stellar evolution

massive 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 – massive 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 – main sequence

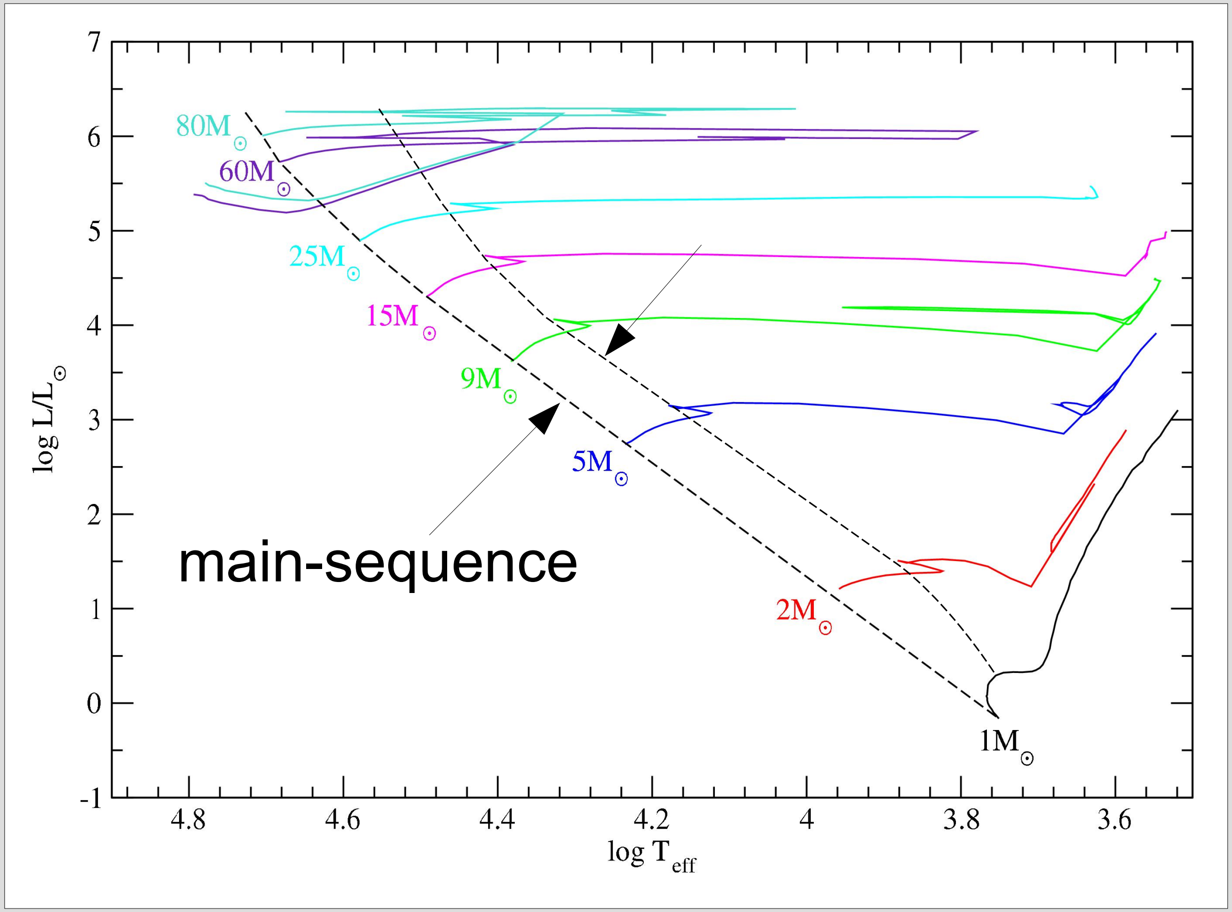
main sequence stars

- note the MS ist not really a line but has a width ↔ within the MS phase a stars changes L and T_{eff}

  Remember

  $$L = 4\pi\sigma r^2 T^4_{eff} \quad PV = nkT$$

  hydrogen burning
  → n decreases due to Fusion → reacts with increasing T_{core} → T_{eff}
  → increases luminosity L
- MS phase ends with lack of H in core



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Stellar evolution – massive stars

classic and important abbreviations

main-sequence O-star ↔ **MS O-star** or **O-star**

Red Supergiant ↔ **RSG**

Yellow Supergiant ↔ **YSG**

Blue Supergiant ↔ **BSG**

Wolf-Rayet star ↔ **WR**

Luminous Blue Variable ↔ **LBV**

Supernova ↔ SN

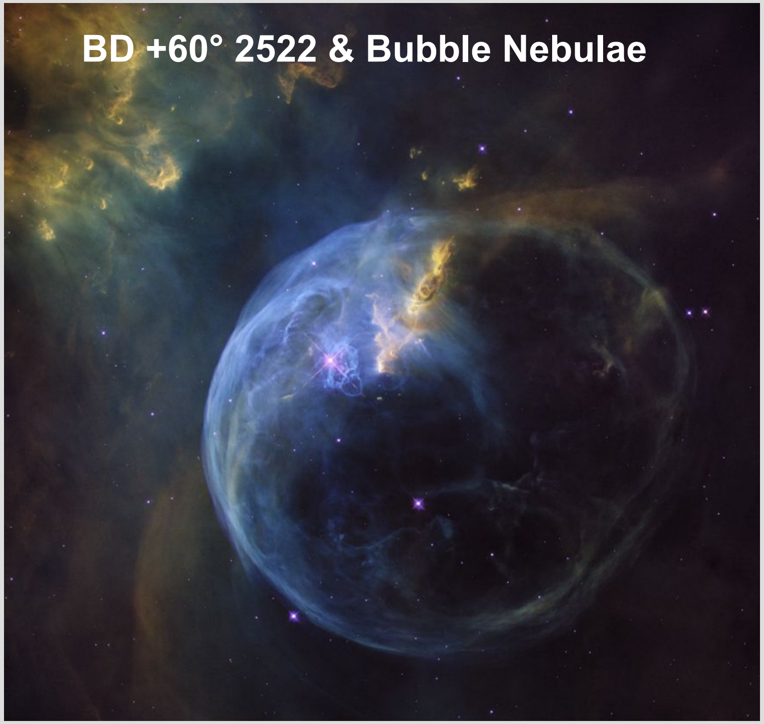
red versus blue

'empirical border'

transition between B and A star → **log T_{eff} ~ 3.98** ~ 9500 K

Stellar evolution – massive stars

main sequence stars



- star in **hydrostatic equilibrium**
- star started **hydrogen core burning**
- **longest** phase a stars, **~90% total lifetime**
- **initial mass M_{ini} > 7 to 120 (200/300) $M_{\odot}$**
- **radius 10 to 100 $R_{\odot}$**
- **T_{eff} = 20000** to **50000 K**
- **Luminosity**

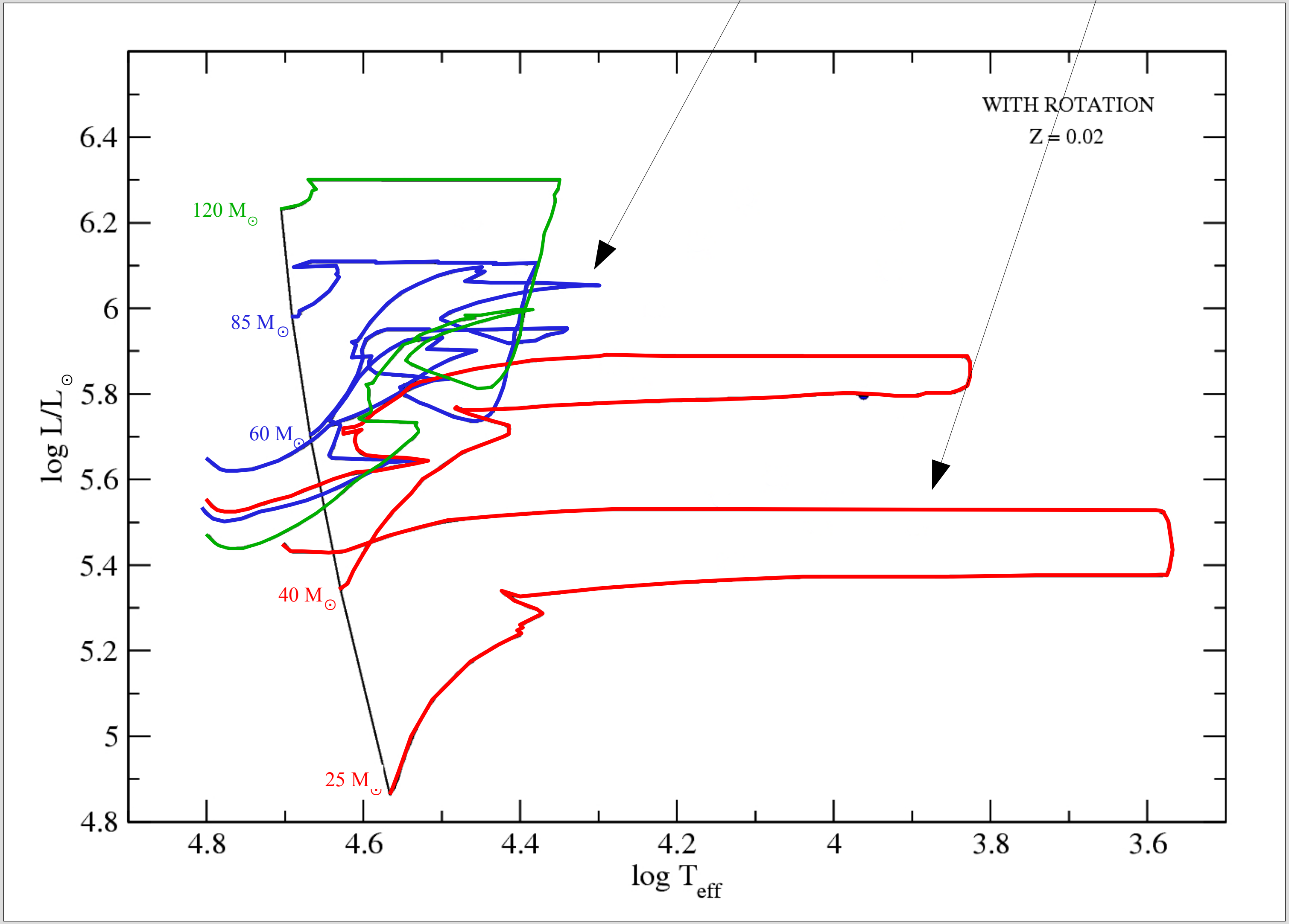
  $\log L / L_{\odot}$ = 5 bis 6

  M_{bol} = -8 bis -11
- **Hydrogen** burning **mainly via CNO cycle**
- Stars **M_{ini} < 1.2 $M_{\odot}$** core **radiativ**

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

Stellar evolution of massive stars

- end MS phase → no fusion → T_{core} drops → pressure drops → star collapses → T rises → onset of **H shell burning and** radius enlarged (~ 50-500 $R_\odot$)* → star turns into a **Blue/Red Supergiant (BSG/RSG)**

