Hands-On Session 1: Exoplanet Occurrence Rates

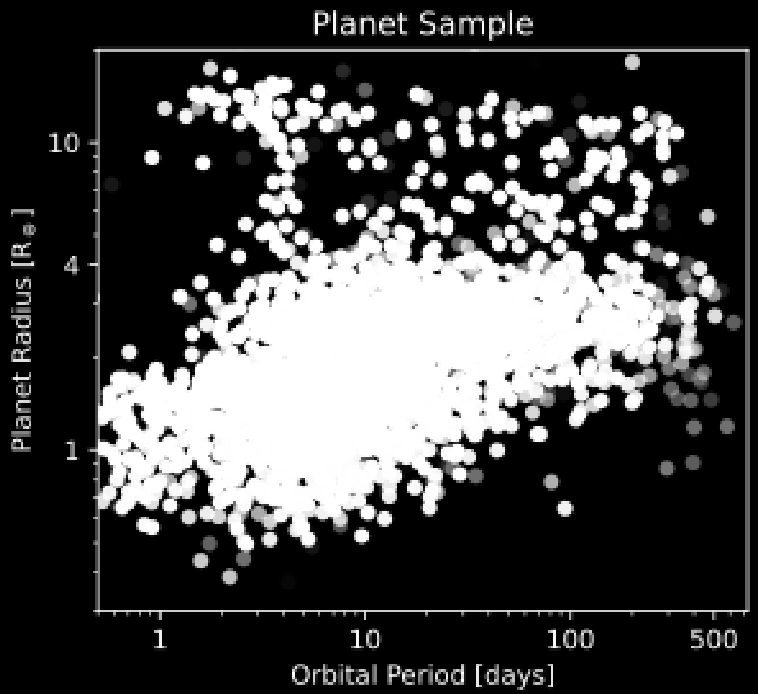
Galen Bergsten, Ilaria Pascucci, Gijs Mulders

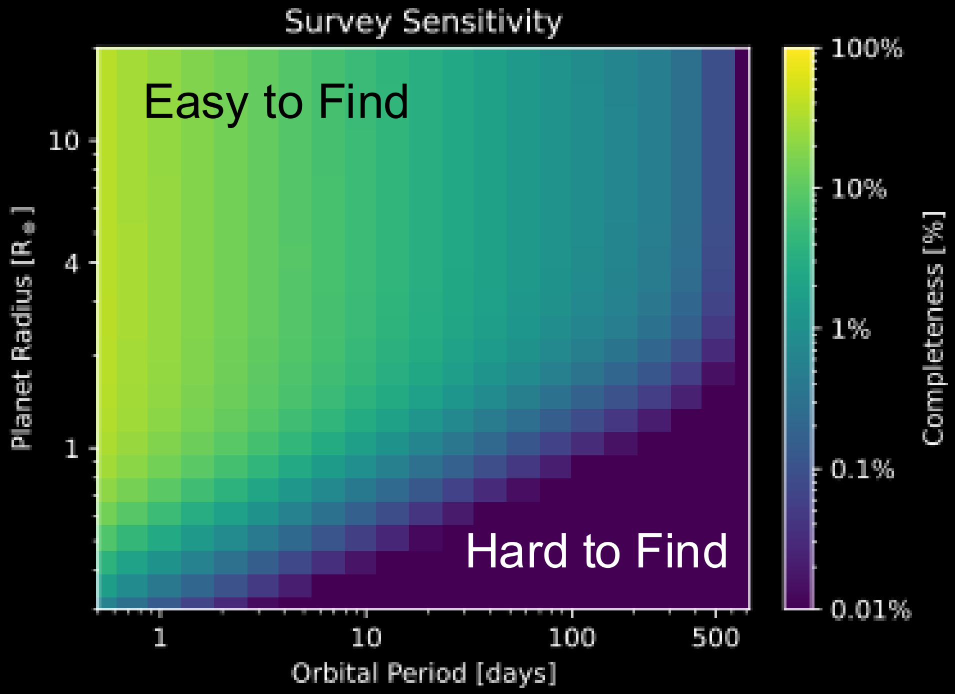
Exoplanet Occurrence Rates: the intrinsic (de-biased) frequencies of planets

You'll learn how to:

- calculate occurrence rates
  - as functions of planet & star properties.
- model occurrence rate distributions
  - using data from one or more surveys.

