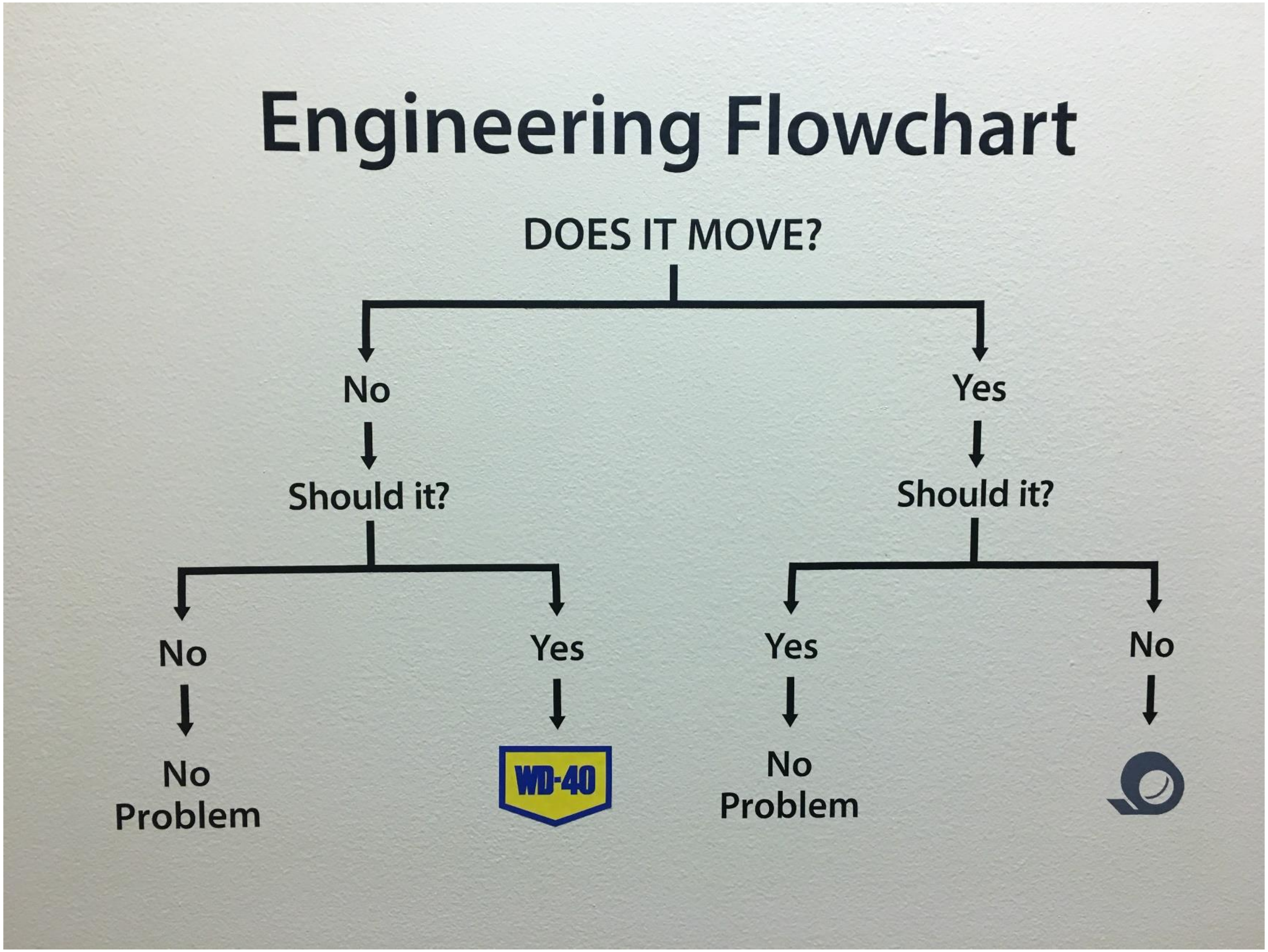
Nuclear Structure and Reactions at NSCL and FRIB through the Lens of Astrophysics: Lecture 1

Chris Wrede

HUGS @ JLab

May 29th, 2019

Painted on the wall of my room at SURA

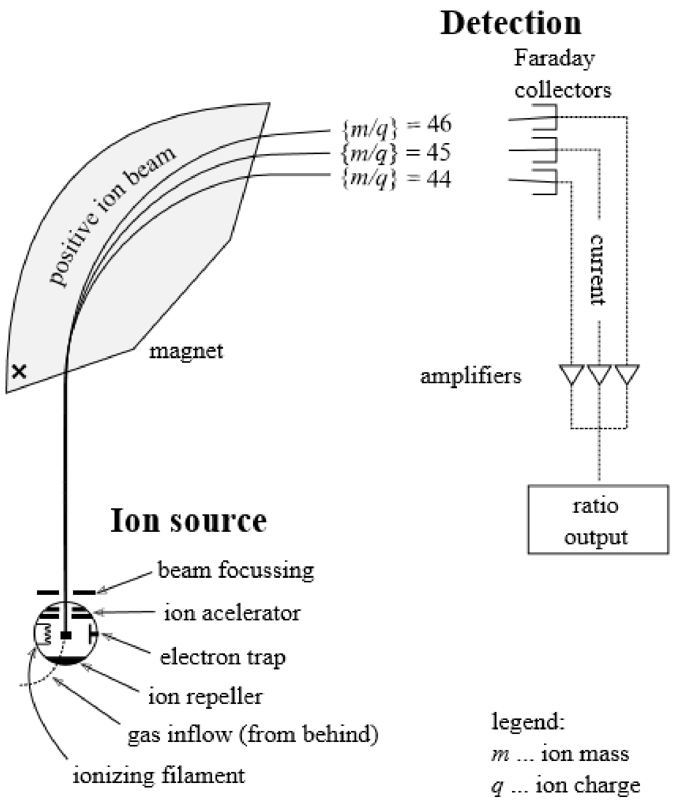


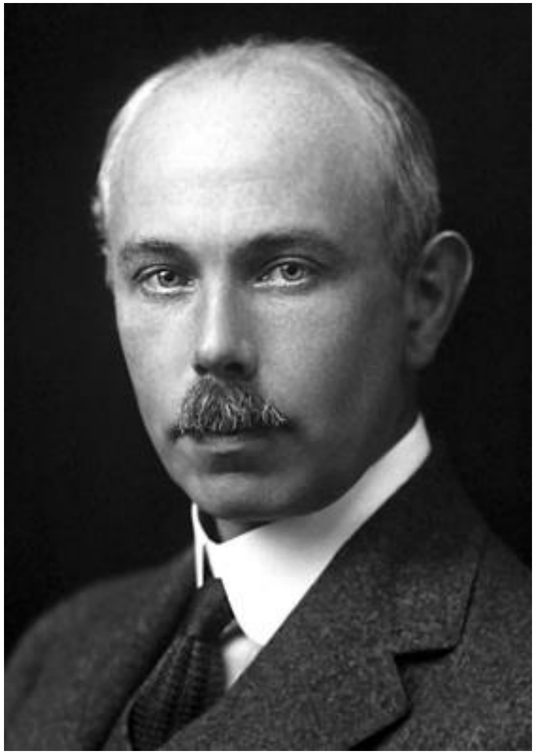
Outline

- **Lecture 1: History, stellar evolution & thermonuclear rates**
- Lecture 2: Charged-particle reactions: direct measurements
- Lecture 3: Charged-particle reactions: indirect measurements
- Lecture 4: Slow neutron capture process: direct measurements
- Lecture 5: Rapid neutron capture process: indirect measurements

H, He atomic masses

- Aston (1920): Uses mass spectrometry to reveal that He atomic mass slightly less than 4 times H mass

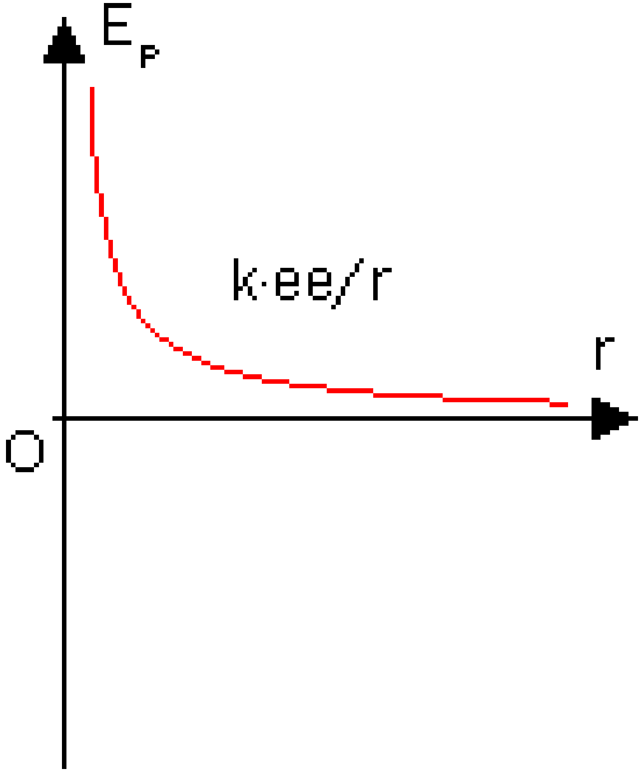




Nuclear Physics of Stars, Iliadis, 2nd Ed.

Solar energy: $E = mc^2$

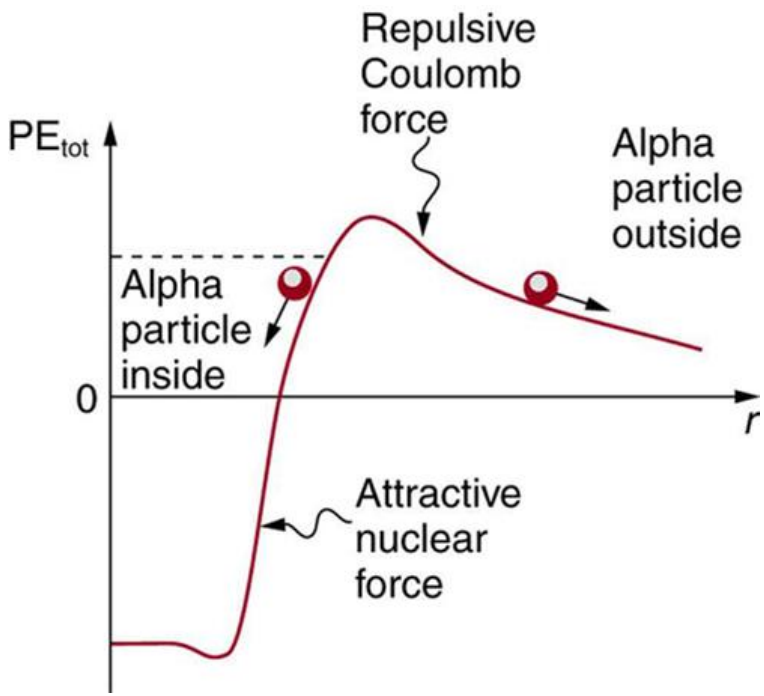
- Eddington (1920): conversion of H to He will explain energy generation in Sun!
- Problem: how do protons overcome Coulomb repulsion?

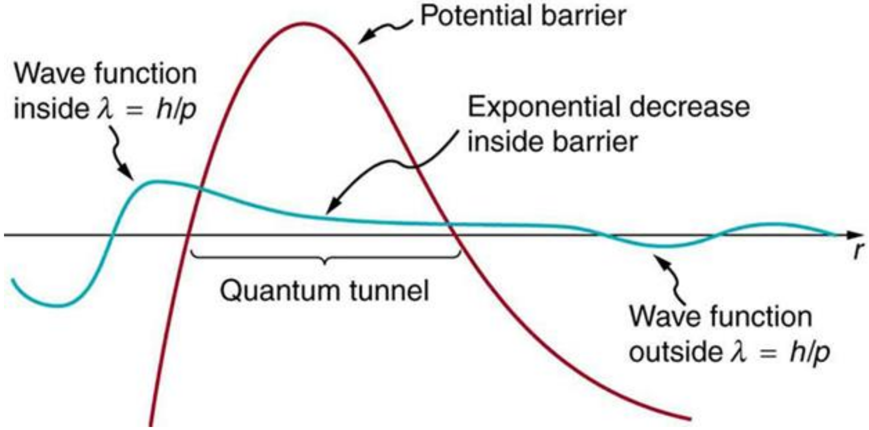


Nuclear Physics of Stars, Iliadis, 2nd Ed.

QM tunneling: decay

- Gamow (1928) & Condon and Gourney (1929): explained alpha decay via quantum mechanical tunneling

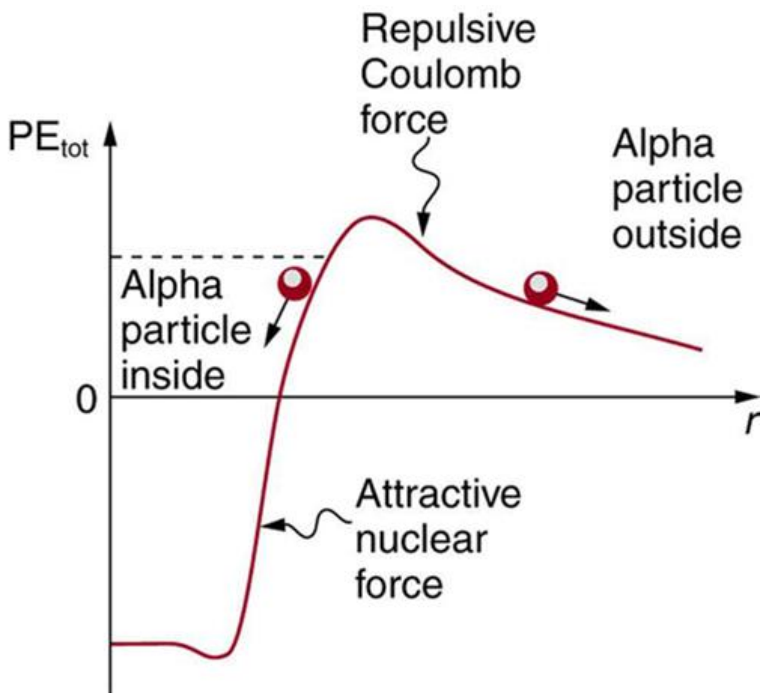


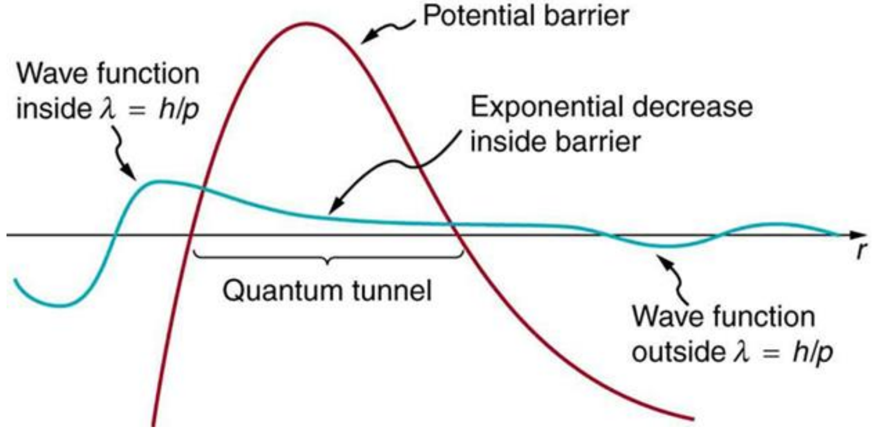


Nuclear Physics of Stars, Iliadis, 2nd Ed.

