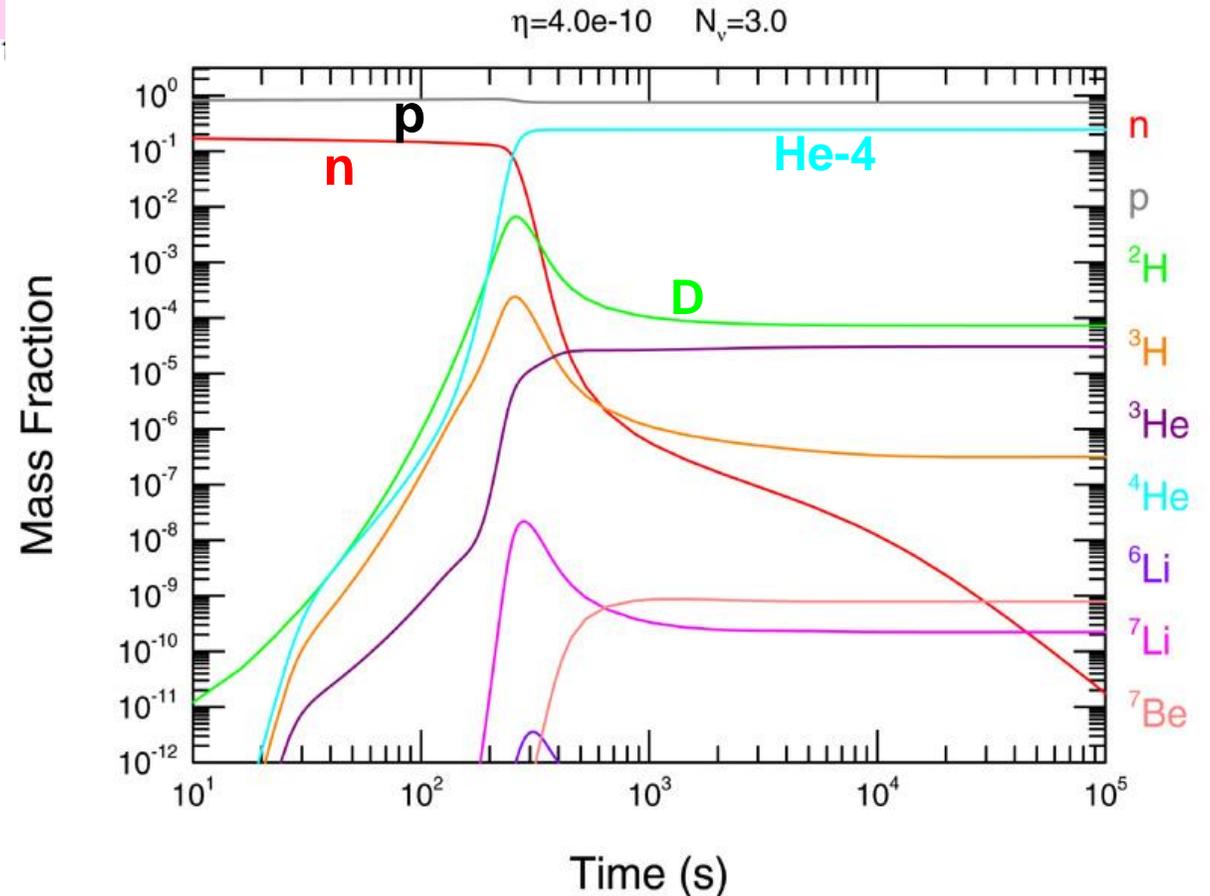
$X(n)/X(p) \sim 0.13$  at freeze-out

$X(\text{He-4}) \sim 2 X(n) \sim 0.25$

-Only way to produce so much He4  
- (25 % by mass)

