# stellar evolution

w mass

stars

# stellar parameters

initial mass: 0.07 – 120 $M_\odot$

**< (approximately) 7 $M_\odot$ low mass stars**

> (approximately) 7 $M_\odot$ massive stars

Luminosity: $10^{-2} – 10^{6}$ $L_\odot$

Radius: 0.01 – 1000 $R_\odot$

temperatur at surface ( ↔ $T_{eff}$): 3000 – 100000 K

temperatur in the core: $10^{6} – 5\ 10^{9}$ K

lifetime: $10^{6} – 10\ 10^{9}$ years

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# Stellar evolution – low mass stars

initial mass: 0.07 – 120 $M_\odot$

**< (approximately) 7 $M_\odot$ low mass stars**

> (approximately) 7 $M_\odot$ massive stars

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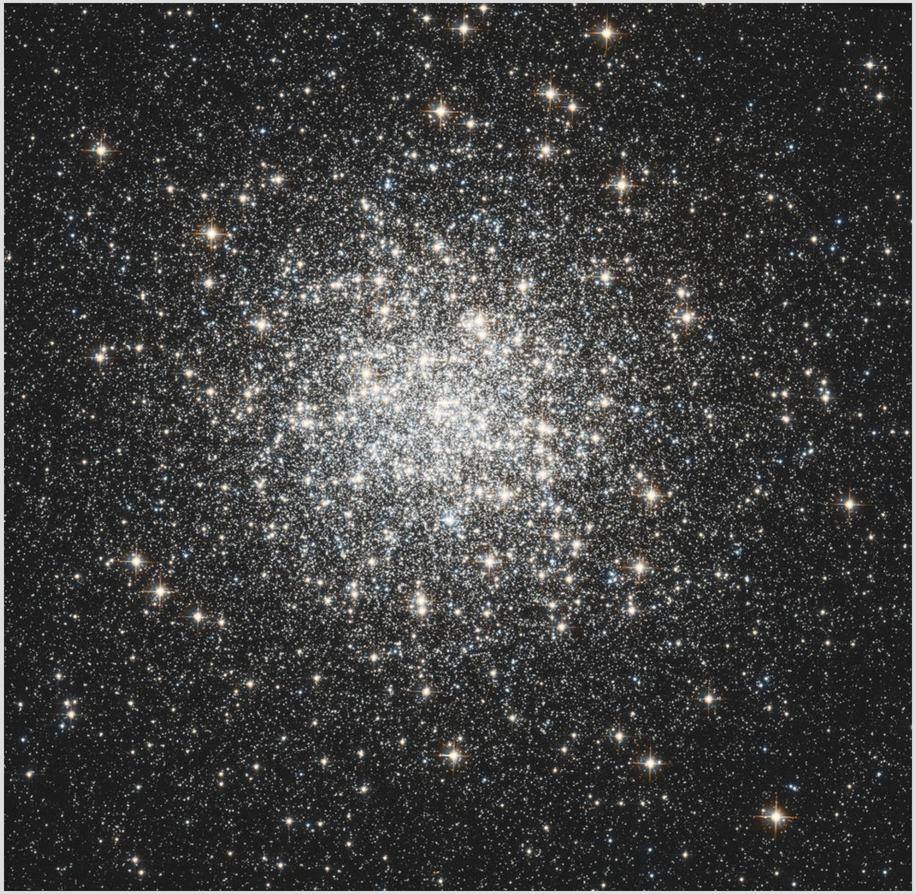
# Stellar evolution – low mass stars

## Messier 3



Example

**Globular cluster**

● all stars about the **same age**

● massive stars gone (faster evolution)

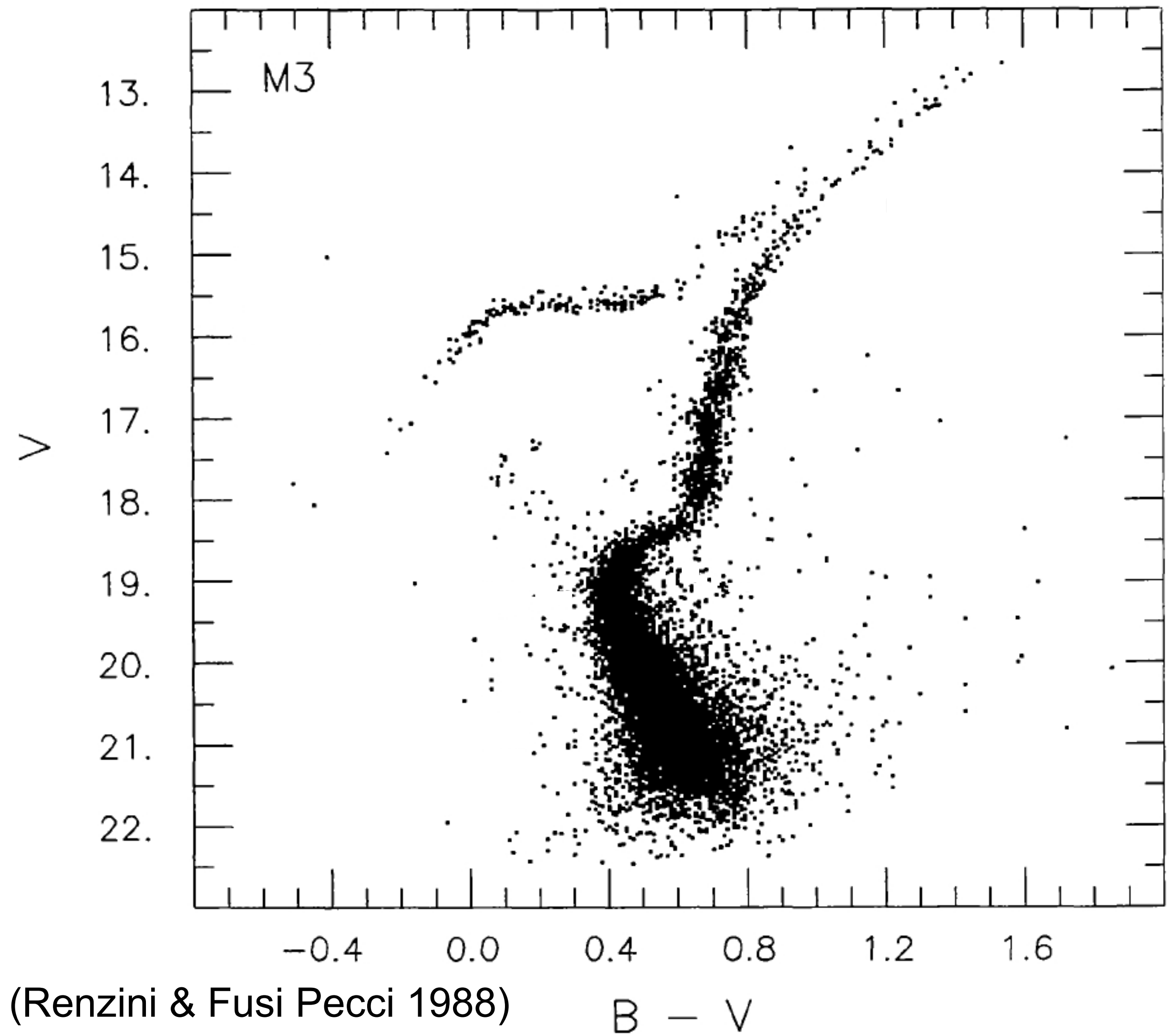
→ only **low mass stars** left/present

# Stellar evolution – low mass stars

## Messier 3 Color-Magnitude-Diagram ↔ HRD

Position of all stars in the cluster

Low mass stars in all possible evolutionary States.




(Renzini & Fusi Pecci 1988)

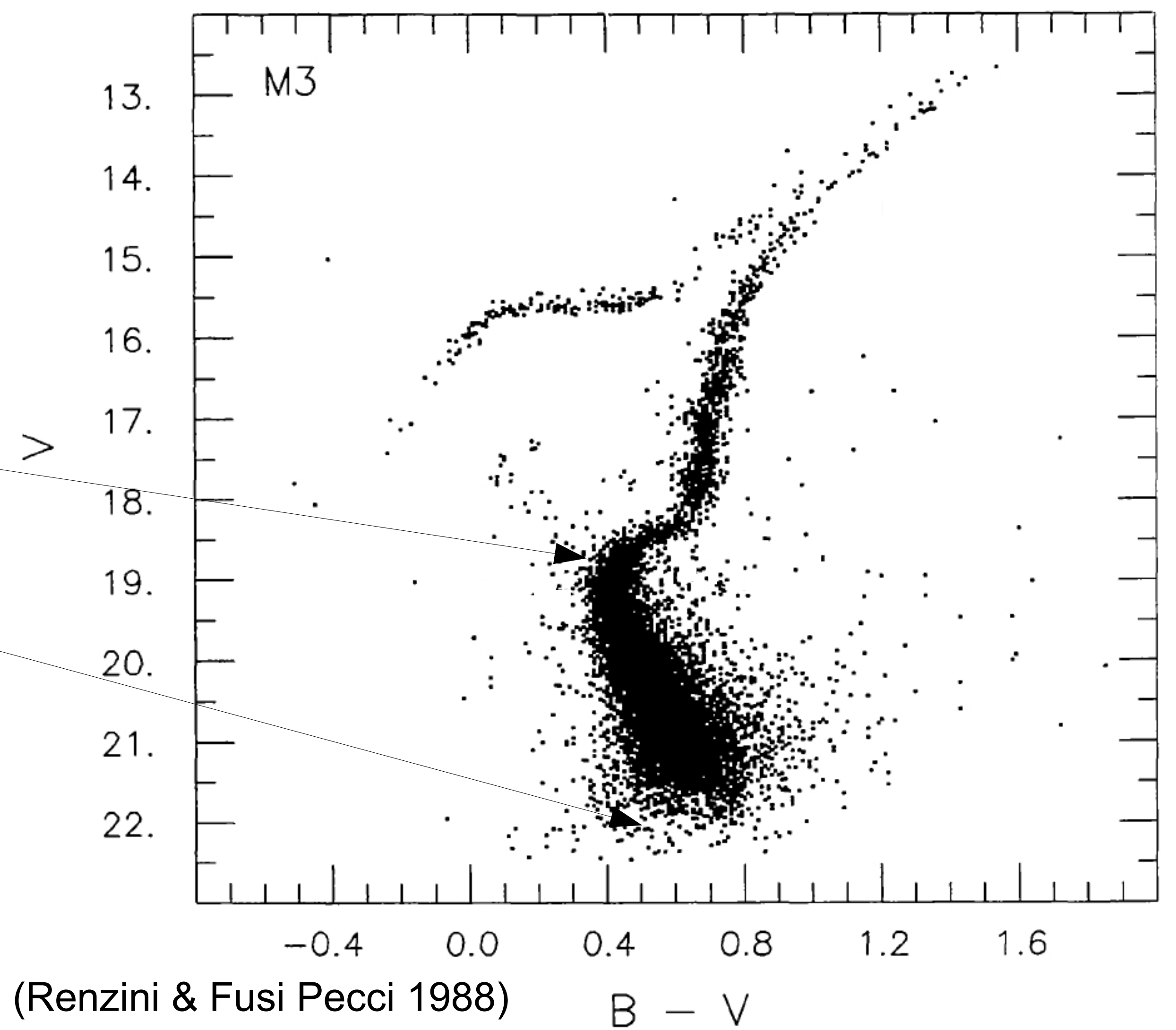
# Stellar evolution – low mass stars

## Messier 3 Color-Magnitude-Diagram ↔ HRD

Position of all stars in the cluster

Low mass stars in all possible evolutionary States.

