STELLAR ASTROPHYSICS CENTRE

Stellar evolution and modelling

Víctor Silva Aguirre

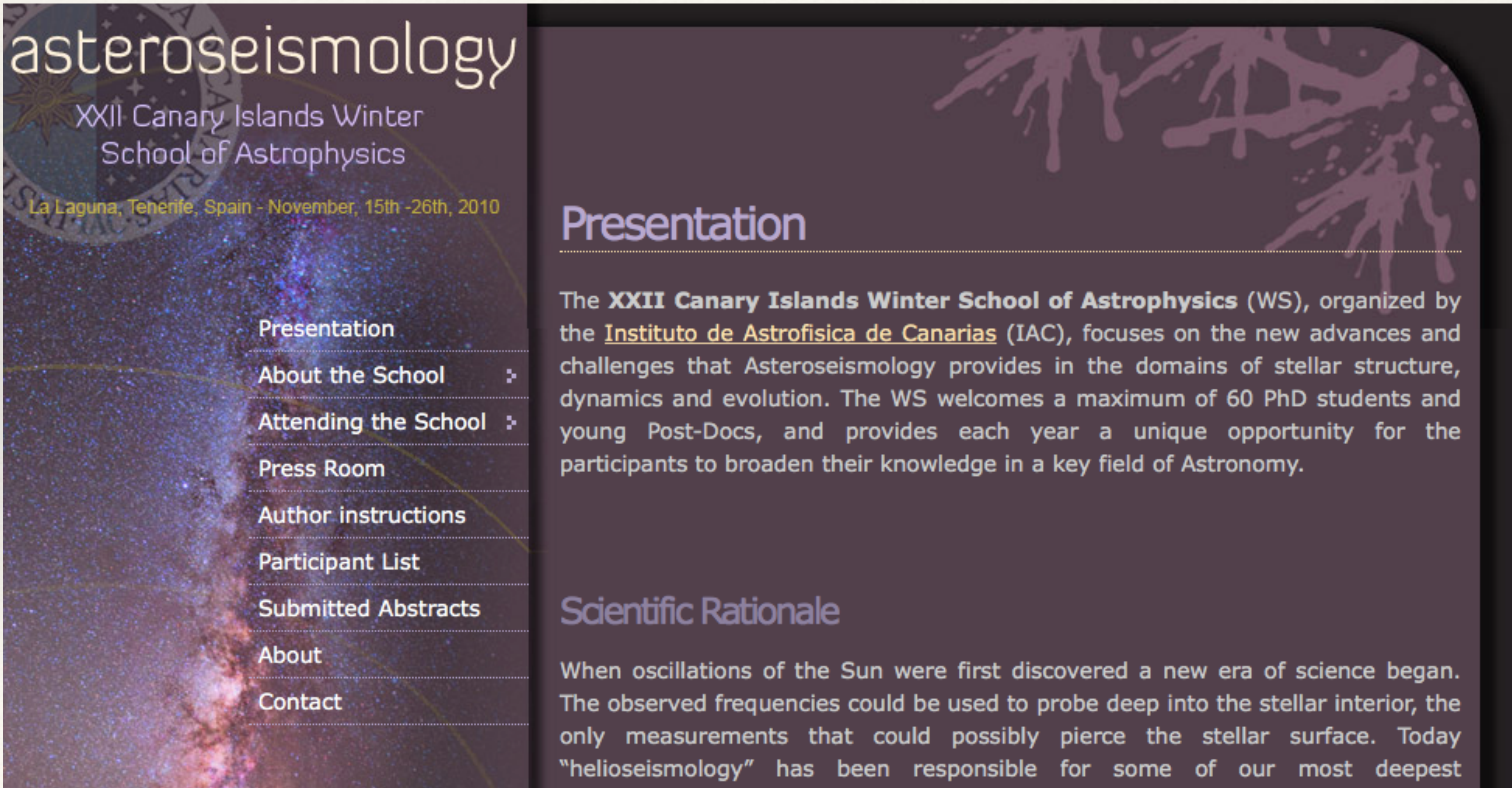
IV Azores School, July 18th 2016

About me

- From Rancagua, Chile
- PhD in MPA, Garching, Germany
- Assistant professor, SAC, Aarhus University, Denmark
- Research interests: stellar evolution, asteroseismology, galactic archaeology

About me

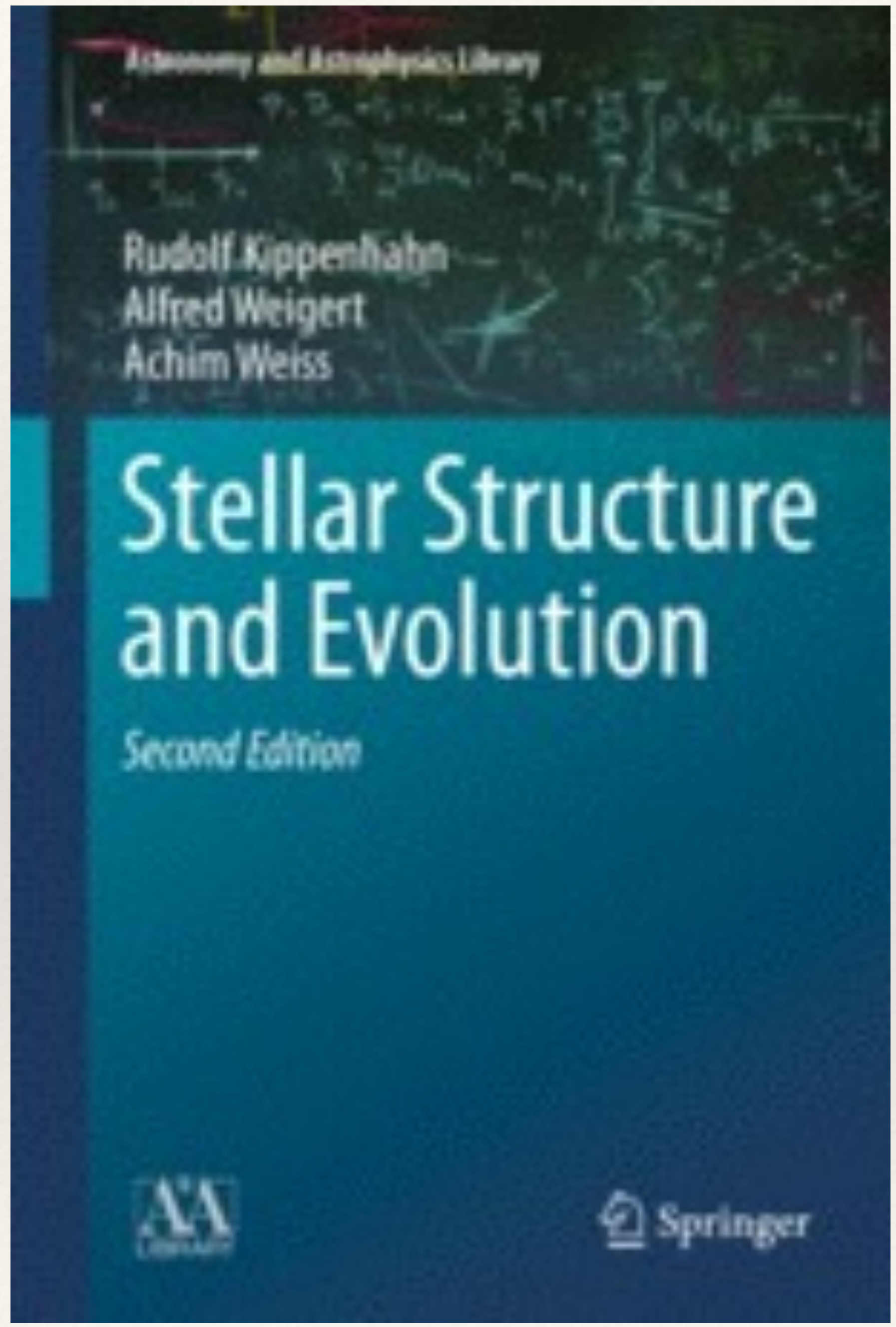
Back in 2010…



Overview

- Stars, why bother?
- Main ingredients and equations
- Modelling stars
- Overview of stellar evolution
- Tracks and isochrones

Class is based on



Class is based on

- I will brush through many topics
- Many (interesting!) details will be skipped due to little time
- Further descriptions in the literature and proceedings
- Ask questions as we go along!

One minute

Stars

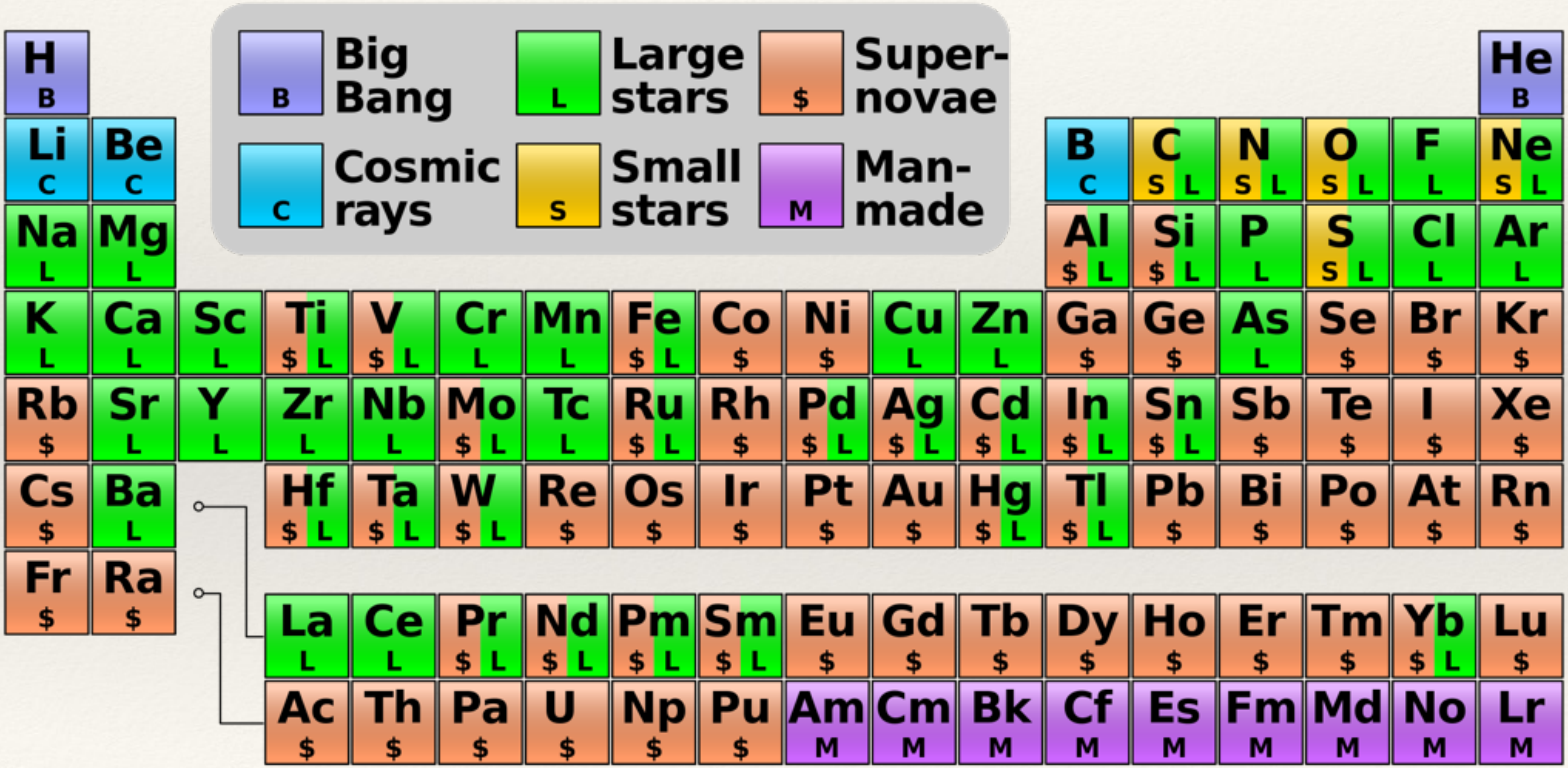
Stars, why do we care?

Stars

Stars, why do we care?

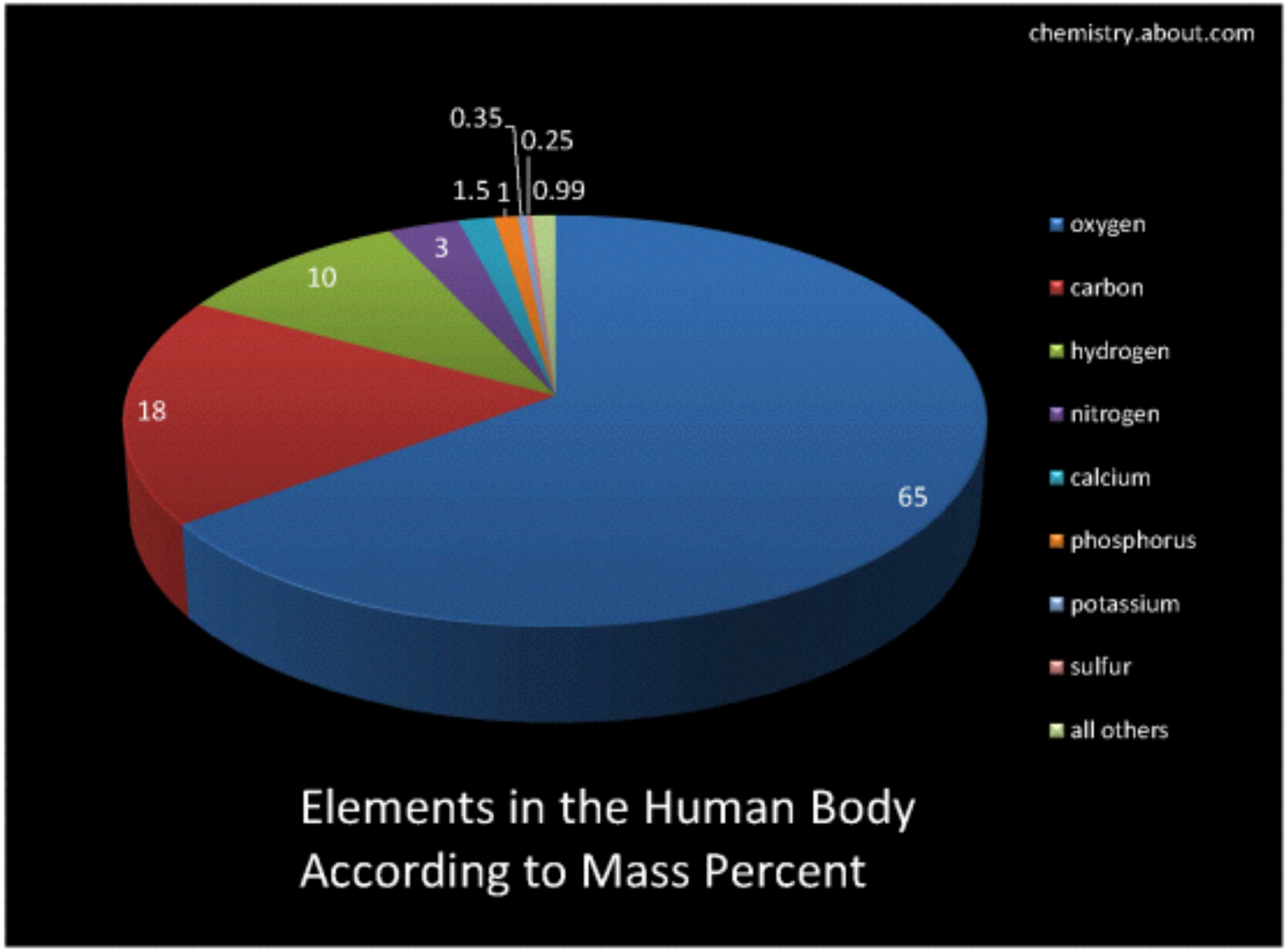
- Source of chemical evolution in the Universe
- Relics of formation history and age of the Galaxy
- Benchmarks for studies of other galaxies
- Progenitors of BHs, SN, GRB, planetary nebulae…
- Host of exoplanets

Stars



B Big Bang
L Large stars
$ Super-novae
C Cosmic rays
S Small stars
M Man-made
H B
He B
Li C
Be C
B C
C S L
N S L
O S L
F L
Ne S L
Na L
Mg L
Al $ L
Si $ L
P L
S S L
Cl L
Ar L
K L
Ca L
Sc L
Ti $ L
V $ L
Cr L
Mn L
Fe $ L
Co $
Ni $
Cu L
Zn L
Ga $
Ge $
As L
Se $
Br $
Kr $
Rb $
Sr L
Y L
Zr L
Nb L
Mo $ L
Tc L
Ru $ L
Rh $
Pd $ L
Ag $ L
Cd $ L
In $ L
Sn $ L
Sb $
Te $
I $
Xe $
Cs $
Ba L
Hf $ L
Ta $ L
W $ L
Re $
Os $
Ir $
Pt $
Au $
Hg $ L
Tl $ L
Pb $
Bi $
Po $
At $
Rn $
Fr $
Ra $
La L
Ce L
Pr $ L
Nd $ L
Pm $ L
Sm $ L
Eu $
Gd $
Tb $
Dy $
Ho $
Er $
Tm $
Yb $ L
Lu $
Ac $
Th $
Pa $
U $
Np $
Pu $
Am M
Cm M
Bk M
Cf M
Es M
Fm M
Md M
No M
Lr M

Stars


chemistry.about.com
0.35
0.25
1.5
1
0.99
3
10
18
65
oxygen
carbon
hydrogen
nitrogen
calcium
phosphorus
potassium
sulfur
all others
Elements in the Human Body
According to Mass Percent

Stars

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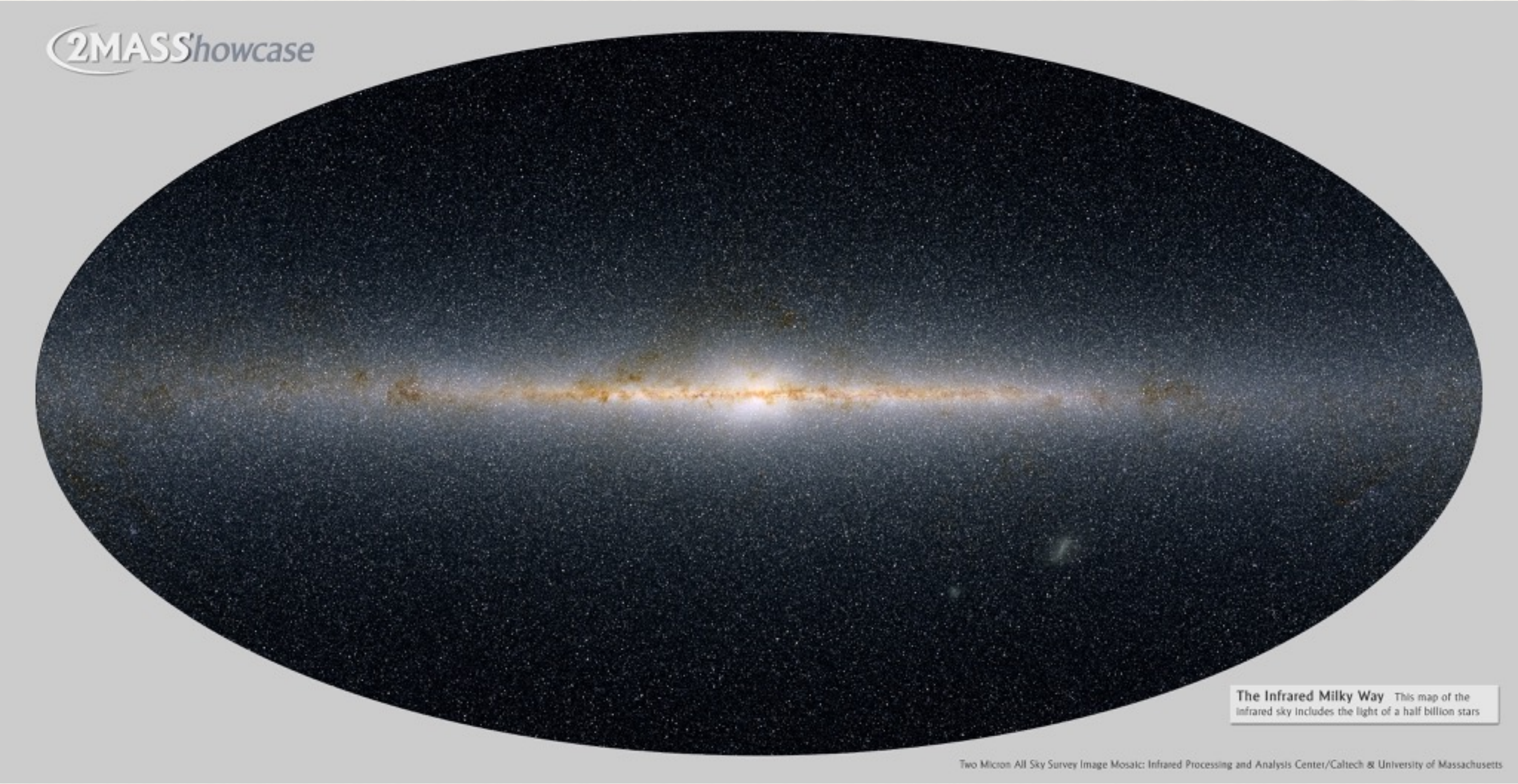
Stars


2MASSShowcase
The Infrared Milky Way This map of the infrared sky includes the light of a half billion stars
Two Micron All Sky Survey Image Mosaic: Infrared Processing and Analysis Center/Caltech & University of Massachusetts

Stars

Stars, why do we care?

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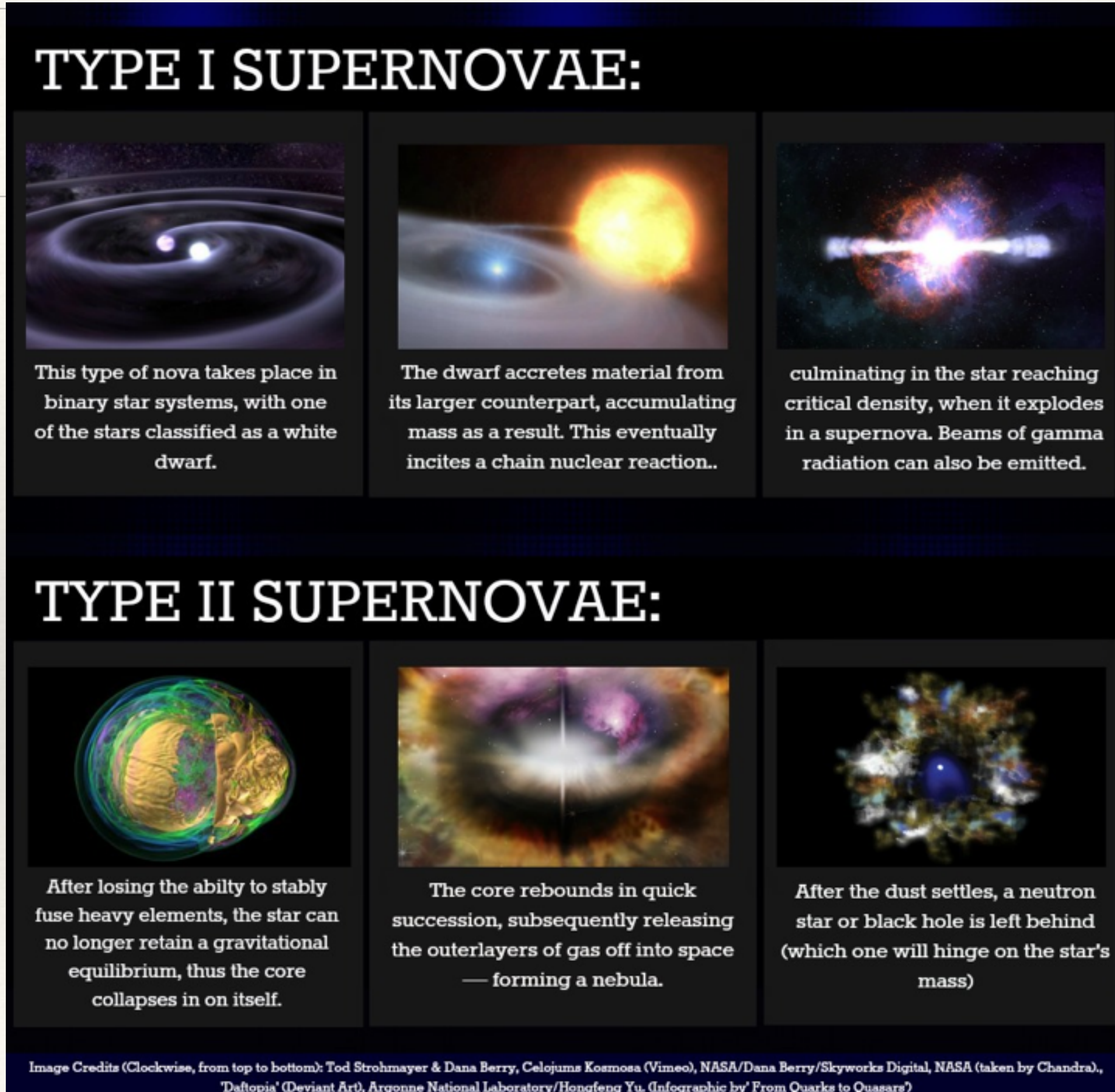
Stars


TYPE I SUPERNOVAE:
This type of nova takes place in binary star systems, with one of the stars classified as a white dwarf.
The dwarf accretes material from its larger counterpart, accumulating mass as a result. This eventually incites a chain nuclear reaction..
culminating in the star reaching critical density, when it explodes in a supernova. Beams of gamma radiation can also be emitted.
TYPE II SUPERNOVAE:
After losing the abilty to stably fuse heavy elements, the star can no longer retain a gravitational equilibrium, thus the core collapses in on itself.
The core rebounds in quick succession, subsequently releasing the outerlayers of gas off into space — forming a nebula.
After the dust settles, a neutron star or black hole is left behind (which one will hinge on the star's mass)
Image Credits (Clockwise, from top to bottom): Tod Strohmayer & Dana Berry, Celojums Kosmosa (Vimeo), NASA/Dana Berry/Skyworks Digital, NASA (taken by Chandra)., 'Daftopia' (Deviant Art), Argonne National Laboratory/Hongfeng Yu. (Infographic by' From Quarks to Quasars')

Stars

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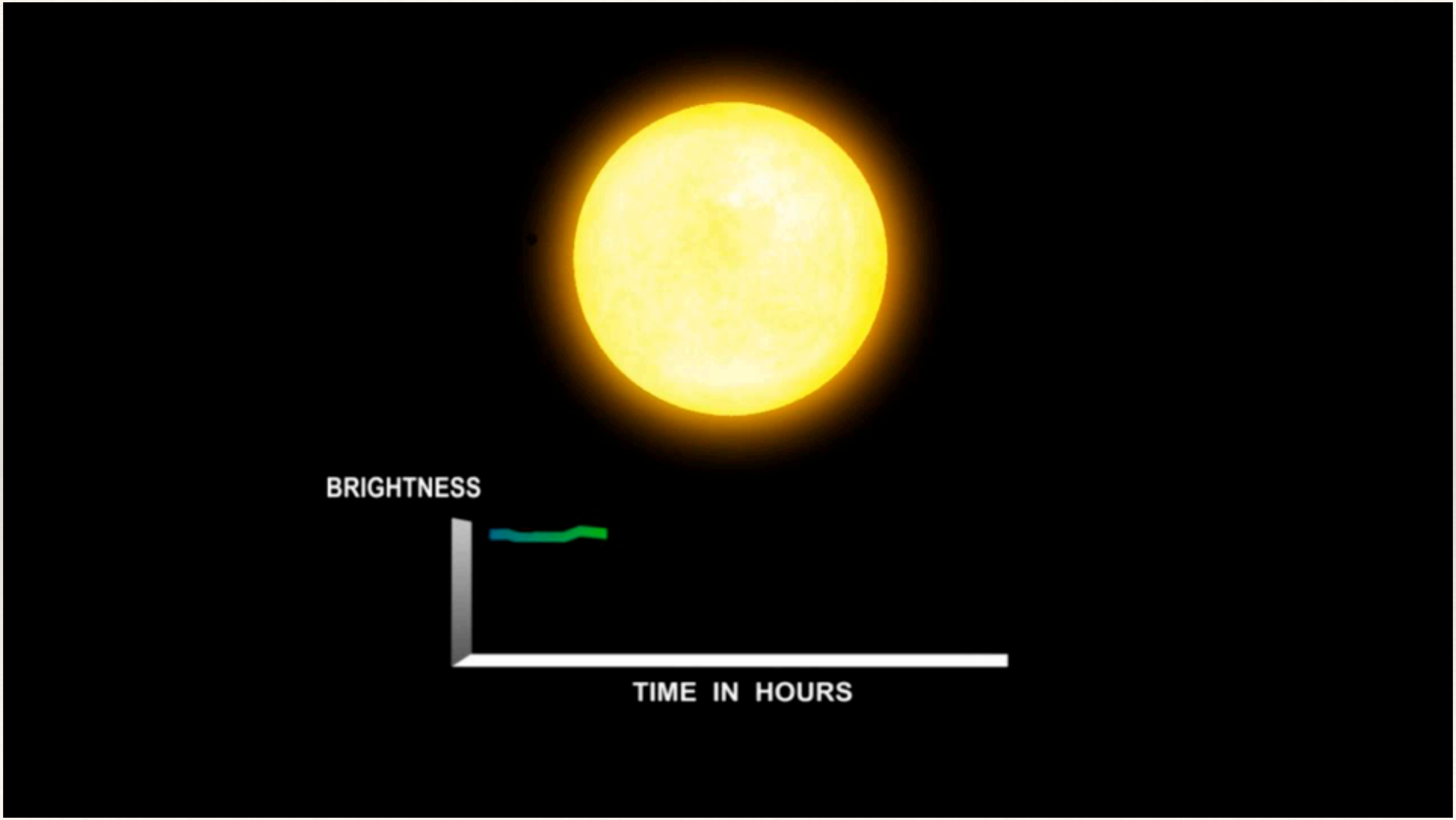
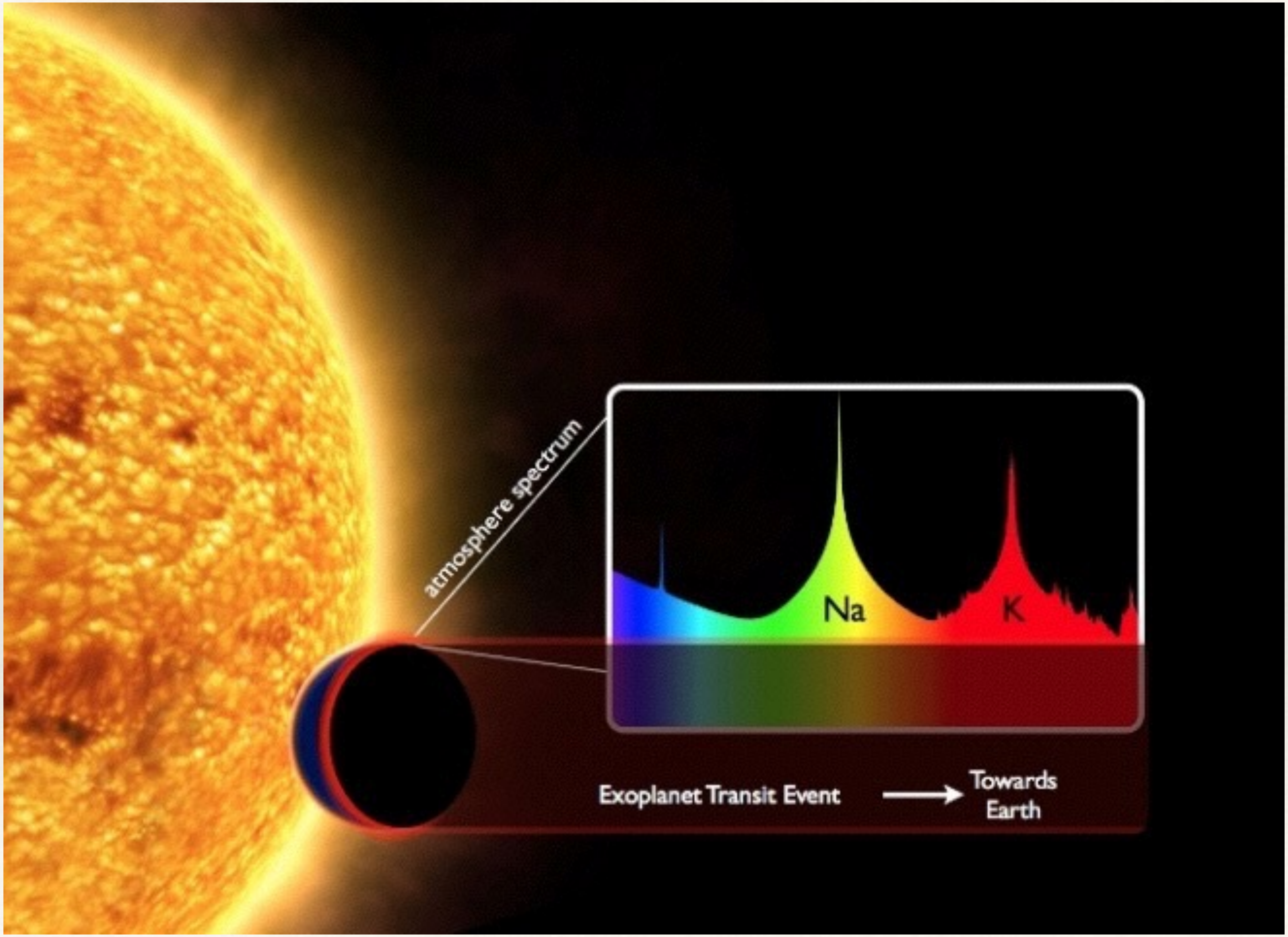
Stars



Stars


atmosphere spectrum
Na
K
Exoplanet Transit Event
Towards Earth

Stars

Stars, why do we care?

- Source of chemical evolutio ... e
- Relics of formation h ... of the Galaxy
- Benchmarks f ... ner galaxies
- Proge ... N, GRB, planetary r
- Ho ... oplanets

Building blocks of astrophysics!

Stars

Yes we care! what do we want to know?

