

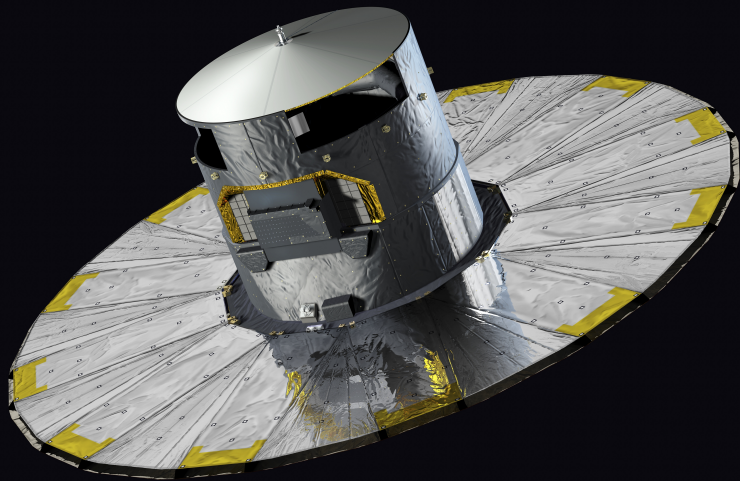
# Exoplanets with Gaia

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University of California, Santa Barbara

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

11 June 2022



*Gaia*: ~1 billion positions, proper motions

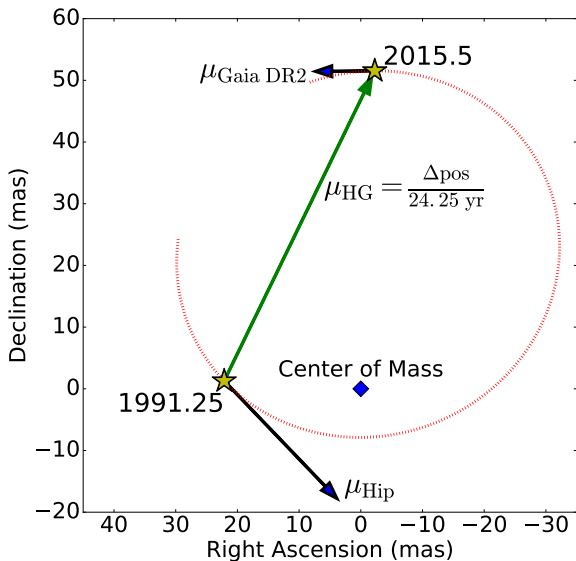
The first accelerations come Monday!

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



**hipparcos**

# Precise astrometric accelerations today



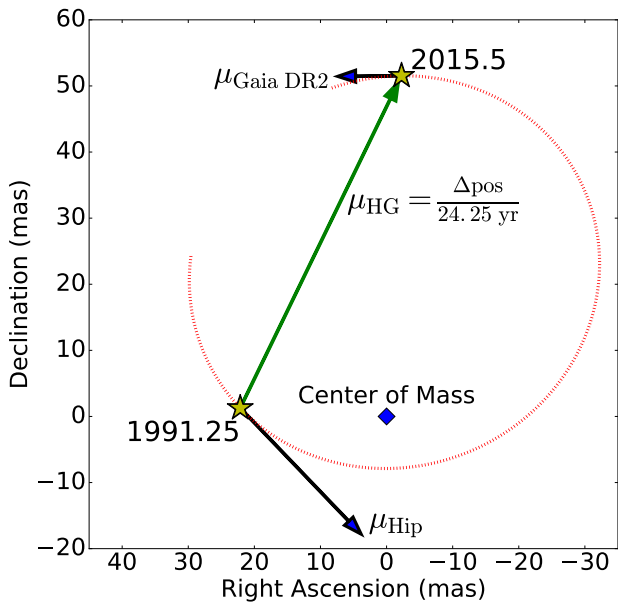
If we also have RV and relative astrometry (from images), we can weigh systems with arbitrarily long-periods:

