Catalogue of new high-mass Pre-Main Sequence and Classical Be stars

A Machine Learning approach to Gaia data

Miguel Vioque

University of Leeds

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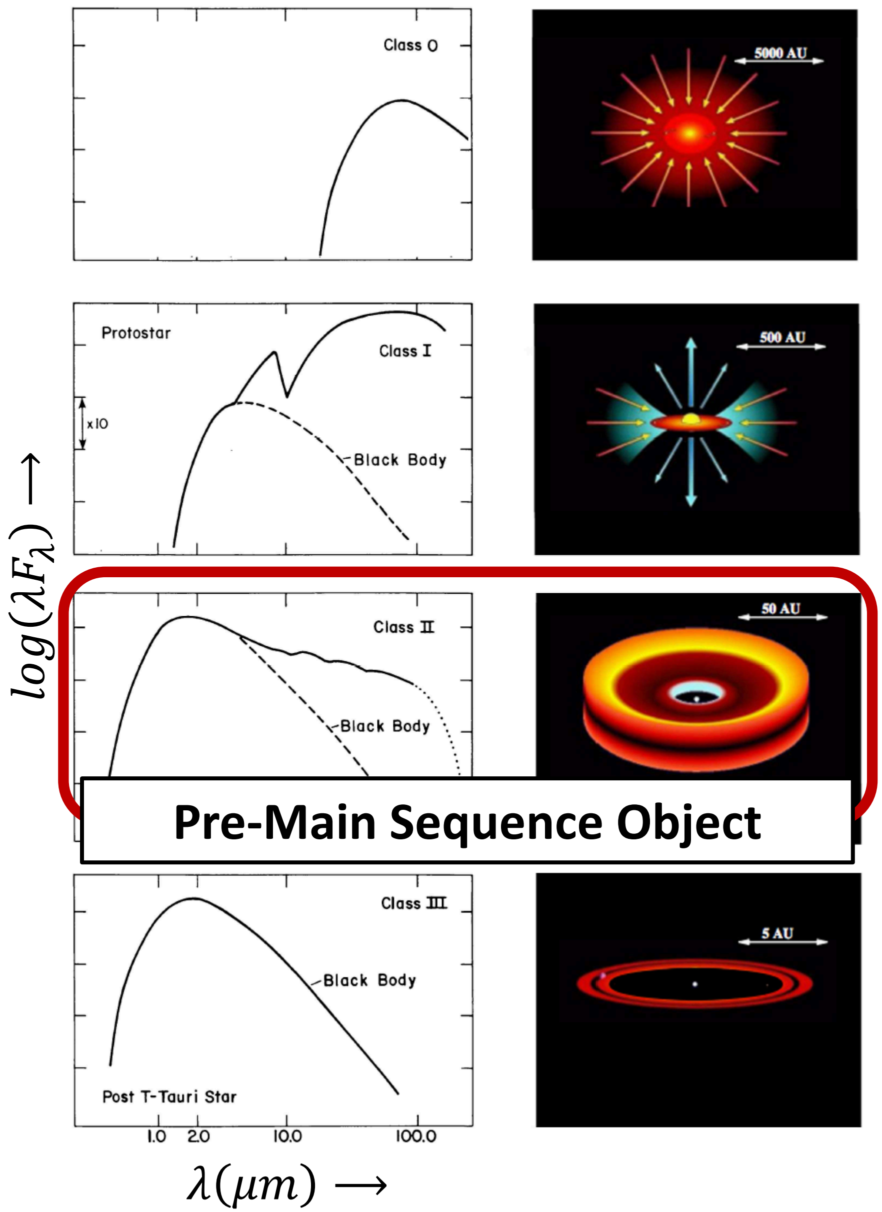
STARRY STARS THAT 'R' YOUNG

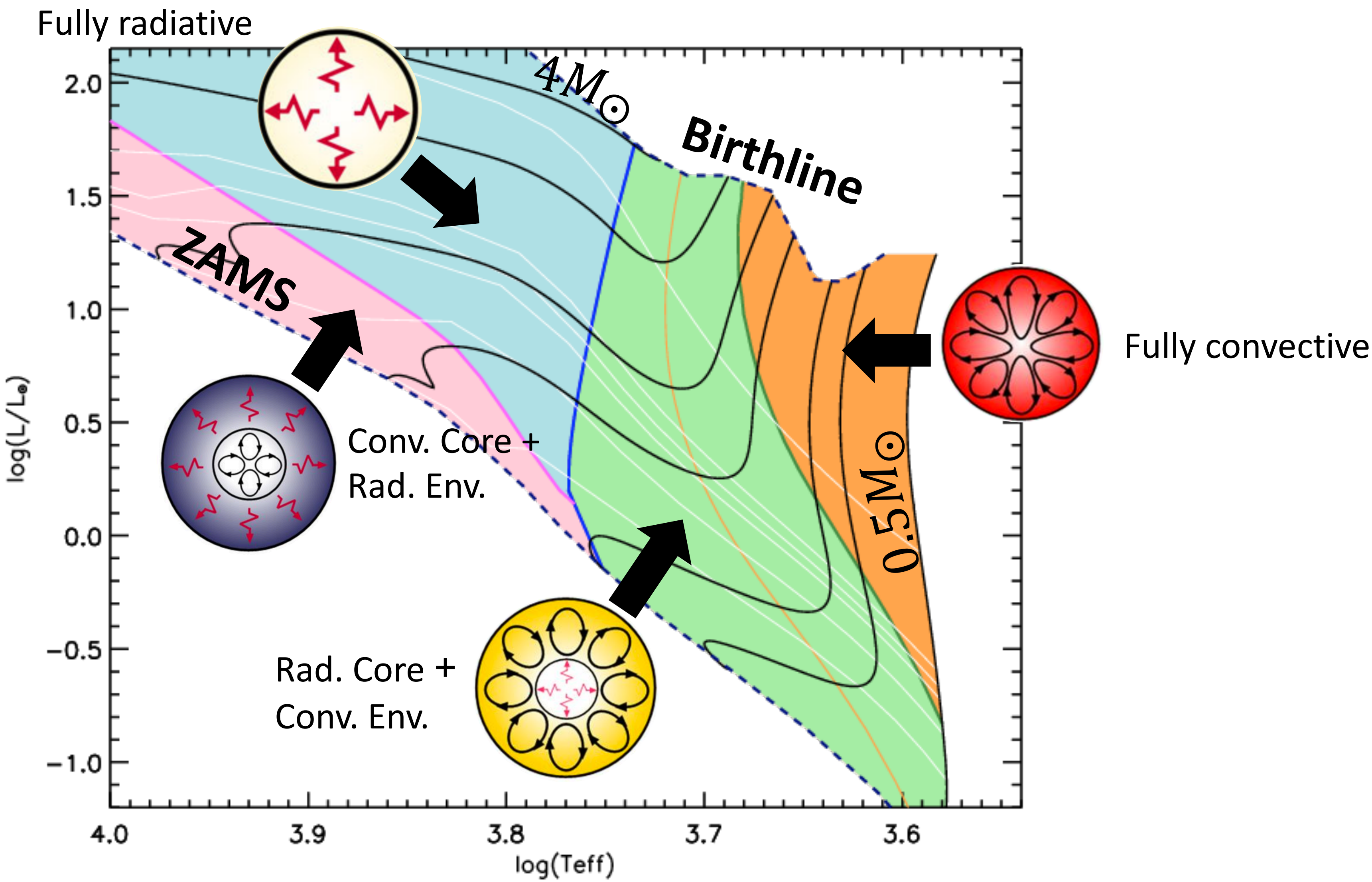
MARIE CURIE ACTIONS

Seminar, Universidad de Chile, September 24 2020

Star Formation in a nutshell

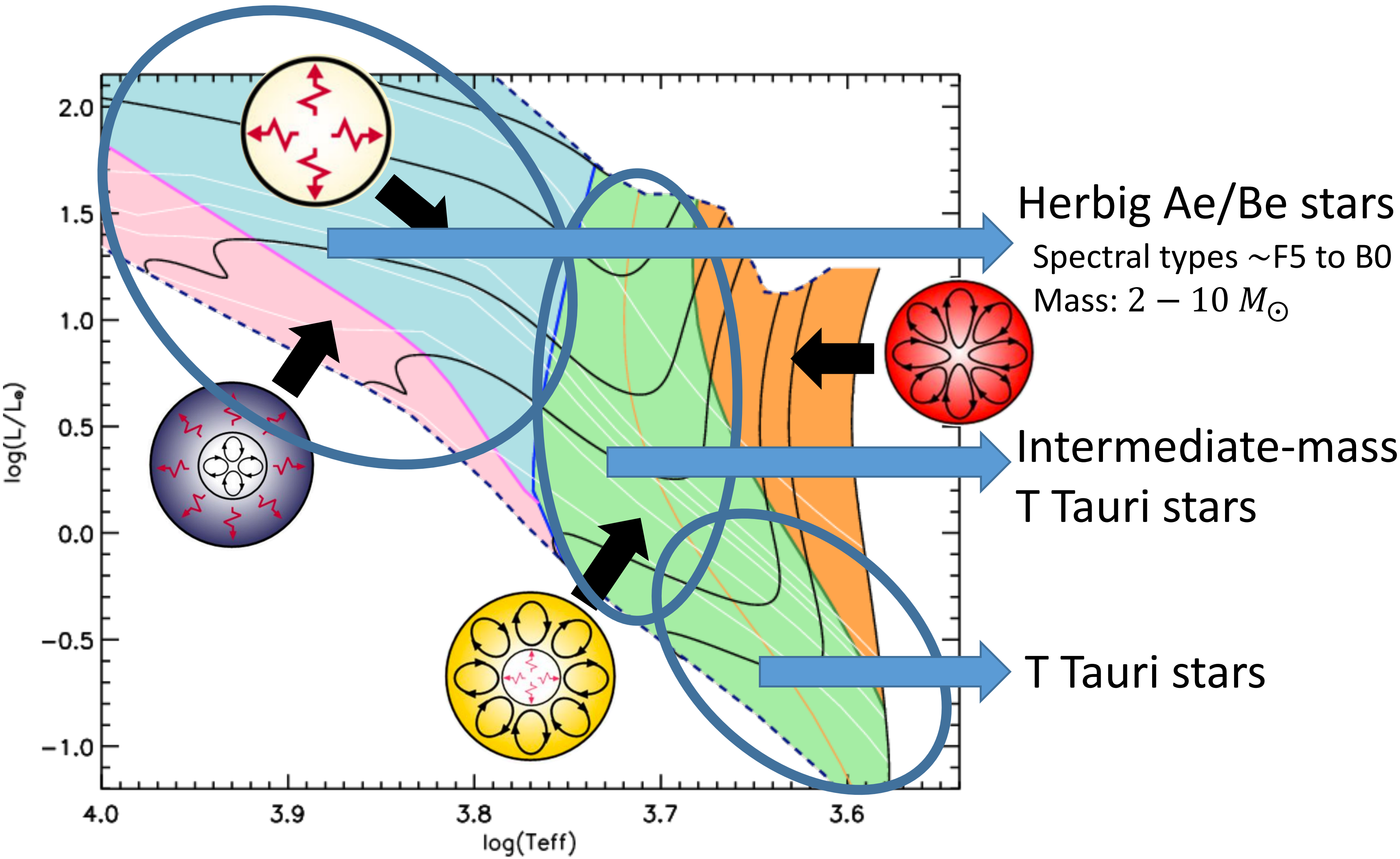


Star Formation in a nutshell



Alecian *et al.* (2013), Villebrun *et al.* (2019)

Star Formation in a nutshell



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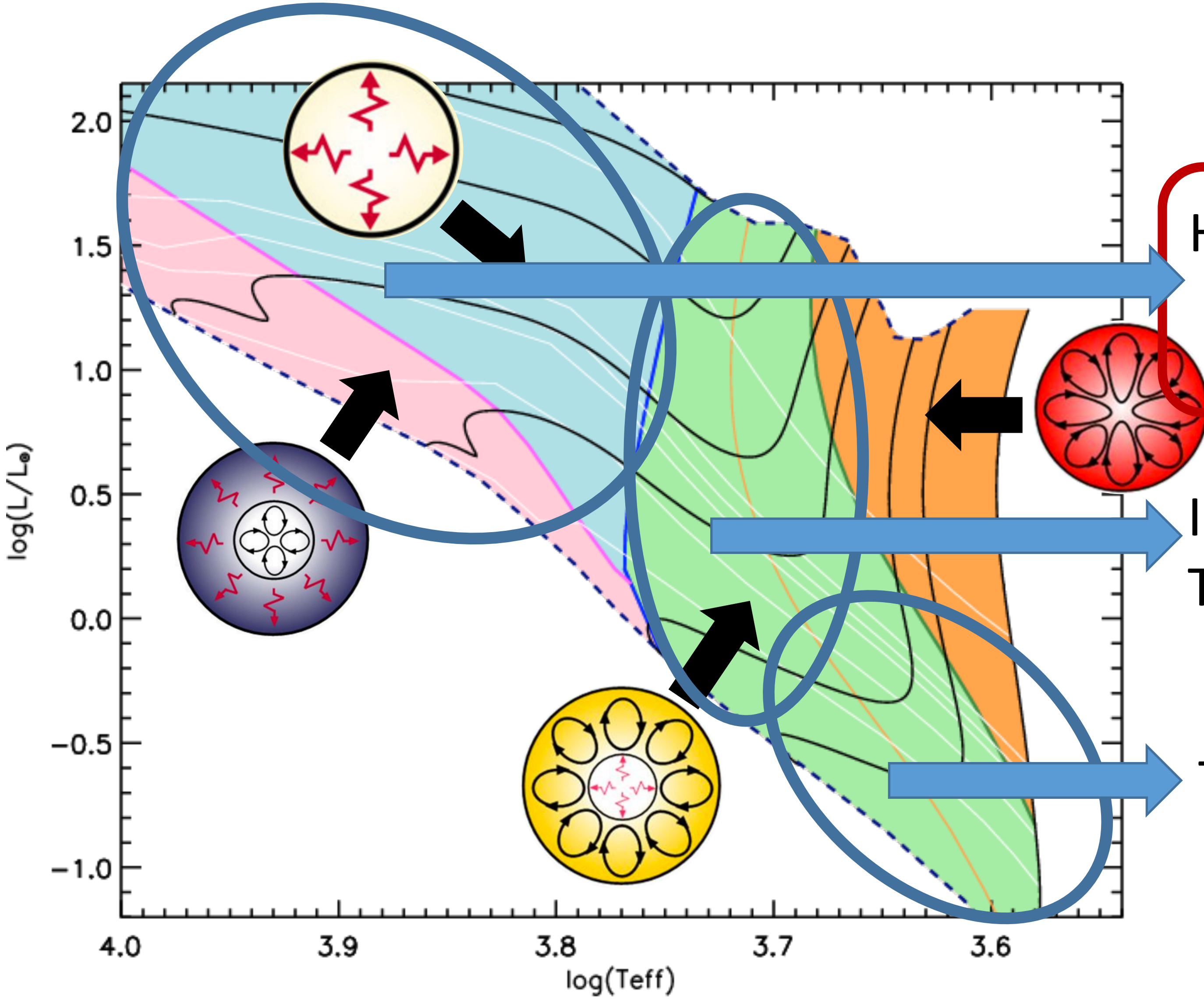