- Understand physical processes:

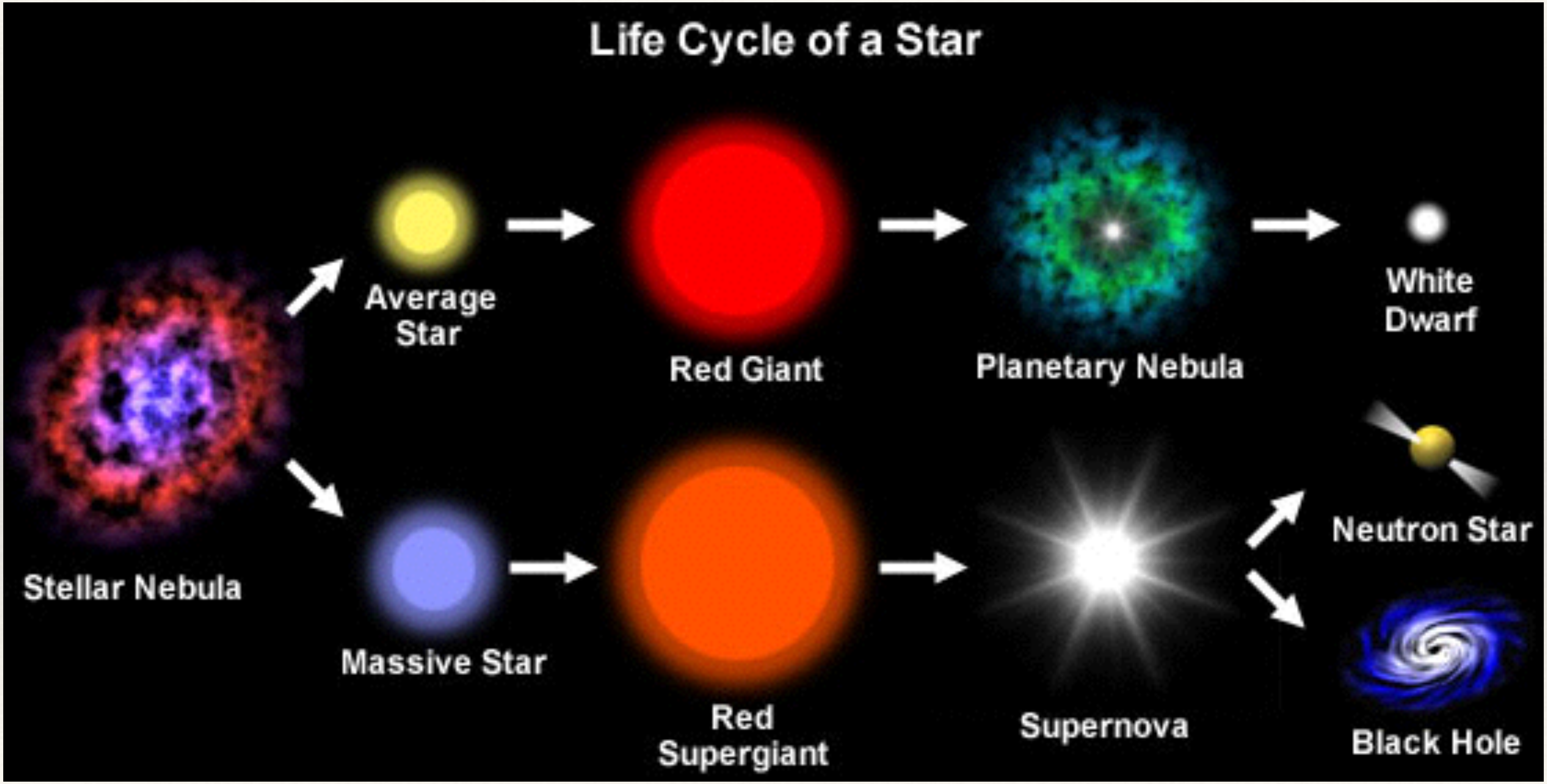
  drivers of evolution in relevant regimes

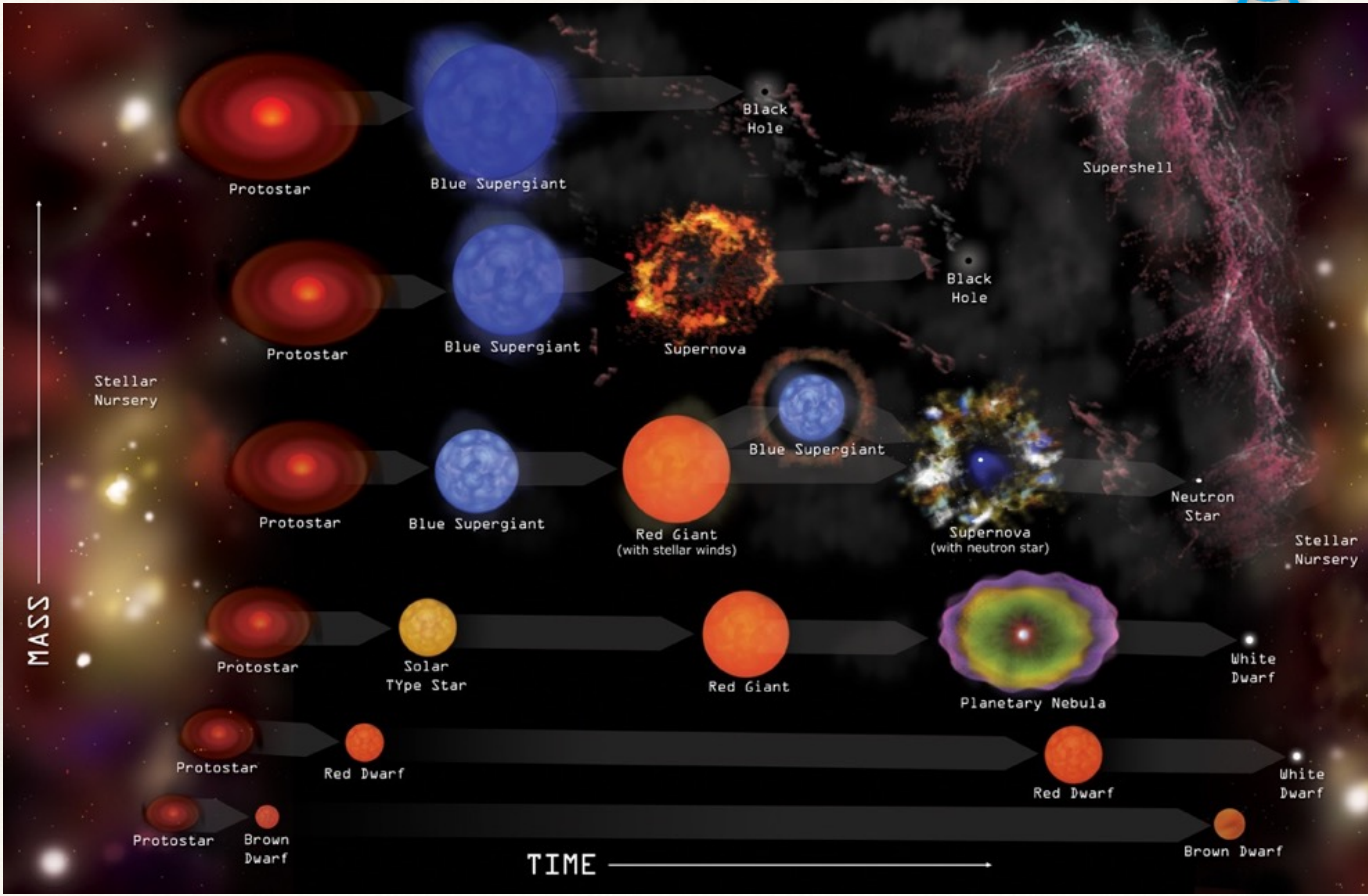
- Predict intrinsic properties:

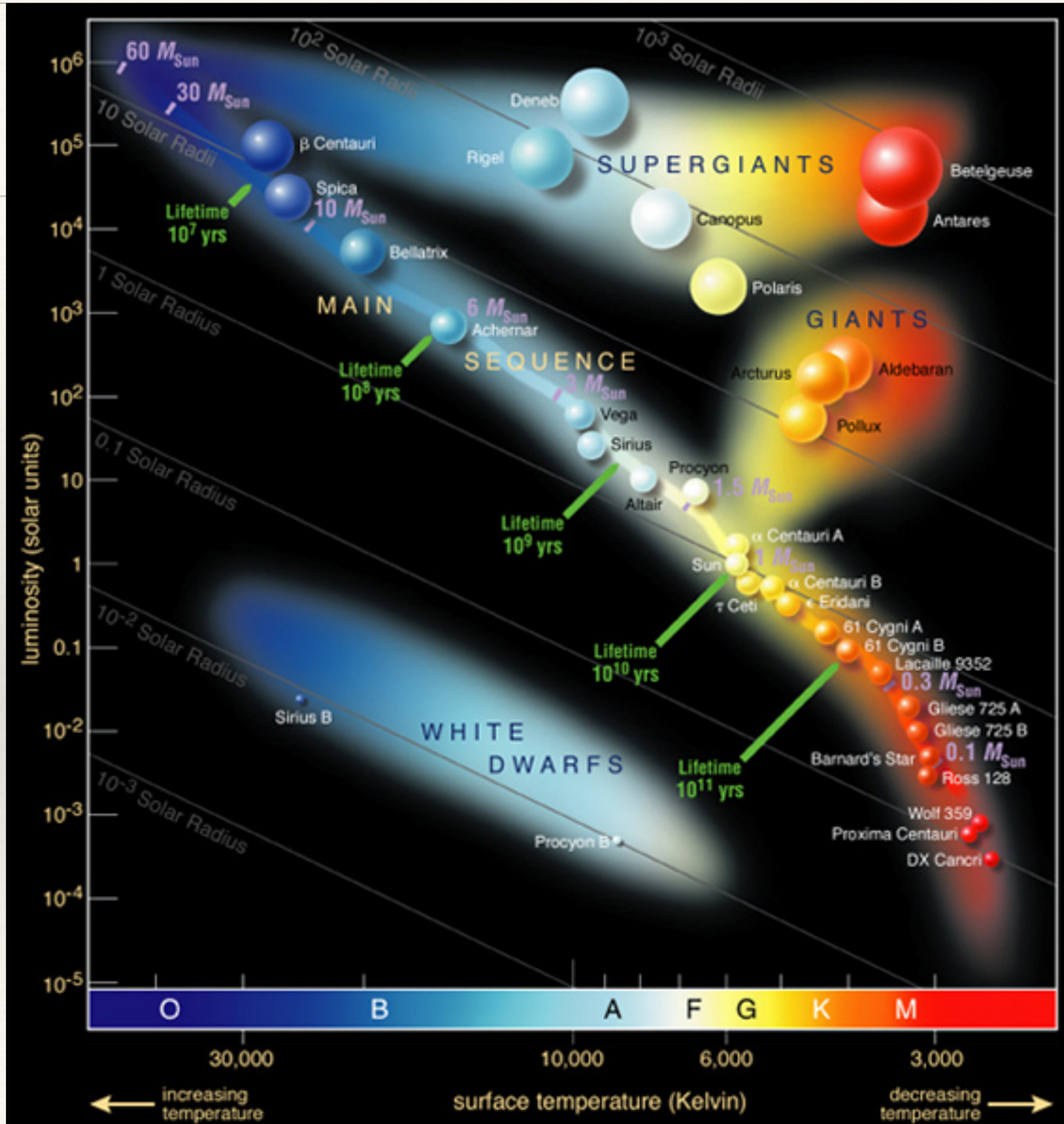
  mass, radius, luminosity, age, distance, etc.

How can we do this?

Stars

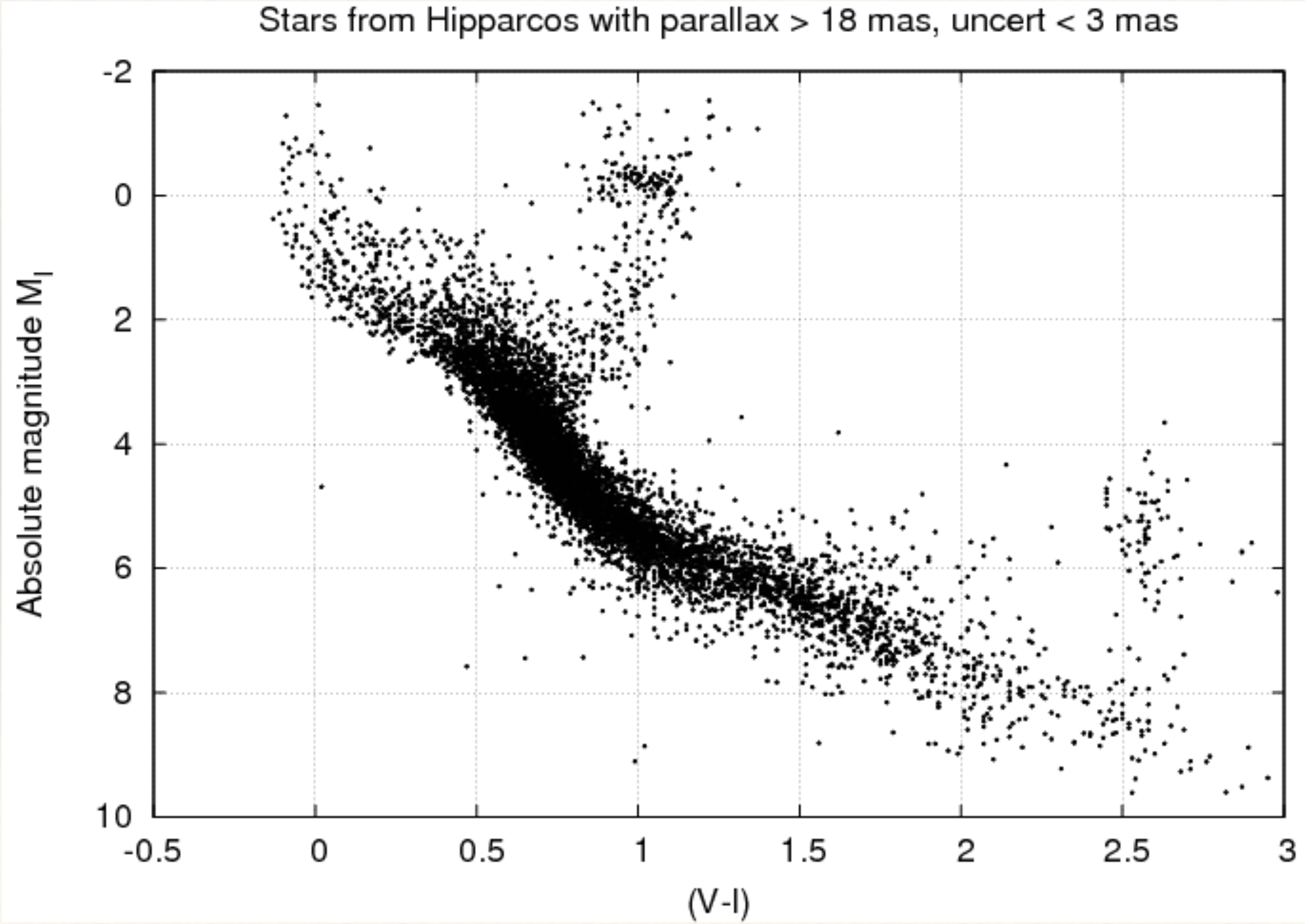

Life Cycle of a Star
Average Star
Red Giant
Planetary Nebula
White Dwarf
Stellar Nebula
Massive Star
Red Supergiant
Supernova
Neutron Star
Black Hole


Protostar
Blue Supergiant
Black Hole
Supershell
Protostar
Blue Supergiant
Supernova
Black Hole
Stellar Nursery
Protostar
Blue Supergiant
Red Giant
(with stellar winds)
Blue Supergiant
Supernova
(with neutron star)
Neutron Star
Stellar Nursery
MASS
Protostar
Solar TYpe Star
Red Giant
Planetary Nebula
White Dwarf
Protostar
Red Dwarf
Red Dwarf
White Dwarf
Protostar
Brown Dwarf
Brown Dwarf
TIME


60 M_{Sun}
30 M_{Sun}
10 M_{Sun}
6 M_{Sun}
3 M_{Sun}
1.5 M_{Sun}
1 M_{Sun}
0.3 M_{Sun}
0.1 M_{Sun}
10^2 Solar Radii
10^3 Solar Radii
10 Solar Radii
1 Solar Radius
0.1 Solar Radius
10^{-2} Solar Radius
10^{-3} Solar Radius
SUPERGIANTS
GIANTS
MAIN
SEQUENCE
WHITE
DWARFS
Deneb
Rigel
Canopus
Polaris
Betelgeuse
Antares
Aldebaran
Arcturus
Pollux
β Centauri
Spica
Bellatrix
Achernar
Vega
Sirius
Altair
Procyon
α Centauri A
Sun
α Centauri B
τ Ceti
ε Eridani
61 Cygni A
61 Cygni B
Lacaille 9352
Gliese 725 A
Gliese 725 B
Barnard's Star
Ross 128
Wolf 359
Proxima Centauri
DX Cancri
Sirius B
Procyon B
Lifetime 10^7 yrs
Lifetime 10^8 yrs
Lifetime 10^9 yrs
Lifetime 10^{10} yrs
Lifetime 10^{11} yrs
luminosity (solar units)
10^6
10^5
10^4
10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
10^{-5}
O
B
A
F
G
K
M
30,000
10,000
6,000
3,000
increasing temperature
surface temperature (Kelvin)
decreasing temperature

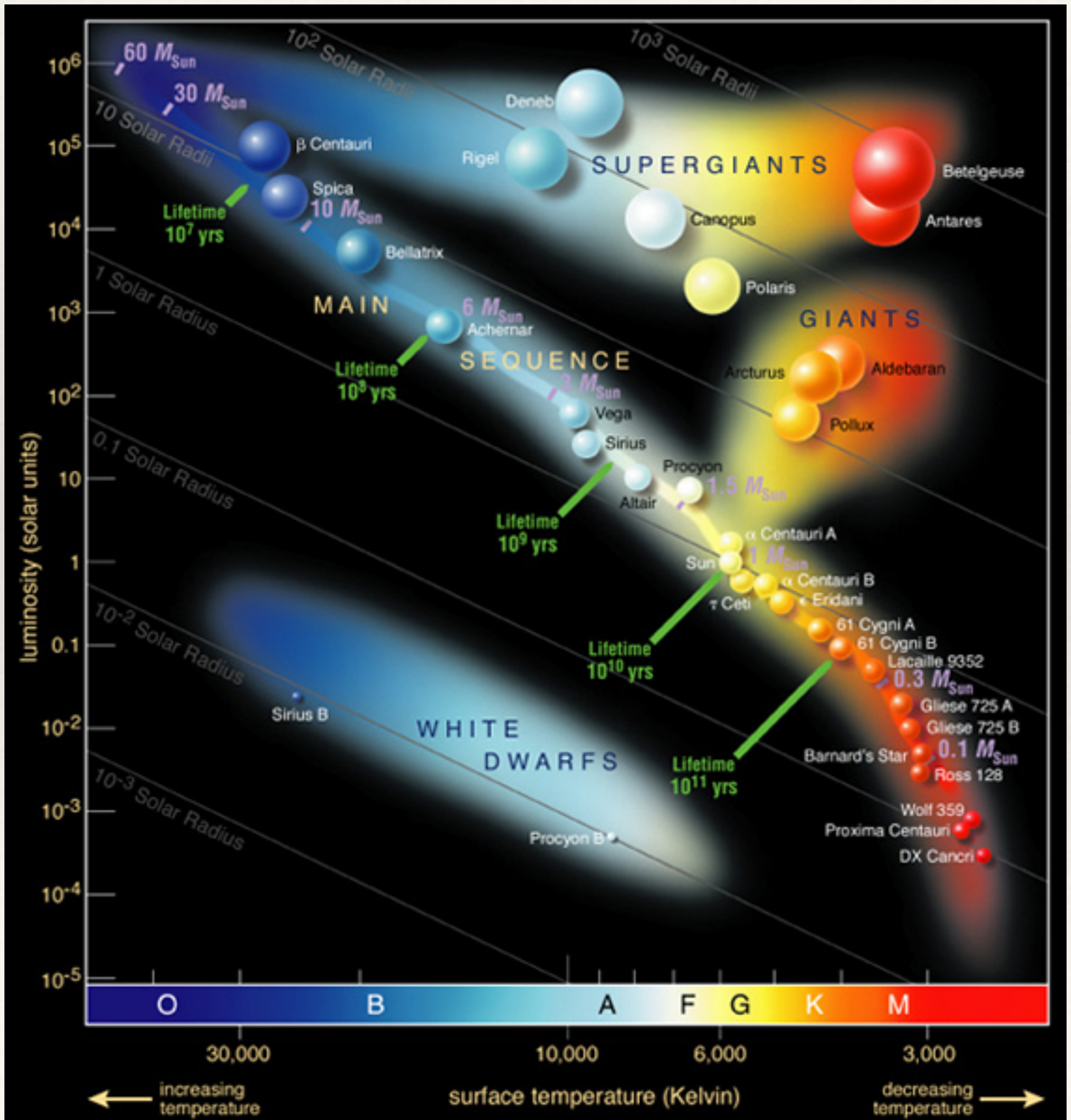
Stars

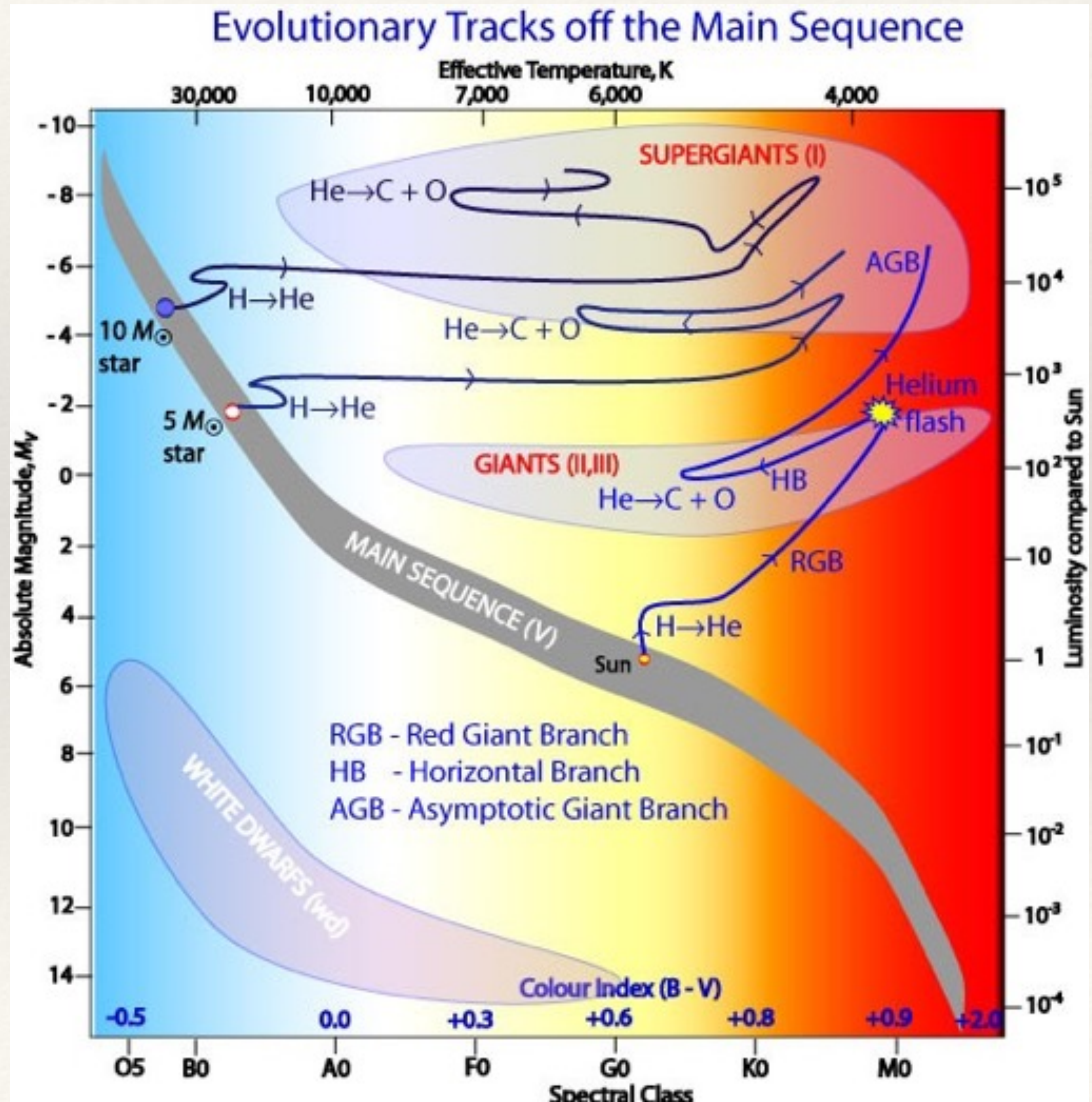
Do we observe this?



Stars

The importance of mass





Modelling Stars

The ingredients

- Understand physical processes:

  drivers of evolution in relevant regimes

- Predict intrinsic properties:

  mass, radius, luminosity, age, distance, etc.

Modelling Stars

Question:

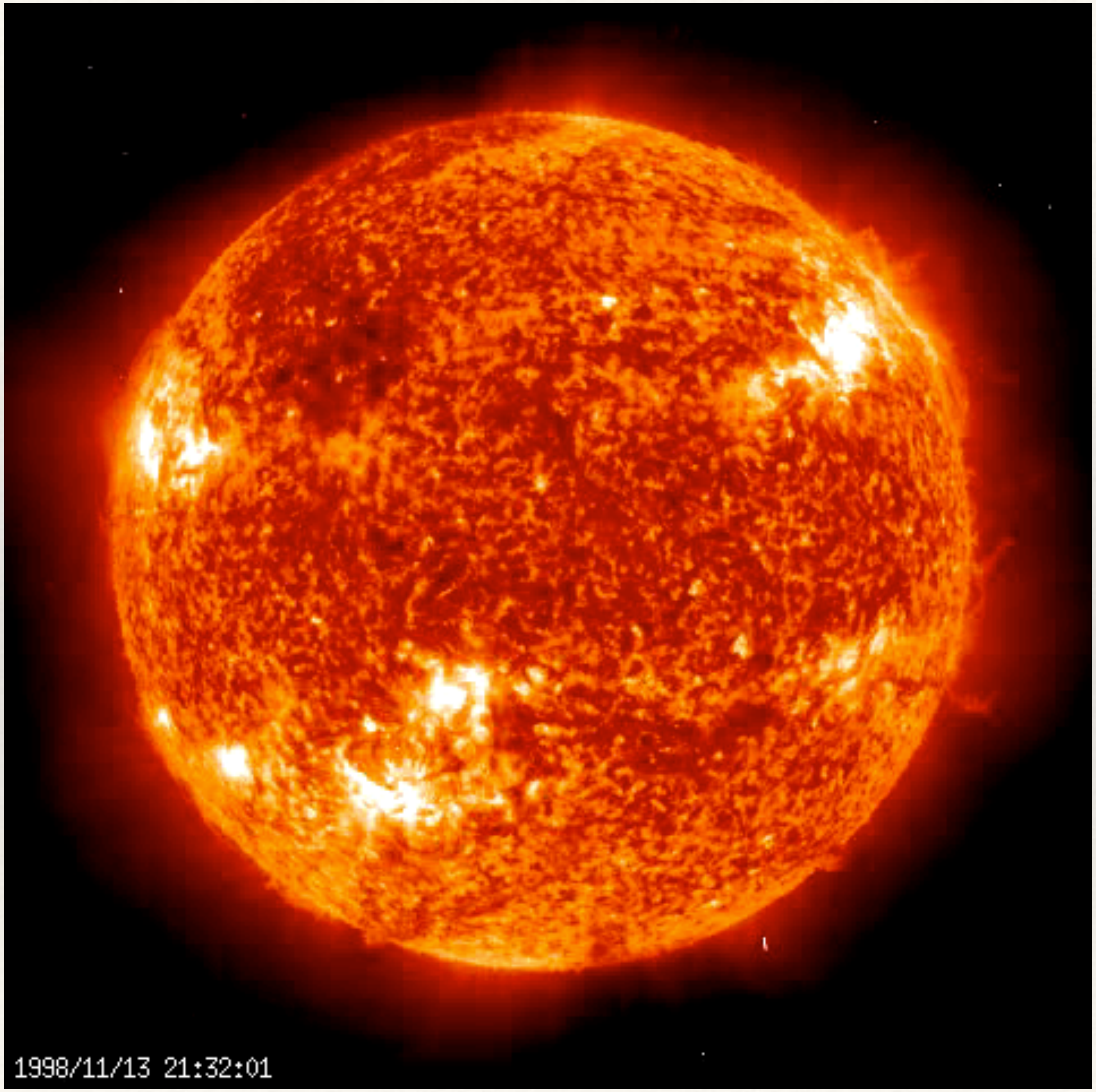
What are the main ingredients needed?

- Think about it (45 secs)
- Discuss it with your neighbour (2 mins)

Modelling Stars

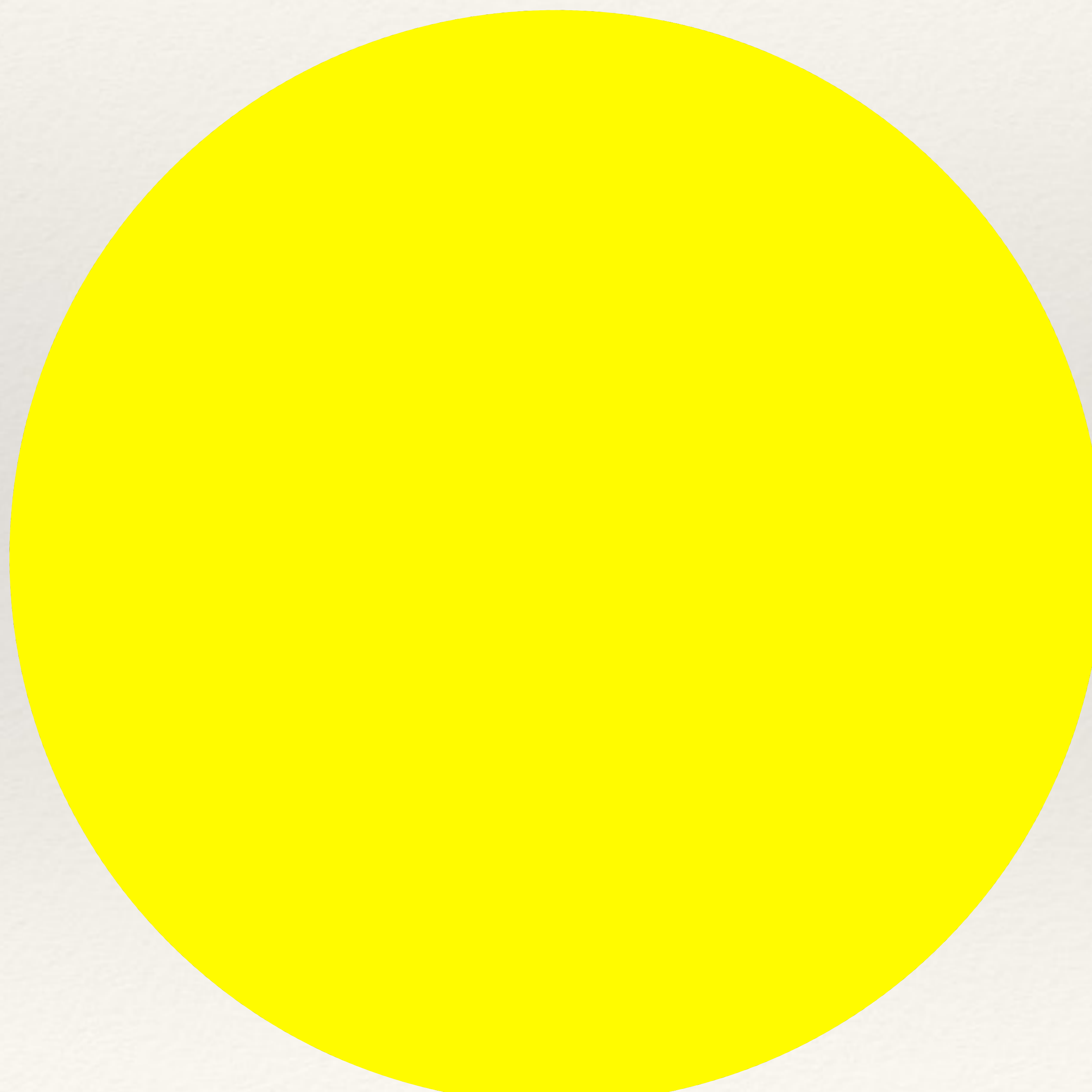
For a given mass

Modelling Stars

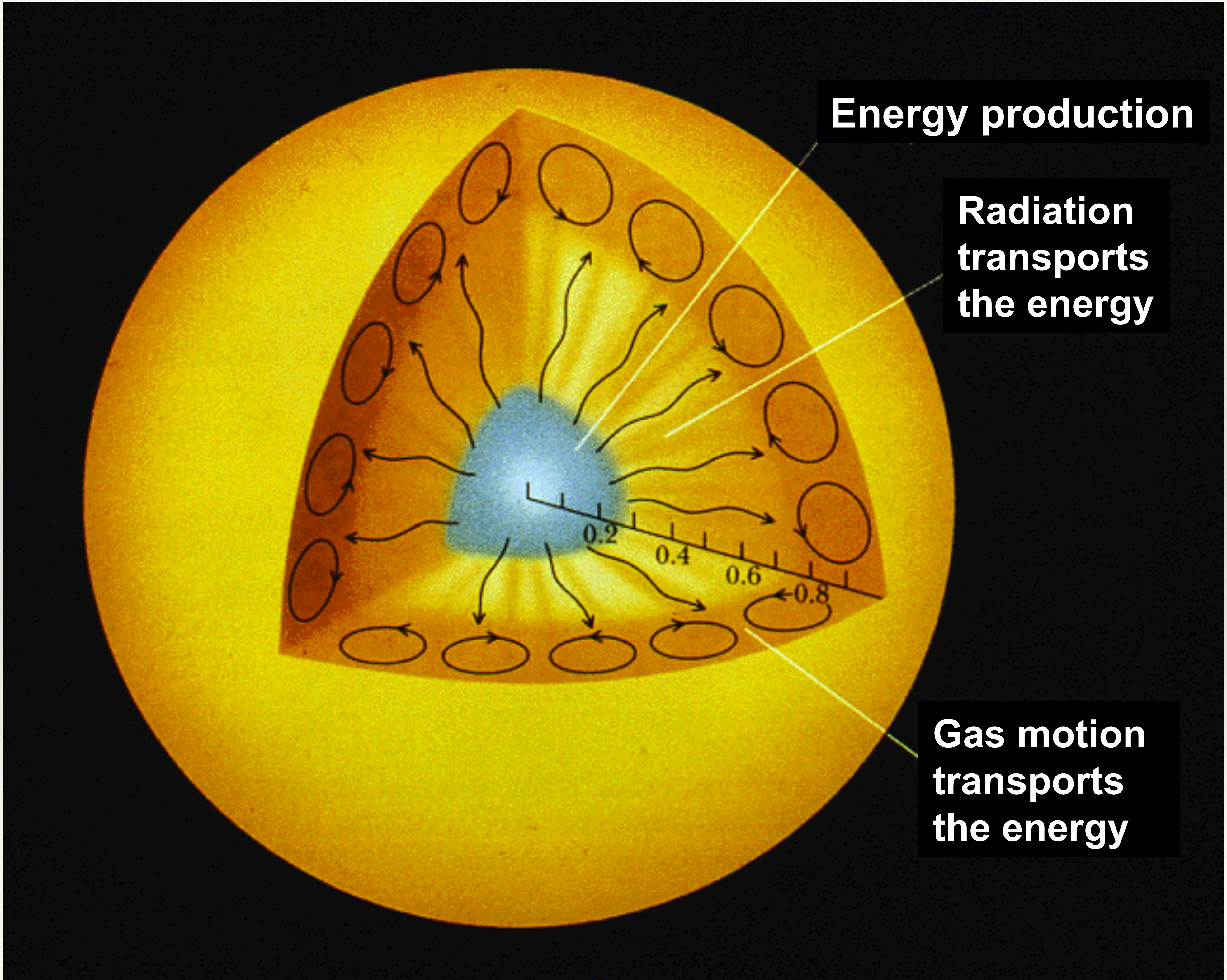


Modelling Stars

Consider a spherical non-rotating star



Modelling Stars



The main equations

Consider a spherical non-rotating star

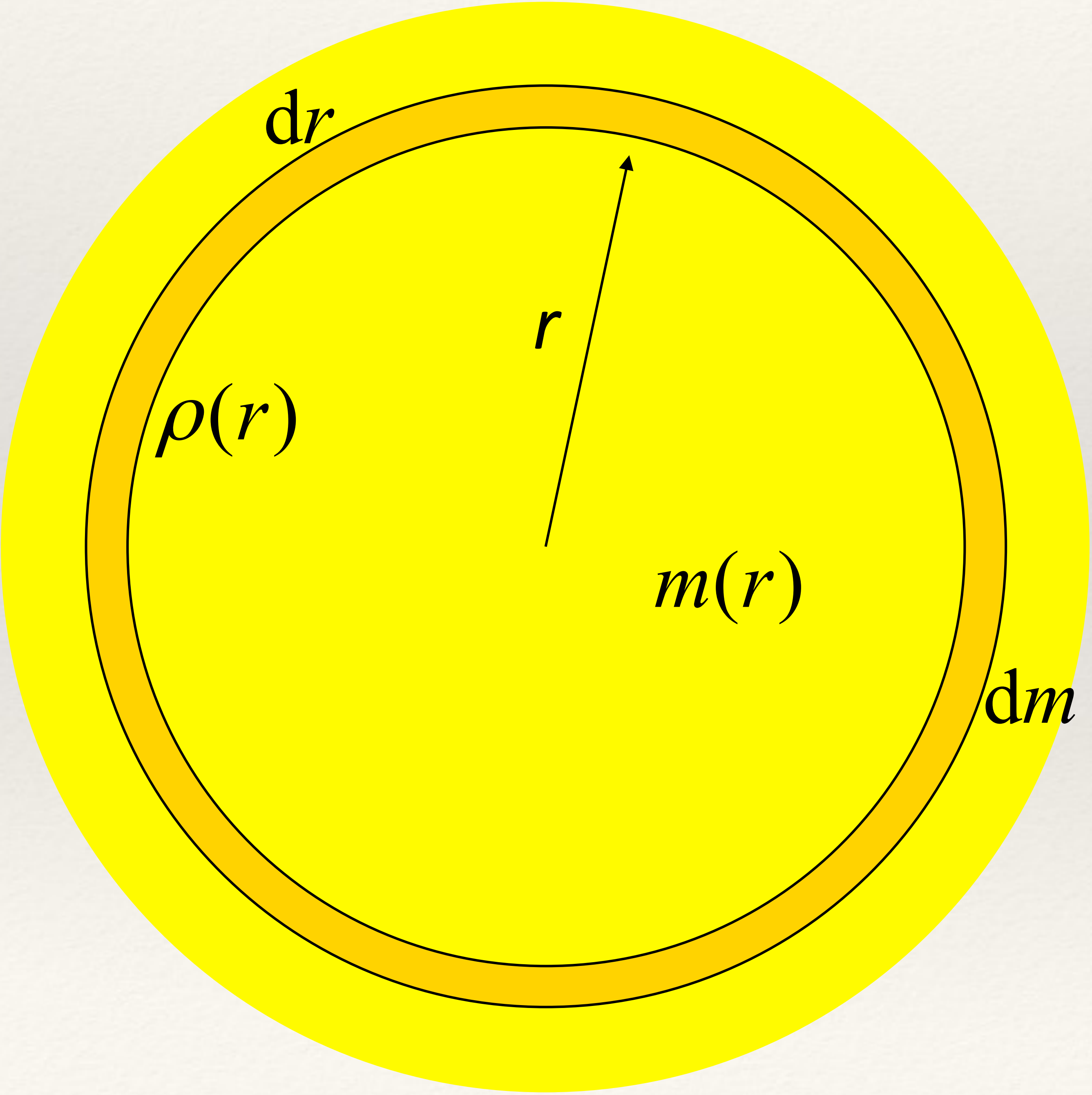
$$\frac{dr}{dP} = \frac{1}{4\pi r^2 \rho} \qquad \frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$$

$$\frac{dL}{dm} = \epsilon - \left[\frac{d}{dt}\left(\frac{u}{\rho}\right) - \frac{P}{\rho^2}\frac{d\rho}{dt}\right]$$

