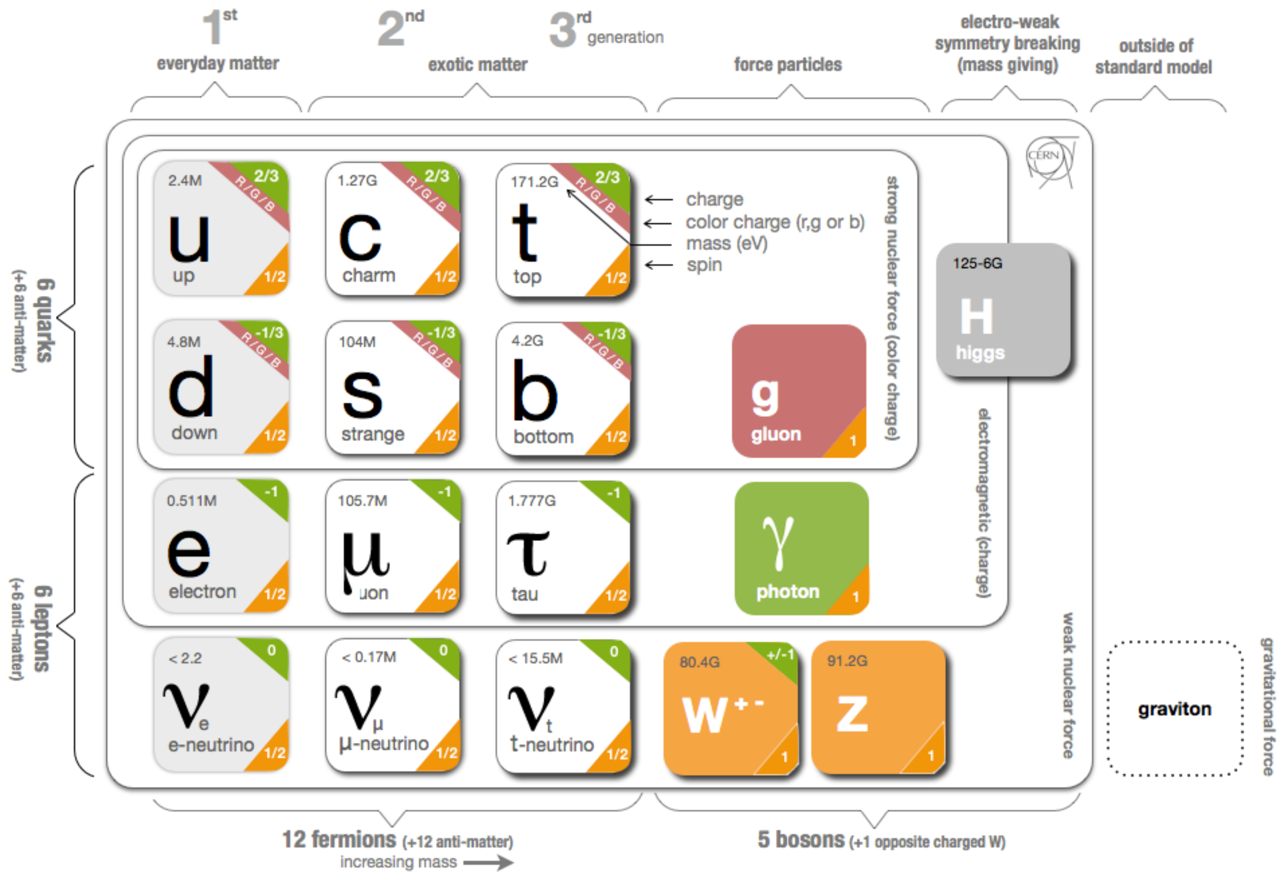
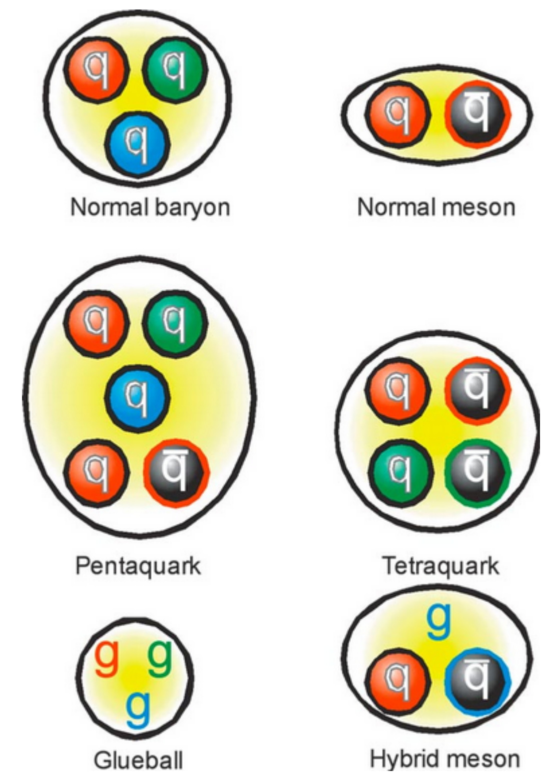
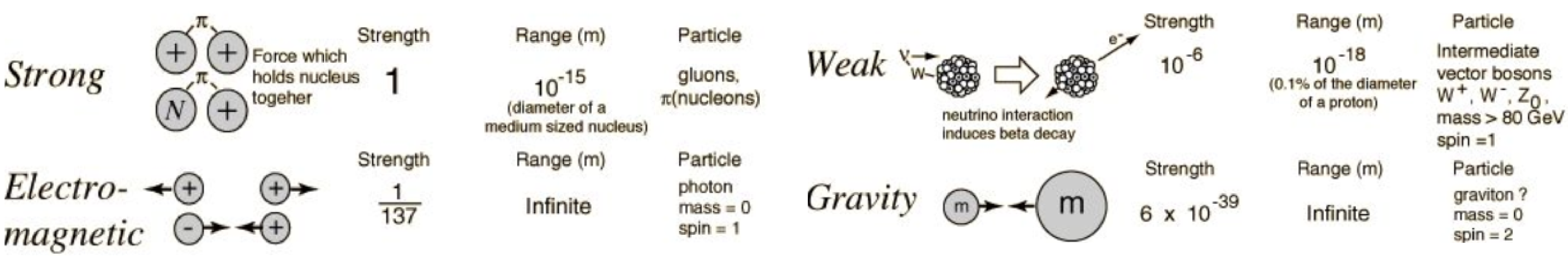
The origin of elements

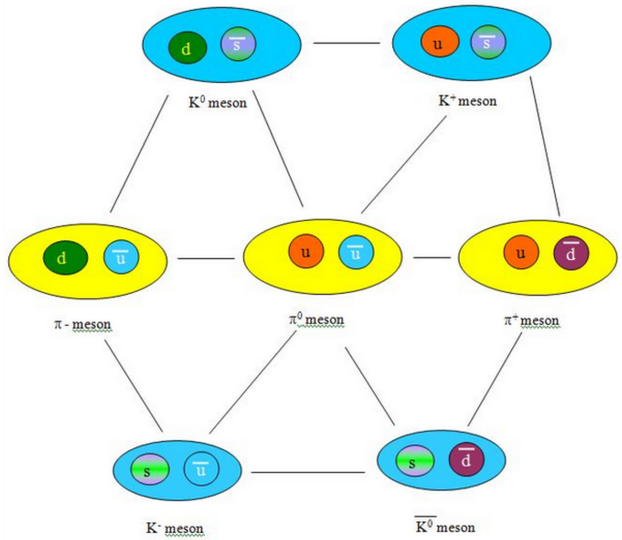
The Standard Model of Particles and Interactions

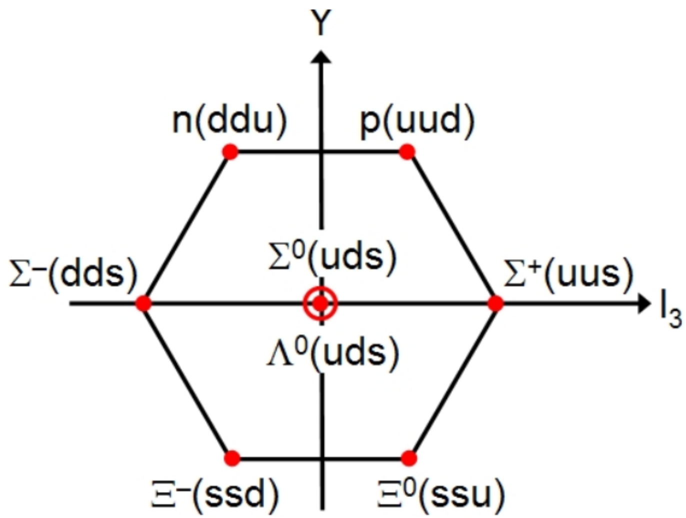


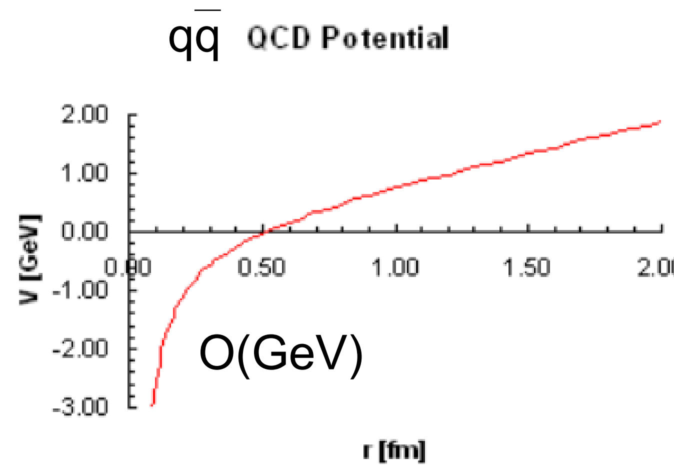


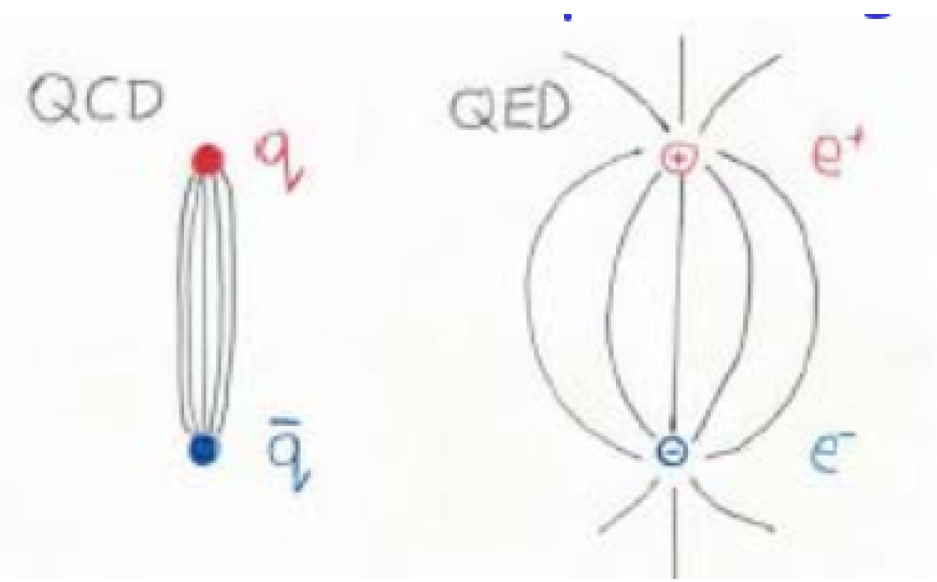


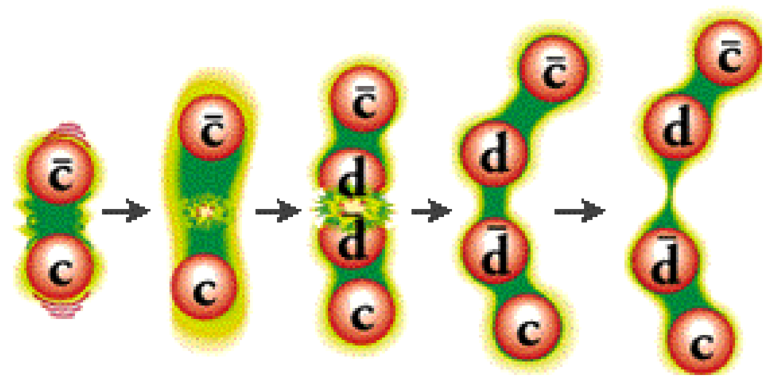
Mesons, interquark potentials



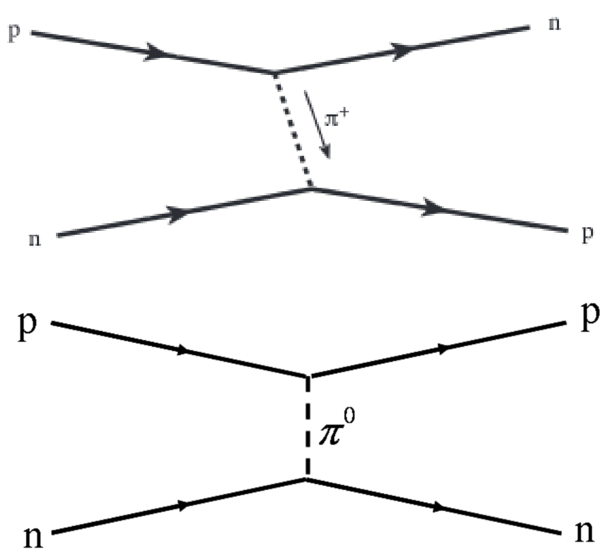


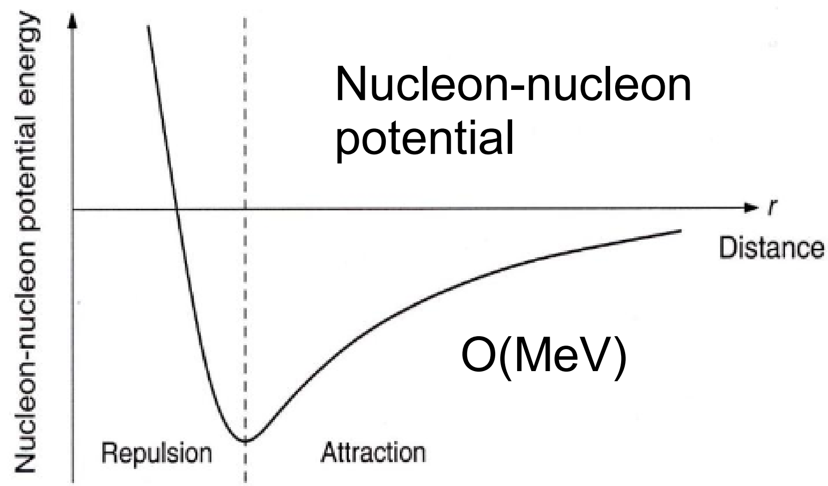




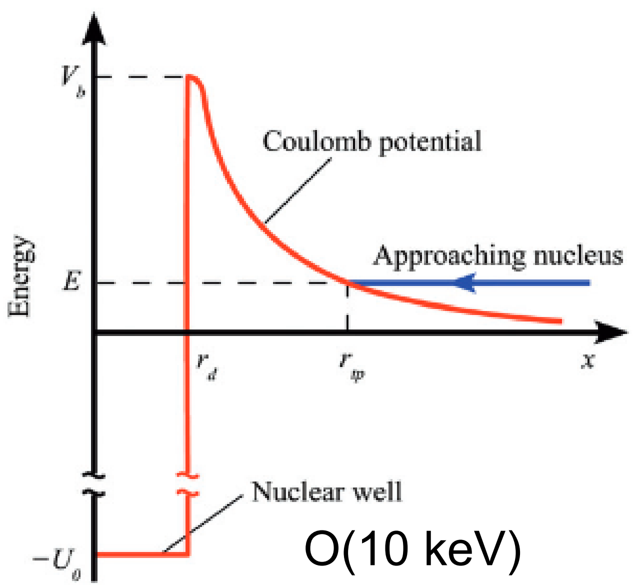


Nuclear forces, fusion

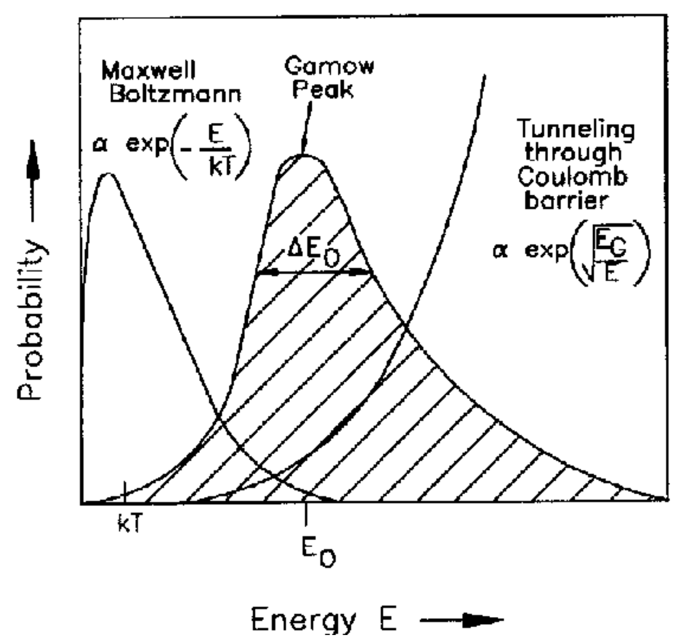




- Strong force > elmag at small distances
  - Charge independence
- Bound nucleons are stable

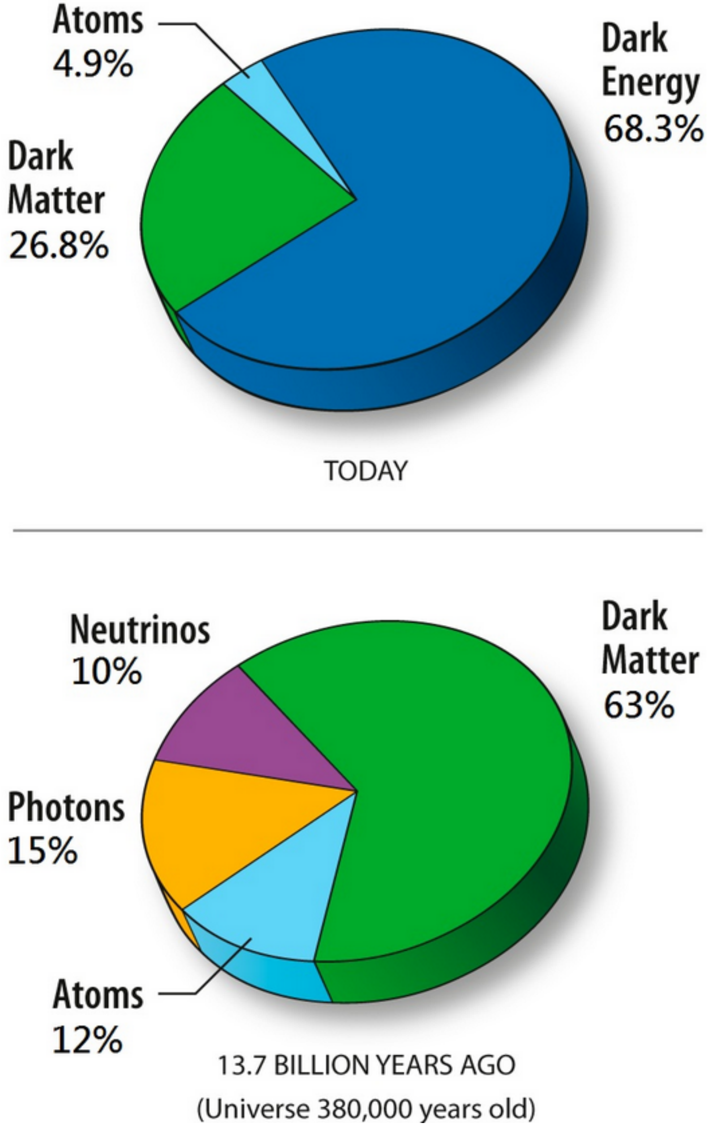


Coulomb force gains relative strength



- Gamow peak
- Most reactions occur here

The Standard Model of Particles and Interactions



Troubles:
1. Gravitation
2. Dark matter / Dark Energy
3. Neutrino masses
4. Matter/antimatter symmetry

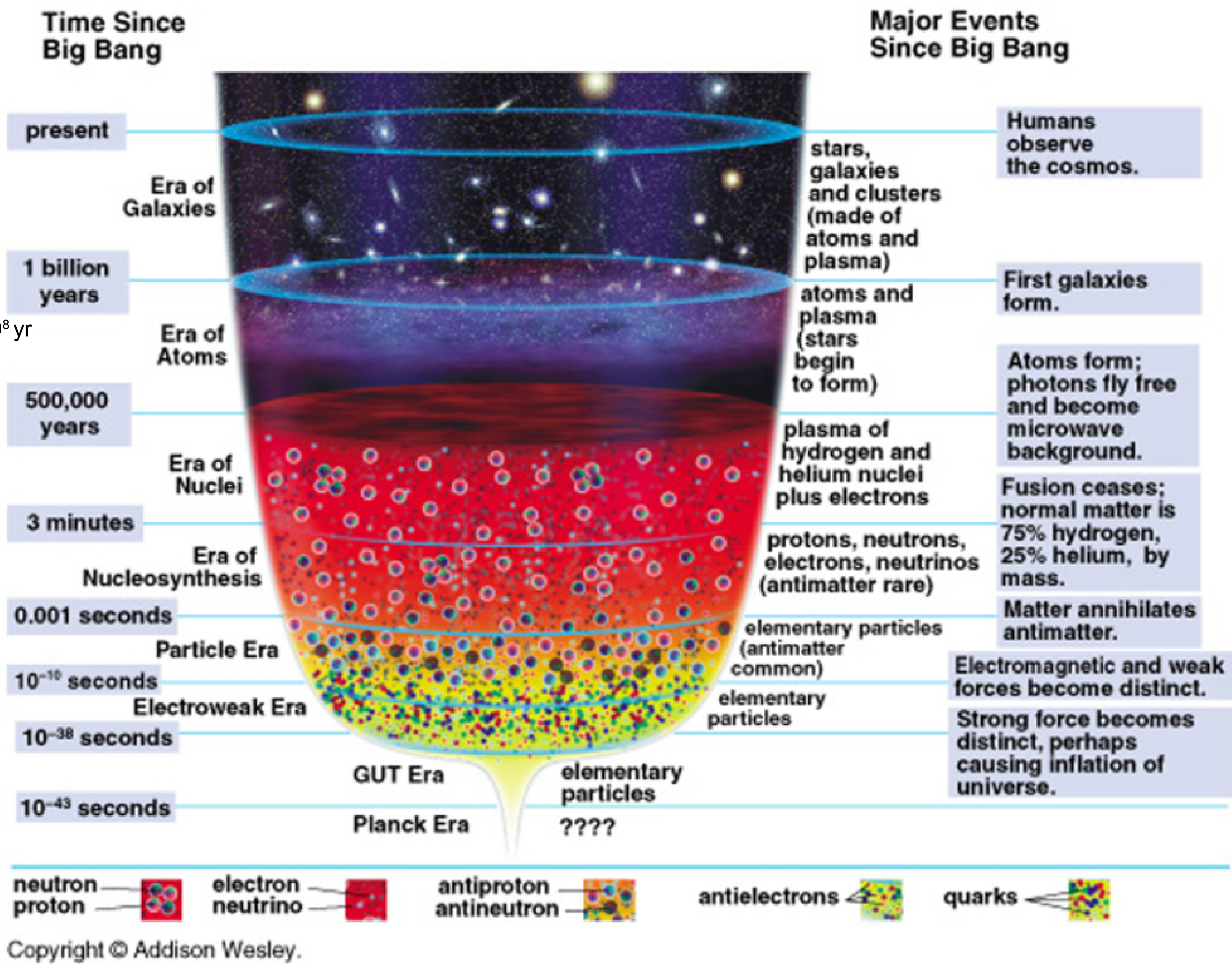
Periodic Table of the Elements

1 1IA 11A	2 IIA 2A	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8	9 VIII 8	10	11 IB 1B	12 IIB 2B	13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A
1 H Hydrogen 1.0079																	2 He Helium 4.00260
3 Li Lithium 6.941	4 Be Beryllium 9.01218											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797
11 Na Sodium 22.989768	12 Mg Magnesium 24.305											13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.732	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium [208.9824]	85 At Astatine 209.9871	86 Rn Radon 222.0176
87 Fr Francium 223.0197	88 Ra Radium 226.0254	89-103	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Uuq Ununquadium [289]	115 Uup Ununpentium unknown	116 Uuh Ununhexium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

Lanthanide Series	57 La Lanthanum 138.9055	58 Ce Cerium 140.115	59 Pr Praseodymium 140.90765	60 Nd Neodymium 144.24	61 Pm Promethium 144.9127	62 Sm Samarium 150.36	63 Eu Europium 151.9655	64 Gd Gadolinium 157.25	65 Tb Terbium 158.92534	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93032	68 Er Erbium 167.26	69 Tm Thulium 168.93421	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
Actinide Series	89 Ac Actinium 227.0278	90 Th Thorium 232.0381	91 Pa Protactinium 231.03588	92 U Uranium 238.0289	93 Np Neptunium 237.0482	94 Pu Plutonium 244.0642	95 Am Americium 243.0614	96 Cm Curium 247.0703	97 Bk Berkelium 247.0703	98 Cf Californium 251.0796	99 Es Einsteinium [254]	100 Fm Fermium 257.0951	101 Md Mendelevium 258.1	102 No Nobelium 259.1009	103 Lr Lawrencium [262]

Alkali Metal	Alkaline Earth	Transition Metal	Basic Metal	Semimetals	Nonmetals	Halogens	Noble Gas	Lanthanides	Actinides

The Big Bang



First stars ~10^8 yr

Photon epoch ends ~380k yr

QGP epoch ends 10^{-6}s

BBN according to the SM

- $t_U < 10^{-6}$ s
  - Particle antiparticle pairs annihilate and are produced by photons, $n_p = n_{\bar{p}} \sim n_\gamma$
- $t_U > 10^{-6}$ s
  - Particle pairs annihilate into photons, but the universe is too cold to produce them ($T < 2m_p$)
- Today
  - All particles and antiparticles have annihilated, there are no galaxies, no stars, no humans

Sakharov's conditions

- Sakharov's conditions
  - Baryon number violation
    - Matter and antimatter are (almost) symmetric, but our
    - part of the universe involves matter only
    - $\frac{n_B - \bar{n}_B}{n_\gamma} = 6.1 \mp 0.3 \times 10^{-10}$
    - Sphalerons convert leptons to baryons, conserving B-L
  - C and CP violation – antimatter behaves differently than matter
    - C is violated by EW
    - CPV is too small in SM (if CKM is the only source, must occur during EW phase)
  - Out of equilibrium B-violating processes
    - Phase transitions
    - Decay of non-SM heavy particles
- 4^{th} Generation of quarks?

