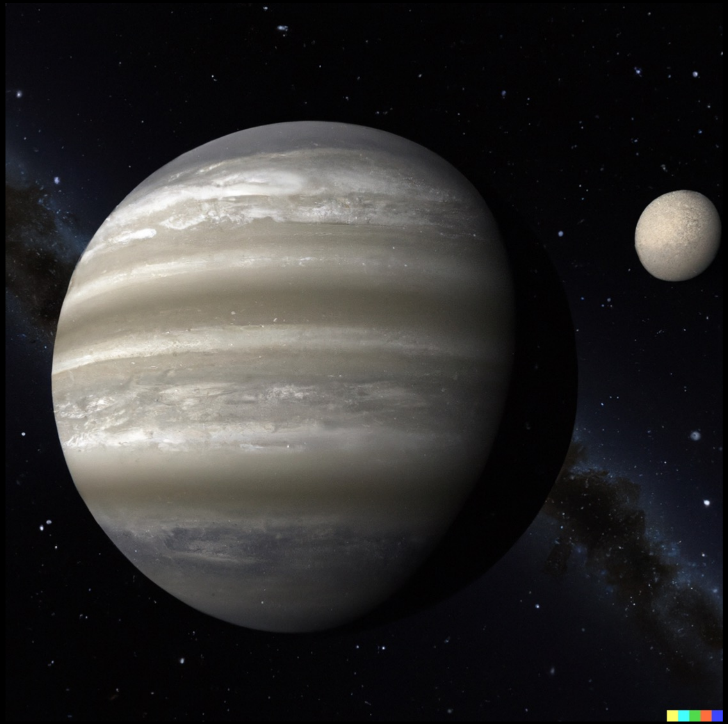
Resolved BD Companions: Combining Gaia and Direct Imaging

G. Mirek Brandt

Sagan Workshop 2022

Outline

- Importance of Brown Dwarfs (BDs)
- Tools to derive masses
- Understanding 1d measurements from Gaia/Hipparcos.
- Fitting orbits/masses to 1d measurements.



Based on work by

Yiting Li, Tim Brandt, Daniel Michalik, Minghan Chen, Trent Dupuy, Brendan Bowler, Thayne Currie, and many others...

On systems such as **HR 8799, beta pic, Gl 229, Gl 758, 51 Eri**, and more!

Precise Dynamical Masses and Orbital Fits for β Pic b and β Pic c

G. Mirek Brandt[4,1], Timothy D. Brandt[1], Trent J. Dupuy[2], Yiting Li[1], and Daniel Michalik[5,3]

Improved Dynamical Masses for Six Brown Dwarf Companions Using Hipparcos and Gaia EDR3

G. Mirek Brandt[9,1], Trent J. Dupuy[2], Yiting Li[1], Minghan Chen[1], Timothy D. Brandt[1], Tin Long Sunny Wong[1], Thayne Currie[3,4,5], Brendan P. Bowler[6], Michael C. Liu[7], William M. J. Best[6], and Mark W. Phillips[8]

Limits on the mass and initial entropy of 51 Eri b from *Gaia* EDR3 astrometry

Get access

Trent J Dupuy, G Mirek Brandt, Timothy D Brandt

Brown Dwarfs

~13x to 80x
Jupiter's mass

Planets & Exoplanets

Up to ~13x
Jupiter's mass

Brown Dwarfs bridge the gap between planet & star formation

Stars
(Fueled by Nuclear Fusion)

Over ~80x
Jupiter's mass

credit: NASA/ Caltech/ R. Hurt (IPAC).

The masses of BD’s and Giant Planets are key

An *independently* measured mass can tell us

- 1. How old the companion is *and*
- 2. How the companion formed* and/or which model(s) it matches

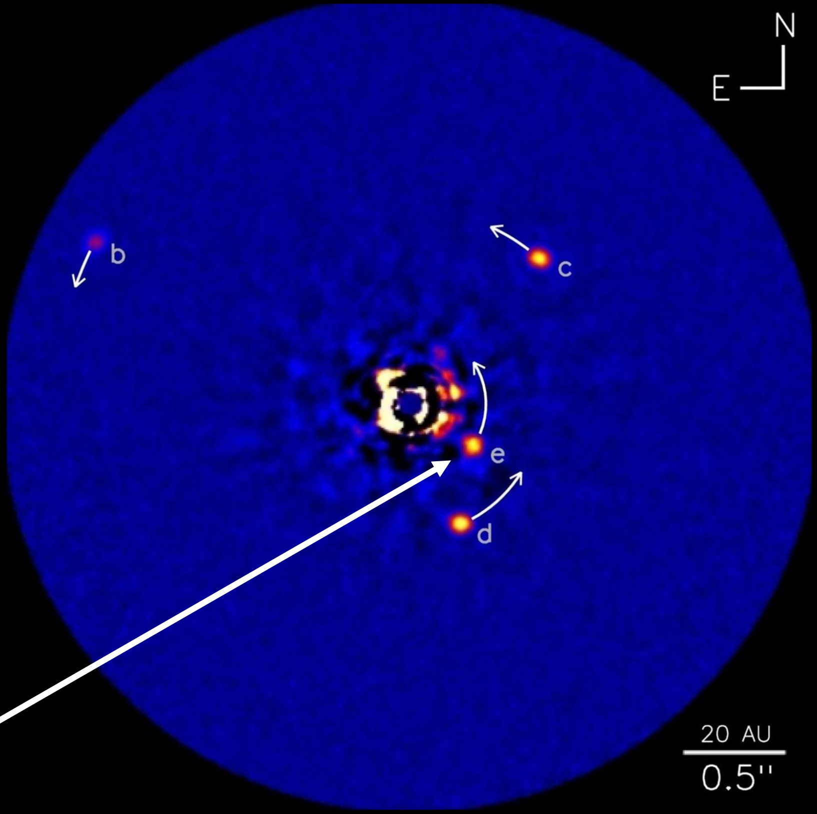
* E.g., differences between cold/hot starts, e.g., Marleau, G. -D. ; Cumming, A. 2014 , or application to Beta pic b/c (Nowak et al. 2020, A&A 642)