Around 250 known to date

Herbig Ae/Be stars

Spectral types ~F5 to B0

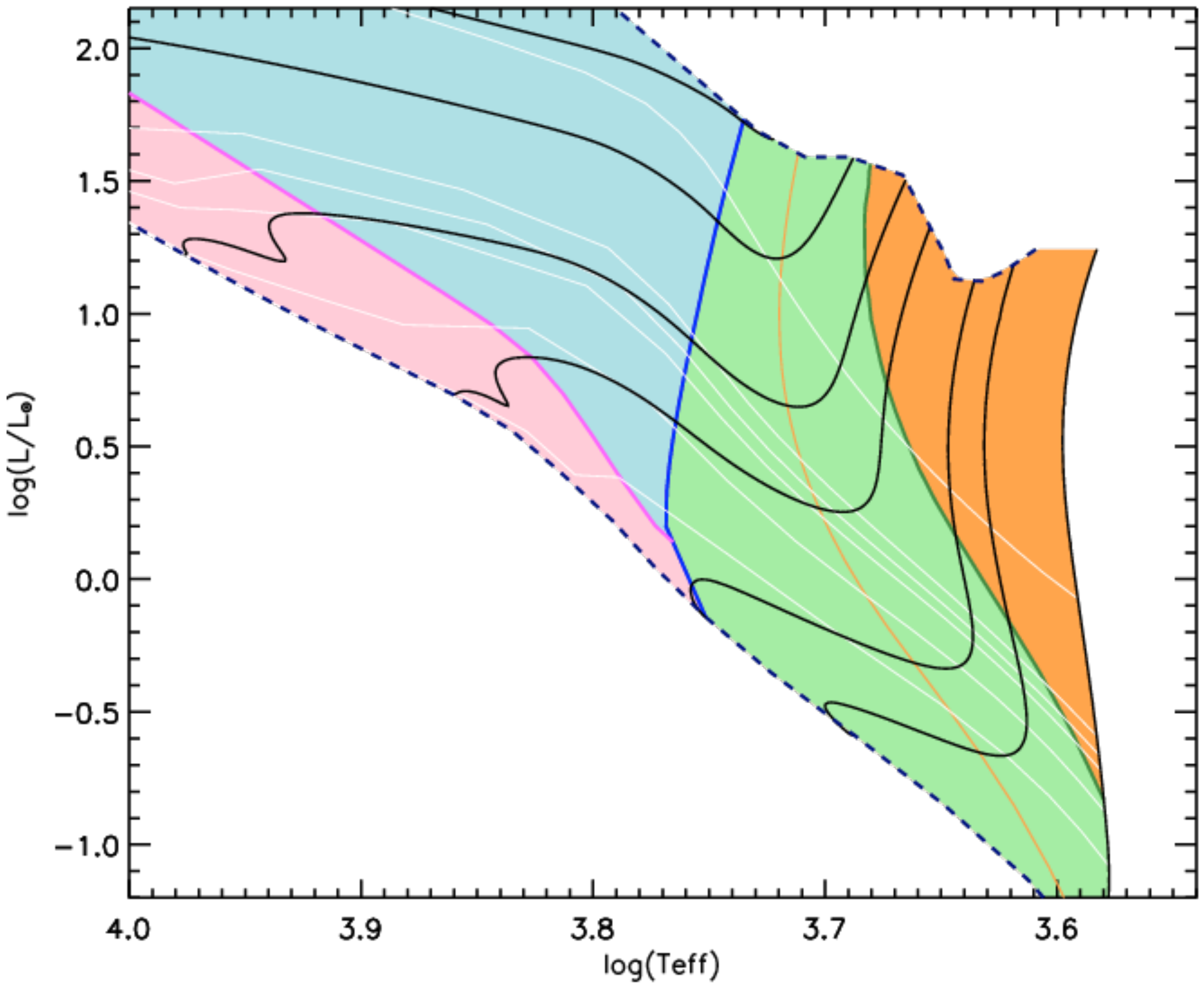
Mass: $2 - 10\ M_{\odot}$

Intermediate-mass T Tauri stars

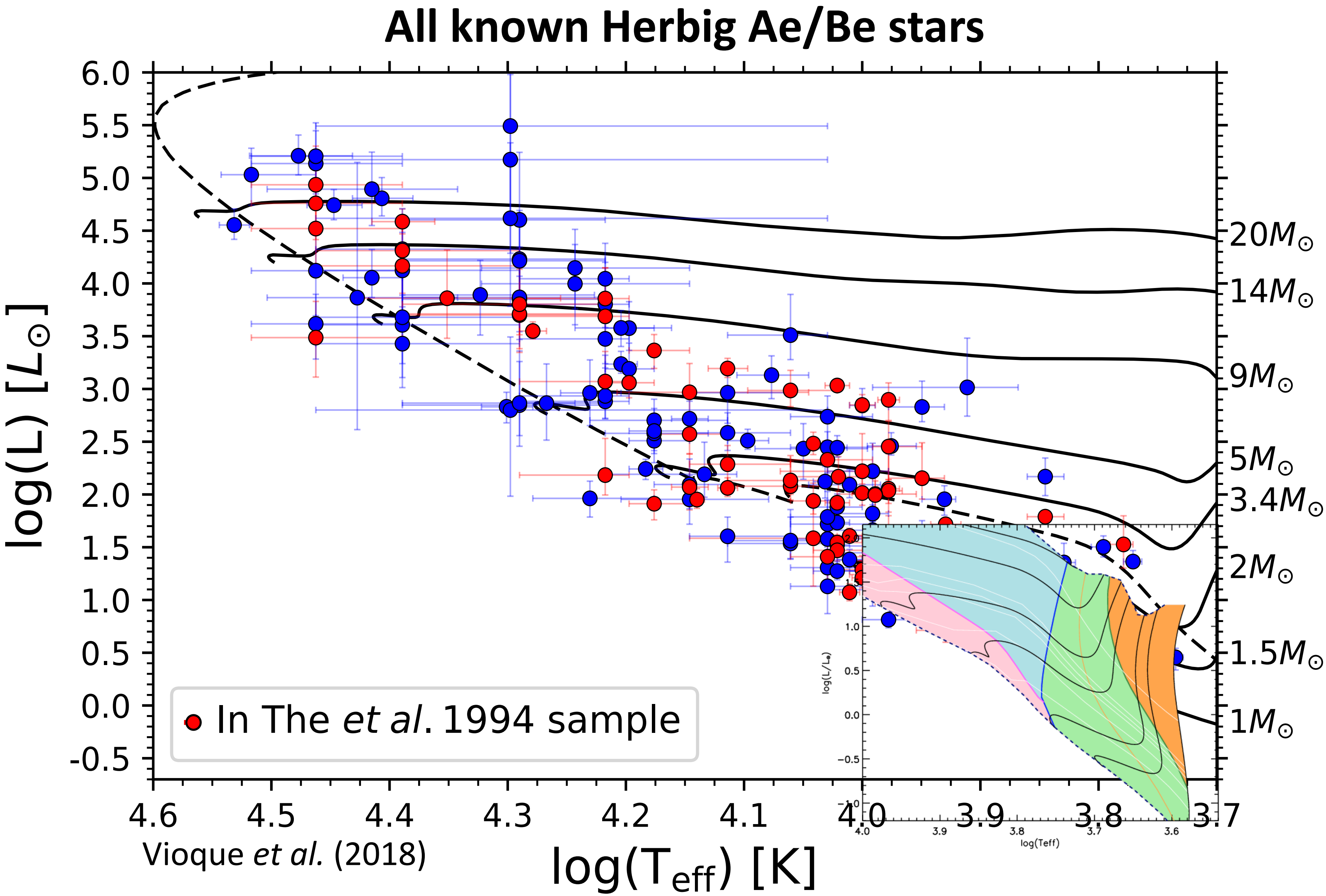
T Tauri stars

Alecian *et al.* (2013), Villebrun *et al.* (2019)

Star Formation in a nutshell

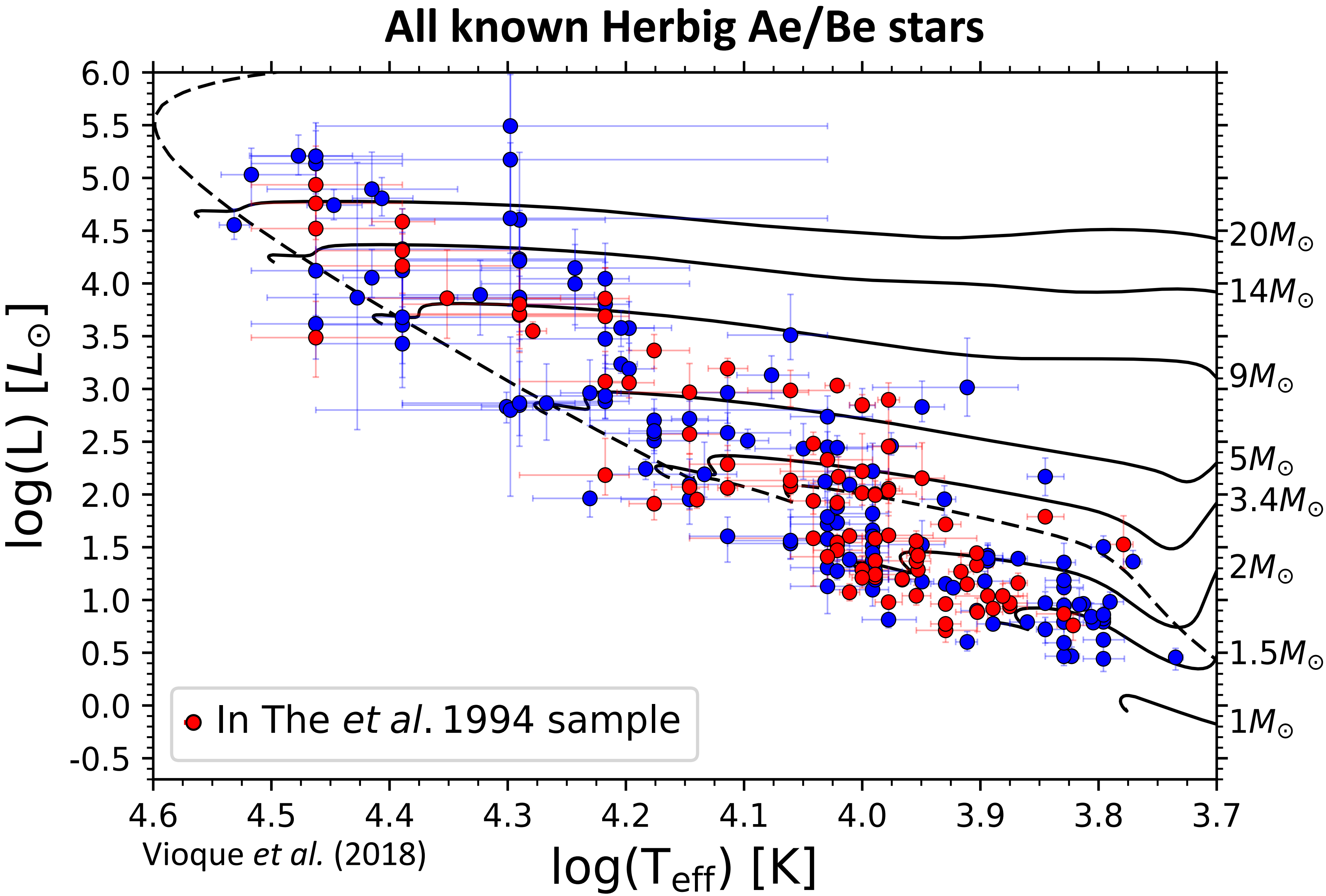


Star Formation in a nutshell



Vioque *et al.* (2018)

Star Formation in a nutshell



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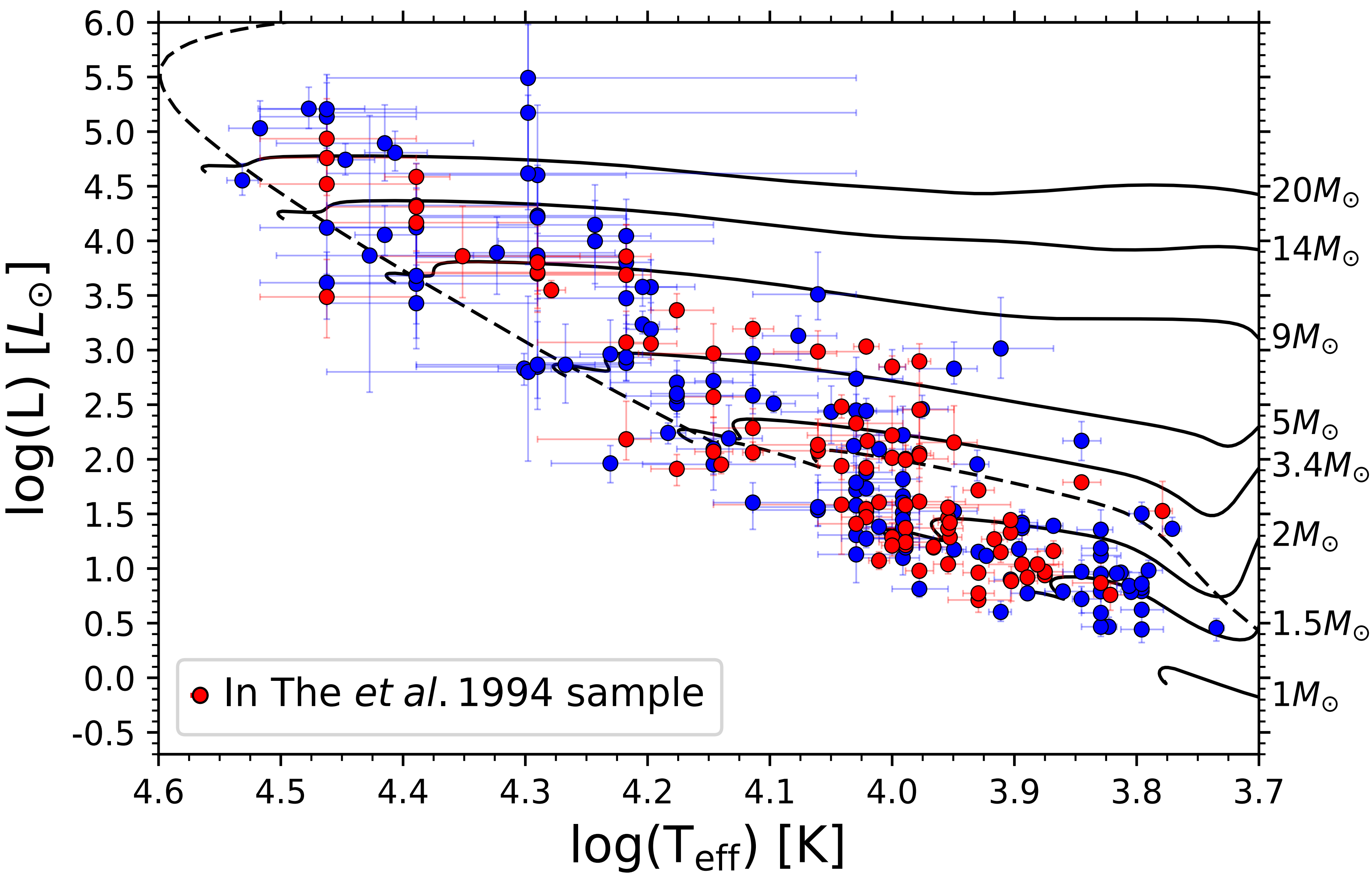
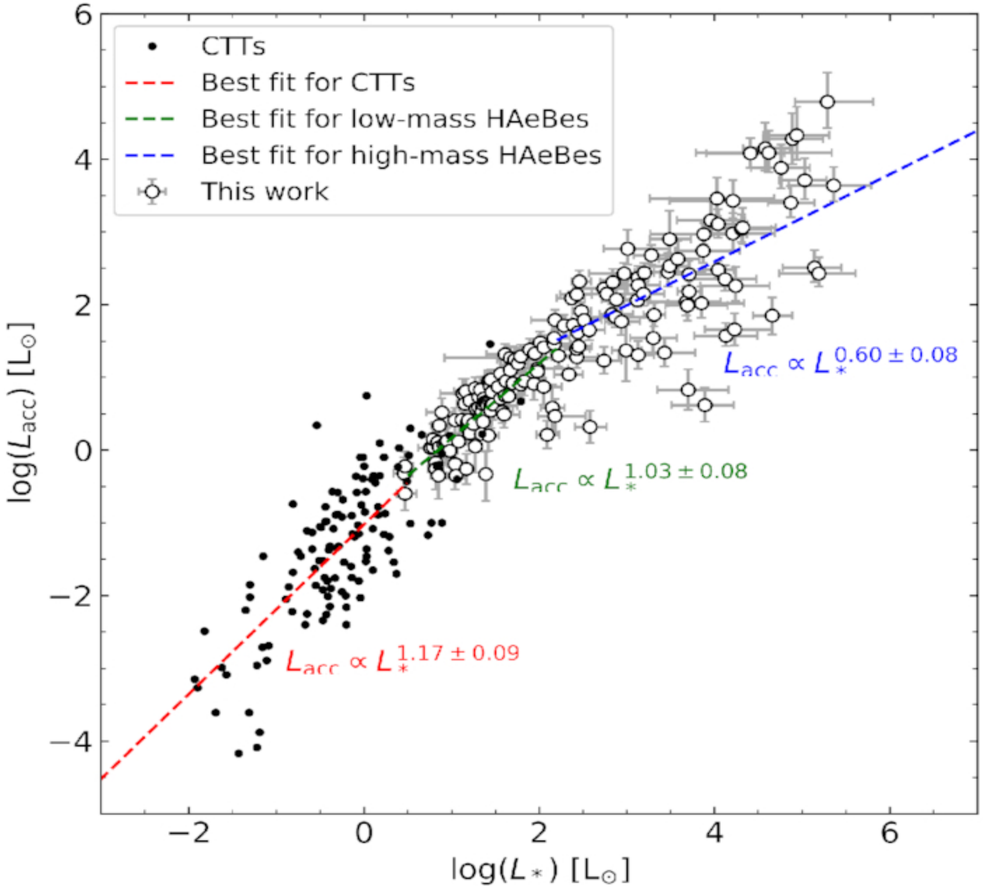
Star Formation in a nutshell

