# The Influence of Stellar Multiplicity on Planet Formation and Evolution


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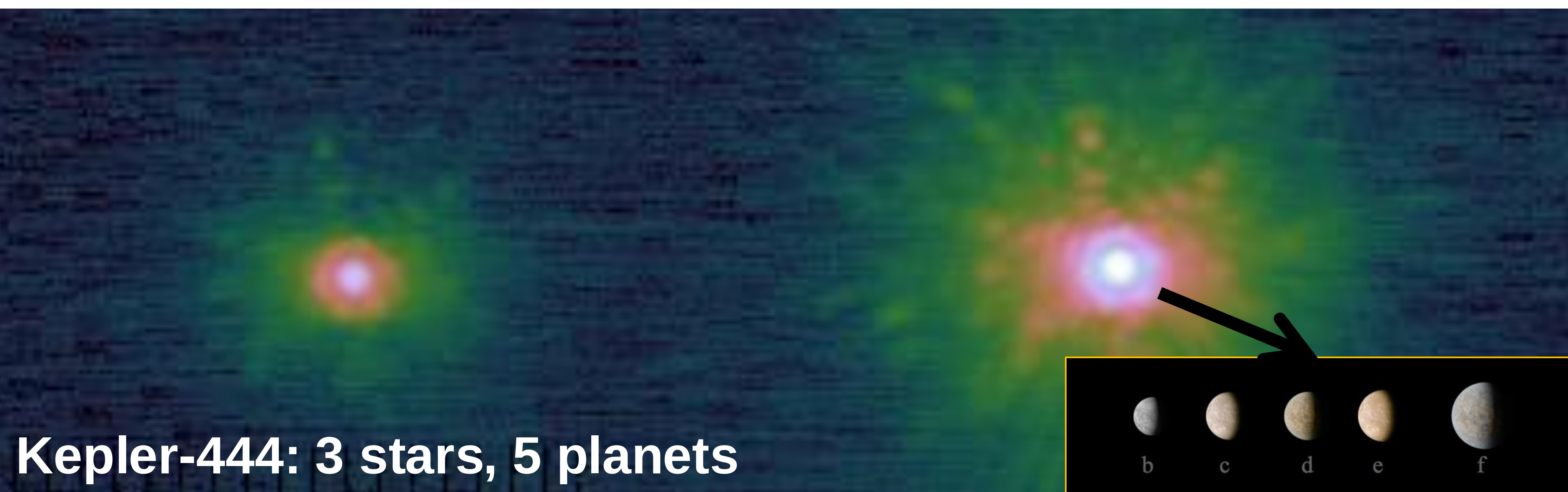
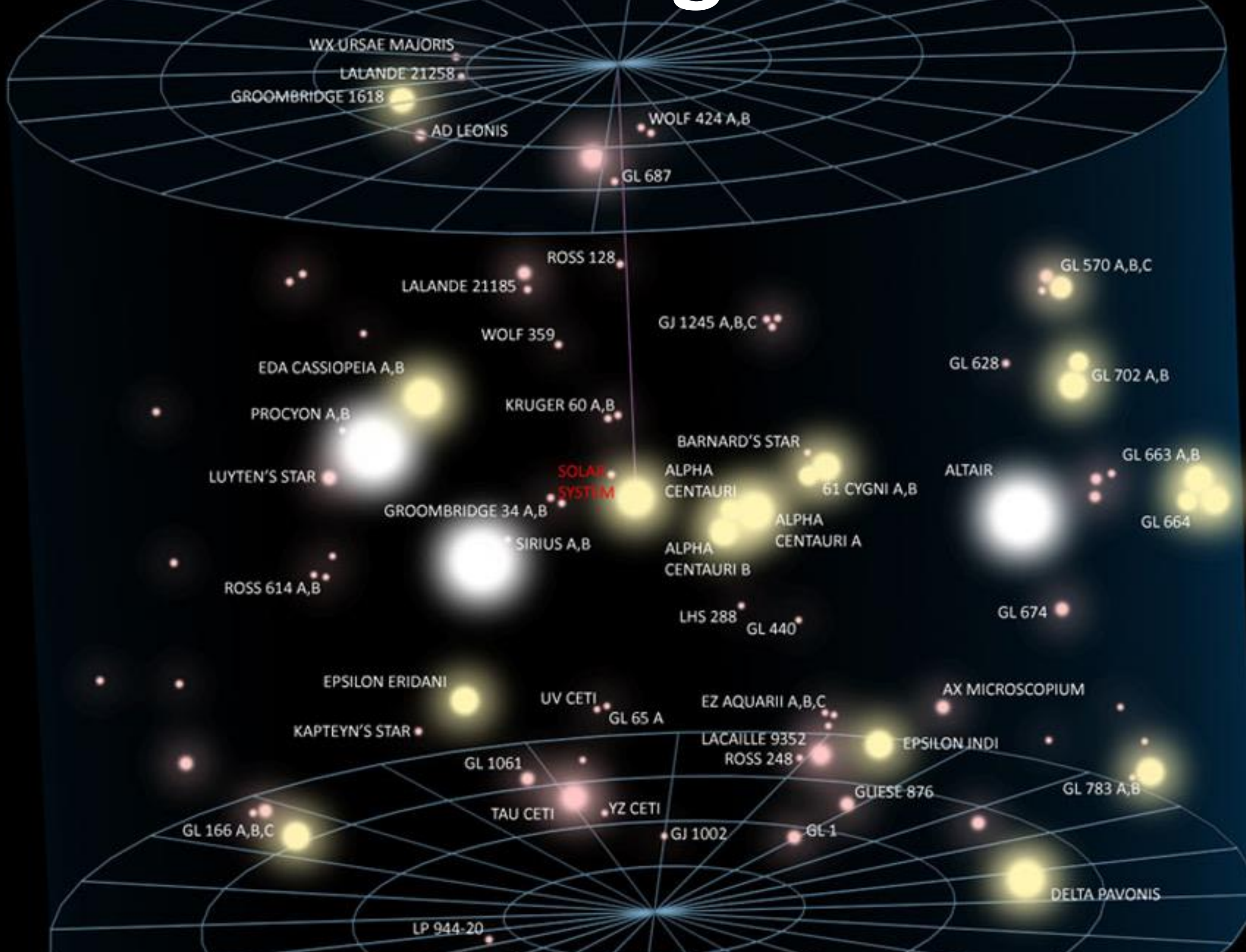


