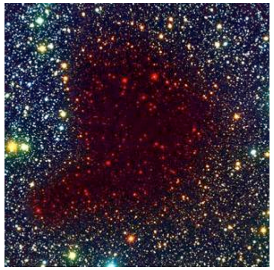
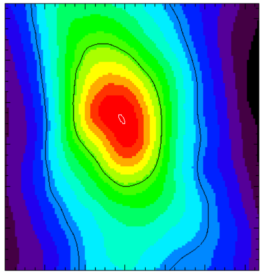
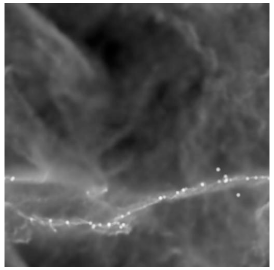
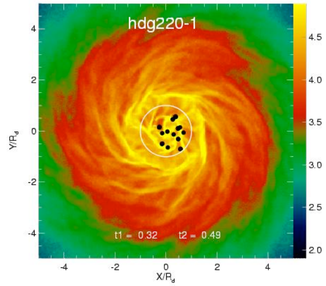
Sterne 3

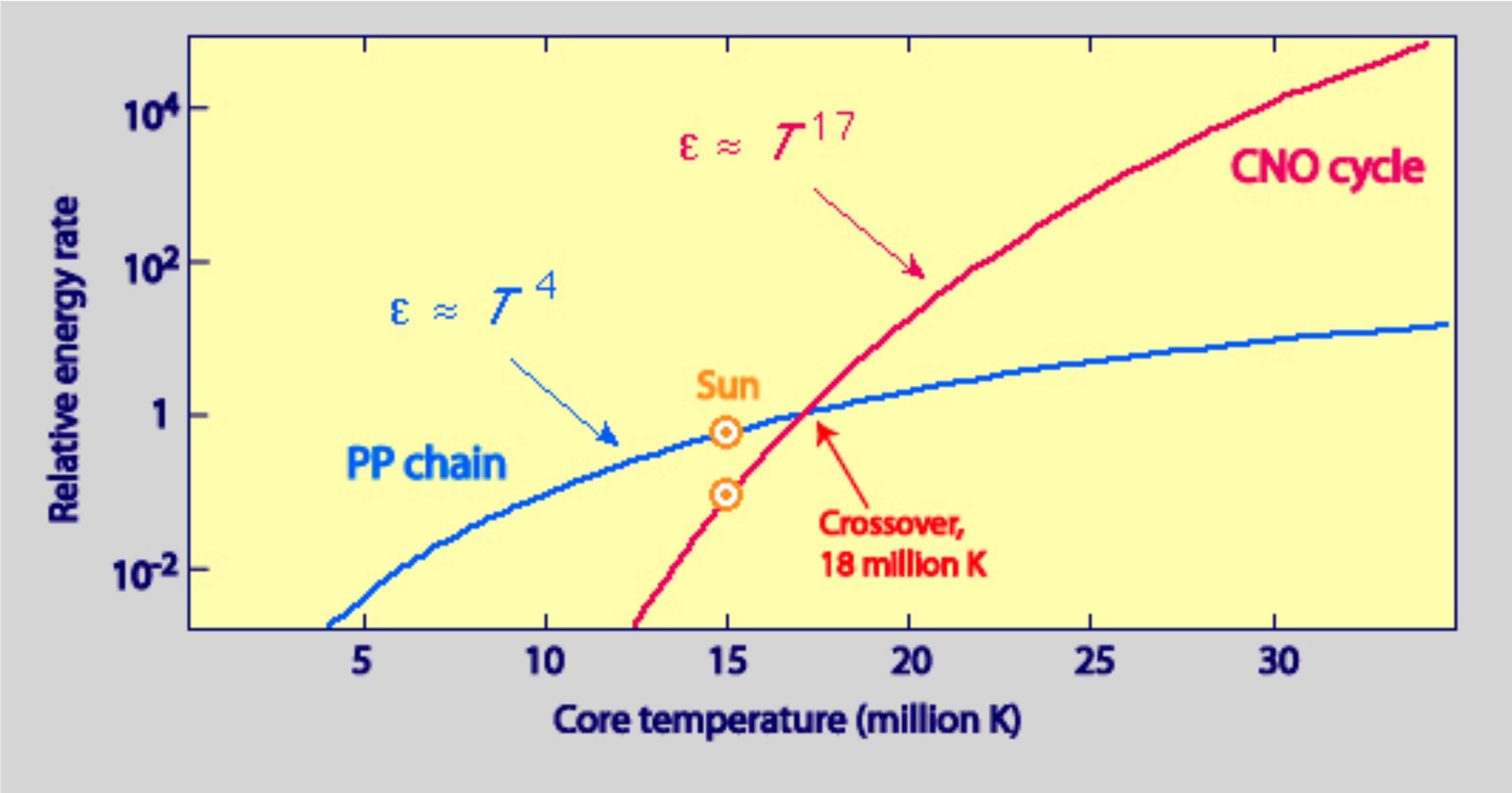
Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg

13.12.2012
Ralf Klessen

Nachhauptreihenentwicklung

- ***Energieerzeugungsprozesse***
  - pp-Kette
  - CNO-Zyklus
  - höhere Brennprozesse
- **Stellare Nukleosynthese**
- **Nachhauptreihenentwicklung**
- **Endphasen der Sternentwicklung**
  - Weiße Zwerge
  - Neutronensterne
  - Supernovae
  - Schwarze Löcher

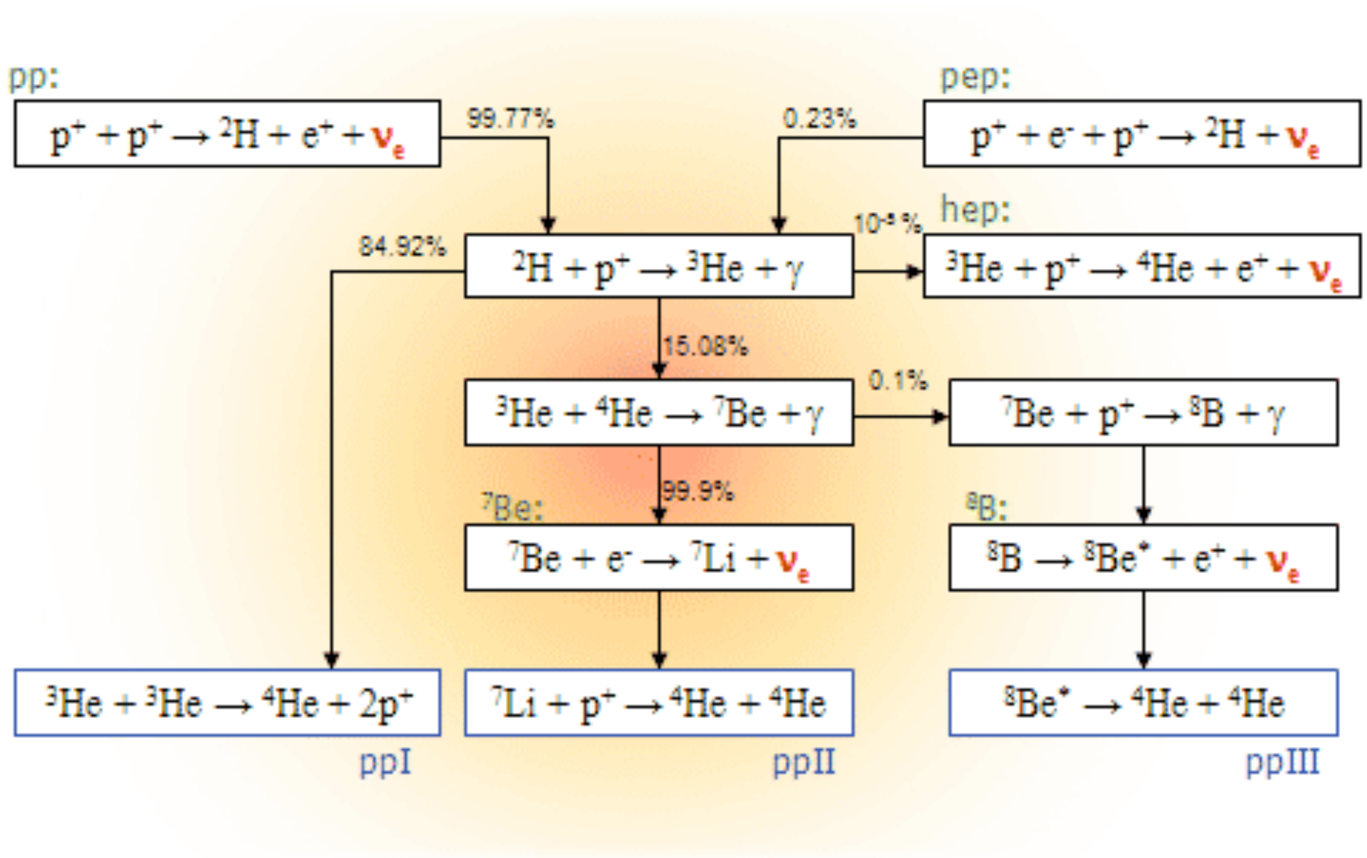


Credit: *Adapted from an image by Mike Guidry, University of Tennessee*

Vergleich pp-Kette und CNO-Zyklus

Sonnenneutrinos

Durch die Kernreaktion im Sonneninneren entstehen Neutrinos, die auf der Erde nachgewiesen werden können.
Problem lange Zeit: Nachweisraten zu gering, Lösung Neutrino-Oszillation.



Bildnachweis: LAGUNA Consortium - Large Apparatus studying Grand Unification and Neutrino Astrophysics

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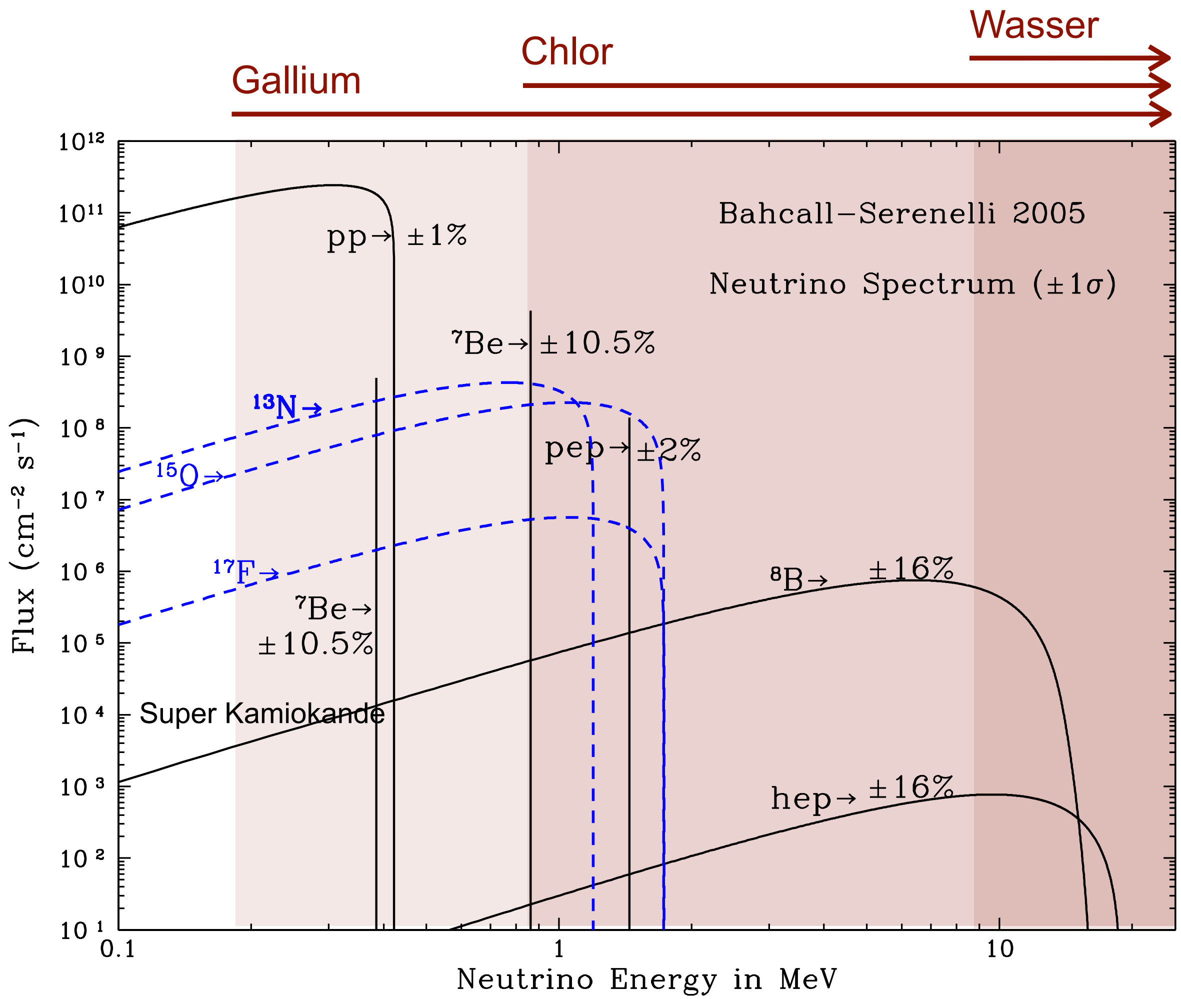
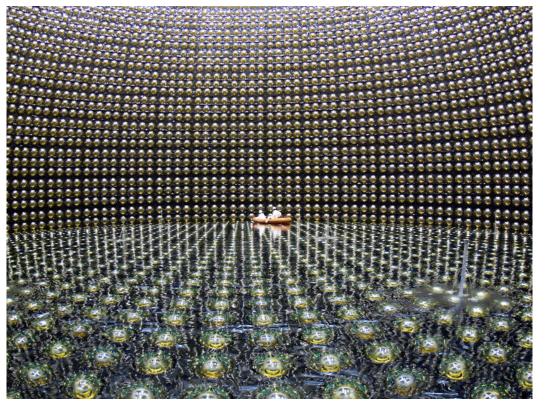


Super Kamiokande



Innerer Aufbau der Sonne und Bereich des zentralen H-Brennens

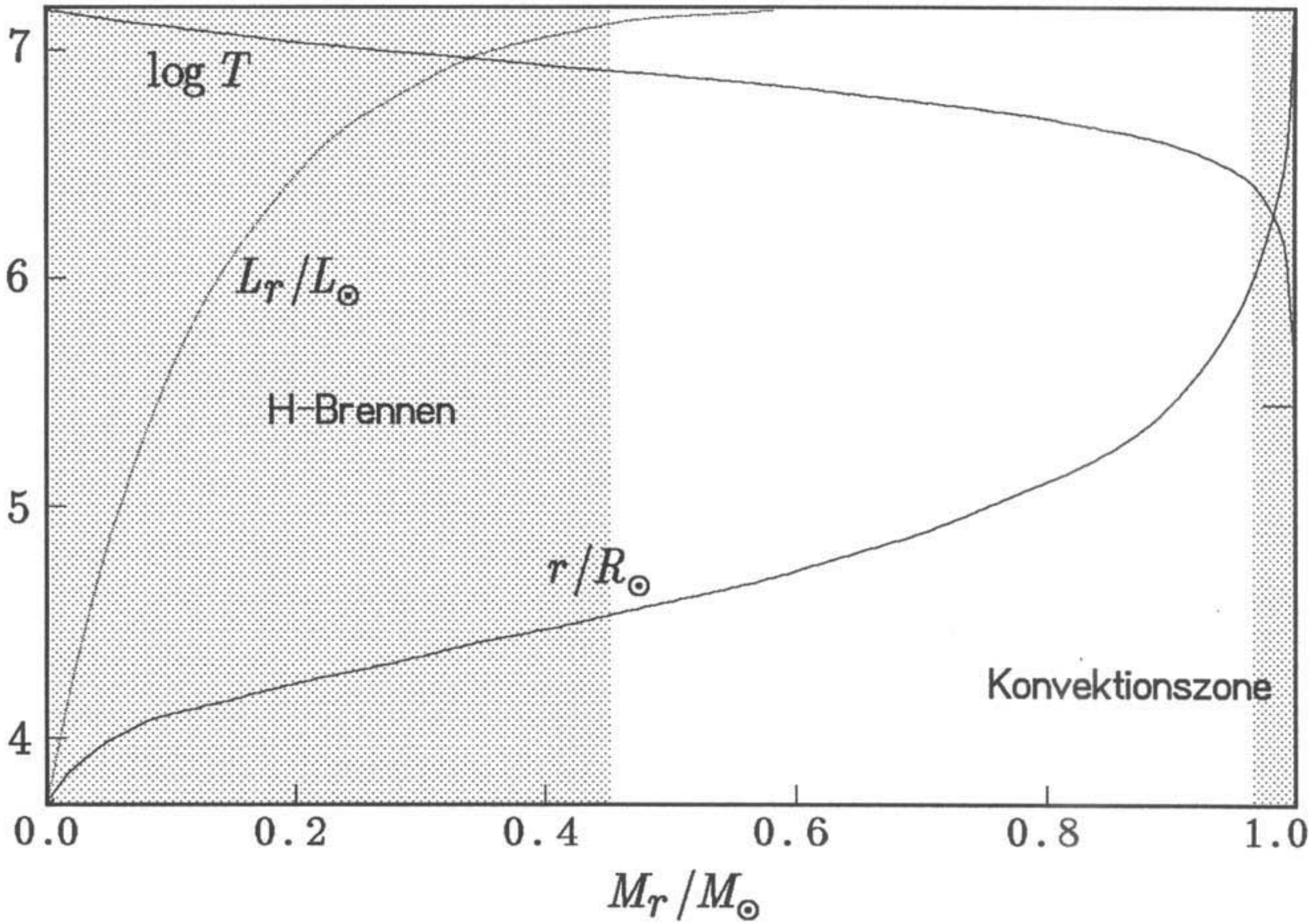
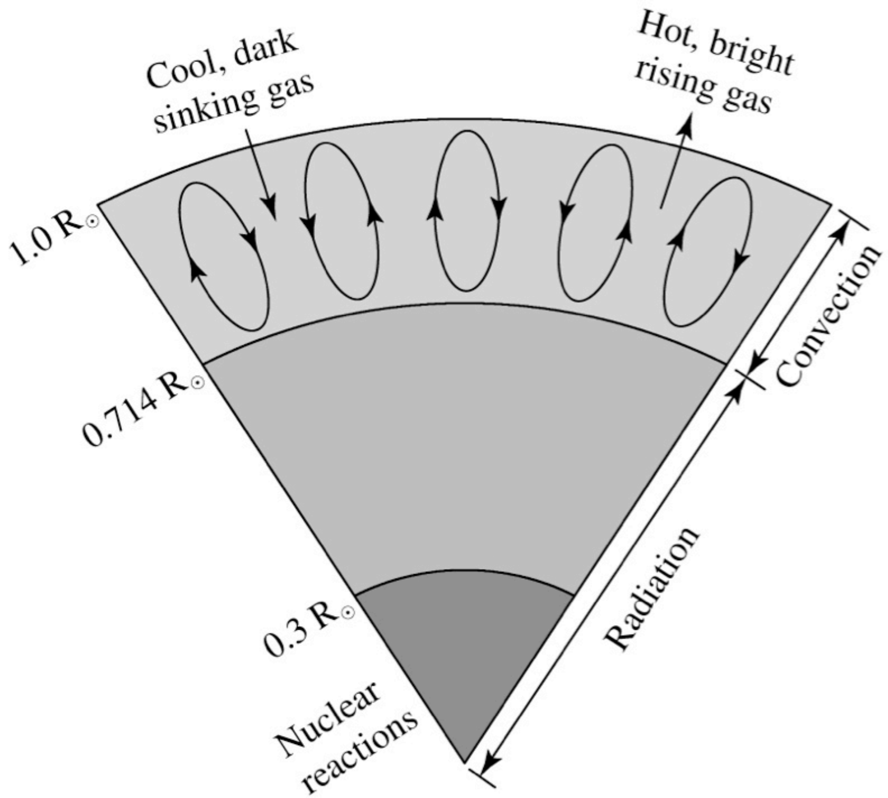


