Unveiling binary populations of hot subdwarfs with Gaia spectra and machine learning

Markus Ambrosch

Carlos Viscasillas Vázquez, Ana Ulla, Enrique Solano

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What are hot subdwarf stars?

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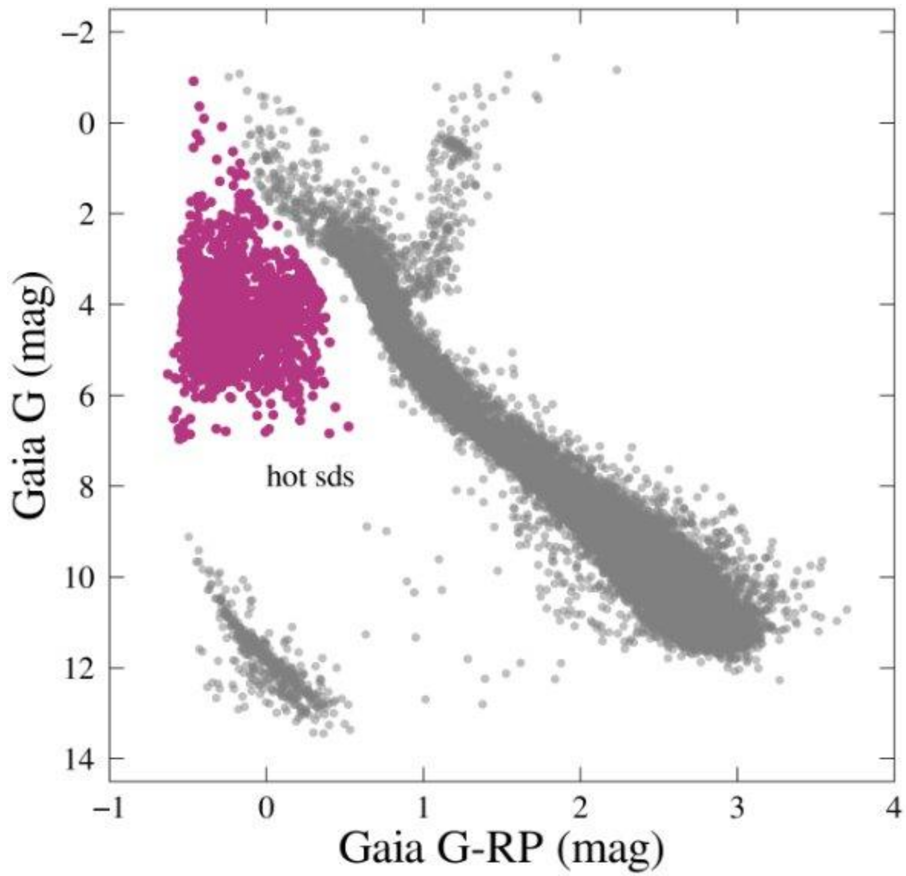
- They are hot
- They are below the normal dwarf stars in the colour-magnitude diagram
- They are rare. Only about 60 000 hot subdwarf candidates among all 1.5 billion Gaia DR3 sources (0.004%, Culpan et al. 2022)
- They are stars: Nuclear fusion processes are still ongoing



What are hot subdwarf stars?

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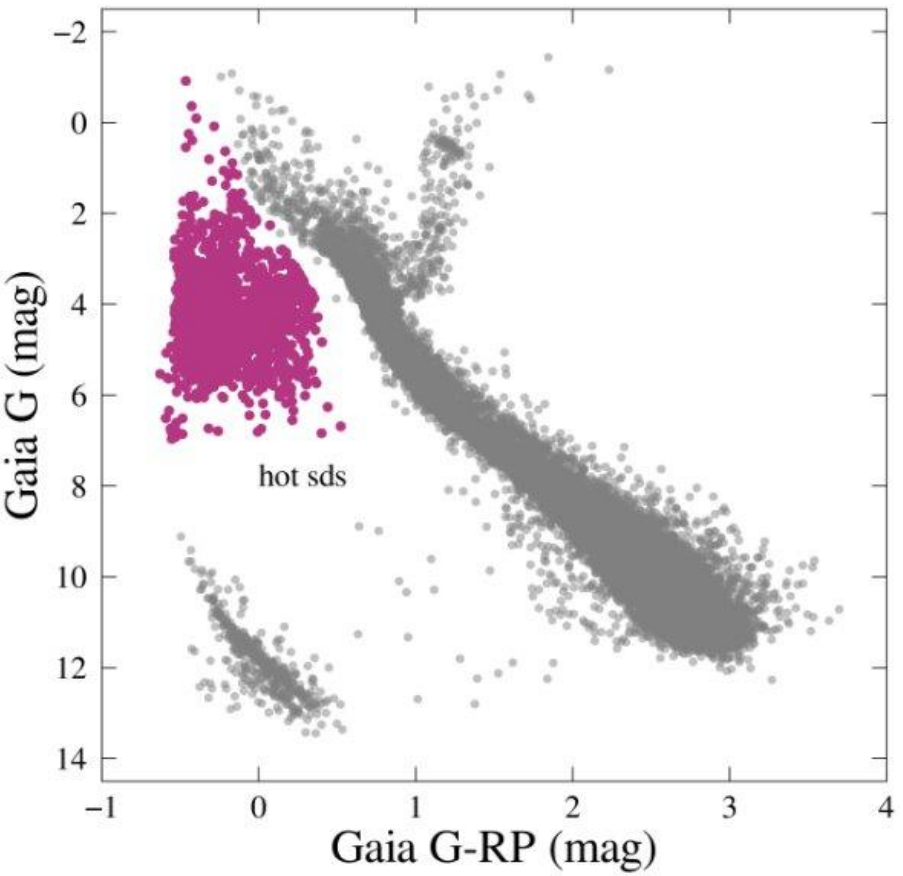
Stellar parameters:

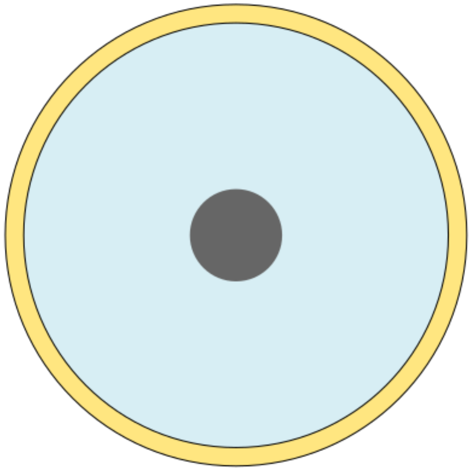
- Mass ≈ 0.5 solar masses
- Radius ≈ 0.2 solar radii
- log(g) ≈ 5.5 dex
- Surface temperature > 19 000 K



What are hot subdwarf stars?

Structure:

- Carbon and oxygen core
- Helium fusion in a shell around the core
- Very thin (almost absent) hydrogen envelope



Very different from dwarf stars, but akin to massive red giant stars.

What are hot subdwarf stars?

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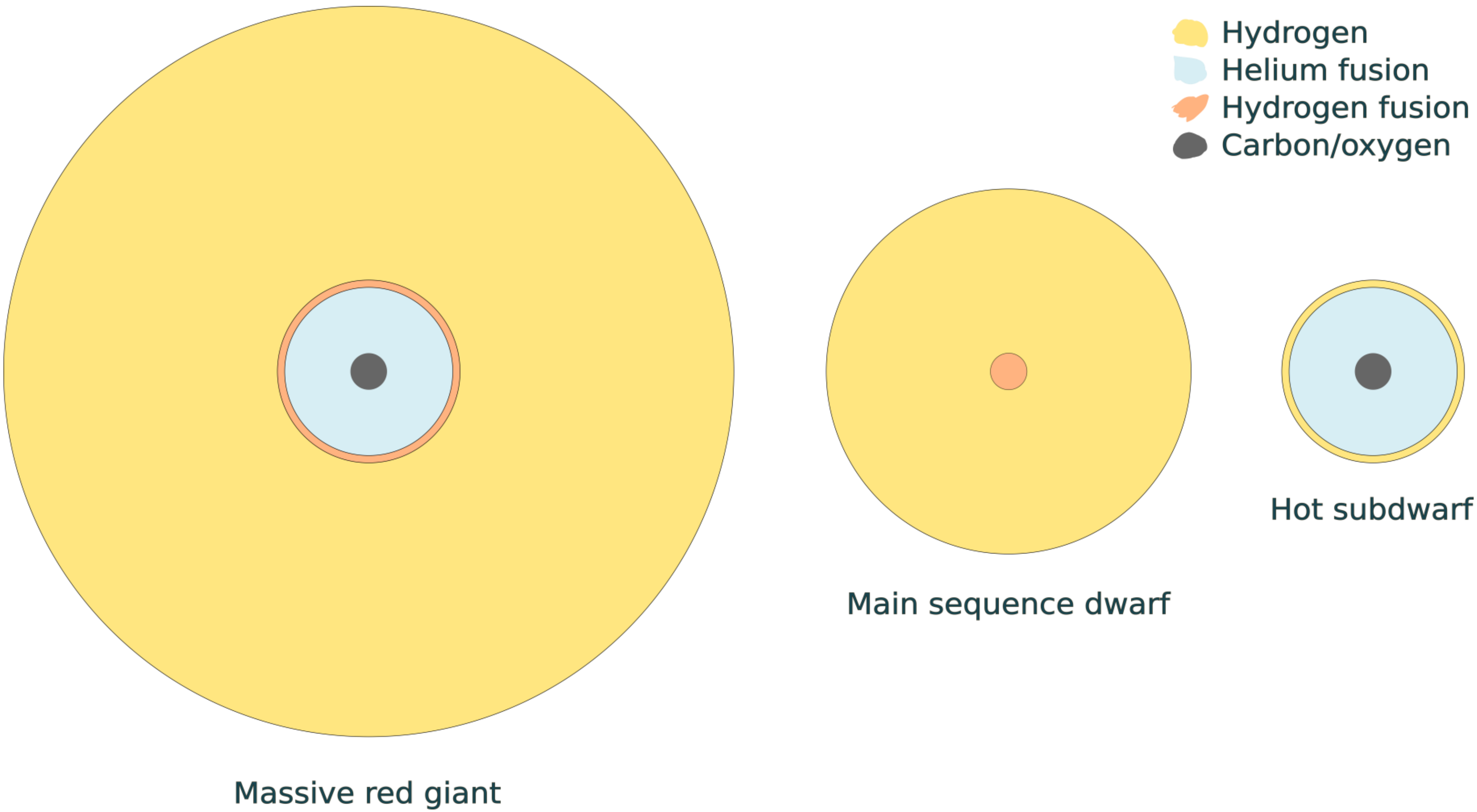

What are hot subdwarf stars?

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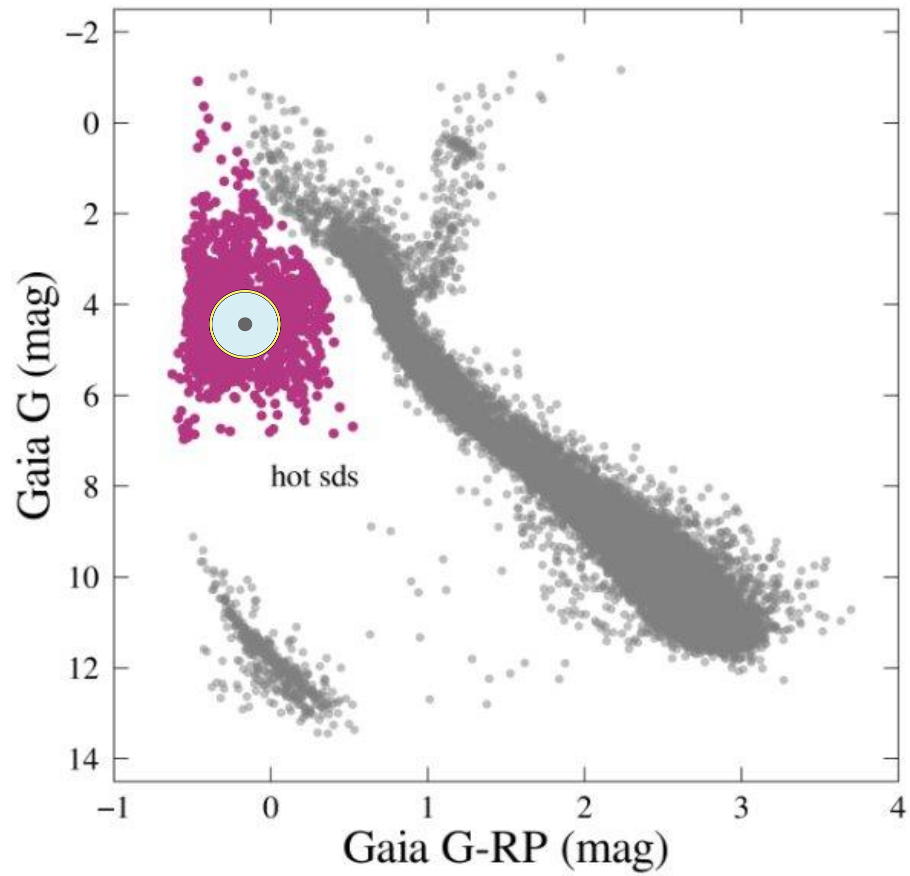
Hot subdwarf stars were massive red giants that ***somehow*** lost their hydrogen envelopes.