**main sequence phase** stars with different mass at the same time




(Renzini & Fusi Pecci 1988)

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# Stellar evolution – low mass stars

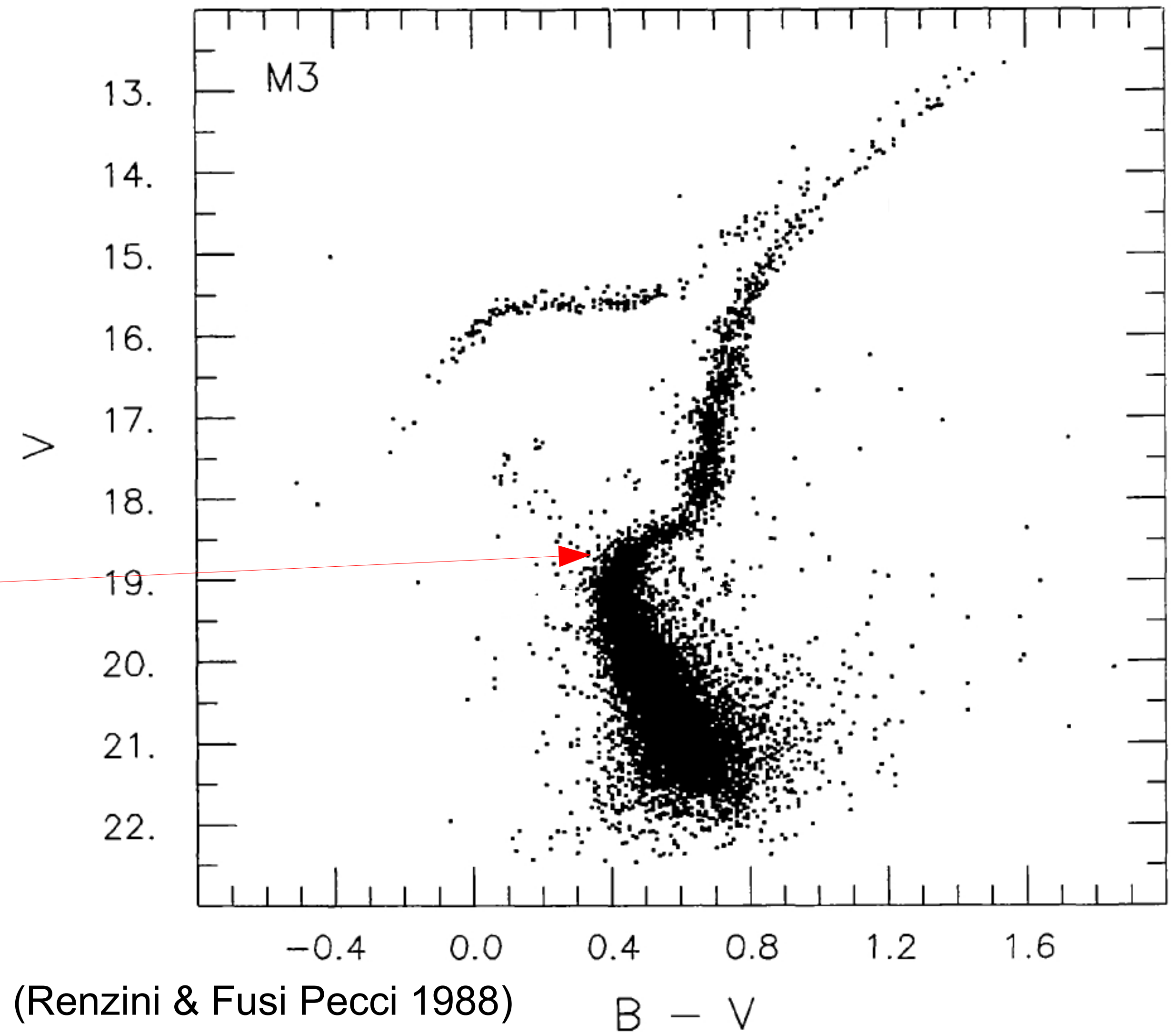
## Messier 3 Color-Magnitude-Diagram ↔ HRD

Position of all stars in the cluster

Low mass stars in all possible evolutionary States.

**main sequence phase**
**Star with highest mass ↔ turn off**

higher mass stars already left the main-sequence




(Renzini & Fusi Pecci 1988)

# Stellar evolution – low mass stars

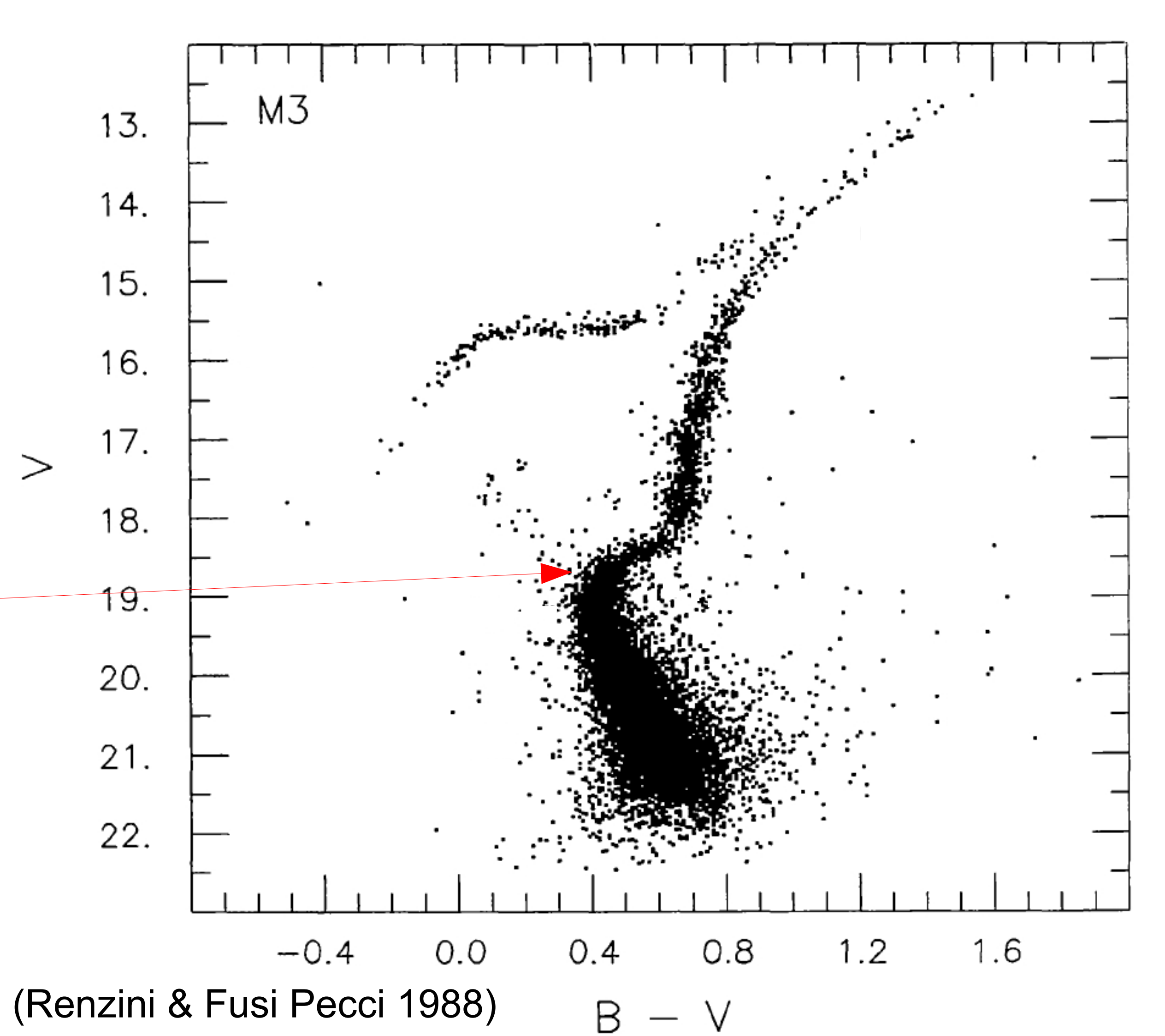
## Messier 3 Color-Magnitude-Diagram ↔ HRD

Position of all stars in the cluster

Low mass stars in all possible evolutionary States.

**main sequence phase**
**Star with highest mass ↔ turn off**

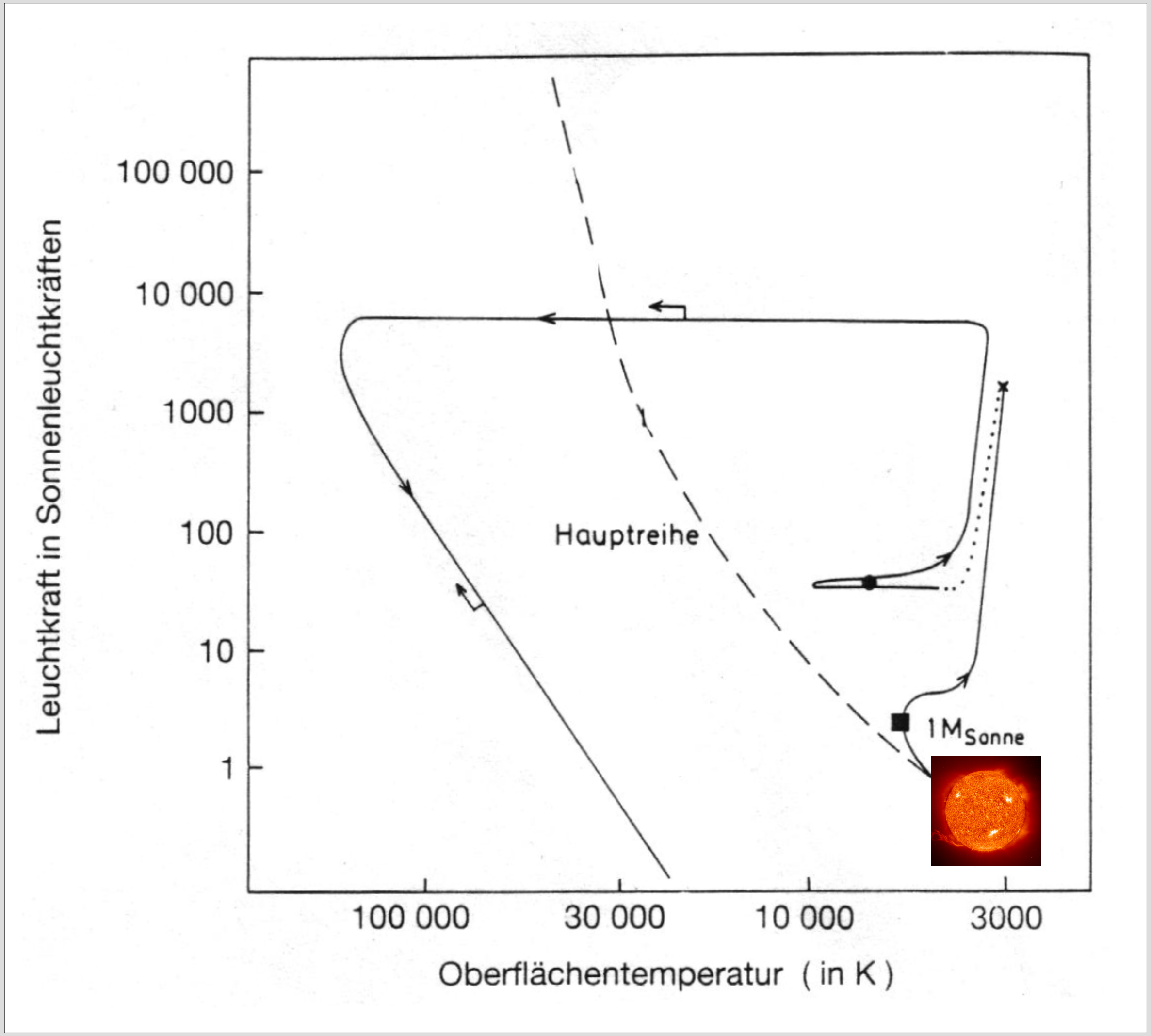
→ compare to models gives an **age** of the **cluster**




(Renzini & Fusi Pecci 1988)

# Stellar evolution – low mass stars

## HRD with the path of a star with 1 $M_{\odot}$

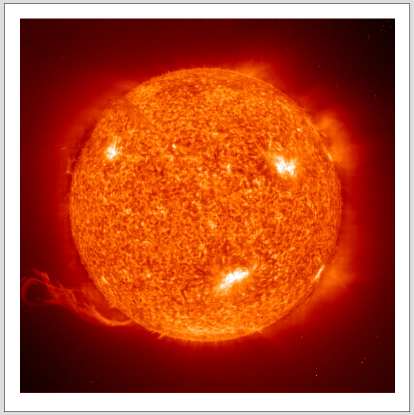



**stage**
example

**Main Sequence**
sun

# Stellar evolution – low mass stars

## main sequence stars

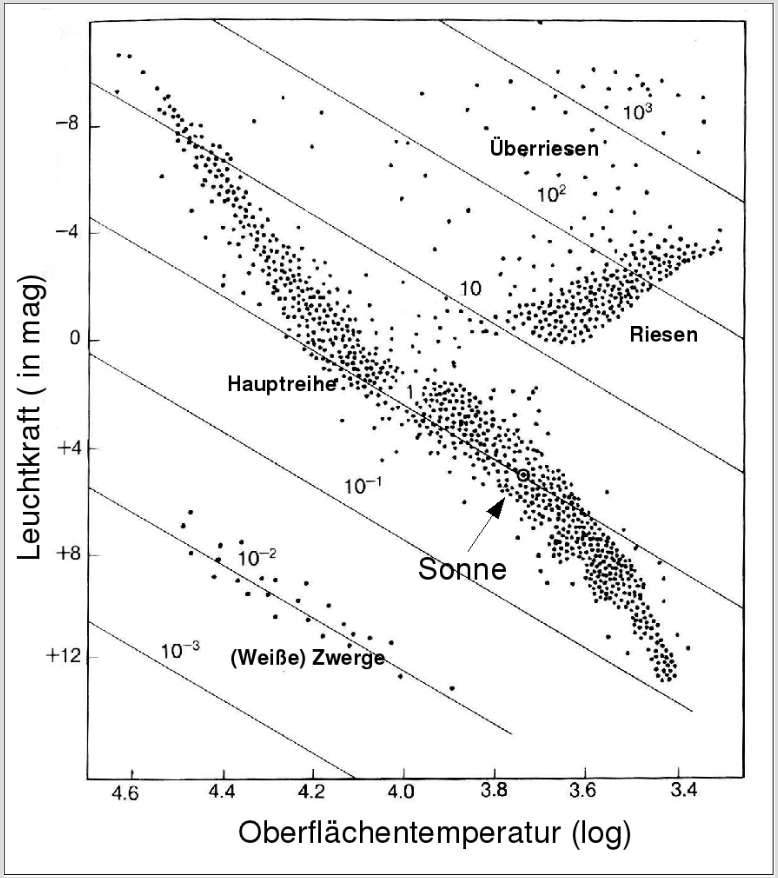


- star in **hydrostatic equilibrium**
- star started **hydrogen core burning**
- **longest** phase of all stars, **~90% total lifetime**
- **initial mass $M_{ini}$ ~ 0.07 to ~ 7 $M_\odot$**
- **radius 0.5 to 1.5 $R_\odot$**
- **$T_{eff}$ = 3500** (→ Hayashi) to **20000 K**
- **Luminosity**

