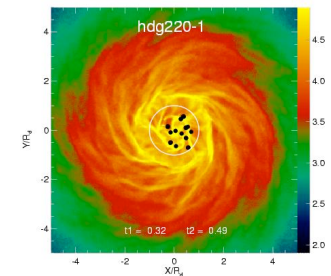
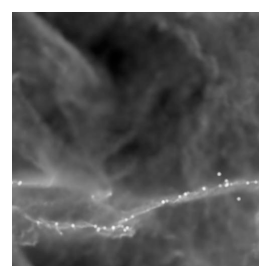
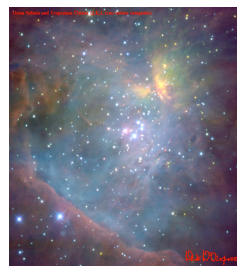
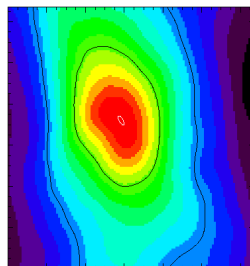
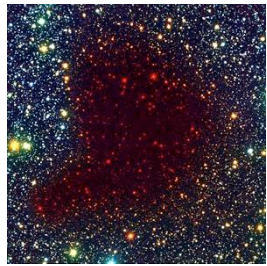


# stellar astrophysics



**Ralf Klessen / Stefan Jordan**

Zentrum für Astronomie der Universität Heidelberg



# important data

- **lecturers:**

- **Ralf Klessen** (ZAH/ITA), Albert-Ueberle-Str. 2, 69120 Heidelberg  
rklessen@ita.uni-heidelberg.de, 06221 / 548978
- **Stefan Jordan** (ZAH/ARI), Möchhofstr. 12-14, 69120 Heidelberg  
jordan@ari.uni-heidelberg.de, 06221 / 541842

- **time and location:**

- Tuesday, 14:15 - 16:00 hours  
Philosophenweg 12 -- Small Lecture Hall

- **tutorial:**

- Tutorial: Tuesday, 16:00 - 17:00 hours  
Philosophenweg 12 -- Small Lecture Hall



# time line

- |     |       |  |                 |
|-----|-------|--|-----------------|
| 1.  | 17.4  | Introduction (stars/stars in the galaxy/observational facts) | Ralf Klessen    |
| 2.  | 24.4. | Star Formation/protostellar collapse                         | Ralf Klessen    |
|     | 1.5.  | <b>Tag der Arbeit</b>  |                 |
| 3.  | 8.5.  | Stellar Structure (basic quantities)                         | Ralf Klessen    |
| 4.  | 15.5. | Stellar Structure (equation of state)                        | Stefan Jordan   |
| 5.  | 22.5. | Energy transport, convection                                 | Stefan Jordan   |
| 6.  | 29.5  | Energy production, pp-cycle                                  | Ralf Klessen    |
| 7.  | 5.6.  | Main sequence, CNO cycle                                     | Ralf Klessen    |
| 8.  | 12.6. | Stellar evolution to the AGB                                 | Thorsten Lisker |
| 9.  | 19.6. | Stellar Pulsations   | Stefan Jordan   |
| 10. | 26.6. | Rotation, Magnetic fields                                    | Ralf Klessen    |
| 11. | 3.7.  | Late Stages of stellar evolution (WD, NS, BH)                | Stefan Jordan   |
| 12. | 10.7. | Radiation, Stellar Atmospheres, Stellar Spectra              | Stefan Jordan   |
| 13. | 17.7. | Stellar Spectra  | Stefan Jordan   |
|     | 24.7. | <b>Study Week, no lecture</b>                                |                 |



# webpage

<http://www.ita.uni-heidelberg.de/research/klessen/people/klessen/lectures/2012-A/Stars/index.shtml>

Uni > ZAH > ITA > Forschung > Sternentstehung > Ralf Klessen > Lehre > Sommersemester 2012 >

## Stellare Astrophysik

<b>Dozenten:</b>	Ralf Klessen ZAH/ITA, Albert-Ueberle-Str. 2, 69120 Heidelberg Stefan Jordan ZAH/ARI, Mönchhofstr. 12-14, 69120 Heidelberg
<b>Zeit und Ort:</b>	Dienstag, 14:15 - 16:00 Uhr, Philosophenweg 12 -- Kleiner Hörsaal
<b>Zeitplan:</b>	Der genaue Zeitplan ist unter diesem <a href="#">LINK</a> zu finden.
<b>Inhalt:</b>	Sternaufbau und Entwicklung / Sternatmosphären / Sternentstehung / die Sonne
<b>Skript:</b>	Ein passwortgeschütztes, komplettes Skript findet man <a href="#">HIER</a> . Das Skript für meinen Teil der Vorlesung findet man <a href="#">HIER</a> im PDF Format.
<b>Übung:</b>	Für die Übungen haben wir die Stunde zwischen Vorlesungsende und dem Astronomischen Kolloquium reserviert. Der genaue Zeitplan wird in der Vorlesung besprochen.
<b>Seminar:</b>	Für das Master Modul MWAstro2 wird begleitend zur Vorlesung die Teilnahme an einem Seminar in Stellarer Astronomie und Astrophysik erwartet. Das Seminar wird als Blockkurs nach dem Ende der Vorlesungszeit abgehalten. Die Details werden in der Vorlesung besprochen.
<b>ECTS-Punkte:</b>	Vorlesung und Seminar ergeben <i>zusammen</i> das Master-Modul MWAstro2. Der Vorlesung Vorlesung entsprechen 4 ECTS-Punkte, das Seminar 2 ECTS-Punkte.
<b>Klausur:</b>	Der Klausurtermin wird noch bekannt gegeben.
<b>Literatur:</b>	Die Literaturliste ist unter diesem <a href="#">LINK</a> zu finden.
<b>Aktuelles:</b>	. . .

Verantwortlich: [Ralf Klessen](#), letzte Änderung am Sunday, 15-Apr-2012 22:21:14 CEST





# literature I

- list of recommended literature for the course

- Carroll, B.W., & Ostlie, D. A. 1996, "In Introduction into Moder Stellar Astrophysics" (Addison Welsey) -- Chapters 7 - 17
- Clayton, D. D. 1968, "Principles of Stellar Evolution and Nucleosynthesis" (McGraw-Hill, New York)
- Hansen, C.J., & Kawaler, S.D. 1994, "Stellar Interiors: Physical Principles, Structure, and Evolution" (Springer Verlag, Heidelberg Berlin New York)
- Kippenhahn, R., & Weigert, A. 1990, "Stellar Structure and Evolution" (Springer Verlag, Heidelberg Berlin New York)
- Phillips, A. C. 2006, The Physics of Stars (Wiley, second edition)
- Prialnik, D. 2010, An Introduction to the Theory of Stellar Structure and Evolution (Cambridge Univ. Press, second edition)
- Ryan, S. G. & Norton, A. J. 2010, Stellar Evolution and Nucleosynthesis (Cambridge University Presse)
- Shore, S. N. 2003, "The Tapestry of Modern Astrophysics" (Wiley, Hoboken, New Jersey) - Chapters 3 - 5



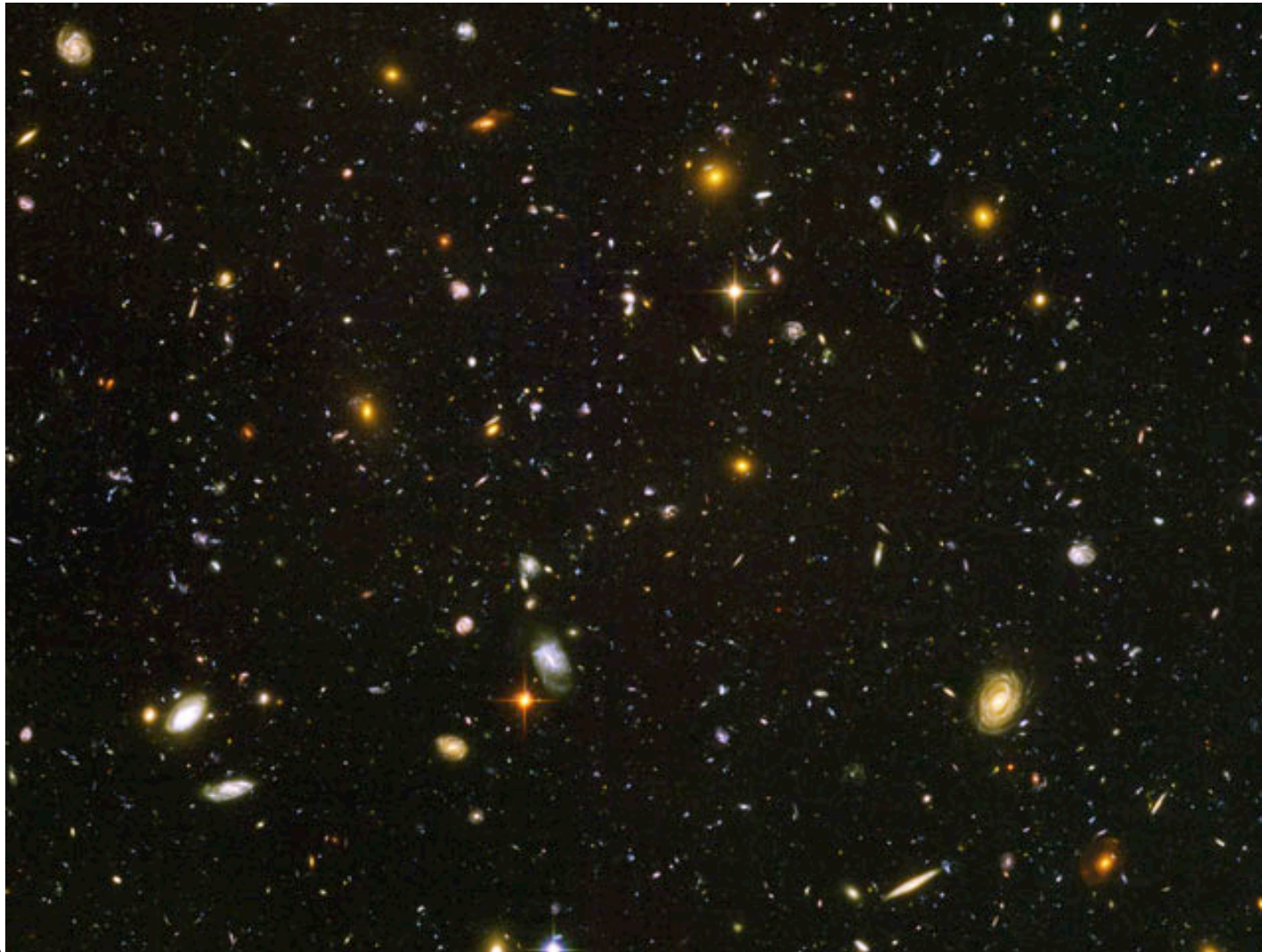
# literature II

- general literature

- Binney, J. & Merrifield, M. 1998, "Galactic Astronomy" (Princeton University Press)
- Scheffler, H. & Elsässer, H. 1990, "Physik der Sterne und der Sonne" (BI, Mannheim Wien Zürich)
- Shu, F. 1991, "The Physical Universe: An Introduction to Astronomy" (University Science Books, Mill Valey, California)
- Shu, F. 1991, "The Physics of Astrophysics I: Radiation" (University Science Books, Mill Valley)
- Shu, F. 1991, "The Physics of Astrophysics II: Gas Dynamics" (University Science Books, Mill Valley)
- Stahler, S. W. & Palla, F. 2004, "The Formation of Stars" (Wiley-VCH, Weinheim)
- Unsöld, A. & Baschek, B. 1991, "The New Cosmos" (Springer Verlag)
- Voigt, H.-H. 2002, "Abriss der Astronomie" (Spektrum Akademischer Verlag)
- Weigert, A, Wendker, H. J., & Wisotzki, L. 2004, "Astronomie und Astrophysik" (Wiley-VCH, Berlin)



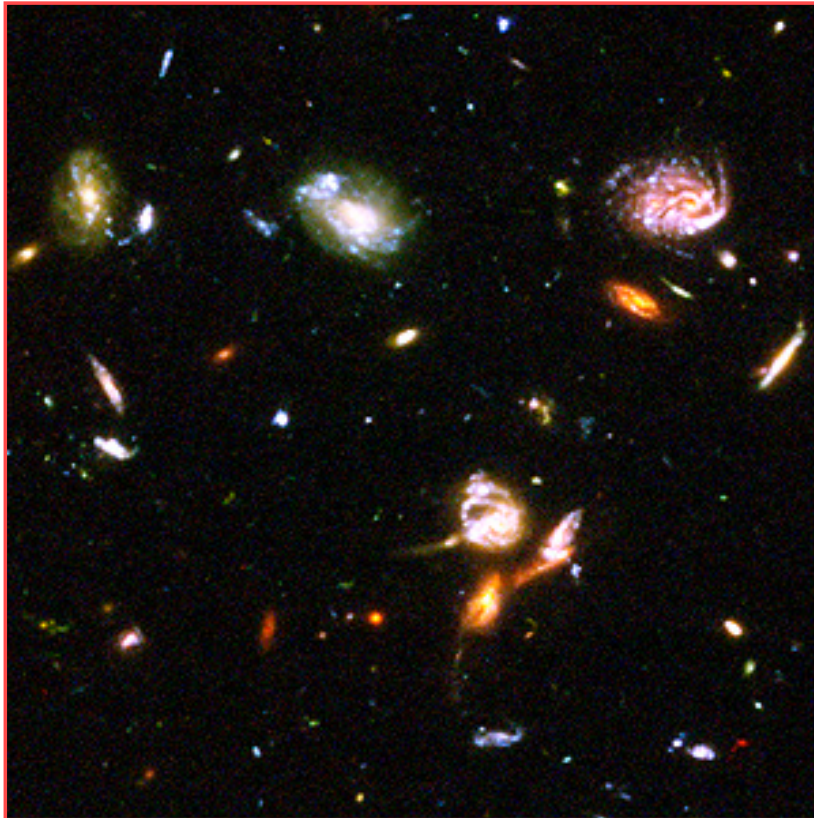
# where we find stars...



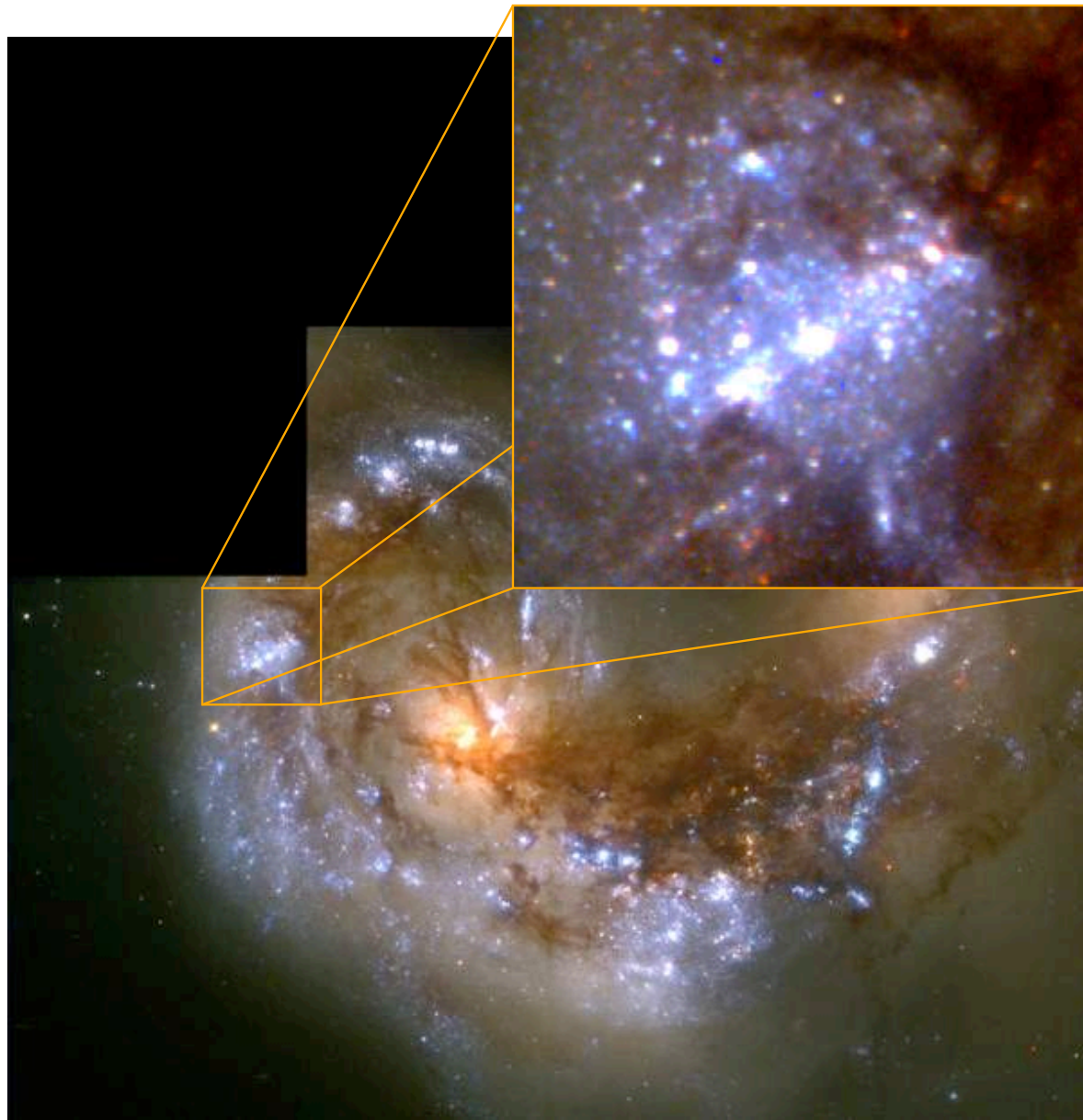
(Hubble Ultra-Deep Field, from HST Web site)