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla \qquad \nabla = \frac{d\ln T}{d\ln P}$$

The main equations

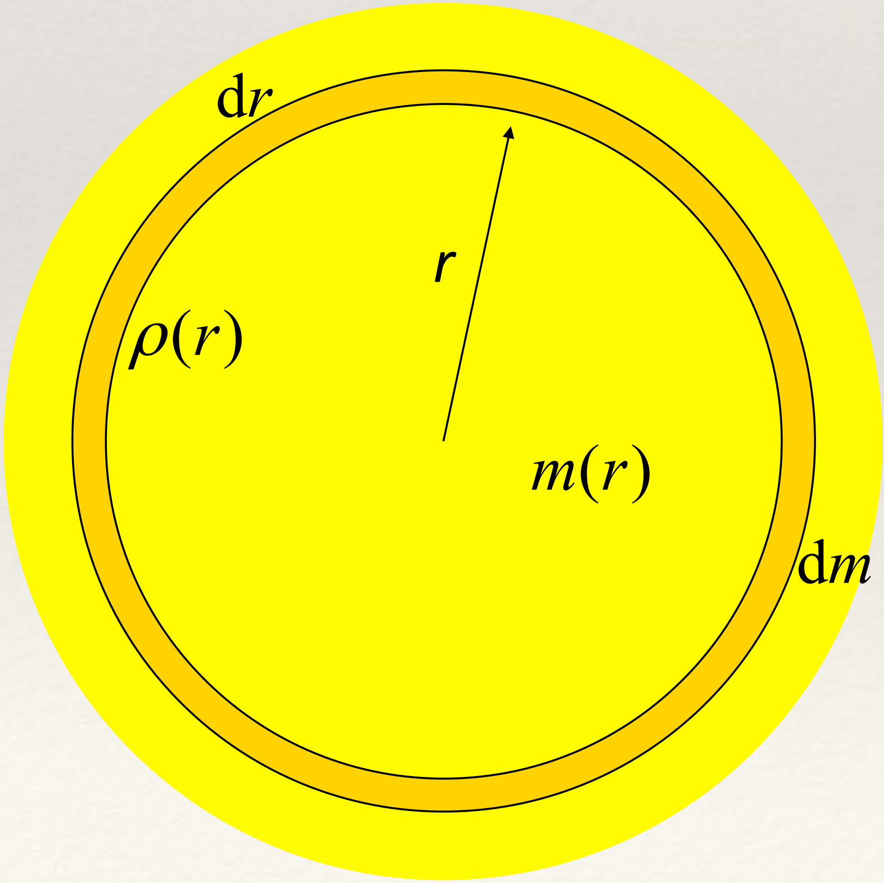
Mass conservation



The main equations

Mass conservation

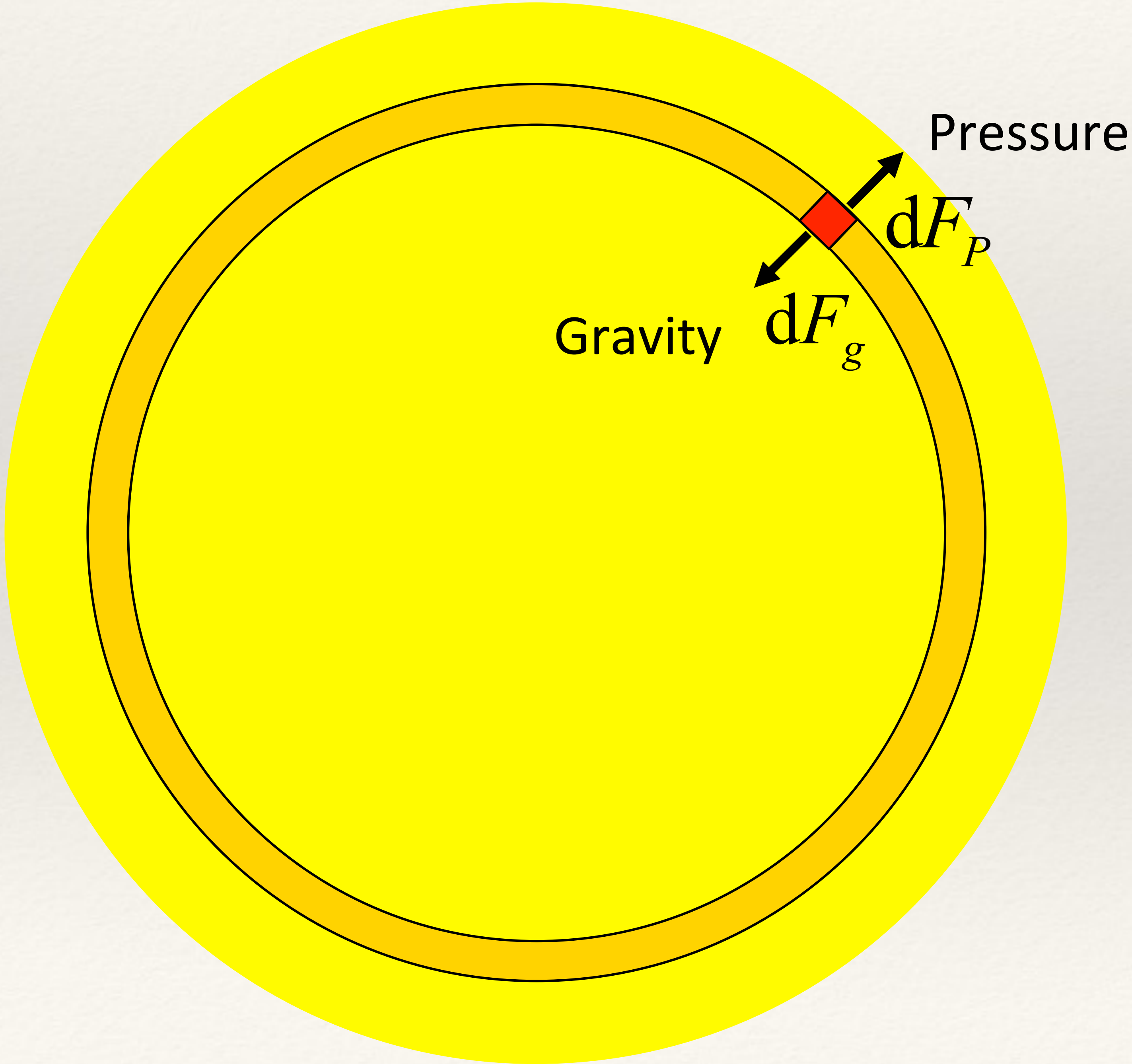
- Only pressure and gravity act on a mass element
- Spherical symmetry



$$\frac{\partial m}{\partial r} = 4\pi r^2 \rho$$

The main equations

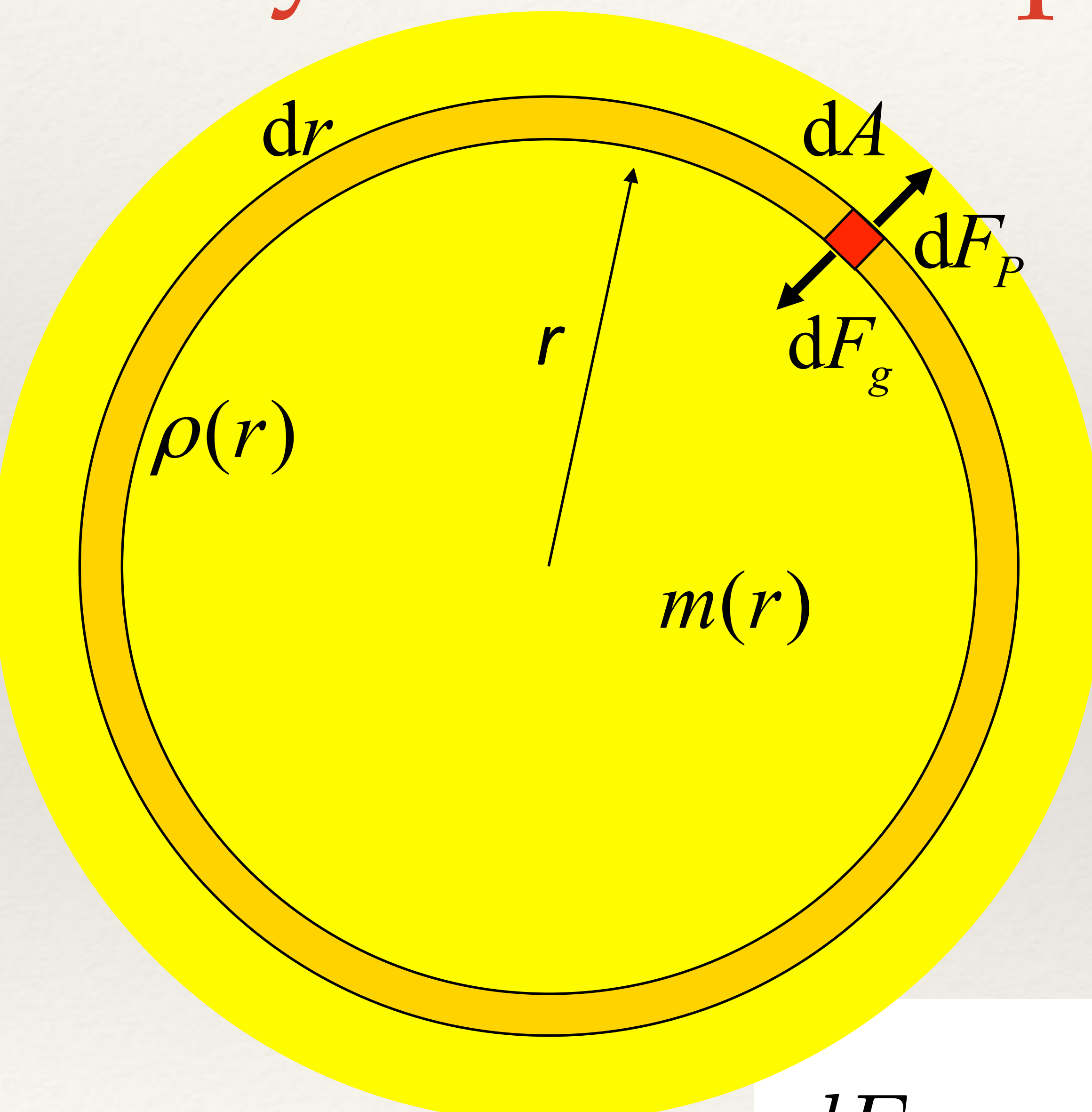
Hydrostatic equilibrium



$$|dF_g| = |dF_P|$$

The main equations

Hydrostatic equilibrium



$$dF_g = -\frac{Gm(r)}{r^2}\rho(r)drdA$$

$$dF_P \simeq P(r)dA - P(r+dr)dA$$

$$dF_P \simeq P(r)dA - P(r+dr)dA \simeq -\frac{dP}{dr}drdA$$

The main equations

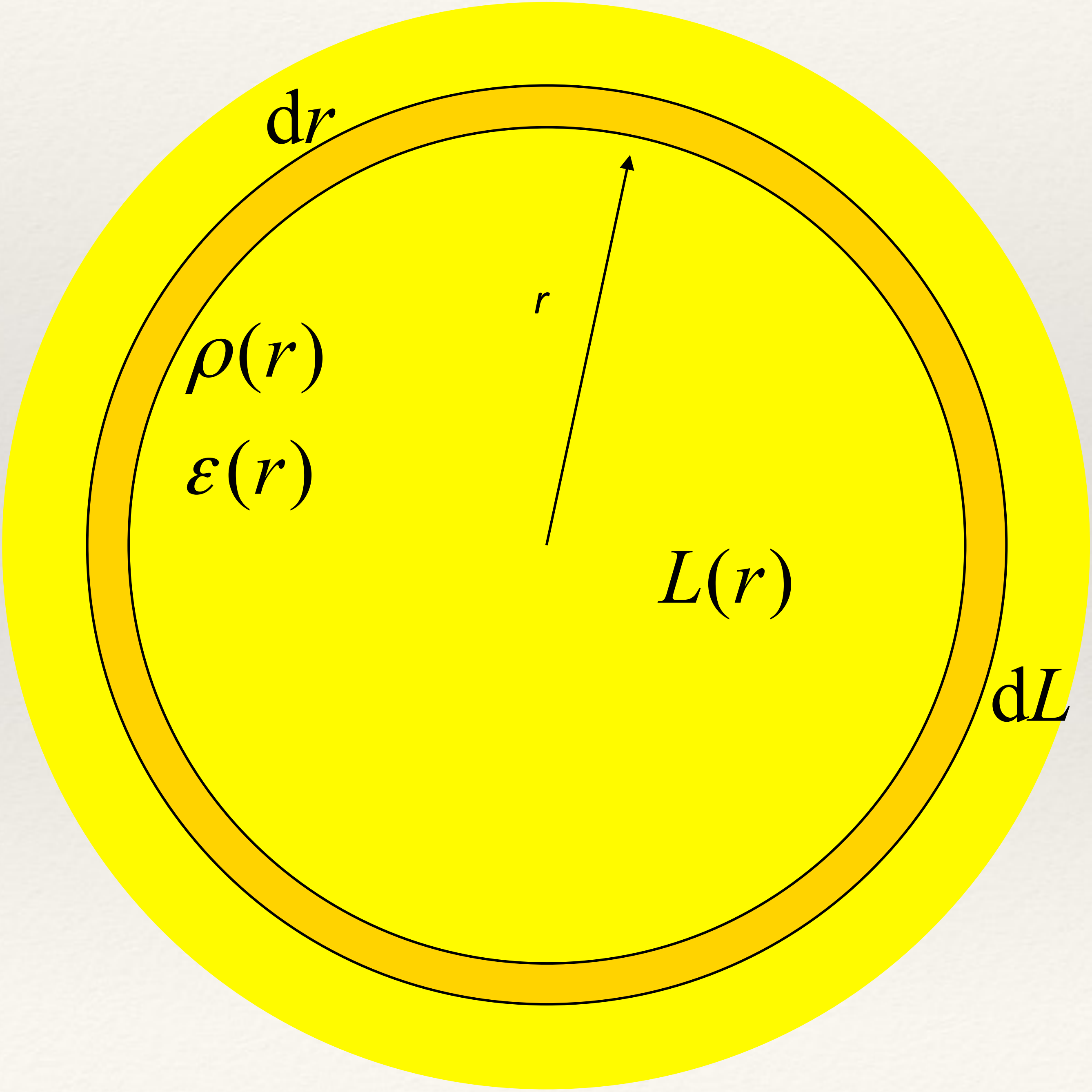
Hydrostatic equilibrium

$$0 = \mathrm{d}F_g + \mathrm{d}F_P = -\frac{Gm(r)}{r^2} \cdot \rho(r)\,\mathrm{d}r\,\mathrm{d}A - \frac{\mathrm{d}P}{\mathrm{d}r}\mathrm{d}r\,\mathrm{d}A$$

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm(r)}{r^2} \cdot \rho(r)$$

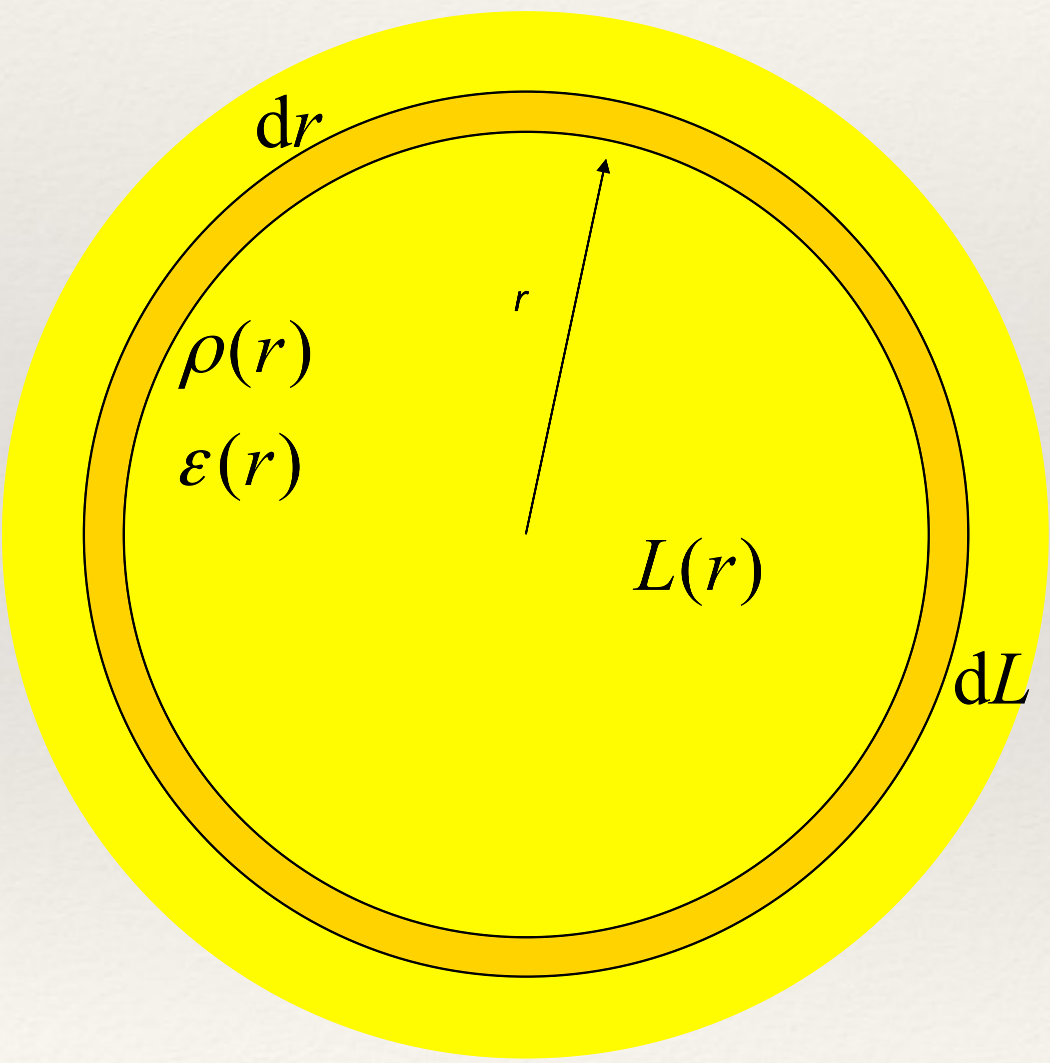
The main equations

Energy conservation



The main equations

Energy conservation



$$dq = du + P dv$$

$$\frac{dL}{dm} = \epsilon$$

$$dq = \left(\epsilon - \frac{dL}{dm}\right) dt$$

$$\frac{dL}{dm} = \epsilon - \frac{du}{dt} - P\frac{dv}{dt}$$

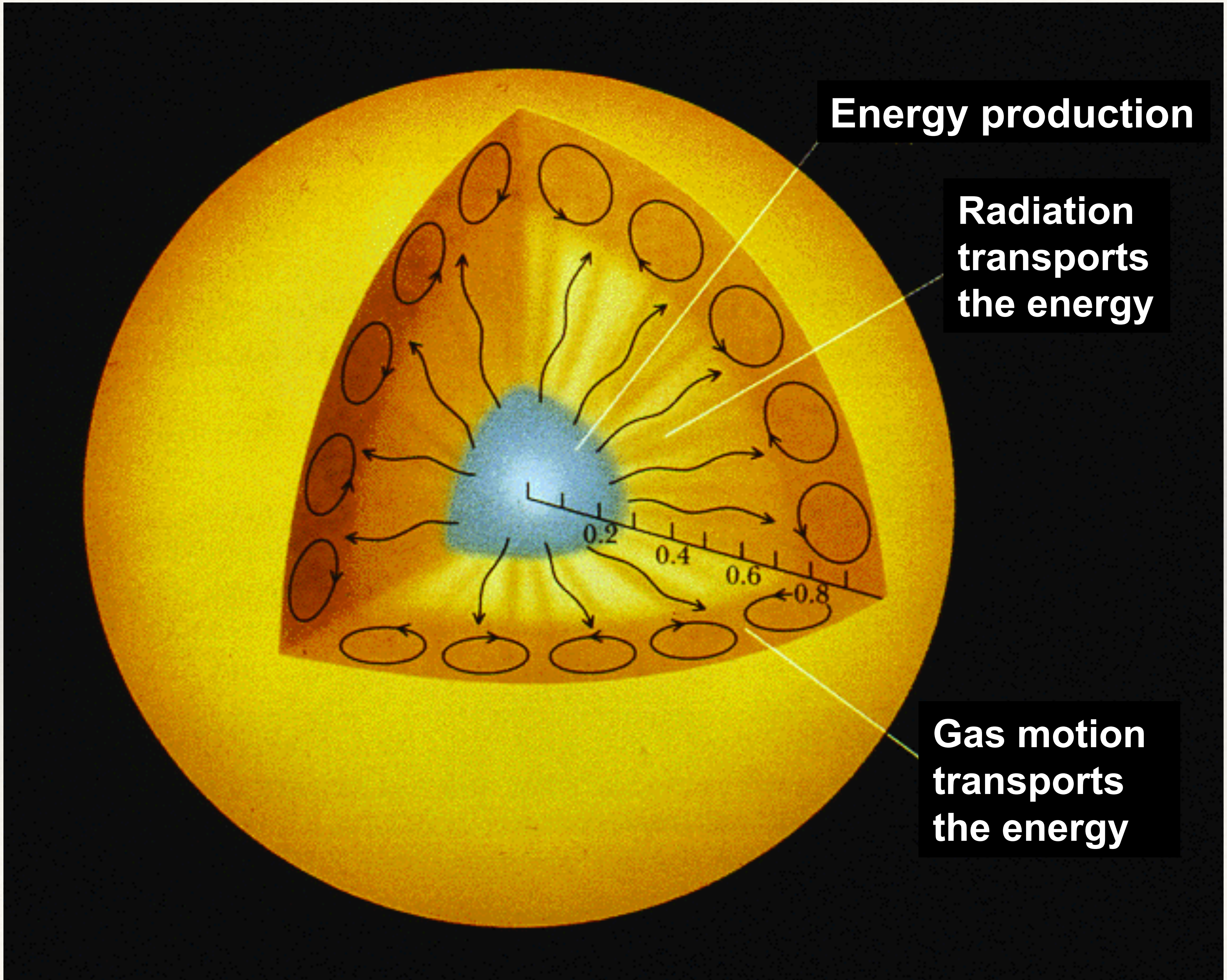
One minute

The main equations

Energy transport

- Occurs via radiation, convection, or conduction
- Regions with different energy transport mechanisms in the same star
- It depends on the thermodynamic state of the layer
- How can we know the mechanism used in each layer?

The main equations



The main equations

Radiative transport

$$\lambda = \frac{1}{\kappa\rho}$$

Photon mean free path

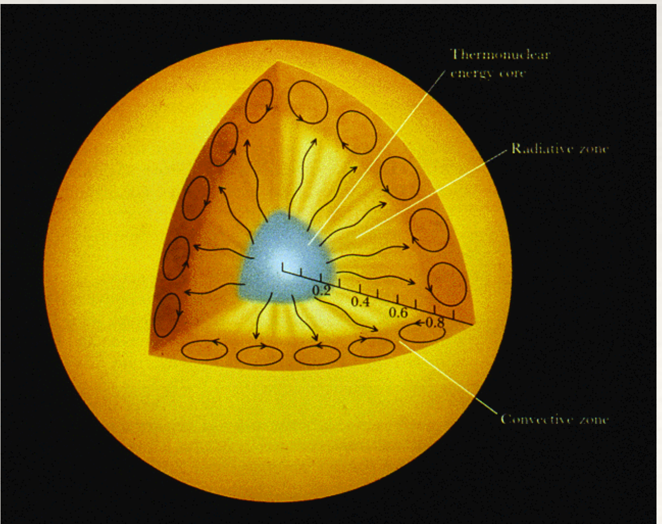
$$F_{\mathrm{R}} = -\frac{\lambda c}{3}\frac{dU_{\mathrm{R}}}{dr}$$

Radiative flux

$$U_{\mathrm{R}} = aT^4$$

Energy density

$$F_{\mathrm{R}} = -\frac{4caT^3}{3\kappa\rho}\frac{dT}{dr}$$



The main equations

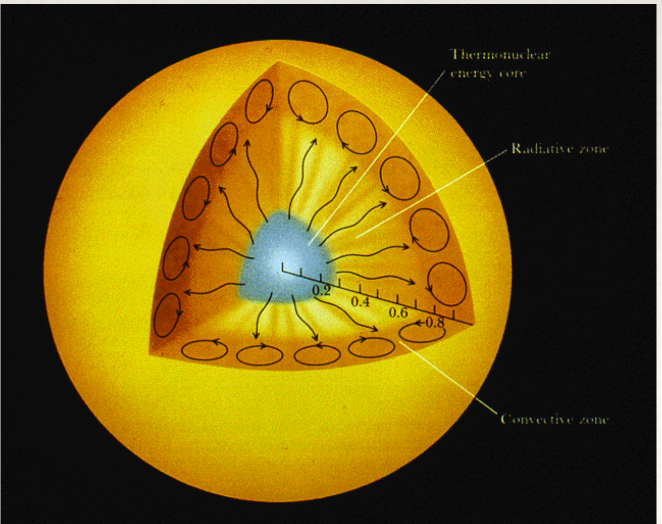
Radiative transport

$$L(r) = 4\pi r^2 F_{\mathrm{R}}$$

Total luminosity

$$\frac{dT}{dr} = -\frac{3\kappa\rho L(r)}{16\pi a c r^2 T^3}$$

$$\frac{dT}{dm} = -\frac{3\kappa}{64\pi^2 a c}\frac{L}{r^4 T^3}$$



The main equations

Radiative transport

- In radiative equilibrium, all energy is transported outwards by photons

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla$$

$$\frac{dT}{dm} = -\frac{3\kappa}{64\pi^2 ac}\frac{L}{r^4 T^3}$$

$$\nabla_{\mathrm{rad}} = \frac{3}{16\pi acG}\frac{\kappa L P}{m T^4}$$

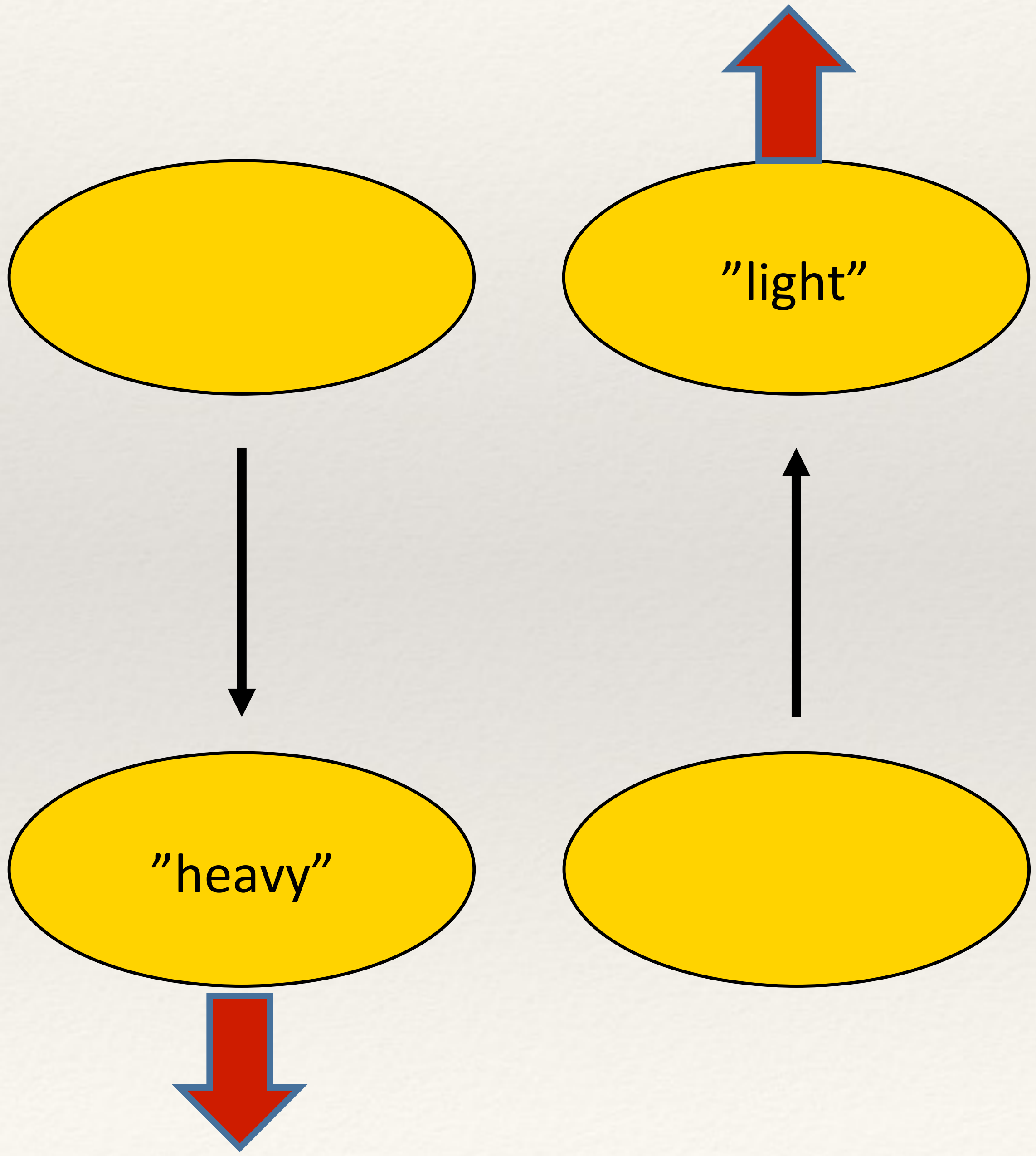
The main equations

Convective transport

It's all about buoyancy!

The main equations

Convective transport



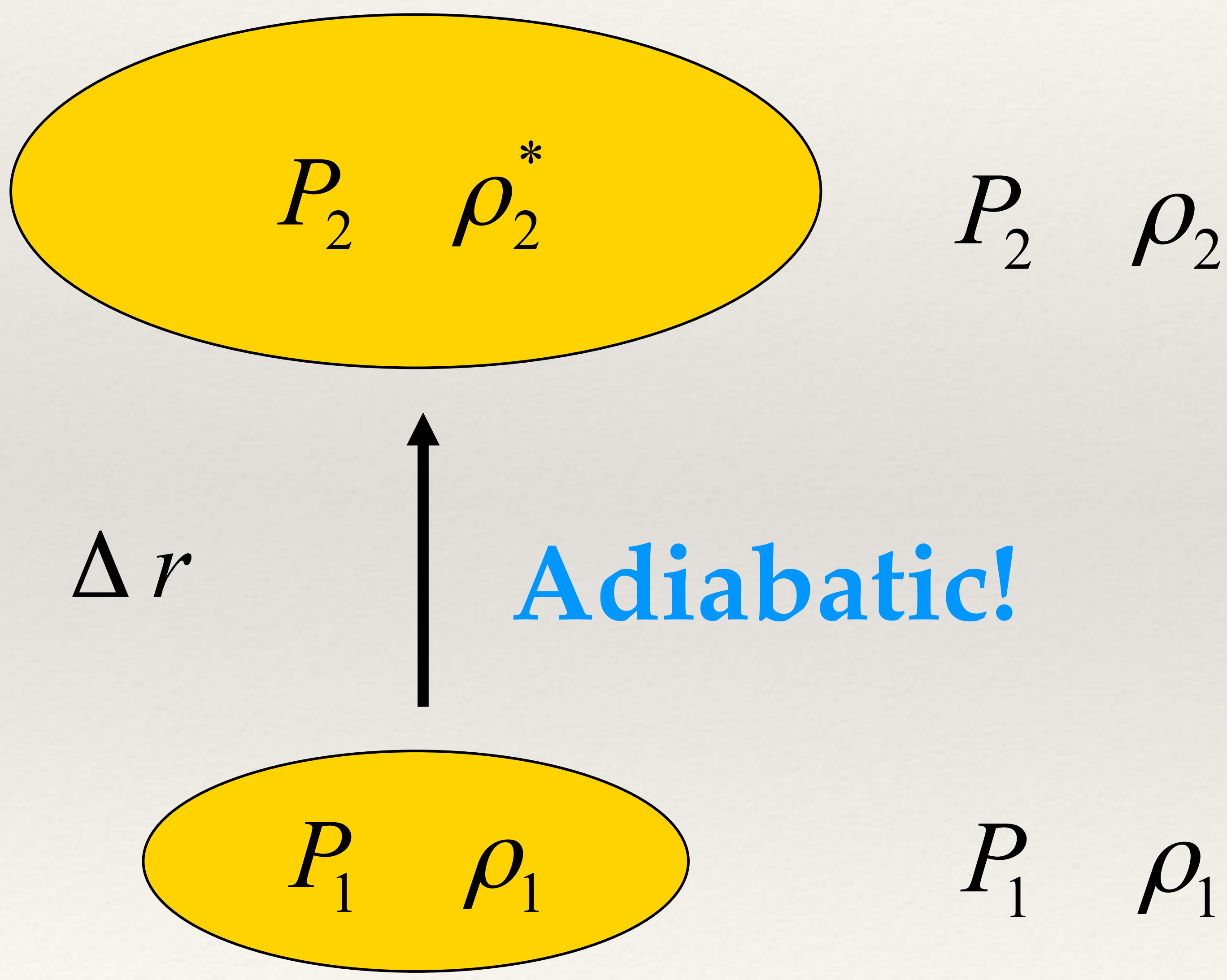
The main equations

Convective transport

- Let us analyse the behaviour of a bubble that displaces a certain distance and consider if it moves back to its original position or continues travelling

The main equations

Convective transport



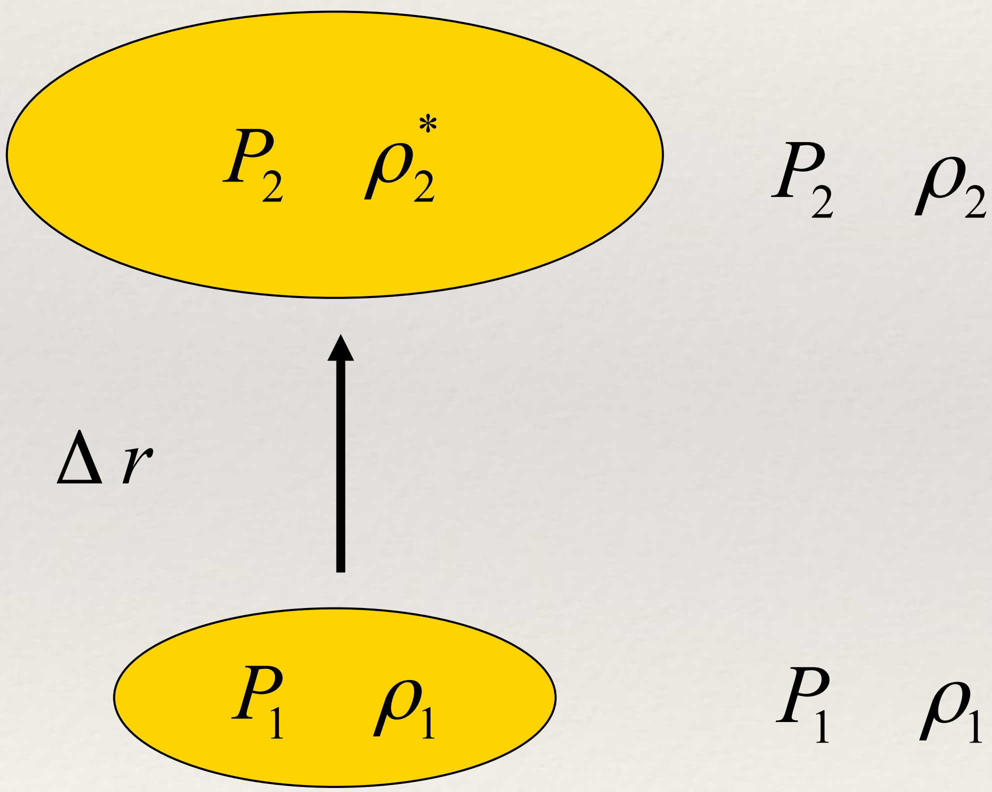
Stability

$$\rho_2 < \rho_2{}^*$$

The main equations

Convective transport

- It can easily be shown that:



$$\rho_2 < {\rho_2}^*,$$

$$\left(\frac{d\ln T}{d\ln P}\right)_2 < \left(\frac{d\ln T}{d\ln P}\right)_{2^*} + \frac{\varphi}{\delta}\left(\frac{d\ln \mu}{d\ln P}\right)_2,$$

$$\nabla_2 < {\nabla_2}^* + \frac{\varphi}{\delta}\nabla_{\mu 2}$$

The main equations

Convective transport

- Think about a radiative layer where a bubble displaces adiabatically

$$\nabla_2 < {\nabla_2}^* + \frac{\varphi}{\delta}\nabla_{\mu_2}$$

Stability criterion

$$\nabla_{\rm rad} < \nabla_{\rm ad} + \frac{\varphi}{\delta}\nabla_\mu$$

Ledoux

$$\nabla_{\rm rad} < \nabla_{\rm ad}$$

Schwarzschild

The main equations

Convective transport

- These criteria tell us if a layer is in convective stability
- If it is:

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla$$

$$\nabla = \nabla_{\rm rad}$$

$$\nabla_{\rm rad} = \frac{3}{16\pi acG}\frac{\kappa LP}{mT^4}$$

g-modes?