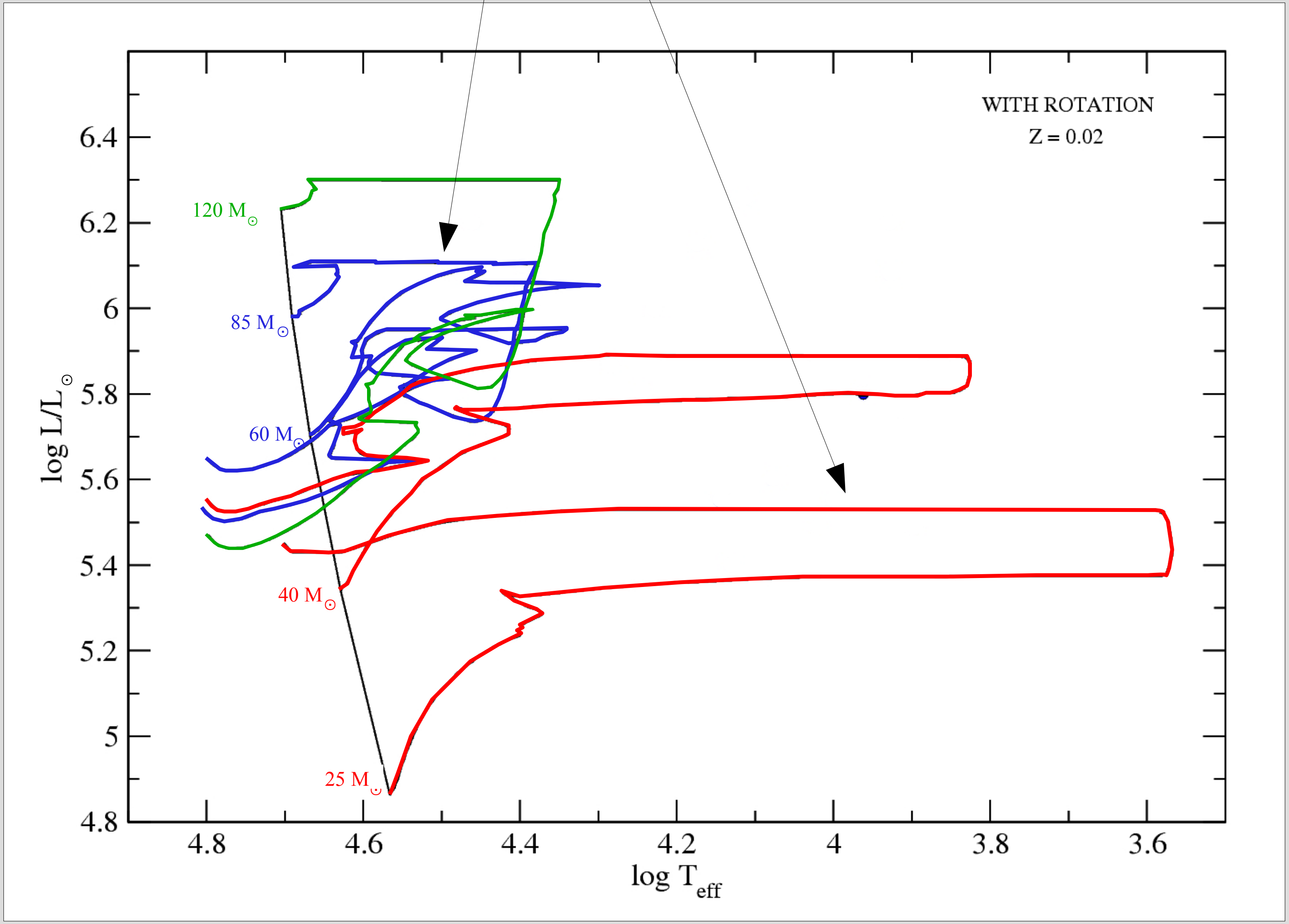


* RSG up to $1000R_\odot$

Using Geneva tracks

Stellar evolution of massive stars

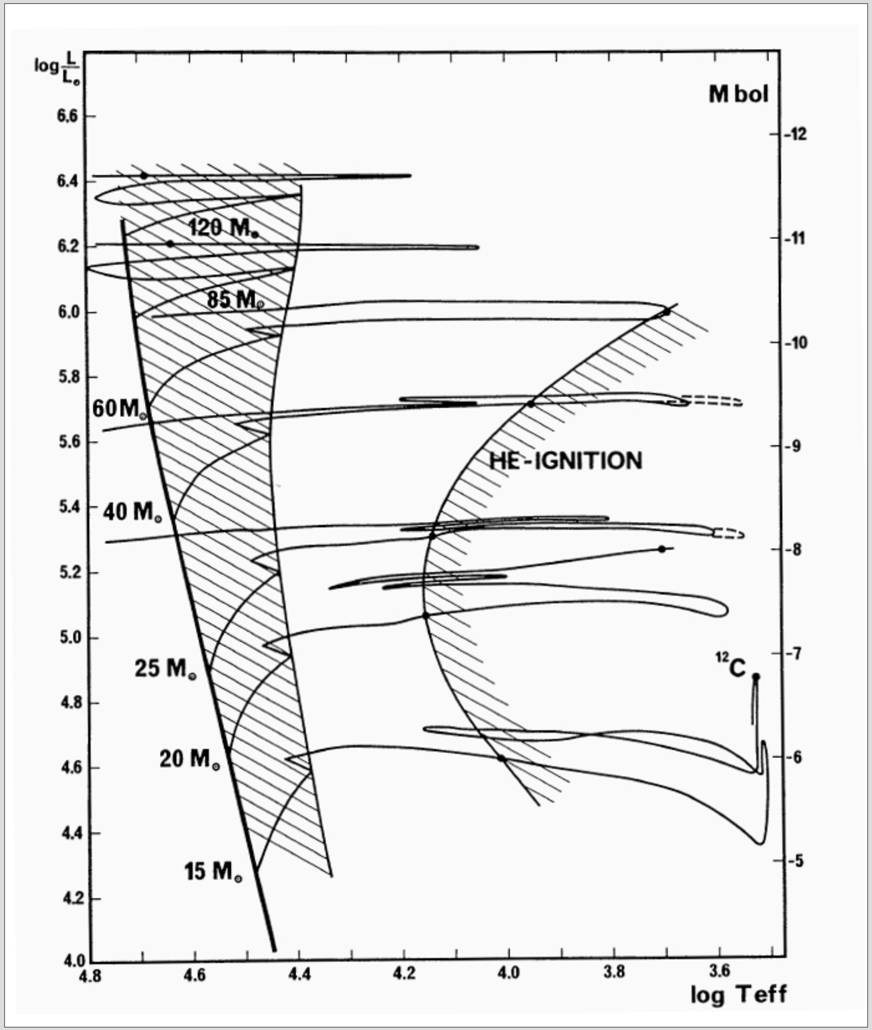
- **Blue/Red Supergiant (BSG/RSG)** first have **H shell burning** later **He core burning** can start
  ….. and



Using Geneva tracks

Stellar evolution – massive stars

Evolution of massive stars – <u>burning phases</u>



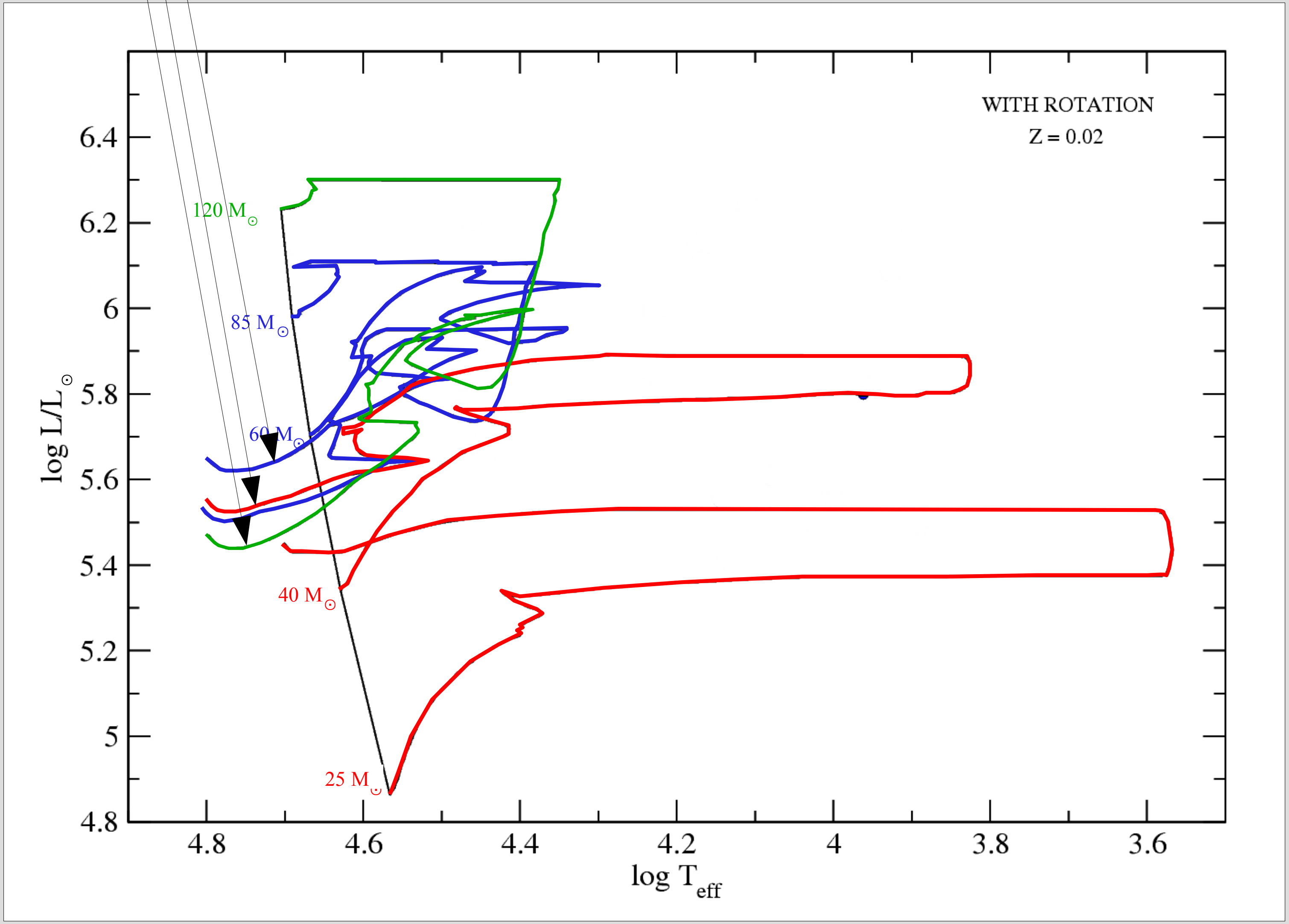
- **main-sequence O-star**
  H-core burning

- **Red/Blue Supergiant**
  first H-shell burning
  later
  C- , O-core burning and
  He- & H- shell burning
  finally
  Si-core burning and
  C- & O- & He- & H-burning shell

massive stars
start **H** up to **Si burning** and **H** to **C shell burning**

Stellar evolution of massive stars

- after the BSG/RSG phase the more massive stars turn into **very hot Wolf-Rayet stars** ↔ **lost a lot of their envelop show hot He core**



Using Geneva tracks

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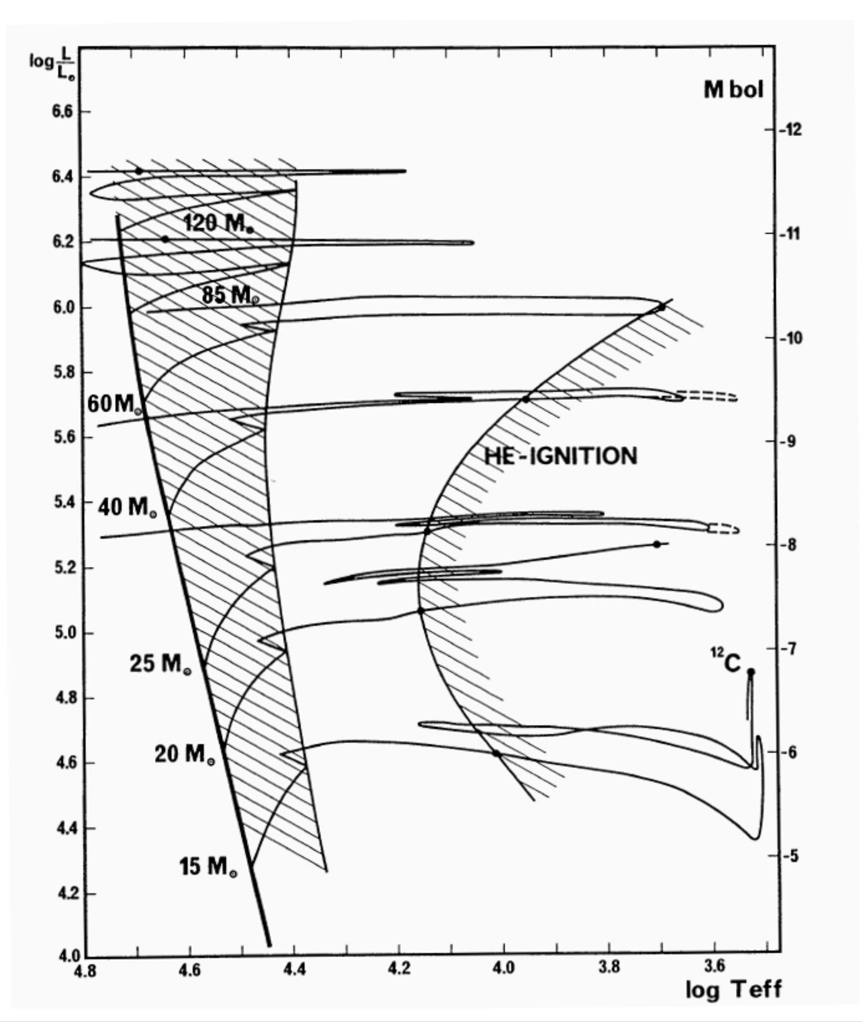
Stellar evolution – massive stars

Evolution of massive stars – burning phases

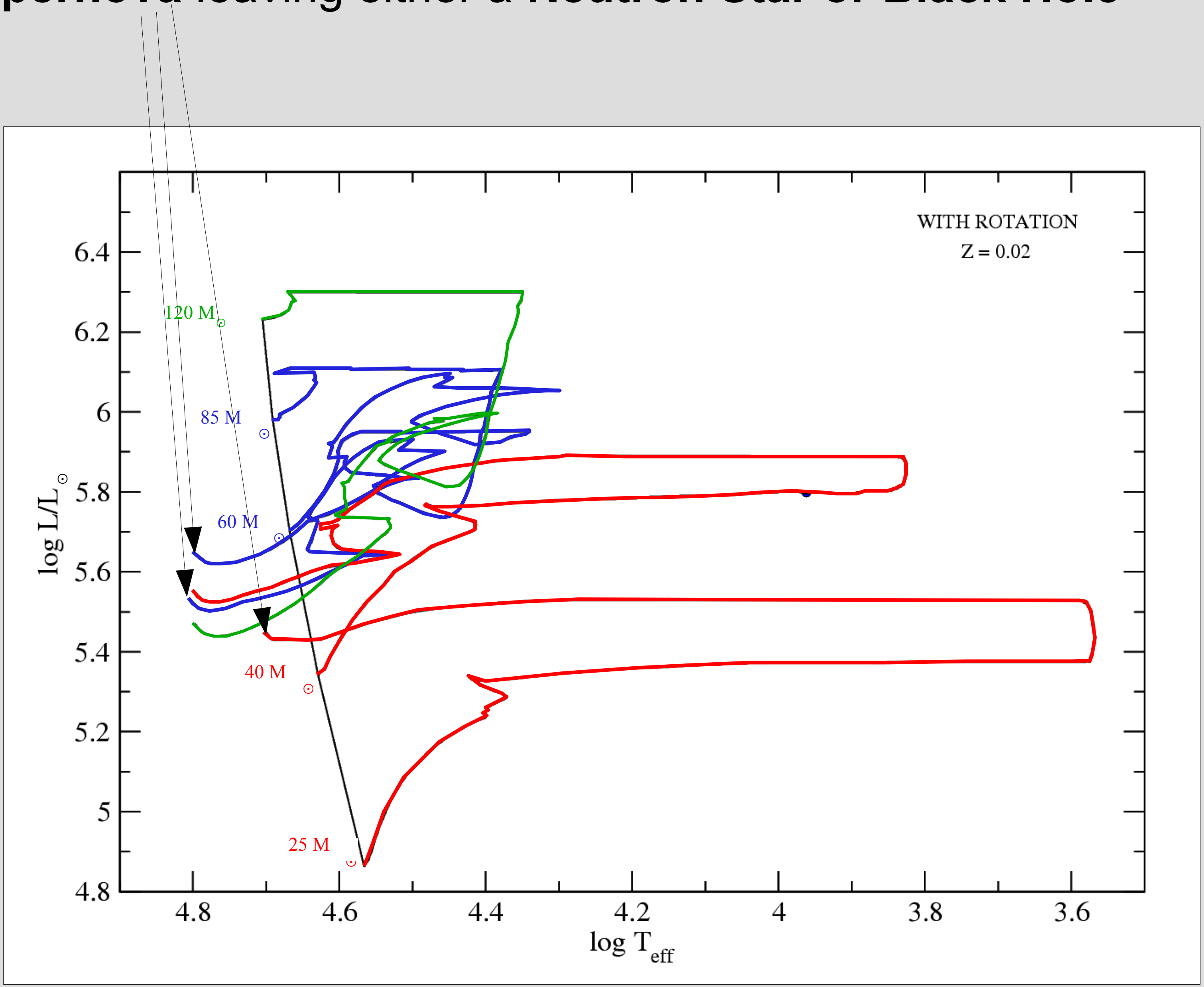


- **Wolf Rayet**
  first He-core burning
  later
  C- & O- & Si-core burning and
  C- & O- & He- & H-shell burning

massive stars
start **H** up to **Si burning** and **H** to **C shell burning**

Stellar evolution of massive stars

- final end of all massive stars after **RSG** or **Wolf-Rayet** phase is → **Supernova** leaving either a **Neutron Star or Black Hole**