# where we find stars...



(Hubble Ultra-Deep Field, from HST Web site)



(HST: Whitmore & Schweizer: Antennae galaxies)






young (massive)  
stars are associated  
with spiral density  
waves

older stars are more  
evenly distributed  
throughout the  
galaxy

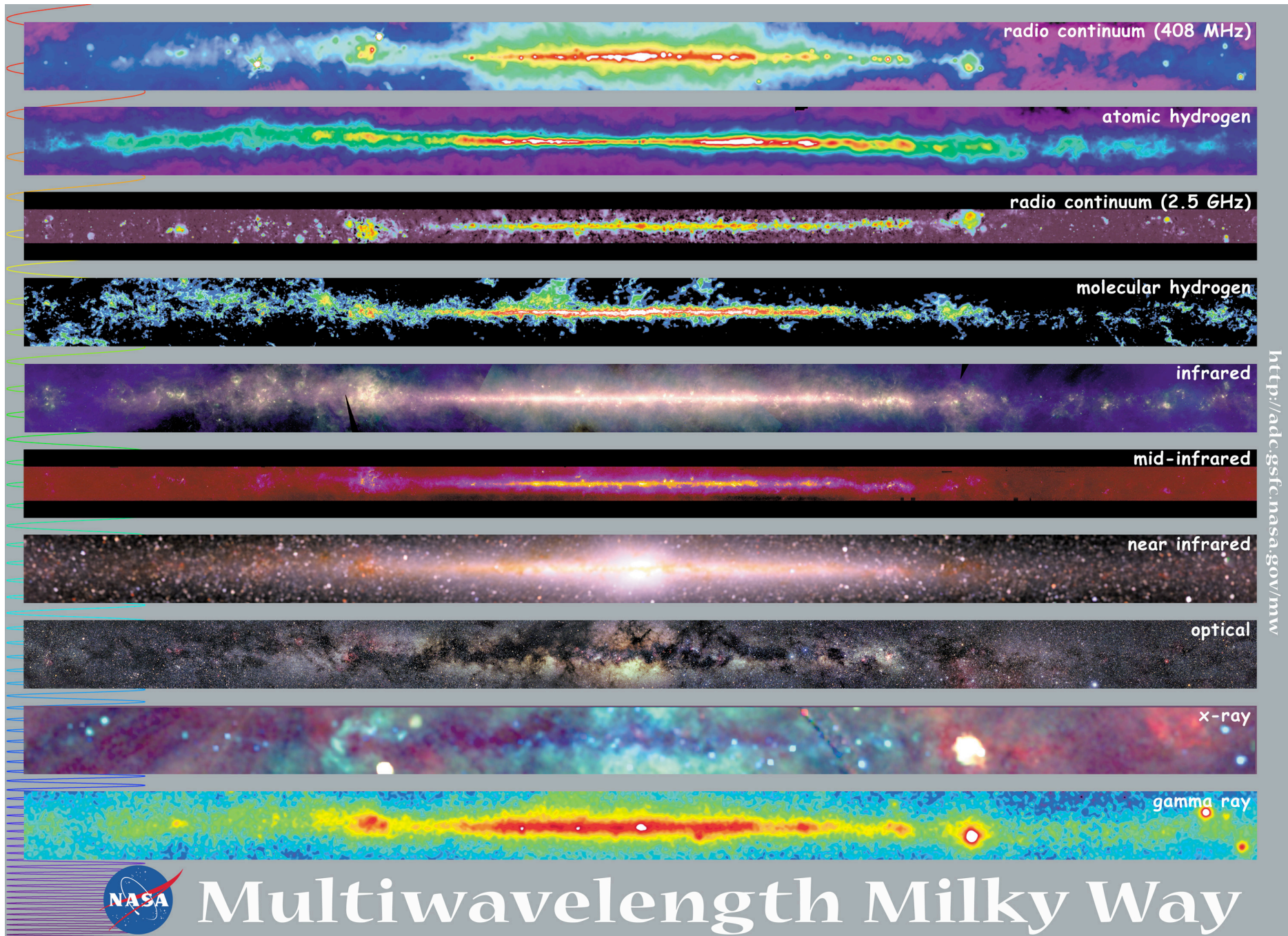


(NGC4622: from the Hubble Heritage Team)



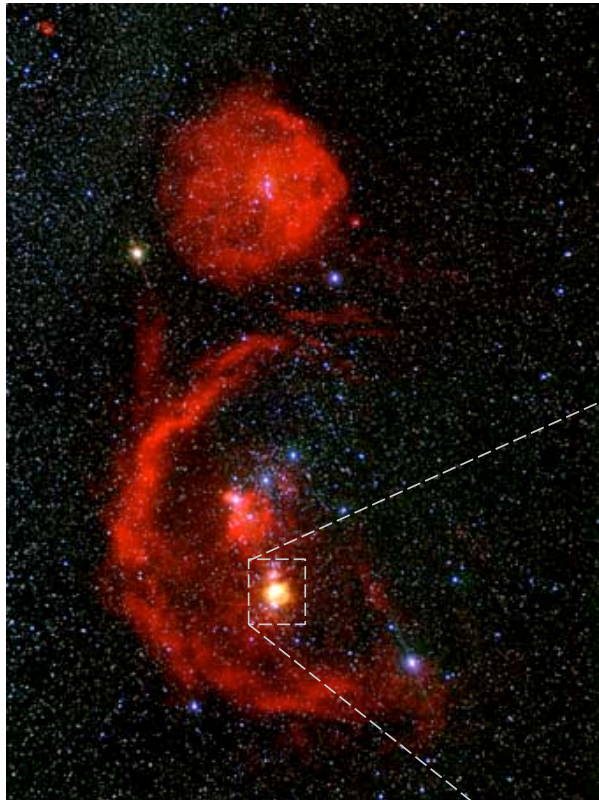
The Sombrero Galaxy — M104  HUBBLESITE.org







# nearby young cluster: the Trapezium in Orion



Orion molecular cloud

The Orion molecular cloud is the birth- place of several young embedded star clusters.  
The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.



Trapezium cluster





## Trapezium Cluster (detail)

- stars form in **clusters**
- stars form in **molecular clouds**
- (proto)stellar **feedback** is important

(color composite J,H,K  
by M. McCaughrean,  
VLT, Paranal, Chile)

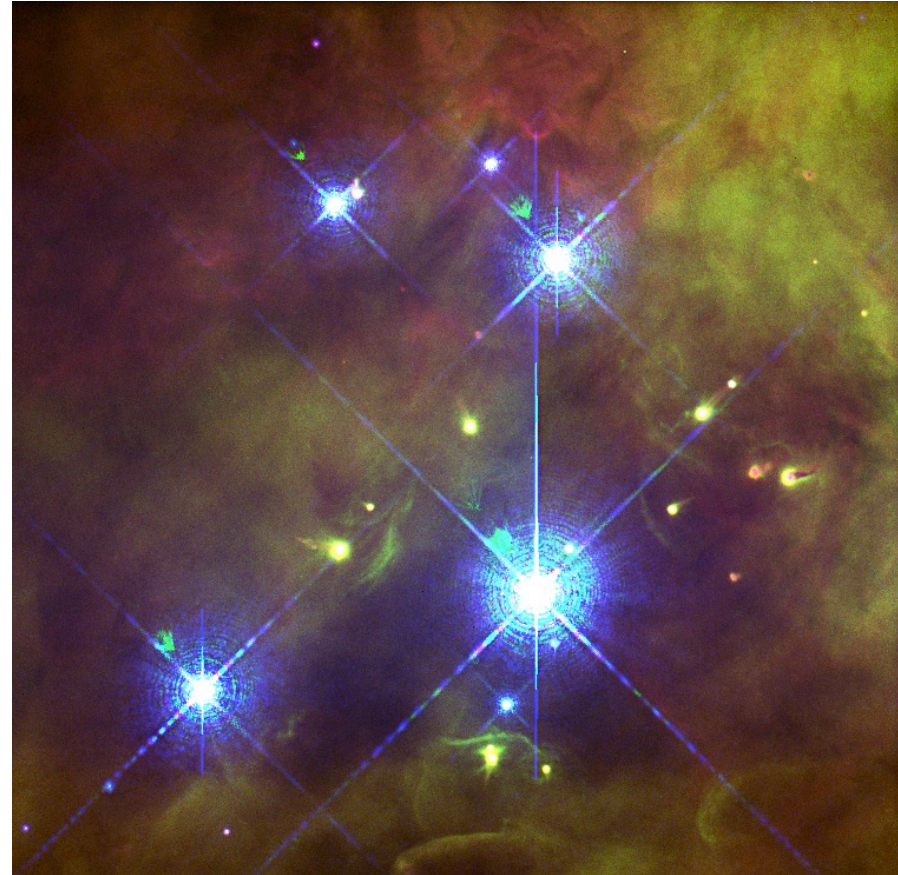
Kiessen /



# Trapezium stars in Orion



Ionizing radiation from central star  
**Θ1C Orionis**



**Proplyds:** Evaporating ``protoplanetary`` disks  
around young low-mass protostars

(images: Doug Johnstone et al.)

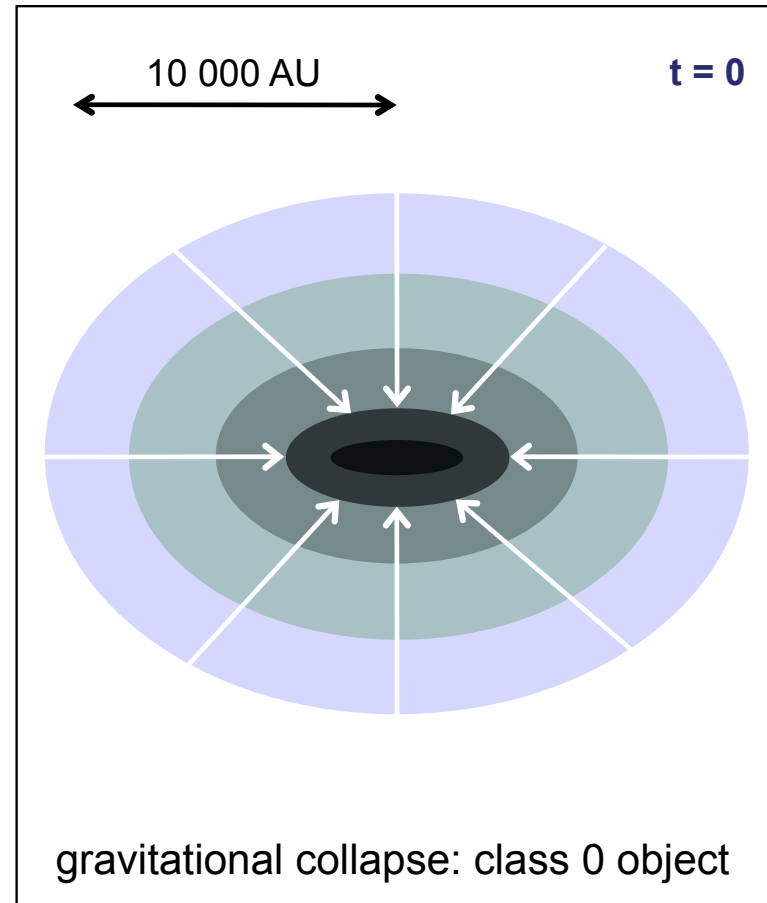
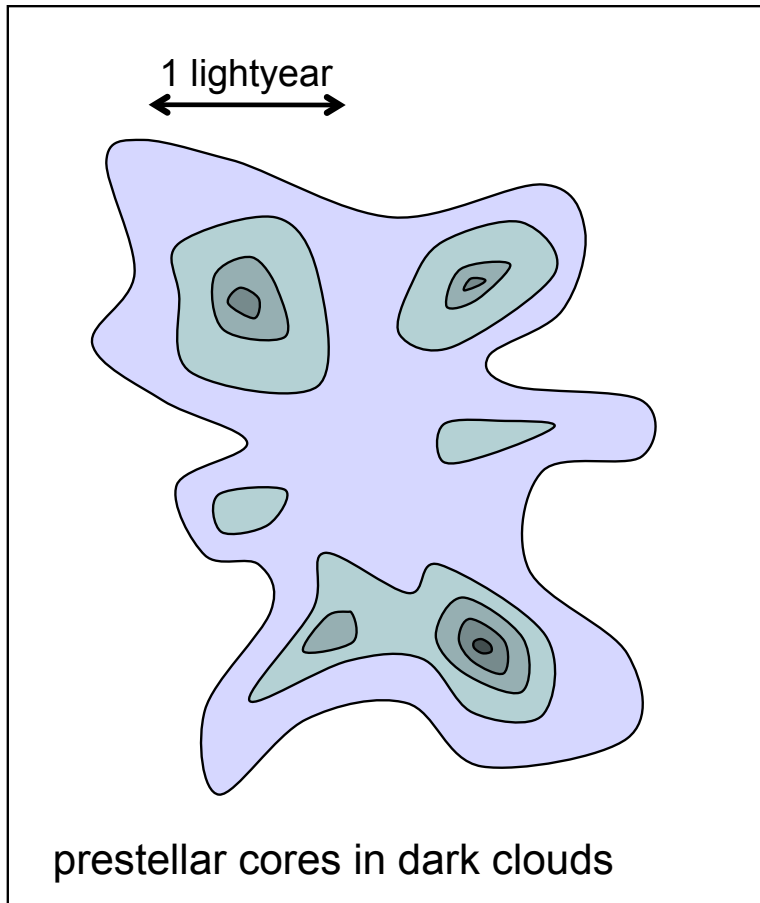




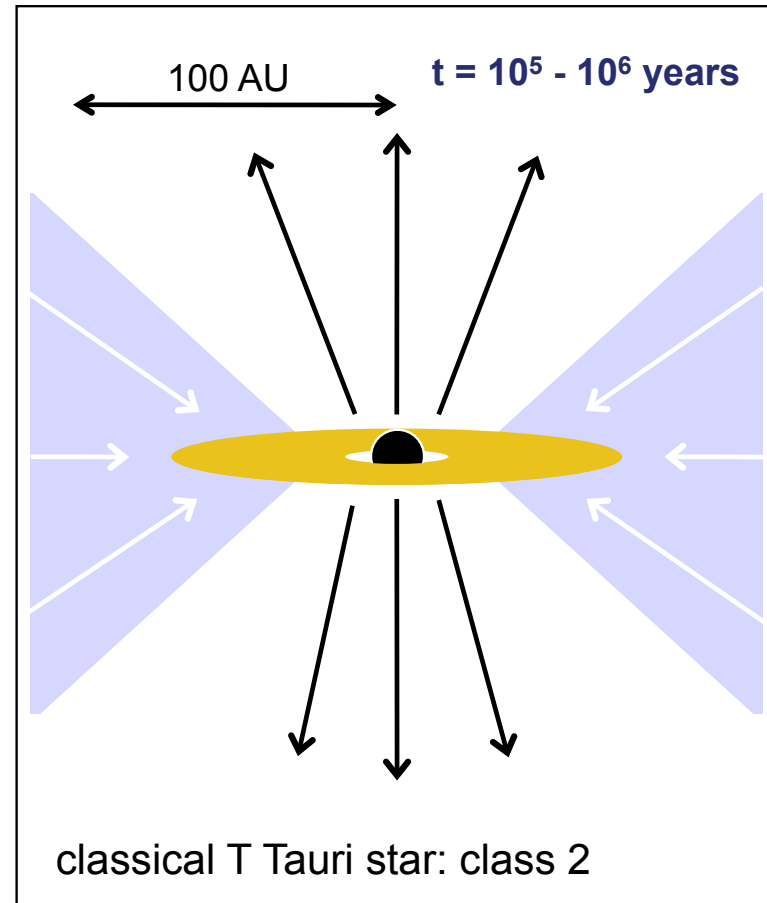
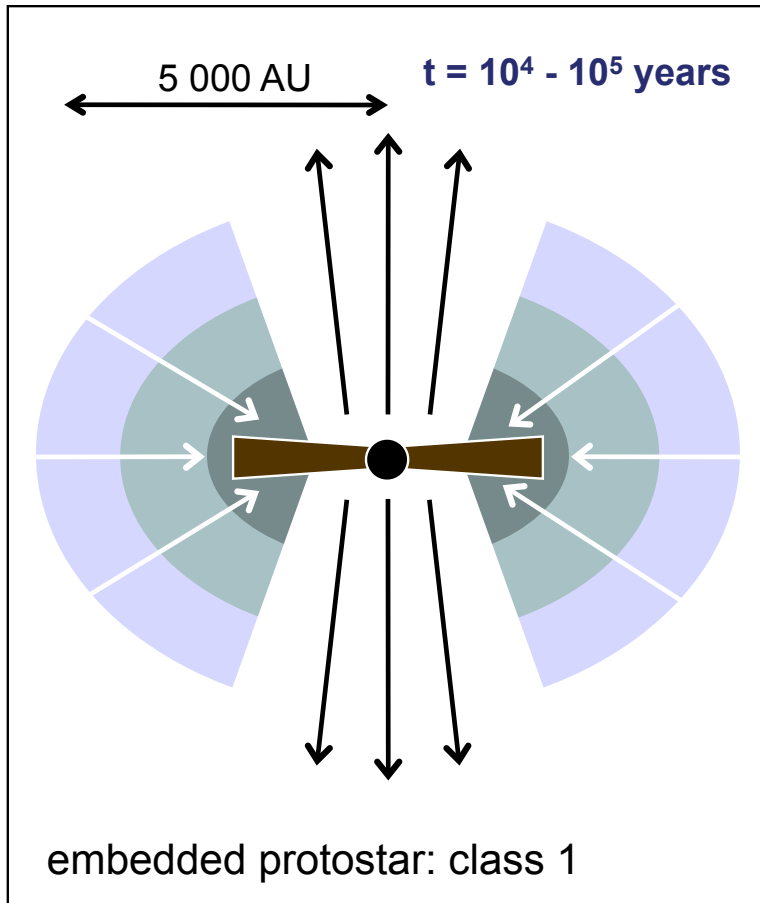
(Pleiades: skyfactory.org)



