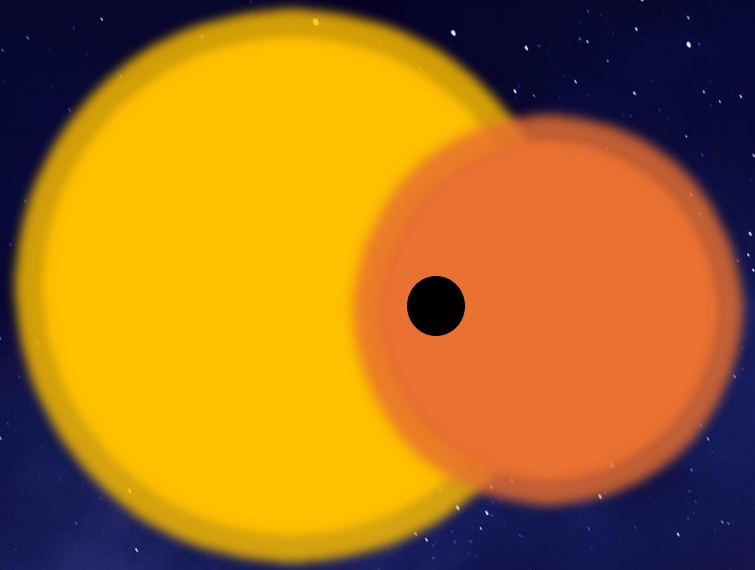
The BEBOP Radial Velocity Survey

Aleyna Adamson



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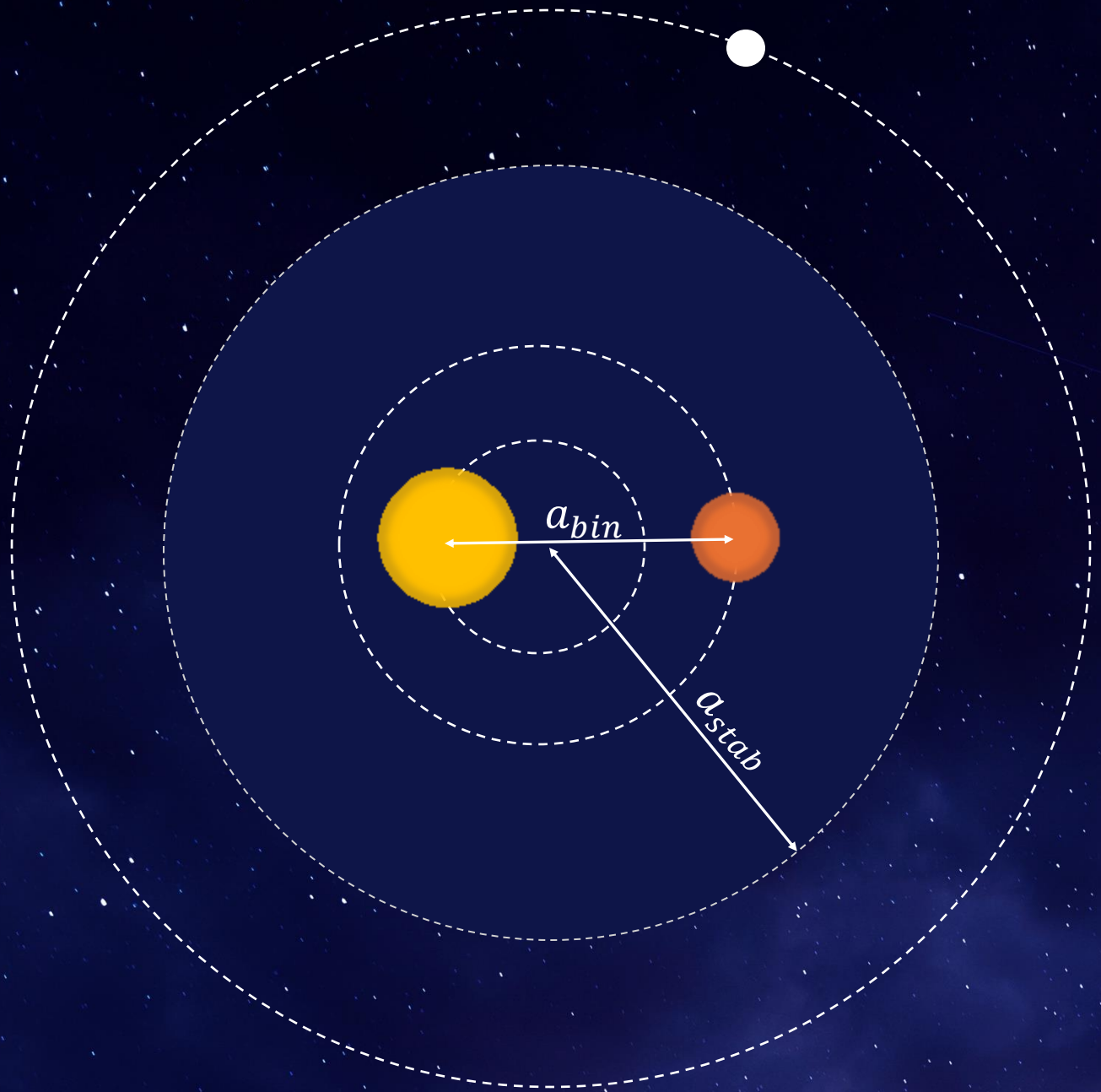

Circumbinary planets

Exoplanets that orbit both stars of the binary

Form outside of the stability limit $a_{\mathrm{stab}} \sim 2.7 a_{\mathrm{bin}}$

Orbit with periods $\sim 4 - 6 P_{\mathrm{bin}}$

About 10% of binaries have a circumbinary planet (Armstrong et al 2014)

