Gaia: Expectations From DR4 and Beyond

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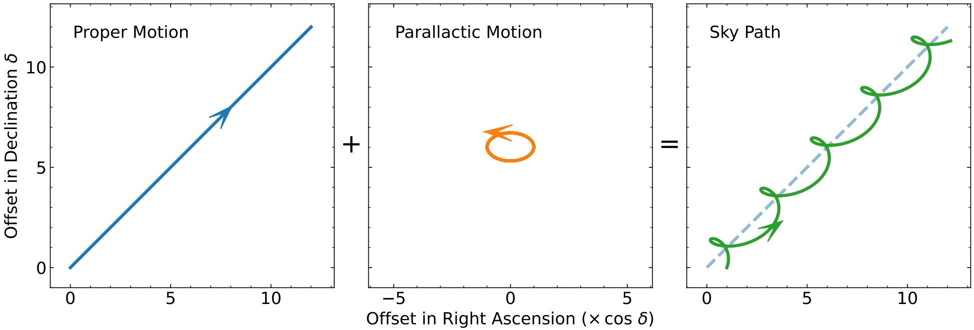
27 March 2026

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.

Credit: European Space Agency

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 ($\pm$6000) high-mass ($\sim$1–15 M_J) long-period planets should be discovered out to distances of $\sim$500 pc for the nominal 5 yr mission (including at least 1000–1500 around M dwarfs out to 100 pc), rising to some 70,000 ($\pm$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.

See also: Lammers+Winn 2026

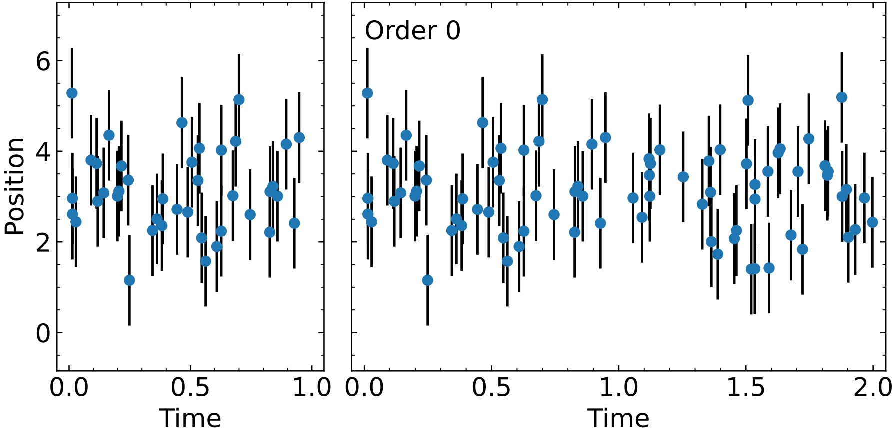
Gaia DR3: $\sim$1 billion positions, proper motions

Gaia collaboration 2018, 2021, 2023; Lindegren+ 2018, 2021

Only a few exoplanets thus far.

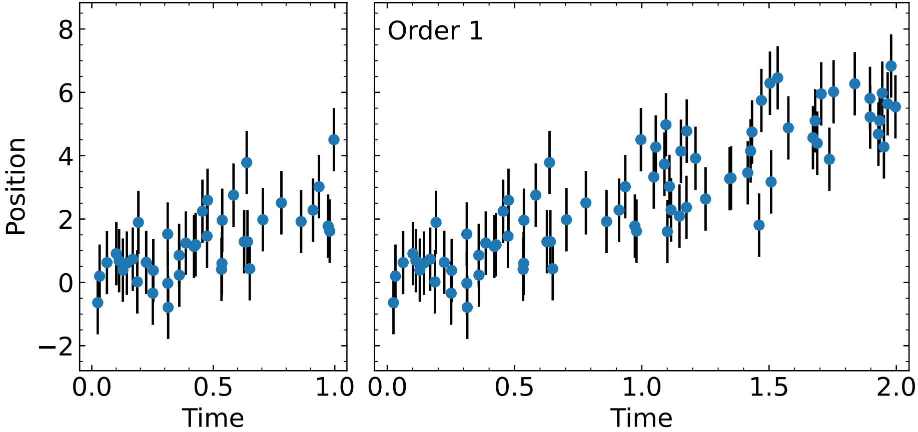
Holl+ 2023, Halbwachs+ 2023, Stefansson+ 2025

