Sagan Workshop 2025 Project Presentation:
I-1. How do occurrence measurements change with different combinations of surveys?

Group members:

Nathanael Burns-Watson

Elina Yuchen Zhang

Rewa Bush

Steven Blodgett

Mariam Haidar

Alex Thomas

How do occurrence measurements change with different combinations of surveys?

- Motivation: No one survey method covers all of exoplanet parameter space.

- To maximize coverage, we need multiple survey types.

A word of warning!

- **Different** survey types contain **different** completeness functions and **different** biases — this requires much caution when attempting to mix them!
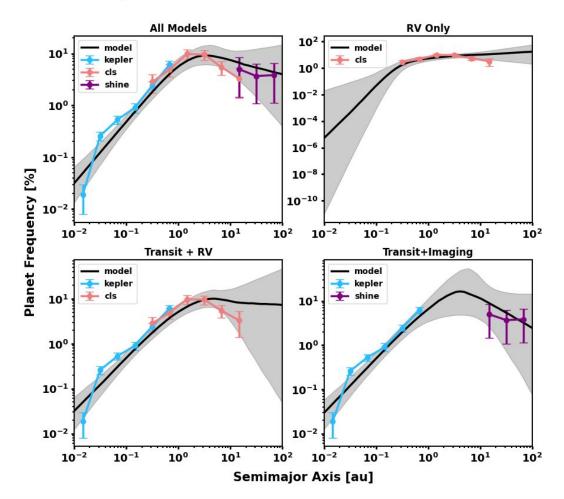

- In our case, `bardic` does the hard work for us!
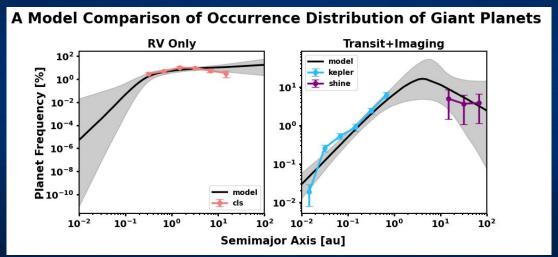(but without `bardic`, much caution is needed!)

Main Results

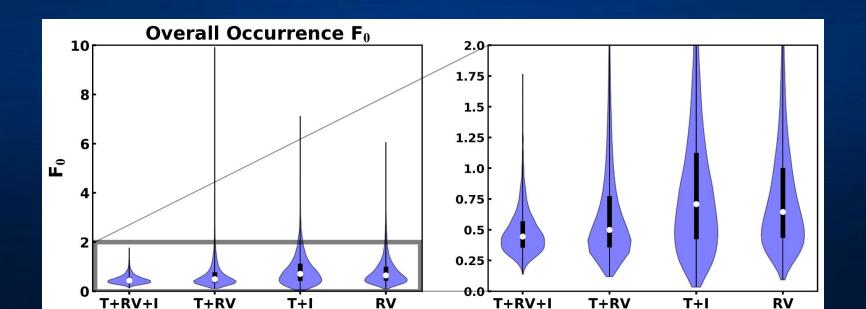A Model Comparison of Occurrence Distribution of Giant Planets

Main Results

- More datasets can help us better constrain the model parameters.
- Using only RV data greatly underestimates the occurence rate of planets at closer *a*, & goes up forever at larger *a*.

- Using the Transit + Imaging data (no RV) does not dramatically fail the fitting, as it is only missing the data at the "peak". But it does overestimate the number of planets at intermediate semi-major axis.
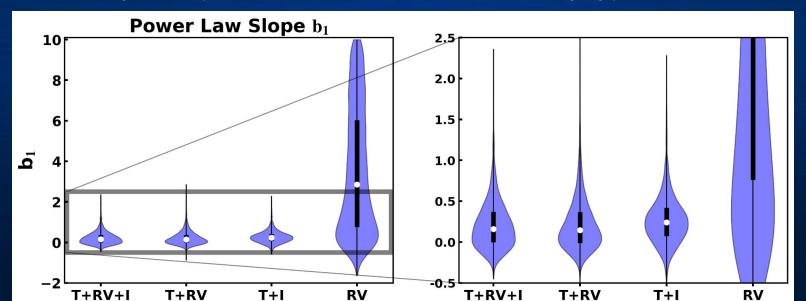
Overall Occurrence of Giant Planets

- Combined model prefers an occurrence rate of ~45%
- Other models prefer slightly higher values
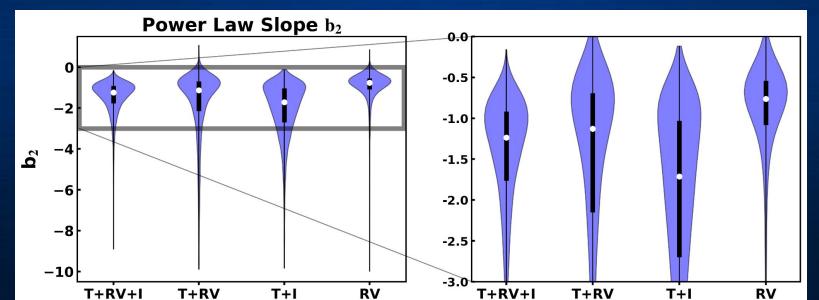- Using all three surveys is necessary to set a reasonable upper limit

Power Law Slope b_1: Small Separations

- RV-only is unable to constrain the low separation slope
- It ends up preferring a much steeper slope that massively underestimates the occurrence of close-in giant planets
- Other survey combinations obtain similar results for this parameter since they incorporate transits, a close-in survey type.
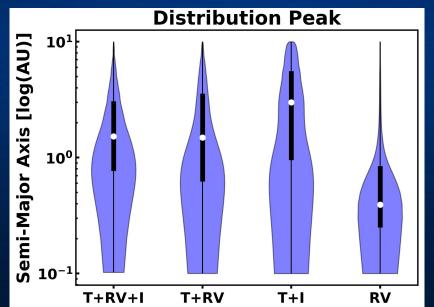
Power Law Slope b$_2$: Large Separations

- All fits prefer a declining occurrence at large separations
- However, there is a difference between survey combinations that include and do not include radial velocity data
- No RV leads to a much steeper decline at large separations
- RV only leads to a shallower decline

Peak Separation

- Best fit is ~1.5 AU for all surveys combined

- No RV leads to peak at higher separations

- RV only leads to peak at much lower separations

Physical Interpretation

Inner region (< 1.5 au)

- Planet freq. increases with distance

Turn-over near snow line (1.5 au)

- Water solidifies, providing more source material enabling larger planets

Outer region (> 1.5 au)

- RV suggests planet freq. decreases
- I suggests planet freq. flattens out

Evolutionary sequence?

- Intrinsic form. rate flat for > 1.5 au
- Giants migrate in over time
- Freq. of outer planets drops over time

Older pop.

Younger pop.

[Gemini Observatory/AURA/Lynette Cook via NASA Astrobiology]

Conclusions

- No one method covers all parameter space
- Each detection method has its own biases, which are important to consider
- Ignoring the data provided by different survey techniques can lead modeling efforts astray
- A homogeneous approach to combining data sources (like `bardic`) is essential to avoiding incompleteness and bias problems

SSW2025: Exoplanet Occurrence Rates – Group 03

Distribution of Giant Planets Based on Stellar Mass

Presented By

Aniruddha Bhattacharya (University of Calcutta, Final yr. M.Sc. Student)
Aritra Bakshi (Presidency University Kolkata, 3rd Year B.Sc. Student in Physics)
Adway Chakraborty(SRMIST, Bachelor of Technology in Aerospace Engineering)

Subhas Hegde (Karnataka University, Bachelor of Science)

Overview

In this group project we have compared giant planet occurrence for two stellar mass bins (0.56–1.1) M☉ and (1.1–1.63) M☉ using the following :
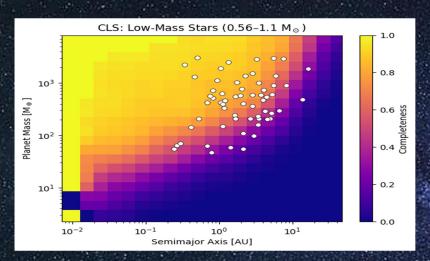
- Used Kepler, CLS and SHINE surveys with detection efficiency corrections
- Visualized completeness maps and compared plots of occurrence vs. semi-major axis
- Found more giant planets around higher-mass stars

Question: How many stars and giant Planets does each survey has in either mass bins?
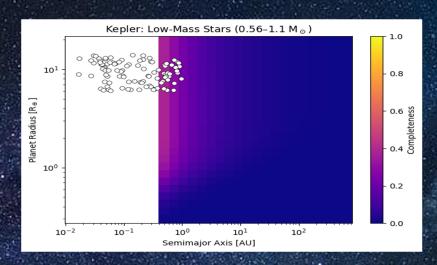
NUMBER OF	MASS BIN	KEPLER	CLS	SHINE
STARS	0.56 - 1.1 M☉	84403	440	440
PLANETS		101	61	0
STARS	1.1 - 1.63 M☉	30136	62	34
PLANETS		51	14	5

We see that Kepler has a high coverage but planet detection falters for high mass stars, whereas CLS returns a fairly good yield. SHINE does not detect any planet for low mass stars.
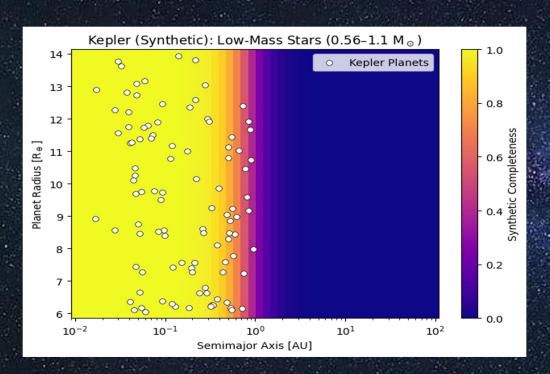
Completeness Plots for low-mass bin

Completeness map works well for CLS survey showing high completeness at intermediate mass and axis. Sharp drop off for low mass, wide separation planets. Few planets fall in low completeness zone indicating likely survey bias.
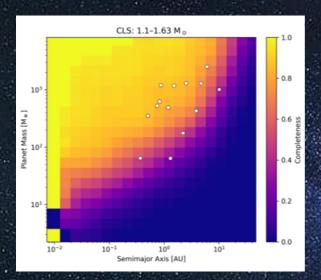
Kepler shows strong completeness for short period planets and sharply declines beyond 1AU. For illustrative purposes, we injected a synthetic completeness model to explore trends at small semimajor axes not covered by the official Kepler maps.
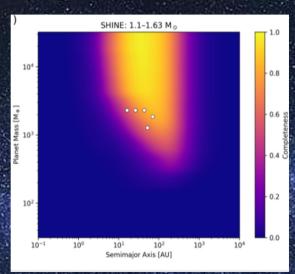
Completeness Plots for low-mass bin