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

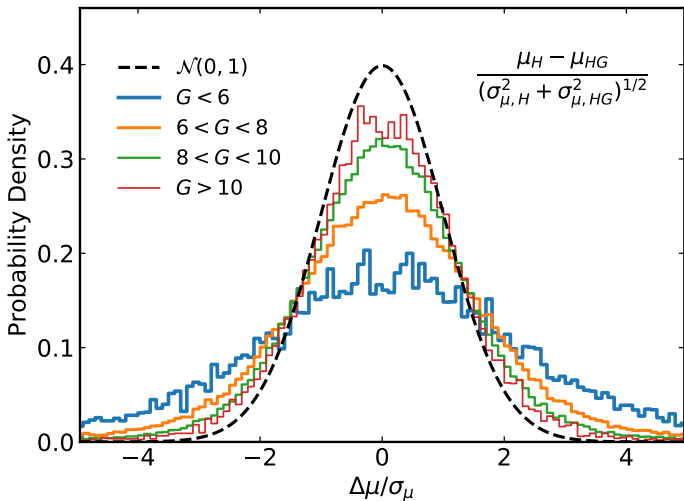
$$a_{\text{RV}} = \frac{GM_2}{r_{12}^2} \sin \varphi$$

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

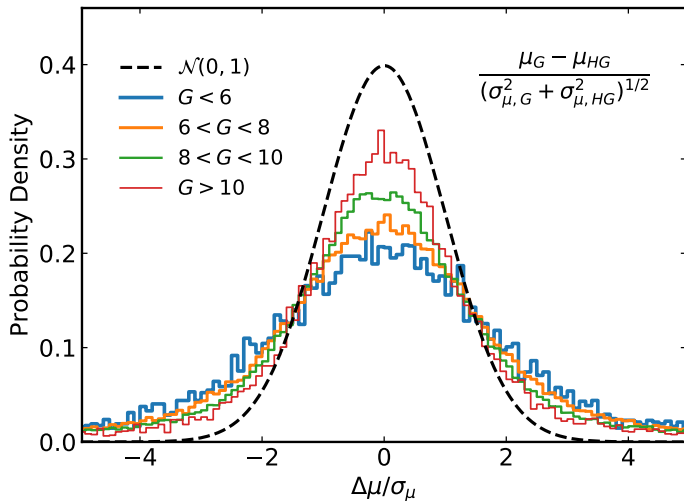
⇒ companion mass  $M_2$ !



# *Hipparcos* residuals from long-term proper motions



# *Gaia* residuals from long-term proper motions





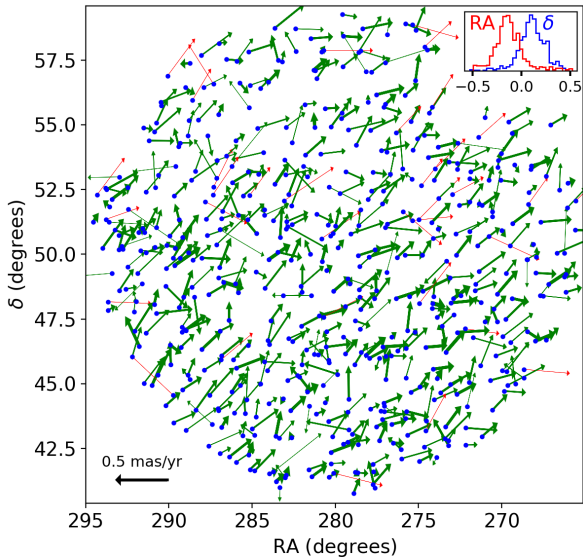
As published, neither *Hipparcos* nor *Gaia* scaled proper motion residuals follow the standard normal distribution.

**Any analysis that assumes they do is incorrect.**

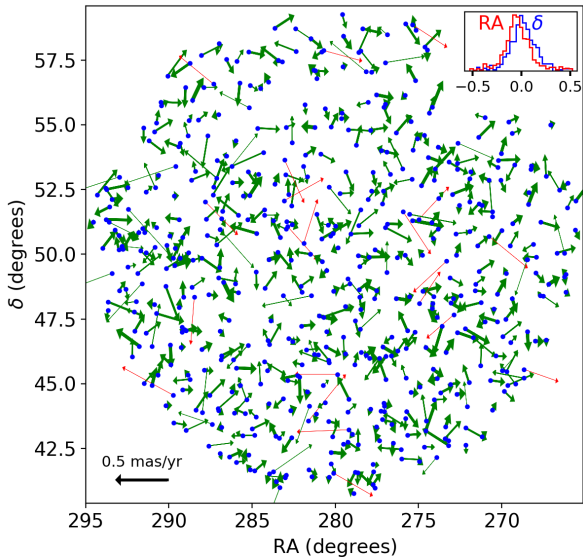
... but this can be fixed with a cross-calibration.