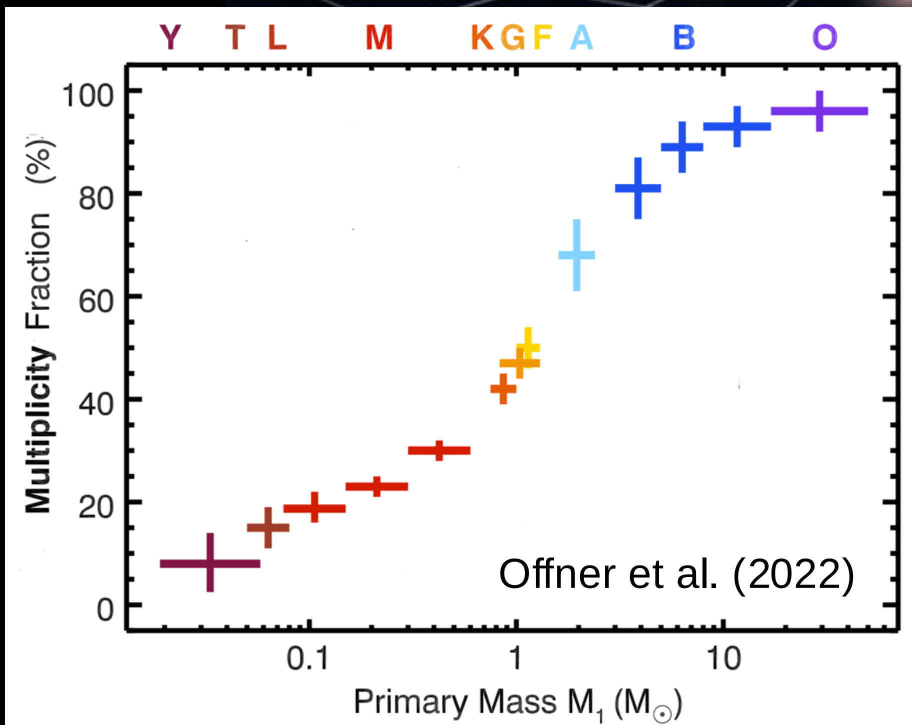
# The Solar Neighborhood

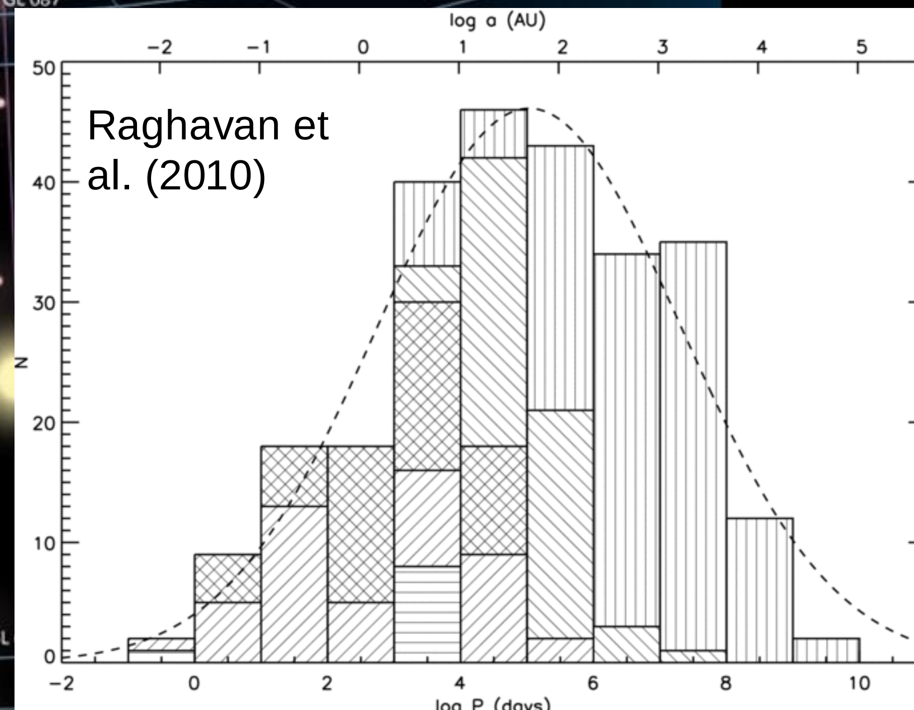



**The majority of all solar-type stars form in binary systems!**

**Do they have planets?**

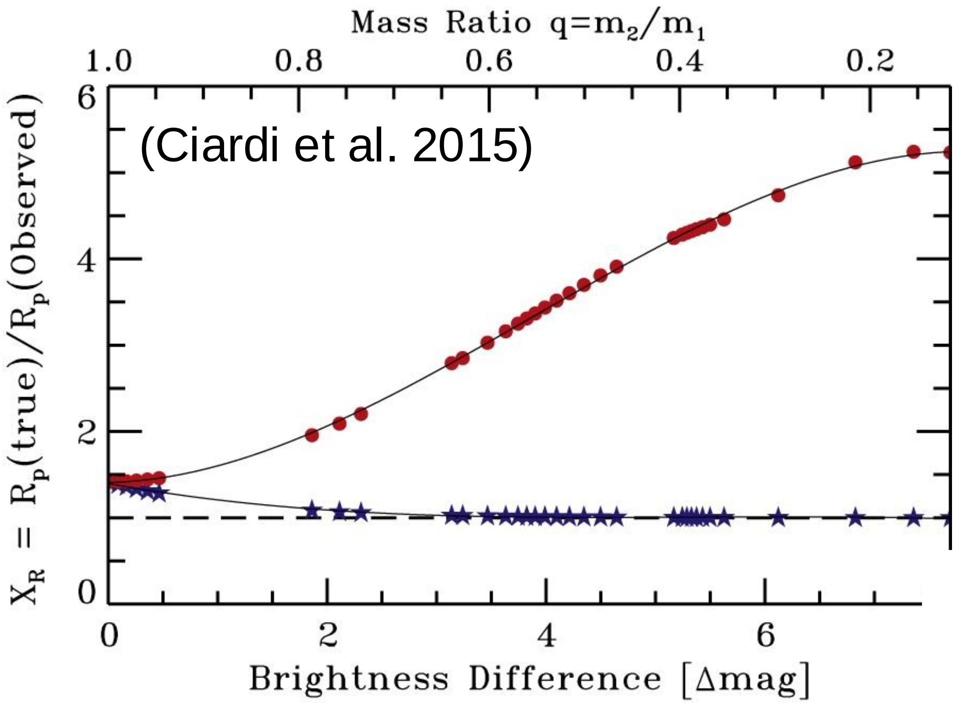
# Binaries are Everywhere



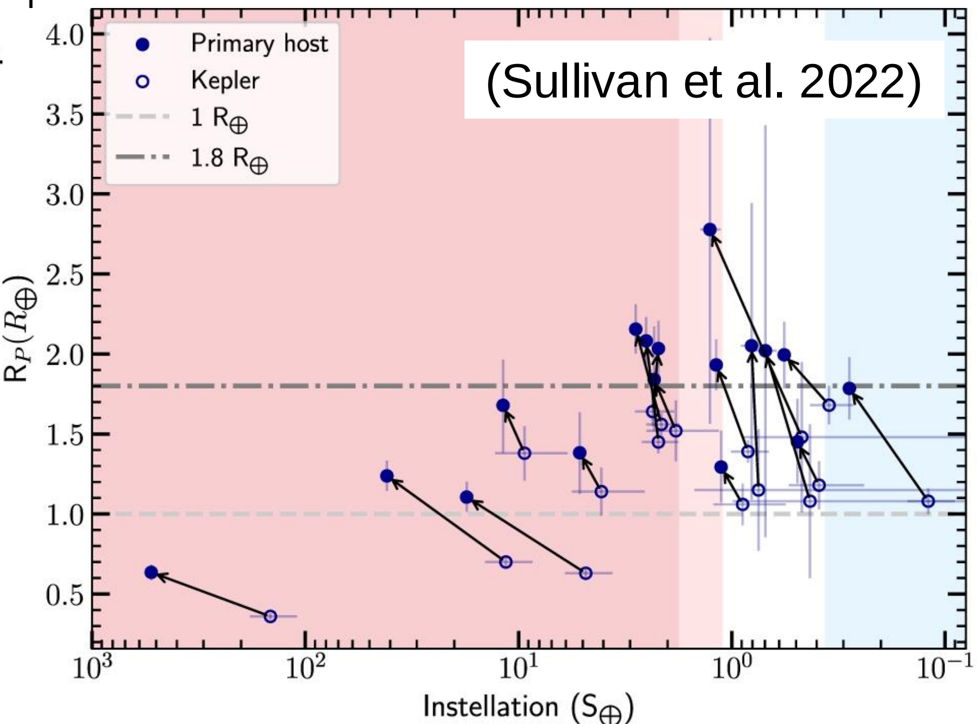

**This is a problem and an opportunity!**

# You Definitely Need to Know Thy Binaries



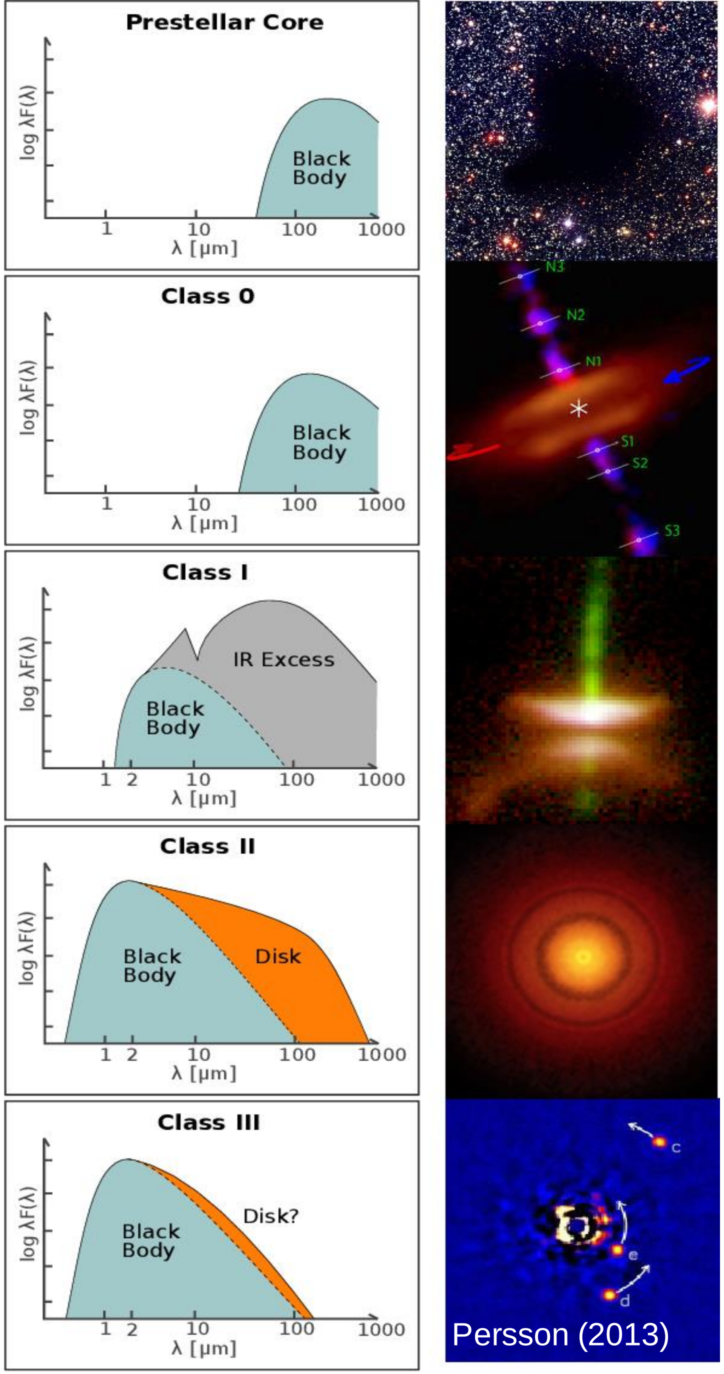

Flux from the unocculted star can bias planet radii and change demographic conclusions

(also see talk by Galen Bergsten)




Incorrect stellar parameters or host can further bias radii and instellation

(also see talk by Nathanael Burns-Watson)




# Also "Opportunities" to Understand Astrophysics

References Include: Alexander, Beust, Haghighipour, Lissauer, Lubow, Martin, etc etc

**Accretion**

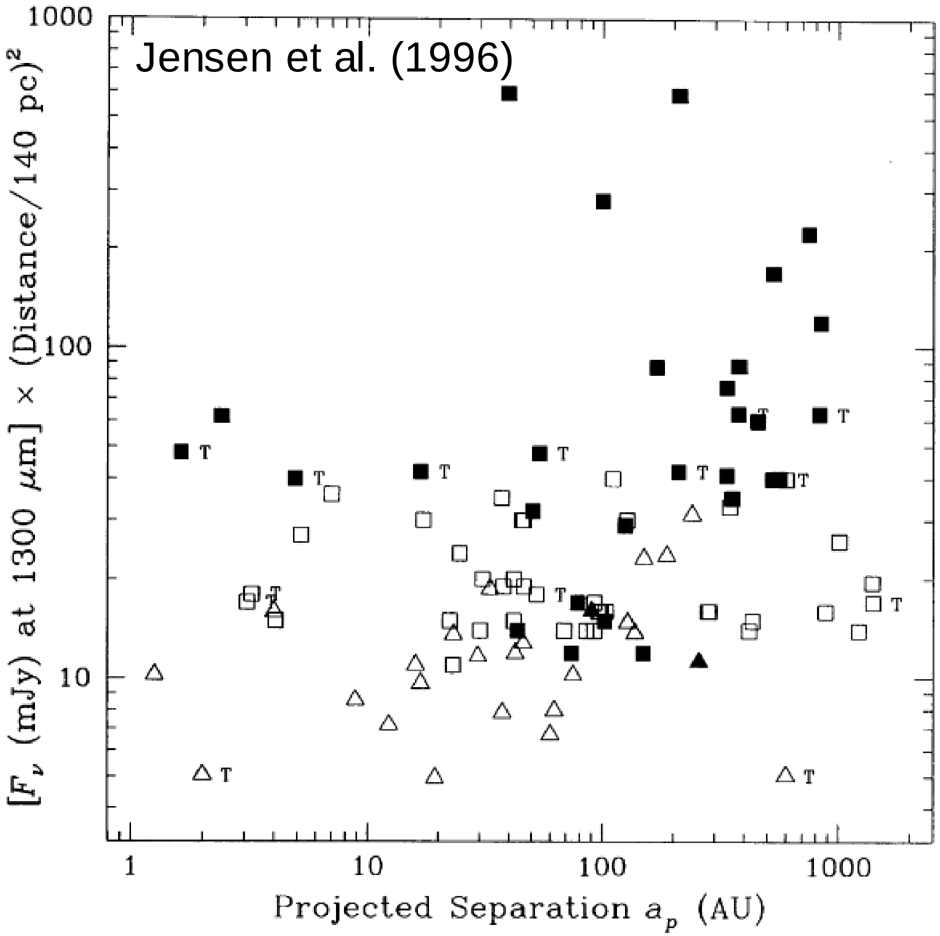
**Disk Truncation**

**Planetesimal Stirring**

**Enhanced Evaporation**

**Ejections**

# Early Evidence: Disks, Yes, but Different Ones?

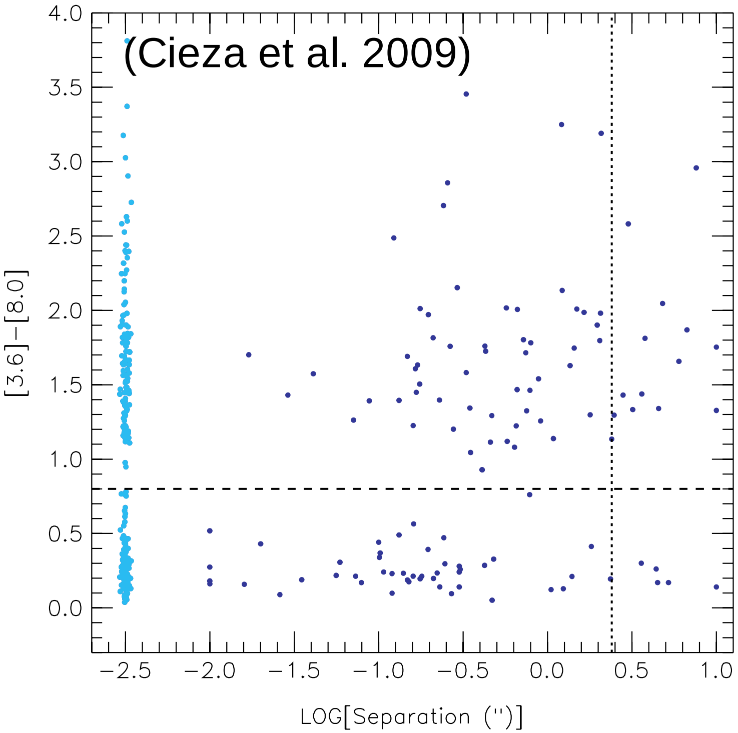


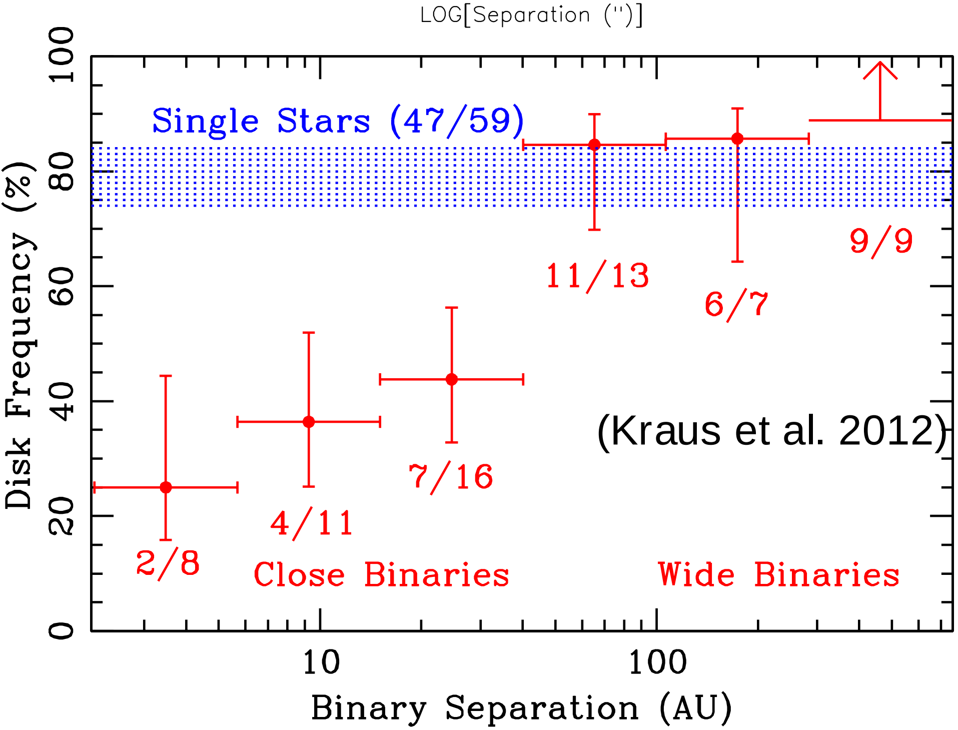

Filled: Detections
Open: Upper Limits

- Jensen et al. (1996) published the first large study of disks in binary systems, using millimeter flux to indicate disk existence + mass
- Found that the most luminous objects were all among the wider binaries; maybe fewer (and less massive?) disks among tighter binaries?