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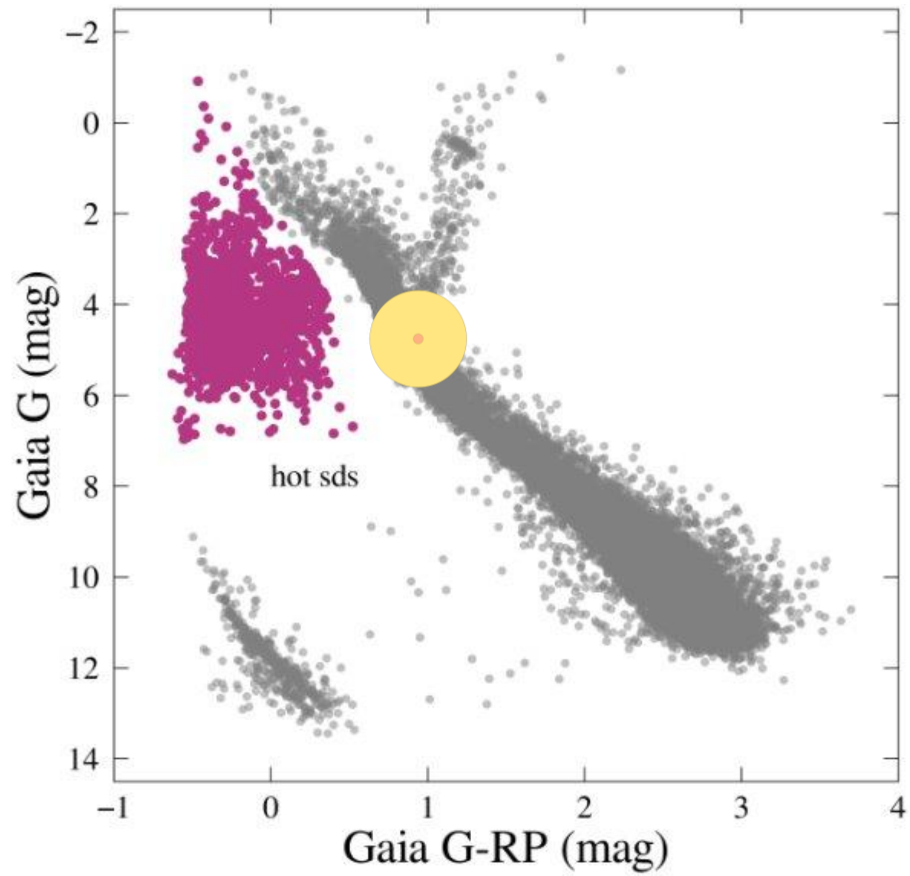

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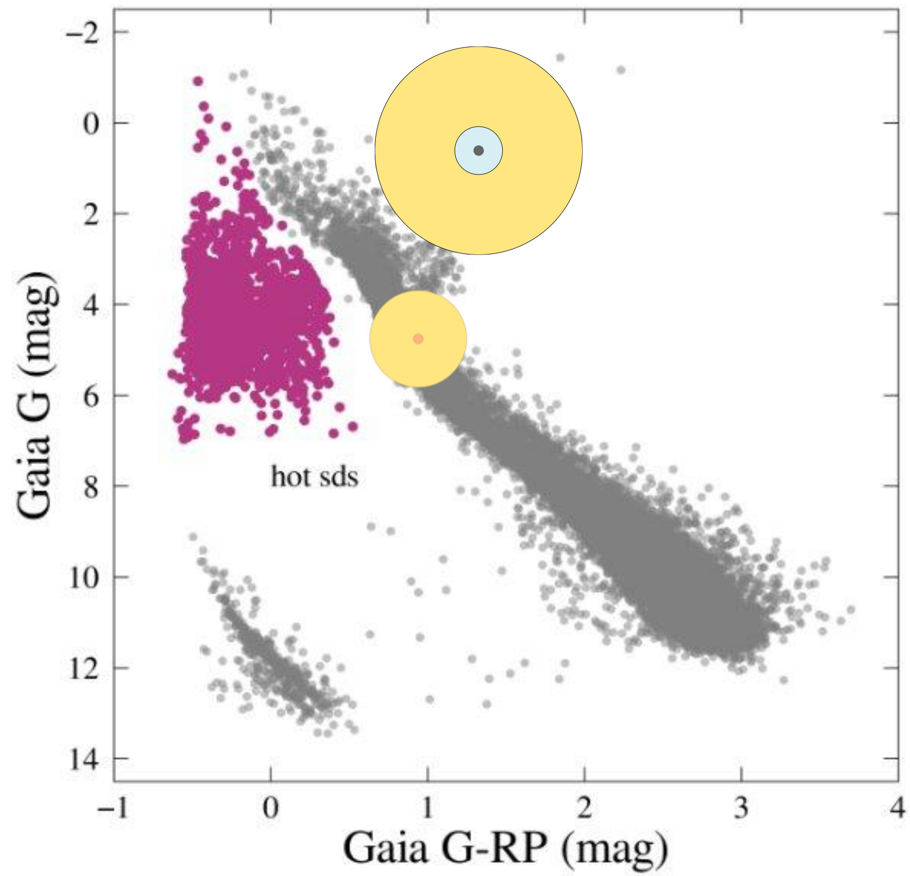

What are hot subdwarf stars?

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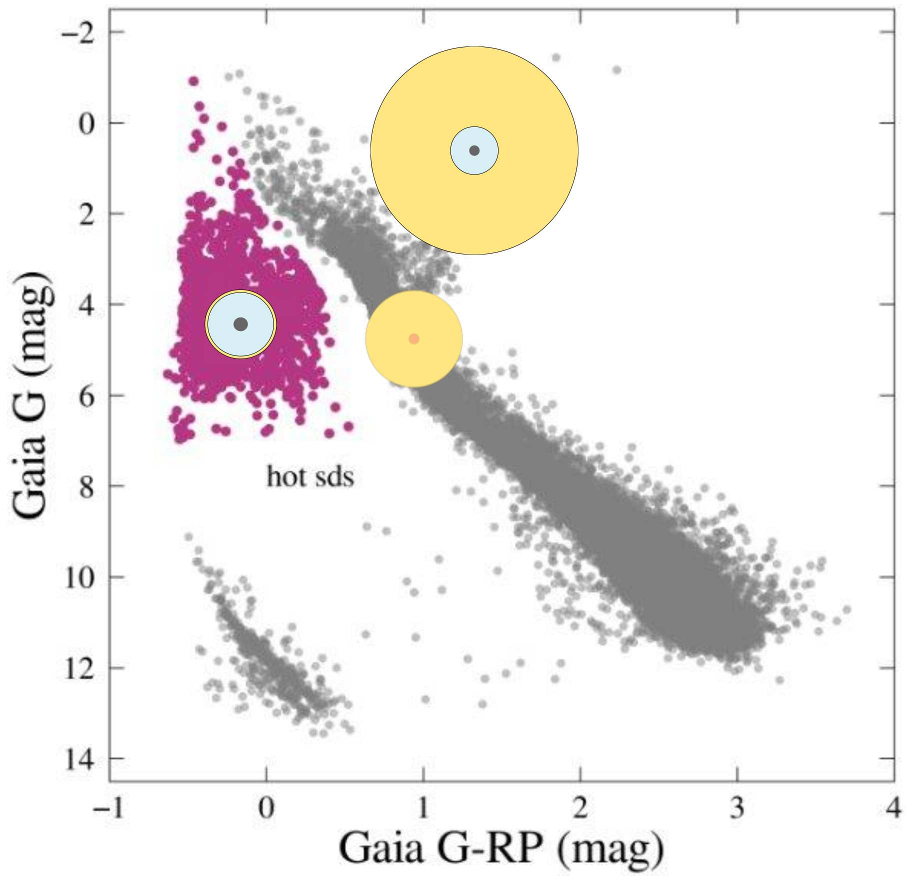
Hot subdwarf stars were massive red giants that ***somehow*** lost their hydrogen envelopes.

Many model calculations agree that the most probable scenario is stripping of the hydrogen envelope by ***interaction with a binary companion star.***



What are hot subdwarf stars?

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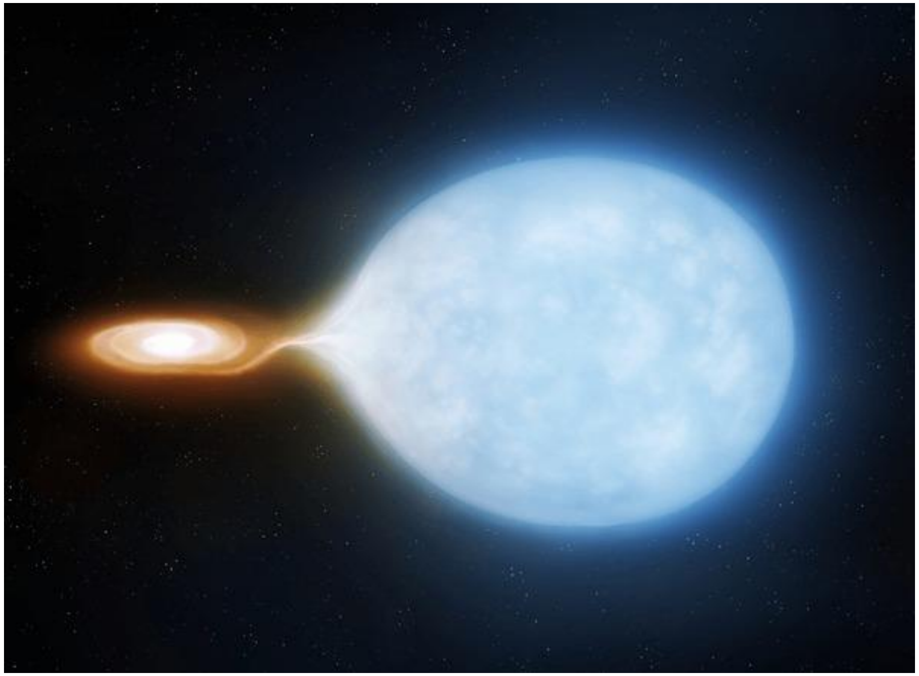
Interaction with a companion star:

1. Both stars were born at the same time, but one was more massive.
2. The massive star evolves into a red giant first and its hydrogen envelope expands.
3. The gravitational field of the smaller companion disturbs the expanded hydrogen envelope and pulls it away.



What are hot subdwarf stars?

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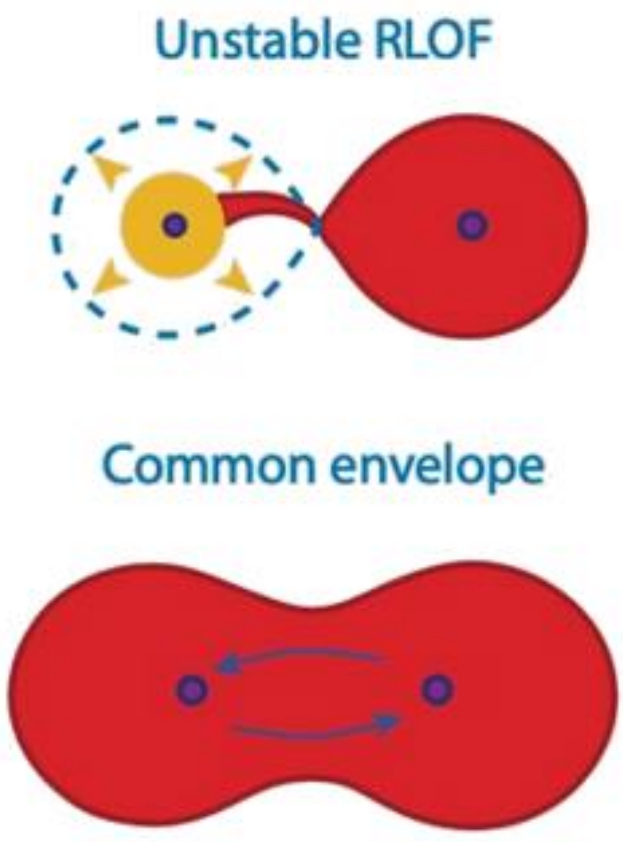
Close binary

Even closer



Geier et al. (2010)

