Mind the gaps: a massive empirical approach to high-mass stellar evolution

with the aid of IACOB, WEAVE, Gaia and TESS

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and the IACOB team



The IACOB project: an ambitious long term observational project

P.I. S. Simón-Díaz

IACOB

EXCELENCIA SEVERO OCHOA

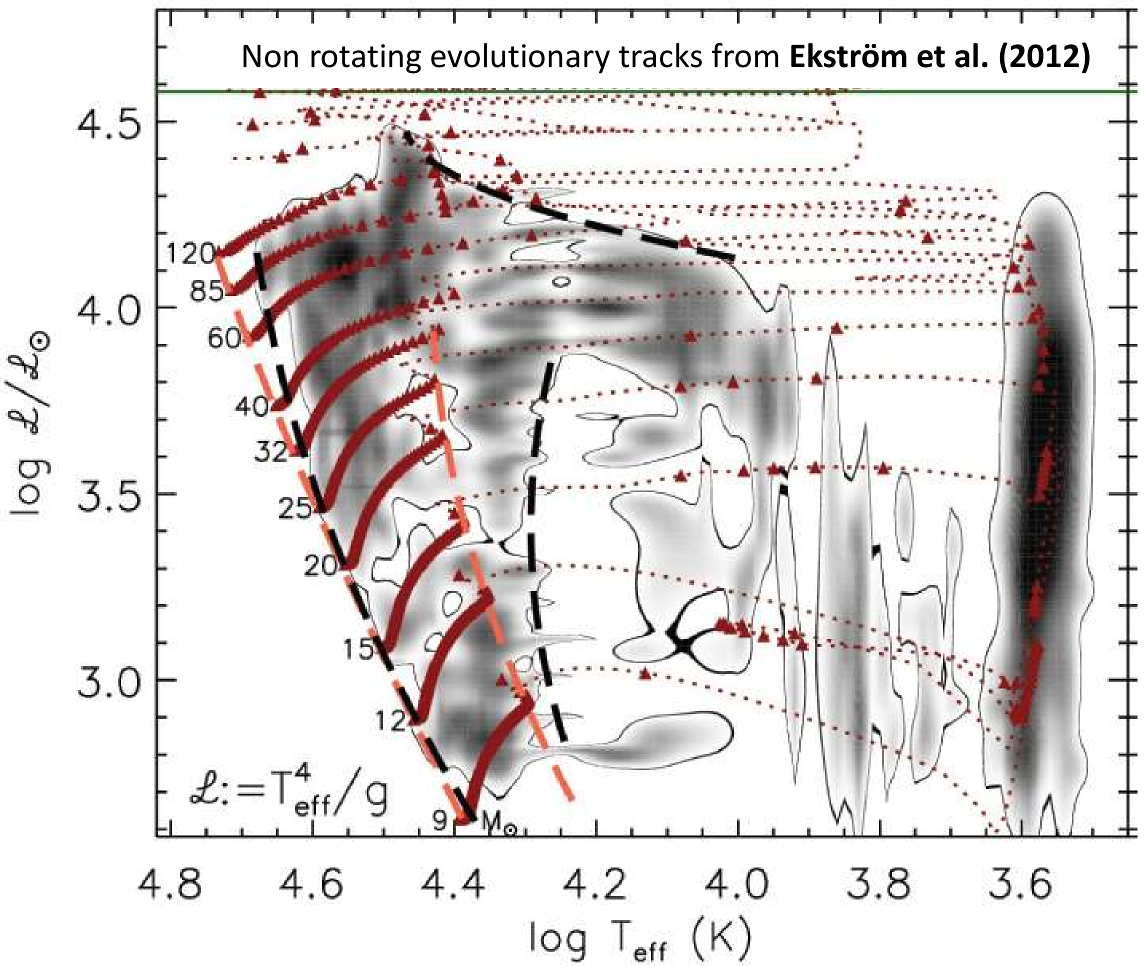
Main Scientific Goal

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.

This story began in November 2008 at the Nordic 2.56m optical telescope (NOT, ORM, La Palma, Spain) …

… 5 years before gaia was launched

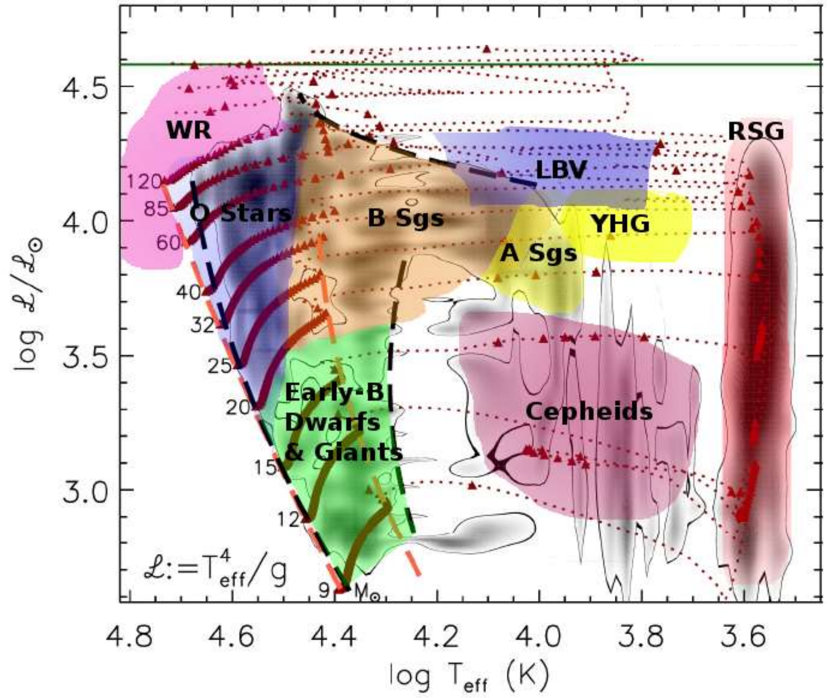
Welcome back to the realm of high-mass (aka massive) stars



Density map (in the sHRD) of ~600 Galactic massive stars with parameters determined spectroscopically (***Castro et al. 2014***)

Physics

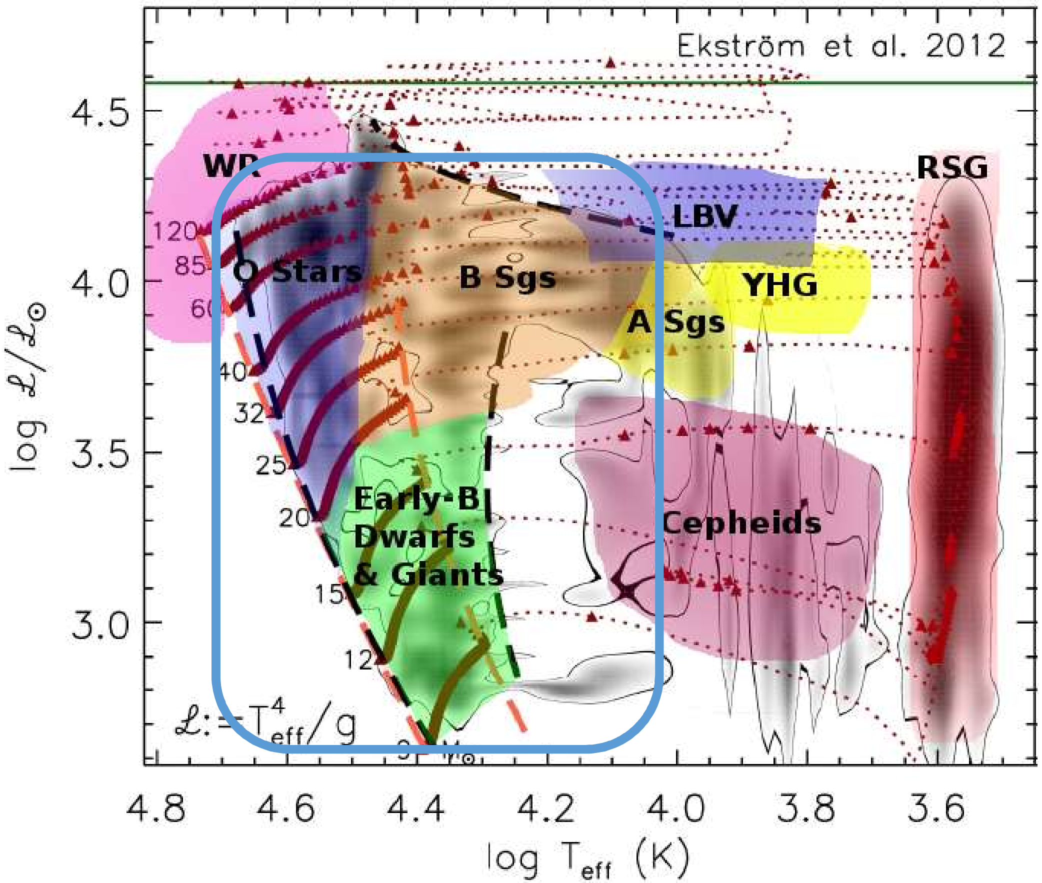
Spectral morphology



G. Holgado (2019, PhD thesis)

Massive star: a star that is massive enough to form a collapsing core at the end of its life and, thus, avoid the white dwarf fate ***(Langer 2012)***

The realm of blue massive (OB-type) 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, mainly O stars)

Young (a few Myr)

* Roughly speaking massive stars spend 90% of their time in the Main Sequence

In the Milky Way …

They are mainly found in (young) star forming regions across the Galactic disk. But not all of them …

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Immediate objective

Thorough 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 and wind parameters**
- Determination of a set of **surface abundances**
- Identification and empirical study of **binary/multiple systems**
- Identification and characterization of **stellar variability**

But … why is so important to consider so many stars?

Establishing the link between the **empirical properties** of an OB star and its **evolutionary status** would be simple if massive star evolution would only depend on mass …

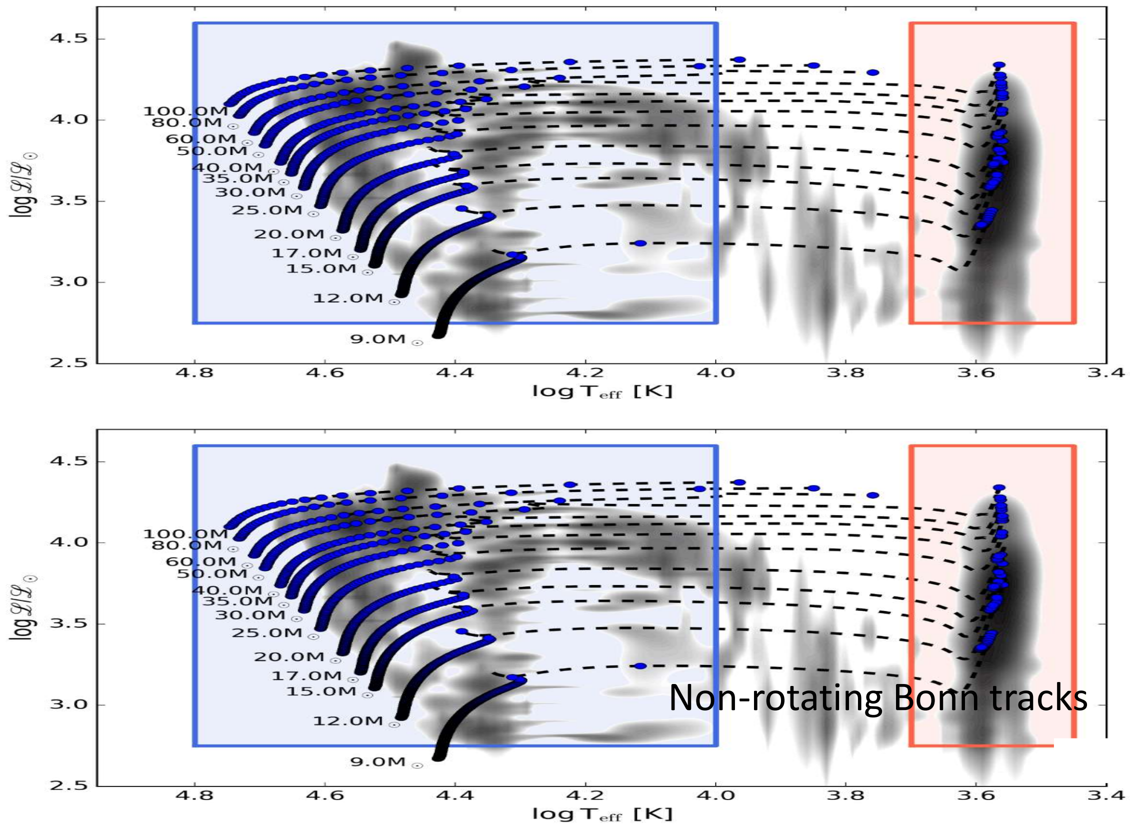

Image adapted from Castro et al. (2014). Courtesy of **N. Castro** *(IAP)*

Immediate objective

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

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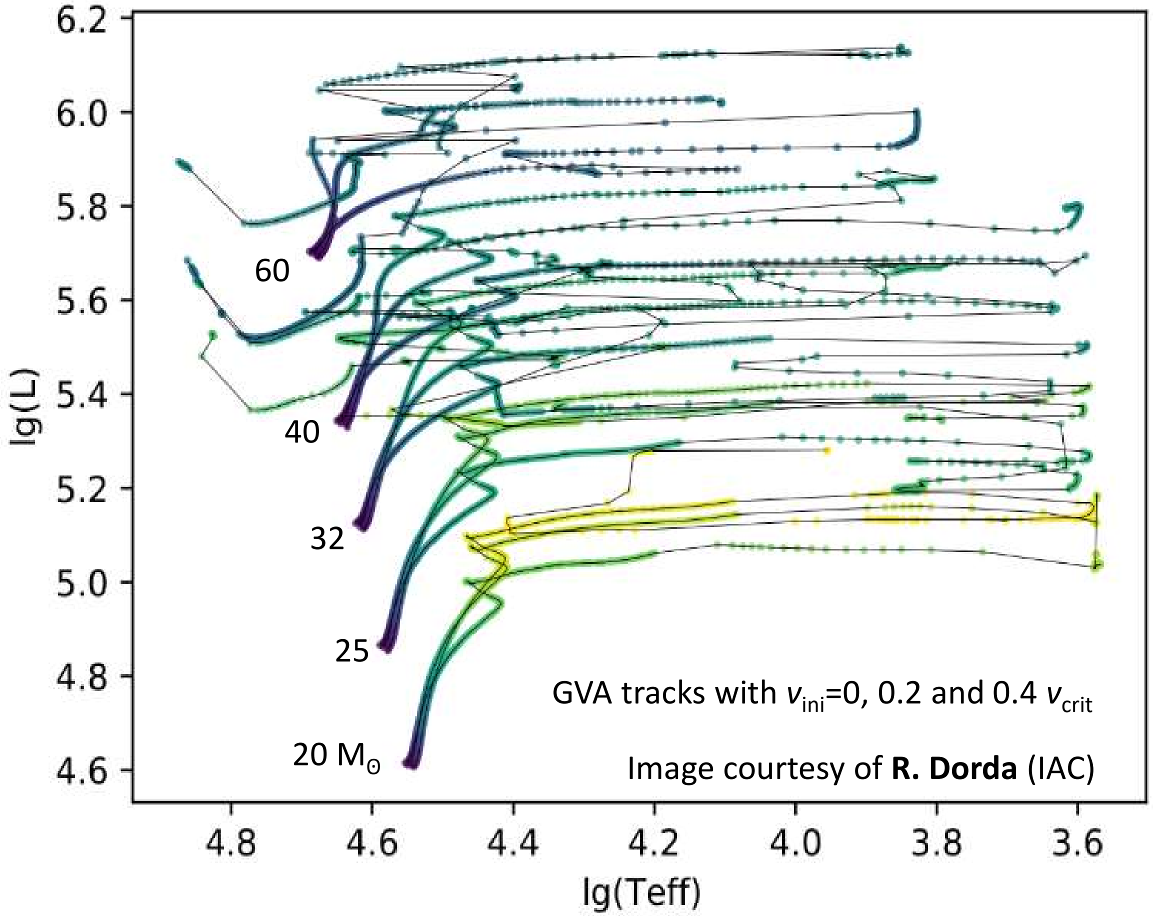
But … why is so important to consider so many stars?

… but massive star evolution does not only depend on mass, but also on **rotation** and **stellar winds**[(1)]



Note 1: The measured **vsini** of massive stars range from a few km/s to 450 km/s (e.g. ***Conti & Ebbet 1977, Holgado 2022***)

Note 2: A massive star can enter the **blue supergiant region** either by evolving directly from the main sequence, or from a previous red supergiant stage (*e.g.,* ***Ekström et al. 2012***)

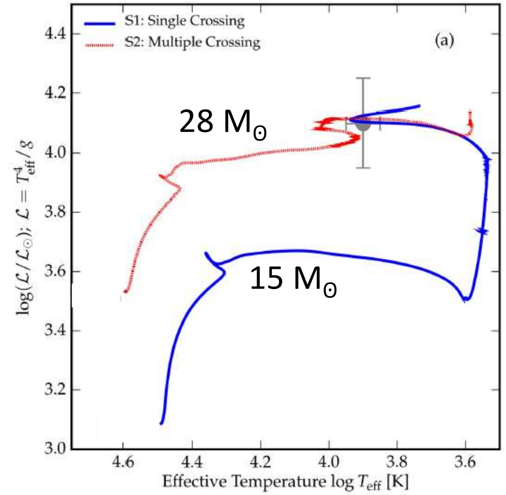


Image courtesy of **E. Moravveji**

(1) Plus core overshooting, internal transport of angular momentum and chemical species, metallicity, …

But … why is so important to consider so many stars?

