The evolution of low-metallicity massive stars

Dorottya Szécsi

Supervisor: Prof. Dr. Norbert Langer

Argelander-Institut für Astronomie

PhD defence

Bonn, 4th July 2016

The night-sky and beyond

The night-sky and beyond

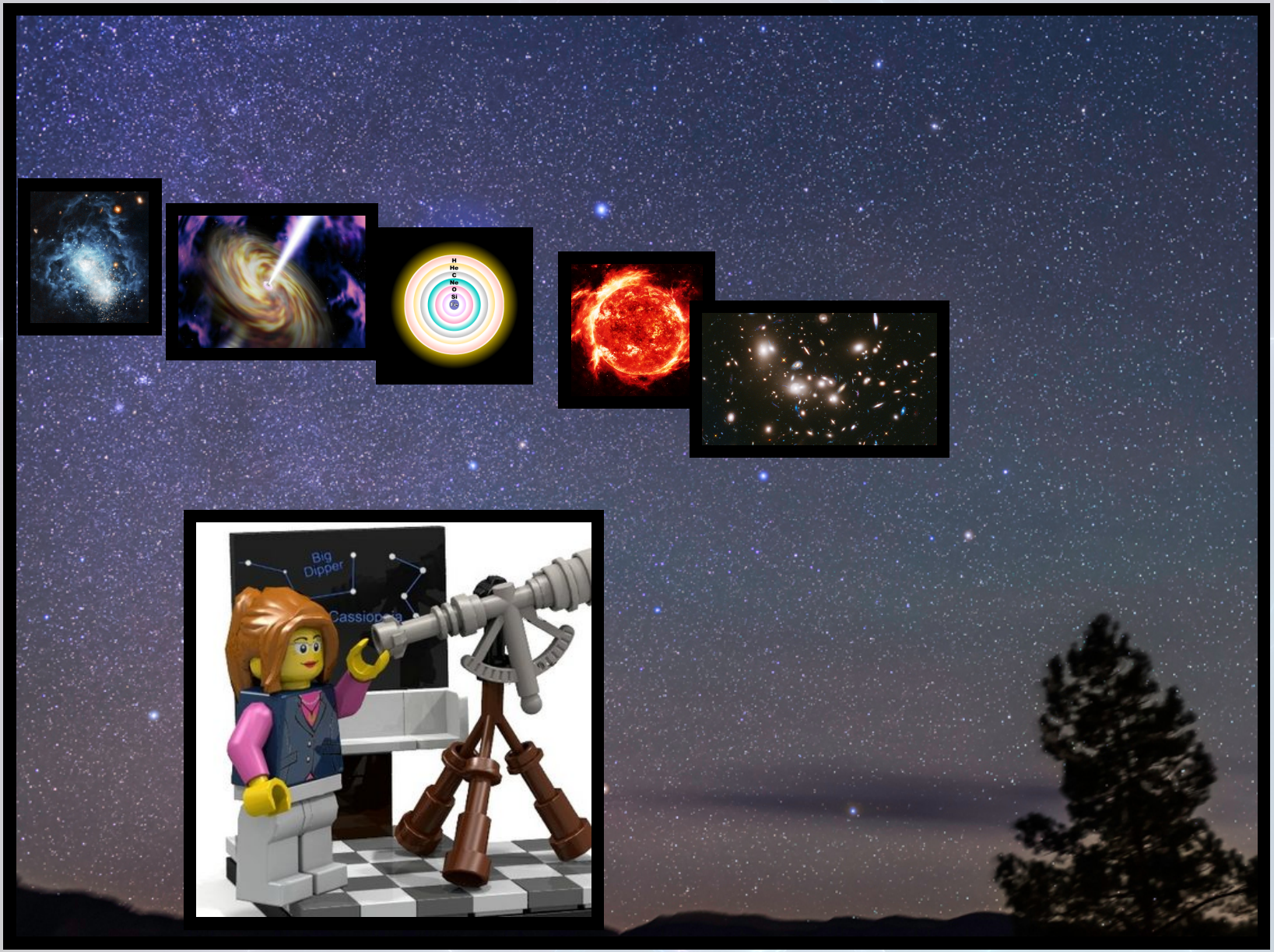
The night-sky and beyond

The night-sky and beyond

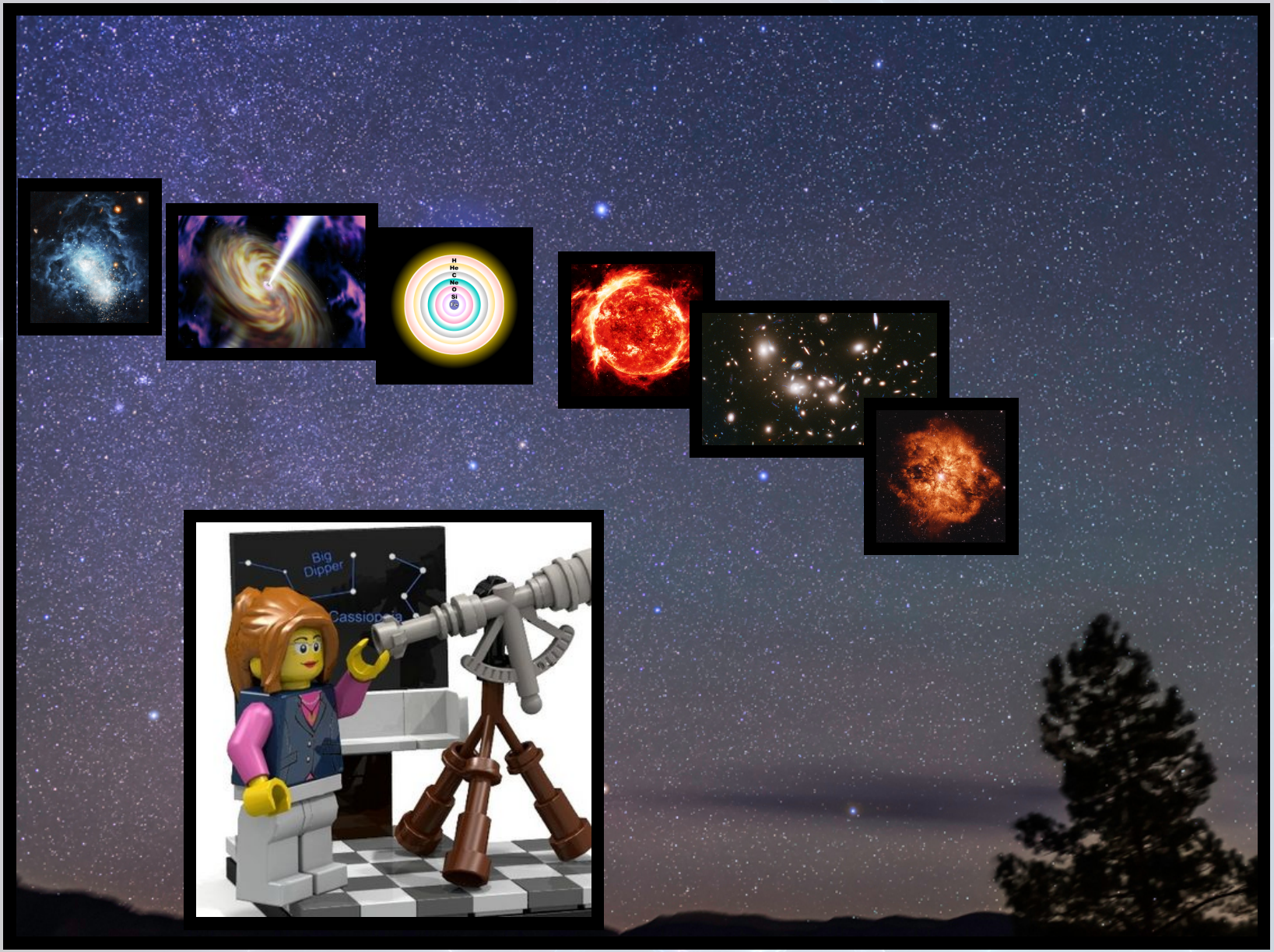
The night-sky and beyond

The night-sky and beyond

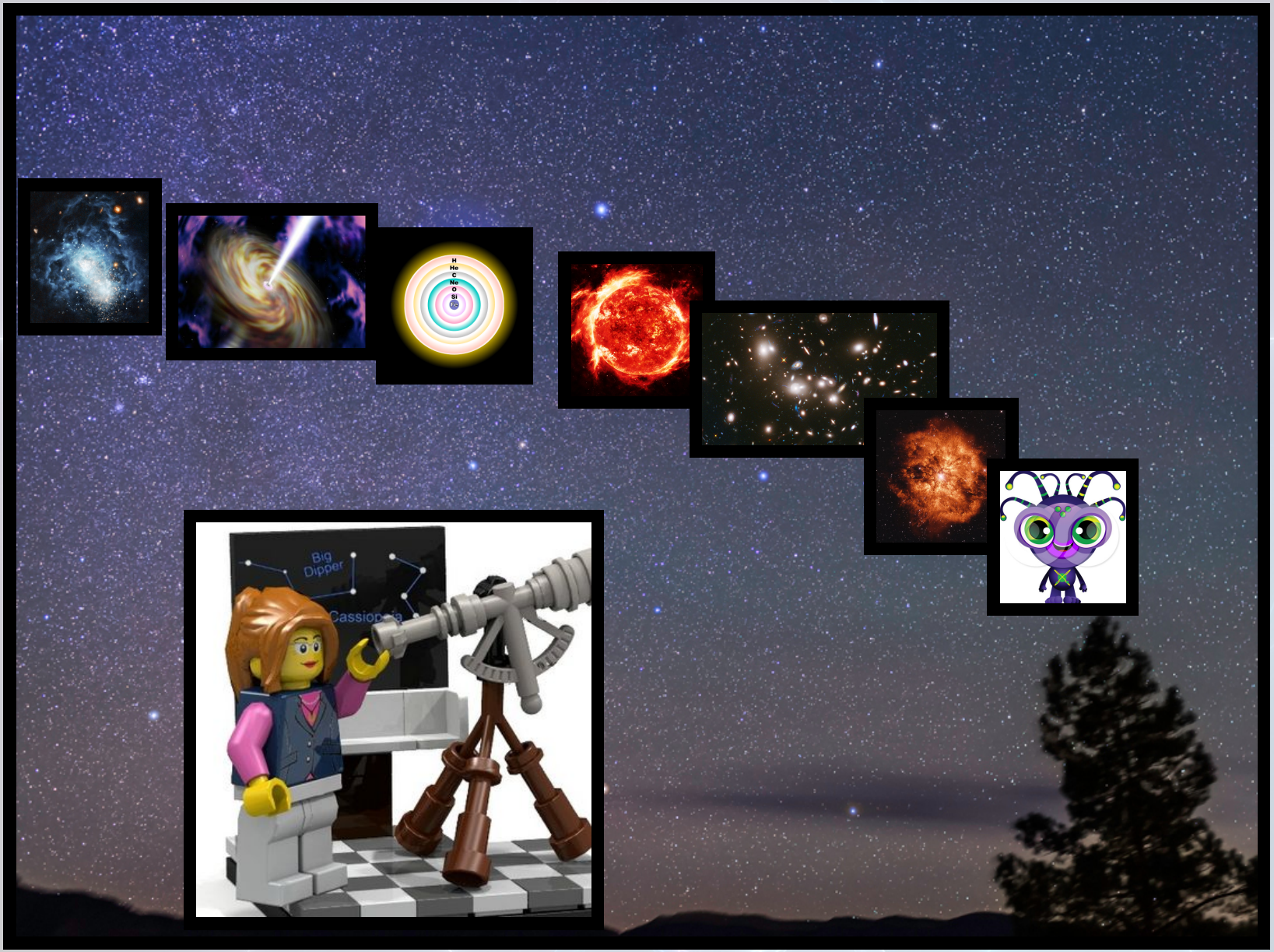
The night-sky and beyond



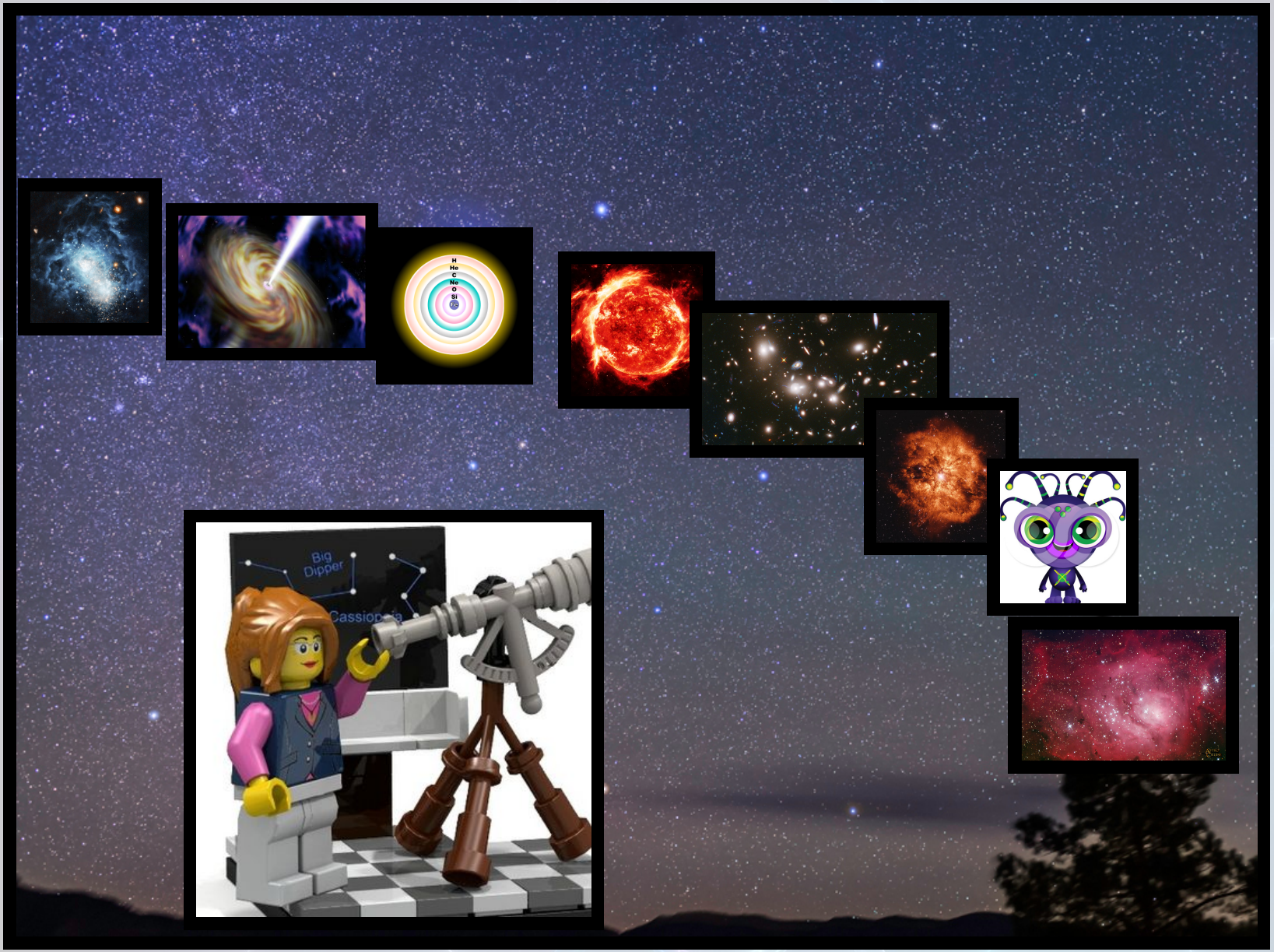
The night-sky and beyond



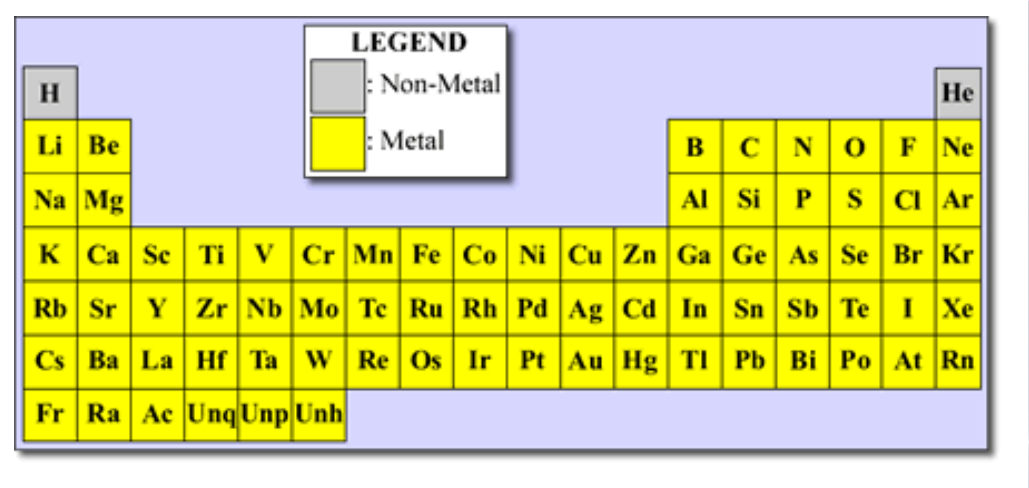
The night-sky and beyond



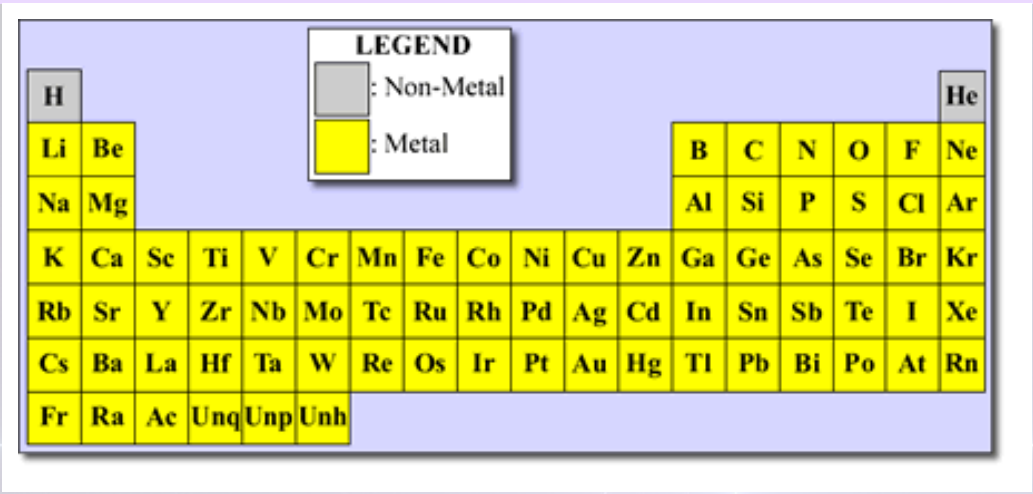
The night-sky and beyond

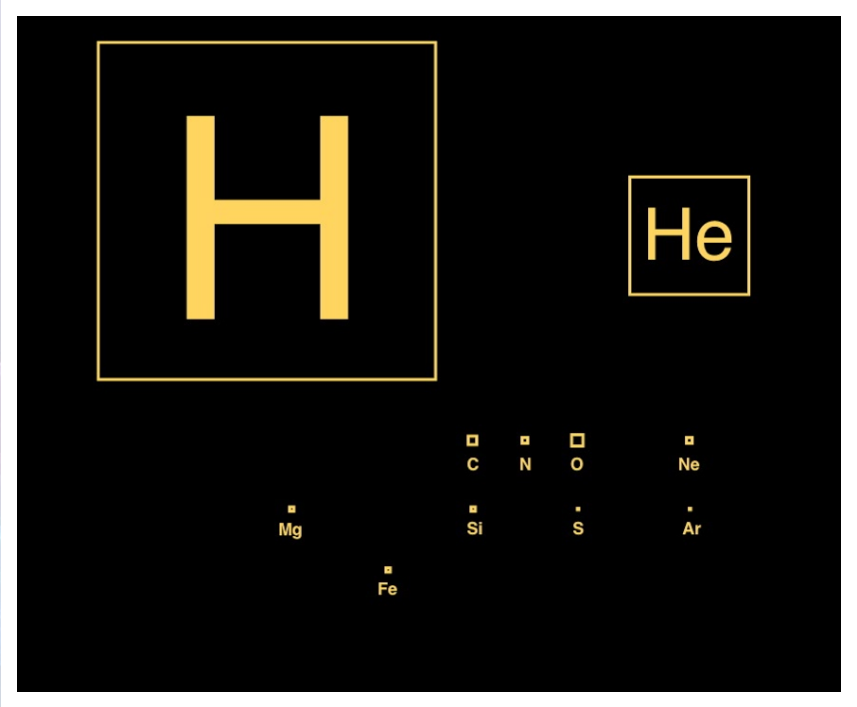


Astronomers and metal

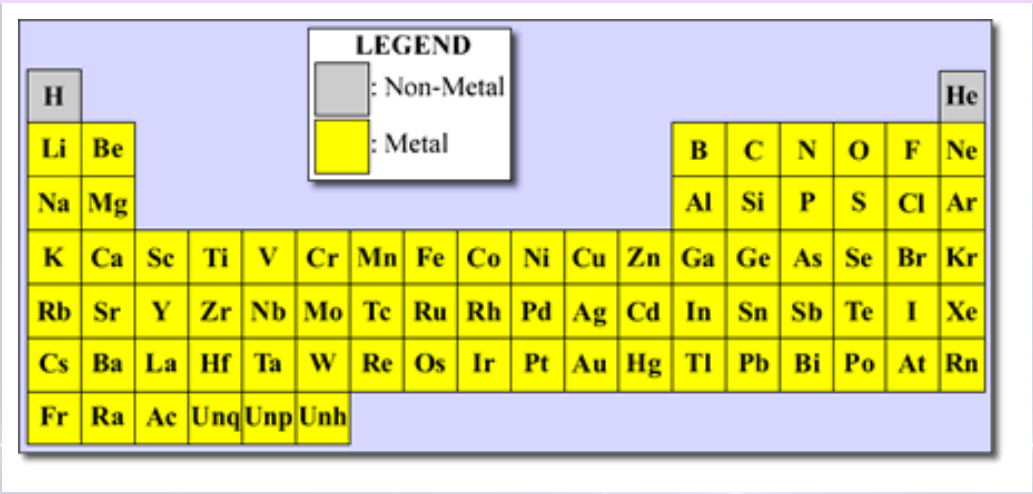


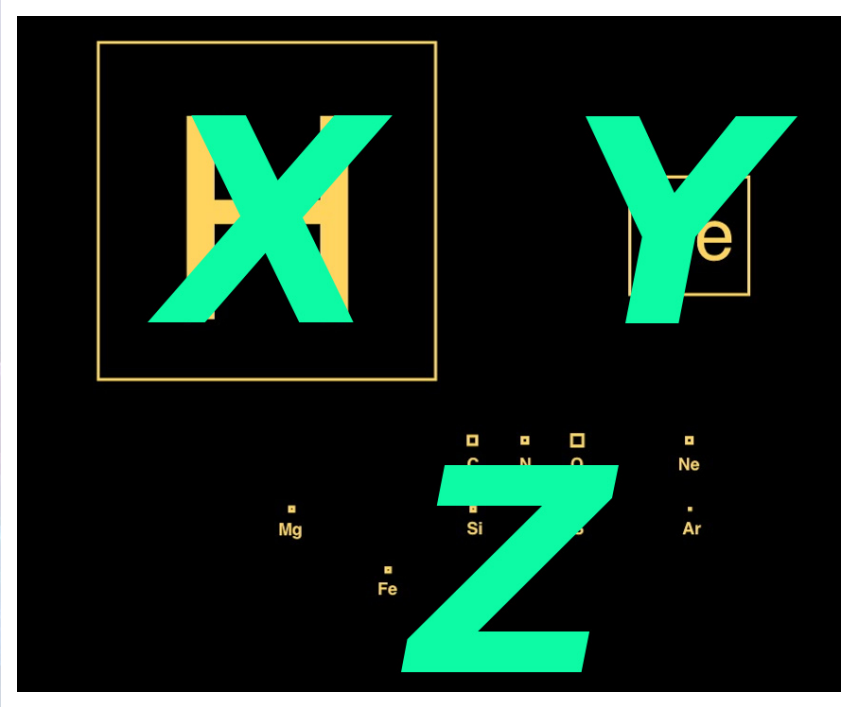
Astronomers and metal



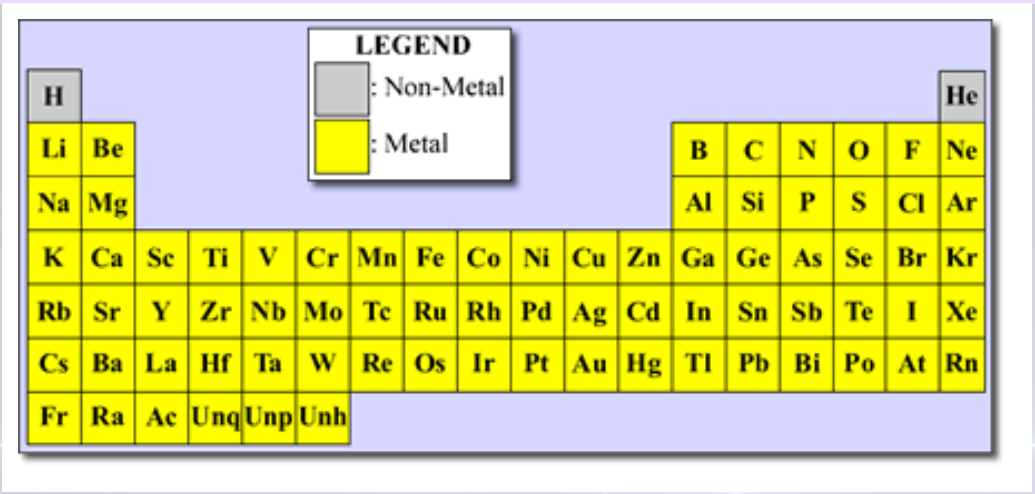


Astronomers and metal

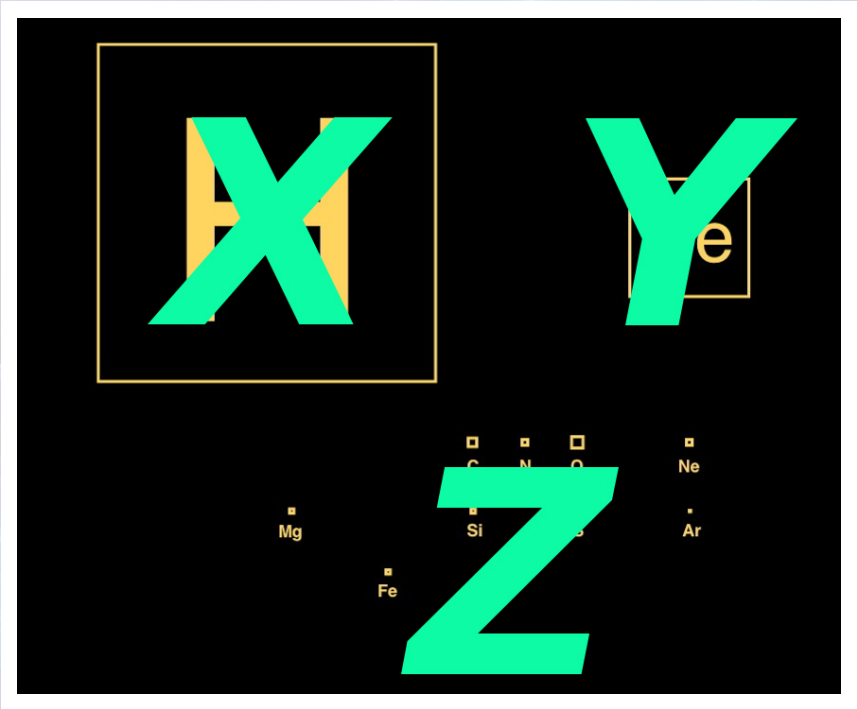




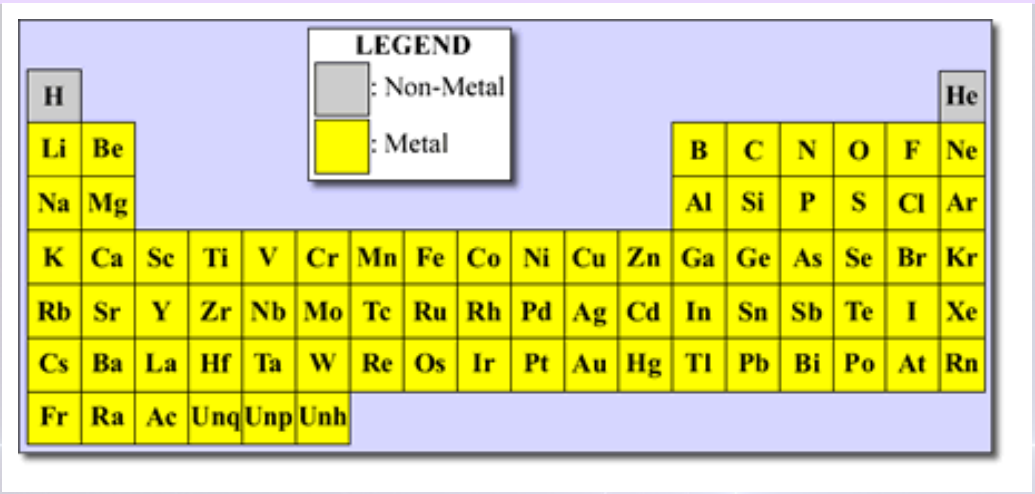
Astronomers and metal



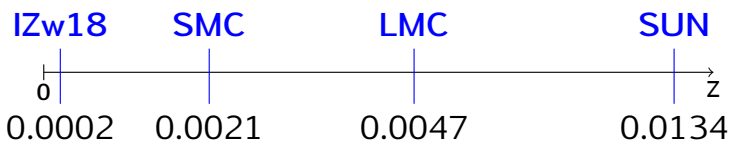
"Z: metallicity"

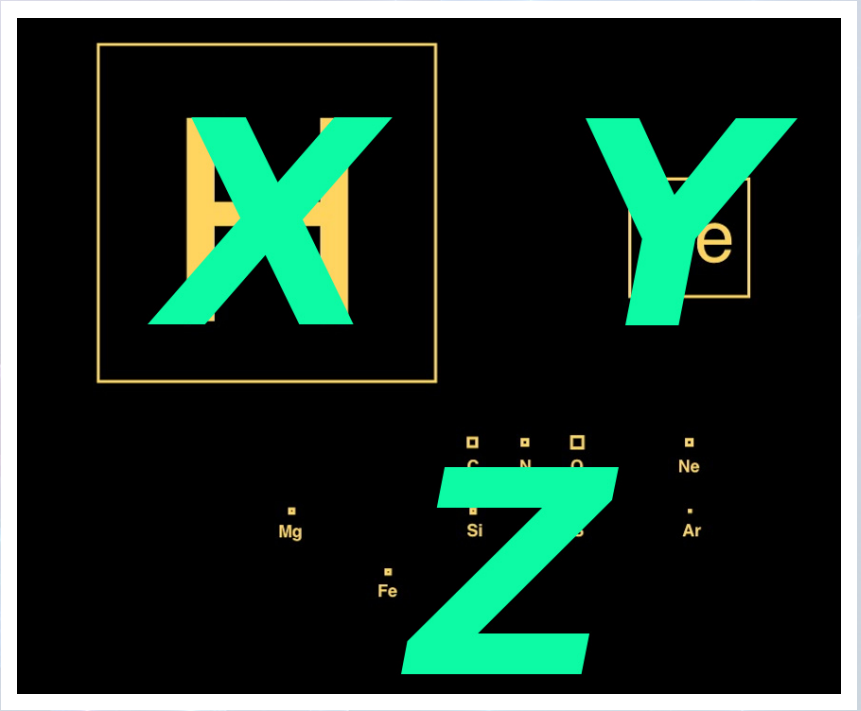


Astronomers and metal

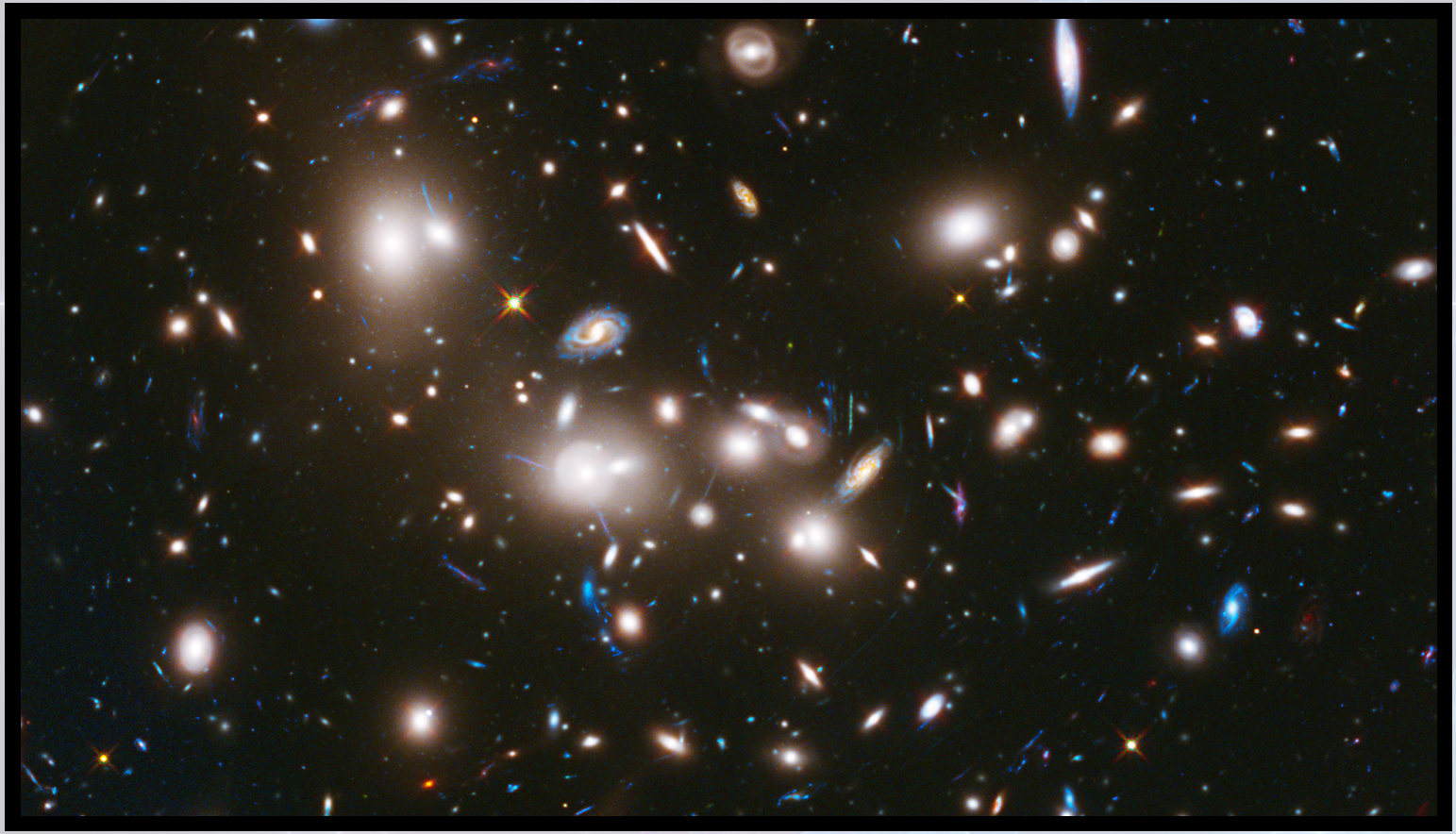


"Z: metallicity"





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!