- What if it is not?

The main equations

Convective transport: the mixing-length theory

- It assumes a bubble travels a characteristic distance and then dissolves

$$\ell = \alpha_{\mathrm{mlt}} H_P$$

- The mixing length parameter scales this distance
- The temperature gradient in convective instability is calculated after some geometrical assumptions and defining the mixing length parameter

The main equations

Question:

What is the value of the mixing length parameter in stars?

- Think about it (45 secs)
- Discuss it with your neighbour (2 mins)

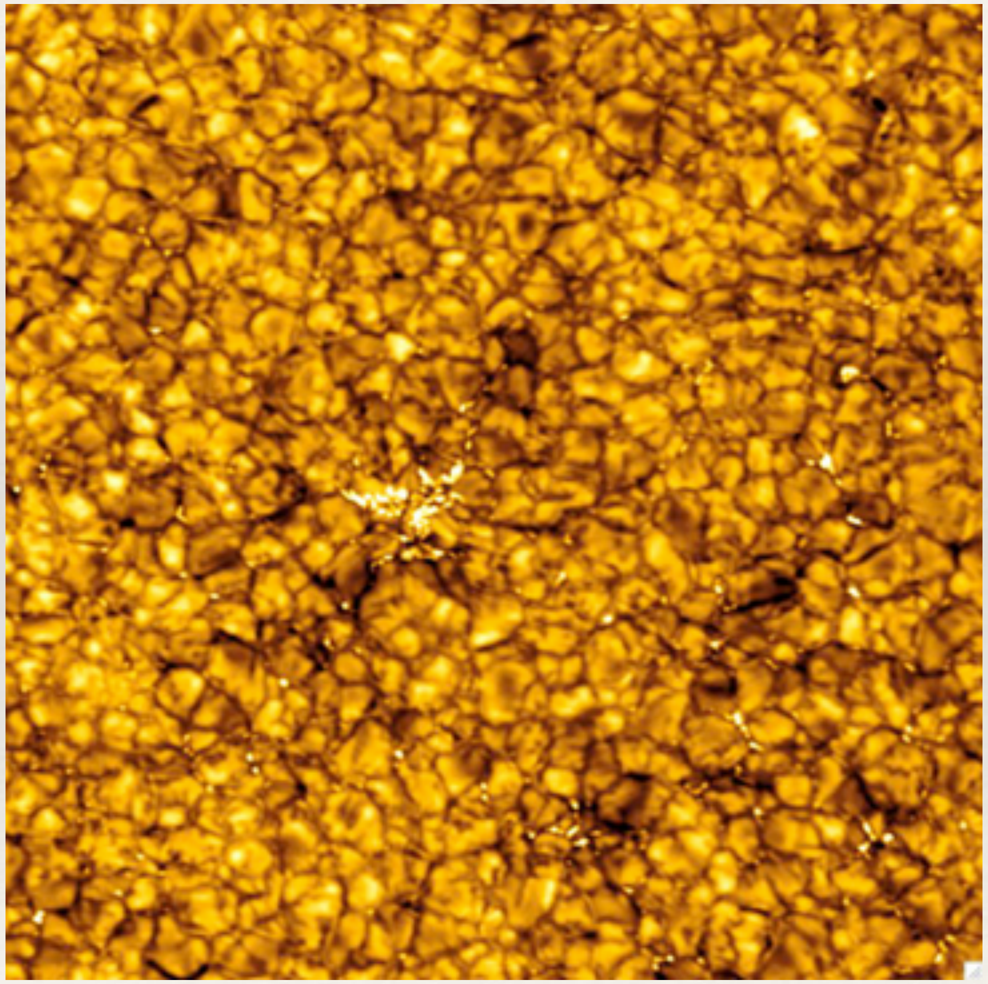
The main equations

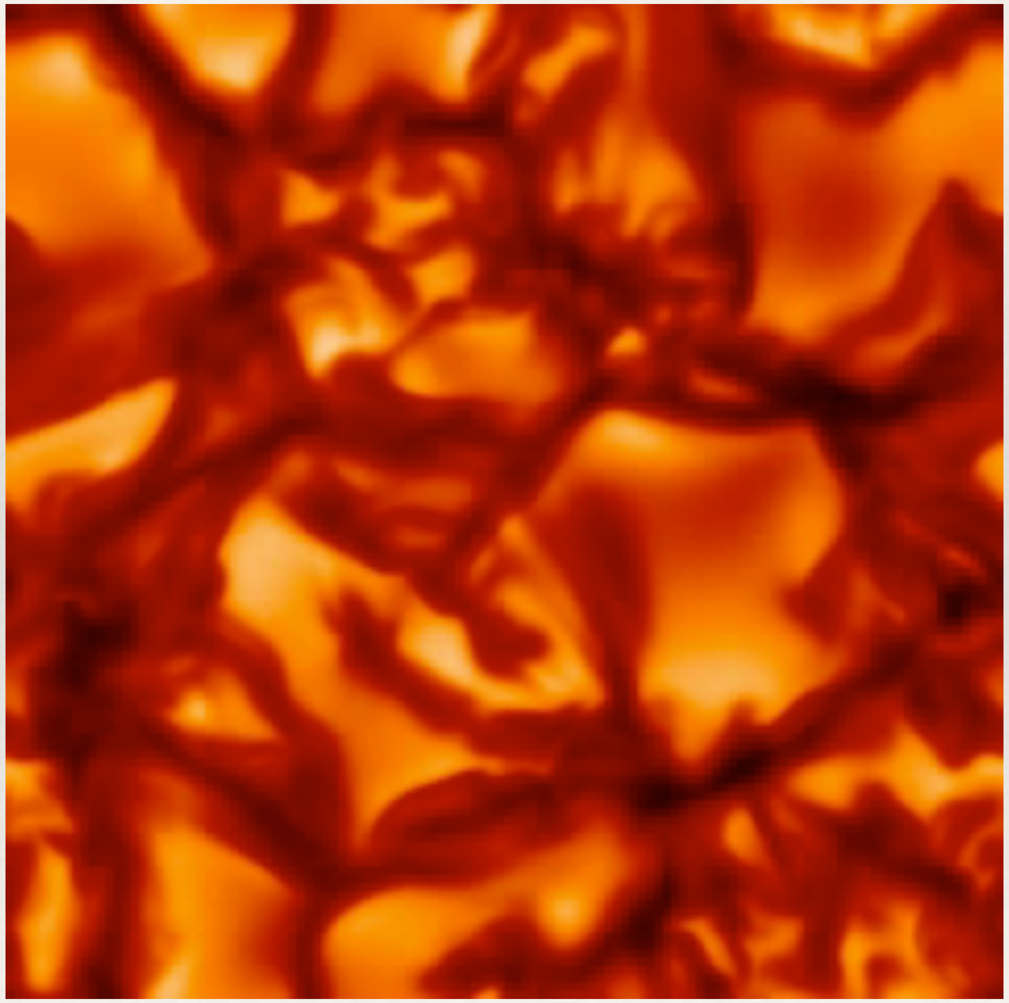
Convective transport: the importance of the Sun

- The mixing length parameter is normally calibrated to reproduce solar properties
- Standard Solar Model (SSM): evolve a fully homogeneous 1 $M_\odot$ model from the pre-MS to solar age
- SSM must match solar radius, luminosity, and surface metals-to-hydrogen ratio at the solar age
- Three adjustable parameters: initial composition and mixing-length parameter

The main equations

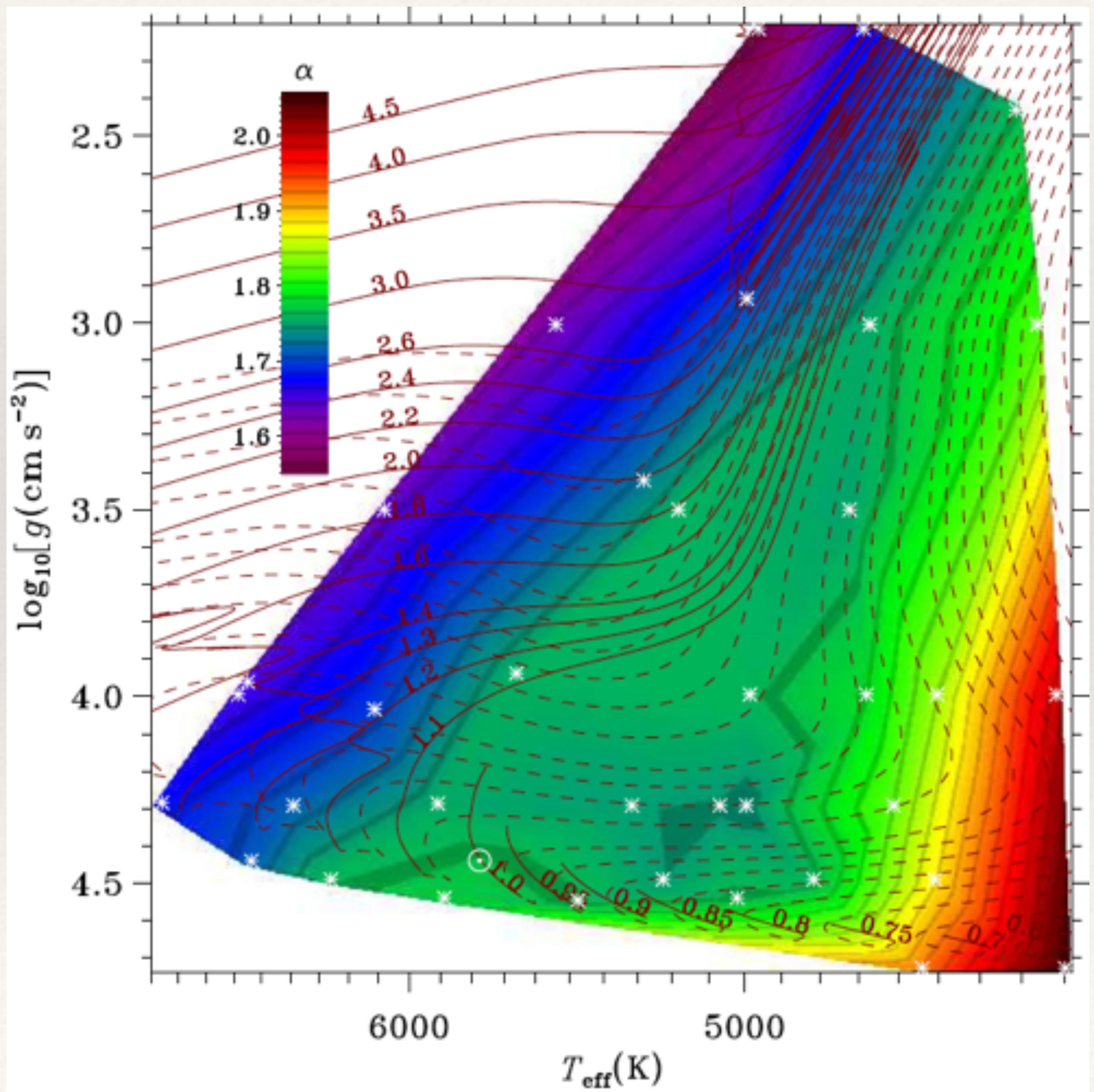
Convective transport: using 3D simulations



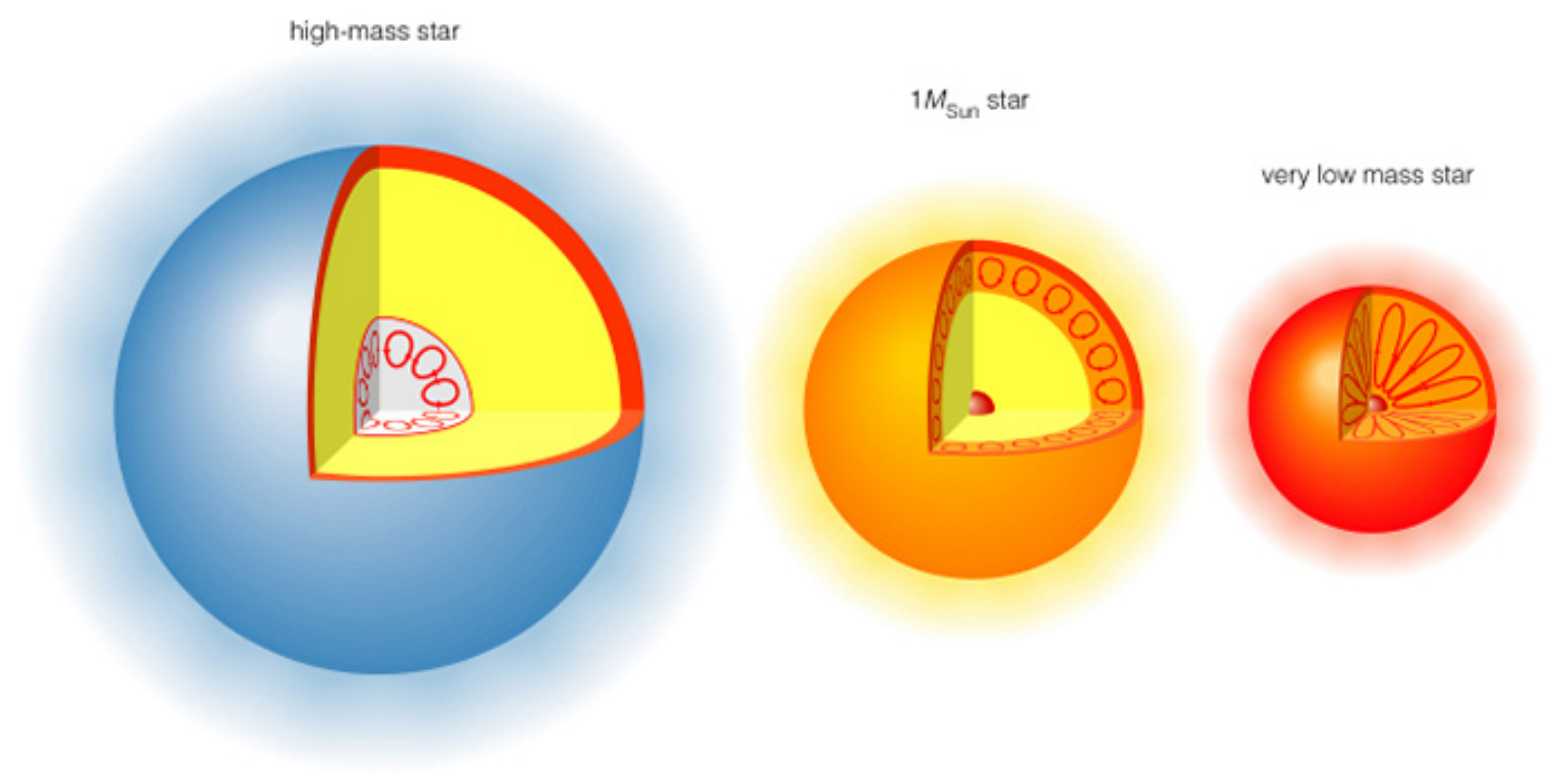


The main equations

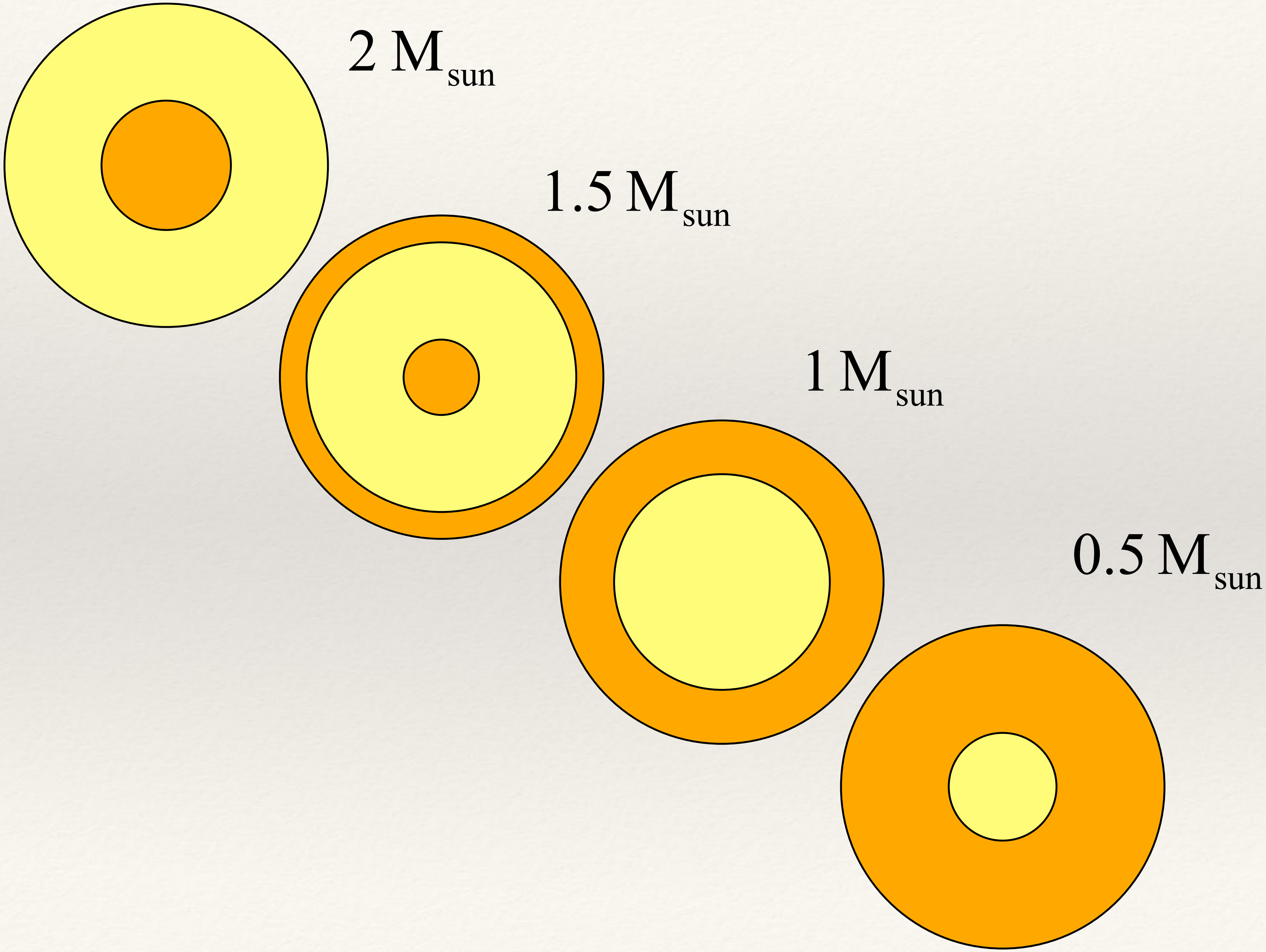
Convective transport: using 3D simulations



The main equations



The main equations



The main equations

How many equations and unknowns?

$$\frac{dr}{dP} = \frac{1}{4\pi r^2 \rho} \qquad \frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$$

$$\frac{dL}{dm} = \epsilon - \left[\frac{d}{dt}\left(\frac{u}{\rho}\right) - \frac{P}{\rho^2}\frac{d\rho}{dt}\right]$$

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla \qquad \nabla = \frac{d\ln T}{d\ln P}$$

The main equations

How many equations and

The Equation of State (EOS)

$$\frac{dr}{dP} = \frac{1}{4\pi r^2 \rho} \qquad \frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$$

$$\frac{dL}{dm} = \epsilon - \left[\frac{d}{dt}\left(\frac{u}{\rho}\right) - \frac{P}{\rho^2}\frac{d\rho}{dt}\right]$$

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla \qquad \nabla = \frac{d\ln T}{d\ln P}$$

The main equations

How many equations and unk

Constitutive Equations

$$\frac{dr}{dP} = \frac{1}{4\pi r^2 \rho} \qquad \frac{dP}{dm} = -\frac{Gm}{4\pi r^4}$$

$$\frac{dL}{dm} = \epsilon - \left[\frac{d}{dt}\left(\frac{u}{\rho}\right) - \frac{P}{\rho^2}\frac{d\rho}{dt}\right]$$

$$\frac{dT}{dm} = -\frac{GmT}{4\pi r^4 P}\nabla \qquad \nabla = \frac{d\ln T}{d\ln P}$$

The main equations

Constitutive equations

$$\rho = \rho(P, T, \mu)$$ **EOS**

$$c_P = c_P(P, T, \mu)$$ **Specific heat**

$$\kappa_\nu = \kappa_\nu(P, T, \mu)$$ **Opacity**

$$r_{jk} = r_{jk}(P, T, \mu)$$ **Nuclear reactions**

$$\epsilon_\nu = \epsilon_\nu(P, T, \mu)$$ **Neutrino losses**

The main equations

Constitutive equations

EOS

$$\rho = \rho(P, T, \mu)$$

- Relates thermodynamical properties of the gas
- Simplest case: ideal gas
- In stellar plasmas, calculated by different groups for different ranges in parameters (e.g.,)

OPAL **MHD** **Irwin** **FreeEOS**

The main equations

Constitutive equations

Opacity

$$\kappa_\nu = \kappa_\nu(P, T, \mu)$$

- The Rosseland mean opacity is used:

$$\frac{1}{\kappa_R} = \frac{\int_0^\infty \frac{1}{\kappa_\nu} \frac{\partial B_\nu}{\partial T} \partial \nu}{\int_0^\infty \frac{\partial B_\nu}{\partial T} \partial \nu}$$

- Determined by different groups (e.g.,)

OPAL **OP**

The main equations

Constitutive equations

Nuclear reactions

$$r_{jk} = r_{jk}(P, T, \mu)$$

$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\rho}\left(\sum_j r_{ji} - \sum_k r_{ik}\right)$$

- Determined by different groups (e.g.,)

Adelberger **NACRE**

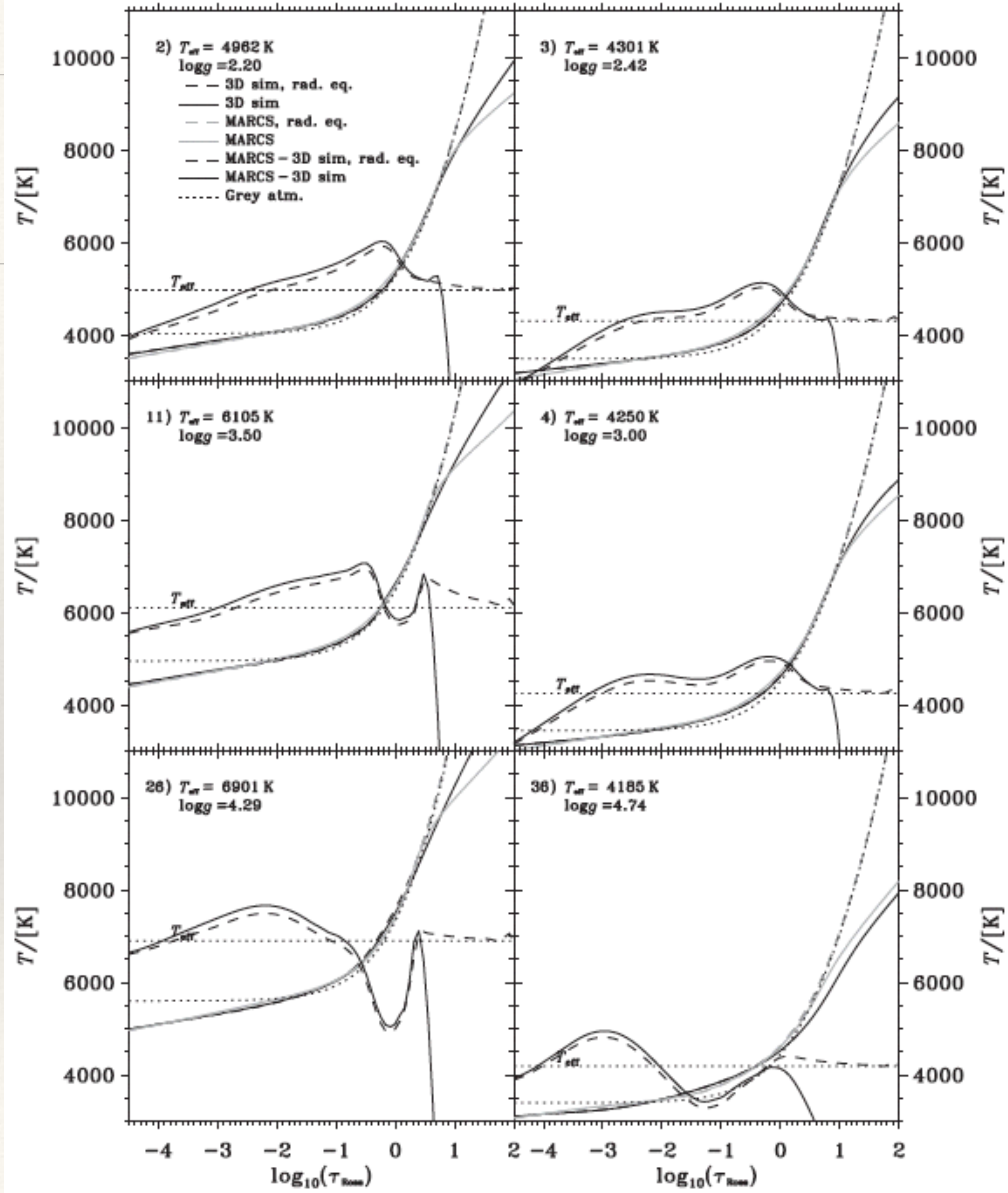
The main equations

Boundary conditions

- Needed to integrate the equations
- Central ones are trivial:

$$r(m=0)=0,\ L(m=0)=0$$

- Other two must specify how T and P vary close to the surface
- Can be analytical, semi-empirical, or from model atmospheres


2) T_{eff} = 4962 K
log$g$ =2.20
3D sim, rad. eq.
3D sim
MARCS, rad. eq.
MARCS
MARCS – 3D sim, rad. eq.
MARCS – 3D sim
Grey atm.
3) T_{eff} = 4301 K
log$g$ =2.42
11) T_{eff} = 6105 K
log$g$ =3.50
4) T_{eff} = 4250 K
log$g$ =3.00
26) T_{eff} = 6901 K
log$g$ =4.29
36) T_{eff} = 4185 K
log$g$ =4.74
T_{eff}
T/[K]
10000
8000
6000
4000
−4
−3
−2
−1
0
1
2
$\log_{10}(\tau_{Ross})$

One minute

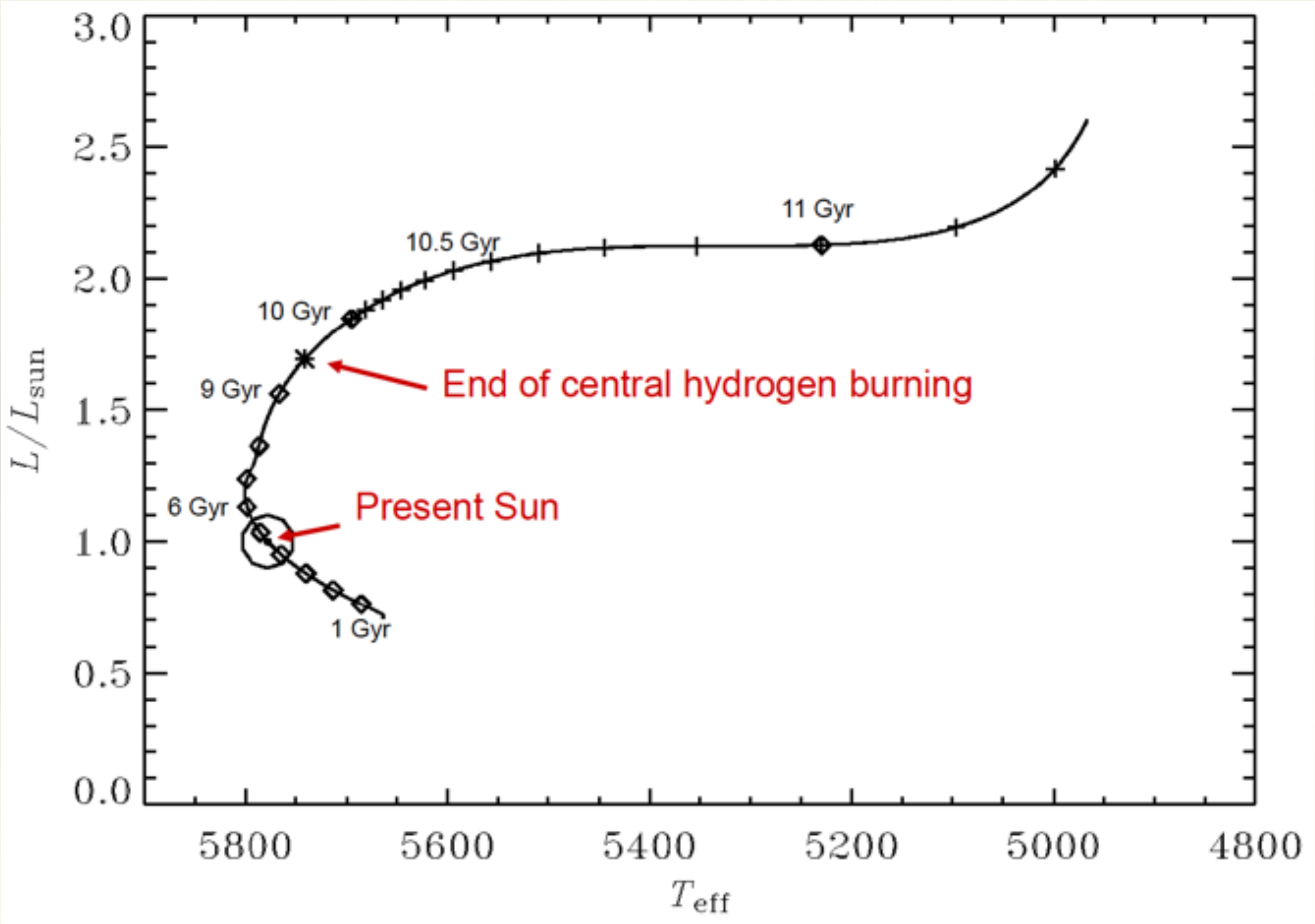
Modelling stars

How is it all combined in a stellar evolution code

1. Homogeneous initial composition
2. Solve equations for stellar structure
3. Determine rate of change in composition
4. Take a step in time and find new composition
5. Solve equations for stellar structure with new composition
6. Back to 3 until reaching target age

Modelling stars

How is it all combined in a stellar evolution code



Modelling stars

The ingredients we need

- Select EOS
- Select nuclear reactions
- Select opacity tables
- Choose stability criterion (Ledoux or Schwarzschild)
- Define the mixing-length parameter
- Select the appropriate composition
- Choose any additional mixing process

Modelling stars

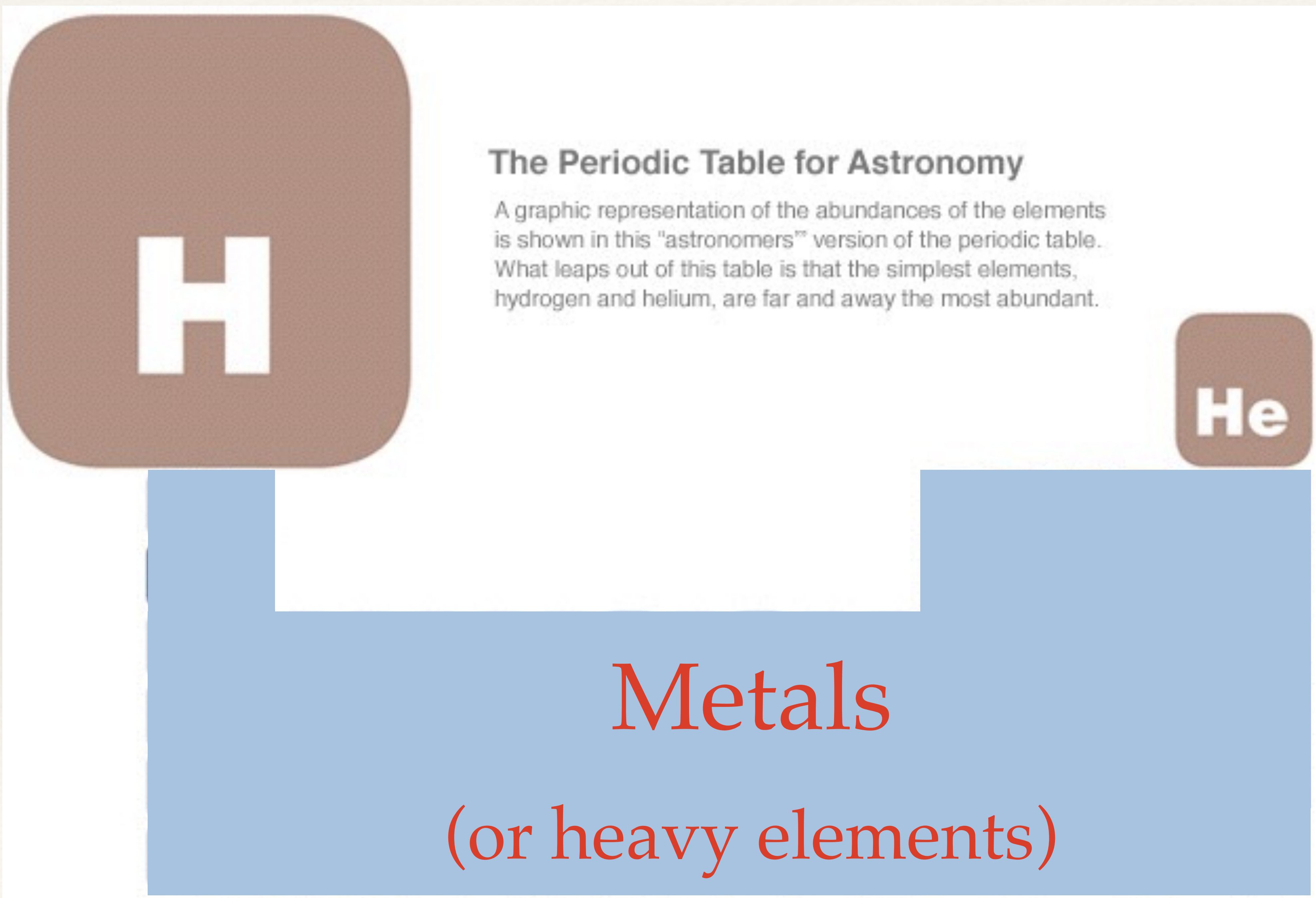
Determining composition

$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\rho}\left(\sum_j r_{ji} - \sum_k r_{ik}\right)$$

$$\sum_i X_i = 1$$

Modelling stars

Determining composition



Modelling stars

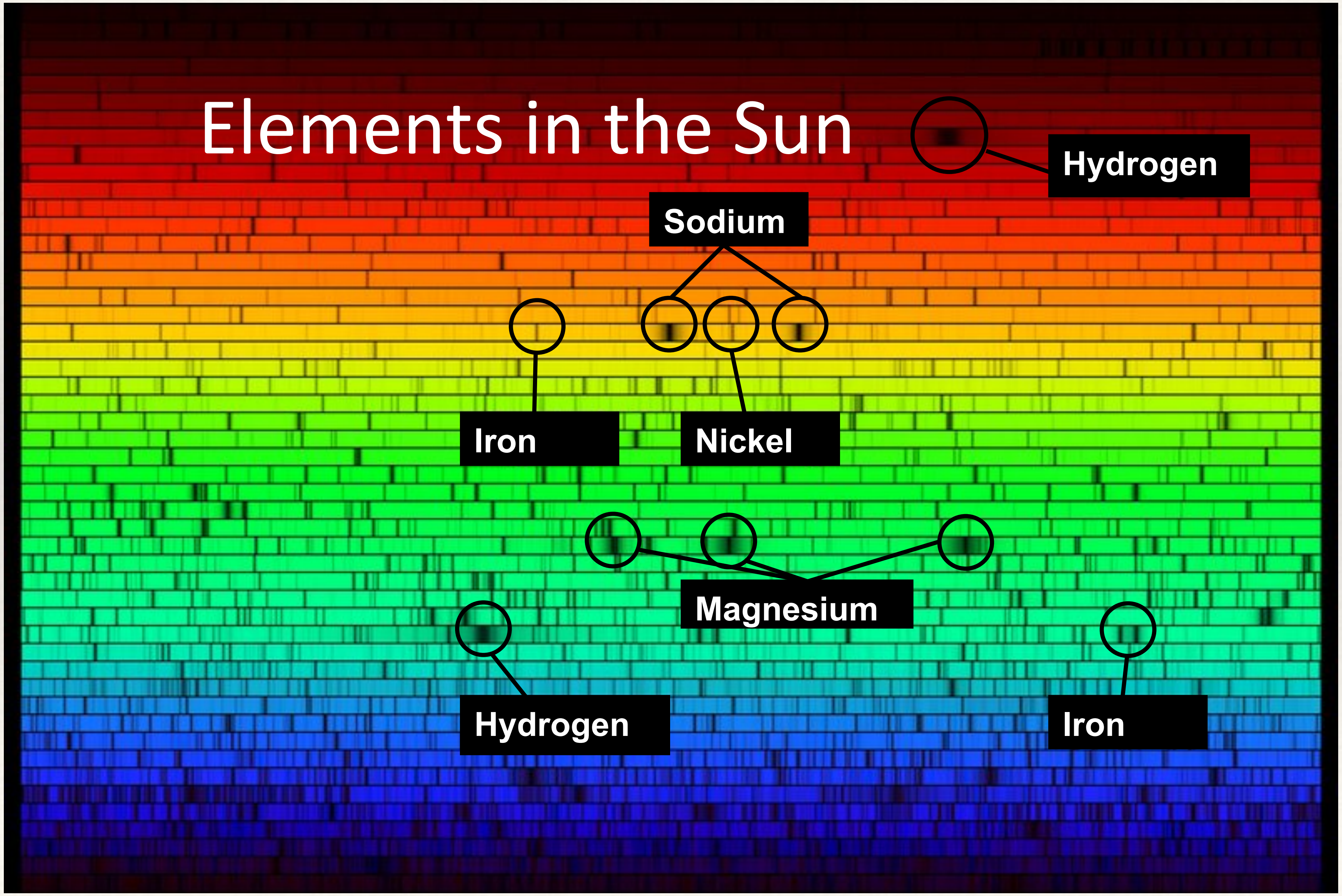
Determining composition

- In evolution models, we work with
  - X = hydrogen mass fraction
  - Y = helium mass fraction
  - Z = heavy elements mass fraction

$$X + Y + Z = 1$$

Modelling stars

Determining composition



Modelling stars

Determining composition

- Observation of a star (e.g., photometry, spectroscopy)
- Determine the bulk "metallicity" of the star [Fe/H]

$$[\mathrm{A/B}] = \log\left(\frac{(\text{number of A atoms}/\text{number of B atoms})_\star}{(\text{number of A atoms}/\text{number of B atoms})_\odot}\right)$$

- If possible, determine some other element (e.g., [C/Fe], [N/Fe], [O/Fe])

Modelling stars

Question:

How to transform the observed [Fe/H] into X, Y, and Z for each star we model?

