

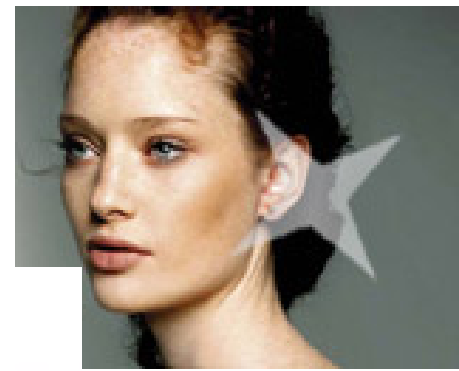
Stjerneudvikling, grundstofsyntese og supernovaer

Jørgen Christensen-Dalsgaard
Dansk AsteroSeismologi Center
Institut for Fysik og Astronomi



SN 1994D

Starmodels ifølge GOOGLE

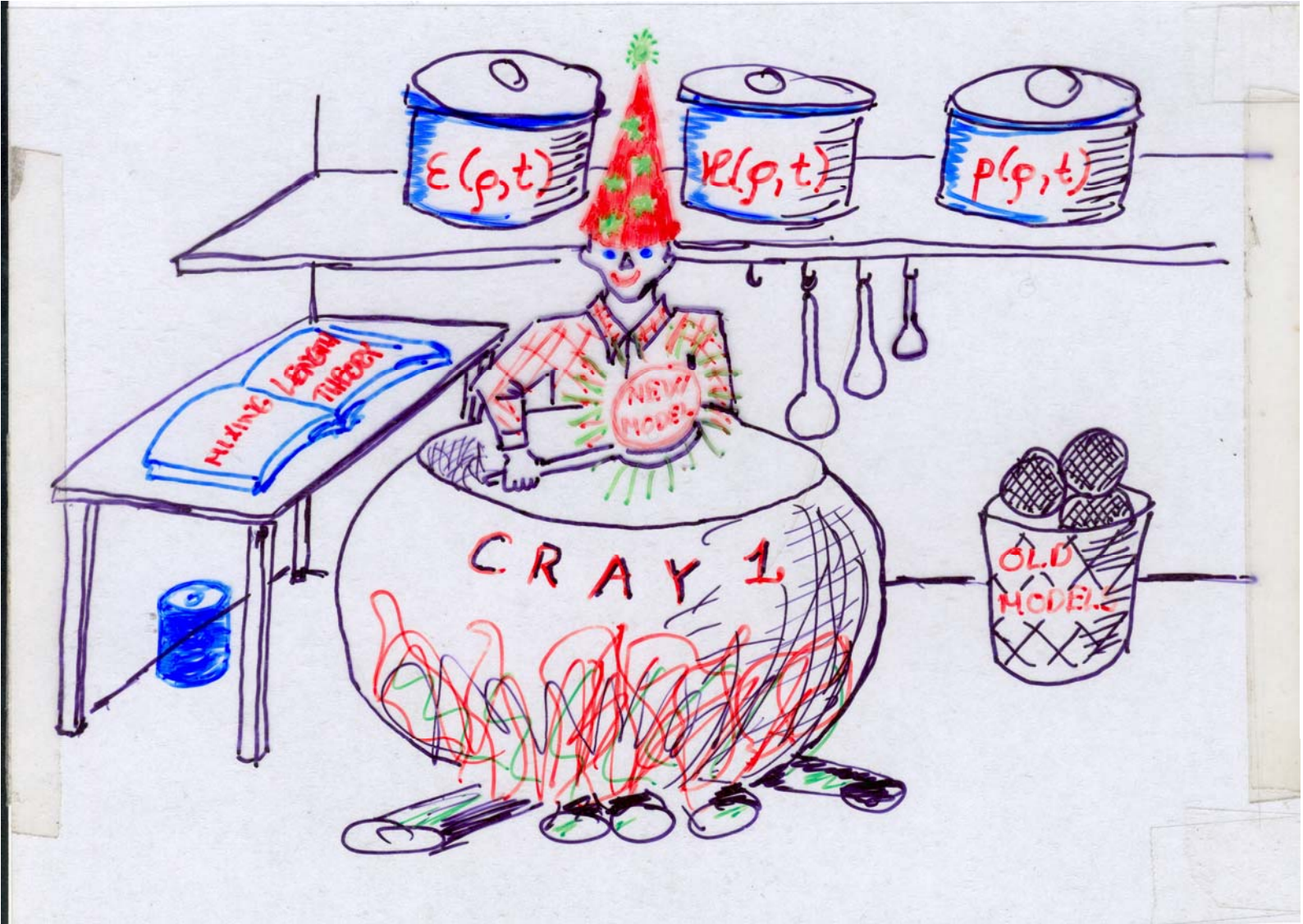


Tromsø Astronomiforening



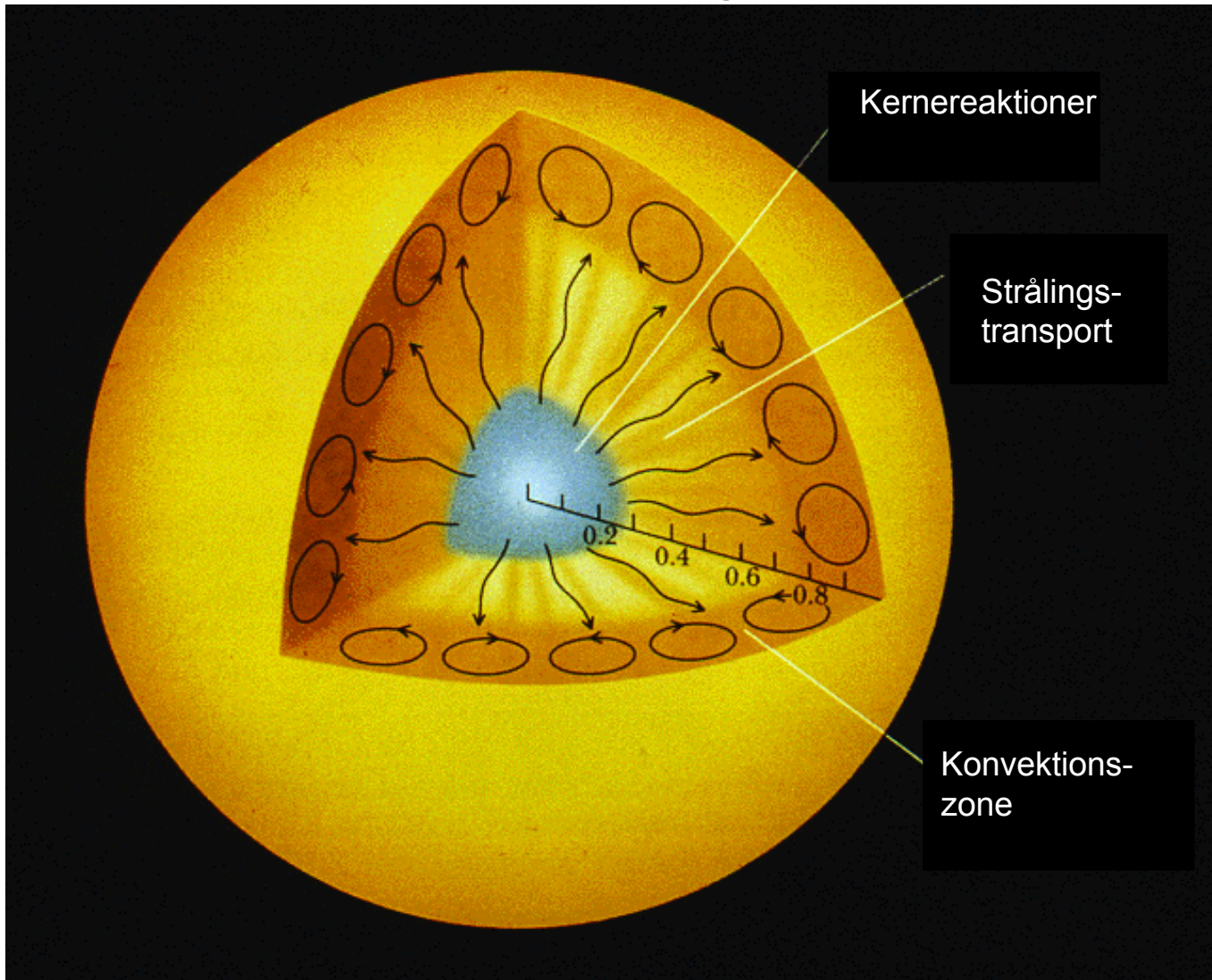
Stjernebrettetskomiteen

Vitensenteret v/Anne stilte med oppskrifter og papir til mange **stjernemodeller**, godt assistert av Ann Kristin



Birte Christensen-Dalsgaard

Ind i en stjerne



Fysikken af stjerneindre

Hydrostatisk ligevægt:

$$\frac{dp}{dr} = -\frac{Gm\rho}{r^2},$$

Simple skøn:

$$\frac{dp}{dr} \sim -\frac{p_c}{R}, \quad \rho \sim \frac{M}{R^3}$$

Så er

$$\frac{p_c}{R} \sim \frac{GM^2}{R^5}, \quad p_c \sim \frac{GM^2}{R^4} \simeq 10^{10} \left(\frac{M}{M_\odot}\right)^2 \left(\frac{R}{R_\odot}\right)^{-4} \text{ atmosfære}$$

Hvis der ikke er hydrostatisk ligevægt

Tidsskala for frit fald:

$$t = \left(\frac{2\ell}{g} \right)^{1/2}$$

$$\ell \simeq R/2, \quad g = \frac{GM}{R^2}$$

$$t \equiv t_{\text{dyn}} = \left(\frac{R^3}{GM} \right)^{1/2} \propto \bar{\rho}^{-1/2}$$

$$t_{\text{dyn}} \simeq 30 \text{ min} \left(\frac{R}{R_{\odot}} \right)^{3/2} \left(\frac{M}{M_{\odot}} \right)^{-1/2}$$

Skøn over temperaturen

Idealgasloven:

$$p \simeq \frac{k_B \rho T}{\mu m_u}$$

Derfor er

$$T_C \sim \frac{GM\mu m_u}{k_B R} \simeq 1.9 \times 10^7 \left(\frac{M}{M_\odot} \right) \left(\frac{R}{R_\odot} \right)^{-1} \left(\frac{\mu_c}{0.85} \right) \text{ K}$$

Bemærk at den afhænger af μ .

Sammensætningen er karakteriseret af:

- X : massebrøken af brint
- Y : massebrøken af helium
- Z : resten

$$\mu \simeq \frac{4}{3 + 5X - Z}$$

Energitransport ved varmeledning (stråling)

$$F = -K \frac{\Delta T}{\Delta l}$$

Middelfri vejlængde for stråling: $\ell = 1/(\kappa\rho)$

Energistransport ved stråling:

$$F = -\frac{4ac}{3} \frac{T^3}{\kappa\rho} \frac{dT}{dr}$$

Bemærk: κ afhænger af den kemiske sammensætning, især **Z**

Temperaturgradient og lysstyrke

$$L = 4\pi r^2 F = -\frac{16\pi ac r^2 T^3}{3} \frac{dT}{dr} \simeq \frac{16\pi ac}{3} r^2 \frac{\langle T \rangle^4}{R \langle \kappa \rho \rangle}$$

$$\kappa \propto \rho T^{-7/2}, \quad \langle T \rangle \propto M\mu/R, \quad \langle \rho \rangle \simeq M/R^3$$

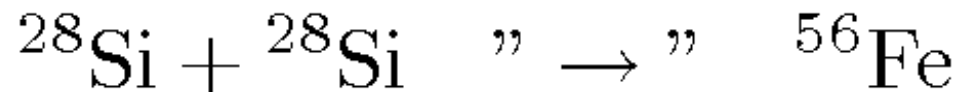
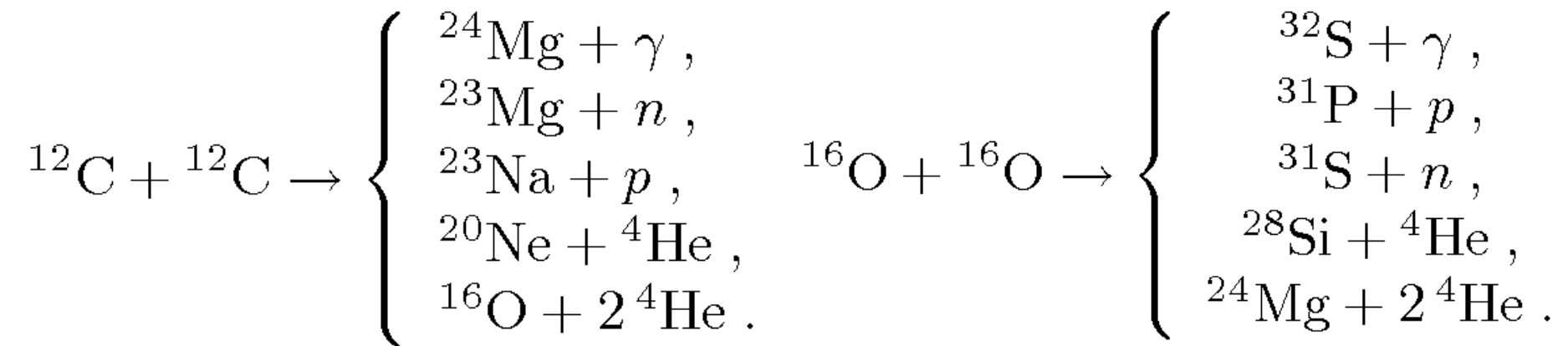
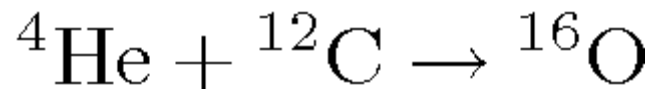
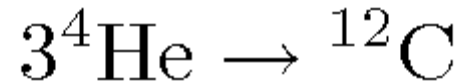
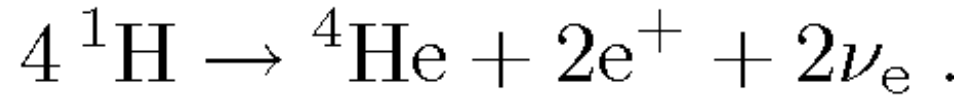
$$L \propto M^{5.5} \mu^{7.5} R^{-0.5}$$

$$\frac{dT}{dr} = -\frac{3}{4ac} \frac{\kappa \rho}{T^3} \frac{L}{4\pi r^2}$$

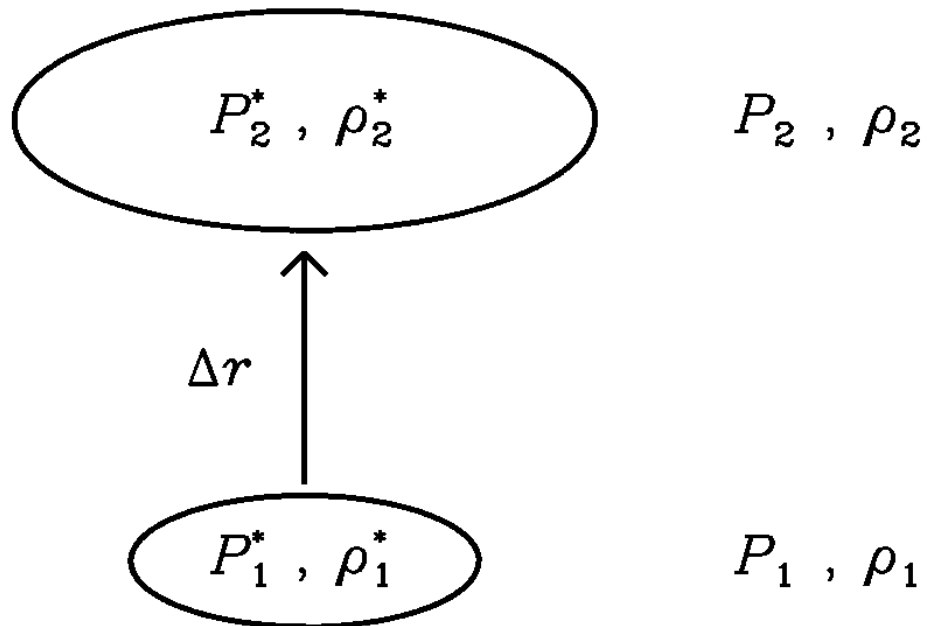
Kernereaktioner i stjerner

- Langsom proces (middellevetiden af en proton i Solens centrum er 5 milliarder år)
- Kræver overvindelse af Coulomb-frastødningen mellem kernerne
- Kerner med lav ladning reagerer først

