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Invisible Monsters & Spider Webs

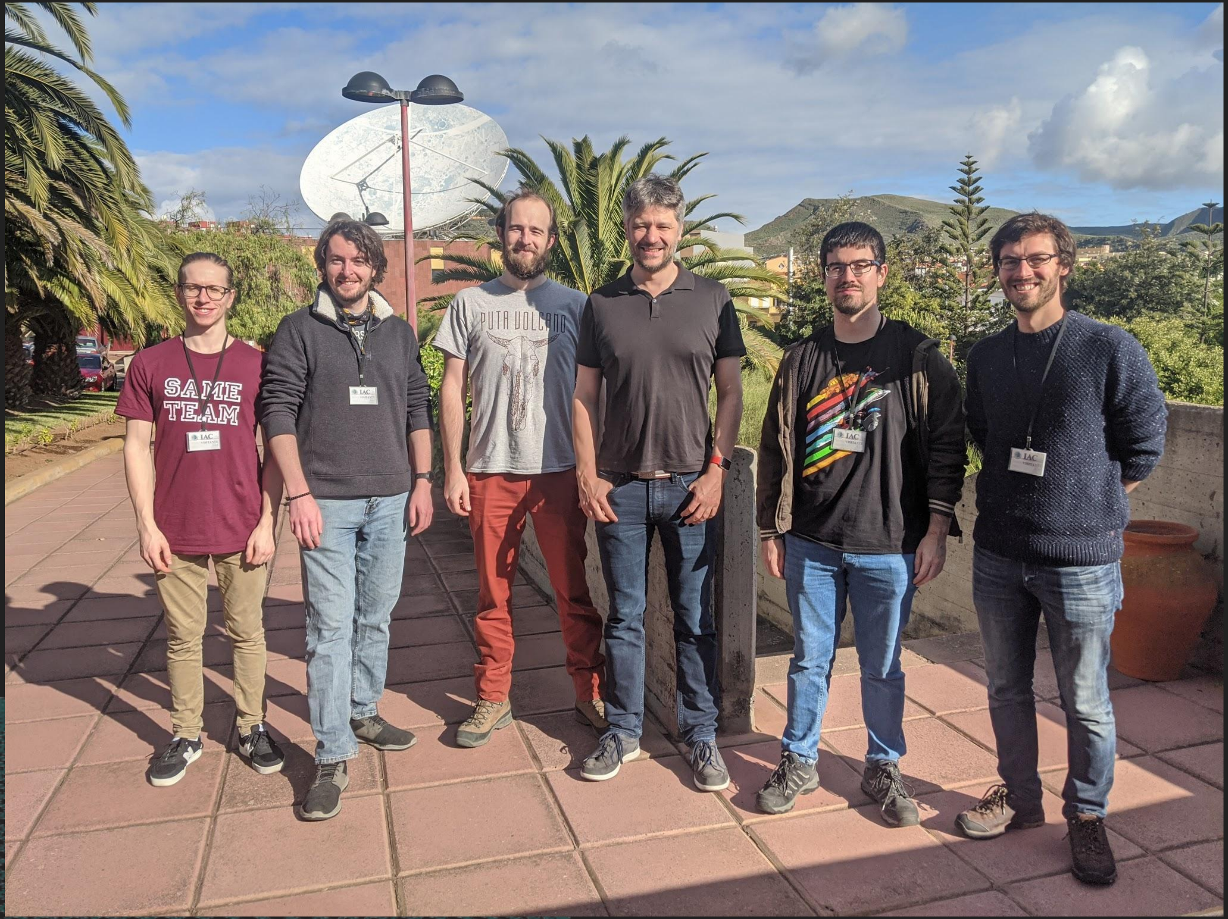
Compact objects in the era of wide field optical surveys

Dr. Mark Kennedy

NTNU Astro & Theory seminar, 26-04-2023

Overview

- The missing galactic black hole population
- The binary treasure map
- Measuring black hole masses
- Current results


SAME
TEAM
PUTA VOLCANO

Compact Objects: Why?

- White dwarfs - stellar fossils that can be accurately age dated, study of material in strong magnetic fields,...

- Neutron Stars - (sort of) Massive star evolution tracers, general relativity tests,...

- (Galactic) Black holes - (actual) Massive star evolution, supernova feedback, stellar formation history

Compact Objects in numbers

- White dwarfs (>5000) - Position on HR diagram, outbursts in CVs.

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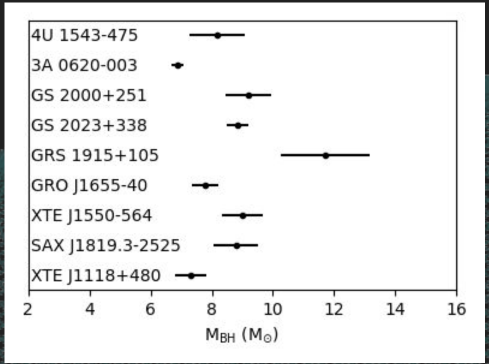

- What is the most massive black hole that can form within the Milky way?
- What is the least massive?
- What is the mass distribution?

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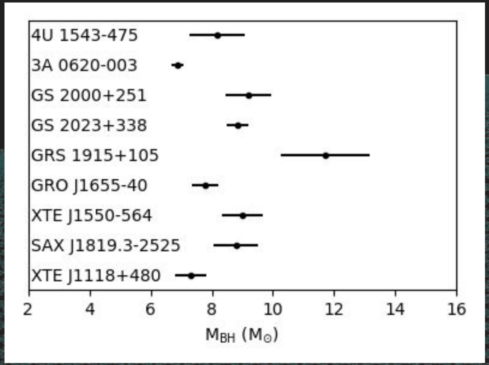

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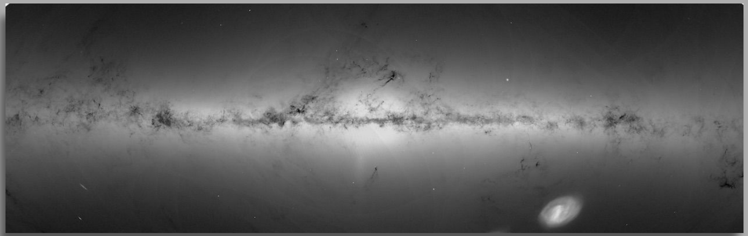
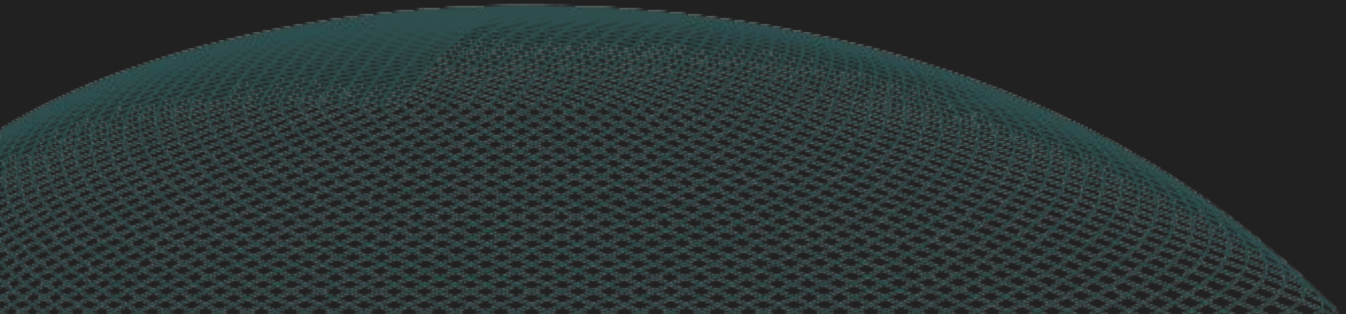
So how do we find more?