QM tunneling: fusion

- Atkinson and Houtermans (1929): tunneling through Coulomb barrier may enable nuclear fusion in stars





Nuclear Physics of Stars, Iliadis, 2nd Ed.

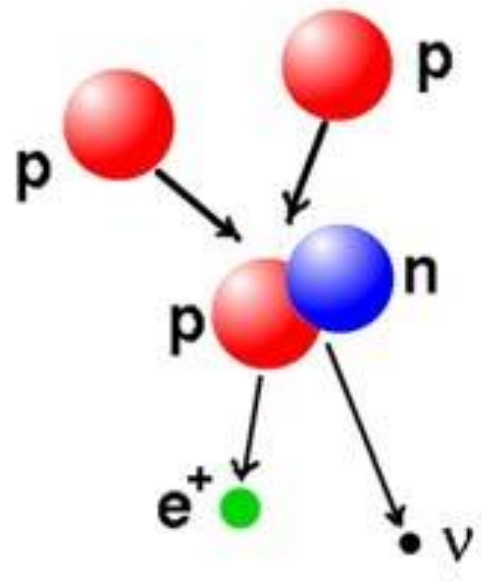
Stellar reactions in the lab

- Cockroft and Walton (1932): first nuclear reaction using artificially accelerated particles
- break-up of Li into two alpha particles under bombardment by ~few 100 keV protons
- part of stellar hydrogen-burning *pp chains*

Nuclear Physics of Stars, Iliadis, 2^{nd} Ed.

pp chains: the first step

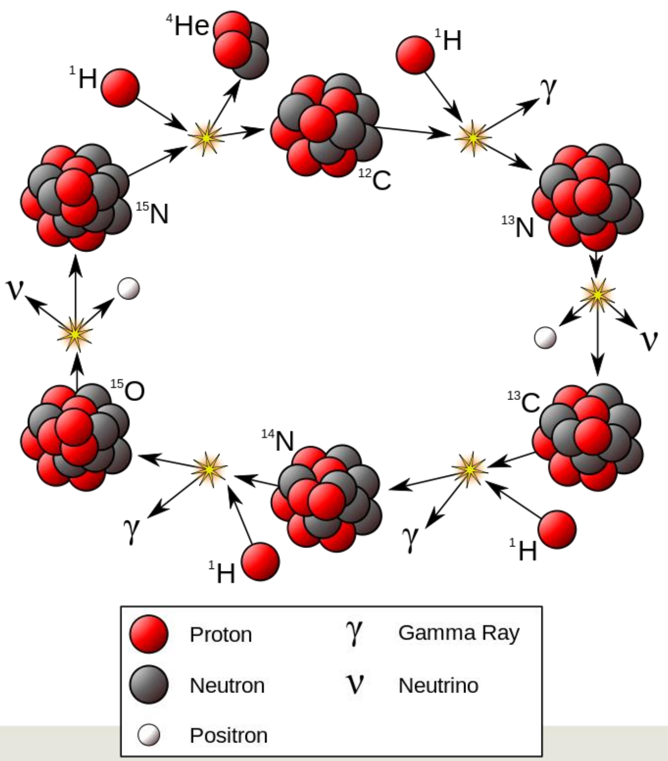
- Atkinson (1936) proposed fusion of two hydrogen nuclei to deuterium as a source of stellar energy generation
- Bethe and Critchfield (1938) showed this reaction gives energy generation of correct order of magnitude to power Sun
- First step of stellar hydrogen-burning *pp chains*



Nuclear Physics of Stars, Iliadis, 2nd Ed.

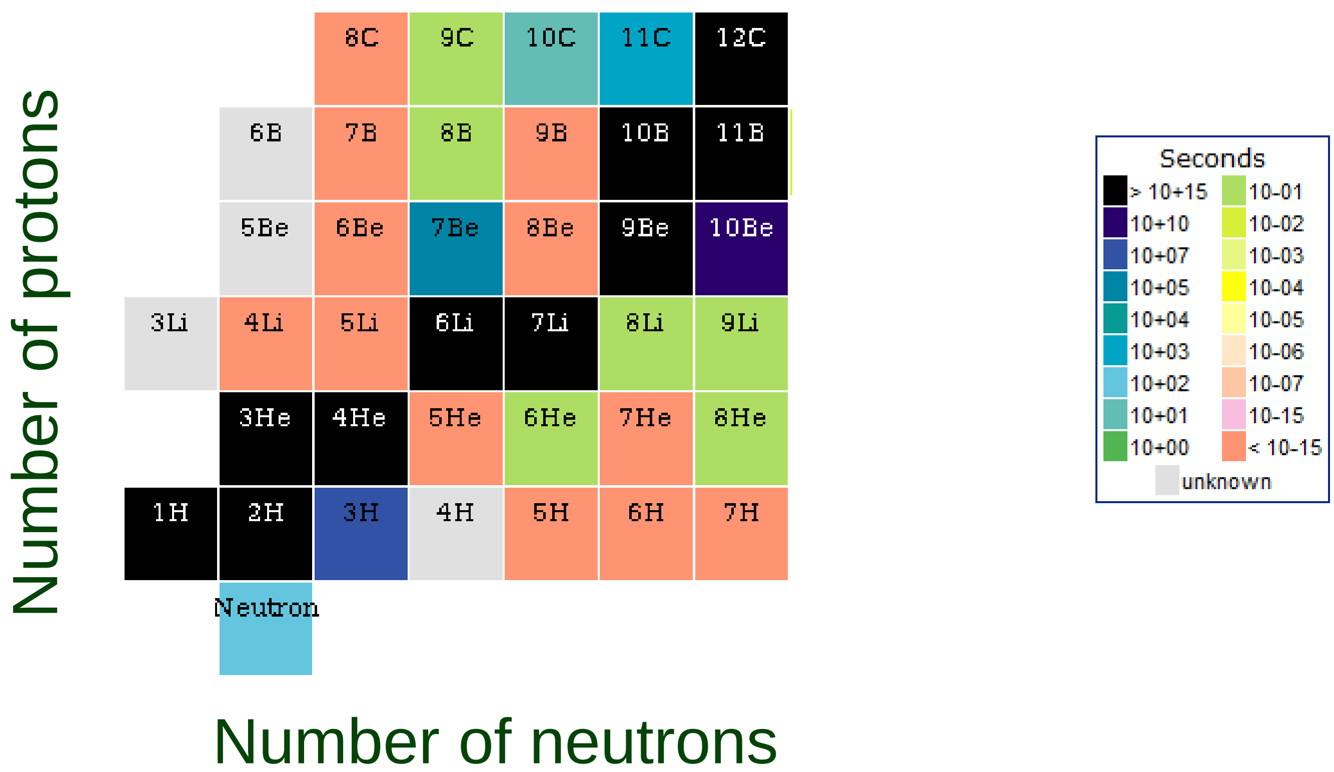
CNO cycle

- Lauritsen and Crane (1934) produced 10-min radioactivity (^{13}N) by bombarding carbon with protons
- Bethe (1939) and von Weizsacker (1938): energy production in stars by CNO cycles discovered: rate and temperature dependence



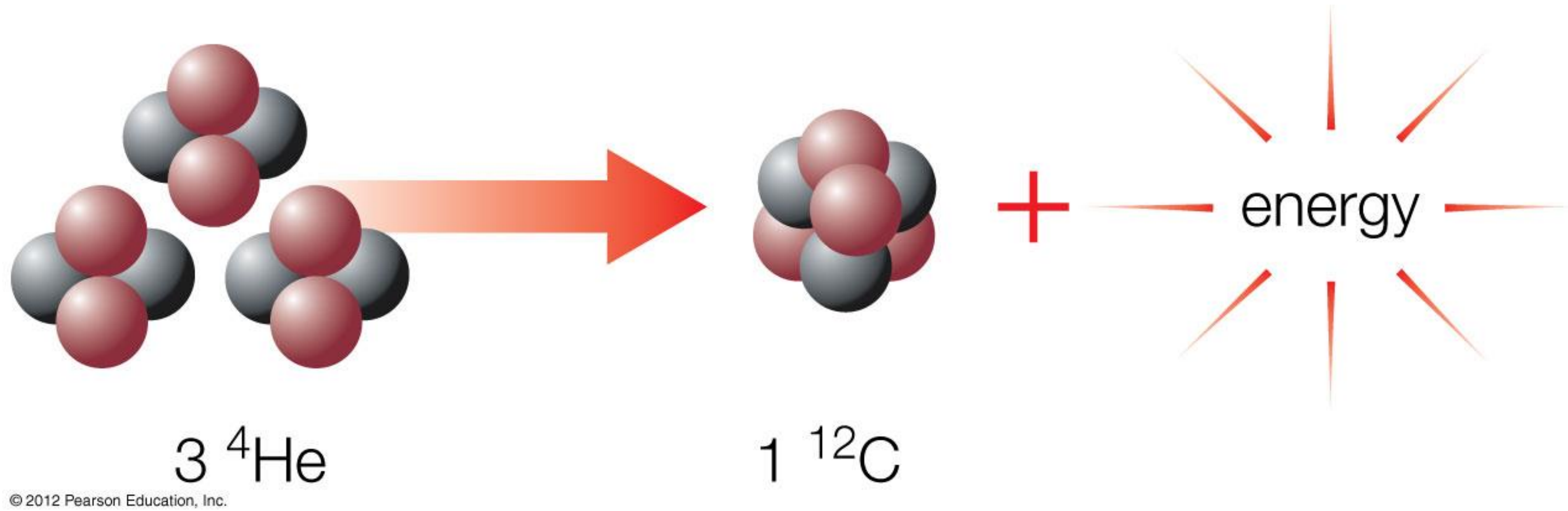
A = 5, 8 nucleosynthesis gaps

- Hoyle (1946, 1954): theory of nucleosynthesis within framework of stellar evolution using available nuclear data
- Problem: no stable nuclei of mass number 5, 8; how to bypass these in stars?



3α reaction

- Salpeter (1952): three helium atoms could combine to form carbon via “triple alpha reaction” powering red giant stars

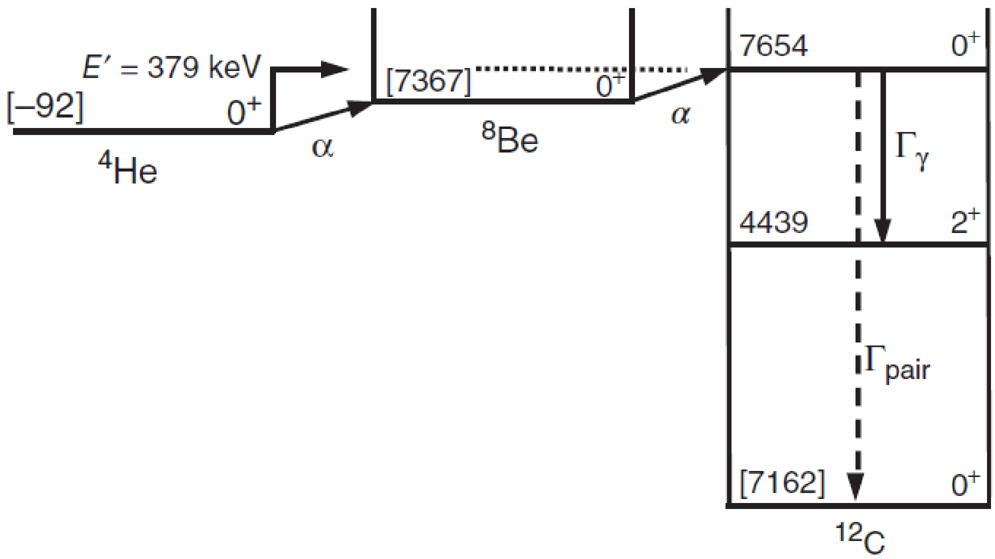


The Essential Cosmic Perspective, Bennett, Donahue, Schneider, Voit, 7th Ed.
Nuclear Physics of Stars, Iliadis, 2nd Ed.

3α reaction: Hoyle state

- Hoyle: must be special ^{12}C excited resonance state at 7.7 MeV to make triple alpha reaction fast enough to power red giant stars
- Dunbar *et al*. (1953), Cook *et al*. (1957): discovered the "Hoyle State" experimentally confirming that the triple alpha reaction can bypass mass 5, 8 gaps

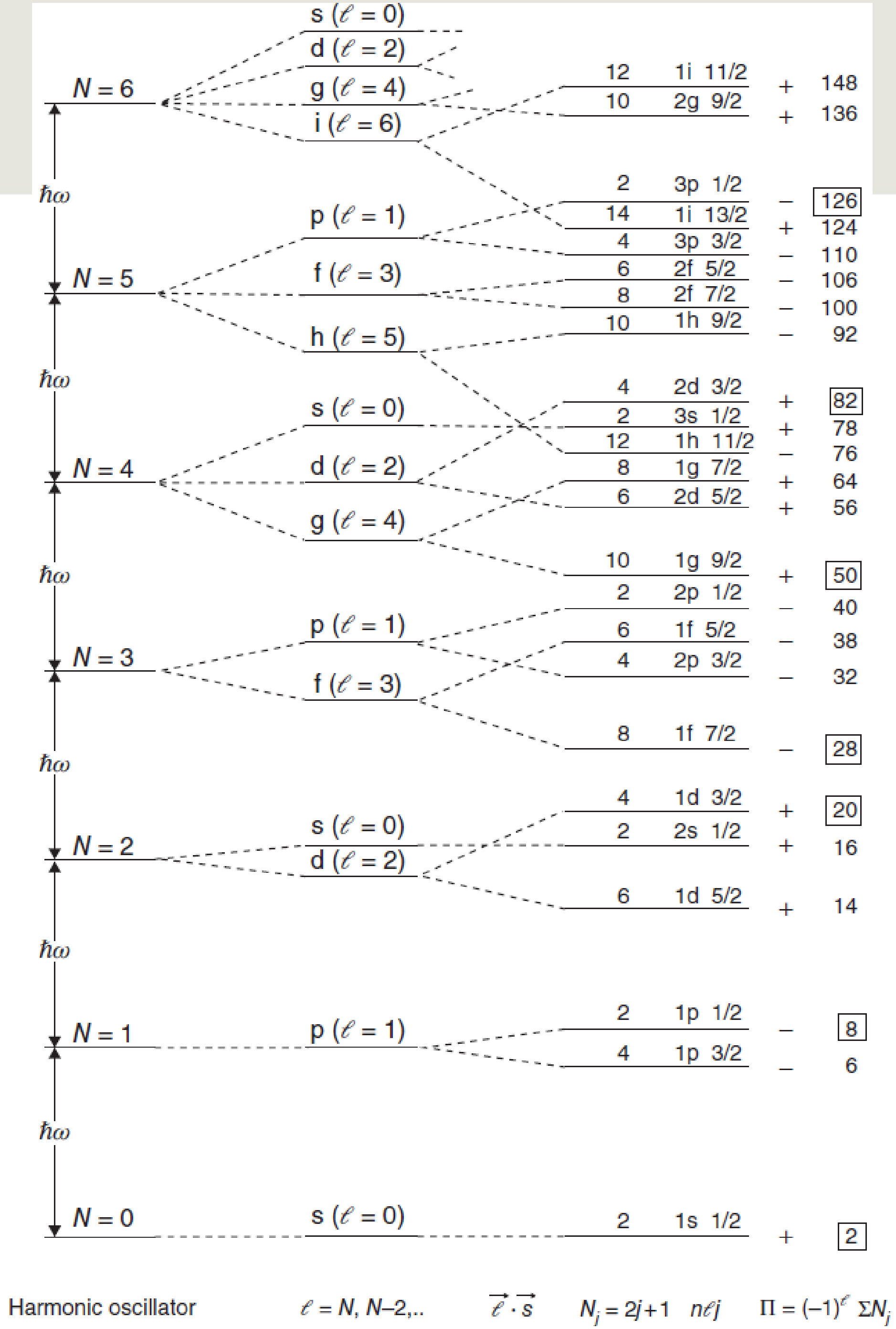
$\tau(^{8}\mathrm{Be}) \sim 10^{-16}$ s



Nuclear Physics of Stars, Iliadis, 2nd Ed.

