The evolution of low-metallicity massive stars

Dorottya Szécsi

Collaborators:
Norbert Langer (Bonn, Germany),
Carolina Kehrig (Granada, Spain), Frank Tramper (Madrid, Spain), Takashi Moriya (Tokyo, Japan), Jonathan Mackey (Dublin, Ireland)
Jiři Kubát (Ondřejov, Czech Rep.)

AKADEMIE VĚD ČESKÉ REPUBLIKY

Astronomický ústav AV ČR

Grant: 13-10589S GA ČR

Ondřejov, 3rd October 2016

The night-sky and beyond

The night-sky and beyond

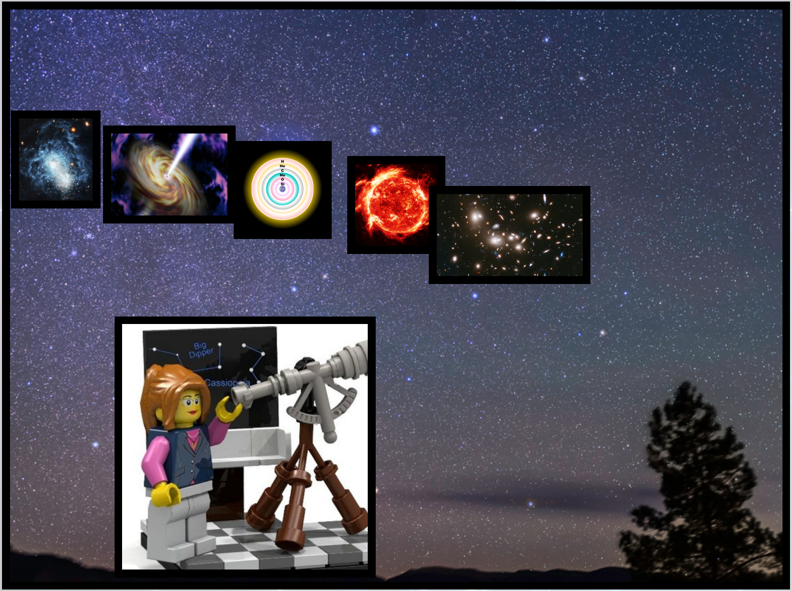
The night-sky and beyond

The night-sky and beyond

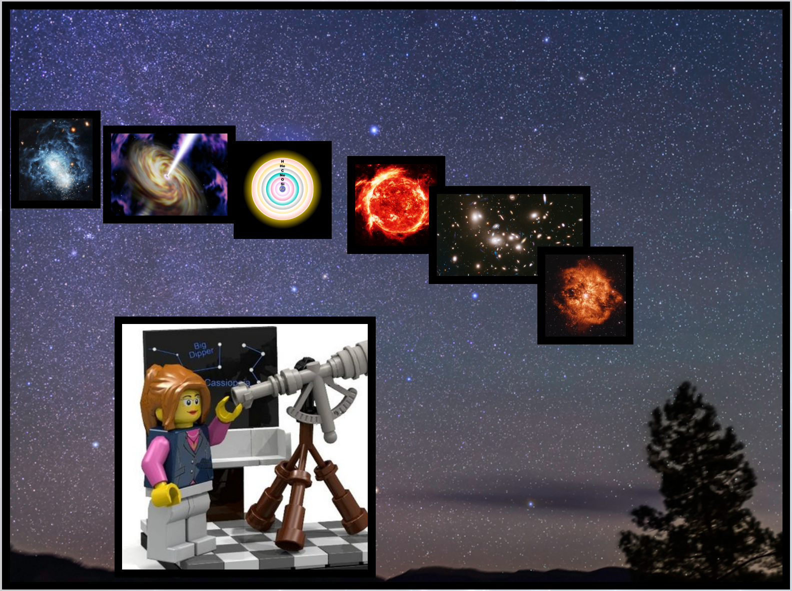
The night-sky and beyond

The night-sky and beyond

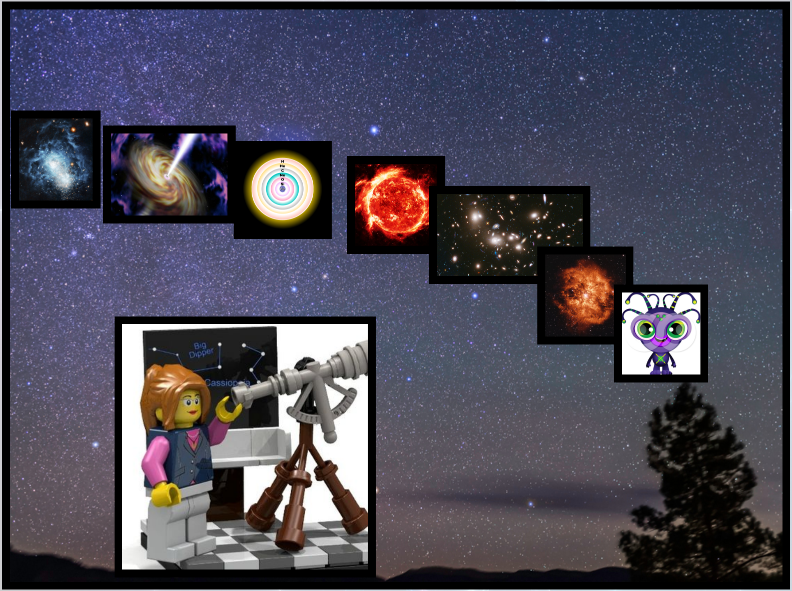
The night-sky and beyond



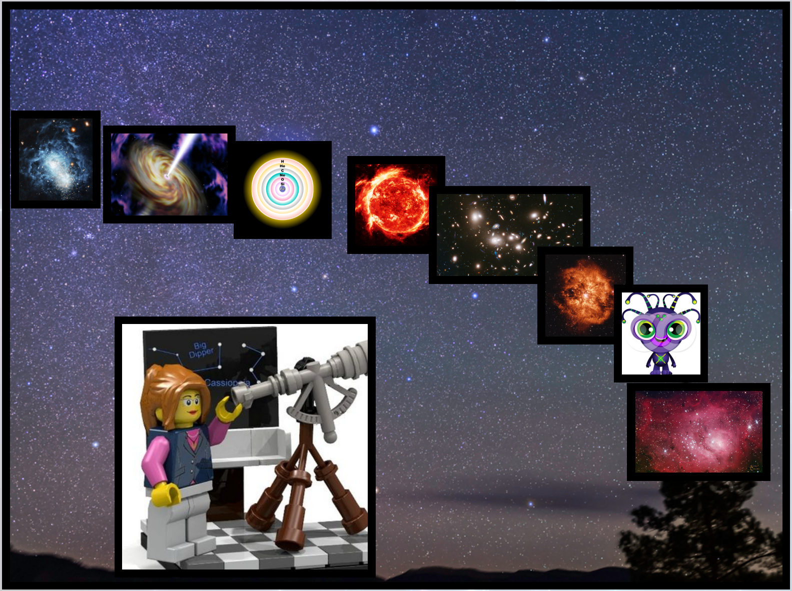
The night-sky and beyond



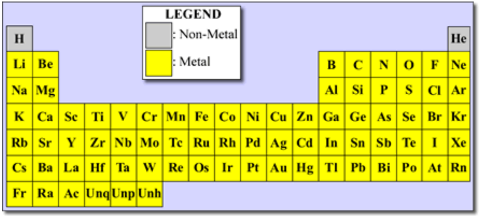
The night-sky and beyond



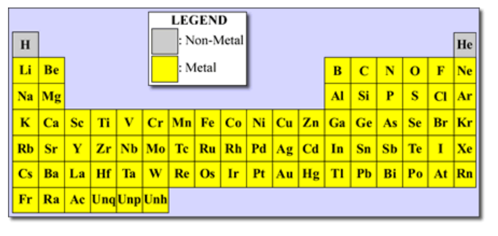
The night-sky and beyond

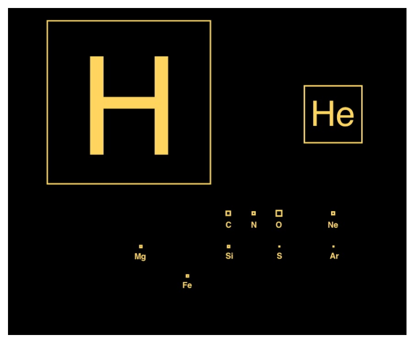


Astronomers and metal

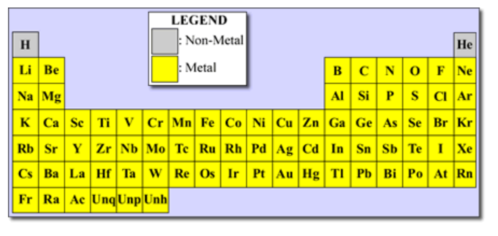


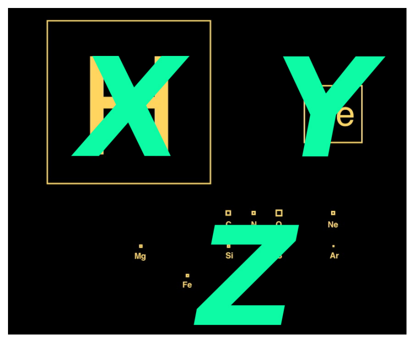
Astronomers and metal



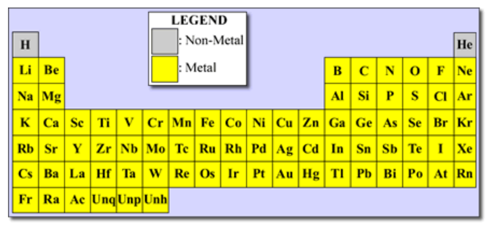


Astronomers and metal

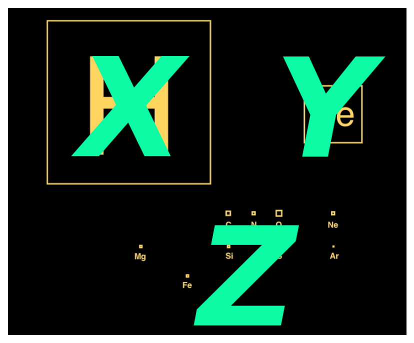




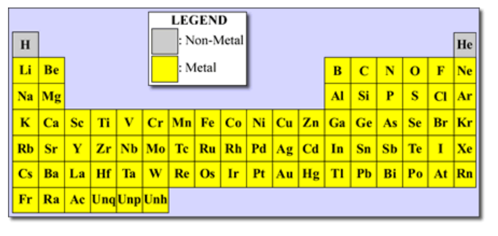
Astronomers and metal



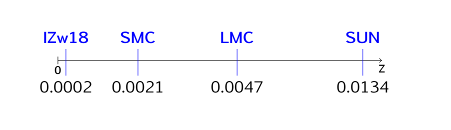
"Z: metallicity"