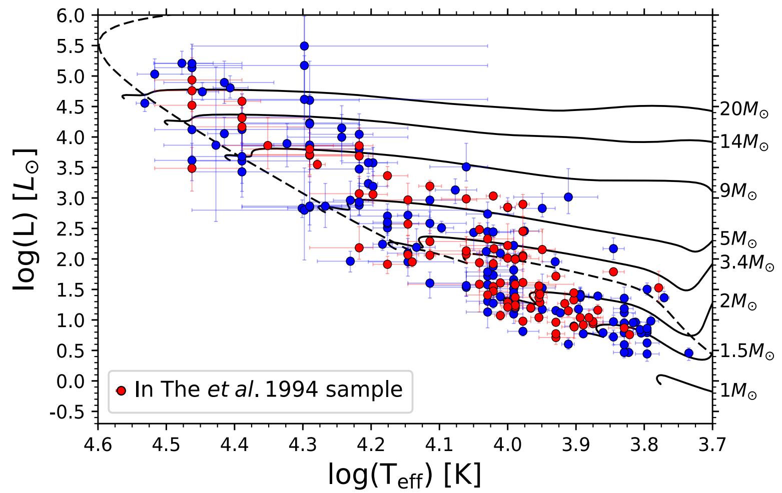


Star Formation in a nutshell

Break in accretion properties between Herbig Ae and Herbig Be



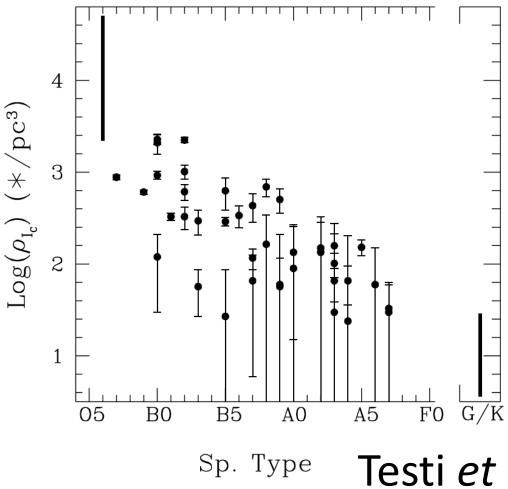
Wichittanakom *et al.* 2020



+ Vink, *et al.* (2002, 2003, 2005), Mottram, *et al.* (2007), Cauley & Johns Krull *et al.* (2014, 2015), Fairlamb *et al.* (2015), Ababakr, *et al.* (2017).

Some other open questions

Clustering



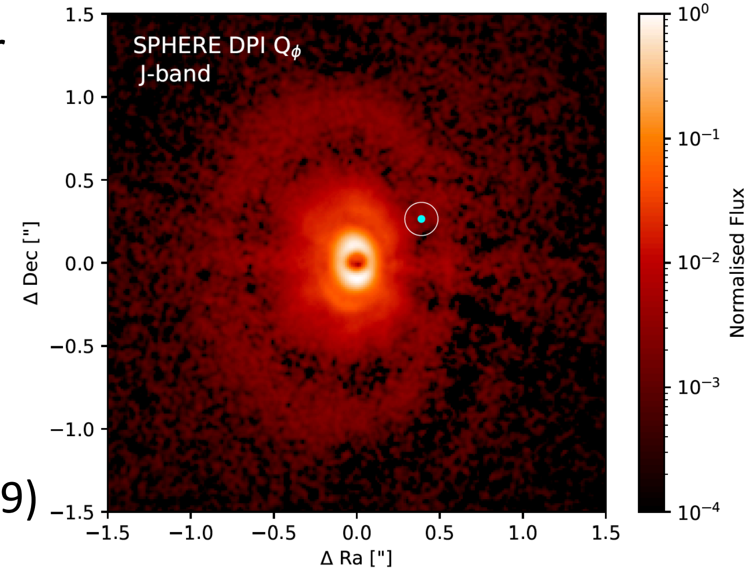
Testi *et al.* (1999)

Do all massive stars form in clusters?

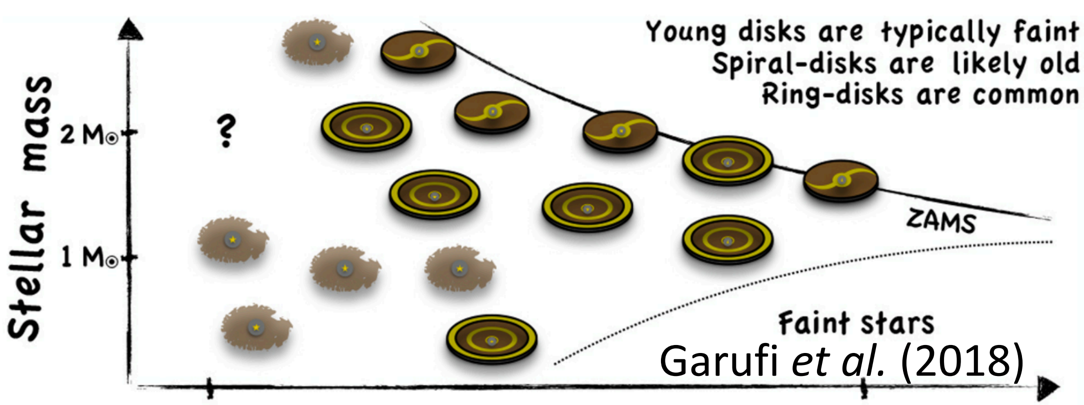
Planet Formation

Planet forming or planet hosting disks - when do we start seeing signatures of planet? Class 1? Class 0?

Pinte *et al.* (2019)

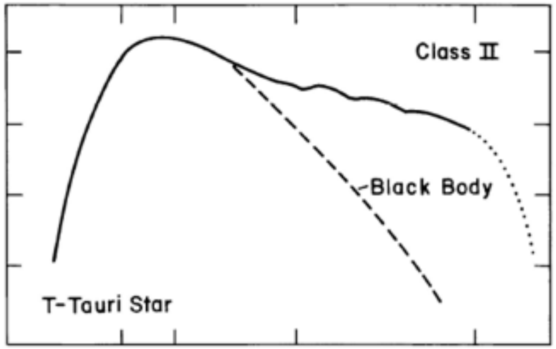


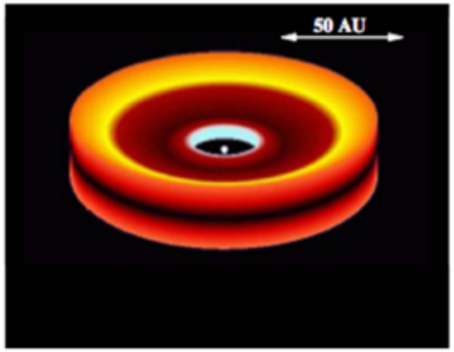
Disk Structure and Evolution



Garufi *et al.* (2018)

Looking for new high-mass Pre-Main Sequence objects





Main characteristics of PMS objects:

- Infrared excesses
- Hα emission
- Photometric variability

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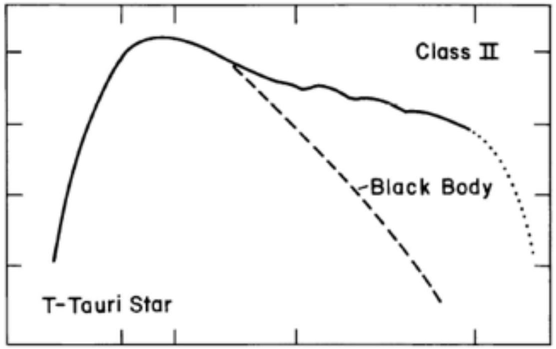

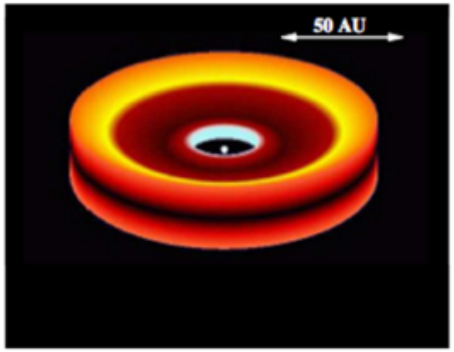

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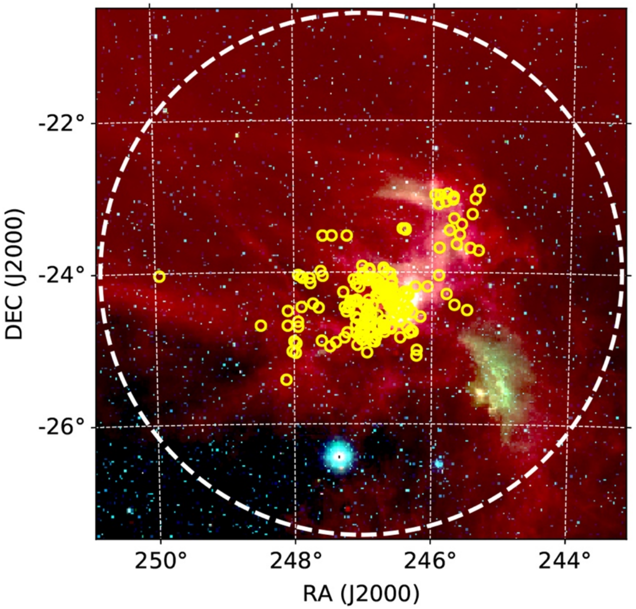
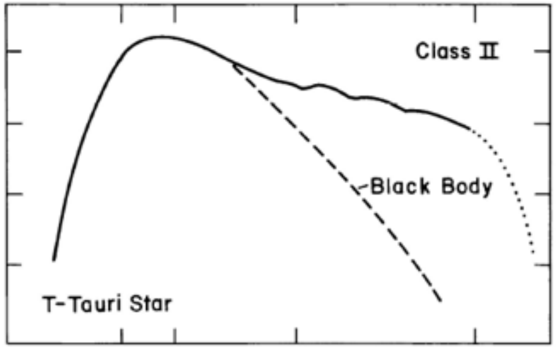
“Easy” to do for low-mass objects:

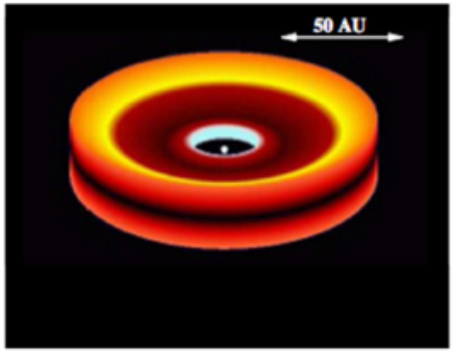
eg., Ksoll et al. (2018), Marton et al. (2019)



Cánovas et al. (2019)

Looking for new high-mass Pre-Main Sequence objects





Main characteristics of PMS objects:

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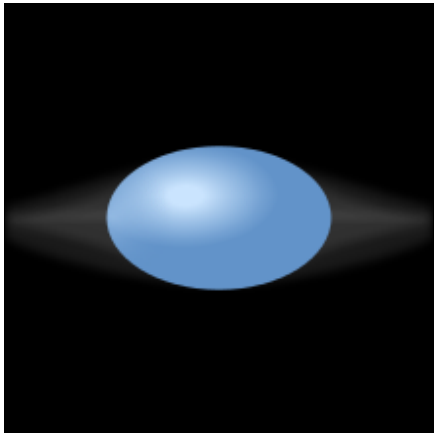
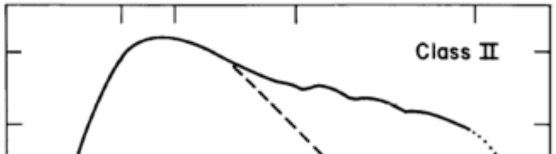
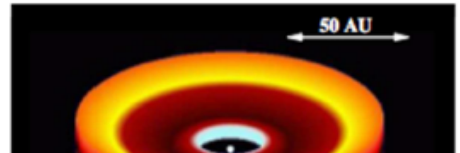
High-mass PMS objects are very similar to **Classical Be stars**

... and supergiants, B[e] stars, ...



