# Finding interesting (accelerated and otherwise) binaries from *Gaia*

## SDSS-V/ZTF

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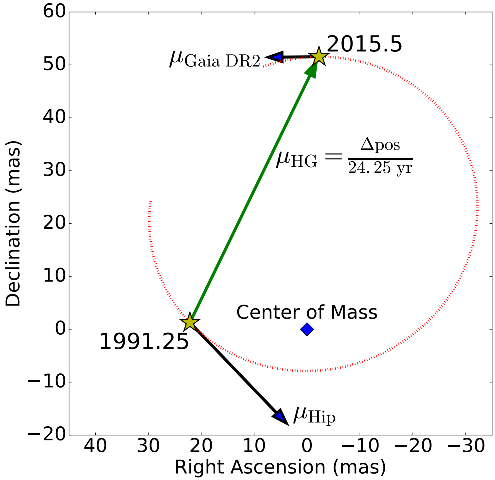
# Part I: Astrometric Accelerators

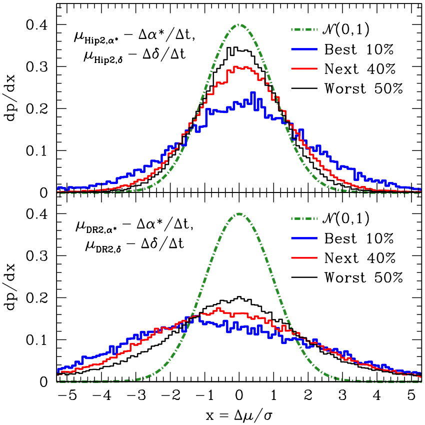
Need detectable acceleration, single-star astrometry

- Separations $\sim 2 - 100$ AU
- Large brightness difference
- Nearby: $\mathrm{d} \lesssim 200$ pc

Basic idea: *Hipparcos* and *Gaia* can detect astrometric accelerations of a few $\mu$as/yr$^2$, a few m/s/yr at 50 pc. *Gaia* DR3 will improve this (ideal case: $\sigma_\mu \sim t^{-3/2}$).



# Use of *Hipparcos* and *Gaia* for fitting orbits & identifying astrometric accelerators requires a *cross-calibration*.




$\Delta$positions/$\Delta$t – proper motions, raw catalogs

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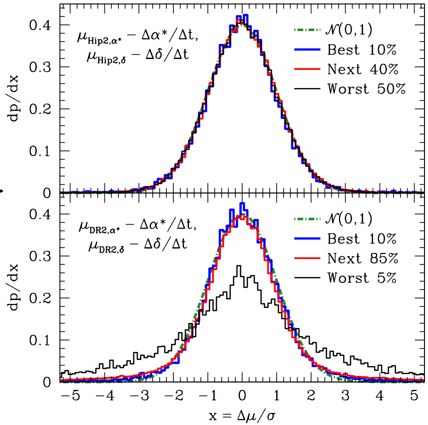



$\Delta$positions/$\Delta$t – proper motions, after cross-calibration

## Full details of the cross-calibration are in Brandt (2018): The *Hipparcos*-*Gaia* Catalog of Accelerations

- Refinement of *Hipparcos* astrometry with *Gaia* parallaxes
- Propagation of all positions to their central epochs
- 60/40 linear combination of the two *Hipparcos* reductions outperforms either reduction individually at 150 $\sigma$ significance
- Spatially variable calibration offsets and frame rotations between the catalogs
- Error inflation in quadrature for *Hipparcos*, spatially dependent multiplicative error inflation for *Gaia*
- Perspective acceleration included
- Three proper motions given on the DR2 reference frame

If we also have RV and relative astrometry from imaging, we can fit orbits even for long-period systems:

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

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

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

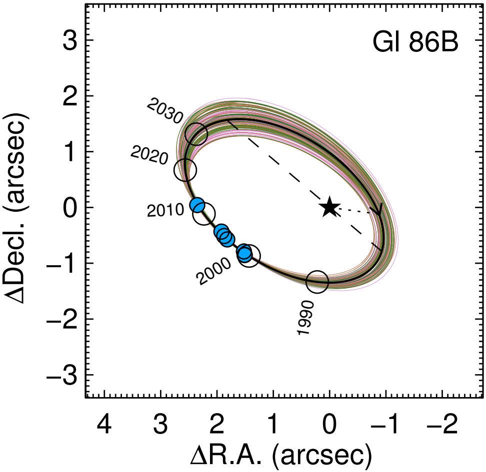
combine to determine the companion mass (though full orbital fits generally remain necessary).

