Near-Term Exoplanet Discovery using Proper Motions

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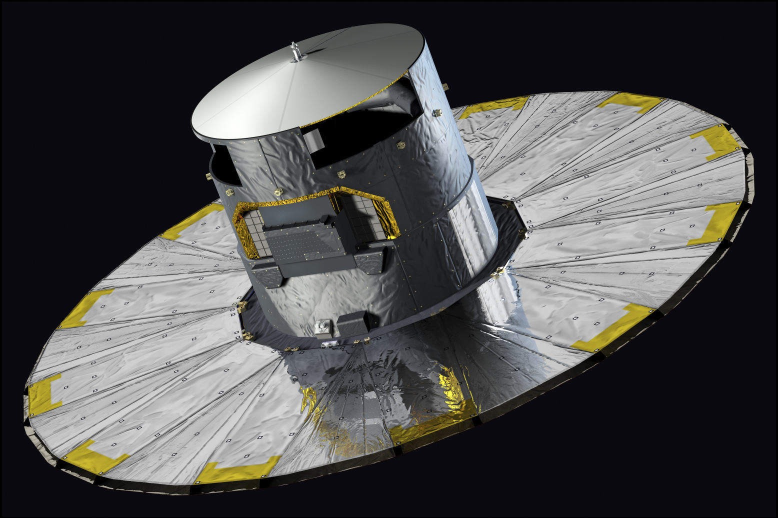
with G. Mirek Brandt, Yiting Li, Minghan Chen, Mikhail Lipatov, Qier An, Hengyue Zhang, Trent Dupuy, Jackie Faherty, Brendan Bowler, Tyler Groff, Jeff Chilcote, Thayne Currie, Motohide Tamura, Masayuki Kuzuhara, the SEEDS and CHARIS teams, and many others

27 July 2022

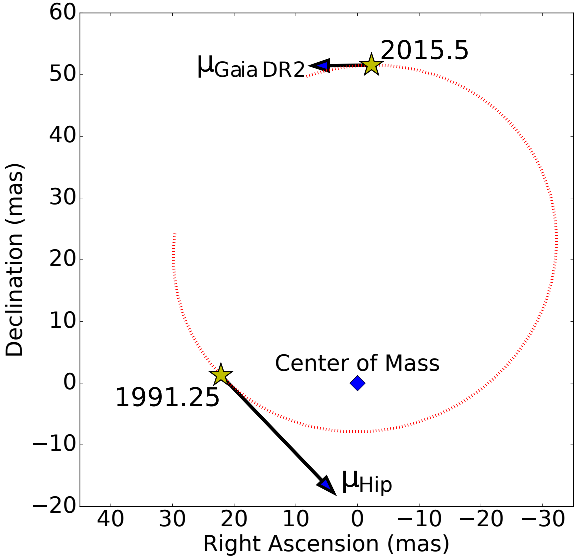


Gaia: ∼1 billion positions, proper motions

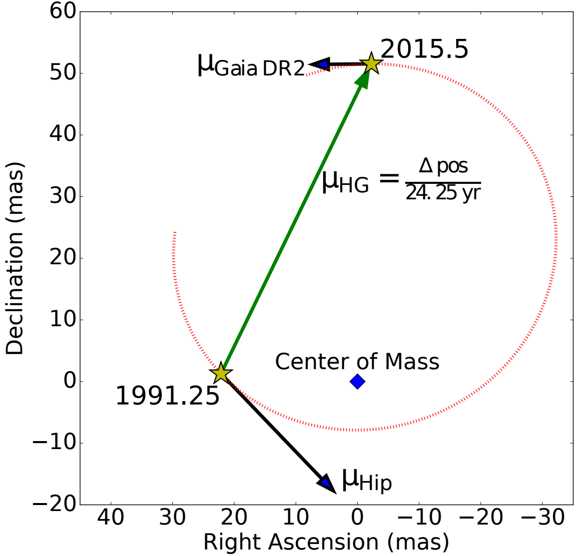
Limited exoplanet results from the first non-single star fits

