Detecting and Weighing Exoplanets with Absolute Astrometry

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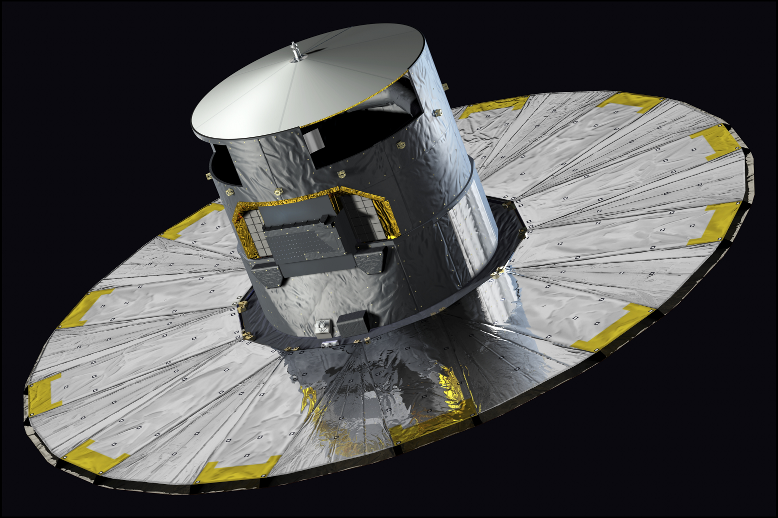
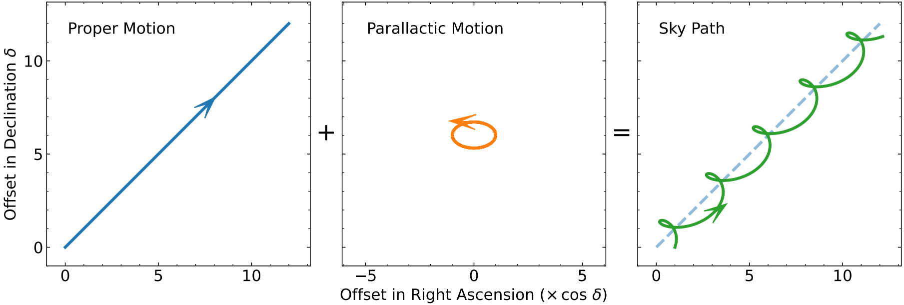
with Qier An, G. Mirek Brandt, Yiting Li, Trent Dupuy, Jackie Faherty, Brendan Bowler, Tyler Groff, Jeff Chilcote, Thayne Currie, Motohide Tamura, Masayuki Kuzuhara, the SEEDS and CHARIS teams, and many others

22 July 2025



Astrometry: measurements of a star's sky position

Figure shows an inertial sky path.



Position $\times 2$, proper motion $\times 2$, parallax $\rightarrow$ 5 parameters

If the star is accelerating, 5 parameters are not enough.

Pre-launch *Gaia* predictions:

ASTROMETRIC EXOPLANET DETECTION WITH *GAIA*

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ABSTRACT

We provide a revised assessment of the number of exoplanets that should be discovered by *Gaia* astrometry, extending previous studies to a broader range of spectral types, distances, and magnitudes. Our assessment is based on a large representative sample of host stars from the TRILEGAL Galaxy population synthesis model, recent estimates of the exoplanet frequency distributions as a function of stellar type, and detailed simulation of the *Gaia* observations using the updated instrument performance and scanning law. We use two approaches to estimate detectable planetary systems: one based on the signal-to-noise ratio of the astrometric signature per field crossing, easily reproducible and allowing comparisons with previous estimates, and a new and more robust metric based on orbit fitting to the simulated satellite data. With some plausible assumptions on planet occurrences, we find that some 21,000 (±6000) high-mass ($\sim$1–15 M_J) long-period planets should be discovered out to distances of $\sim$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 them $\sim$25–50 intermediate-period ($P \sim$ 2–3 yr) transiting systems.

Gaia DR3: ∼1 billion positions, proper motions
Gaia collaboration 2018, 2021, 2023; Lindegren+ 2018, 2021

Only a few exoplanets thus far.
Holl+ 2023, Halbwachs+ 2023, Stefansson+ 2025

- Why are Gaia planet results slow to come out?
- What can we do in the meantime?
- What should we expect in the near future?

Why are Gaia planet results slow to come out?