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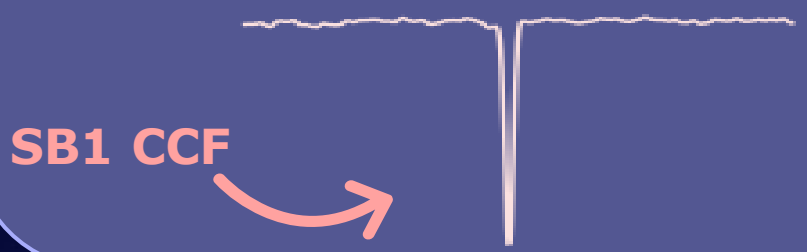
Spectroscopic Binaries

- Spectroscopic binary stars have an angular separation too small to distinguish between the two components
- The two stars can be detected in the observed spectrum

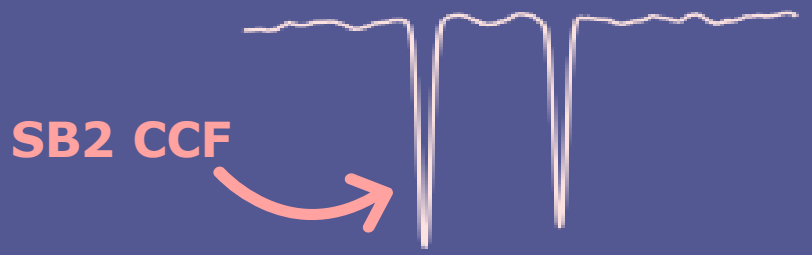
Single-lined (SB1)

- One of the stars is smaller and less bright than the other
- The second star doesn't appear in the spectrum and can be treated as a planetary signal



Double-lined (SB2)

- Both stars are similar brightness and size
- Spectral lines from both stars appear in the observed spectrum



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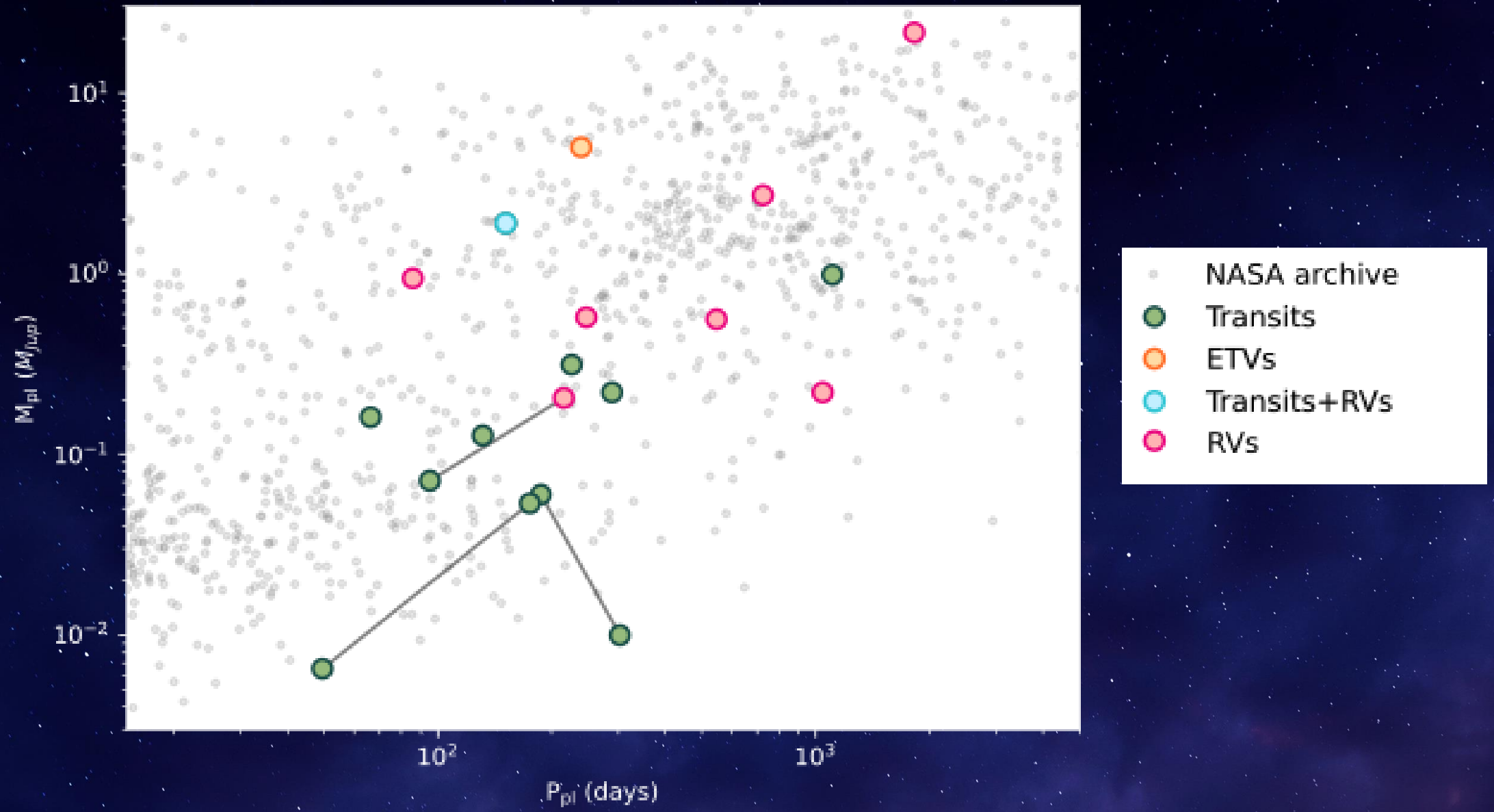
Confirmed circumbinary planets so far



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The BEBOP radial velocity survey

***B**inaries **E**scorted **B**y **O**rbiting **P**lanets*

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BEBOP survey

Binaries Escorted By Orbiting Planets

Goals of the survey

1 Demonstrate circumbinary planets can be detected with RVs

2 Attempt to get dynamical masses of the binary to get the absolute planet masses

3 Measure occurrence rates of circumbinary planets

4 Eventually compare the circumbinary population to exoplanets around single stars

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BEBOP survey

Binaries Escorted By Orbiting Planets

BEBOP Survey: Phase 1

- A blind radial velocity (RV) search
- Measurements taken with SOPHIE and HARPS spectrographs
- Over 100 single-lined spectroscopic binaries (SB1) in both the northern and southern hemispheres
- All binaries are eclipsing
- Binary mass ratio <0.3