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

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

Published catalogs are fits to observed sky paths

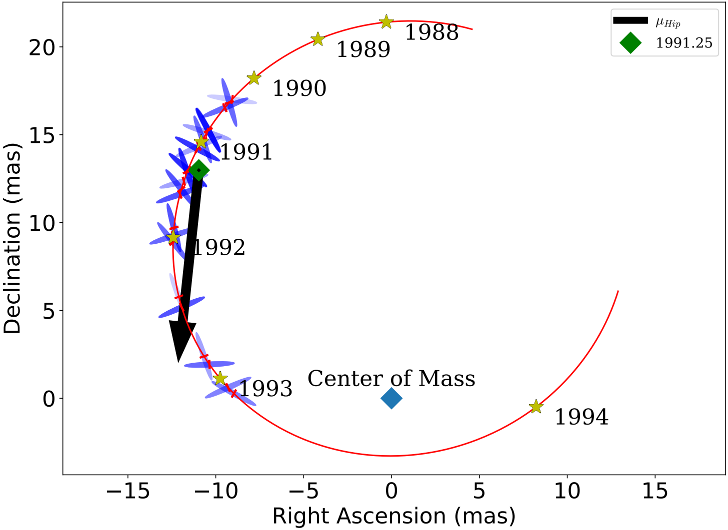


Figure by G. Mirek Brandt

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

Numbers and equivalents

- Change of 0.1 $\mathrm{mas\,yr^{-1}}$ between μ_{HG} and μ_{G}
- Acceleration of $\approx$0.01 $\mathrm{mas\,yr^{-2}}$
- Acceleration of $\approx$2 $\mathrm{m\,s^{-1}\,yr^{-1}}$ at 40 pc (= 25 mas parallax)

$$\frac{M}{M_{\mathrm{Jup}}} \approx \left(\frac{\mathrm{separation}}{10\,\mathrm{au}}\right)^2 \left(\frac{\mathrm{distance}}{40\,\mathrm{pc}}\right) \left(\frac{\mathrm{acceleration}}{0.01\,\mathrm{mas\,yr^{-2}}}\right)$$

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

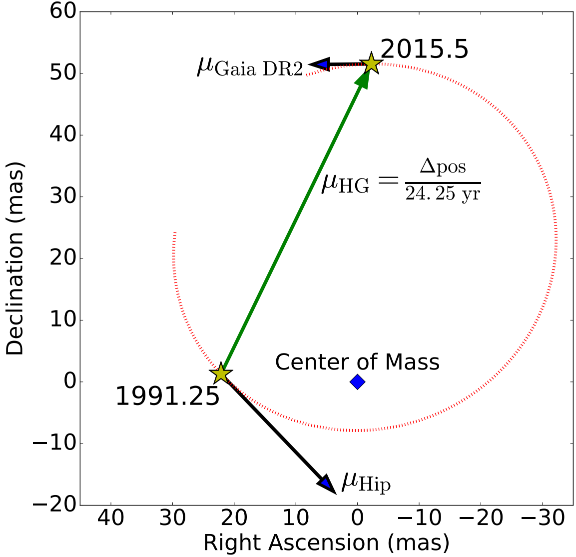
$$a_{\mathsf{astrometric}} = \frac{GM_2}{r_{12}^2} \cos\varphi$$

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

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

$\Rightarrow$ companion mass M_2!

So what might stop us?



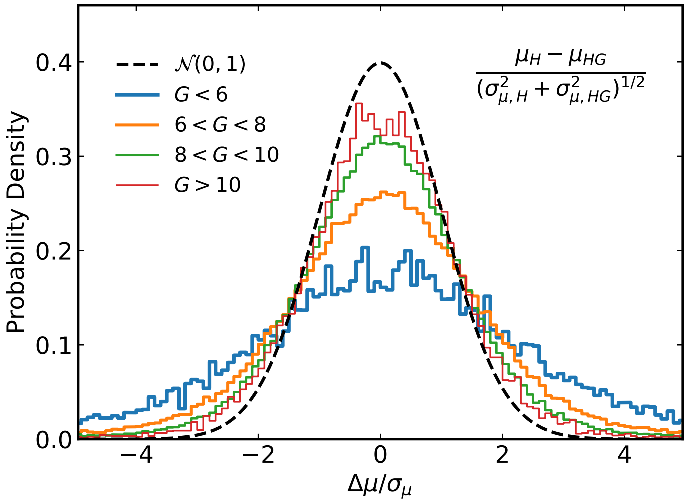
We want to use proper motion differences to look for accelerating stars and measure accelerations.