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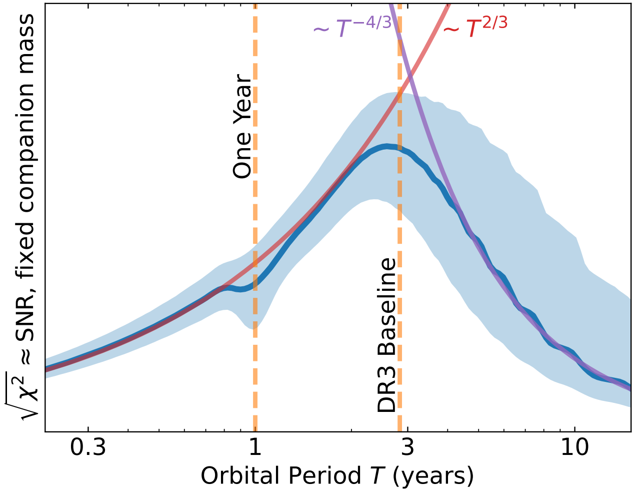
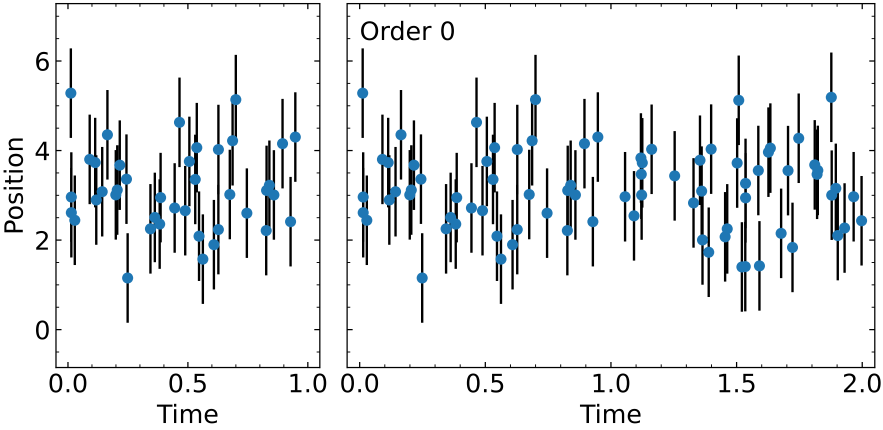
How does Gaia's sensitivity depend on companion period and observing baseline?

