A BRIEF HISTORY OF NUCLEAR ASTROPHYSICS

PART I

THE ENERGY OF THE SUN AND STARS

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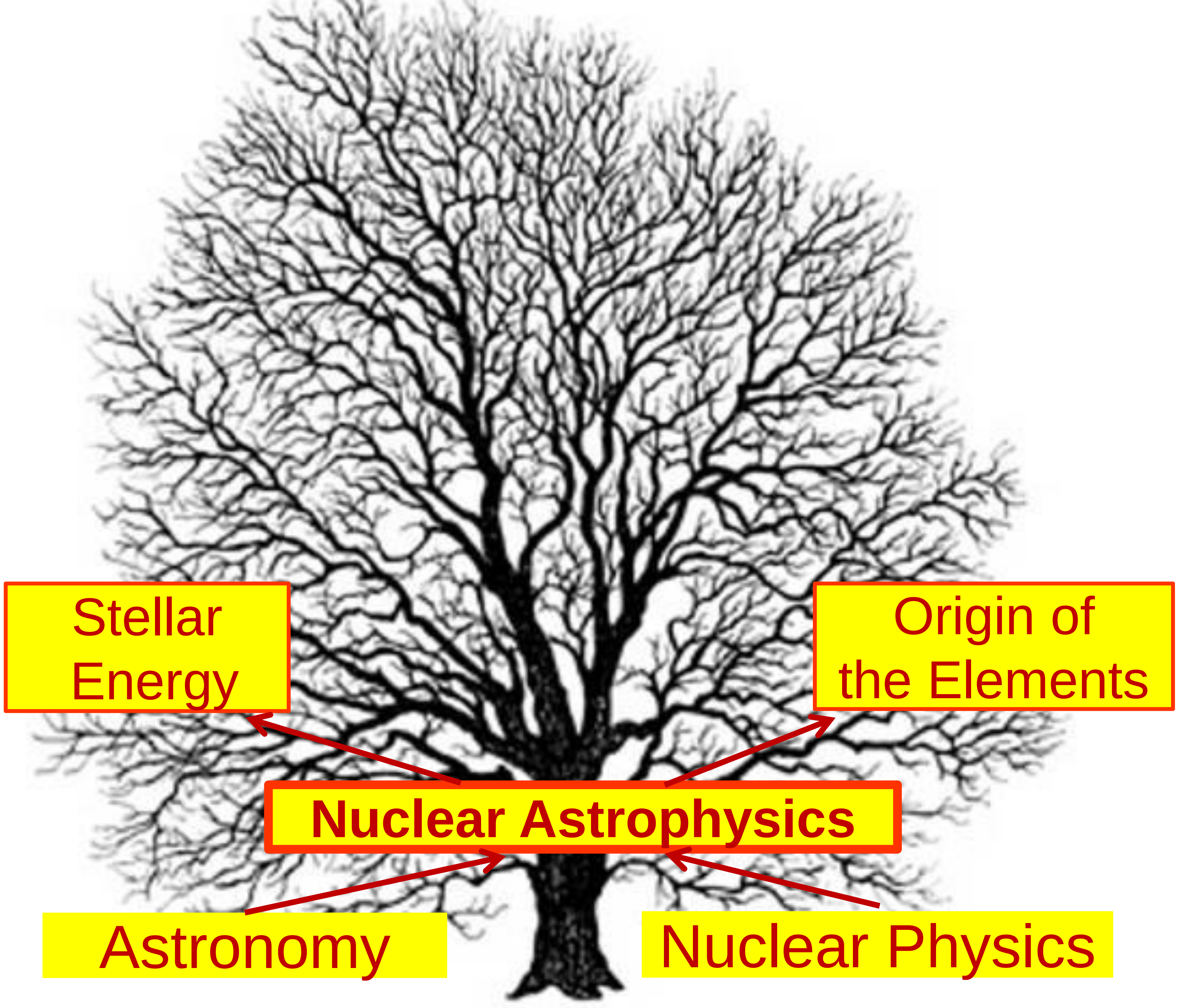
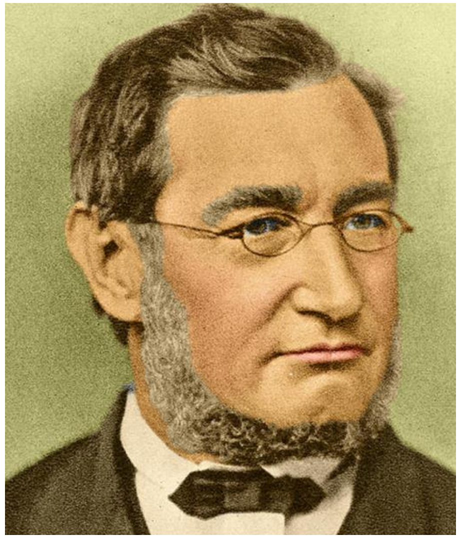
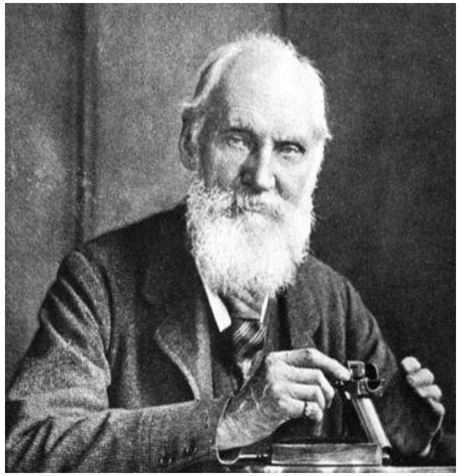

Stellar Energy
Origin of the Elements
Nuclear Astrophysics
Astronomy
Nuclear Physics

Thermodynamics: the energy of the Sun and the age of the Earth

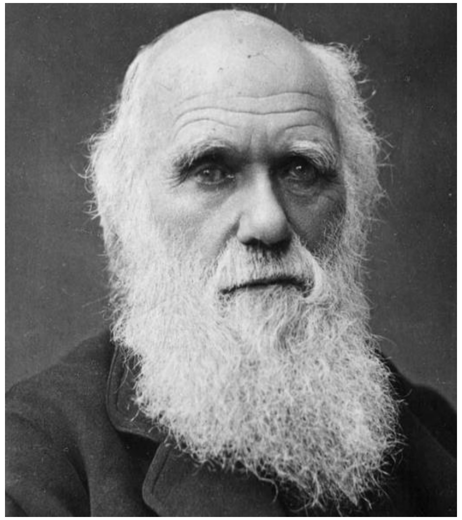


1847 : Robert Julius von Mayer
Sun heated by fall of meteors

1854 : Hermann von Helmholtz
Gravitational energy of Kant's
contracting protosolar nebula of gas and dust
turns into kinetic energy
Timescale ~ E_{Grav}/L_{Sun} ~ **30 My**



1850s : William Thompson (Lord Kelvin)
Sun heated ***at formation*** from meteorite fall,
now « an incadescent liquid mass » cooling
Age **10 – 100 My**



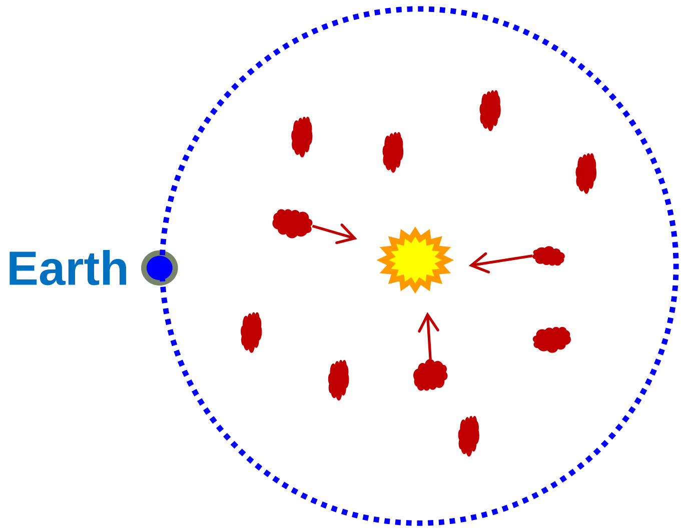
1859: Charles Darwin ***Origin of species*** :
Rate of erosion of the Weald valley is 1 inch/century
or 22 miles wild (X 1100 feet high) **in 300 My**
Such large Earth ages also required by geologists, like Charles Lyell

A gaseous, contracting and heating Sun

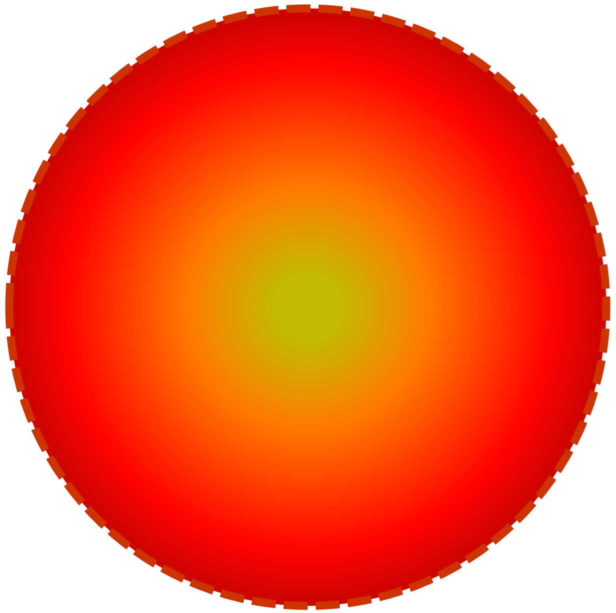
Mean solar density : $\rho = \dfrac{M_\odot}{\frac{4\pi}{3} R_\odot^{\,3}}$ **~1.35 g/cc** Sun liquid $\Rightarrow$ Incompressible

1870s: J. Homer Lane ; 1880s :August Ritter : Sun gaseous $\Rightarrow$ Compressible

As it shrinks, it releases gravitational energy AND it gets hotter



Mayer – Kelvin - Helmholtz



Helmholtz - Ritter

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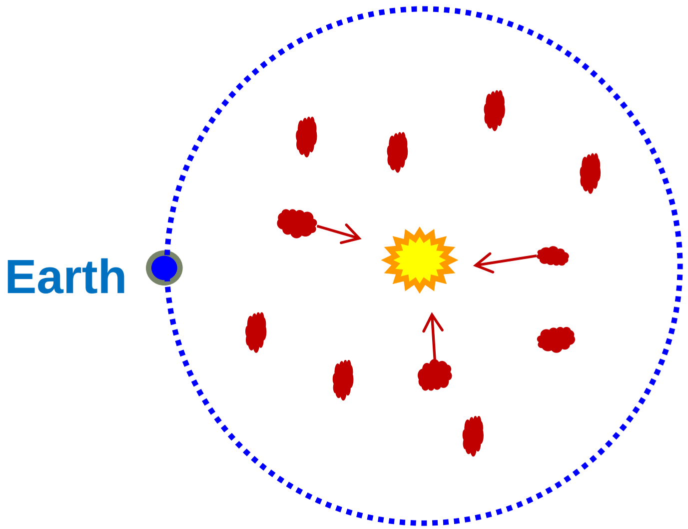

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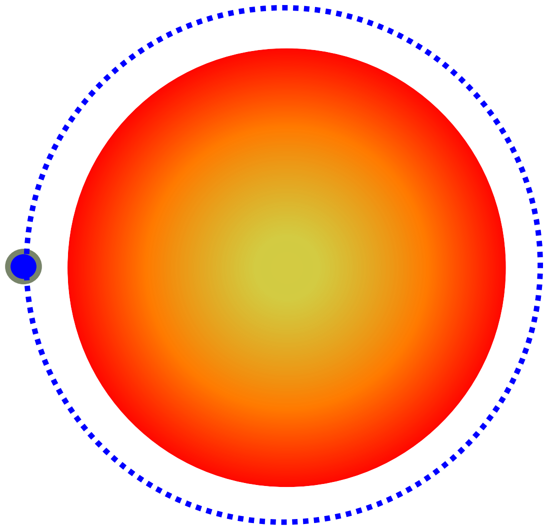