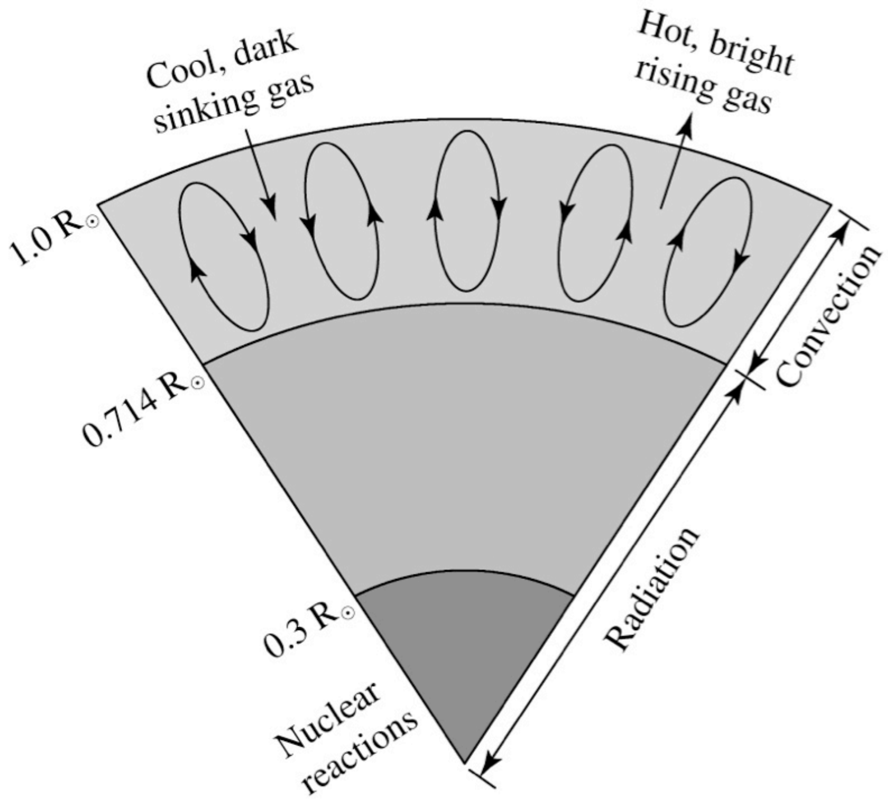
Bild: Thomas Gehren München

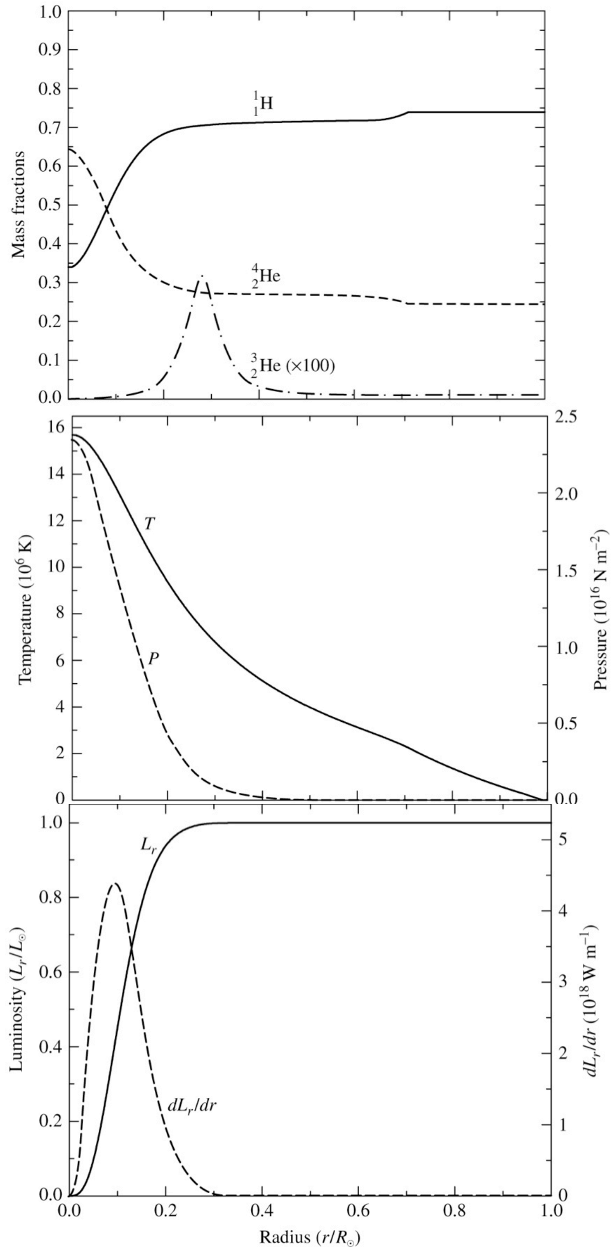
Innerer Aufbau der Sonne und Bereich des zentralen H-Brennens



Carroll & Ostlie, Abbildung 11.2

Innerer Aufbau der Sonne und Bereich des zentralen H-Brennens



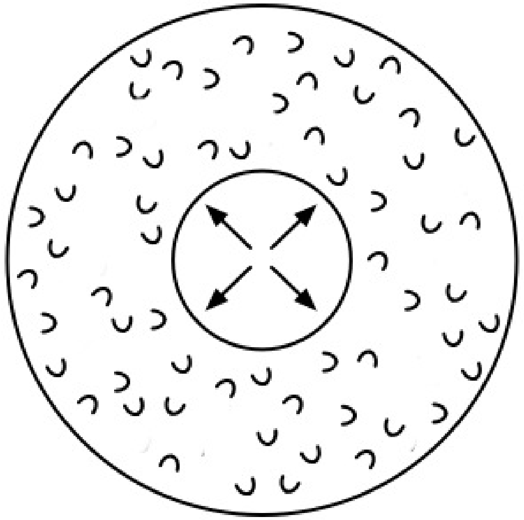
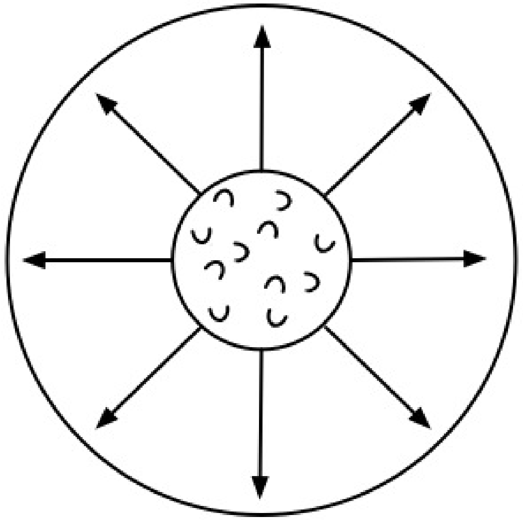


Carroll & Ostlie, Abbildung 11.2 - 11.5

Vergleich massearmer Stern / massereicher Stern

lower main sequence	upper main sequence
$M < 1.5\,\mathrm{M}_\odot$ (M to F0)	$M > 1.5\,\mathrm{M}_\odot$ (F0 to O)
pp-chain	CNO-cycle
$\epsilon_{\mathrm{pp}} \propto T^4$	$\epsilon_{\mathrm{CNO}} \propto T^{20}$
low T-dependency; less concentrated energy source → small T-gradients	in center larger flux and steep temperature gradient
Radiative Core	**Convective Core**

$$T_c \quad > \quad 20 \cdot 10^6 \quad > \quad T_c$$

surface H neutral ; then ionization and rapid increase of opacity → steep T gradient.	surface hot and ionized modest temperature gradient.
convective envelope	**radiative envelope**
	
the smaller M, the further convective zone reaches into star.	the larger m, the larger the convective core

Triple α-Process of Helium Burning

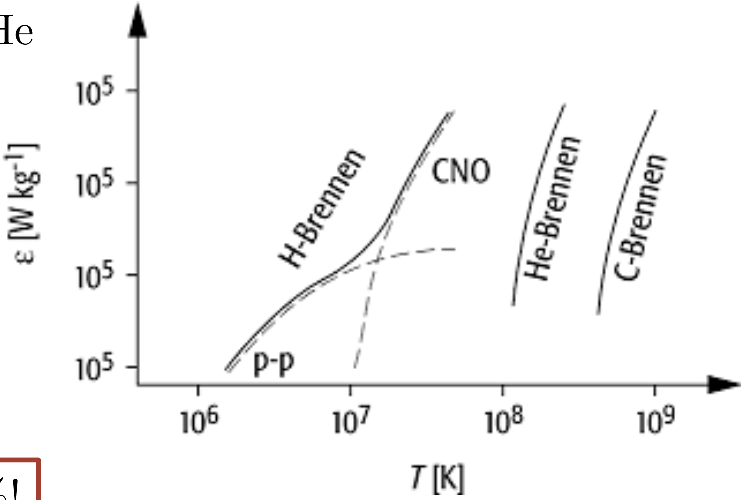
once the central density and temperature gets high enough, He burning can set in:

$$
\begin{aligned}
{}^4_2\mathrm{He} + {}^4_2\mathrm{He} &\longleftrightarrow {}^8_4\mathrm{Be}^* \\
{}^8_4\mathrm{Be} + {}^4_2\mathrm{He} &\longrightarrow {}^{12}_6\mathrm{C} + \gamma
\end{aligned}
$$

$$\Delta E_{\mathrm{eff}} = 7.3\,\mathrm{MeV}$$

* unstable, decays back to $2\,{}^4_2\mathrm{He}$ if not hit by other ${}^4_2\mathrm{He}$

$$\epsilon_{3\alpha} = \epsilon_{0.3\alpha}\,\varrho^2\,Y^3\,T_8^{41} \quad (Y = \text{He fraction})$$



very steep T dependence: $\Delta T = 10\% \rightarrow \Delta L$ of 5000%!

Bildnachweis: http://www.techniklexikon.net/d/energieerzeugung_der_sterne/energieerzeugung_der_sterne.htm

Carbon and Oxygen Burning

$$
\begin{aligned}
{}^{12}_{6}\mathrm{C} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{16}_{8}\mathrm{O} + \gamma \\
{}^{16}_{8}\mathrm{O} + {}^{4}_{2}\mathrm{He} &\longrightarrow {}^{20}_{10}\mathrm{Ne} + \gamma
\end{aligned}
$$

Production of α-Elements!

Near $6 \cdot 10^8$K:

$$
{}^{12}_{6}\mathrm{C} + {}^{12}_{6}\mathrm{C} \longrightarrow \begin{cases}
{}^{16}_{8}\mathrm{O} + 2\,{}^{4}_{2}\mathrm{He} & \Delta E < 0 \\
{}^{20}_{10}\mathrm{Ne} + {}^{4}_{2}\mathrm{He} & \Delta E > 0 \\
{}^{23}_{11}\mathrm{No} + \mathrm{p}^{+} & \Delta E > 0 \\
{}^{23}_{11}\mathrm{Mg} + \mathrm{n} & \Delta E < 0 \\
{}^{24}_{12}\mathrm{Mg} + \gamma & \Delta E > 0
\end{cases}
$$

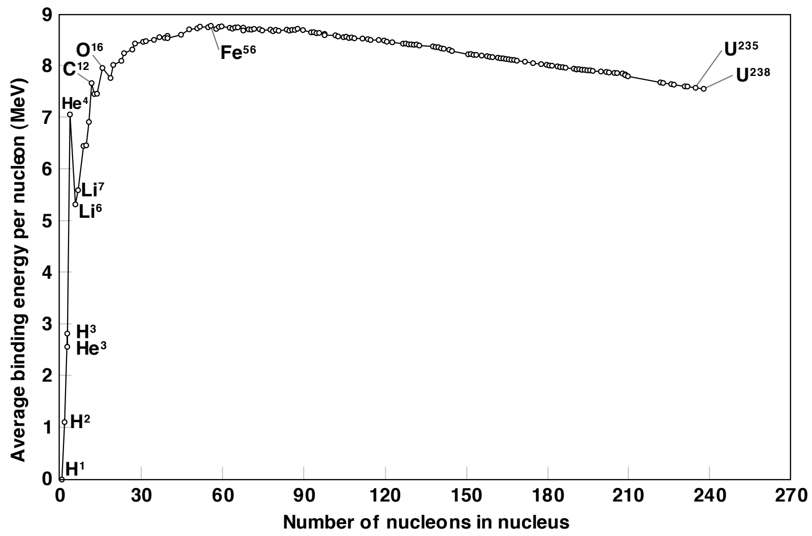
Further oxygen burning at $T > 10^9$ K

$$
{}^{16}_{8}\mathrm{O} + {}^{16}_{8}\mathrm{O} \longrightarrow \begin{cases}
{}^{24}_{12}\mathrm{Mg} + 2\,{}^{4}_{2}\mathrm{He} & \Delta E < 0 \\
{}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} & \Delta E > 0 \\
{}^{31}_{15}\mathrm{P} + \mathrm{p}^{+} & \Delta E > 0 \\
{}^{31}_{16}\mathrm{S} + \mathrm{n} & \Delta E > 0 \\
{}^{32}_{16}\mathrm{S} + \gamma & \Delta E > 0
\end{cases}
$$

$\Delta E < 0$: energy is absorbed rather than released.

Fusion goes up to ^{56}Fe!

This is the most stable element.



Photodisintegration:

For T > 10^9 K also photodisintegration can become important!

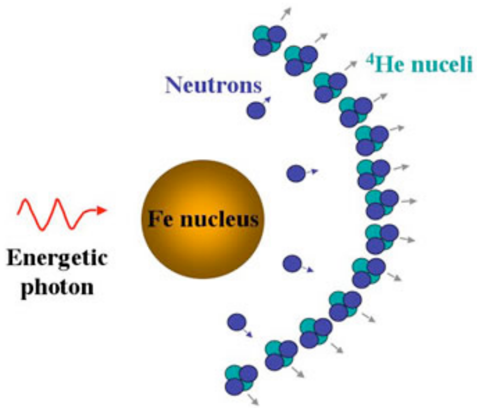
At that temperature more and more photons reach energies in the MeV range, comparable to the binding energy of the nucleus. Photon absorption can lead to α-decay, breaking up heavier nuclei.

Example: Neon

$^{20}Ne + \gamma \longrightarrow {}^{16}O + {}^{4}He \quad Q = -4{,}73 \text{ eV}$

As T goes up, more and more bound nuclei can become disintegrated by photonabsorption and subsequent α-decay. As iron is most strongly bound it may survive as dominant species (iron core).

At T > 5×10^9 K even ^{56}Fe breaks up leaving behind only α-particles (^4He), reversing all previous burning processes. This is relevant, or example, in the core collapse phase of supernovae.