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

As pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

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

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

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

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm^3.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t = 0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty} (10^6/t^2)dt \cong 5 \times 10^4, \tag{2}$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5 \times 10^4$ g sec./cm^3. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^4 g sec./cm^3 which can possibly be understood if we

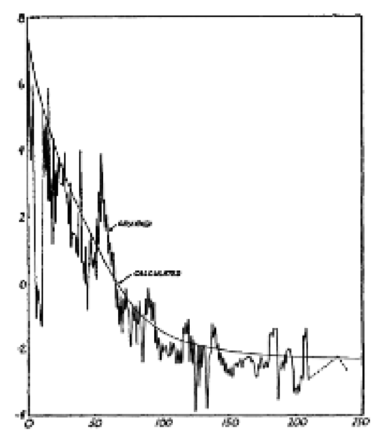


FIG. 1.
Log of relative abundance
Atomic weight

The Origin of Chemical Elements

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BBN

- $t_U < 10^{-11}$ s - CPV interactions distinguish matter over antimatter, $(n_p - n_{\bar{p}})/(n_p + n_{\bar{p}}) \sim 10^{-7}$

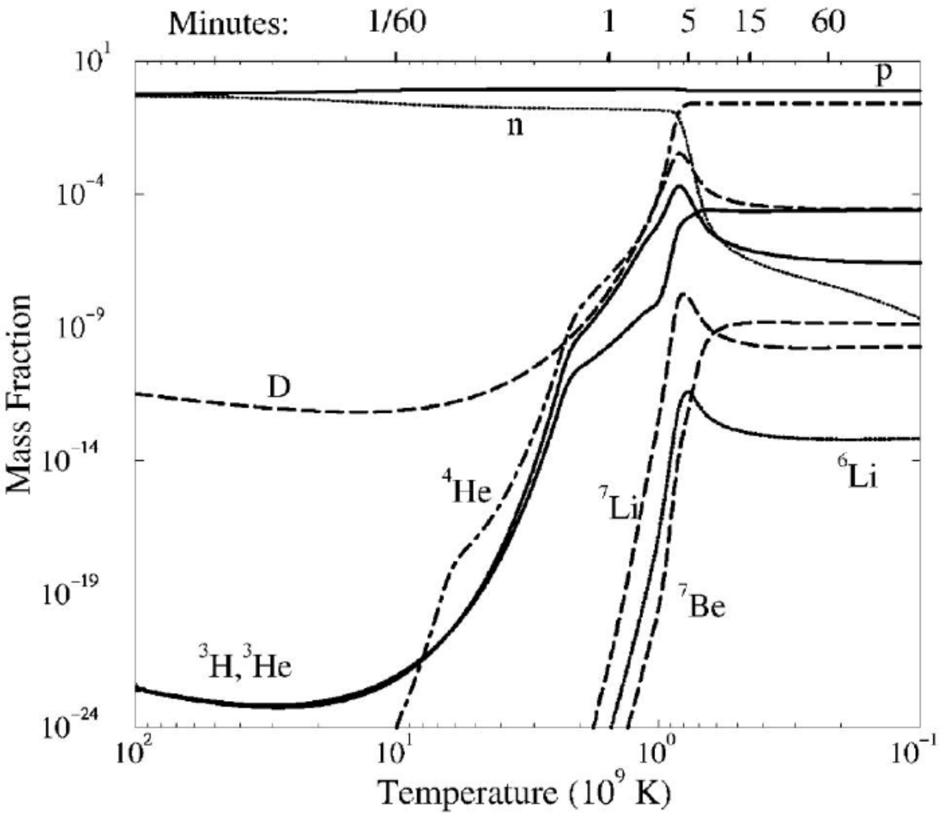
- $t_U < 10^{-6}$ s - Particle antiparticle pairs annihilate and are produced by photons, $n_p \approx n_{\bar{p}} \sim n_\gamma$

- $t_U > 10^{-6}$ s Particle pairs annihilate into γ, but $T < 2\ m_p$, $n_n \approx n_p$
  - $\nu_e + n \Leftrightarrow p + e^-$
  - $e^+ + n \Leftrightarrow p + \bar{\nu}_e$
  - $n \Leftrightarrow p + e^- + \bar{\nu}_e$
  - $e^+ + e^- \Leftrightarrow \gamma + \gamma$

- $t_U > 1$ s – Annihilation stops as all antiparticles have annihilated
  - Weak interaction cannot maintain equilibrium between all particles; neutrons decouple
  - $n_n / n_p \sim 1/6$
  - $n \rightarrow p + e^- + \bar{\nu}_e$
  - $p + n \rightarrow D + \gamma$
  - ….

- Today – Tiny surplus of particles that remained makes galaxies, stars, and humans

Big Bang nucleosynthesis



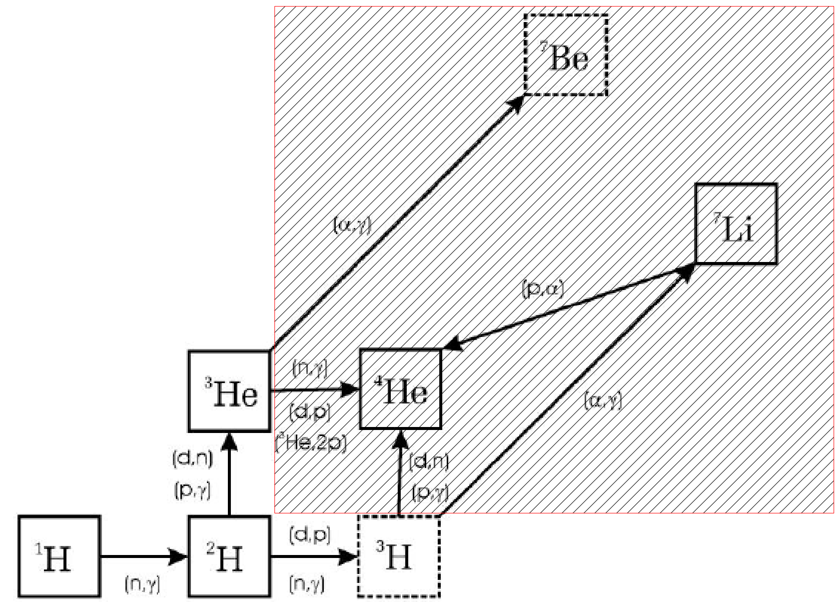
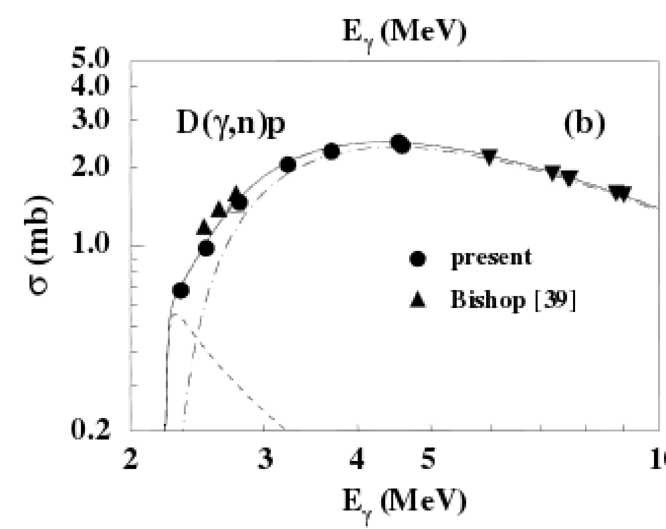


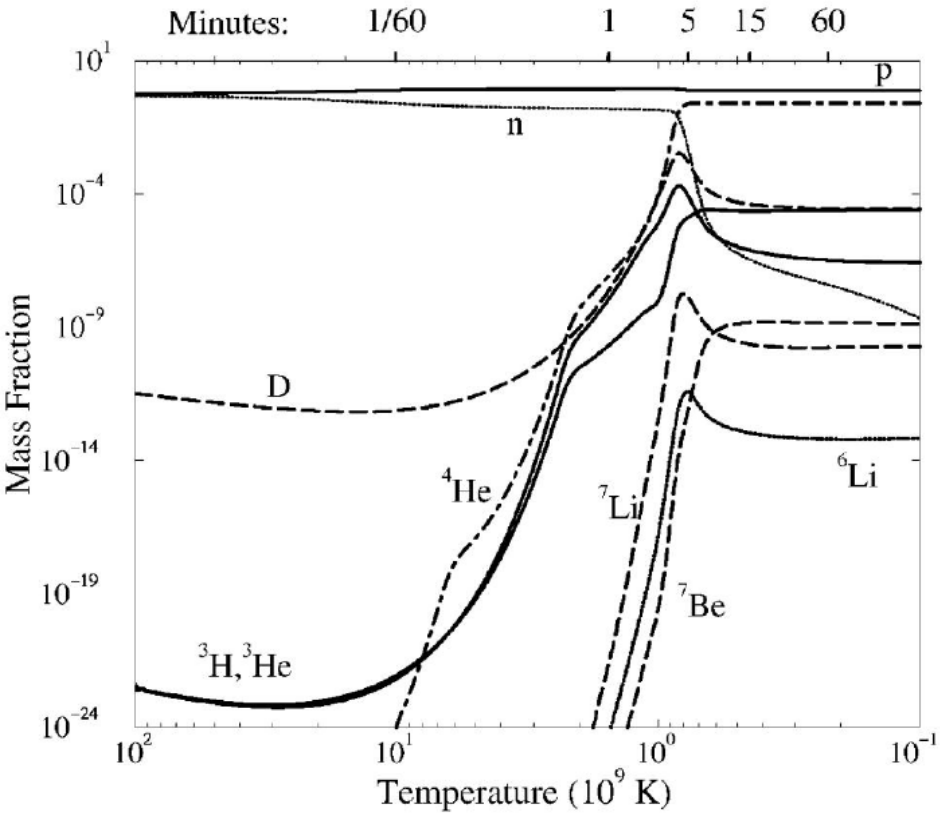
FIGURE 4. The reaction network of standard big bang nucleosynthesis. Unstable nuclear species are marked by dashed boxes. When all reactions are stopped, the unstable ^{7}Be decays to ^{7}Li and ^{3}H decays to ^{3}He.

1eV = 11605 K
10^{10}eV $\cong 1$ MeV



- p^+ and n^0 soup
- ^{2}H in equilibrium (photodisintegration, E_B ~ 2.2 MeV),
- ^{2}H bottleneck - any deuterium that was created was destroyed
- E_B for ^{3}He ~ 7.72 MeV, ^{3}H ~ 8.48 MeV

Big Bang nucleosynthesis



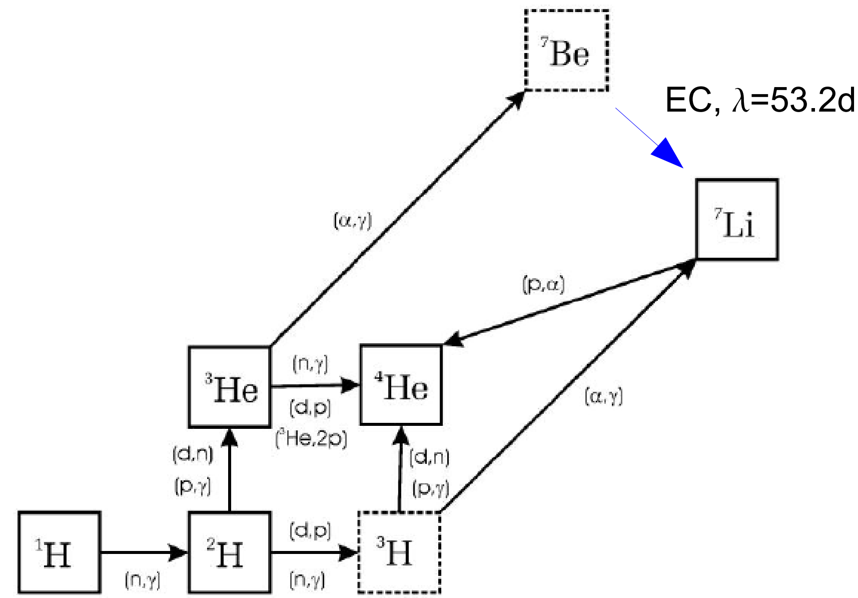
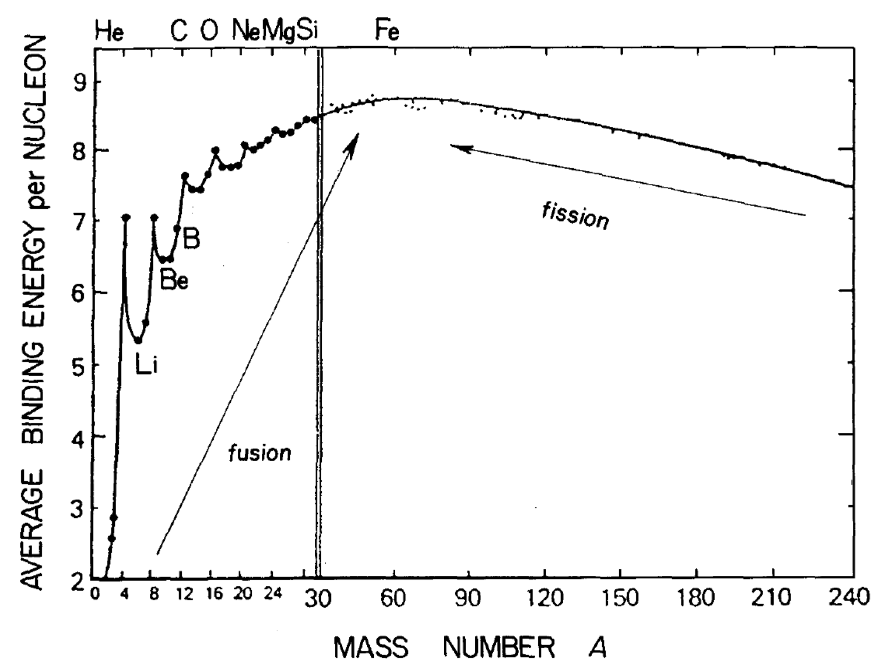
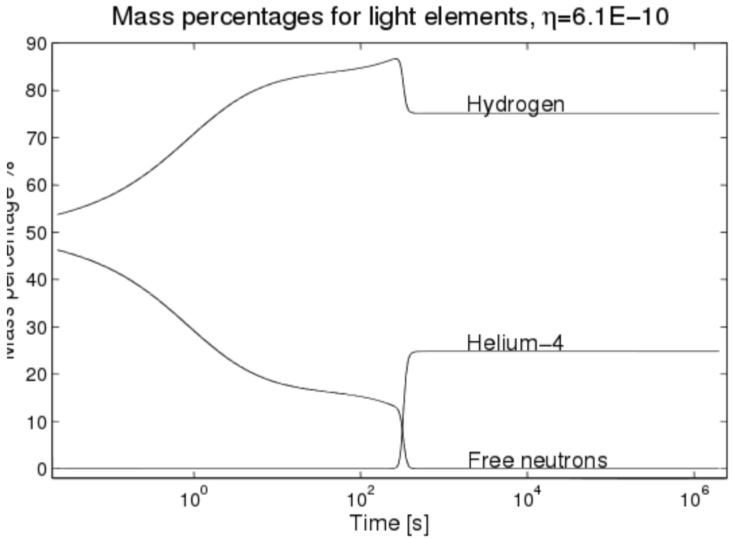


FIGURE 4. The reaction network of standard big bang nucleosynthesis. Unstable nuclear species are marked by dashed boxes. When all reactions are stopped, the unstable ^{7}Be decays to ^{7}Li and ^{3}H decays to ^{3}He.

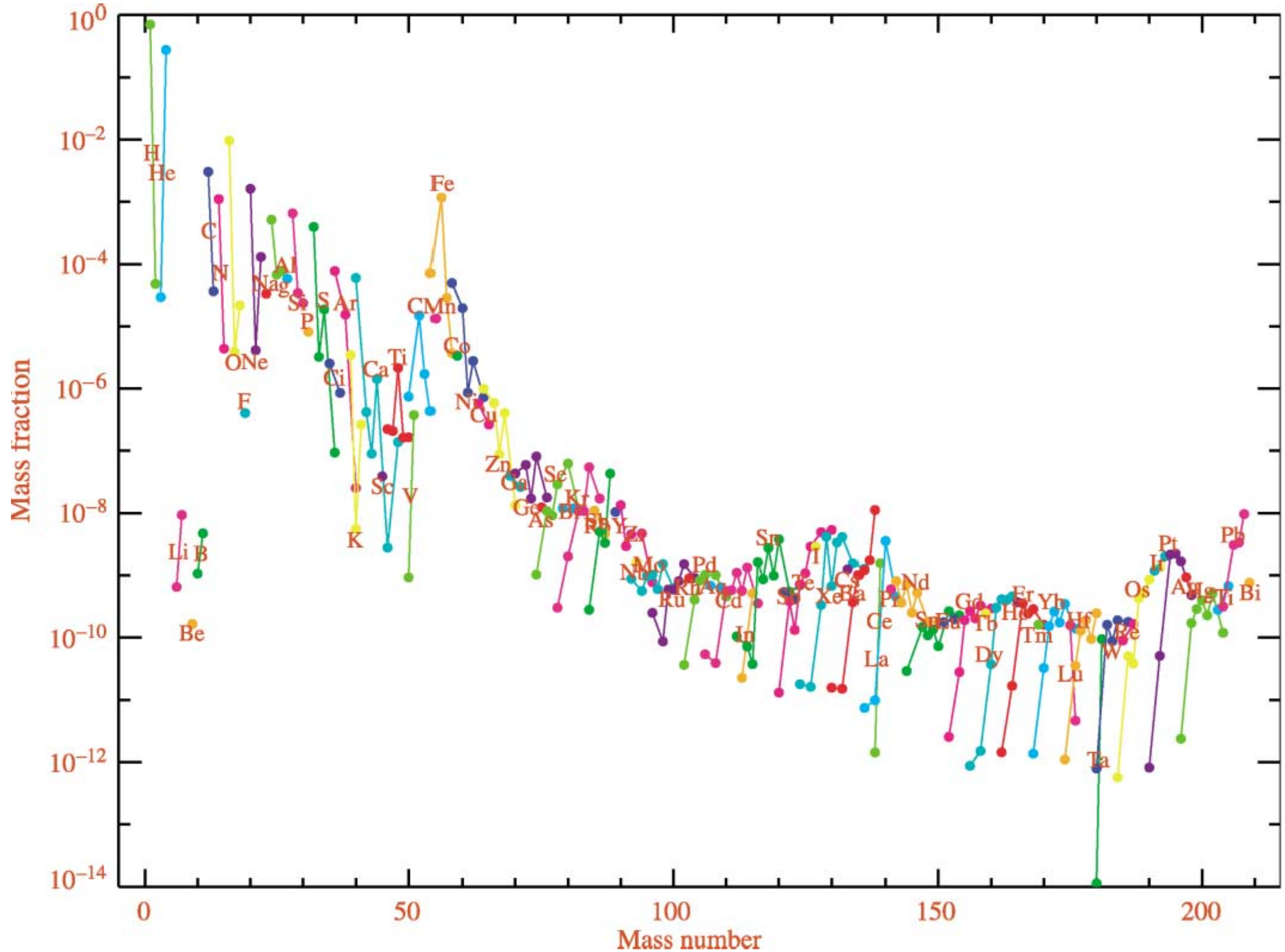
- After temperature drop to about 1 MeV (1s), ^{2}H, ^{3}H and ^{3}He abundance increases
- BBN functions during 1s to 3 minutes after BB
- ^{4}He is stable – very high binding energy (~28 MeV)
- Ladder-wise creation of would follow ...
- There are no *stable* elements with N=5,8
  - Cannot proceed to higher N



Elemental abundances in the solar system



Element	Mass percentage	Particles per hydrogen
H	75.2	1
n	0	0
d	3.90E-03	2.58E-05
t	0	0
^{3}He	2.40E-03	1.04E-05
^{4}He	24.8	0.0825
^{6}Li	5.06E-12	1.12E-14
^{7}Li	1.50E-08	2.85E-11
^{8}Li	7.40E-13	1.23E-15
^{7}Be	2.21E-07	4.20E-10



Stellar nucleosynthesis

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

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)

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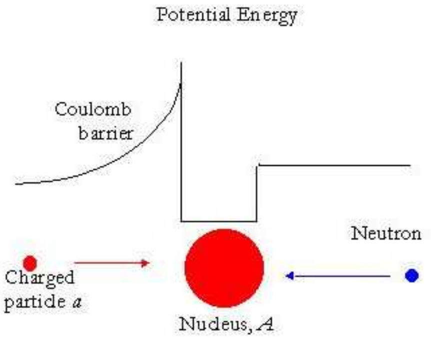
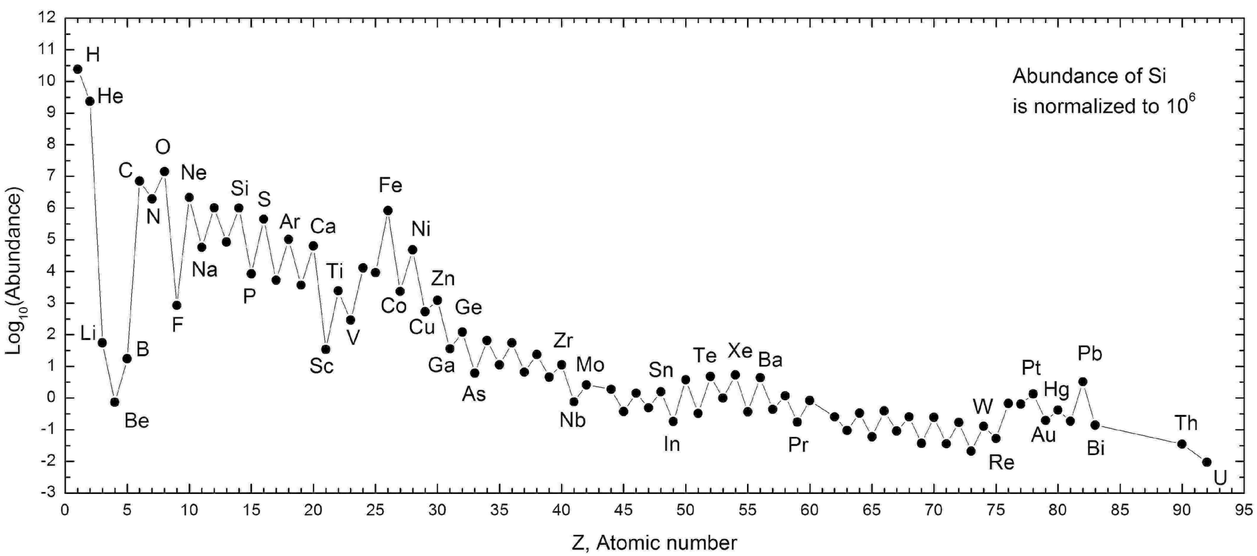
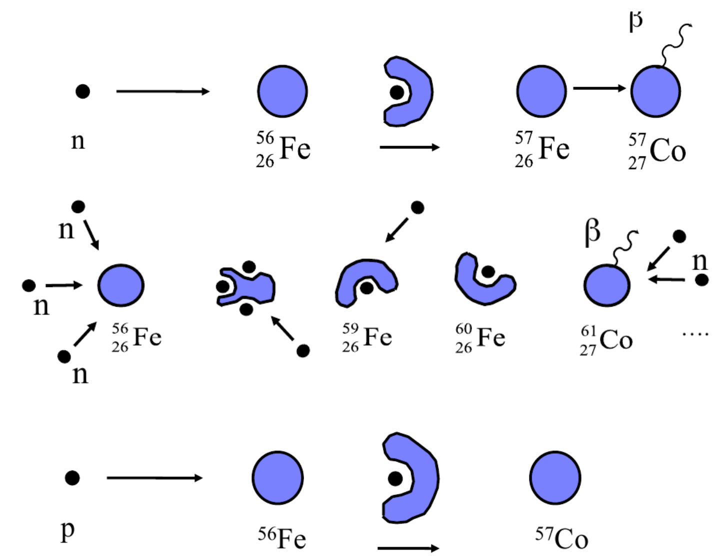
The Potential Energy of a Positively Charged Particle as it Approaches a Nucleus.