Short orbital period: **signal amplitude** $\sim MR \sim MT^{2/3}$

Long orbital period: **acceleration** $\sim M/R^2 \sim MT^{-4/3}$

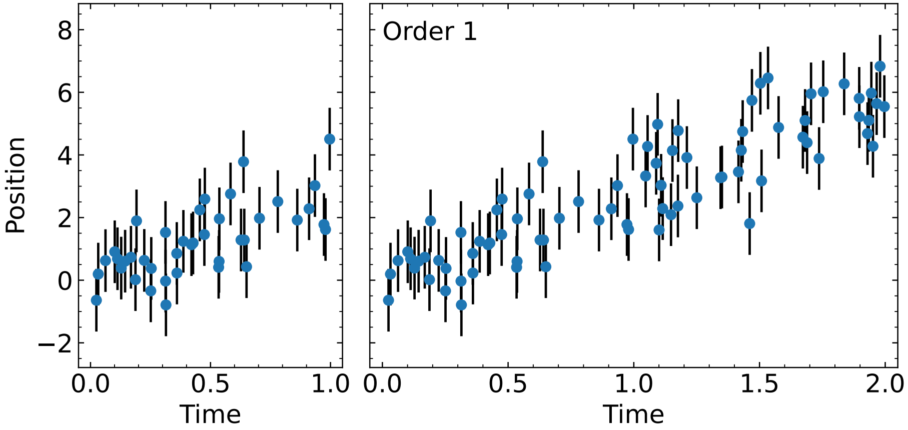


Astrometry measurement scalings: **position & parallax**



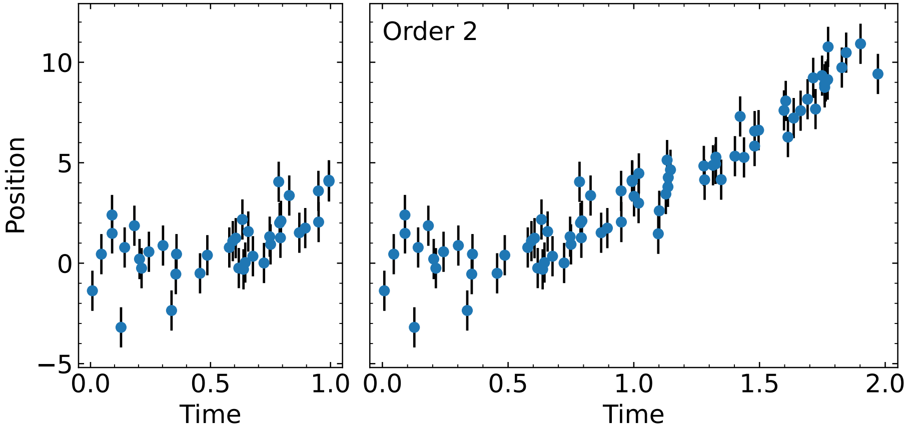
Precision $\sim t^{1/2}$

Astrometry measurement scalings: **proper motion**



Precision $\sim t^{3/2}$

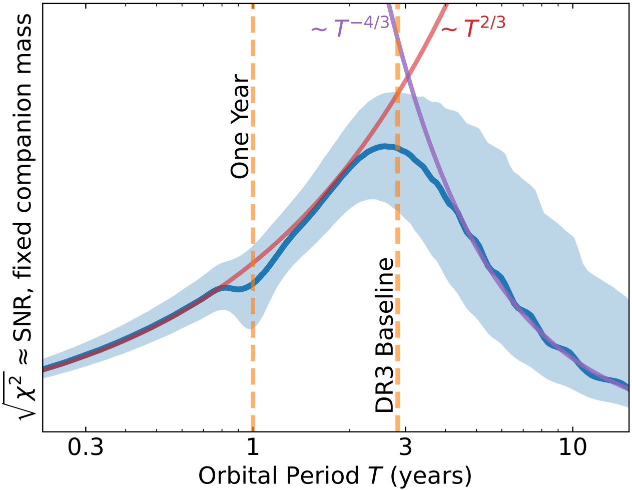
Astrometry measurement scalings: **acceleration**



Precision $\sim t^{5/2}$

Short orbital period: **signal amplitude** $\sim MR \sim MT^{2/3}$

Long orbital period: **acceleration** $\sim M/R^2 \sim MT^{-4/3}$

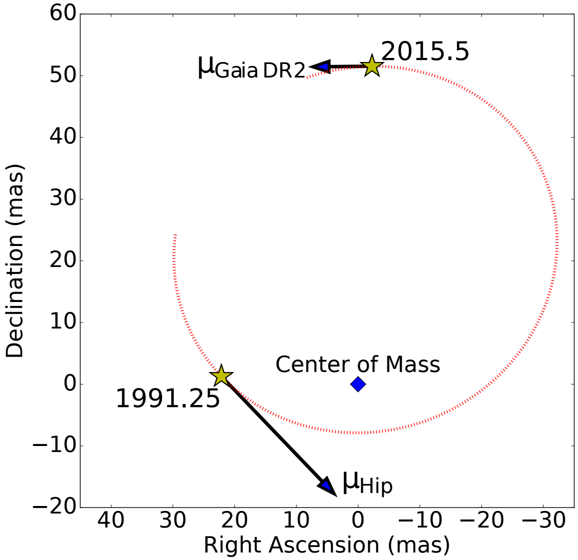


For now, Gaia is mostly just positions and proper motions (DR3 = 33 months of data)

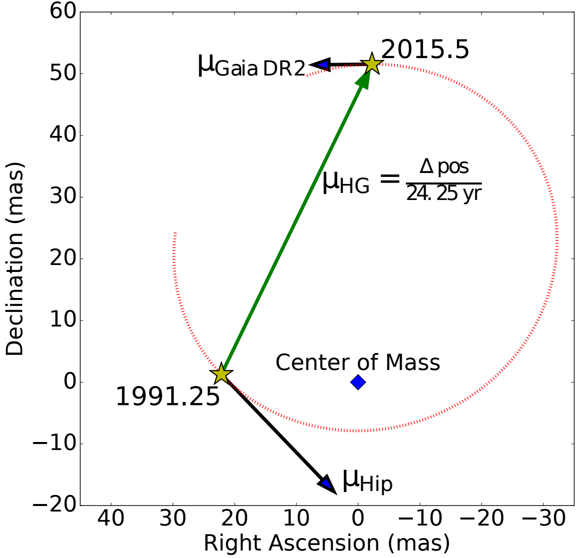
. . . but *Hipparcos* measured ∼100,000 positions and proper motions almost 30 years ago.

What can we do in the meantime?

How many proper motion measurements?



How many proper motion measurements? three

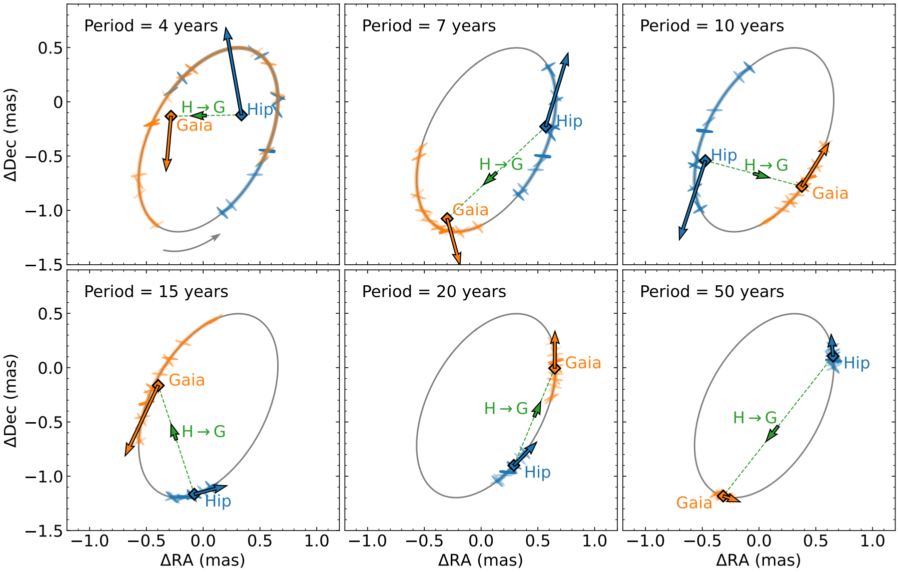


25-year baseline between Hipparcos and Gaia makes up for Hipparcos' lower precision