Looking for new high-mass Pre-Main Sequence objects





Perform an homogeneous selection, distance and position independent!

High-mass PMS objects are very similar to **Classical Be stars**

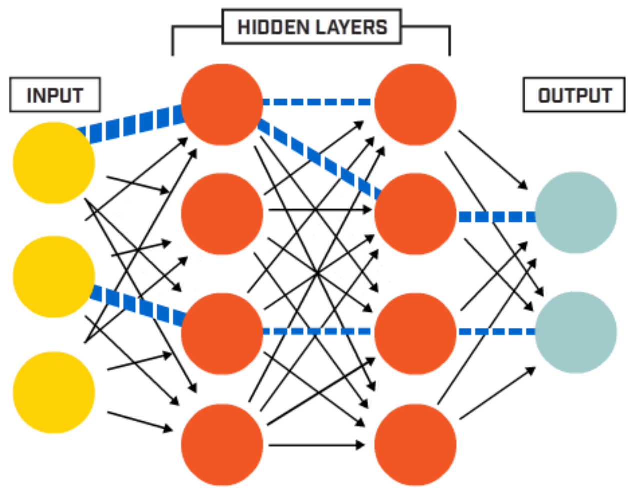
... and supergiants, B[e] stars, ...

Neural Network

Algorithm is trained with known labelled data

Before training:

- Training Set
- Set of characteristics
- Set of categories



After generalizing:

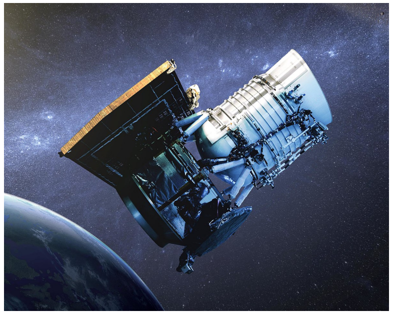
- Each category gets a probability
- Efficiency of the algorithm

The best architecture is selected

Neural Network

Selection of the **characteristics**:

AllWISE (WISE+2MASS)



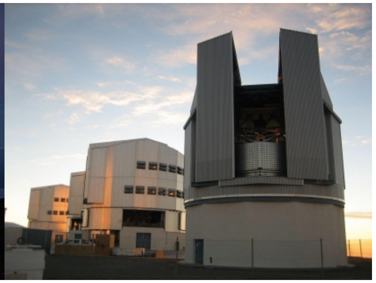
- Infrared excess

$\boldsymbol{W1, W2, W3, W4}$

$\boldsymbol{J, H, K_s}$

IPHAS

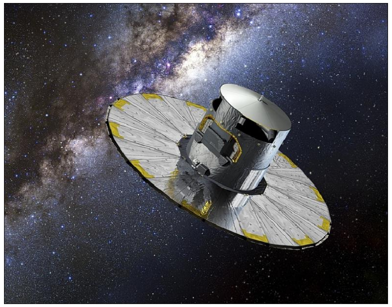
VPHAS+



- Hα emission

$\boldsymbol{r - H_\alpha}$

Gaia



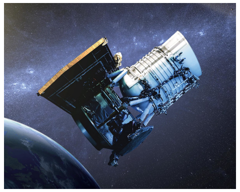
- Photometric variability

2 variability indicators

$\boldsymbol{B_p, G, R_p}$

Selection of the **Training Set**:

AllWISE



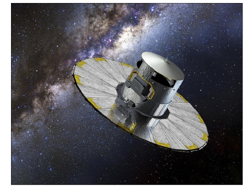
+

IPHAS

VPHAS+

+

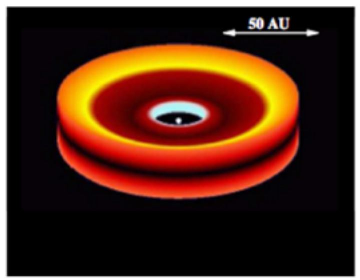
Gaia



=

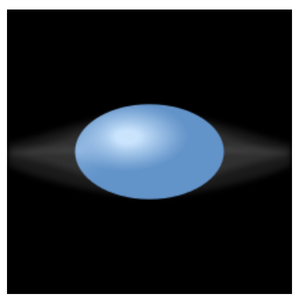
4 151 538 sources

PMS category



- **848** Pre-Main Sequence objects (**163** Herbig Ae/Be)

Classical Be category



- **775** Classical Be stars

Other sources

- **470 263** random sources

Training the Neural Network

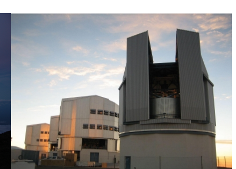
Trained Neural Network

AllWISE

+

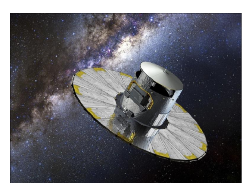
IPHAS

VPHAS+



+

Gaia



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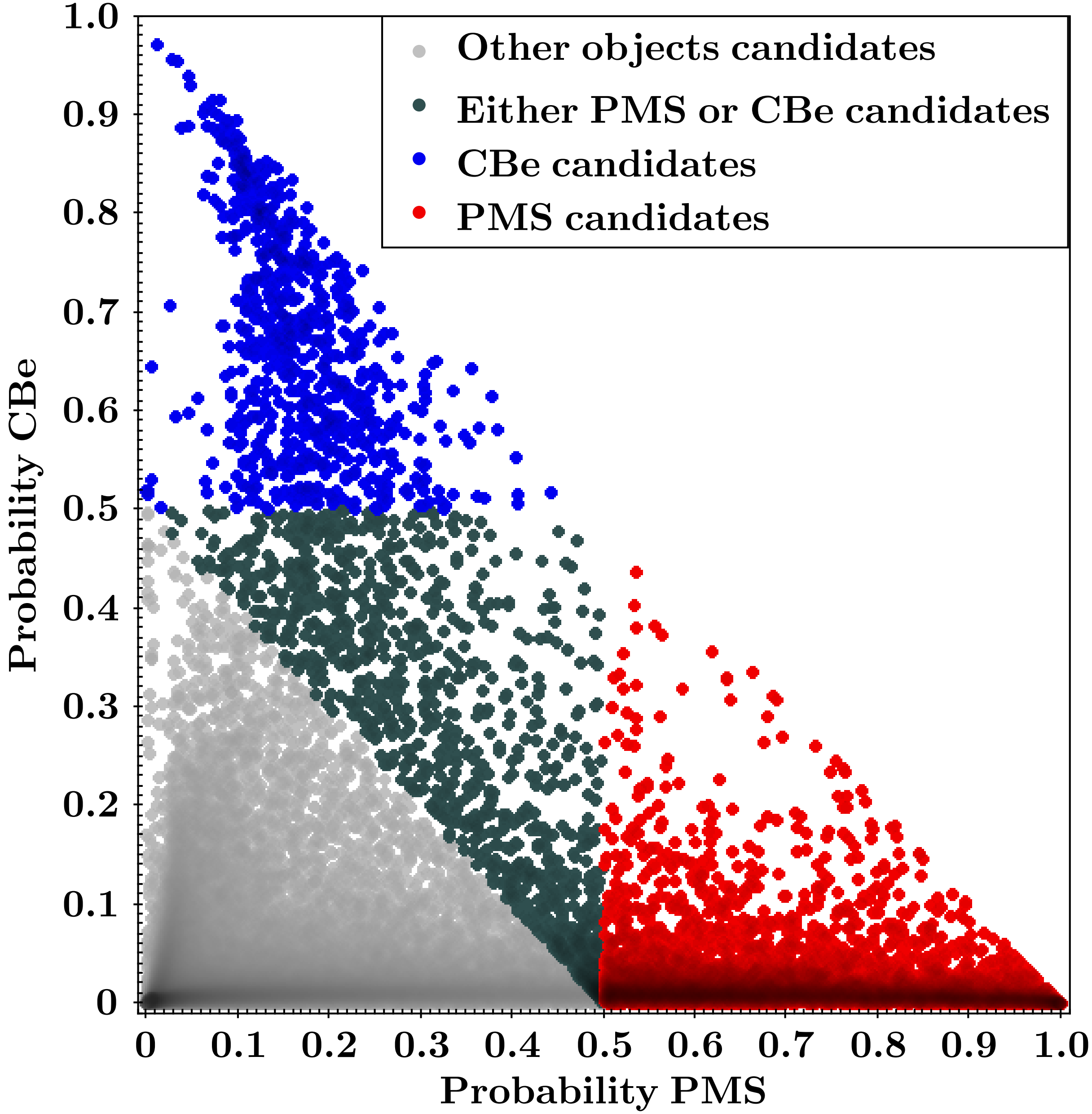
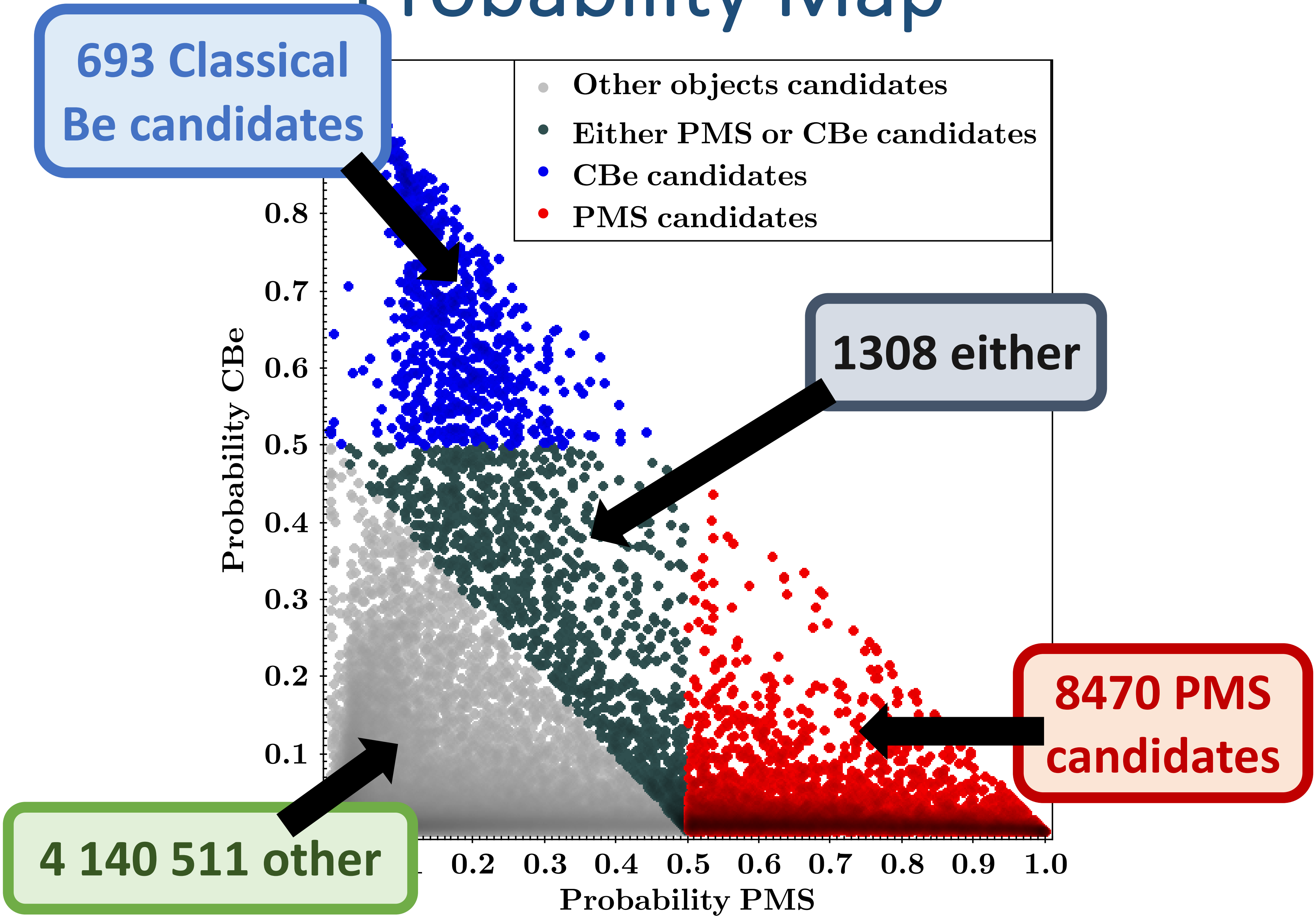
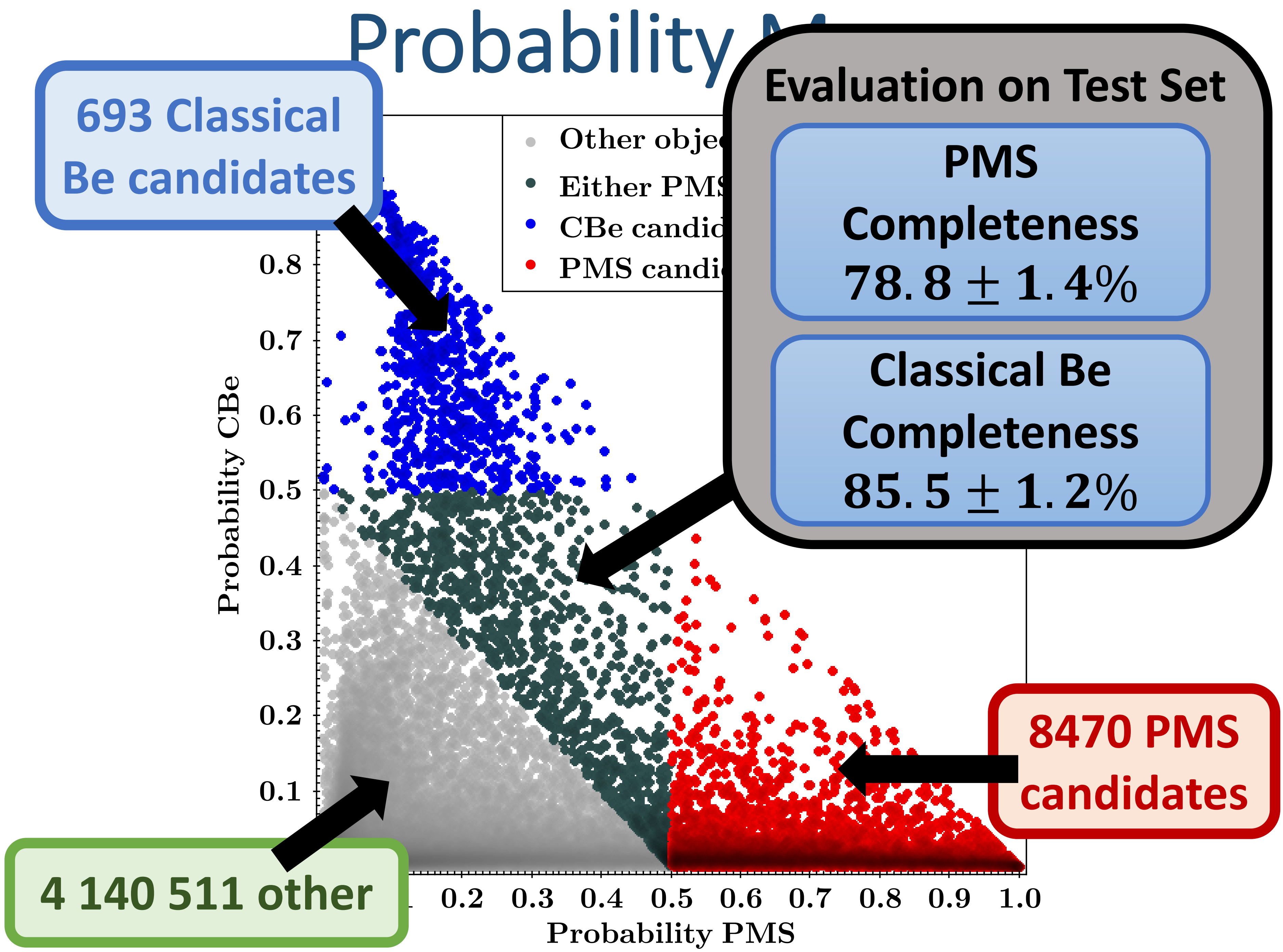
4 151 538 sources