(Also Ghez et al. 1997, Prato & Simon 1997, White & Ghez 2001)

# Close Binaries Might Be Hazardous!



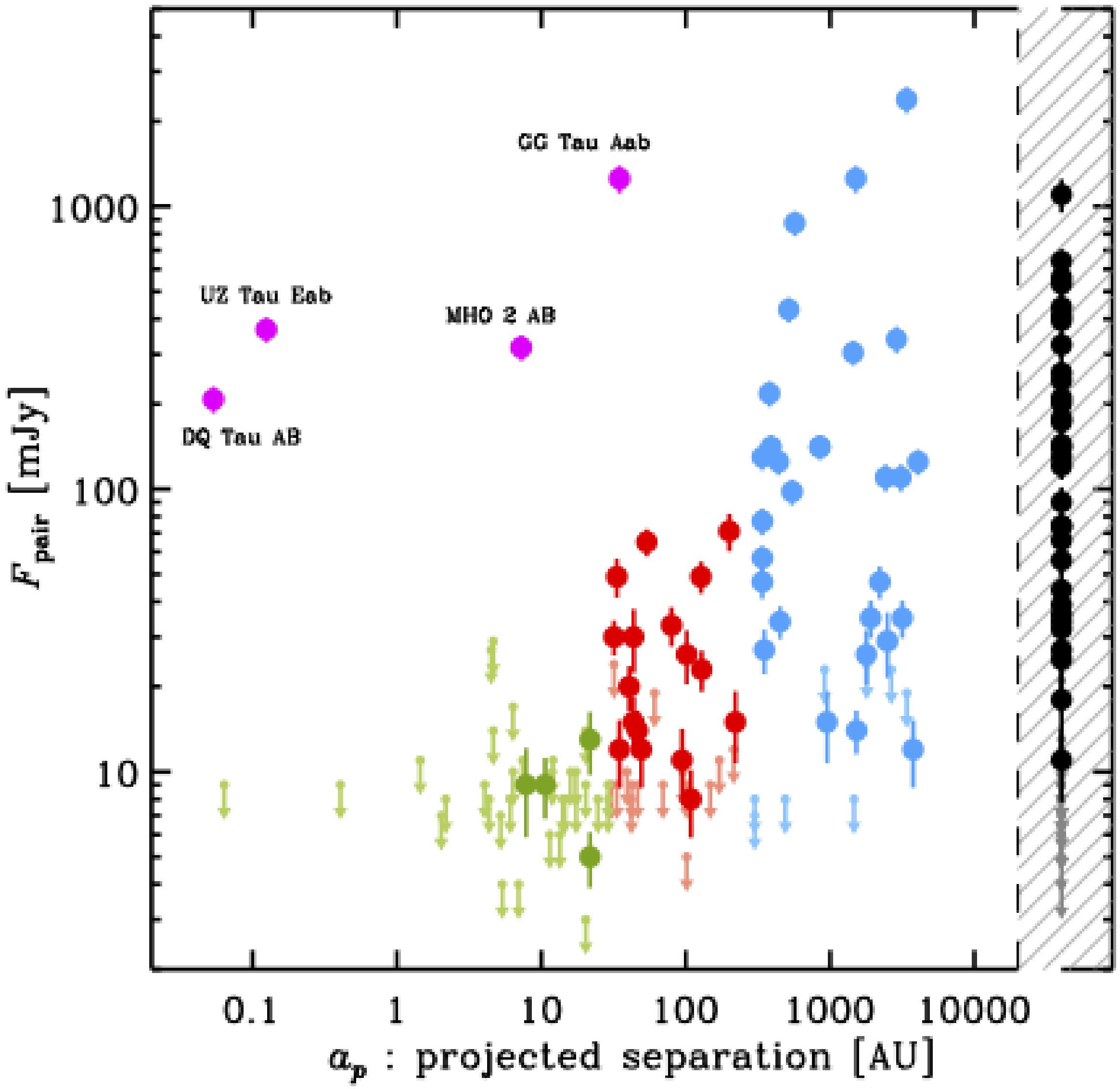

During planet formation, the disk fraction is high for single stars and wide binaries, but lower by a factor of 3 for <40 AU binaries. Now broadly confirmed.

(Cieza et al. 2009, Kraus et al. 2012, Cheetham et al. 2015, Barenfeld et al. 2019, Zurlo et al. 2020)

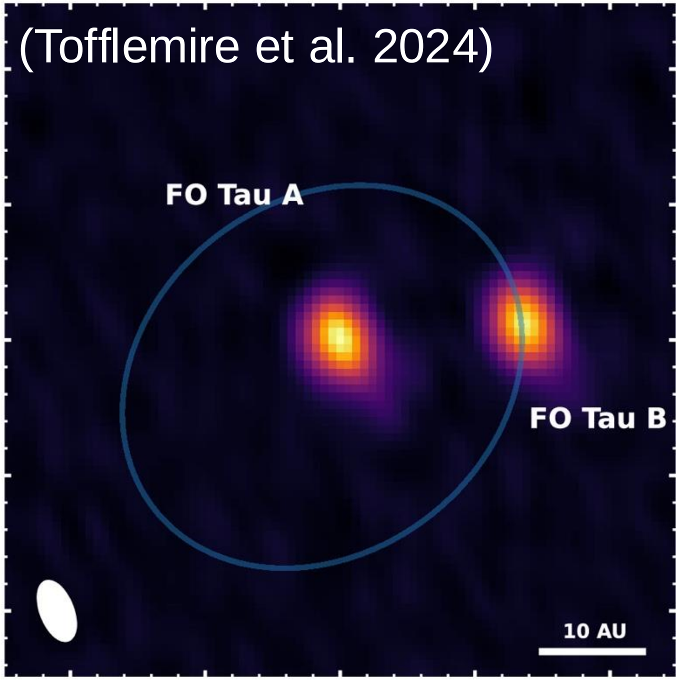
# Are Disks Less Massive, or Just Smaller?

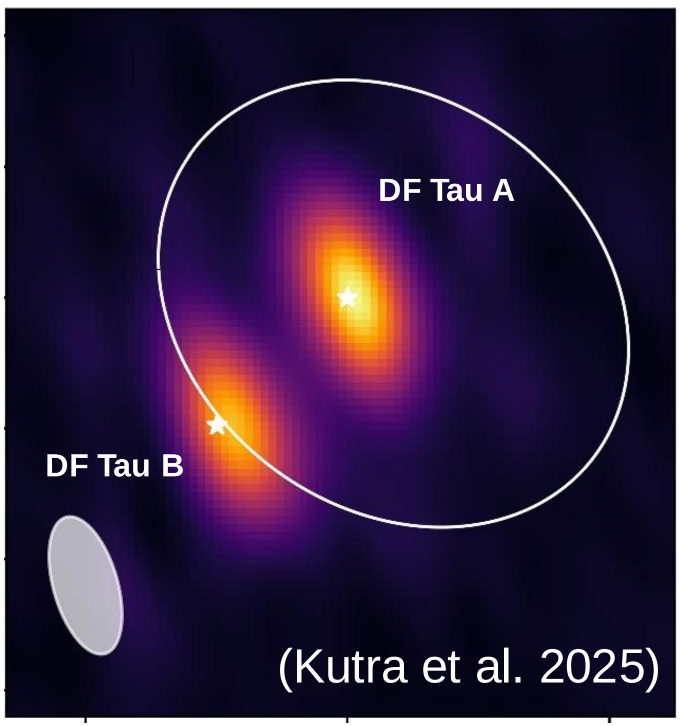
Compared to single stars and wide binaries, even 40-400 AU binaries have mm fluxes suppressed by a factor of 5, while 4-40 AU binaries are suppressed by another factor of 5. (Harris et al. 2012)

Pre-ALMA, though! ALMA shows the disks are smaller than the truncation radius, perhaps due to radial drift. If optically thick, then flux indicates emitting area, not total dust mass. (Manara et al. 2019, Zurlo et al. 2020)



# Disks in Unlikely Places



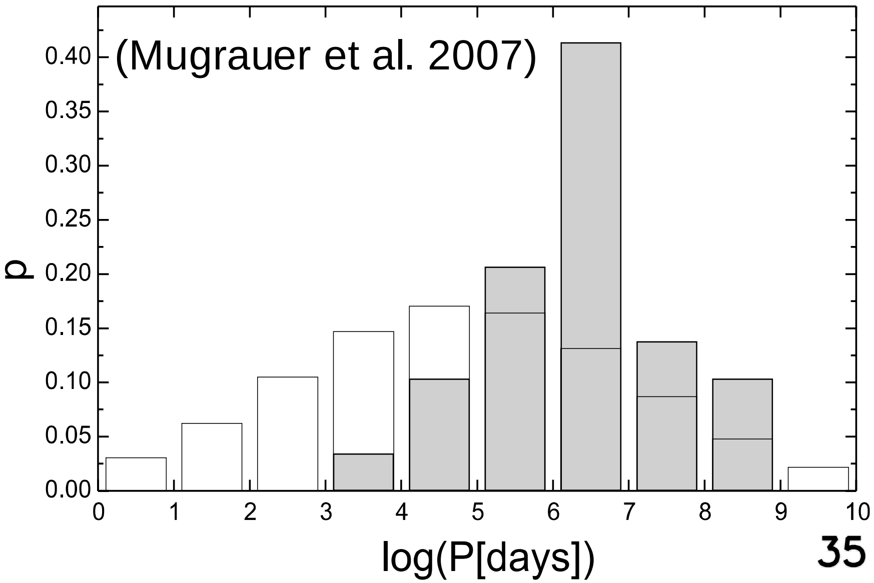




ALMA long-baseline observations are starting to spatially resolve disks in 5-20 AU binaries. Alignment seems common (maybe not surprising), but the configurations surprise me.

No evidence of circumbinary material – where's the mass reservoir?

DF Tau B has no inner disk – what's clearing it?

# Close Binaries Really Are Hazardous!

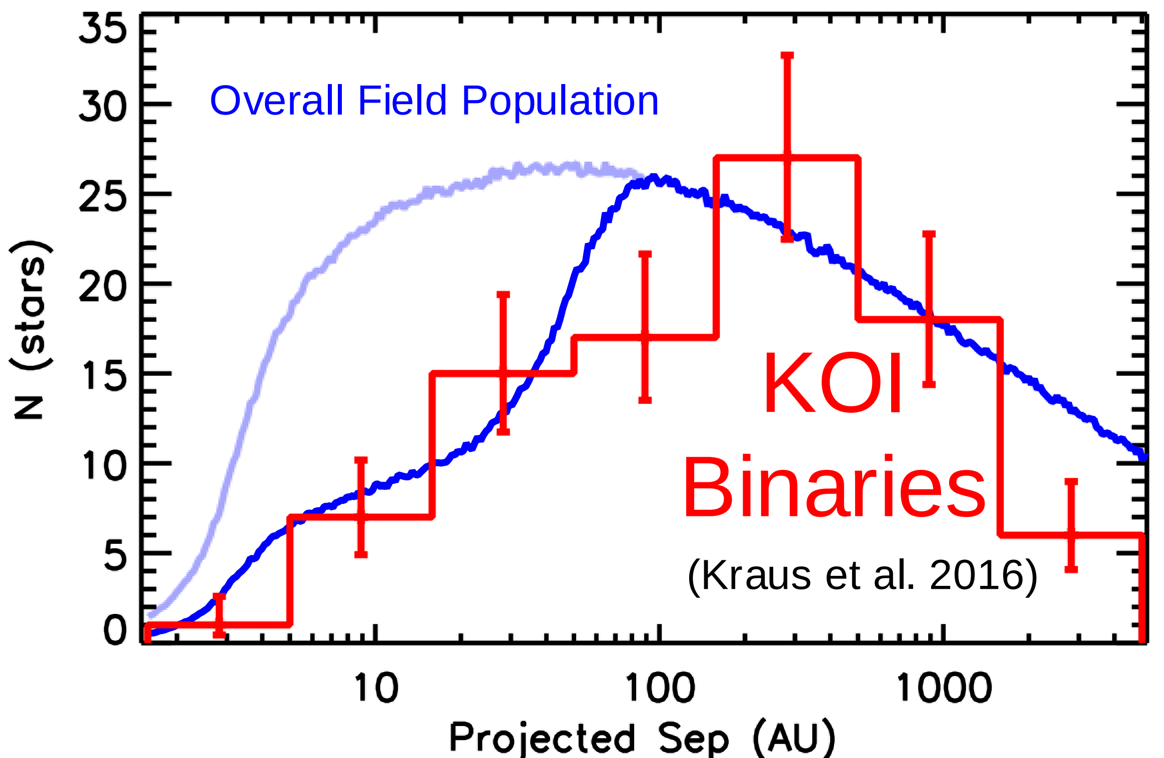



RV planet hosts appear to have fewer close binaries, albeit with caveats from planet discovery selection biases.