Search for hot subdwarf binaries

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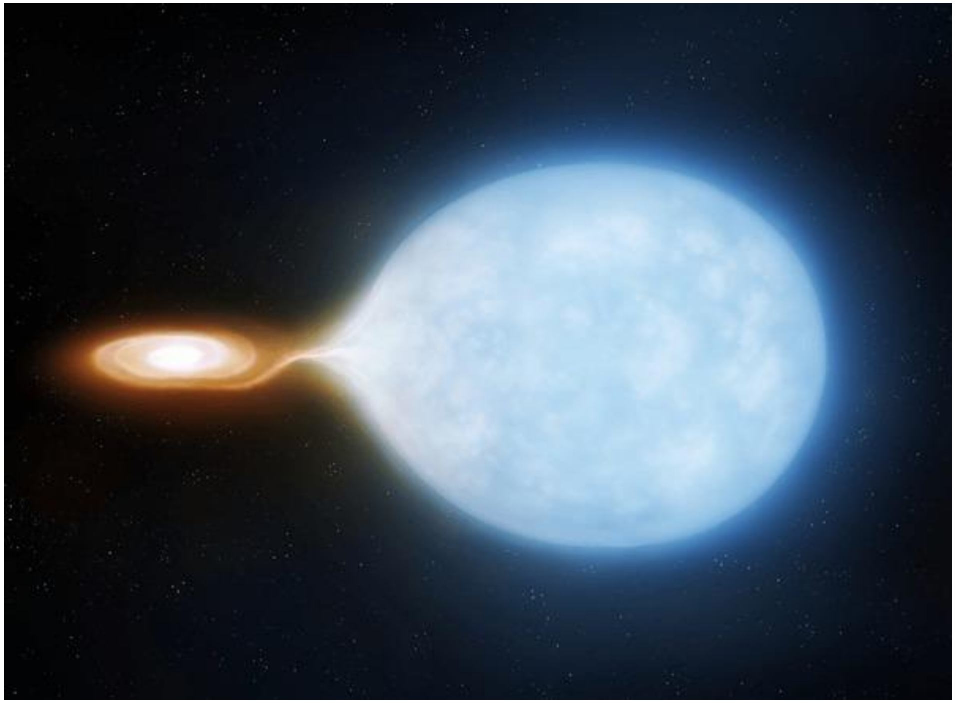
Key Question: What fraction of hot subdwarfs are formed through binary interaction?

Indirect methods are needed:

- Signatures of two stars in spectrum
- Radial velocity method
- Analysis of spectral energy distribution of hot subdwarfs



How to find binary hot subdwarfs?

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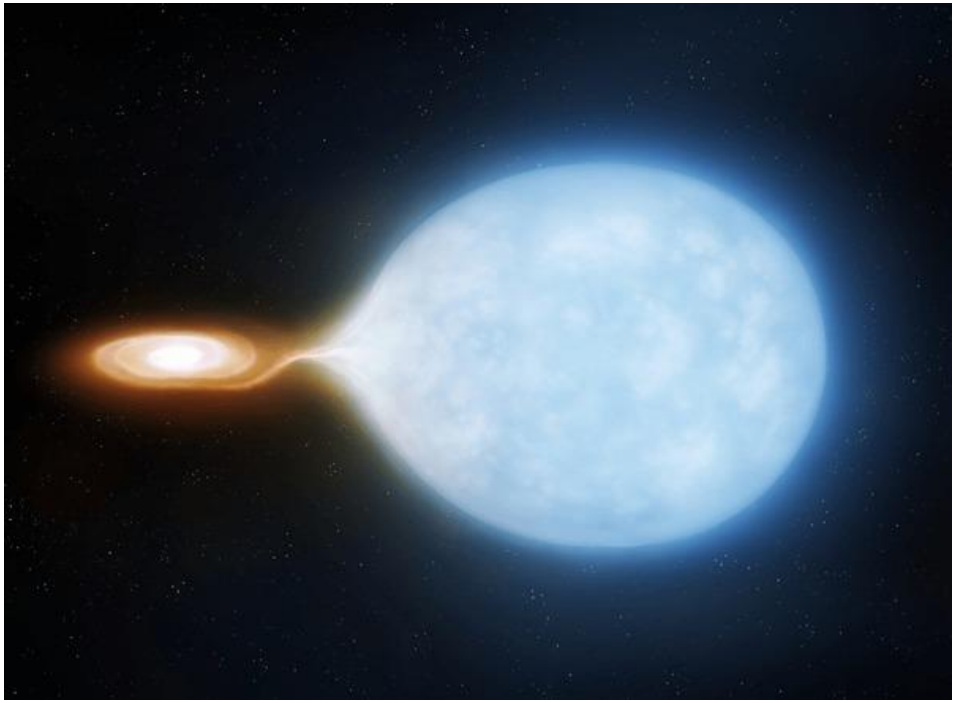

How to find binary hot subdwarfs?

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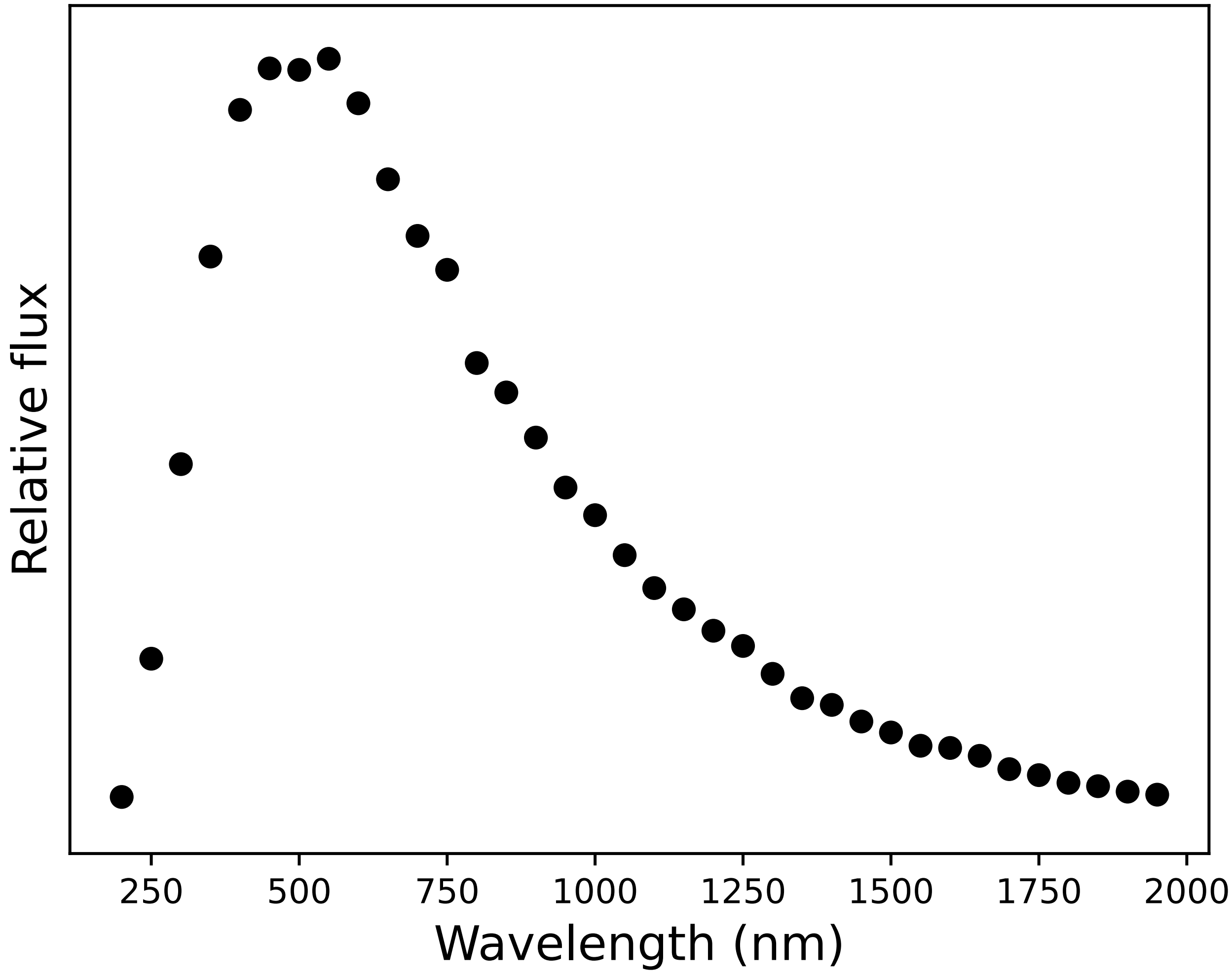

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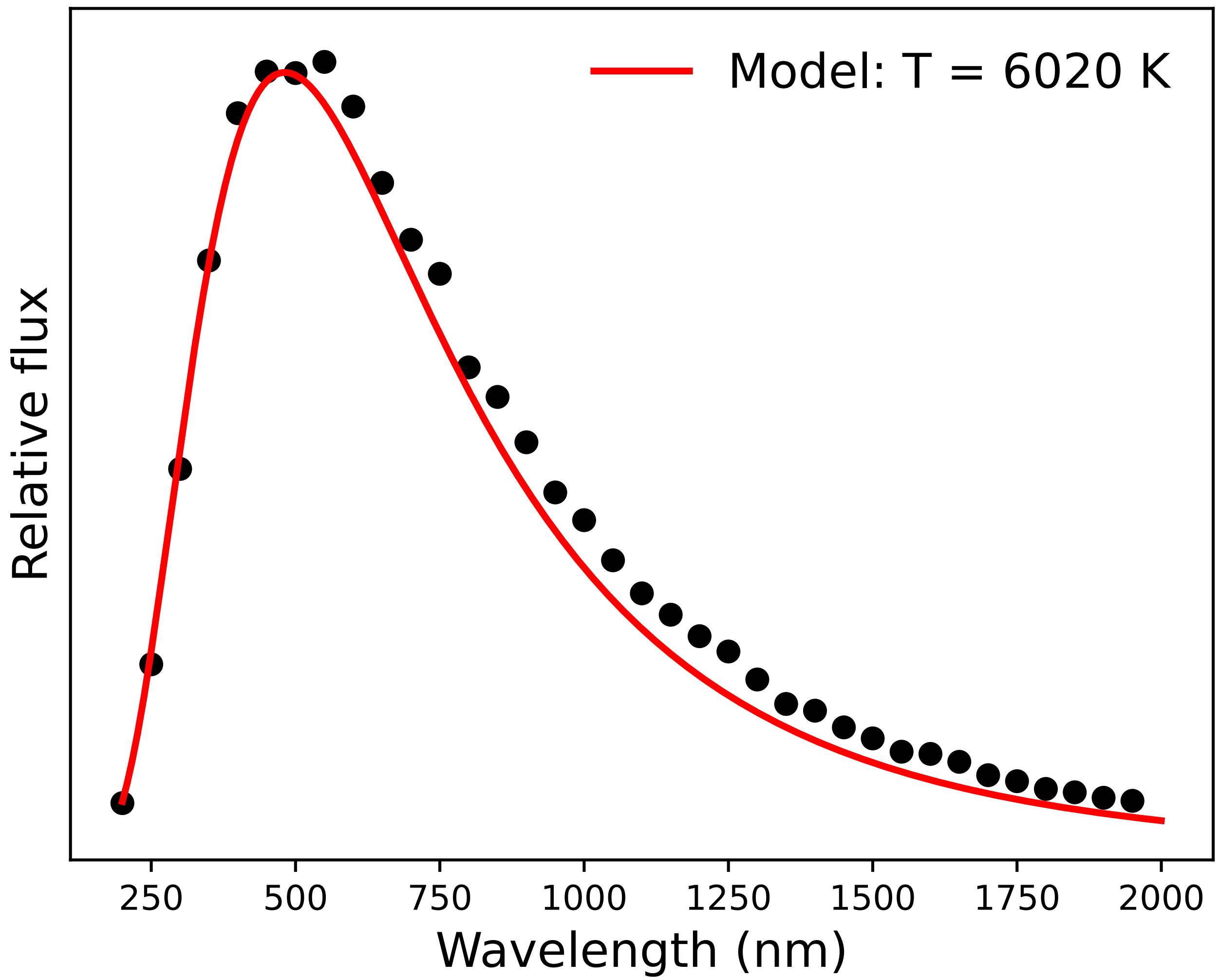

