Karlsruher Institut für Technologie

Kern- und Teilchenphysik

Johannes Blümer

SS2012

Vorlesung-Website

V12, 31. Mai 2012

KIT-Centrum Elementarteilchen- und Astroteilchenphysik KCETA

~~v11 29.~~ Mai 2012 Kernphysik im Labor und im Universum

v12 31.

- Elementsynthese:
  - Urknall
  - Sternentwicklung
  - Kernfusion
  - Supernovae

Elementsynthese Überblick

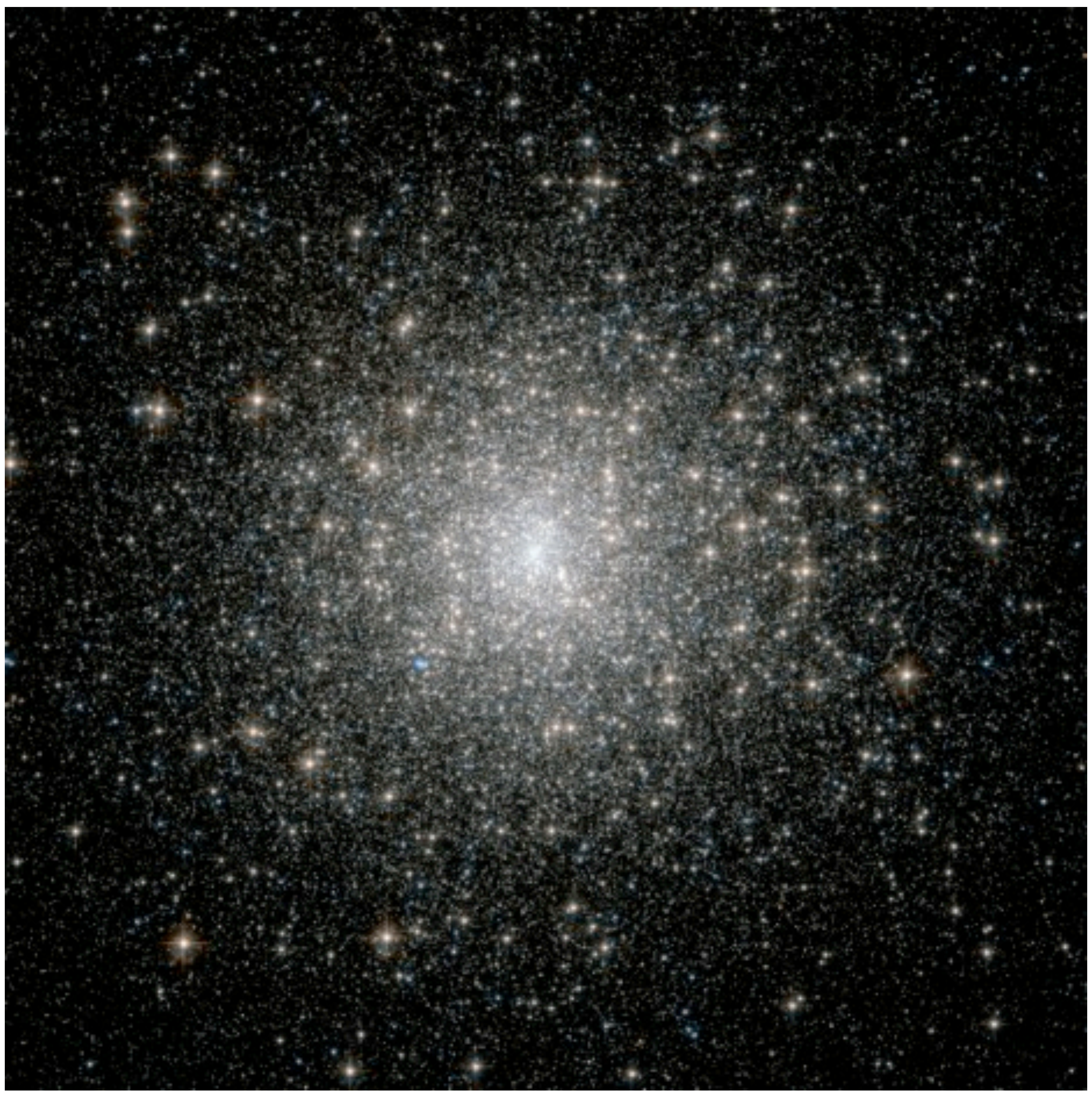
leichte Elemente H...Li	bis $A \lesssim 56$	Schwere Elemente
entstanden im Urknall „BBN" im Zeitintervall $10\,s \lesssim t \lesssim 10^3\,s$	Kernfusion in Sternen	extrem n-reiche Umgebungen: Supernova-Explos.
← "zu heiss" ↦ „zu kalt"	M-L-T-Relationen	
	HRD-Diagramm	
	Sternmasse – Schalenbrennen	SN I: thermonukl. Explos. eines Weissen Zwerges
n-p Massendifferenz	B/A-Verlauf!	SN II: Kernkollaps eines schweren Sterns $M \gtrsim 8..10\,M_\odot$
n-Lebensdauer		
N_ν & Abkühlrate ($N_\nu = 3$)		
N_ν & ^4He-Produktion		
$\eta = N_{Bar}/N_\gamma = 10^{-10}$		

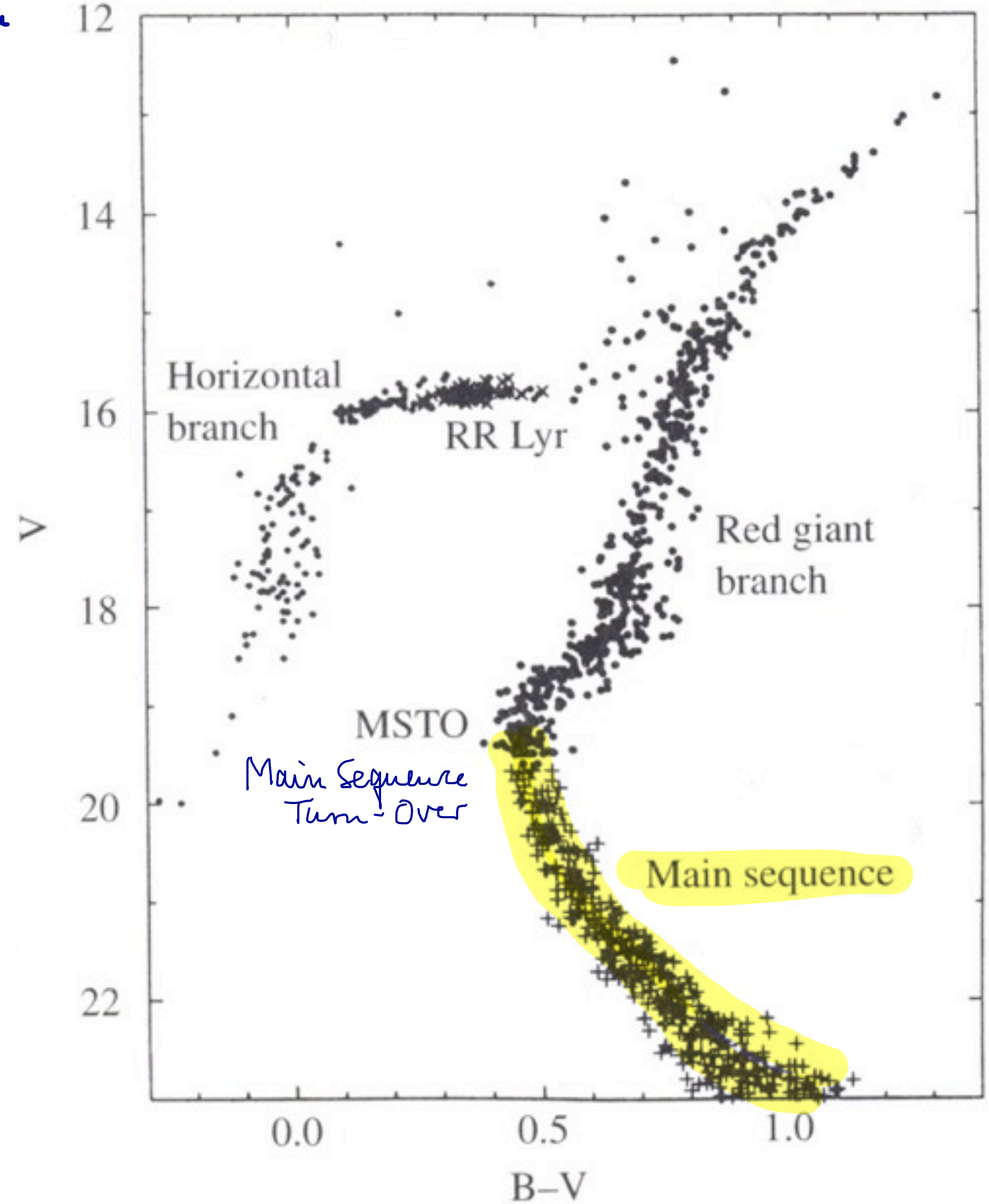
Messier M15

"Kugelsternhaufen"
grav. gebunden

$L \sim M^{3.8}$

$T \sim M/L = M^{-2.8}$





Sternleben im Hertzsprung-Russel-Diagramm

Supernova

Sonne jetzt stabil über > 10^9 Jahre

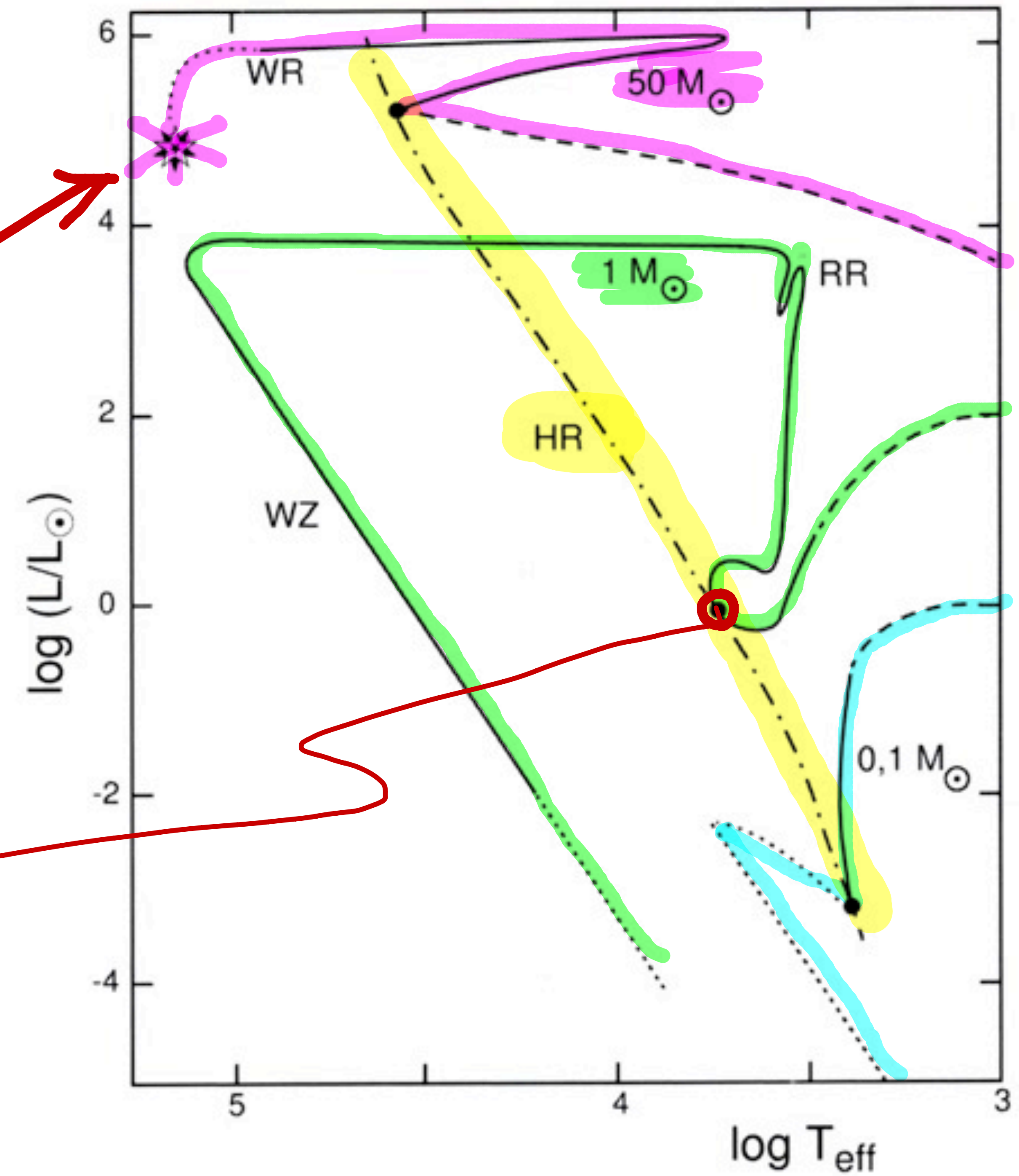


Abbildung 8-1: Schematische Entwicklungswege von Sternen im HRD. Die drei verschiedenen Alter-Null-Massen stehen für drei qualitativ verschiedene Wege mit ihren jeweiligen Endprodukten: massereiche Sterne enden in Supernova-Explosionen, massearme als Weiße Zwerge und sehr massearme als kristalline Kugeln. Nur die einigermaßen mit guten Modellen und Beobachtungen belegten Strecken sind durch ausgezogene Linien angezeigt, die Vor-Hauptreihenwege (gestrichelt) sind grob geschätzt, unsichere Teile der Nach-Hauptreihenwege sind punktiert. (WR bedeutet Bereich der Wolf-Rayet-Sterne, WZ Weiße Zwerge, RR Rote Riesen und HR Hauptreihe.)