- Think about it (45 secs)
- Discuss it with your neighbour (2 mins)

Modelling stars

Determining composition

$$[M/H] \simeq [Fe/H]\left(0.638 \times 10^{[\alpha/Fe]} + 0.362\right)$$

$$[M/H] \simeq [Fe/H]$$

1.- $$[M/H] \simeq \log(Z/X)_{\rm star} - \log(Z/X)_{\odot}$$

Modelling stars

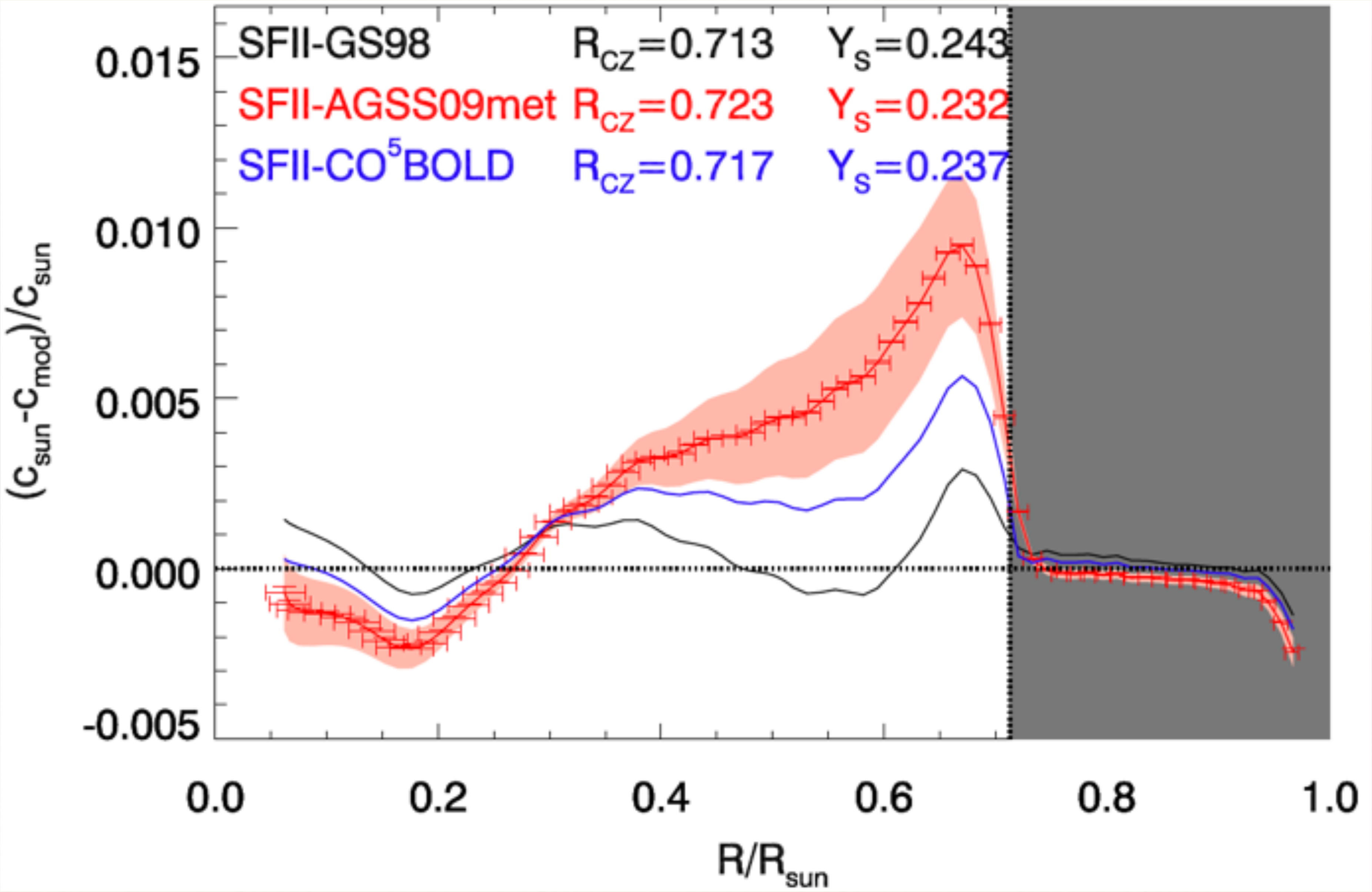
The solar abundance problem…

- History of the solar surface composition
  - GN93: 0.0245
  - GS98: 0.0230
  - AGS05: 0.0165
  - AGS09: 0.0180
  - C11: 0.0209

Impact of 3D atmospheric simulations

Modelling stars

The solar abundance problem…



Modelling stars

The solar abundance problem…

El.	GN93	GS98	AGSS09	C11	AGSS15
C	8.55	8.52	8.43	8.50	–
N	7.97	7.92	7.83	7.86	–
O	8.87	8.83	8.69	8.76	–
Ne	8.08	8.08	7.93	8.05	7.93
Mg	7.58	7.58	7.60	7.54	7.59
Si	7.55	7.55	7.51	7.52	7.51
S	7.33	7.33	7.13	7.16	7.13
Fe	7.50	7.50	7.50	7.52	7.47
$(Z/X)_\odot$	0.0245	0.0230	0.0180	0.0209	–

Modelling stars

The solar abundance problem…

- Choose a set of solar abundances, but be consistent
- It defines the zero-point for [Fe/H] with a difference of up to 0.13 dex!
- It defines also the distribution of heavy elements among different species
- This has a large impact on the opacities
- You need specifically computed opacity tables for the solar mixture you are using

Modelling stars

Determining composition

$$[M/H] \simeq [Fe/H]\left(0.638 \times 10^{[\alpha/Fe]} + 0.362\right)$$

$$[M/H] \simeq [Fe/H]$$

1.- $$[M/H] \simeq \log(Z/X)_{\rm star} - \log(Z/X)_{\odot}$$

2.- $$X + Y + Z = 1$$

3?

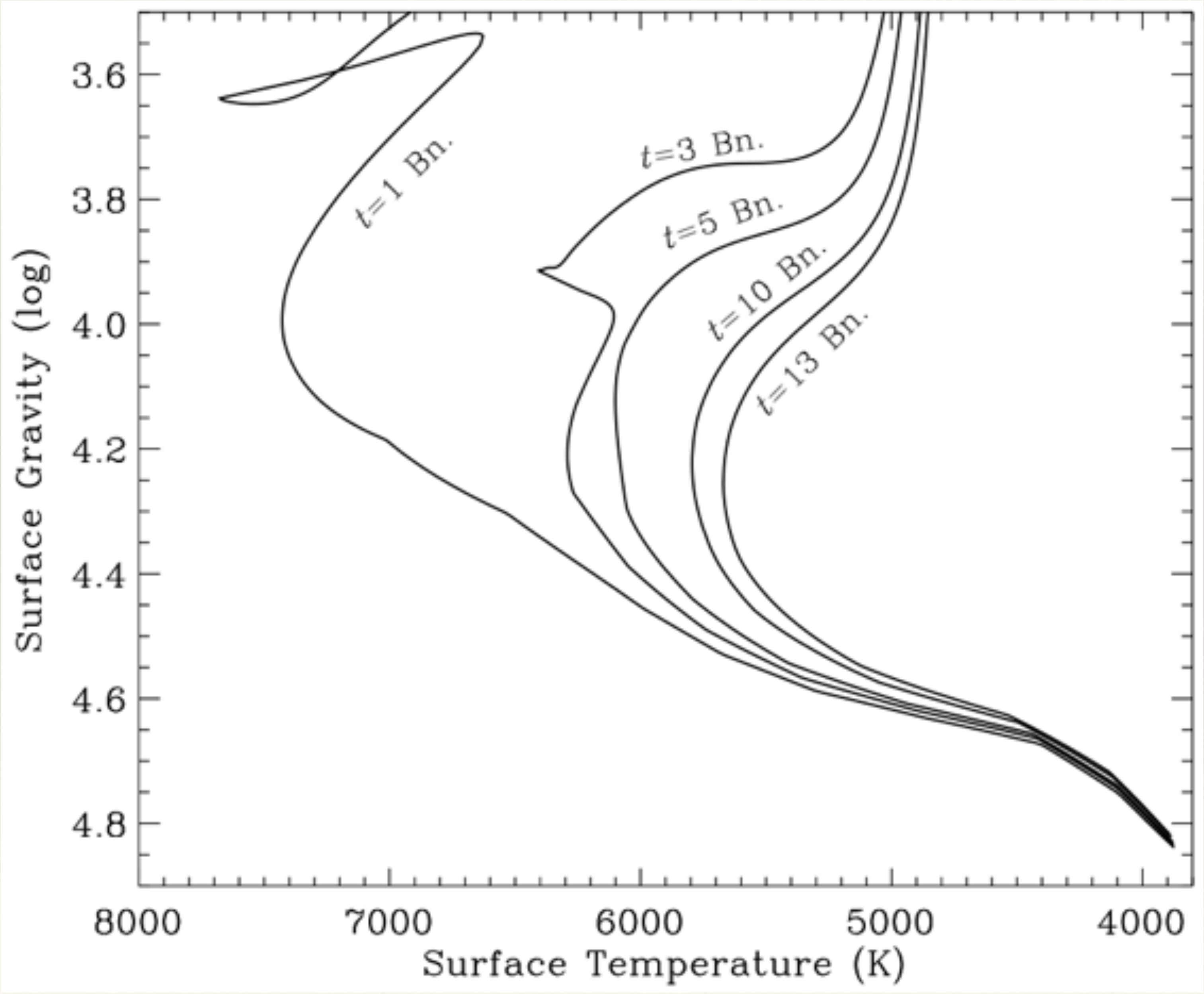
Galactic chemical evolution law

- The initial mass fractions in the Universe Z=0, Y=0.248
- The Sun was formed with Z~0.02, Y~0.27
- Is there a relation between helium abundance as the universe gets enriched in metals?

$$\frac{\Delta Y}{\Delta Z} \simeq 1 - 3$$

Modelling stars

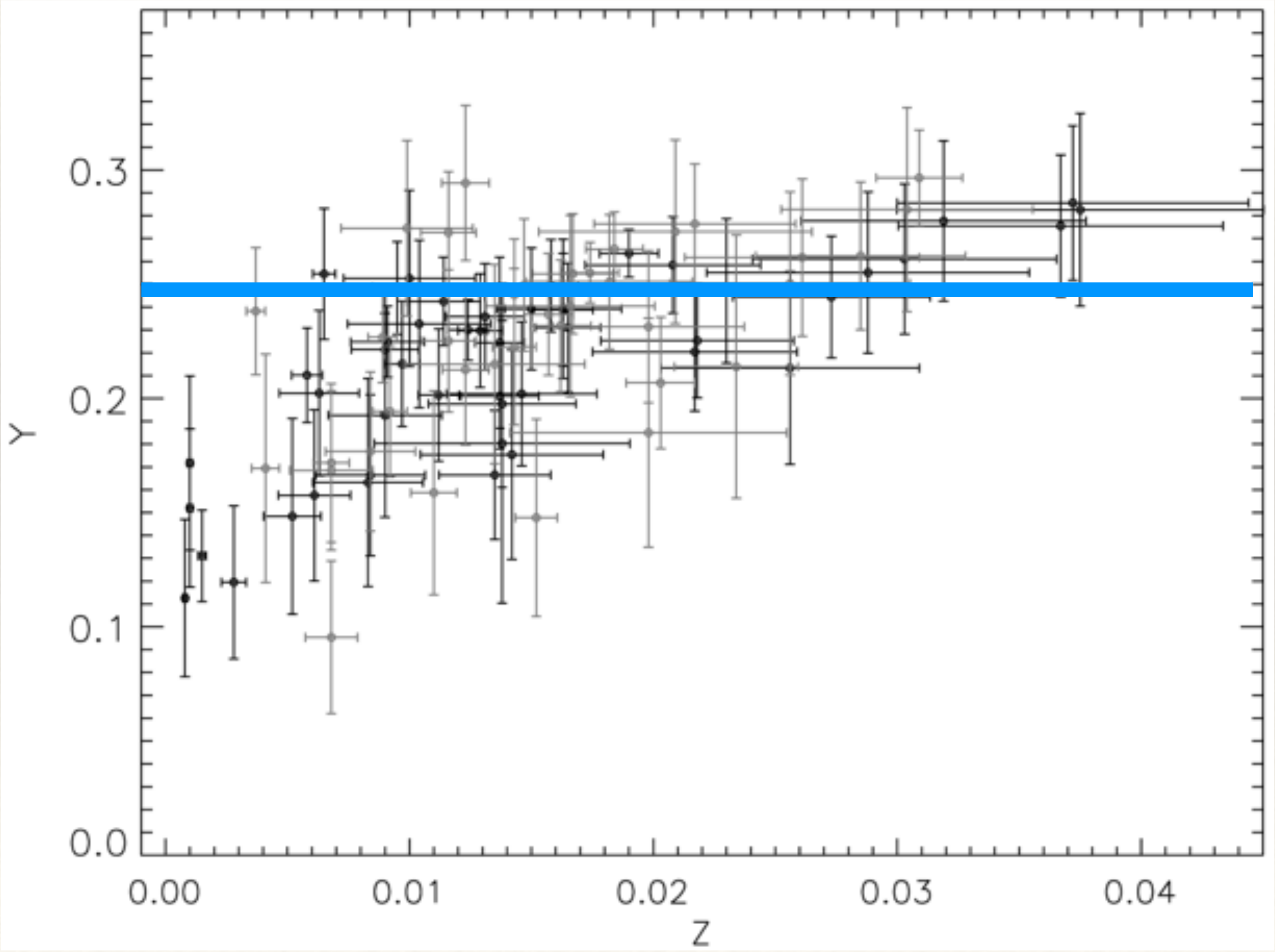
Galactic chemical evolution law



$$L \propto \mu^{7.5}$$

Modelling stars

Galactic chemical evolution law



$$L \propto \mu^{7.5}$$

Modelling stars

Determining composition

$$[M/H] \simeq [Fe/H]\left(0.638 \times 10^{[\alpha/Fe]} + 0.362\right)$$

$$[M/H] \simeq [Fe/H]$$

1.- $$[M/H] \simeq \log(Z/X)_{\rm star} - \log(Z/X)_{\odot}$$

2.- $$X + Y + Z = 1$$

3.- $$\frac{\Delta Y}{\Delta Z}$$

Modelling stars

The ingredients we need

- Select EOS
- Select nuclear reactions
- Select opacity tables
- Choose stability criterion (Ledoux or Schwarzschild)
- Define the mixing-length parameter
- Select the appropriate composition
- Choose any additional mixing process

Modelling stars

Additional mixing

- Overshooting
- Microscopic diffusion
- Rotation
- Thermohaling mixing
- Semiconvection
- Radiative levitation
- etc…

Modelling stars

Additional mixing

- Overshooting
- Microscopic diffusion
- Rotation
- Thermohaling mixing
- Semiconvection
- Radiative levitation
- etc…

Modelling stars

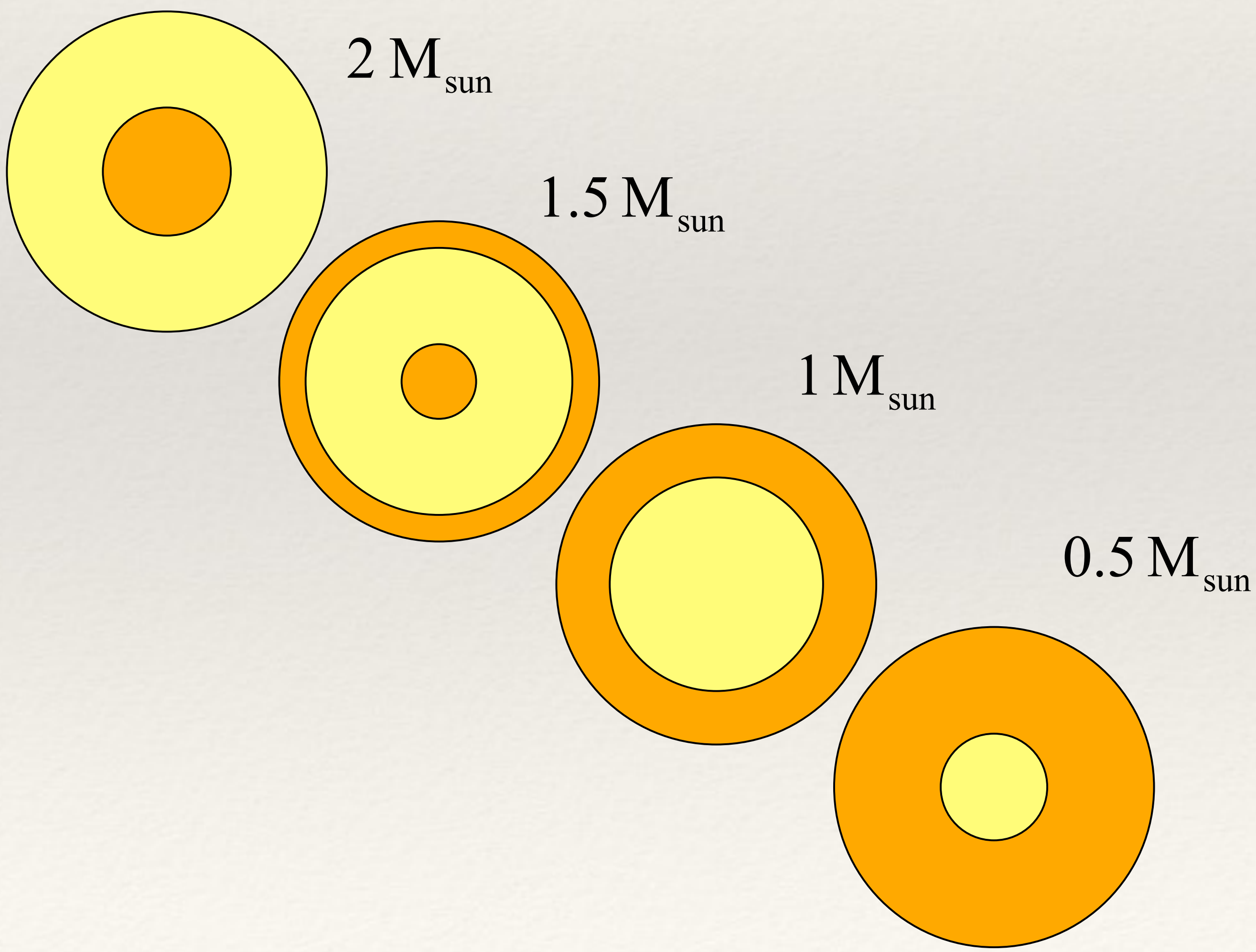
Additional mixing: overshooting

- In the mixing-length formalism, bubbles travel a characteristic distance and then dissolve
- The distance is determined in the models by the stability criterion selected (Ledoux or Schwarzschild)
- But bubbles do not reach the convective border with zero velocity —> they overshoot
- How much do they overshoot?

Modelling stars

Overshooting: yet another parameter to calibrate

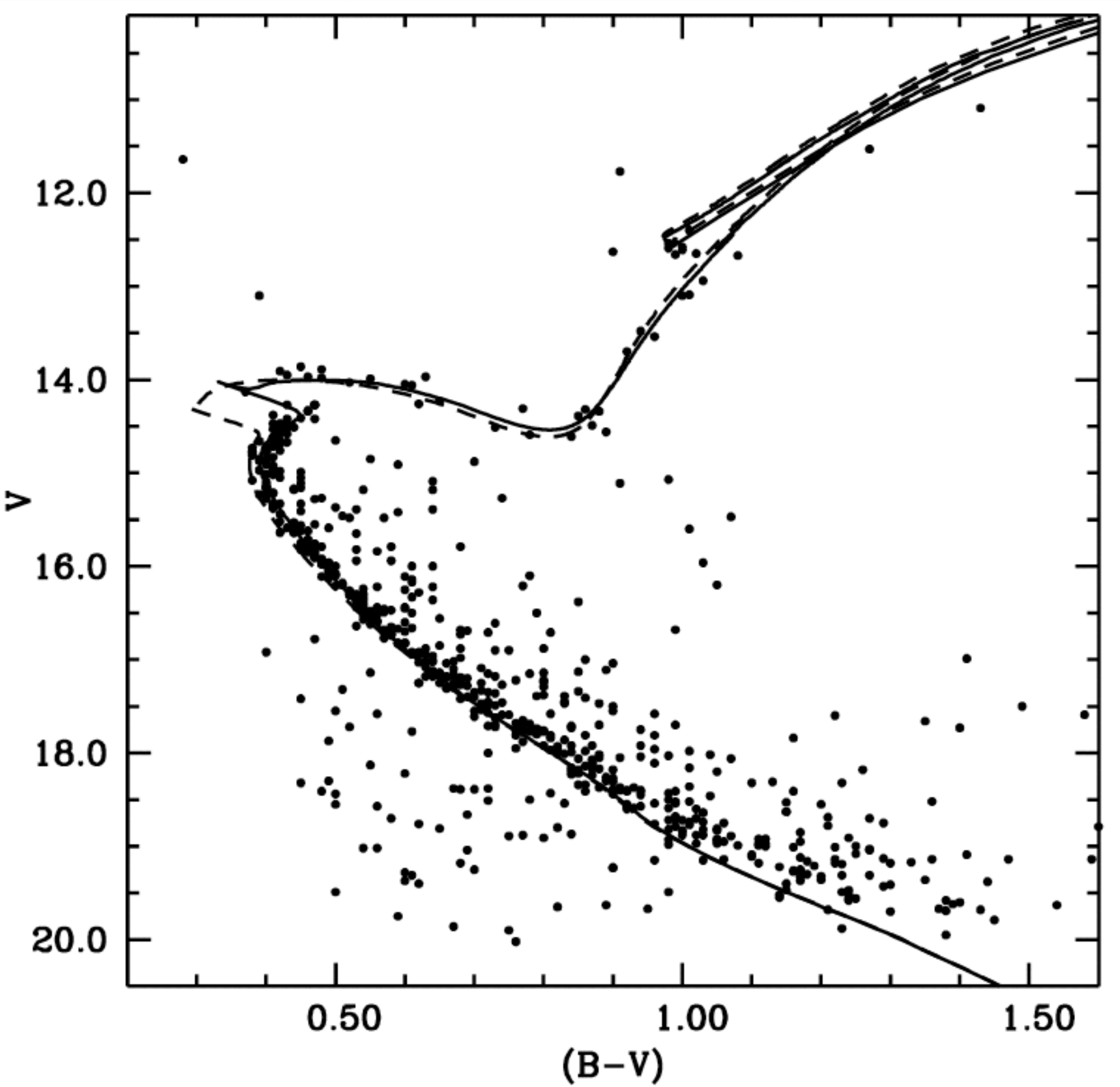
- It can happen in every convective region



Modelling stars

Overshooting: yet another parameter to calibrate

- Parametrisation: $$\mathrm{d}_{\mathrm{ov}} = \alpha_{\mathrm{ov}} H_P$$
- Increases the size of convective cores in the hydrogen-burning phase, and thus the main-sequence lifetime
- Changes the morphology of the MS turn-off
- Increase the size of He core at the MS end
- Changes luminosity of the RGB bump



12.0
14.0
16.0
18.0
20.0
V
0.50
1.00
1.50
(B−V)

Modelling stars

Additional mixing: microscopic diffusion

- Element diffusion is driven by pressure, temperature, and composition gradients
- Heavier elements sink downwards while lighter elements diffuse upwards
- Sun is used to calibrate diffusion coefficients

$$[M/H] \simeq \log(Z/X)_{\mathrm{star}} - \log(Z/X)_{\odot}$$

One minute

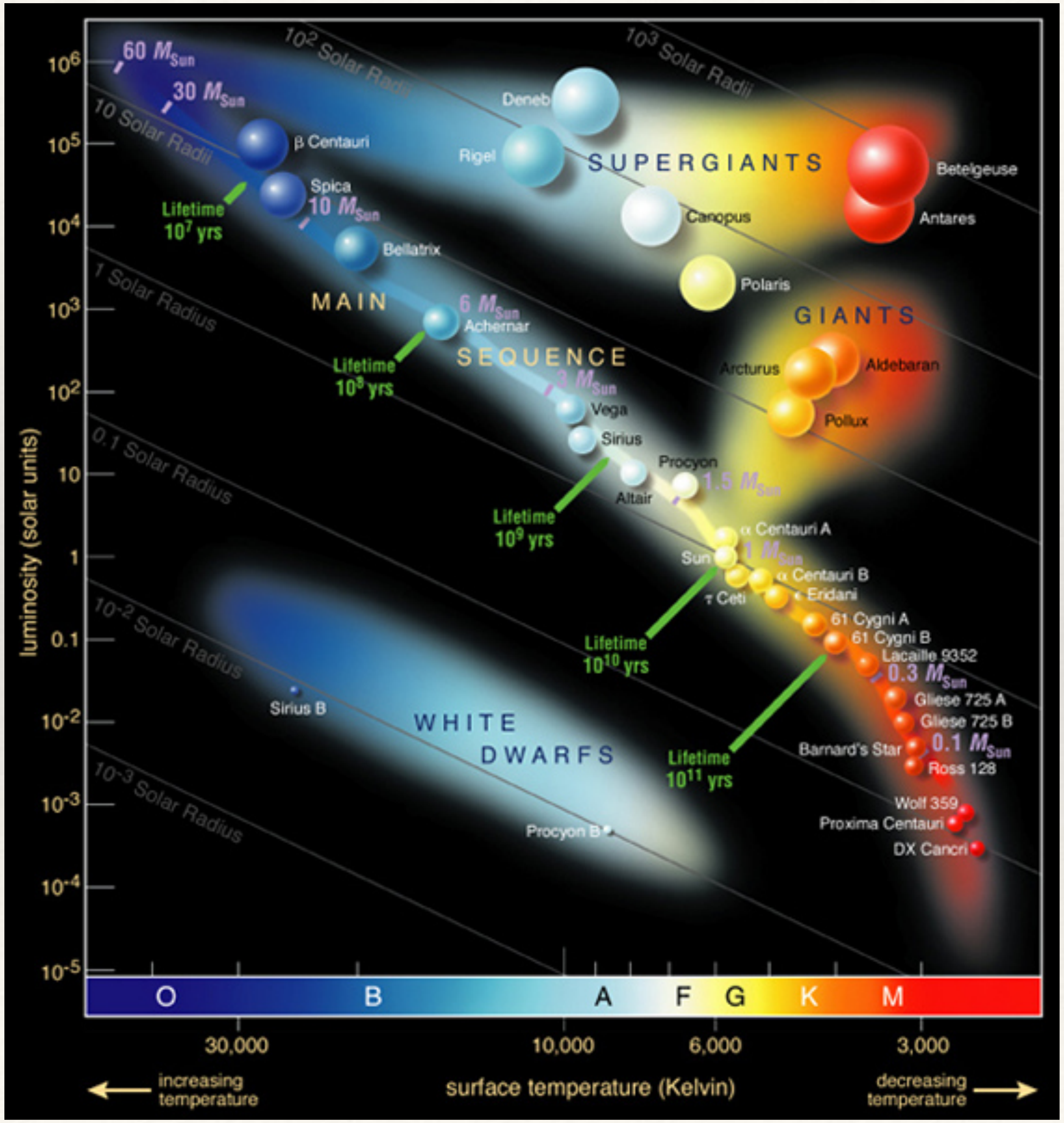
Stellar evolution

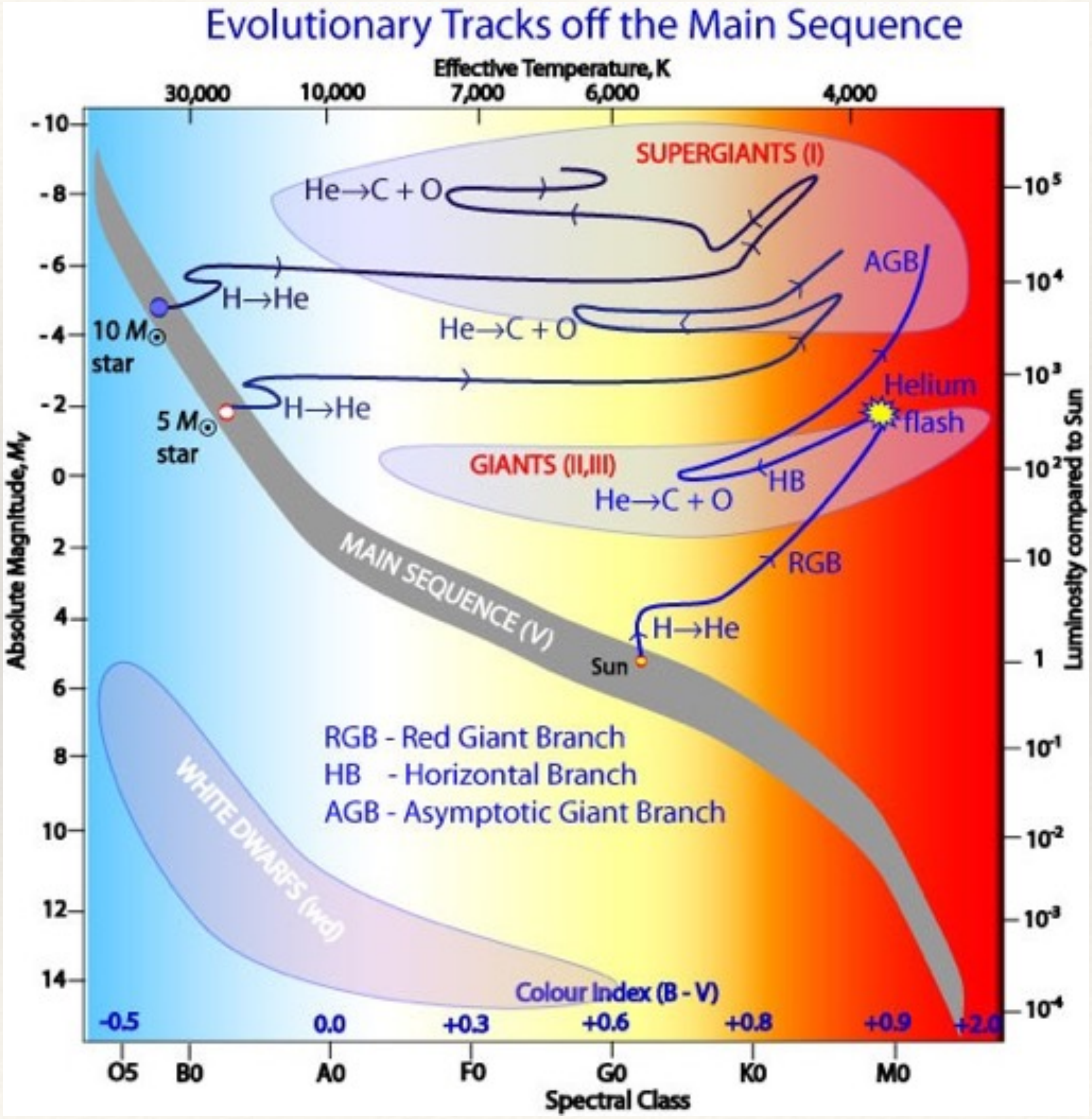
- We know they main equations
- We know the constitutive equations
- We know about mass, composition, and additional mixing processes
- With all this information, do evolutionary codes reproduce stars in the sky?