Kernereaktionen



Konvektiv ustabilitet

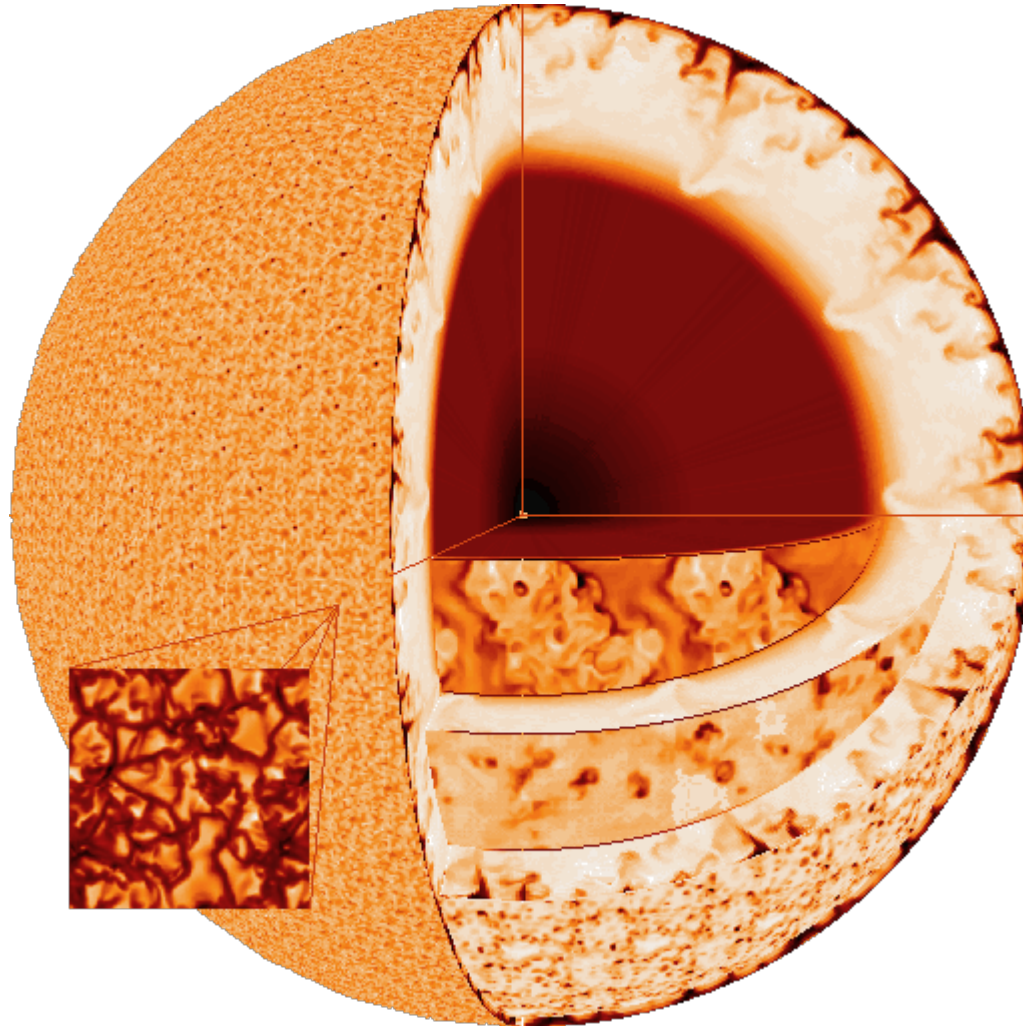


Ifølge Archimedes er der ustabilitet hvis $\rho_2^* < \rho_2$

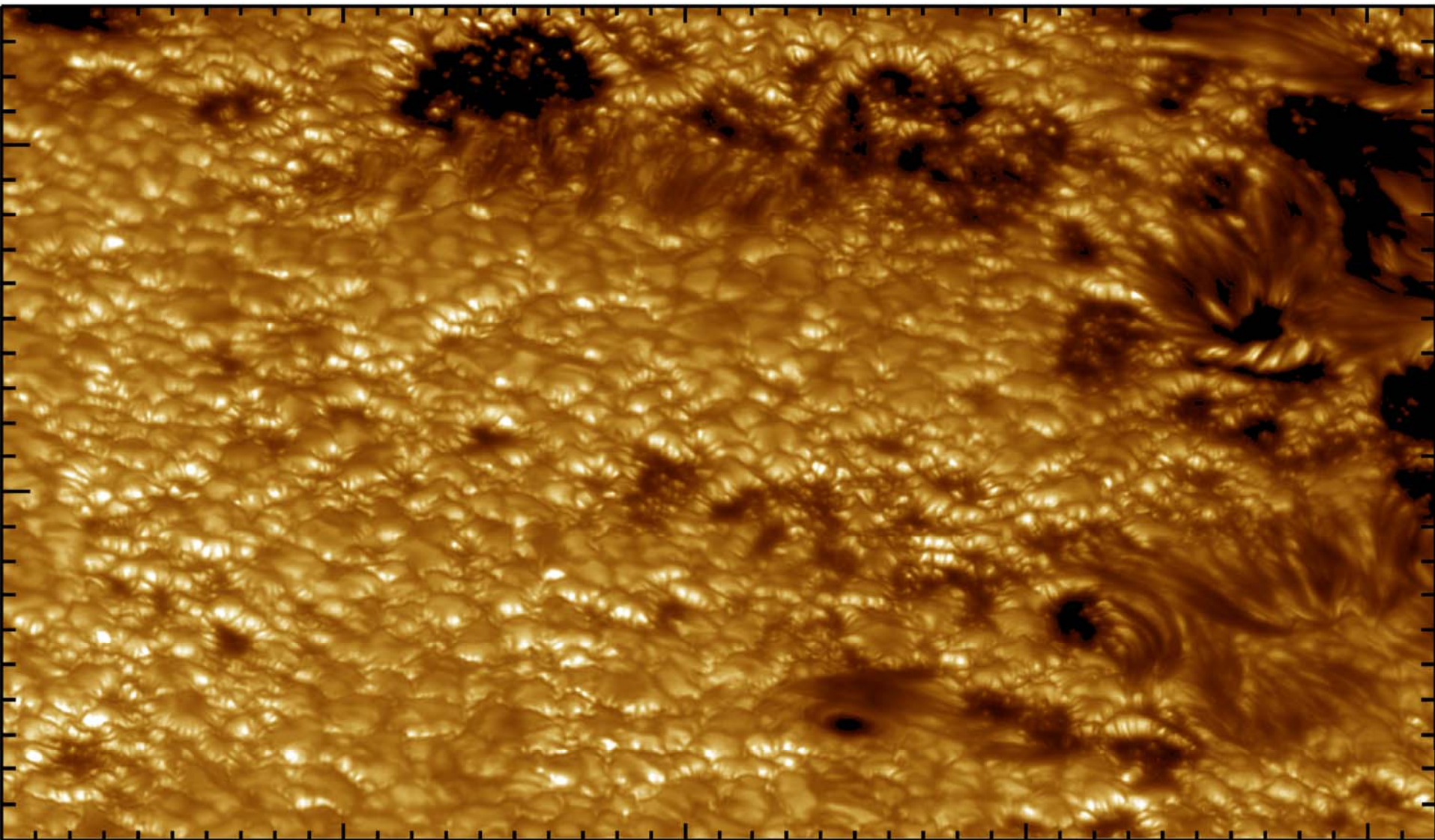
ρ_2^* følger P_2^*

Så ρ_2 må ikke aftage for langsomt

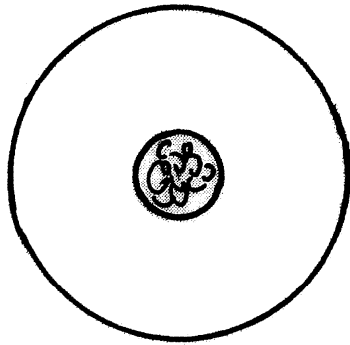
Konvektion



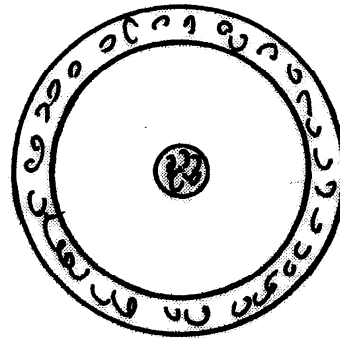
Konvektion nær solranden



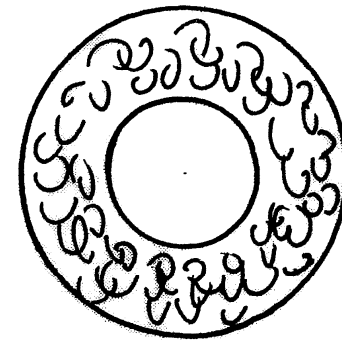
Konvektive områder i stjerner



$$M > 2 M_{\odot}$$

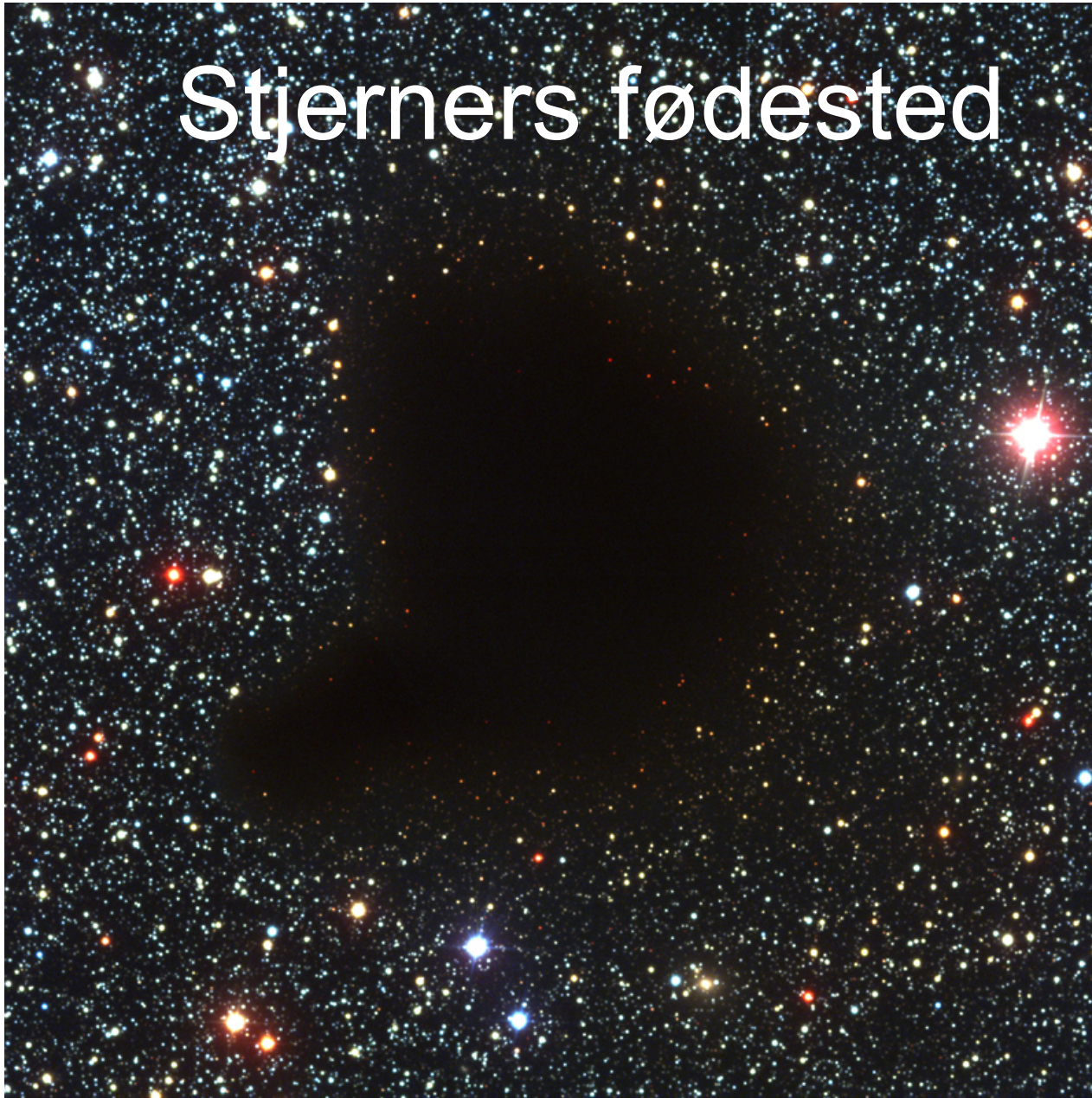


$$2 M_{\odot} > M > 1.2 M_{\odot}$$



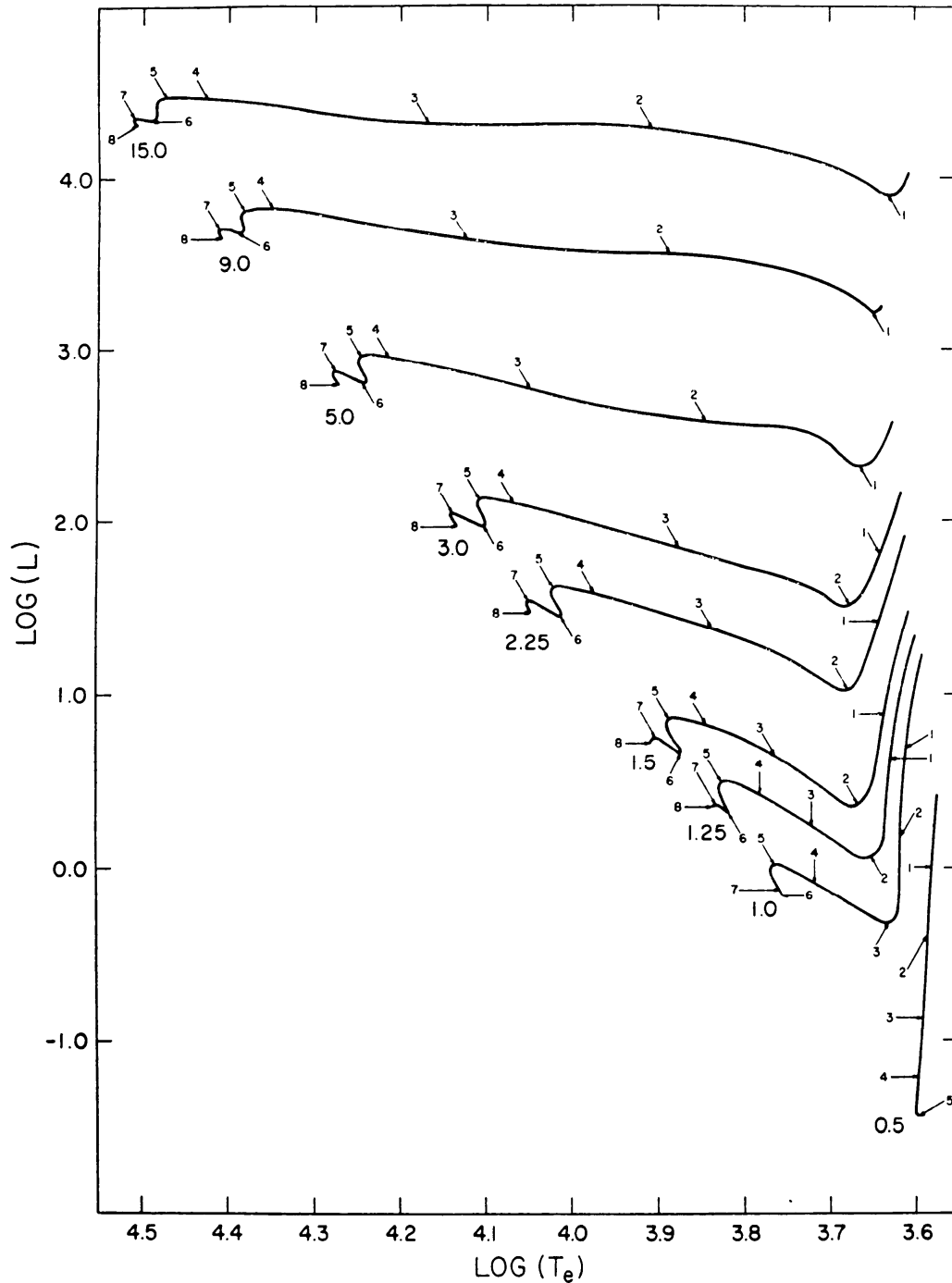
$$1.2 M_{\odot} > M$$

Stjernerens fødested



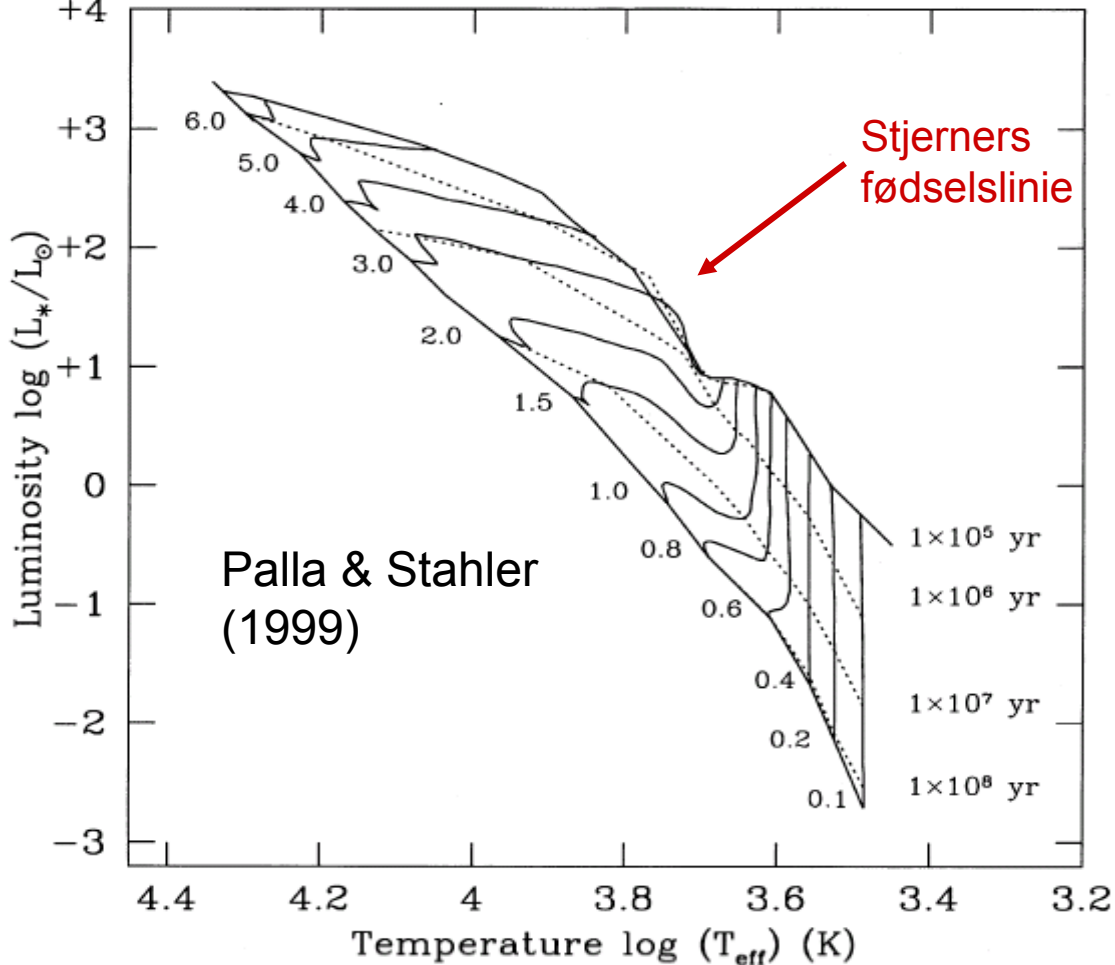
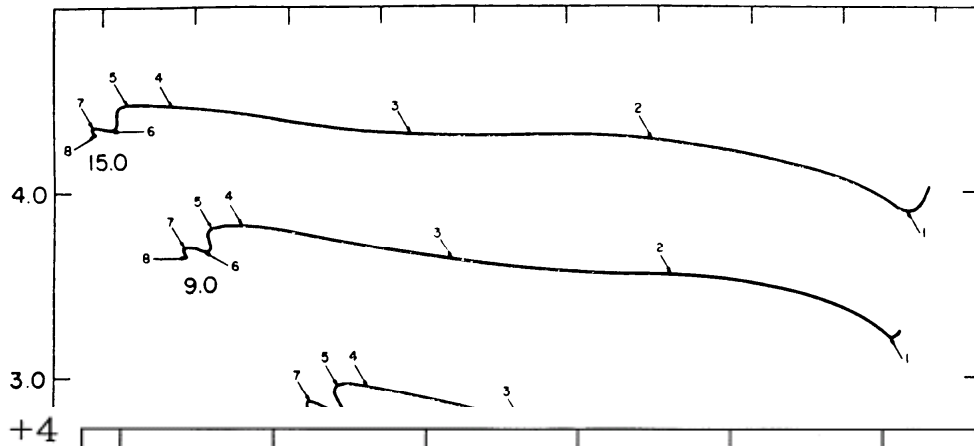
The "Black Cloud" B68
(VLT ANTU + FORS1)

Stjerner generelle udvikling



Udvikling før hovedserien
(Iben 1965)

Stjerner generelle udvikling

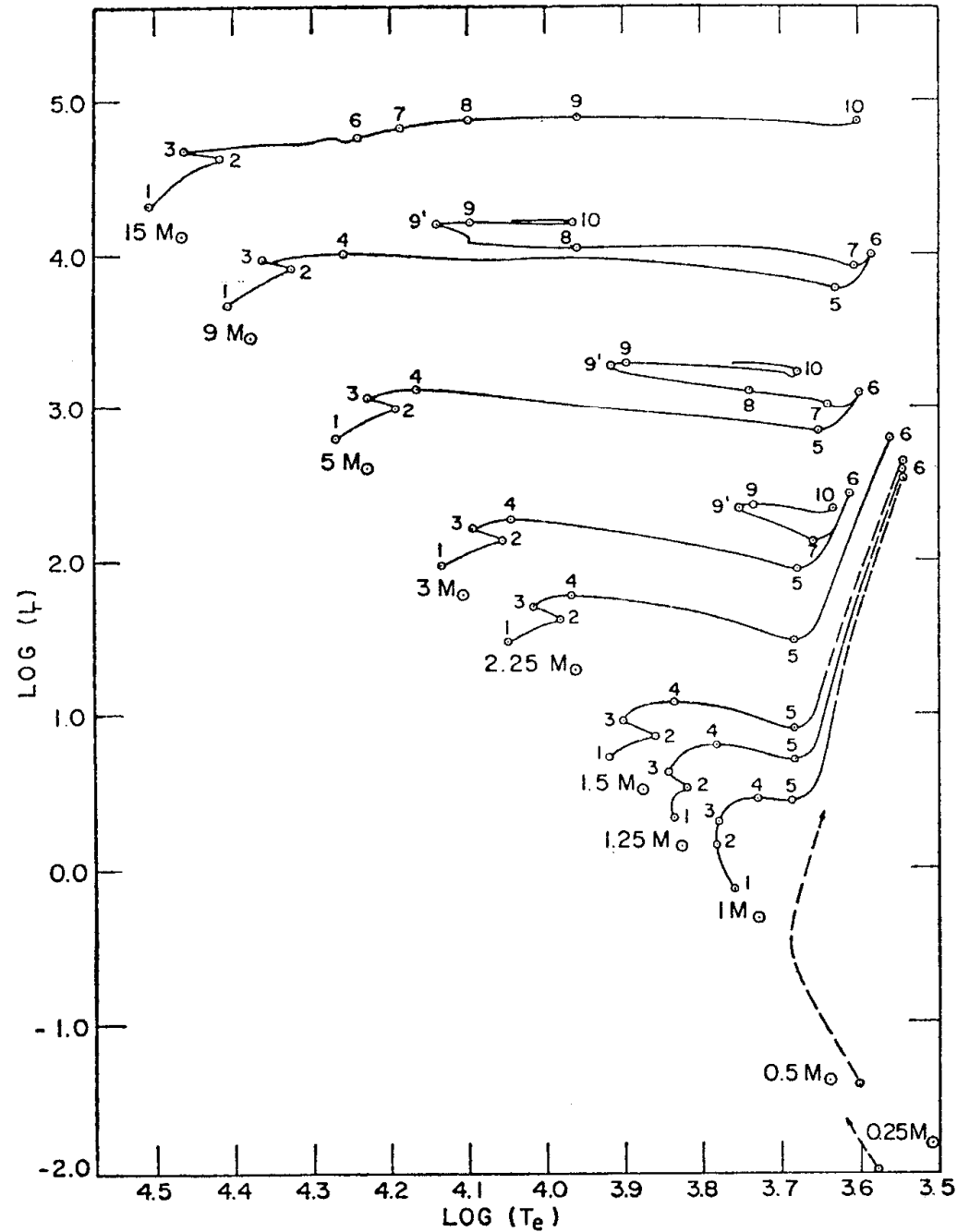


Udvikling før hovedserien
(Iben 1965)

