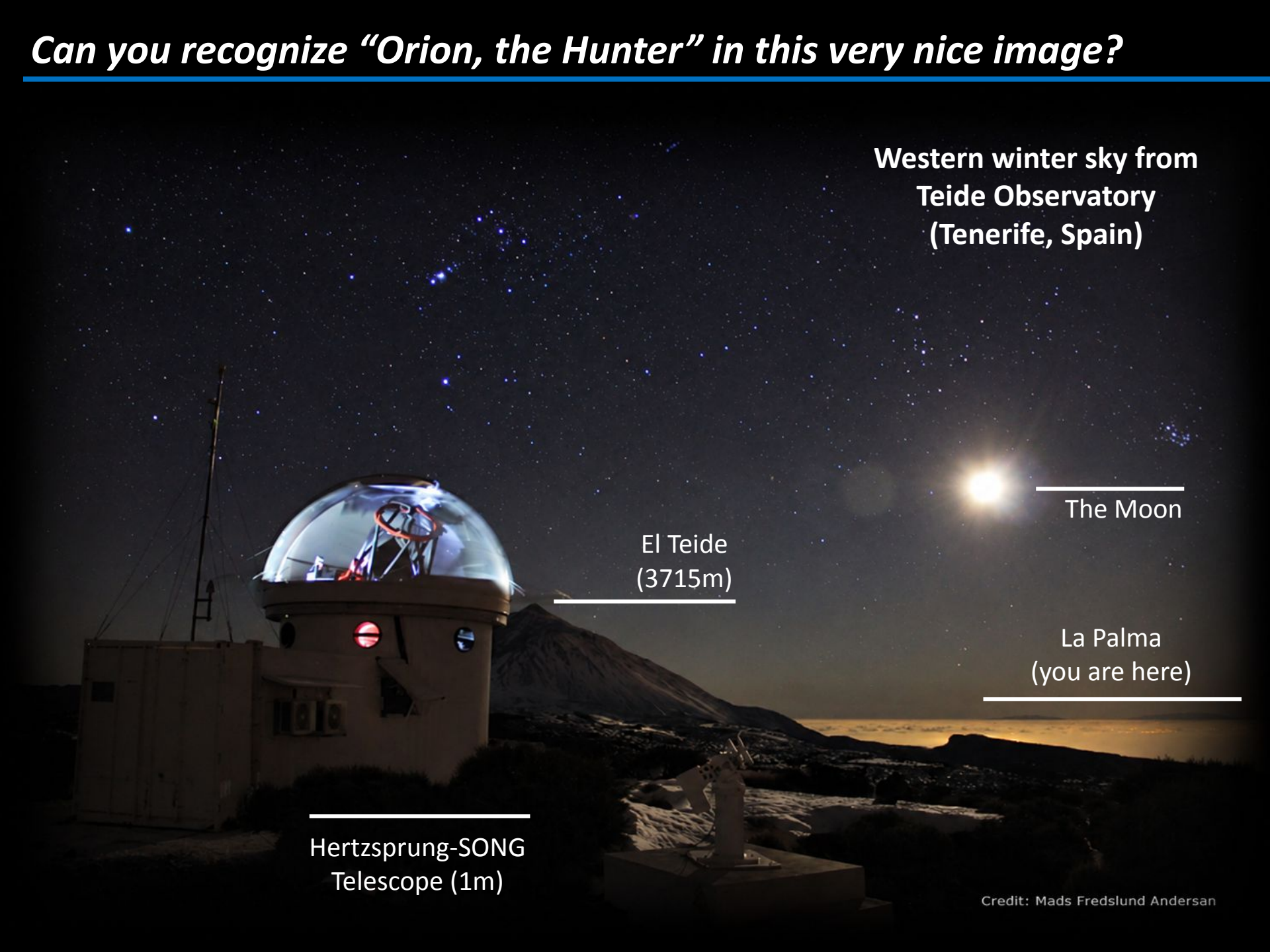
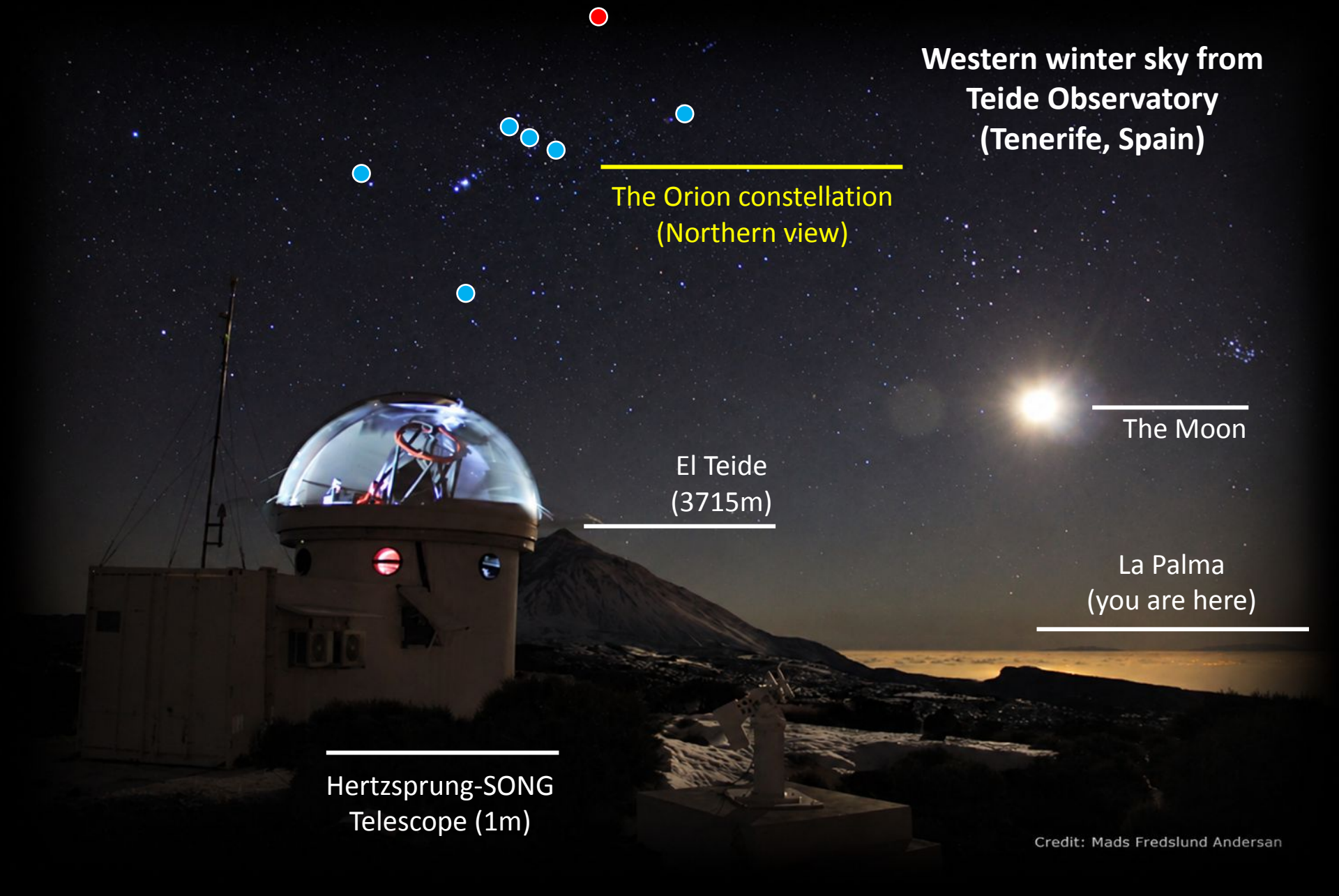

Credit: Mads Fredslund Andersan

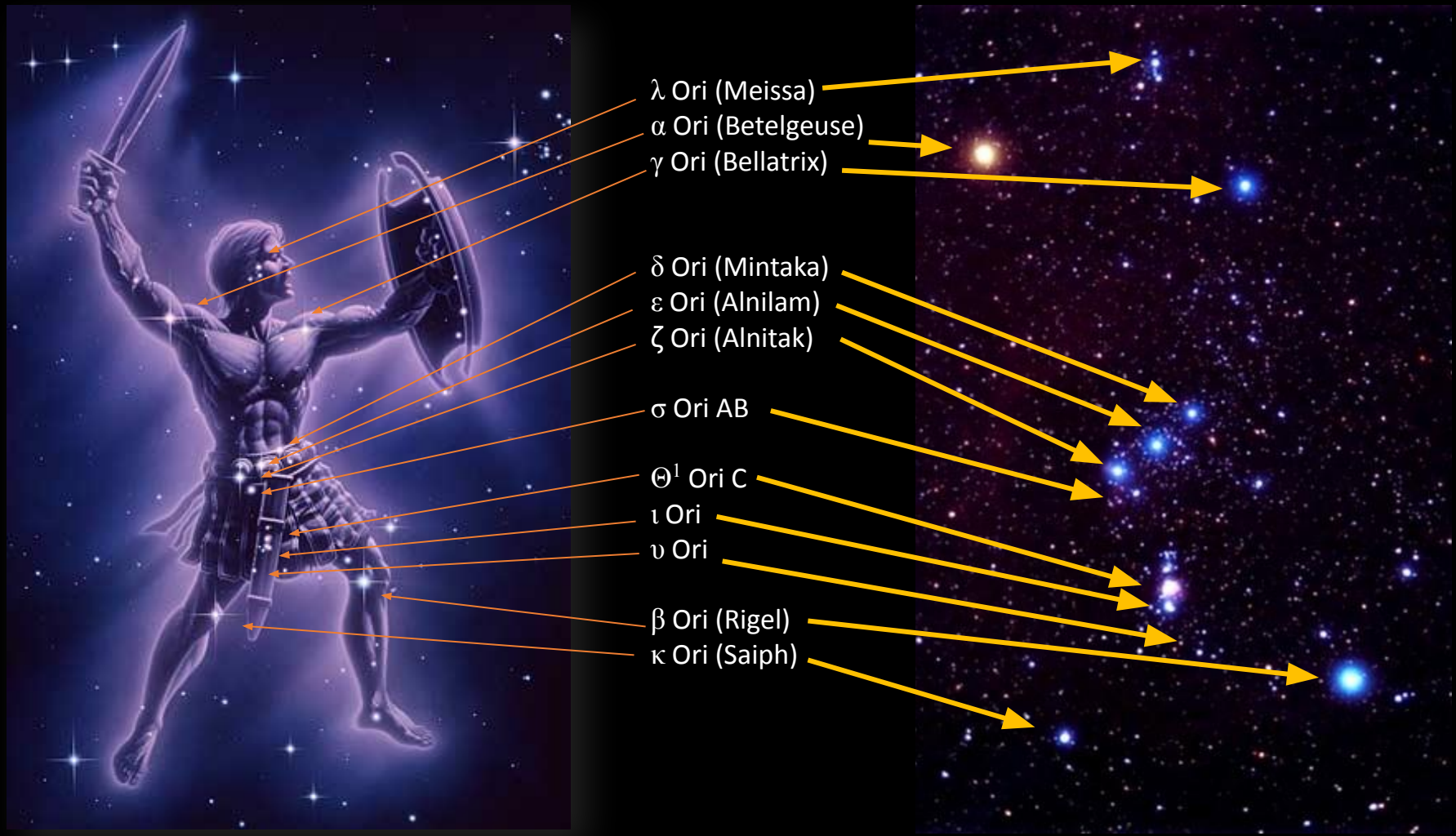
# *Can you recognize "Orion, the Hunter" in this very nice image?*



# *Can you recognize "Orion, the Hunter" in this very nice image?*



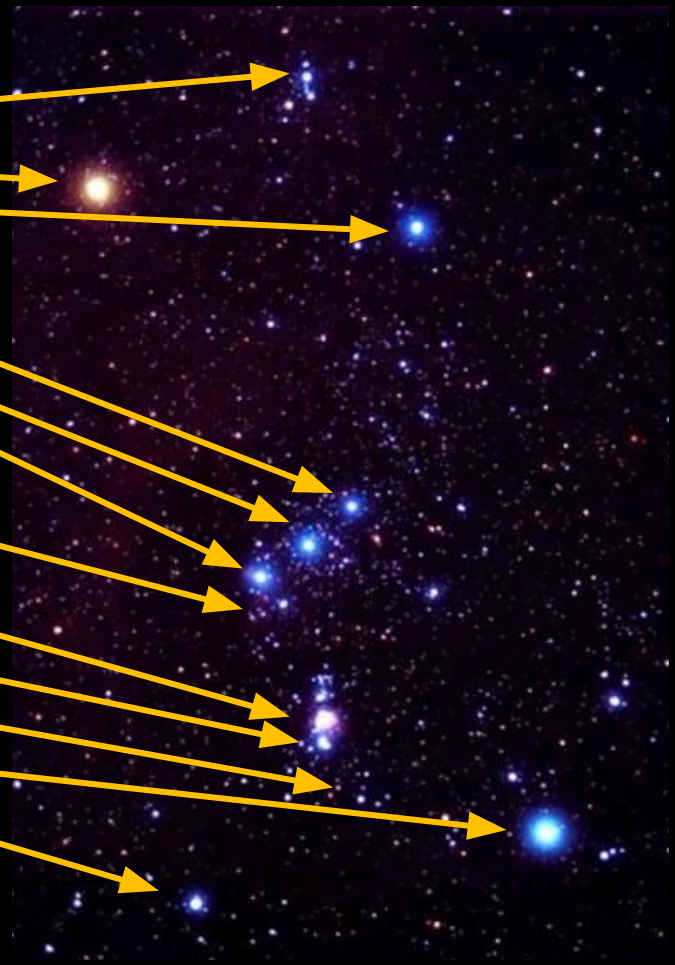
# *The brightest stars in the Orion constellation*



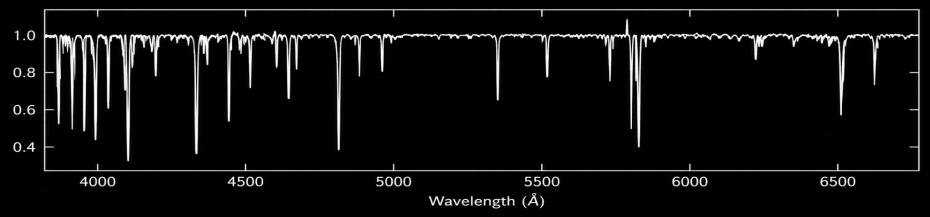
# *The brightest stars in the Orion constellation*

Golden SII certificate

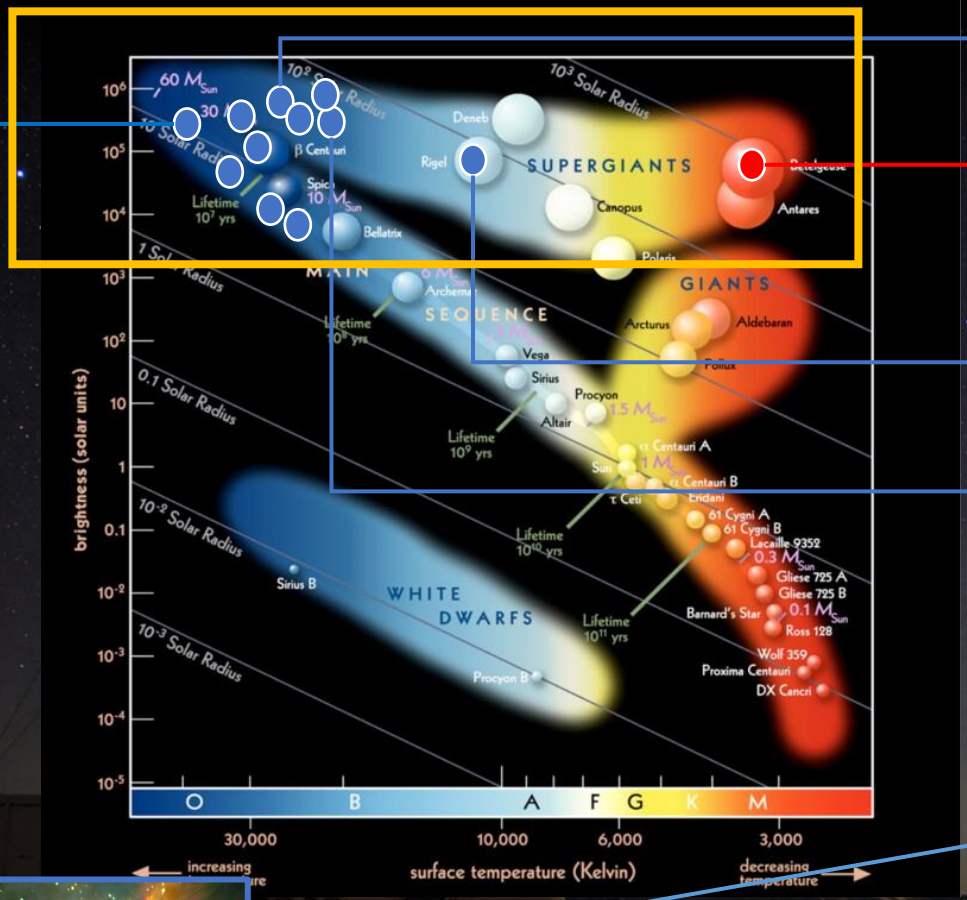
| | |
|---|---|
| V=3.47 | O8 III((f)) |
| V=0.42 | M1-M2 Ia-Ib |
| V=1.64 | B2 V |
| V=2.41 | B0 III (SB1) |
| V=1.69 | B0 Ia |
| V=1.79 | O9.7 Ib (SB3) |
| V=3.80 | O9.5 V (SB3) |
| V=5.13 | O7 Vp |
| V=2.77 | O9 III (SB2) |
| V=4.63 | O9.7 V |
| V=0.13 | B8 Ia |
| V=2.06 | B0.5 Ia |




**All of them *(but Betelgeuse)* are**
**OB-type stars**
***hence blue massive stars***



# *Massive stars in Orion: different masses and evolutionary stages*




λ Ori (O8 III)

Betelgeuse (M1-M2 Ia-Ib)

Alnilam (B0Ia)

Rigel (B8 Ia)

Θ¹ Ori C (O7Vp)

The Orion nebula

and distances …

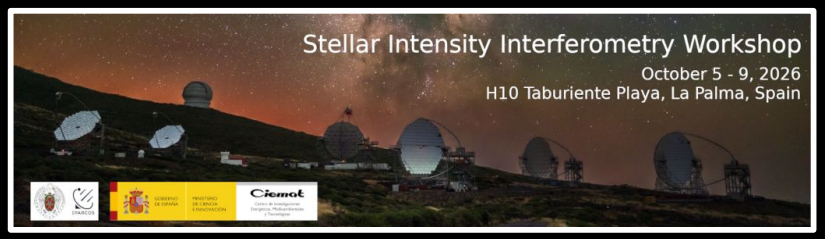
Betelgeuse: 130 pc
Rigel: 240 pc
λ Ori: 330 pc
i Ori: 410 pc
Θ¹ Ori C: 420 pc
Alnilam: 420 pc

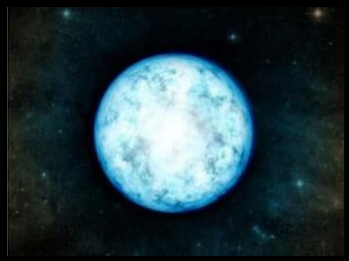
Golden SII certificate

Credit: Mads Fredslund Andersan

EXCELENCIA SEVERO OCHOA
Universidad de La Laguna
IACOB
GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
OCEANS
Cofunded by the European Union





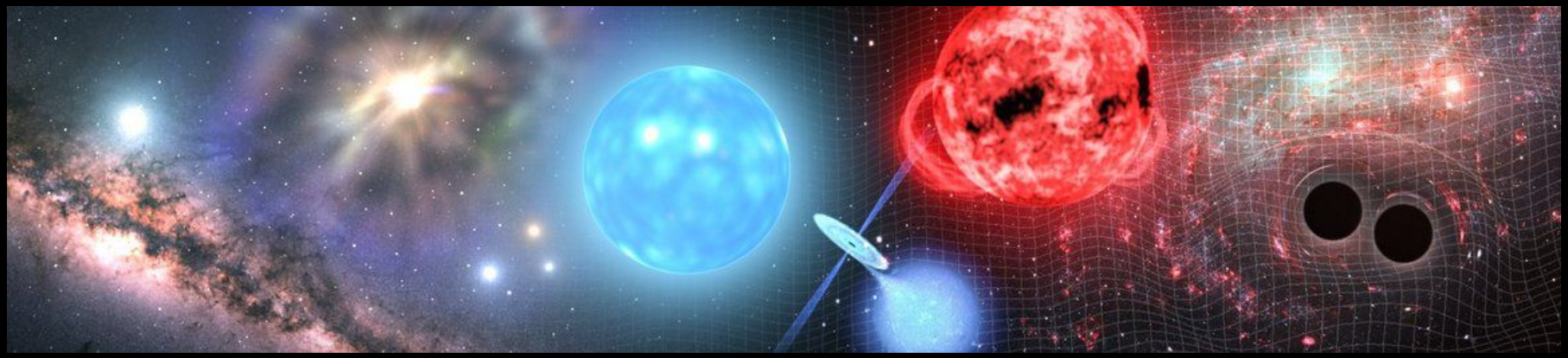



## A (brief) guided tour through

# the world of Massive OB Stars

## (Exploring synergies with Stellar Intensity Interferometry)

*Sergio Simón-Díaz*



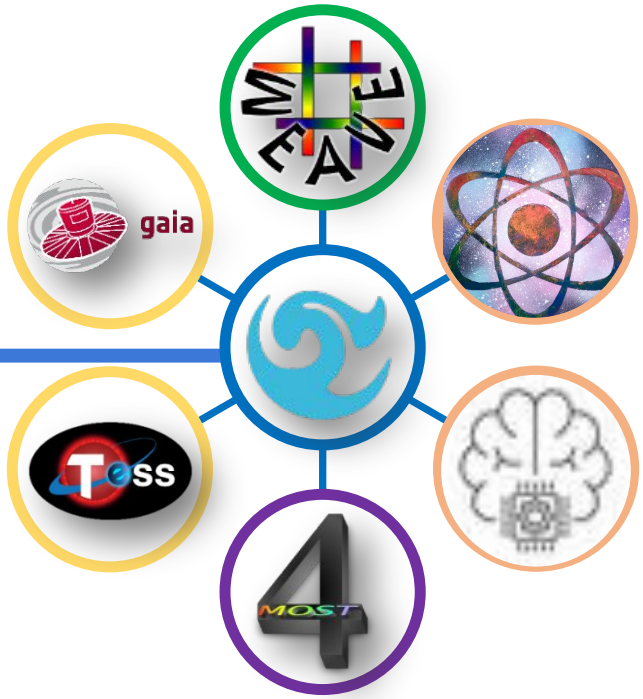
# About me



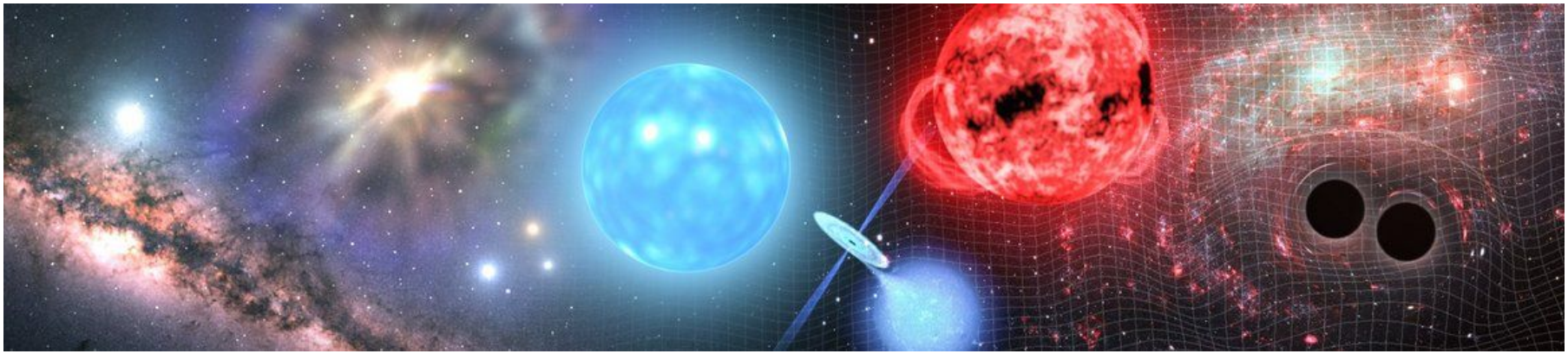
**Sergio Simón-Díaz**

Staff researcher @IAC

Leader of the group: *Physical properties and evolution of massive stars*




- Stellar astrophysicist (Observer)
- Expert in quantitative spectroscopy of **OB stars**
- Key role in development and exploitation of several modern large-scale spectroscopic surveys of **massive OB-type stars**



# Motivation of this talk

Aim of the meeting:

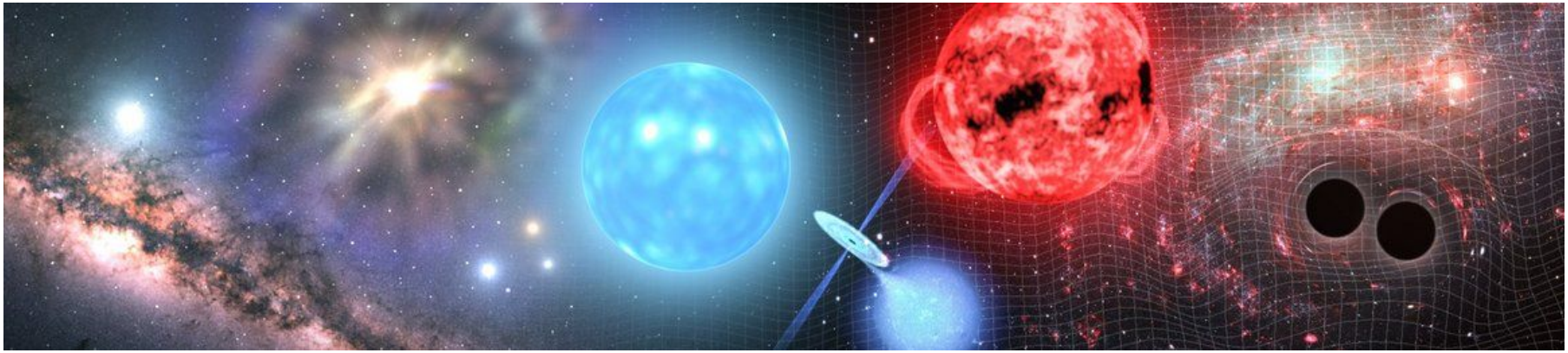



*Fostering discussions and collaborations on recent advances and future challenges in the area of stellar intensity interferometry*

Kind invitation by Tarek Hassan:

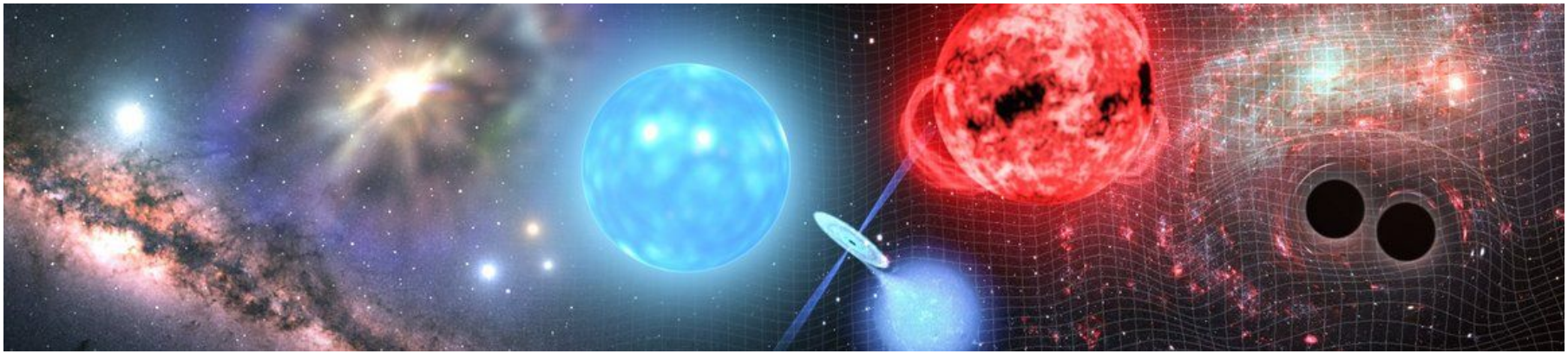


*We would appreciate it if you could give a presentation reviewing the state of the art of **OB stars**, ideally giving a focus to morphological effects and, In your eyes, the potential of long-baseline optical interferometry to study them.*



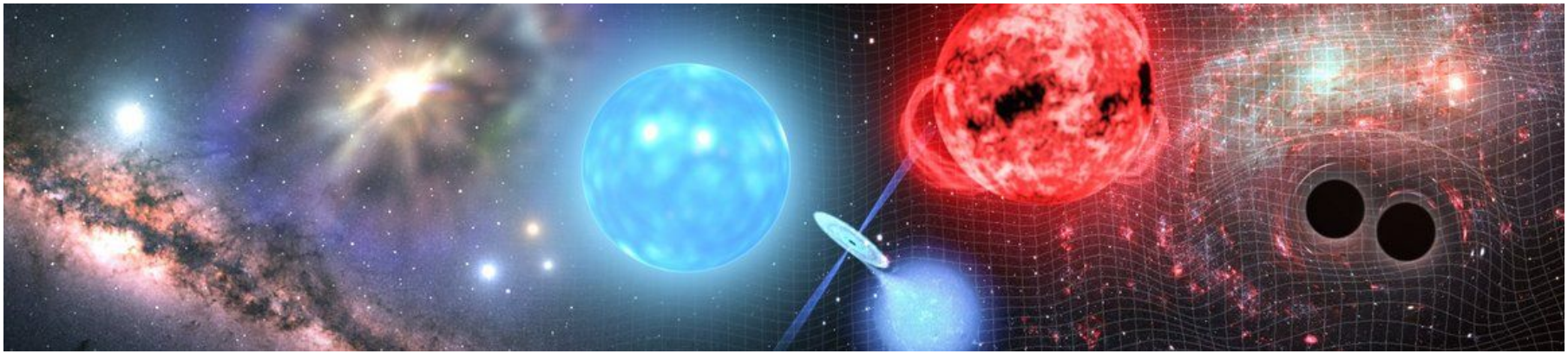
# *Structure of the talk*

- OB stars in a nutshell
- How massive stars evolve
- The IACOB project
- What can SII bring to massive-star research?

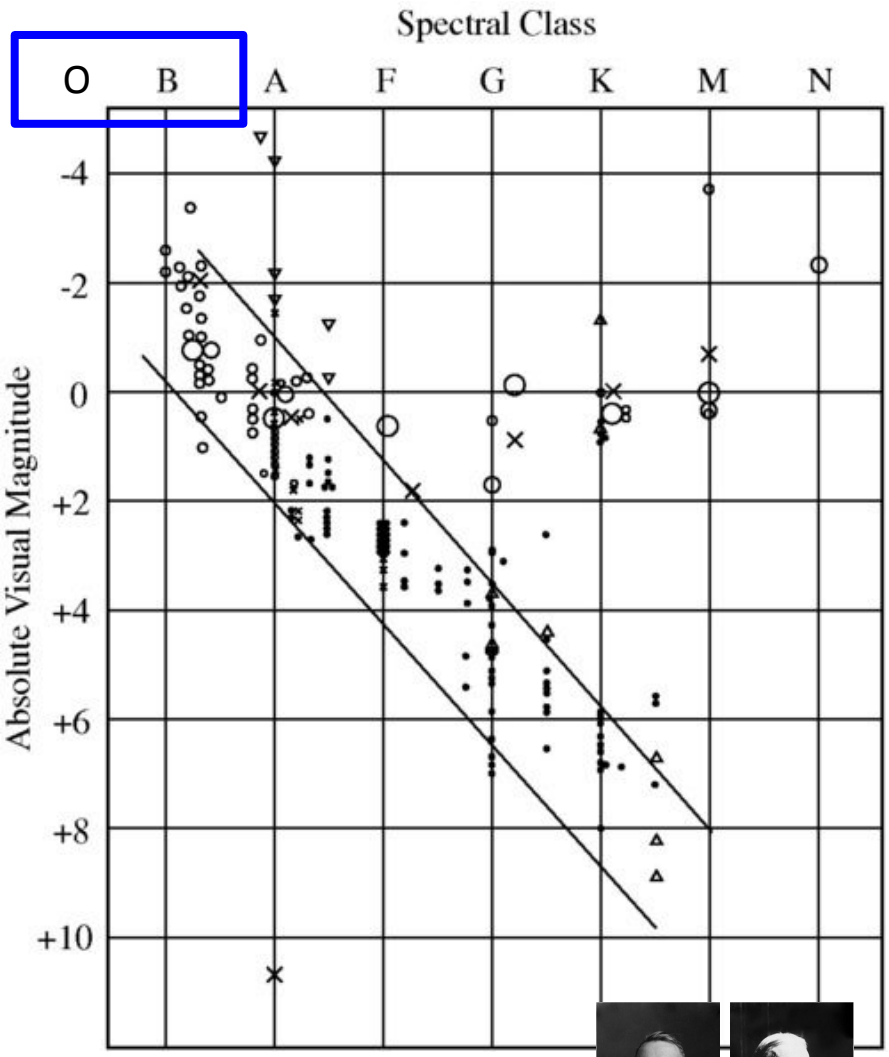


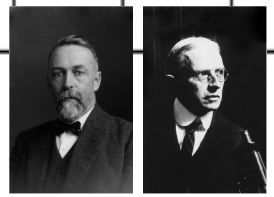
# *Structure of the talk*

- OB stars in a nutshell
- How massive stars evolve
- The IACOB project
- What can SII bring to massive-star research?

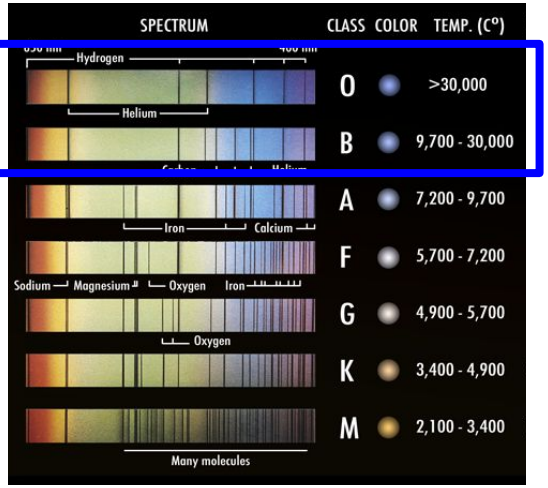


# The Hertzsprung-Russell diagram



1905 - 1913: **E. Hertzprung & H. Russell** (+ a few others)







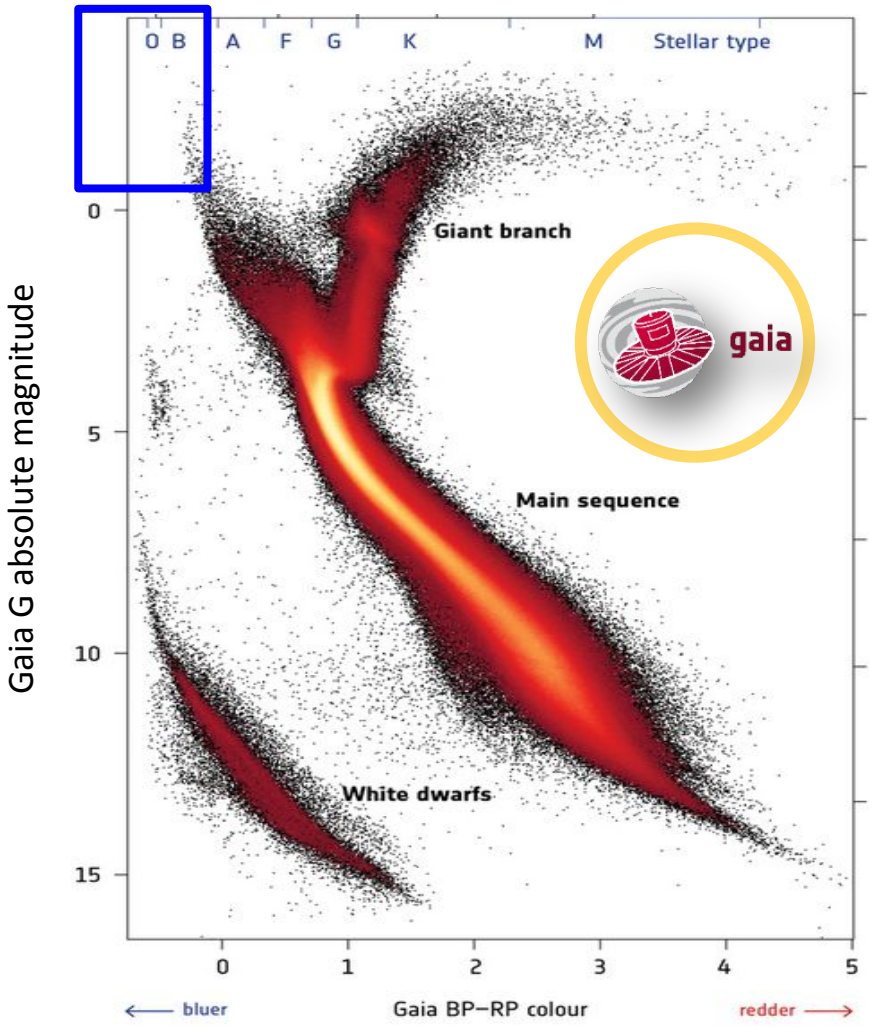

1901 - 1925: **A. Cannon & C. Payne** (+ some others)

The most important diagram in stellar astrophysics
+
a cornerstone to investigate stellar evolution

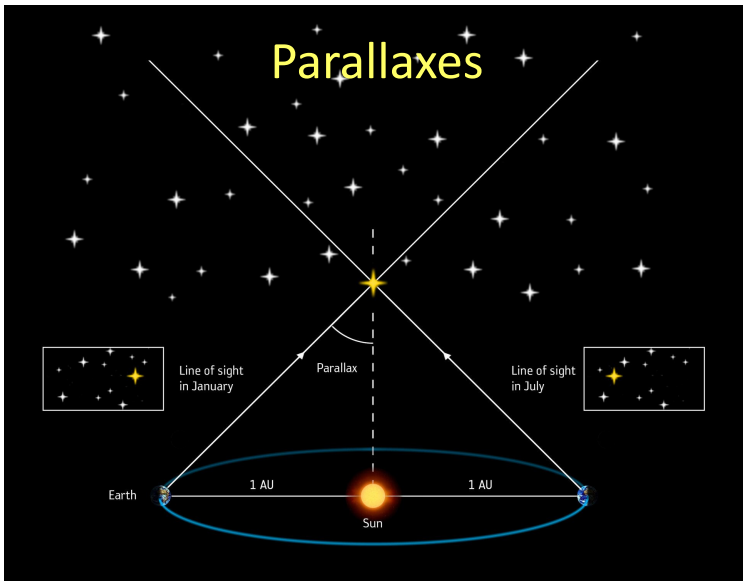
A clear (**Main Sequence**) band comprising 80-90% of all stars was already identified in that first HR diagram

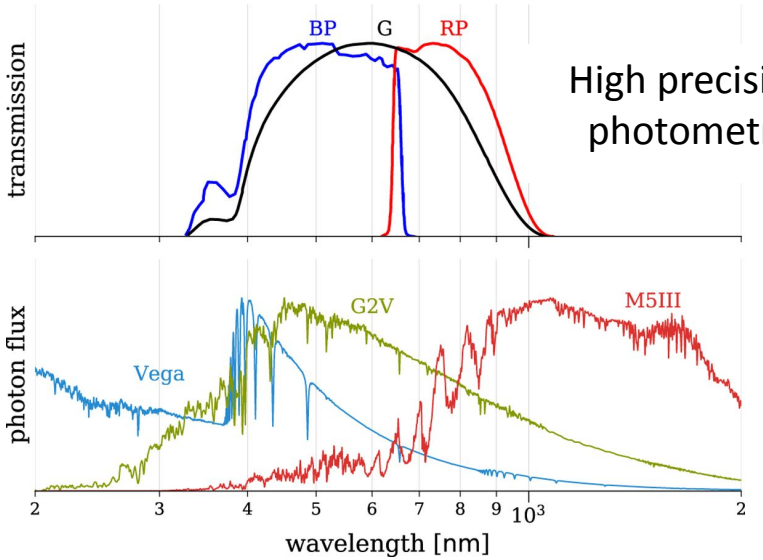
# The Hertzsprung-Russell diagram (HRD): one century later

Gaia/ESA: the 1.7 billion star space mission




© **ESA/Gaia/DPAC**, CC BY-SA 3.0 IGO (2018)



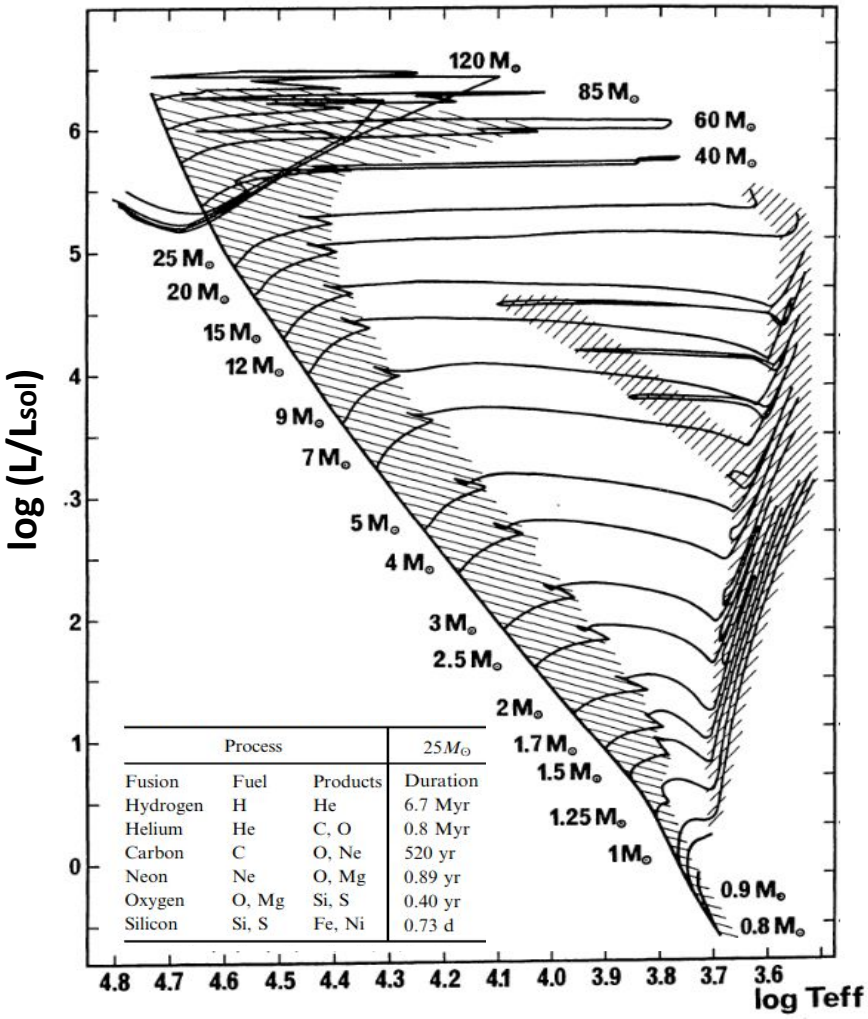




High precision photometry

# HRD - it all seems to revolve around stellar mass and evolution

Thanks to the development of the **theory of stellar interiors** (+ single star evolution codes)

see books/notes by, e.g., **Kippenhahn, Prialnik, Maeder, Pols,** (+ many other recent papers, e.g. **Brott+11**, **Ekström+12**)



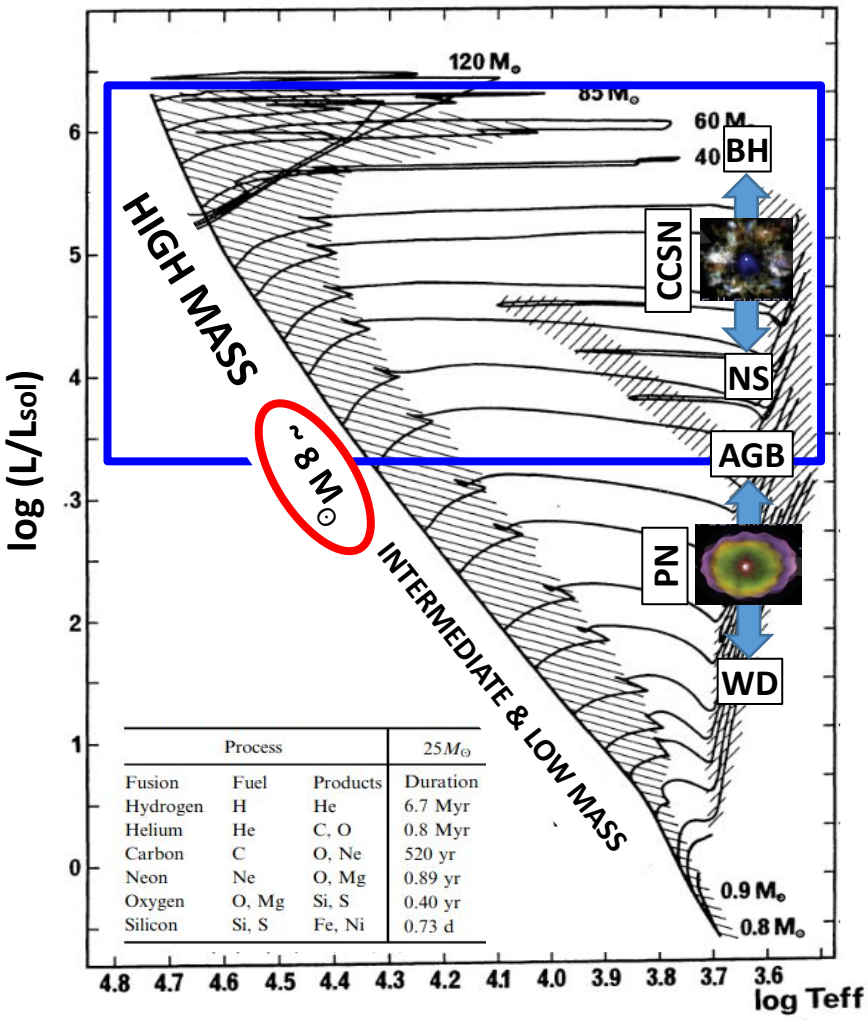

- The **Main Sequence** (MS) consists of stars with varying initial masses, all burning H in their cores.
- The time a star spends on the Main Sequence decreases with increasing mass

  (e.g. $t_{MS}$ – 1 $M_{sol}$: ~10 Gyr *vs.* 25 $M_{sol}$: ~7 Myr)
- All other regions of the HRD are populated by stars evolving from the MS.
- The rate of evolution for stars of a given mass is not always constant.
- Stars of different masses evolve following distinct paths and have different ultimate fates.