Stellar evolution

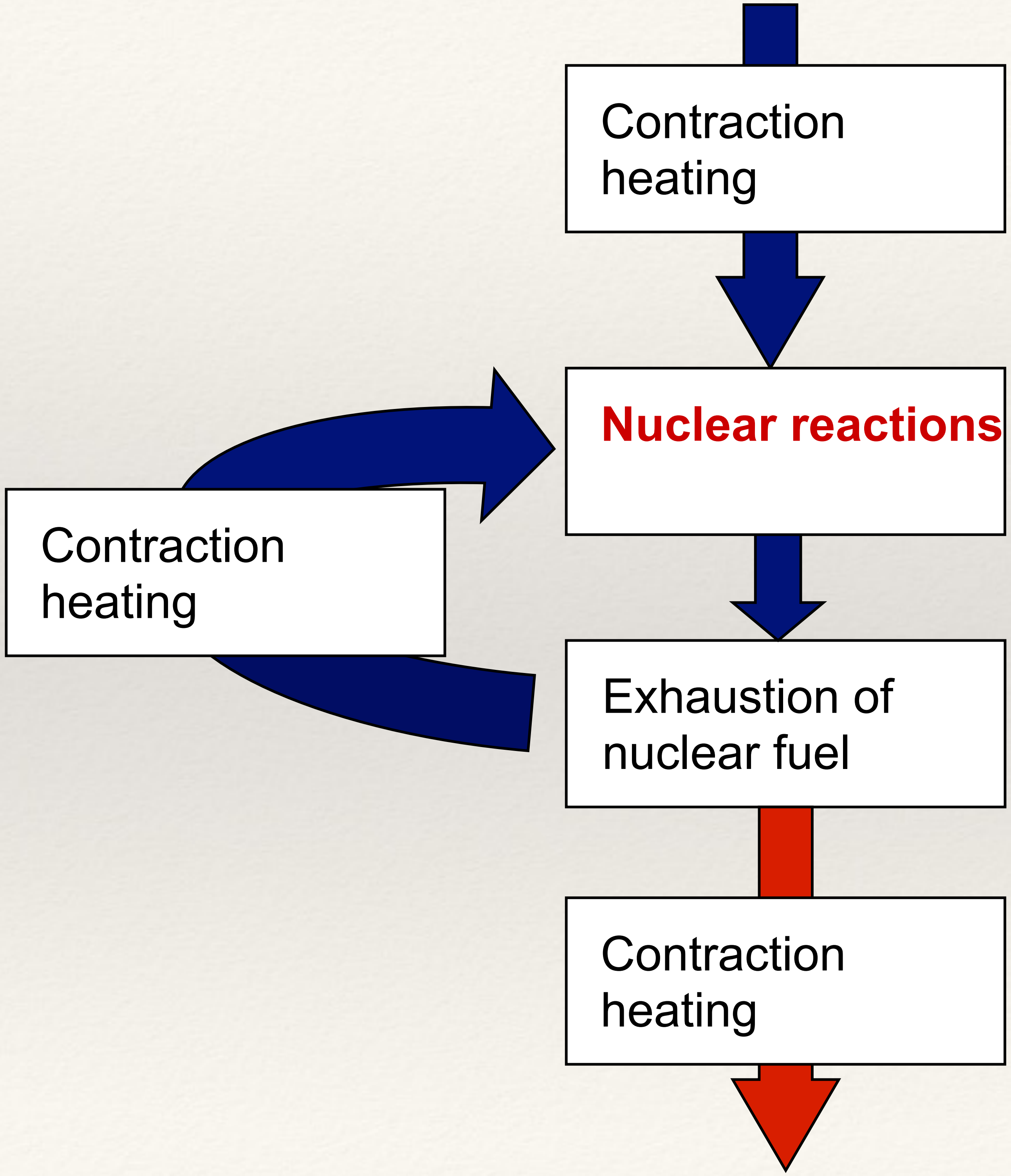
For a given mass

Stellar evolution





Stellar evolution



Stellar evolution

Contraction

- Initially a cloud of gas contracts and heats up
- Can contraction/heating occur indefinitely?
- No: since stellar matter is made of ions and electrons, the temperature required for nuclear burning is achieved or electrons become degenerate

Stellar evolution

The Hayashi track

$$\nabla = \frac{d\ln T}{d\ln P}$$

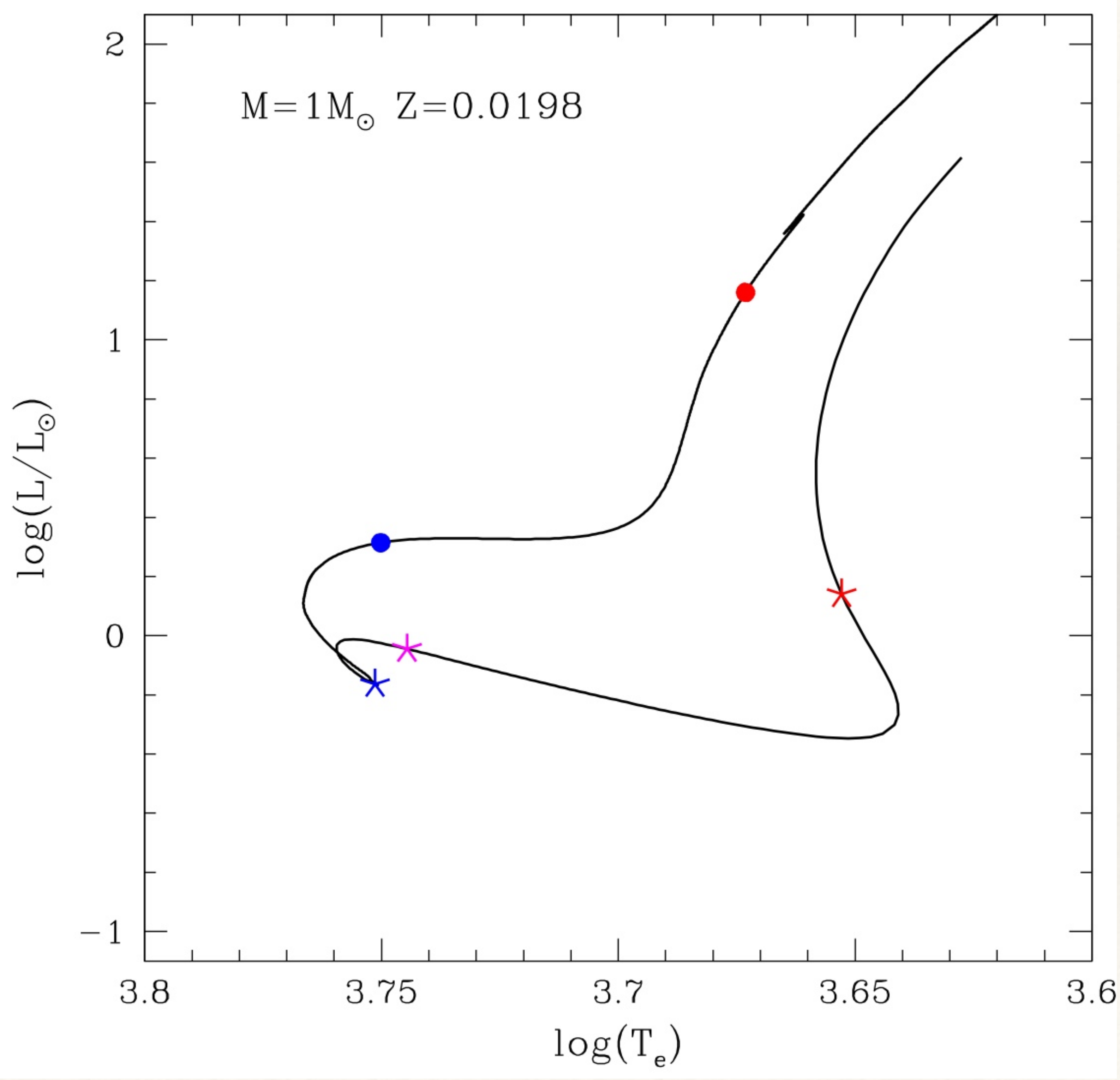
- For a given luminosity, the effective temperature decreases when nabla increases
- But the Schwarzschild criterion gives an upper limit to the temperature gradient
- And the equality holds only for fully convective structures

Stellar evolution

The Hayashi track

- For a given mass, chemical composition and luminosity there is a minimum effective temperature corresponding to a fully convective structure

Stellar evolution



Stellar evolution

The Hayashi track

- As the central temperature increases, a radiative core appears

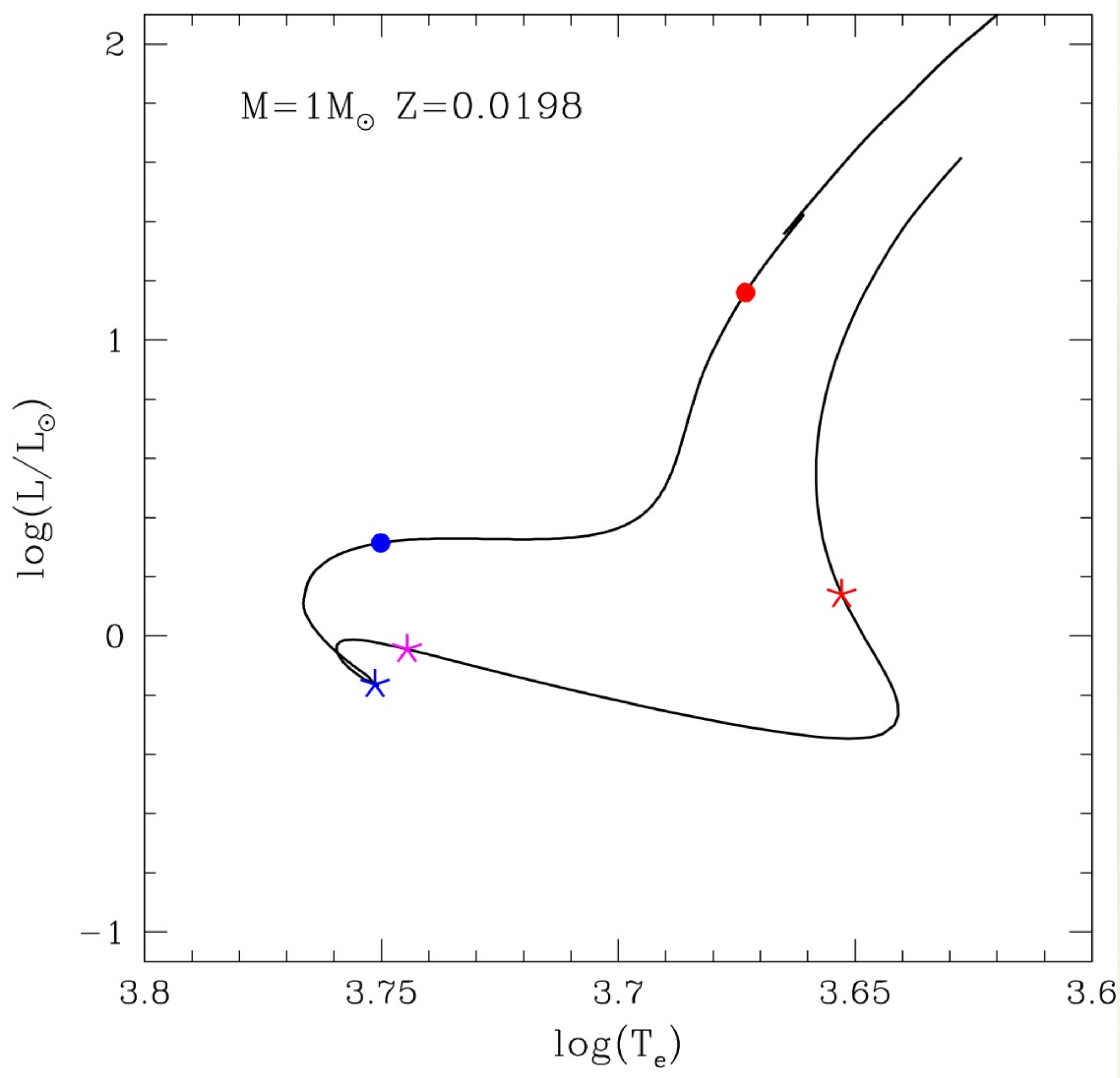
$$\nabla_{\rm rad} < \nabla_{\rm ad}$$

$$\nabla_{\rm rad} = \frac{3}{16\pi acG}\frac{\kappa LP}{mT^4}$$

Schwarzschild

- The star is no longer fully convective and departs the Hayashi track

Stellar evolution



The rightmost boundary in the evolution of a star

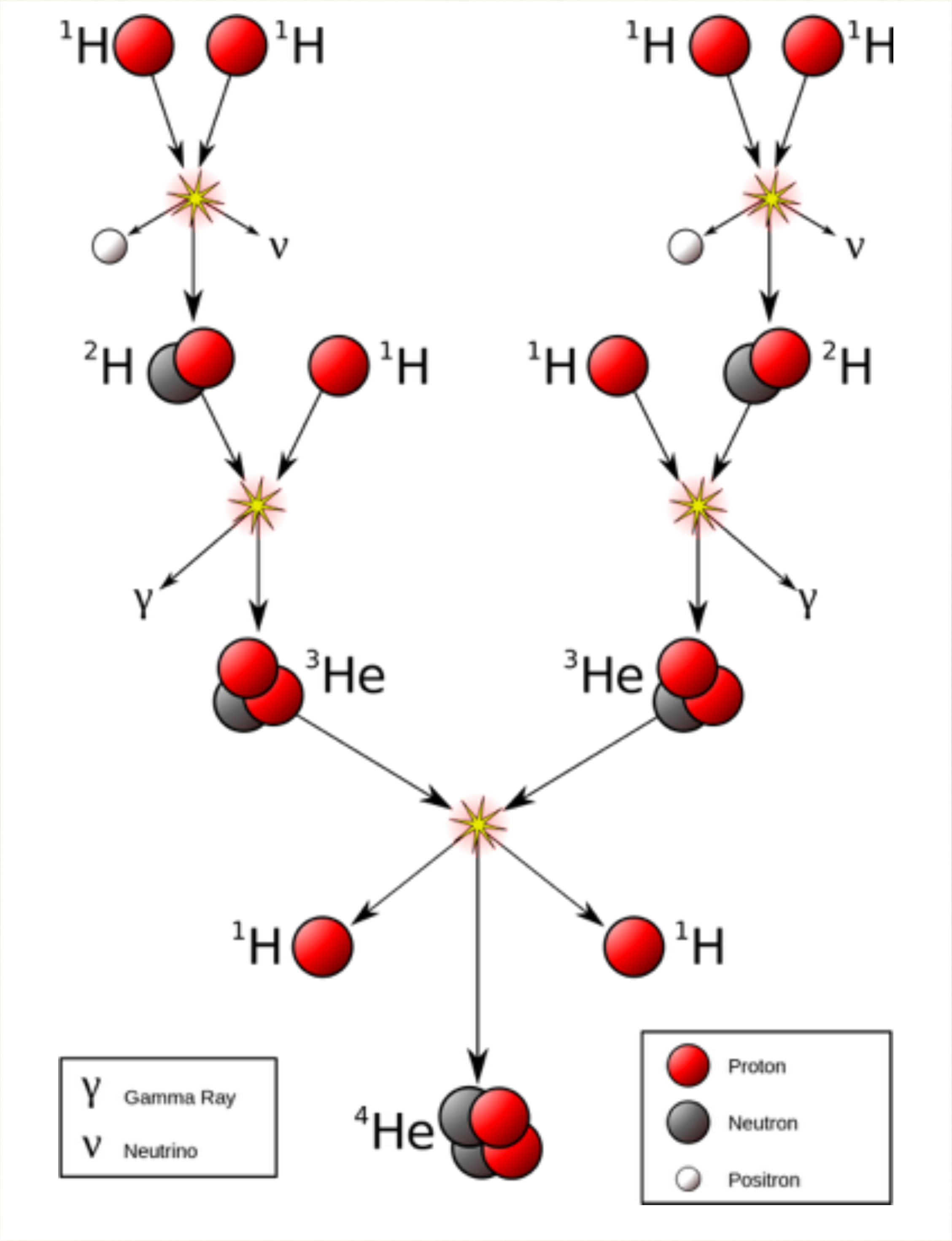
Stellar evolution

The main sequence

- Transformation of hydrogen into helium (and other species)
- Is the longest lived phase of nuclear burning in star
- Nuclear burning via the p-p chain or the CNO-cycle

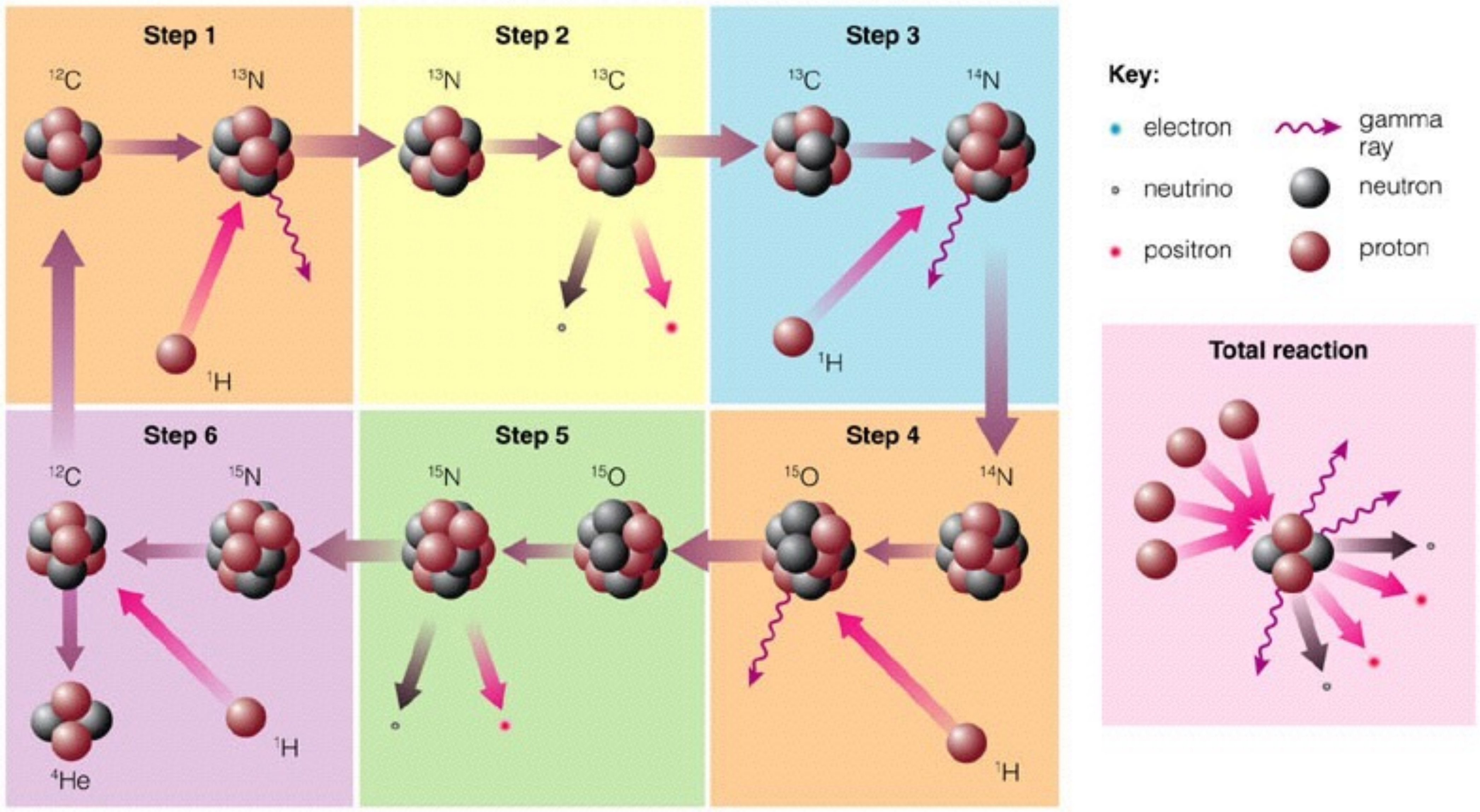
Stellar evolution

p-p chain



Stellar evolution

CNO-cycle



Stellar evolution

Constitutive equations **Nuclear reactions**

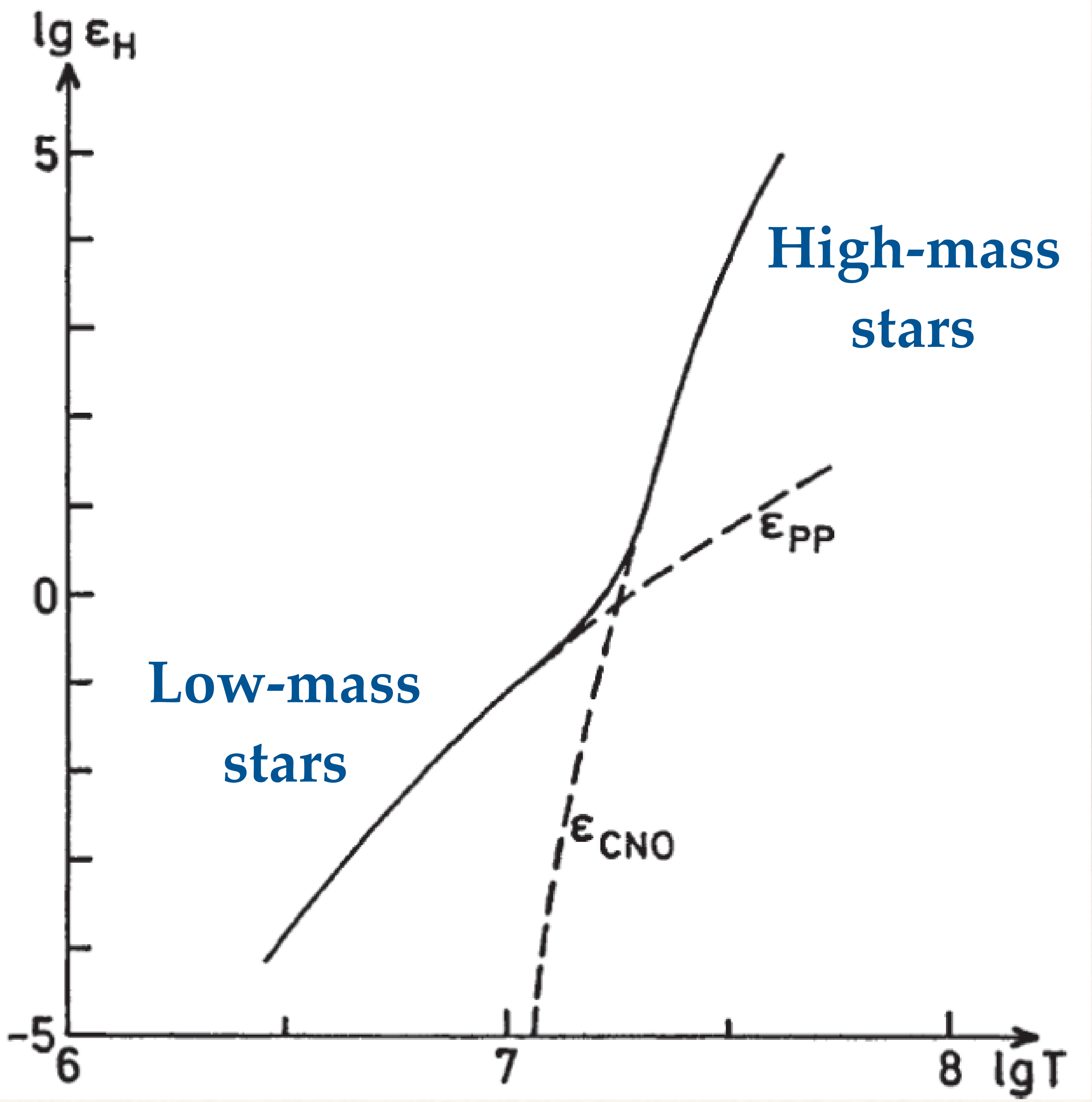
$$r_{jk} = r_{jk}(P, T, \mu)$$

$$\frac{\partial X_i}{\partial t} = \frac{m_i}{\rho} \left(\sum_j r_{ji} - \sum_k r_{ik} \right)$$

- Determined by different groups (e.g.,)

Adelberger **NACRE**

Stellar evolution

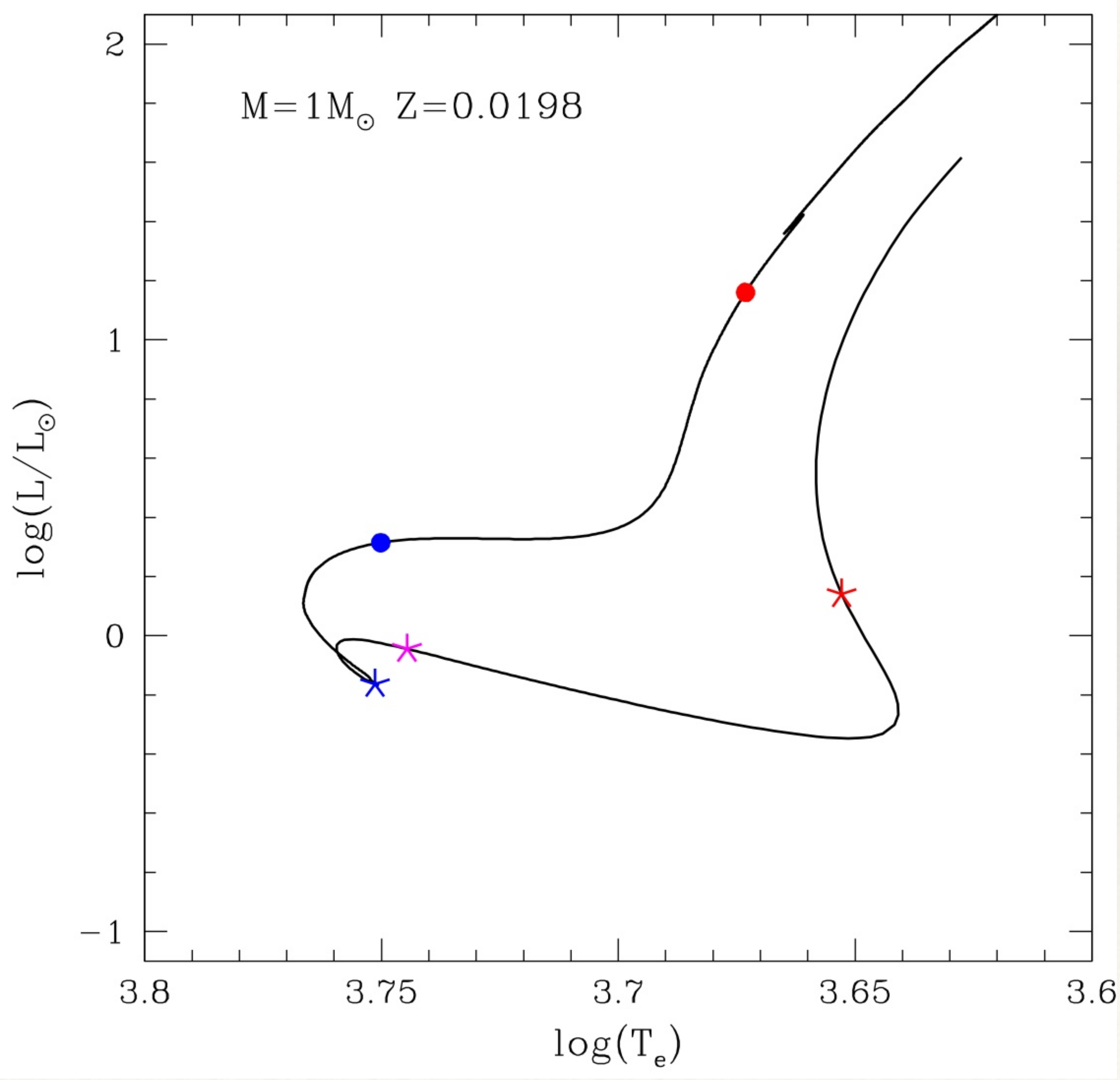


Stellar evolution

Zero-age main sequence

- Luminosity is basically governed by stellar mass and not by efficiency nuclear reactions
- Thus, for a hydrostatic evolutionary phase the star "regulates" its burning rate to enforce hydrostatic equilibrium
- This defines the ZAMS as the first main-sequence model fully supported by H-burning and secondary elements in equilibrium

Stellar evolution



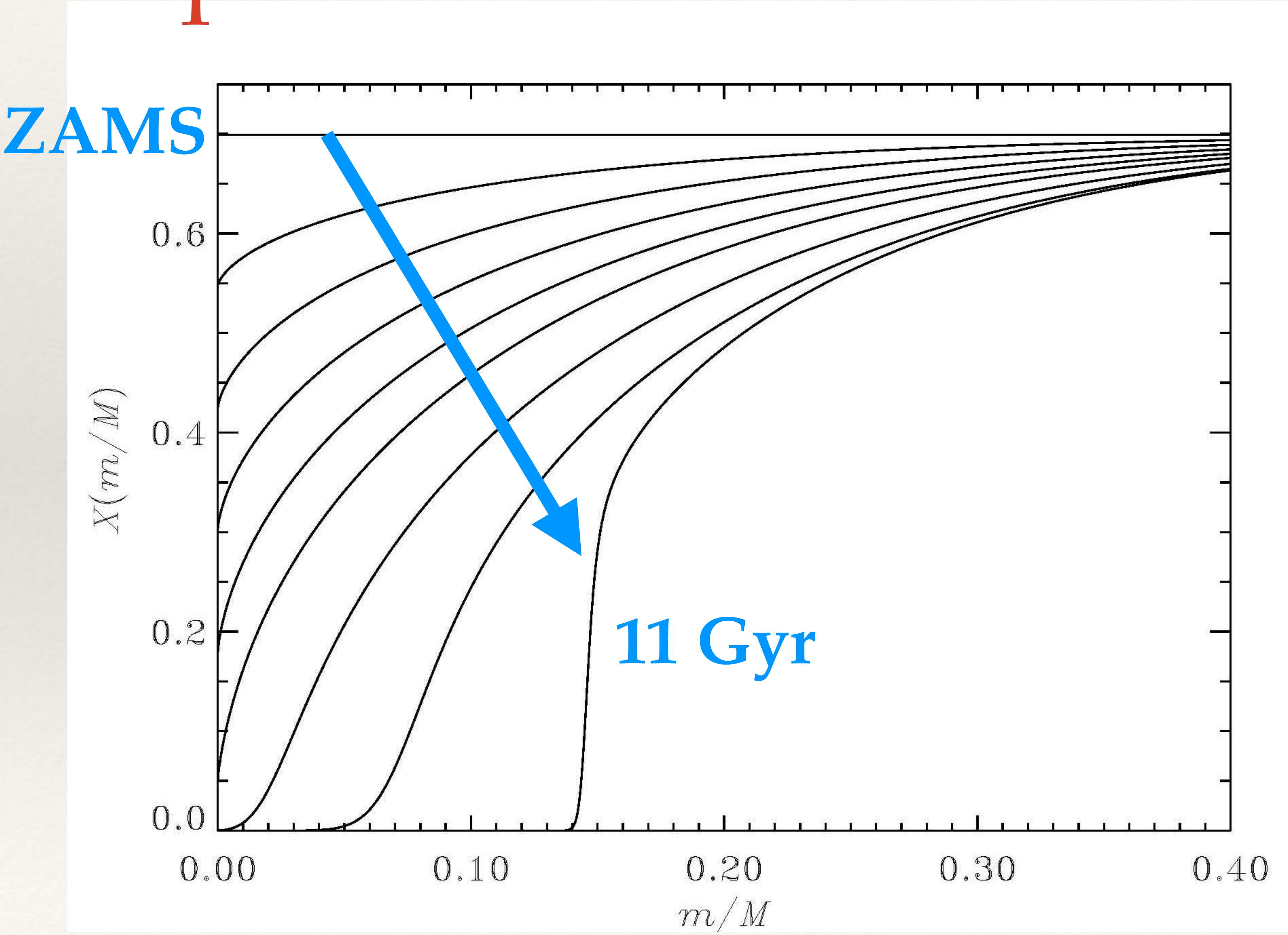
Stellar evolution

Main sequence: low-mass stars

- Stars with masses below ~1.2 $M_\odot$ burn hydrogen via the p-p chain
- Radiative interior and convective envelope

Stellar evolution

Main sequence: low-mass stars

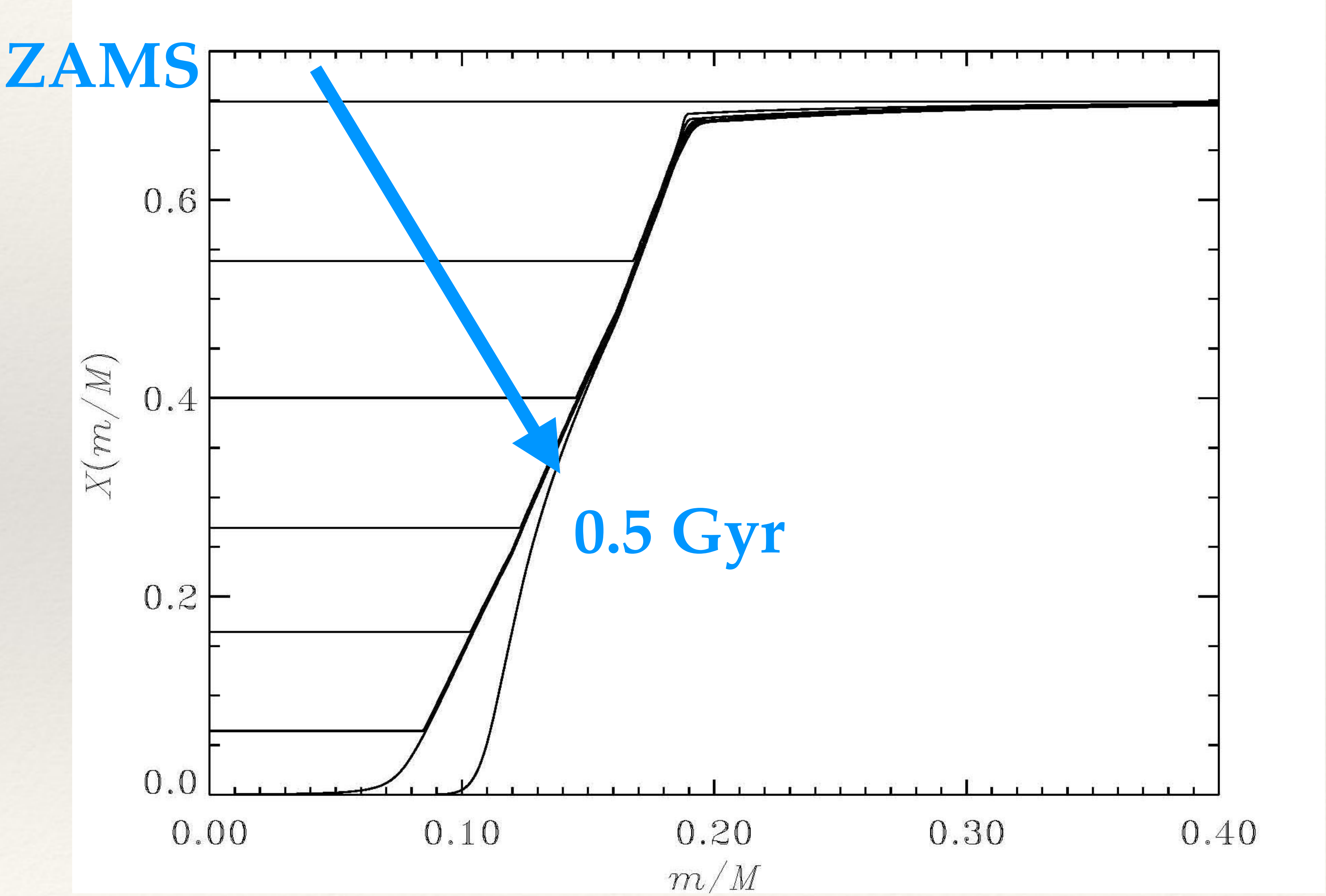


Stellar evolution

Main sequence: intermediate-mass

- Stars with masses above ~1.2 $M_\odot$ burn hydrogen via the CNO-cycle
- Convective core and radiative envelope (convective outer layer)