… but massive star evolution does not only depend on mass, but also on **rotation** and **stellar winds** (+ in **binary systems**, **mass/angular momentum transfer** and the occurrence of **merger events**)

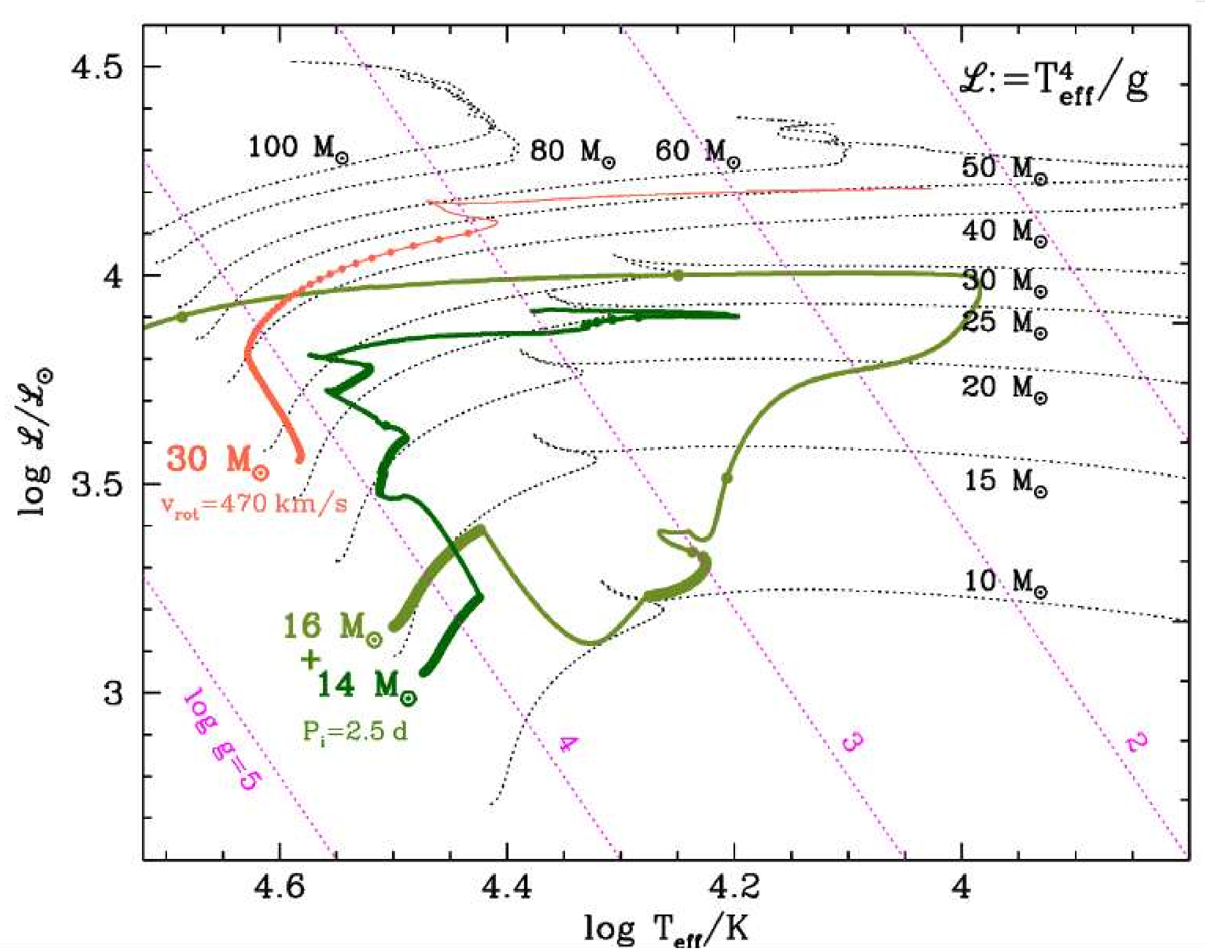
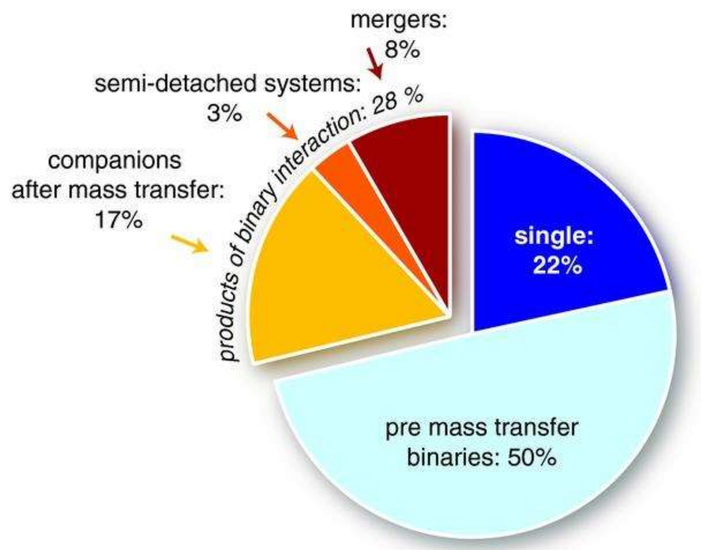


Image extracted from ***Langer & Kudritzki (2014)***

Note 3: More than 70% of all massive stars is predicted to **exchange mass** with a companion along their life (***Sana et al. 2012***); in particular 30% will do during the Main Sequence (***de Mink et al. 2014***)

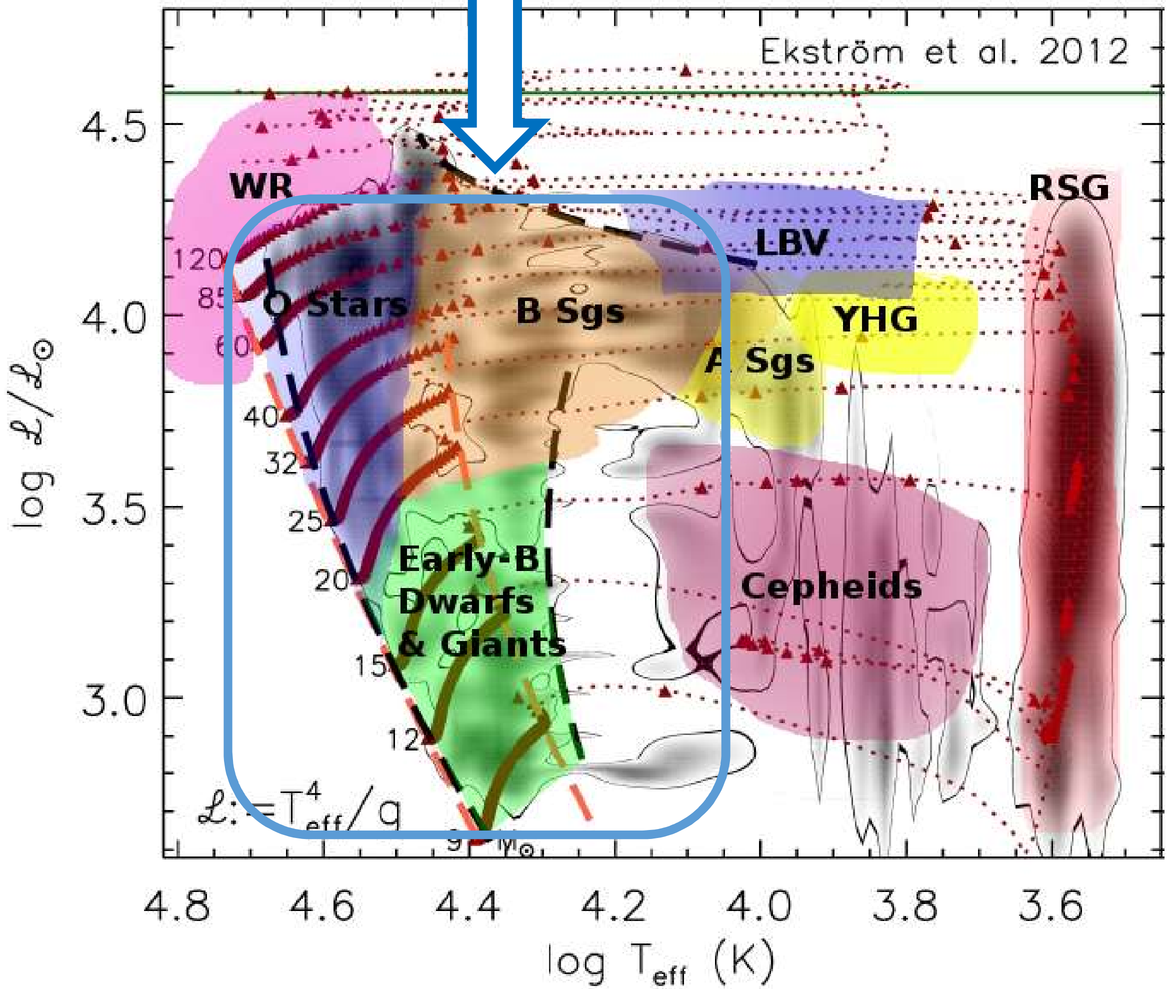
Note 4: The incidence of stellar **mergers** during the Main Sequence is predicted to be 8% (***de Mink et al. 2014***)



de Mink et al. (2014)

But … why is so important to consider so many stars?

Let's try to compile as much empirical information as possible in this part of the HRD



Immediate objective

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

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Observations, an important pillar of the IACOB project

< 2008 – 2022+

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

Ground-based optical spectroscopy

Single snapshot, multi-epoch & time-series

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

+ 1978 - 1996

UV spectroscopy

- Stellar wind parameters

+ gaia

Lauched in 2013

Parallaxes & proper motions

- Fundamental parameters
- Cluster membership
- Runaways

+ TESS

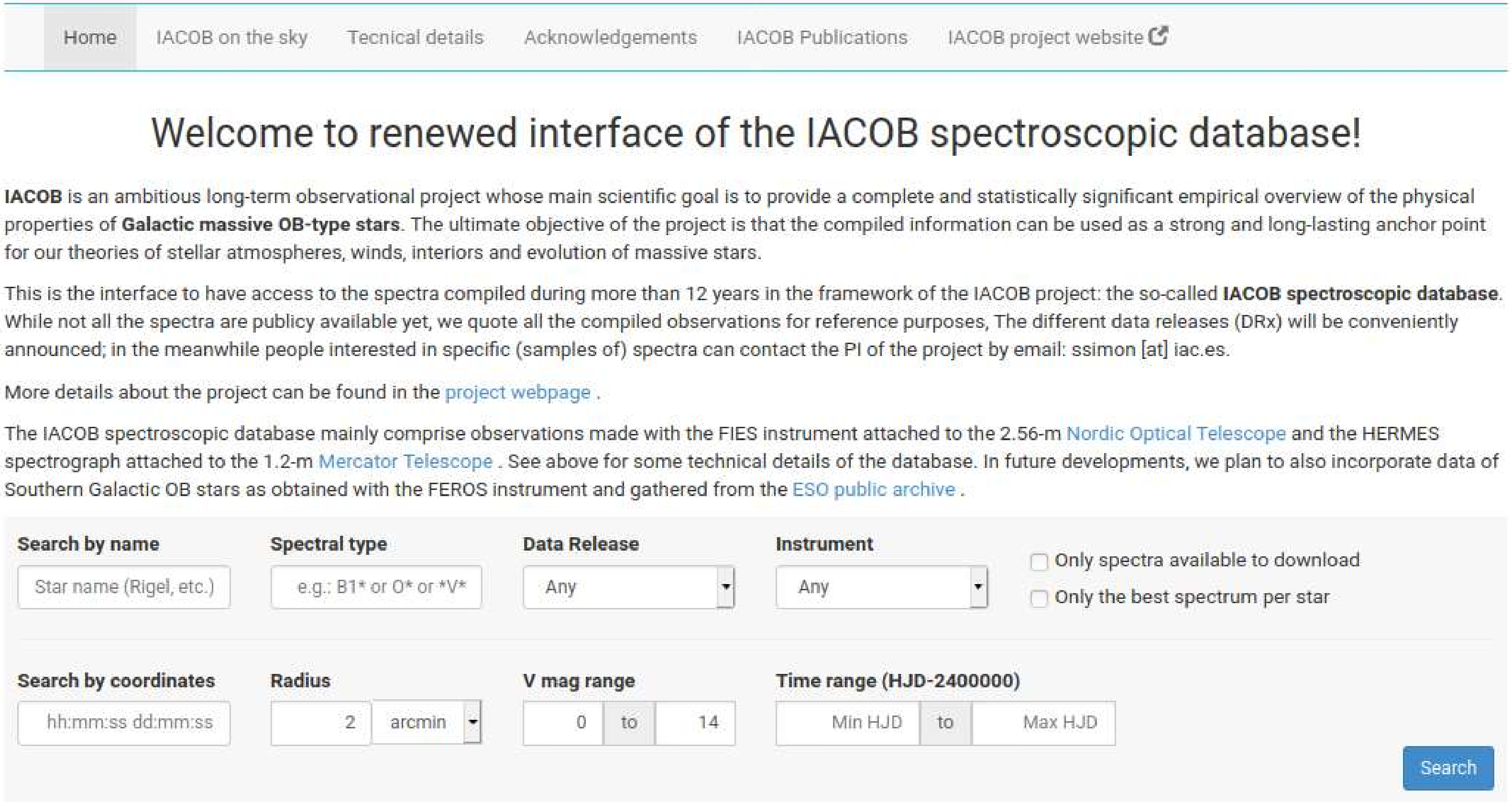
Lauched in 2018

Time resolved photometry

- Stellar variability
- Eclipsing binaries
- Ellipsoidal variables

Spectroscopic observations in the IACOB project: present status

IACOB
Spectroscopic database



 # spectra: *FIES, HERMES ≈ **9800+*** *STELLA ≈ **1300+*** *FEROS ≈ **3650*** *SONG ≈ **22500+***

SpT coverage: ***O2 – B9*** (1) *LC coverage:* ***V, IV, III, II, Ib, Iab, Ia, Ia$^+$*** *# stars:* ***1750+***

On-going observations: *LP (HERMES+FIES): **60n (2yr)*** *STELLA monitoring: 200h* *SONG time-series*

(1) *Plus a few tens of **A0-A2 Sgs***

And in the next 5 years we will jump from ~10³ to ~10⁴ stars

WEAVE-SCIP (PI. Drew): An upcoming 5-year multi-object spectroscopic survey

[1] Northern Galactic plane (R=5000, 3800-9000 A) ***≈ 5x10⁴ O-B3 star candidates (G ≈ 11 – 17)***

[2] Cygnus-X (R=20000, 4040-4650 A + 5950-6850 A) ***≈ 5x10³ O-B3 star candidates (G ≈ 9 – 15)***

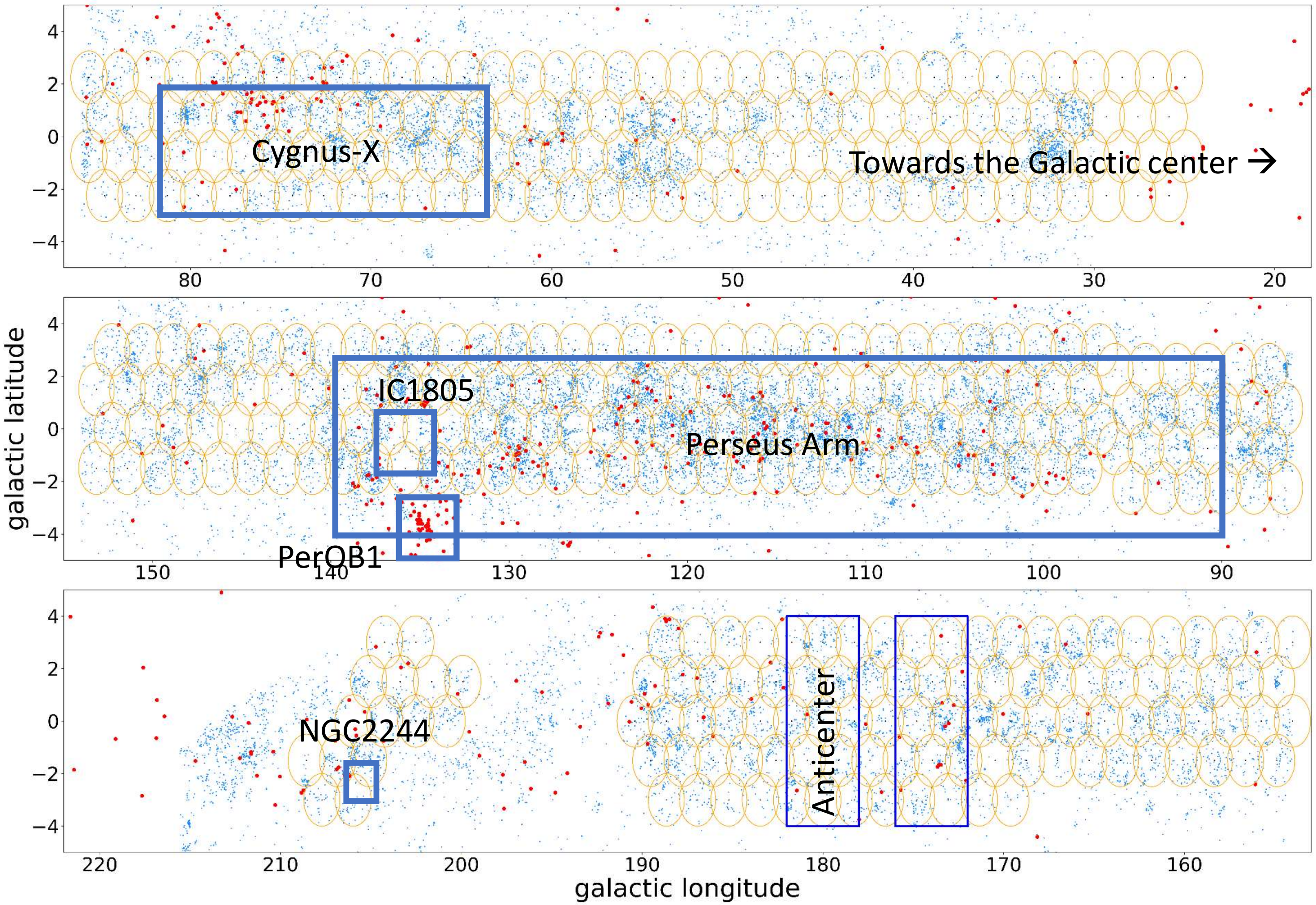


Image courtesy of **A. de Burgos** (IAC)

