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# Circumbinary planets with *Gaia*

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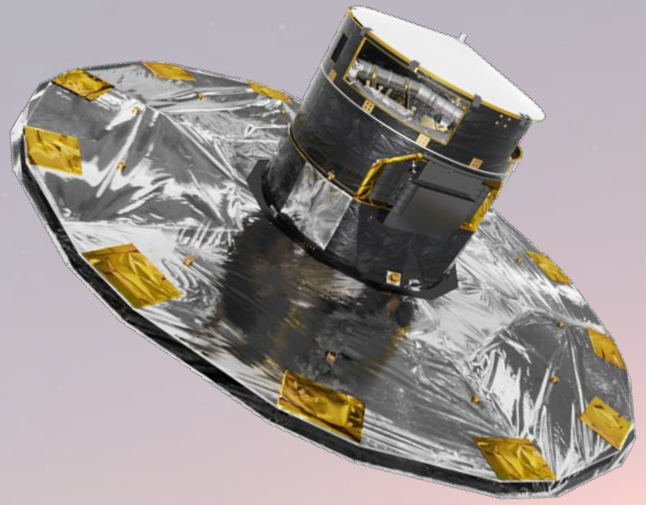
# Outline

- Overview of *Gaia*
- Predicting *Gaia* yield of circumbinary planets orbiting main-sequence binaries
- *Gaia* and known circumbinary systems
- *Gaia* sensitivity to a circumbinary population around post common-envelope binaries

# Gaia



All-sky astrometric ESA mission

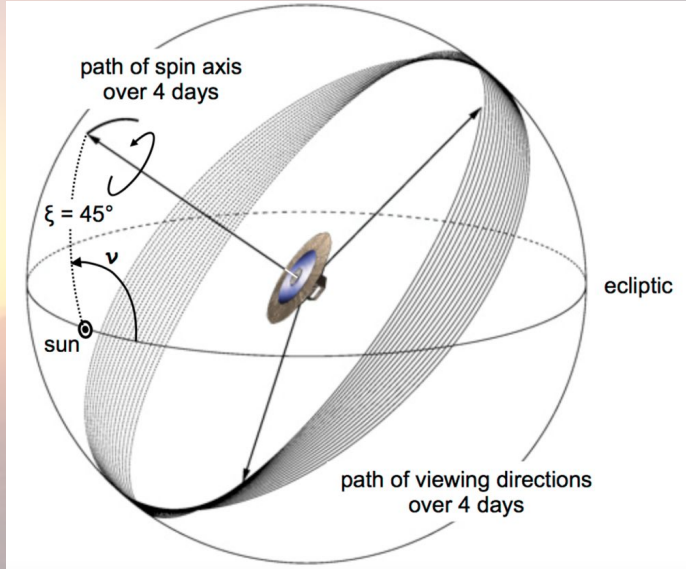
Launched December 2013, scientific operations began in July 2014

Scientific mission ended: Wednesday

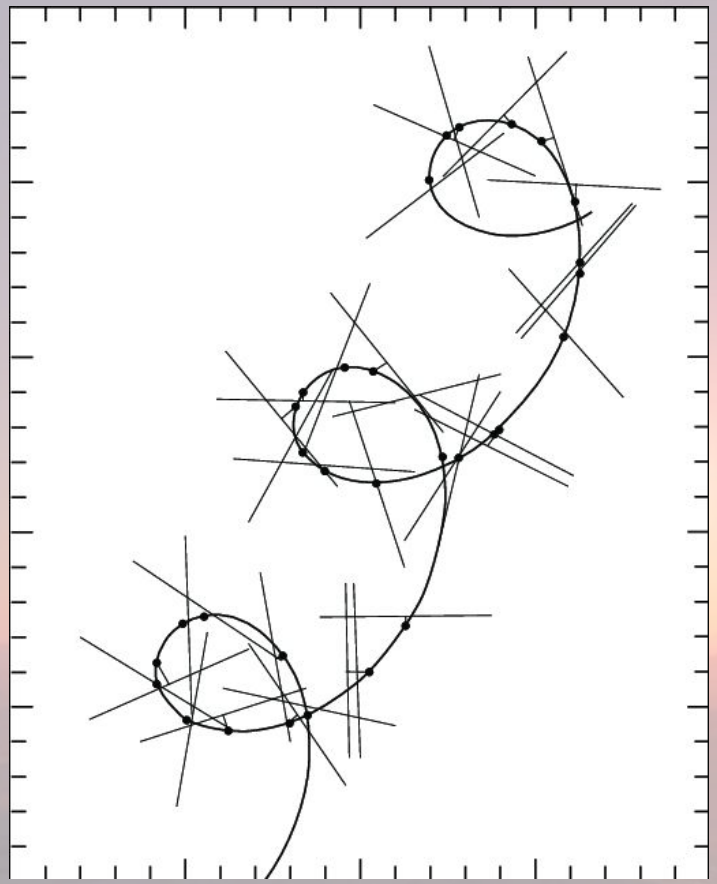
Location: Earth-Sun L2

Scanning mission precessing on its axis

Has taken 2.6 trillion astrometric CCD measurements

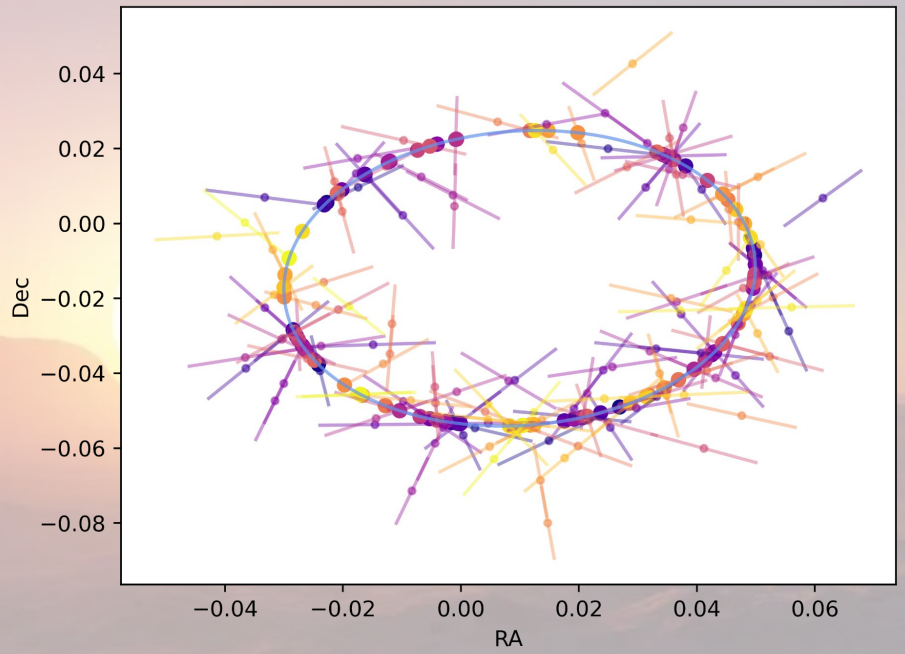


# How *Gaia* detects orbits



1D measurements

Parallactic motion (5 parameters) + Orbital motion (7 parameters)



# Predictions for *Gaia* yield of exoplanets

Estimates from *Perryman et al. 2014* in range 20,000 - 70,000 exoplanets

*Gaia* mostly sensitive to massive planets at long periods

**DR4** (not before mid 2026) 66 months of data

- Full astrometric, photometric, and radial-velocity catalogues.
- All available variable-star and non-single-star solutions.
- Source classifications (probabilities) plus multiple astrophysical parameters.
- An exoplanet candidate list.
- All epoch and transit data for all sources.

**DR5** (not before end of 2030) Full mission (136 months) data

# Predictions for *Gaia* yield of Circumbinary exoplanets

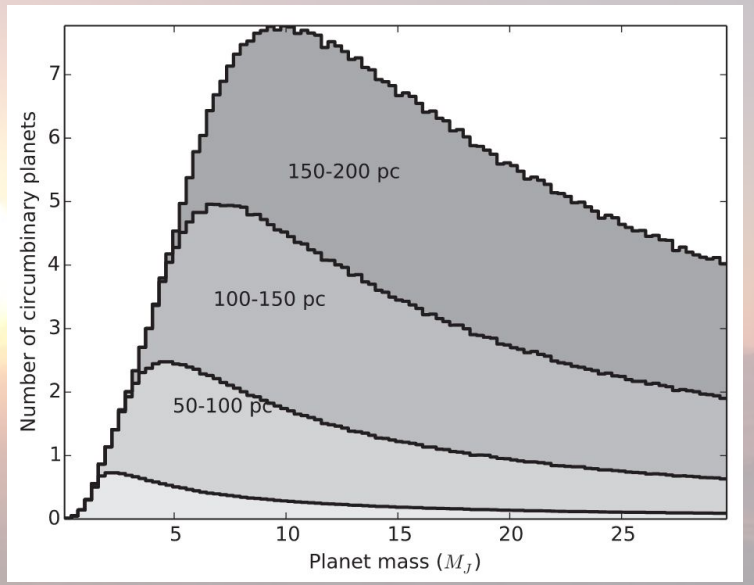
*Sahlmann, Triaud, & Martin 2015* gave a prediction of *Gaia* DR4 yield of circumbinary exoplanets.

Within 200pc they expected ~ 500 planets, majority > 5 $M_J$

Assumptions:

-Planet mass distribution from single-star population

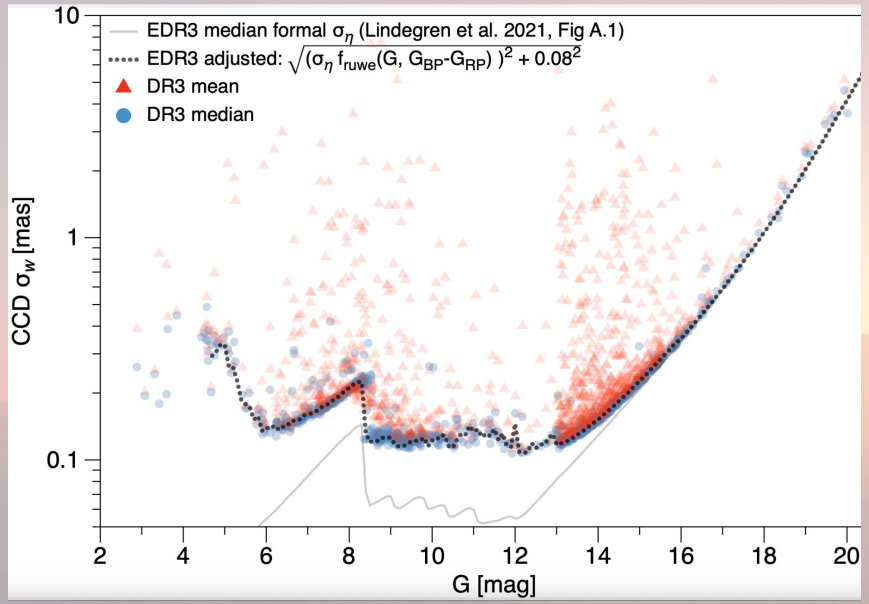
-All planets piled-up at 6x binary period

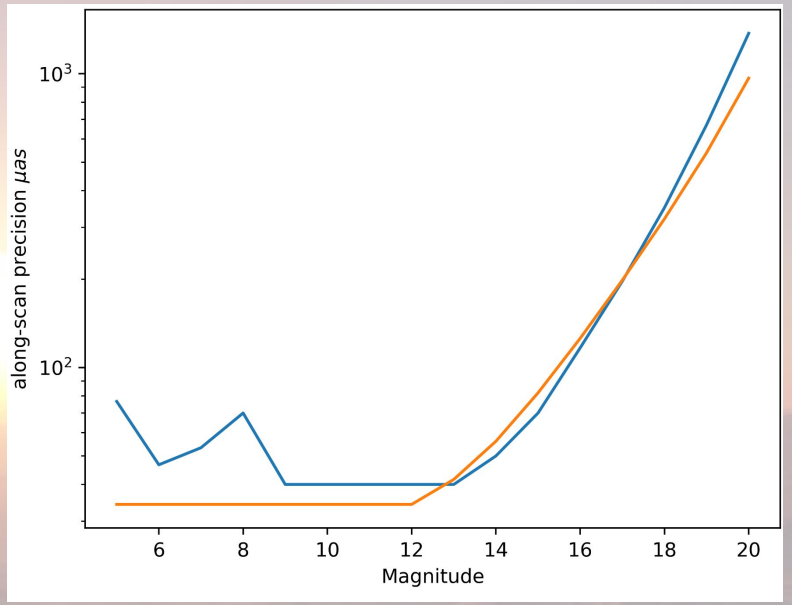


# Revisiting with new knowledge

We know *Gaia* precision better, depends on Magnitude (may still improve with DR4 and DR5)

Extended mission to 10.5 years will alter both number of measurements and timespan of data.