Targeted Searchers (O-B star clusters)

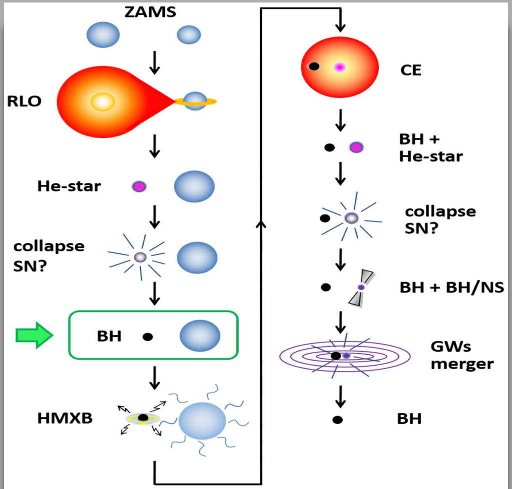
Systematic Searches (Surveys)





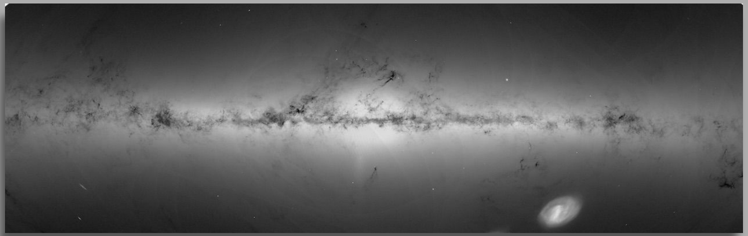
Targeted Searchers (O-B star clusters)

- On going studies to search for these binaries in the LMC (Saracino et al. 2022; Shenar et al. 2022).
- Assumes evolutionary models are correct,
  and expensive to do (long targeted observations of the LMC).

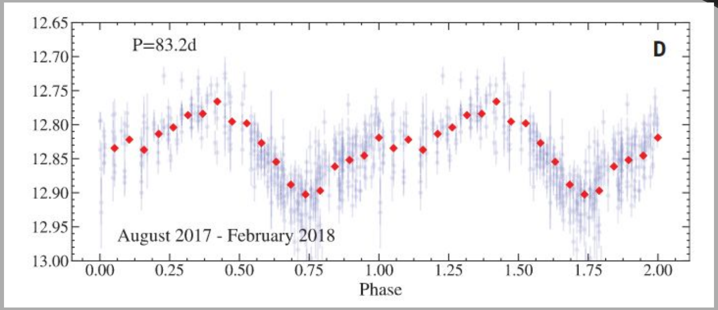


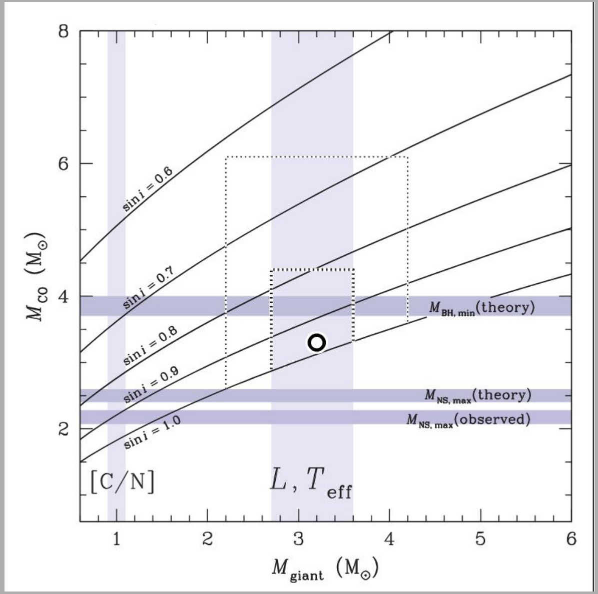
- OB star binaries - search for tidally distorted stars which are orbiting an Invisible companion.
  - Original idea dates back to Guseinov & Zel'dovich, 1966.
  - Recent modelling (Langer et al. 2020) suggests 3% of O and B stars in the LMC should be have black hole companions.

Systematic Searches (Surveys)



- Search for periodic stars throughout night sky.
- Obtain follow up radial velocity studies to constrain the orbital parameters.
- Very expensive to do, unless produced as by product.





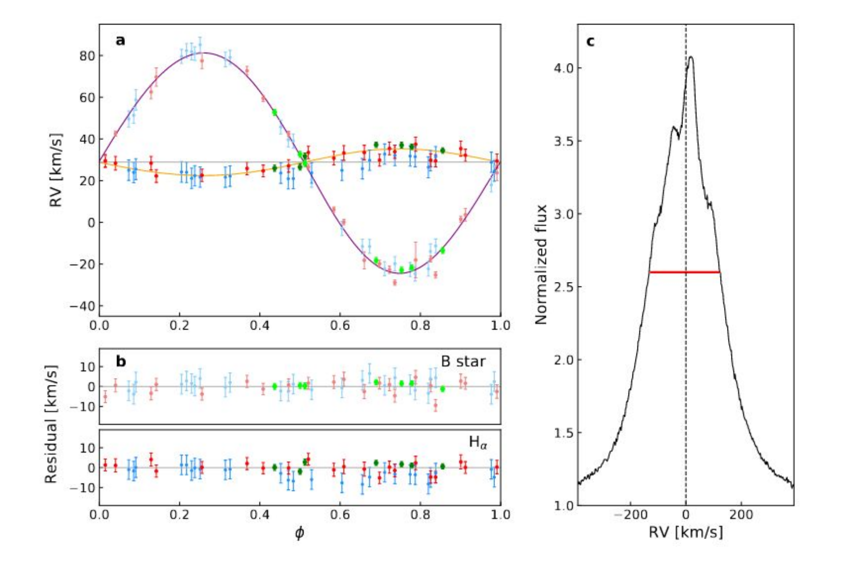
From Thompson et al. 2019

A cautionary tale

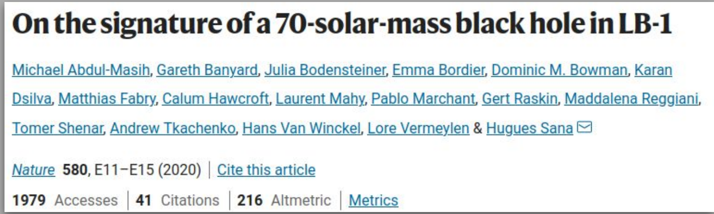
A wide star–black-hole binary system from radial-velocity measurements

Jifeng Liu, Haotong Zhang, Andrew W. Howard, Zhongrui Bai, Youjun Lu, Roberto Soria, Stephen Justham, Xiangdong Li, Zheng Zheng, Tinggui Wang, Krzysztof Belczynski, Jorge Casares, Wei Zhang, Hailong Yuan, Yiqiao Dong, Yajuan Lei, Howard Isaacson, Song Wang, Yu Bai, Yong Shao, Qing Gao, Yilun Wang, Zexi Niu, Kaiming Cui, ... Xiangqun Cui + Show authors

Nature **575**, 618–621 (2019) | Cite this article

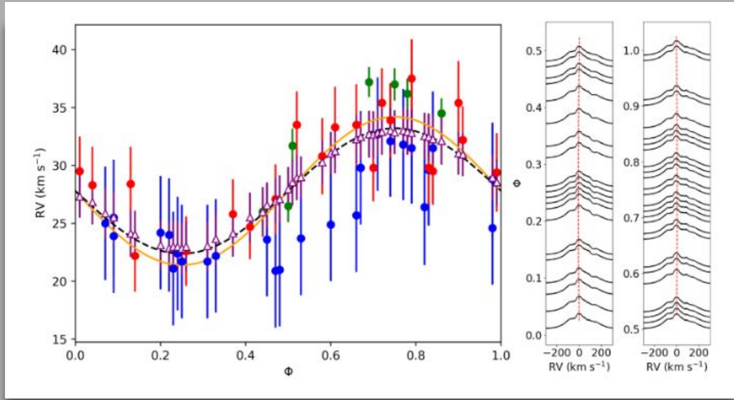


A cautionary tale


On the signature of a 70-solar-mass black hole in LB-1

Michael Abdul-Masih, Gareth Banyard, Julia Bodensteiner, Emma Bordier, Dominic M. Bowman, Karan Dsilva, Matthias Fabry, Calum Hawcroft, Laurent Mahy, Pablo Marchant, Gert Raskin, Maddalena Reggiani, Tomer Shenar, Andrew Tkachenko, Hans Van Winckel, Lore Vermeylen & Hugues Sana