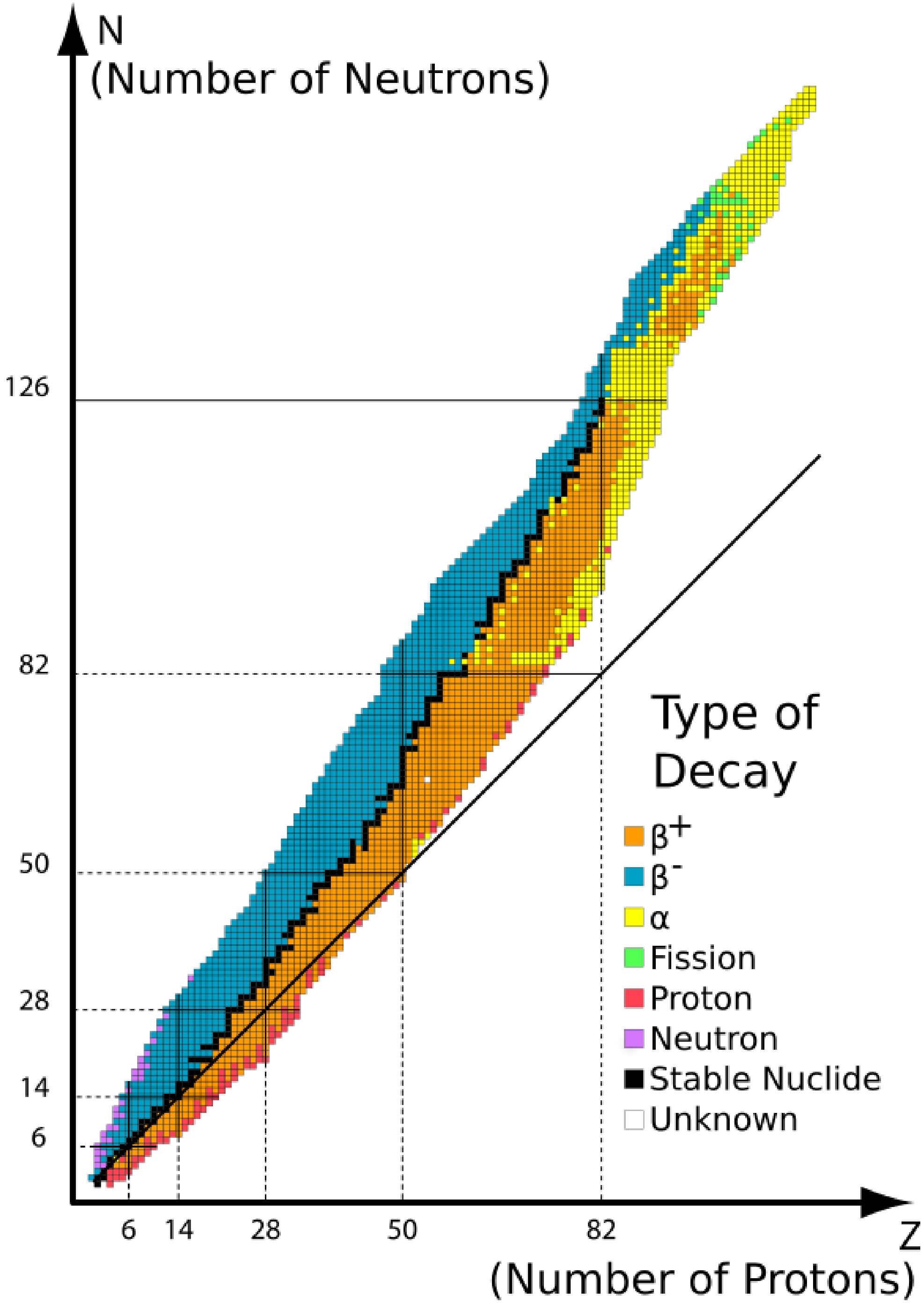
s, r, p processes

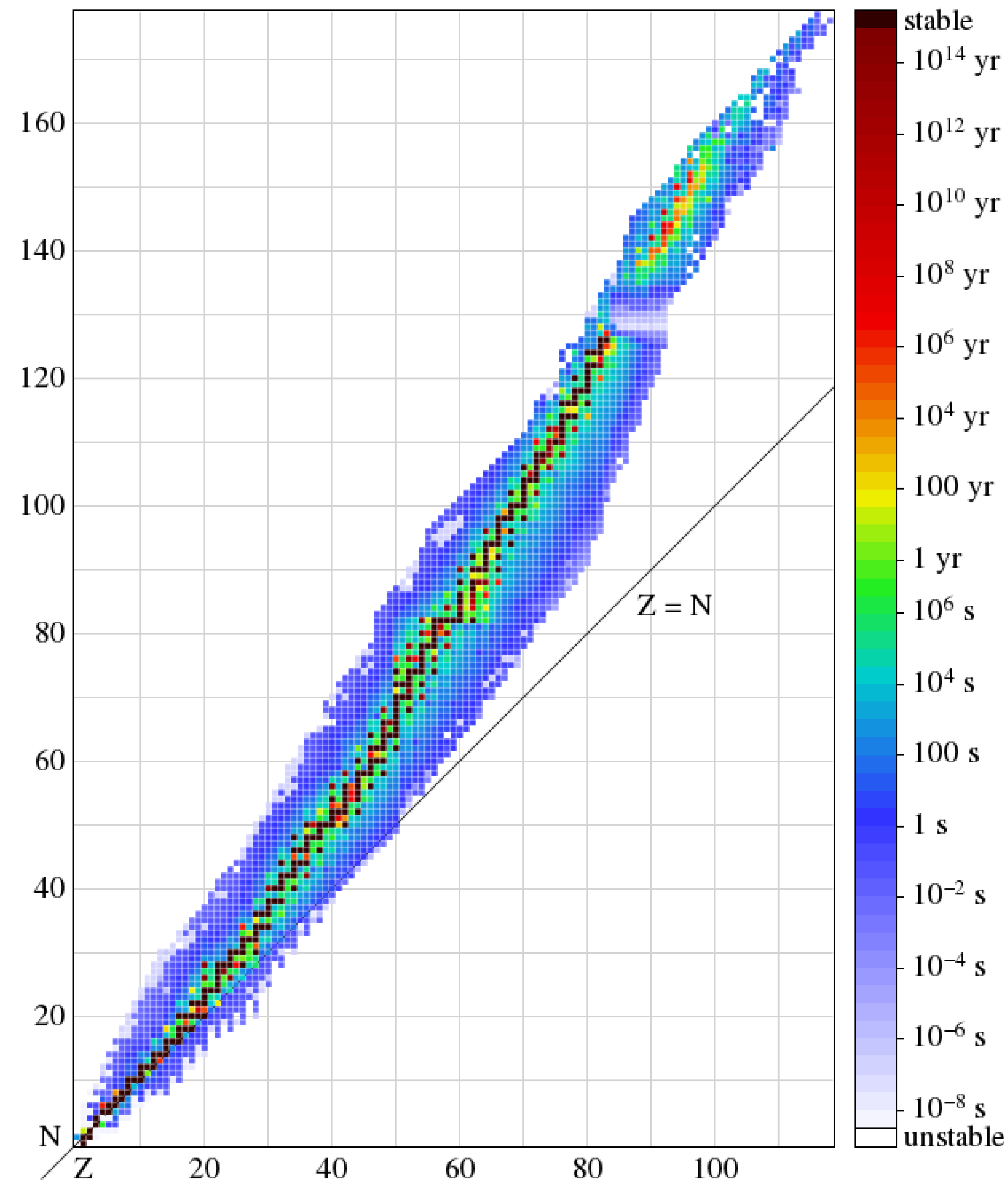




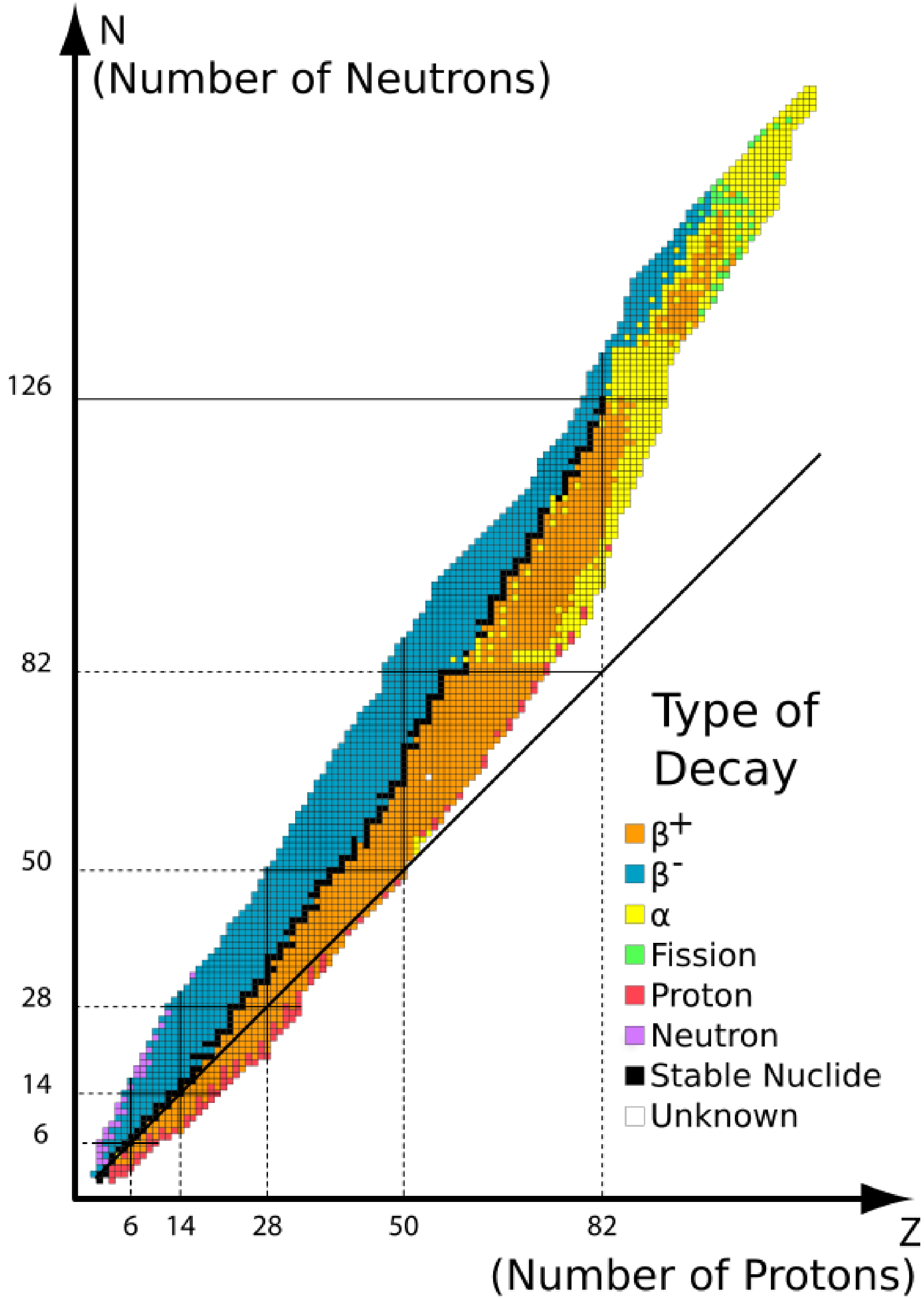
process	conditions	timescale	site
s-process (n-capture, ...)	T~ 0.1 GK τ_n~ 1-1000 yr, n_n~$10^{7\text{-}8}$/cm^3	10^2 yr and $10^{5\text{-}6}$ yrs	Massive stars (weak) Low mass AGB stars (main)
r-process (n-capture, ...)	T~1-2 GK τ_n ~ μs, n_n~10^{24} /cm^3	~ 1s	Core collapse Supernovae Neutron Star Mergers?
p-process ((γ,n), ...)	T~2-3 GK	~ 1s	Core collapse Supernovae

Graph of isotope stability

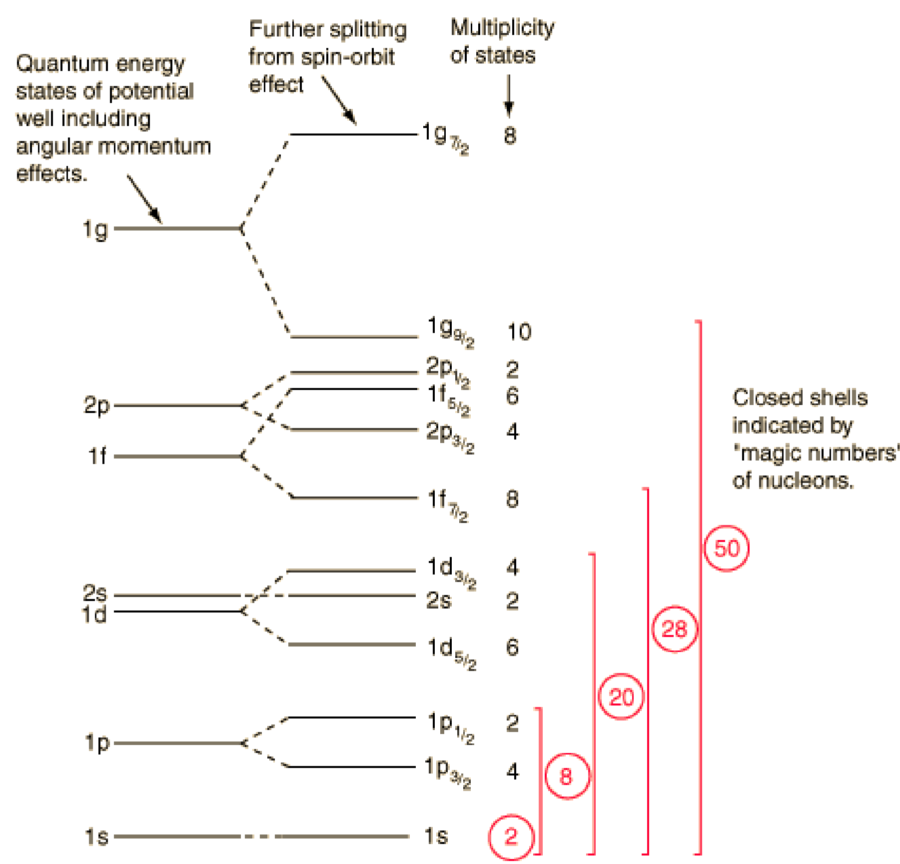




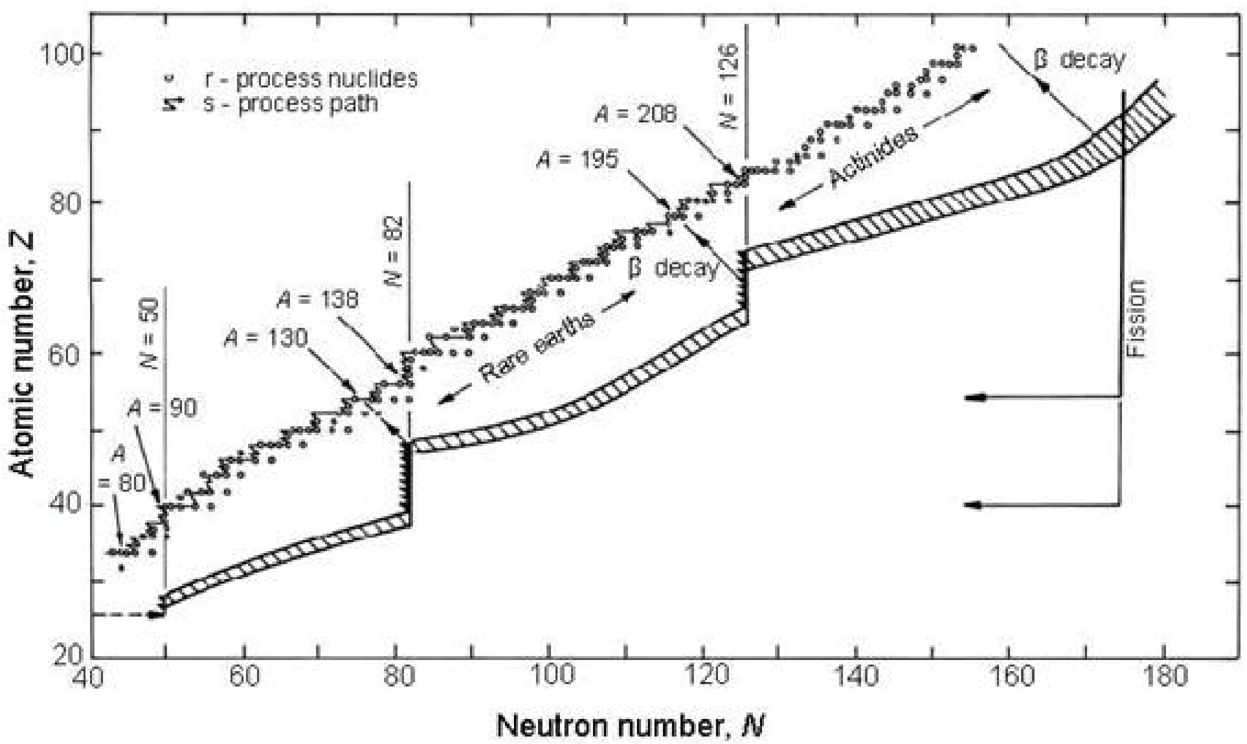
Graph of isotope stability



- Z,N = 2, 8, 20, 28, 50, 82,126...
- Higher binding energy per nucleon
- Doubly magic – n & p
  - ^{4}He, ^{16}O, ^{40}Ca … ^{208}Pb
- Closed shell model, similar to inert gases

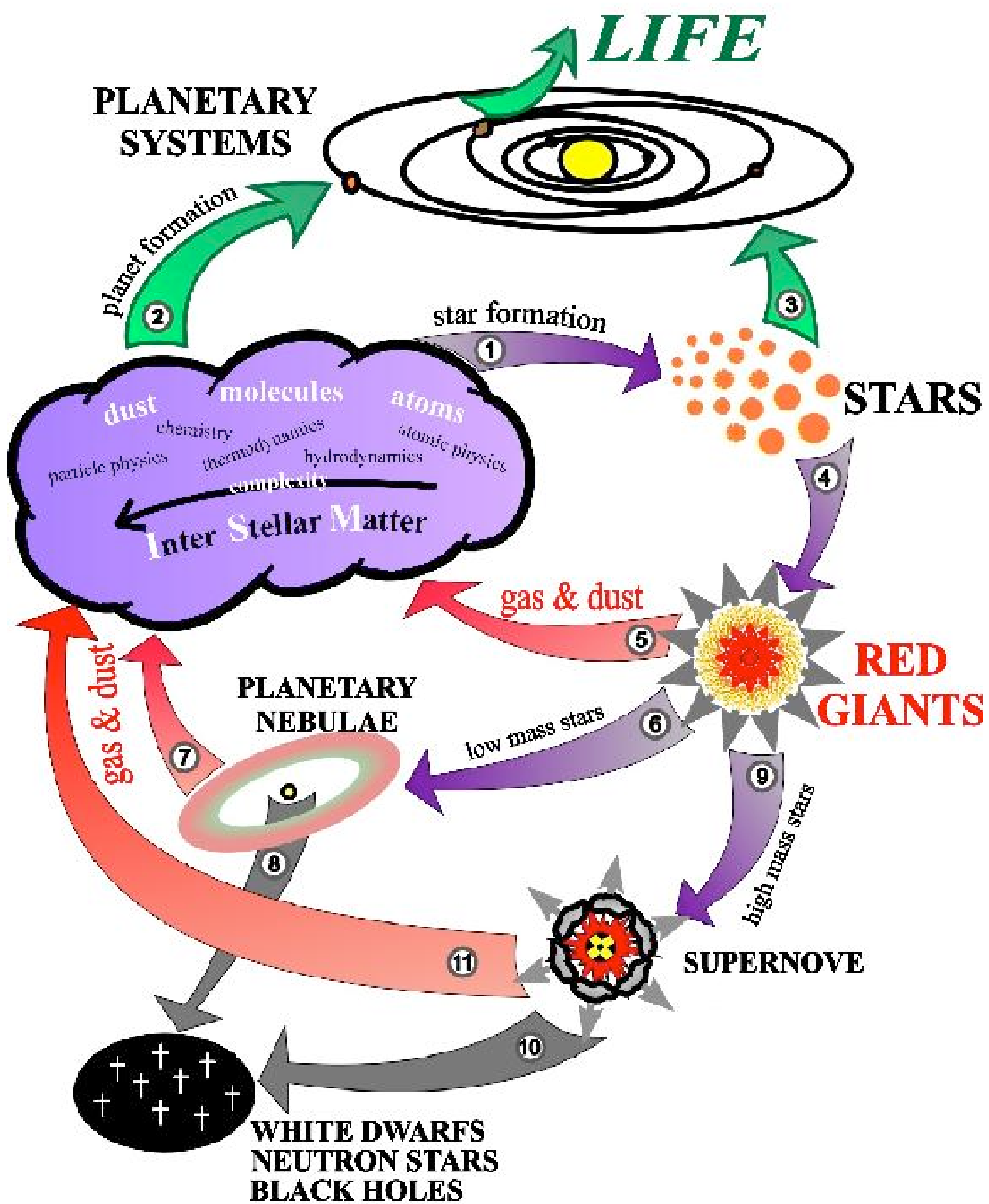


s, r processes



process	conditions	timescale	site
s-process (n-capture, ...)	T~ 0.1 GK τ_n~ 1-1000 yr, n_n~10^{7-8}/cm^3	10^2 yr and 10^{5-6} yrs	Massive stars (weak) Low mass AGB stars (main)
r-process (n-capture, ...)	T~1-2 GK τ_n ~ μs, n_n~10^{24} /cm^3	~ 1s	Core collapse Supernovae

The great matter cycle



Initial mass (M_{sun})	Main sequence lifetime (Myr)	Total stellar lifetime (Myr)
25	6.7	7.5
15	11	13
5	78	102
2	8.7×10^2	1.2×10^3
1	9.2×10^3	1.2×10^4
0.8	2.0×10^4	3.2×10^5

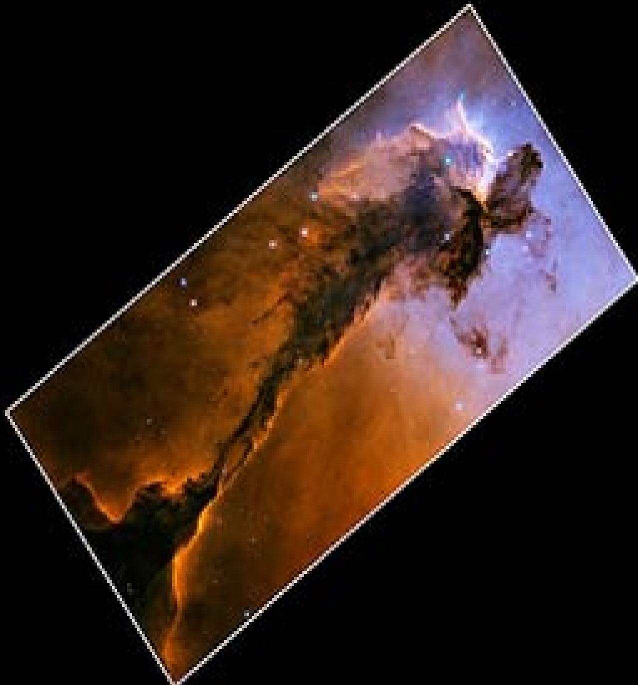
Age of the galaxy ≈1.2×10^{10} years;
Universe ≈1.37×10^{10} years

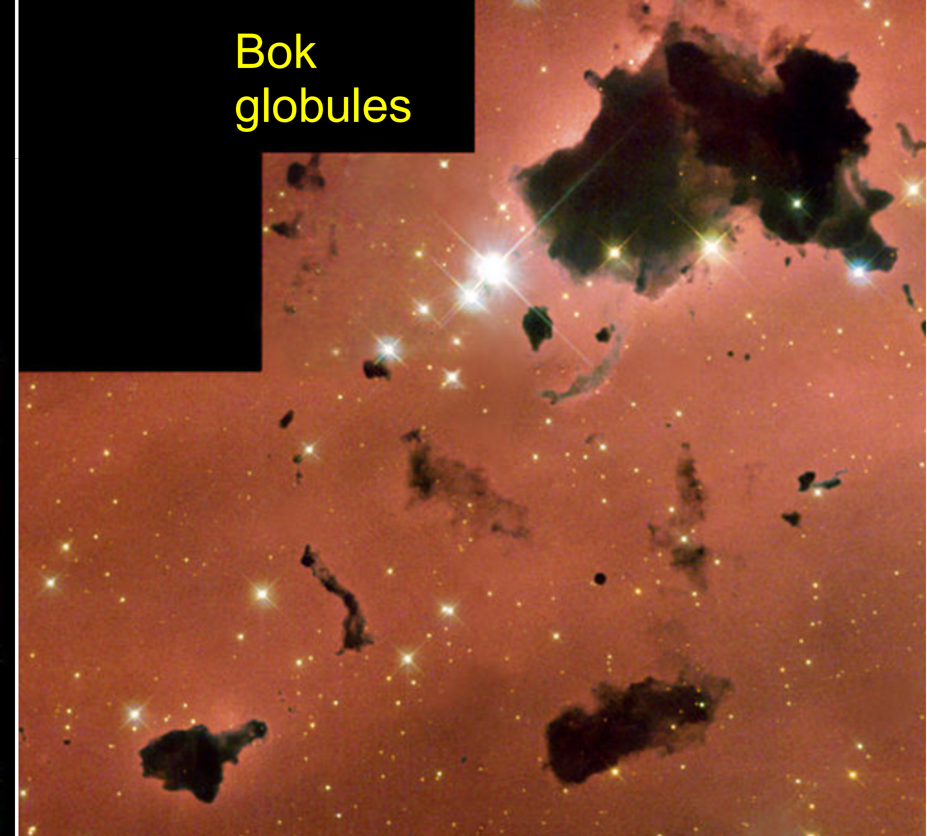
Ultra low mass stars
– Initial masses from 0.08 to 0.8 M_{Sun}

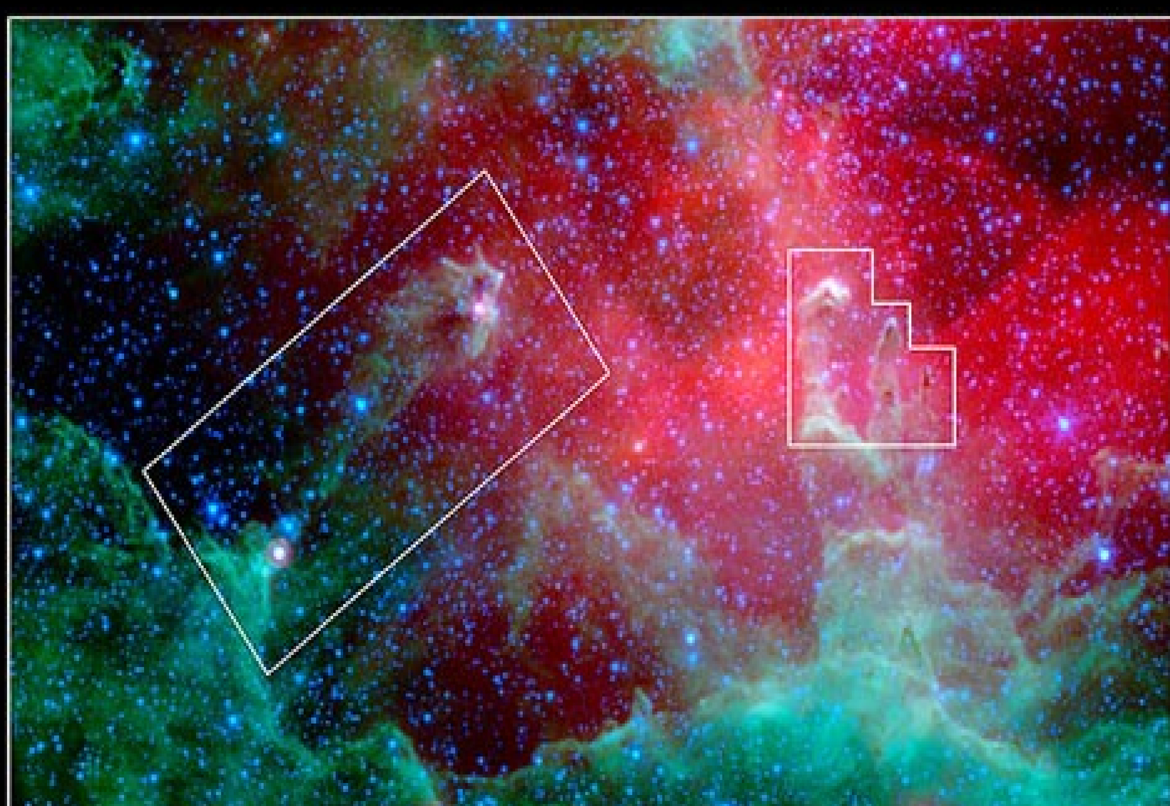
Low-mass stars:
– Initial masses from 0.8 to ~ 2.25 M_{Sun}

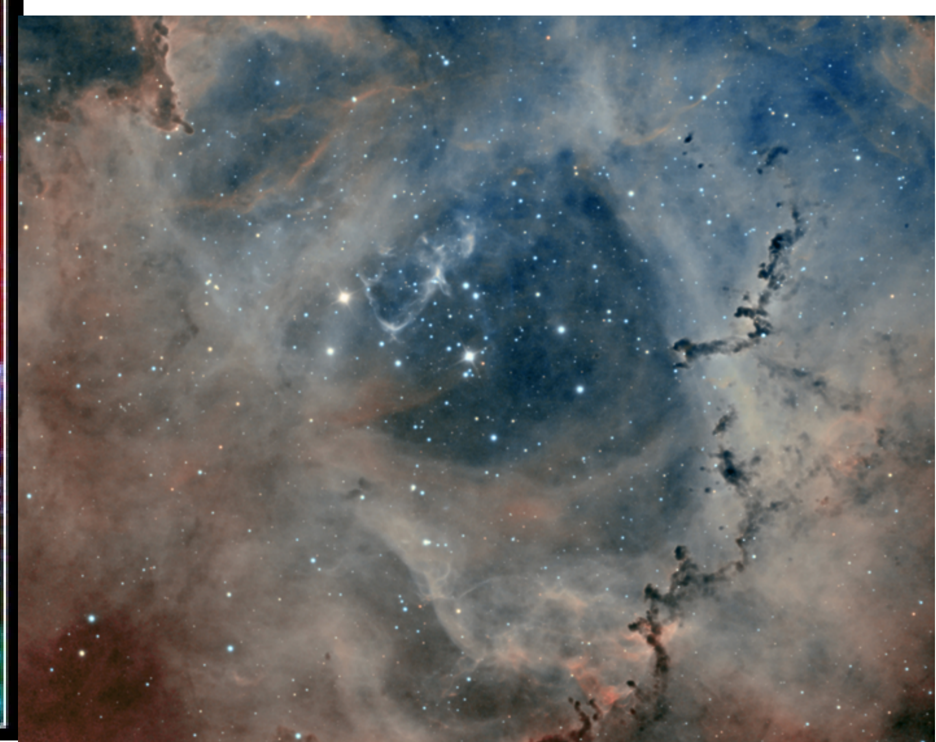
Intermediate-mass stars:
– Initial masses from ~2.25 to 8M_{Sun}