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

Compact Dwarf Galaxies

I Zwicky 18

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

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

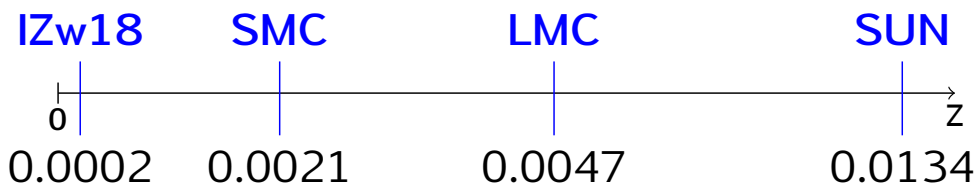
Legrand+07, Aloisi+09, Annibali+13, Kehrig+13, Lebouteiller+13

Compact Dwarf Galaxies

I Zwicky 18

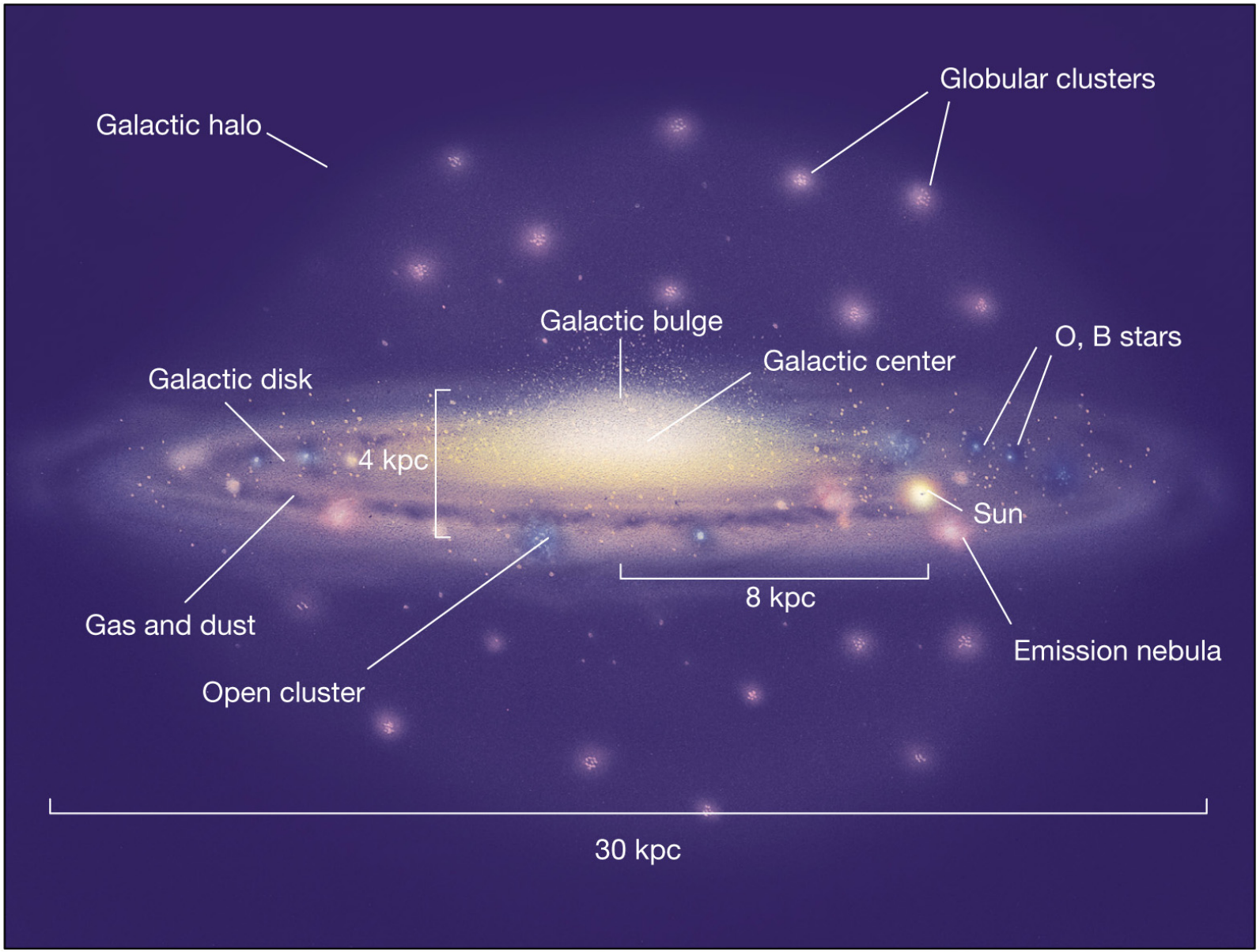
- Blue Compact Dwarf Galaxy
- 60 million lightyears → local
- star formation rate: 0.1 $M_\odot$/yr
- ionized gas
- low metallicity!

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

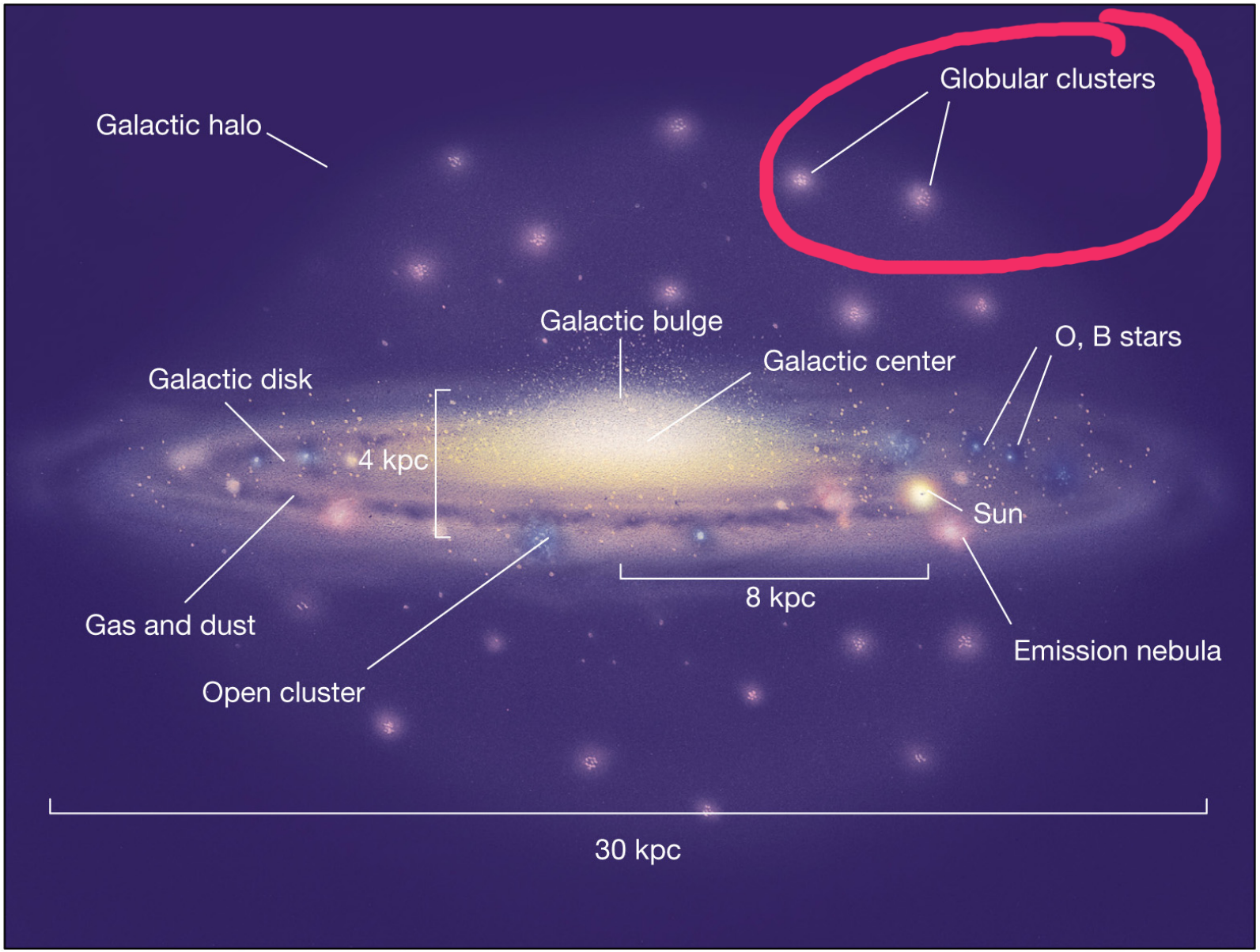


Legrand+07, Aloisi+09, Annibali+13, Kehrig+13, Lebouteiller+13

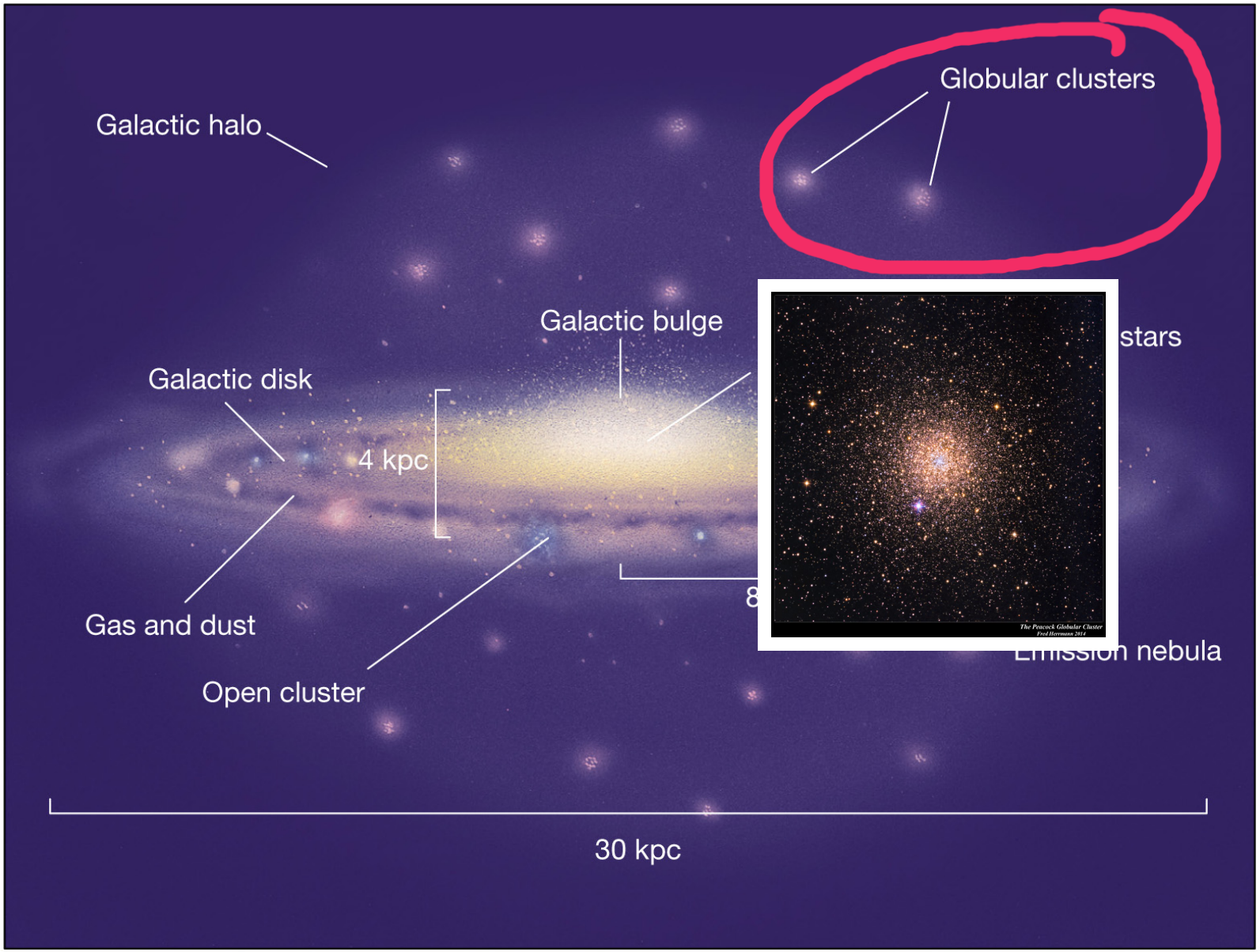
Globular Clusters



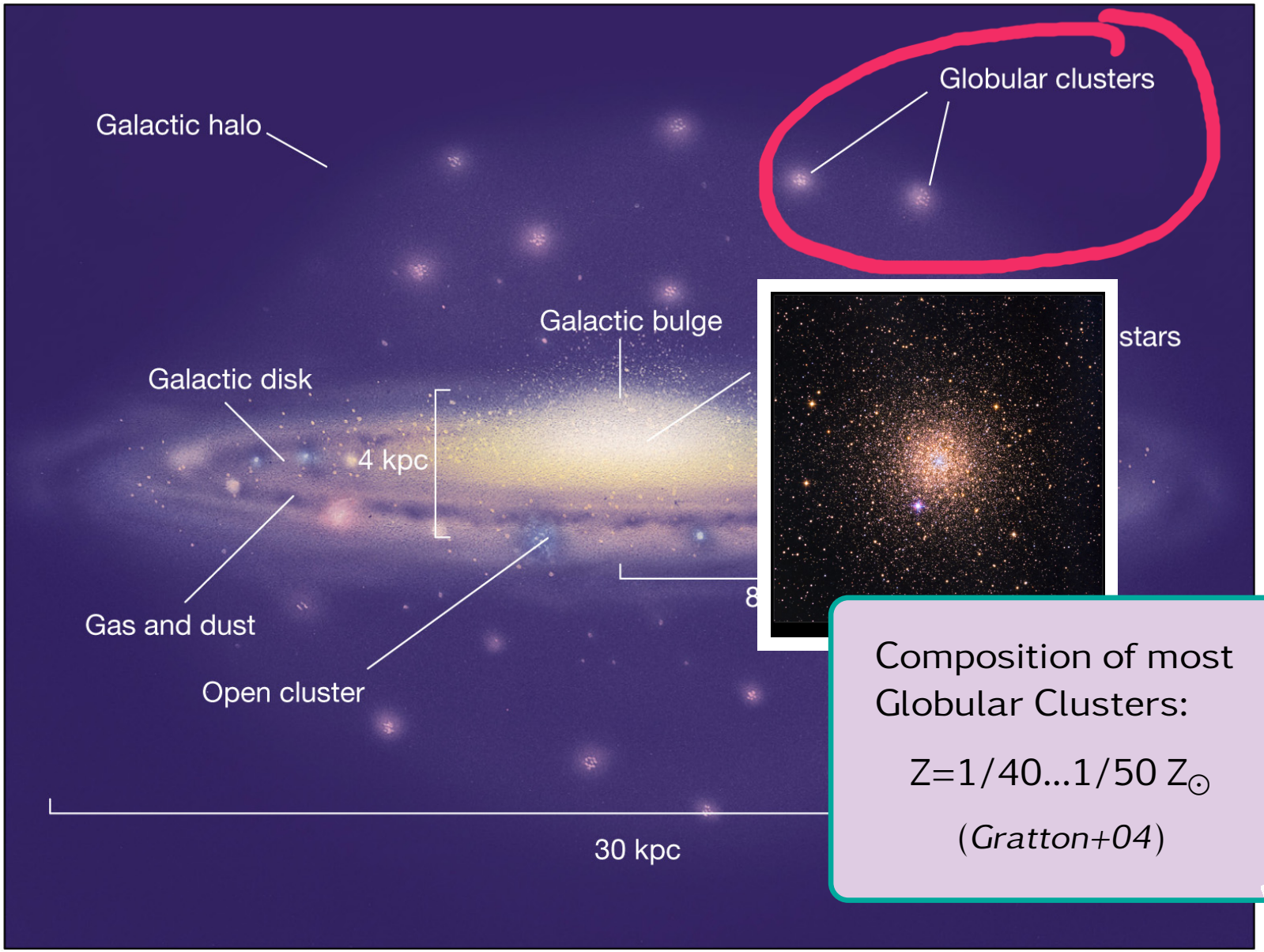
Globular Clusters



Globular Clusters



Globular Clusters



Composition of most Globular Clusters:

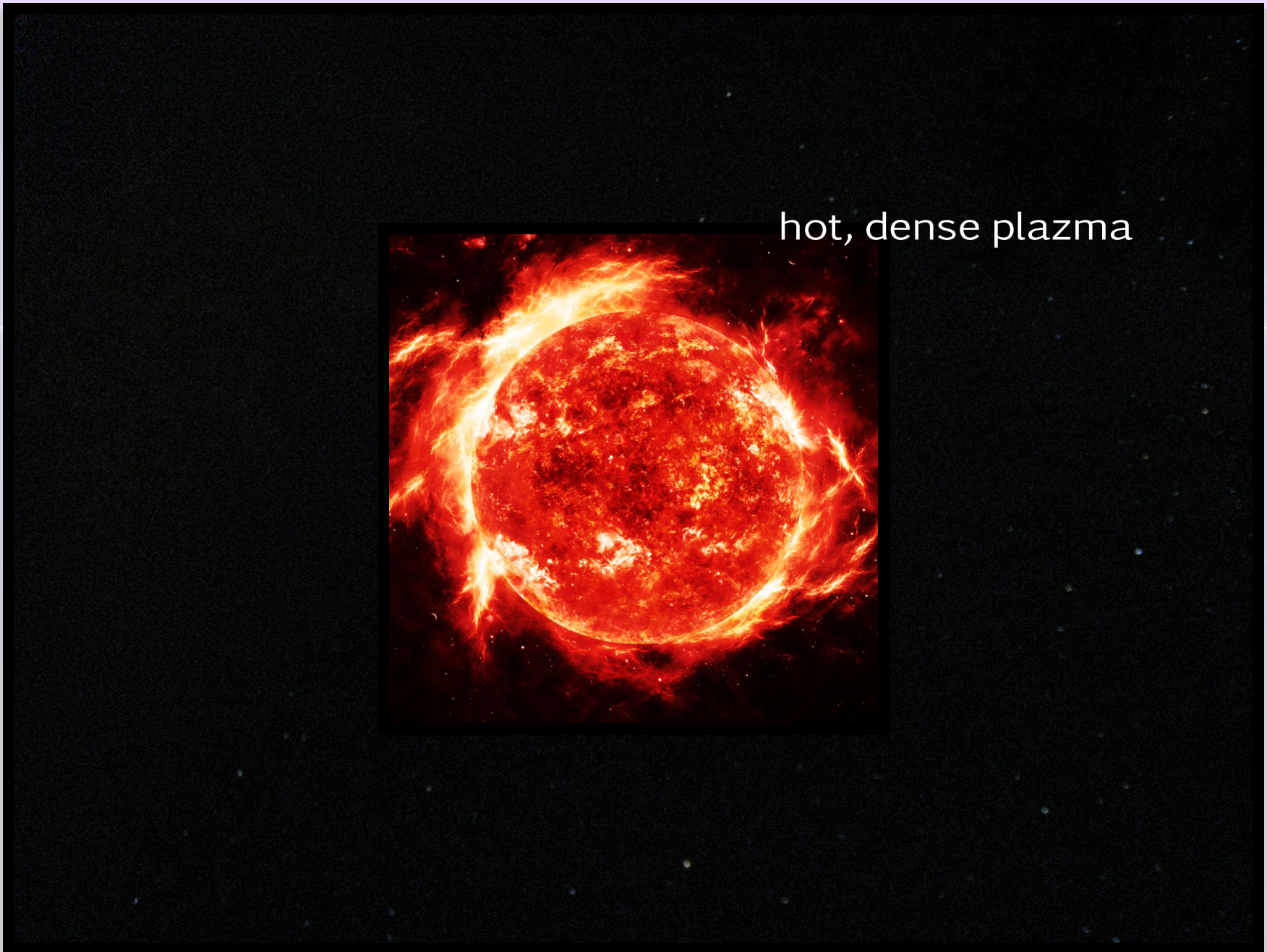
$Z=1/40...1/50\ Z_{\odot}$

(*Gratton+04*)

What is a star?

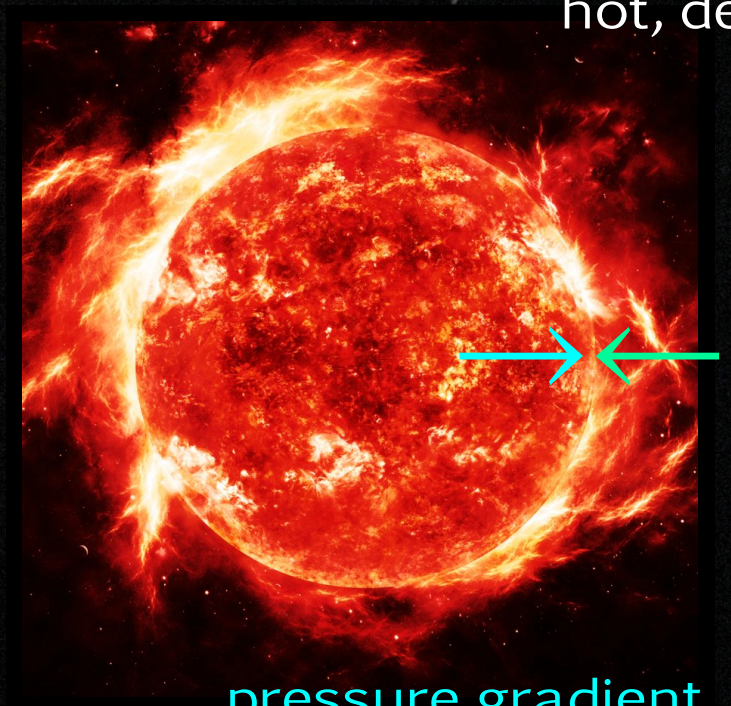
What is a star?

What is a star?



What is a star?

hot, dense plazma

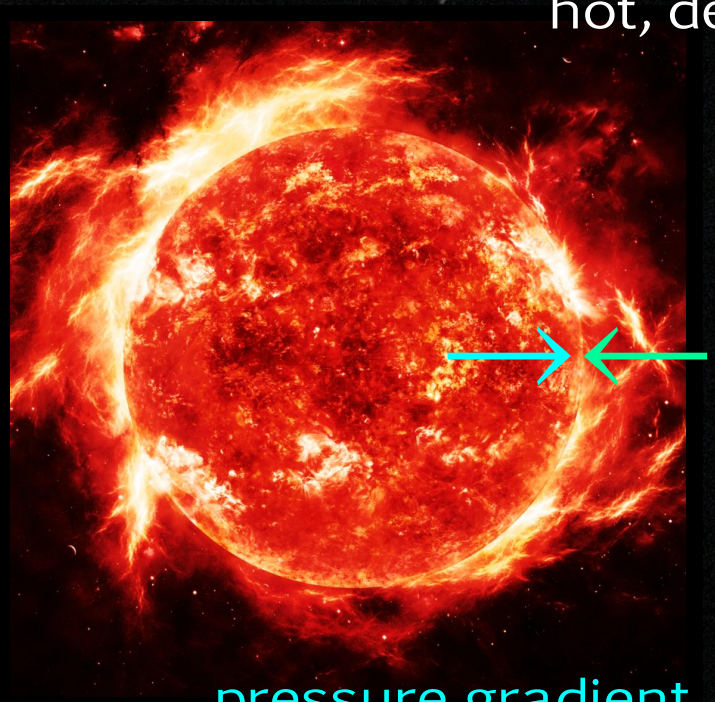


equilibrium: pressure gradient gravity

What is a star?

surface?

hot, dense plazma

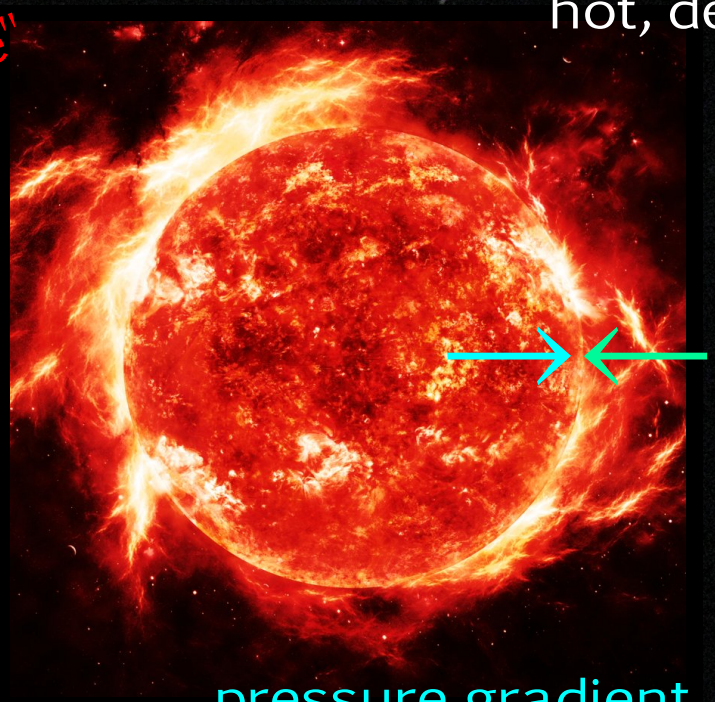


equilibrium: pressure gradient gravity

What is a star?

surface?
→ photons escape
"photosphere"

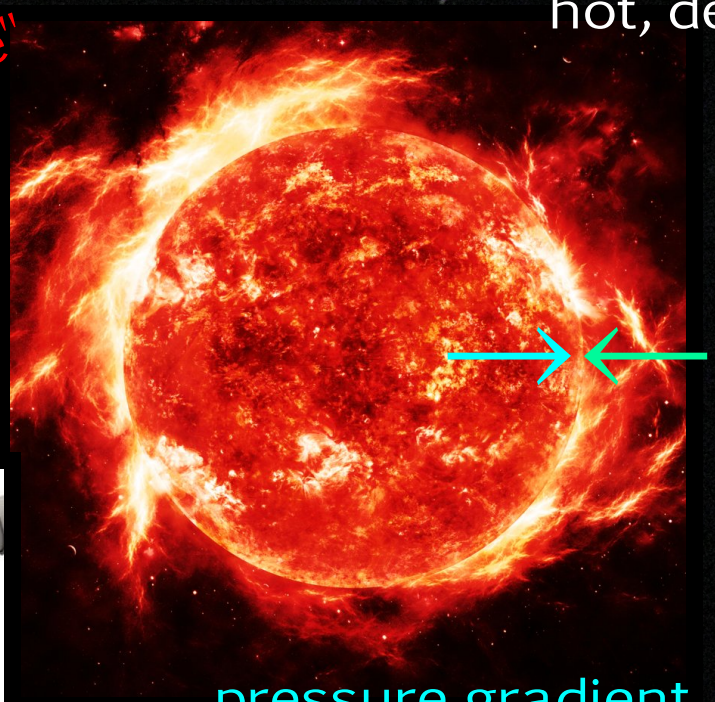
hot, dense plazma



equilibrium: pressure gradient gravity

What is a star?

surface?
→ photons escape
"photosphere"



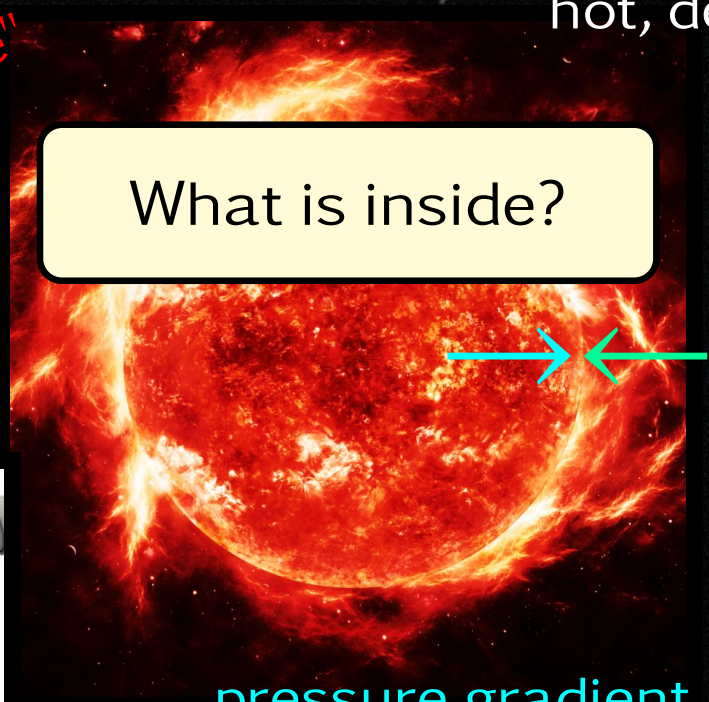
hot, dense plazma

pressure gradient gravity

What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma

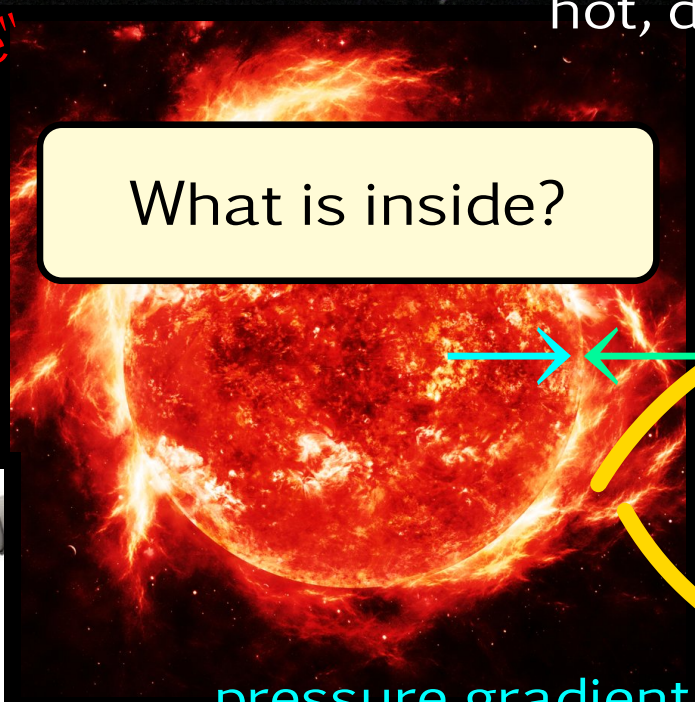


What is inside?

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

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

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

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

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

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

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

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

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

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

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

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

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

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

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

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

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

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

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

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

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

Guilera et al. 2011

Theoretical modelling of the stellar structure

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

mass conservation

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

momentum conservation

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

energy conservation

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

transport of energy

Guilera et al. 2011

composition change due to nuclear burning ?!

Theoretical modelling of the stellar structure

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

mass conservation

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

momentum conservation

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

energy conservation

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

transport of energy

Guilera et al. 2011

composition change due to nuclear burning ?!

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

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 ?!

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

+ Rotation.