BARDIC


Planet Sample
Planet Radius [R⊕]
10
4
1
1
10
100
500
Orbital Period [days]


Survey Sensitivity
Easy to Find
Hard to Find
Planet Radius [R⊕]
10
4
1
1
10
100
500
Orbital Period [days]
100%
10%
1%
0.1%
0.01%
Completeness [%]

Example:

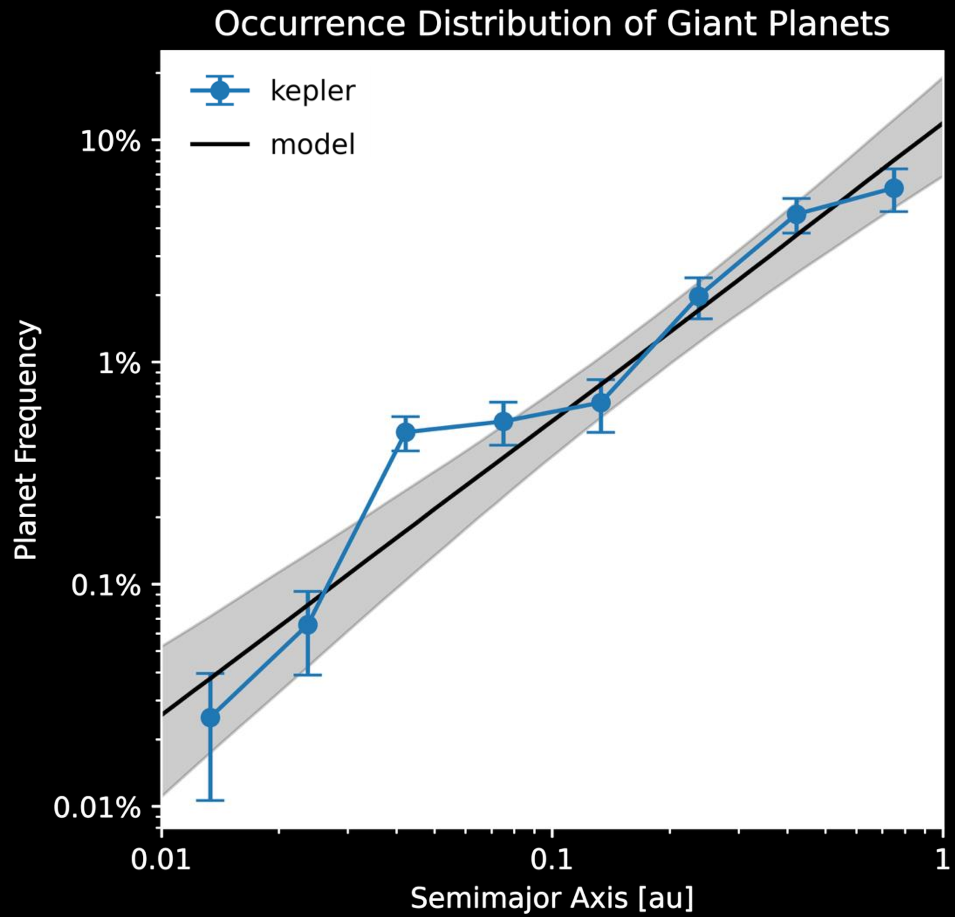
You look at 10 stars,
and find 1 planet.