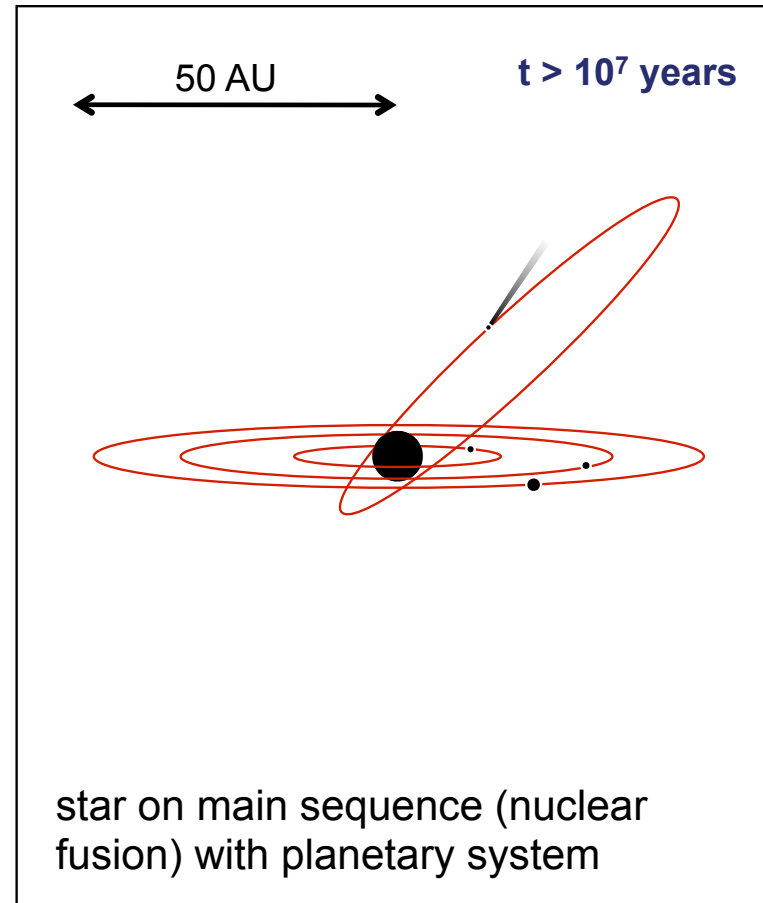
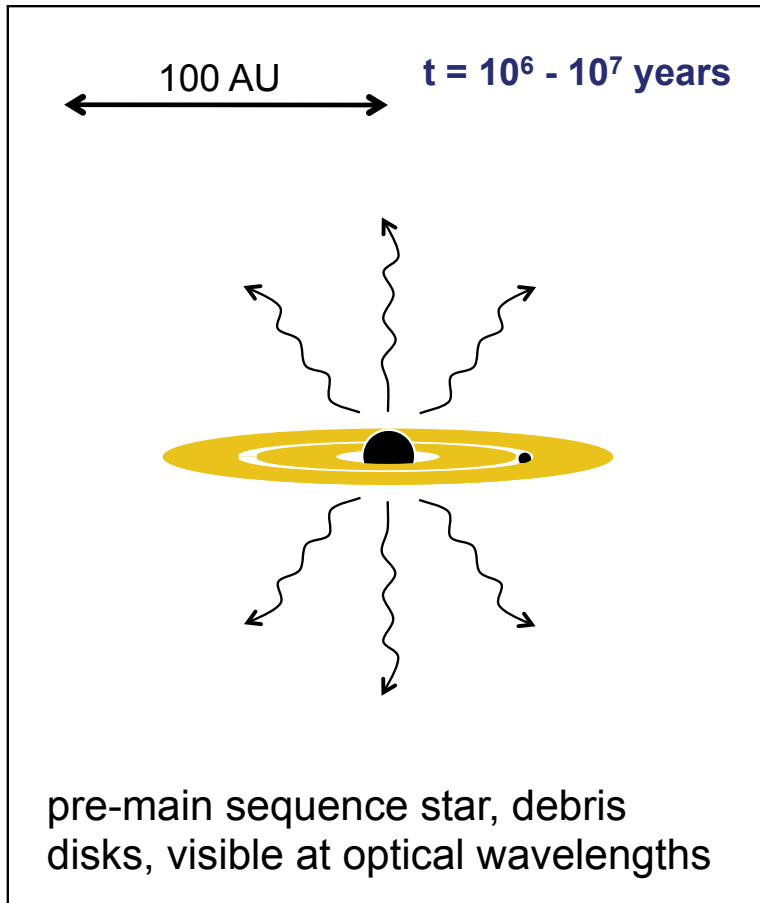
# Phases of star formation



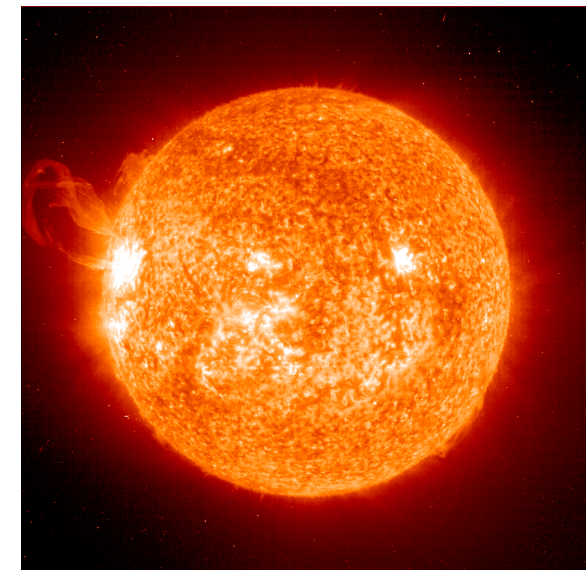
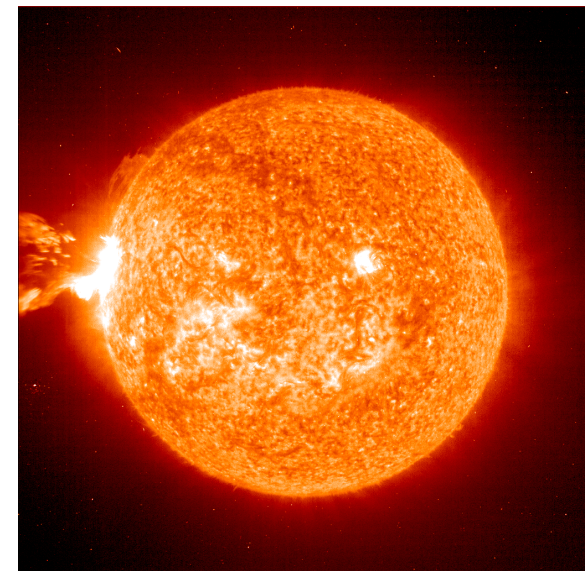
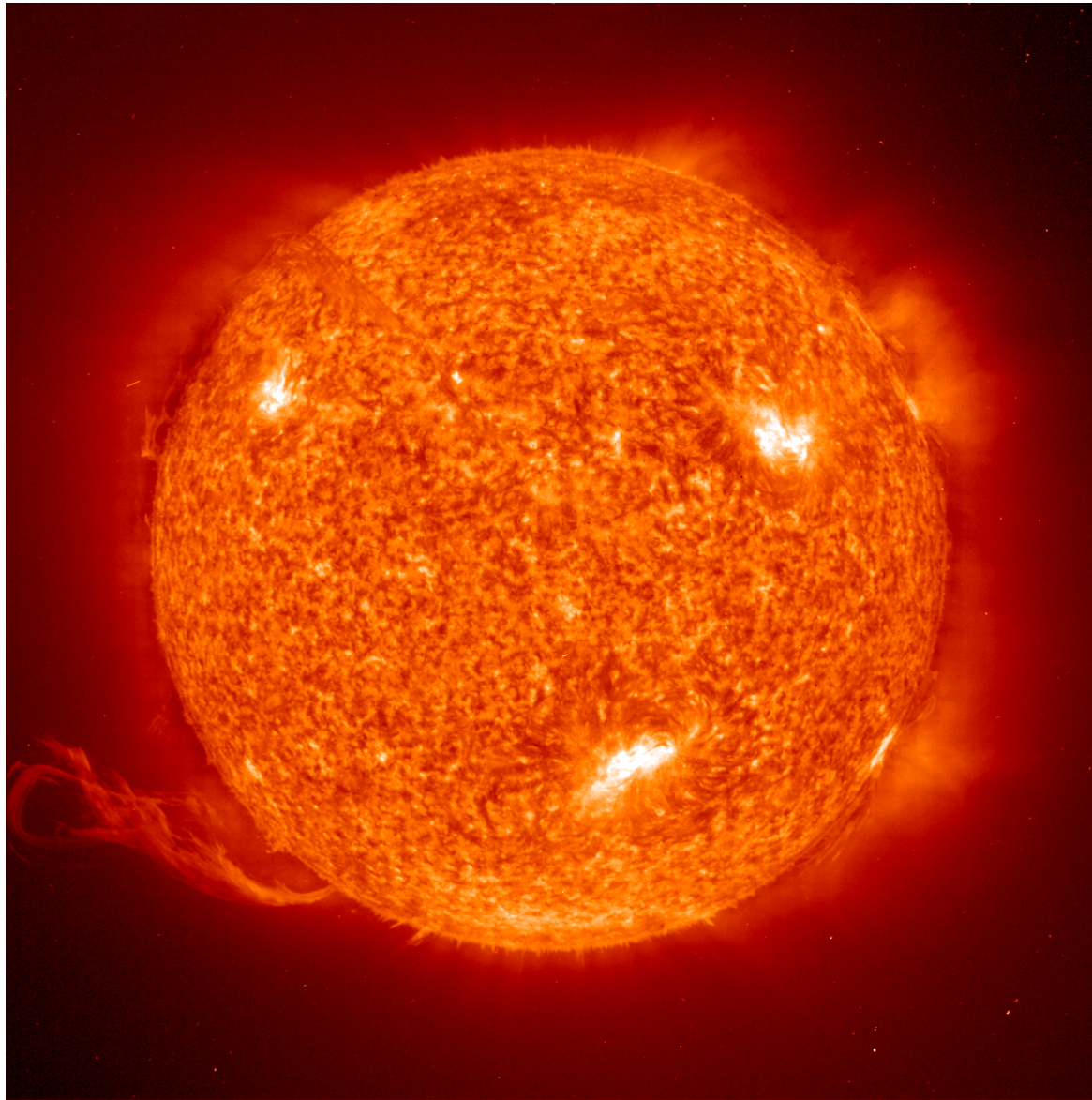
# Phases of star formation