*Holl et al. 2023*

# Predicting yield of circumbinary planets orbiting main-sequence binaries

# Yield estimate for circumbinary planets

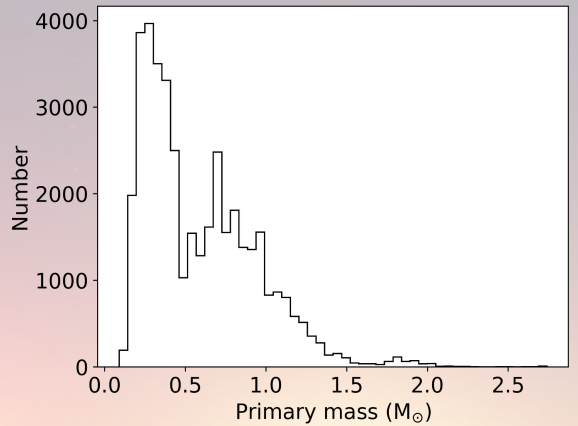
- Create synthetic binary sample
- Inject **synthetic circumbinary planets** around 10% of the binaries
- Calculate *Gaia* SNR of the binaries and the planets
- Select detectable binaries
- Select detectable planets around detectable binaries
- **Obtain yield estimate**

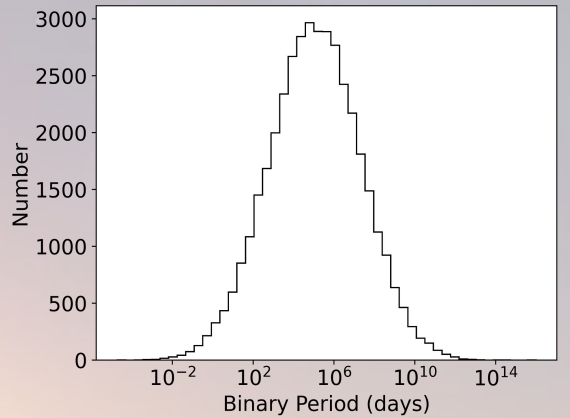
# Synthetic binary population

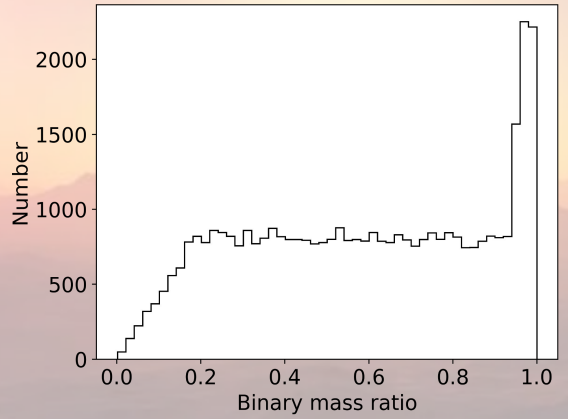
Gaia sources within 200pc

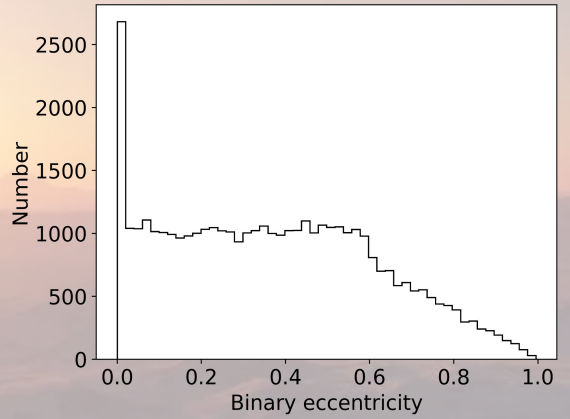
Binary fraction by spectral type:
B: 75%
A: 70%
F: 50%
G: 45%
K: 40%
M: 20%
*(Raghavan et al. 2010)*

Period, Mass-ratio, and eccentricity distributions also based on *Raghavan et al. 2010*

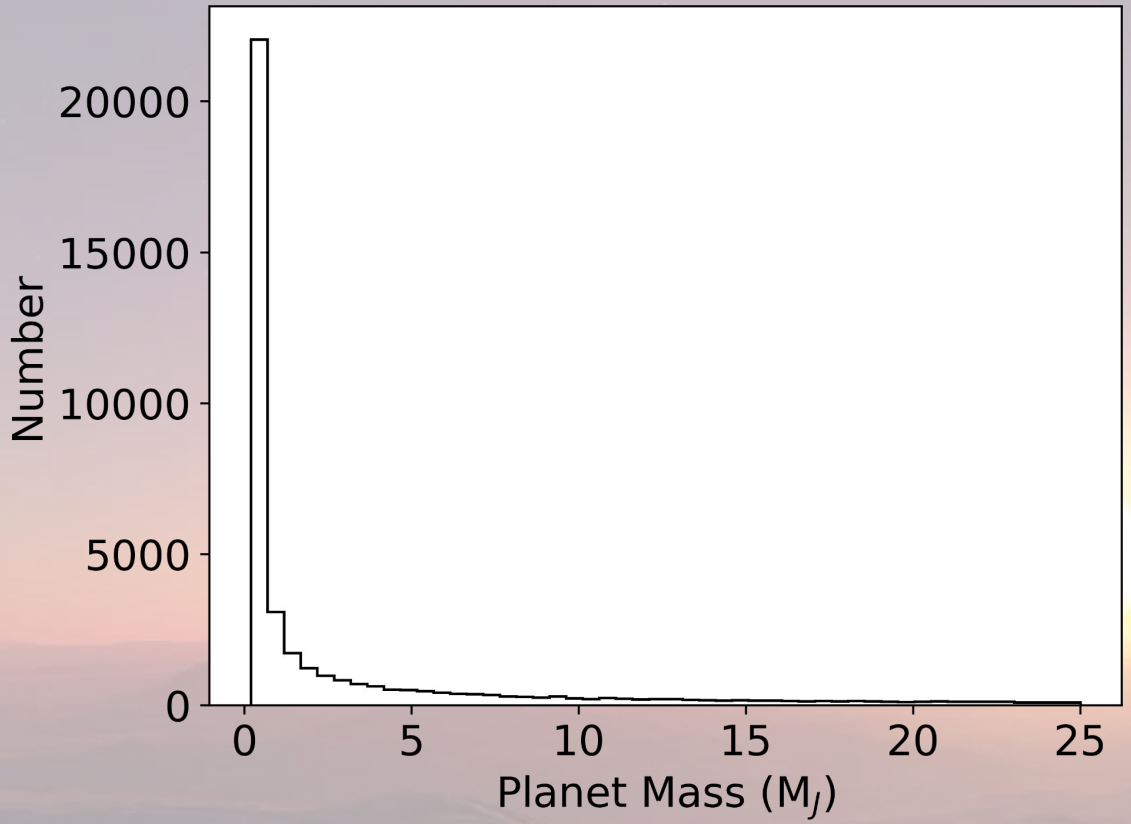


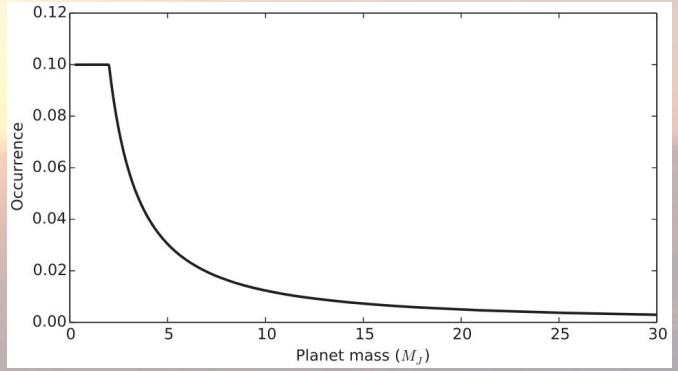
# Synthetic circumbinary planets: Mass



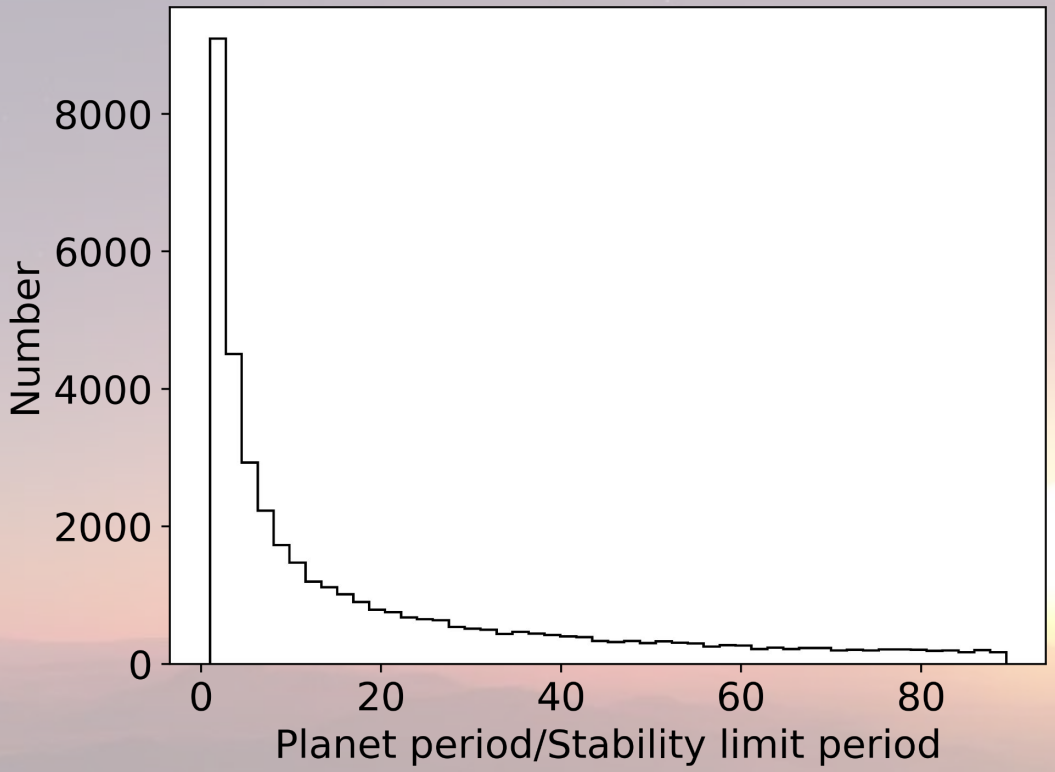

Planet mass distribution:

Equal mixture of:
Gaussian around $M_{sat}$ and
LogUniform between $M_{sat}$ - 25x$M_{jup}$

Note: Lower-mass than in
*Sahlmann et al. 2015*



# Synthetic circumbinary planets: Periods




Distribution of orbital periods:

Actually distribute in planet semi-major-axis/radius of instability zone.