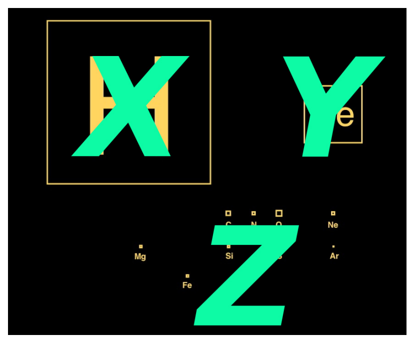


Astronomers and metal

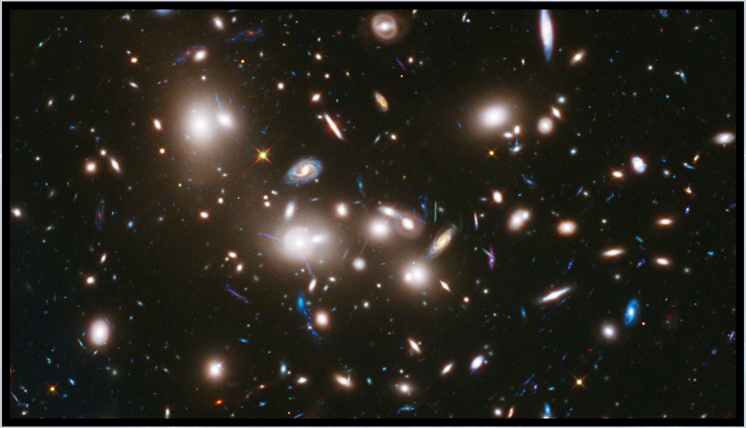


"Z: metallicity"





The early Universe (Z≈0)



Credit: hubblesite.org

Compact Dwarf Galaxies

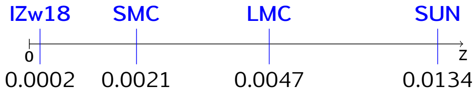
Legrand+07, Aloisi+09, Annibali+13, Kehrig+13, Lebouteiller+13

Compact Dwarf Galaxies

I Zwicky 18

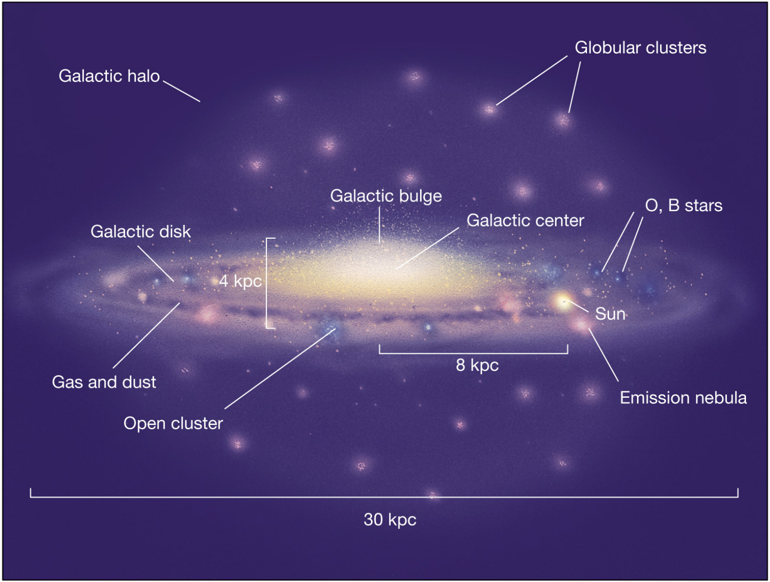
- Blue Compact Dwarf Galaxy
- 60 million lightyears $\rightarrow$ local
- star formation rate: 0.1 $M_\odot$/yr
- ionized gas
- low metallicity!

$$12+\log(O/H)=7.17$$
$$\downarrow$$
$$Z=1/50\ Z_\odot \approx 0.0002$$

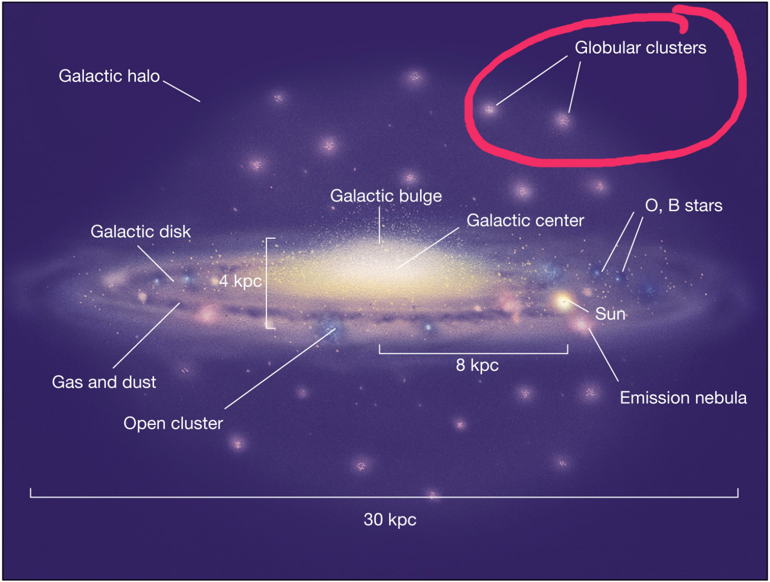


Legrand+07, Aloisi+09, Annibali+13, Kehrig+13, Lebouteiller+13

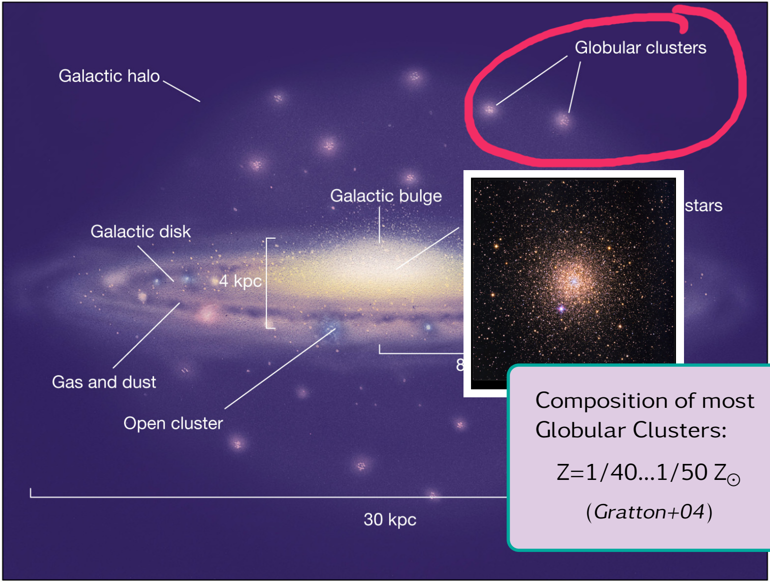
Globular Clusters



Globular Clusters



Globular Clusters



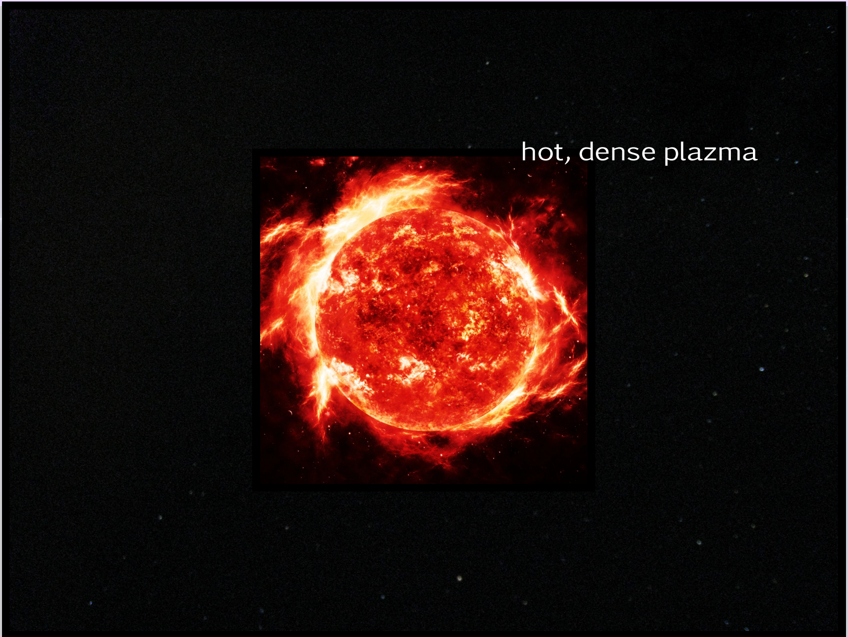
Composition of most Globular Clusters:

$Z = 1/40 ... 1/50\ Z_{\odot}$

(*Gratton+04*)

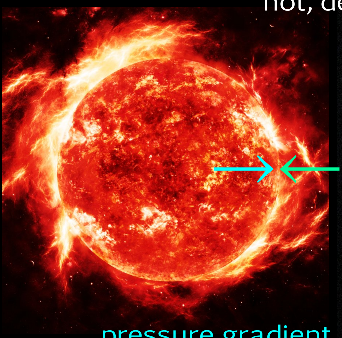
What is a star?

What is a star?