Probability Map



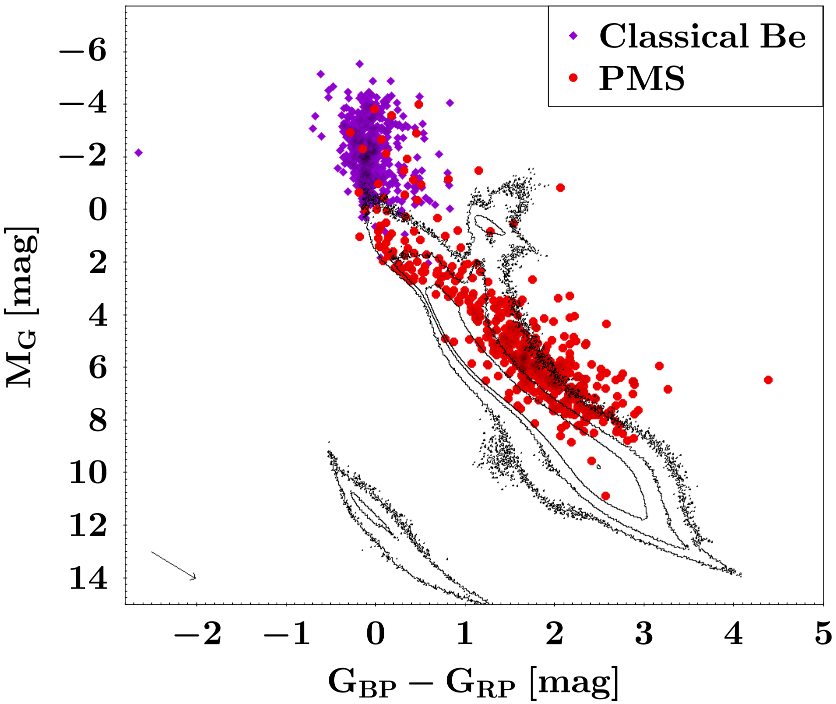
Probability Map



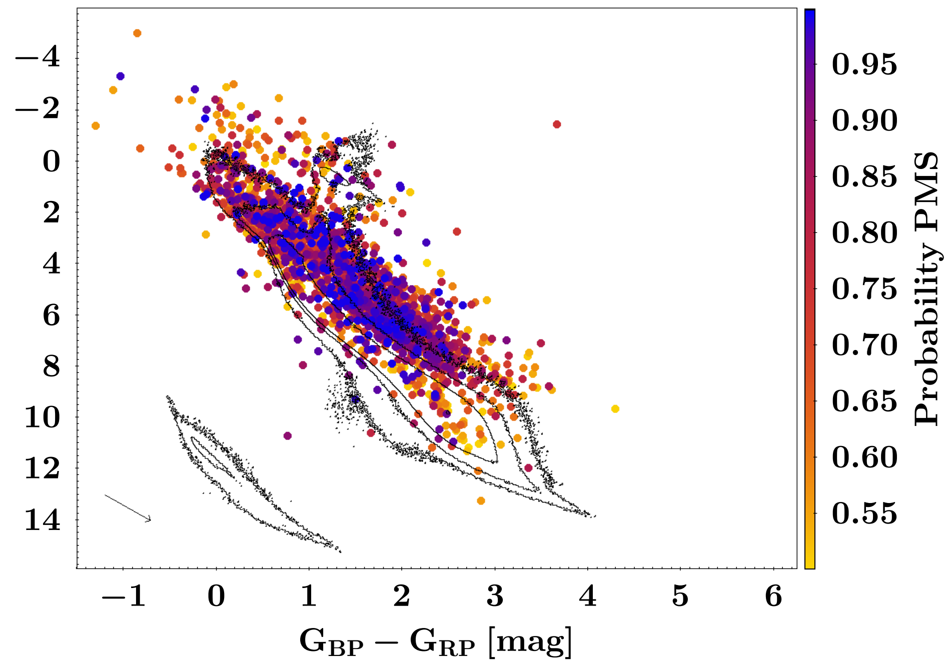

Probability M
693 Classical Be candidates
Evaluation on Test Set
PMS Completeness $78.8 \pm 1.4\%$
Classical Be Completeness $85.5 \pm 1.2\%$
Other obje
Either PMS
CBe candid
PMS candi
Probability CBe
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
Probability PMS
8470 PMS candidates
4 140 511 other