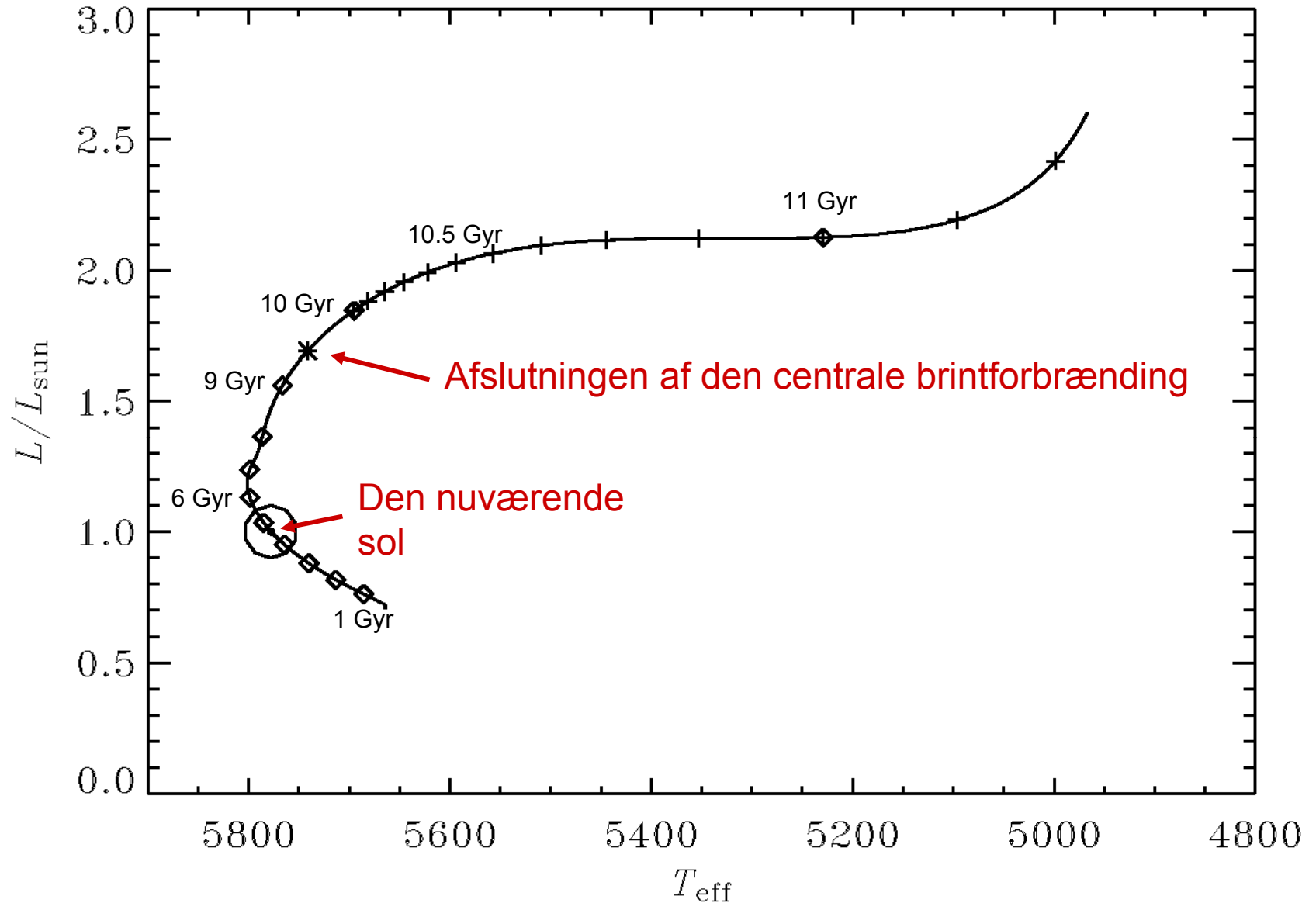
Stjernerne generelle udvikling

Hovedserien og hvad der følger

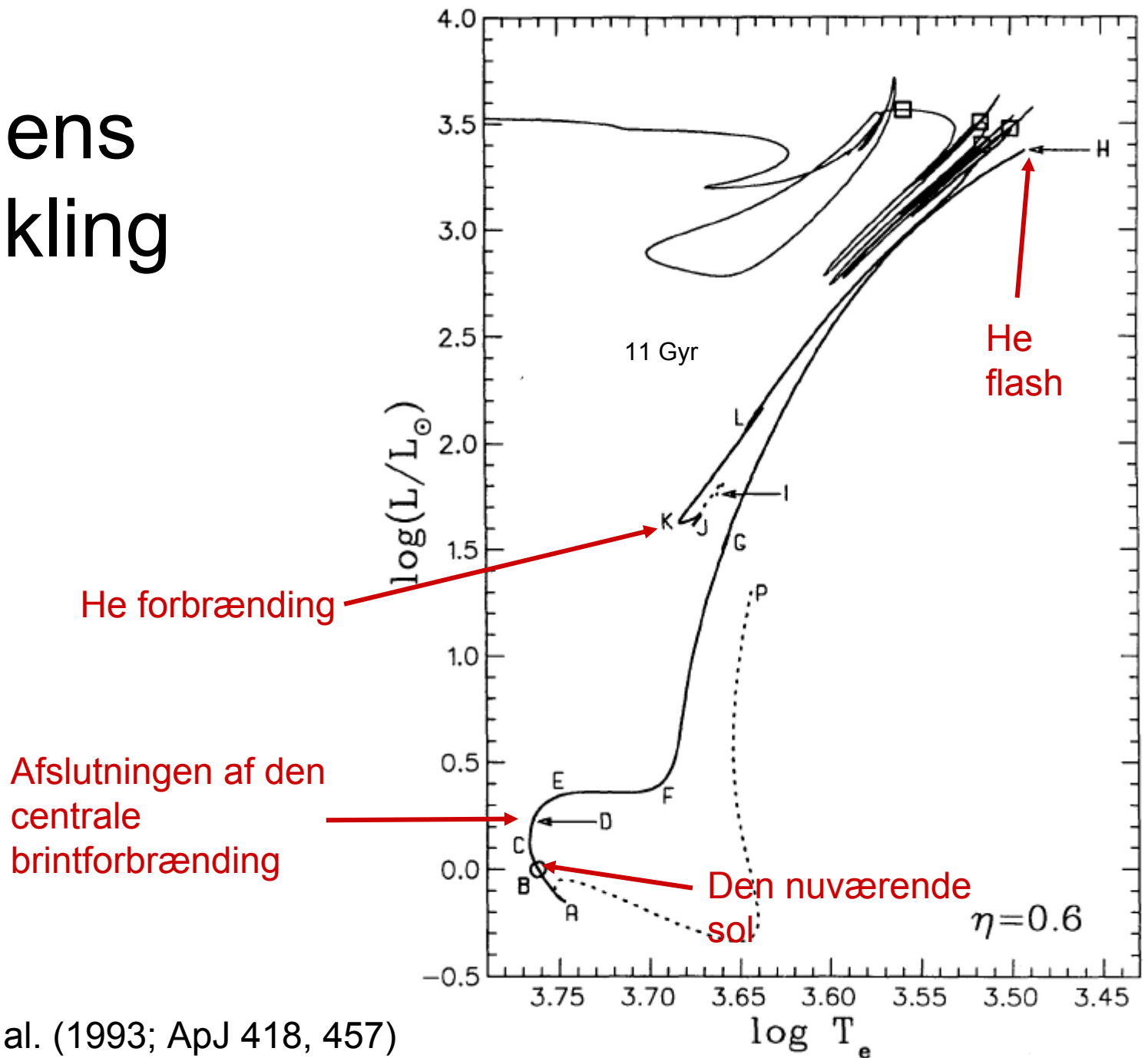
(Iben 1967)



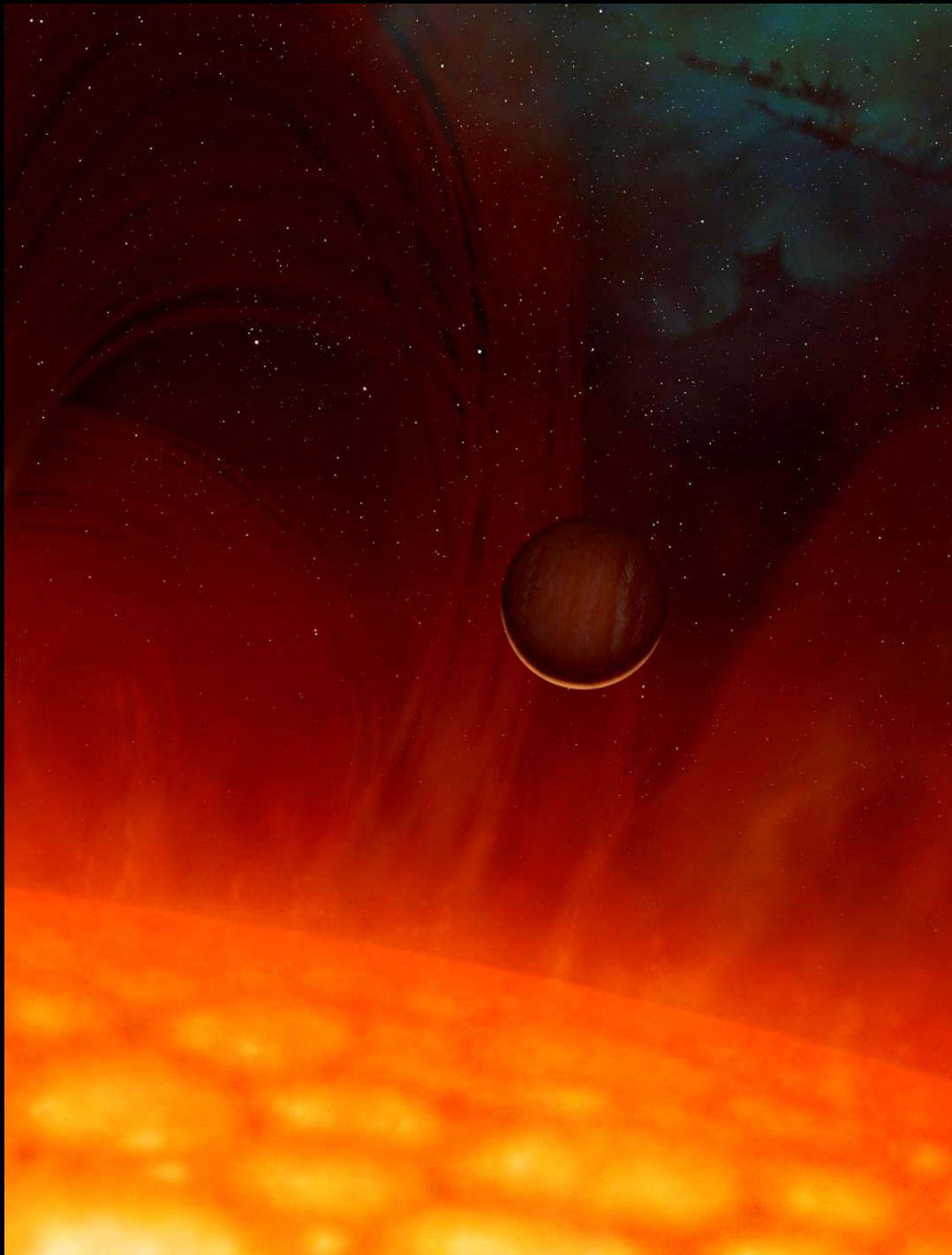
Solens udvikling



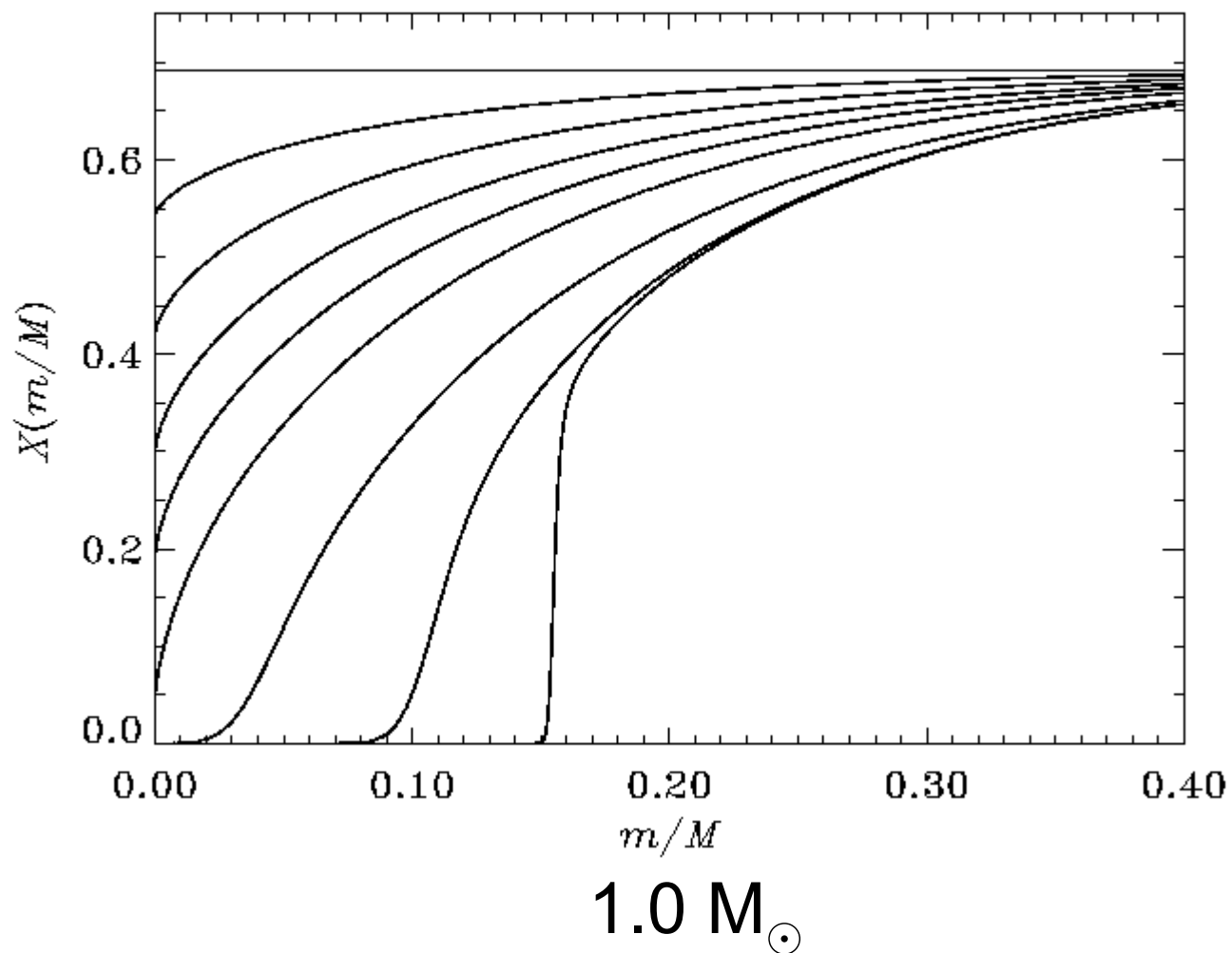
Solens udvikling



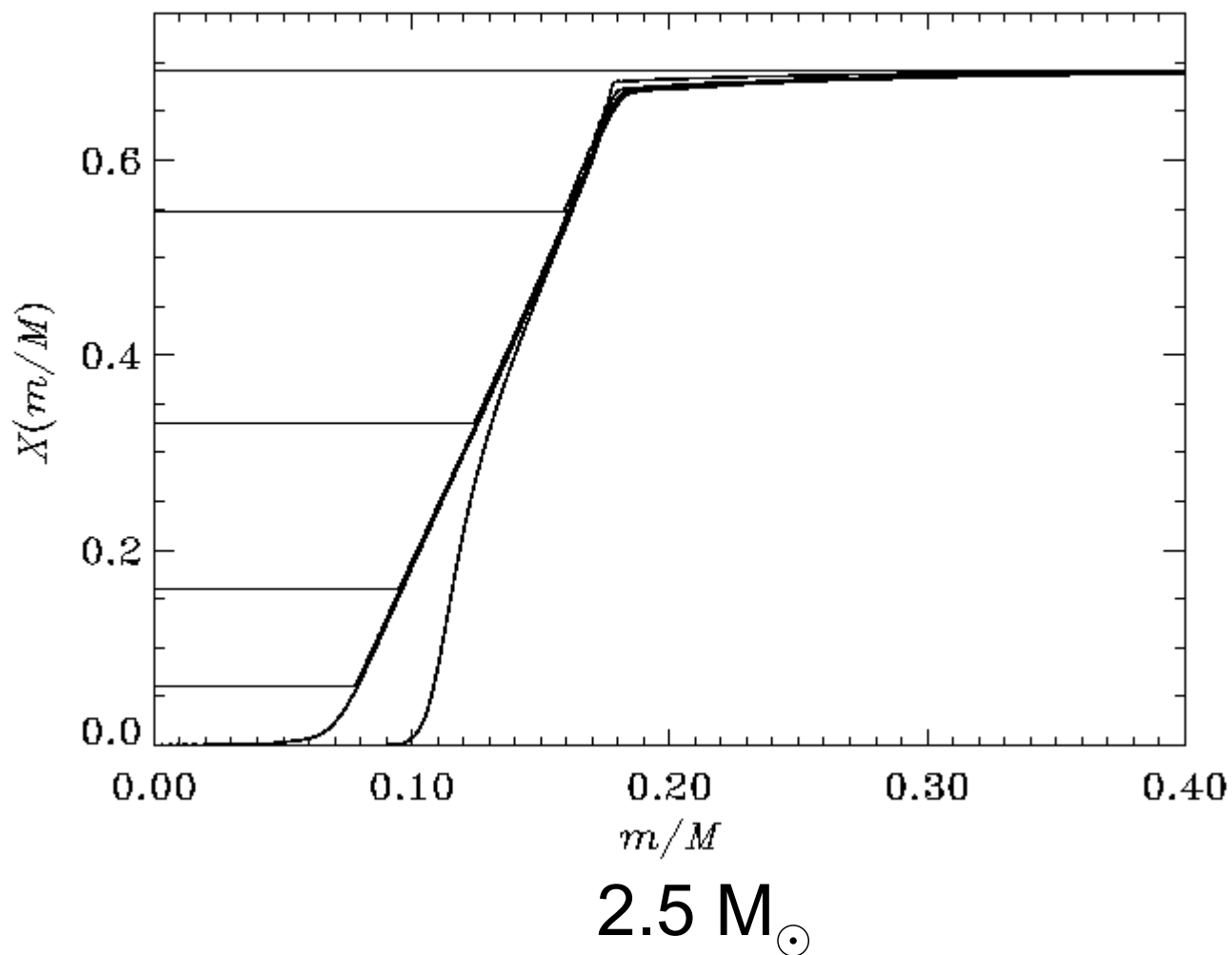
Solsystemet
om 7
milliarder år?