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BEBOP survey: Radial velocity analysis

***B**inaries **E**scorted **B**y **O**rbiting **P**lanets*

Analysis

- *Kima*, *a* Diffusive Nested Sampler python package (Faria et al 2018)
- Simultaneously analyse models with 1,2,3,… planets

Model comparison

- Compare the models by calculating a Bayes Factor (BF)
- Detection: BF>150
- Candidate: BF<150

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BEBOP survey: Radial velocity analysis

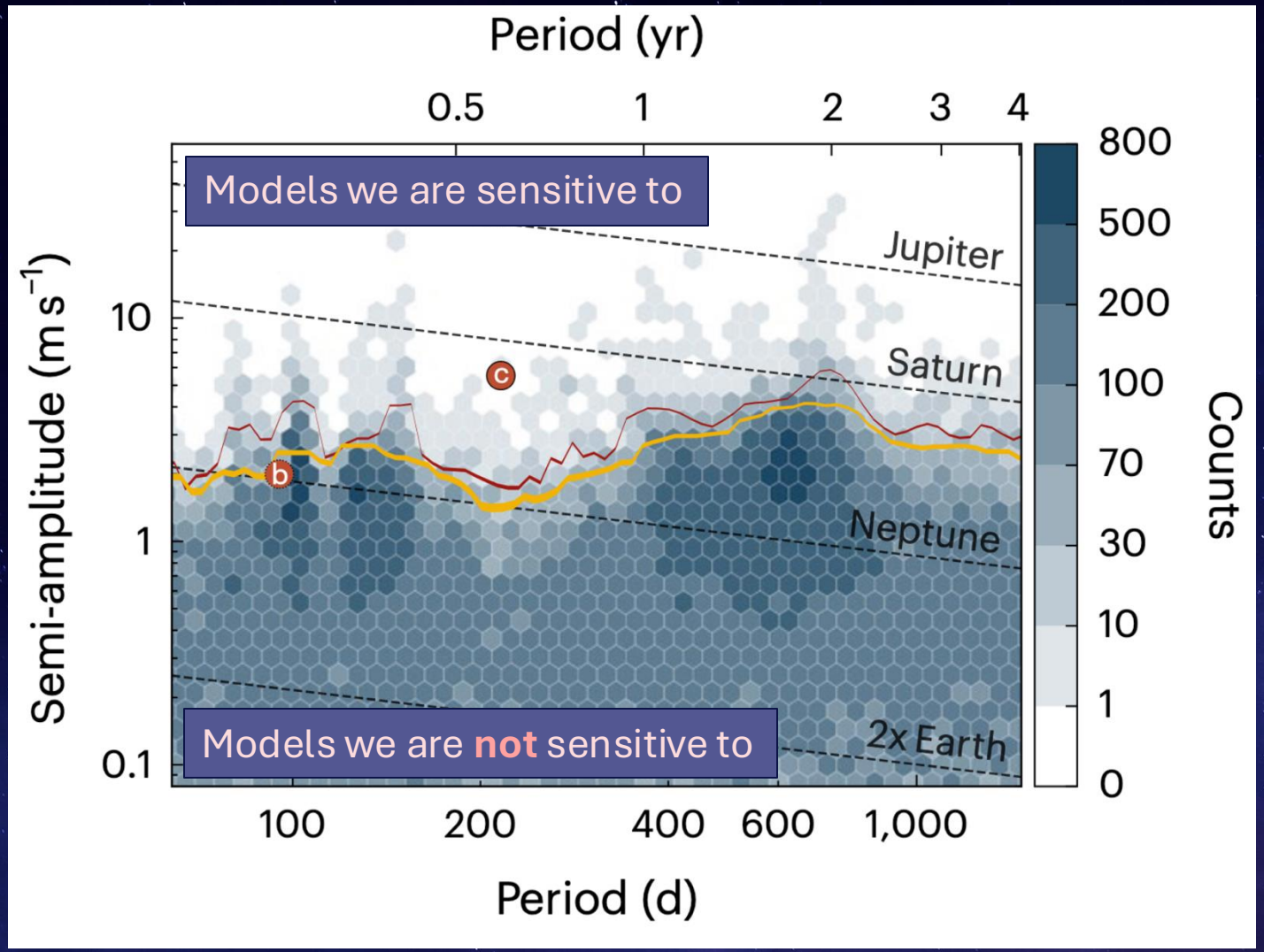
Binaries Escorted By Orbiting Planets

Detection Limits

- Fix number of planets to 1
- Detection limit: upper 99th percentile in each bin

Advantages

- Produces density map of all models compatible with the data
- Can marginalise over more orbital parameters than traditional injection recovery