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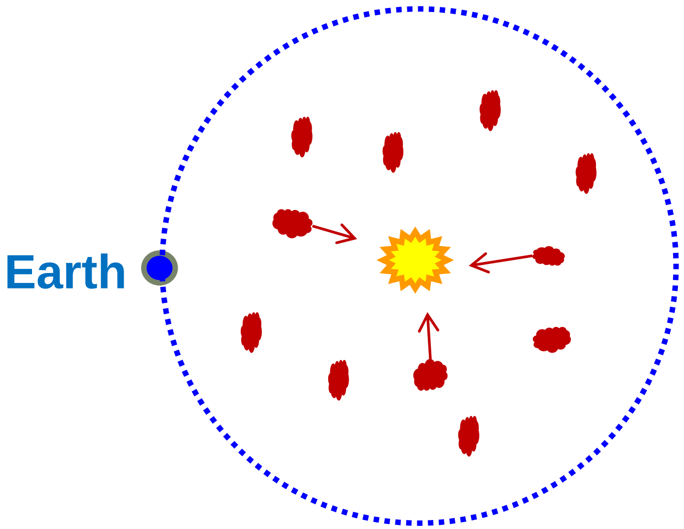
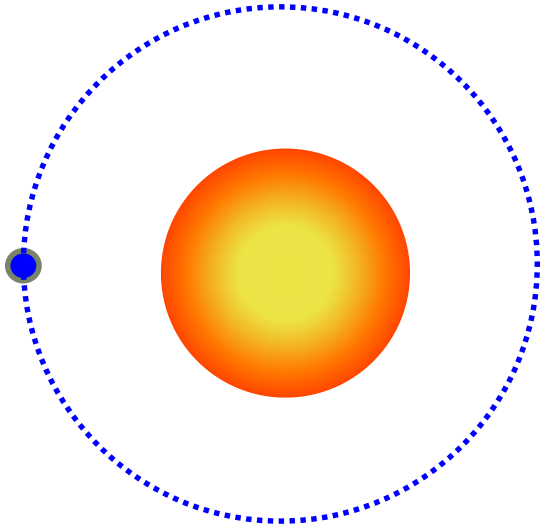


Mayer – Kelvin - Helmholtz



Helmholtz - Ritter

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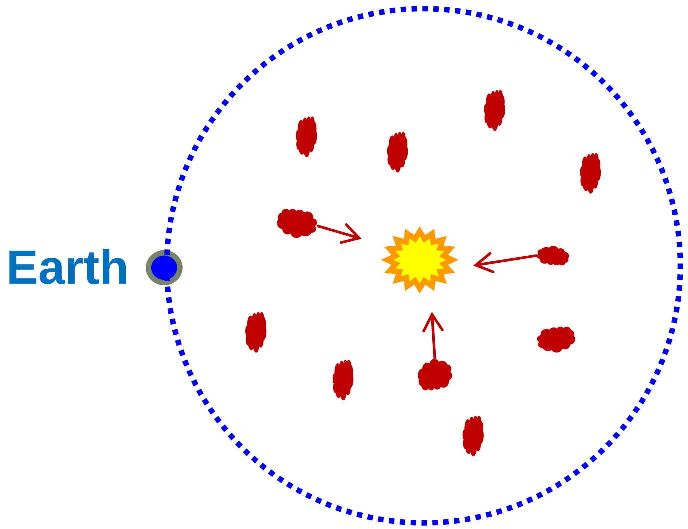
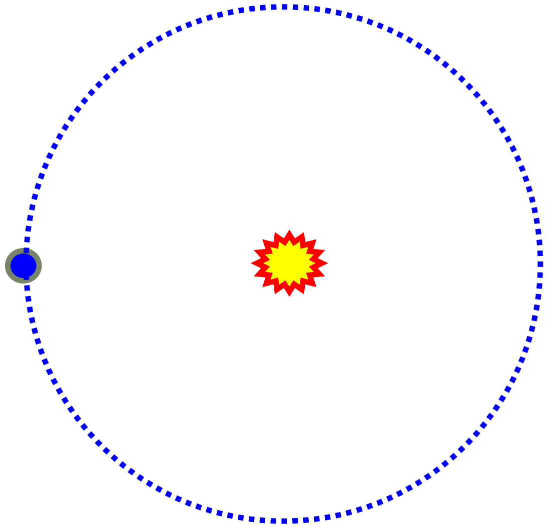


Mayer – Kelvin - Helmholtz



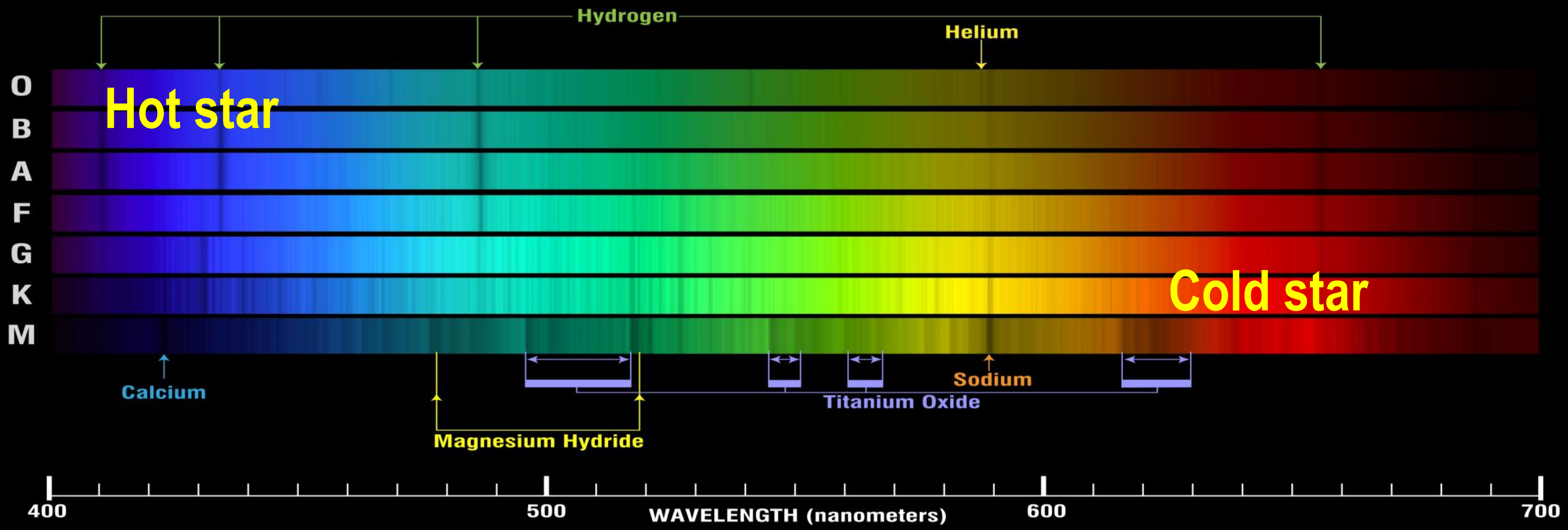
Helmholtz - Ritter

Source of solar energy : **gravitational contraction** $\mathrm{Energy} \sim \dfrac{G\ M_\odot^2}{R_\odot}$

Characteristic timescale of contraction : $T_{contraction} \sim = \dfrac{\mathrm{Energy}}{\mathrm{Luminosity}}$ **~ 30 My**

Kelvin – Helmholtz - Ritter timescale

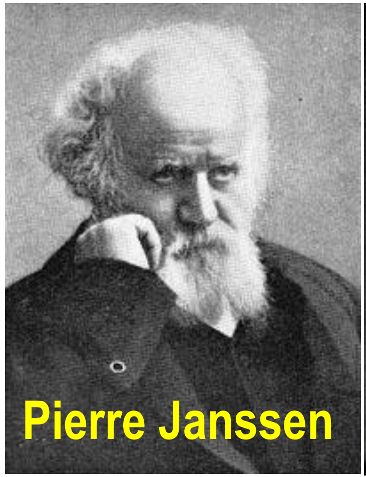
Stellar spectroscopy reveals
the chemical composition and physical conditions of stellar surfaces

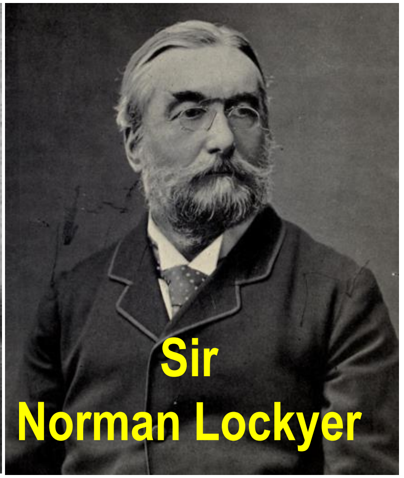


Father Secchi's stellar classification of 1866

Class	Properties	Prototypes	Color
Type I	Strong hydrogen lines	Sirius, Vega	White–blue
Type II	Numerous metallic lines (Na, Ca, Fe), weak hydrogen lines	Sun, Capella, Arcturus	Yellow–orange
Type III	Bands of lines which get darker towards the blue (TiO_2), and metallic lines as in Type II above	Betelgeuse, Antares	Red
Type IV	Bands that shade in the other direction. Faint stars, few visible to naked eye		Deep red

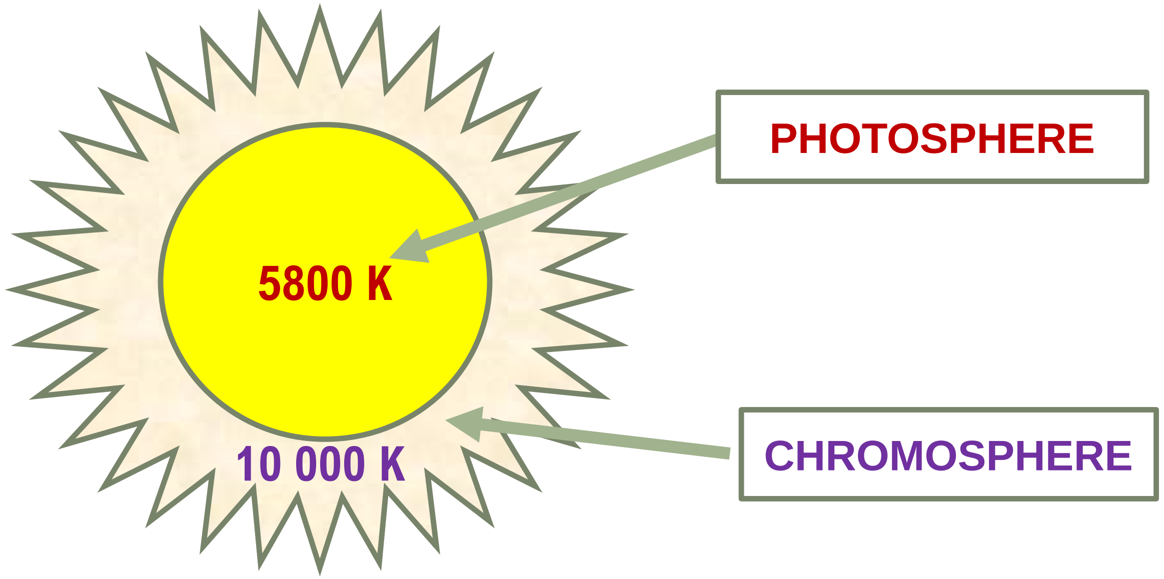
Spectroscopy reveals *Helium* in the Sun