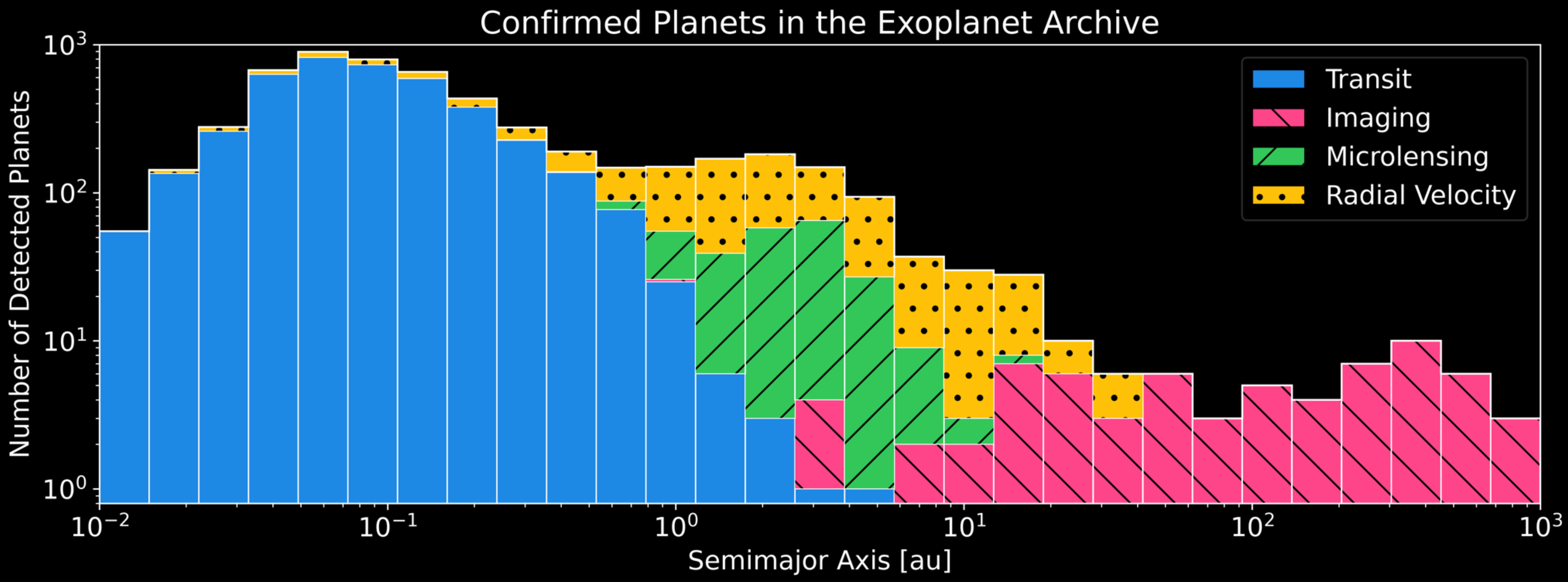
Observed Frequency: 10%

But you're only 50% complete to finding that kind of planet.

(i.e., you miss half of them)