Sanding et al 202, Sanding et al 2023

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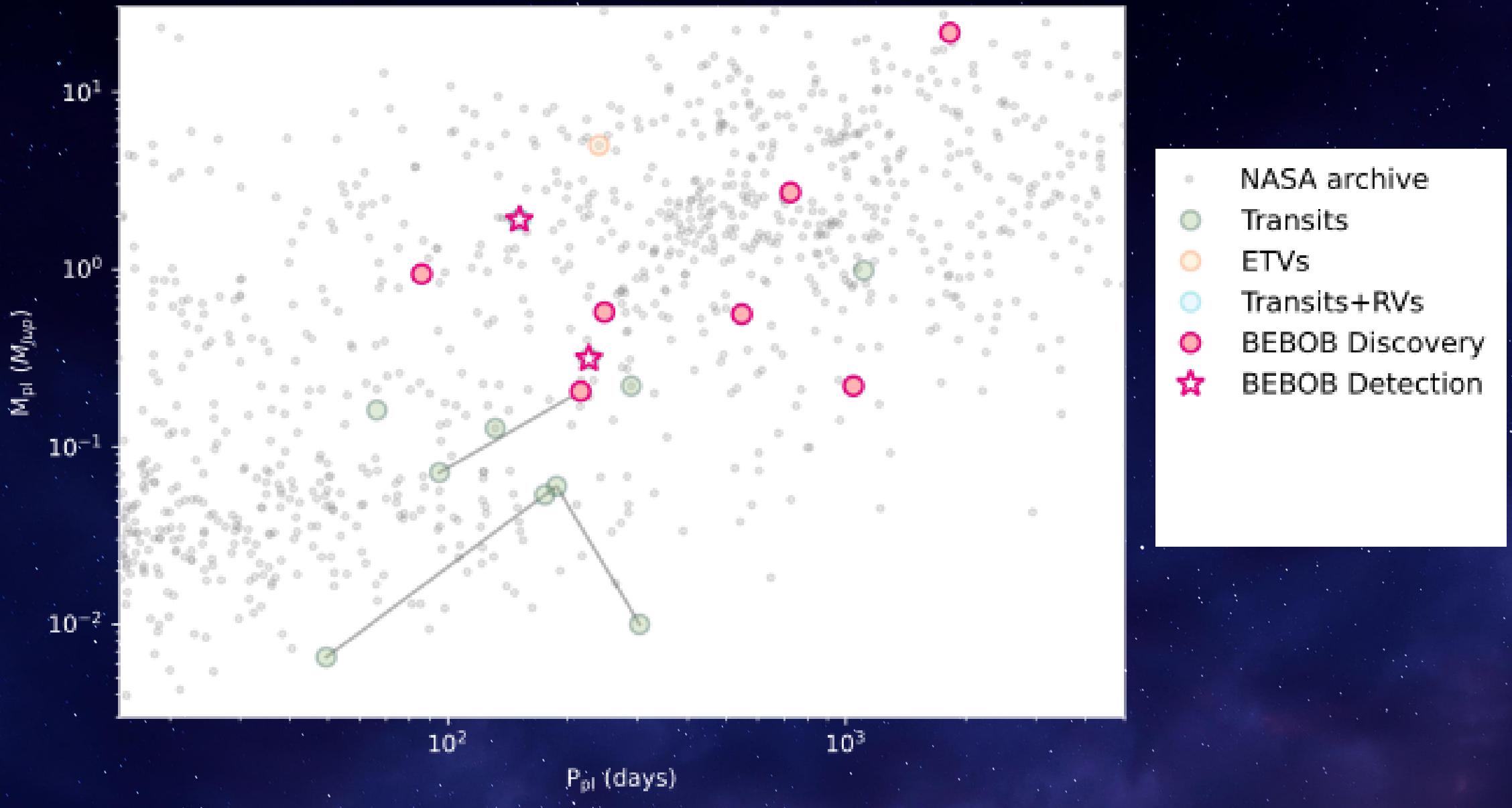
BEBOP survey: Phase 1, results so far



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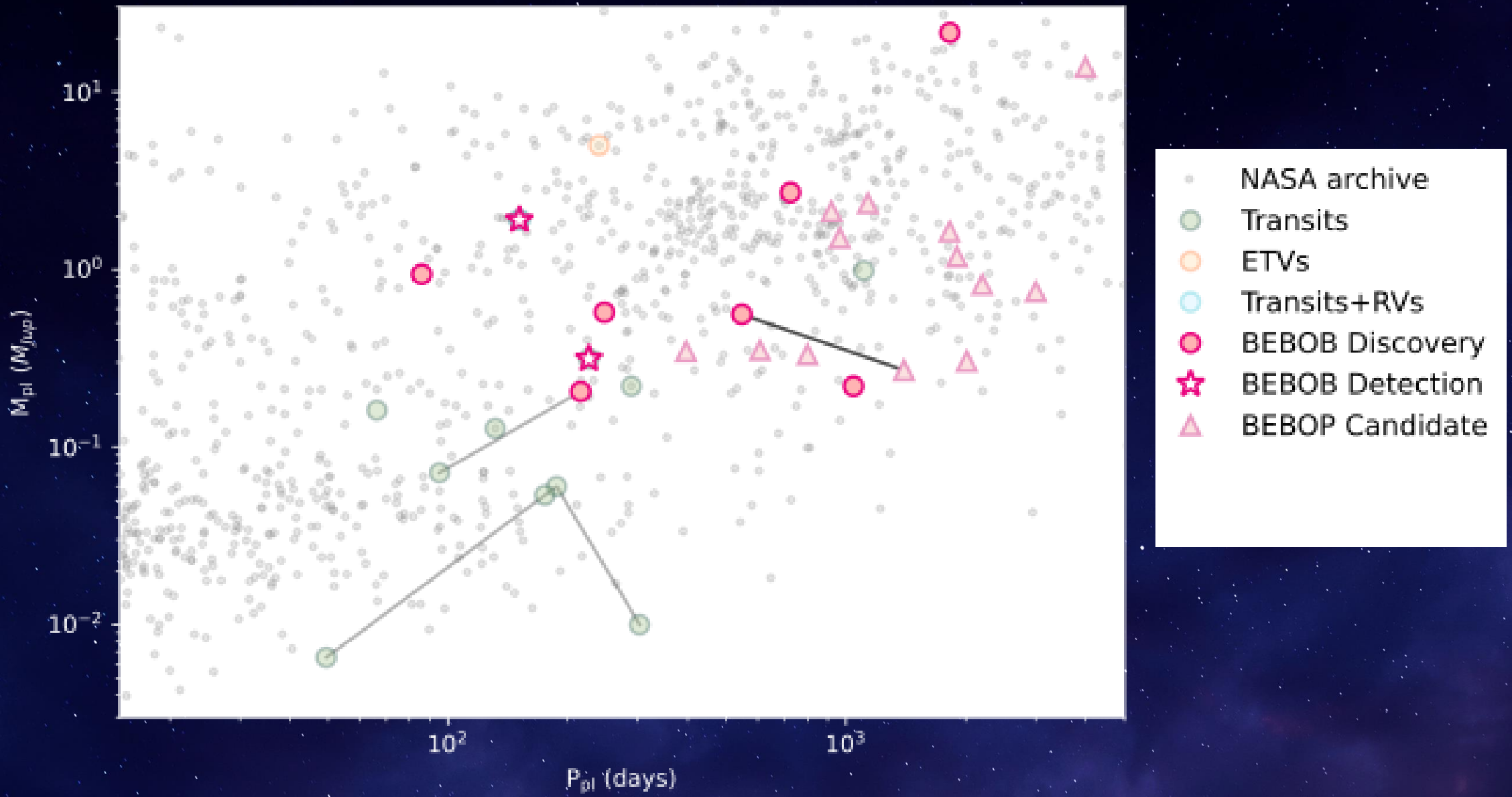

