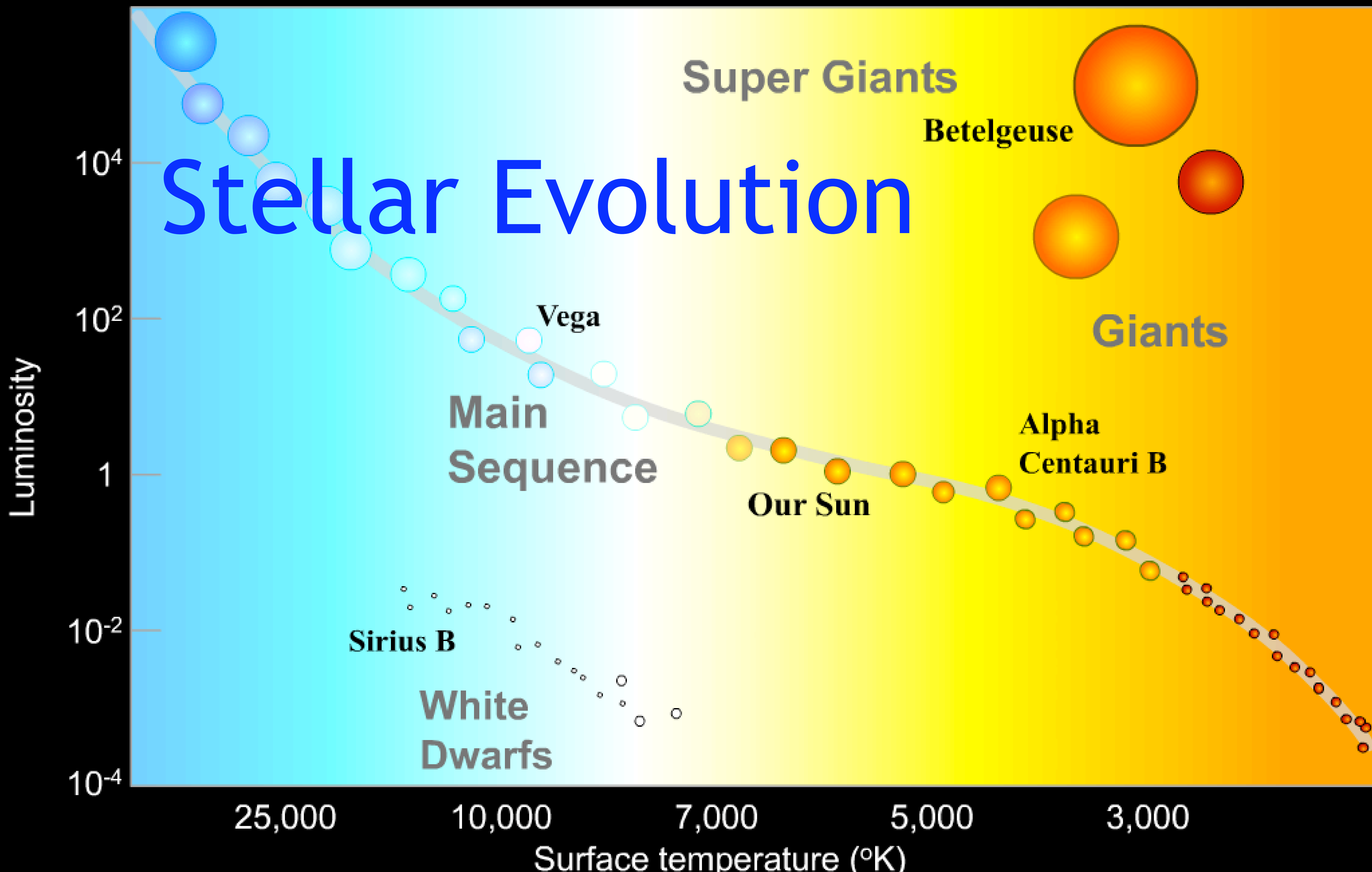
Stellar Evolution

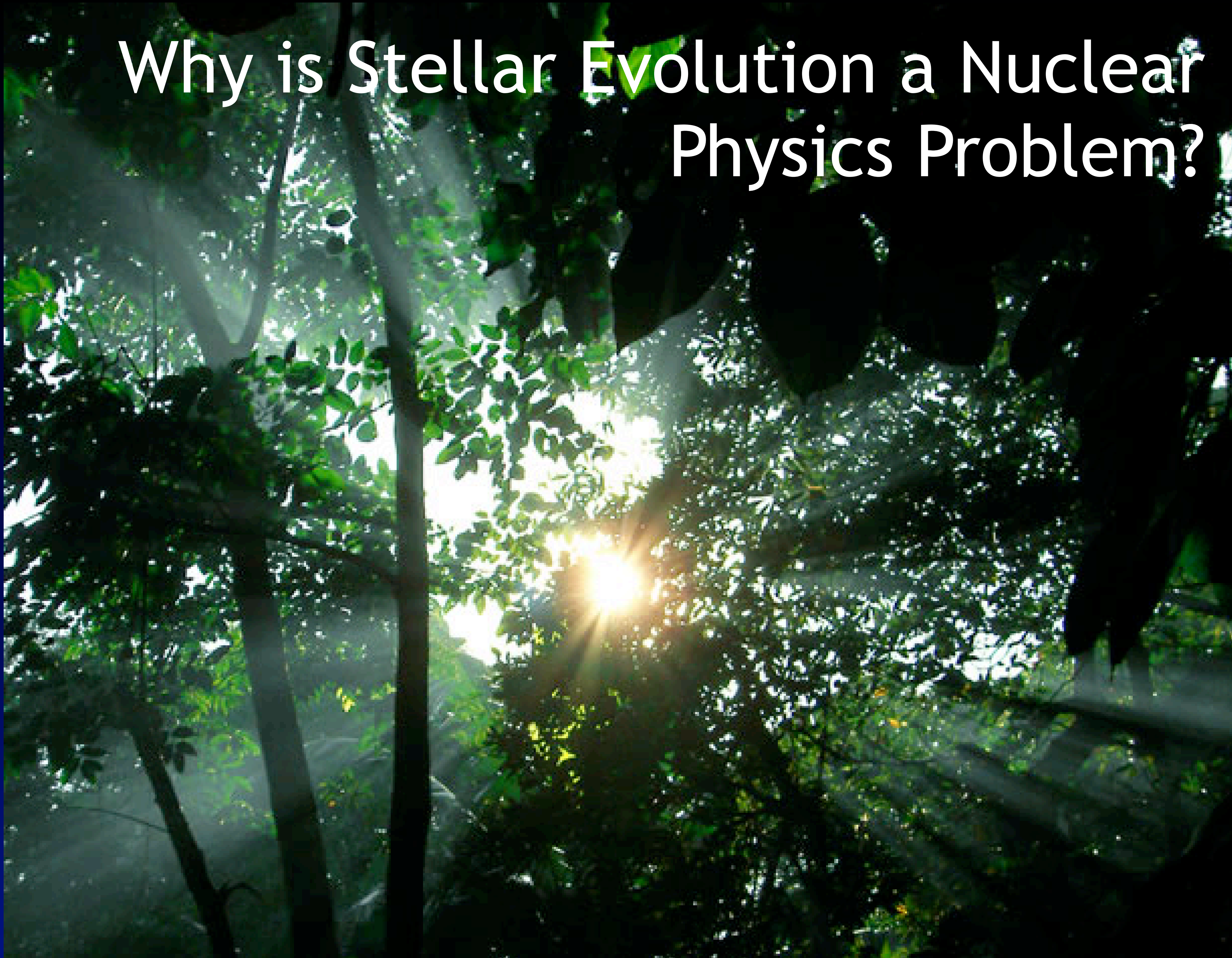


W. R. Hix, CNS Summer School, August 2007

Lecture Schedule

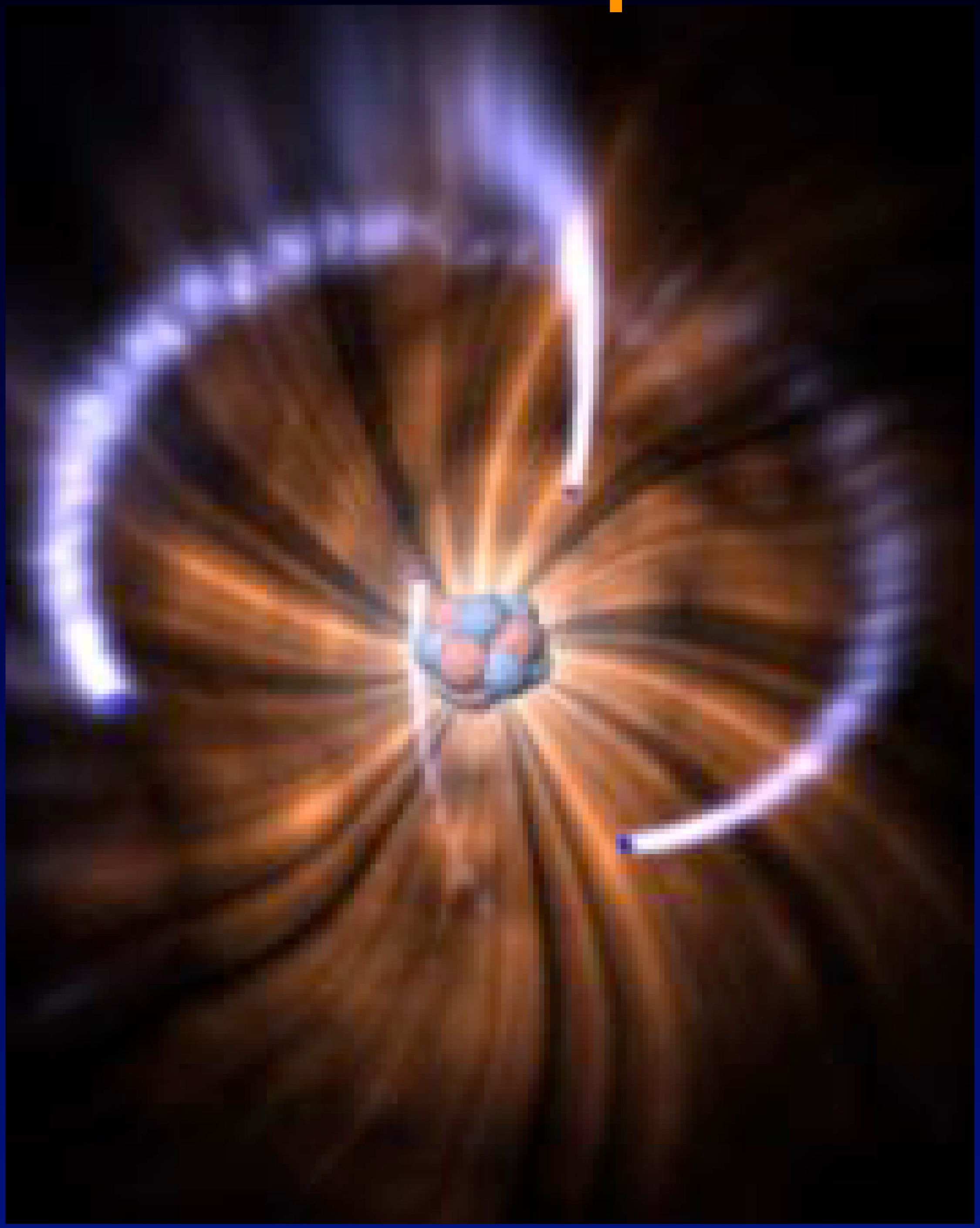
1. Nuclear Physics for Astrophysics
2. Lives of Stars
    1. What is the lifecycle of stars?
    2. How does Nuclear Physics drive this lifecycle?
3. Supernovae
4. Stellar Afterlife

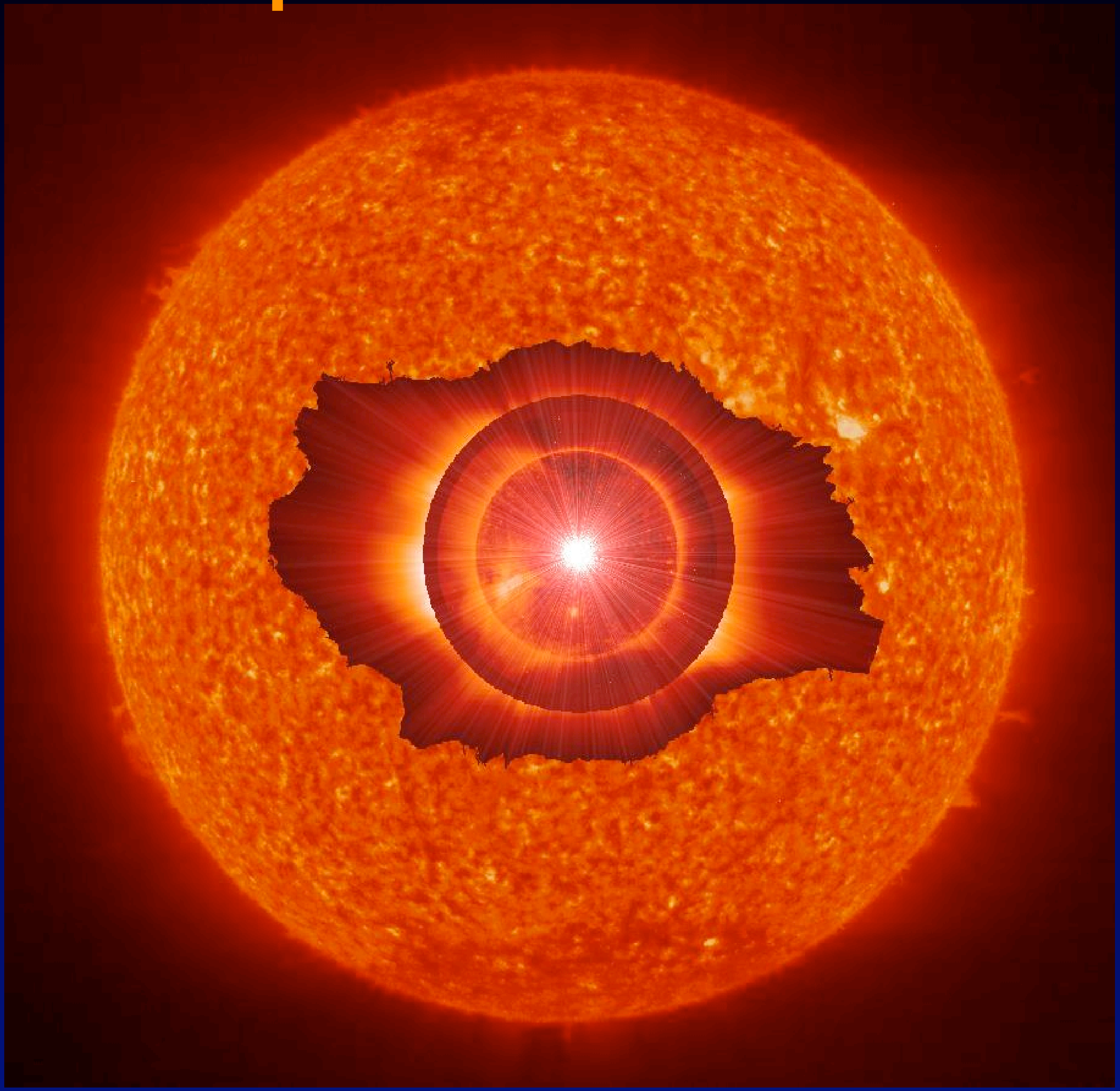
Why is Stellar Evolution a Nuclear Physics Problem?



Nuclear reactions cause stars to shine & drive their *structural* & *compositional* evolution in time.

Microscopic-Macroscopic Connection





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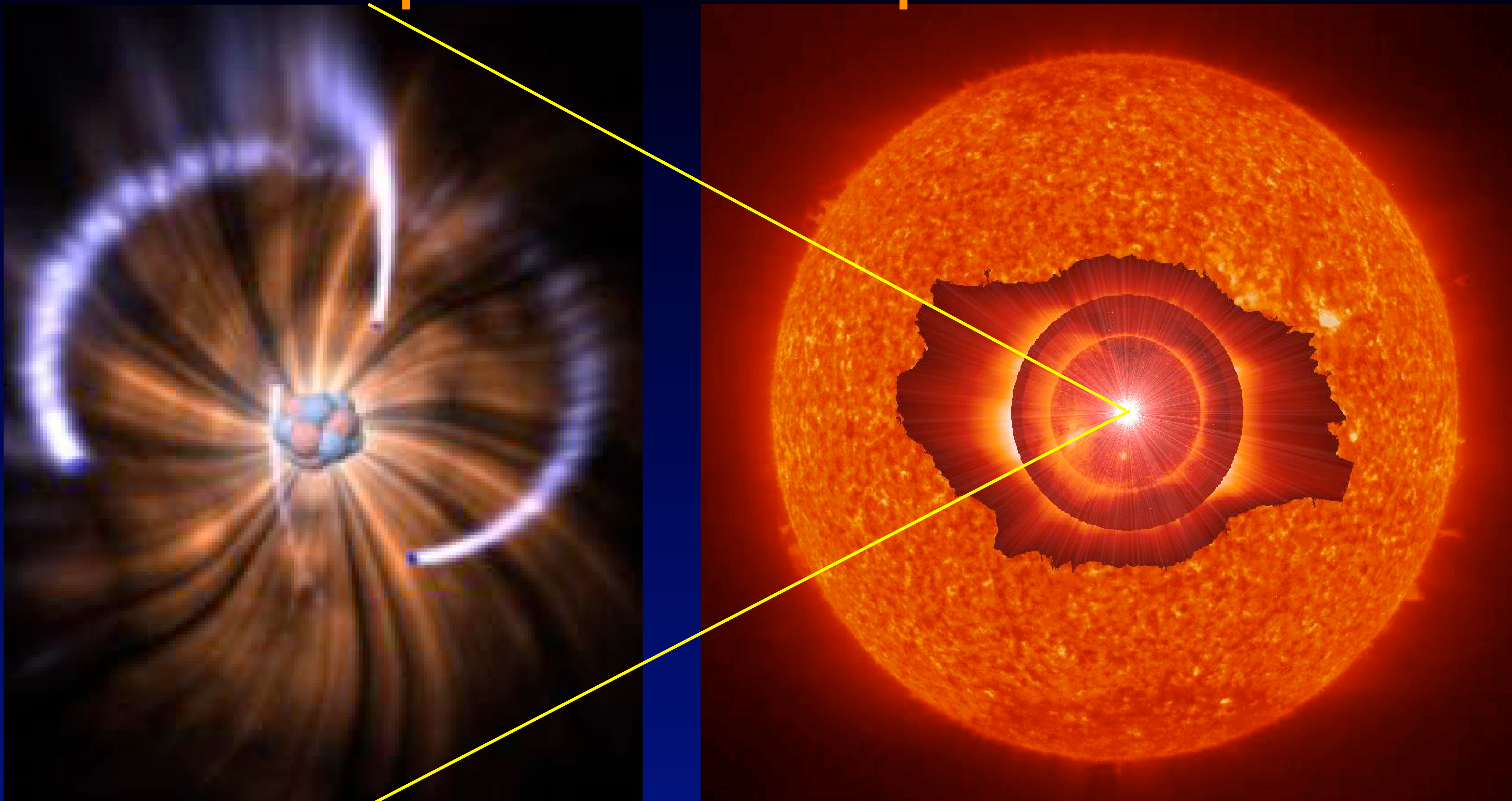
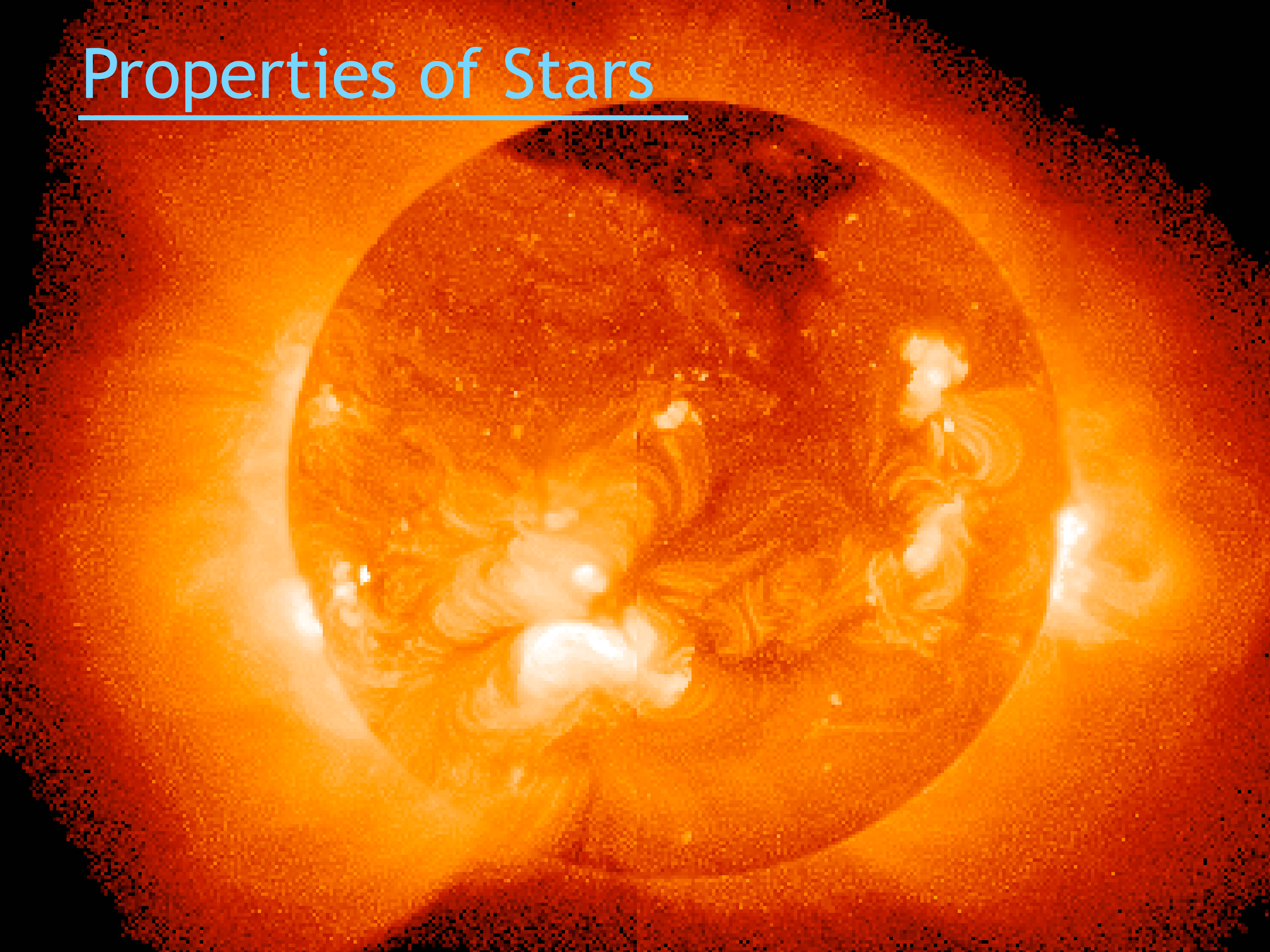


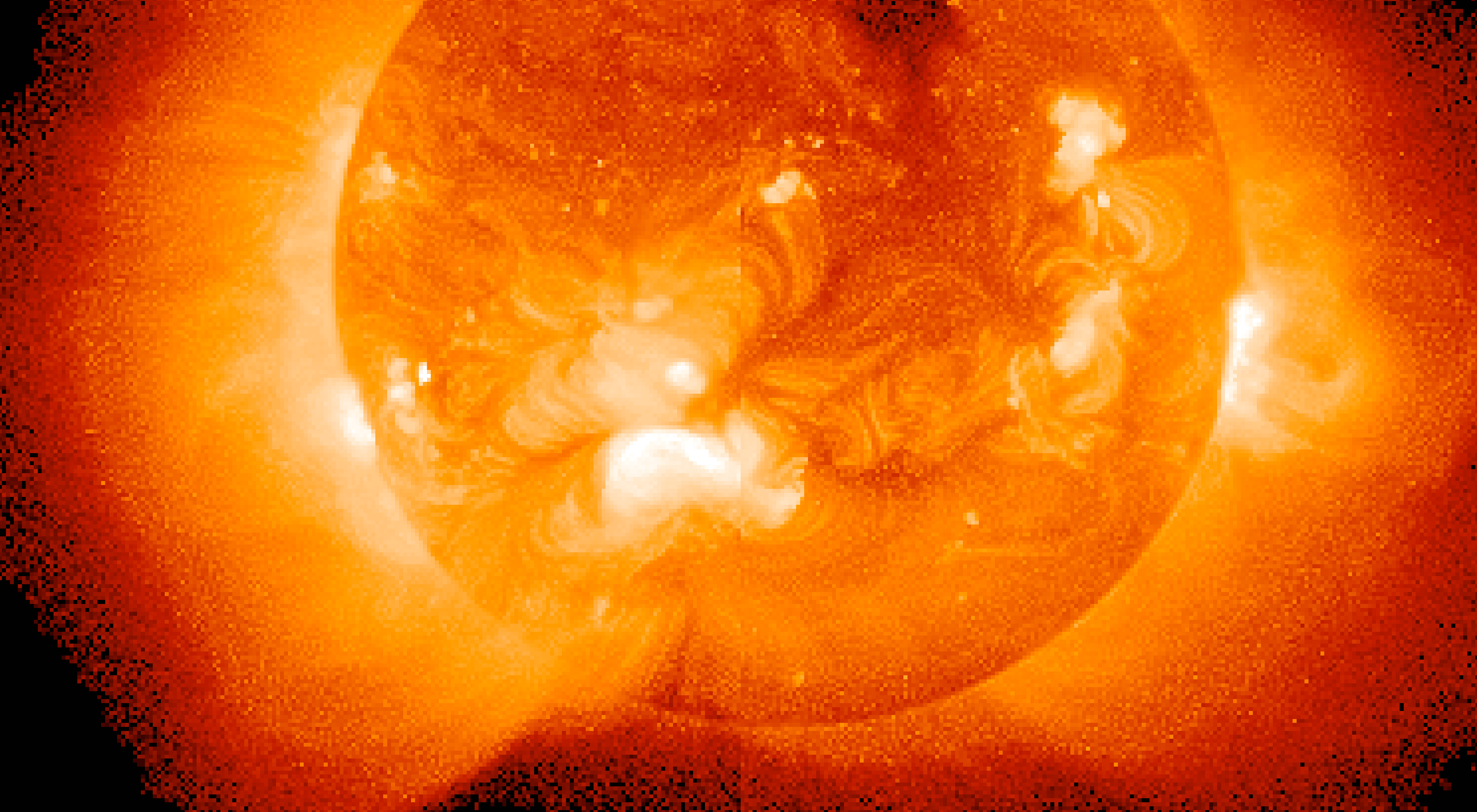
10^{-13} cm **10^{11} cm**

Properties of Stars



Properties of Stars

"Macroscopic": $\gtrsim 10^{11}$ cm in diameter
Massive: $\gtrsim 10^{30}$ kg, gravitational energy of $\sim 10^{41}$ J