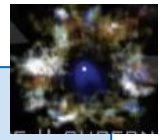
# HRD - it all seems to revolve around stellar mass and evolution

Thanks to the development of the **theory of stellar interiors** (+ single star evolution codes)

see books/notes by, e.g., **Kippenhahn, Prialnik, Maeder, Pols,** (+ many other recent papers, e.g. **Brott+11**, **Ekström+12**)



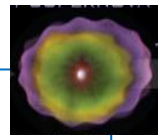

| Process | | | $25M_\odot$ |
|---|---|---|---|
| Fusion | Fuel | Products | Duration |
| Hydrogen | H | He | 6.7 Myr |
| Helium | He | C, O | 0.8 Myr |
| Carbon | C | O, Ne | 520 yr |
| Neon | Ne | O, Mg | 0.89 yr |
| Oxygen | O, Mg | Si, S | 0.40 yr |
| Silicon | Si, S | Fe, Ni | 0.73 d |



## Massive stars

Those stars that are massive enough to form a collapsing core at the end of their lives and then avoid the white dwarf fate

Core collapse (SN) ⟶ Neutron star // Black hole



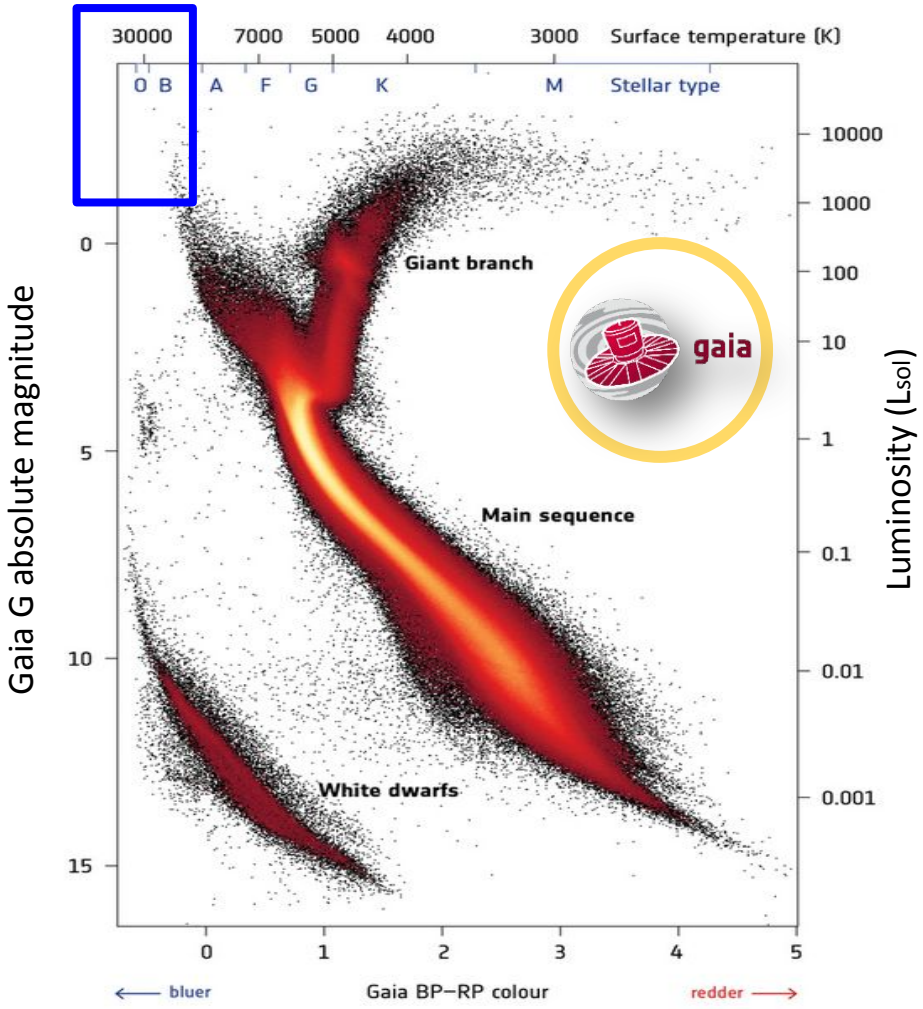
## Intermediate and low mass stars

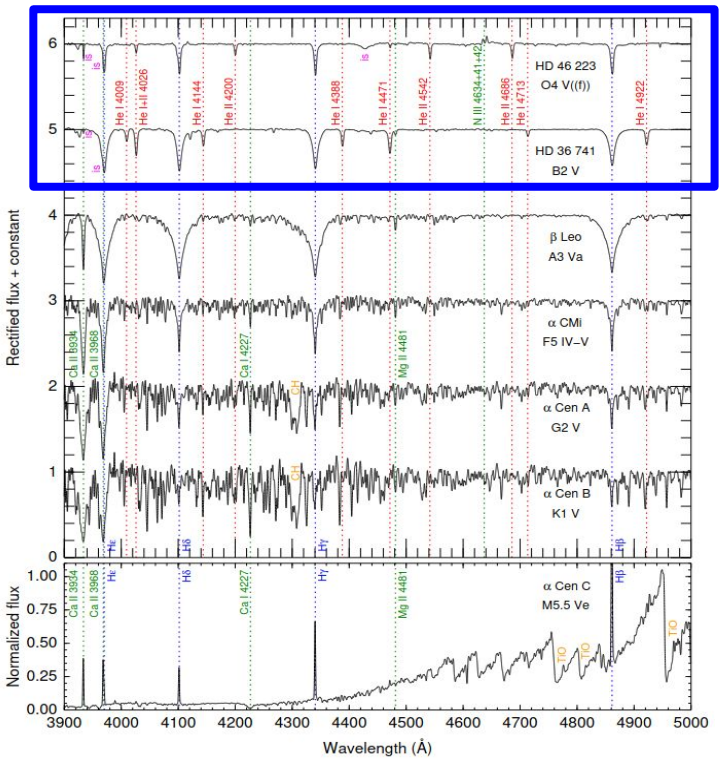
Those stars with a mass not high enough to be able to ignite C and O burning at their cores and end their lives as a white dwarf

AGB star ⟶ Planetary nebula ⟶ White dwarf

# The Hertzsprung-Russell diagram (HRD): one century later

+ Improved observational capabilities allowing the compilation of **high-quality spectra** of increasingly larger samples of stars




**Maíz Apellániz, Negueruela & Caballero** (2024, Encyclopedia of Astrophysics)

+ Development of theory of radiative transfer and **stellar atmosphere codes**

see also recent review by **Puls, Herrero & Allende** (2024, Encyclopedia of Astrophysics)

© **ESA/Gaia/DPAC**, CC BY-SA 3.0 IGO (2018)

# *Quantitative spectroscopy (QS) - A key tool for stellar astrophysics*

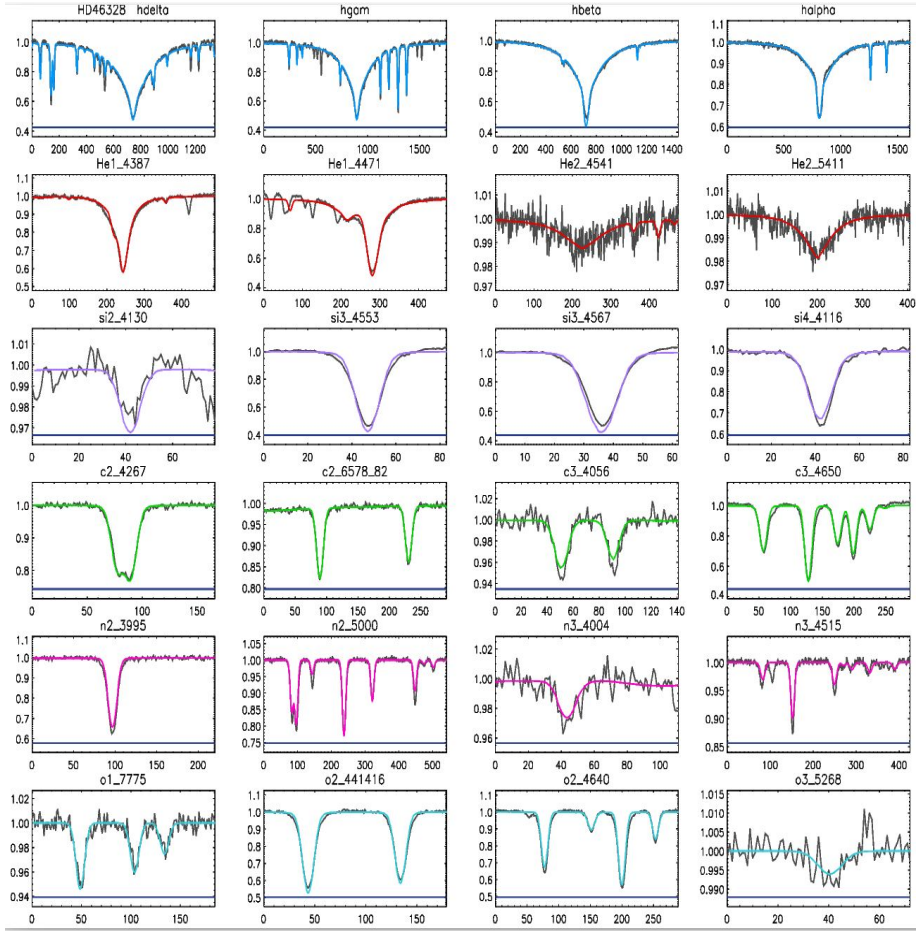
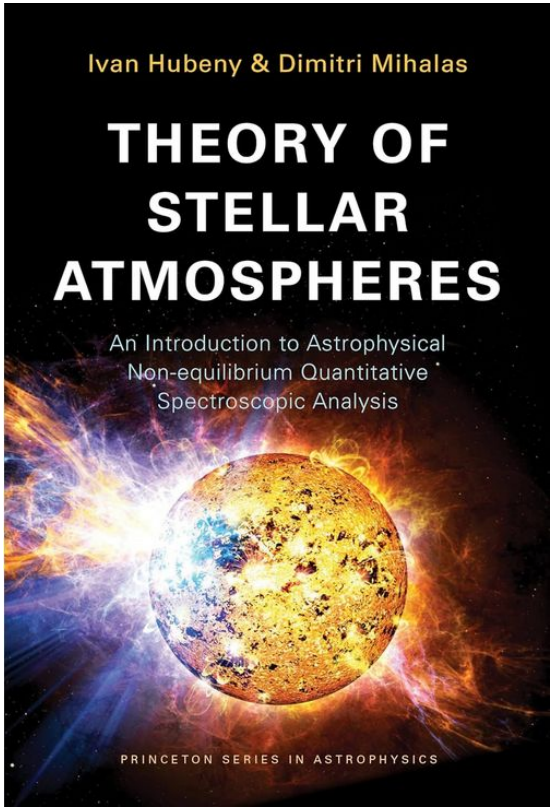



Figure courtesy by **M. A Urbaneja** (University of Innsbruck)




**QS opens the door to acquire valuable information about the properties of the stellar atmosphere**

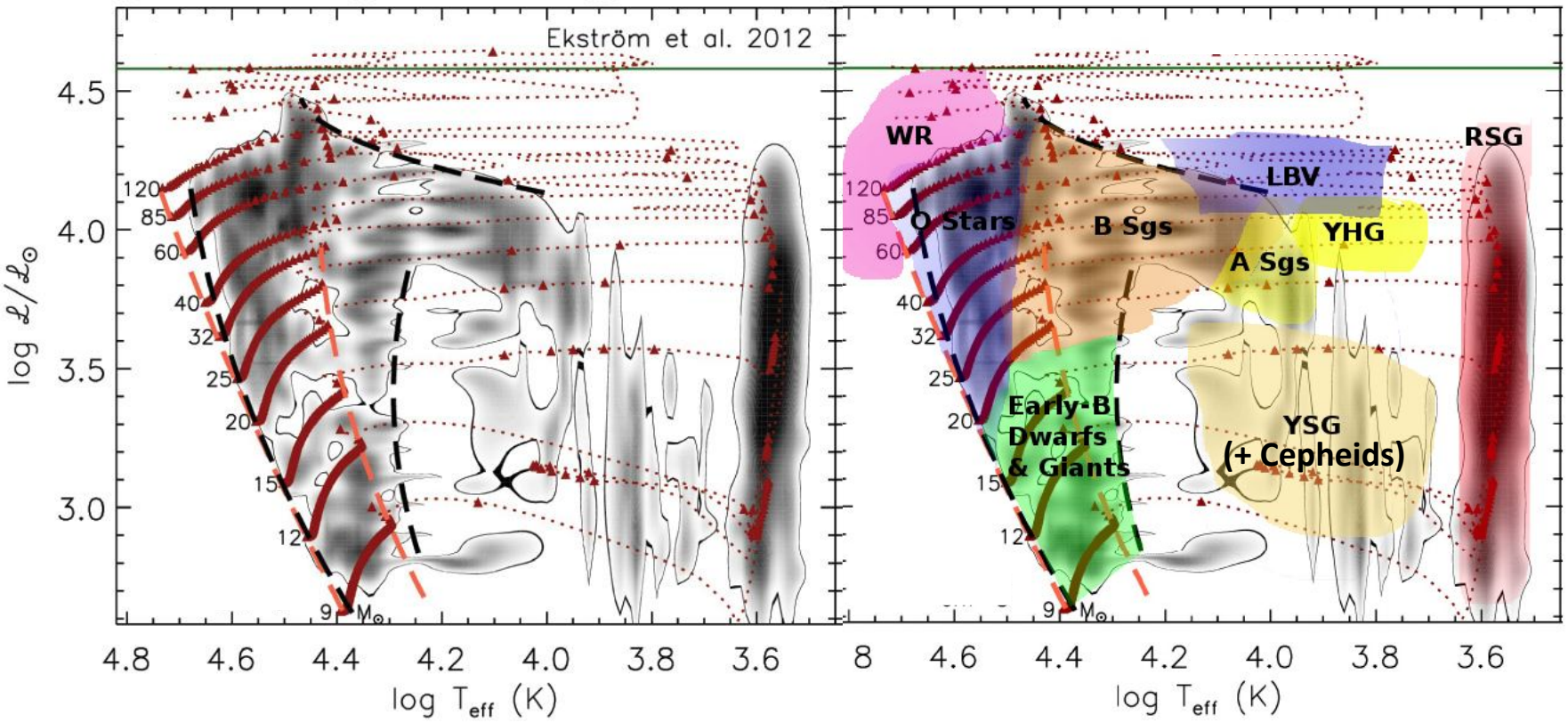
*v*sin*i*, $T_{eff}$, log*g*, surface abundances, wind parameters

\+ Development of theory of radiative transfer and **stellar atmosphere codes**

see also recent review by **Puls, Herrero & Allende** (2024, Encyclopedia of Astrophysics)

# The upper HRD: the realm of massive stars

**Physics / Models** | **Phenomenology from observations**




Density map (in the spectroscopic HRD) of ~600 Galactic massive stars with parameters determined spectroscopically (**Castro+14**)

$$\mathcal{L} := T_{eff}^4 / g$$

*N.B.: This is the so-called spectroscopic luminosity (a proxy of the quantity L/M)*

# *The upper HRD: the realm of massive stars*

Massive stars spent most of their time* as: **OB stars**

## Main physical properties

Massive ($M > 8\ M_\odot$)

Hot ($T_{eff} > 10$ kK, $T_{eff,\ ZAMS} > 20$ kK)

Large ($R = 5 - 80\ R_\odot$)

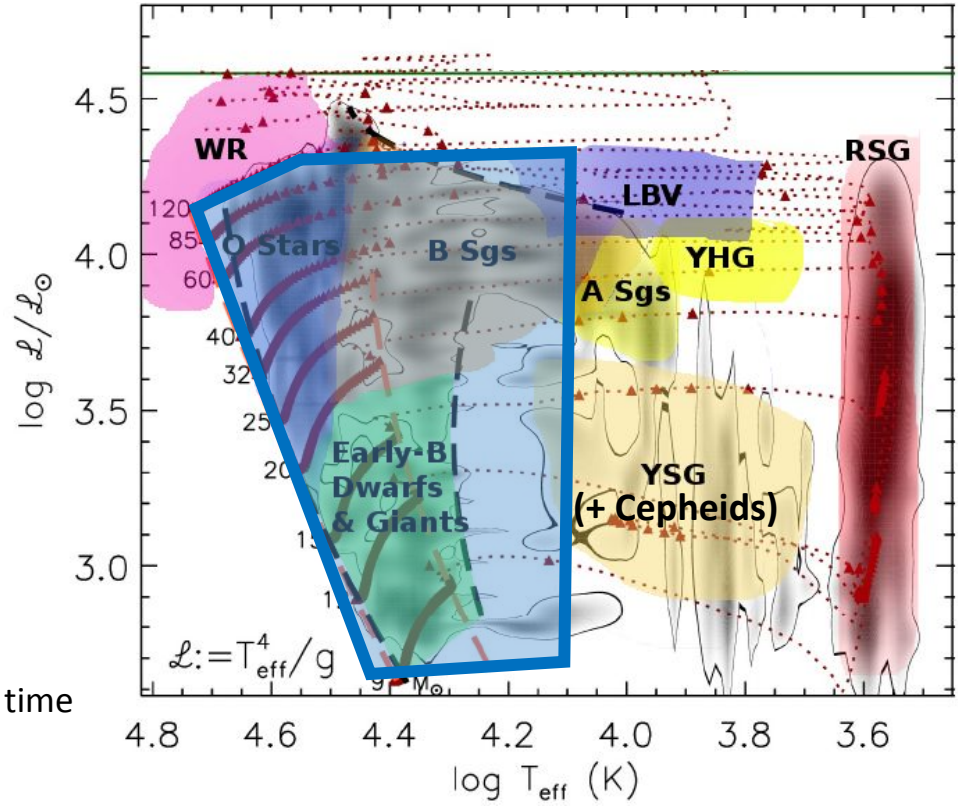
Luminous ($L = 10^3 - 10^6\ L_\odot$)

Windy ( $M_{dot} = 10^{-9} - 10^{-5}\ M_\odot$/yr)

Strong ionizing radiation ($T_{eff} > 30$ kK, O stars)

Young (a few Myr)

Broad range of spin rates (up to 450 km/s)




* Roughly speaking massive stars spend 90% of their time in the Main Sequence (i.e. burning H in their cores)

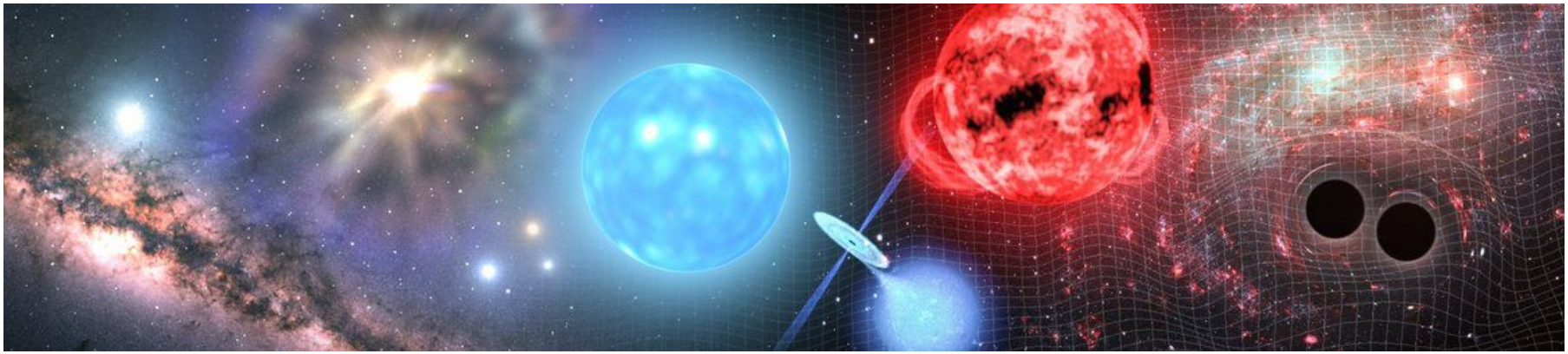
## In the Milky Way …

They are mainly found in or close to (young) star forming regions across the Galactic disk.

- All O-type stars
- Early-B (B0-B3) dwarfs and giants (V/IV/III)
- All B-type supergiants (I/II)

# *Structure of the talk*

- OB stars in a nutshell
- How massive stars evolve
- The IACOB project
- What can SII bring to massive-star research?

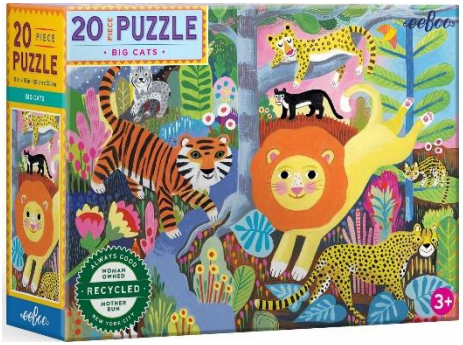


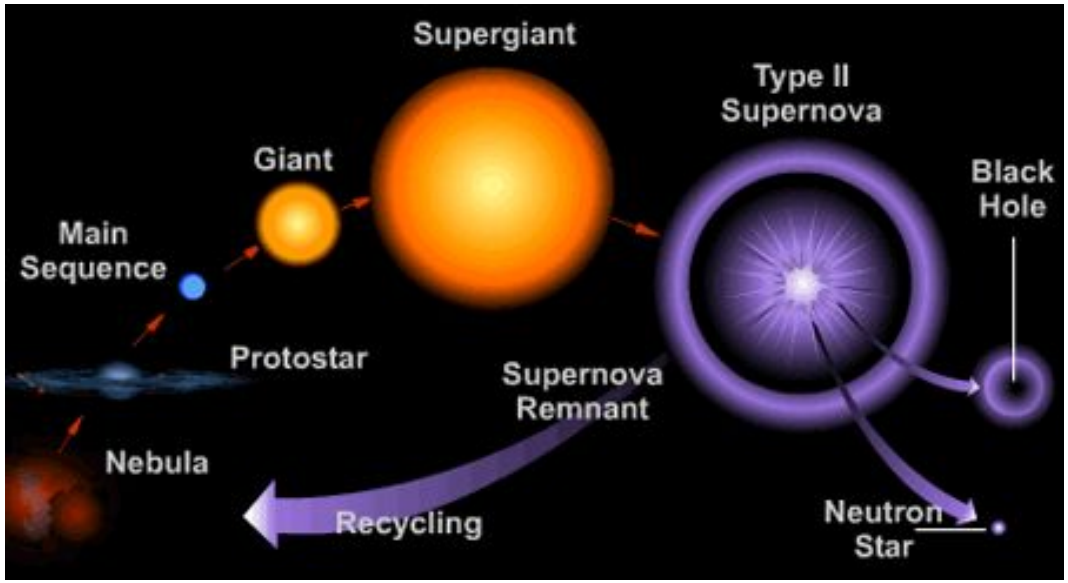
# *Solving the puzzle of high-mass star evolution (general public version)*

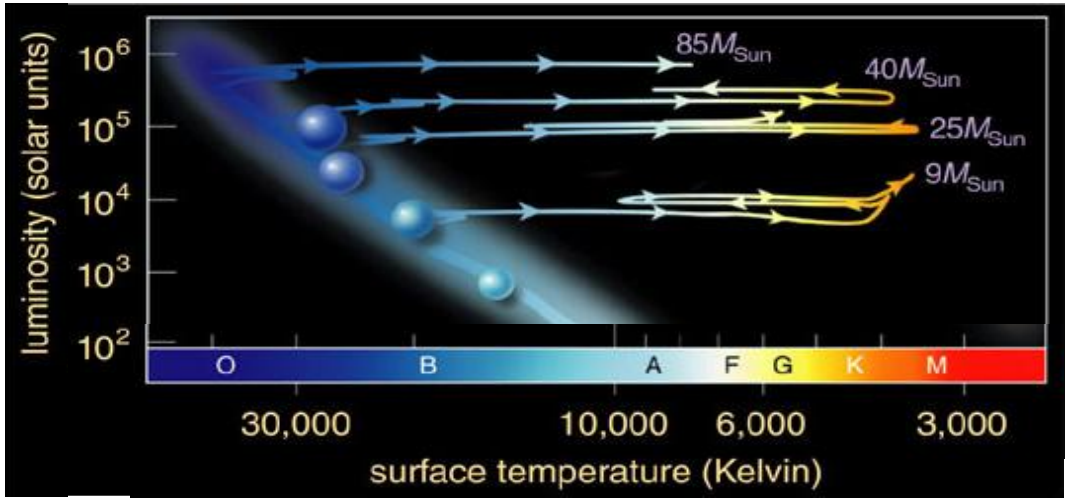


**Initial mass** dominates

- evolution,
- and final fate of stars




## Massive stars ($M_{ini} \gtrsim 8\ M_{\odot}$)

Stars massive enough to end their lives as a CCSN, leaving behind a neutron star or black hole as their stellar remnants

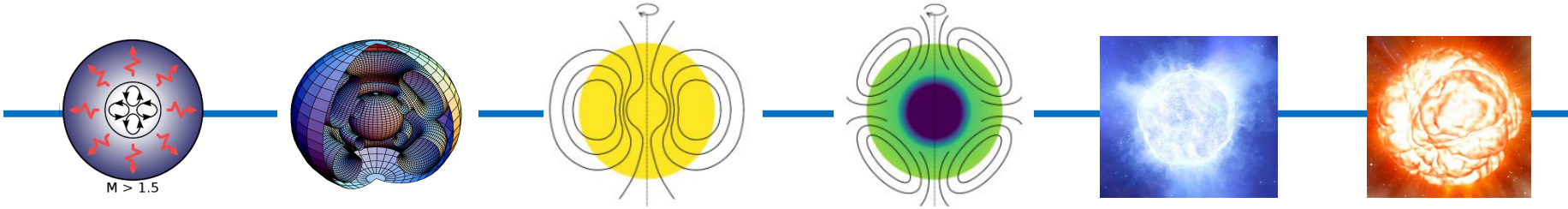
# *Solving the puzzle of high-mass star evolution (MSc student version)*

**Initial mass** dominates

- the internal structure,
- evolution,
- and final fate of stars

But be also aware of:

- ✔ Core/shell-burning events
- ✔ Convective/radiative regions
- ✔ Time-scales of evolution
- ✔ Core overshooting
- ✔ **Stellar rotation**
- ✔ **Internal transport**
- ✔ Magnetic fields
- ✔ **Stellar winds *(radiation/dust)***