Astrometry measurement scalings: **position & parallax**



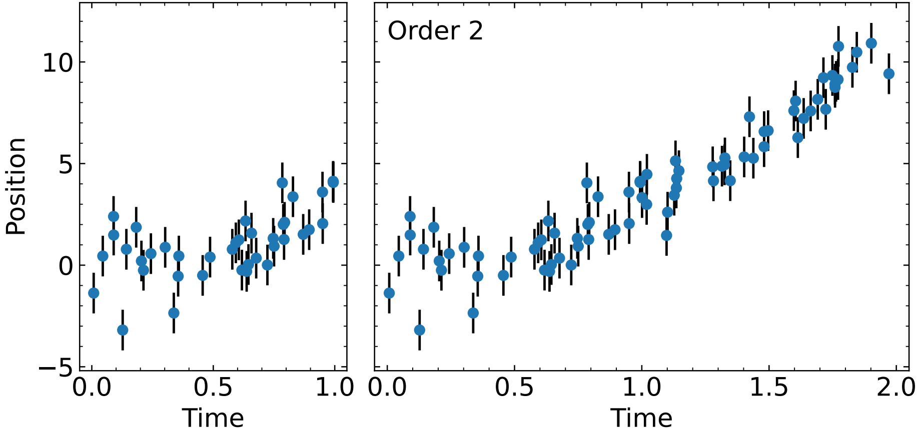
Precision $\sim t^{1/2}$

Astrometry measurement scalings: **proper motion**



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

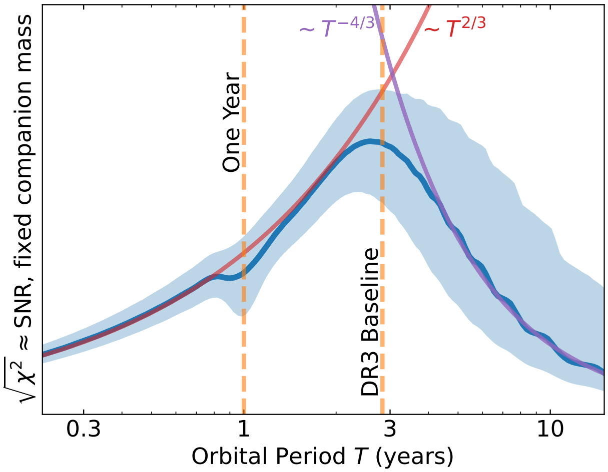
Astrometry measurement scalings: **acceleration**



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

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

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



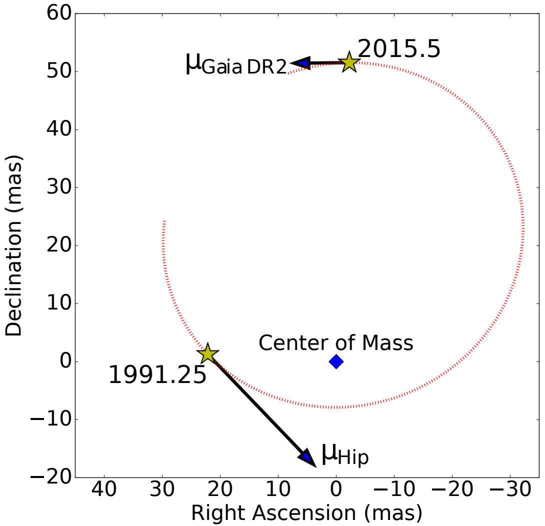
As Gaia's observing baseline t increases:

- The red curve goes up as $t^{1/2}$
- The purple curve goes up as $t^{5/2}$
- Peak sensitivity moves to longer periods as t

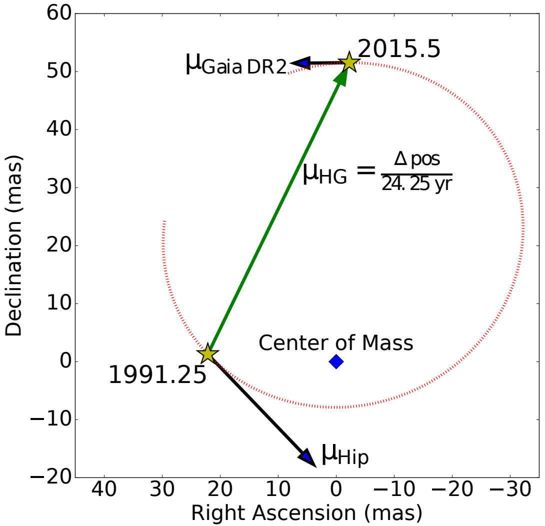
For now, Gaia is mostly just positions and proper motions (DR3 = 33 months of data)