Kepler (Synthetic): Low-Mass Stars (0.56–1.1 M$_\odot$)
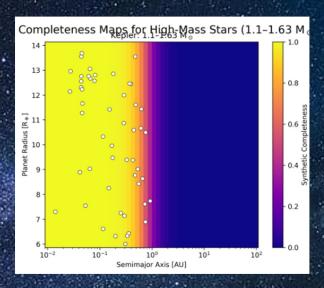
We modeled completeness to be high (yellow) for close-in orbits and to drop off sharply beyond 1 AU, mimicking Kepler's known detection limits. Most observed planets (white circles) fall within the high-completeness region. This synthetic map extends sensitivity below 0.5 AU, allowing fairer comparison with other surveys like CLS and SHINE
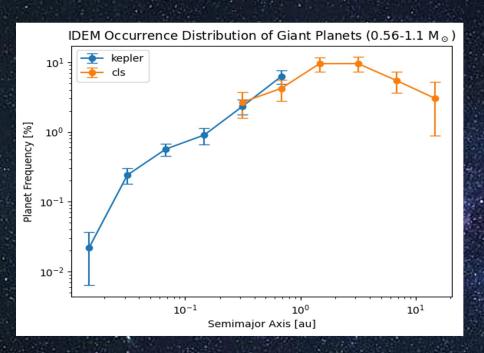
Completeness Plots for high-mass bin
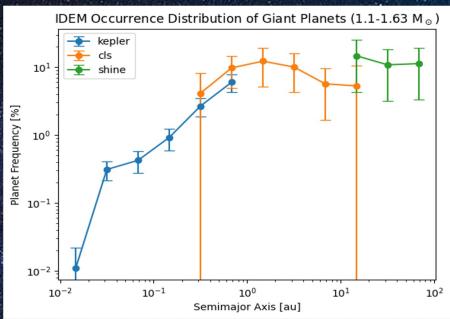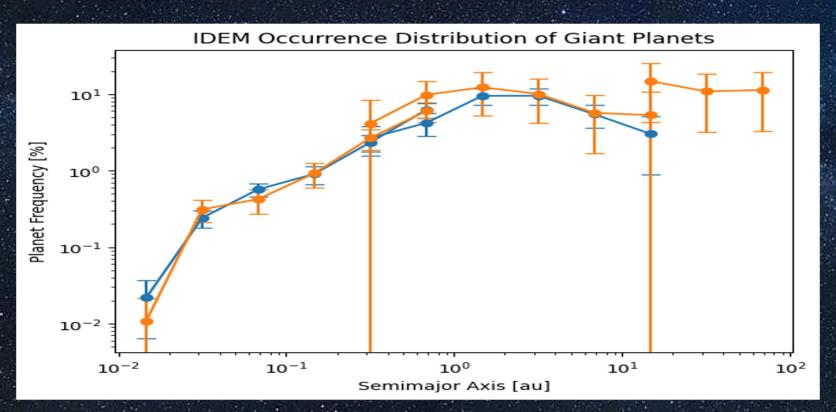
IDEM Occurrence Rate
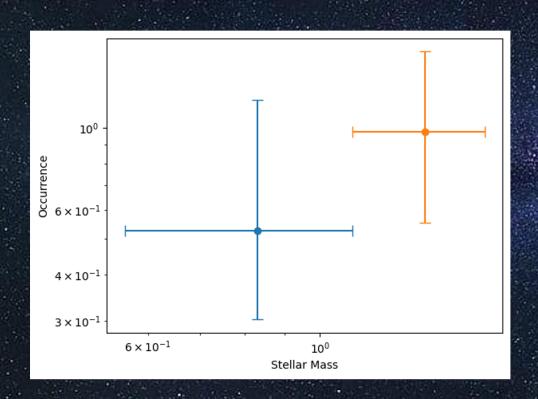
Combined IDEM Occurrence Rate for both the Mass Bins

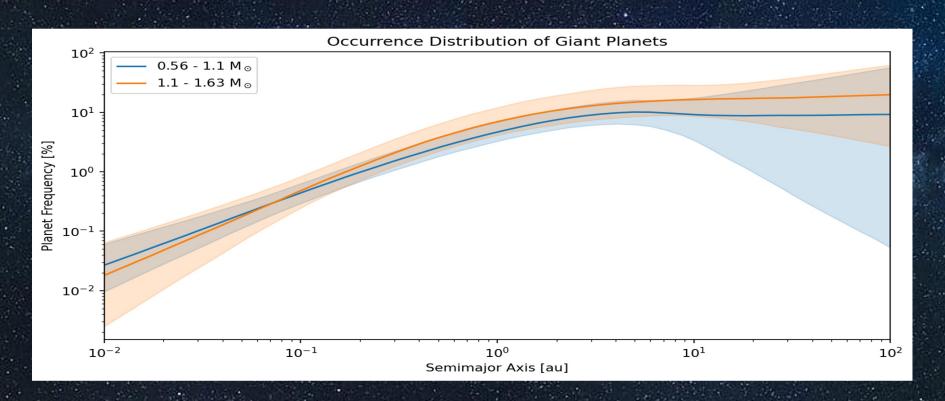IDEM Occurrence Distribution of Giant Planets

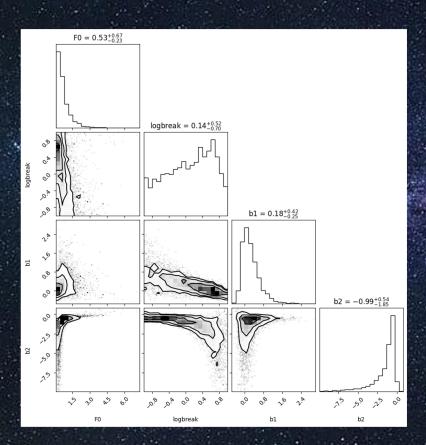# Comparing the Fitted Model for both the Mass Bins
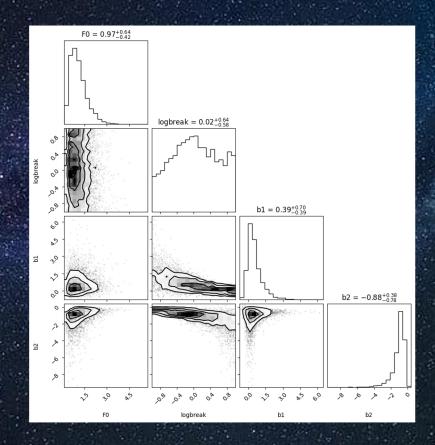
For our model, we have chosen the broken power law model. We have used 10,000 steps, 32 walks and 2 chains for our sampling.

Comparing the Fitted Model for both the Mass Bins

Occurrence Distribution of Giant Planets

The Parameters of the Model
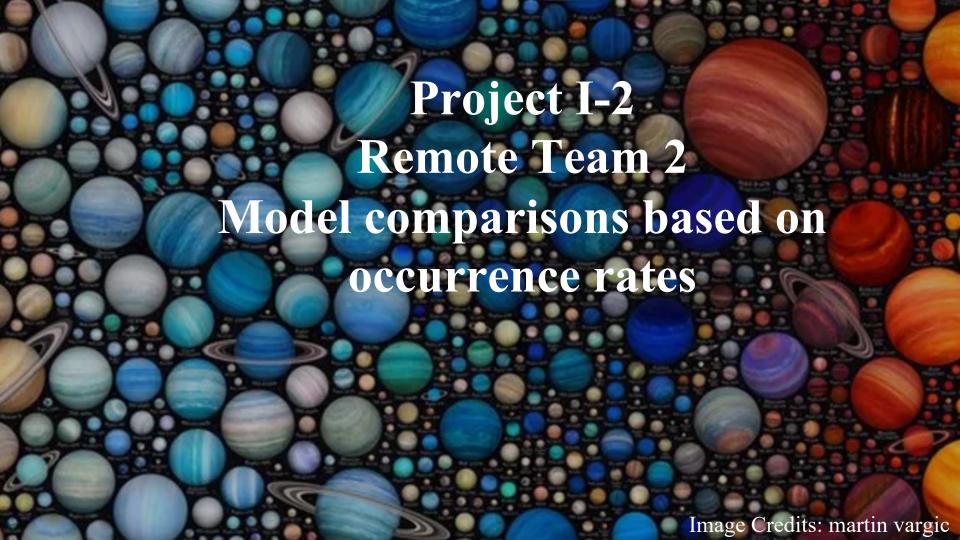
Conclusion

- We investigated how giant planet occurrence varies with stellar mass using data from Kepler, CLS, and SHINE.

- Stars were split into two bins:
  - Low-mass (0.56–1.1 M☉)
  - High-mass (1.1–1.63 M☉)

- We applied the Inverse Detection Efficiency method to correct for survey completeness and estimate true occurrence rates.

- Kepler had a large sample but detected few giant planets, mostly at short periods.

- CLS, despite a smaller sample, found many giant planets due to better sensitivity at wider separations.

- SHINE contributed very little in this stellar mass range due to limited sample size.

- Overall, we found that giant planets are more frequent around higher-mass stars, supporting previous studies.

- This highlights the strong link between stellar mass and planet formation efficiency.

Thank You For This Opportunity

Project I-2
Remote Team 2
Model comparisons based on occurrence rates

Image Credits: martin vargic

Functional Forms evaluated

➢ **Polynomial**: Models occurrence with a quadratic polynomial in log (a) and a power law in M, capturing flexible trends.

➢ **Log-Normal**: Uses a log-normal distribution for semimajor axis and a power law for mass, ideal for peaked distributions.

➢ **Step Function**: Applies a piecewise constant function for semimajor axis with a mass power law, modeling abrupt changes.

➢ **Gaussian Mixture**: Combines two log-normal distributions for semimajor axis with a power law in mass, modeling bimodal populations.

➢ **Exponential**: Models occurrence with an exponential decay in semimajor axis and a power law in mass, capturing smooth declines.

Polynomial with Mass Power Law

$$f(a, M) = F_0 \cdot \max\left(0, a_0 + a_1 \log(a) + a_2(\log(a))^2\right) \cdot |M^a|$$

F_0 : Normalization factor, scales overall occurrence rate.

a_0 : Constant term in polynomial, sets baseline.

a_1 : Linear coefficient for log (a), controls linear trend.

a_2 : Quadratic coefficient for (log (a))^2, captures curvature.

a : Mass power-law exponent, describes mass dependence.

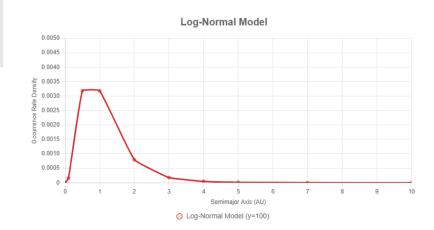# Log Normal with Mass Power Law

$$f(a, M) = F_0 \cdot \frac{1}{a\sigma\sqrt{2\pi}} \exp\left(-\frac{(\log(a) - \mu)^2}{2\sigma^2}\right) \cdot M^a$$

F_0 : Normalization factor, scales occurrence rate.

m : Mean of log (a), sets peak of semimajor axis distribution.

σ : Standard deviation of log (a), controls distribution width.

a : Mass power-law exponent, describes mass dependence.

Log-Normal Model

Step Function with Mass Power Law

$$f(a, M) = F_0 \cdot \begin{cases} s_1 & \text{if } a < 10^{\log x_b} \\ s_2 & \text{if } a \geq 10^{\log x_b} \end{cases} \cdot M^a$$

F_0 : Normalization factor , scales occurrence rate.
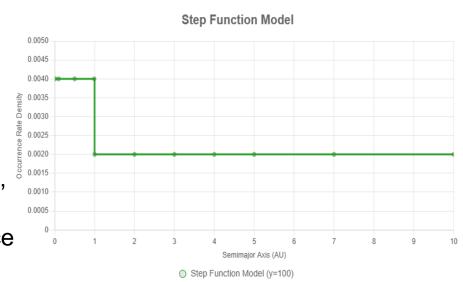
$\log x_b$: Log of breakpoint in semimajor axis, defines transition point.

s_1 : Step height for $a < 10^{\log x_b}$, sets occurrence before breakpoint.

s_2 : Step height for $a \geq 10^{\log x_b}$, sets occurrence after breakpoint.

a : Mass power-law exponent, describes mass dependence.

Step Function Model

○ Step Function Model (y=100)

Gaussian Mixture with Mass Power Law

$$f(a, M) = F_0 \cdot \left(w_1 \cdot \frac{1}{a\sigma_1\sqrt{2\pi}} \exp\left(-\frac{(\log(a) - \mu_1)^2}{2\sigma_1^2} \right) + w_2 \cdot \frac{1}{a\sigma_2\sqrt{2\pi}} \exp\left(-\frac{(\log(a) - \mu_2)^2}{2\sigma_2^2} \right) \right) \cdot M^a$$

F_0 : Scales the overall occurrence rate.
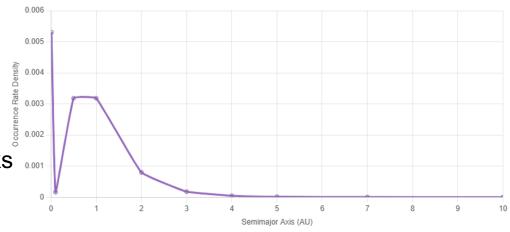
w_1 : Weight of the first log-normal

(fraction of planets in the first peak).

μ_1, μ_2 : log (a) values for the two peaks

σ_1, σ_2 : Widths of the two peaks.

a : Power-law exponent for mass.

