

The evolution of low-metallicity massive stars

Dorottya Szécsi

Supervisor: Prof. Dr. Norbert Langer



PhD defence

Bonn, 4th July 2016

The night-sky and beyond



The night-sky and beyond



The night-sky and beyond



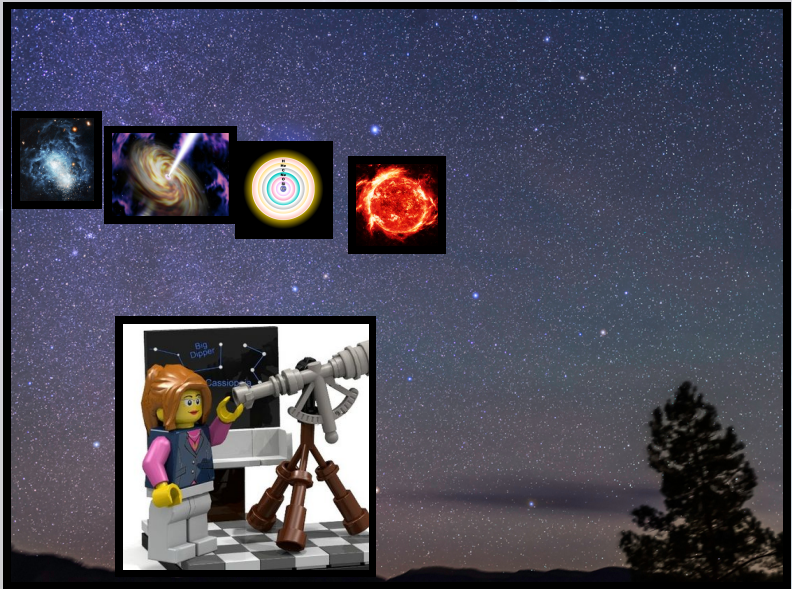
The night-sky and beyond



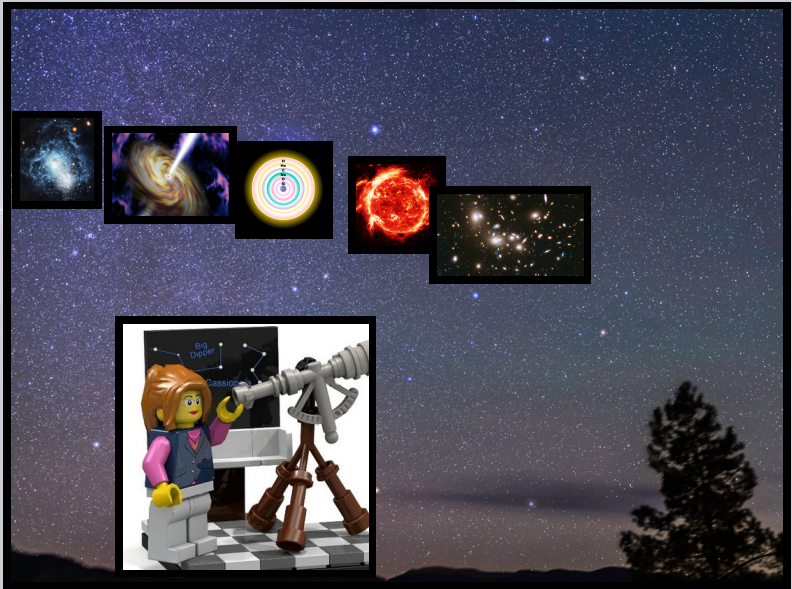
The night-sky and beyond



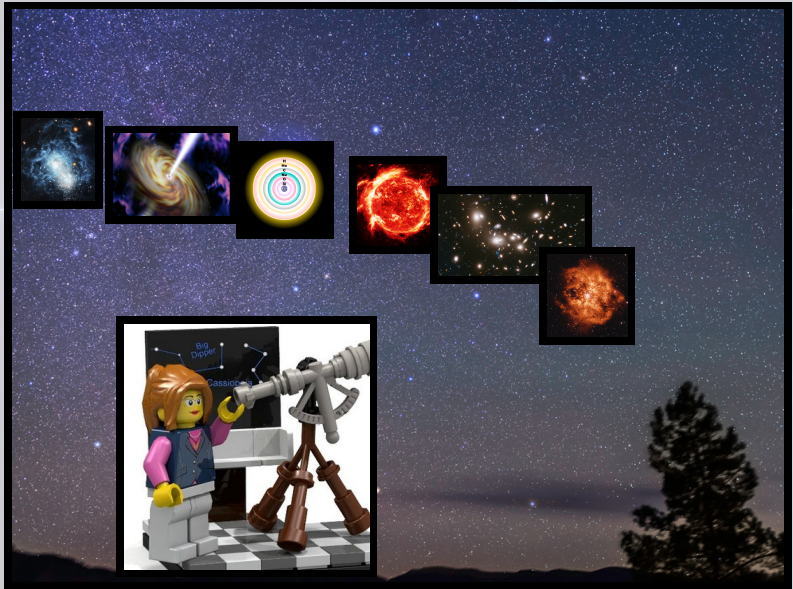
The night-sky and beyond



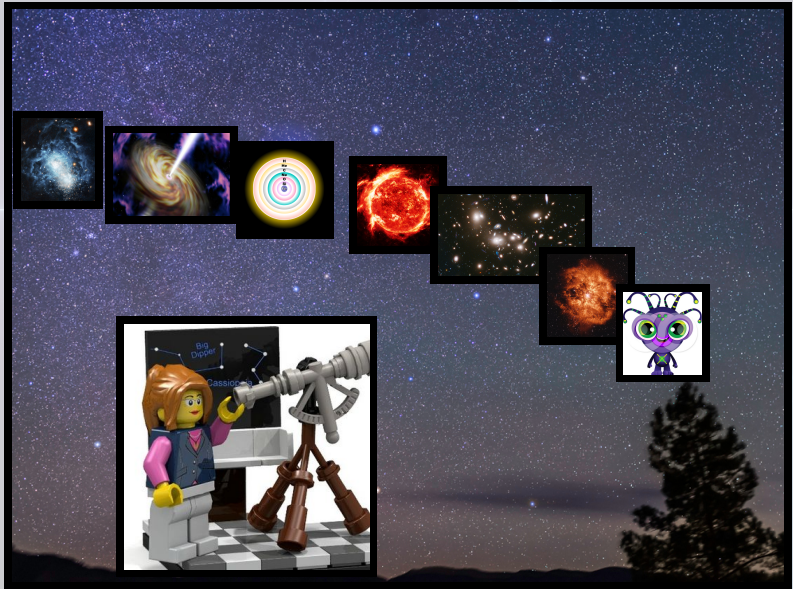
The night-sky and beyond



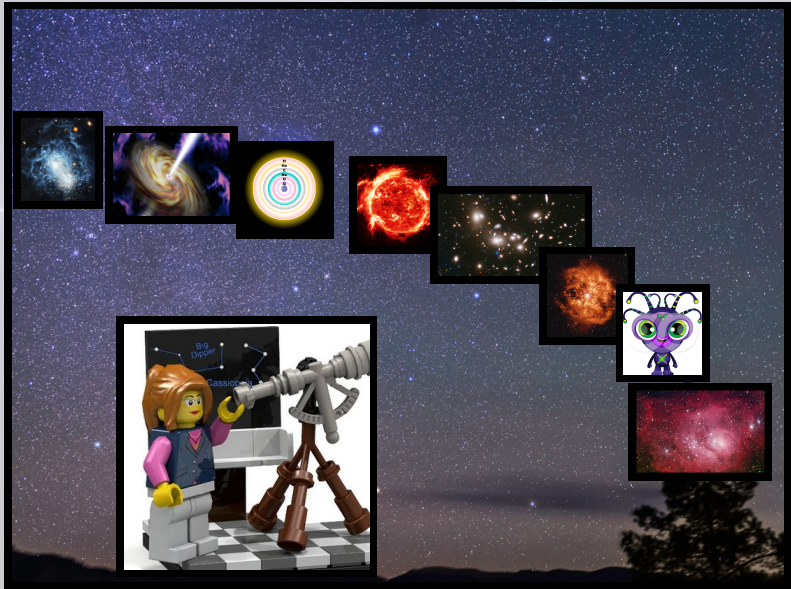
The night-sky and beyond



The night-sky and beyond



The night-sky and beyond



Astronomers and metal

LEGEND

- Non-Metal
- Metal

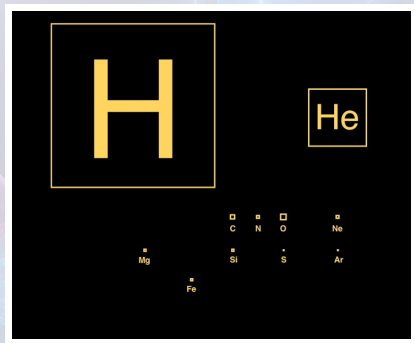
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh												

Astronomers and metal

LEGEND

- ☐ : Non-Metal
- ☐ : Metal

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh												

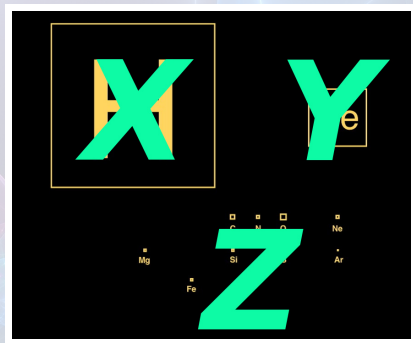


Astronomers and metal

LEGEND

- Non-Metal
- Metal

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh												



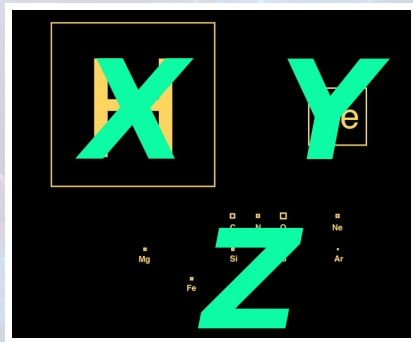
Astronomers and metal

LEGEND

- Non-Metal
- Metal

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh												

"Z: metallicity"



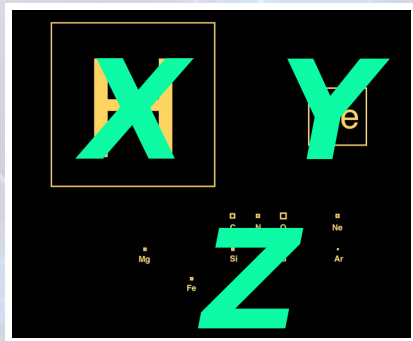
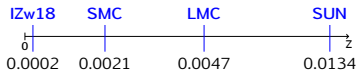
Astronomers and metal

LEGEND

□ : Non-Metal
 □ : Metal

H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh												

"Z: metallicity"



The early Universe ($Z \approx 0$)



Credit: hubblesite.org

Compact Dwarf Galaxies



Compact Dwarf Galaxies

I Zwicky 18

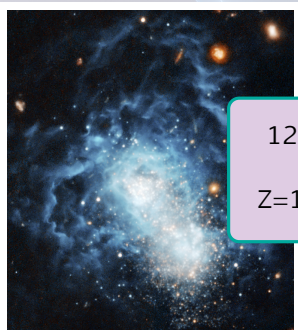
- Blue Compact Dwarf Galaxy
- 60 million lightyears
→ local
- star formation rate:
 $0.1 M_{\odot}/\text{yr}$
- ionized gas
- low metallicity!



Compact Dwarf Galaxies

I Zwicky 18

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



$$12 + \log(\text{O}/\text{H}) = 7.17$$

↓

$$Z = 1/50 Z_{\odot} \approx 0.0002$$

Compact Dwarf Galaxies

I Zwicky 18

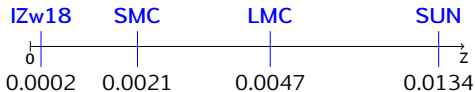
- Blue Compact Dwarf Galaxy
- 60 million lightyears
→ local
- star formation rate:
 $0.1 M_{\odot}/\text{yr}$
- ionized gas
- low metallicity!



