

The evolution of low-metallicity massive stars

Dorottya Szécsi

Collaborators:

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Carolina Kehrig (Granada, Spain), Frank Tramper
(Madrid, Spain), Takashi Moriya (Tokyo, Japan),
Jonathan Mackey (Dublin, Ireland)
Jíří Kubát (Ondřejov, Czech Rep.)

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Brno, 17th October 2016



AKADEMIE VĚD
ČESKÉ REPUBLIKY



Astronomický
ústav
AV ČR

The night-sky and beyond



The night-sky and beyond



The night-sky and beyond



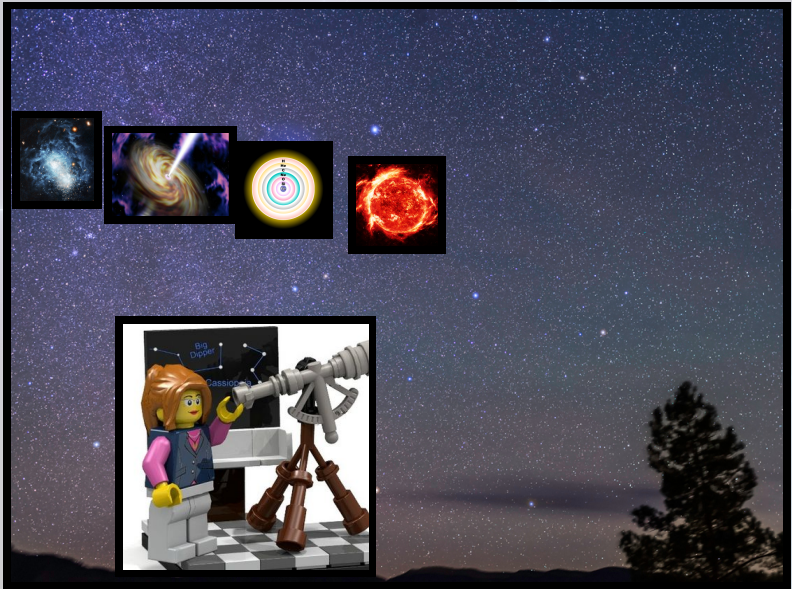
The night-sky and beyond



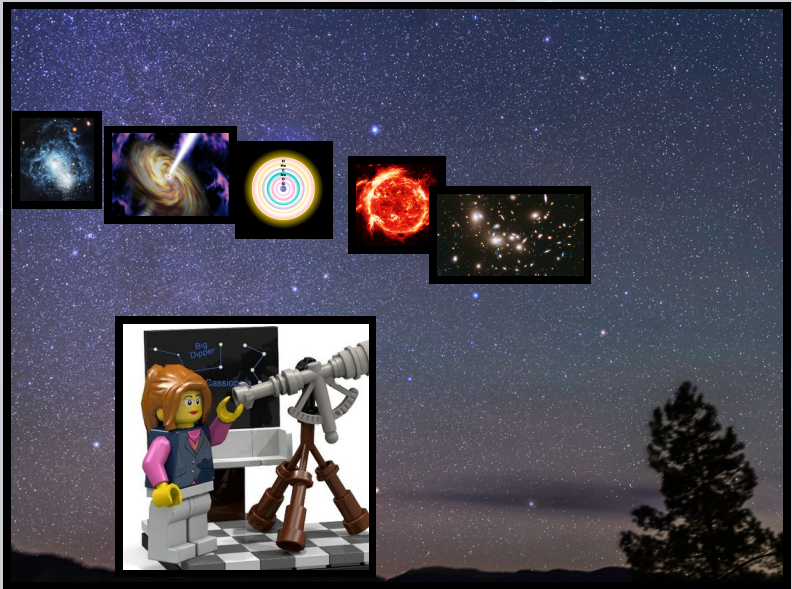
The night-sky and beyond



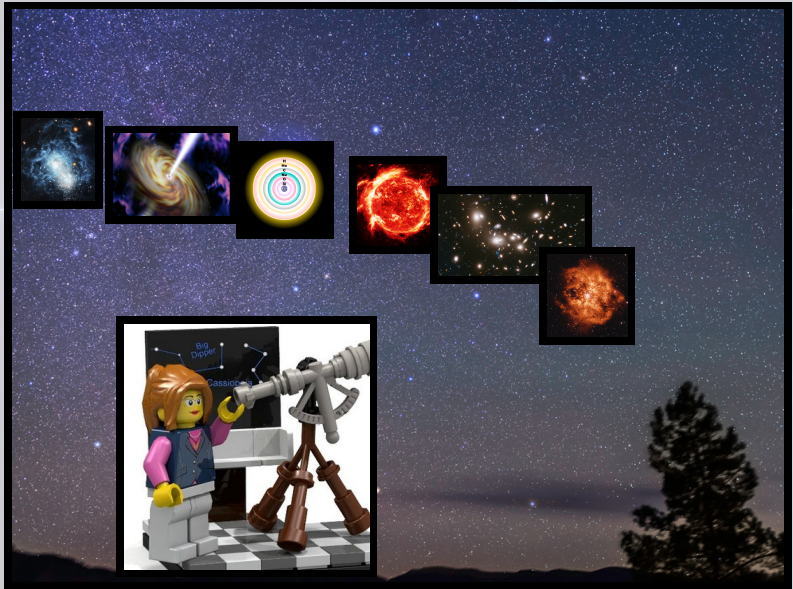
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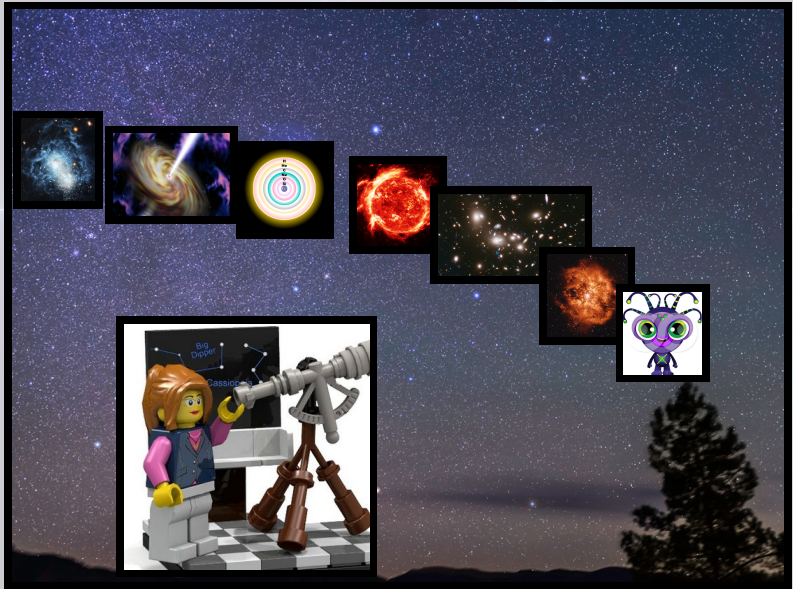
The night-sky and beyond



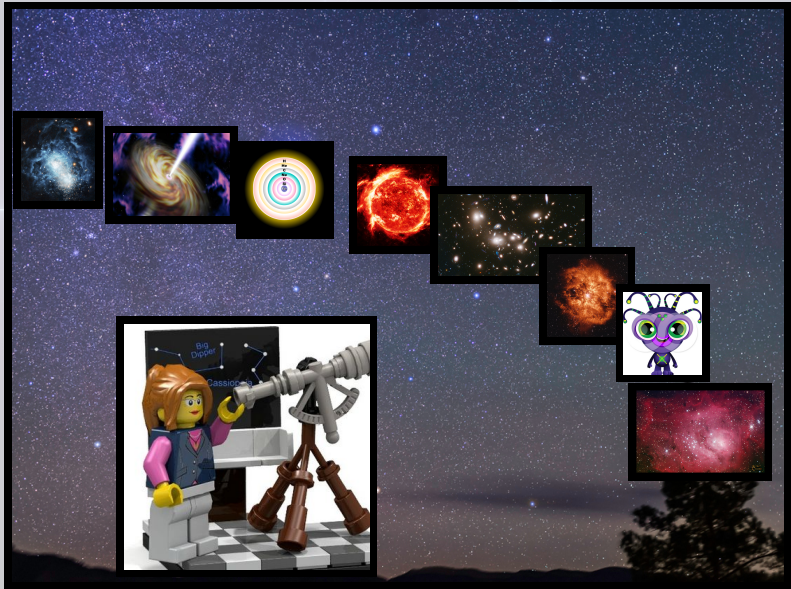
The night-sky and beyond



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The night-sky and beyond



Astronomers and metal

LEGEND

- Non-Metal
- Metal

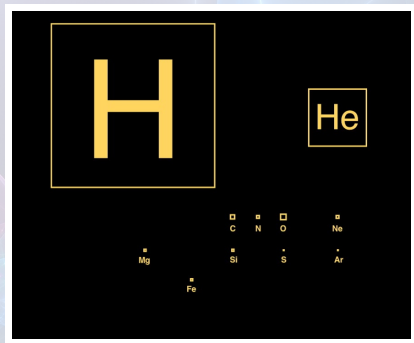
H																	He
Li	Be											B	C	N	O	F	Ne
Na	Mg											Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd	In	Sn	Sb	Te	I	Xe
Cs	Ba	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
Fr	Ra	Ac	Unq	Unp	Unh												

Astronomers and metal

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- ☐ : Non-Metal
- ☐ : Metal

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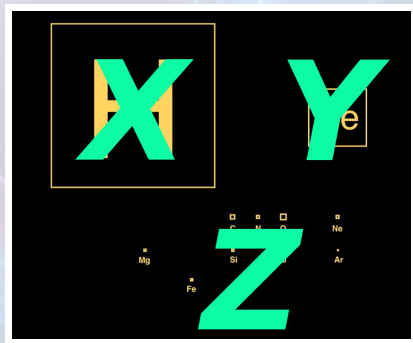


Astronomers and metal

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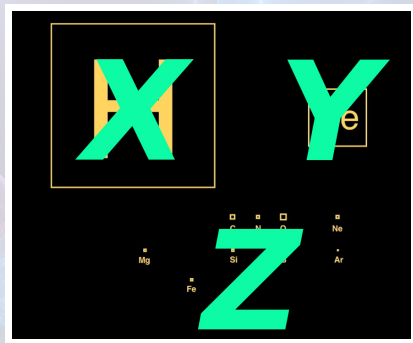
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"Z: metallicity"



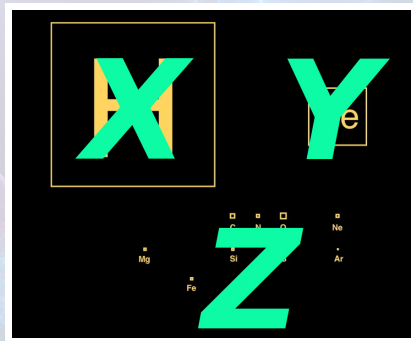
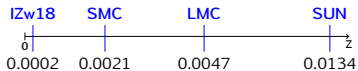
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"Z: metallicity"