# Phases of star formation





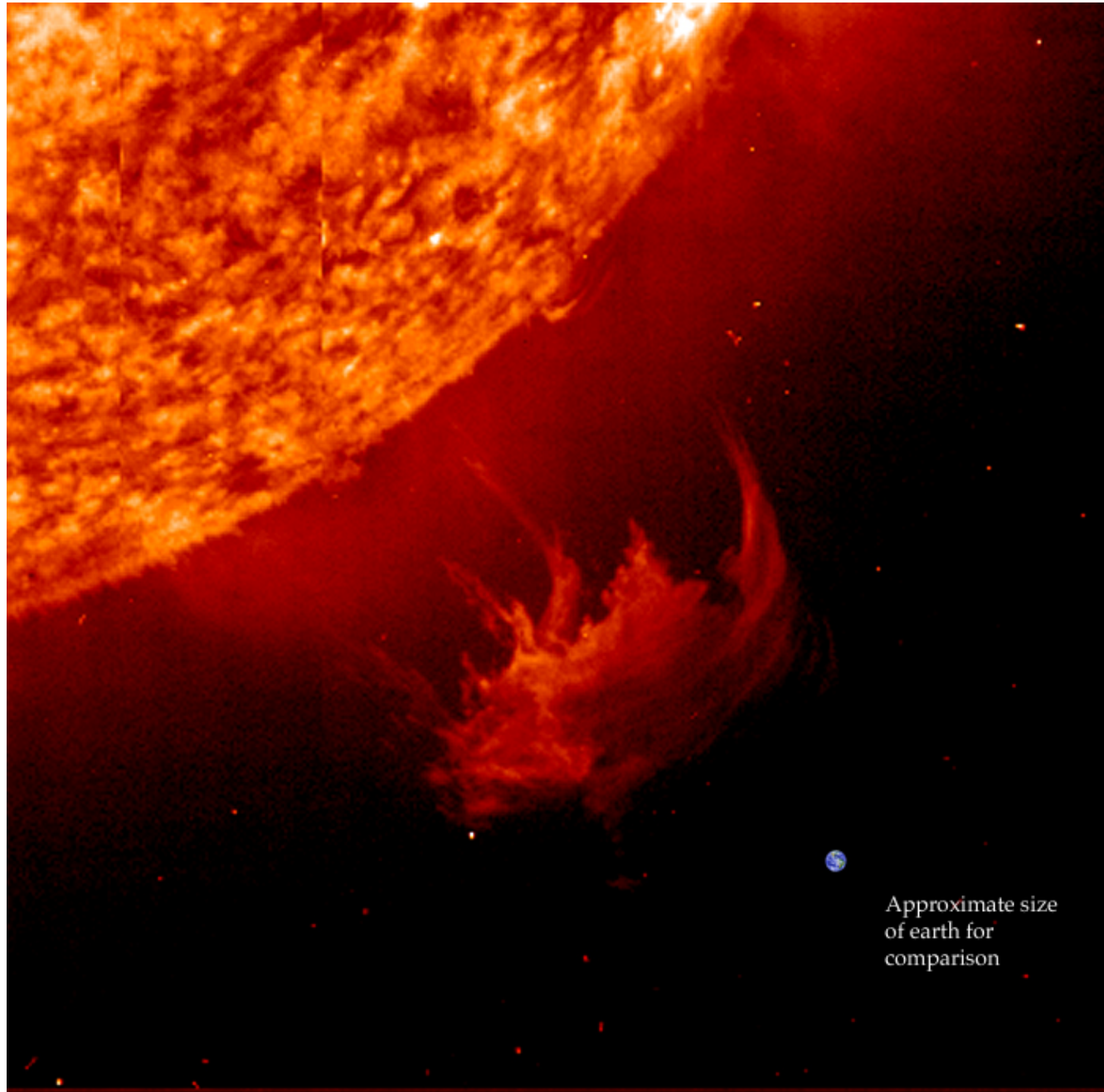


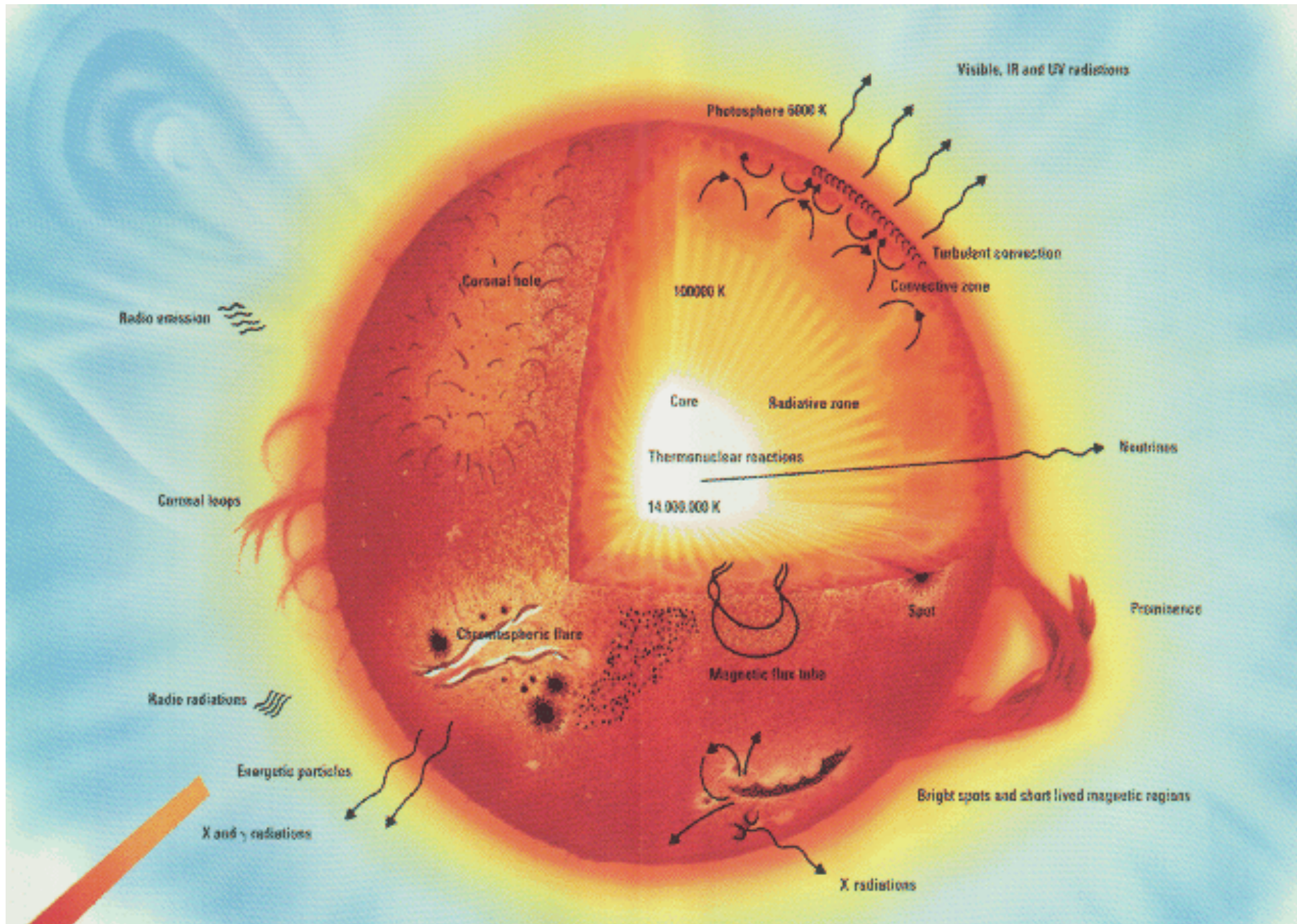
## Unsere Sonne in verschiedenen Aktivitätsphasen





# Größenvergleich: Sonne - Erde







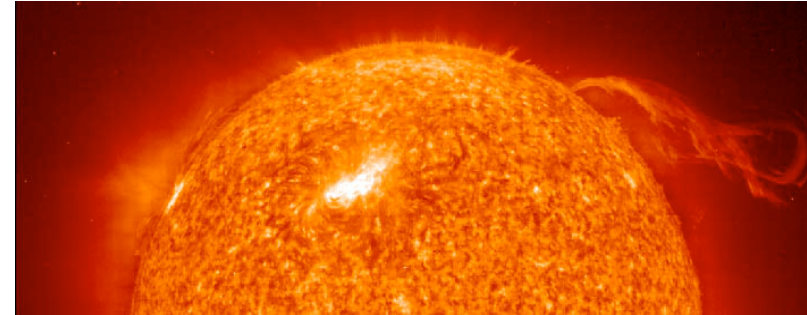
# public stellar evolution codes

- public stellar structure codes:
  - MESA stellar evolution code:  
<http://www.astro.wisc.edu/~townsend/static.php?ref=mesasdk>
  - online stellar evolution code:  
<http://www.astro.wisc.edu/~townsend/static.php?ref=ez-web>
  - STELLAR code in Bodenheimer's book "Numerical Methods in Astrophysics"
  - STATSTAR code in Carroll & Ostriker "Introduction to Modern Astrophysics"  
<http://homepages.wmich.edu/~korista/statstar.f>



# Sterne: die Sonne

Eigenschaften der Sterne  
(Stellare Zustandsgrößen):



**Unsere Sonne** ☉ als Referenzstern

Radius	$R_{\odot}$	696 000 km
Masse	$M_{\odot}$	$1,989 \times 10^{30}$ kg
Leuchtkraft	$L_{\odot}$	$3,86 \times 10^{26}$ W
effektive Temperatur	$T_{\text{eff}}$	5800 K (Oberfläche)
Zentraltemperatur	$T_{\text{zentral}}$	$15 \times 10^6$ K
Alter	$t_{\odot}$	$4.5 \times 10^9$ a

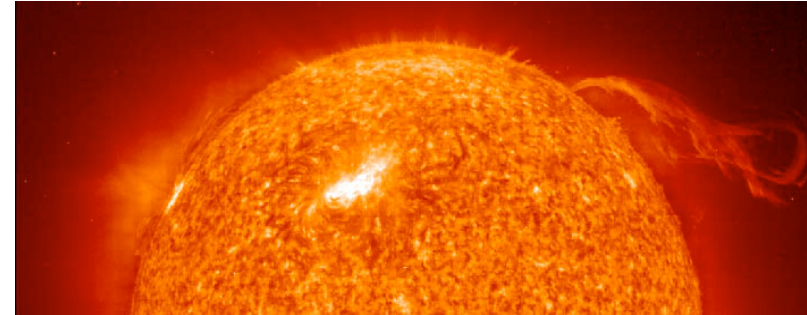
auf der Erde:  
Solarkonstante  
 $1.37 \text{ kW/m}^2$

Spektraltyp G2  
Leuchtkraftklasse V  
chemische Zusammensetzung (Massenanteil)  
73% Wasserstoff X  
25% Helium Y  
2% Metalle Z



# Sterne: die Sonne

Eigenschaften der Sterne  
(Stellare Zustandsgrößen):



**Unsere Sonne ☉ als Referenzstern**

Radius	$R_{\odot}$	$7 \times 10^{10}$ cm
Masse	$M_{\odot}$	$2 \times 10^{33}$ g
Leuchtkraft	$L_{\odot}$	$4 \times 10^{33}$ erg/s
effektive Temperatur	$T_{\text{eff}}$	5800 K
Zentraltemperatur	$T_{\text{zentral}}$	$15 \times 10^6$ K
Alter	$t_{\odot}$	$1.7 \times 10^{17}$ s

in cgs Einheiten

Spektraltyp G2  
Leuchtkraftklasse V  
chemische Zusammensetzung (Massenanteil)  
73% Wasserstoff X  
25% Helium Y  
2% Metalle Z



# Sterne: Statistische Charakteristika

## Massenverteilung:

minimale Masse  $\approx 0,07 M_{\odot}$

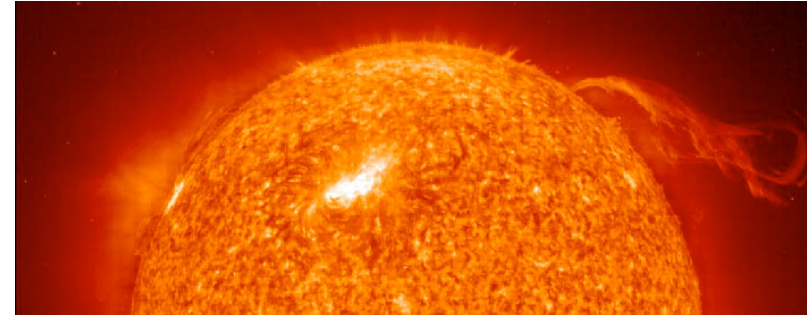
Grenze des Wasserstoffbrennens

maximale Masse  $\approx 120 M_{\odot}$

Eddington-Limit,  $F_{\text{rad}} = F_{\text{grav}}$

Ursprüngliche Massenverteilung

$dN(M) \propto M^{\alpha} dM$ ,  $\alpha \approx -2.3$  für Sterne massereicher als die Sonne

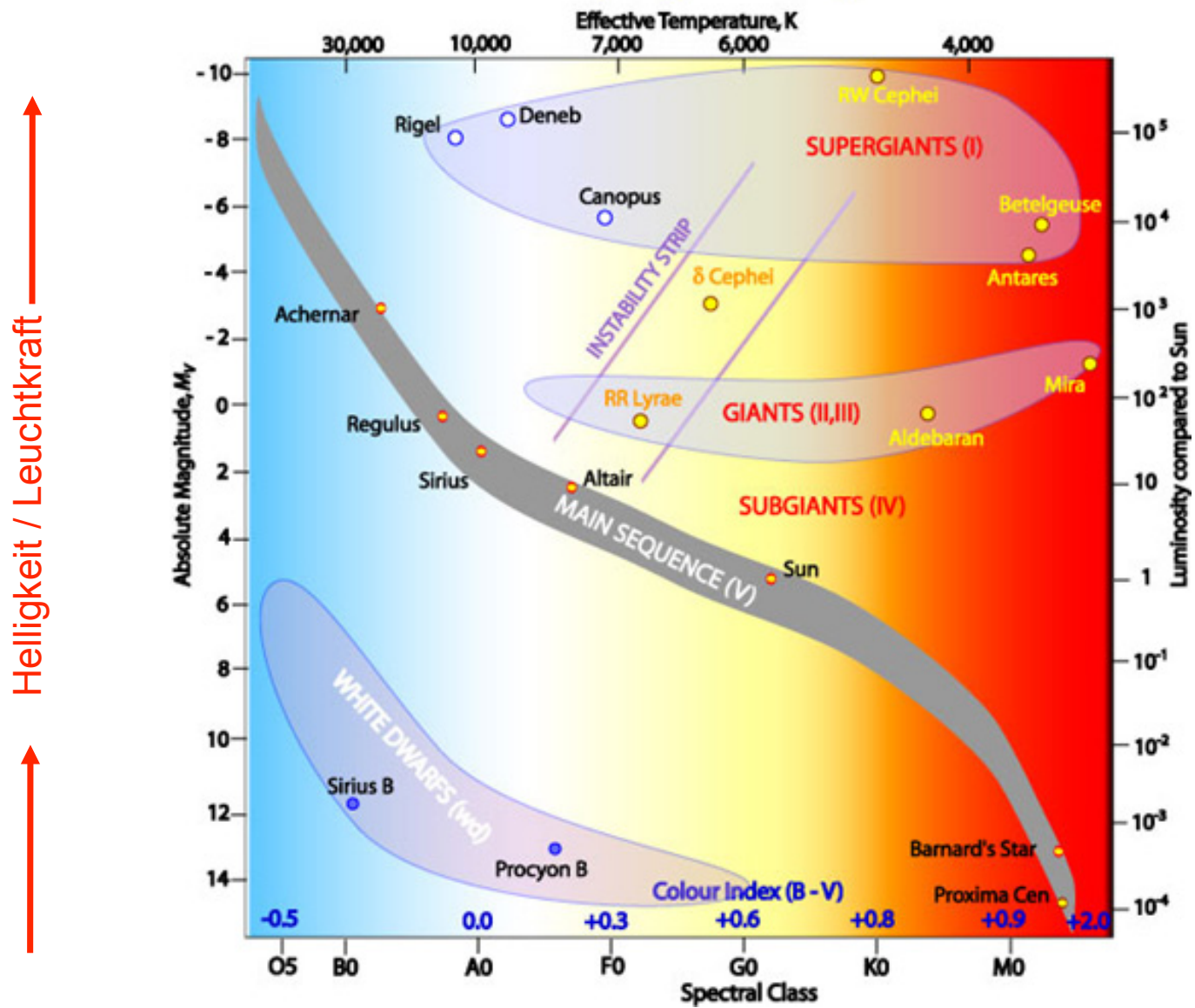


## Weitere Eigenschaften:

Spektraltyp	$T_{\text{eff}}$ [K]	$M[M_{\odot}]$	$L [L_{\odot}]$	$T_{\text{HR}}$ [a]
O7.5	38 000	25	80 000	$2 \times 10^6$
B0	33 000	16	10 000	$1 \times 10^7$
B5	17 000	6	600	$6 \times 10^7$
A0	9 500	3	60	$3 \times 10^8$
F0	6 900	1,5	6	$1.5 \times 10^9$
G0	5 800	1	1	$6 \times 10^9$
K0	4 800	0,8	0,4	$12 \times 10^9$
M0	3 670	0,5	0,08	$35 \times 10^9$



# Hertzsprung-Russell Diagram

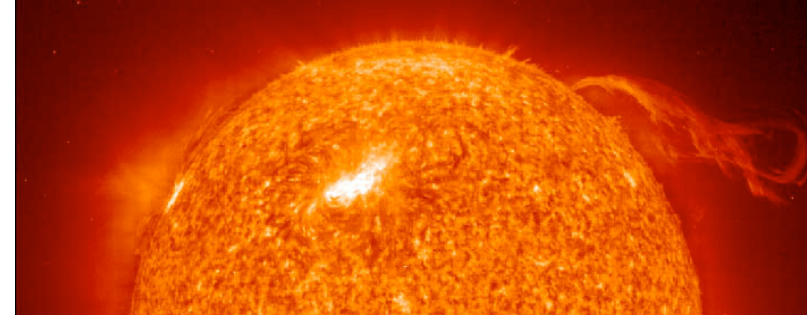


↑ Helligkeit / Leuchtkraft ↑

← Farbe / Temperatur ←



# Sterne: Statistische Charakteristika



Sterndichte in der Sonnenumgebung

$$n_* \approx 0,05 \text{ pc}^{-3}$$

Sterndichte im Orion-Trapezhaufen

$$n_* \approx 10^3 \text{ pc}^{-3}$$

Sterndichte in Starburst-Regionen

$$n_* \approx 10^4 \text{ pc}^{-3}$$

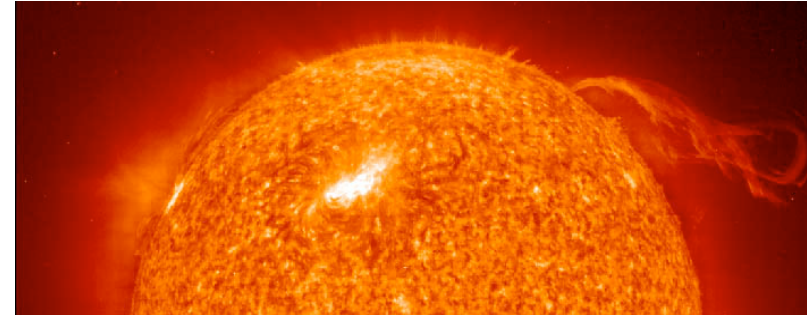
$$1 \text{ pc} = 3,086 \times 10^{18} \text{ cm}$$

**Anzahl der Sterne in der Milchstraße:  $\approx 10^{11}$**

**Sternentstehungsrate:  $\approx 2 M_{\odot} / \text{Jahr}$**



# Sterne: Statistische Charakteristika



Sterndichte in der Sonnenumgebung  
Sterndichte im Orion-Trapezhaufen  
Sterndichte in Starburst-Regionen

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**Anzahl der Sterne in der Milchstraße:  $\approx 10^{11}$**

**Sternentstehungsrate:  $\approx 2 M_{\odot} / \text{Jahr}$**

## Skalen:

Milchstraße

$$\varnothing \approx 30 \text{ kpc} \approx 10^{23} \text{ cm} \approx 100.000 \text{ Lichtjahre}$$

Sonnensystem (Pluto-Bahn)

$$\varnothing \approx 80 \text{ AU} \approx 10^{15} \text{ cm} \approx 11 \text{ Lichtstunden}$$

Erdbahn

$$\varnothing \approx 2 \text{ AU} \approx 3 \times 10^{15} \text{ cm} \approx 17 \text{ Lichtminuten}$$

Sonnendurchmesser

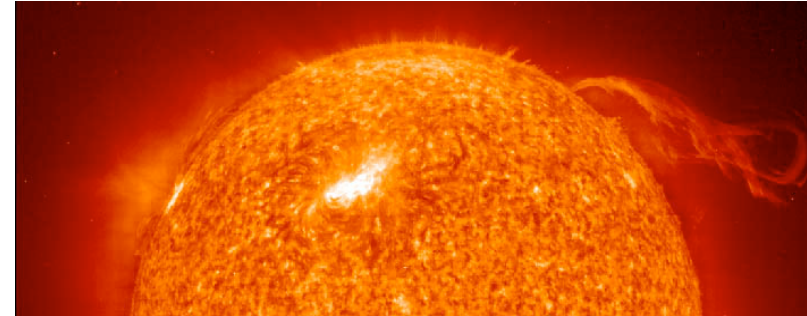
$$\varnothing \approx 1,4 \times 10^{11} \text{ cm}$$