Normal frequency for wider binaries.
(Mugrauer et al. 2007, Desidera & Barbieri 2009 and Duchene 2010)

**Much clearer in transits.**
Inside ~50-100 AU, planet occurrence suppressed by a factor of ~3. This is now verified for Kepler, K2, TESS, M dwarfs, and other samples.

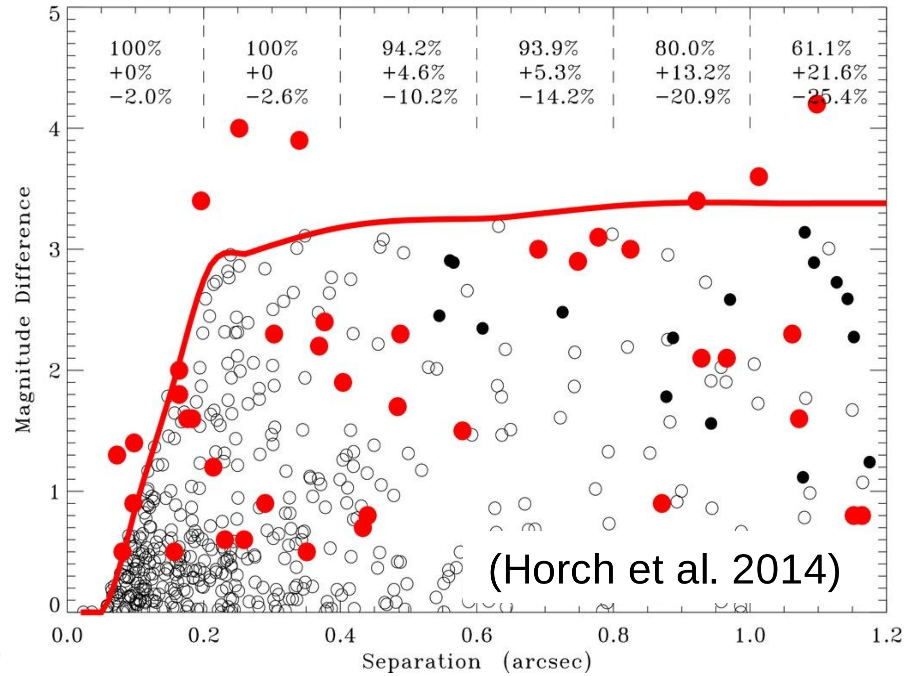
(Also Matson et al. 2018; Ziegler et al. 2020,22; Moe et al. 2020, Clark et al. 2022, 24, and more)

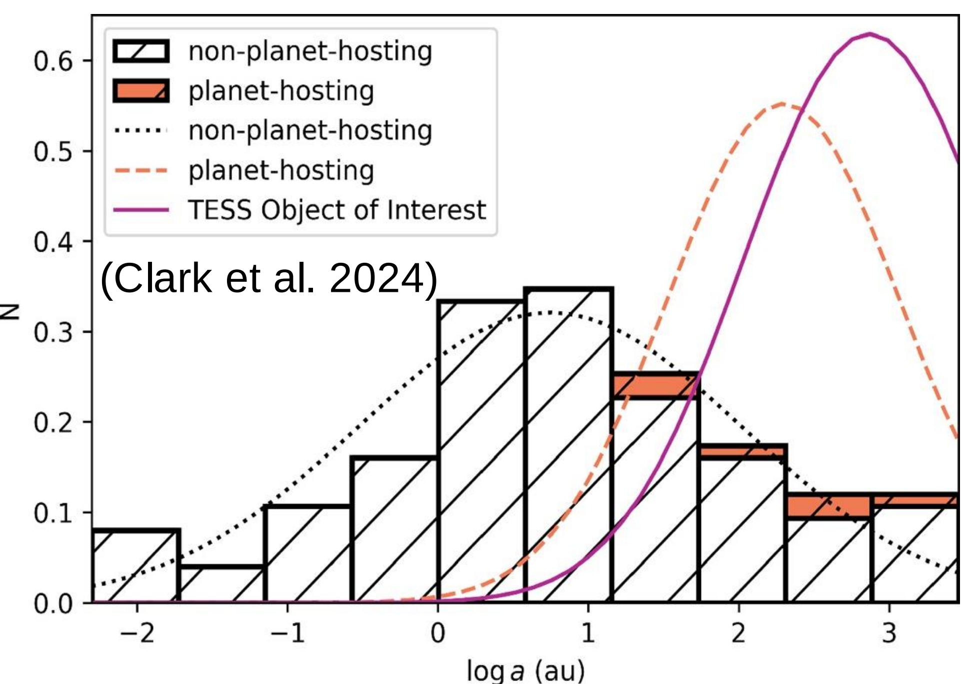


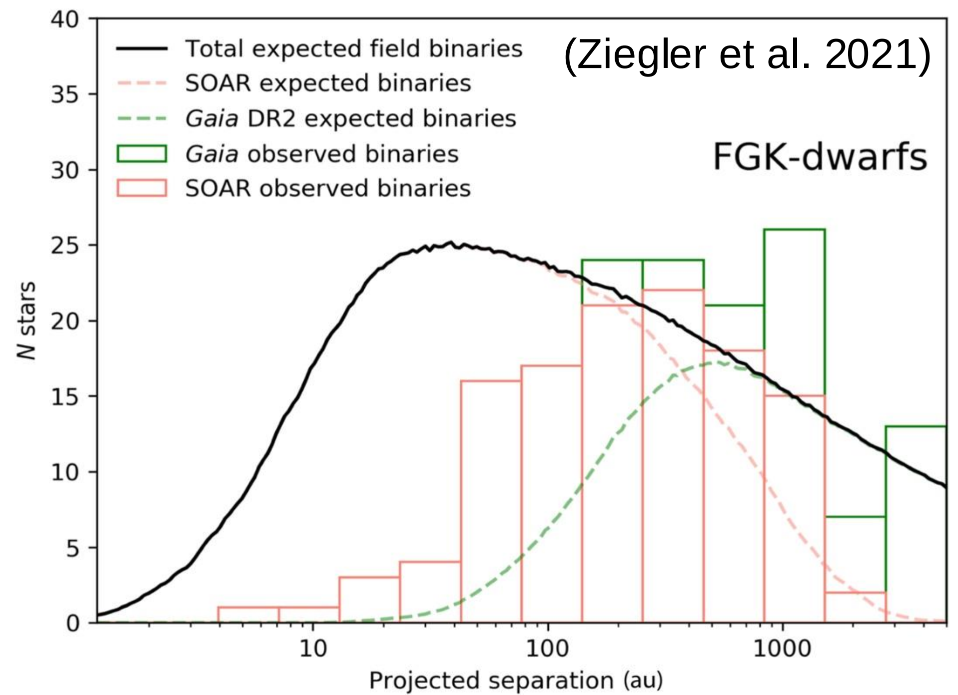
# At ~100-2000 AU, Broad Consistency With Field

### No large suppression/excess for planet samples from Kepler, K2, TESS, or nearby M dwarfs.

(See papers by Horch, Wang, Kraus, Baranec, Ziegler, Furlan, Matson, Hirsch, Howell, Clark, Fontanive, and others, based on followup by so many folks in our community!)

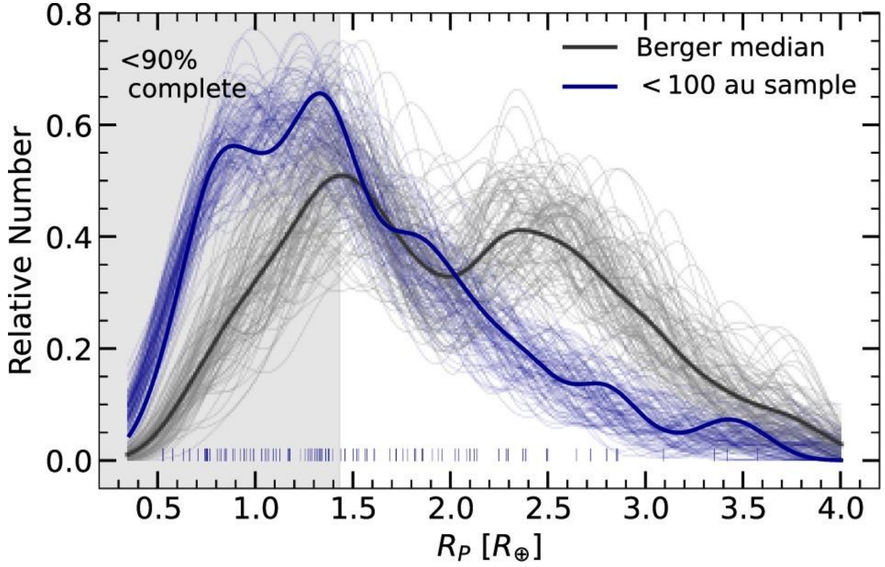


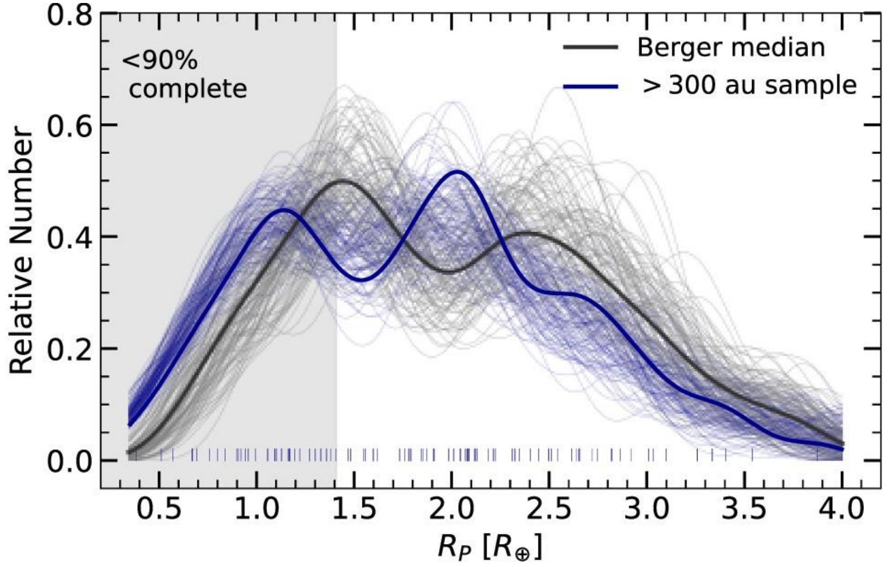



# Do Binaries Make Different Planets?

From Sullivan et al. (2024):




Close binaries (<100 AU) have few sub-Neptunes, but many super-Earths.