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

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

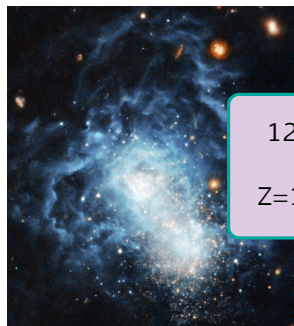
↓

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

Compact Dwarf Galaxies

I Zwicky 18

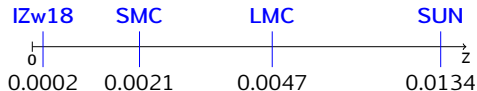
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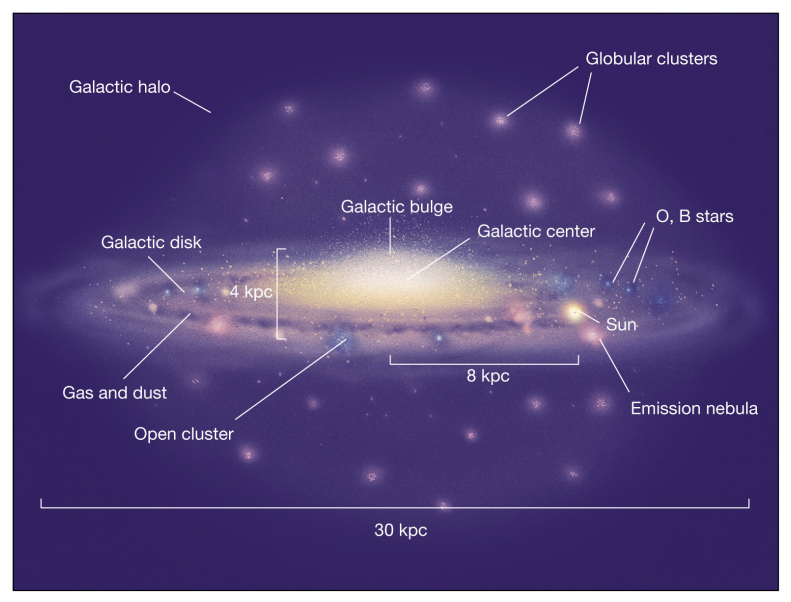
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↓

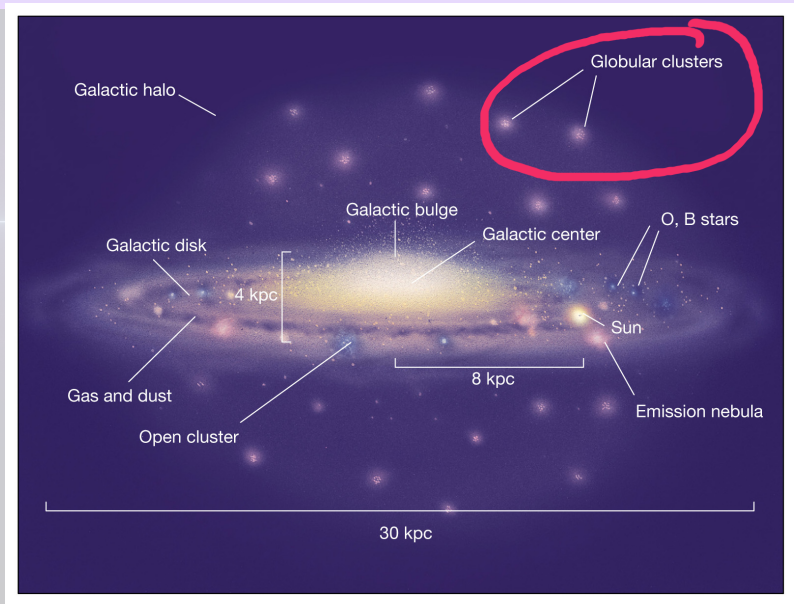
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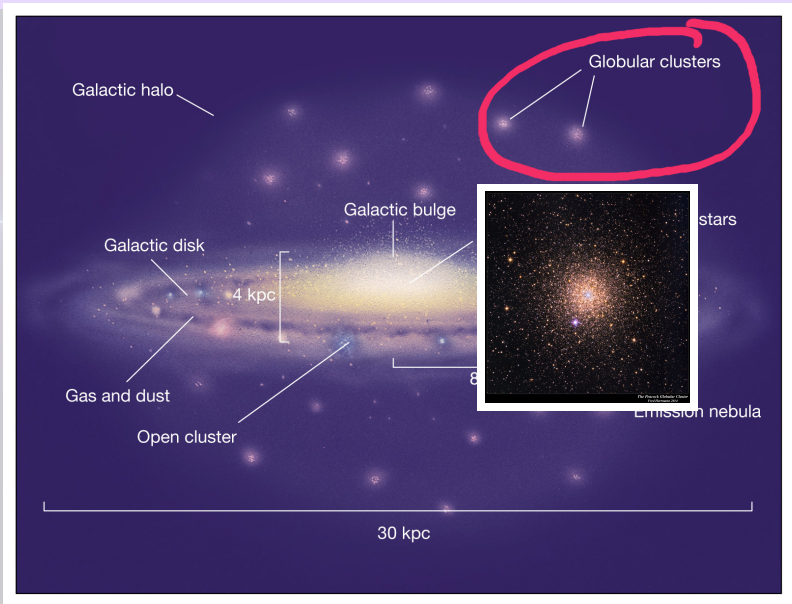
Globular Clusters



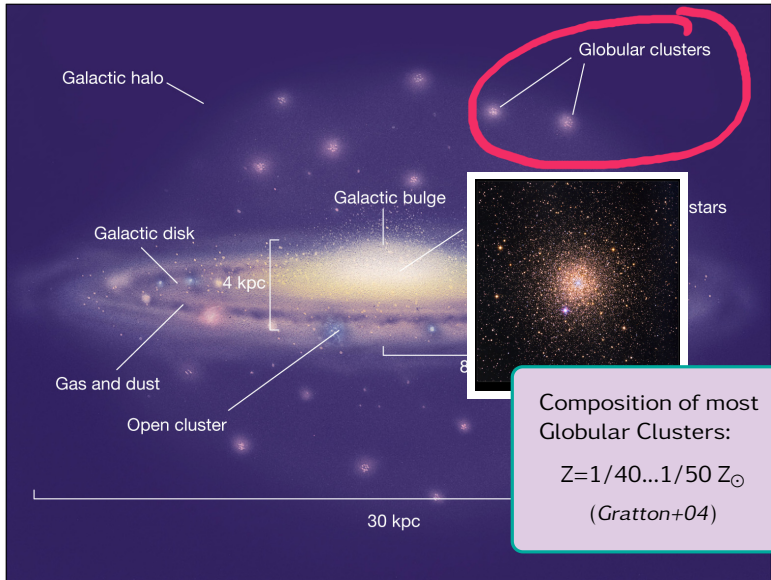
Globular Clusters



Globular Clusters



Globular Clusters



Composition of most
Globular Clusters:

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

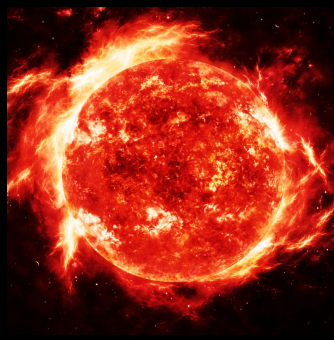
(Gratton+04)



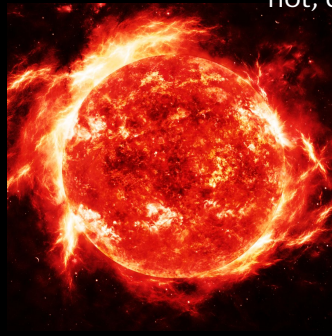
The background features a large, semi-transparent white circle centered in the upper half. Overlaid on this are several thin, glowing lines in shades of cyan, magenta, and white. These lines form a complex, web-like pattern that resembles a fractal or a network of connections. The overall aesthetic is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

What is a star?

What is a star?

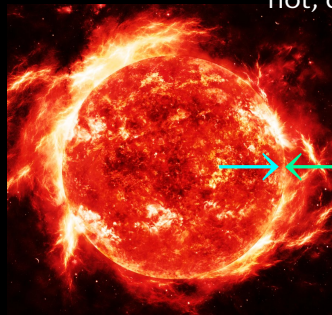


What is a star?



hot, dense plazma

What is a star?



hot, dense plazma

equilibrium:

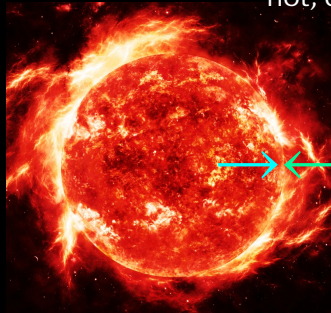
pressure gradient

gravity

What is a star?

surface?

hot, dense plazma



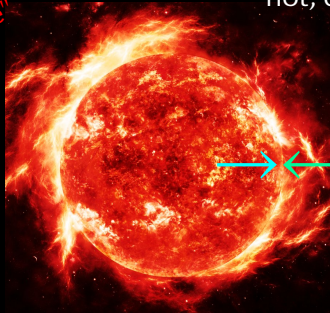
equilibrium:

pressure gradient gravity

What is a star?

surface?
→ photons escape
"photosphere"

hot, dense plazma



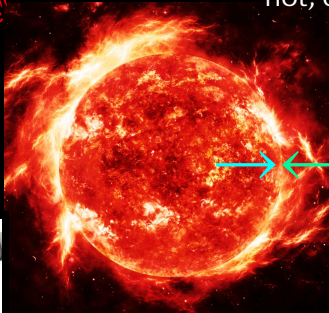
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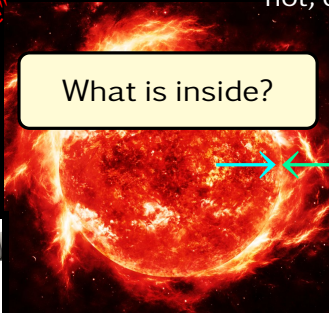
What is a star?

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

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

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Guilera et al. 2011

composition change due to nuclear burning ?!

Theoretical modelling of the stellar structure

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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

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

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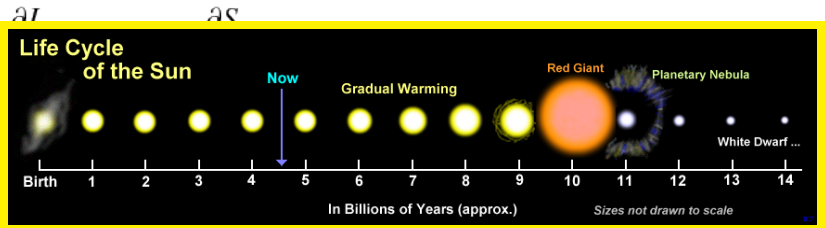
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+ Rotation.