$$^{56}\mathrm{Fe} + \gamma \quad \rightarrow \quad 13\ {}^{4}\mathrm{He} + 4n$$

$$^{4}\mathrm{He} + \gamma \quad \rightarrow \quad 2p^{+} + 2n$$

Bildnachweis: http://astronomy.swin.edu.au/cosmos/P/Photodisintegration

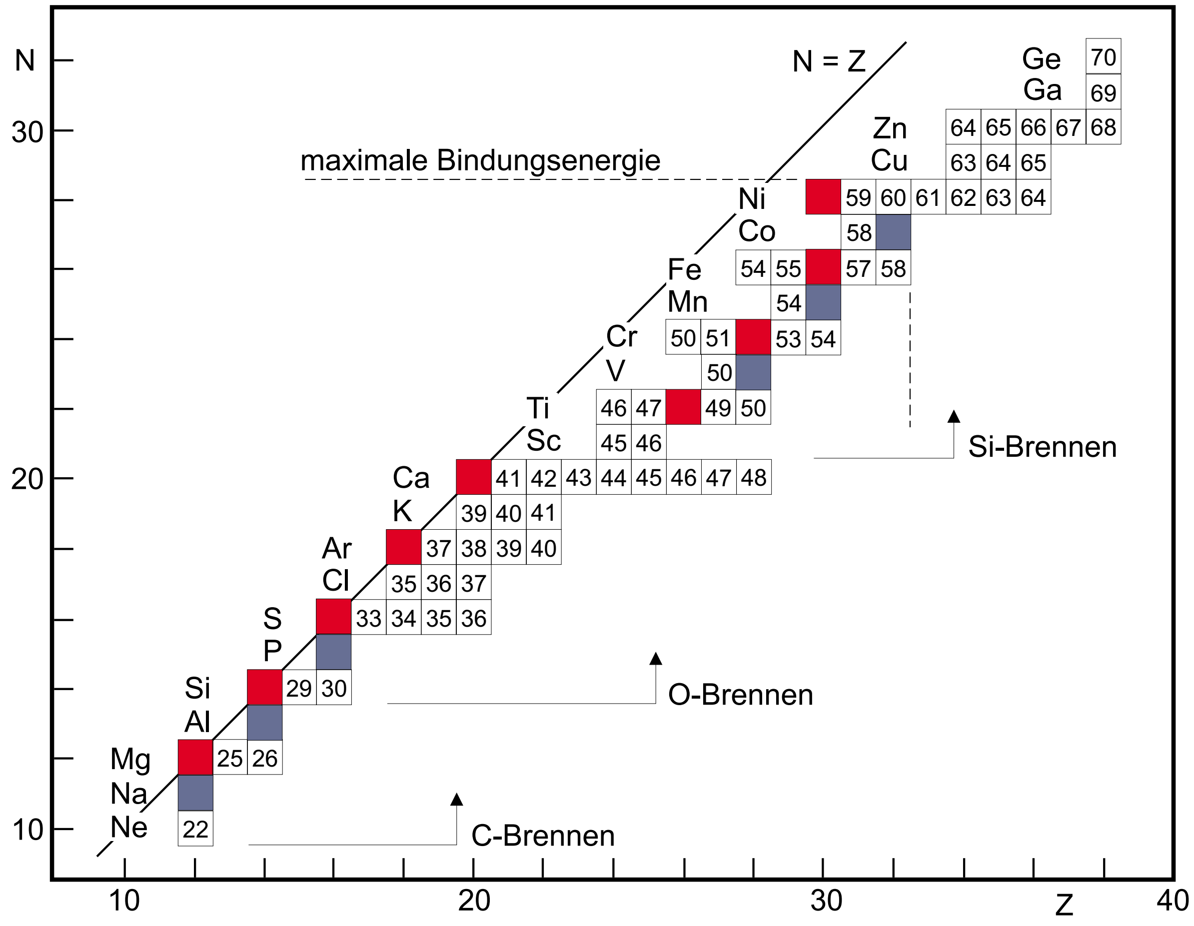
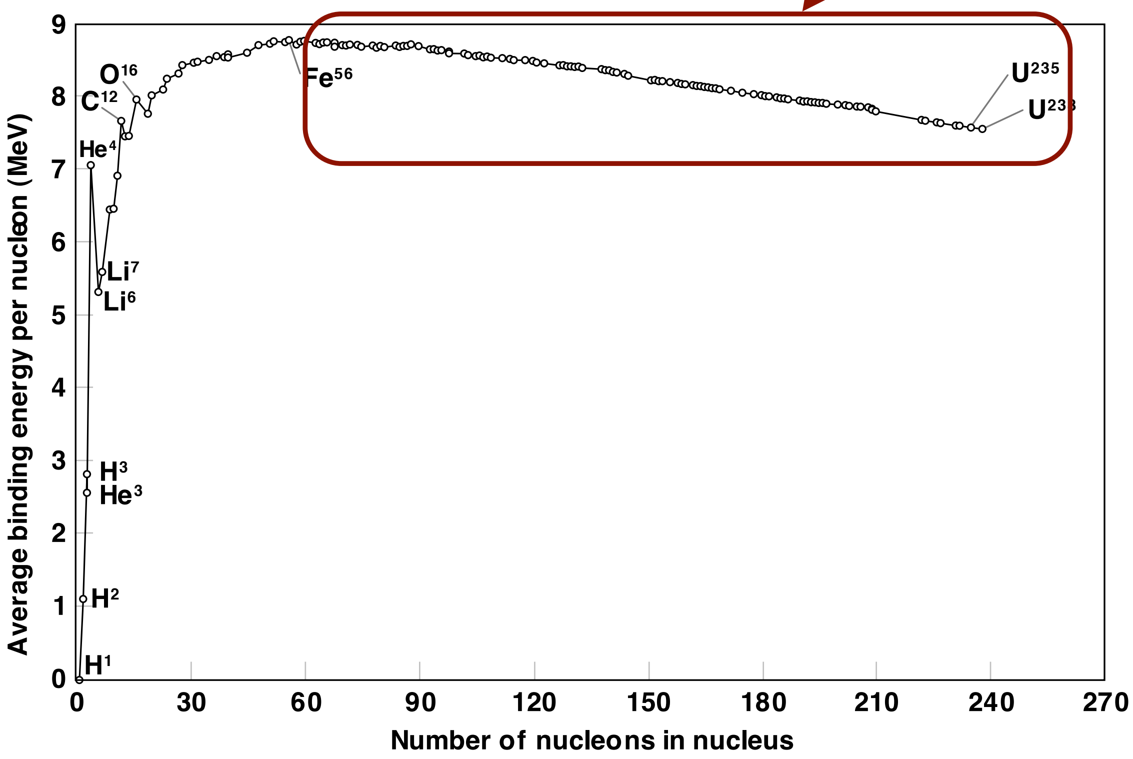
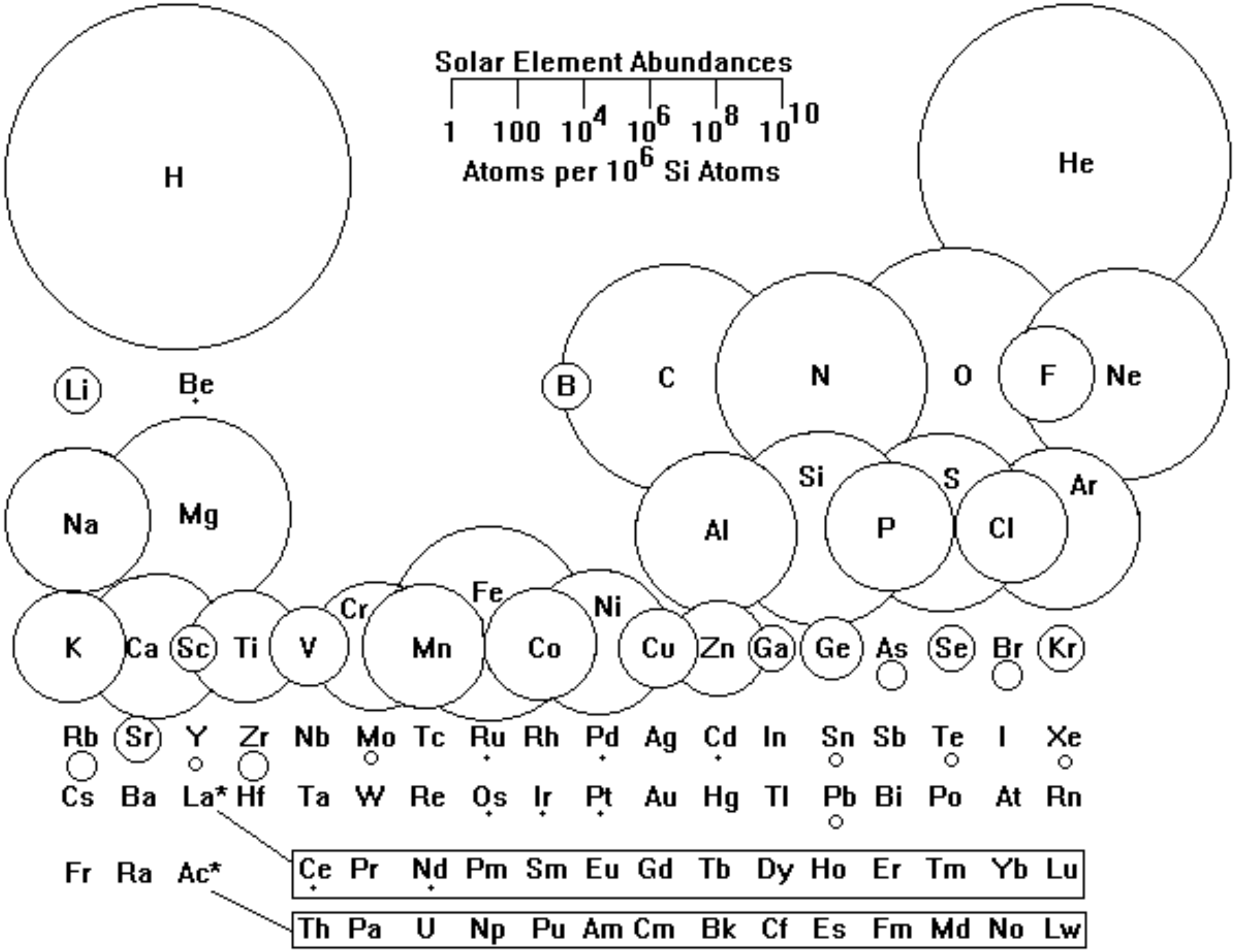


Bild von Thomas Gehren (München)

Wie kann man diese Elemente erzeugen?



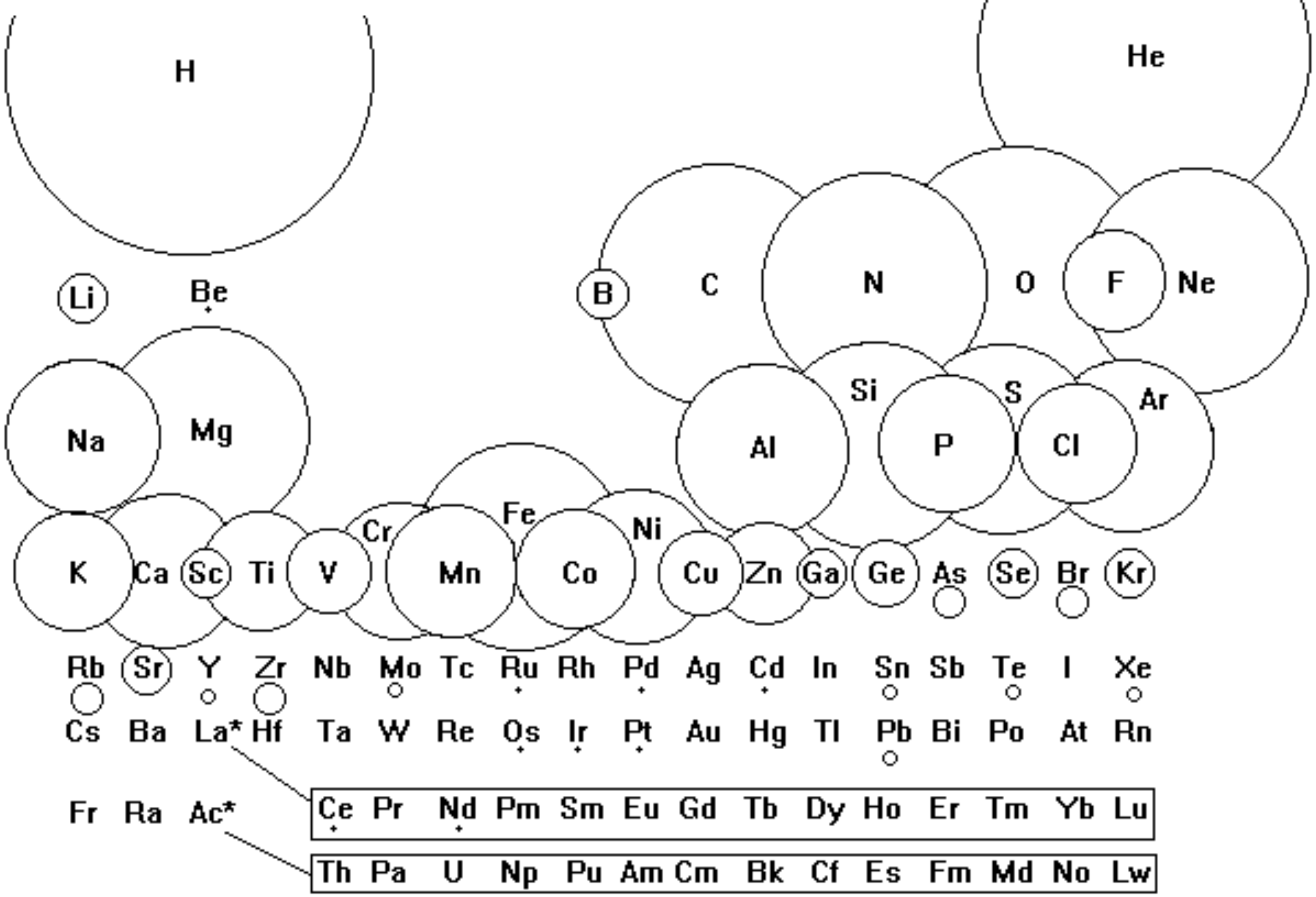
Elemental composition of the Sun. Silicon is used as a basis for comparison for convenient comparison wtih planetary element abundances. Note that the abundance scale is *logarithmic*.



Bildnachweis: https://www.uwgb.edu/dutchs/PLANETS/Geochem.htm

Elemental composition of the Sun. Silicon is used as a basis for comparison for convenient comparison wtih planetary element abundances. Note that the abundance scale is *logarithmic.*

- Dominance of light elements
- Strong preference for even-numbered elements
- Abundance peak at iron, followed by a steady decrease.



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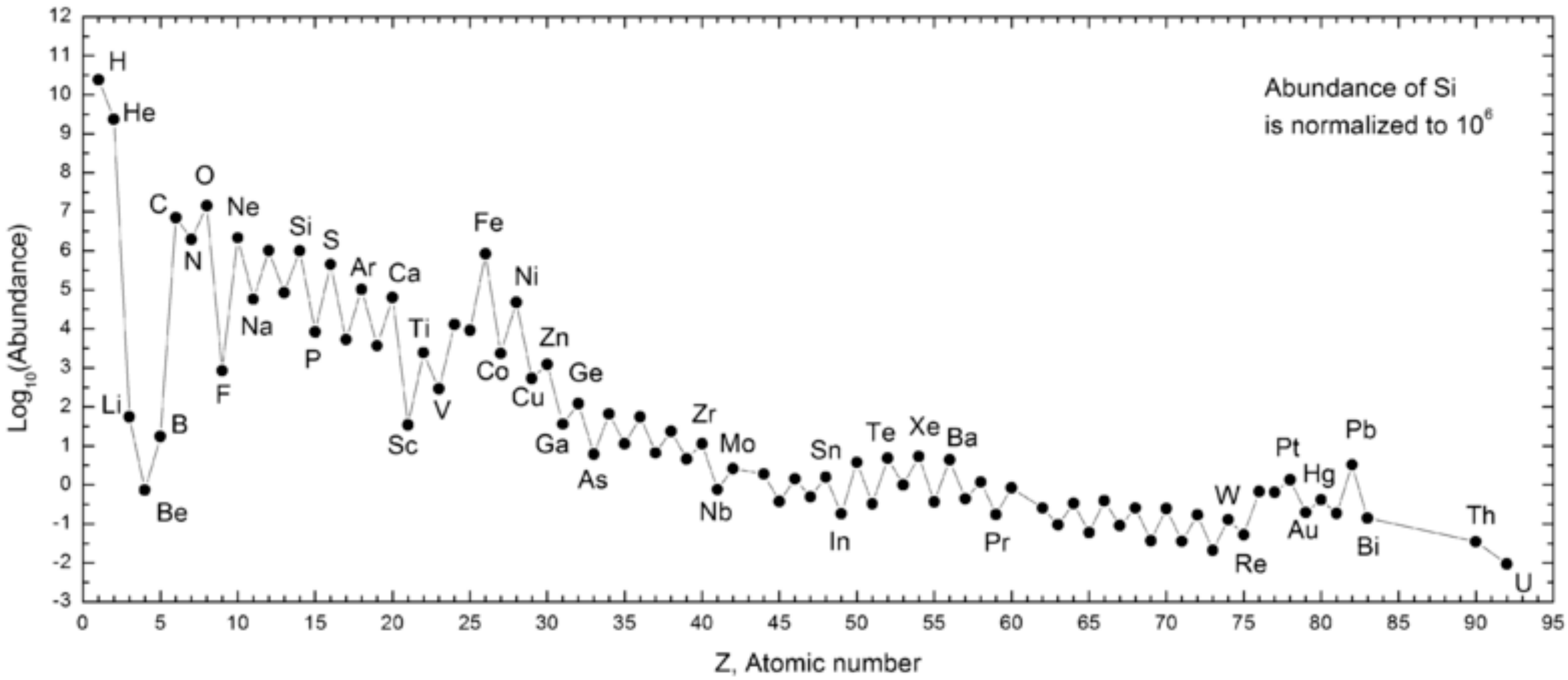
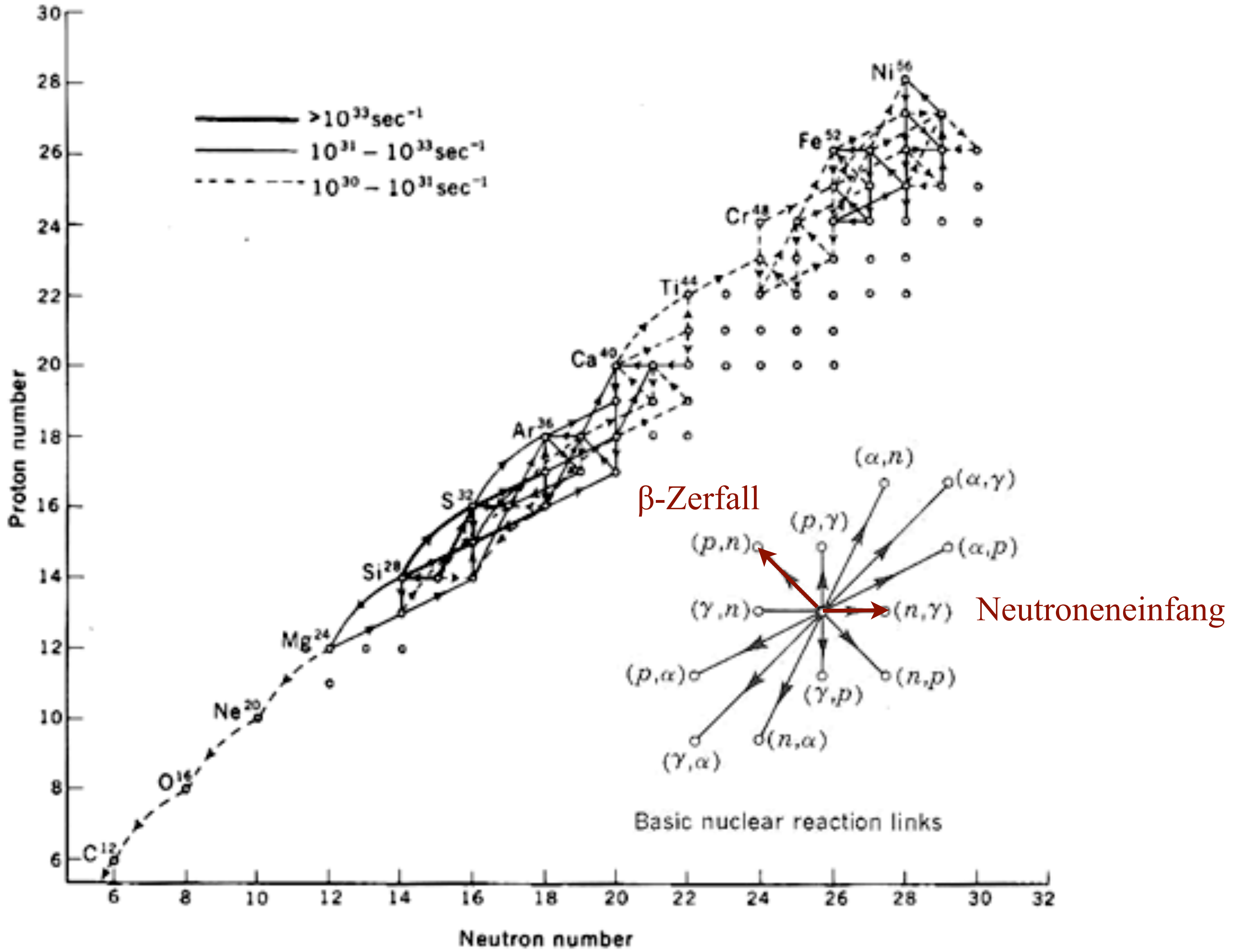


Bildnachweis: Wikipedia: http://en.wikipedia.org/wiki/Abundance_of_the_chemical_elements

Kernreaktionspfade



Nach Truran, Cameron, Gilbert (1966, Can. J. Phys, 44, 576)