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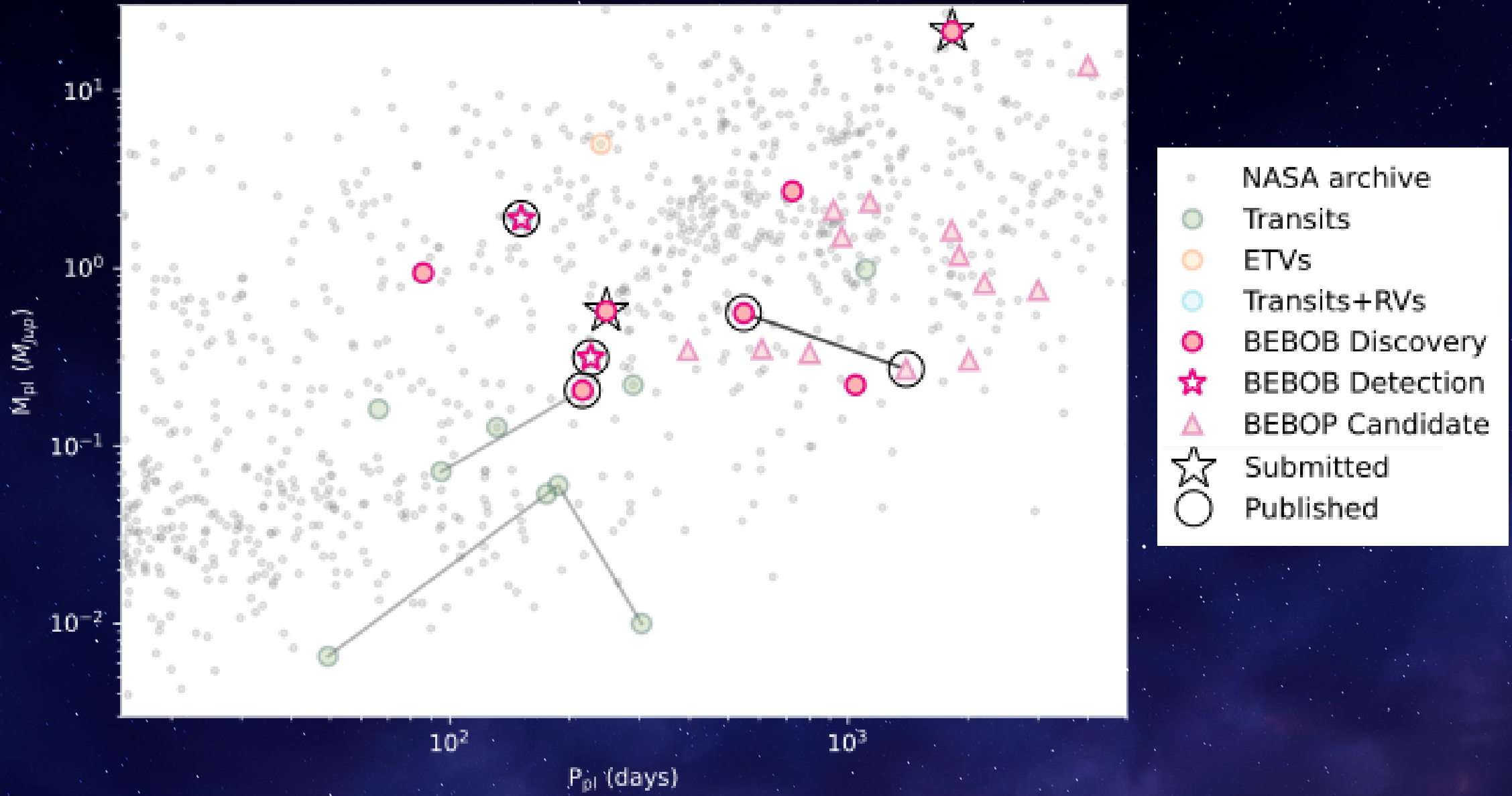
BEBOP survey: Phase 1, results so far