Sternentwicklung

MARCH 1, 1939 PHYSICAL REVIEW

Energy Production in Stars*

H. A. BETHE
Cornell University, Ithaca, New York

(Received September 7, 1938)

It is shown that the *most important source of energy in ordinary stars is the reactions of carbon and nitrogen with protons*. These reactions form a cycle in which the original nucleus is reproduced, *viz.* $C^{12}+H=N^{13}$, $N^{13}=C^{13}+\epsilon^+$, $C^{13}+H=N^{14}$, $N^{14}+H=O^{15}$, $O^{15}=N^{15}+\epsilon^+$, $N^{15}+H=C^{12}+He^4$. Thus carbon and nitrogen merely serve as catalysts for the combination of four protons (and two electrons) into an α-particle (§7).

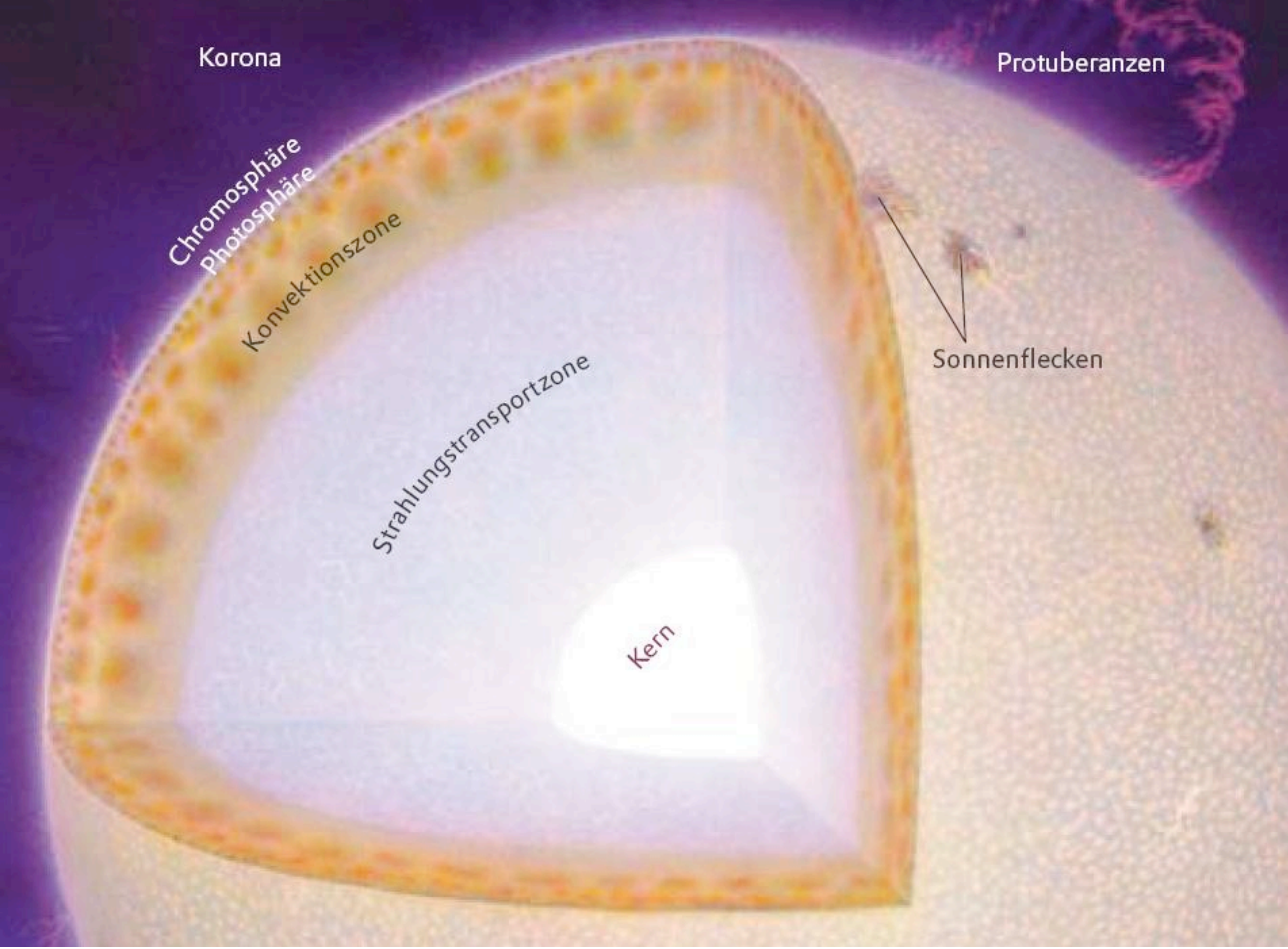
The carbon-nitrogen reactions are unique in their cyclical character (§8). For all nuclei lighter than carbon, reaction with protons will lead to the emission of an α-particle so that the original nucleus is permanently destroyed. For all nuclei heavier than fluorine, only radiative capture of the protons occurs, also destroying the original nucleus. Oxygen and fluorine reactions mostly lead back to nitrogen. Besides, these heavier nuclei react much more slowly than C and N and are therefore unimportant for the energy production.

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

For fainter stars, with lower central temperatures, the reaction $H+H=D+\epsilon^+$ and the reactions following it, are believed to be mainly responsible for the energy production. (§10)

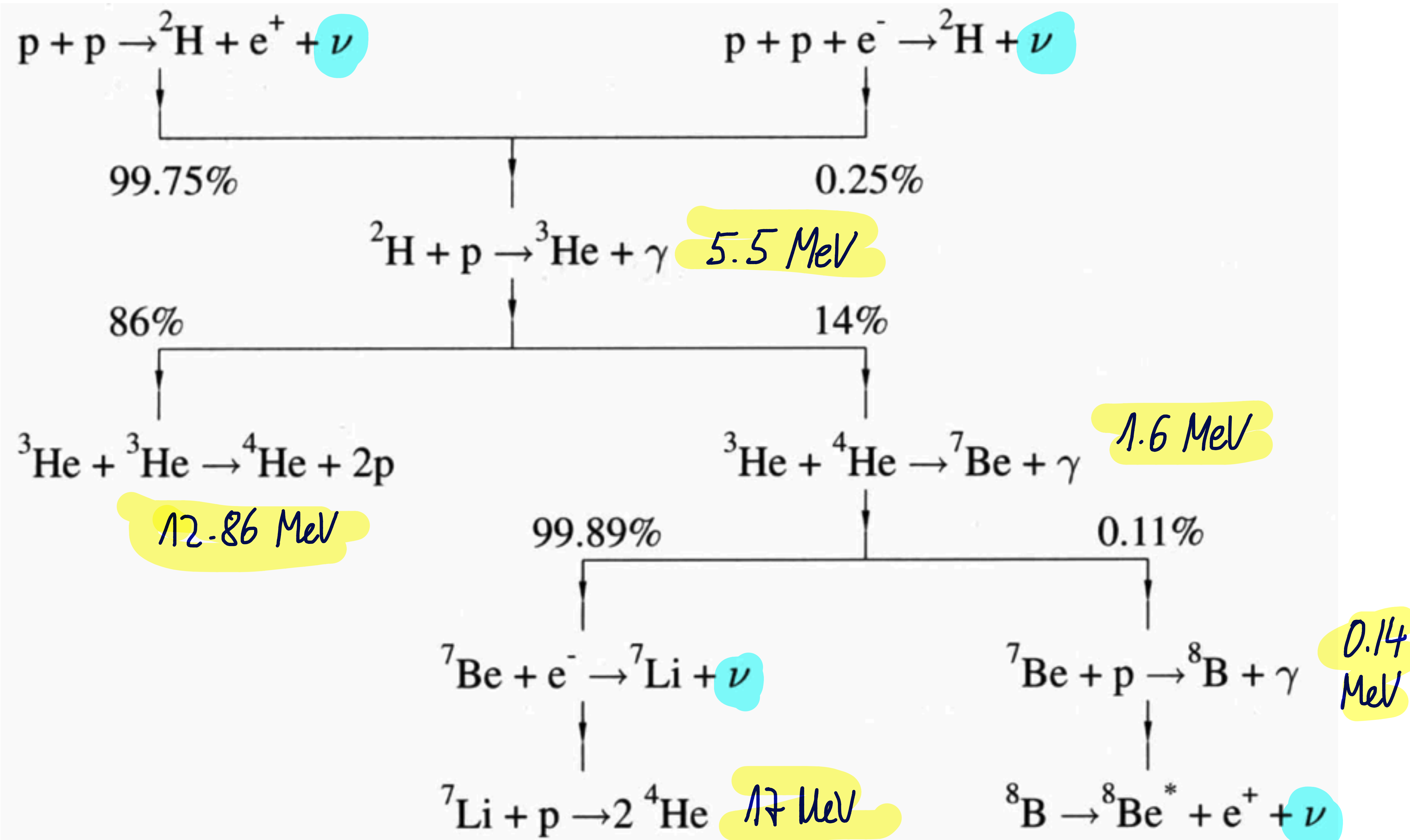
It is shown further (§5–6) that *no elements heavier than He^4 can be built up in ordinary stars*. This is due to the fact, mentioned above, that all elements up to boron are disintegrated by proton bombardment (α-emission!) rather than built up (by radiative capture). The instability of Be^8 reduces the formation of heavier elements still further. The production of neutrons in stars is likewise negligible. The heavier elements found in stars must therefore have existed already when the star was formed.

Finally, the suggested mechanism of energy production is used to draw conclusions about astrophysical problems, such as the mass-luminosity relation (§10), the stability against temperature changes (§11), and stellar evolution (§12).

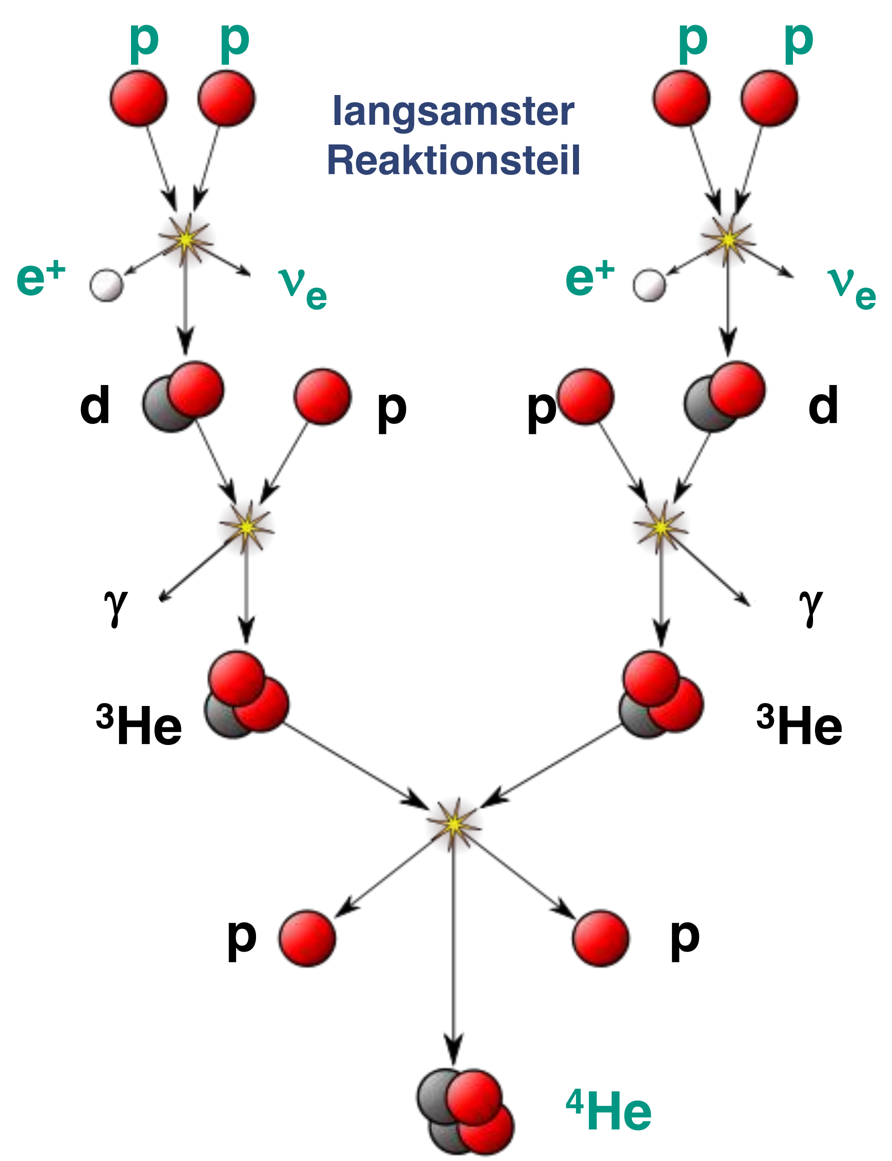

Korona
Protuberanzen
Chromosphäre
Photosphäre
Konvektionszone
Strahlungstransportzone
Sonnenflecken
Kern