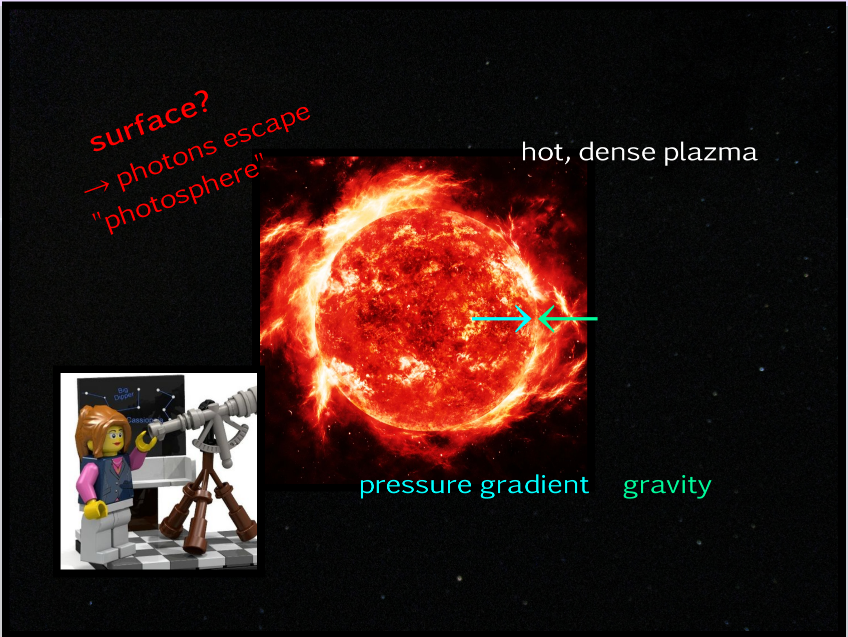
What is a star?

hot, dense plazma

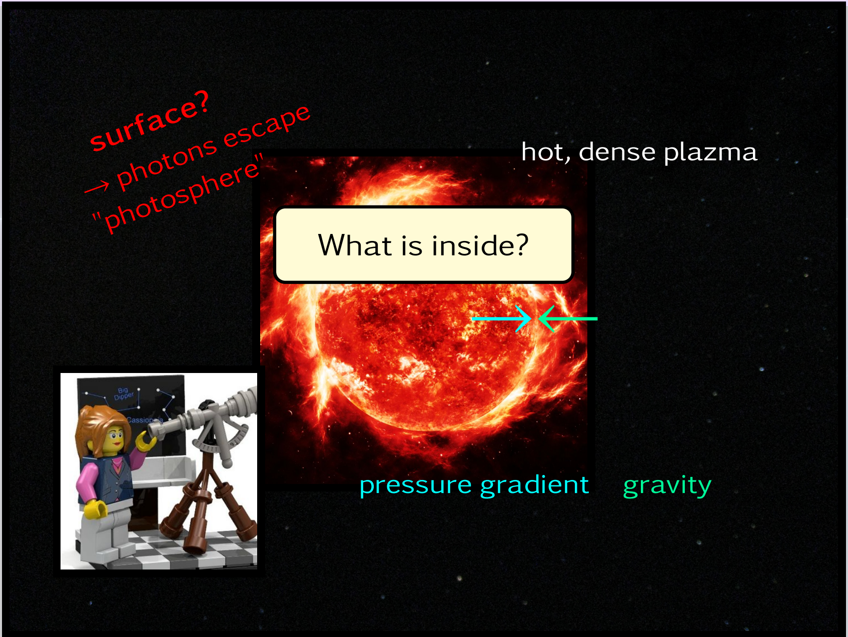


equilibrium: pressure gradient gravity

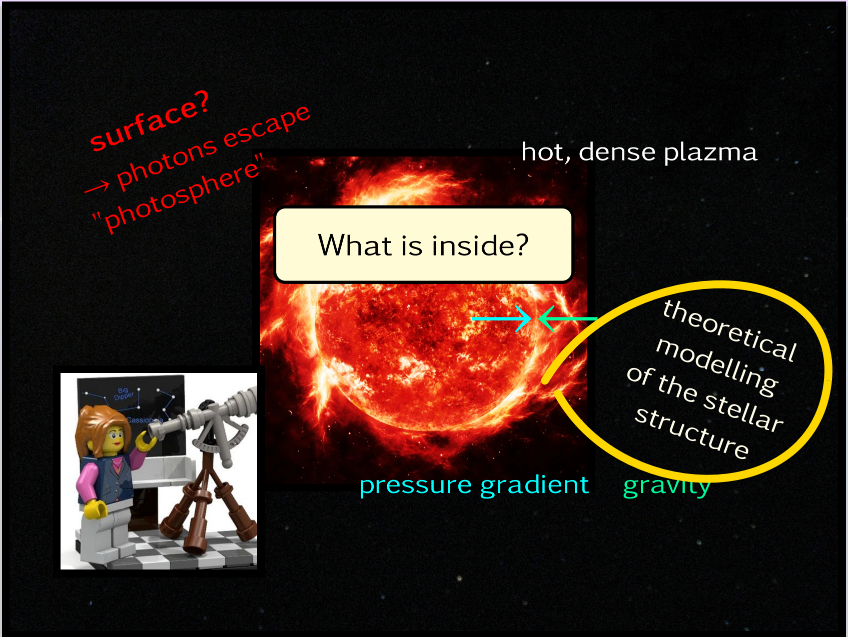
What is a star?



What is a star?



What is a star?



Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \qquad (9)$$

mass conservation

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \qquad (10)$$

momentum conservation

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T\frac{\partial S}{\partial t} \qquad (11)$$

energy conservation

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad (12)$$

transport of energy

Guilera et al. 2011

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \qquad \text{mass conservation} \qquad (9)$$

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \qquad \text{momentum conservation} \qquad (10)$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T\frac{\partial S}{\partial t} \qquad \text{energy conservation} \qquad (11)$$

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad \text{transport of energy} \qquad (12)$$

Guilera et al. 2011

composition change due to nuclear burning ?!

$$\frac{\partial X_i}{\partial t} = \frac{A_i m_u}{\rho}\left(-\Sigma_{j,k} r_{i,j,k} + \Sigma_{k,l} r_{k,l,i}\right) \qquad (13)$$

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \qquad \text{mass conservation} \tag{9}$$

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \qquad \text{momentum conservation} \tag{10}$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\rm pl} - T\frac{\partial S}{\partial t} \qquad \text{energy conservation} \tag{11}$$

$$\frac{\partial T}{\partial m_r} = -\frac{G m_r T}{4\pi r^4 P}\nabla \qquad \text{transport of energy} \tag{12}$$

Guilera et al. 2011

composition change due to nuclear burning ?!

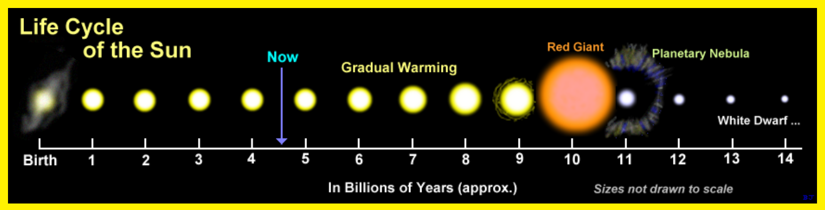
$$\frac{\partial X_i}{\partial t} = \frac{A_i m_u}{\rho}\left(-\Sigma_{j,k} r_{i,j,k} + \Sigma_{k,l} r_{k,l,i}\right) \tag{13}$$

+ Rotation.

Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \qquad \text{mass conservation} \qquad (9)$$

$$\frac{\partial P}{\partial m_r} = -\frac{G m_r}{4\pi r^4} \qquad \text{momentum conservation} \qquad (10)$$



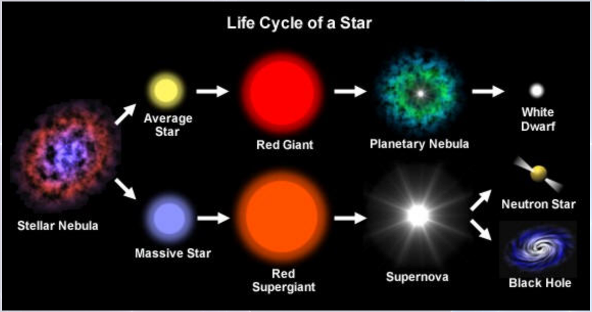
composition change due to nuclear burning ?!

$$\frac{\partial X_i}{\partial t} = \frac{A_i m_u}{\rho}\left(-\Sigma_{j,k} r_{i,j,k} + \Sigma_{k,l} r_{k,l,i}\right) \qquad (13)$$

+ Rotation.

Massive vs. low-mass stars

Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9\ M_\odot$)



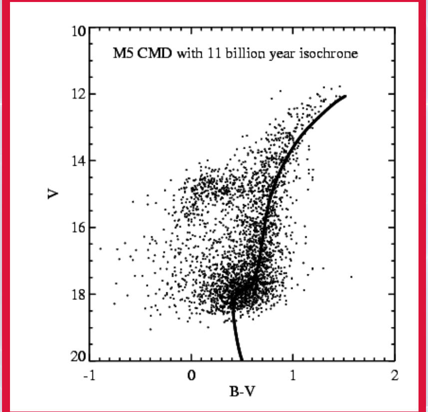
- nuclear reactions, final composition
- number of stars: massive stars are rare
- lifetime: massive stars have shorter lives
- final fate

Matching theory to observations

Surface properties! → temperature (i.e. colour) X axis
→ luminosity (i.e. brightness) Y axis

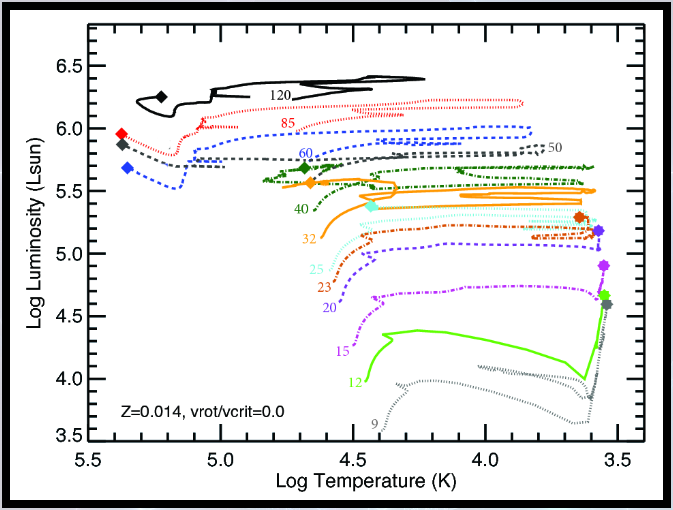
Matching theory to observations

Surface properties! → temperature (i.e. colour) X axis
→ luminosity (i.e. brightness) Y axis