  **$\log L / L_\odot$ = -1 bis 3.25**

  **$M_{bol}$ = 7 bis -3.5**
- **Hydrogen** burning **mainly via pp**
- Stars **$M_{ini}$ < 1.2 $M_\odot$** core **radiativ**

  **> 1.2 $M_\odot$** core **convectiv**

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# Stellar evolution – low mass stars

## main sequence stars

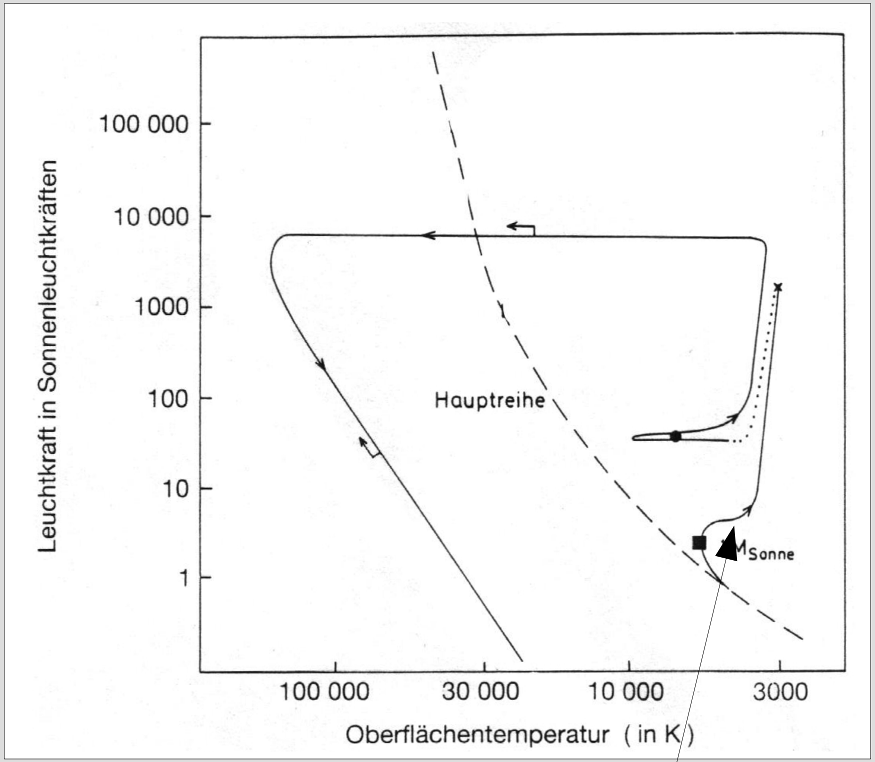
- is the supply of hydrogen exhausted
  → hydrogen burning stops
  = end main sequence phase

  → pressure drops

  → core is collapsing BUT the core temperature not gets hot enough for helium burn to start

  → shell above core heated up

  → shell hydrogen burning begins
  star restructured no core burning
  (remnant He core) only shell burning → less energy → T decreases

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# Hayashi – Limit / Line and Red Giants

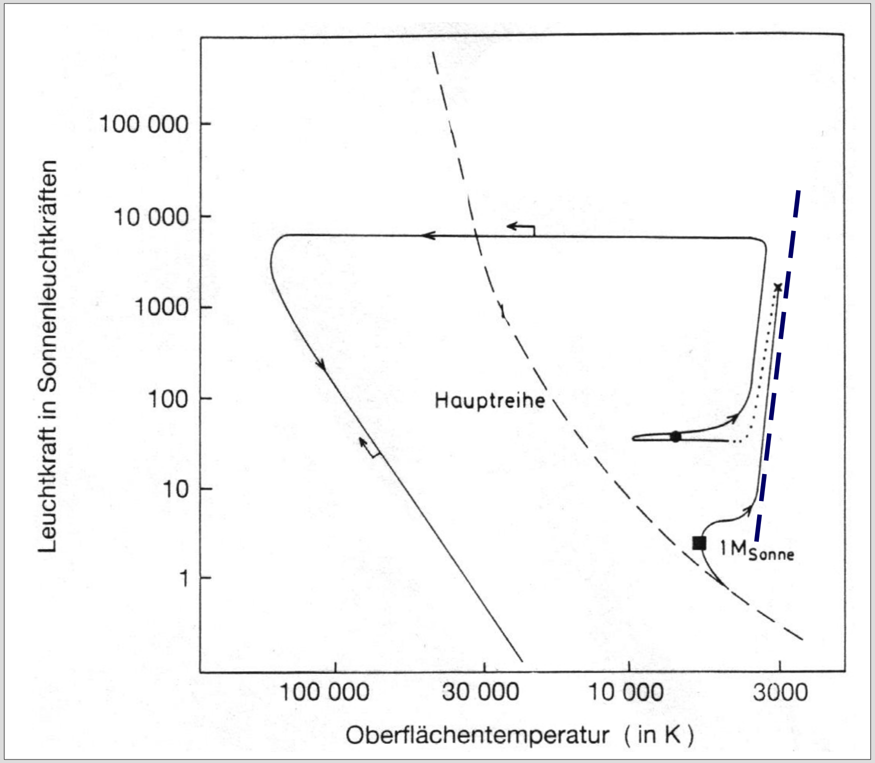
further cooling until the star reaches the Hayashi limit ↔ **fully convective**

→ most efficient energy release ↔ maximum energy output no further cool possible !!

→ star reacts by **increasing** the **radius**/surface

→ due to **$L=4\pi r^2T^4_{eff}$** the **luminosity increases**

The stars turned into a




**Hayashi Line**

**Red Giant**

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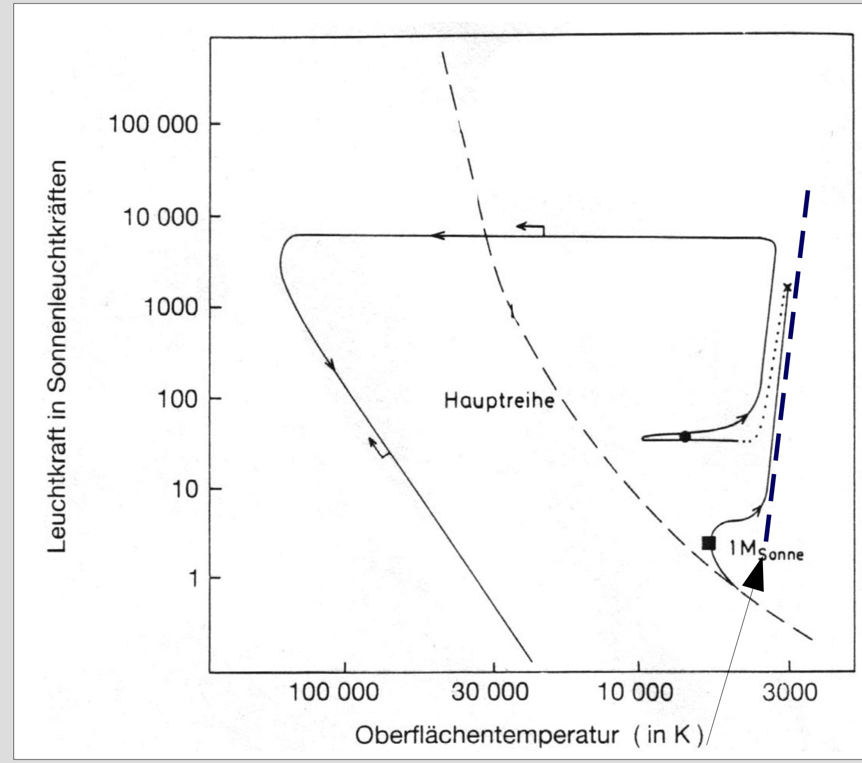
# Red Giant

## Red Giant

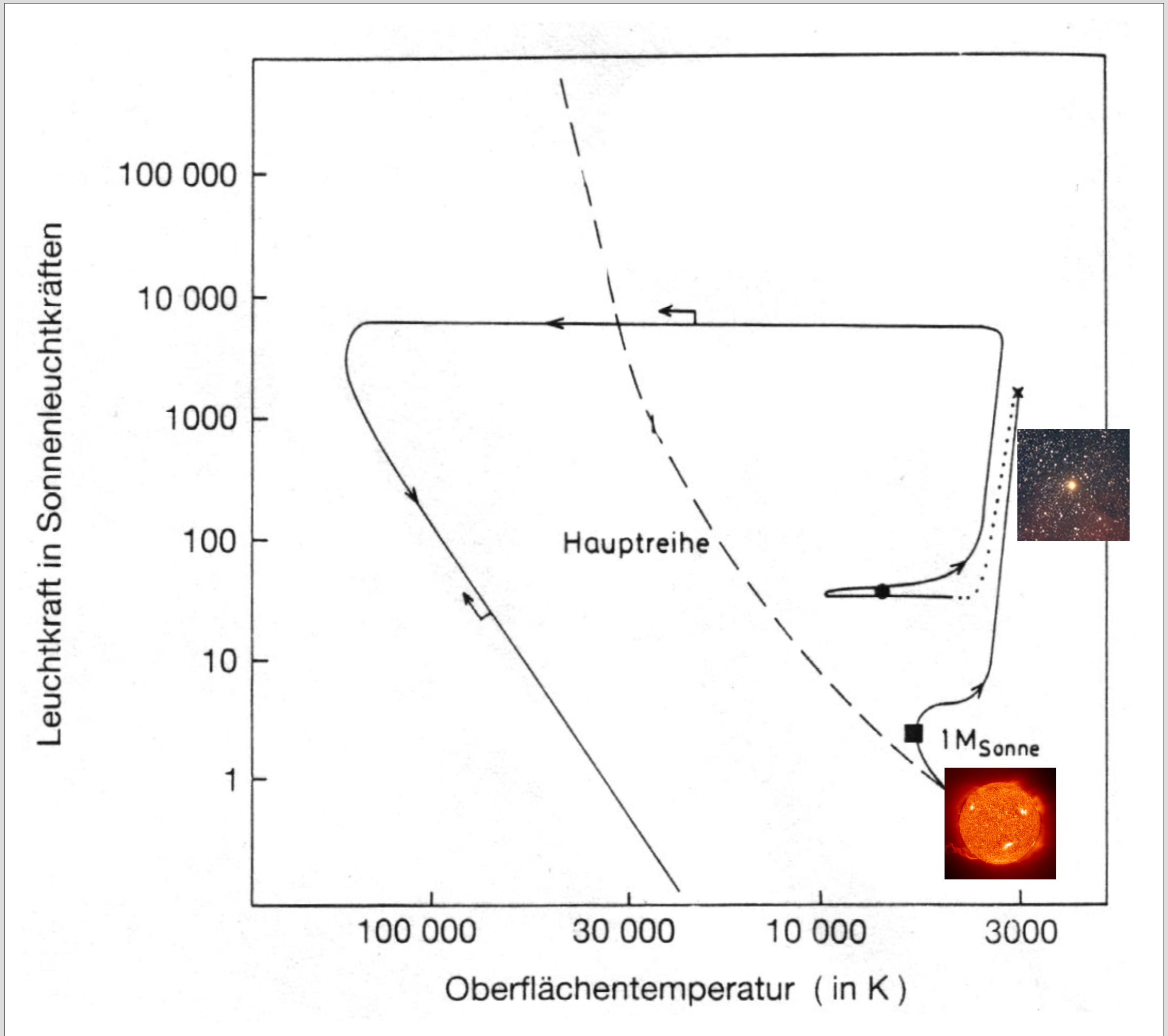
- Radius 10 to 1000 $R_\odot$
- $T_{eff}$ ~ 3500 (→ Hayashi) K
- Leuchtkraft  $\log L / L_\odot = 3 – 4$
  $M_{bol}$ = -3 bis -6 mag


Hayashi Line

# Stellar evolution – low mass stars

## HRD with the path of a star with 1 $M_\odot$




**stage**
example

**Main Sequence**
sun

**Reg Giant**
$\mu$ Cepheus (Granat star)

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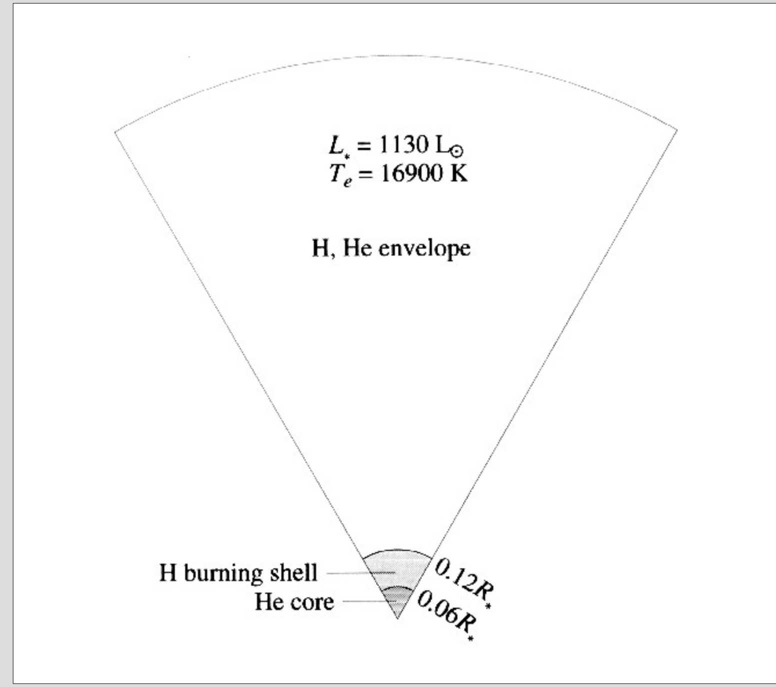
# Shell burning and degeneracy

→ **Shell burning feeds the core**

- shell and core **develop**
  (apart from feeding)
  **independently from each other**

- the **nucleus grows steadily**
  and the **density increases**
  → **no** longer a **pure ideal gas**
  → **but evolves into a** (non-relativistic)
  **degenerate gas (Pauli principle)**




In such a gas the **pressure** is **independent** of the **temperature it depends only on the density**

$$P \propto \rho^{5/3}$$

(Mitteilung aus dem Astrophysikalischen Observatorium, Institut für Sonnenphysik, Potsdam.)