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

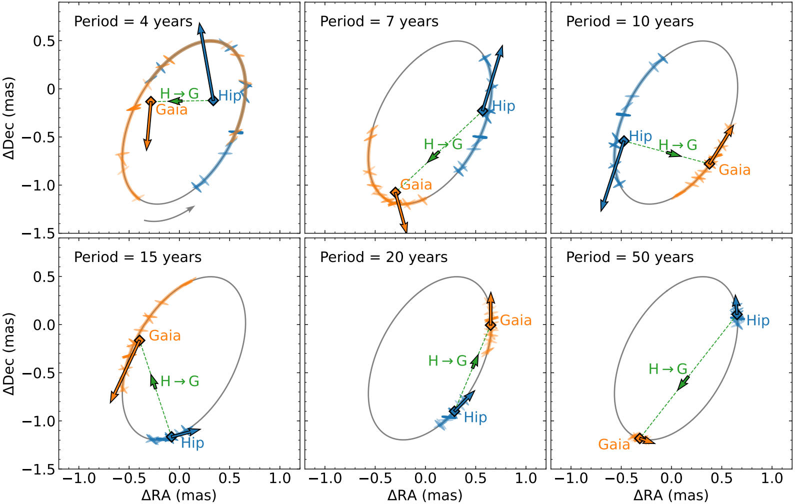
How many proper motion measurements?



How many proper motion measurements? three



Published catalogs are fits to observed sky paths



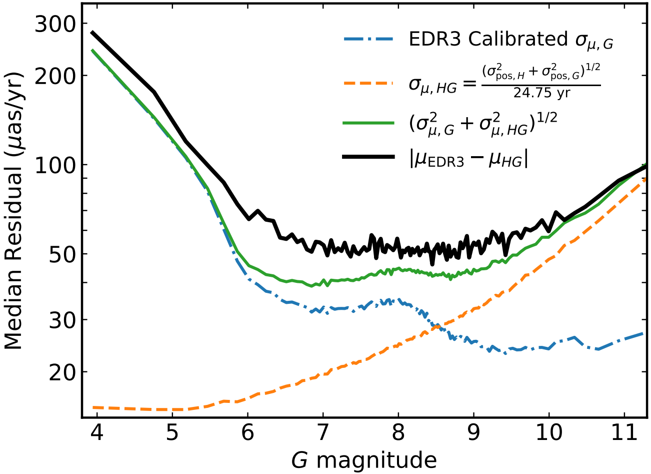
Keep in mind:

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

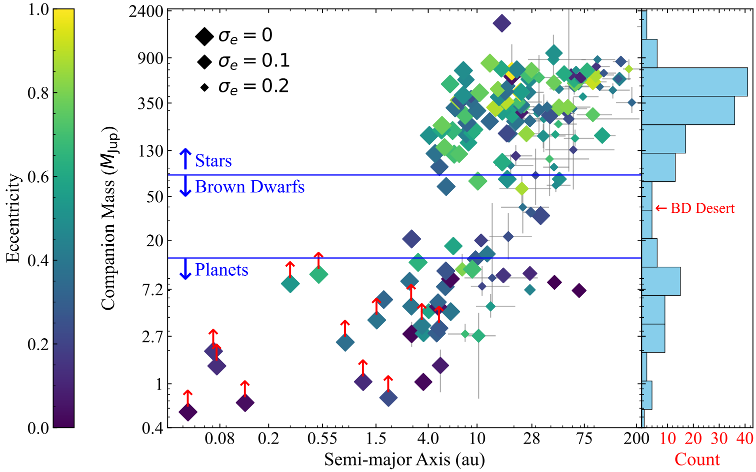
Need motion across Gaia and Hipparcos baselines: need orbital periods $\gtrsim$ 5 years.

Much more sensitive around nearby stars.