## Correcting an example field, DR2

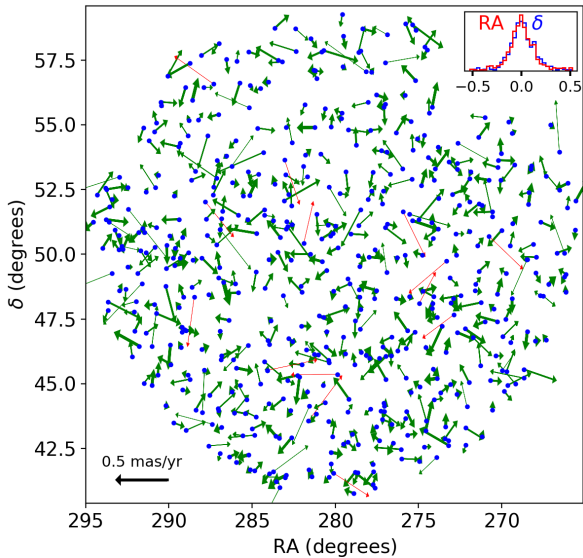
$$\Delta\mu_{\alpha^*} = \mu_{\alpha^*, Gaia} - \frac{\alpha_{Gaia} - \alpha_{Hip}}{t_{Gaia} - t_{Hip}} \cos \delta$$
$$\Delta\mu_{\delta} = \mu_{\delta, Gaia} - \frac{\delta_{Gaia} - \delta_{Hip}}{t_{Gaia} - t_{Hip}}$$



**No correction for frame rotation**



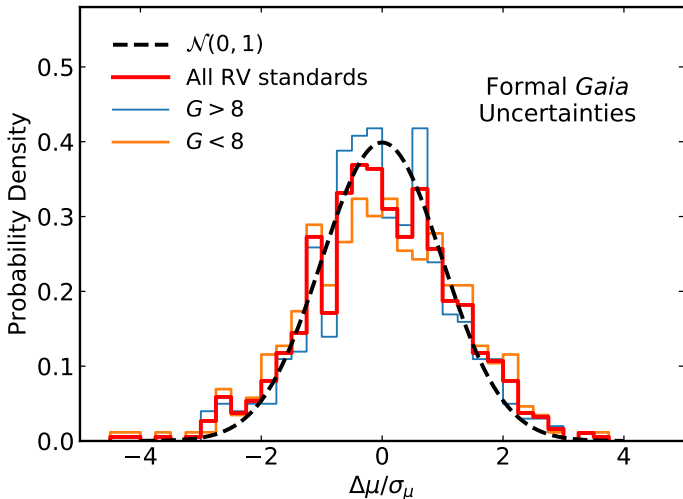
**Global correction for frame rotation**



**Locally variable correction for frame rotation**

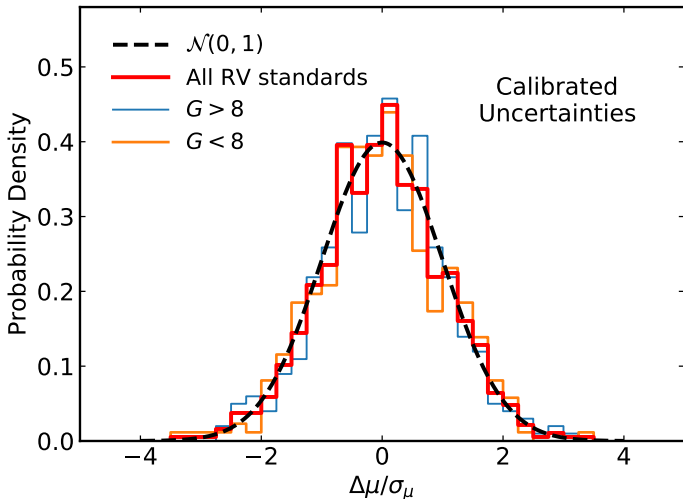
# Calibration of *Gaia* EDR3 Uncertainties