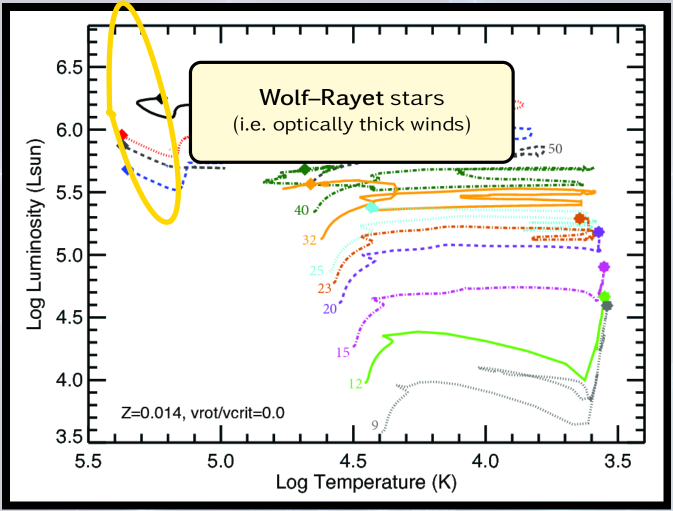
Hertzsprung–Russell diagram (HR diagram)

Hertzsprung–Russell diagram



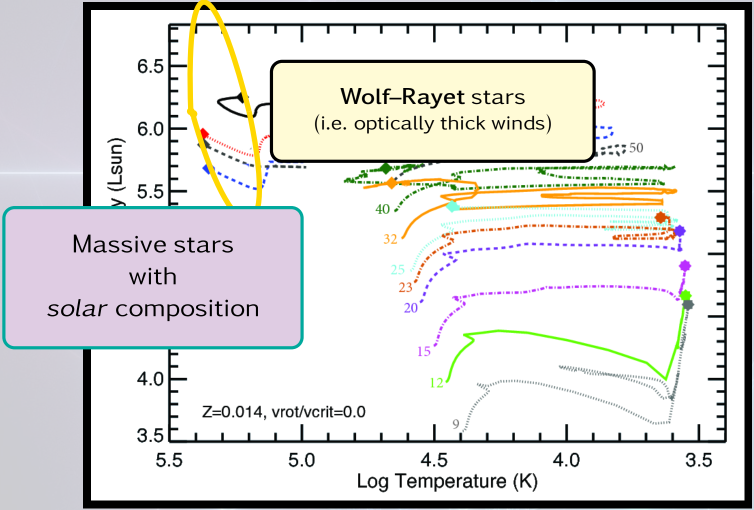
Groh et al. 2013

Hertzsprung–Russell diagram



Groh et al. 2013

Hertzsprung–Russell diagram

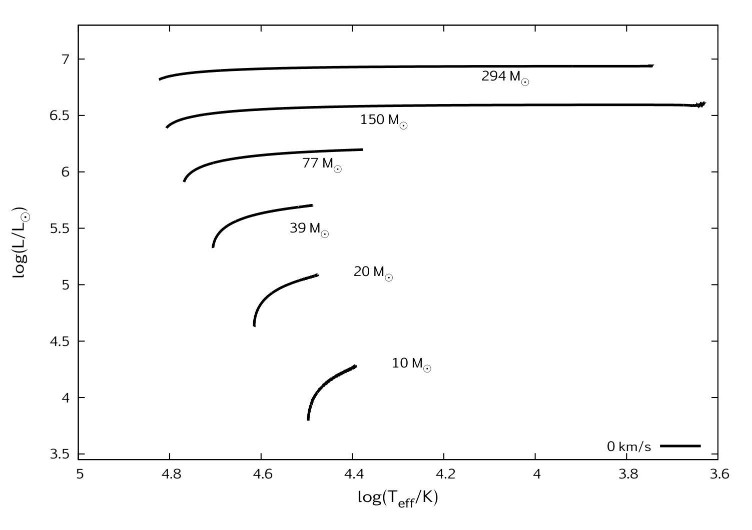


Groh et al. 2013

Low Metallicity Massive Stars

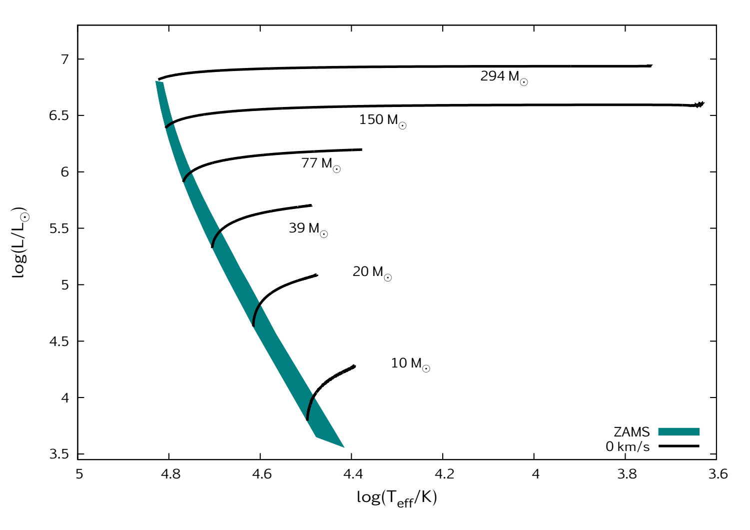
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



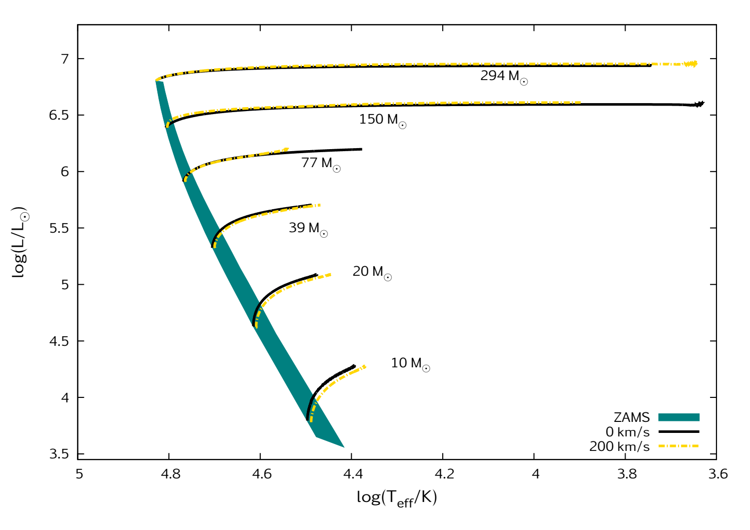
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



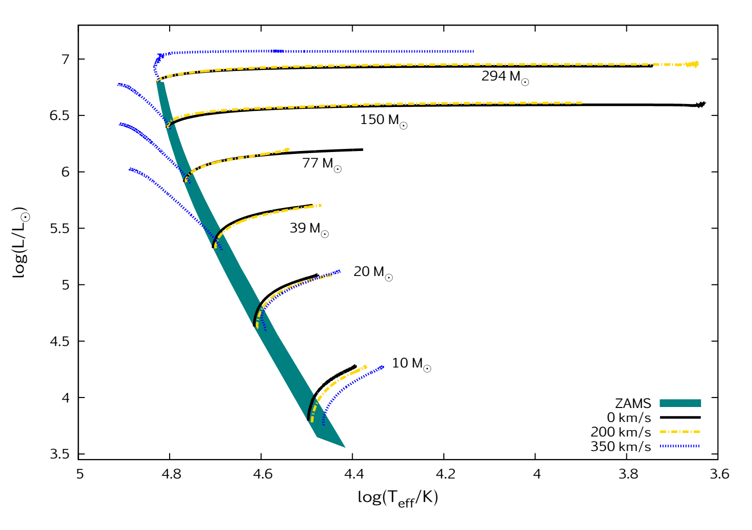
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



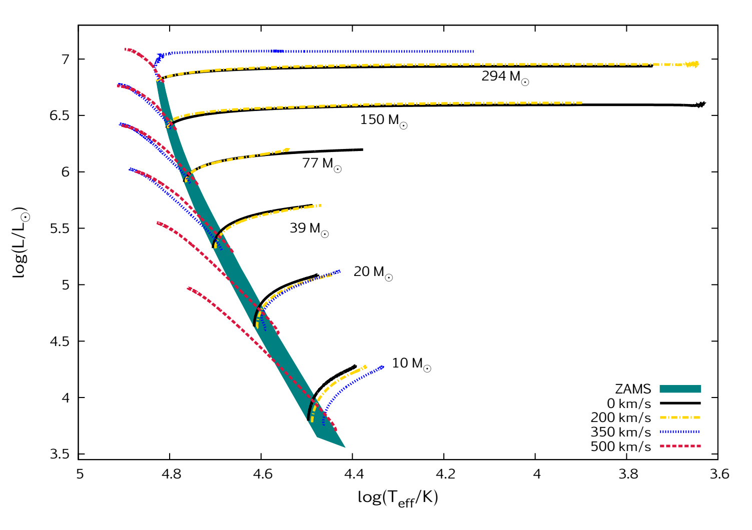
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



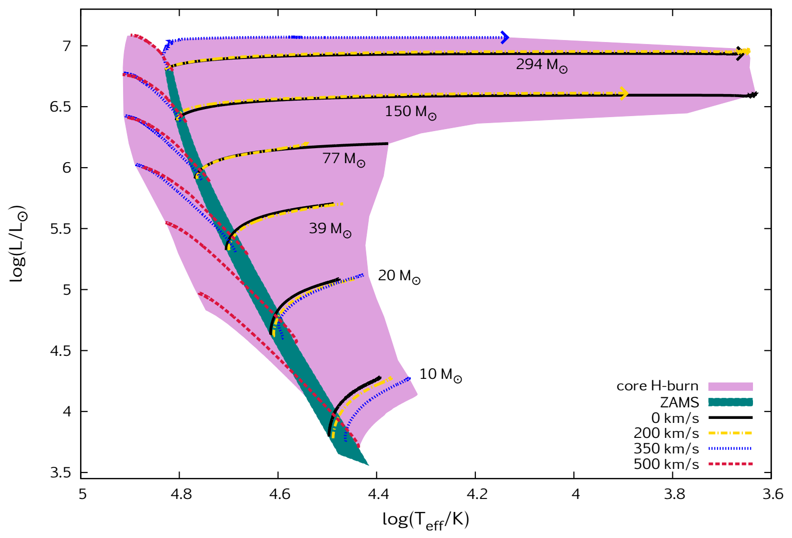
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