● IACOB sample ● WEAVE-SCIP-OB candidates

Cygnus-X

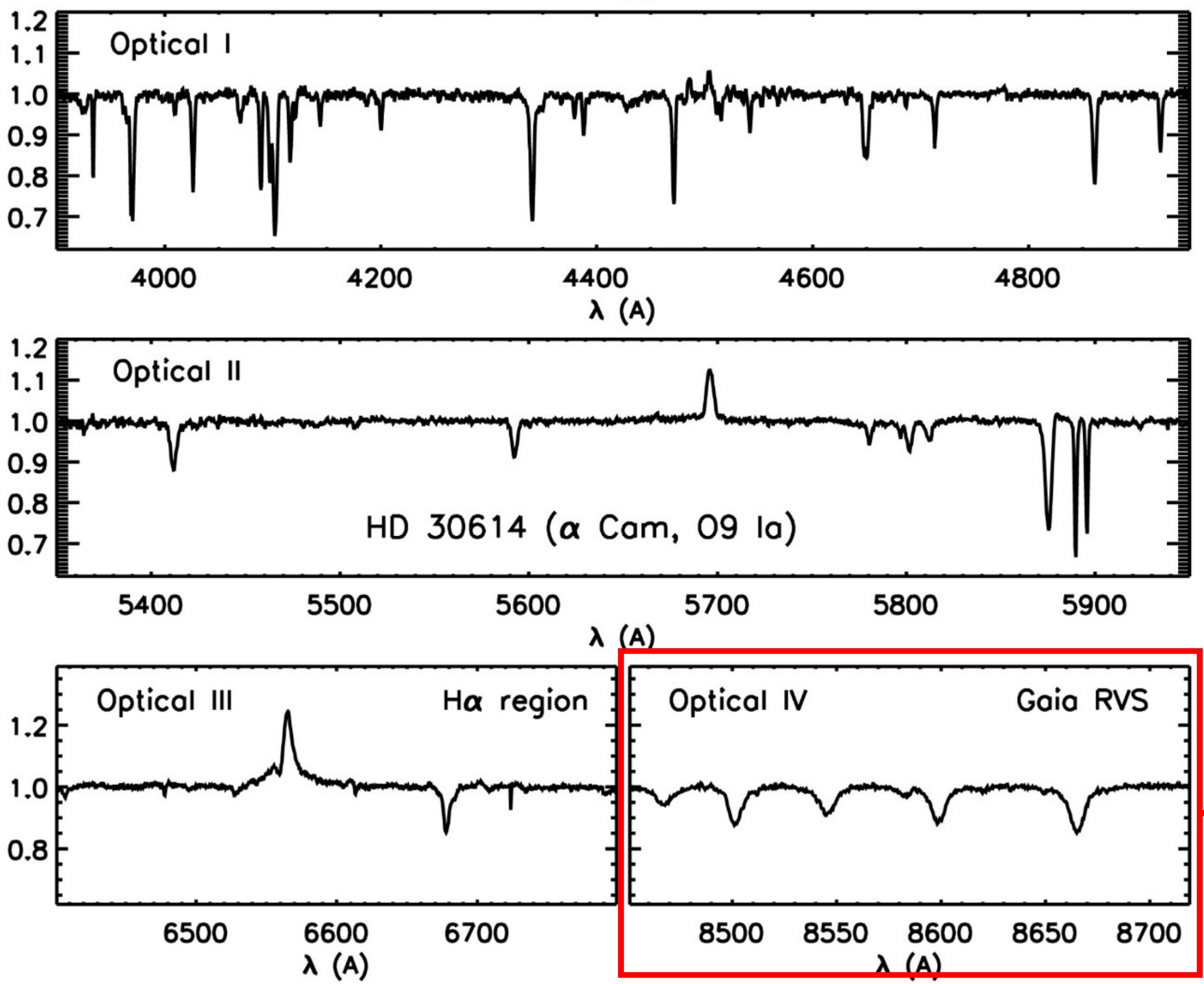
IC1805

NGC2244

IACOB Spectroscopic database (+ WEAVE*) vs. gaia

Were/are these (ground based) observational efforts really needed in the Gaia era?

* Hopefully also 4MOST

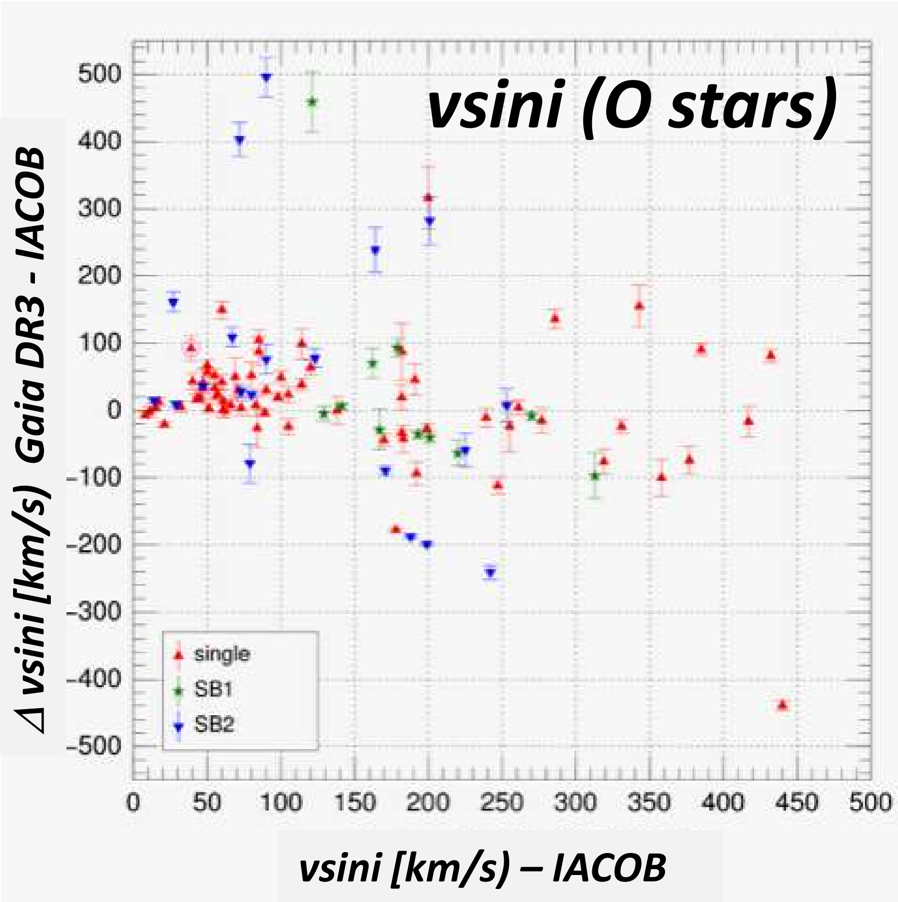


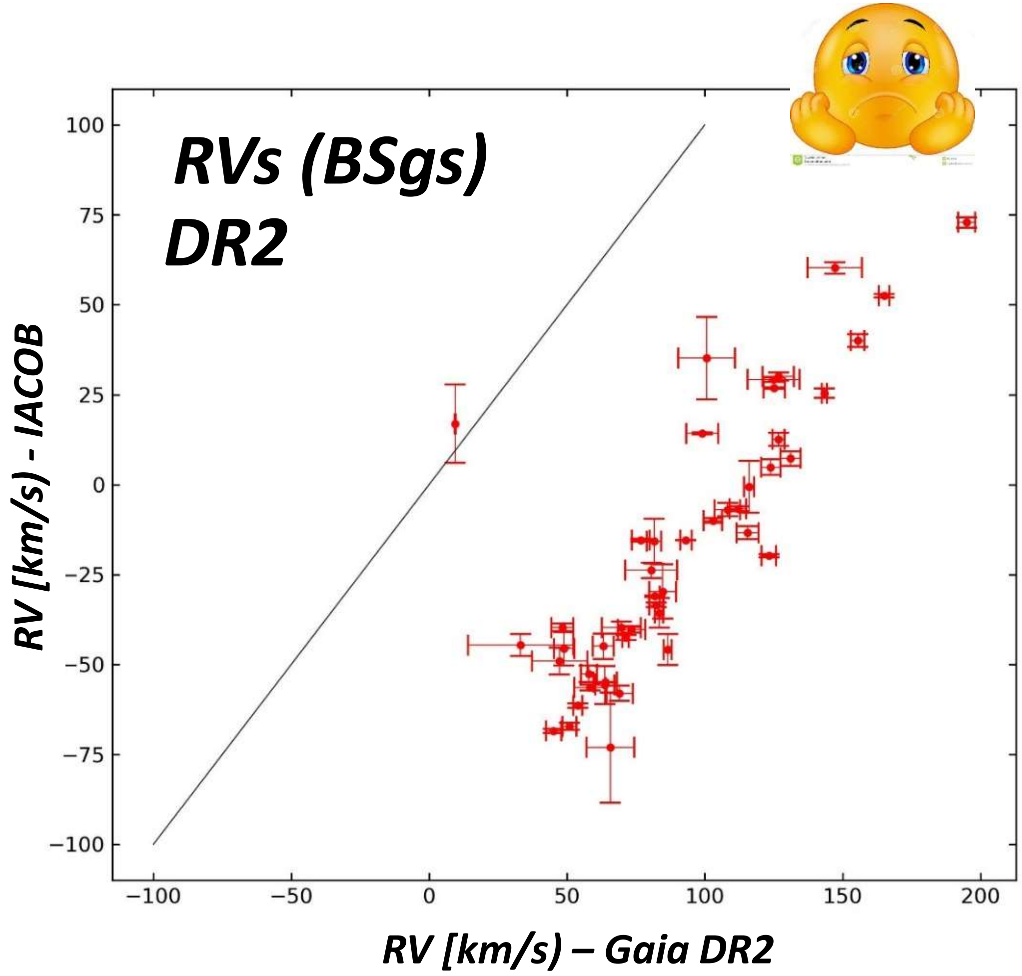
The **Gaia-RVS** range is quite boring in the case of OB stars

Optical spectroscopy is a MUST to get accurate info on:

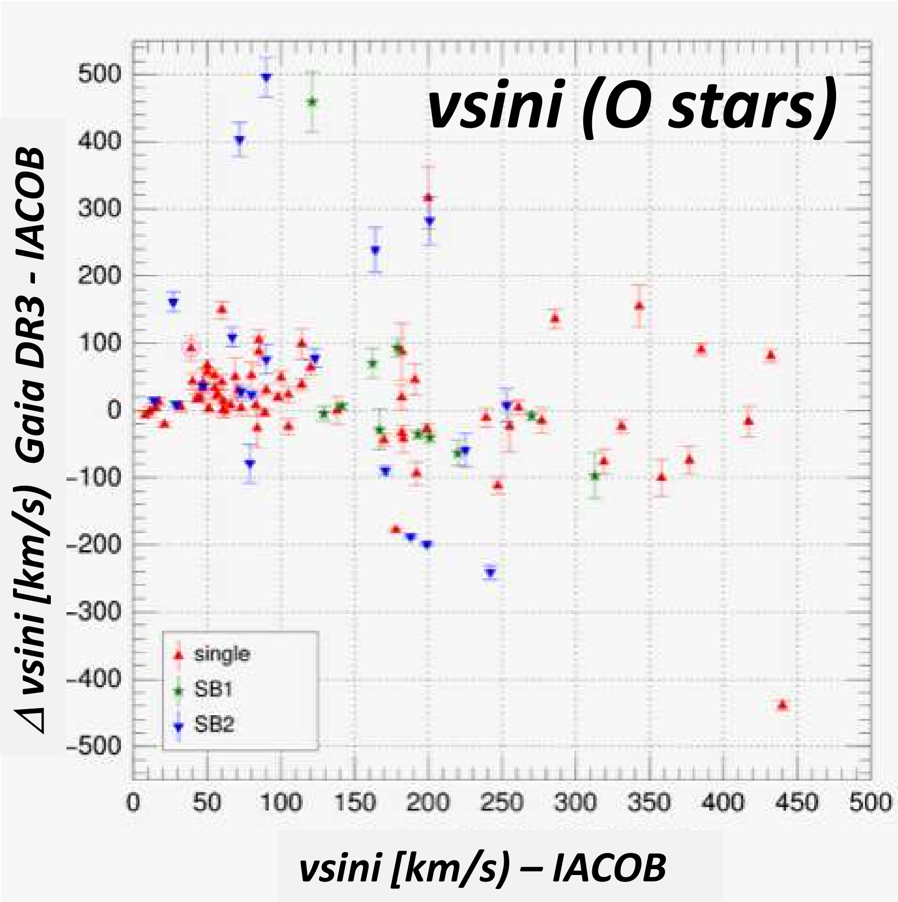
- RV
- vsini
- Spectr. parameters
- Surface abundance