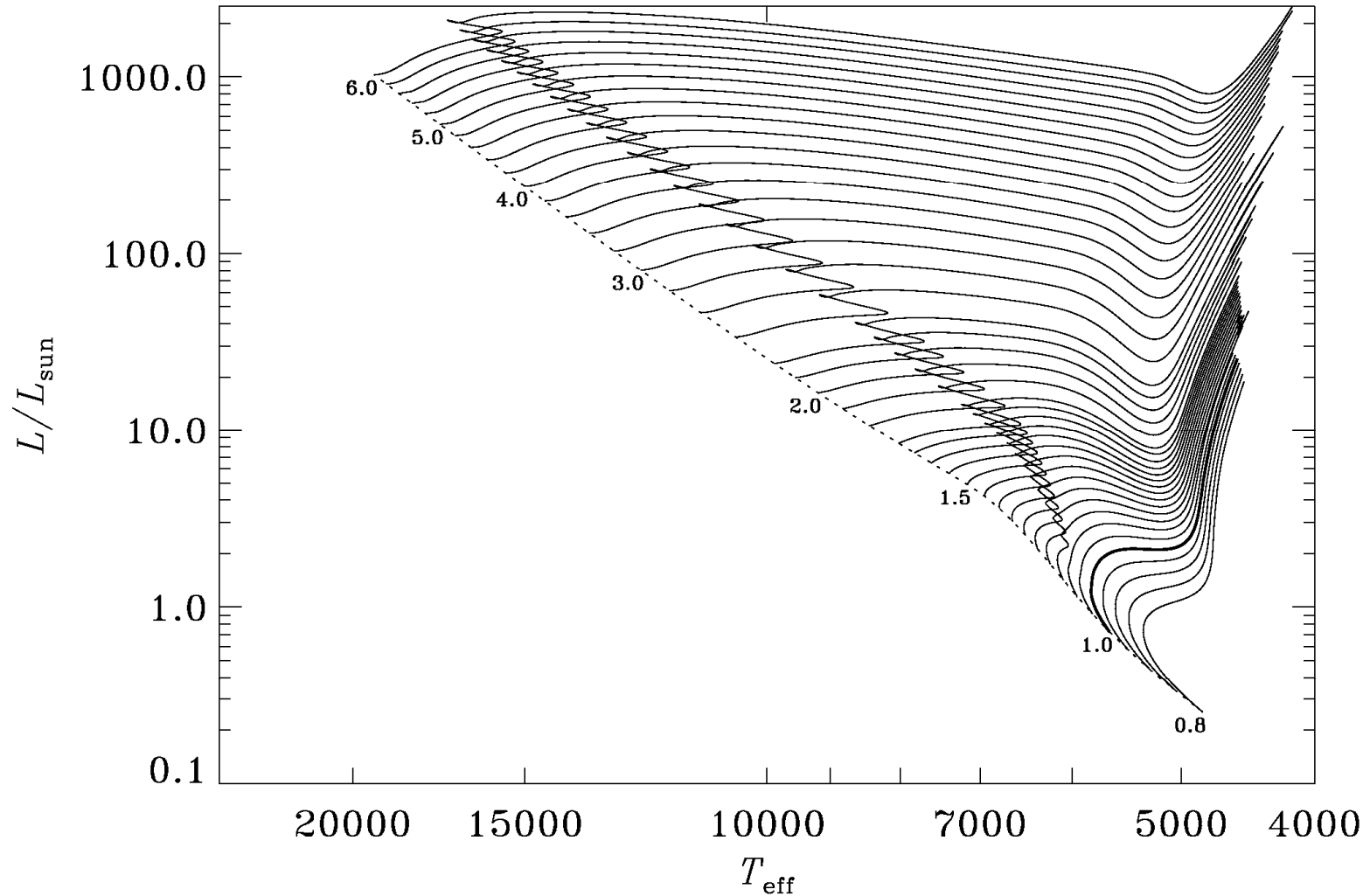
Ændringer i grundstofsammensætningen



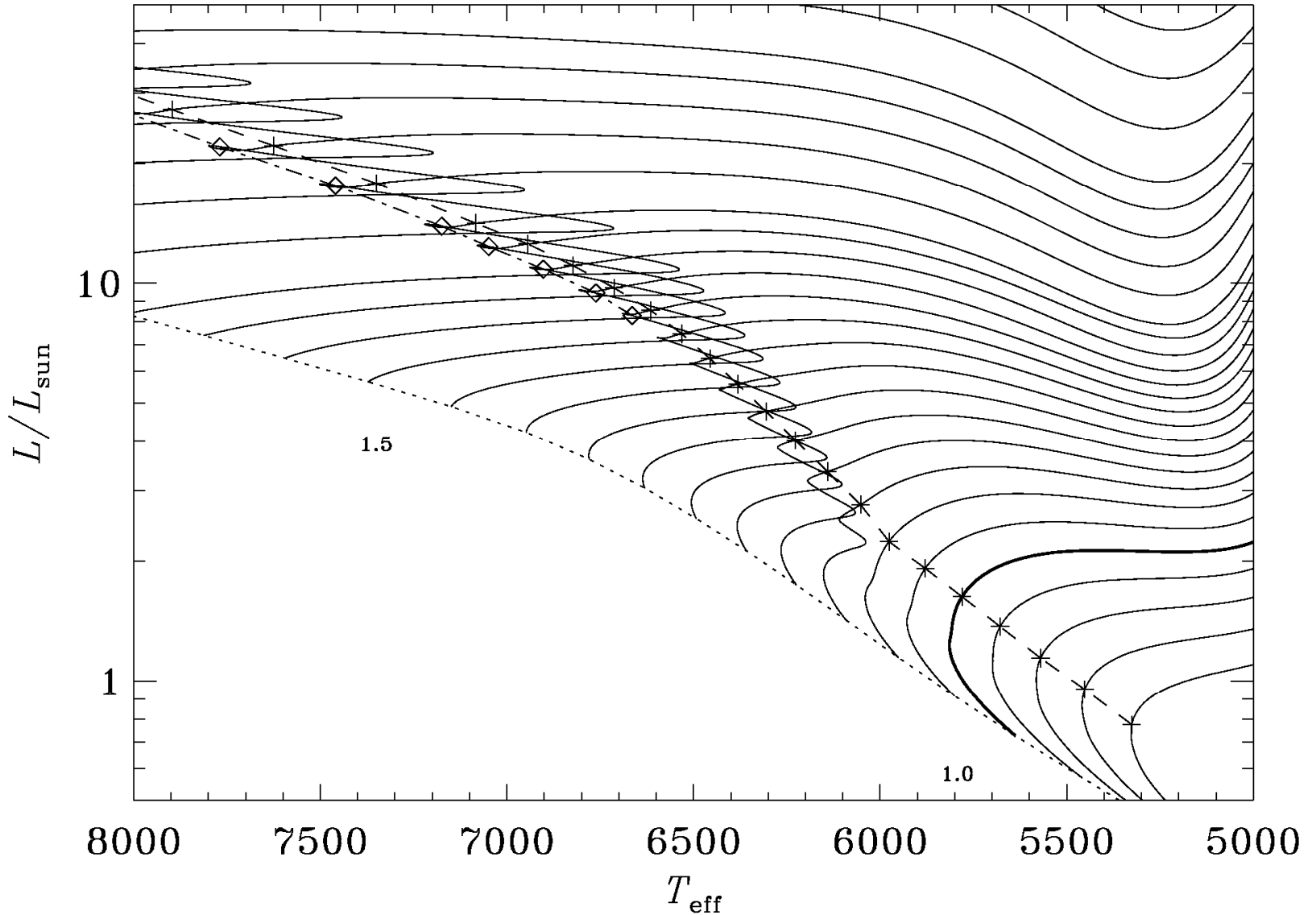
Ændringer i grundstofsammensætningen



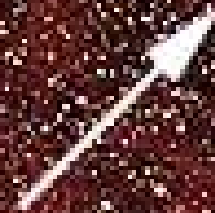
Effekten af konvektive kerner



Effekten af konvektive kerner

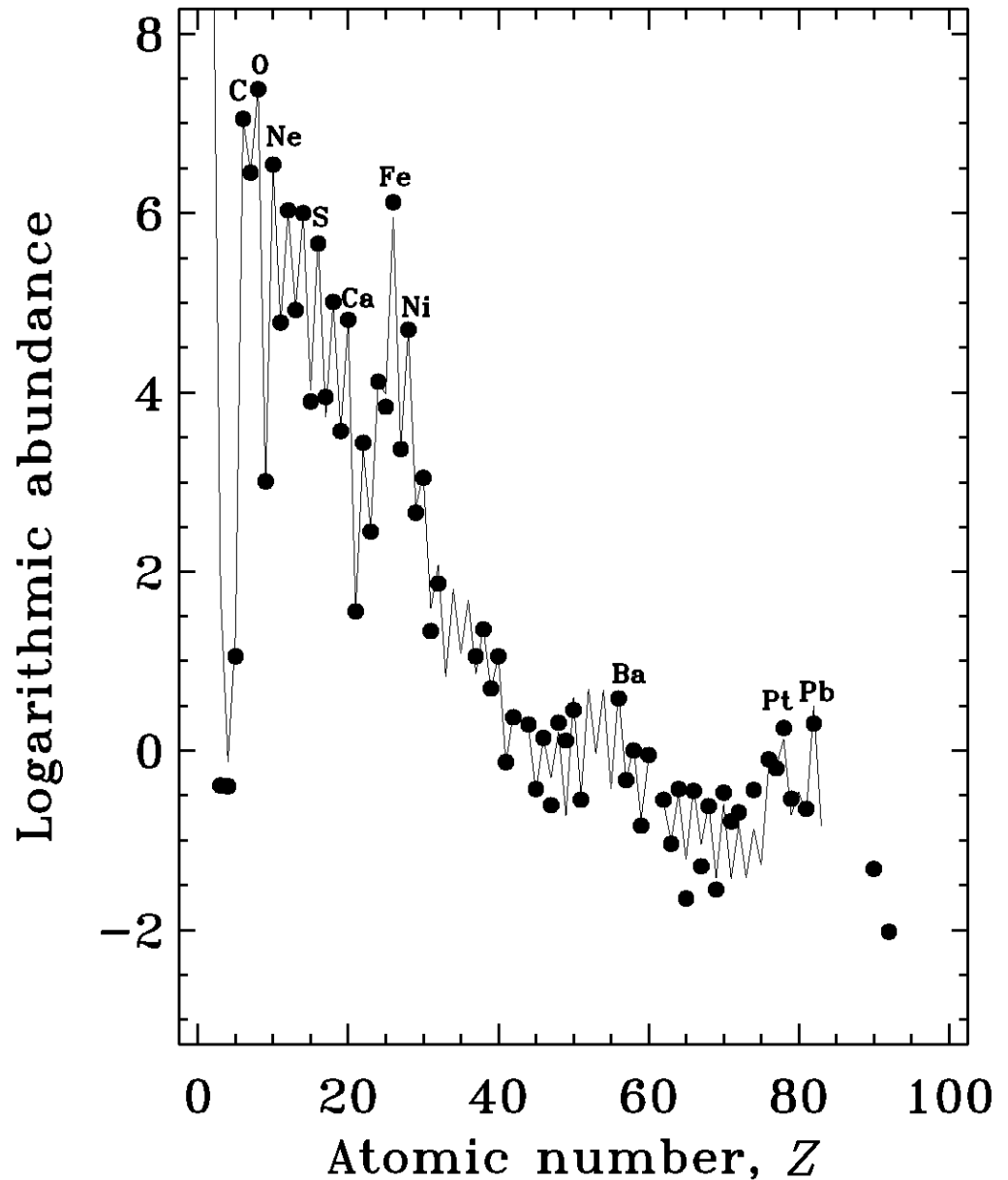


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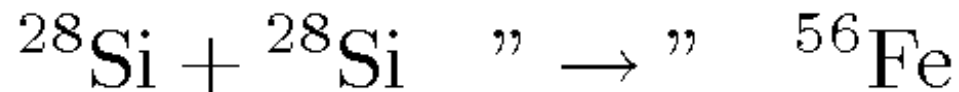
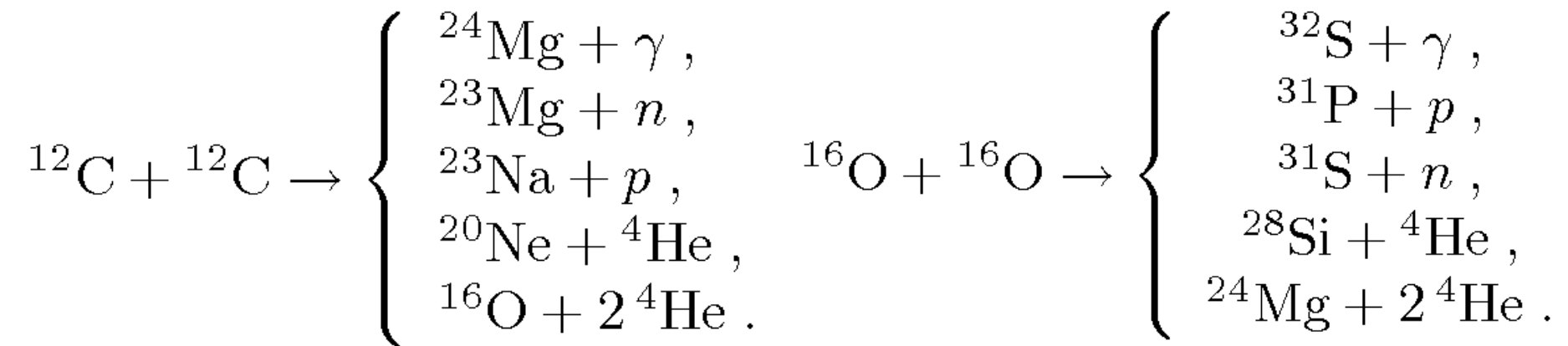
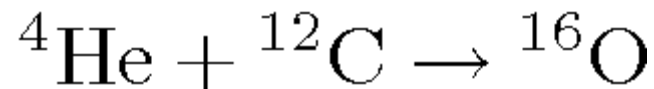
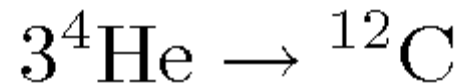
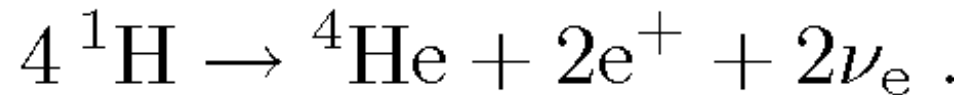


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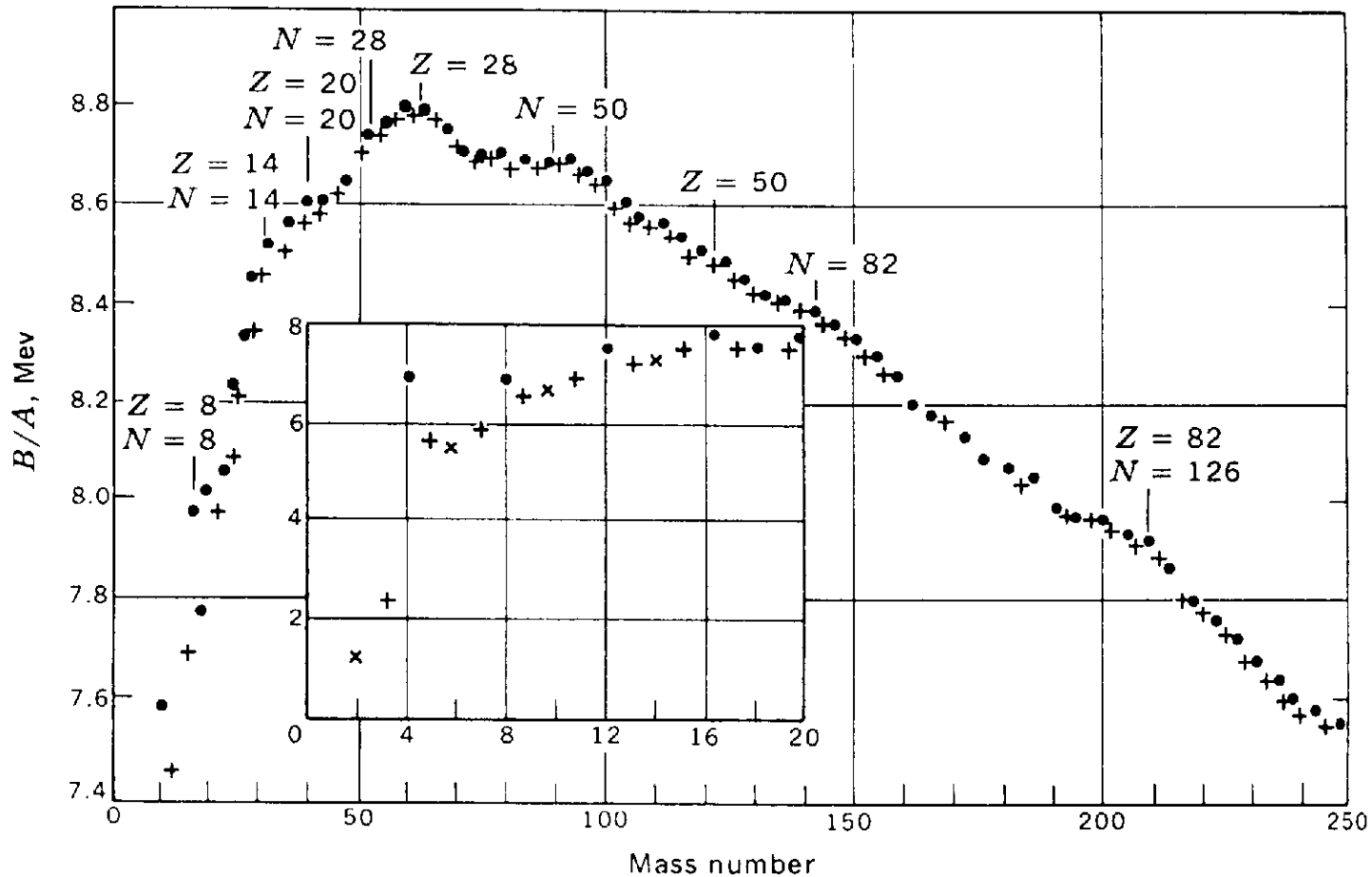
Solsystemets grundstof- sammensætning



Kernereaktionen



Kernebindungsenergi



Degenereret stof (I)

- Ekstremt høj massefylde
- Pauli-princippet presser partikler (elektroner eller neutroner) op i højere kvantetilstande, højere energier og dermed større bidrag til trykket.
- Endeligt tryk ved forsvindende lille temperatur
- For rigtig høj massefylde bliver partiklerne ekstremt relativistiske

Degenereret stof (II)

Ikke-relativistisk degeneration:

$$P = K\rho^{5/3}$$

$$\begin{aligned}\frac{dP}{dr} &\simeq \frac{P}{R} \simeq \frac{GM\rho}{r^2} \simeq \frac{GM^2}{R^5} \\ &= K \frac{M^{5/3}}{R^6}\end{aligned}$$

dvs

$$R \simeq \frac{K}{G} M^{-1/3}$$

$$M \simeq 1 M_{\odot}$$

Elektroner: $R \simeq 10^4$ km

Neutroner: $R \simeq 10$ km

Degenereret stof (III)

Ekstremt relativistisk degeneration:

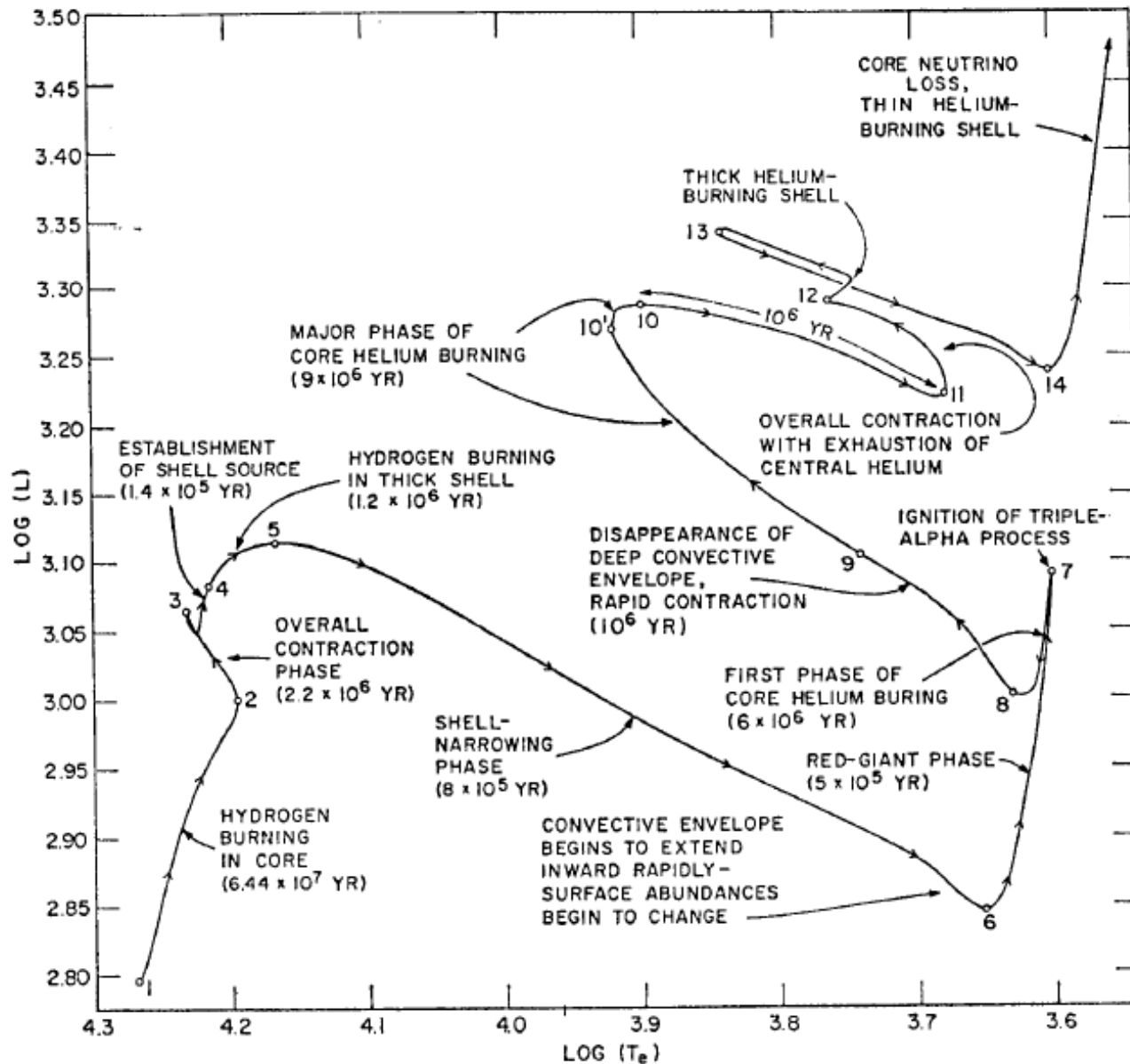
$$P = C\rho^{4/3}$$

$$\begin{aligned}\frac{dP}{dr} &\simeq \frac{P}{R} \simeq \frac{GM\rho}{r^2} \simeq \frac{GM^2}{R^5} \\ &= C\frac{M^{4/3}}{R^5}\end{aligned}$$

dvs

$$M \simeq \left(\frac{C}{G}\right)^{3/2} = M_{\text{Ch}} \simeq 1.5M_{\odot}$$

Forholdene i centrum



Nuclear burning stages

(e.g., 20 solar mass star)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4 \text{ H} \xrightarrow{\text{CNO}} \text{}^4\text{He}$

Nuclear burning stages

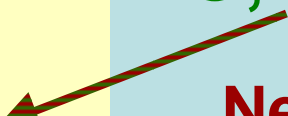
(e.g., 20 solar mass star)

Fuel	Main Product	Secondary Product	T (10^9 K)	Time (yr)	Main Reaction
H	He	^{14}N	0.02	10^7	$4 \text{ H} \xrightarrow{\text{CNO}} \text{}^4\text{He}$
He	O, C	^{18}O , ^{22}Ne s-process	0.2	10^6	$3 \text{ He}^4 \rightarrow \text{}^{12}\text{C}$ $^{12}\text{C}(\alpha, \gamma) \text{}^{16}\text{O}$

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C	Ne, Mg	Na	0.8	10^3	$\text{}^{12}\text{C} + \text{}^{12}\text{C}$



Nuclear burning stages

(e.g., 20 solar mass star)

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C	Ne, Mg	Na	0.8	10^3	$\text{}^{12}\text{C} + \text{}^{12}\text{C}$
Ne	O, Mg	Al, P	1.5	3	$\text{}^{20}\text{Ne}(\gamma, \alpha)\text{}^{16}\text{O}$ $\text{}^{20}\text{Ne}(\alpha, \gamma)\text{}^{24}\text{Mg}$

Nuclear burning stages

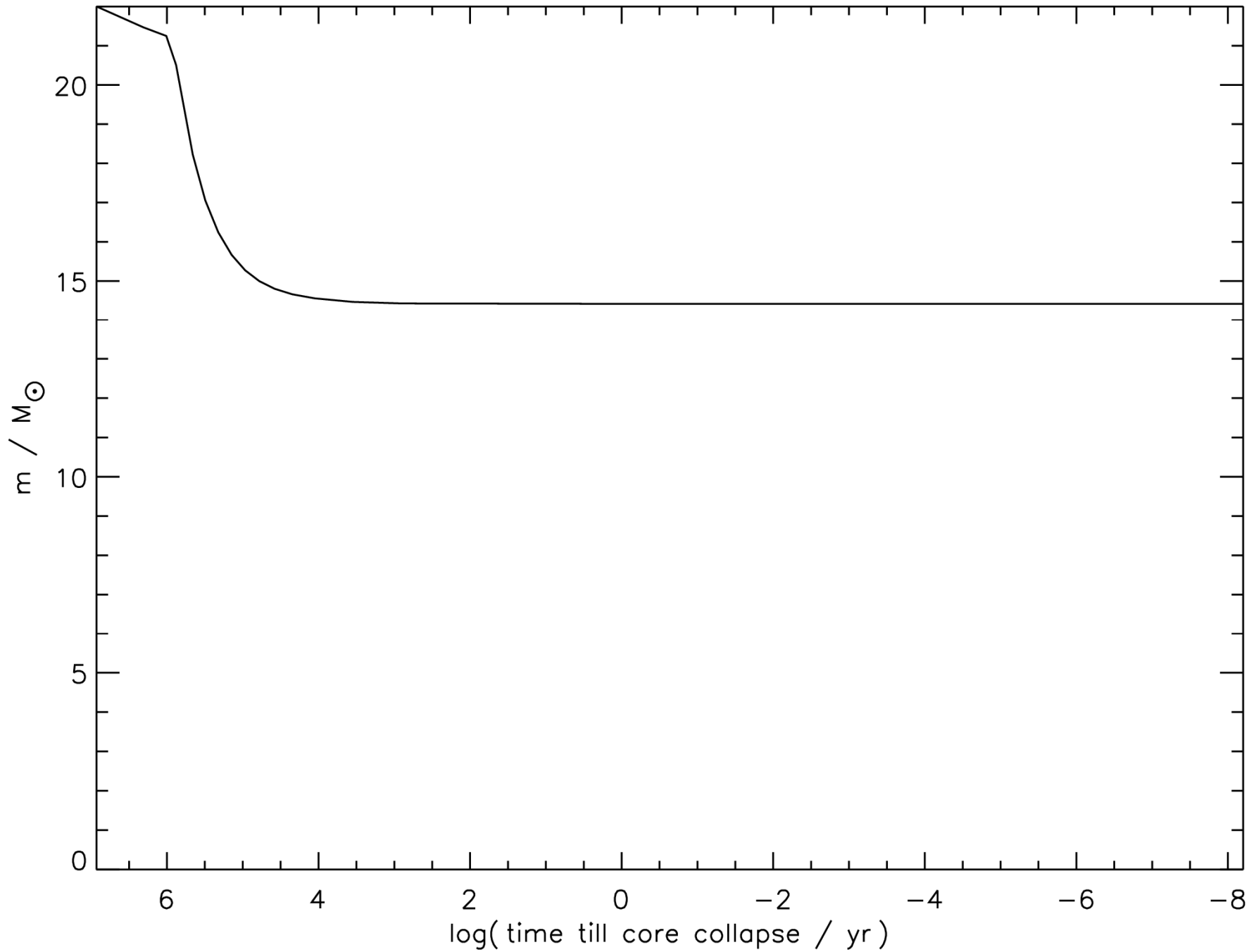
(e.g., 20 solar mass star)