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



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

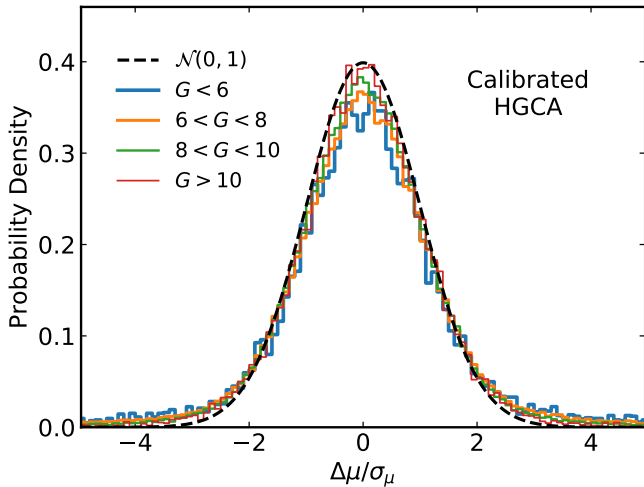
- Three proper motions in the EDR3 frame
- Calibrated uncertainties
- Suitable for orbit fitting

### Notes of Caution

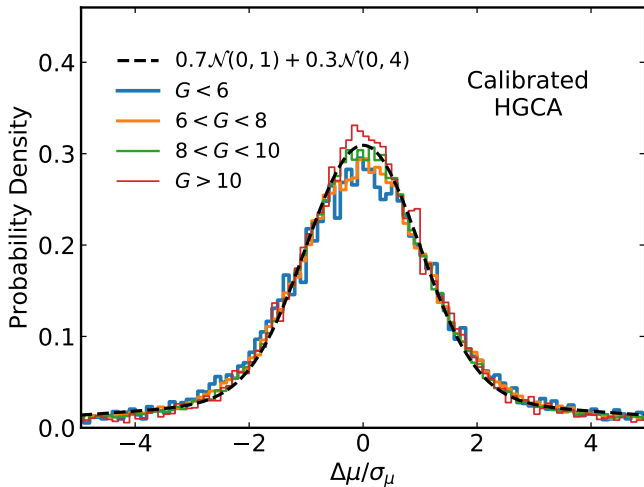
- Be careful of the *Hipparcos* IAD
- Proper motions are not instantaneous measurements
- Epochs of positions, proper motions  $\neq$  catalog epochs



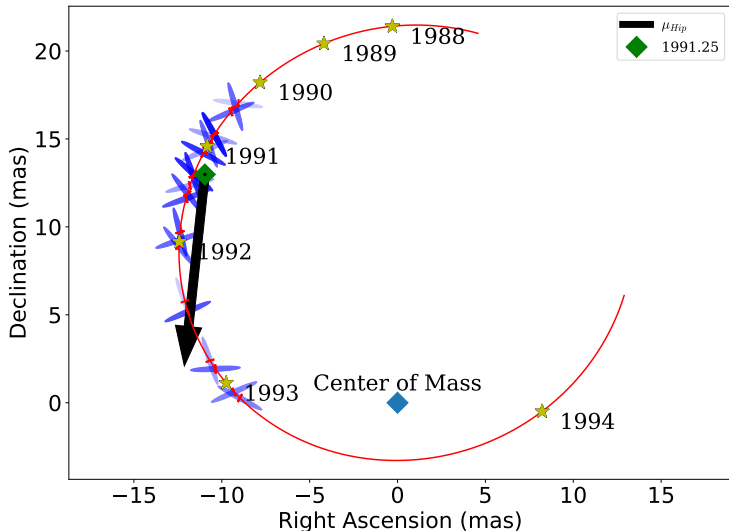
## Final *Hipparcos* residuals



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



# Caveat: nobody ever measures velocities directly



Mirek Brandt et al. (2021)