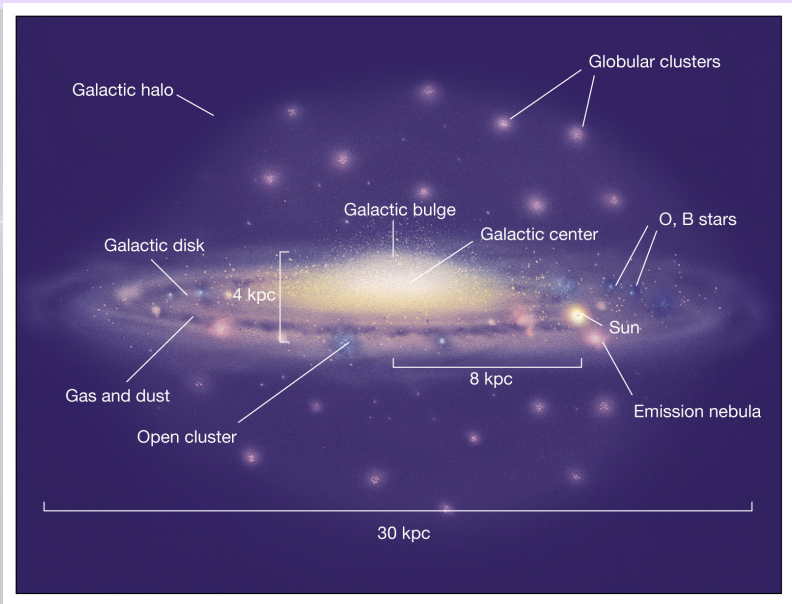
$$12 + \log(\text{O}/\text{H}) = 7.17$$

↓

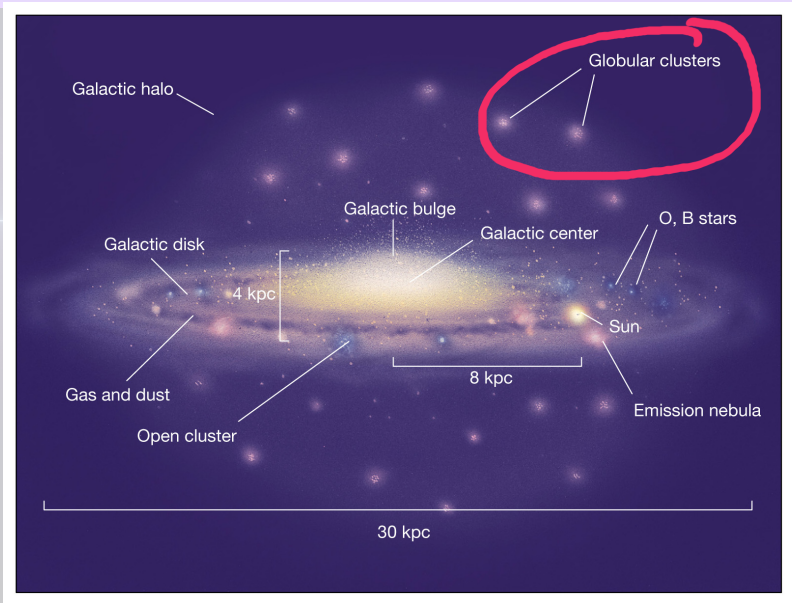
$$Z = 1/50 Z_{\odot} \approx 0.0002$$



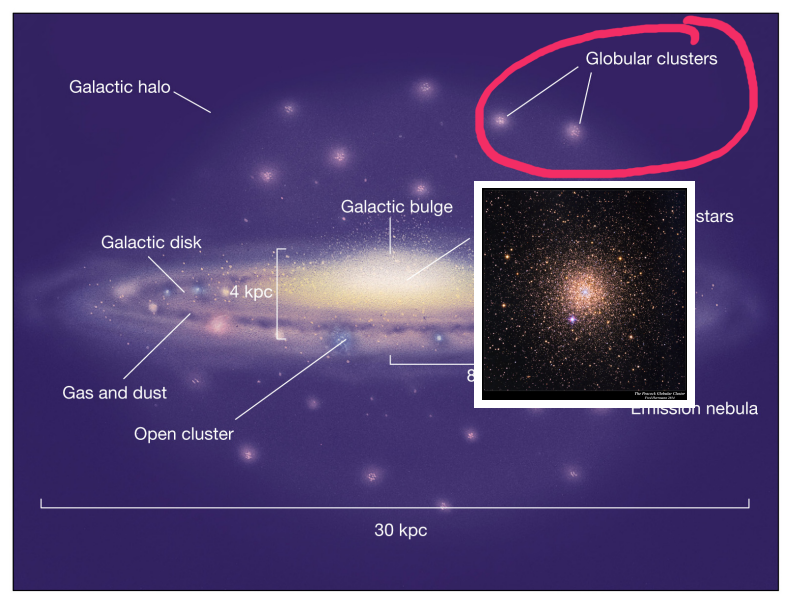
Globular Clusters



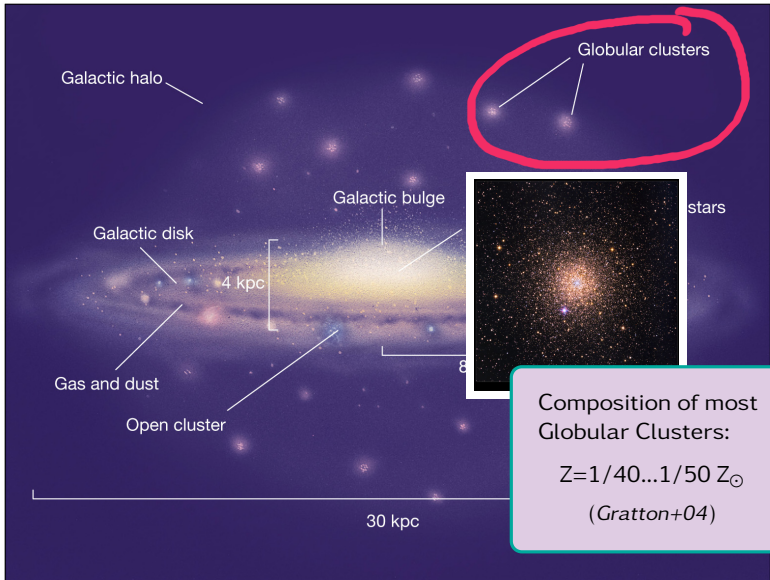
Globular Clusters



Globular Clusters



Globular Clusters



Composition of most
Globular Clusters:

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

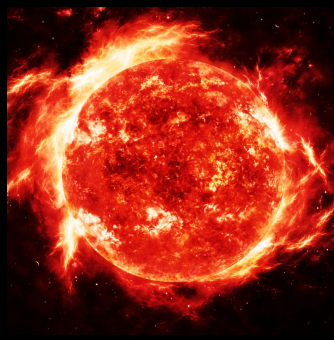
(Gratton+04)



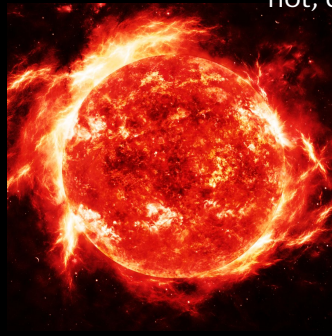
The background features a large, semi-transparent circle in the center. Overlaid on this are several thin, glowing lines in shades of blue, cyan, and magenta. These lines form a complex, web-like pattern that resembles a fractal or a network of connections. The overall aesthetic is futuristic and scientific.

What is a star?

What is a star?

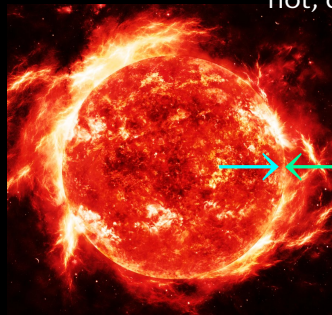


What is a star?



hot, dense plazma

What is a star?



hot, dense plazma

equilibrium:

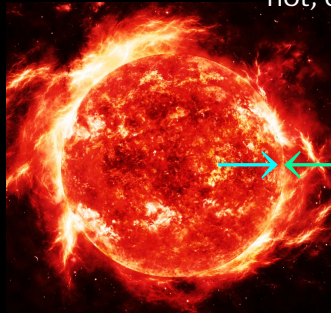
pressure gradient

gravity

What is a star?

surface?

hot, dense plazma



equilibrium:

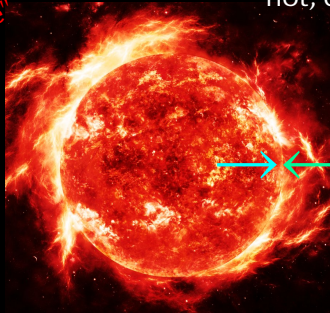
pressure gradient

gravity

What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



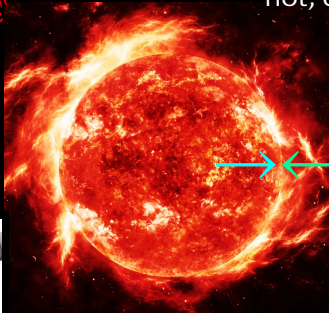
equilibrium:

pressure gradient gravity

What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



pressure gradient gravity



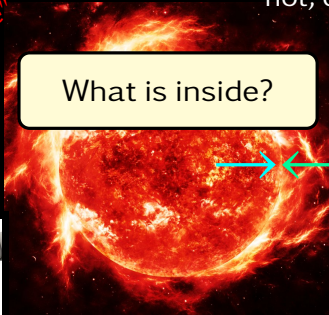
What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma

What is inside?

pressure gradient gravity



What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma

What is inside?

theoretical
modelling
of the stellar
structure

pressure gradient gravity



Theoretical modelling of the stellar structure

$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \quad \text{equation of definition of mass} \quad (9)$$

$$\frac{\partial P}{\partial m_r} = -\frac{Gm_r}{4\pi r^4} \quad \text{equation of hydrostatic equilibrium} \quad (10)$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\text{pl}} - T \frac{\partial S}{\partial t} \quad \text{equation of energetic balance} \quad (11)$$

$$\frac{\partial T}{\partial m_r} = -\frac{Gm_r T}{4\pi r^4 P} \nabla \quad \text{equation of energy transport,} \quad (12)$$

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

$$\frac{\partial P}{\partial m_r} = -\frac{Gm_r}{4\pi r^4} \quad \text{equation of hydrostatic equilibrium} \quad (10)$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\text{pl}} - T \frac{\partial S}{\partial t} \quad \text{equation of energetic balance} \quad (11)$$

$$\frac{\partial T}{\partial m_r} = -\frac{Gm_r T}{4\pi r^4 P} \nabla \quad \text{equation of energy transport,} \quad (12)$$

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

$$\frac{\partial P}{\partial m_r} = -\frac{Gm_r}{4\pi r^4} \quad \text{equation of momentum conservation} \quad (10)$$

$$\frac{\partial L_r}{\partial m_r} = \epsilon_{\text{pl}} - T \frac{\partial S}{\partial t} \quad \text{equation of energetic balance} \quad (11)$$

$$\frac{\partial T}{\partial m_r} = -\frac{Gm_r T}{4\pi r^4 P} \nabla \quad \text{equation of energy transport,} \quad (12)$$

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

$$\frac{\partial P}{\partial m_r} = -\frac{Gm_r}{4\pi r^4} \quad \text{equation of momentum conservation} \quad (10)$$

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

$$\frac{\partial T}{\partial m_r} = -\frac{Gm_r T}{4\pi r^4 P} \nabla \quad \text{equation of energy transport,} \quad (12)$$

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

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

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

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

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

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

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

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

Guilera et al. 2011

composition change due to nuclear burning ?!

Theoretical modelling of the stellar structure

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

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

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

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

Guilera et al. 2011

composition change due to nuclear burning ?!

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

Theoretical modelling of the stellar structure

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

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

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

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

Guilera et al. 2011

composition change due to nuclear burning ?!