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

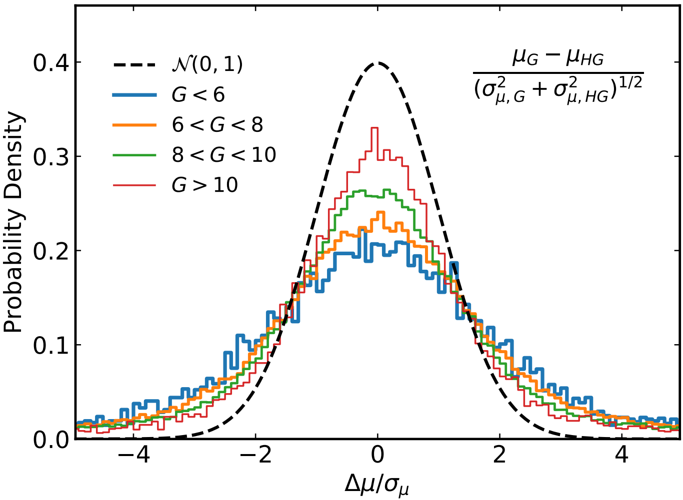
Hypothesis: most stars are not accelerating (much)

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

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.

Tricks and Subtleties

Astrometric parameters are covariant: a better measurement of one improves the others

- *Gaia* parallax $\Rightarrow$ better *Hipparcos* proper motion

Characterisitic observational epoch varies star-by-star

- Propagate everything to the epoch with minimum positional uncertainty.

Nuances of Hipparcos

There are two reductions of the raw data:

- FAST & NDAC (merged in the 1997 catalog)
- Hipparcos 2 (van Leeuwen, 2007)

Which is best?

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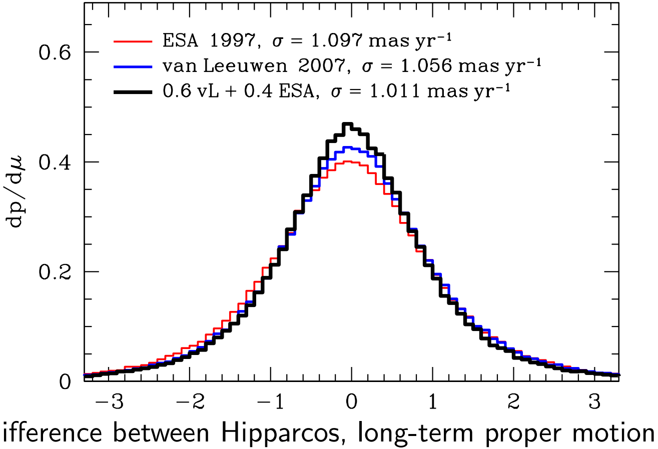
$$0.6\,\mathrm{Hip2} + 0.4\,\mathrm{Hip1} > \mathrm{Hip2} > \mathrm{Hip1}$$

Nuances of Hipparcos

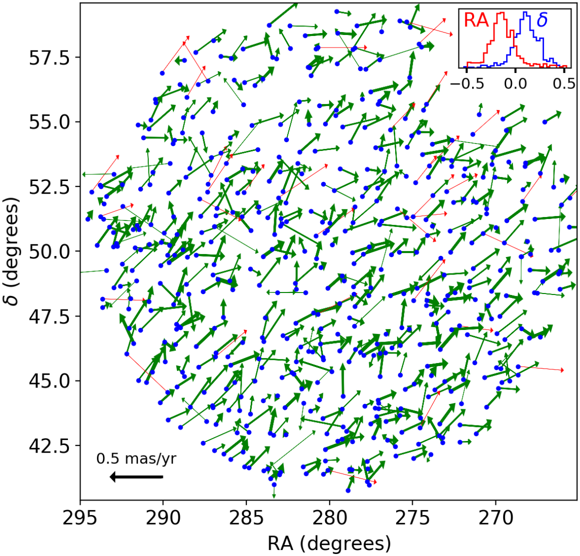


60/40 linear combination of the two *Hipparcos* reductions beats either one on its own (at 150σ significance)