Large stars
– Initial masses above 8M_{Sun}

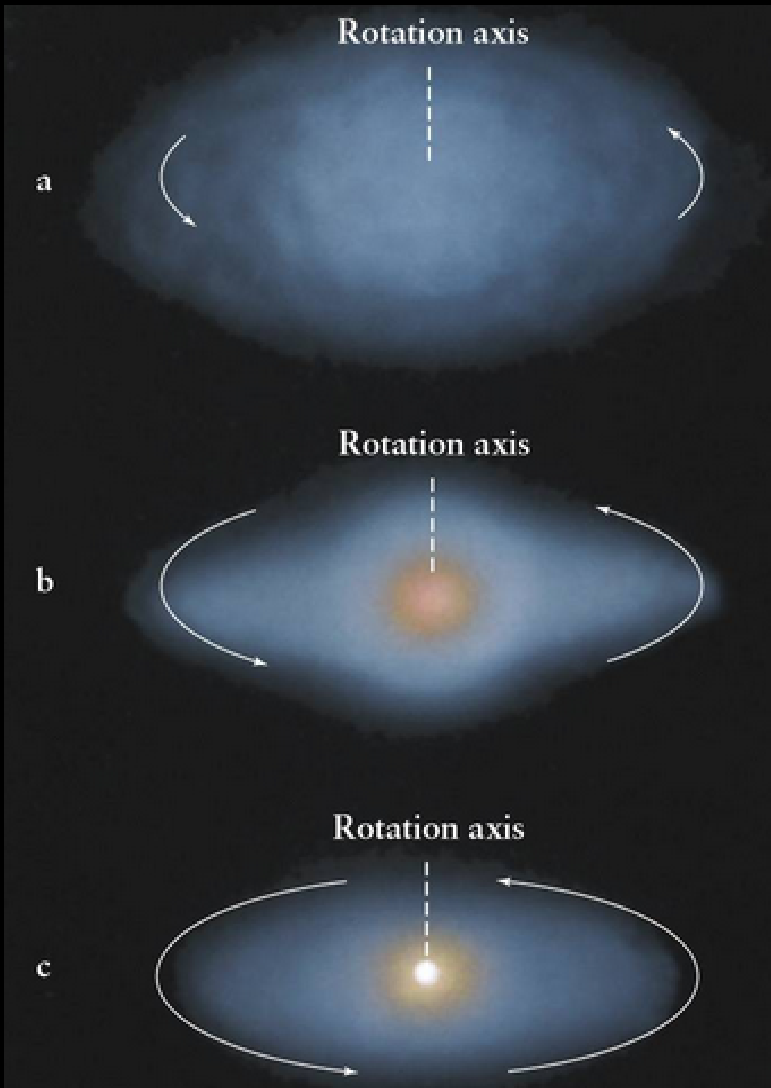


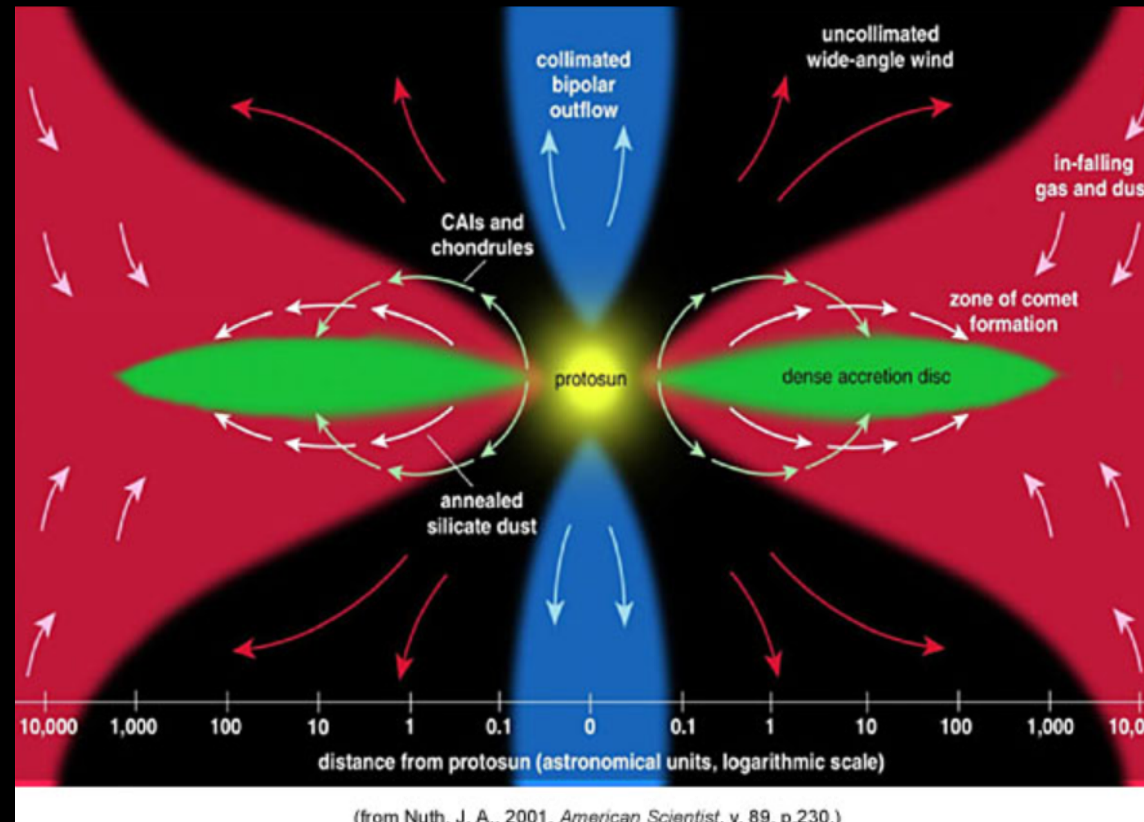

Bok
globules





Protostar nebulae





- Proto-star is heated by a gravitational compression
- Stars below 0.08 M_{Sun} not form
  - Core temp does not reach required for fusion.
  - (brown dwarfs may burn deuterium)
  - ($M_{Jupiter}$ ~ 1/1000 M_{Sun})
- How can we observe proto-stars obscured by dust?
  - Infrared observations

Visible

Infrared

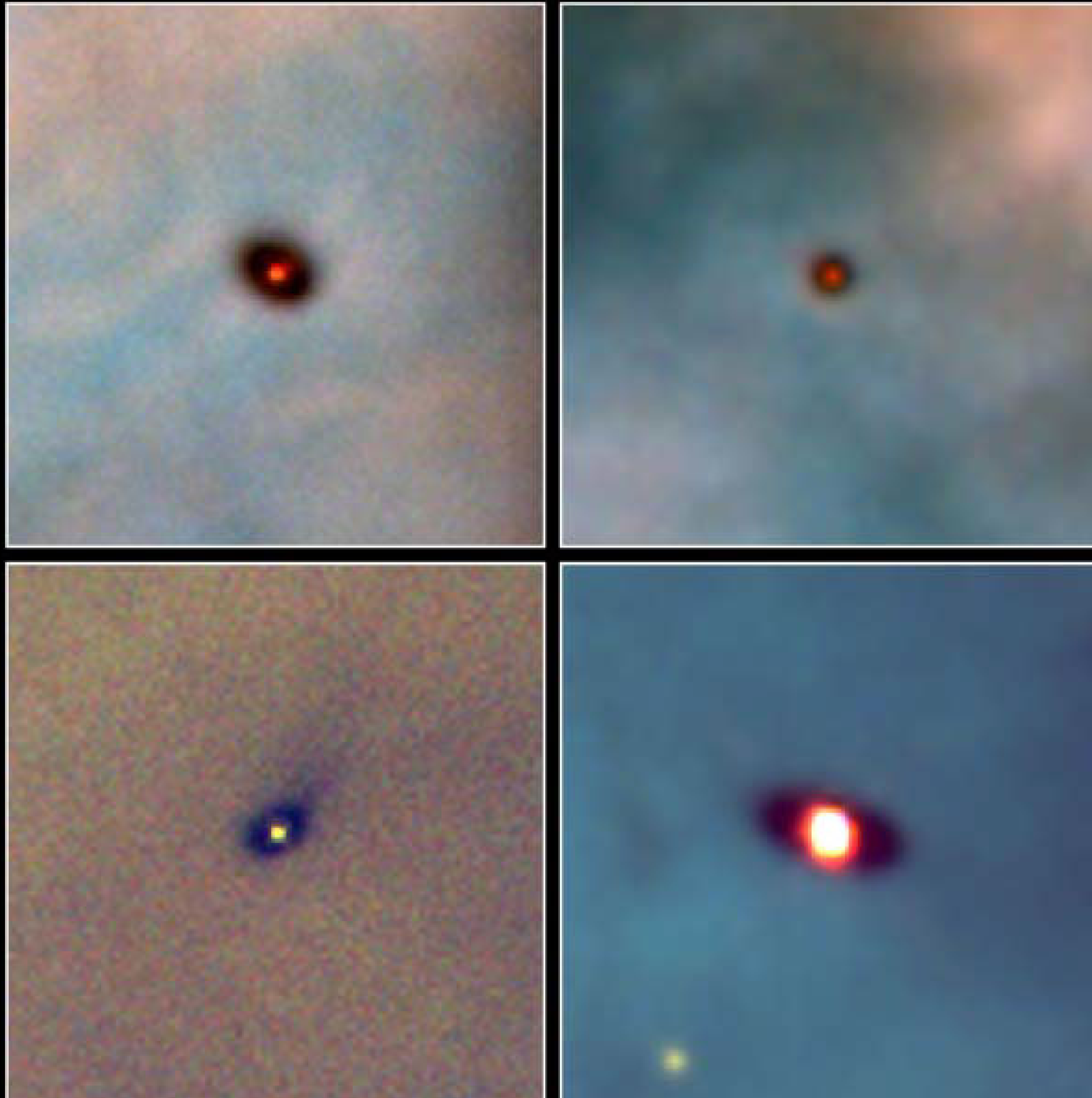
“Starless” Core L1014

Spitzer Space Telescope • IRAC • MIPS

Visible: DSS

NASA / JPL-Caltech / N. Evans (Univ. of Texas at Austin)

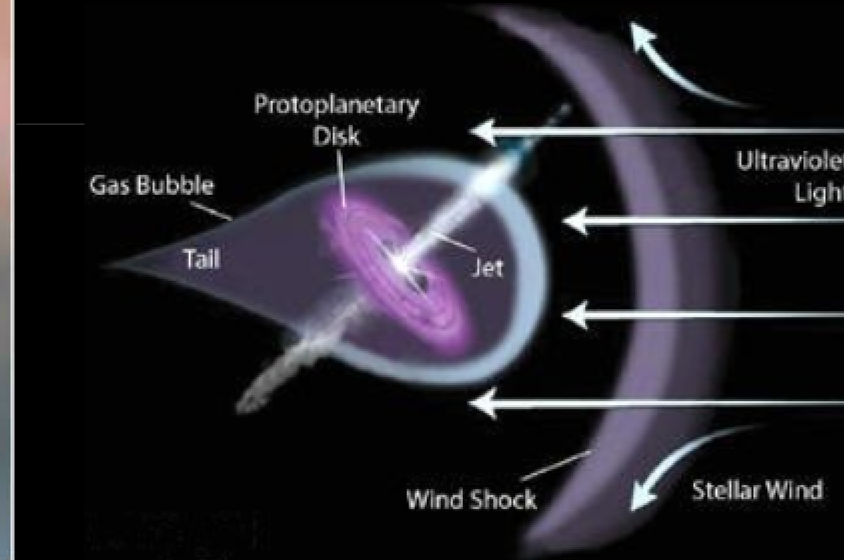
ssc2004-20a



Protoplanetary Disks
Orion Nebula

HST • WFPC2

PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

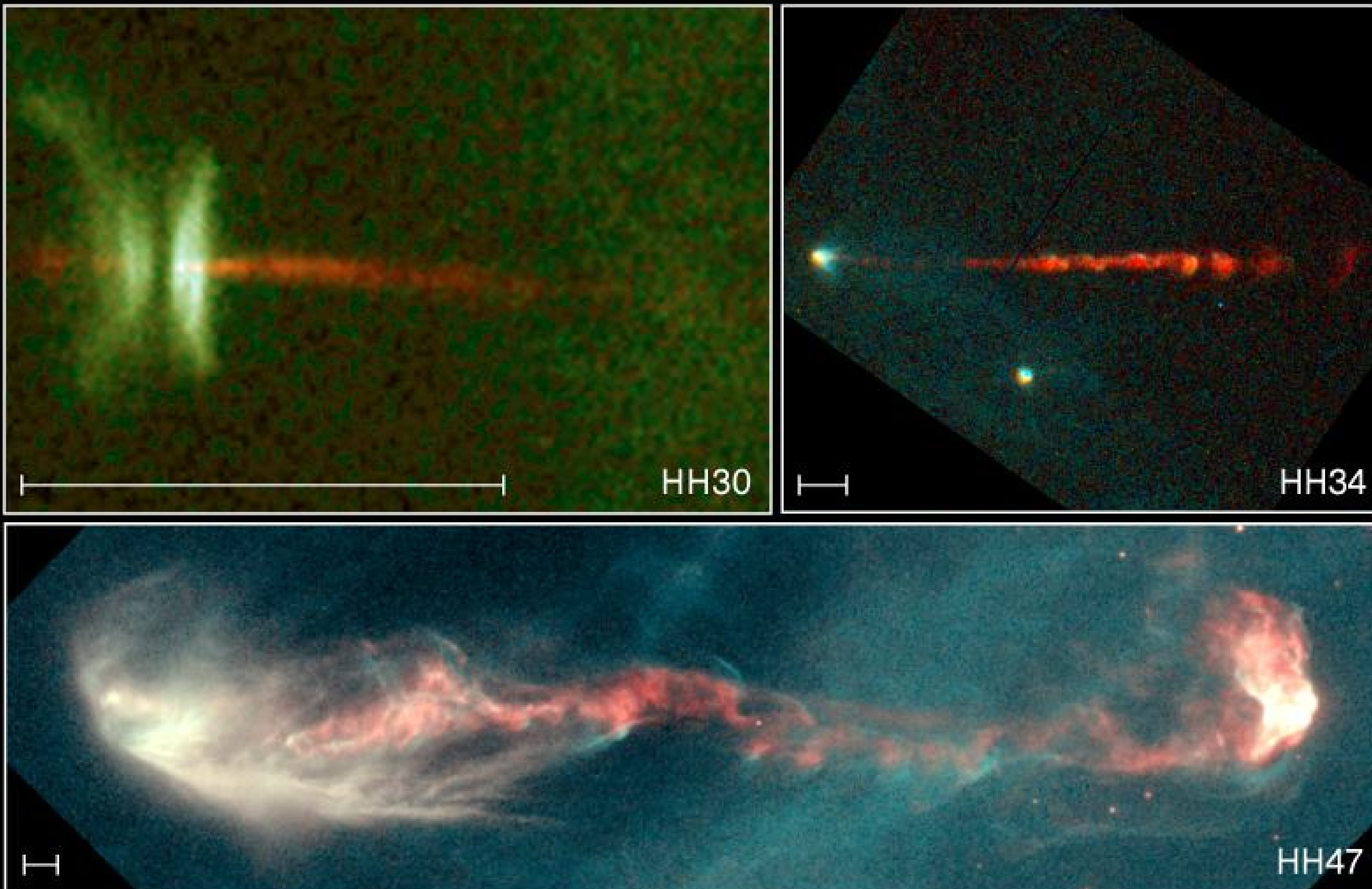


Edge-On Protoplanetary Disk
Orion Nebula

HST • WFPC2

PRC95-45c • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

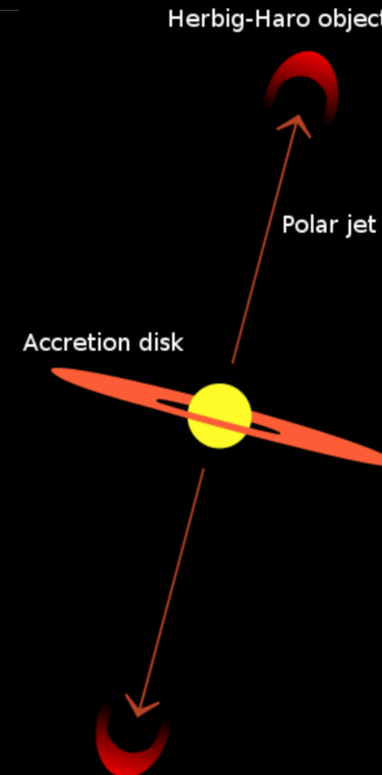
Herbig-Haro objects

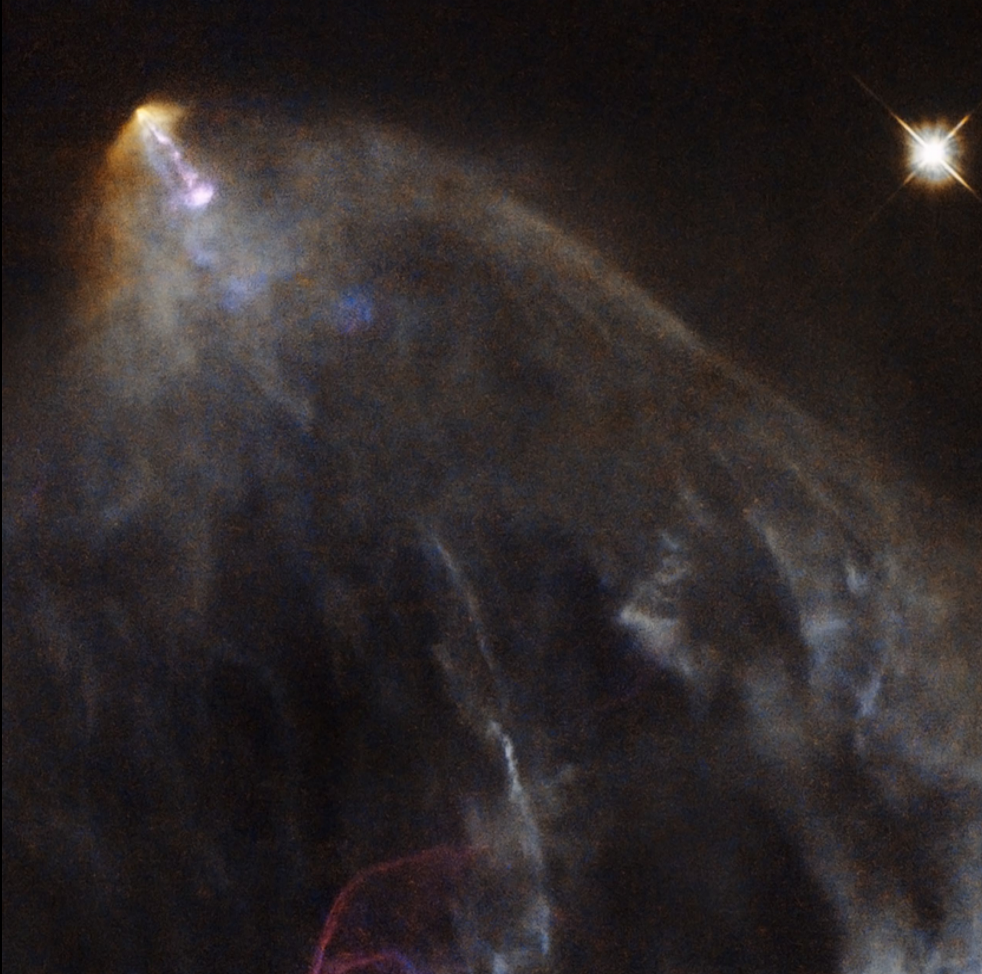


Jets from Young Stars HST • WFPC2

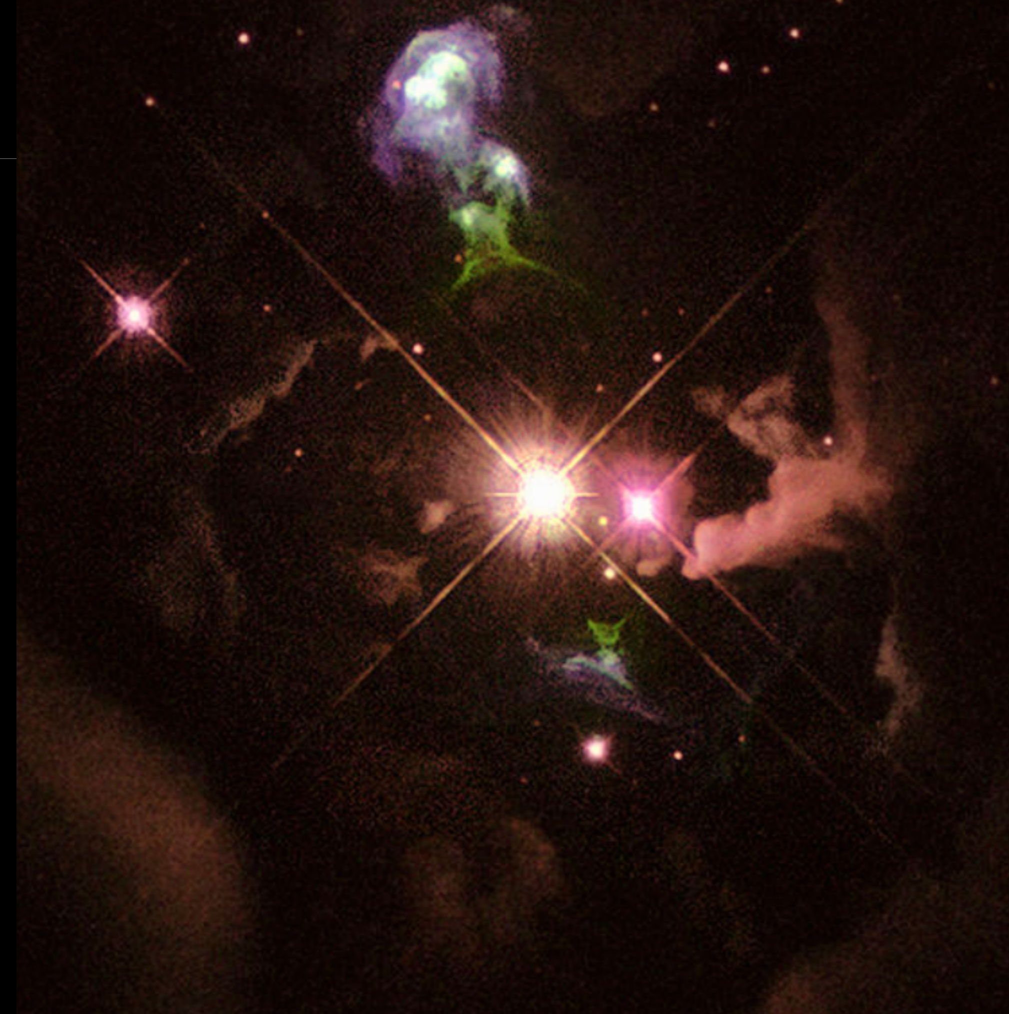
PRC95-24a • ST ScI OPO • June 6, 1995

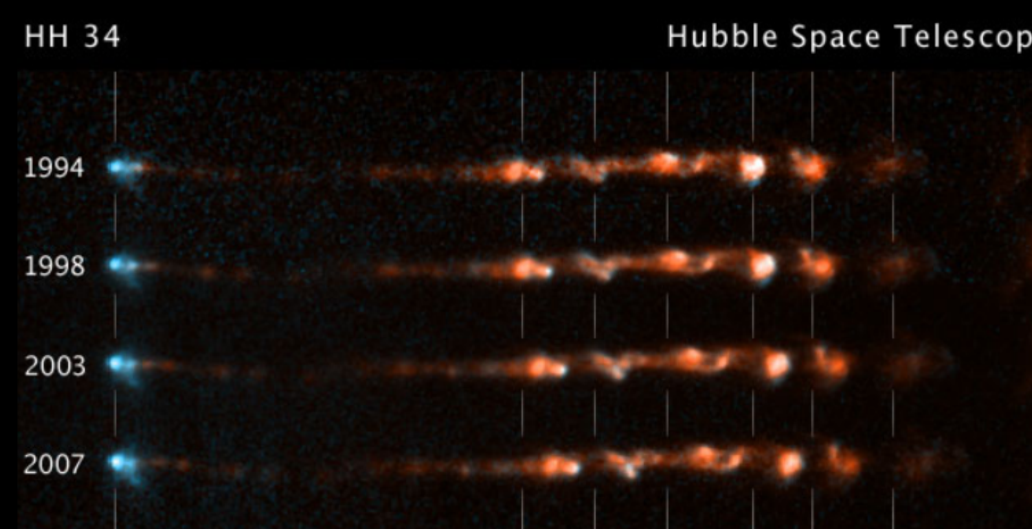
C. Burrows (ST ScI), J. Hester (AZ State U.), J. Morse (ST ScI), NASA





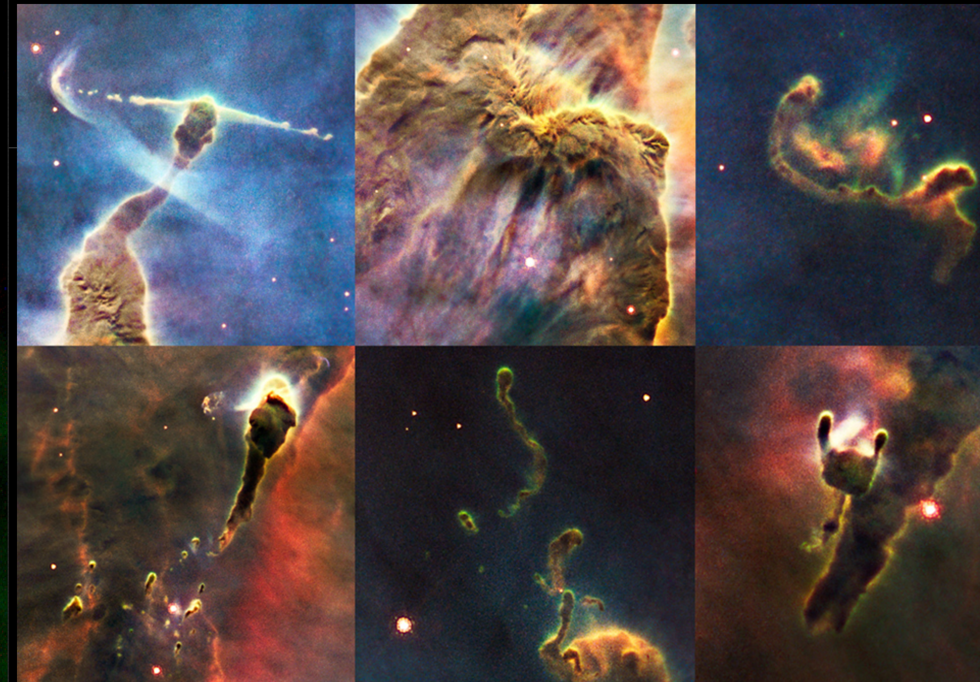
HH 151, a bright jet of glowing material trailed by an intricate, orange-hued plume of gas and dust. It is located some 460 light-years away in the constellation of Taurus , near to the young, tumultuous star HL Tau.





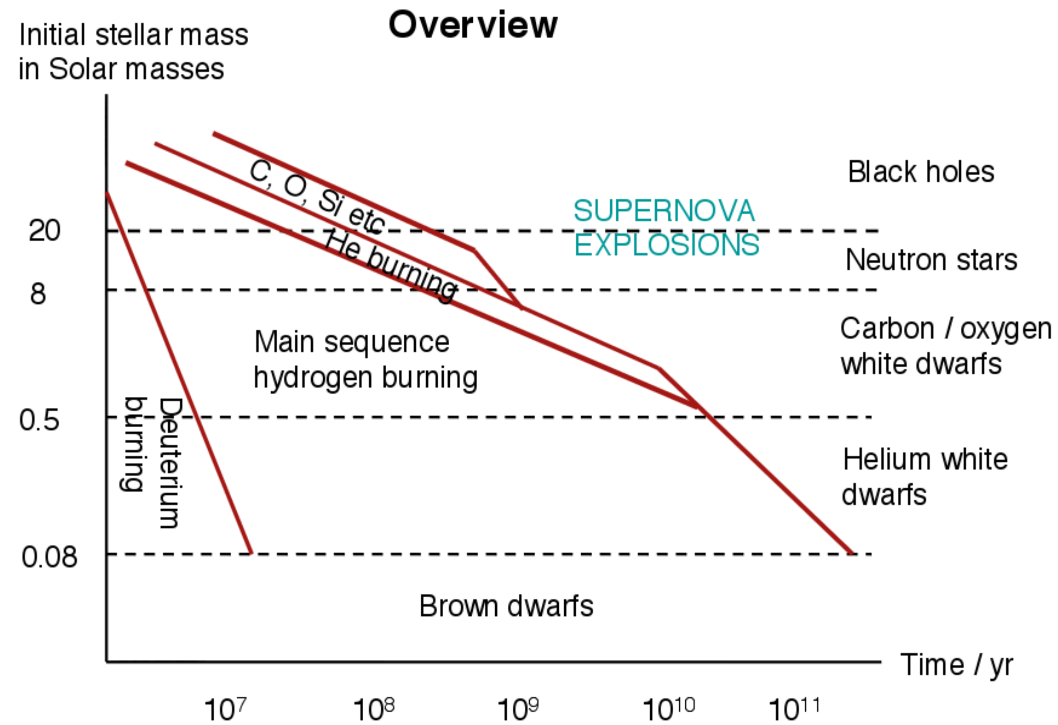
Protostar HH-34 in Orion (VLT KUEYEN + FORS2)

ESO PR Photo 40b/99 (17 November 1999)



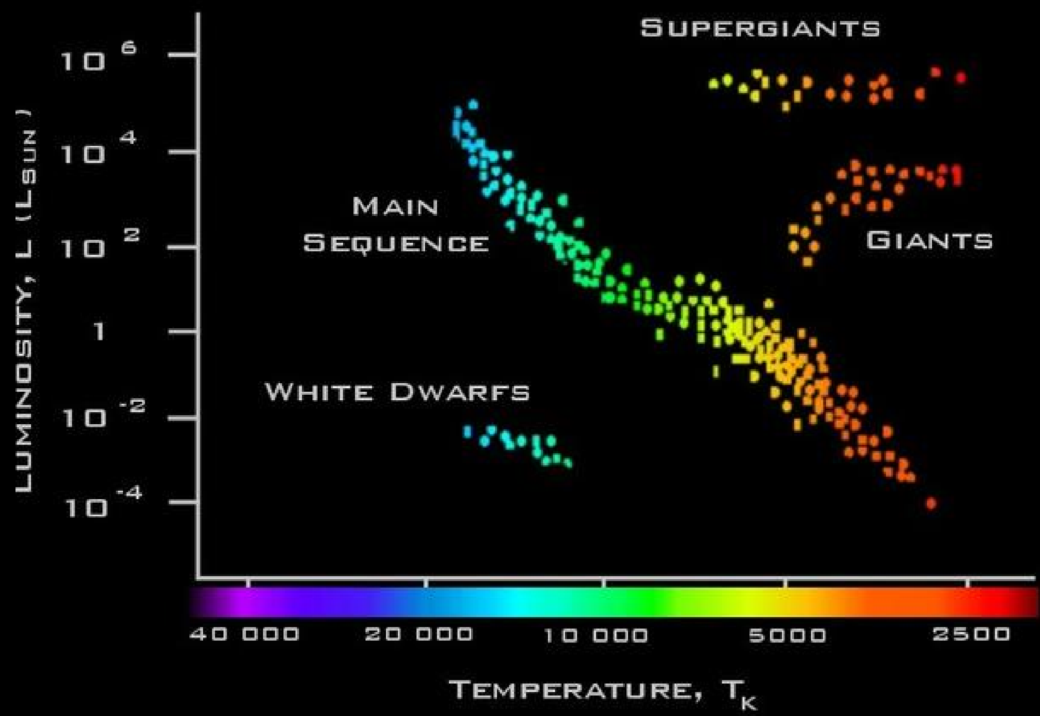
The birth of stars

- Low-mass protostars become stars slowly
  - Weaker gravity causes them to contract slowly, so they heat up gradually
  - Weaker gravity requires low-mass stars to compress their cores more to get hot enough for fusion
  - Low-mass stars have higher density!
- High-mass protostars become stars quickly
  - They contract quickly due to stronger gravity
  - Core becomes hot enough for fusion at a lower density
  - High-mass stars are less dense!