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



True masses of RV-detected companions



An+2025, c.f. Li+2021, Feng+2022, Philipot+2023

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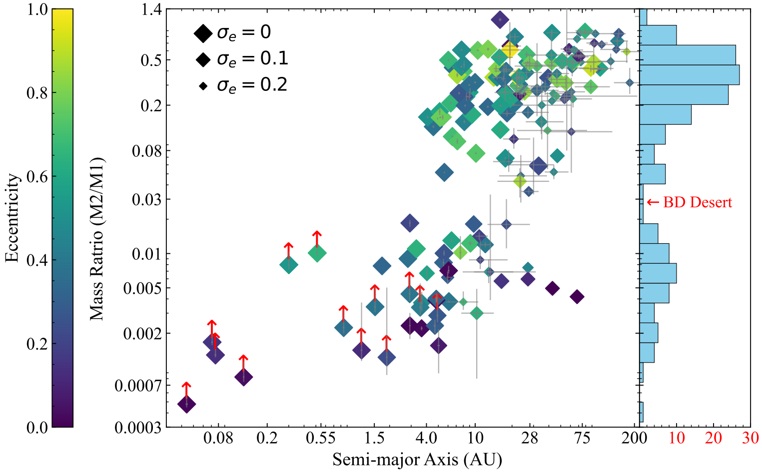
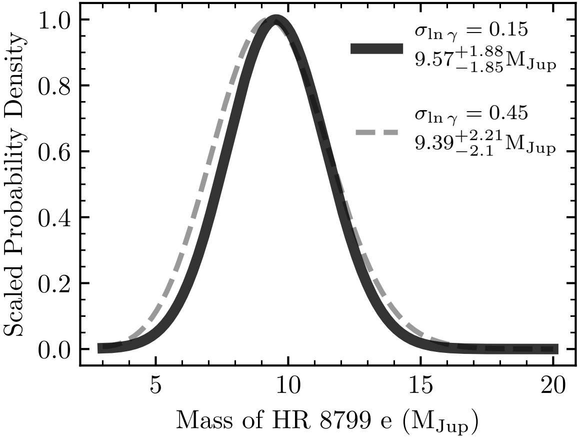