Theoretical modelling of the stellar structure

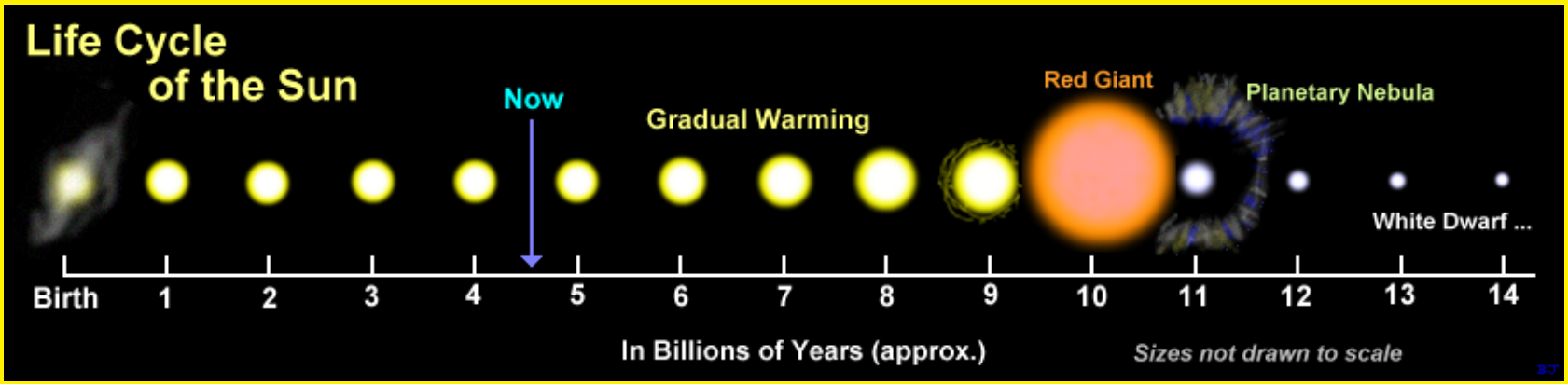
$$\frac{\partial r}{\partial m_r} = \frac{1}{4\pi r^2 \rho} \qquad \text{eq} \qquad (9)$$

mass conservation

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

momentum conservation

$$\frac{\partial L}{\partial} \qquad \frac{\partial S}{}$$



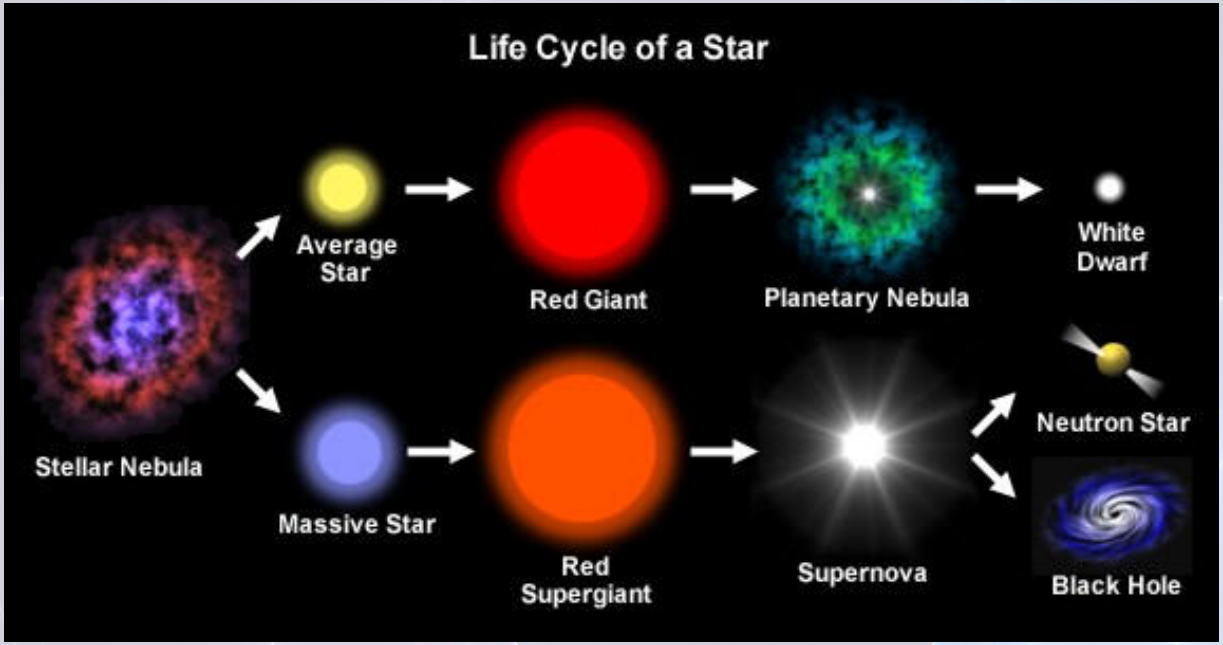
composition change due to nuclear burning ?!

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

+ Rotation.

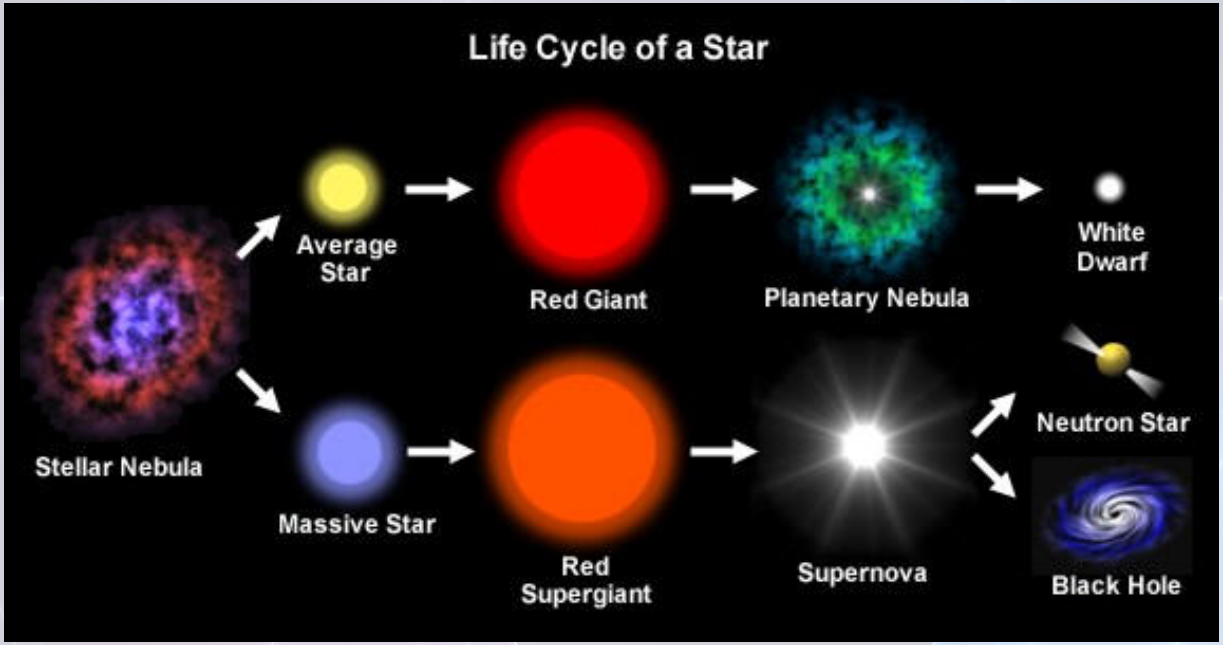
Massive vs. low-mass stars

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



Massive vs. low-mass stars

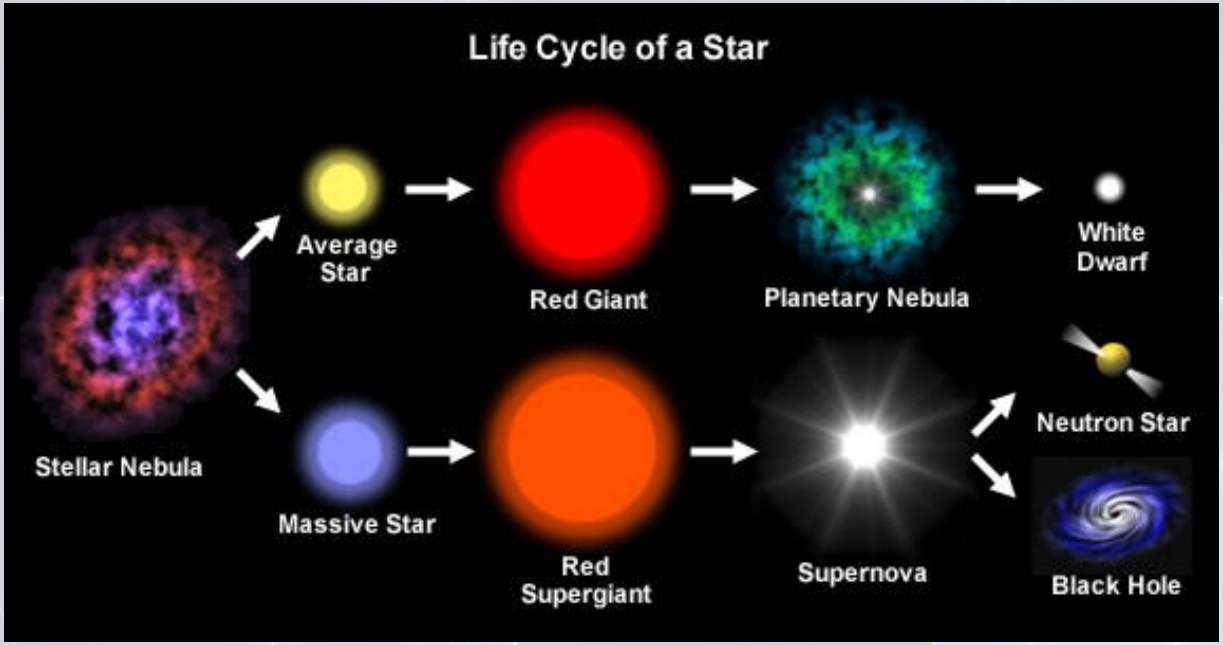
Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9\ M_\odot$)



- nuclear reactions, final composition

Massive vs. low-mass stars

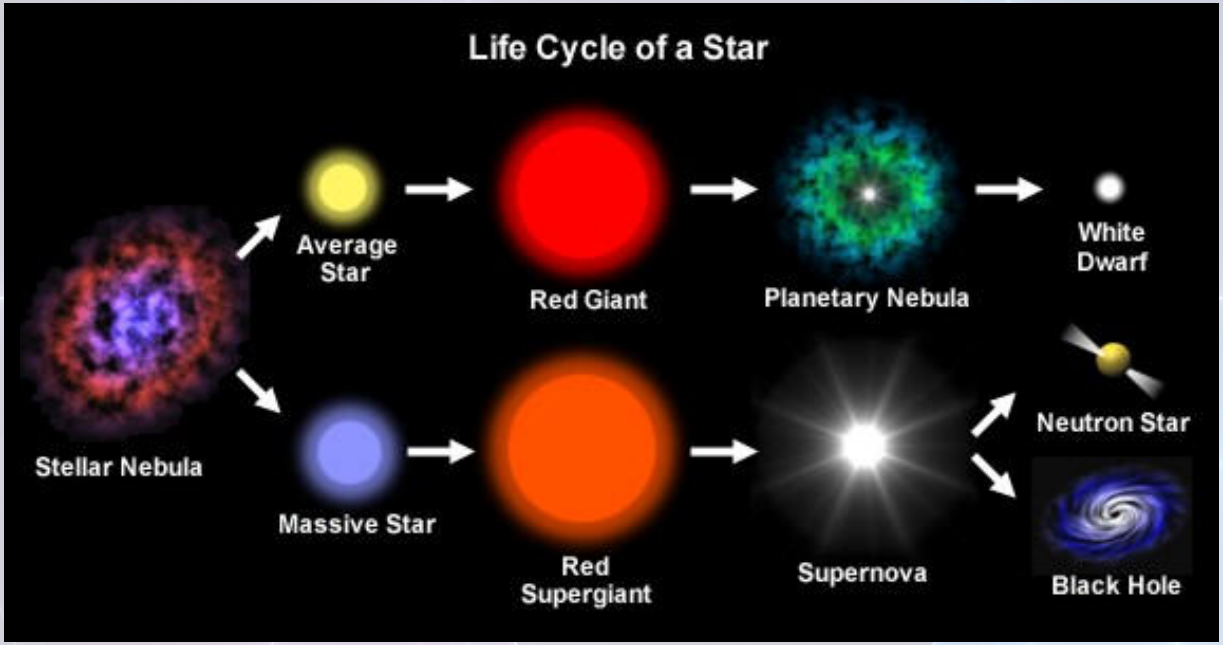
Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9\ M_\odot$)



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

Massive vs. low-mass stars

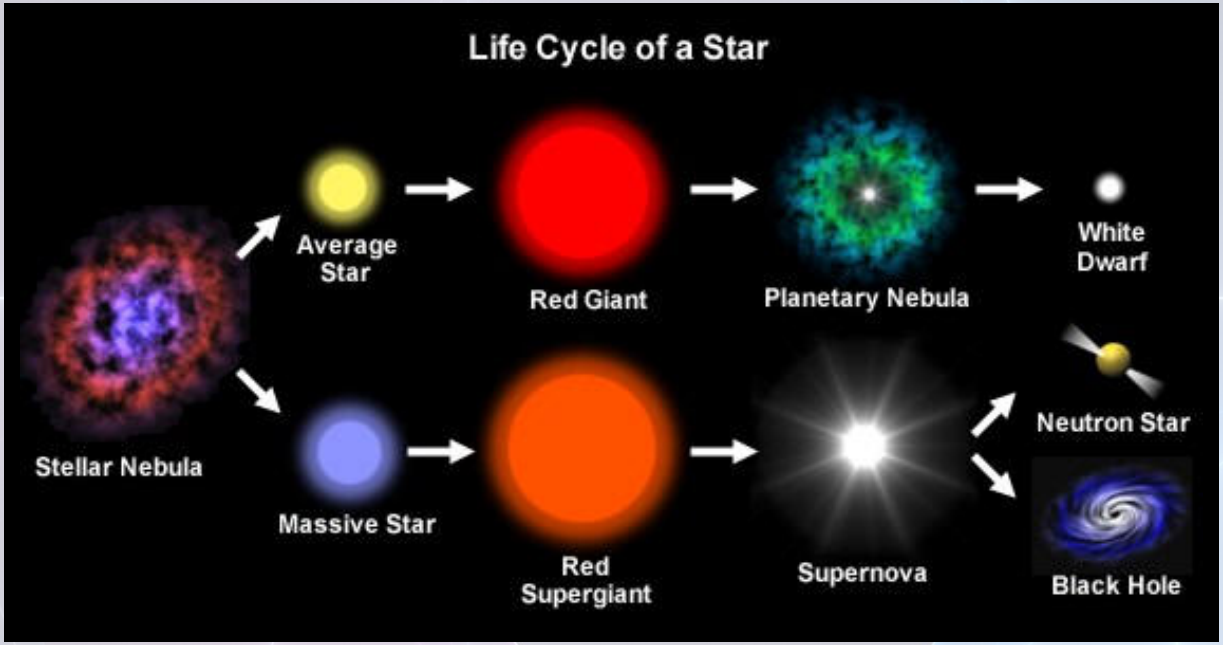
Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9\ M_\odot$)



- 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

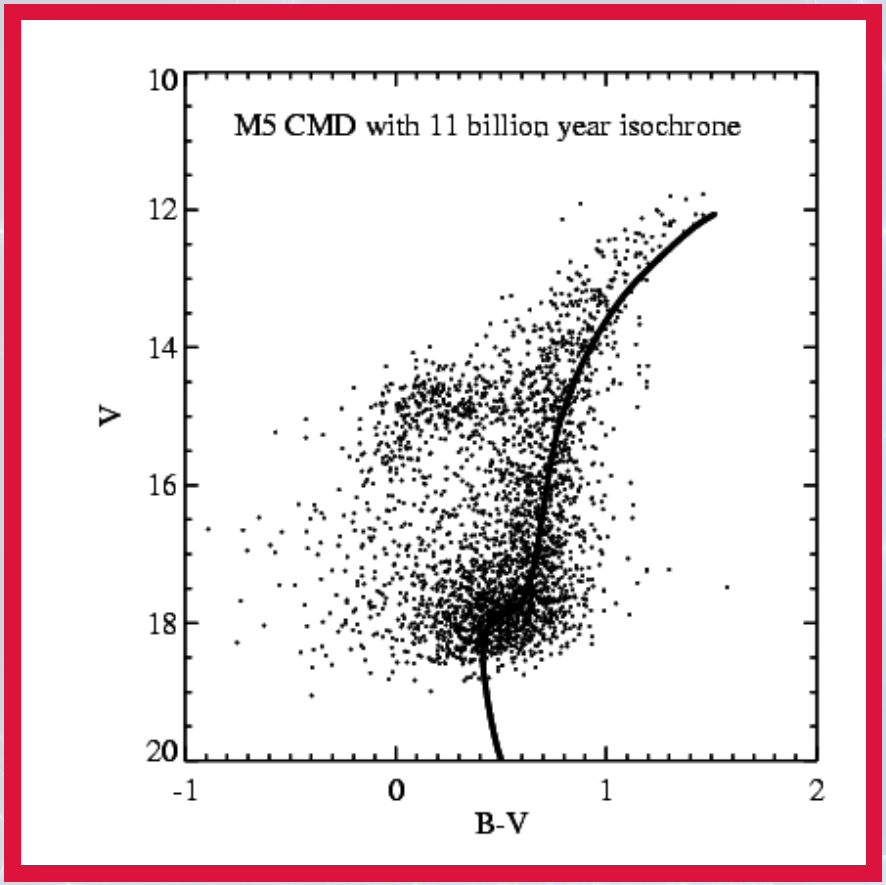
Surface properties!

Matching theory to observations

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

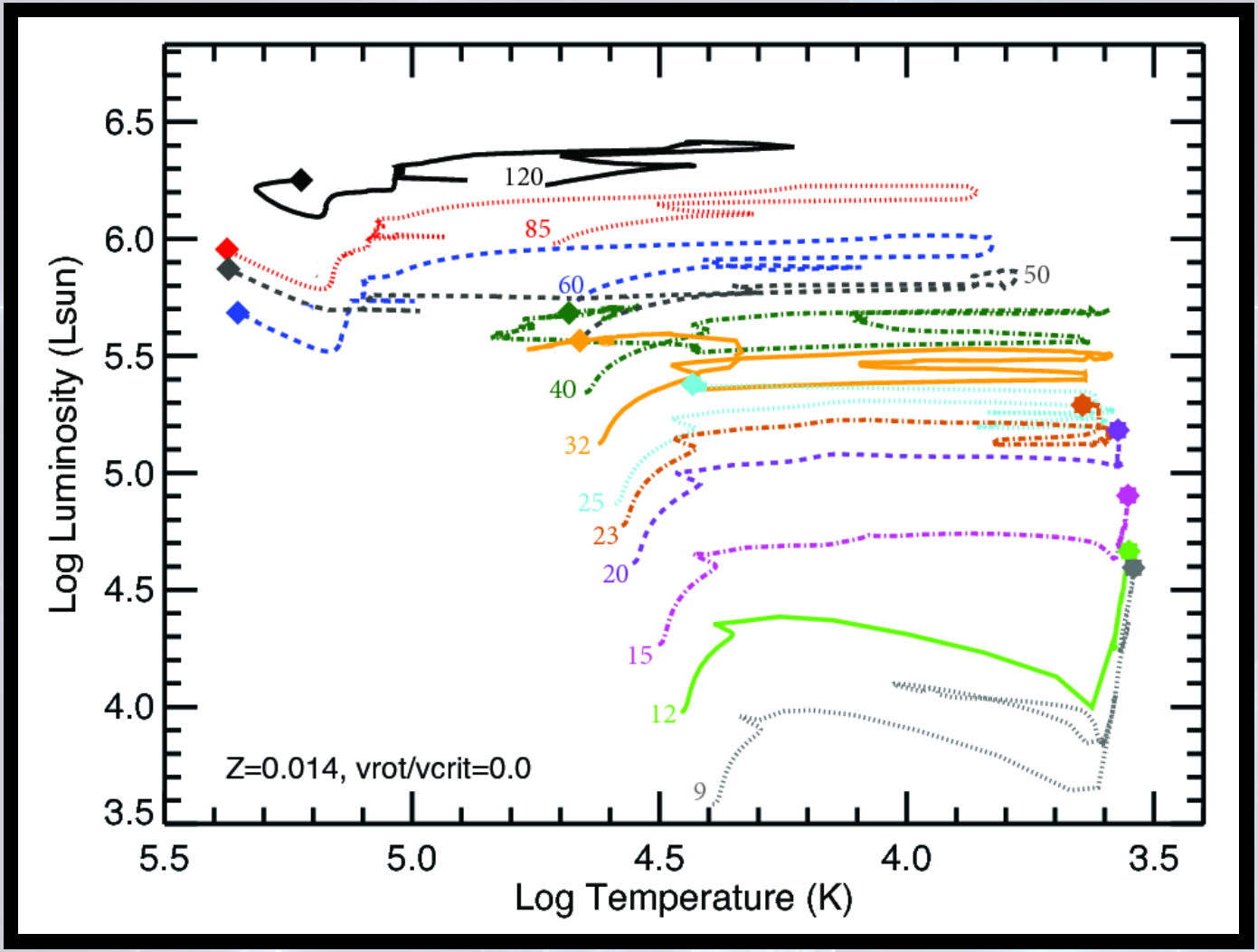
Matching theory to observations

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



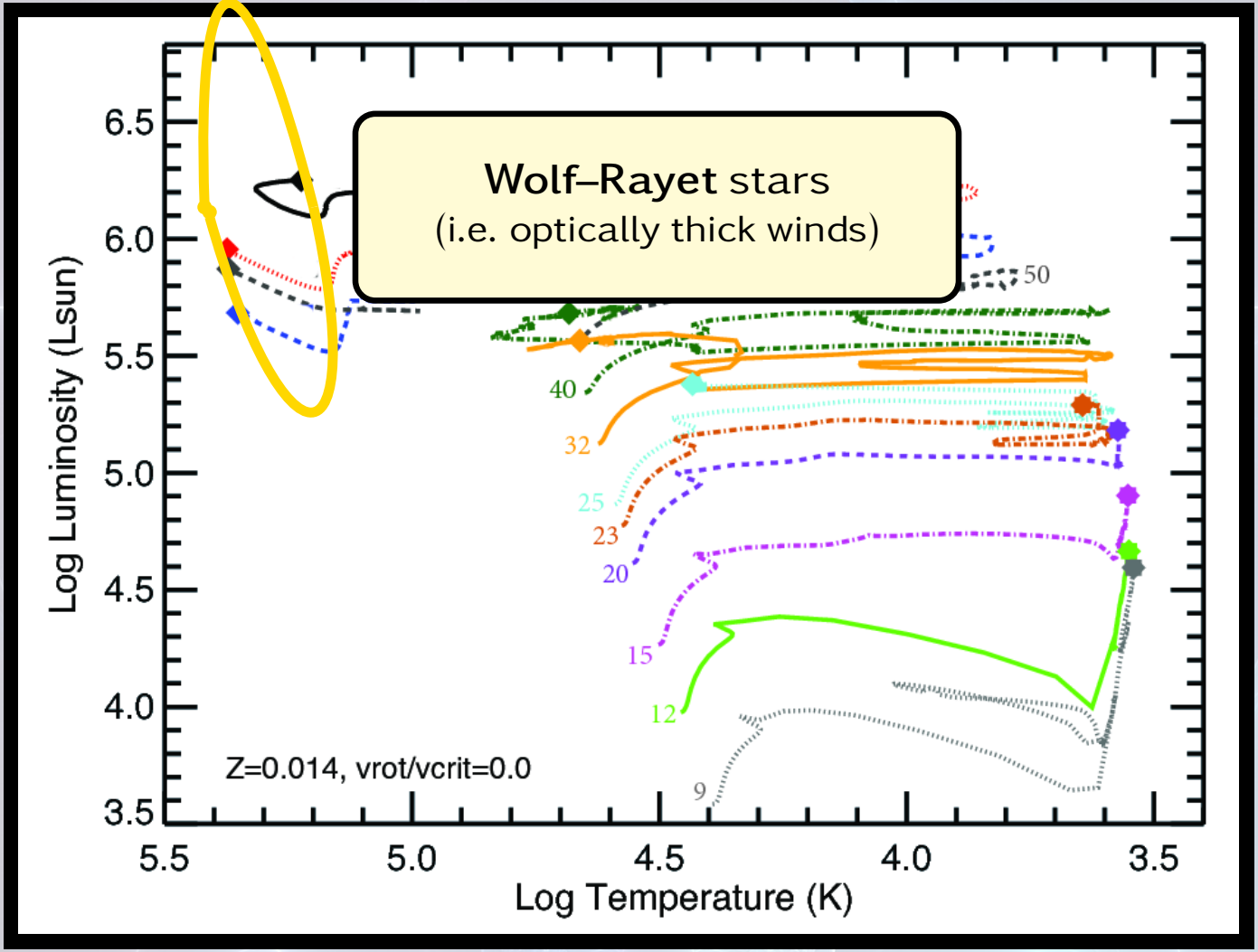
Hertzsprung–Russell diagram (HR diagram)