The gaia view of massive OB-type stars

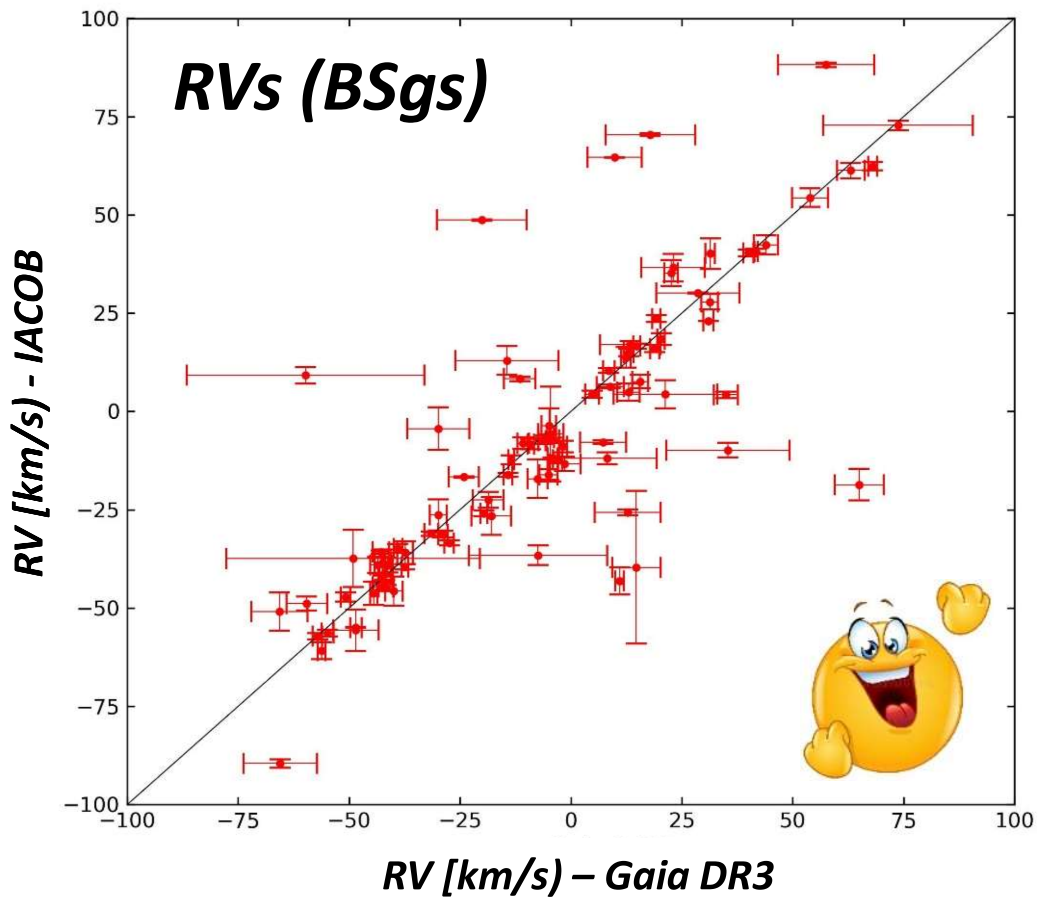




gaia vs. IACOB

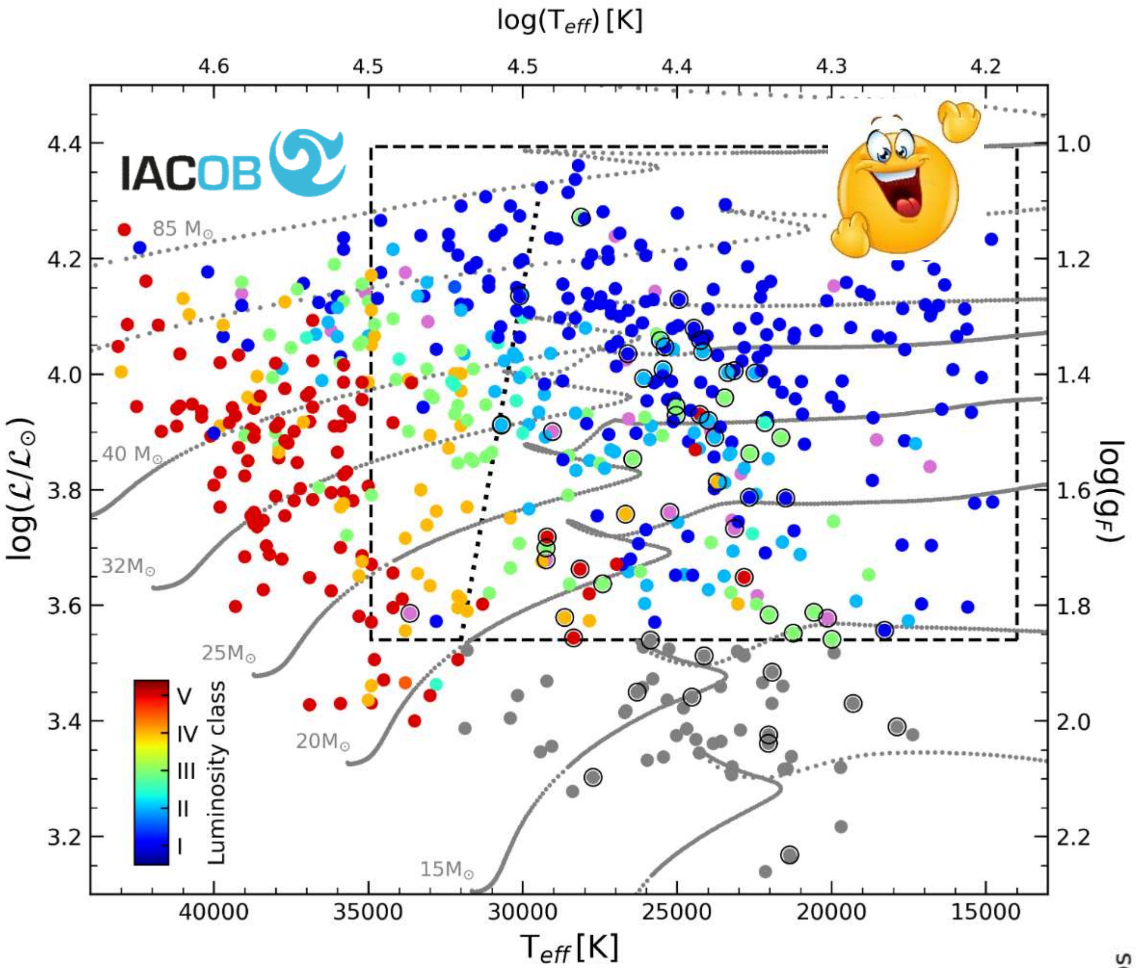


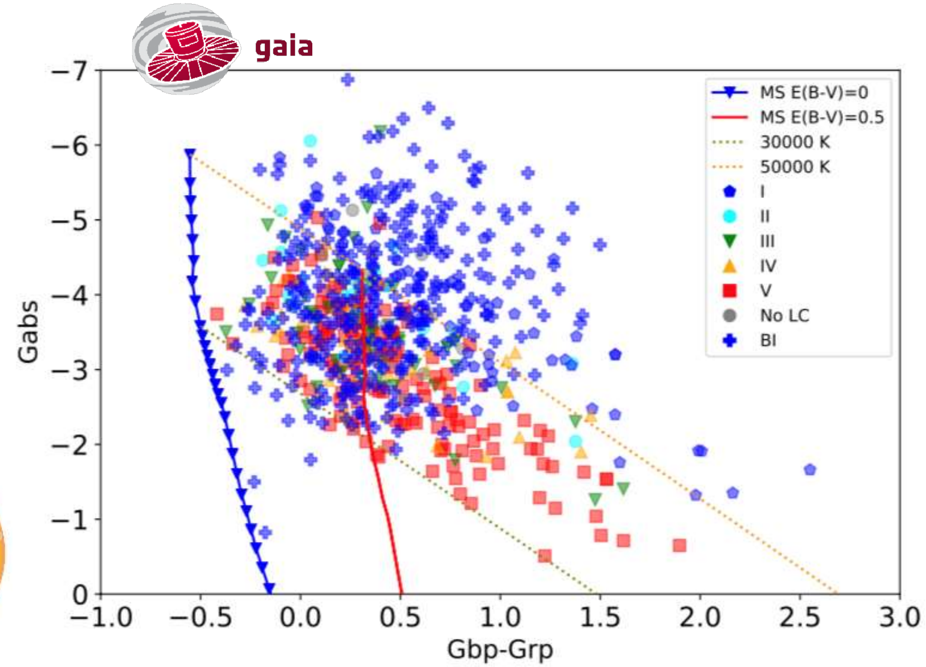
DR3 – Blomme et al. (2022)



gaia vs. IACOB

The gaia view of massive OB-type stars





A **Gaia-CMD** is a very limited tool to provide any constraint on stellar evolution in the high mass domain (extinction + T_{eff} estimation not straightforward). Better to use a (s)HRD

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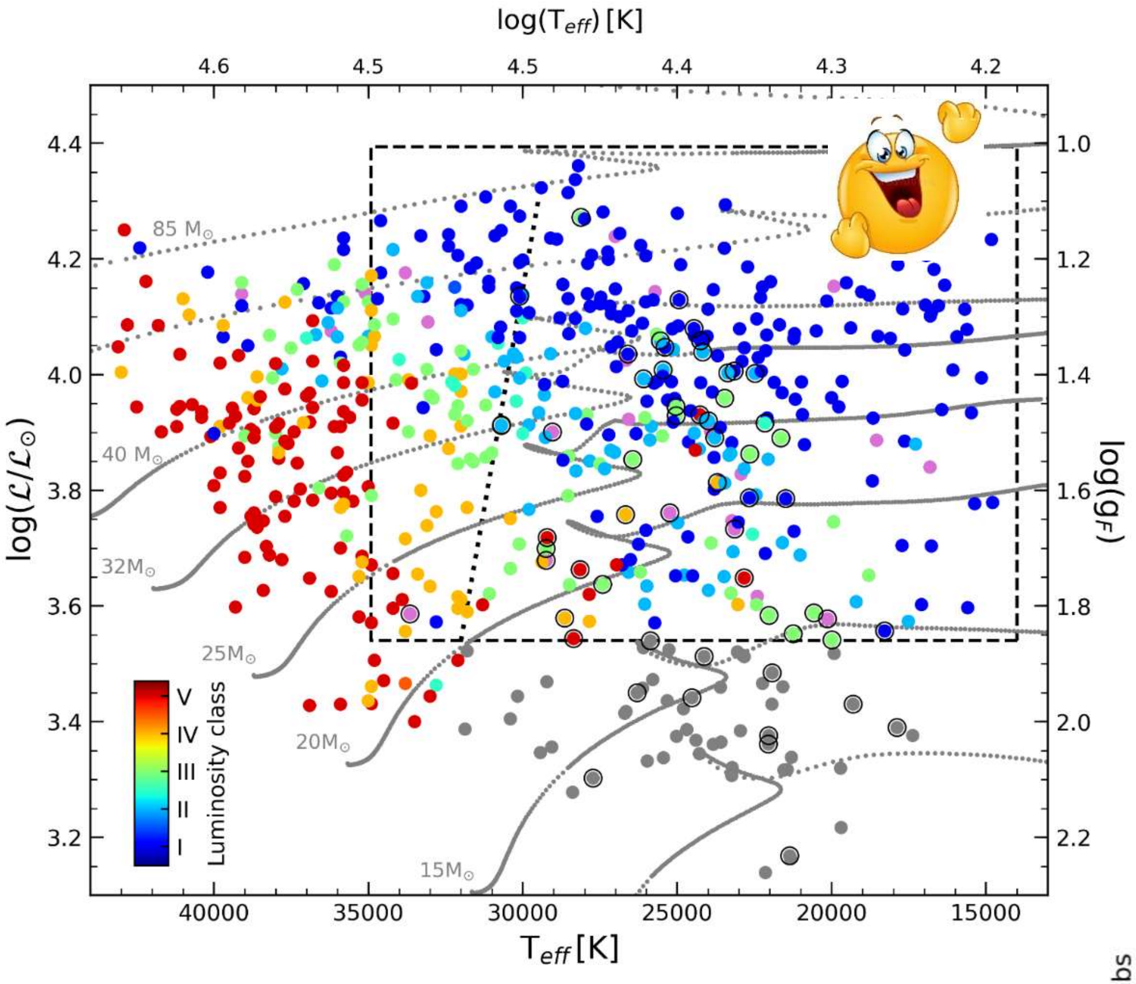

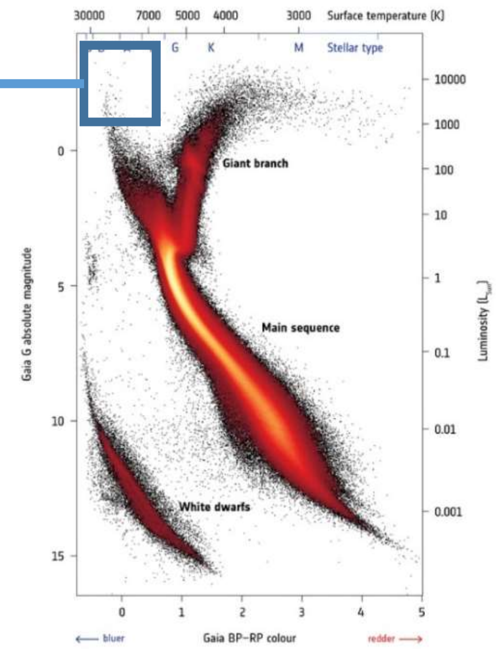

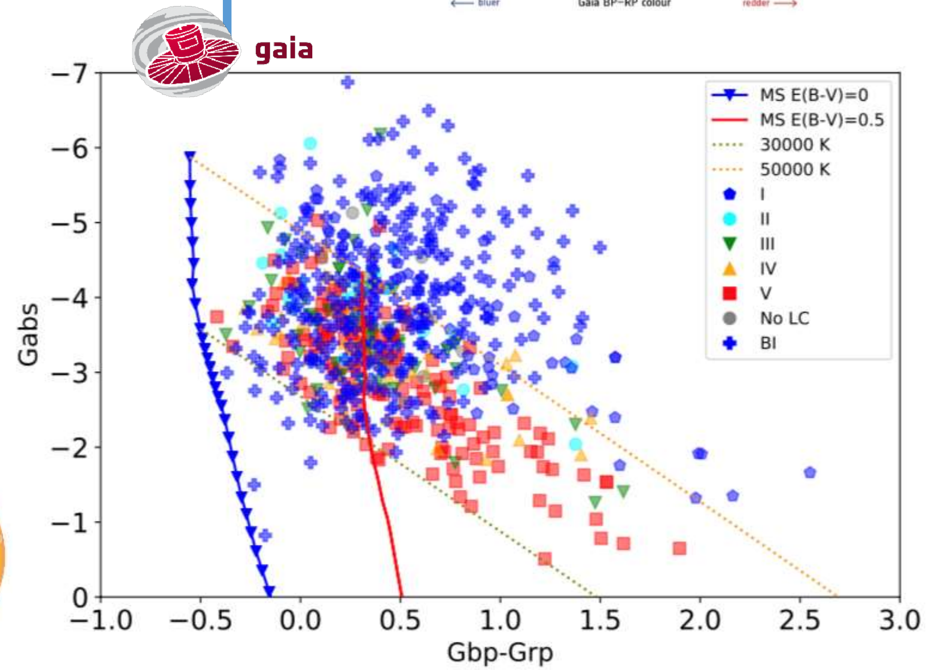

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IACOB: from spectra to astrophysical quantities

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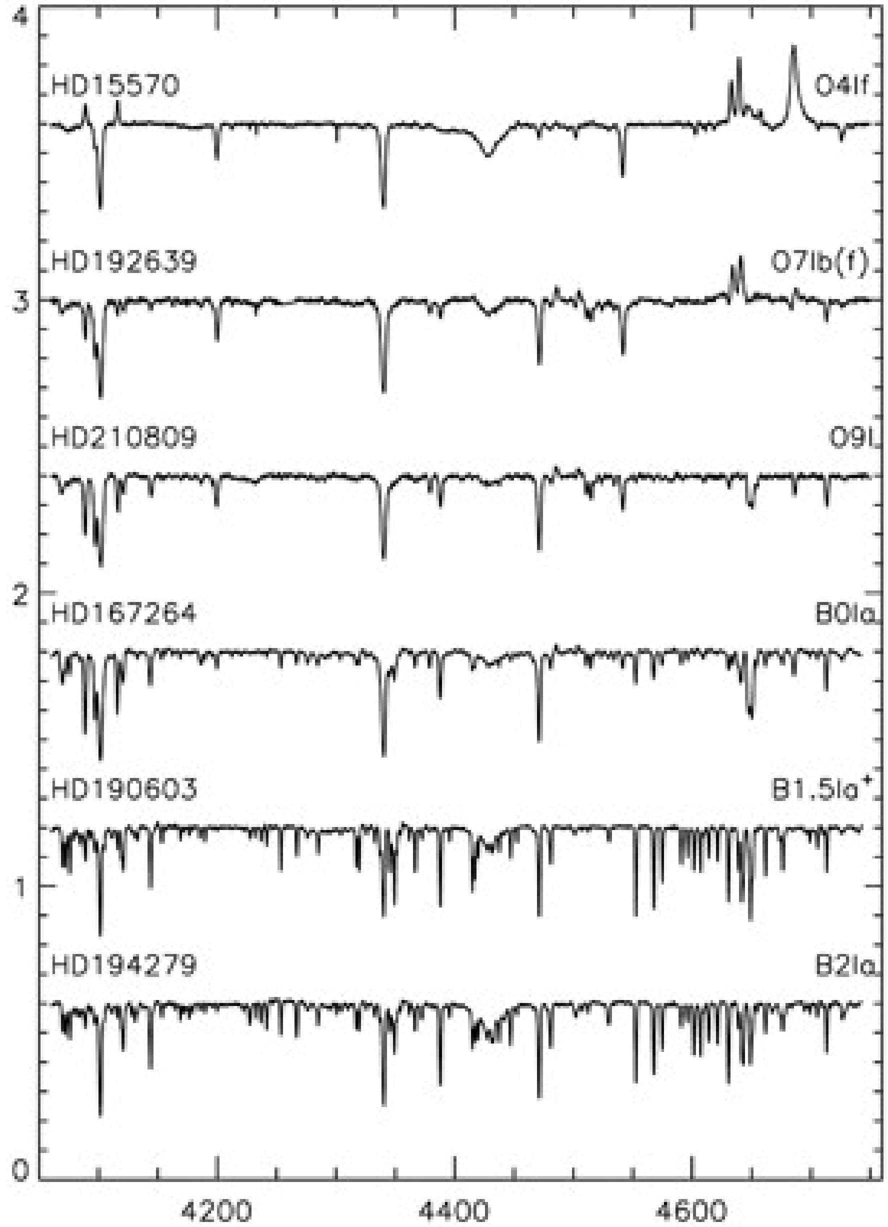


The largest sample of Galactic O-type stars spectroscopically analyzed to date

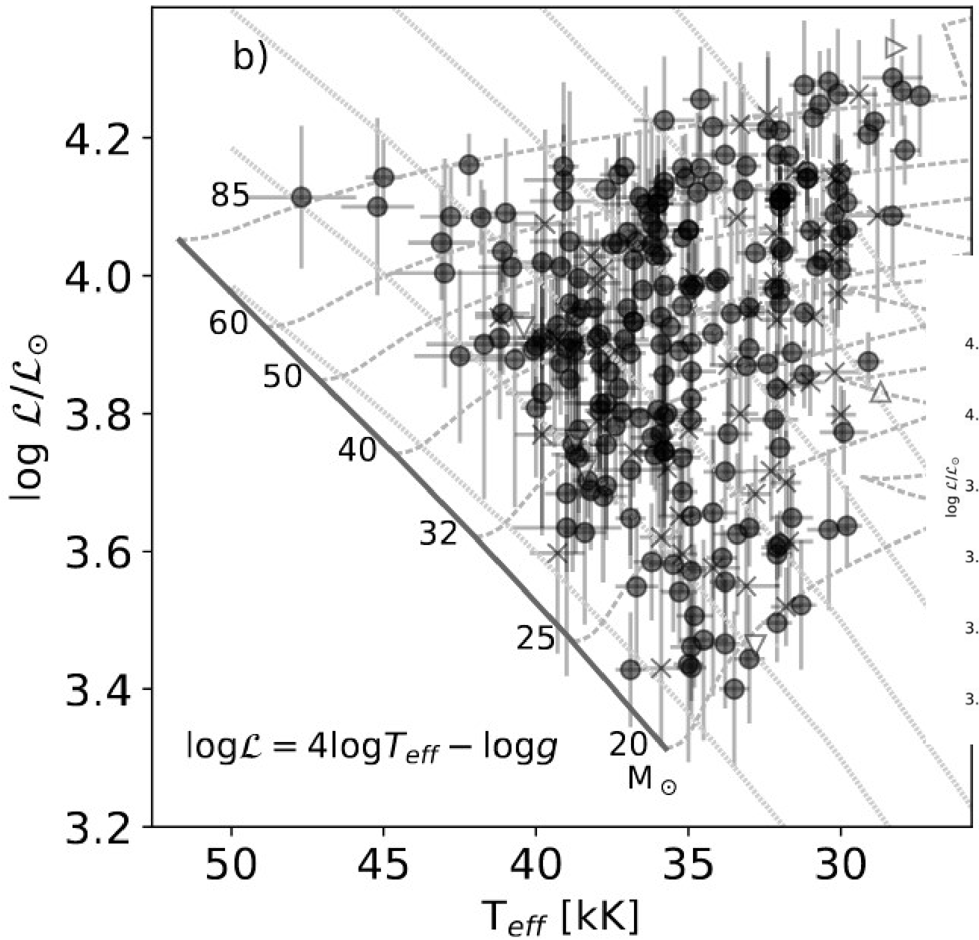
Gonzalo Holgado **(PhD, ULL, 2019)**

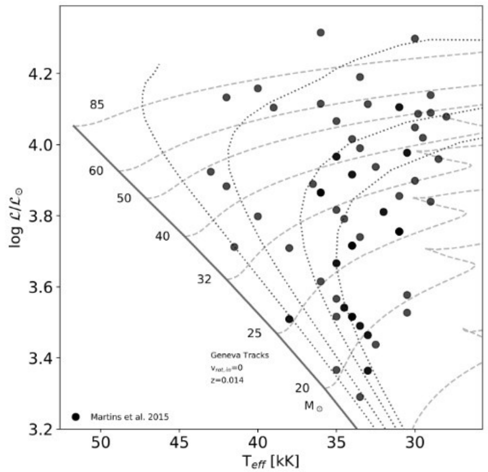
415 Galactic O stars
(70% GOSC)
2900 spectra

Spectroscopic binaries
59 SB1 (14%)
113 SB2 (27%)

Spectroscopic parameters[2]
(+ He abundances)
for 285 likely single and SB1 stars

Increasing the statistics[1] of Galactic O-type stars with spectroscopically determined parameters





Martins et al. 2015)