Nature **580**, E11–E15 (2020) | Cite this article



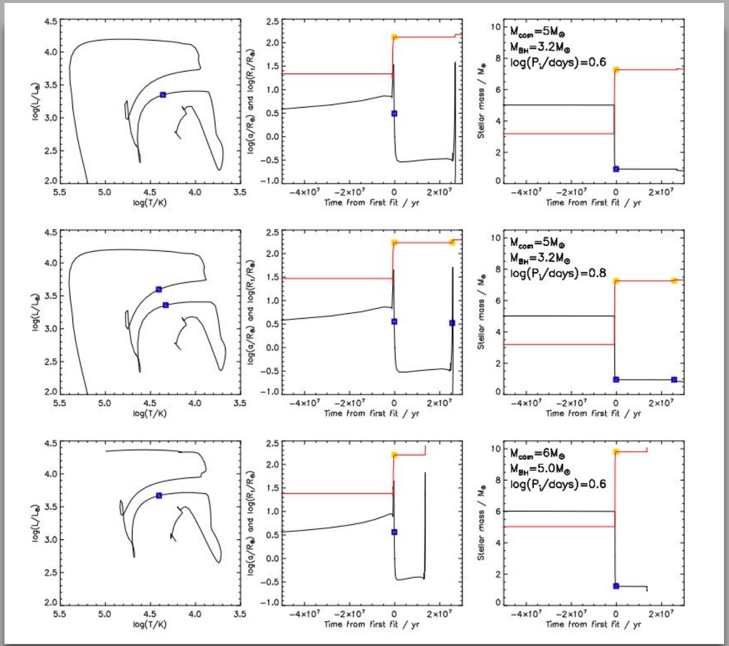
A cautionary tale

Weighing in on black hole binaries with BPASS: LB-1 does not contain a 70 $M_\odot$ black hole

J J Eldridge ✉, E R Stanway, K Breivik, A R Casey, D T H Steeghs, H F Stevance

Monthly Notices of the Royal Astronomical Society, Volume 495, Issue 3, July 2020, Pages 2786–2795, https://doi.org/10.1093/mnras/staa1324

Published: 23 May 2020 **Article history ▾**



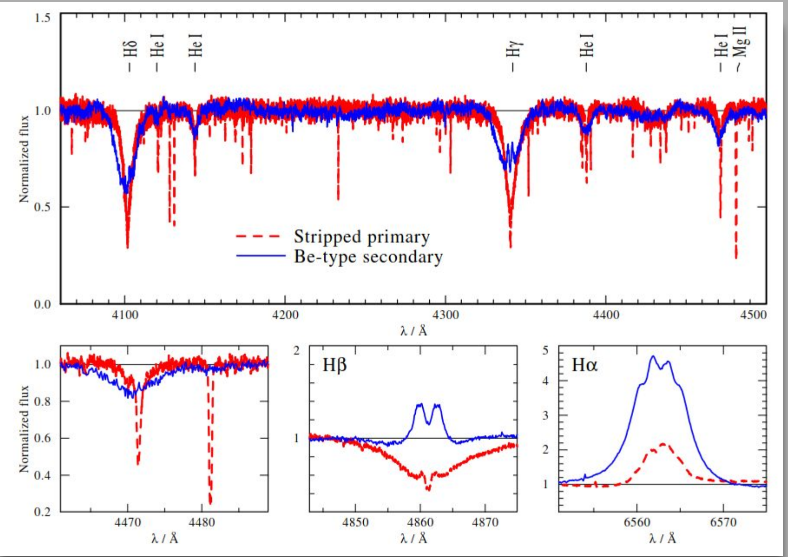
A cautionary tale

A&A 639, L6 (2020)

Letter to the Editor

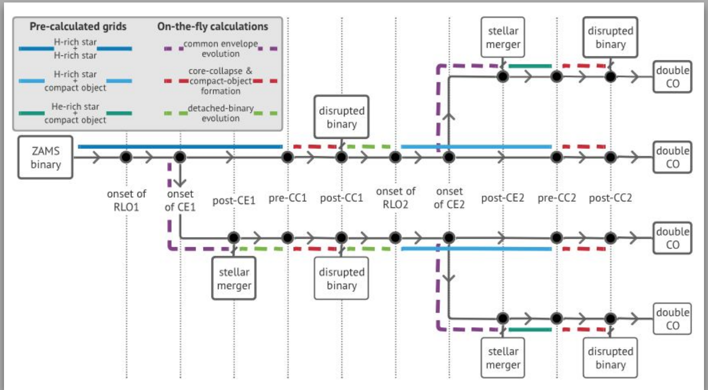
The "hidden" companion in LB-1 unveiled by spectral disentangling★,★★

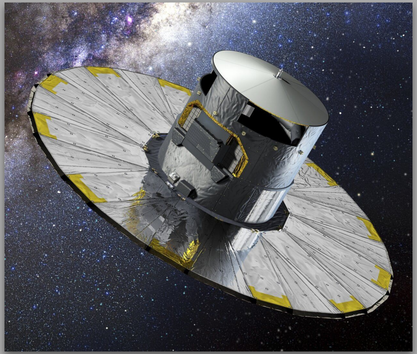
T. Shenar, J. Bodensteiner, M. Abdul-Masih, M. Fabry, L. Mahy, P. Marchant, G. Banyard, D. M. Bowman, K. Dsilva, C. Hawcroft, M. Reggiani and H. Sana



So where to next?

Binary evolution codes
(Posydon, BPASS, StarTrack)





Classifying light curves

Zwicky Transient Factory:

The products include ~30.9 million single-exposure images, ~157,000 co-added images, accompanying source catalog files containing ~495 billion source detections extracted from those images, and ~3.7 billion lightcurves constructed from the single-exposure extractions. Note: transient alerts extracted from difference-images commenced public distribution on June 4, 2018. These alerts continue to be generated and distributed as the public survey proceeds.

GAIA:

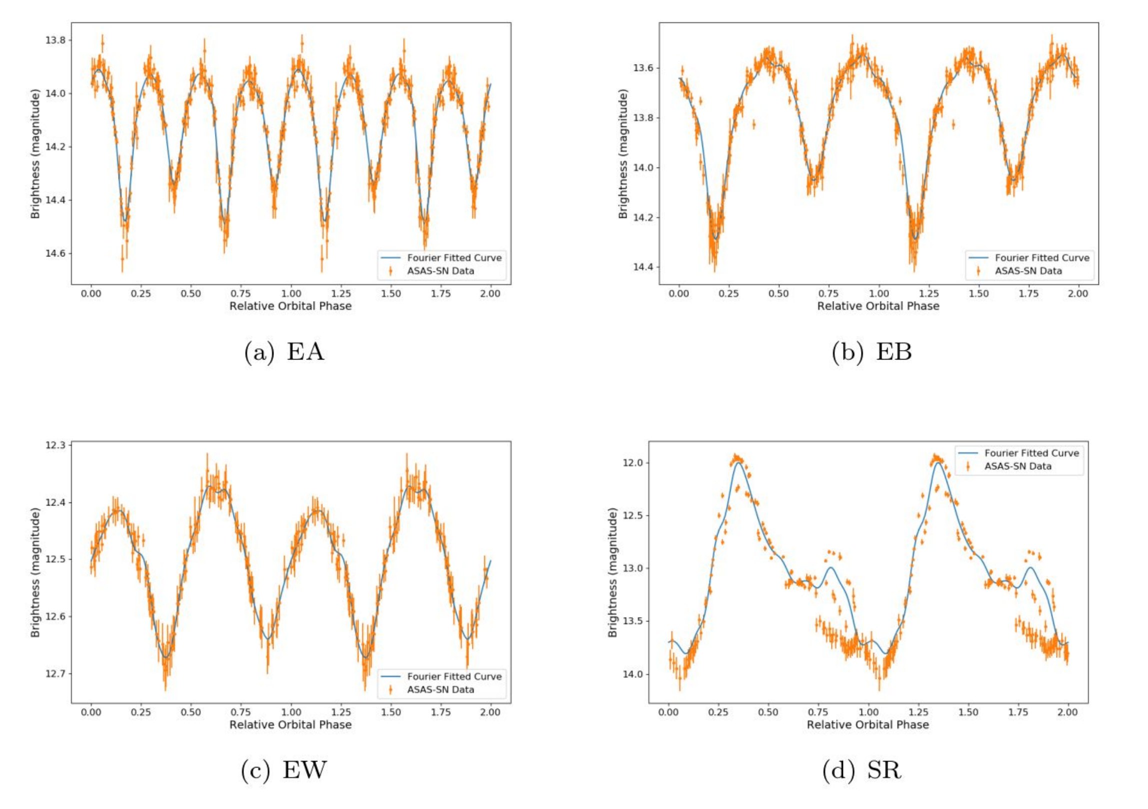
	# sources in Gaia EDR3
Total number of sources	**1,811,709,771**
Number of 5-parameter sources	585,416,709
Number of 6-parameter sources	882,328,109
Number of 2-parameter sources	343,964,953
Sources with mean G magnitude	1,806,254,432
Sources with mean G_{BP}-band photometry	1,542,033,472
Sources with mean G_{RP}-band photometry	1,554,997,939
Gaia-CRF sources	1,614,173
Sources with radial velocities	7,209,831 (Gaia DR2)
Variable sources	expected with Gaia DR3 / see Gaia DR2
Known asteroids with epoch data	expected with Gaia DR3 / see Gaia DR2
Effective temperatures (T_{eff})	expected with Gaia DR3 / see Gaia DR2
Extinction (A_G) and reddening ($E(G_{BP}-G_{RP})$)	expected with Gaia DR3 / see Gaia DR2
Sources with radius and luminosity	expected with Gaia DR3 / see Gaia DR2
and more...	expected with Gaia DR3

Random Forests: Feature Extraction

- Fit the light curve with a Fourier series.
  - Penalise high frequency terms to avoid over-fitting.
  - See Chen et al. 2020 for current classification.