Erdurchmesser

$$\varnothing \approx 1,3 \times 10^9 \text{ cm}$$



# Sterne: Statistische Charakteristika



Sterndichte in der Sonnenumgebung  
Sterndichte im Orion-Trapezhaufen  
Sterndichte in Starburst-Regionen

$$n_* \approx 0,05 \text{ pc}^{-3}$$

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$$1 \text{ pc} = 3,086 \times 10^{18} \text{ cm}$$

**Anzahl der Sterne in der Milchstraße:  $\approx 10^{11}$**

**Sternentstehungsrate:  $\approx 2 M_{\odot} / \text{Jahr}$**

## Skalen:

Druck im Sonneninneren  $2,5 \times 10^{11} \text{ bar} \approx 7,8 \times 10^{25} \text{ Teilchen / cm}^3$  (130 g/cm<sup>3</sup>)

Druck in Erdatmosphäre  $10^{13} \text{ bar} \approx 2,5 \times 10^{19} \text{ Teilchen / cm}^3$

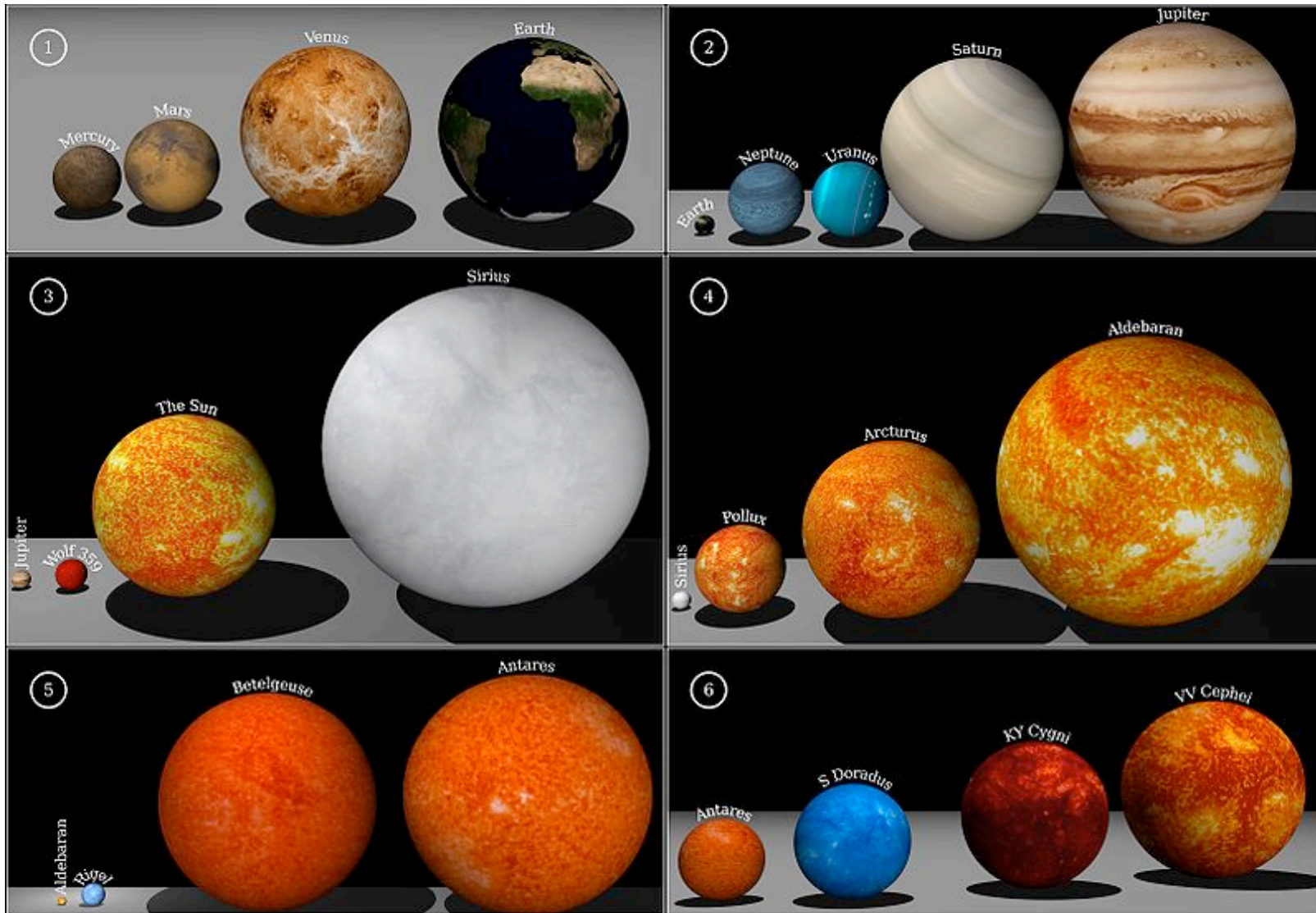
Ultrahochvakuum (auf Erde)  $10^{-9} \text{ bar} \approx 2,5 \times 10^7 \text{ Teilchen / cm}^3$

Sternbildendes Gas  $10^3 - 10^4 \text{ Teilchen / cm}^3$

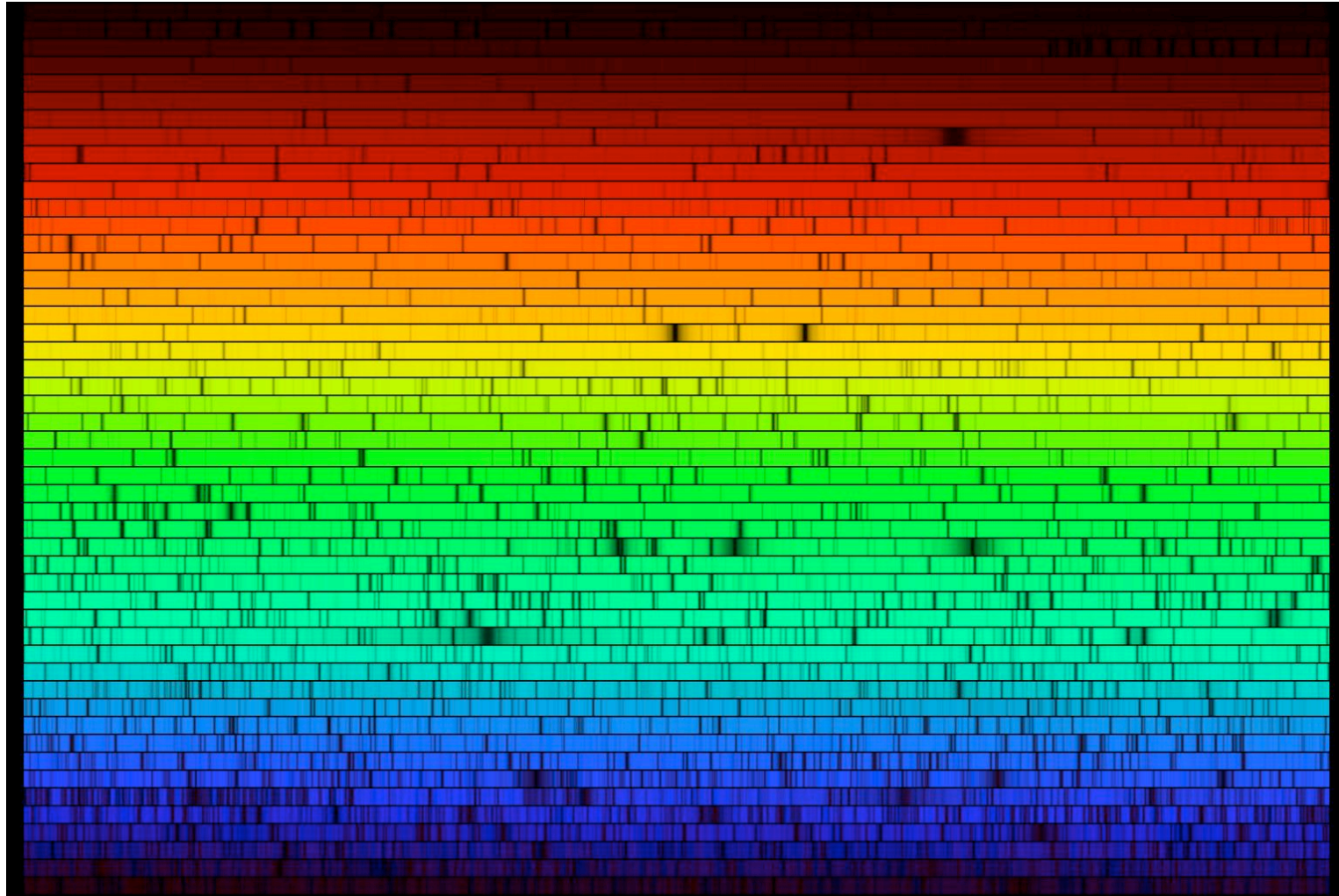
Interstellares Gas im Mittel *einige* Teilchen / cm<sup>3</sup>



# stellar sizes



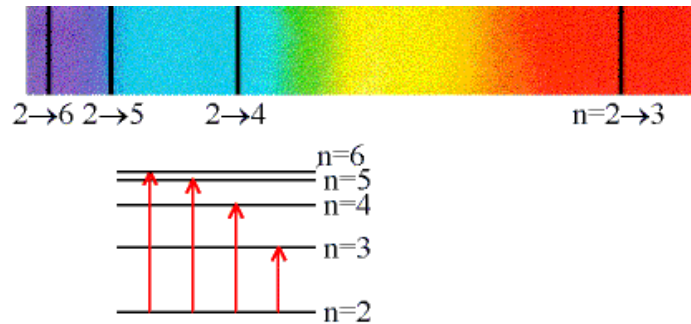
# spectrum of Sun



(credit: NOAO)

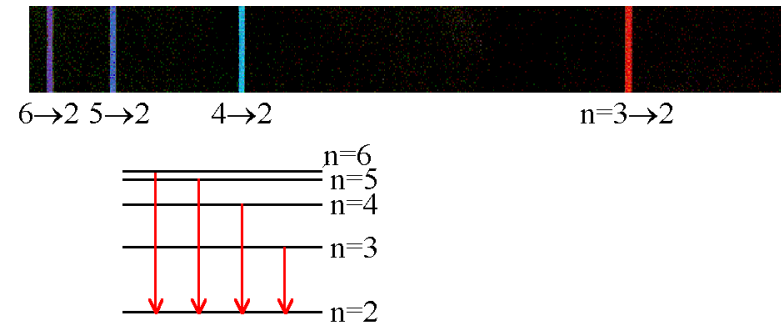


# atomic lines



————— n=1 (Ground State)

absorption lines

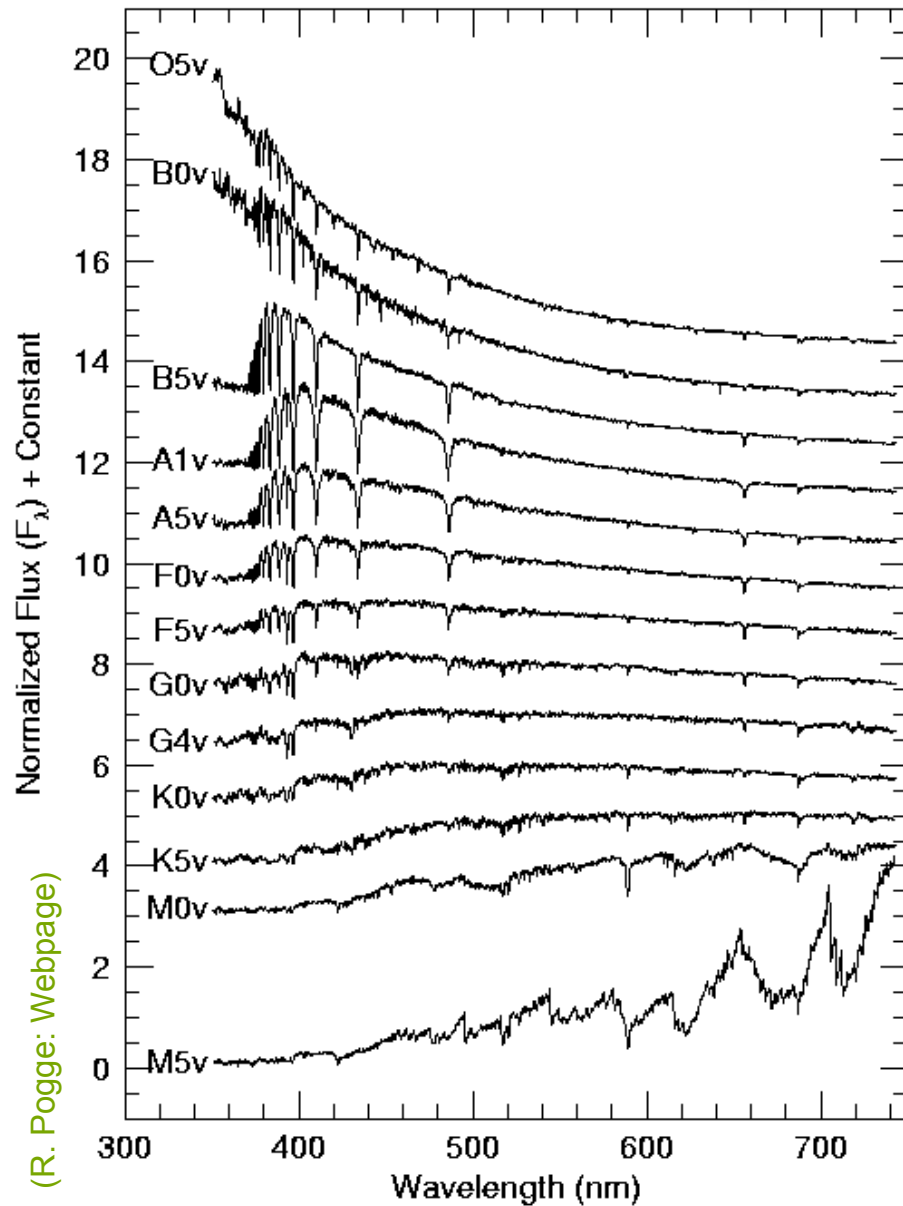


————— n=1 (Ground State)

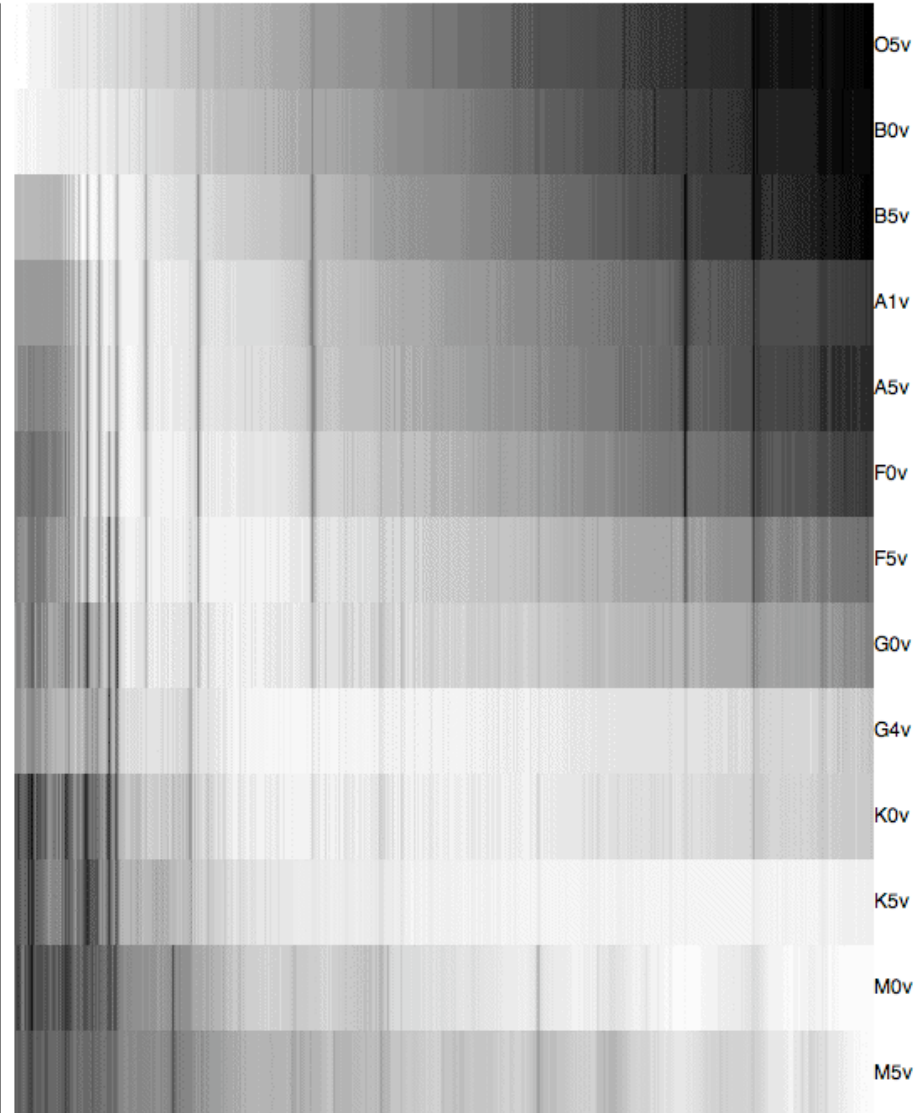
emission lines



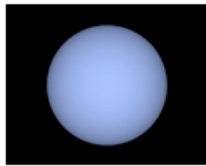
# sample spectra



(R. Pogge: Webpage)



### O Stars

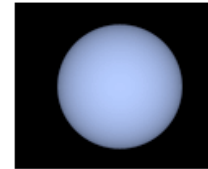


Hottest Stars:  $T > 30,000$  K; Strong  $\text{He}^+$  lines; no H lines (or only very weak at O9).