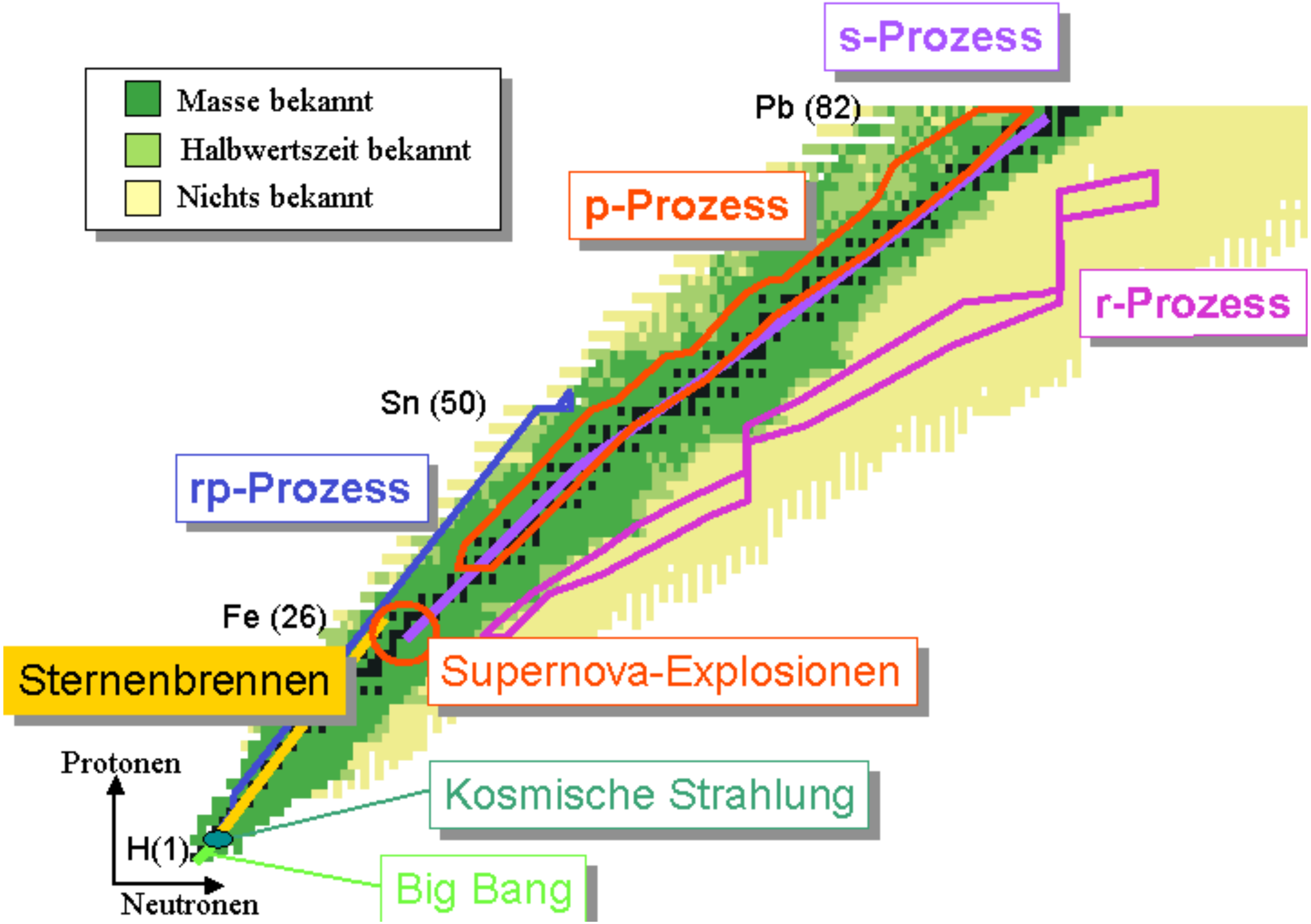
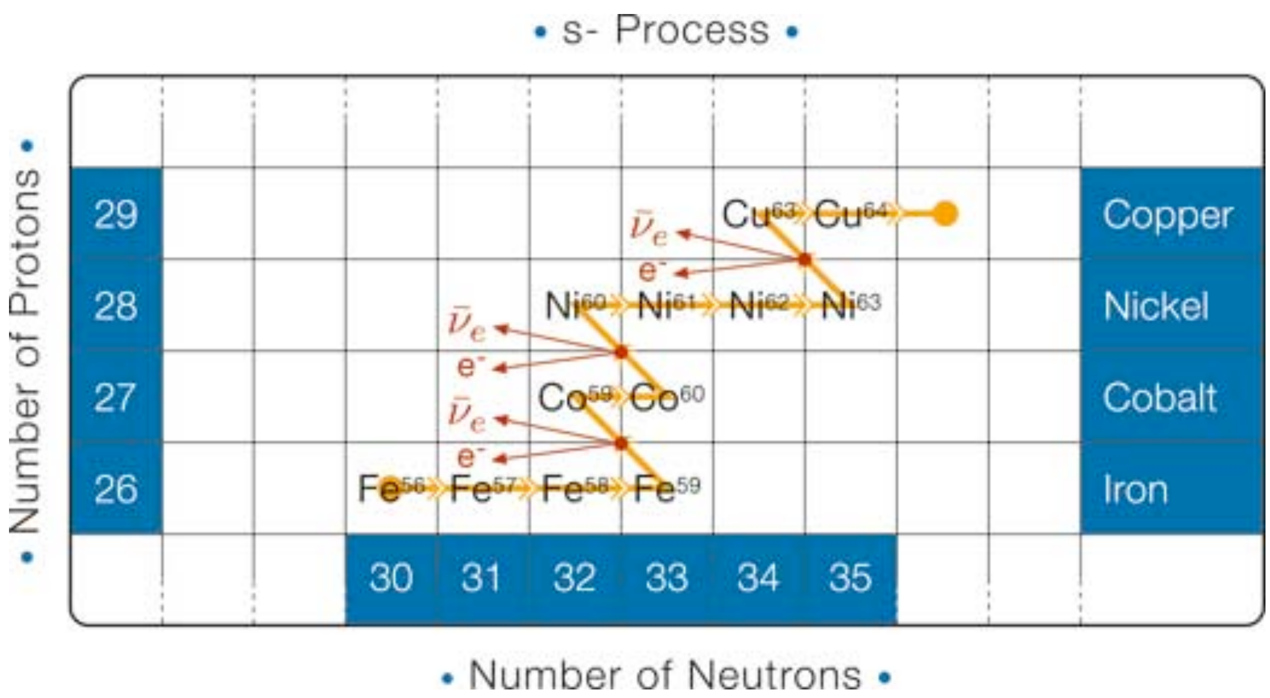


Bild: Helmholtz-Zentrum Rossendorf

s-Prozess: s = slow = langsam; **Neutroneneinfang auf langen Zeitskalen** (mehrere Jahre) bei geringer Neutronenrate

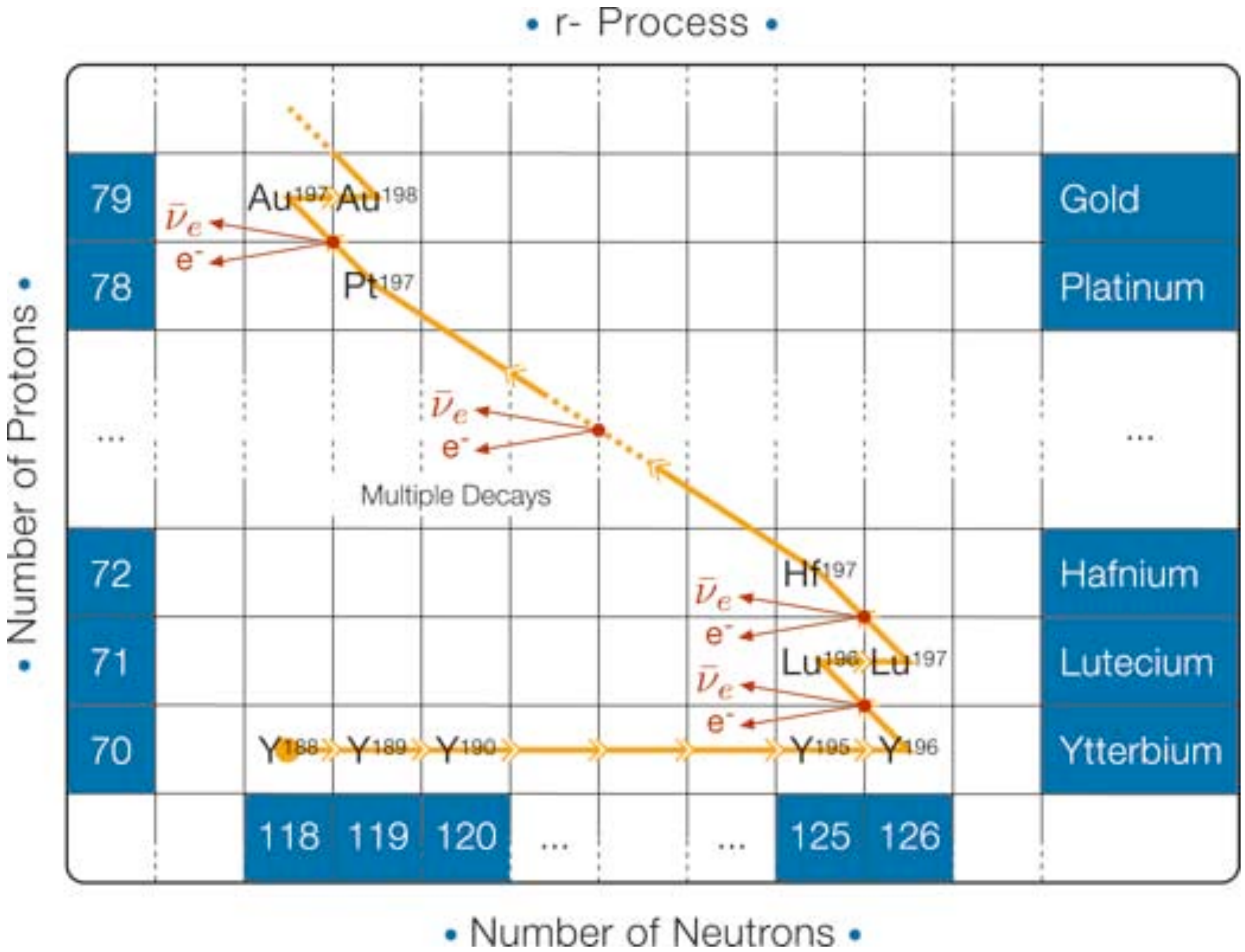
Die gebildeten instabilen, neutronenreichen Kerne haben genug Zeit durch β-Zerfall zu stabilen Kernen zu zerfallen. Der s-Prozess kann auf der Nachhauptreihe stattfinden und führt, ausgehend von Saatkernen um Eisen herum, zur Bildung von Kernen bis zum Blei.



Helmholtz-Zentrum Rossendorf, und www.scienceinschool.org

r-Prozess: r = rapid = schnell; **Neutroneneinfang in sehr kurzer Zeit** (ca. 10^{-3} s) bei hoher Neutronenrate

Es werden neutronenreiche Isotope gebildet, die ca. 10-20 Neutronen mehr als stabile Kerne des gleichen Elementes besitzen. Nach Ende dieses hohen Neutronenflusses werden durch β-Zerfälle neutronenreiche, aber stabile schwere Kerne gebildet. Der r-Prozess findet in Supernovae statt.



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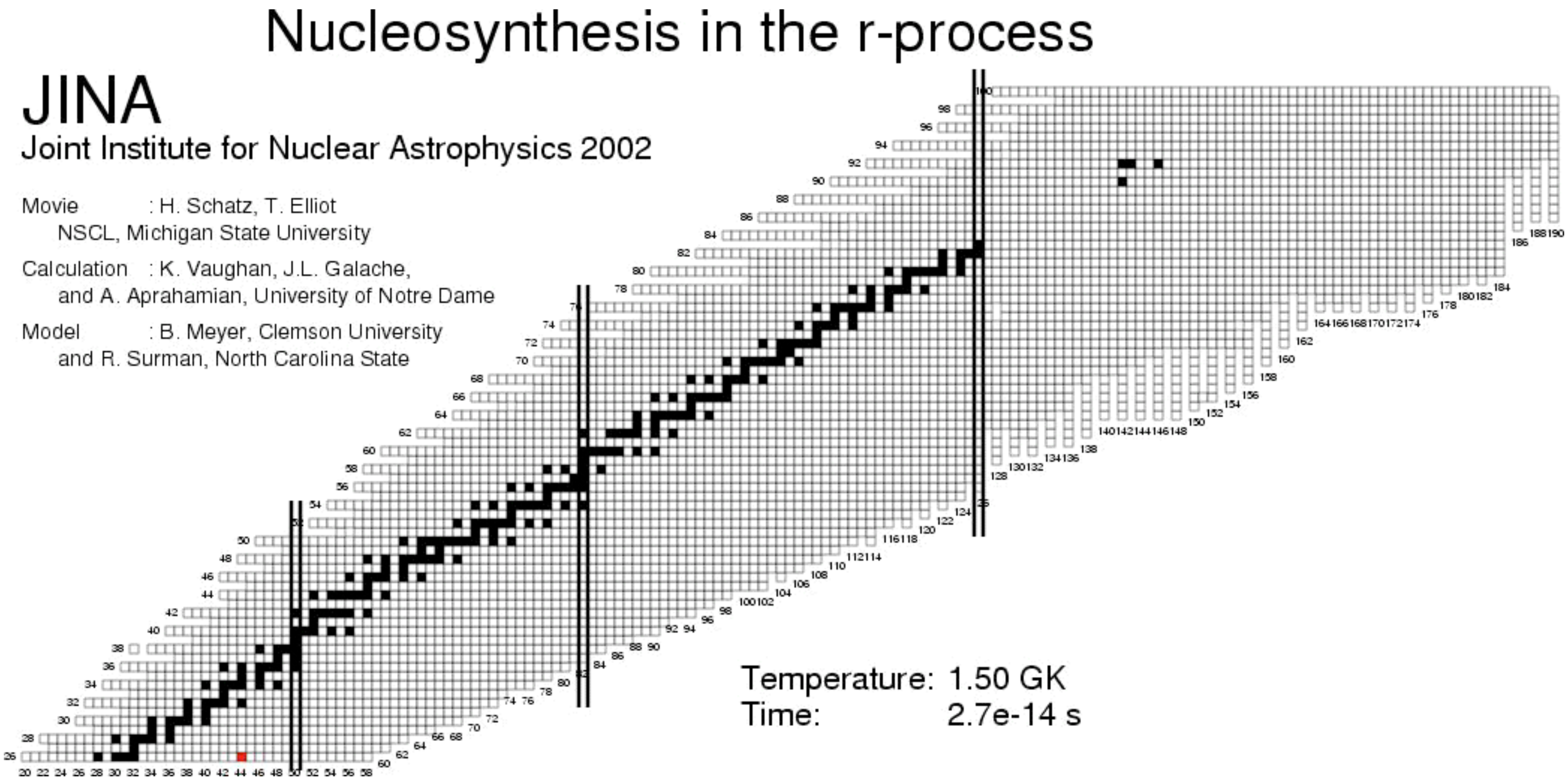
p-Prozess: p = Proton; **Protoneneinfang auf langer Zeitskala** (Jahre)

Auf der neutronenarmen Seite der Nuklidkarte gibt es stabile Kerne, die durch Neutroneneinfang und anschließenden Beta-Zerfall nicht gebildet werden können. Diese p-Prozess-Kerne werden entweder durch Protoneneinfang während einer Supernova-Explosion gebildet oder auch durch Photodissoziation aus r- und s-Prozess Saatkernen.

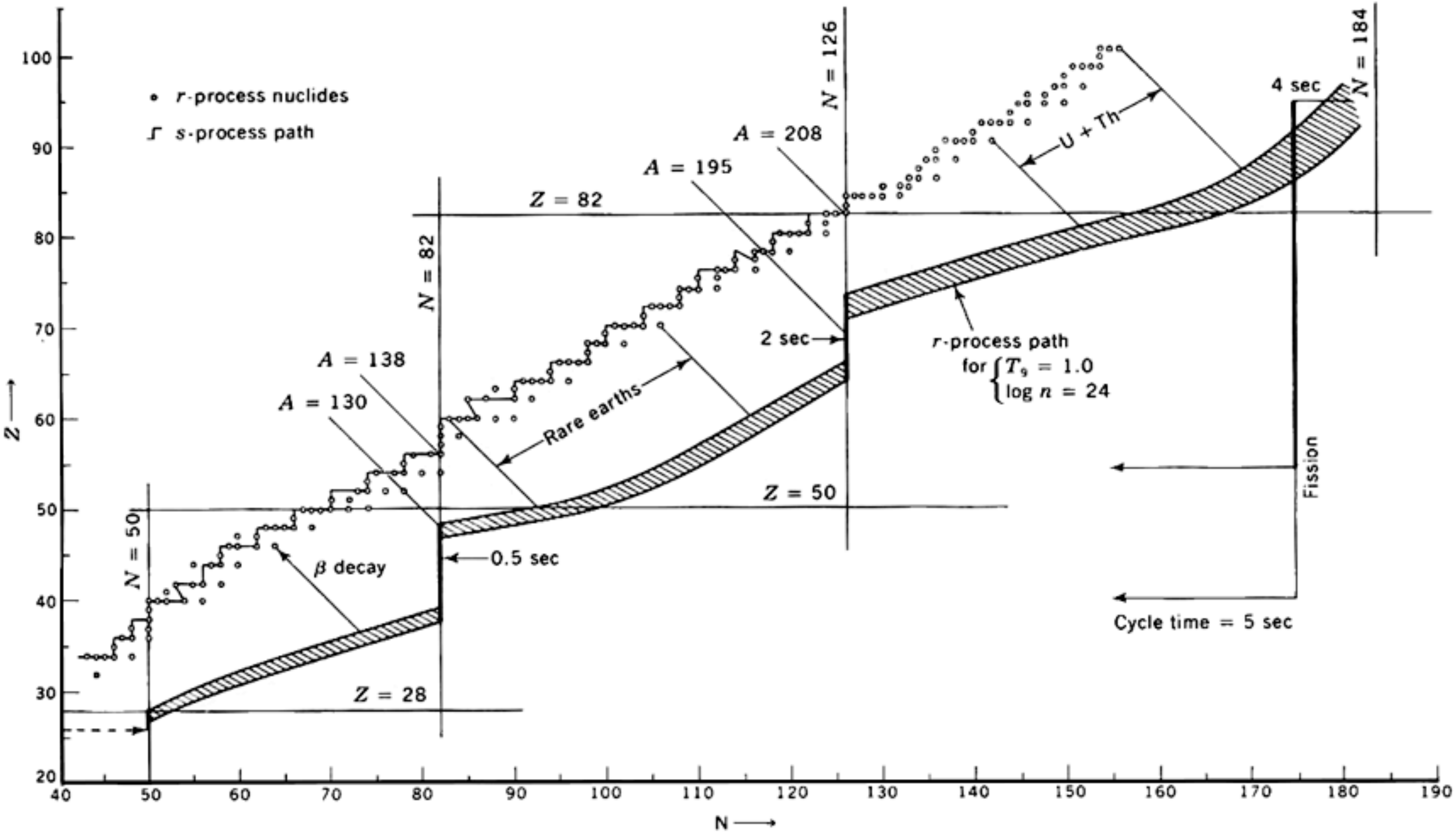
rp-Prozess: rp = rapid protons = schnelle Protonen; **Schneller Protoneneinfang** (wie beim r-Prozess, jedoch mit Protonen) im Sekunden- oder Minutenbereich

Es können mittelschwere Kerne bis etwa Zinn gebildet werden. Der Protonenfluss wird wahrscheinlich in einem Nova-Ausbruch erzeugt.