Properties of Stars

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Long-lived: lifetimes of millions - billions of years

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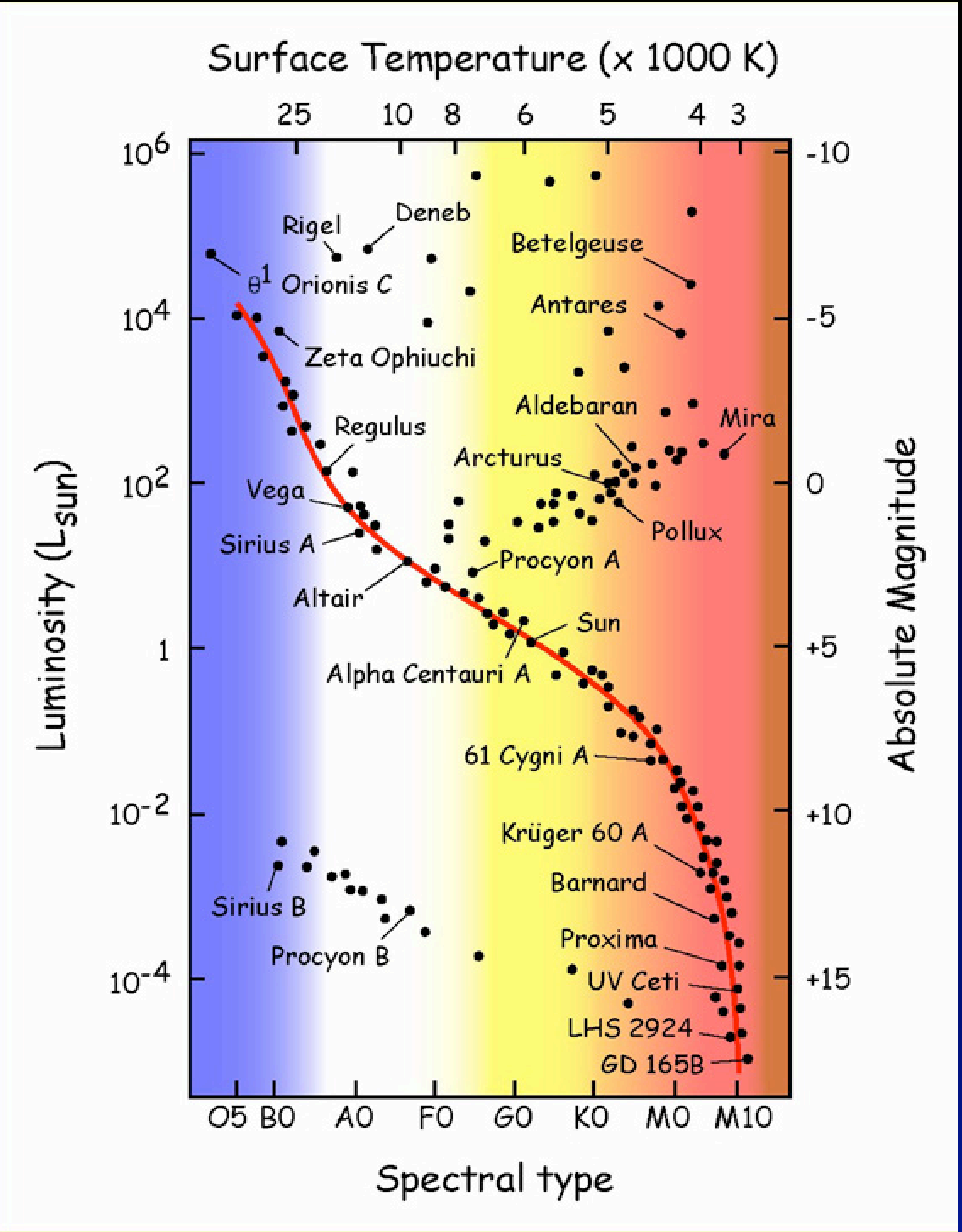
Variety: different populations of stars - metal-rich, metal-poor; dwarfs, giants …
Familiar: atomic emission spectra show their composition is (primarily) Earth-like & Solar system-like.

Of Dwarves & Giants

Hertzprung-Russell Diagram plots Brightness verses Temperature.

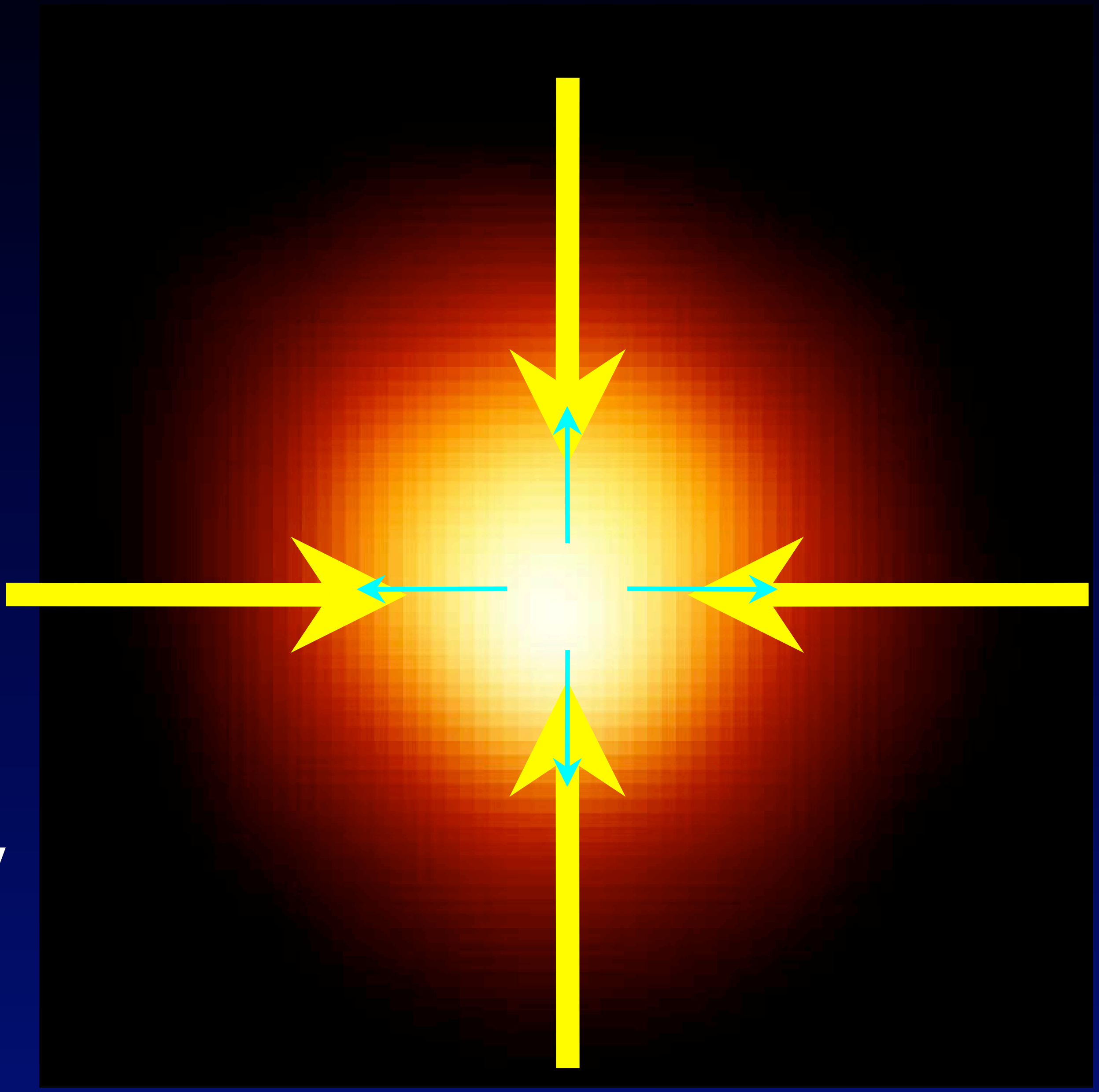
Luminosity is proportional to Temperature and Radius ($L \propto T^4 R^2$).

Radius increases to the upper right, so Giants are at the top, Dwarves at the bottom.



Opposing Gravity

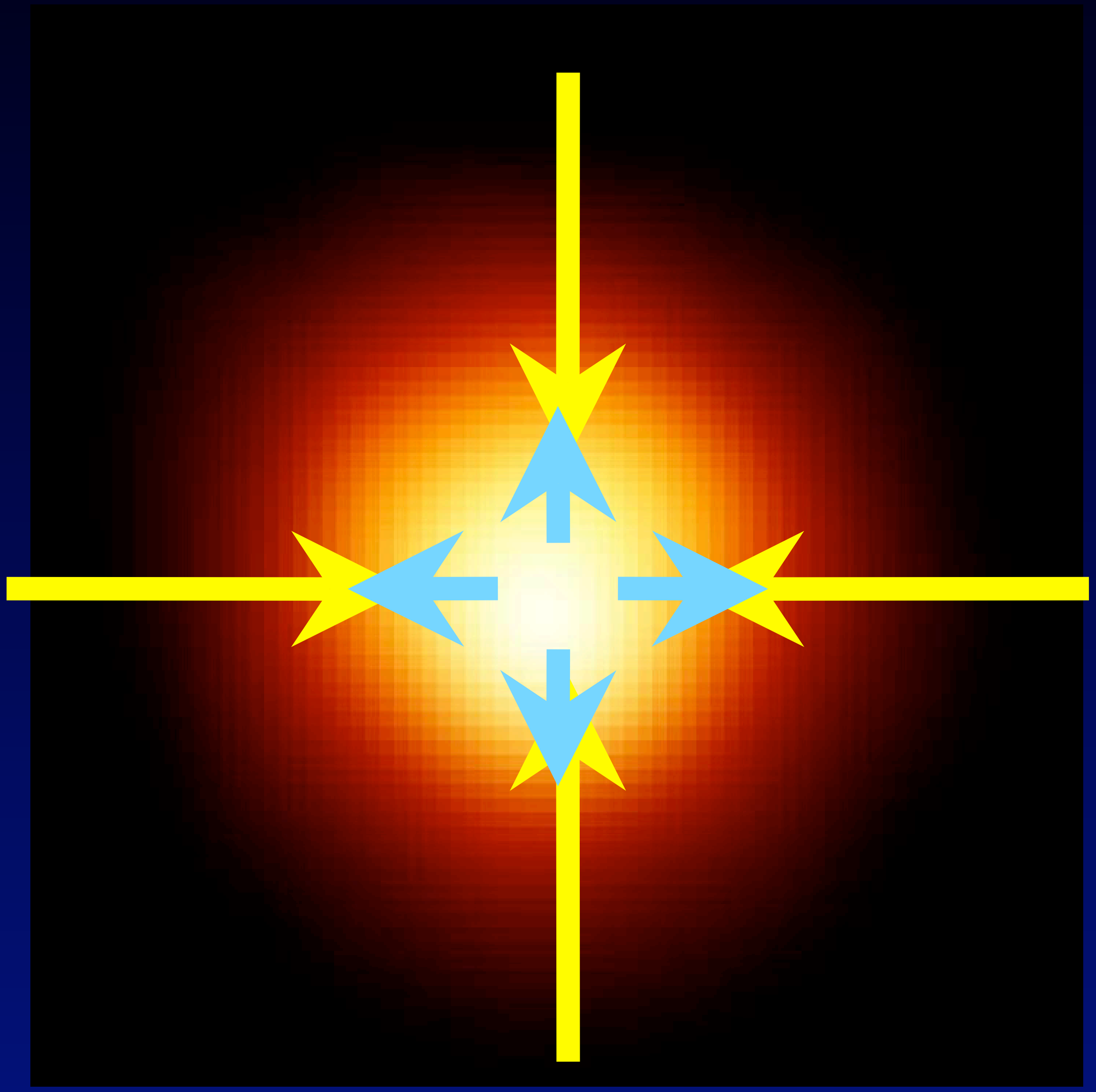
Stars are luminous, hot, massive, self-gravitating collections of nuclei (and electrons).



To generate sufficient light via release of gravitational potential energy due to contraction, a star would only live for ~ 10^7 years.

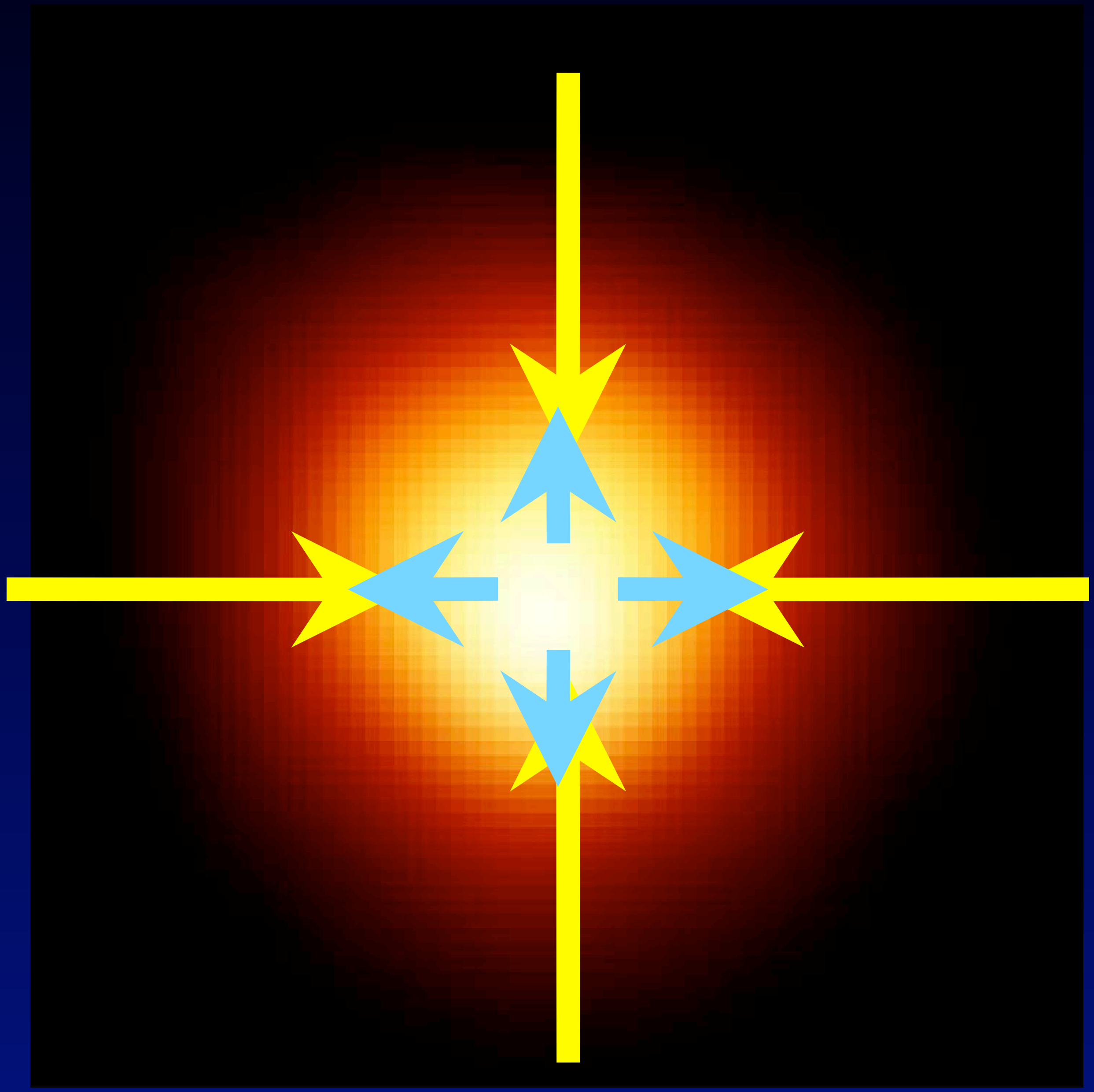
Stars must have an internal energy source to prevent gravitational collapse faster than "observed" lifetimes (~ 10^8 - 10^9 years).

Power Source?



Power Source?

Release of chemical energy due to breaking molecular bonds:
$\sim 10^5$ years, also too short



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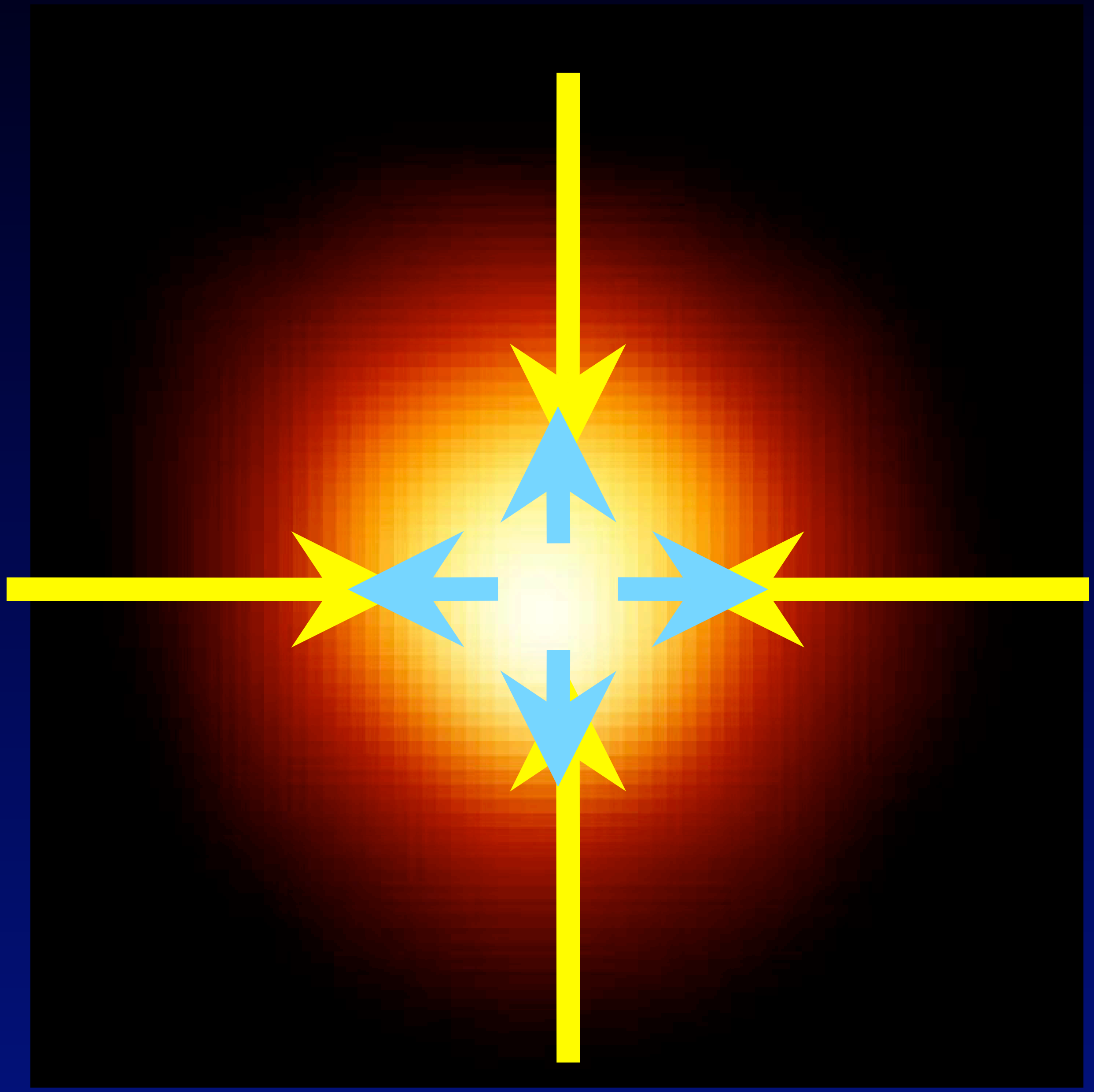
Suggested in 1920 by Eddington that energy from nuclear fusion reactions (e.g., 4 ^{1}H --> 1 ^{4}He) can balance gravity …



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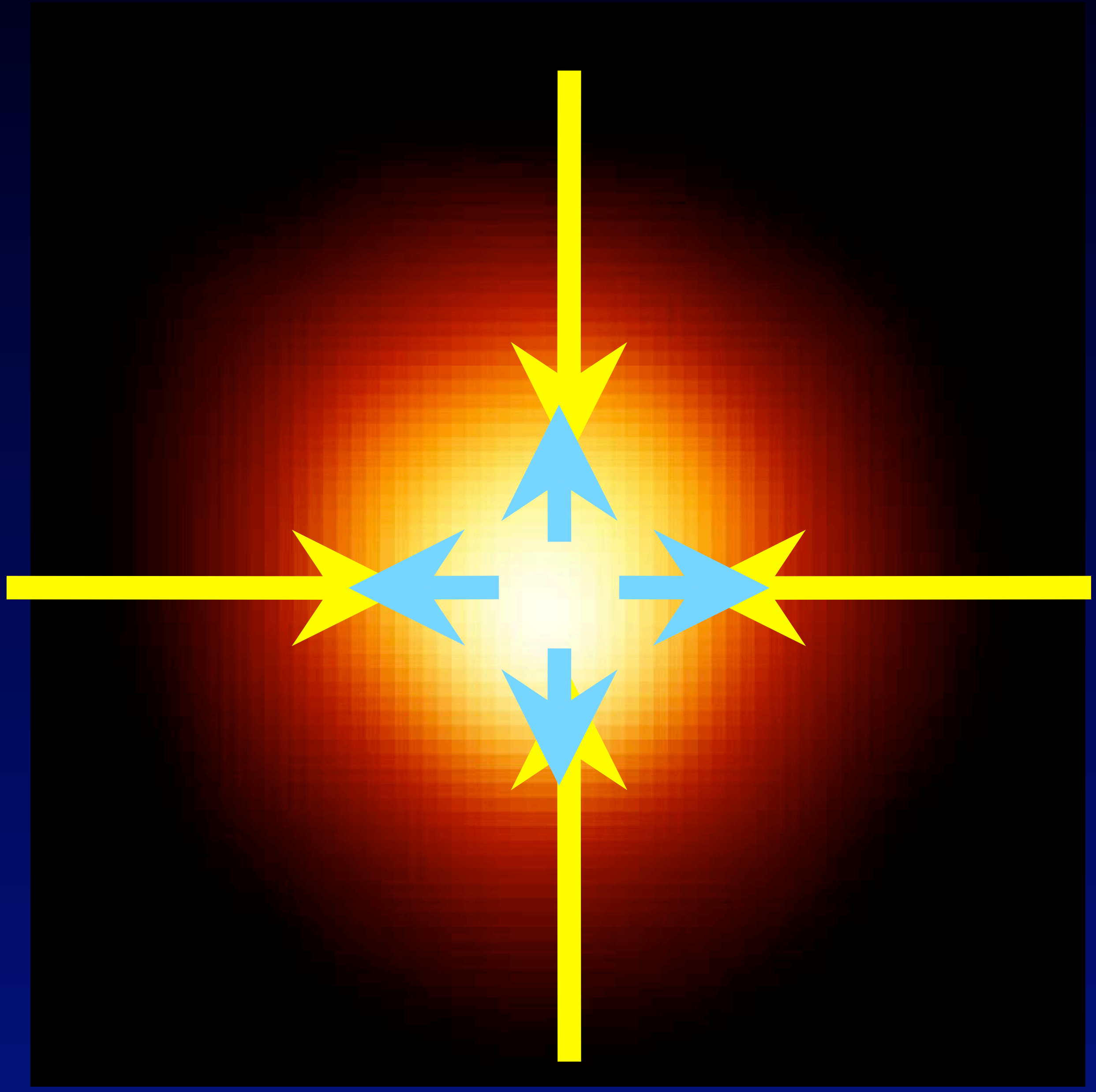

Does this generate enough energy?

Energy Generation from H to He Conversion

$4\ ^1H \Longrightarrow\ ^4He + \text{energy}$

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mass of $4\ {}^{1}H = 6.693 \times 10^{-27}$ kg

Energy Generation from H to He Conversion

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mass of $4\ ^1H = 6.693 \times 10^{-27}$ kg

mass of $1\ ^4He = 6.645 \times 10^{-27}$ kg

Energy Generation from H to He Conversion

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mass difference released as energy = $0.048 \bullet 10^{-27}$ kg / reaction

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SOLAR PARAMETERS

RADIUS	7.0×10^{8} meters
MASS	2.0×10^{30} kgm
LUMINOSITY	3.9×10^{26} joules/sec
SURFACE TEMPERATURE	~6000°K

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$$= 4.3 \times 10^{-12}\ \text{Joules/reaction}$$

$\Rightarrow 9.1 \times 10^{37}$ reactions/sec

or 6.0×10^{11} kg/sec of ^1H is converted to ^4He.

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Conversion of H to He

Two sequences of nuclear reactions were proposed for stellar energy generation by Eddington (1926), Gamow (1928), Weizacker (1937), Bethe & Critchfield (1938), and Bethe (1939).