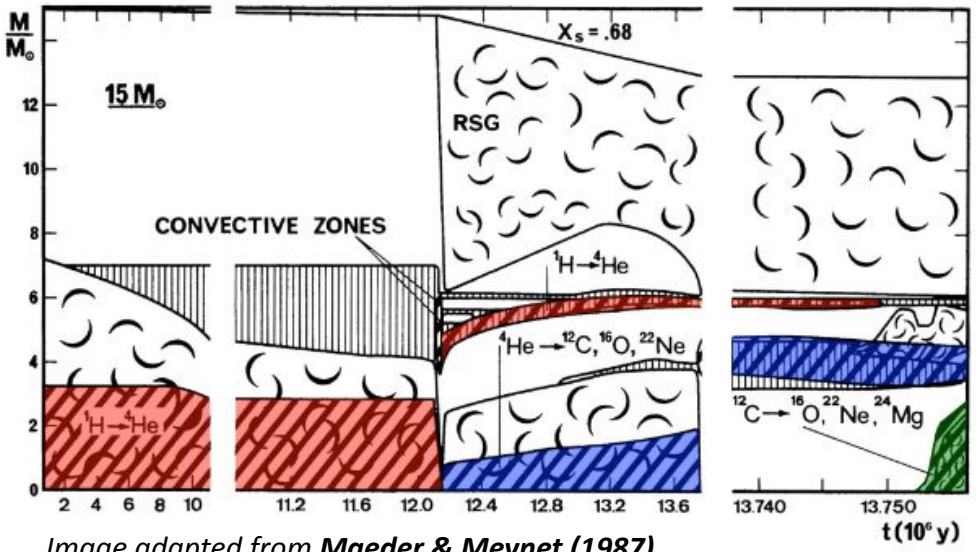



*Image adapted from* ***Maeder & Meynet (1987)***

# *Solving the puzzle of high-mass star evolution (PhD student version)*

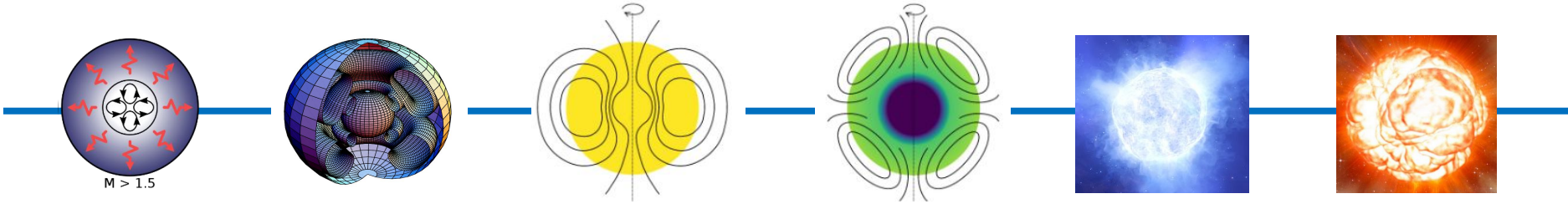


**Initial mass** dominates

- the internal structure,
- evolution,
- and final fate of stars

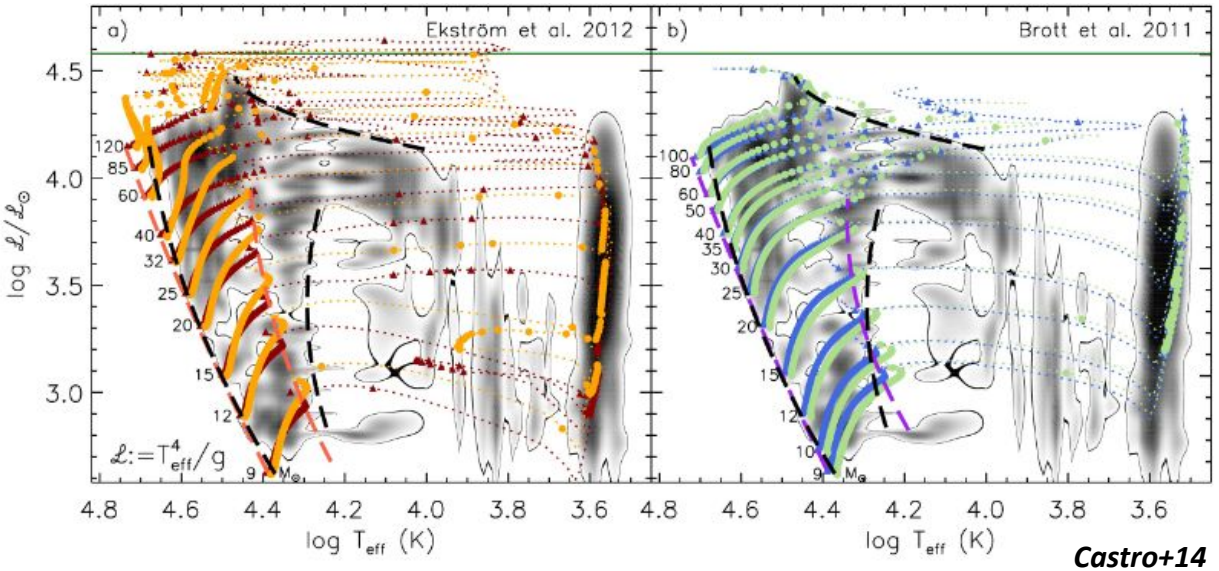
But be also aware of:

- ✔ Core/shell-burning events
- ✔ Convective/radiative regions
- ✔ Time-scales of evolution
- ✔ Core overshooting
- ✔ **Stellar rotation**
- ✔ **Internal transport**
- ✔ Magnetic fields
- ✔ **Stellar winds *(radiation/dust)***










*Castro+14*

# *Solving the puzzle of high-mass star evolution (PhD student version)*

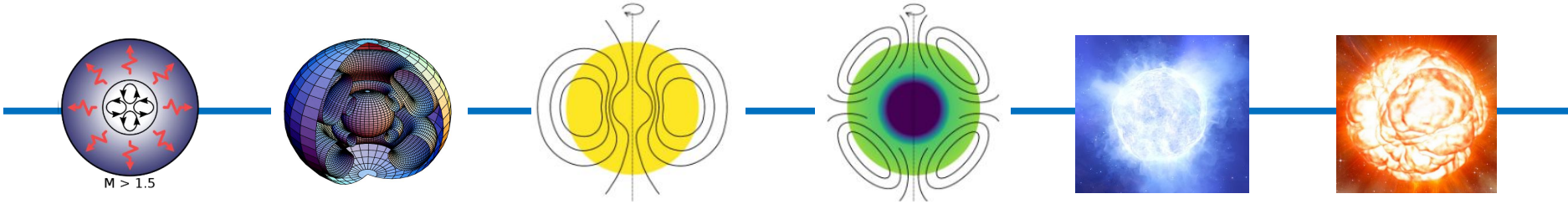


**Initial mass** dominates

- the internal structure,
- evolution,
- and final fate of stars

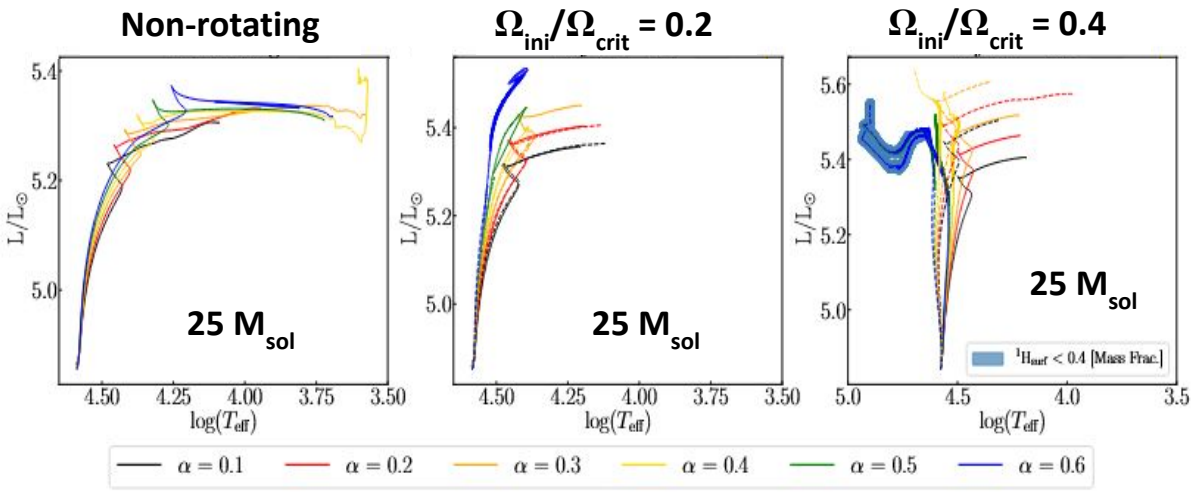
But be also aware of:

- ✔ Core/shell-burning events
- ✔ Convective/radiative regions
- ✔ Time-scales of evolution
- ✔ Core overshooting
- ✔ **Stellar rotation**
- ✔ **Internal transport**
- ✔ Magnetic fields
- ✔ **Stellar winds *(radiation/dust)***










***Martinet+21***

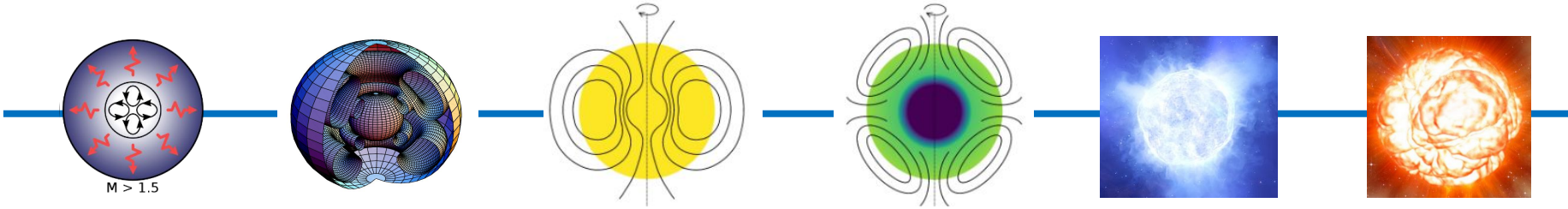
# *Solving the puzzle of high-mass star evolution (PhD student version)*

**Initial mass** dominates

- the internal structure,
- evolution,
- and final fate of stars

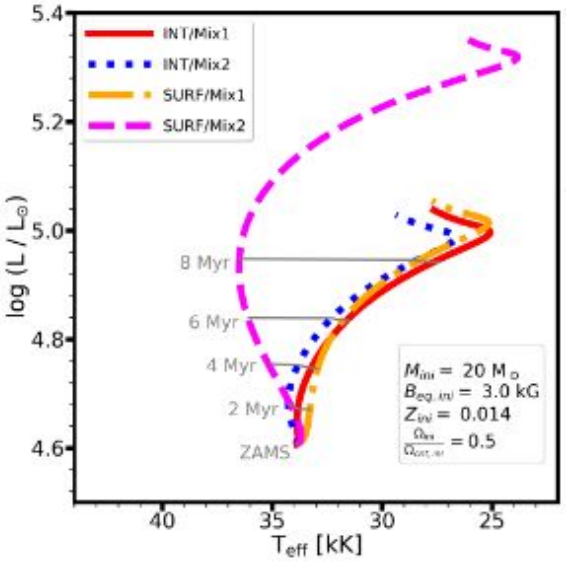
But be also aware of:

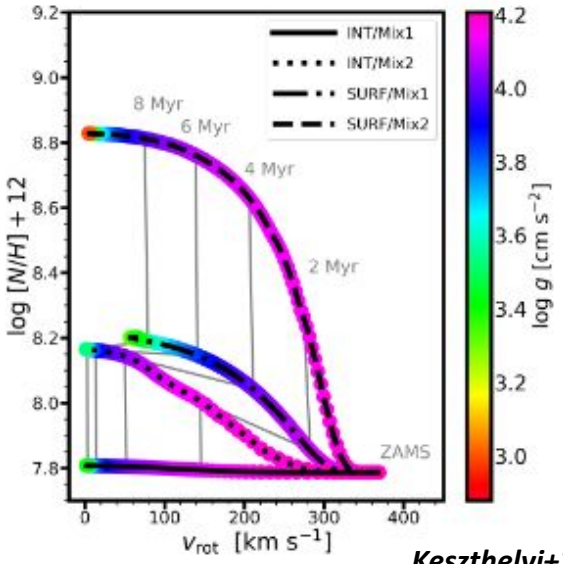
- ✔ Core/shell-burning events
- ✔ Convective/radiative regions
- ✔ Time-scales of evolution
- ✔ Core overshooting
- ✔ **Stellar rotation**
- ✔ **Internal transport**
- ✔ Magnetic fields
- ✔ **Stellar winds *(radiation/dust)***









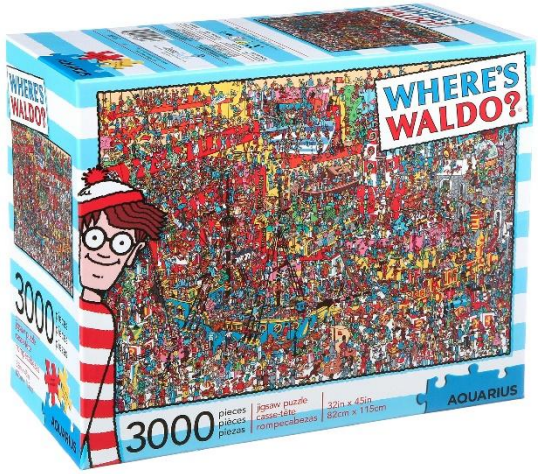

***Keszthelyi+22***

# Solving the puzzle of high-mass star evolution *(advanced version)*

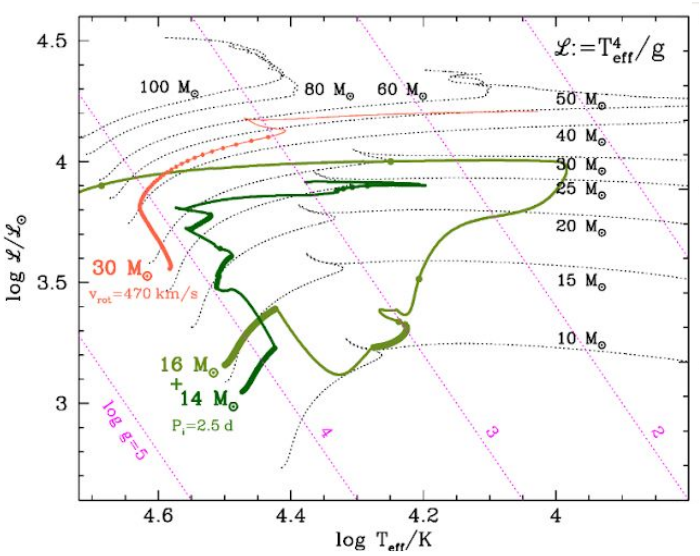


~~Initial mass dominates~~
- ~~the internal structure,~~
- ~~evolution,~~
- ~~and final fate of stars~~

**Only if born as single**




*Langer & Kudritzki (2014)*



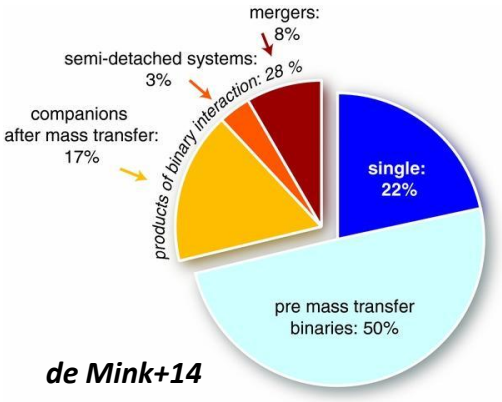

But be also aware of:

- ✔ Core/shell-burning events
- ✔ Convective/radiative regions
- ✔ Time-scales of evolution
- ✔ Core overshooting
- ✔ Internal transport
- ✔ Magnetic fields

- ✔ **Stellar rotation**
- ✔ **Stellar winds** *(radiation/dust)*

## ✔ Binary interaction !!!

***(Tides, mass-transfer, mergers)***

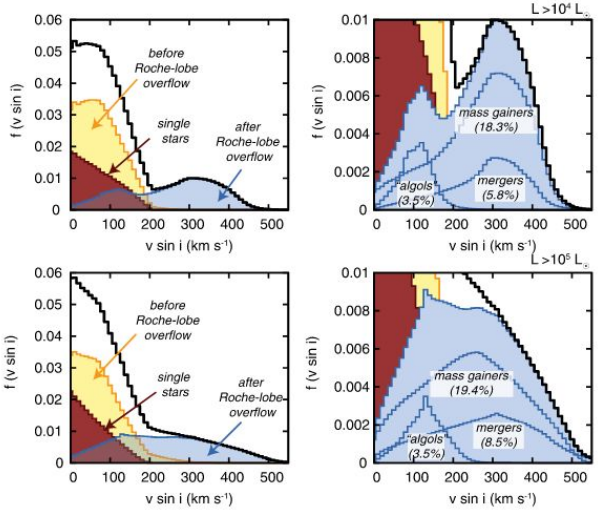



***de Mink+14***

More than **70%** of all massive stars is predicted to **exchange mass** with a companion along their life (***Sana+12***).

In addition, the incidence of stellar **mergers** during the Main Sequence is predicted to be **~8%** (***de Mink+14***)

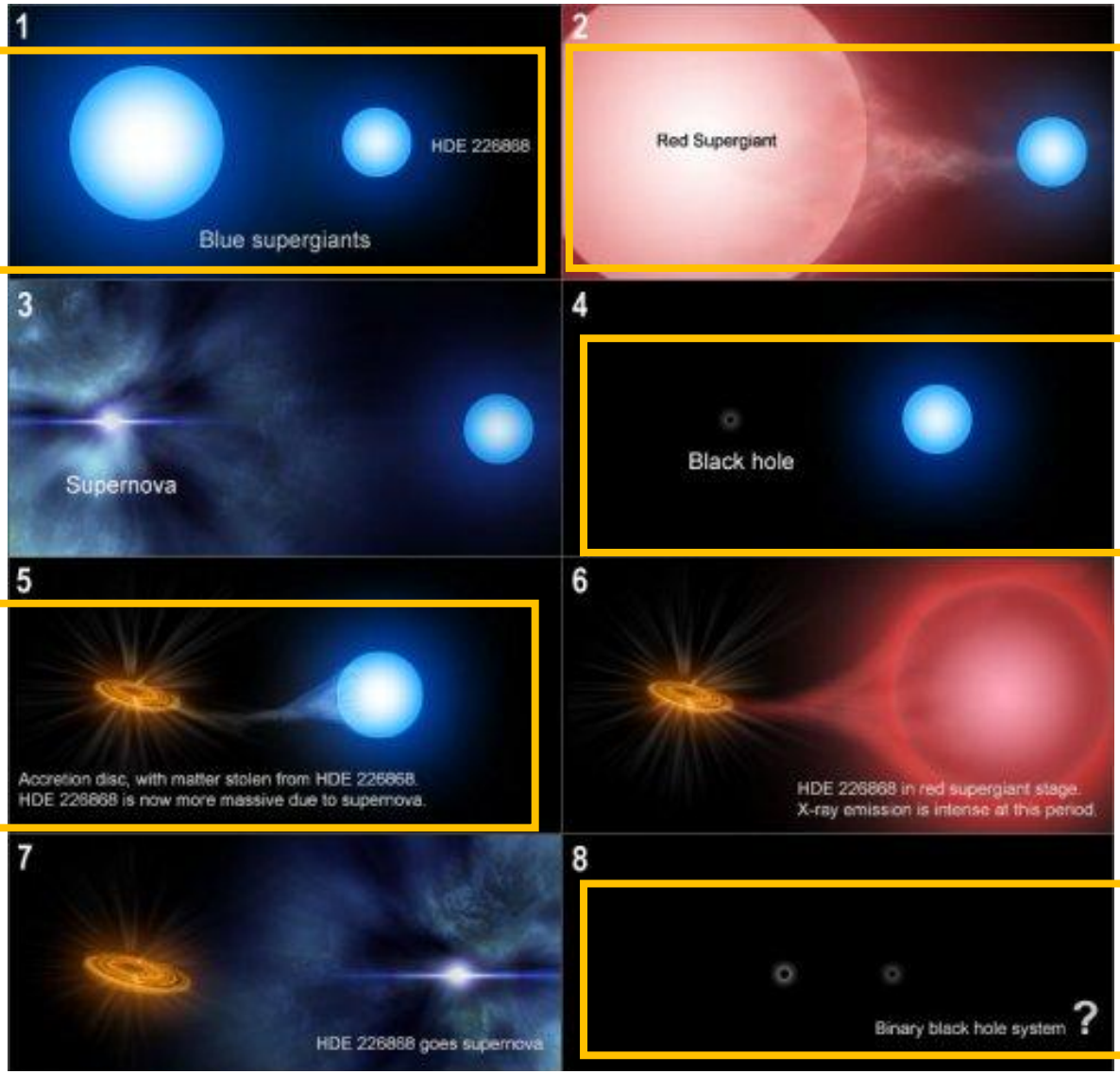
In particular **~30%** of them will interact during the **Main Sequence** (***de Mink+14***)




***de Mink+13***

# *Binary evolution makes the interpretation of observables more difficult (and funny!)*

Detected as a SB2 system




Dominant RSG component

Detected as a SB1 system

Detected as a HMXR binary (SB1+disc)



Detected as GW event (if they merge)

© Fahad Sulehria (2005). http://www.novacelestia.com

# *Binary evolution makes the interpretation of observables more difficult (and funny!)*




Disrupted binary after SN explosion

Detected as a (fast rotating?) runaway



Detected as a SB2 system

Detected as a (fast rotating?) SB1 system



© Navid Marvi, courtesy of the Carnegie Institution for Science.

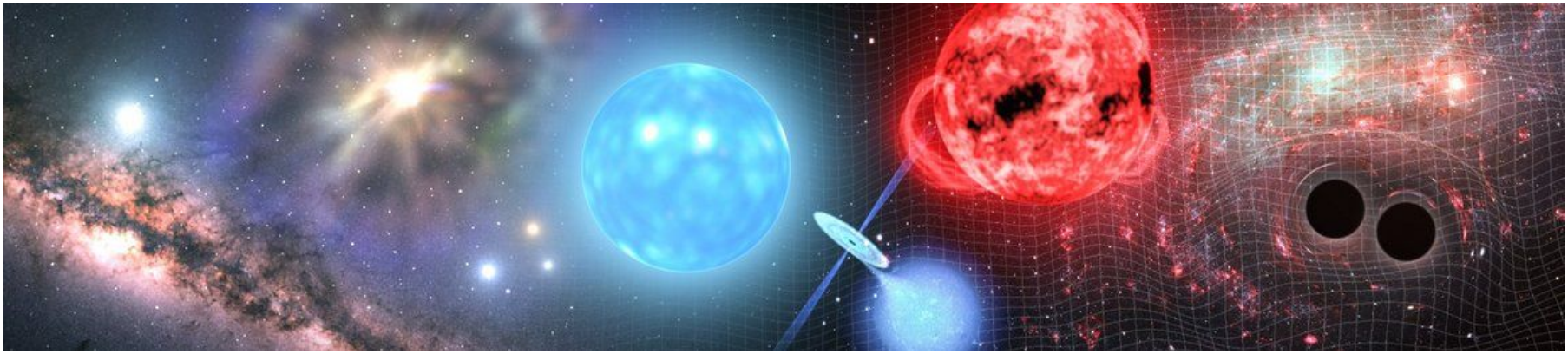
# How massive stars evolve



Take-away messages …

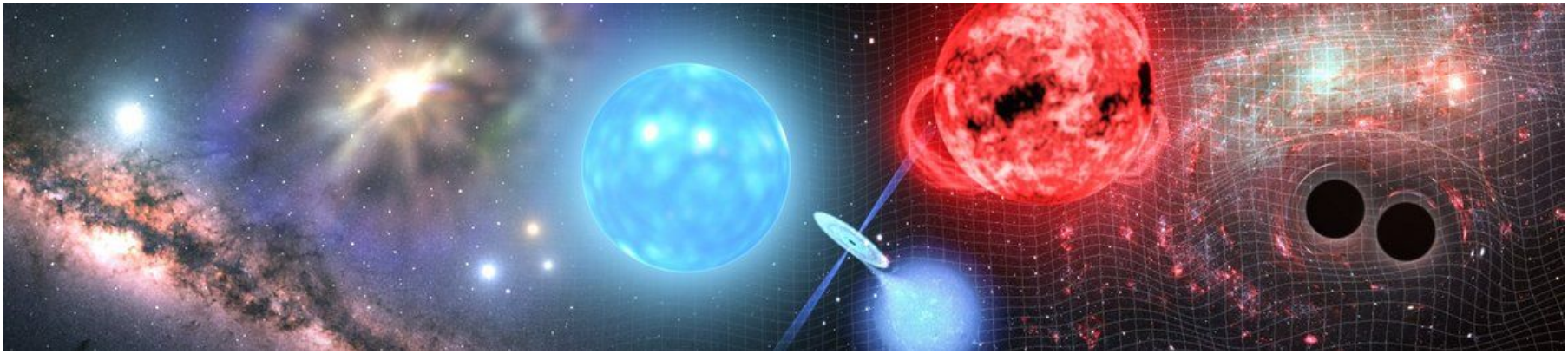
Massive star evolution is importantly affected not only by mass, but also by rotation, stellar winds, the efficiency of internal transport mechanisms and binary interaction

Beware of interpreting the properties of apparently single OB-type stars as if they were born-alone



# *Structure of the talk*

- OB stars in a nutshell
- How massive stars evolve
- The IACOB project
- What can SII bring to massive-star research?



# *The IACOB project: an ambitious long term observational project*

P.I. S. Simón-Díaz

IACOB

EXCELENCIA SEVERO OCHOA

## *Main scientific goal*

Provide an **(unprecedented) holistic empirical overview** of the main physical properties of Galactic massive O- and B-type stars which can be used as reliable and long-lasting **anchor point** for our theories of stellar atmospheres, winds, interiors and evolution of massive stars.

## *Immediate objective*

Comprehensive empirical characterization of a **statistically meaningful sample**[(1)] of Galactic massive stars covering the full OB star domain.