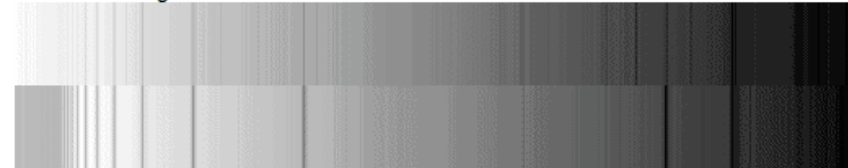


Spectrum of an O5v star

### B Stars

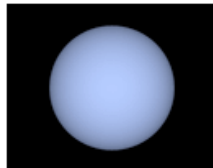


$T = 11,000 - 30,000$  K; Strong neutral He lines; very weak H lines, getting stronger from B0 through B9.

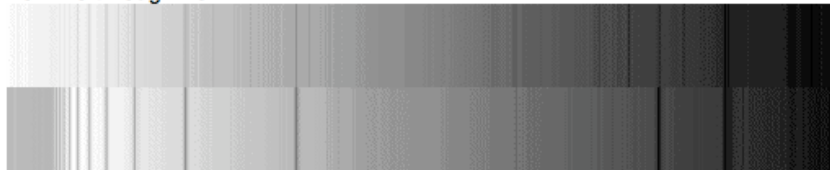


Spectra of B0v (top) and B5v (bottom) stars

### B Stars

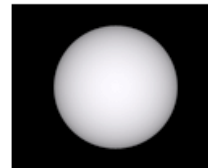


$T = 11,000 - 30,000$  K; Strong neutral He lines; very weak H lines, getting stronger from B0 through B9.

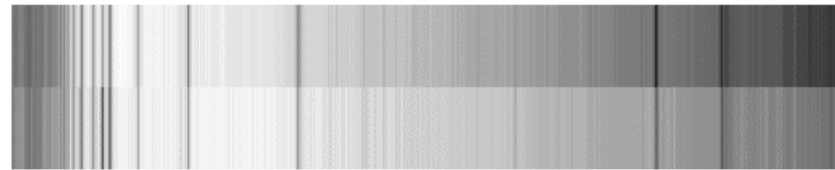


Spectra of B0v (top) and B5v (bottom) stars

### F Stars



$T = 5900 - 7500$  K; H grows weaker through F9,  $\text{Ca}^+$  grows stronger, weak metals begin to emerge.

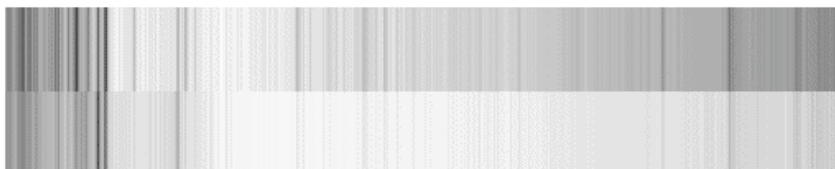


Spectra of F0v (top) and F5v (bottom) stars

### G Stars

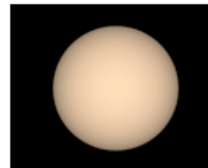


$T = 5200 - 5900$  K; Strong  $\text{Ca}^+$ ,  $\text{Fe}^+$  and other metals dominate, H grows weaker through the class.

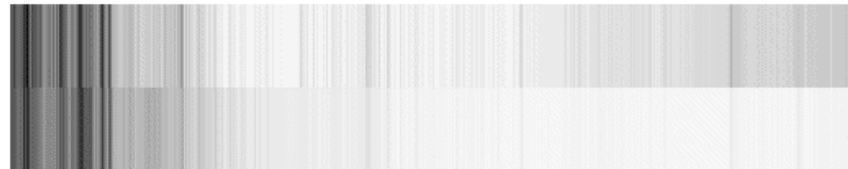


Spectra of G0v (top) and G4v (bottom) stars

### K Stars



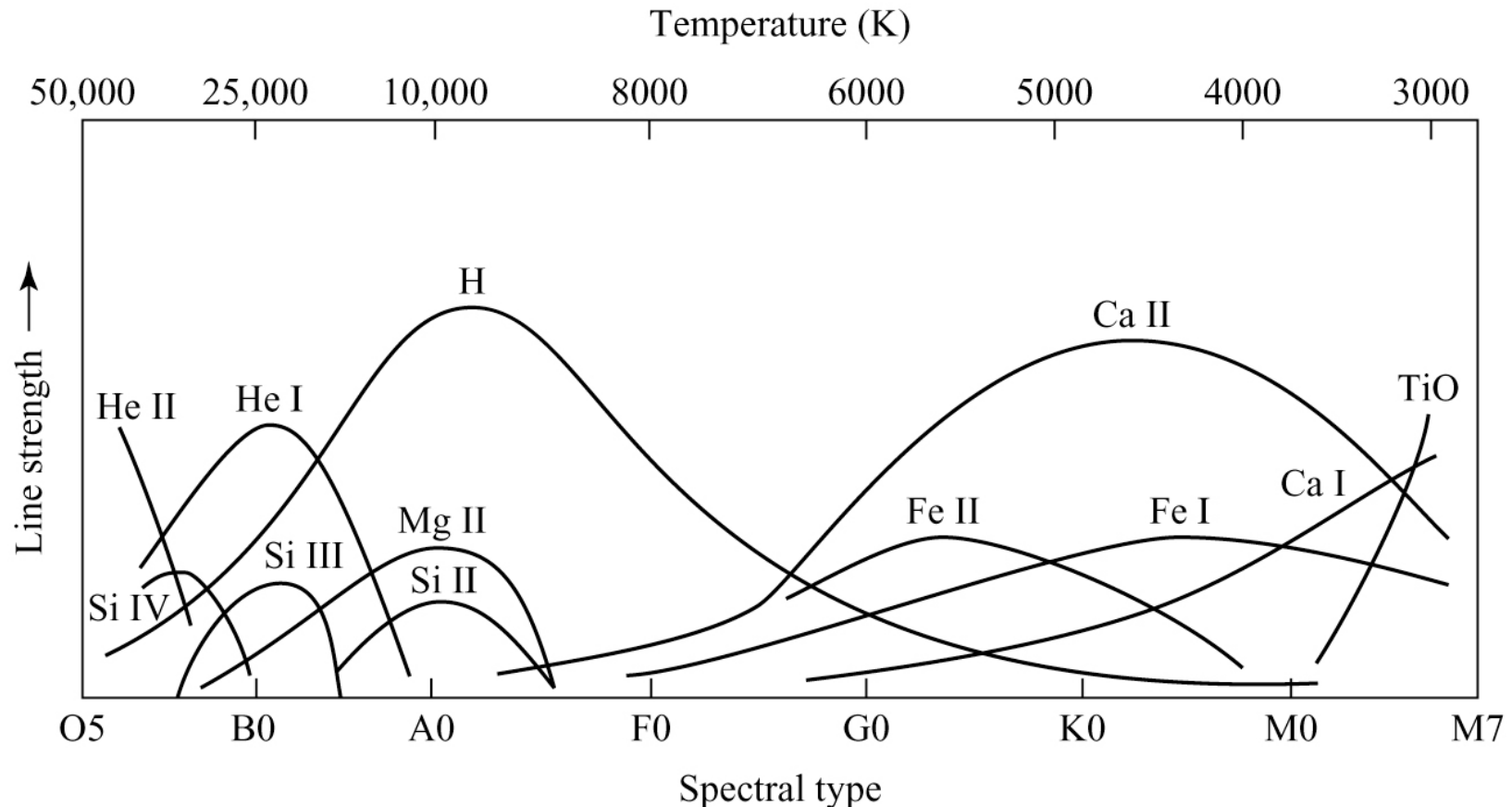
$T = 3900 - 5200$  K; Strong metal lines, weak CH & CN molecular bands begin to appear, growing through the class. H lines nearly gone.



Spectra of K0v (top) and K5v (bottom) stars

(R. Pogge: Webpage)

# spectroscopic classification



stars of different mass (and temperature) show different absorption and emission lines --> this can be used to build a *spectral classification scheme*

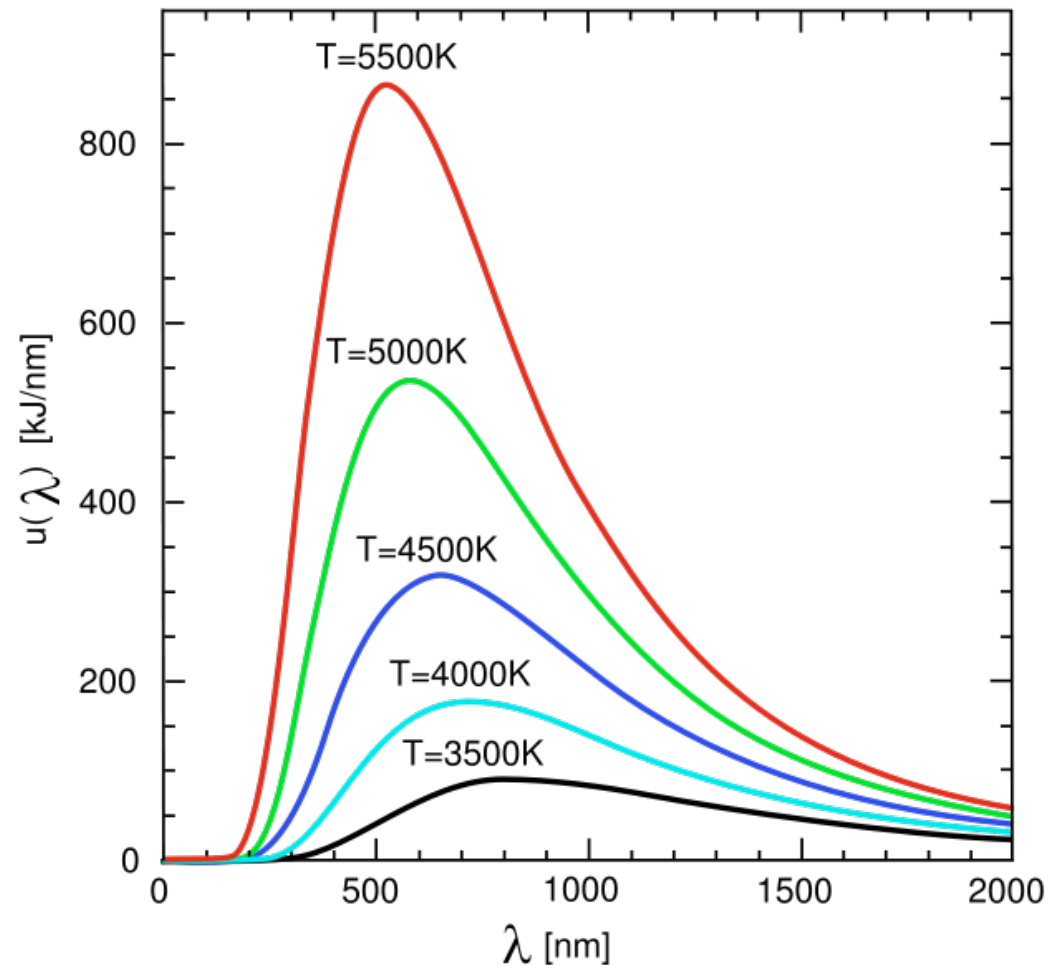


(Carroll & Ostlie: Figure 8.11)

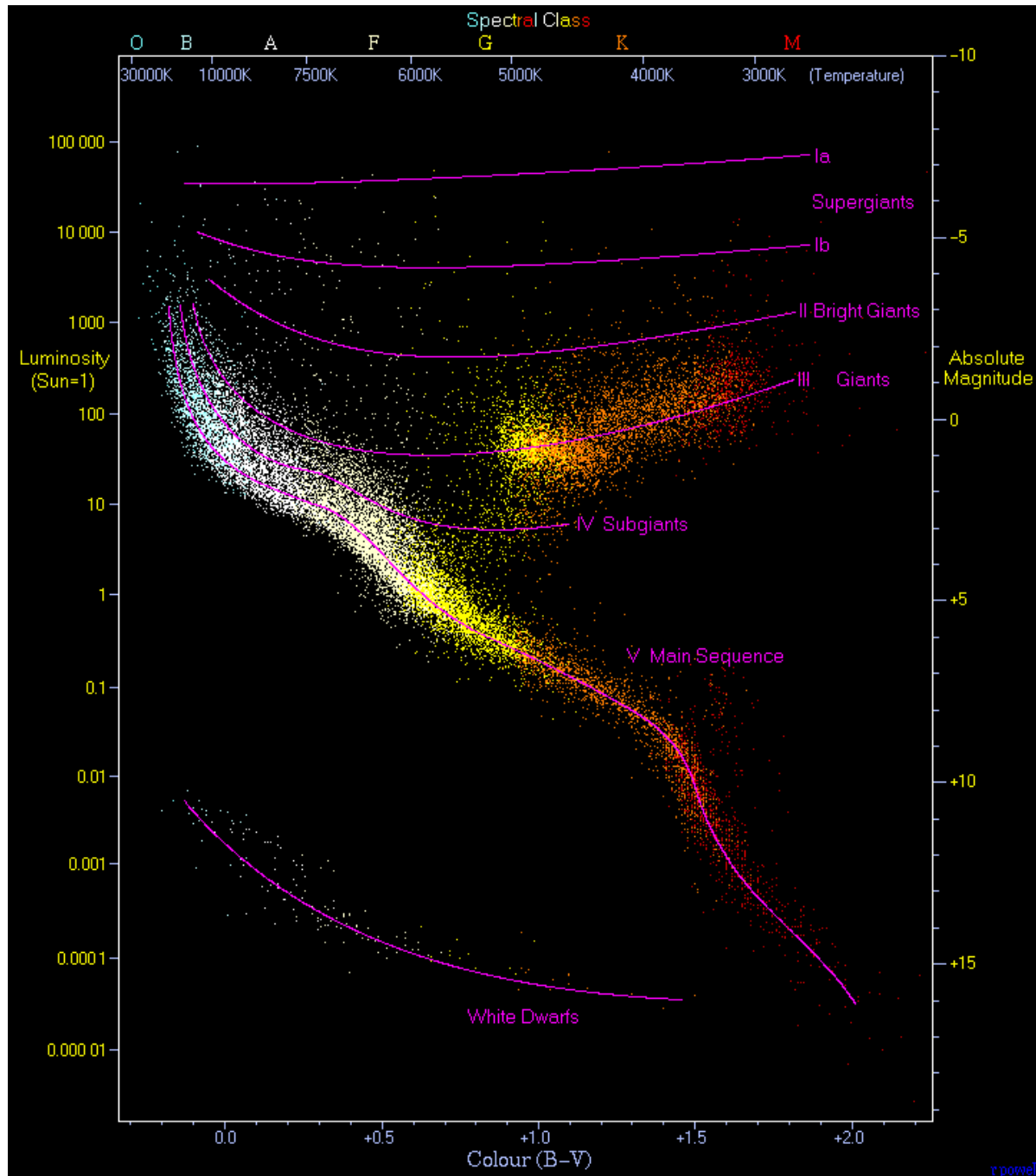


# statistical characteristics

- Hertzsprung Russell diagram: using **color** and **(absolute) magnitude**
- **spectral type** corresponds to specific **color** (and **temperature**)