Intrinsic Occurrence: 20%



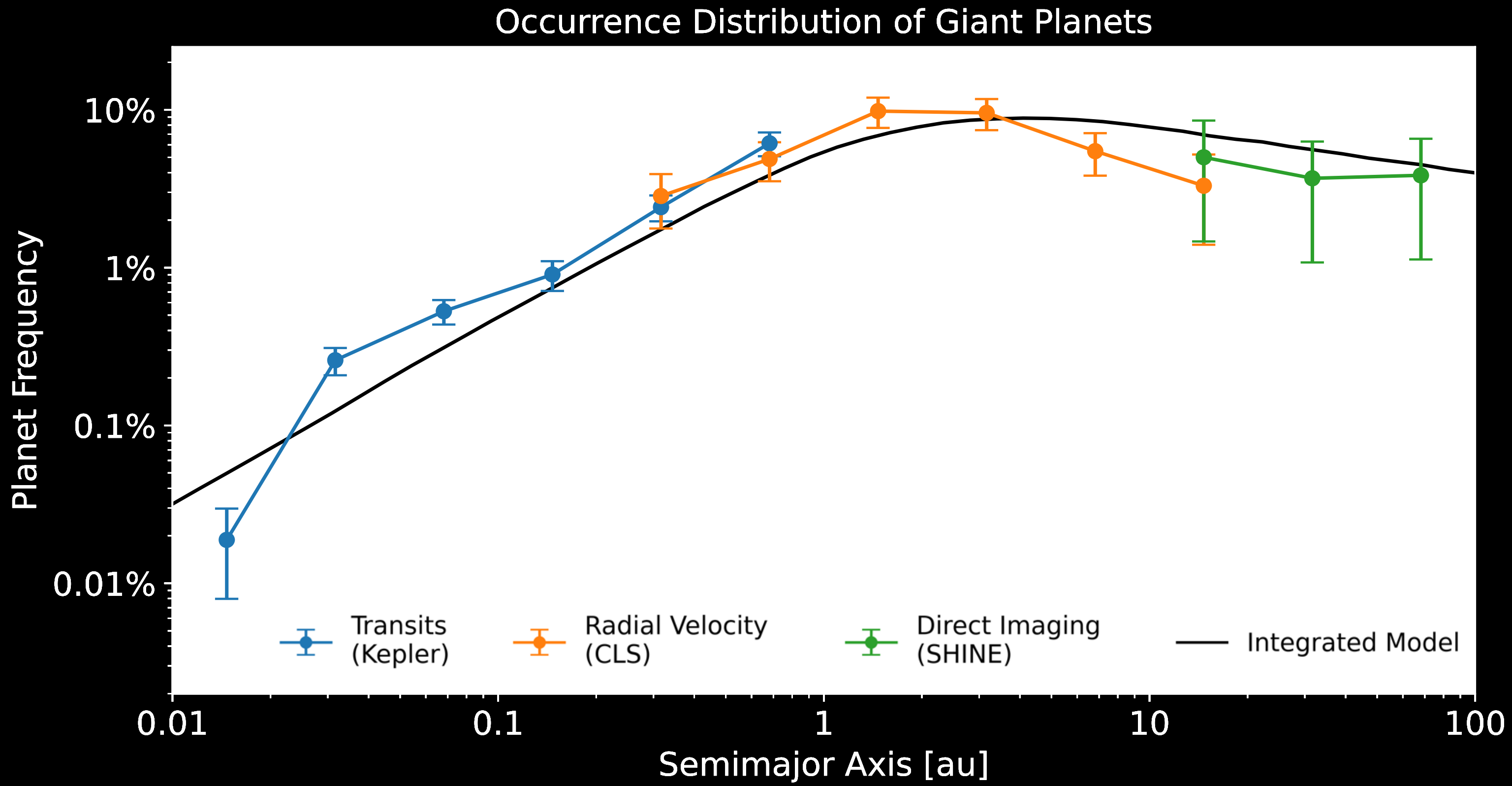


Combined Demographics:
using data from multiple surveys/methods to better study planet populations

Clanton & Gaudi (2014, 2016); Kunimoto & Bryson (2021)

Samples from three different surveys: transits, radial velocity, & direct imaging

Every method is good at finding giant planets.



How do occurrence measurements change:

1. with different combinations of survey data?
2. depending on what type of model you fit?
3. as a function of stellar mass?

Introduction to Hands-On Session II

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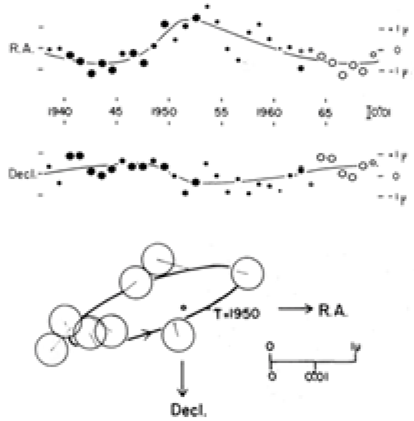
Astrometry for Exoplanets



Radial Velocities (RVs) for Exoplanets: since late 1980s

Astrometry for Exoplanets: since 1963 (even 1855!)