LogUniform between $a_{stab}$ and 20 x $a_{stab}$

Note: *Sahlmann et al. 2015* only considered pile-up at 6 x $P_{bin}$

# Detectability

Select only detectable binaries:

-*Gaia* SNR>100 (Astrometric binaries)

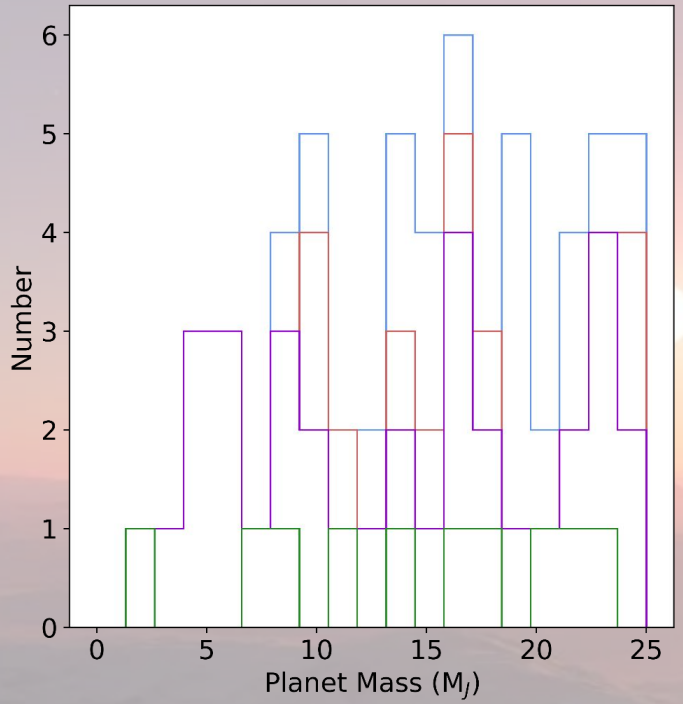
-Gmag < 12 and q>0.4 (Spectroscopic binaries)

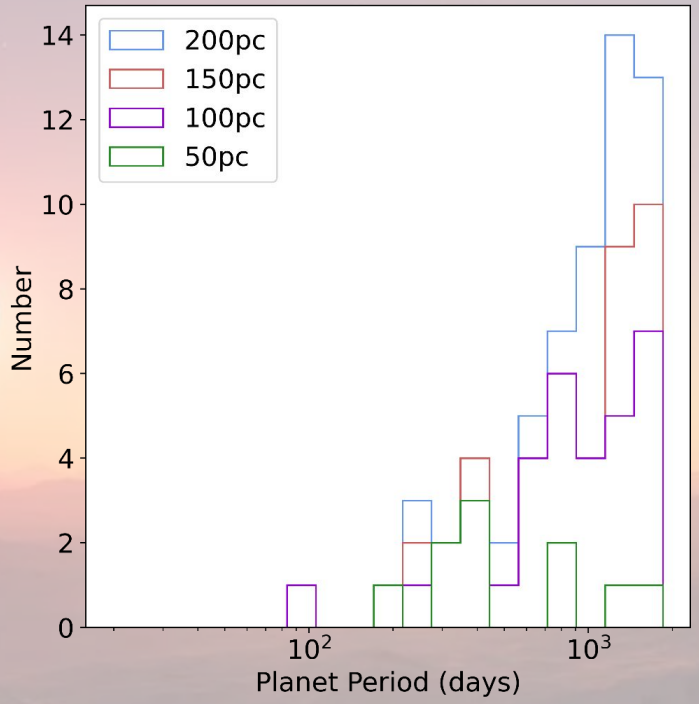
-Eclipsing configuration (Eclipsing binaries)

Planet detection threshold: *Gaia* SNR > 20 and P < dataspan (Astrometric planet)

# Yield estimate for circumbinary planets: DR4 ~ 60 planets

Predicted yield for Gaia DR4
Planets within 200pc = 61
Planets within 150pc = 44
Planets within 100pc = 35
Planets within 50pc = 10



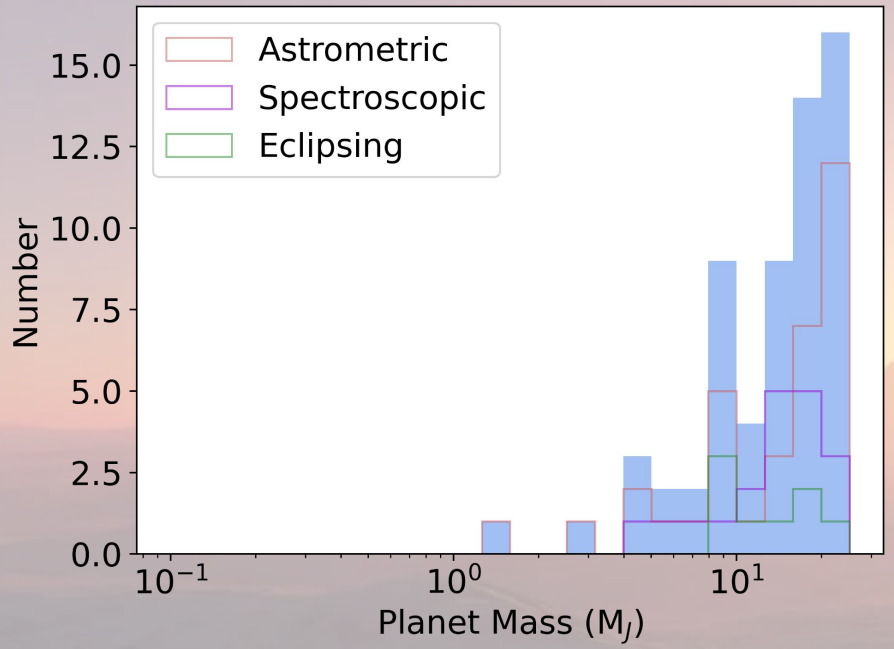



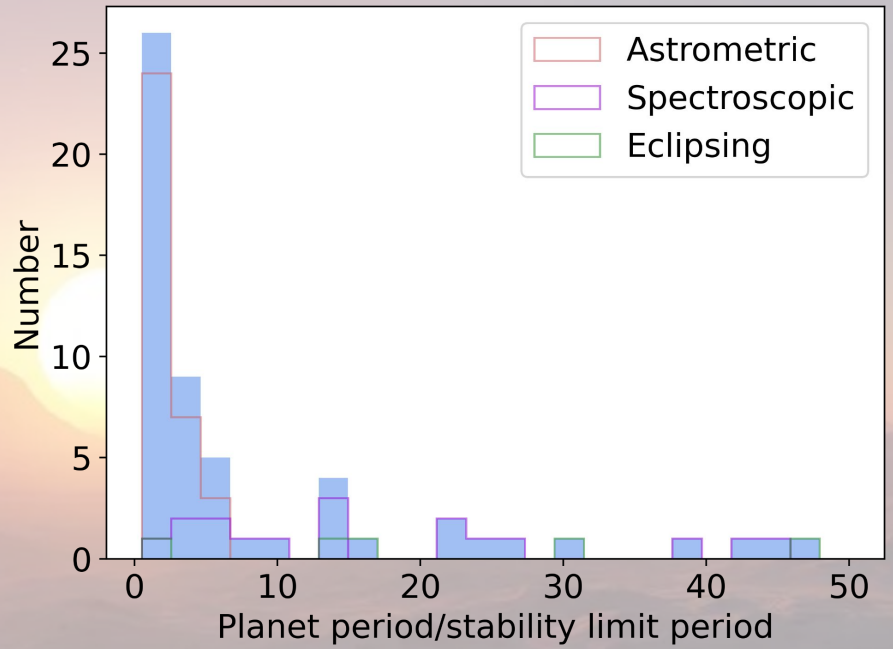

Equivalent numbers from *Sahlmann et al. 2015*

200pc: 516
150pc: 297
100pc: 124
50pc: 25

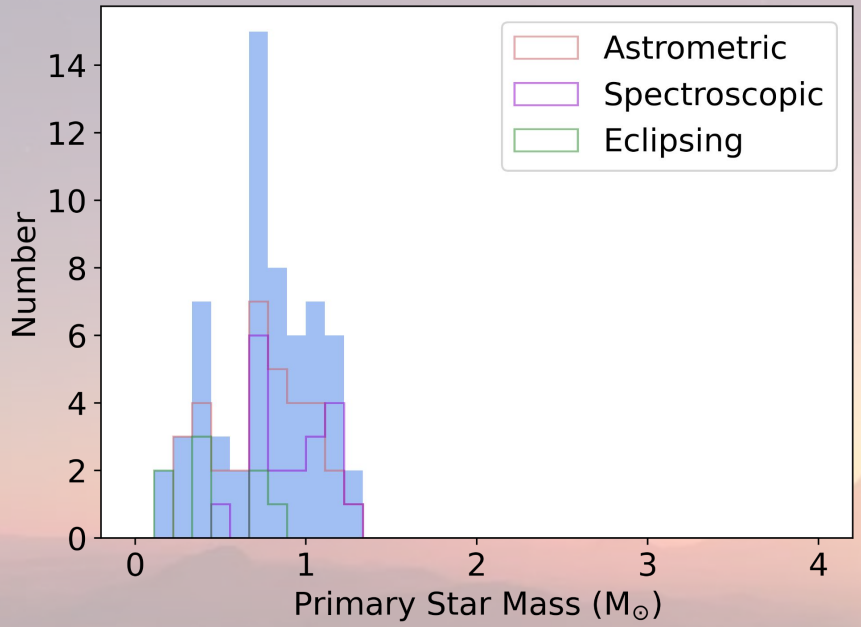
# Yield estimate for circumbinary planets

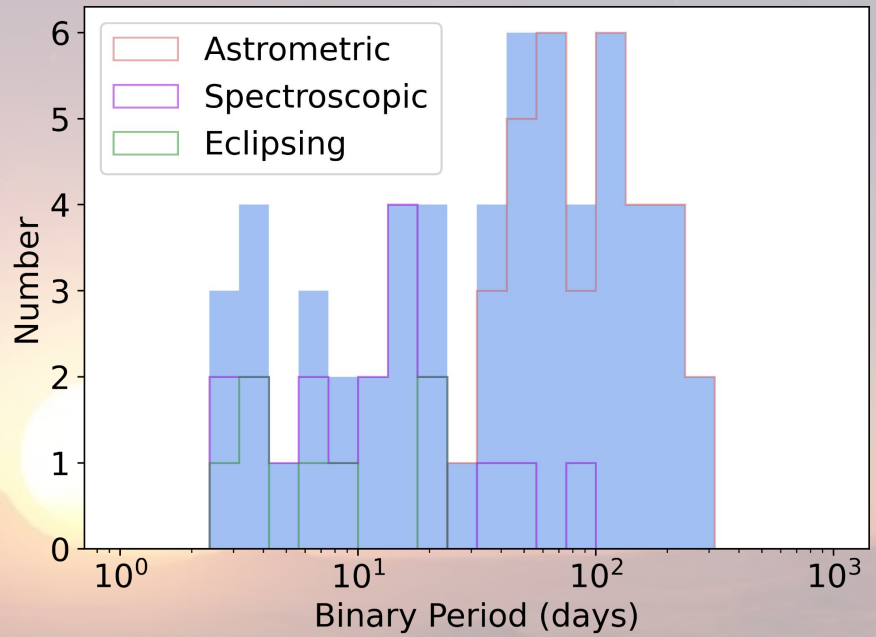
34 around astrometric binaries
19 around spectroscopic binaries
8 around eclipsing binaries



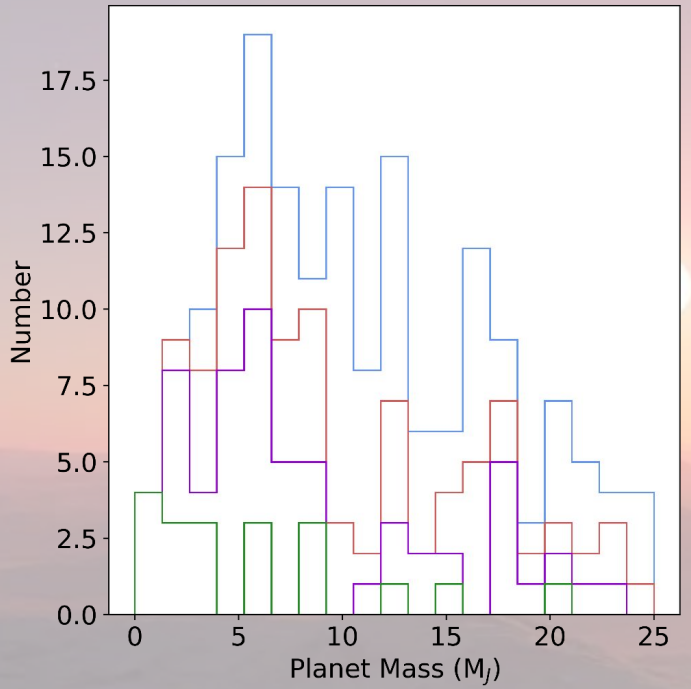
# Yield estimate for circumbinary planets