**Über das Eintreten von Elektronenentartung im Sterninnern.**

Von **P. ten Bruggencate** in Potsdam.

Mit 1 Abbildung. (Eingegangen am 11. Januar 1936.)

1. Physikalische Bedeutung der ROSSELANDschen Transformation der Grundgleichungen des Sternaufbaues. 2. Die Grundgleichungen und die Lösungstypen für den Fall des idealen Gases. 3. Die Gleichungen für den Fall gewöhnlicher und relativistischer Elektronenentartung. Allgemeine Bemerkungen über die physikalische Realisierbarkeit der *M*- und *F*-Lösungen. 4. Die SOMMERFELDsche Entartungsbedingung und ihre zweckmäßige Umformung. 5. Bedingungen für Zonen gewöhnlicher Elektronenentartung im Sterninnern.

# Helium flash

## Degeneracy

The **pressure** is **independent** of the temperature **it depends only on the <u>density</u> P $\propto$ $\rho^{5/3}$**

Shell burning feeds the core ↔ stellar core growths

→ **T rises** BUT **pressure stays constant**

→ is T high enough He burning starts BUT with $\varepsilon \propto$ **$T^n$ energy production** builds up **extremly** fast and T rises even futher

→ due to the indepency of the pressure from T

→ no change in pressure but core heats up more

run away process so He burning starts not slowly but instantly in a **<u>Helium Flash</u>**

→ **star 'jumps' in the HRD to the Horizonal Branch** parts of the outer layer are pushed off.

## Horizontal Branch Stars

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# Horizontal branch stars

**Star 'jumps' in the HRD to the Horizonal Branch**

## Horizontal branch star

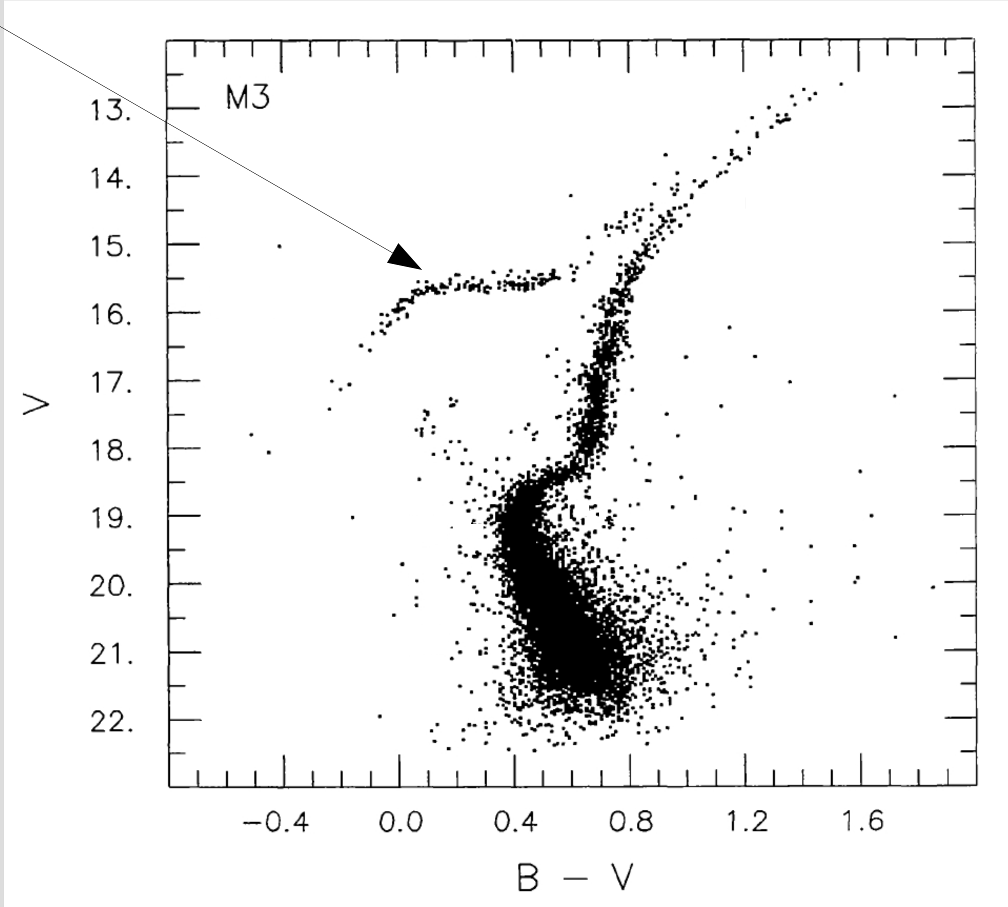
star with Helium burning

- **Radius 5 – 10 $R_\odot$**
- **Luminosity log $L / L_\odot \sim 1.5$**
  **$M_{bol} \sim +1$**

depending on how much of the outer layer was shed its temperature

- **$T^{eff} \sim 6000$ to 30000 K**

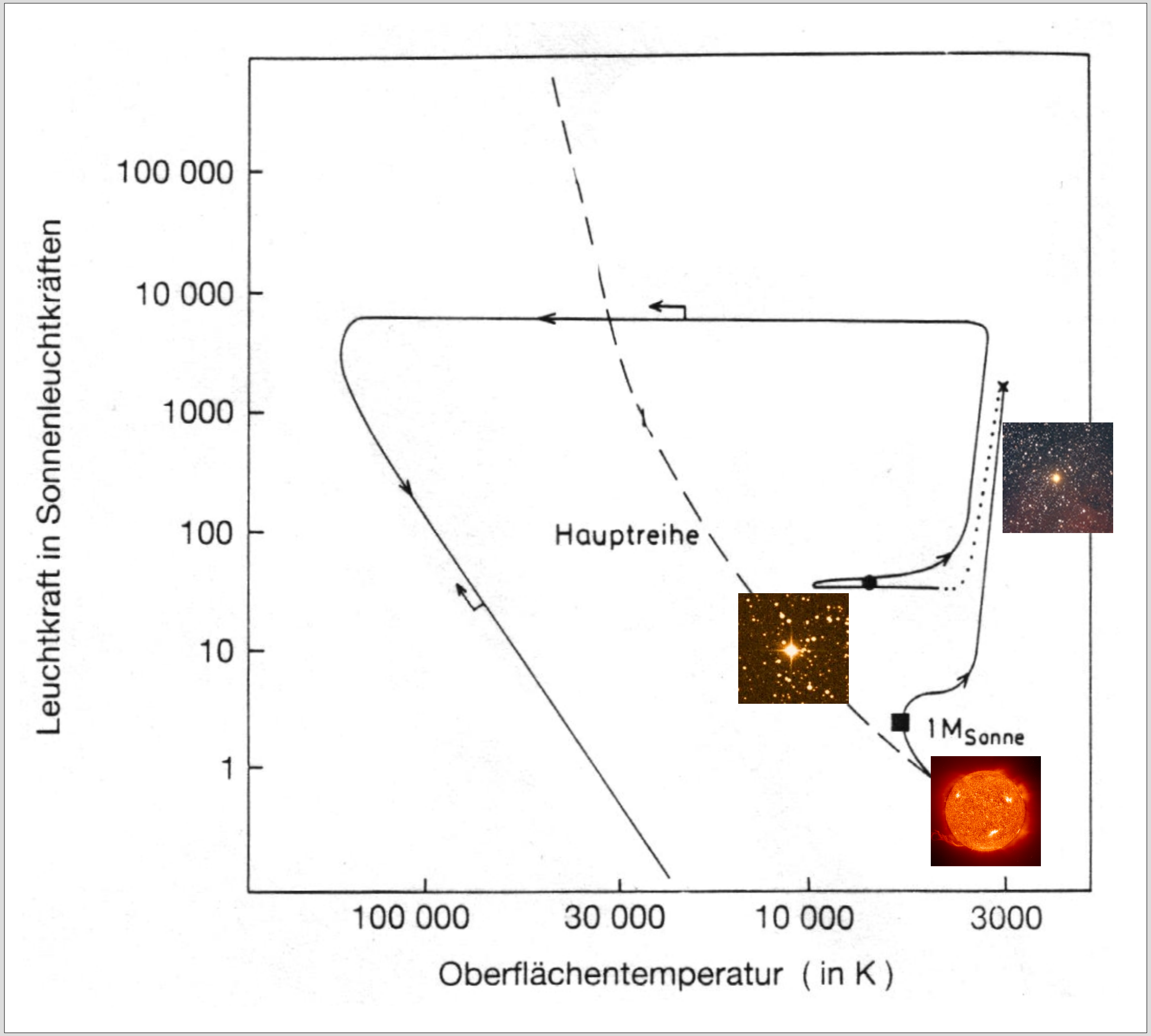
Since all horizontal branch stars have the same absolute magnitude ↔ **horizontal** they can be used to measure distances




(Renzini & Fusi Pecci 1988)

# Stellar evolution – low mass stars

## HRD with the path of a star with 1 $M_\odot$




**stage**
example

**Main Sequence**
sun

**Reg Giant**
μ Cepheus (Granat star)

**Horizontal Branch star**
RR Lyrae

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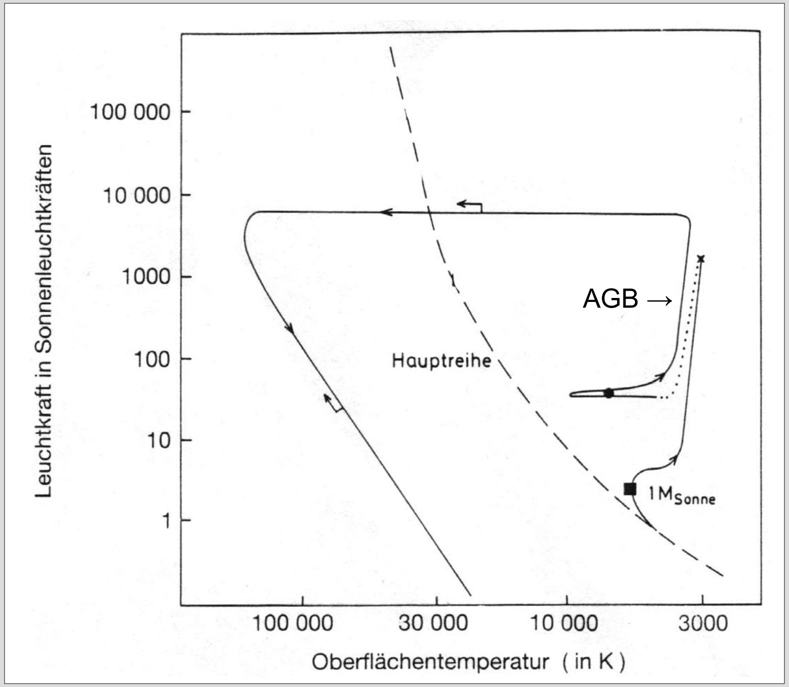
# Horizontal branch to AGB

→ is He used up → pressure drop → a collapse until shell He burning begins
→ no further nuclear burnings are possible, but multiple shell !!!
→ r increases, $T_{eff}$ decreases
→ evolves again towards Hayashi line
→ fully convective
→ similar evolution as Red Giant
→ now **asymptotic giant branch** (AGB)