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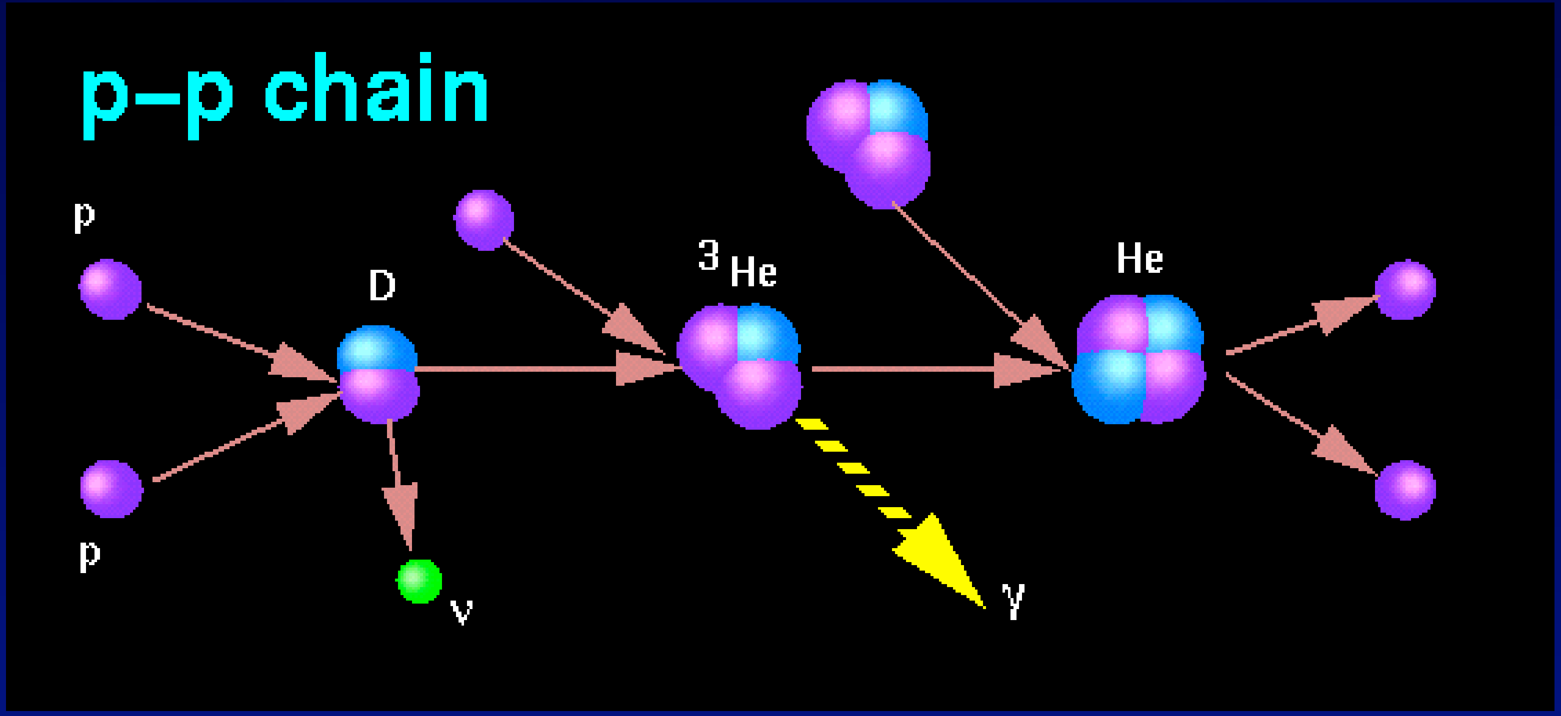
The pp-chain [proton-proton chain] occurring in our Sun & other low-mass stars



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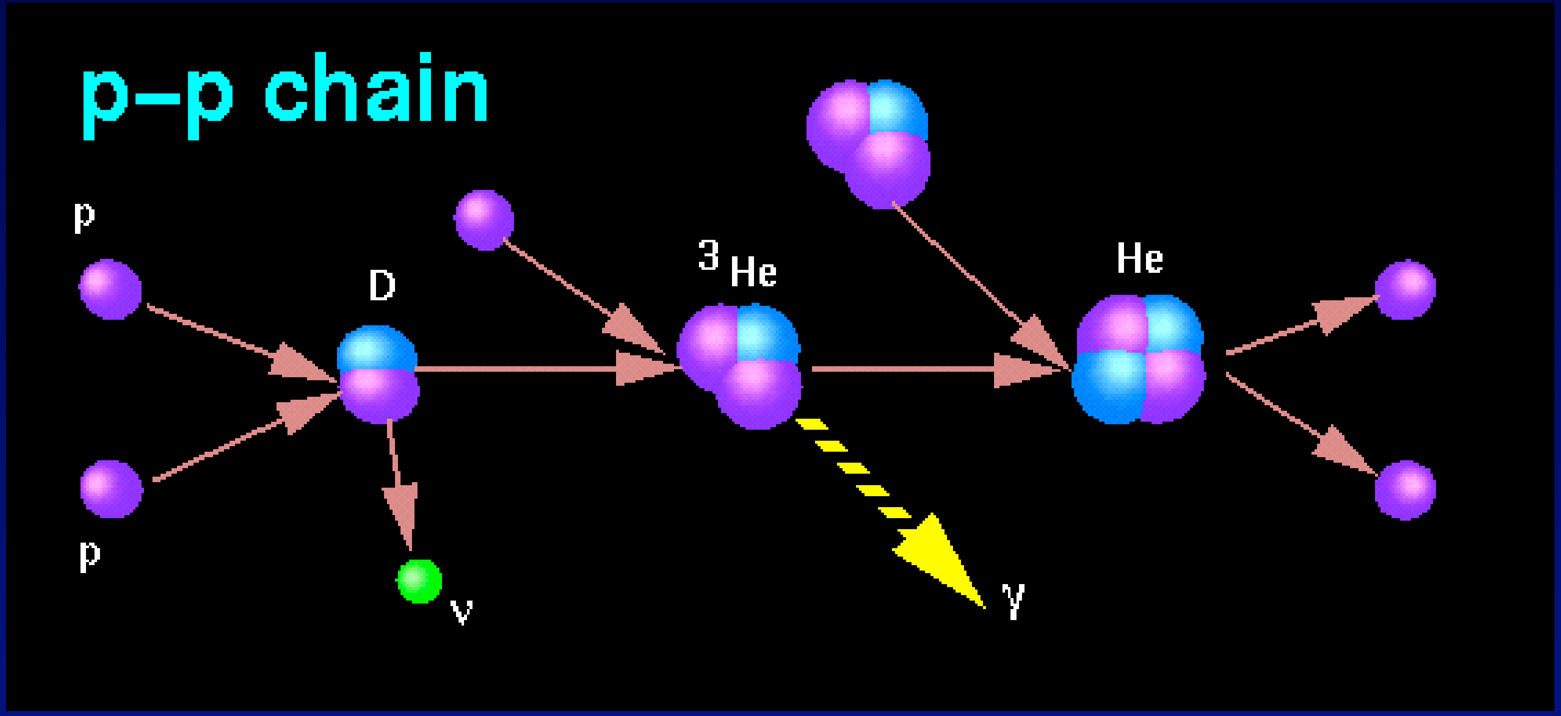
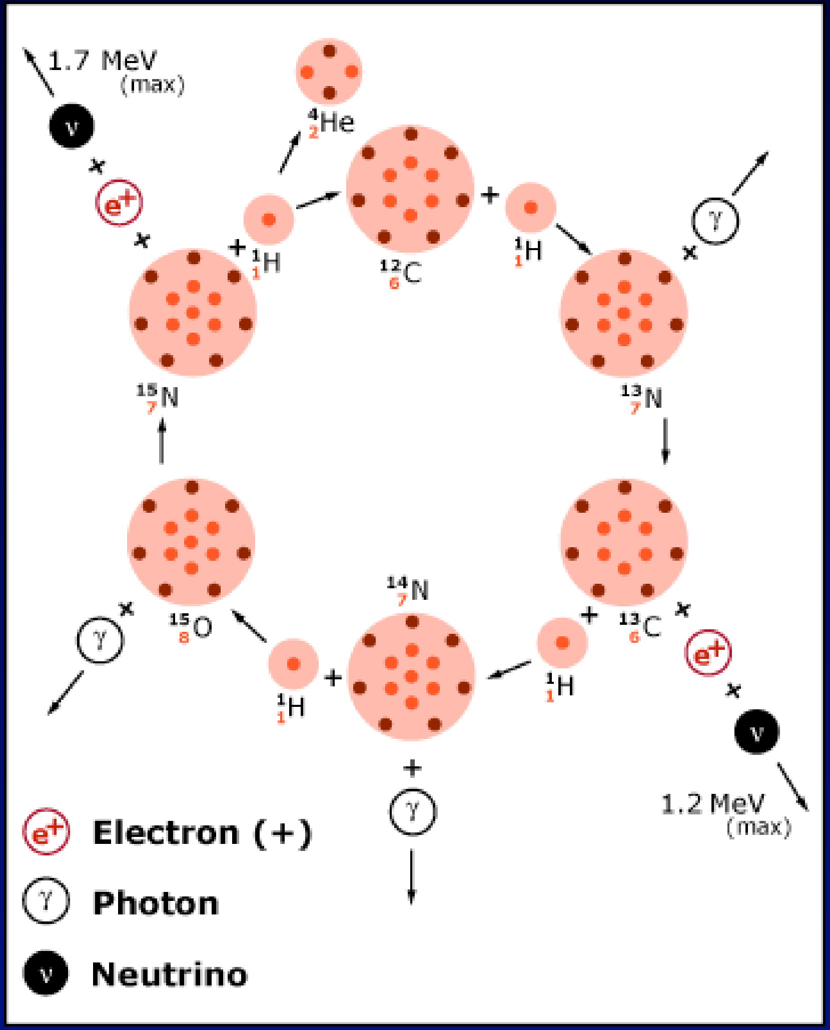
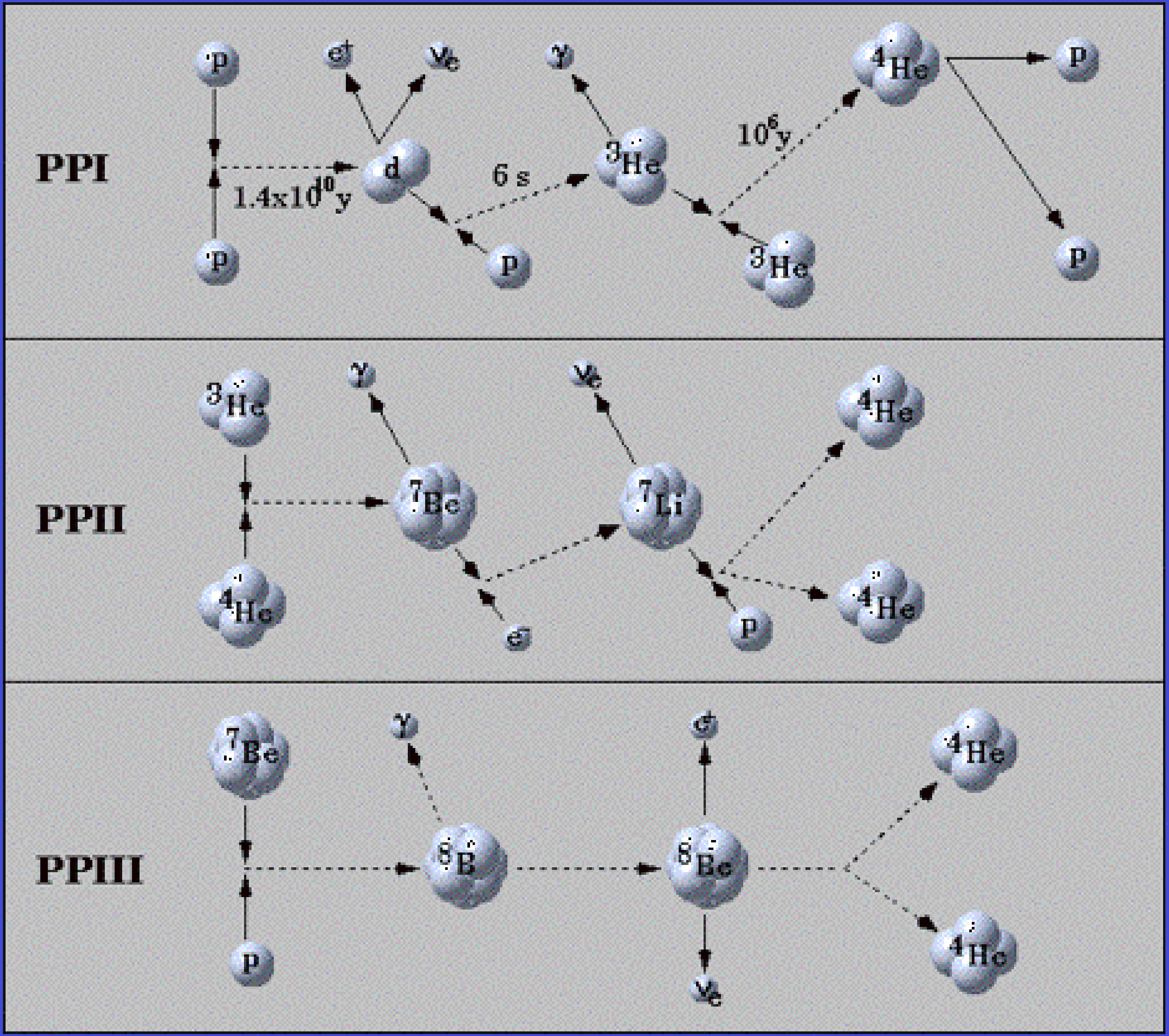




CNO cycle dominates in stars with mass > 1.5 M_{sun}

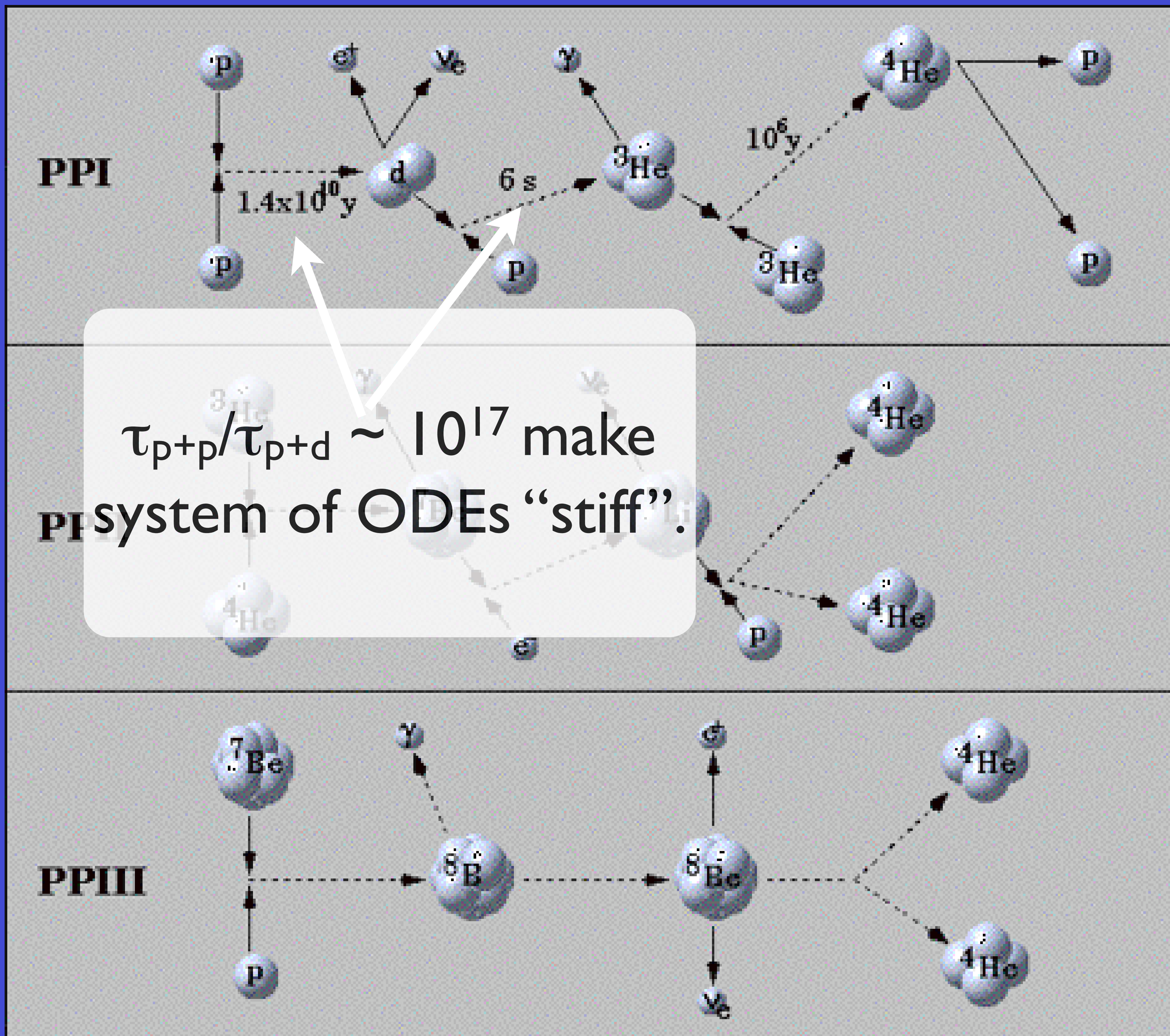
PP chains



Relative importance of PPI and PPII chains (*branching ratios*) depend on conditions of H-burning (T, ρ , abundances). The transition from PPI to PPII occurs at temperatures in excess of 1.3×10^7 K.

Above 3×10^7 K the PPIII chain dominates over the other two, but another process takes over in this case.

PP chains



$\tau_{p+p}/\tau_{p+d} \sim 10^{17}$ make system of ODEs “stiff”.

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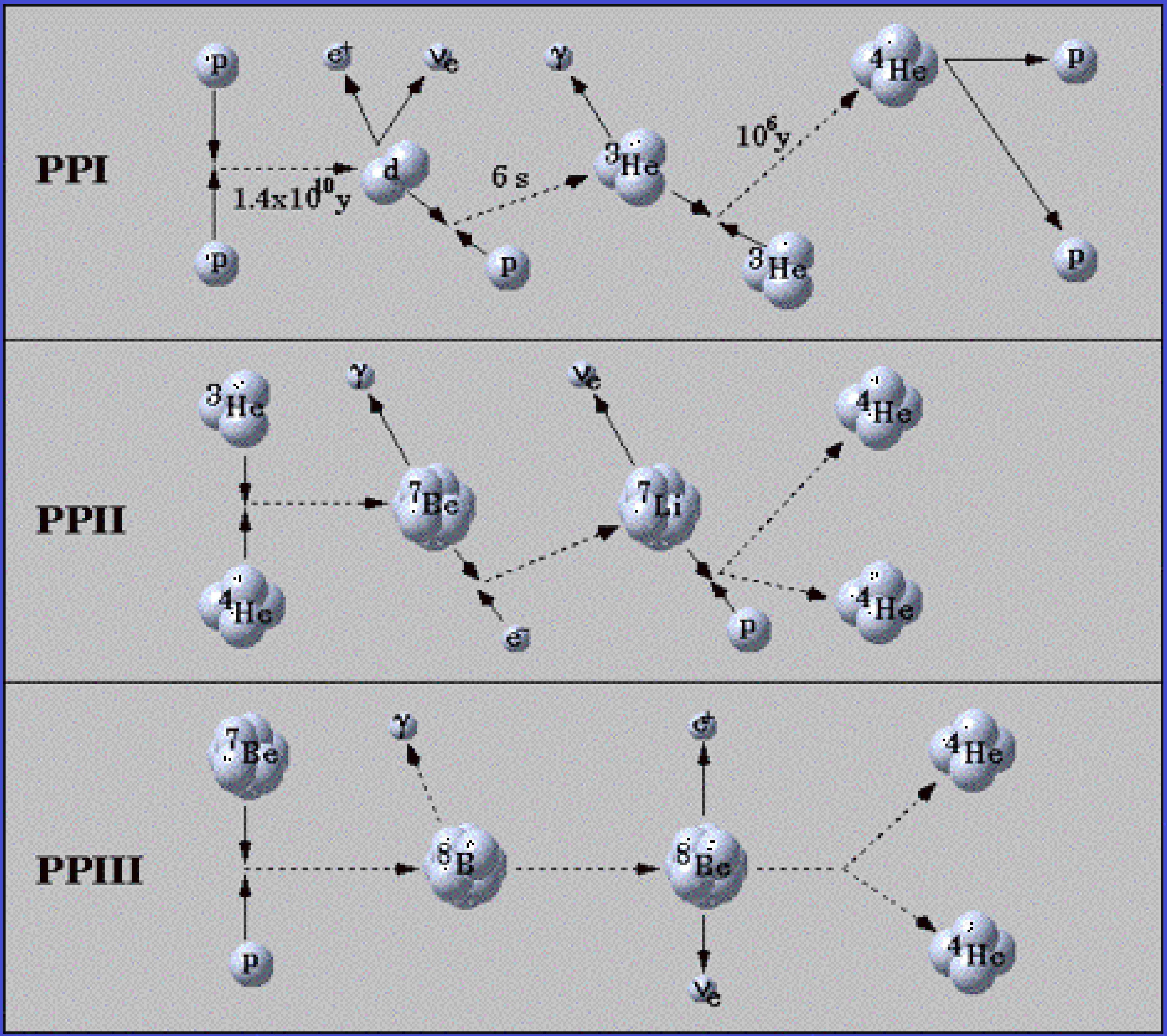

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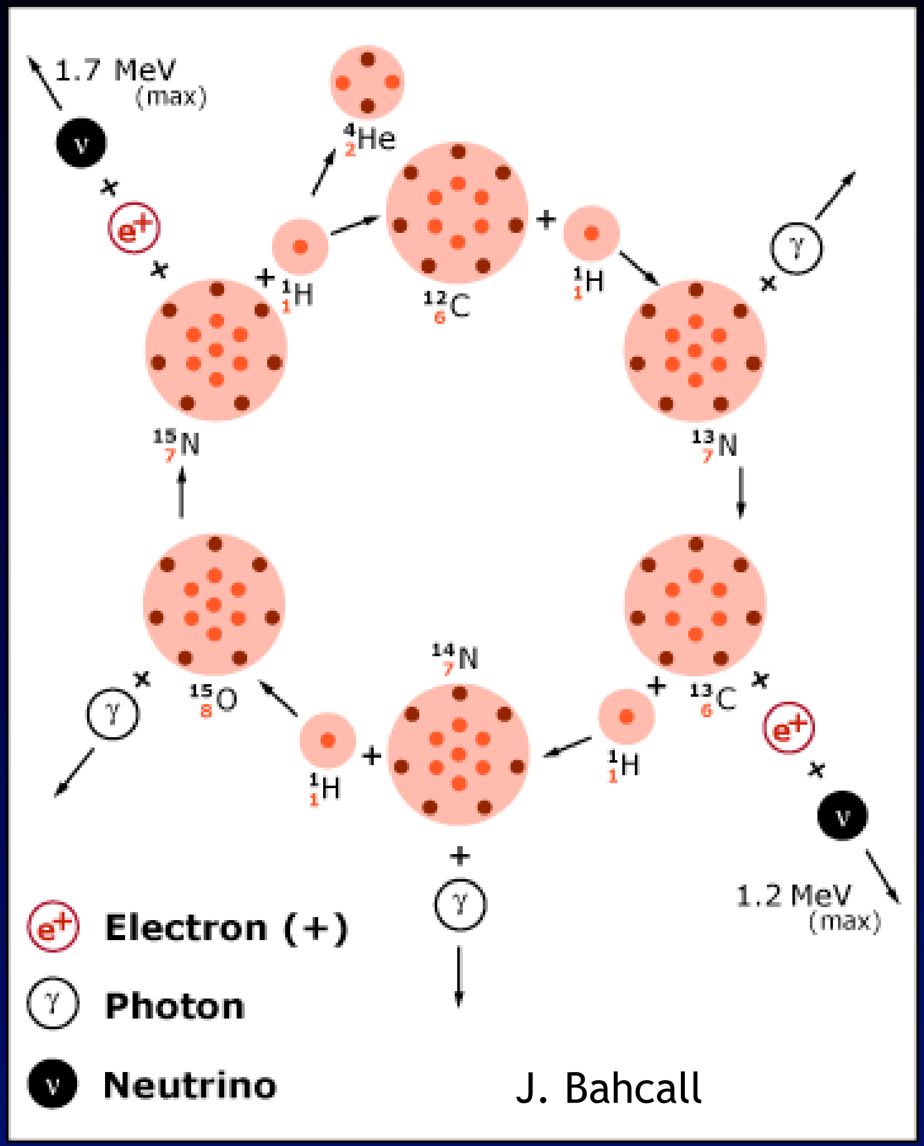

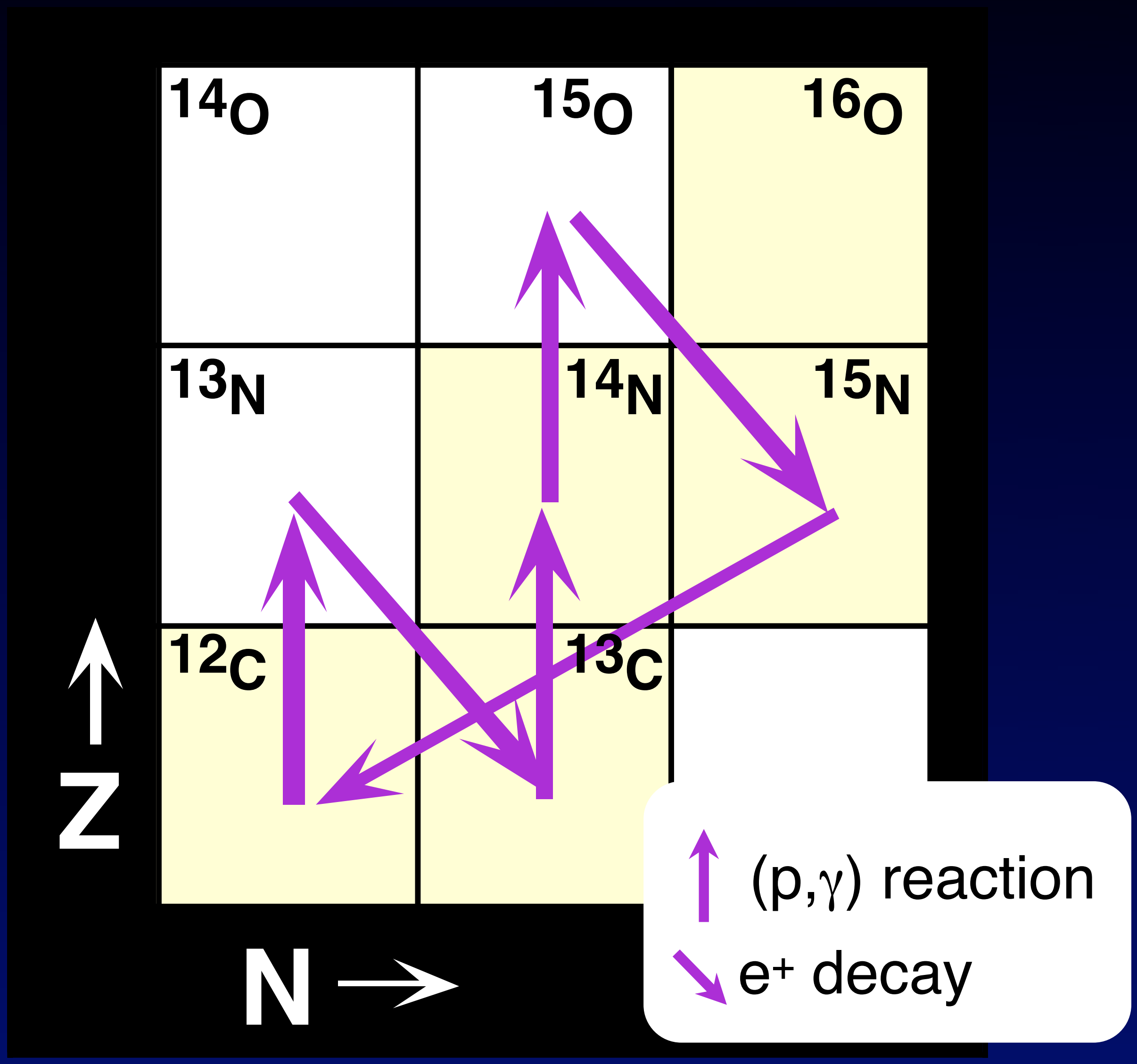

Catalytic cycle: reaction sequence starts from a “seed” (C or N) nucleus, consumes 4 protons (“fuel”) & regenerates seed.