## Shameless Self Promotion: Tools from UCSB

*Hipparcos-Gaia* Catalog of Accelerations

Hundred Thousand Orbit Fitter: Mirek Brandt+, 2021

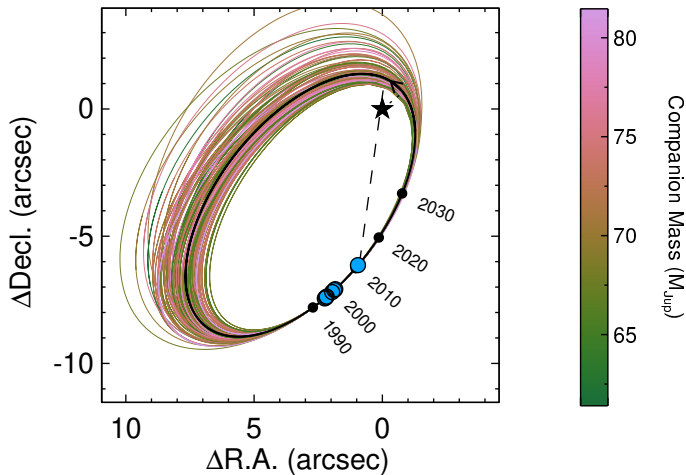
- Simulate *Hipparcos* and *Gaia* results for any orbit

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

- Fast and efficient orbit fitting

We can fit orbits with *Gaia* today!

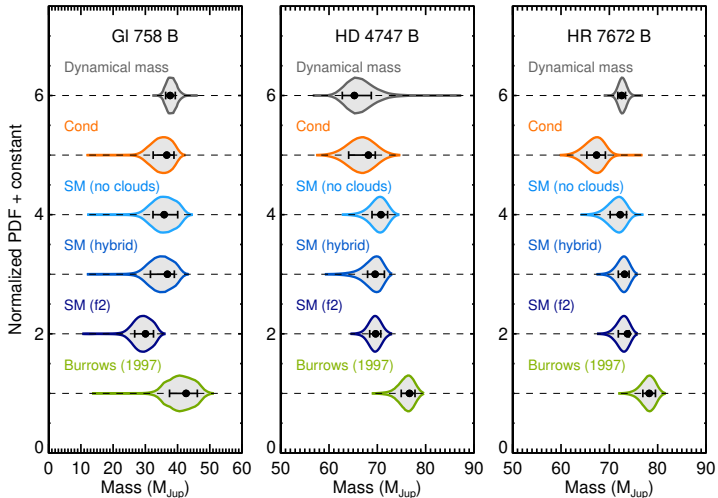
# Example: Gl 229B (first brown dwarf imaged!)



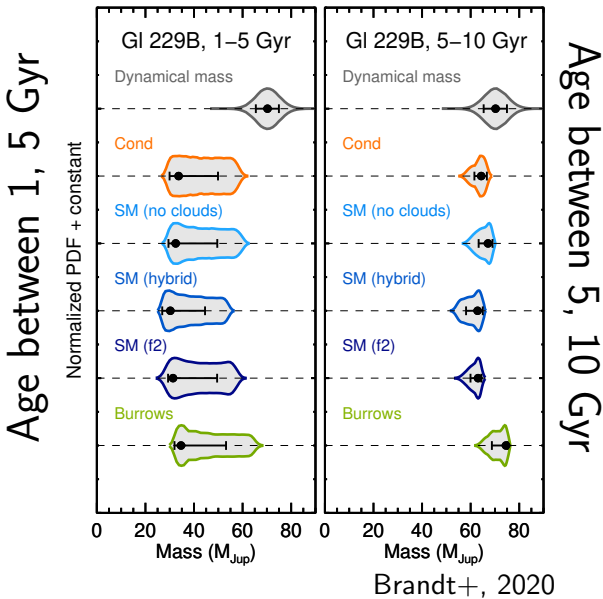
$M = 70 \pm 5 M_{\text{Jup}}$ . Almost a star! (Brandt+, 2020)

# Brown dwarf cooling: $L_{\text{um}} = L_{\text{um}}(\text{Age}, \text{Mass})$

Finally, we have masses to test these models!

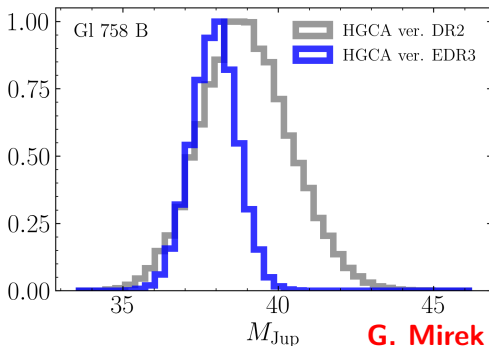


And Gl 229B is surprisingly heavy.