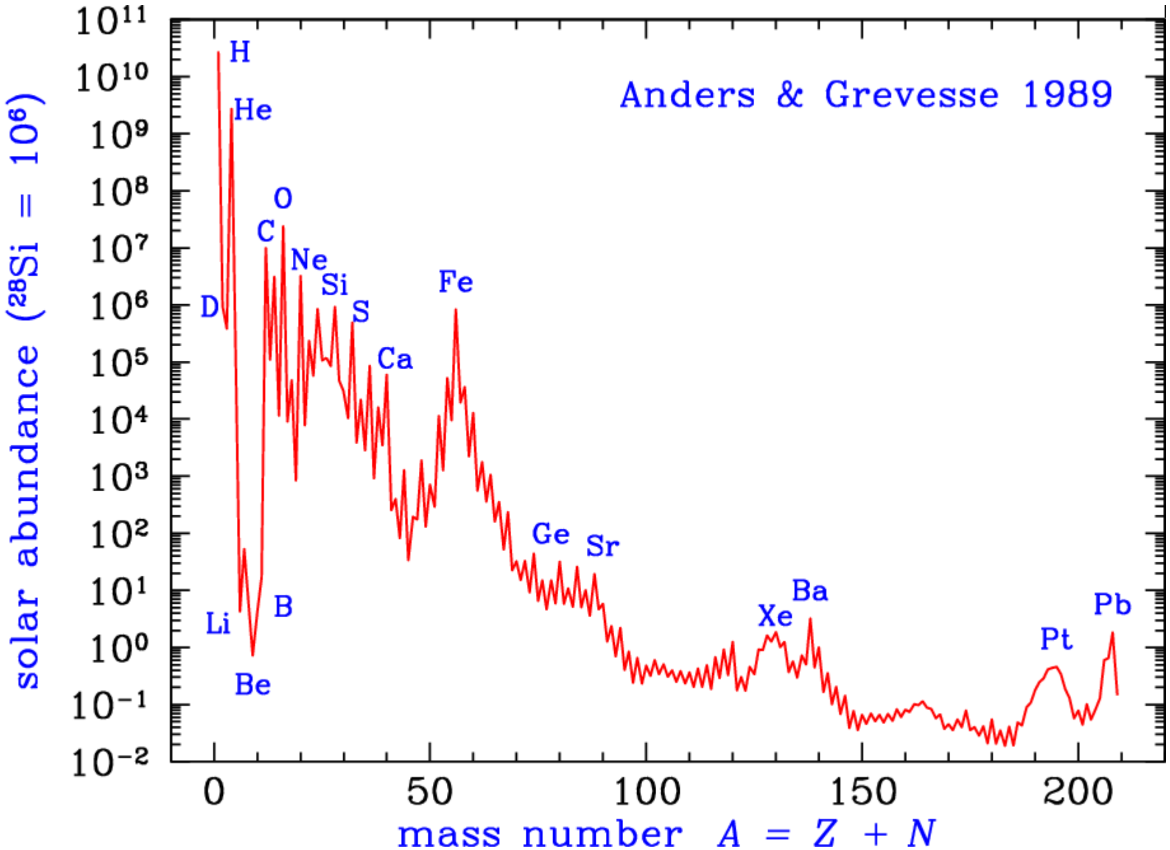
Nuclear shell model

- Jensen and Goeppert Mayer (1949) develop nuclear shell model and discover magic numbers



Solar abundances & nuclear shell model

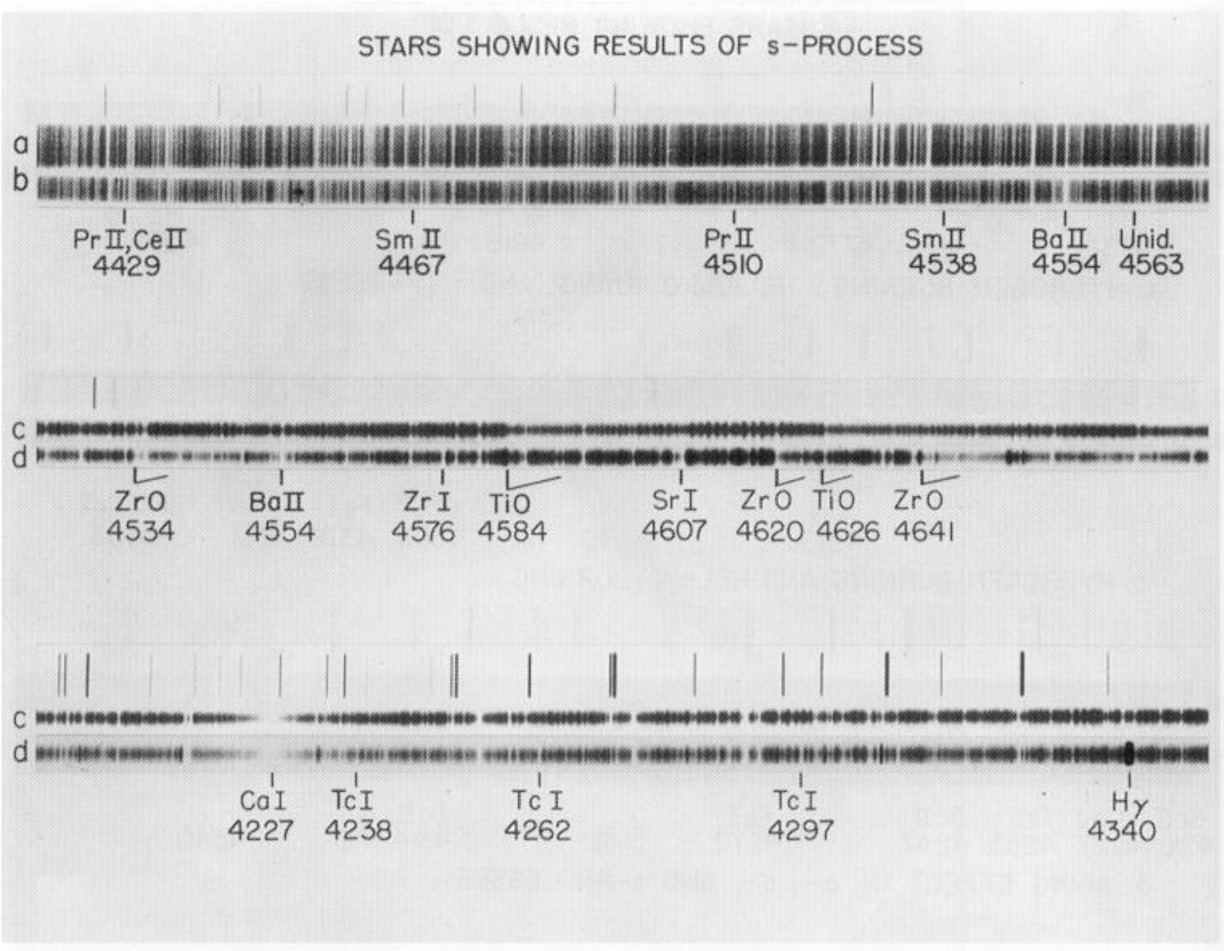
- Suess and Urey (1956): discovered peaks in solar system abundances, related to magic numbers motivating nucleosynthesis theory for heavy elements via *s*, *r* processes



Nuclear Physics of Stars, Iliadis, 2nd Ed.

Stellar nucleosynthesis: a smoking gun

- Merrill (1952): discovery of unstable Tc in red giant stars showing that nuclear reactions are producing heavy elements in stars



Nuclear Physics of Stars, Iliadis, 2nd Ed.

Foundations of nuclear astrophysics: B^2FH

REVIEWS OF

MODERN PHYSICS

VOLUME 29, NUMBER 4 OCTOBER, 1957

Synthesis of the Elements in Stars*

E. MARGARET BURBIDGE, G. R. BURBIDGE, WILLIAM A. FOWLER, AND F. HOYLE

+ Al Cameron

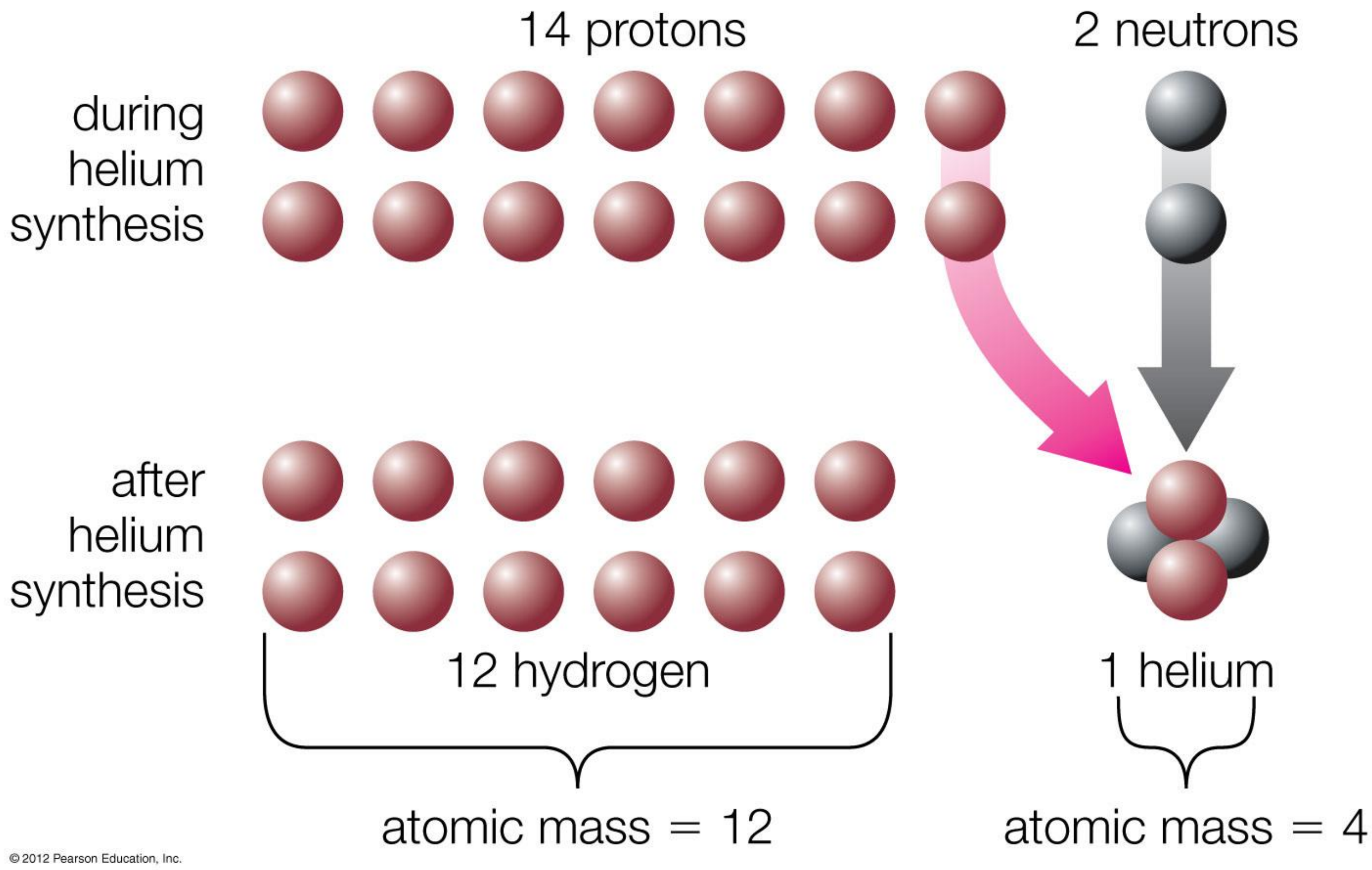
independently in Chalk River internal report

Nuclear reactions in stars are responsible for energy generation and creation of elements