Gaussian Mixture Model

Exponential with Mass Power Law

$$f(a, M) = F_0 \cdot \exp\left(-\frac{a}{\lambda}\right) \cdot |M^a|$$
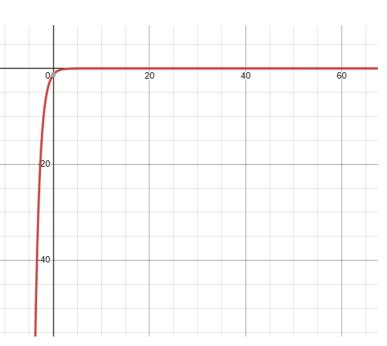
F_0 : Scales the overall number of planets (like a volume knob for occurrence rate)
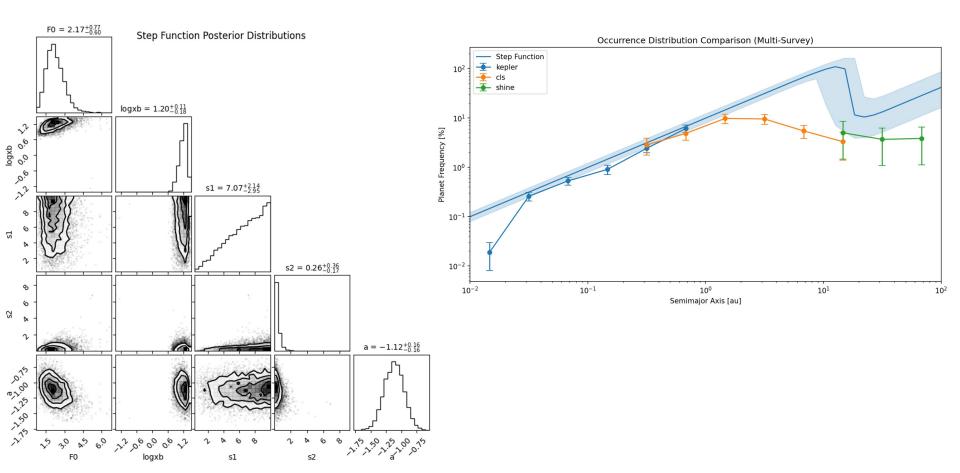
λ : Controls how quickly the planet frequency drops with distance (larger λ means slower decline).

a : Determines how mass affects occurrence
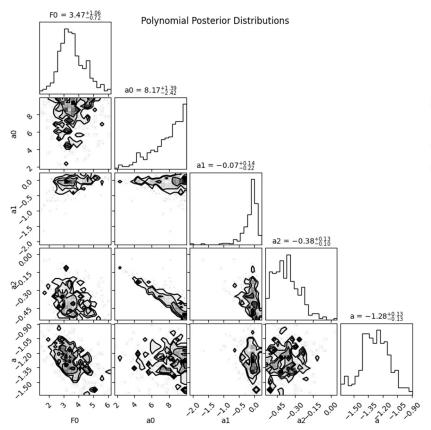
$|M^a|$ ensures the mass term is positive, even if a is negative.

Step Prior (nstep=10,000)

Step Function Posterior Distributions

Occurrence Distribution Comparison (Multi-Survey)
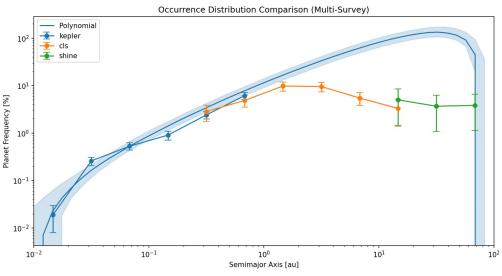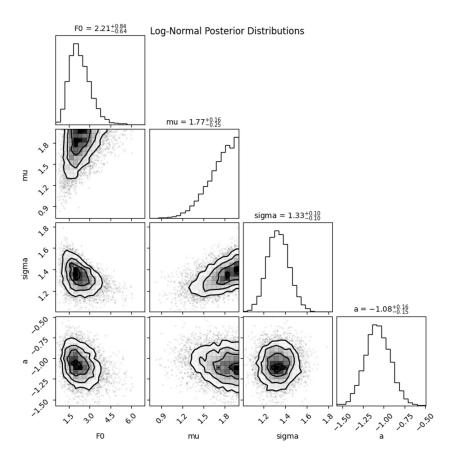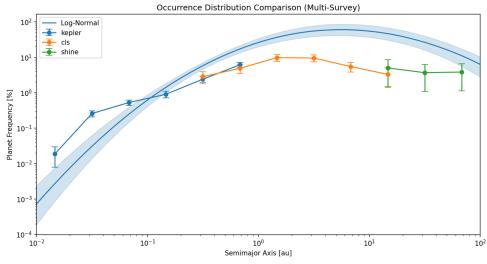
Polynomial (nstep=1,000)
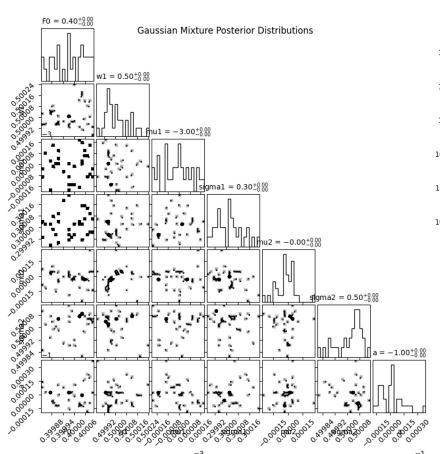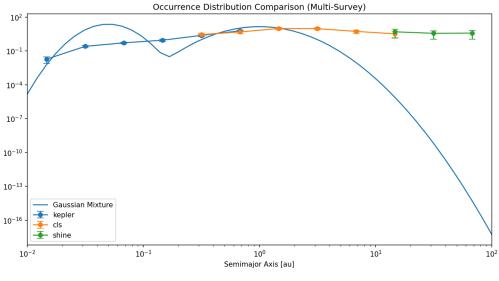
Log Normal (nstep=10,000)
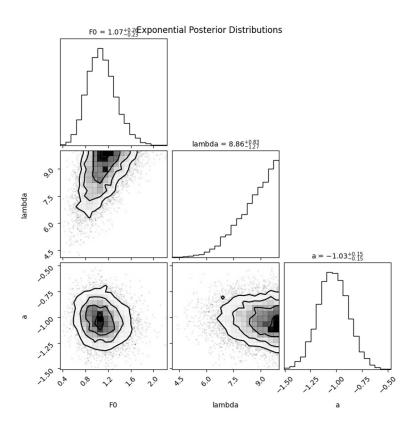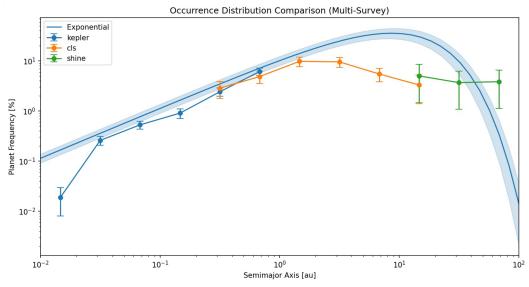
Gaussian (nstep=10,000)

Exponential (nstep = 10000)
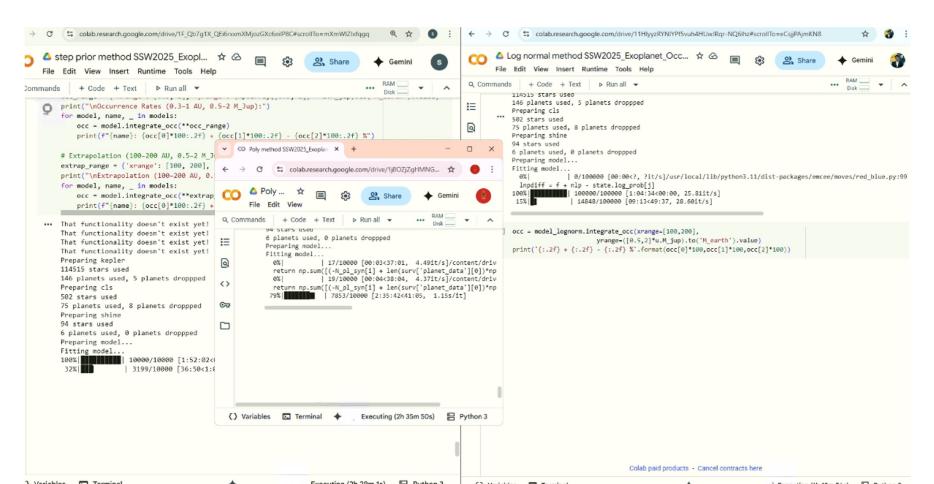
Results - BIC Comparison

Model	Polynomial	Step Function	Log Normal	Gaussian	Exponential
Steps	1000	10000	10000	10000	10000
Kepler	264 +263/-46	248 +268/-48	265 +252 / -21	NC	255 +260/-35
CLS	267 +277/-39	268 +266/-48	255 +261 / -18	NC	250 +267/-45
Shine	267 +272/-41	262 +263/-29	274 +245 / -44	NC	243 +271/-36
All	258 +265/-35	260 +266/-51	273 +251/ -21	NC	257 +264/-36
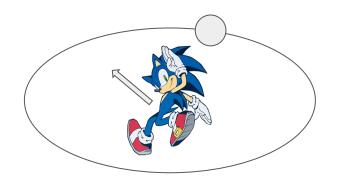
Results - Occurrence Rates

Model	Polynomial	Step Function	Log Normal	Gaussian	Exponential
Steps	1000	10000	10000	10000	10000
0.3–1 AU, 0.5–2 M_Jup	2 +0.36/-0.41%	1.82 +0.41/-0.37%	4.46 +1.12/-0.96%	NC	1.96 +0.43/-0.38 %
Extrapolation 100–200 AU, 0.5–2 M_Jup	0%	10.92 +11.79/-6.61%	0.68 +0.48/-0.40%	NC	0%

AND..................
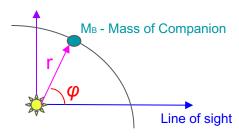
Session II, Project 3

In-Person Team 1: Jangho Bae, Joshua Bromley, William DeRocco, Risinie Perera, Pranav Premnath, Brandon Radzom

A Mass from an Astrometric or Radial Velocity Trend

- Long-period companions to main sequence stars can induce accelerations

- RV Acceleration (along the line-of-sight):

$$a_{\mathrm{RV}} = \frac{GM_B}{r^2} \cos\varphi$$

M_B - Mass of Companion

r

φ

Line of sight
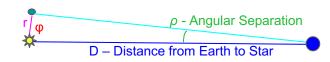
- Astrometric Acceleration (in the plane of the sky):
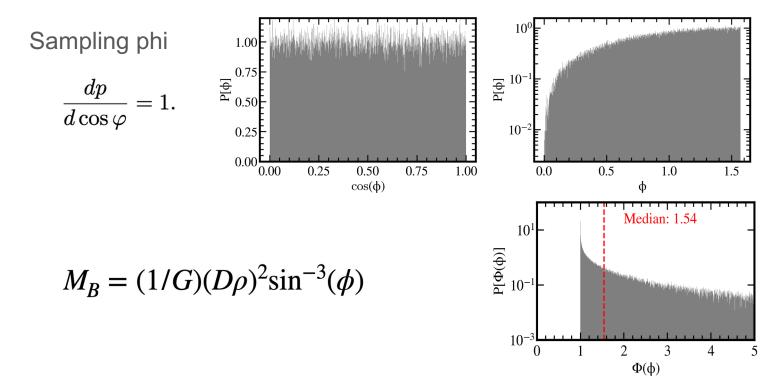
$$a_{\mathrm{astrometric}} = \frac{GM_B}{r^2} \sin\varphi$$

- The projected separation:

$$D\rho = r\sin\varphi$$

r φ

ρ - Angular Separation

D – Distance from Earth to Star

Acceleration + Projected Separation + Monte Carlo ⟶ Mass
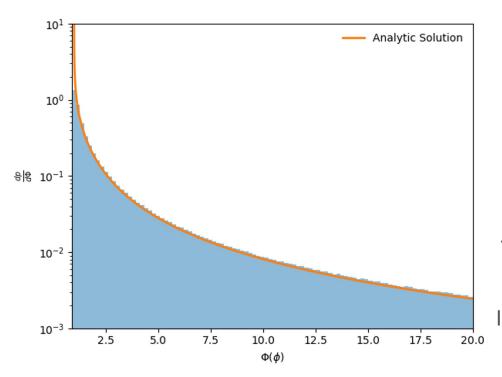
1. M_B from Astrometry, Φ_{astro} MC Distribution