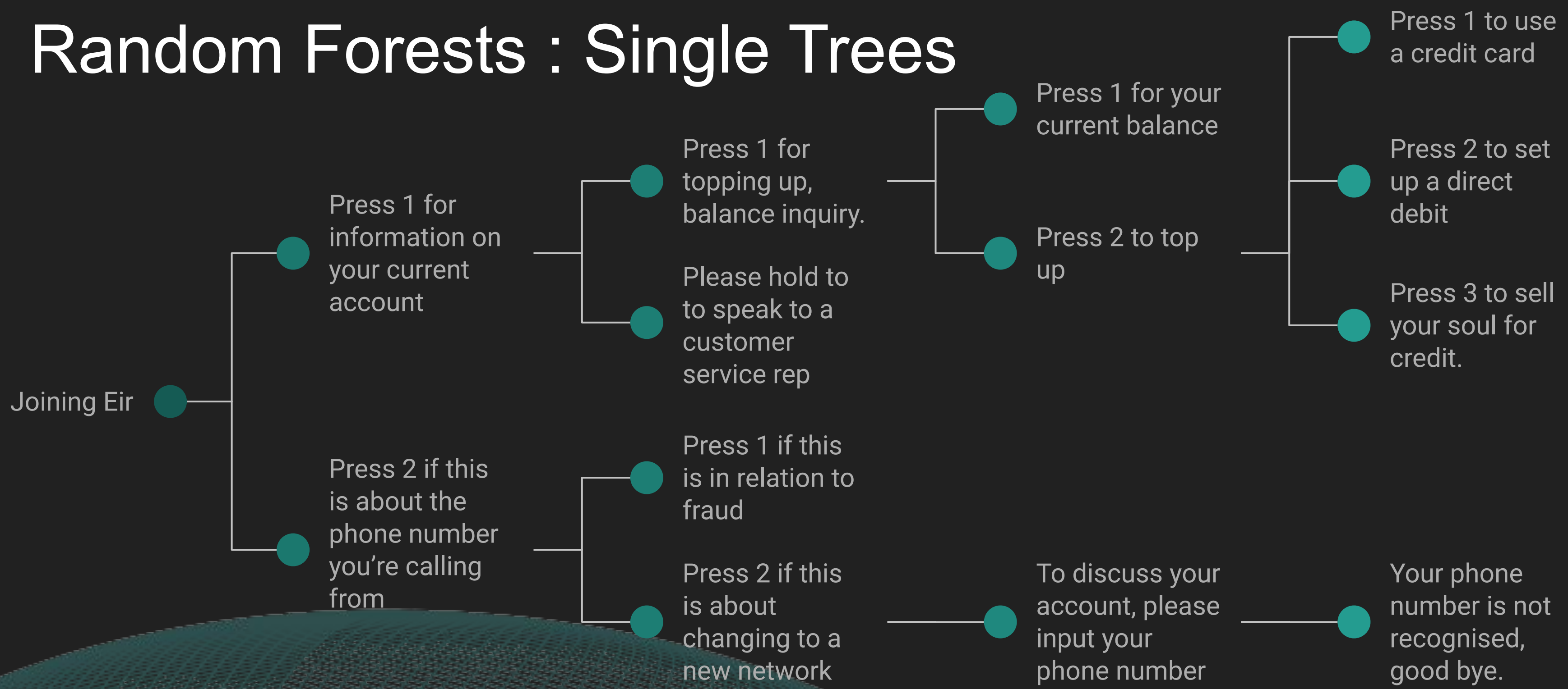
- Extract coefficients for amplitude ratios and phase offsets.

- Label the data.



(a) EA (b) EB (c) EW (d) SR

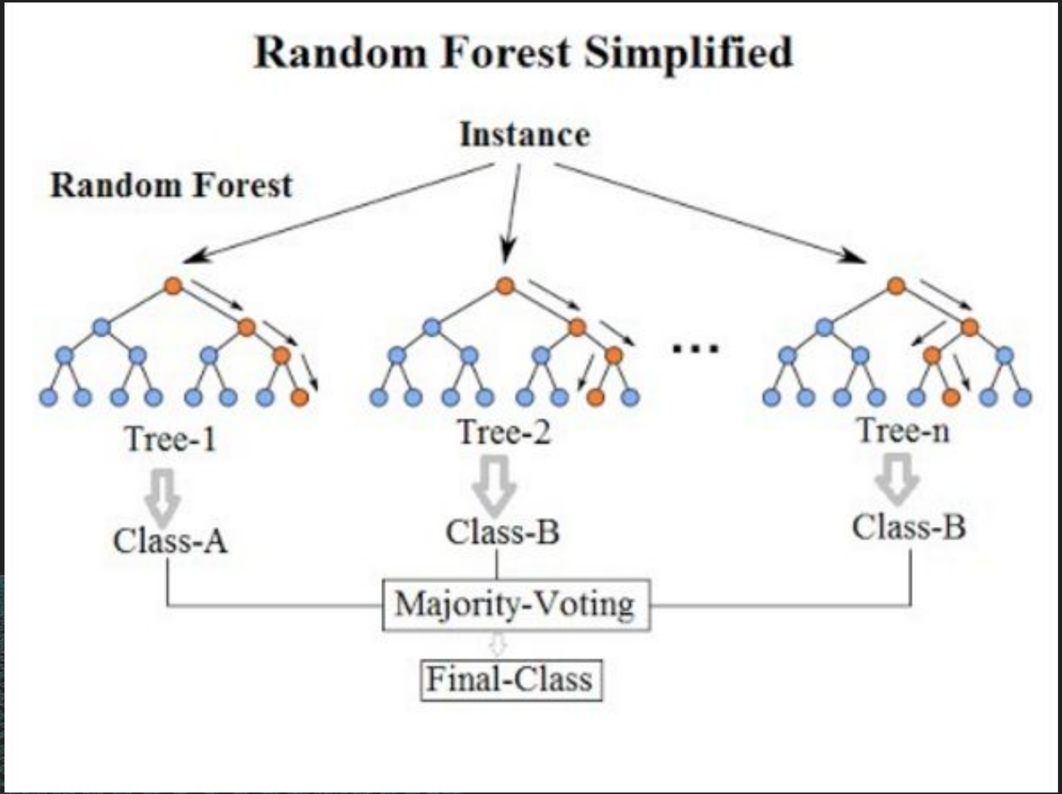
Random Forests : Single Trees



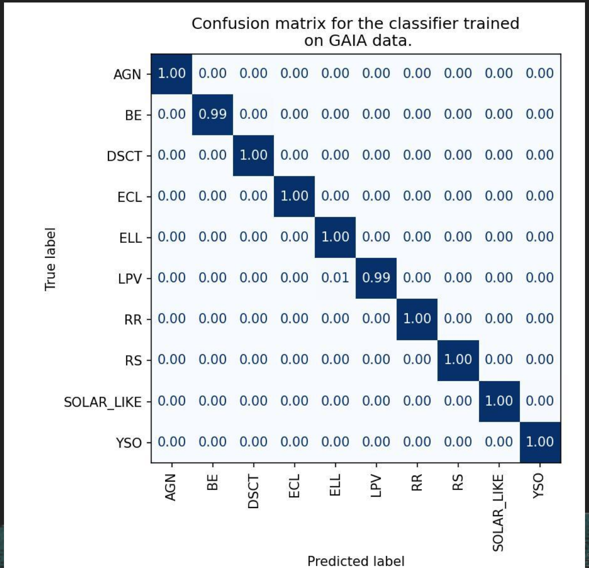
Random Forests : Single Trees

Random Forests: Training

- Split your data into training/validation/test set (80/10/10 split).
- Optimise a forest using training/validation sets.
- Test ONLY ONCE using test set. This will tell you if your classifier is any good on data it has never seen before.