Astrometric Study of Barnard's Star from Plates Taken with the 24-inch Sproul Refractor

PETER VAN DE KAMP

Sproul Observatory, Swarthmore College

(Received 21 June 1963)

Twenty-five consecutive years of photographic observations of Barnard's star show deviations from uniform proper motion and secular acceleration which can be represented by Keplerian motion with a period of 24 yr and semi-axis major of $''.0245 \pm ''.002$ (p.e.). Assuming a value of $0.15\odot$ for the mass of Barnard's star, the mass of the companion proves to be $0.0015\odot$, or 1.6 times the mass of Jupiter.

Astrometry for Exoplanets

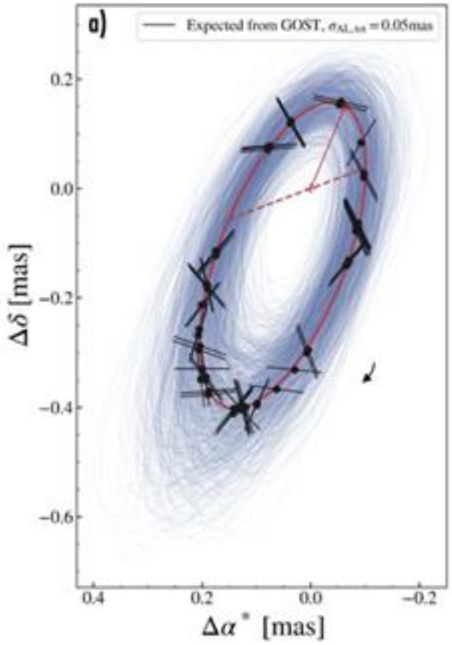
Radial Velocities (RVs) for Exoplanets: since late 1980s

Astrometry for Exoplanets: since 1963 (even 1855!)

First confirmed RV discoveries: 1995

First confirmed astrometric discoveries:

Gaia (2023 astrometric orbit, 2025 RV confirmation)



Holl et al. (2023)
Stefansson et al. (2025)

This Workshop’s Hands-On Session

2022 Sagan workshop hands-on sessions: use Gaia astrometry to fit exoplanet and brown dwarf orbits. Materials: https://nexsci.caltech.edu/workshop/2022/

This workshop:

- Use Gaia astrometry for planet discovery
- Connect observable astrometric signals to the properties of the unseen planet
- Distinguish stellar companions from planets/brown dwarfs in Gaia

Motivation

Astrometry's fundamental advantage: it looks at **every star in the sky**

- c.f. transits, microlensing, but unlike RV
- With sufficient sensitivity, planets cannot hide from astrometry!
- ALL stellar ages and masses can be probed with this method

Fundamental question for us: **are the position measurements of the star consistent with an inertial (non-accelerating) sky path? If not, what kind of companion(s) is/are tugging it?**

- Most sensitive to massive planets orbiting nearby stars on intermediate/long-periods (few years- or decades-long) orbits.
- More on astrometry in the background reading, Tuesday's talk.

Motivation

Pre-launch Gaia predictions (Perryman+ 2014):

on orbit fitting to the simulated satellite data. With some plausible assumptions on planet occurrences, we find that some 21,000 (±6000) high-mass (~1–15M_J) long-period planets should be discovered out to distances of ~500 pc for the nominal 5 yr mission (including at least 1000–1500 around M dwarfs out to 100 pc), rising to some 70,000 (±20,000) for a 10 yr mission. We indicate some of the expected features of this exoplanet population, amongst