## Asymptotic Giant Branch Star

- **Radius 100 to 1000 $R_\odot$**
- **$T_{eff}$ ~ 3500 to 4000 K (~ Hayashi)**
- **Luminsity log $L / L_\odot$ = 3 bis 4   $M_{bol}$ = -3 bis -6**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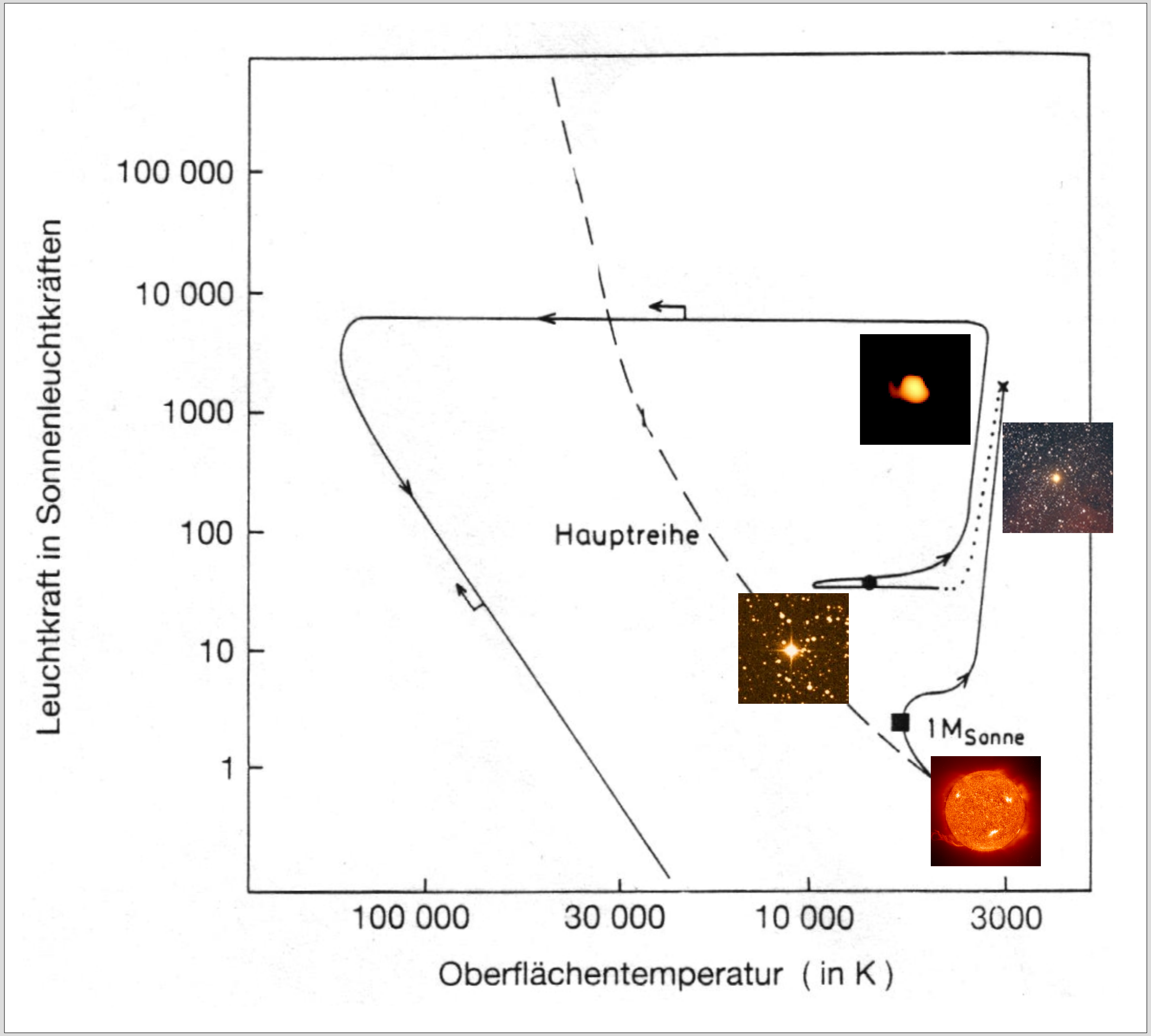
# Stellar evolution – low mass stars

## HRD with the path of a star with 1 $M_\odot$




**stage**
example

**Main Sequence**
sun

**Reg Giant**
μ Cepheus (Granat star)

**Horizontal Branch star**
RR Lyrae

**Asymptotic Giant Branch star**
Mira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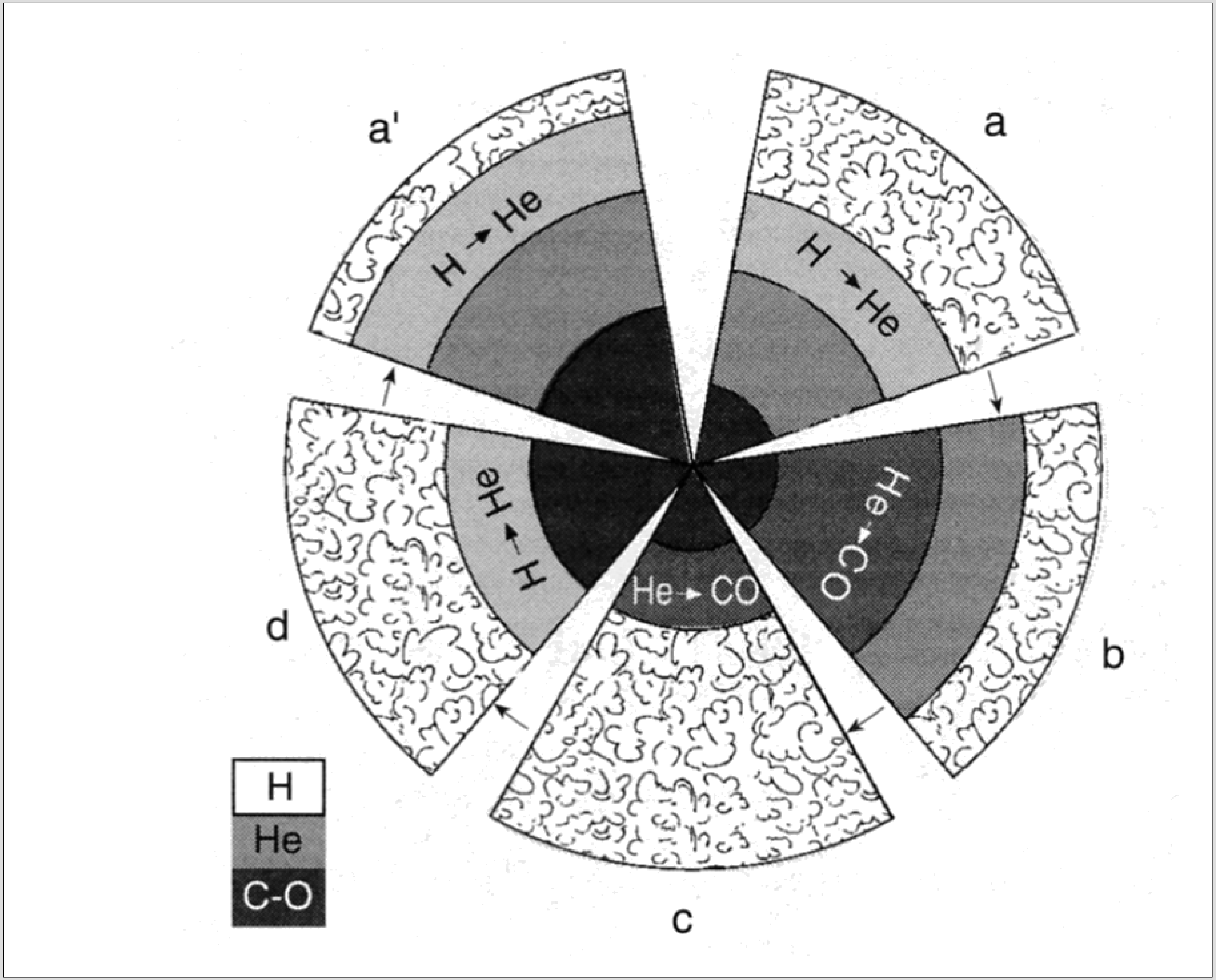
# AGB Phase – Thermal Pulse

Starting point a : H but no He burning shell

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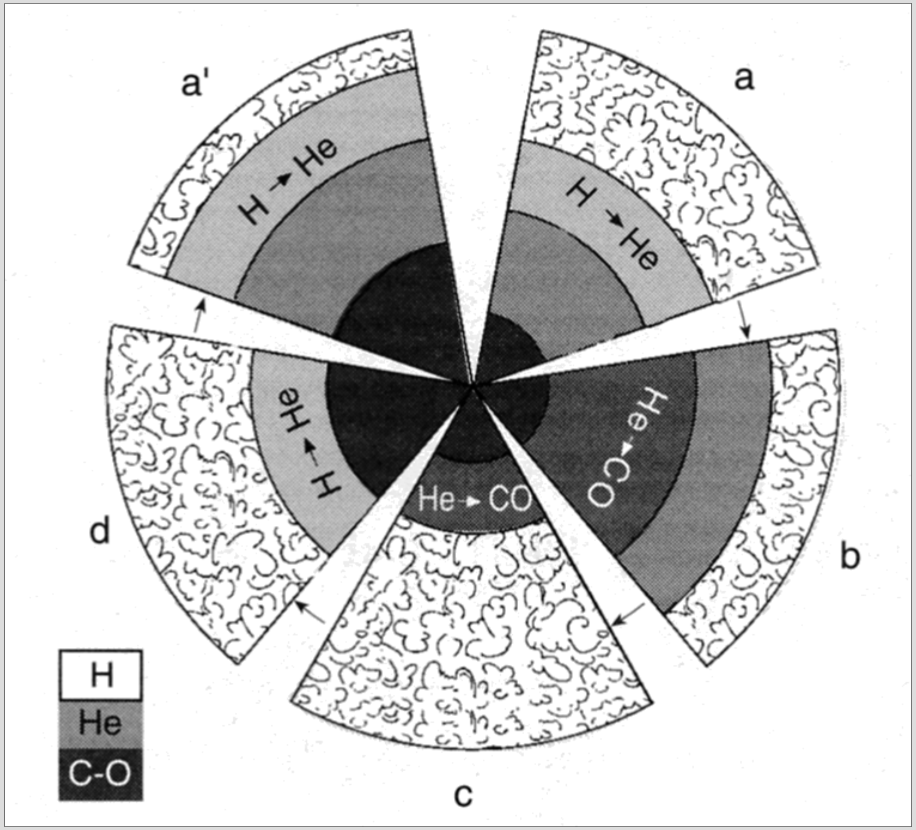
# AGB Phase – Thermal Pulse

**a → b:**

H shell burning leaves He layer behind, further out T drops → H shell burning ends and T sinks further
→ pressure drops
→ star contracts

this heats up the He layer and **He burning** starts in shell

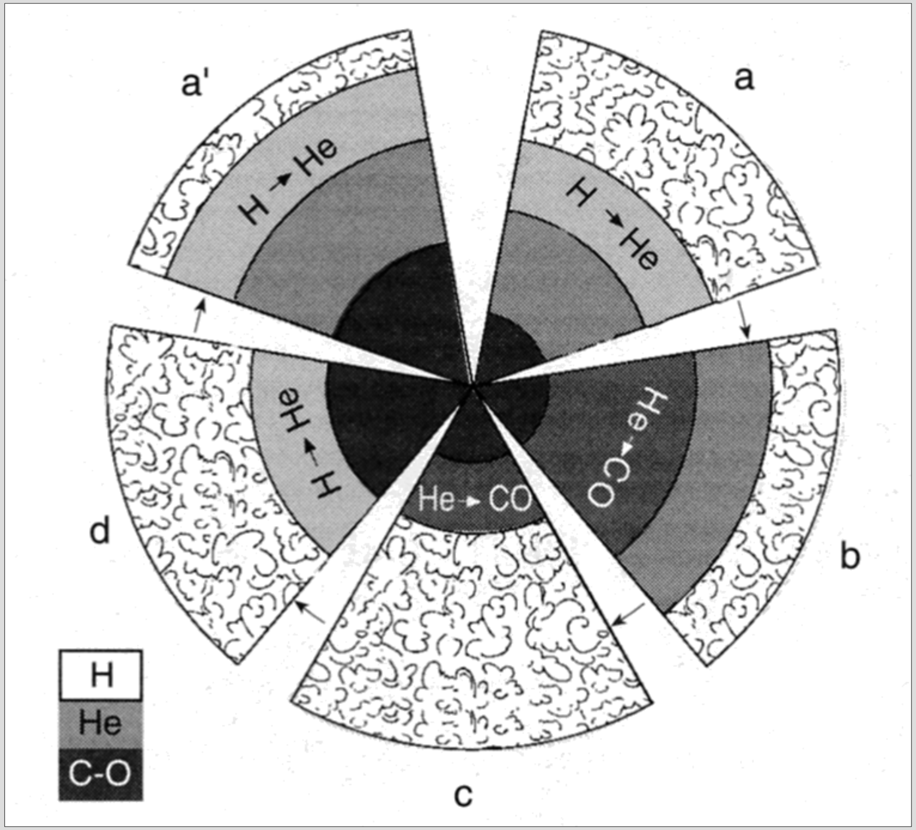


# AGB Phase – Thermal  Pulse

**c → d:**

He shell moves inward
→ He **burning stops** because there is not enough He left
→ heating of the H layers above leads