Random Forests: Applying it to Gaia DR3



	AGN	BE	DSCT	ECL	ELL	LPV	RR	RS	SOLAR_LIKE	YSO
AGN	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
BE	0.00	0.99	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
DSCT	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
ECL	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	0.00
ELL	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00
LPV	0.00	0.00	0.00	0.00	0.01	0.99	0.00	0.00	0.00	0.00
RR	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00
RS	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0.00
SOLAR_LIKE	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
YSO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00

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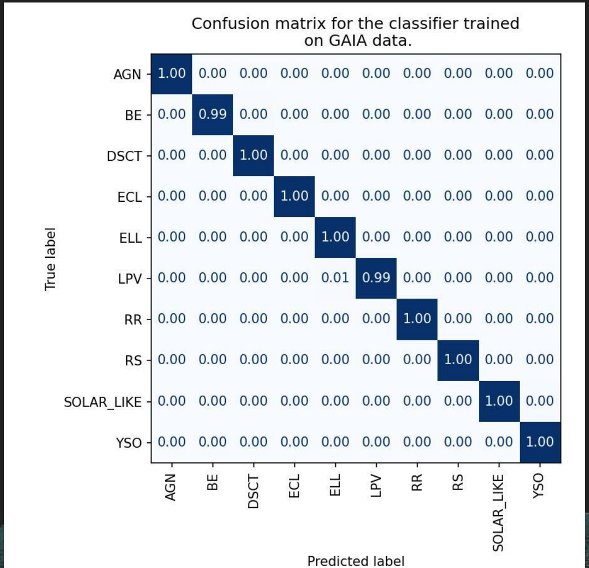
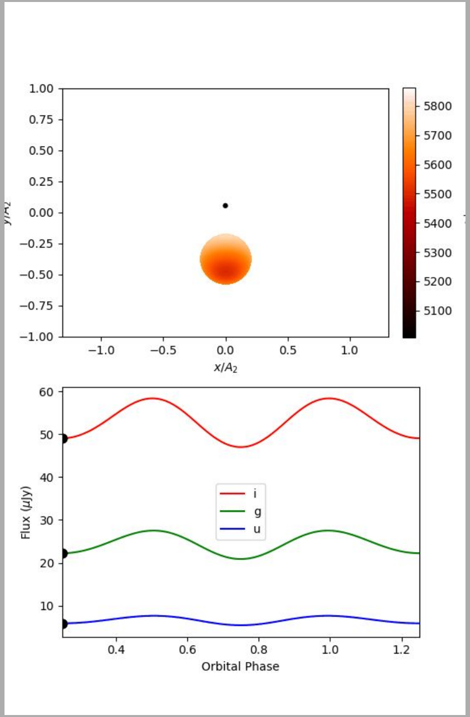


- Not a new idea! See:
  - SDSS: Geier et al. 2011
  - TESS: Masuda & Hotokezaka 2019
  - ASAS-SN: Rowan et al. 2021.
- No successes yet, despite predictions that GAIA could find 4,000-12,000 black holes (Breivik et al. 2017)

So why are we not finding them?

Aside: Spiders - Red backs and black widows

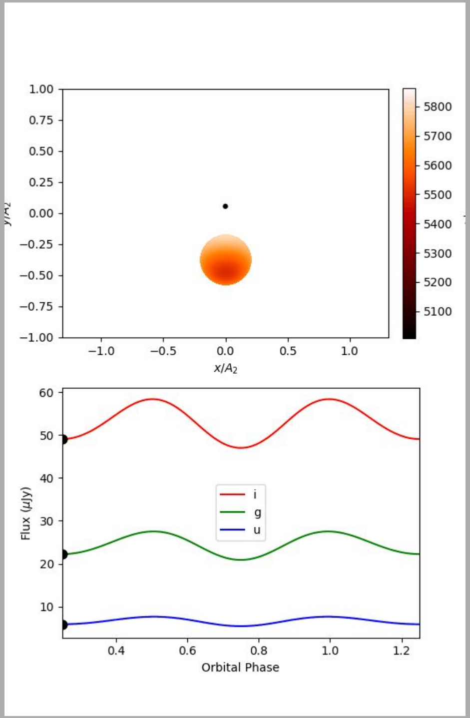
Redbacks



- Companion masses Between 0.1 and 1.0$M_\odot$.
- Weak/No irradiation.
- Base temperatures of 4000-6000 K.
- Some evidence for radiative envelopes

Aside: Spiders - Red backs and black widows

Redbacks



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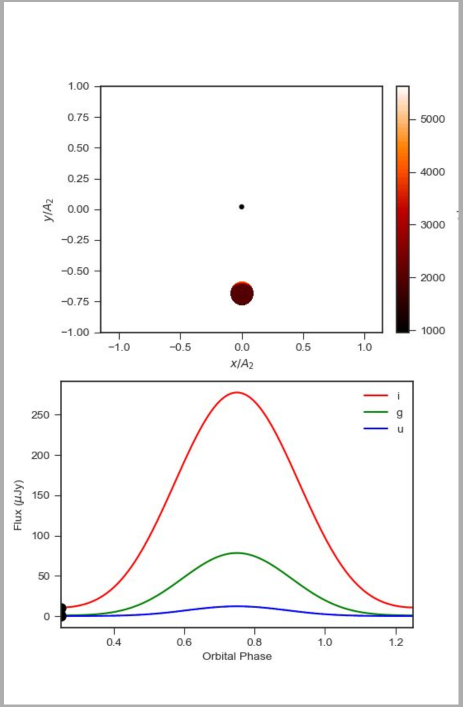
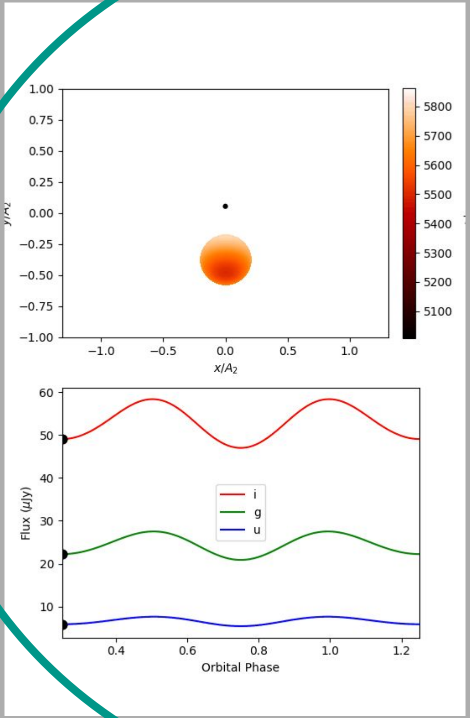
Black Widows



- Companion masses $< 0.1 M_\odot$.
- Strongly irradiated.
- Base temperatures of 2000-3000 K.
- Some evidence for convective envelopes.

Aside: Spiders - Red backs and black widows

Redbacks



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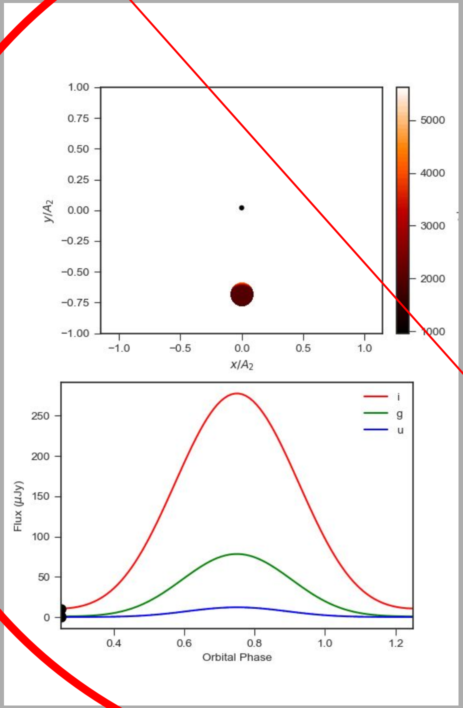