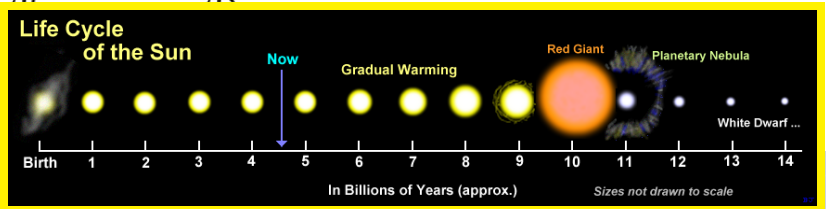
$$\frac{\partial X_i}{\partial t} = \frac{A_i m_u}{\rho} (-\Sigma_{j,k} r_{i,j,k} + \Sigma_{k,l} r_{k,l,i}) \quad (13)$$

+ Rotation.

Theoretical modelling of the stellar structure

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

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



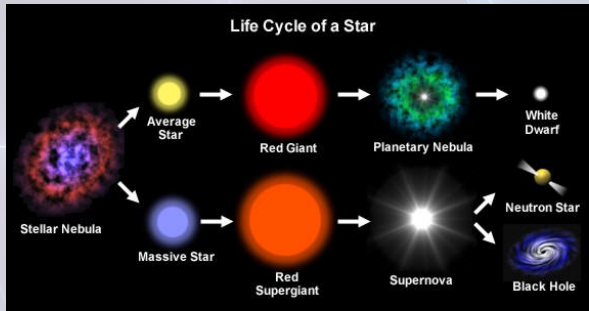
composition change due to nuclear burning !?

$$\frac{\partial X_i}{\partial t} = \frac{A_i m_u}{\rho} (-\sum_{j,k} r_{i,j,k} + \sum_{k,l} r_{k,l,i}) \quad (13)$$

+ Rotation.

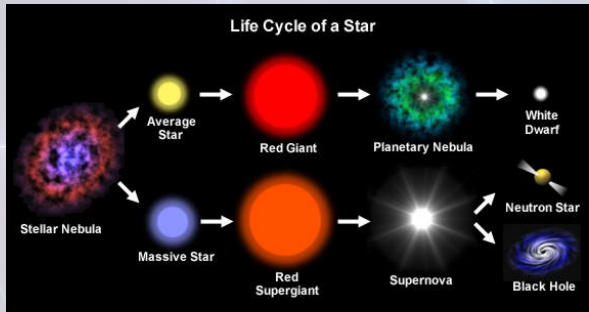
Massive vs. low-mass stars

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



Massive vs. low-mass stars

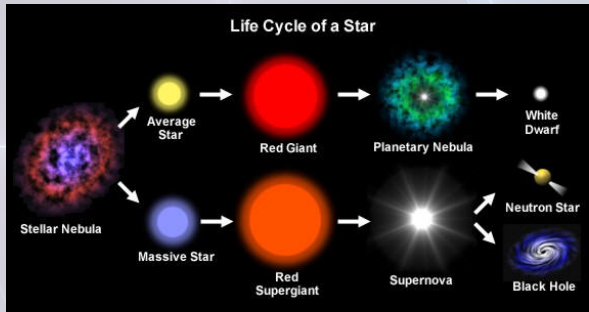
Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9 M_{\odot}$)



- nuclear reactions, final composition

Massive vs. low-mass stars

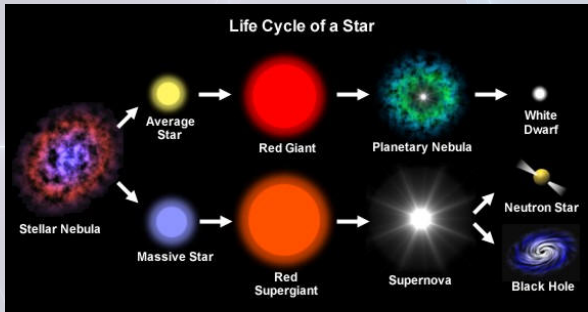
Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9 M_{\odot}$)



- nuclear reactions, final composition
- number of stars: massive stars are rare

Massive vs. low-mass stars

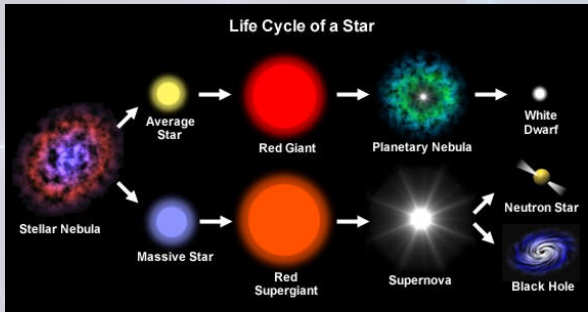
Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9 M_{\odot}$)



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

Massive vs. low-mass stars

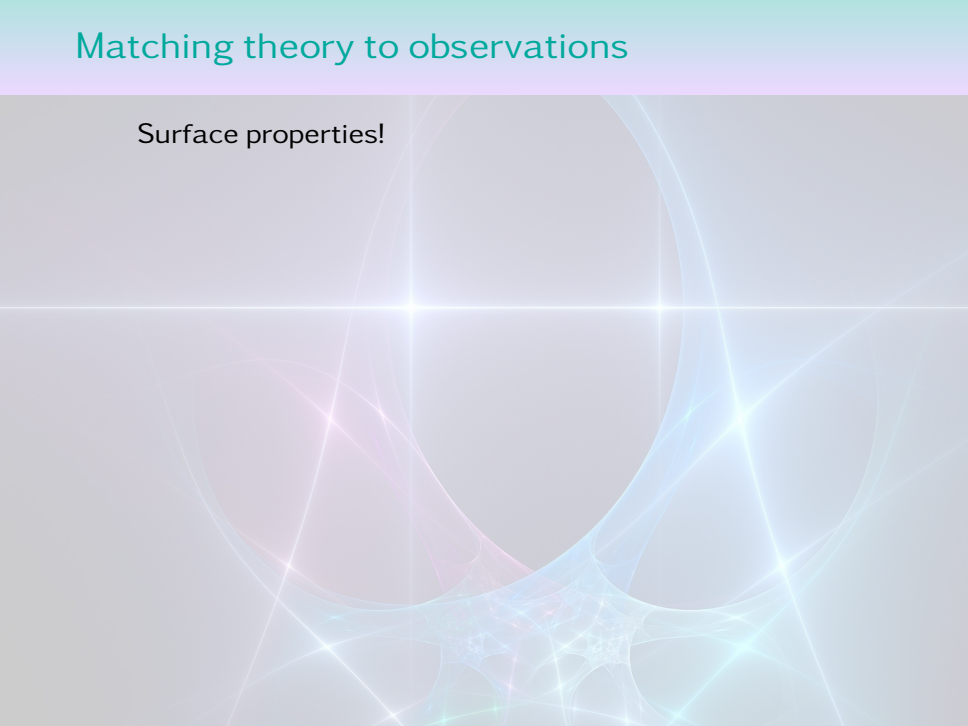
Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9 M_{\odot}$)



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

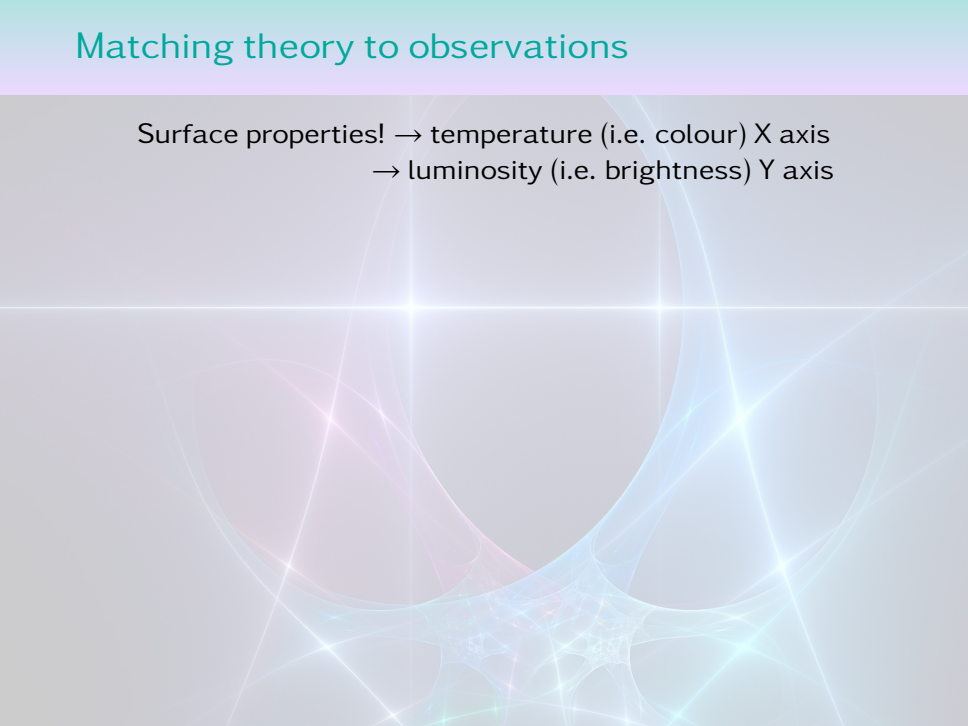
Matching theory to observations

Surface properties!

The background of the slide is a complex, abstract composition. It features a large, semi-transparent sphere in the center, which appears to be a celestial body or a lens. Overlaid on this and the entire background are numerous thin, glowing lines in various colors, including cyan, magenta, and white. These lines intersect and curve, creating a sense of depth and movement. The overall aesthetic is futuristic and scientific, with a focus on light and geometric forms.

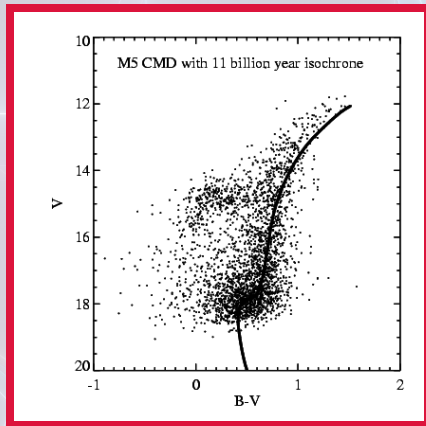
Matching theory to observations

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

The background of the slide features a complex, abstract pattern of glowing, overlapping lines and shapes. A prominent horizontal line of light crosses the center, with a bright, multi-colored starburst or lens flare at its intersection with a vertical line. The overall color palette is soft and ethereal, with shades of light blue, pink, and white. The lines appear to be part of a larger, intricate geometric or fractal-like structure.

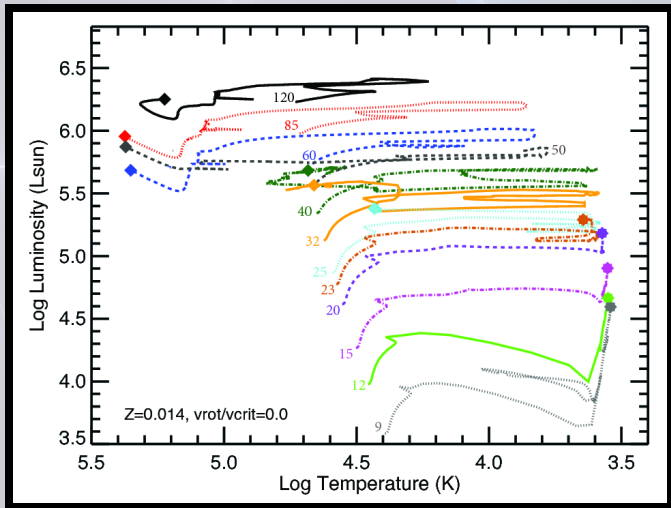
Matching theory to observations

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

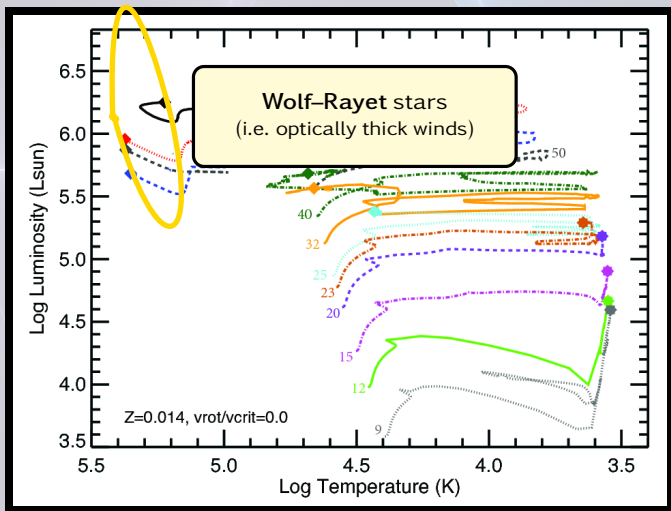


Hertzsprung–Russell diagram (HR diagram)

Hertzprung–Russell diagram



Hertzprung–Russell diagram



The background features a large, semi-transparent circle in the center. Overlaid on this are several thin, glowing lines in shades of blue, cyan, and magenta. These lines form a complex, web-like pattern that resembles a fractal or a network of connections. The overall aesthetic is clean, modern, and scientific.