Gaia HR diagram

Training Set

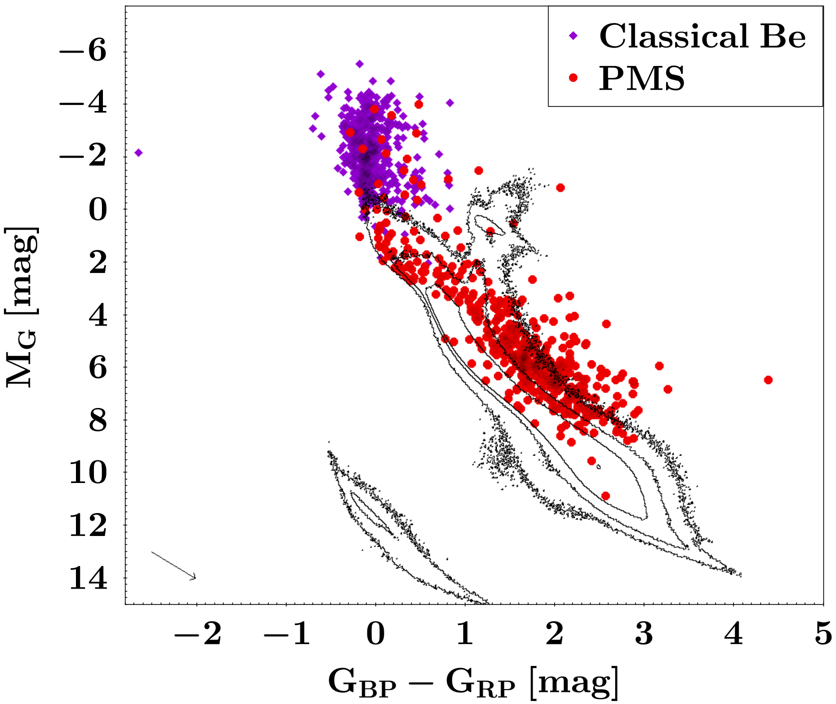


PMS candidates

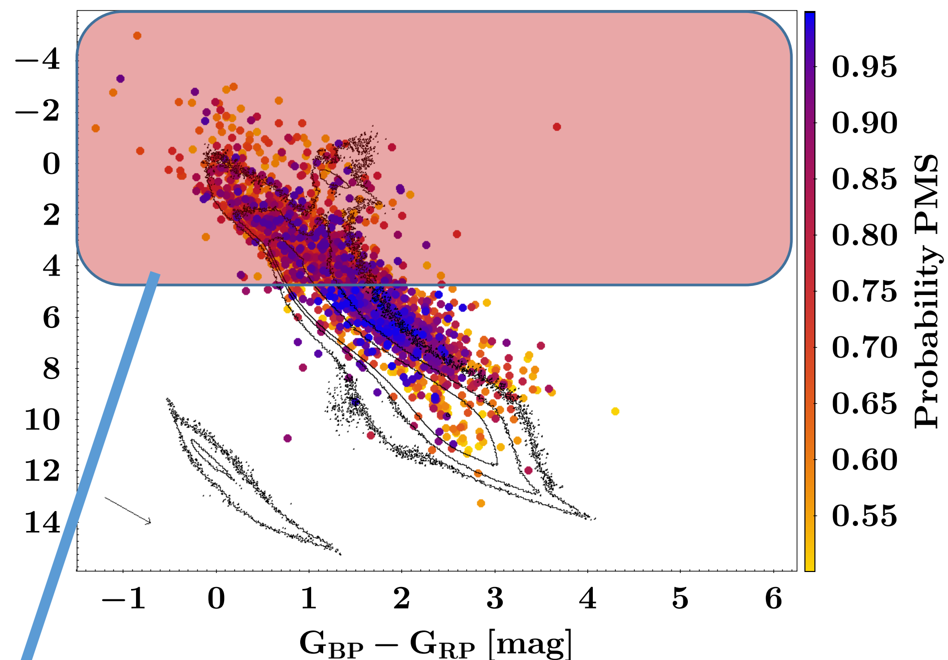


Gaia HR diagram

Training Set



PMS candidates

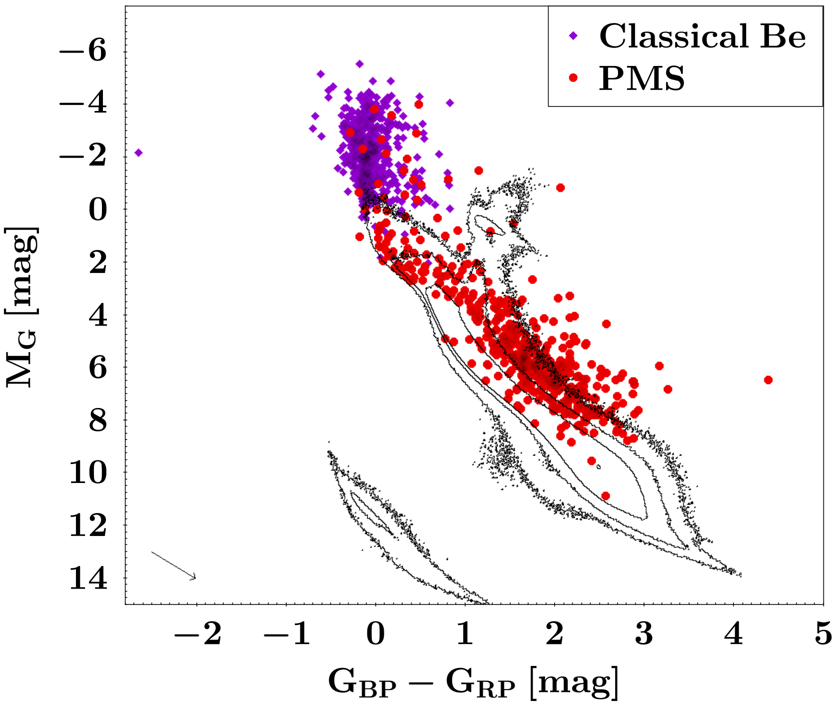


~2226 Herbig Ae/Be candidates with parallax/σ(parallax) > 5

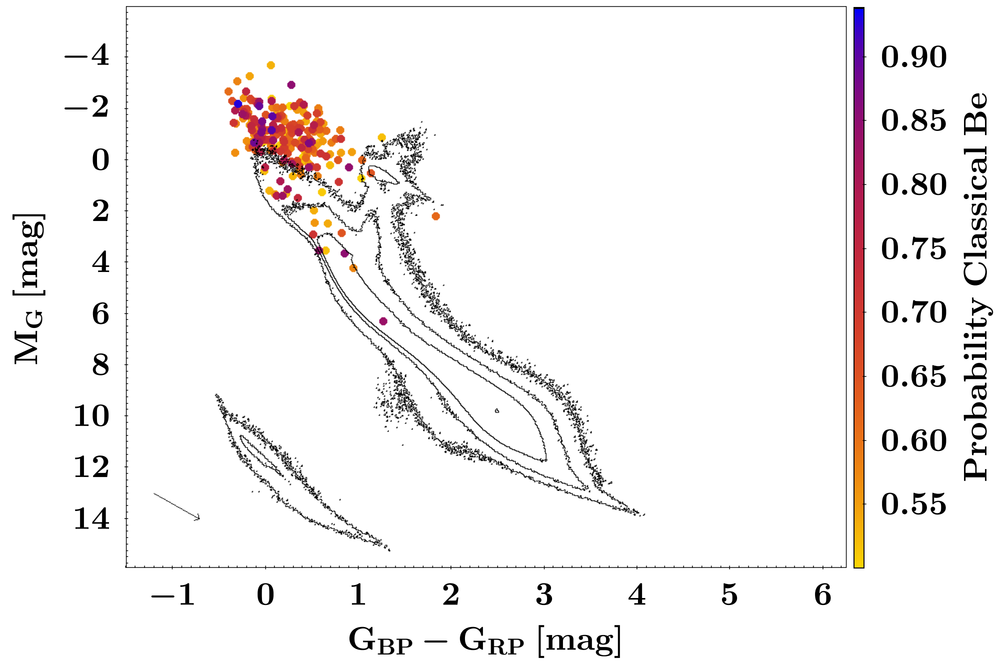
Before ~250

Gaia HR diagram

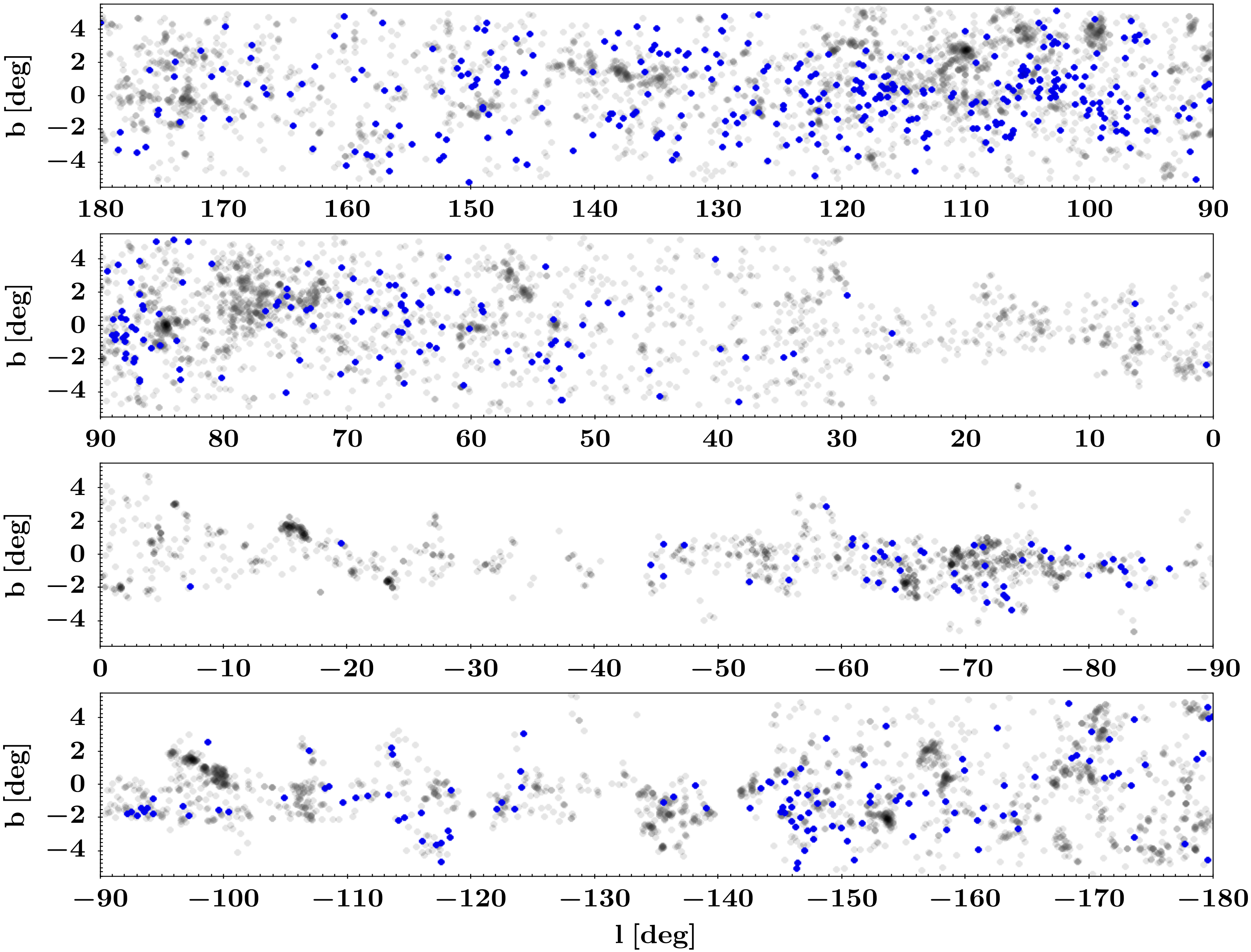
Training Set



Classical Be candidates



Coordinates



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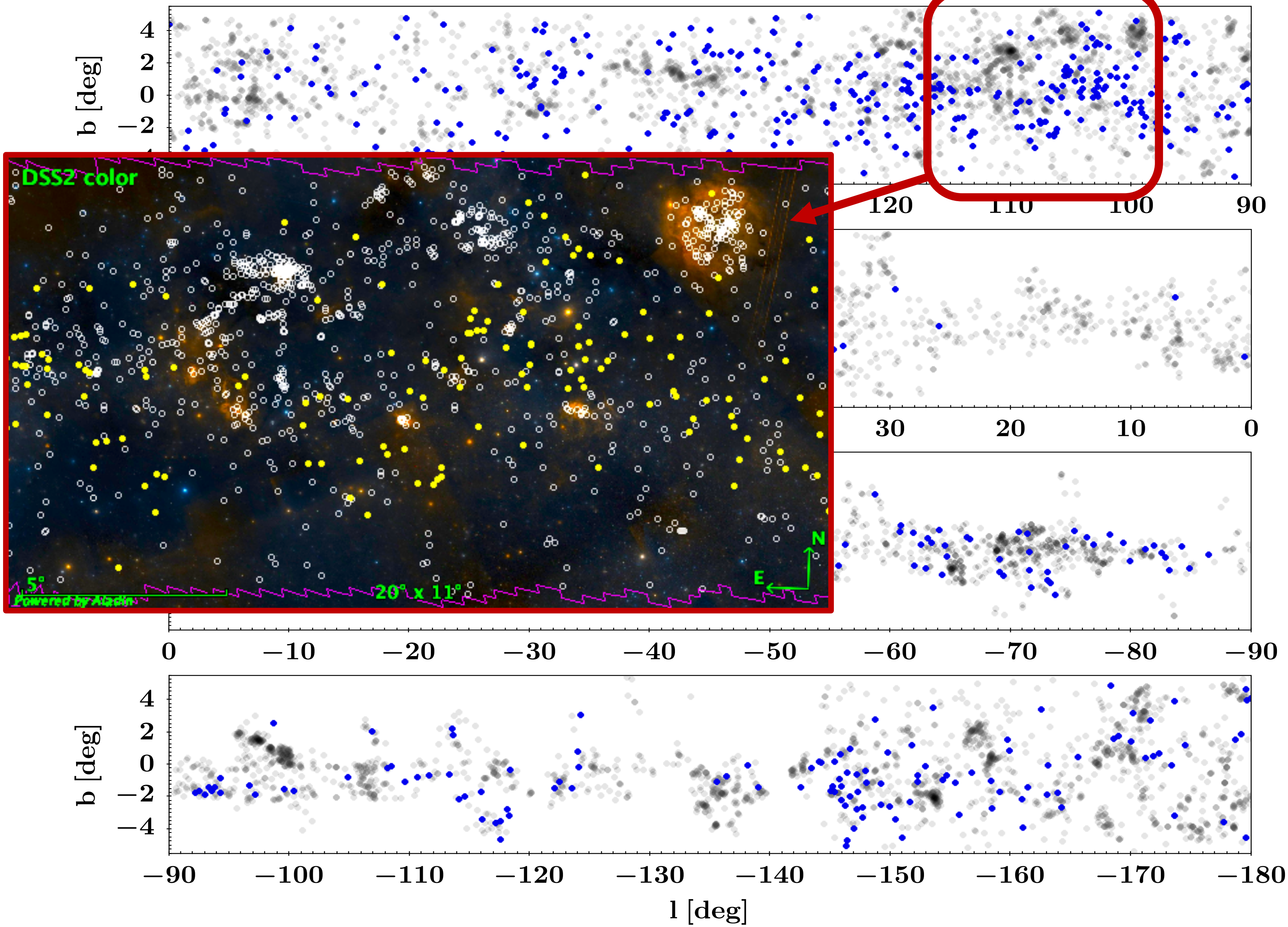

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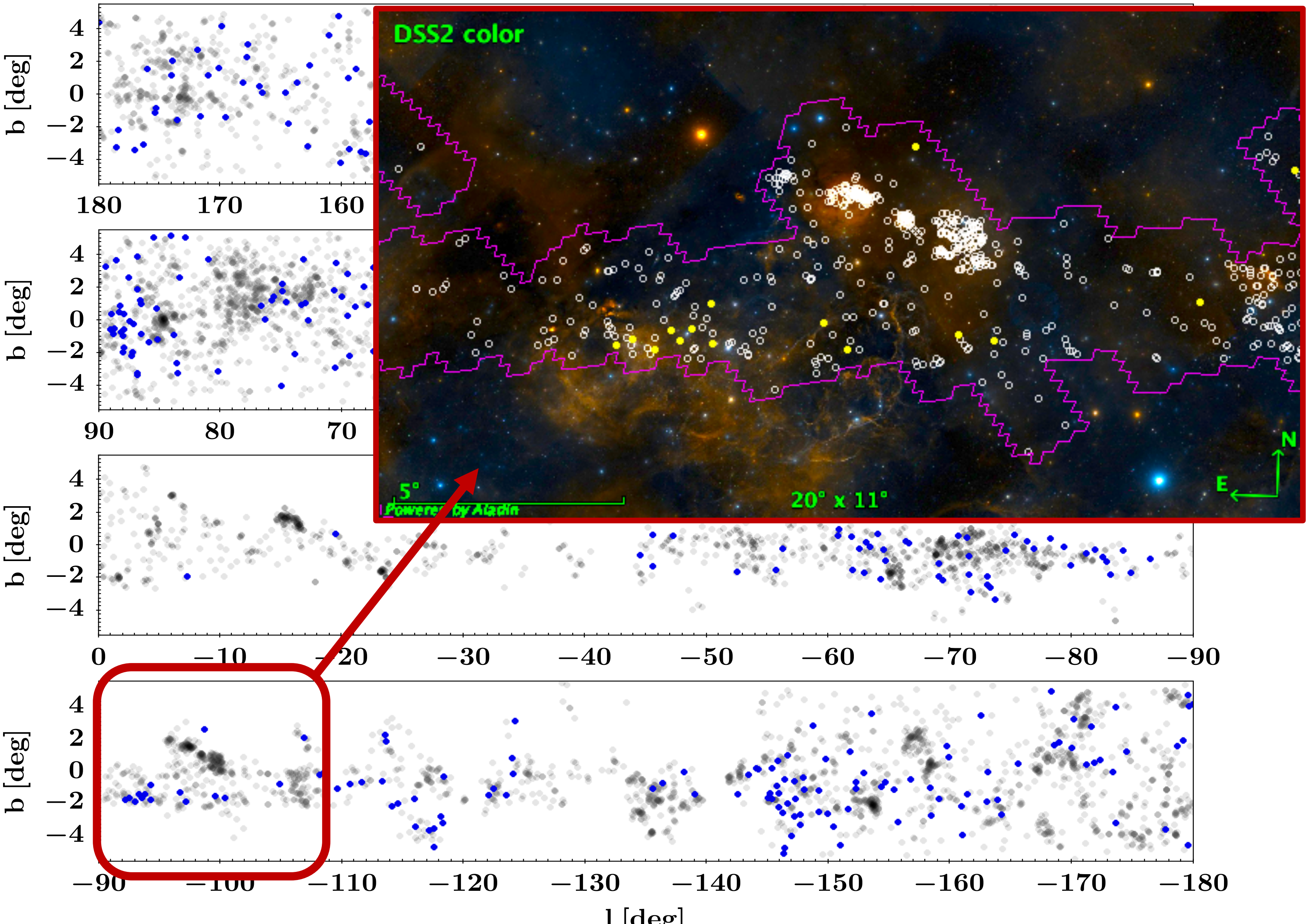


Caveats

Planetary Nebula!

… as Pre-Main Sequence candidate

See also *Akras et al. 2019a, 2019*b

Caveats

Planetary Nebula!

Possible contaminants have been analyzed and flagged in the catalogues

Caveats

Planetary Nebula!

Possible contaminants have been analyzed and flagged in the catalogues

M. Vioque, R. D. Oudmaijer, M. Schreiner, et al. 2020, A&A, 638, A21

Caveats

Planetary Nebula!

Contaminants are interesting e.g. B[e] stars

Possible contaminants have been analyzed and flagged in the catalogues

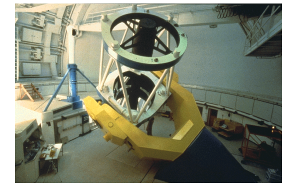
M. Vioque, R. D. Oudmaijer, M. Schreiner, et al. 2020, A&A, 638, A21

We went observing

Optical spectroscopy

- 145 new Herbig Ae/Be candidates
  - 14 new Classical Be candidates
    - 9 contaminants


INT


2.2m Calar Alto


NTT

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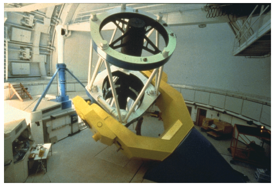


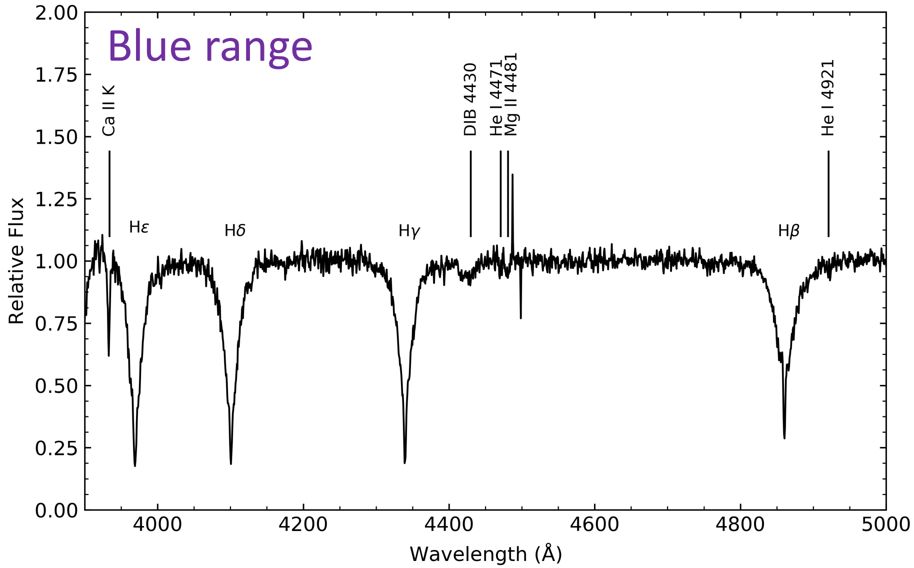
2.2m Calar Alto

NTT

Gaia DR2 428909457258627200

Catalogue: Herbig Ae/Be star candidate

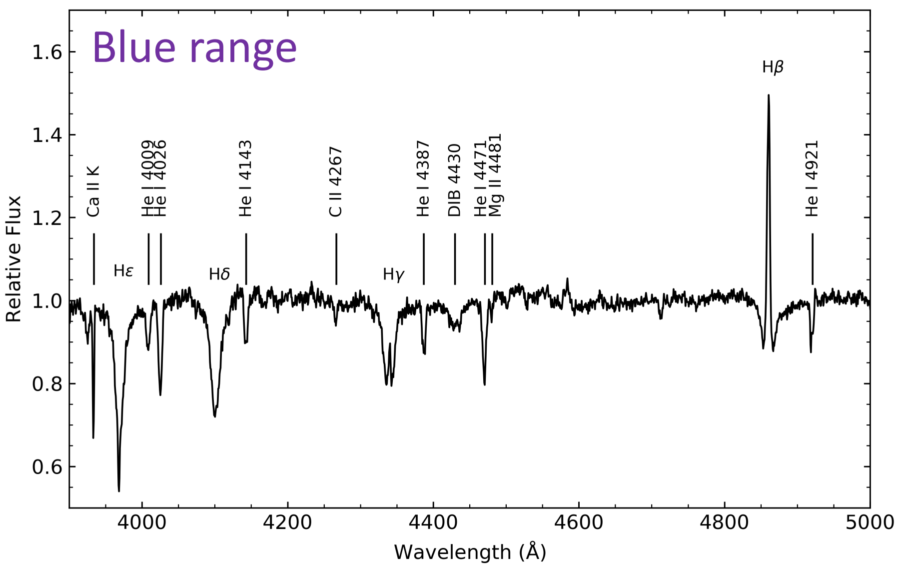
Probability: 97%, Distance: 2590^{+200}_{-170} pc



Gaia DR2 431592948519739136

Catalogue: Classical Be star candidate

Probability: 89%, Distance: 3470^{+340}_{-280} pc



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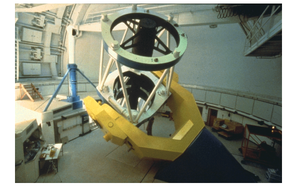