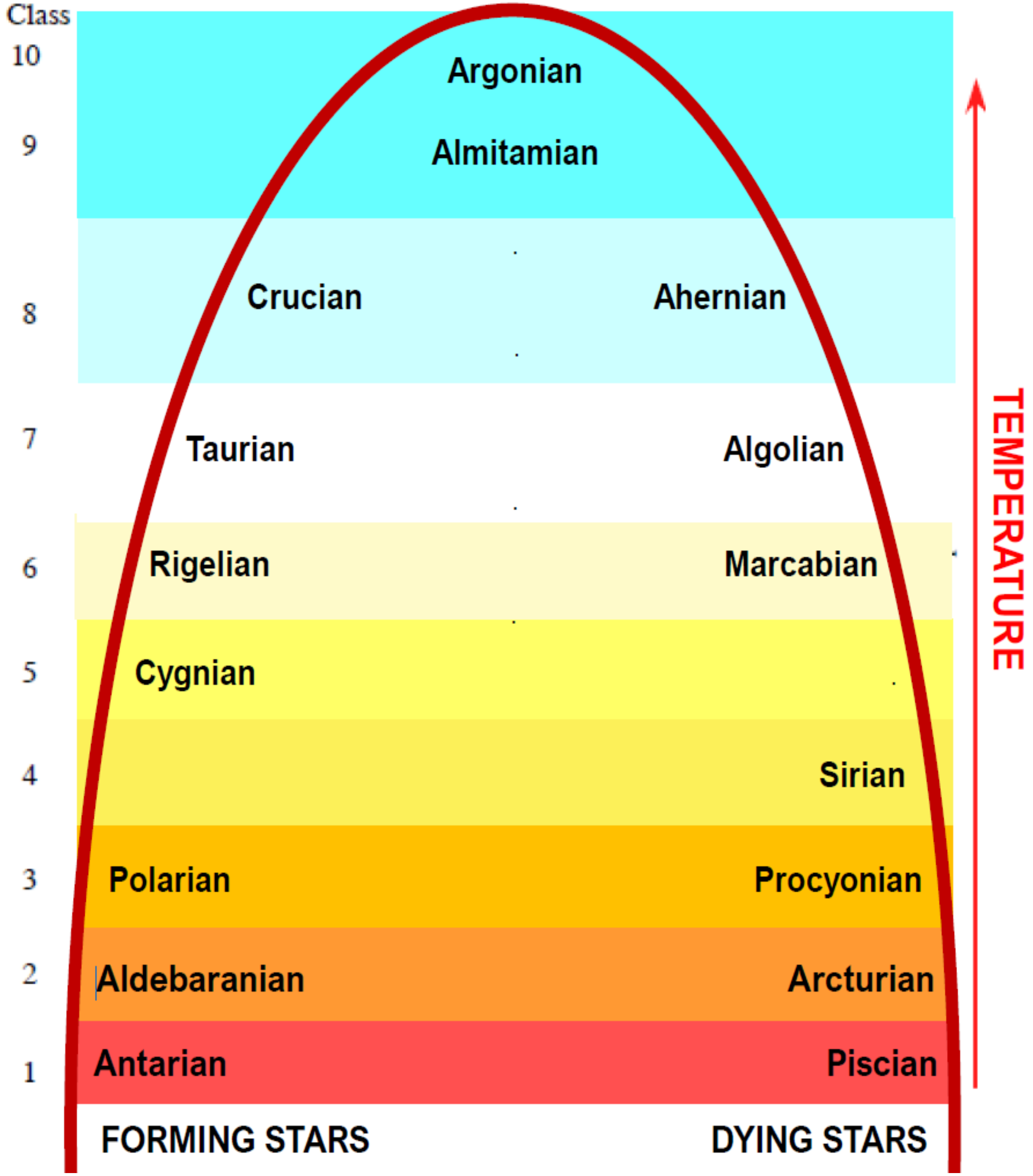
1868
co-discovery of ***Helium***
in the Sun' *chromosphere*
during a solar eclipse

(Ηλιος = Sun)

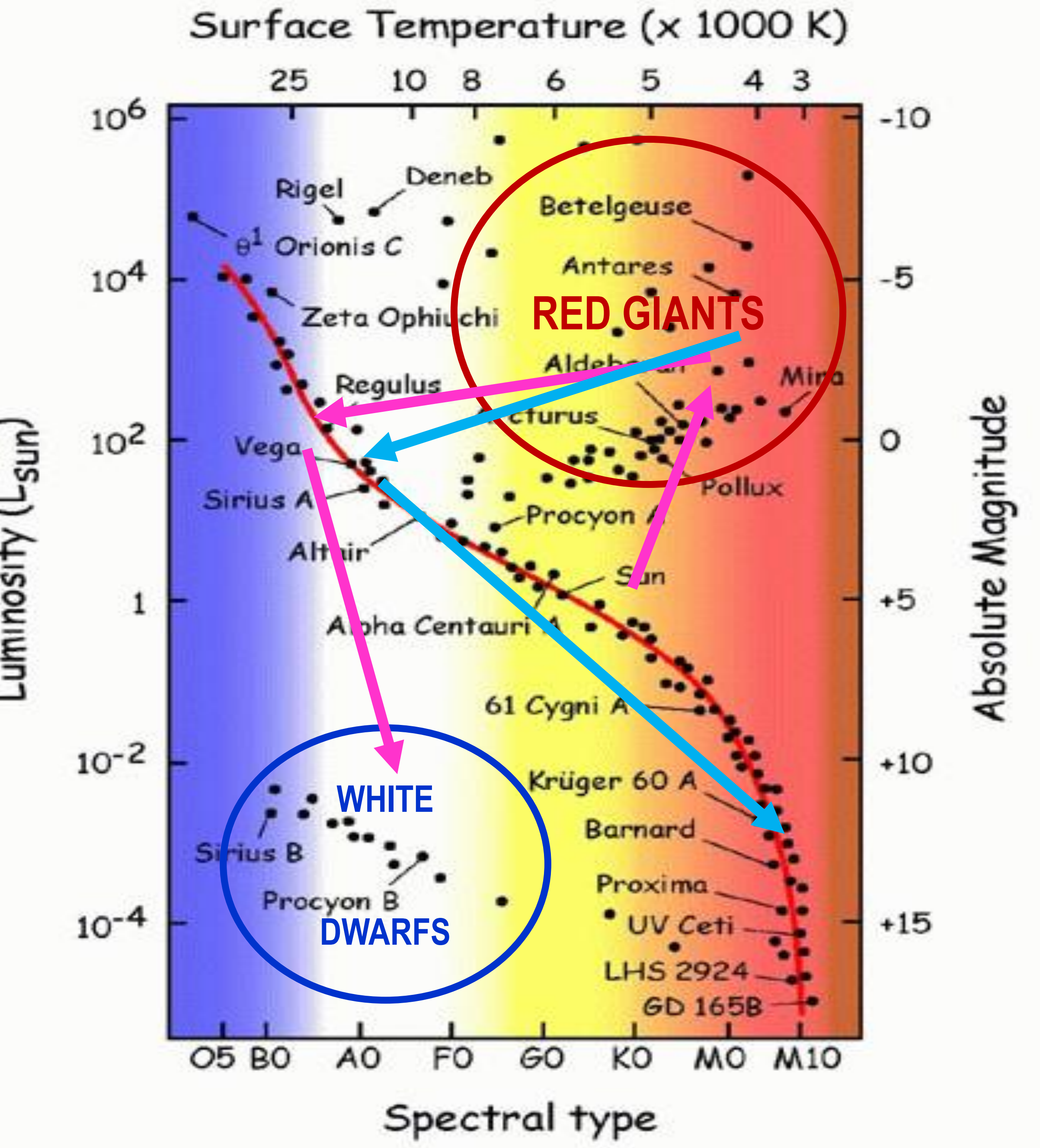


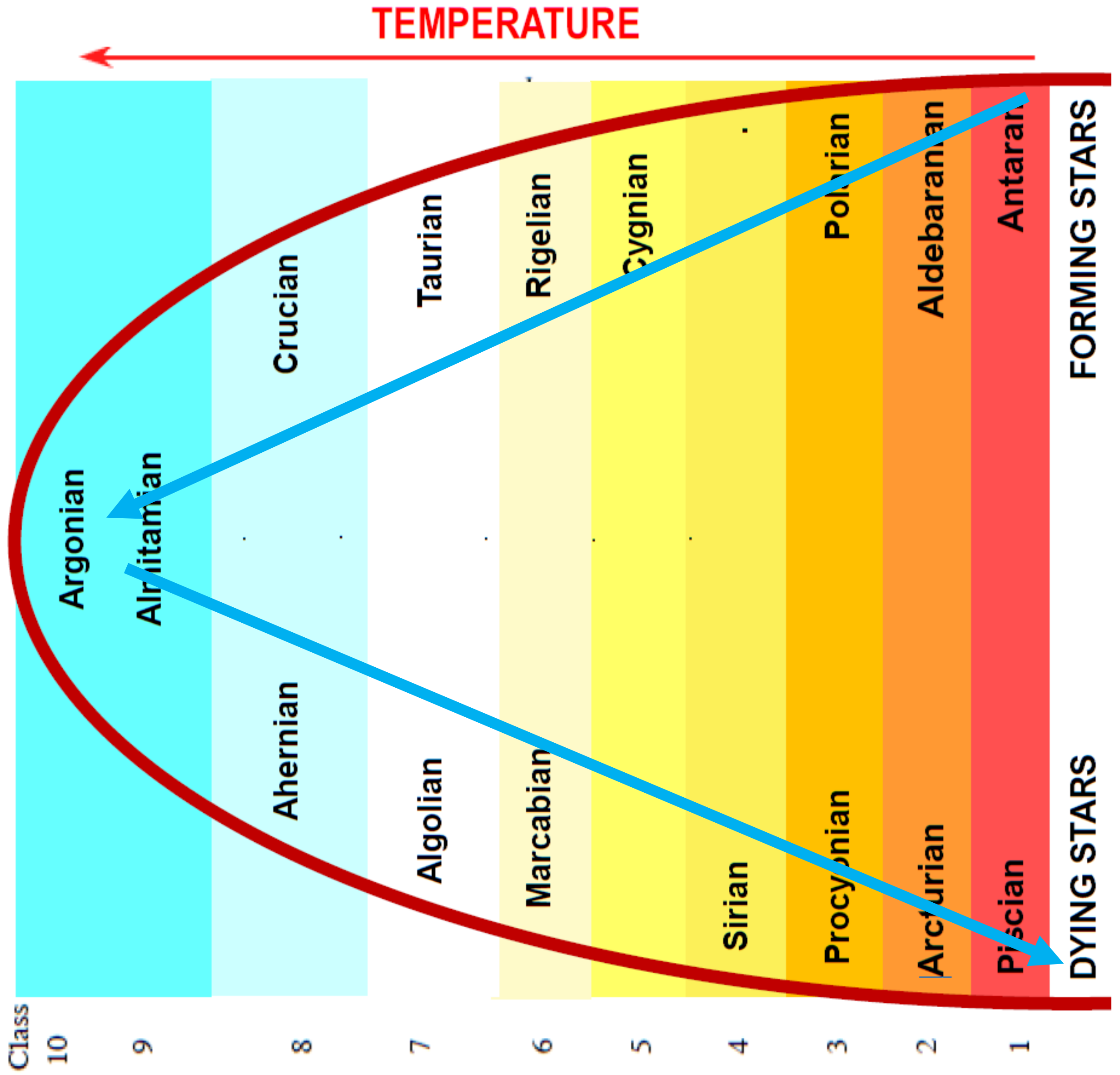
1882 : discovery of ***Helium*** on **Earth**
in the lava of Mount Aitna
by **Luigi Palmieri**