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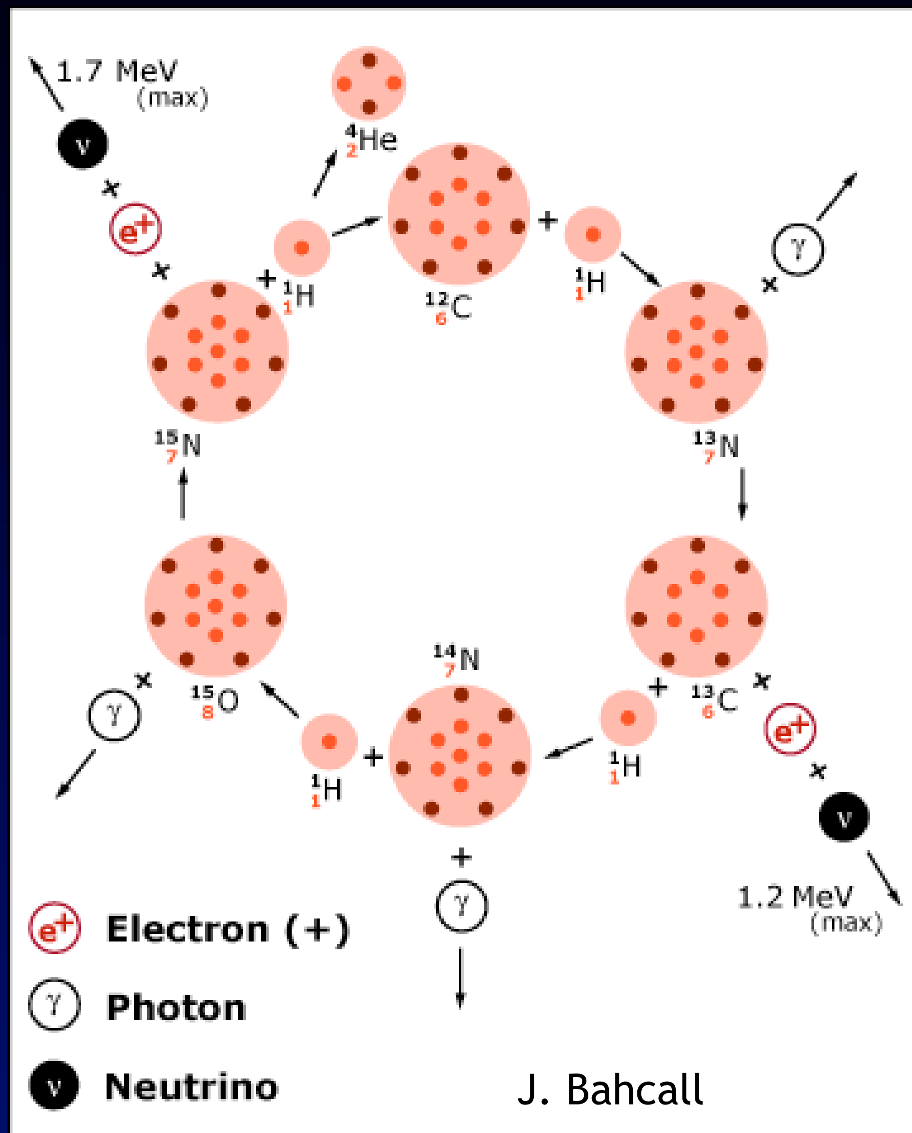

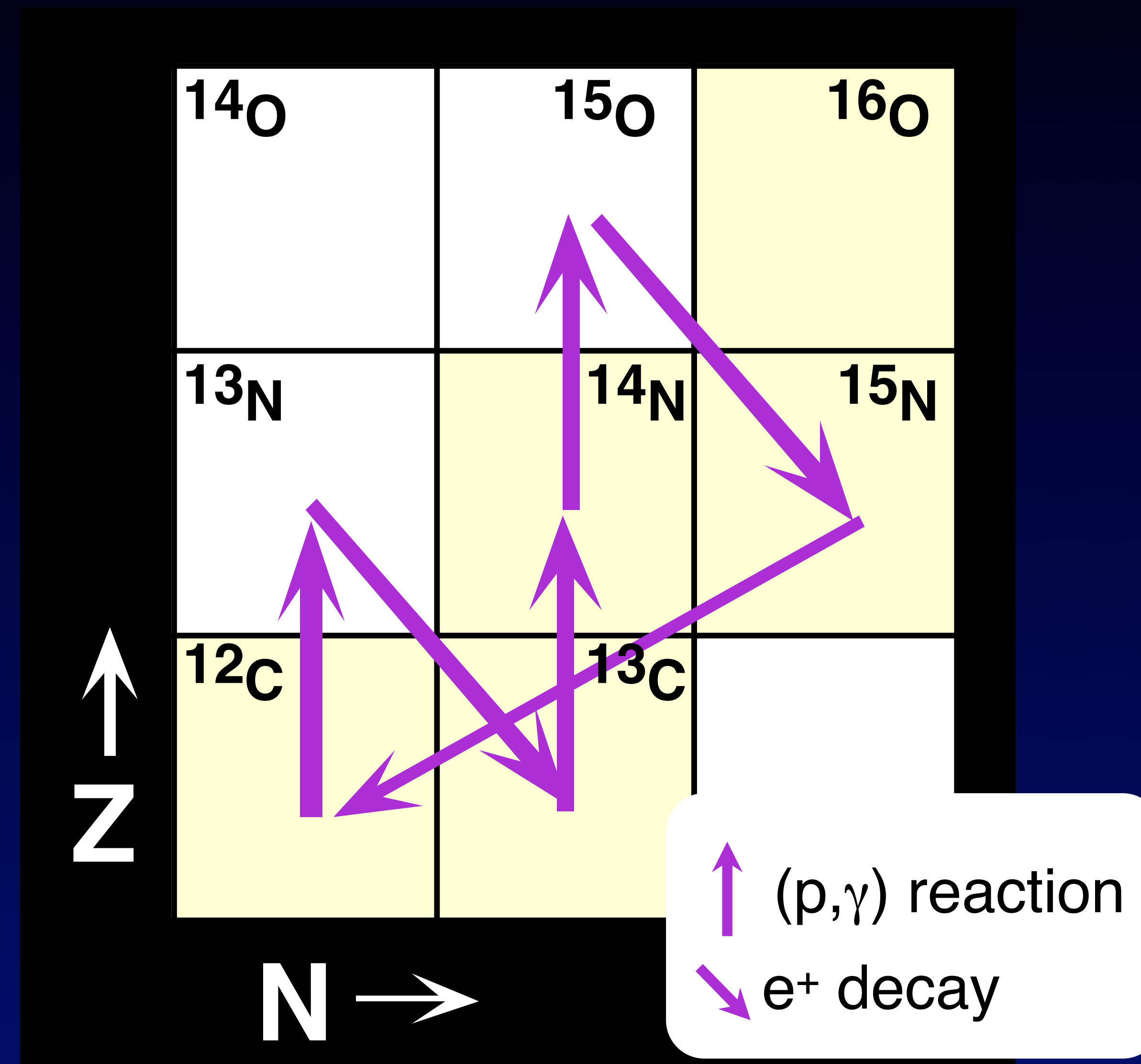

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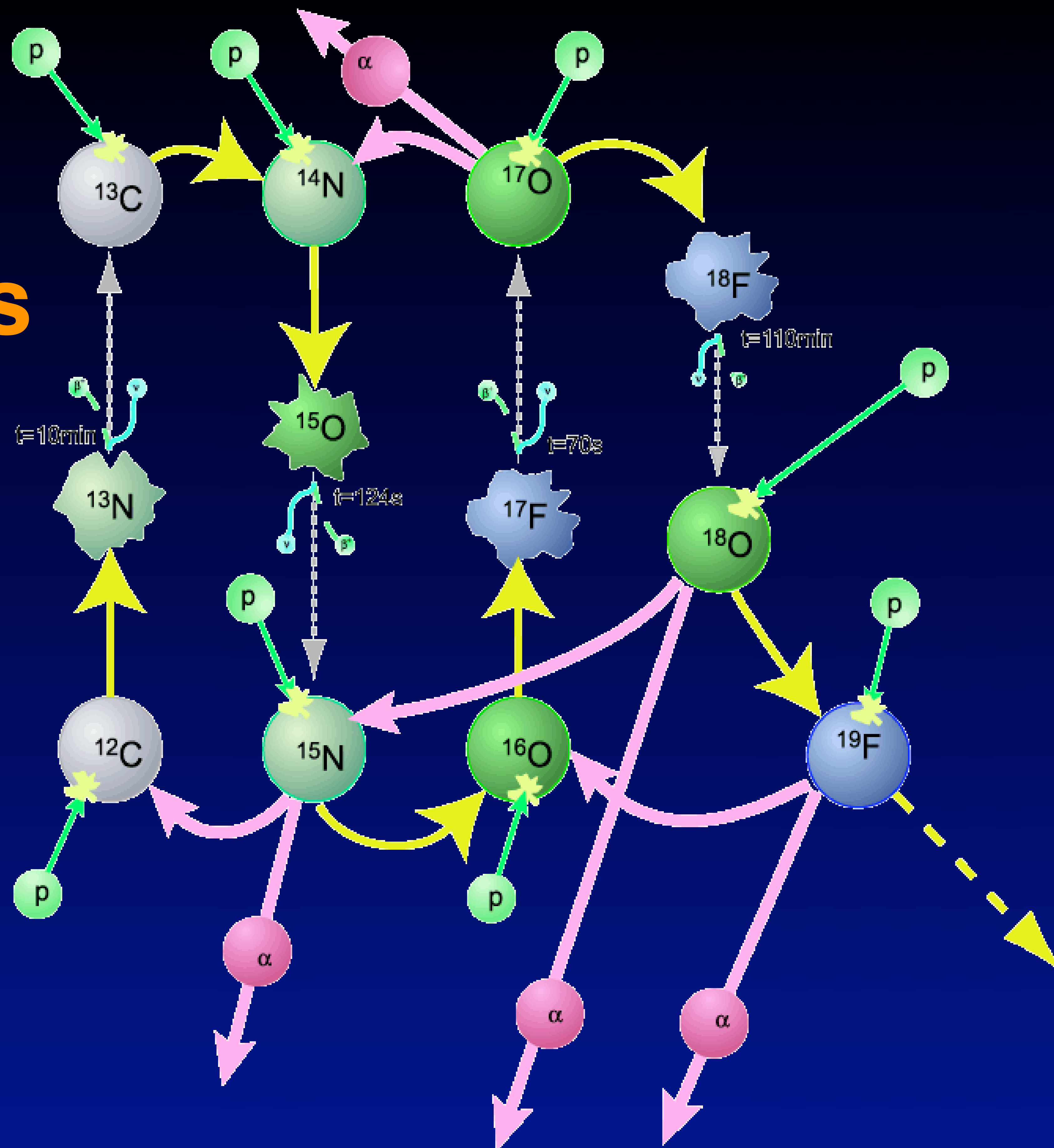
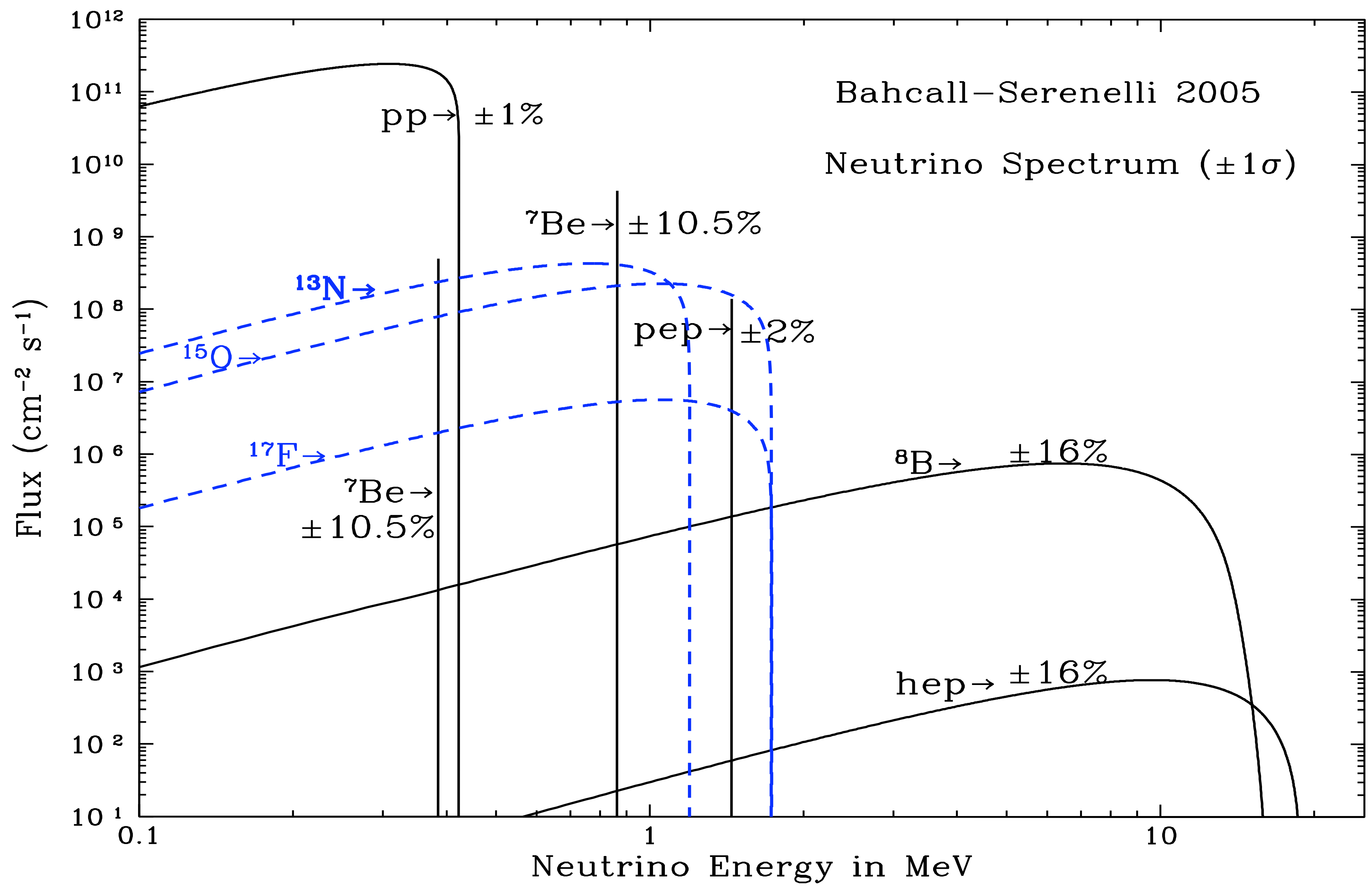
Involves stable nuclei: capture reaction times are much longer (>10^8 - 10^{12} yr) than beta decays for modest (10^7 K) temperatures.

CNO Cycles



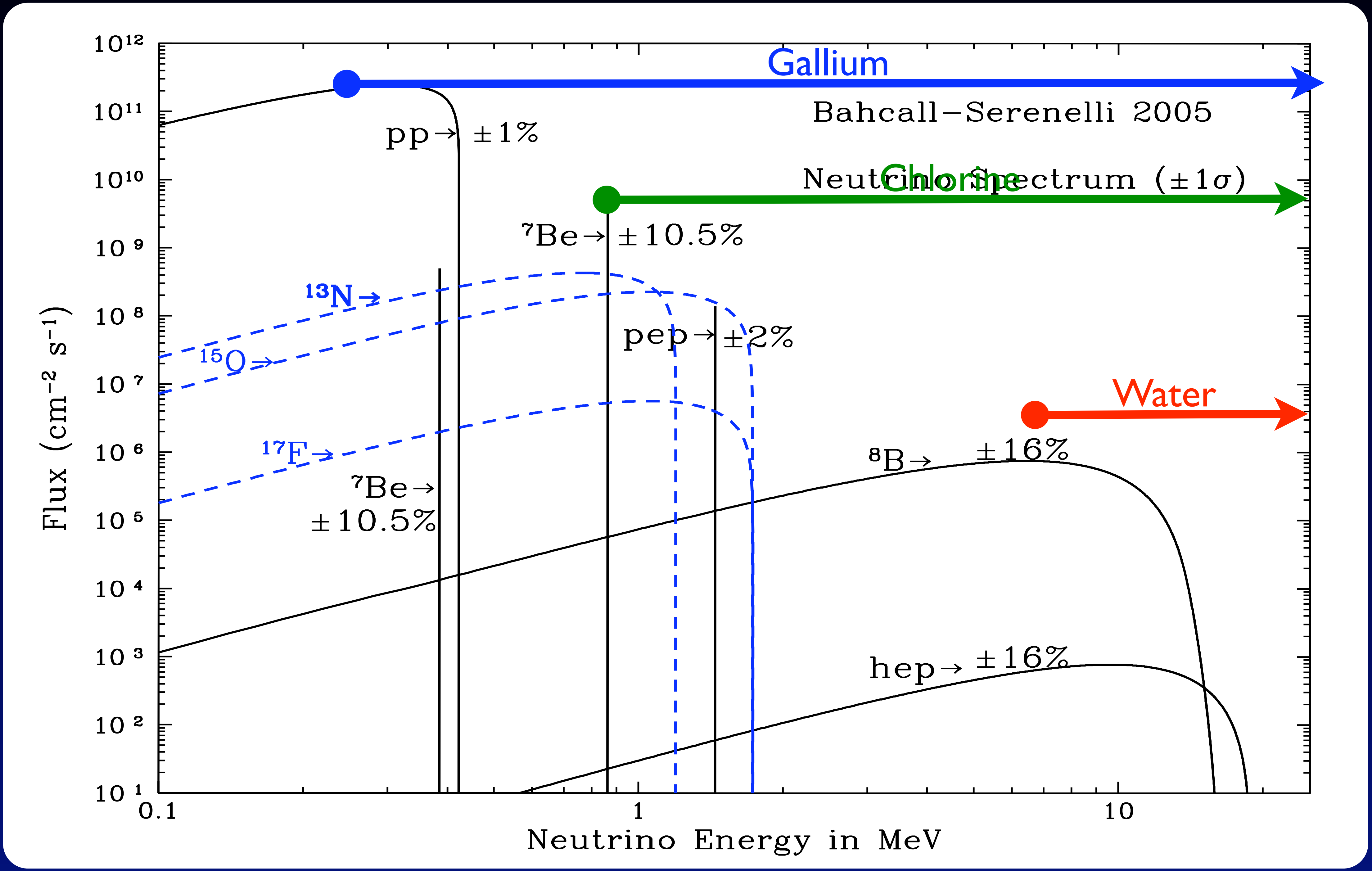
With Increasing Temperature multiple additional reaction cycles contribute.

Solar Neutrinos



Both PP and CNO neutrinos contribute to Solar Neutrino Flux.

Solar Neutrinos



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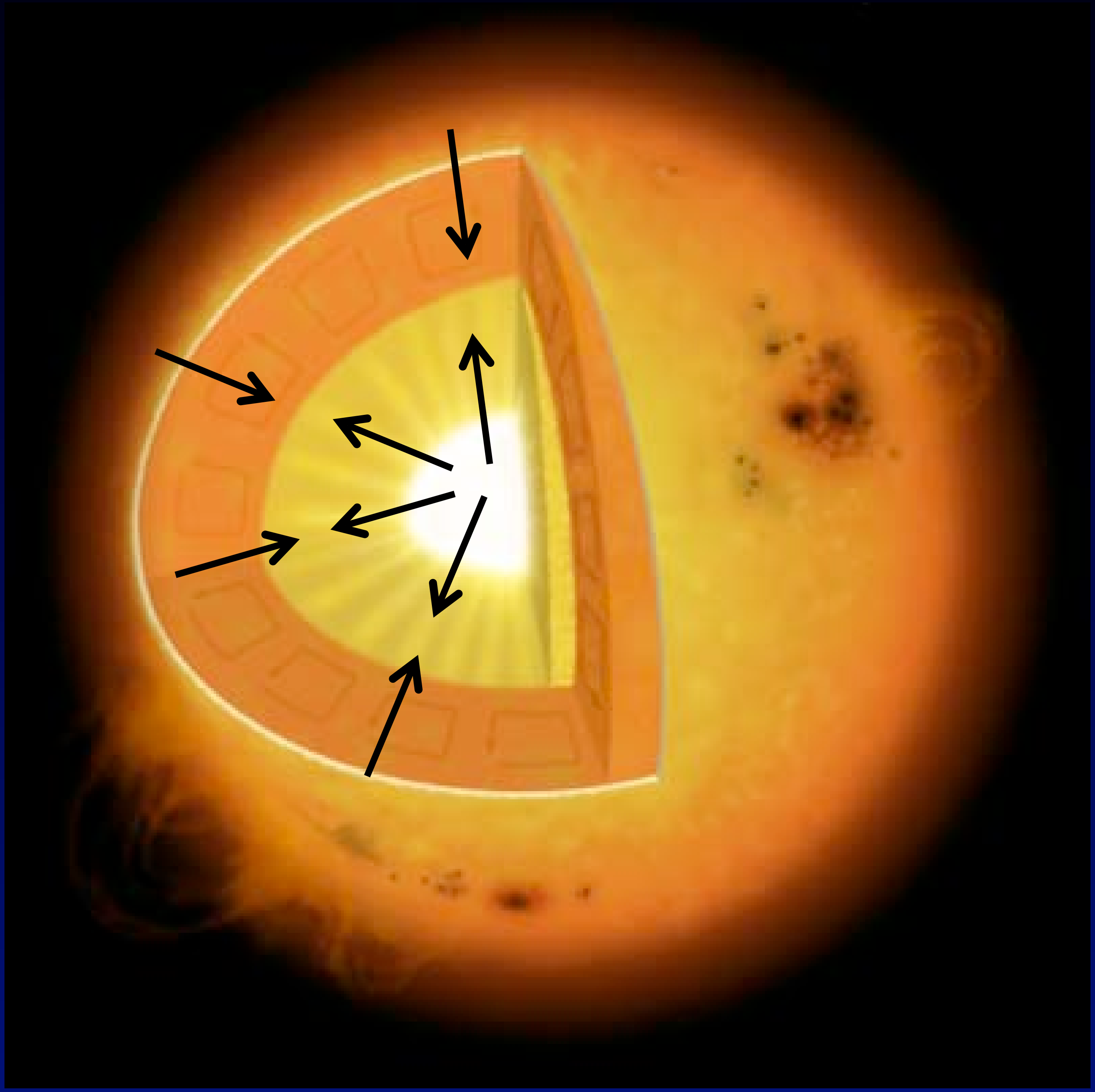
Digging Deeper into Stellar Evolution

How are thermonuclear reaction rates used to determine the evolution of the structure & composition of a star?



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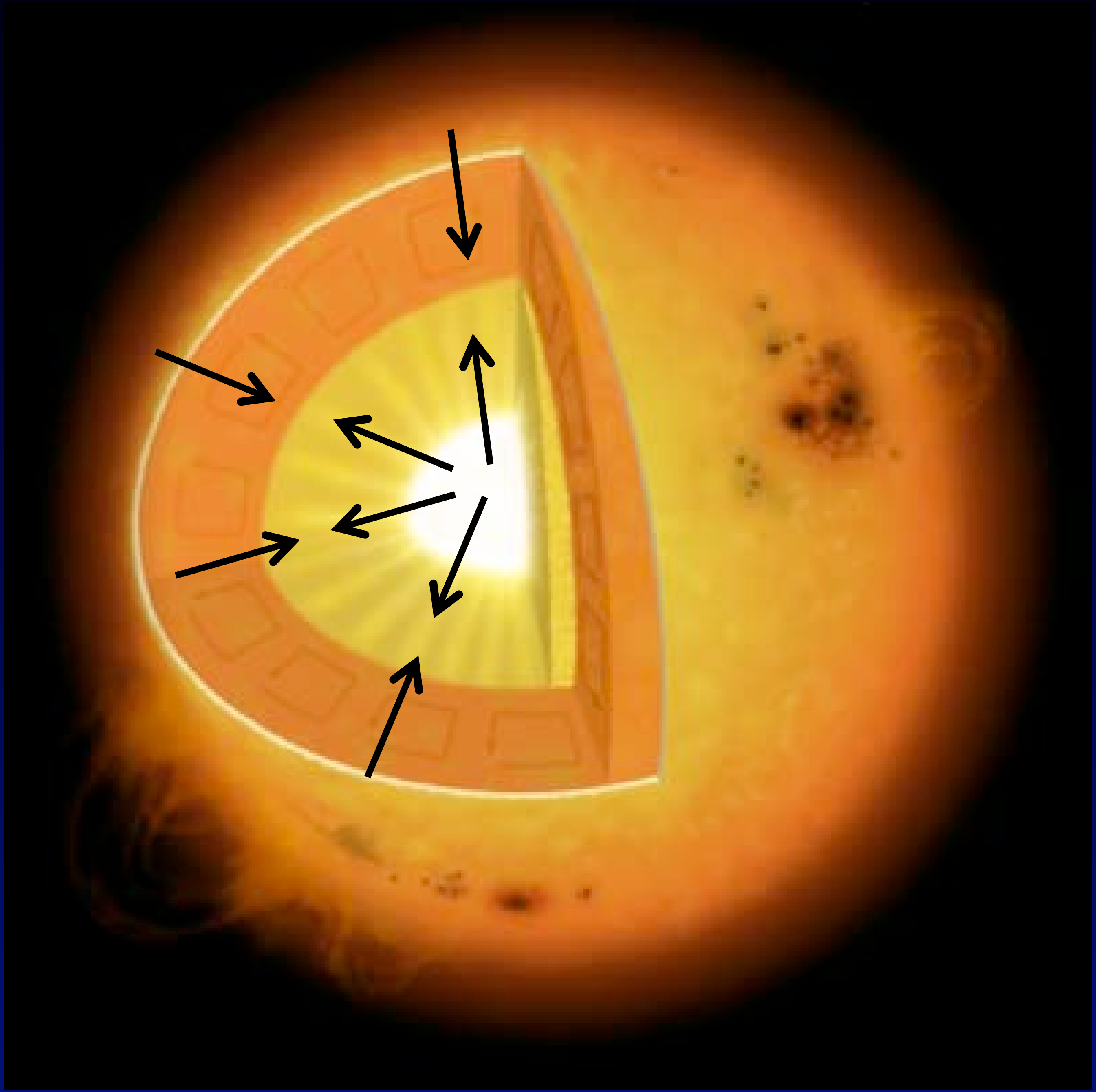

What other physical ingredients at work in a star?