pp-Zyklus

Erinnerung → Tunnelwahrscheinlichkeit, Gamow-Faktor

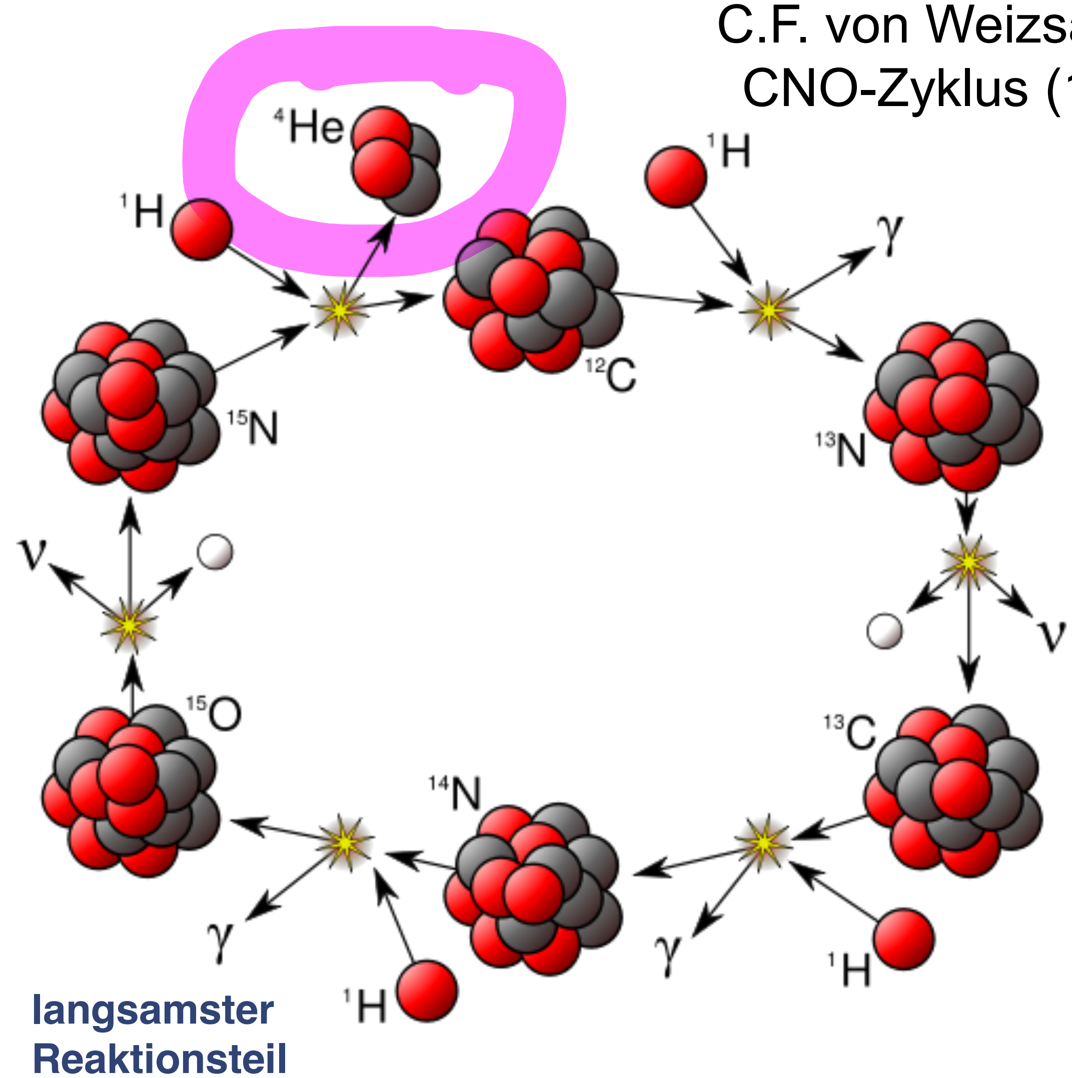


Hauptreihensterne: Fusionsenergie $\Delta E = 4.28 \times 10^{-12}$ J = 26.73 MeV



pp-I Kette: $4p \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e$

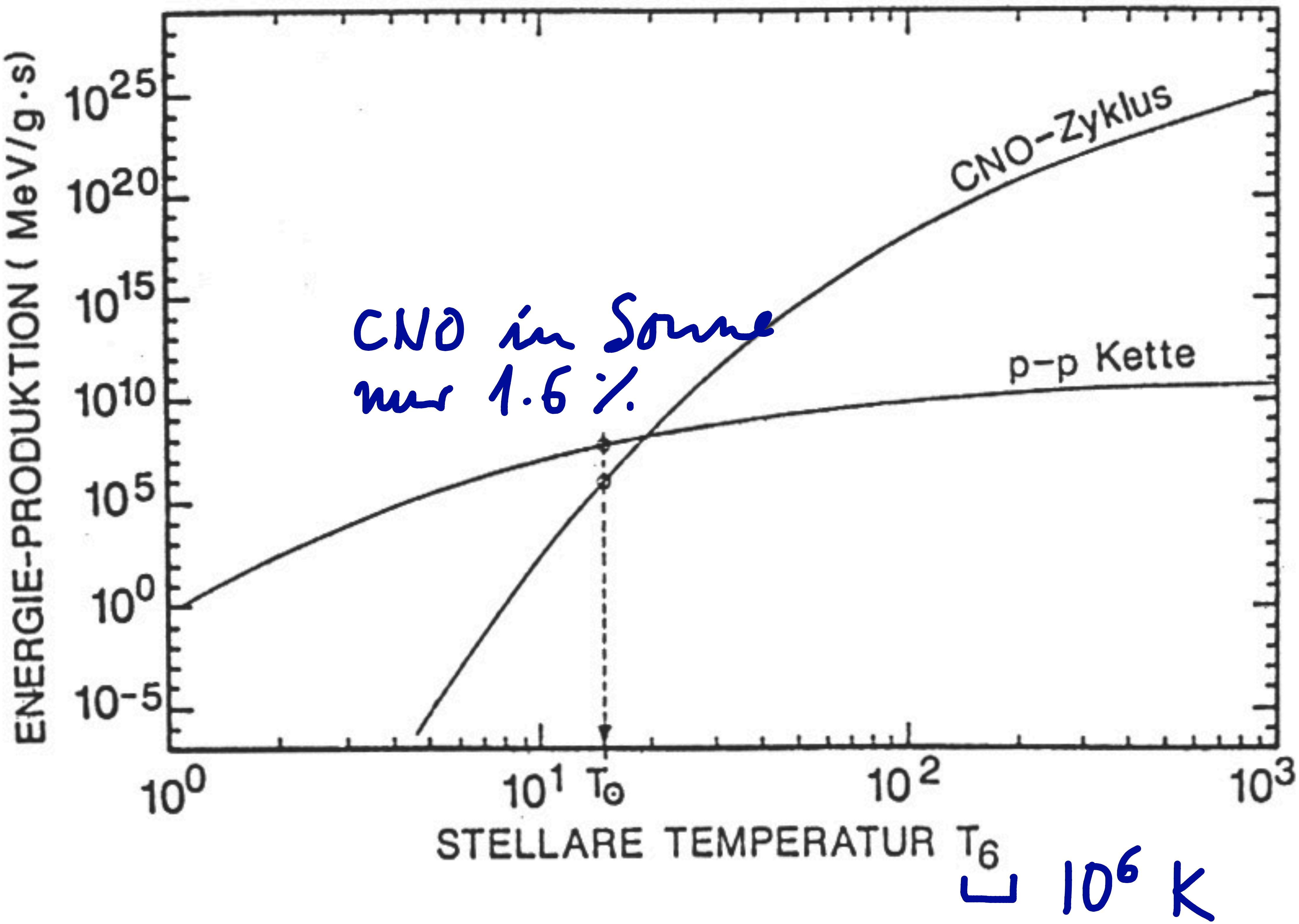
C.F. von Weizsäcker
CNO-Zyklus (1938)



wichtig für schwere Sterne ($T_z > 1.8 \times 10^7$ K)

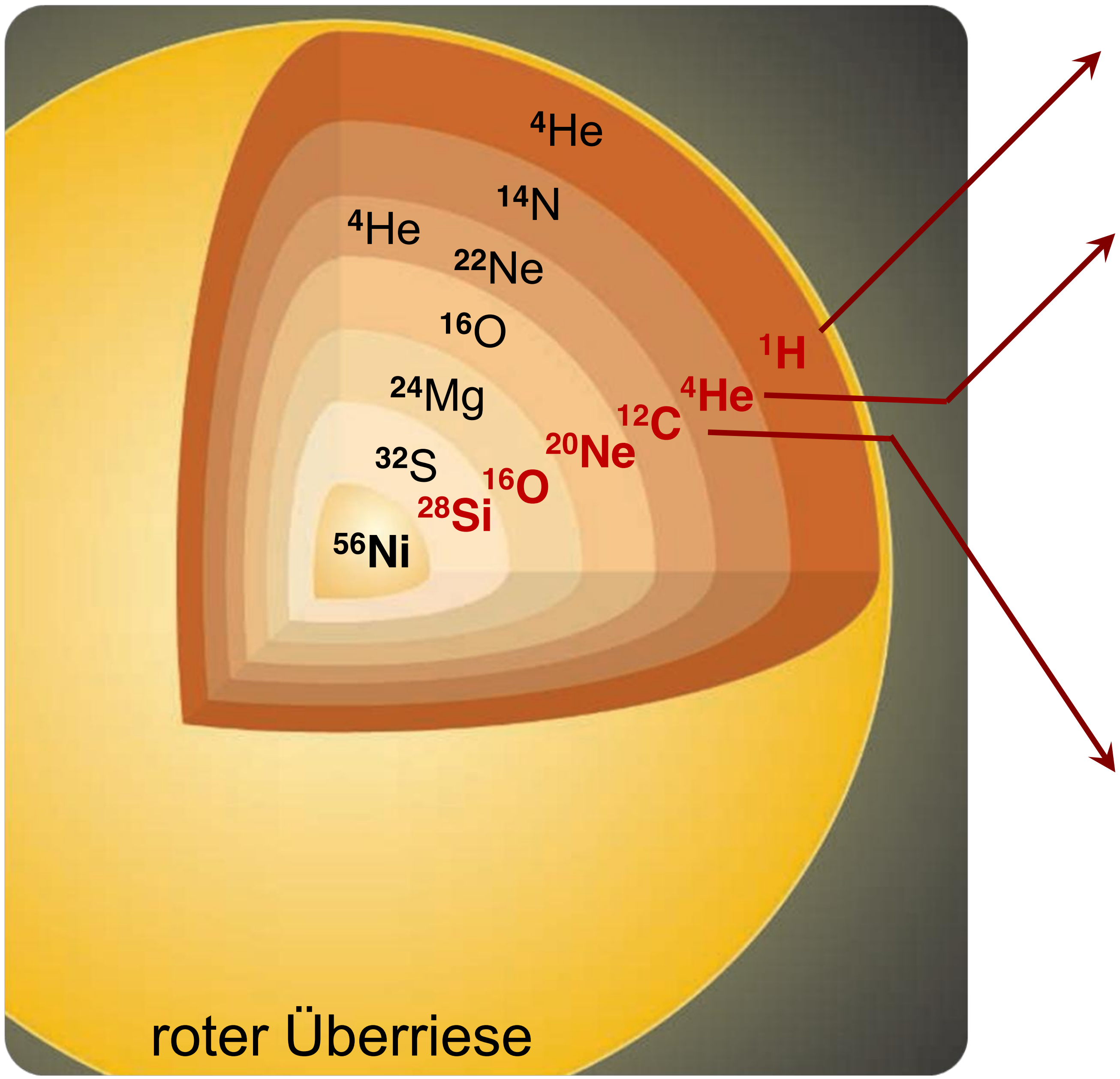
CNO-Zyklus: $4p \rightarrow {}^4He + 2\,e^+ + 2\,\nu_e$

Energieproduktion in pp- und CNO-Zyklen



Kernschalenbrennen I

innere Zwiebelschalenstruktur eines massereichen Sterns $M > 10\,M_\odot$



Wasserstoffbrennen

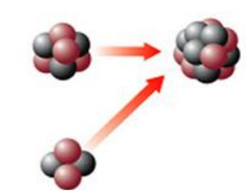
$$4\,p + 2\,e^- \rightarrow {}^{4}\mathrm{He} + 2\,\nu_e$$

Heliumbrennen (3α) (T = 2 × 10⁸ K)

$${}^{4}\mathrm{He} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He} \rightarrow {}^{12}\mathrm{C} + \gamma$$