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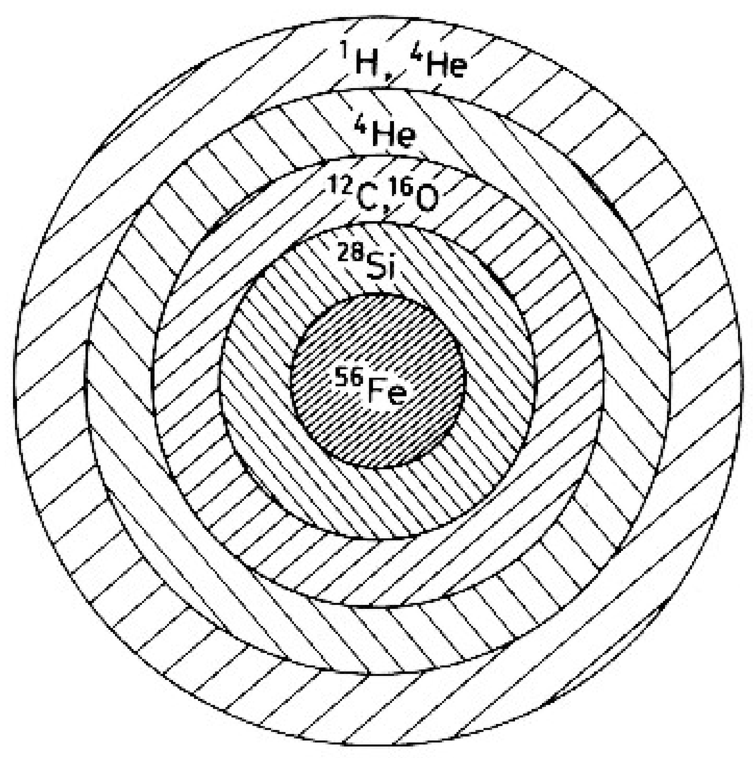
Stellar evolution – massive stars



scetch – not drawn to scale

→ core and shell burning leaves a structure with rings of different / higher elements from the inside out

→ like an onion

The "onion shell" model

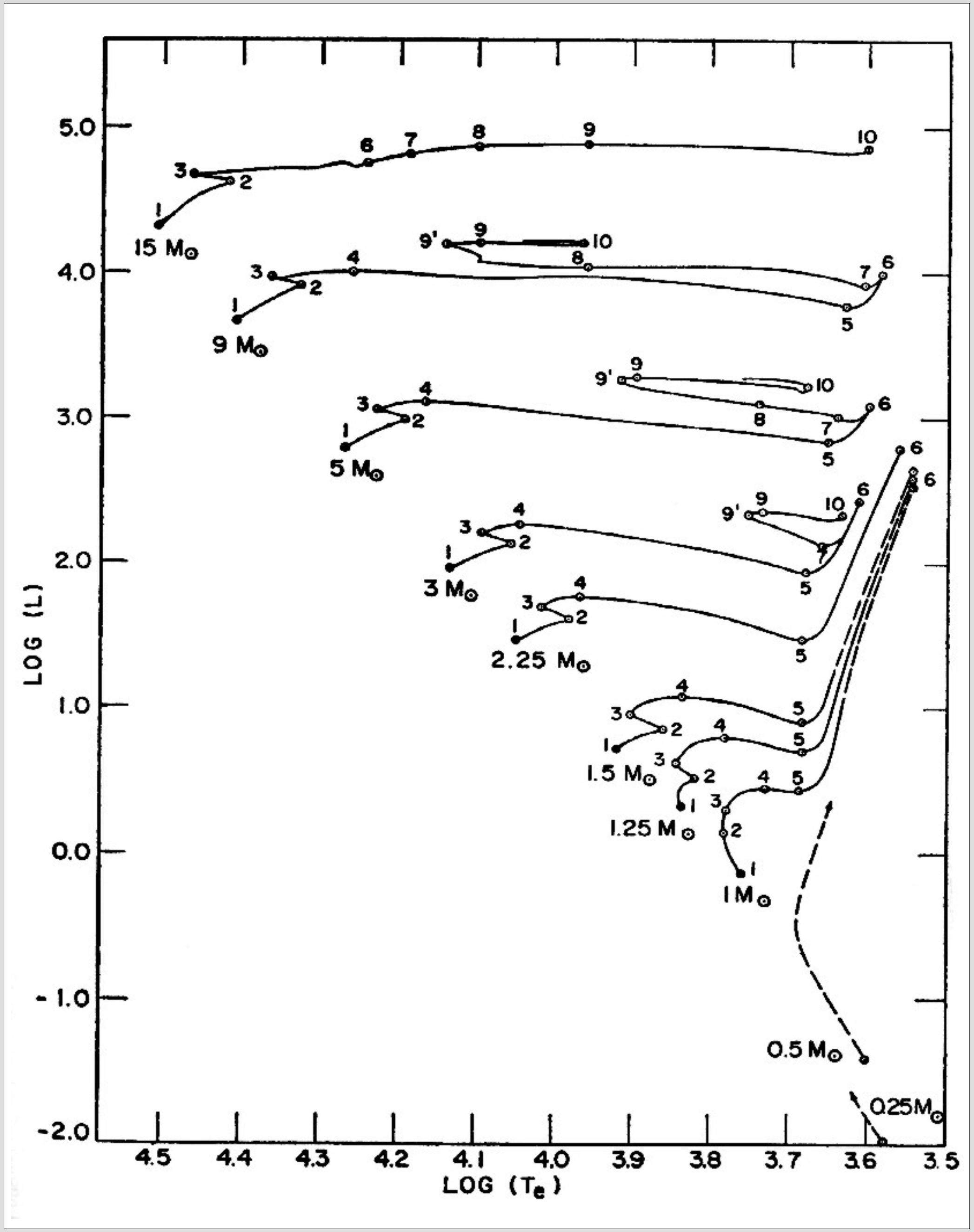
Stellar evolution – massive stars

stellar evolution tracks

are the calculated path a star follows in the HRD
they highly depend on
● the input Parameters
● the stellar model

so tracks show the changes in L, r, T_{eff} of a star during its life

Nevertheless...



Iben 1967

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Stellar evolution – massive stars

stellar evolution ↔ Tracks
the beginning in 1960ies

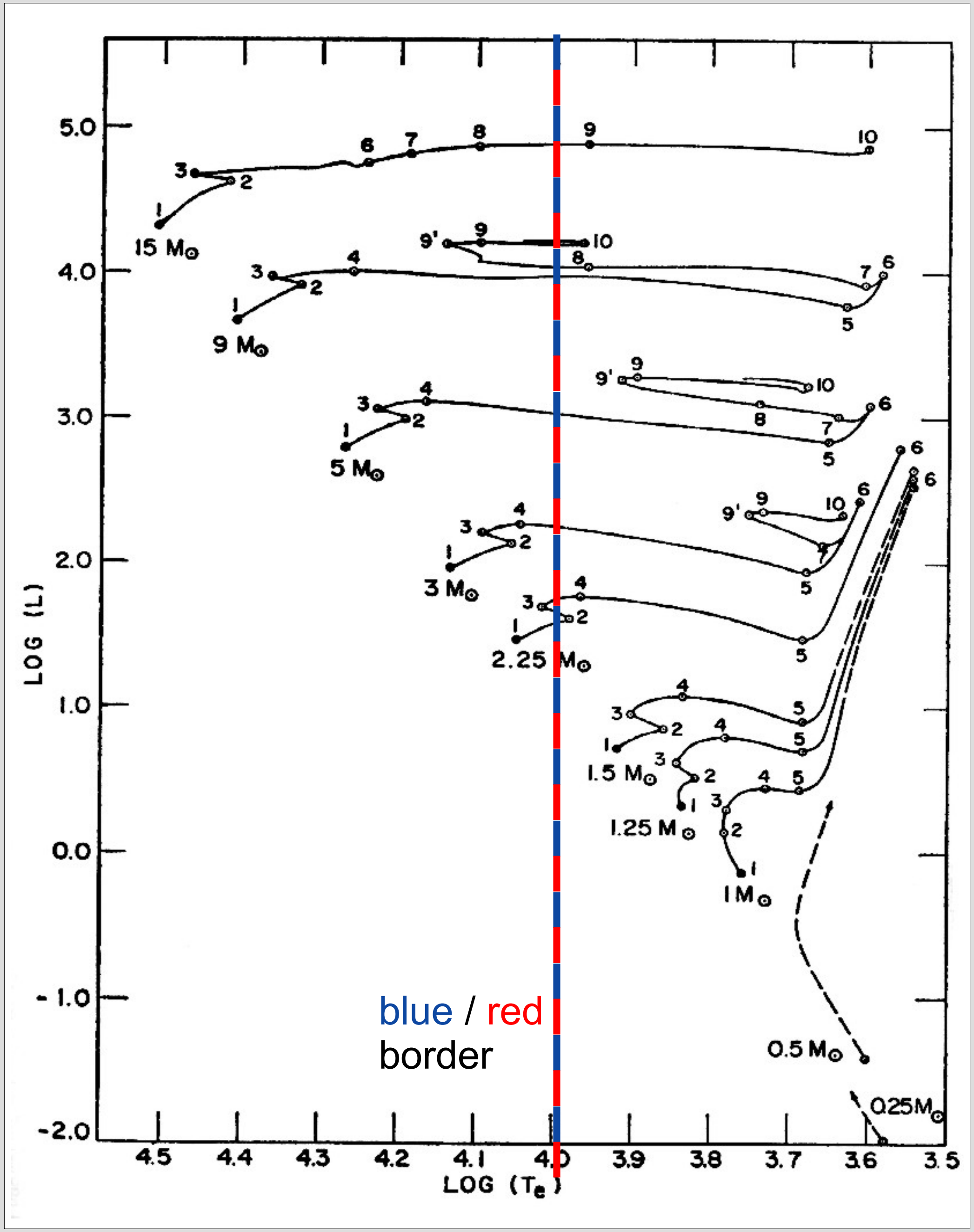
All look very much alike
Independent of mass

Massive stars evolved

MS O-star
→ RSG → SN

MS O-star
→ RSG (maybe blue loop) → SN

stars end all as **red** supergiants



Iben 1967

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Track in 1980ies SN1987A Problem

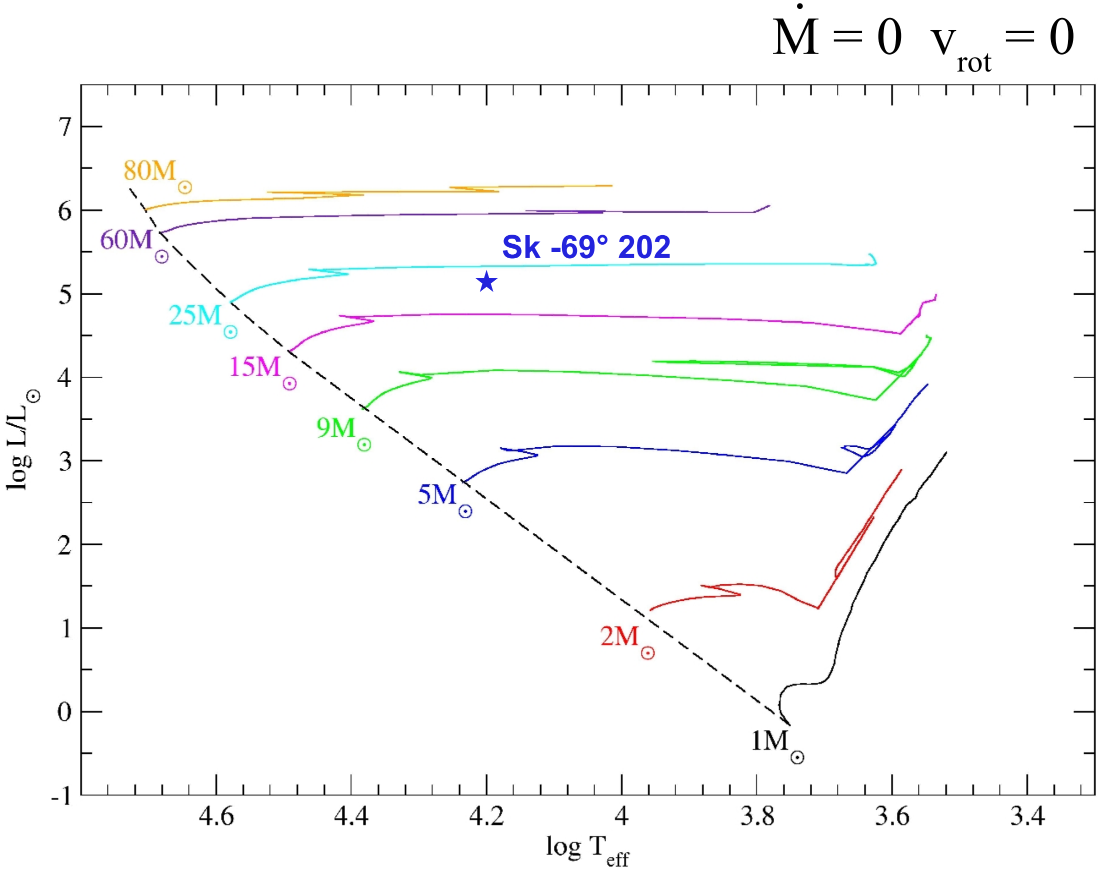
Problem SN 1987A

Progenitor star **Sk -69° 202**
was **Blue Supergiant !!**

A) CONSTRAINTS FROM SN 1987

Let us begin by briefly quoting the main constraints from SN 1987A, which are also studied in other papers presented at this meeting :

- 1. The progenitor : With type B3 and mv = 12.3, Sk -69 202 had log $L/L_\odot \simeq 5.1$ and log $T_{eff} \simeq 4.2$.