Theoretical modelling of the stellar structure

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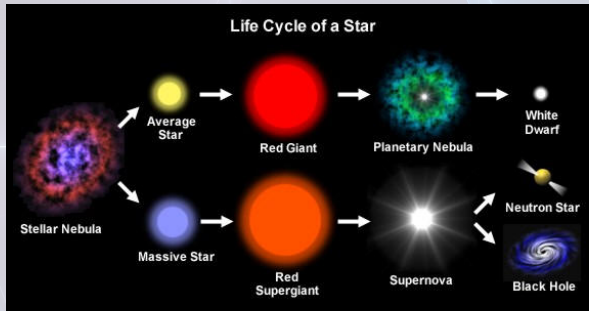
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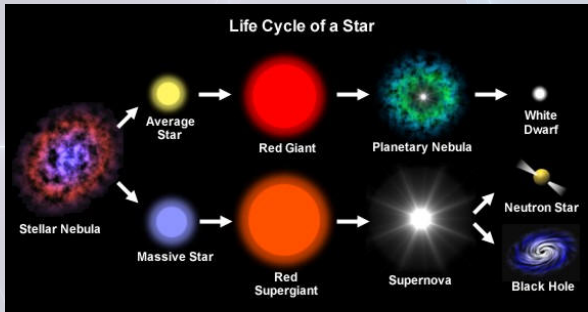
Massive vs. low-mass stars

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



Massive vs. low-mass stars

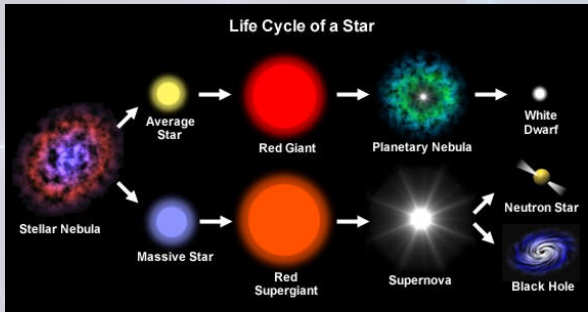
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- nuclear reactions, final composition

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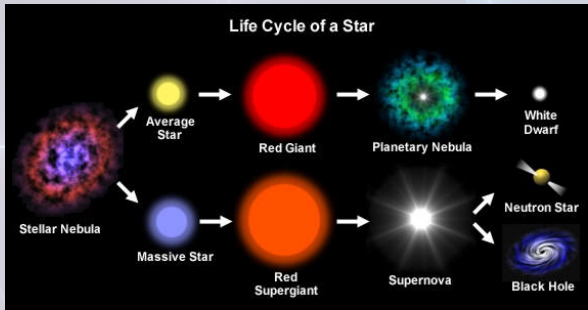
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- nuclear reactions, final composition
- number of stars: massive stars are rare

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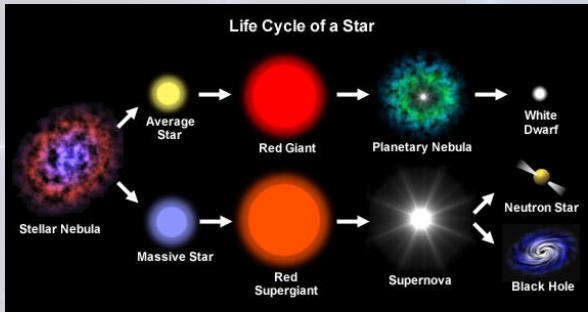
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- lifetime: massive stars have shorter lives

Massive vs. low-mass stars

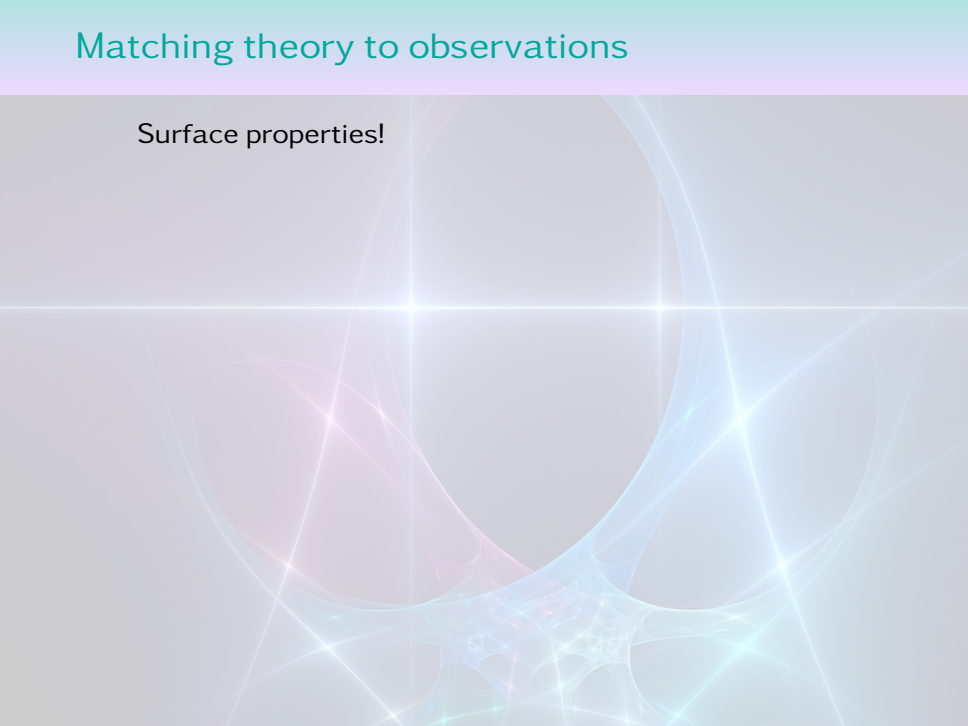
Massive stars: $\gtrsim 9$ times the Sun ($\gtrsim 9 M_{\odot}$)



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

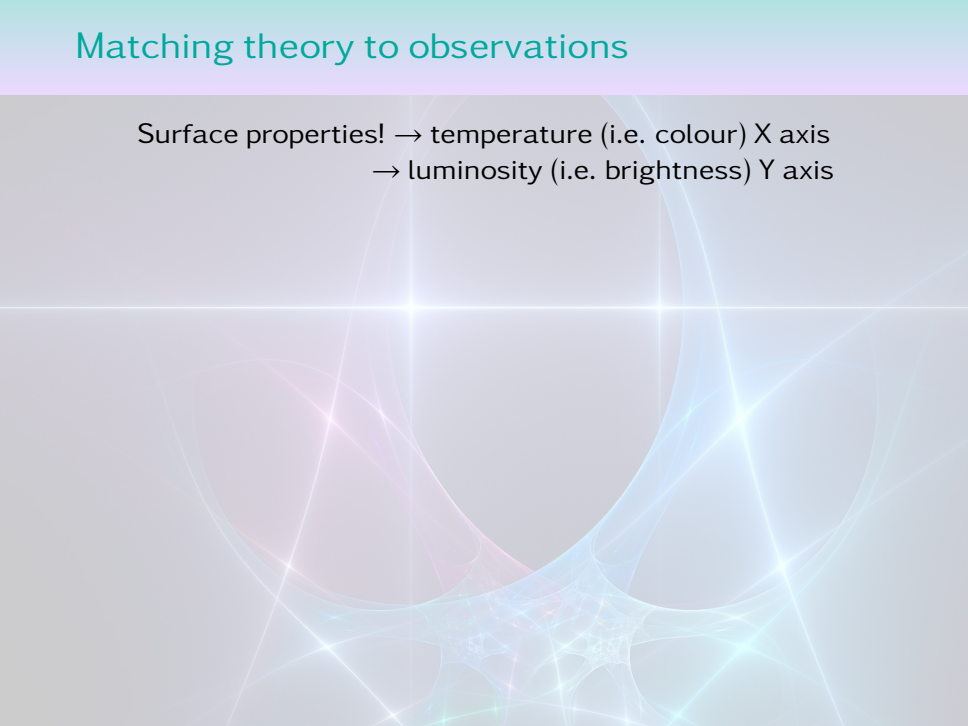
Matching theory to observations

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.

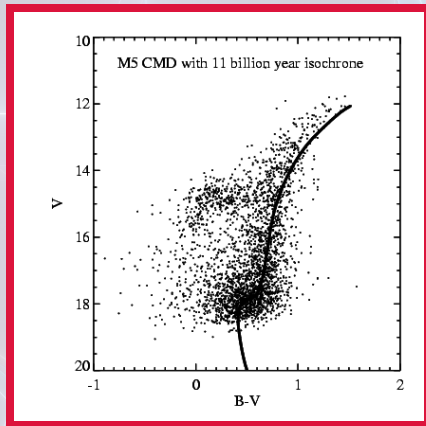
Matching theory to observations

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



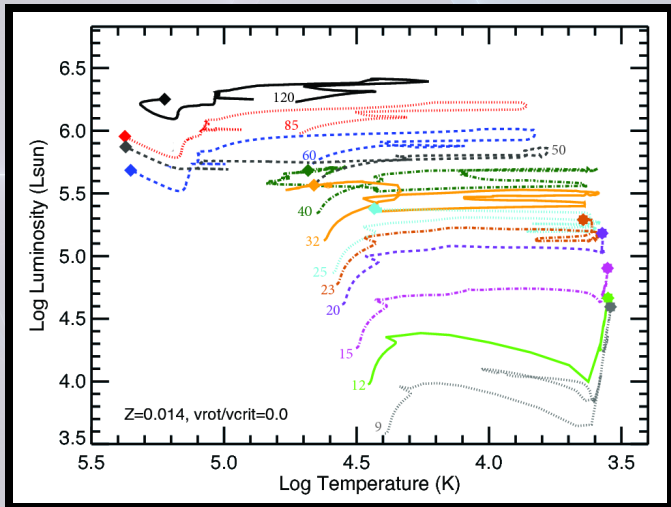
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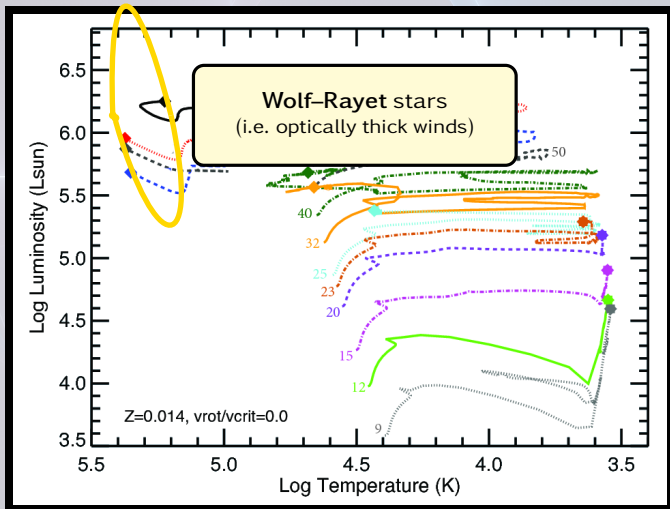


Hertzsprung–Russell diagram (HR diagram)

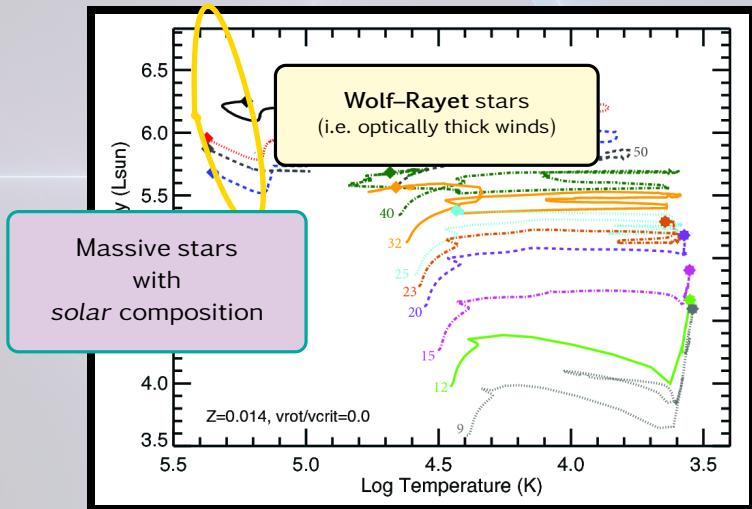
Hertzprung–Russell diagram



Hertzprung–Russell diagram



Hertzprung–Russell diagram



Low Metallicity Massive Stars

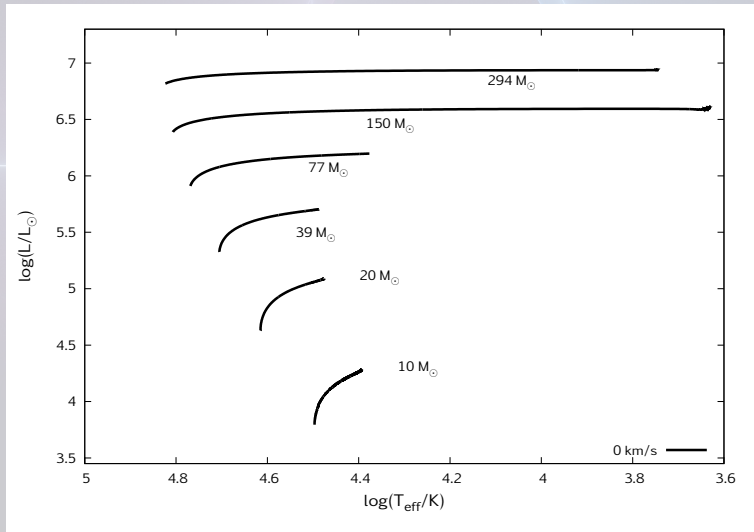
The background features a large, dark, semi-transparent circle centered in the upper half. Overlaid on this are intricate, glowing patterns of light blue and pink lines that resemble a complex, fractal-like structure or a network of fibers. The lines are thin and have a soft, ethereal glow, with some points appearing brighter than others. The overall color palette is cool, dominated by blues and pinks, set against a light gray background.