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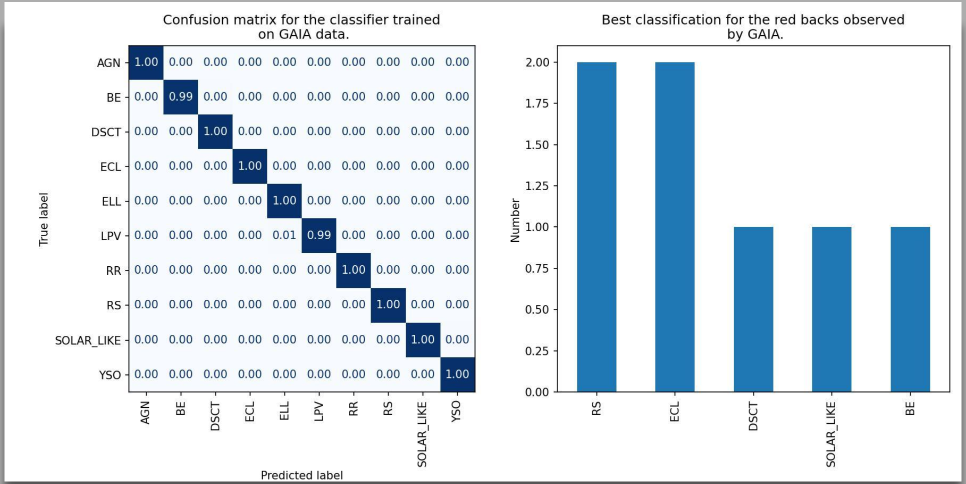
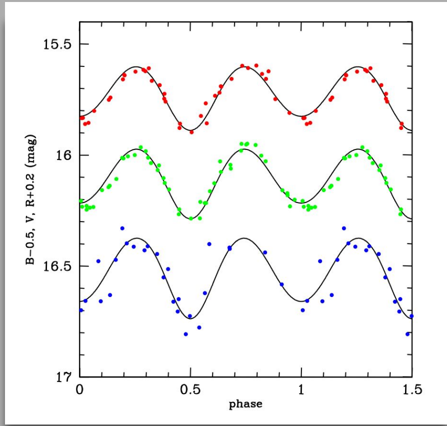
Applying it to Gaia DR3





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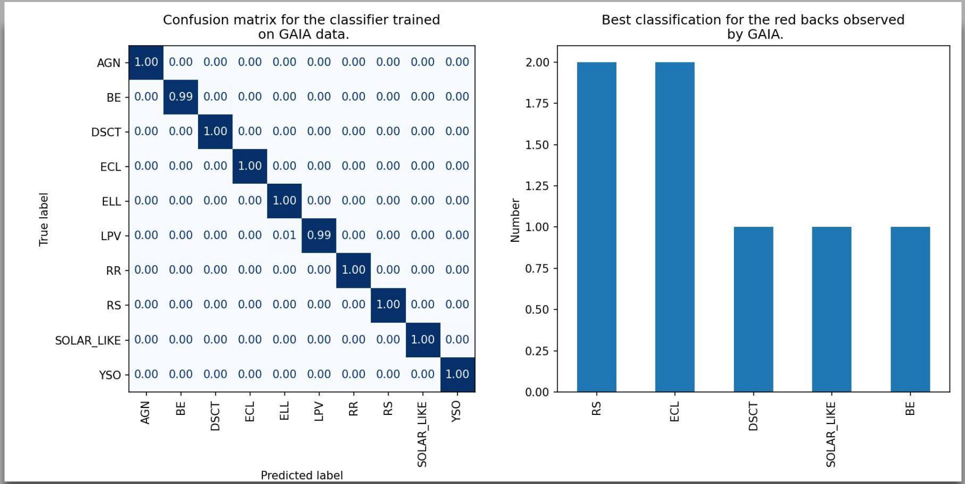

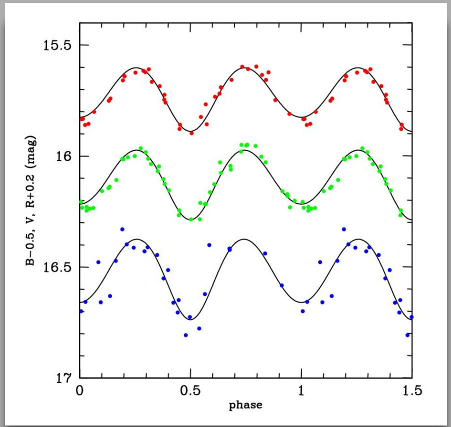

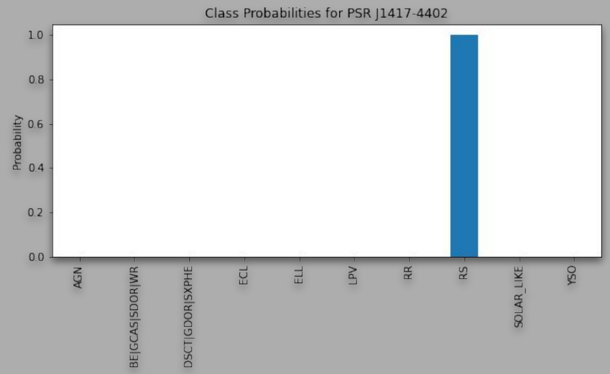

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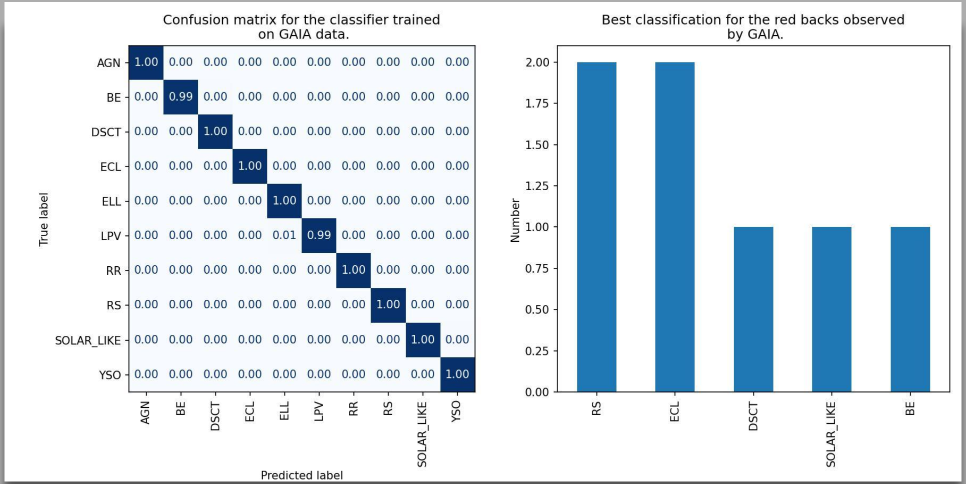
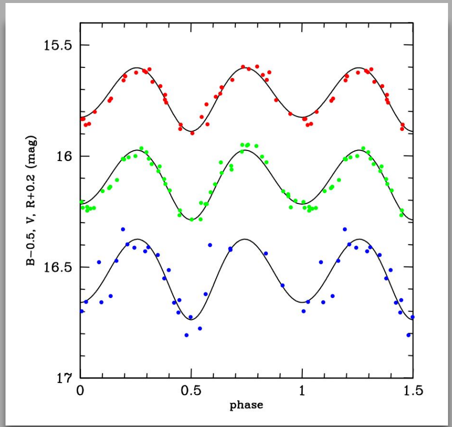
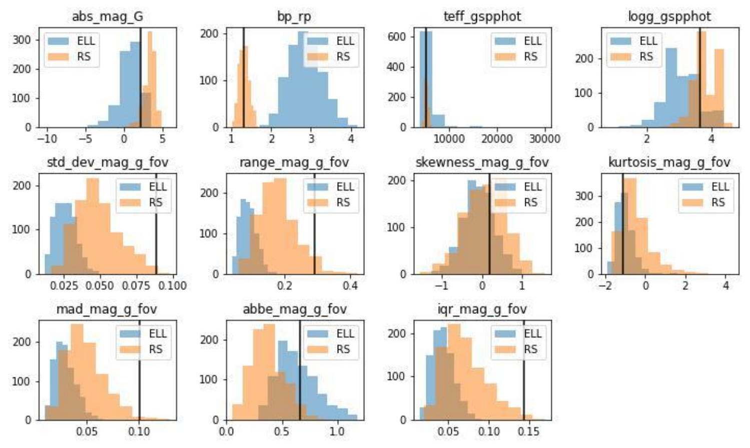
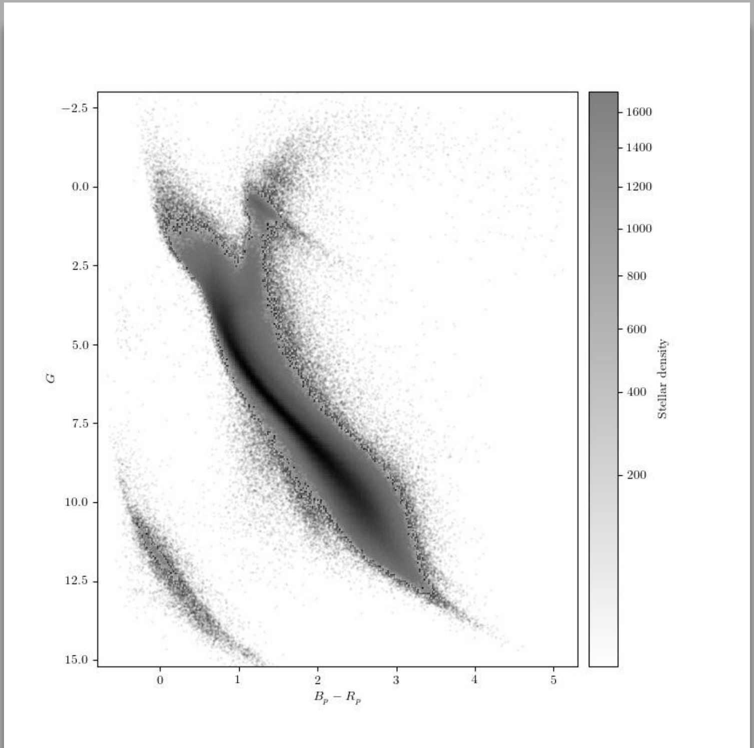






Random Forests III: Outliers

- Returning quickly to the GAIA H-R diagram
  - Binaries with “normal” main sequence stars should Lie close to the MS line.