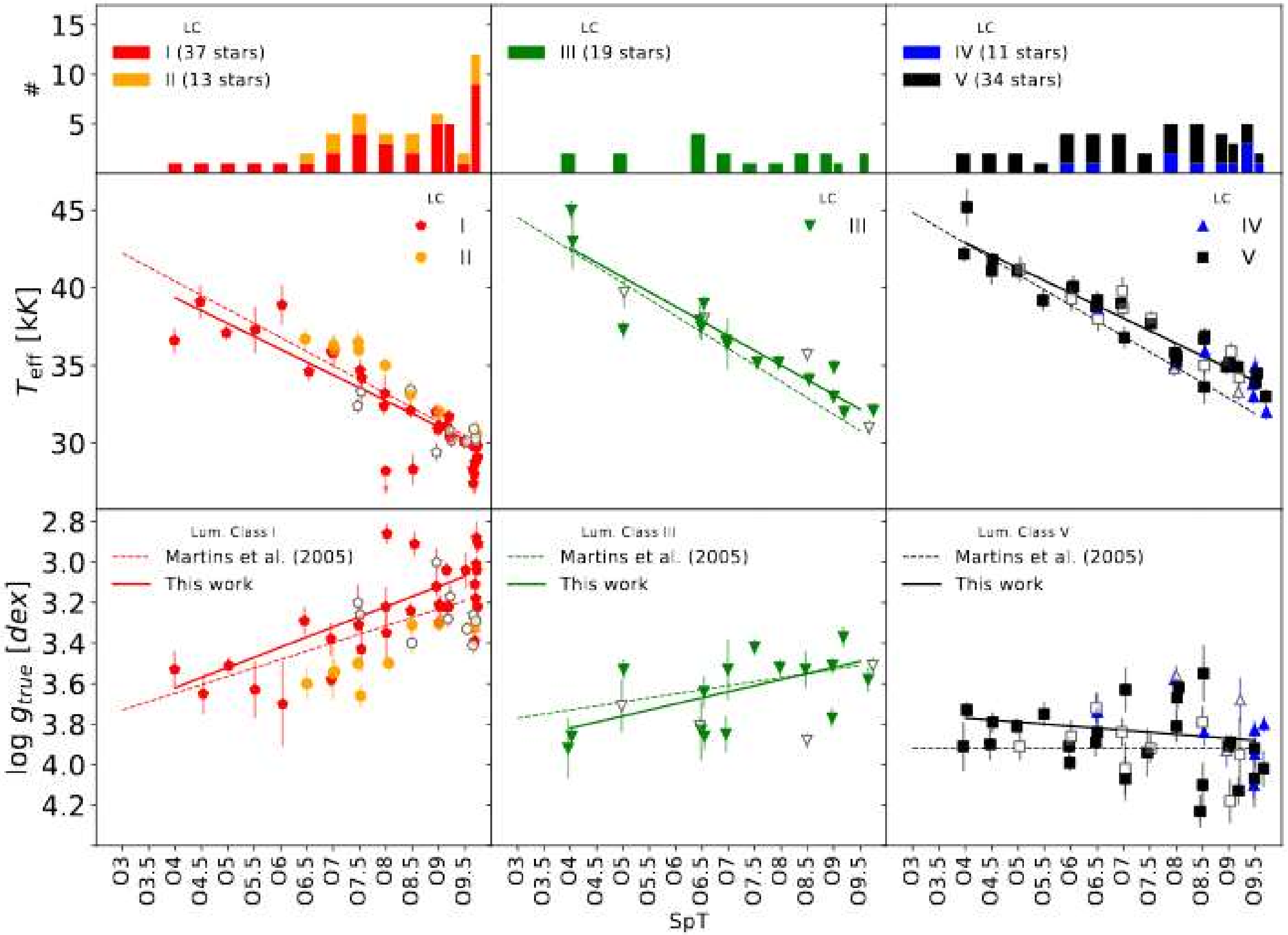
[1] Previous studies included no more than 70 stars (*e.g.,* ***Herrero et al. 1992, Repolust et al. 2004, Martins et al. 2015***)

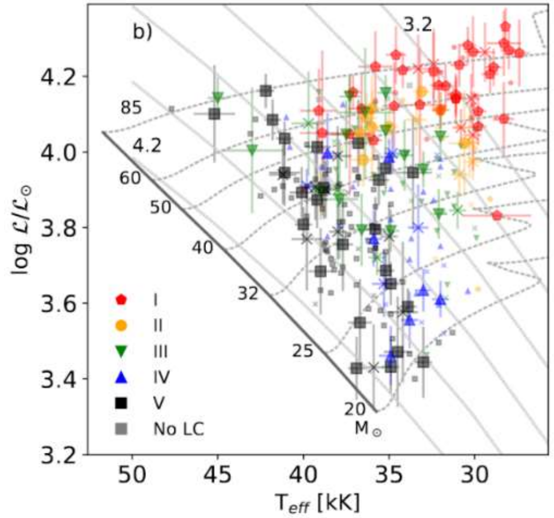
[2] Analysis tools: **IACOB-BROAD** ***(Simón-Díaz & Herrero 2014)*** & **IACOB-GBAT/FASTWIND** ***(Simón-Díaz et al. 2012)***

The largest sample of Galactic O-type stars spectroscopically analyzed to date

Building more robust **SpT/LC – T_{eff}/*logg* calibrations** in Galactic O-type stars (***Holgado et al. 2018***)

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



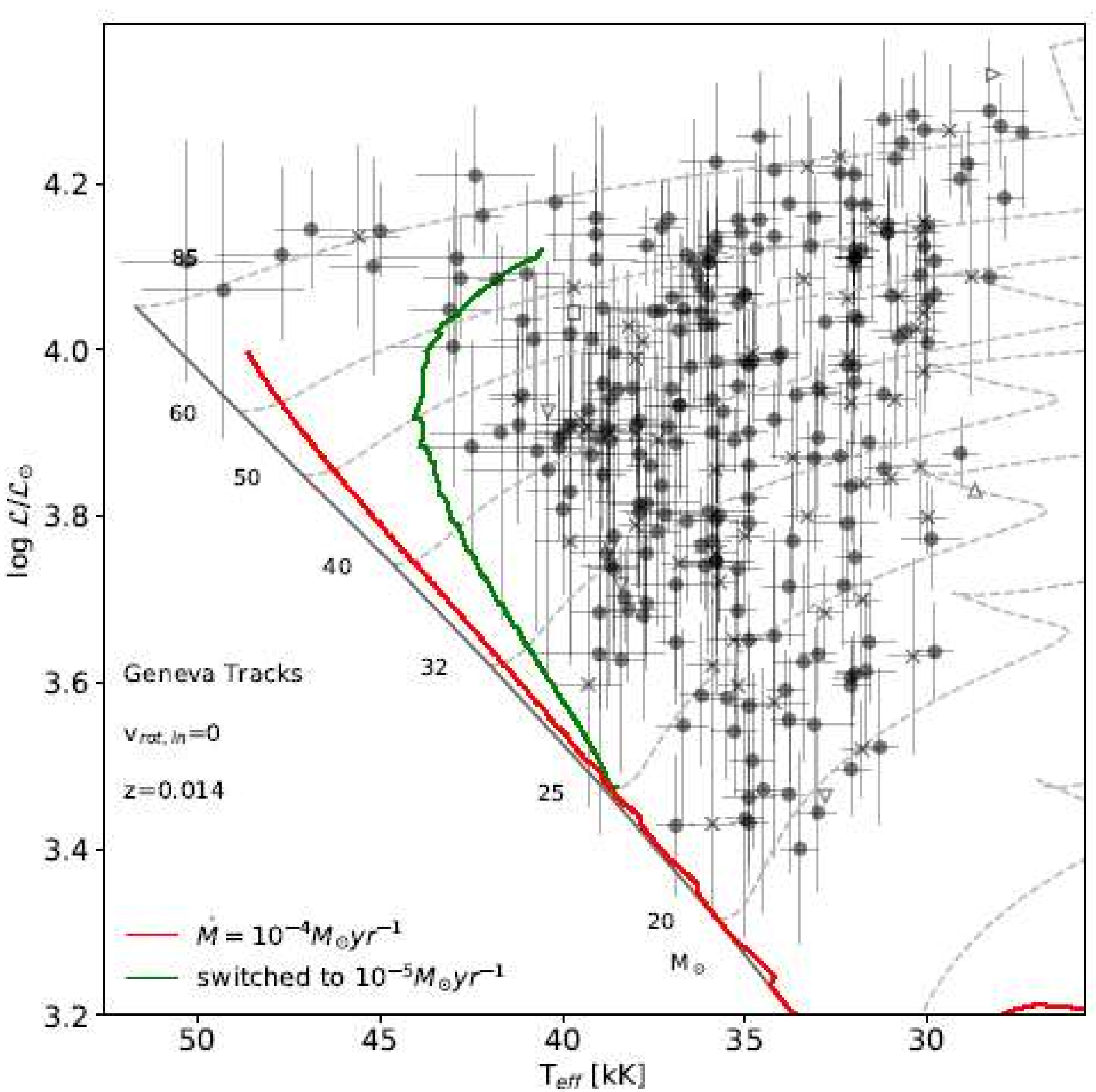


- Larger sample
- Standards + revised SpC
- Homogeneous analysis
- Identification of SB systems

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

The largest sample of Galactic O-type stars spectroscopically analyzed to date

Providing stronger empirical evidence of the **dearth of O-type stars close to the ZAMS** ***(Holgado et al. 2020)***



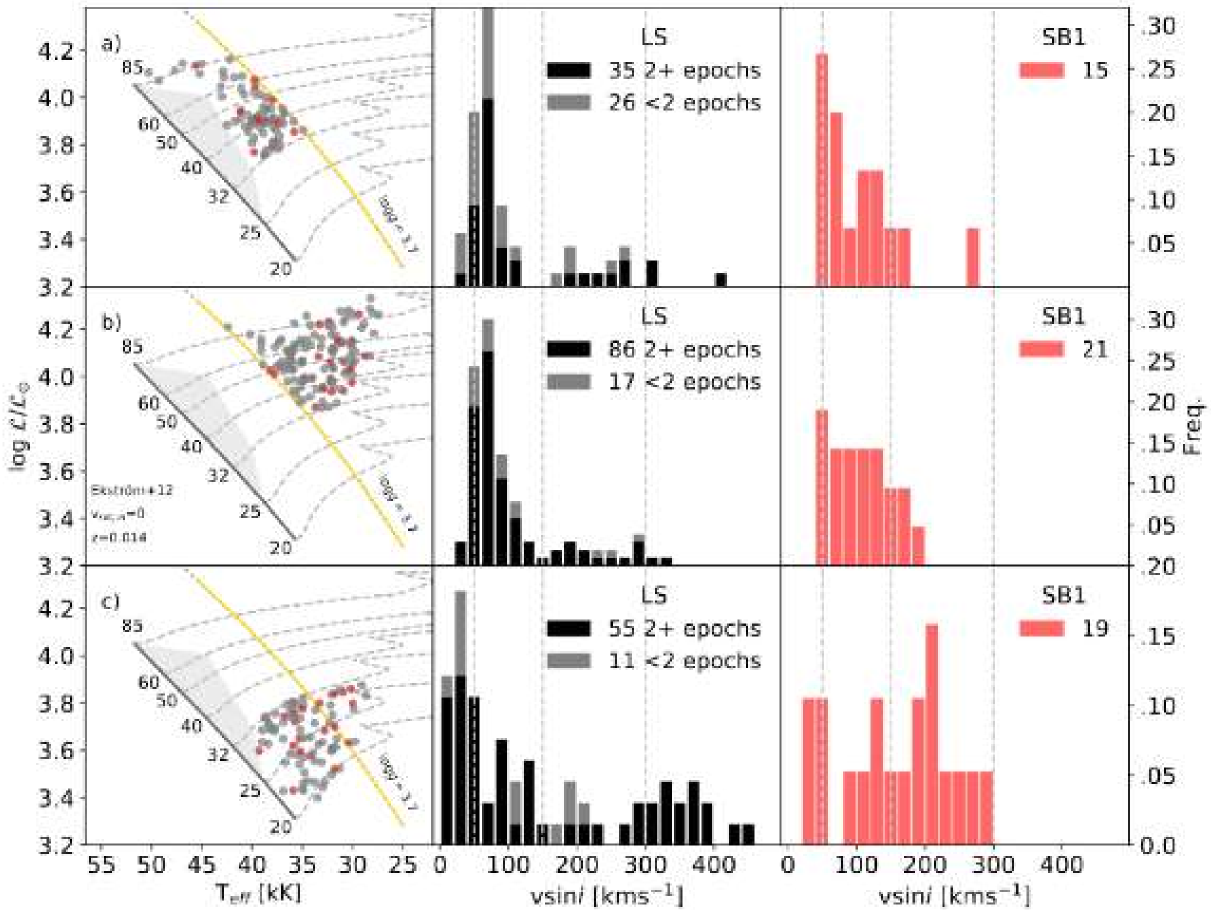
See also talk by G. Meynet

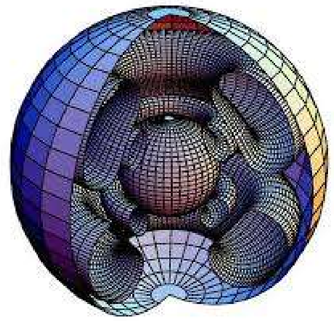
Distribution of 285 Galactic O-type stars in the sHRD (***Holgado et al. 2020***)

+ 2 theoretical stellar birthlines assuming a different accretion rate (***Haemmerle et al. 2019***)

The largest sample of Galactic O-type stars spectroscopically analyzed to date

Improving and extending further our empirical knowledge about **rotational velocities** in Galactic O-type stars … as well as the **efficiency of internal angular momentum transport and rotational mixing**[1]





[1] On the importance of rotation in massive stars: ***Maeder & Meynet (2000)***

+ rotational mixing drives core processed chemical elements to the stellar surface

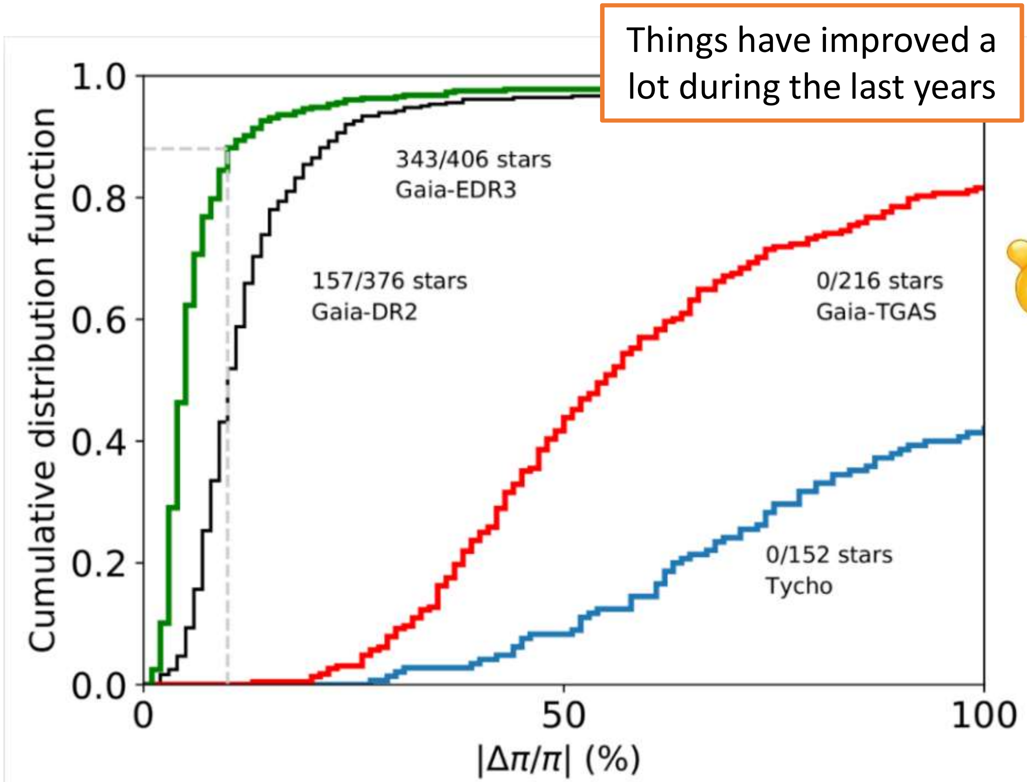
+ Next step … He, C, N, O abundances

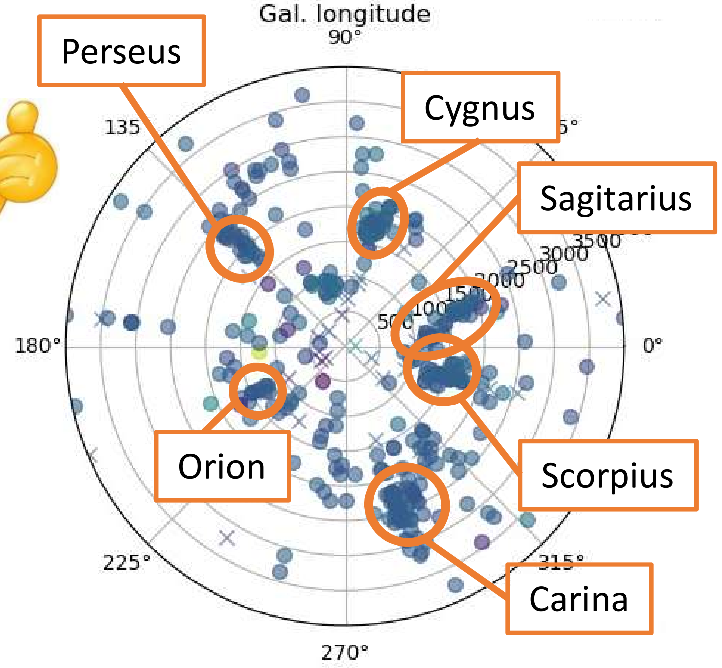
- **No important surface braking effect** is detected during MS evolution even for M > 30 $M_{\odot}$
- **O stars are born with less than 20% critical velocity**. Following de Mink et al. (2013, 2014), the tail of fast rotators (vsini > 200 km/s, 25% of the sample) is most likely populated by mass gainers.