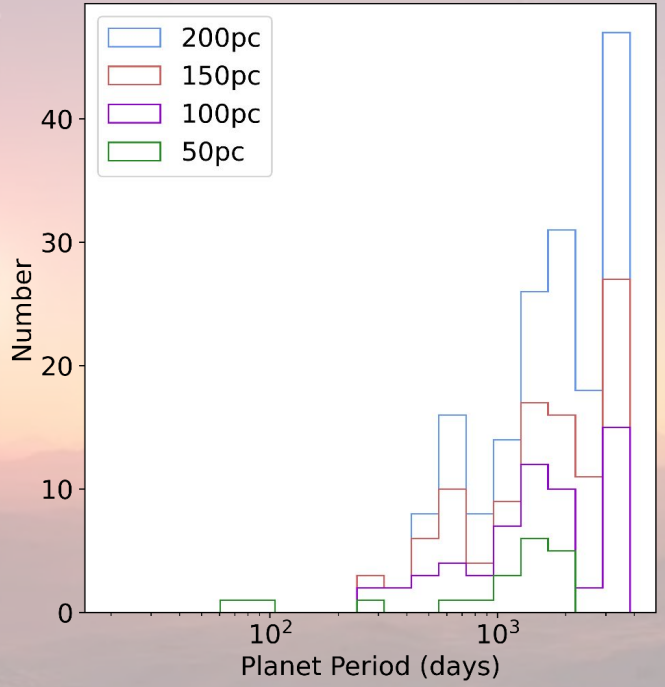


# Extension to DR5: ~200 planets

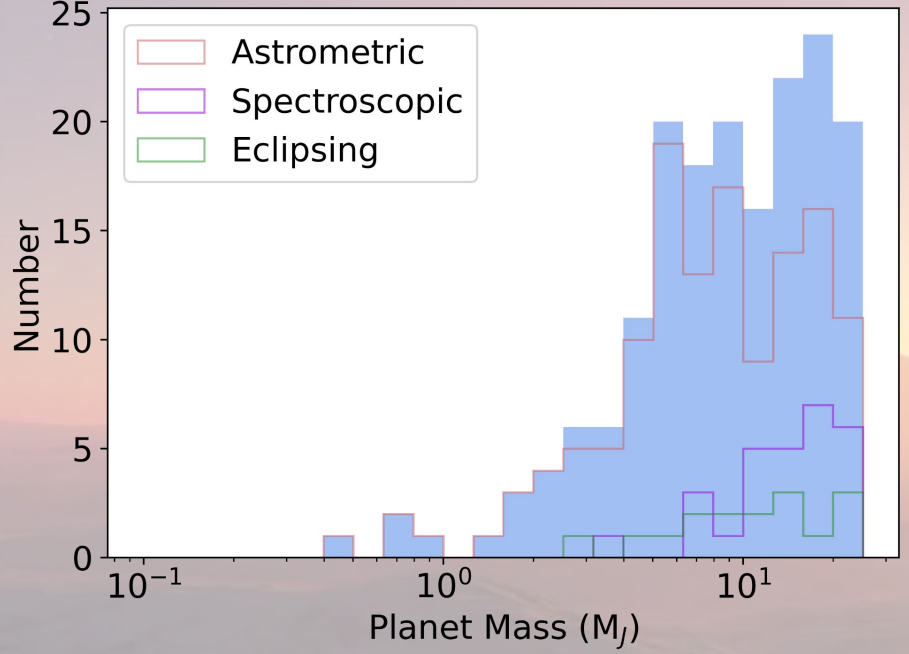
Predicted yield for Gaia DR5
Planets within 200pc = 175
Planets within 150pc = 107
Planets within 100pc = 62
Planets within 50pc = 19

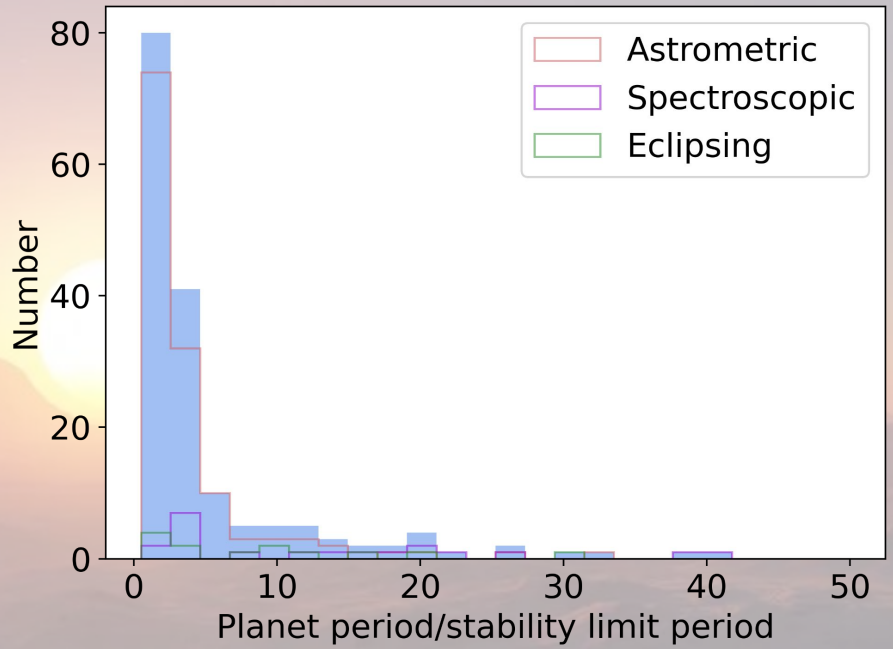


# Extension to DR5

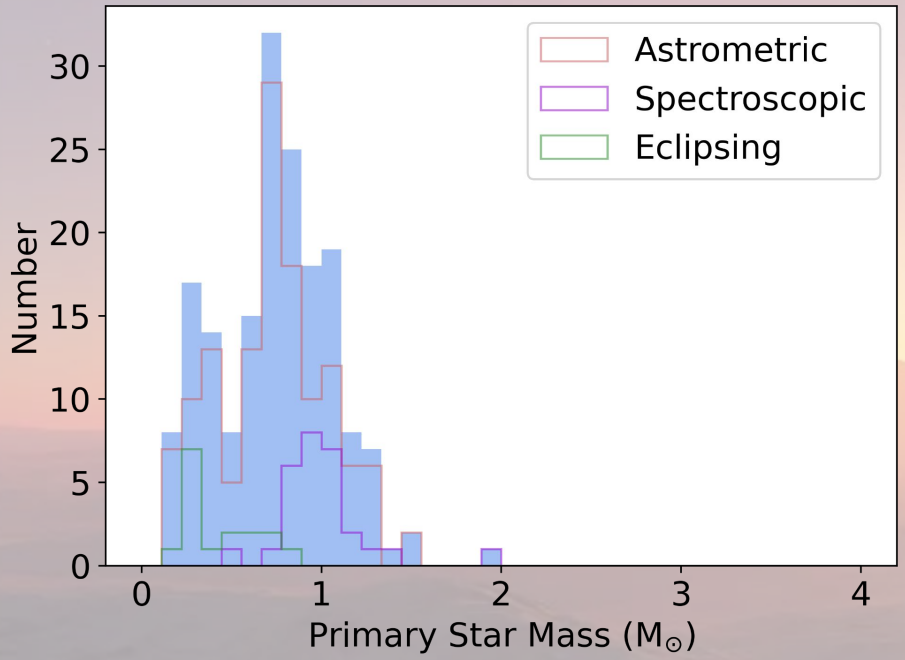
131 around astrometric binaries (up from 34)
28 around spectroscopic binaries (up from 19)
16 around eclipsing binaries (up from 8)



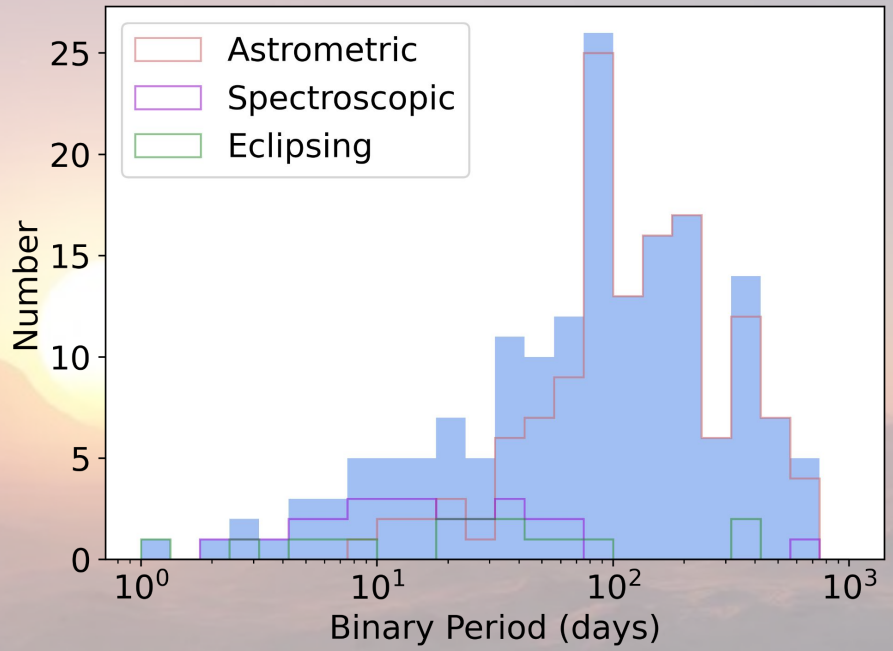



# Extension to DR5

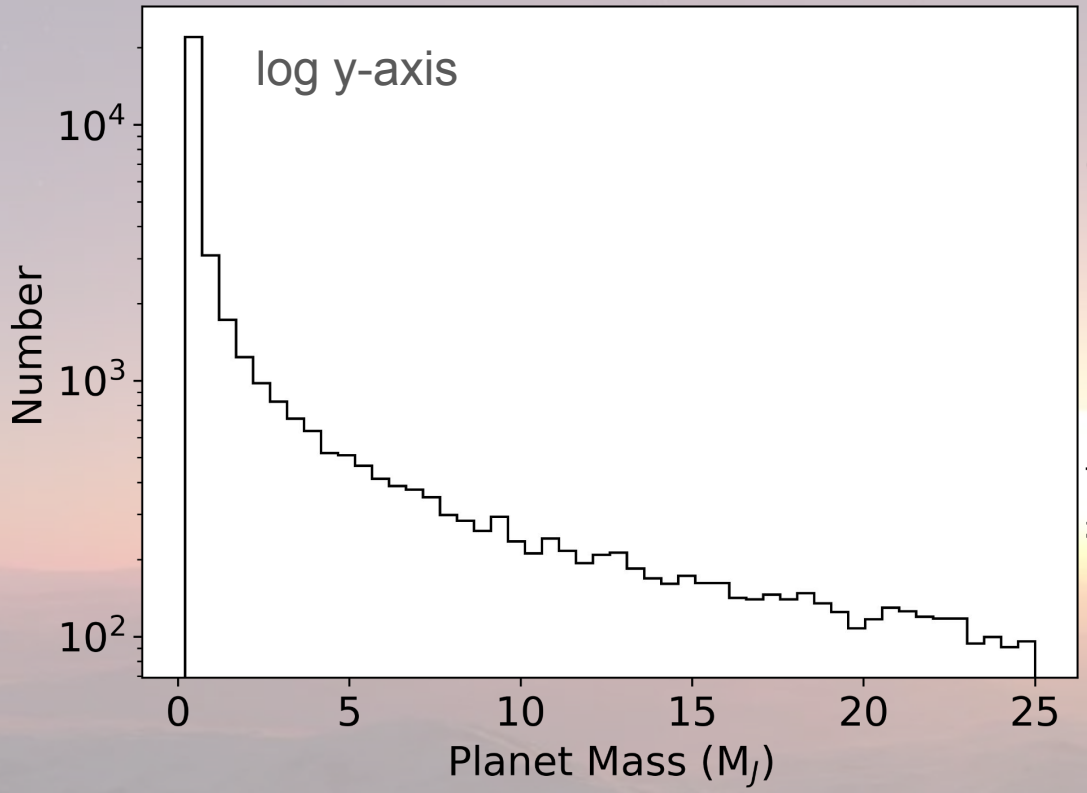
Stellar mass distribution remains similar