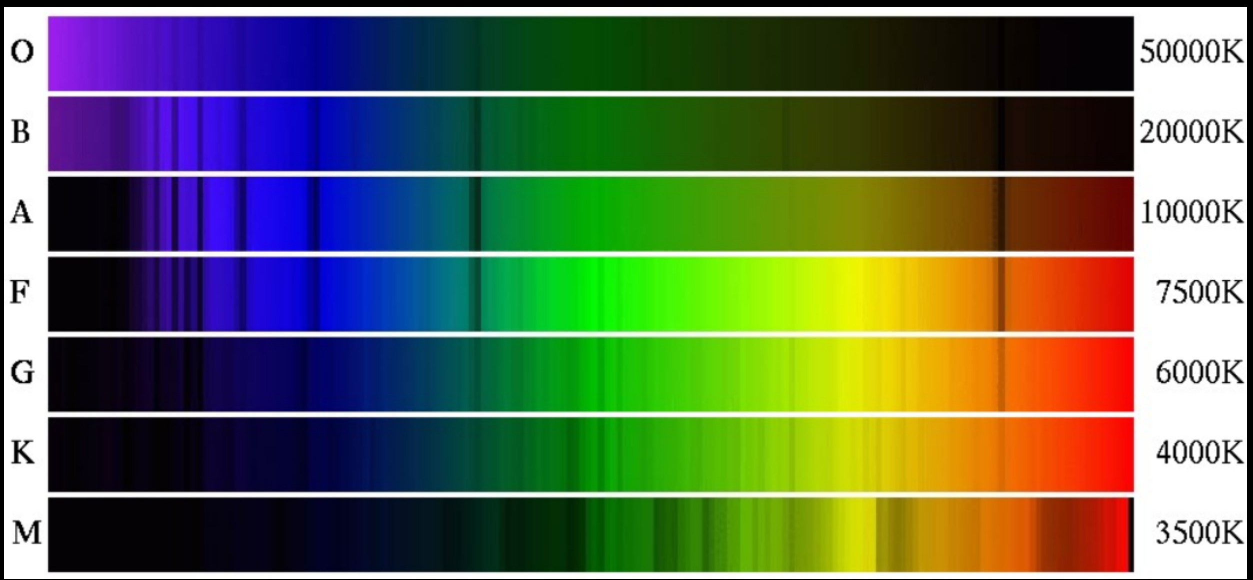


- Deuterium burning allows stars with M > 2-3 M_s in the pre-main-sequence phase
  - hydrogen burning would occur while the object was still accreting matter
  - deuterium burning acts as a thermostat that stops the central temperature rising above 1 MK
  - after energy transport switches from convective to radiative, forming a radiative barrier around a deuterium exhausted core, central deuterium burning stops
  - then central temperature of the protostar can increase

Hertzsprung - Russell Diagram



- For every massive star, there are ~ 1000 intermediate mass stars and 10000 low mass stars
- About 60% of stars are born in binary systems
  - A small fraction are born in triple and quadruple systems



Class	Color	Prominent Spectral Lines	Surface Temp. (K)
O	Blue	Ionized helium, hydrogen	> 25,000 K
B	Blue-white	Neutral helium, hydrogen	11,000 – 25,000 K
A	White	Hydrogen, ionized sodium and calcium	7,500 – 11,000 K
F	White	Hydrogen, ionized and neutral sodium and calcium	6,000 – 7,500 K
G	Yellow	Neutral sodium and calcium, ionized calcium, iron, magnesium	5,000 – 6,000 K
K	Orange	Neutral calcium, iron, magnesium	3,500 – 5,000 K
M	Red	Neutral iron, magnesium, and neutral titanium oxide	< 3,500 K

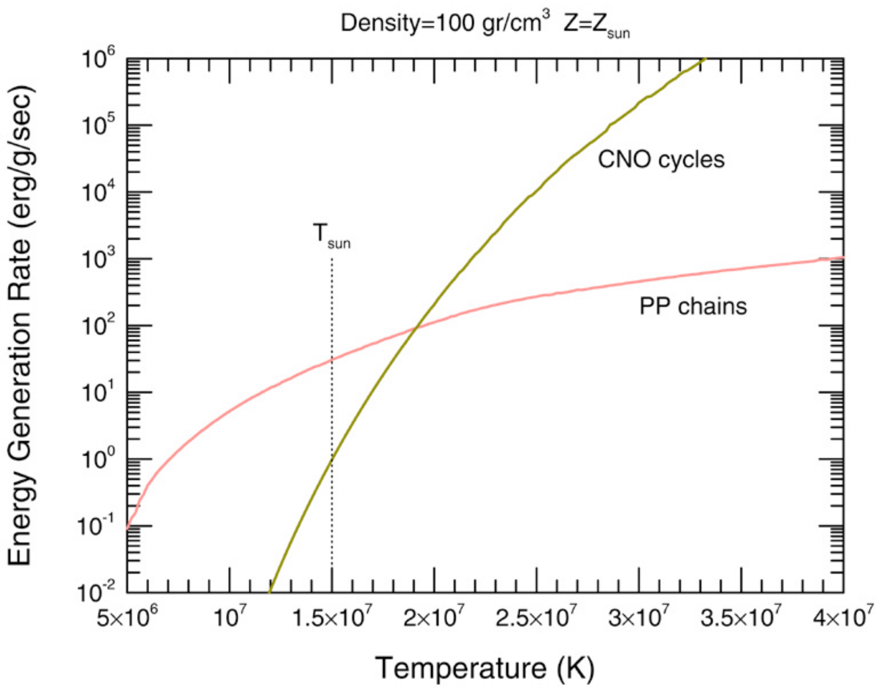
Main sequence

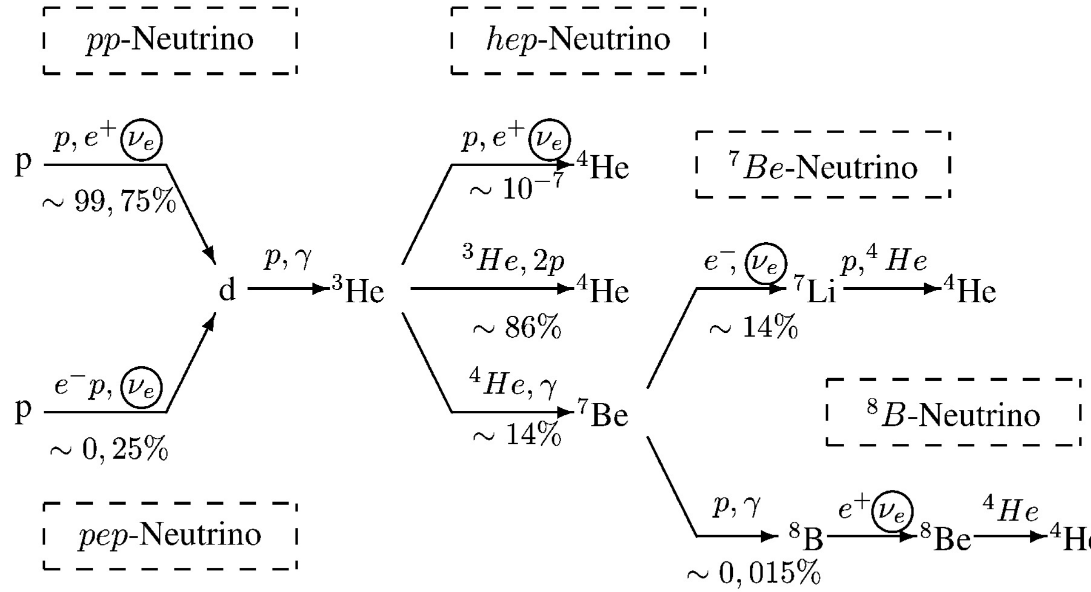
- Stars enter the main-sequence phase when the fusion of H to He begins

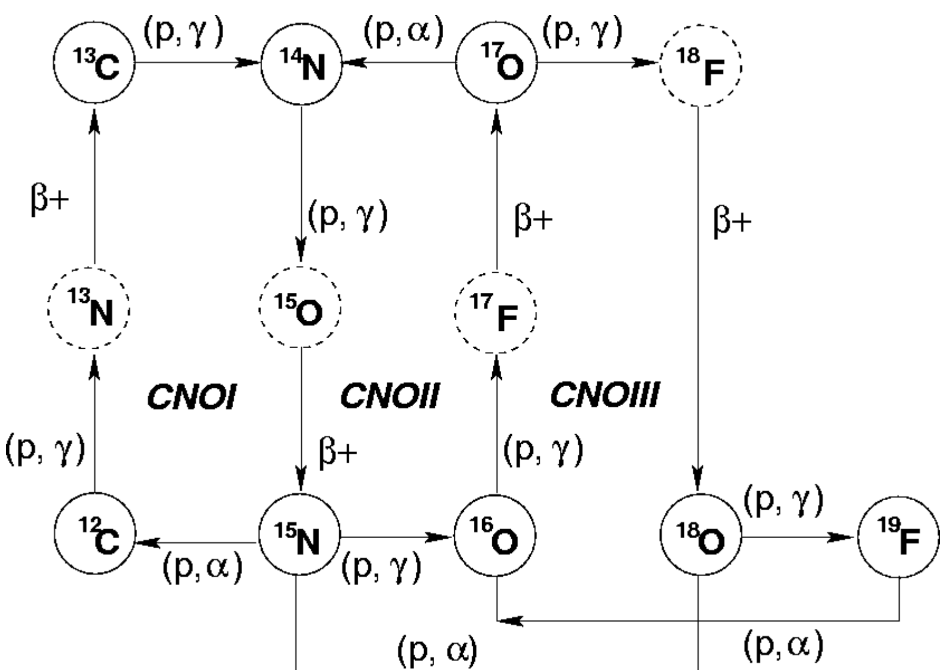
- List in order from lowest to highest temp requirement: Triple alpha, CNO, proton-proton fusion
  - P-P ~ 5 million Kelvin (H->He)
  - CNO ~ 20 million Kelvin (H->He)
  - Triple alpha ~ 100 million Kelvin (He->C)
- Why are main sequence stars so stable?
  - Compression -> T⇑ -> fusion ⇑ -> P ⇑ -> expansion
  - Expansion -> T⇓ -> fusion⇓ -> P ⇓ -> compression

Eulerian coordinates (r,t)	Lagrangian coordinates (m,t)
$\frac{dm}{dr} = 4\pi r^2 \rho$	$\frac{dr}{dm} = \frac{1}{4\pi r^2 \rho}$
$\frac{dP}{dr} = -\frac{Gm\rho}{r^2}$	$\frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$

pp and CNO cycles



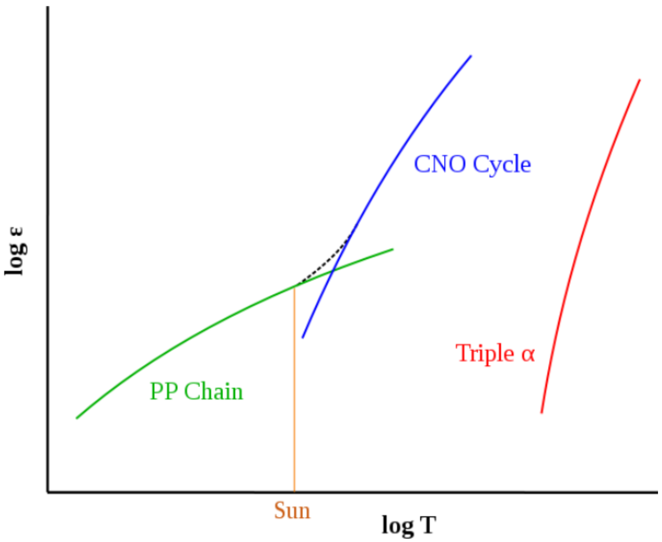


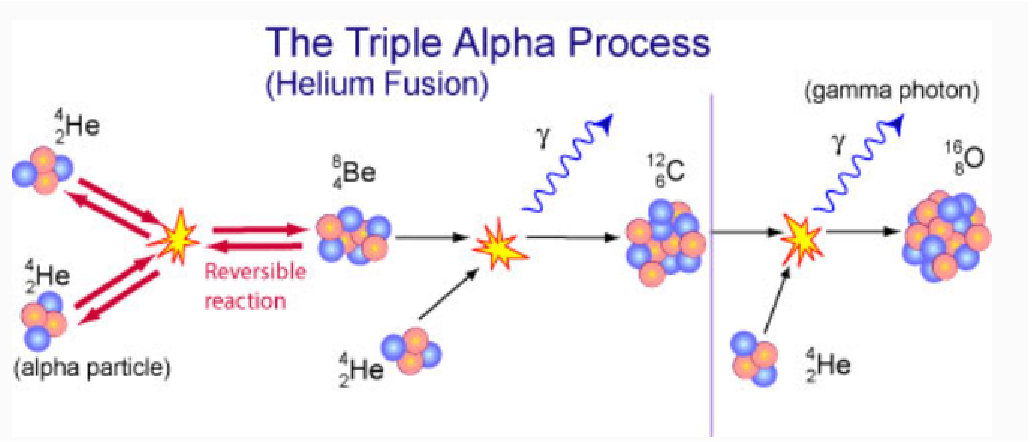


Solar Elemental Abundances

Element	Number %	Mass %
Hydrogen	92.0	73.4
Helium	7.8	25.0
Carbon	0.02	0.20
Nitrogen	0.008	0.09
Oxygen	0.06	0.8
Neon	0.01	0.16
Magnesium	0.003	0.06
Silicon	0.004	0.09
Sulfur	0.002	0.05
Iron	0.003	0.14

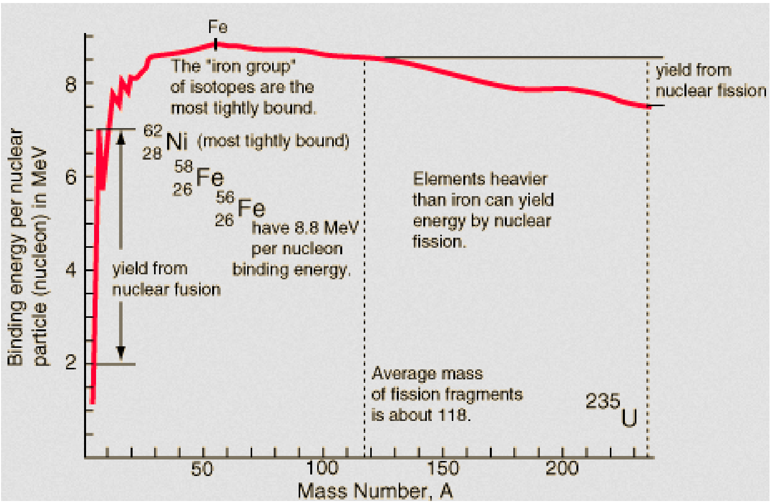
Triple-alpha





- $\varepsilon(pp) \sim T^4$
- $\varepsilon(CNO) \sim T^{17}$
- $\varepsilon(\text{triple } \alpha) \sim T^{40}$

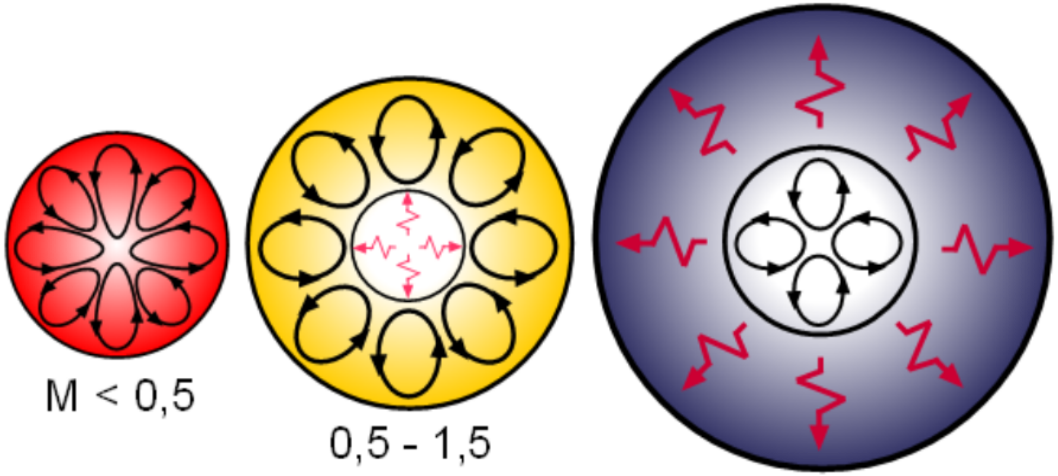
Nuclear Fuel	Process	$T_{threshold}$ 10^6K	Products	Energy per nucleon (MeV)
H	PP	~4	He	6.55
H	CNO	15	He, N	6.25
He	3α	100	C,O	0.61
C	C+C	600	O,Ne,Na,Mg	0.54
O	O+O	1000	Mg,S,P,Si	~0.3
Si	Nuc eq.	3000	Co,Fe,Ni	<0.18



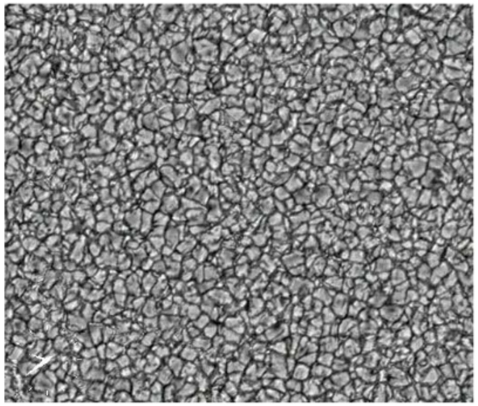
Energy transport in stars

Energy is transported by these mechanisms:

- **Radiation** - photons carry energy away from the star's center
- **Convection** - cells of hot gas move up, cells of cool gas move down (boil)
- **Conduction** - collisions between electrons can move energy outwards, relevant in degenerate matter
- **Neutrino radiation** – advanced burning stages, supernovae

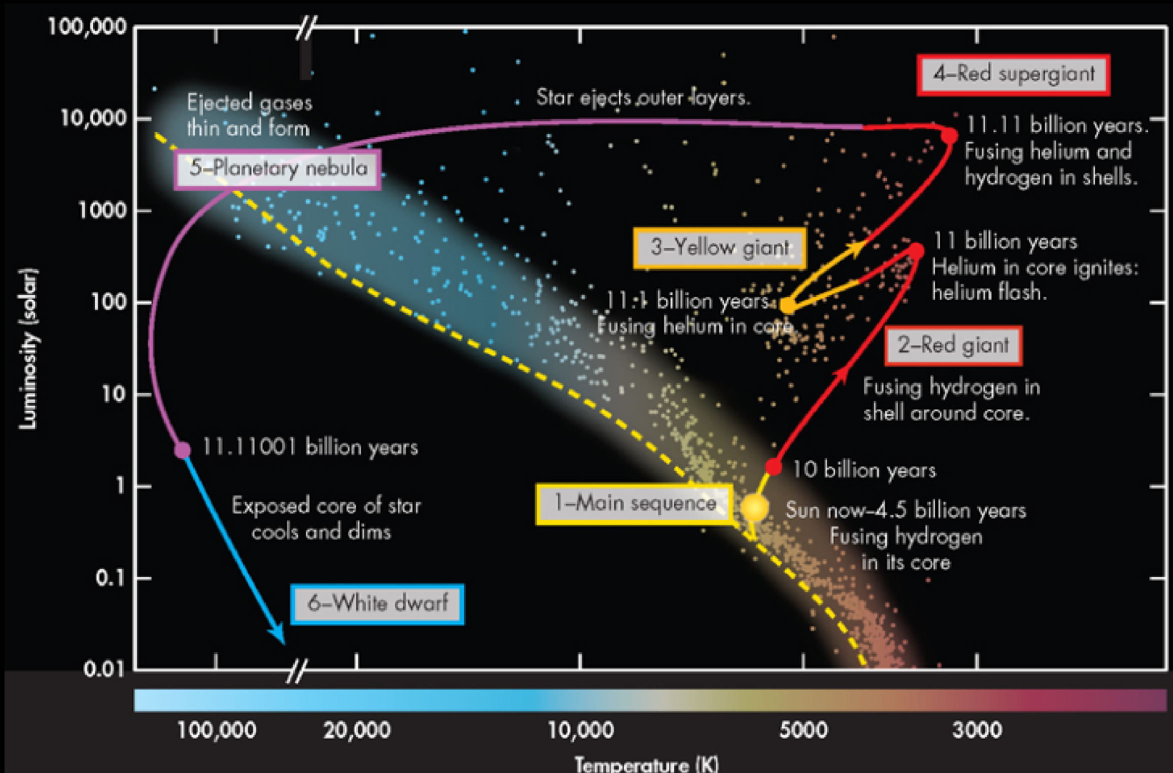


- Convection takes over once radiation becomes inefficient.
- Radiation becomes noneffective when there is a large temperature gradient. ($\sim T^4$, $\sim T^{17}$, $\sim T^{40}$)
- Efficiency of the radiative transport also depends on the opacity

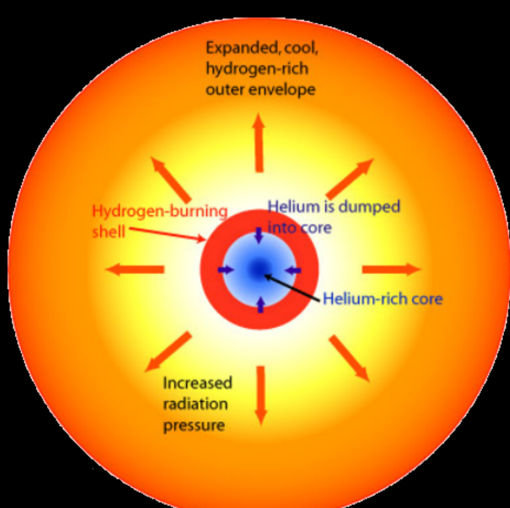


$\Delta T \simeq 100$ K $\quad v \sim$ few km/s

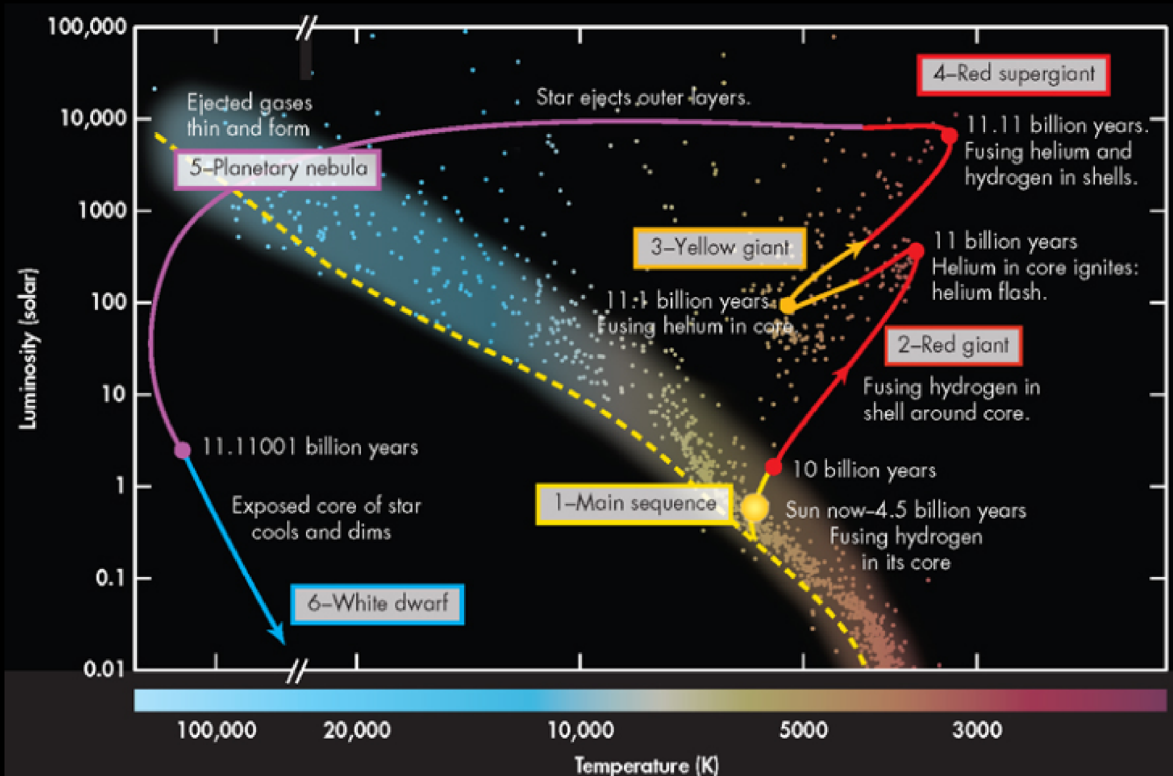
Red Giant Branch



- H in core has become depleted
- H shell burns
- As the core continues to shrink, the outer layers of the star expand and cool
- It is now a red giant, extending out as far as the orbit of Mercury
- Despite its cooler temperature, its luminosity increases enormously due to its larger size
- First dredge-up occurs: The convection in the envelope moves in when the stars is near the bottom of the RGB and "dredges up" material that has been through partial hydrogen burning by the CNO cycle and pp chains.