Nuclear astrophysics today

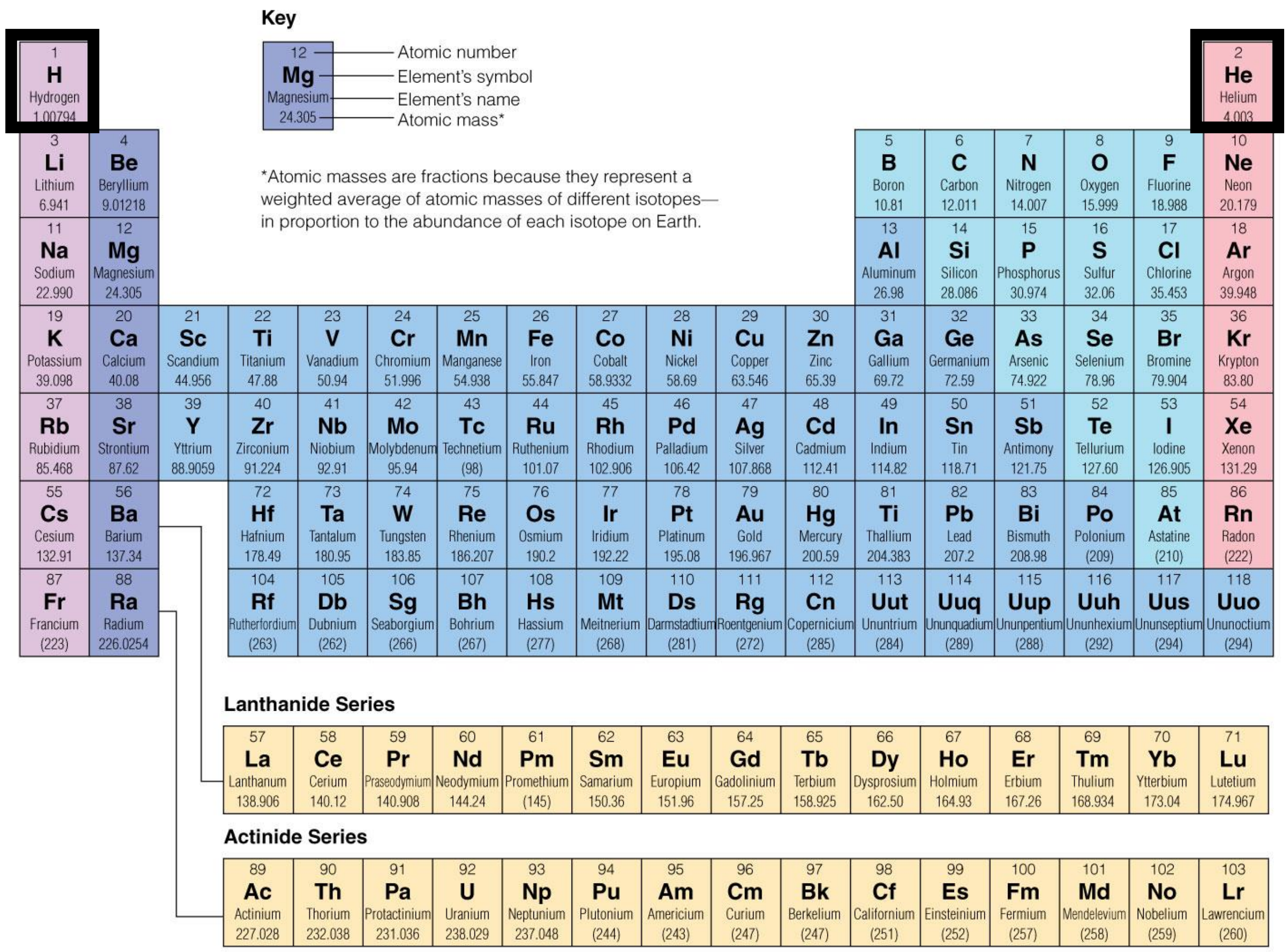
- Nuclear astrophysics has grown into a broad and vibrant field that links topics such as astronomical observation, nuclear physics experiment, nuclear theory, stellar evolution, and hydrodynamics

Big Bang nucleosynthesis



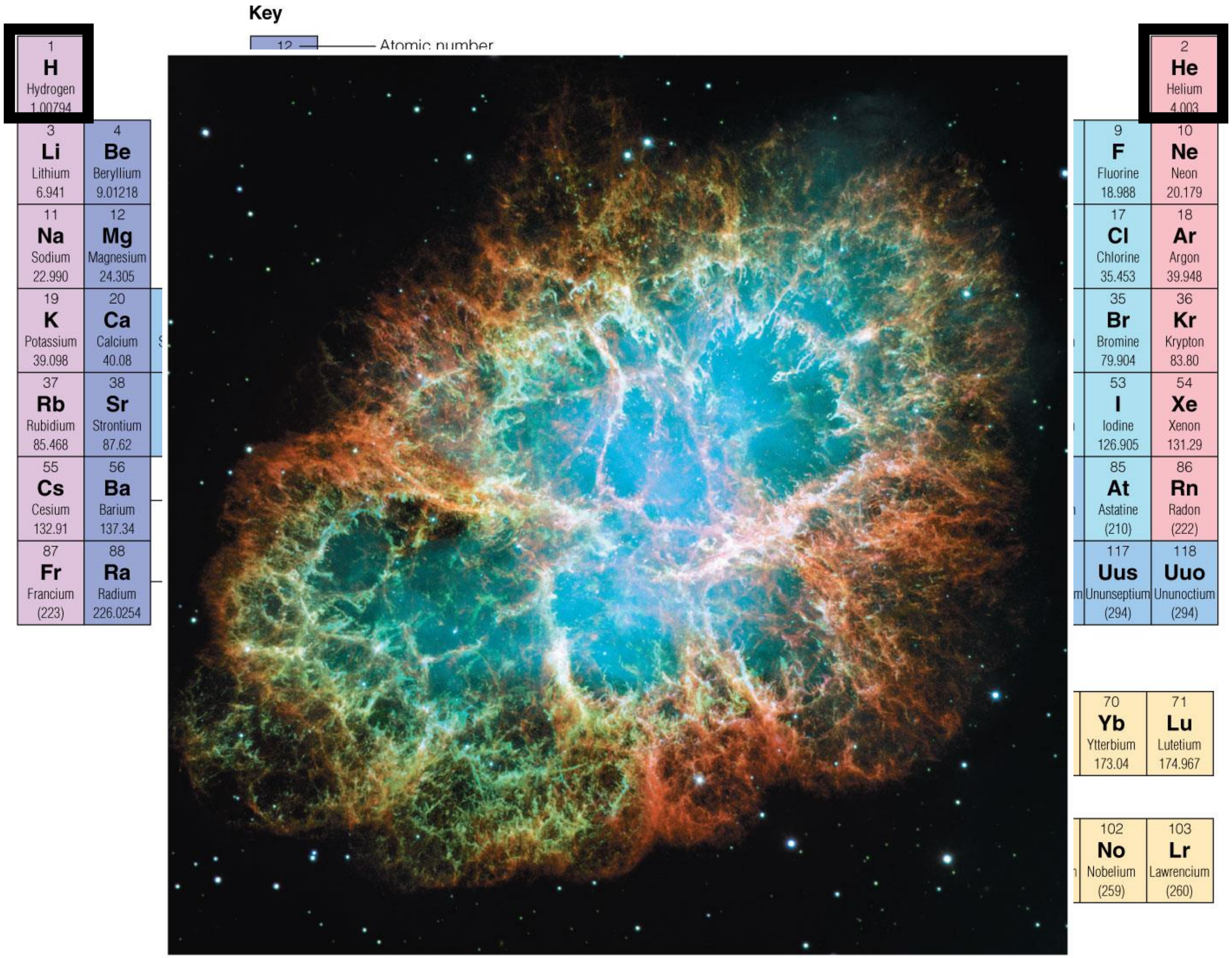
Big Bang made 75% H and 25% He, by mass, in about 1000s

How were other elements made?



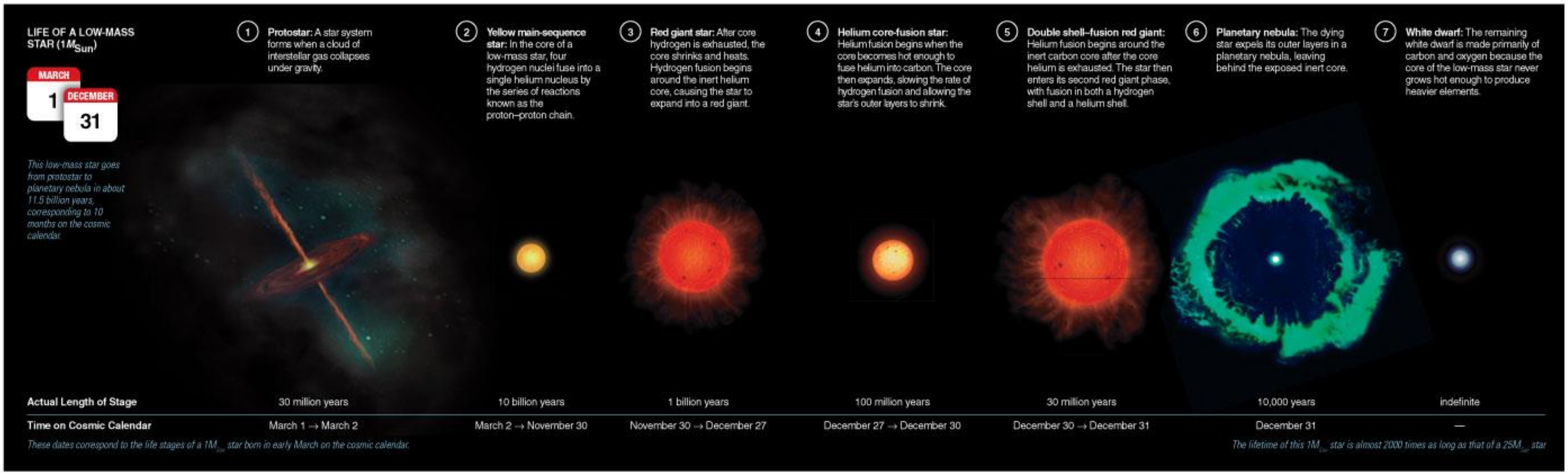
The Essential Cosmic Perspective, Bennett, Donahue, Schneider, Voit, 7th Ed.

In stars and stellar events!



Life of a low-mass star
(less than about 8 solar masses)

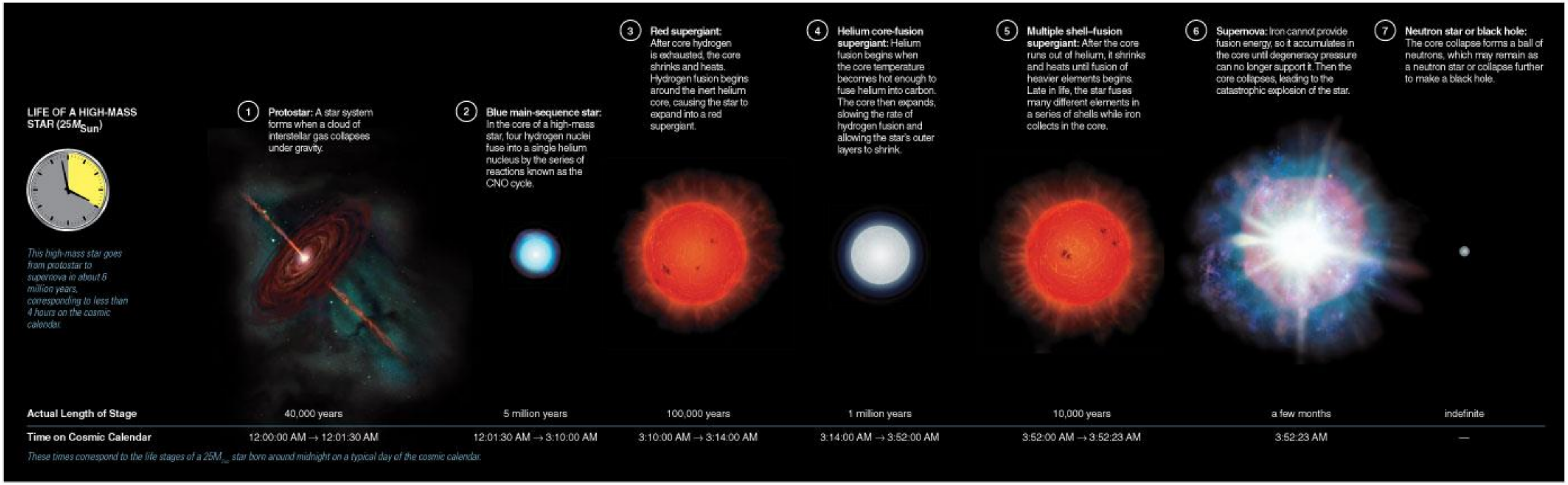
1. Protostar: cloud of cold gas collapses under gravity
2. Main Sequence: H fuses to He in core
3. Red Giant: H fuses to He in shell around inert He core until He flash
4. Helium Core Fusion: He fuses to C, O in core while H fuses to He in shell
5. Double Shell Fusion: H and He both fuse in shells around inert C, O core
6. Planetary Nebula: outer layers expelled
7. White dwarf star left behind



The Essential Cosmic Perspective, Bennett, Donahue, Schneider, Voit, 7th Ed.

Life of a massive star
(more than about 8 solar masses)

1. Protostar: cloud of cold gas collapses under gravity
2. Main Sequence: H fuses to He in core
3. Red Supergiant: H fuses to He in shell around inert He core
4. Helium Core Fusion: He fuses to C, O in core while H fuses to He in shell
5. Multiple Shell Fusion: many elements fuse in shells around Fe core
6. Supernova (type II) explosion after Fe core collapses
7. Neutron star or black hole left behind