SN 1987A → mass loss

Since 1987

- added stellar winds
  mass loss !
  → explained SN1987

(Maeder 1988)

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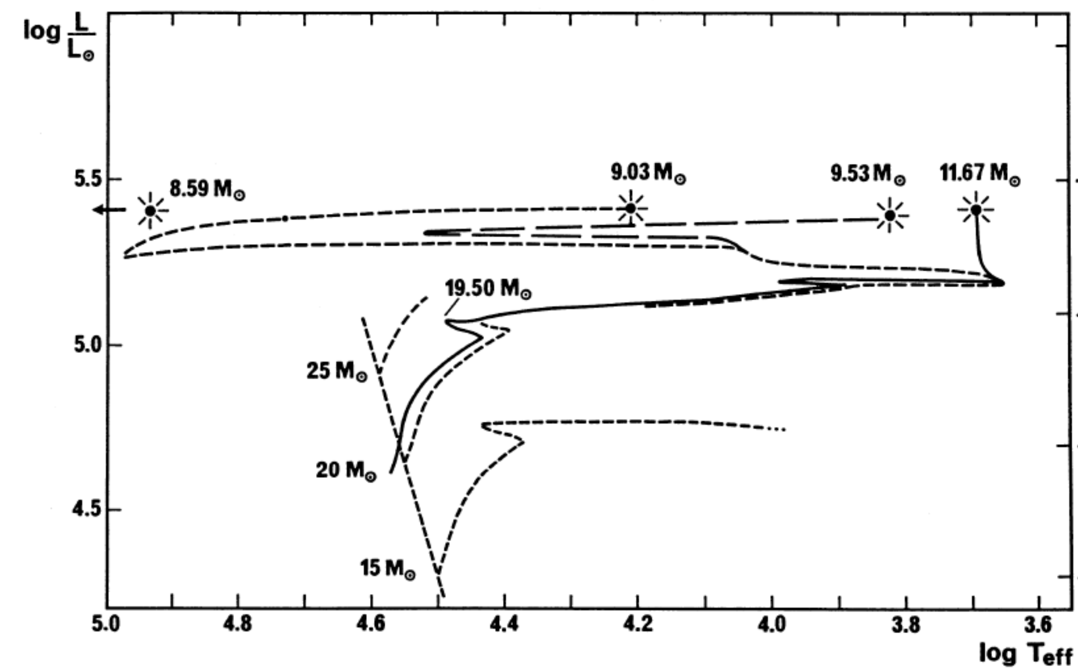

Figure 1 : Evolutionary tracks in the HR diagram for a model with an initial mass of 20 $M_\odot$ and composition X = 0.744 and Z = 0.006. Various cases of mass loss in post-MS evolution are considered and the remaining final masses are indicated.

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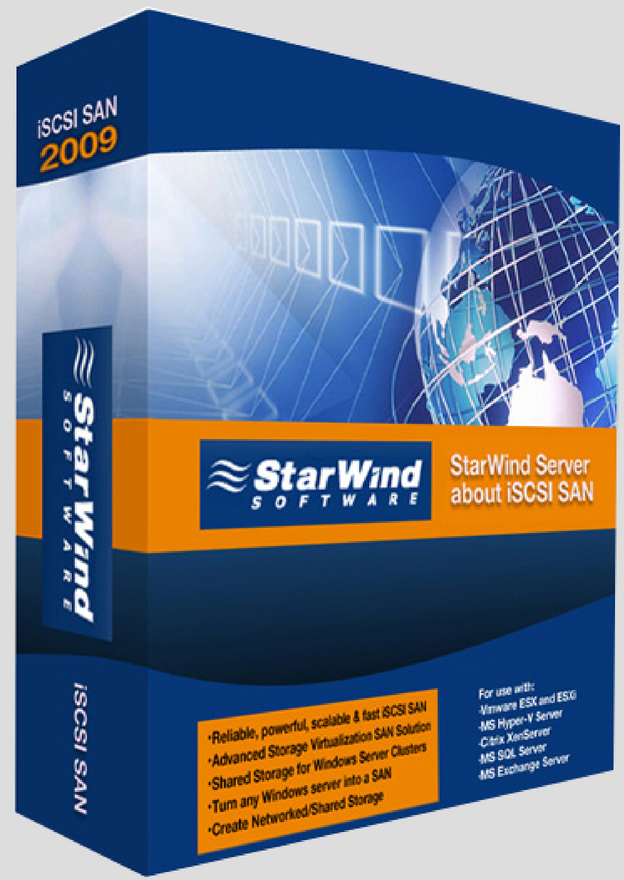
Stellar evolution – massive stars – mass loss

include stellar wind/mass loss
SN 1987A
showed that **stellar winds** are **<u>essential</u>**
→ **need track with stellar winds**



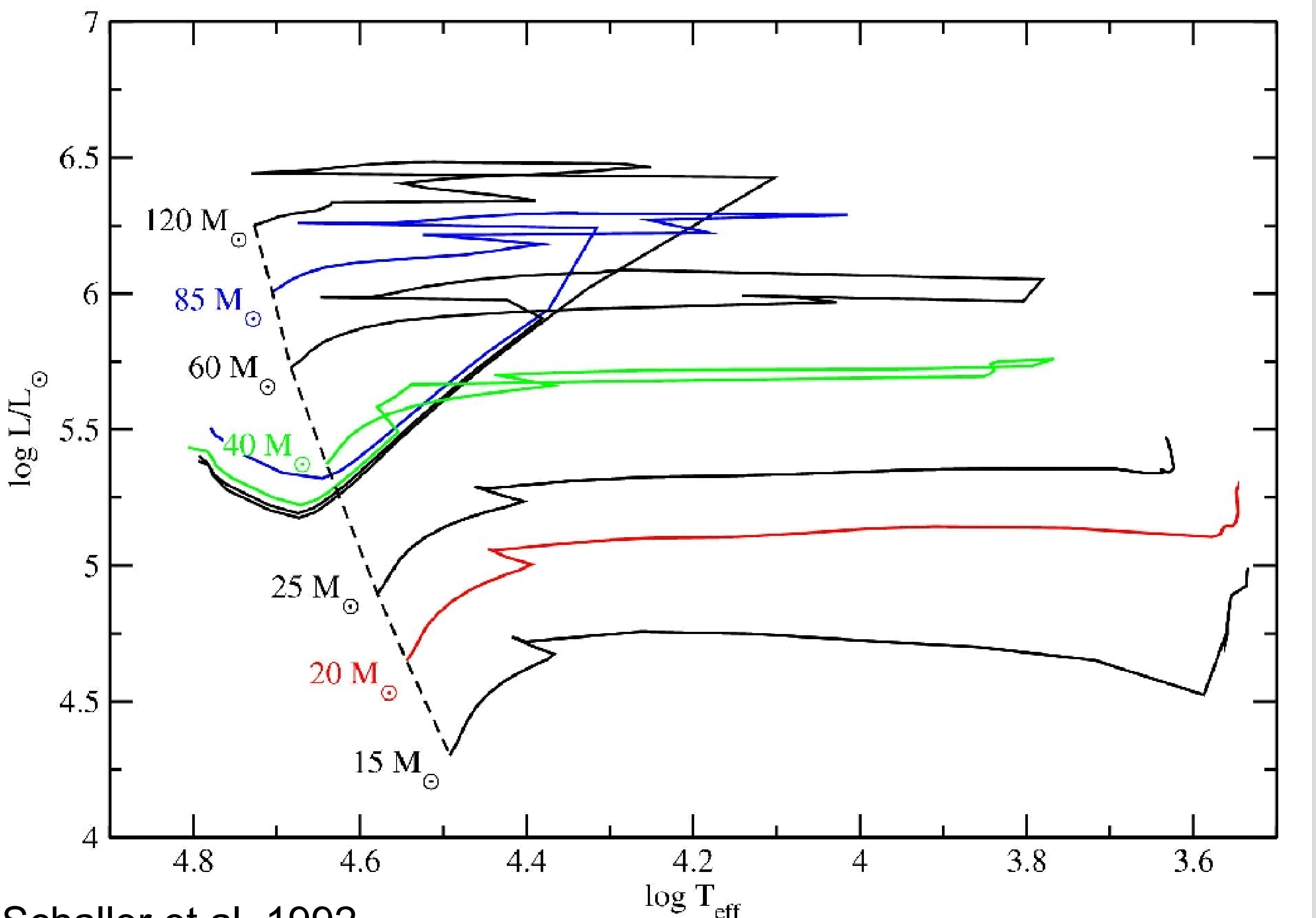
- added stellar winds
  mass loss !
  → explained SN1987

Stellar evolution – massive stars

Stellar evolution of massive stars with mass loss

$M = 15 - 120\ M_\odot$

$Z = 0.02$



Schaller et al. 1992

Stellar evolution – massive stars

Stellar evolution of massive stars with mass loss

3 different pathes

> 50$M_\odot$

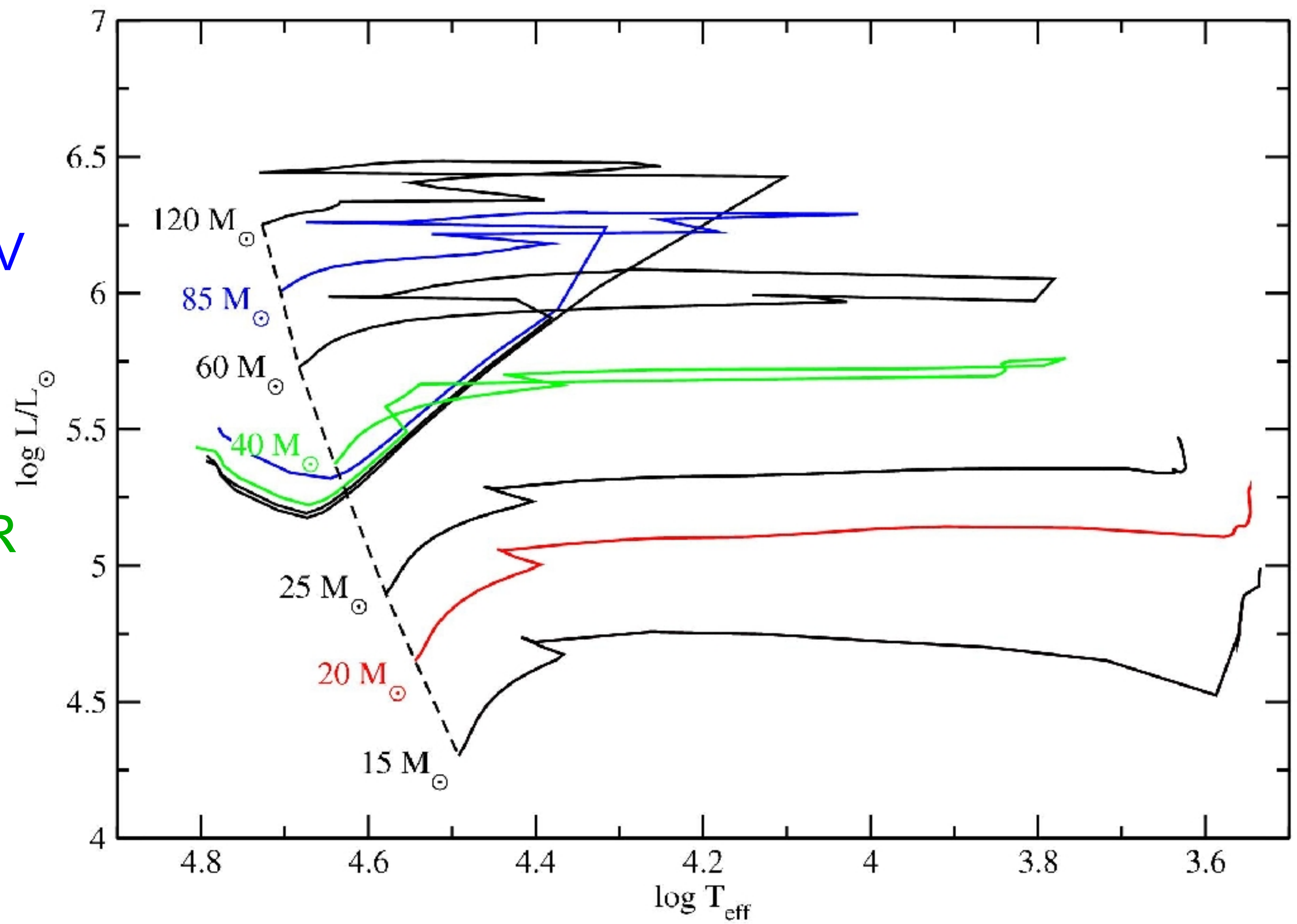
O-star → BSG → LBV → WR → SN

> 35$M_\odot$ and < 50$M_\odot$

O-star → RSG → WR → SN

> 8$M_\odot$ and < 35$M_\odot$

O-star → RSG → SN



Schaller et al. 1992

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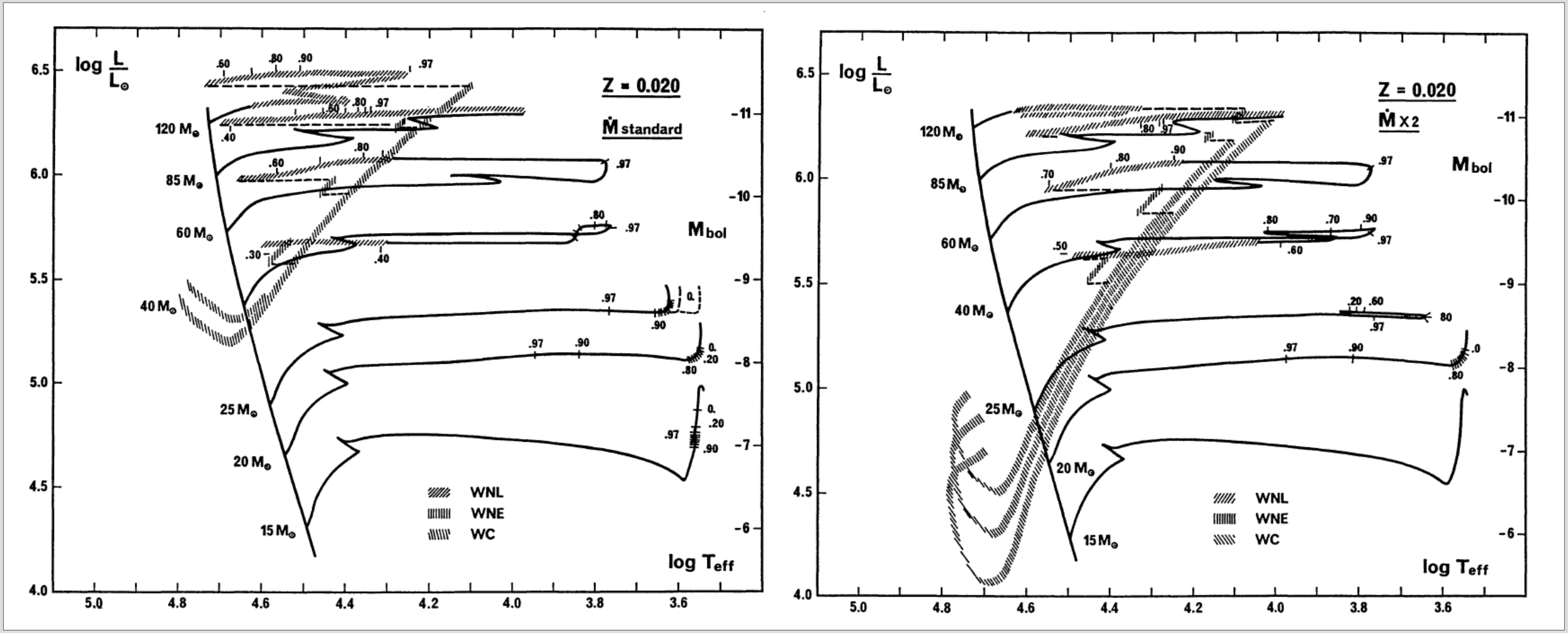
Stellar evolution – massive stars