Hertzsprung–Russell diagram



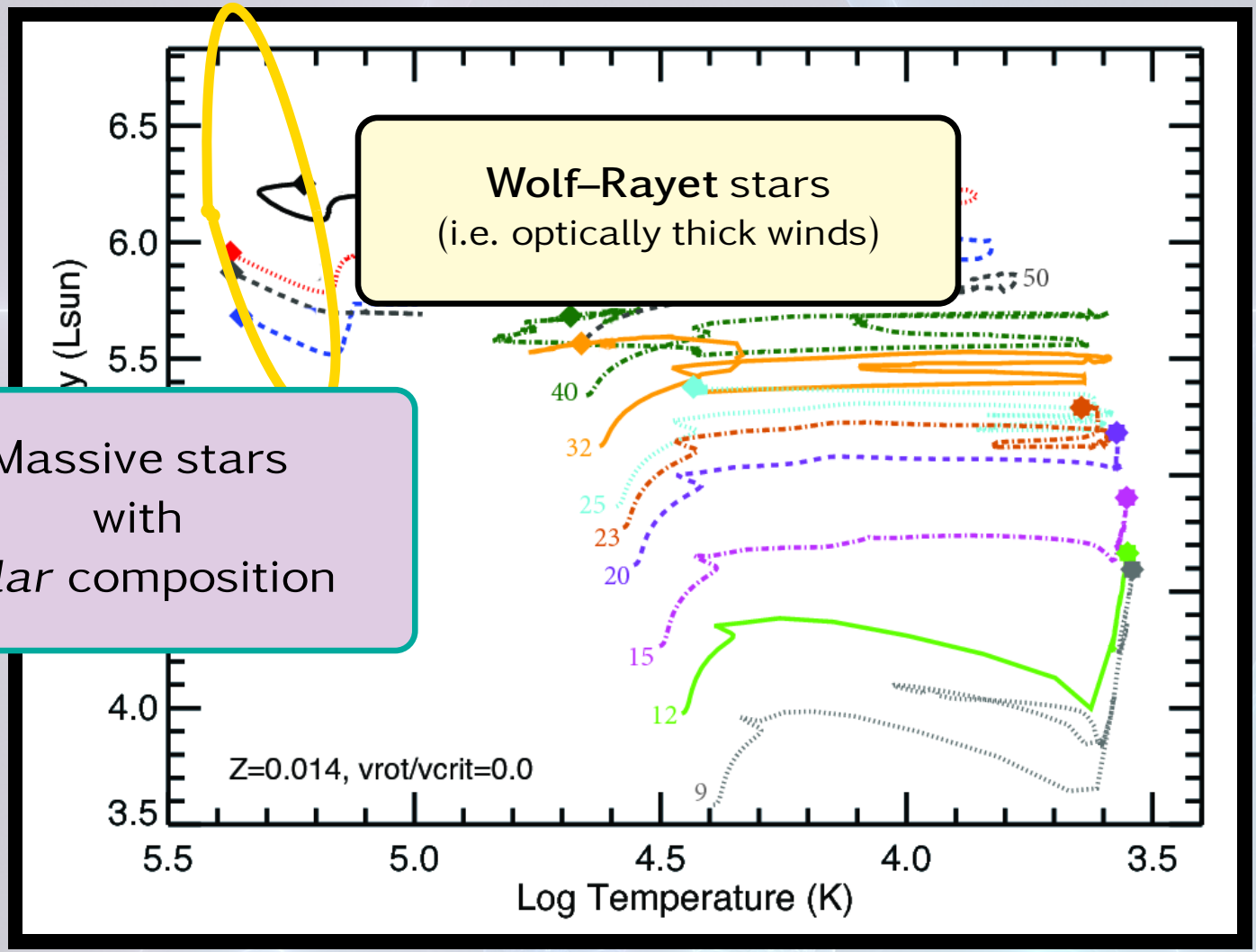
Groh et al. 2013

Hertzsprung–Russell diagram



Groh et al. 2013

Hertzsprung–Russell diagram



Groh et al. 2013

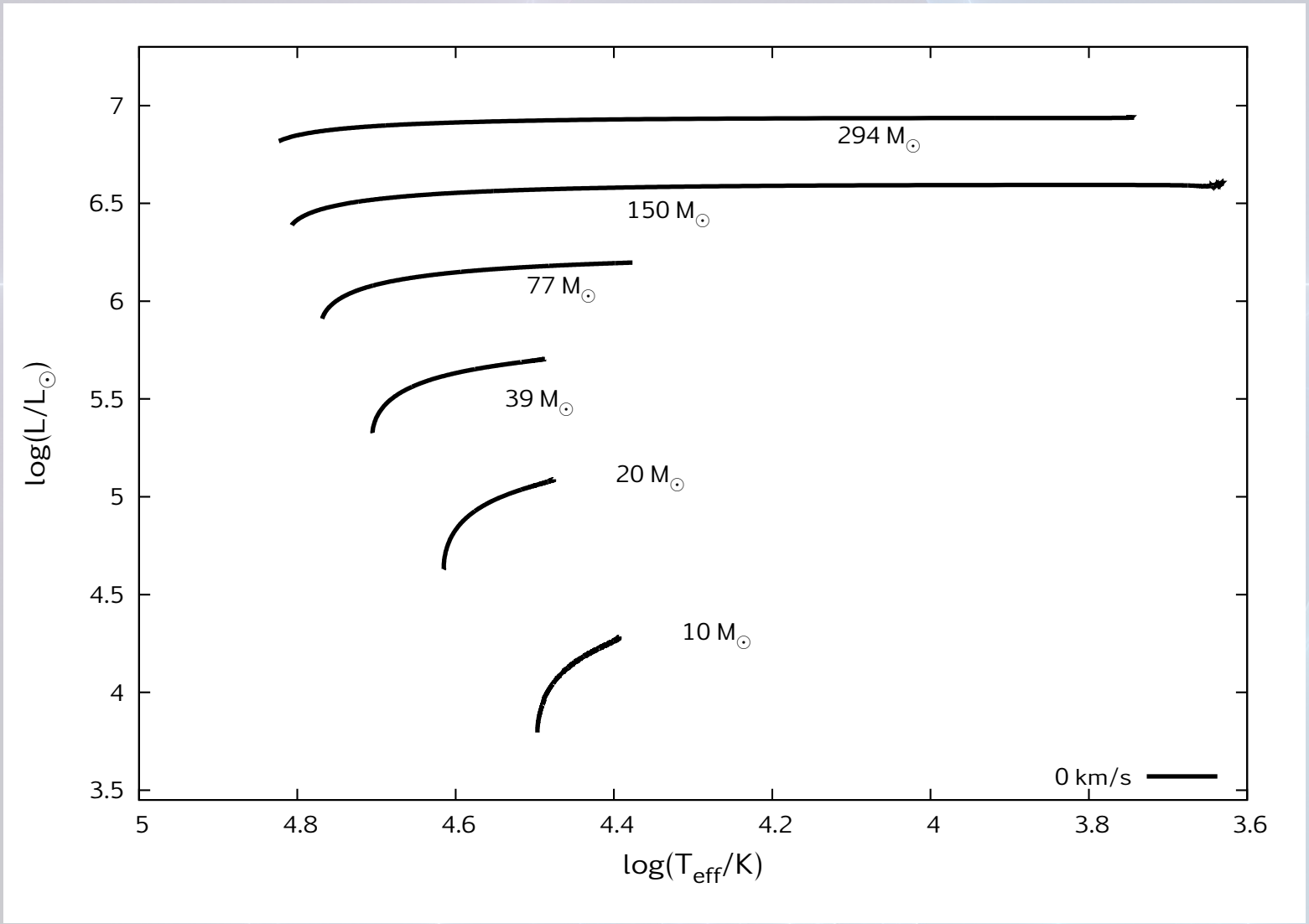
Low Metallicity Massive Stars

Low Metallicity Massive Stars

– my thesis ☺

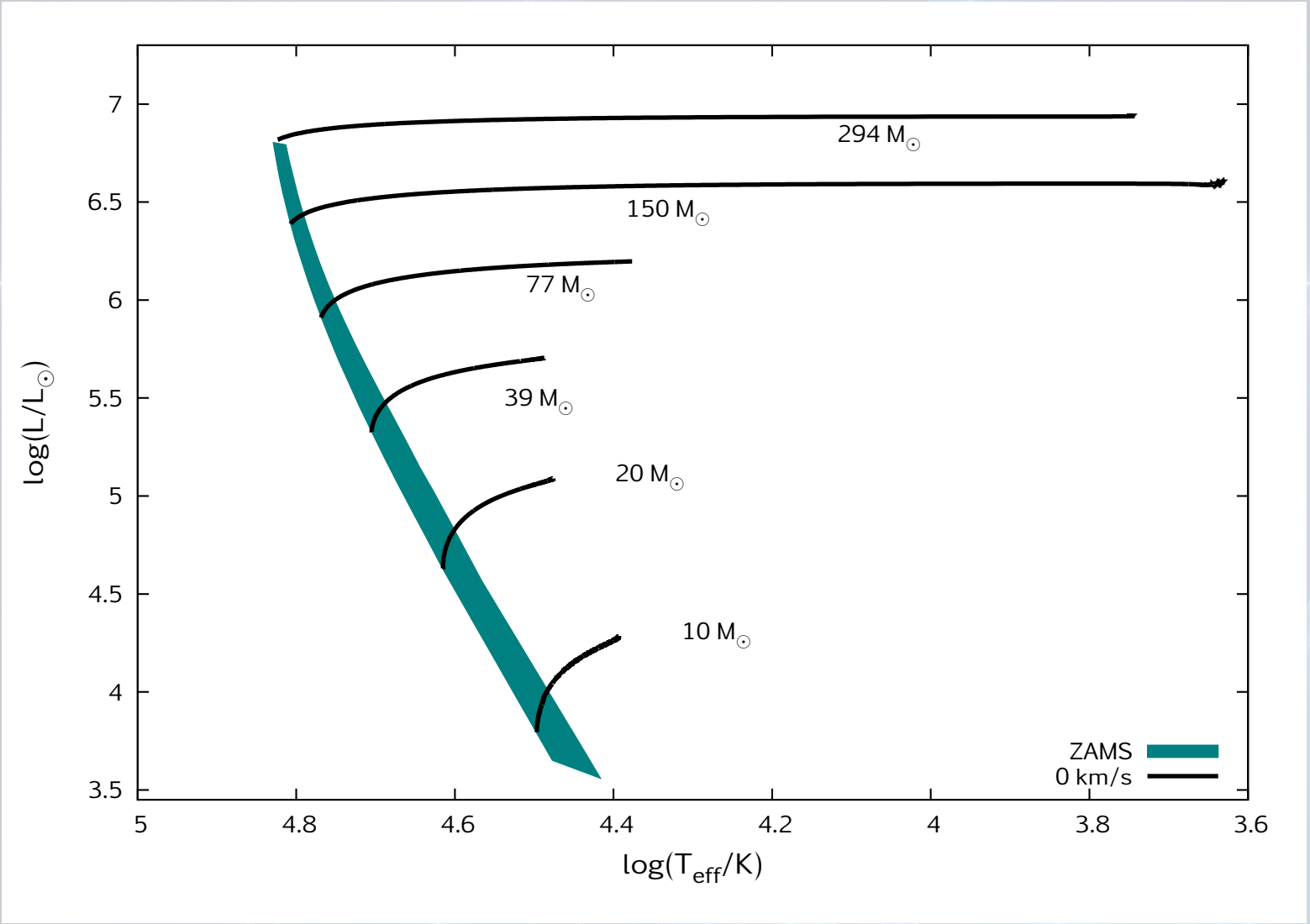
Low Metallicity Massive Stars

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



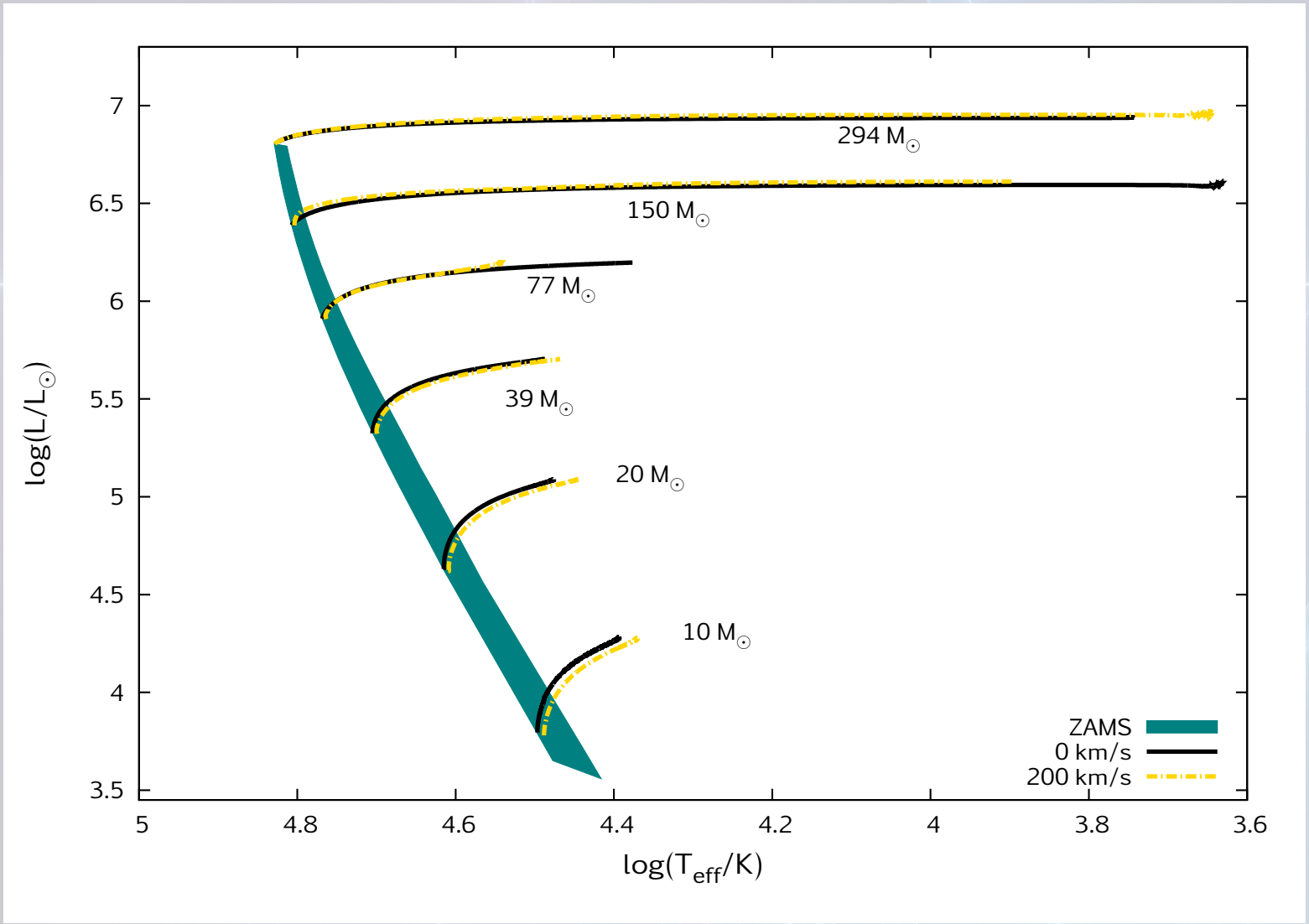
Low Metallicity Massive Stars

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



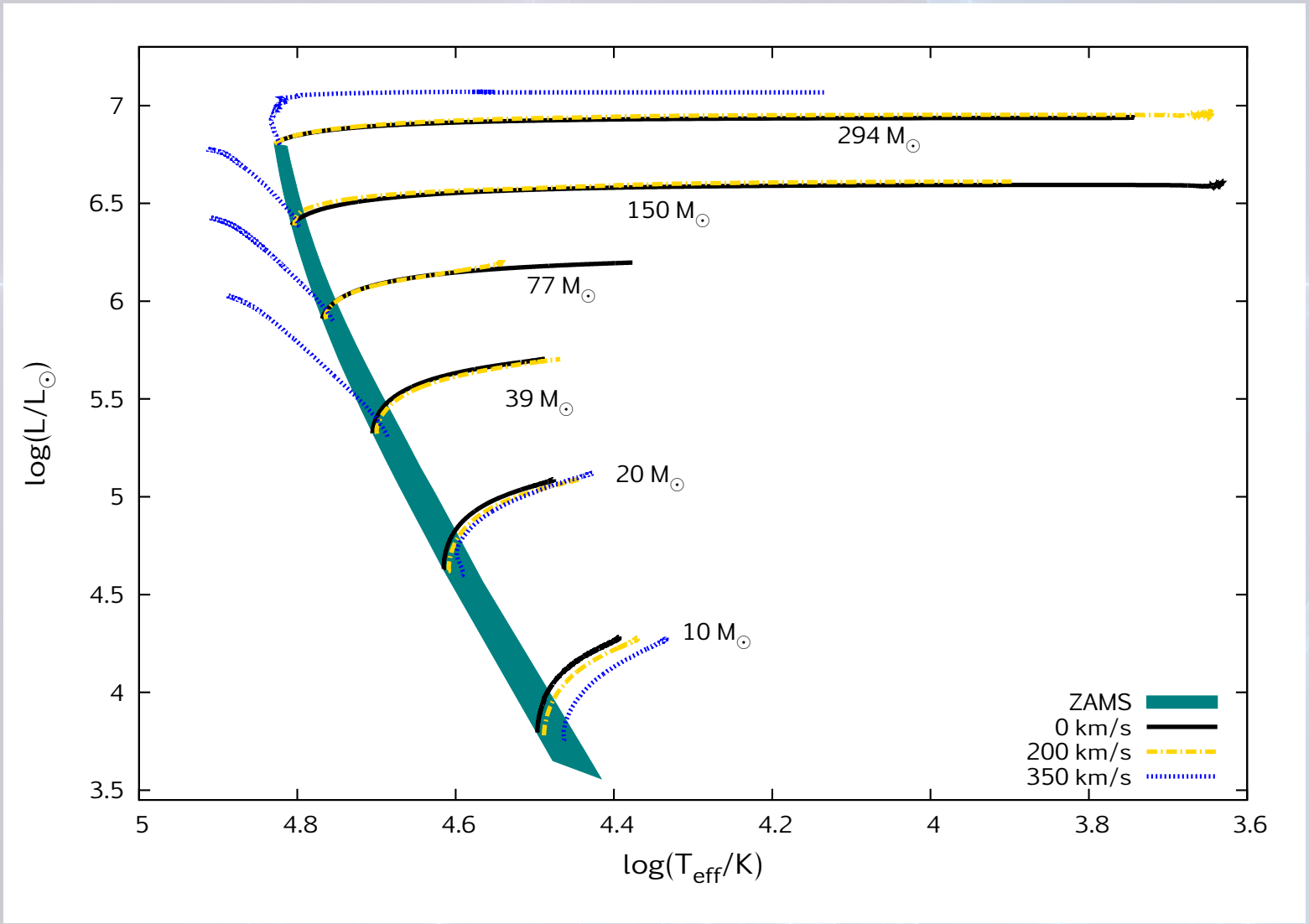
Low Metallicity Massive Stars

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



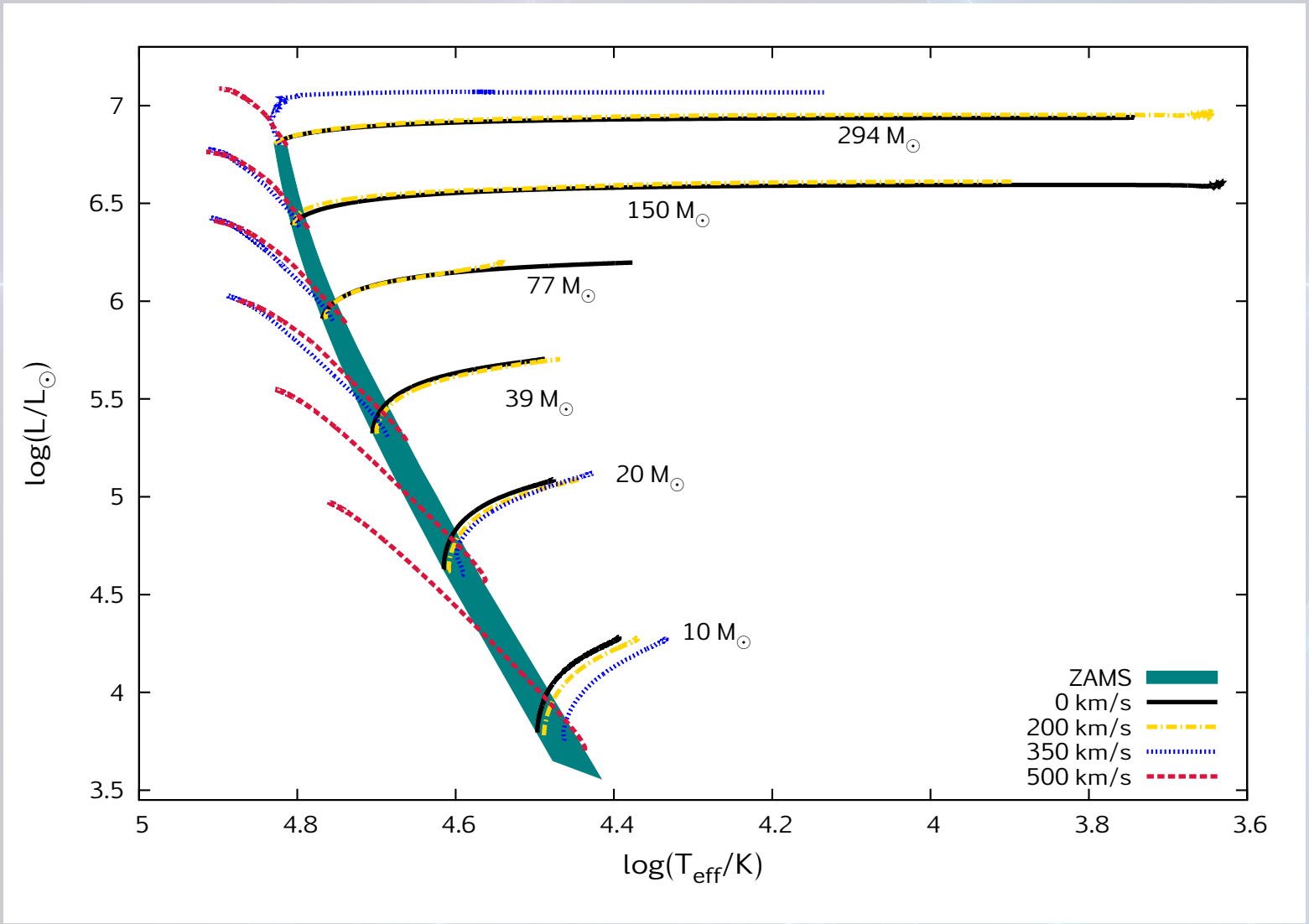
Low Metallicity Massive Stars

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



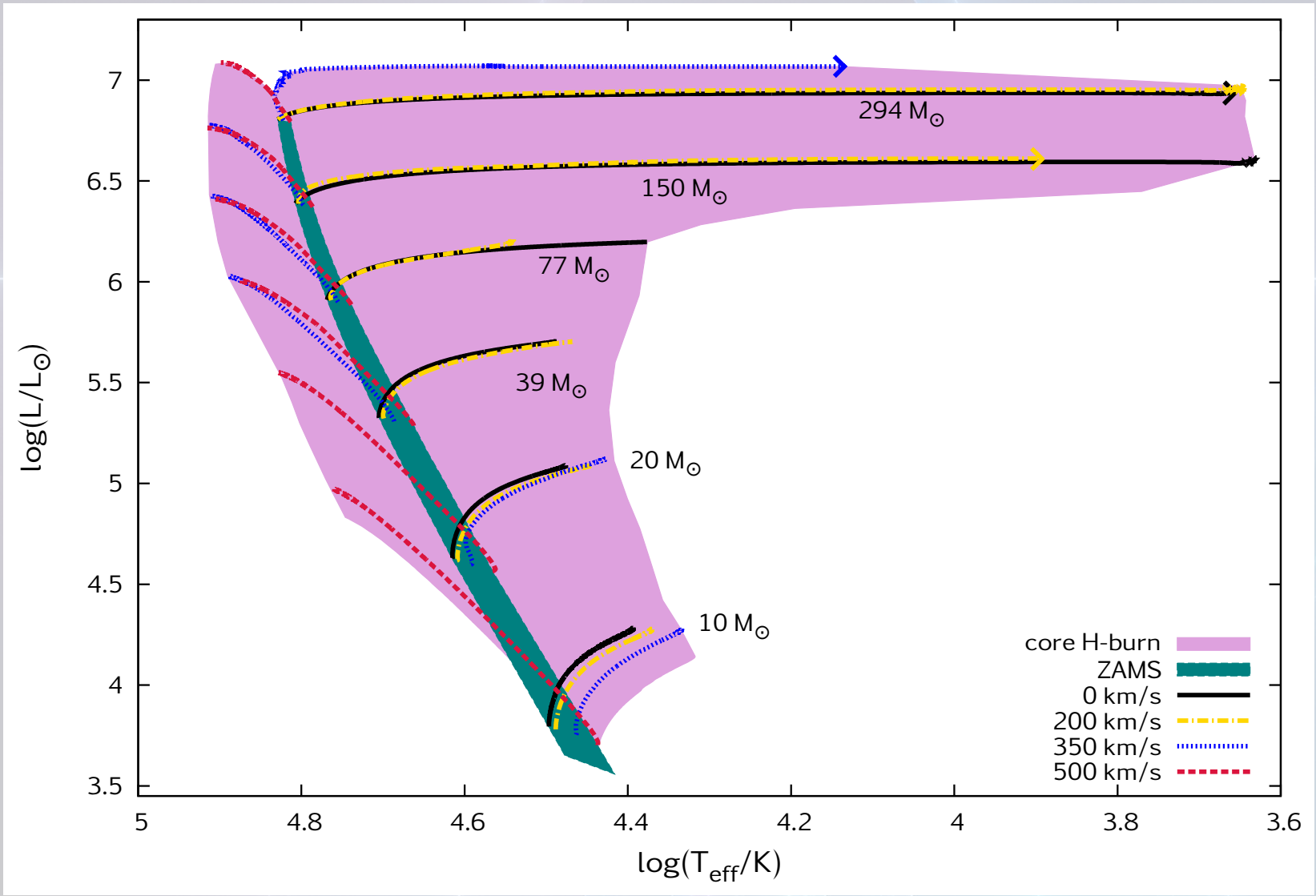
Low Metallicity Massive Stars

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



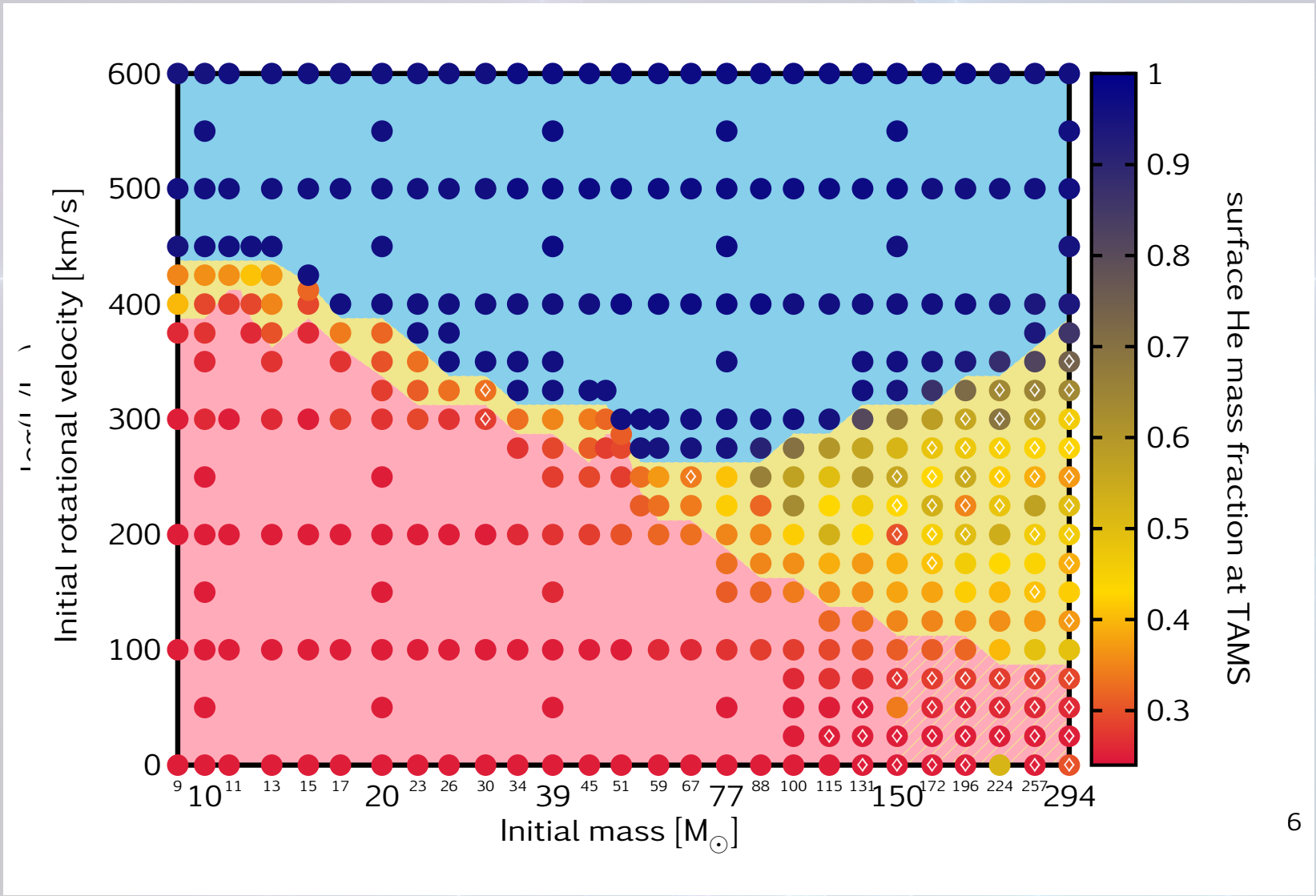
Low Metallicity Massive Stars

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



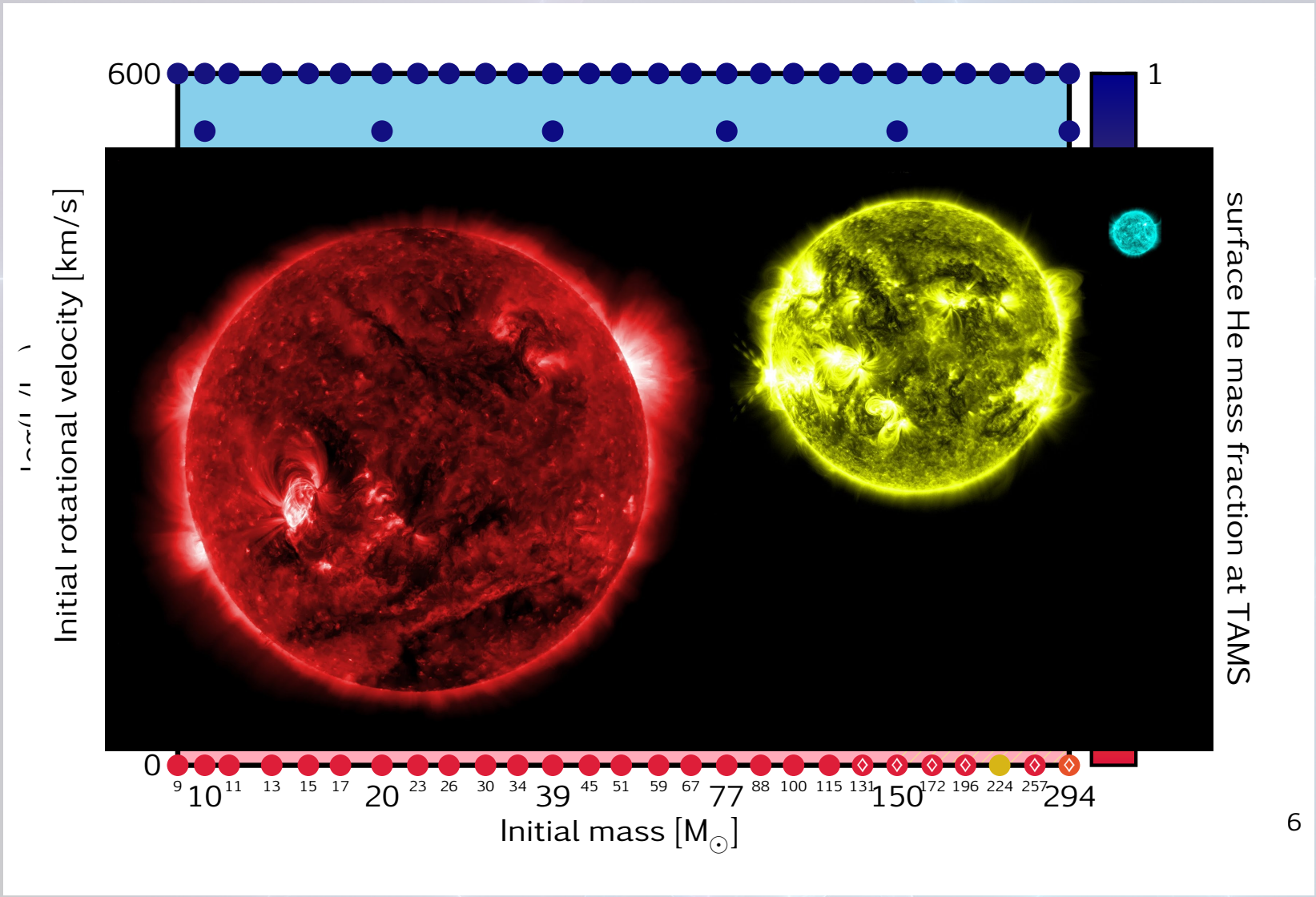
Low Metallicity Massive Stars

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



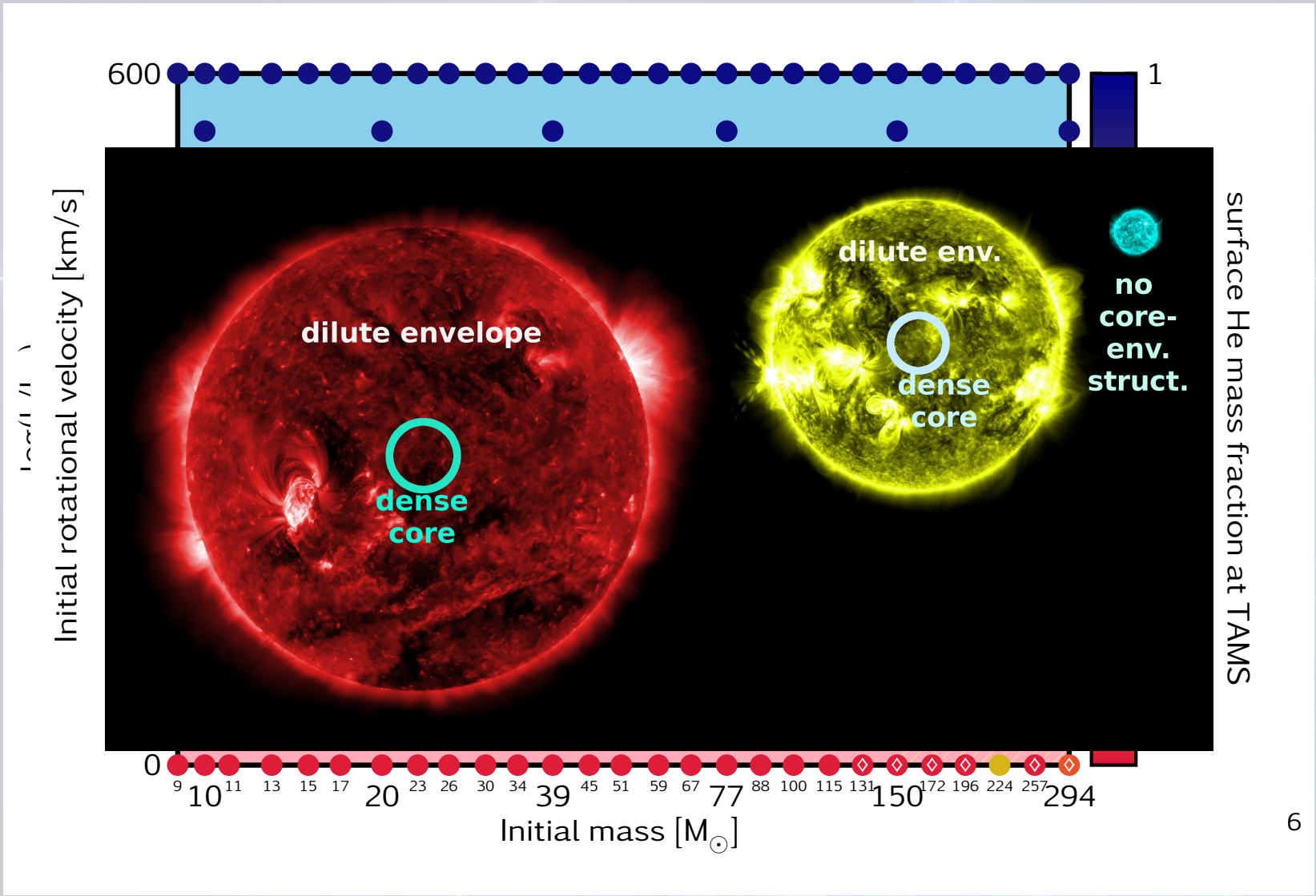
Low Metallicity Massive Stars

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



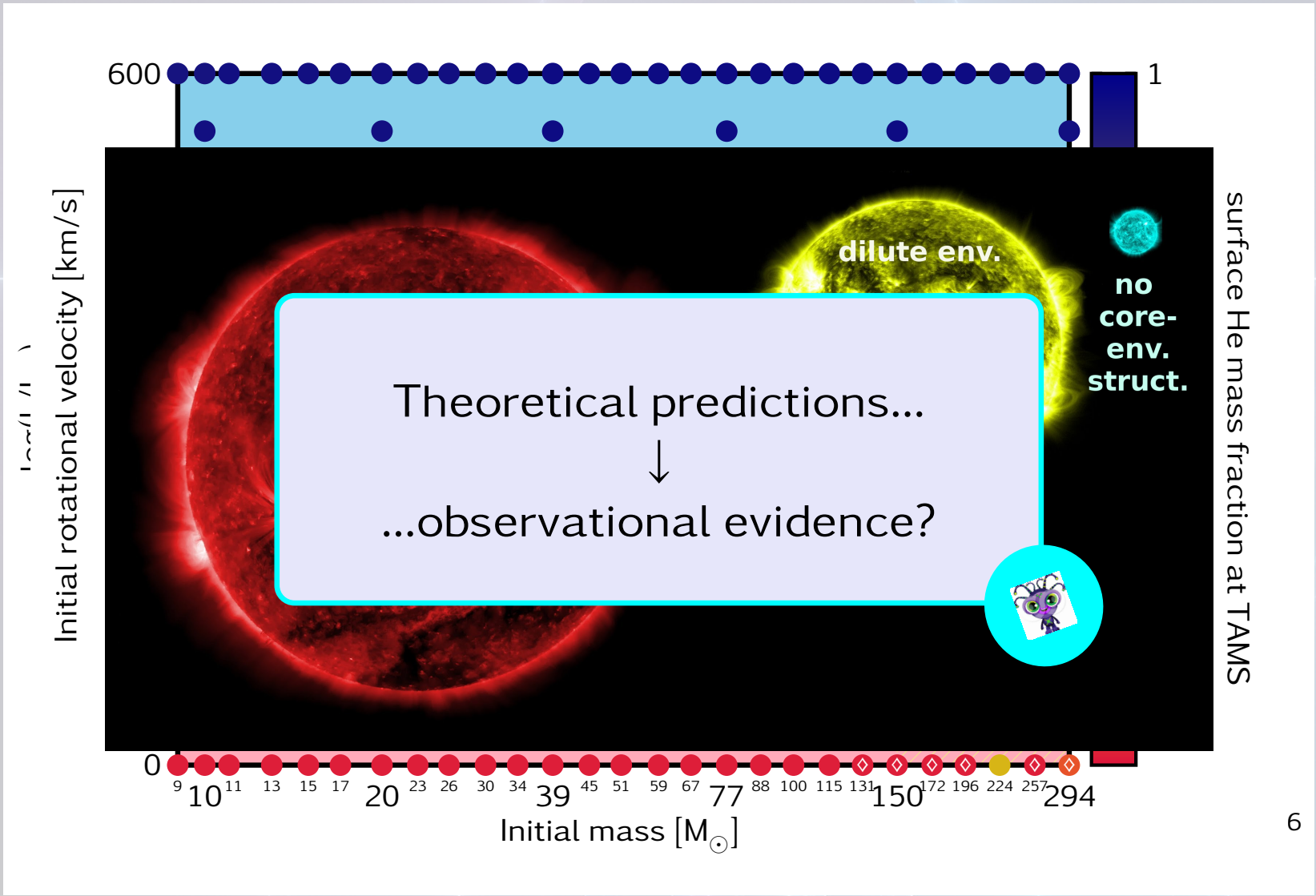
Low Metallicity Massive Stars

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



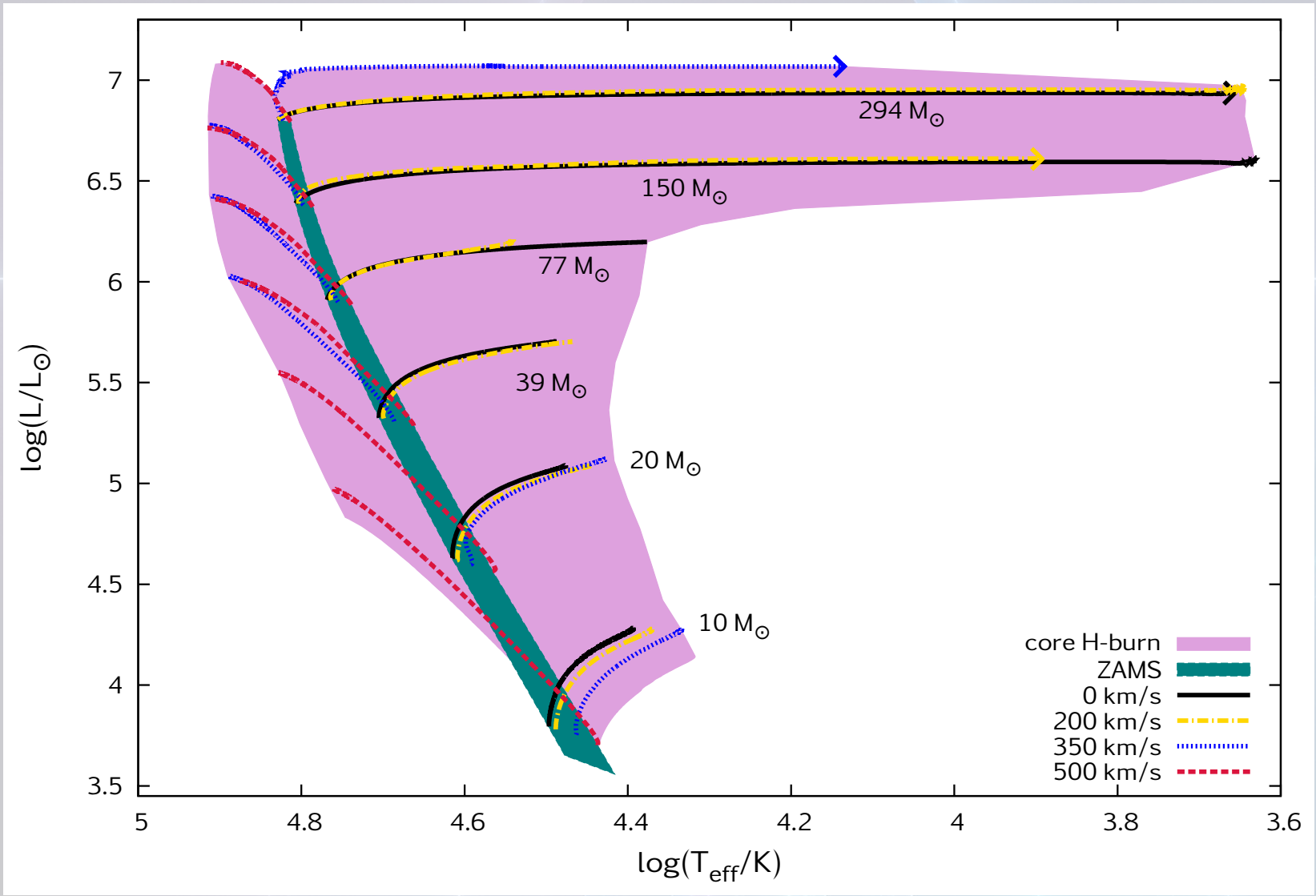
Low Metallicity Massive Stars

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



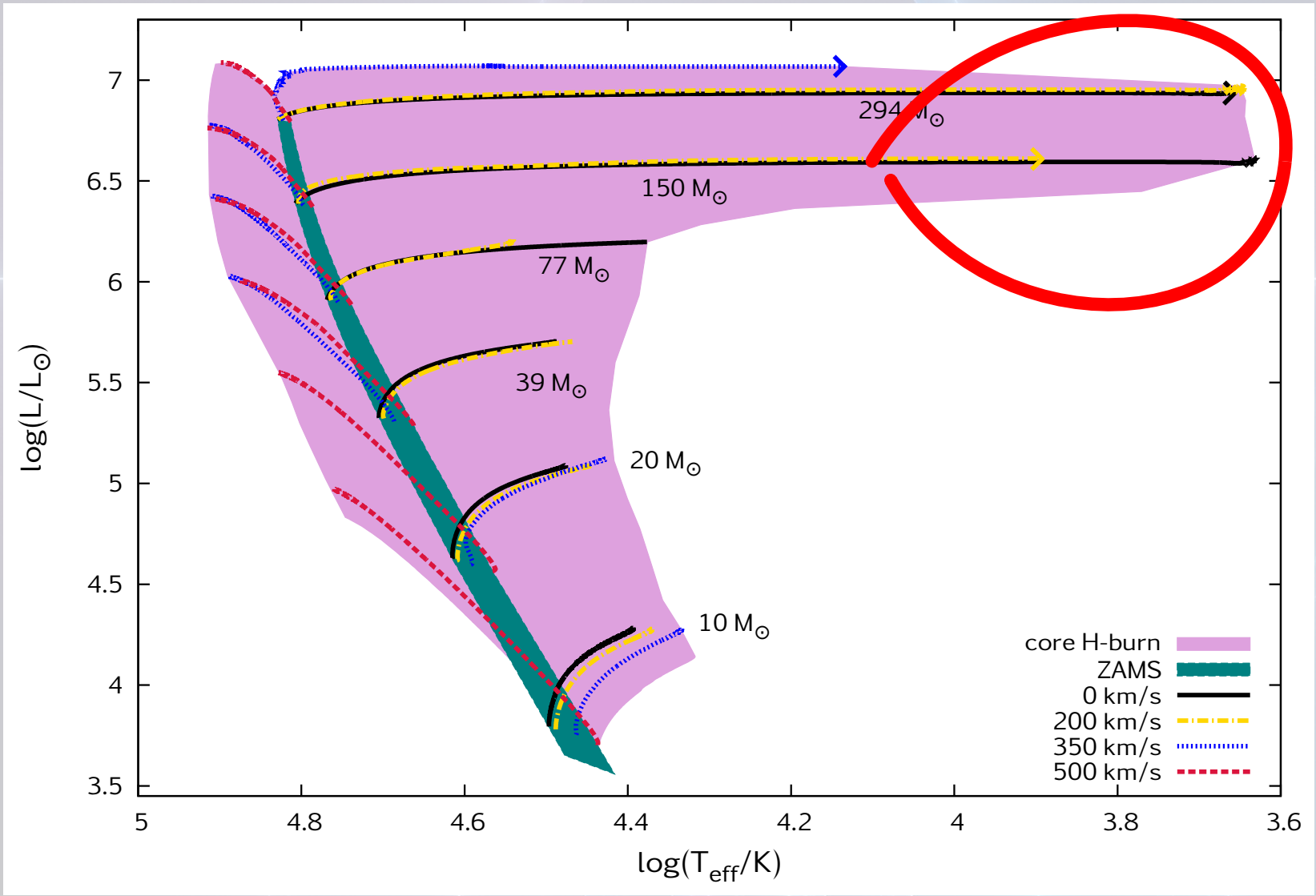