**H shell burning starts**



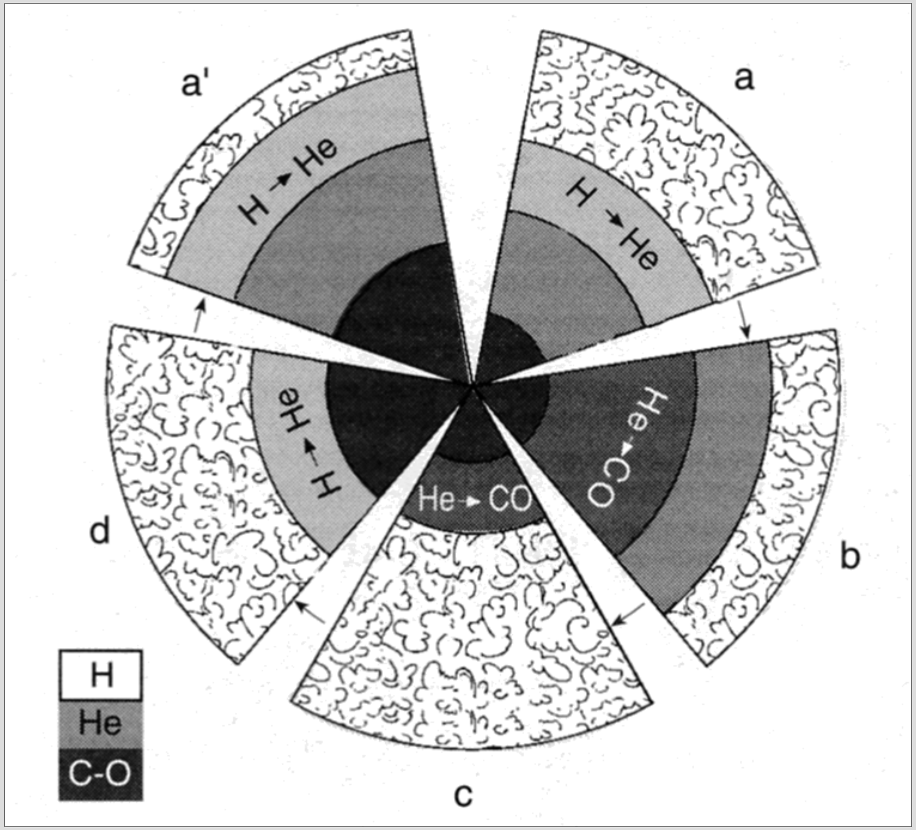
# AGB Phase – Thermal Pulse

**d → a′:**

H burning shell moves up and leaves a He layer

→ **reached the starting point**
**same situation**

starts again at somewhat higher radius the same procedure as




# From AGB to Proto-Planetary Nebula

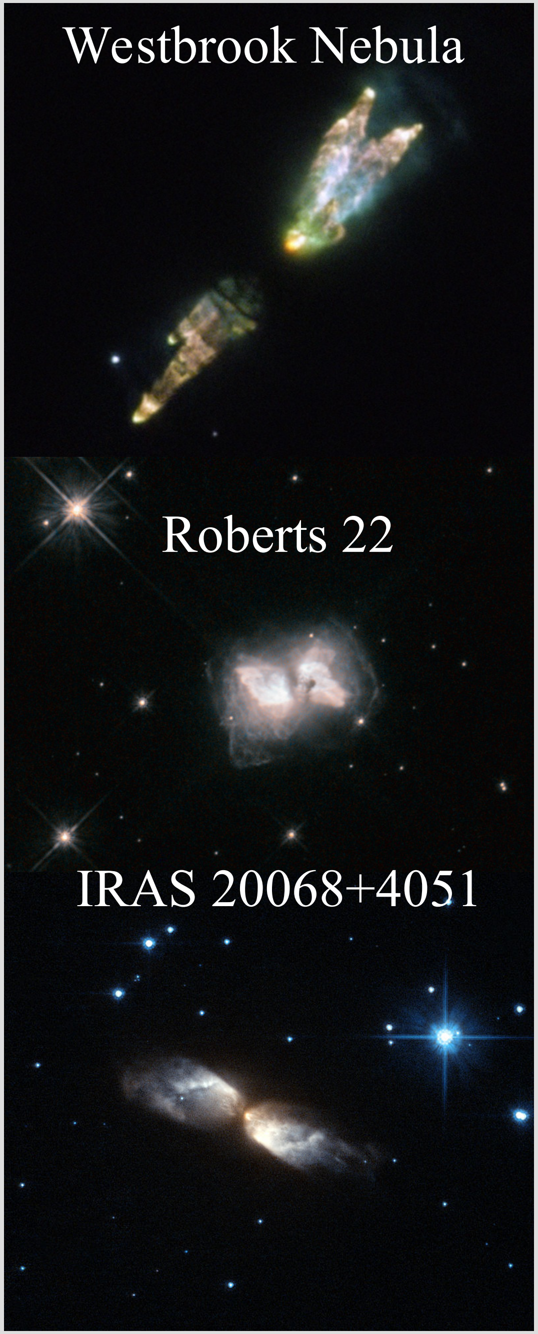
shell burning ends. It leaves

- the degenerate CO nucleus
  from the helium burning

- circumstellar material ↔ old stellar shells
  removed by wind and thermal pulses

The material is atomic or molecular
($CO$, $H_2$) → visible in IR it forms

**Proto-Planetary Nebulae**

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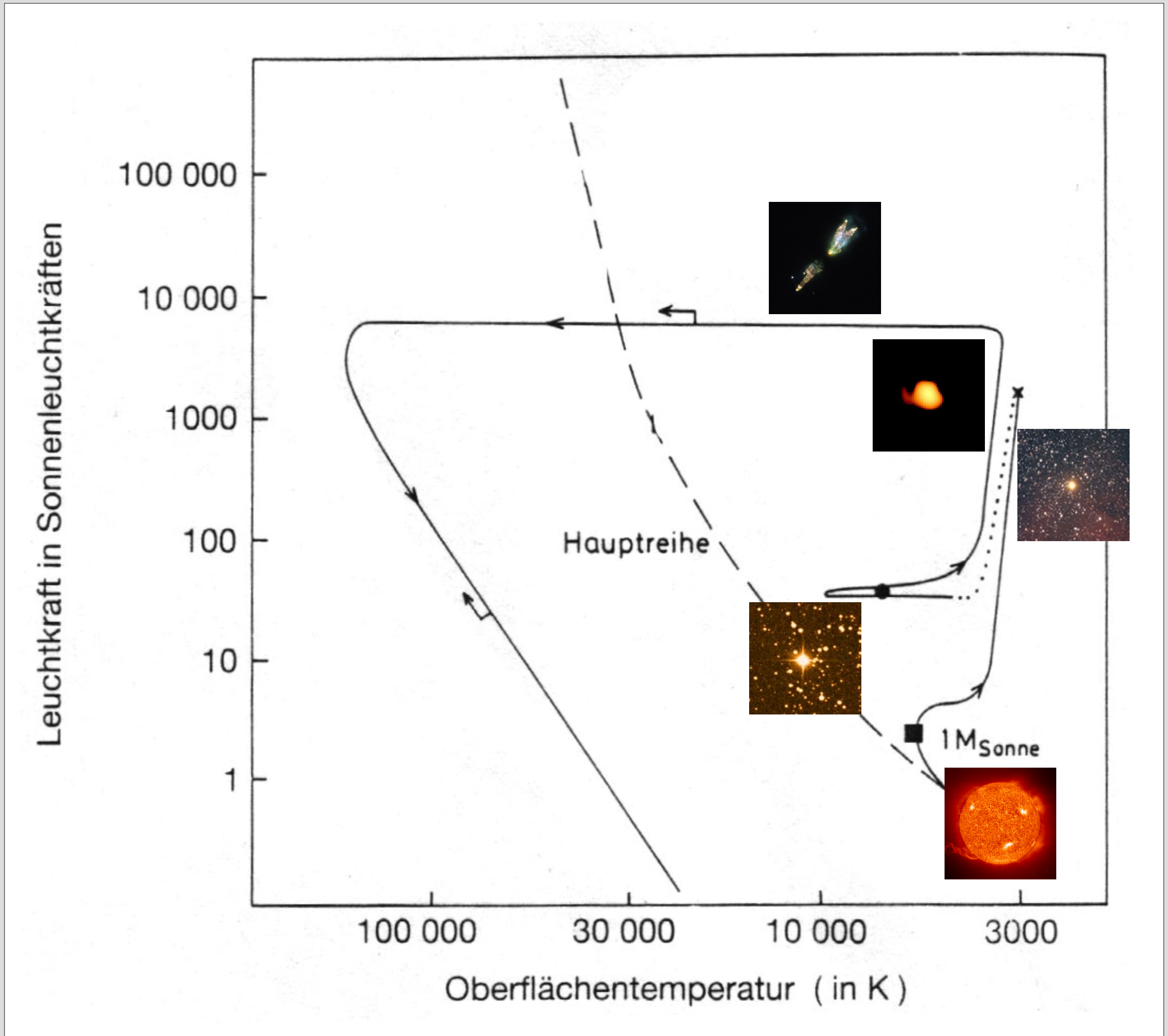
# Stellar evolution – low mass stars

## HRD with the path of a star with 1 $M_\odot$




**stage**
example

**Main Sequence**
sun

**Reg Giant**
μ Cepheus (Granat star)

**Horizontal Branch star**
RR Lyrae

**Asymptotic Giant Branch star**
Mira

**Proto Planetary Nebula**
Westbrook Nebula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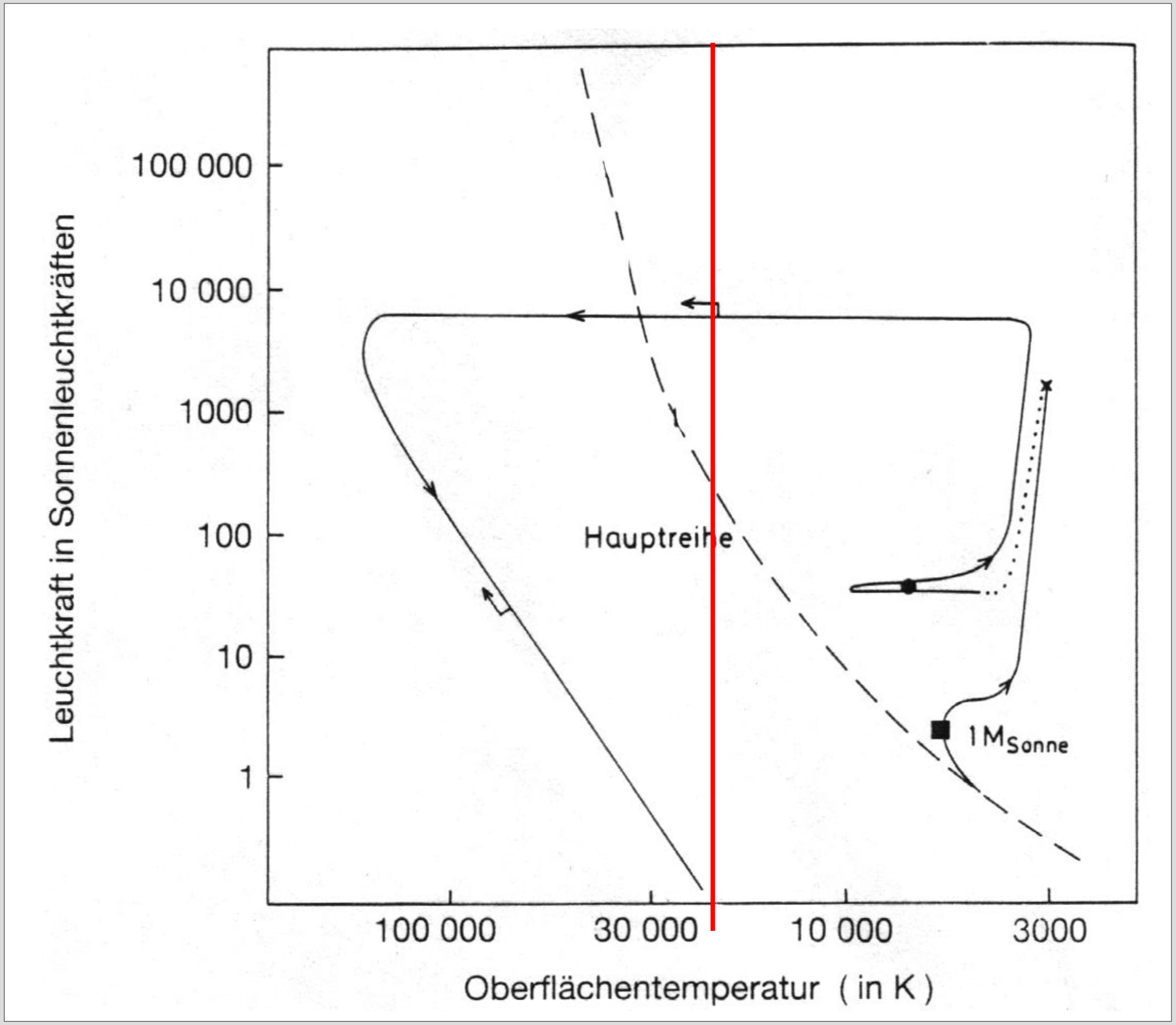
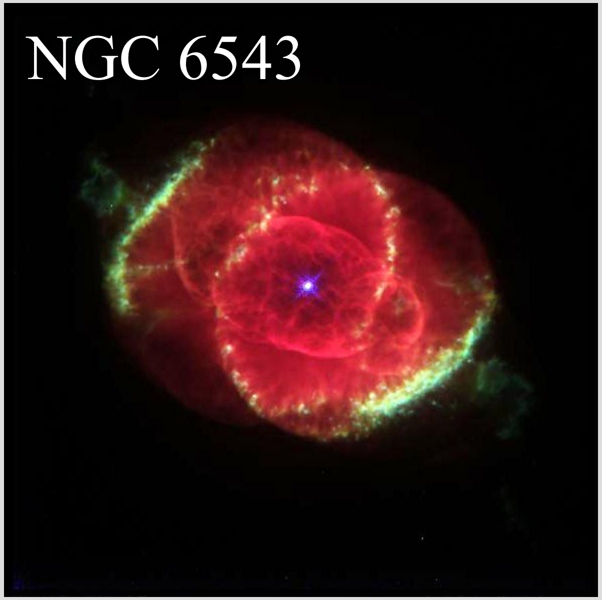
# Proto PN to PN

Planetary Nebulae (PN)

→ star is hot enough → proto-PN ionized → now visible as PN




HST image in $H_\alpha$,[NII],[OIII],[SII]