Extend to longer binary periods

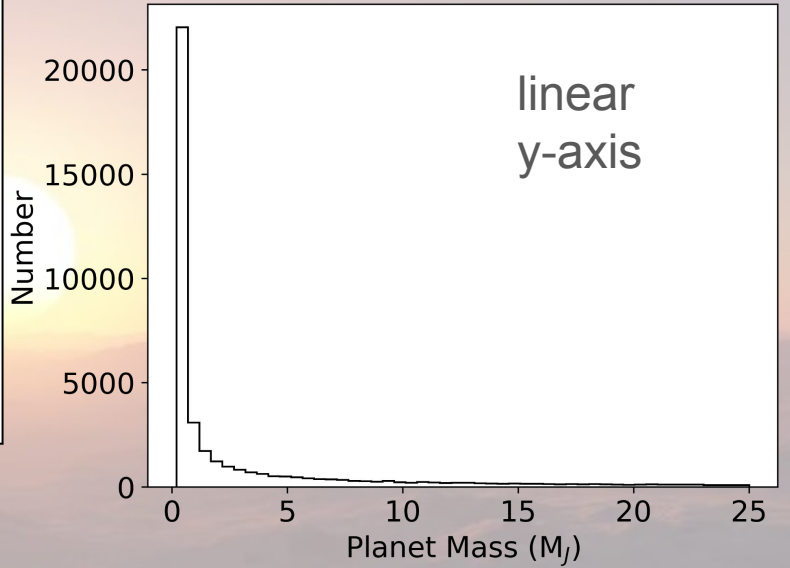


# Varying the planet mass distributions

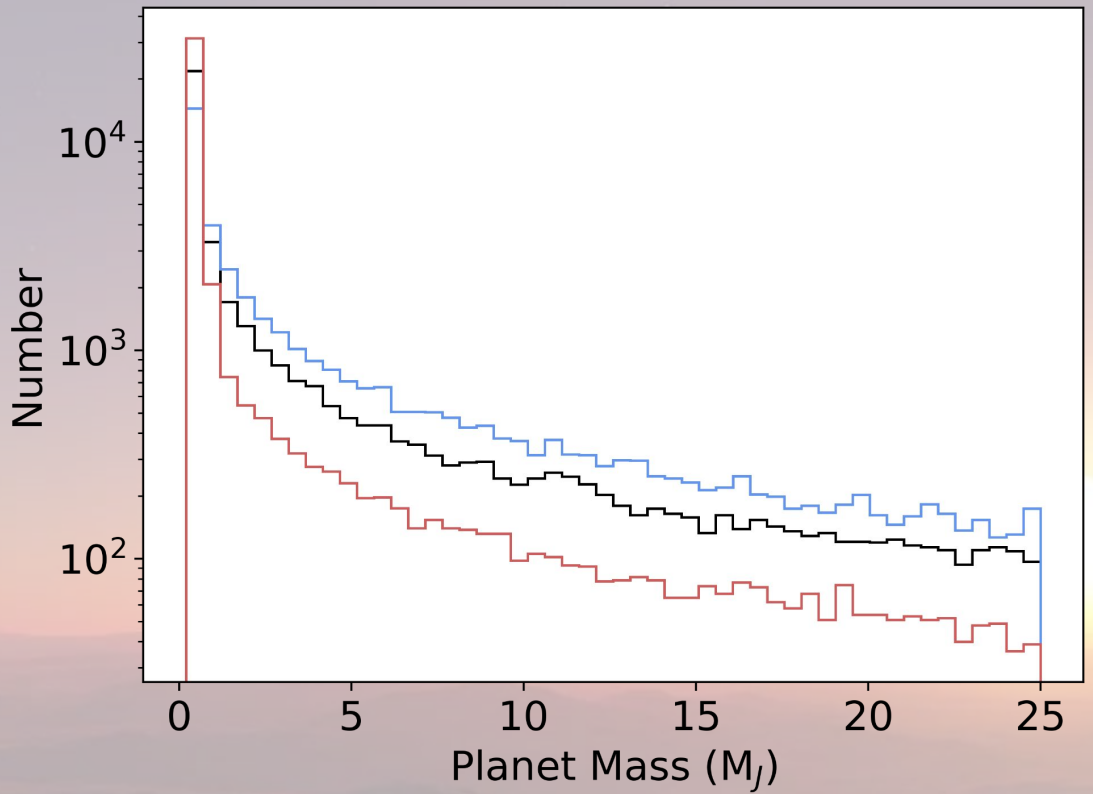



Main mass distribution used so far.

Gaussian + LogUniform



# Varying the planet mass distributions




Planet mass distributions:

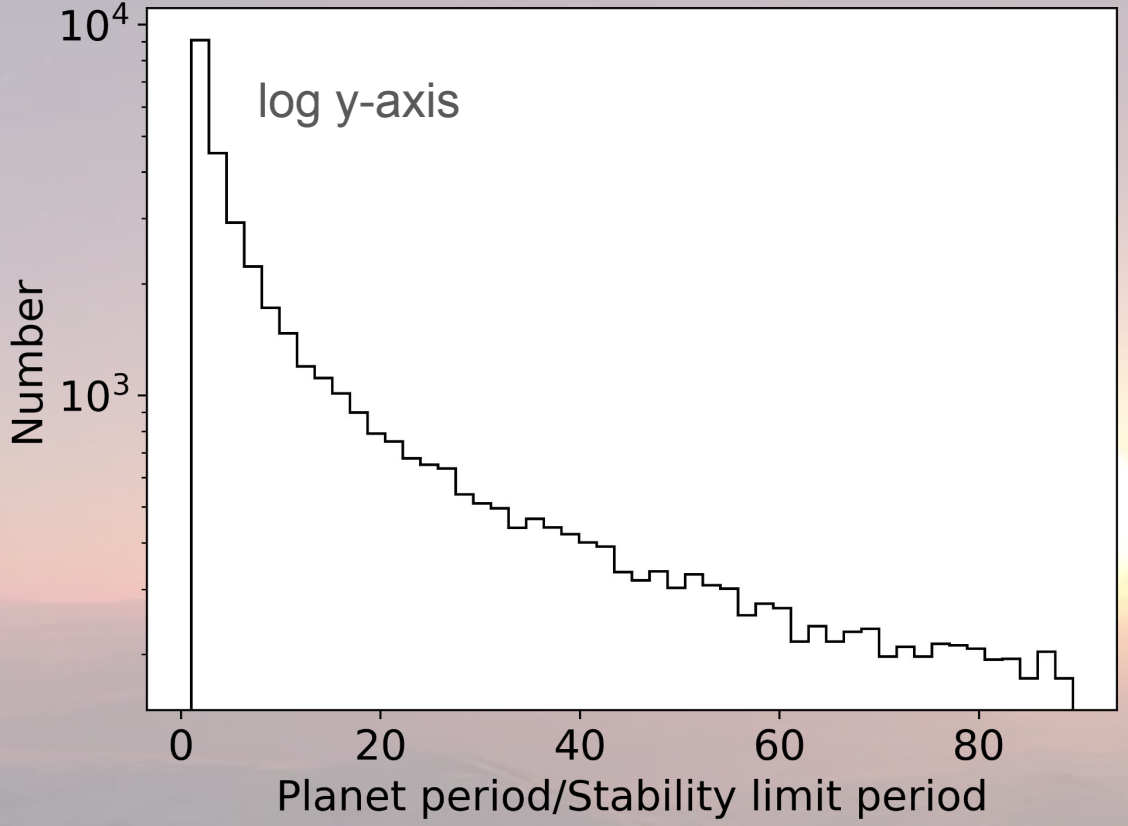
Mixture of:
Gaussian around $M_{sat}$ and
LogUniform between $M_{sat}$ - 25x$M_{jup}$

**Main**: equal mixture

Alternatives:
Red: 2:1 mixture
Blue: 1:2 mixture

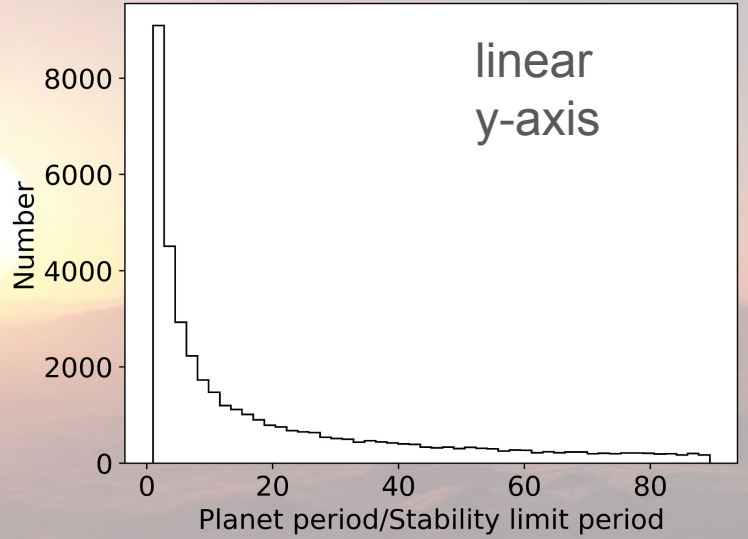
Other alternative: as in Main but scaled by total mass of the binary

# Varying the planet period distributions

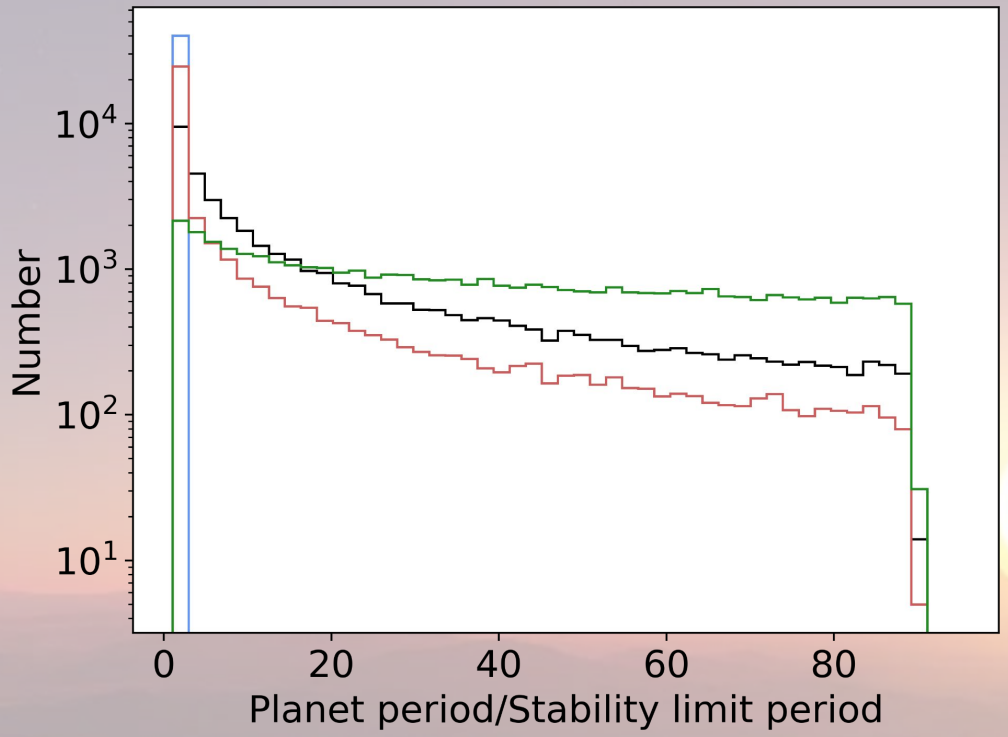



Main period distribution used so far.

LogUniform



# Varying the planet period distributions




Distributions of orbital periods:

Actually distribute in planet semi-major-axis/radius of instability zone.