Lockyer's theory of stellar evolution



Lockyer's theory of stellar evolution: running OPPOSITE to current

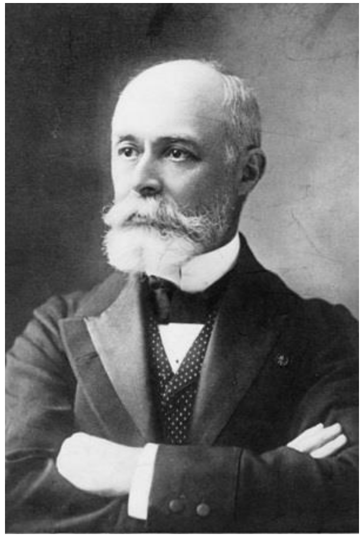




Herbert George Wells
THE TIME MACHINE
1897

So I travelled, stopping ever and again,
in great strides of a thousand years or more,
drawn on by the mystery of the earth’s fate, watching with a strange fascination *the sun grow larger and duller* in the westward sky, and the life of the old earth ebb away. At last, more than ***thirty million years hence, the huge red-hot dome of the sun*** had come to obscure nearly a tenth part of the darkling heavens

Subatomic physics



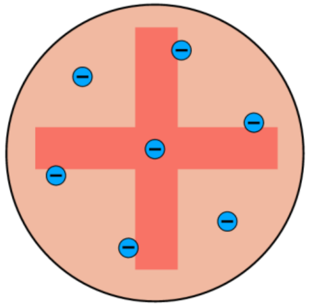
1896 : discovery of ***radioactivity*** **(Uranium)**
by **Henri Bequerel**

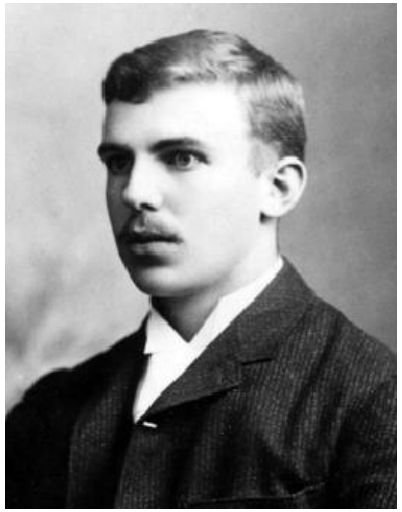
(*Physics Nobel 1903*)

1896-1897 : identification of radioactive **polonium and radium**
by **Pierre and Marie Curie**

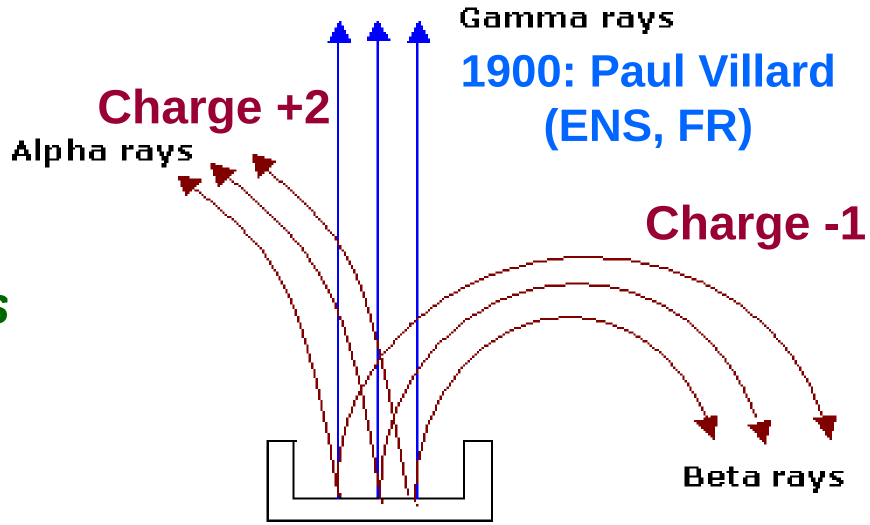
1897 : discovery of the ***electron***
by **Joseph John Thomson**
(***Physics Nobel 1906***)

1903: Thomson's atom





1897 : identification of ***alpha*** *and* ***beta rays***
by **Ernest Rutherford**
(*Chemistry Nobel 1908*)

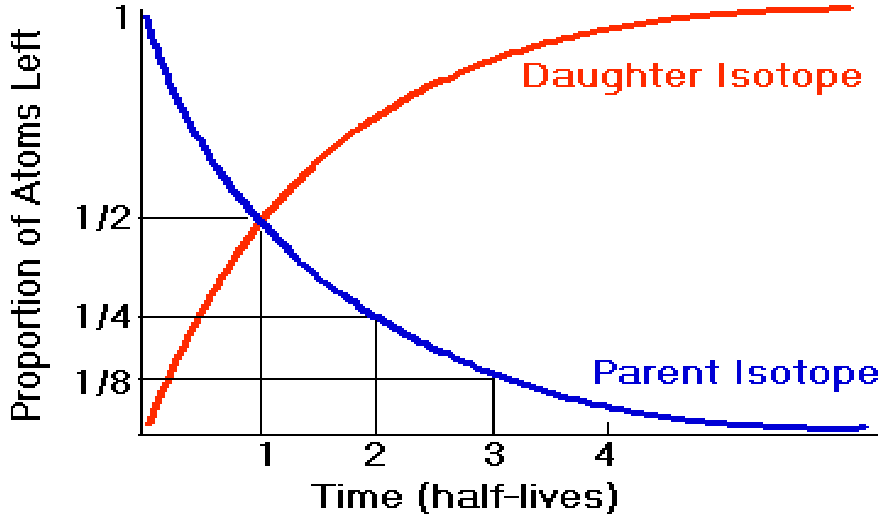


Radioactivity: dating of rocks and energy source

1902: Rutherford-Soddy's

law of **radioactive decay**

$$N = N_0 \exp(-t/\tau)$$



1902: Rutherford shows that **alpha** radiation is **Helium** nuclei
suggests to use **Uranium/Helium** for **dating**

1907 : Bertram Boltwood : Old rocks are **400 My to 2 Gy old** , the Earth is even older

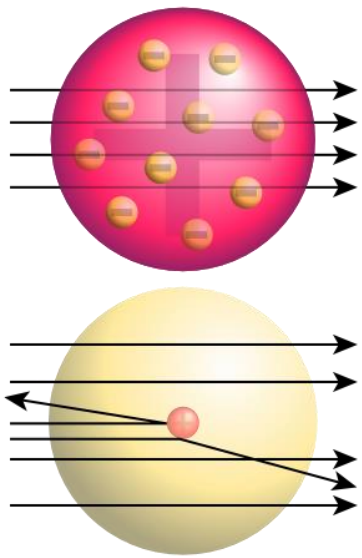
The maintenance of solar energy [. . .] no longer presents any fundamental difficulty if the internal energy of the component elements is considered to be available, i.e., if processes of sub-atomic change are going on.

Rutherford and Soddy 1903

1907 Rutherford : Helium in the Sun results from radioactivity and so does Solar energy

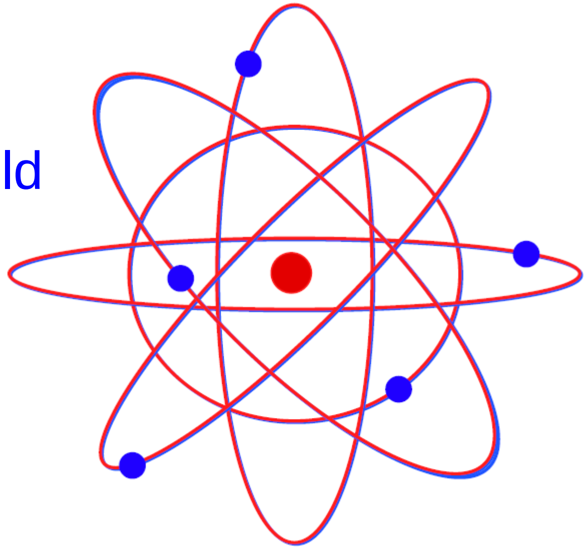
But what makes substances radioactive and how is the energy put there ?

The atomic nucleus and the proton



1909: Geiger-Marsden experiment
Strong deflection of some α particles bombarding a foil of gold

1911: Rutherford *:* The atom is mostly void :
the volume of the positive charge (nucleus)
is 1000 trillion times smaller than the volume of the atom
Nuclear radius ~ 10^{-13} cm

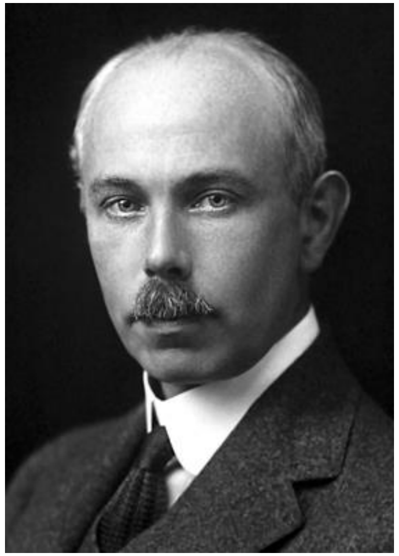


1919: Rutherford produces hydrogen nuclei bombarding nitrogen with alpha particles

$$\mathbf{N14 + \alpha \Rightarrow O17 + H}$$

1920 : Rutherford names the hydrogen nucleus **proton (charge +1)**

1910ies : development of **mass spectrograph**,
by **Francis William Aston (*Chemistry Nobel 1922*)**



Identification of isotopes and measurements of their masses
(=multiples of same « elementary » mass)

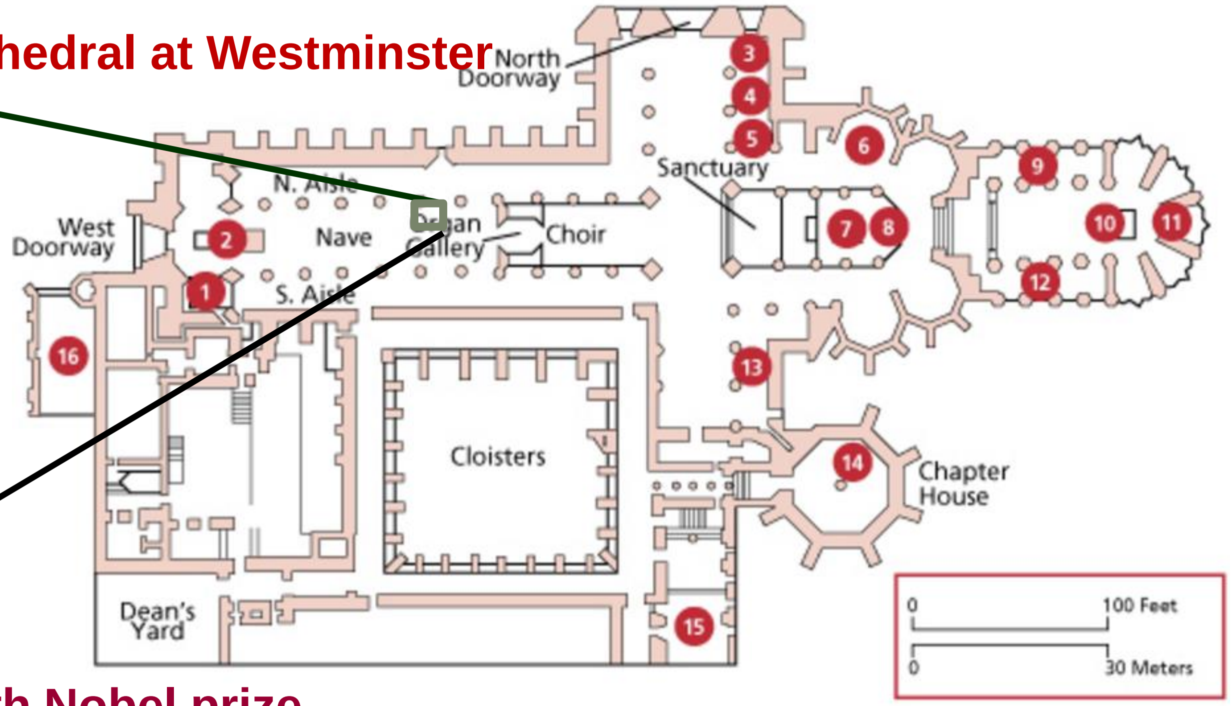
1919: Mass(He4) = Mass(4 protons) x (1 – 0.007)