Low Metallicity Massive Stars



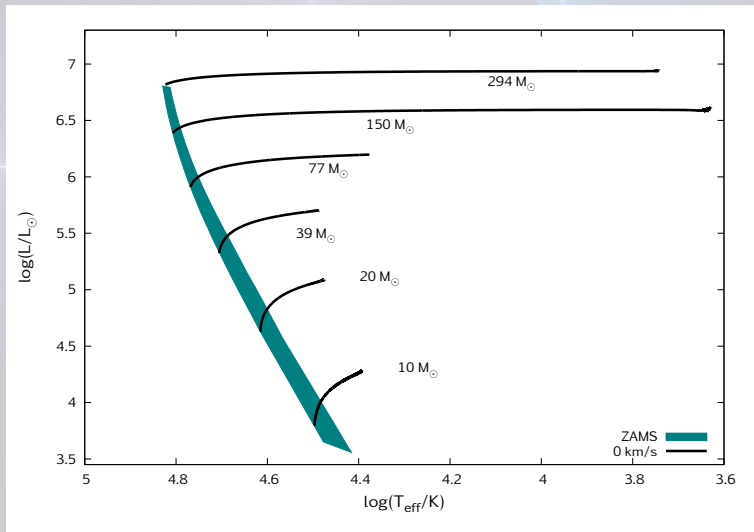
Low Metallicity Massive Stars

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



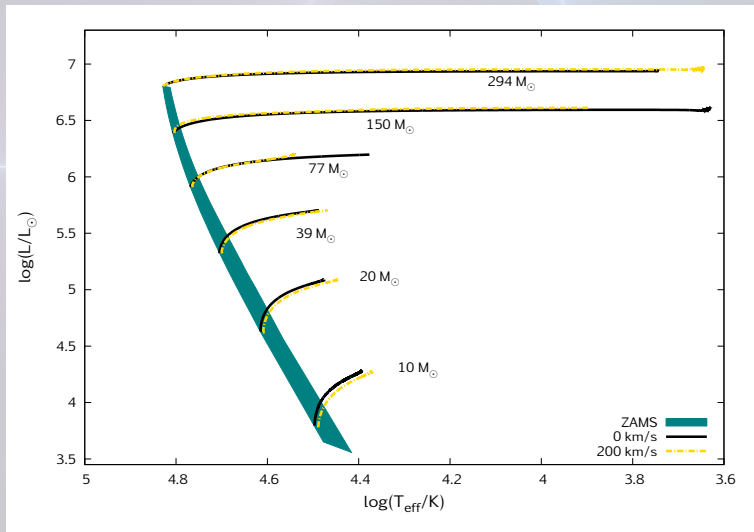
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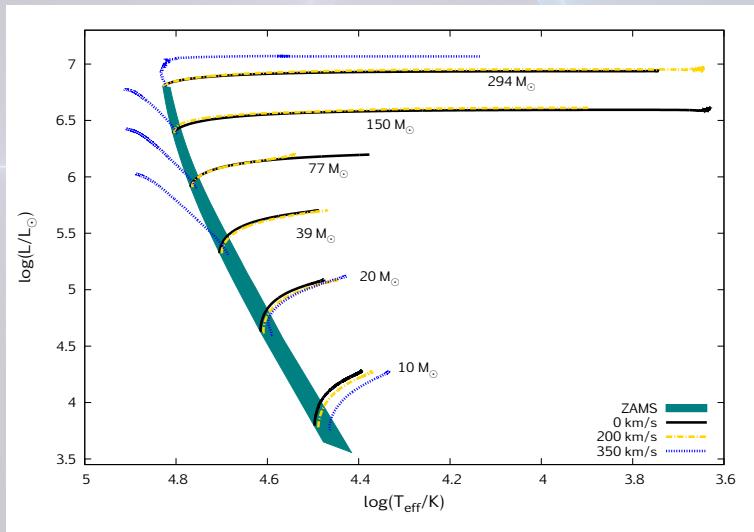
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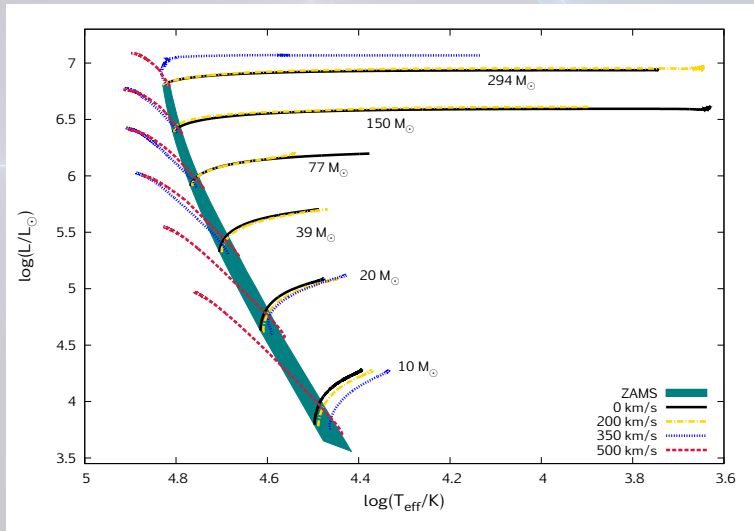
Low Metallicity Massive Stars