[(1)] Ideally, **several thousand**

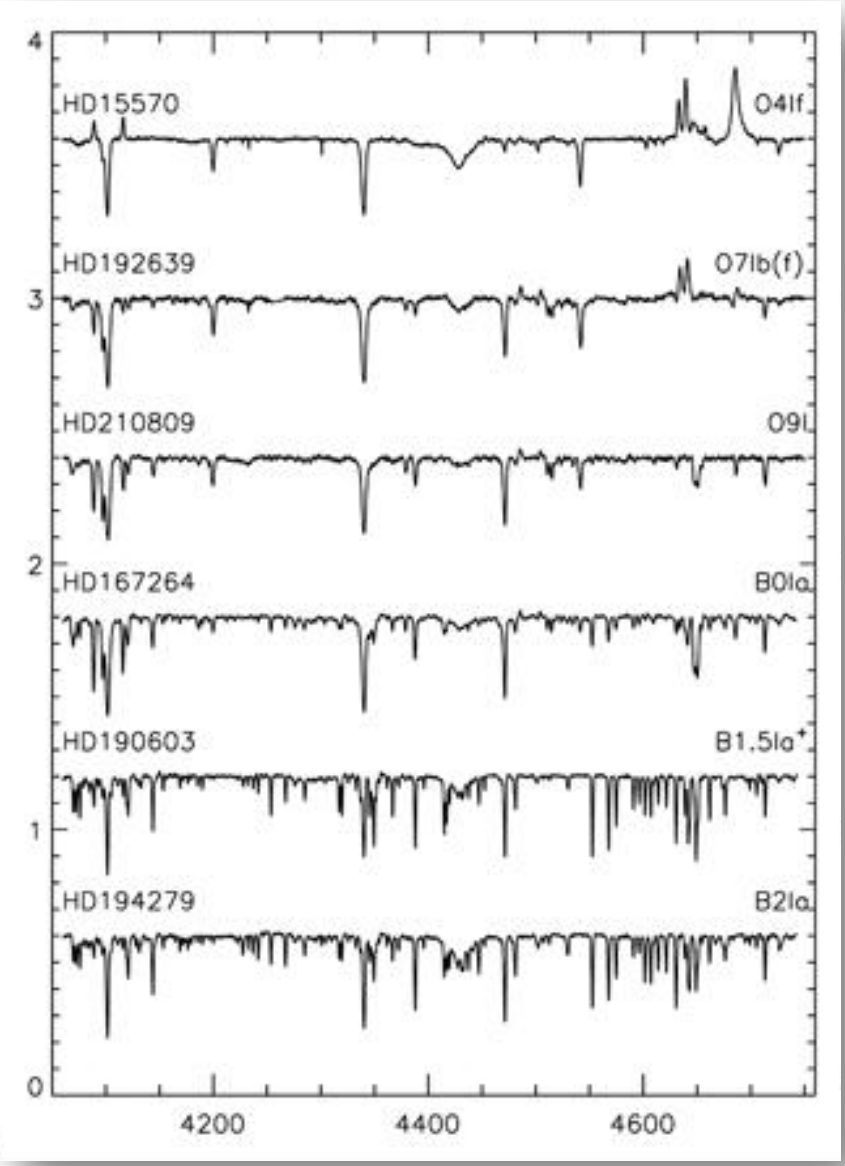
## *More specific objectives*

- Compilation of the required **observations**
- Determination of the whole set of **stellar+wind parameters**
- Determination of a set of **surface abundances**
- Identification and empirical study of **binary/multiple systems**
- Identification and characterization of **stellar variability**
- Foster progress in the fields of **quantitative spectroscopy** and massive star **evolution**.

# *Observations, an important pillar of the IACOB project*

- ***High-resolution (R>25000)***
- ***Multi-epoch (3+ epochs)***
- ***Optical (3800 - 7000 A)***
  *spectroscopy with*
- ***1-3m telescopes***
  *was specifically chosen*

⇒ ***B < 9 mag***




## Ground-based optical spectroscopy

Single snapshot, multi-epoch & time-series

- Radial velocities
- Line-broadening parameters
- Spectroscopic parameters
- Surface abundances
- Spectroscopic binaries
- Spectroscopic variability

# *Observations, an important pillar of the IACOB project*

< 2008 – 2024+



HERMES@Mercator-1.2m
380-900 nm
R=85000



FIES@NOT-2.56m
375-715 nm
R=46000/25000



Hetzsprung-SONG-1m
440-690 nm
R=77000



STELLA-1.2m
390-870 nm
R=55000



FEROS@MPG/ESO-2.2m
353-922 nm
R=48000

\+

1978 - 1996

## UV spectroscopy

- Stellar wind parameters



\+

Launched in 2013

## Parallaxes & proper motions

- Fundamental parameters
- Cluster membership
- Runaways



## Ground-based optical spectroscopy

Single snapshot, multi-epoch & time-series

- Radial velocities
- Line-broadening parameters
- Spectroscopic parameters
- Surface abundances
- Spectroscopic binaries
- Spectroscopic variability



\+

Launched in 2018

## Time resolved photometry

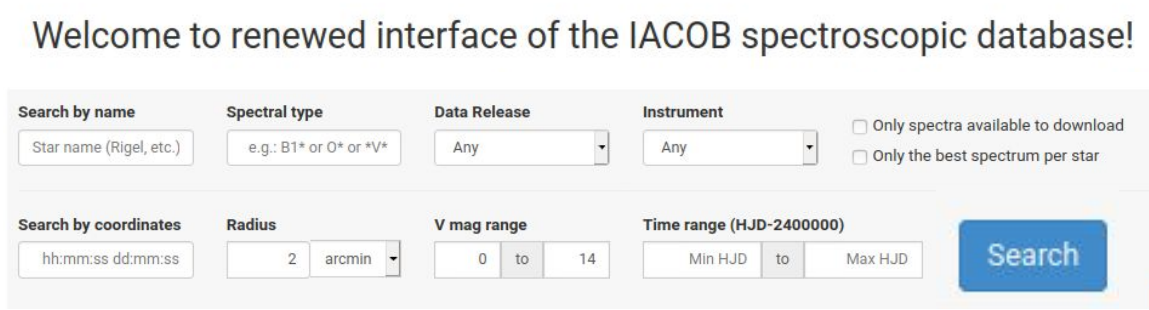
- Stellar variability
- Eclipsing binaries
- Ellipsoidal variables



# Spectroscopic observations in the IACOB project: present status

***Simón-Díaz+20***

IACOB Spectroscopic database



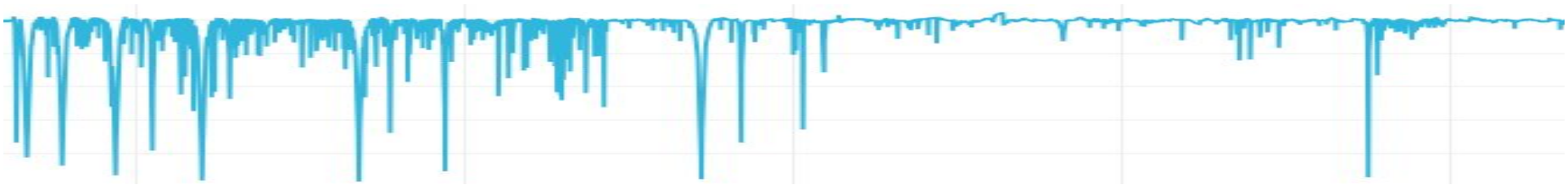

http://research.iac.es/proyecto/iacob/iacobcat/

## *The IACOB spectroscopic database in a nutshell*

*SpT coverage:* ***O2 – B9*** [(1)] *LC coverage:* ***V, IV, III, II, Ib, Iab, Ia, Ia$^+$*** *# stars:* ***≈ 2800***

[(1)] *Plus a few tens of* ***A0-A9 Sgs***  *$\lambda$ coverage:* ***≈ 3800 – 9000 A***  *Res. Power (R):* ***25k – 85k***

*# spectra:* *FIES, HERMES* ***≈ 10000+***  *STELLA* ***≈ 1500+***  *FEROS* ***≈ 5000+***  *SONG* ***≈ 23000+***

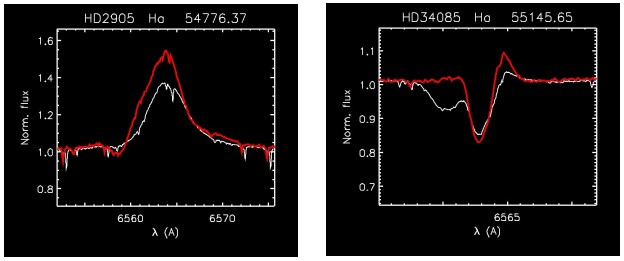


# *The interest/importance of adding multi-epoch information*

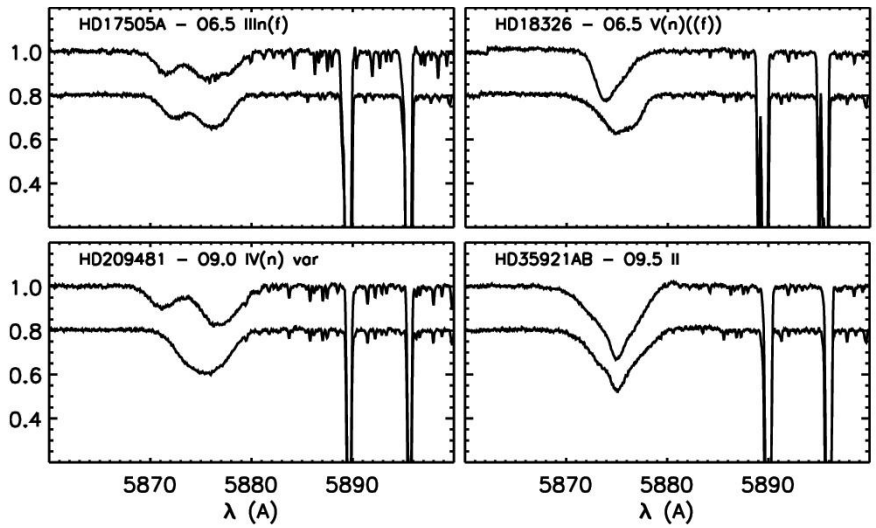
**Time-domain** spectroscopy is a MUST for the identification and study of:

- **Spectroscopic binaries**
- **Stellar variability phenomena**

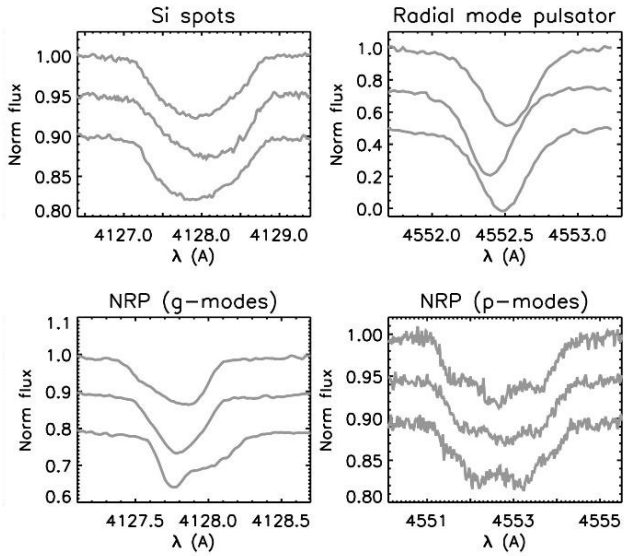
**Wind variability**



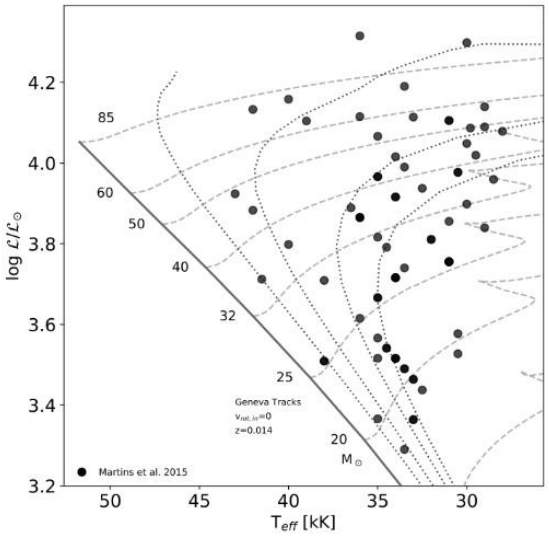

**Spectroscopic binaries and multiple systems (SBx, x=1,2,3 …)**




**Spots and stellar oscillations**



# The impact of increasing the statistics + multi-epoch (e.g. the O star domain)




Adapted from ***Martins+15***

**74** Galactic O-type **stars**

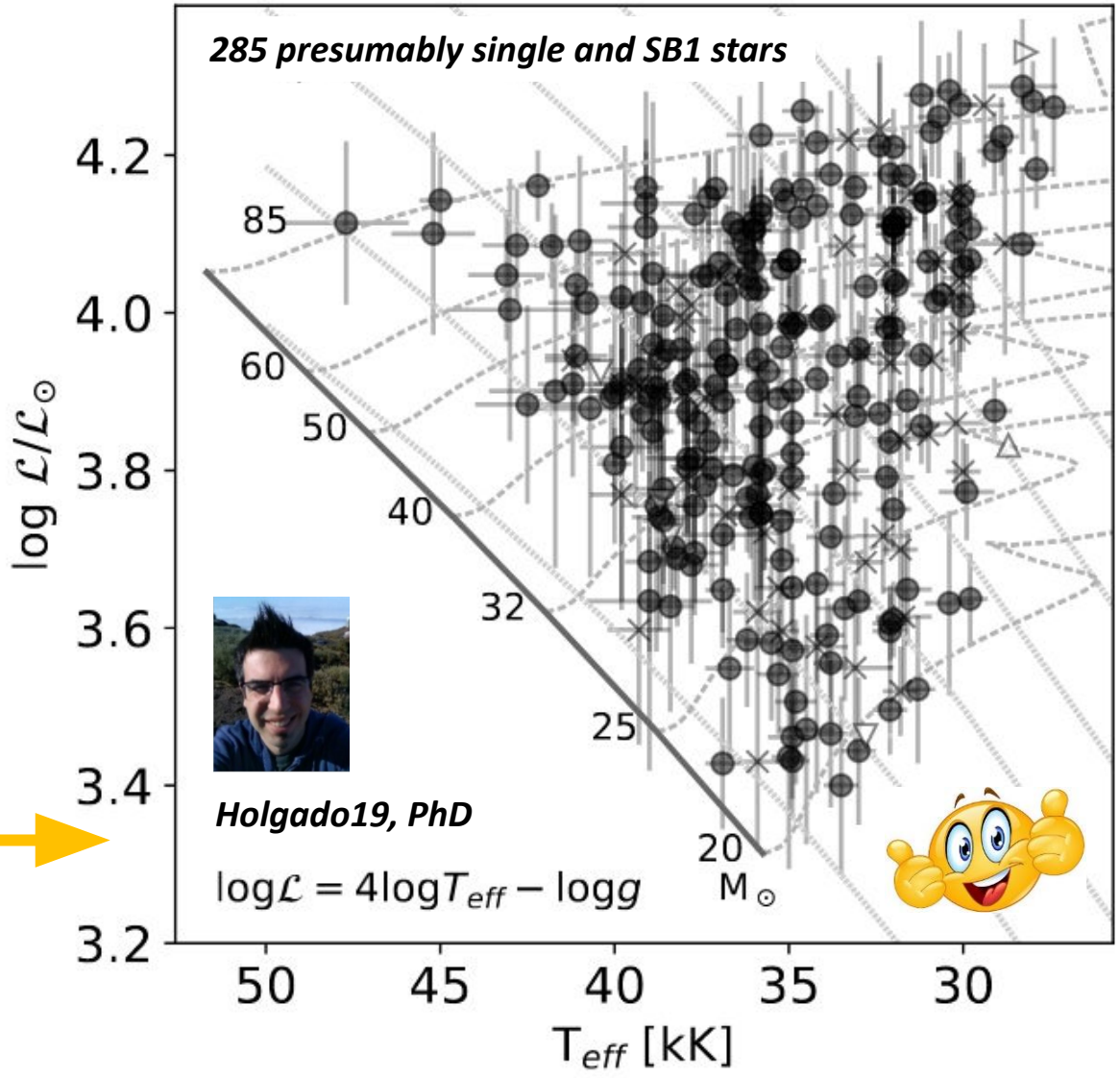
IACOB

**415** Galactic O-type **stars**
(70% of stars in GOSC)

*Presumably single: 59%*

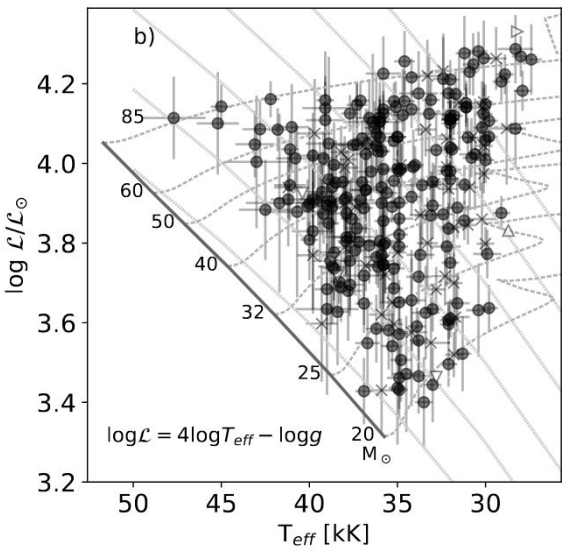
*SB1: 14%*

*SB2: 27%*



# The impact of increasing the statistics (and extending the parameter coverage)

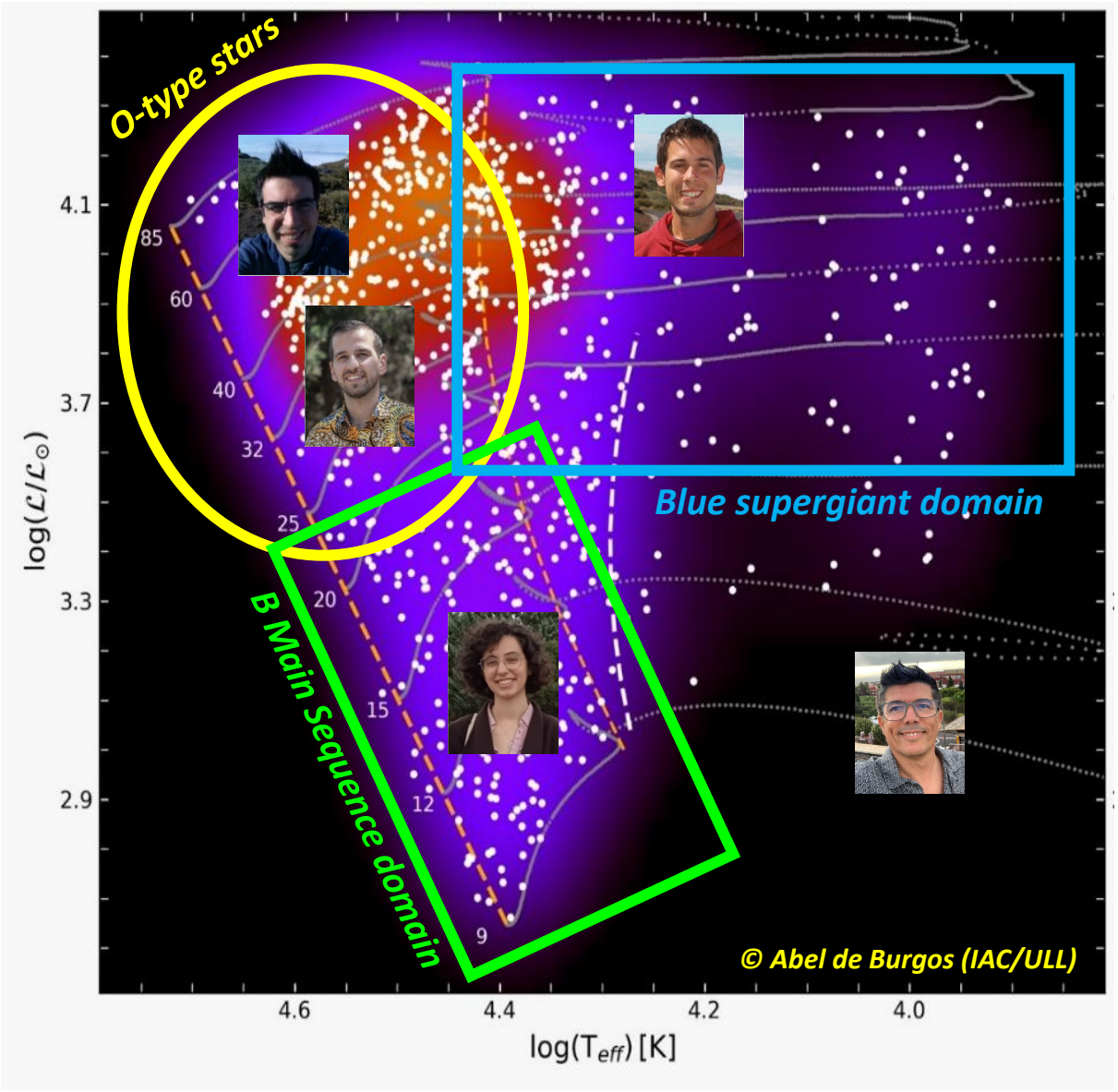
***Holgado+20***



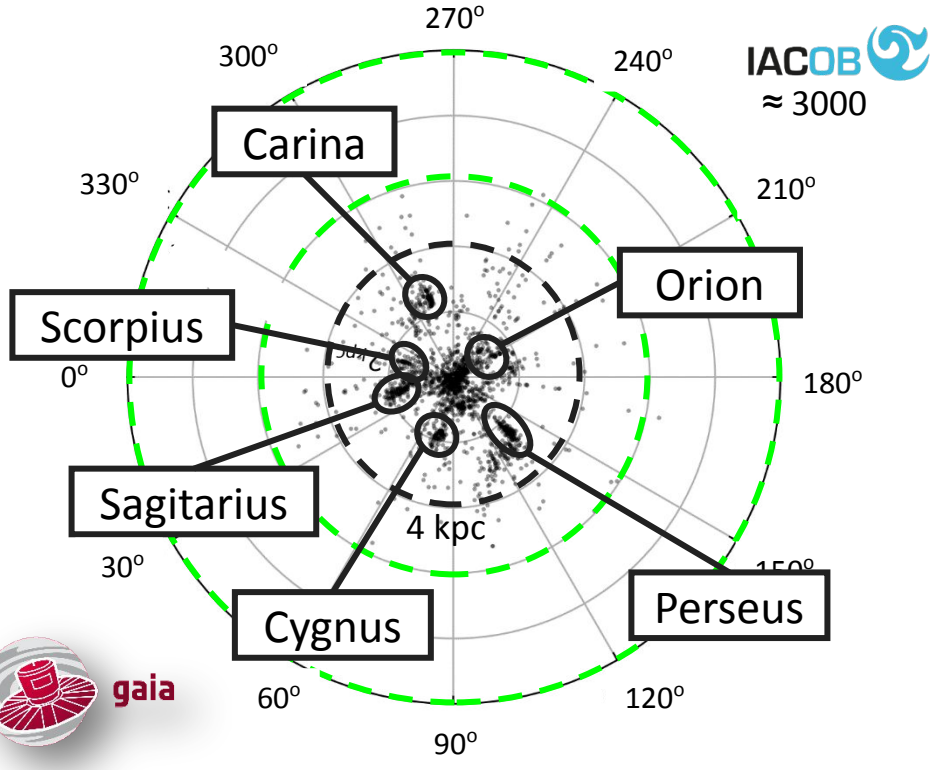

In the framework of

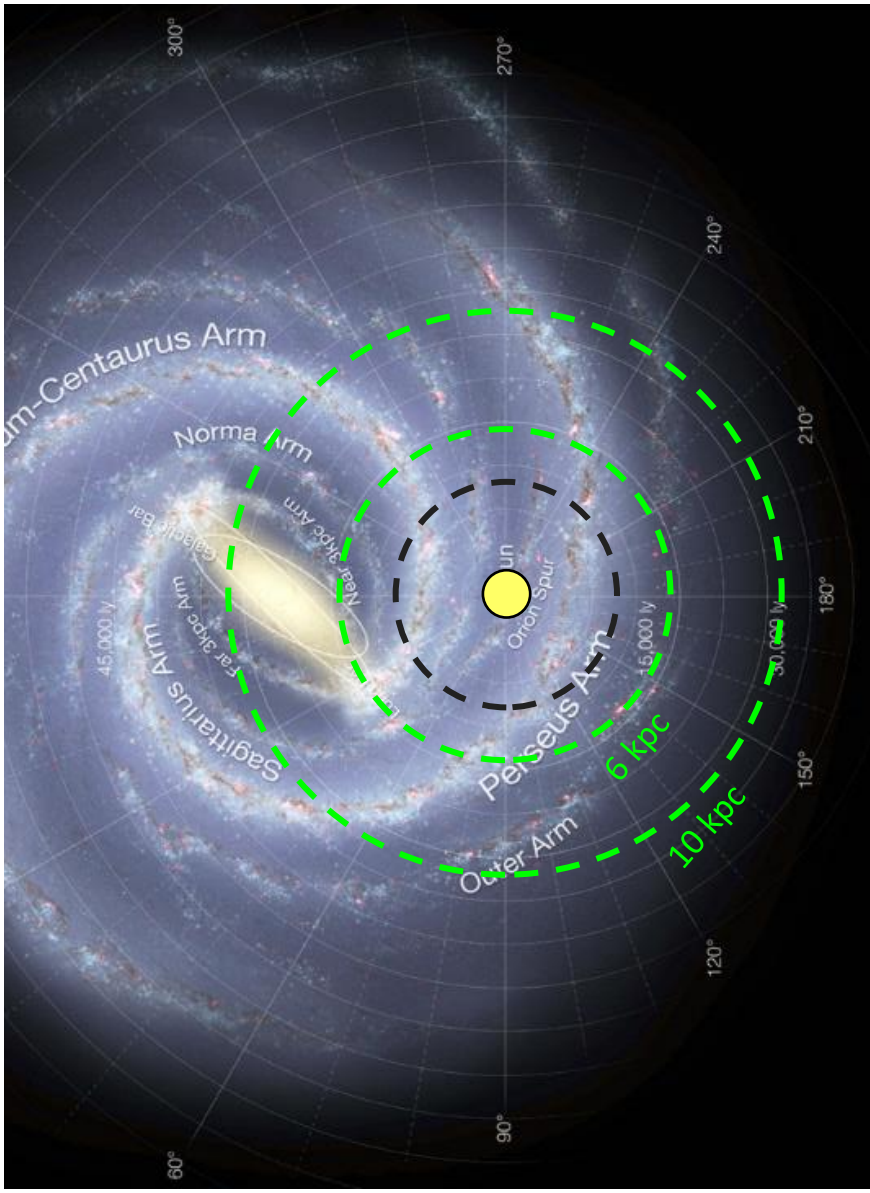
IACOB

we have obtained at least
1 high-resolution spectrum
for ≈3000 bright (B < 9 mag)
Galactic OB stars with
initial masses above ~ 8 $M_{sol}$