Kohlenstoffbrennen (T = 5-8 × 10⁸ K)

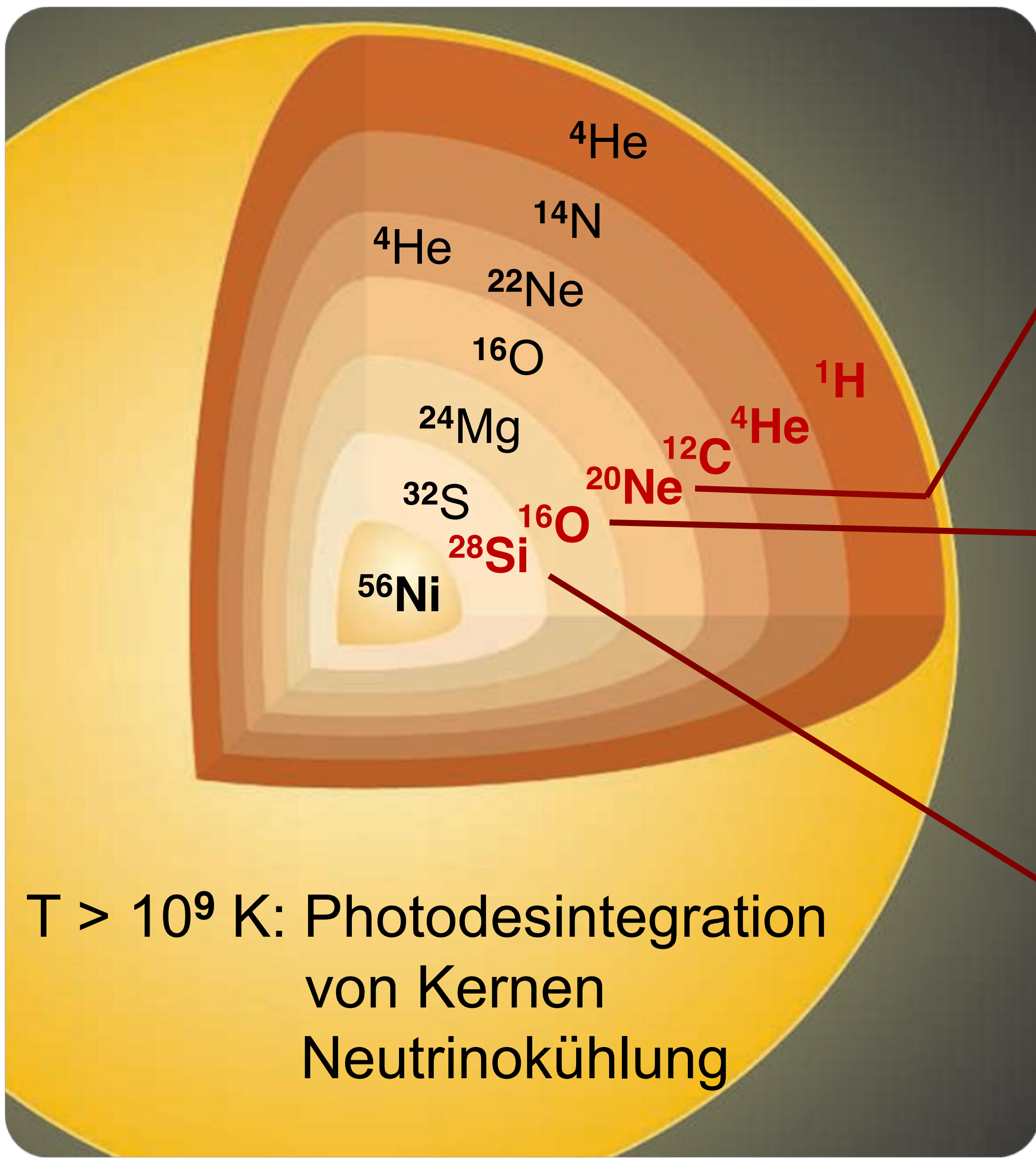
$${}^{12}\mathrm{C} + {}^{4}\mathrm{He} \rightarrow {}^{16}\mathrm{O} + \gamma$$
$${}^{16}\mathrm{O} + {}^{4}\mathrm{He} \rightarrow {}^{20}\mathrm{Ne} + \gamma$$



$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{24}\mathrm{Mg} + \gamma$$
$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{23}\mathrm{Mg} + n$$
$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{23}\mathrm{Na} + p$$
$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{20}\mathrm{Ne} + {}^{4}\mathrm{He}$$
$${}^{12}\mathrm{C} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + 2 \times {}^{4}\mathrm{He}$$

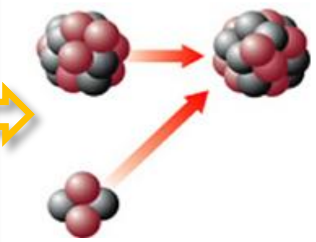
Kernschalenbrennen II

innere Zwiebelschalenstruktur eines massereichen Sterns $M > 10\,M_\odot$



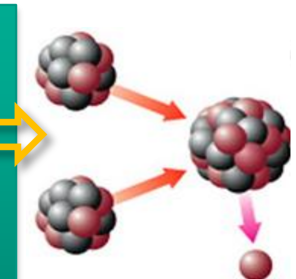
Neonbrennen ($T = 10^9$ K)

$$^{20}\text{Ne} + \gamma \rightarrow {}^{16}\text{O} + {}^{4}\text{He}$$
$$^{20}\text{Ne} + {}^{4}\text{He} \rightarrow {}^{24}\text{Mg} + \gamma$$
$$^{20}\text{Ne} + n \rightarrow {}^{21}\text{Ne} + \gamma$$
$$^{21}\text{Ne} + {}^{4}\text{He} \rightarrow {}^{24}\text{Mg} + n$$



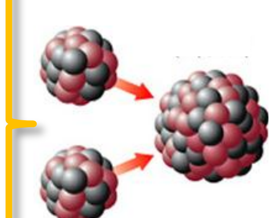
Sauerstoffbrennen ($T = 2 \times 10^9$ K)

$$^{16}\text{O} + {}^{16}\text{O} \rightarrow {}^{32}\text{S} + \gamma$$
$$^{16}\text{O} + {}^{16}\text{O} \rightarrow {}^{31}\text{S} + n$$
$$^{16}\text{O} + {}^{16}\text{O} \rightarrow {}^{31}\text{P} + p$$
$$^{16}\text{O} + {}^{16}\text{O} \rightarrow {}^{28}\text{Si} + {}^{4}\text{He}$$
$$^{16}\text{O} + {}^{16}\text{O} \rightarrow {}^{24}\text{Mg} + 2 \times {}^{4}\text{He}$$



Siliziumverschmelzen ($T > 3.5 \times 10^9$ K)

$$^{28}\text{Si} + \gamma \rightarrow {}^{24}\text{Mg} + {}^{4}\text{He}$$
$$^{28}\text{Si} + {}^{4}\text{He} \leftrightarrow {}^{32}\text{S} + \gamma$$
$$^{32}\text{S} + {}^{4}\text{He} \leftrightarrow {}^{36}\text{Ar} + \gamma$$
$$\vdots$$
$$^{52}\text{Fe} + {}^{4}\text{He} \leftrightarrow {}^{56}\text{Ni} + \gamma$$

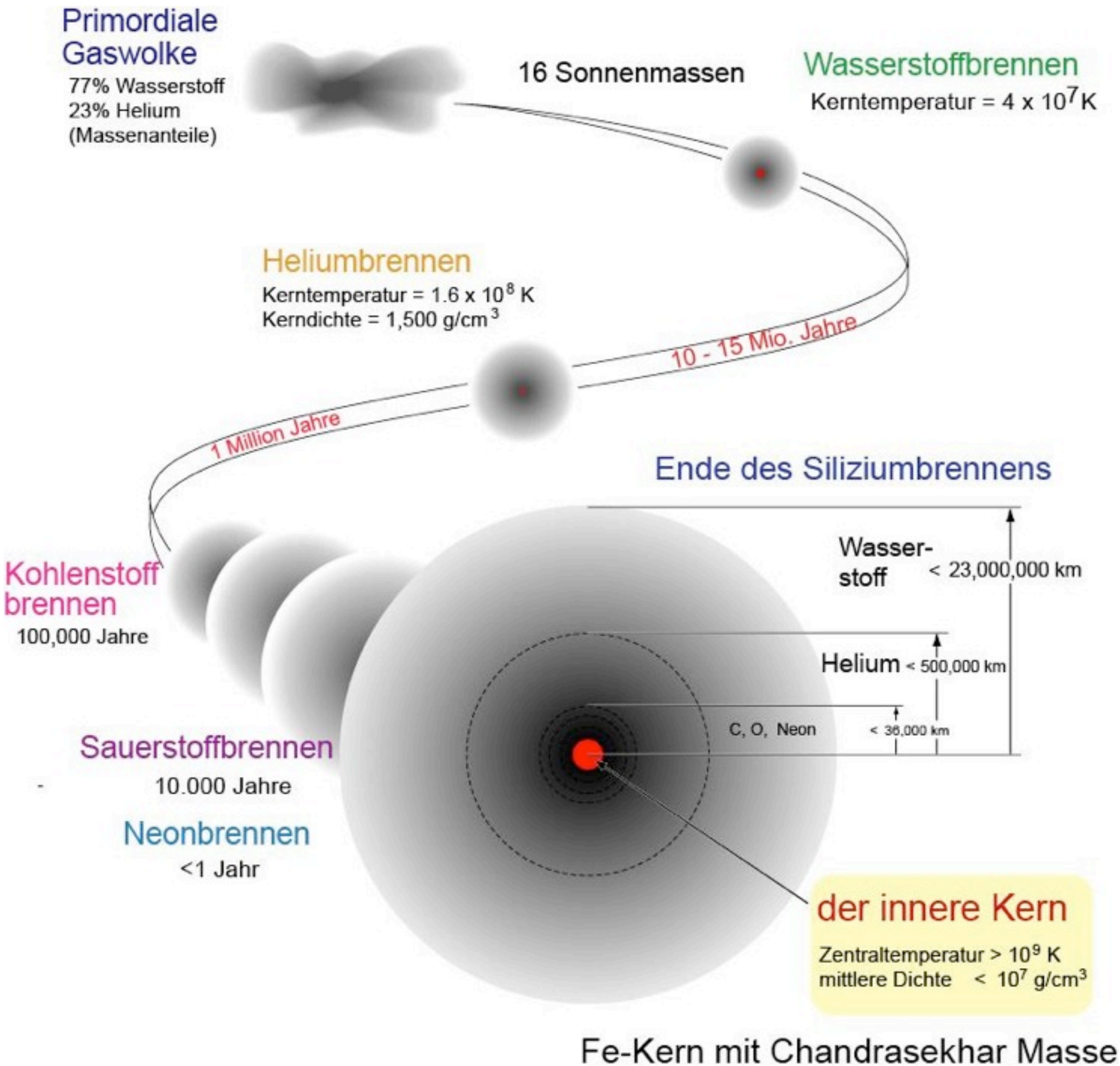


Zeitskalen der Kernfusion

[Perkins, Particle Astrophysics]

Table 7.1 Nuclear fusion timescales for a star of $25M_{\odot}$ (after Rolfs and Rodney 1988)

Fusion of	Time to complete	Core temperature (K)	Core density ($kg\,m^{-3}$)
H	7×10^6 yr	6×10^7	5×10^4
He	5×10^5 yr	2×10^8	7×10^5
C	600 yr	9×10^8	2×10^8
Ne	1 yr	1.7×10^9	4×10^9
O	0.5 yr	2.3×10^9	1×10^{10}
Si	1 day	4.1×10^9	3×10^{10}


Primordiale Gaswolke
77% Wasserstoff
23% Helium
(Massenanteile)
16 Sonnenmassen
Wasserstoffbrennen
Kerntemperatur = 4 x 10^7 K
Heliumbrennen
Kerntemperatur = 1.6 x 10^8 K
Kerndichte = 1,500 g/cm^3
10 - 15 Mio. Jahre
1 Million Jahre
Ende des Siliziumbrennens
Kohlenstoff brennen
100,000 Jahre
Wasser-stoff
< 23,000,000 km
Helium < 500,000 km
C, O, Neon
< 36,000 km
Sauerstoffbrennen
10.000 Jahre
Neonbrennen
<1 Jahr
der innere Kern
Zentraltemperatur > 10^9 K
mittlere Dichte < 10^7 g/cm^3
Fe-Kern mit Chandrasekhar Masse

Stabilität von Sternen: Chandrasekhar-Grenze

Zustandsbesetzung bis p_F ! $T=0 \rightarrow T>0$

allg. Zusammenhang zwischen Druck und Energie aus $dE = -P dV$
$P = \frac{2}{3} \varepsilon$ - Dichte ε

nicht-relativistisch : $P_{NR} \sim n^{5/3}$ stets $> P_{grav}$
relativistisch : $P_R \sim n^{4/3}$ $= P_{grav}$