Low Metallicity Massive Stars

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



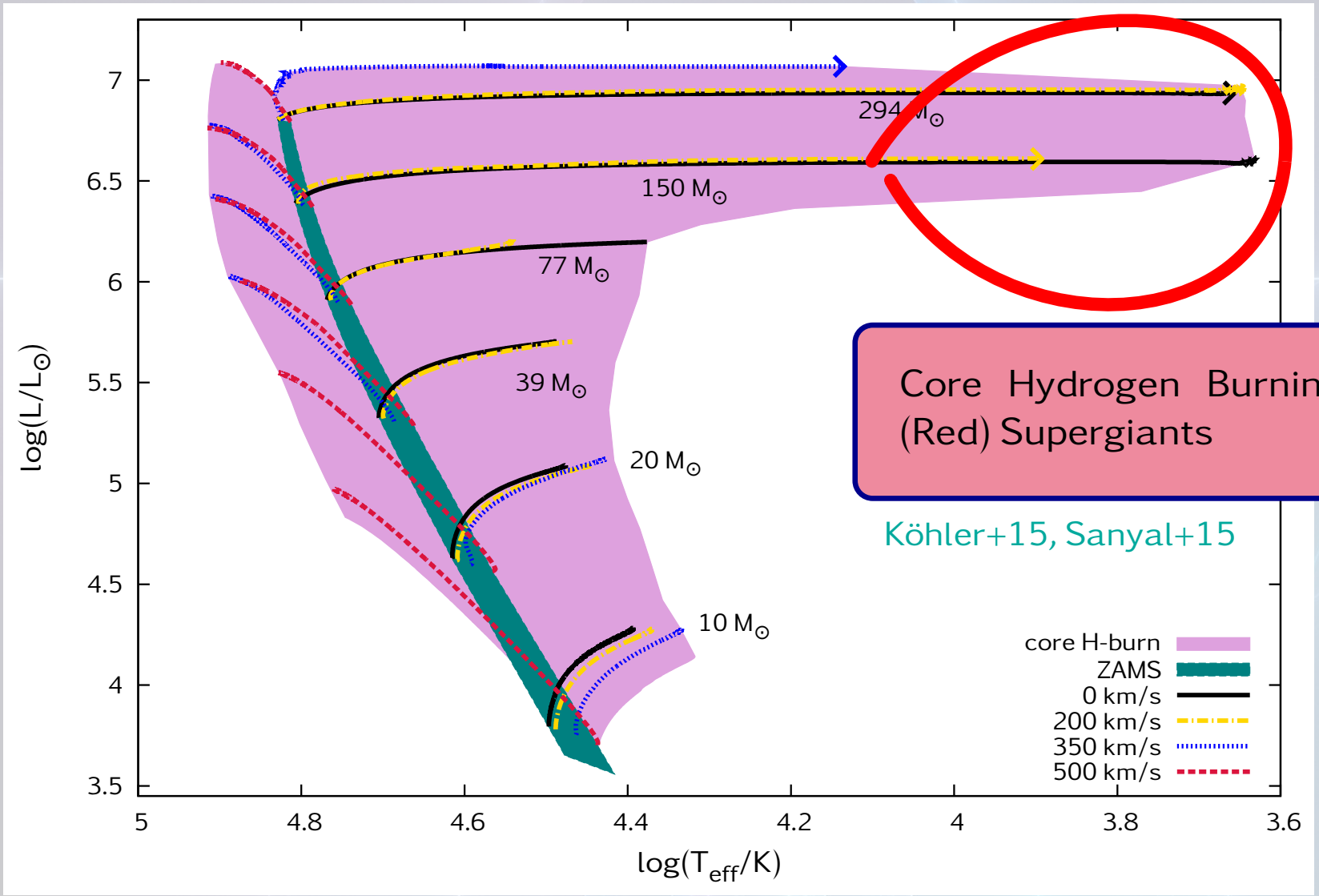
Low Metallicity Massive Stars

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



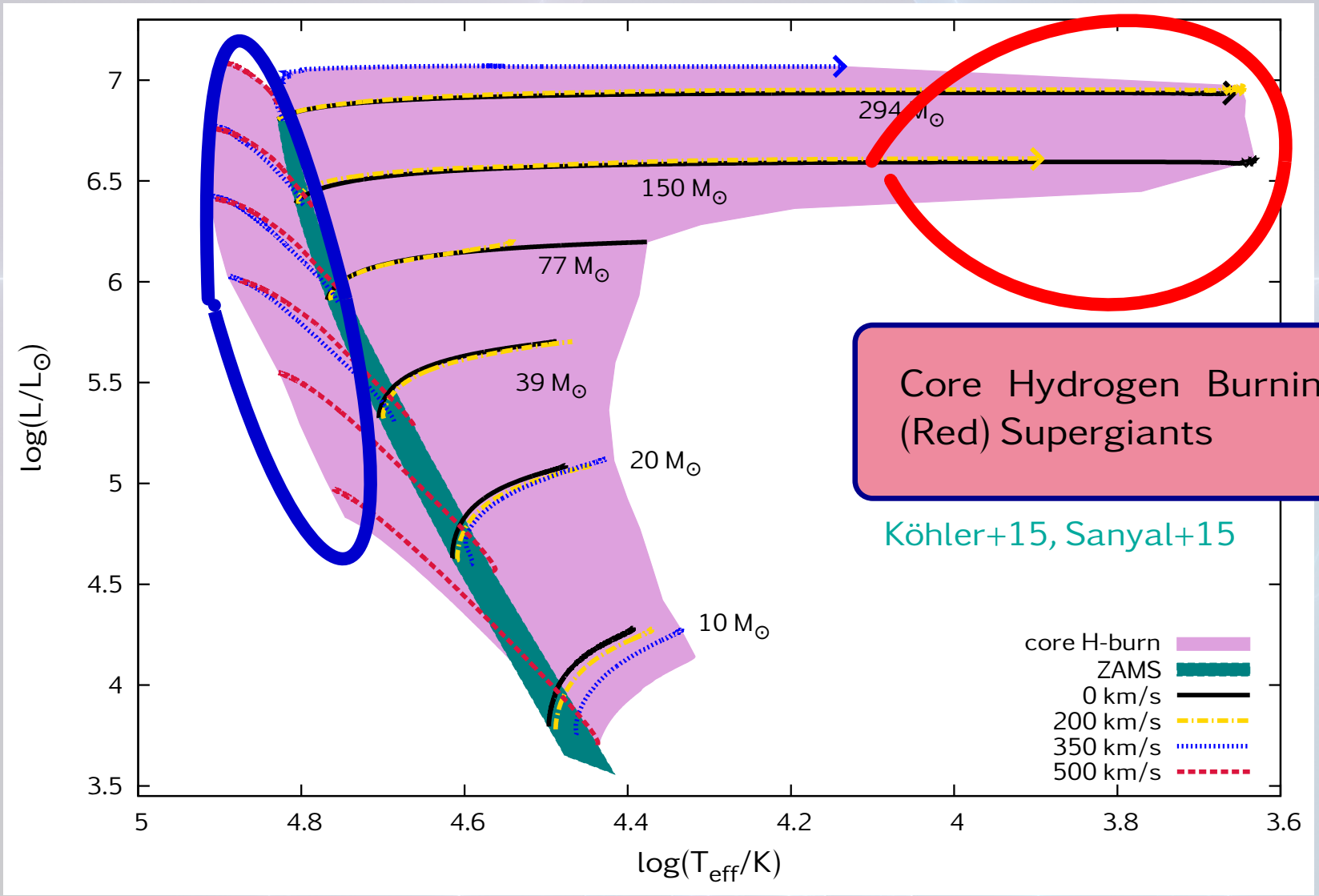
Low Metallicity Massive Stars

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



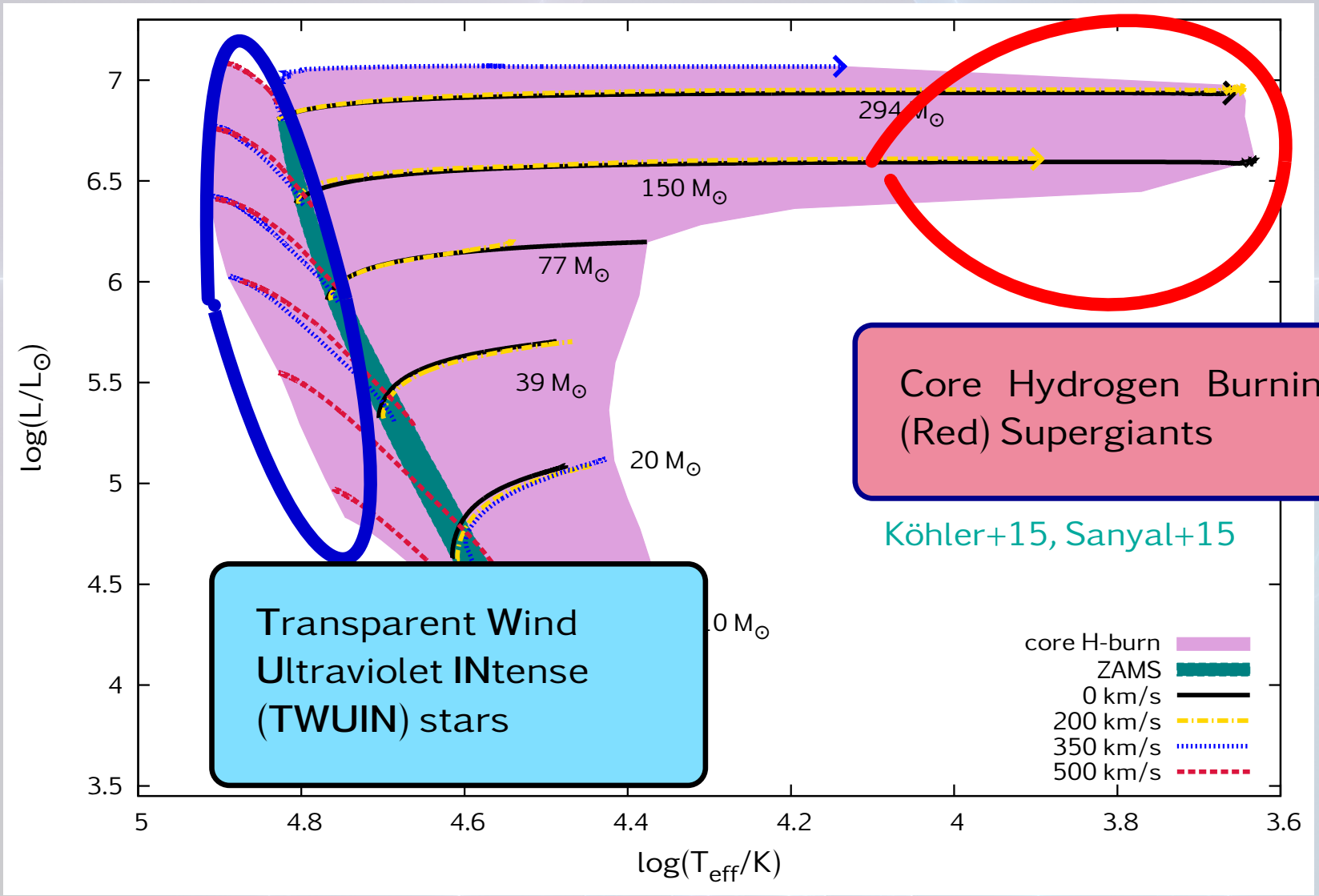
Low Metallicity Massive Stars

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



Low Metallicity Massive Stars

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



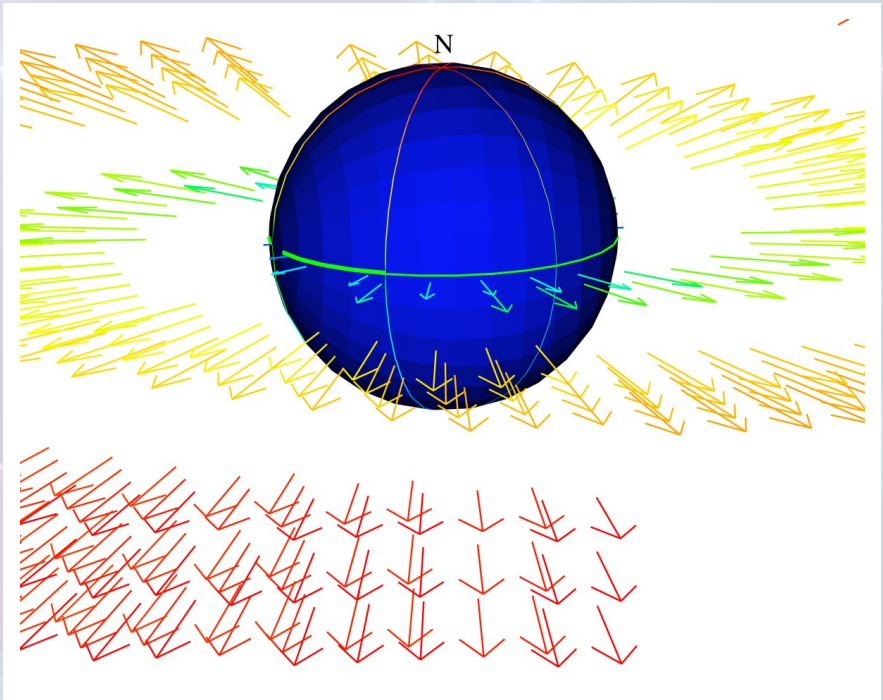
Transparent Wind
Ultraviolet INtense stars
(TWUIN stars)

– in the

starburst galaxy I Zwicky 18

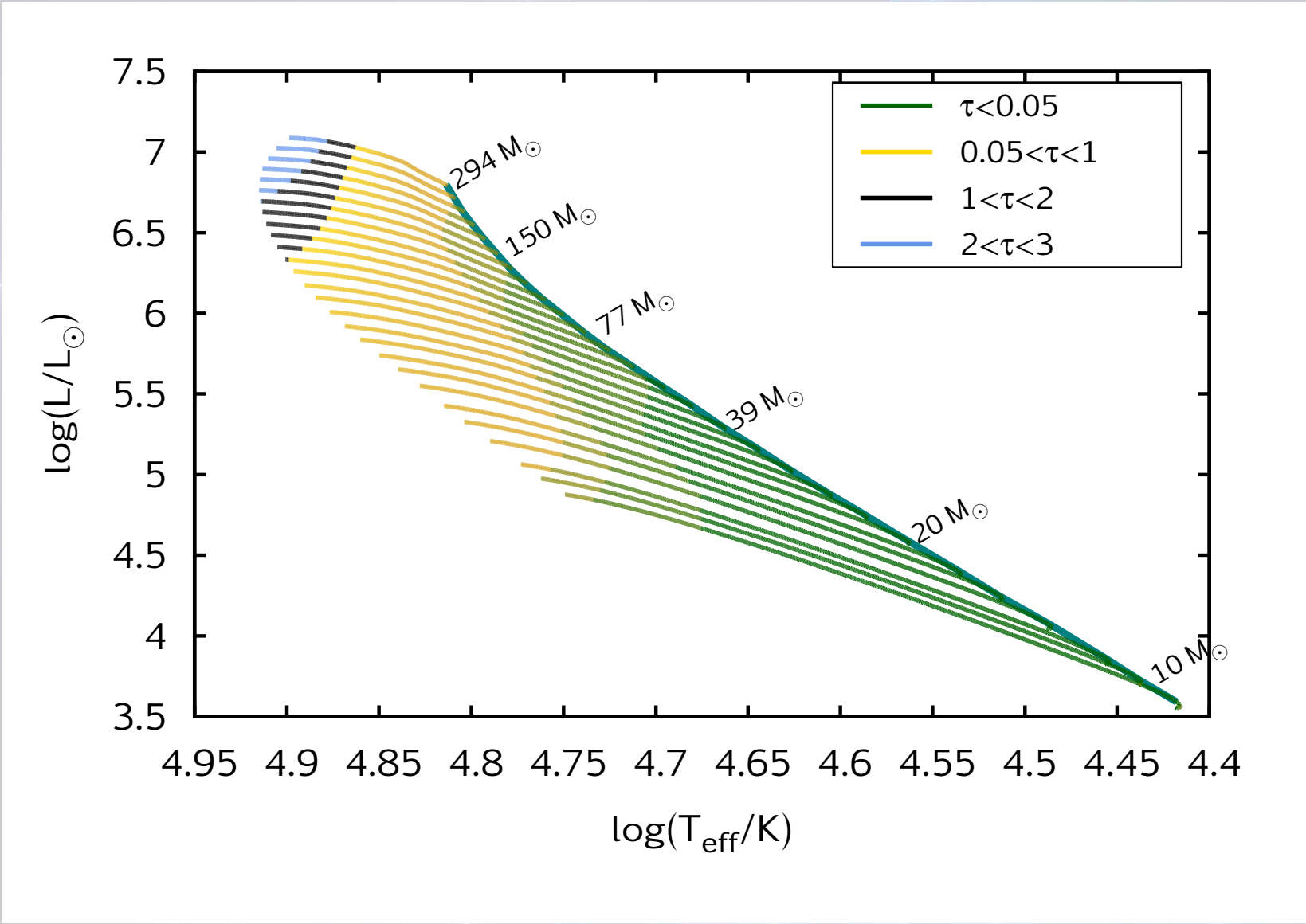
Stellar winds

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



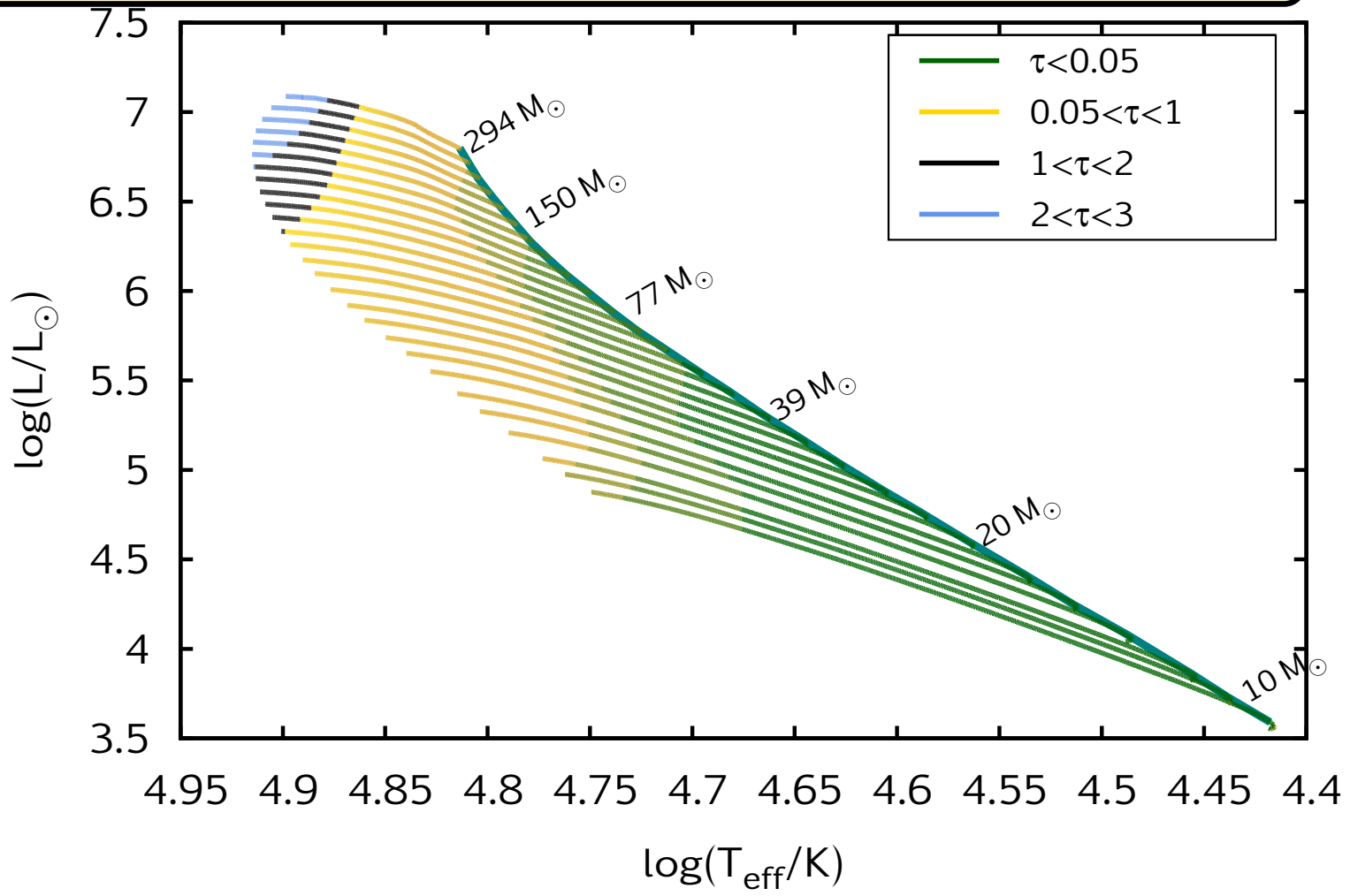
Hot stars at low Z: transparent wind!

Hot stars at low Z: transparent wind!



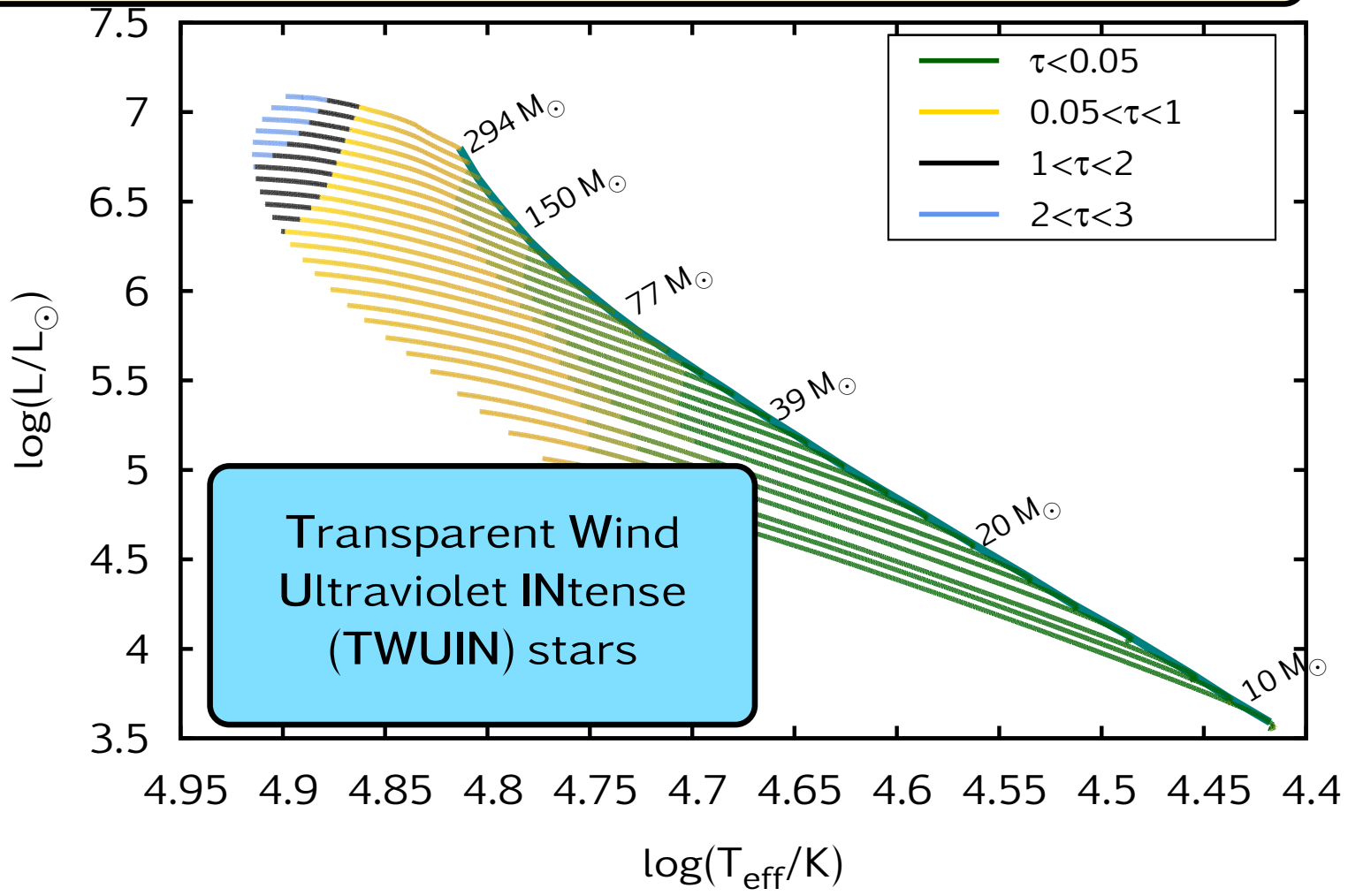
Hot stars at low Z: transparent wind!

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

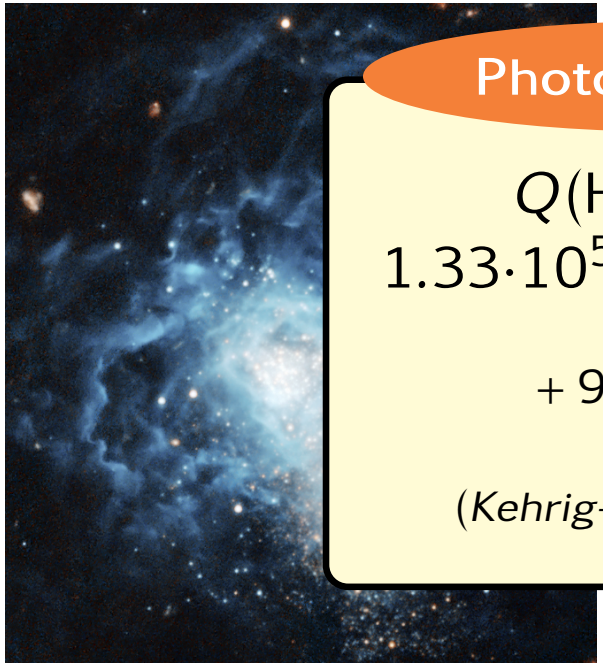
- Blue Compact Dwarf Galaxy
- 60 million lightyears $\rightarrow$ local
- star formation rate: 0.1 $M_\odot$/yr
- ionized gas
- low metallicity: Z=1/50 $Z_\odot$

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

Back to I Zw 18

I Zwicky 18

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



Photoionization

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

+ 9 WC stars

(*Kehrig+15, Crowther+06*)

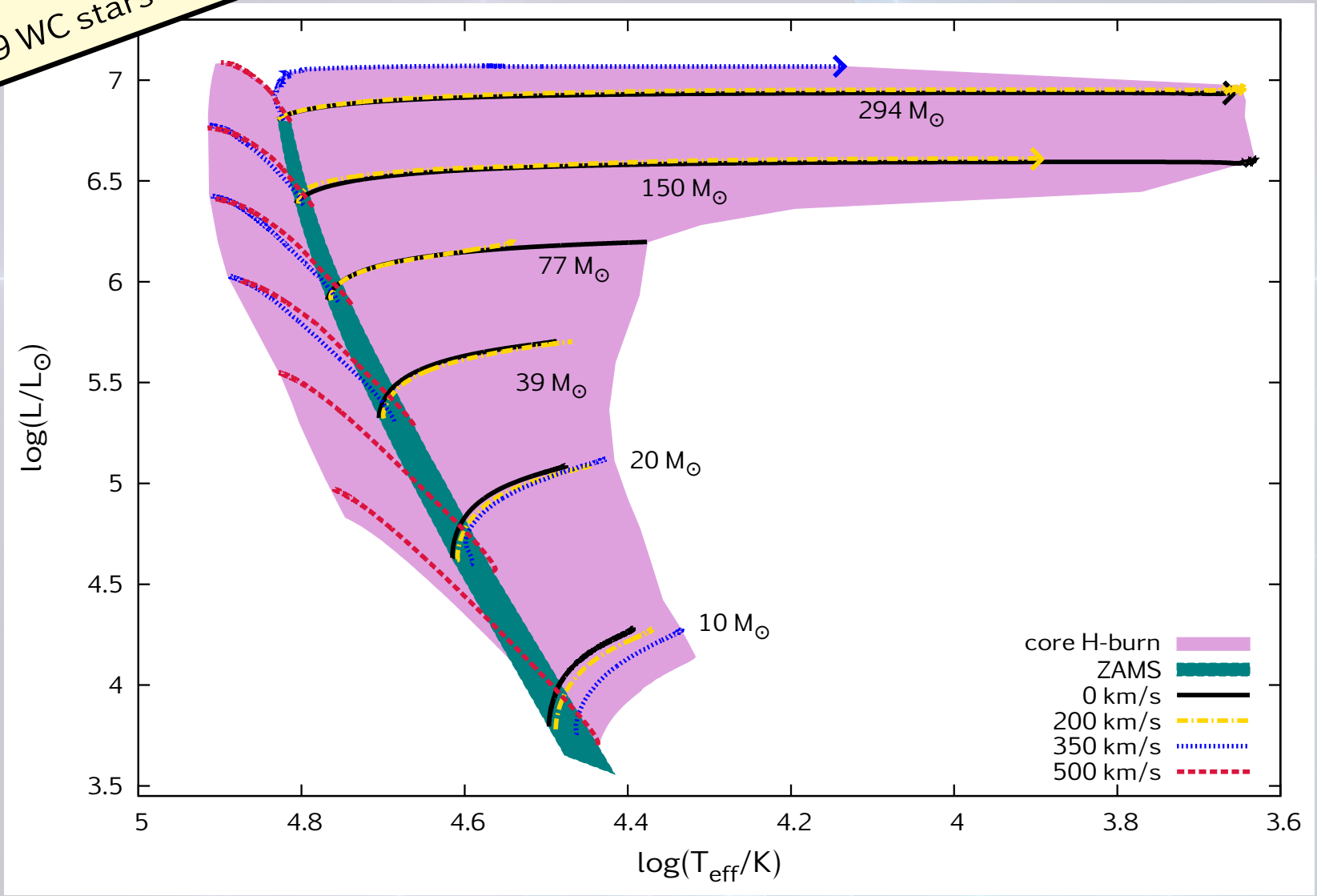
Legrand+07, Aloisi+09, Annibali+13, Kehrig+13, Lebouteiller+13