Change in proper motion
$\rightarrow$ acceleration in an inertial reference frame

Newton says $a = \dfrac{GM}{r^2}$

Published catalogs are fits to observed sky paths



Keep in mind:

$$\frac{\text{acceleration}}{\text{au}\,\text{yr}^{-2}} = \left(\frac{\text{acceleration}}{\text{arcsec}\,\text{yr}^{-2}}\right) \times \left(\frac{\text{distance}}{\text{parsecs}}\right)$$

Need motion across Gaia and Hipparcos baselines: need orbital periods $\gtrsim 5$ years.

Much more sensitive around nearby stars.

If we also have RV and relative astrometry (from images), we can weigh systems with arbitrarily long periods:

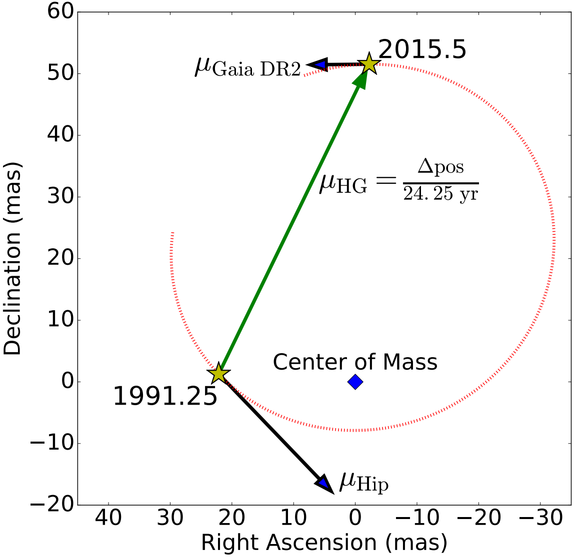
$$a_{\text{astrometric}} = \frac{GM_2}{r_{12}^2} \cos \varphi$$

$$a_{\text{RV}} = \frac{GM_2}{r_{12}^2} \sin \varphi$$

$$\rho_{\text{projected}} = r_{12} \cos \varphi$$

$\Rightarrow$ companion mass M_2!

So what might stop us?



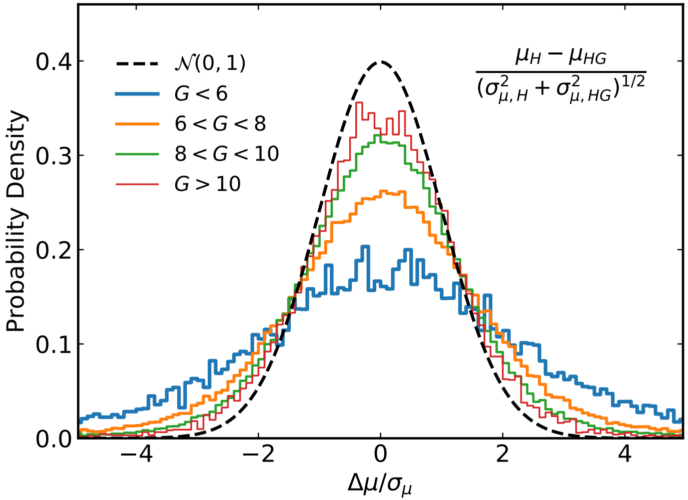
We want to use proper motion differences to look for accelerating stars and measure accelerations.

- Are all of the proper motion measurements in the same reference frame?
- Are the uncertainties correct? How can we tell?

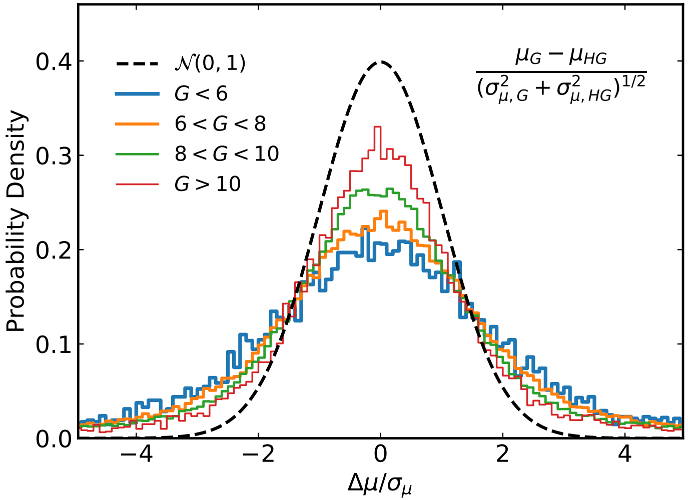
Hypothesis: most stars are not accelerating (much)

$$\underbrace{\left(\frac{\mu_{\rm Gaia} - \mu_{\rm HG}}{\sqrt{\sigma^2_{\rm Gaia} + \sigma^2_{\rm HG}}}\right)}_{\text{z-score}} \in \text{unit Gaussian?}$$

Hipparcos residuals from long-term proper motions



Gaia EDR3 residuals from long-term proper motions



As published, neither *Hipparcos* nor *Gaia* scaled proper motion residuals follow the standard normal distribution.