$E_{Grav} = \frac{3}{5} \frac{GM^2}{R}$ Grav.energie eines Sterns

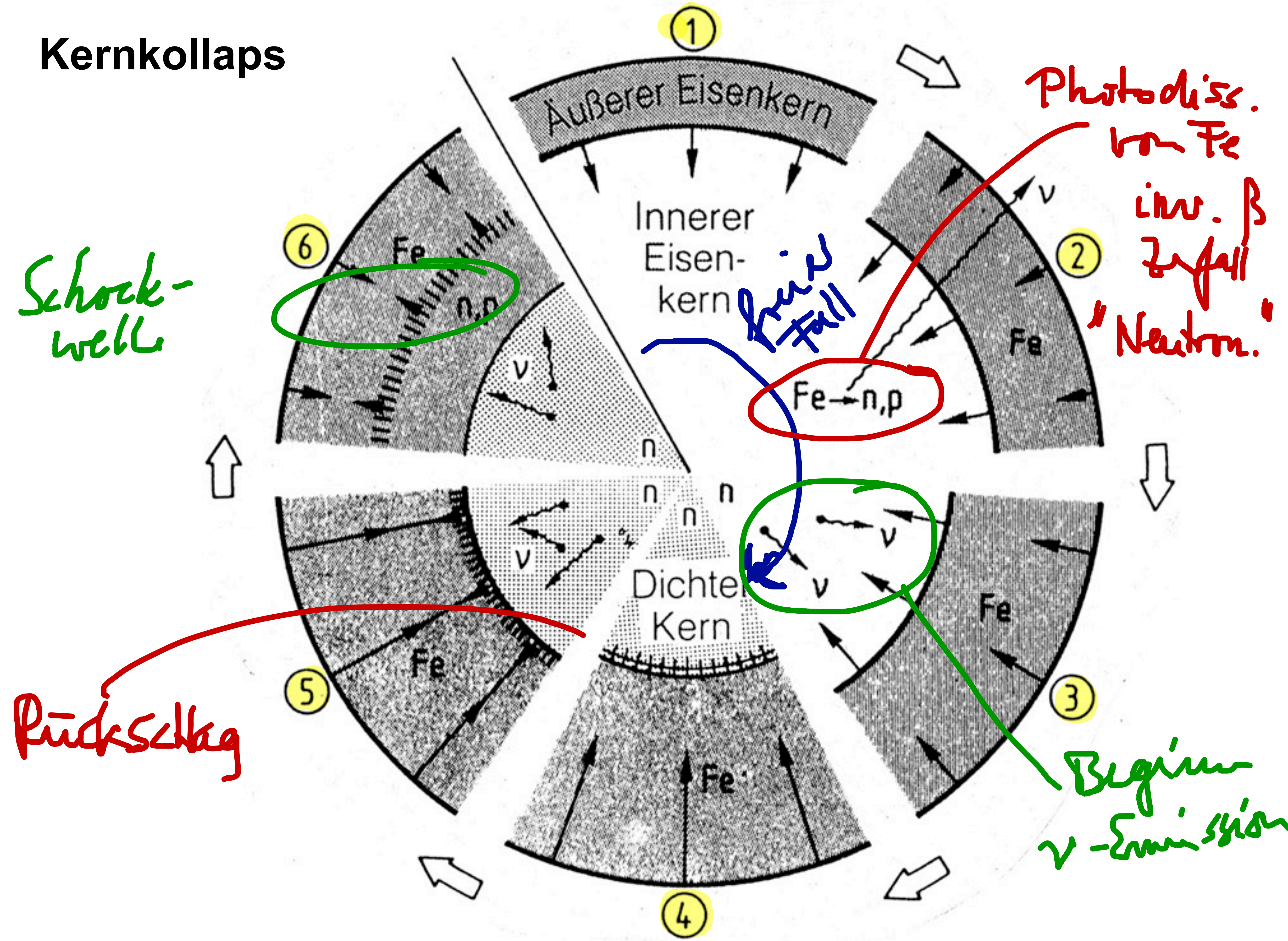
n tragen nur zum Grav.druck bei, e halten dagegen ...

$P_{Grav} = \frac{E_{Grav}}{3V} \rightarrow$ Elektrondichte verwenden, Nukleonen, Z/A,
Abstand der e (NR) $> \lambda_{Compton} \Rightarrow \rho_0$ „mikrosk. Formulierung"
$P_{Grav} = P_{ent.}$ setzen [Perkins Gl. 7.29 – nachrechnen?] $\rightarrow \rho = \ldots \stackrel{!}{=} \rho_0 \Rightarrow M$

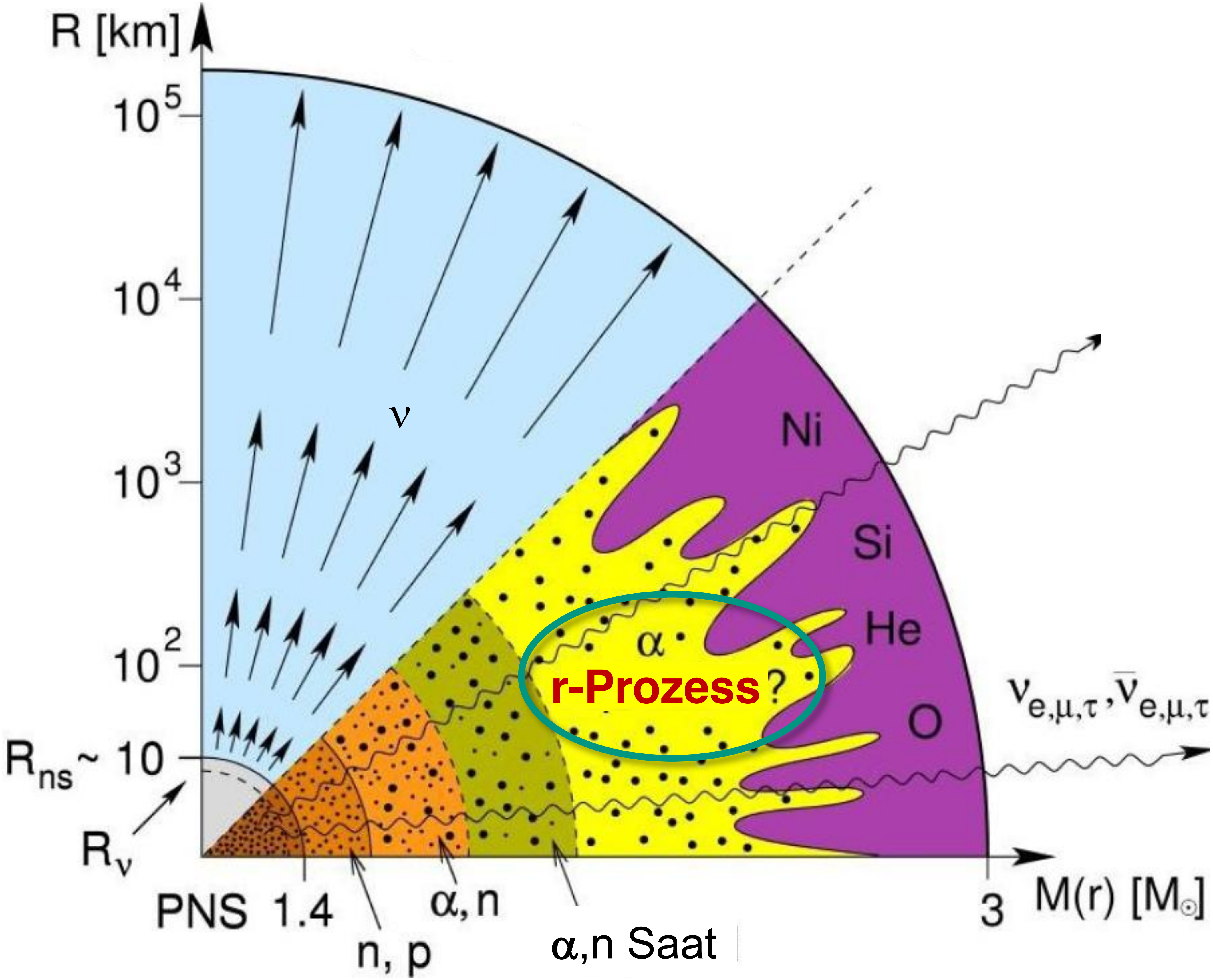
$$M_{Ch.} = \left(\frac{3\sqrt{2}}{8\pi}\right)\left(\frac{hc}{G}\right)^{3/2}\left(\frac{Z}{A\, m_p}\right)^2 = 4.91\left(\frac{Z}{A}\right)^2 M_\odot \simeq 1.2\, M_\odot$$