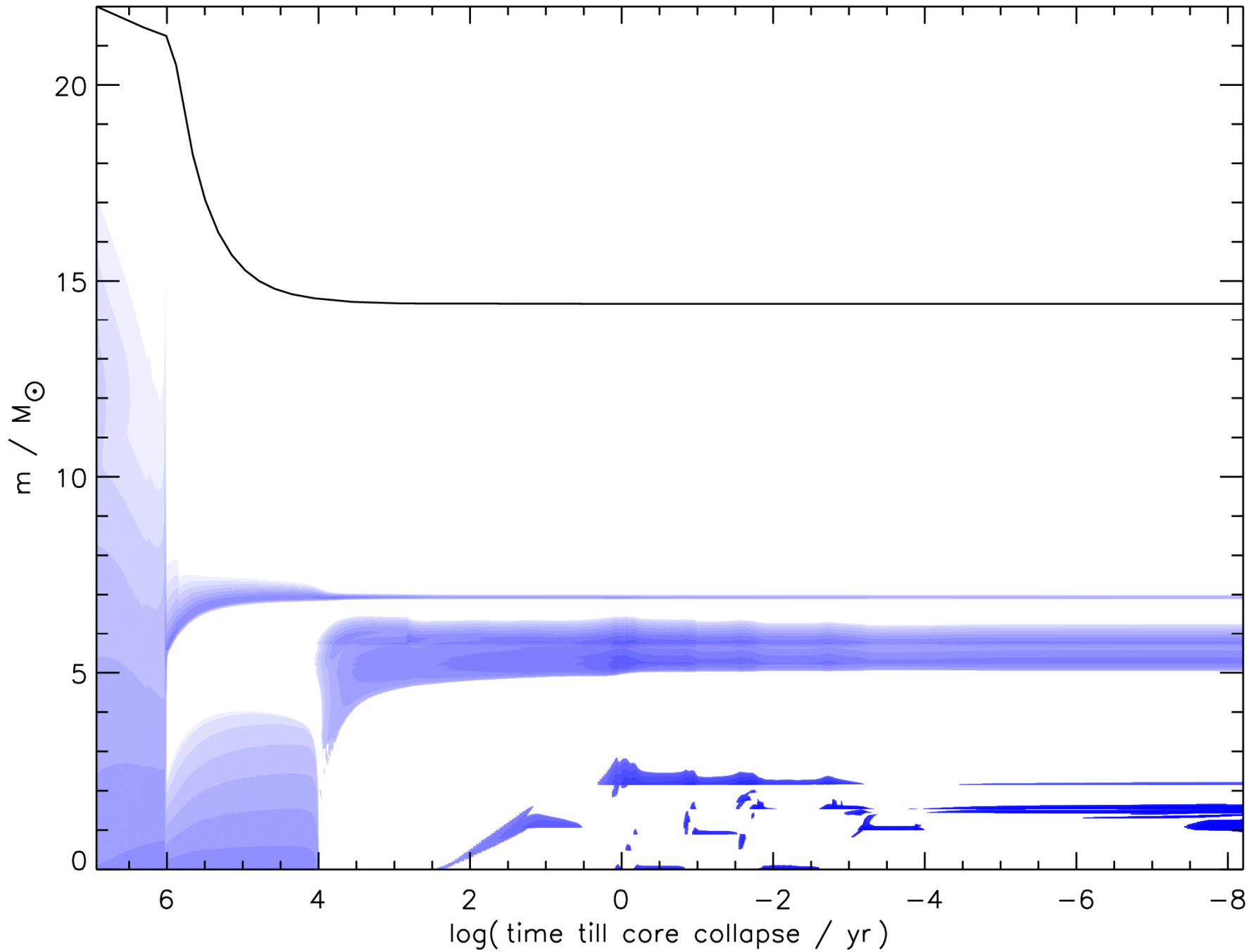
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O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$^{16}\text{O} + ^{16}\text{O}$

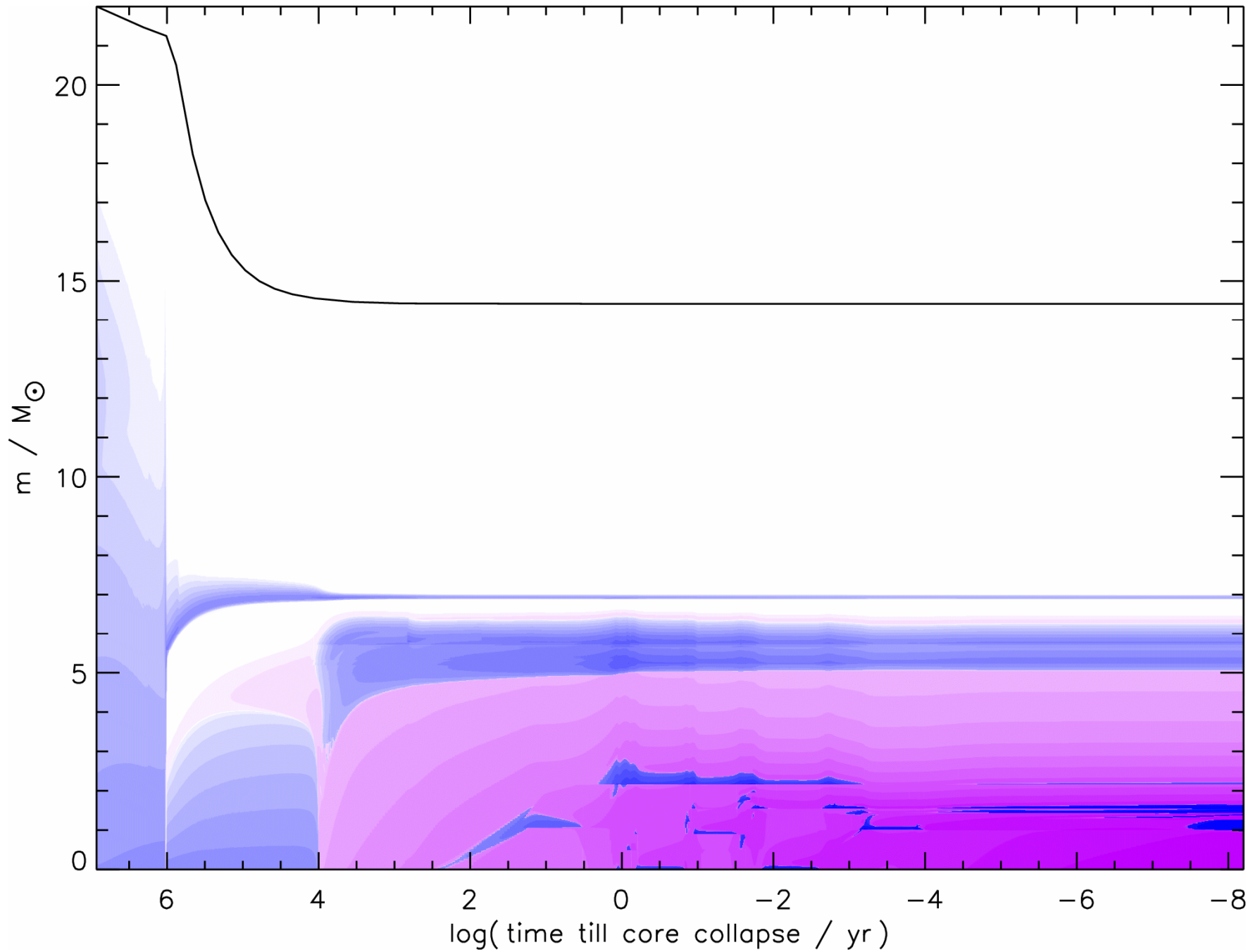
Nuclear burning stages

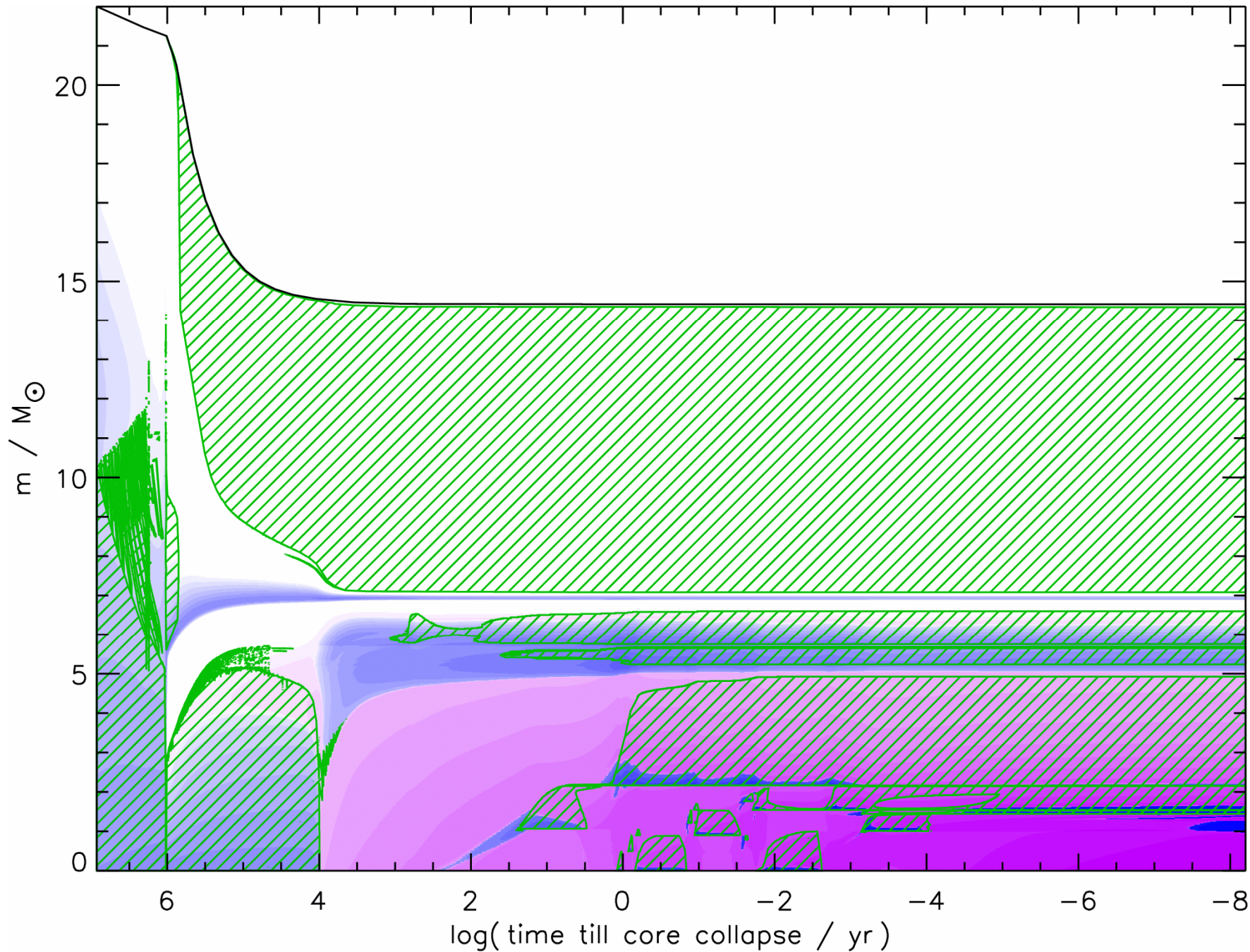
(e.g., 20 solar mass star)

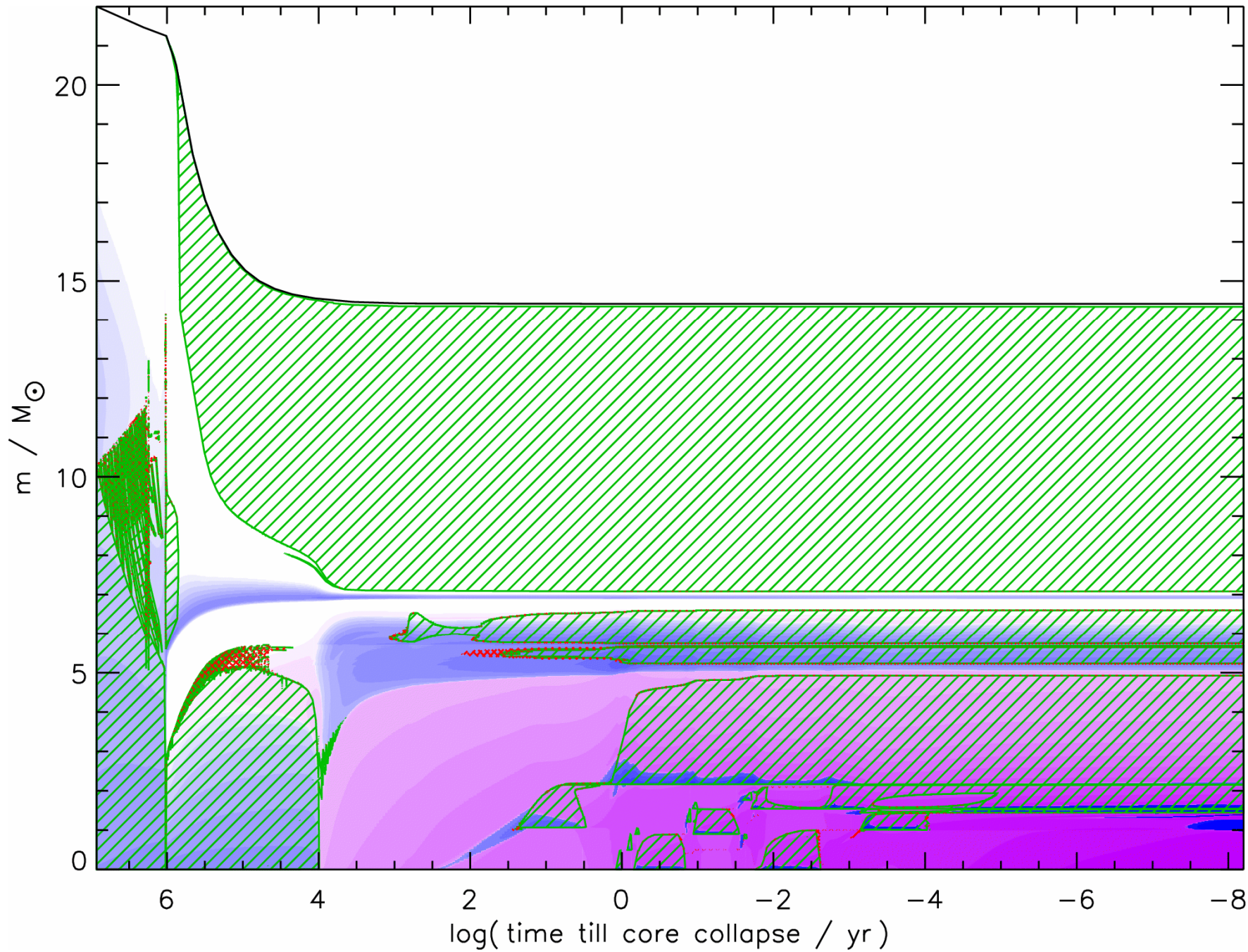
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O	Si, S	Cl, Ar, K, Ca	2.0	0.8	$\text{}^{16}\text{O} + \text{}^{16}\text{O}$
Si	Fe	Ti, V, Cr, Mn, Co, Ni	3.5	0.02	$\text{}^{28}\text{Si}(\gamma, \alpha)\dots$