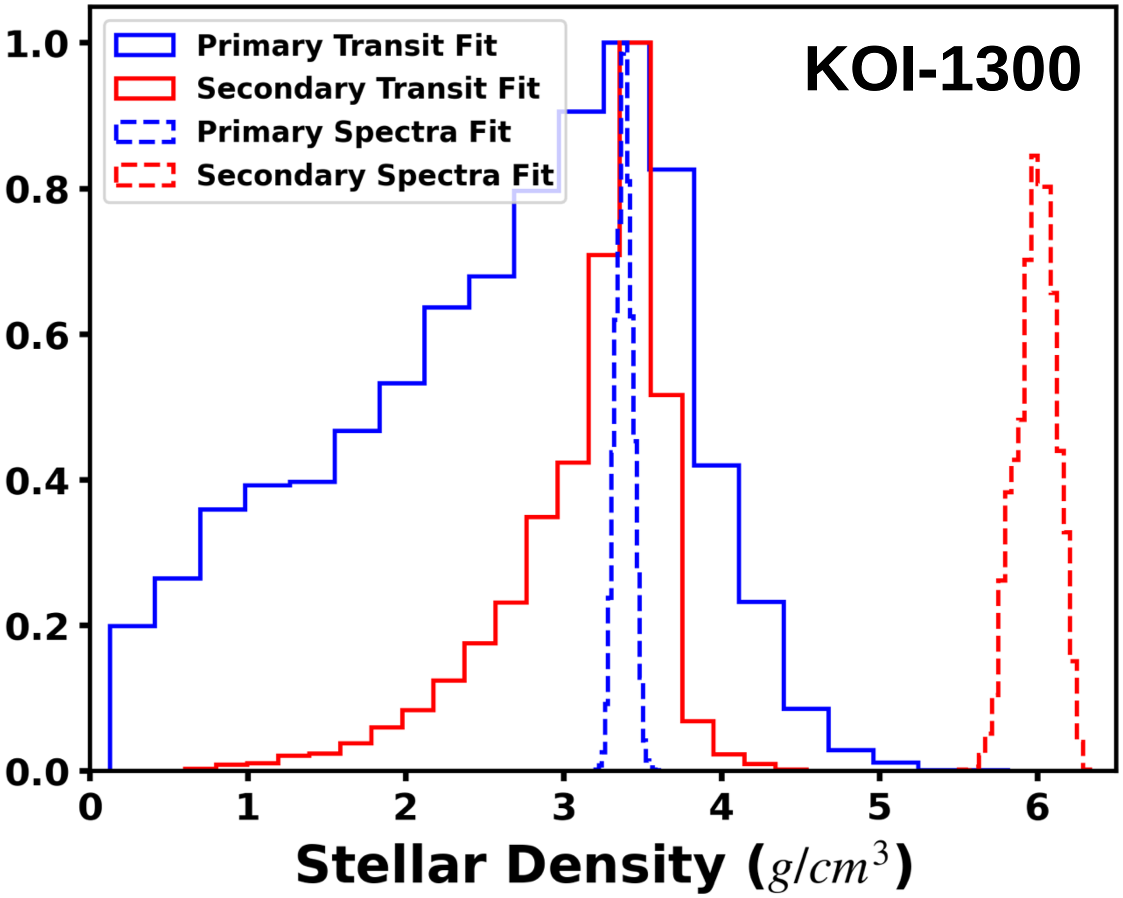

Wide binaries (>300 AU) have a distribution more like the full KOI sample (but still no radius gap?)

Does tidally truncating the disk change the mass budget or mix of ingredients? Truncate inside a given ice line, and you lose those ices from your planets.

**Is this a route to controlled experiments in planet formation?**

# Do Both Stars Form Planets?

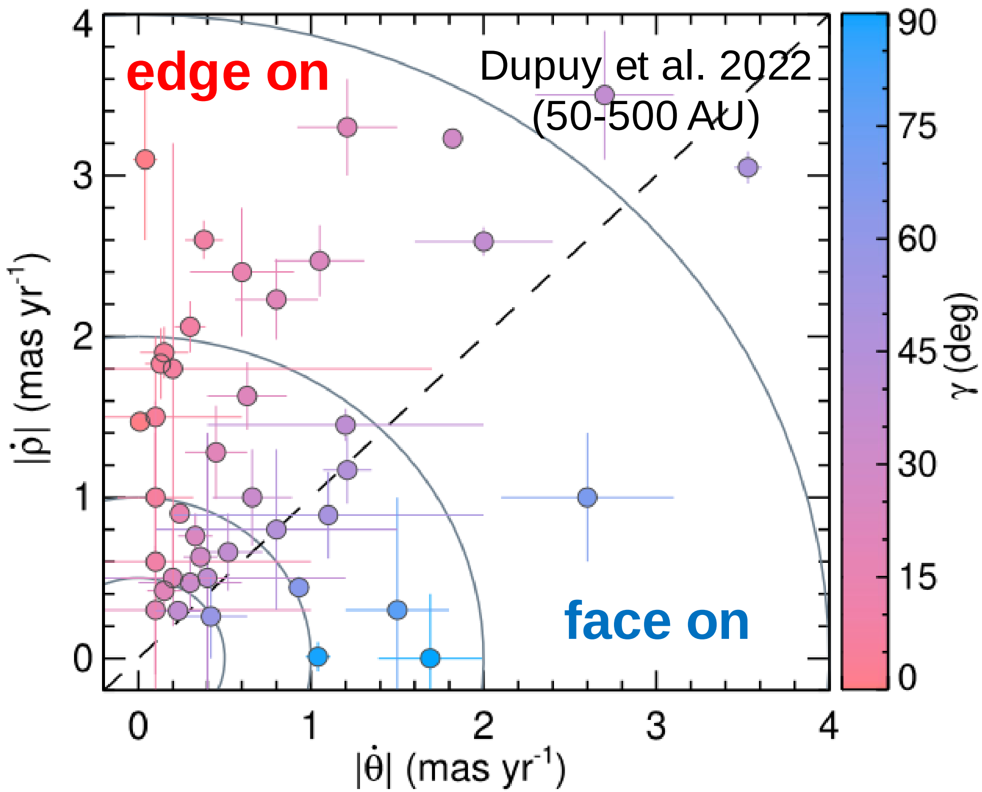
From Nathanael Burns-Watson's Talk:

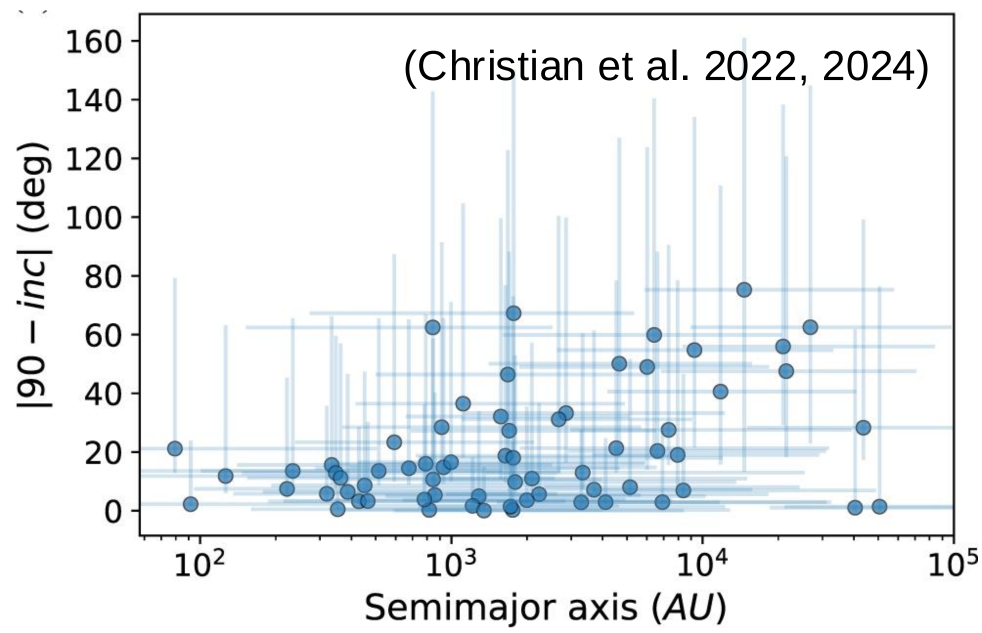



(An unambiguously circumprimary planet)

**Can the frequency and properties of circum-primary versus circum-secondary planets reveal the mass budgets and accretion/disk histories of planet formation?**

# Do Binary-Planet Dynamics Matter?




If close binary suppression is from late-time ejection, dynamically calm orbits (aligned, circular) might be the key. Planet-Binary correlation (but not strict alignment) is common at <700 AU.

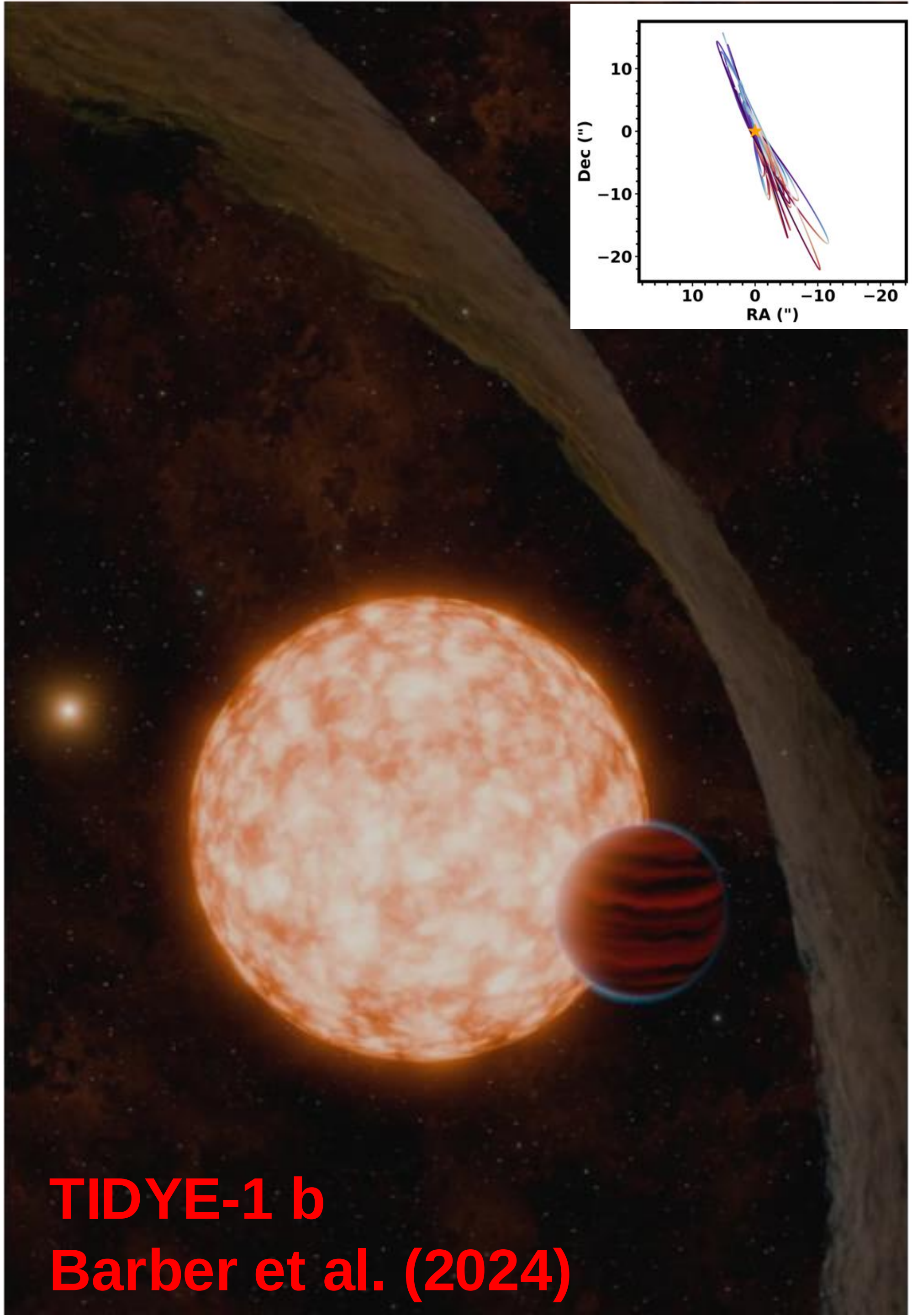
**What is the degree of alignment in the <50 AU regime where planet occurrence is suppressed?**