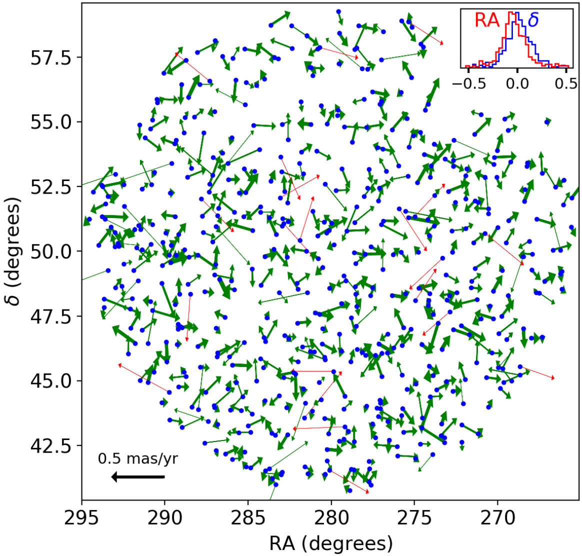
Correcting an example field, DR2

$$\Delta\mu_{\alpha*} = \mu_{\alpha*,Gaia} - \frac{\alpha_{Gaia} - \alpha_{Hip}}{t_{Gaia} - t_{Hip}} \cos\delta$$

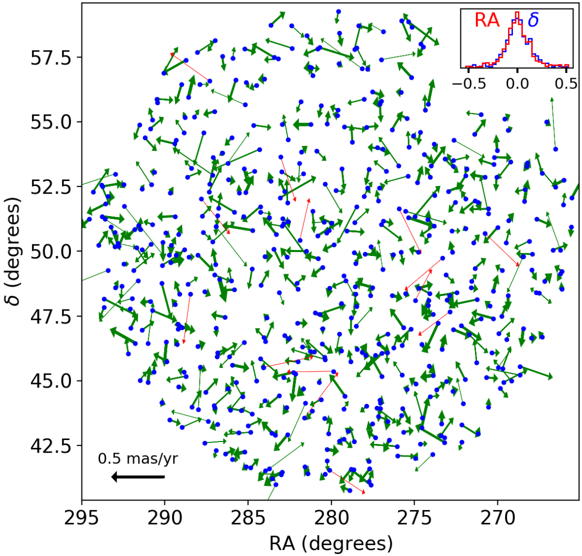
$$\Delta\mu_{\delta} = \mu_{\delta,Gaia} - \frac{\delta_{Gaia} - \delta_{Hip}}{t_{Gaia} - t_{Hip}}$$



No correction for frame rotation



Global correction for frame rotation



Locally variable correction for frame rotation

What about the uncertainties?

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

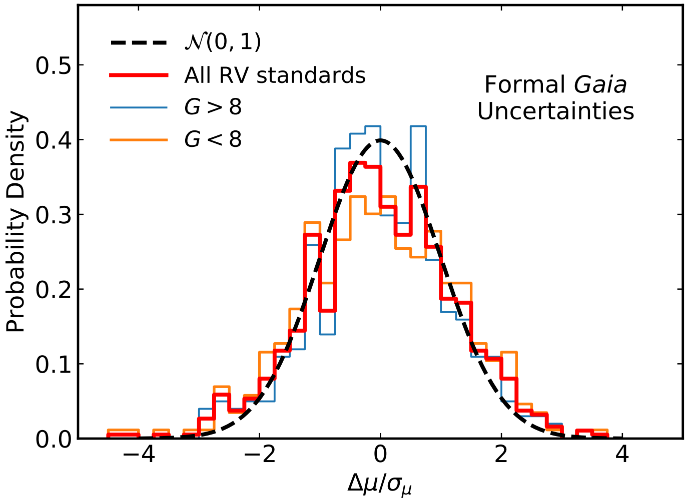
- Calibrated uncertainties much larger than Hip2 for bright stars