Photoionization in I Zw 18

Photoionization

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

+ 9 WC stars

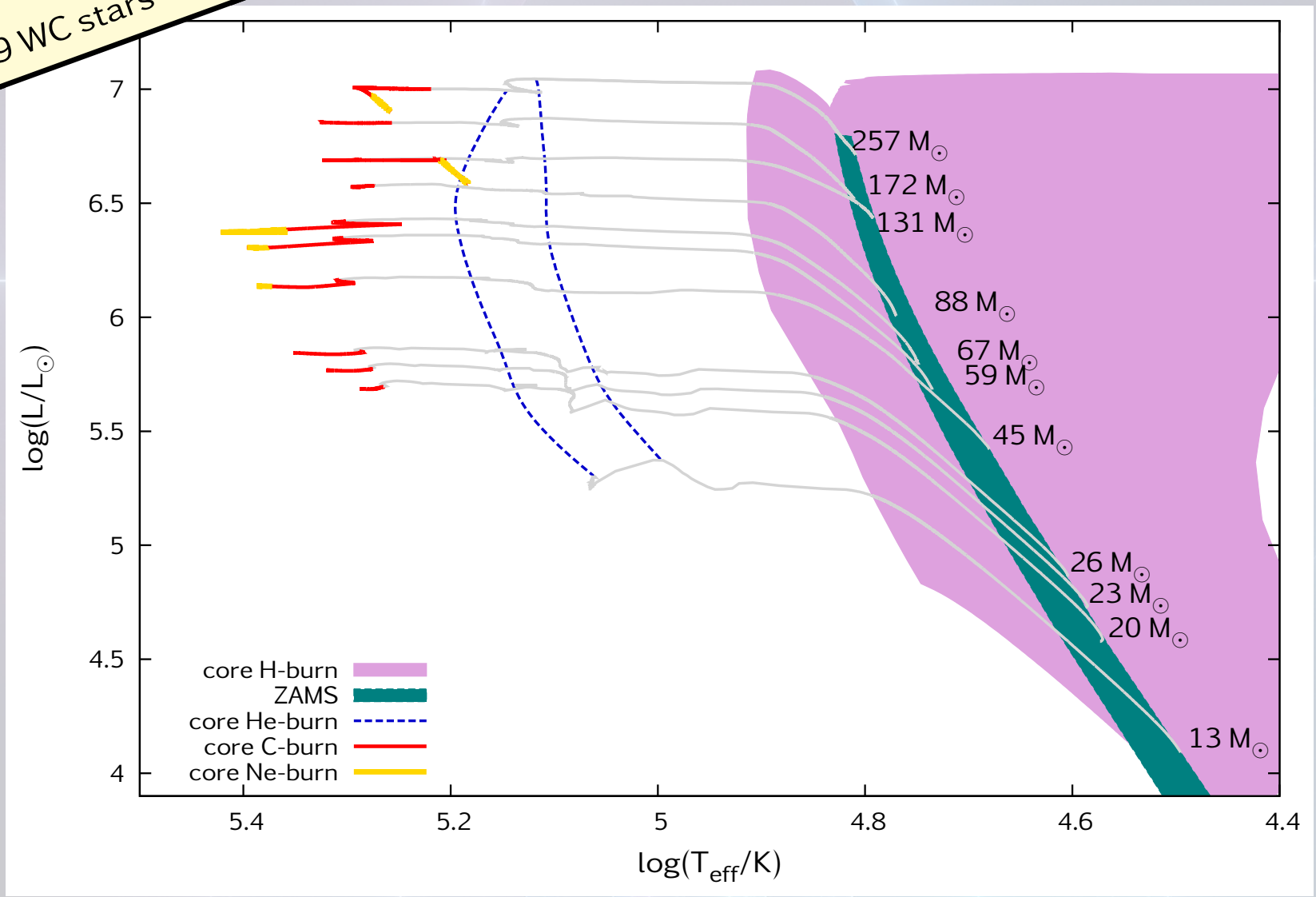


Photoionization in I Zw 18

Photoionization

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

+ 9 WC stars

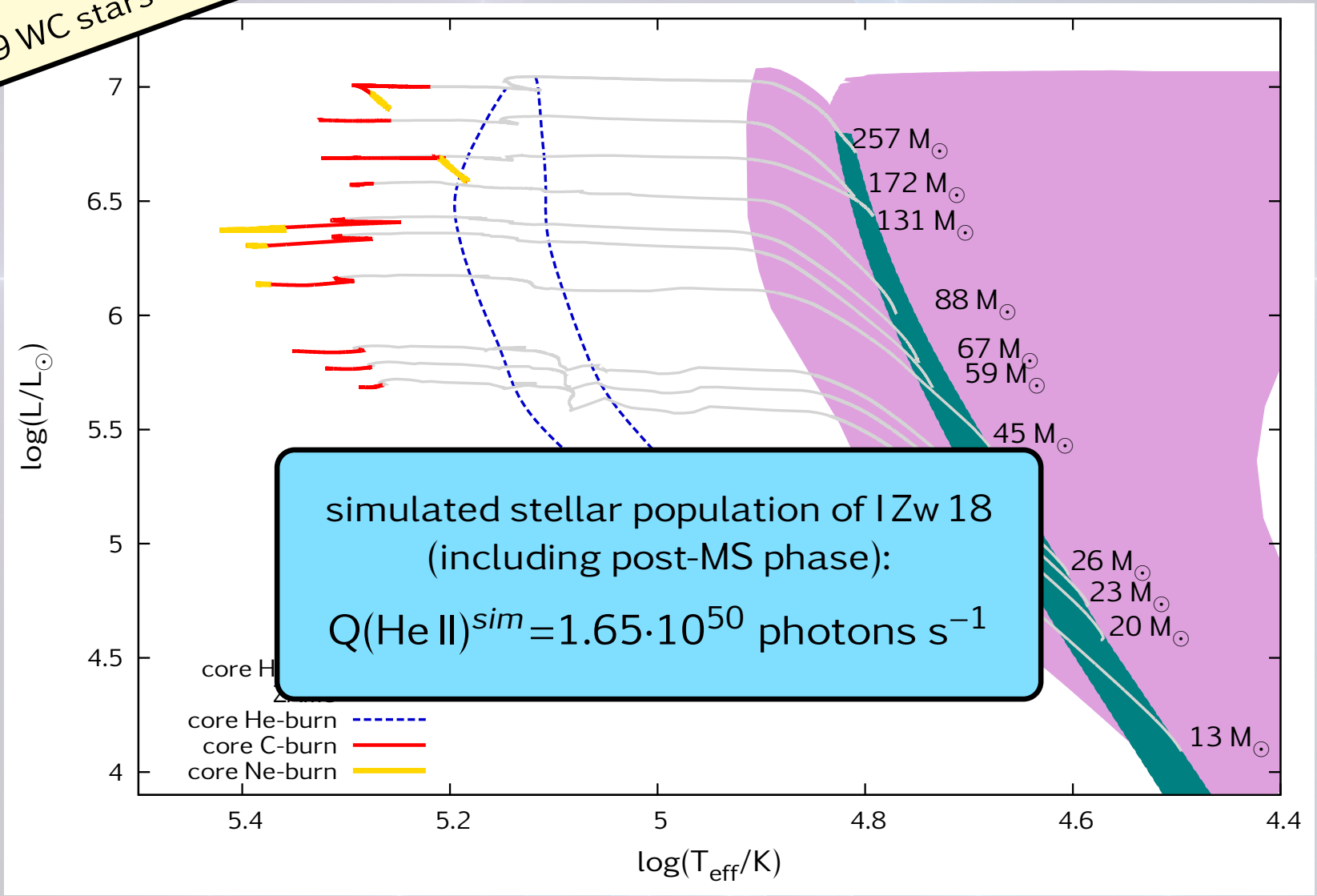


Photoionization in I Zw 18

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):

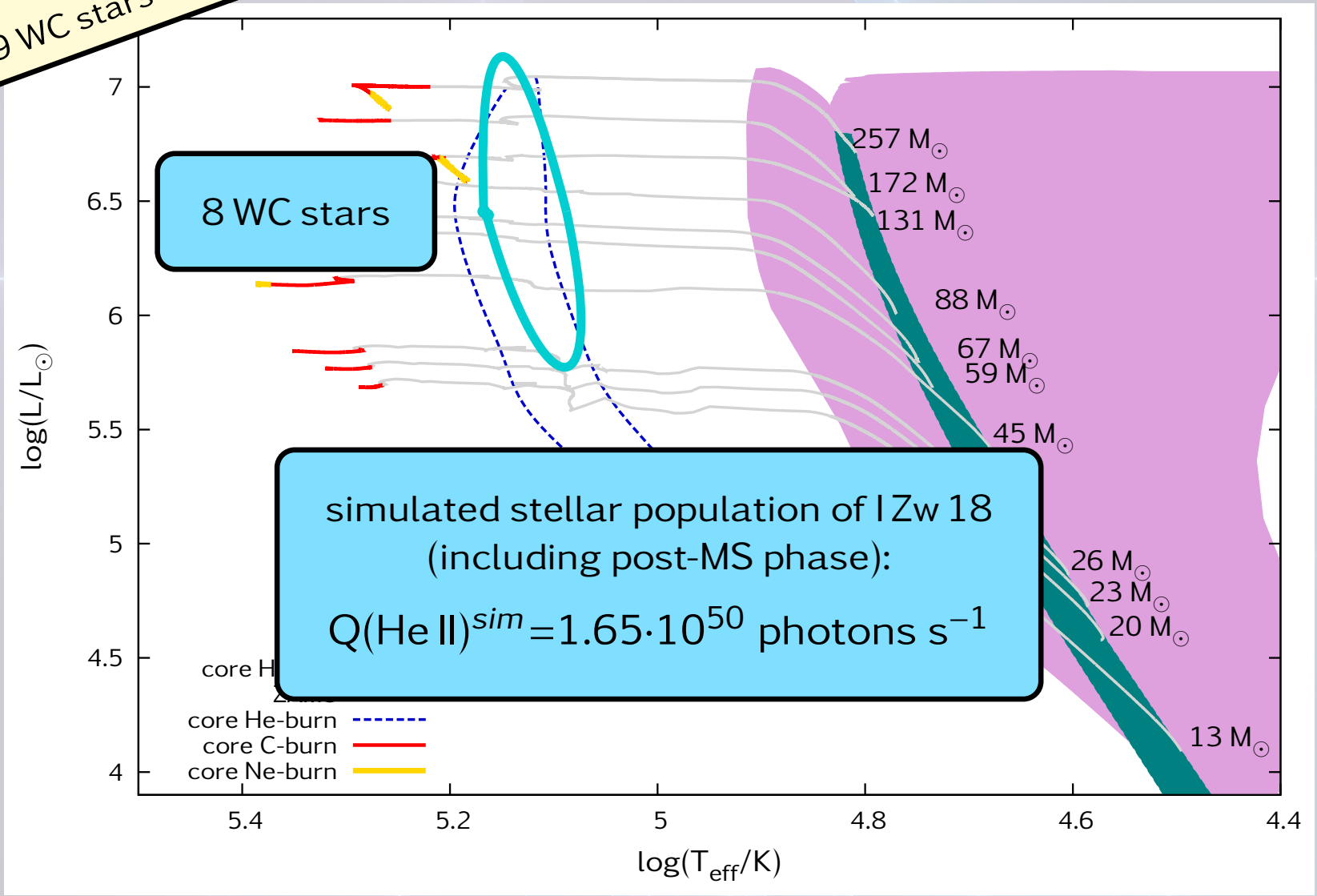
$Q(\mathrm{He\,II})^{sim} = 1.65 \cdot 10^{50}$ photons s^{-1}

Photoionization in I Zw 18

Photoionization

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

+ 9 WC stars

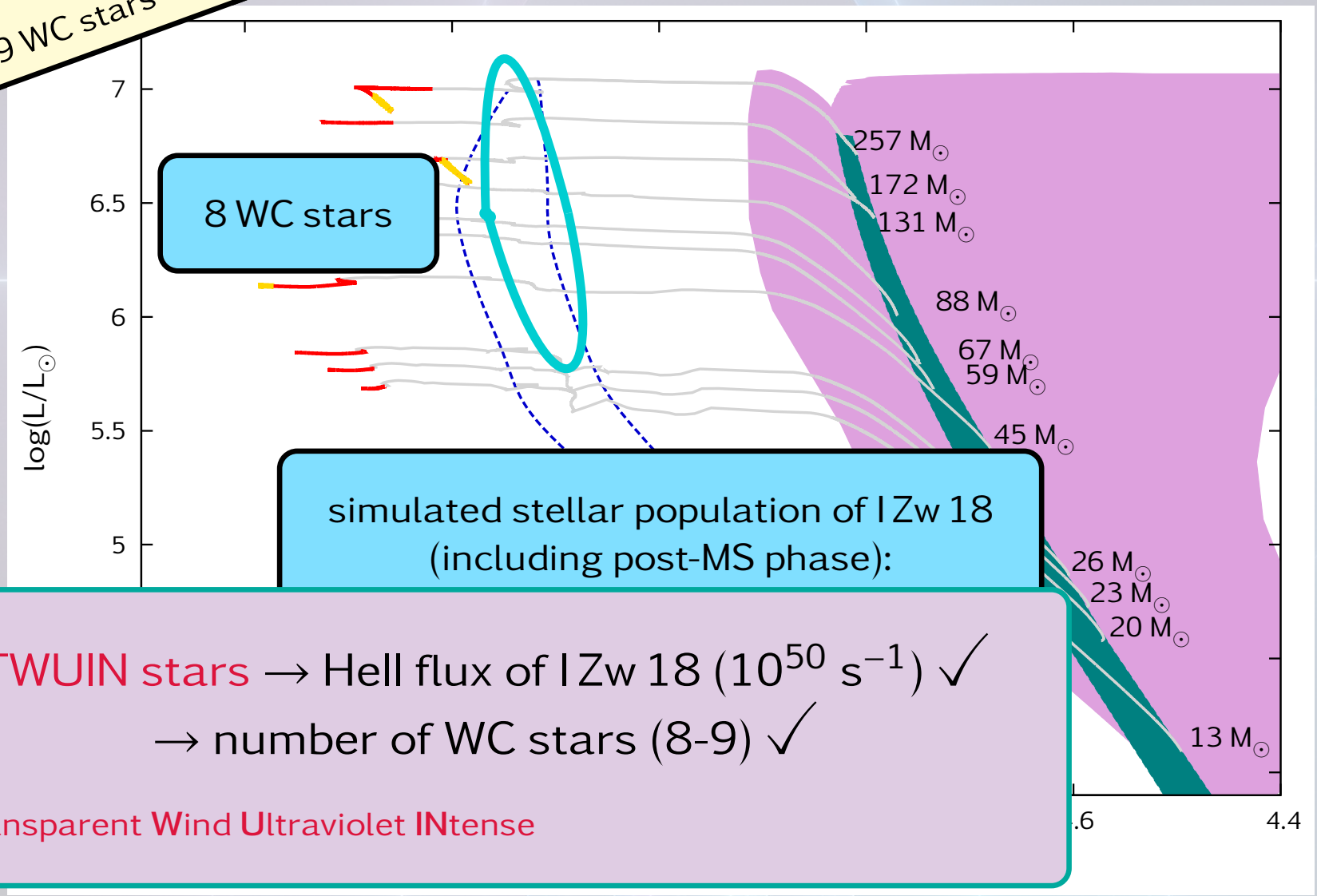


Photoionization in I Zw 18

Photoionization

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

+ 9 WC stars



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

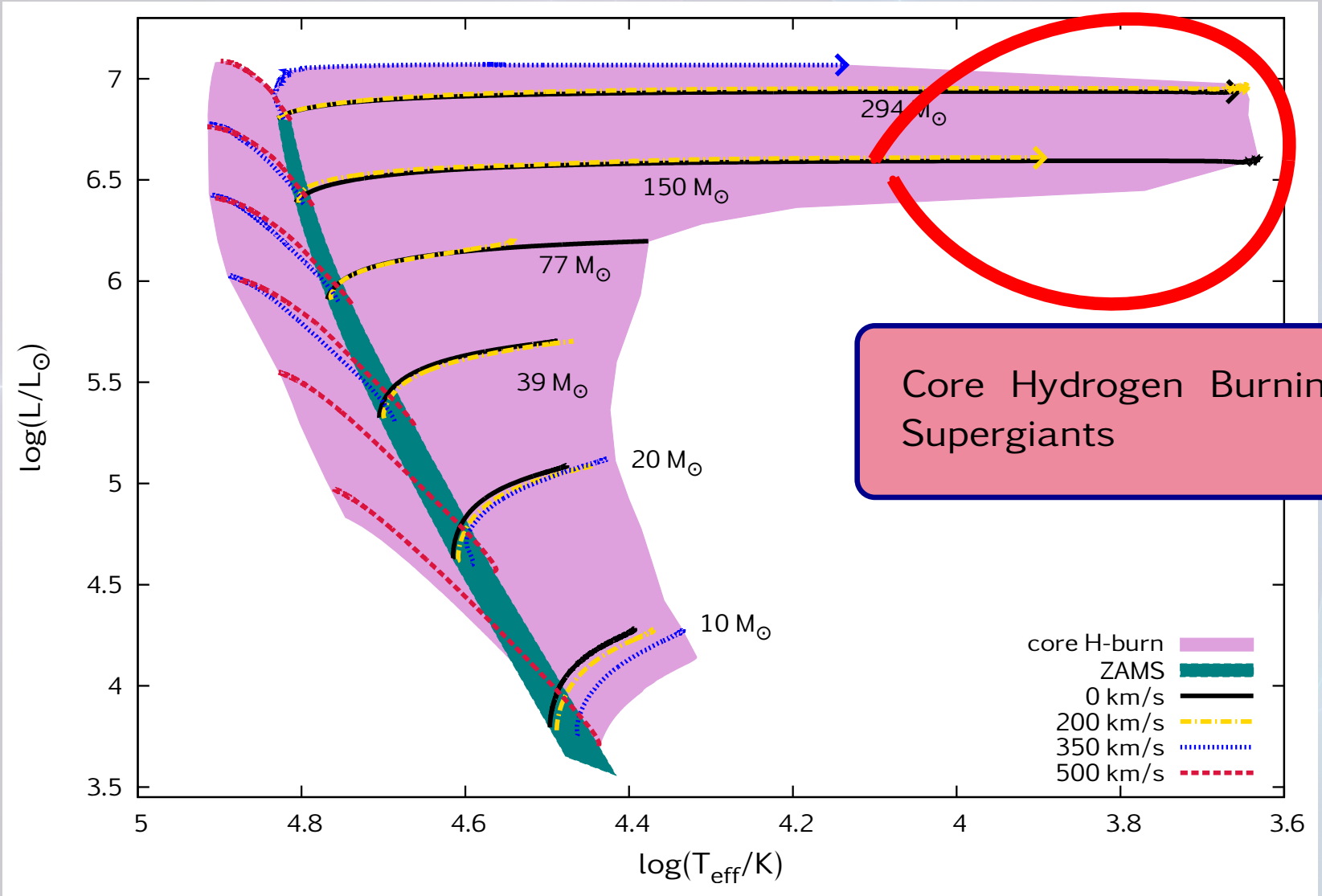
→ number of WC stars (8-9) ✓

Transparent **W**ind **U**ltraviolet **IN**tense

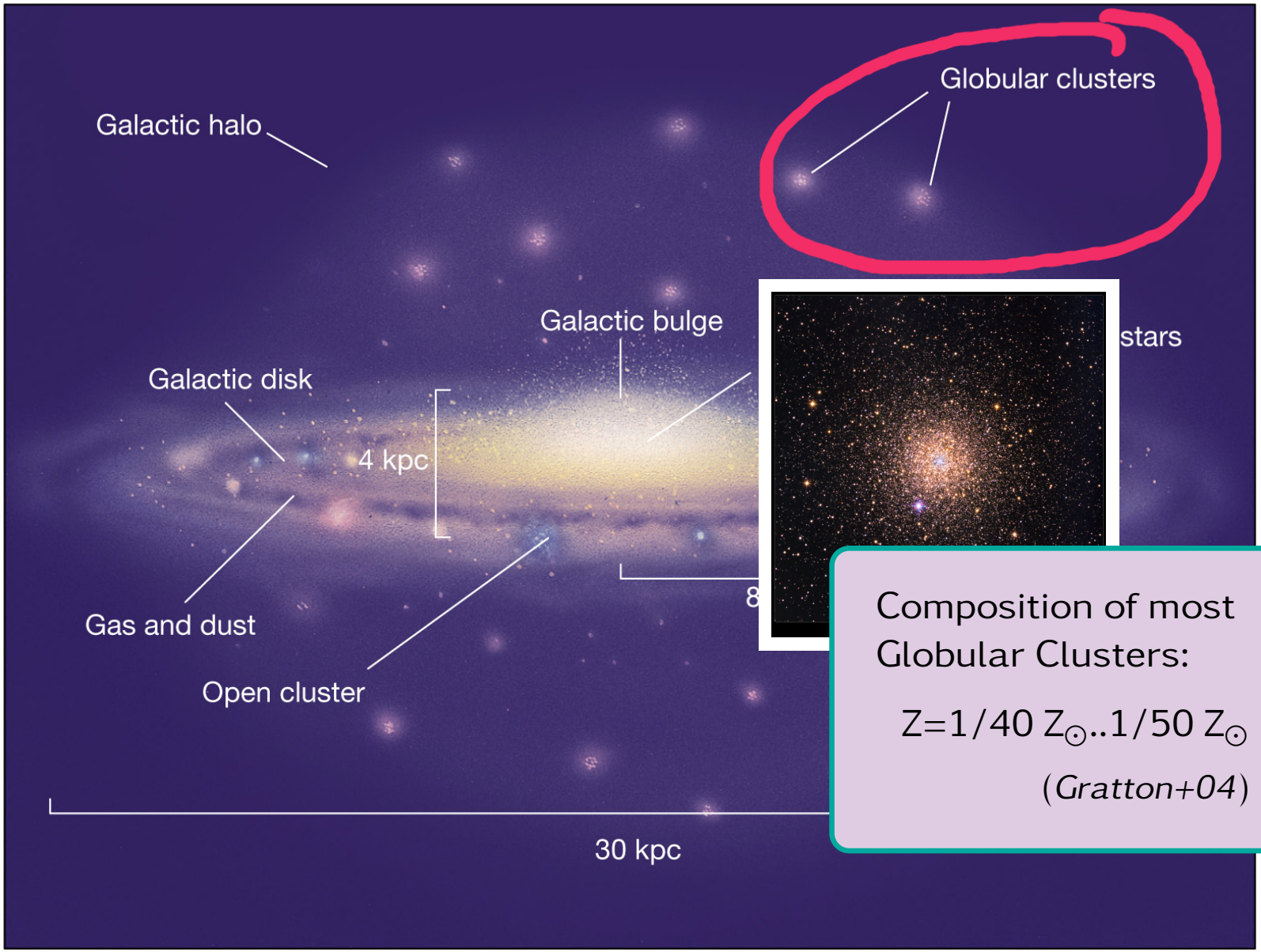
Core Hydrogen Burning Supergiants

– in the

Early Globular Clusters


294 M⊙
150 M⊙
77 M⊙
39 M⊙
20 M⊙
10 M⊙
Core Hydrogen Burning Supergiants
core H-burn
ZAMS
0 km/s
200 km/s
350 km/s
500 km/s
log(L/L⊙)
log(T_eff/K)
7
6.5
6
5.5
5
4.5
4
3.5
5
4.8
4.6
4.4
4.2
4
3.8
3.6

Globular Clusters & Abundance Anomalies

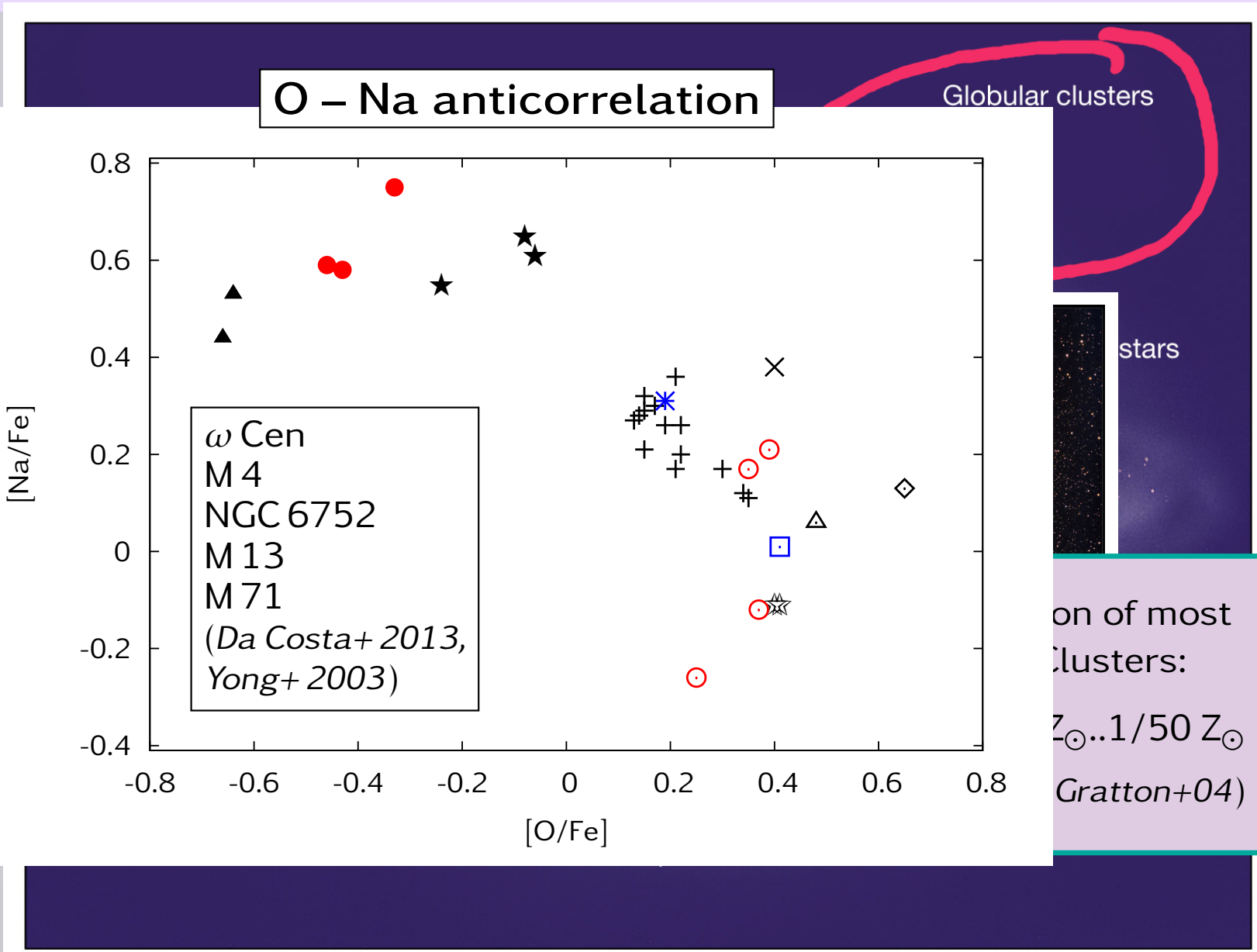


Composition of most Globular Clusters:

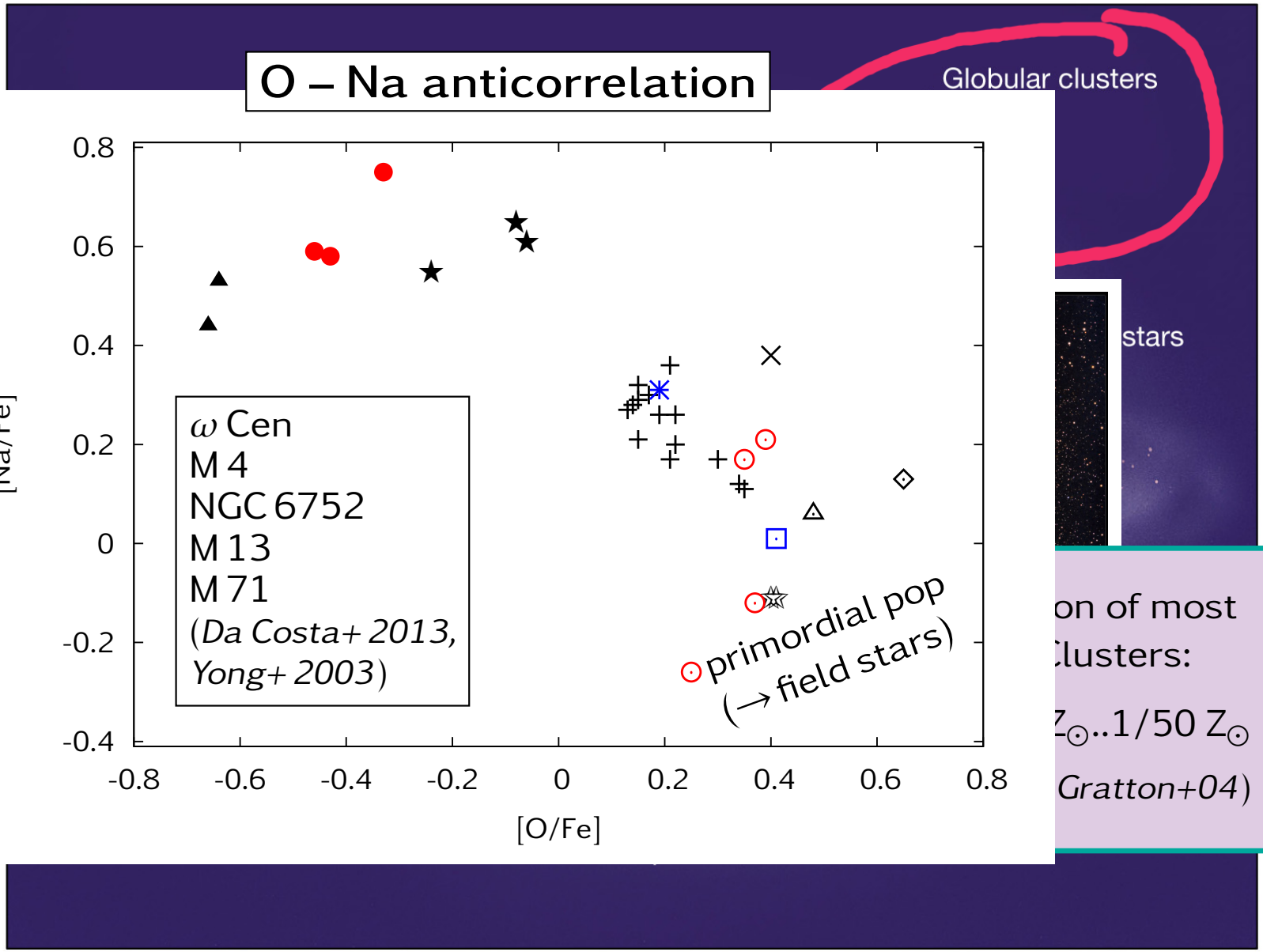
$Z=1/40\ Z_{\odot}..1/50\ Z_{\odot}$

(*Gratton+04*)