# Can We Catch The Physics in Action?

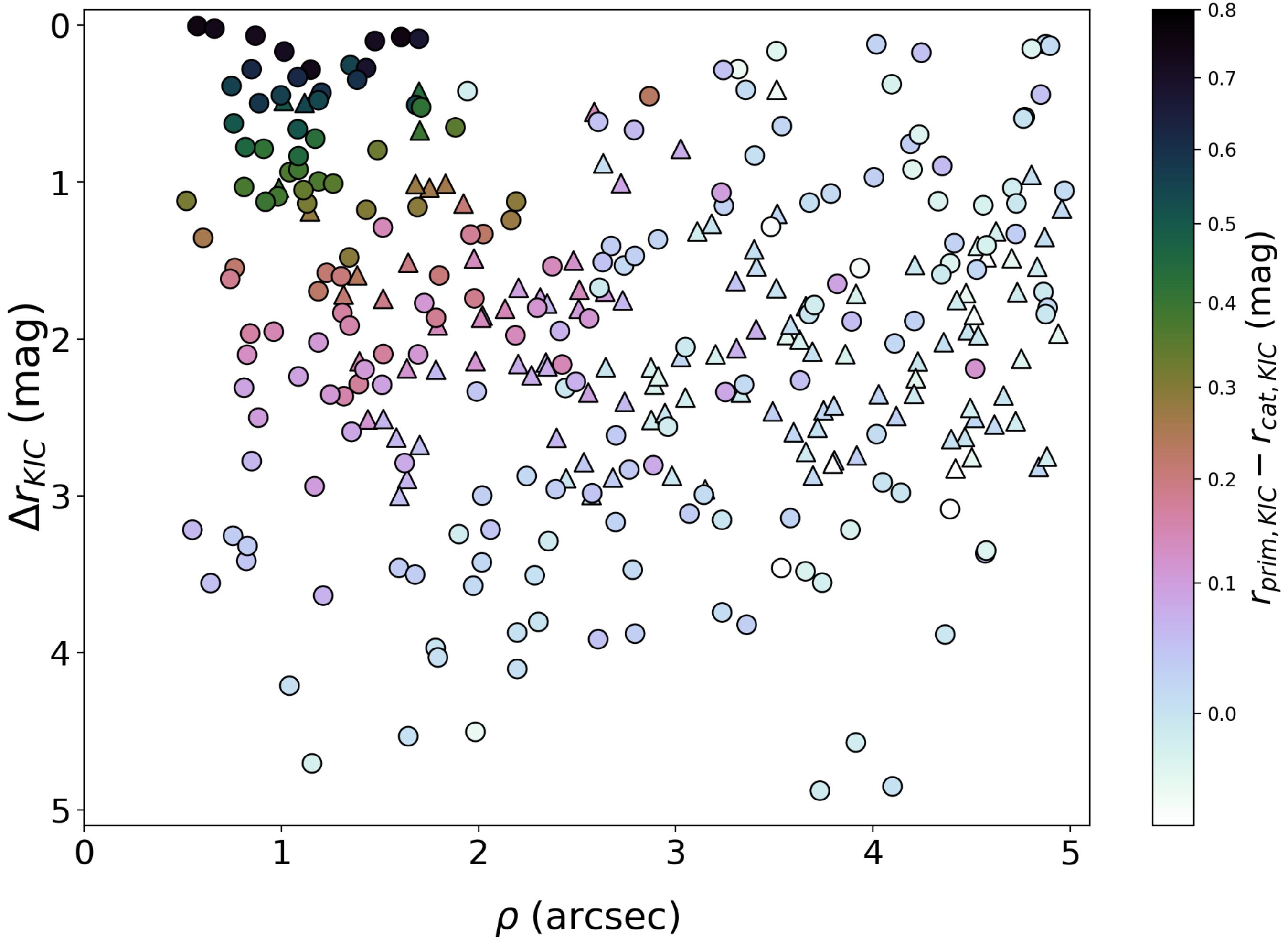
TIDYE-1 (IRAS 04125+2902) is a 3 Myr binary system that hosts a transiting planet and a disk. The planet, primary star spin, and outer binary orbit are all seen edge-on.

However, the disk is tilted by 60 degrees!

**Can we model the past (and future) of these systems to connect initial conditions with final configurations?**

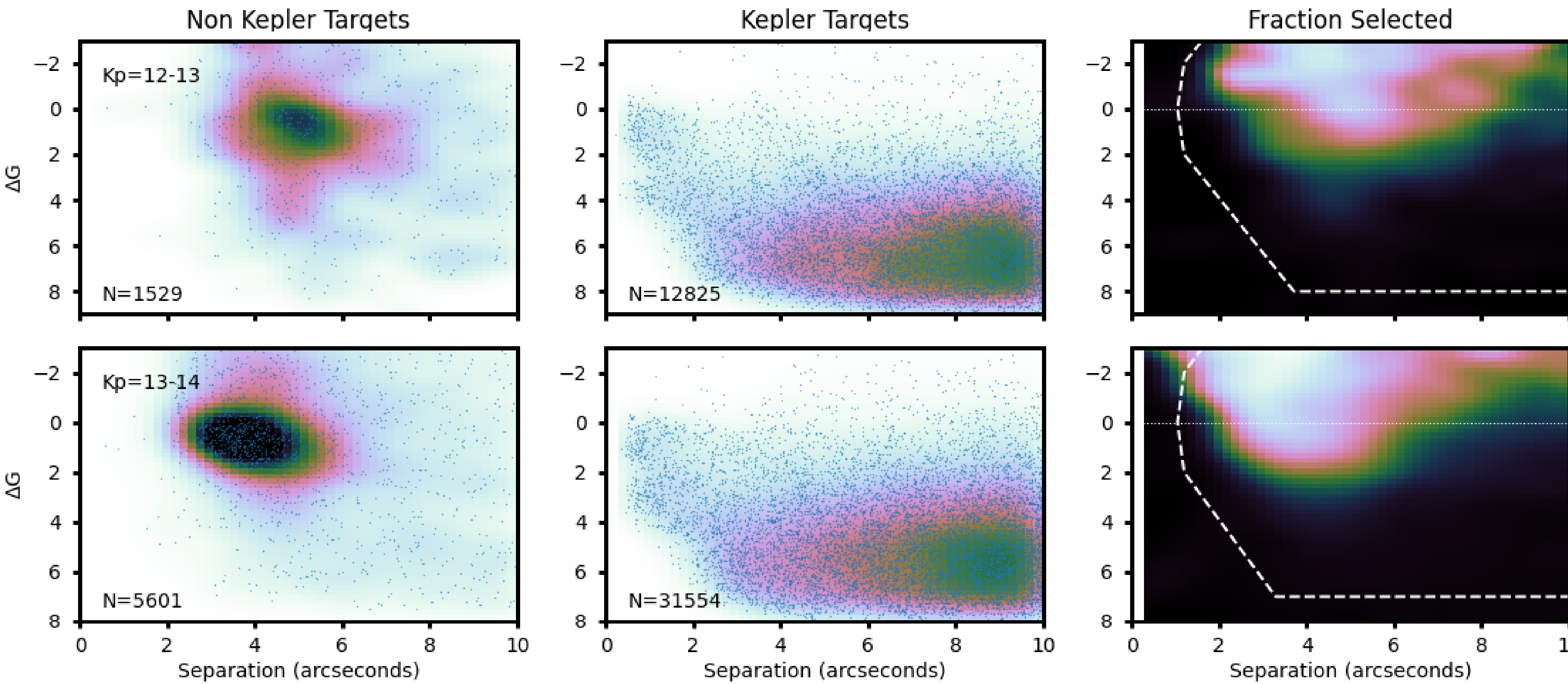


# We Need to Control Sample Biases



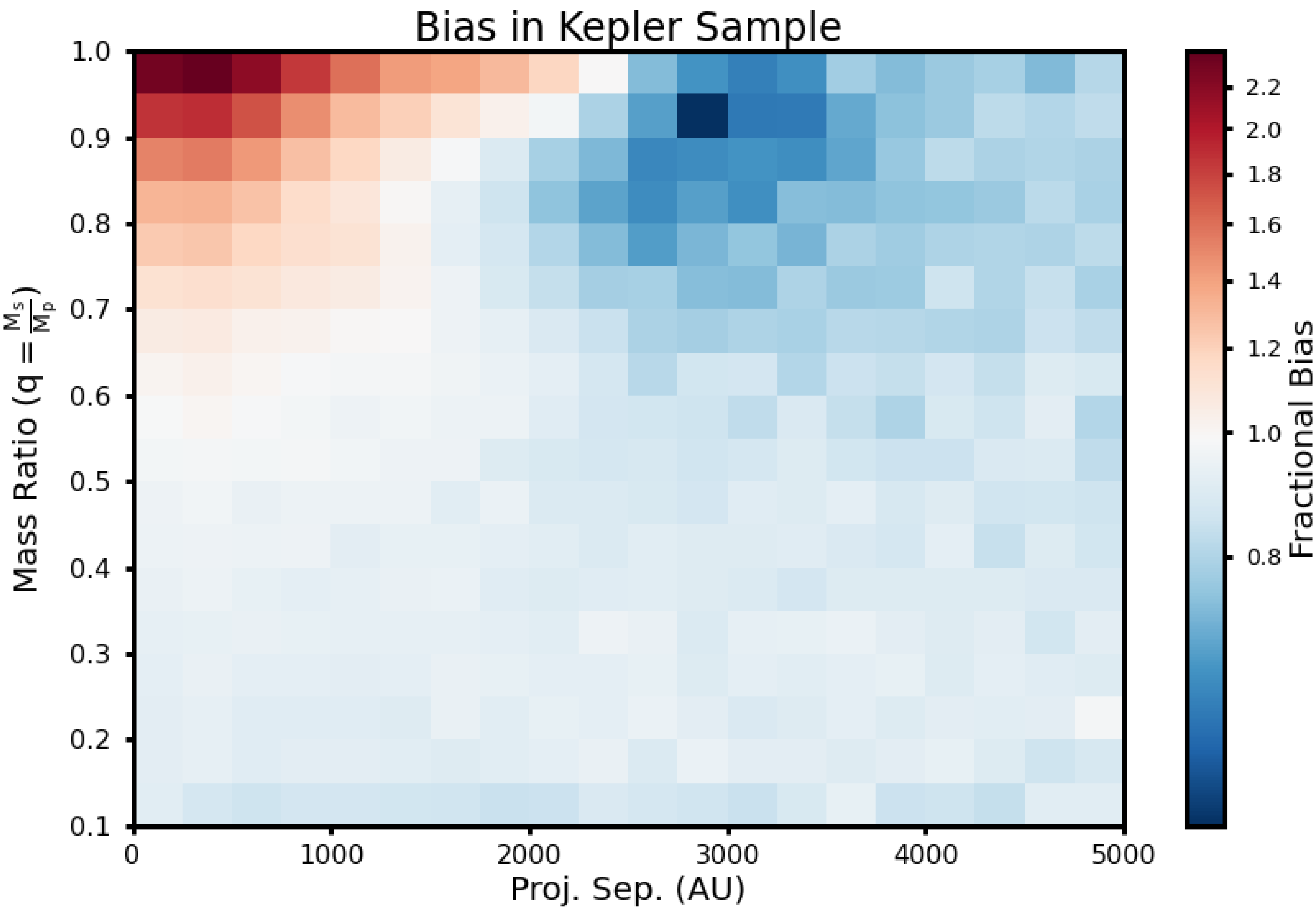

As a pre-Gaia survey, the Kepler sample is **Malmquist biased** – spatially unresolved binaries are over-represented. In the Gaia era, this is easy enough to calibrate.

# We Need to Control Sample Biases



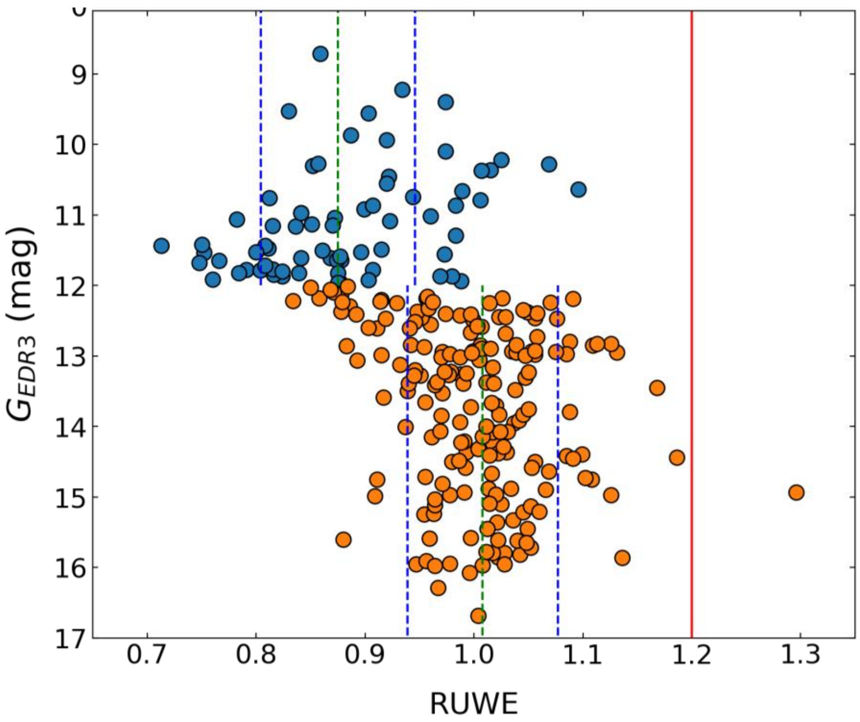

Kepler target selection down-weighted stars with bright neighbors that would dilute away the Earths. This **flux-dilution bias** was great for maximizing sensitivity to small planets, but rejected many intermediate- and wide-separation binaries!