Sampling phi

$$\frac{dp}{d\cos\varphi} = 1.$$

$$M_B = (1/G)(D\rho)^2\sin^{-3}(\phi)$$

Analytic Solution for Astrometric Acceleration

For astrometry, we find $\Phi = \sin^{-3}(\varphi)$

Using chain rule, we get

$dp/d\Phi = \sin^5(\varphi)/3\cos(\varphi)$

Solving for Φ, we get

$dp/d\Phi = \frac{1}{3} * (\Phi^{10/3} - \Phi^{8/3})^{-1/2}$
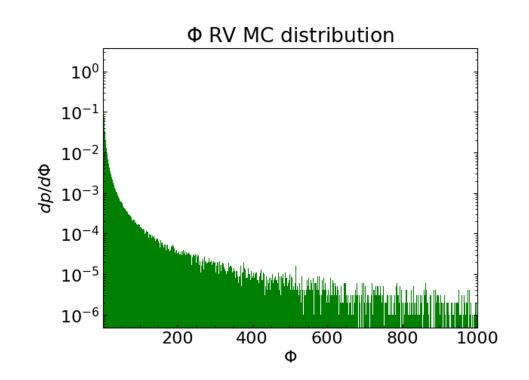
The analytic solution matches the monte carlo simulation

Integrating the analytic solution, we find a median of 1.539

2. M_B from Radial Velocity, Φ_{RV} MC Distribution

$$M_B = \frac{1}{G}(D\rho)^2 a_{\mathrm{RV}} \Phi(\varphi)$$

$$\Phi = \frac{1}{\cos\varphi \sin^2\varphi}$$

$$= \frac{1}{\cos\varphi - \cos^3\varphi}$$

Φ RV MC distribution
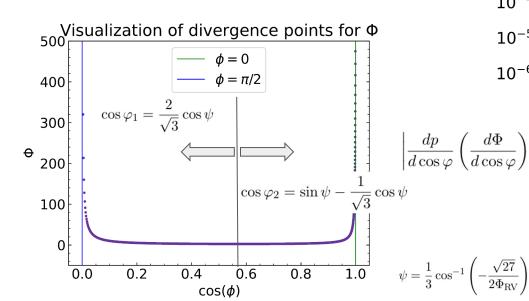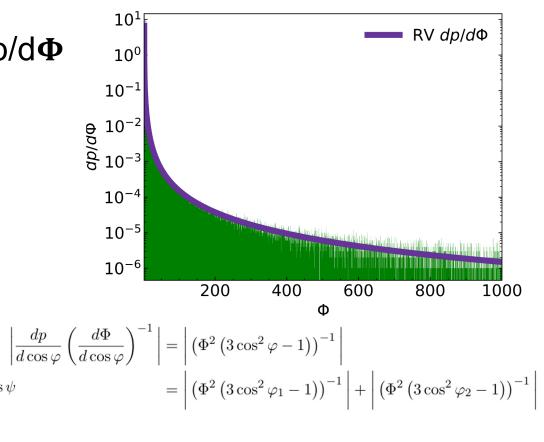
2. Analytic Solution for dp/dΦ

$$\frac{d\Phi}{d\cos\varphi} = \frac{3\cos^2\varphi - 1}{(\cos\varphi - \cos^3\varphi)^2}$$
$$= \Phi^2\left(3\cos^2\varphi - 1\right)$$
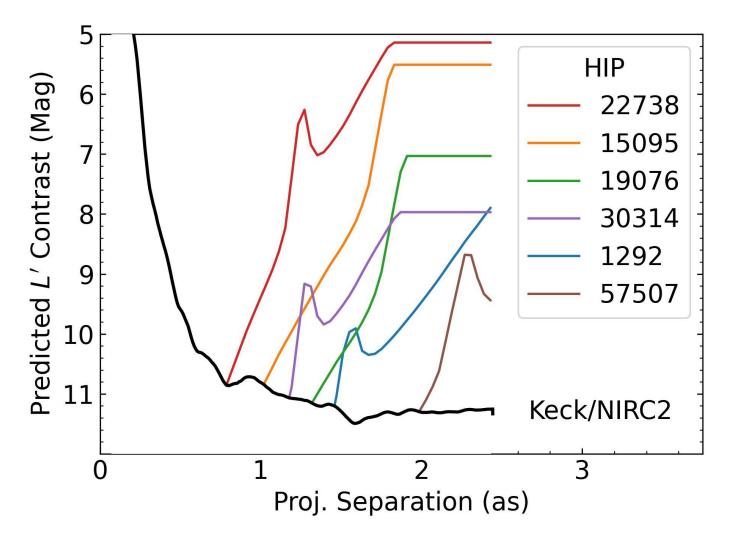
Visualization of divergence points for Φ

$$\cos\varphi_1 = \frac{2}{\sqrt{3}}\cos\psi$$

$$\cos\varphi_2 = \sin\psi - \frac{1}{\sqrt{3}}\cos\psi$$

$$\left|\frac{dp}{d\cos\varphi}\left(\frac{d\Phi}{d\cos\varphi}\right)^{-1}\right| = \left|\left(\Phi^2\left(3\cos^2\varphi - 1\right)\right)^{-1}\right|$$

$$= \left|\left(\Phi^2\left(3\cos^2\varphi_1 - 1\right)\right)^{-1}\right| + \left|\left(\Phi^2\left(3\cos^2\varphi_2 - 1\right)\right)^{-1}\right|$$

$$\psi = \frac{1}{3}\cos^{-1}\left(-\frac{\sqrt{27}}{2\Phi_{\mathrm{RV}}}\right)$$

Initial Target-Selection Criteria

- "Default" WD exclusion criteria

- RUWE >= 1.4, ipd_frac_multi_peak >= 5% (binaries)

- **χ^2 >= 6.18 (2+ σ) astrometric accel. from HGCA**

- 90%+ probability of young-association membership (BANYAN Σ)

- **<70 M$_J$ predicted mass at 0.5"**

- 53 targets remaining: compare to the Keck/NIRC2 *L'* contrast curve:

  - ATMO2020 models for (mass, age) => luminosity at *L'*

  - **6 targets with a reasonable range of predicted substellar masses at resolvable contrasts/proj. separations** from the ground

Individual Target-Vetting

- Each group member investigated one of the six promising targets
  - SIMBAD, WDS, Spectroscopic/RV surveys, etc.
- Cut our targets based off of the following criteria:
  - Is there previous measurements/observations on this star/system?
  - Is the star in a binary, either visual or spectroscopic?
  - What kind of additional literature is there on this star/system?

HIP 19076 - A Close Visual Binary in the WDS Catalog

- Other names: 39 Tau, WDS 04053+2201

- Resolved with Speckle Interferometry by Hartkopf, W. & Mason, B. 2009 at 0.41'' (observed 2003 w/speckle interferometry at Mt. Wilson)

  - Also seen at 0.22'' in 1988 w/speckle interferometry at CFHT

  - Unresolved in 2002 with 3.6-m AO at the AEOS telescope

- The close stellar companion can plausibly explain this star's astrometric acceleration.

HD 1237 (GJ 3021, HIP 1292) system

- Binary system: host star HD 1237 A (SpT G6, Naef+2001) and M-dwarf stellar companion HD 1237 B (sep. 68 AU, SpT M4, Chauvin+2006)
- HD 1237 A hosts a planet, GJ 3021 b, at a projected separation of ~0.49 AU (Naef+2001)
- GJ 3021 b was discovered with RVs from CORALIE in 2000, with an $m_p \sin(i)$ of 3.37 M_{Jup}
- The system is around 400 Myr old (Rathsam+2023), and resides in the southern constellation Hydrus
- The system was imaged by VLT/NACO and CFHT/PUEO-KIR, which discovered the M-dwarf companion but did not recover the planet (Chauvin+2006)*
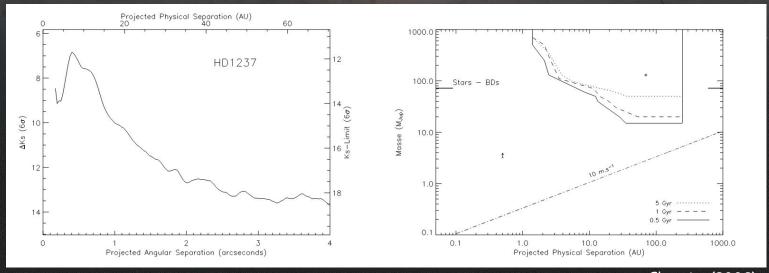
HD1237 17"x12"
VLT/NACO

HD 1237 B

HD 1237 A

Chauvin+(2006)

*Survey only sensitive to companions with masses greater than 30 M_{Jup} at 0.5 Gyr with CFHT and 15 M_{Jup} at 0.5 Gyr with VLT, at 2" (~60 AU) from the primary
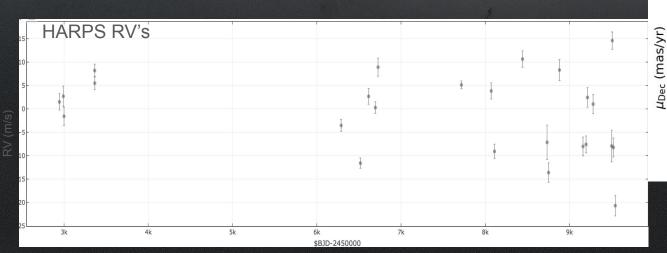
The case for observing the HD 1237 system
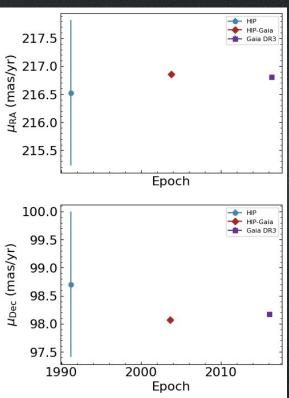
- Unsure if the acceleration is caused by the planet or the binary companion; available Hipparcos data was "not precise enough to show that a significant part of the planetary candidates could be of stellar nature" (Pourbaix+2001)
- The projected separation of 0.5 AU at a distance of ~17 pc (Naef+2001) would give an angular separation of ~0.03" or 30 mas, which would be very difficult (if not impossible) to detect with direct imaging, even with a coronagraph

Chauvin+(2006)

HIP 15095 / GJ 131
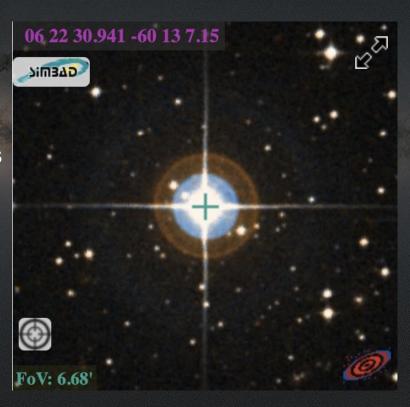
- K star, 18pc away, χ^2 = 6.29 (~2σ)
- No nearby stars in GAIA or WDS
- Observed 36 times by SPHERE (HARPS & Echelle) and 14 times by Keck (HIRES)
- No candidate or known companions
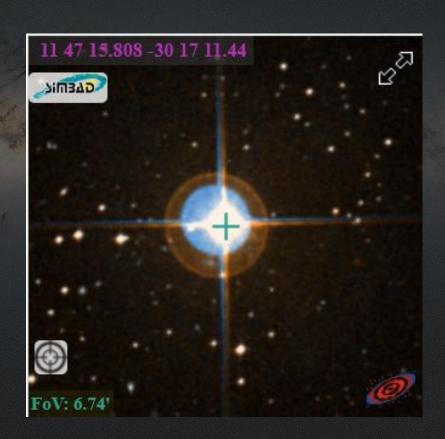
HIP 30314

- G1 star at distance of 23.87 pc

- Radial velocity observations with HARPS determined that there were 2 companions (Kervella+2022)

    - 1.66 M$_J$ at 3 AU

    - 1.40 M$_J$ at 10 AU

- Previously observed with SPHERE but could not find candidates due to bad weather conditions during observations (Mesa+2022)

- Worth observing again

06 22 30.941 -60 13 7.15
SIMBAD
FoV: 6.68'

HIP 57507

- A G6 star located ~57 parsecs away
- A single star, no detected companion with Gaia, WDS, or in the literature
- Has been observed with HARPS, ESPRESSO, and CRIRES
- No current confirmed exoplanet
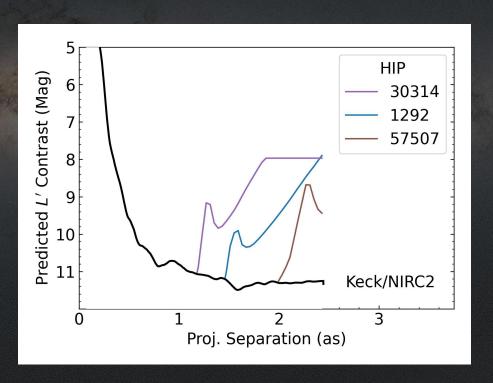
HIP 22738