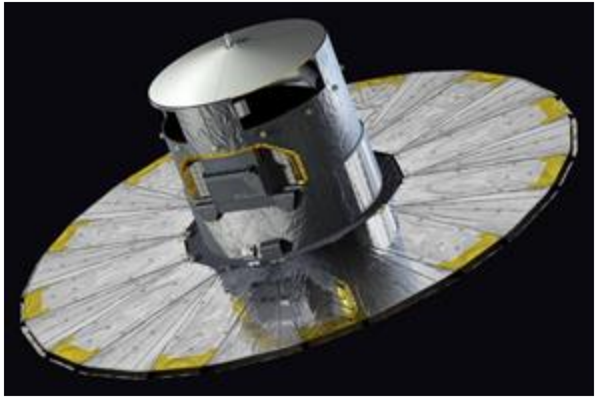
This is not yet possible (DR4, with 5 years of data, will be out in about 1.5 years). But there is still much that can be done now.

- Identify stars being tugged across the sky → guided planet discovery.
- If we have other data, astrometry can still be used to measure masses and fit orbits.
- Demographics: difficult now, but immense promise in the near future.

Motivation

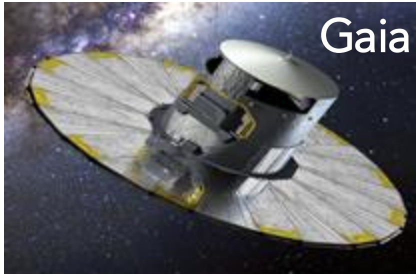
Gaia is the definitive astrometry mission today. Recently decommissioned, 10+ years of data in total, 33 months analyzed in DR3 (most recent release)

Hipparcos was a similar mission 35 years ago, with lower precision and only sensitive to bright stars, but Hipparcos and Gaia complement one another.