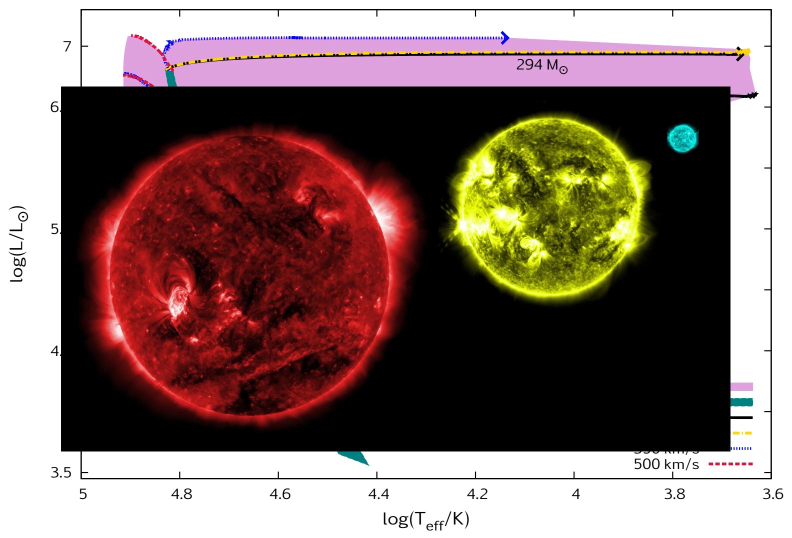
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



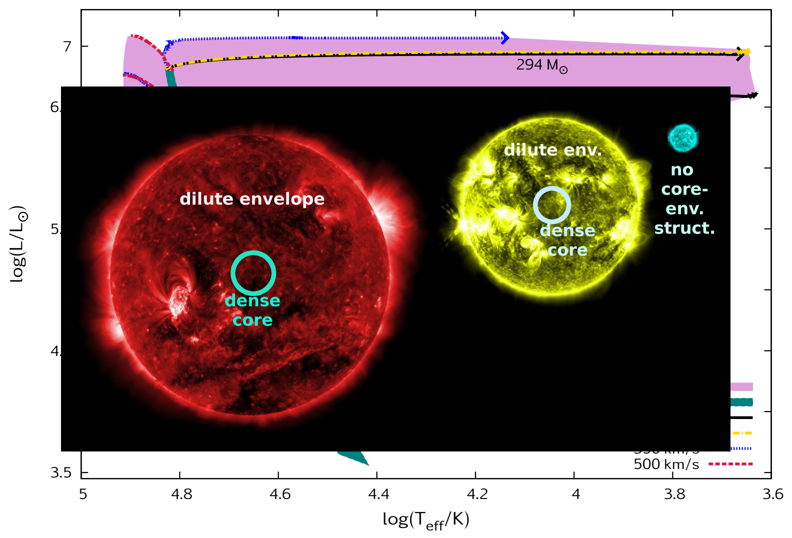
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



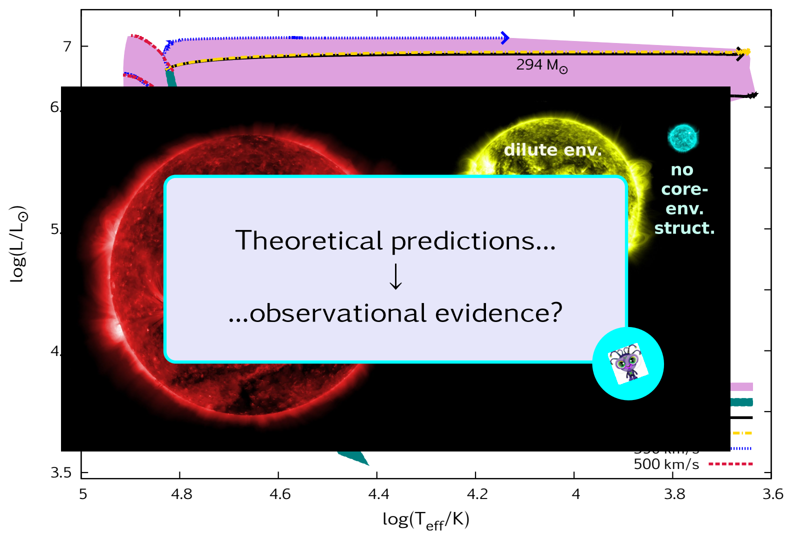
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



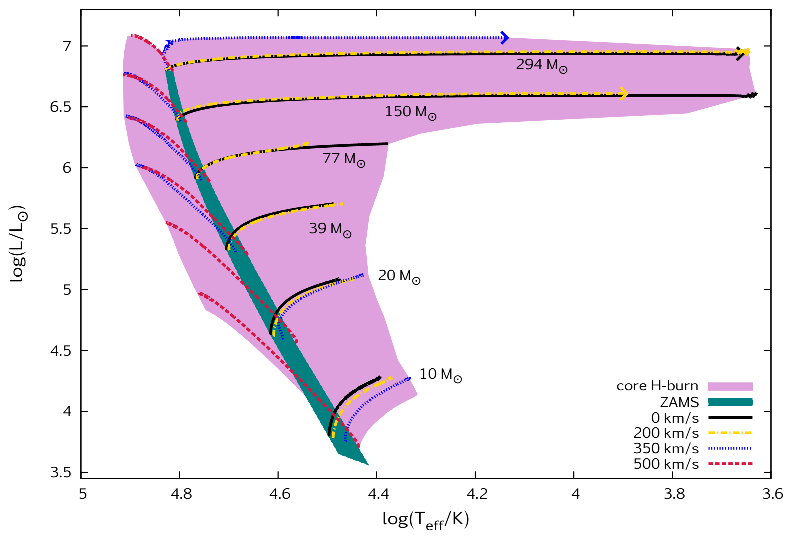
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



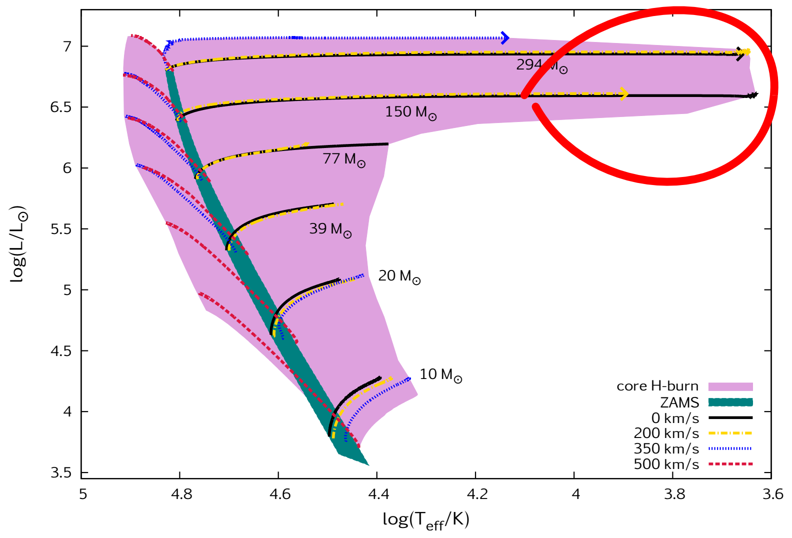
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



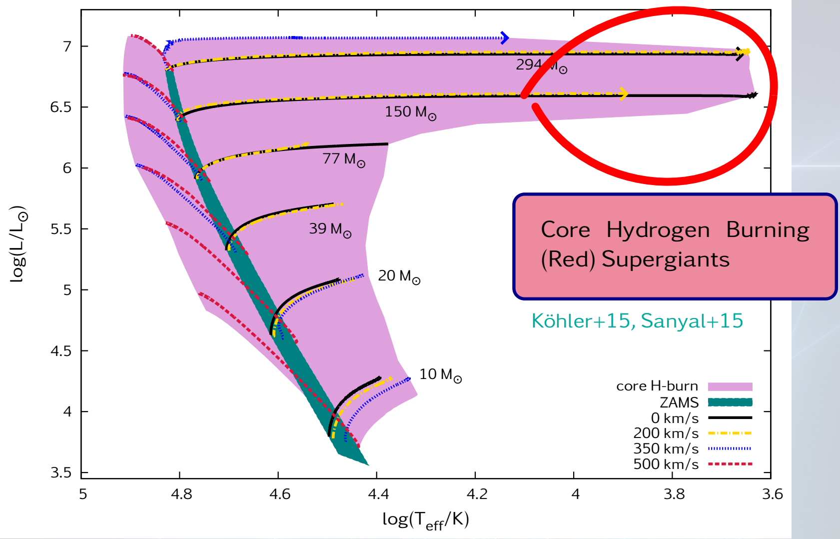
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



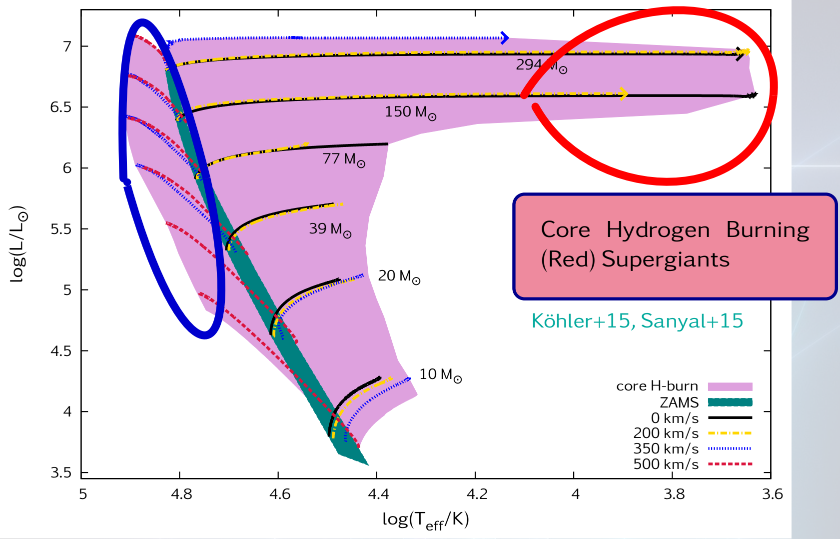
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