- Classified in SIMBAD as an M3 object 90.02 mas away
- Gaia accelerations identified it as a potential target
- SIMBAD classifies it as a spectroscopic binary
- It is a target in the WDS
  - Observed a few times since 1920
- NOT a target

04 53 31.208 -55 51 37.12

SIMBAD

FoV: 3.98'
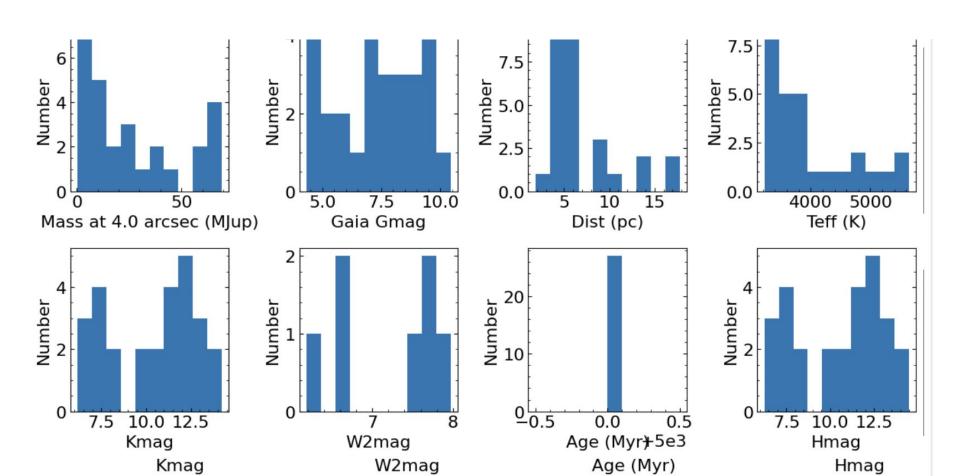
Final Target List

- **HIP 30314** - two RV planets (3, 10 au)
  - 1 night at VLT/SPHERE (limited by poor seeing)

- **HIP 57507** - no known companions!

- **HIP 1292** - has an RV planet around one star of a binary
  - ~0.03" planet separation may be resolvable with e.g., ELTs — but not Keck/NIRC2
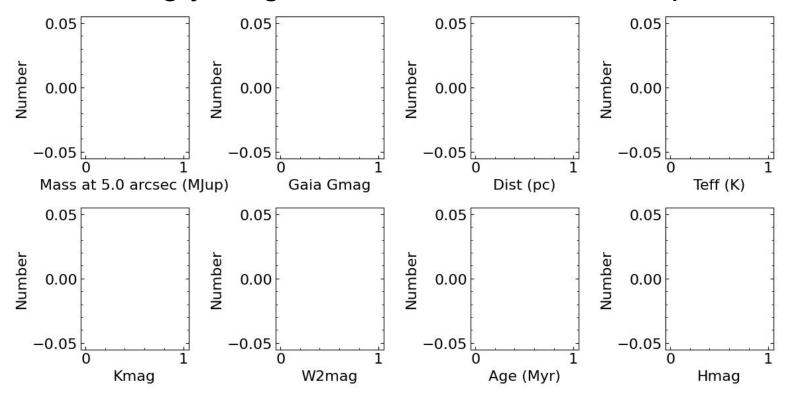
Separations between 4.0 - 5.0 arcseconds

At a Projected Separation of 4.0 arcseconds

At a projected separation of 5.0 arcseconds, no accelerating young stars have substellar companions

Separations between 0-3.0 arcseconds

Object	Already observed?	Has a planet (s)?	Visual binary?	Spectroscopic binary	Literature
1292	RVs, spectroscopy, and imaging with AO	Yes	Yes		Naef et al. (2001); Han et al. (2001); Chauvin et al. (2006); Chauvin et al. (2007); Mugrauer et al. (2007); Huang et al. (2025)
15095	Yes! By HARPS, UVES, and HIRES	????	No	No	None

Session 1:Project 3 Team 3

Aleyna Adamson, Ali Crisp, Matt Lastovka, Maddy Scott, Cole Smith, & Yuling Zhou
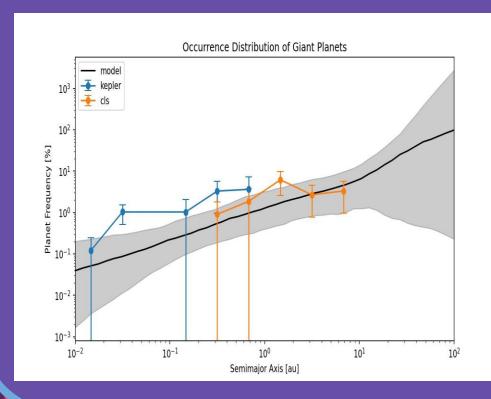
Setting The Scene...

→ The evolution of a protoplanetary disc is influenced by the mass of its host star.
  ◆ This has direct consequences for the types of planets, and how many planets, are formed in that system.

→ From core-accretion planet formation theories, it is expected that higher-mass stars will host giant, gaseous planets, whereas around low-mass stars, these are predicted to be rare.

→ Recently, there have been numerous discoveries of giant planets orbiting low-mass stars, that call into question planet formation theories.

→ Do the expected trends in planet occurrence rates based on planet formation theories agree with our observations?

To investigate these, we split our sample into 3 stellar mass bins

Low-Mass Stars 0.1-0.7M$_\odot$

Mid-Mass Stars 0.7-1.3M$_\odot$

High-Mass Stars 1.3-2M$_\odot$

Low-Mass Stars: 0.1-0.7M☉

Occurrence Distribution of Giant Planets

Kepler
n🪐=3, n⭐=9197
Occurrence rate:
0.00 +/- 0.00 %
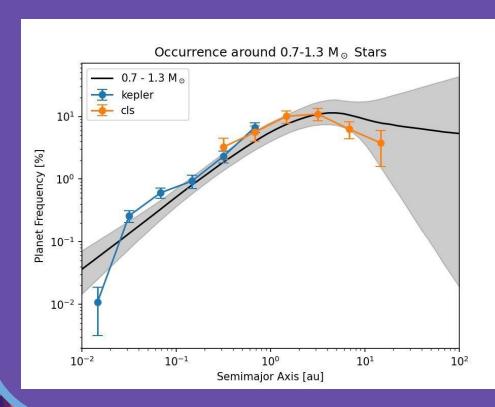
CLS
n🪐=9, n⭐=161
Occurrence rate:
11.46 +/- 3.82 %

Shine
n🪐=0, n⭐=22
Occurrence rate:
0.00 +/- nan %

Mid-Mass Stars: 0.7-1.3M☉

Occurrence around 0.7-1.3 M☉ Stars

Kepler
n🪐=24, n⭐=95548
Occurrence rate:
0.00 +/- 0.00 %
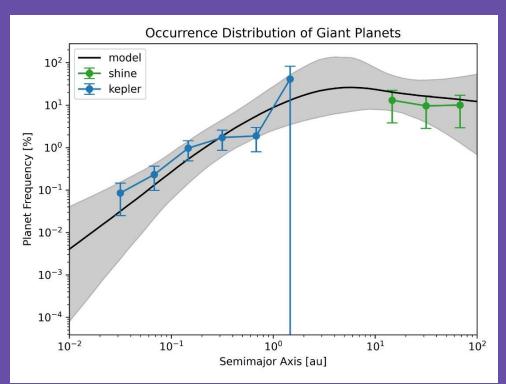
CLS
n🪐=74, n⭐=439
Occurrence rate:
30.58 +/- 3.55 %

Shine
n🪐=0, n⭐=62
Occurrence rate:
0.00 +/- nan %

High-Mass Stars: 1.3-2M☉

Occurrence Distribution of Giant Planets

Kepler
n🪐=11, n⭐=15459
Occurrence rate:
0.00 +/- 0.00 %
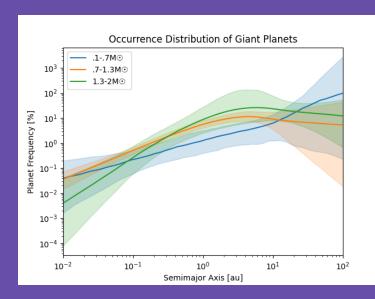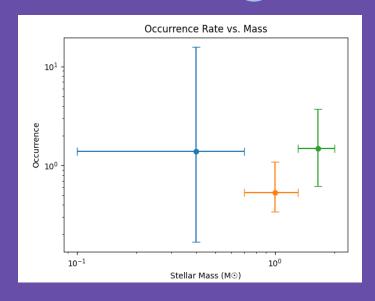
CLS
n🪐=0, n⭐=9
Occurrence rate:
0.00 +/- nan %

Shine
n🪐=6, n⭐=36
Occurrence rate:
25.12 +/- 10.25 %

Full Model: 0.1-2M☉

0.1-0.7M☉:
Occurrence rate:
$1.387^{+14.28\%}_{-1.22\%}$

0.7-1.3M☉:
Occurrence rate:
$0.53^{+0.55\%}_{-0.19\%}$

1.3-2M☉:
Occurrence rate:
$1.49^{+2.22\%}_{-0.87\%}$

Take-aways

→ Higher mass stars have a larger occurrence rate of giant planets. This agrees with planet formation theories.

→ Even though the calculated occurrence rate of giant planets for low-mass stars is almost that of high-mass stars, it is very uncertain.

○ i.e. its unconstrained for low-mass stars — this is not unexpected, as these surveys were optimized to observe bright Sun-like stars.

Giant Planet Distribution Dependence on Stellar Mass

Beatrice Caccherano, Nino Greco, Carlos Ortiz
Sarah Stamer, Kishor Baniya, Akanksha Khandelwal, Stuart Taylor

Goal/Setup

- Look at the occurrence rates of giant planets as a function of stellar masses

- Criteria to select giant planets
  - Mass (for CLS and SHINE) = 32-3200 Earth masses
  - Radius (for Kepler) = 6-14 Earth radii

- What stellar mass bins did we use?
  - Low-mass bin: 0.56-1.1 solar masses
  - High-mass bin: 1.1-1.63 solar masses

The Sample
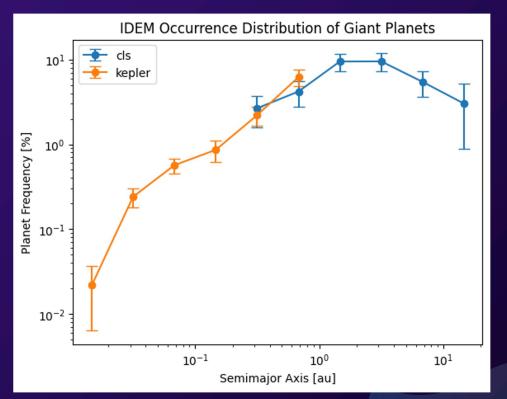
- Low-mass bin
  - Kepler: 84403 stars, 101 planets
  - CLS: 440 stars, 61 planets
  - SHINE: 61 stars, 0 planets

- High-mass bin
  - Kepler: 30007 stars, 40 planets
  - CLS: 62 stars, 14 planets
  - SHINE: 34 stars, 6 planets
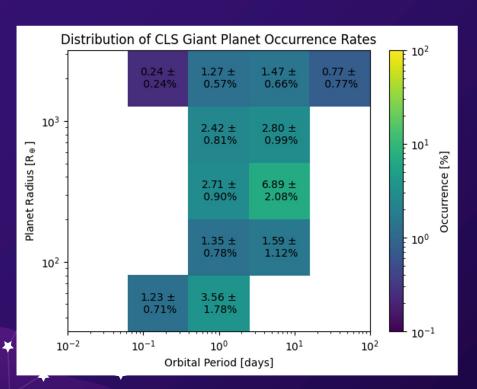
- CLS: California Legacy Survey
- SHINE: SPHERE INfrared survey for Exoplanets
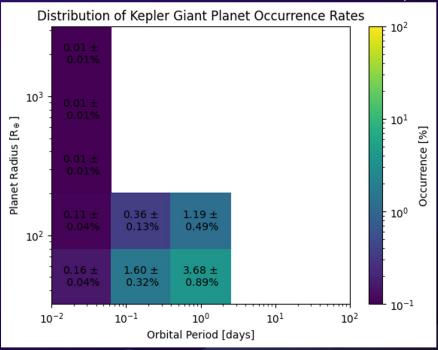
- Planets– giant planets