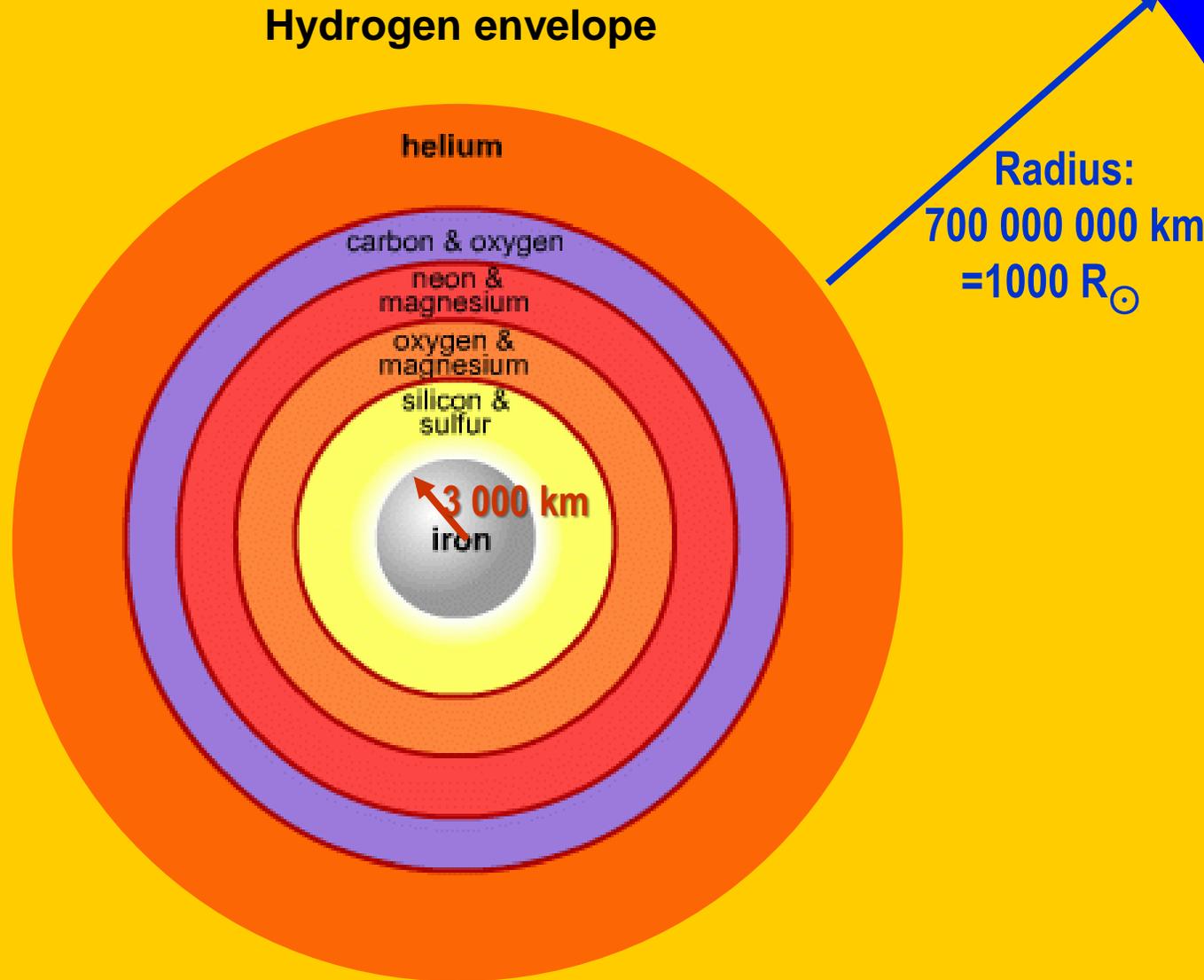
-Only way to produce Deuterium  
(destroyed in stellar interiors)