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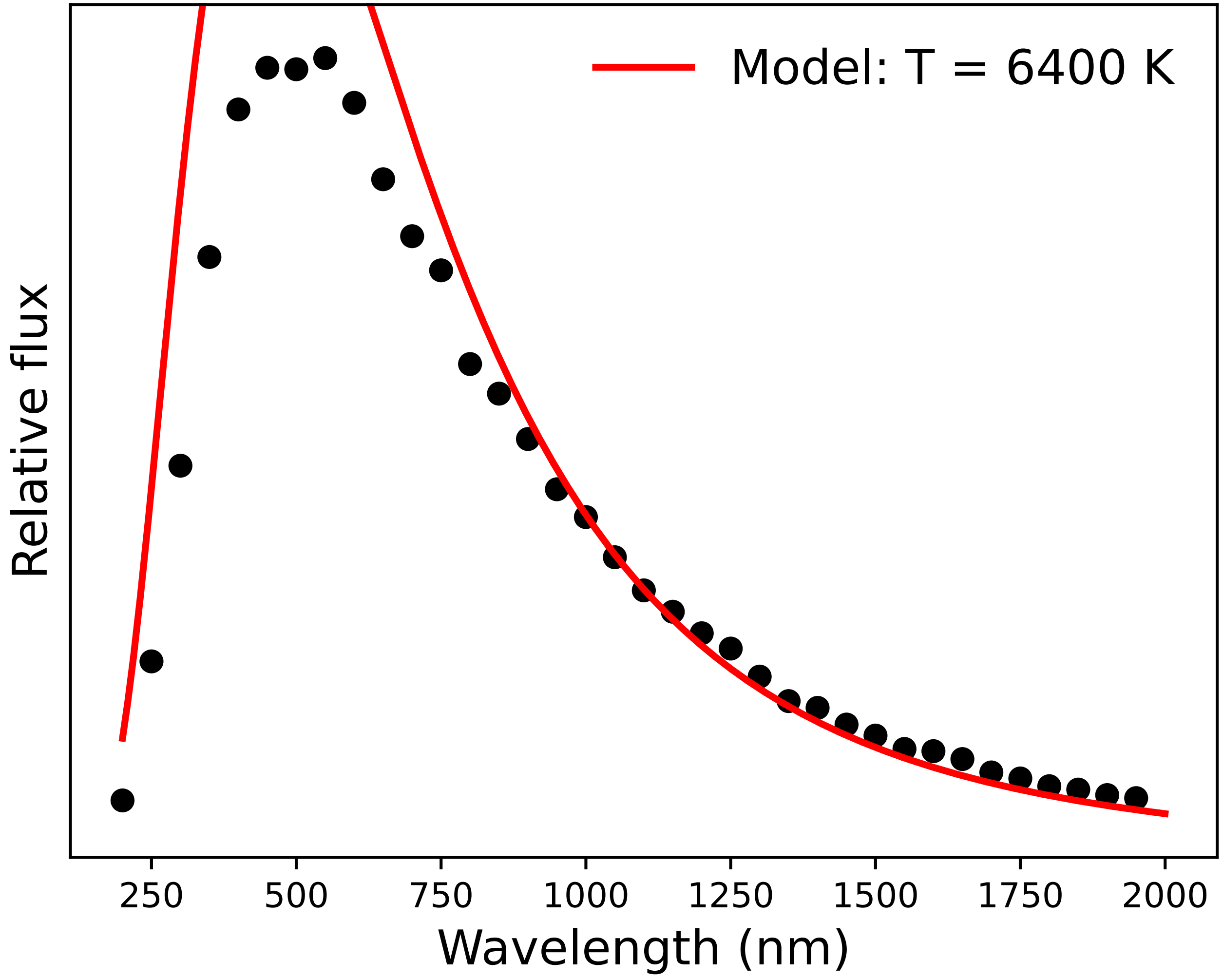

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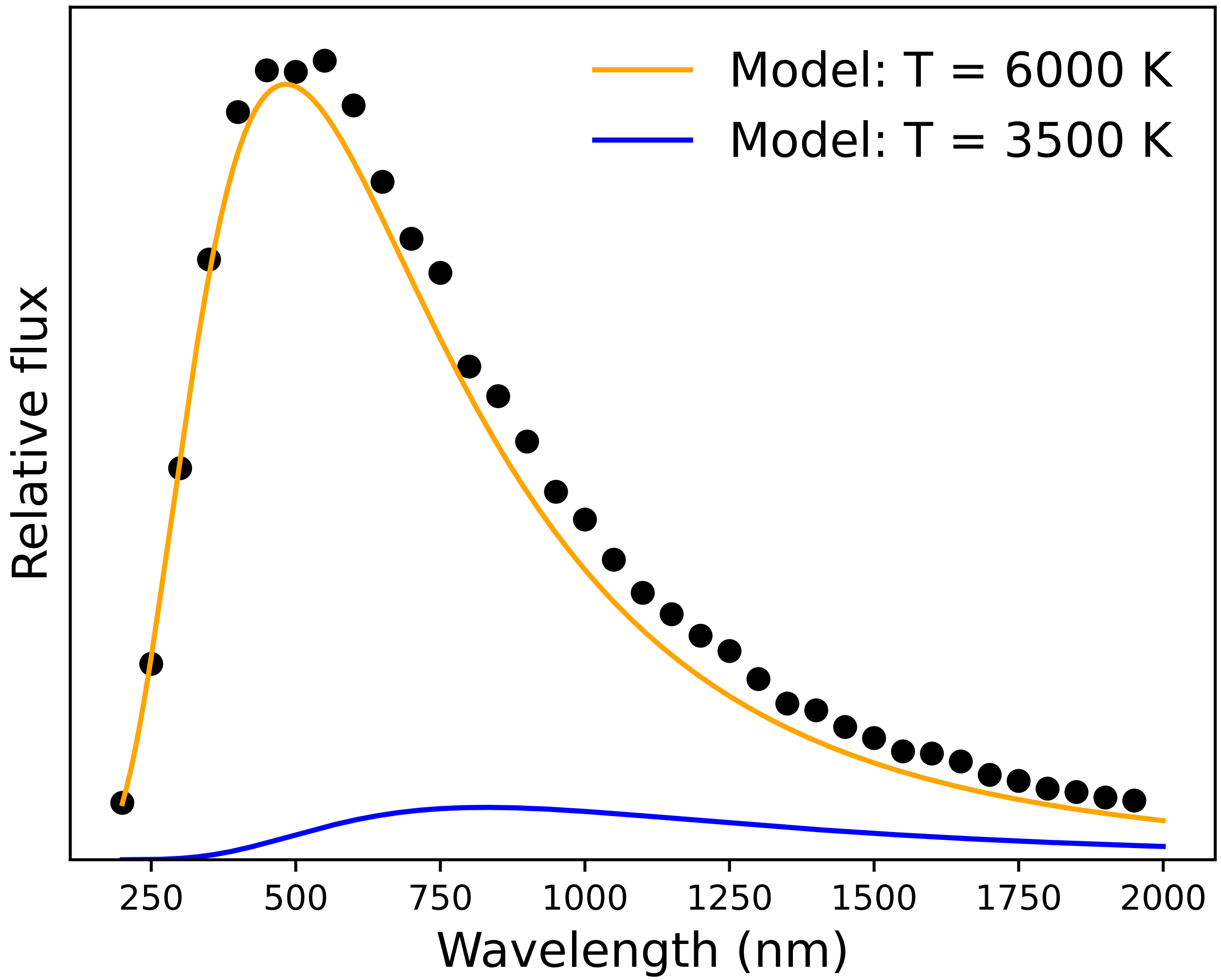

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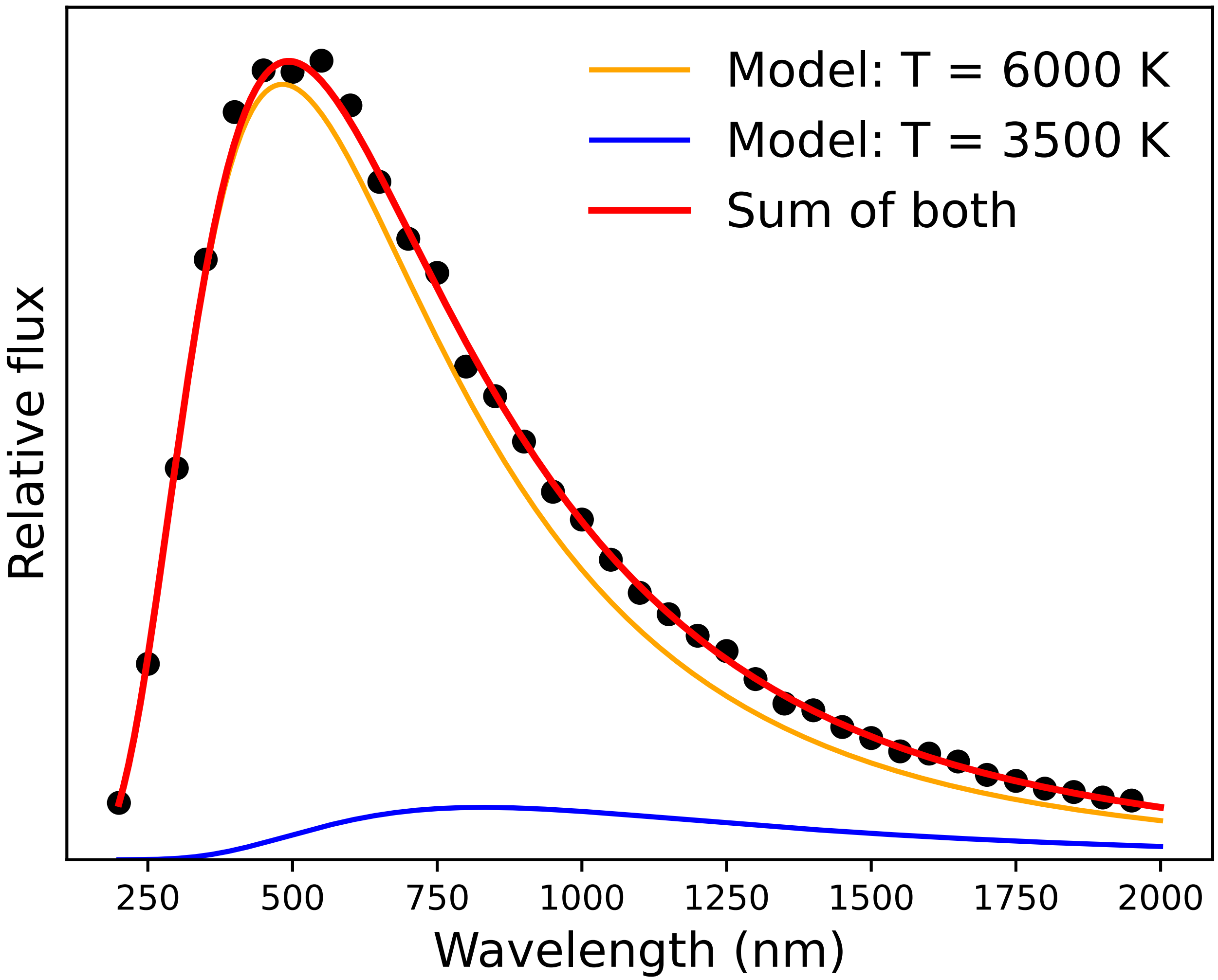

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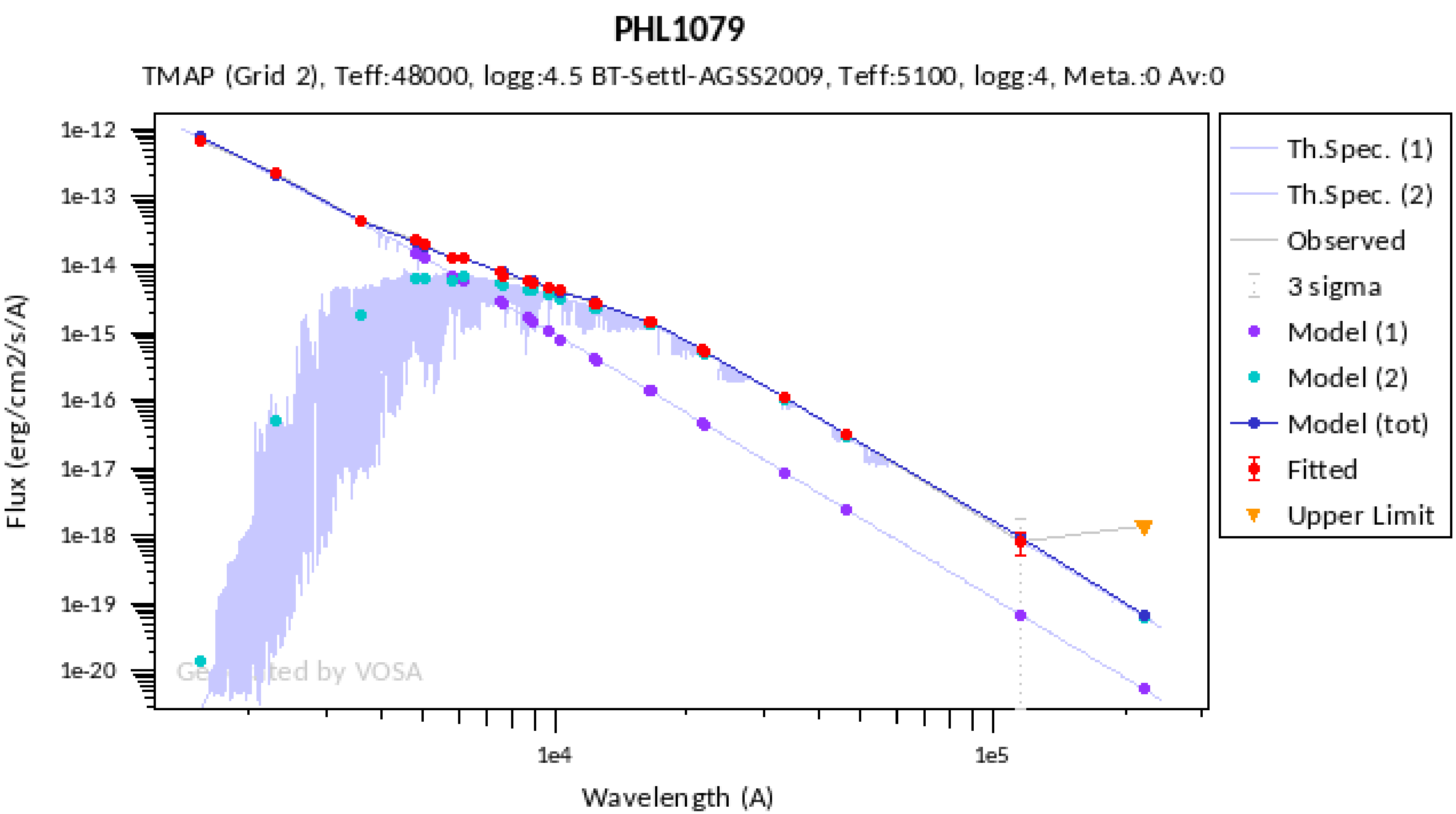

Enrique Solano et al. (2022) fit spectral energy distributions of ≈ 2500 hot subdwarfs, using the Virtual Observatory SED fitting tool (VOSA, Bayo et al. 2008)

How to find binary hot subdwarfs?