2.2m Calar Alto

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Gaia DR2 428909457258627200

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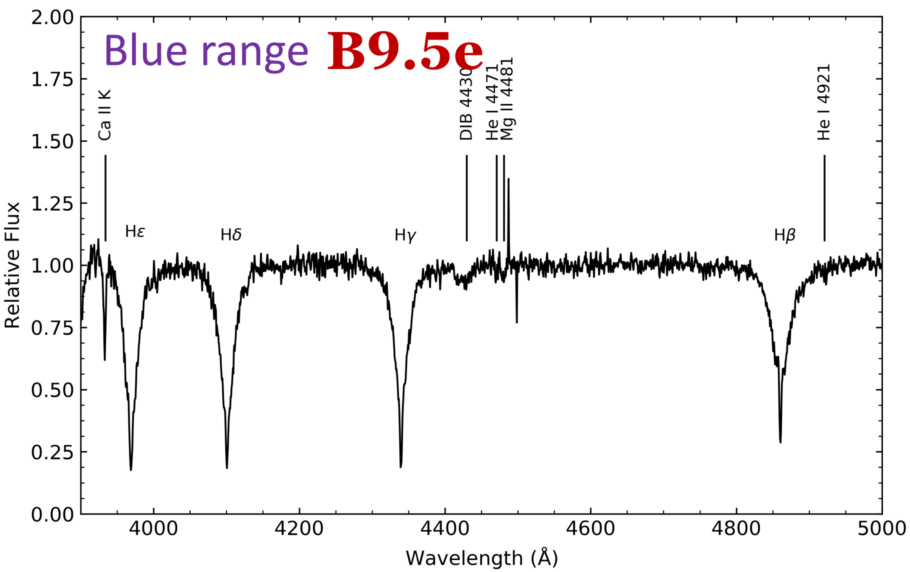
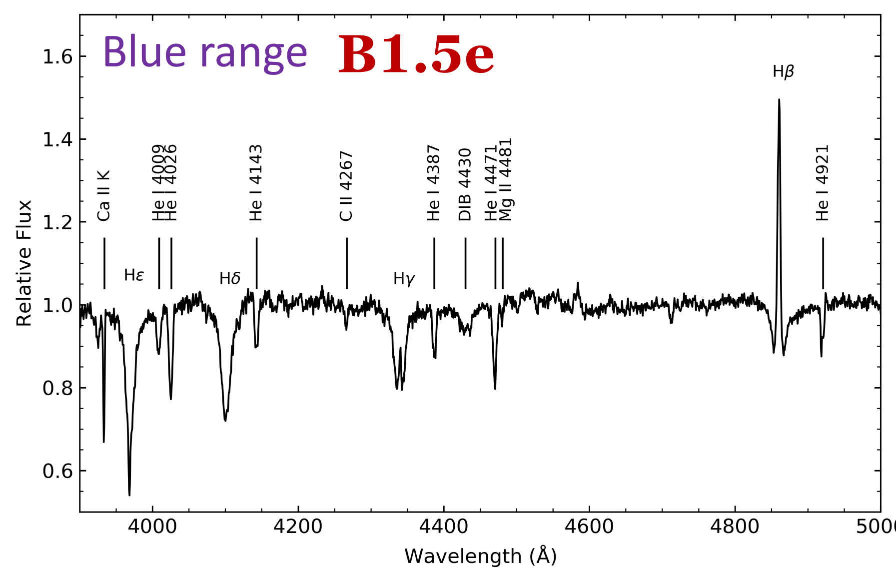
Probability: 97%, Distance: 2590^{+200}_{-170} pc



Gaia DR2 4315929485197391136

Catalogue: Classical Be star candidate

Probability: 89%, Distance: 3470^{+340}_{-280} pc



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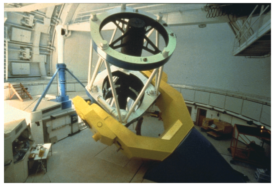


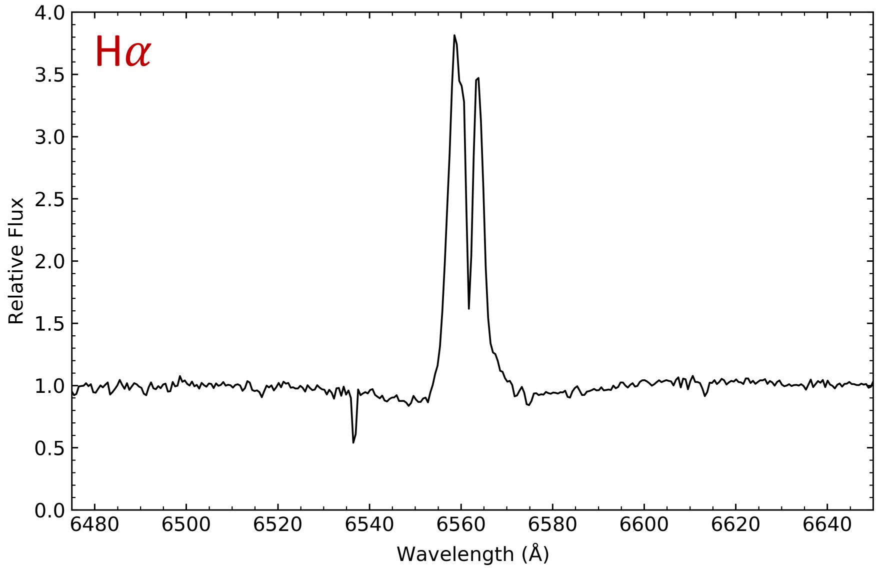
2.2m Calar Alto

NTT

Gaia DR2 4289094572586272OO

Catalogue: Herbig Ae/Be star candidate

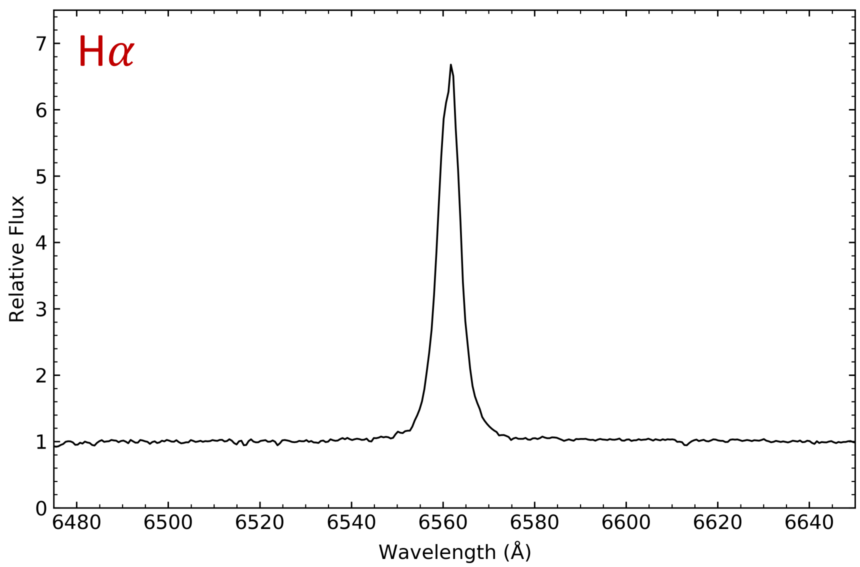
Probability: 97%, Distance: 2590^{+200}_{-170} pc



Gaia DR2 4315929485197391 36

Catalogue: Classical Be star candidate

Probability: 89%, Distance: 3470^{+340}_{-280} pc



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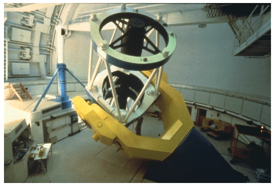

2.2m Calar Alto

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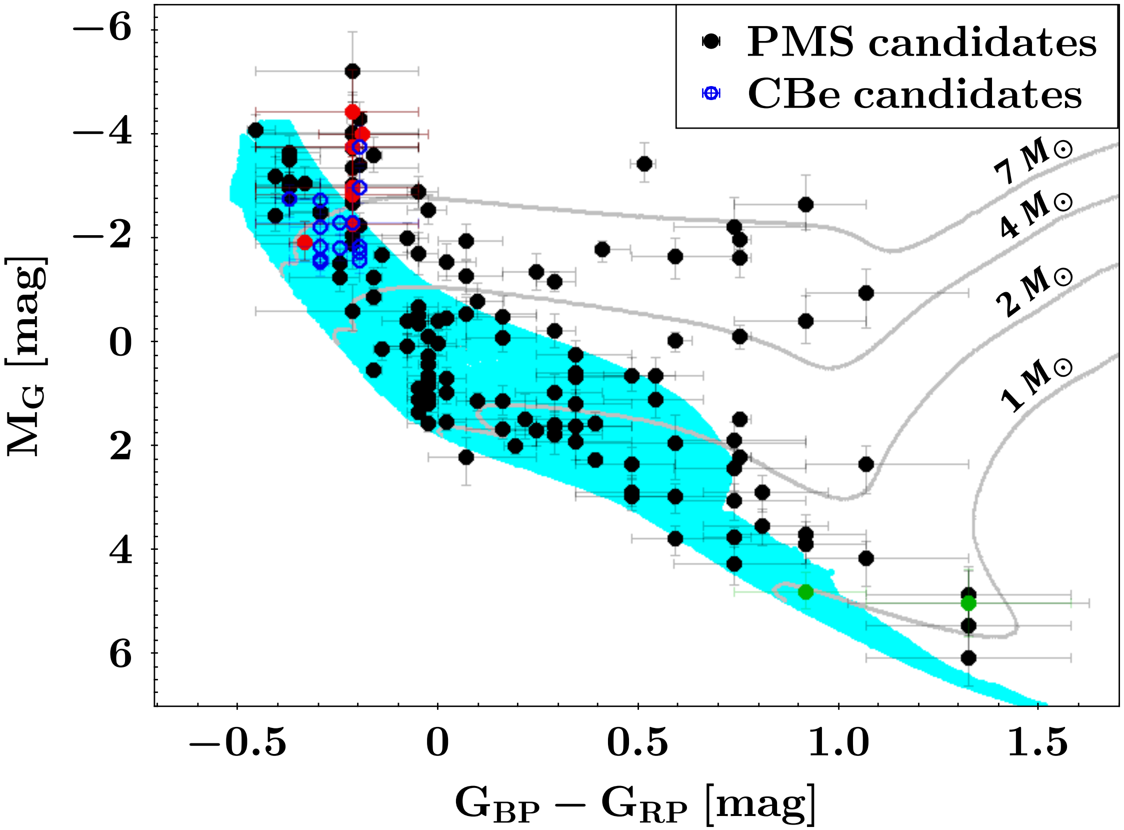

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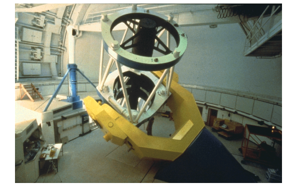
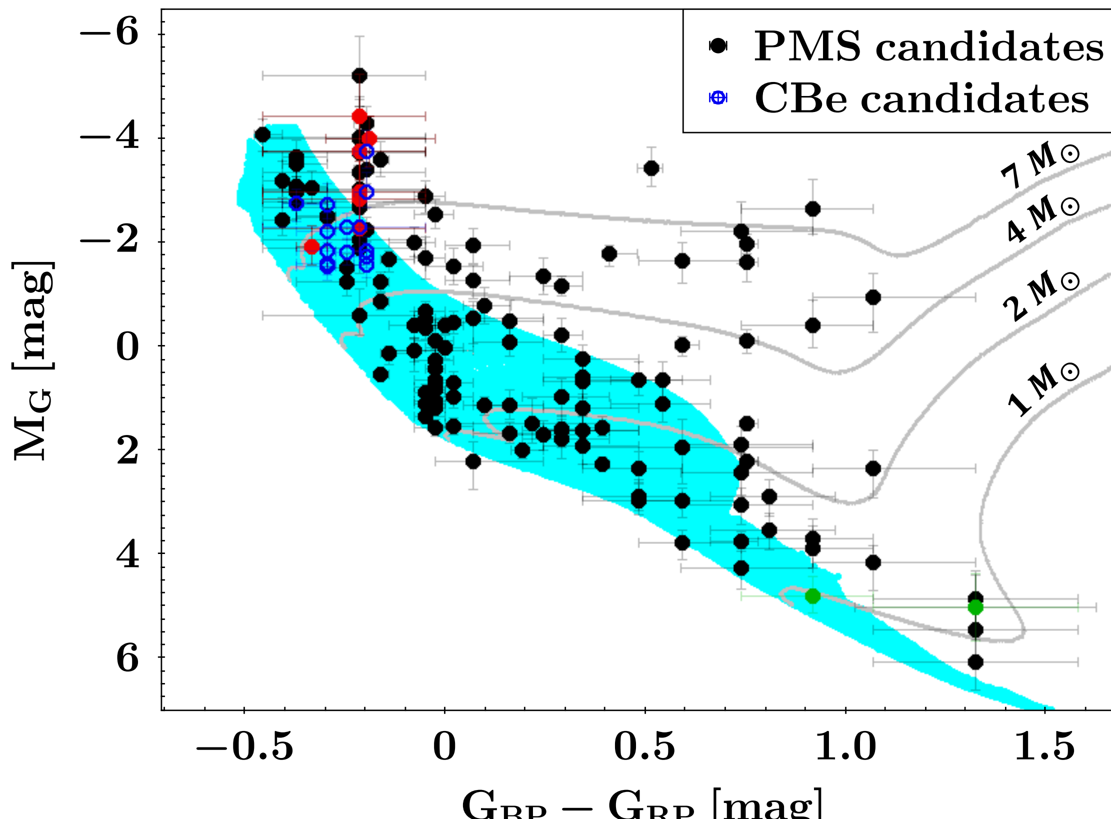
INT



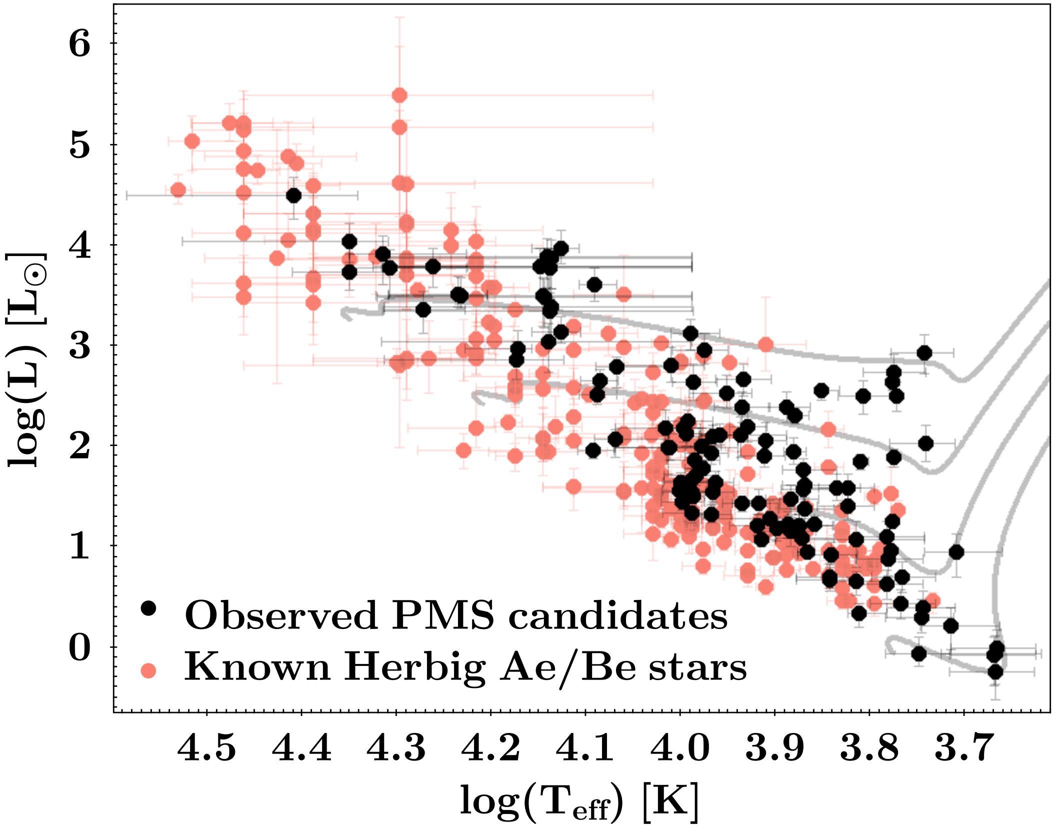
2.2m Calar Alto

NTT

- 120/145 Herbig Ae/Be candidates observed were confirmed as positive detections.
- 14/14 Classical Be candidates observed were confirmed as positive detections.
- 7/9 flagged contaminants in the catalogue are indeed contaminants.