In the Nave of St Peter's Cathedral at Westminster

GRAVES OF

Charles Darwin
Sir John Herschel
Sir Isaac Newton
Ernest Rutherford
William Thomson (Kelvin)
Joseph John Thomson

Stephen Hawking (2018)



<u>Students of J. J. Thompson with Nobel prize</u>

Ernest Rutherford	Chemistry	1908	Radioactivity
Francis William Aston	Chemistry	1922	Mass spectrograph,isotopic masses
William Henry Bragg	Physics	1915	Crystal structure
Charles Glover Barkla	Physics	1917	X-ray spectroscopy
Niels Bohr	Physics	1922	Atom model, QM
Max Born	Physics	1954	Wave function QM
Owen Willams Richardson	Physics	1928	Thermionic emission
Charles T. Rees Wilson	Physics	1927	Cloud chamber
George Paget Thomson	Physics	1937	Electron diffraction

Paul Langevin
J. Robert Oppenheimer

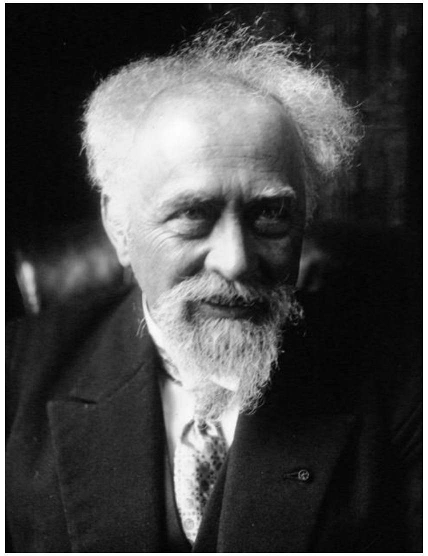
Sun’s energy: **Conversion of H to He**

Energy production : $E = \Delta m\, c^2$

First ideas (rather confused):

1915: William Draper Harkins

1919: Jean Perrin
(Physics Nobel 1926)

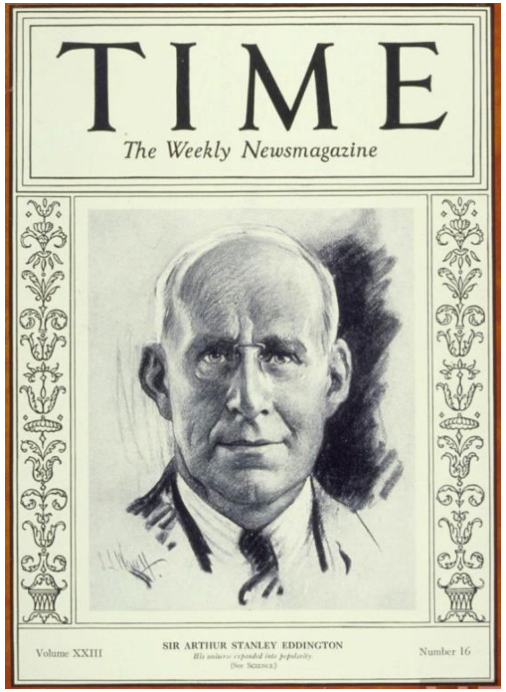


Sir Arthur Stanley Eddington

Stellar physics

Mean molecular weight - Stellar opacities -
Radiative transfer – Role of radiation pressure
Mass-luminosity relation – Cepheid pulsations
Eddington limit on stellar luminosity

Standard model of stellar structure :
$T_{CENTRAL}$(Sun)~20 MK



The energy source of the Sun

Eddington's Presidential address to the British Association (24/8/1920)

Only the inertia of tradition keeps the contraction hypothesis alive – or rather, not alive, but an unburied corpse. A star is drawing on some vast reservoir of energy by means unknown to us. This reservoir can scarcely be other than the subatomic energy which, it is known, exists abundantly in all matter; we sometimes dream that man will one day learn how to release it and use it for his service.

If indeed the subatomic energy is set free in stars [. . .] it seems to bring a little nearer to fulfillment our dream of controlling this latent power for the well-being of the human race – or for its suicide.

If only 5% of the mass of the star consists initially of hydrogen, the total heat liberated will more than suffice for our demands. Is this possible? pondered Eddington and argued: *If Rutherford could break down the atoms of oxygen in his lab, driving out an isotope of helium, then what is possible in the Cavendish laboratory may not be too difficult in the Sun.*

The energy of the Sun

Luminosity $L_{\odot} = 4\ 10^{33}$ erg/s
Time $T = 4{,}5$ Gy $= 1.35\ 10^{17}$ s

Energetic demands: **Energy** = Luminosity x Time **$= 5\ 10^{50}$ ergs** **(1)**

Efficiency of transformation of mass to energy through 4p → He4 : $\varepsilon = 0.007$

Mass $M_{\odot} = 2\ 10^{33}$ gr

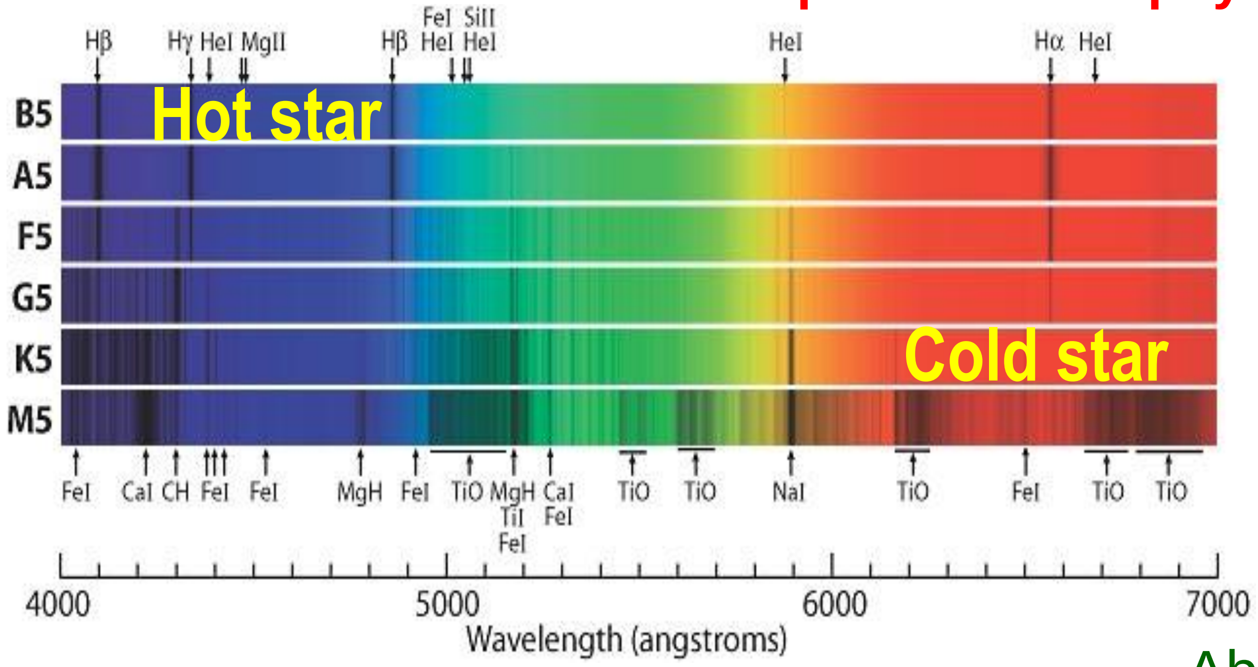
Nuclear energy **available : E(nuclear) = $\varepsilon\ f\ M_{\odot}\ c^2$** **(2)**

(1) + (2) : Fraction of Sun's mass (<u>in hydrogen</u>) which participated in nuclear reactions in the past T=4.5 Gy :

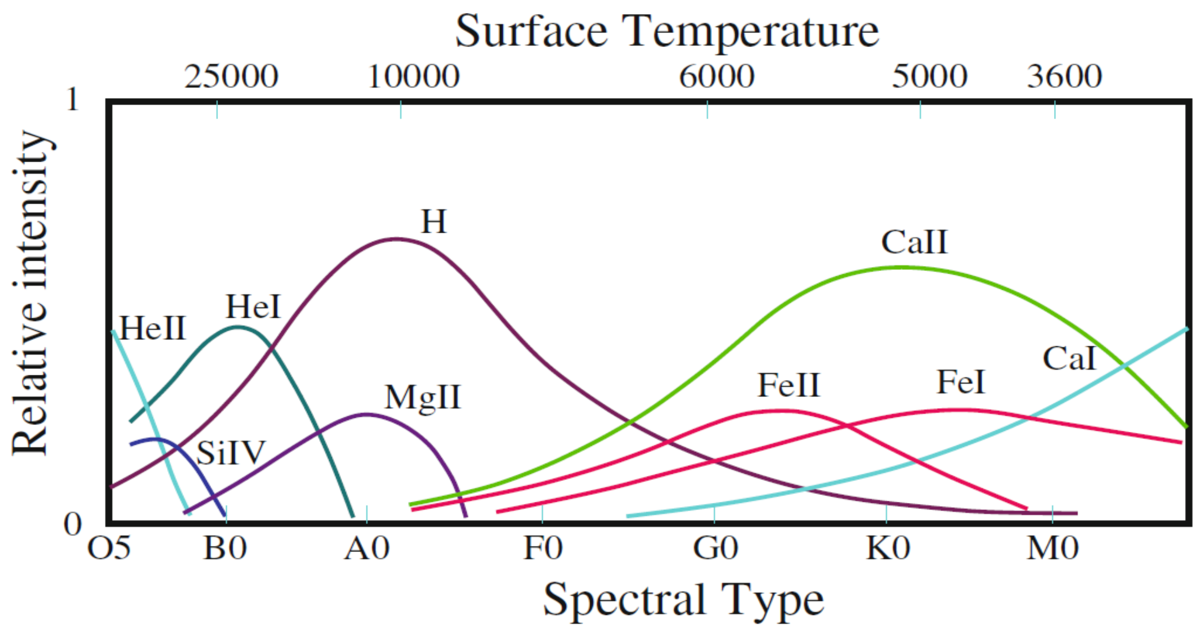
$$f \sim \frac{L_{\odot} T}{\epsilon M_{\odot} c^2} \sim 0.05$$

How much hydrogen is there in the Sun ?