. . . but this can be fixed with a cross-calibration.

How can we check the uncertainties?

Hipparcos: use Gaia to select stars that are not accelerating ($\mu_{HG} \approx \mu_G$), check z-scores

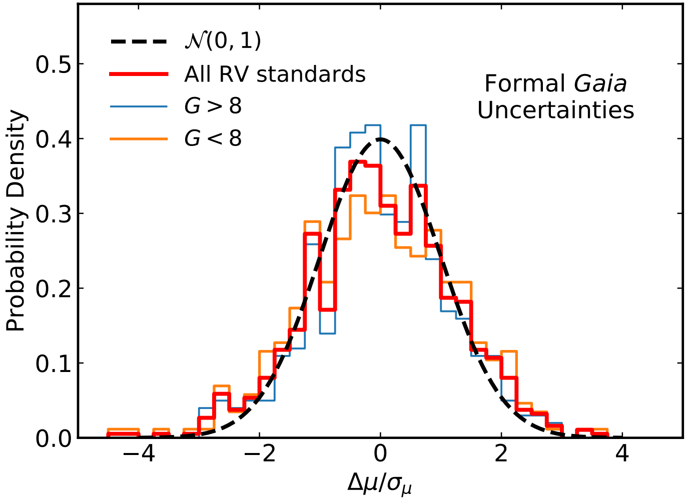
- Calibrated uncertainties much larger than Hipparcos 2007 values for bright stars

Gaia: use stars with constant RV (no acceleration along the line-of-sight)

- Need to inflate Gaia DR3 uncertainties by ≈35-40%

Calibration of *Gaia* Uncertainties

thank you to the HARPS, HIRES, and Lick teams!



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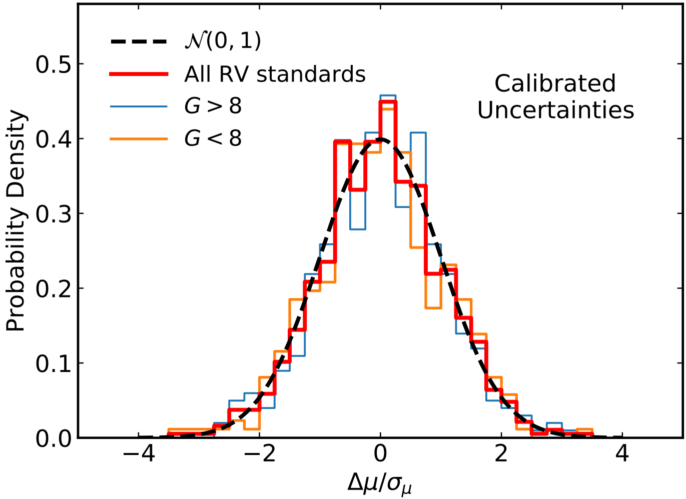
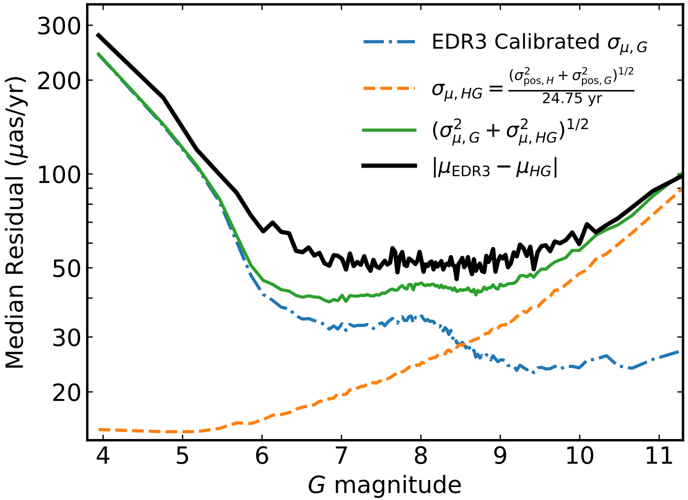


Typical acceleration precision: $\sim 5\,\mu\mathrm{as\,yr}^{-2}$!