Giant Planet Occurrence around Low Mass Stars

IDEM Occurrence Distribution of Giant Planets

Giant Planet Occurrence around Low Mass Stars

Distribution of CLS Giant Planet Occurrence Rates

Distribution of Kepler Giant Planet Occurrence Rates
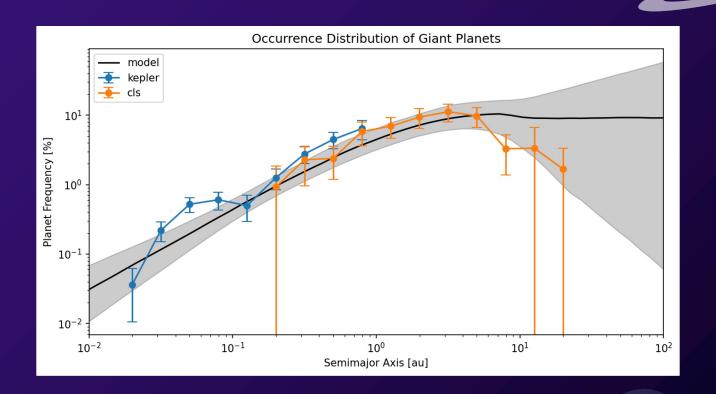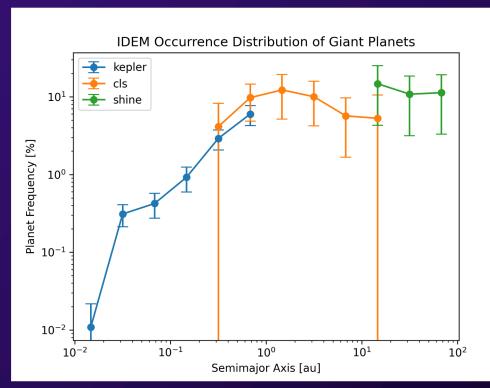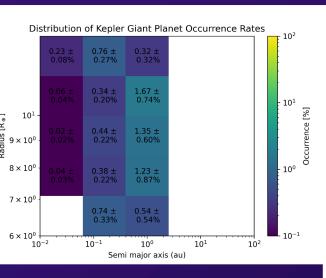
Power Law Fitting for Low Mass Regime
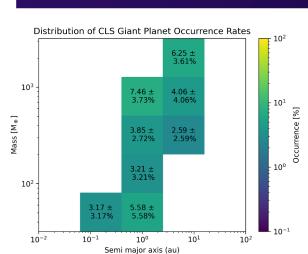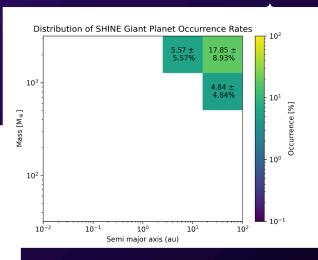
Occurrence Distribution of Giant Planets

Giant Planet Occurrence around High Mass Stars

IDEM Occurrence Distribution of Giant Planets

Giant Planet Occurrence around High Mass Stars

Distribution of Kepler Giant Planet Occurrence Rates

Distribution of CLS Giant Planet Occurrence Rates

Distribution of SHINE Giant Planet Occurrence Rates
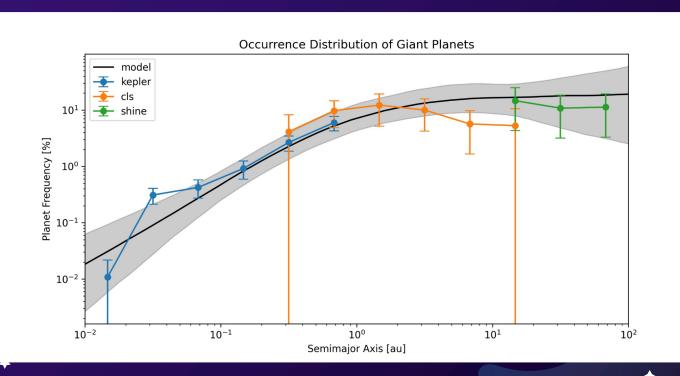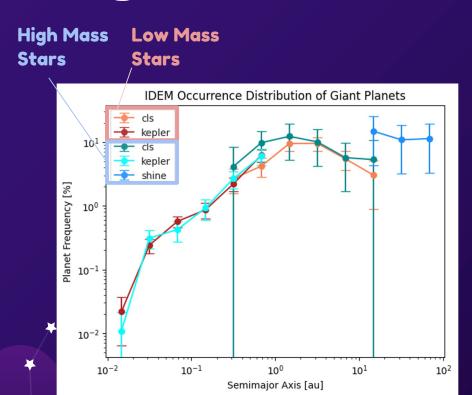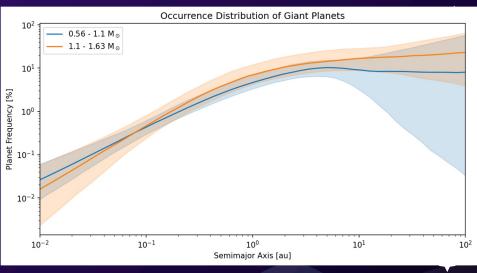
Power Law Fitting for High Mass Regime

Occurrence Distribution of Giant Planets
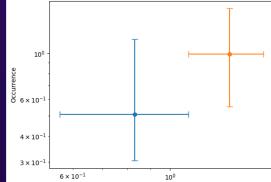
Occurrence across Low and High-Mass Regimes

High Mass Stars

Low Mass Stars

Conclusions

- Giant planets more common around higher-mass stars
  - *$F_0 = 0.51_{-0.20}^{0.66}$ around low mass stars*
  - *$F_0 = 0.97_{-0.40}^{0.61}$ around high mass stars*

- No directly imaged planets in the low-mass bin
  - Slope of the power law at far-out orbital distances has more uncertainty

- There are directly-imaged planets in the high-mass bin
  - Better constraints on the slope at far-out orbital distances

Thanks to the Organizers, all the speakers, hands-on leaders and helpers, and conference attendees!!

Group Project I3: How do the small and giant planet distributions depend on stellar mass?
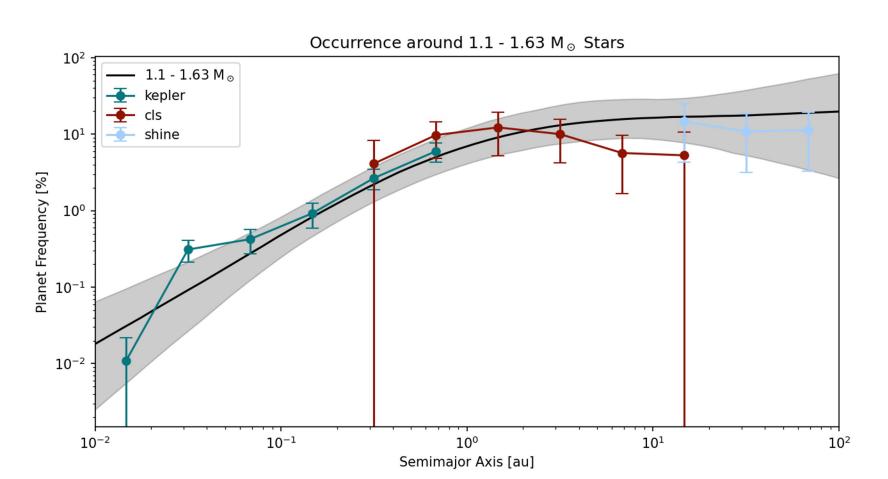
Sagan Workshop 2025

Amy Glazier, Dax Feliz, Himanshu Verma,
Patrick McCreery, Rachel Huchmala, Stephen Schmidt
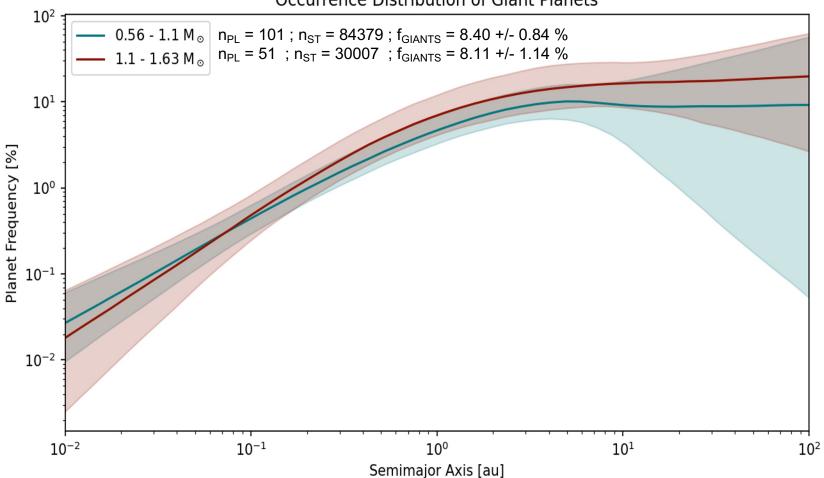
Questions we explored
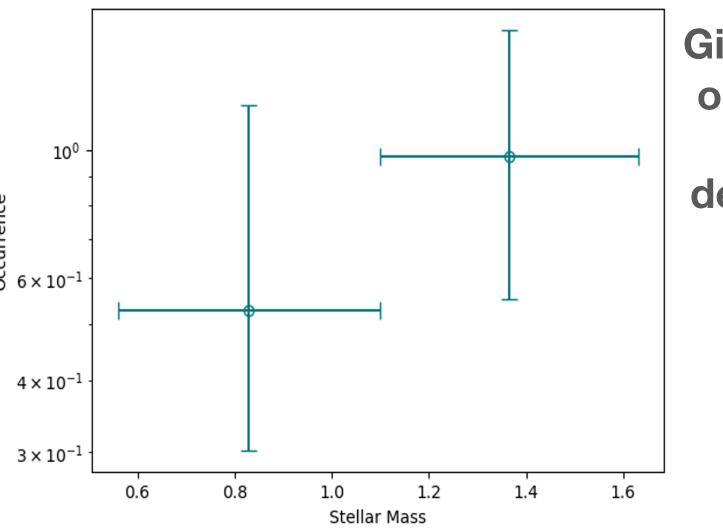
1. How does the giant planet distribution depend on stellar mass?
   a. We used giant planets from all three surveys with semimajor axes between 0.01-100 au and masses between 0.1-10 M_{Jup}

2. How does the small planet distribution depend on stellar mass?
   a. We used small planets from Kepler with semimajor axes between 0.01-100 au and radii smaller than 6 $R_{\oplus}$

Giant planet distribution dependence on host mass

Occurrence around 1.1 - 1.63 M$_\odot$ Stars

Occurrence Distribution of Giant Planets

Legend:
- 0.56 - 1.1 $M_\odot$: n_{PL} = 101 ; n_{ST} = 84379 ; f_{GIANTS} = 8.40 +/- 0.84 %
- 1.1 - 1.63 $M_\odot$: n_{PL} = 51 ; n_{ST} = 30007 ; f_{GIANTS} = 8.11 +/- 1.14 %

Planet Frequency [%] vs Semimajor Axis [au]
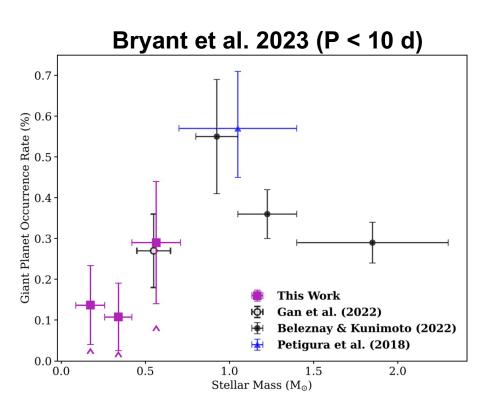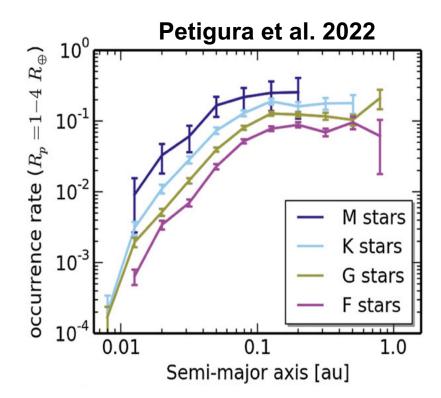
Giant planet occurrence rate as it depends on host star mass