Use combinations of piled-up at 1.2 x $a_{stab}$ and distributions between $a_{stab}$ and 20 x $a_{stab}$

**Main**: LogUniform between limits

Alternatives:
Blue: all piled-up (similar to *Sahlmann+ 2015*)
Red: half piled-up and half LogUniform between limits
Green: Uniform between limits

# 7 different setups

Main setup

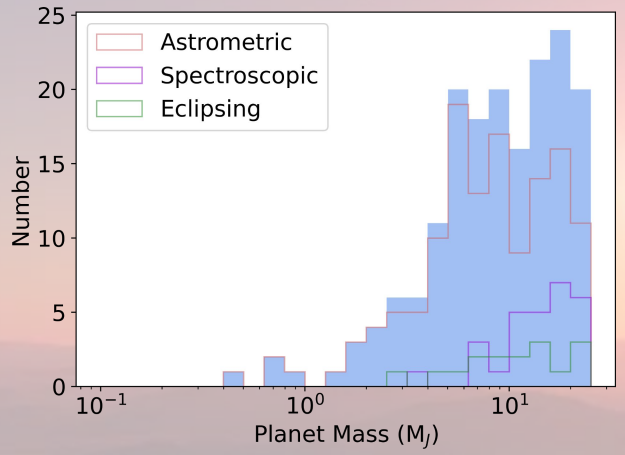
Keep period distribution as in main then:
- 2 different mass distributions
- 1 binary-dependent mass distribution

Keep mass distribution as in main then:
- 3 different period distributions

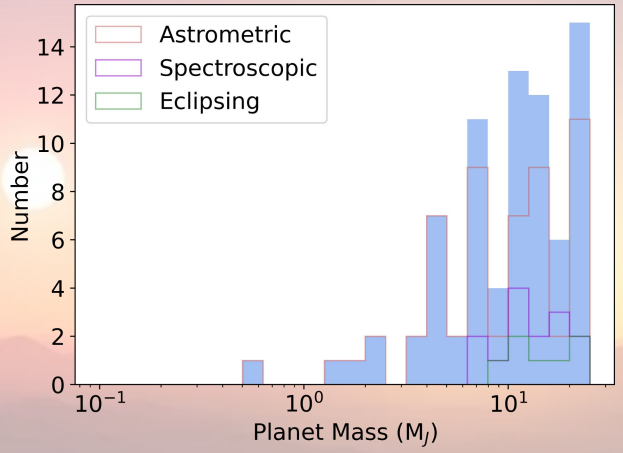
Across the 7 different setups number of detected CBPs ranges
40 to 140 in DR4
75 to 450 in DR5

# Changing the mass distribution

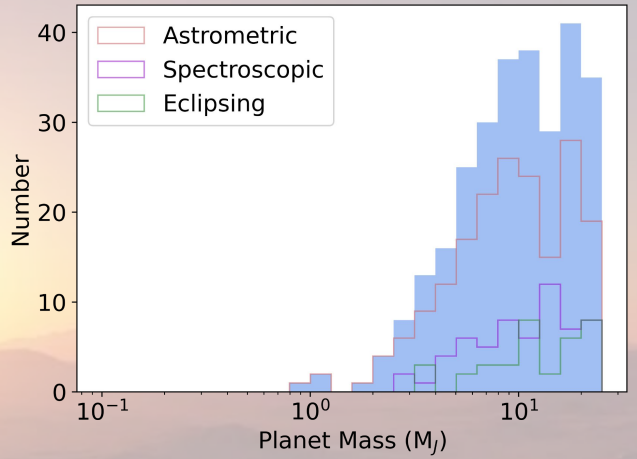
Main
DR4: 64
DR5: 175




Mixture 2:1
DR4: 25
DR5: 77




Mixture 1:2
DR4: 91
DR5: 280



# Changing the mass distribution

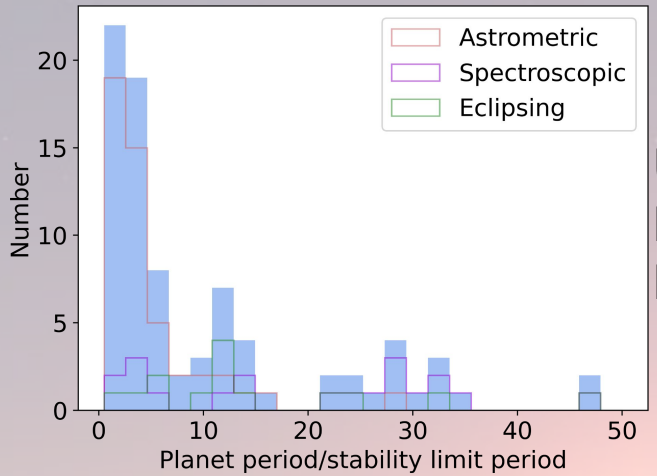
Mass distribution affects numbers around all types of binaries similarly.

For Astrometric Binaries (DR5): 56 - 131 - 186

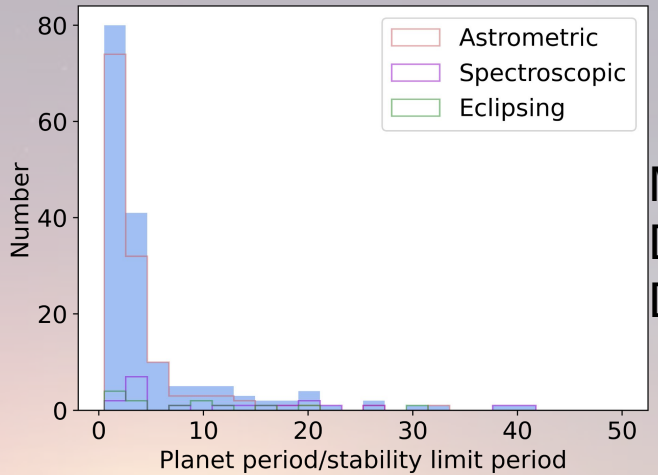
For Spectroscopic Binaries (DR5): 14 - 28 - 59

For Eclipsing Binaries (DR5): 7 - 16 - 35

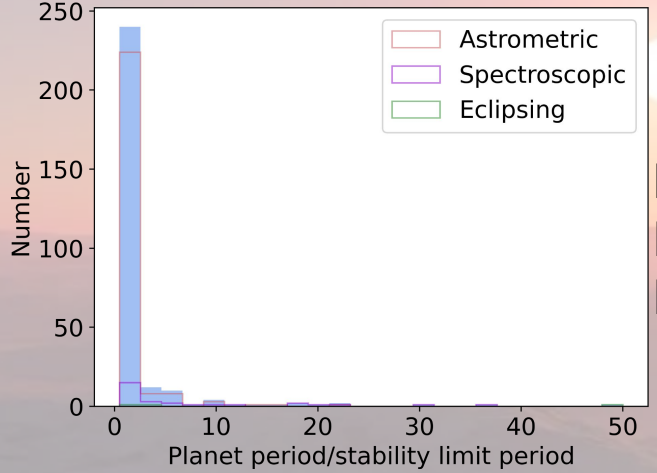
# Changing the Period distribution



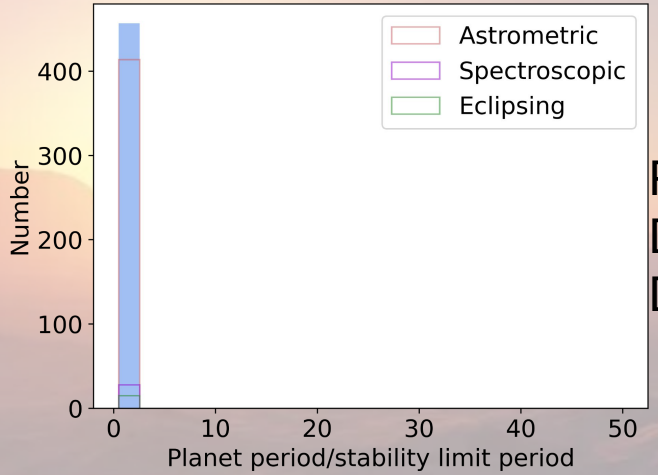

Uniform
DR4: 26
DR5: 102




Main
DR4: 64
DR5: 175




Mixed
DR4: 95
DR5: 282




Piled-up
DR4: 137
DR5: 457

# Period bias towards pile-up

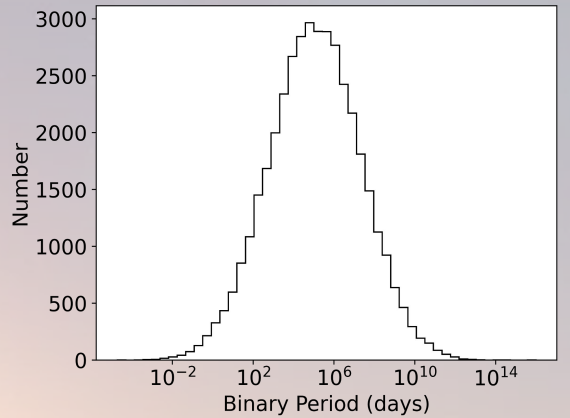
More binaries are long-period

Planets easiest to detect are near the *Gaia* integration time (i.e. 5-10 years)

More of these will therefore be around long-period binaries

Leads to a bias of detecting planets near the stability limit

Longer period binaries also easier to detect astrometrically




Assumptions: Full orbit required to detect planet, binary SNR > 100

# Changing the Period distribution

Period distribution affects the number around astrometric binaries, but much less the others.

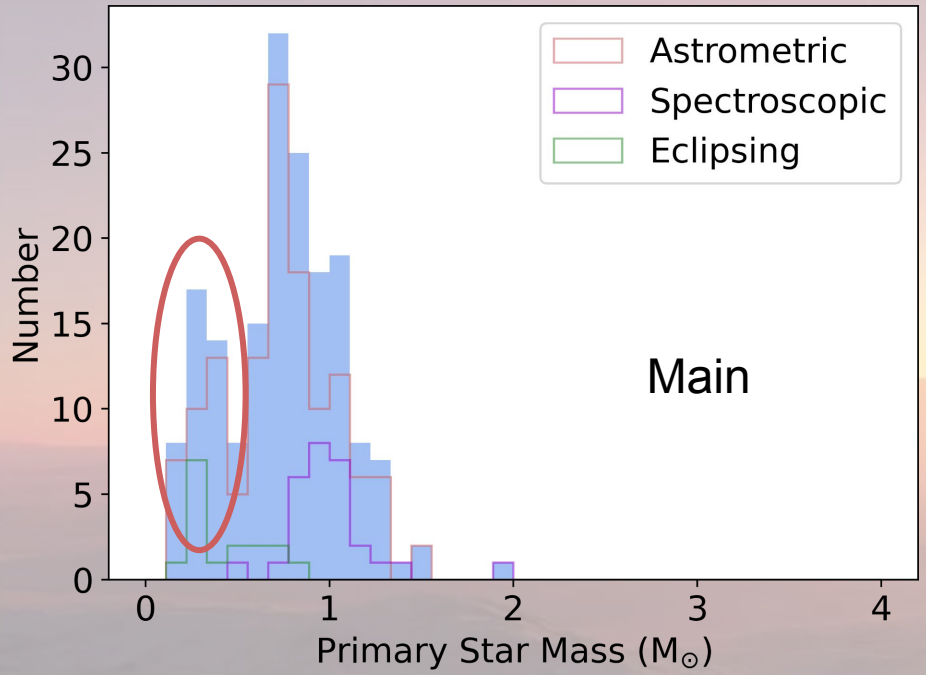
For Astrometric Binaries (DR5): 46 - 140 - 241 - 378

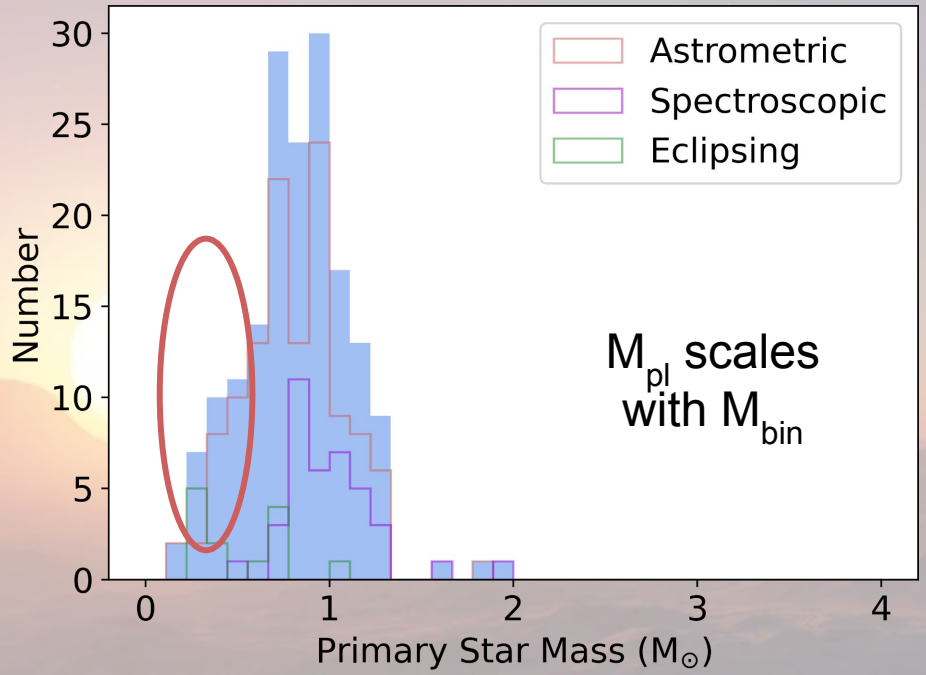
For Spectroscopic Binaries (DR5): 32 - 34 - 31 - 16

For Eclipsing Binaries (DR5): 25 - 14 - 13 - 6

# Mass dependence on disc mass

Will be visible in the comparative rate of CPBs orbiting M-dwarf binaries



# General outlook for Main-sequence binaries

- *Gaia* will detect CBPs (detecting none would be unlikely but would be very informative).