*Gaia* EDR3: up to  $\sim 1\%$  mass measurements for brown dwarfs on century-long orbits! (G. Mirek Brandt+, 2021, Franson+2022, Bowler+2021, Maire+2020)

Precise masses and inclinations for long-period RV planets! (Yiting Li+, 2021, Feng+ 2019, Venner+ 2021, Xuan+Wyatt 2020, Damasso+ 2020, Hill+ 2021, Bardalez Gagliuffi+ 2021)

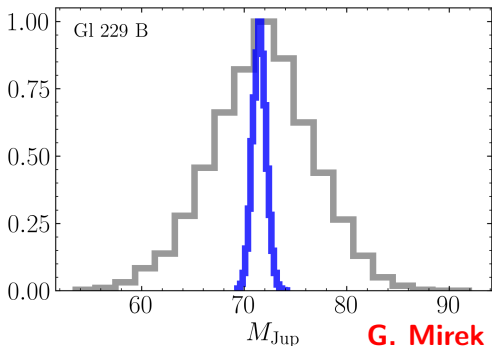


G. Mirek Brandt+, 2021



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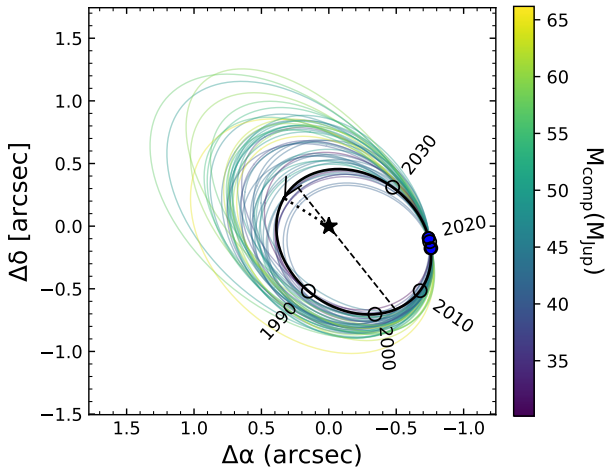


G. Mirek Brandt+, 2021

We are finding and weighing new brown dwarfs . . .

New imaged  
companions,  
**instant masses!**

HD 33632B  
 $46.4^{+8.1}_{-7.6} M_{\text{Jup}}$



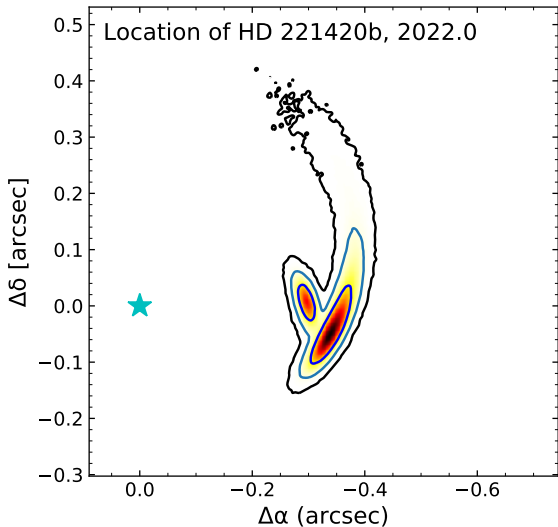
Currie, Brandt et al, 2020

... and more discoveries are waiting to be made.

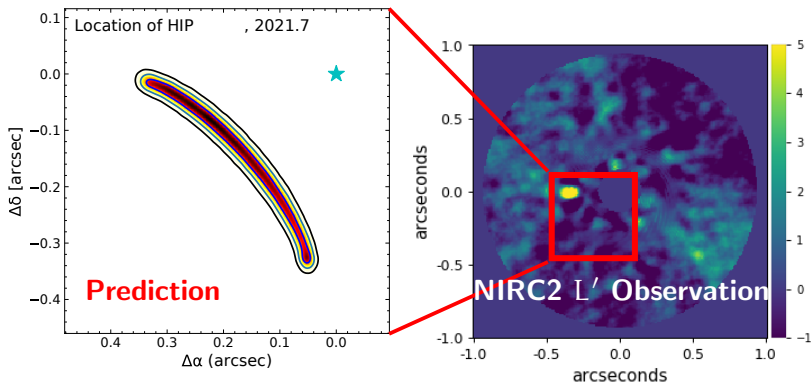
Position and mass  
are known *before*  
*imaging*

$$20.6_{1.6}^{+2.0} M_{\text{Jup}}$$

Yiting Li+ 2021



We can *predict* masses and locations,  
and then image new brown dwarfs!