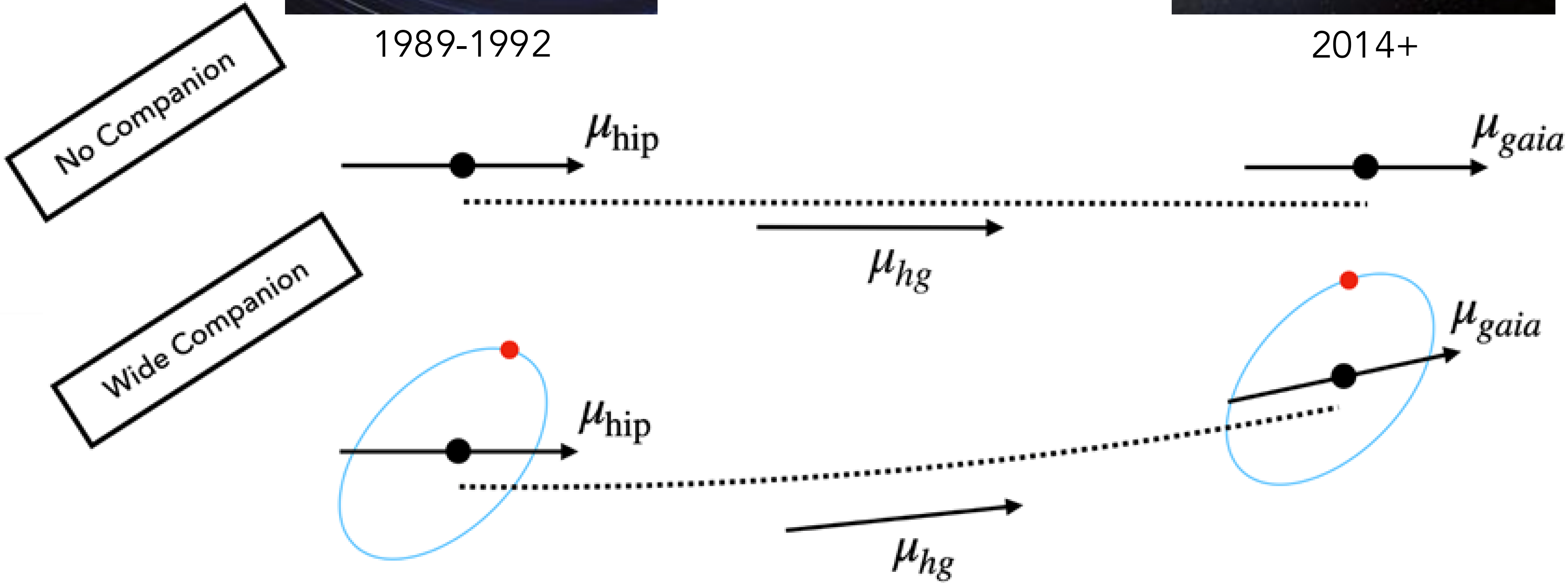


Studying Wide Companions *Now* by Combining Gaia and Hipparcos

1989-1992

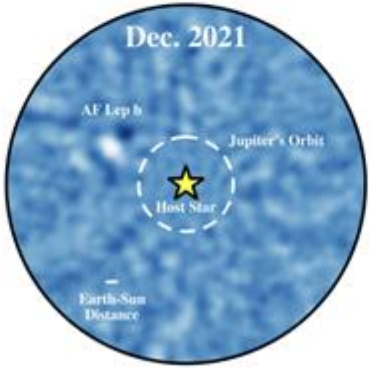


2014+

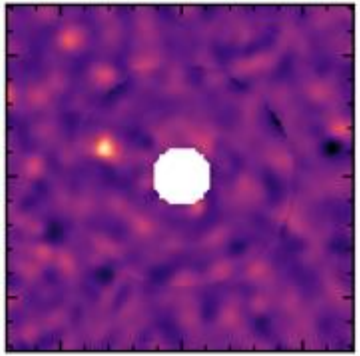


Motivating Example: AF Lep b

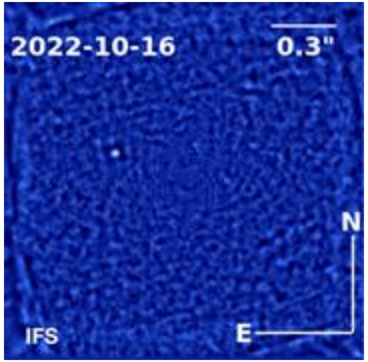
- AF Lep: young, nearby star targeted with exoplanet imaging surveys for years without success
- Astrometry showed AF Lep being tugged across the sky (non-inertial sky path); we imaged it again
- Three groups independently discovered AF Lep b. It is currently the imaged exoplanet with the lowest dynamical mass (about 3 Jupiter masses)



Franson et al. (2023)