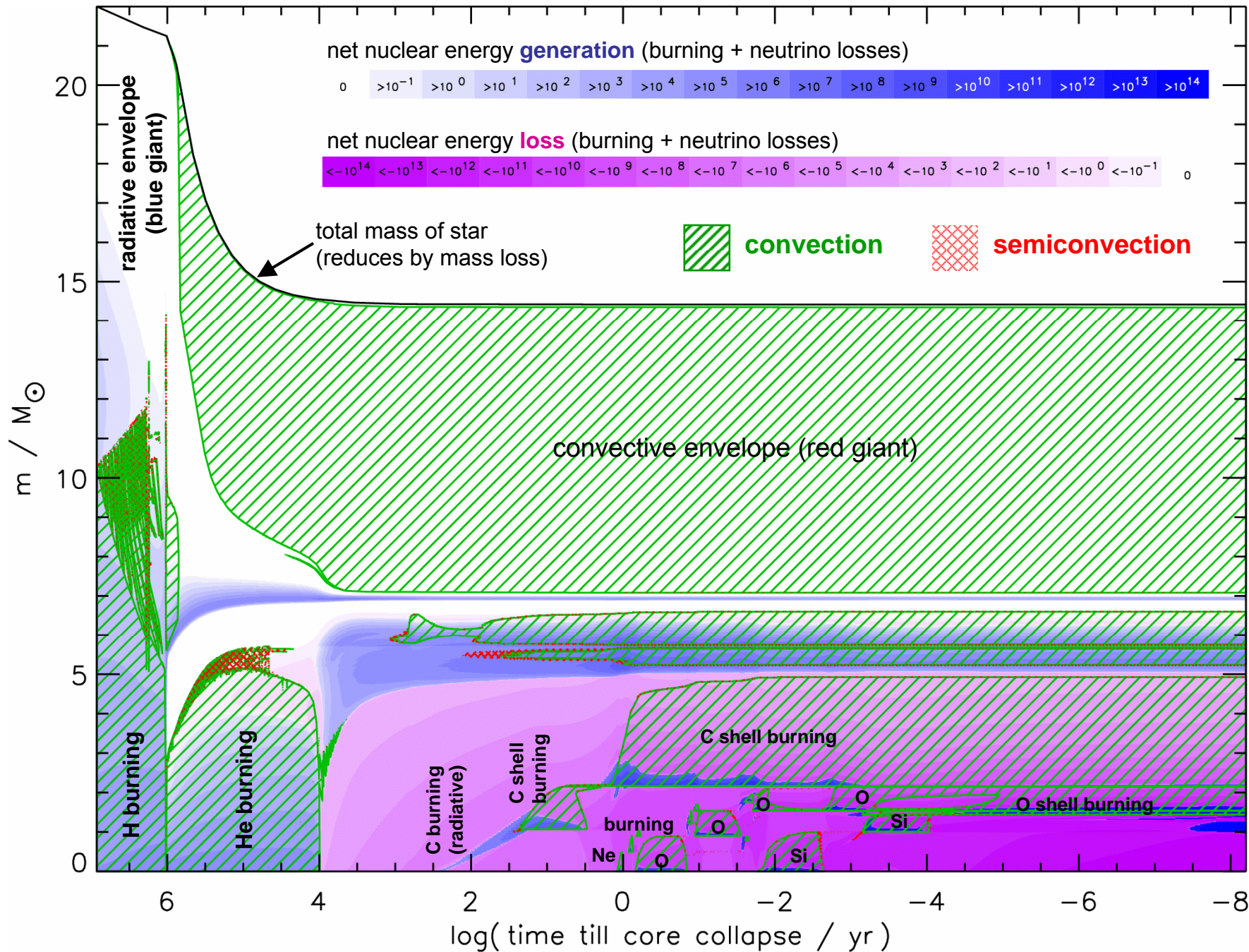




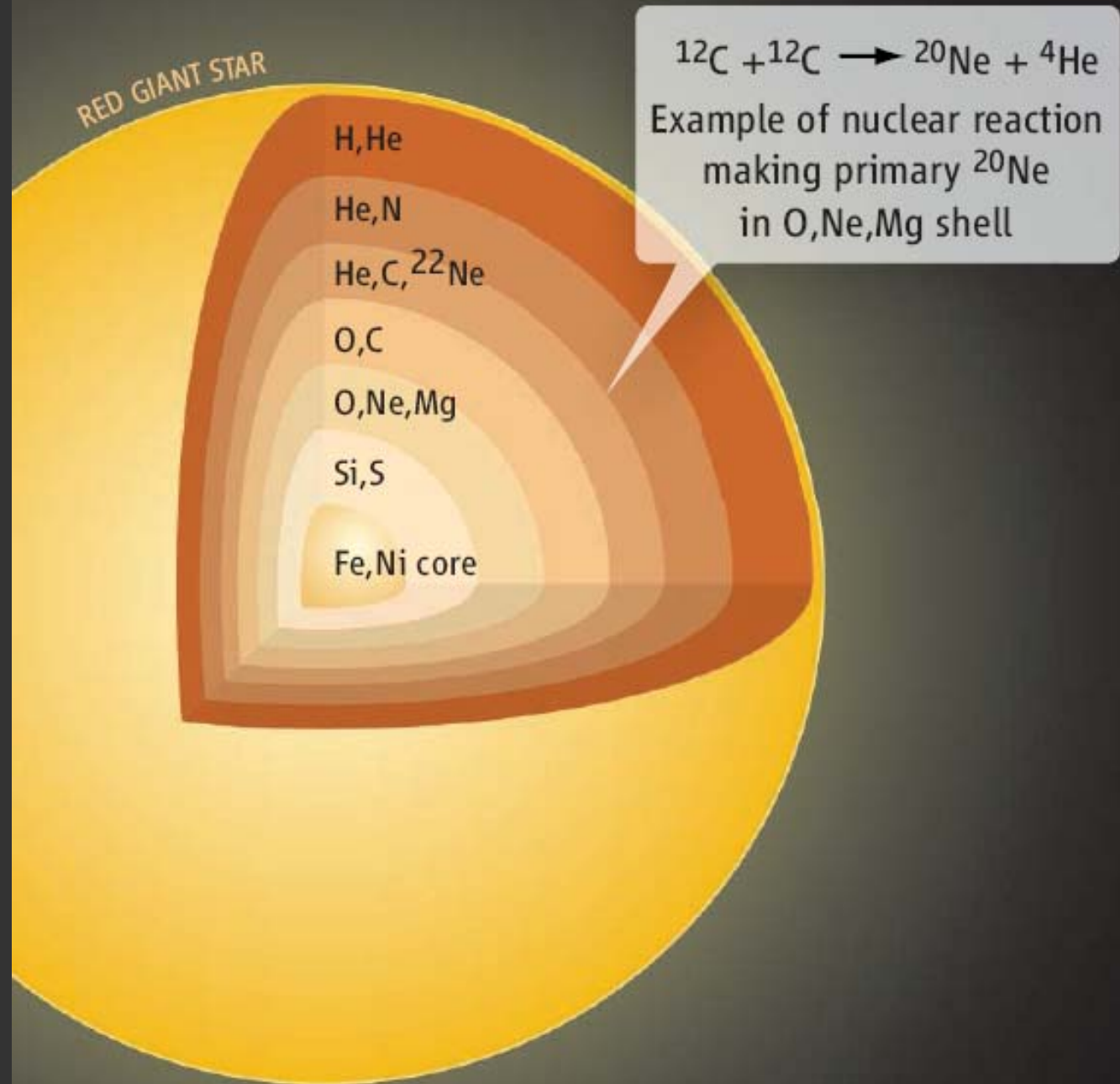




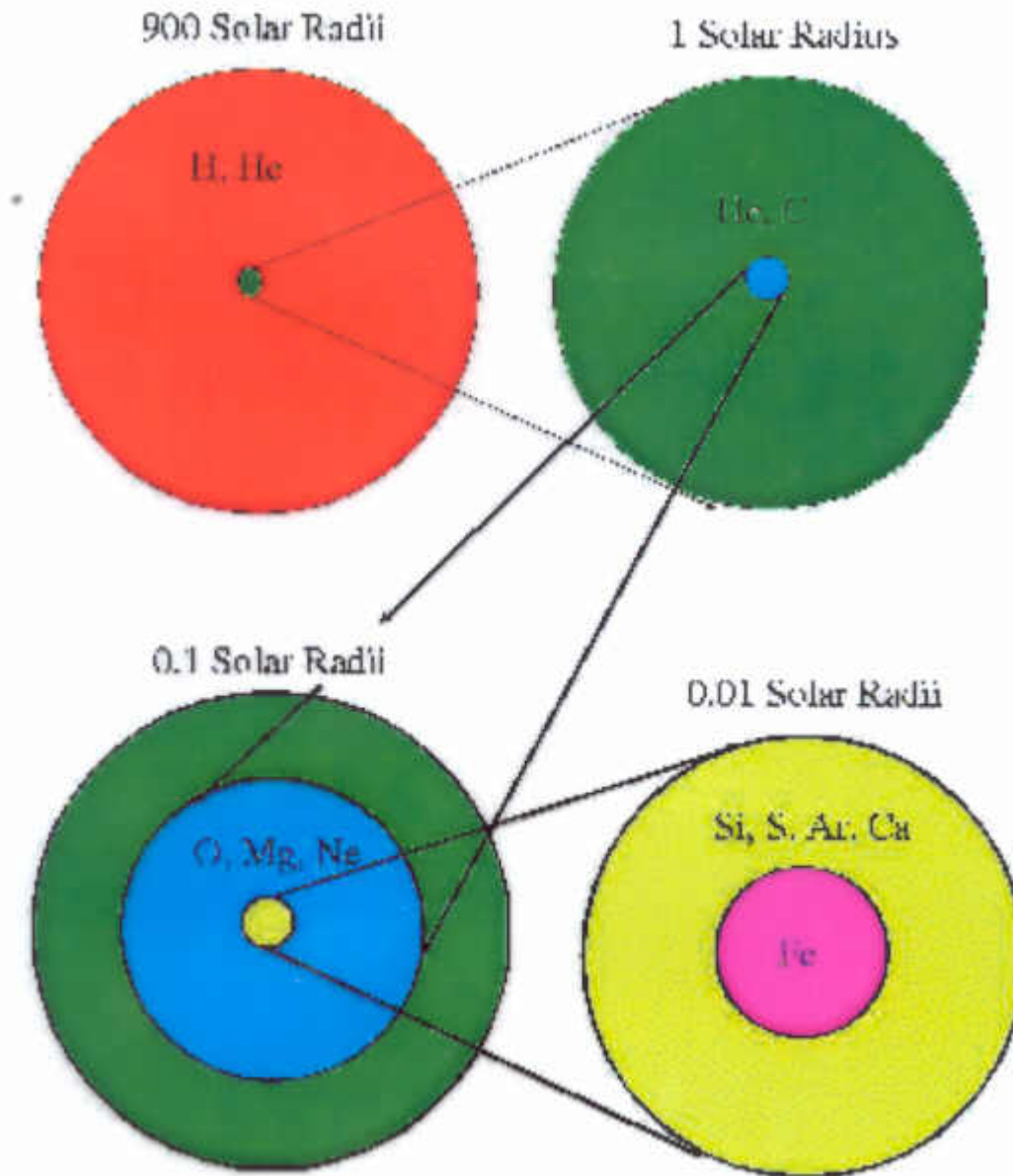




Det stellare løg



25 Solar Mass PreSupernova Star



KOLLAPS!

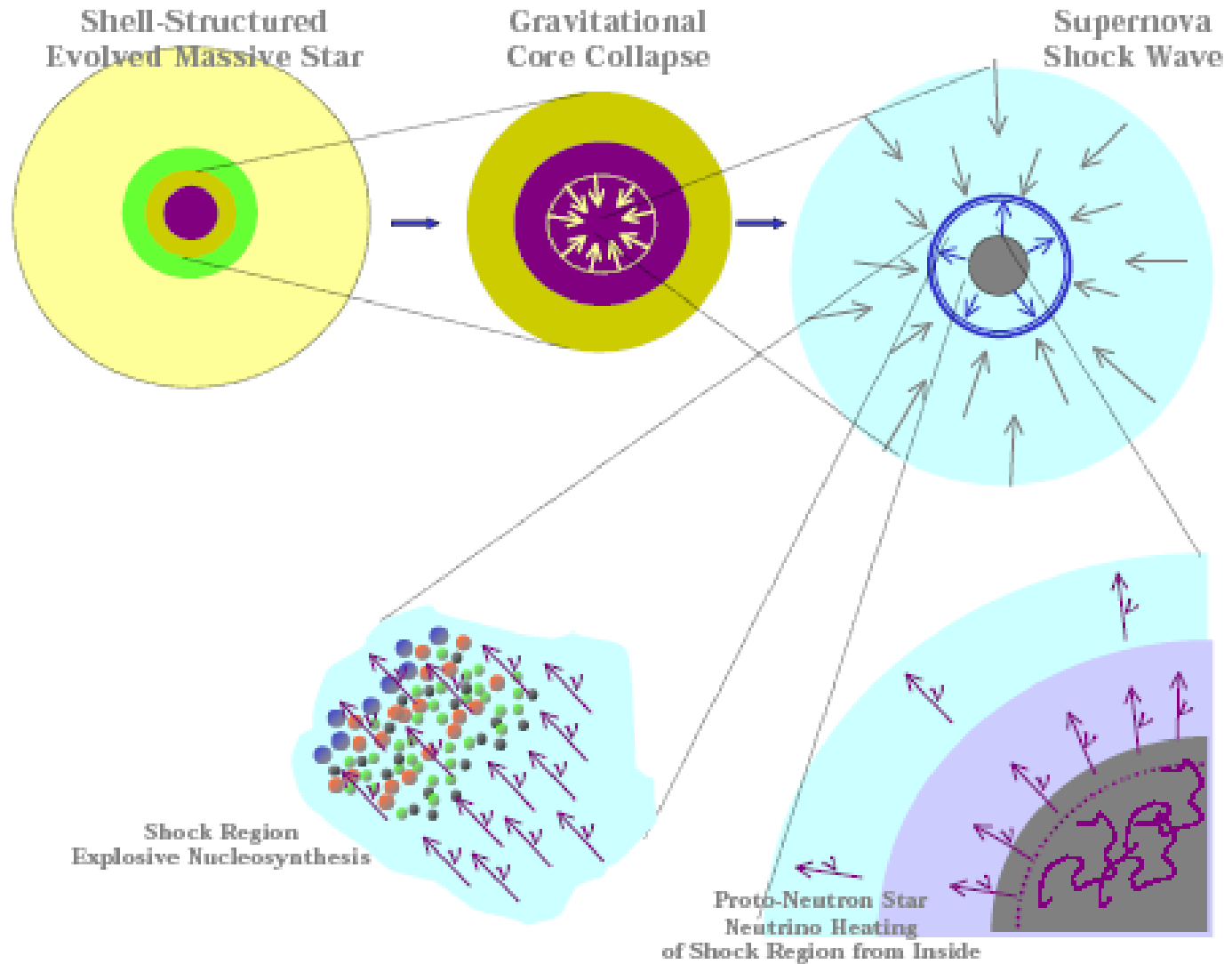
- Jernkernens masse overstiger Chandrasekhar-massen
- Kollaps på kernens dynamiske tidskala (millisekunder)
- Resten af stjernen aner ikke hvad der foregår (men det finder den ud af!)

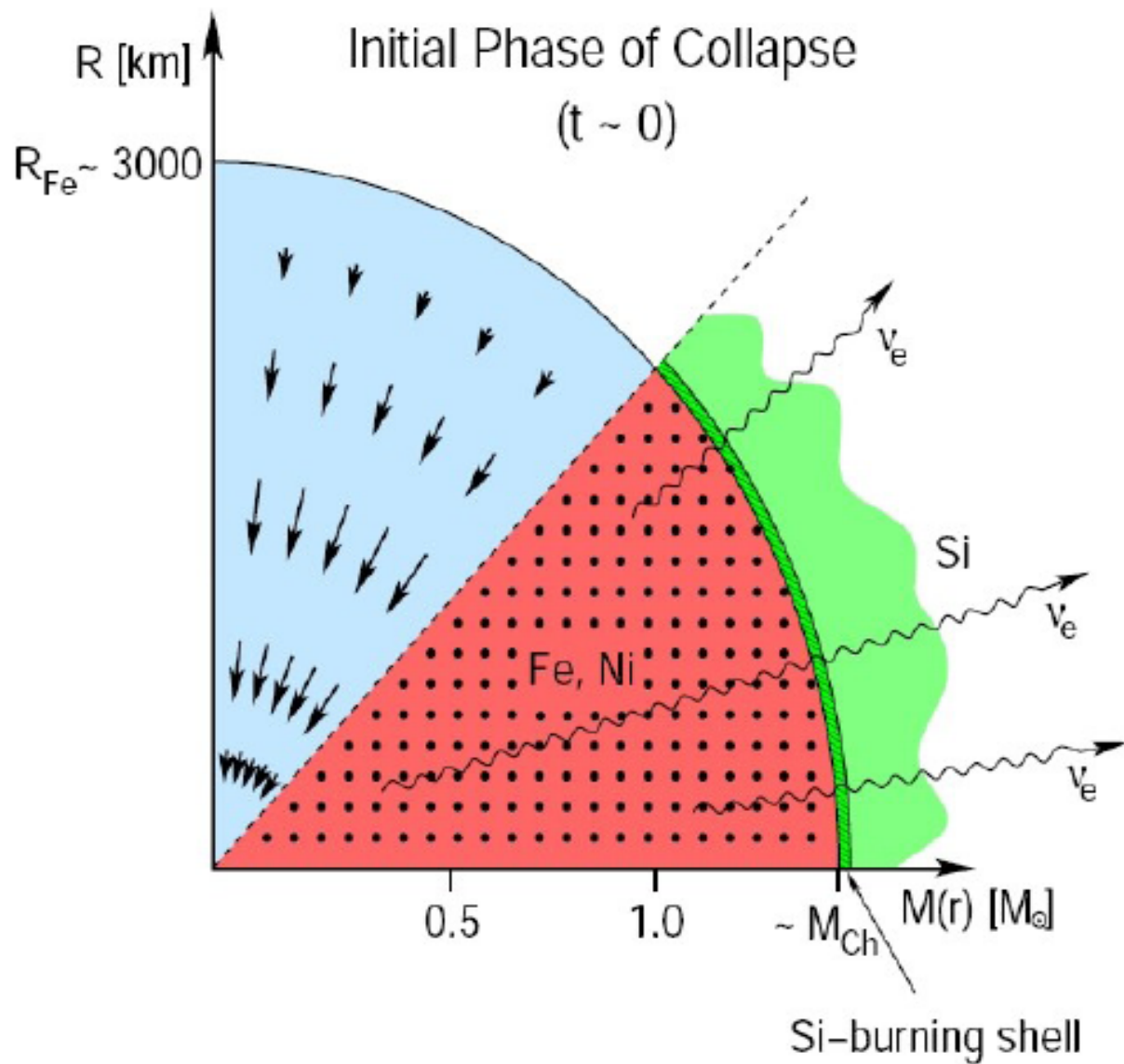
Energifrigivelse ved kollaps

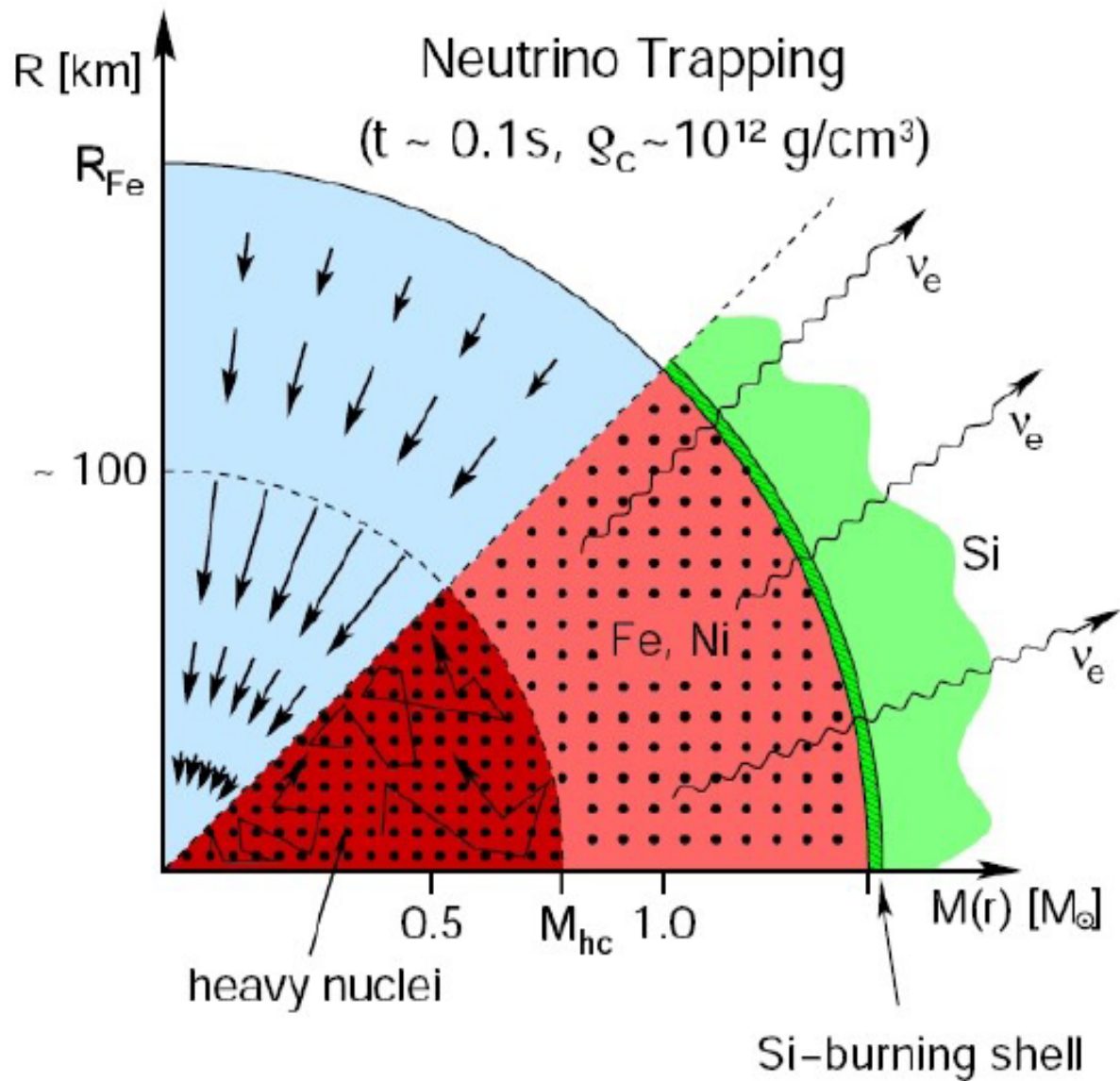
Kollaps af $1.5M_{\odot}$ til 10 km:

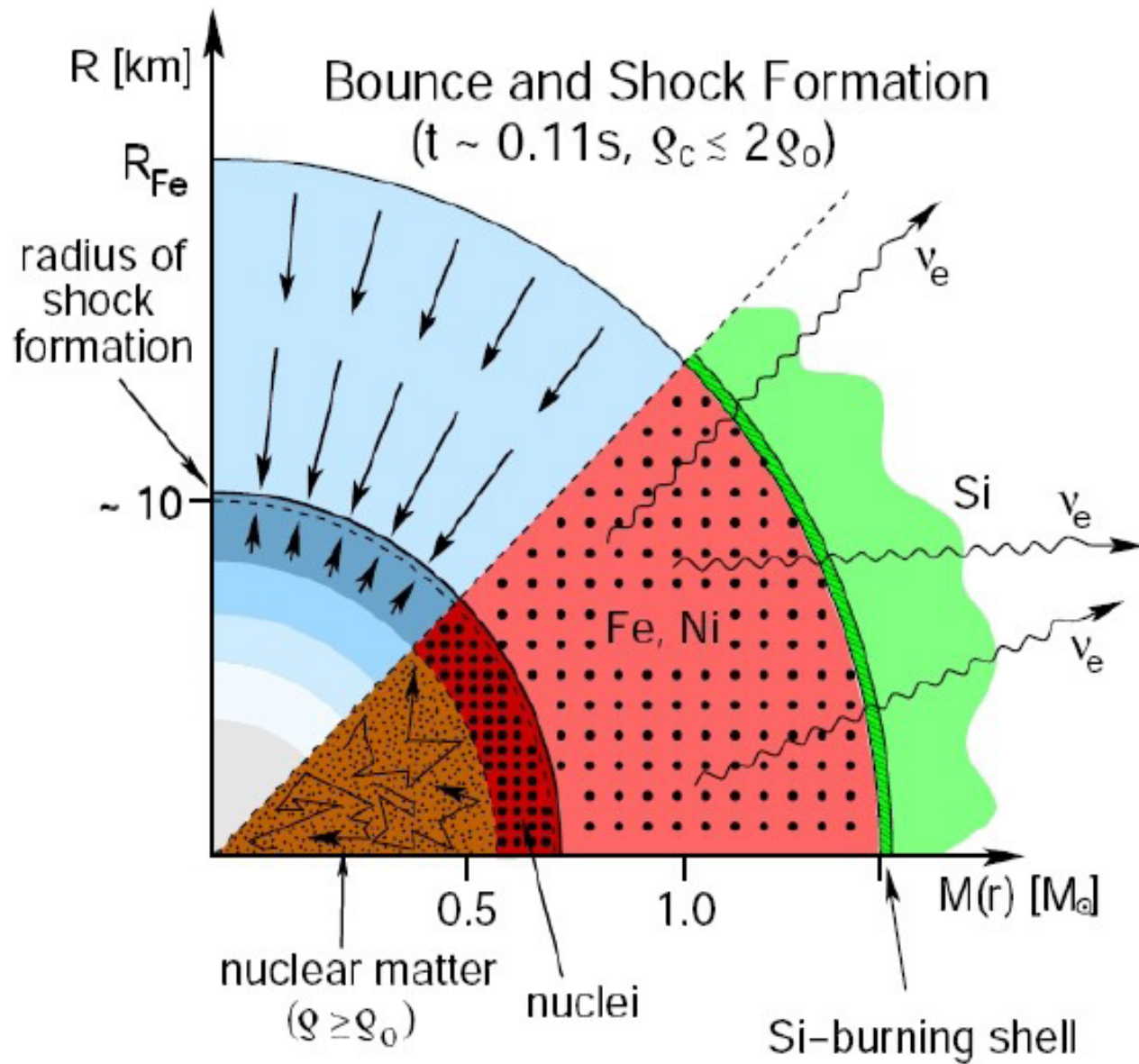
$$|E_{\text{grav}}| \simeq \frac{GM}{R} M \simeq 3 \times 10^{53} \text{ erg}$$