Parallaxes & proper motions

Having access to:

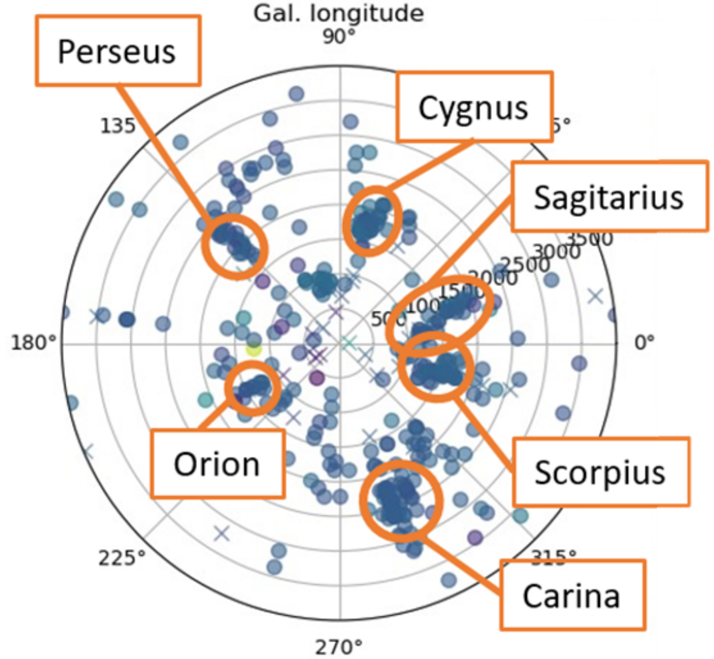
(1) distances is critical to obtain the **fundamental stellar parameters** (R, L, M)
(2) **kinematical** and **environmental information** is an important plus for the interpretation of results (e.g. cluster membership, runaways, …)

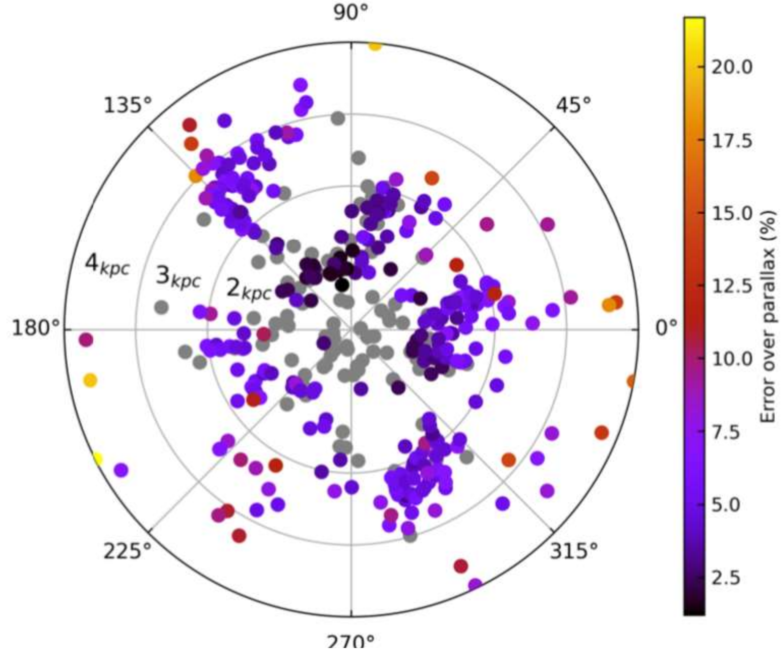




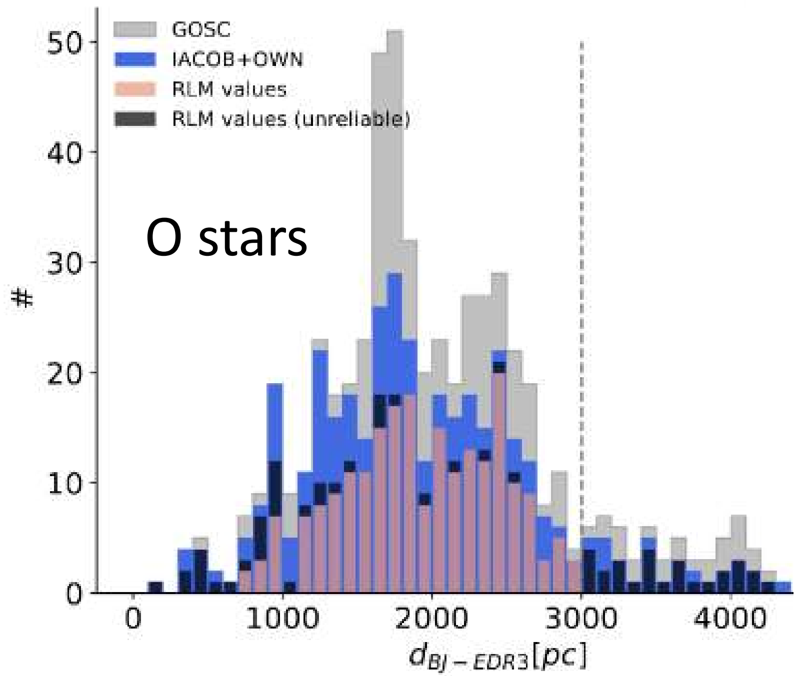
Figures from the ***PhD thesis of G. Holgado (2019, Univ. La Laguna)*** updated with data from EDR3

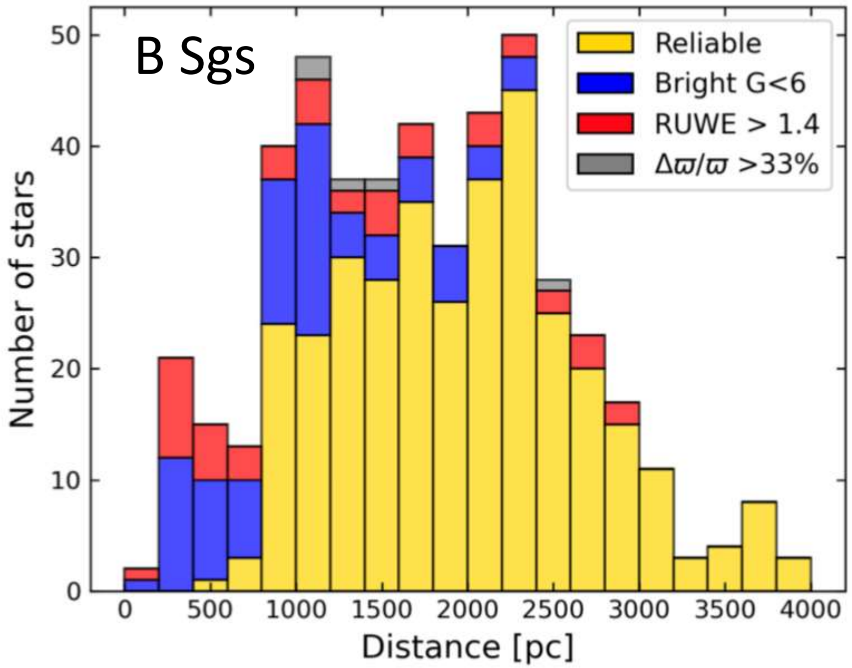
IACOB and Gaia (parallaxes: e.g. the O and B Sg samples)

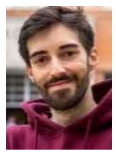


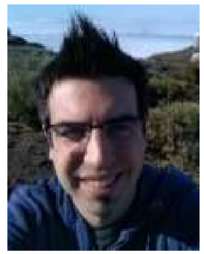


gaia
EDR3

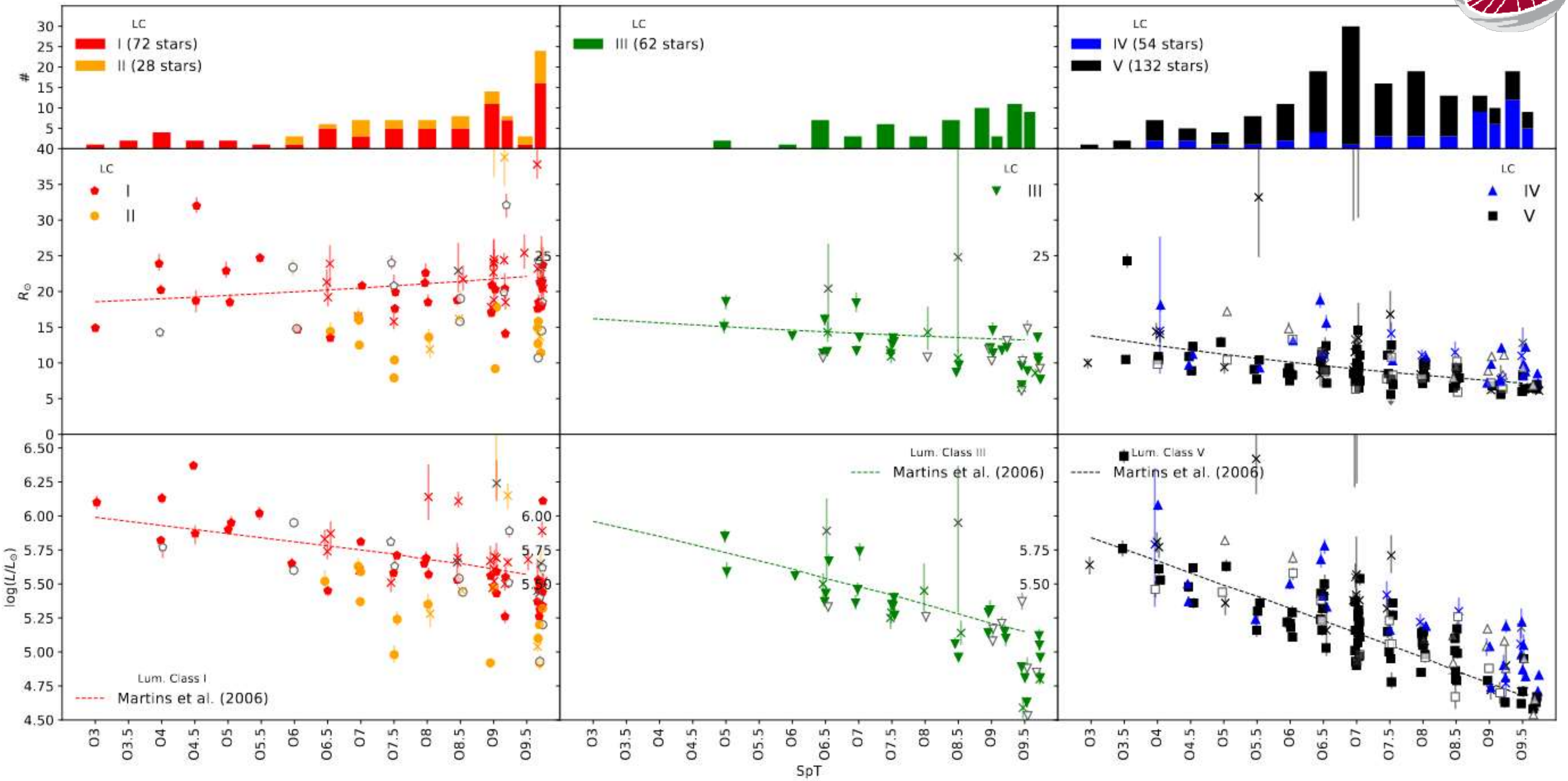






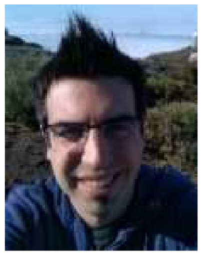


The importance of Gaia for IACOB: parallaxes → fundamental parameters

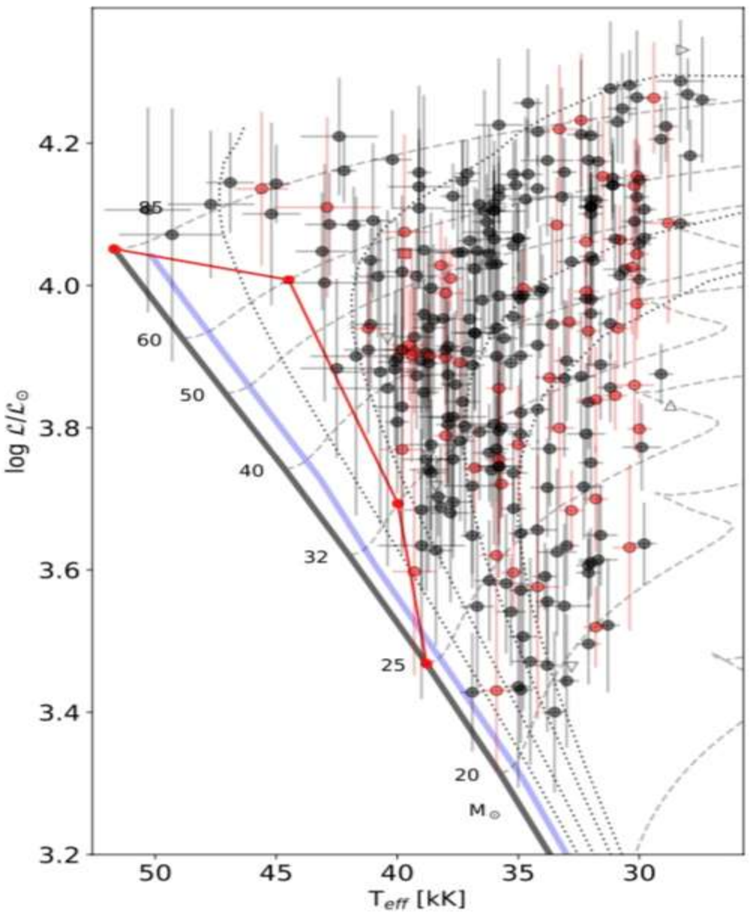


X. Updated empirical calibrations of fundamental parameters of Galactic O-type stars using *Gaia* DR3

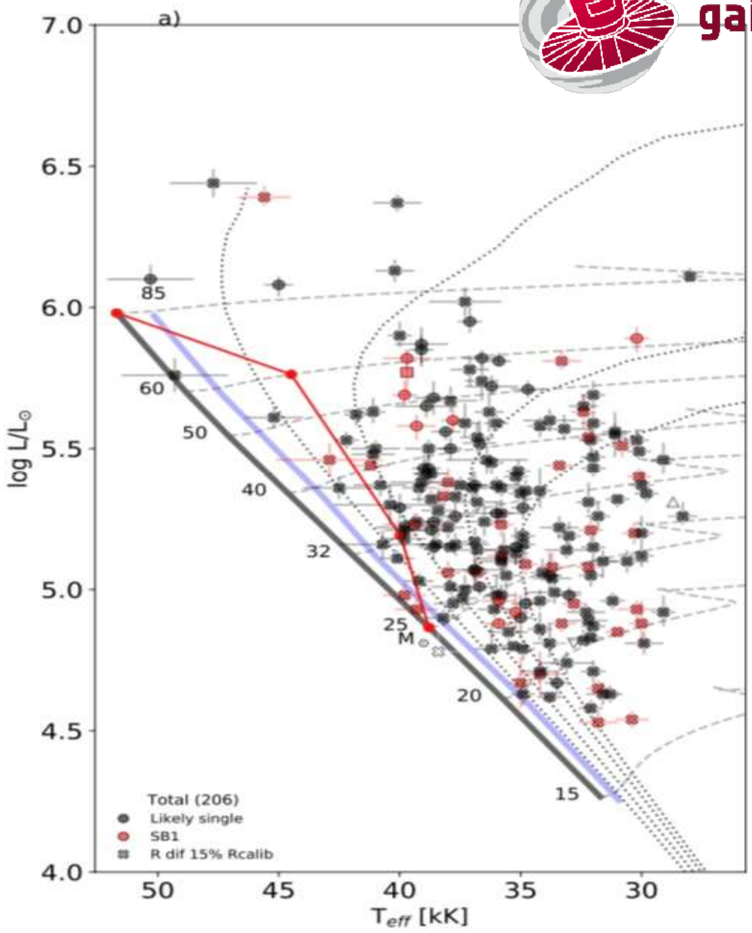
G. Holgado[1,2,3], S. Simón-Díaz[2,3], A. Herrero[2,3], R. H. Barbá[4]



The importance of Gaia for IACOB: sHRD→ HRD



Mind the different location of the stars in the (s)HRD



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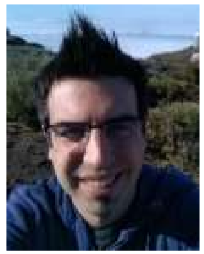


+ We will be able to revisit the longstanding mass discrepancy problem (***Herrero et al. 1992***)

IACOB and Gaia (joining parallaxes and proper motions)

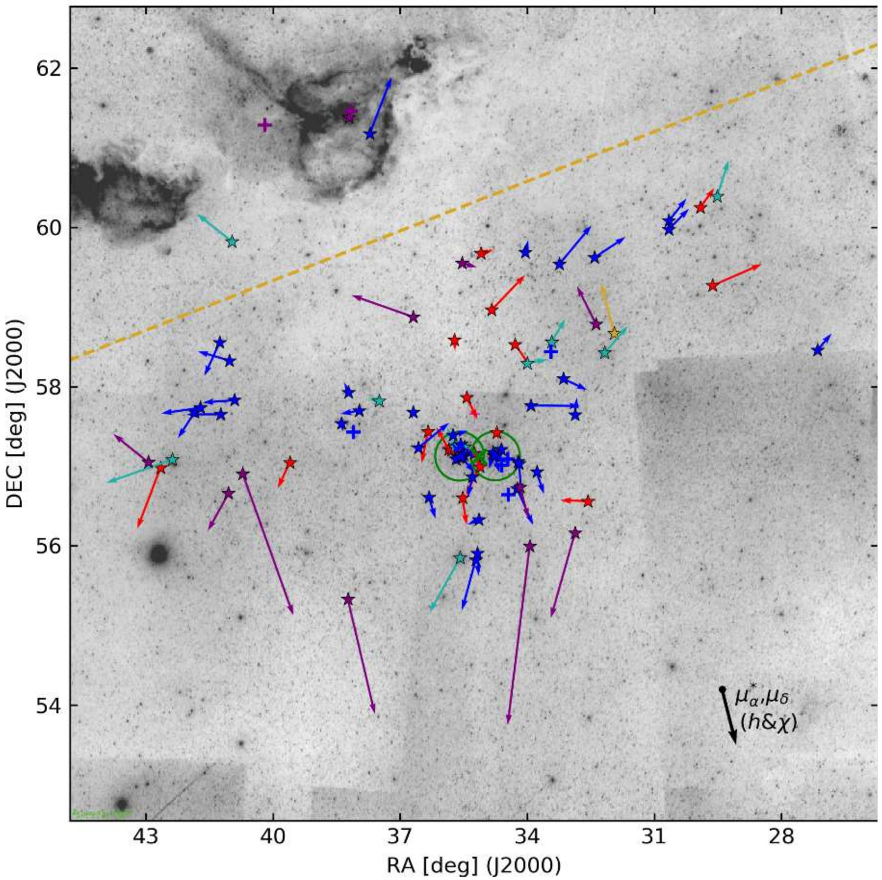
High-resolution spectroscopic study of massive blue and red supergiants in Perseus OB1