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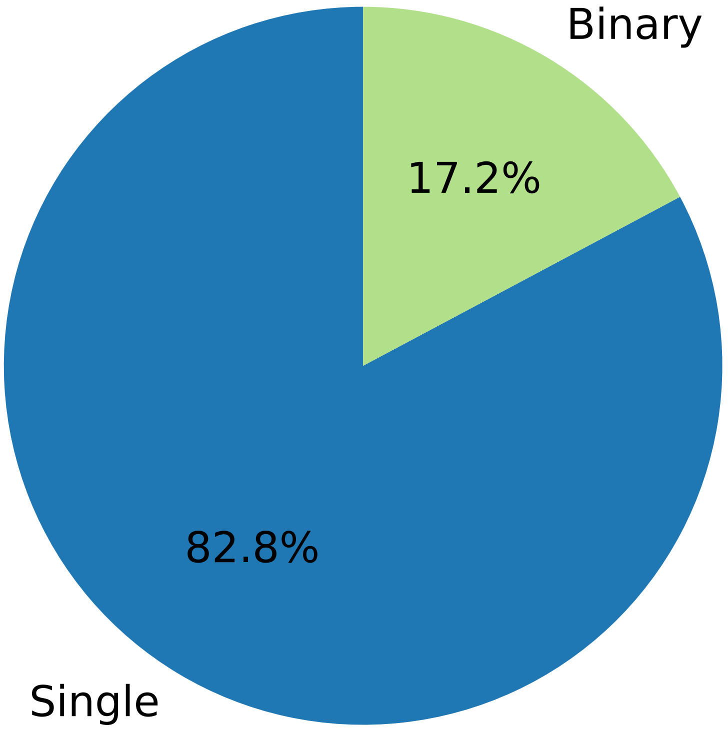
They found that only 17% are in binary systems.



How to find binary hot subdwarfs?

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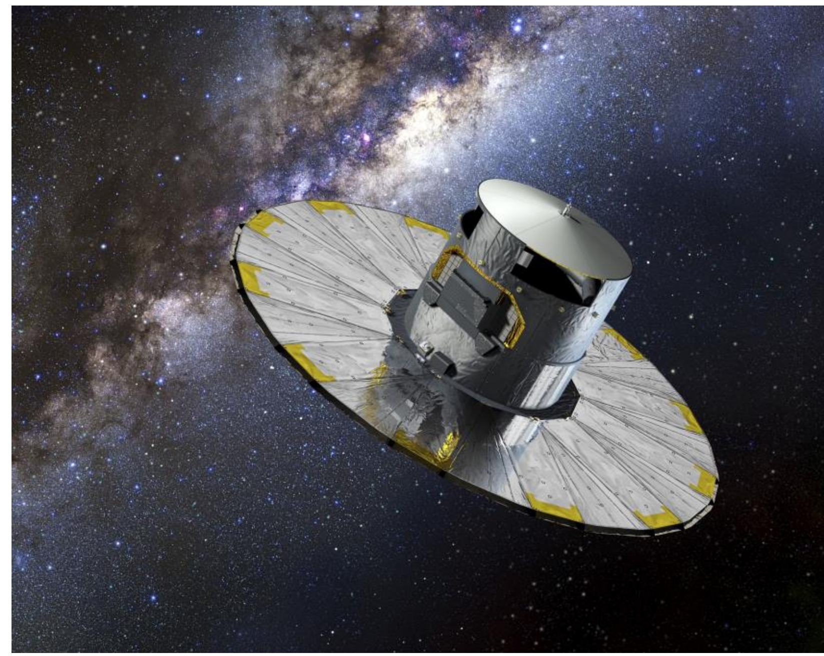
Enrique Solano et al. (2022) fit spectral energy distributions of ≈ 2500 hot subdwarfs.

They found that only 17% are in binary systems.

In our recent work (Ambrosch et al. 2026), we analyzed spectra of ≈ 20 000 hot subdwarfs from the Gaia space observatory.



ESA–D. Ducros, 2013

How to find binary hot subdwarfs?

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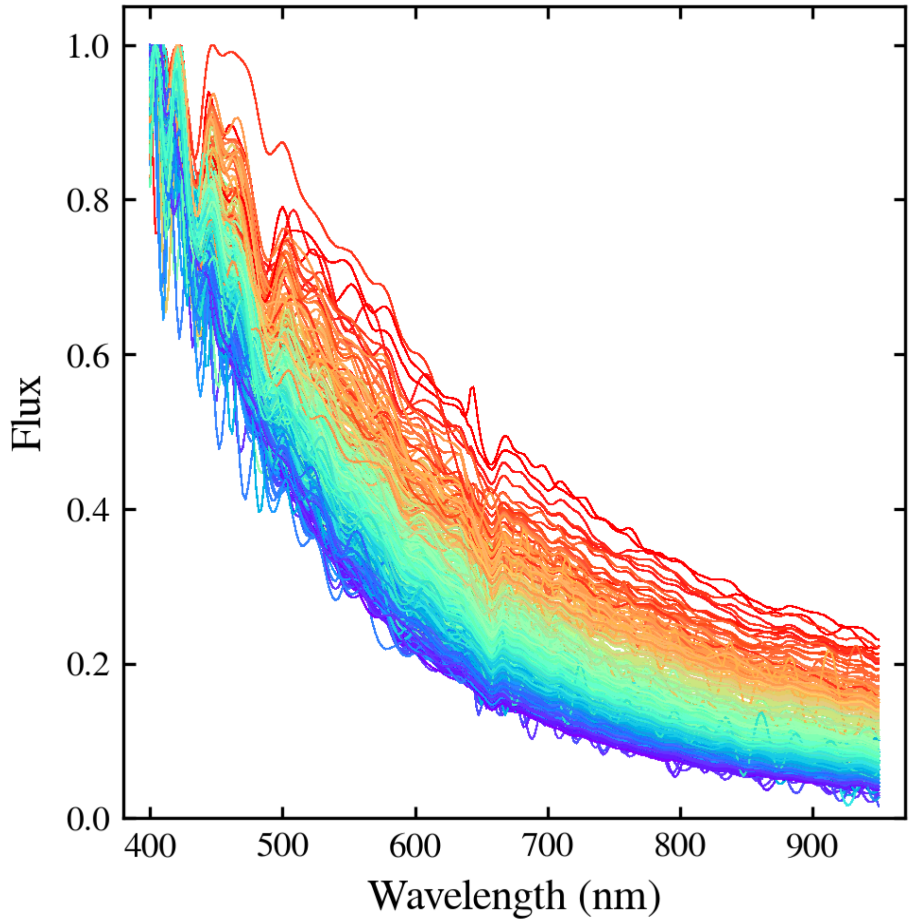

Our dataset:

- 20 000 Gaia DR3 XP spectra of hot subdwarfs.
- Very low resolution (R < 100)

Large number of spectra requires efficient data analysis methods.

How to find binary hot subdwarfs?

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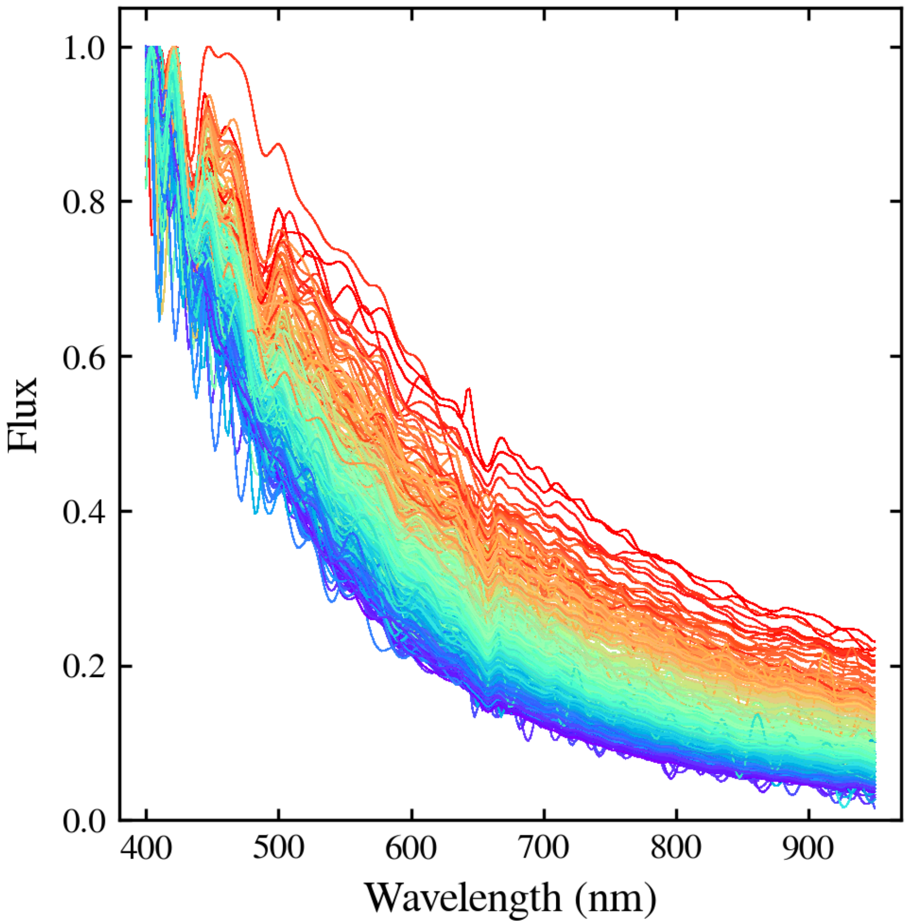

Our dataset:

- 20 000 Gaia DR3 XP spectra of hot subdwarfs.
- Very low resolution (R ≈ 50)

Large number of spectra requires efficient data analysis methods.

Machine learning!

How to find binary hot subdwarfs?