# Example: white dwarf companion to Gl 86

| Proper Motion Difference | Significance |
|---|---|
| $\mu_{\alpha*,Hip} - \mu_{\alpha*,H\to G} = -14.98 \pm 0.43\ \mathrm{mas\,yr^{-1}}$ | **35σ** |
| $\mu_{\alpha*,Gaia} - \mu_{\alpha*,H\to G} = -17.80 \pm 0.13\ \mathrm{mas\,yr^{-1}}$ | **133σ** |
| $\mu_{\delta,Hip} - \mu_{\delta,H\to G} = 12.73 \pm 0.46\ \mathrm{mas\,yr^{-1}}$ | **27σ** |
| $\mu_{\delta,Gaia} - \mu_{\delta,H\to G} = -3.53 \pm 0.12\ \mathrm{mas\,yr^{-1}}$ | **31σ** |

Orbital period is ∼70 years, but we have a ∼1% measurement of the astrometric acceleration!

RVs from UCLES/AAT, relative astrometry from *HST*




Orbit fit by Trent Dupuy: mass of the white dwarf Gl 86B improves from $0.5 \pm 0.1$ to $0.60 \pm 0.01$ $M_\odot$ (Brandt et al. 2018).

. . . and we can use the *Hipparcos* and *Gaia* scanning laws to fit individual observations, *even without the full epoch astrometry*. **Very important, especially for DR3.**

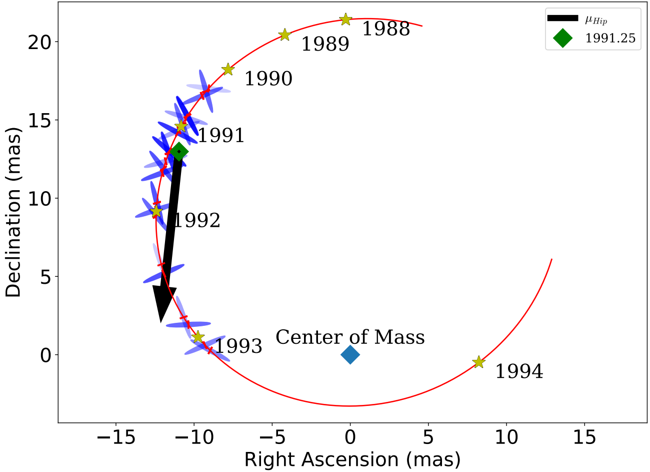



image by G. Mirek Brandt

Note that **DR3 will release accelerations, not orbits!** Fitting orbits to DR3 accelerations with the scanning law (epochs and scan angles) will be the only way to go.

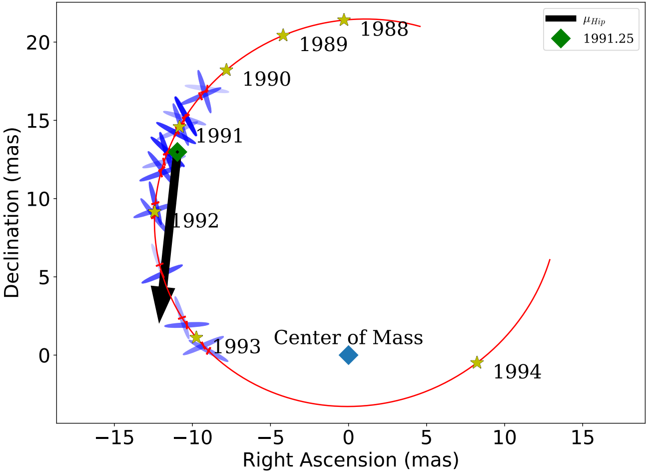



image by G. Mirek Brandt

# Current work

with Trent Dupuy, Brendan Bowler, Jackie Faherty, G. Mirek Brandt, Yiting Li, Daniel Michalik, Daniella Bardalez-Gagliuffi, Mark Popinchalk

- Fitting exoplanet orbits, breaking $\sin i$ degeneracy
- Masses and orbits for long period brown dwarfs, low-mass stars, white dwarfs
- Searches for new companions, targets for RV and imaging follow-up

Great way to find and weigh Sirius-like binaries!