Stellar spectroscopy reveals
the chemical composition AND physical conditions of stellar surfaces

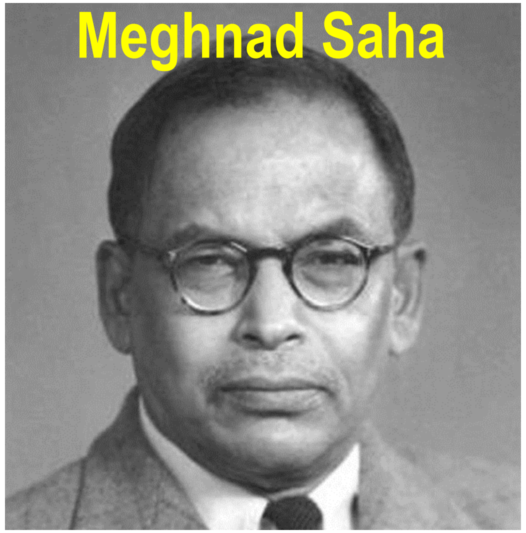


The intensity and width of spectral lines
depends not only
on the abundances of the elements,
but also on the conditions
(temperature, pressure and ionization)
of the stellar atmosphere



Abundant elements may appear underabundant

Quantum Mechanical
models are required
to infer true abundances,
through the
Saha ionisation equation
(1925)



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

Table 3.2 The first table of relative abundances in stellar atmospheres

Z	Atom	[A]	Z	Atom	[A]
1	H	11	19	K	3.5
2	He	8.3	20	Ca	4.8
2	He^+	12	20	Ca^+	5.0
3	Li	0.0	22	Ti	4.1
6	C^+	4.5	23	V	3.0
11	Na	5.2	24	Cr	3.9
12	Mg	5.6	25	Mn	4.6
12	Mg^+	5.5	26	Fe	4.8
13	Al	5.0	30	Zn	4.2
14	Si	4.8	38	Sr	1.8
14	Si^+	4.9	38	Sr^+	1.5
14	Si^{+++}	6.0	54	Ba^+	1.1

Payne's Ph.D. thesis, 1925. H and He were omitted from the PNAS publication. The notation is $[A] \equiv \mathrm{Log}\,A$. All abundances are relative to hydrogen, which is 10^{11}

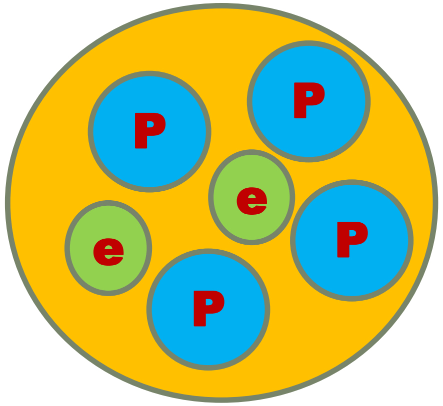
Cecilia Payne

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

From H to He : an impossible reaction ?

***Problem 1*: How to make an alpha particle**

(masse = 4 m_P ; charge = 2 +)



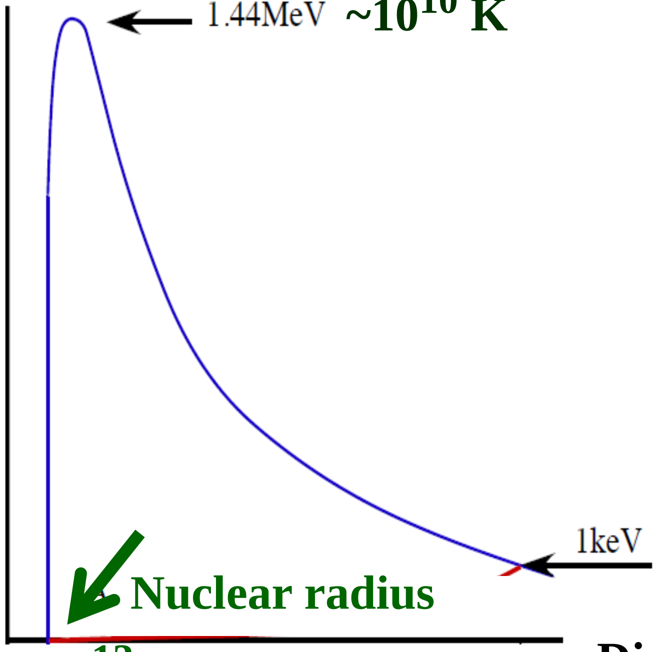
4 protons + 2 electrons should be brought together

HOW ? *(neutron unknown then)*

***Problem 2:* How to bring just 2 protons together**

Enormous temperatures (T> 10^{10} K)
are required, so that particles have
enough kinetic energy E~kT
to overcome their repulsive Coulomb barrier

whereas Eddington's stellar model suggested
T~10^7 K



We do not argue with the critic who urges that the stars are not hot enough for this process; we tell him ***to go and find a hotter place.***

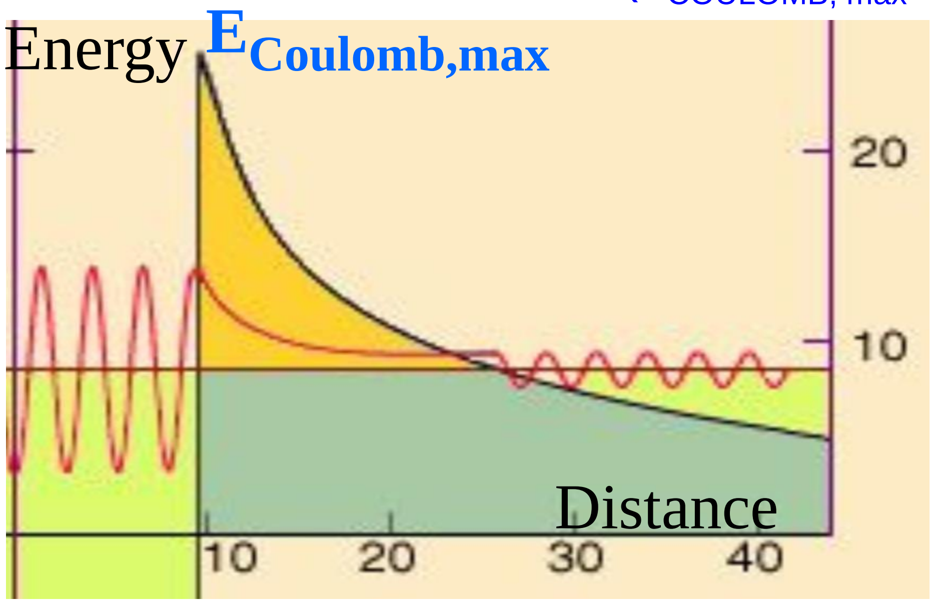
A. S. EDDINGTON, The Internal Constitution of Stars (1926)

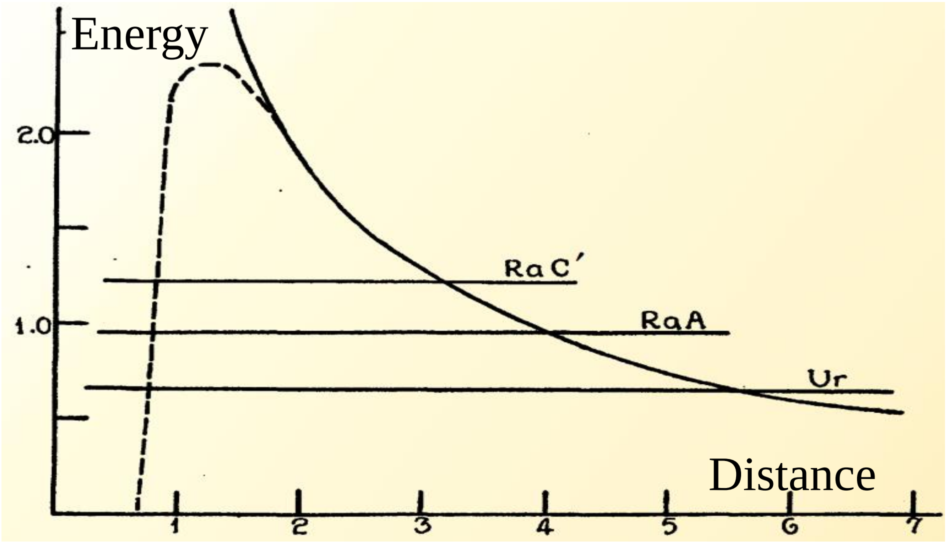
1928 : Light in the end of the tunnel

How do the emitted α particles get out of the potential well of radioactive nuclei ?

Why their observed energies are < $E_{COULOMB,\ max}$ of those nuclei ?

($E_{COULOMB,\ max}$ being observed in scattering experiments)





Probabilistic quantum-mechanical
TUNNEL EFFECT (1928)

Particles with E < $E_{COULOMB,\ max}$
have a finite probability to escape

$$e^{-\frac{2\pi Z_1 Z_2 e^2}{h\upsilon}}$$

Gamow factor

It also explains quantitatively
why nuclei with larger half-lives
eject α particles
with smaller energies

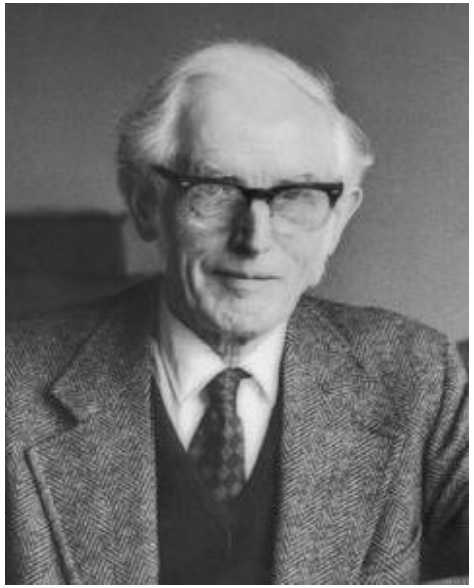
1928-1929
R. Gurney & E. Condon

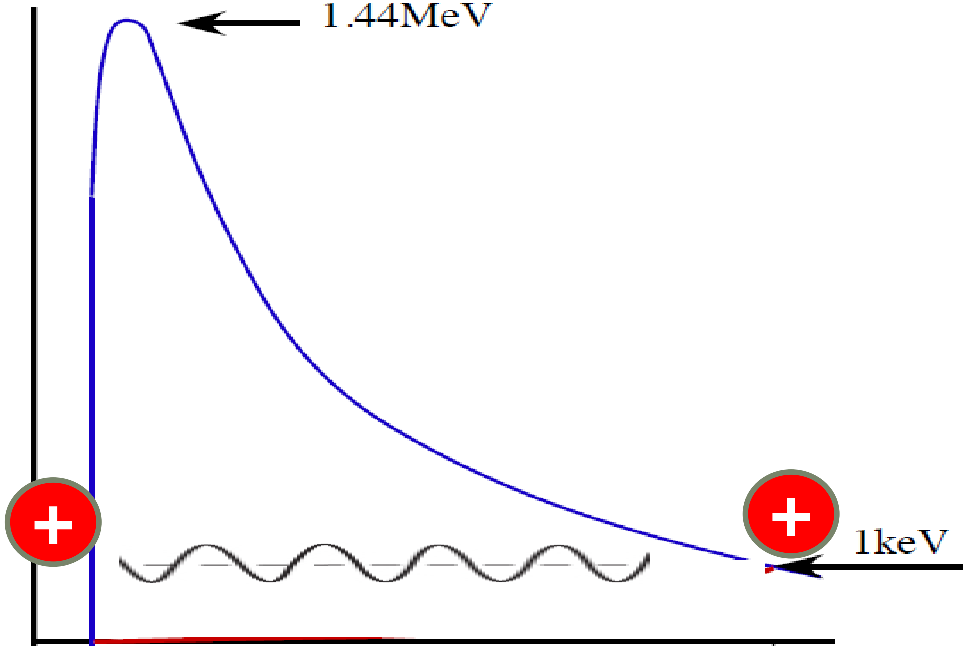
Zur Frage
der Aufbaumöglichkeit der Elemente in Sternen.