# *The impact of increasing the statistics (and extending the space coverage in the MW)*




We have reached a high level of completeness in terms of the known Galactic massive OB star population up to a distance of 4 kpc (excluding regions with a high extinction, e.g. Cygnus)

# *Papers published to date in the framework of the IACOB project*

I. Revisiting vsini in OB stars + macroturbulent broadening ***(Simón-Díaz+14)***
II. Scatter in SpT-$T_{eff}$ calibrations ***(Simón-Díaz+14)***
III. Origin of macroturbulent broadening ***(Simón-Díaz+17)***
IV. Instability domains ***(Godart+17)***
V. SpT calibrations in O-type stars ***(Holgado+18)***
VI. Lack of ZAMS O stars ***(Holgado+20)***
VII. vsini in O-type stars ***(Holgado+22)***
VIII. Empirical signatures of binarity in fast rotating O-type stars ***(Britavskiy+23)***
IX. Empirical database of BSG ***(de Burgos+23)***
X. QSA of BSgs ***(de Burgos+24)***
XI. No wind bi-stability jump ***(de Burgos+24)***
XII. New grid of SpC B standards ***(Negueruela+24)***
XIII. He enrichment in O stars as tracer of BIPs ***(Martínez-Sebastián+25)***
XIV. Empirical TAMS ***(de Burgos+25)***
XV. Updated calibrations fundamental parameters in O stars ***(Holgado+25)***
XVI. Surface He enrichment as hints of BIPs ***(Simón-Díaz+26)***
XVII. N abundances in O stars ***(Martínez-Sebastián+26)***
XVIII. He enrichment in O-type SB1 stars ***(Martínez-Sebastián+26)***
XIX. Revisiting massive-star evolution with empirical TAMS constraints ***(Sciarini+26)***
XX. SpT calibrations in B-type stars ***(Casasbuenas+26, in prep.)***

CVIII. Hunting for SB in O stars and B Sgs ***(Simón-Díaz+24)***



# *Improving the stellar parameter vs. SpT / LC calibrations (O star case)*

128/131 O-type stars from the **GOSSS v2.0 grid of standards** for spectral classification (***Maíz Apellániz et al. 2015***)

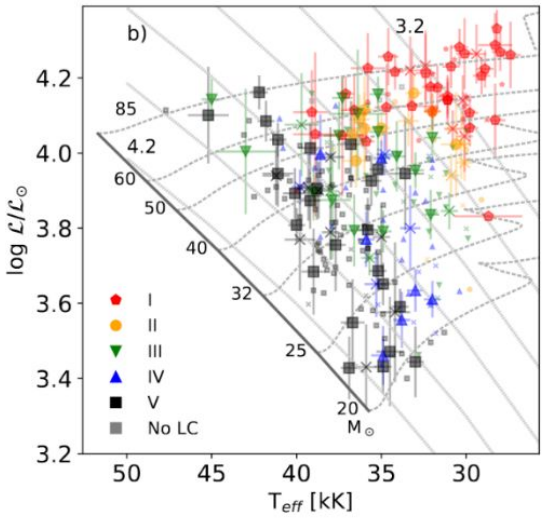


$T_{eff}$ | log*g*

**IACOB - V**

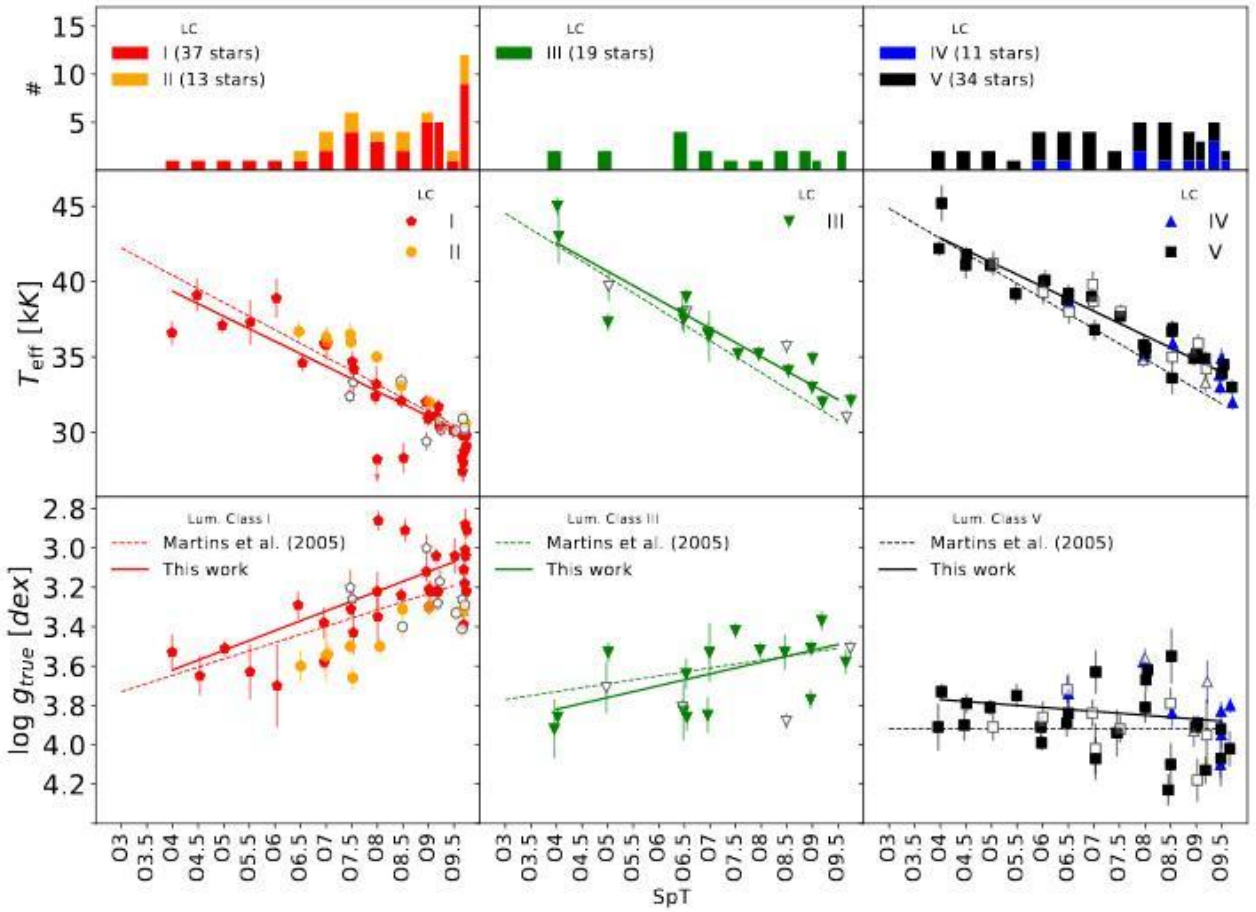
***Holgado+18***



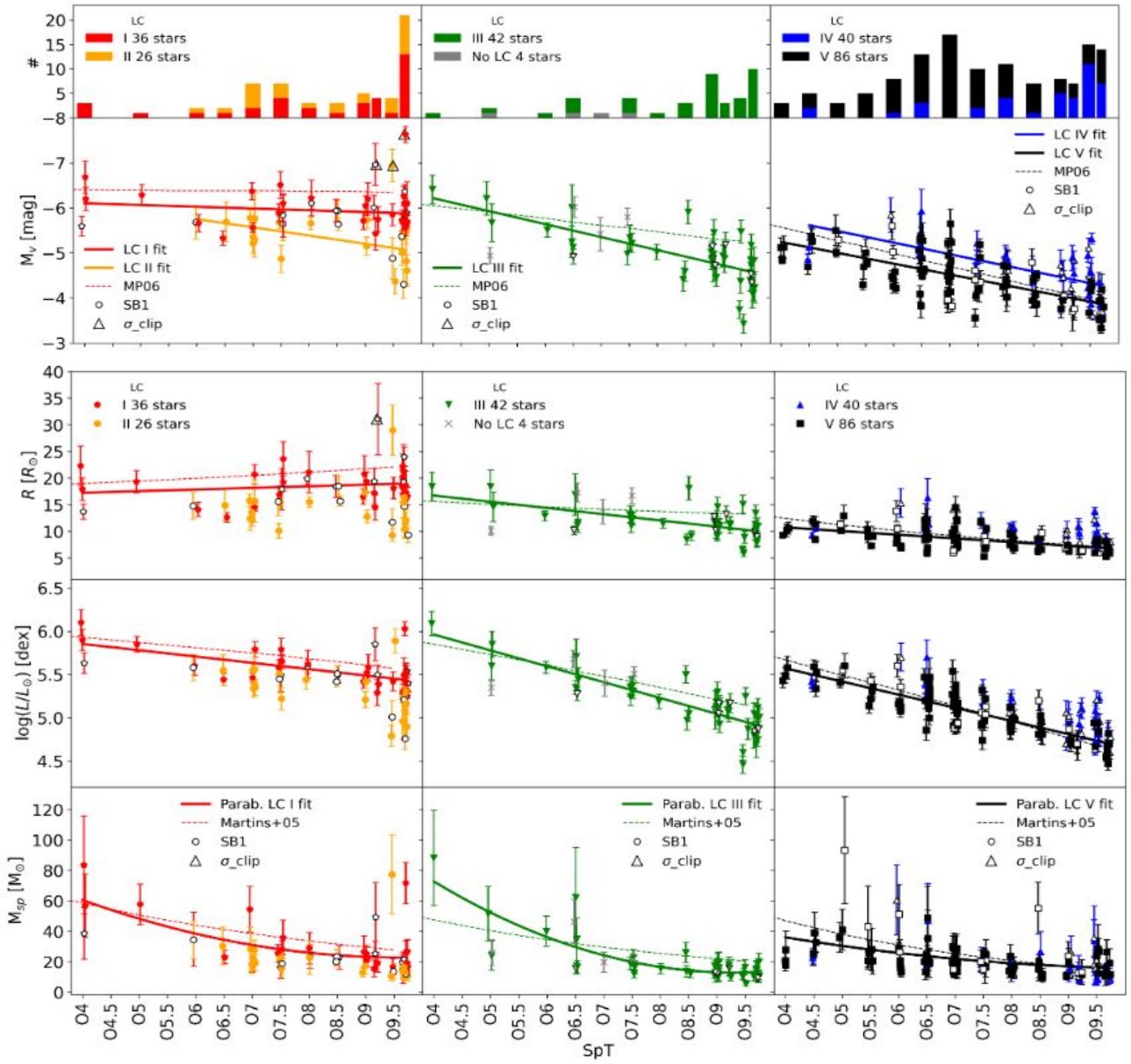



- Larger sample
- Standards + revised SpC
- Homogeneous analysis
- Identification of SB systems

N.B.: 1216 spectra (28 SB1 + 7 SB2)



# *Improving the stellar parameter vs. SpT / LC calibrations (O star case)*




**IACOB - XV**

***Holgado+25***

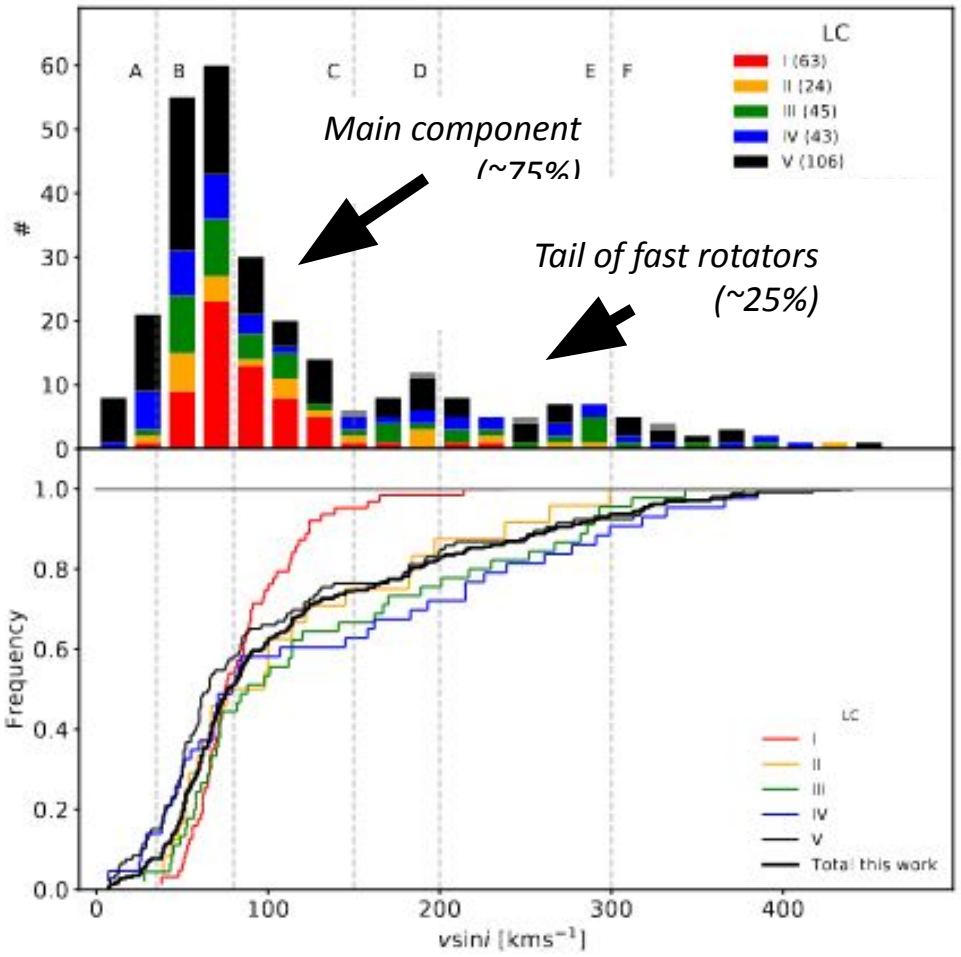


| | |
|---|---|
| $M_V$ | log$L$ |
| $R$ | $M_{sp}$ |




**234 O-type stars**
with good quality data
on Gaia paralaxes

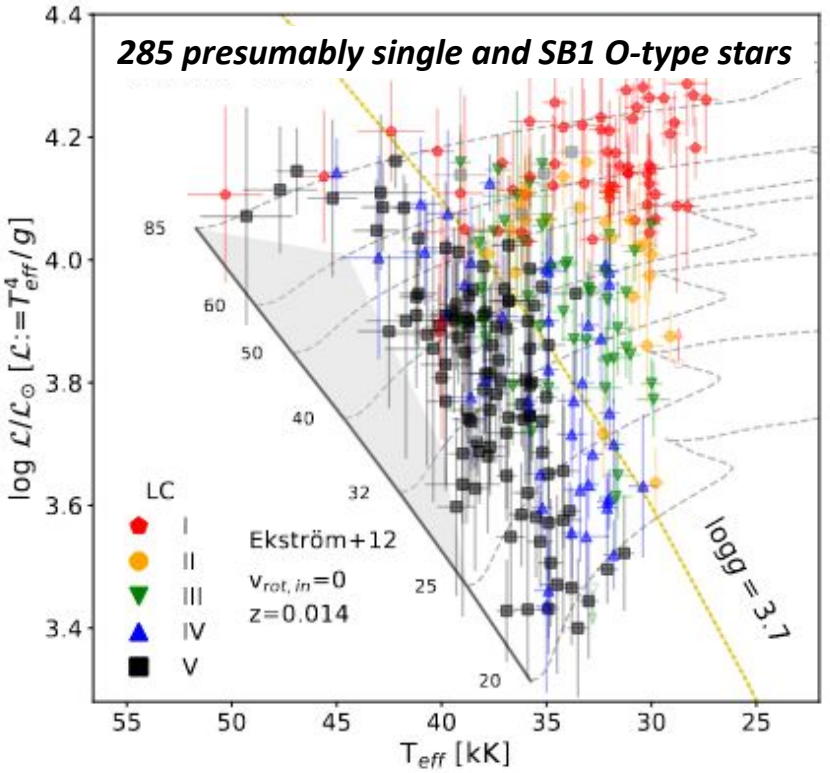
# Rotation in massive stars: initial conditions and evolution




**IACOB - VII**

***Holgado+22***






The general consensus *(since **Conti & Ebbets 1977**)* to explain this distribution was that
(1) massive stars are born as fast rotators and
(2) their surfaces are spun-down due to angular momentum loss by stellar winds.

# Rotation in massive stars: the impact of binaries

*(Tides, mass/angular momentum transfer, mergers)*

Because of **binary interaction**, ~20% of all massive main-sequence stars are expected to **spin up** to projected rotational velocities in excess of 200 km $s^{-1}$ (***de Mink+13***)

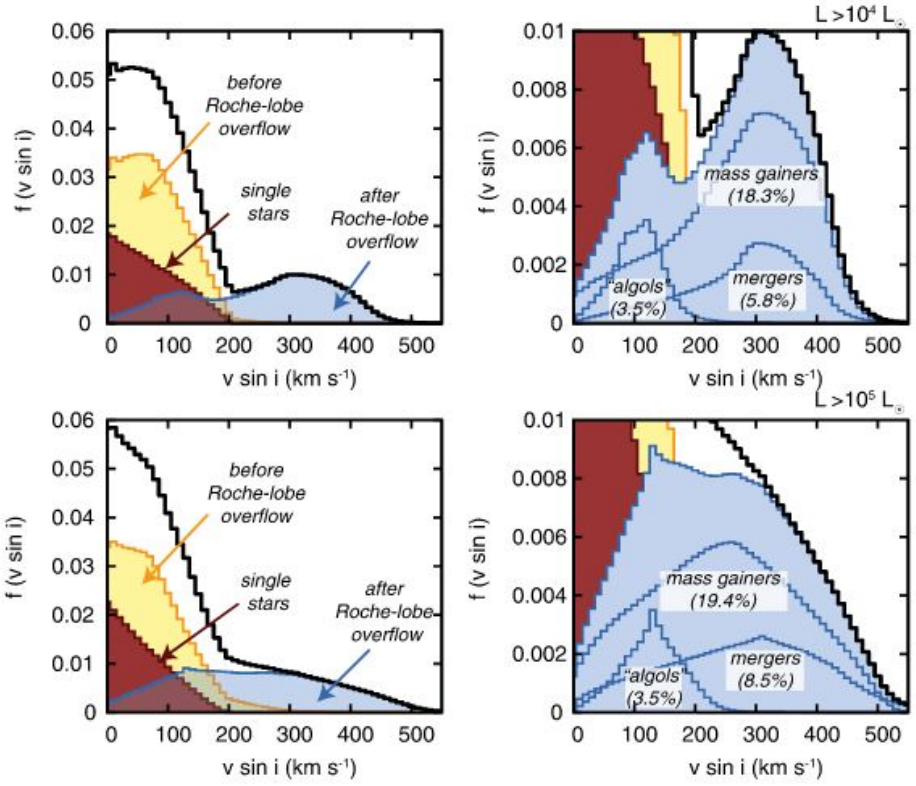
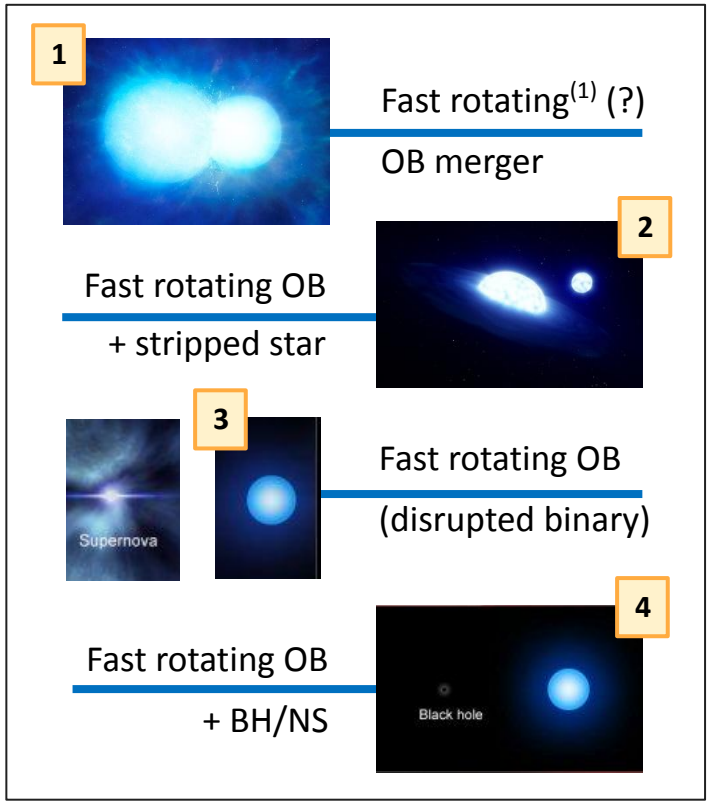
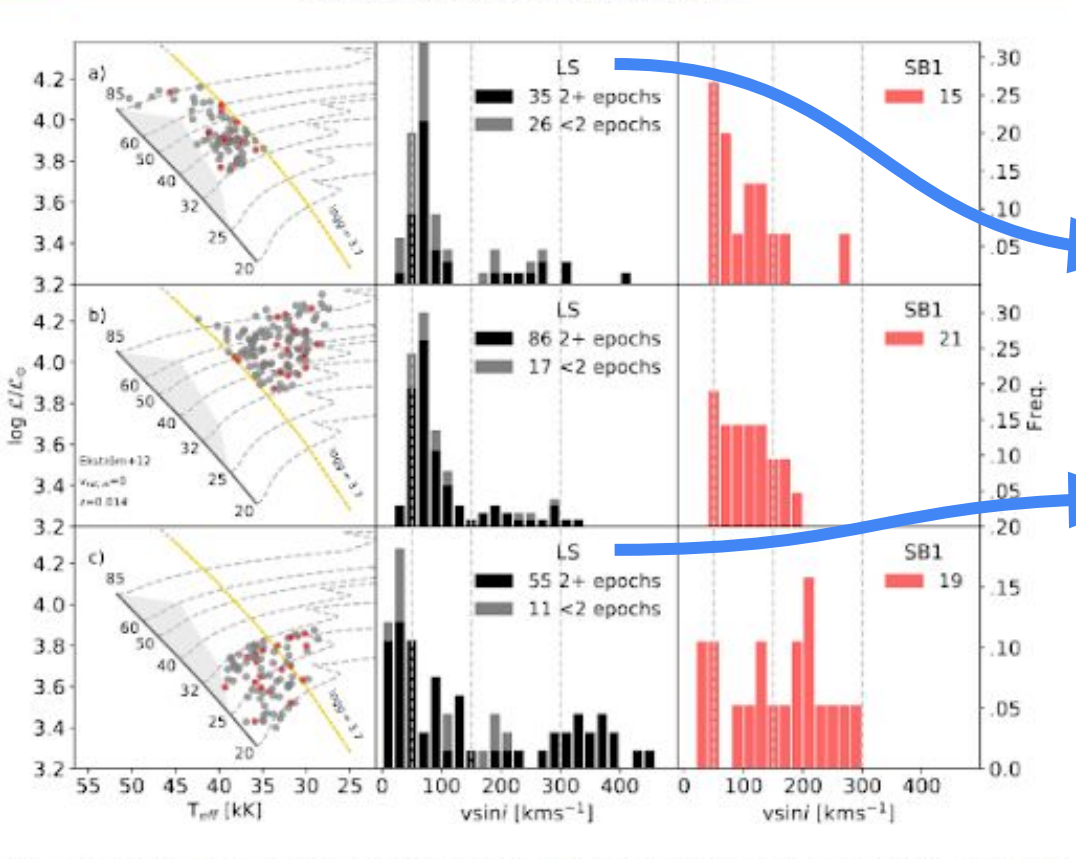



Image extracted from ***de Mink+13***



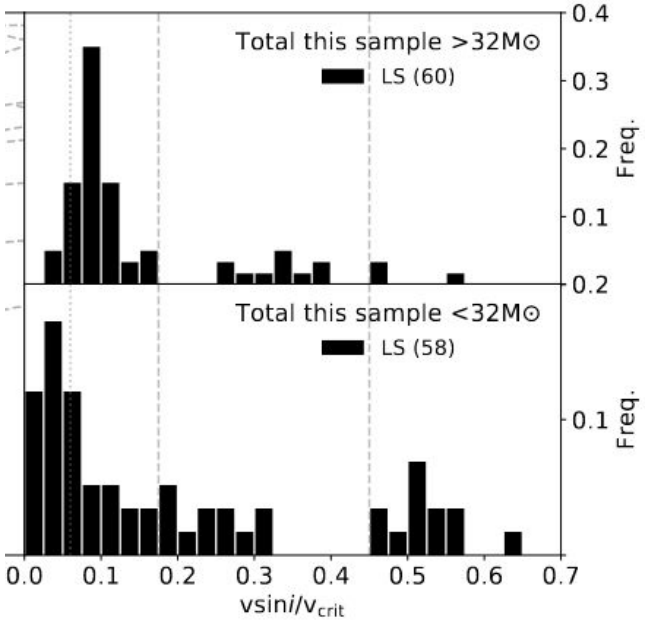

(1) See, however, Schneider+20

# Spin rates of massive stars: Born fast, but … not so fast




***285 (presumably single and SB1) O stars***

***Initial conditions???***




***Holgado+22***

- **No important surface braking effect** is detected during MS evolution (even for M > 30 $M_{\odot}$ , where stellar winds are important)
- **O stars are most likely born with less than 20% critical velocity**

  + tail of fast rotators populated by mass gainers (as proposed by *de Mink+13, +14*).