Weak relationship

Does small planet occurrence depend on stellar mass?
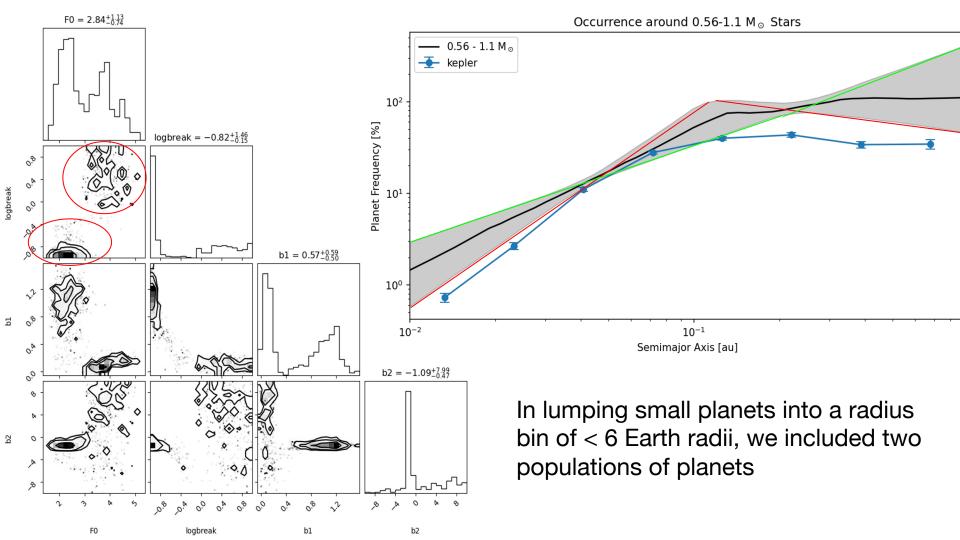
Literature Research of Small Planets

Bryant et al. 2023 (P < 10 d)

Petigura et al. 2022
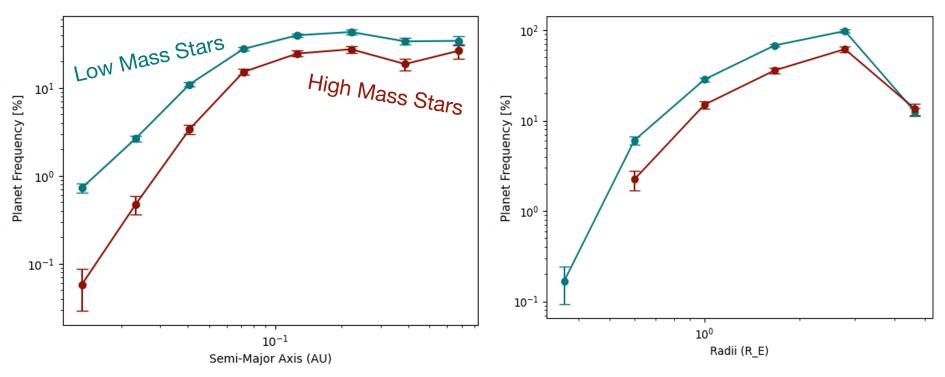
Fun Fact

"Small planets hard"
-Dr. Galen

Occurrence around 0.56-1.1 M$_\odot$ Stars

In lumping small planets into a radius bin of < 6 Earth radii, we included two populations of planets

Small Planet Distribution

While the semi-major axis looks like it could be easily fit,
the radii are not a flat line like the model expects.

In conclusion…
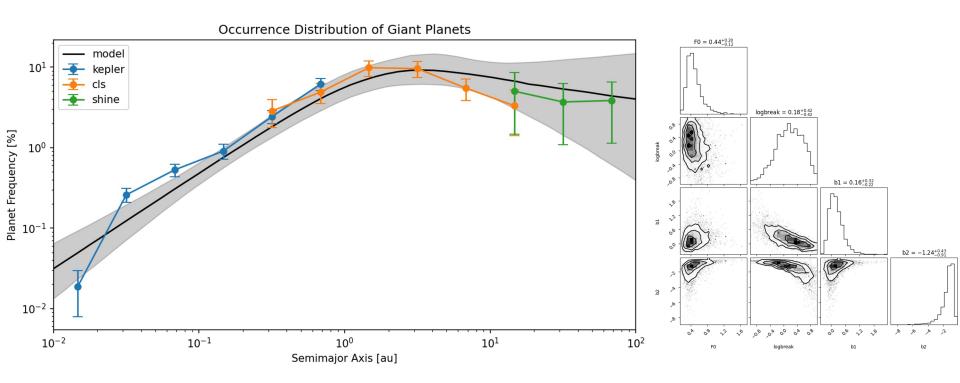
1. Unlike the "large" Planets (6-14 Earth Radii) the "small" planets (<6 Earth Radii) show two different populations of planet types whose masses can not be described by a simple line.
2. Because of this, trying to fit one occurrence rate to the "small" planets as we defined them, did not work.
3. If we had more time, we would look into breaking the small planets into two groups: Super Earths & Sub Neptunes.
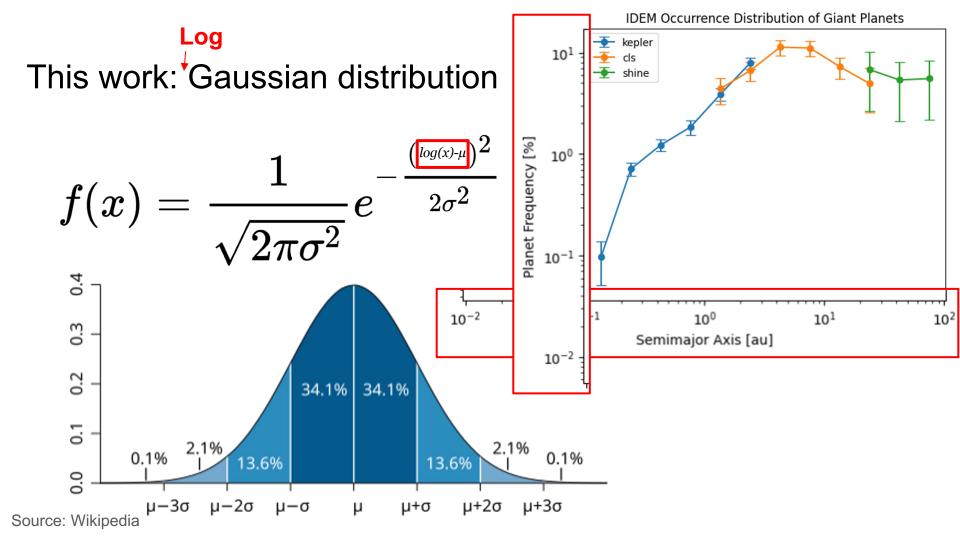
Project I-2

Exoplanet Occurrence Rates with Different Models

Laura Chin (BU), Shishir Dholakia (UniSQ), Charles Holloway (University of Arkansas), David Shaw (Notre Dame)

Previous work: Broken power law

Log

This work: Gaussian distribution

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(log(x)-\mu)^2}{2\sigma^2}}$$

IDEM Occurrence Distribution of Giant Planets

Source: Wikipedia

Methodology:

- Modifying the Monday Google CoLab notebook, we replaced the broken power law with our normal (Gaussian) distribution to describe the shape of the occurrence rate.

- New free parameters:
    - σ ~ Standard Deviation (spread) of the curve
    - μ ~ Mean (Center of the normal Curve)
    - F0 ~ need parameter to govern the total occurrence rate.

- Then, we modified the prior function defined during our Monday session with the above free parameters.
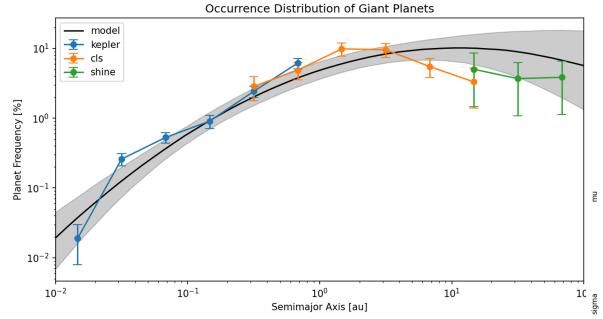
- Data :
    - 'X' and 'Y' refers to the planet orbital separation and Occurrence Rate respectively.

Methodology:
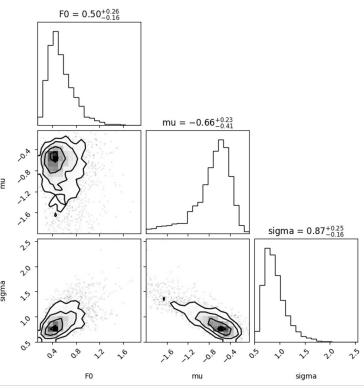
- Modeling Procedure:
  - The new fit_model function fits the data with our gaussian distribution.
  - As usual with modeling, determining our initial guesses became the fun part.
  - Then, we adjust our MCMC Optimization parameters.
    - Nstep = 10,000 (This value must be reasonable.)
    - Nwalks = 16
    - # of draws = 2

Results:

$$f(x; F_0, \text{mu}, \text{sigma}) = F_0 \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln x - \mu)^2}{2\sigma^2}\right)$$
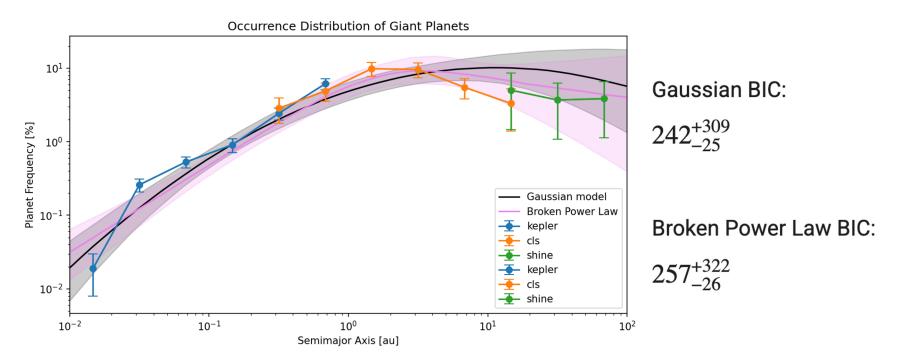
Occurrence Distribution of Giant Planets

F_0	mu	sigma
$0.5^{+0.26}_{-0.16}$	$-0.66^{+0.23}_{-0.41}$ log(AU)	$0.87^{+0.25}_{-0.16}$ log(AU)

Model Comparison

Occurrence Distribution of Giant Planets

Gaussian BIC:

242^{+309}_{-25}

Broken Power Law BIC:

257^{+322}_{-26}
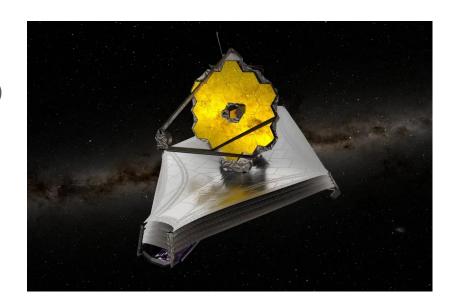
The Gaussian model is more parsimonious!

Hands-on Session II:
Distant Giant Planets with Astrometry Group Project 1

Manon Lizzana - Paul Smith

How can astrometry be used to identify the best targets for imaging exoplanets or brown dwarfs with JWST?