An+2025, c.f. Li+2021, Feng+2022, Philipot+2023

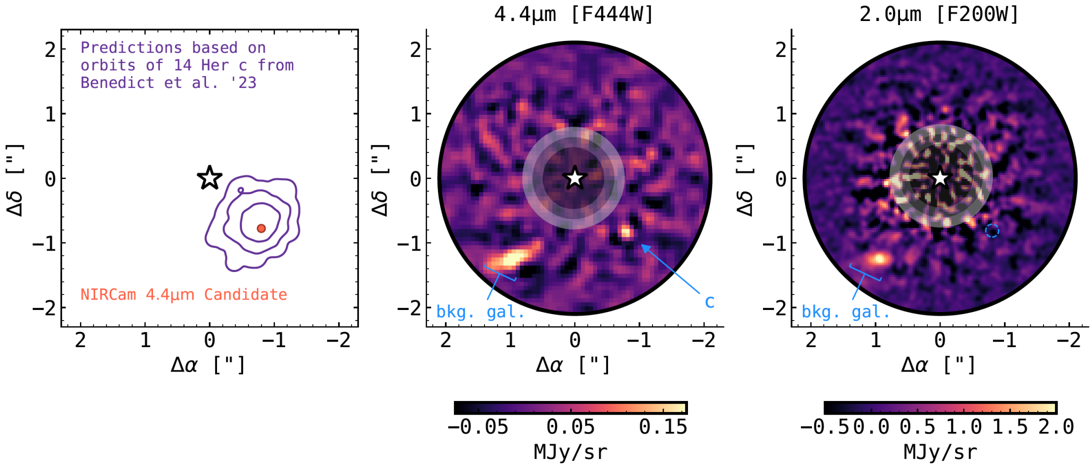
Movie credit: Jason Wang

Masses of imaged planets: a 20% mass of HR 8799 e



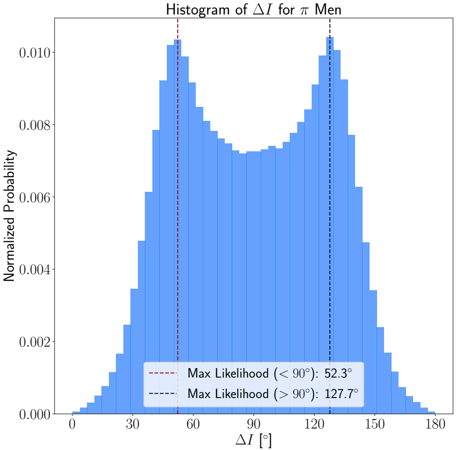
G. Mirek Brandt+, 2021

A Predicted Mass+Location: 14 Her c

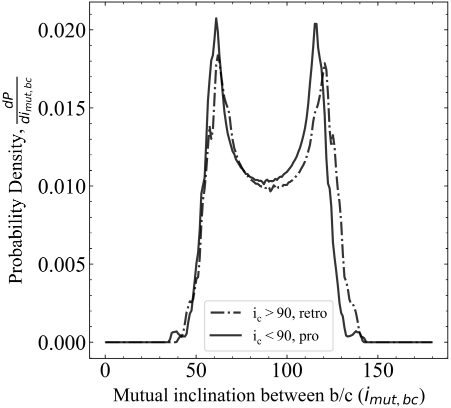


JWST: Bardalez Gagliuffi & Balmer+2025

Mutual inclinations between short, long period planets

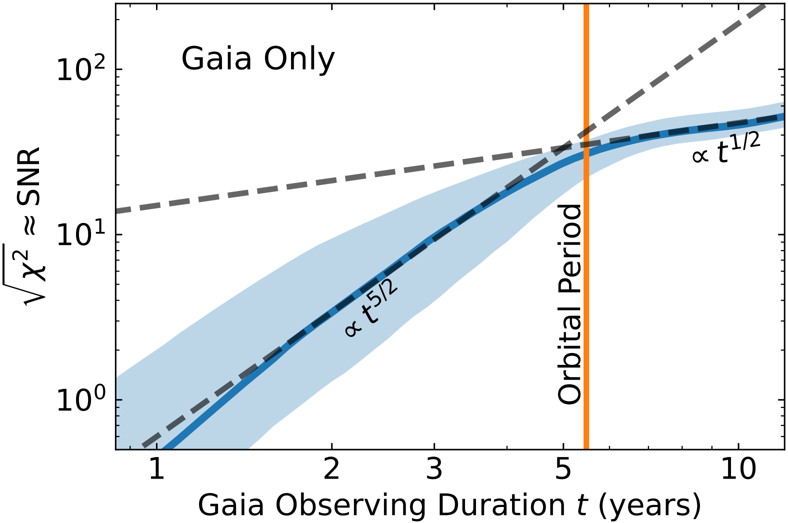


π Men: Xuan+Wyatt 2020



HAT-P-11: An+2024

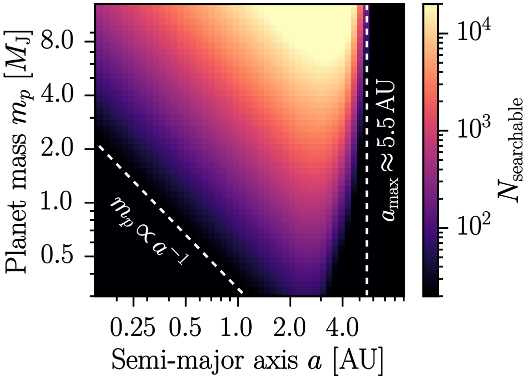
DR4 and DR5: Scalings and Expectations


Gaia Only
$\sqrt{\chi^2} \approx$ SNR
10^2
10^1
10^0
$\propto t^{5/2}$
$\propto t^{1/2}$
Orbital Period
1
2
3
5
10
Gaia Observing Duration t (years)

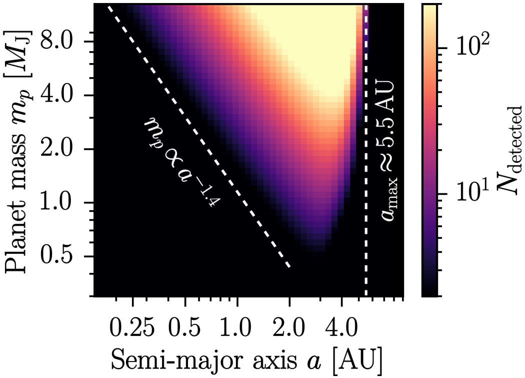
Gaia-only predictions

Detectability → Detections

$\sim$7M searchable stars



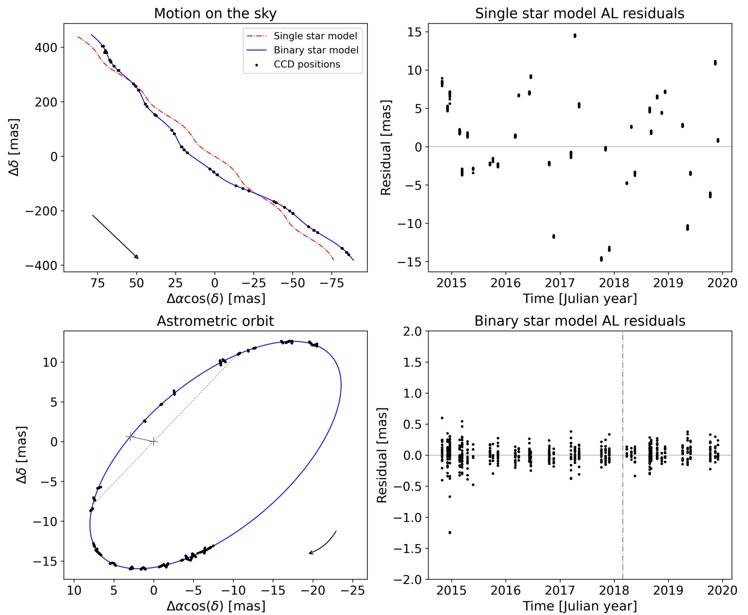
$\sim$130,000 planet detections



Lammers+Winn 2026

So far, **one result** with individual astrometric measurements

Gaia-BH3, Panuzzo+2024



A few words about the fitting:

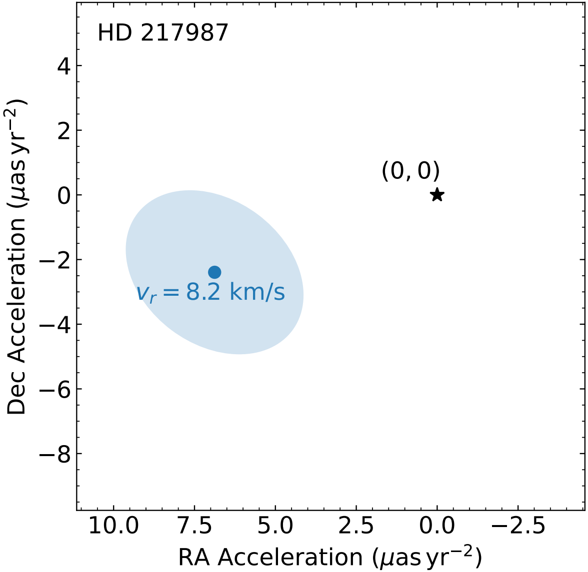
- Astrometric excess noise, both source-specific and statistically based on the calibration, added to get reduced $\chi^2 \approx 1$.
- Renormalized unit weight error (RUWE): how does the excess noise (=astrometric jitter) for a star compare to similar stars?
- Orbit fitting is problematic for variable sources, specific periods, periods > observing baseline. See Holl+2023, Halbwachs+2023.

Some big questions and my best guesses

- Will there be hundreds of high-SNR planets in the DR4 catalog? **Yes**
- Can we use the DR4 catalog for planet statistics? **Maybe–be careful!**
- Can we trust our own fits to the intermediate data? **Maybe–be careful!**
- What about the uncertainties? **My dream: freedom from the RUWE, "astrometric jitter"**

One more caveat:
perspective acceleration

$$\dot{\mu} = -2\mu v_r / D$$



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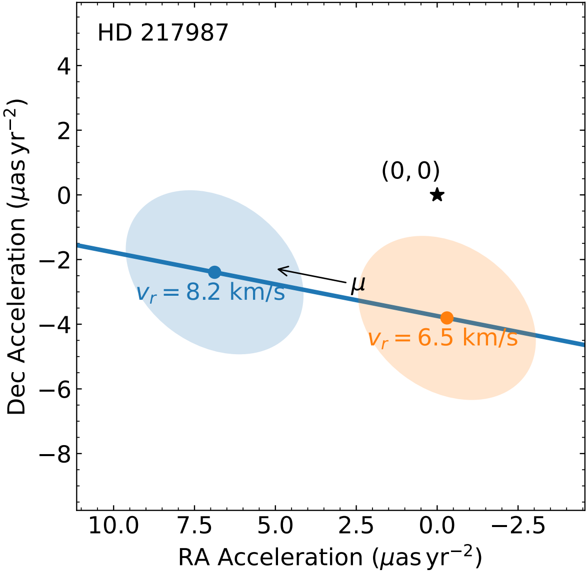

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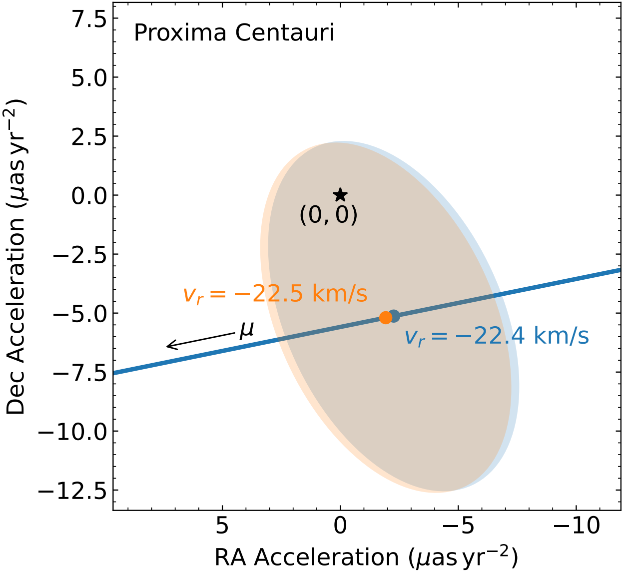