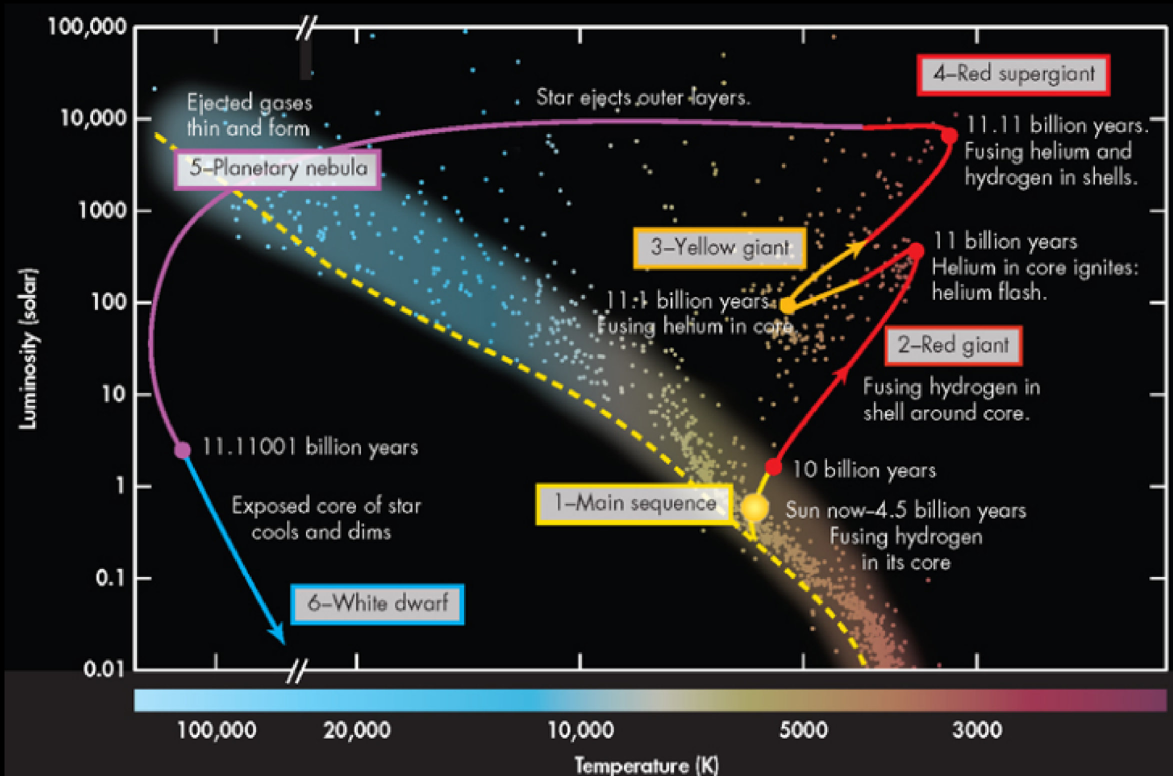


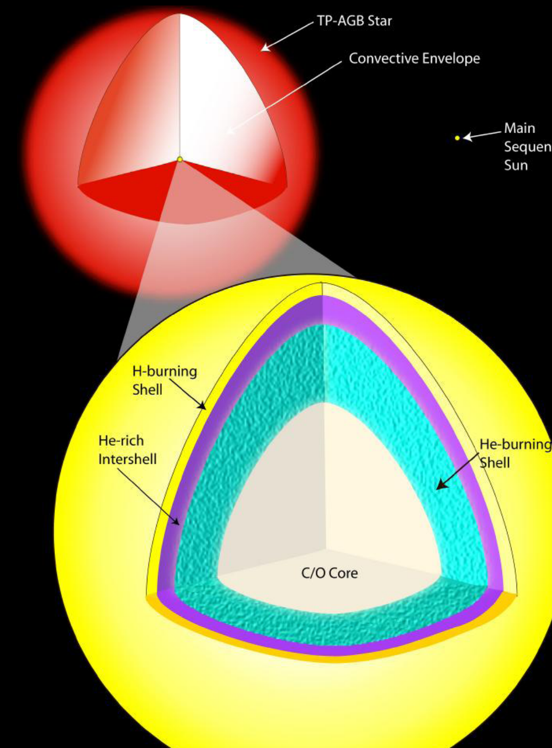
Helium flash and horizontal branch



- Low-mass stars (0.8 ~ 2.2 M_s) have He degenerate core
- Density 10^6 gcm^{-3}
- As M_{core} increases, it shrinks
- Increase in T!=increase in p, degeneracy pressure is not dependent on T
- He fusion commences at 10^8K
- Helium begins to fuse extremely rapidly (triple alpha ~ T^{40})
- H fusion in shell is extinguished by this source of energy, it takes O(10^3) years to reignite
- High Z stars occupy region known as red clump
- Low Z live in the horizontal branch

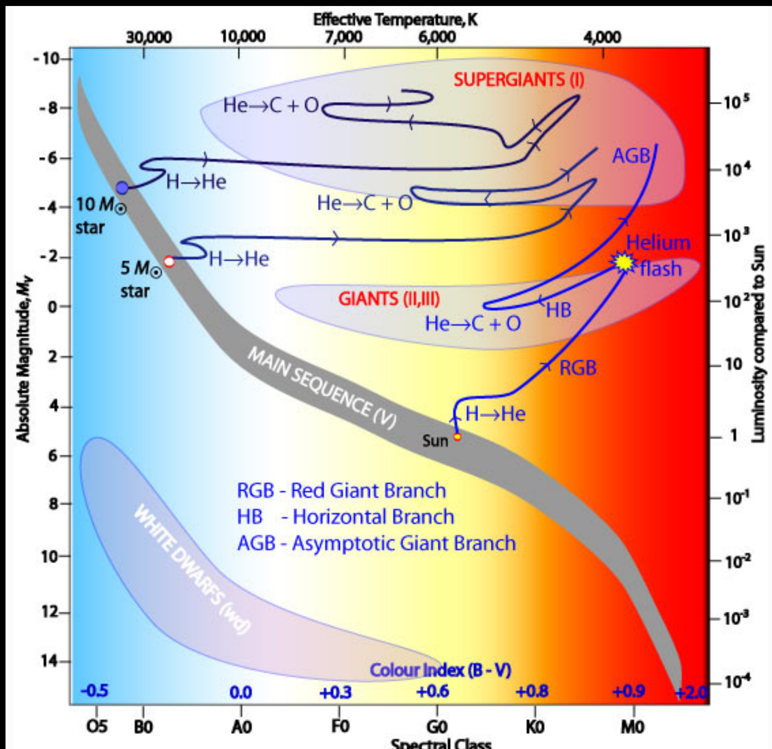
Asymptotic Giant



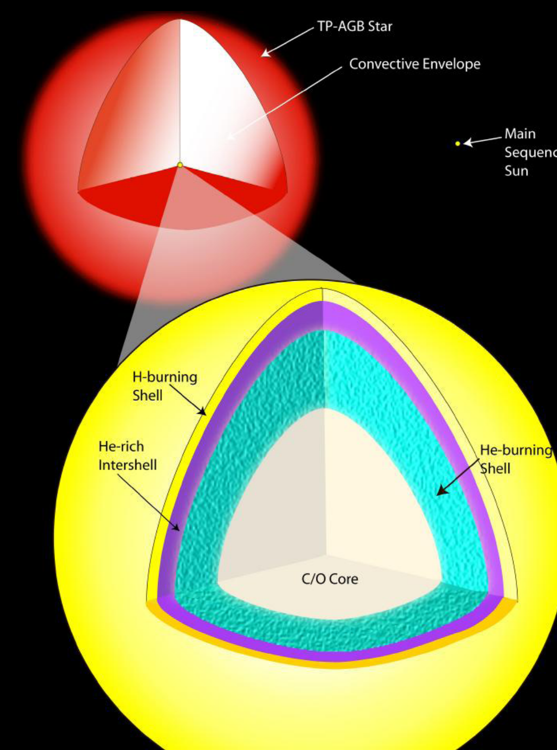


- Final nuclear burning phase for all stars with masses 0.8 to 8 M_{sun}
- After core He-burning, the C-O core contracts and star becomes a giant again
- Lasts less than 1% of the main-sequence lifetime
- Helium begins to fuse extremely rapidly (triple alpha ~ T^{40})
- At the end – pulsations as the He and H burning shells get close together, mixing
- Strong stellar winds blow away outer shells (pulsations, dust)
- The core left becomes white dwarf

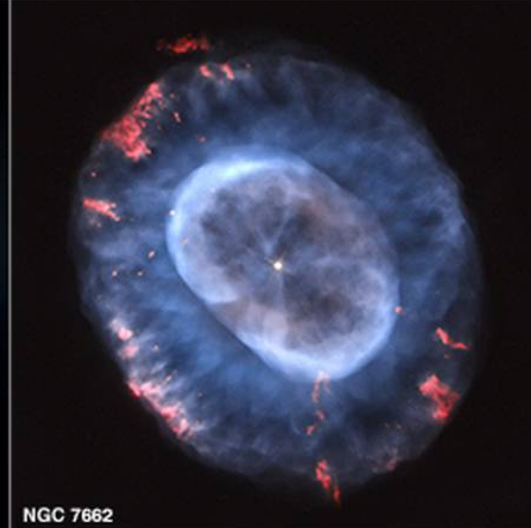
Masses above 2.2 M_S



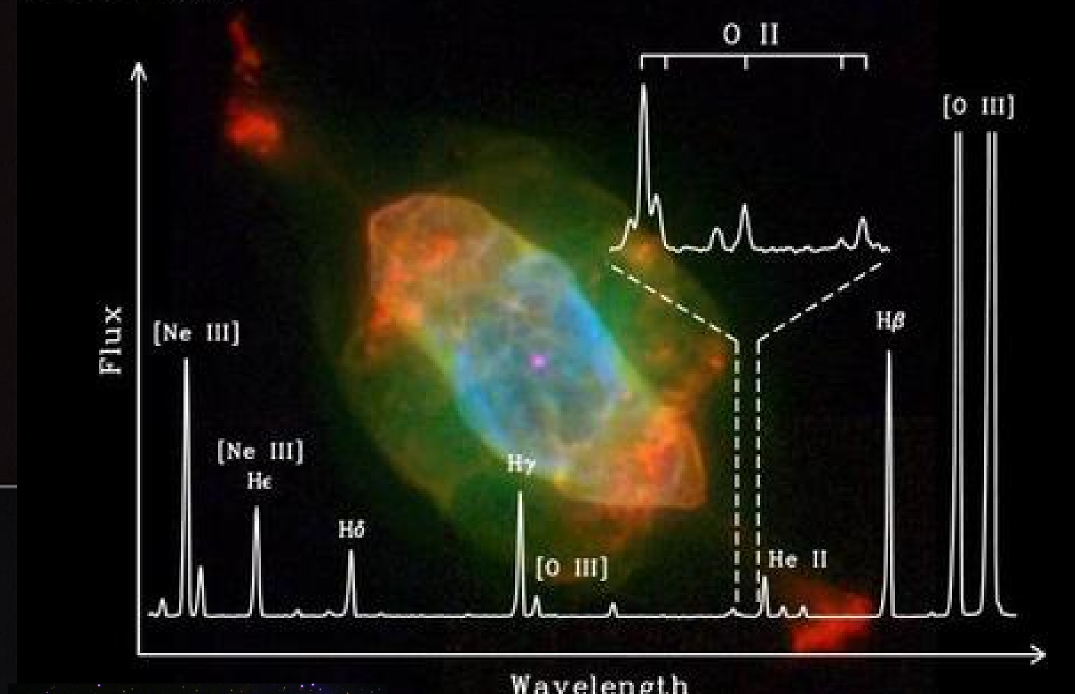
- Core non-degenerate, no helium flash
- Develop a CO core, in AGB phase shet their envelopes
- IF M > 8 M_S, carbon burning
- White dwarf + nebula result
- IF M > ~11 M_S, up to Fe



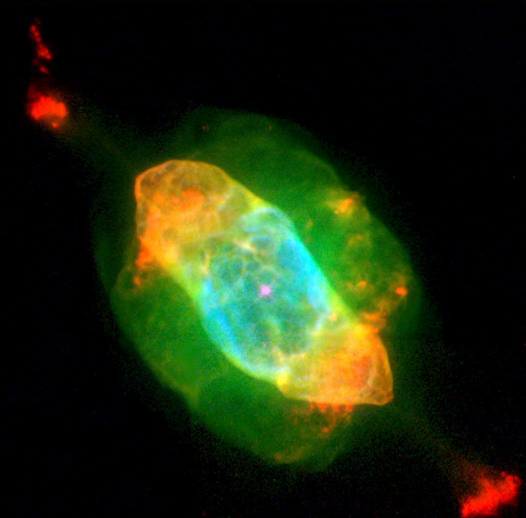

CAT'S EYE


NGC 7662

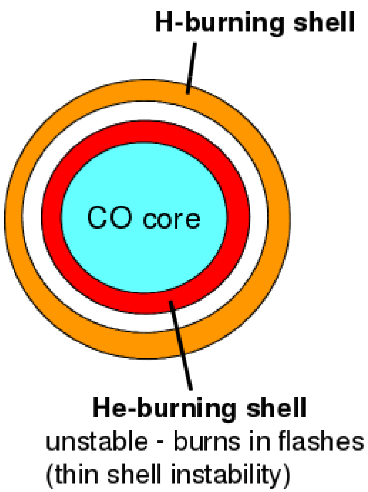
NGC 7009

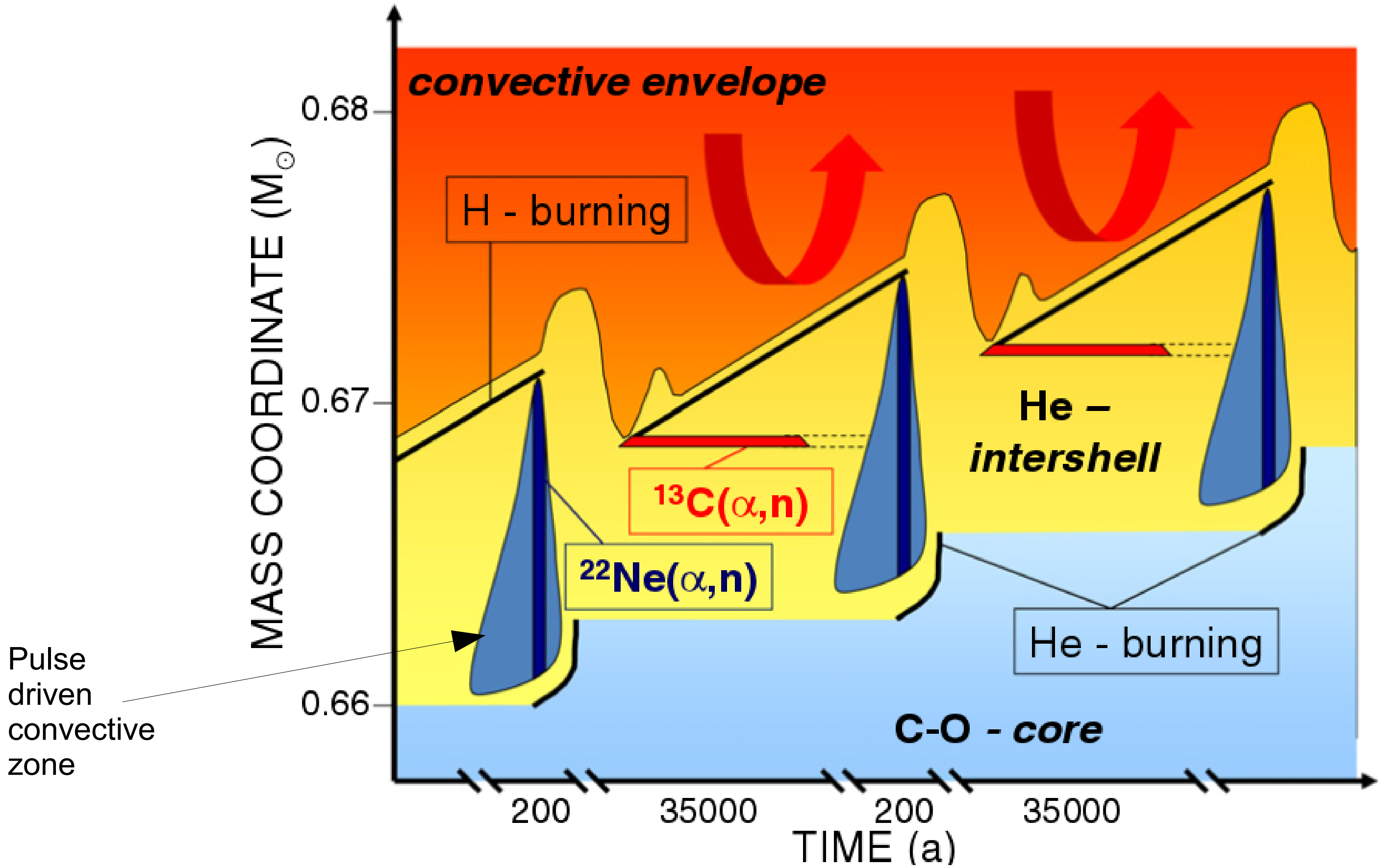

O II
[O III]
Flux
[Ne III]
[Ne III]
Hϵ
Hδ
Hγ
[O III]
He II
Hβ
Wavelength


IGC 6826



TP-AGB





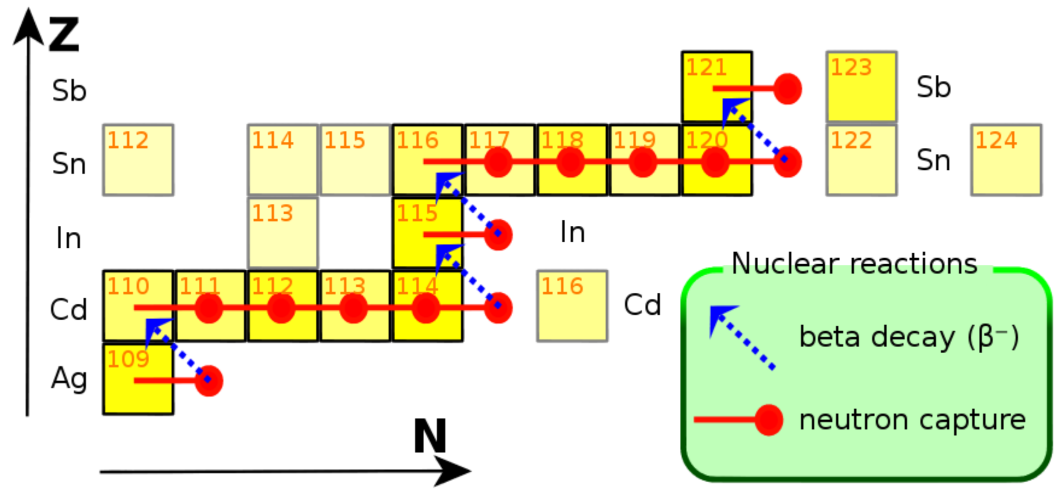
- H burning produces ashes in the intershell
- When enough He is accumulated in the intershell, He Shell Explosively fuses
- This thermonuclear runaway drives formation of a convective zone
- Expansion powered by convection kills H burning layer
- Accumulation of CO elements, protons mixed downward from convective envelope
- Regions heat during interpulse, creating ^{13}C pocket ($^{12}C(p,\gamma)^{13}N(\beta+v)^{13}C$)
- This carbon isotope waits until next pulse... $^{13}C(\alpha,n)^{16}O$
- Intense neutron flux ~10^7 cm^{-3}
- This pocket is strongly enriched in newly created elements

The s-process

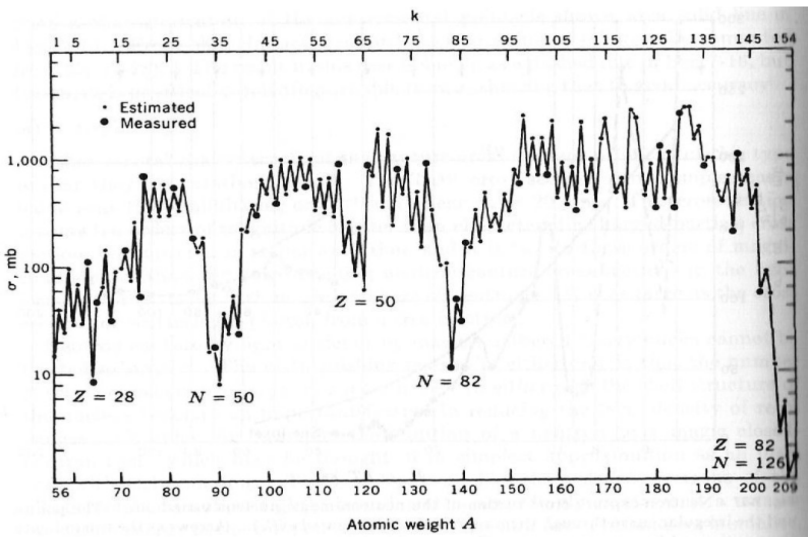
$^{13}_{6}C + ^{4}_{2}He \rightarrow ^{16}_{8}O + n$

$^{22}_{10}Ne + ^{4}_{2}He \rightarrow ^{25}_{12}Mg + n$

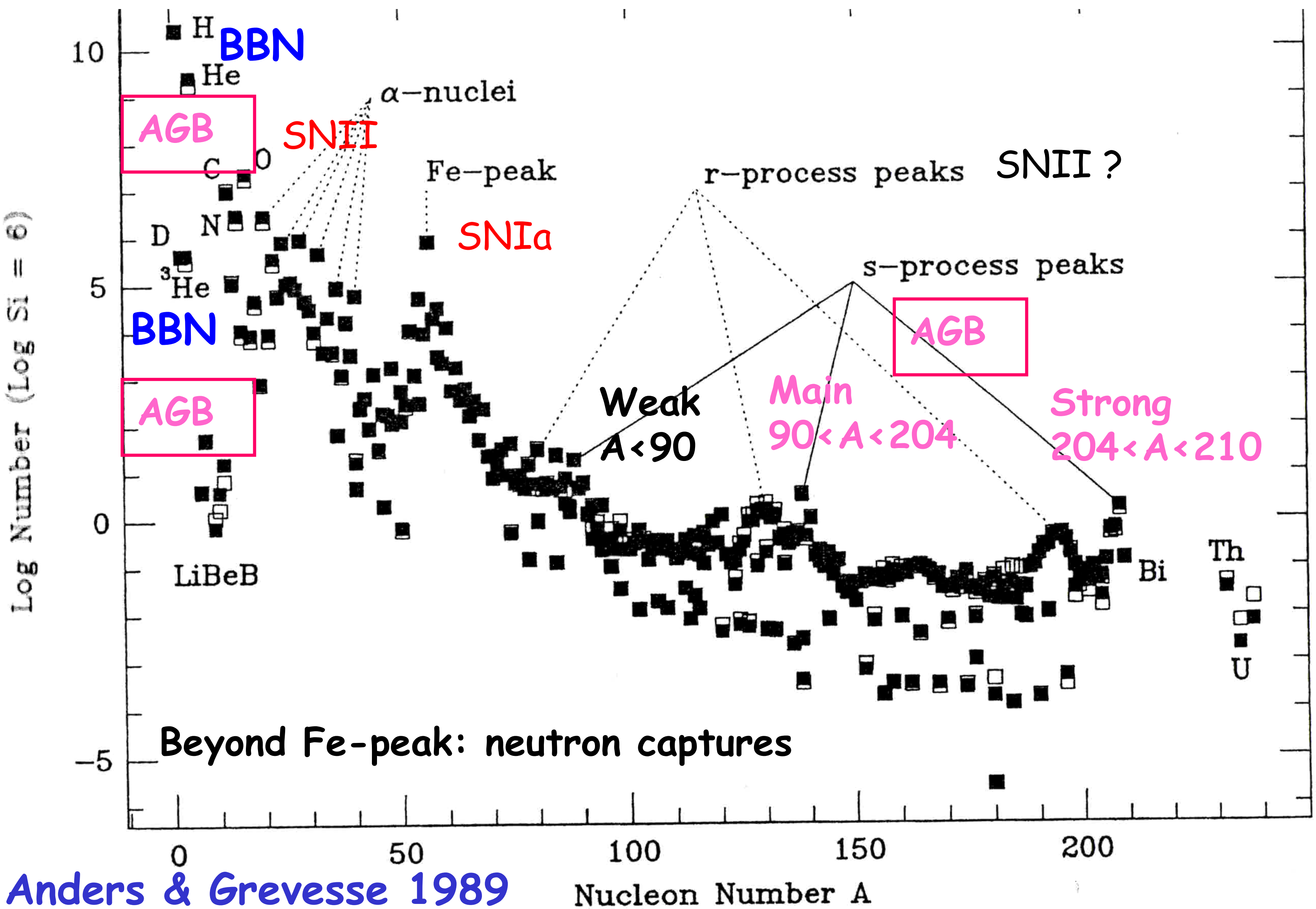
Neutron captures are not hindered by coulomb repulsion



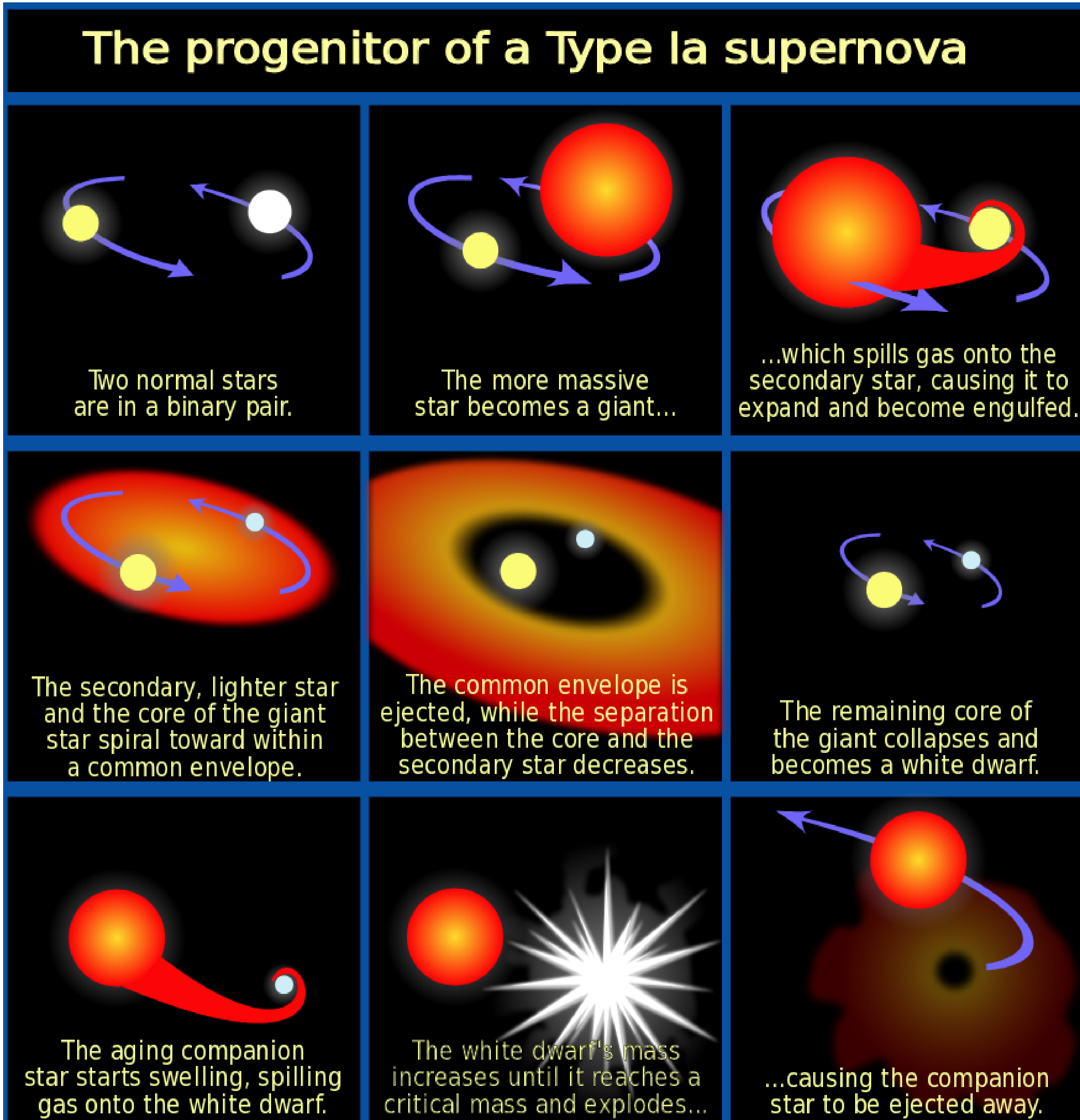
$$\frac{dN_A}{dt} = - < \sigma v >_A n_n(t) N_A(t) + < \sigma v >_{A-1} n_n(t) N_{A-1}(t)$$



- Neutron captures increase the mass number through (n,γ) reactions
- Time scale for n capture << Beta decay times
- The products will beta-decay until a stable (or long-lived) isotope is reached
- Nuclei with magic number of neutrons stable against neutron capture, act as bottlenecks
- The process thus terminates in ^{209}Bi, the heaviest "stable" element.