- Use astrometric data (Gaia + Hipparcos)
- Direct imaging of exoplanets
- instruments : NIRcam or MIRI

Built a short list of targets

- Hipparcos-Gaia Catalog of Accelerations

Built a short list of targets

- Hipparcos-Gaia Catalog of Accelerations
- Calculate the acceleration for each star
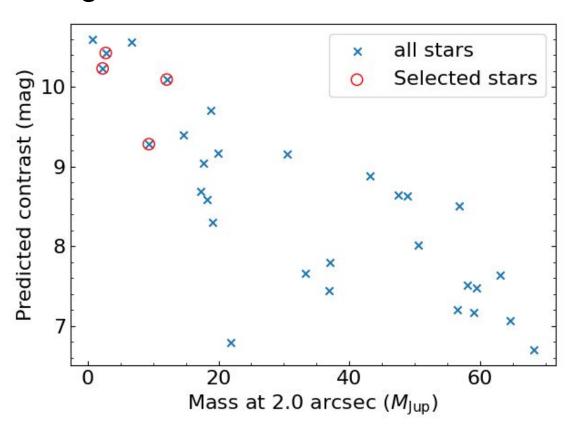
Built a short list of targets

- Hipparcos-Gaia Catalog of Accelerations (HGCA)
- Calculate the acceleration for each star
- Estimate the mass of the companion causing the acceleration (depends on separation)

Built a short list of targets

- Hipparcos-Gaia Catalog of Accelerations (HGCA)
- Calculate the acceleration for each star
- Estimate the mass of the companion causing the acceleration (depends on separation)
- Select stars with :
  - $\chi2 > 11.8$ (>3σ) deviation in the HGCA proper motions from a model of constant proper motion
  - companion_mass < 70 M_Jup (avoid stellar companions)
  - not white dwarf
  - not multiple system ('non_single_star','ipd_frac_multi_peak')

Built a short list of targets

- Hipparcos-Gaia Catalog of Accelerations (HGCA)
- Calculate the acceleration for each star
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- Estimate the contrast (thanks to typical contrast curve models)

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- Select stars with :
  - $\chi2$ >11.8 (>3σ) deviation in the HGCA proper motions from a model of constant proper motion
  - companion_mass < 70 M_Jup (avoid stellar companions)
  - not white dwarf
  - not multiple system ('non_single_star','ipd_frac_multi_peak')
- Estimate the contrast (thanks to typical contrast curve models)
- Select targets with :
  - contrast < 10.5 mag
  - companion_mass < 14 M_Jup

Short list of targets

Selected targets

HIP	Gaia	RA_ICRS	DE_ICRS	RV	e_RV	r_RV	plx	e_plx	pmRA	pmDE	chi2	estimated_contrast_0.5_arcsec	Predicted Mass at 2.0 arcsec	predicted_contrast_F1550C
73184	6232511606838403968	224.371597	-21.423117	26.808	0.128	Gaia_DR2	169.8843	0.0653	1031.472	-1723.619	354.60	18.333792	9.354129	9.283093
84405	4109030160308317312	258.835112	-26.608021	-0.100	0.500	Gaia_DR2	168.1303	0.1081	-465.861	-1141.168	29.24	18.453796	2.758113	10.427947
97944	6863535898551993472	298.573326	-23.942837	-5.100	0.200	Gaia_DR2	70.7010	0.0350	-124.167	-410.681	15.46	19.473628	12.076944	10.094687
108870	6412595290592307840	330.872242	-56.797468	-40.504	0.230	Gaia_DR2	274.8431	0.0956	3966.661	-2536.192	287.50	18.294209	2.280698	10.233932

HIP108870

- already observed many times by JWST
- 1 planet already found (arstrometry + RV)

HIP	Gaia	RA_ICRS	DE_ICRS	RV	e_RV	r_RV	plx	e_plx	pmRA	pmDE	chi2	estimated_contrast_0.5_arcsec	Predicted Mass at 2.0 arcsec	predicted_contrast_F1550C
73184	6232511606838403968	224.371597	-21.423117	26.808	0.128	Gaia_DR2	169.8843	0.0653	1031.472	-1723.619	354.60		18.333792	9.354129	9.283093
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HIP97944 (HD 188088)

- χ2 small
- no known companion but a "common proper motion" star

HIP	Gaia	RA_ICRS	DE_ICRS	RV	e_RV	r_RV	plx	e_plx	pmRA	pmDE	chi2	estimated_contrast_0.5_arcsec	Predicted Mass at 2.0 arcsec	predicted_contrast_F1550C
73184	6232511606838403968	224.371597	-21.423117	26.808	0.128	Gaia_DR2	169.8843	0.0653	1031.472	-1723.619	354.60	18.333792	9.354129	9.283093
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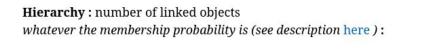
HIP84405

- Complex system with at least 4 stars
- already observe with JWST (3 times by MIRI)

Hierarchy : number of linked objects
whatever the membership probability is (see description here) :

parents : 1   children : 2   siblings : 1   Display criteria : All

HIP	Gaia	RA_ICRS	DE_ICRS	RV	e_RV	r_RV	plx	e_plx	pmRA	pmDE	chi2	estimated_contrast_0.5_arcsec	Predicted Mass at 2.0 arcsec	predicted_contrast_F1550C
73184	6232511606838403968	224.371597	-21.423117	26.808	0.128	Gaia_DR2	169.8843	0.0653	1031.472	-1723.619	354.60		18.333792	9.354129	9.283093
84405	4109030160308317312	258.835112	-26.608021	-0.100	0.500	Gaia_DR2	168.1303	0.1081	-465.861	-1141.168	29.24		18.453796	2.758113	10.427947
97944	6863535898551993472	298.573326	-23.942837	-5.100	0.200	Gaia_DR2	70.7010	0.0350	-124.167	-410.681	15.46		19.473628	12.076944	10.094687
108870	6412595290592307840	330.872242	-56.797468	-40.504	0.230	Gaia_DR2	274.8431	0.0956	3966.661	-2536.192	287.50		18.294209	2.280698	10.233932

HIP73184 (HD 131977)

- never been observed by JWST
- but we have already a lot of info about the star :
  - observed by Gemini / ZORRO imager (2025)
  - observed by Keck / HIRES (High Resolution Echelle Spectrometer) (1997)
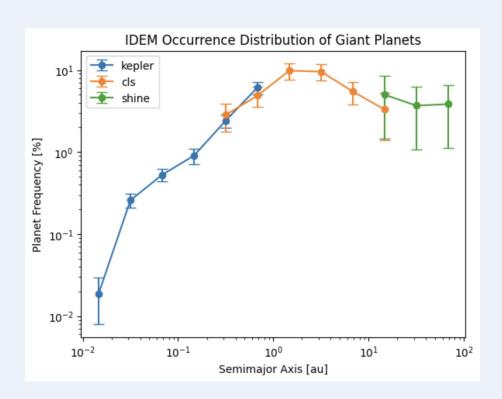 - observed by Keck / NIRC2 (2002)
  - observed by VLT / Amber spectrograph

HIP	Gaia	RA_ICRS	DE_ICRS	RV	e_RV	r_RV	plx	e_plx	pmRA	pmDE	chi2	estimated_contrast_0.5_arcsec	Predicted Mass at 2.0 arcsec	predicted_contrast_F1550C
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Occurrence Rates Given Different Surveys

Alex Howe
Karina Kimani-Stewart
Maleah Rhem
Honorable Mention: Marie Tagliavia & Disha Chakraborty

Introduction

- Studying the occurrence rates of giant planets detected by three different surveys
- Kepler (transit), California Legacy Survey (RV), SHINE (imaging)
- Fitting models to this distribution
- "**How do occurrence measurements change with different combinations of surveys?**"
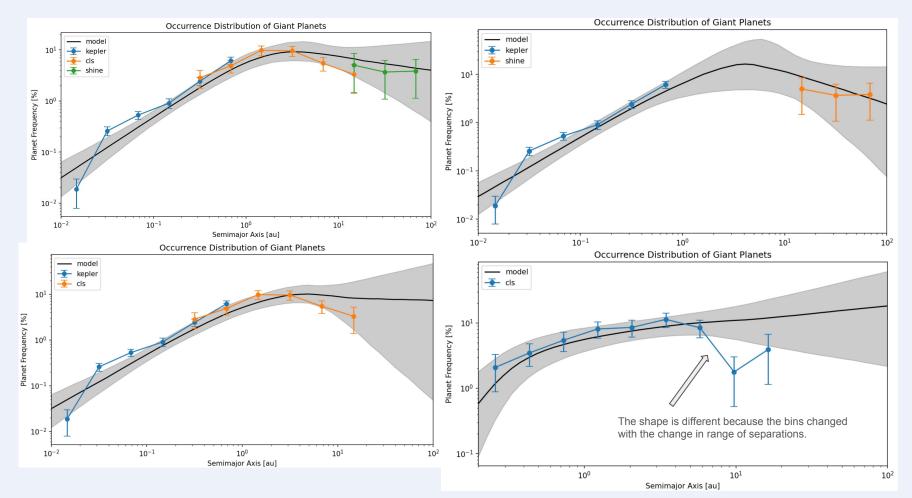
Disclaimers
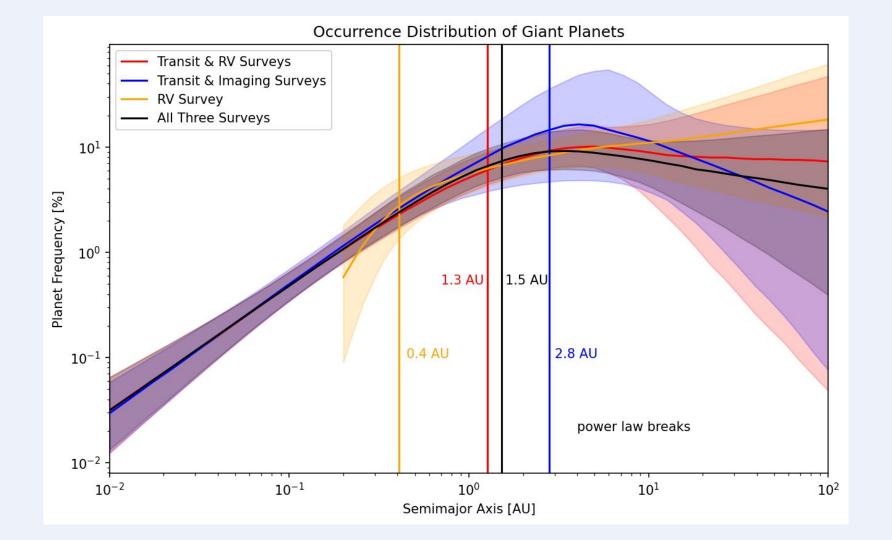
- **Note:** the RVs-only fit used a narrower range of separations than the others, beginning at 0.2 AU instead of 0.01 AU.
  - This was because the "standard" fit drove the occurrence rates down to exponentially small values at close separations (slope of 2.8 versus 0.16 for the 3-survey fit).
- The fits will depend partly on the binning, which is dependent on the range of separations used.
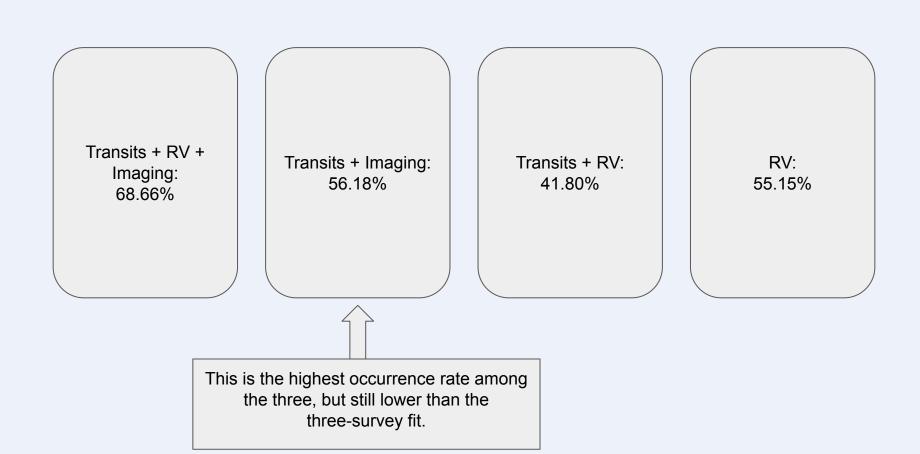
Survey Combinations

Transits + RV + Imaging (control)

Transits + Imaging

Transits + RV

RV only

Results

The shape is different because the bins changed with the change in range of separations.

Occurrence Distribution of Giant Planets

Occurrence Rates

| Transits + RV + Imaging: 68.66% | Transits + Imaging: 56.18% | Transits + RV: 41.80% | RV: 55.15% |

This is the highest occurrence rate among the three, but still lower than the three-survey fit.

Discussion/Conclusions

- RVs alone provide a poor fit to the population as a whole.
  - Probably because of the smaller range in periods.
  - But might plausibly also be related to the differences between populations that formed *in situ* versus migrating inward.
- Transits + Imaging provide a surprisingly good fit, given the data quality
  - Although the uncertainties are larger at moderate separations where RVs provide more information.
- Similar results appear for Transits + RVs.
  - Omitting Imaging alone unsurprisingly had the smallest impact because of its small number of data points.
- Each survey allows for robust fits within its range of separations; the risk lies in extrapolating beyond its limits.
  - Even then interpolating across the gap between transits and imaging turns out better than pure extrapolation.