**In excellent agreement with observations**



# Back to the stars

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



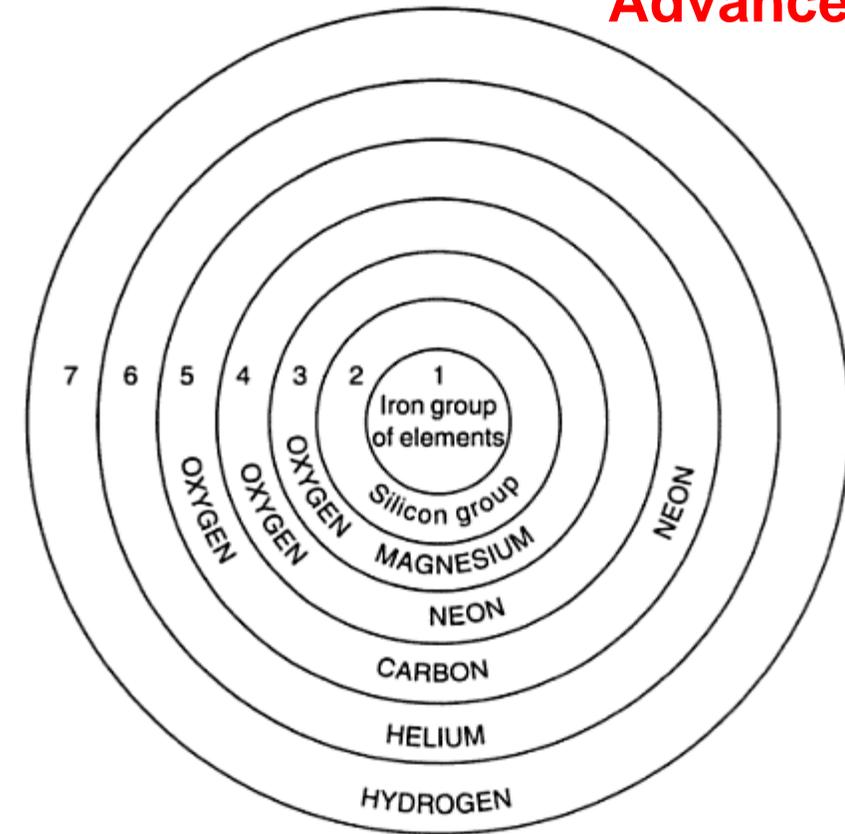
Fe-56 is the most stable nucleus in nature  
(its reactions are endothermic).  
No nuclear energy source available in the core

## Advanced 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 « onion skin » model (Hoyle 1955)

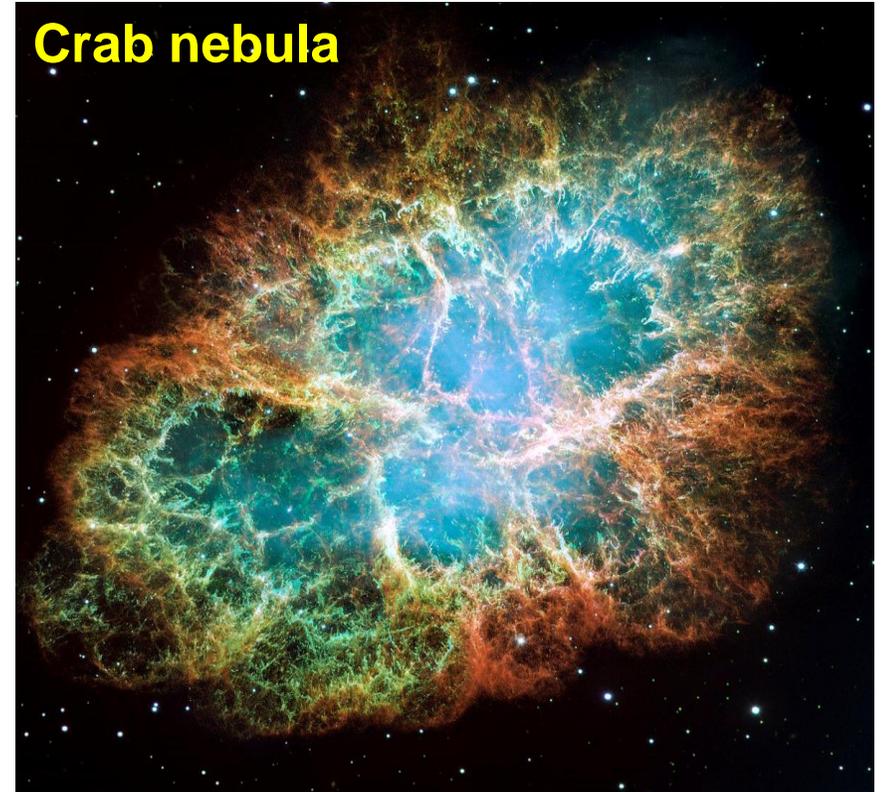
The outer layers keep (partially) the products of previous phases of stellar nucleosynthesis