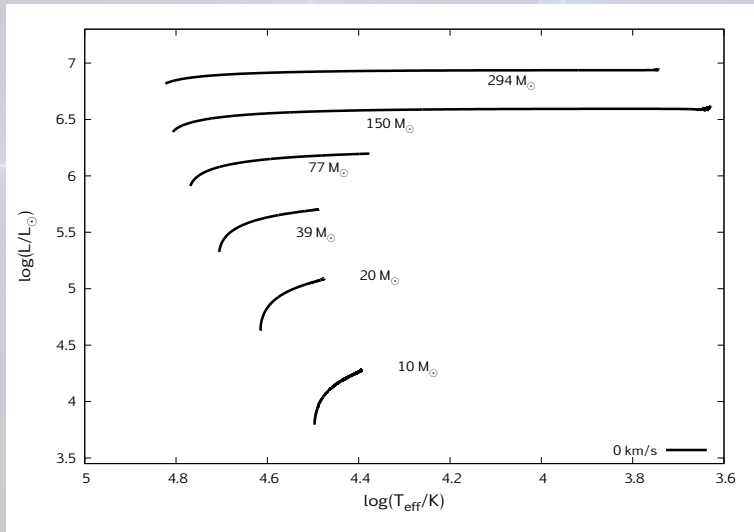
Low Metallicity Massive Stars

Low Metallicity Massive Stars

– my thesis 😊

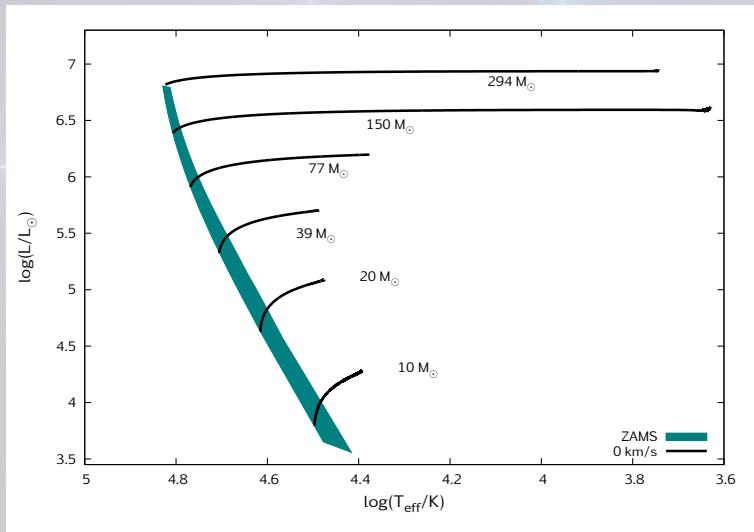
Low Metallicity Massive Stars

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



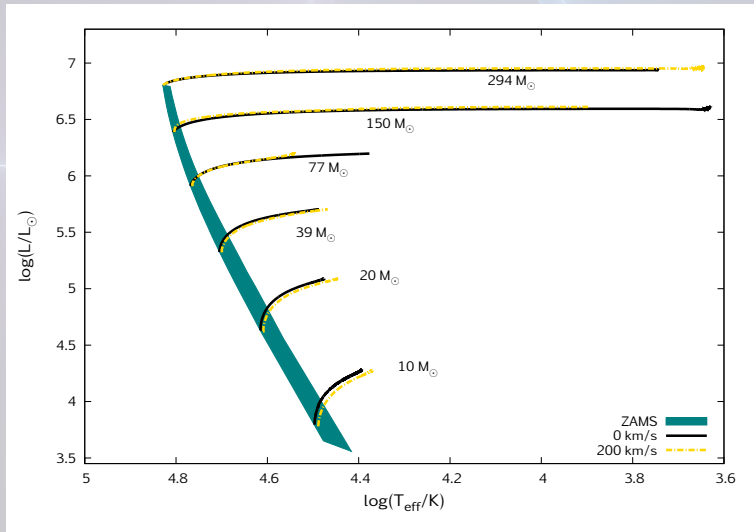
Low Metallicity Massive Stars

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



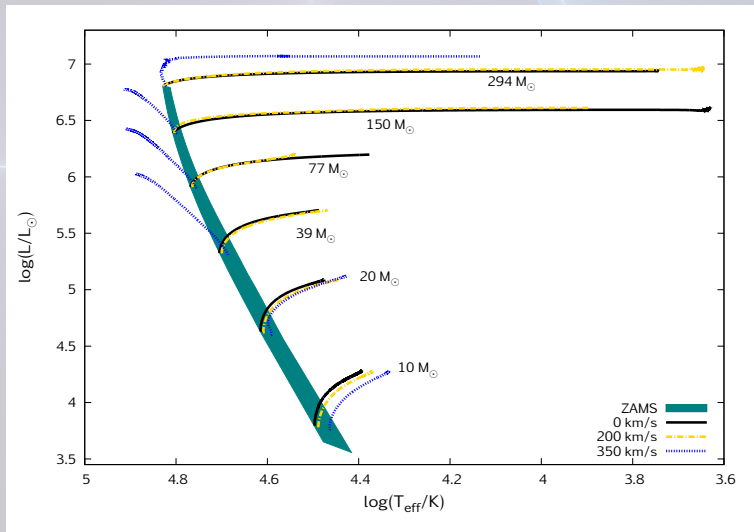
Low Metallicity Massive Stars

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



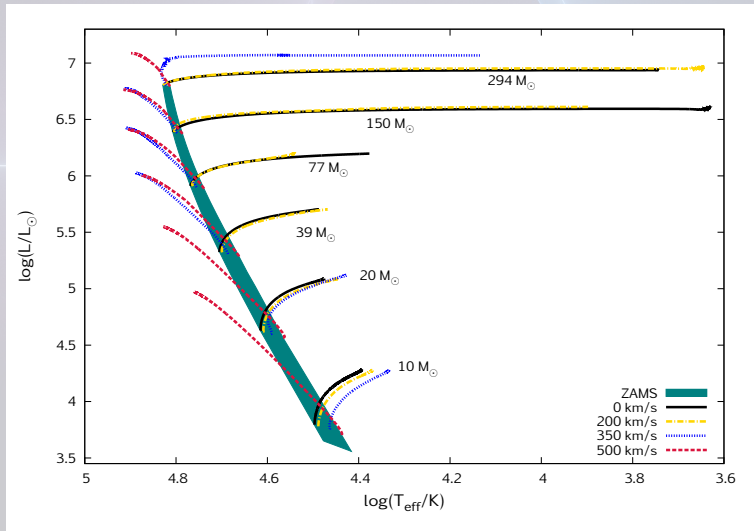
Low Metallicity Massive Stars

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



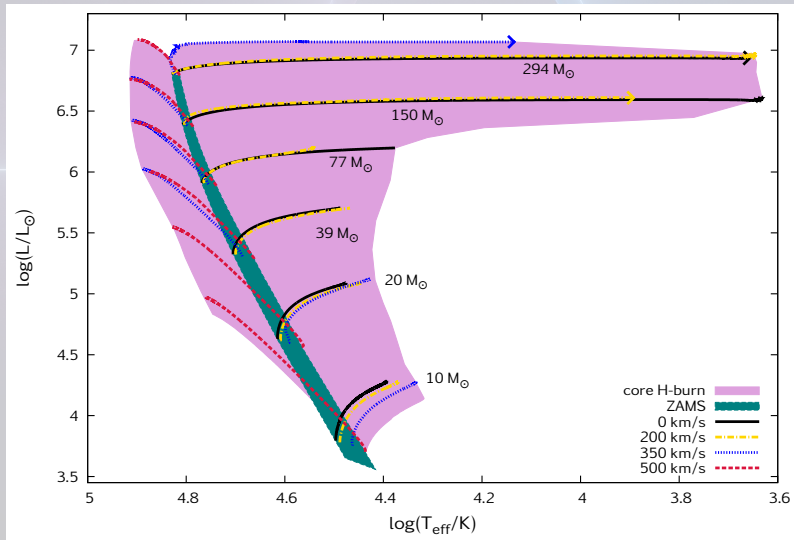
Low Metallicity Massive Stars

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



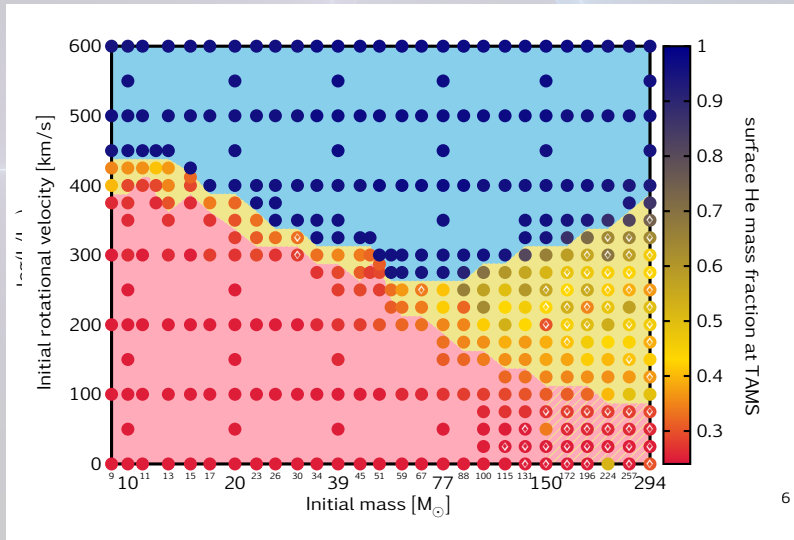
Low Metallicity Massive Stars

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



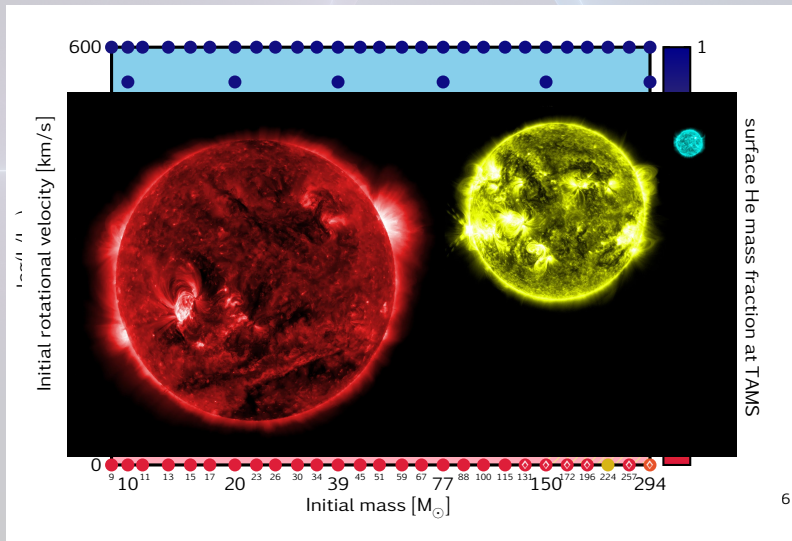
Low Metallicity Massive Stars

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



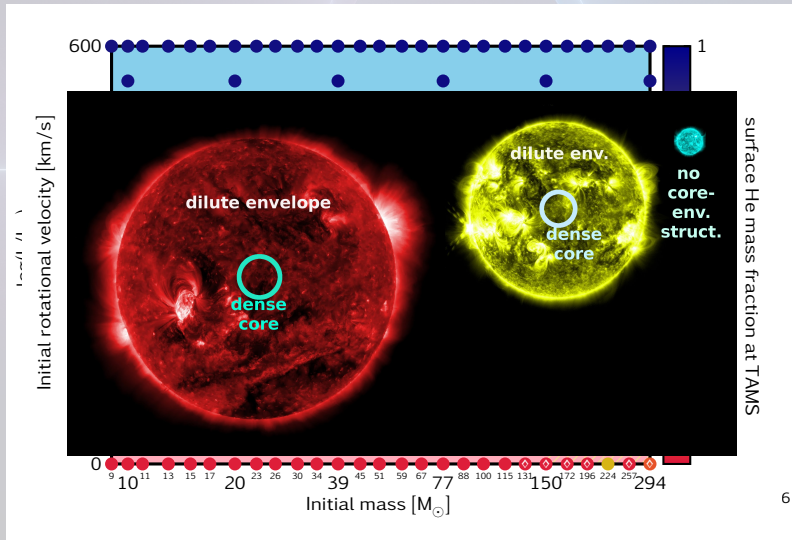
Low Metallicity Massive Stars

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



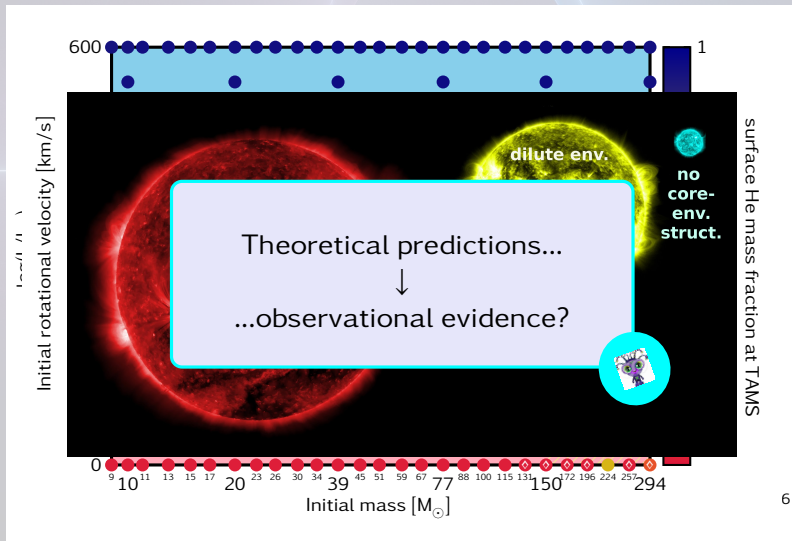