- Most of these planets will be >5$M_J$ with almost all >1$M_J$

- Predictions of detection rates depend heavily on the assumed planet population, this means that *Gaia* will be able to constrain the population of giant exoplanets orbiting main-sequence binaries.

# Known circumbinary systems

# Transiting circumbinary planets

Gaia will not be able to detect any of the Kepler circumbinary planets.

For the very nearest it may be able to constrain potential massive outer companions but these would have to have: P ~ 10 years, M ~ 5 Jupiter

Similarly TESS transiting circumbinary planets will not be detected

# RV circumbinary planets

Of the BEBOP circumbinary planets (see talk by *Amaury Triaud*), *Gaia* will only have constraining power on 1 of them (BEBOP-4b: M ≈ 15 $M_{Jup}$ P ≈ 1500 days).

For BEBOP-4b *Gaia* SNR ≈ 50

HD 202206: circumbinary brown dwarf M ≈ 17 $M_{Jup}$ will have *Gaia* SNR ≈ 250

Even in lowest mass case of sini =1 and M ≈ 2.5 $M_{Jup}$ then *Gaia* SNR ≈ 70

*Gaia* can help constrain inclination of non-eclipsing binaries for RV circumbinary planet searches.

# Post common-envelope binaries

# Claimed planets

Most of the claimed planets around post common-envelope binaries are high mass and long period, ideal for *Gaia* (actually some are a bit too long period…)

There are 31 circumbinary planets claimed orbiting 23 post common-envelope binaries (that I could find).

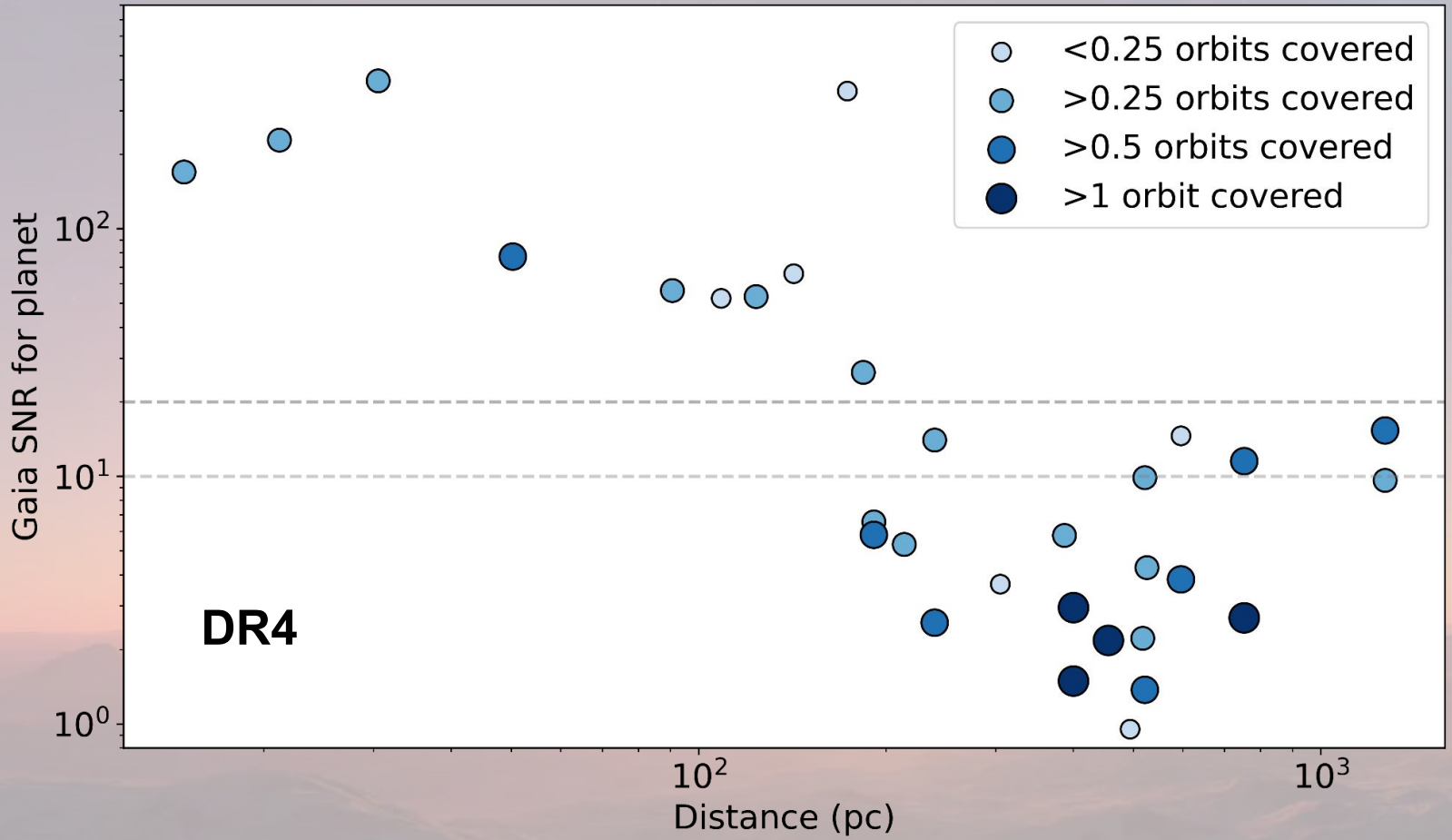
Some have been refuted (e.g. V471 Tau *Hardy et al. 2015*)

There is some doubt that all are real (e.g. *Pulley et al. 2021*)

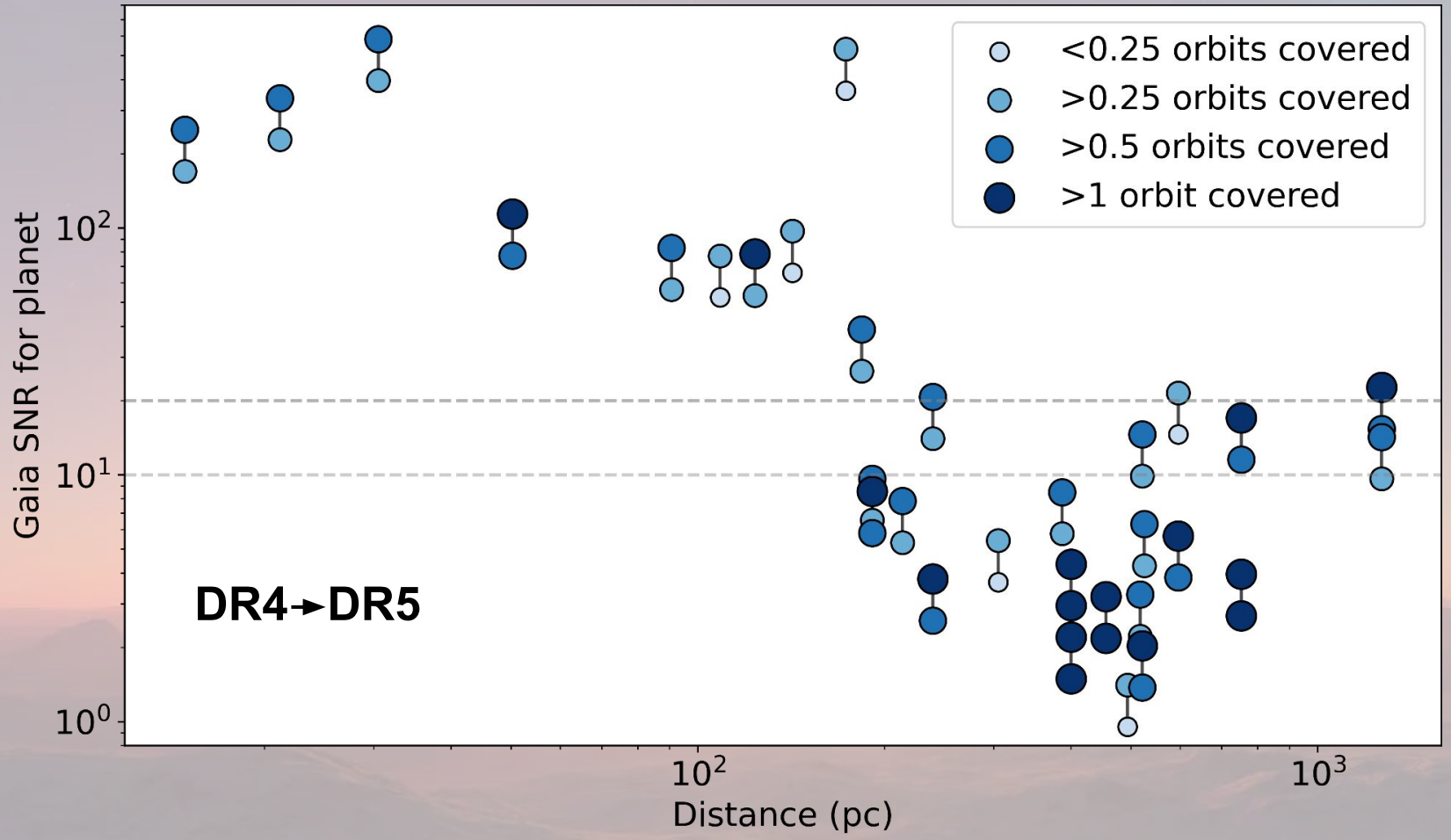
Evidence from *Gaia-Hipparcos* astrometry that there may be a planet orbiting HW Vir (*Baycroft et al. 2023*)

Planets are expected to exist around post-common envelope binaries but we don’t know which to trust.