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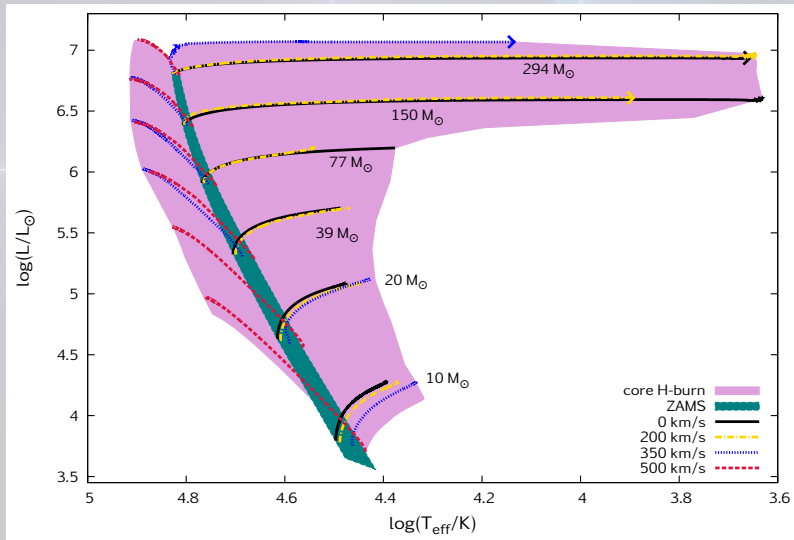
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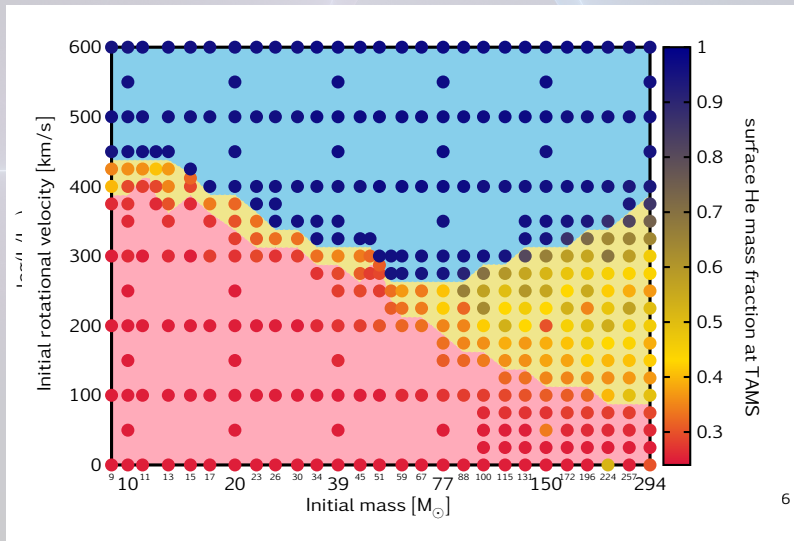
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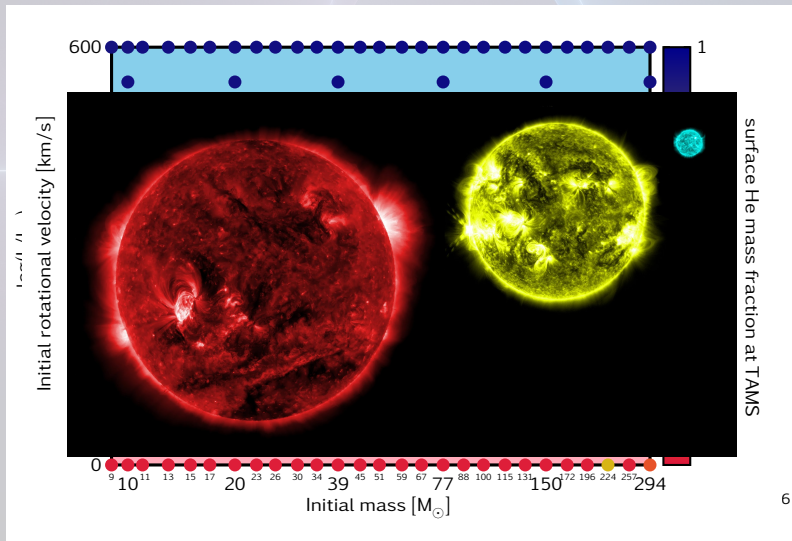
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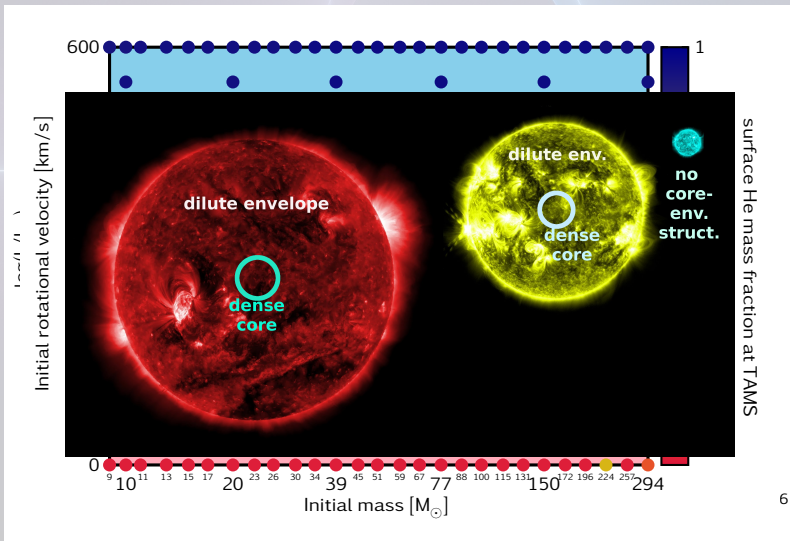
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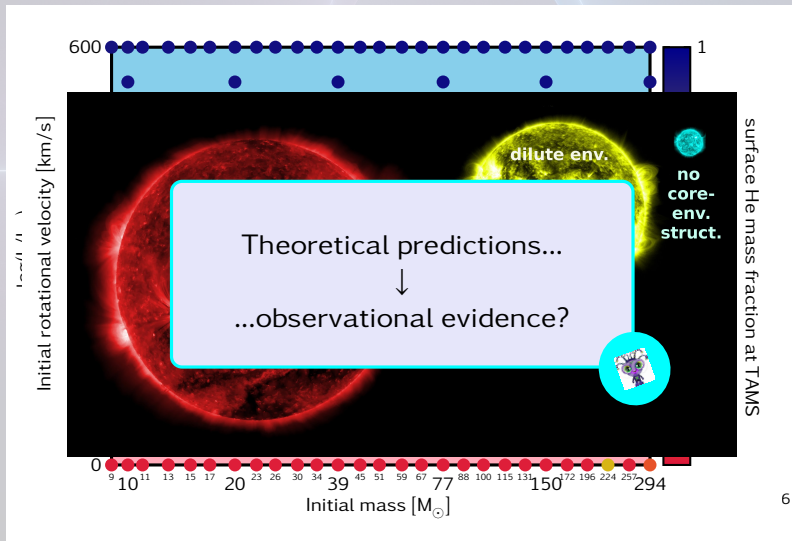
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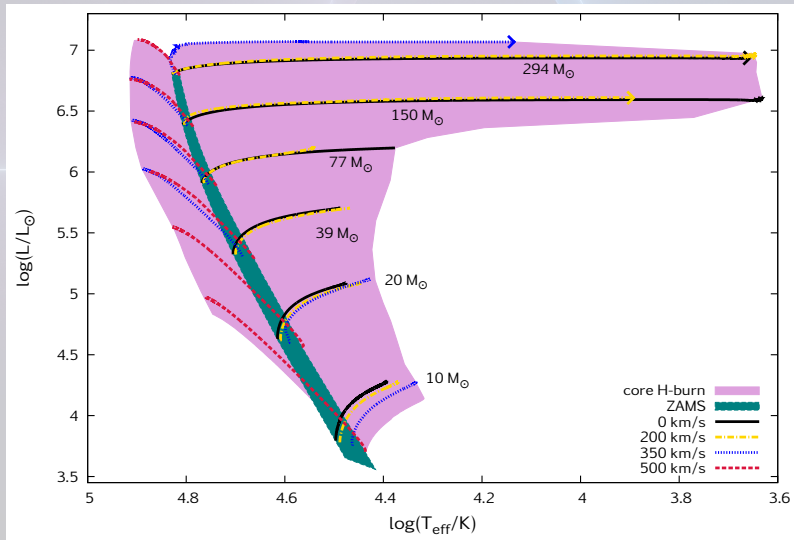
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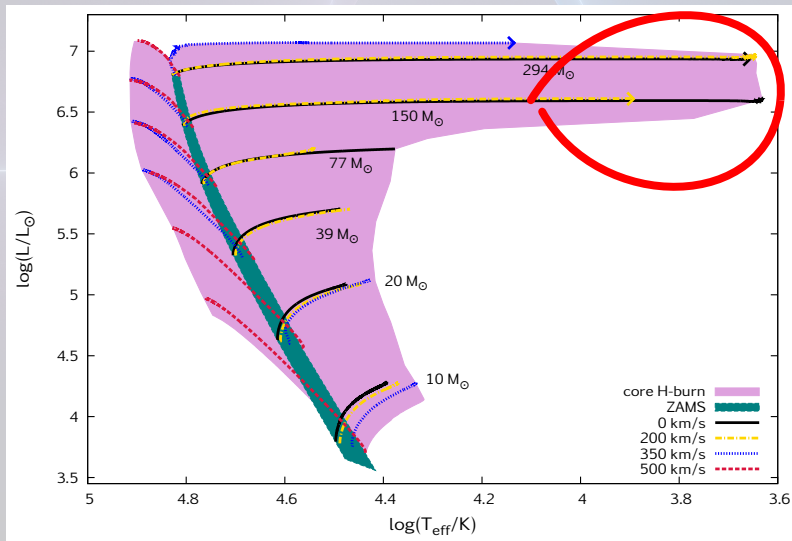
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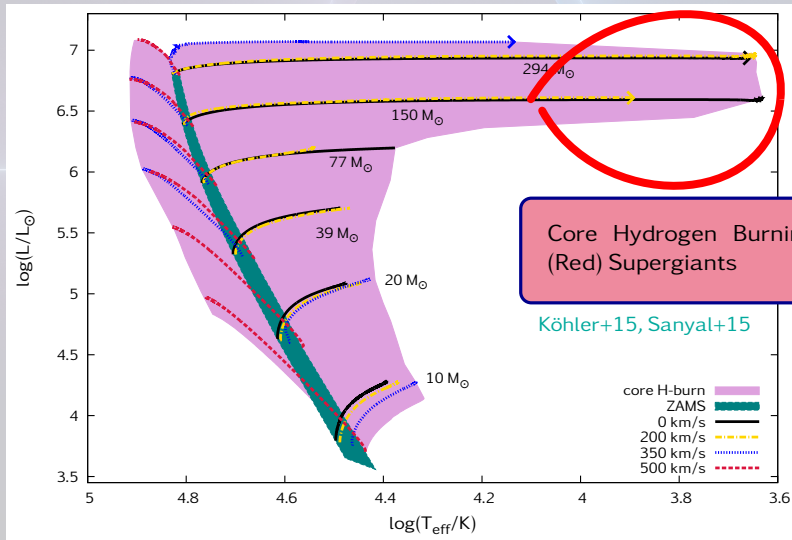
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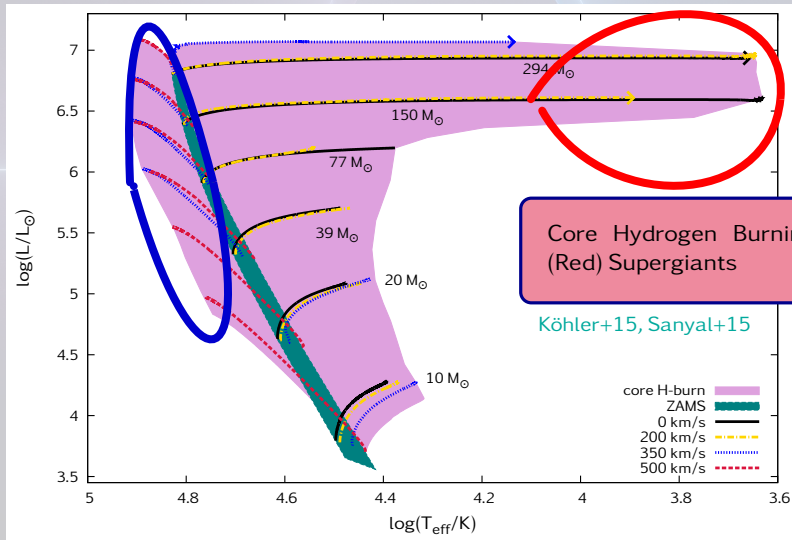
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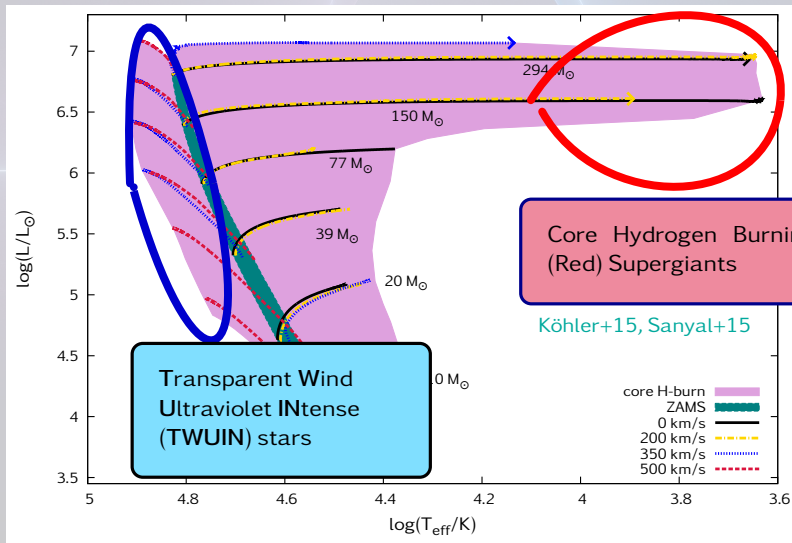
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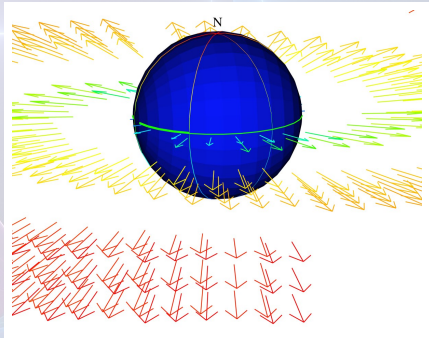


Transparent Wind
Ultraviolet Intense stars
(TWUIN stars)

– in the
starburst galaxy | Zwicky 18

Stellar winds

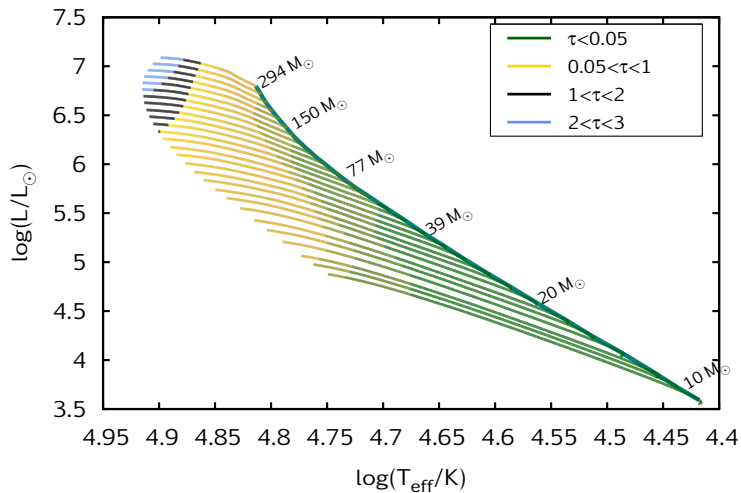
- stellar 'wind': accelerated particle flow
- hot stars at **solar Z**: **Wolf-Rayet (WR)** stars
 - opaque wind → strong emission lines
- hot stars at **low Z**?