Hipparcos-*Gaia* Catalog of Accelerations (Brandt 2021, c.f. Kervella+2022)

- Three proper motions in the Gaia frame
- Calibrated uncertainties
- Suitable for orbit fitting

Notes of Caution

- Proper motions are not instantaneous measurements
- Epochs of positions, proper motions $\neq$ catalog epochs

Next Ingredient: Orbit Fitting

`orvara` Tim Brandt+, 2021, with Yiting Li

- Uses Hundred Thousand Orbit Fitter (Mirek Brandt+, 2021) to forward-model Gaia data

`orbitize!` Blunt+ 2020

- Open-source Python Monte Carlo

`octofitter` Thompson+, 2023

- In julia, uses Hamiltonian Monte Carlo

Planet Discovery from Astrometry

You have a $\Delta\mu$, i.e., an acceleration $a \sim M/r^2$. Could be:

- A wide stellar companion
- A somewhat closer brown dwarf companion
- A closer-in exoplanet

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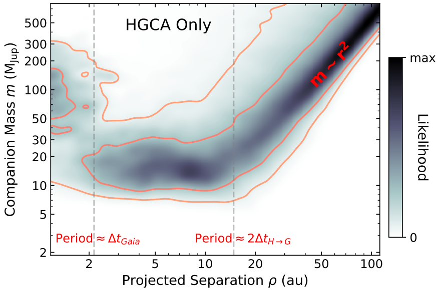
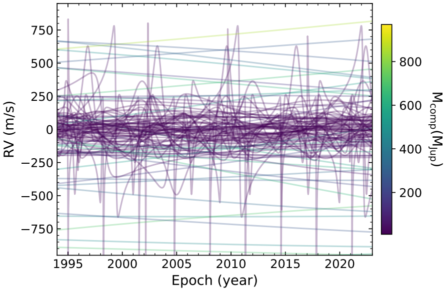
Do you also have precision RVs?

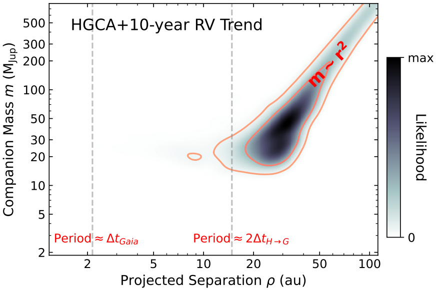
- Masses, orbits, inclinations: Li+, 2021, Feng+ 2019, Venner+ 2021, Xuan+Wyatt 2020, Damasso+ 2020, Hill+ 2021, Bardalez Gagliuffi+ 2021, Phillipot+ 2023, Xuan+2025, An+ 2025, etc.

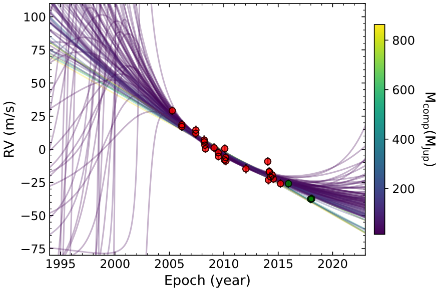
Clues to the projected separation of a companion



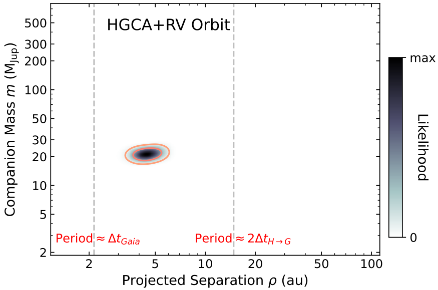


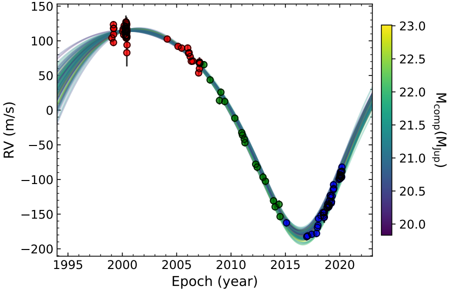
Clues to the projected separation of a companion





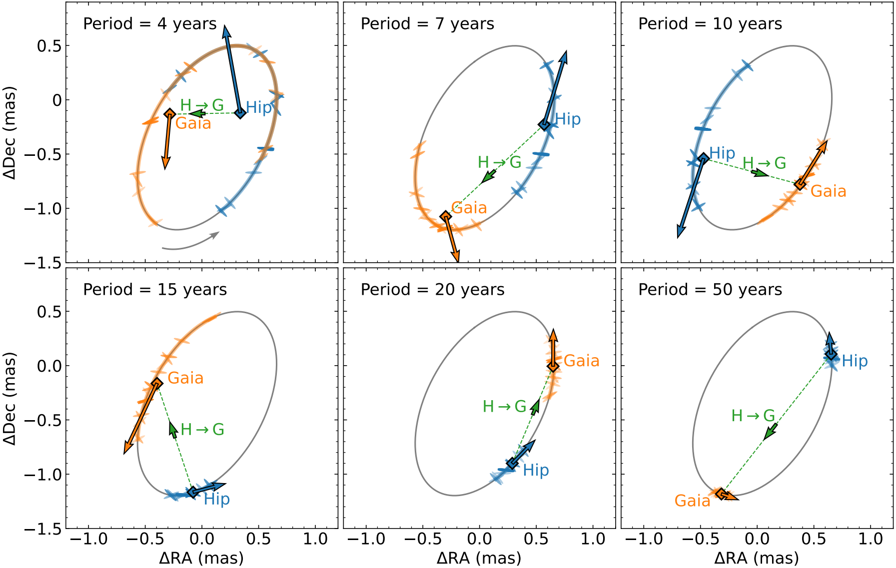
Clues to the projected separation of a companion