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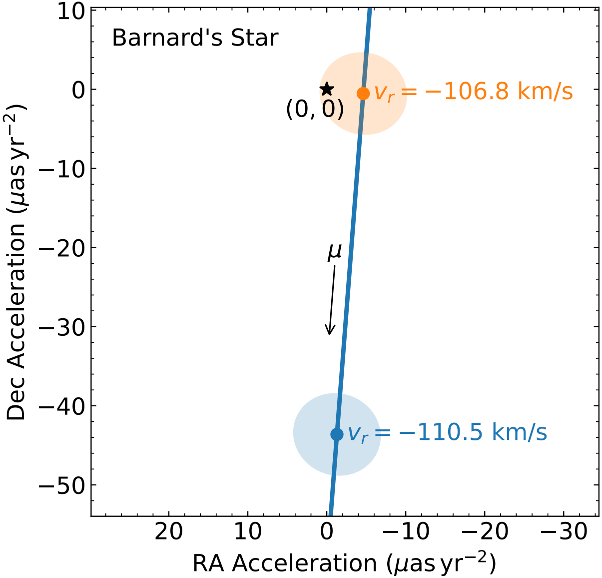

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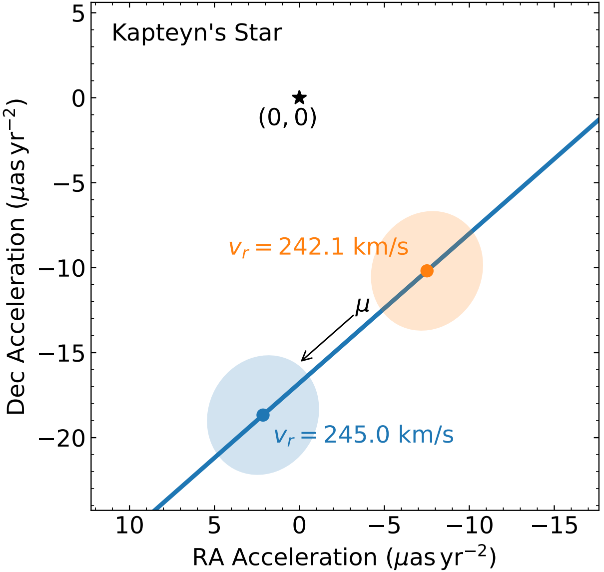

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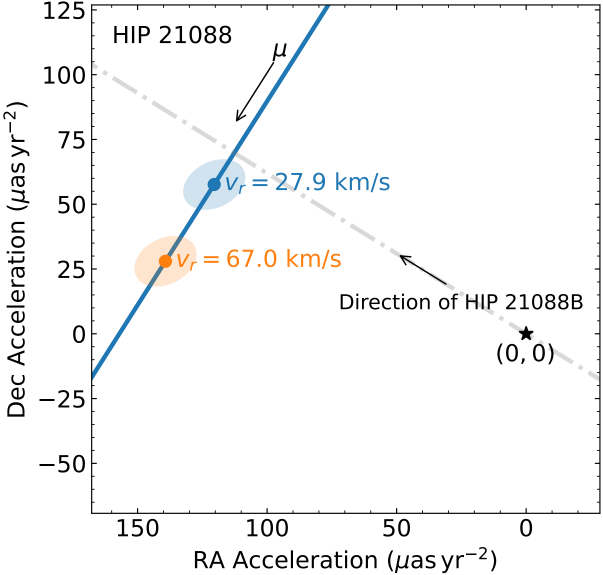
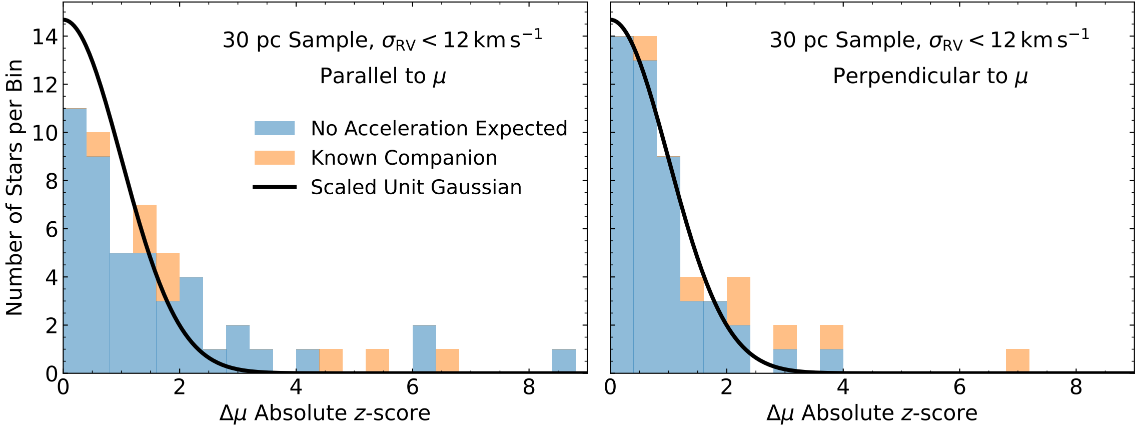




Similar to differential atmospheric refraction:
an astrometric systematic affecting only one direction.