We went observing



- 120 new Herbig Ae/Be stars
- 42 of them are above 4 $M_\odot$
- Some of them are significantly less evolved than the previously known Herbig Ae/Be stars of the same mass.

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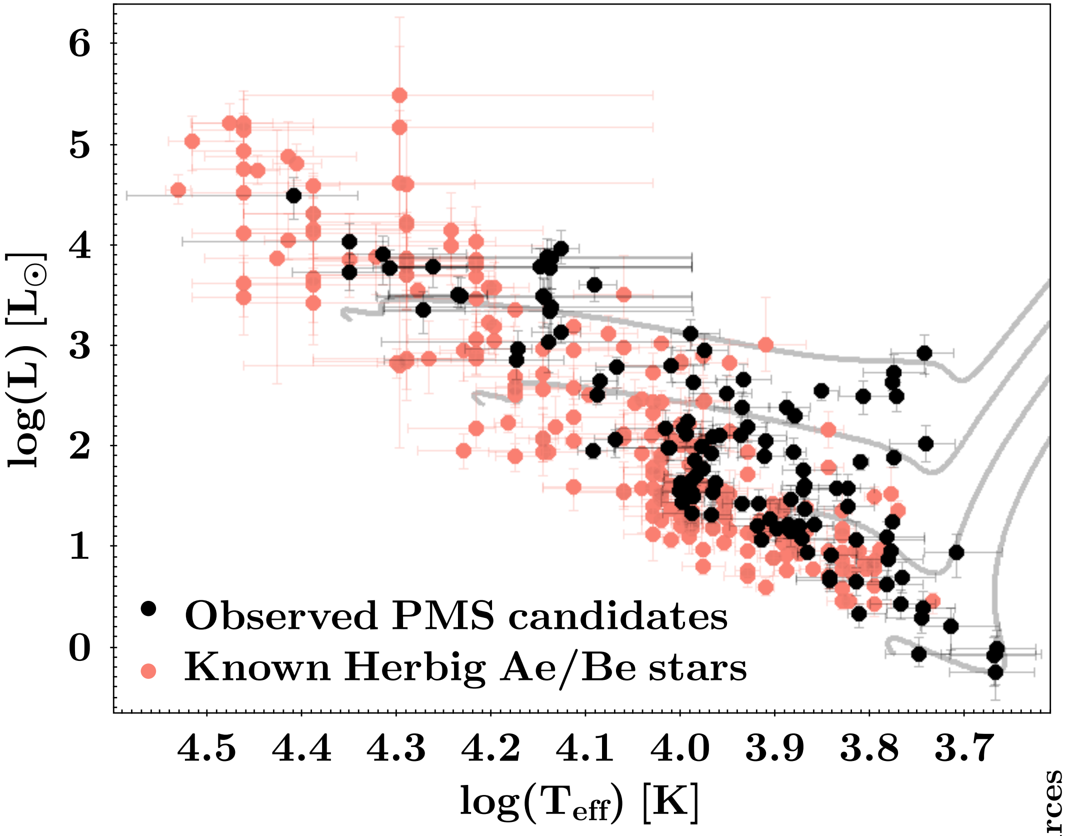

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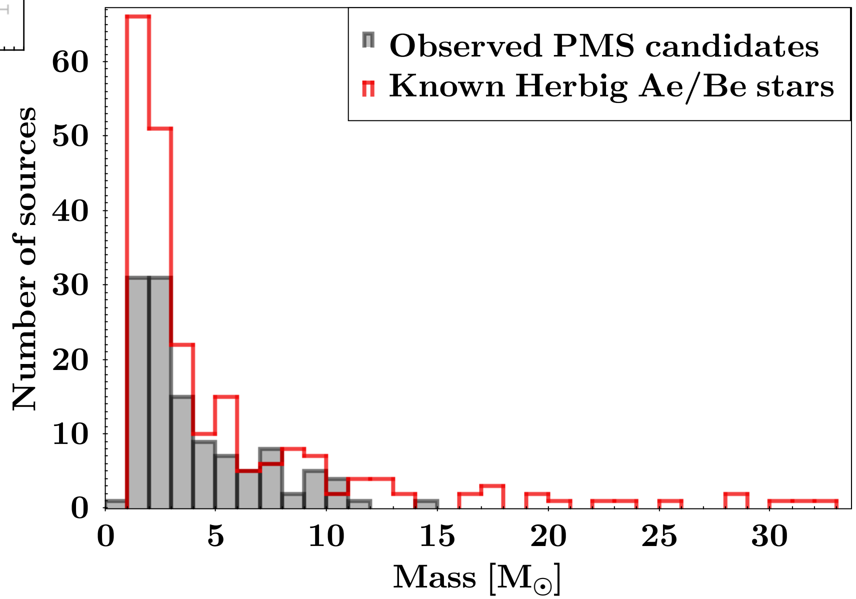
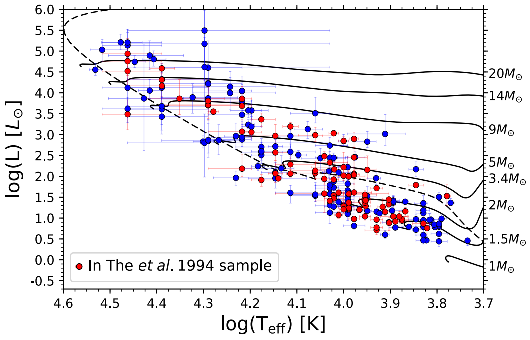


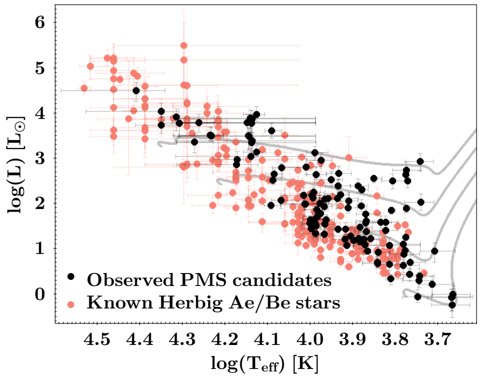
Future work

250 stars



+

120 stars

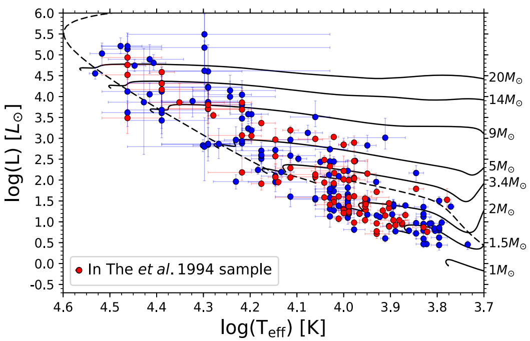


+

~2000 stars

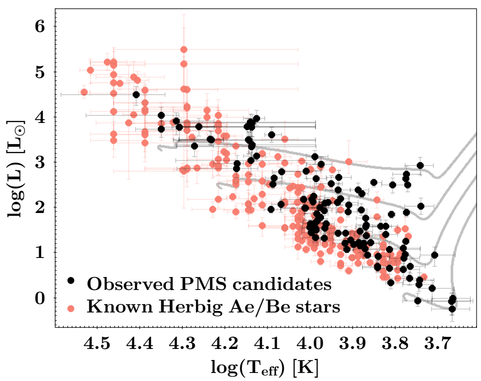
Future work

250 stars



+

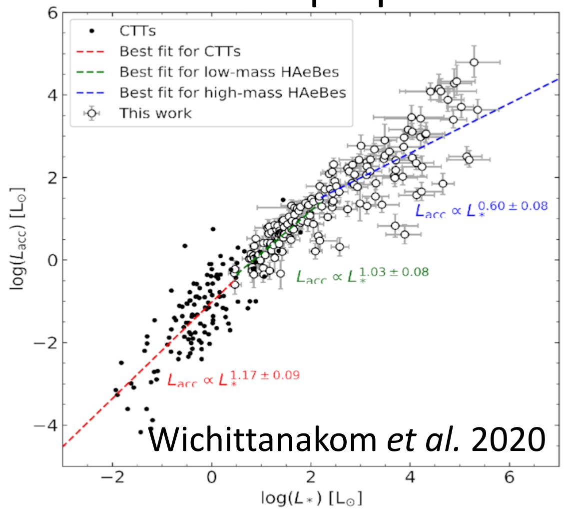
120 stars



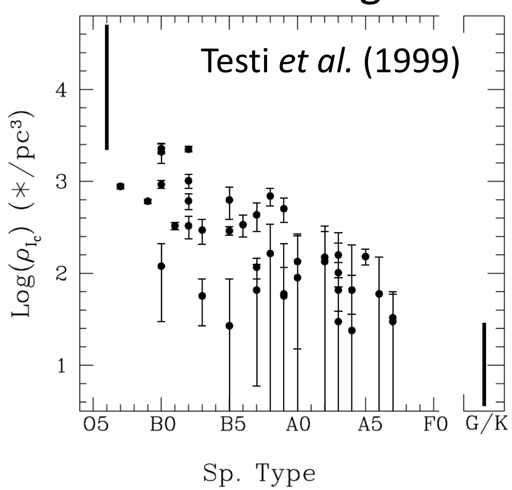
+

~2000 stars

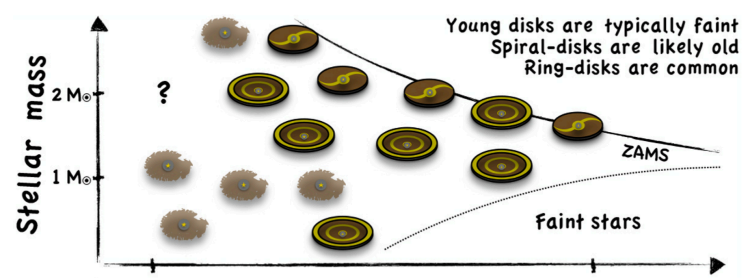
Accretion properties



Clustering



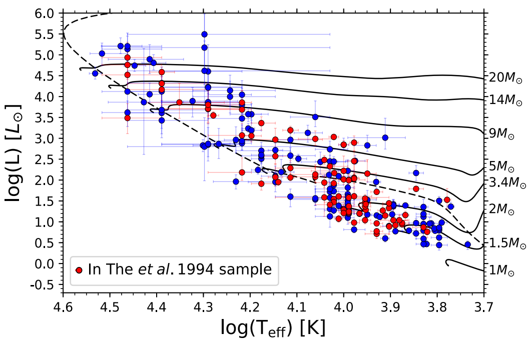
Disk Structure and Evolution



Garufi *et al.* (2018)

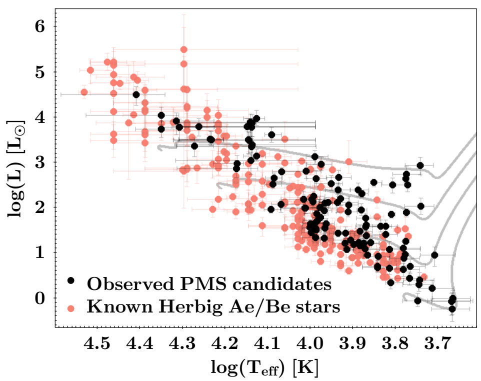
Future work

250 stars



+

120 stars



+

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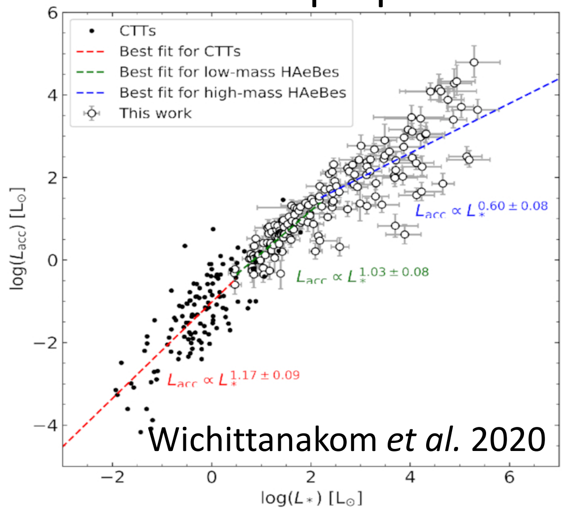
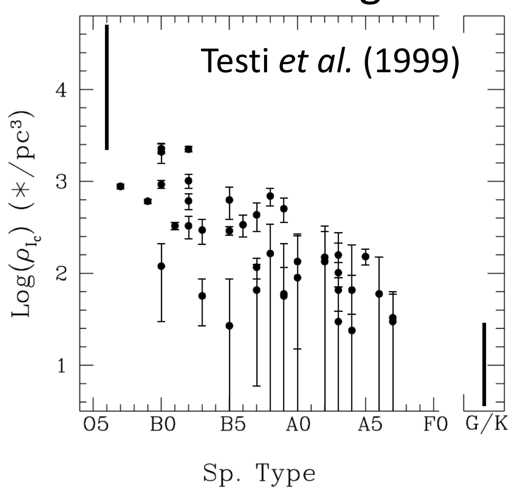
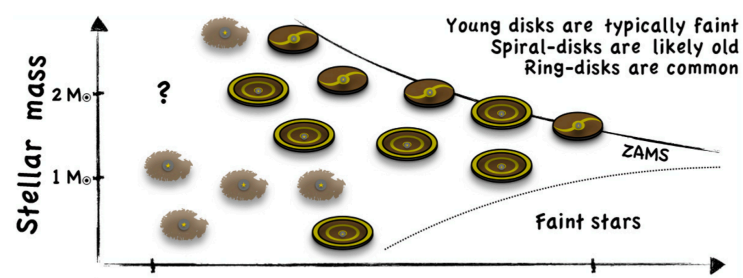


Clustering



Wide-field spectroscopic survey at *William Herschel Telescope*

Disk Structure and Evolution



Garufi *et al.* (2018)

Conclusions

- We have obtained **8470 new PMS candidates. 2226 potential Herbig Ae/Be stars.**

Completeness
$\mathbf{78.8 \pm 1.4\%}$

- We retrieve **693 new Classical Be stars candidates.**

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$\mathbf{85.5 \pm 1.2\%}$

- We retrieve **1309** candidates of belonging to either one of the two categories.

- The catalogues contain flags for possible contaminants.

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Independent observations confirm the accuracy of the classification!