– $T_{eff}$ of white dwarf high → UV photons to ionize the gas → PN

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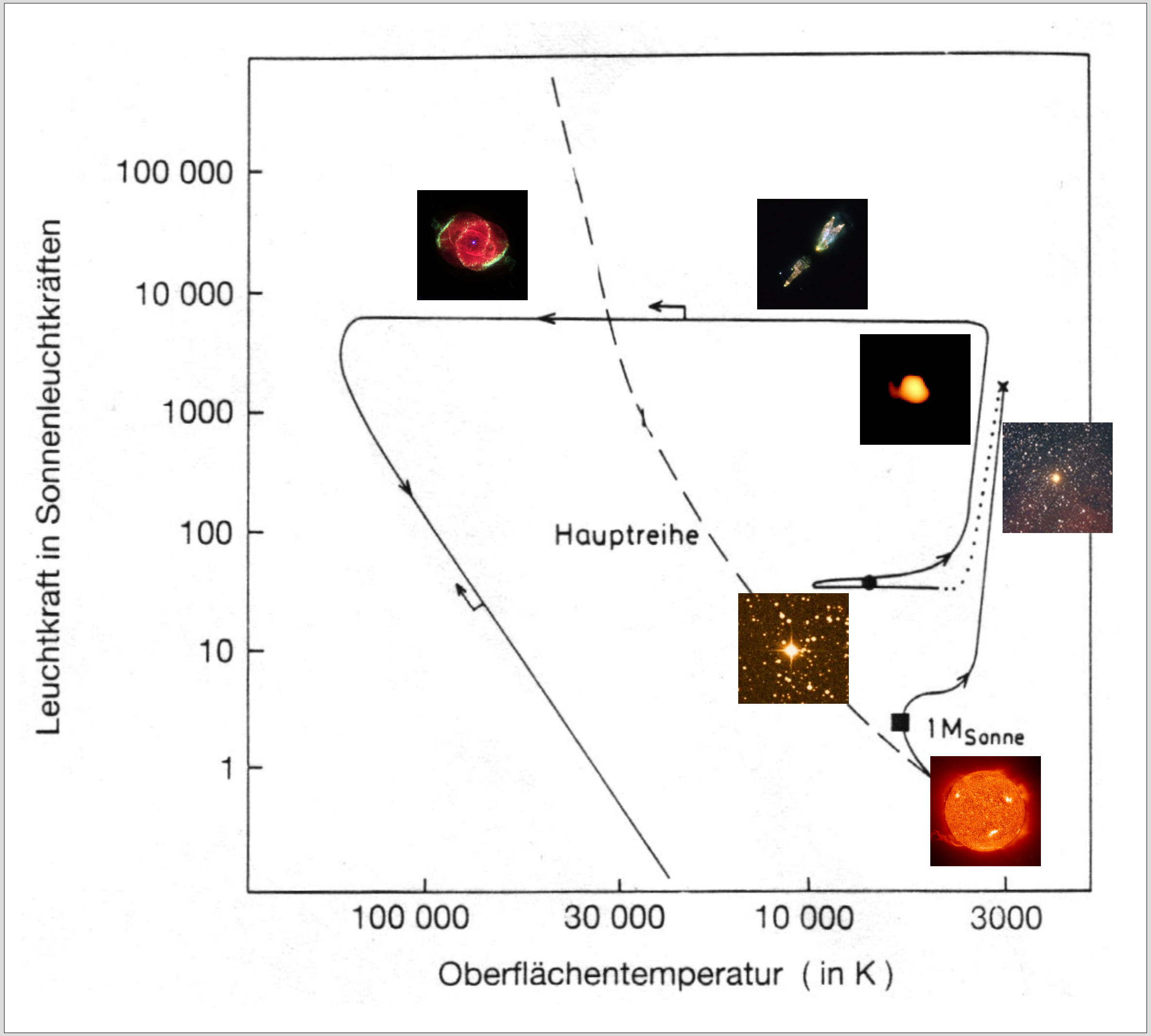
# Stellar evolution – low mass stars

## HRD with the path of a star with 1 $M_\odot$




**stage**
example

**Main Sequence**
sun

**Reg Giant**
μ Cepheus (Granat star)

**Horizontal Branch star**
RR Lyrae

**Asymptotic Giant Branch star**
Mira

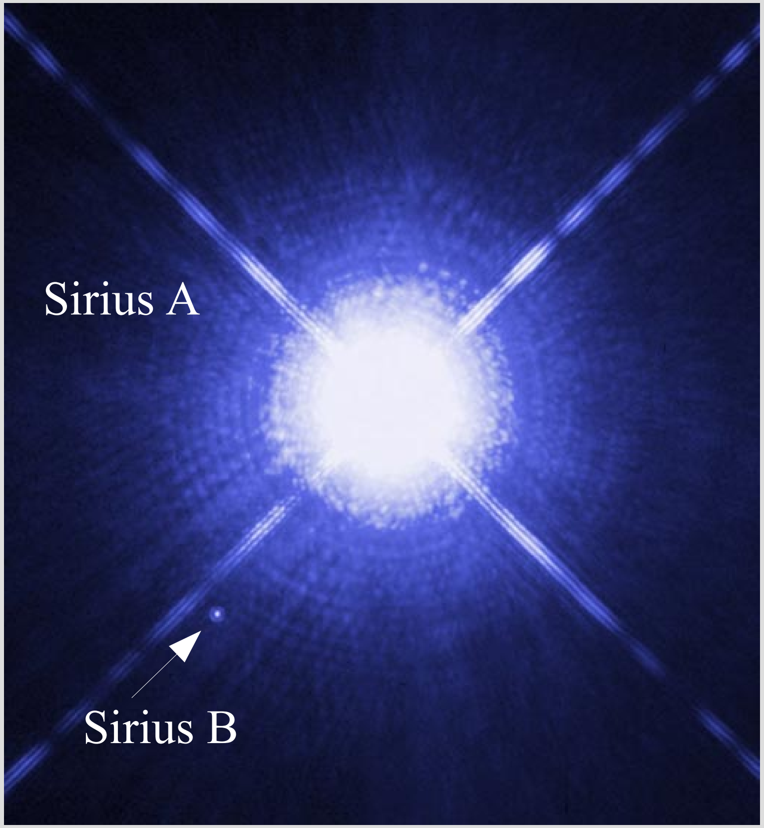
**Proto Planetary Nebula**
Westbrook Nebula

**Planetary Nebula**
NGC 6543

# Proto PN to PN to White Dwarf

During the Proto-PN and PN phase from the stars only the degenerate CO core remains.
The thermal pulses removed all outer shells.

The core now forms the remaining final central star, a

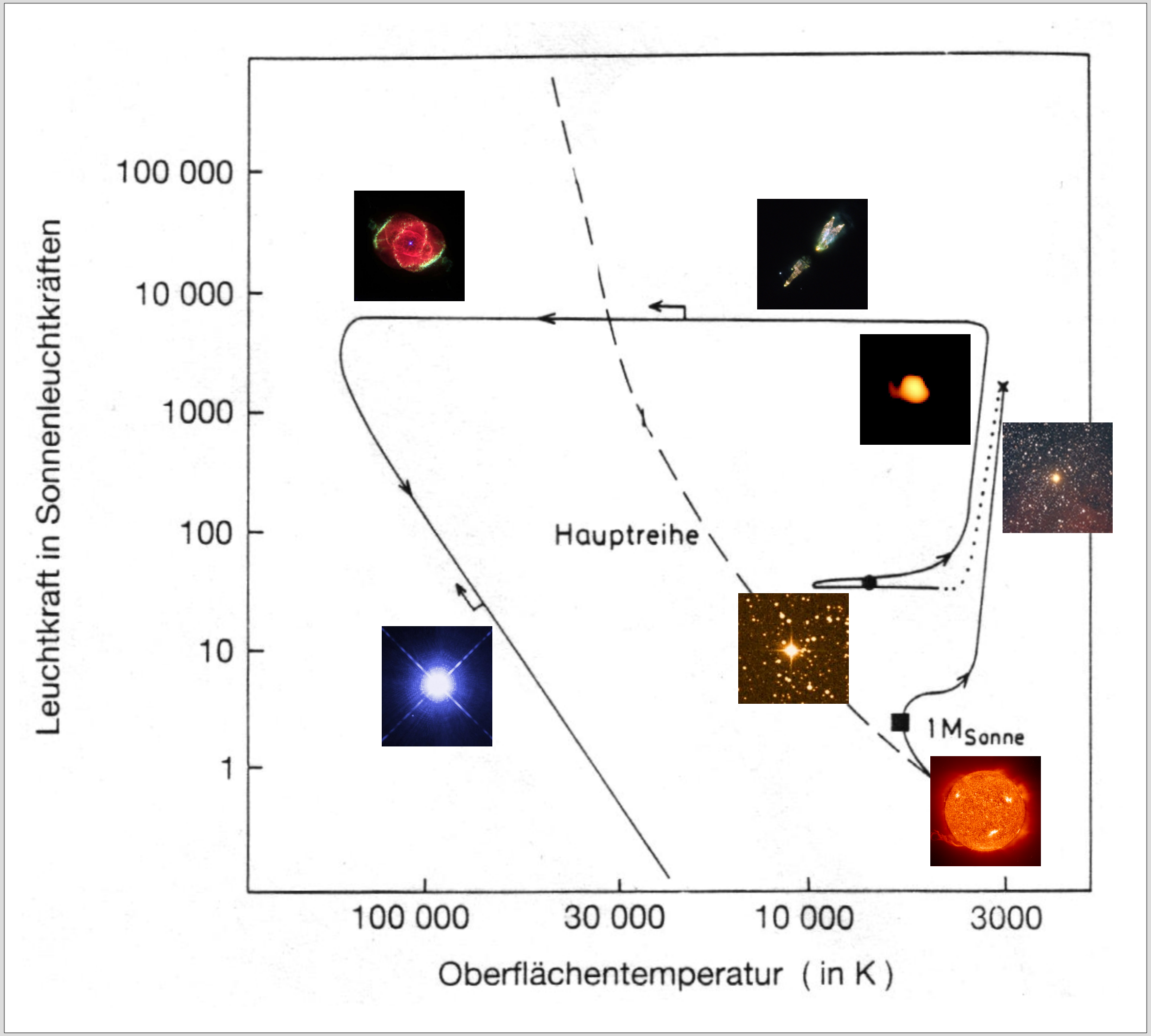



## White Dwarf

- **Radius ~ 0.01 $R_\odot$**
- **$T_{eff}$ ~ 5000 – 50000 K**
- **Luminosity log $L / L_\odot$ = 1 bis -5** **$M_{bol}$ = 2 bis 17**

# Stellar evolution –  low mass stars

## HRD  with the path of a star with 1 $M_\odot$




**stage**
example

**Main Sequence**
sun

**Reg Giant**
μ Cepheus (Granat star)

**Horizontal Branch star**
RR Lyrae

**Asymptotic Giant Branch star**
Mira

**Proto Planetary Nebula**
Westbrook Nebula

**Planetary Nebula**
NGC 6543

**White  Dwarf**
Sirius B

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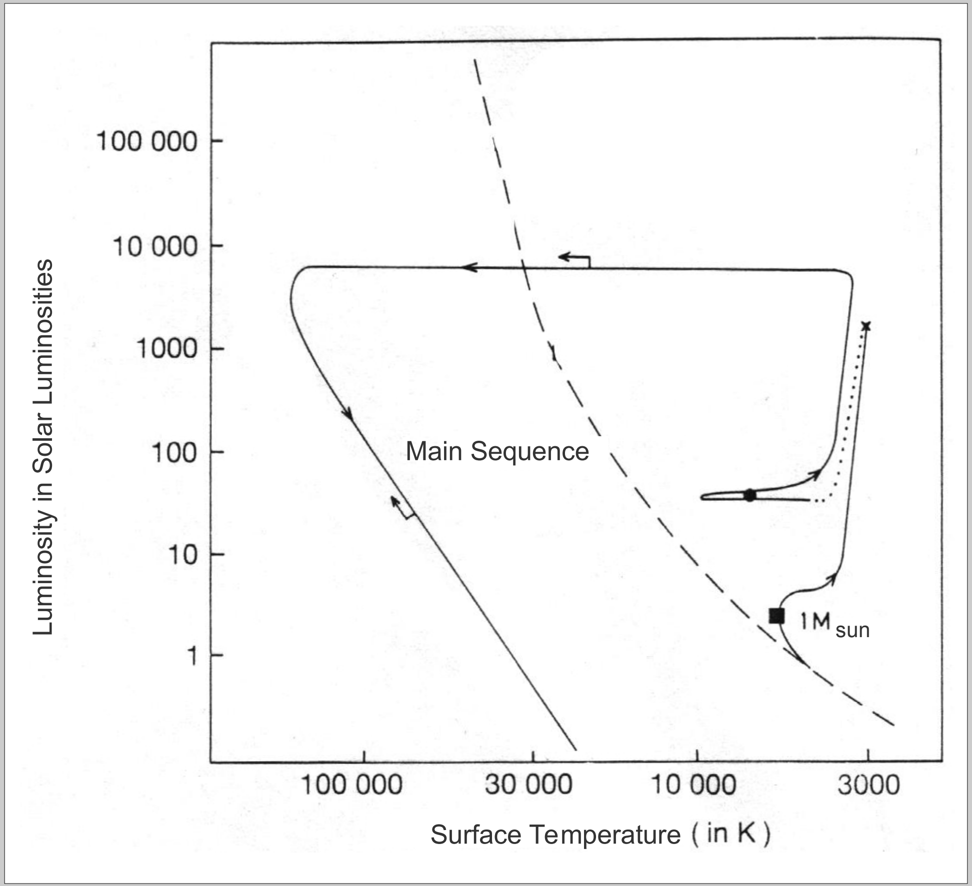
# Stellar evolution of low mass stars

Main-Sequence star **MS**
↓
Red Giant **RG** (Helium Flash)
↓
Horizonal Branch star **HB**
↓
Asymptotic Giant Branch star **AGB** (Thermal Pulses)
↓
Post Asymptotic Giant Branch star **P-AGB** + Proto Planetary Nebula **P-PN**
↓
White Dwarf **WD + Planetary** Nebula **PN**)
↓
White Dwarf **WD**

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# Stellar evolution of low mass stars

Main-Sequence star **MS**

↓

Red Giant Branchstar **RGB** (Helium Flash)

↓

Horizonal Branch star **HB**

↓

Asymptotic Giant Branch star **AGB** (Thermal Pulses)