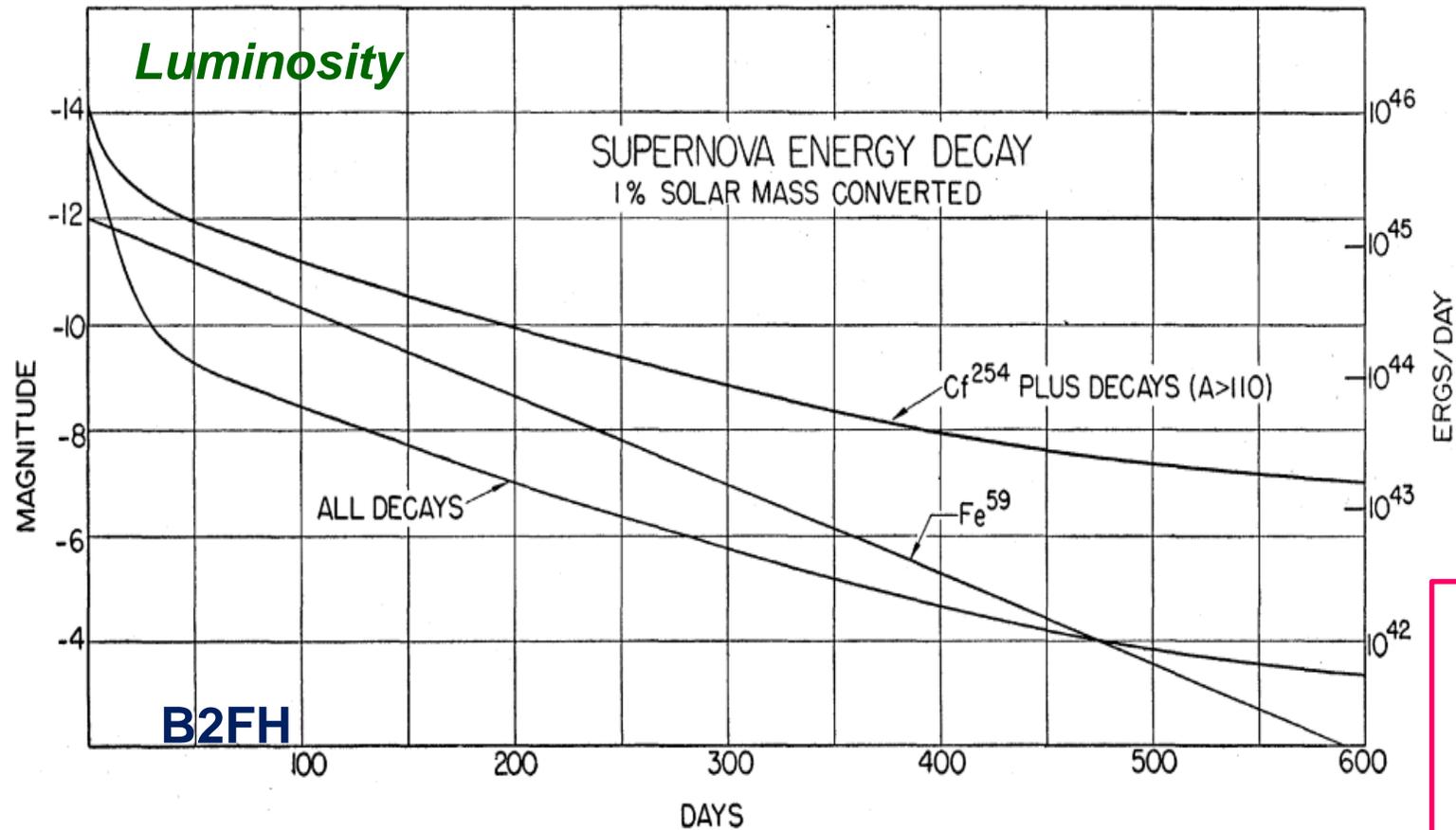
This material, synthesized by nuclear reactions in stellar interiors must come out through the final event of a **supernova explosion**

The explosion produces also new elements (*explosive nucleosynthesis*) including short-lived **radioactive ones**