Film: Helmholtz-Zentrum Rossendorf http://www.hzdr.de/FW/populaer/fwk/astrokern/film/movie_r2d_self.mov

r-Prozess zu verschiedenen Zeiten

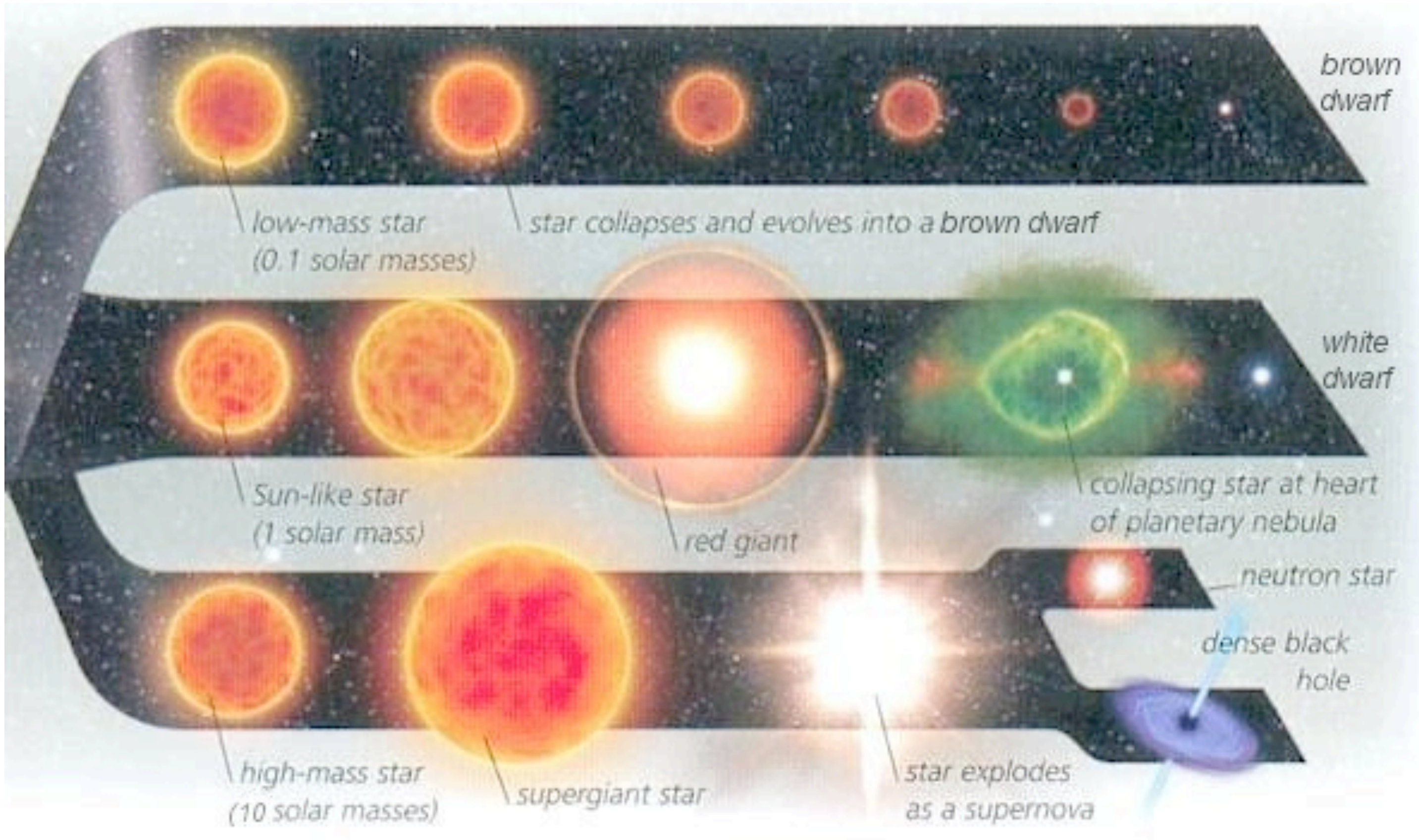


Nach Seeger, Fowler, Clayton (1965, ApJSS, 11, 121)

Ausgewählte Elemente und ihre Produktionsprozesse

Element	Prozeß	Massenbereich	Sternentwicklungsstadium
H	primordial		
He	primordial		
	pp-Kette	$M \geq 0.1 M_{\odot}$	Hauptreihe und Riesenast
	CNO-Zyklus	$M \geq 2 M_{\odot}$	Hauptreihe und Riesenast
C, O, Ne	3α-Prozeß	$M \geq 1 M_{\odot}$	Riesenast und asymptotischer Riesenast
N	CNO-Zyklus	$M \geq 1.5 M_{\odot}$	Hauptreihe und Riesenast (Anreicherung)
Na, Mg, Al	C-Brennen	$M \geq 5 \ldots 8 M_{\odot}$	asymptotischer Riesenast, Supernovae
Si ... Ca	O-Brennen		Supernovae (explosiv)
Ti ... Ni	Si-Brennen und NSE		Supernovae (explosiv)
Sr, Y	s-Prozeß	$M \geq 2 M_{\odot}$	asymptotischer Riesenast
Ba			
Ba, Eu	r-Prozeß		Supernovae (explosiv)

Nach Thomas Gehren München



Bildnachweis: http://universe-review.ca/F08-star.htm

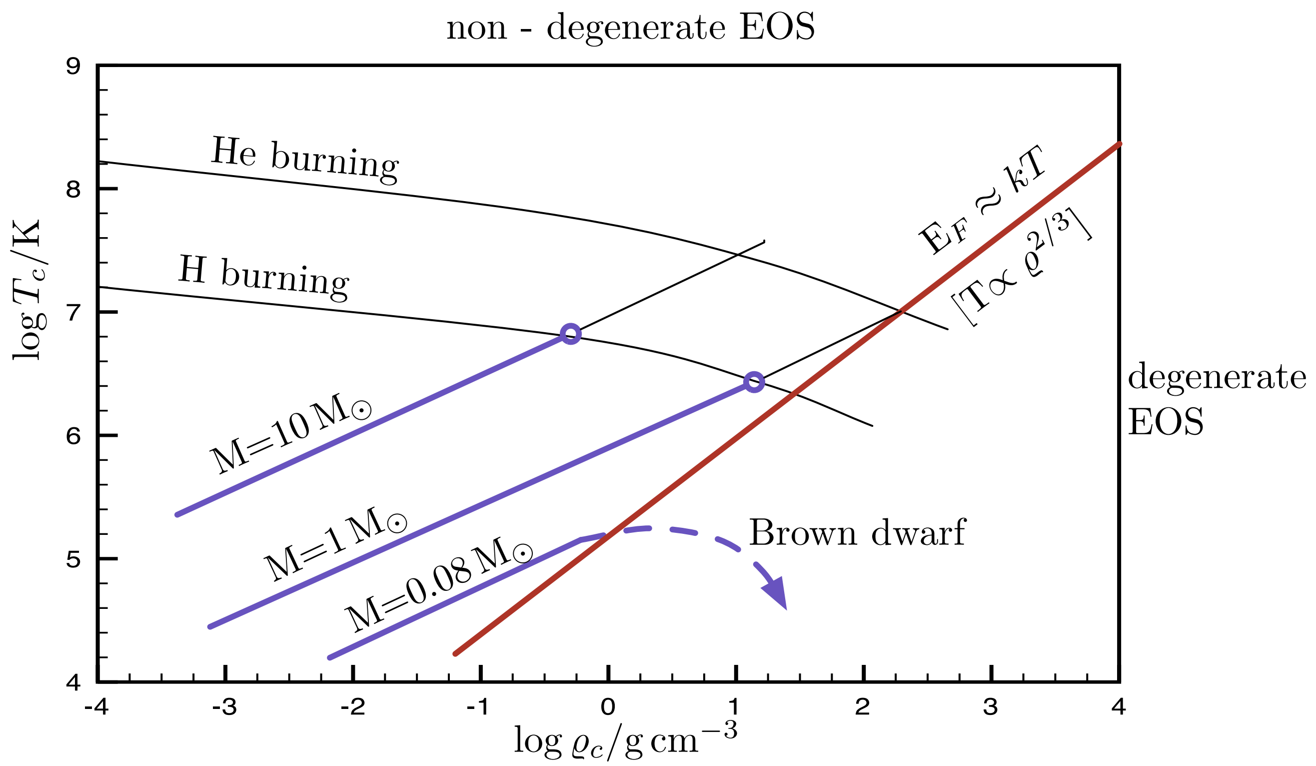


Figure 13.1: non-degenerate/degenerate EOS. [for more details see Iben, 1985]

Hydrostatische Kontraktion

$$T_c \approx 2 \cdot 10^6\, K \left(\frac{M}{1\, M_\odot}\right)^{2/3} \left(\frac{\varrho}{1\, g/cm^3}\right)^{1/3}$$

Kritische Temperatur für Entartung

$$T_c \approx 3 \cdot 10^5\, K \left(\frac{\varrho}{1 g/cm^3}\right)^{2/3}$$

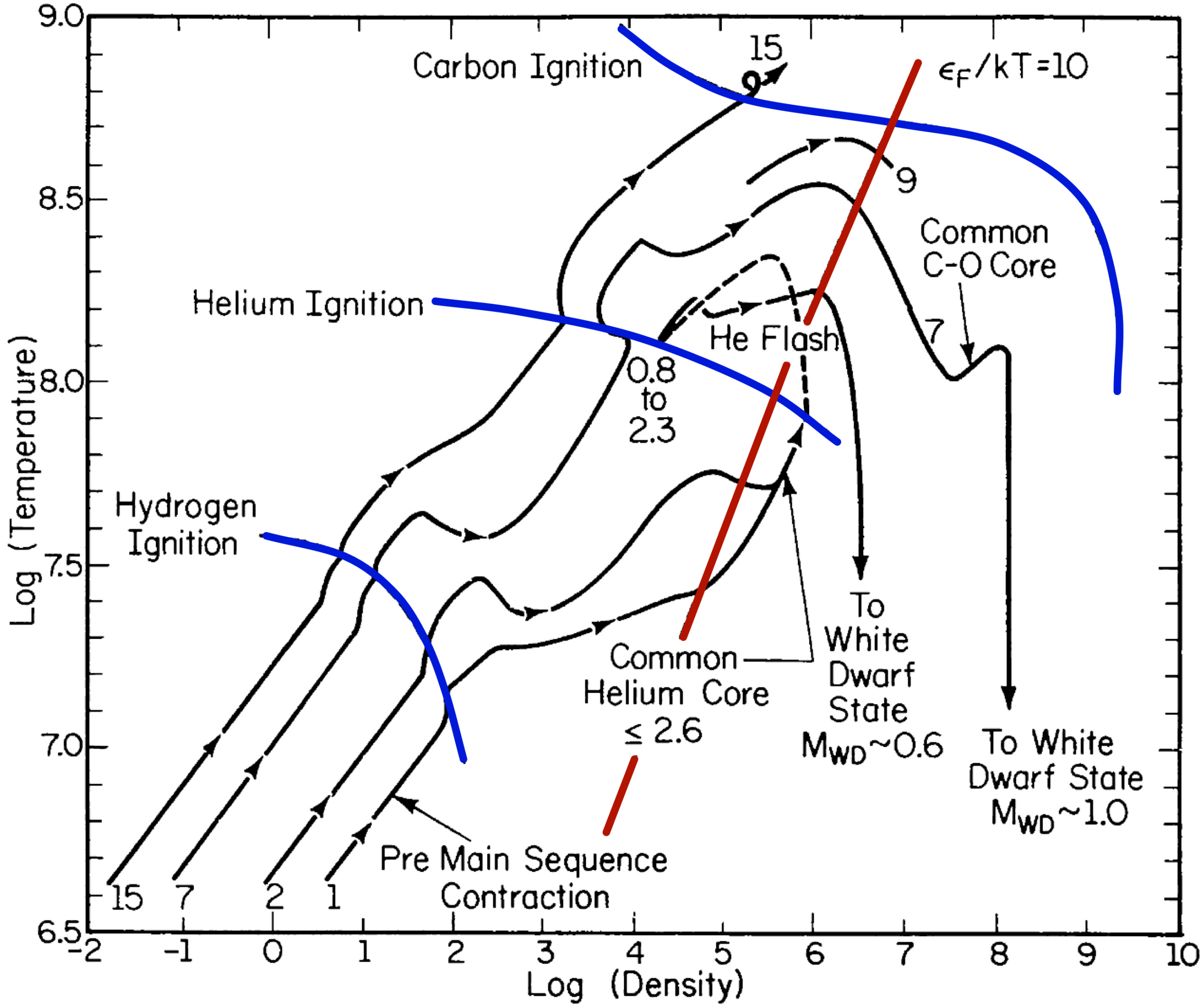
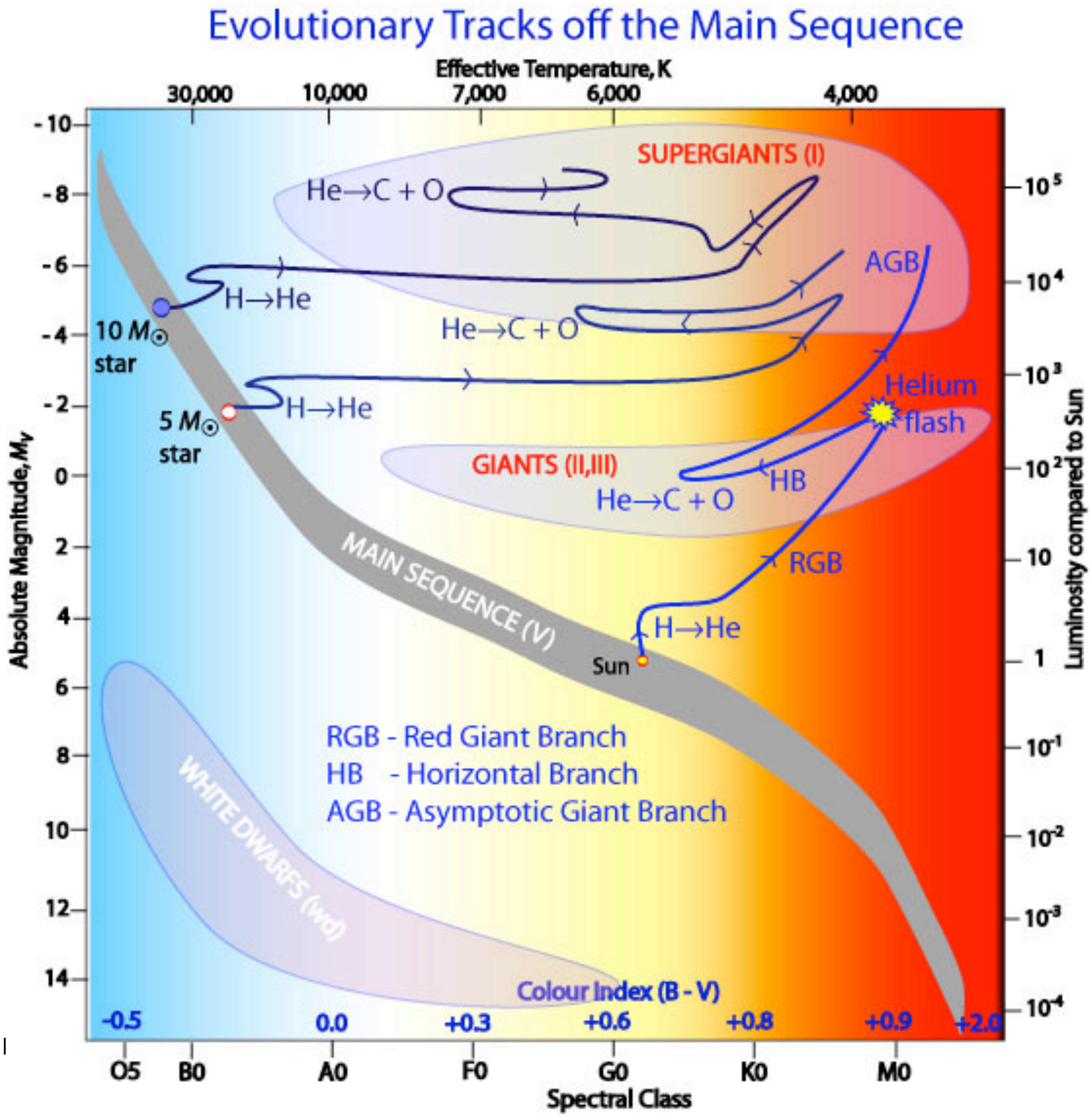


Figure 13.2: [Iben, 1985, Figure 2]

- Stars with initial mass below $\approx 10\,M_\odot$ will turn into white dwarfs after heavy mass loss.
- low-mass stars develop e^--degeneracy core before He burning starts (He burning then may occur in degenerate phase)
- low-to intermediate-mass stars can burn He and develop e^--degenerate core made of carbon and oxygen (C,O core)



Bildnachweis: Australia Telescope National Facility

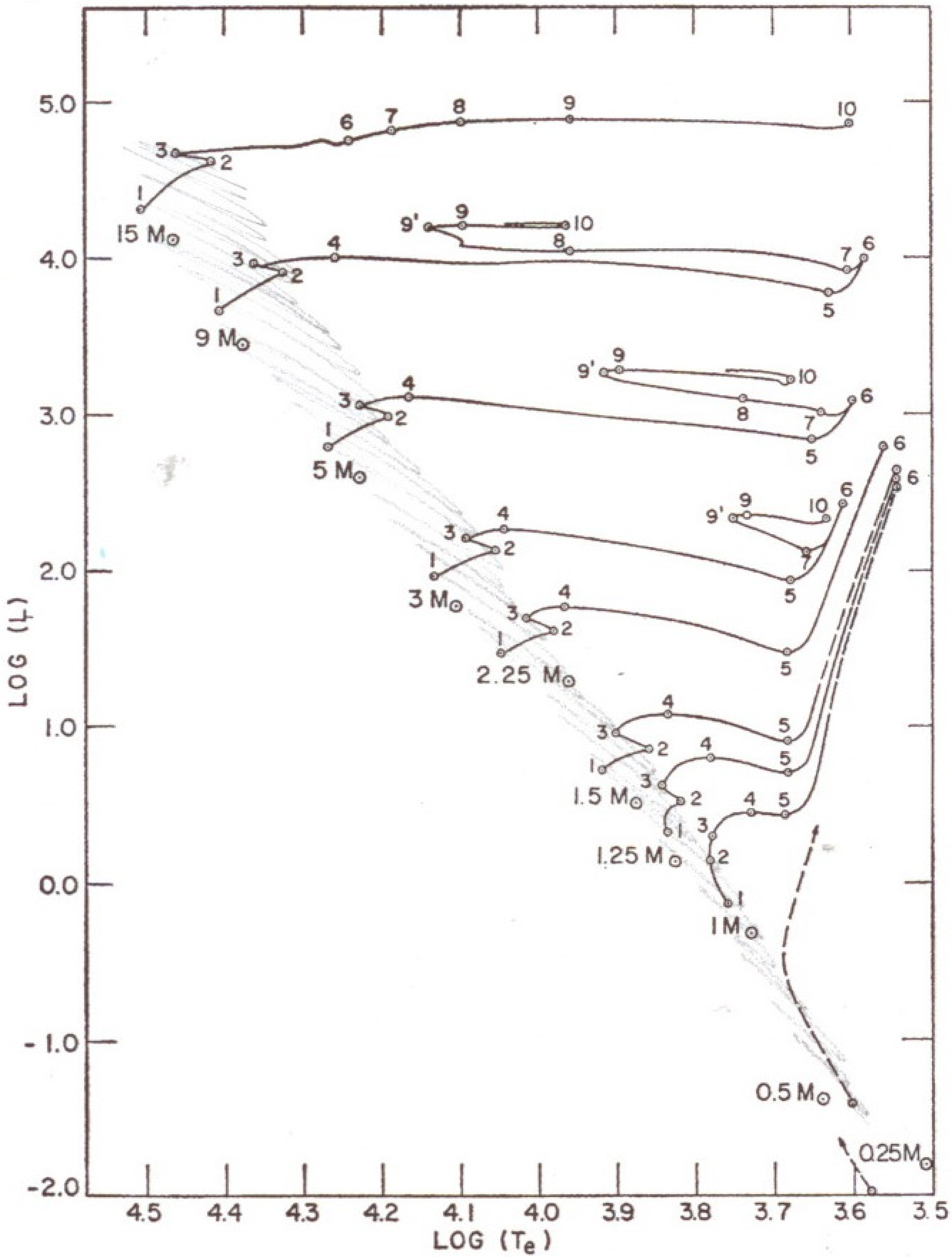


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_\odot)=15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths are estimates.