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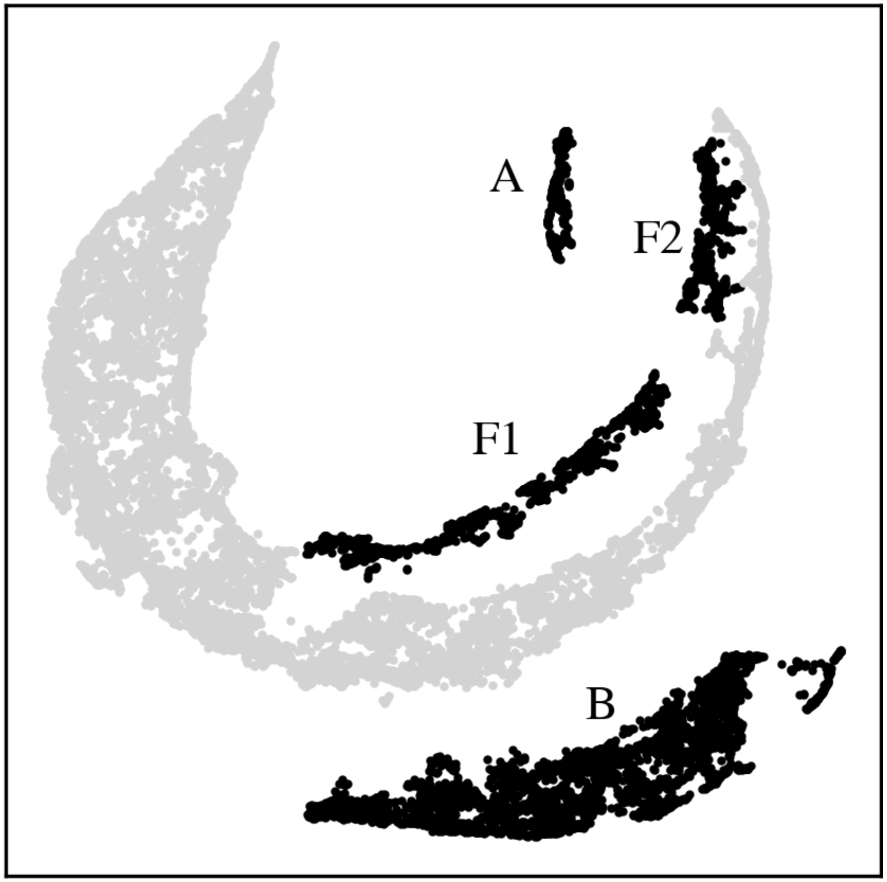

Similarity analysis with UMAP

- Every hot subdwarf spectrum is represented by one point in the similarity map
- Similar spectra are close together in the map, different spectra are far apart

Similarity is measured purely by the shape of the spectra.

How to find binary hot subdwarfs?

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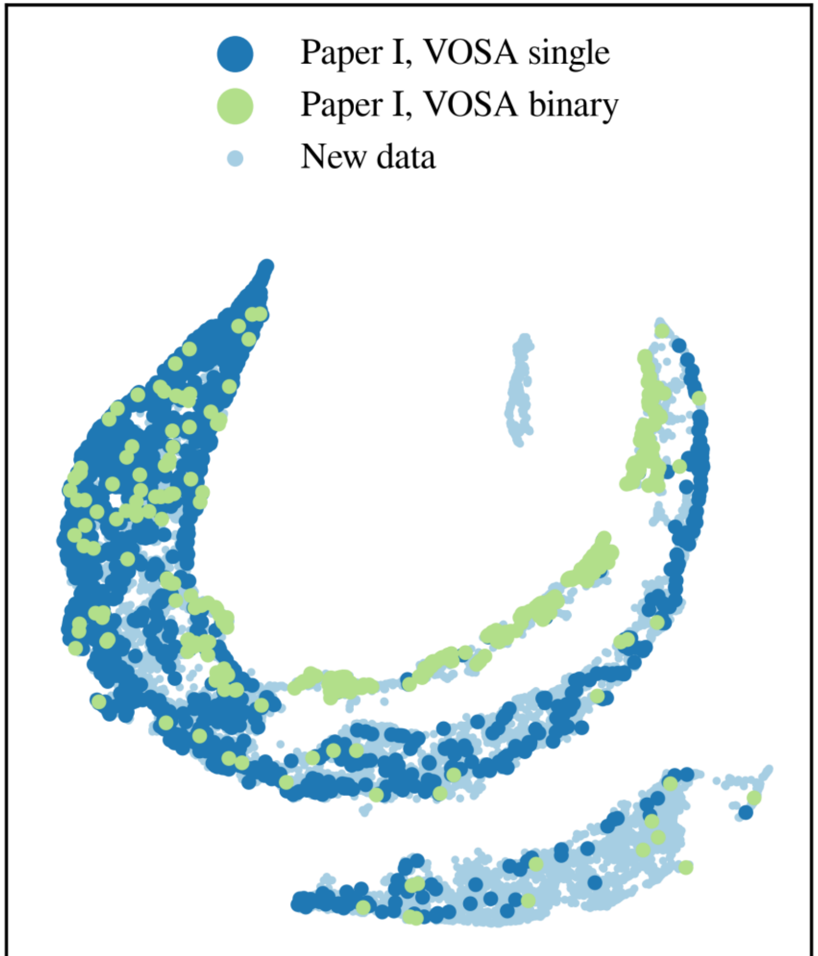

Paper I: Viscasillas Vázquez (2024)

Similarity analysis with UMAP:

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- Similar spectra are close together in the map, different spectra are far apart

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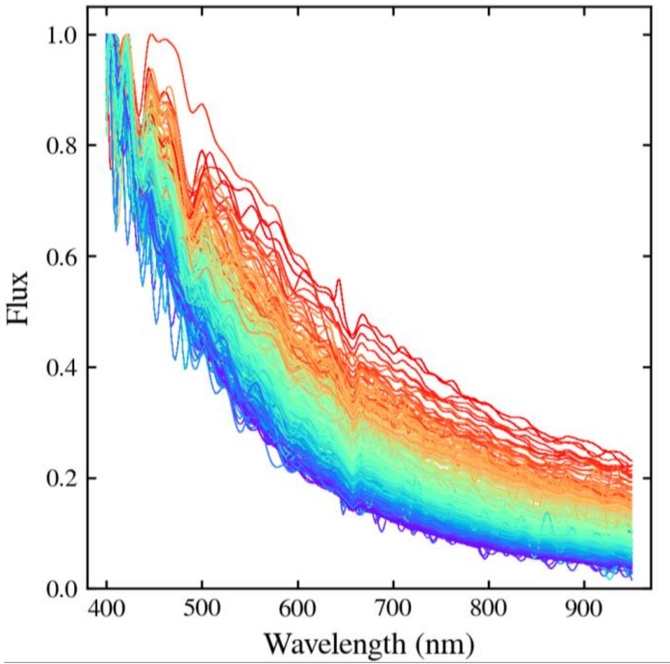
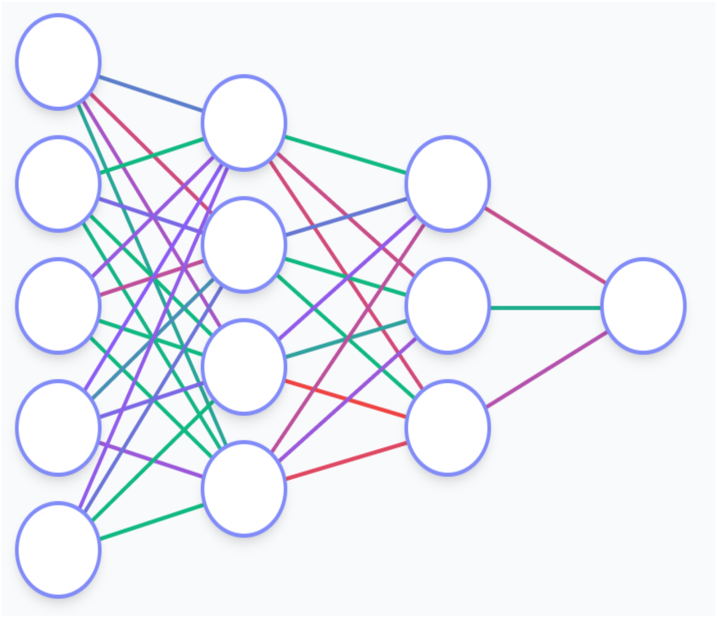
Neural network for classification

1. Network learns what spectra of binary hot subdwarfs look like

2. Then it can classify all 20 000 spectra in our sample very quickly





binary
or
single

Results of binary search

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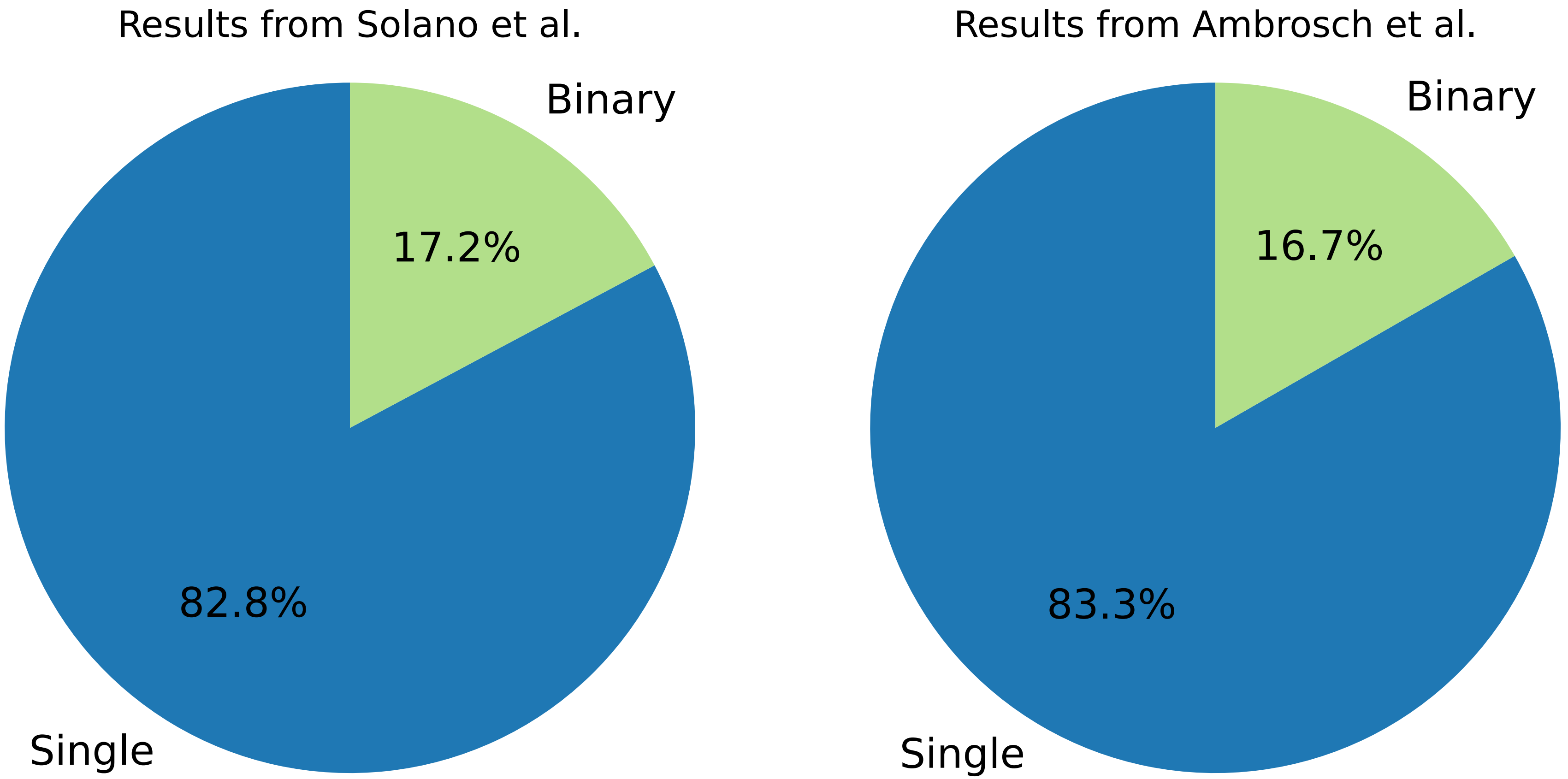

Binarity and stellar variability

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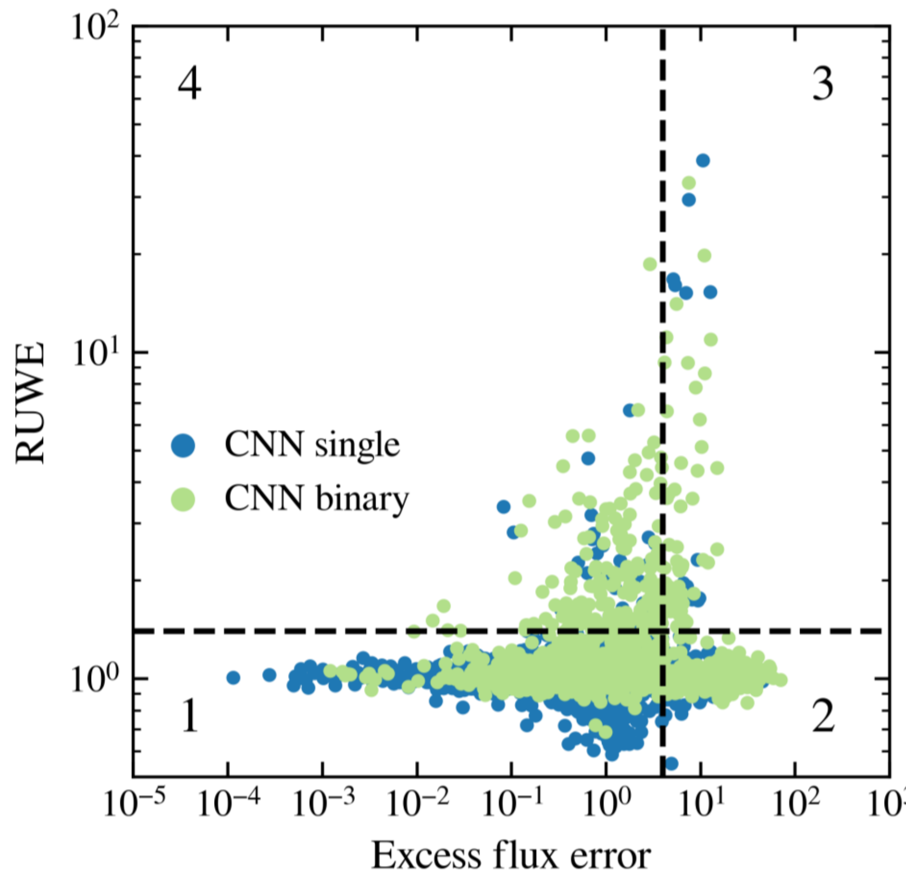
Binary fraction increases with increased stellar variability.