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

- Need to inflate EDR3 uncertainties by ≈35-40%

Calibration of *Gaia* EDR3 Uncertainties

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



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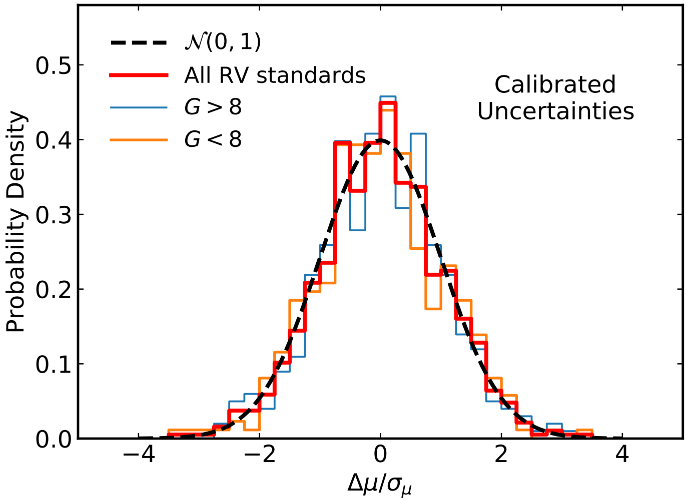
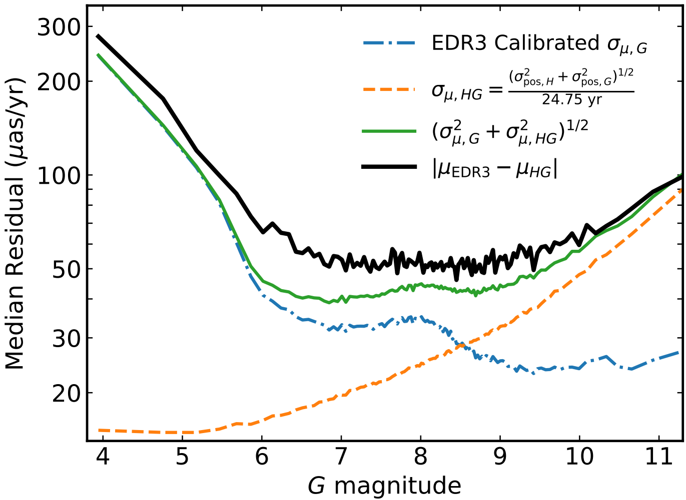
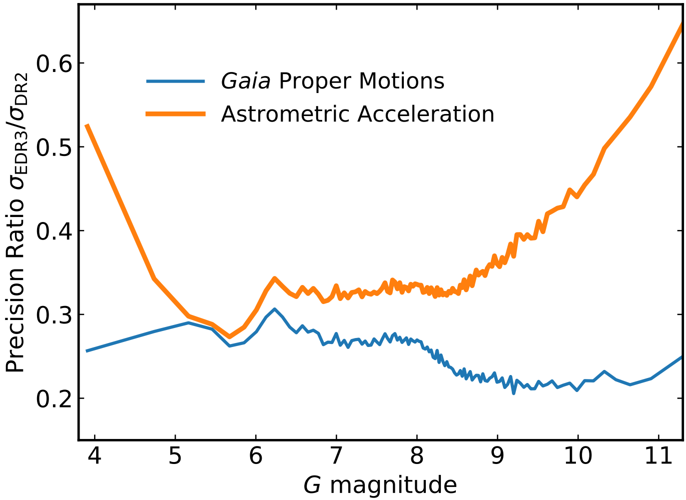


Typical acceleration precision: ~5 µas yr^{-2}!