Low Metallicity Massive Stars

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



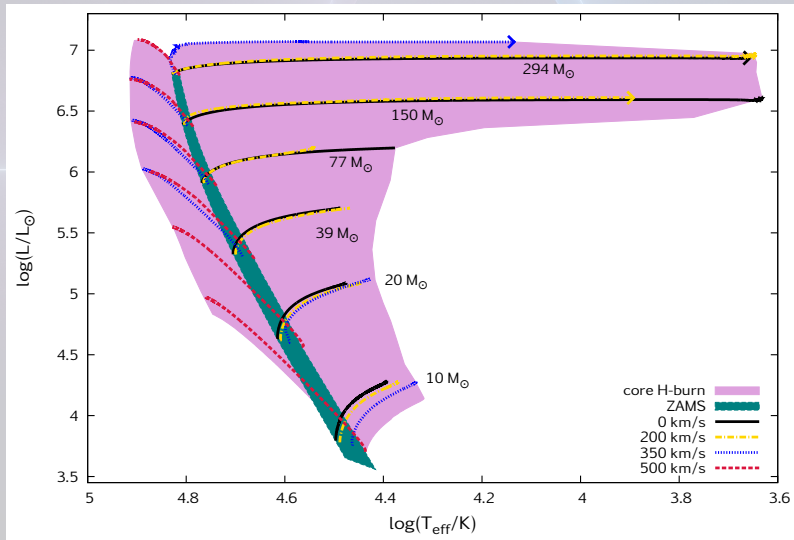
Low Metallicity Massive Stars

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



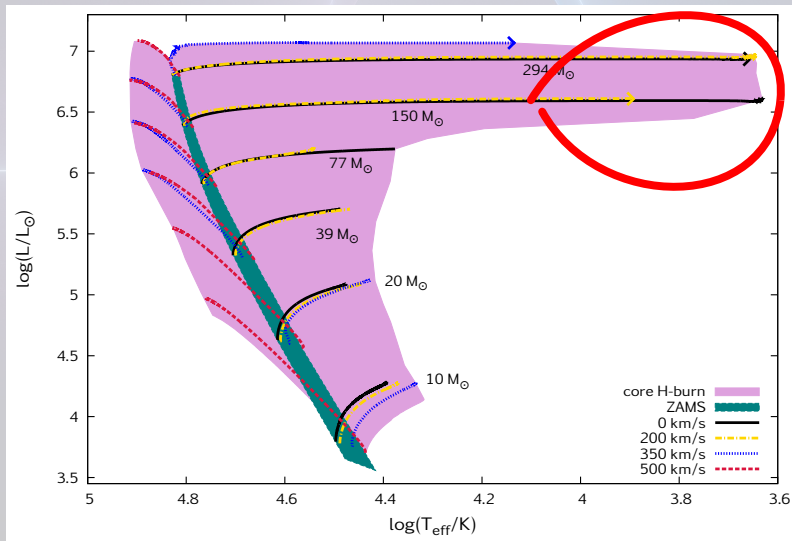
Low Metallicity Massive Stars

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



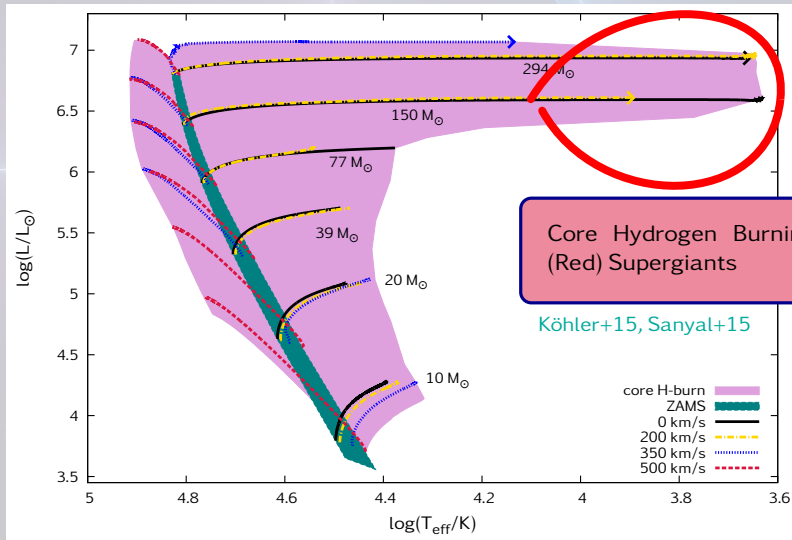
Low Metallicity Massive Stars

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



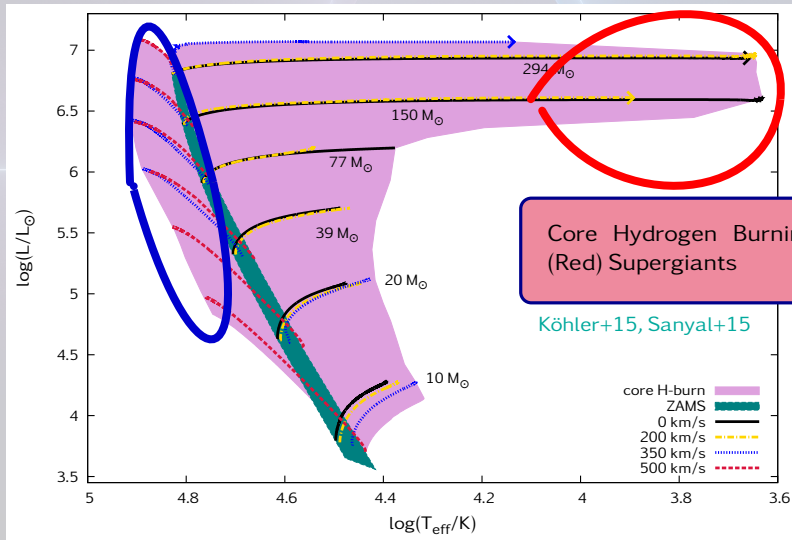
Low Metallicity Massive Stars

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



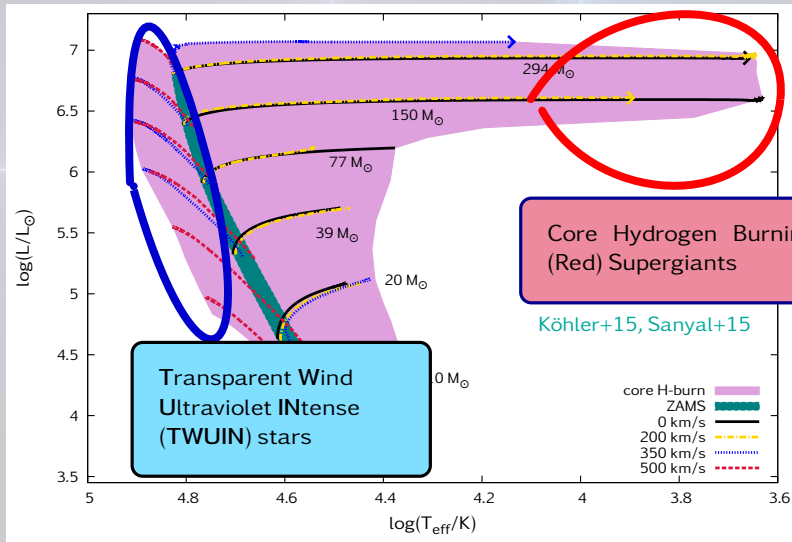
Low Metallicity Massive Stars

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



Low Metallicity Massive Stars

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

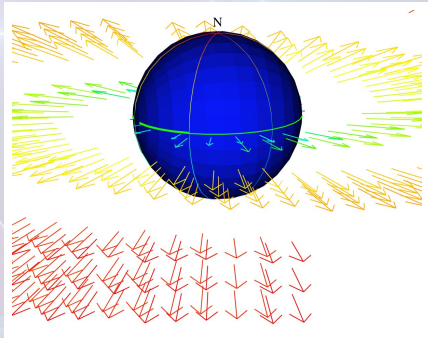


Transparent Wind
Ultraviolet Intense stars
(TWUIN stars)

– in the
starburst galaxy | Zwicky 18

Stellar winds

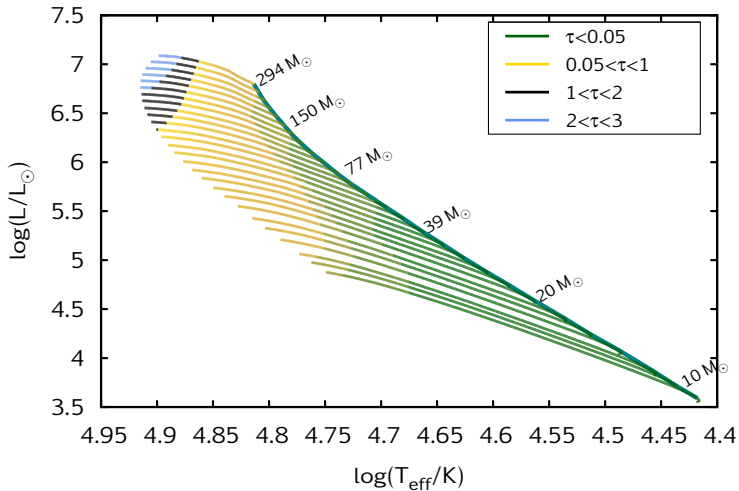
- stellar 'wind': accelerated particle flow
- hot stars at **solar Z**: **Wolf-Rayet (WR)** stars
 - opaque wind → strong emission lines
- hot stars at **low Z**?



Hot stars at low Z: transparent wind!