Anders & Grevesse 1989
Cameron 1982

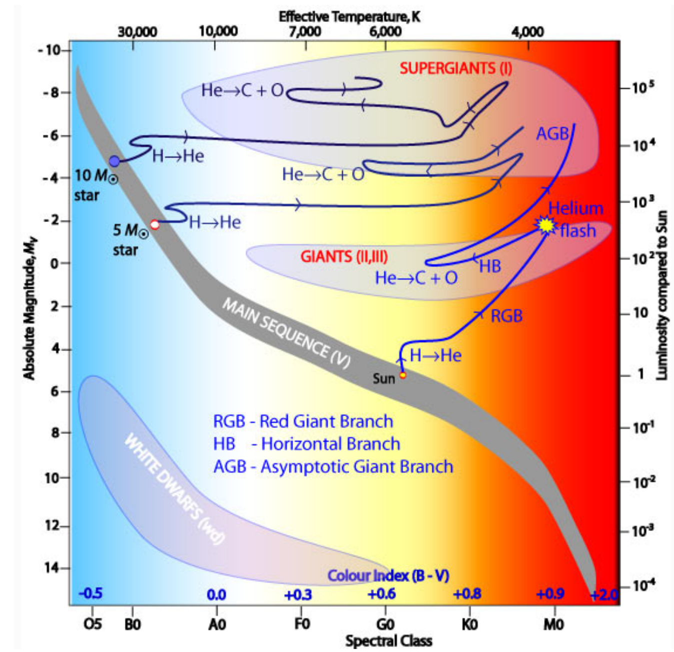


Start off with a binary system

- One star comes to end of its life – forms a “white dwarf” (made of helium, or carbon/oxygen)
- If close enough, tidal forces of the white dwarf pull matter off the other star... adds to mass of white dwarf (accretion)
- If accretion pushes white dwarf over the Chandrasekhar Mass Limit (1.4 M_S), it starts to collapse
- Rapid compression initiates thermonuclear runaway... burn whole mass of white dwarf to iron/nickel in few seconds
- Liberated energy blows the star apart... no remnant.

Supergiant stage of heavy stars

- $L \propto M^{3\text{-}4}$, $Fuel \propto M$ $\Rightarrow$ $Lifetime \propto 1/M^2 (M/M^3)$
- Massive stars live fast, die young
- Higher T ⇒ CNO Cycle on MS
- No core degeneracy (higher T⇒higher P) means no helium flash
- Higher T⇒more nuclear burning stages (it is the high mass stars that make the elements heavier than C,N,O and even most of the C,N,O that goes into the ISM.
- Star goes through stages of H core burning, H shell burning and He core fusion as medium mass star
- Then it continues with further stages up to Iron



Nuclear Fuel	Process	$T_{threshold}$ 10^6K	Products	Energy per nucleon (MeV)
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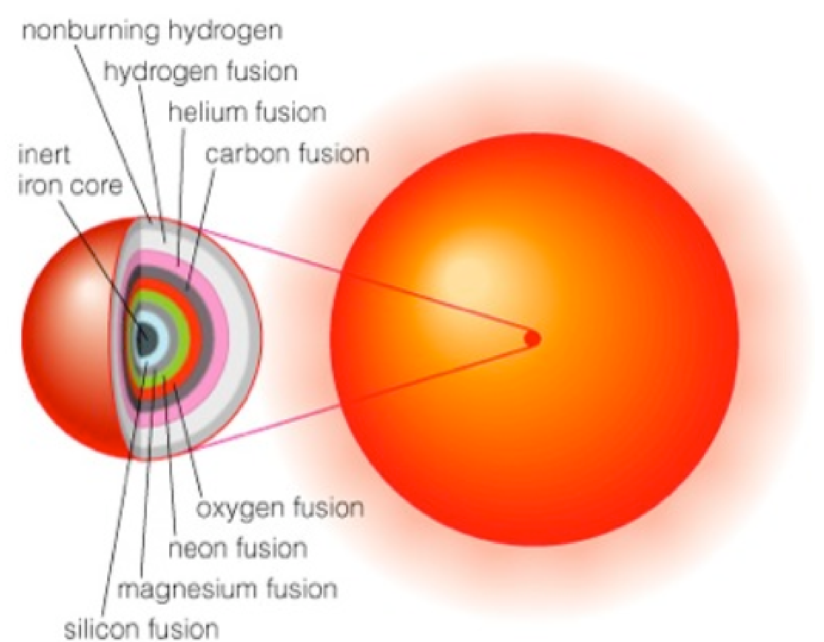
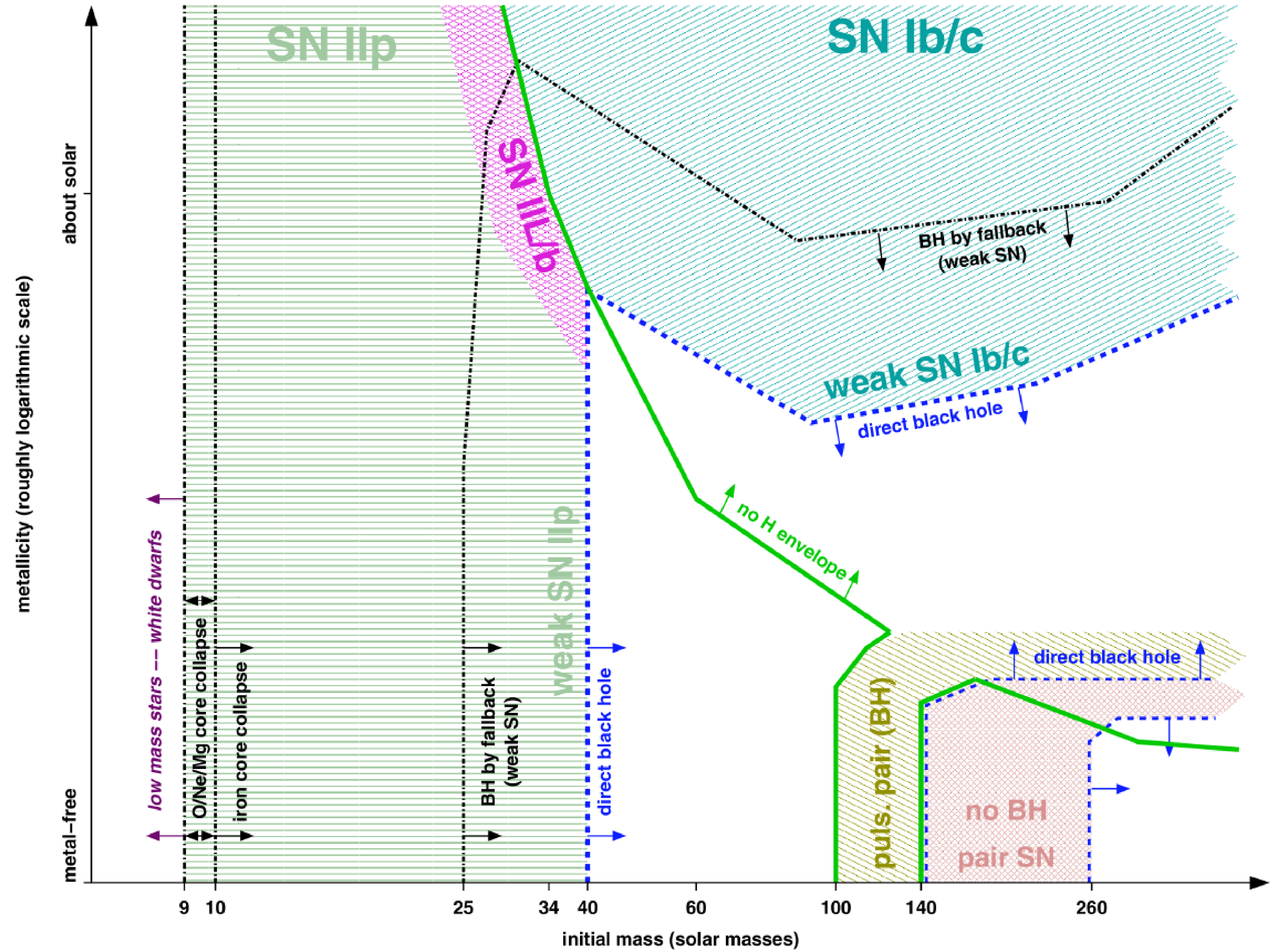


Massive star fate

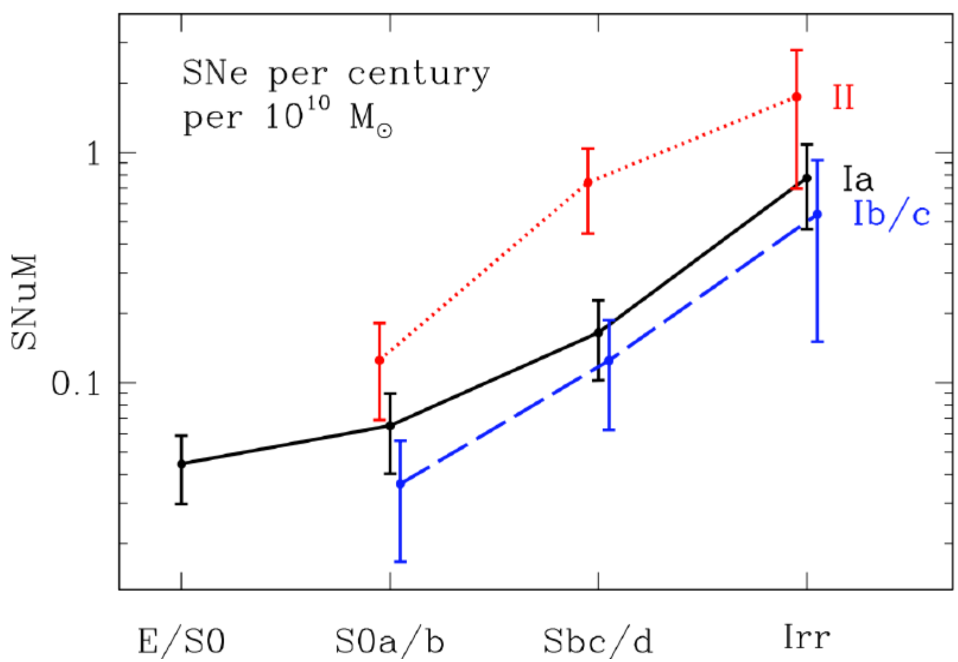


Released energy

Energetics of supernovae

Supernova	Approximate total energy (foe)[c]	Ejected Ni (solar masses)	Neutrino energy (foe)	Kinetic energy (foe)	Electromagnetic radiation (foe)
Type Ia[97][98][99]	1.5	0.4 – 0.8	0.1	1.3 – 1.4	~0.01
Core collapse[100][101]	100	(0.01) – 1	100	1	0.001 – 0.01
Hypernova	100	~1	100	1	~0.1
Pair instability[77]	5–100	0.5 – 50	low?	1–100	0.01 – 0.1

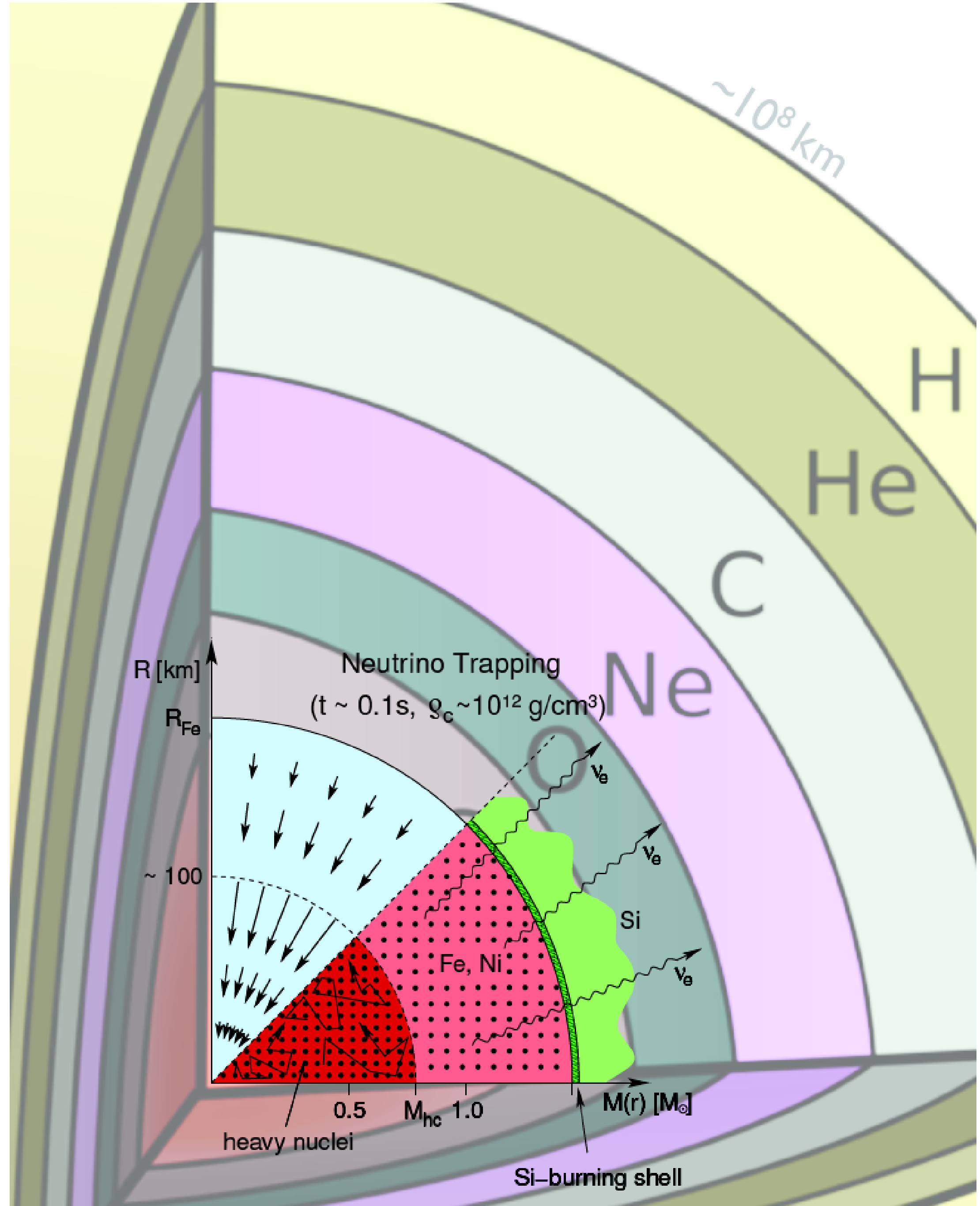
- 1 foe = 10^(fifty-one) ergs (~ 10^{44} J)
- Sun will produce 1.2 foe over its lifetime

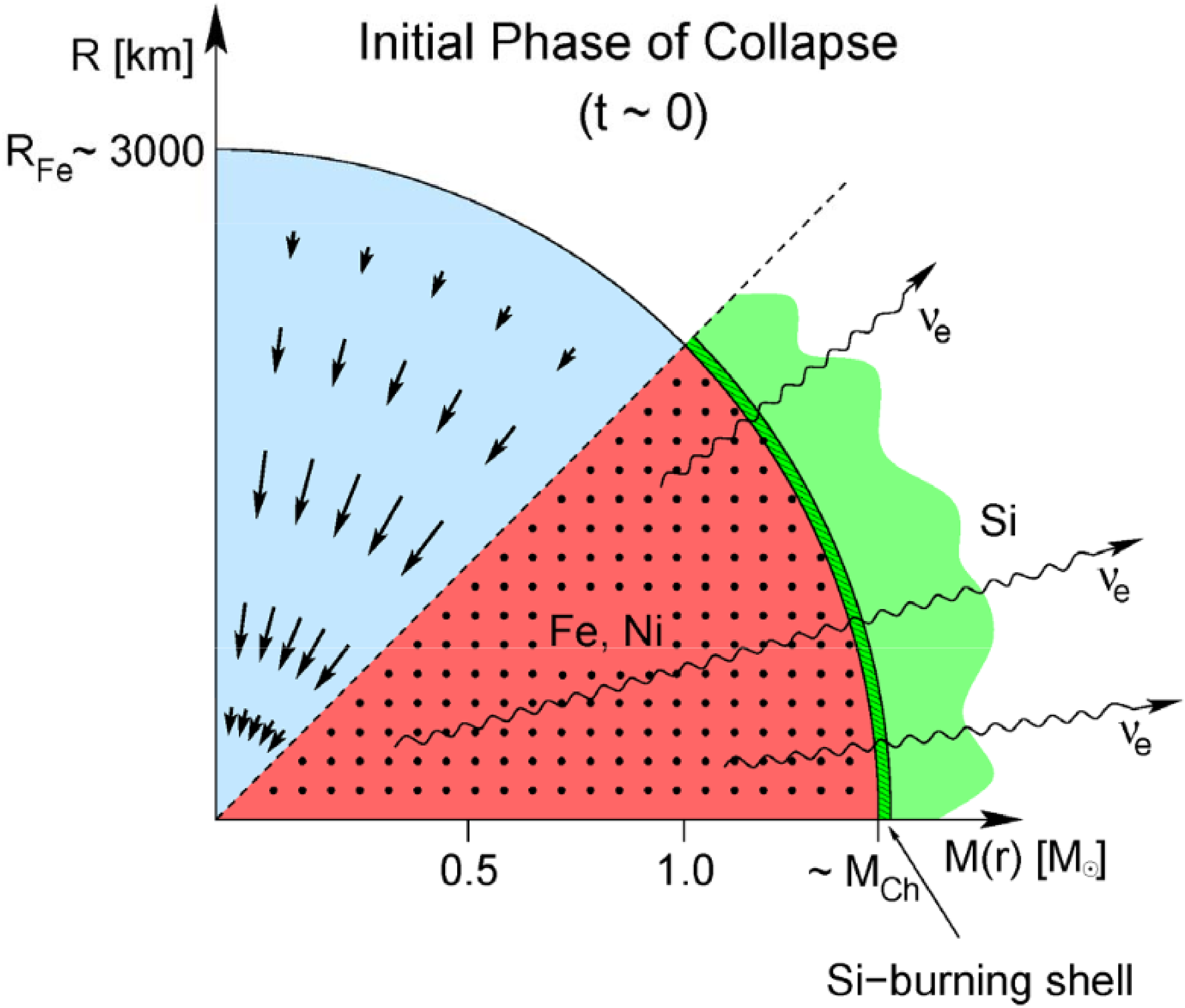


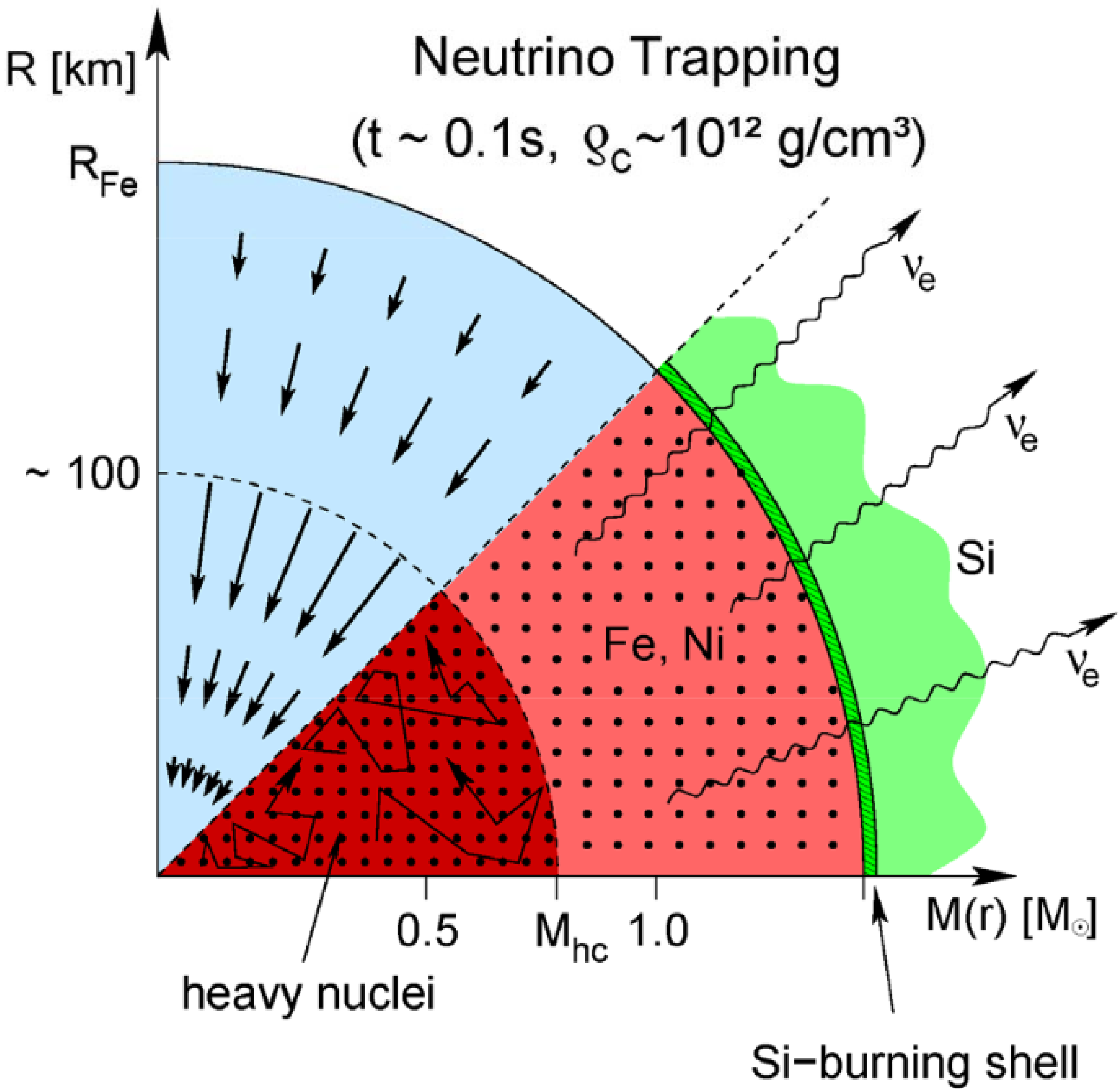
- Energy density of the core is equivalent to 1MT TNT per cubic micron
  - 99% of energy released is in the form of neutrinos
- ~1% is in the KE of the exploding matter
- ~0.01% is in light – and that's enough to make it as bright as an entire galaxy.

Upper bound on supernovae in Milky Way 13 supernovae per century 90% CL.

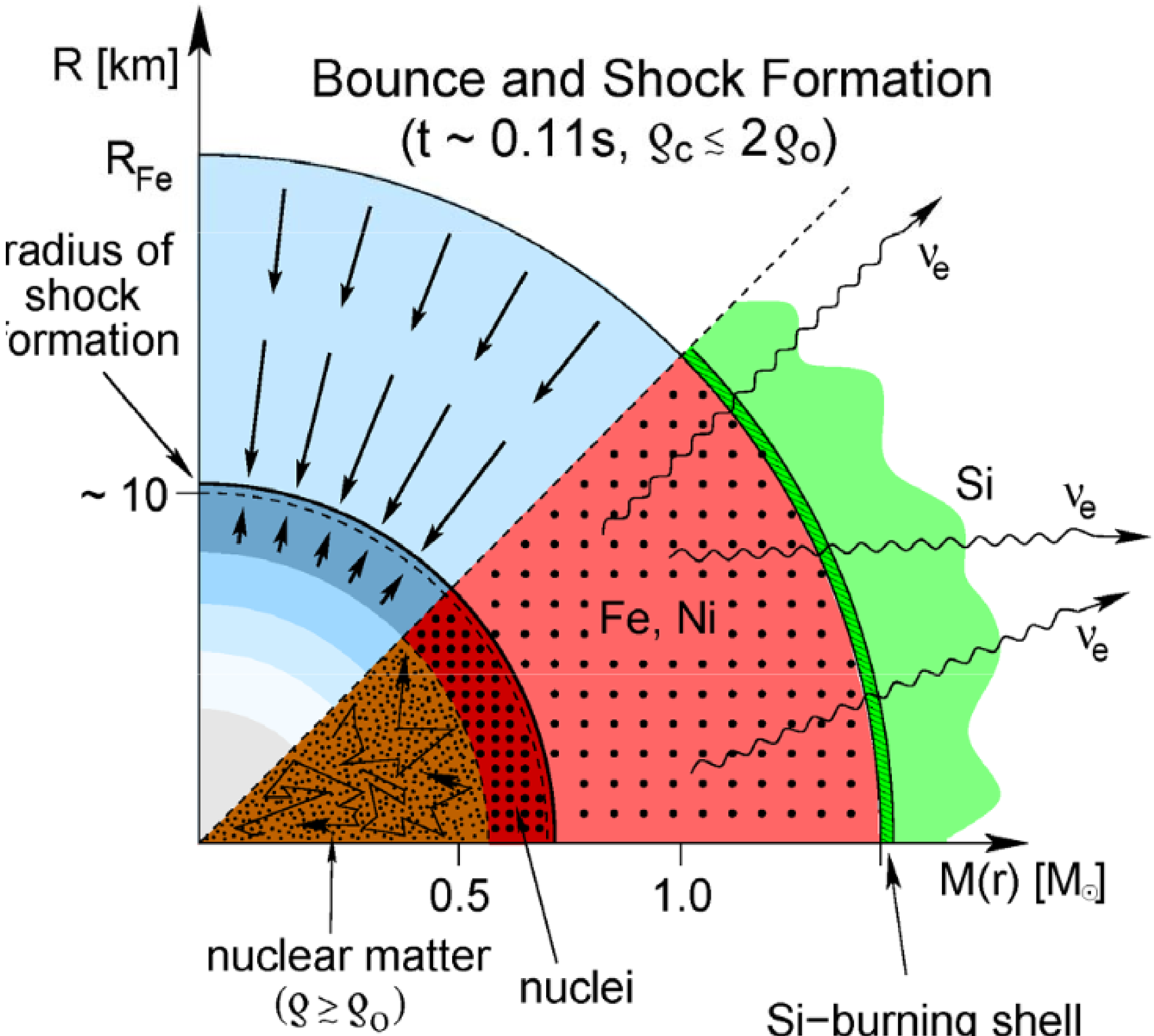
- Pressure is dominated by degenerate electrons
- Si burning at core surface increases Fe-core mass
- Chandrasekhar mass limit
- Collapse starts: gravitational energy is transformed into internal energy: $E \sim 10^{53}$ erg
- Most of the internal energy escapes in form of neutrinos
- $\rho_{crit} \sim 10_{12}$ g/cm^{-3} neutrinos are trapped