$\rightarrow 1.4\, M_\odot$ genauer

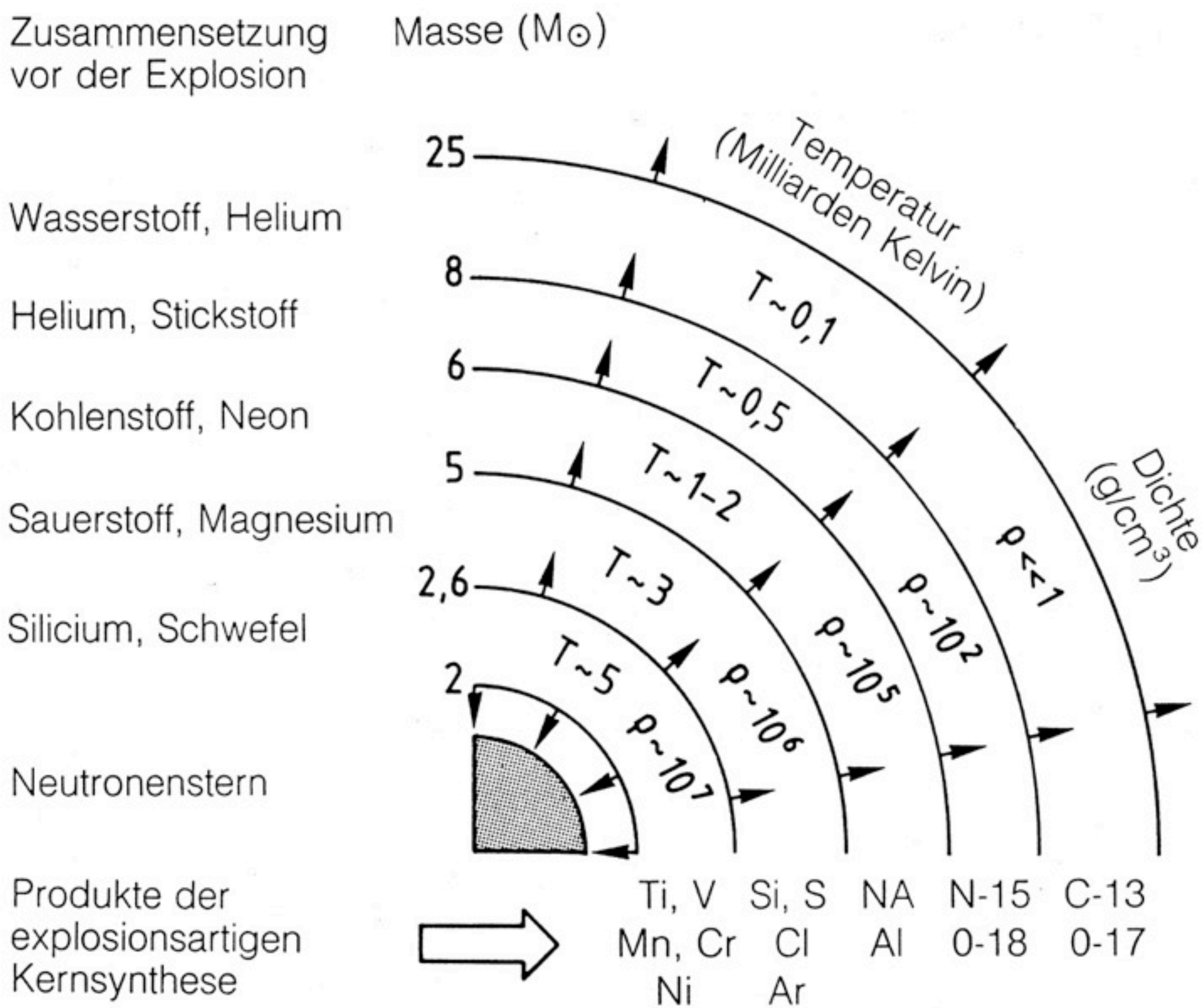
Kernkollaps



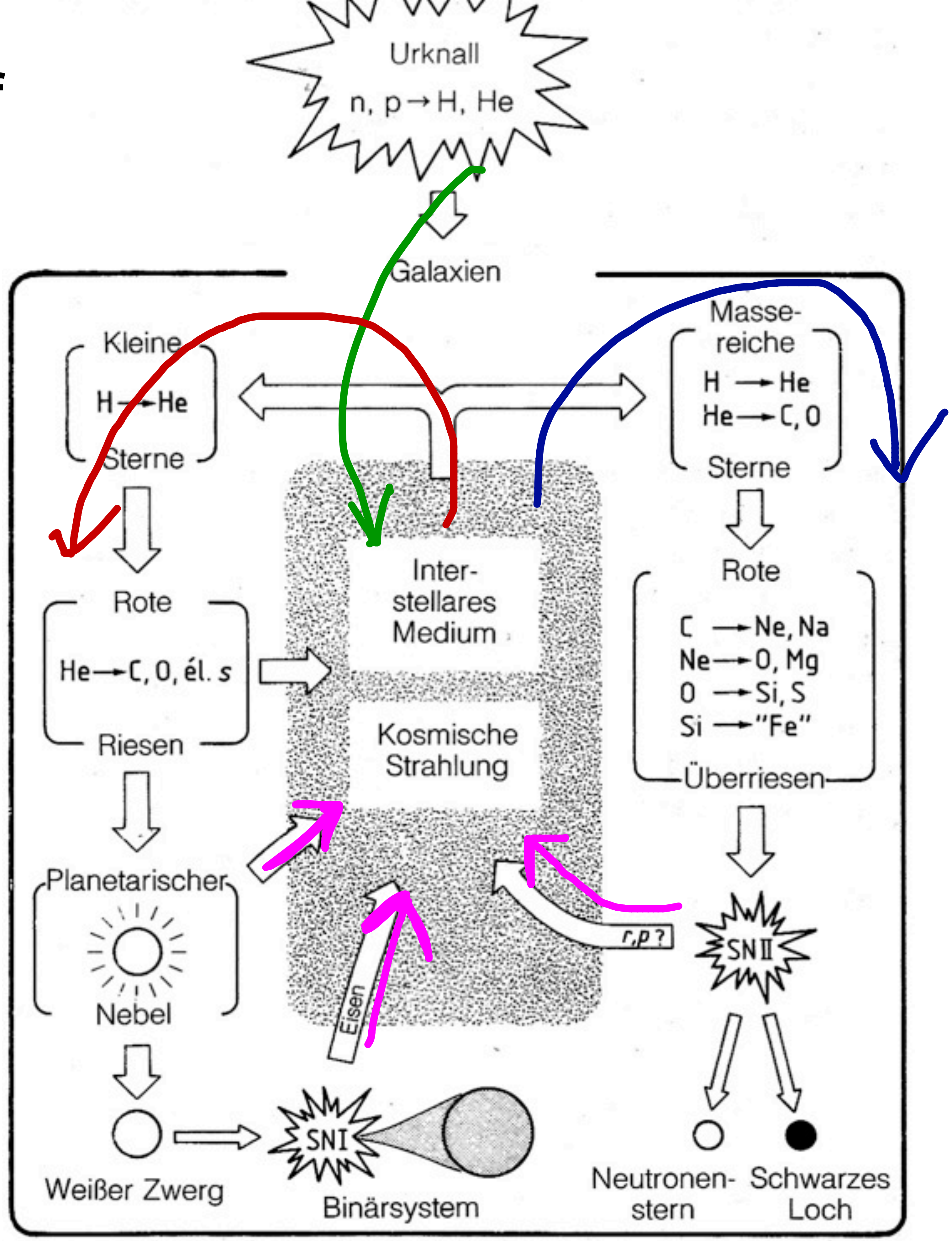
Supernova II, r-Prozess

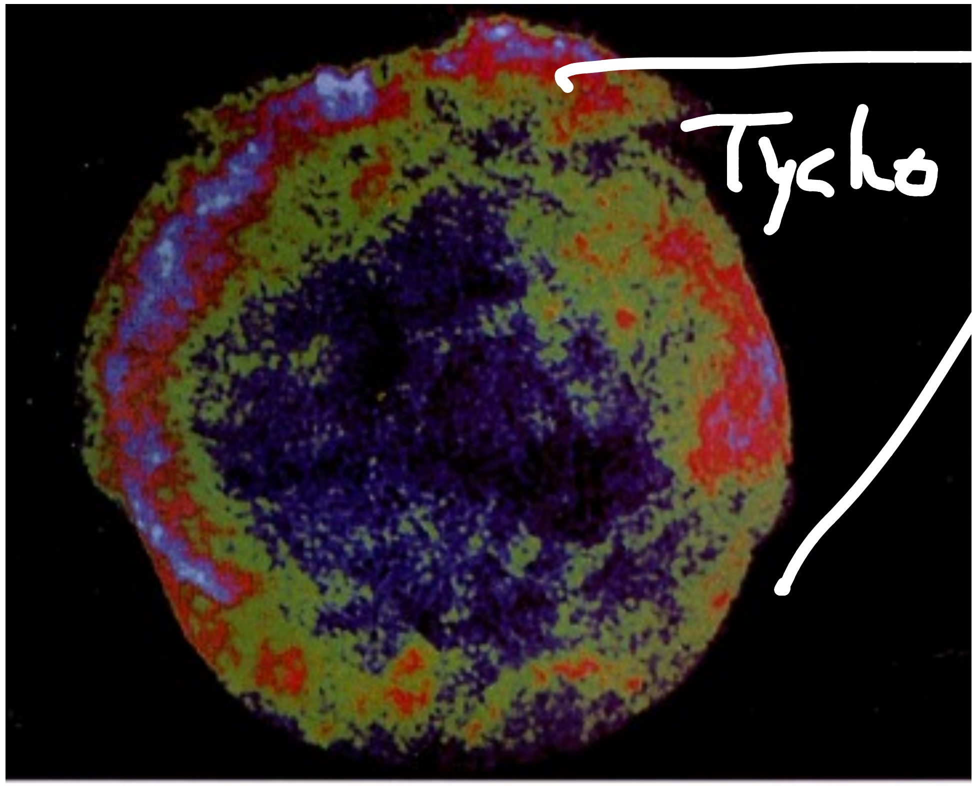


Supernova II, r-Prozess



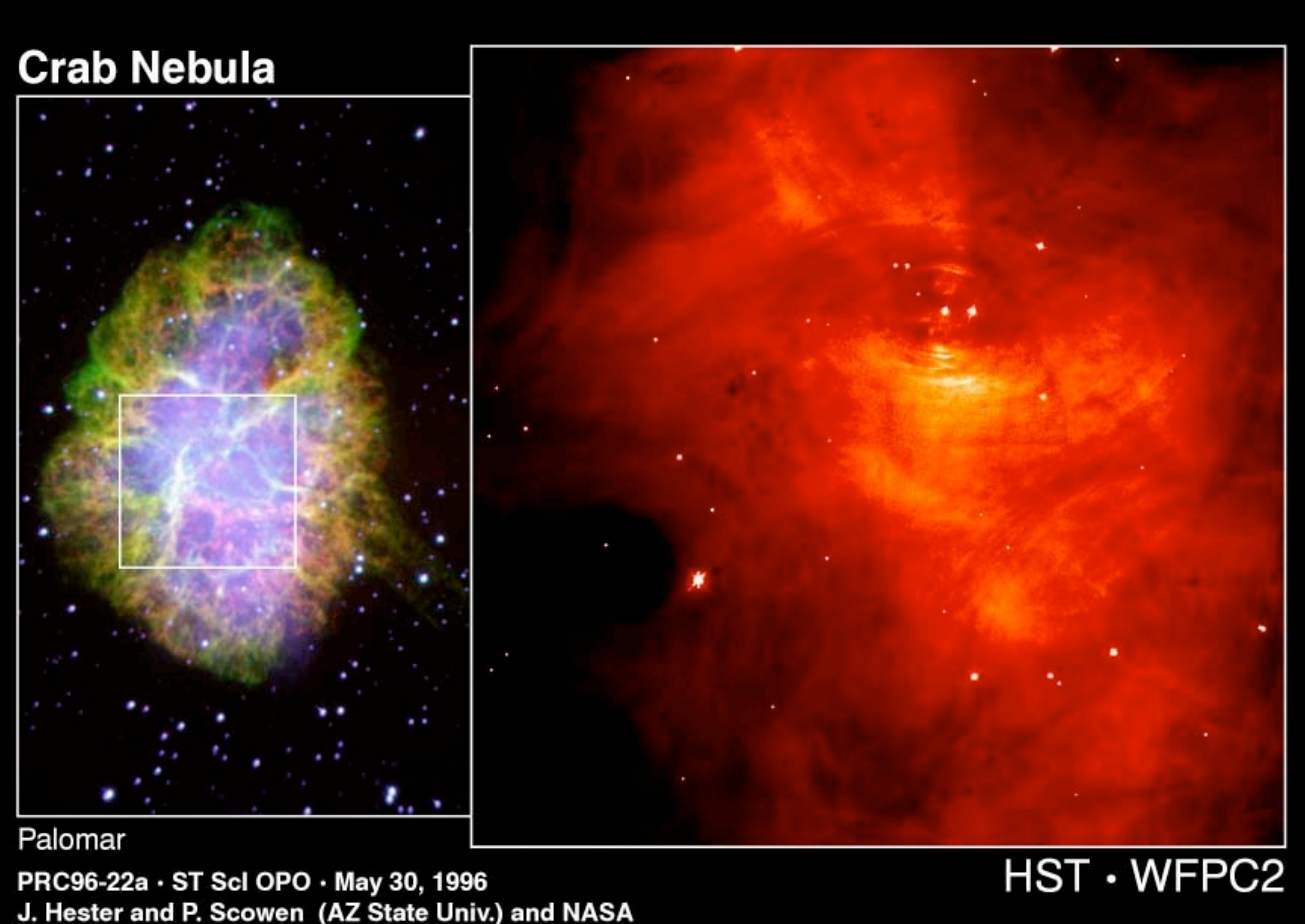
Elementkreislauf



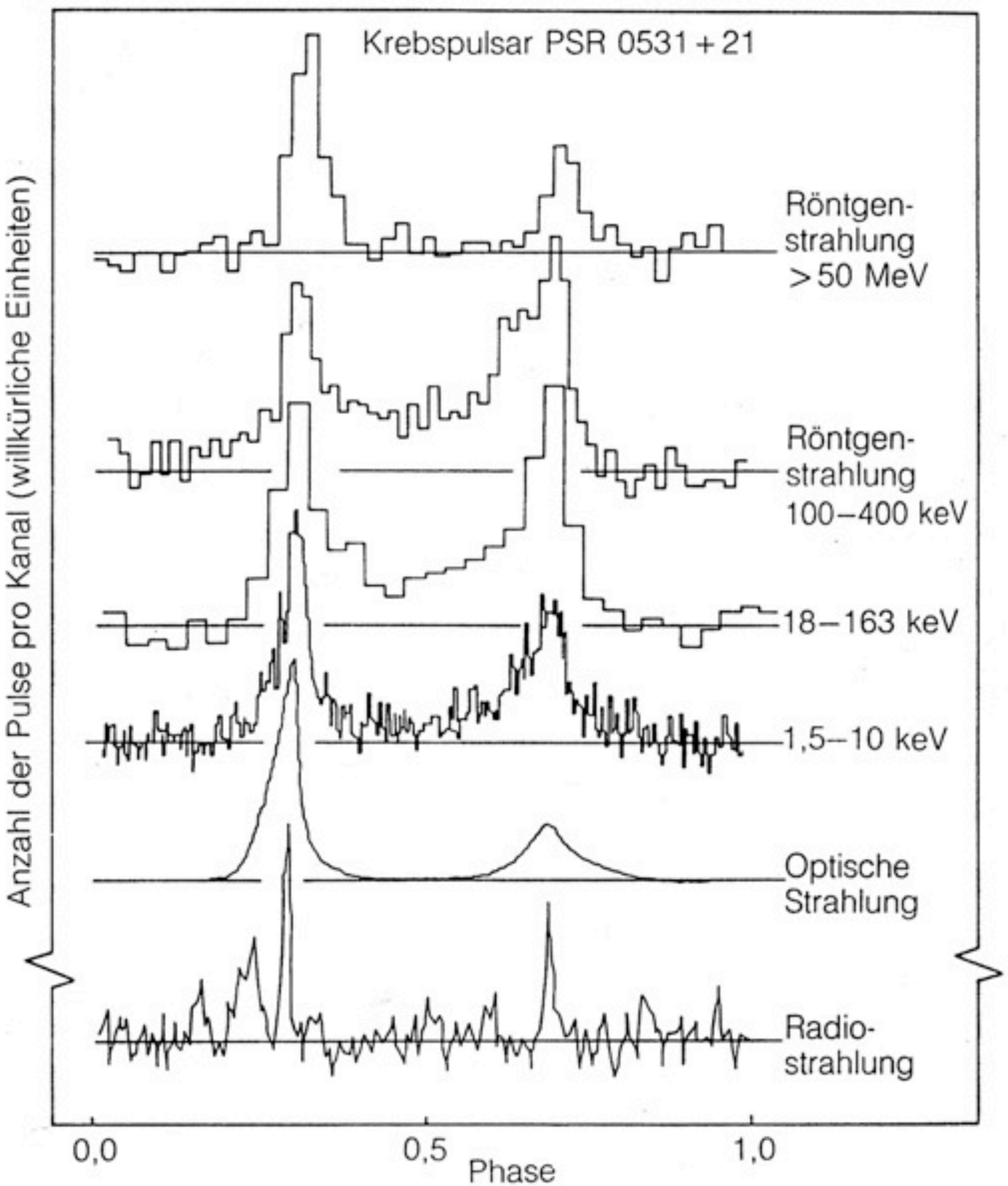


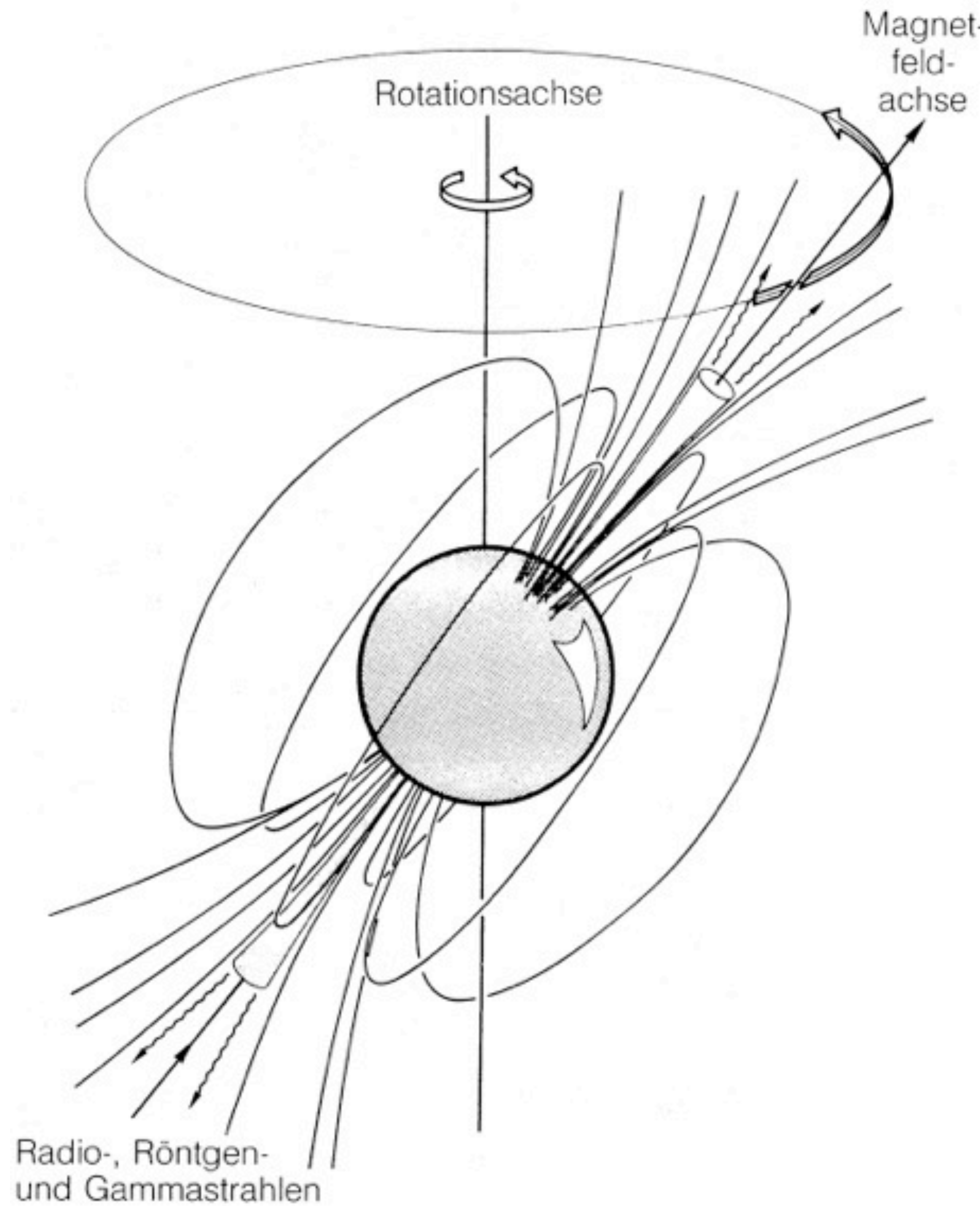
Supernova-Beobachtungen

Jahr	Sternbild	Beobachtung	Helligkeit	Bezeichnung
185	Zentaur	China, Rom	-2 mag	RCW 86
393	Skorpion	China	-3 mag	CTB 37 A/B
1006	Lupus	Ägypten, China, Europa, Japan	-9 mag	PKS 1459-41
1054	Stier	China, Anasazi	-6 mag	Krebsnebel
1181	Cassiopeia	China, Japan	-1 mag	3C 58