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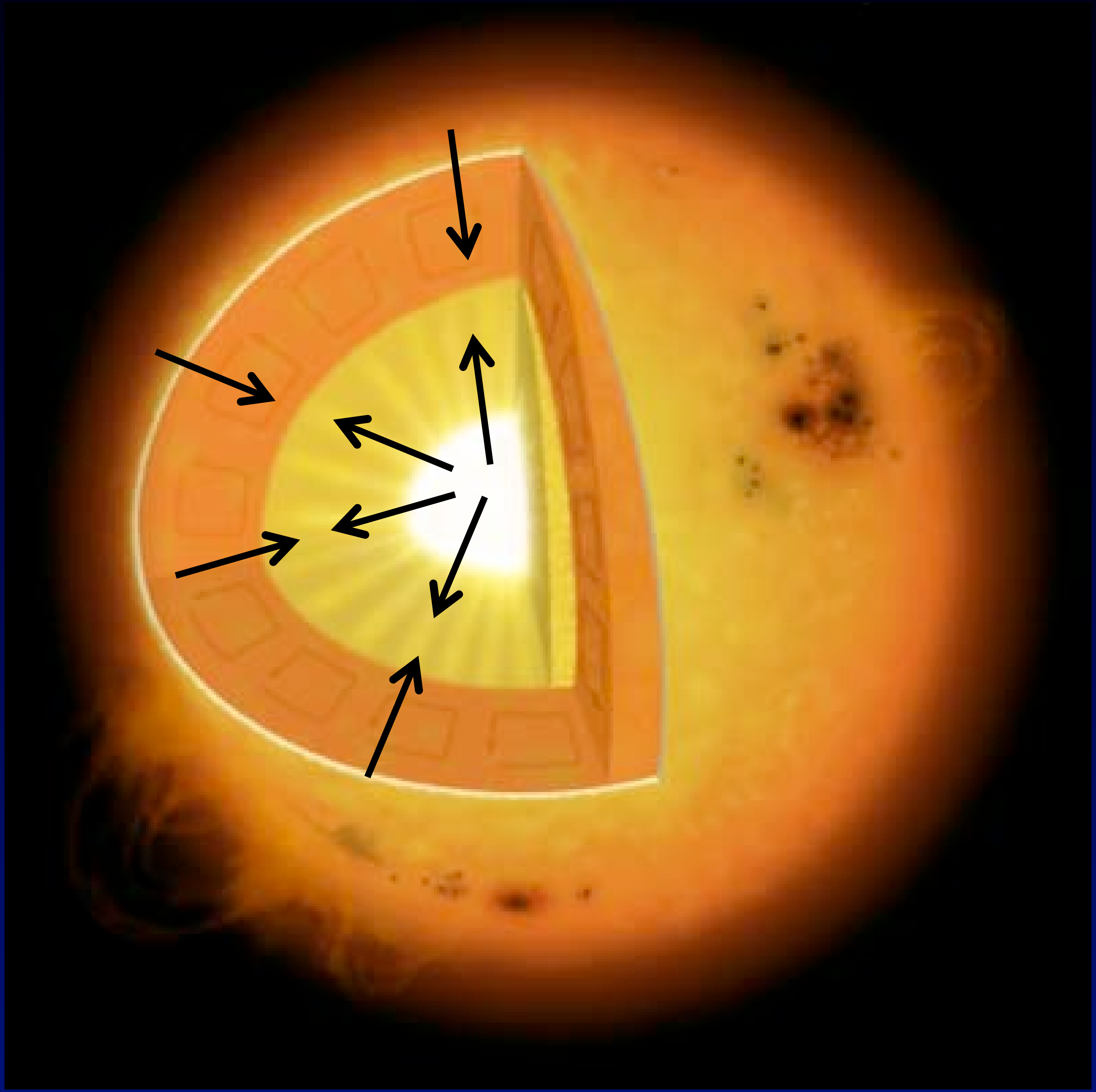

What other physical ingredients at work in a star?

How does one model the life of a star?

Principles of Stellar Evolution

Hydrostatic Equilibrium

forces due to pressure differences balance gravity at each radius

$$P(r+dr) = P(r) + \frac{dP}{dr}\,dr$$

Conservation of Mass

relates mass within a given radial shell of the star and the local density

$$M(r+dr) = M(r) + \frac{dM}{dr}\,dr$$

Conservation of Energy

change in energy flux equals local rate of energy release at each radius

$$L(r+dr) = L(r) + \frac{dL}{dr}\,dr$$

Radiative Energy Transport

relates energy flux and local temperature gradient at each radius

$$T(r+dr) = T(r) + \frac{dT}{dr}\,dr$$

Microphysics of Stellar Evolution

Equation of State

pressure of the stellar material as function of density & temperature

Opacity

how opaque the stellar material is to radiation [atomic physics]

Nuclear Energy Generation Rate

requires thermonuclear reaction rates [nuclear physics]

All are functions of density, temperature,and chemical composition.

Composition

abundances of the different subatomic nuclei in the stellar material

Principles of Stellar Evolution

Hydrostatic Equilibrium

$dP(r)/dr = -G\, M(r)\, \rho(r) / r^2$

where

$P(r)$ = pressure

$\rho(r)$ = density

$M(r) = \int_0^r 4\pi\, (r')^2 \rho(r')\, dr'$ = mass with radius *r* of star

Conservation of Mass

$dM(r)/dr = 4\pi\, r^2 \rho(r)$

Principles of Stellar Evolution

Conservation of Energy

$$dL(r)/dr = 4\pi r^2 \rho(r) (\varepsilon - T(r)\, dS/dt)$$

where

$L(r)$ = luminosity (energy/s) generated with shell of radius r

ε = nuclear energy generation rate per gm of stellar material (erg/g/s)

S = entropy

Radiative Energy Transport

$$dT(r)/dr = -(3/16\pi\, ac)\, L(r)\, \kappa\, \rho(r) / r^2\, T(r)^3$$

where

κ = opacity = absorption cross section per gm stellar material

a = Stefan-Boltzmann constant = 4 σ / c

Principles of Stellar Evolution

nuclear energy term

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requires knowledge of thermonuclear reaction rates

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Microphysics of Stellar Evolution

Equation of State - Ideal Gas Law

$$P(r) = \rho(r)\, k\, T(r) \,/\, \mu\, m_H$$

where

μ = mean molecular weight

m_H = mass of hydrogen

Kramer's Opacity Law

$$\kappa = \kappa_0\ \rho\ T(r)^{-7/2}$$

where

κ_0 = opacity constant

Microphysics of Stellar Evolution

Entropy

$$dS = dQ / T = [\, d(3P/2\,\rho) + (P\, d(1/\rho)\,] / \; T$$

Composition (Example)

$$dY_p/dt = -4\, R_{pp} - 4\, R_{cn}$$

$$dY_\alpha/dt = R_{pp} + R_{cn} - 3R_{3\alpha}$$

where

Y_p = hydrogen abundance
Y_α = ^{4}He abundance
R_{pp} = *rate* of p+p fusion reaction in pp-cycle
R_{cn} = *rate* of ^{14}N+p reaction in CNO cycle
$R_{3\alpha}$ = *rate* of triple alpha reaction $\alpha+\alpha+\alpha$ --> ^{12}C

Stellar Evolution Equations

Variables

$M, P, r, L, T, \rho\ , S, \varepsilon, \kappa, Y_p, Y_\alpha, Y_z$

Choose M as dependent variable for Lagrangian Coordinates.

Solve for $\rho\ , S, \varepsilon, \kappa, Y_p, Y_\alpha, Y_z$ from microphyics equations

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Resulting Equations

$$dP/dM = -G\,M / 4\pi\, r^4\,(M)$$

$$dr/dM = 1/4\pi\, r^2\,(M)\,\rho(M)$$

$$dL/dM = \varepsilon - T\; dS/dt$$

$$dT/dM = -(3/64\pi^2 ac)\, L(M)\,\kappa / r^4(M)\, T^3(M)$$

Solving the stellar evolution equations

Solving the stellar evolution equations

Set Boundary Conditions

$M = 0$: $P=Pc$, $r = 0$, $L = 0$, $T = Tc$

$M = M_{star}$: $P=P_{eff}$, $r = R_{star}$, $L = L_{star}$, $T = T_{eff}$

Solving the stellar evolution equations

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Set initial concentrations Y_p, Y_α, Y_z ; guess at P_c, T_c, R_{star}, L_{star}

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Solve boundary value problem $P(M)$, $r(M)$, $L(M)$, $T(M)$ at $t = 0$ using method of integration from surface in and center out, matching solutions in the middle

Solving the stellar evolution equations

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Calculate $\rho(M)$ & $S(M)$ at $t = 0$ via constitutive equations

Evolve composition Y_p, Y_α, Y_z in time via constitutive equations

Solving the stellar evolution equations

Set Boundary Conditions

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$M = M_{star}$: $P = P_{eff}$, $r = R_{star}$, $L = L_{star}$, $T = T_{eff}$

Set initial concentrations Y_p, Y_α, Y_z ; guess at P_c, T_c, R_{star}, L_{star}

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Calculate $\rho(M)$ & $S(M)$ at $t = 0$ via constitutive equations

Evolve composition Y_p, Y_α, Y_z in time via constitutive equations

Mix composition Y_p, Y_α, Y_z over convective zones, if any

Solve boundary value problem $P(M)$, $r(M)$, $L(M)$, $T(M)$ at $t = \delta t$

Solving the stellar evolution equations

Set Boundary Conditions

$M = 0$: $P=P_c$, $r = 0$, $L = 0$, $T = T_c$
$M = M_{star}$: $P=P_{eff}$, $r = R_{star}$, $L = L_{star}$, $T = T_{eff}$

Set initial concentrations Y_p, Y_α, Y_z ; guess at P_c, T_c, R_{star}, L_{star}

Solve boundary value problem $P(M)$, $r(M)$, $L(M)$, $T(M)$ at $t = 0$ using method of integration from surface in and center out, matching solutions in the middle

Calculate $\rho(M)$ & $S(M)$ at $t = 0$ via constitutive equations

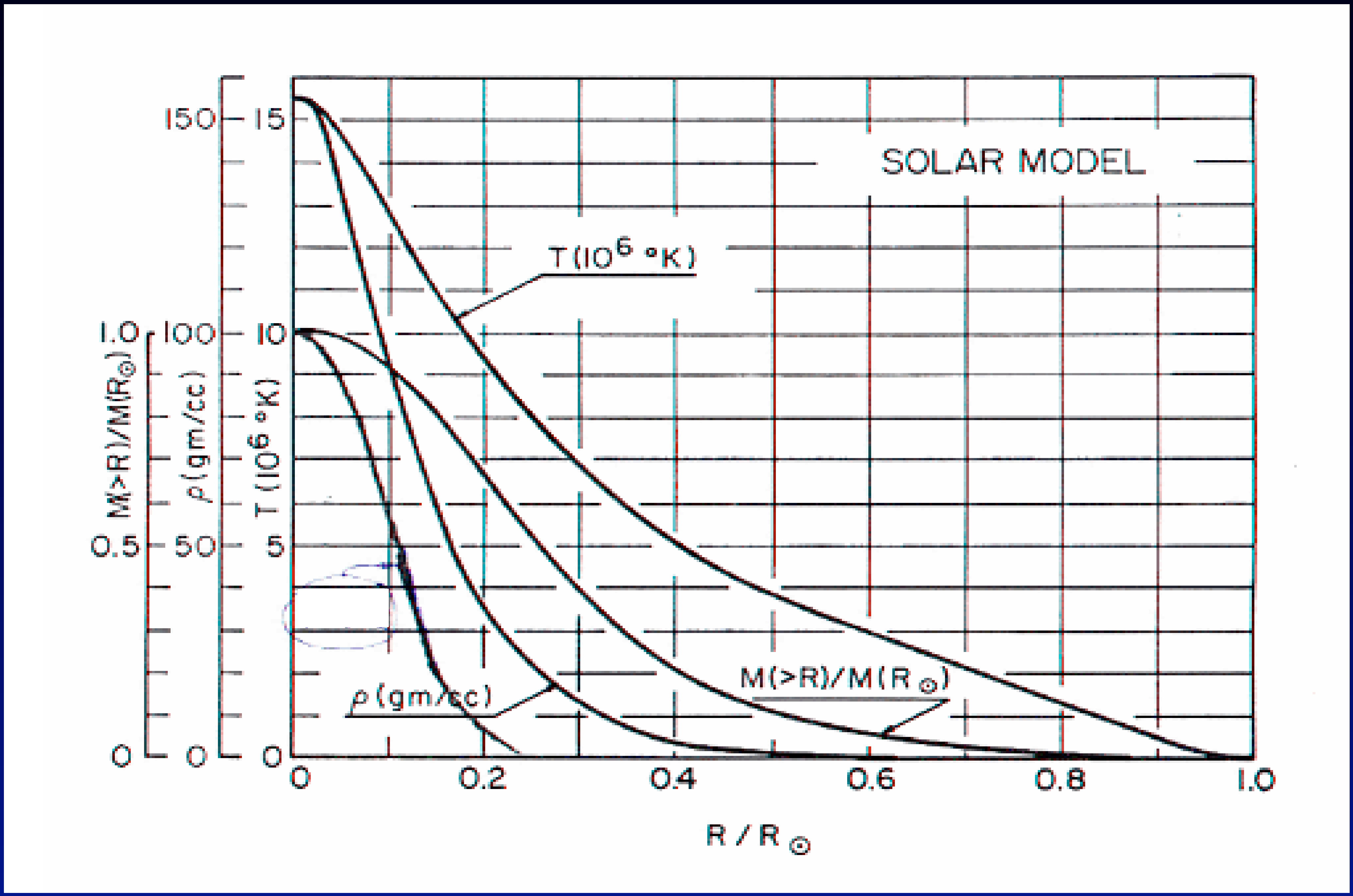
Evolve composition Y_p, Y_α, Y_z in time via constitutive equations

Mix composition Y_p, Y_α, Y_z over convective zones, if any

Solve boundary value problem $P(M)$, $r(M)$, $L(M)$, $T(M)$ at $t = \delta t$

Continue until t = age of star, tracking P, r, L, and T vs. M in time
Compare final values of R_{star}, L_{star}, T_{eff} with observables

Stellar Evolution Solutions



Nuclear Physics of Stellar Evolution

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Nuclear Reactions

generate energy
change number density of nuclear species in the star

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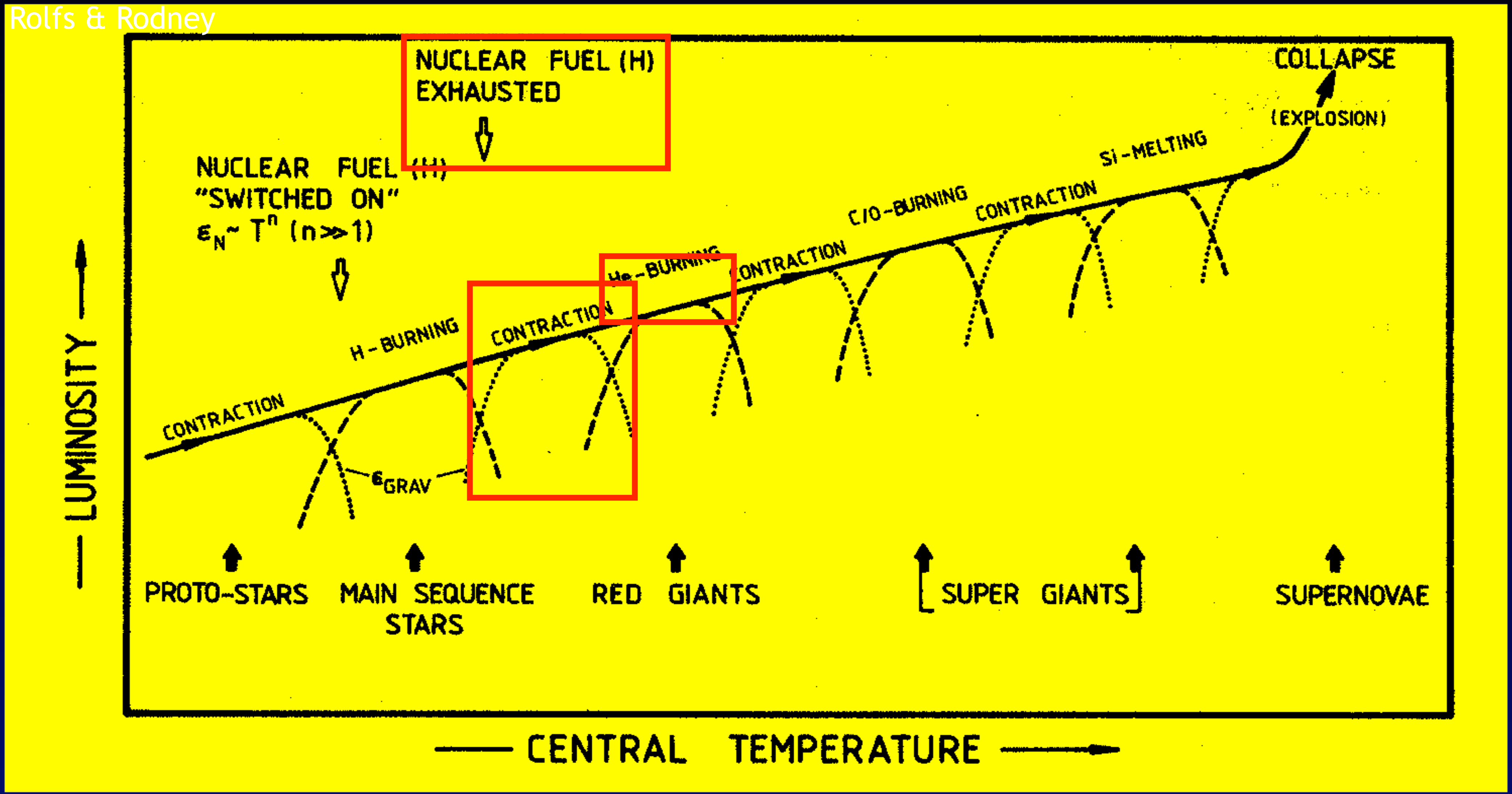
Determination of reaction rates absolutely necessary to understand how nuclear physics influences energy generation & element production in stars.

Stellar Stages and Nuclear fuel

Rolfs & Rodney



Eventually H fuel exhausted (converted to He)

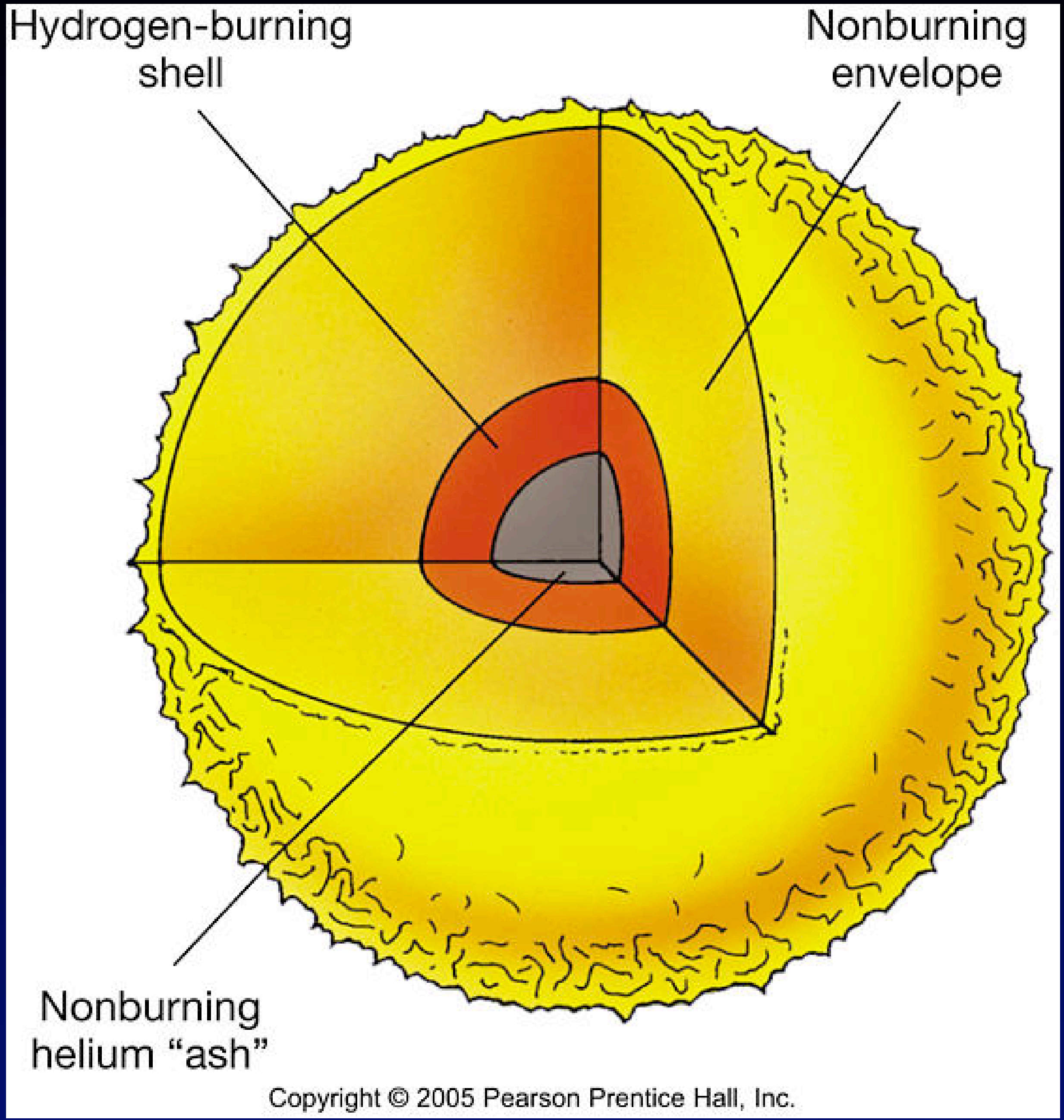
Without nuclear energy to balance, Gravitational contraction resumes.

Core temperature rises as it contracts until He becomes a "fuel" for new thermonuclear burning.

Edge Effects

Contraction of the core raises the temperature and density of the H-rich matters lying above it, leading to the ignition of a H burning “Shell” around the core.

Rate of burning is governed by the gravitational gradient of the core, not it’s own hydrostatic evolution.



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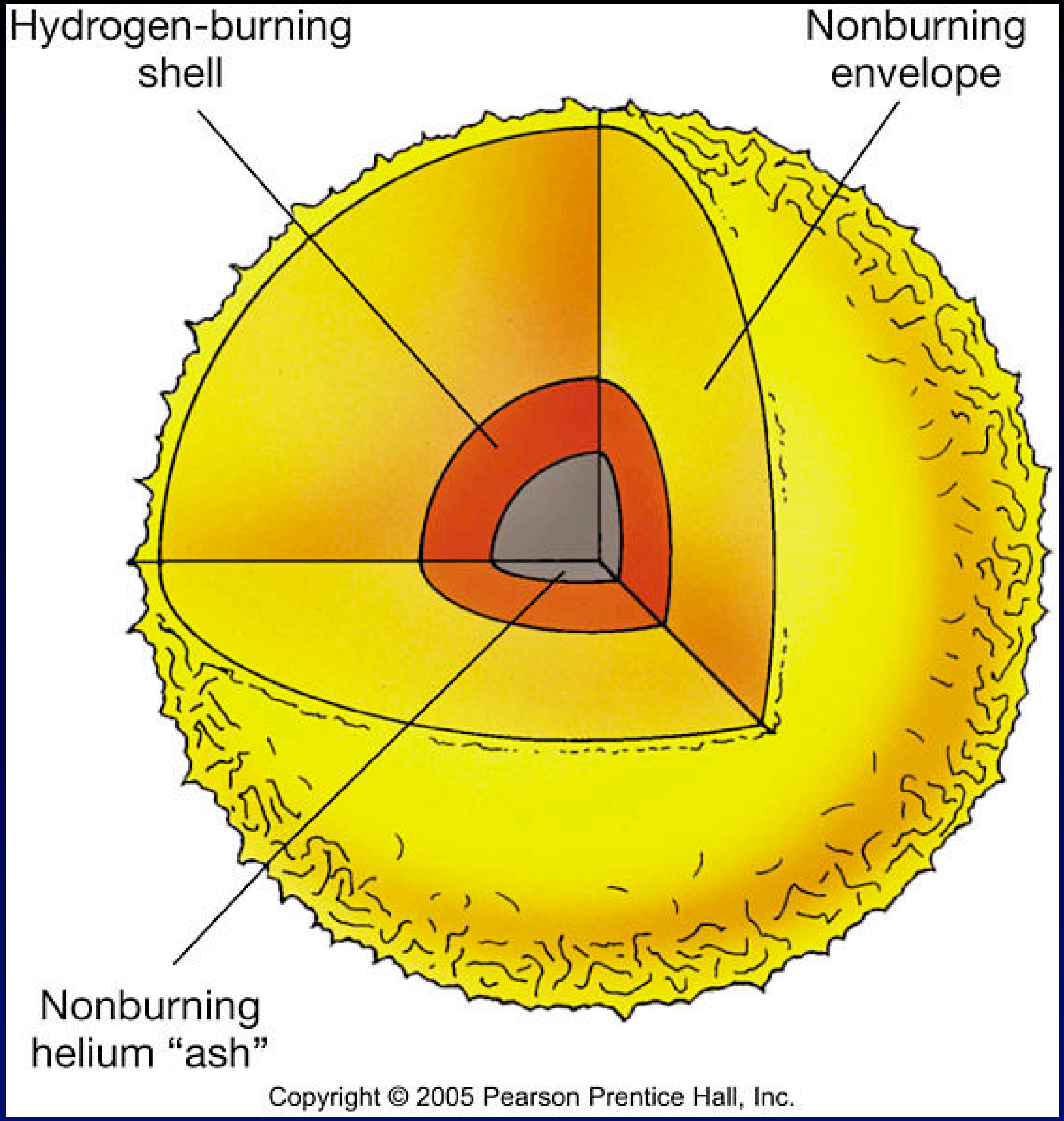


Rate of burning is governed by the gravitational gradient of the core, not it's own hydrostatic evolution.