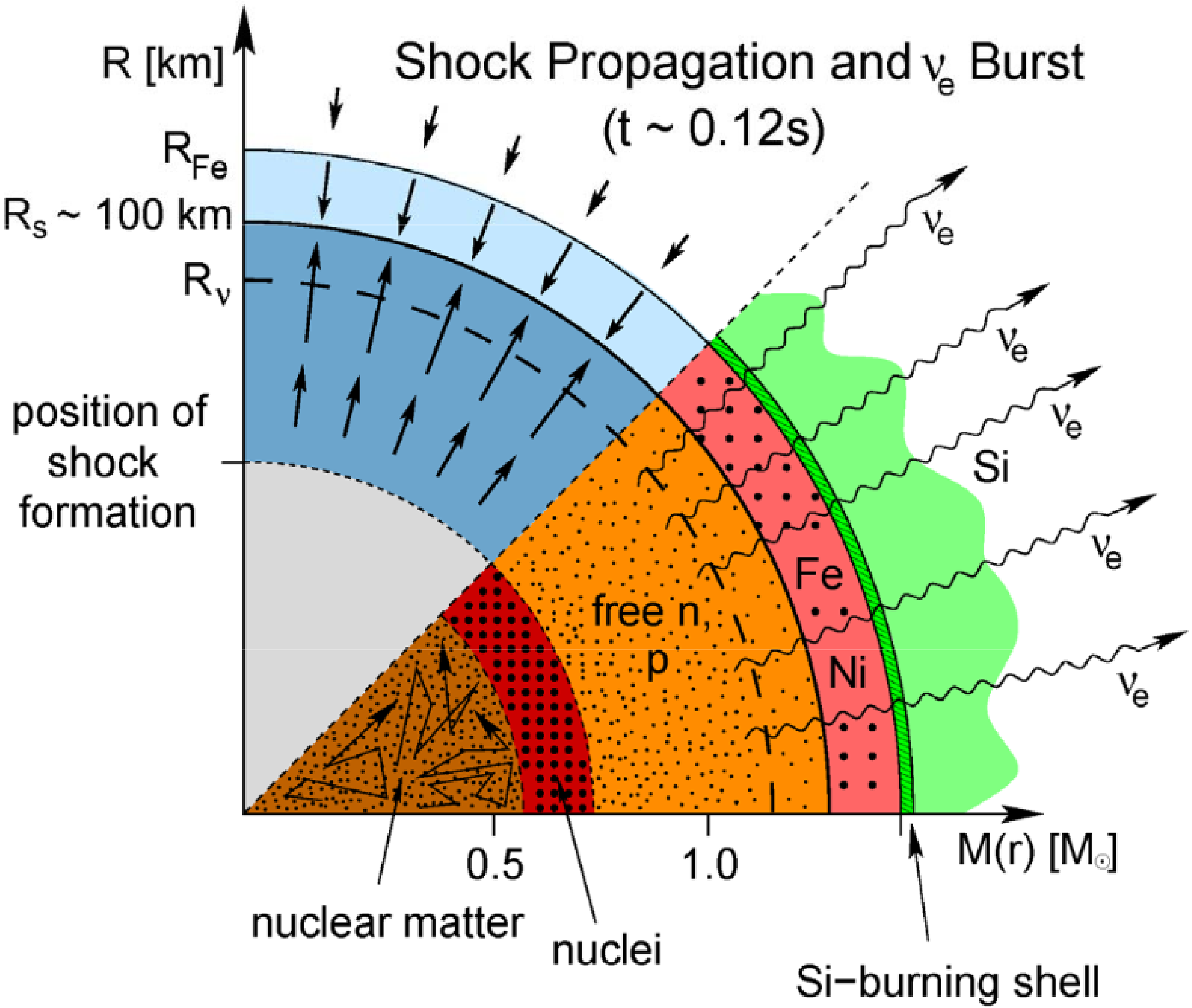


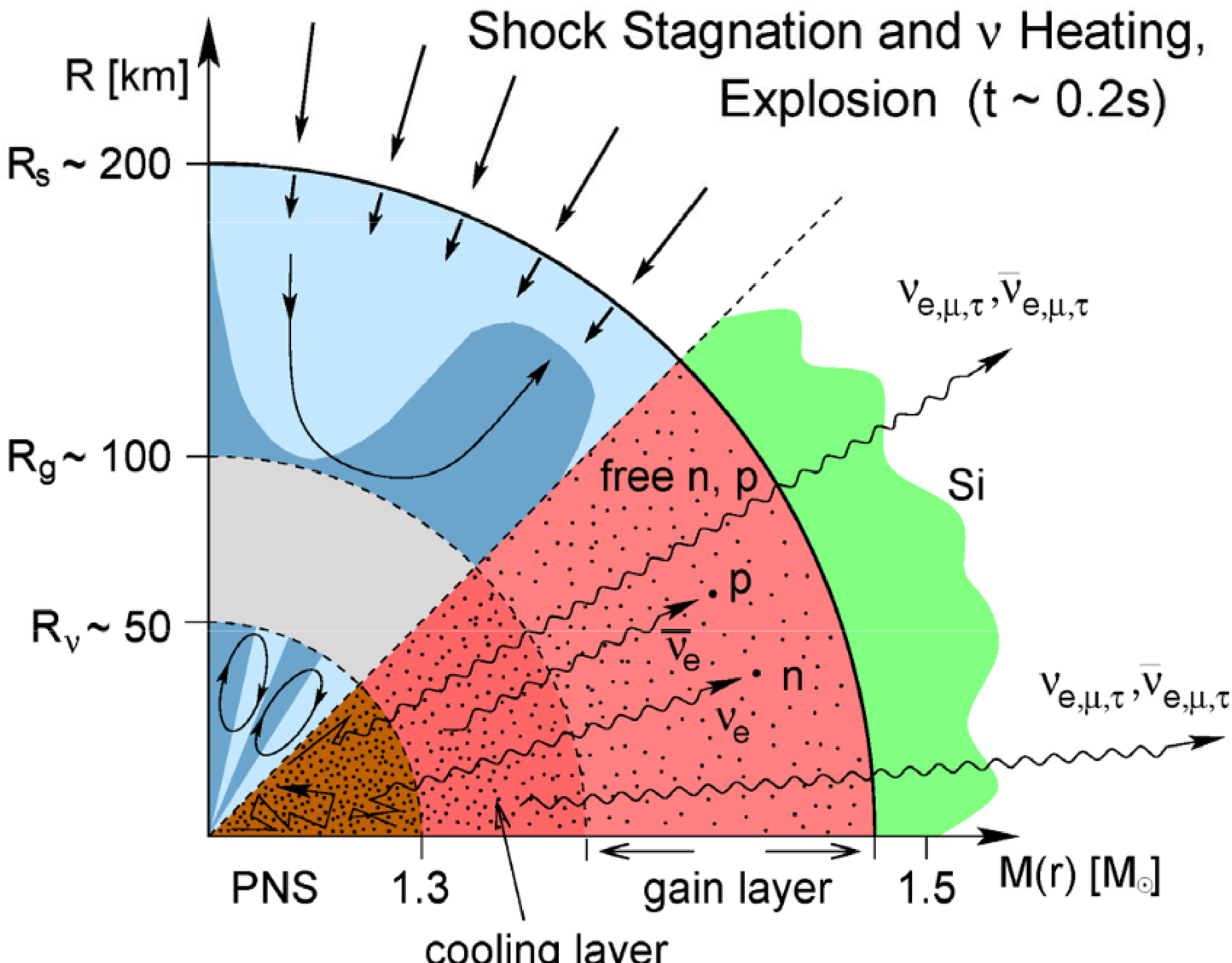

Initial Phase of Collapse
(t ~ 0)
R [km]
R_Fe ~ 3000
Fe, Ni
Si
ν_e
ν_e
ν_e
0.5
1.0
~ M_Ch
M(r) [M_⊙]
Si−burning shell



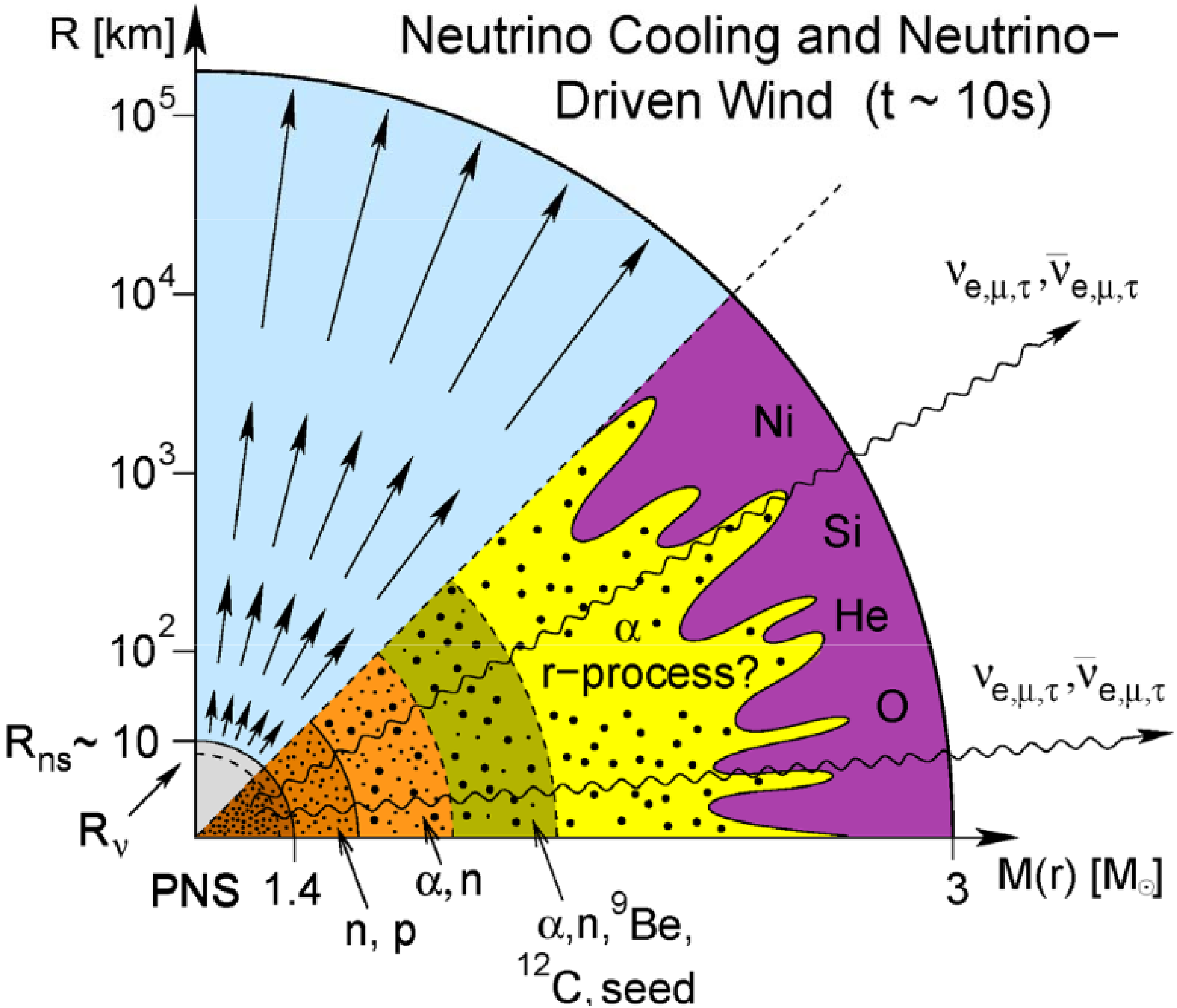
Neutrino Trapping
(t ~ 0.1s, ϱc~10¹² g/cm³)
R [km]
RFe
~ 100
νe
νe
νe
Si
Fe, Ni
0.5
Mhc
1.0
M(r) [M⊙]
heavy nuclei
Si−burning shell


R [km]
Bounce and Shock Formation
(t ~ 0.11s, $\varrho_c \lesssim 2\varrho_o$)
R_{Fe}
radius of
shock
formation
~ 10
ν_e
Si
ν_e
Fe, Ni
ν_e
0.5
1.0
M(r) [$M_\odot$]
nuclear matter
($\varrho \gtrsim \varrho_o$)
nuclei
Si−burning shell


Shock Propagation and ν_e Burst
(t ~ 0.12s)
R [km]
R_{Fe}
R_s ~ 100 km
R_ν
position of shock formation
free n, p
Fe
Ni
Si
ν_e
0.5
1.0
M(r) [$M_\odot$]
nuclear matter
nuclei
Si−burning shell

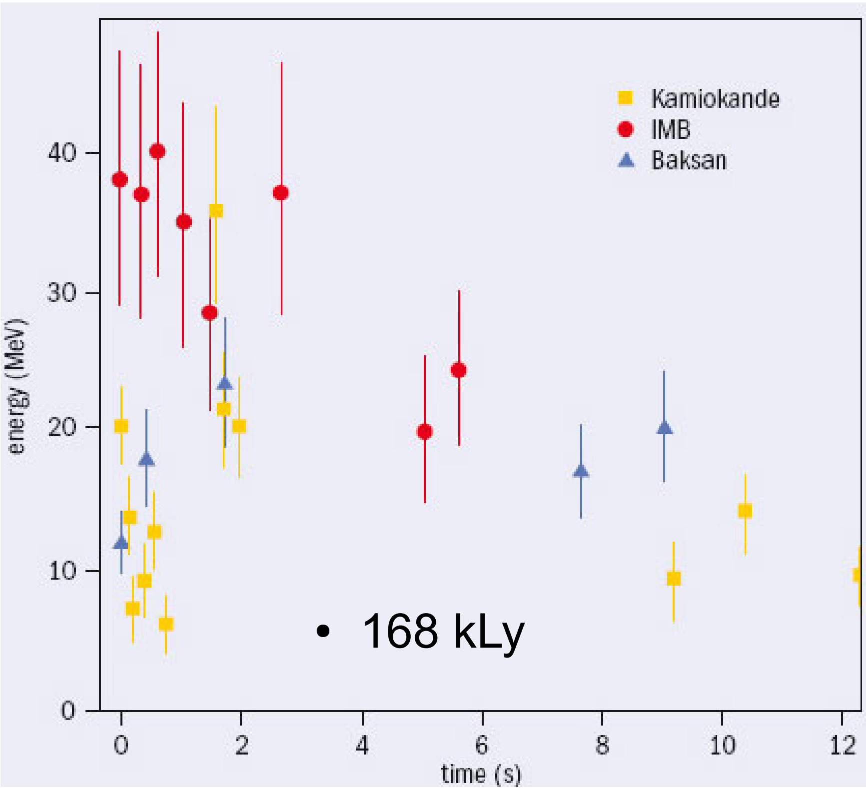


Shock Stagnation and ν Heating,
Explosion (t ~ 0.2s)
R [km]
R_s ~ 200
R_g ~ 100
R_ν ~ 50
$\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$
free n, p
Si
p
$\bar{\nu}_e$
n
ν_e
$\nu_{e,\mu,\tau}, \bar{\nu}_{e,\mu,\tau}$
PNS
1.3
gain layer
1.5
M(r) [$M_\odot$]
cooling layer

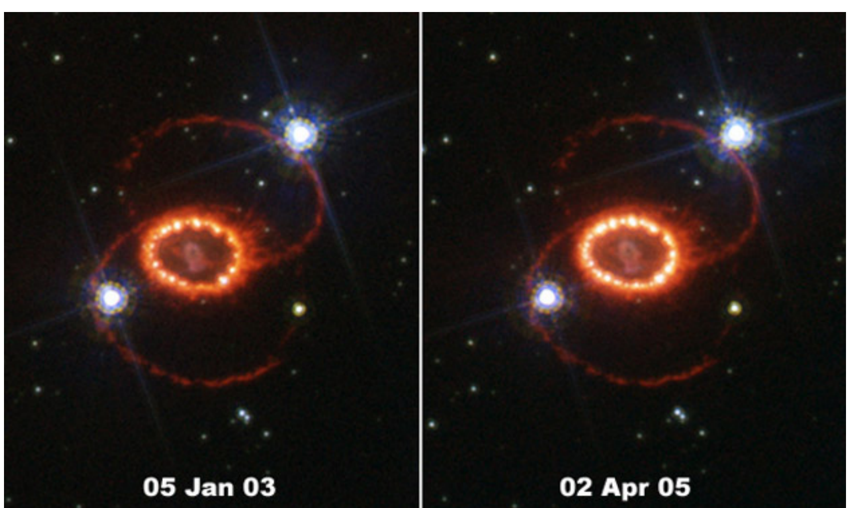


Neutrino Cooling and Neutrino−Driven Wind (t ~ 10s)
R [km]
10^5
10^4
10^3
10^2
R_ns ~ 10
R_ν
PNS
1.4
n, p
α, n
α, n, 9Be, 12C, seed
3
M(r) [M⊙]
Ni
Si
He
O
α
r−process?
ν_e,μ,τ, ν̄_e,μ,τ
ν_e,μ,τ, ν̄_e,μ,τ

Sn1987a



- 168 kLy



The r-process

- Occurs in core collapse supernovae
- Responsible for about half elements with Z > 26
- Neutron density up to 10^{30} ncm^{-3}

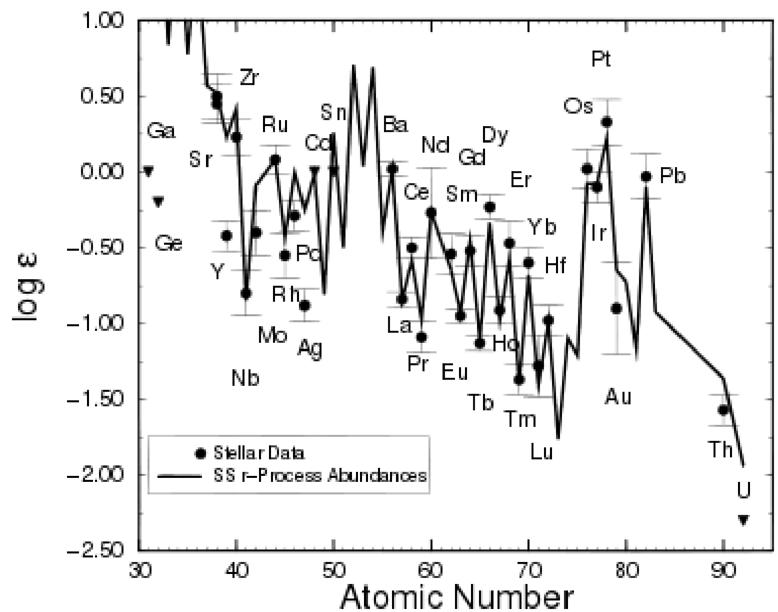
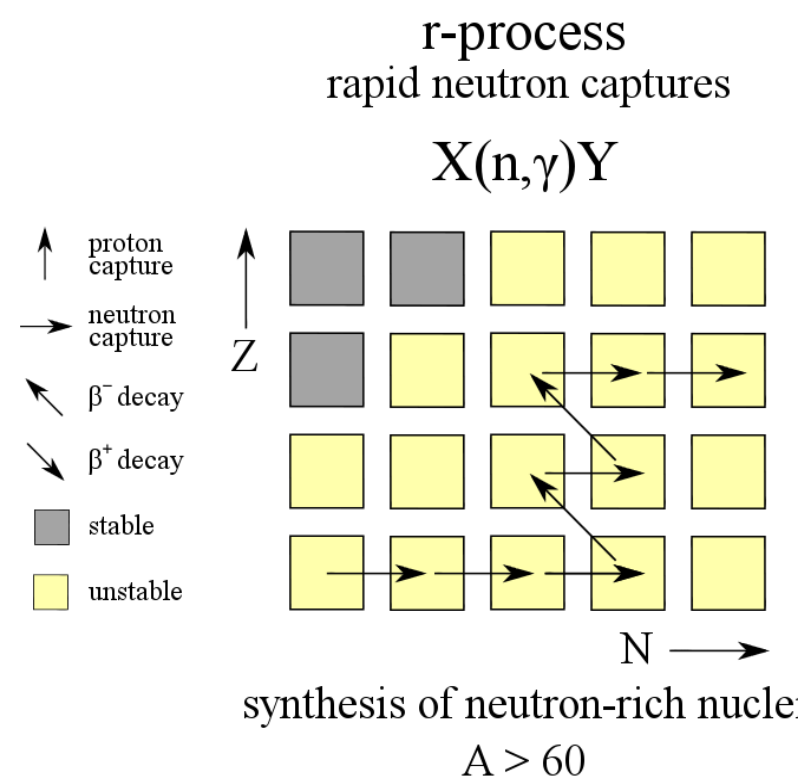
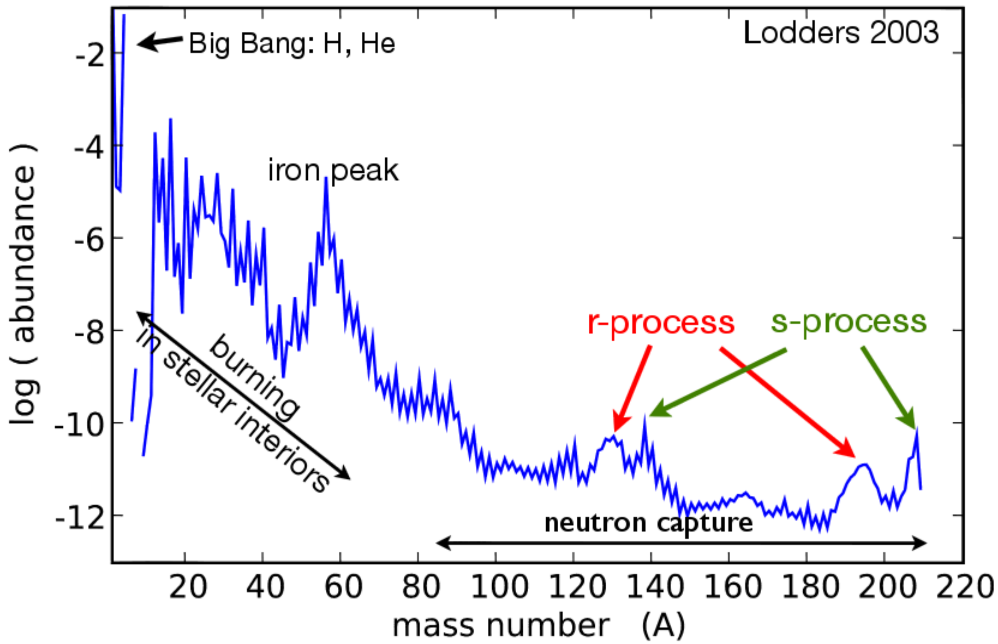


Fig. 1.2. Comparison of the observed n-capture abundances in CS 22892−052 from Sneden et al. (2003) and the solar system r-process abundance curve. Upper limits indicated by inverted triangles.



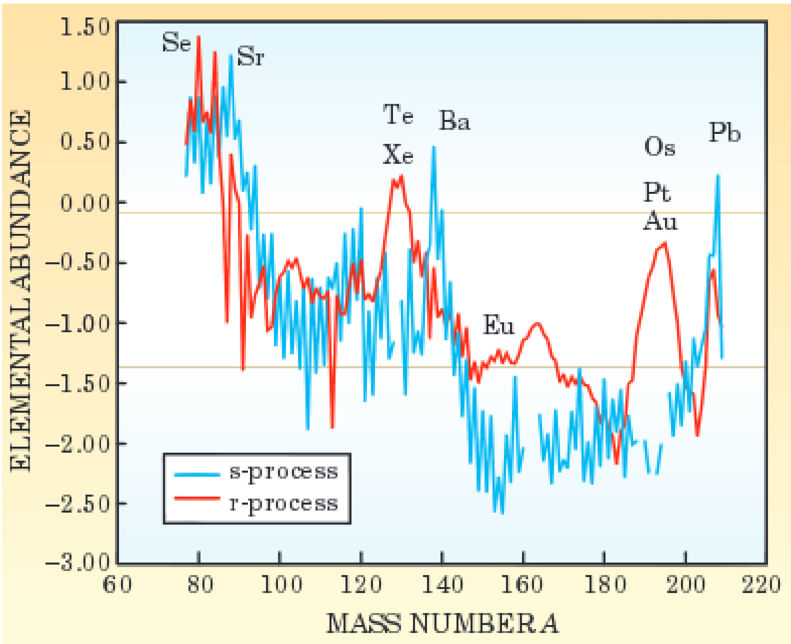
s,r-processes

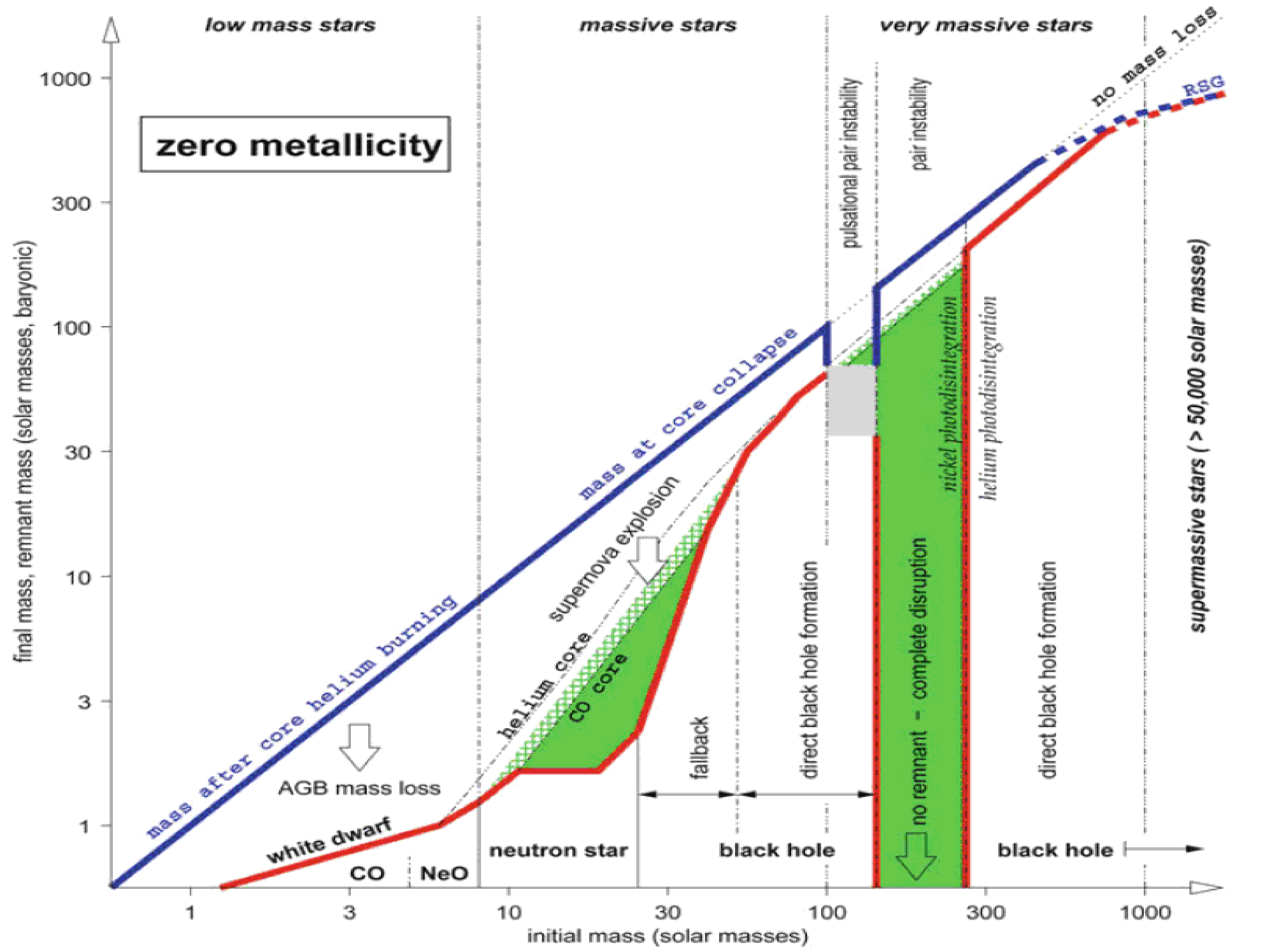


- Solar system abundaces produced by r ans s processes. Abundance peaks are caused by minimal n-capture rates at magic numbers(corresponding to full neutron shells).
- Because the r-process carries nuclei farther from the valley of stability than does the s-process, it en-counters each closed shell at slightly lower mass number.
- Hence the r-process peaks are offset to lower A. The two processes really have contributed about equally to the solar system's inventory of heavy elements. (Adapted from ref.

s-process: slow neutron capture

r-process: rapid neutron capture





low mass stars
massive stars
very massive stars
zero metallicity
final mass, remnant mass (solar masses, baryonic)
initial mass (solar masses)
1000
300
100
30
10
3
1
10
30
100
300
1000
no mass loss
RSG
mass after core helium burning
mass at core collapse
supernova explosion
helium core
CO core
AGB mass loss
white dwarf
CO
NeO
neutron star
black hole
black hole
fallback
direct black hole formation
direct black hole formation
pulsational pair instability
pair instability
nickel photodisintegration
helium photodisintegration
no remnant - complete disruption
supermassive stars (> 50,000 solar masses)