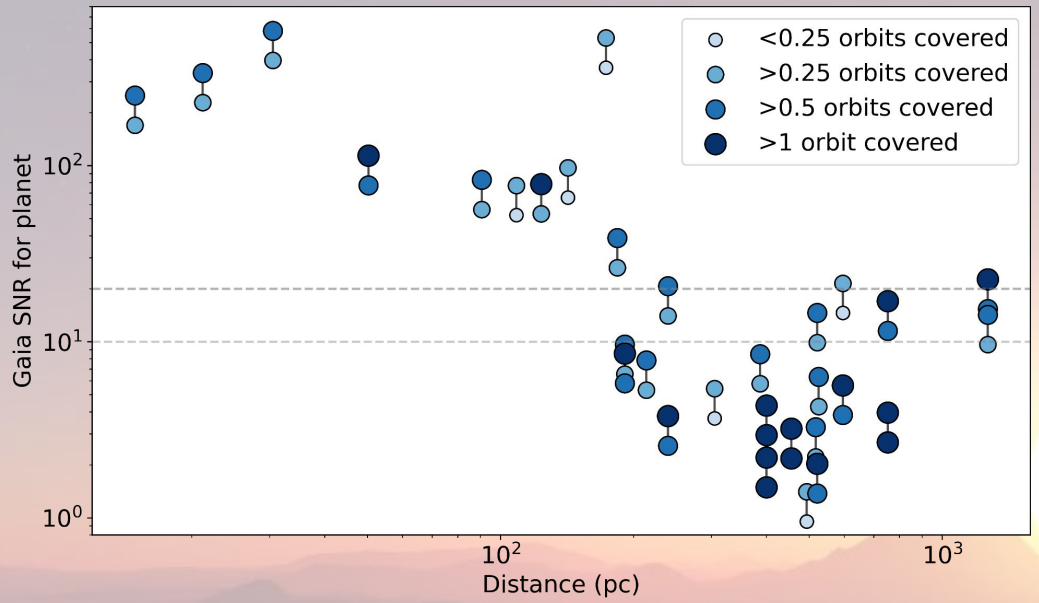
# *Gaia* on the claimed planets



# *Gaia* on the claimed planets



# *Gaia* on the claimed planets




>1 orbit and SNR>20: 3 planets

>½ an orbit and SNR>20: 9 planets

>½ an orbit and SNR>10: 12 planets

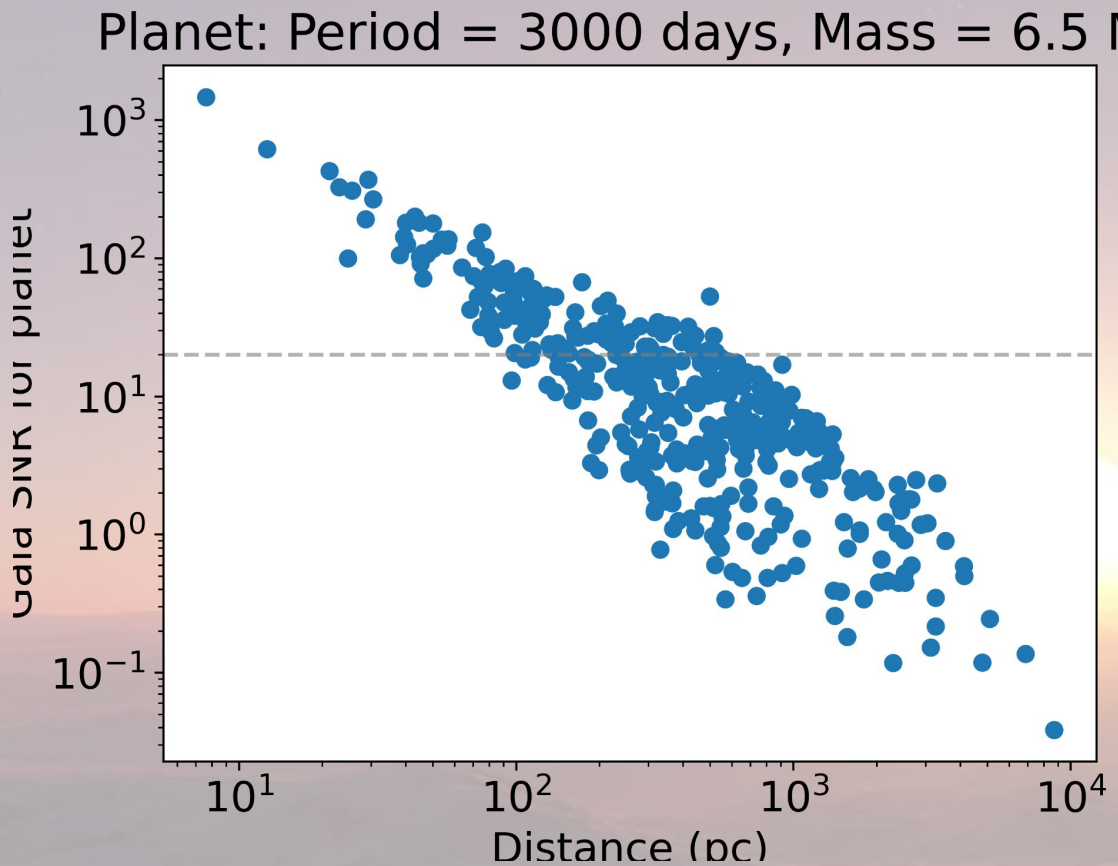
# Post common-envelope binaries

Catalogue of post common envelope binary candidates (*Kruckow et al. 2021*)

Test sensitivity *Gaia* will have to circumbinary planets around these

Catalogue contains 432 suitable entries (magnitude limits, distance limits, mass measurements)

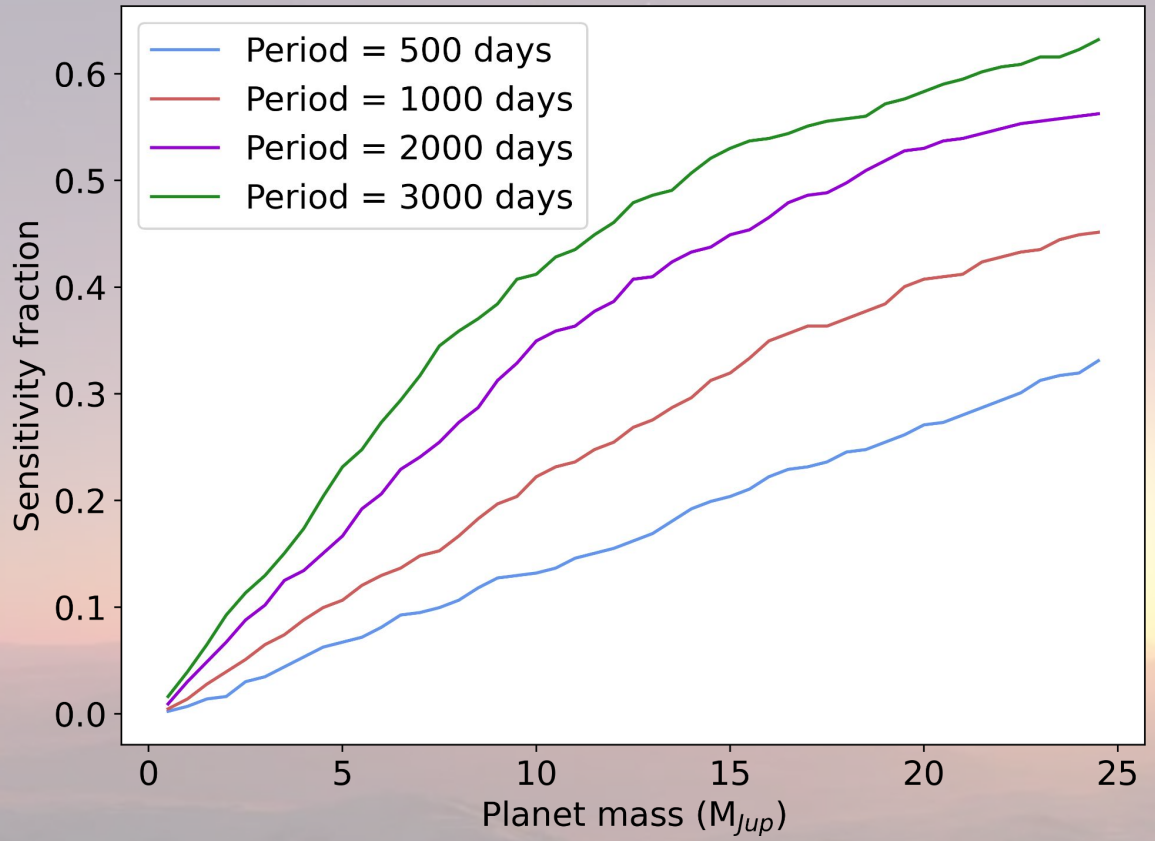
# Post common-envelope binaries




Inject a QS Vir type planet around all of these.

127 (30%) are detected

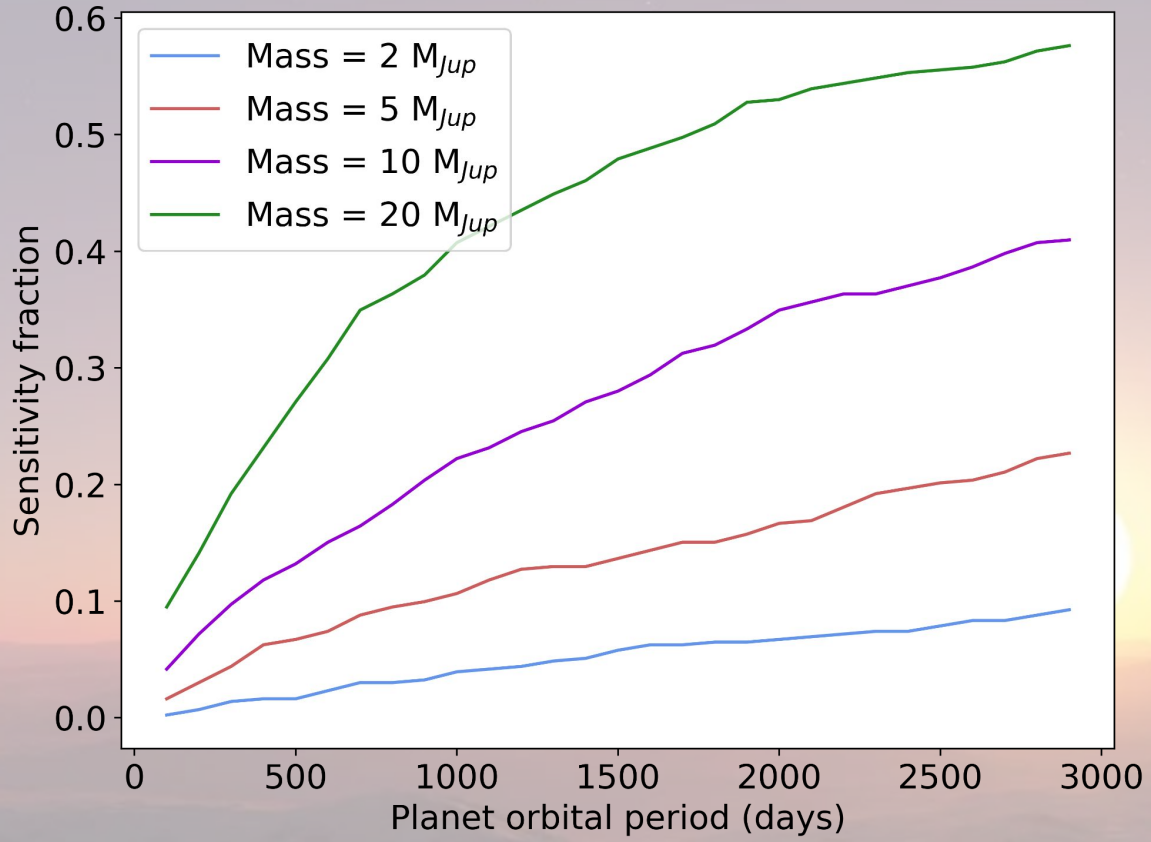
# Sensitivity around post common-envelope binaries




Fraction of systems to which *Gaia* (DR5) would be sensitive to certain planets.

4 different orbital periods, range of masses

# Sensitivity around post common-envelope binaries




Fraction of systems to which *Gaia* (DR5) would be sensitive to certain planets.

4 different masses, range of orbital periods

# What should be done when DR4 comes out

- Investigate known systems
- *Gaia* binary catalogue, take consortium one and/or create your own and search for planets around them
- Search around known binaries not identified Astrometrically (e.g. TESS EB catalogue, post common-envelope binary catalogue,...)
- Search for close inner binaries to “single star” planets identified by *Gaia*

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# Conclusions

- *Gaia* will make valuable contributions to circumbinary science
- Many new planets detected, 10s to 100s
- It will be able to constrain the distributions of masses and periods around main sequence binaries
- Currently known planets will gain additional information and be put to the test, in particular planets around post common-envelope binaries
- A population of giant planets orbiting post common-envelope binaries is attainable

Thank you for listening, happy to take questions now, later today, or by email