Stellar evolution of massive stars with mass loss

normal

enhanced (2x)



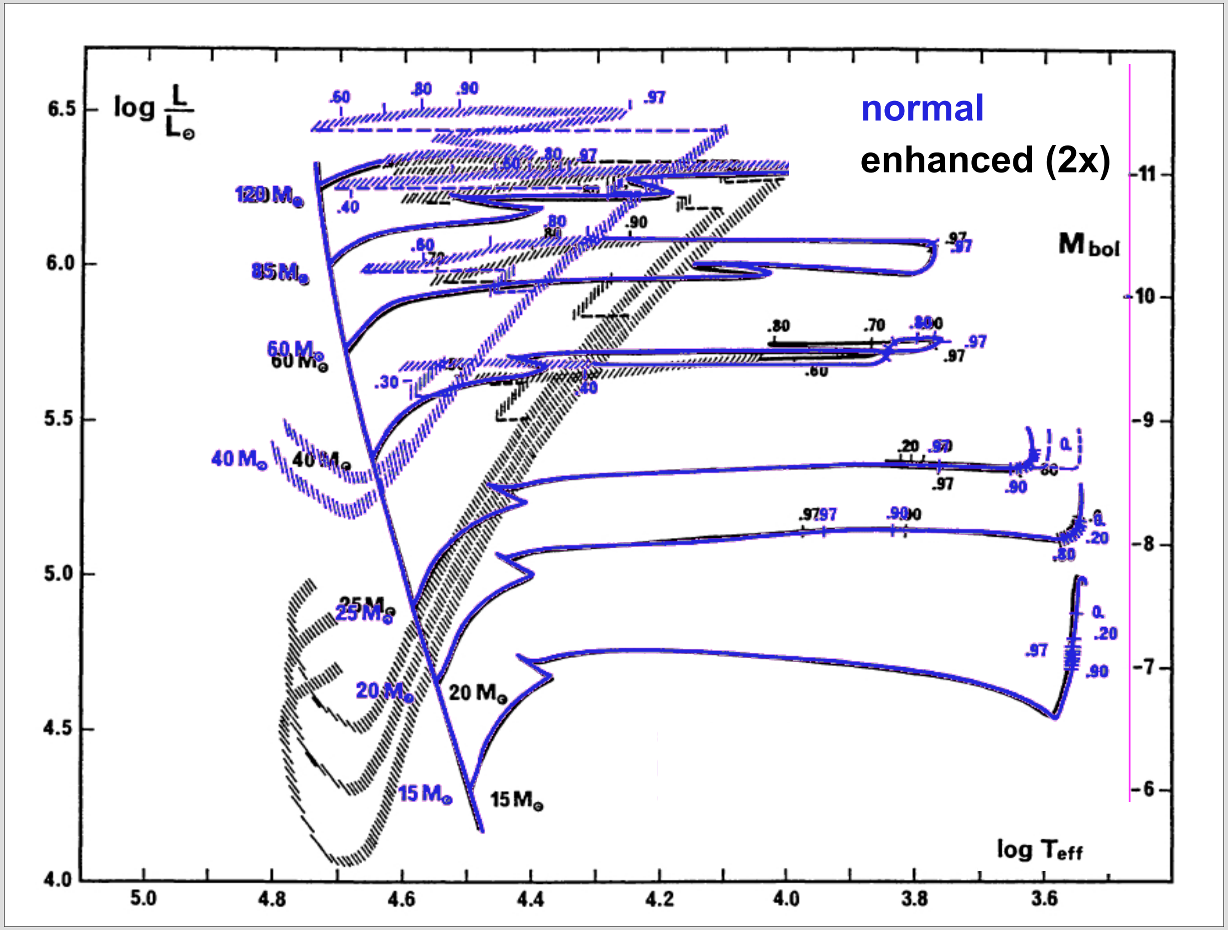
Geneva models (Schaller et al. 1992)

Stellar evolution – massive stars

Stellar evolution of massive stars with mass loss

Enhanced ↔ more mass loss

- changes the loops
- somewhat more blue
- less luminous WR ↔ star lost more mass ↔ like less massive stars



Geneva models (Schaller et al. 1992)

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Stellar evolution – massive stars

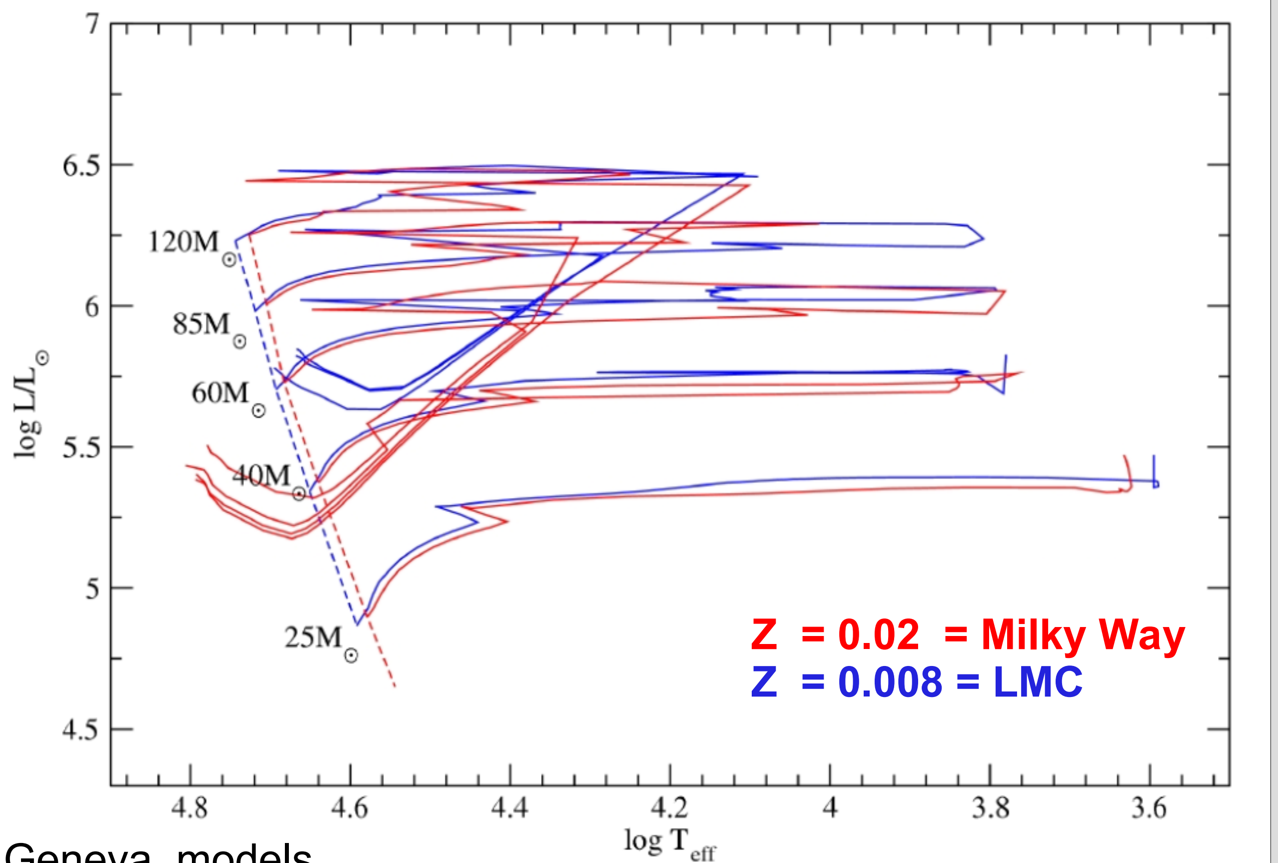
Stellar evolution of massive stars different metalicity

Lower metalicity

- star hotter on main-sequence
- turn redder (smaler T_{eff})
- more luminous WR

→ partly be explained by the fact that

Stellar winds and the mass loss depends on the metalicity !



Geneva models

Stellar evolution – massive stars – ROTATION

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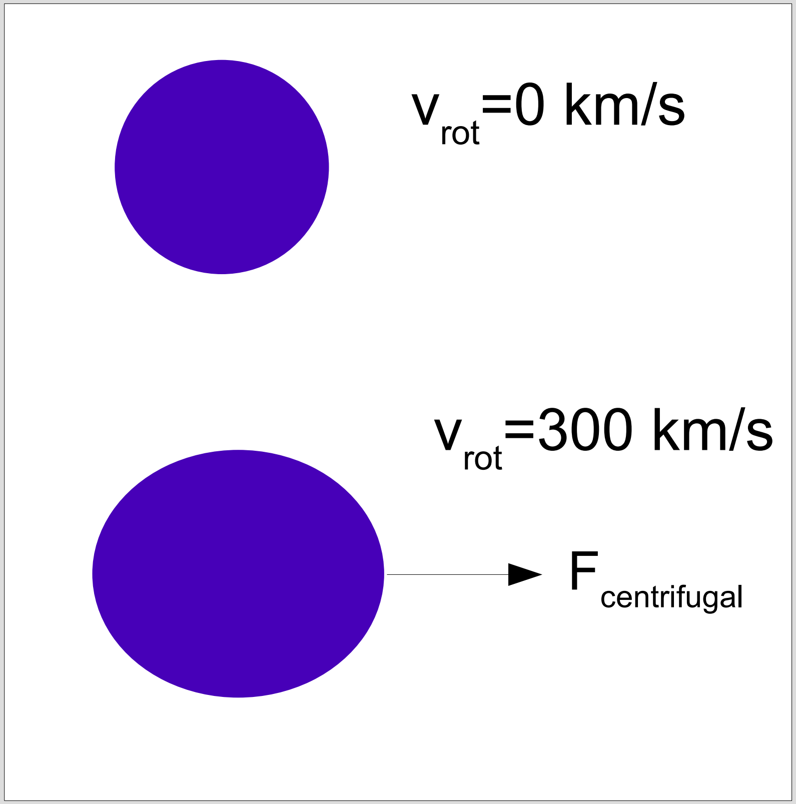
Stellar evolution – massive stars – ROTATION

Addtional force, **centrifugal force** needed in stellar strucute equation !

- flattening pols → ellipoid
- stronger wind
- additional mixing
- change in luminosity
- change in effective Temperature



typical rotation velocities

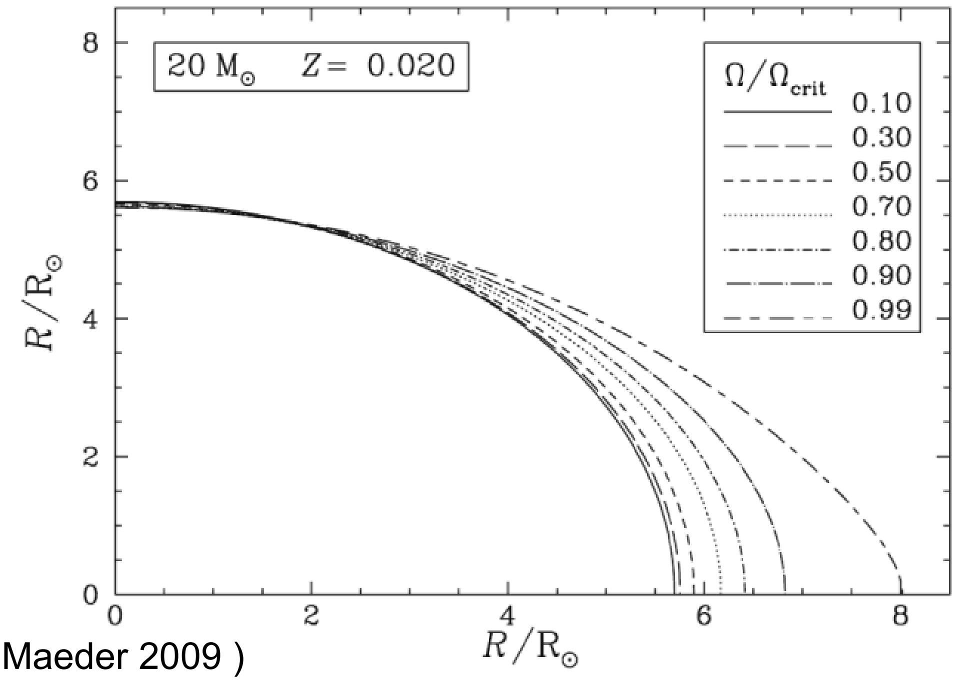
massive star	einige 100 km/s
Low mass star, i.e. sun	2 km/s

Stellar evolution – massive stars – ROTATION

- star is no longer a sphere but
  ellipsoid

  v_{rot} of 75-80% $v_{critical}$
  → **10 – 20% larger radius at Equator**

- additionaly in the inner structure
  → **core is larger**



(Maeder 2009)