Stellar evolution



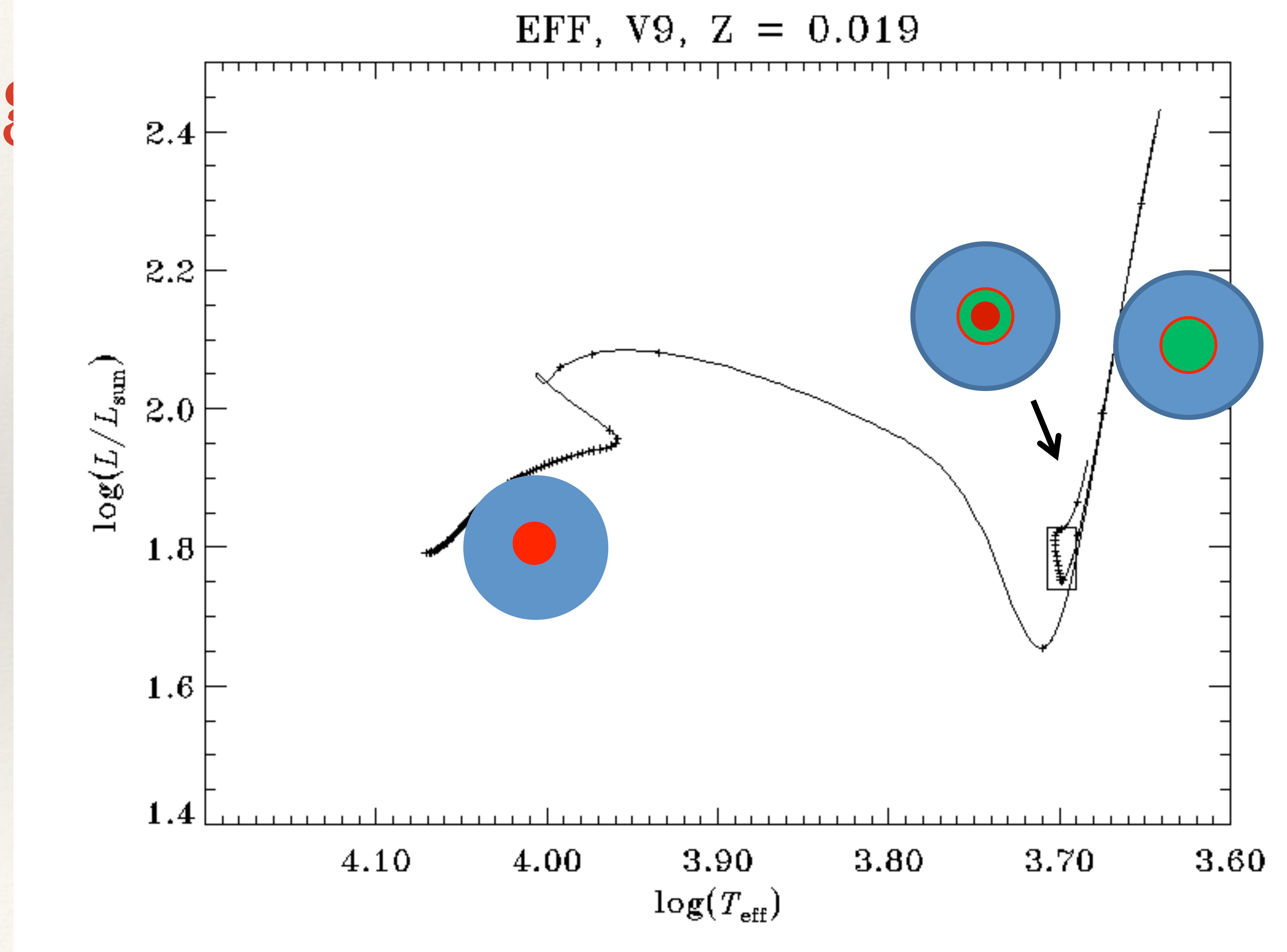
Stellar evolution

Post main-sequence evolution

- Once fuel exhaust in the centre, the core contracts while the envelope expands (dredge up)
- Nuclear burning continues in a thin shell outside the core
- Evolution is slightly different for stars below and above ~2.0 $M_\odot$

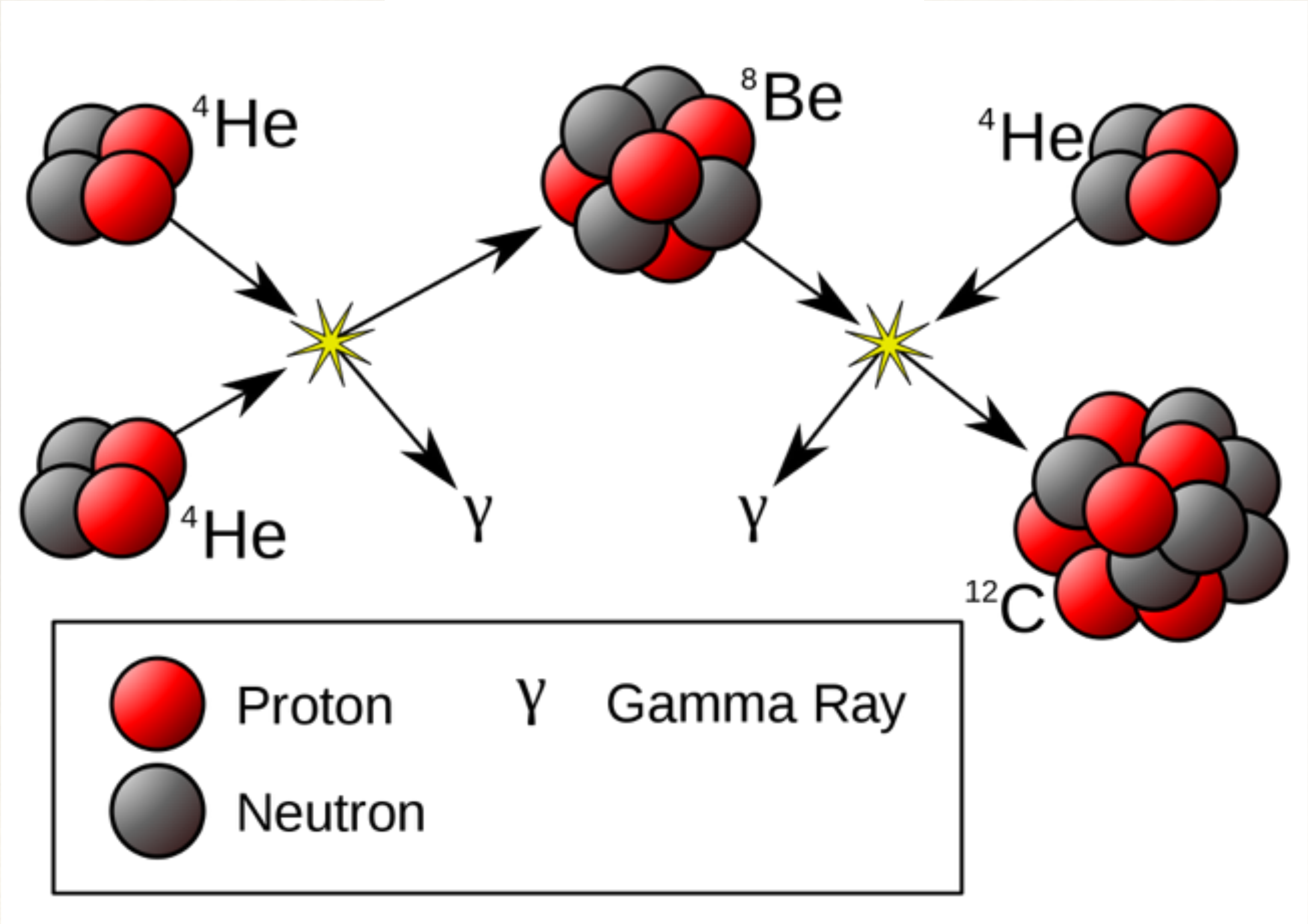
Stellar evolution

Hi



Stellar evolution

Triple-alpha reaction



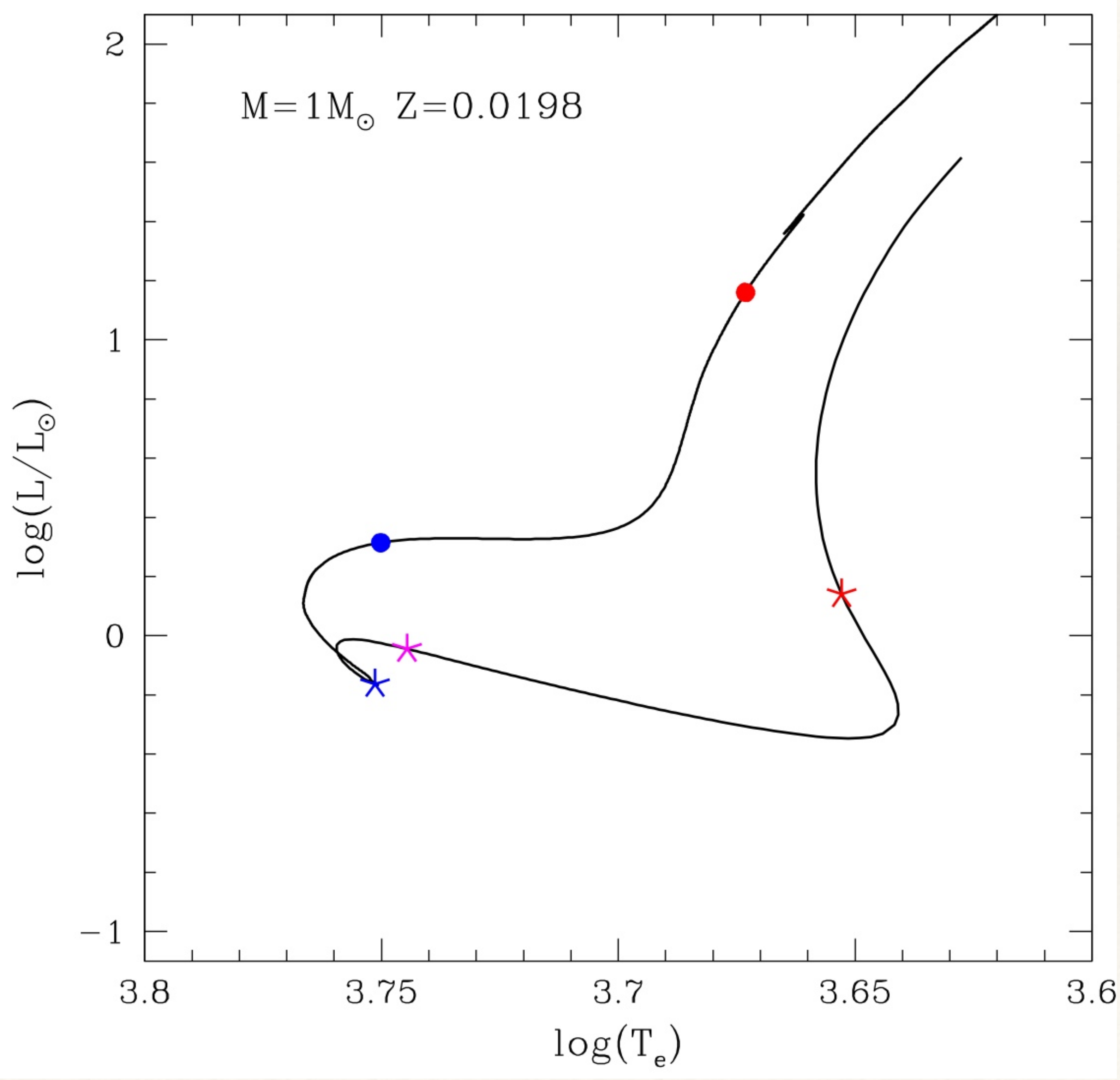
Stellar evolution

Low-mass stars

- Helium cores become electron degenerate
- Luminosity is controlled by the helium-core size (core-luminosity relation)
- They a change in luminosity known as the RGB bump
- Helium ignition is degenerate in a runaway process: the helium flash

Stellar evolution

Low-m



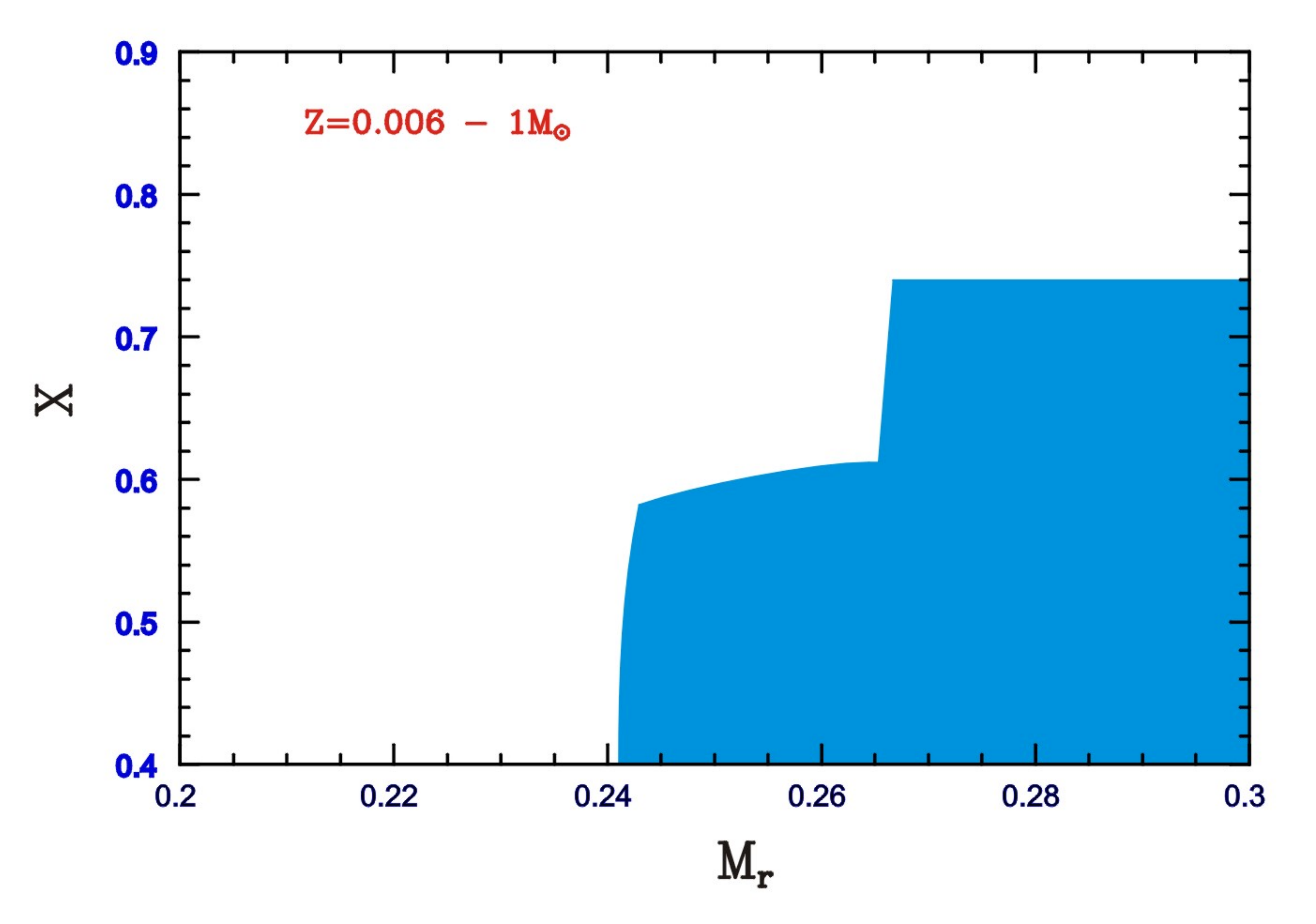
Stellar evolution

Low-mass stars: first dredge up

- Convective envelope penetrates to the interior
- Chemical profile changes
- Surface abundances change

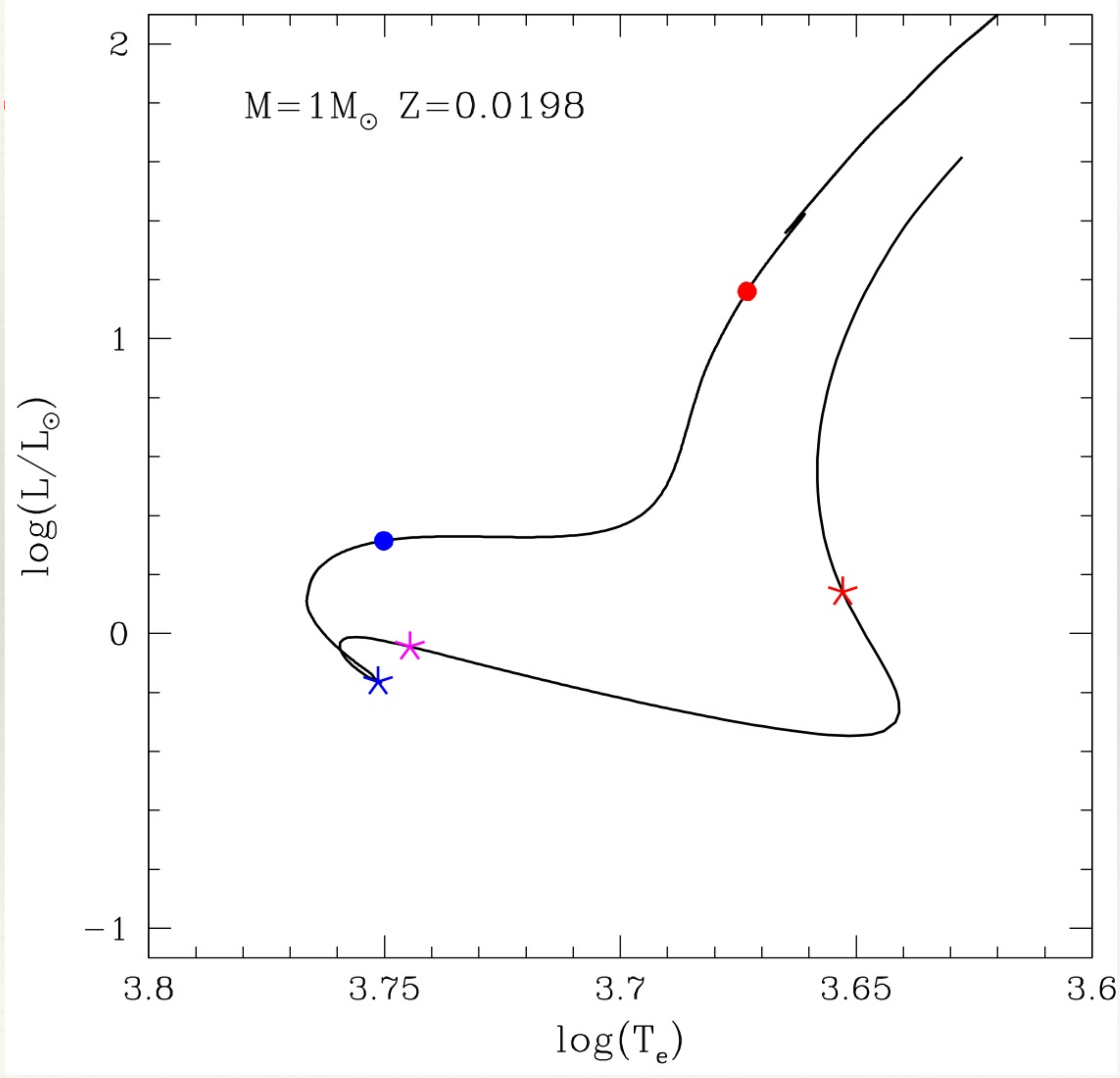
Stellar evolution

Low-mass stars: first dredge up



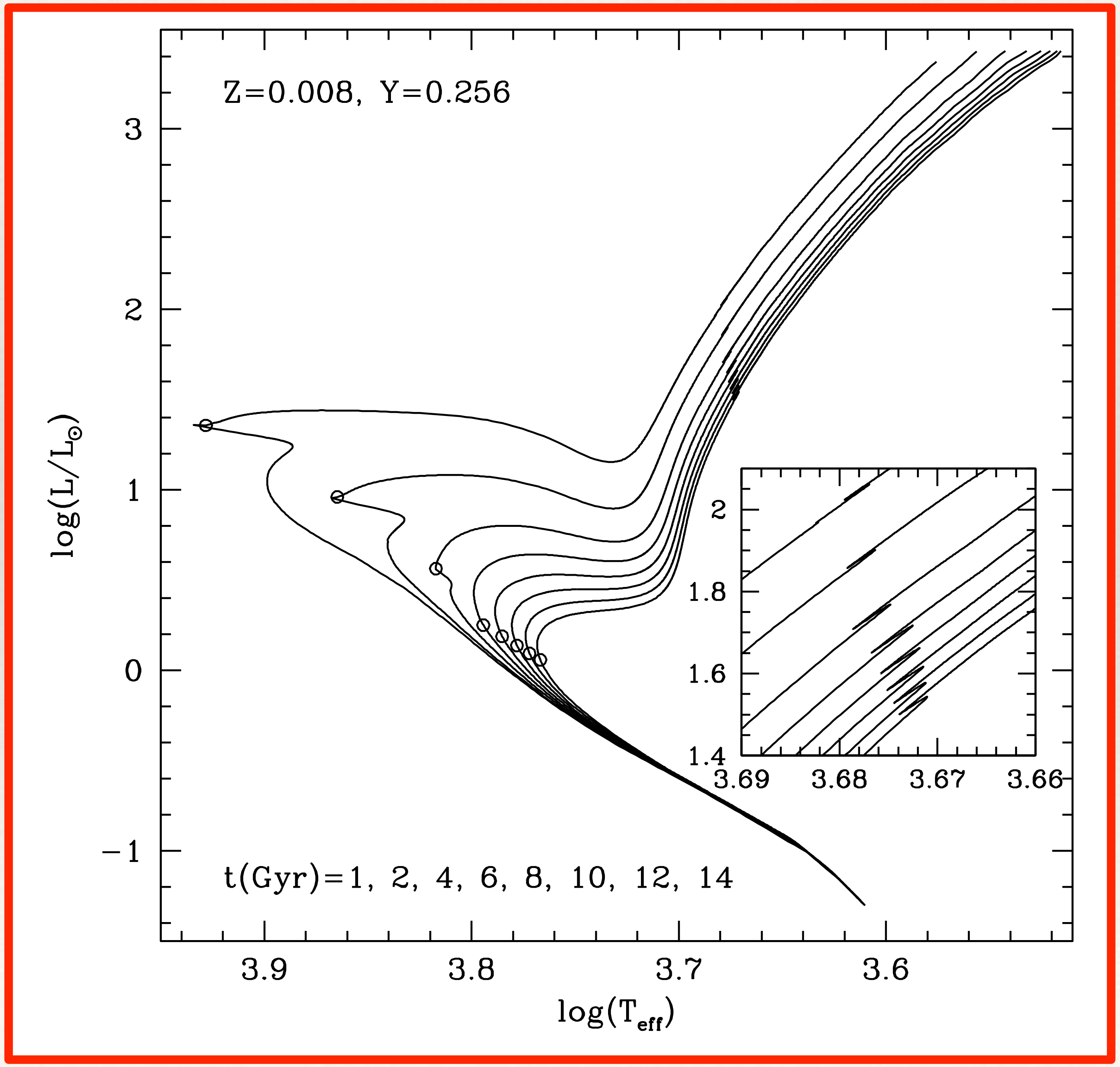
Stellar evolution

Low-m



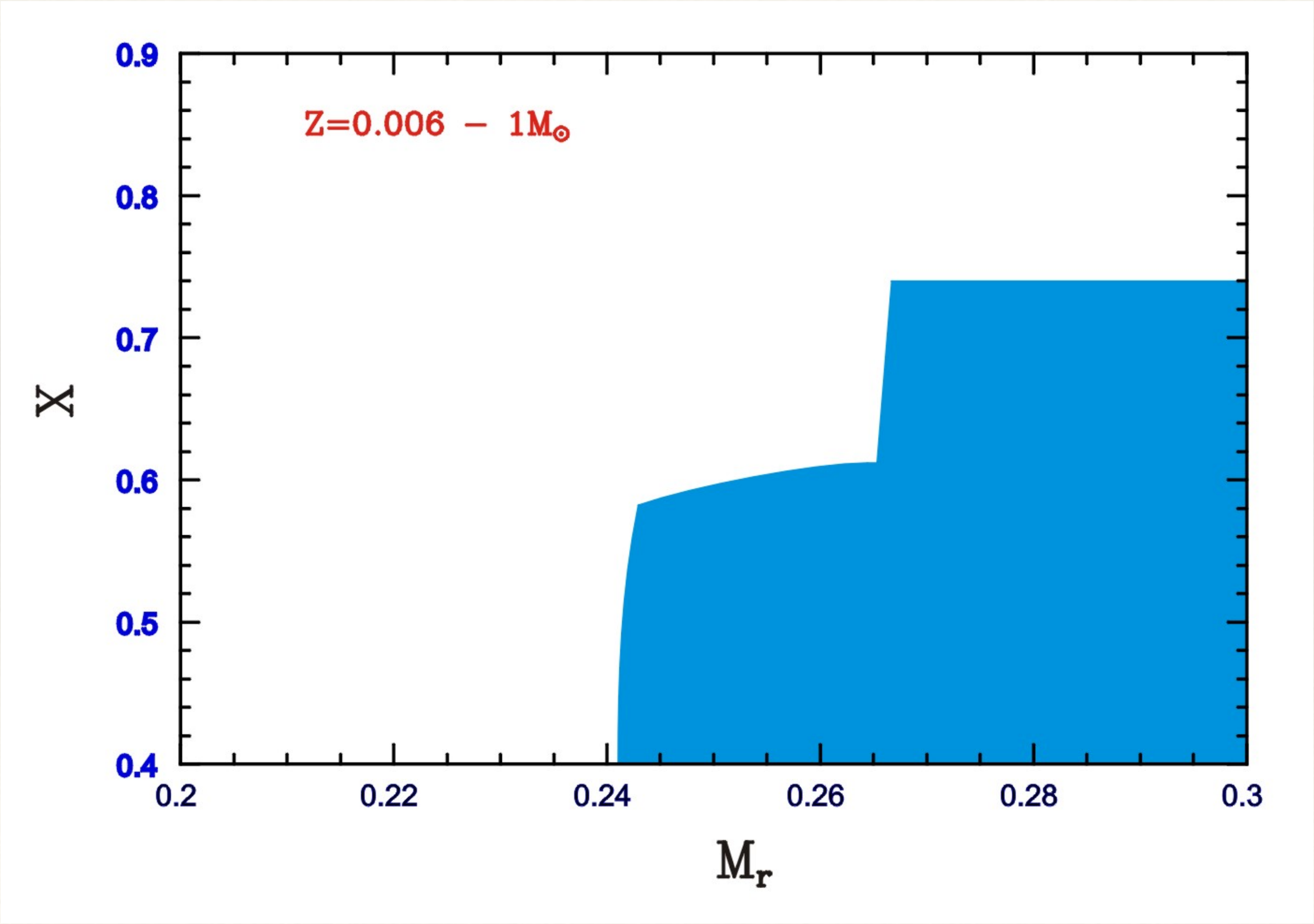
Stellar evolution

Low-mass stars: RGB bump



Stellar evolution

Low-mass stars: RGB bump



Stellar evolution

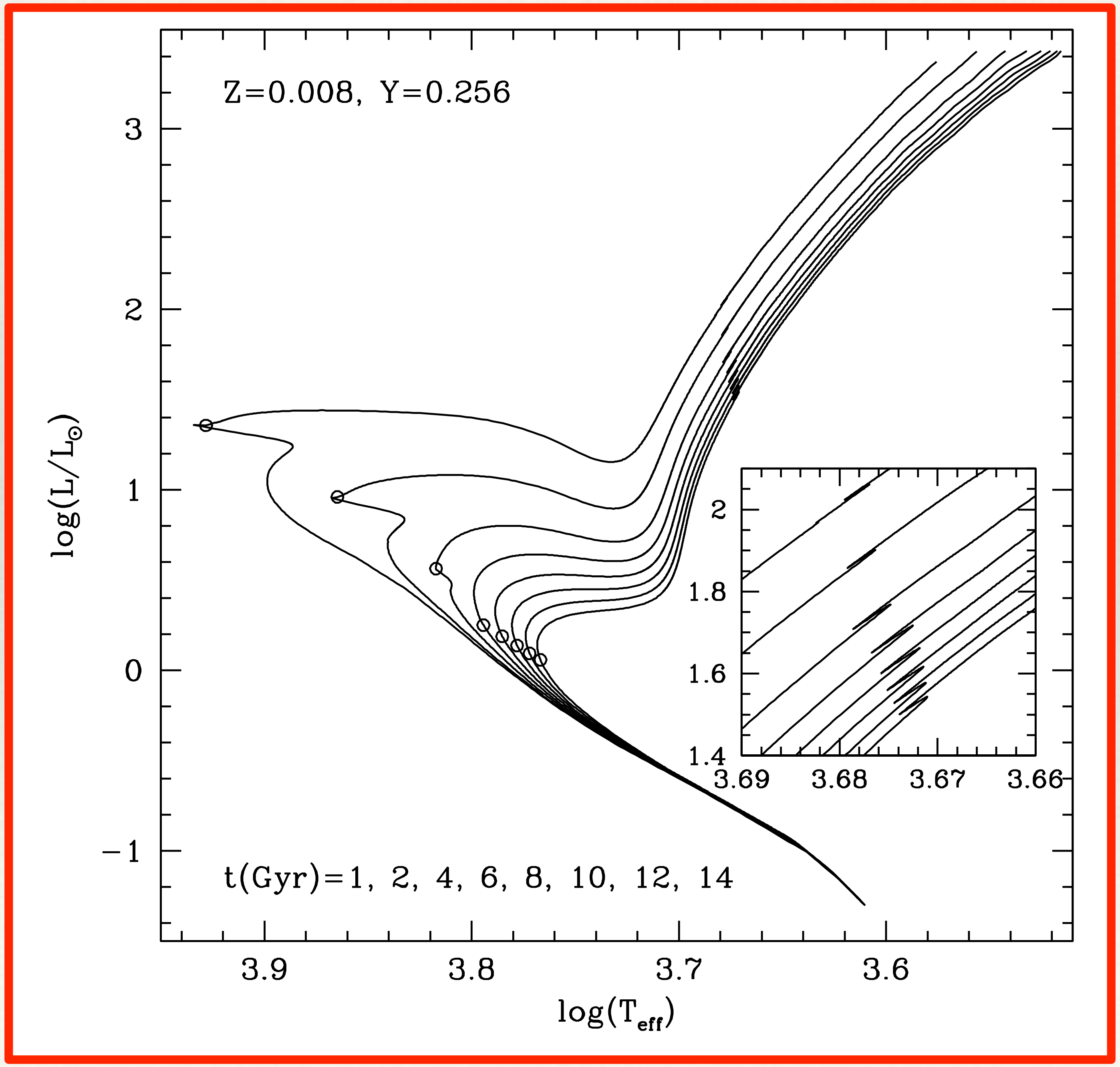
Question:

What causes the luminosity drop during the RGB bump?

- Think about it (45 secs)
- Discuss it with your neighbour (2 mins)

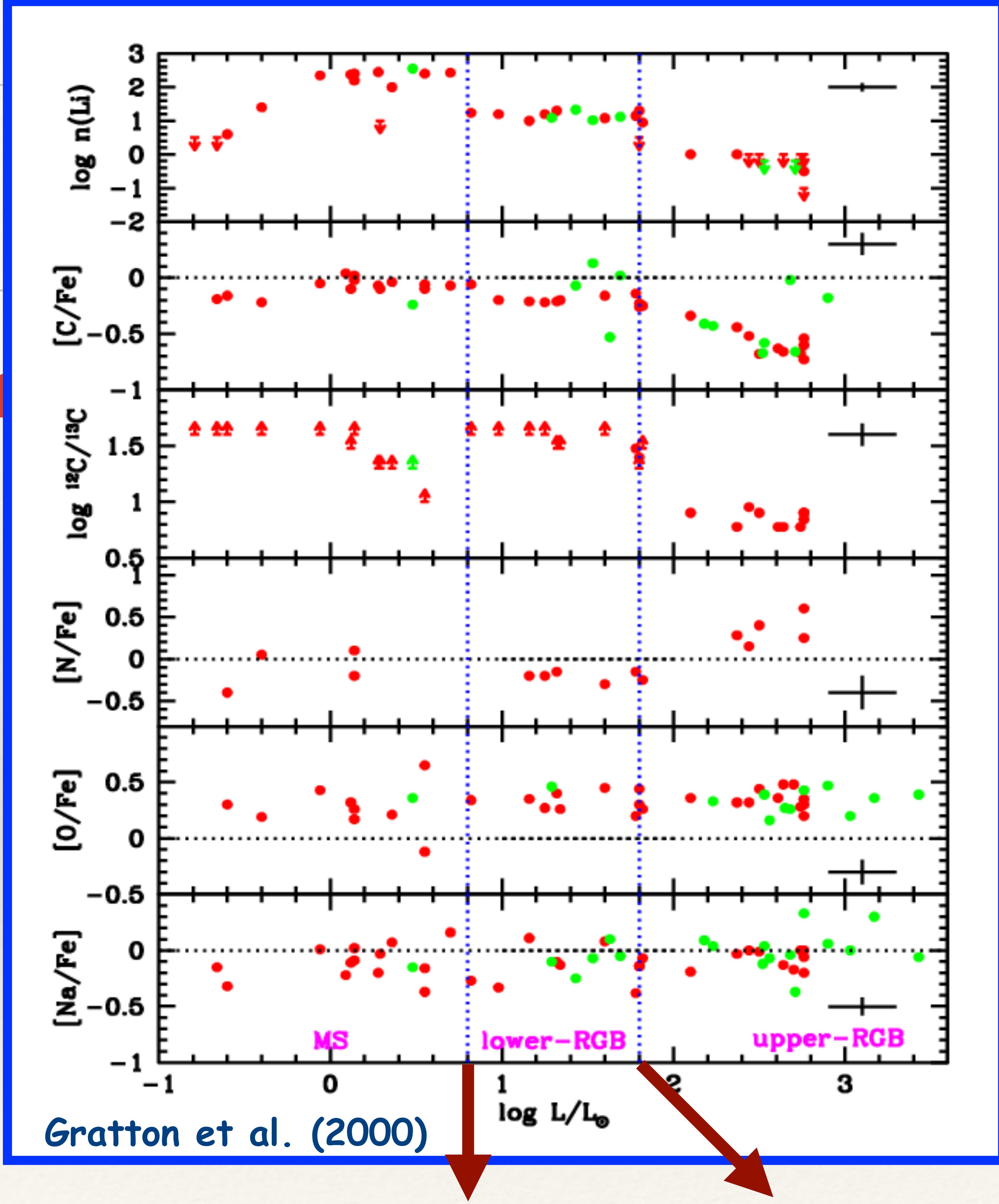
Stellar evolution

Low-mass stars: RGB bump



$$L \propto \mu^{7.5}$$

Low-



1st dredge up **RGB bump**

Stellar evolution

Low-mass stars: the helium flash

- Consider nuclear reactions under non-degenerate conditions:

$$\rho = \rho(P, T, \mu)$$

EOS

- If T increases, P increases, the gas expands, material cools down and therefore the nuclear rate does not increase

- Self-regulating process or quiescent burning

Stellar evolution

Low-mass stars: the helium flash

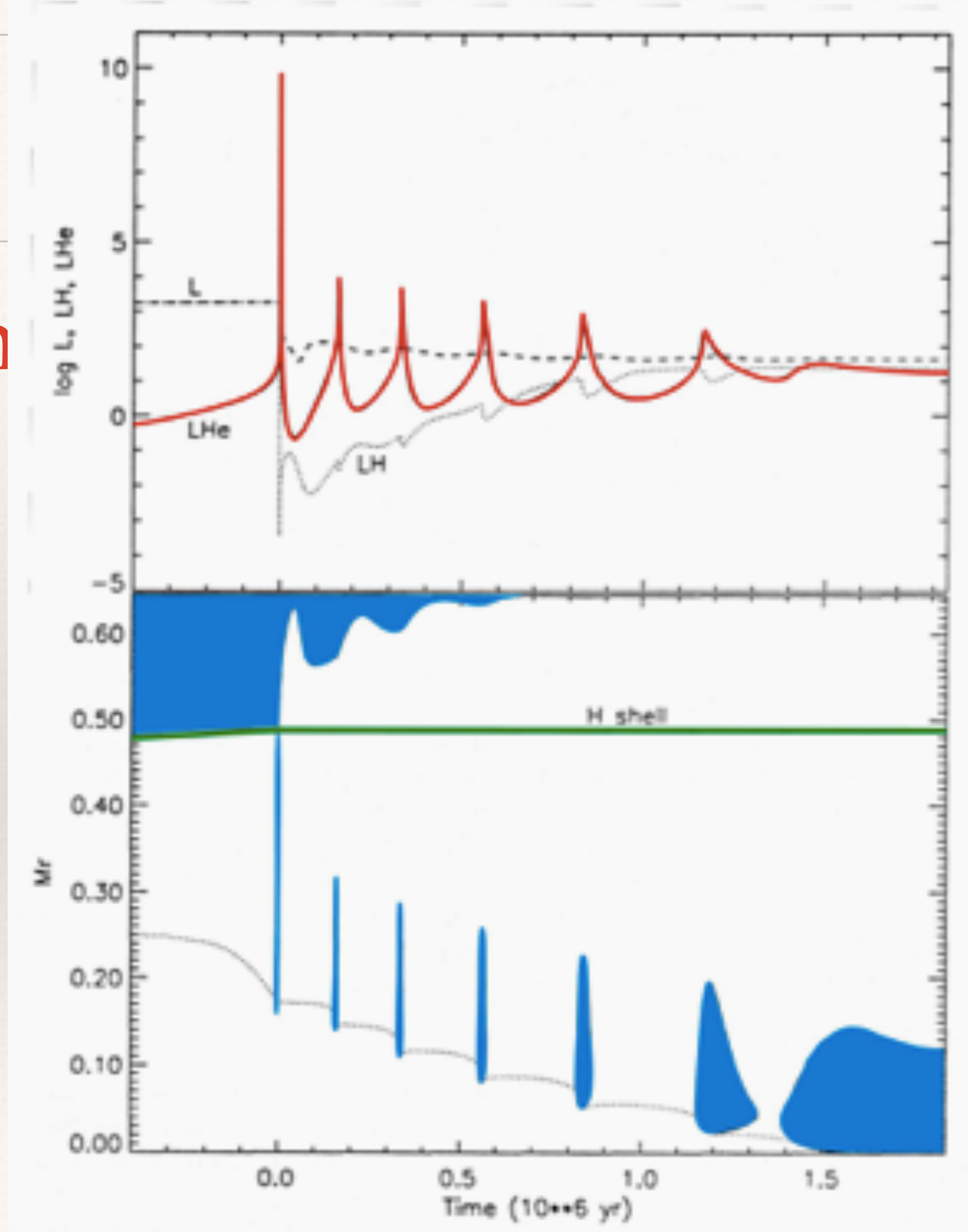
- Now under degenerate conditions

$$\rho = \rho(P, \cancel{T}, \mu)$$

EOS

- If T increases, P does not and the region cannot expand and cool down
- This leads to an increase in the reaction rates
- And this leads to a further T increase….. ????