(E)DR3 improves sensitivity by a factor of ≈3



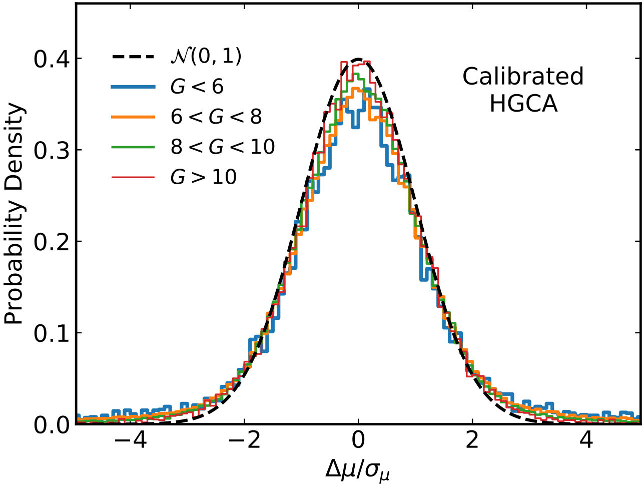
Hipparcos-*Gaia* Catalog of Accelerations, EDR3 (Brandt 2021)

- Three proper motions in the EDR3 frame
- Calibrated uncertainties
- Suitable for orbit fitting

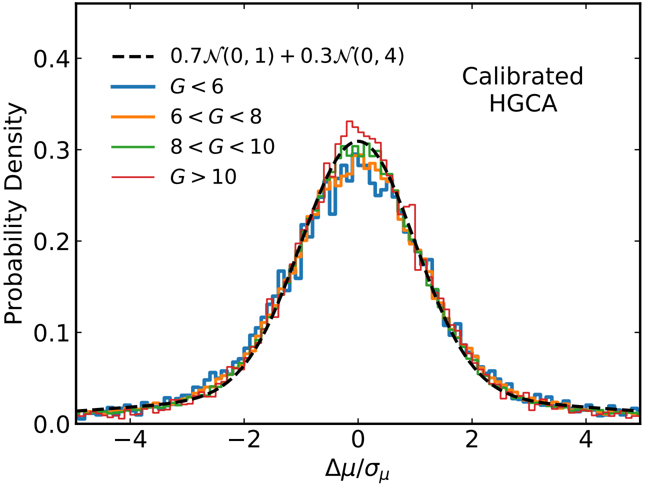
Notes of Caution

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

Final *Hipparcos* **residuals**



Final *Gaia* **EDR3 residuals:** lots of real accelerators!



Shameless Self Promotion: Tools from UCSB

Hipparcos-Gaia Catalog of Accelerations

Hundred Thousand Orbit Fitter: Mirek Brandt+, 2021

- Simulate *Hipparcos* and *Gaia* results for any orbit

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

- Fast and efficient orbit fitting

We can fit orbits with *Gaia* today!

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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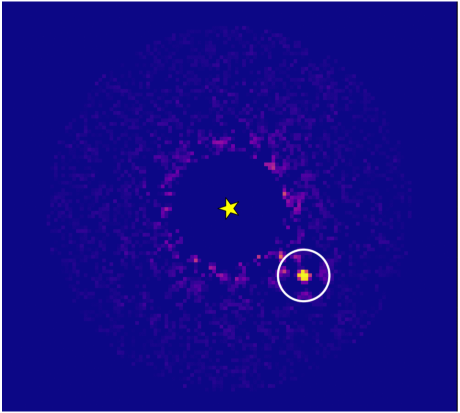
Do you also have precision RVs?

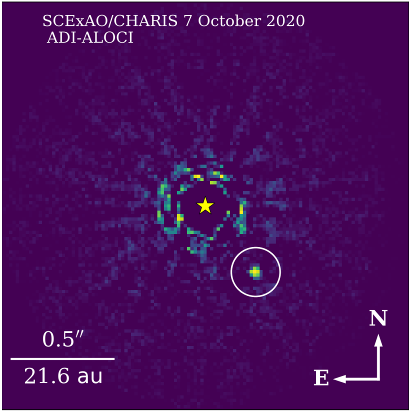
- **Pierre Kervella's talk!**
- Masses, orbits, inclinations: Yiting Li+, 2021, Feng+ 2019, Venner+ 2021, Xuan+Wyatt 2020, Damasso+ 2020, Hill+ 2021, Bardalez Gagliuffi+ 2021

How about direct imaging?