**Crab nebula**



# What powers the exponentially decreasing lightcurves of supernovae ?



Radioactivity,  
of lifetime ~2 months

Be-7 : Borst 1950

Cf-254: Baade, B2FH 1956

Titus Pankey Jr 1963

Ni56 → Co56 → Fe56  
7 days 2 months

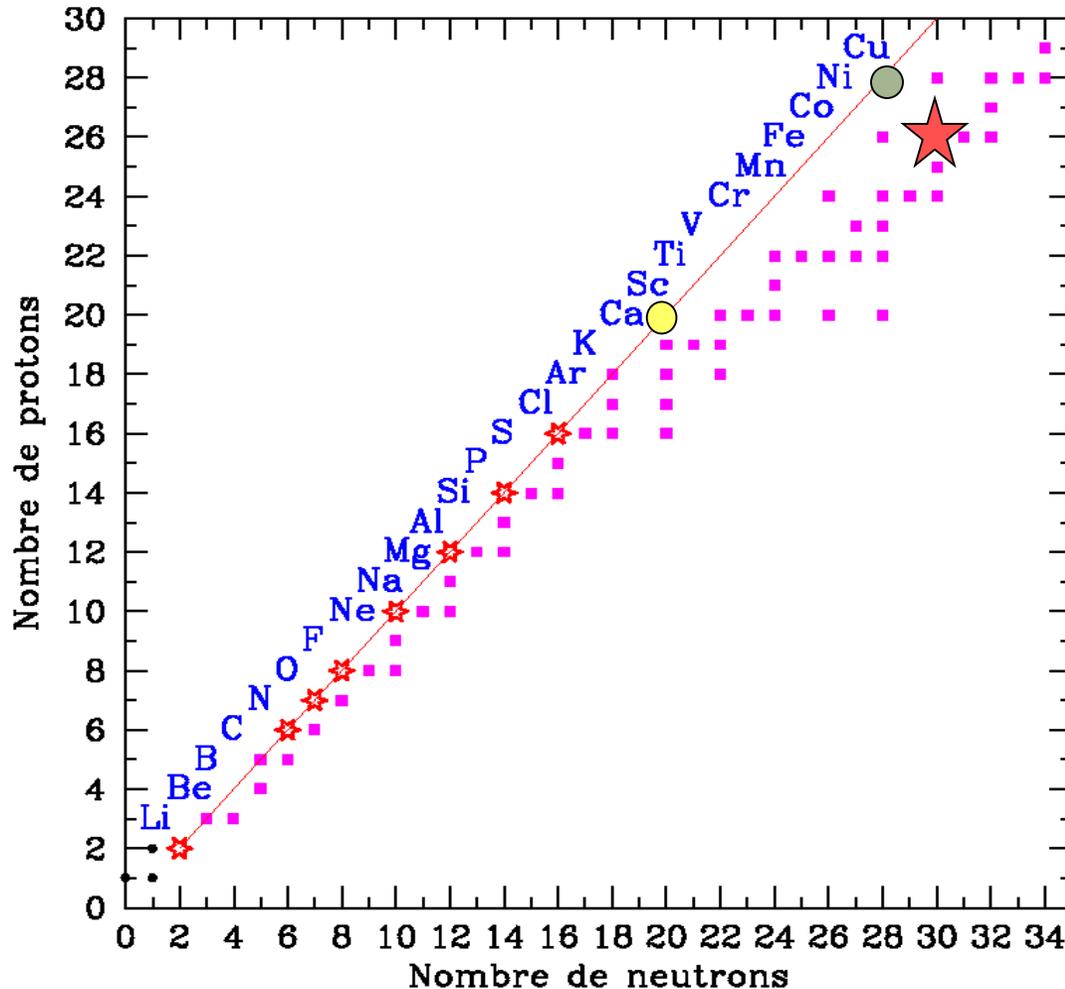
Fe56, the most stable nucleus in nature  
is produced as unstable Ni56

Hoyle's greatest regret

## 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<sup>254</sup> 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<sup>238</sup>. 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.