Rotating stars are not spherical but ellipsoidal

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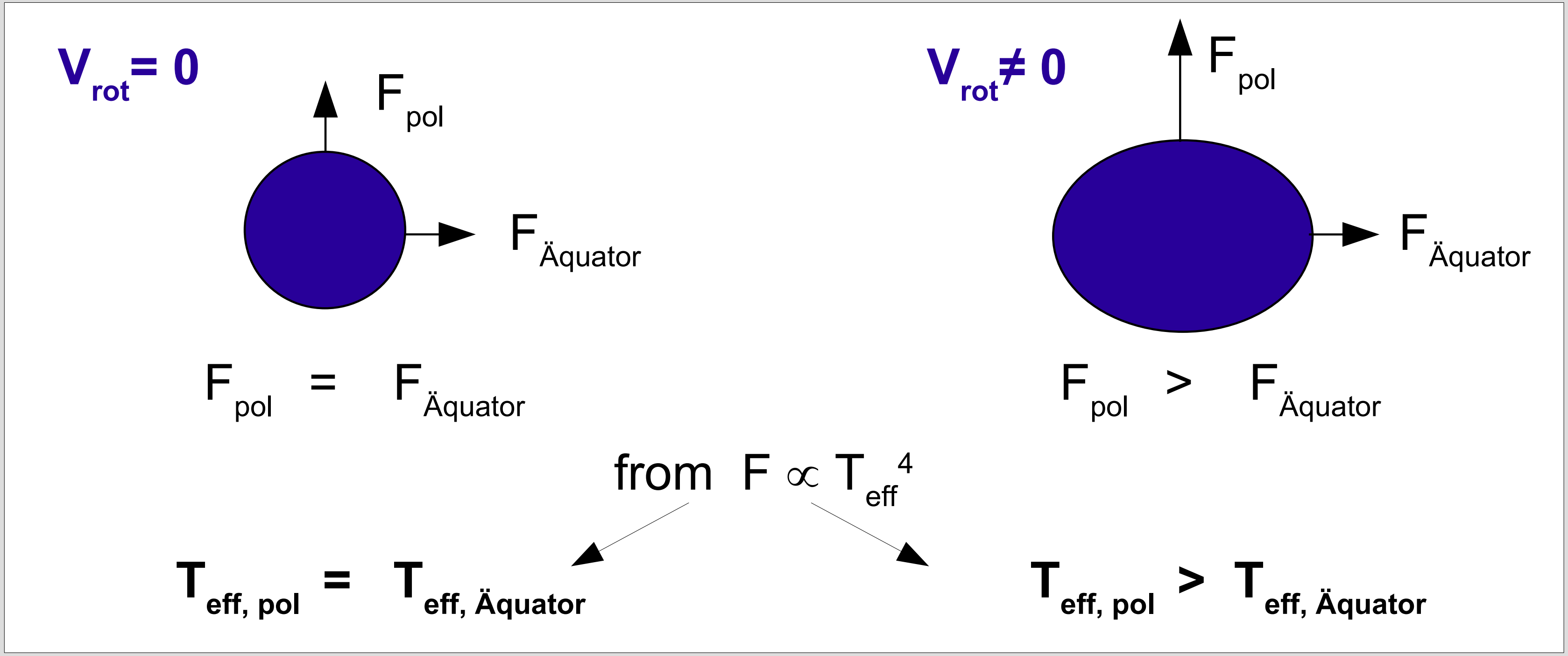
Stellar evolution – massive stars – ROTATION

Von Zeipel theorem
Flux is proportional to effective gravity $F \propto g_{eff}$

for **non rotating star** is $\mathbf{g_{eff}}$ **the same everywhere**

for **rotating star** is $\mathbf{g_{eff}}$ **smaller at the Equator** ↔ reduced by centrifual force



rotating stars are **more luminous** and **hotter** at the **pols !**

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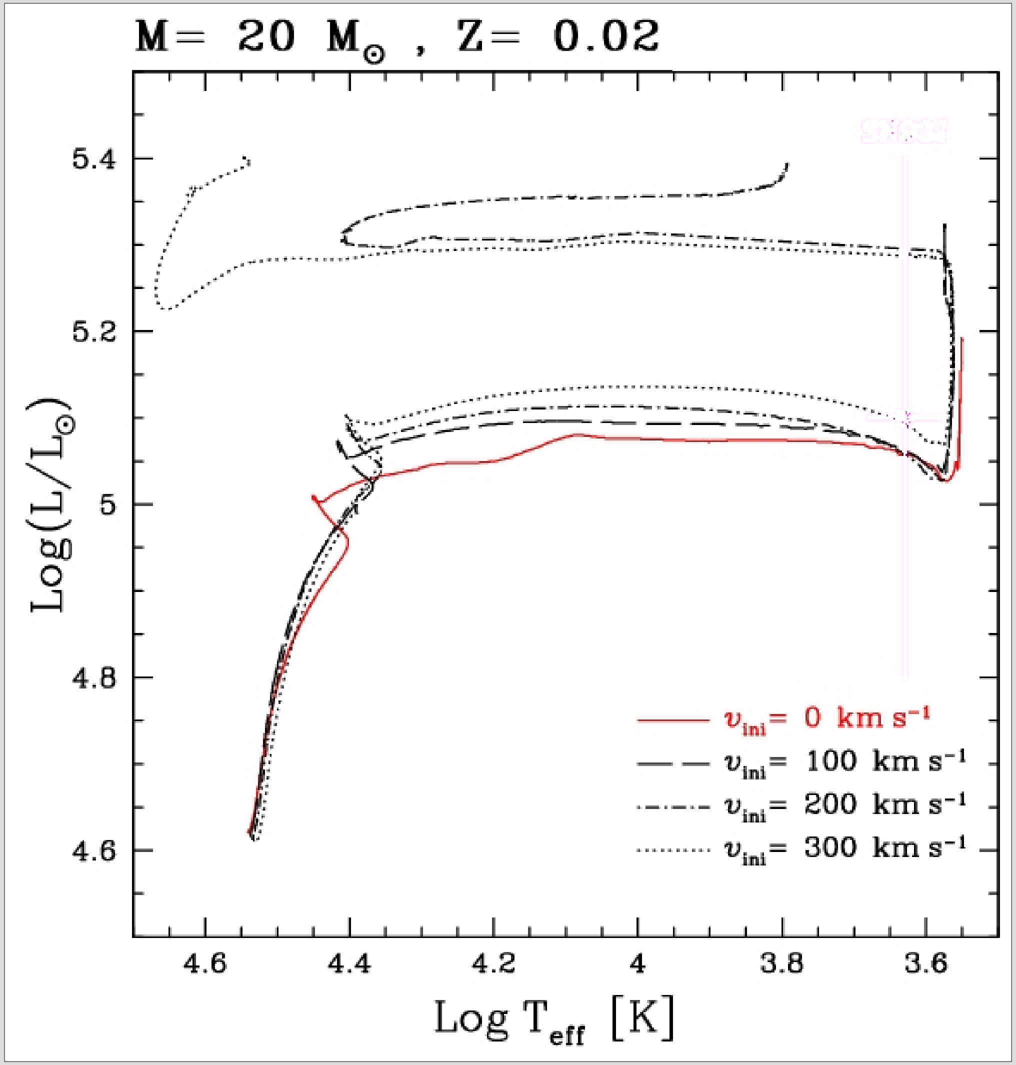
Stellar evolution – massive stars – ROTATION

Example: Stellar evolution the influence of rotation for a **$20M_\odot$ Star**

higher velocity leads to

- **evolution into blue**
- **stars end** in **BSG** or **WR** not as **RSG** phase



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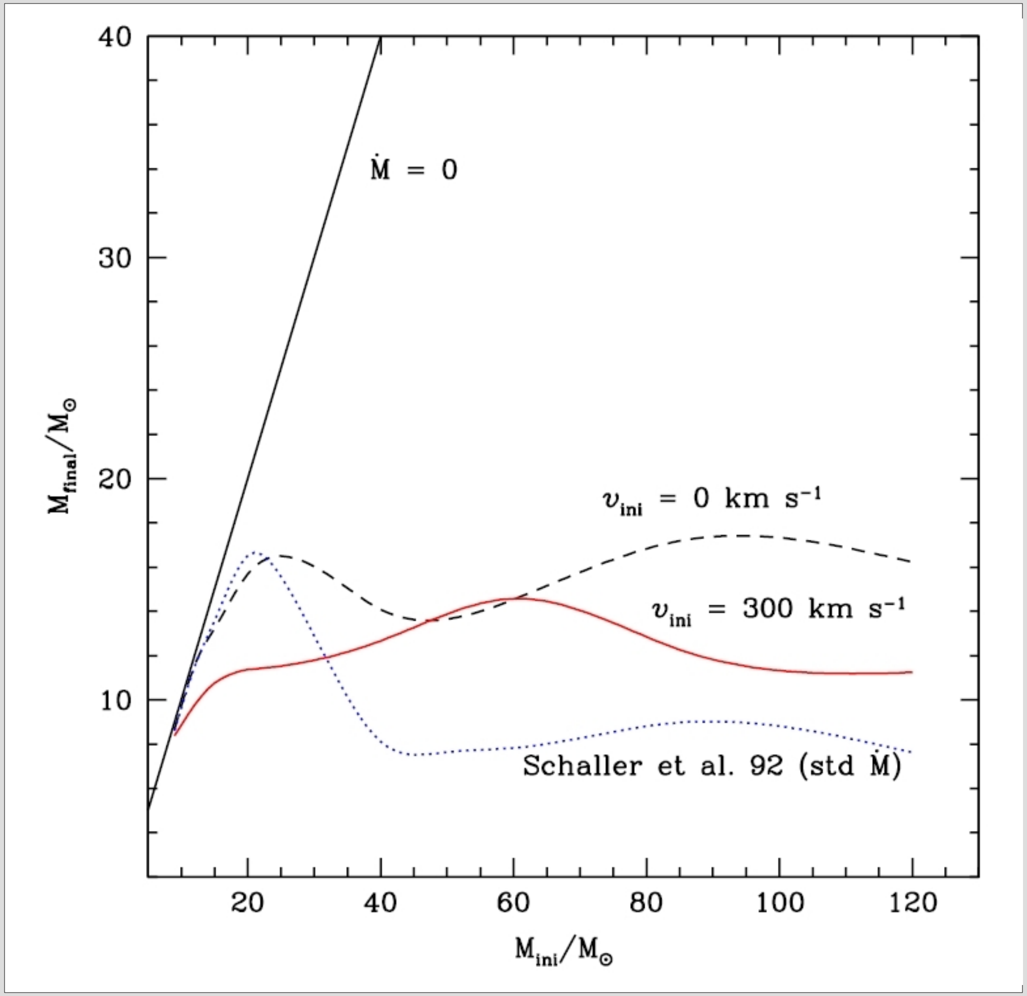
Stellar evolution – massive stars – ROTATION

Rotation and mass loss



(Meynet & Maeder 2003)

difference of initial to final mass

O Stern rotating with **350 km/s** has a **30%** higher mass loss as the non rotating star with the same mass.

$$\dot{M}(v_{rot}) = \dot{M}(v=0) \times (1-v_{rot}/v_{crit})^{-0.43}$$

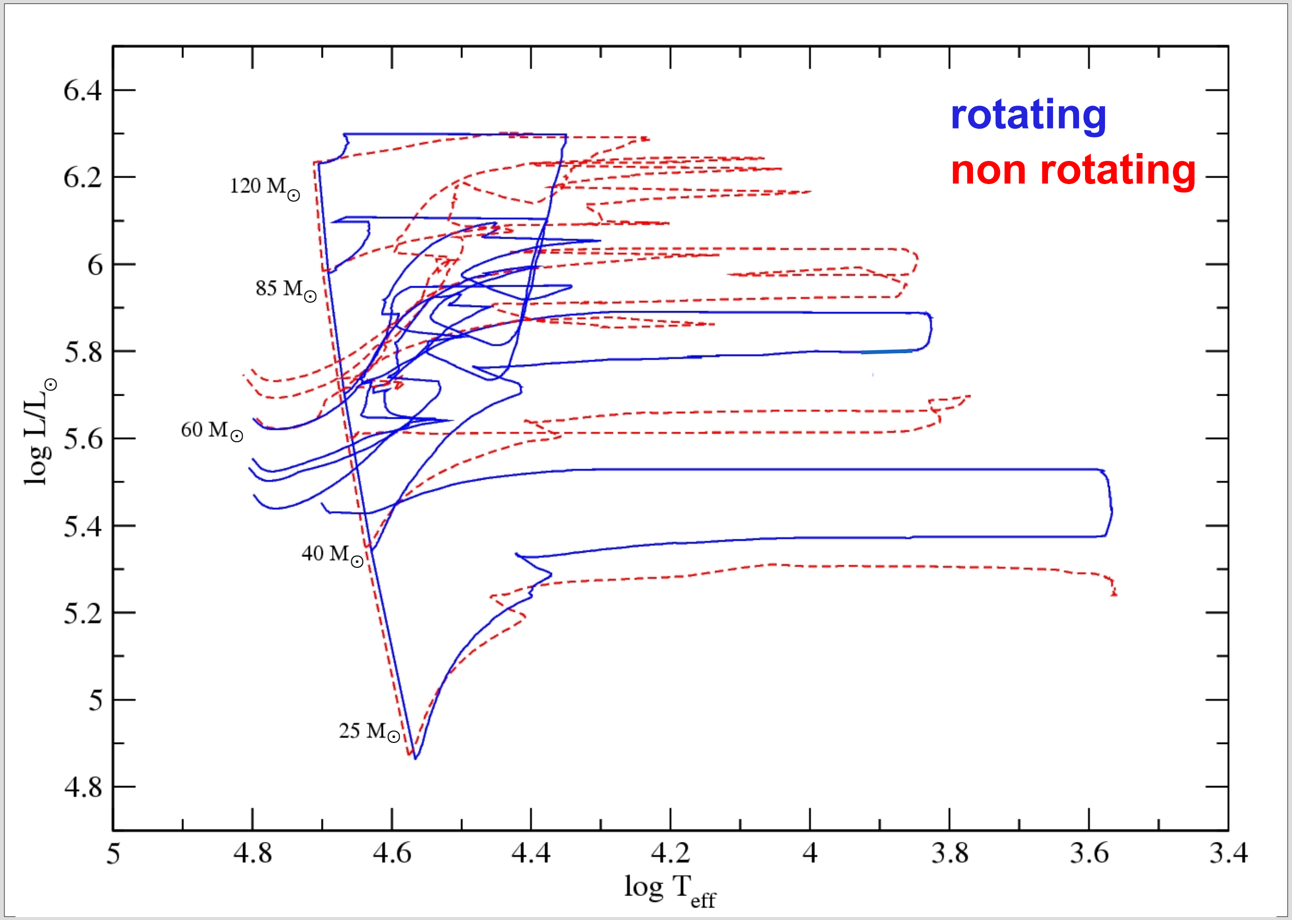
v_{crit} = critical or break up velocity