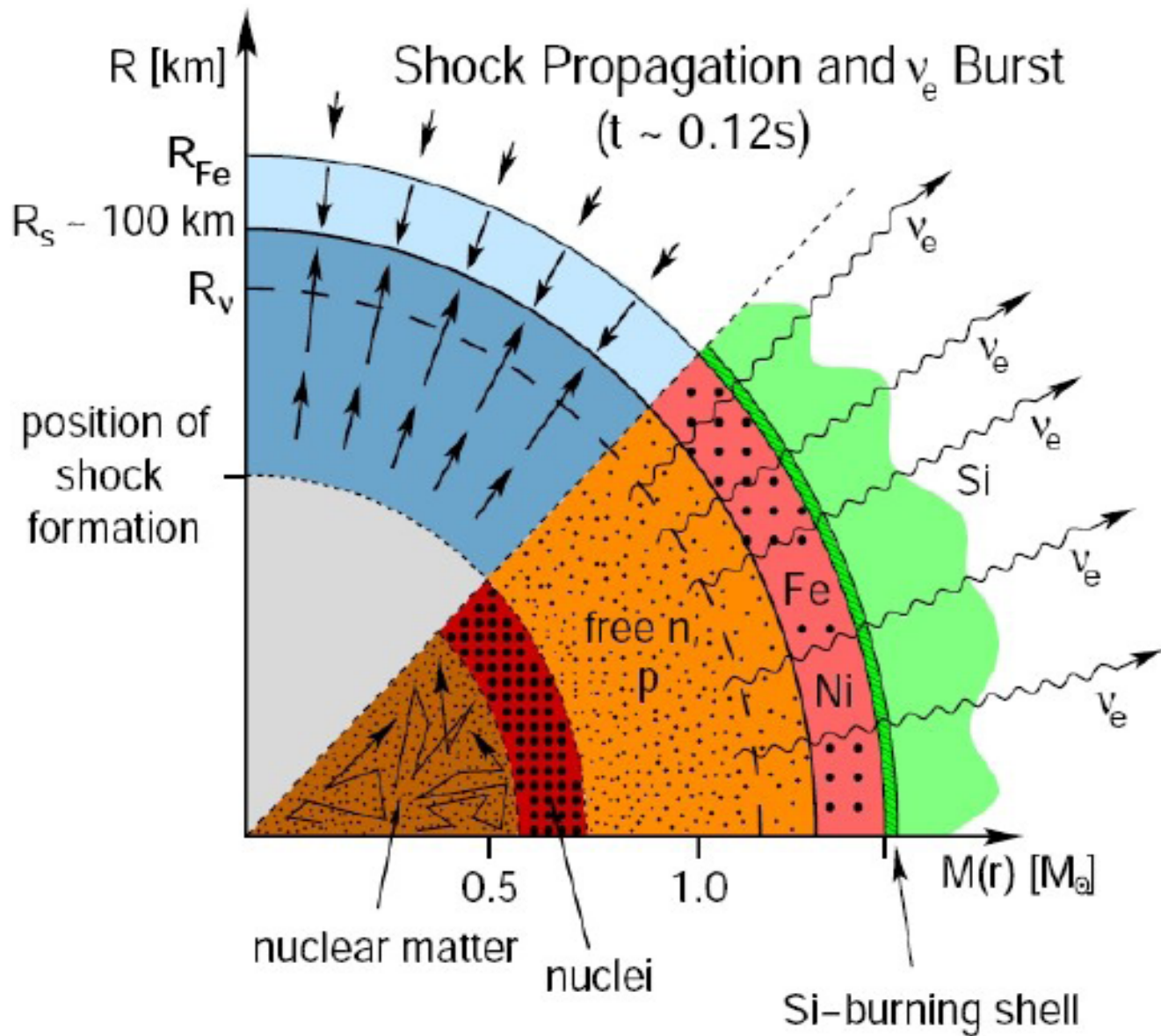
Core-Collapse Supernovae

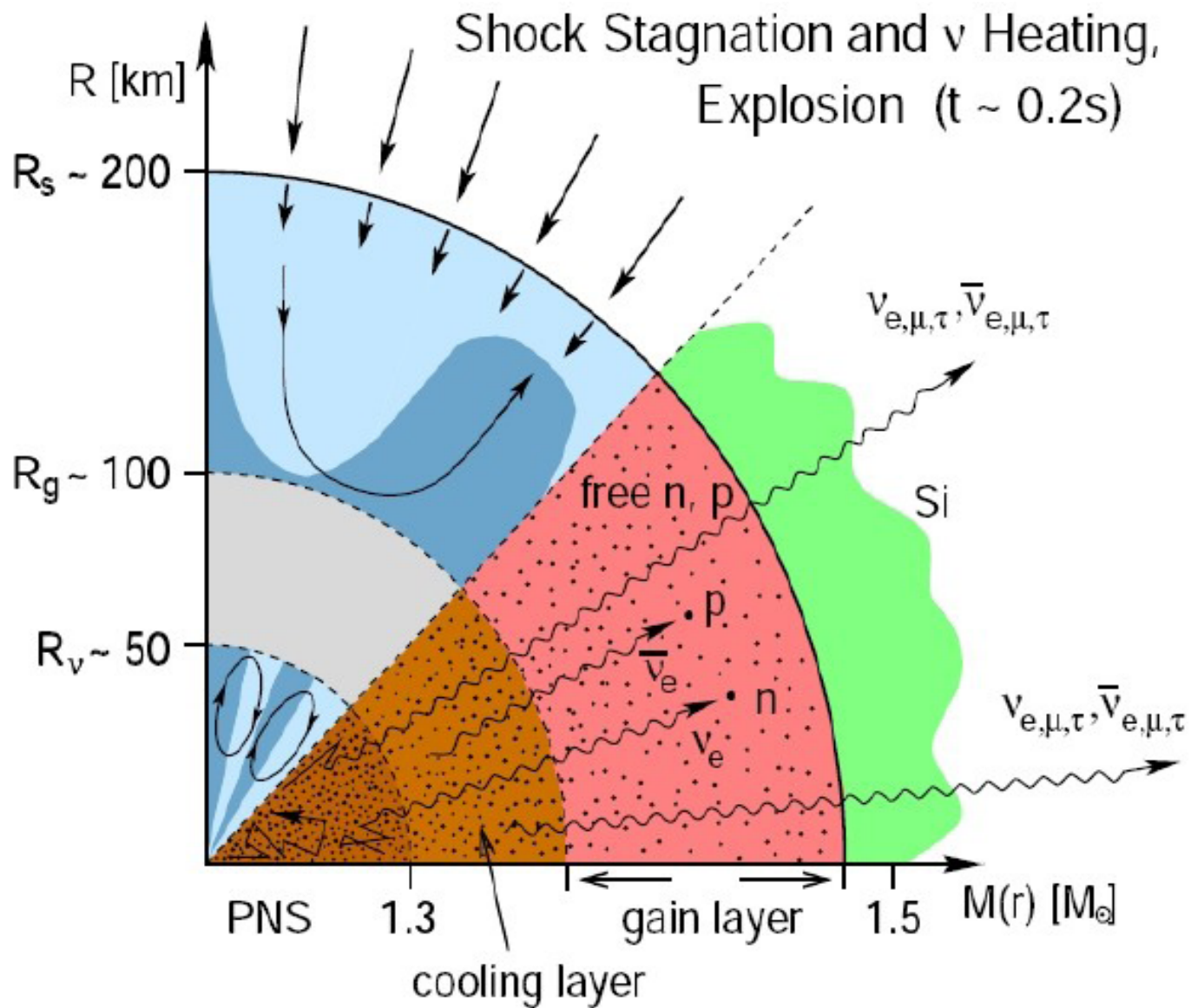


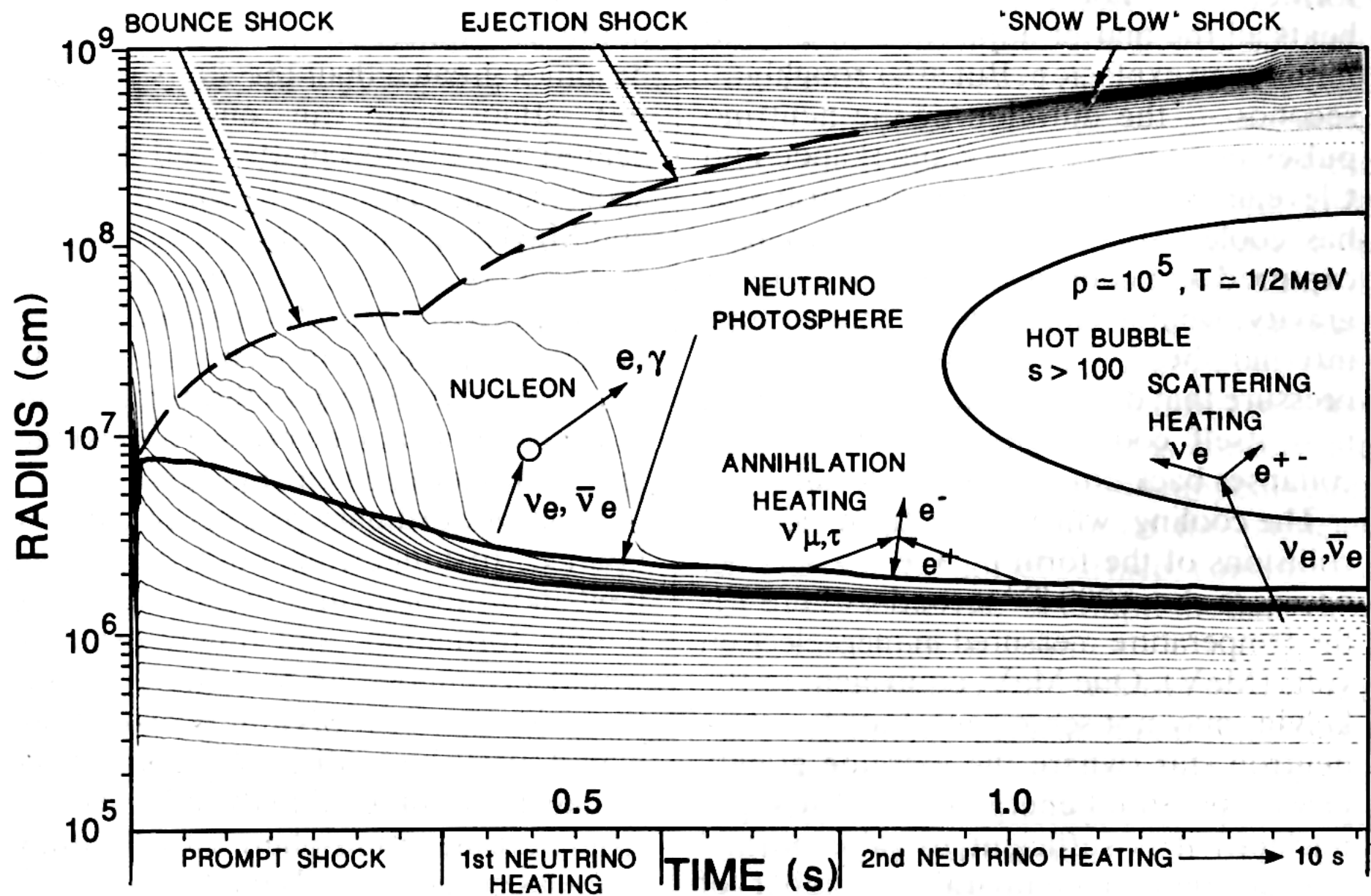




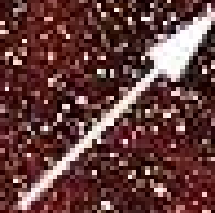






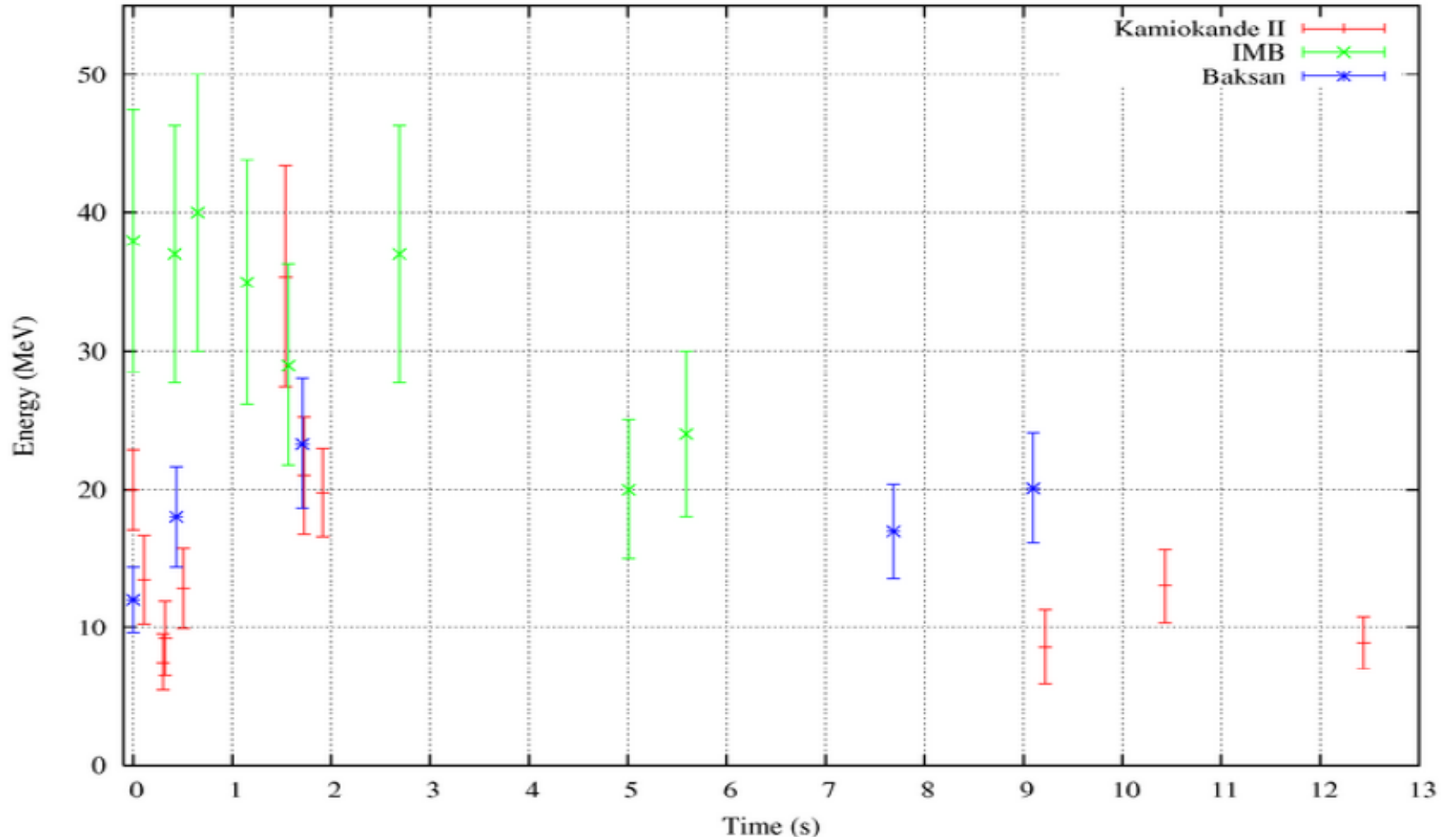


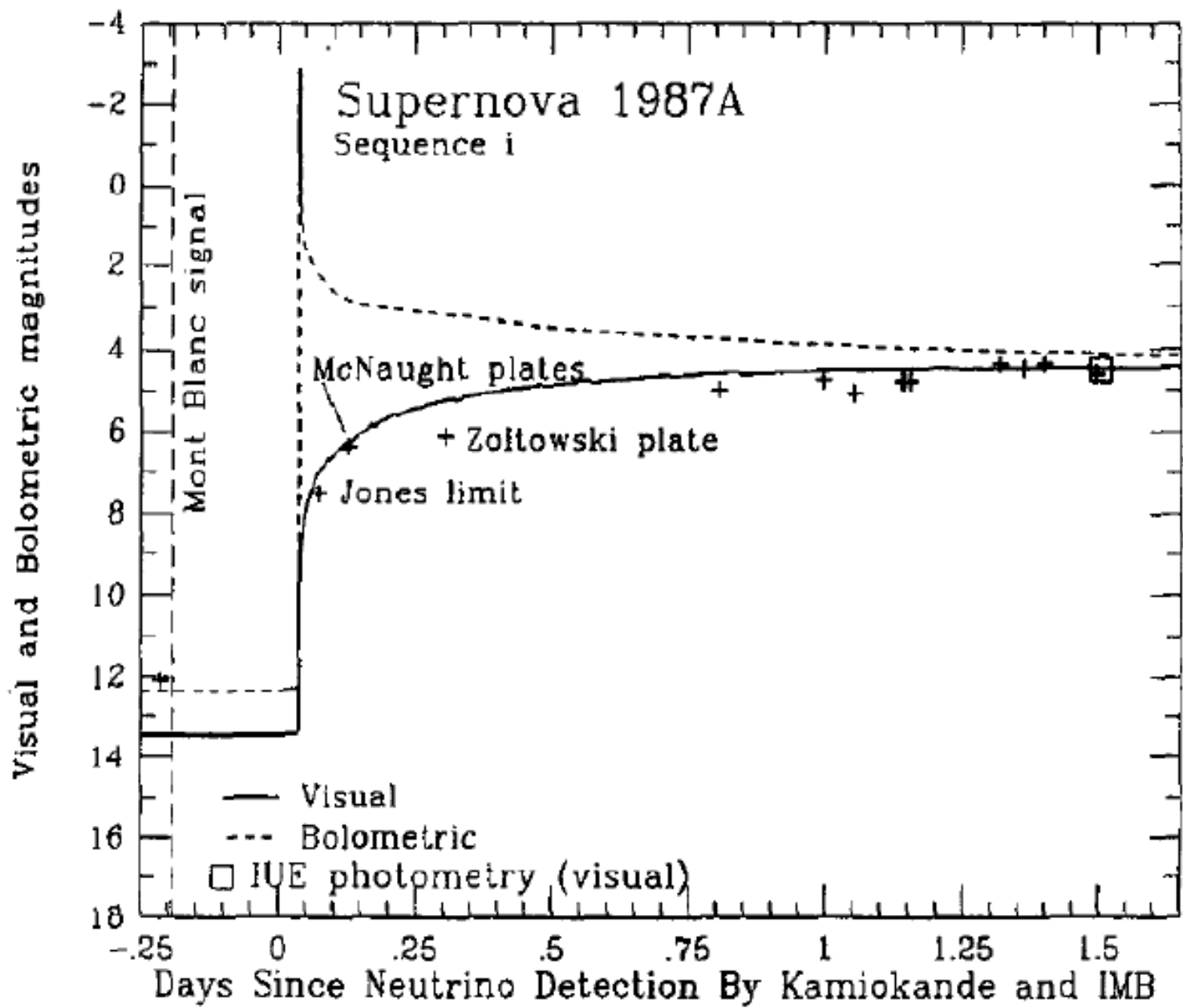
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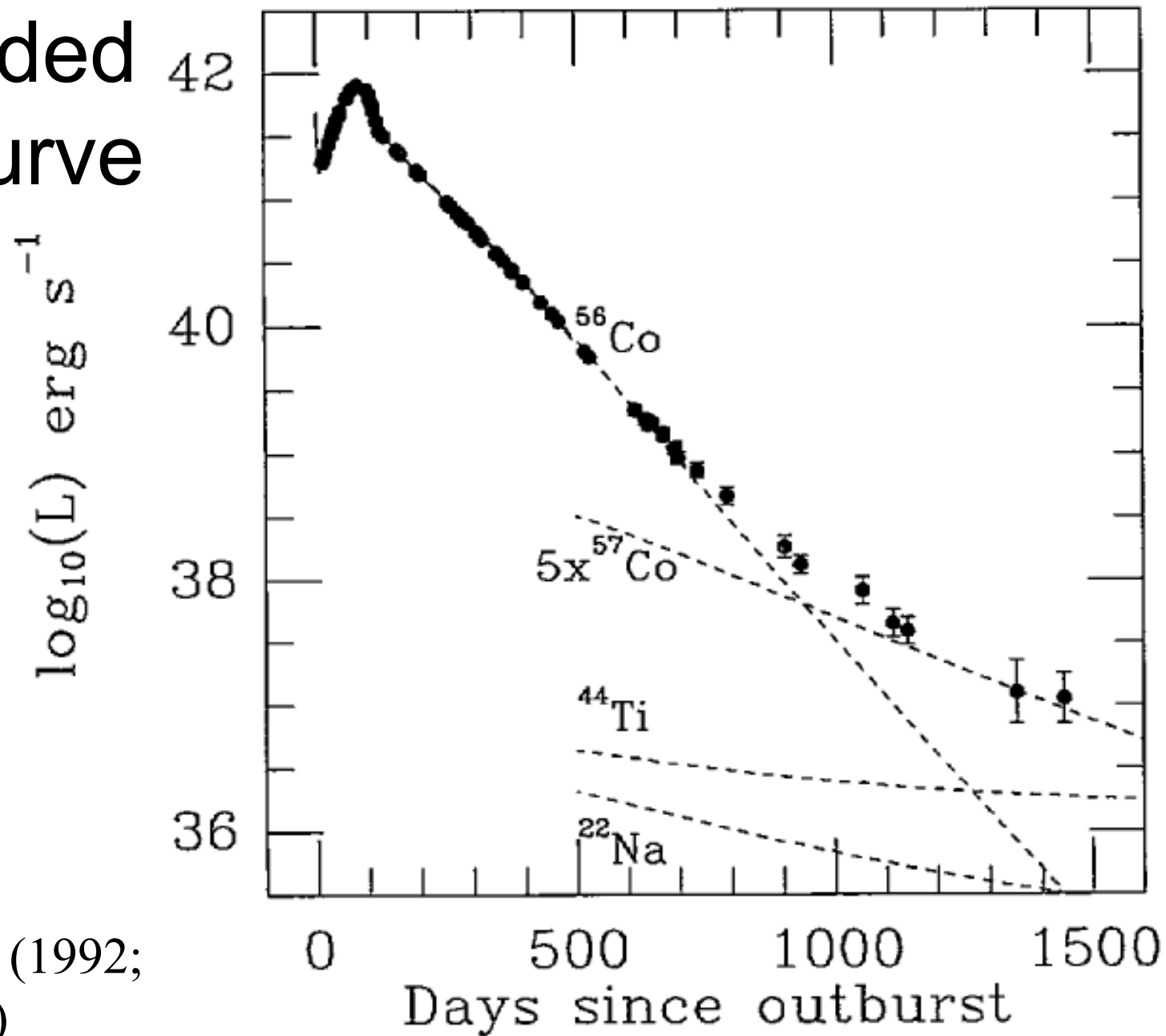
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Neutrinoer fra SN1987A