## The way towards the Fe-peak: hydrostatic vs explosive

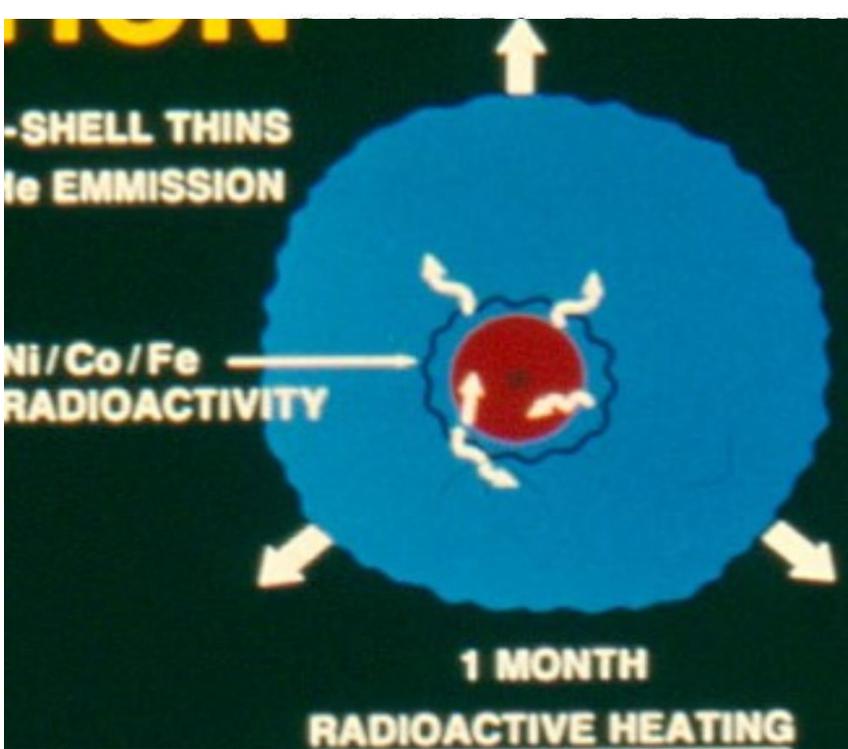


Ca40 is the last stable nucleus with  $N=Z$  on the way of Si-melting towards the Fe-peak

In the stellar core  
weak interactions  
( $p + e^+$ )  
turn some protons  
into neutrons  
and Fe56 dominates  
the composition  
in nuclear  
statistical equilibrium

In explosive nucleosynthesis, weak (=slow) interactions have no 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



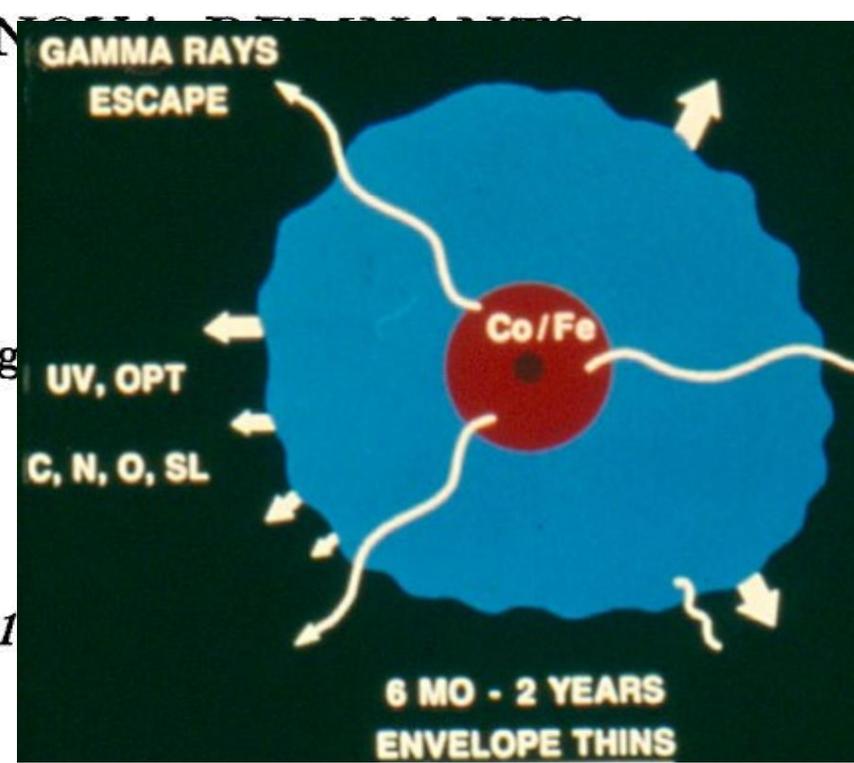
# ES FROM YOUNG SUPERNOVA

DONALD D. CLAYTON\*  
 Rice University, Houston, Texas

STIRLING A. COLGATE  
 Colorado Institute of Mining and Technology

AND  
 GERALD J. FISHMAN  
 Rice University, Houston, Texas  
 received May 20, 1968; revised June 24, 1968

## 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  $\text{Ni}^{56}$ . It is expected that  $\text{Ni}^{56}$  is the most abundant nucleus resulting from silicon burning in the supernova shock conditions. The requisite mass of  $\text{Ni}^{56}$  ( $0.14 M_{\odot}$ ) 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  $\text{Ti}^{44}$ .

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.