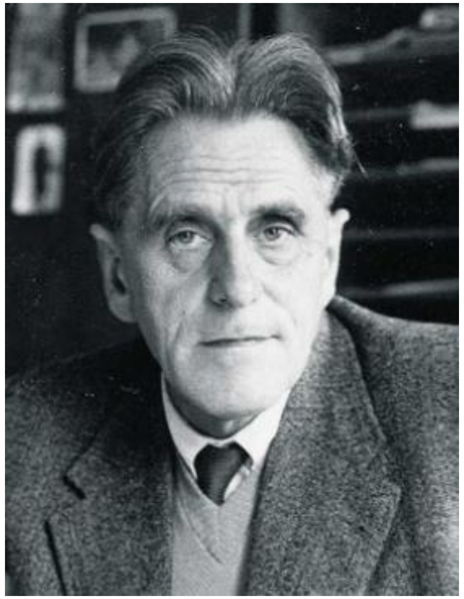
Von R. d'E. Atkinson und F. G. Houtermans in Berlin-Charlottenburg.

(Eingegangen am 19. März 1929.)

Die quantenmechanische Wahrscheinlichkeit dafür, daß ein Proton in einen Atomkern eindringt, wird nach der Methode von Gamow berechnet. Dabei zeigt sich, daß unter den Temperatur- und Dichteverhältnissen im Innern der Sterne die Ein-





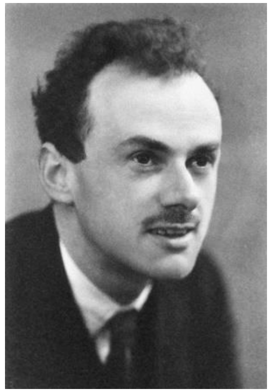


Proton fusion may indeed occur in temperatures at the center of the Sun, thanks to the tunnel effect

But fusion of two protons gives a di-proton which cannot exist !

Particle discoveries in the 1930ies

1930 : Prediction of the **neutrino** (mass ~ 0 , charge =0)
Wolfgang Pauli *(Physics Nobel 1945)*



1931: Prediction of **Positron** (positively charged electron)
P. A.M. Dirac (*Physics Nobel 1933*)

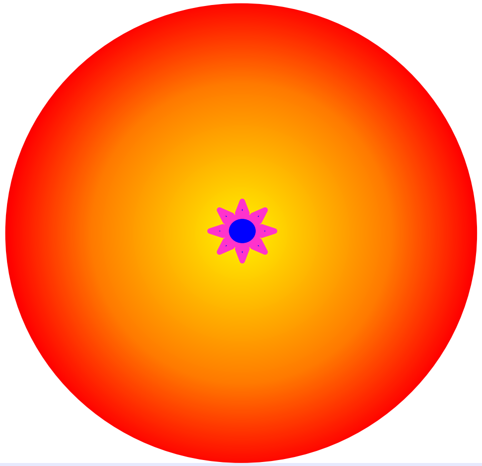
1931: Discovery of **Deuterium** (heavy hydrogen with mass ~2 m_P)
Harold Urey (*Chemistry Nobel 1934*)

1932 : Discovery of **neutron** (mass ~ m_P , charge =0)
James Chadwick *(Physics Nobel 1935)*

1932 : Discovery of **positron** (mass ~ m_e , charge =1 +)
Carl Anderson *(Physics Nobel 1936)*

1934 : development of the **theory of β decay** (weak interactions of radioactivity)
Enrico Fermi *(Physics Nobel 1938)*

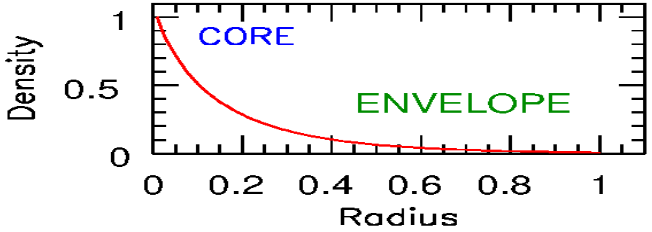
Lev Davidovich Landau (1908-1968)
(Physics Nobel 1962)



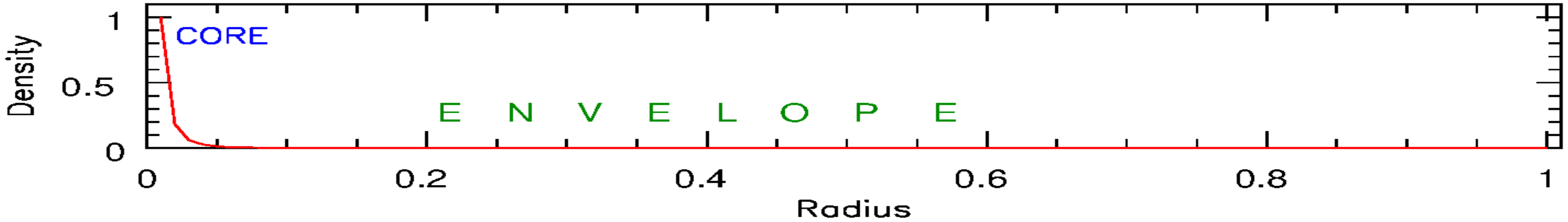
Origin of stellar energy *(Nature, Febr. 1938)*
accretion of inner layers onto
a small neutron star found in the stellar core

Thus we can regard a star as a body which has a neutronic core the steady growth of which liberates the energy which maintains the star at its high temperature ; the condition at the boundary between the two phases is as usual the equality of chemical potentials. The detailed investigation of such a model should make possible the construction of a consistent theory of stars.

1932: Formulates concept of ***Neutron stars***
Calculates minimum and maximum mass



Hydrostatic equilibrium dictates the density profile of a normal star
An increase of the core density inflates the envelope as in Red Giants, *reducing the mean density*



The Problem of Stellar Energy

NATURE MAY 28, 1938, VOL. 141

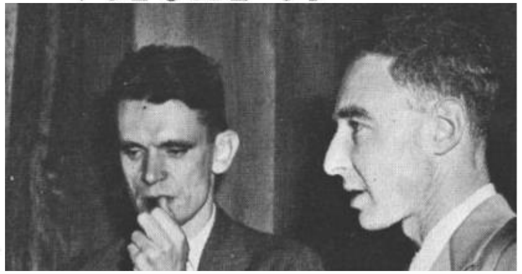
S. CHANDRASEKHAR (Yerkes Observatory).
G. GAMOW (George Washington University).
M. A. TUVE (Carnegie Institution of Washington).

The problem of stellar energy was the subject of discussion of the Fourth Annual Conference on Theoretical Physics sponsored by the George Washington University and the Carnegie Institution of Washington, and held in Washington, D.C., on March 21-23. The Conference was attended by astrophysicists studying the internal constitution of the stars (S. Chandrasekhar, B. Stromgren, T. Sterne, D. Menzel and others) as well as by physicists working on different branches of nuclear physics (H. Bethe, G. Breit, G. Gamow, J. v. Neumann, E. Teller, M. Tuve, L. Hafstad, N. Heydenburg and others).

The possibility of an extremely dense neutron core at the centre of the star (as proposed by L. Landau) was also discussed. The study of a number of known stars does not indicate a central condensation of more than what corresponds to 90 per cent of the total mass within half the radius....... **It was therefore concluded that stellar models with a concentrated nuclear core cannot represent real stars.** *[idea explored by Thorne+Zytkow 1975, 1977]*

As another possibility the reaction ${}^1_1H + {}^1_1H \rightarrow {}^2_1H + \beta^+$ was suggested. It seems that the rate of such a reaction under the conditions in stellar interiors would be just enough to account for the radiation of the sun, though for stars much brighter than the sun other more effective sources of energy are required.

AUGUST 15, 1938 PHYSICAL REVIEW VOLUME 54

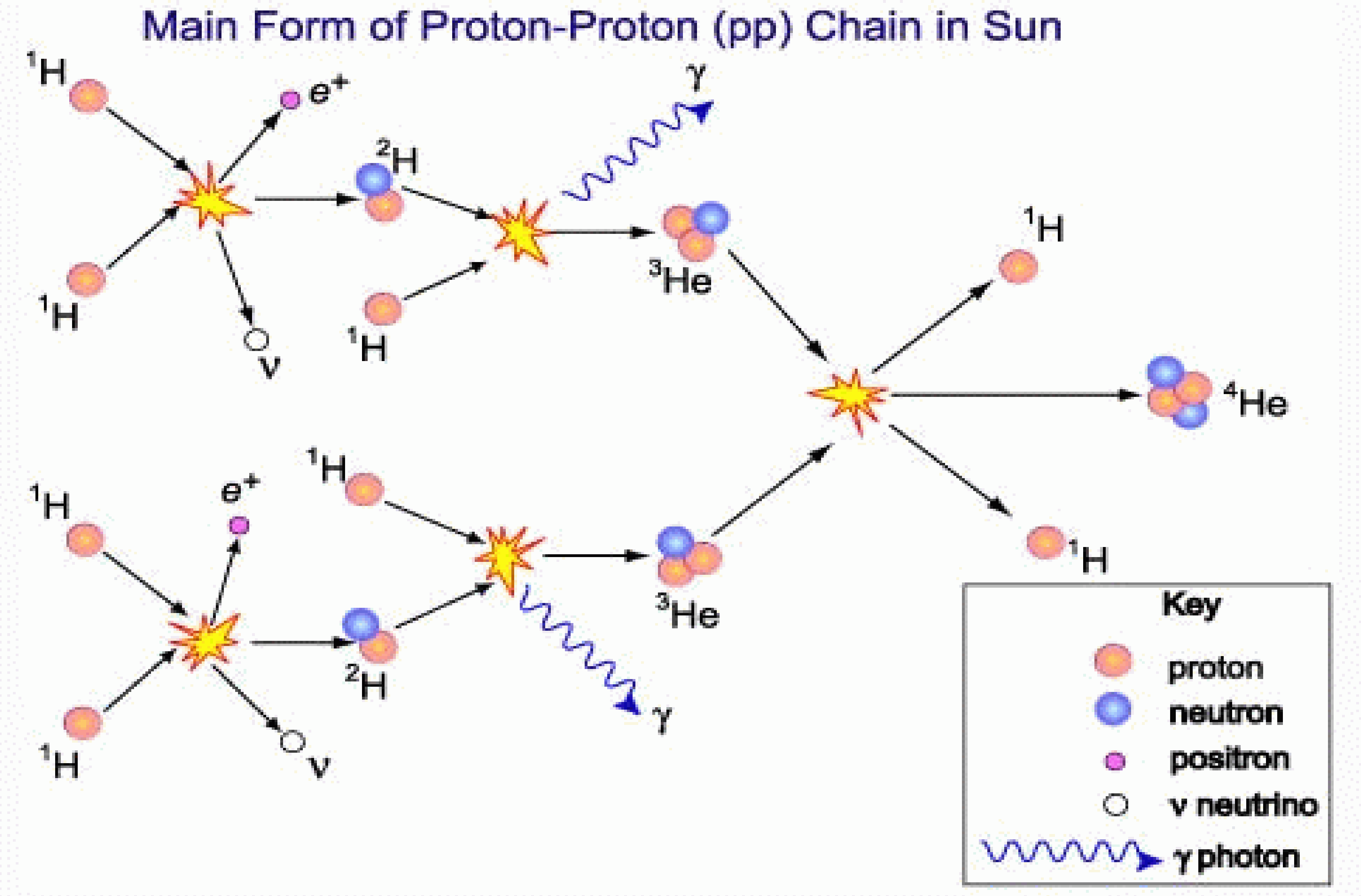


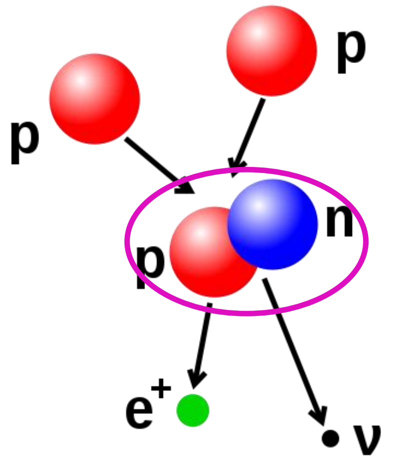
The Formation of Deuterons by Proton Combination