Hot stars at low Z: transparent wind!

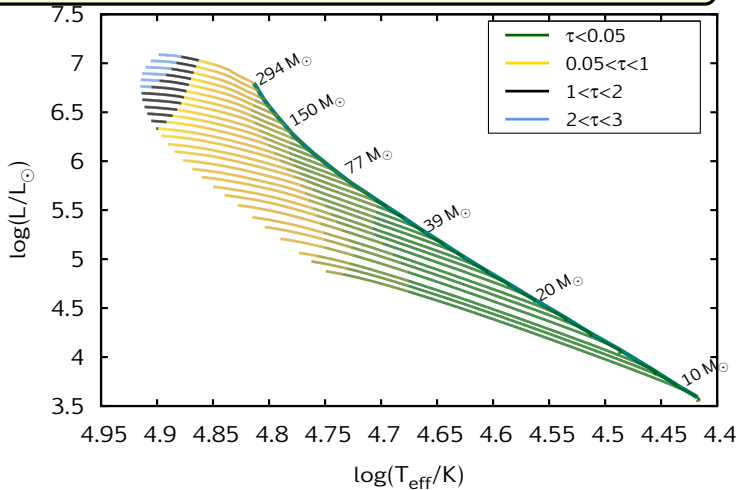


Hot stars at low Z: transparent wind!



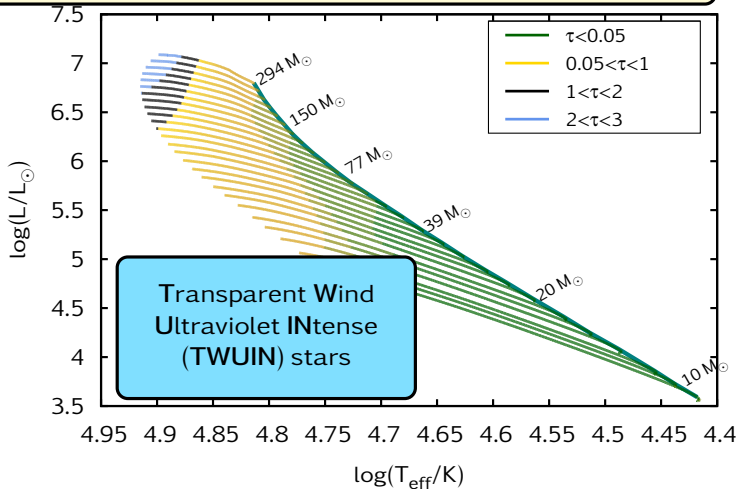
Hot stars at low Z: transparent wind!

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



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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:
 $Z=1/50 Z_{\odot}$

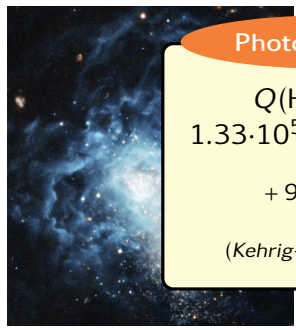


Legrand+07, Aloisi+09, Annibali+13, Kehrig+13, Leboutteiller+13

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Photoionization

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

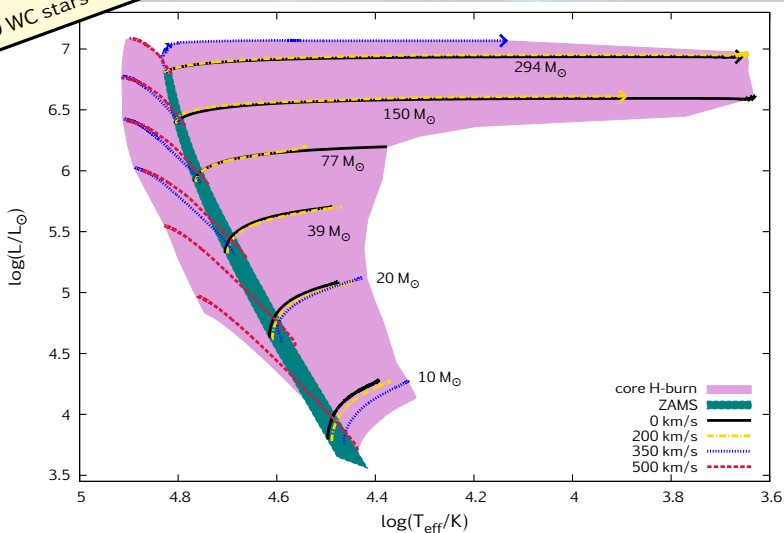
+ 9 WC stars

(Kehrig+15, Crowther+06)

Photoionization in I Zw 18

Photoionization

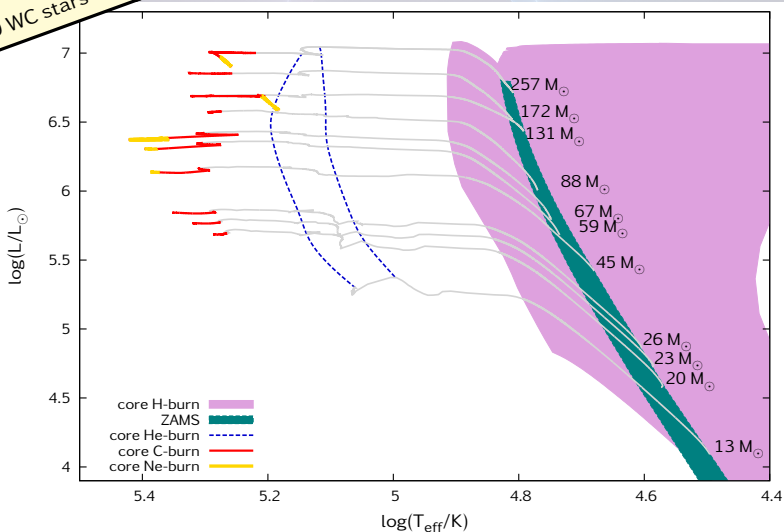
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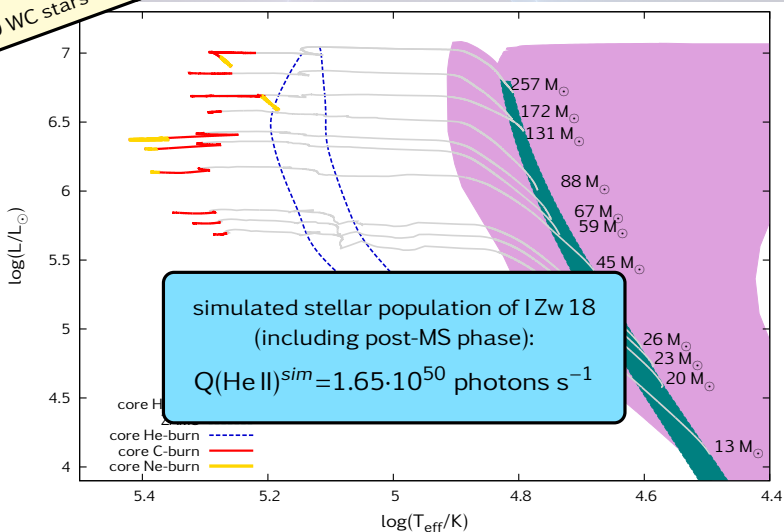
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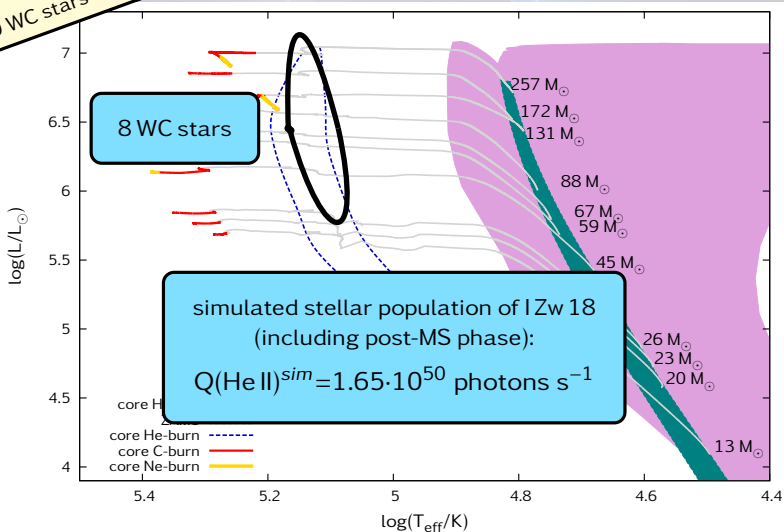
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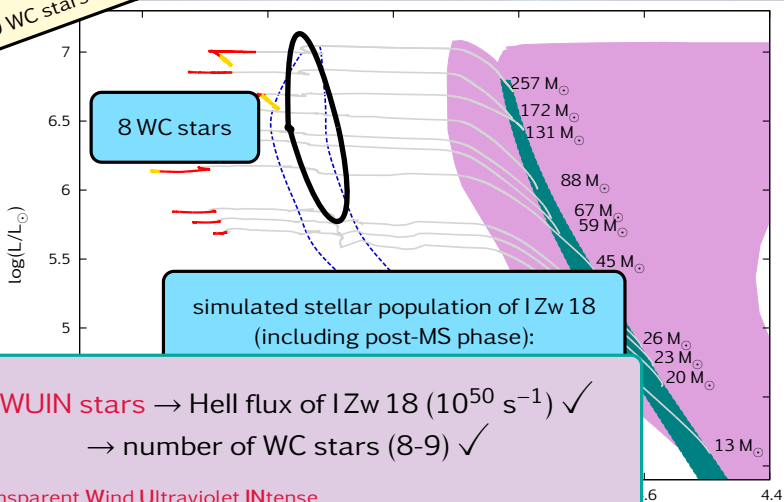
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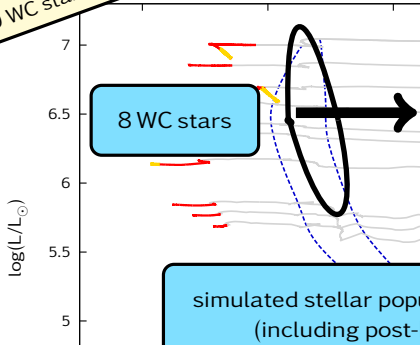
TWUIN stars \rightarrow HeII flux of I Zw 18 (10^{50} s^{-1}) \checkmark
 \rightarrow number of WC stars (8-9) \checkmark