Results in tremendous luminosity that causes the envelope to expand.

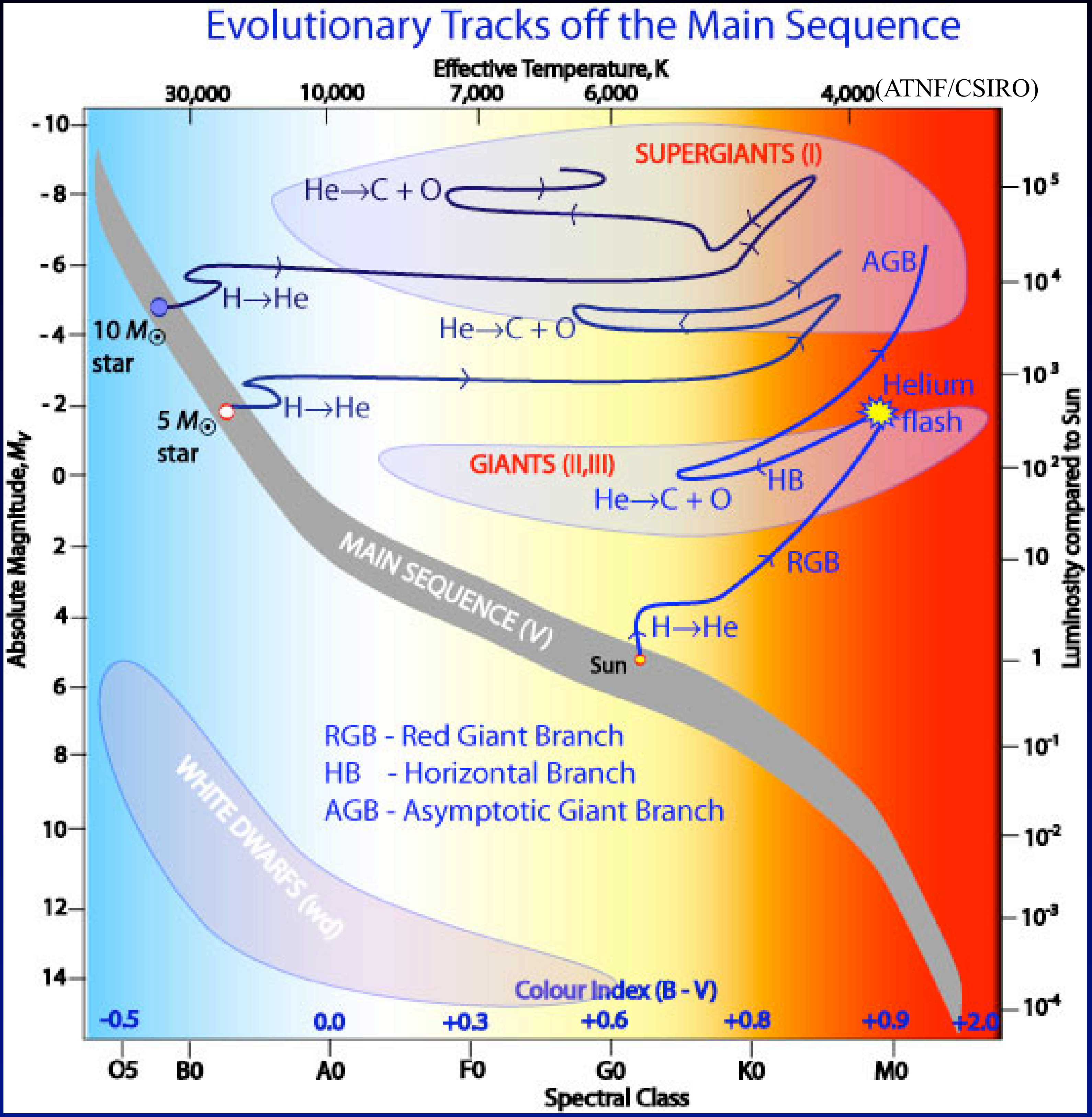
$\Rightarrow$ Red Giant

Stellar Stages

When H is exhausted in core, hydrogen burning ignites in shell around the core.

Once hot enough, He burning begins in the core, until He is exhausted.

Another round of contraction leads to H and He burning shells around a C+O core producing a Asymotic Giant Branch (AGB) Star for solar-like stars and a Supergiant for massive stars.



Nuclear Impact: $^{12}C(\alpha,\gamma)^{16}O$

$^{12}C(\alpha,\gamma)^{16}O$ determines ratio of $^{12}C/^{16}O$ at the end of helium burning.

Rate is determined by a sub-threshold resonance.

S(300) in keV barn Measurement:

Kunz et al. (2002)

165 ± 50

Buchmann (1996)

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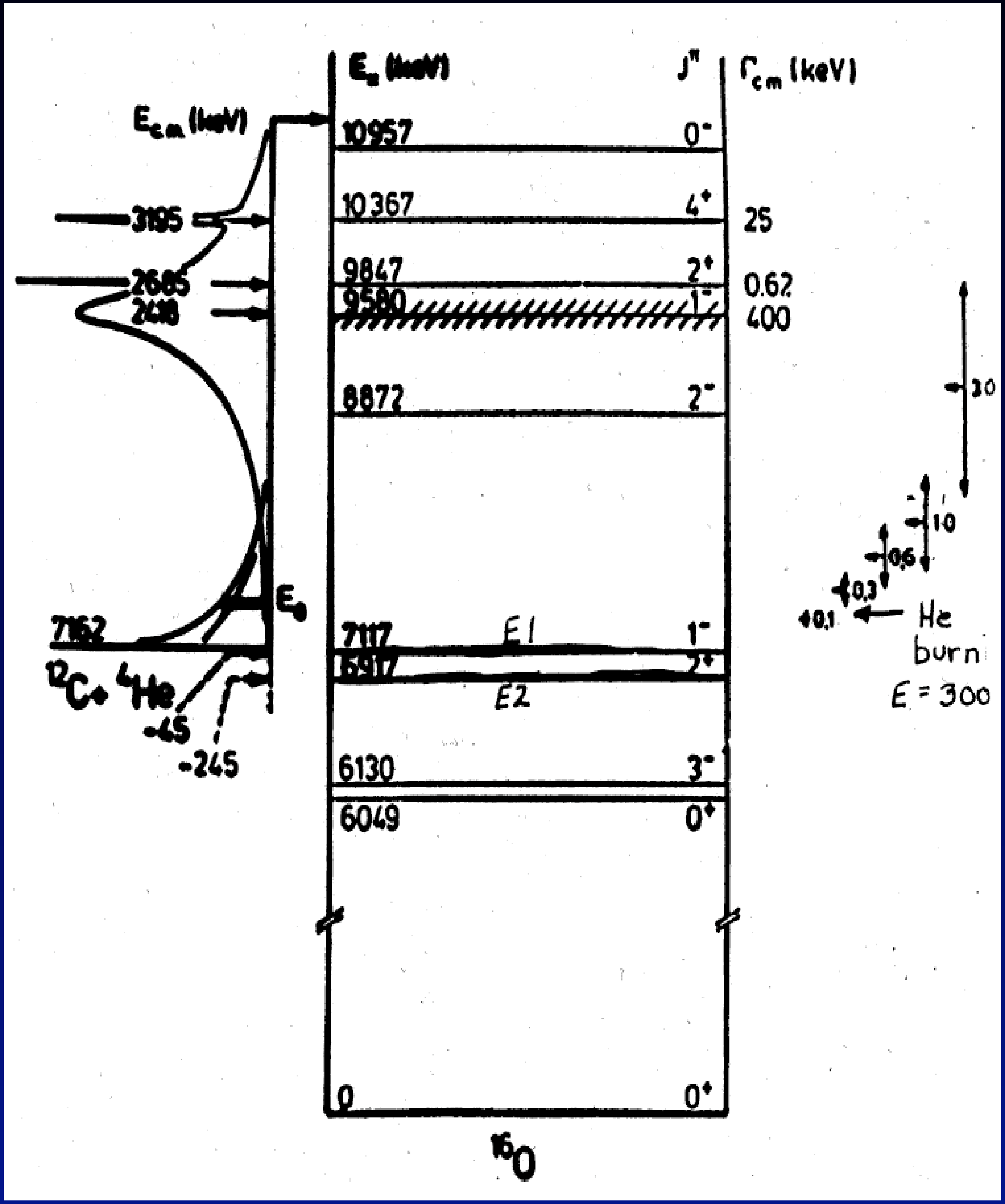

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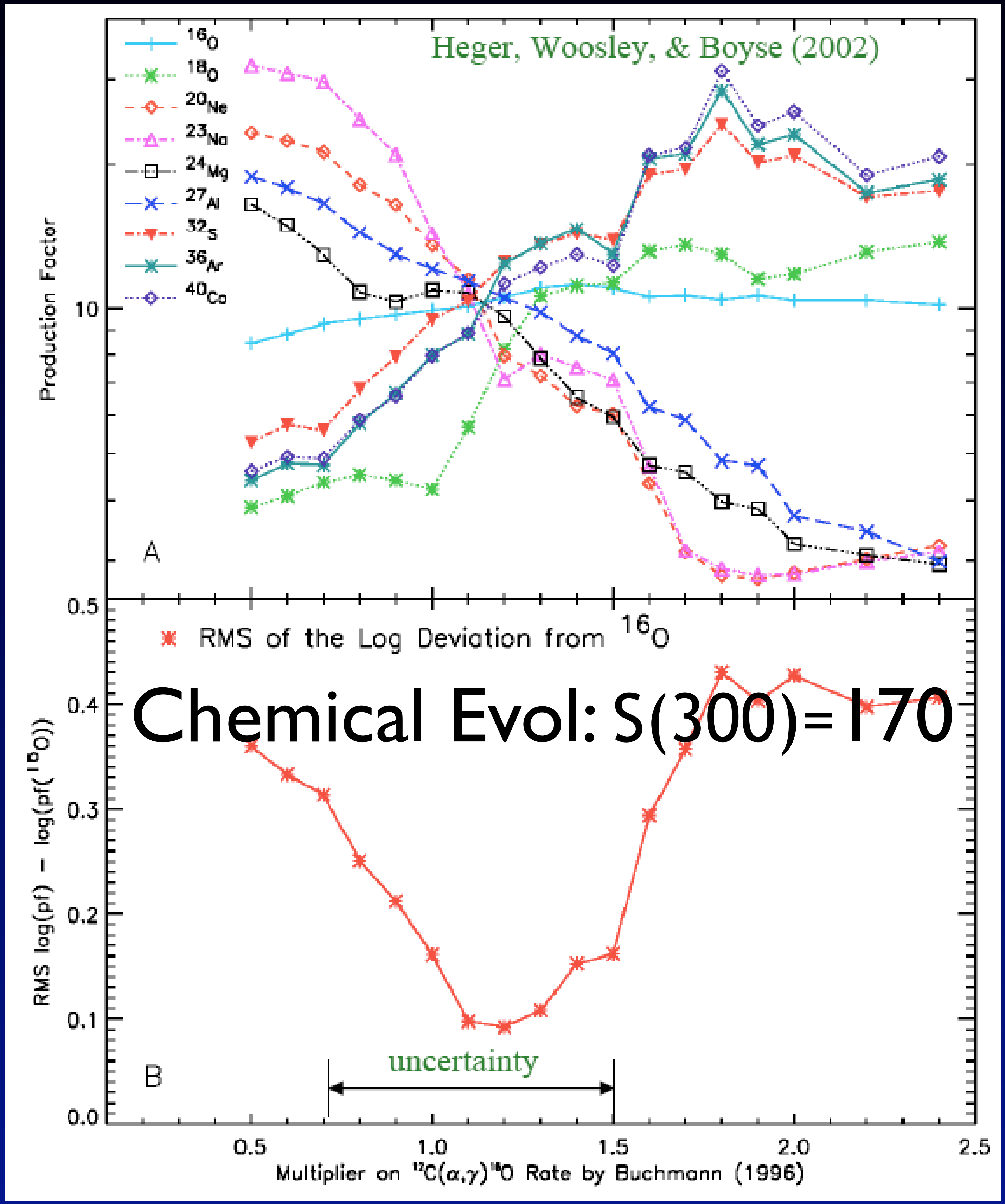
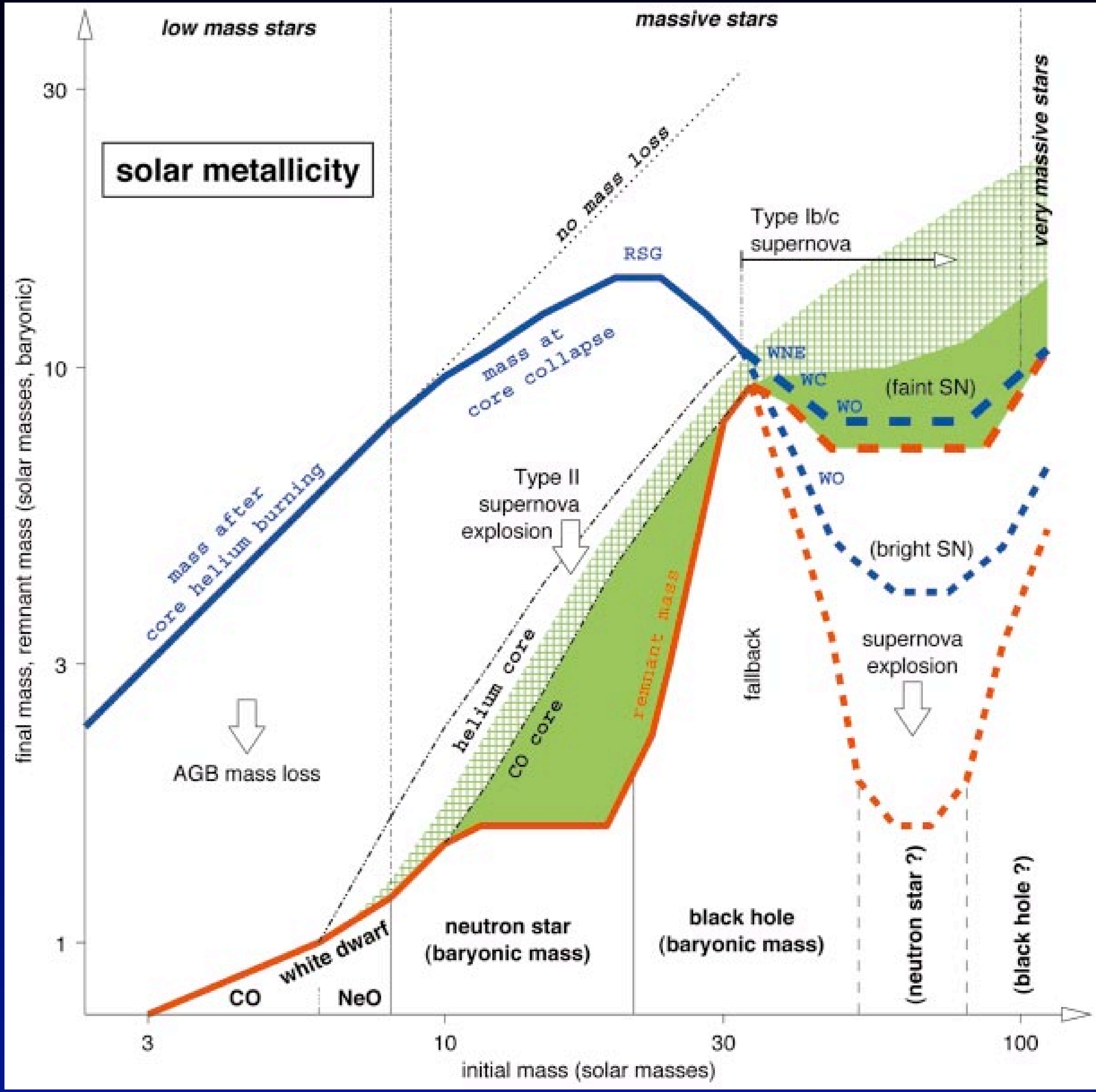


Mass is Destiny

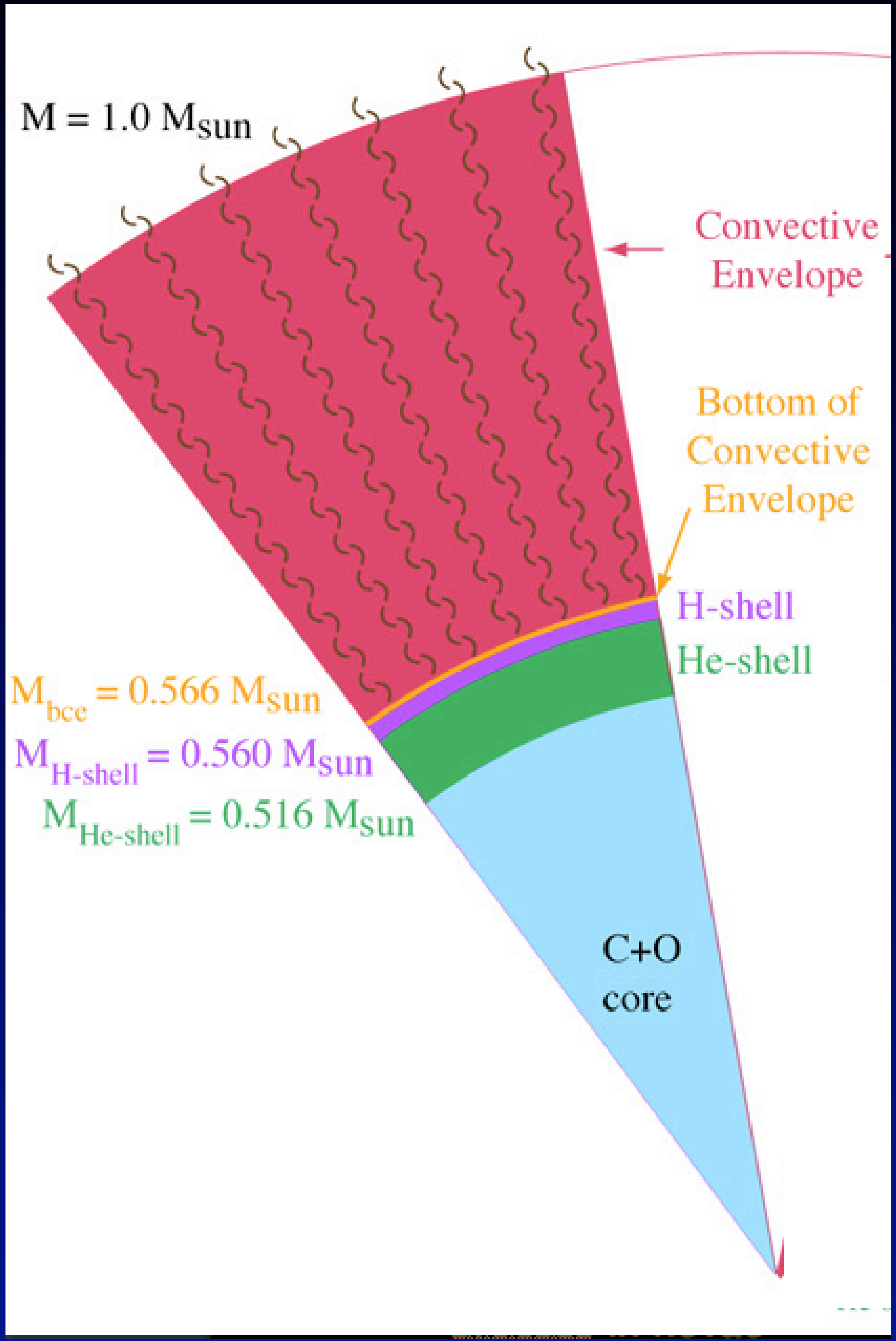
The final fate of a single star depends on many facets, the most important is its mass at birth. Mass loss is also important.

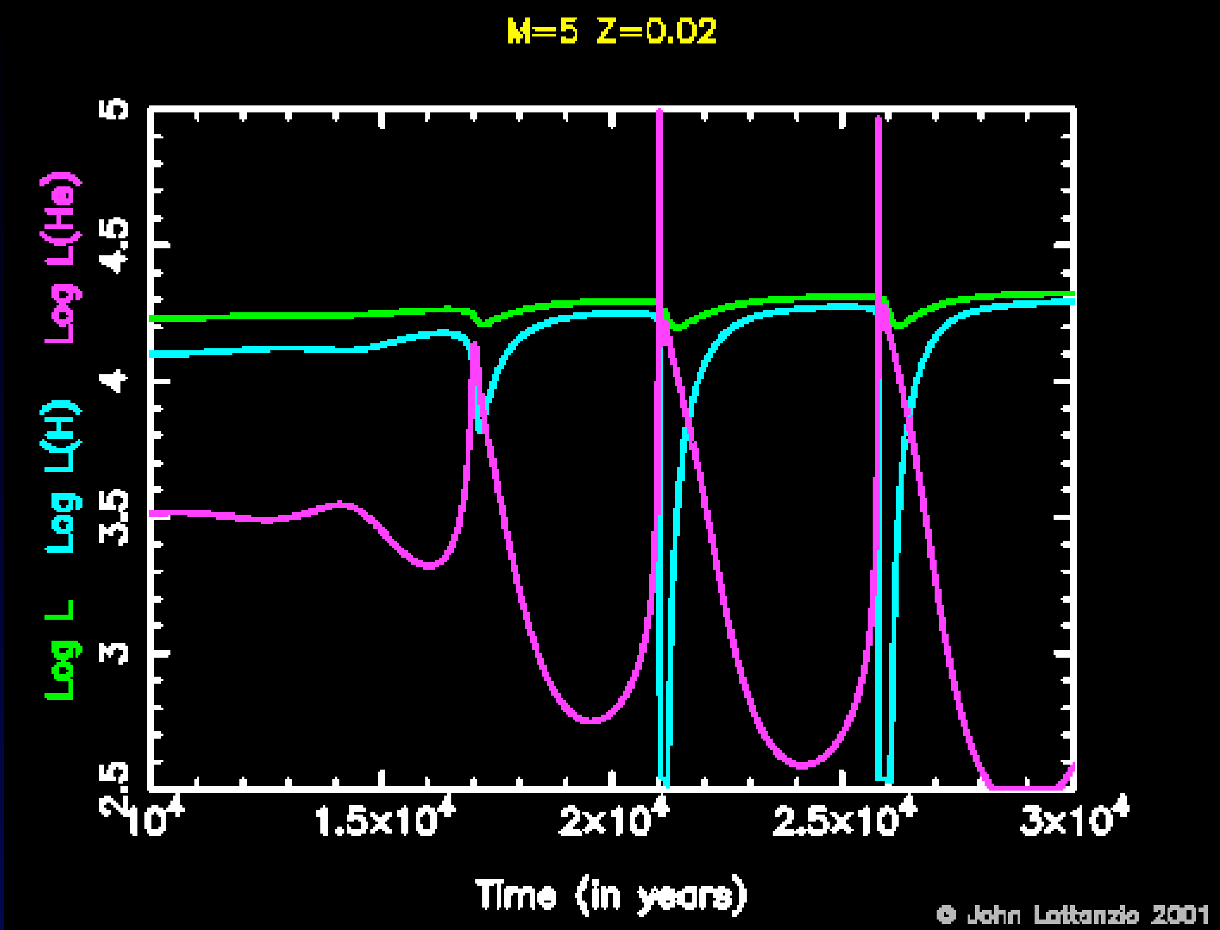
Metallicity, the abundance of non H and He is also important.

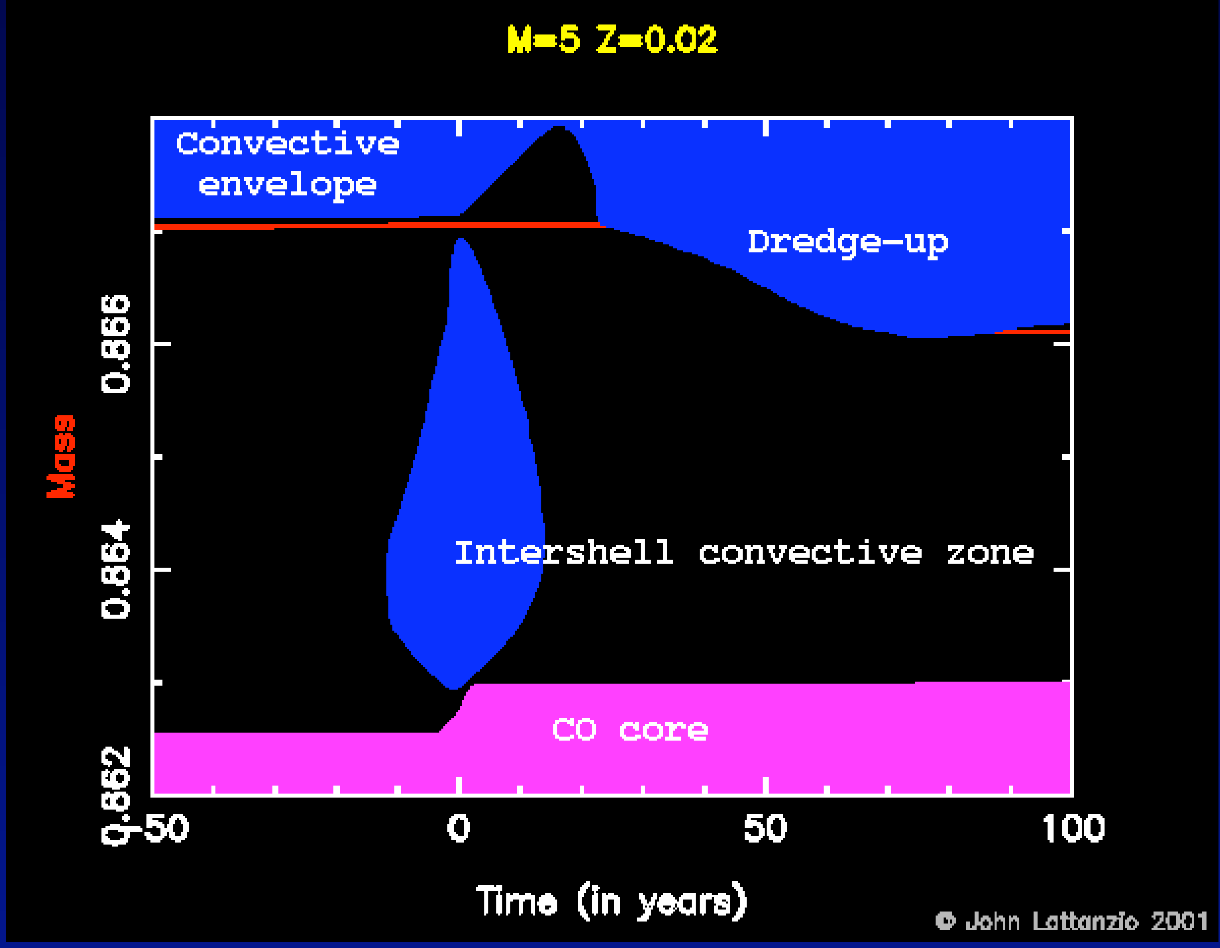
Very Massive stars can lose much of their envelope leaving the He or C/O core visible.