↓

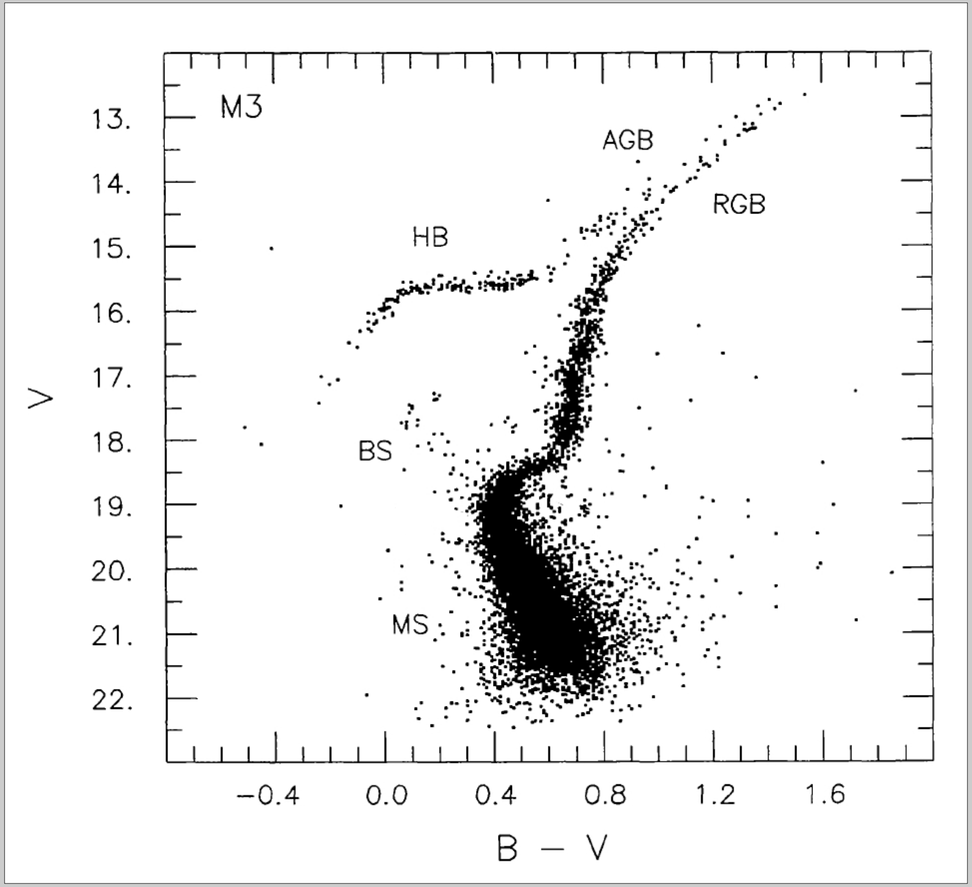
Post Asymptotic Giant Branch star **P-AGB** + Proto Planetary Nebula **P-PN**

↓

White Dwarf **WD +** Planetary Nebula **PN**)

↓

White Dwarf **WD**




(Renzini & Fusi Pecci 1988)

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# Stellar evolution of low mass stars

Main-Sequence star **MS**

↓

Red Giant Branchstar **RGB** (Helium Flash)

↓

Horizonal Branch star **HB**

↓

Asymptotic Giant Branch
star **AGB** (Thermal Pulses)

↓

Post Asymptotic Giant Branch
star **P-AGB** + Proto Planetary
Nebula **P-PN**

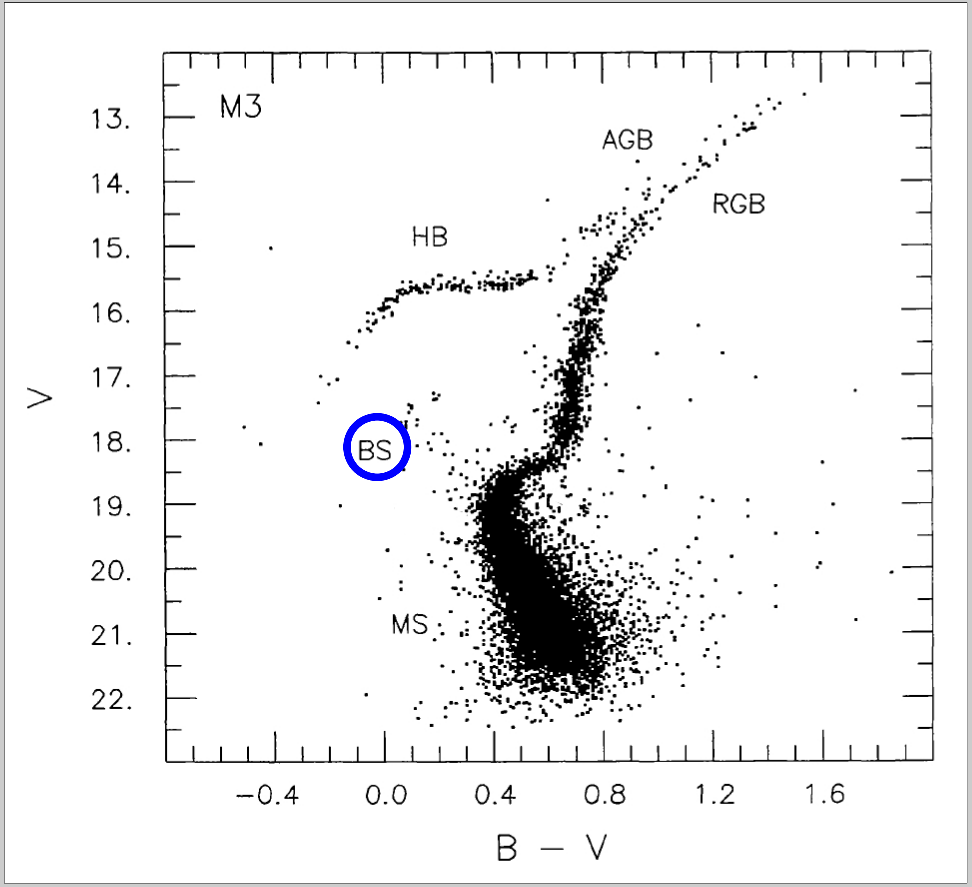
↓

White Dwarf **WD +** Planetary
Nebula **PN**)

↓

White Dwarf **WD**

**BS ???**




(Renzini & Fusi Pecci 1988)

# BS ↔ Blue Stragglers

Blue Stragglers

Position of the stars in HRD → would have to be main sequence stars

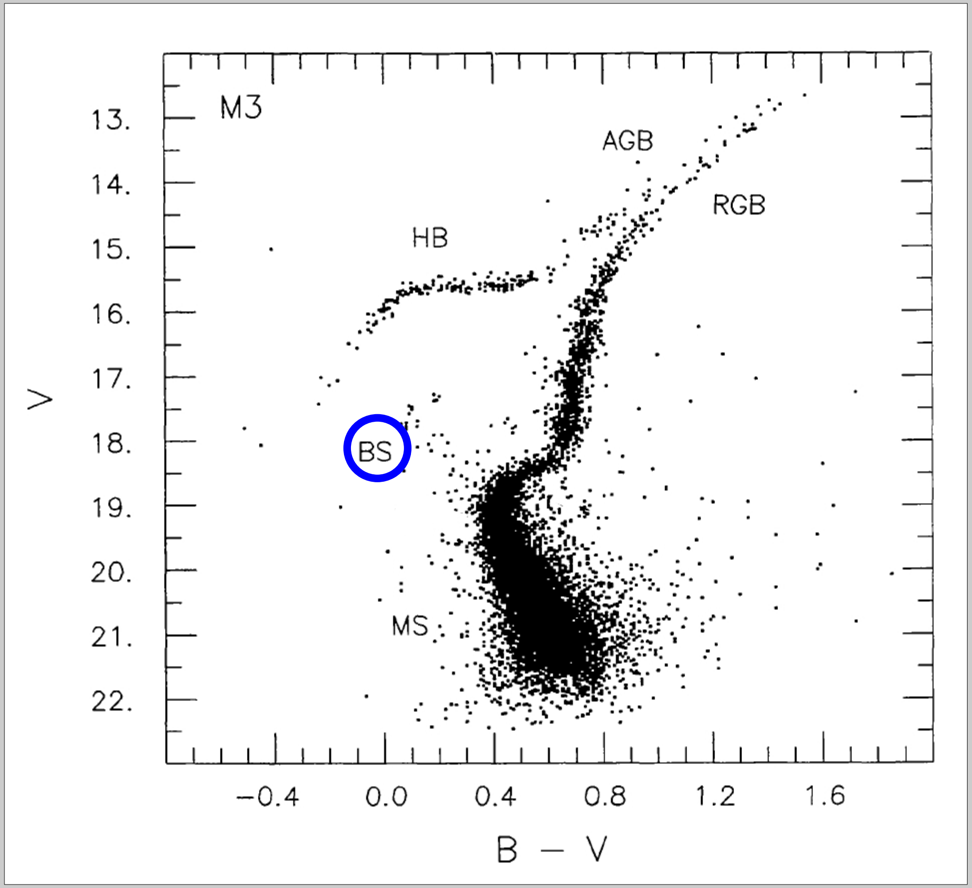
→ **contradiction with age!**

**BS ???**

in cluster all the stars are of the same age if BS are main sequence stars they are more massive stars and above the turn off !!!

**But !** more massive main star have already evolved into Red Giant Stars !!

**REJUVENATION ?**




(Renzini & Fusi Pecci 1988)

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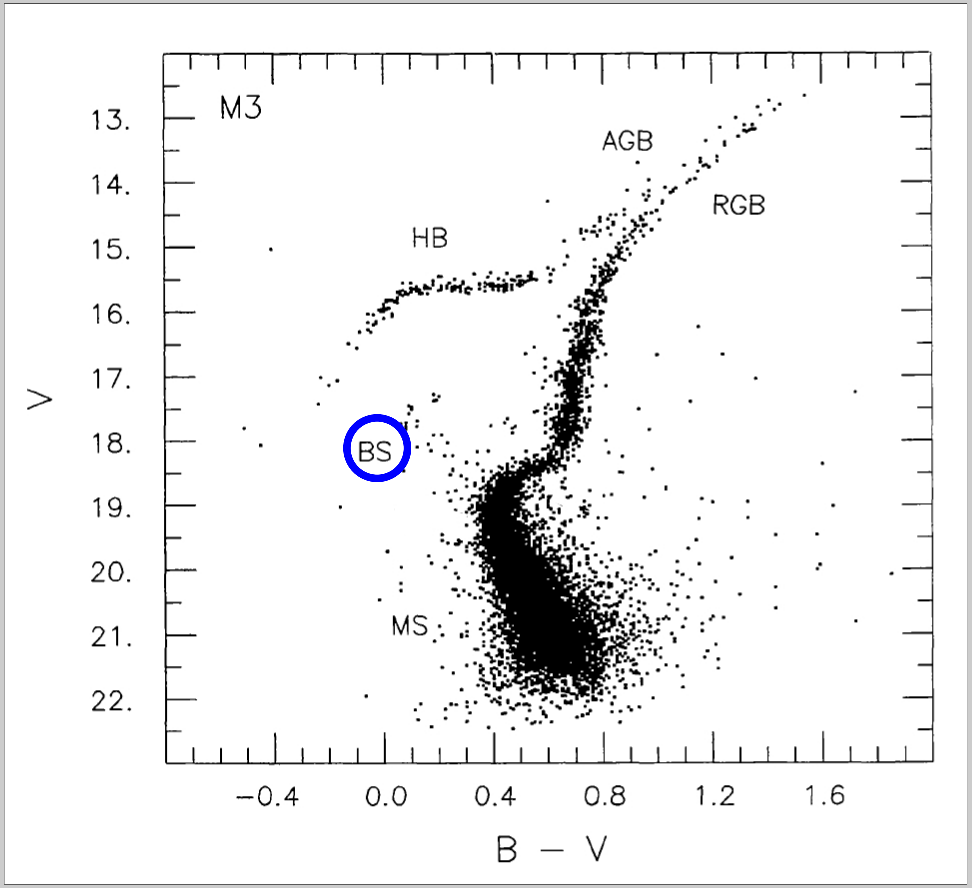
# BS alias Blue Stragglers

Blue Stragglers

**REJUVENATION ?     YES !**

**low mass ★ + low mass ★ = more massive low mass★**

By merging of two low mass stars a low mass star with higher mass is formed. This star now correctly lies on the main-sequence above the turn off




(Renzini & Fusi Pecci 1988)

**BS ?**

**BS = Blue Stragglers**

✔

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# Summary: Stellar evolution – low mass stars

- initial mass **below ~ 7 $M_\odot$** (depends on metallicity & rotation)

- < **1.7 $M_\odot$** degenerate core in **Red Giant phase**

- **> 1.7 $M_\odot$** degenerate core in **AGB Phase**

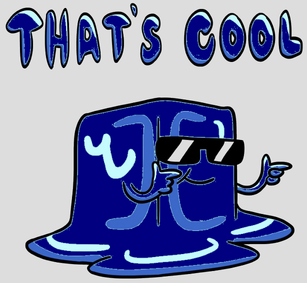
- low mass stars are able to start **only H and He burning**

- in **AGB phase** simultaneous He and H shell burning ↔ Thermals pulses

- in **AGB phase** higher elements are generated in the **s-process**
  (He in shell reacts in with C → n free)

- after the AGB phase ↔ mass lost in TP the circumstellar material forms a **Proto PN** that later becomes a **Planetary Nebula**

- **low mass stars** end as **White Dwarf (WD)**,
  that now **cool … and cool …**

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