Transparent Wind Ultraviolet INTense

Photoionization in I Zw 18

Photoionization

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



Collapsar → IGRB

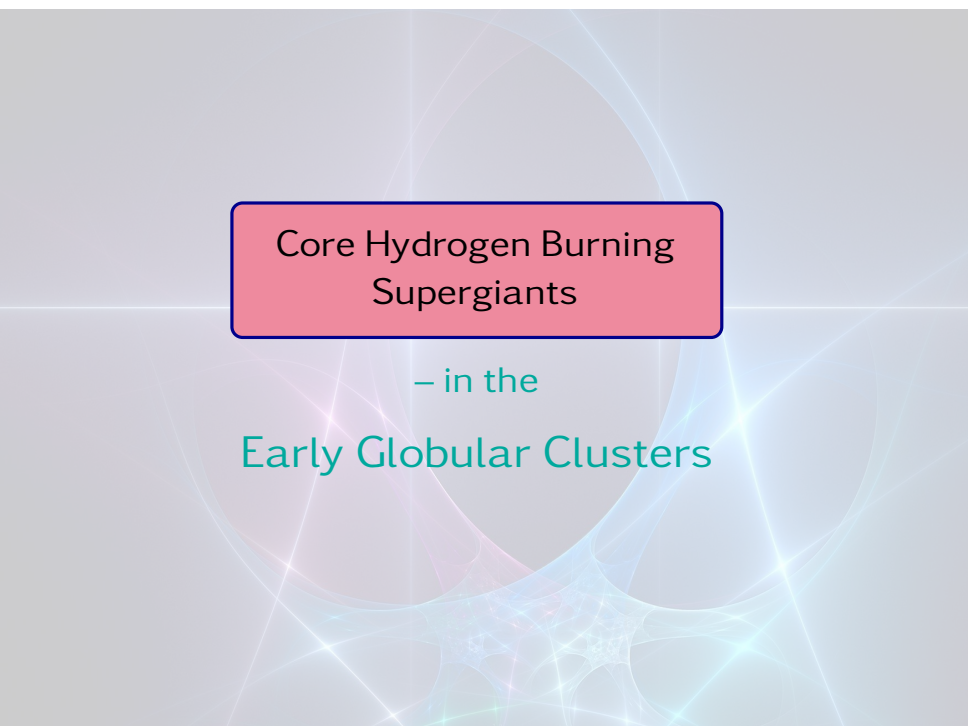


long-duration Gamma-Ray Burst (IGRB)

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

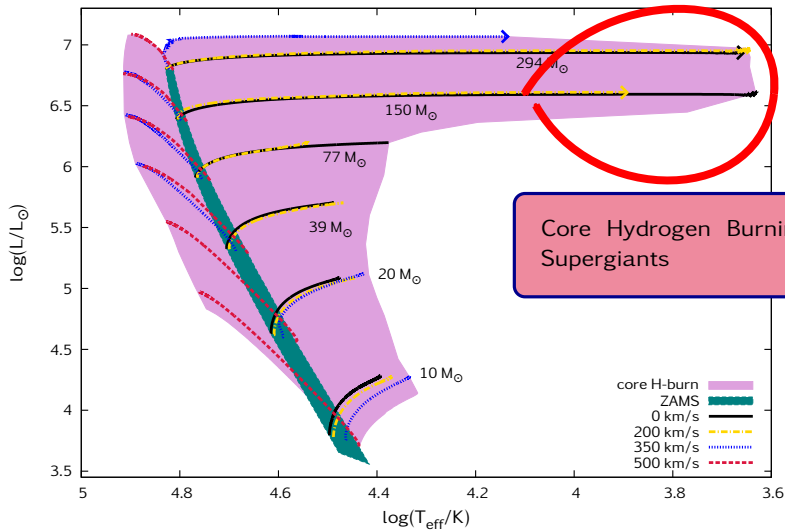
TWUIN stars → Hell flux of I Zw 18
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Transparent Wind Ultraviolet INTense

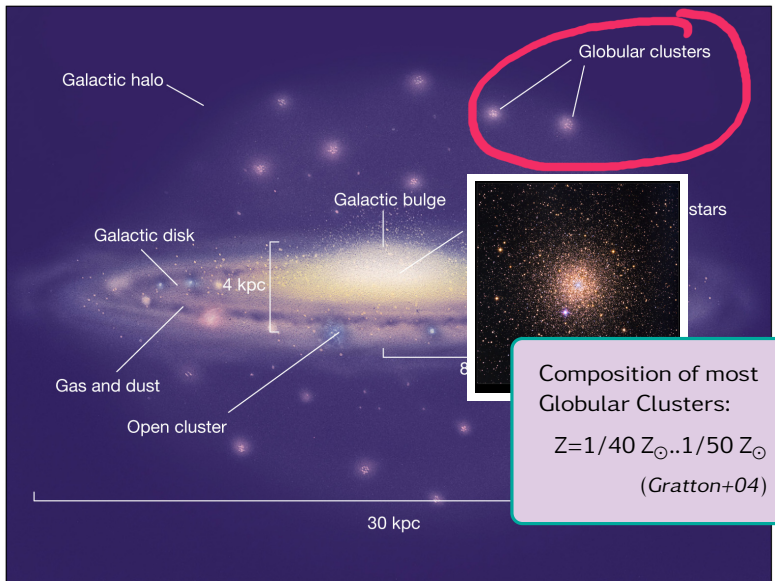


Core Hydrogen Burning
Supergiants

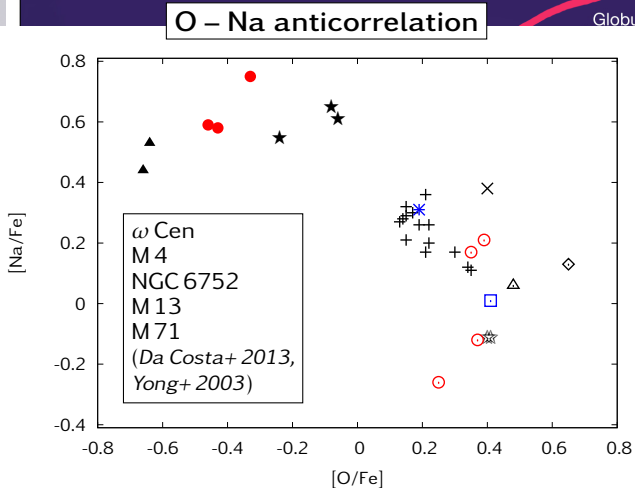
– in the
Early Globular Clusters



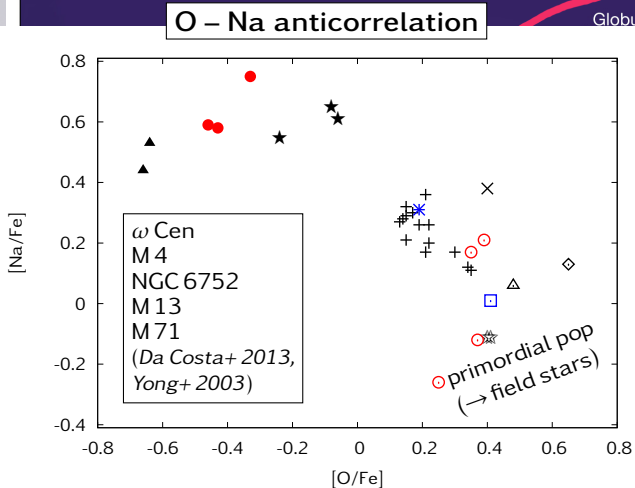
Globular Clusters & Abundance Anomalies



Globular Clusters & Abundance Anomalies



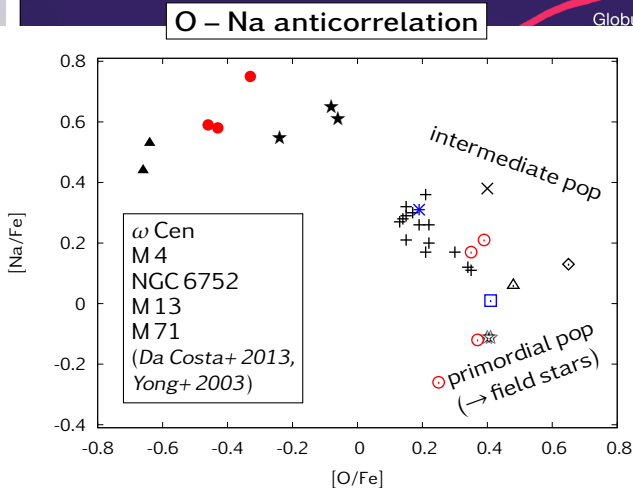
Globular Clusters & Abundance Anomalies



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



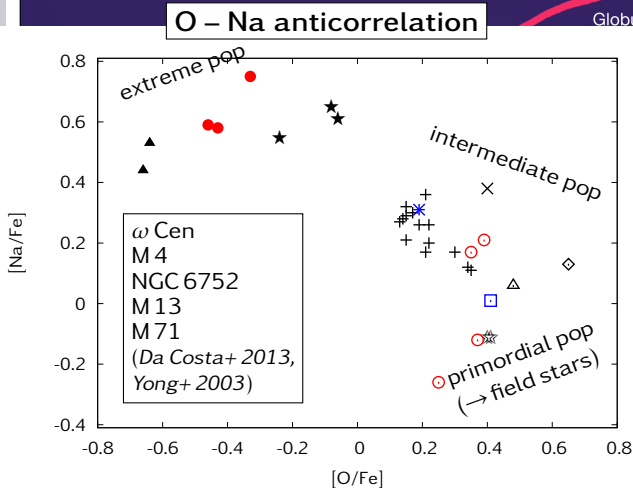
Globular Clusters & Abundance Anomalies



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Globular Clusters & Abundance Anomalies

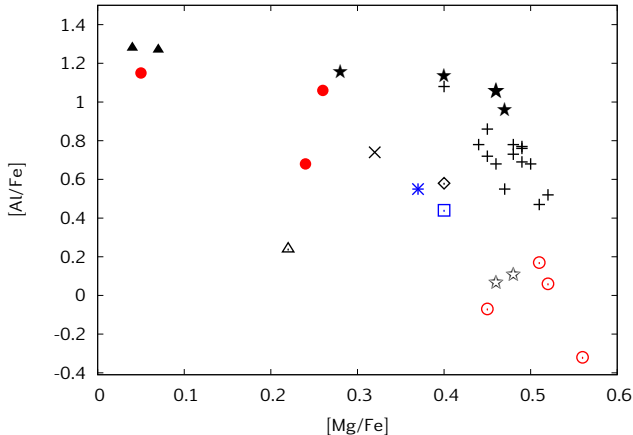


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Globular Clusters & Abundance Anomalies

Mg - Al anticorrelation



Globular clusters

stars

most
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 $Z_{\odot} \approx 0.1/50 Z_{\odot}$
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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

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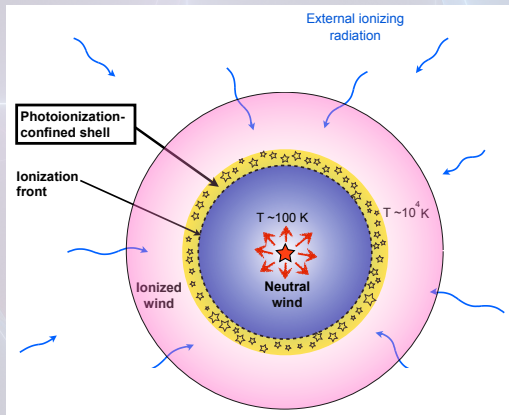
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→ **New scenario...**

New scenario:
Starforming Supergiant Shells

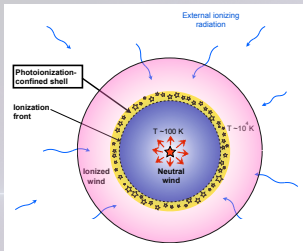
The background features a large, semi-transparent white circle centered in the upper half. Overlaid on this are several glowing, ethereal lines in shades of blue, cyan, and magenta. These lines form a complex, web-like pattern that resembles a star-forming region or a supergiant shell. The lines are most concentrated in the lower half, where they intersect to form a dense, crystalline structure. The overall effect is one of dynamic energy and cosmic scale.