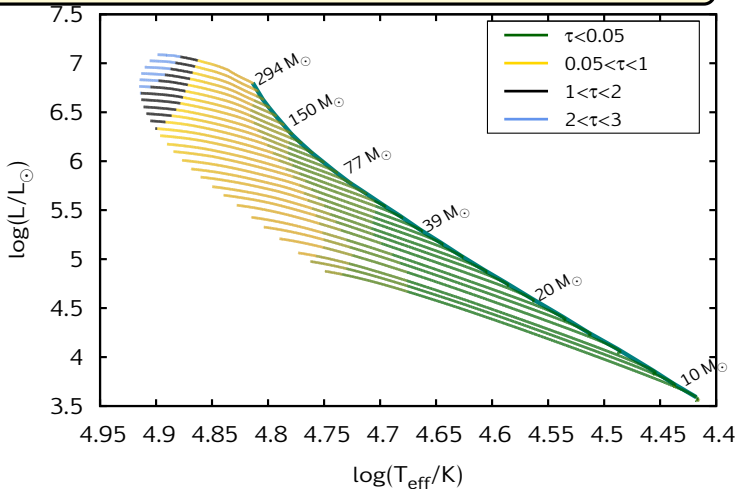


Hot stars at low Z: transparent wind!



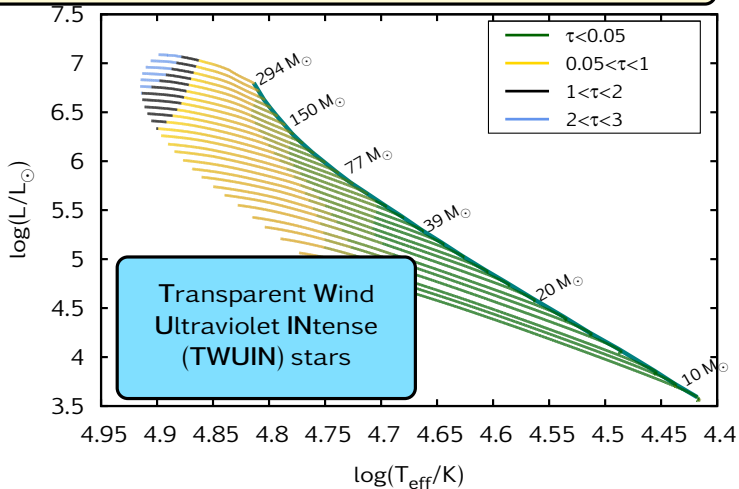
Hot stars at low Z: transparent wind!

Core-H-burning lifetime: wind optical depth is $\tau \lesssim 1$



Hot stars at low Z: transparent wind!

Core-H-burning lifetime: wind optical depth is $\tau \lesssim 1$



Back to I Zw 18

I Zwicky 18

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

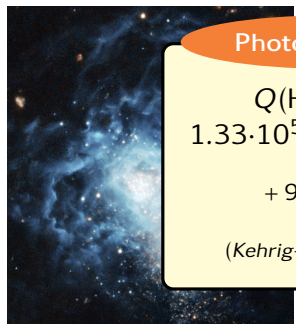


Legrand+07, Aloisi+09, Annibali+13, Kehrig+13, Leboutteiller+13

Back to I Zw 18

I Zwicky 18

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



Photoionization

$$Q(\text{H}\alpha)^{\text{obs}} = 1.33 \cdot 10^{50} \text{ photons s}^{-1}$$

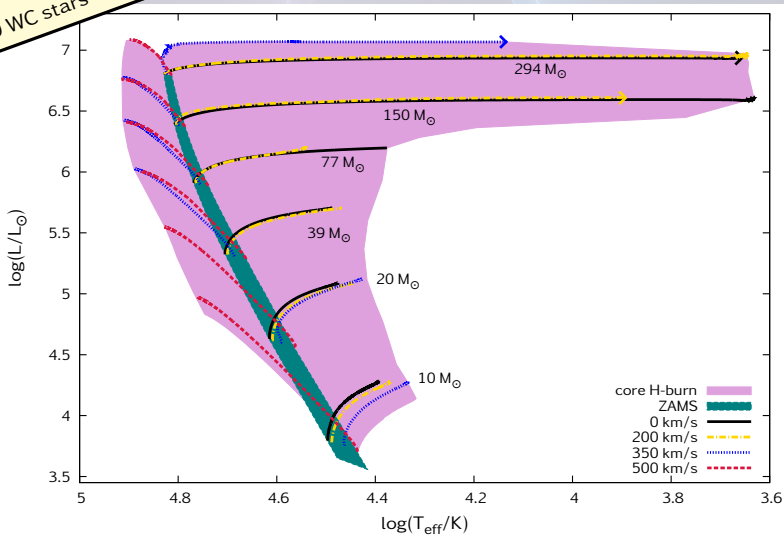
+ 9 WC stars

(Kehrig+15, Crowther+06)

Photoionization in I Zw 18

Photoionization

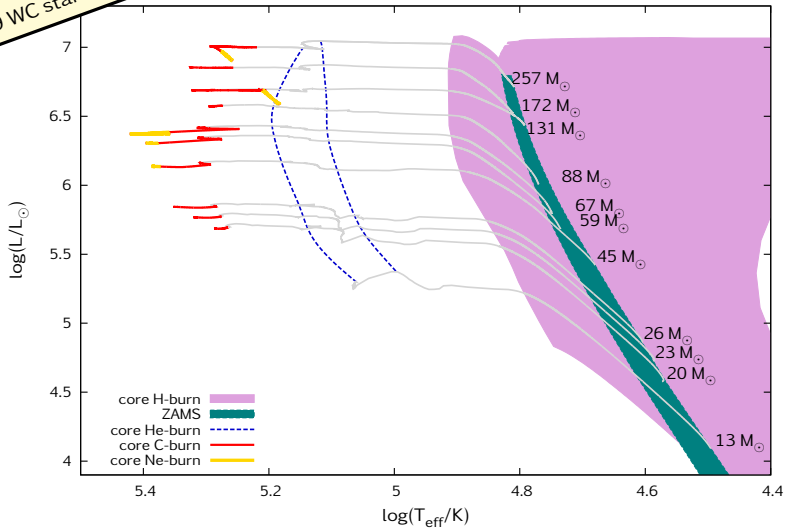
$Q(\text{HeII})^{\text{obs}} =$
 $1.33 \cdot 10^{50} \text{ photons s}^{-1}$
+ 9 WC stars



Photoionization in I Zw 18

Photoionization

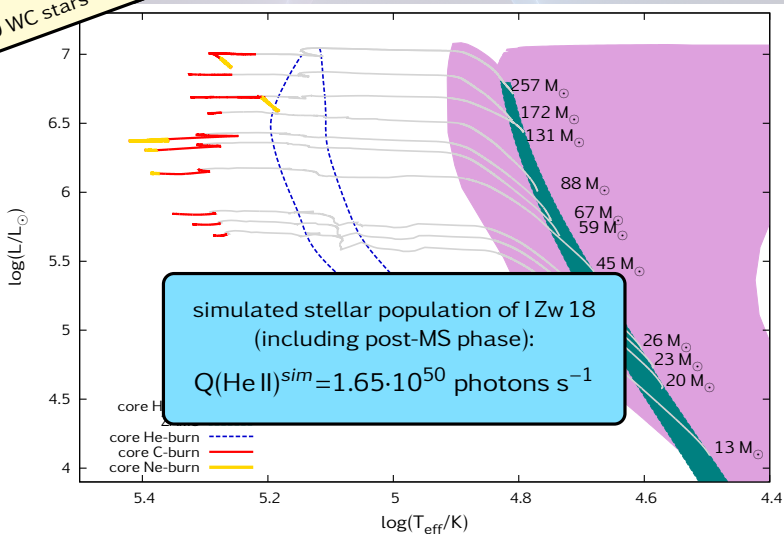
$Q(\text{HeII})^{\text{obs}} =$
 $1.33 \cdot 10^{50} \text{ photons s}^{-1}$
+ 9 WC stars



Photoionization in I Zw 18

Photoionization

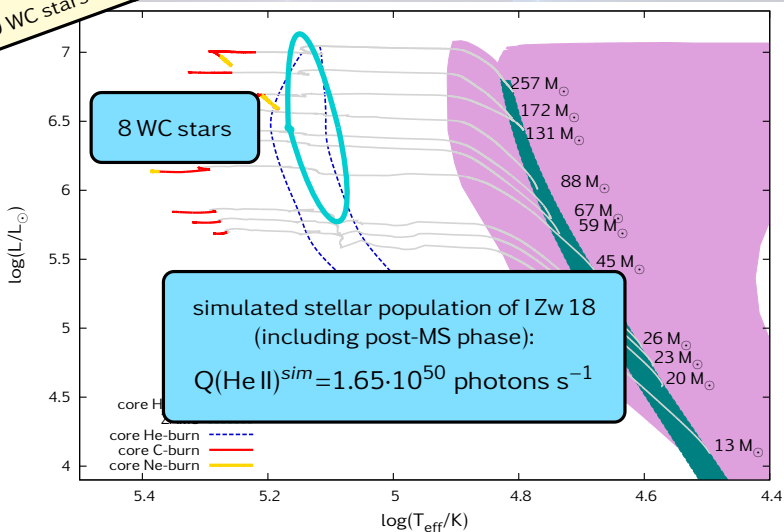
$Q(\text{HeII})^{\text{obs}} =$
 $1.33 \cdot 10^{50} \text{ photons s}^{-1}$
+ 9 WC stars



Photoionization in I Zw 18

Photoionization

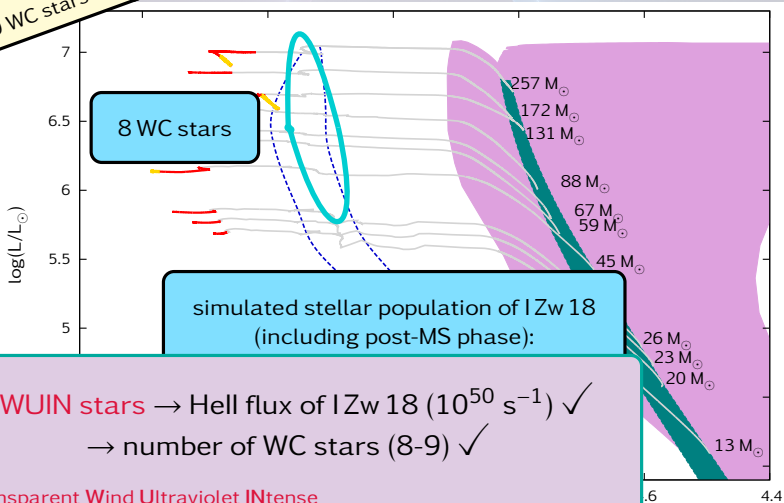
$$Q(\text{HeII})^{\text{obs}} = 1.33 \cdot 10^{50} \text{ photons s}^{-1} + 9 \text{ WC stars}$$