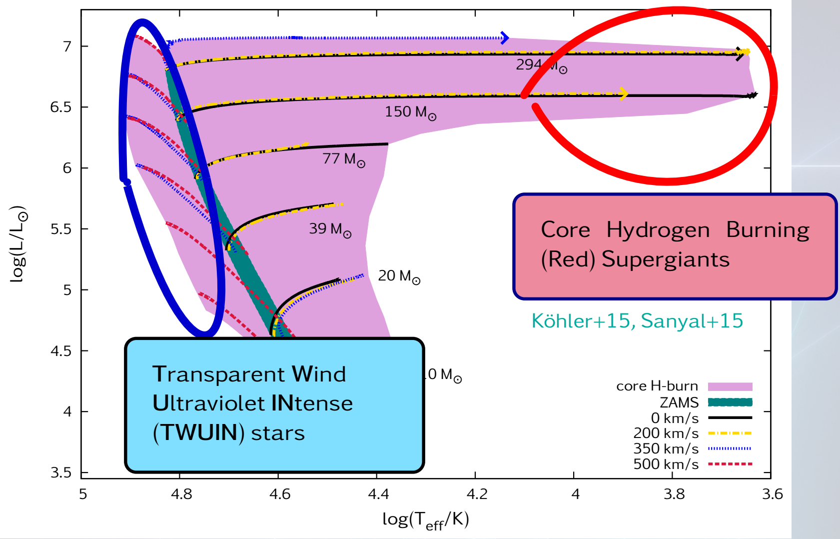
Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



Low Metallicity Massive Stars

Szécsi et al. 2015 (Astronomy & Astrophysics, v.581, A15)



Transparent Wind
Ultraviolet INtense stars
(TWUIN stars)

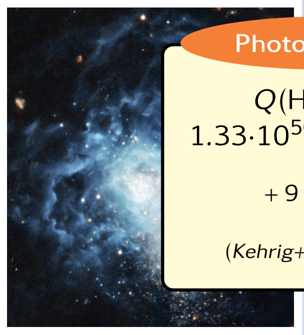
– in the

starburst galaxy I Zwicky 18

Back to I Zw 18

I Zwicky 18

- Blue Compact Dwarf Galaxy
- 60 million lightyears → local
- star formation rate: 0.1 $M_\odot$/yr
- ionized gas
- low metallicity: $Z = 1/50\ Z_\odot$



Photoionization

$$Q(\mathrm{HeII})^{obs} = 1.33 \cdot 10^{50}\ \mathrm{photons\ s^{-1}}$$

+ 9 WC stars

(*Kehrig+15, Crowther+06*)

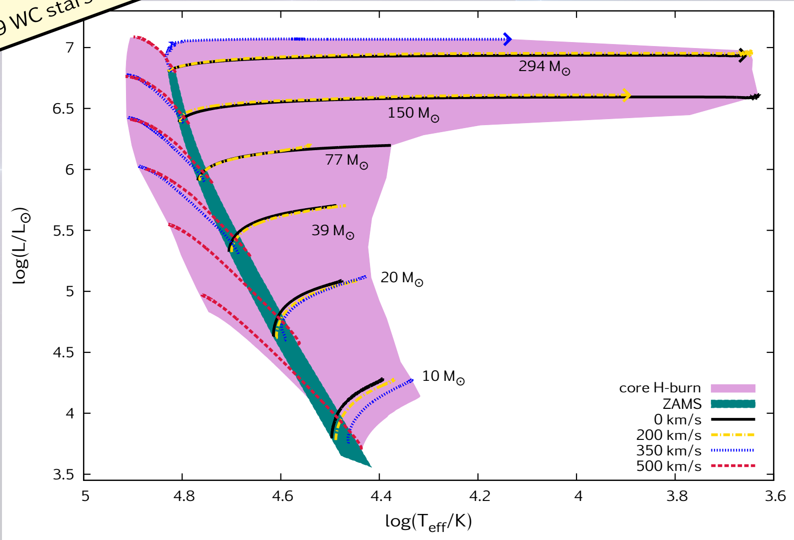
Legrand+07, Aloisi+09, Annibali+13, Kehrig+13, Lebouteiller+13

Photoionization in I Zw 18

Photoionization

$Q(\mathrm{HeII})^{obs} = 1.33 \cdot 10^{50}$ photons s^{-1}

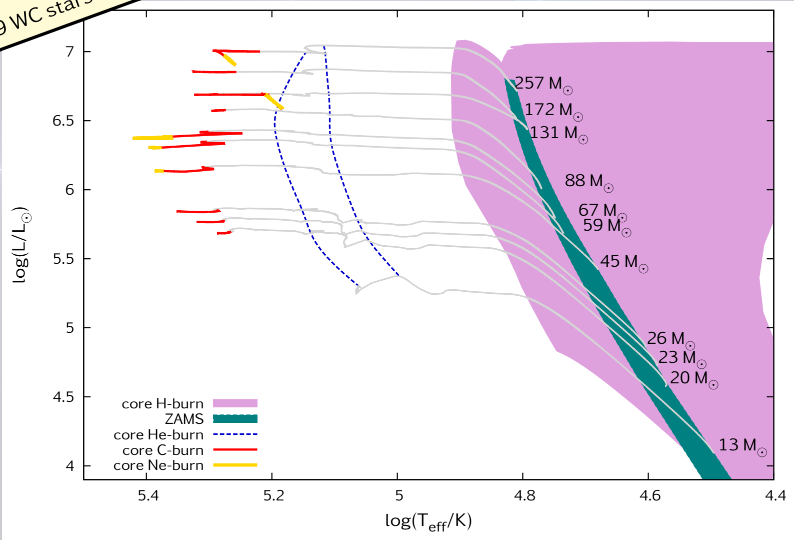
+ 9 WC stars



Photoionization in I Zw 18

Photoionization

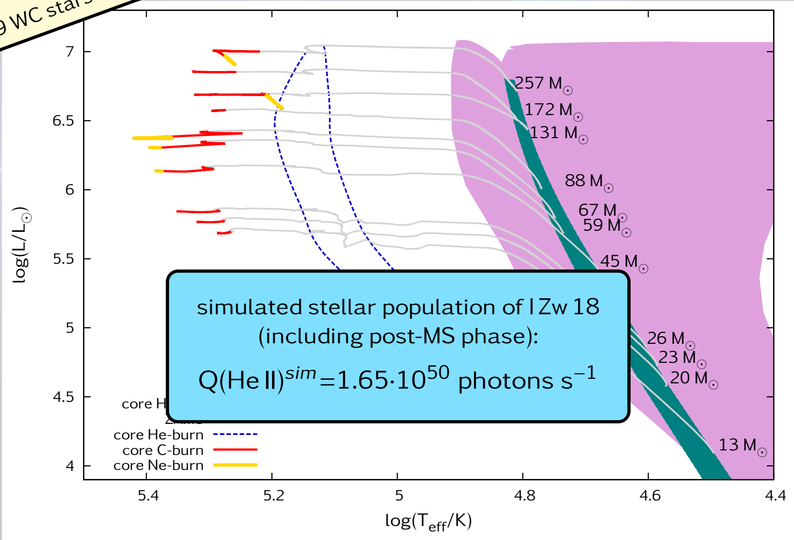
$Q(\text{HeII})^{obs} =$
$1.33 \cdot 10^{50}$ photons s^{-1}
+ 9 WC stars



Photoionization in I Zw 18

Photoionization

$Q(\mathrm{HeII})^{obs} =$
$1.33 \cdot 10^{50}$ photons s^{-1}
+ 9 WC stars



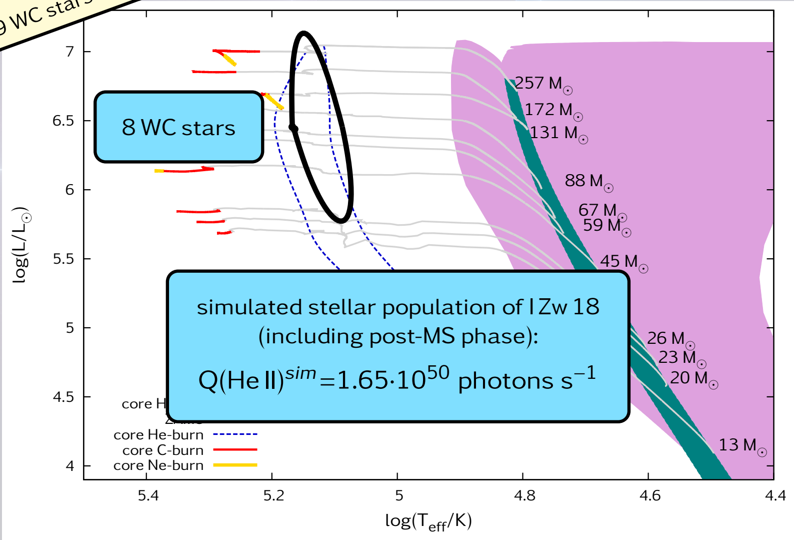
simulated stellar population of I Zw 18
(including post-MS phase):

$Q(\mathrm{He\,II})^{sim} = 1.65 \cdot 10^{50}$ photons s^{-1}

Photoionization in I Zw 18

Photoionization

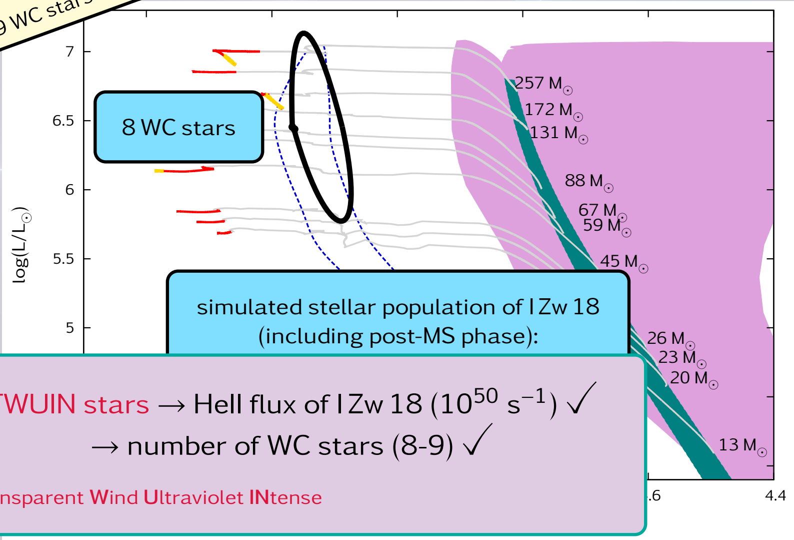
$Q(\text{He II})^{obs} =$
$1.33 \cdot 10^{50}$ photons s^{-1}
+ 9 WC stars