Random Forests III: Outliers

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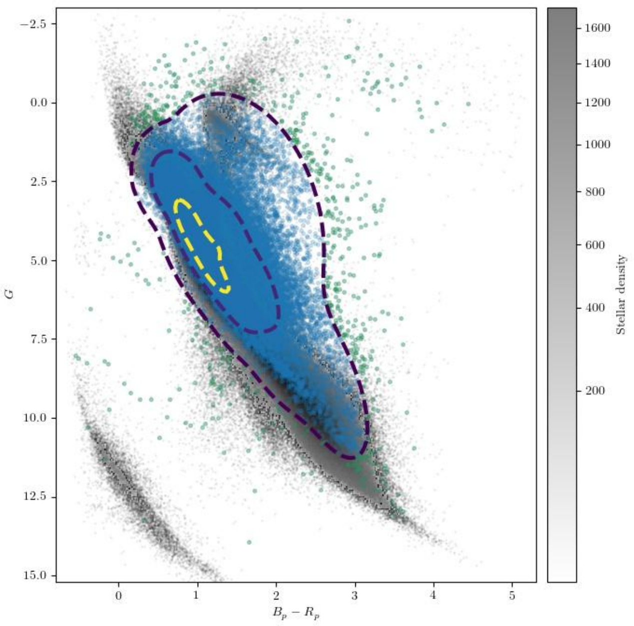
- Combine with a given class of variables from ZTF, and focus on “outliers”. Clearly not normal main sequence binaries.
  - In this case, we’ve plotted EW stars, which should just be two main sequence stars which are in contact.



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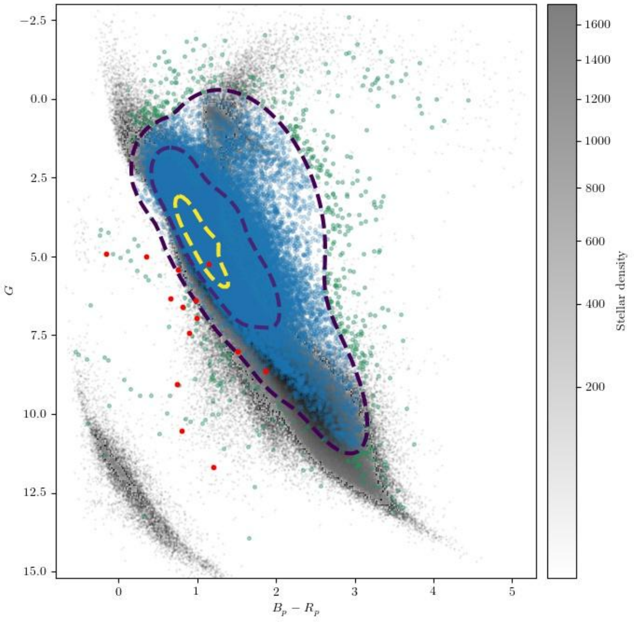
- As a test, look for known binaries with neutron stars which are bright enough to have had their parallax measured.



What do we find?

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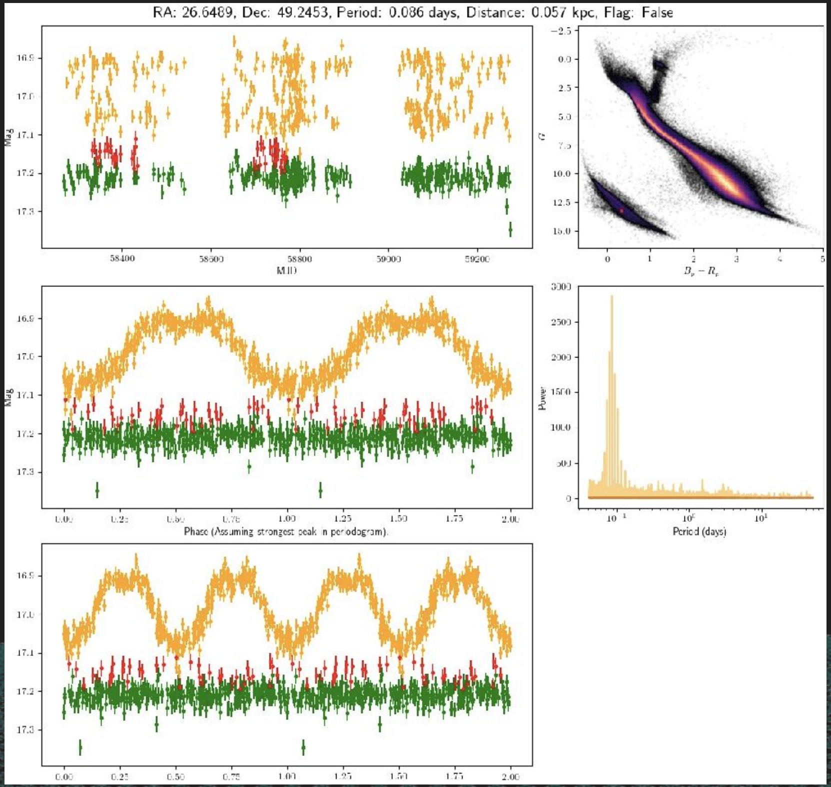

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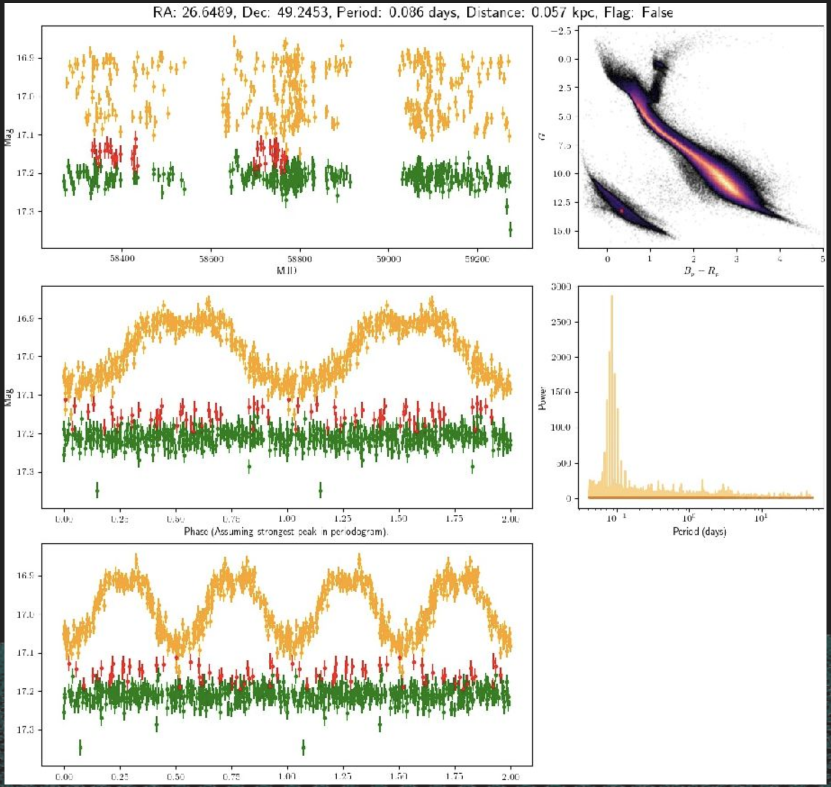