1572	Cassiopeia	Tycho Brahe	-4 mag	3C 10
1604	Ophiuchus	Johannes Kepler	-2,5 mag	3C 358
1885	Estonia	Ernst Hartwig	6 mag	M31
1987	Dorado	Ian Shelton	2,9 mag	Magellansche Wolke


Crab Nebula
Palomar
HST • WFPC2
PRC96-22a • ST ScI OPO • May 30, 1996
J. Hester and P. Scowen (AZ State Univ.) and NASA

Pulsar im Krebsnebel





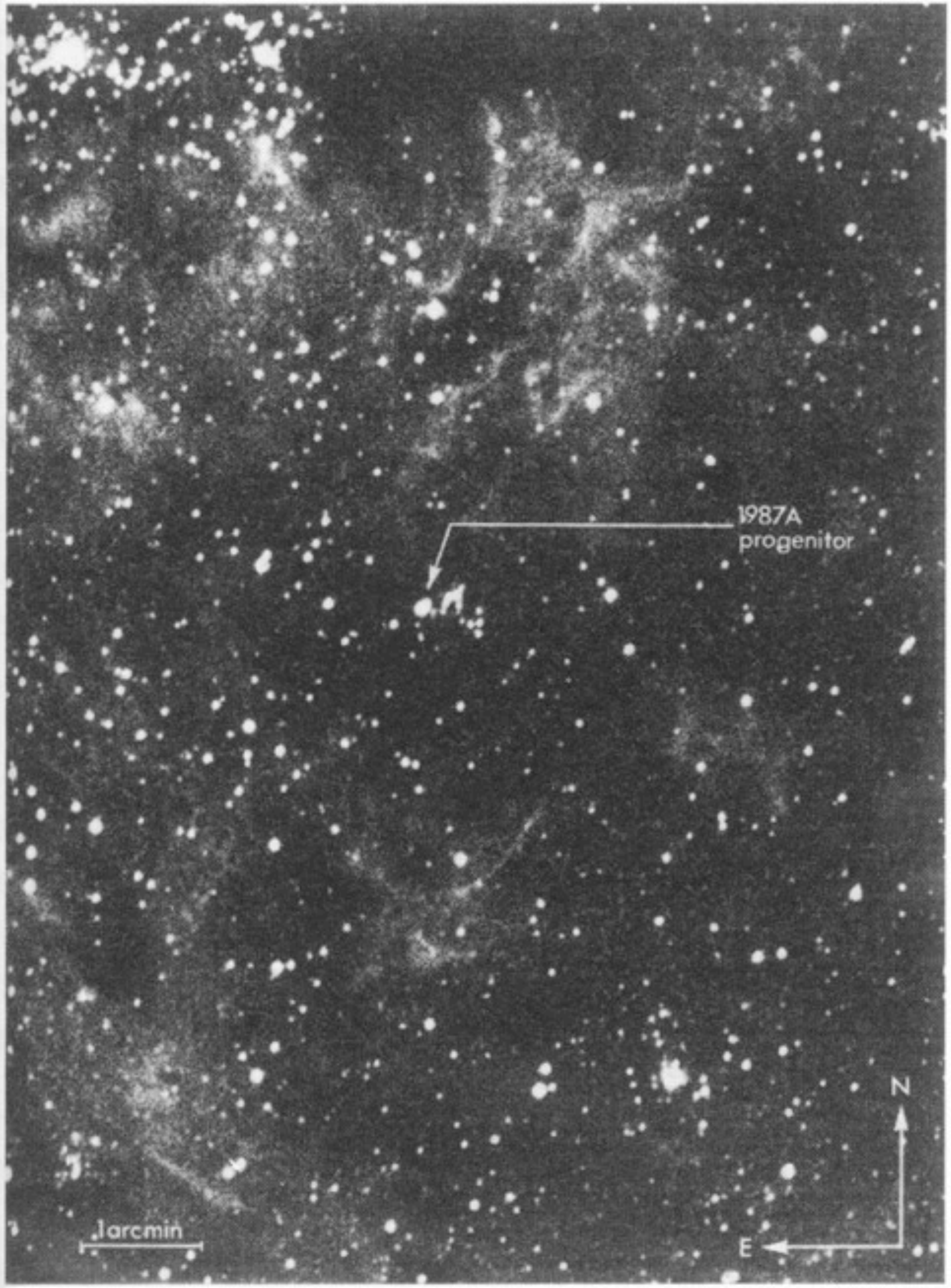
UNSERE SUPERNOVA

Das größte kosmische Drama seit 383 Jahren

74 WISSENSCHAFT

Heller als Millionen Sonnen

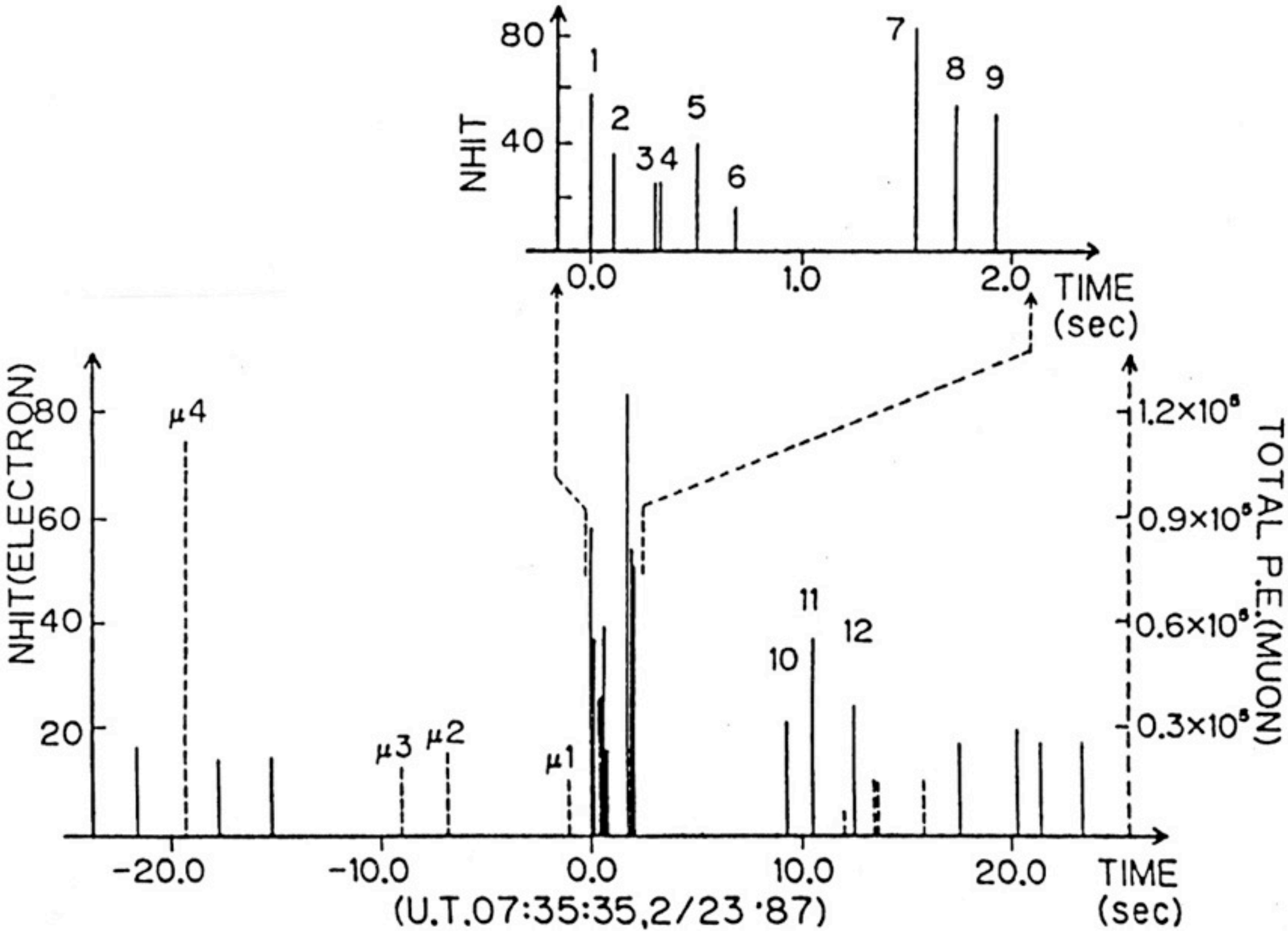
Das Jahrhundertereignis einer nahen Supernova, die Explosion eines sterbenden Sternes, erregt die Astronomen / Von Rudolf Kippenhahn