Photoionization in I Zw 18

Photoionization

$Q(\text{HeII})^{obs} =$
$1.33 \cdot 10^{50}$ photons s^{-1}
$+ 9$ WC stars



TWUIN stars → HeII flux of I Zw 18 (10^{50} s^{-1}) ✓

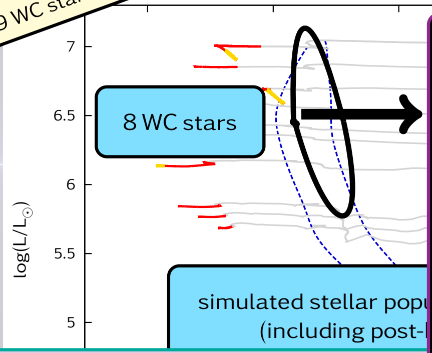
→ number of WC stars (8-9) ✓

Transparent Wind Ultraviolet INtense

Photoionization in I Zw 18

Photoionization

$Q(\text{HeII})^{obs} =$
$1.33 \cdot 10^{50}$ photons s^{-1}
+ 9 WC stars



TWUIN stars → HeII flux of I Zw 18
→ number of WC stars (8-

Transparent Wind Ultraviolet INtense

Collapsar → lGRB

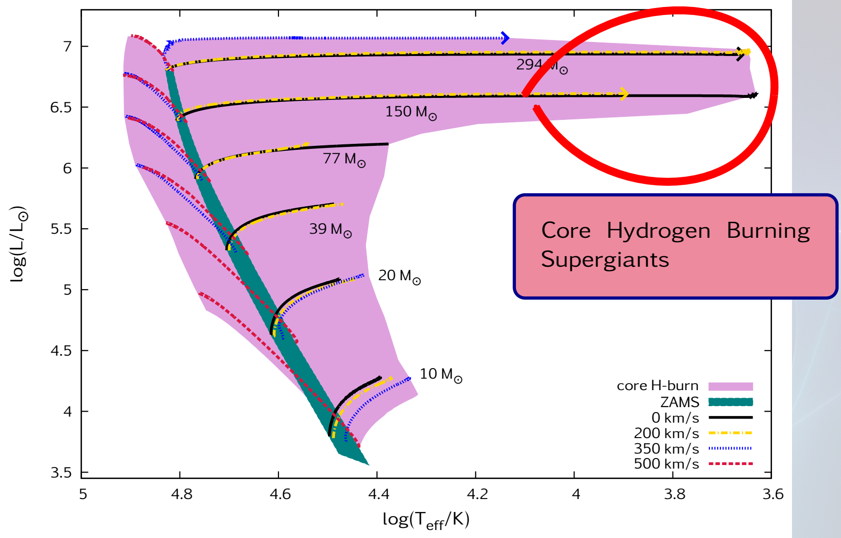
long-duration Gamma-Ray Burst (lGRB)

"angular momentum in the core is higher than the critical limit for the formation of an accretion disc around a rotating black hole"

Core Hydrogen Burning Supergiants

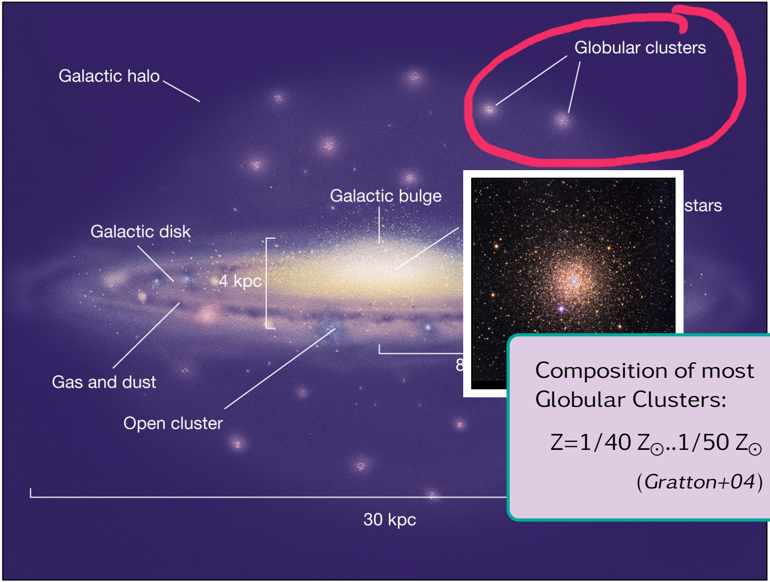
– in the

Early Globular Clusters



log(L/L⊙)
log(Teff/K)
294 M⊙
150 M⊙
77 M⊙
39 M⊙
20 M⊙
10 M⊙
core H-burn
ZAMS
0 km/s
200 km/s
350 km/s
500 km/s
Core Hydrogen Burning Supergiants

Globular Clusters & Abundance Anomalies

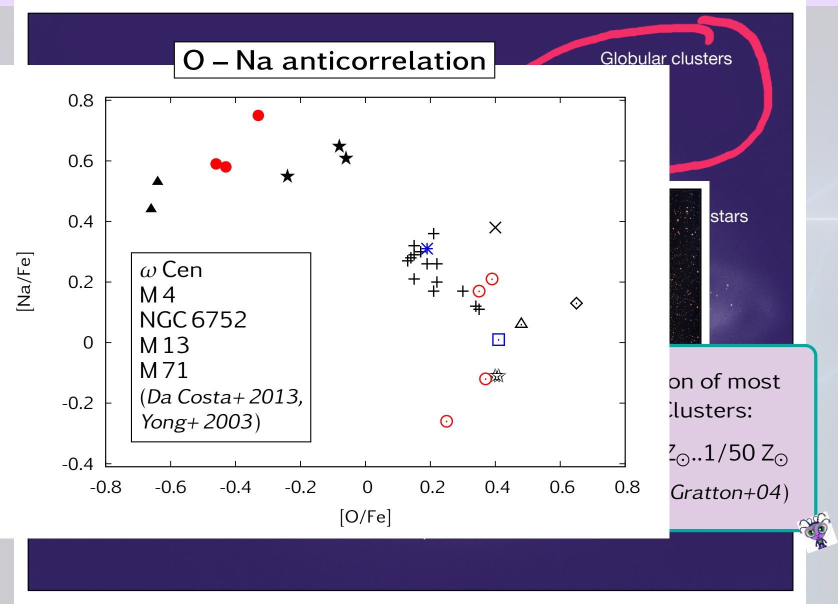


Composition of most Globular Clusters:

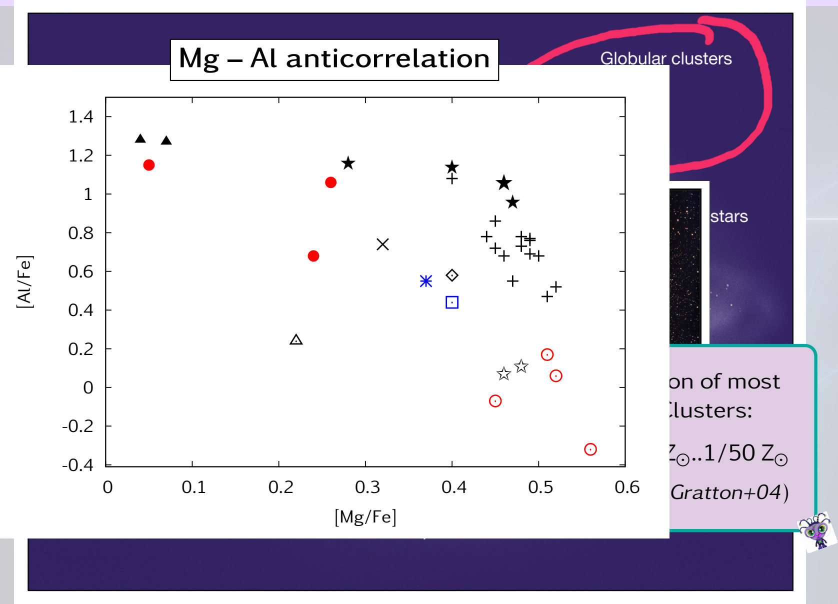
$Z=1/40\ Z_{\odot}..1/50\ Z_{\odot}$

(*Gratton+04*)

Globular Clusters & Abundance Anomalies



Globular Clusters & Abundance Anomalies



Globular Clusters & Abundance Anomalies

Mg – Al anticorrelation

Globular clusters

- extreme & intermediate pop: **polluted** by hot hydrogen burning
  - CNO-cycle, Ne-Na and Mg-Al chains
- need: **astrophysical source** that can pollute the ISM
  - AGB stars: hot bottom burning (*Ventura+ 2001*)
  - fast rotating massive stars: close to break-up (*Decressin+ 2007*)
  - supermassive stars (10^4 $M_\odot$): continuum-driven wind (*Denissenkov+ 2014*)
  - massive binaries: non-conservative mass transfer (*de Mink+ 2009*)
- still open question (problems with mass budget, surface helium etc.)

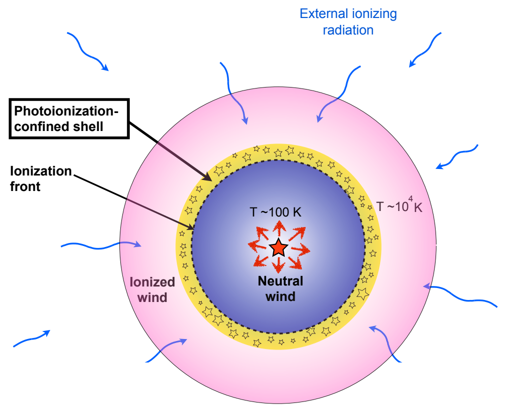
→ New scenario...