Yiting Li+, in prep

# Masses and orbits for imaged planets!

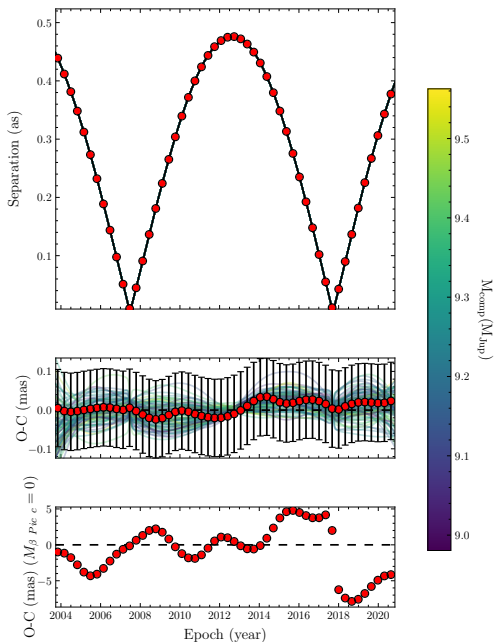
$\beta$  Pic bc

(**G. Mirek Brandt**+ 2021)

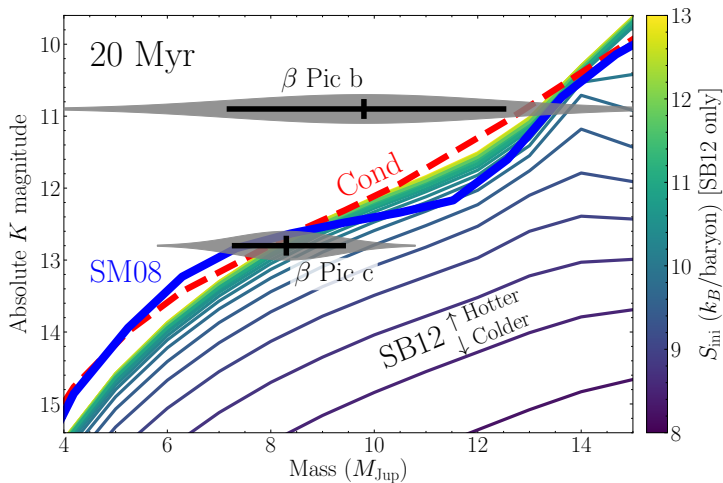
Follow-up from Dupuy+ 2019  
with GRAVITY astrometry,  
new RVs