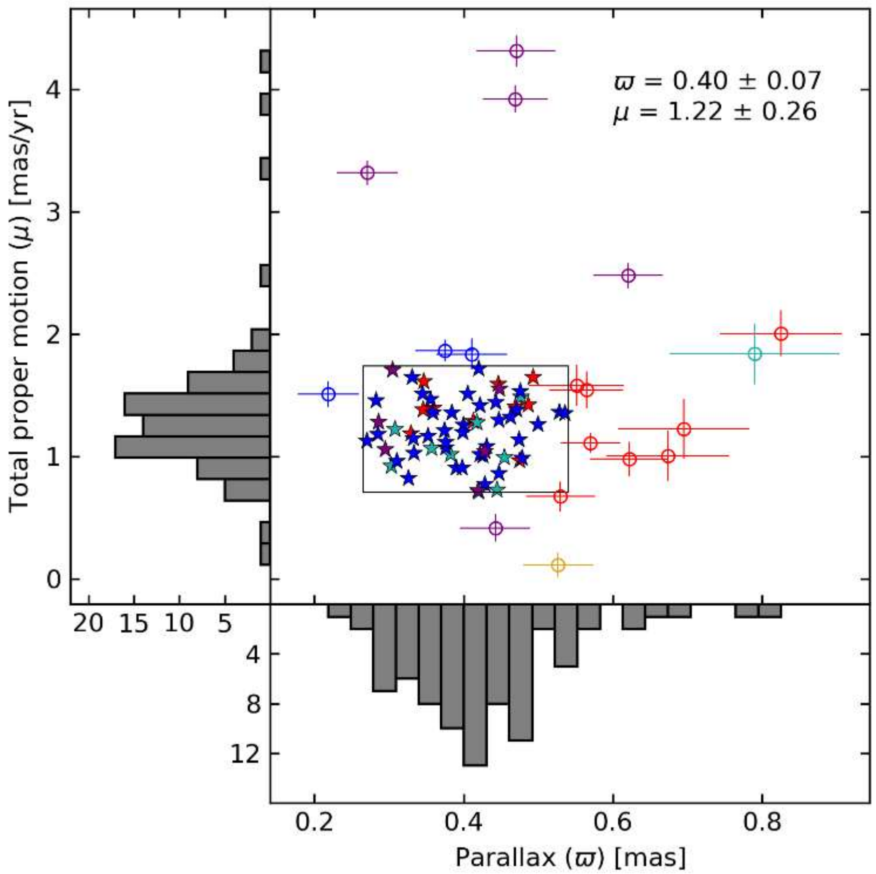
I. Definition of the sample, membership, and kinematics*

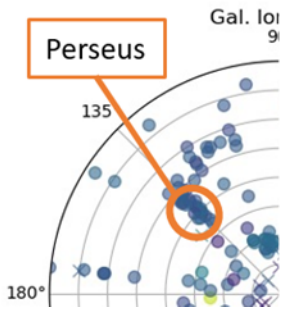
A. de Burgos[1,2,3], S. Simon-Díaz[3,4], D. J. Lennon[3,4], R. Dorda[3,4], I. Negueruela[5], M. A. Urbaneja[6], L. R. Patrick[3,4,5], and A. Herrero[3,4]

gaia

DR2







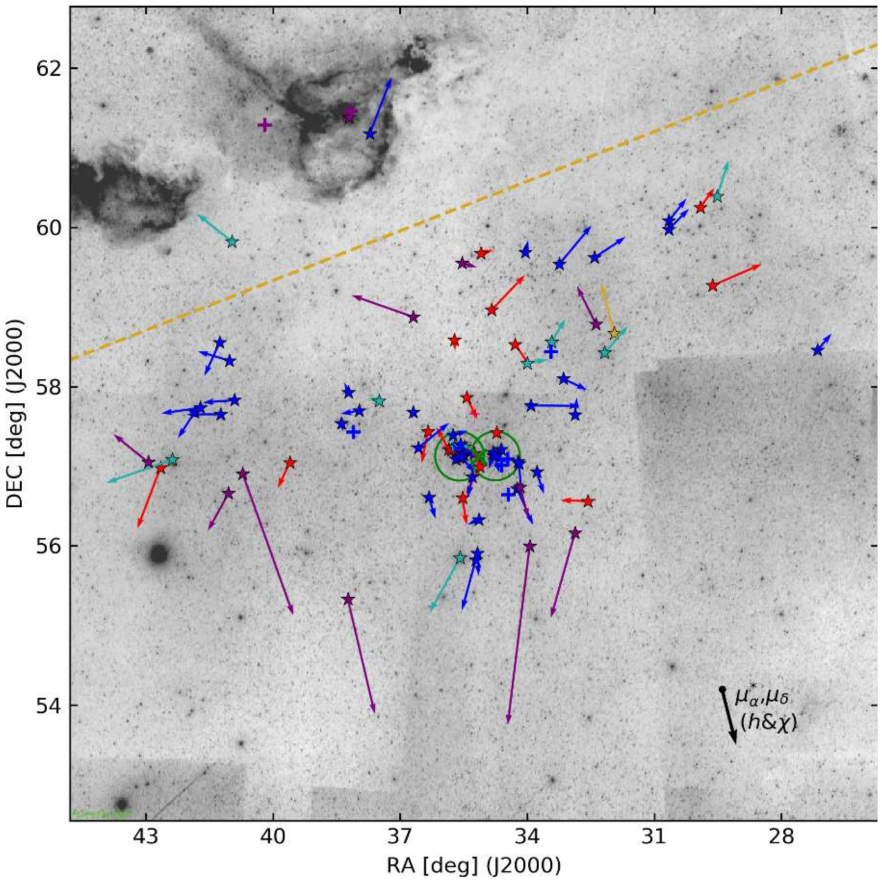
IACOB and Gaia (joining parallaxes and proper motions)

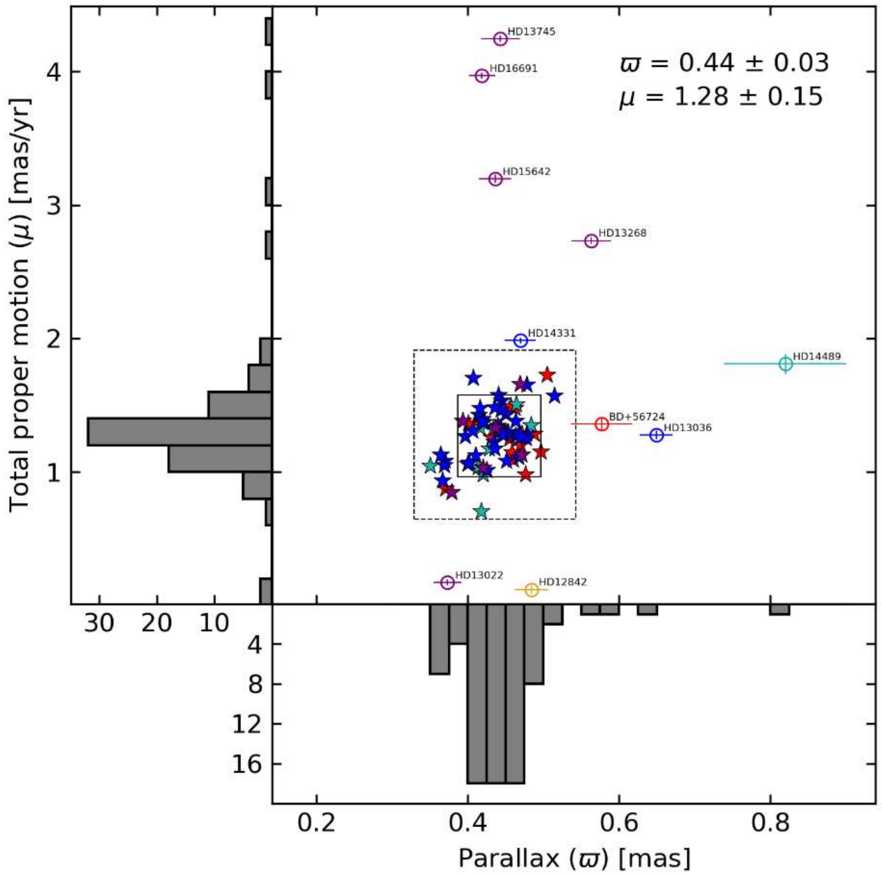
High-resolution spectroscopic study of massive blue and red supergiants in Perseus OB1

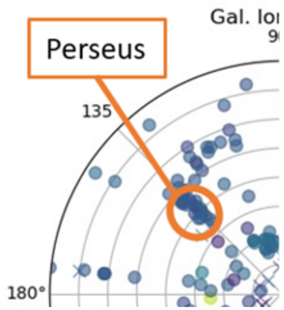
I. Definition of the sample, membership, and kinematics*

A. de Burgos[1,2,3], S. Simon-Díaz[3,4], D. J. Lennon[3,4], R. Dorda[3,4], I. Negueruela[5], M. A. Urbaneja[6],
L. R. Patrick[3,4,5], and A. Herrero[3,4]

gaia
EDR3





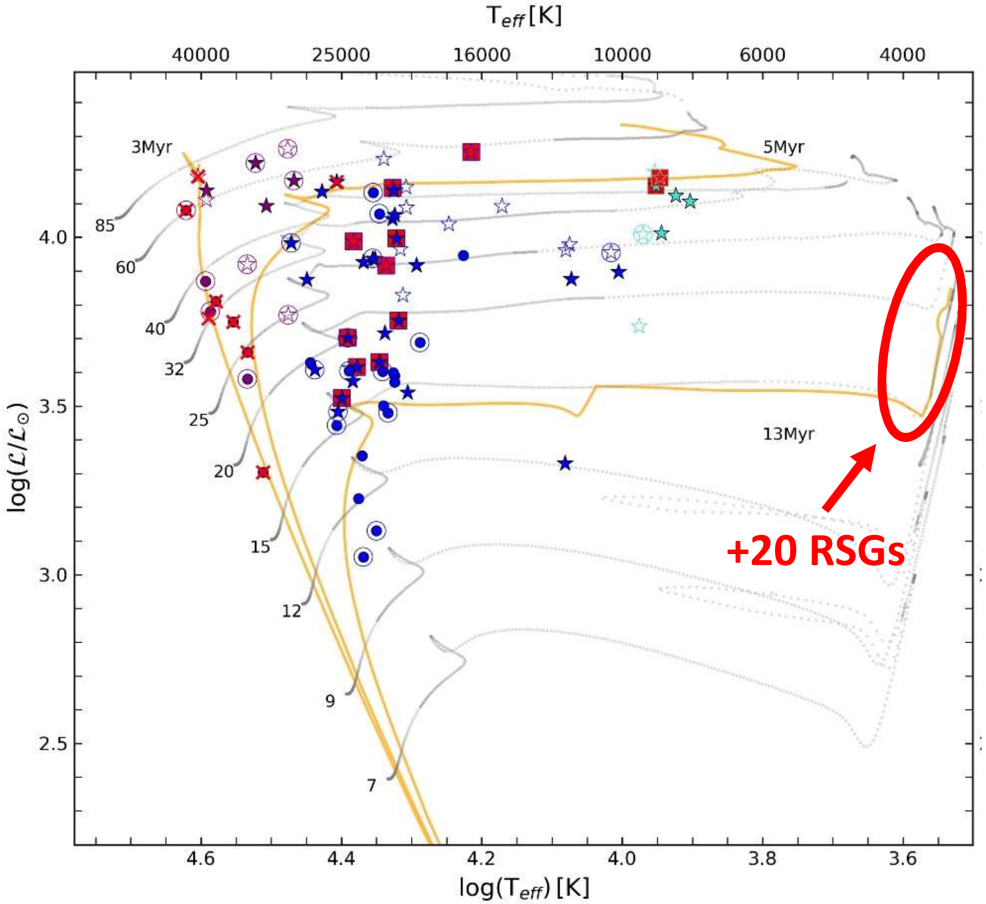


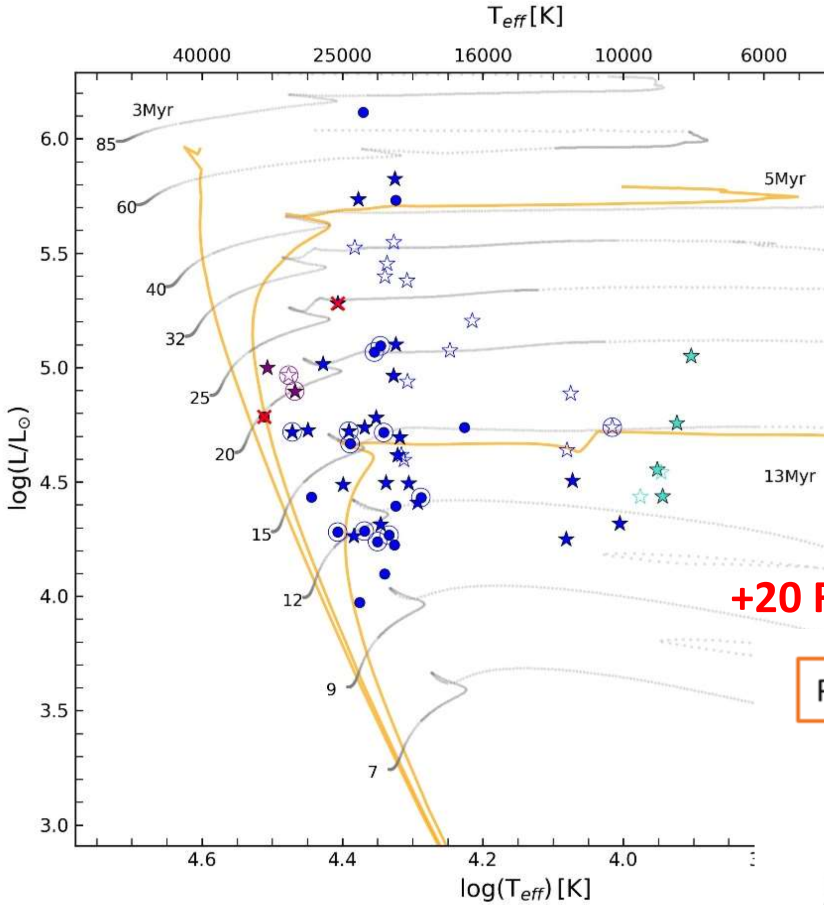
IACOB and Gaia (joining parallaxes and proper motions)

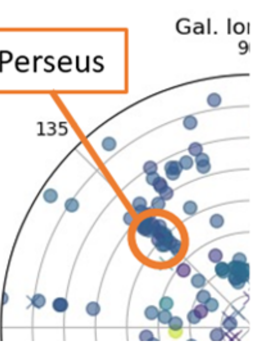
High-resolution spectroscopic study of massive blue and red supergiants in Per OB1

II. Spectroscopic and stellar parameters.

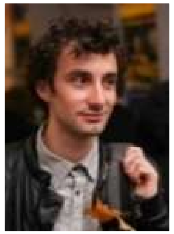
de Burgos, A.[1], Simon-Díaz, S.[1,2], Urbaneja, M. A.[3]



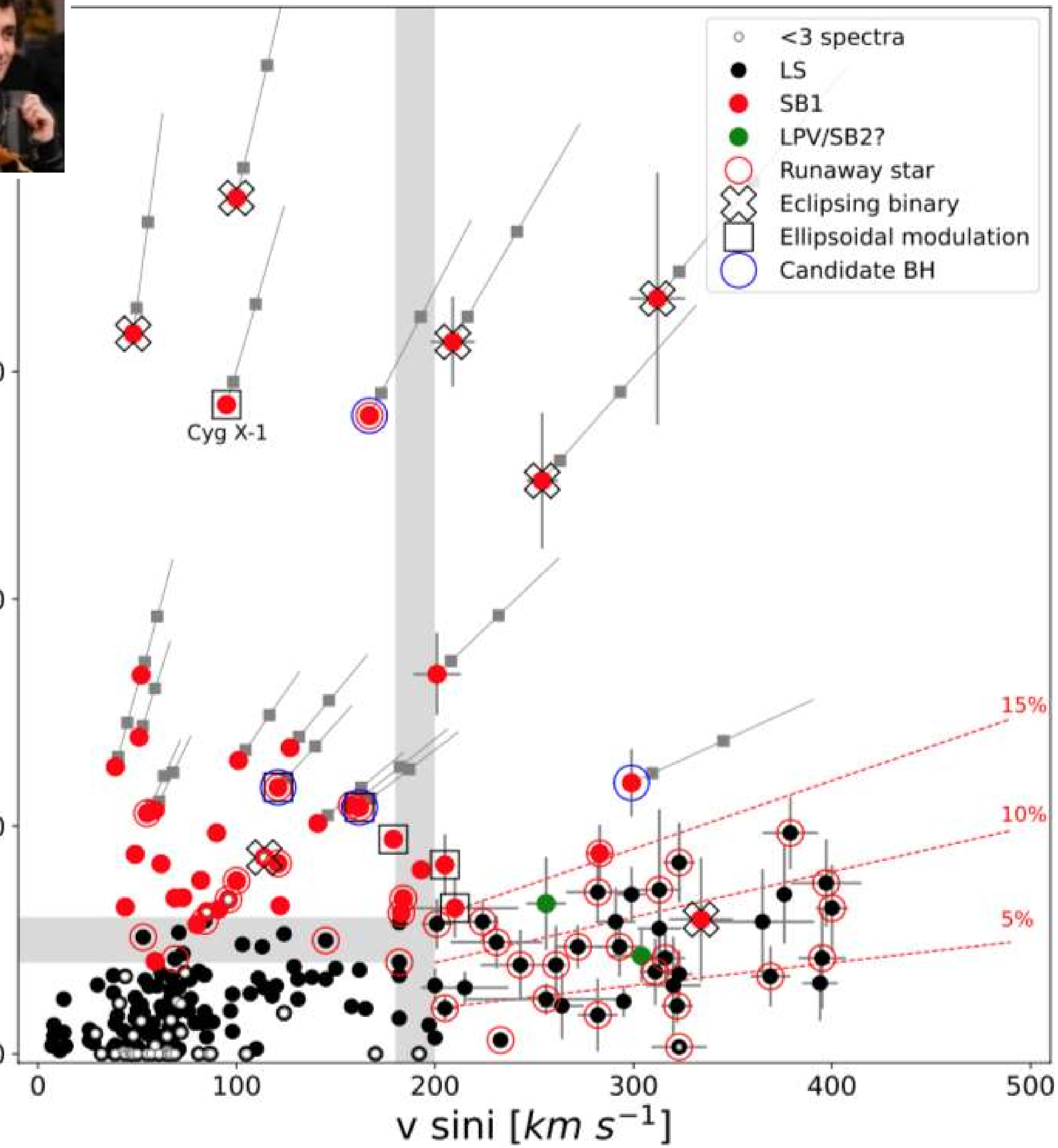




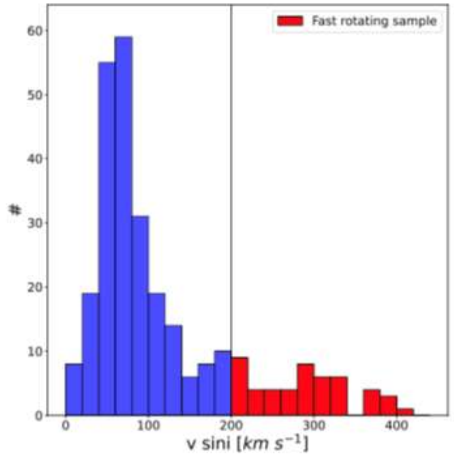
Are all fast rotators the products of binary interaction?