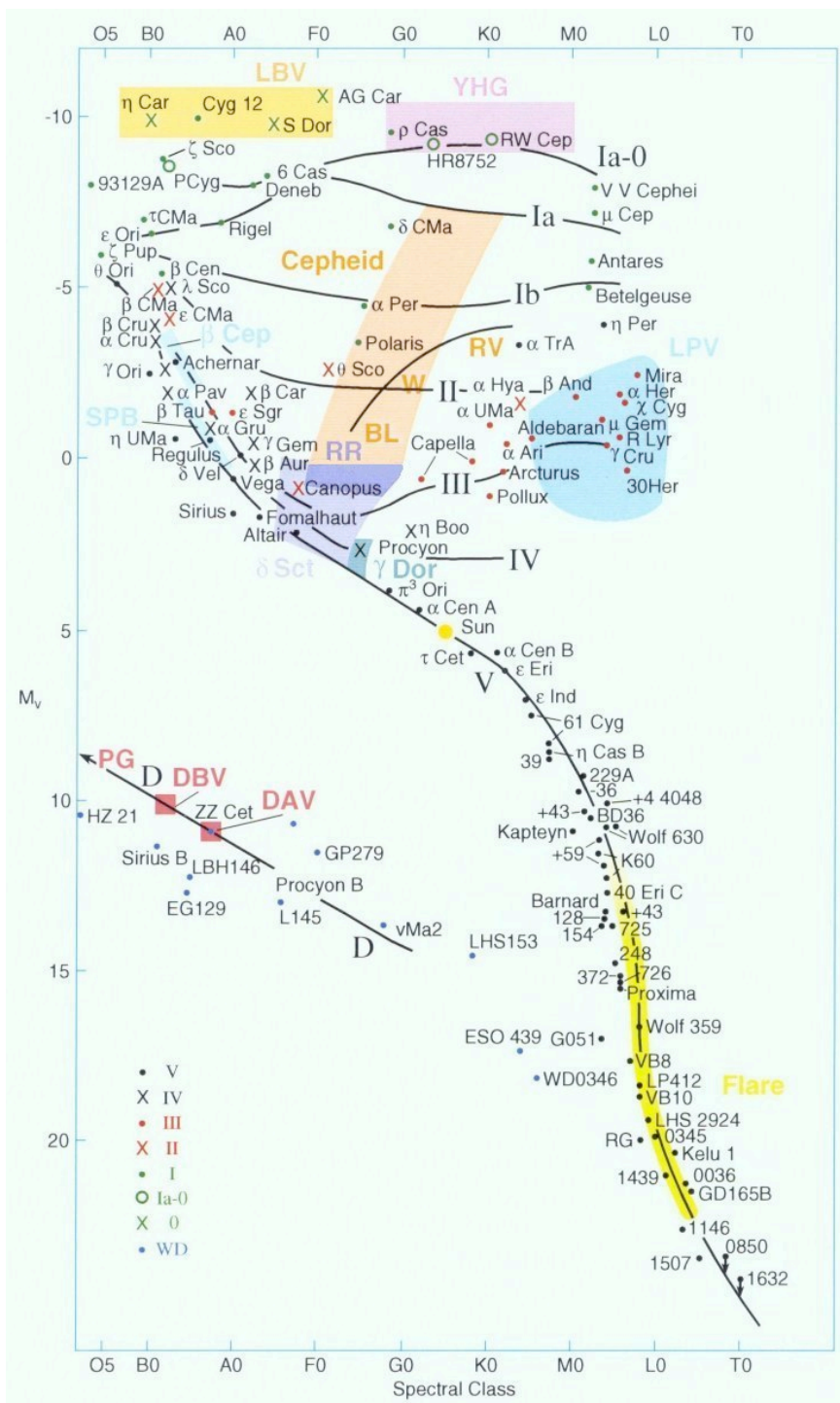


(color magnitude diagram: copyright Creative Commons)



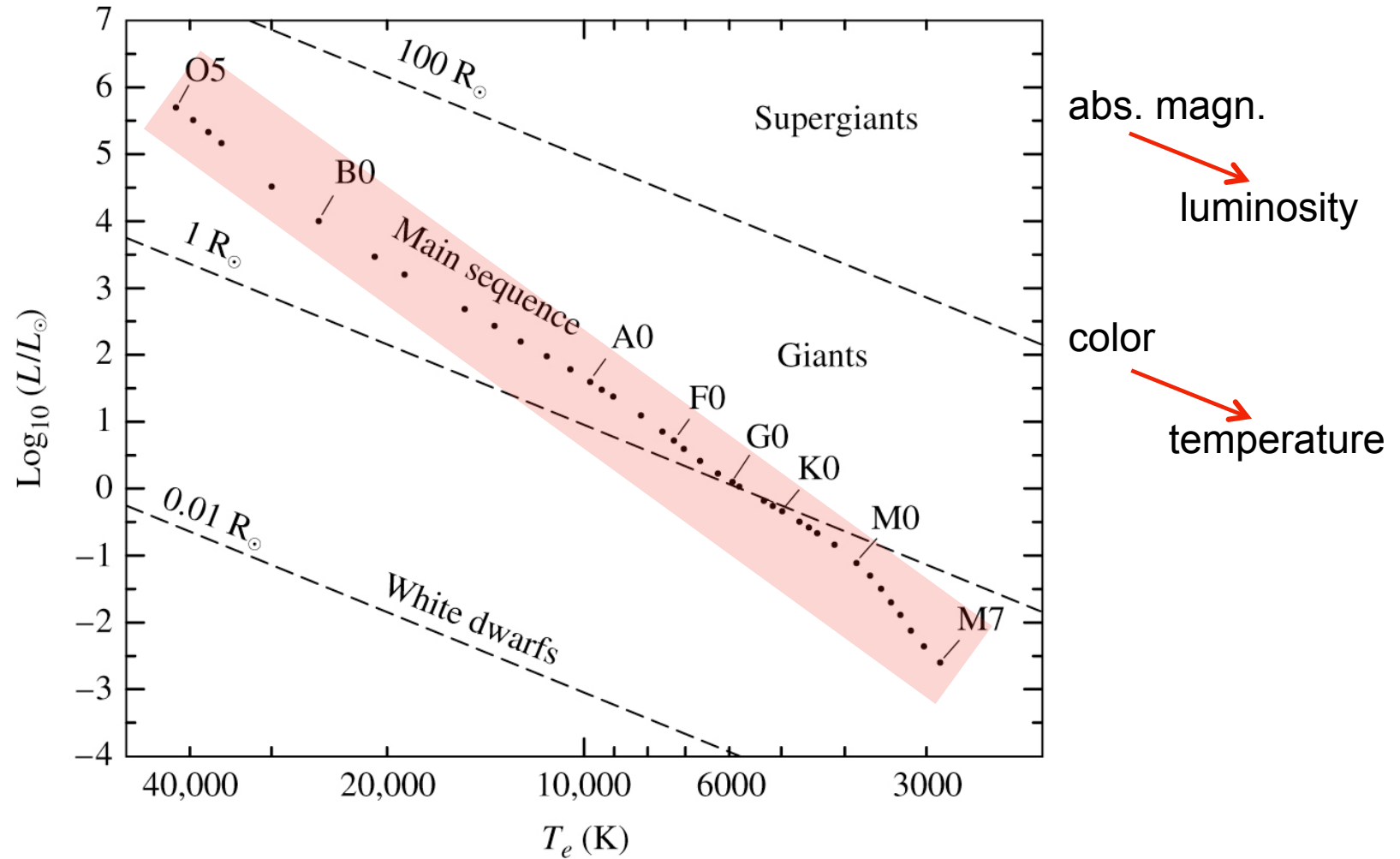
### Stellar classification scheme:

- supergiants (I)
- bright giants (II)
- normal giants (III)
- subgiants (IV)
- main-sequence (dwarf) stars (V)
- subdwarfs (VI)
- white dwarfs



Herzprung Russell diagram with known stars (from Kaler: Stars and Stellar Spectra)

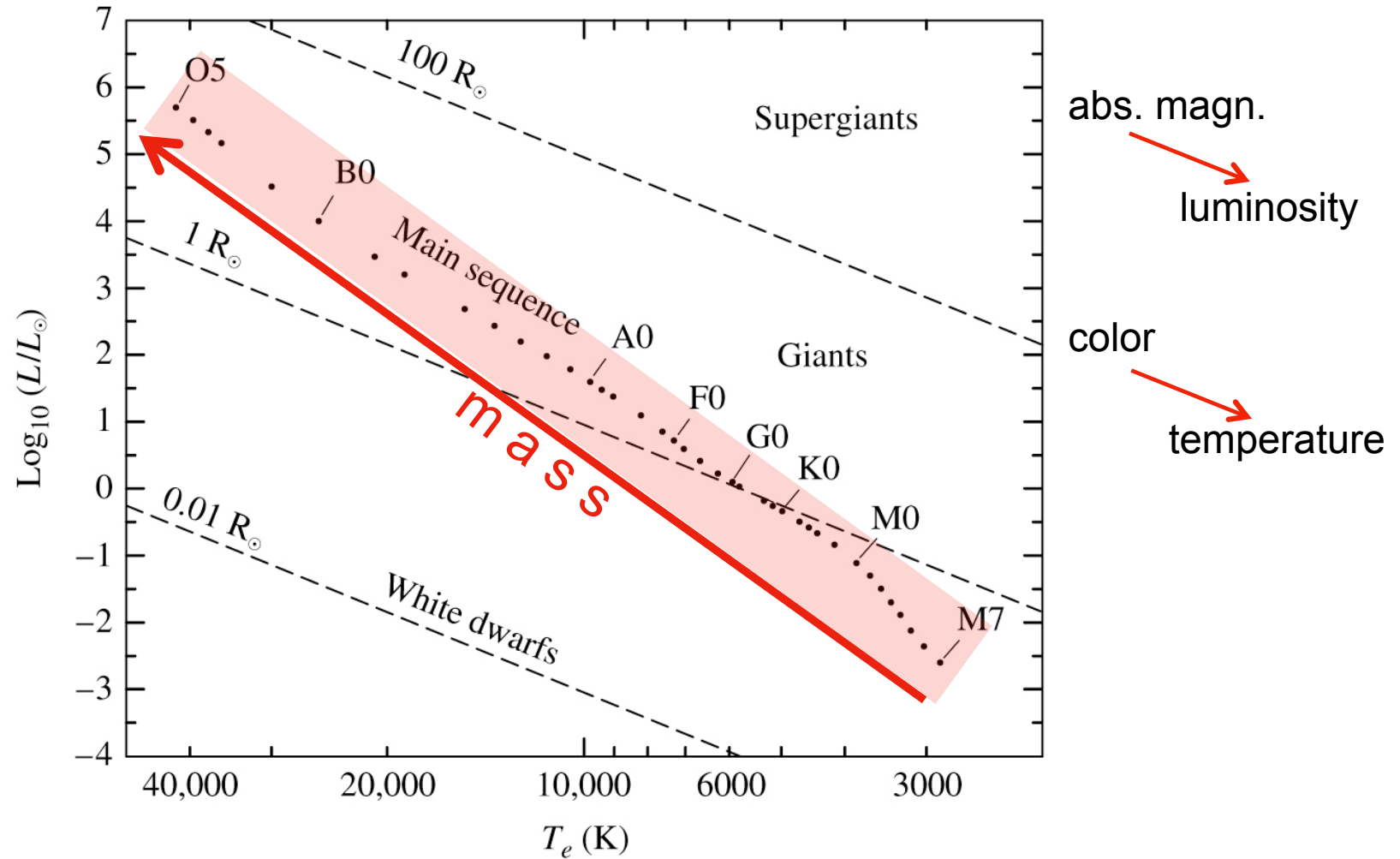
# physical interpretation



(Carroll & Ostlie: Figure 8.14)



# physical interpretation

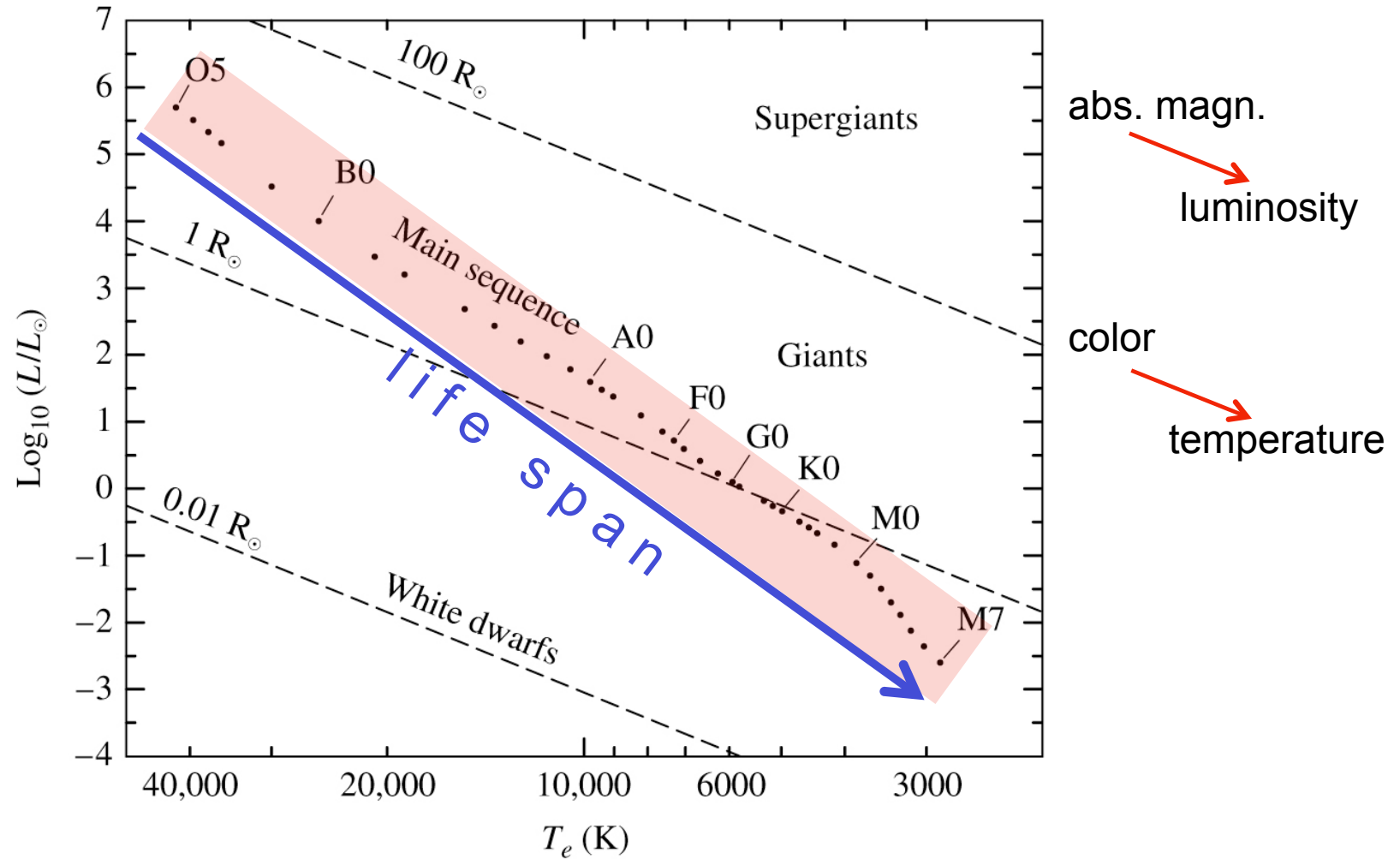


(Carroll & Ostlie: Figure 8.14)