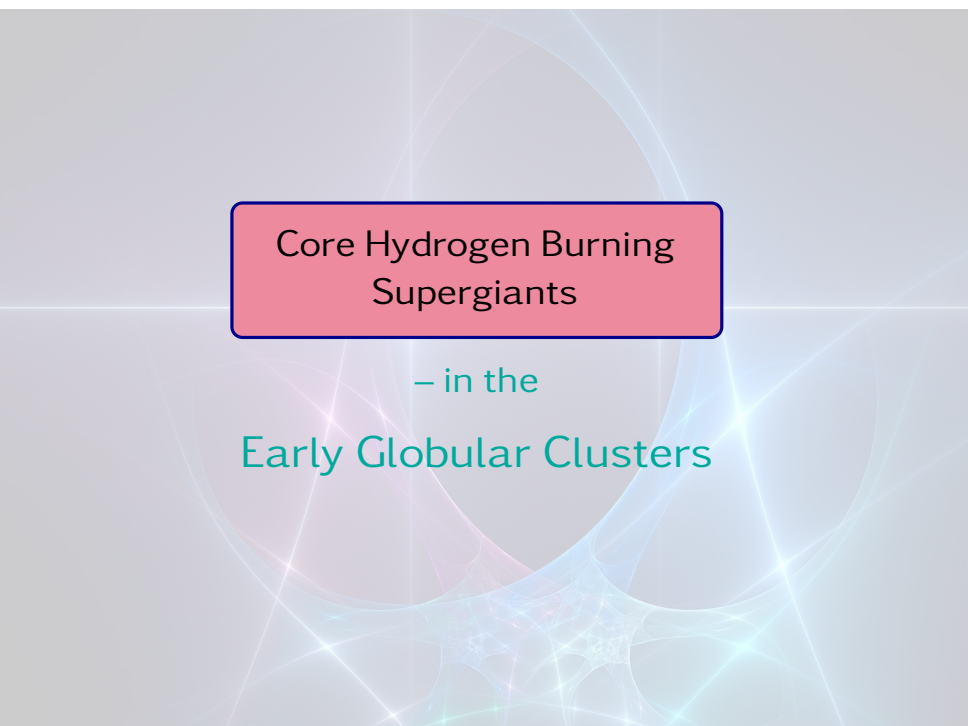


Photoionization in I Zw 18

Photoionization

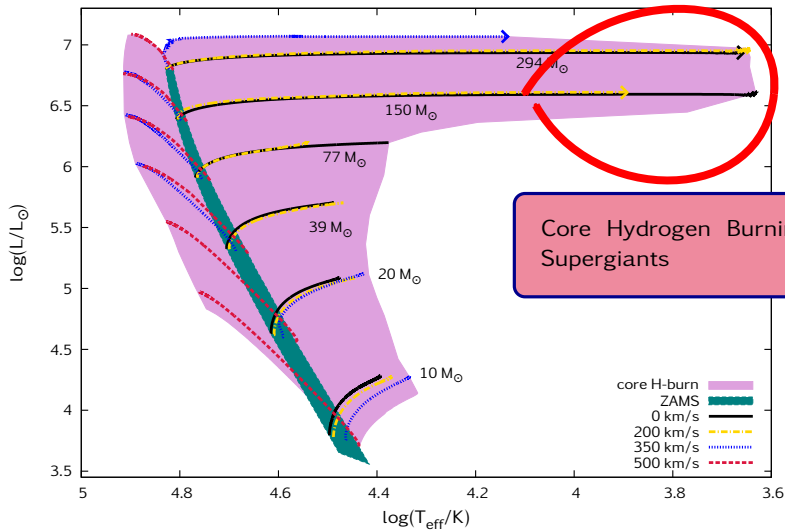
$$Q(\text{HeII})^{\text{obs}} = 1.33 \cdot 10^{50} \text{ photons s}^{-1} + 9 \text{ WC stars}$$



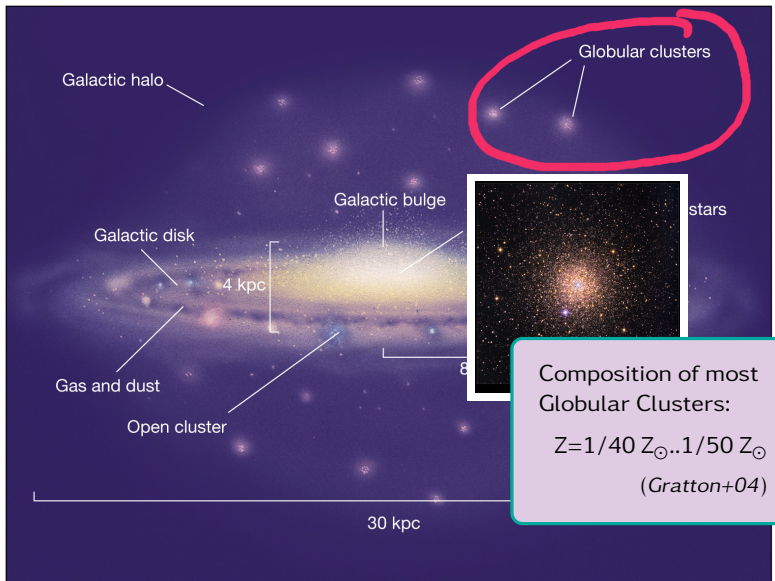


Core Hydrogen Burning
Supergiants

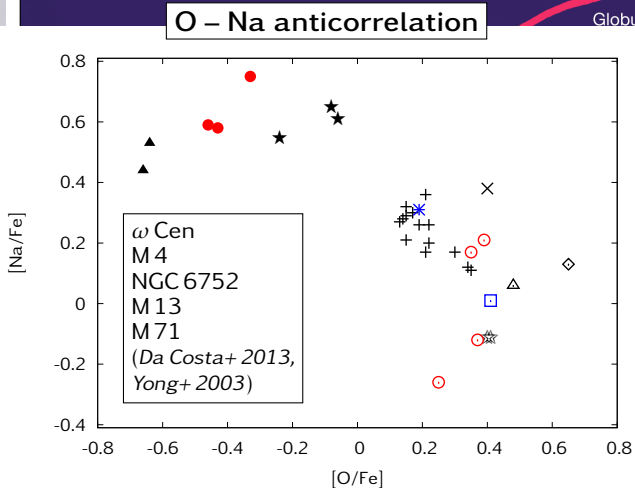
– in the
Early Globular Clusters



Globular Clusters & Abundance Anomalies



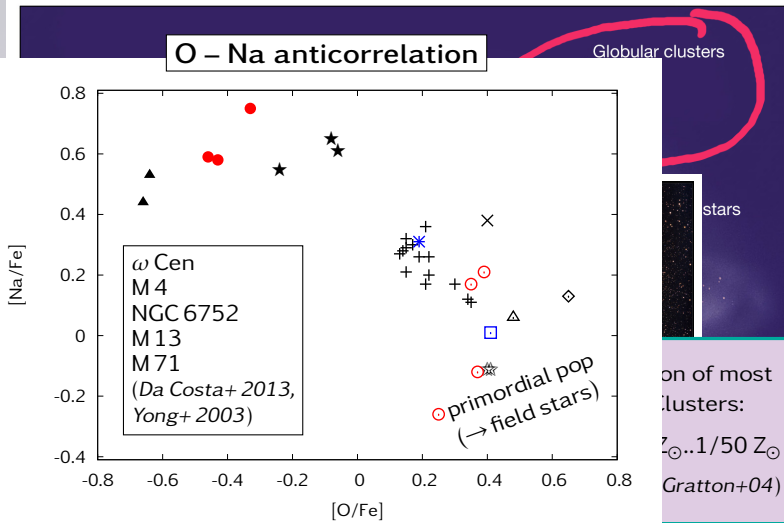
Globular Clusters & Abundance Anomalies



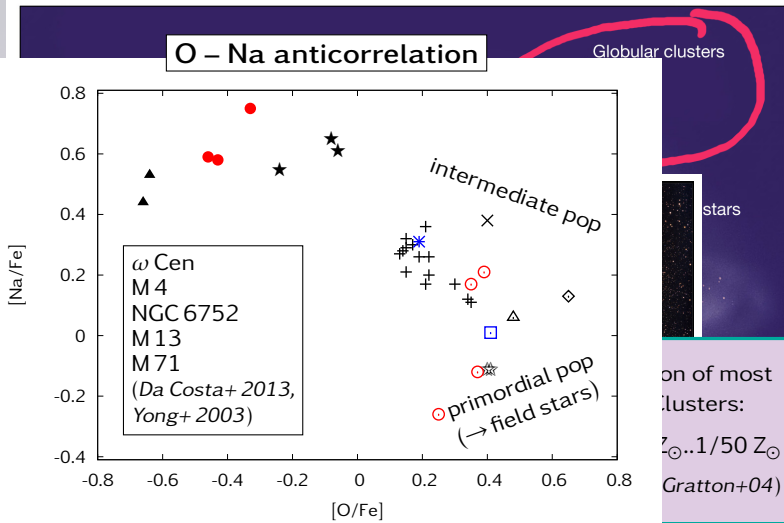
ion of most
clusters:
 $Z_{\odot} \sim 0.1/50 Z_{\odot}$
(Gratton+04)



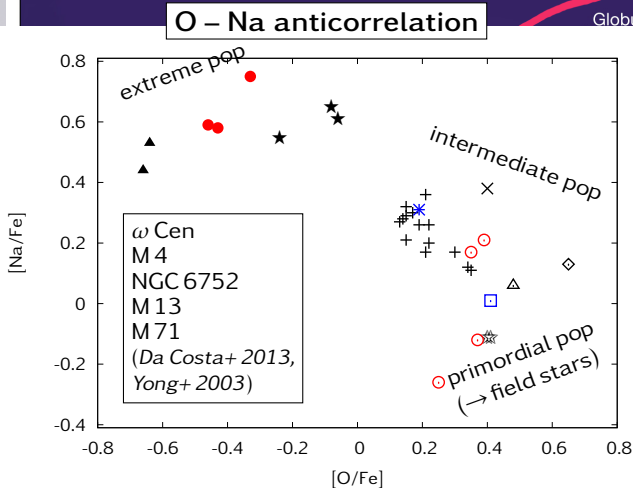
Globular Clusters & Abundance Anomalies



Globular Clusters & Abundance Anomalies



Globular Clusters & Abundance Anomalies

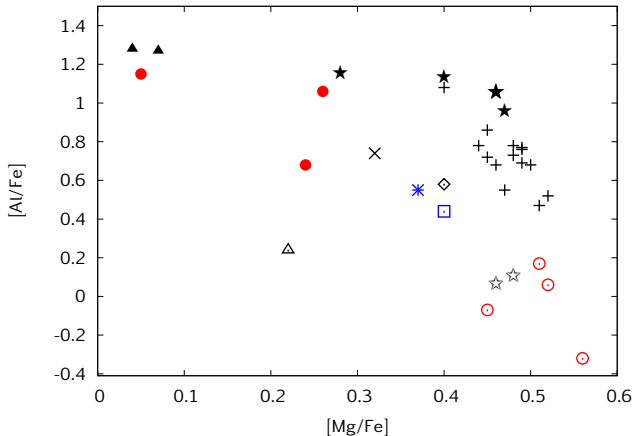


most
clusters:
 $Z_{\odot} \approx 0.1/50 Z_{\odot}$
(Gratton+04)



Globular Clusters & Abundance Anomalies

Mg - Al anticorrelation



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

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

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*)

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.)

Globular Clusters & Abundance Anomalies

Mg – Al anticorrelation

Globular clusters

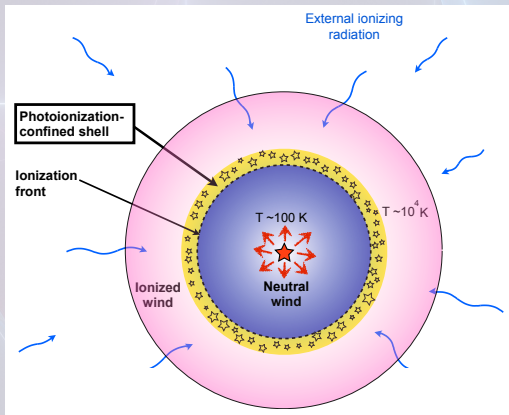
- extreme & intermediate pop: **polluted** by hot hydrogen burning
 - CNO-cycle, Ne-Na and Mg-Al chains
- need: **astrophysical source** that can pollute the ISM
 - **AGB stars**: hot bottom burning (*Ventura+ 2001*)
 - **fast rotating massive stars**: close to break-up (*Decressin+ 2007*)
 - **supermassive 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...**

The background features a large, semi-transparent sphere in the upper center. A network of glowing, multi-colored lines (pink, blue, green, and purple) crisscrosses the scene, creating a complex, web-like structure. A bright horizontal line of light passes through the center of the sphere, with a small starburst effect at its intersection. The overall aesthetic is futuristic and ethereal.