# We Need to Control Sample Biases




These biases combine to bias binary occurrence at the 30-100% level - must be corrected to understand binary demographics.

# We Need to Build Larger Samples




**RUWE measures the excess scatter in Gaia astrometry.**

High RUWE (>1.2) indicates likely binarity, calibrated via KOIs with AO imaging and no companions.

**Renormalized Unit Weight Error = RUWE (roo-ee?)**

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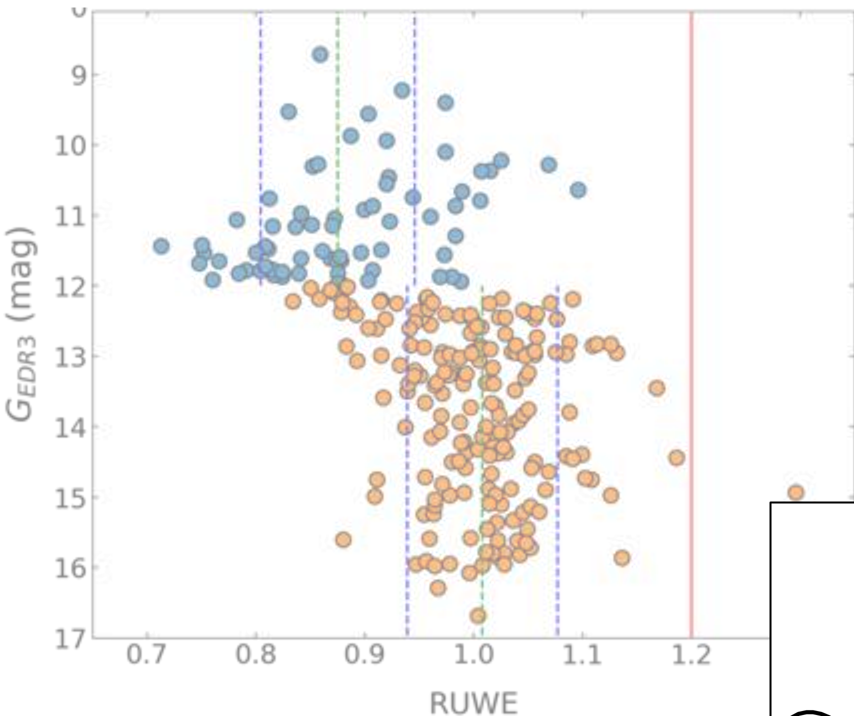
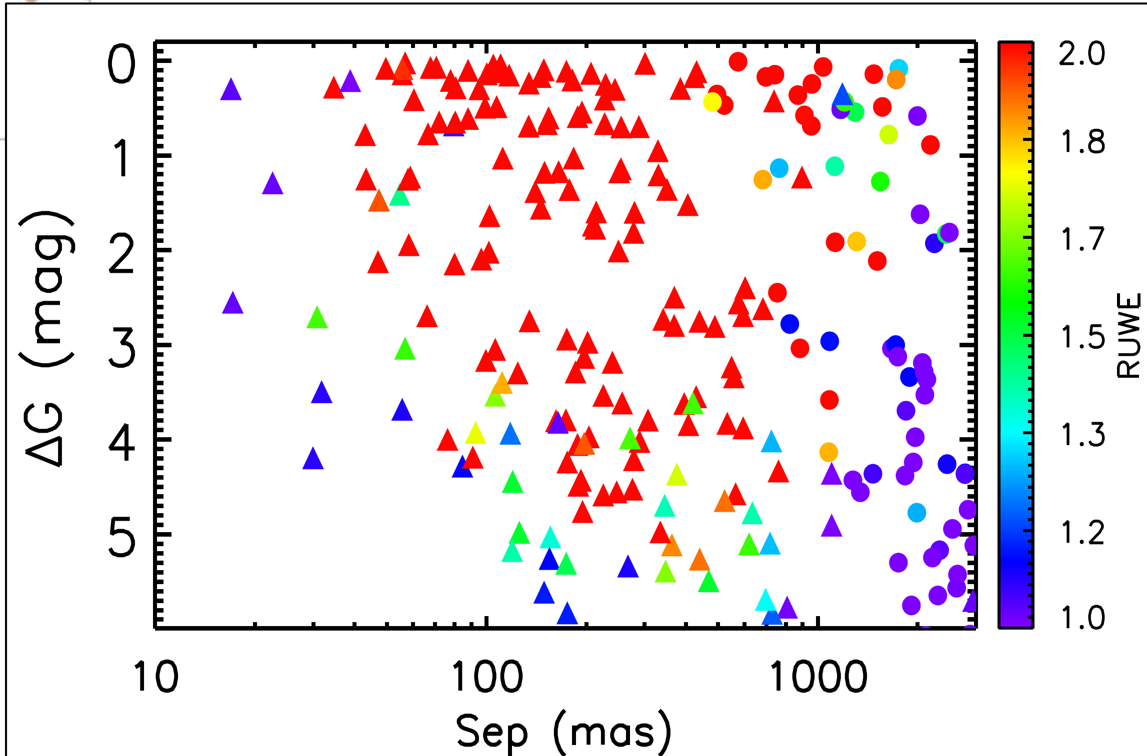



**RUWE measures the excess scatter in Gaia astrometry.**

High RUWE (>1.2) indicates likely binarity, calibrated via KOIs with AO imaging and no companions.

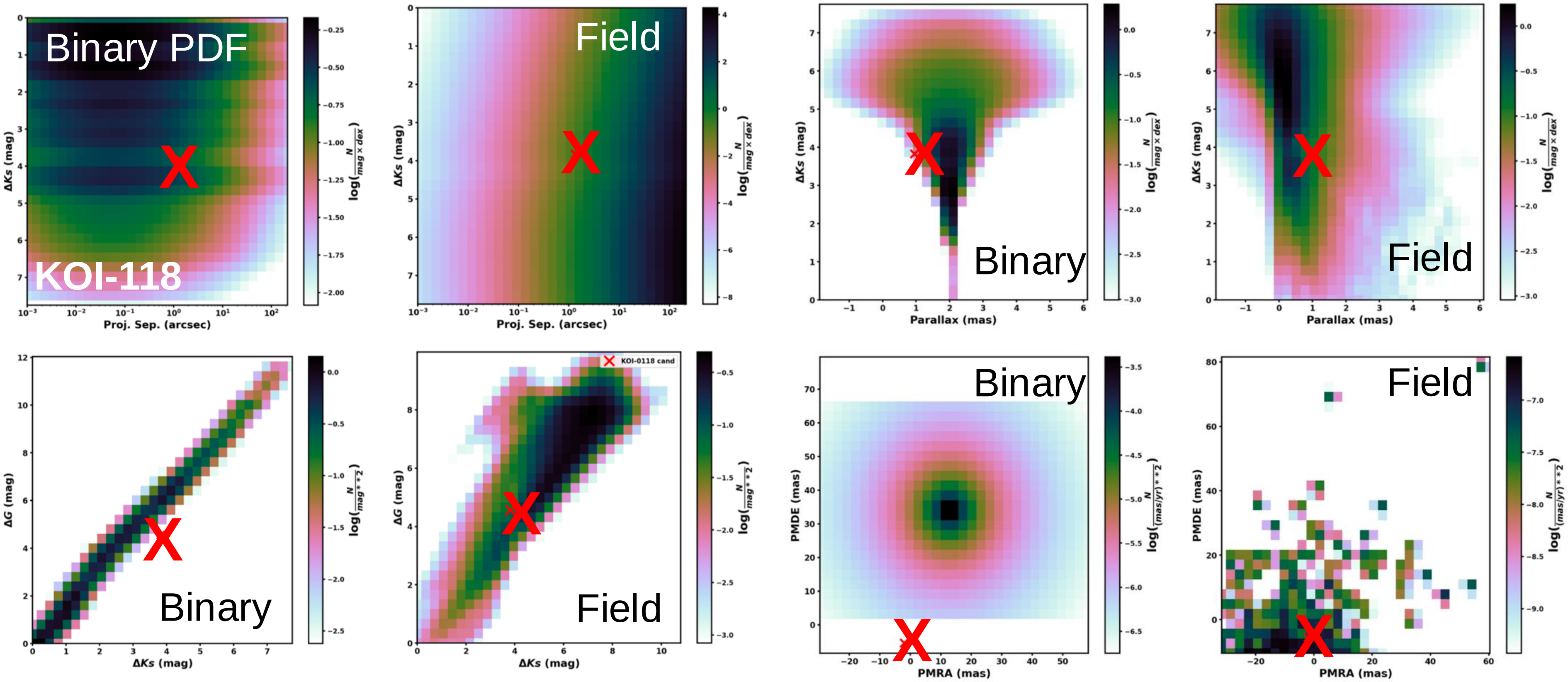
**RUWE maps to separation+contrast!**

RUWE < 1.2 rules out companions as well as AO/speckle on 8-10m telescopes, while never observing 85% of sample.



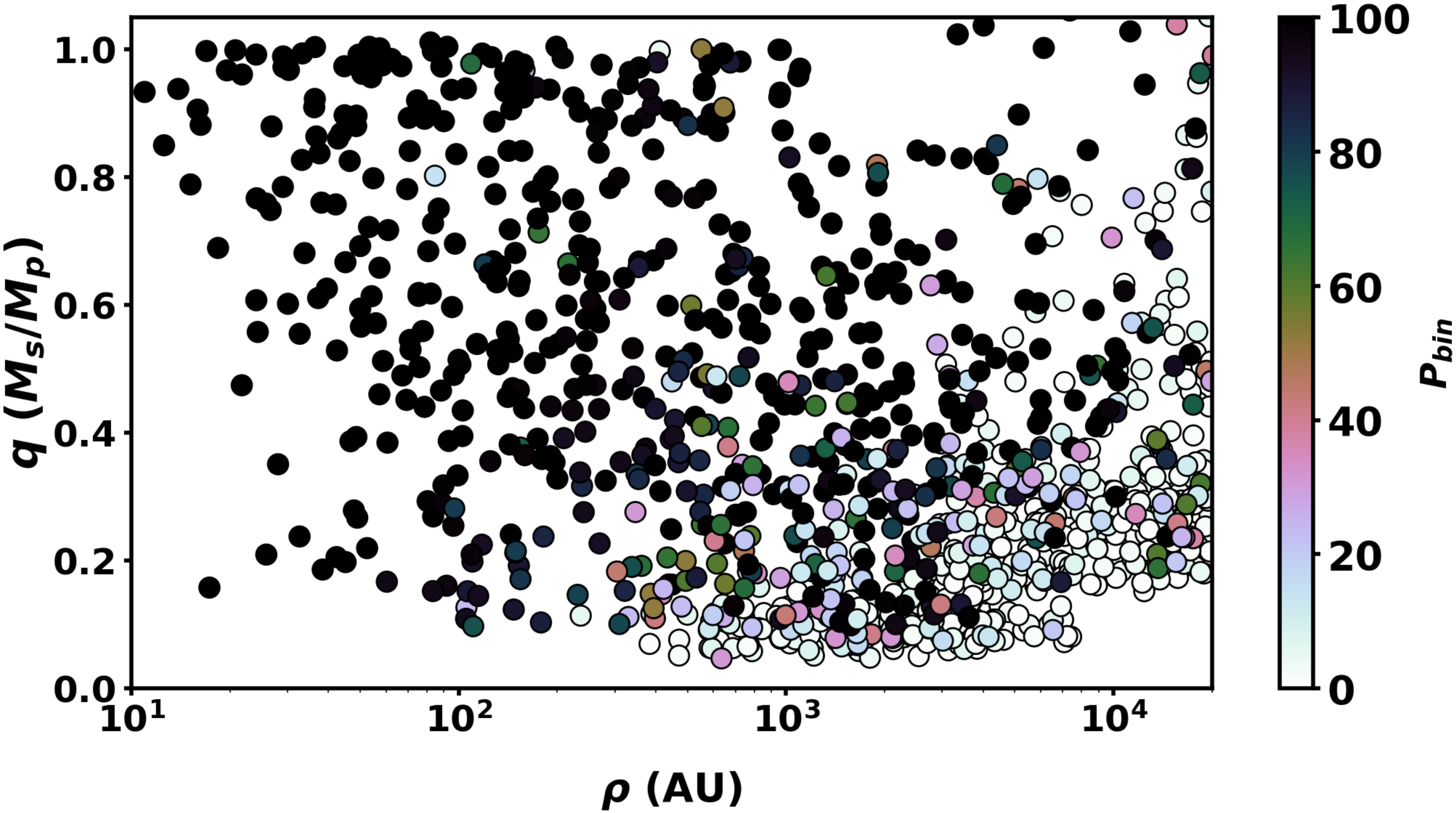
# We Need to Clean the Chance Alignments

Is a “candidate companion” a binary? There have been past assessments via astrometry (e.g., Colton, Dupuy, Lester) and CMDs (Hirsch, Atkinson).