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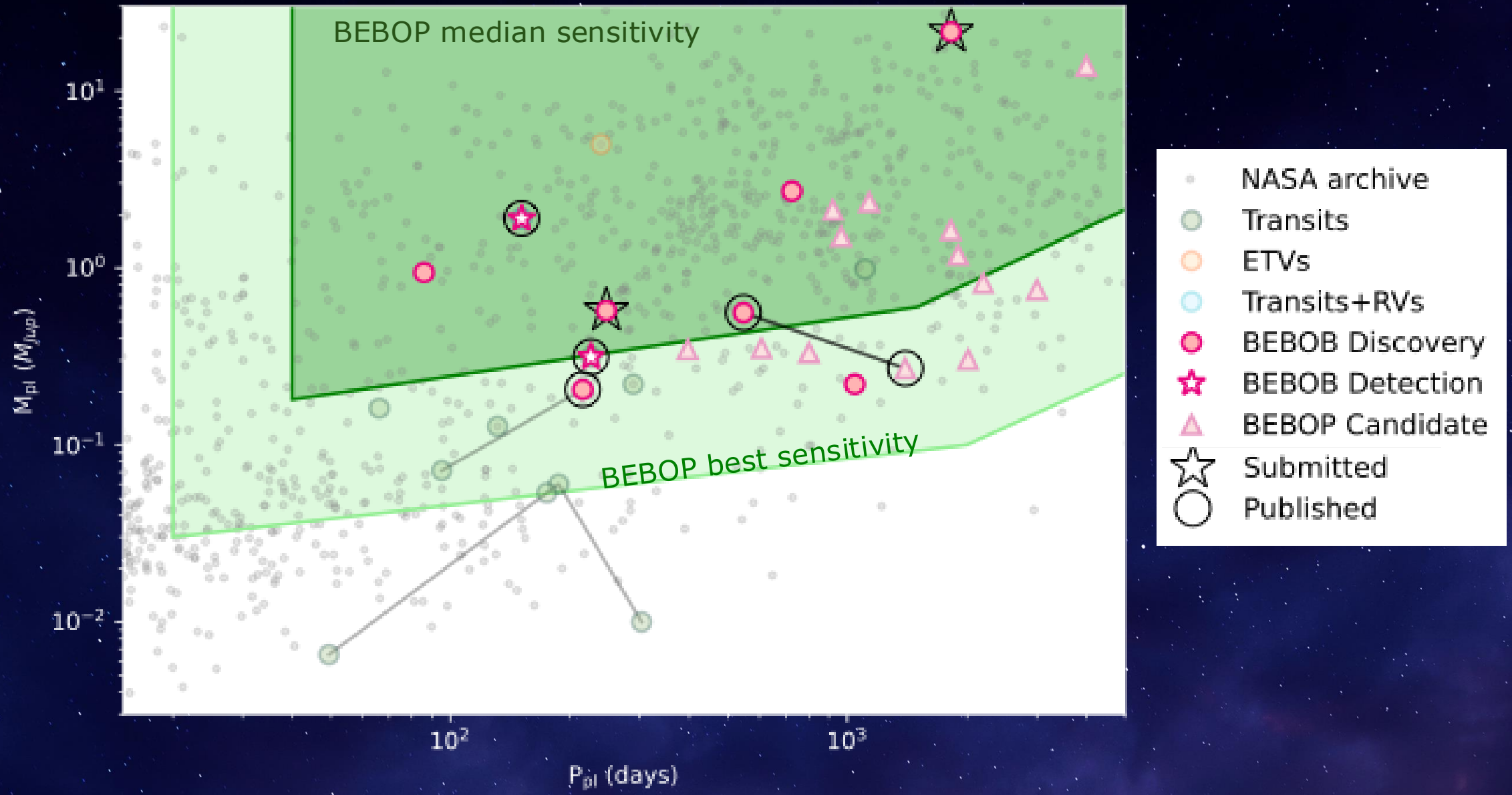

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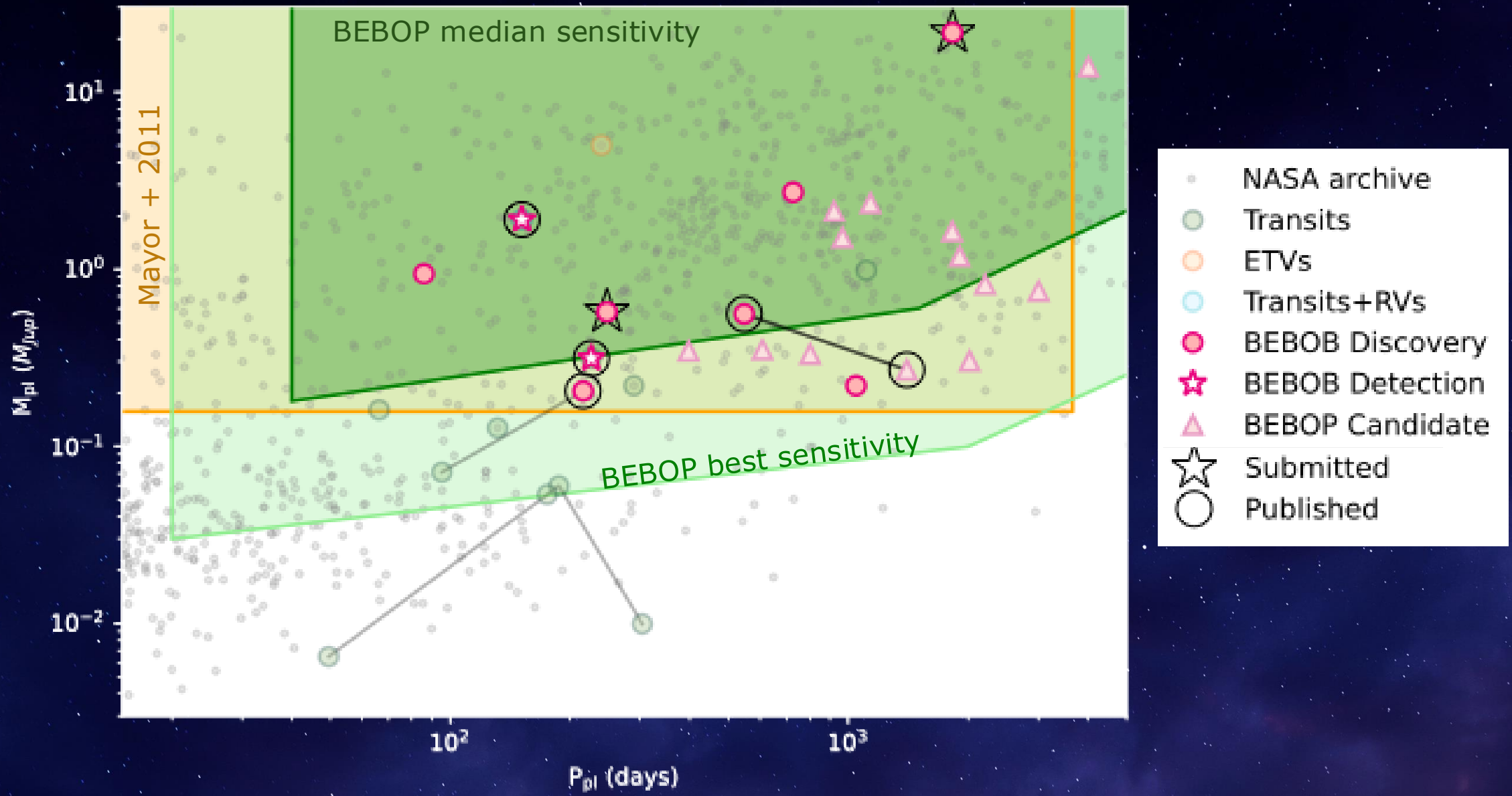