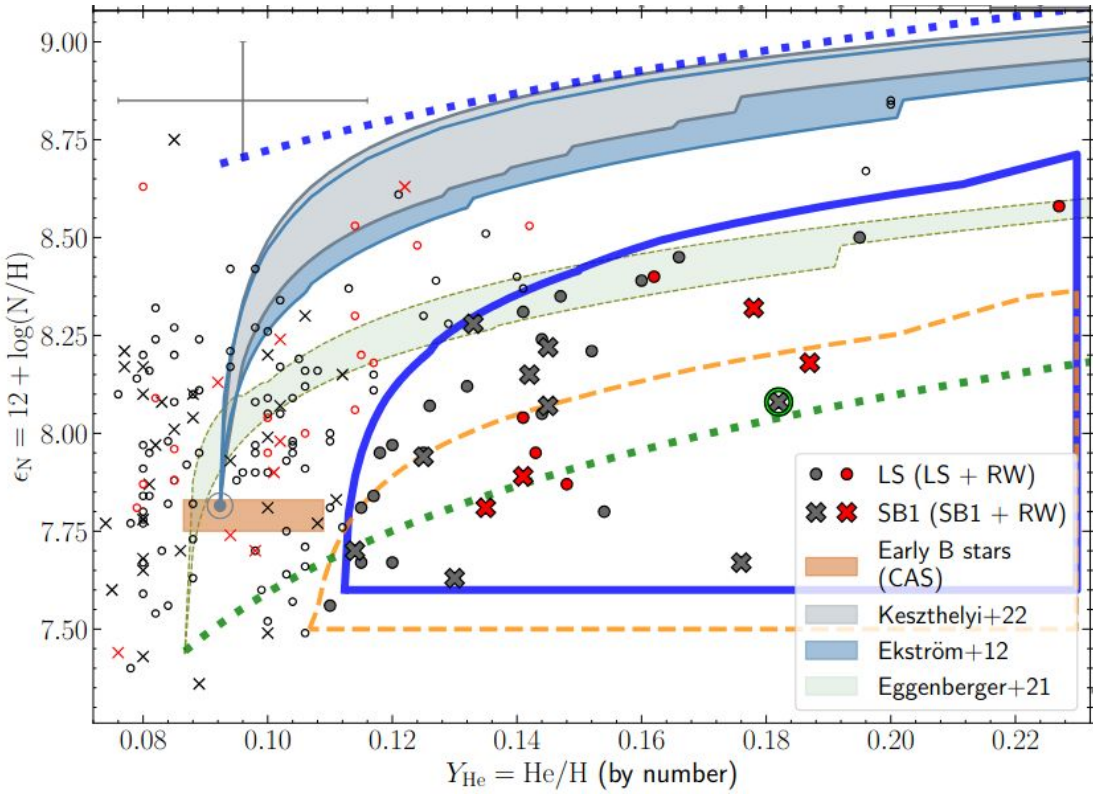
# *Stepping further in the identification of "hidden" binary products*

We have recently found an interesting population of O-type stars with **unexpected surface enrichment in N and He** (if based on predictions by single-evolution models)

**IACOB - XIII**

***Britavskiy+23***






**180** Galactic **O stars** with **vsini < 150 km/s** (LS and SB1)

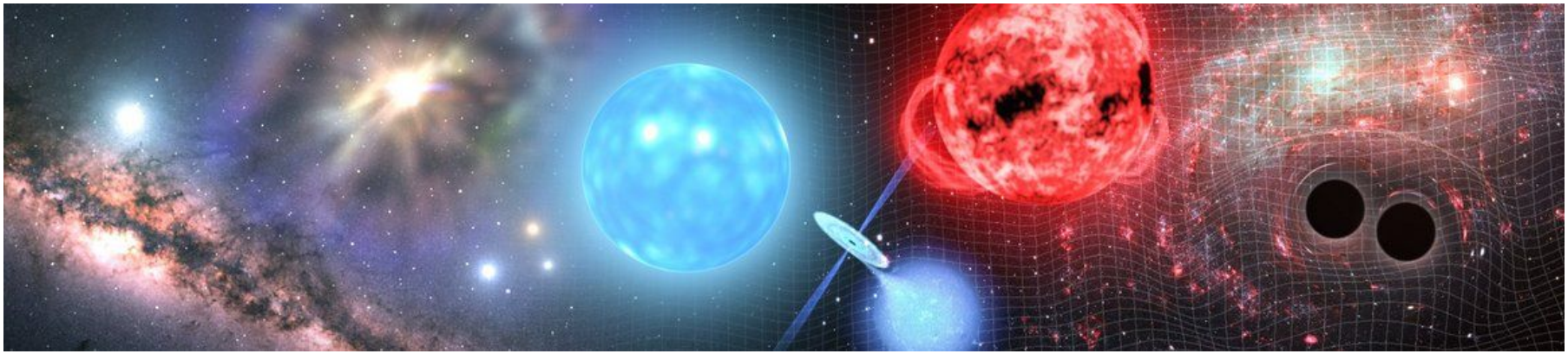
**~80%** of the stars with $Y_{He} \geq 0.12$ (**~20%** of total sample)

$Y_{He}$ and N combined pattern **unexplainable by single-star evolution**

No internal mixing driven by rotation

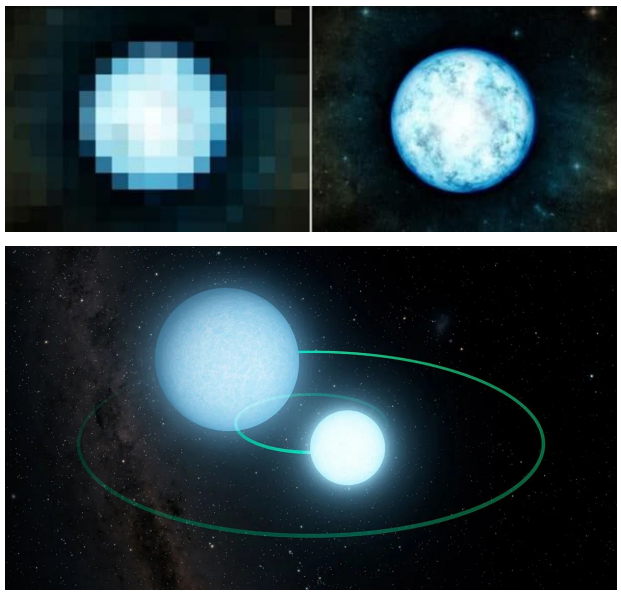
# *Structure of the talk*

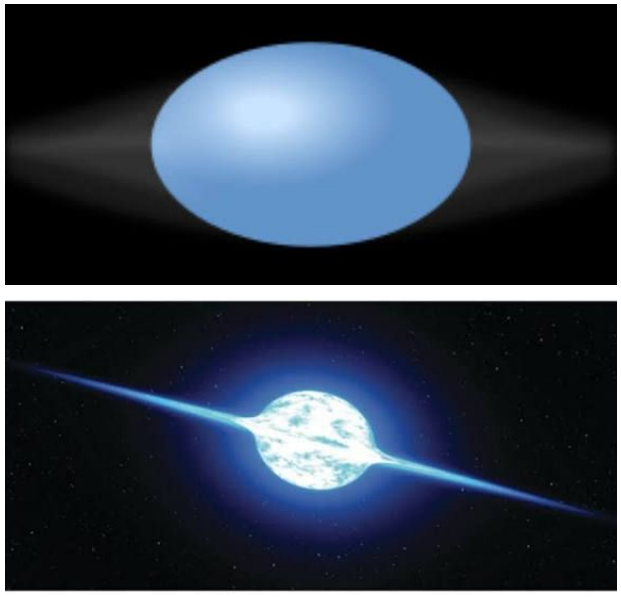
- OB stars in a nutshell
- How massive stars evolve
- The IACOB project
- What can SII bring to massive-star research?

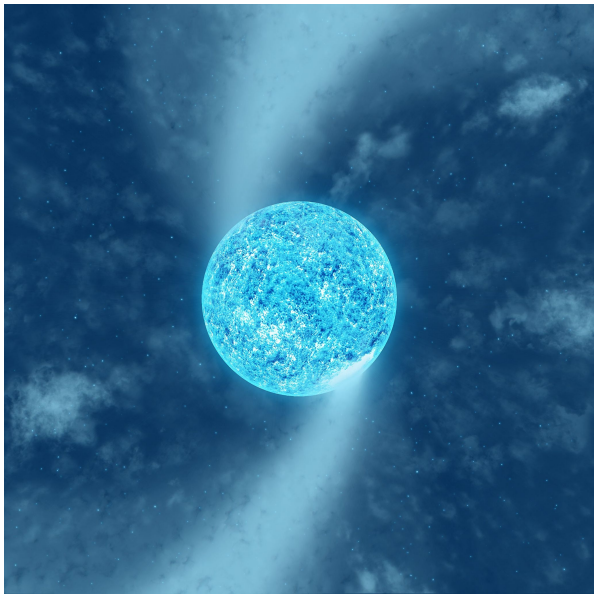


# *What can SII bring to massive-star research*

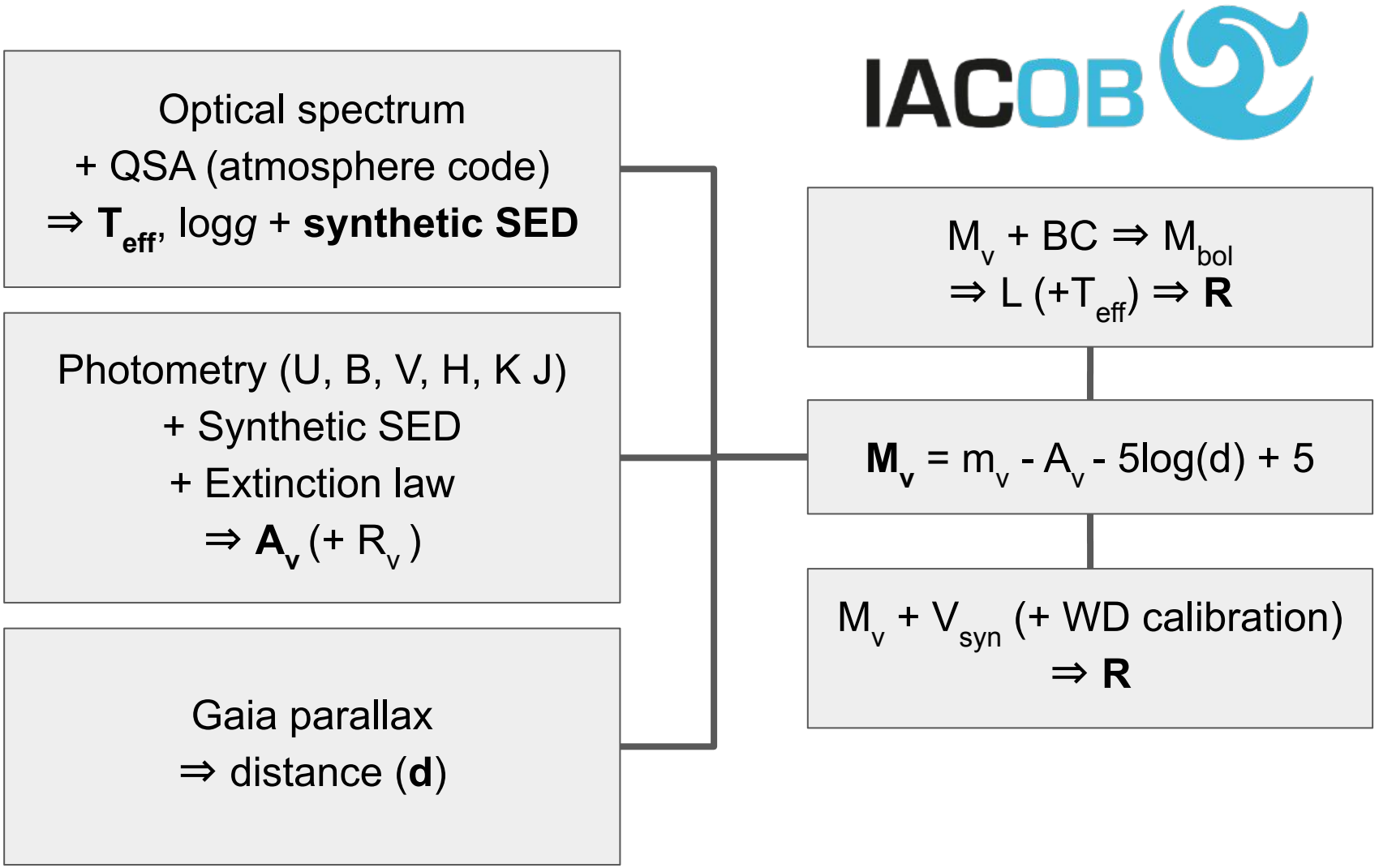
- Stellar sizes
- Binaries
- Fast rotators
- Circumstellar/wind macro-structures





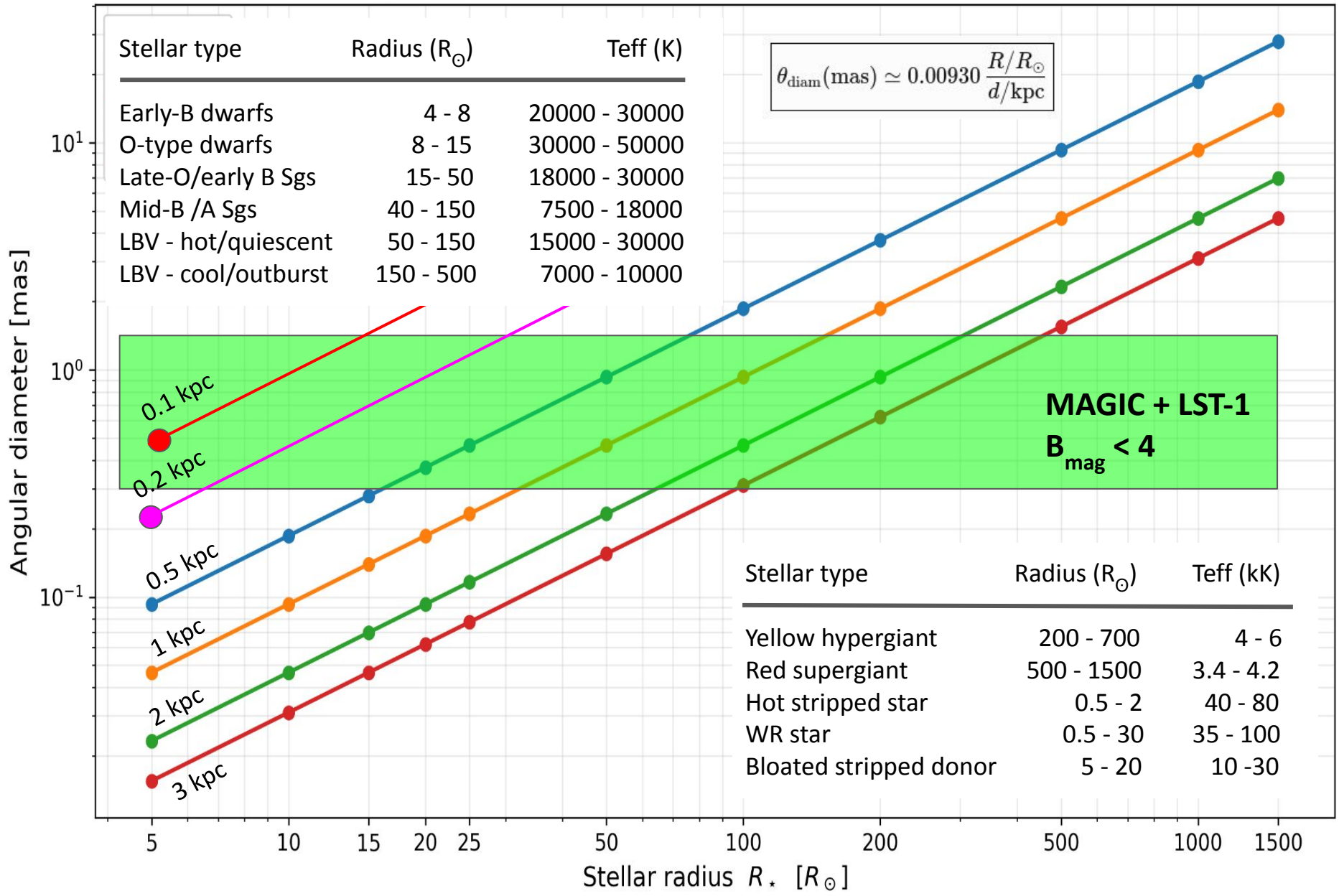


# *Stellar sizes - Two complementary methodologies*

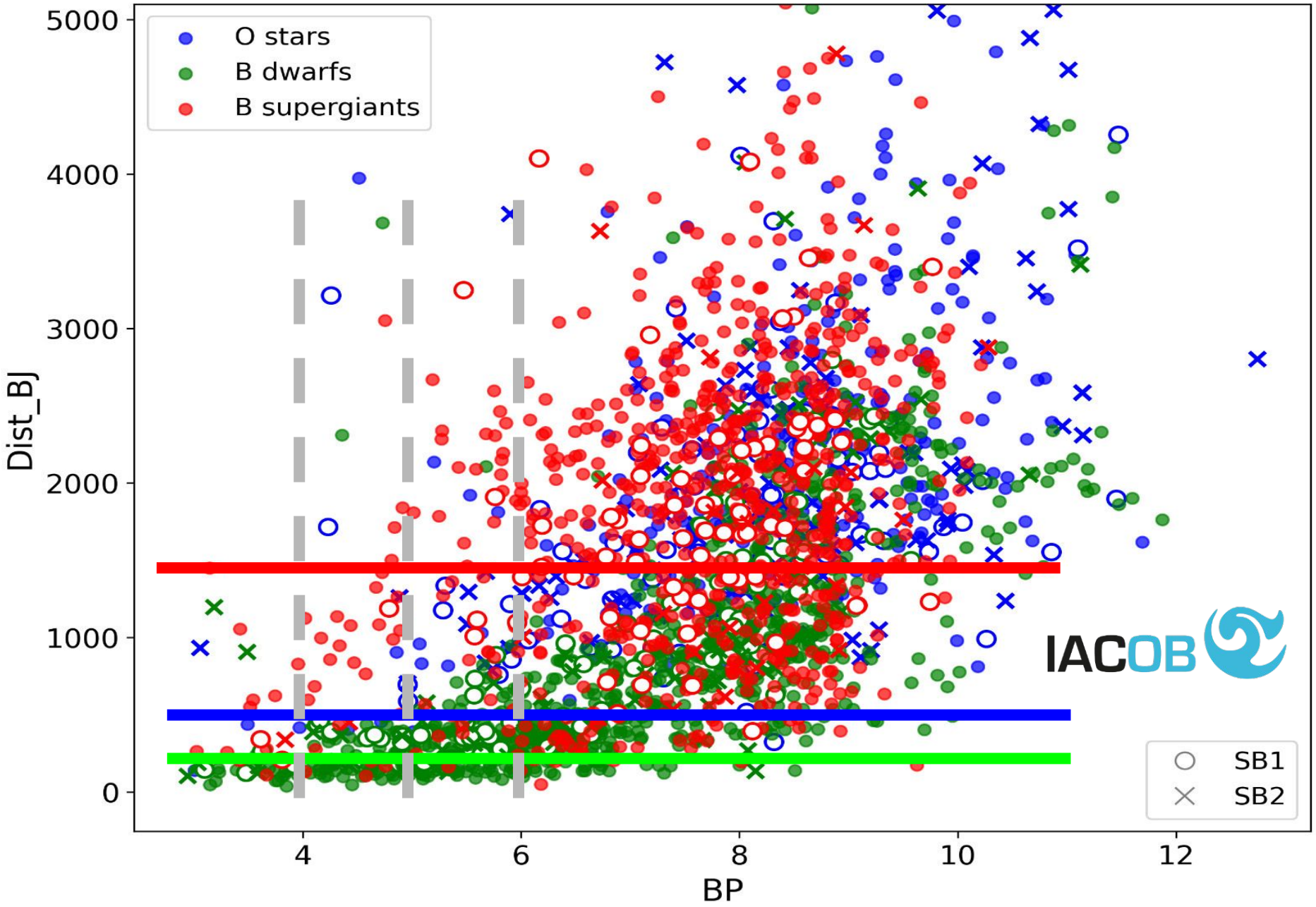



* SII: Apparent diameter + distance ⇒ **R**

# Stellar sizes - SII measurements (state-of-the-art)

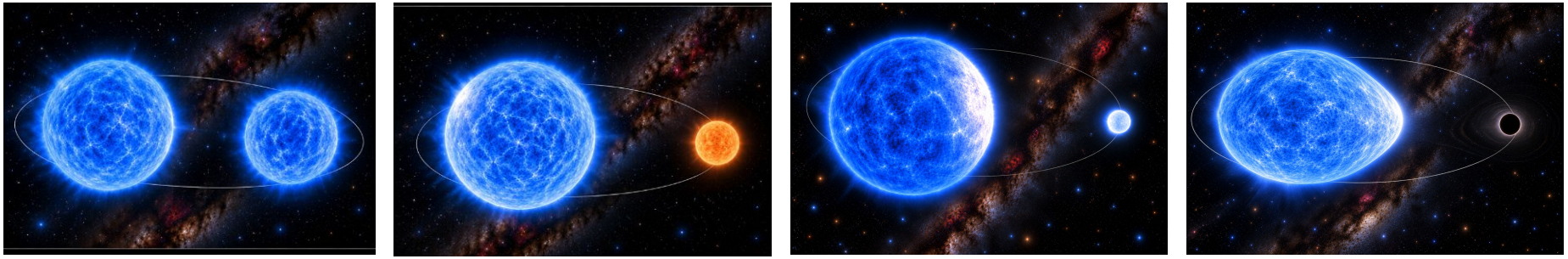


# Stellar sizes - Towards a systematic comparison

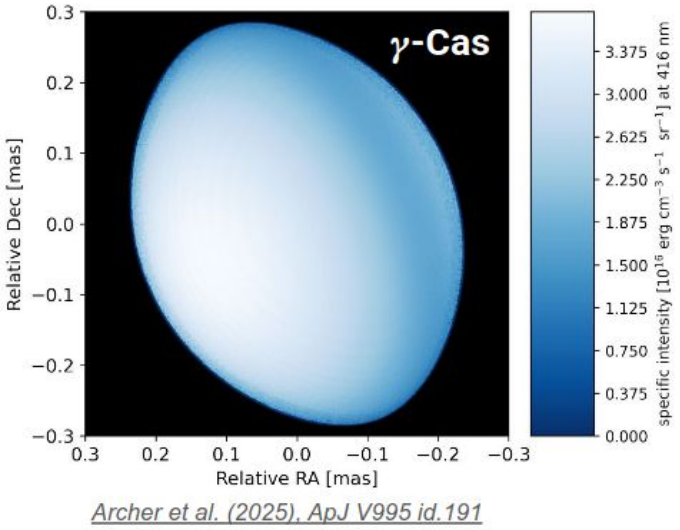


# Binaries

- Identification of close-by companions
  - Pre-interaction case (similar or lower mass)
  - Post-interaction (hidden companions in SB1 systems)
    - Hot stripped stars (+ direct measurement of sizes during eclipses?)
    - Compact object (specially quiescent BH systems)
- Characterization of astrometric orbits in SB2 systems
  - Direct estimations of absolute masses (no eclipses needed)
  - Investigation of mass discrepancy problem



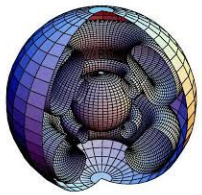
# Fast rotators



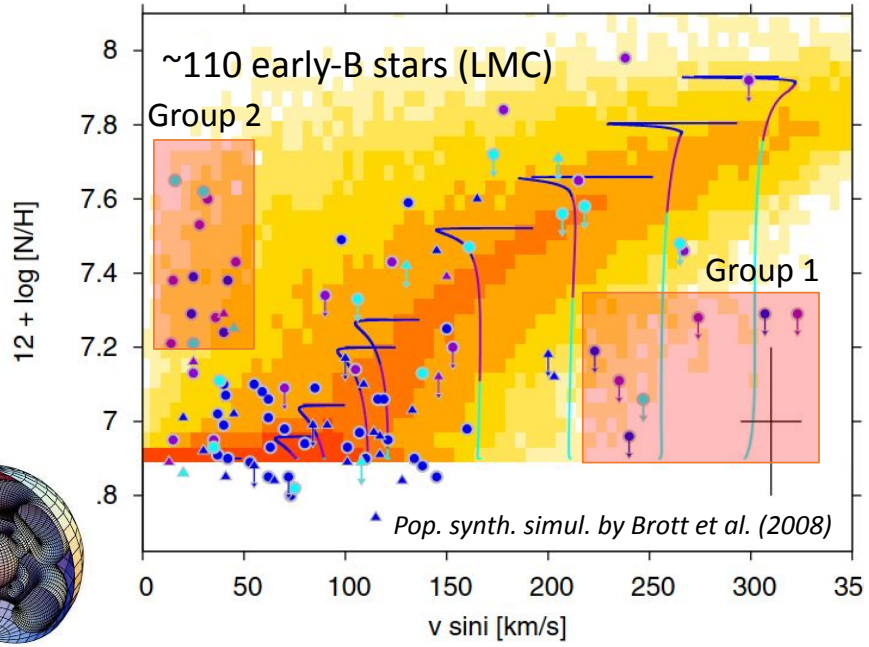

Archer et al. (2025), ApJ V995 id.191

- Spectroscopy only allows to obtain *v*sin*i* estimates
- SII allows an independent estimation of the rotation rate and inclination angle of the star.