New scenario: Starforming Supergiant Shells

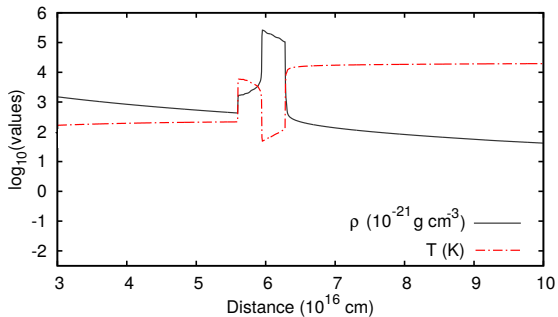
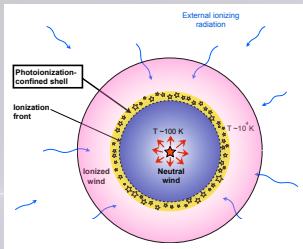


PICO shell: Mackey+ 2014 (*Nature*)

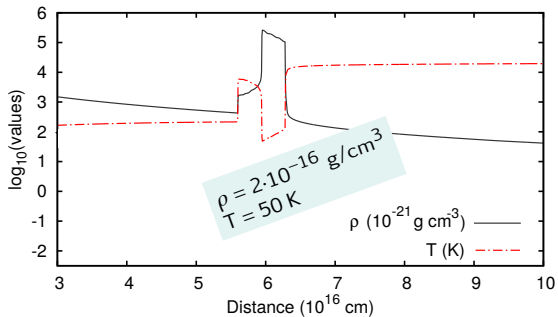
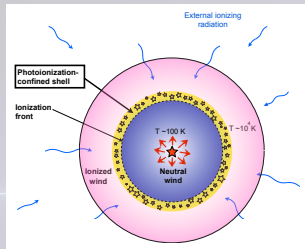
Simulating the PICO shell



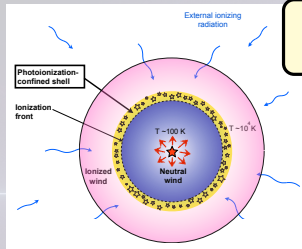
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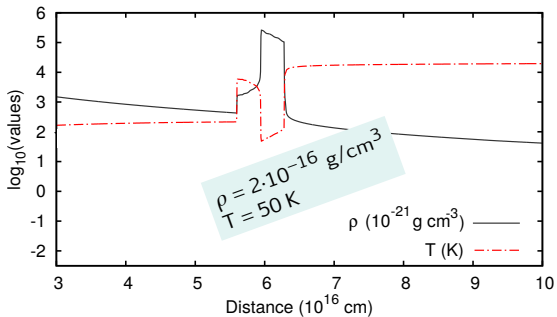
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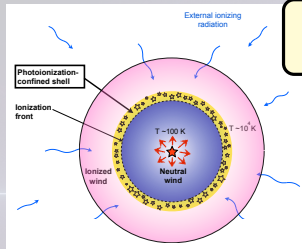
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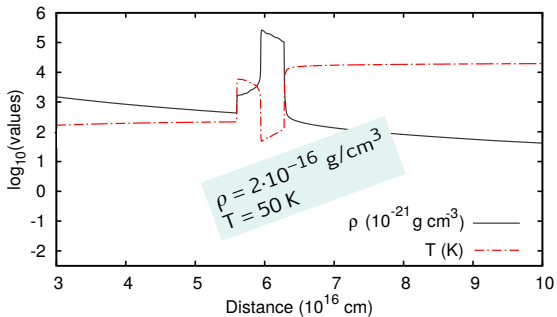
Mass of the photoionization-confined (PICO) shell: $\sim 14 M_{\odot}$



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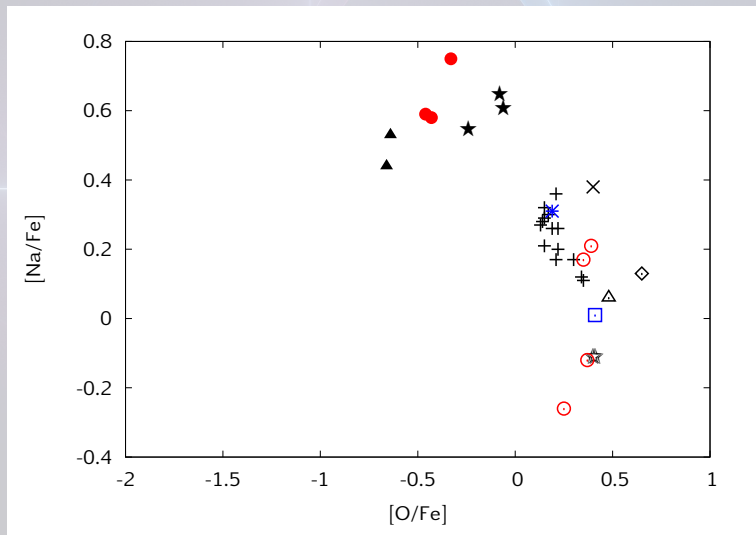


Lifetime of the shell: $\sim 10^5 \text{ yr}$

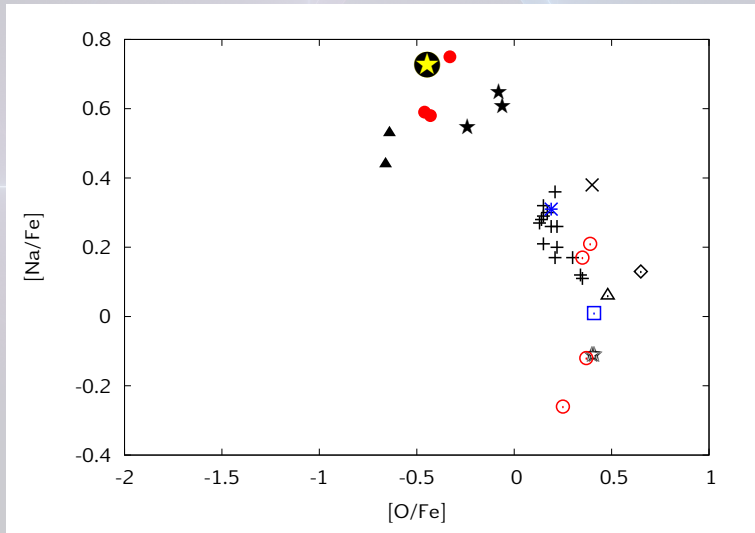
\gg

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

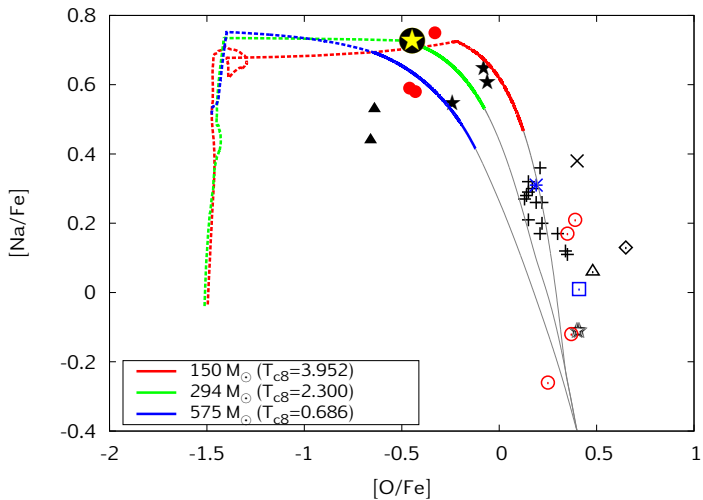
Compared to observations: O – Na anticorr.



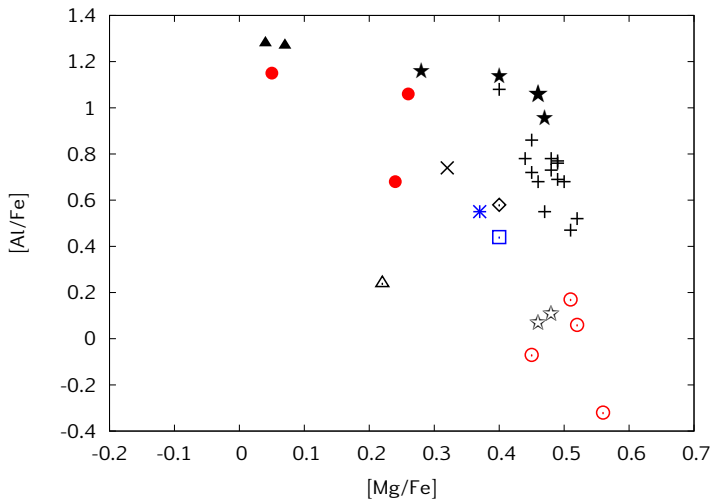
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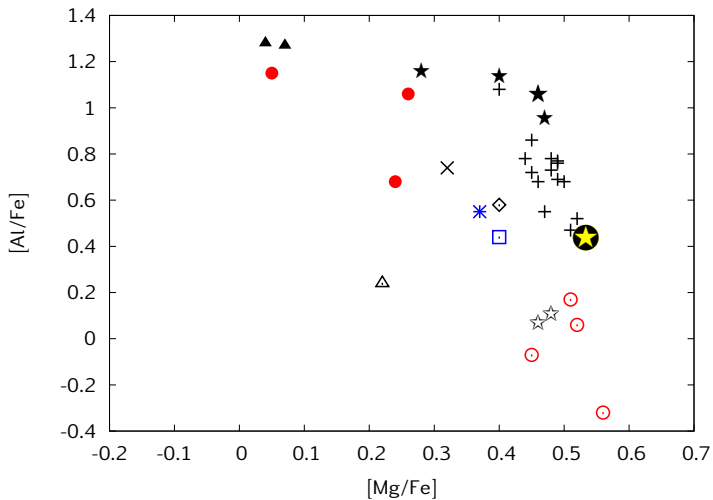
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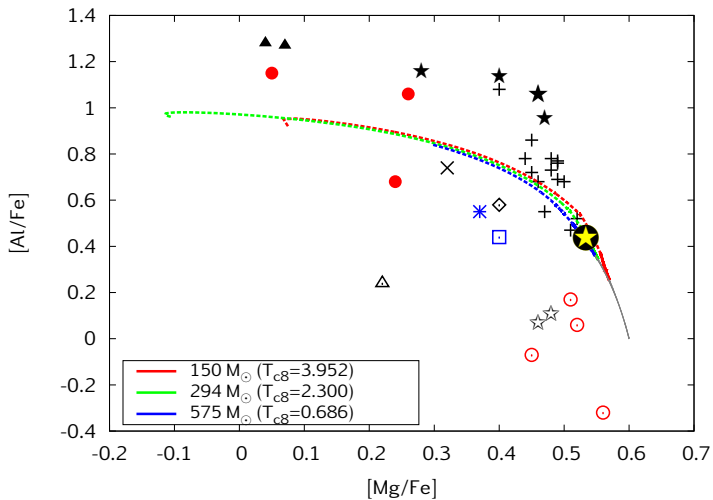
Compared to observations: Mg – Al anticorr.



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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...



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- other metal-poor environments (Green Peas galaxies, metal-poor halo stars, etc.)
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Thank you
for your
attention!