New scenario:

Starforming Supergiant Shells

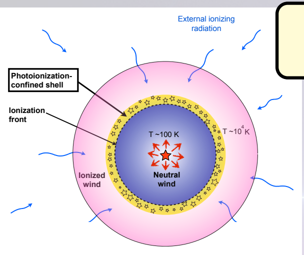
New scenario:

Starforming Supergiant Shells

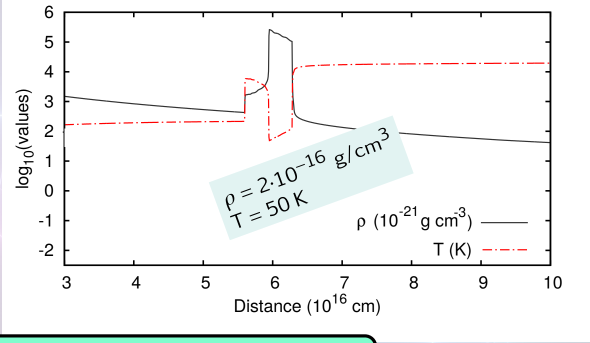


PICO shell: *Mackey+ 2014 (Nature)*

Simulating the PICO shell



Mass of the photoionization-confined (PICO) shell: $\sim 14\ M_\odot$

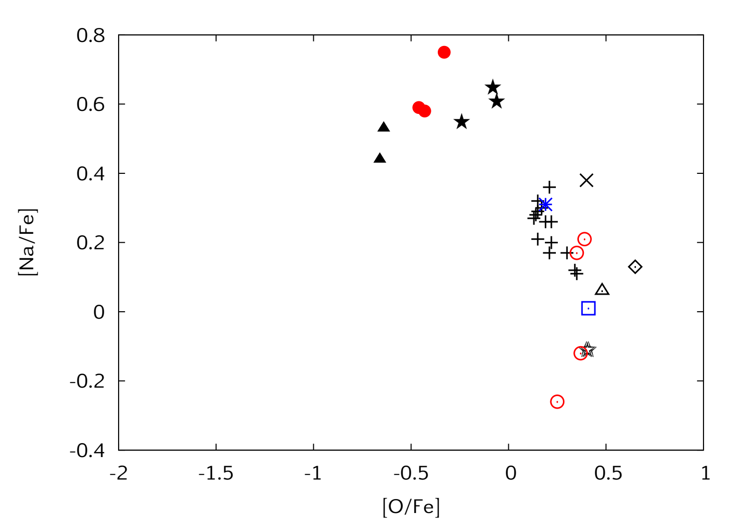


Lifetime of the shell: $\sim 10^5$ yr

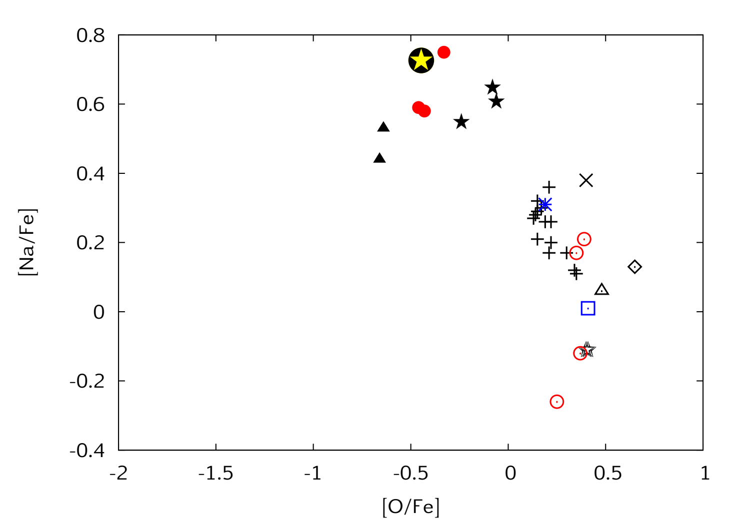
>>

Growth timescale of grav. unstable perturbations: $\sim 10^4$ yr

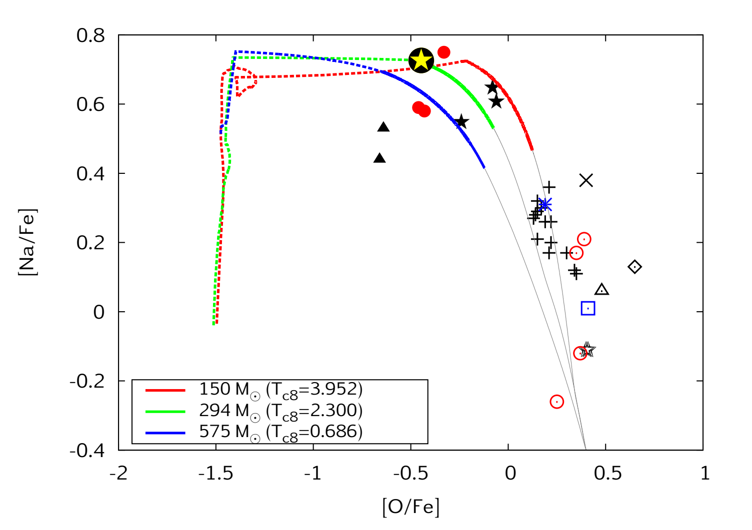
Compared to observations: O – Na anticorr.



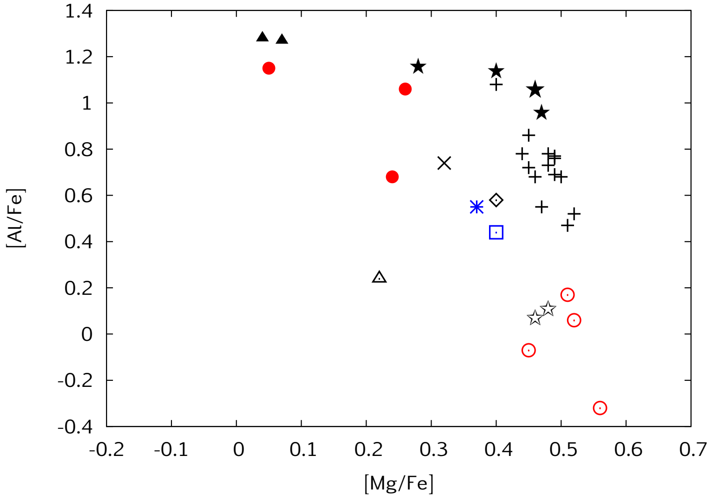
Compared to observations: O – Na anticorr.



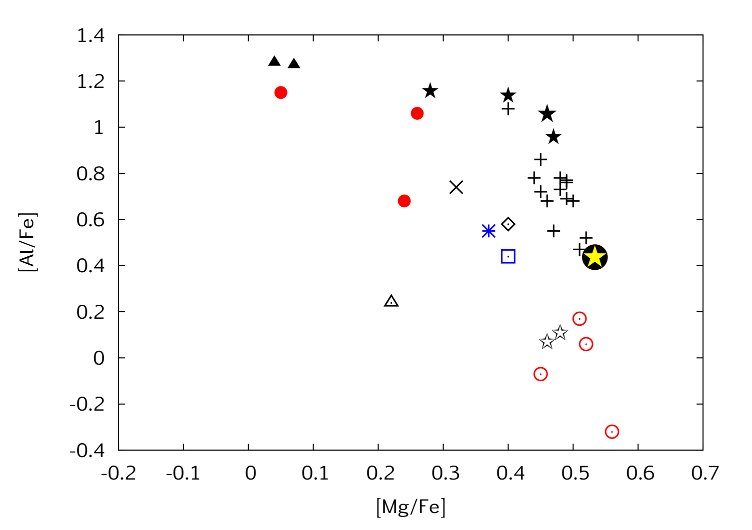
Compared to observations: O – Na anticorr.



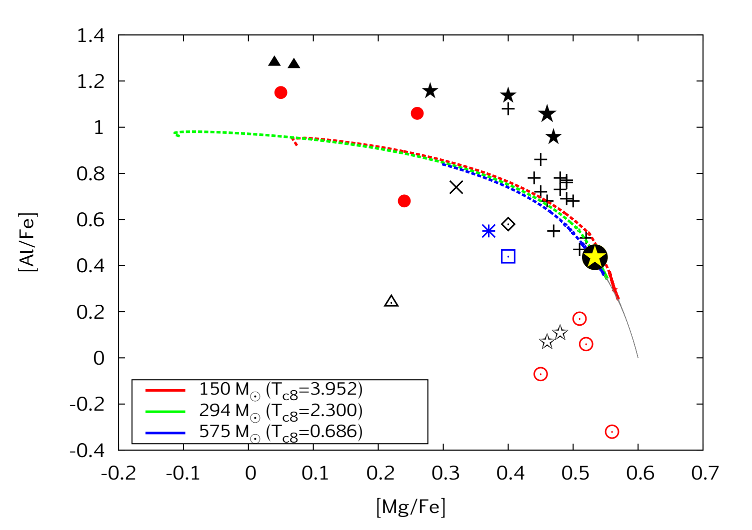
Compared to observations: Mg – Al anticorr.



Compared to observations: Mg – Al anticorr.



Compared to observations: Mg – Al anticorr.



Future plans at the Astronomický ústav AV ČR

Future plans at the Astronomický ústav AV ČR

Evolutionary models of low-metallicity massive stars

- between 9-300 $M_{\odot}$
- with and without rotation

↓

Next steps...

Future plans at the Astronomický ústav AV ČR

Evolutionary models of low-metallicity massive stars

- between 9-300 $M_\odot$
- with and without rotation

$\downarrow$

Next steps...

- model spectrum of TWUIN stars → ***Ondřejov***

Future plans at the Astronomický ústav AV ČR

Evolutionary models of low-metallicity massive stars

- between 9-300 $M_{\odot}$
- with and without rotation

↓

Next steps...

- model spectrum of TWUIN stars → ***Ondřejov***
- apply SG models as input for dinamical GC simulations → ***Spořilov***

Future plans at the Astronomický ústav AV ČR

Evolutionary models of low-metallicity massive stars

- between 9-300 $M_{\odot}$
- with and without rotation

$\downarrow$

Next steps...

- model spectrum of TWUIN stars → ***Ondřejov***
- apply SG models as input for dinamical GC simulations → ***Spořilov***
- gamma-ray bursts ↔ TWUIN stars!
- the early Universe
- other metal-poor environments (Green Peas galaxies, metal-poor halo stars, etc.)
- binary stars... gravitational waves!

Future plans at the Astronomický ústav AV ČR

Evolutionary models of low-metalli

- between 9-300 $M_\odot$
- with and without rotation

↓

Next steps...

- model spectrum of TWUIN stars → ***Ondřejov***
- apply SG models as input for dinamical GC simulations → ***Spořilov***
- gamma-ray bursts ↔ TWUIN stars!
- the early Universe
- other metal-poor environments (Green Peas galaxies, metal-poor halo stars, etc.)
- binary stars... gravitational waves!

Thank you for your attention!