(***Britavskiy et al., subm.***)

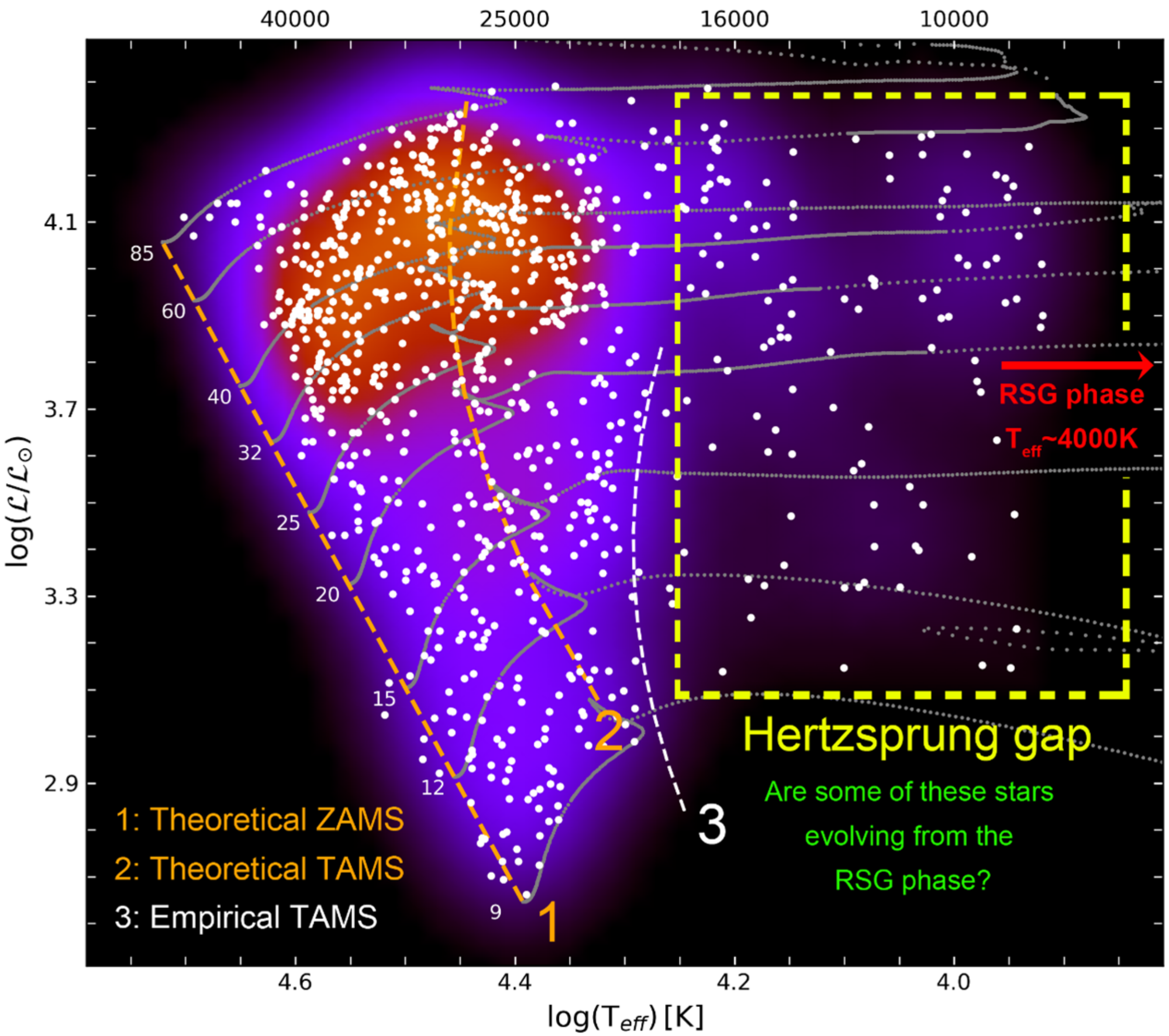


	Slow (365)	Fast (50)
SB2	≈ 25 %	≈ 1 %
SB1	≈ 10-20 %	≈ 10-20 %
LS	≈ 55-60 %	≈ 75-80 %
RW	≈ 20-30 %	≈ 35-50 %



More than 70% of the fast rotating O-type stars detected as LS are also runaways

Jumping to the B supergiant domain (they shouldn't be there!)



Abel de Burgos (PhD thesis, started Oct. 2019)

On the evolutionary nature of massive B-type Sgs: a modern empirical reappraisal using data from IACOB, Gaia and TESS

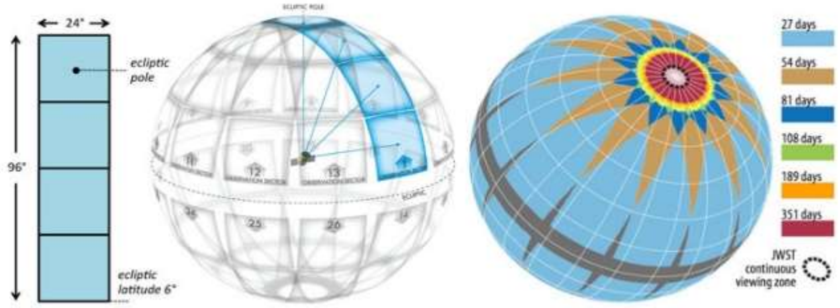
- ≈ **700 Galactic B-Sgs**
- > 4500 high-resolution spectra
- SB and LPV detection
- Spectroscopic parameters and surface abundances
- Gaia astrometry + TESS variability

IX. New empirical constraints for 700 BSGs within 12 – 85 $M_\odot$ range

de Burgos, A.[1,2], Simon-Díaz, S.[1,2], Urbaneja, M. A.[3], and a few Others

First paper in prep.

The interest of establishing synergies between IACOB *and* TESS



Despite not being its main scientific objective TESS is delivering

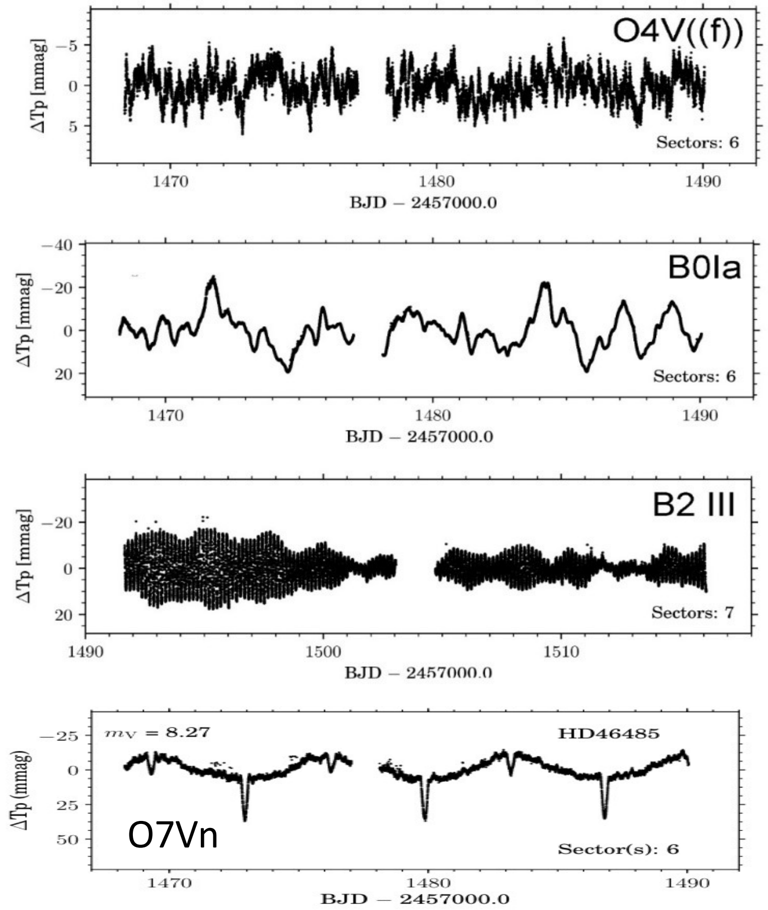
- high-cadence (2 & 30 min)
- high-precision (at μmag)

light curves for several thousands of OB stars with a minimum time-span of 27 days

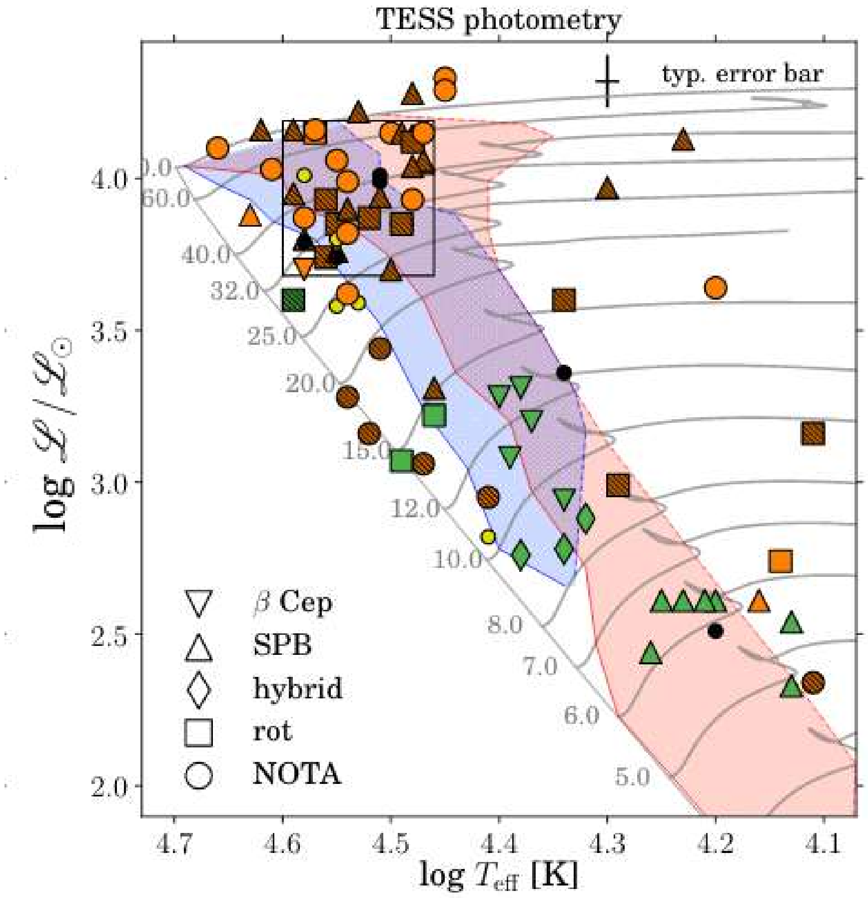
But the identification and physical characterization of the OB stars cannot be done with the light curves alone. Having access to optical spectroscopy is a MUST for it

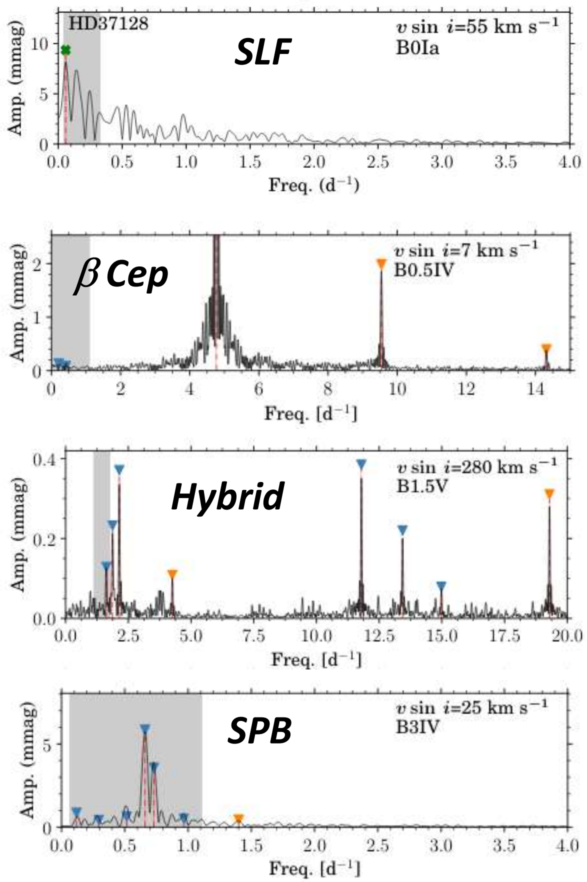
TESS is definitely opening the doors to the interior of high-mass OB-type stars

Examples of photometric variability of OB stars in TESS sectors 1-13 ***(Burssens et al. 2020)***



Joining efforts in a very promising "novel" line of research





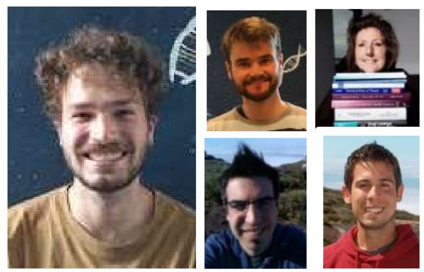
MAMSIE + IACOB

Most important origins of the photometric variability which is being detected in the TESS LCs of OB-type stars:

- **Stellar oscillations**
  - Heat driven modes
  - Internal gravity waves
- **Eclipsing binaries**
- **Rotational modulation**
  - Spots
  - Stellar winds
  - Circumstellar discs
  - Magnetospheres

Variability of OB stars from TESS southern Sectors 1–13 and high-resolution IACOB and OWN spectroscopy★

S. Burssens[1], S. Simón-Díaz[2,3], D. M. Bowman[1], G. Holgado[2,3,4], M. Michielsen[1], A. de Burgos[2,3,5], N. Castro[6], R. H. Barbá[7], and C. Aerts[1,8,9]




STOP

Main take-away messages (for this conference)

IACOB

(1) Gaia revolution will certainly have an impact on our understanding of massive star evolution (parallaxes, proper motions, detection of EB and Evs).

BUT

(2) Contrarily to the case of FGK-star, making progress in massive star evolution with Gaia requires to have access to ground-based spectroscopic support.

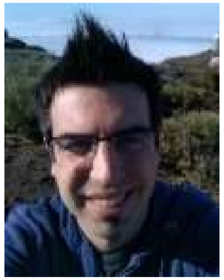
FORTUNATELLY

(3) … we've put a lot of efforts in the last 15 years to make this a reality (and we will keep going for at least 5-10 years more.

STAY TUNED, BECAUSE …

(4) … the IACOB project (with the aid of Gaia, TESS and WEAVE) is helping to produce and updated (more realistic) view of massive star evolution

DIRECTLY CONTRIBUTING TO RESULTS PRESENTED IN THIS TALK:


Gonzalo Holgado

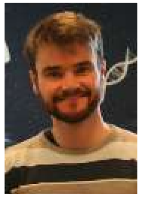

Abel de Burgos


Siemen Burssens

SOME OTHER GROUP MEMBERS AND COLLABORATORS (IN ALPHABETIC ORDER):


Conny Aerts


Rodolfo Barbá


Dominic Bowman


Nikolay Britavskyi


Alba Casasbuenas


Ricardo Dorda


Sylvia Ekström


Roberto Gamen


Miriam Garcia


Artemio Herrero


Norbert Langer


Danny Lennon


Jesús Maíz Apellaniz


Carlos Martínez


Sébastien Martinet


Georges Meynet


Athira Menon


Paco Najarro


Kaila Nathaniel


Ignacio Negueruela


Miki Pantaleoni


Jo Puls


Sara Rodríguez


Klaus Rübke


Alejandro Santos


Miguel Urbaneja

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EXCELENCIA SEVERO OCHOA
Universidad de La Laguna
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES
Unión Europea
Fondo Europeo de desarrollo Regional
"Una manera de hacer Europa"