Takeaways:

- For short-period planets ($\lesssim 3\,\mathrm{yr}$), DR4 will be $\approx \sqrt{2}$ times as sensitive as DR3
- For long-period planets, DR4 will be $\approx$6 times as sensitive as DR3
- A DR4-based Hipparcos-Gaia catalog will be little better than DR3 for stars fainter than $V \approx 8$. It will likely be somewhat better for brighter stars.
- Be careful of astrometric acceleration parallel to proper motion.
- Biggest question for me: **how well can we calibrate and understand Gaia DR4 intermediate data?**

Thank you!

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

If we also have RV (line of sight velocities) and the separation of a faint companion (from images), we can weigh systems with arbitrarily long periods:

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

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

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

$\Rightarrow$ companion mass M_2!

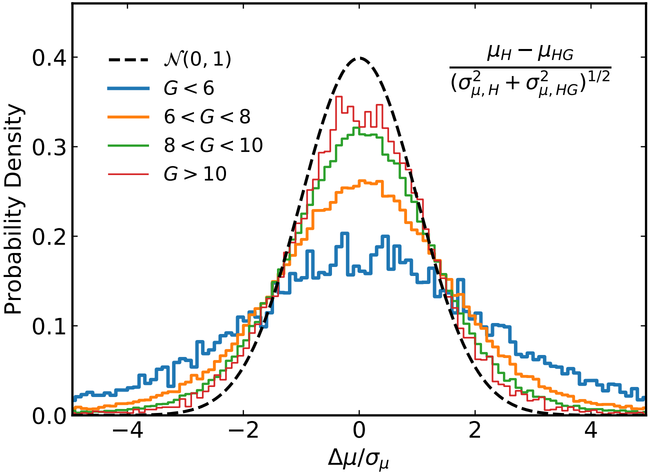
We want to use proper motion differences to look for accelerating stars and measure accelerations.

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

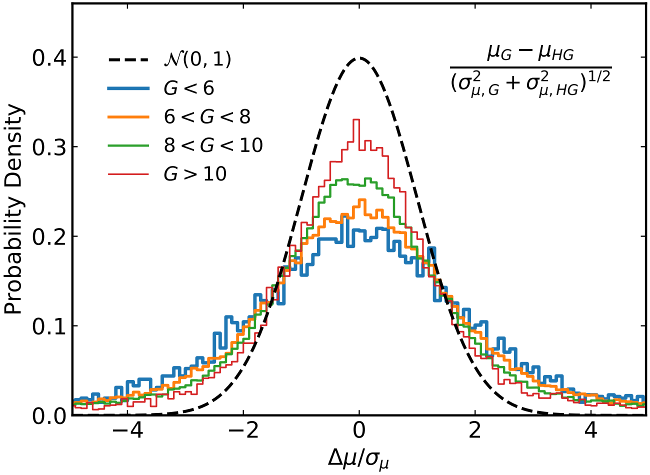
Hypothesis: most stars are not accelerating (much)

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

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 ($\mu_{\rm HG} \approx \mu_{\rm G}$), check z-scores

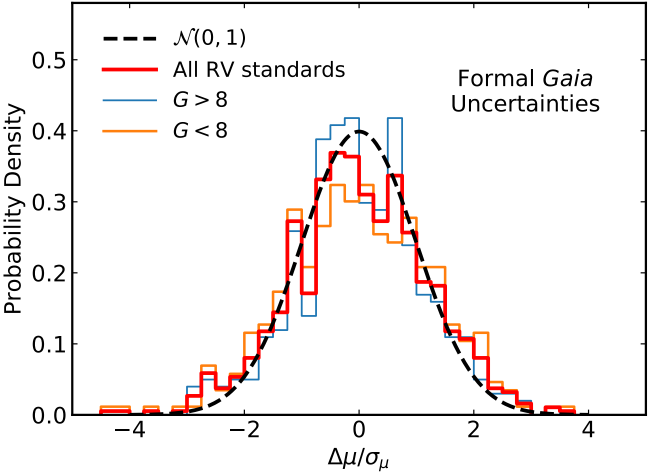
- Calibrated uncertainties much larger than Hipparcos 2007 values for bright stars

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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