Stellar evolution – massive stars – ROTATION

Stellar evolution the influence of rotation

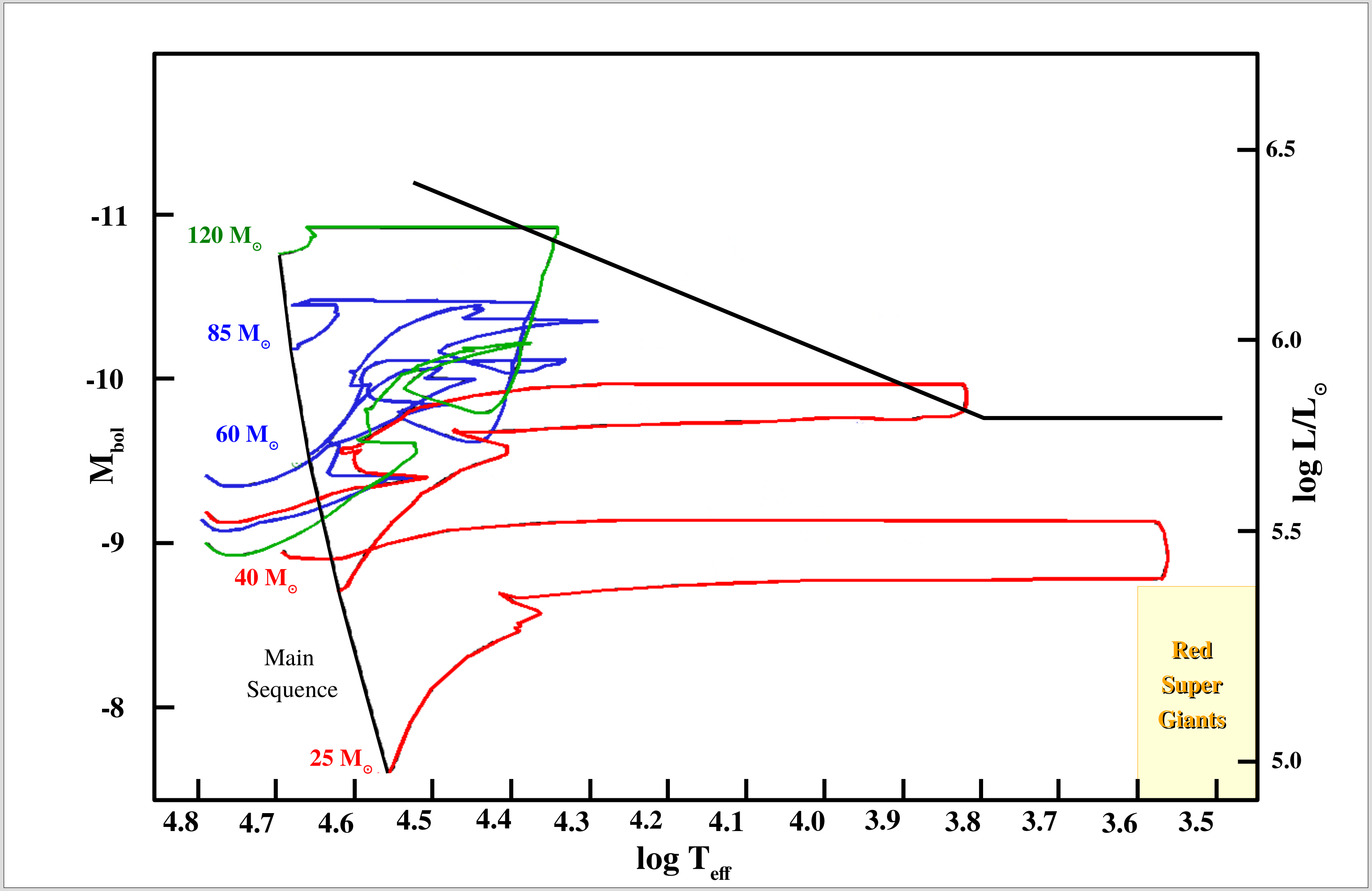
rotation leads to

- **stars stay/turn hotter**
- **earlier loop back**
- **generally more luminous**
- **hotter but less luminous WR stars**



Stellar evolution – massive stars – ROTATION

Four major **scenarios** for the **post main** sequence evolution of massive stars.



Stellar evolution – massive stars – ROTATION

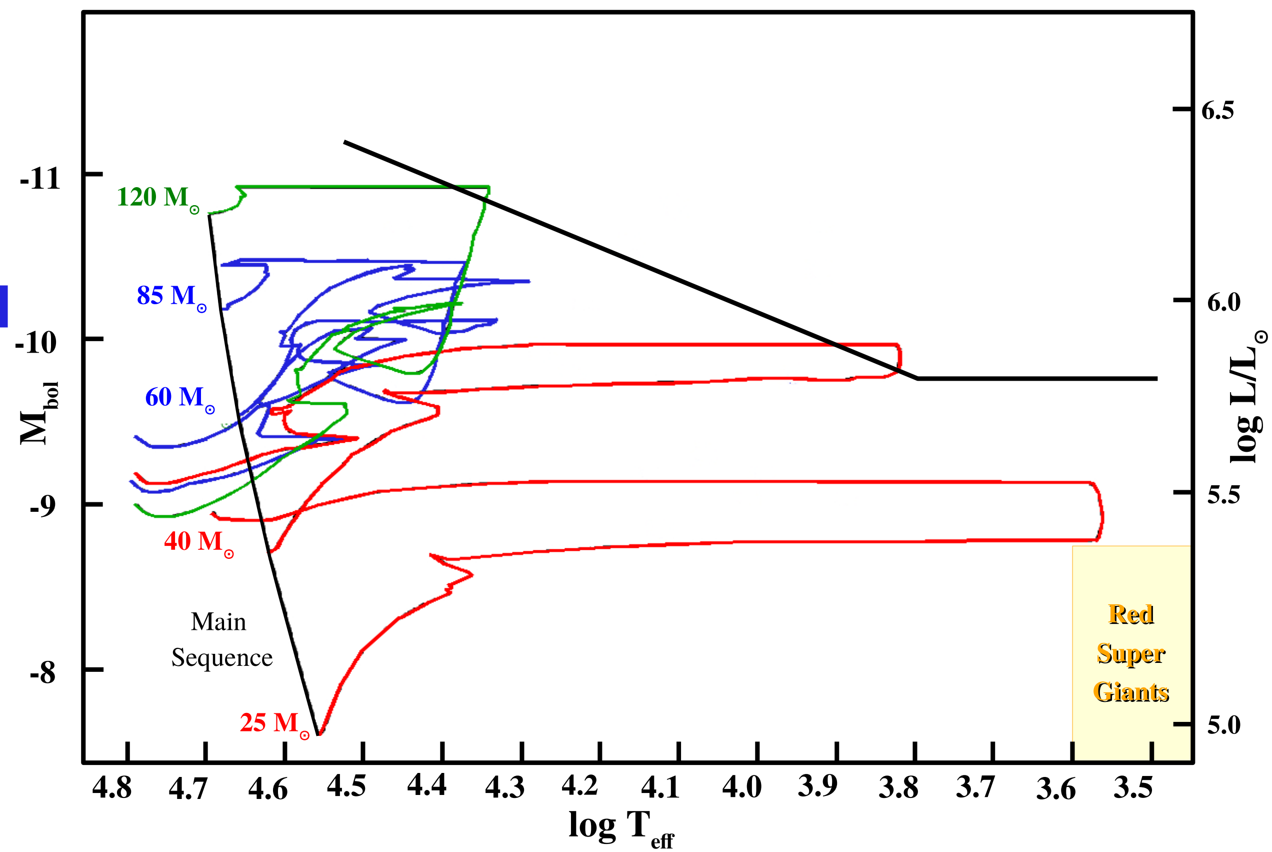
Four major **scenarios** for the **post main** sequence evolution of massive stars.

> 90 $M_\odot$
→ **WR – SN**

45 - 90$M_\odot$
→ **BSG – LBV – WR – SN**

22-45$M_\odot$
→ **BSG – LBV – SN**
or
→ **RSG – BSG – SN**

< 22 $M_\odot$
→ **RSG – SN**



mass ranges (here for Z=0.02) change slightly with metalicity
Z ↓ M↑

data taken from Meynet & Maeder (2005 & 2015)

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Stellar evolution – massive stars – ROTATION

stellar ZOO since 2005

(Maeder et al. 2005)

$M > 90 M_\odot$: O - Of - WNL - (WNE) - WCL - WCE - SN (Hypernova low Z ?)

$60 - 90\ M_\odot$: O - Of/WNL< – >LBV - WNL(H poor)- WCL-E - SN(SNIIn?)

$40 - 60\ M_\odot$: O - BSG - LBV < – > WNL -(WNE) – WCL-E - SN(SNIb)
- WCL-E - WO SN (SNIc)

$30 - 40\ M_\odot$: O - BSG - RSG – WNE - WCE - SN(SNIb)
OH/IR < – > LBV ?

$25 - 30\ M_\odot$: O -(BSG)- RSG – BSG (blue loop) – RSG – SN(SNIIb, SNIIL)

$10 - 25\ M_\odot$: O - RSG - (Cepheid loop, $M < 15\ M_\odot$) RSG – SN (SNIIL, SNIIP)

O	O Hauptreihenstern	WNE	Wolf-Rayet Nitrogen Early Type
Of	" with Emissionlinies	WCE	Wolf-Rayet Carbon Early Type
BSG	Blue Supergiant	WNL	Wolf-Rayet Nitrogen Late Type
RSG	Red Supergiant	WCL	Wolf-Rayet Carbon Late Type
OH/IR	OH Maser , IR emission (RSG)	WCL-E	
LBV	Luminous Blue Variable	WO	Wolf-Rayet Oxygen

SN Supernovae:

SNIIL	linear decline in lightcurve
SNIIP	plateau in "
SNIb	no hydrogen but Helium (removed envelop)
SNIc	no hydrogen and no Helium (removed envelop even further)
SNIIn	narrow lines (cirkumstellare material)

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Stellar evolution – massive stars – ROTATION

impact of rotation...

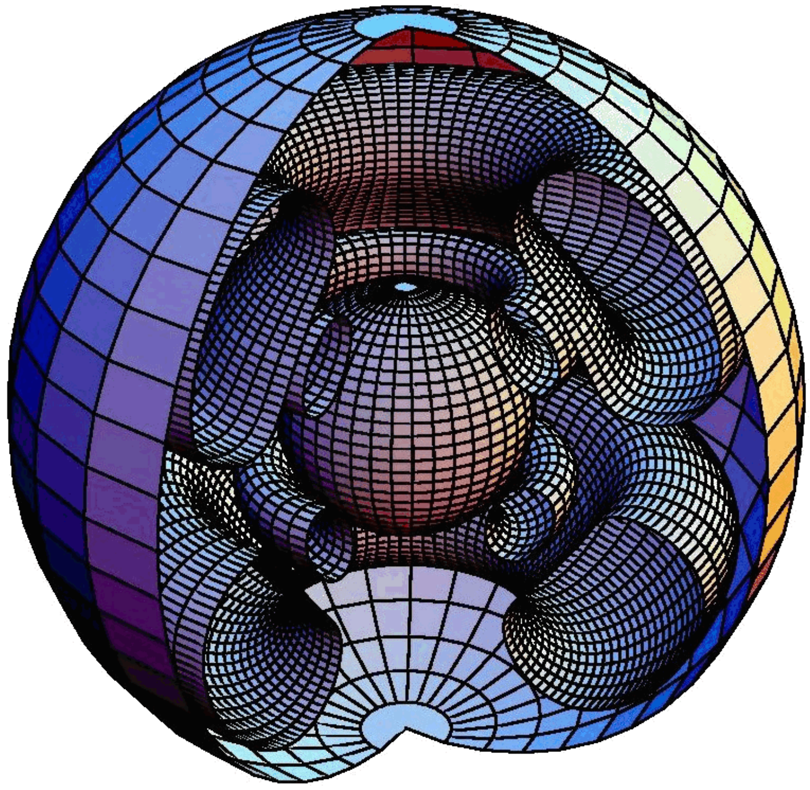
Stellar evolution – massive stars – ROTATION

meridionale circulation (Eddington – Sweet cirkulation)

consequences

- mixing in the star more efficient
  → He und N CNO burning reaches faster (and erlier) upper regions.

- all burning phases are **longer**
  Mixing → "fresh" material mixed in burning regions → adds fuel from outer regions can burn longer
  ↔ lifes longer



circulation
up at pols – down at equator

Meynet & Maeder (2002)

rotating stars live longer as the non rotating stars with the same mass

Stellar evolution – massive stars – ROTATION

impact of rotation...

rotating stars are
more luminous and **hotter** at the **pols !**

rotating stars live longer as
non rotating stars with the same mass

Stellar evolution – models with mass loss AND ROTATION

Starting in 2000

→ model now include **Mass loss** and **Rotation**

First idea and theoretical approaches already 1955

→ no chance to caculate with the Computers at that time
→ **need 3D**

Zeitschrift für Astrophysik, Bd. 38. S. 166—189 (1955)

Kleine Veröffentlichungen der Remeis-Sternwarte Bamberg Nr. 10

Untersuchungen über rotierende Sterne

I. Die Theorie nullter Ordnung

Von

Rudolf Kippenhahn, Bamberg

Mit 1 Textabbildung

(Eingegangen am 21. September 1955)

Es wird die Theorie nullter Ordnung aufgestellt, die das Rotationsgesetz extrem langsam rotierender Sterne bestimmt. Es zeigt sich, daß ein Stern nach hinreichend langer Zeit einem Rotationsgesetz zustrebt, das zwar wegen des ständigen Drehimpulsverlustes durch Strahlung nicht stationär ist, das aber vom Anfangsrotationsgesetz nicht mehr abhängt. Die Bestimmung dieses Gesetzes und die Frage, wie ein Stern aus einem beliebigen Anfangszustand heraus dieses Rotationsgesetz erreicht, führen unter vereinfachenden Annahmen (spezielle Vorschriften für den