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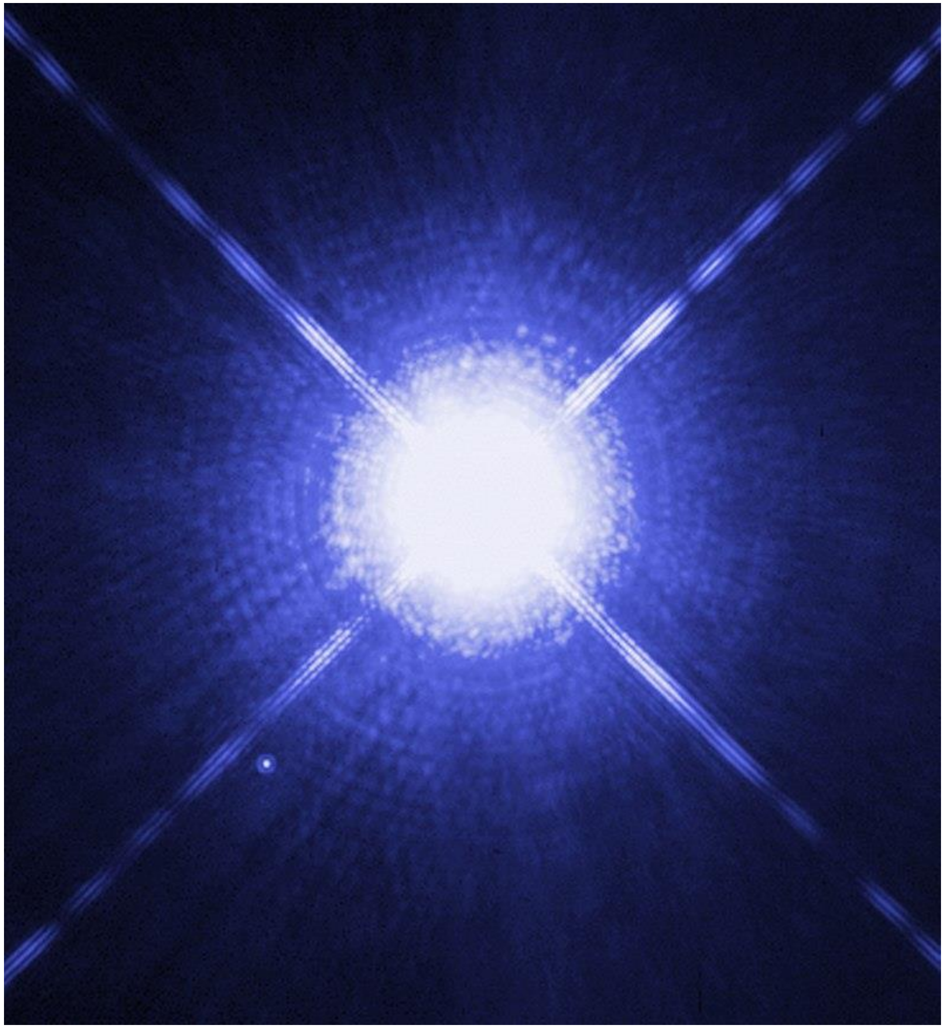
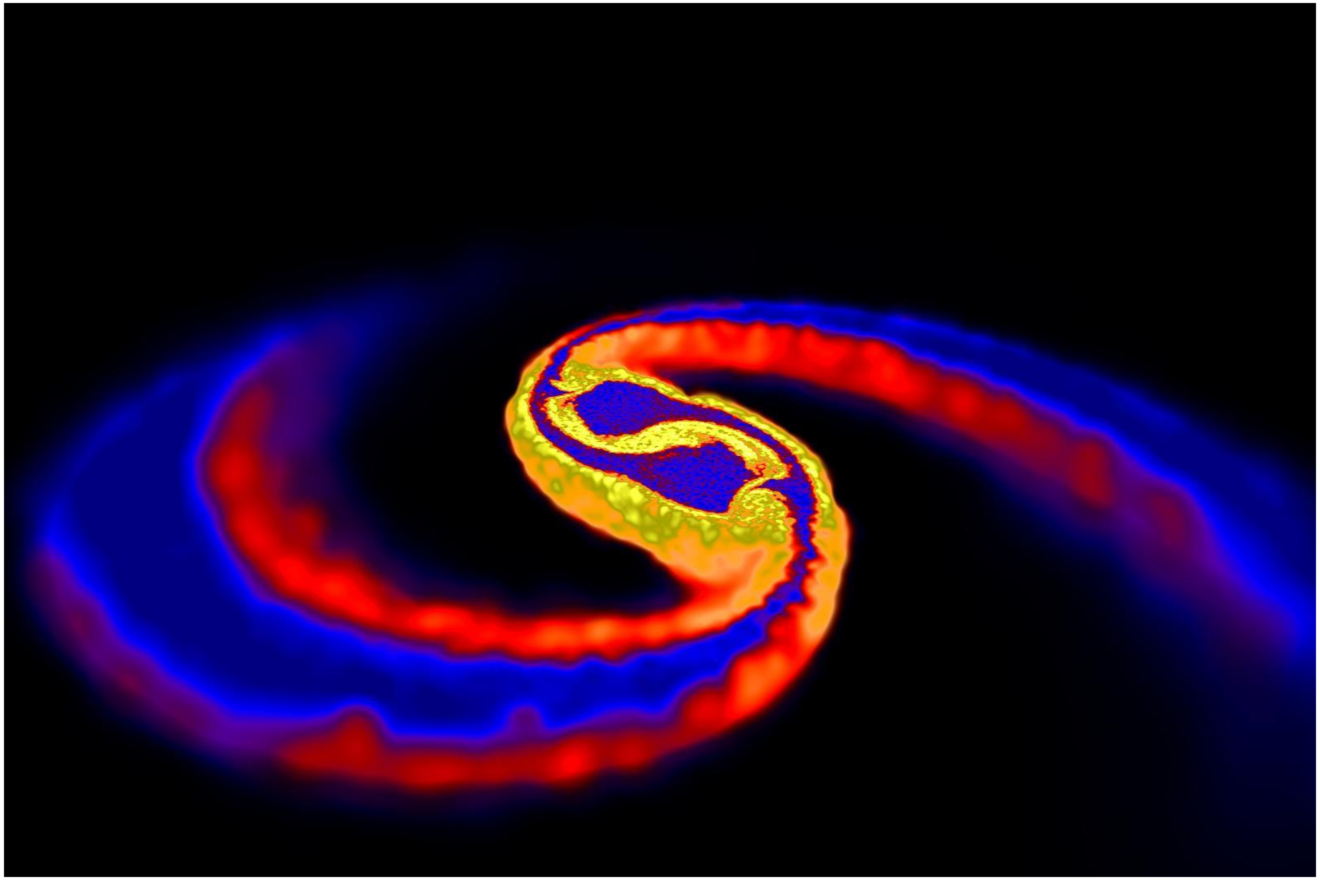
Binary star systems

Half of all stars are in binary systems. For example, the brightest star system in our sky Sirius.



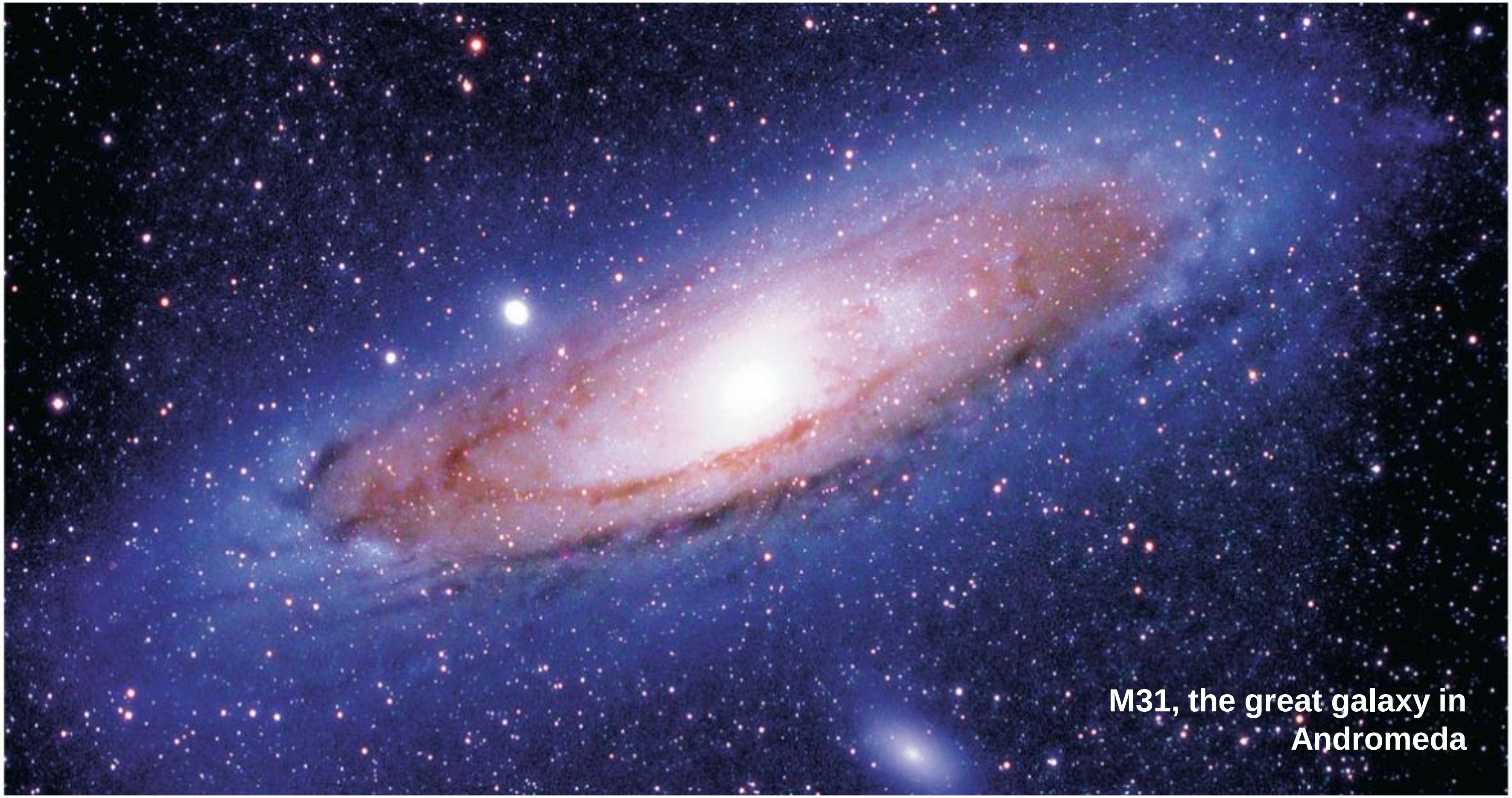
NASA, ESA, H. Bond (STScI), and M. Barstow (University of Leicester)

Close binary star systems

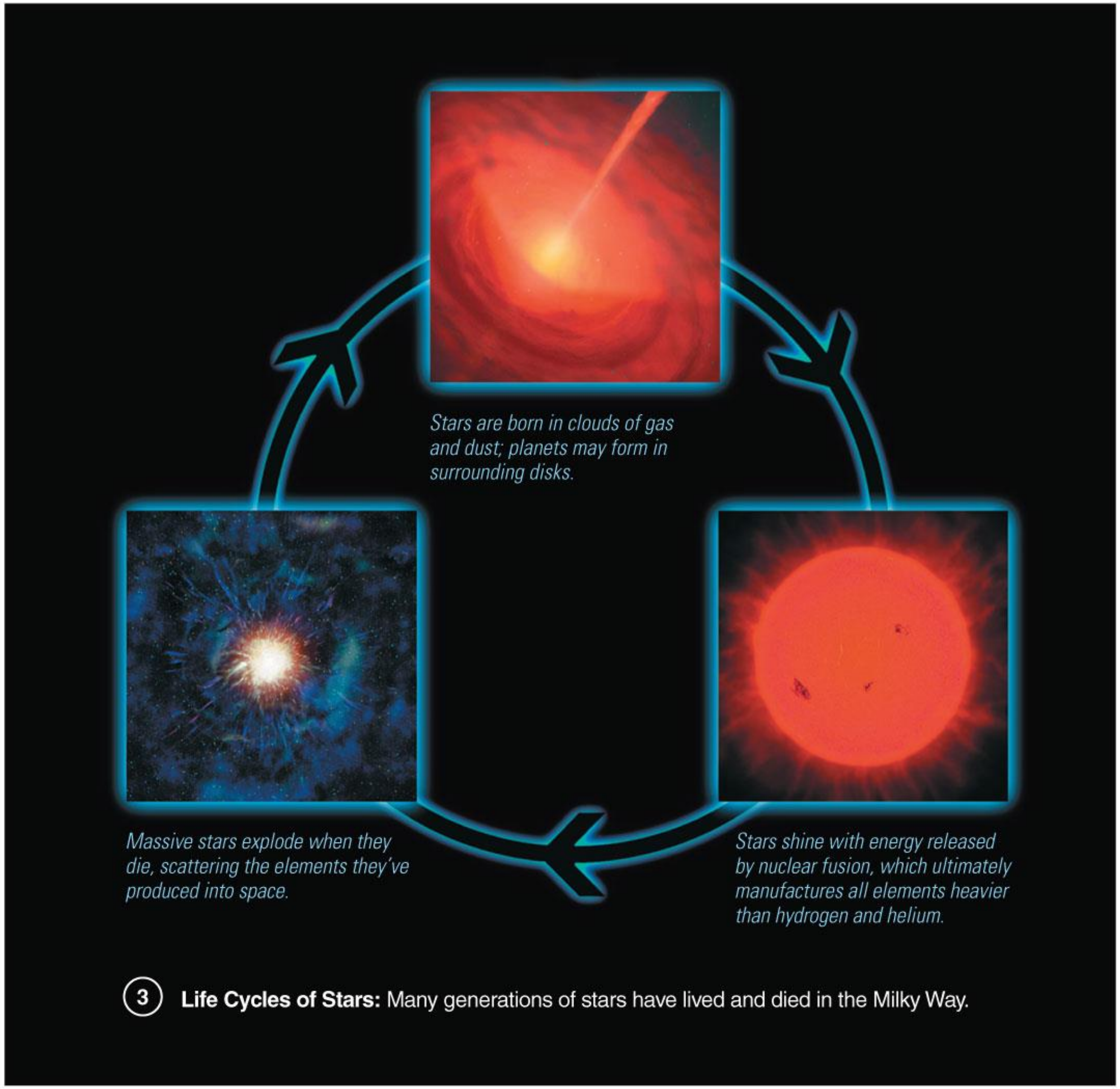


Interactions can lead to mass exchange and co-evolution, or rebirth of compact objects through neutron-star mergers, thermonuclear (Ia) supernovae, classical novae, X-ray bursts, …

The Milky Way: a cosmic recycling plant



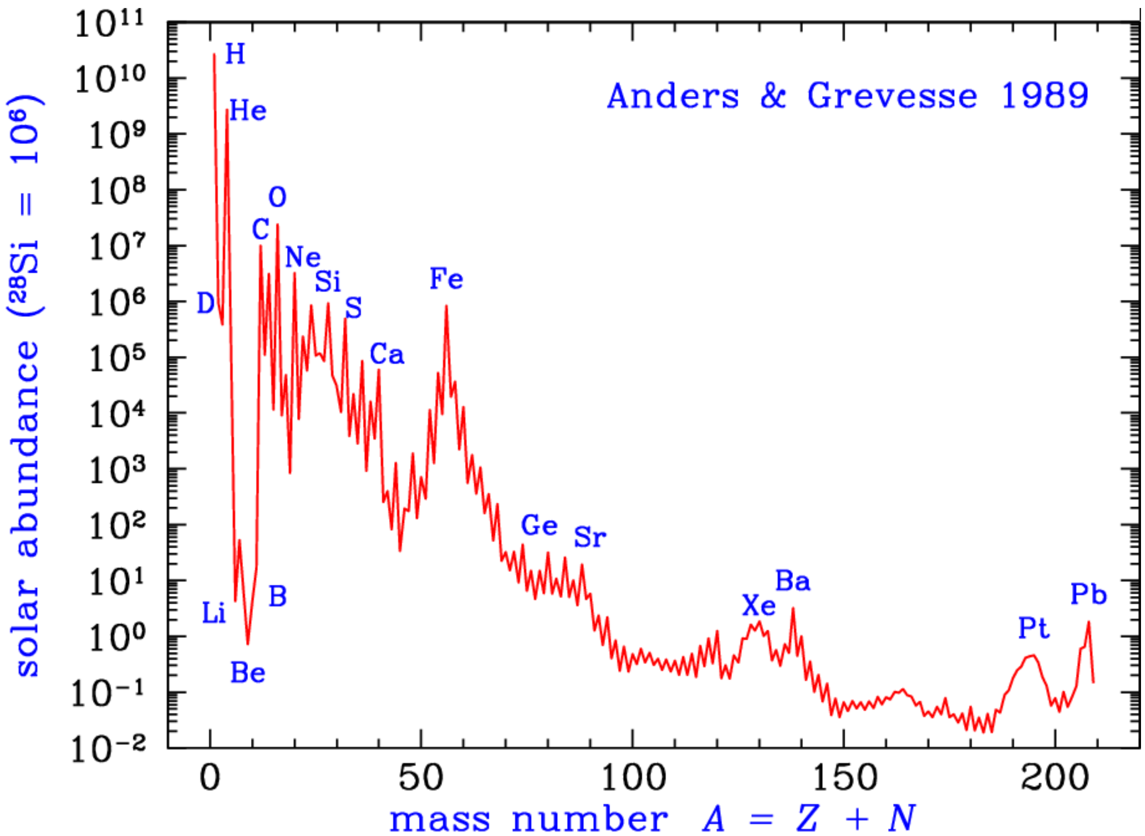
The Milky Way: a cosmic recycling plant



The Essential Cosmic Perspective, Bennett, Donahue, Schneider, Voit, 7th Ed.