# THE HYDRODYNAMIC BEHAVIOR OF SUPERNOVAE EXPLOSIONS\*

STIRLING A. COLGATE AND RICHARD H. WHITE

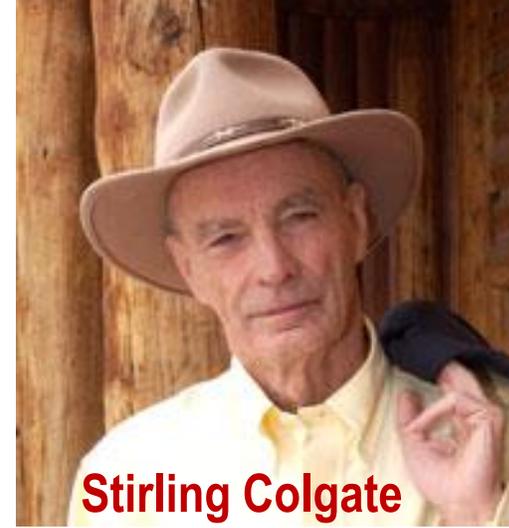
Lawrence Radiation Laboratory, University of California, Livermore, California

Received June 29, 1965

## ABSTRACT

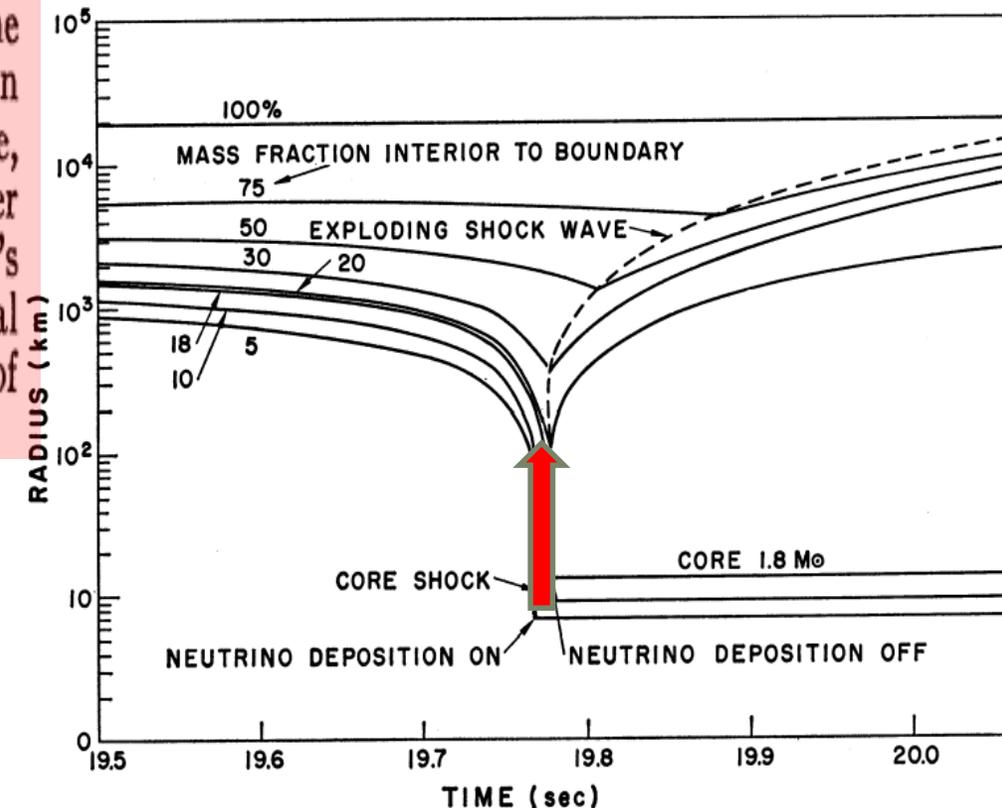
We regard the release of gravitational energy attending a dynamic change in configuration to be the primary energy source in supernovae explosions. Although we were initially inspired by and agree in detail with the mechanism for initiating gravitational instability proposed by Burbidge, Burbidge, Fowler, 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; the transfer of energy takes place by the emission and deposition of neutrinos.

99% of the enormous amount of gravitational energy from the dynamical collapse of the Fe core is released in the form of **neutrinos**; **Some of them interact with the stellar mantle and expel it, making a supernova**



Stirling Colgate

1959:  
Suggests satellites for search of  $\gamma$ -rays from supernovae,  
*In fact to cover monitoring of soviet test explosions*



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