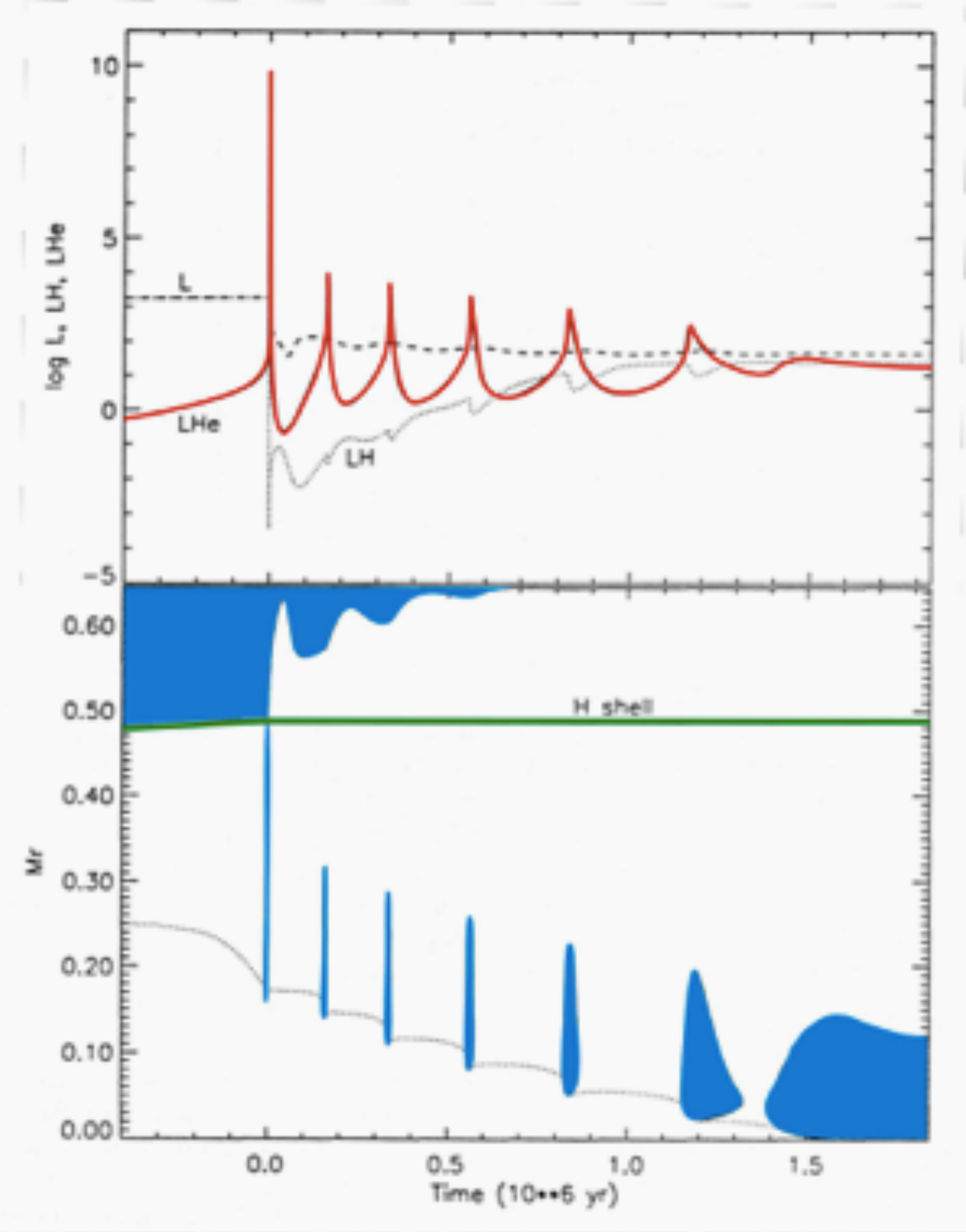
Low-n ash



log L, LH, LHe
10
5
0
−5
L
LHe
LH
Mr
0.60
0.50
0.40
0.30
0.20
0.10
0.00
H shell
0.0
0.5
1.0
1.5
Time (10**6 yr)

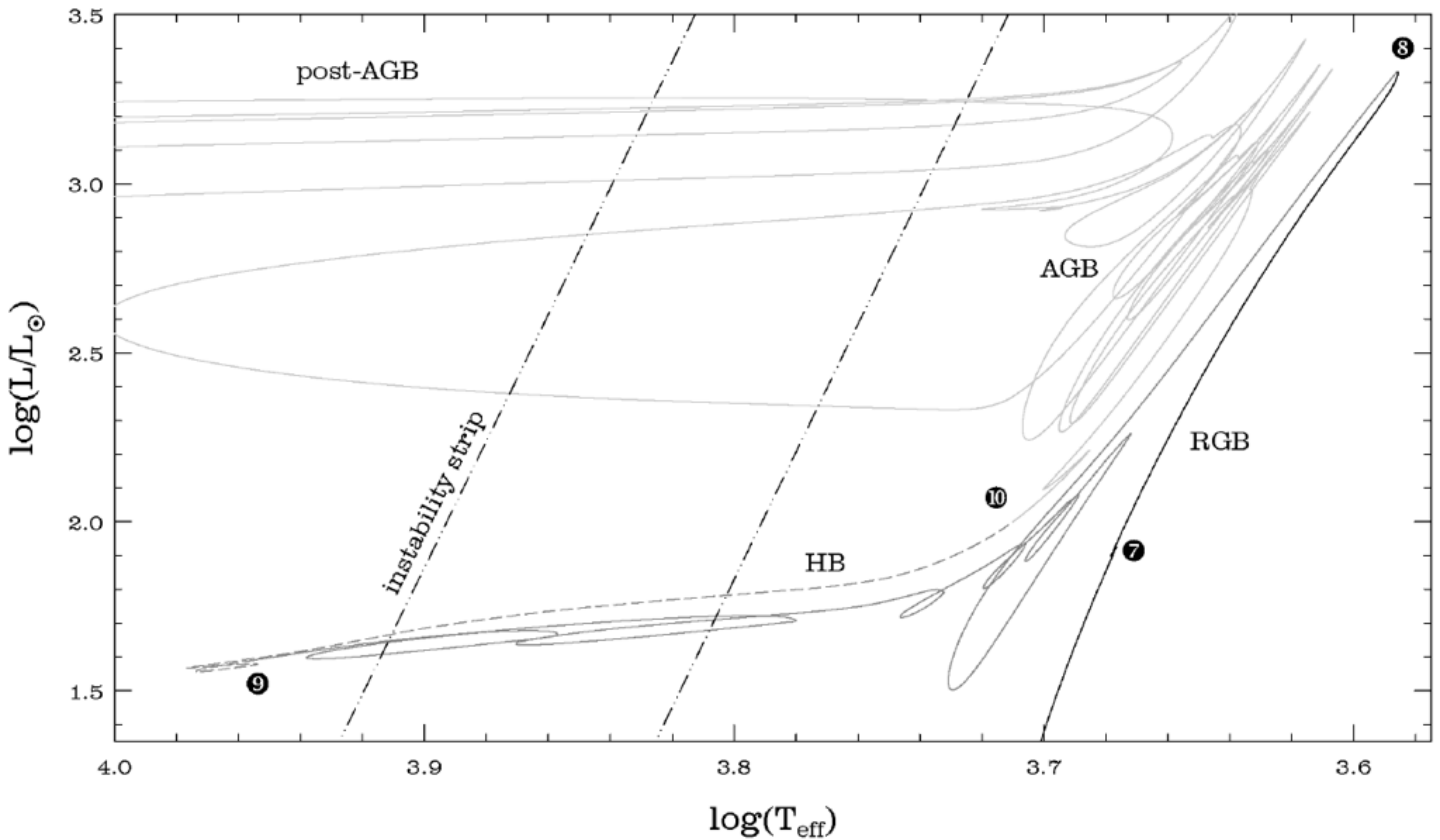
Stellar evolution

Low-mass stars: the helium flash



- Off-centre ignition (neutrino losses)
- Most energy used to lift degeneracy
- Secondary flashes
- Convective core and He-burning phase starts

Stellar evolution



Stellar evolution

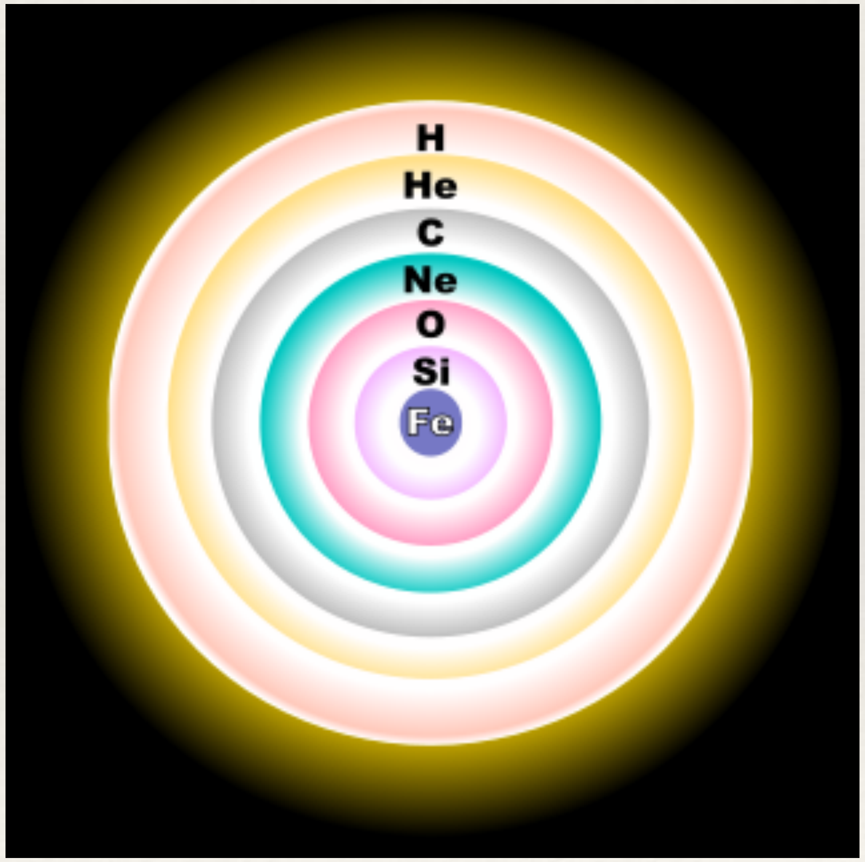
What is next?

- For stars of $0.08M_\odot < M_{ini} < 8M_\odot$: no more burning beyond helium
- Dredge-up events transport material to the surface
- Neutron capture produce new elements via s-process
- Return to ISM via thermal pulses, winds, planetary nebulae phase
- Final stage: white dwarf

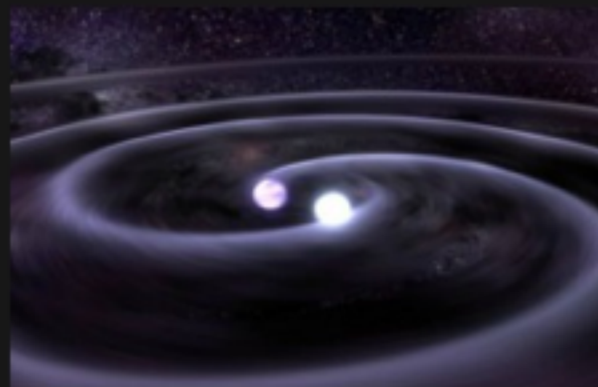
Stellar evolution

What is next?

- For stars of $M_{ini}>8M_{\odot}$: carbon and silicon burning
- "Onion-skin" structure in the interior
- New elements produced via r-process
- Return to ISM in supernova explosion



TYPE I SUPERNOVAE:

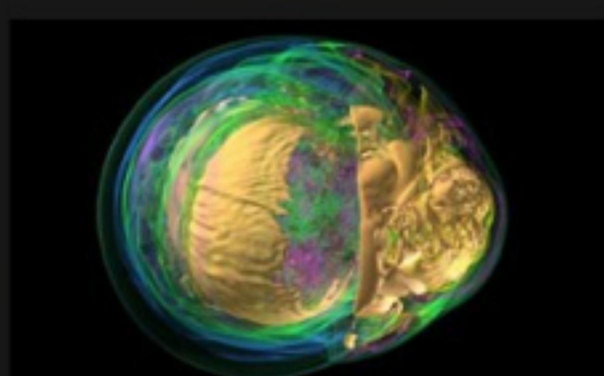


This type of nova takes place in binary star systems, with one of the stars classified as a white dwarf.

The dwarf accretes material from its larger counterpart, accumulating mass as a result. This eventually incites a chain nuclear reaction..

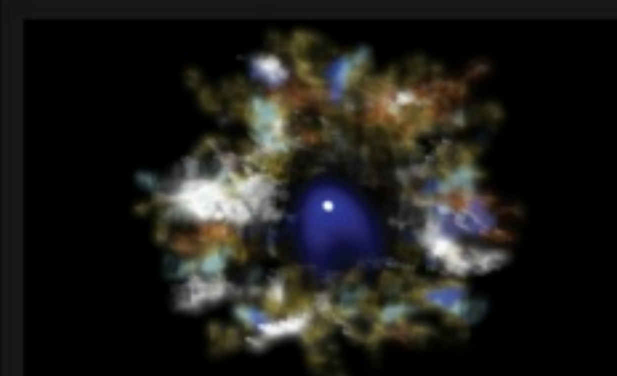
culminating in the star reaching critical density, when it explodes in a supernova. Beams of gamma radiation can also be emitted.

TYPE II SUPERNOVAE:



After losing the abilty to stably fuse heavy elements, the star can no longer retain a gravitational equilibrium, thus the core collapses in on itself.

The core rebounds in quick succession, subsequently releasing the outerlayers of gas off into space — forming a nebula.



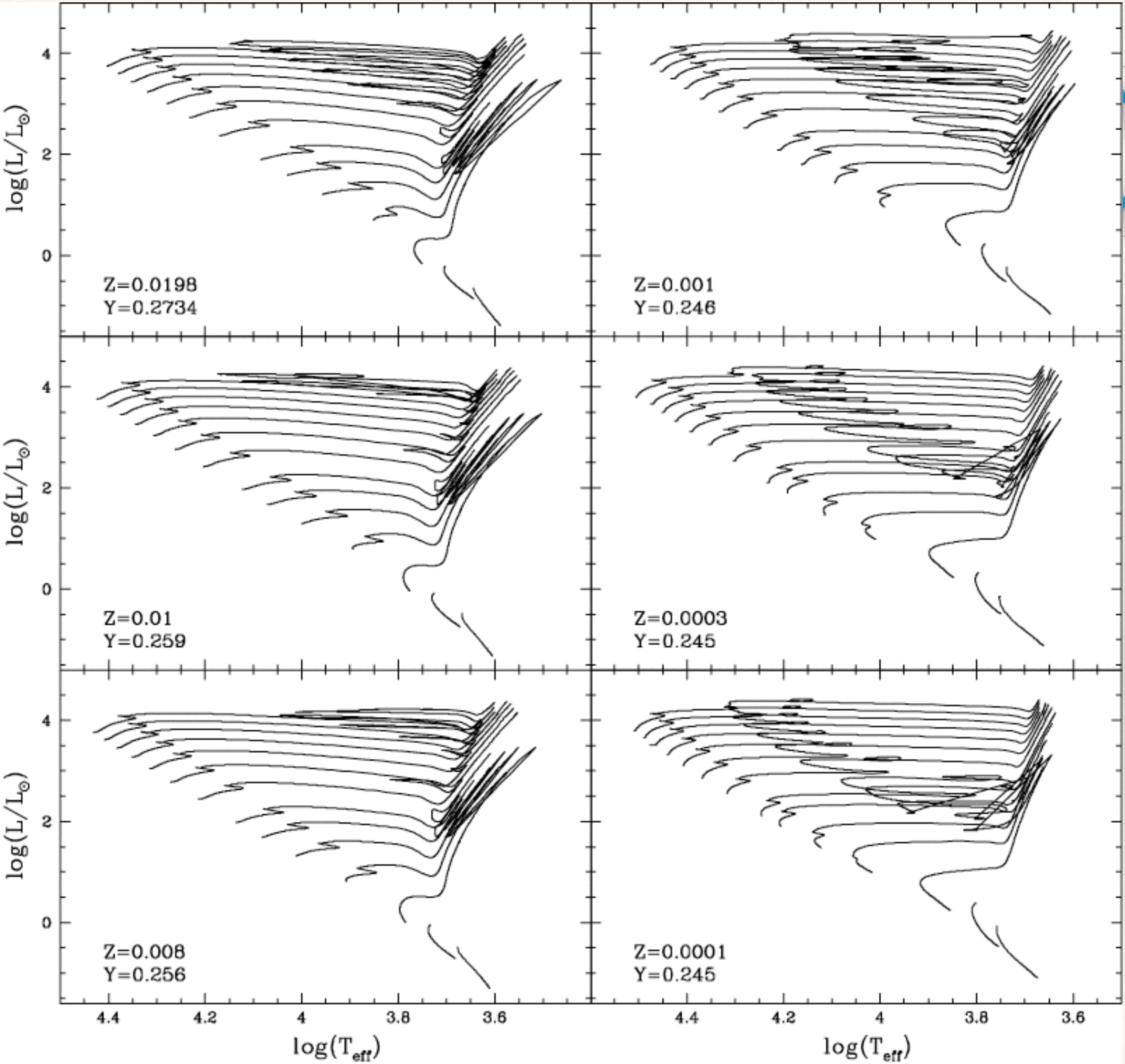
After the dust settles, a neutron star or black hole is left behind (which one will hinge on the star's mass)

One minute

Tracks and isochrones

Some tips

- Several large collections available
- Computed with different codes, input physics, and assumptions
- They vary on the predicted properties available, select carefully based on what you need
- Vary in the tests they have done of their results
- My advise: build your own!



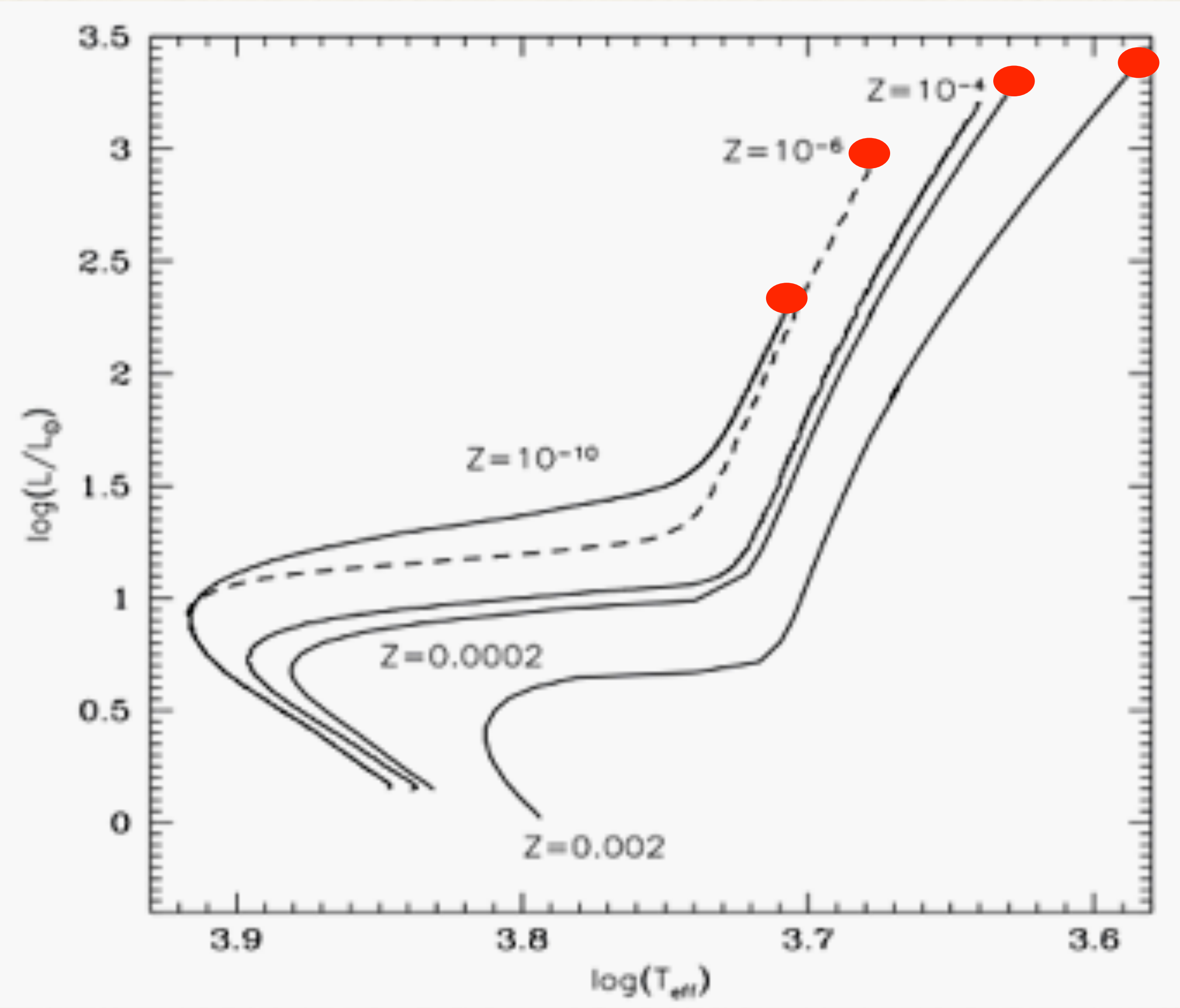
Z=0.0198
Y=0.2734
Z=0.001
Y=0.246
Z=0.01
Y=0.259
Z=0.0003
Y=0.245
Z=0.008
Y=0.256
Z=0.0001
Y=0.245
log(L/L⊙)
log(T_eff)
4.4
4.2
4
3.8
3.6
0
2
4

Tracks and isochrones

Play with the code and parameters, learn what is the physics behind any change in the models. It will surely help you fit your favourite star, and learn some physics

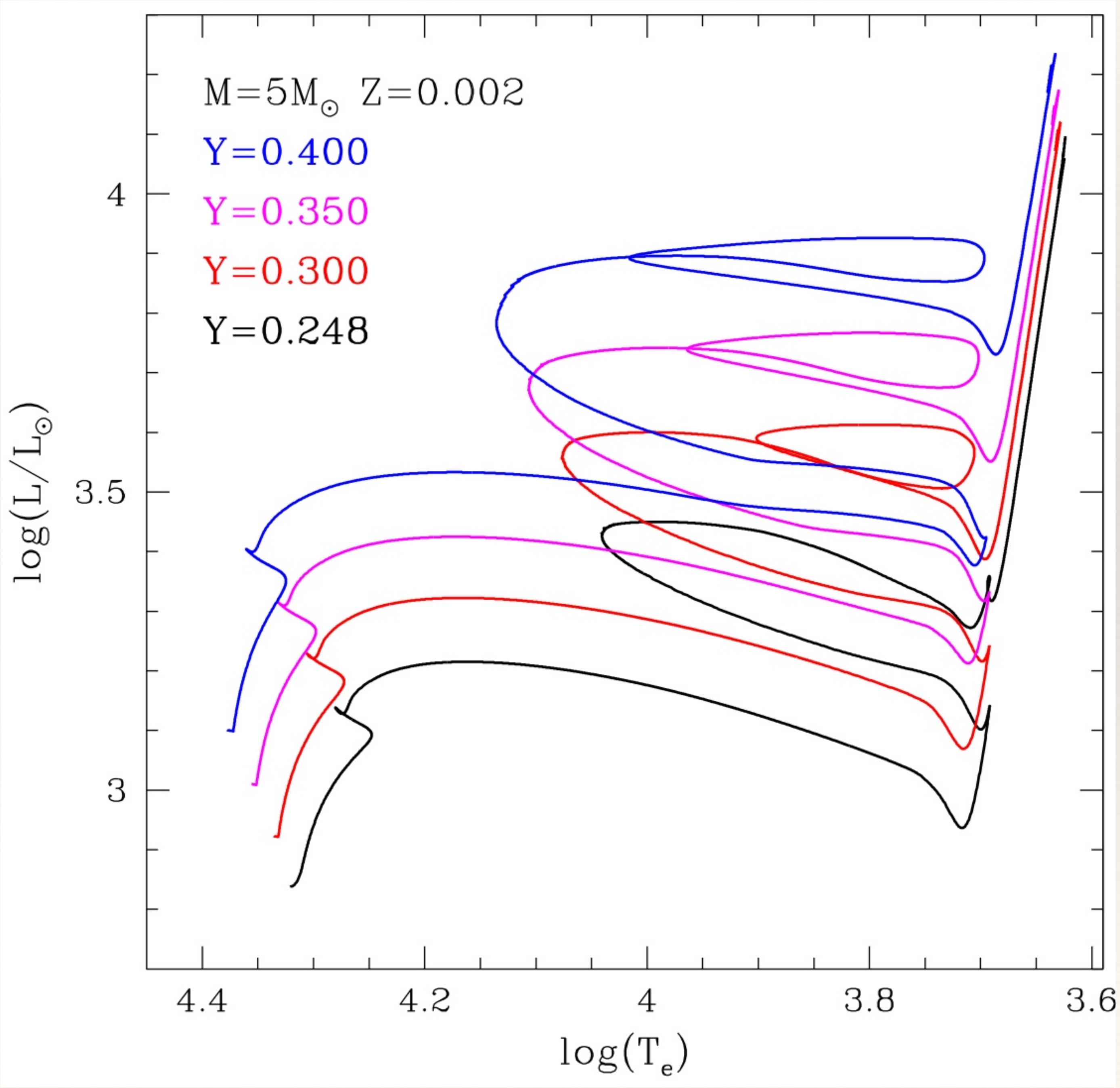
Tracks and isochrones

What happens if you change…



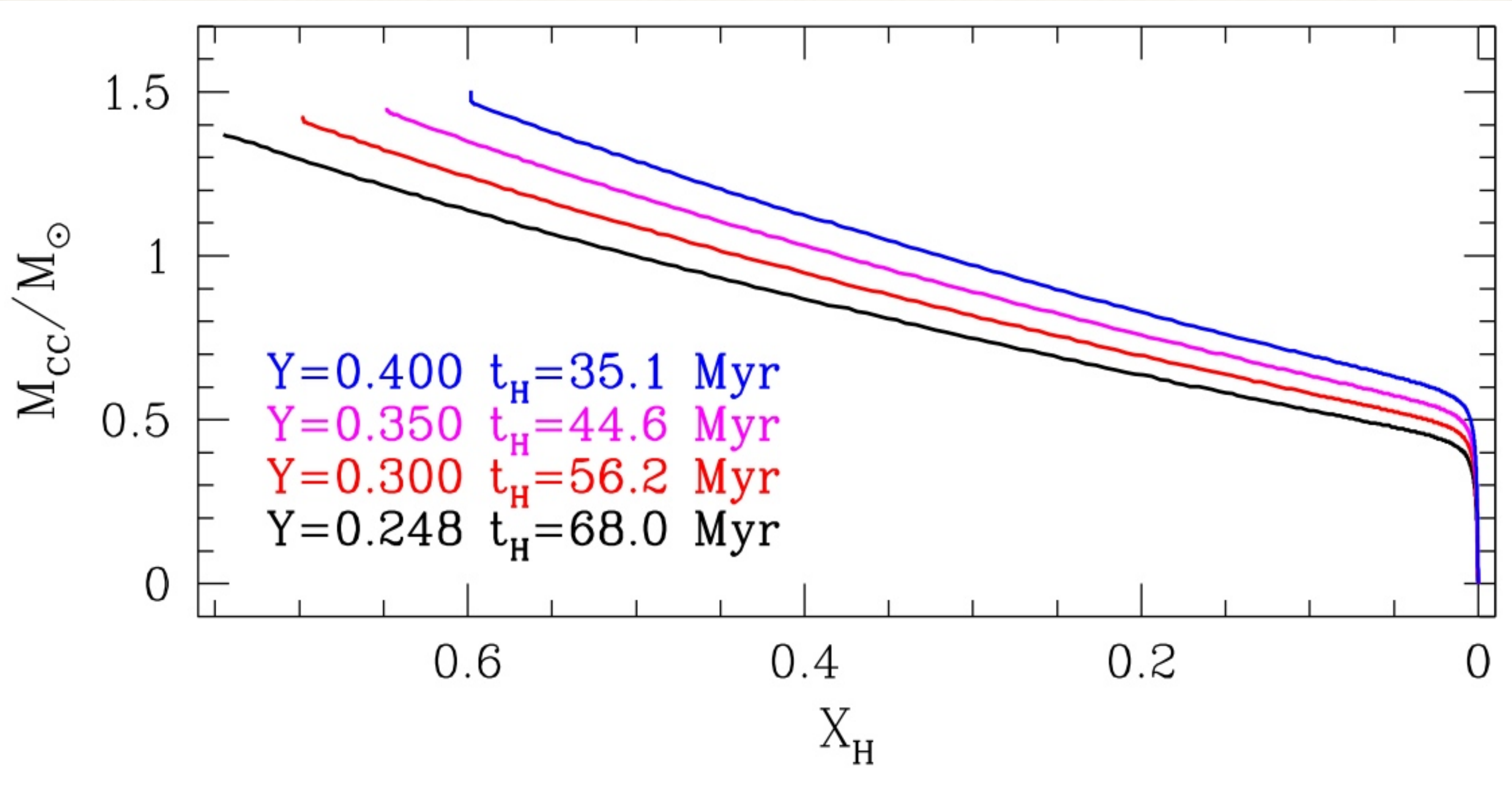
Tracks and isochrones

What happens if you change…

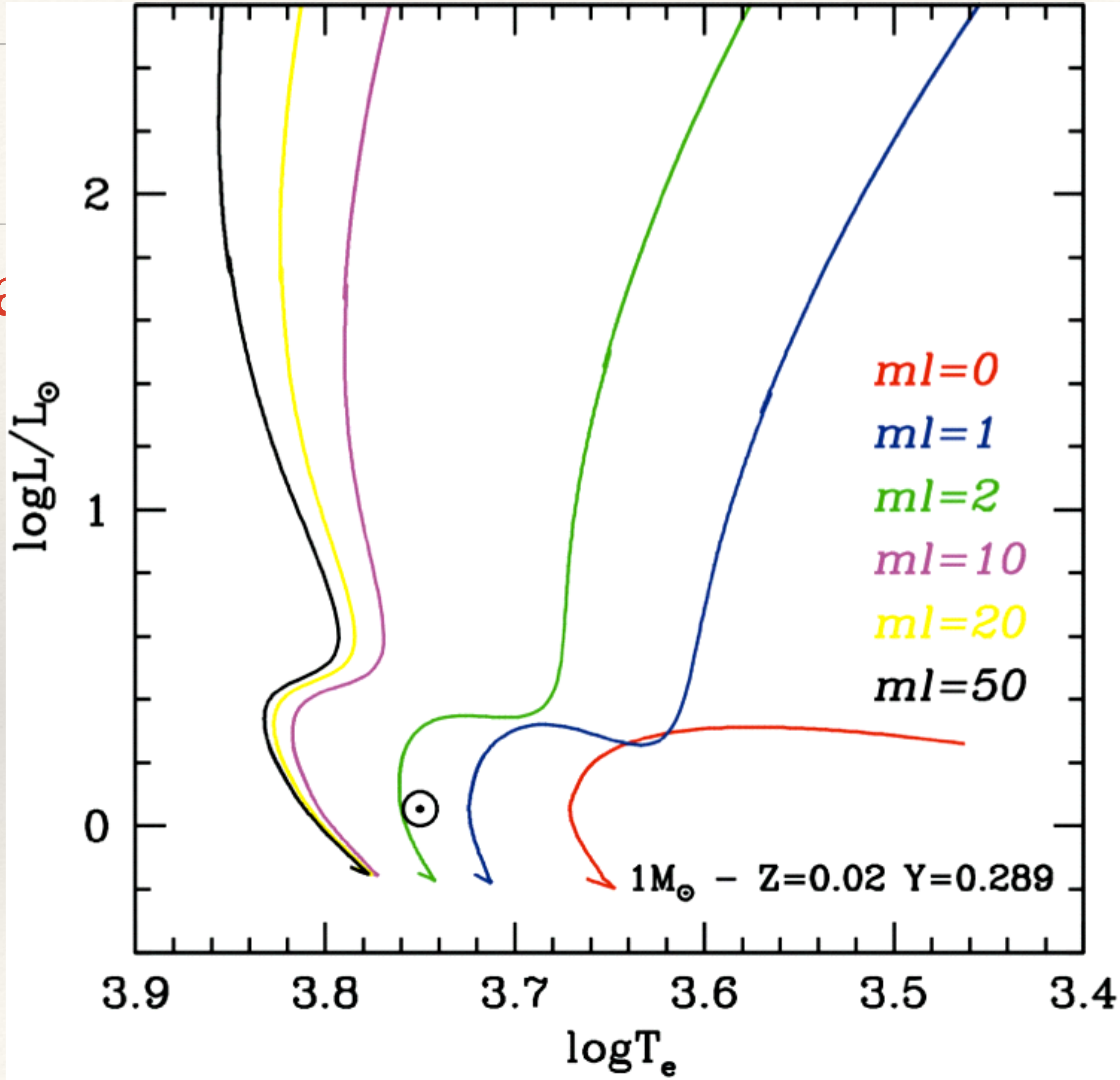


Tracks and isochrones

What happens if you change…



Wha



2
1
0
logL/L⊙
ml=0
ml=1
ml=2
ml=10
ml=20
ml=50
1M⊙ – Z=0.02 Y=0.289
3.9
3.8
3.7
3.6
3.5
3.4
logTe

STELLAR ASTROPHYSICS CENTRE

Stellar evolution and modelling

Víctor Silva Aguirre

IV Azores School, July 18th 2016