Solar abundances

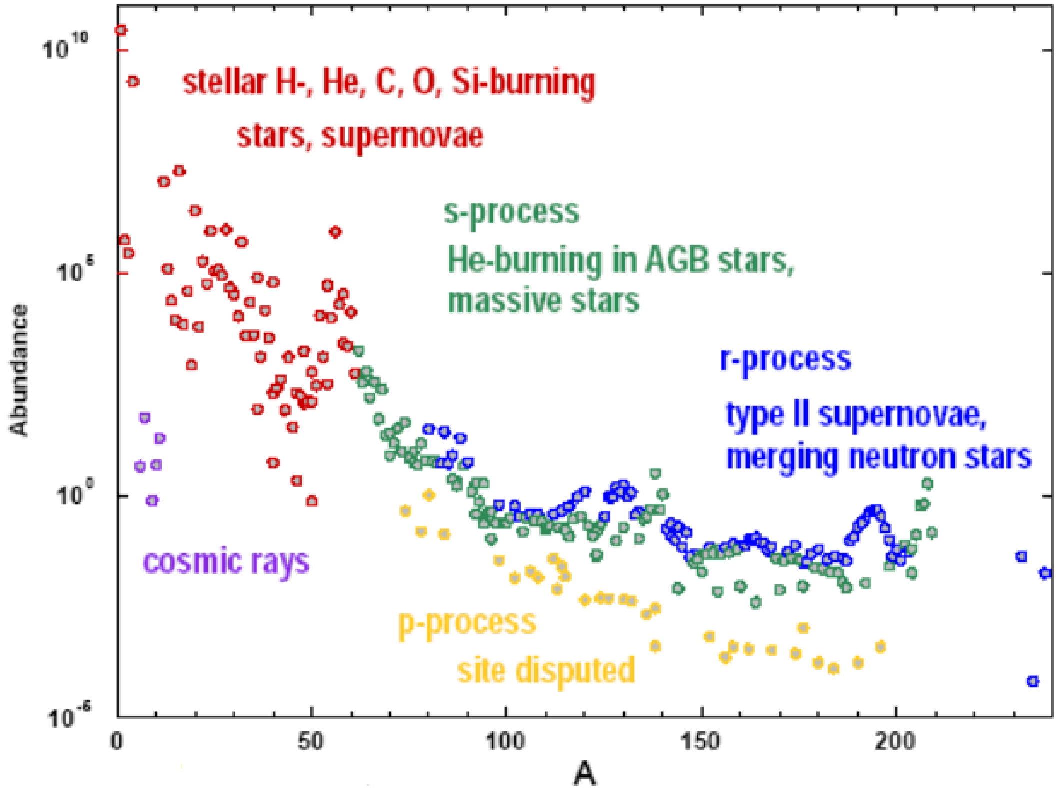
- Abundances determined by spectroscopy of the solar photosphere & mass spectrometry of primitive meteorites



Synthesis of elements in stars

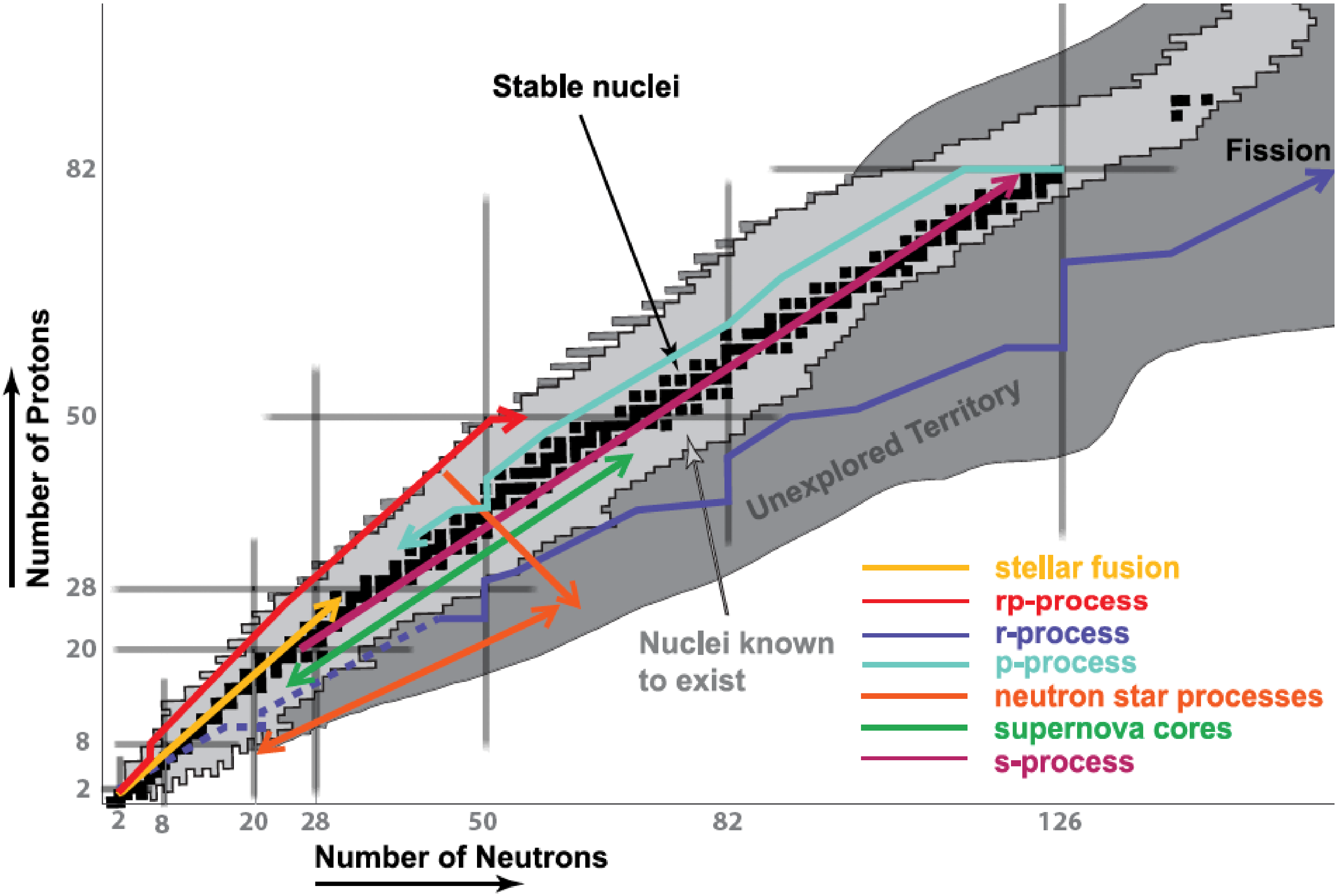
1. H burning → conversion of H to He
2. He burning → conversion of He to C, O ...
3. C, O and Ne burning → production of A: 16 to 28
4. Si burning → production of A: 28 to 60
5. s-, r- and p-processes → production of A>60
6. Li,Be, and B from cosmic rays

Solar abundances



M. Wiescher / A. Tumino

Nuclear astrophysics processes



Need stellar nuclear reaction rates to understand nucleosynthesis processes

Nuclear Mass and Binding Energy

Nuclear mass:

$$m_{\mathrm{nuc}} = Zm_{\mathrm{p}} + Nm_{\mathrm{n}} - \Delta m$$

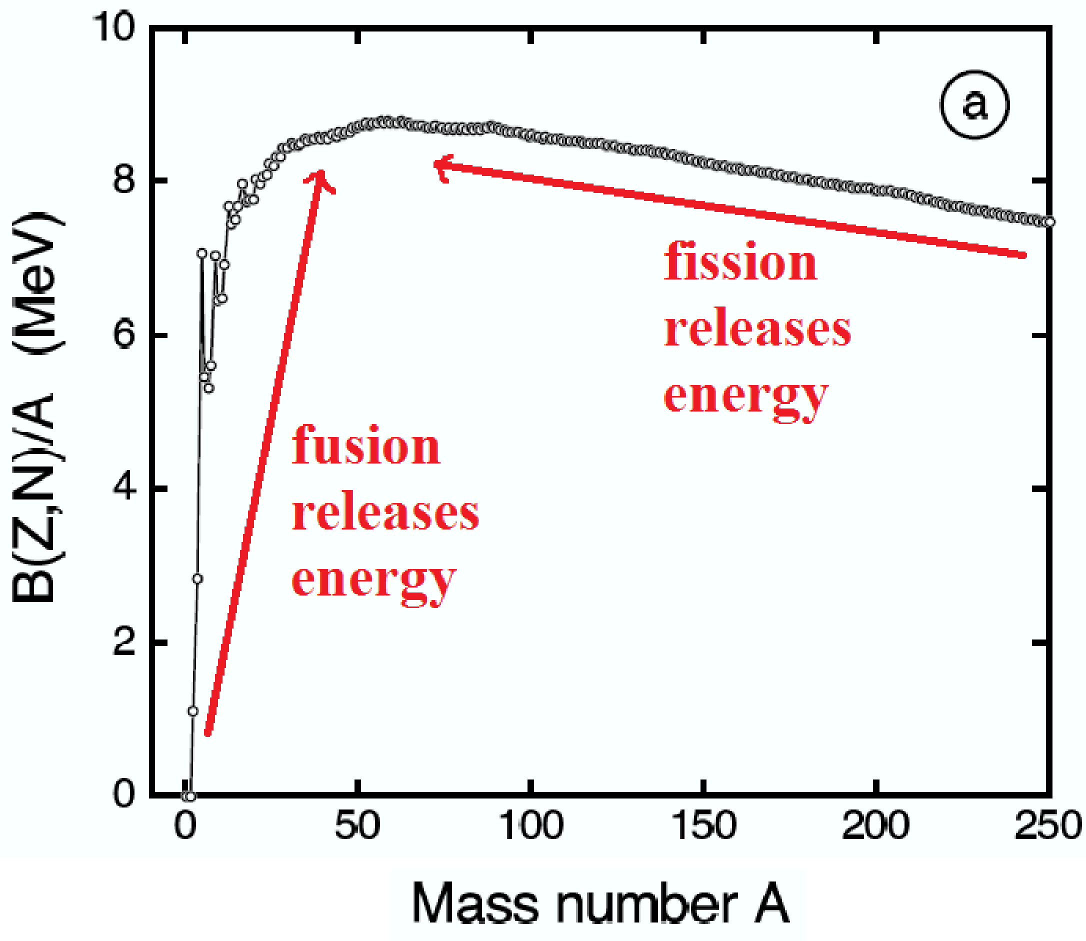
Nuclear binding energy:

$$\Delta m \cdot c^2 = \Delta E = B(Z, N)$$

$$B(Z, N) = \left(Zm_{\mathrm{p}} + Nm_{\mathrm{n}} - m_{\mathrm{nuc}}\right) c^2$$

Nuclear Physics of Stars, Iliadis, 2nd Ed.

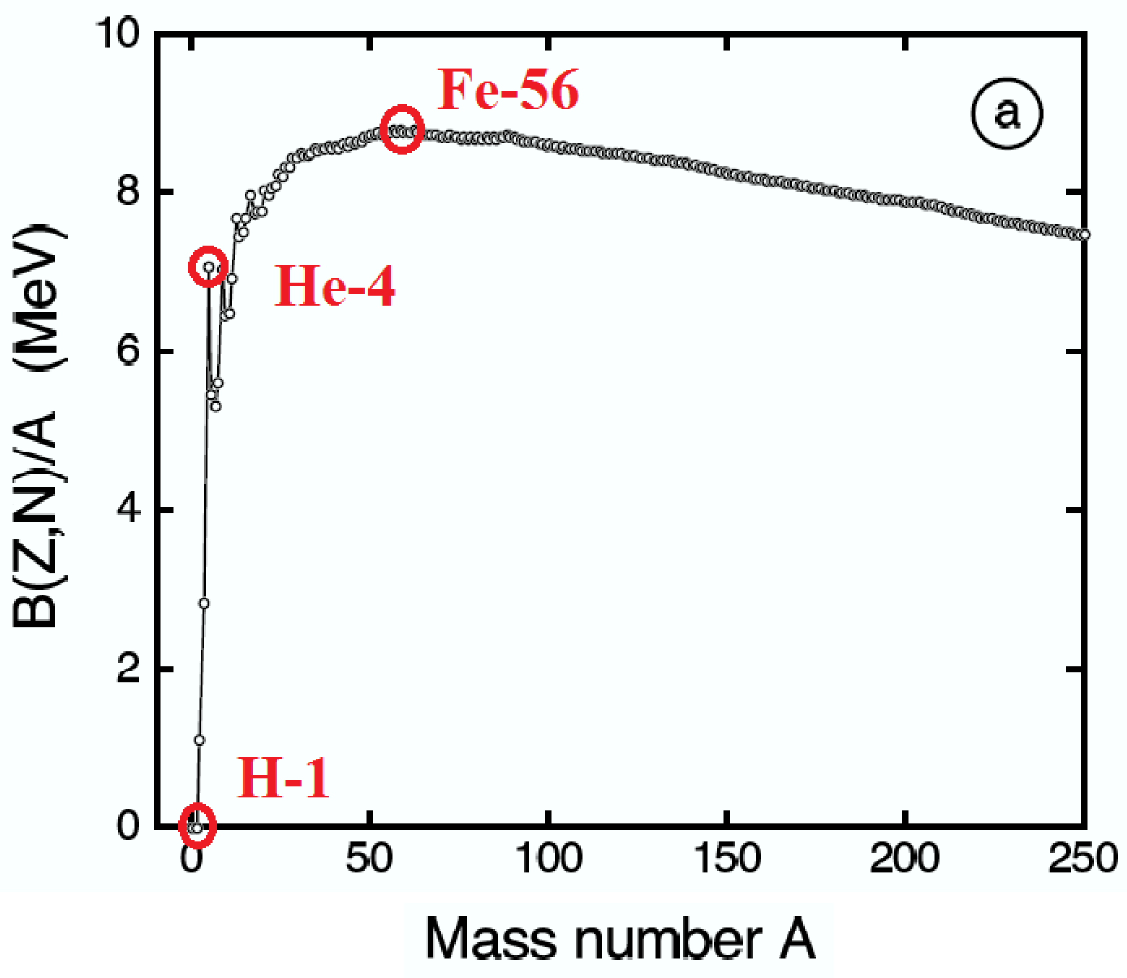
Binding energy per nucleon



General trends:
Fusion of light nuclei releases energy; fission of heavy nuclei releases energy.
Fusion of heavy nuclei consumes energy; break-up of light nuclei consumes energy.

Nuclear Physics of Stars, Iliadis, 2^{nd} Ed.