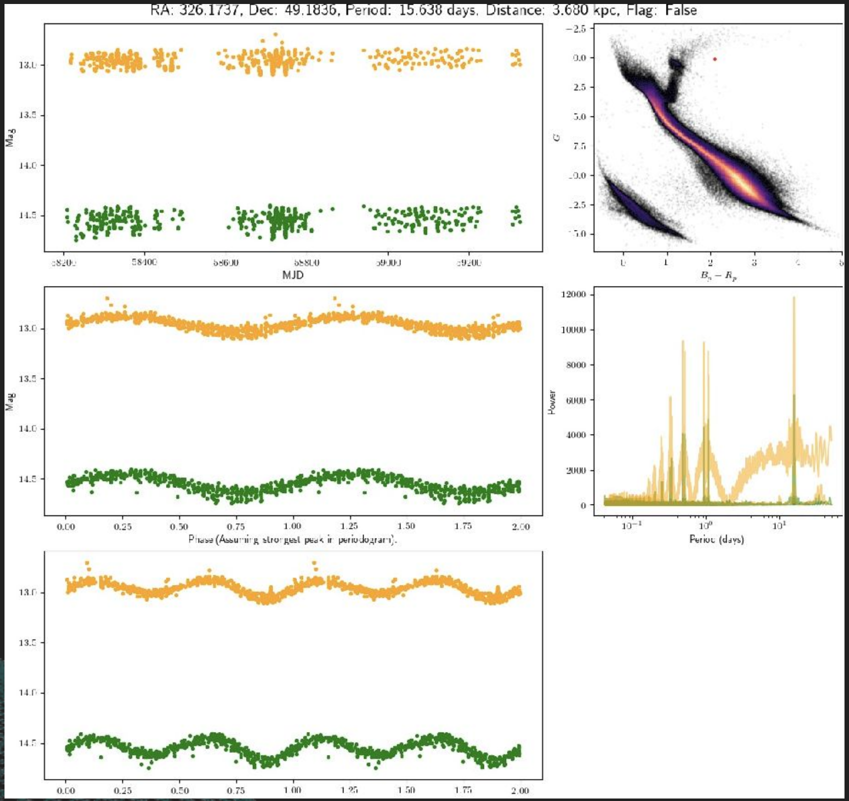

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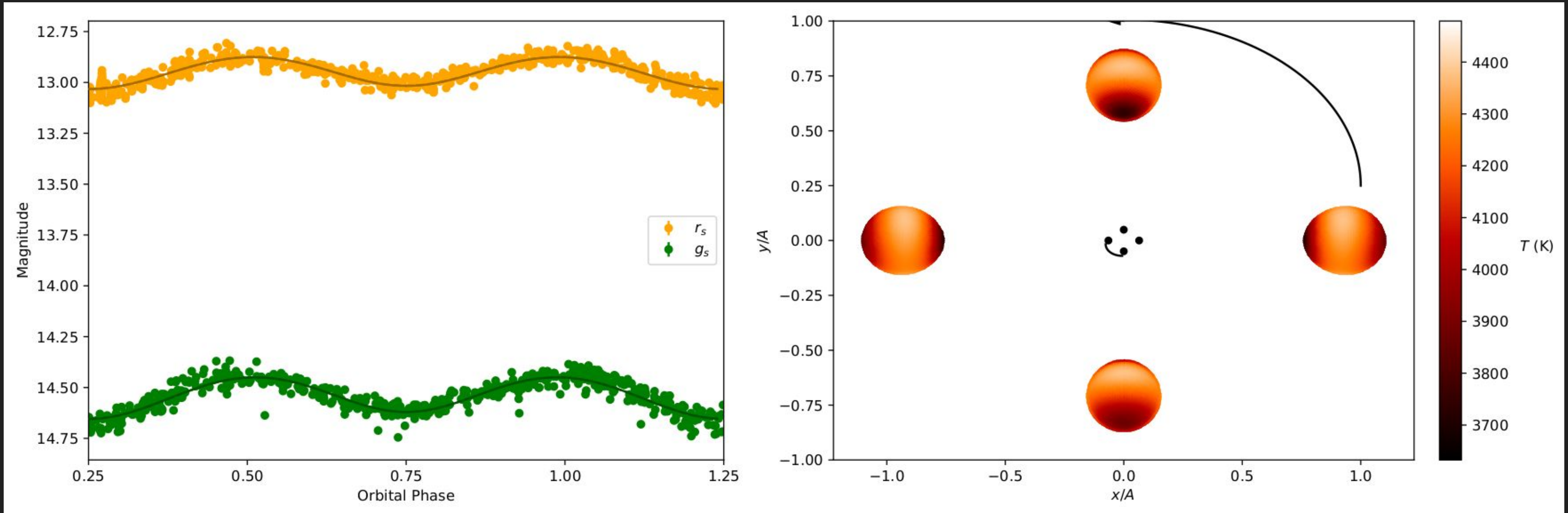
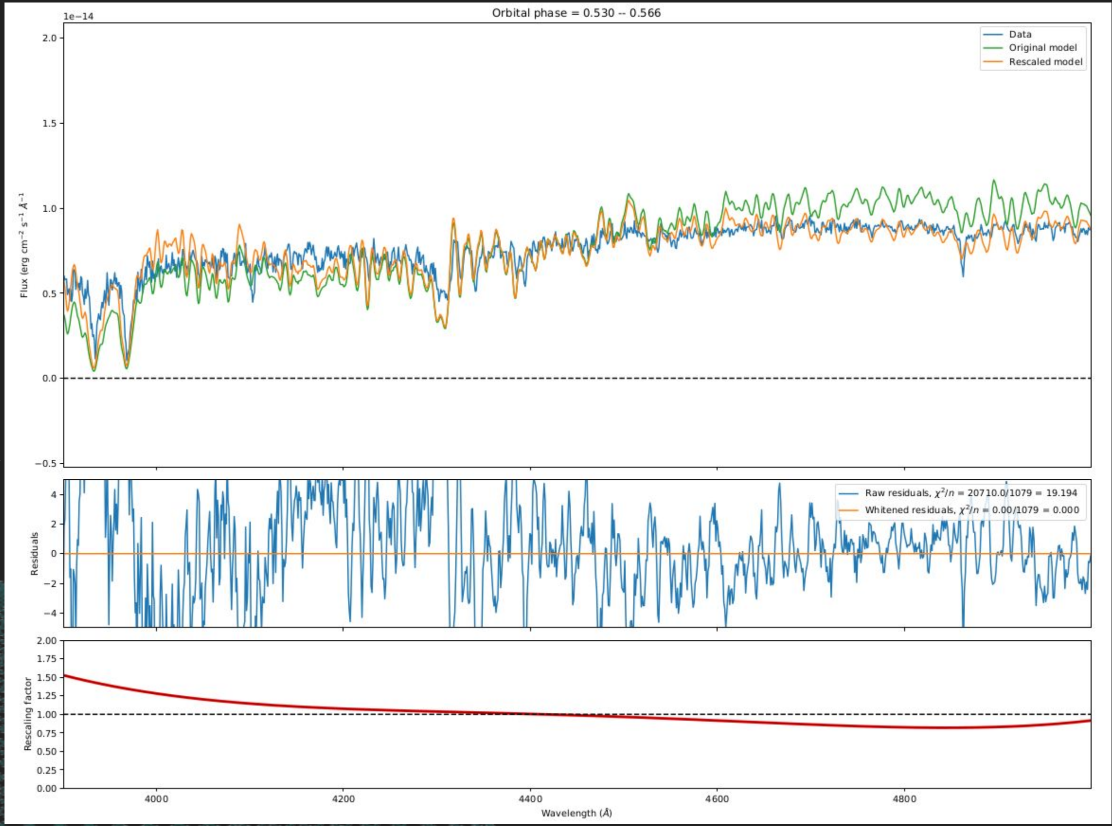


What do we find?

- Manually inspect the outliers
- If light curve looks ellipsoidal, perform light curve modelling.
- If fit seems acceptable, obtain follow up spectroscopy to look for RV, confirm temperature, measure log(g)



Current status of the project

- 953 outliers identified, all visually inspected to check shape of light curve.

- 8 very strong candidates.
    - 1 with LAMOST spectra, temperature and log(g) match the single visible star model.
    - 7 to be observed in collaboration with Uni. of Sheffield this month.

- To Do:
    - Refine light curve classifier (on going).
    - Develop a catalogue of synthetic black hole binary light curves to train on.

- Combine observed parameters with binary evolution models (on going, see for example Eldridge et al, 2020 and Stevance et al. 2021).