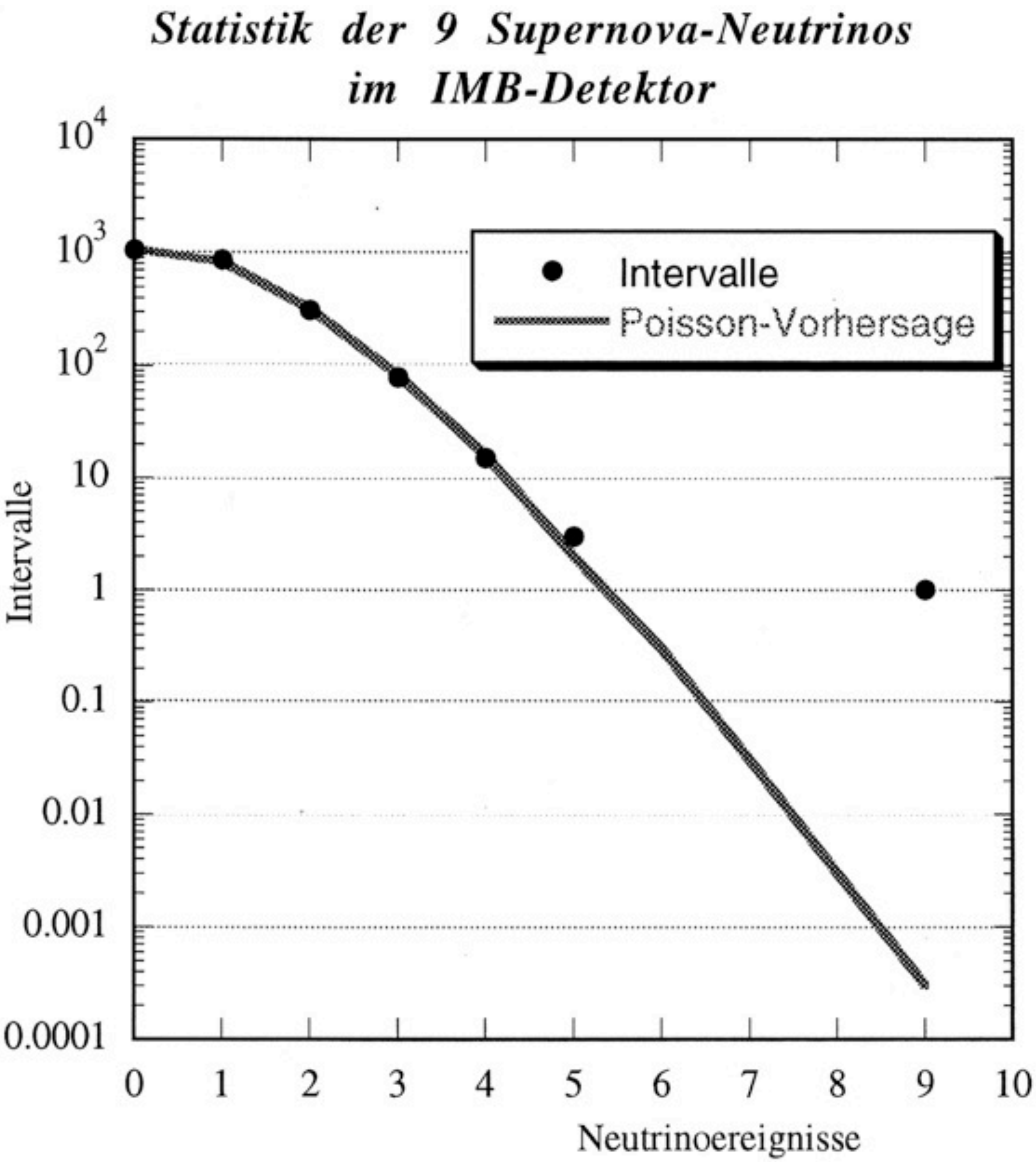

1987A
progenitor
1arcmin
N
E


1 arc min
N
E

Kamiokande-Beobachtung von SN-Neutrinos

[Hirata et al., PRL 58(1987)1490]



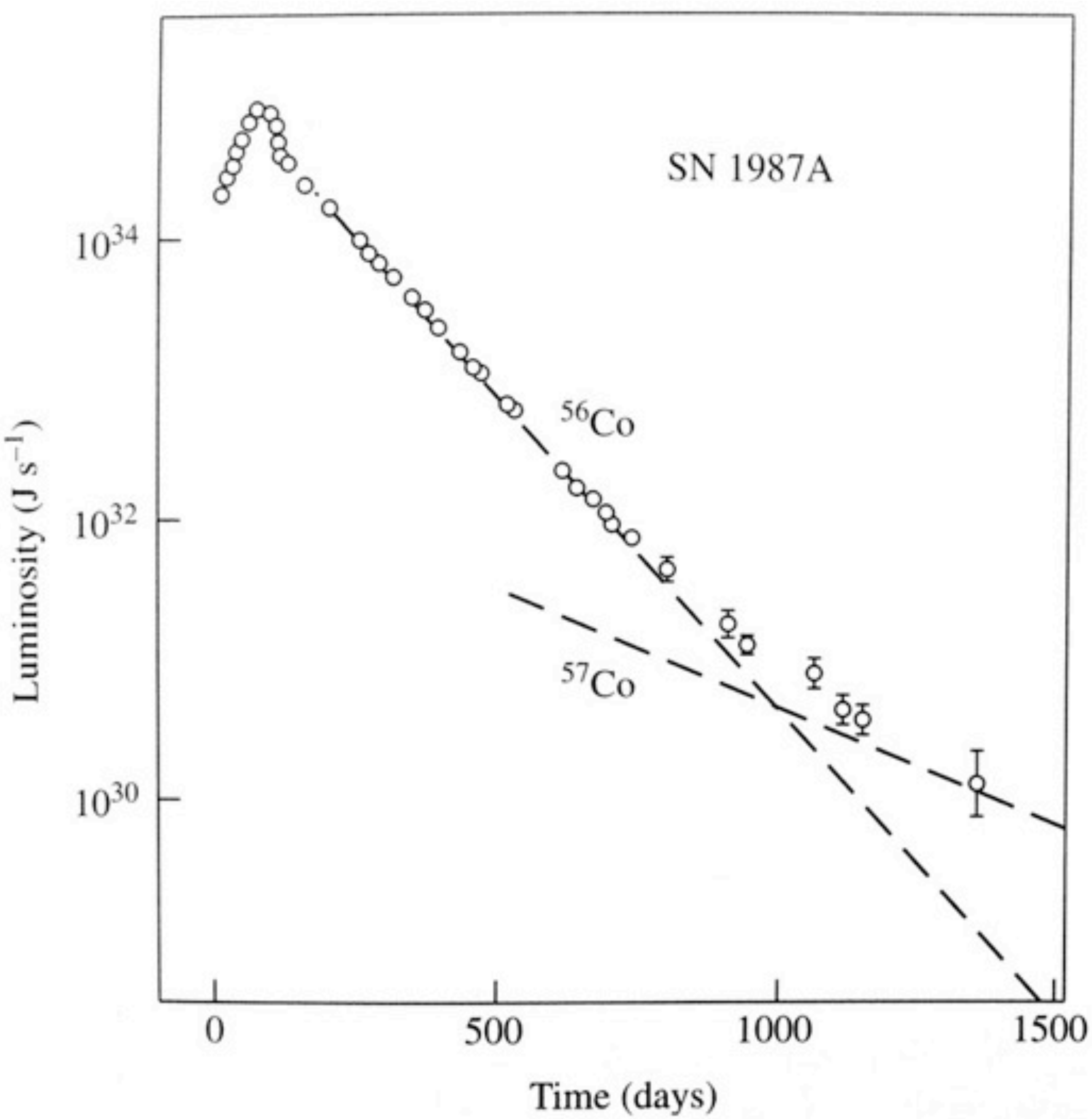


The signal of a supernova is expected to be a burst of low-energy neutrinos occurring over a period of seconds. In the search for low-energy neutrino events, an upper limit of 100 PMTs firing was set as an off-line acceptance criterion. To search for such a burst of neutrinos, a 6.4 h period starting at UT February 23, 5 h 00 mm 00 s (when the PMTs were inoperative) was selected and divided into non-overlapping 10 s intervals; the number of events with fewer than 100 PMTs firing (N) was determined for each interval. For $N \leq 5$, this distribution is fitted well by a Poison distribution with $\langle N \rangle = 0.77$ events per interval. However, one interval is found to contain nine events.

[NEUTRINOS FROM SN1987a IN THE IMB DETECTOR, NIM A264, 1988]

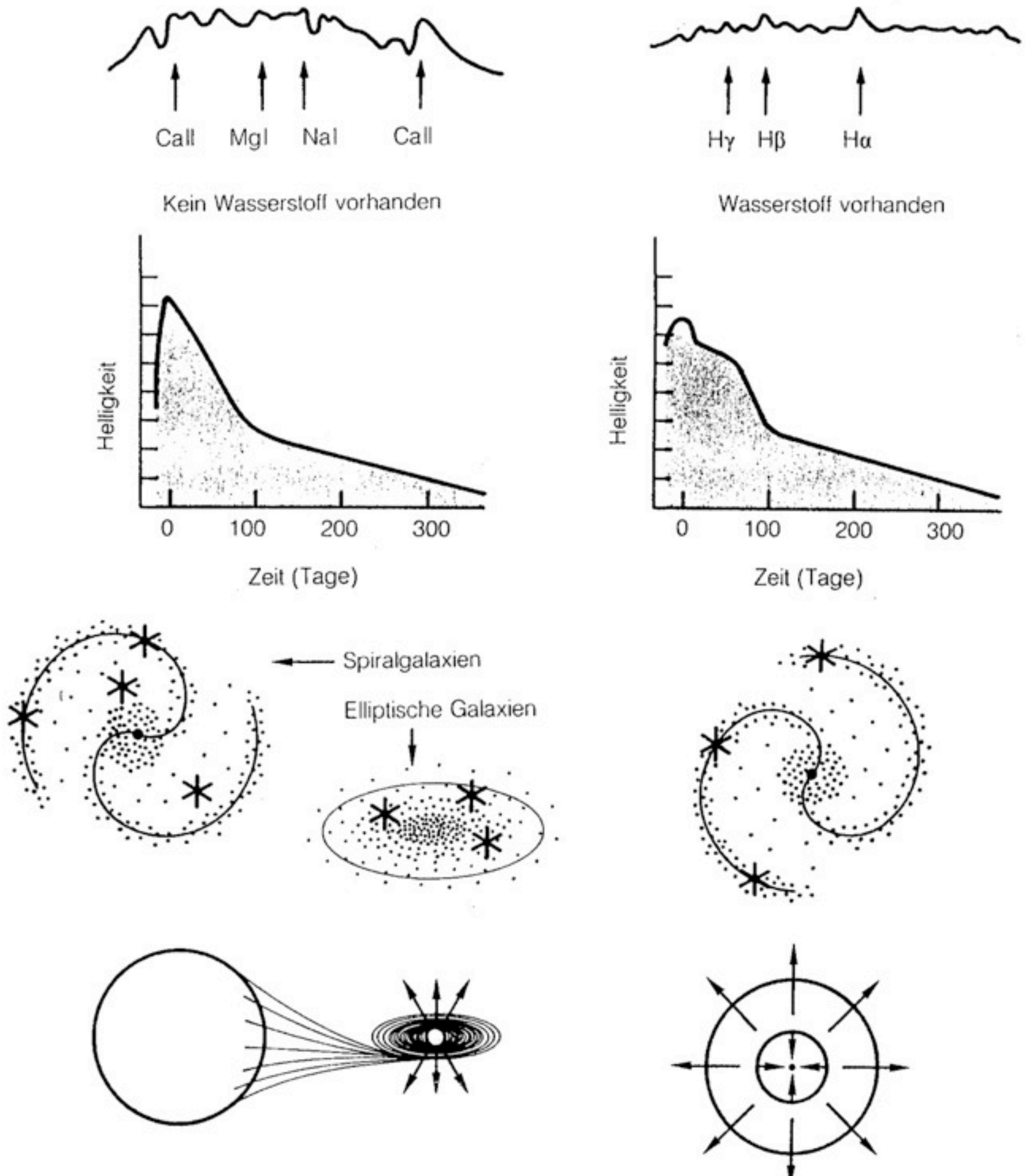
[Bionta et al., PRL 58 (1987) 1494]

Leuchtkurve SN1987a



[Perkins]

Fig. 7.8 The light curve of supernova SN 1987A. After the initial outburst, the luminosity fell rapidly over the first 100 days, being dominated by the beta decay of ^{56}Ni to ^{56}Co, with a mean lifetime $\tau = 9$ days. From time $t = 100$ to $t = 500$ days, the energy release was dominated by the beta decay of ^{56}Co to ^{56}Fe, with $\tau = 111$ days. Beyond $t = 1000$ days, the important decay is of ^{57}Co to ^{57}Fe ($\tau = 391$ days) as well as that of other long-lived isotopes. Most of the heavy nuclei would have been produced in rapid absorption reactions of neutrons with the material of the infalling envelope. Interestingly enough, no neutron star has been detected following this particular supernova (after Suntzeff *et al.* 1992).



CaII
MgI
NaI
CaII
Hγ
Hβ
Hα
Kein Wasserstoff vorhanden
Wasserstoff vorhanden
Helligkeit
0
100
200
300
Zeit (Tage)
Helligkeit
0
100
200
300
Zeit (Tage)
Spiralgalaxien
Elliptische Galaxien

Kosmische Teilchen in der Galaxie