- Having access to actual rotation rates allows to investigate whether some low vsini stars with unexpected surface abundance patterns are actually fast rotators seen pole-on



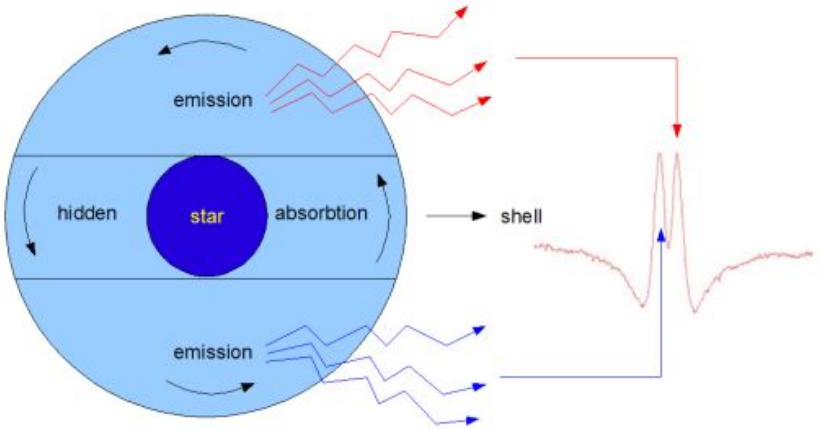
*Hunter et al. (2008)*



# Circumstellar/wind macro-structures

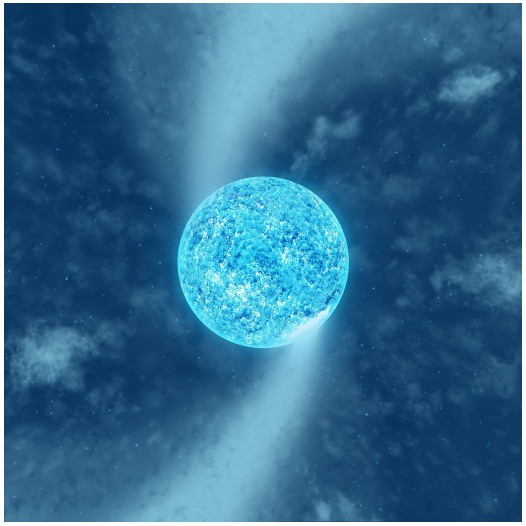
- A non-negligible percentage of B-type stars (and a few O-stars) shows spectroscopic signatures of the presence of discretion discs (Oe/Be phenomenon)
- Likely all of them fast-rotators, but not always high vsini
- Increasing evidence of connection with mass transfer events (+ bloated stars and hot stripped stars companions)
- SII provides a complementary view to spectroscopic studies (Balmer lines - mostly Ha, Hb + Balmer jump)

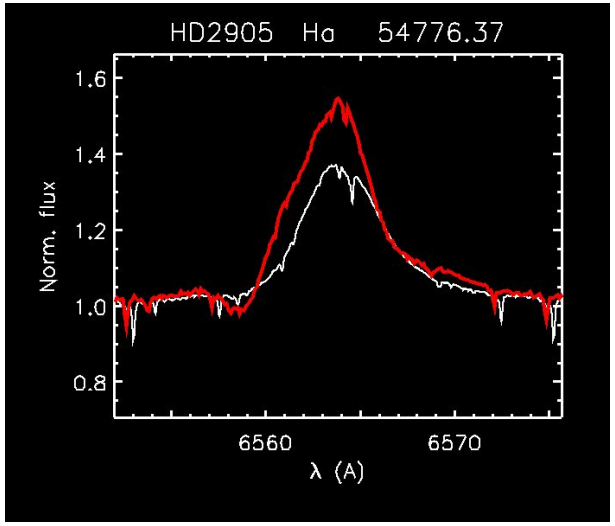


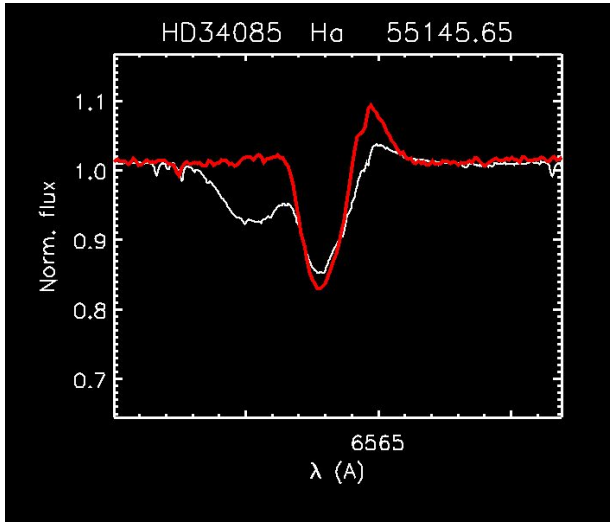


# *Circumstellar/wind macro-structures*

- A large percentage of O and B supergiants (also WR and LBVs) shows variability in the most prominent wind diagnostic lines
- This variability has been proposed to be originated by the occurrence of macrostructures in the stellar wind which corrotate with the stellar surface
- Could this macrostructures be detected with SII?

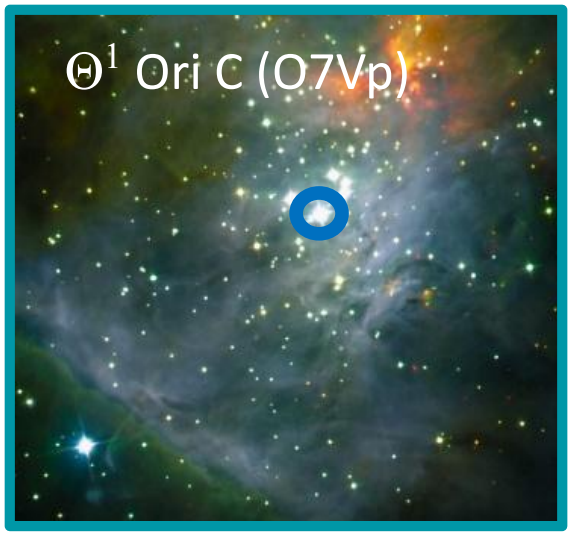


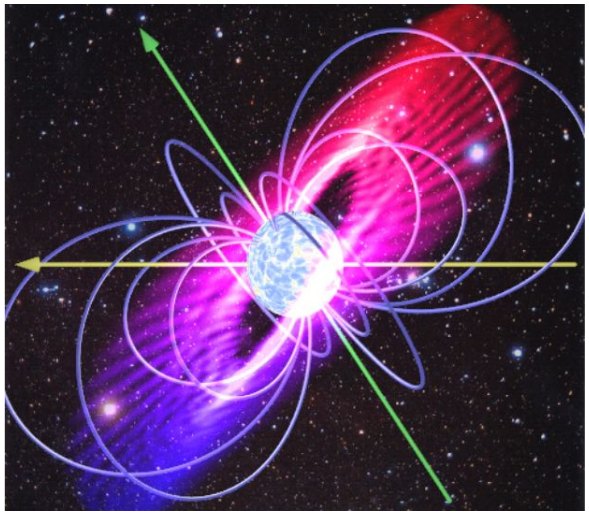


# *Circumstellar/wind macro-structures*

- There are several O-type star with a surface magnetic field strong enough to produce a confined wind and an accretion disc.
- One of them is Theta 1 Ori C (the ionizing star of the Orion Nebula)
- With a radius of ~10 Rsol and a distance of ~400 pc this star has an expected angular diameter of ~0.23 mas.
- Will future SII developments allow the characterization of the surface/wind/magnetosphere of this star?

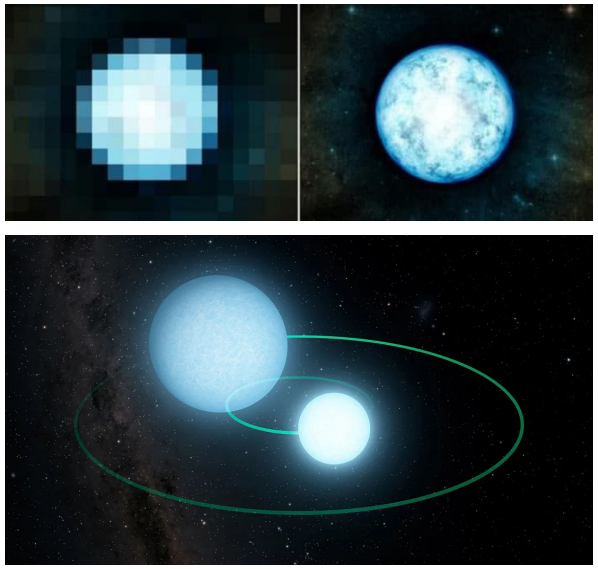


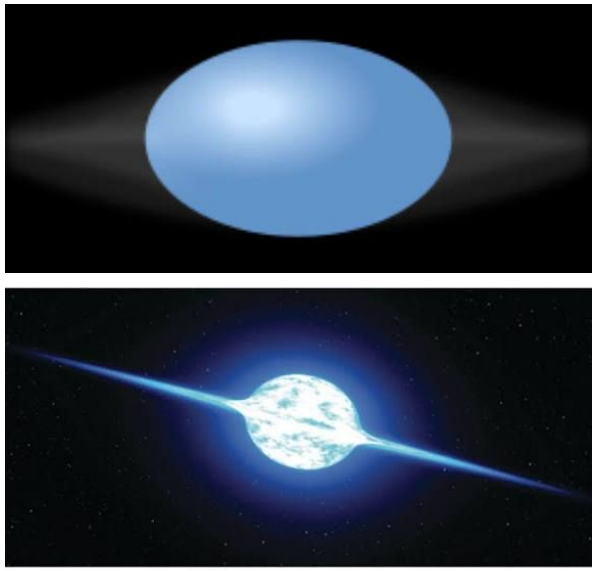



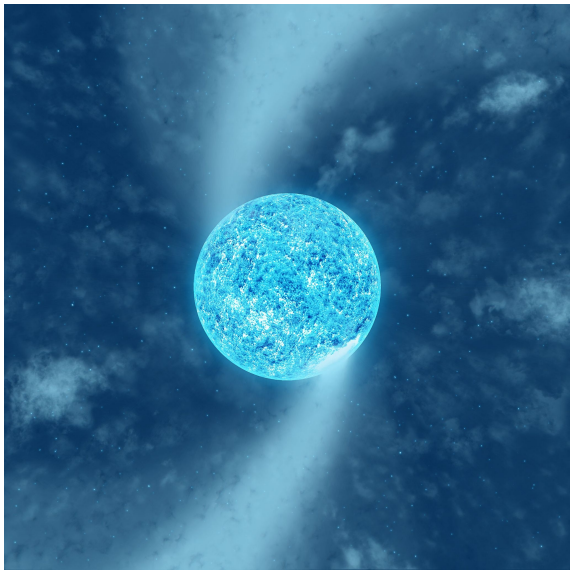
# What can SII bring to massive-star research

- Stellar sizes
- Binaries
- Fast rotators
- Circumstellar/wind macro-structures
- …



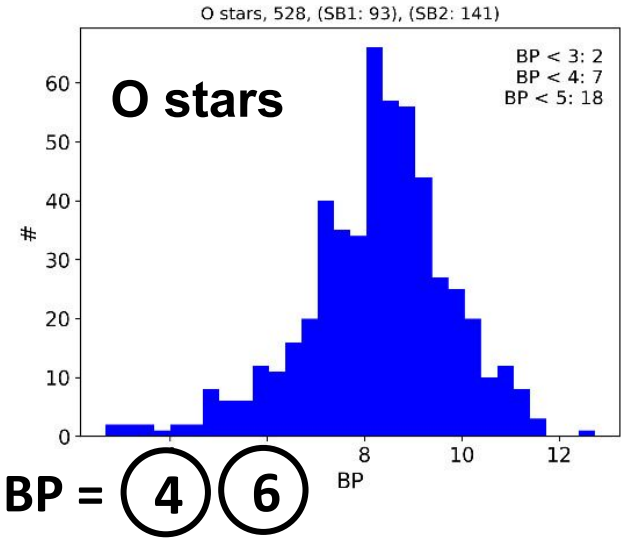



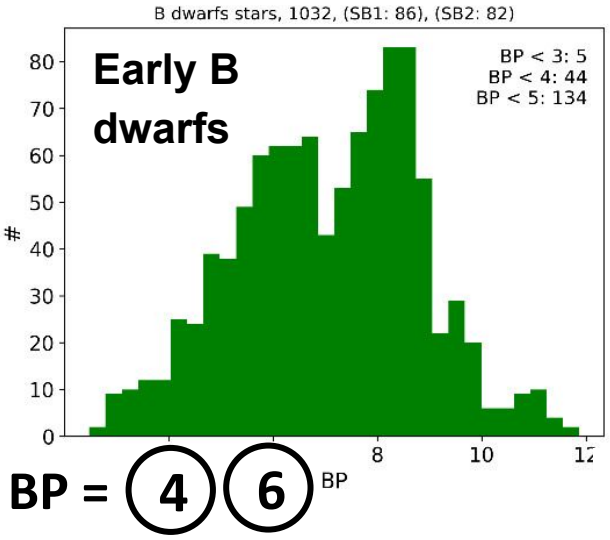


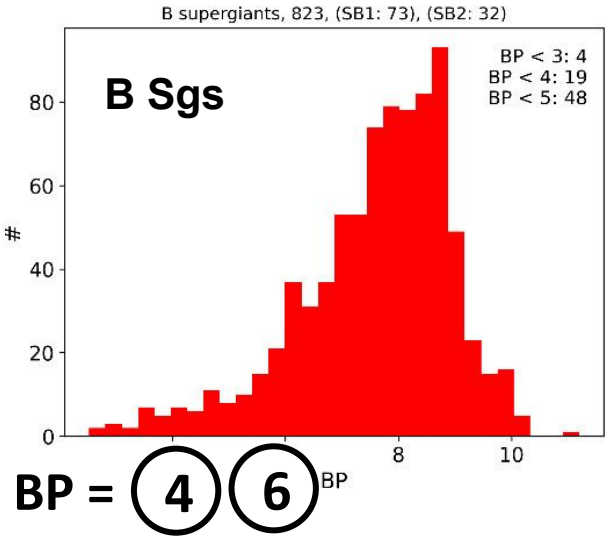


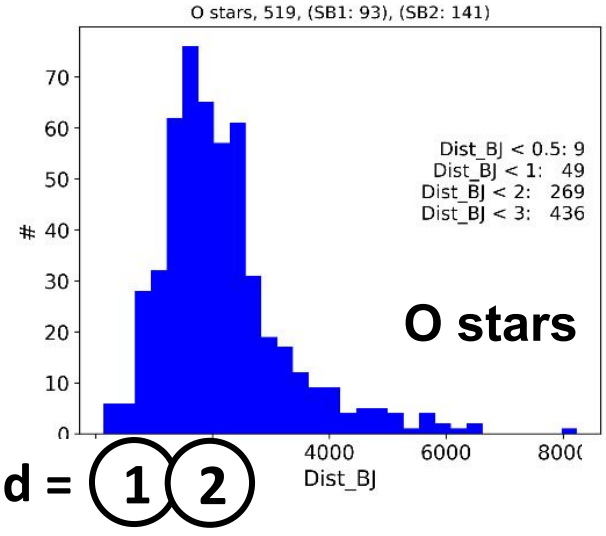
# *Every little step toward improvement is worth it!!!*

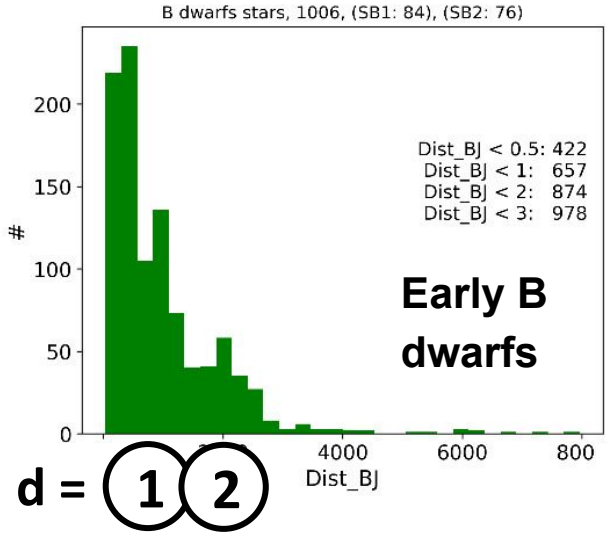
Histogram distribution of the IACOB sample as a function of BP and distance

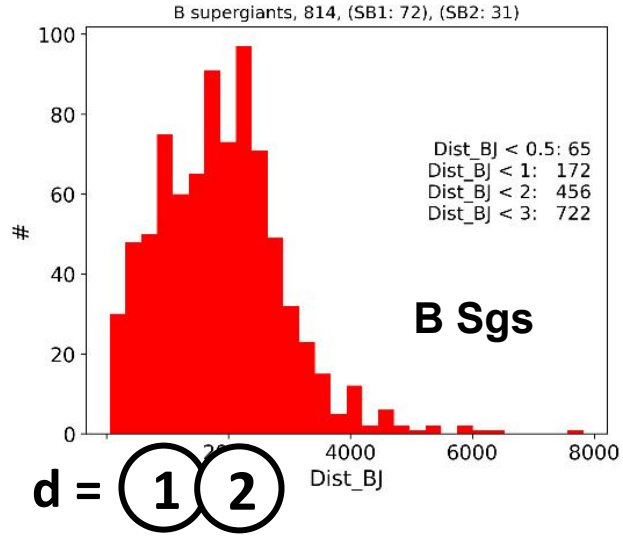


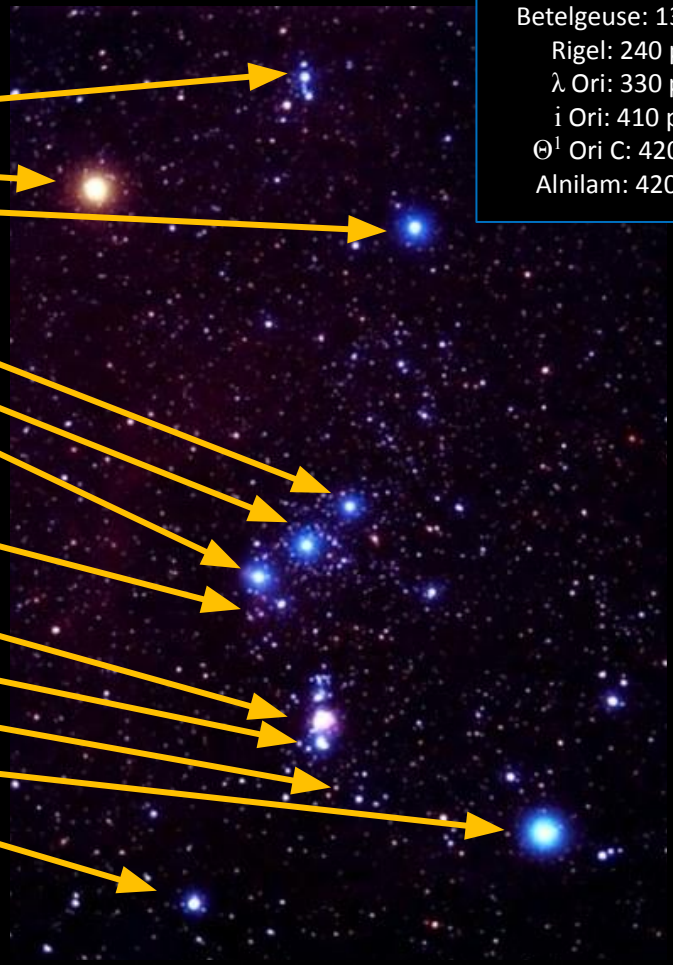



# *The brightest stars in the Orion constellation*

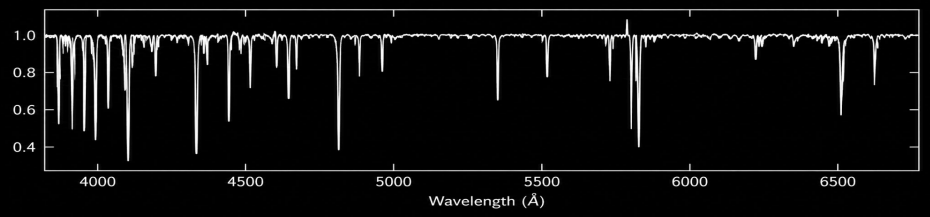
Golden SII certificate

| | |
|---|---|
| V=3.47 | O8 III((f)) |
| V=0.42 | M1-M2 Ia-Ib |
| V=1.64 | B2 V |
| V=2.41 | B0 III (SB1) |
| V=1.69 | B0 Ia |
| V=1.79 | O9.7 Ib (SB3) |
| V=3.80 | O9.5 V (SB3) |
| V=5.13 | O7 Vp |
| V=2.77 | O9 III (SB2) |
| V=4.63 | O9.7 V |
| V=0.13 | B8 Ia |
| V=2.06 | B0.5 Ia |



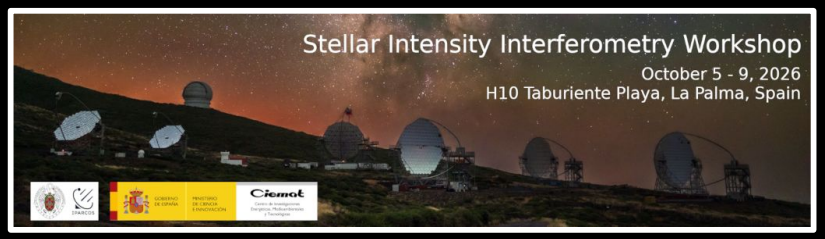

Betelgeuse: 130 pc
Rigel: 240 pc
λ Ori: 330 pc
i Ori: 410 pc
$\Theta^1$ Ori C: 420 pc
Alnilam: 420 pc

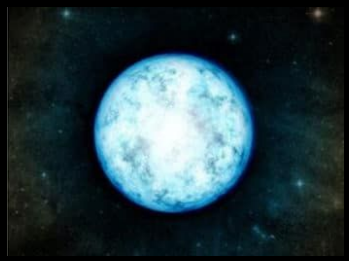
**All of them *(but Betelgeuse)* are**
**OB-type stars**
***hence blue massive stars***



EXCELENCIA SEVERO OCHOA
Universidad de La Laguna
IACOB
GOBIERNO DE ESPAÑA · MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
OCEANS
Cofunded by the European Union





## A (brief) guided tour through

# the world of Massive OB Stars

## (Exploring synergies with Stellar Intensity Interferometry)

*Sergio Simón-Díaz*