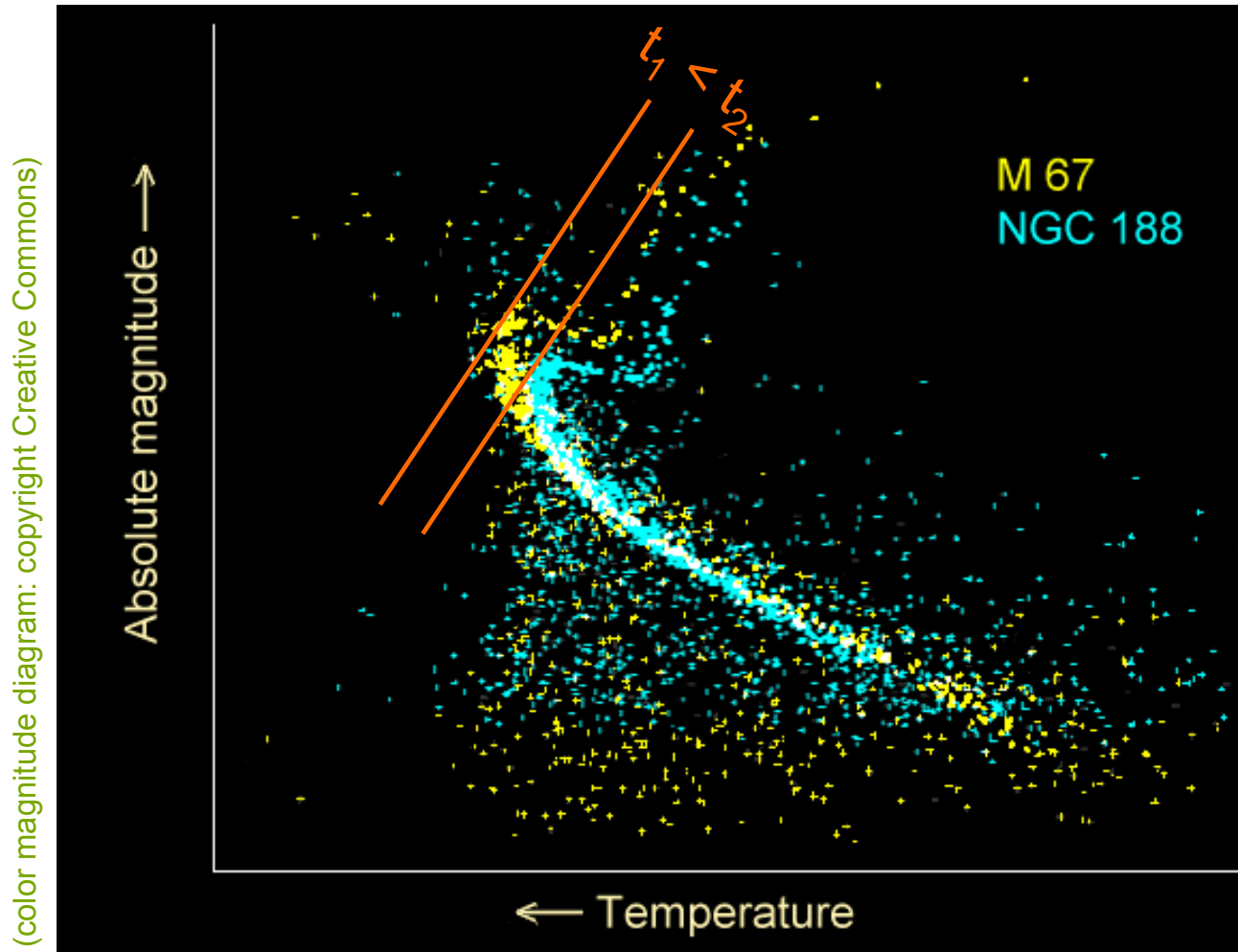
# physical interpretation



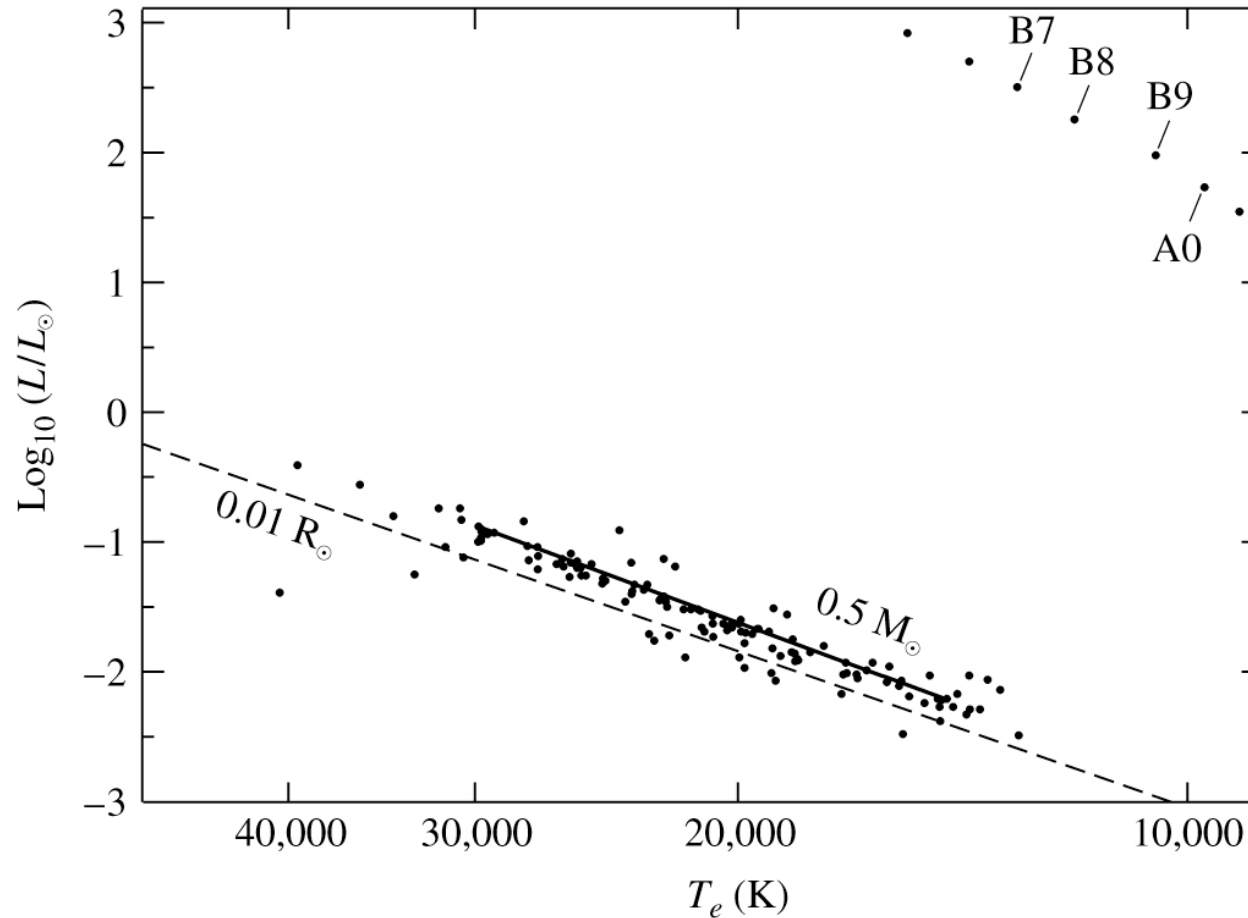
(Carroll & Ostlie: Figure 8.14)



# application: age of cluster



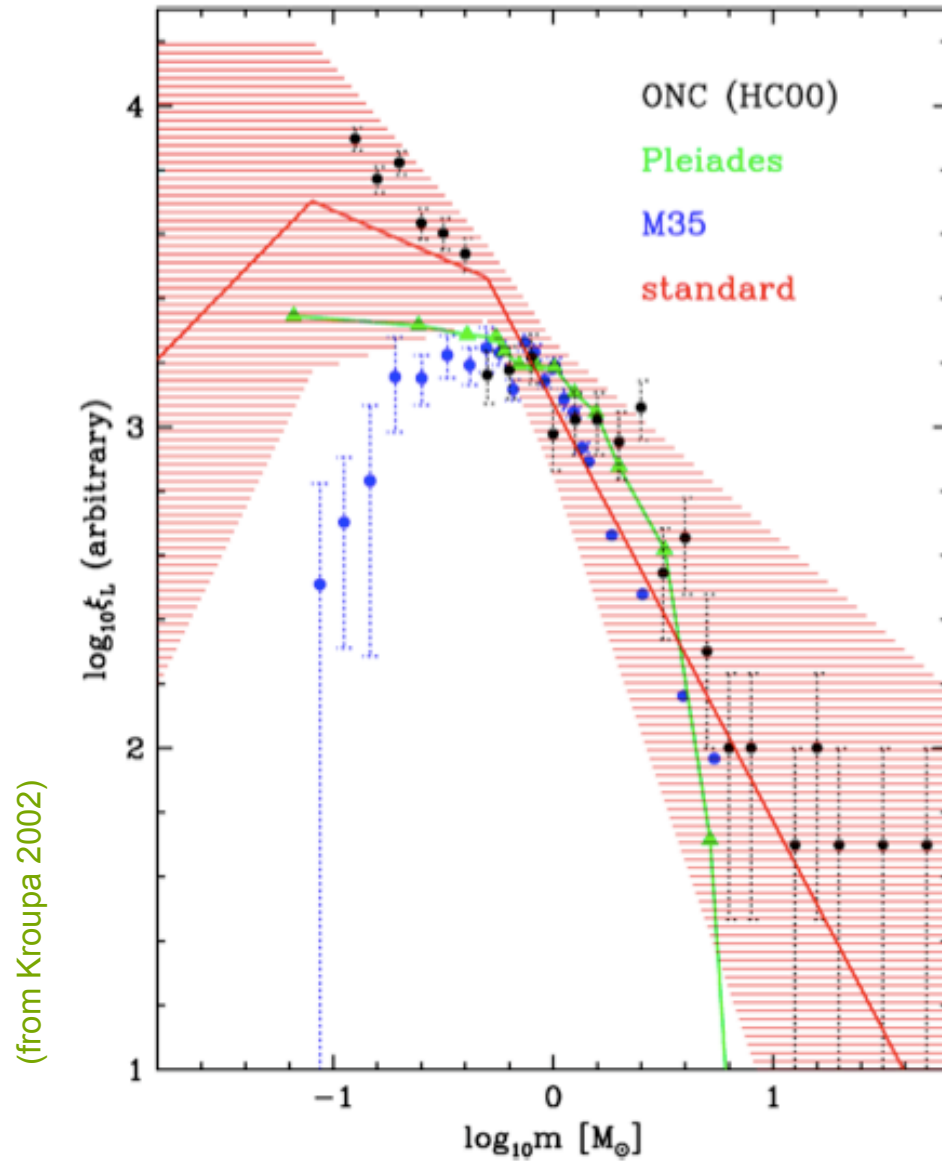
# white dwarfs



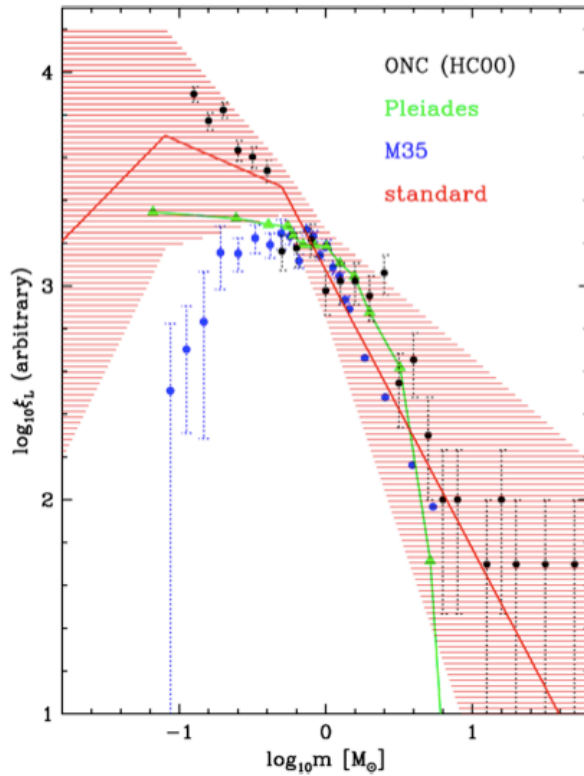
(Carroll & Ostlie: Figure 16.3)



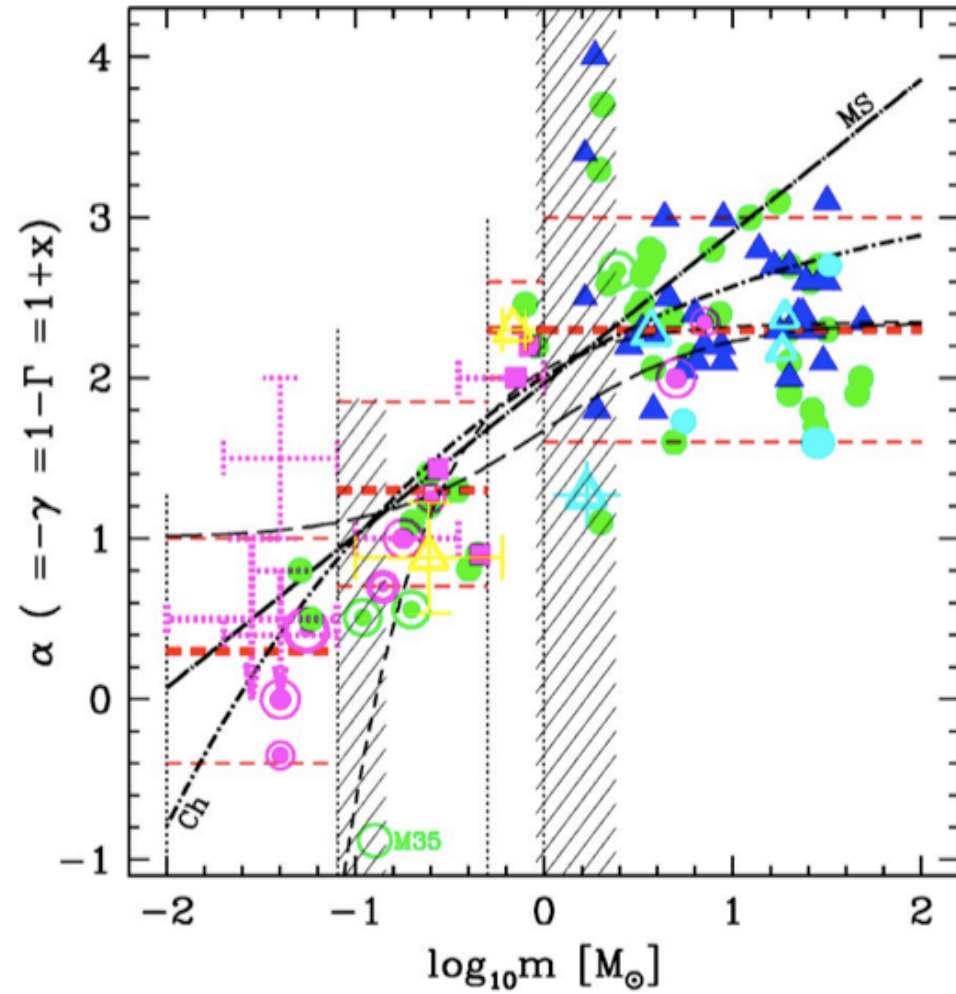
# distribution of stellar masses: IMF



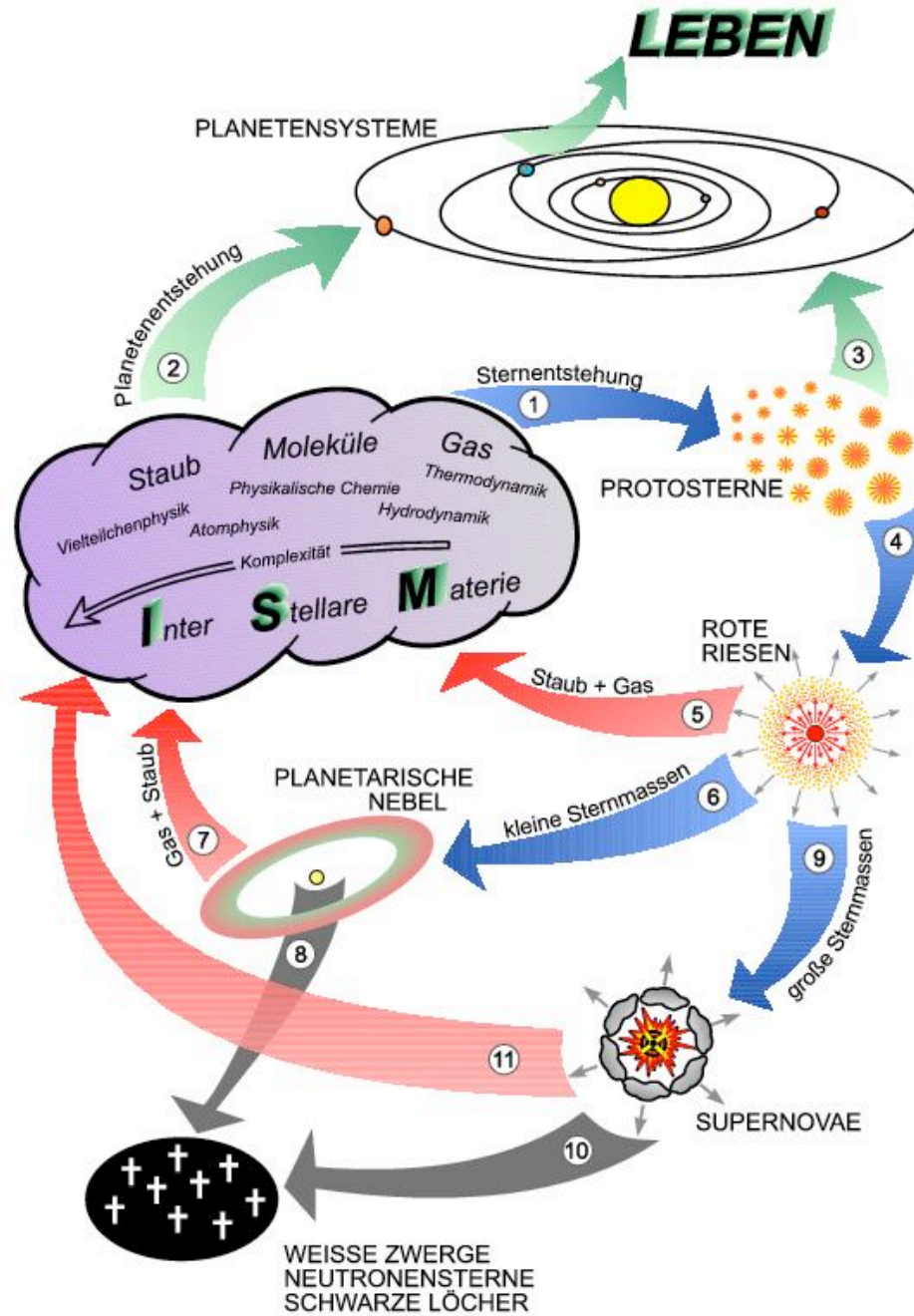
# distribution of stellar masses: IMF



(from Kroupa 2002)









Dienstag, 17. April 12

Klessen / Jordan: Stellar Astrophysics (17.04.2012)