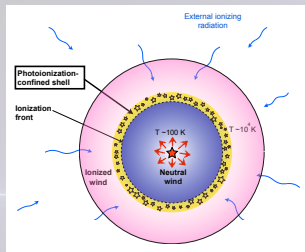
New scenario:
Starforming Supergiant Shells

New scenario: Starforming Supergiant Shells

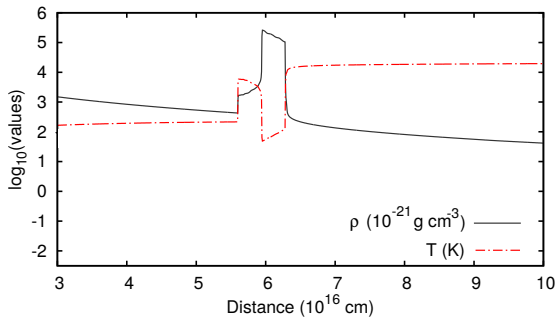
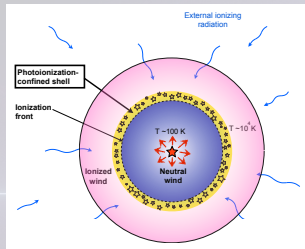


PICO shell: Mackey+ 2014 (*Nature*)

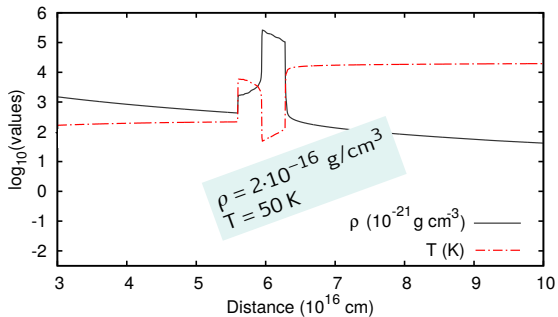
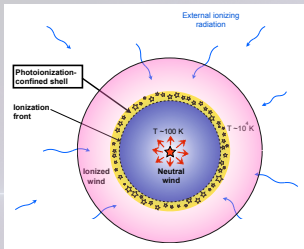
Simulating the PICO shell



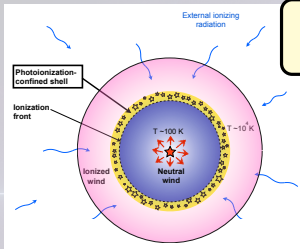
Simulating the PICO shell



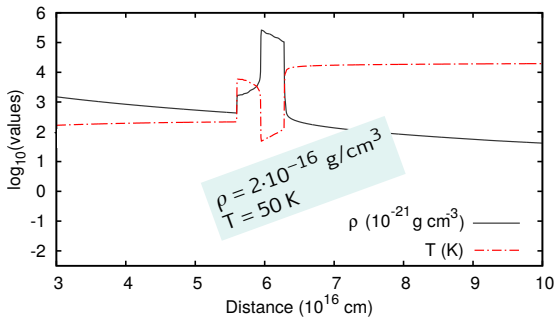
Simulating the PICO shell



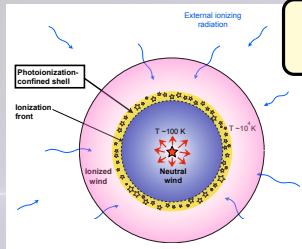
Simulating the PICO shell



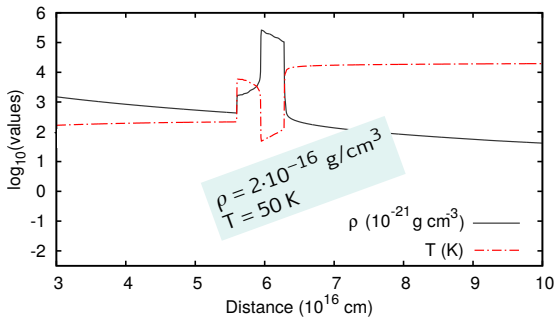
Mass of the photoionization-confined (PICO) shell: $\sim 14 M_{\odot}$



Simulating the PICO shell



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

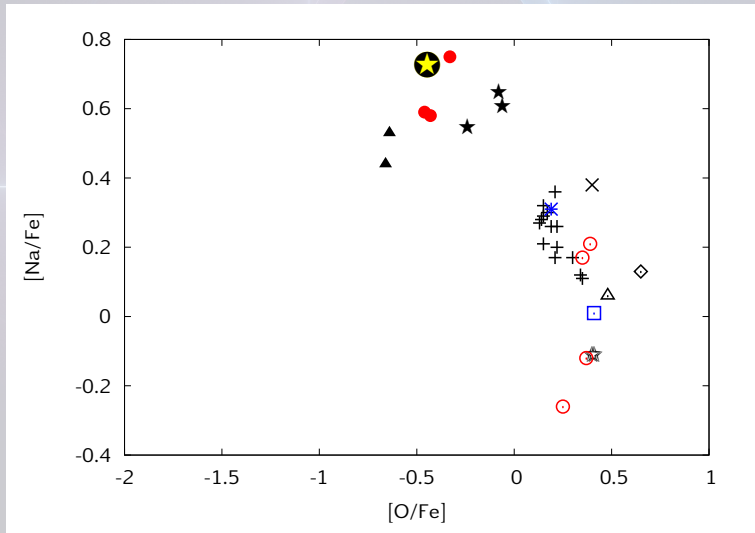


Lifetime of the shell: $\sim 10^5 \text{ yr}$

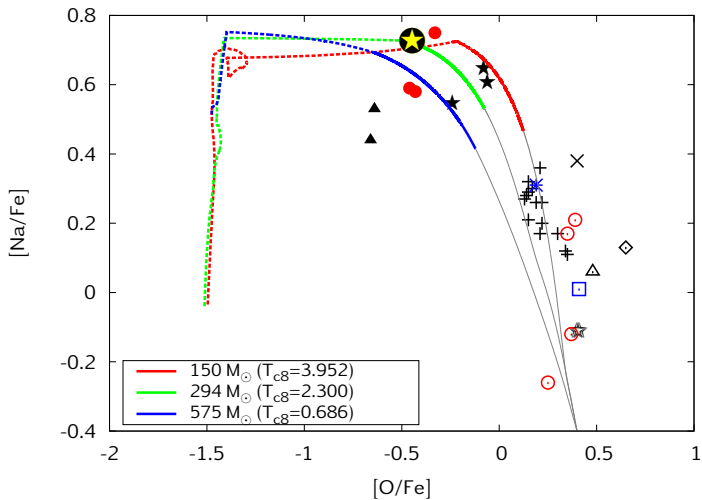
\gg

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

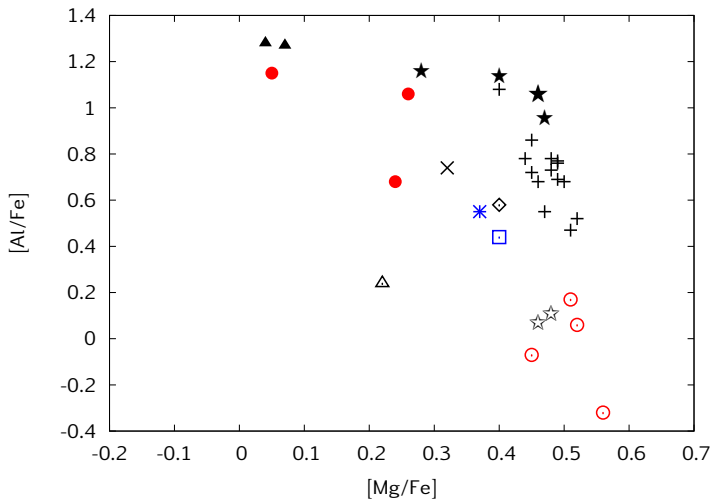
Compared to observations: O – Na anticorr.



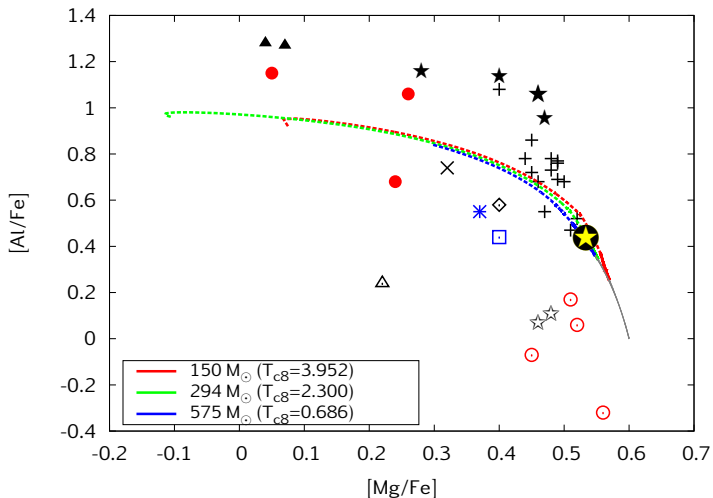
Compared to observations: O – Na anticorr.



Compared to observations: Mg – Al anticorr.



Compared to observations: Mg – Al anticorr.



Conclusions



Conclusions

A large grid of low- Z massive star models

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



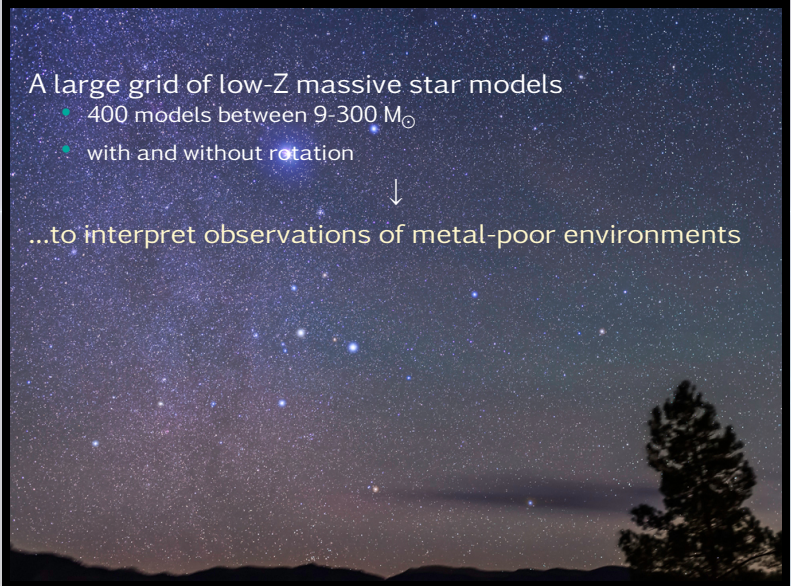
Conclusions

A large grid of low-Z massive star models

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



...to interpret observations of metal-poor environments



Conclusions

A large grid of low-Z massive star models

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



...to interpret observations of metal-poor environments

- ionization and WR stars in I Zw 18 ✓
- core-H-burning supergiants in glob.clusters ✓

Conclusions

A large grid of low-Z massive star models

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



...to interpret observations of metal-poor environments

- ionization and WR stars in I Zw 18 ✓
- core-H-burning supergiants in glob.clusters ✓
- gamma-ray bursts ↔ TWUIN stars!

Conclusions

A large grid of low-Z massive star models

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



...to interpret observations of metal-poor environments

- ionization and WR stars in I Zw 18 ✓
- core-H-burning supergiants in glob.clusters ✓
- gamma-ray bursts ↔ TWUIN stars!
- the early Universe

Conclusions

A large grid of low-Z massive star models

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



...to interpret observations of metal-poor environments

- ionization and WR stars in I Zw 18 ✓
- core-H-burning supergiants in glob.clusters ✓
- gamma-ray bursts ↔ TWUIN stars!
- the early Universe
- other metal-poor environments (Green Peas, metal-poor halo stars, etc.)

Conclusions

A large grid of low-Z massive star models

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



...to interpret observations of metal-poor environments

- ionization and WR stars in I Zw 18 ✓
- core-H-burning supergiants in glob.clusters ✓
- gamma-ray bursts ↔ TWUIN stars!
- the early Universe
- other metal-poor environments (Green Peas, metal-poor halo stars, etc.)
- binary stars... gravitational waves!

Conclusions

A large grid of low-Z massive star models

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



...to interpret observations of metal-poor environments

- ionization and WR stars in I Zw 18 ✓
- core-H-burning supergiants in glob. clusters ✓
- gamma-ray bursts ↔ TWUIN stars!
- the early Universe
- other metal-poor environments (Green Peas, metal-poor halo stars, etc.)
- binary stars... gravitational waves!



Thank you
for your
attention!