Iben (1967, ARAA, 5, 571)

Sternentwicklung

- auf der Hauptreihe kaum Veränderungen mit der Zeit (1 .. 2), H-Brennen
- Entwicklung nach der Hauptreihe ist sehr komplex (3 . . . 10)
- starke Massenabhängigkeit
- breites Spektrum verschiedener physikalischer Prozesse werden wichtig (höhere Brennprozesse, Entartung, explosives Brennen, usw.)

TABLE III

STELLAR LIFETIMES (yr)[a]

Mass ($M_\odot$) \ Interval ($i-j$)	(1–2)	(2–3)	(3–4)	(4–5)	(5–6)
15	1.010 (7)	2.270 (5)		7.55 (4)	
9	2.144 (7)	6.053 (5)	9.113 (4)	1.477 (5)	6.552 (4)
5	6.547 (7)	2.173 (6)	1.372 (6)	7.532 (5)	4.857 (5)
3	2.212 (8)	1.042 (7)	1.033 (7)	4.505 (6)	4.238 (6)
2.25	4.802 (8)	1.647 (7)	3.696 (7)	1.310 (7)	3.829 (7)
1.5	1.553 (9)	8.10 (7)	3.490 (8)	1.049 (8)	≥2 (8)
1.25	2.803 (9)	1.824 (8)	1.045 (9)	1.463 (8)	≥4 (8)
1.0	7 (9)	2 (9)	1.20 (9)	1.57 (8)	≥1 (9)

[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

Entwicklung: 1 $M_\odot$ Stern

- core completely convective $\rightarrow$ is always well mixed
  $\rightarrow$ H burning stops when
  $\approx 0.2\,M_\odot$ He has been produced.

- now: He **core contracts:**

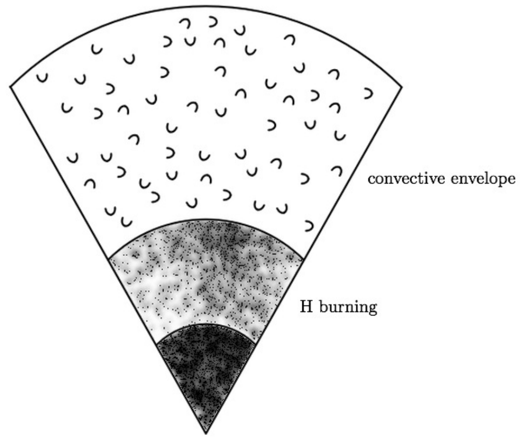
  $\hookrightarrow$ T_c increases and H ignites in **SHELL** around core
  $\hookrightarrow$ Star moves up red giant branch.

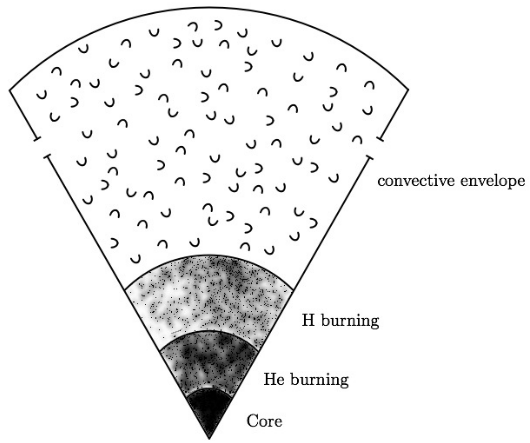
- He flash ignites (off center)
  - this is an almost explosive event (He ignition under electron degenerate conditions)
  - released energy goes into heat T increases, **but** because of e^--degeneracy the pressure is not increased!
    $\hookrightarrow$ star **cannot** cool by expansion!
  - as T increases rapidly, the energy production in 3α process increases dramatically (eventually the outer convective zone depends and begins to transport away the energy released) [1]
  - He core burns quietly. star expands dramatically (and reddens) [2]
  - Red giant phase

- while He burns (quietly) in core C and O build up and eventually He burning ceases.
  - He shell burning still continues
  - **Asymptotic Giant BRANCH** (He shell dominates)

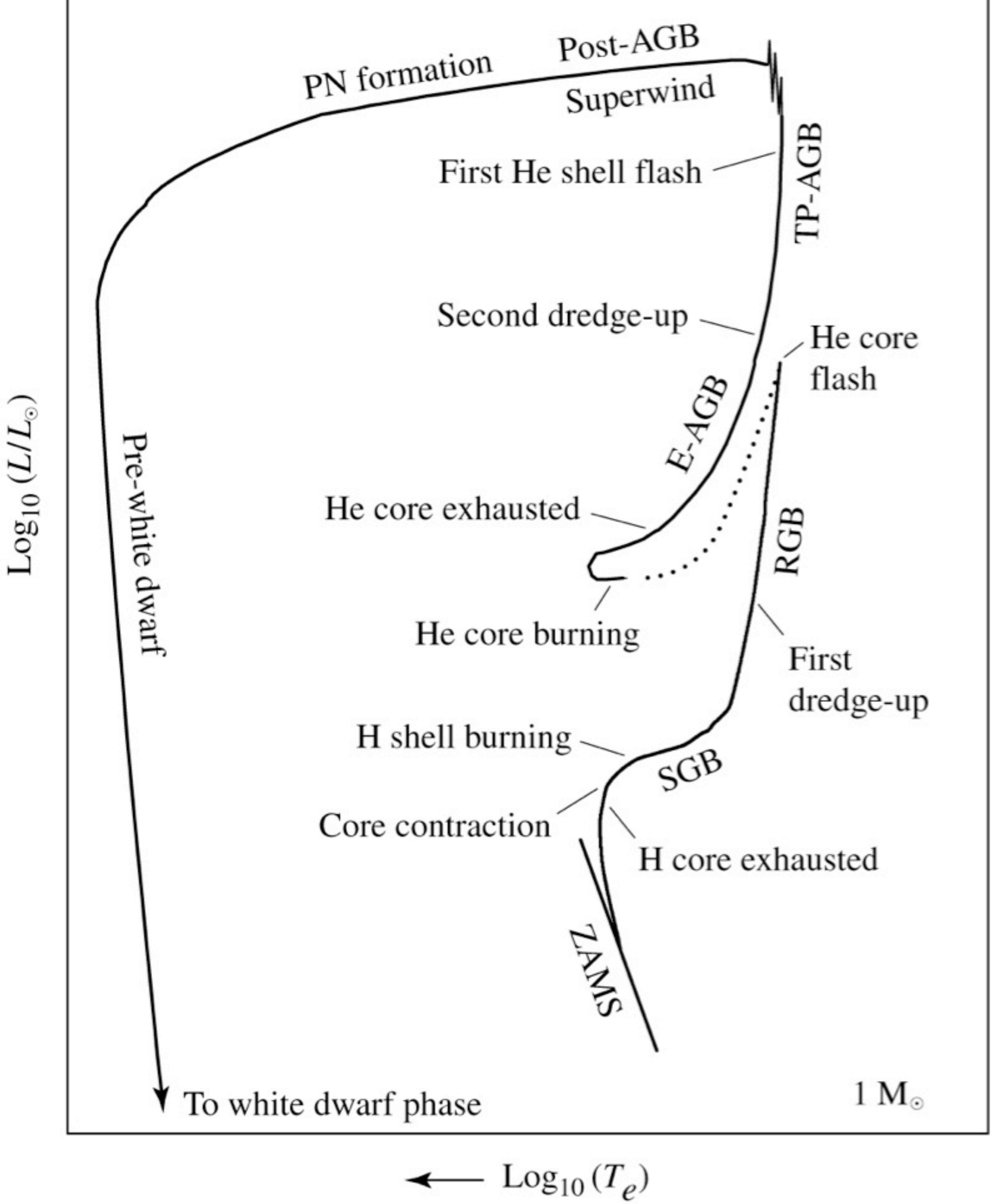
- there is the possibility for He shell flashes (and additional dredge ups) and for higher mass objects: thermal pulses that can revitalize H burning outer shells.

- now heavy mass loss in post-AGB phase (line driven winds)
  $\hookrightarrow$ formation of planetary nebulae
  $\hookrightarrow$ remnant $\approx 0.6\,M_\odot$ CO white dwarf





Entwicklung: 1 $M_\odot$ Stern



Bildnachweis: Carroll &Ostlie, Abbildung 13.4

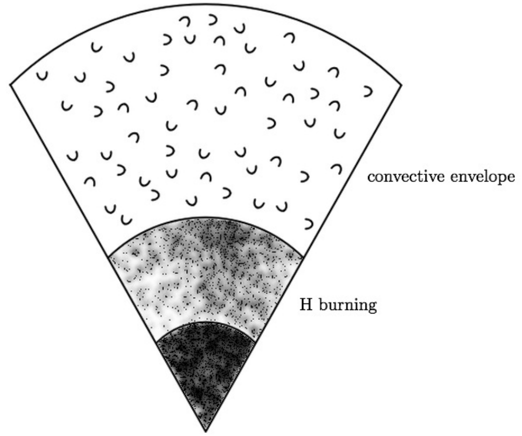
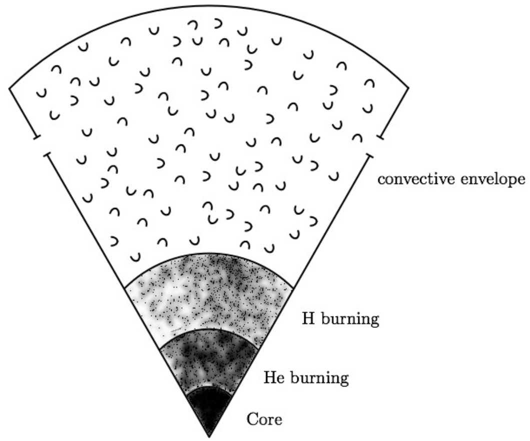
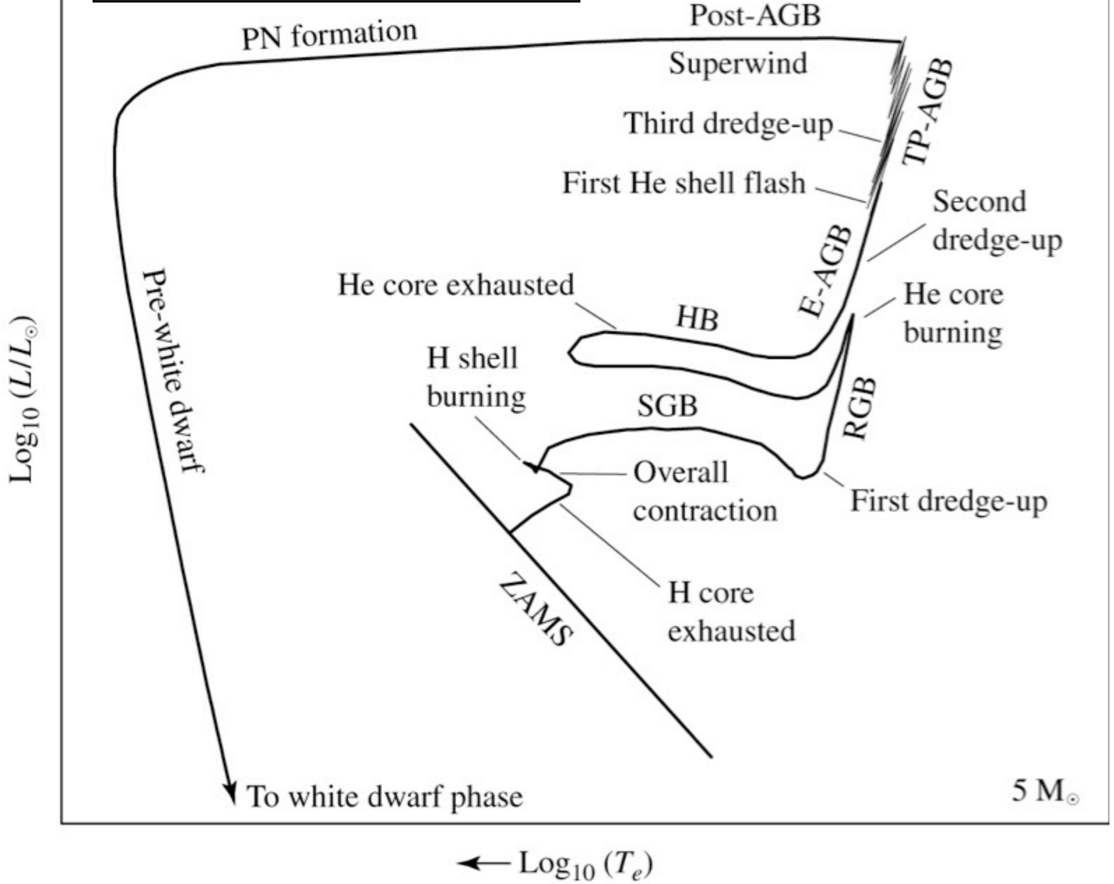


Figure 13.4:

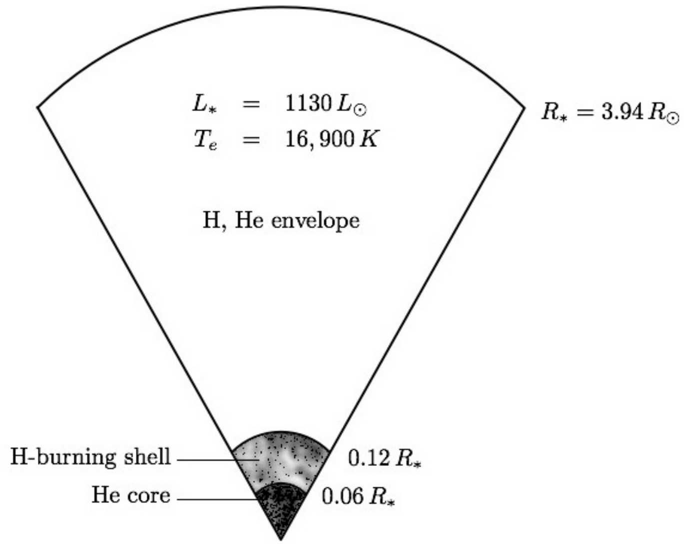


Entwicklung: 5M$_\odot$ Stern



Bildnachweis: Carroll &Ostlie, Abbildung 13.5

structure of star during RGB, shortly after H-burning shell ignited.

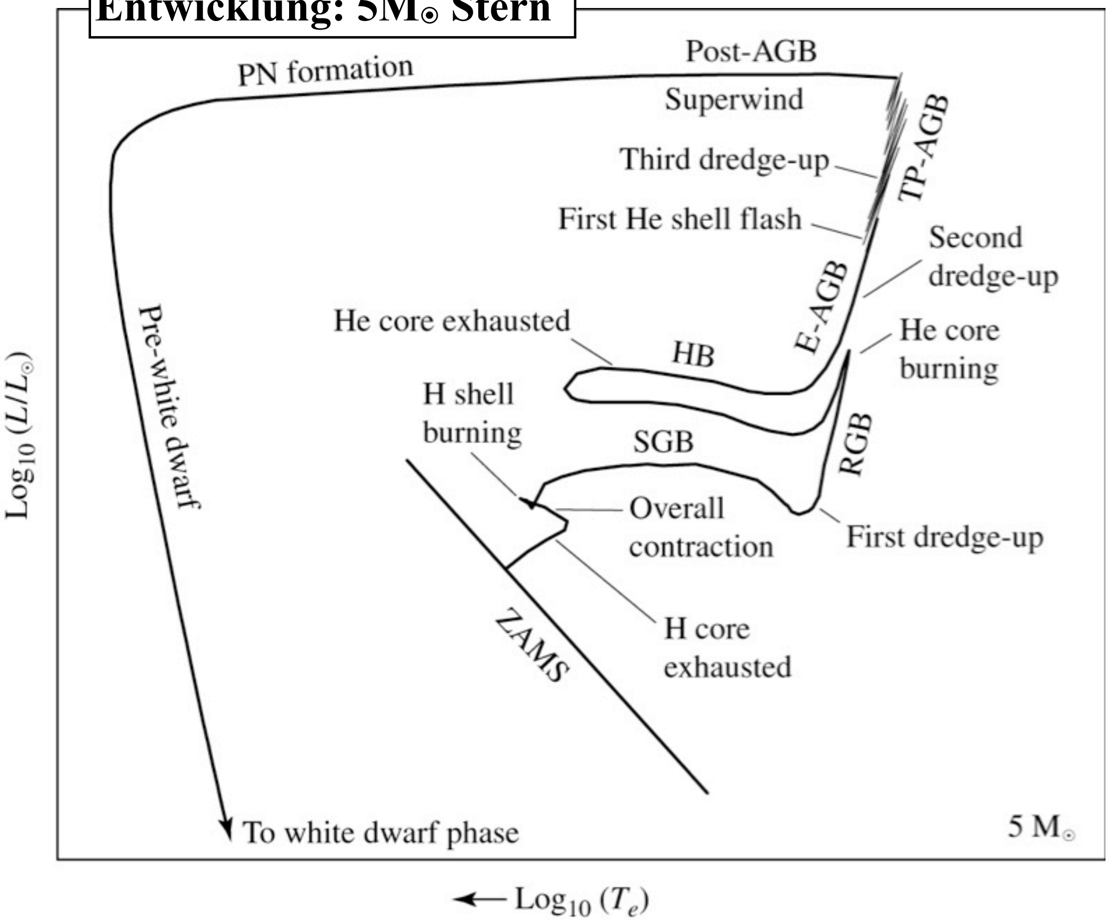


The *HB* occurs when He burns in the core which becomes convective (no longer electron degenerate). *HB* is the analog to the fully convective CNO H-burning cores of upper-main sequence stars.