Binding energy per nucleon



Eg. fusing four ^{1}H into ^{4}He releases ~7 MeV per nucleon;
fusing many ^{1}H into ^{56}Fe releases ~9 MeV per nucleon.

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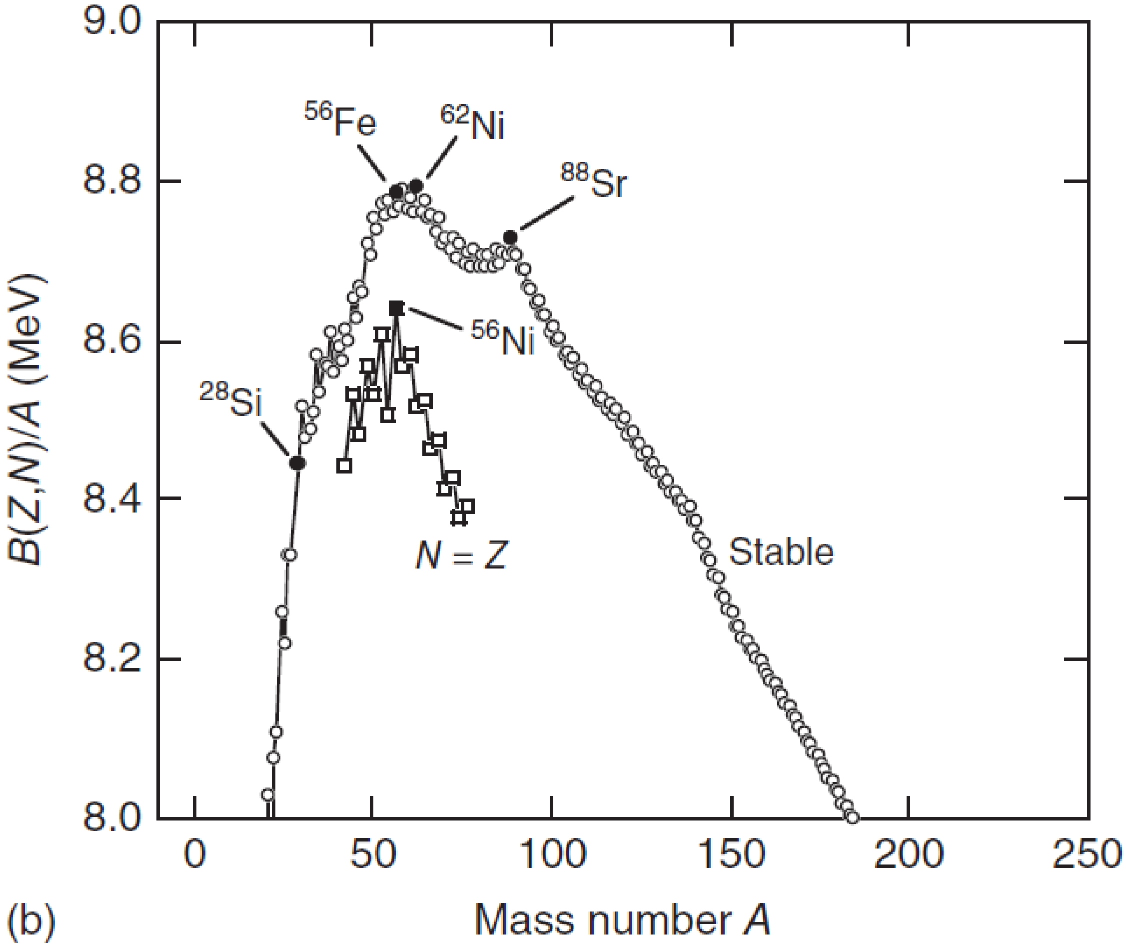
Binding energy per nucleon



Peak in the range of A = 50-65: iron peak nuclei! Nature favors production of the most tightly bound and stable nuclides. ^{62}Ni, ^{58}Fe, and ^{56}Fe are most bound.

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Nuclear reactions: notation and terminology

A nuclear reaction can be represented symbolically as:

$$0 + 1 \rightarrow 2 + 3 \qquad \text{or} \qquad 0(1,2)3$$

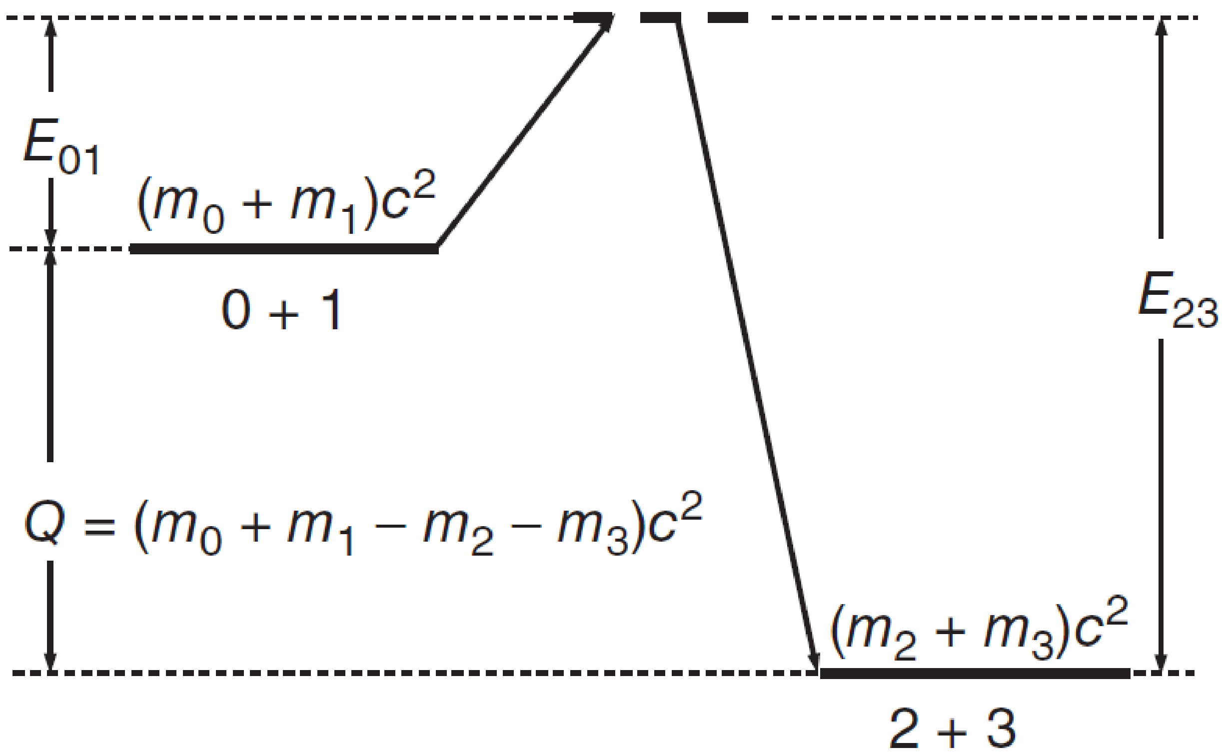
0,1 are colliding nuclei before reaction
2,3 are the interaction products

If 0,1 identical to 2,3 then *elastic* or *inelastic scattering*; otherwise *nuclear reaction*

If 2 is a photon: *radiative capture reaction*
If 1 is a photon: *photodisintegration reaction*

Nuclear Physics of Stars, Iliadis, 2nd Ed.

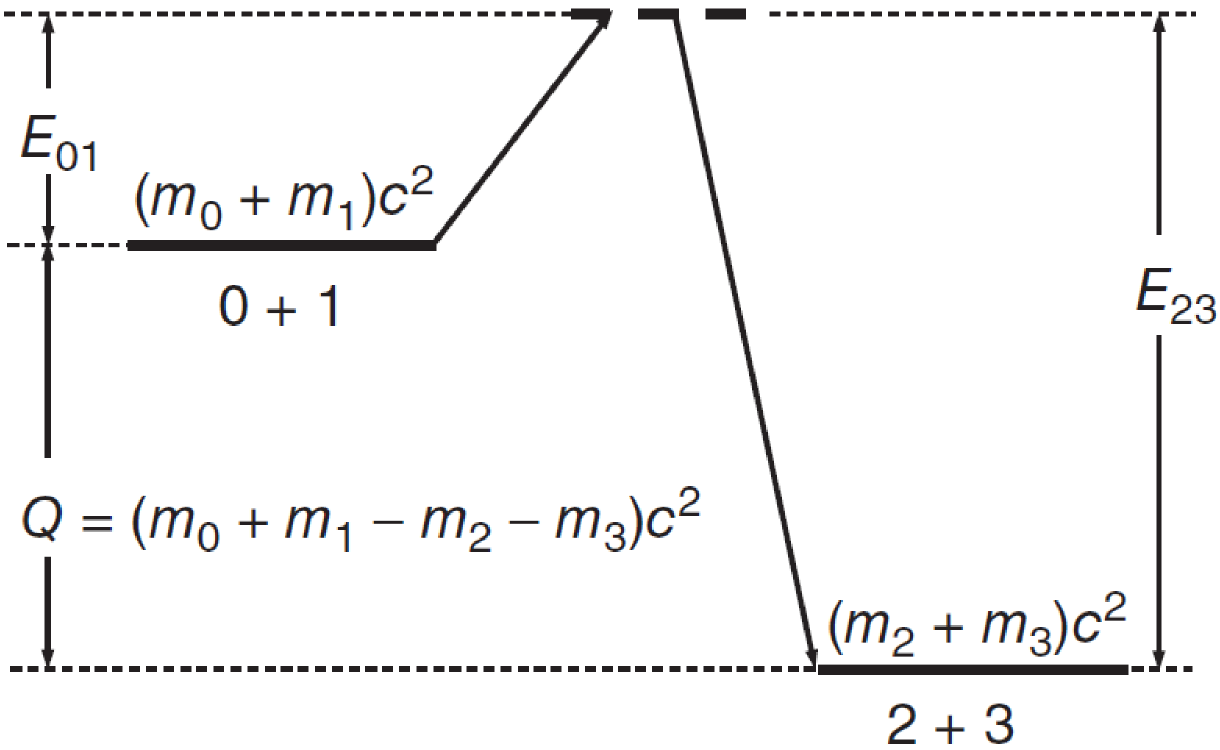
Energetics of nuclear reactions: 0(1,2)3



Conservation of energy:

$$m_0c^2 + m_1c^2 + E_0 + E_1 = m_2c^2 + m_3c^2 + E_2 + E_3$$

Energetics of nuclear reactions: 0(1,2)3



Definition of *Q value*:

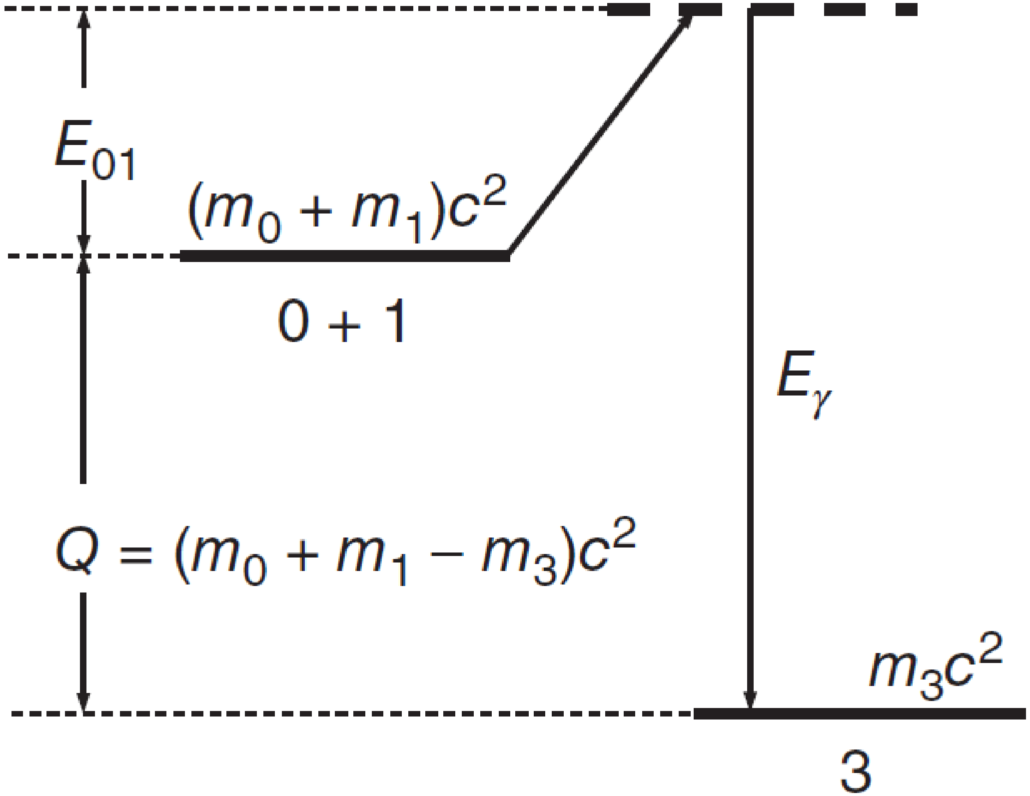
$$Q_{01\rightarrow 23} \equiv m_0c^2 + m_1c^2 - m_2c^2 - m_3c^2 = E_2 + E_3 - E_0 - E_1$$

If $Q > 0$: reaction releases energy (exothermic)

If $Q < 0$: reaction consumes energy (endothermic)

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Radiative Capture Reactions: 0(1,γ)3

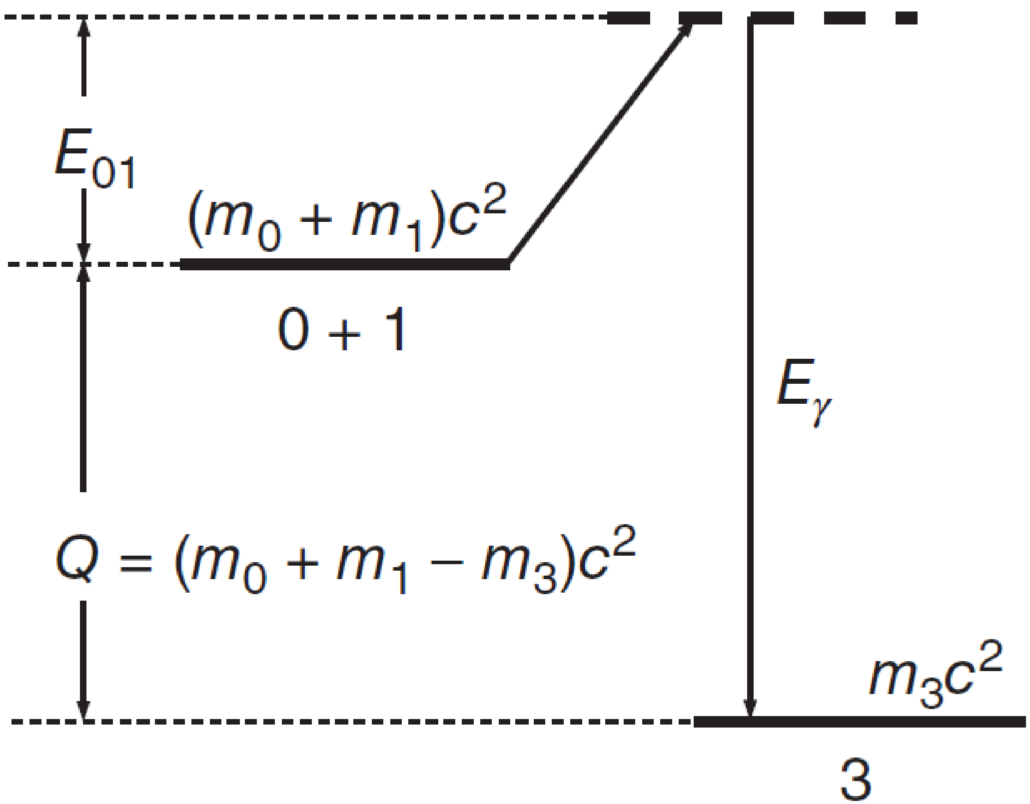


$$m_0c^2 + m_1c^2 + E_0 + E_1 = m_3c^2 + E_3 + E_\gamma \qquad \text{or}$$

$$Q_{01\to\gamma 3} \equiv m_0c^2 + m_1c^2 - m_3c^2 = E_3 + E_\gamma - E_0 - E_1$$

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Photodisintegration Reactions: 3(γ,1)0



If one adds energy >Q to nucleus 3, then it becomes energetically possible for nucleus 3 to separate into fragments 0,1. Define *particle separation energy*:

$$S_{3\to 01} = Q_{01\to\gamma 3}$$

Nuclear Physics of Stars, Iliadis, 2nd Ed.