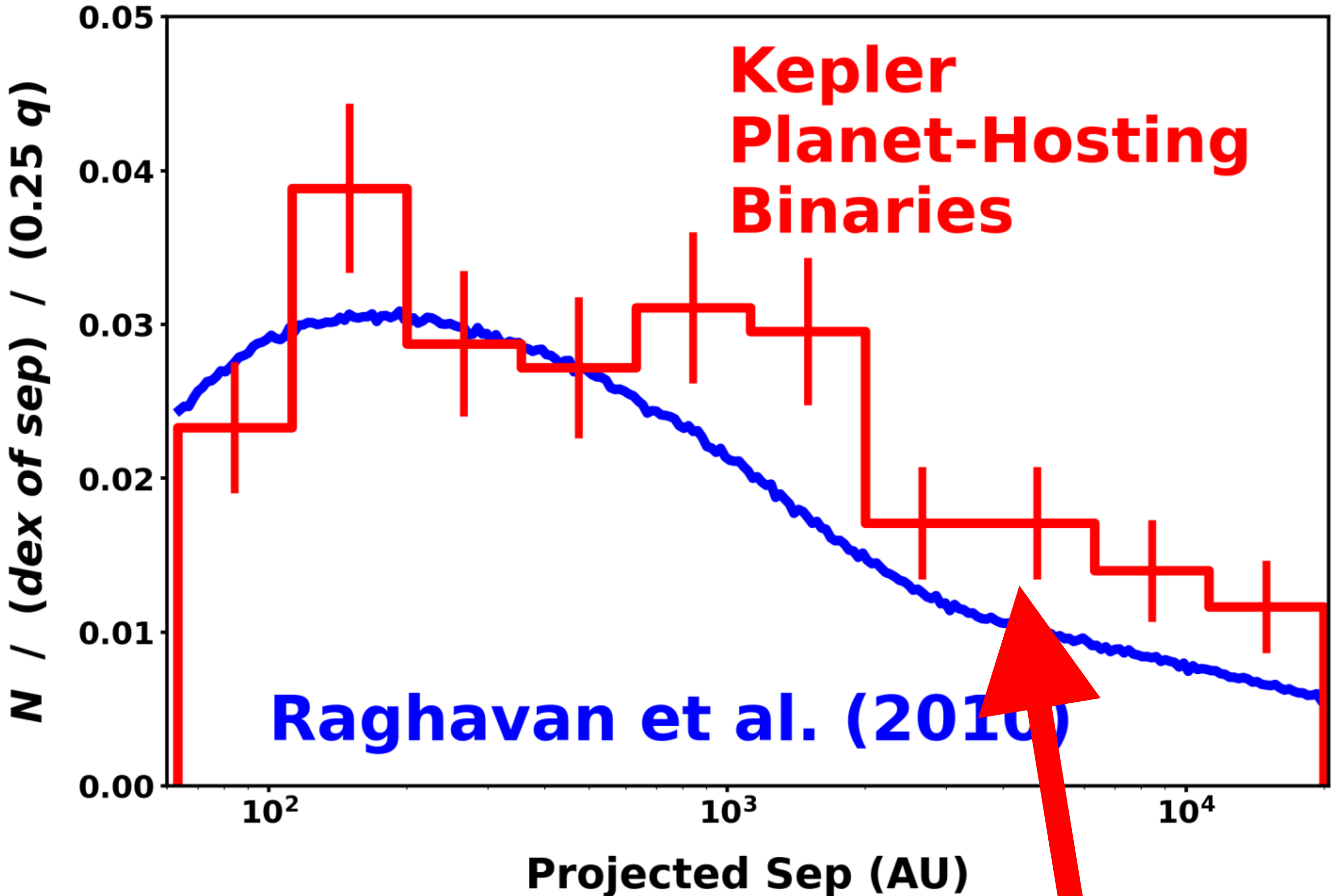

Merging it all and being uniformly probabilistic: **What is the relative likelihood of drawing on object with the candidate binary’s properties (separation, contrast(s), proper motion, parallax) from a field model (empirical Gaia) or a binary model (simulated Raghavan)?**

# We Need to Clean the Chance Alignments




Out of **~2500** AO/speckle candidates and **~90,000** wider Gaia neighbors, there are **626** with $P_{binary}$ > 80% and **191** with 20%<Pbinary<80%. All the rest can be ignored.

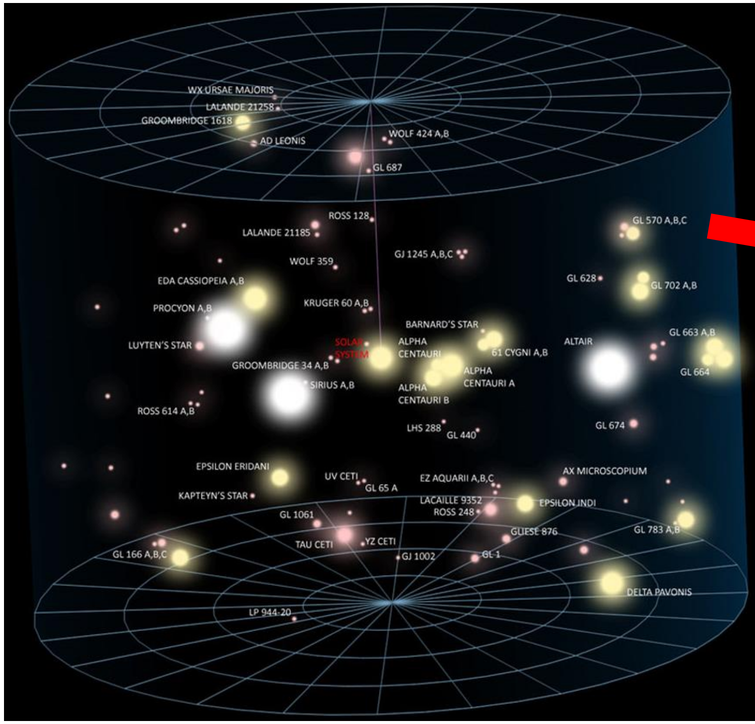
# Unexpected Discoveries Await




We can mock-survey the Kepler field, assuming planet-hosting stars match known field-binary demographics.

**Beyond 1000 AU, planets are more common in binary systems! Unexpected, but should it be? Perhaps a case of (environmental) correlation, rather than causation?**

# And Binaries Await in Your Future Surveys!

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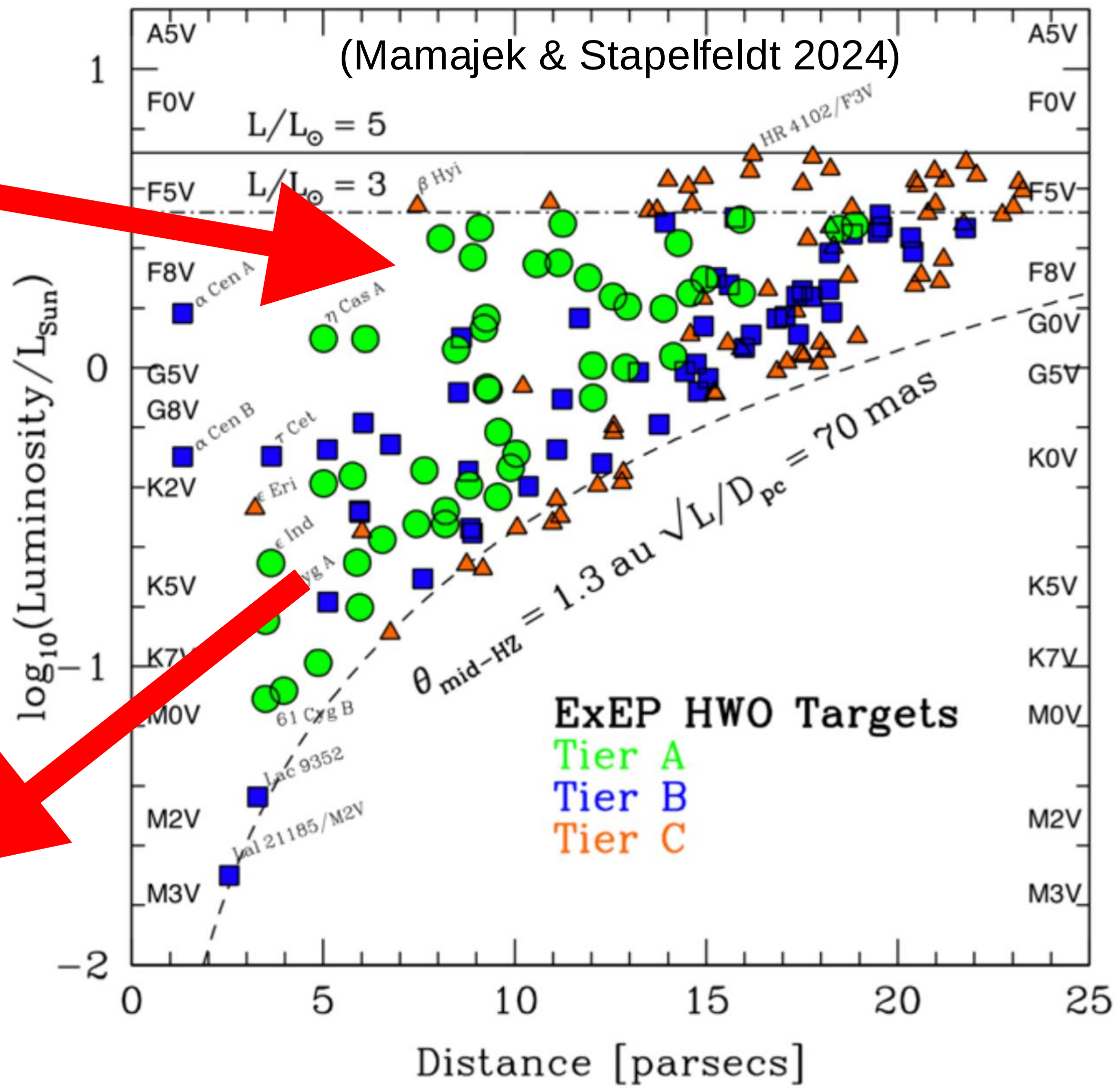
|---|---|
| Alessandro Sozetti INAF) | The Gaia Mission and DR4 |
| Knicole Colon (GSFC) | NASA's Pandora SmallSat Mission: Mu |
| Davy Kirkpatrick (IPAC-Caltech) | The SPHEREx Mission: An All-sky S |
| Rob Zellem (GSFC) | NASA's Nancy Grace Roman Spac |
| Annelies Mortier (U Birmingham) | The PLATO Mission |
| Peter Plavchan (GMU) | The Landolt mission |
| Mark Swain (JPL) | The Ariel Mission |
| Joshua Pepper (NASA HQ) | NASA's Habitable Worlds Observatory: |




(See posters by Clark, Harada, Hartman, Howell, Kesseli, Rawle, and more.)

# Takeaway Points

Planet-hosting binaries pose challenges. **They are pervasive in our samples and bias our demographics, and the influences are blurred across astrophysical processes.**

They also offer a valuable and rare opportunity to pose testable predictions. **Differences in planetary outcomes can be tied to predictable influences by the binary companion.**

We must look beyond planet existence. **What planets and what system architectures form/survive in binaries?**

They're going to remain a fundamental part of every future exoplanet mission, including HWO. **We must understand their influence to optimize our mission planning/execution.**