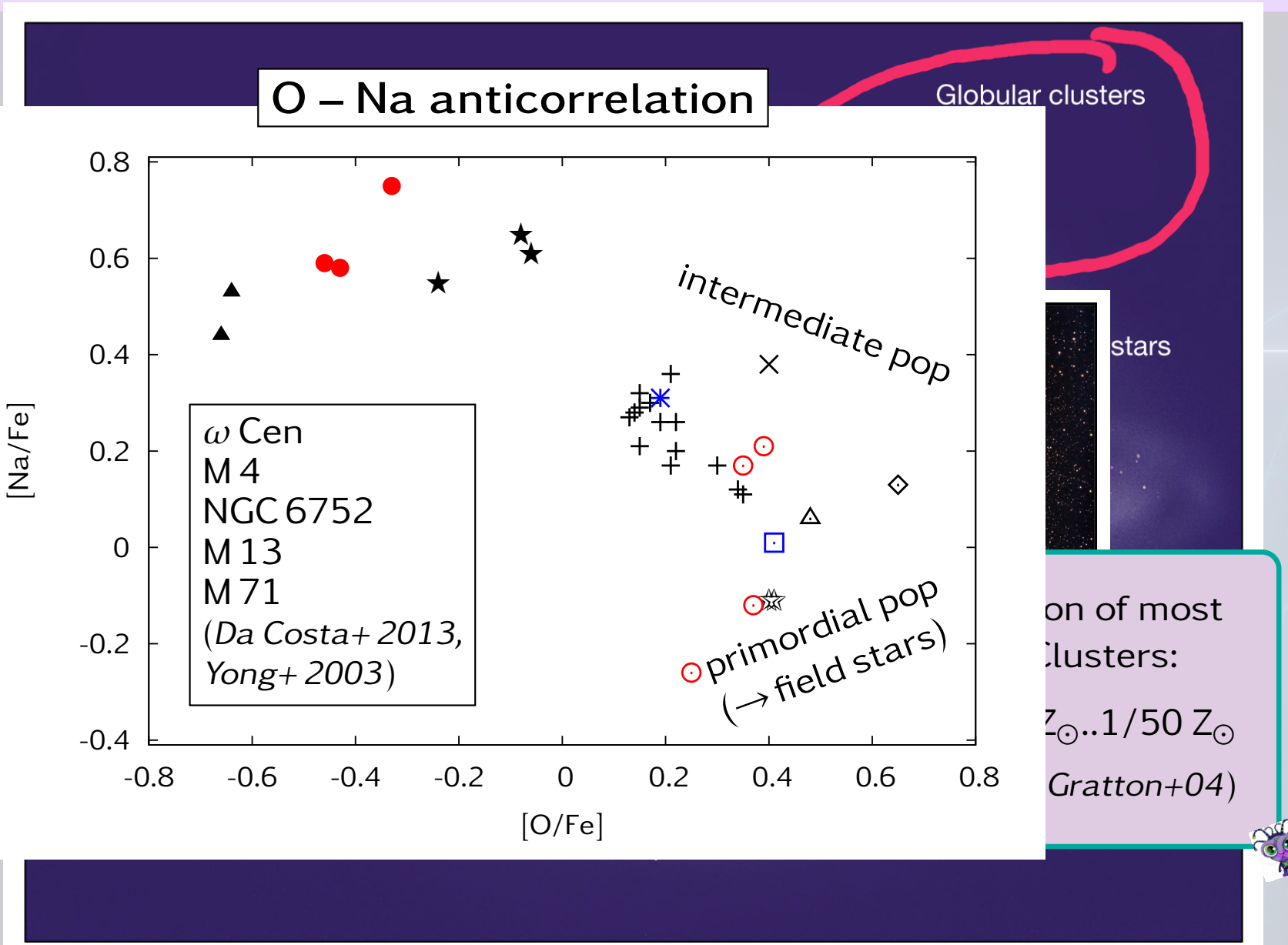
Globular Clusters & Abundance Anomalies



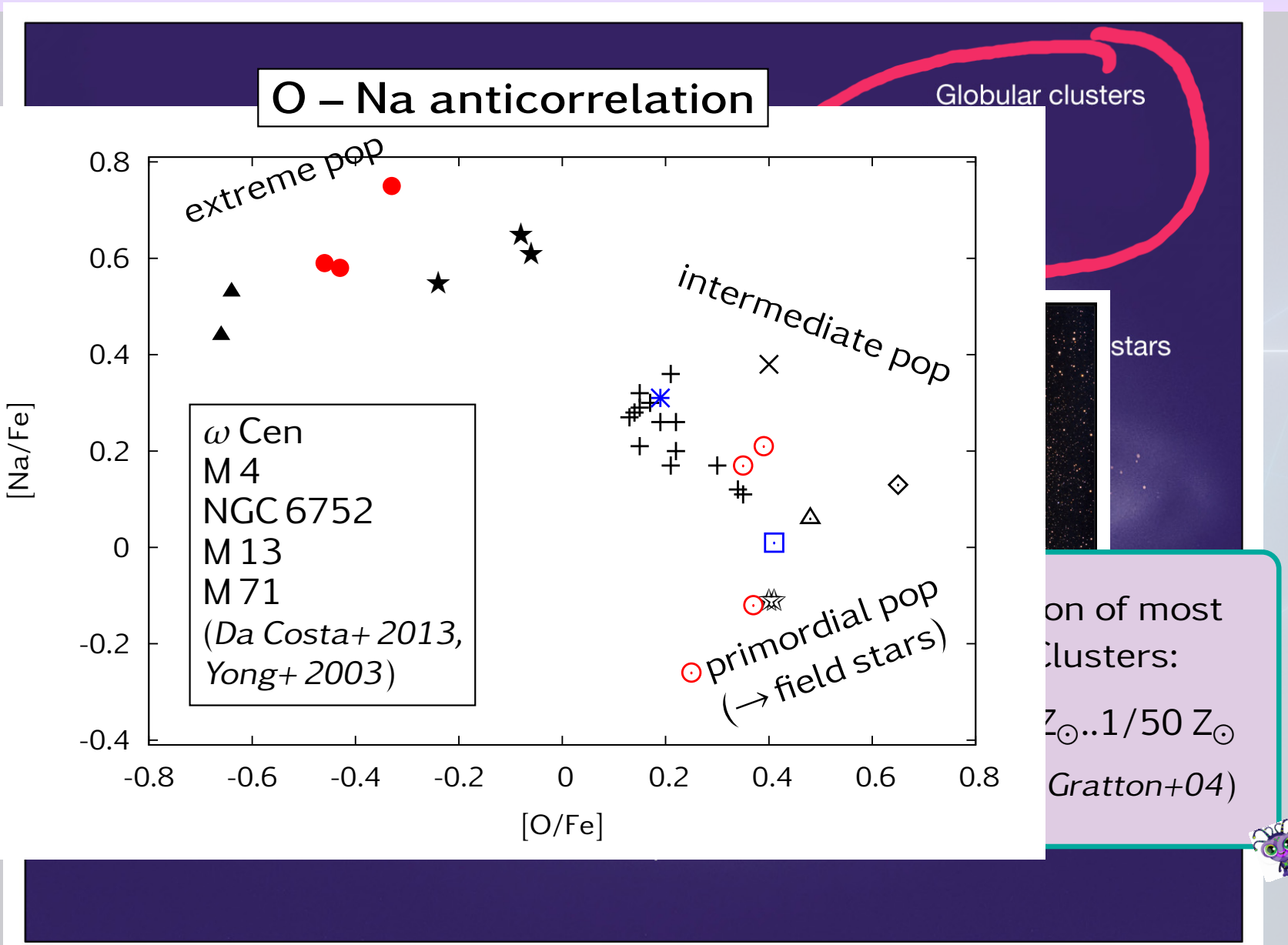
Globular Clusters & Abundance Anomalies



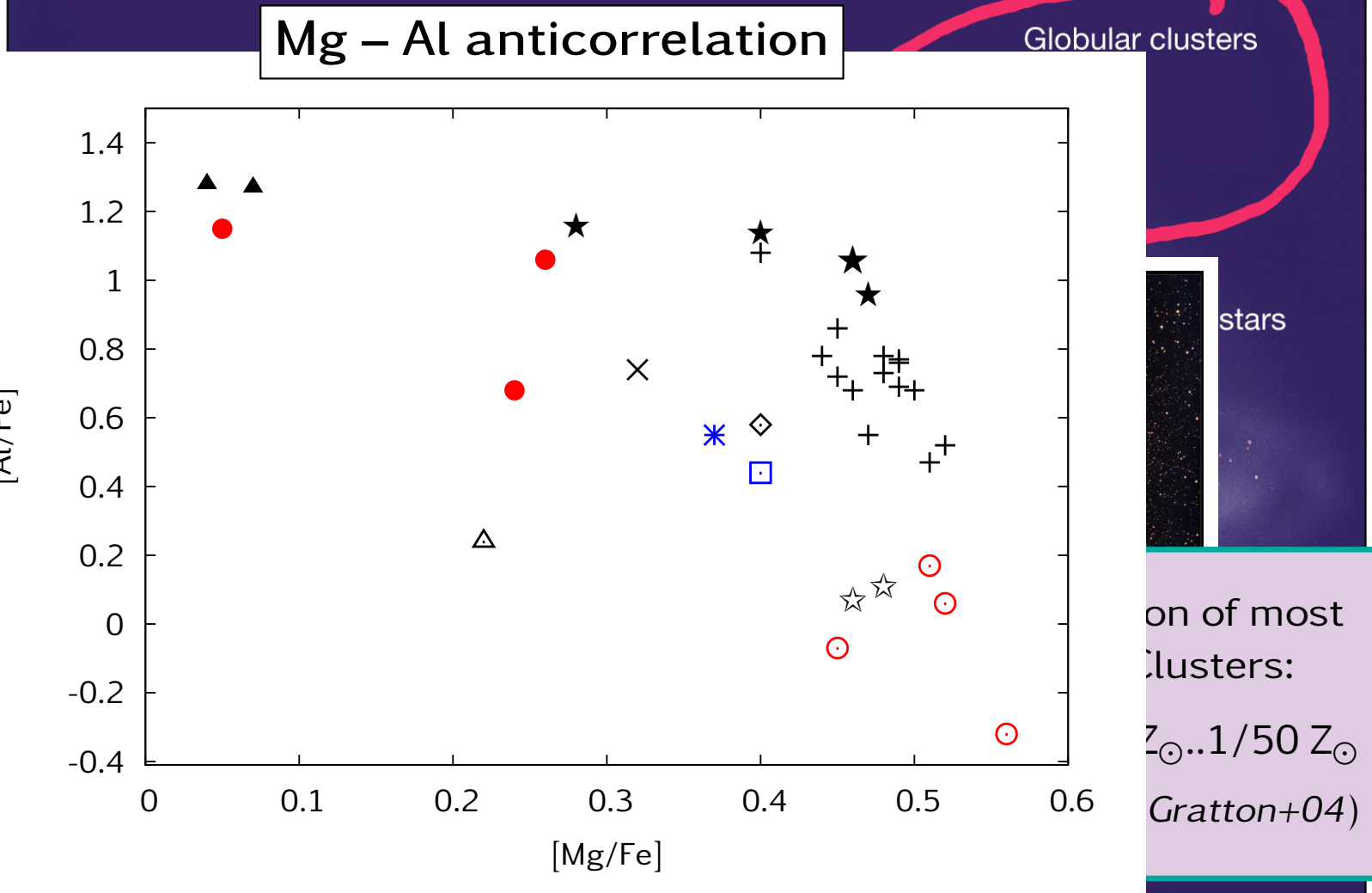
Globular Clusters & Abundance Anomalies



Globular Clusters & Abundance Anomalies



Globular Clusters & Abundance Anomalies



Globular Clusters & Abundance Anomalies

Mg – Al anticorrelation

- extreme & intermediate pop: **polluted** by hot hydrogen burning
  - CNO-cycle, Ne-Na and Mg-Al chains

Globular Clusters & Abundance Anomalies

Mg – Al anticorrelation

- 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

- 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

- 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

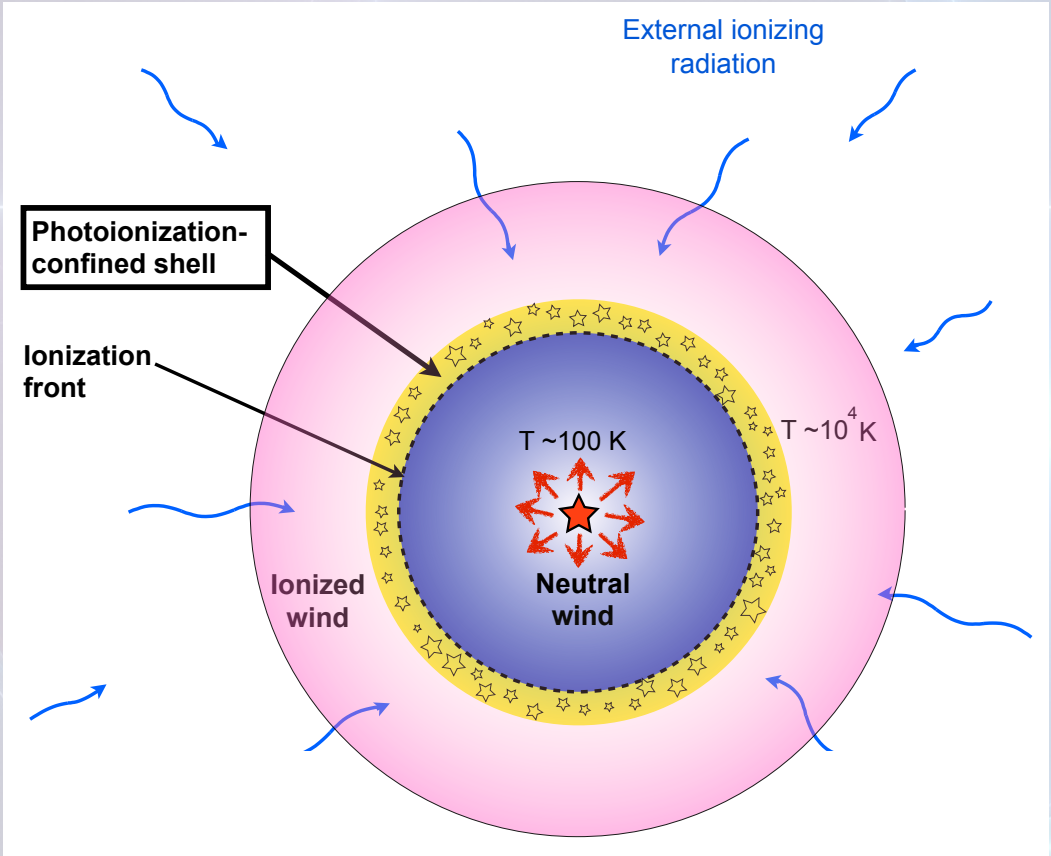
- extreme & intermediate pop: **polluted** by hot hydrogen burning
  - CNO-cycle, Ne-Na and Mg-Al chains
- need: **astrophysical source** that can pollute the ISM
  - AGB stars: hot bottom burning (*Ventura+ 2001*)
  - fast rotating massive stars: close to break-up (*Decressin+ 2007*)
  - supermassive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

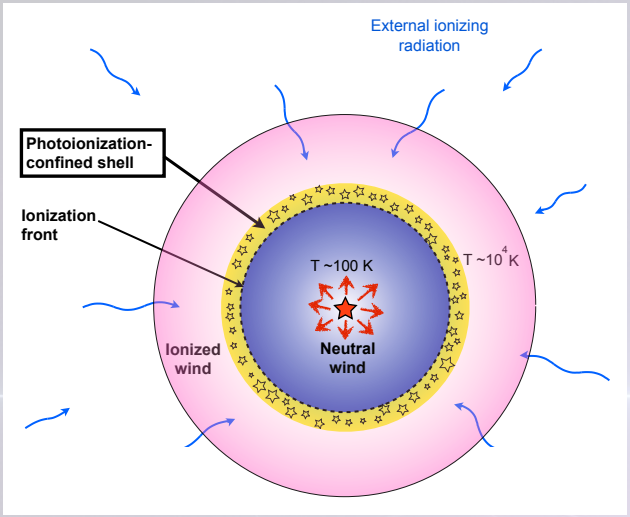
Starforming Supergiant Shells

New scenario:
Starforming Supergiant Shells

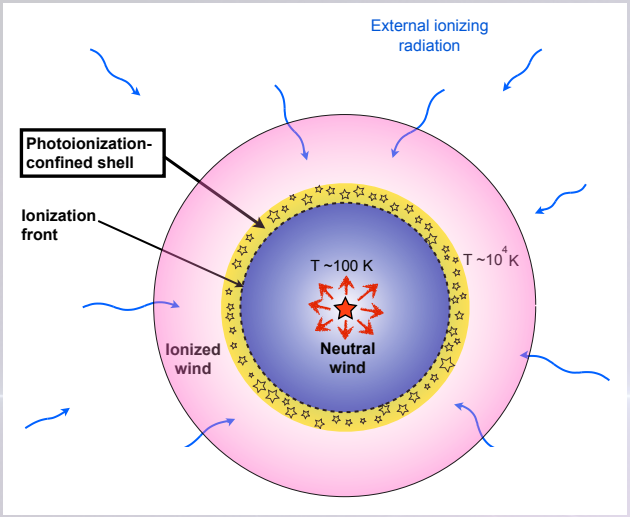


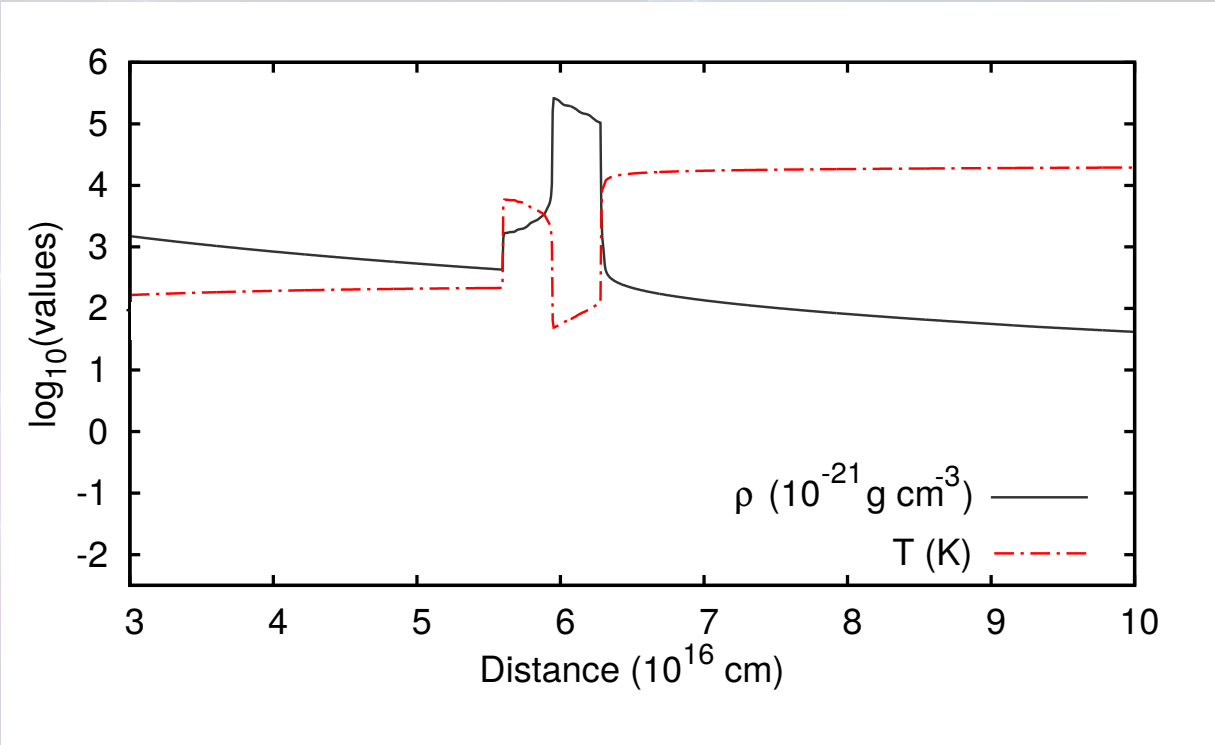
PICO shell: *Mackey+ 2014 (Nature)*

Simulating the PICO shell

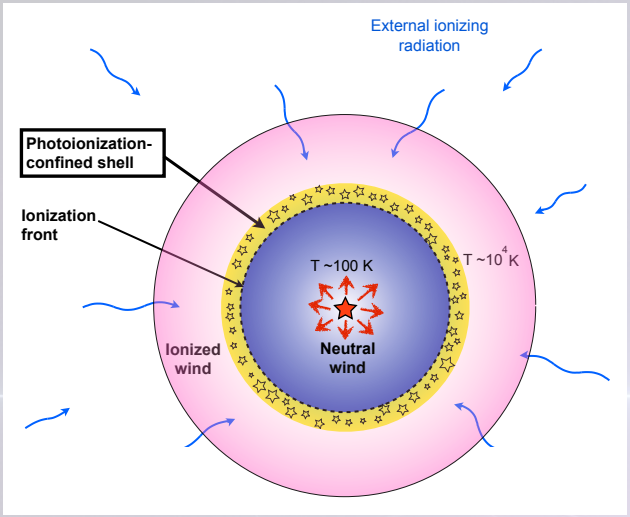


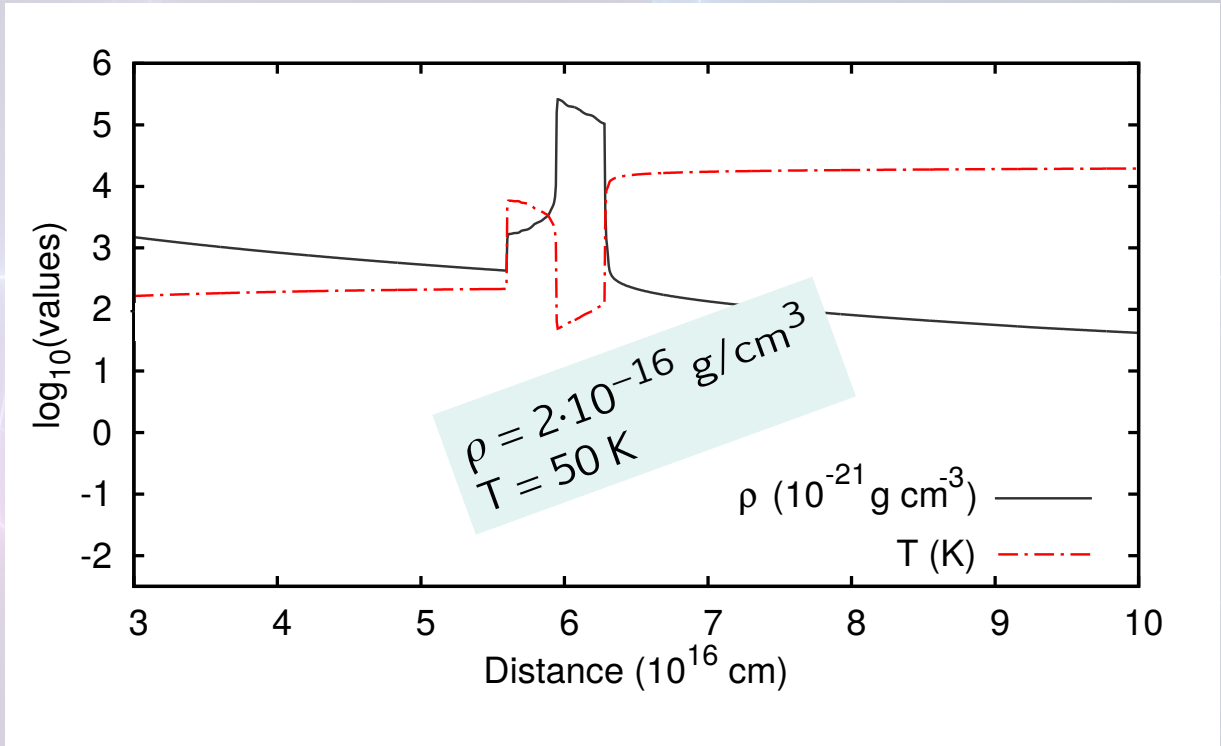
Simulating the PICO shell



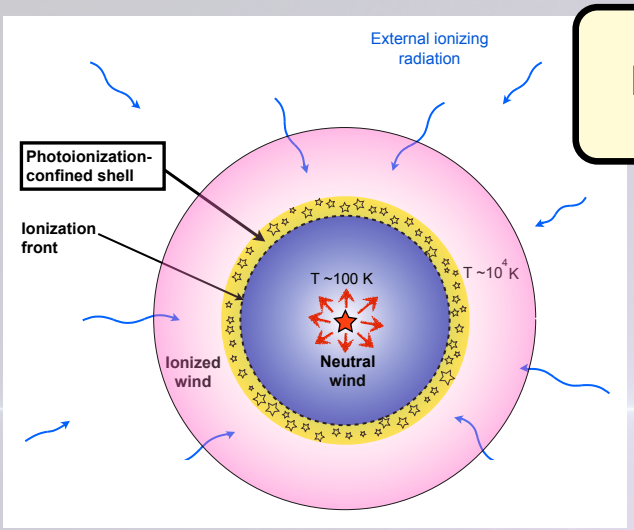


Simulating the PICO shell

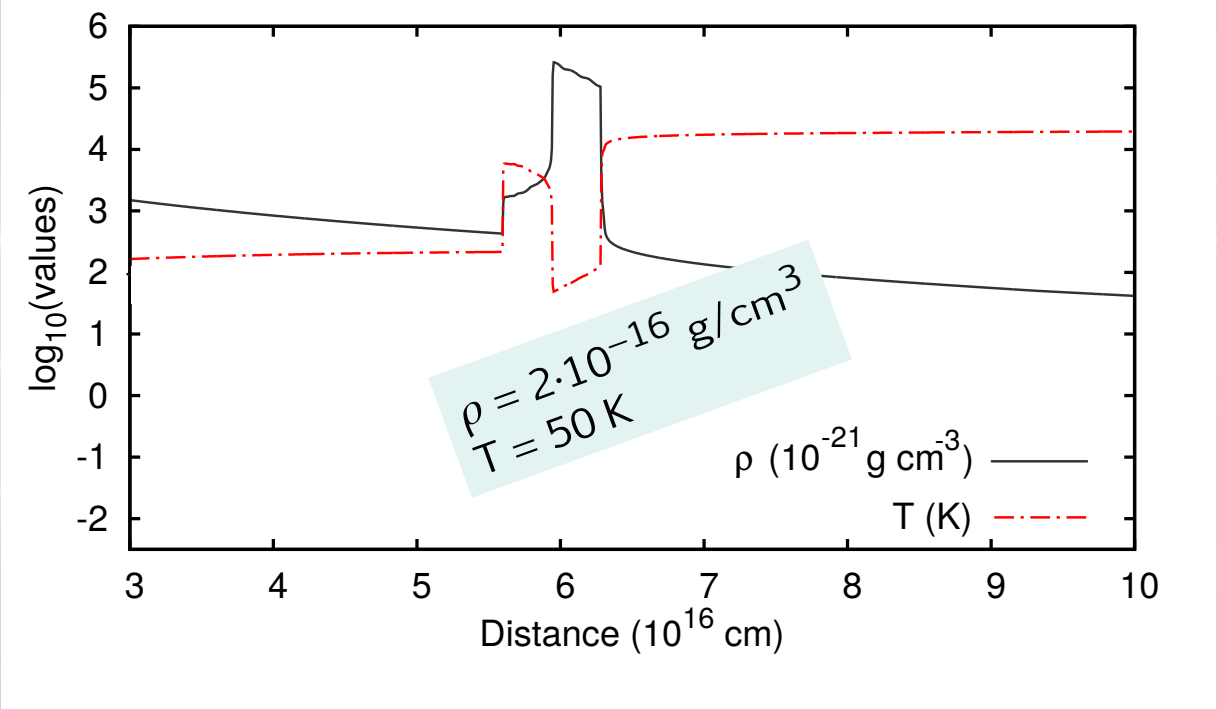




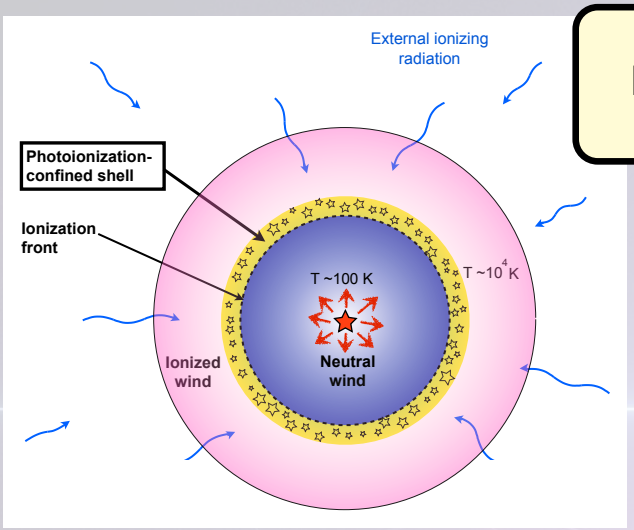
Simulating the PICO shell



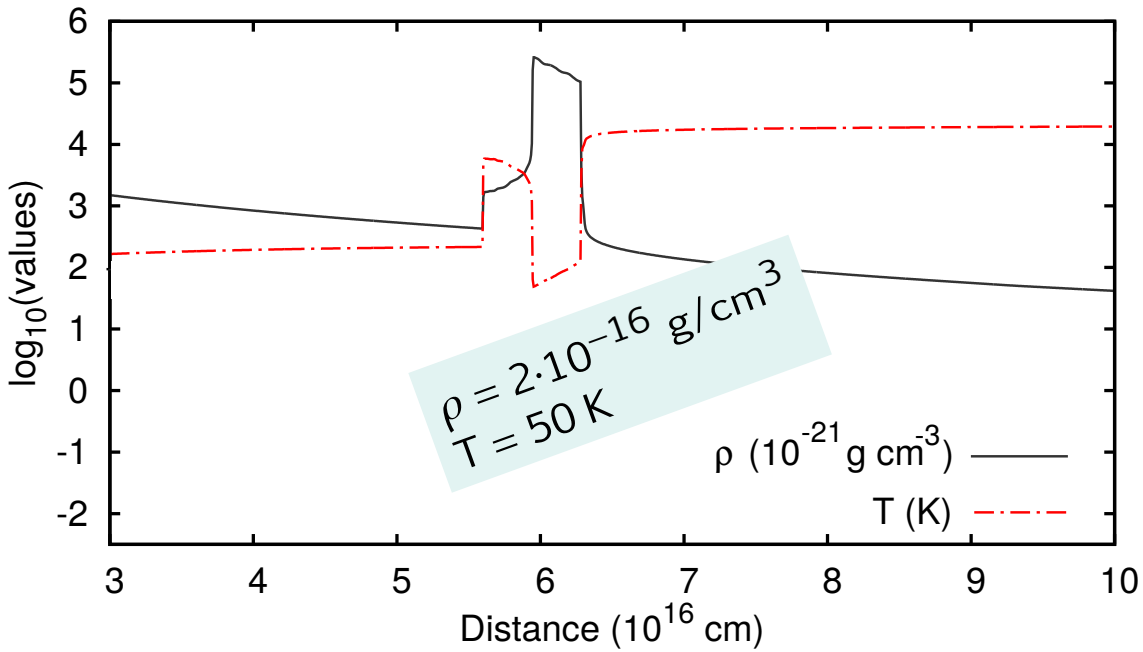
Mass of the photoionization-confined (PICO) shell: ~14 $M_\odot$



Simulating the PICO shell

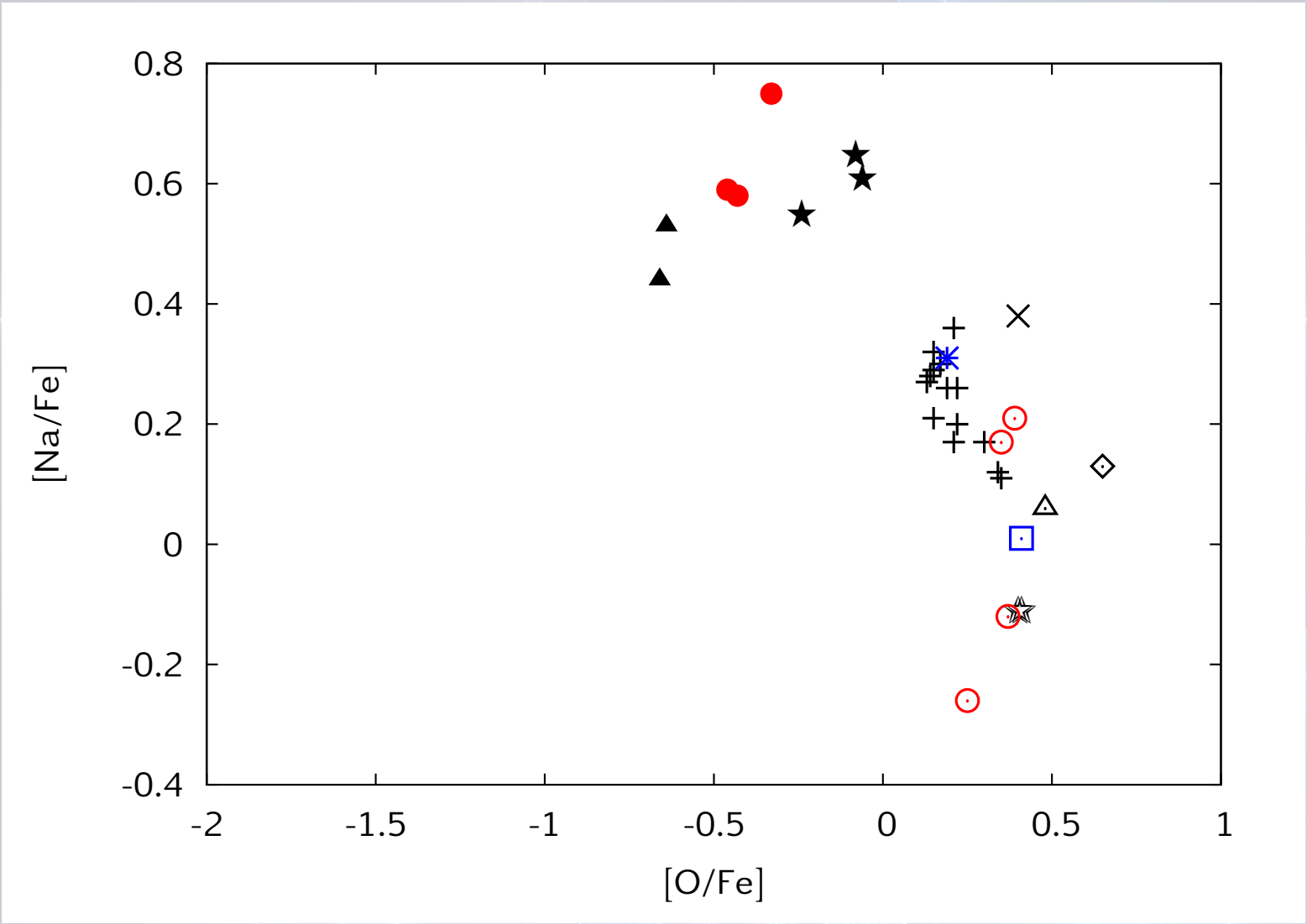


Mass of the photoionization-confined (PICO) shell: ~14 $M_\odot$

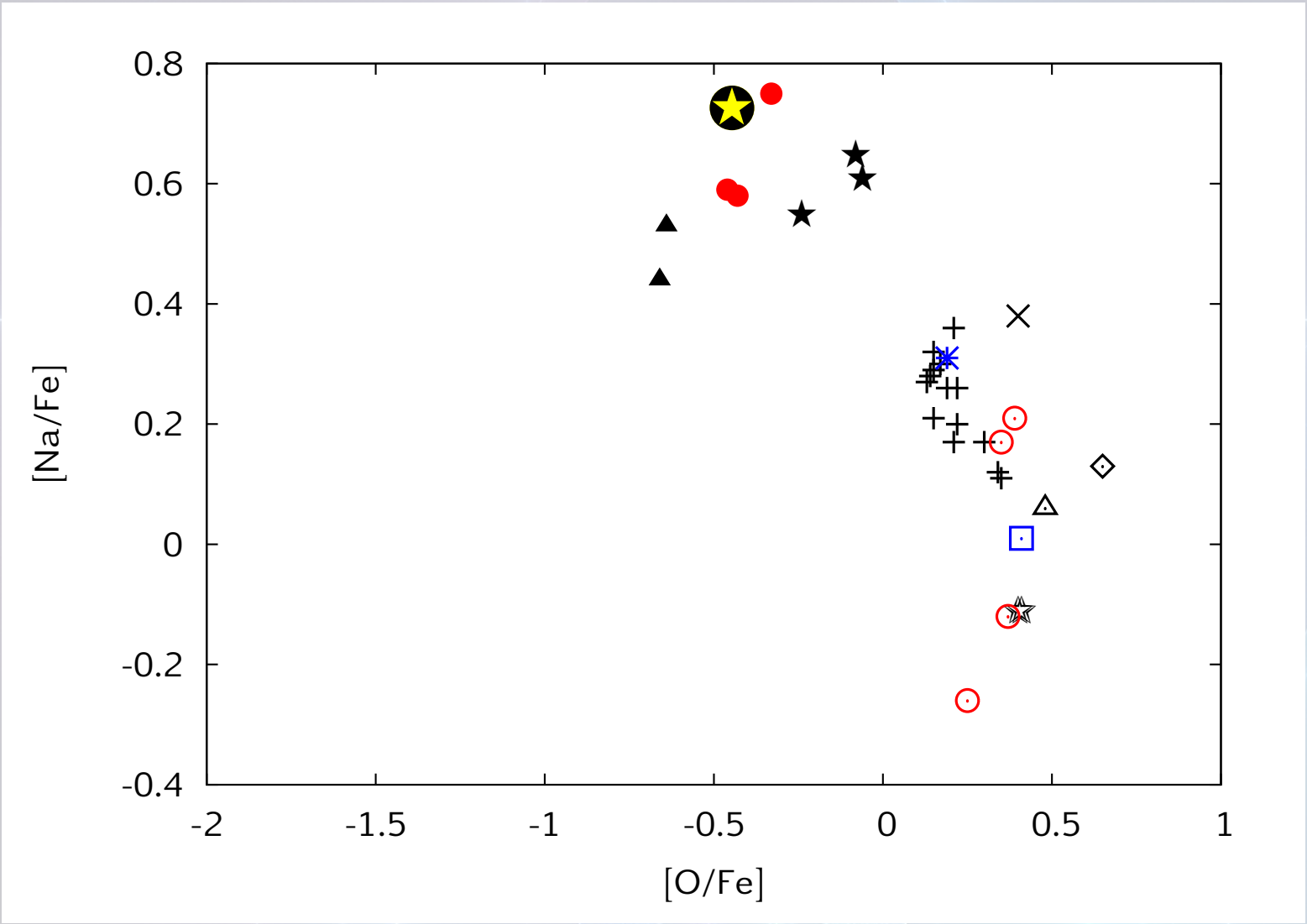


Lifetime of the shell: ~10^5 yr
>>
Growth timescale of grav. unstable perturbations: ~10^4 yr

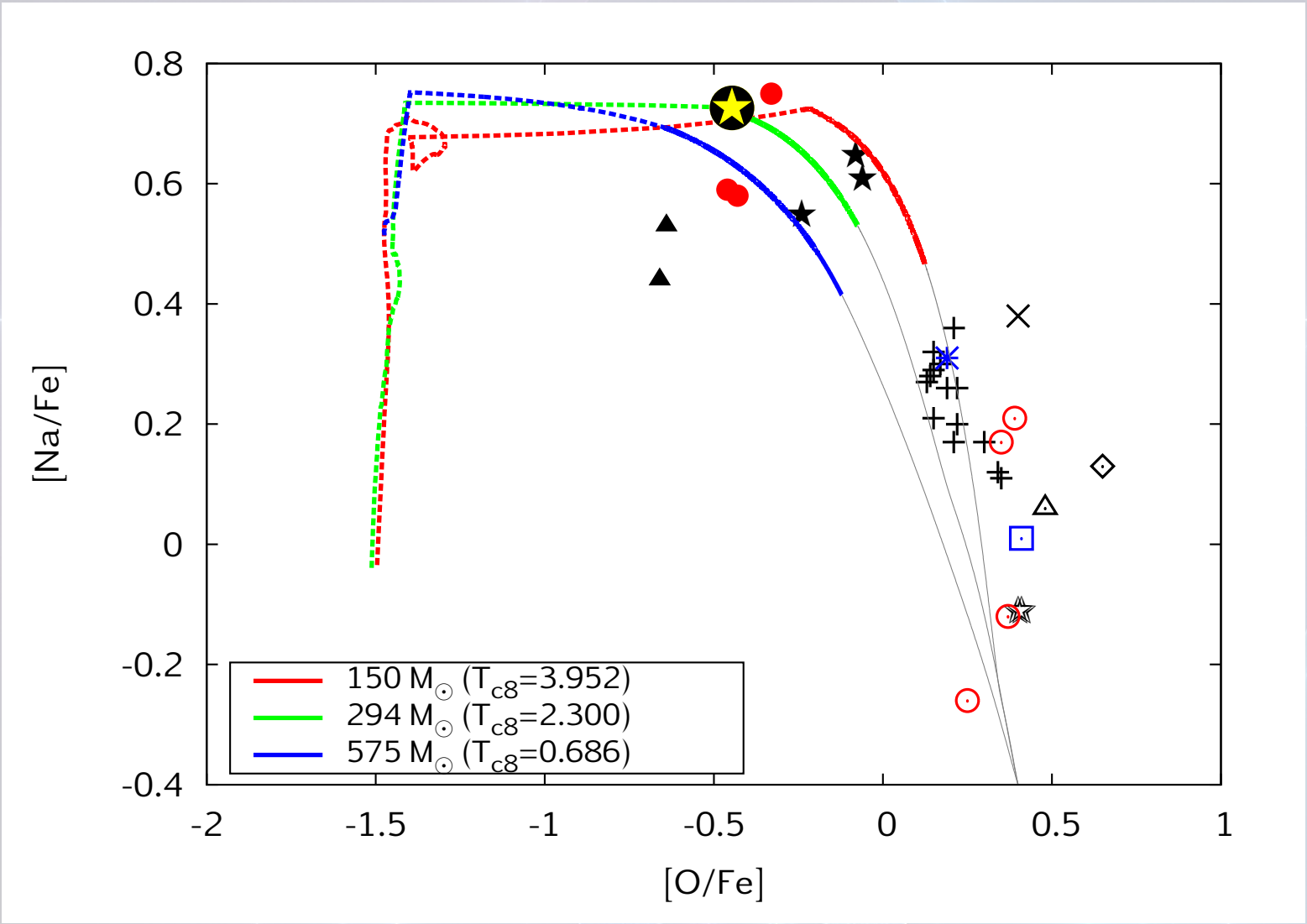
Compared to observations: O – Na anticorr.