New targets for imaging searches



Thayne Currie's Poster



Masayuki Kuzuhara's Poster

How about direct imaging?

If we have imaging:

- Can get precise dynamical masses and orbits!
- Directly measure exoplanet/brown dwarf spectra!

See **Mirek Brandt's talk**, **posters from Masayuki Kuzuhara, Qier An, Mariangela Bonavita, Kyle Franson, Alexander Venner, and Thayne Currie**

Current significance of astrometric acceleration

Planet Hosts

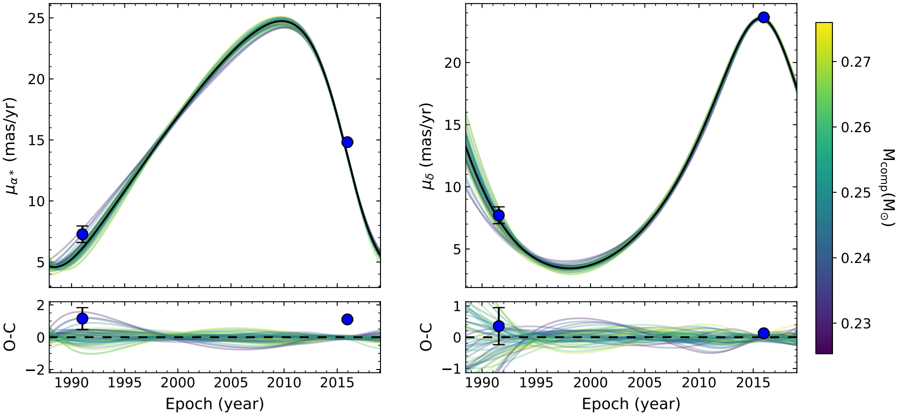
- β Pic: 3σ
- HR 8799: 5σ
- 51 Eri: 0σ
- π Mensae: 8σ

Brown Dwarf Hosts

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

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

A note on proper motions as plotted by orvara:



Three constraints, **none** are truly points.

The Future: another position can extend Gaia's sensitivity to longer periods! **Friday talks**

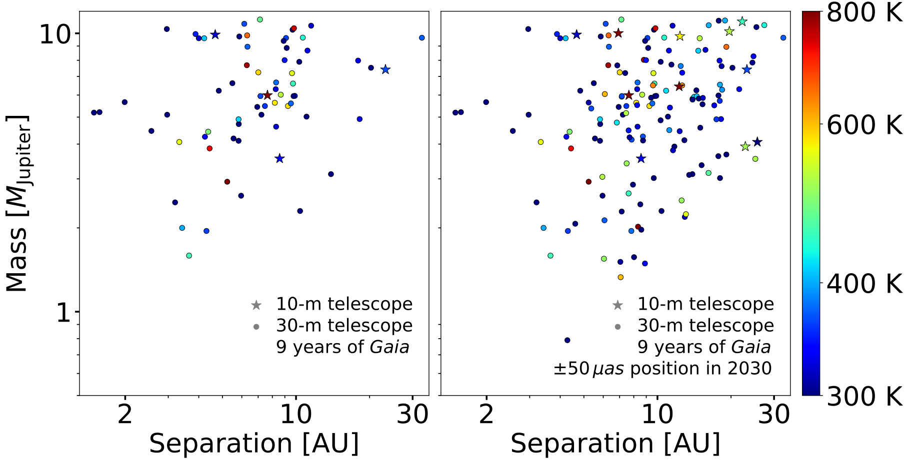


Figure by Zack Briesemeister

Summary

- Absolute astrometry gives accelerations in an inertial reference frame! (must ensure values, uncertainties are calibrated)
- Dynamical beacons indicate unseen companions
- Masses and orbits today (many talks and posters here)
- Big sensitivity improvements coming with DR4 and beyond (perhaps with calibration challenges!)