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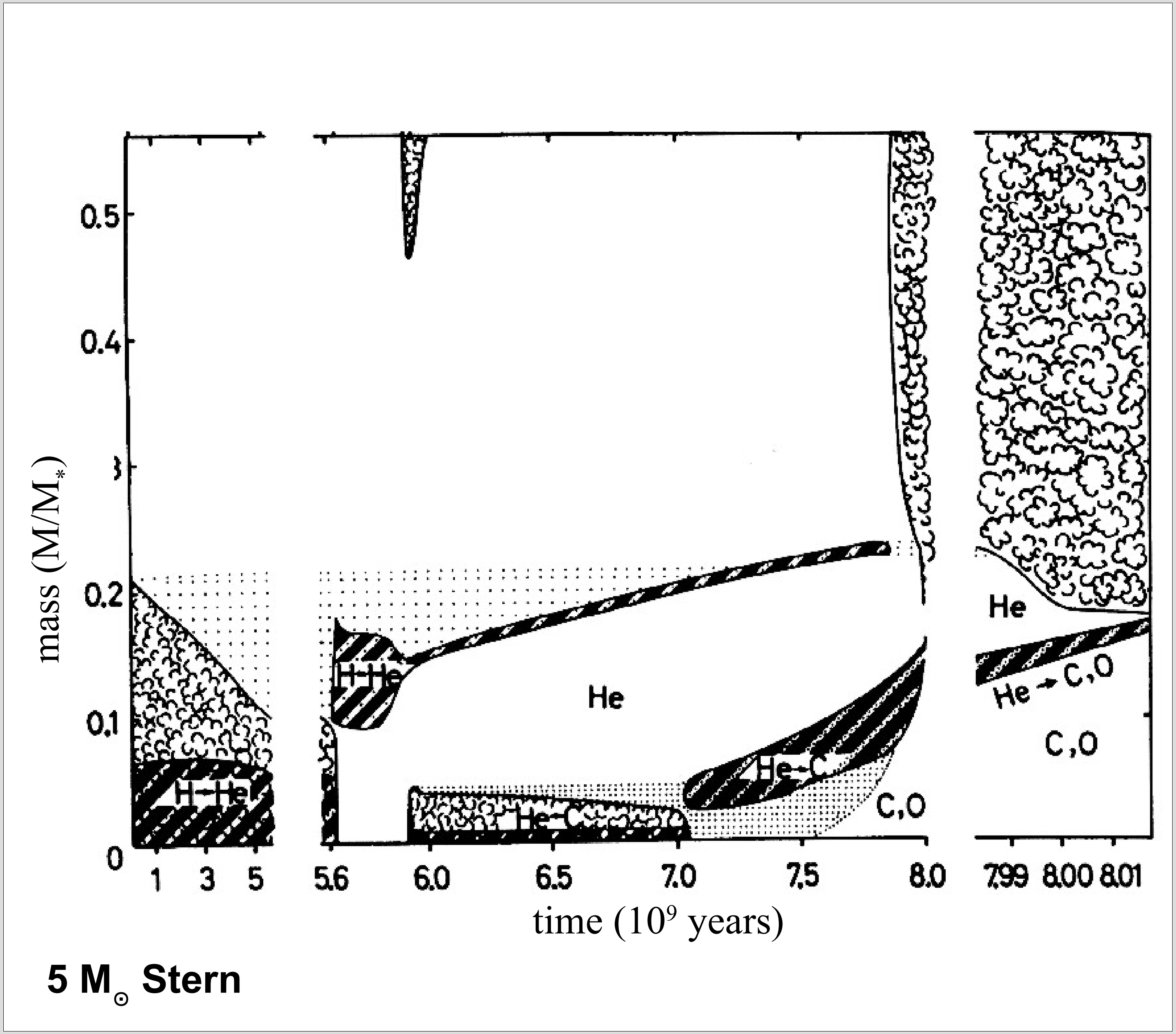
one more diagram to stellar evolution



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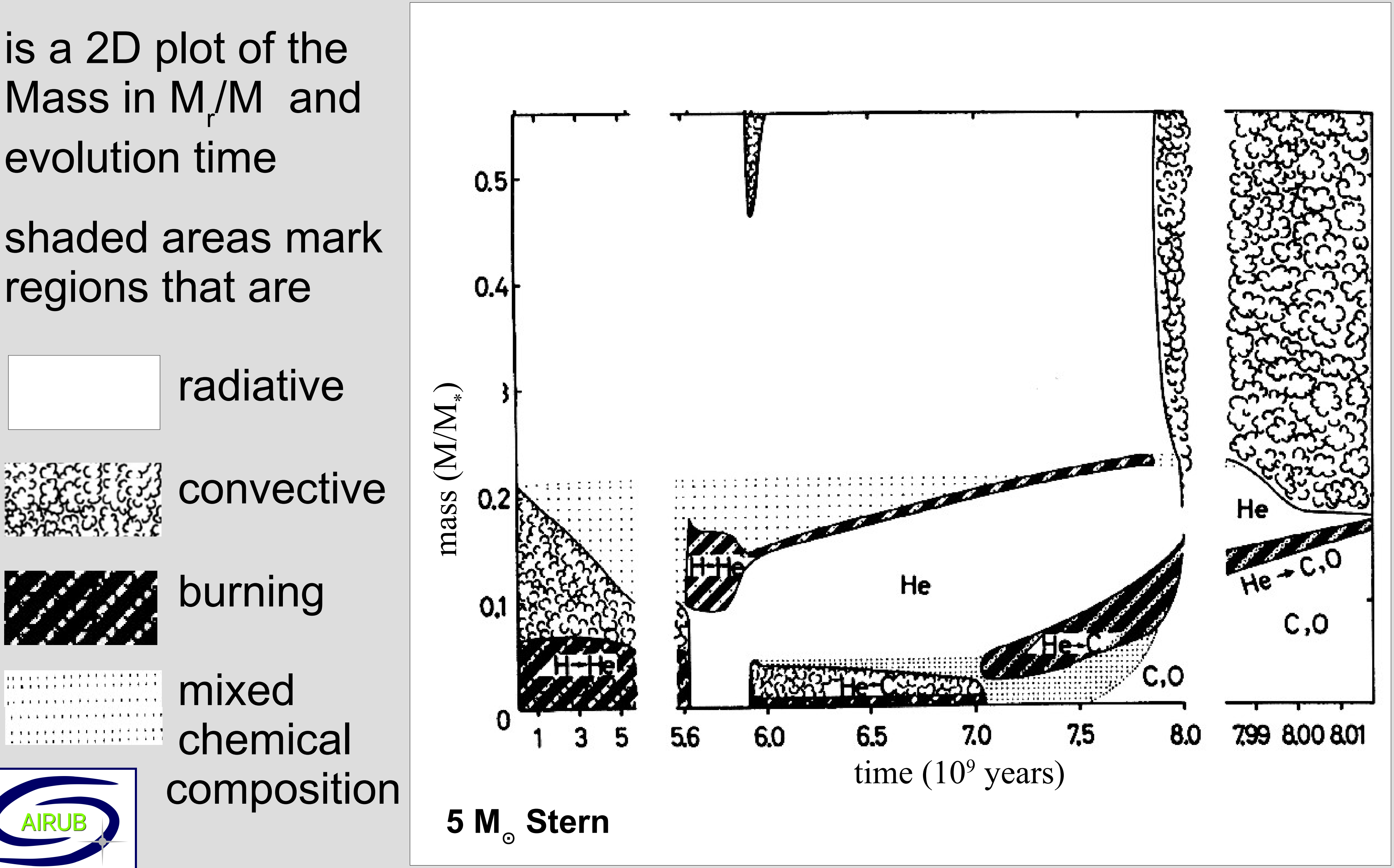
Kippenhahn - diagram

introduced by Rudolf Kippenhahn

is a 2D plot of the Mass in M_r/M and evolution time

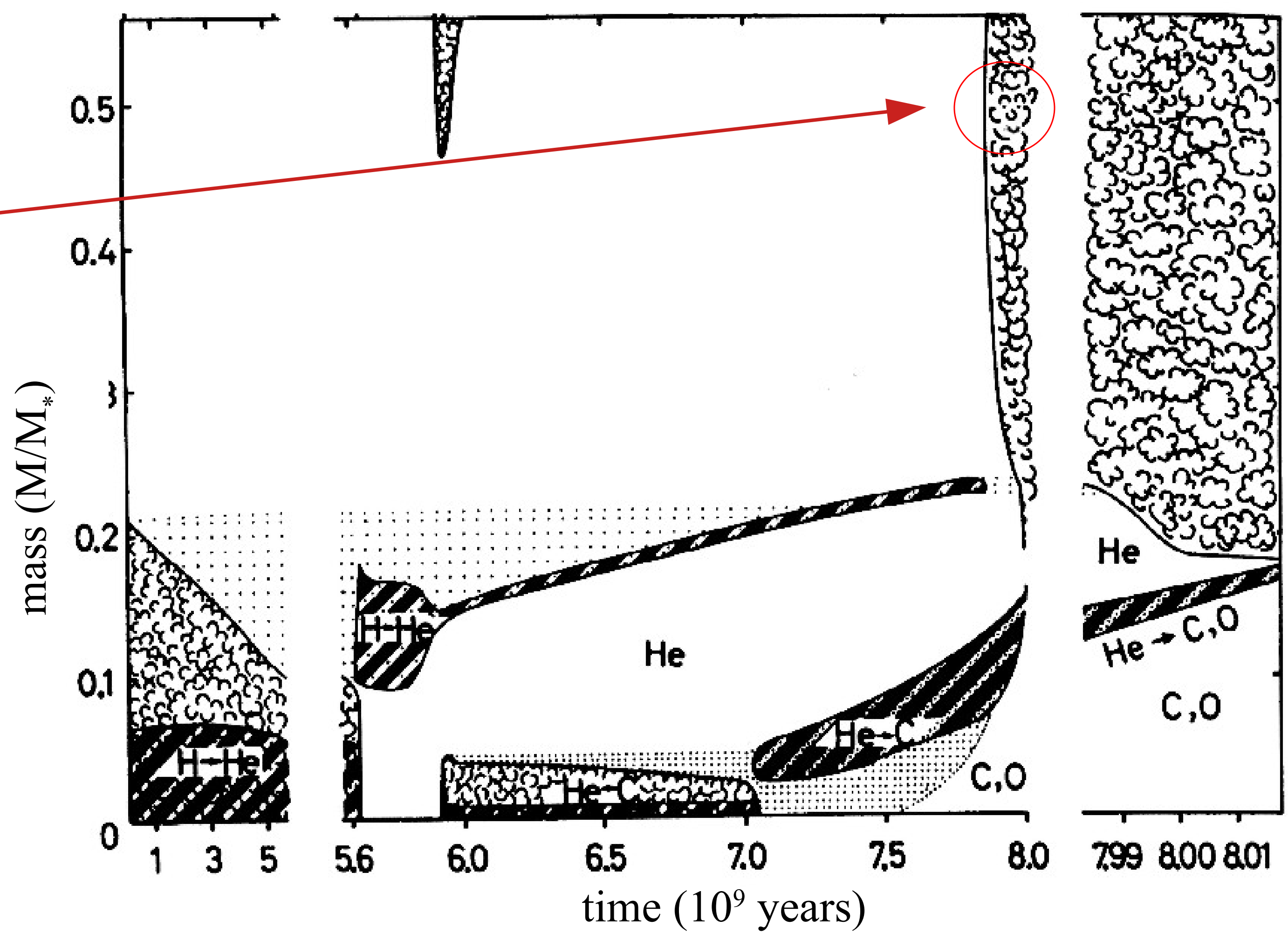
shaded areas mark regions that are



Stellar evolution – low mass stars

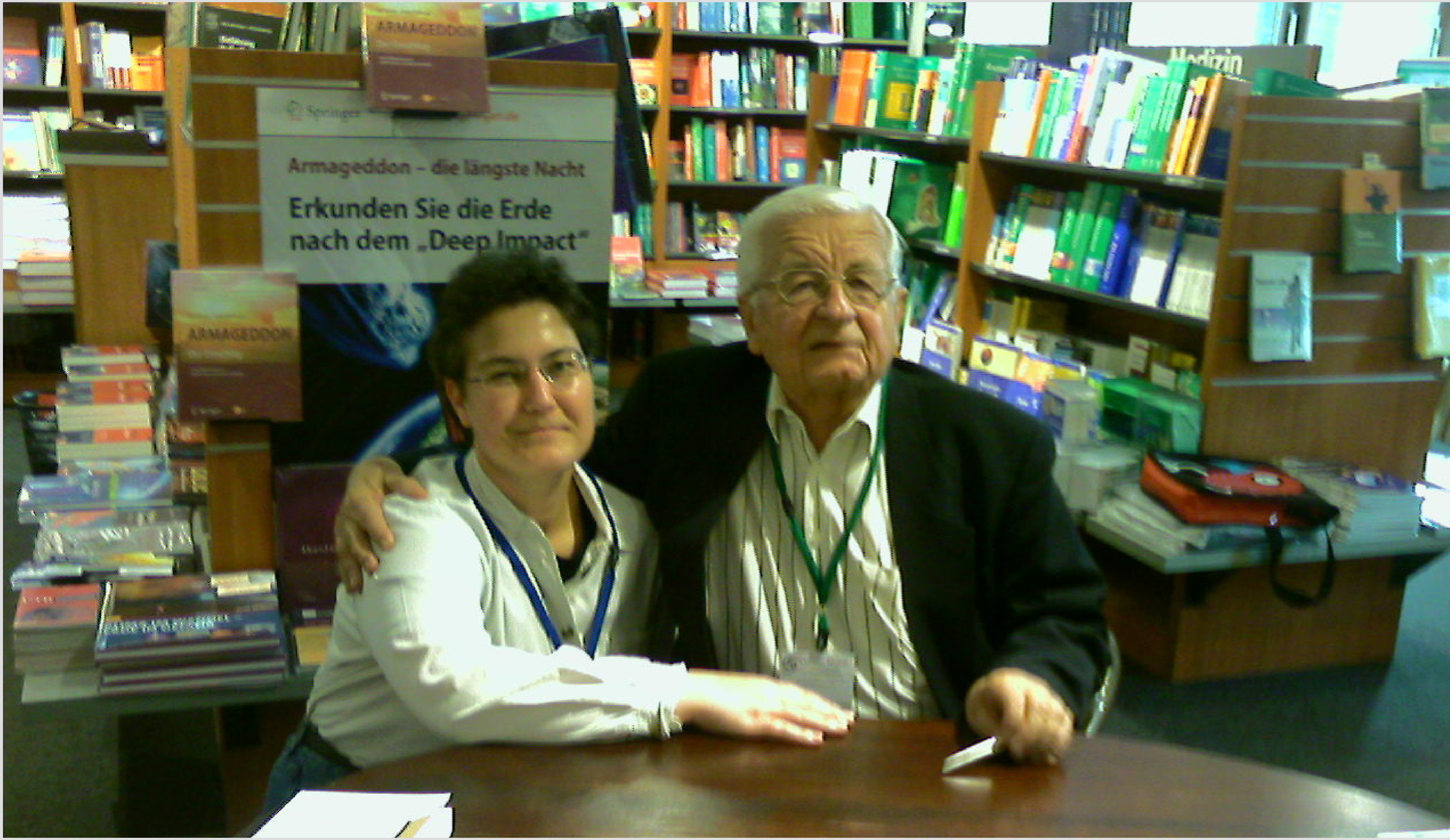
introduced by Rudolf Kippenhahn

In this case it's a real Kippenhahn ↕ made by himself



5 $M_\odot$ Stern

Rudolf Kippenhahn & Kerstin Weis



...he is my acadmic grand daddy

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