Intermediate-mass stars then may go through *thermal pulses*: narrow He shell may turn and off:

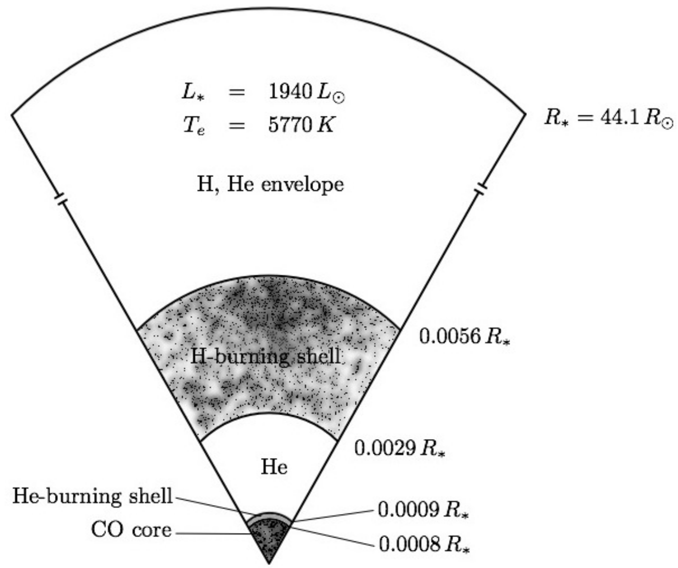
- as star contracts, dormant H shell wakes up.
- H shell produces He ashes that rain down on He shell.
- as mass of He shell increases it may become slightly degenerate.
- then, when the temperature at the base of the shell increases sufficiently, He may ignite again and a He flash occurs (analogous to the earlier He flash of low-mass stars).
- eventually He burning ceases and H burning recovers and the process repeats.

Entwicklung: $5M_{\odot}$ Stern



Bildnachweis: Carroll &Ostlie, Abbildung 13.5

structure of star during He flash



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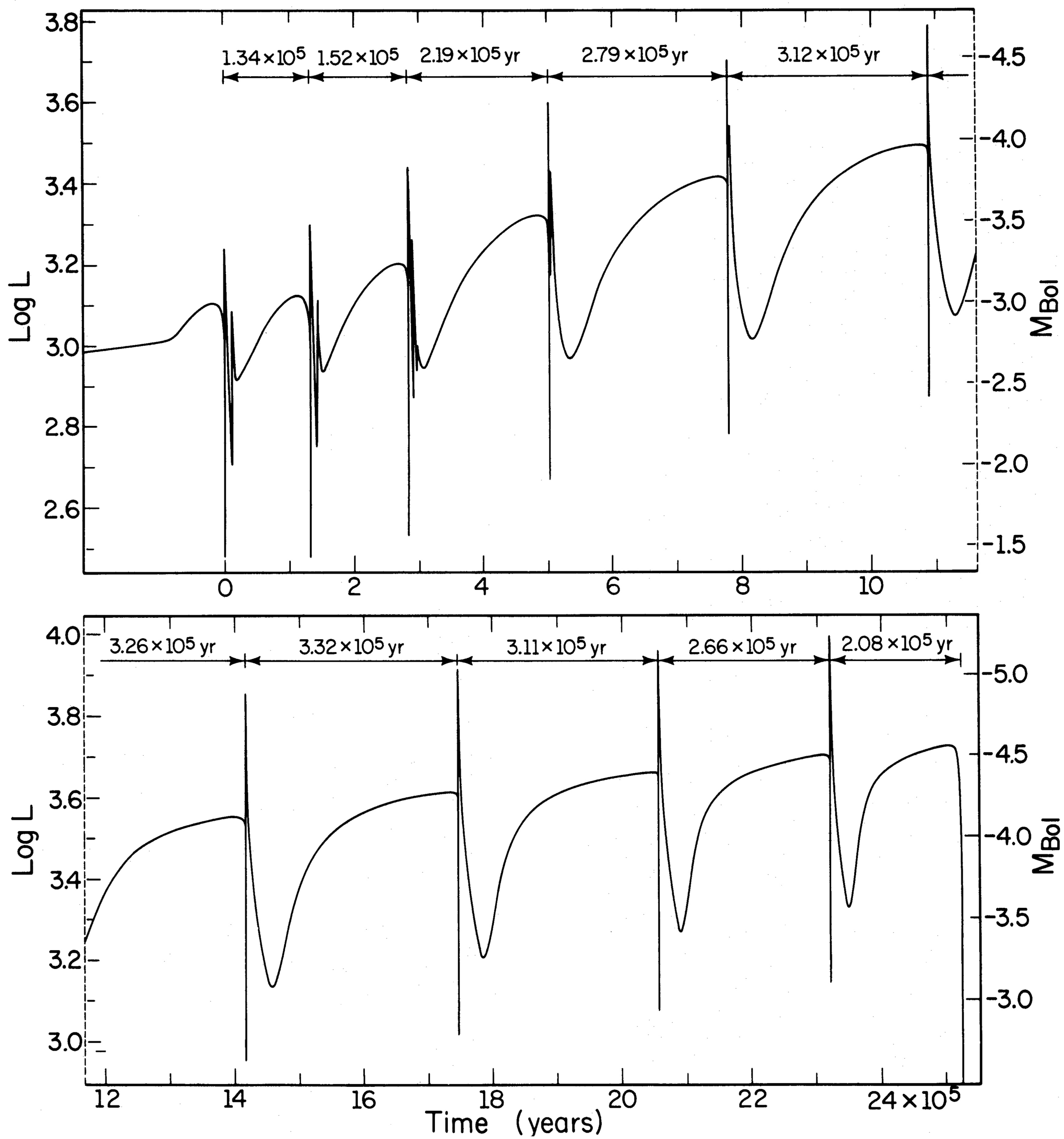
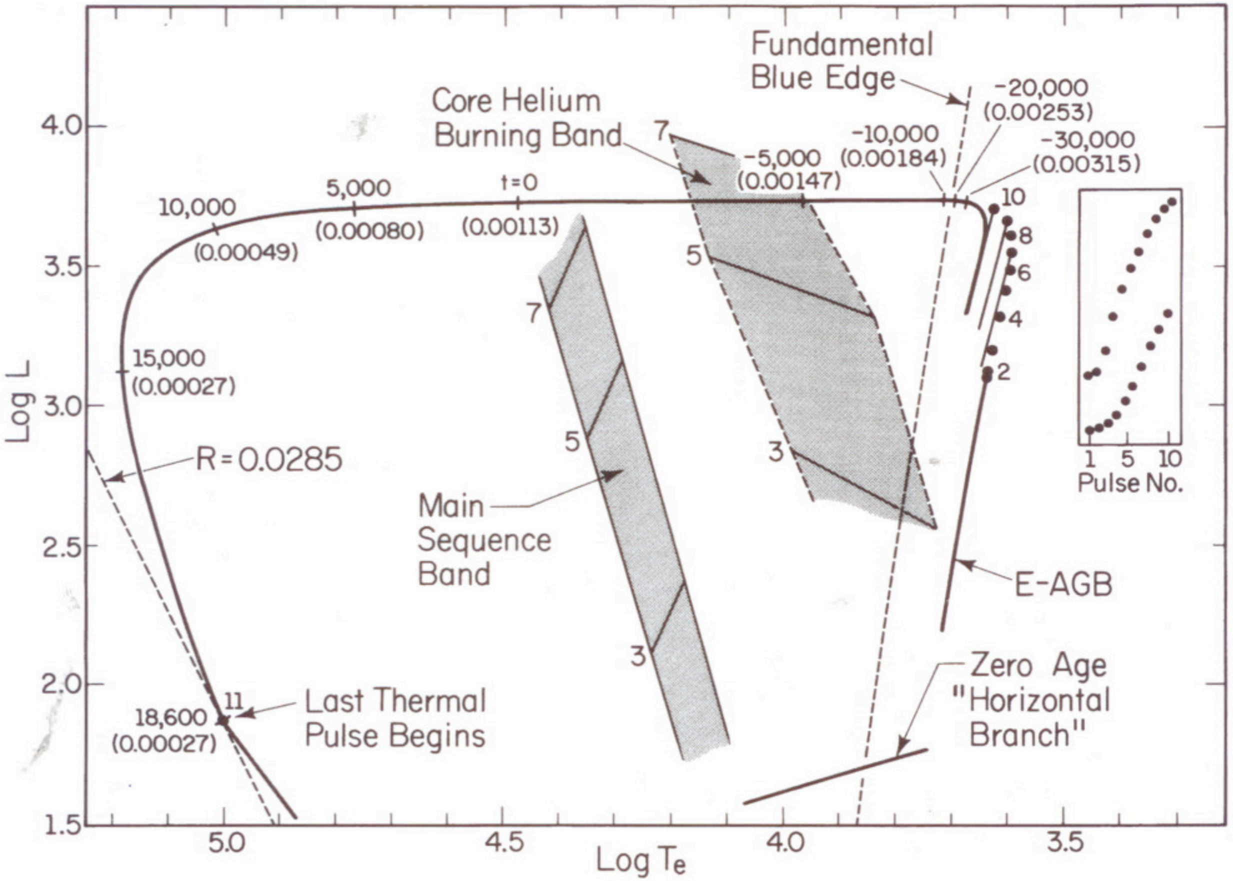
Thermische Pulse am Ende der AGB Phase:



Time dependence of luminosity and bolometric magnitude during the thermally pulsing phase [see Iben, 1982, Figure 2]



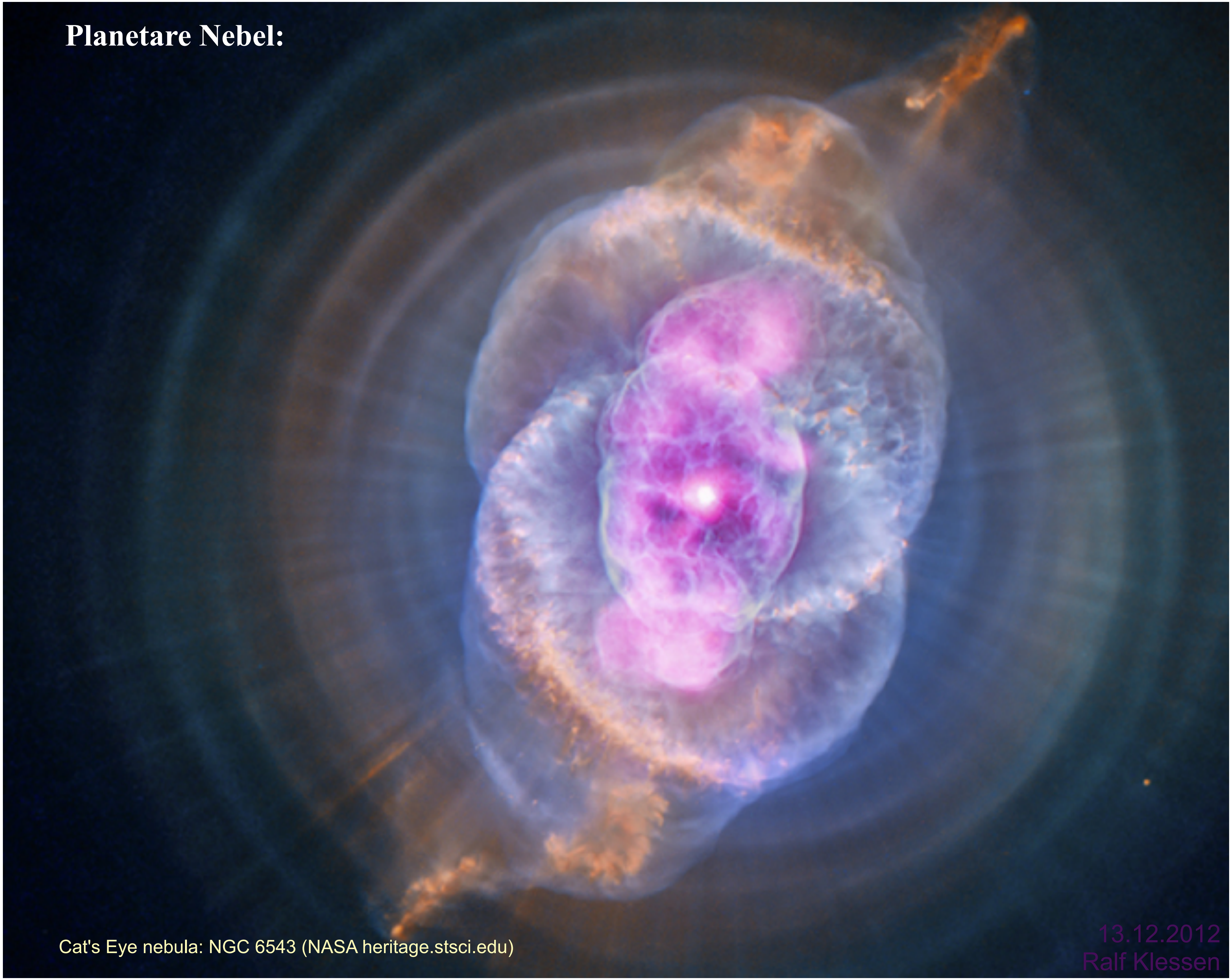
Iben (1985, Fig. 16), Carroll and Ostlie (2006)

- AGB stars are know to lose mass at high rate (up to $dM/dt = 10^{-4}\, M_\odot$ / yr)
- surface temperature ≈ 300 K, that means they are quit cool → dust can form
  - silicates in O-rich environment
  - graphite in C-rich stars
- this dust may couple to radiation and this radiation may drive the large mass loss. (not well understand, maybe thermal pulses)
- as the envelope expands, it eventually becomes optical thin.
  thus exposing the central star, which typically shows spectrum of F-type or G-type super-giant.
  the evolutionary track moves more or less horizontally to the blue
- eventual expelled envelope + central white dwarf make up a planetary nebula (PN)

Planetare Nebel:

Planetary Nebula NGC 2440 (NASA, heritage.stsci.edu)

Planetare Nebel:

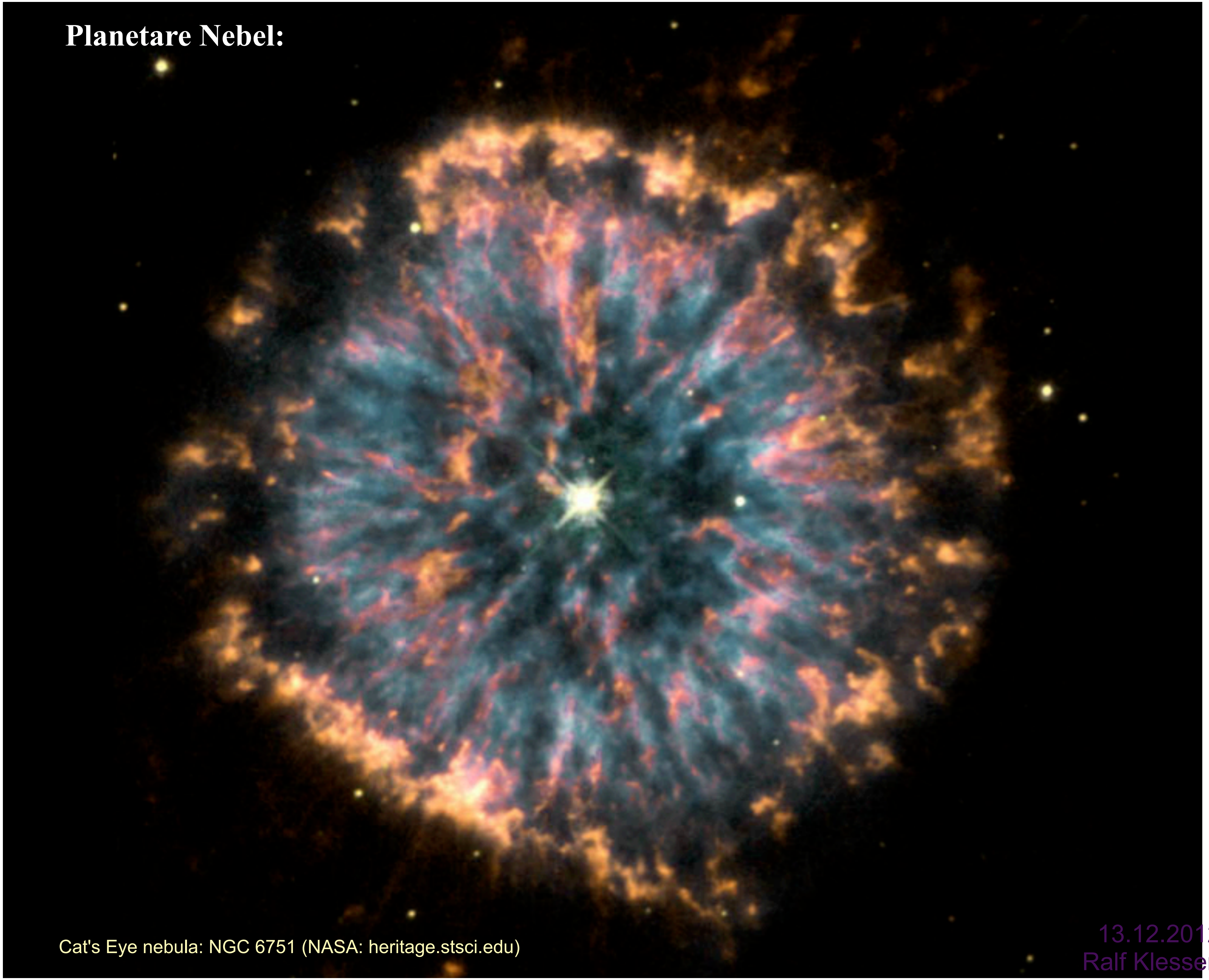


Cat's Eye nebula: NGC 6543 (NASA heritage.stsci.edu)

Planetare Nebel:

Cat's Eye nebula: IC 418 (NASA heritage.stsci.edu)

Planetare Nebel:



Cat's Eye nebula: NGC 6751 (NASA: heritage.stsci.edu)

Entwicklung eines sehr massereichen Sterns ($M > 8\,M_\odot$)

- stars initially more massive than $\sim 8 \ldots 10\,\mathrm{M}_\odot$ end their lives in supernova explosions.
- before that, they go through several higher-element nuclear burning phases and several mass-loss phases.
  - **luminous blue variables** (LBVs)
    - have surface temperatures, luminosities and masses

      $$\begin{aligned} T &\approx 15,000\,\mathrm{K} - 30,000\,\mathrm{K} \\ L &\gtrsim 10^6\,\mathrm{L}\odot \\ M &\geqslant 85\,\mathrm{M}_\odot \end{aligned}$$