1: No variability

2: Only photometric

3: Photometric + astrometric

4: Only astrometric



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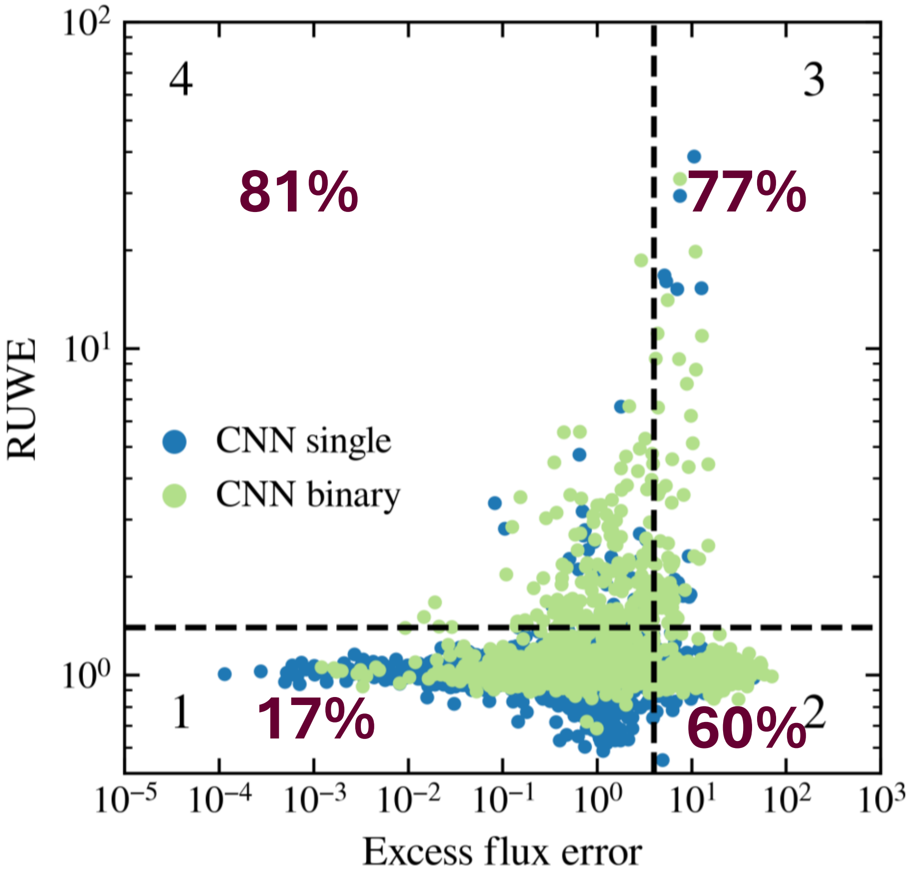

Conclusions

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1. Gaia with machine learning methods enables us to study hot subdwarfs on a population-level scale.

2. Models say that binary interaction is needed for hot subdwarf formation, but we find only ~17% binary rate. High resolution spectra, multi-epoch observations from Gaia DR4 could help to solve this contradiction.

3. Photometric and astrometric variability measures can serve as indicators for hot subdwarf binarity.

All results and Python code for their reproduction are available on GitHub (https://github.com/mambr-astro/Hot_sds_GaiaXP)!

Check out Vladas Šatas' poster!

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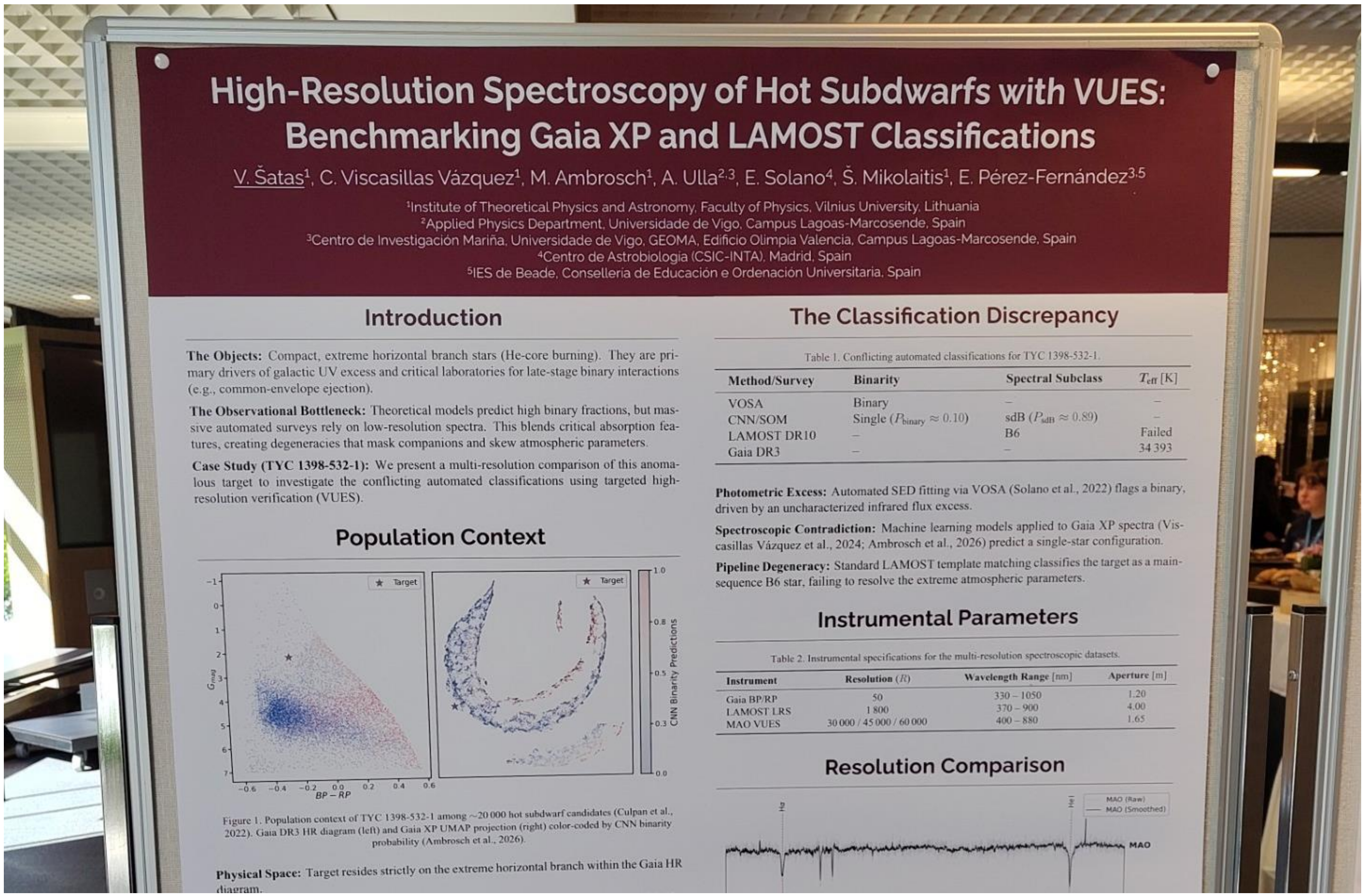

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Thank you!

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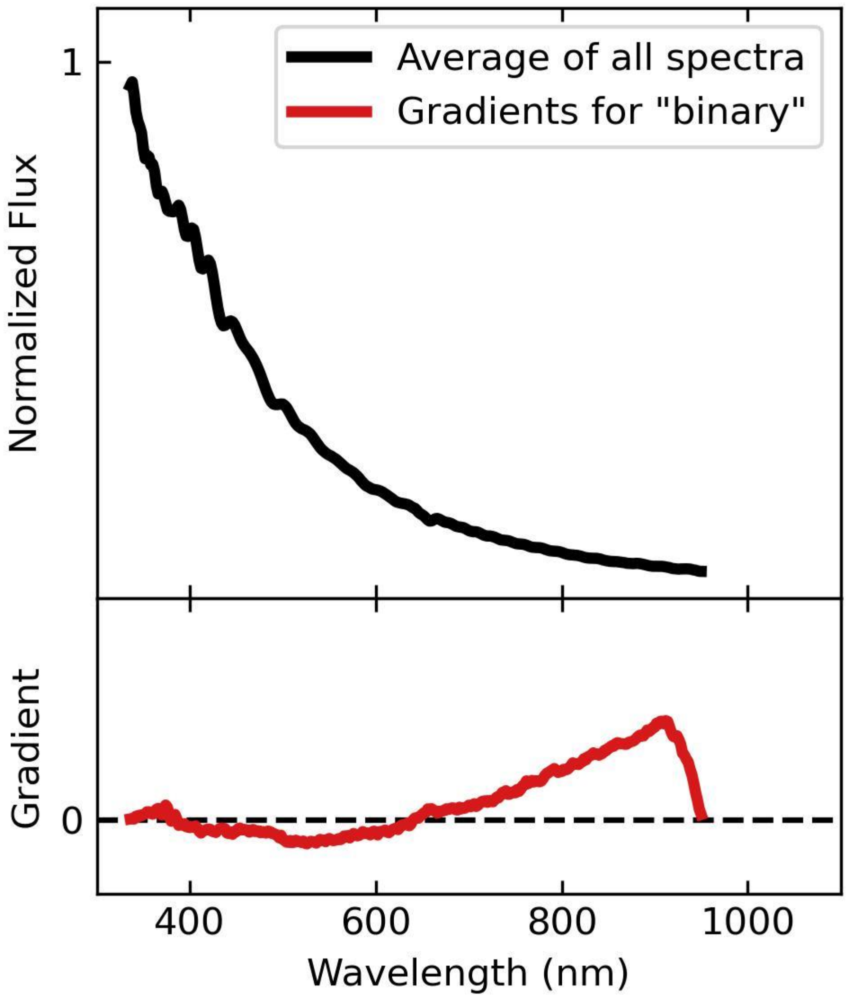
Solano, E., Ulla, A., Pérez-Fernández, E., et al. 2022, MNRAS, 514, 4239

Viscasillas Vázquez, C., Solano, E., Ulla, A., et al. 2024, A&A, 691, A223

Additional slides

Interpretation of CNN decisions



Network gradients show which parts of spectra influence CNN classification.

Larger gradient values show strong correlation between flux values at given wavelength and binary probability.

Consistent with classical physics-based classification by infrared flux excess.

What else can we do?