rebound: superposition of  
Keplerians is sufficient

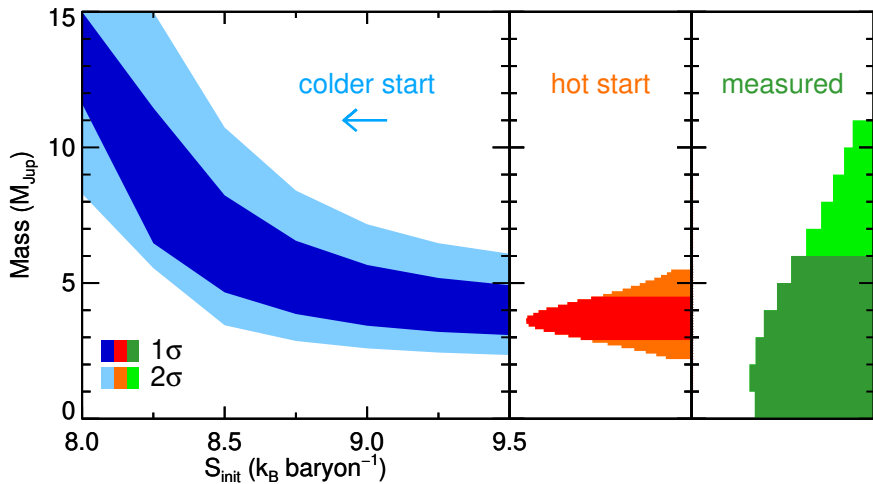
Two-planet fit using orvara



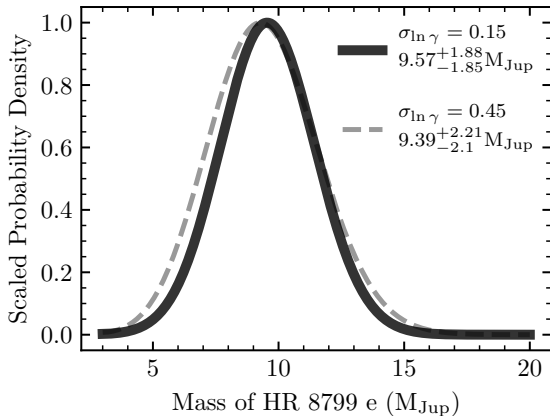
Masses for  $\beta$  Pic bc: **G. M. Brandt**+, 2021



# Ruling out a very cold start for 51 Eri b: Dupuy+ 2022



... Even a 20% mass of HR 8799 e, the famous planet imaged by Marois+!

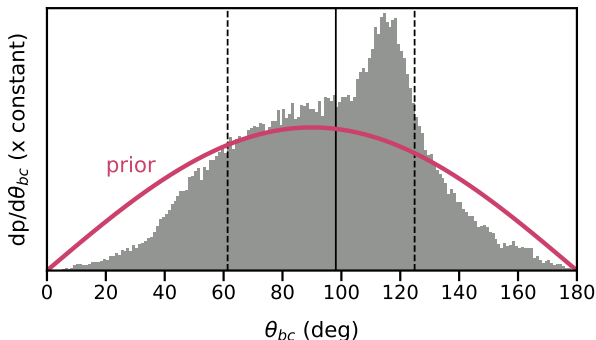


G. Mirek Brandt+, 2021



## Mutual inclinations: clues to the dynamical history

- High mutual inclinations for  $\pi$  Men b, c: Xuan+Wyatt 2020, Damasso+ 2020, De Rosa+ 2020
- High mutual inclinations for 14 Her b, c: Bardalez Galiuffi+ 2021  
... but beware of the  $\sin i$  prior! Bardalez Galiuffi+ 2021



# And potential synergies with future NASA missions

Planets imageable and detectable with a single **WFIRST-WFI** astrometric point!

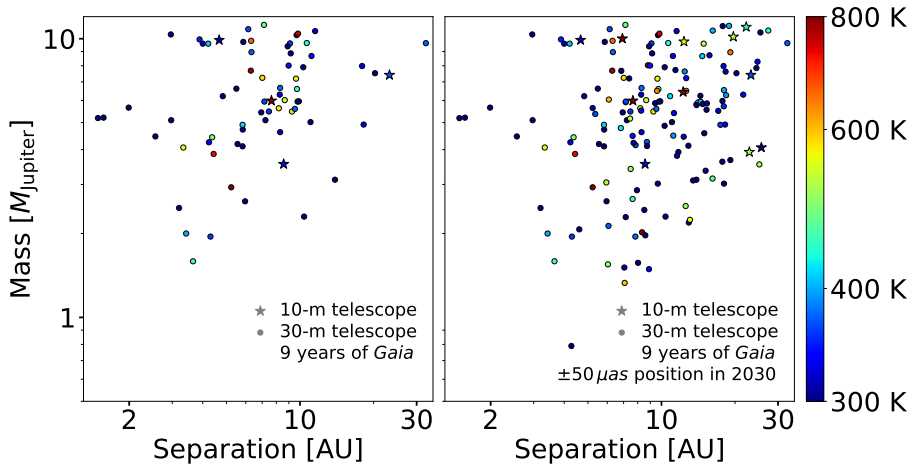


Figure by Zack Briesemeister

## Massive brown dwarfs are easily detectable

- New discoveries, and precise dynamical masses at periods of centuries
- Finally: anchors to evolutionary and atmosphere models!

## Long-period RV planets induce detectable astrometric accelerations today

- Masses, inclinations, and mutual inclinations! (but beware the priors)

## Opportunities for synergies with future NASA missions

- Guaranteed, localized targets for HabEx, LUVOIR
- Long-baseline astrometry with WFIRST-WFI

DR3 will have accelerations and maybe a few new planets!  
The main planet haul, though, will be with DR4.

Thank you!