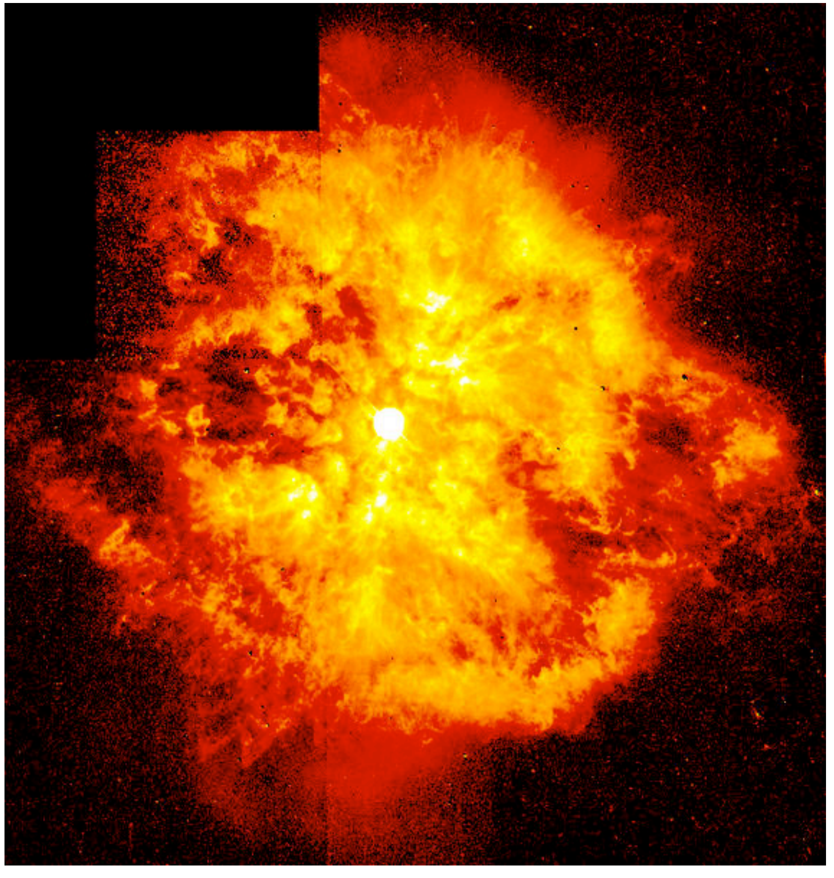
      $\hookrightarrow$ sit in upper left of H-R diagram.
    - these stars have huge mass loss rates and they are rapid rotators.
  - **Wolf-Rayet stars** (WR)
    - are closely related to LBVs
    - there are $\sim 1000 - 2000$ WRs in the Galaxy
    - have $T_{\mathrm{eff}} \approx 25.000\,\mathrm{K} - 100.00\,\mathrm{K}$ and show very strong emission lines
    - have huge mass loss rate $10^{-5}\,\mathrm{M}_\odot/\mathrm{yr}$ with wind speeds $\gtrsim$ 800km/s
    - have masses $\gtrsim 20\,\mathrm{M}_\odot$
    - three classes:

WC	have emission lines of C and He (**no** N & H)
WN	have N and He
WO	have strong O-lines
  - there are also **blue super-giants** (BSG), **red super-giants** (RSG), and **OF stars** (O super-giants with pronounced emission lines)

Entwicklung eines sehr massereichen Sterns ($M > 8\,M_\odot$)

- the general evolutionary sequence is as follows:

$$\begin{array}{lllllll}
10 < M/M_\odot < 20: & O \rightarrow RSG \rightarrow BSG \rightarrow \mathbf{SN} \\
20 < M/M_\odot < 25: & O \rightarrow RSG \rightarrow WN \rightarrow \mathbf{SN} \\
25 < M/M_\odot < 40: & O \rightarrow RSG \rightarrow WN \rightarrow WC \rightarrow \mathbf{SN} \\
40 < M/M_\odot < 85: & O \rightarrow Of \rightarrow WN \rightarrow WC \rightarrow \mathbf{SN} \\
85 < M/M_\odot : & O \rightarrow Of \rightarrow LBV \rightarrow WN \rightarrow WC \rightarrow \mathbf{SN}
\end{array}$$



- sehr starke Winde
- Massen zwischen 10 und 250 Sonnenmassen
- Oberflächentemperatur zwischen 30.000 und 120.000 K

Wolf-Rayet-Stern WR-124 mit umgebendem Planetaren Nebel M 167 (Aufnahme mit dem HST)

Entwicklung eines sehr massereichen Sterns ($M > 8\,M_\odot$)

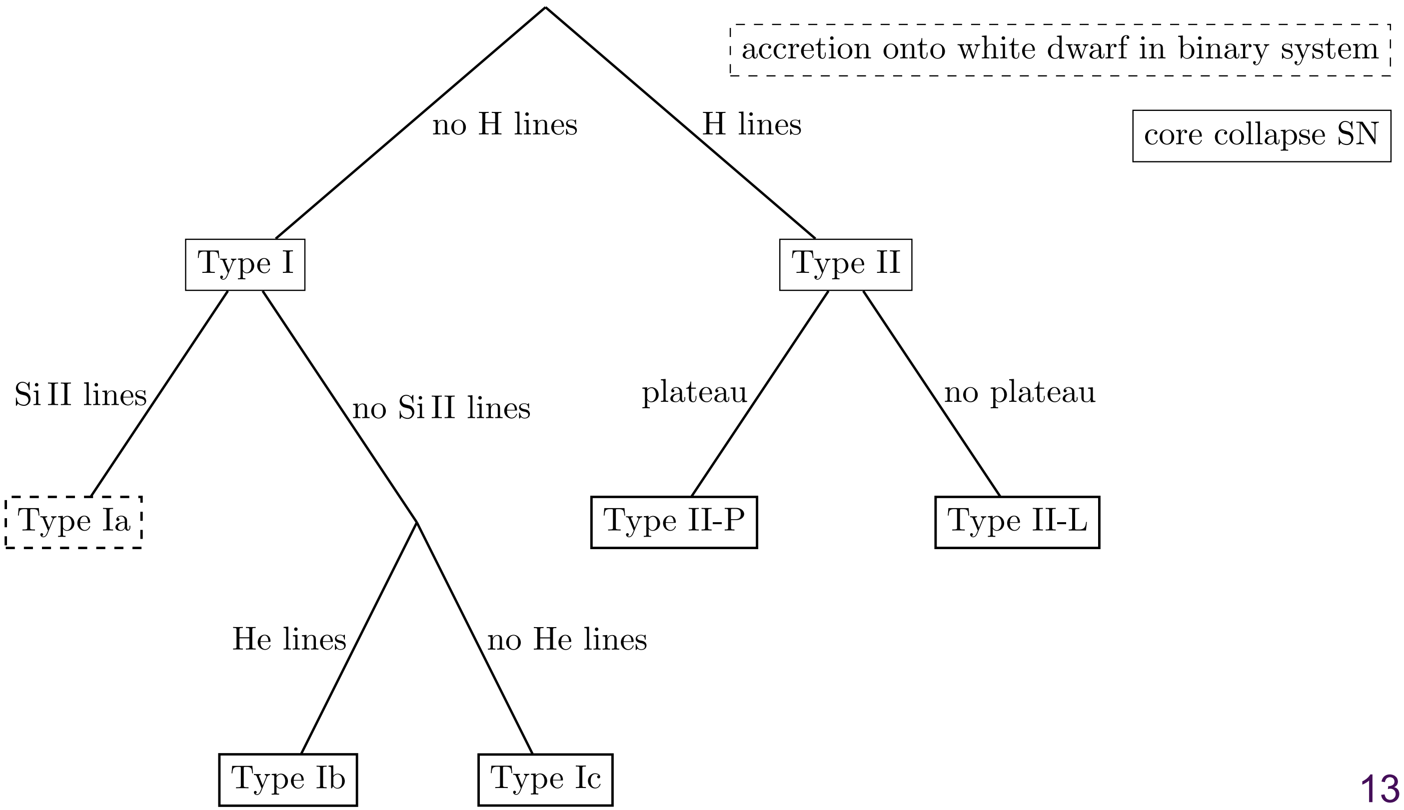
Supernovae:

- supernovae describe the explosive, sudden mass loss (very-)massive stars experience at the end of their lives.
- there are two classes of SN

Type I:	no hydrogen	lines
Type II:	strong H	lines

Type I´s are sub-classified according to other spectral features:

Type Ia:	strong Si II	line (615 nm)
Type Ib:	strong He I	line
Type Ic:	no He I	line



Entwicklung eines sehr massereichen Sterns ($M > 8\,M_\odot$)

Supernovae:

- a typical Type II SN releases 10^{53} erg energy:

  $\sim 99\%$ in neutrinos
  $\sim 1\%$ in kinetic energy of ejecta   similar values for Type Ib and Ic
  $\sim 0.01\%$ in radiation

- Type II, Ib and Ic are core collapse supernovae

  Type Ia occur in binary system, when mass transfer onto white dwarf causes ignition of degenerate He and sends a shock wave into CO core which ignites carbon and oxygen burning as well.
  The WD gets completely disrupted, leaving the binary companion "alone".

- core collapse SN:

  this type of SN occurs in shell-burning massive stars.
  He-shell adds C and O ashes to CO core, as the core continues to contract (not degenerate!) it ignites C burning, generating elements like

  $${}^{16}_{8}\mathrm{O},\ {}^{20}_{10}\mathrm{Ne},\ {}^{23}_{11}\mathrm{Na},\ {}^{23}_{12}\mathrm{Mg},\ {}^{24}_{12}\mathrm{Mg}$$

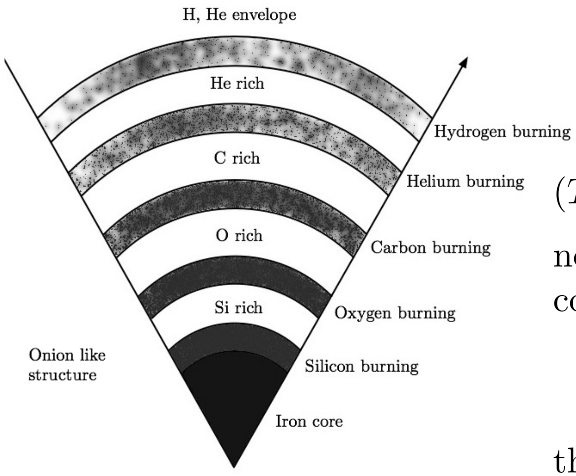
  this triggers a variety of further burning processes:
  Ne-O core will burn to Si.

  $$\begin{aligned} {}^{28}_{14}\mathrm{Si} + {}^{4}_{2}\mathrm{He} &\rightleftharpoons {}^{32}_{16}\mathrm{S} + \gamma \\ {}^{32}_{16}\mathrm{S} + {}^{4}_{2}\mathrm{He} &\rightleftharpoons {}^{36}_{18}\mathrm{Ar} + \gamma \\ {}^{52}_{24}\mathrm{Cr} + {}^{4}_{2}\mathrm{He} &\rightleftharpoons {}^{56}_{28}\mathrm{Ni} + \gamma \end{aligned}$$

  eventually an iron-rich core builds up

Entwicklung eines sehr massereichen Sterns ($M > 8\,M_\odot$)

Supernovae:



- at very high temperatures in the core **photo-disintegration** of heavy elements occurs:

$$
\begin{aligned}
{}^{56}_{26}\mathrm{Fe} + \gamma &\longrightarrow 13\,{}^{4}_{2}\mathrm{He} + 4\mathrm{n} \\
{}^{4}_{2}\mathrm{He} + \gamma &\longrightarrow 2\mathrm{p}^{+} + 2\nu
\end{aligned}
$$

$(T_c \approx 8 \cdot 10^9\,\mathrm{K}$ & $\varrho_c \approx 10^{10}\,\mathrm{g\,cm^{-3}})$

now, the free electrons that had assisted in supporting the star against further collapse (by degeneracy pressure) are captured by protons:

$$\mathrm{p}^{+} + \mathrm{e}^{-} \rightarrow \mathrm{n} + \nu_\mathrm{e}$$

there is a gigantic burst of neutrino emission, the neutrino luminosity is orders of magnitude larger than nuclear burning luminosity.

$\hookrightarrow$ degeneracy pressure is gone + enormous energy loss by ν_e emission.

$\hookrightarrow$ **core collapse extremely rapidly.**

depending on mass a **neutron star** remnant builds up in center
(for stars with $M_{ZAMS} \lesssim 25\,\mathrm{M}_\odot$)

$\hookrightarrow$ reverse shock expels outer layers

for stars with $M_{ZAMS} \gtrsim 25\,\mathrm{M}_\odot$ the remnant is too heavy and cannot be stabilized by n degeneracy $\rightarrow$ collapse to **black hole**!
still a reverse shock expels material just like with neutron star.

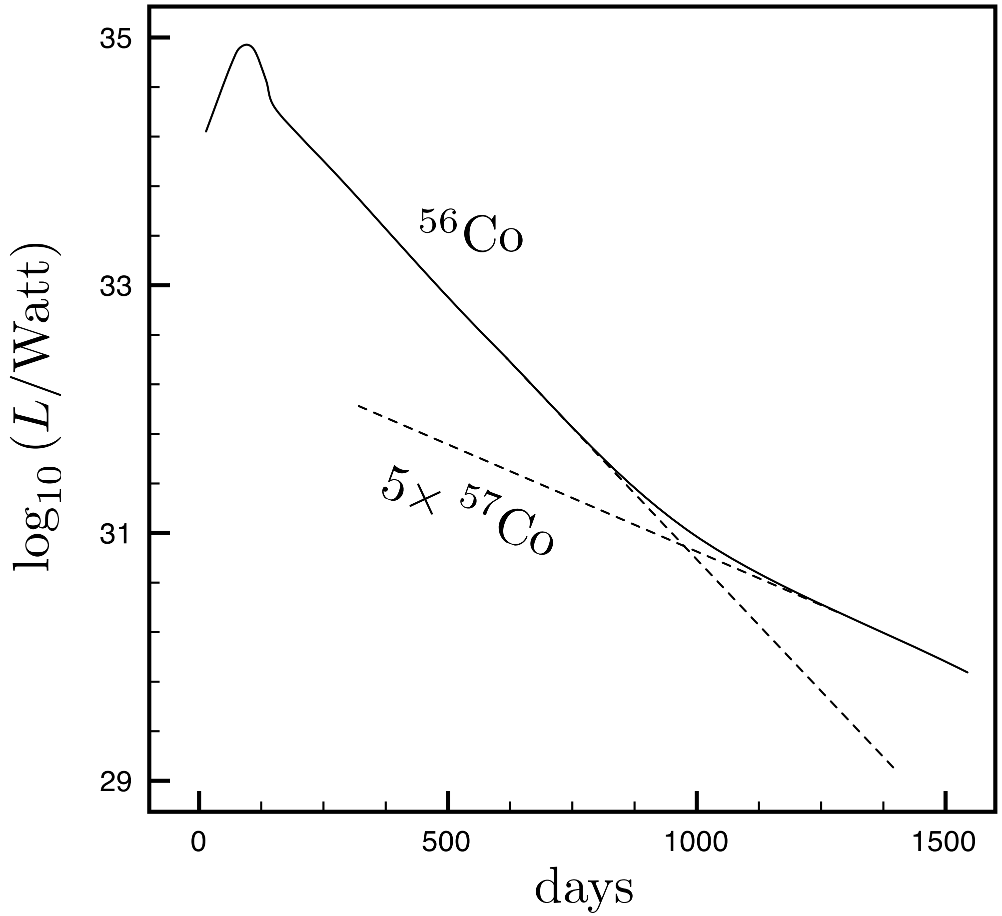
Entwicklung eines sehr massereichen Sterns ($M > 8\ M_\odot$)

Supernovae:

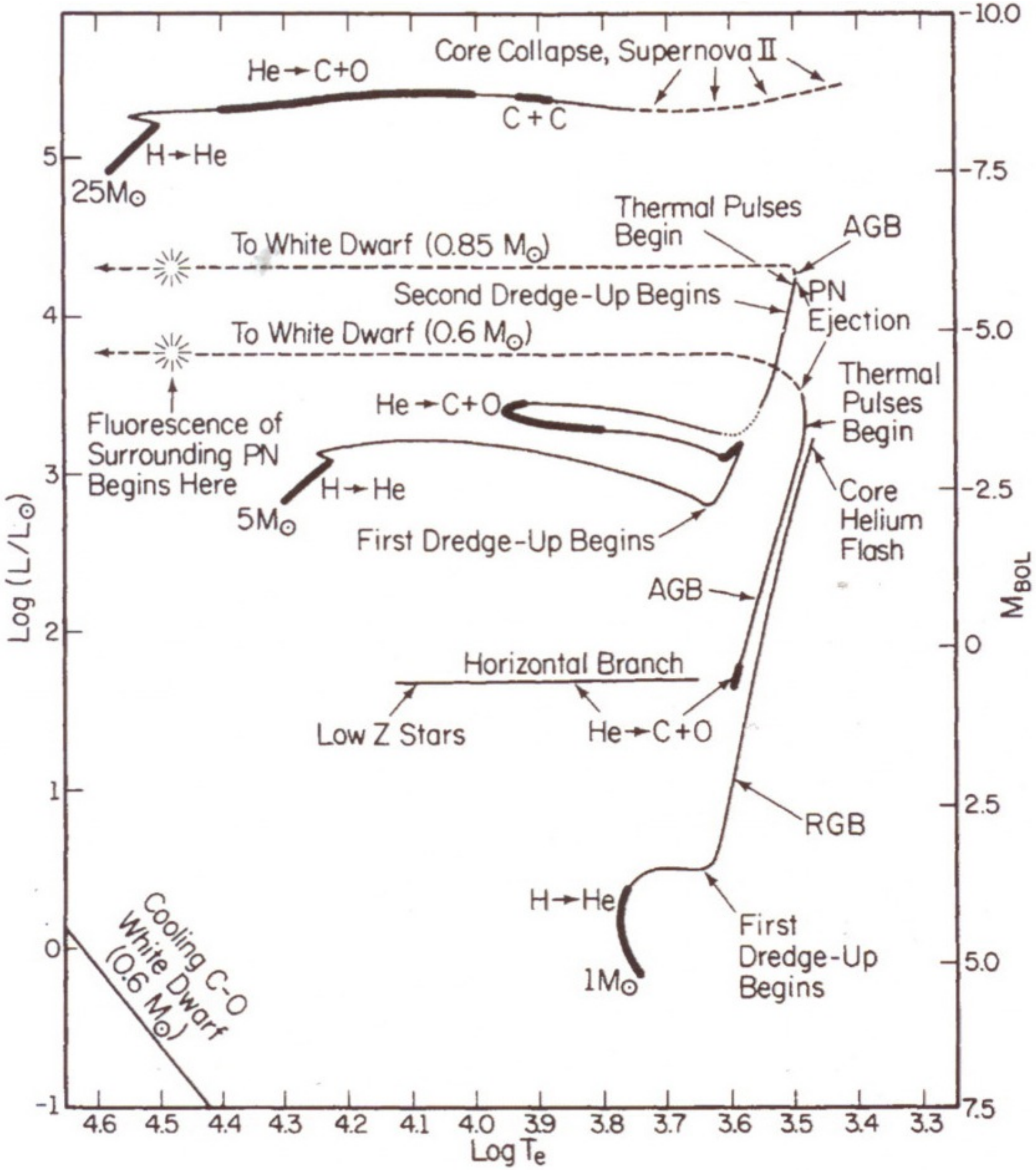
- the energy in the light curve comes from **radioactive decay** of expelled material:

$$^{56}_{28}\mathrm{Ni} \;\rightarrow\; ^{56}_{27}\mathrm{Co} + \mathrm{e}^+ + \nu_\mathrm{e} + \gamma \quad (\tau = 6.1\,\mathrm{days})$$
$$^{56}_{27}\mathrm{Co} \;\rightarrow\; ^{56}_{26}\mathrm{Fe} + \mathrm{e}^+ + \nu_\mathrm{e} + \gamma \quad (\tau = 77.7\,\mathrm{days})$$

- typical light curve:



Zusammenfassung der Nachhauptreihenentwicklung:



Tracks in the HR diagram of a representative selection of stars.
[see Iben, 1985, Figure 15]