H. A. BETHE, *Cornell University, Ithaca, N. Y.*

AND

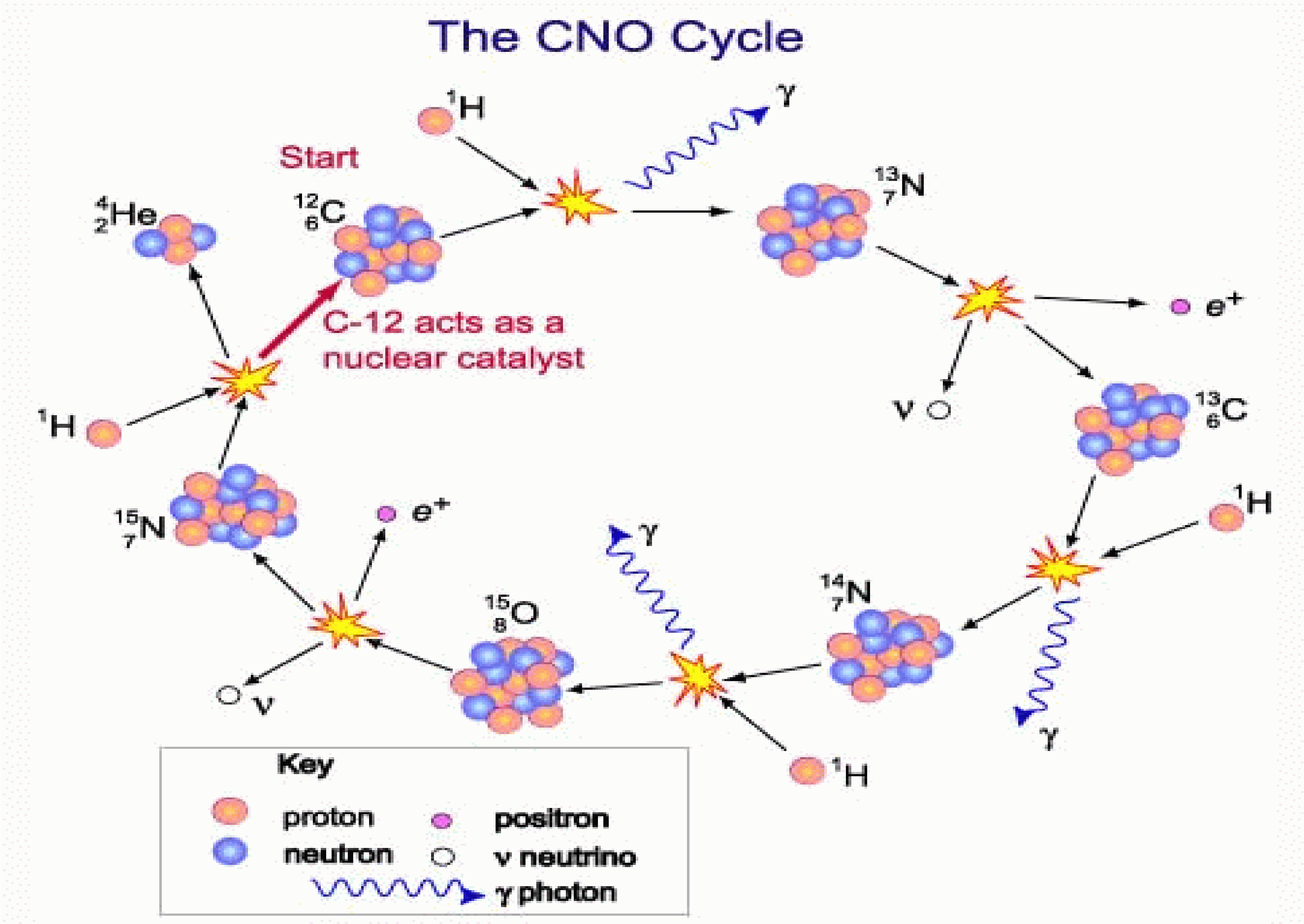
The probability of t
the probability of pos
through their mutual
can be calculated exa
evolution due to the re
at the center of the sun
degrees). This is almos
tion of the sun (2 ergs

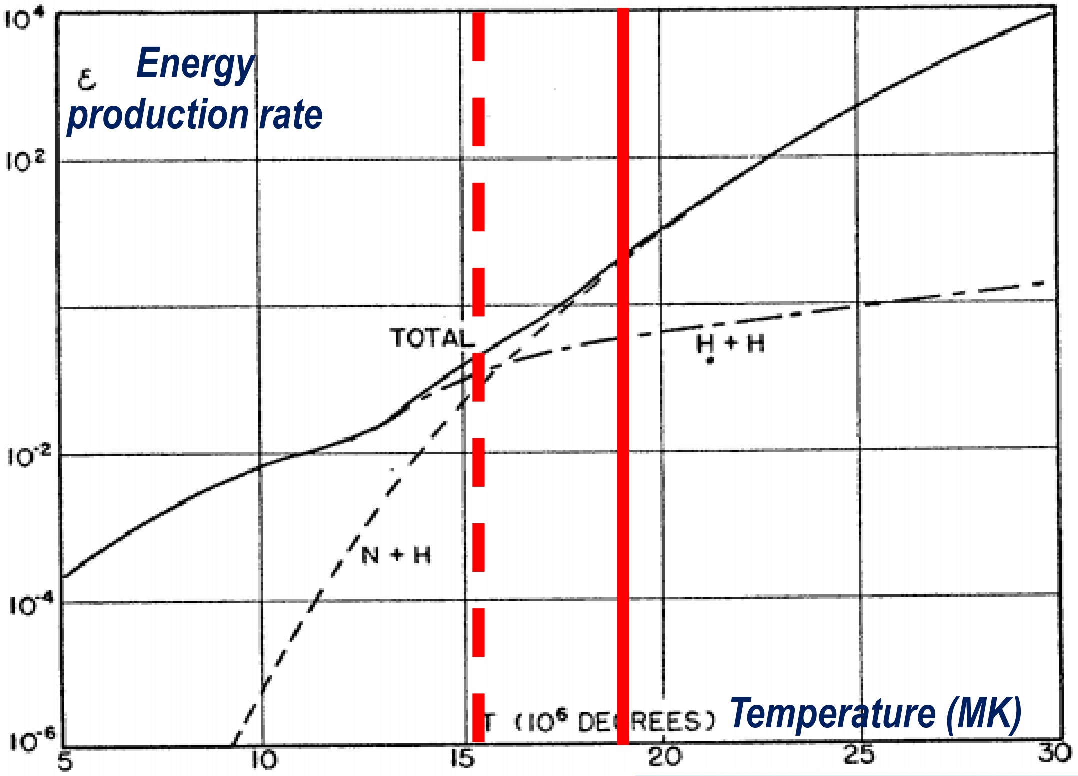




Energy Production in Stars*

MARCH 1, 1939 PHYSICAL REVIEW





The agreement of the carbon-nitrogen reactions with observational data (§7, 9) is excellent. In order to give the correct energy evolution in the sun, the central temperature of the sun would have to be 18.5 million degrees while integration of the Eddington equations gives 19. For the brilliant star Y Cygni the corresponding figures are 30 and 32. This good agreement holds for all bright stars of the main sequence, but, of course, not for giants.

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.

What about elements heavier than He ?

Why does the Sun shine?

Because it is hot

and it is hot because it is massive

Why does the Sun shine *for so long*?

Because its interior is so hot that thermonuclear reactions

ignite and produce huge amounts of energy

released in long timescales

Hans Albrecht Bethe (1906 - 2005)

Atomic physics and spectroscopy
Interactions of fast particles with matter
Solid state physics
Hydrodynamics, especially shock waves
Nuclear physics (from 'pure' physics to bombs)
Nuclear astrophysics (stellar energy, SN, solar ν)
Gravitational wave sources
Nuclear weapons, the arms race, national security
Energy policy, including fission power

1947 Henry Draper Medal
1959 Franklin Medal
1961 Eddington Medal
1961 Enrico Fermi Award
1963 Rumford Prize
1975 National Medal of Science
1989 Lomonosov Gold Medal
1993 Oersted Medal
2001 Bruce Medal
2005 Benjamin Franklin Medal

First publication: 1924 (aged 18) A. Bethe and Y. Terada *"Experiments Relating to the Theory of Dialysis"* Zeitschrift f. Physik. Chemie, **112**, pp. 250-269

Last research publication : 2002 (aged 96) G. C. McLaughlin, R.A.M.J. Wijers, G. E. Brown, H. Bethe *"Broad and Shifted Iron-Group Emission Lines in Gamma-Ray Bursts as Test of the Hypernova Scenario"* Astrophysical Journal, **567**, 454-462

Physics Nobel prize 1967

for his discoveries concerning the energy production in stars

"Professor Bethe, you may have been astonished that among your many contributions to physics, several of which have been proposed for the Nobel Prize, we have chosen one which contains less fundamental physics than many of the others and which has taken only a short part of your long time in science […]. **Your solution of the energy source of stars is one of the most important applications of fundamental physics in our days, having led to a deep going evolution of our knowledge of the universe around us."**

From the presentation speech of Professor Oskar Klein, member of the Swedish Academy of Sciences

Head of Theory Division of Manhattan Project (1943-1946)

Calculation of critical mass and efficiency of U-235

Formula for the atomic bomb's explosive yield
(*with Richard Feynman*)

Bethe Fermi Teller Feynman

Bethe vs Teller in Oppenheimer affair (1955)

President's Science Advisory Committee (1956-1959)

Member, US Delegation to Discussions on Discontinuance of Nuclear Weapons Tests, 1958-59

Scientists movement against the projects of anti-ballistic missiles (60ies) and Star wars (80ies)

« If there were a computation to make, with the survival of mankind depending on its outcome, the only person I would trust for that would be Hans Bethe »

After HB showed (1943) that a nuclear explosion would not ignite a chain reaction of atmospheric Nitrogen

APPROVED FOR PUBLIC RELEASE

IGNITION OF THE ATMOSPHERE BY NUCLEAR BOMBS

E. Konopinski
C. Marvin
E. Teller

ABSTRACT

It is shown that, whatever the temperature to which a section of the atmosphere may be heated, no self-propagating chain of nuclear reactions is likely to be started. The energy losses to radiation always overcompensate the gains due to the reactions. This is true even with rather extravagant assumptions concerning the reactivity of the nitrogen nuclei of the air. The only disquieting feature is that the "safety factor", i.e. the ratio of losses to gains of energy, decreases rapidly with initial temperature, and descends to a value of only about 1.6 just beyond a 10-Mev temperature. It is impossible to reach such temperatures unless fission bombs or thermonuclear bombs are used which greatly exceed the bombs now under consideration. But even if bombs of the required volume (i.e., greater than 1000 cubic meters) are employed, energy transfer from electrons to light quanta by Compton scattering will provide a further safety factor and will make a chain reaction in air impossible.