Even better for (heavier) non-interacting neutron stars and black holes?

*Gaia* DR3 will measure accelerations for millions of stars, but **confirmation** and **masses** really need RV curves. **Whence the RVs?**

## SDSS-V Ideas:

- MARVELS for dark remnants. 100 $\mu$as yr$^{-2}$ at 200 pc is 100 m s$^{-1}$ yr$^{-1}$—not crazy.
- Can we find the nearest neutron star or black hole?
- Chemical compositions of main sequence stars with dark companions?

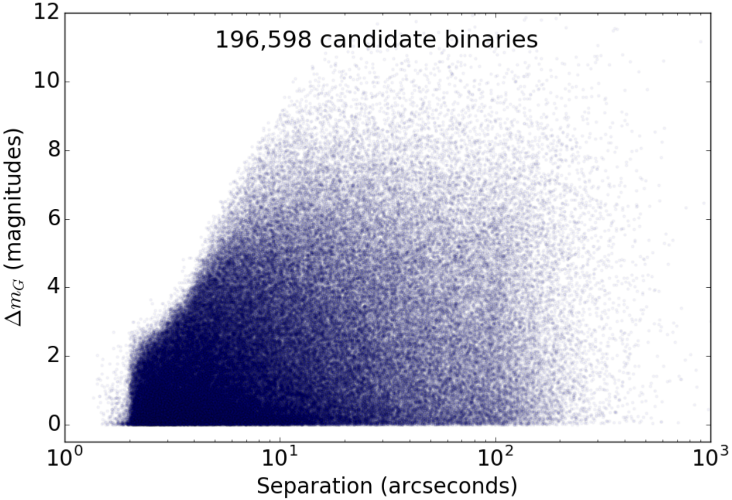
## ZTF Idea:

- Gyrochonology+masses to constrain pre-main-sequence of low-mass stars, evolution of brown dwarfs and remnants? C.f. Lynne Hillenbrand's talk.

# Part II: Non-Accelerating Binaries

- Wide: separations $\gtrsim$ 20 AU
- More distant: up to at least $\sim$500 pc
- Favors stars of comparable brightness
- Major credit to Kareem El-Badry!

# ~200,000 systems within 500 pc have compatible parallaxes and proper motions. Most are binaries.



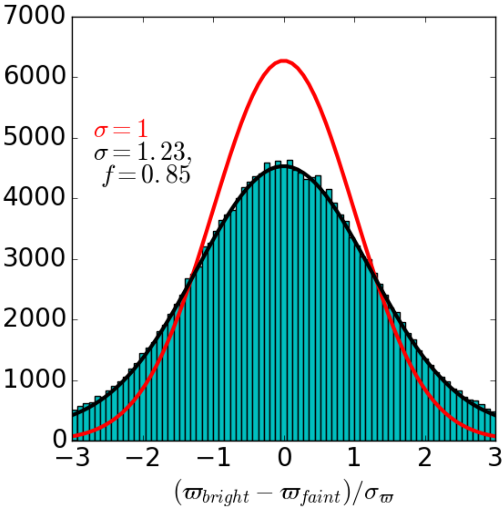

Sample from Kareem El Badry

So much about the distribution of stellar binaries is hidden in that sample!

- Mass ratio distribution
- Semimajor axis distribution
- Eccentricity distribution (isothermal???)
- Trends with age, metallicity?
- Hierarchical triples??

**We can have it all** . . . once we deal with *Gaia* systematics and underestimated uncertainties, and the *Gaia* selection function.

# Example: DR2 parallax errors underestimated by 20–30%?



Really want more data—like RVs—to model orbits and back out *Gaia* systematics. Recall 100 μas/yr at 200 pc is ∼100 m/s.

**SDSS-V to the rescue?**

∼200,000 binaries would also be great for understanding scatter in gyrochronology.

Typical brightness of $G \sim 14$ mag is well-matched to the ZTF saturation limit.

Back to the title (my perspective):

- Interesting individually: the accelerators
- Interesting statistically: the wide binaries

A philosophical comment on "rare and/or interesting systems:" searching for **outliers** in a large survey like *Gaia* will inevitably uncover **pathologies** in the data.

Independent supporting measurements are vital!

- RVs and chemistry from SDSS-V!
- Light curves from ZTF!