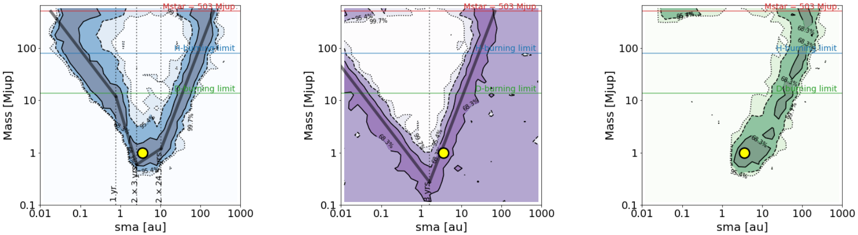
One more clue: *Gaia* provides a number for how well an inertial sky path describes each star's data.

Called renormalized unit weight error, or RUWE.
≈ 1 = good fit, $>>1$ = bad fit.


Period = 4 years
Period = 7 years
Period = 10 years
Period = 15 years
Period = 20 years
Period = 50 years
Hip
Gaia
H → G
ΔDec (mas)
ΔRA (mas)
0.5
0
−0.5
−1.0
−1.5
0.0
−1.0
−0.5
0.5
1.0

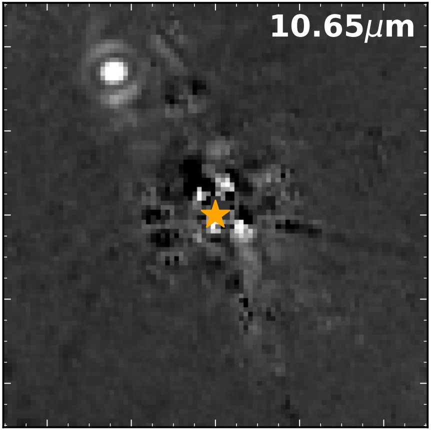
Can rule out (or in) close, massive companions.

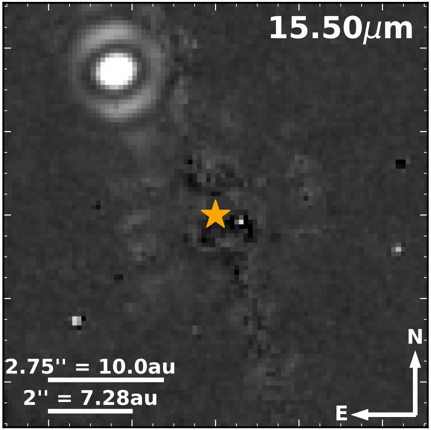
Δμ RUWE Both



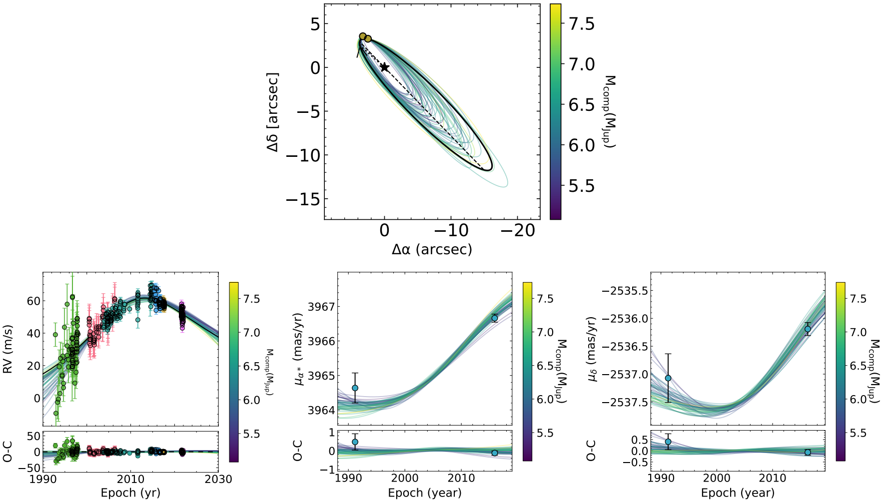
PMEx, Kiefer+ 2025

Newly imaged planets



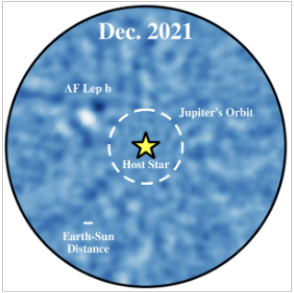


ε Indi b, Matthews+ 2025, with JWST. Maybe the oldest imaged exoplanet.