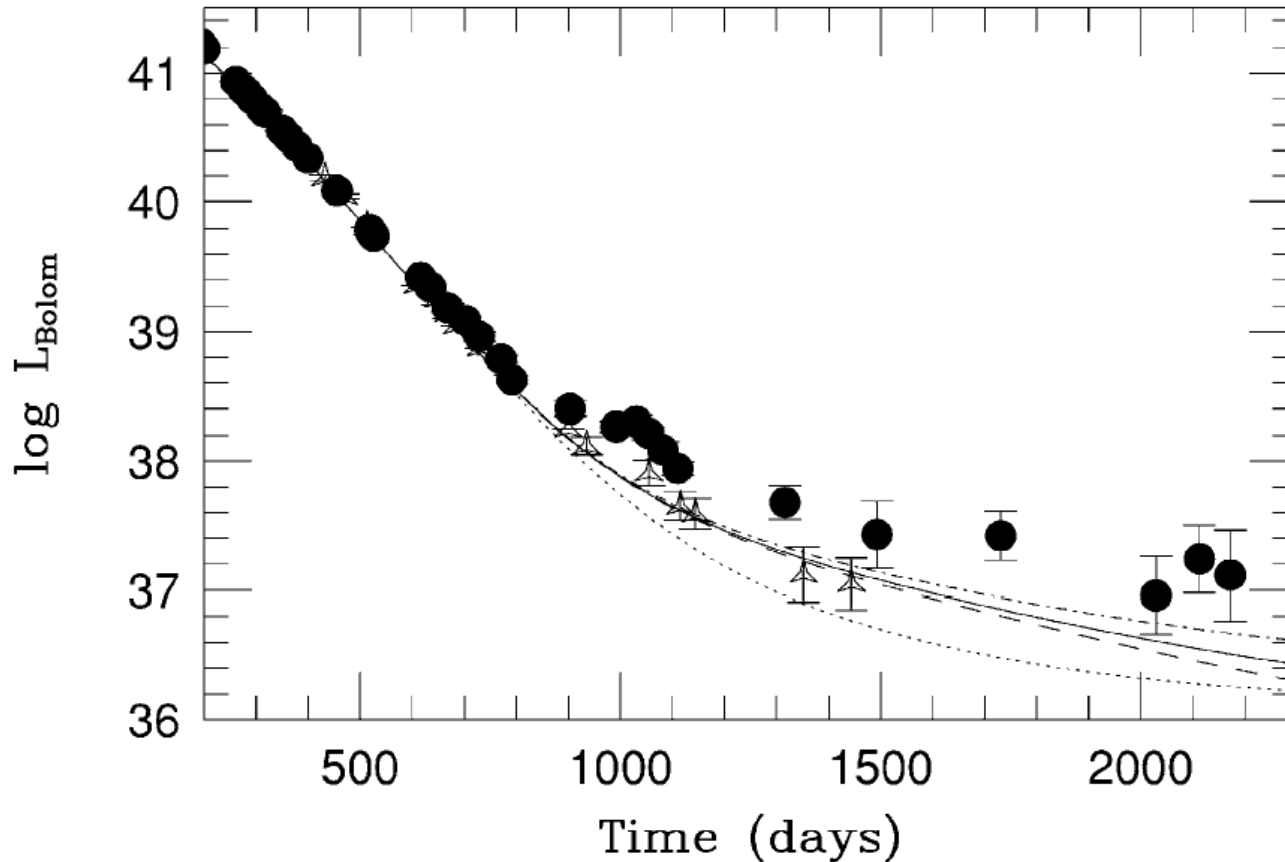


1987A, extended lightcurve



Suntzeff et al. (1992;
ApJ 384, L33)

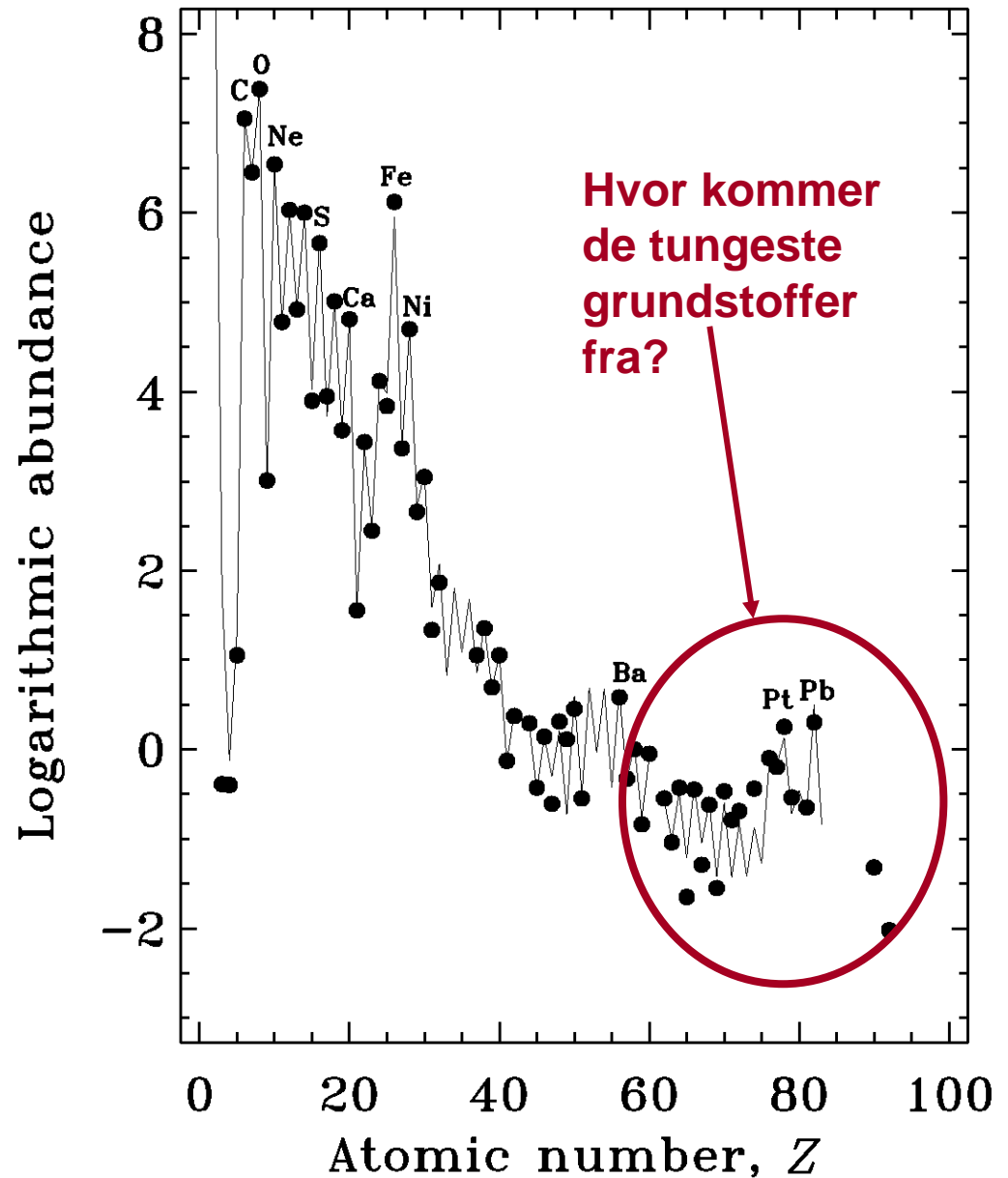
1987A, late stages



$M(^{56}\text{Co})=0.07 M_{\odot}$, $M(^{57}\text{Co})=3.3 \times 10^{-3} M_{\odot}$, and $M(^{44}\text{Ti})=1 \times 10^{-4} M_{\odot}$.
 $\tau_{1/2} = 278 \text{ d}$ $\tau_{1/2} = 60 \text{ yr}$

Fransson & Kozma (2002; New Astron. Rev. 46, 487)

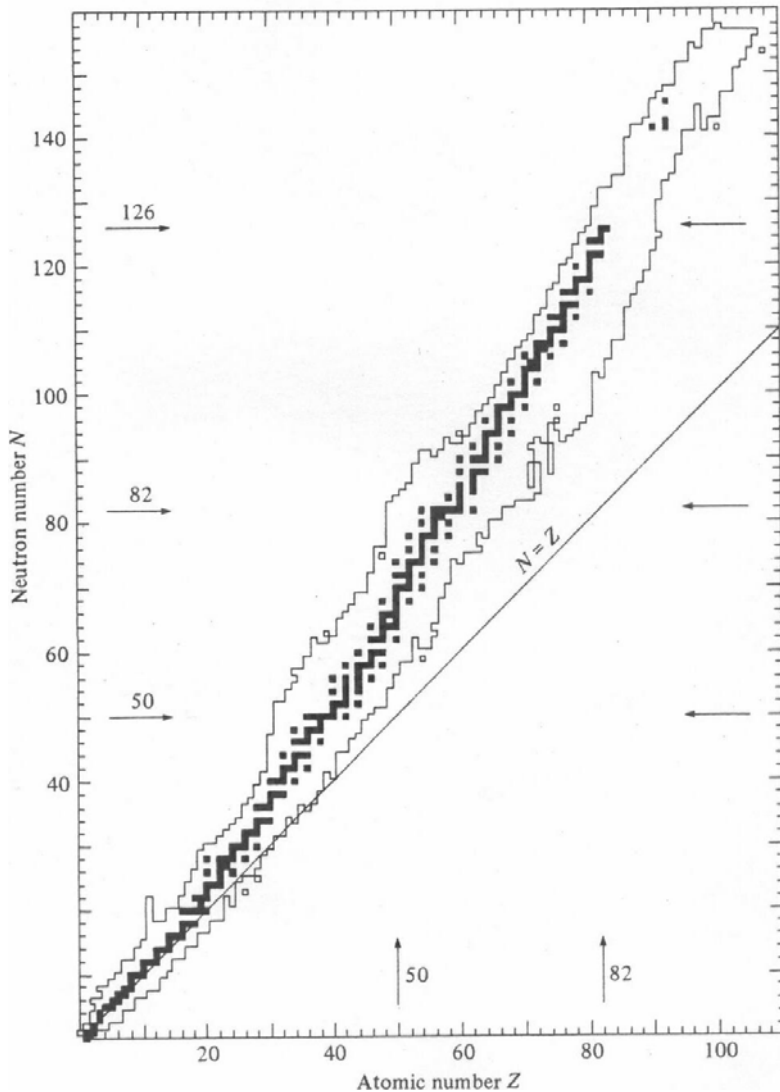
Solsystemets grundstof- sammensætning



Hvor kommer de tungeste grundstoffer fra?

- Kernereaktioner er endoterme og Coulomb-barrieren er enorm.
- Neutroner kan intet holde tilbage!
- s-processen: langsom neutron-indfangning
- r-processen: hurtig neutron-indfangning

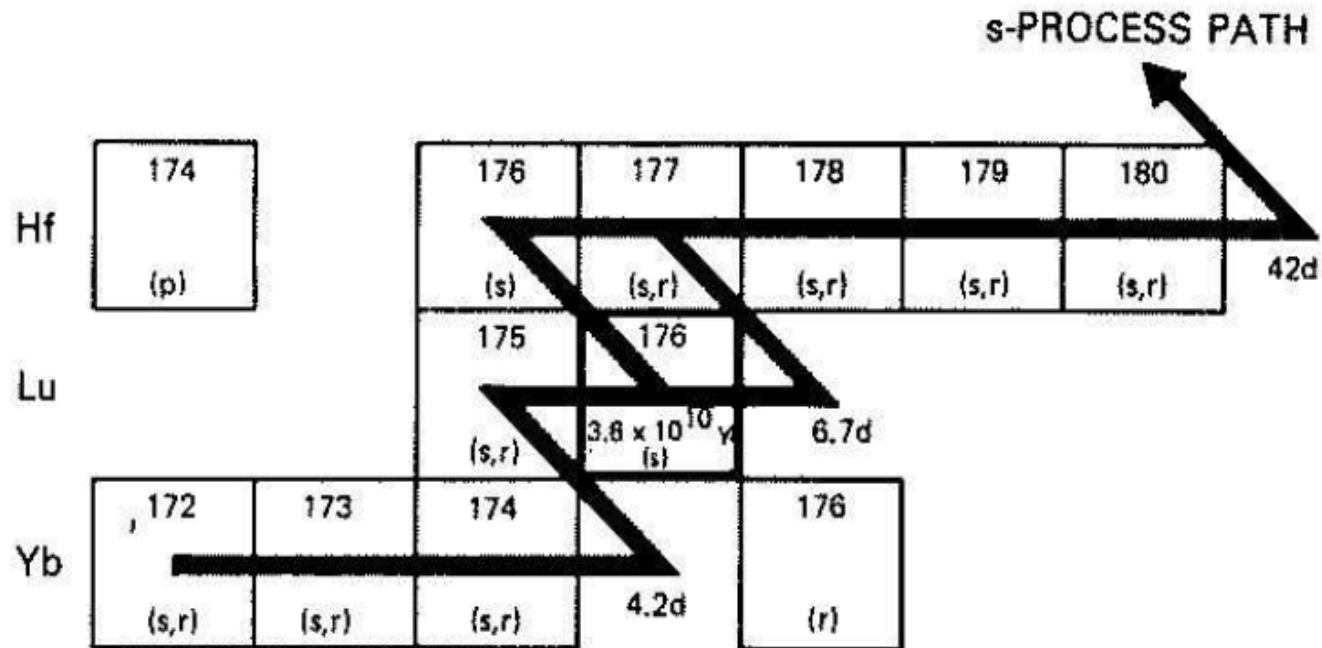
4.6 The β -stability valley. Filled squares denote the stable nuclei and long-lived nuclei occurring in nature. Neighbouring nuclei are unstable. Those for which data on masses and mean lives are known fill the area bounded by the lines. For the most part these unstable nuclei have been made artificially. (Data taken from *Chart of the Nuclides* (1977), Schenectady: General Electric Company.)



s-Processen

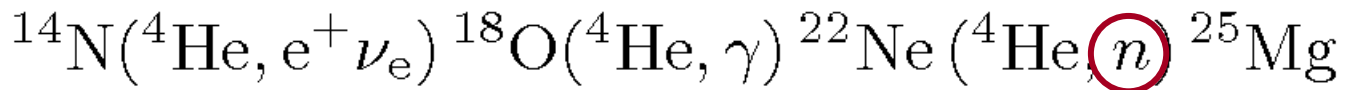
- Producerer stabile kerner langs β -stabilitets-dalen
- Opererer på lange tidsskalaer

s-stien



Hvor finder den sted?

- Asymptotiske kæmpestjerner
- Ustabil variation mellem brint- og heliumforbrænding
- Neutronproduktion ved



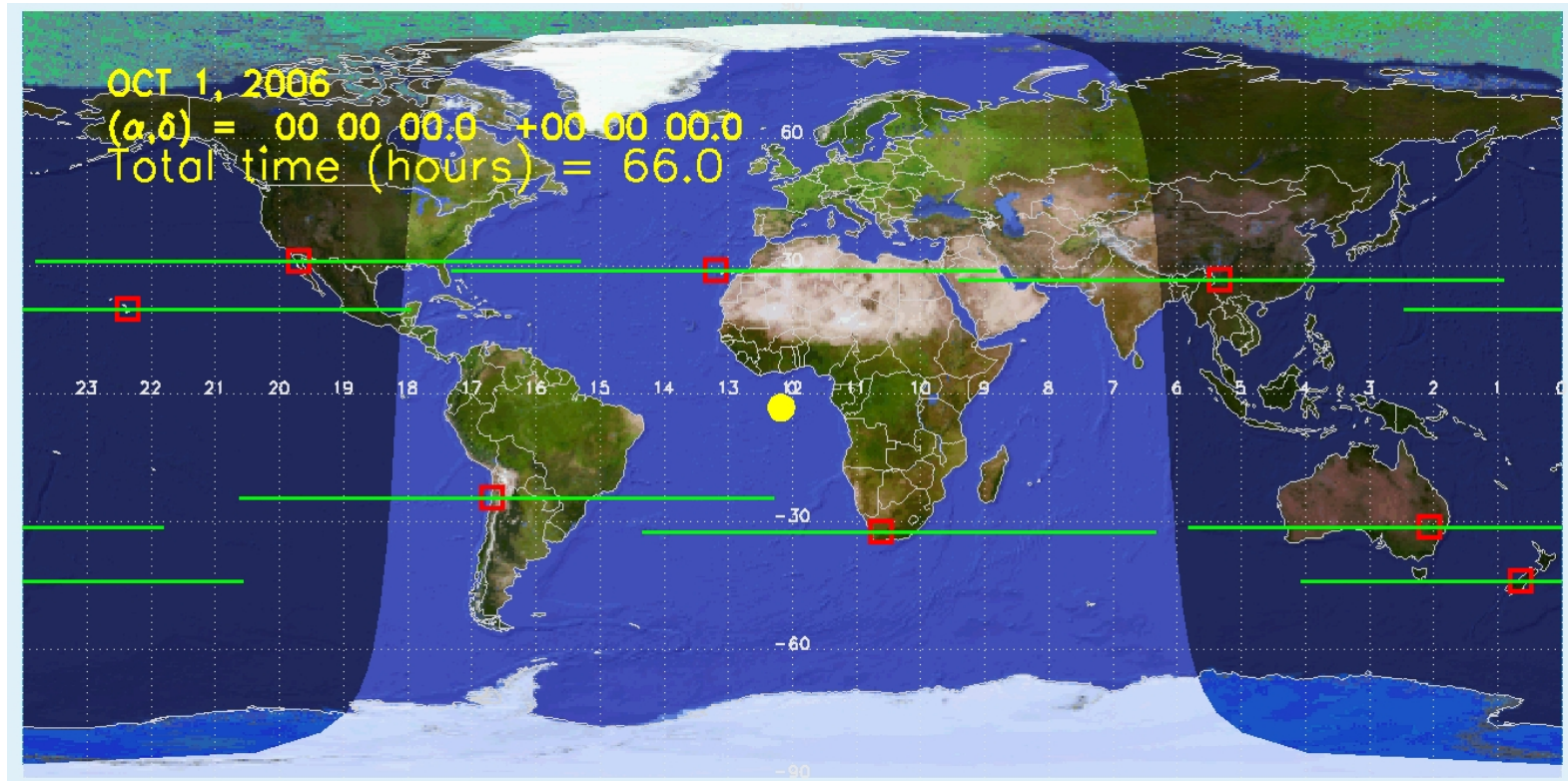
SONG: the Stellar Oscillations Network Group

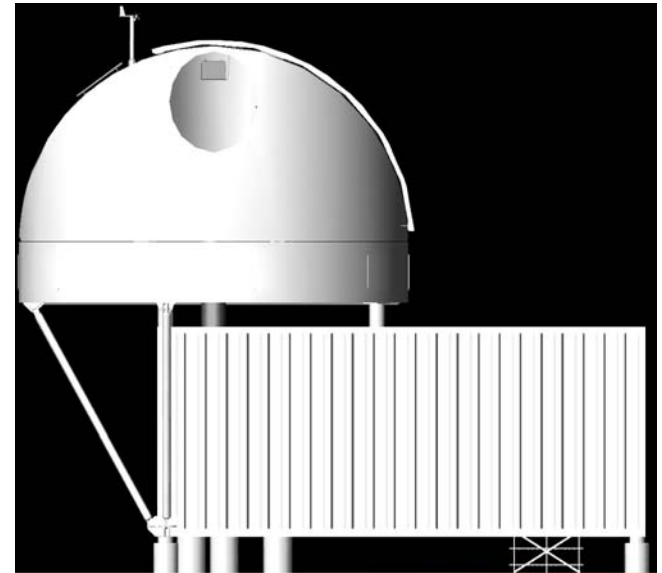
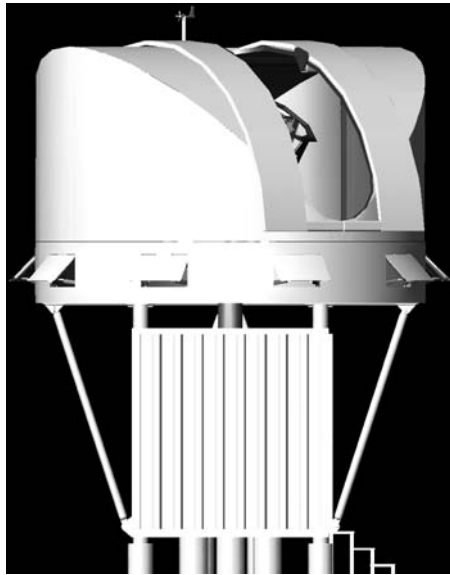
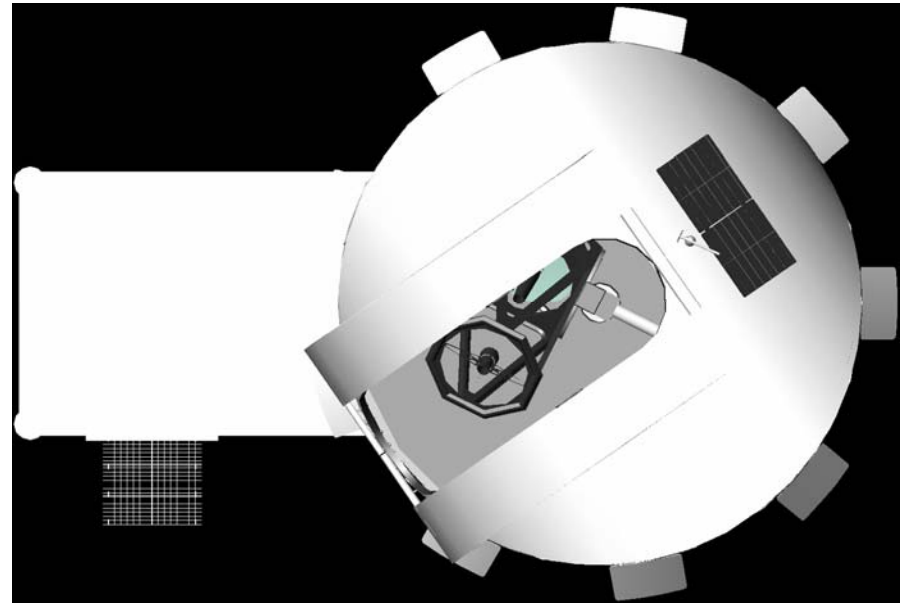


SONG-conceptet

- 1-m klasse teleskoper
- Coude focus, iod-stabiliseret spektrograf
- Billedobservationer
- Robot-operationer
- 8 enheder fordelt på den nordlige og sydlige halvkugle

Mulig fordeling af SONG enhederne.





4 måneders SONG observationer