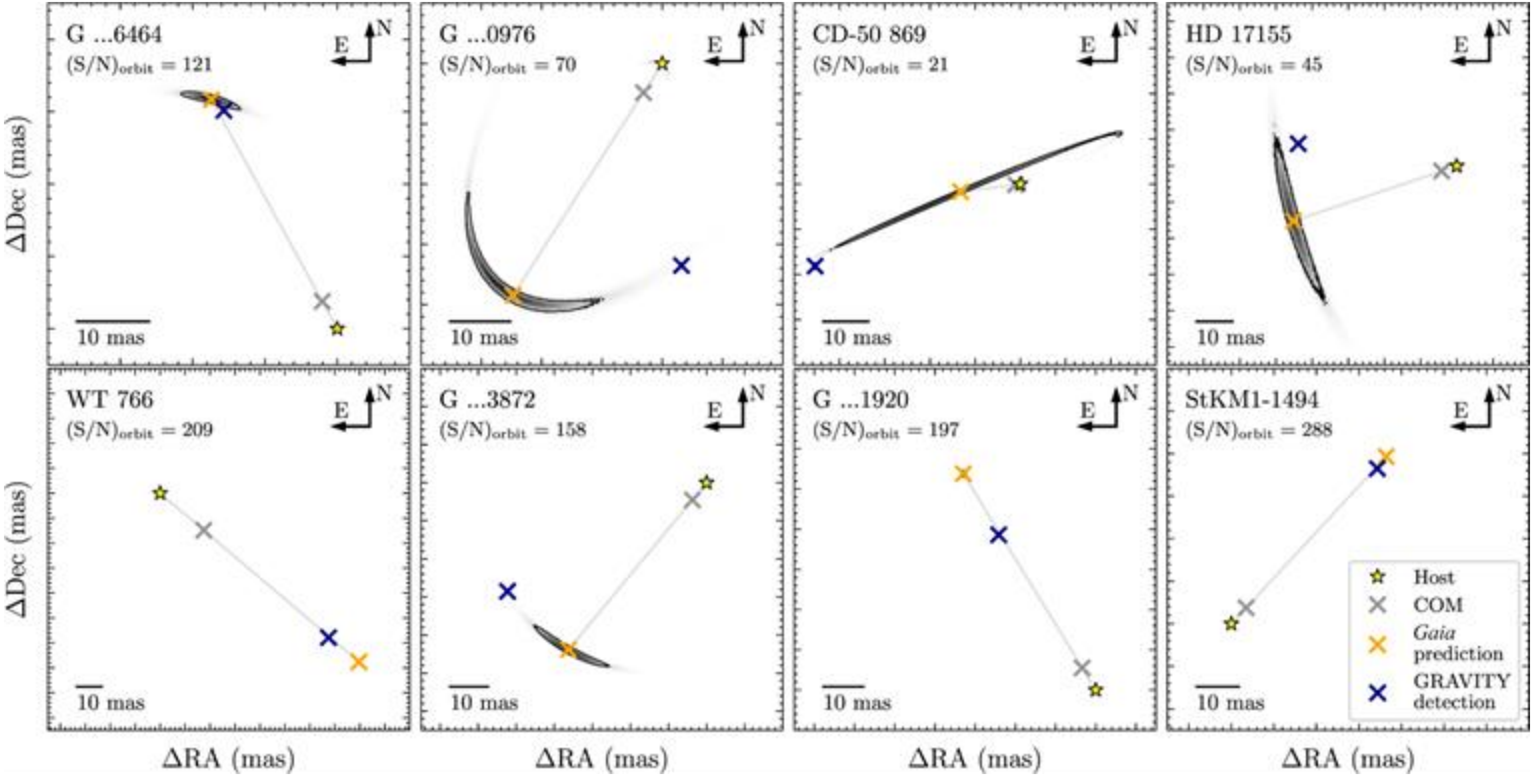


De Rosa et al. (2023)



Mesa et al. (2023)

Gaia Orbits → Imaging Brown Dwarf Companions with GRAVITY



Winterhalder et al. (2024)

Session structure/goals

- Introduction to astrometric catalogs, ancillary information (e.g. stellar ages, cross-matches)
- Exploration of Gaia data
- Gotchas, systematics, binary stars
- Identifying targets for follow-up imaging
- Statistical relationships between companion mass and astrometric & RV tugs

Session structure/goals

We hope to help you build:

- A facility and understanding of Gaia data, including its limitations
- An ability to use astrometry to complement other data/observing techniques
- Informed expectations for Gaia DR4/demographics

Group projects

Three options:

1. A detailed look at how to use astrometry to pre-select the best stars for imaging and discovering new planets
2. Gaia astrometry and binary stars: how to identify them with ancillary Gaia data, either to weed them out or to study them in their own right
3. A more theoretical exercise deriving the probabilistic relationship between an RV or astrometric acceleration, a companion’s projected separation, and its mass

Preparation

Background reading (https://nexsci.caltech.edu/workshop/2025/handson.shtml):

- Astrometry as a Tool for Discovering and Weighing Faint Companions to Nearby Stars, Brandt 2024
- Gaia: Ten Years of Surveying the Milky Way and Beyond, Brown 2025
- Gaia's binary star renaissance, El-Badry 2024

If you are a newcomer to Python:

- https://nexsci.caltech.edu/workshop/Python_Introduction_Timothy_Brandt.pdf