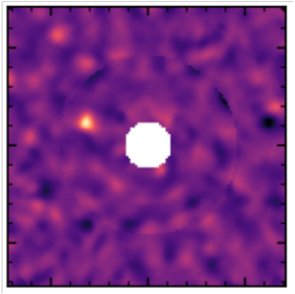


$$\mathrm{Mass} = 6.3 \pm 0.6\,\mathrm{M_{Jup}},\ \mathrm{Eccentricity} = 0.4 \pm 0.2$$

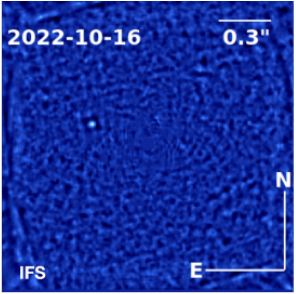
AF Lep b



Franson+ 2023



De Rosa+ 2023



Mesa+ 2023

Mass $= 3.75 \pm 0.50\, \mathrm{M_{Jup}}$, Eccentricity $\lesssim 0.05$, Balmer+ 2025

Current significance of astrometric acceleration

Planet Hosts

- β Pic: 3σ
- HR 8799: 5σ
- π Mensae: 8σ
- ε Indi: 17σ
- AF Lep: 9σ

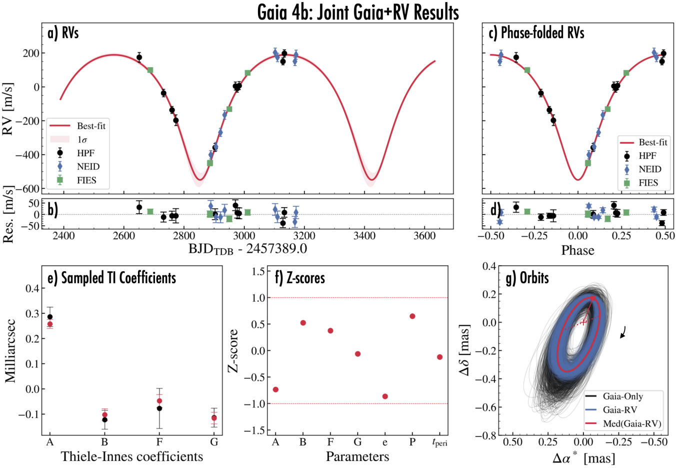
Brown Dwarf Hosts

- Gl 229: 115σ
- Gl 758: 40σ
- HR 7672: 180σ
- HD 4113: 8σ
- HIP 21152: 13σ

Depends **a lot** on companion mass, system proximity to Earth, companion semimajor axis.

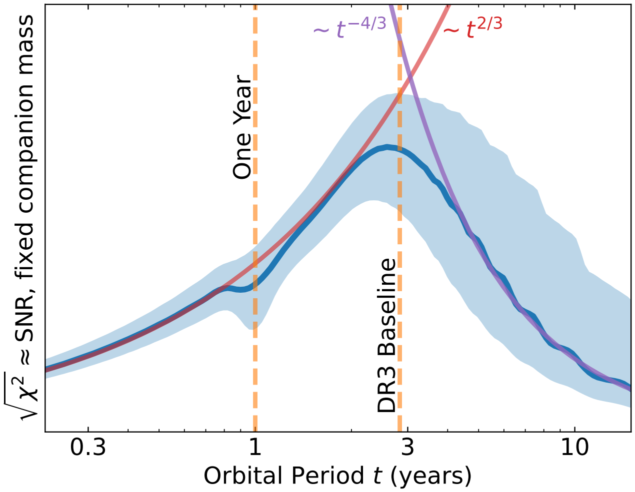
What should we expect in the near future?

First Astrometric Gaia Planet Now Confirmed!



Mass $= 11.8 \pm 0.7 M_{\rm Jup}$, Period $= 1.564 \pm 0.004$ yr, Stefansson+ 2025

Planets from Gaia Alone: Sensitivity



My Expectations:

- Data Release 4 (DR4) (in ≈1.5 years) will include many new planets. **How many is uncertain.**
- DR4 will be based on **twice as much** data as DR3, include individual position measurements of stars.
- Peak sensitivity will be at ≈5 year periods. Longer period fits may be unreliable, short-period sensitivity will be worse.

Suggestions to Prepare:

- **Be careful with the catalog uncertainties.** Factor of 1.5-2 underestimation is likely, even expected.
  - Brandt 2021, El Badry+ 2021, Chakrabarti+ 2023, Nagarajan & El Badry 2024, Winterhalder+2024
- The data will probably be excellent, but small systematics and correlations are likely.

Good news/bad news for demographics: hard work needed, but huge potential payoff.

Summary

- Absolute astrometry gives accelerations in an inertial reference frame!
- Already, masses and orbits for planets with imaging and/or RVs. See Hands-On Session II.
- Big sensitivity improvements coming with DR4 and beyond (perhaps with calibration challenges!)
- The big demographics prize is coming, but we will have to rise to the data analysis challenge.