Themal Pulsations in AGB





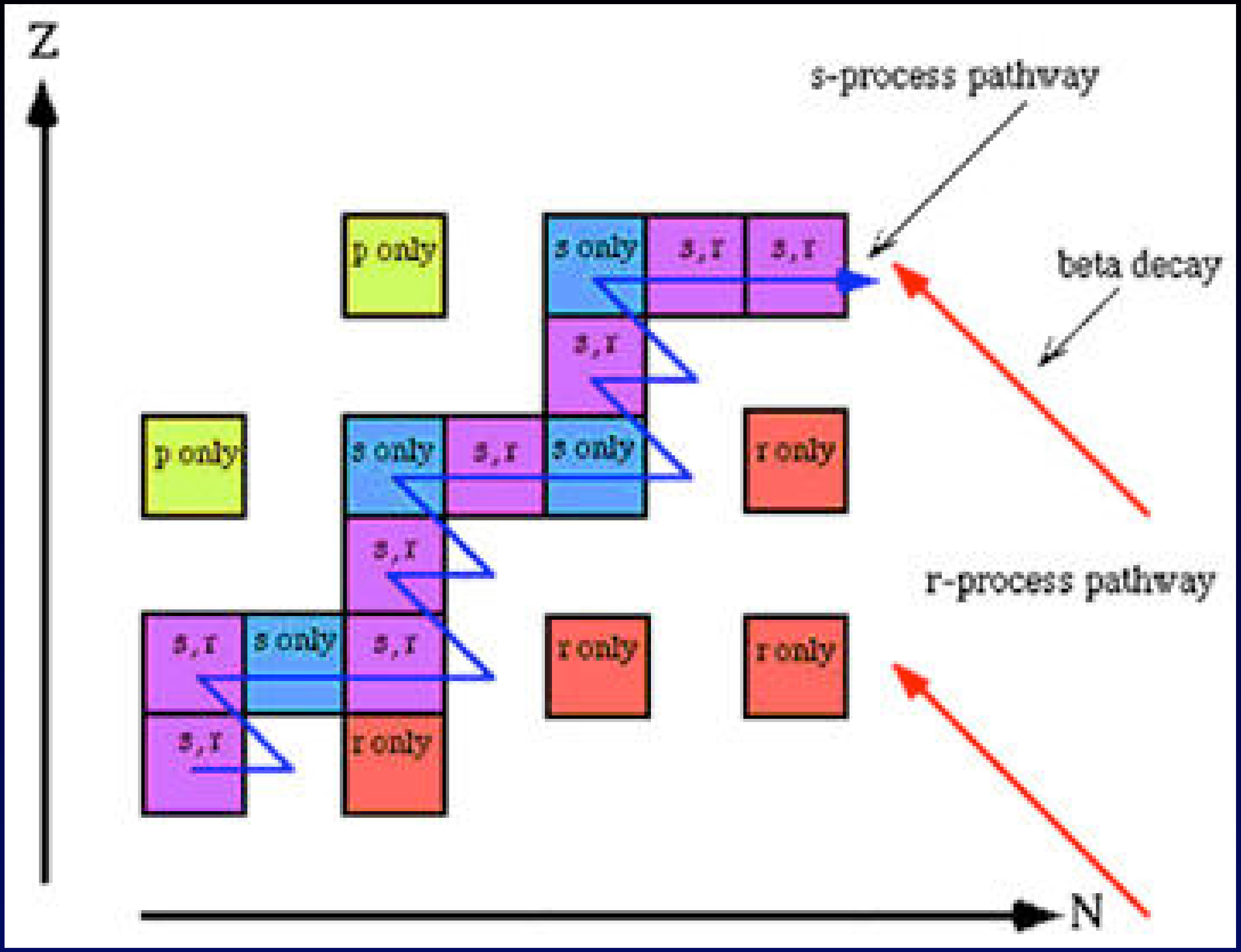


s-Process

The slow neutron capture process (s-process) creates ~ half of all nuclei more massive than Fe.

Occurs during pulsations in red giant stars via series of (n,γ) reactions.

Neutrons are produced by $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$. Production of ^{13}C requires 1H to be mixed into C-rich region.



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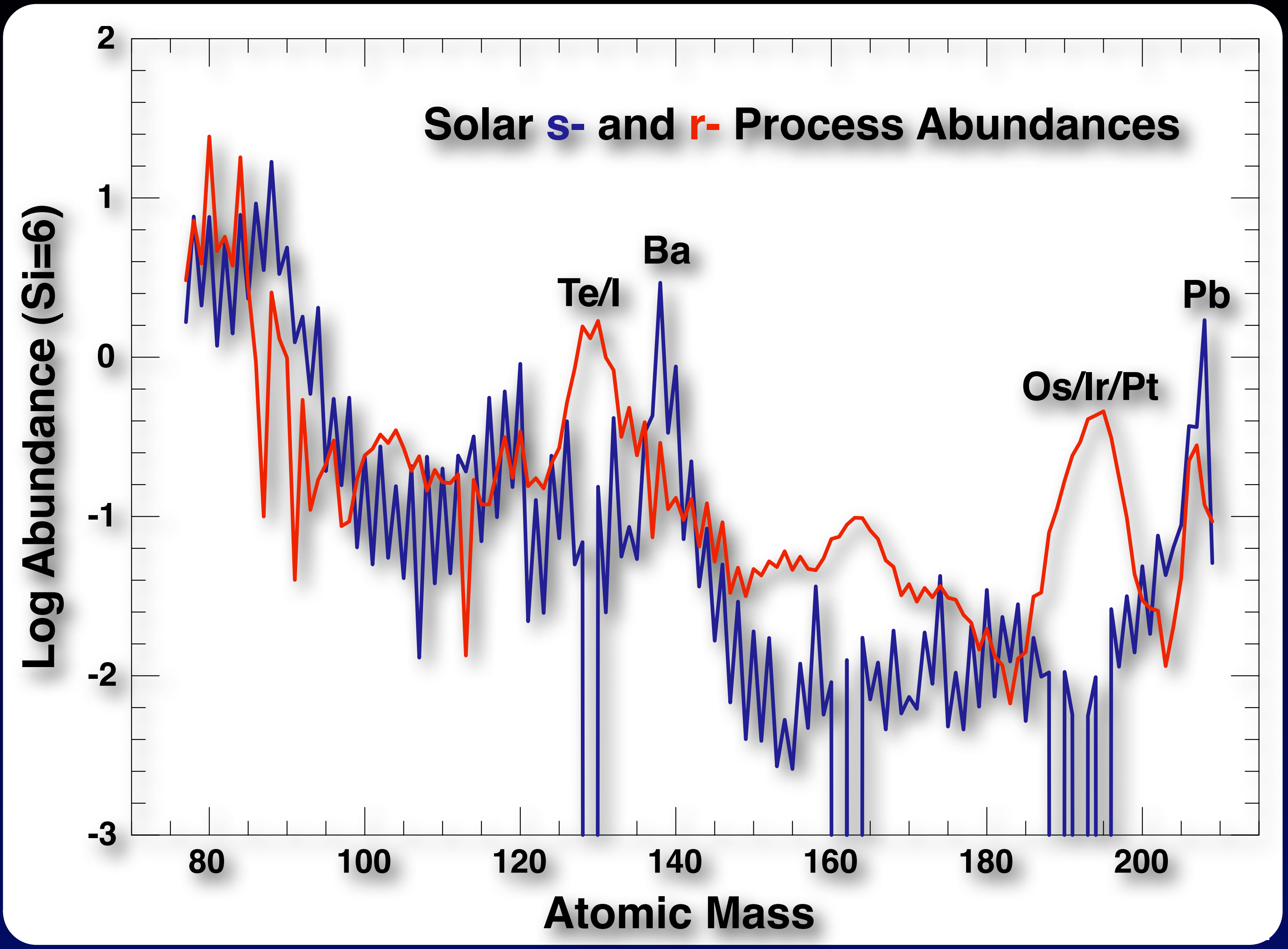
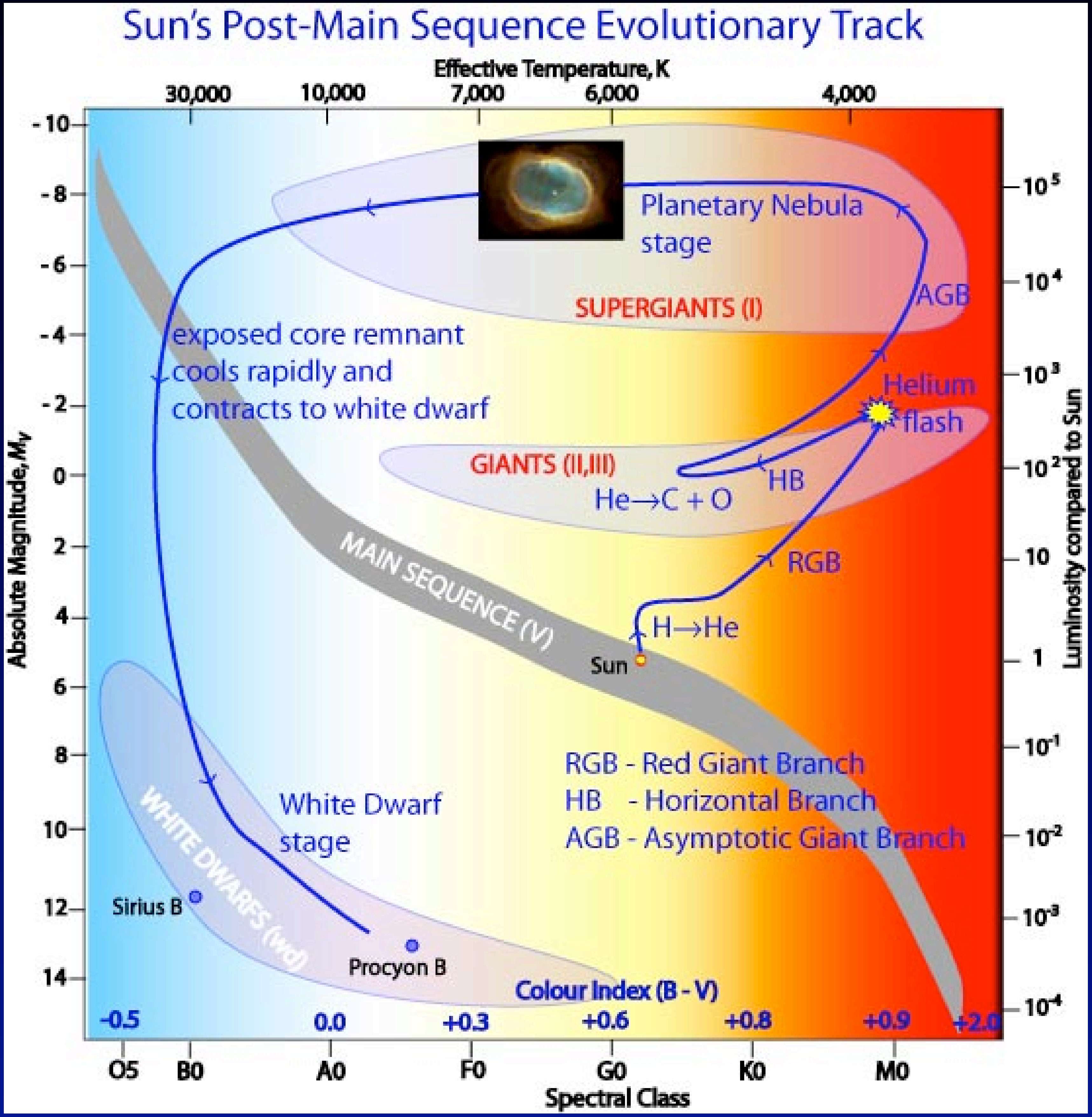


Neutron capture rate is slower than beta decays, so s-process path follows the value of stability. Slowest rates at closed shells accumulate flow, producing s-process peaks.

Stars Like Ours



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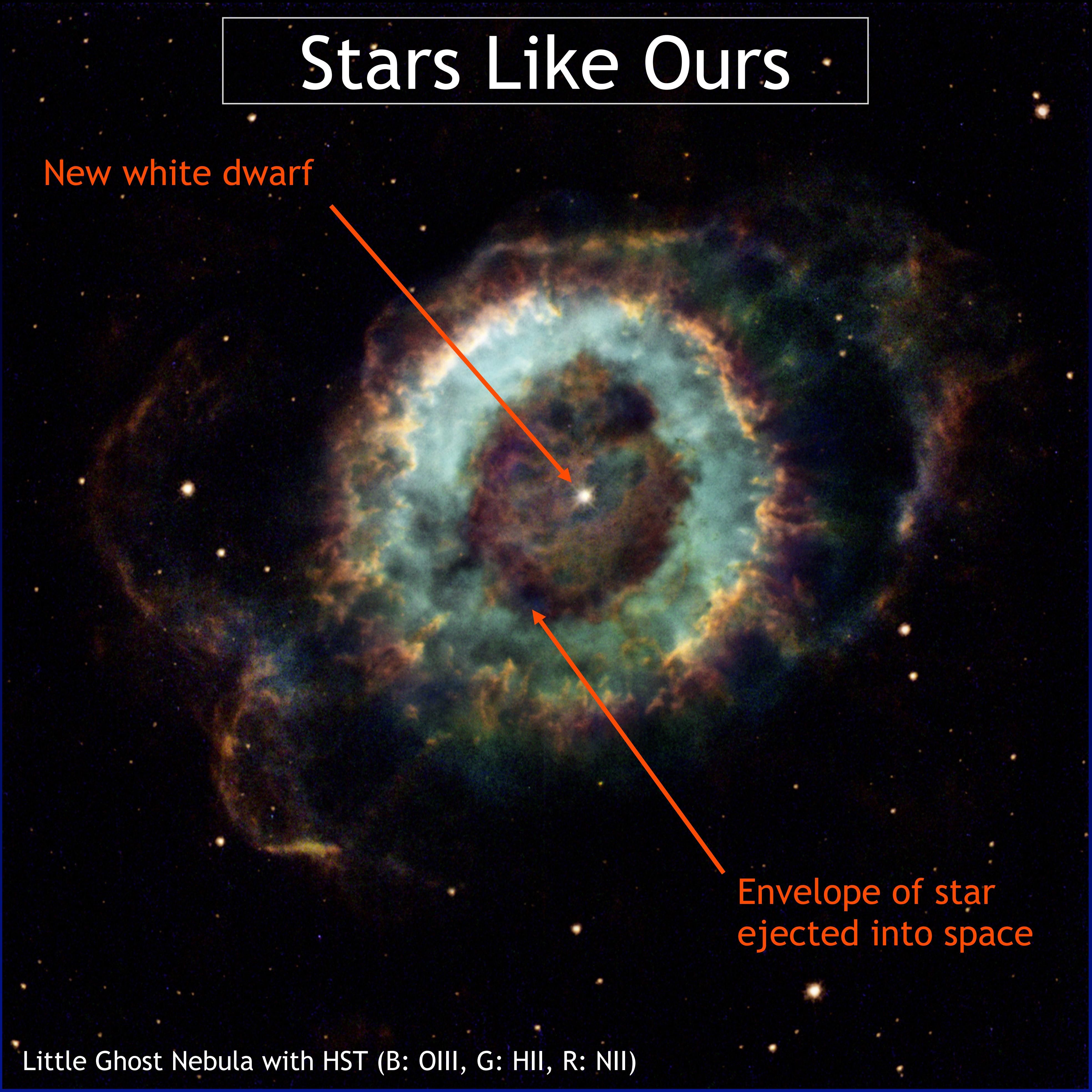

White Dwarves

Pressure in a white dwarf results from degenerate electrons.

As WD mass increases, electron velocities approach the speed of light and provide decreasing pressure.

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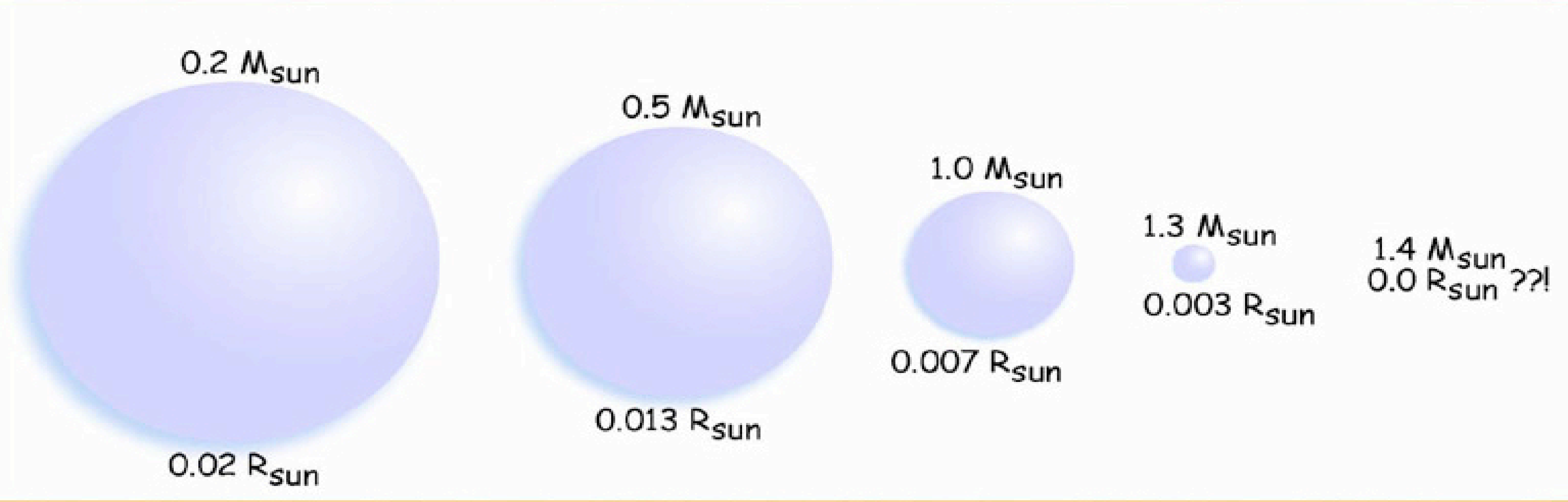

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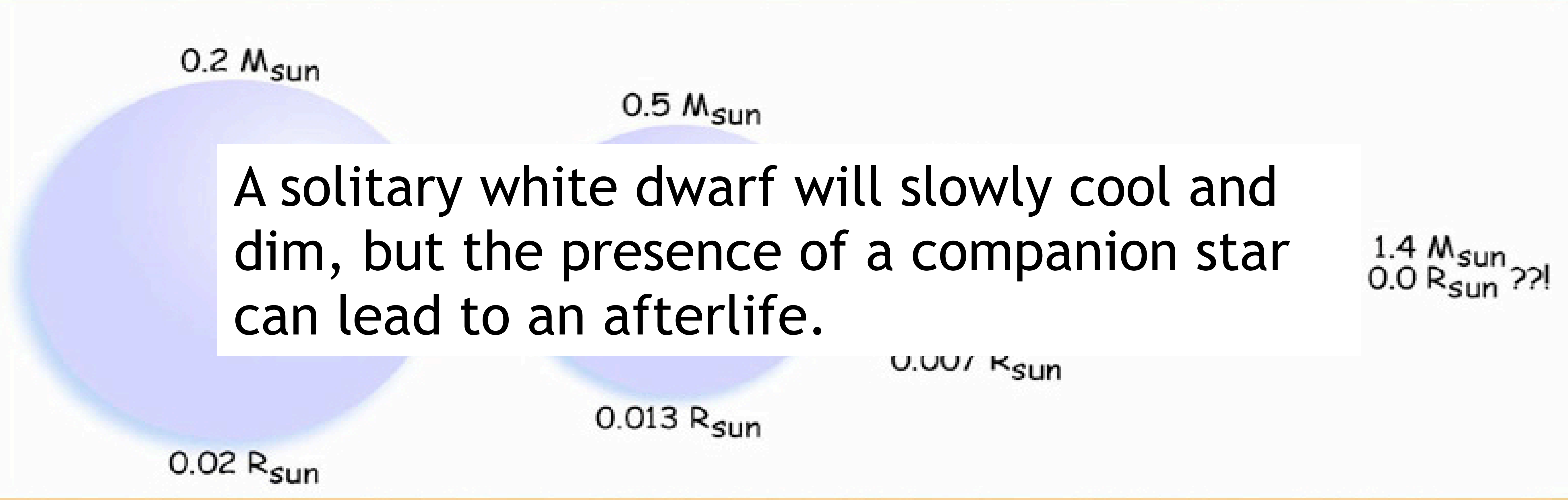
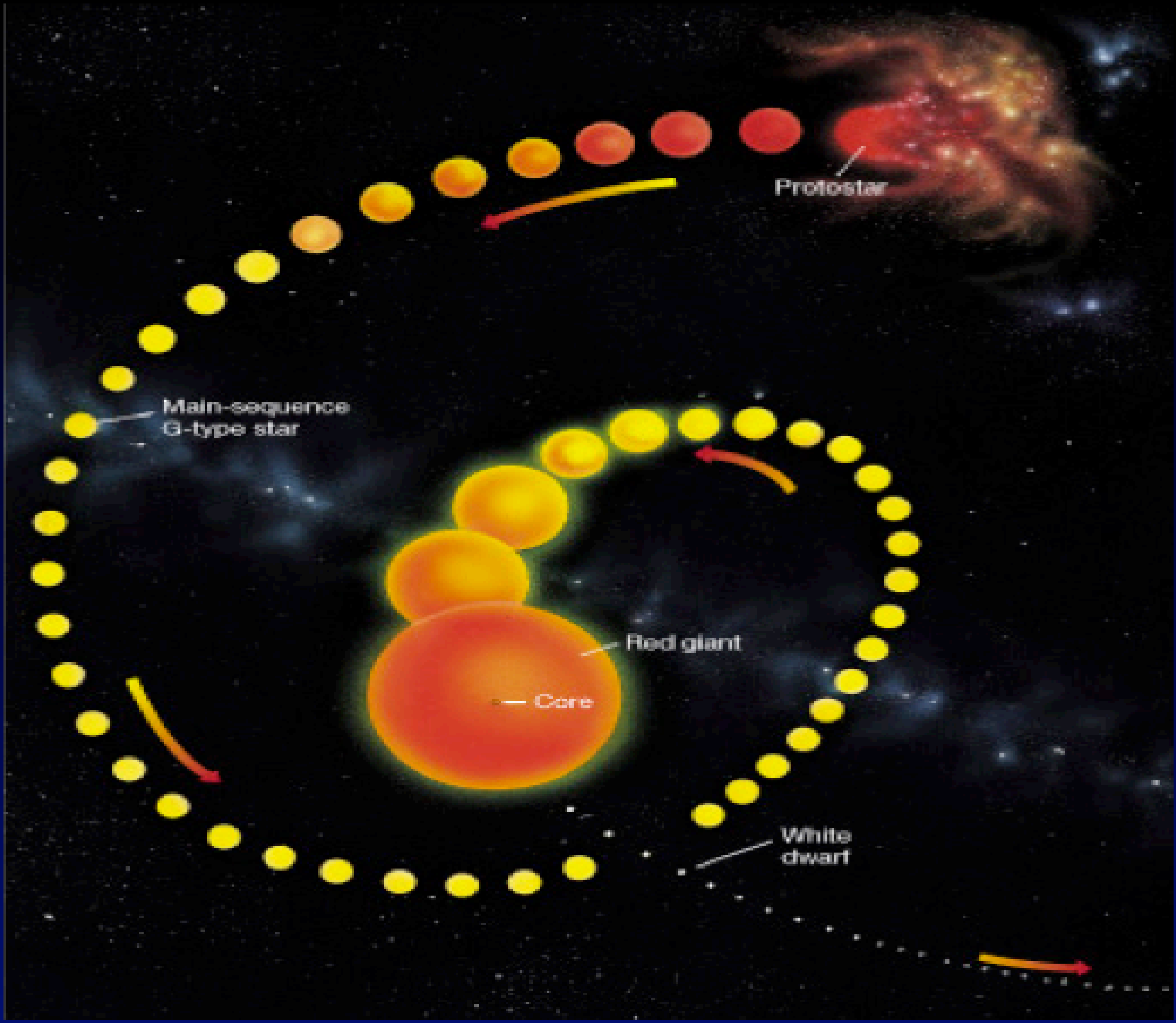


A solitary white dwarf will slowly cool and dim, but the presence of a companion star can lead to an afterlife.