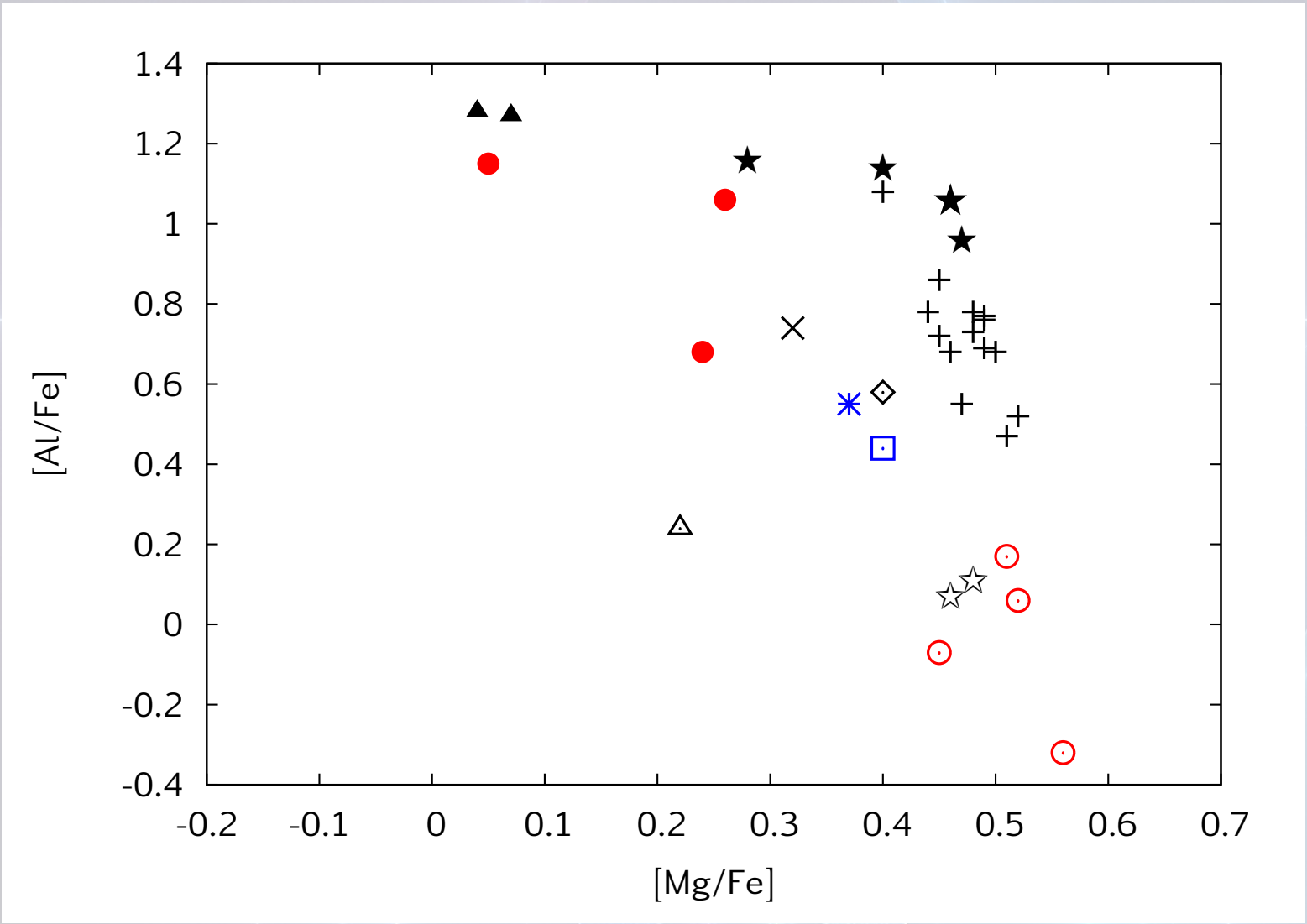
Compared to observations: O – Na anticorr.



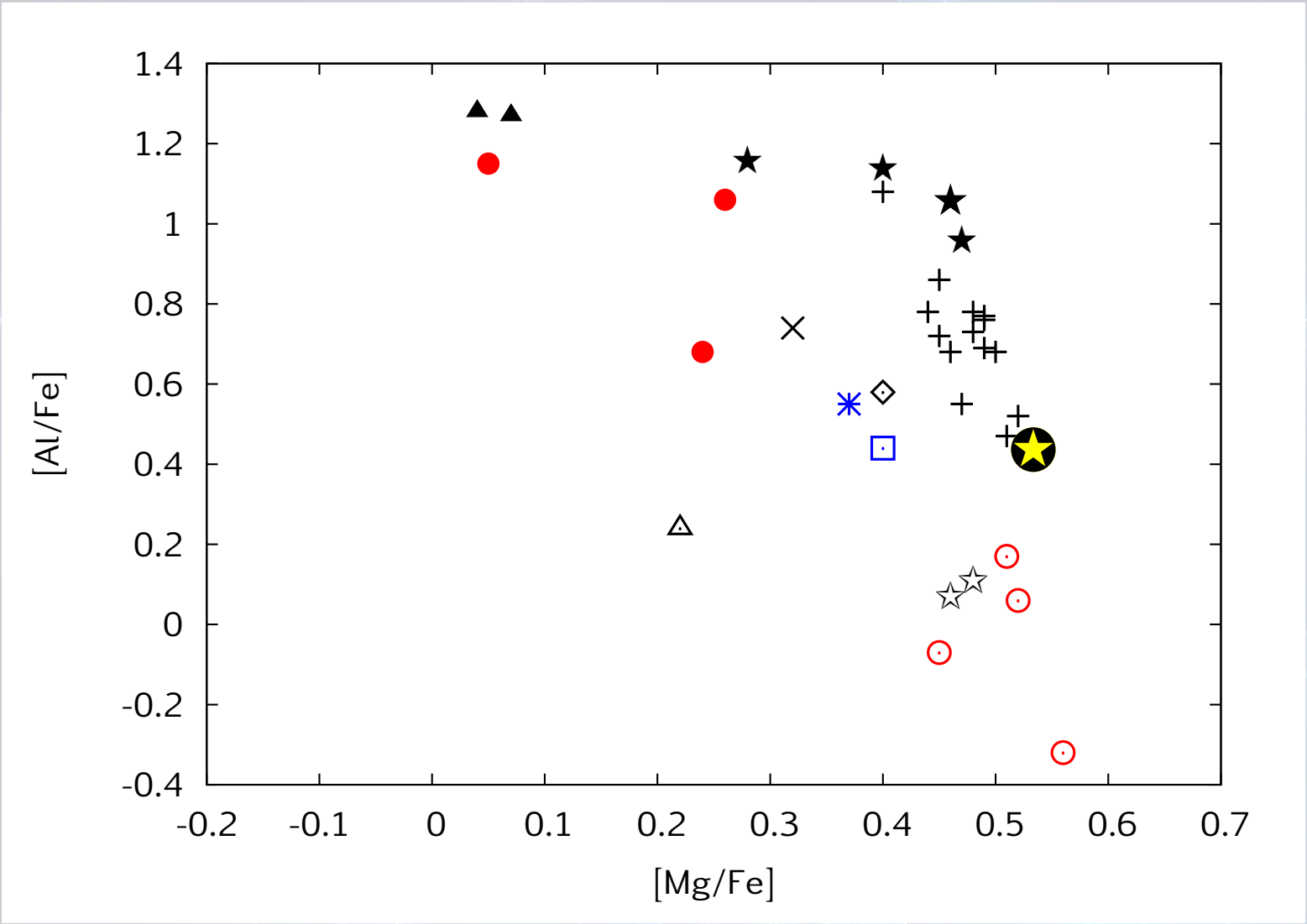
Compared to observations: O – Na anticorr.



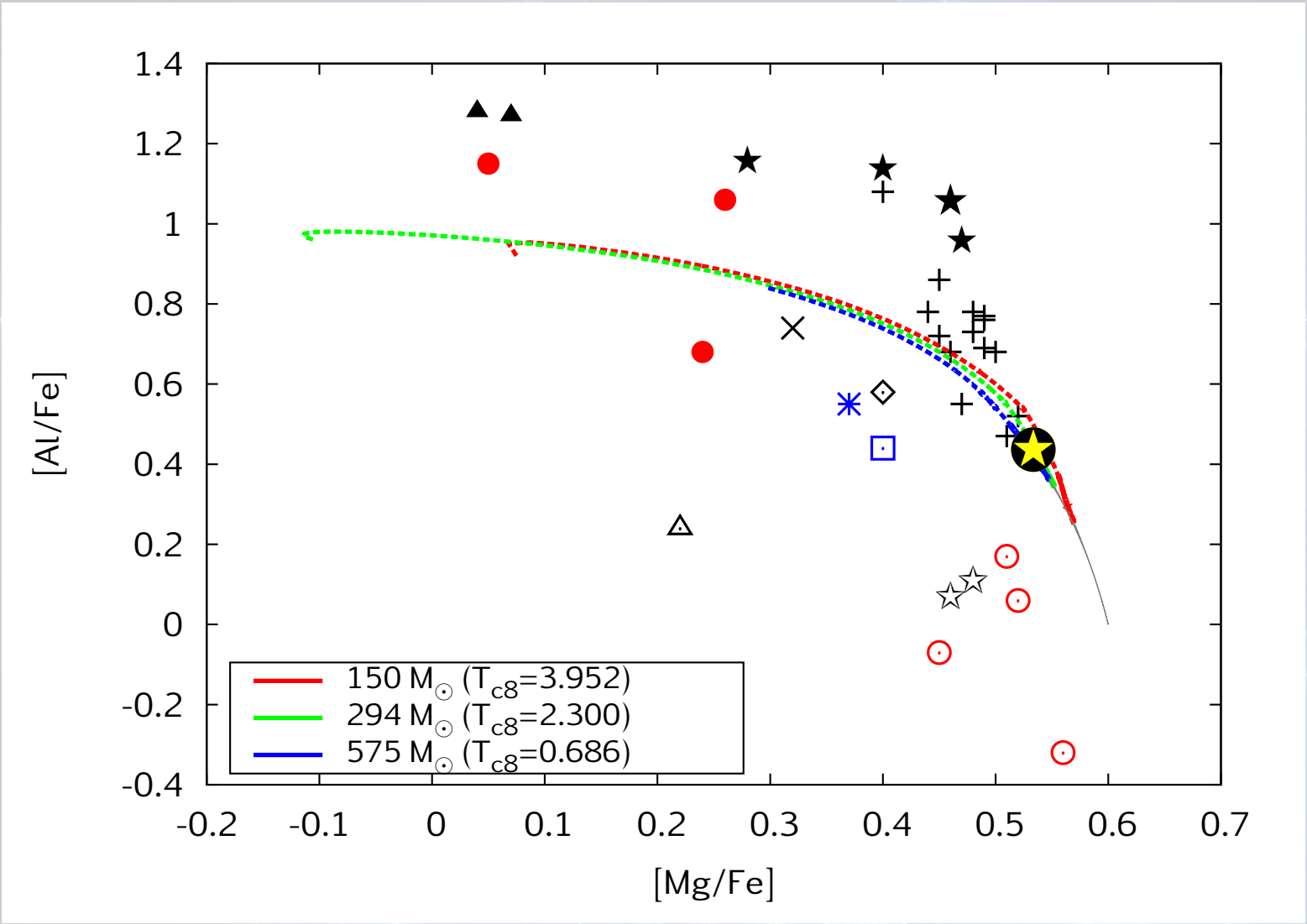
Compared to observations: Mg – Al anticorr.



Compared to observations: Mg – Al anticorr.

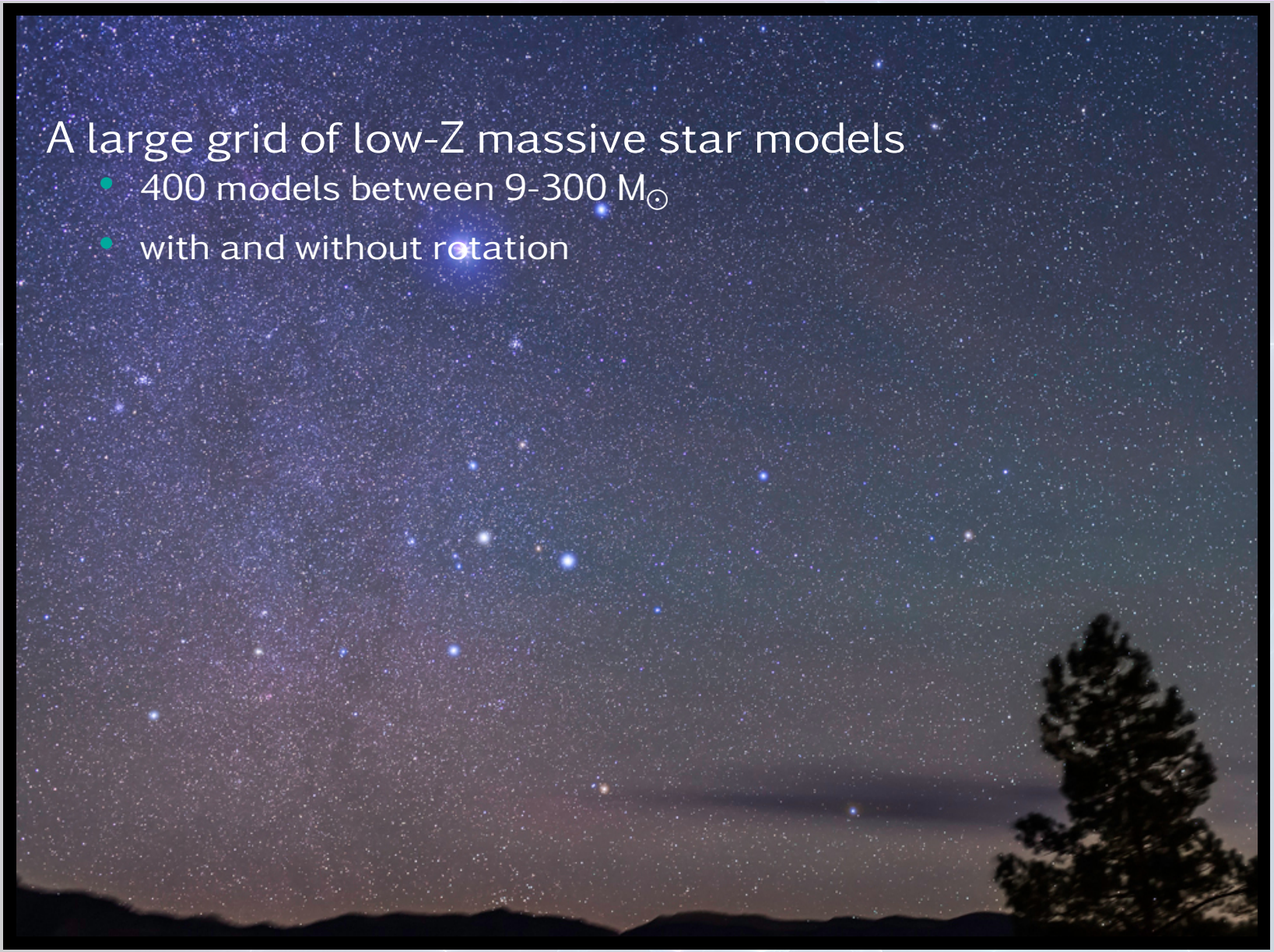


Compared to observations: Mg – Al anticorr.

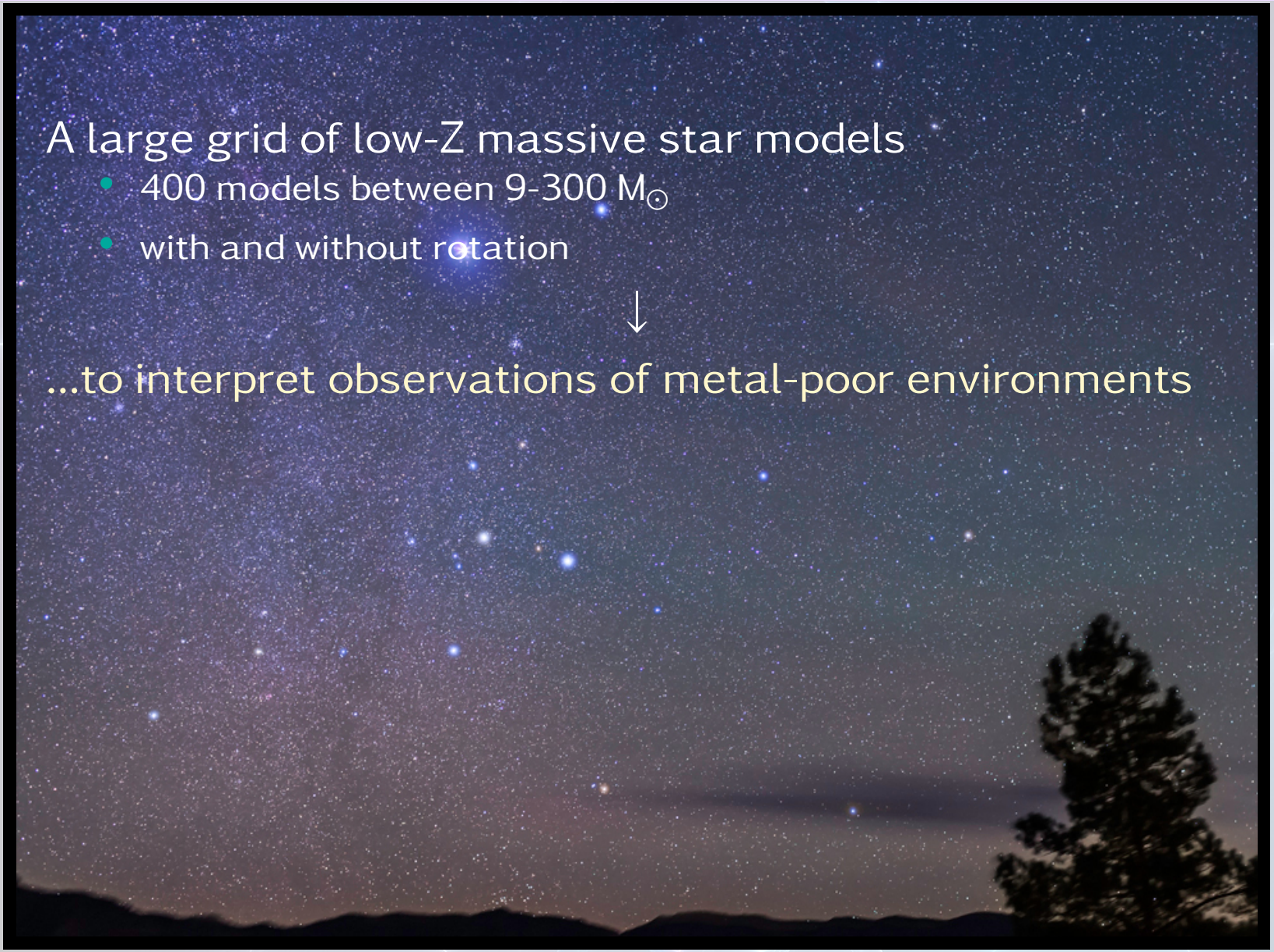


Conclusions

Conclusions



Conclusions



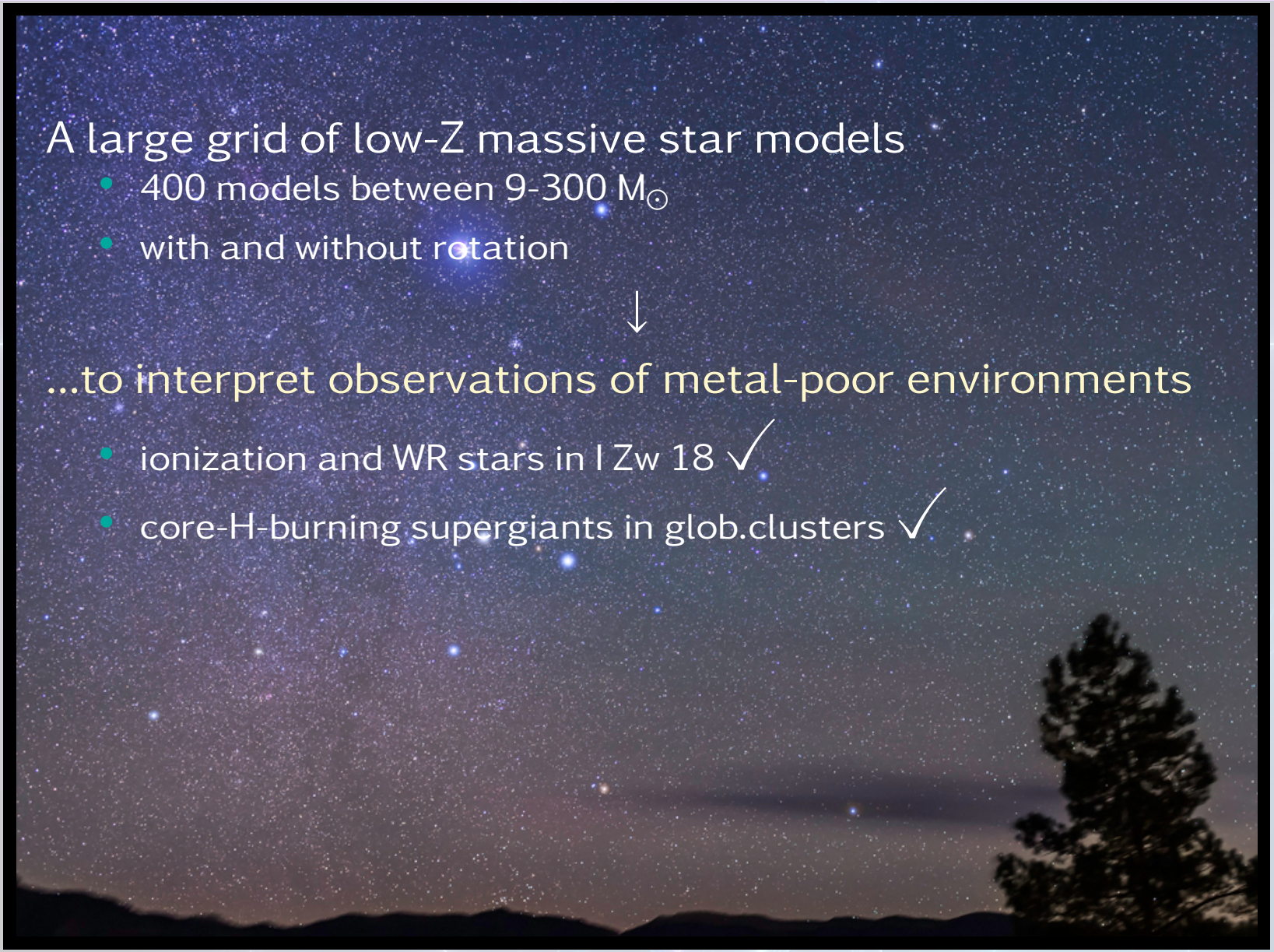
A large grid of low-Z massive star models

- 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

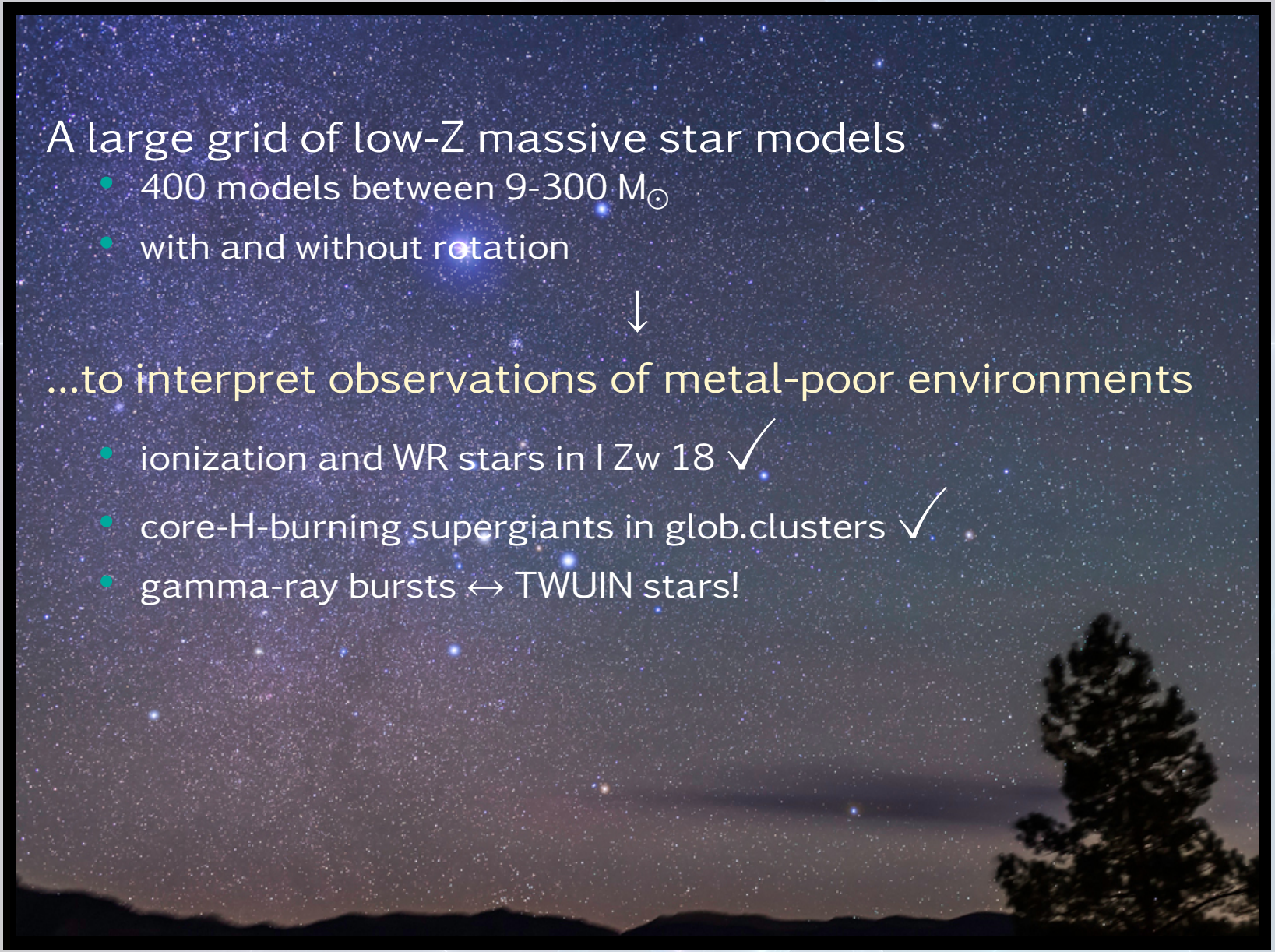
- 400 models between 9-300 $M_{\odot}$
- with and without rotation

↓

...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

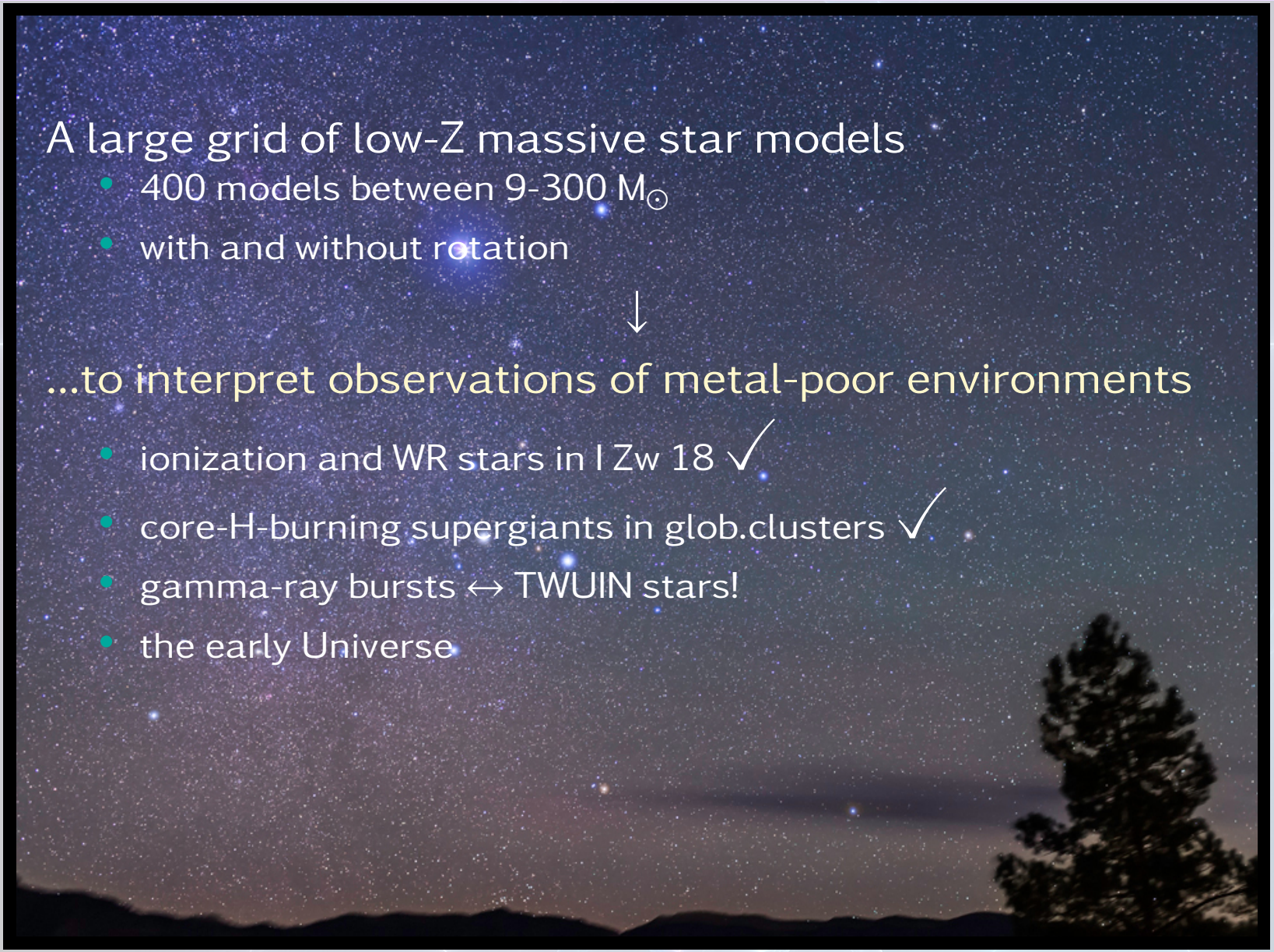
- 400 models between 9-300 $M_{\odot}$
- with and without rotation

↓

...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 m

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

Thank you for your attention!

↓

...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!