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BEBOP survey: Phase 1 preliminary results

***B**inaries **E**scorted **B**y **O**rbiting **P**lanets*

Overview

- Circumbinary planets can be detected with RVs in SB1s!
- 7 circumbinary planets discovered and 13 candidates
- BEBOP circumbinary planets are giant ($\gtrsim 0.2\, M_{\rm Jup}$) and long period ($\gtrsim 5\, {\rm P_{bin}}$)
- RV and transit circumbinary planet population appear to be different

Physical and orbital properties

- Circumbinary planets $> 3{\rm M_{Jup}}$ are 5 x rarer than than for single stars
- Circumbinary planets can have significant eccentricities

Occurrence Rates

- Circumbinary planets have an occurrence rate of about 10%

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BEBOP survey: Phase 1 preliminary results

Binaries Escorted By Orbiting Planets

Overview

- Circumbinary planets can be detected with RVs in SB1s!
- 7 circumbinary planets discovered and 13 candidates

What about double-lined binaries?

- Circumbinary planets can have significant eccentricities

Occurrence Rates

- Circumbinary planets have an occurrence rate of about 10%

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BEBOP survey: Next Steps

Binaries Escorted By Orbiting Planets

What about double-lined binaries (SB2s)?

- Both stars are of similar mass, size, and brightness
- SB2s account for ~90% of binaries (Kovaleva et al 2016)
- Spectral lines from both stars are combined into the observed spectrum
- Get 2 RVs per measurement!

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BEBOP survey: Next Steps

Binaries Escorted By Orbiting Planets

Extracting RVs from SB2s is challenging

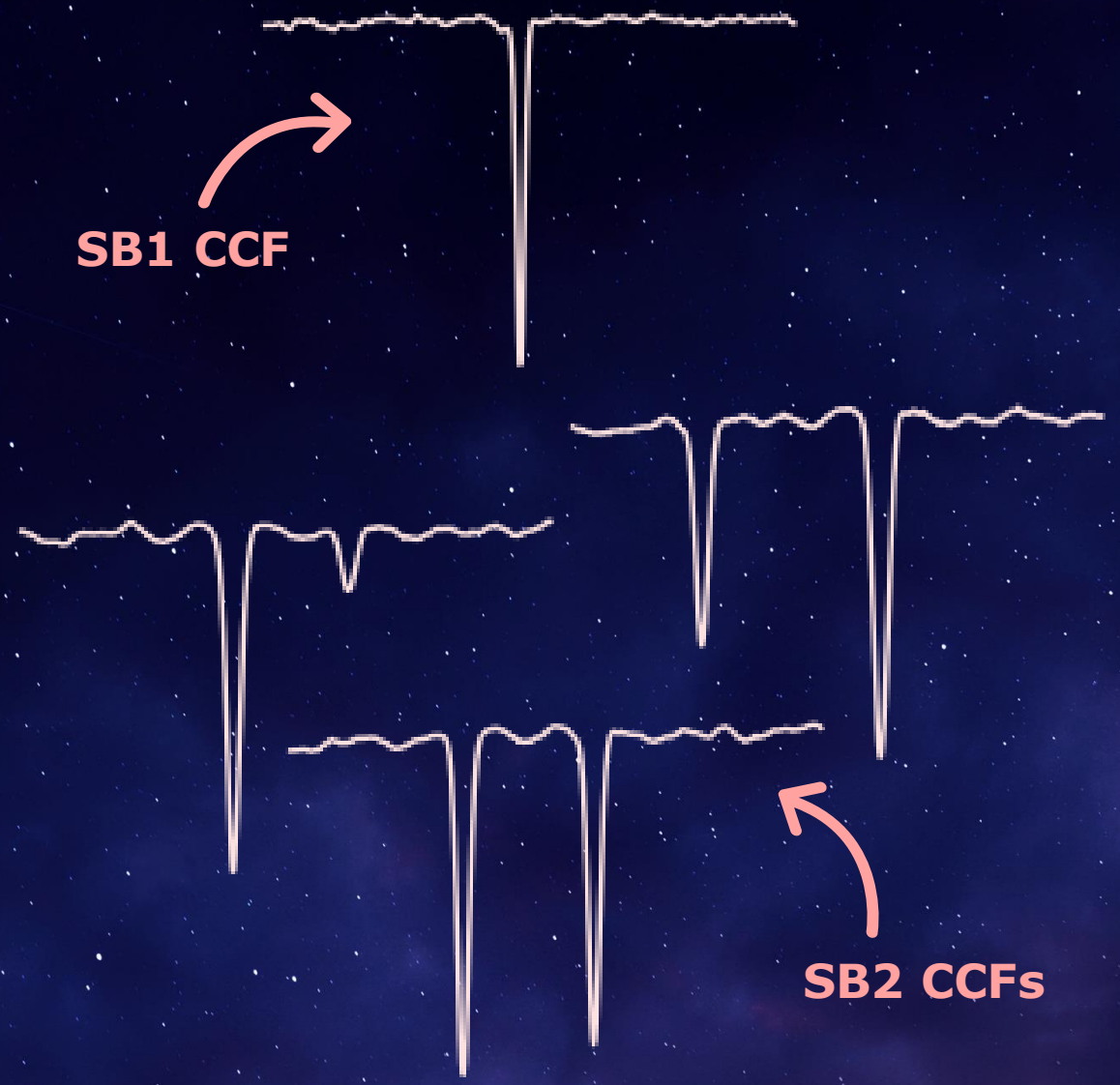
- Spectral lines interfere with each other in the standard cross-correlation technique for RV extraction