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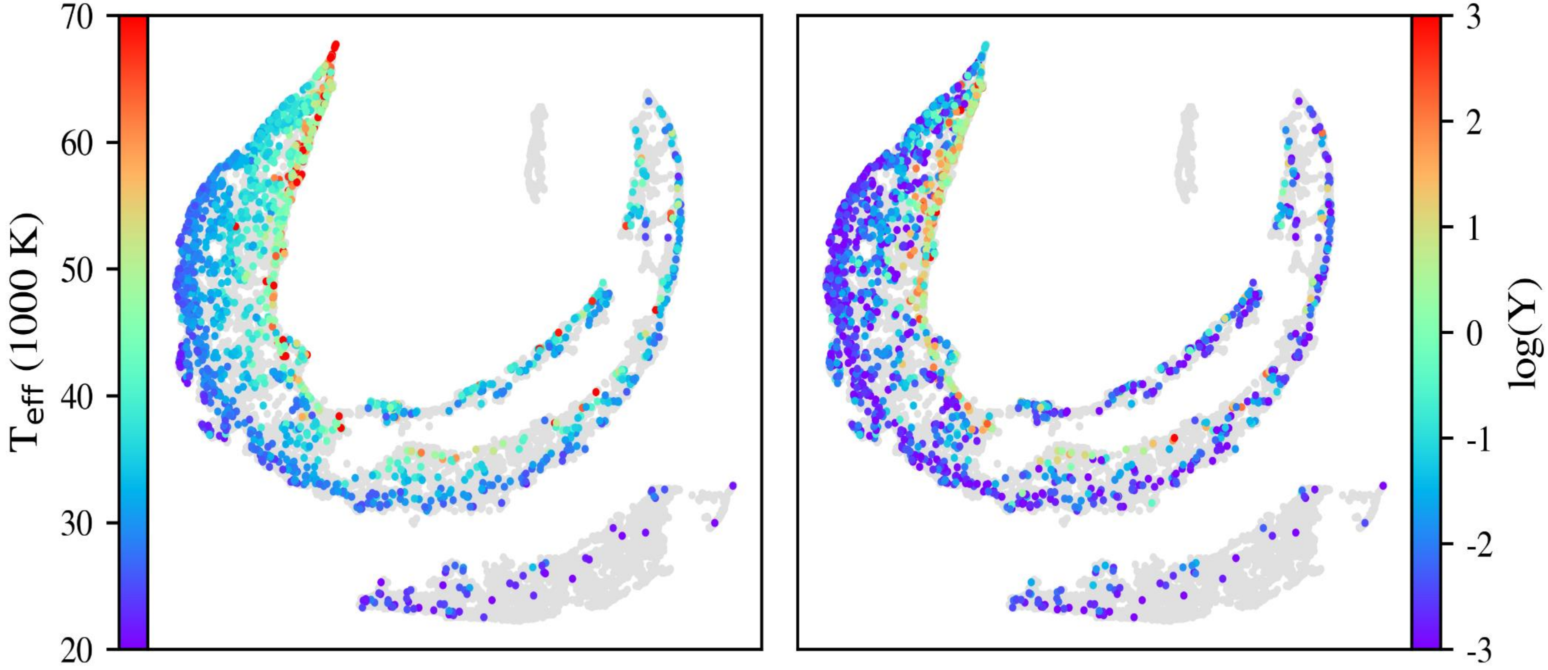

Define two hot subdwarf types:

- **sdB:** T_{eff} < 35 000 K AND log(Y) < -1.0
- **hot/He-rich:** everything else

Neural network for classification

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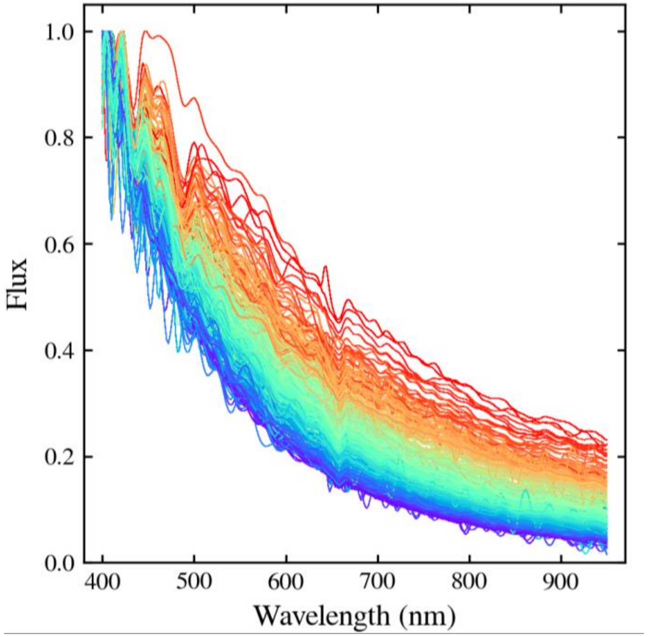
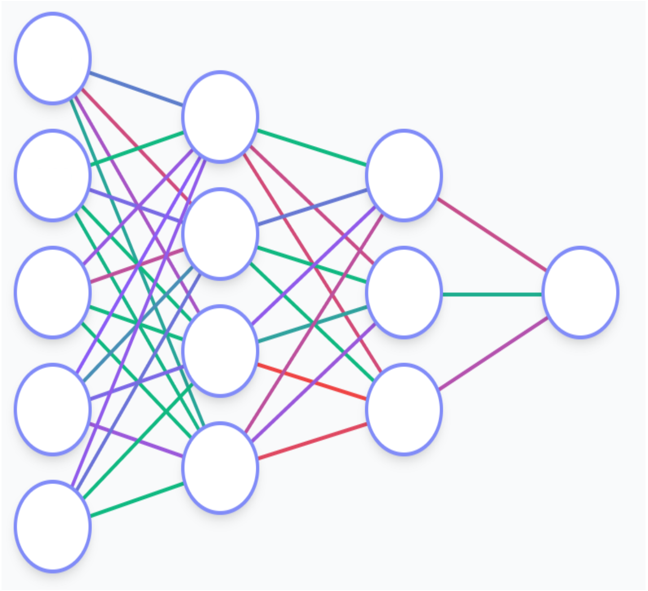
1. Network learns what spectra of sdB hot subdwarfs look like
2. Then it can classify all 20 000 spectra in our sample very quickly





sdB
or
Hot/He-rich

Results of sdB search

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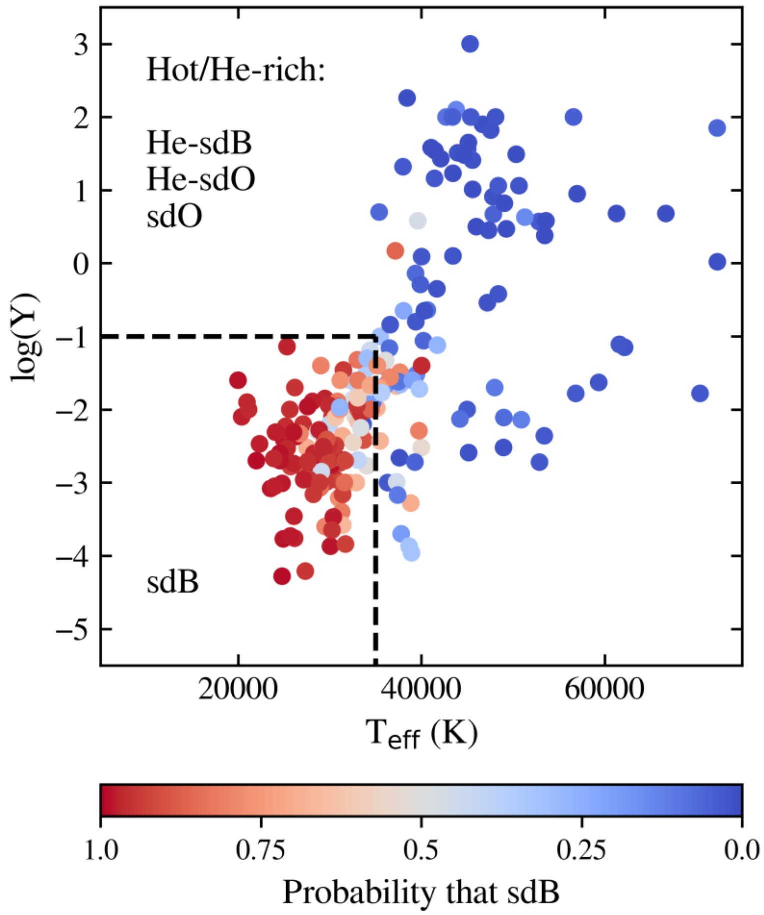
Our neural network can successfully separate hot/He-rich hot subdwarfs from the cooler sdB type.

About 66% of our sample are sdB.



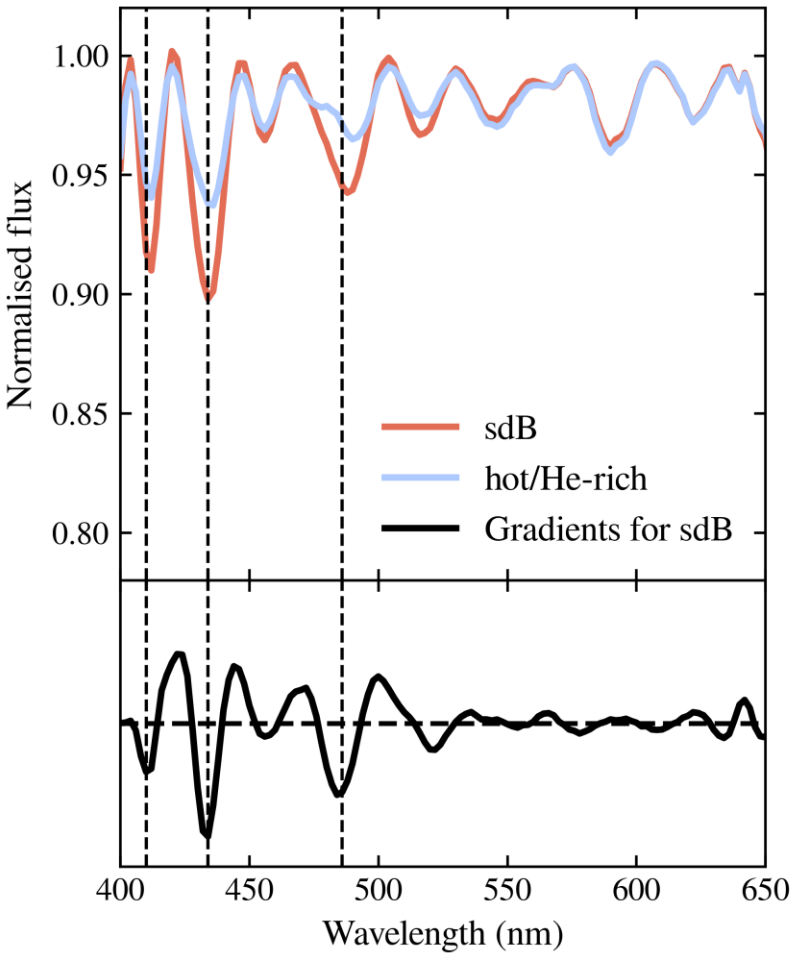
Results of sdB search

Vilnius University

Our neural network can successfully separate hot/He-rich hot subdwarfs from the cooler sdB type.

About 66% of our sample are sdB.

Saliency map shows that the network focuses on physically meaningful spectral features when deciding if sdB or not.



Observing hot subdwarfs from Lithuania

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Observing hot subdwarfs from Lithuania

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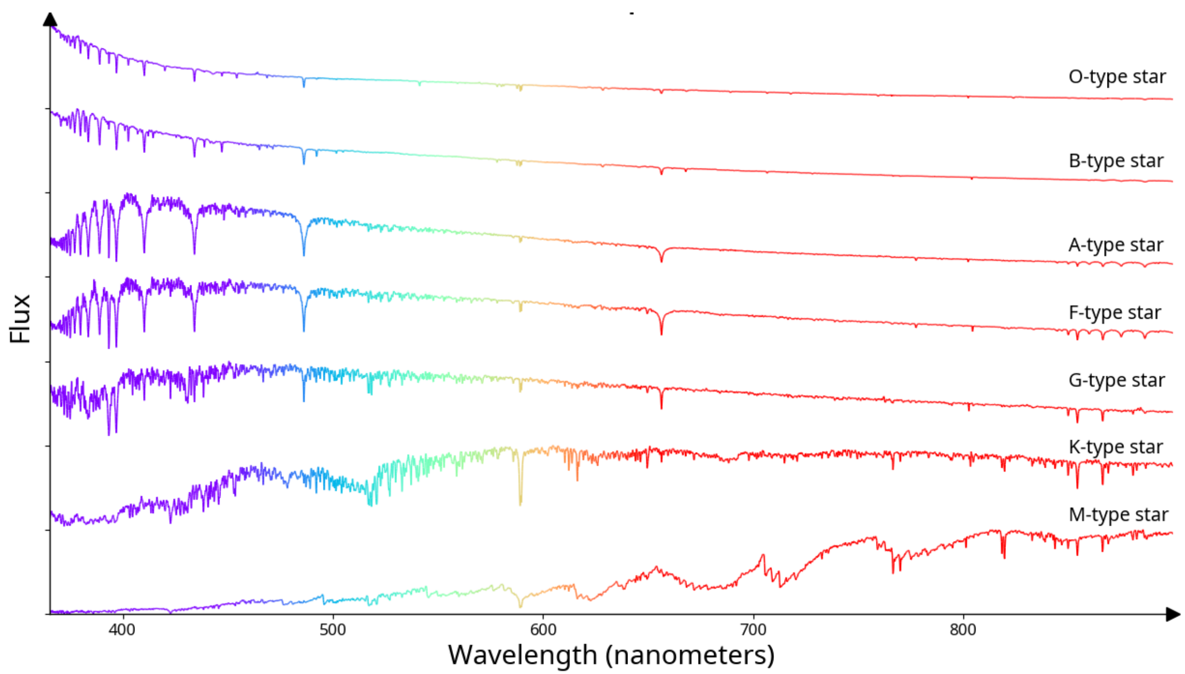
Spectrograph at MAO has much higher resolution than Gaia XP spectra

We can detect spectral features from hot subdwarf star and its cooler companion star



Hot subdwarfs
Teff > 19000 K

Cooler companions
Teff < 6000 K

Binary companions

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Different companion types contribute in different ways to the Gaia XP spectra.