Stellar reaction rates: *thermo*nuclear

stellar reaction rate $\langle \sigma v \rangle = \int \sigma(v)\phi(v) v dv$

need: a) velocity distribution $\phi(v)$

b) cross section $\sigma(v)$

a) velocity distribution

interacting nuclei in plasma are in thermal equilibrium at temperature T

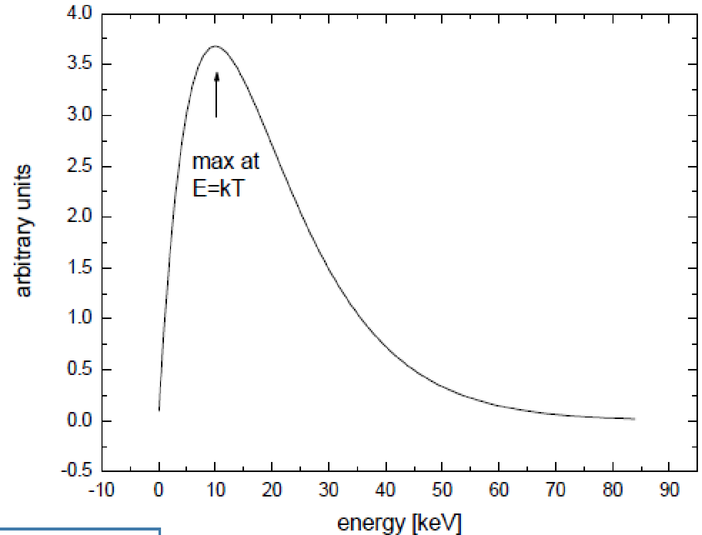
also assume non-degenerate and non-relativistic plasma

$\Rightarrow$ Maxwell-Boltzmann velocity distribution

$$\phi(v) = 4\pi \left(\frac{\mu}{2\pi kT} \right)^{3/2} v^2 \exp\left(-\frac{\mu v^2}{2kT} \right)$$

with $\mu = \frac{m_p m_T}{m_p + m_T}$ reduced mass

v = relative velocity



kT ~ 8.6 x 10^{-8} T[K] keV

example: Sun T ~ 15×10^6 K $\Rightarrow$ kT ~ 1 keV

M. Aliotta

Stellar reaction rates: thermo*nuclear*

b) cross section — Probability for reaction between nuclei (units of area)

no nuclear theory available to determine reaction cross section a priori

cross section depends sensitively on:

- the properties of the nuclei involved
- the reaction mechanism

and can vary by orders of magnitude, depending on the interaction

examples:

Reaction	Force	σ (barn)	E_{proj} (MeV)
$^{15}N(p,\alpha)^{12}C$	strong	0.5	2.0
$^{3}He(\alpha,\gamma)^{7}Be$	electromagnetic	10^{-6}	2.0
$p(p,e^{+}\nu)d$	weak	10^{-20}	2.0

1 barn = 10^{-24} cm^2 = 100 fm^2

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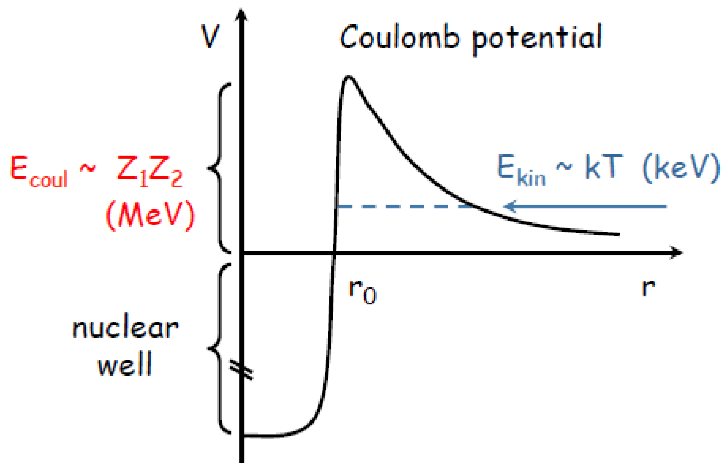
Stellar reaction rates: *thermonuclear*
(charged particles)

charged particles ➡ Coulomb barrier



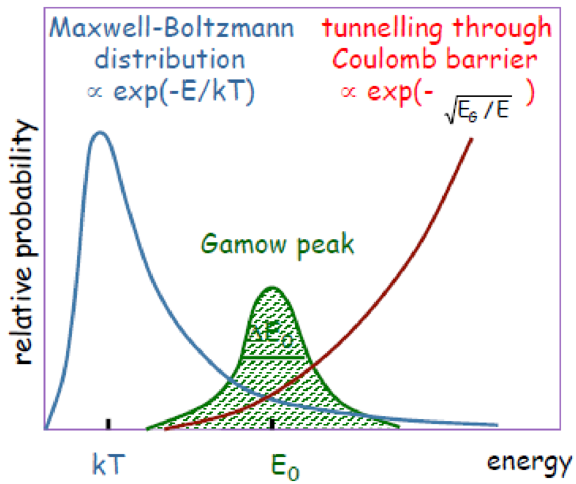
energy available: from thermal motion

during static burning: $kT \ll E_{coul}$

$T \sim 15\times10^6$ K (e.g. our Sun) $\Rightarrow$ $kT \sim 1$ keV

reactions occur through TUNNEL EFFECT

➡ tunneling probability $P \propto \exp(-2\pi\eta)$



Gamow peak: energy of astrophysical interest where measurements should be carried out

$kT \ll E_0 \ll E_{coul}$

10^{-18} barn < σ < 10^{-9} barn

⬇

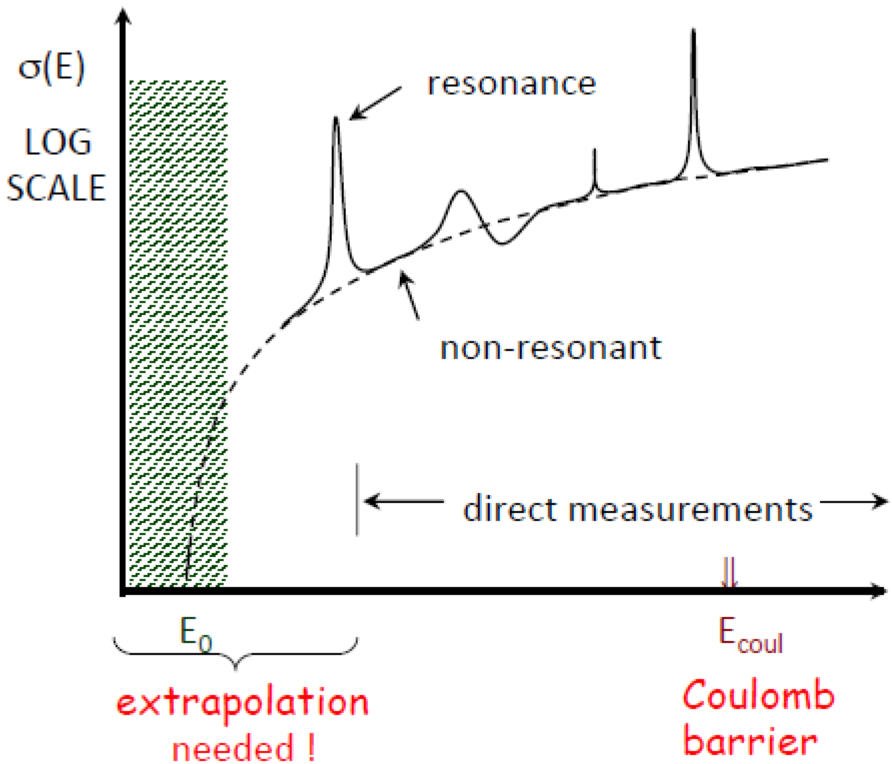
major experimental challenges

Experimental approach
(charged particles)

Measure $\sigma(E)$ as low as possible in energy and extrapolate if necessary

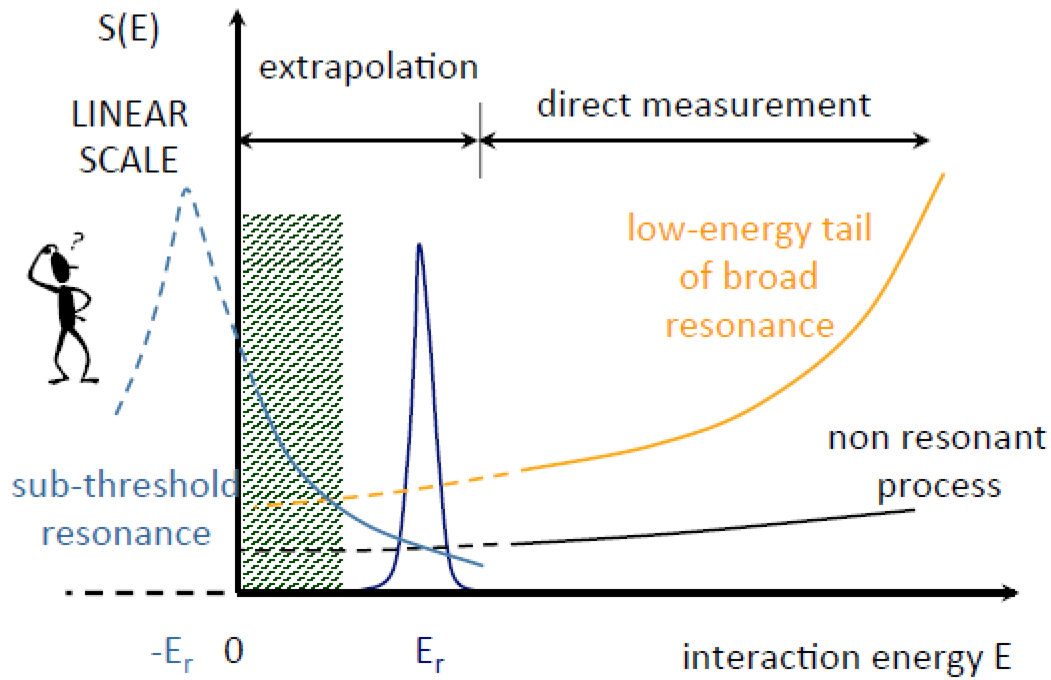
CROSS SECTION

$$\sigma(E) = \frac{1}{E} \exp(-2\pi\eta)\, S(E)$$



S-FACTOR

$$S(E) = E\sigma(E) \exp(2\pi\eta)$$



DANGER OF EXTRAPOLATION !

Neutron capture reaction rates

- No Coulomb barrier, so cross sections are larger at low energies

$$\langle \sigma v \rangle = \int \sigma(v)\phi(v) v dv = \int \sigma(E) \exp(-E/kT) E dE$$

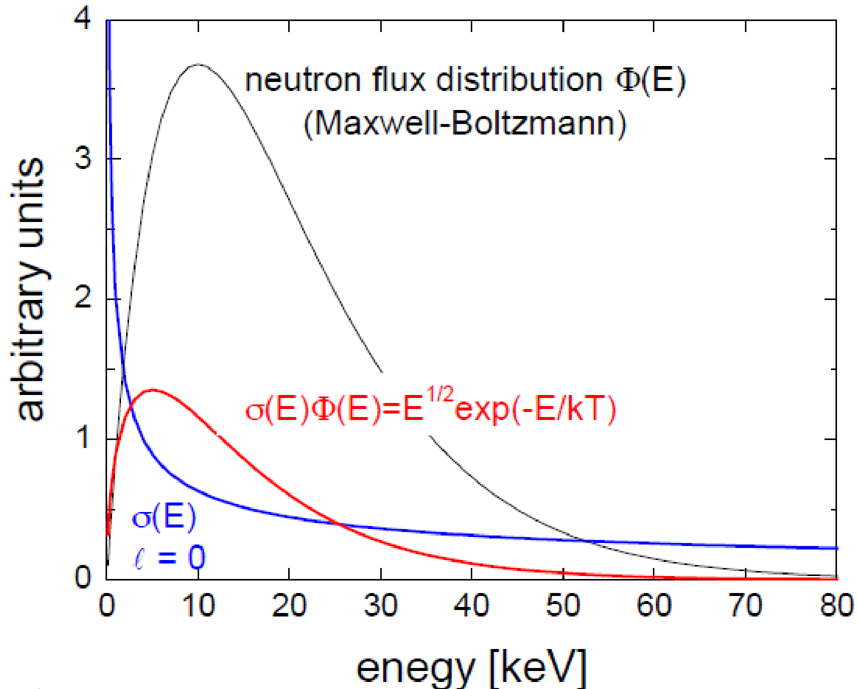
s-wave neutron capture

energy range of interest E ~ kT

$$\sigma \propto \frac{1}{v} \quad \rightarrow \quad \sigma v = \text{const} = \langle \sigma v \rangle$$

stellar reaction rate

$$\langle \sigma v \rangle = v_T \sigma_{th}$$



σ_{th} = measured cross section for thermal neutrons

$$v_T = \sqrt{\frac{2kT}{\mu}}$$ most probable velocity, corresponding to E_{cm} = kT

- Need low-energy neutron beams to bombard stable targets and measure yield

M. Aliotta

Summary

- Historical development of nuclear astrophysics
- Stellar evolution and galactic chemical evolution
- Thermonuclear reaction rates
- Next: direct measurements of charged-particle reactions

Thank you for your attention!