- This leads to extra scatter in the data making detecting planets difficult

Solution

- Use *DOLBY-CCF* to extract accurate and precise RVs (Sairam et al 2024a,b)

- Can reach precision $< 10\ \mathrm{m\ s^{-1}}$



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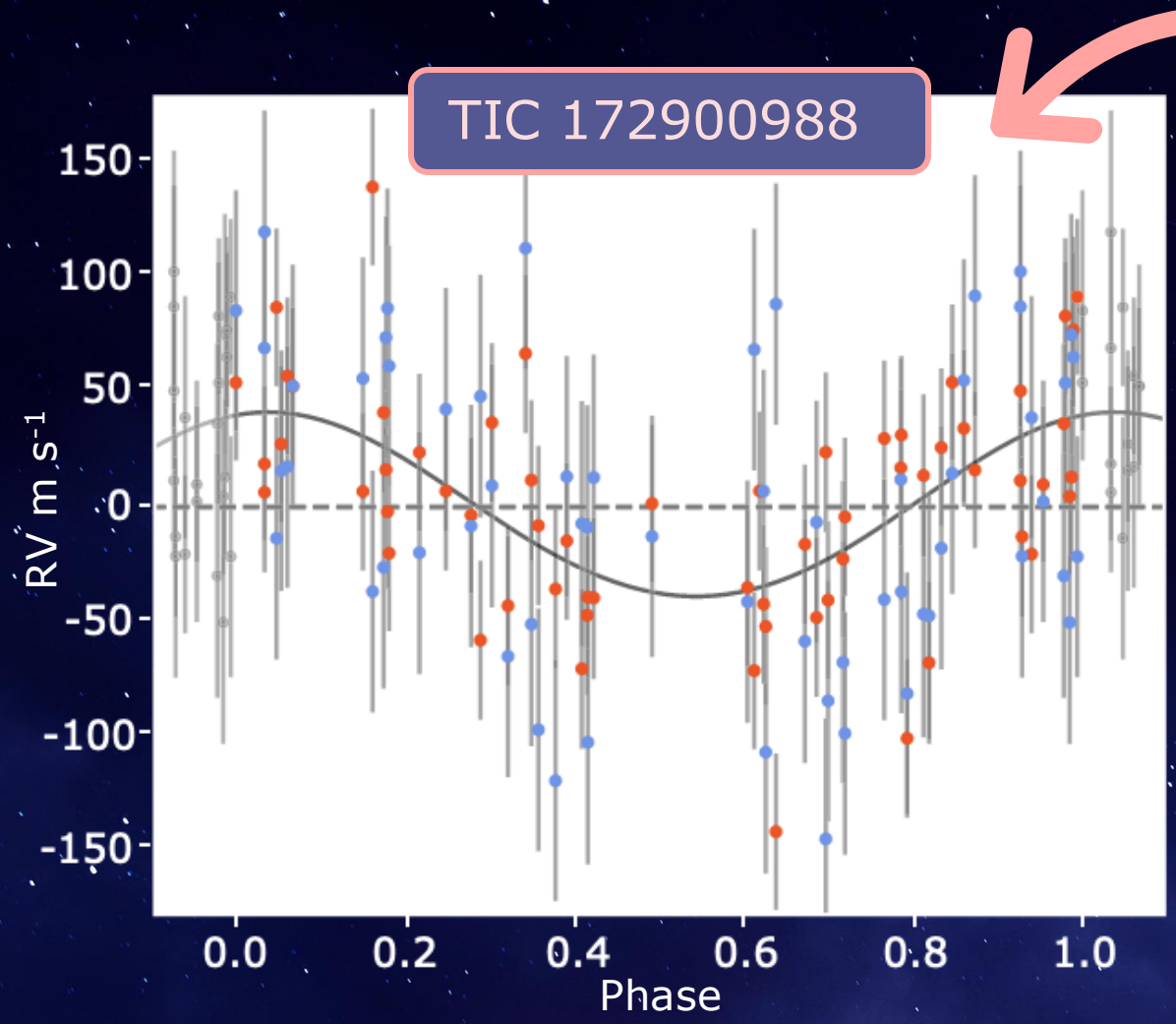
BEBOP survey: Next Steps

Binaries Escorted By Orbiting Planets



We made the 1st RV detection of a circumbinary planet in an SB2!

TIC 172900988:

- $M_{\mathrm{A}} = 1.23\ \mathrm{M}_{\odot}$
- $M_{\mathrm{B}} = 1.20\ \mathrm{M}_{\odot}$
- $P_{\mathrm{bin}} = 19.65$ days

TIC 172900988 b:

– $M_{\mathrm{pl}} = 1.90 \pm 0.25\ \mathrm{M}_{\mathrm{Jup}}$

- $P_{\mathrm{pl}} = 151.2 \pm 1.8$ days

Sairam et al 2024a
Kostov et al 2021

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BEBOP survey

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BEBOP Survey: Phase 2

- Over 100 bright spectroscopic binaries including SB2s in both the northern and southern hemispheres
- Sample picked from *Gaia* and *TESS*
- Binary mass ratio $\gtrsim$ 0.3
- A blind radial velocity (RV) search
- Measurements are being taken with SOPHIE and HARPS spectrographs

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BEBOP survey: Summary

***B**inaries **E**scorted **B**y **O**rbiting **P**lanets*

The BEBOP survey

- Blind RV survey searching for circumbinary planets
- BEBOP Phase 1 – focused on SB1s
- BEBOP Phase 2 – focused on bright SB2s and SB1s

Preliminary results

- Circumbinary planets can be detected with RVs!
- Made the 1st RV detection of a circumbinary planet in an SB2 and SB1
- 7 circumbinary planets detected and 13 circumbinary planet candidates
- Circumbinary planets $> 3M_{Jup}$ are 5 x rarer than than for single stars
- RV and transit circumbinary planet population appear to be different
- Circumbinary planets have an occurrence rate of ~ 10%

Extracting RVs of SB2s can be challenging

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