Solar Odyssey

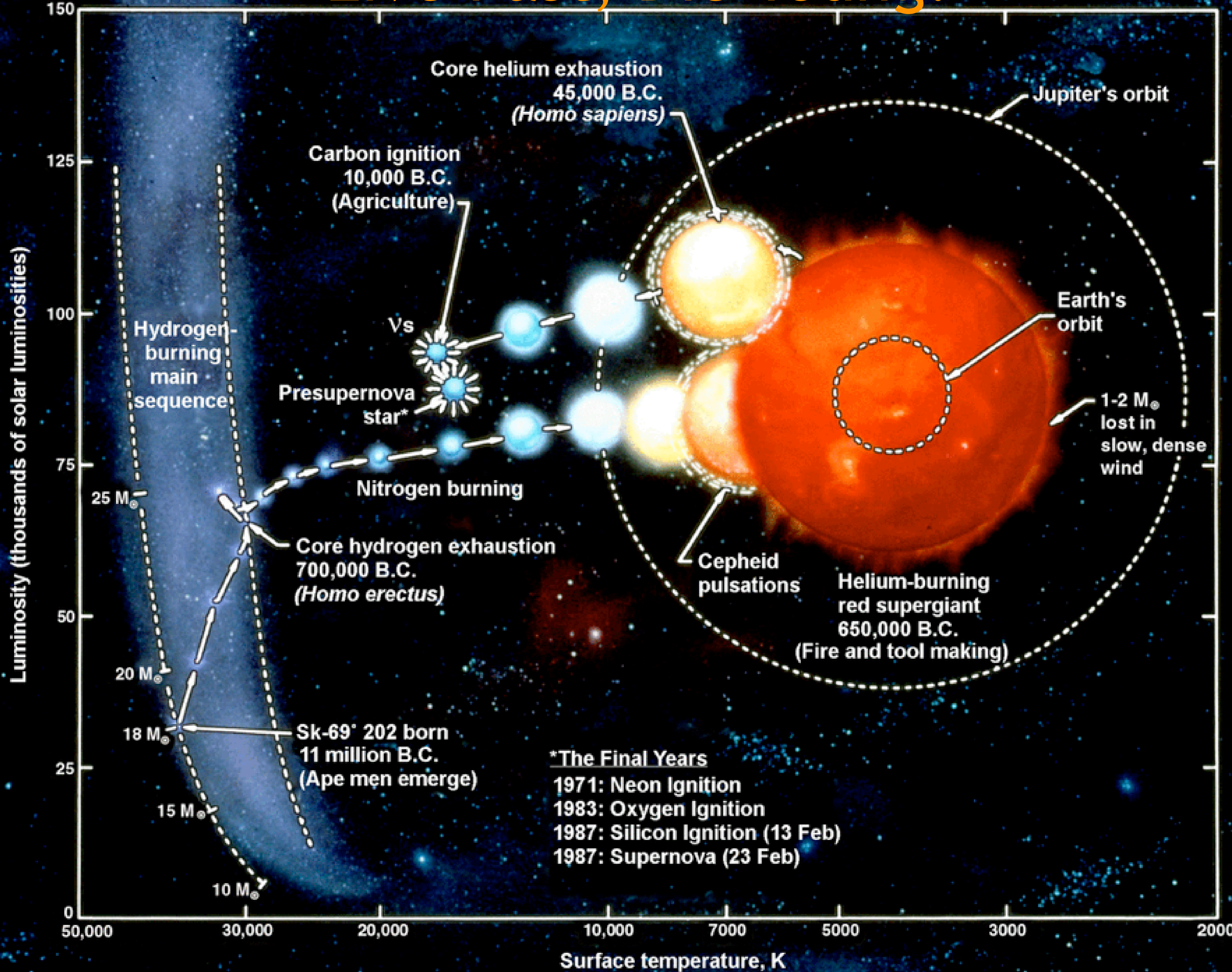
From its genesis in a molecular cloud, the sun's own inexorable gravity drives its contraction, halted periodically by nuclear reactions.

With each change in the interior comes corresponding changes in the surface temperature & luminosity.



From Main Sequence to Red Giant to White Dwarf, stars up to 8 solar masses follow the same path as the Sun.

Live Fast, Die Young!



Scientific American

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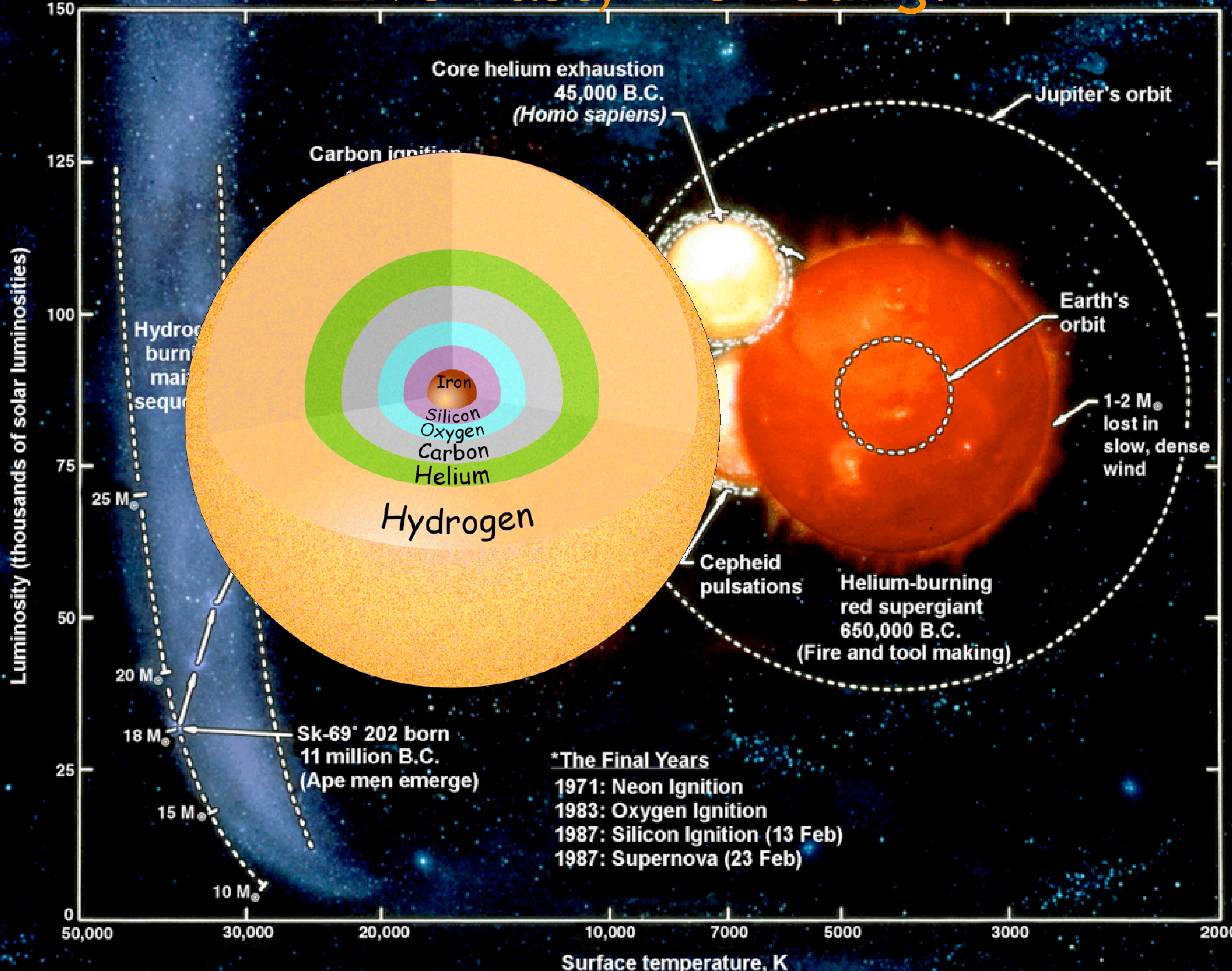
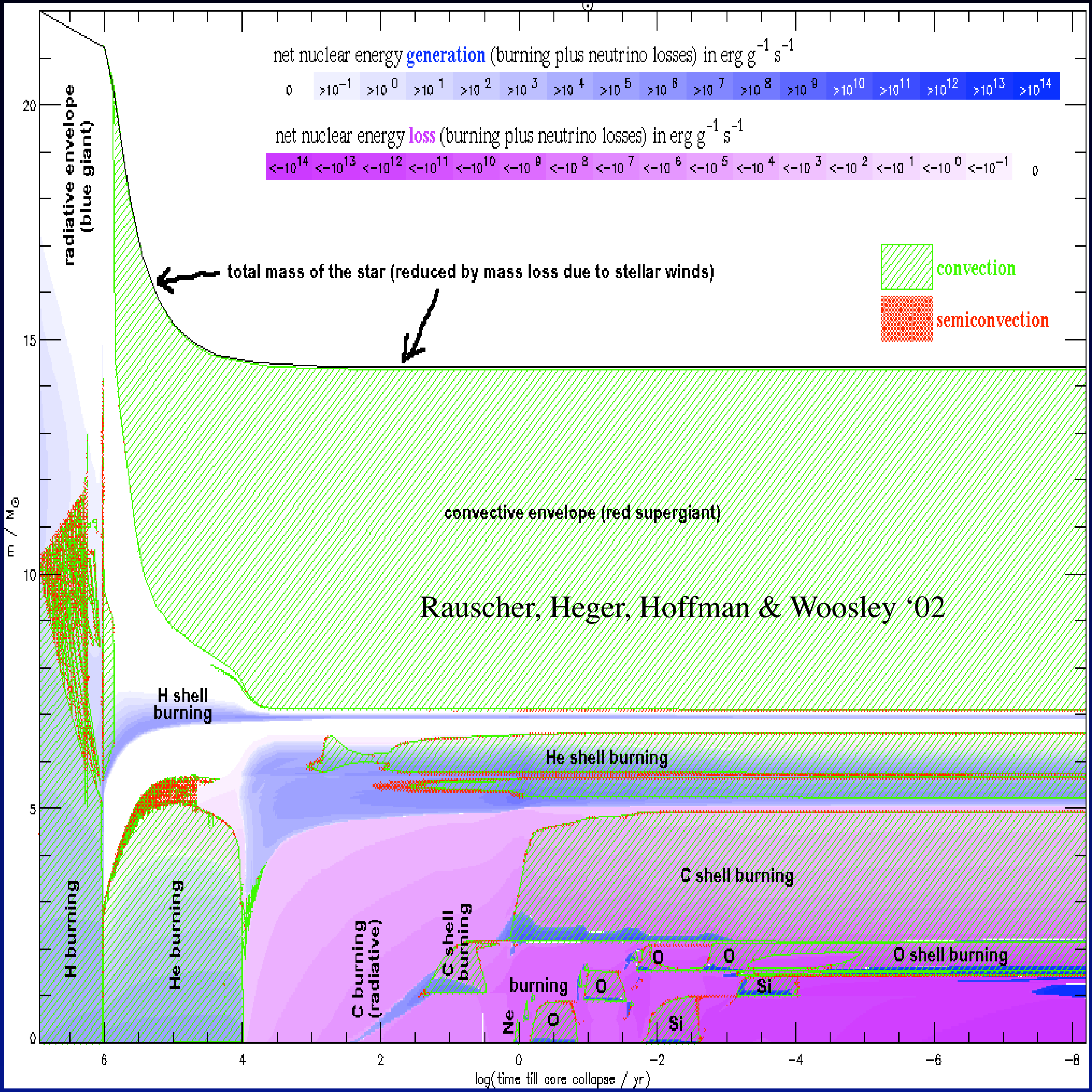


Scientific American

Inside a Massive Star

Stars that ignite Carbon burning meet a very different fate.

They progress through Carbon, Neon, Oxygen and Silicon burning, leaving a core of Iron surrounded by concentric layers of lighter elements.

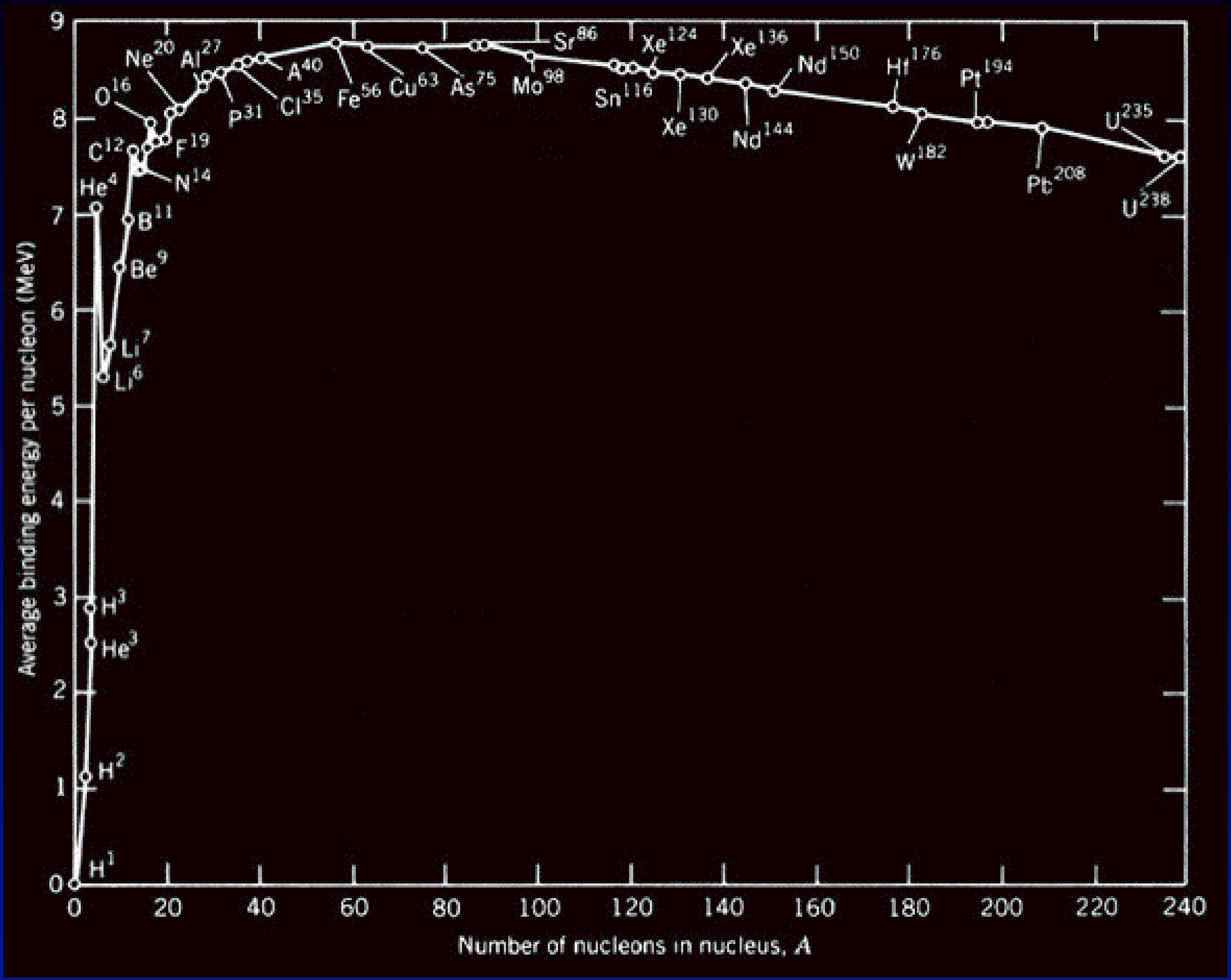


Massive stellar burning stages

nuclear reactions drive the evolution of stars

Process	Fuel	Products	Temp	Duration
H Burning	H	He	10 - 30 MK	10^{14} s
He Burning	He	C	200 MK	10^{13} s
C Burning	C	O, Ne, Na, Mg	800 MK	10^{9} s
Ne Burning	Ne	O, Mg	1.5 GK	10^{7} s
O Burning	O	Mg to S	2 GK	10^{7} s
Si Burning	Si	Fe peak	3 GK	10^{5} s
Collapse		up to Th	> 3 GK	0.3 s

Why Stop at Iron?



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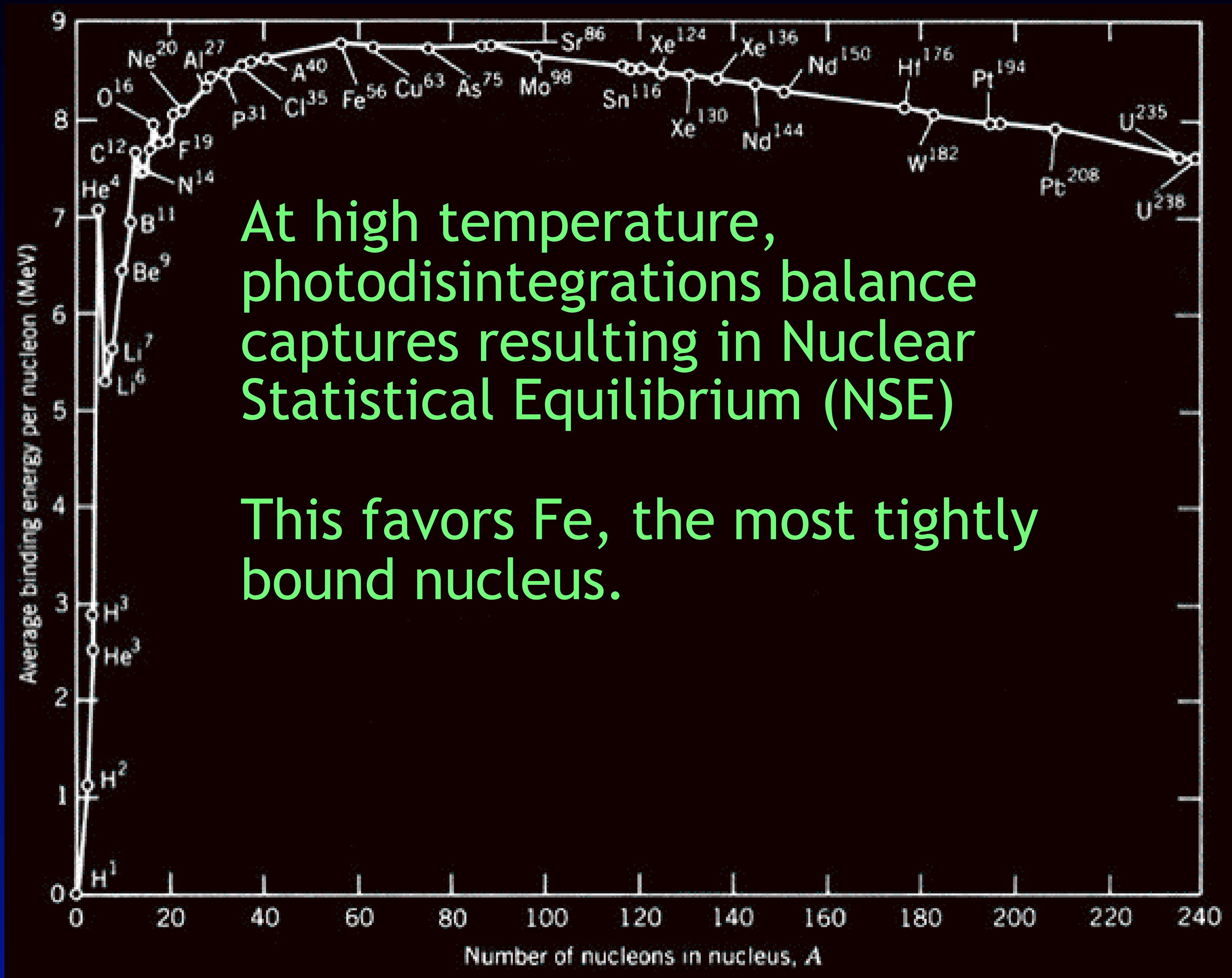

At high temperature, photodisintegrations balance captures resulting in Nuclear Statistical Equilibrium (NSE)

This favors Fe, the most tightly bound nucleus.

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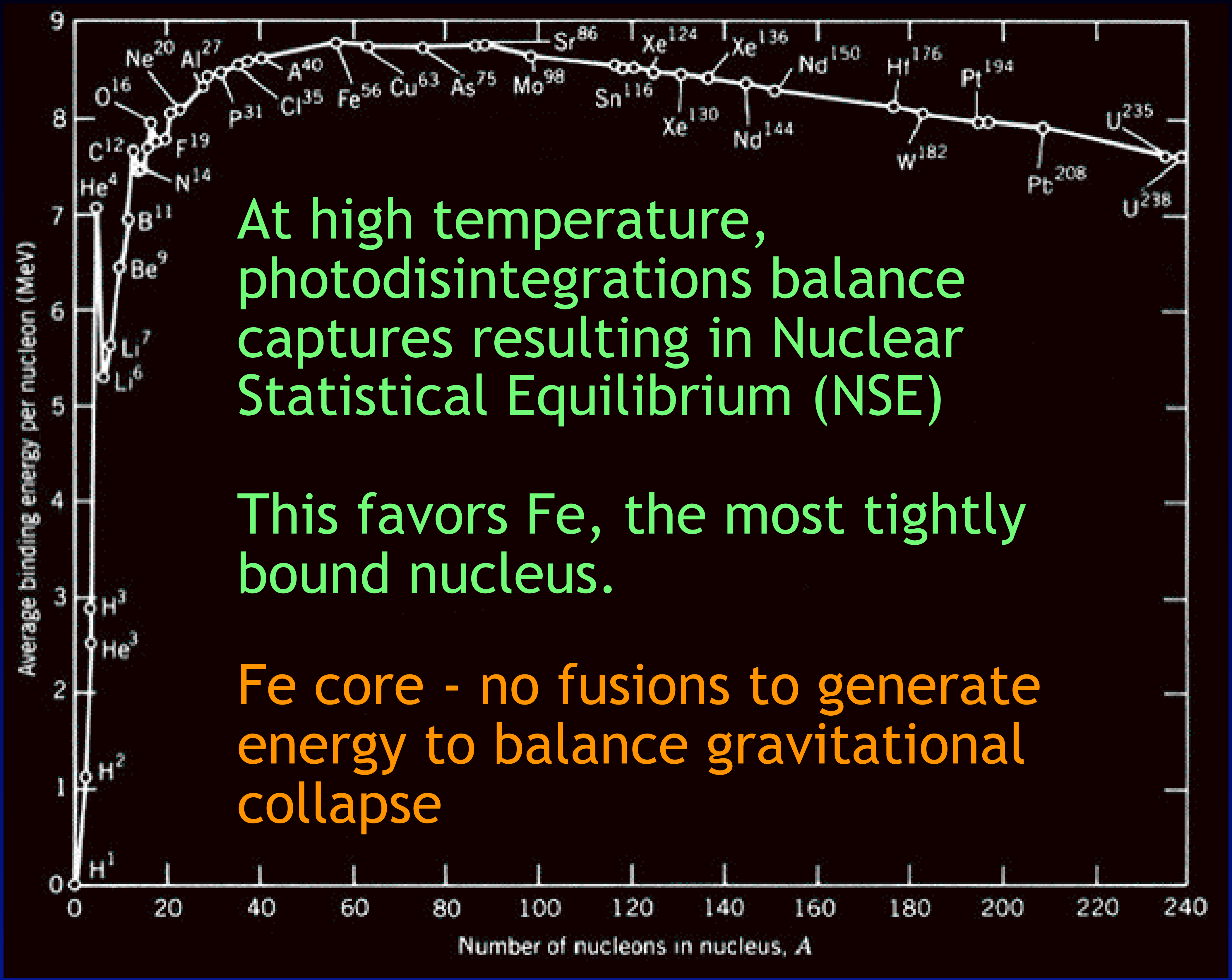

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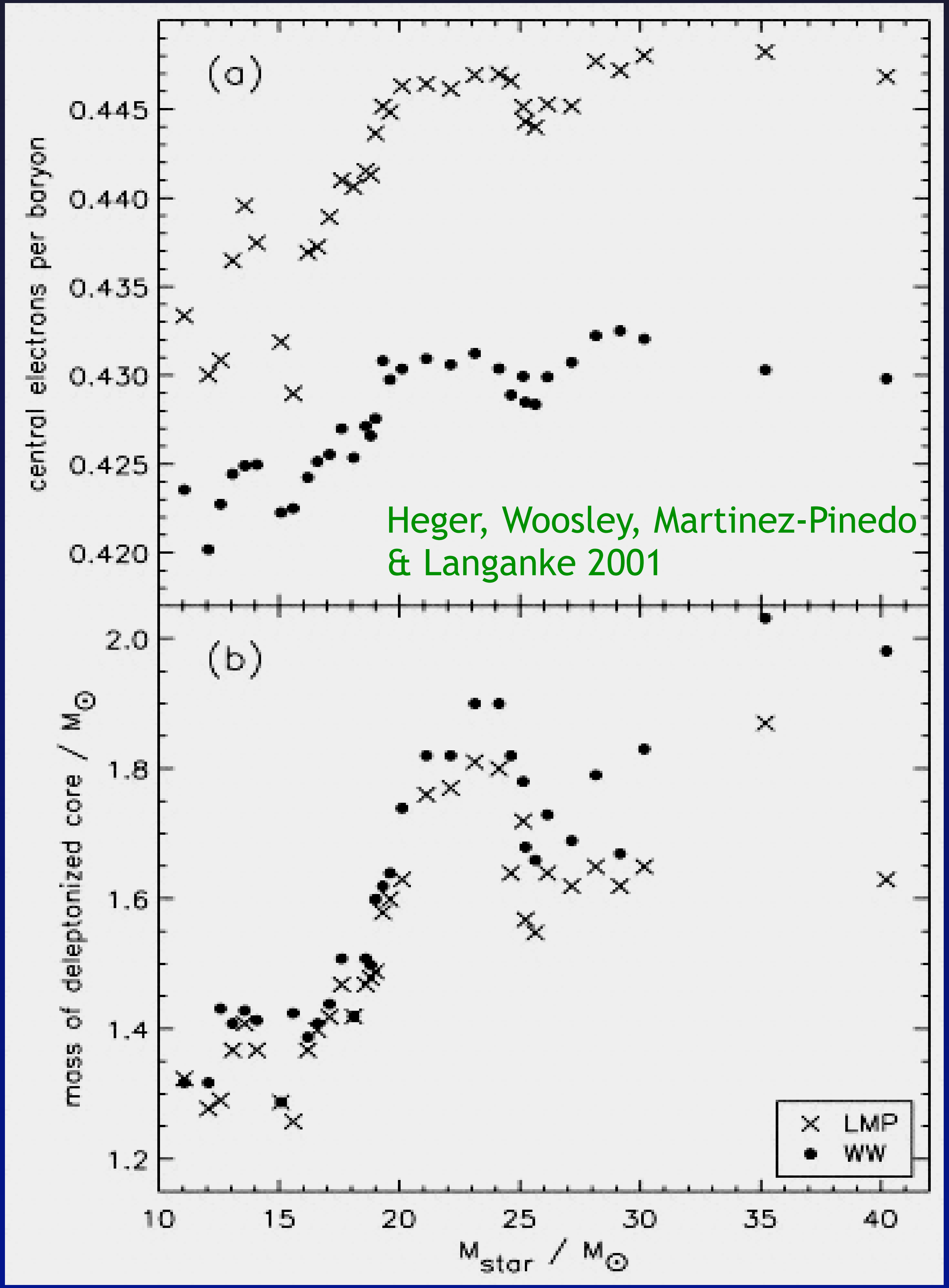
Fe core - no fusions to generate energy to balance gravitational collapse

Nuclear Impact: Weak reactions on Iron Peak Nuclei

In the iron core of a massive star the electron chemical potential becomes large, enhancing electron capture.



Iron core mass and leptonization depend on e^- capture and ß decay rates for A~65. Recent Shell Model calculations reduce the ec rate, altering stellar models.

Nuclear Physics in Stars

1) What is the lifecycle of stars?
    a) Stars have a complex lifecycle that depends on their mass and initial composition.
2) How does Nuclear Physics drive this lifecycle?
    a) The balances of thermonuclear energy generation and the self-gravitation of the star determines the star's structure.
    b) The various nuclear burning stages and especially the exhaustion of nuclear fuels signal important milestones in the stellar evolution