The age and mass of the innermost HR 8799 planet

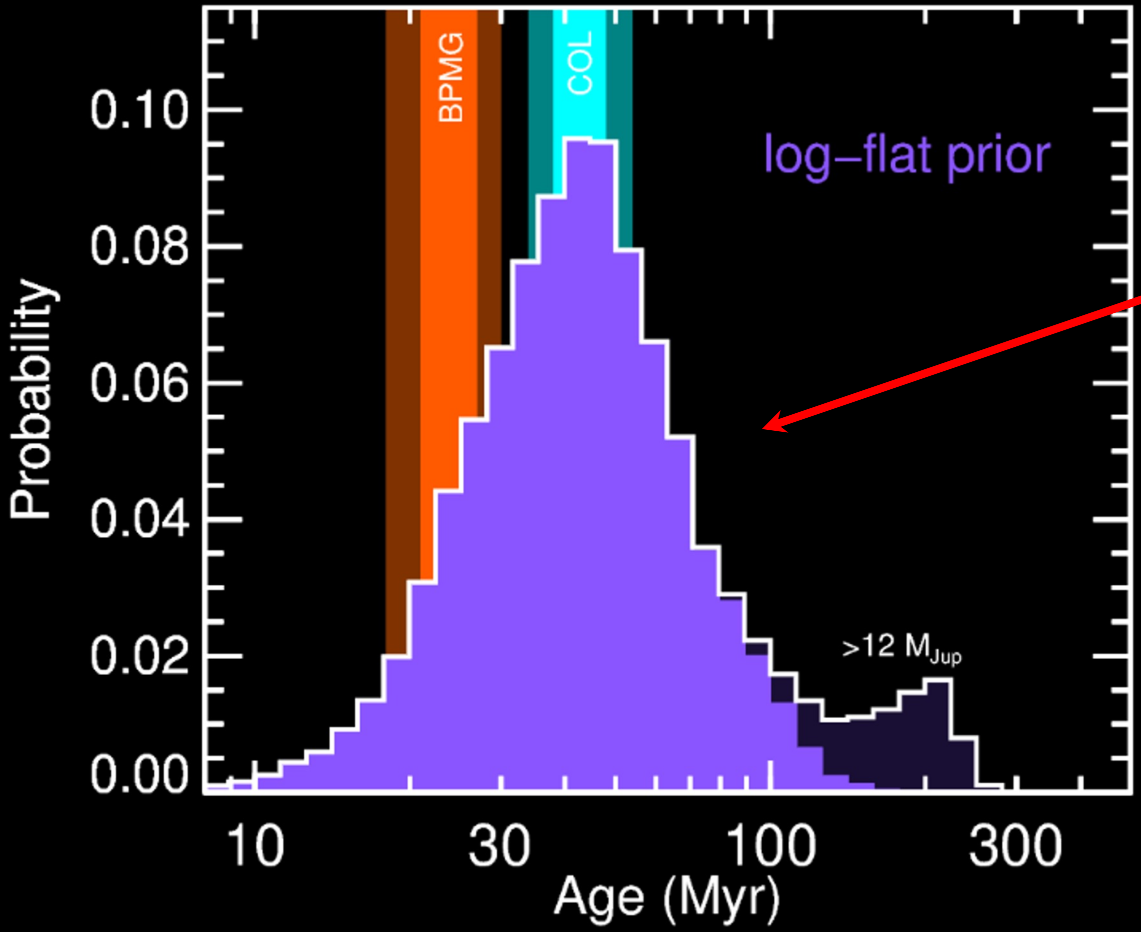
The First Dynamical Mass Measurement in the HR 8799 System

G. Mirek Brandt[7,1], Timothy D. Brandt[1], Trent J. Dupuy[2], Daniel Michalik[3], and Gabriel-Dominique Marleau[4,5,6]

HR 8799 e



NRC-HIA, C. Marois, and Keck Observatory



The planet's age from its mass!

M. Brandt et al. 2021, arxiv: 2105.12820

The HR 8799 work was a result of coupling **HTOF** with REBOUND.

UCSB

htof: A New Open-source Tool for Analyzing Hipparcos, Gaia, and Future Astrometric Missions

G. Mirek Brandt[5,1], Daniel Michalik[6,2], Timothy D. Brandt[1], Yiting Li[1], Trent J. Dupuy[3], and Yunlin Zeng[1,4]

HTOF: all things absolute astrometry

github.com/gmbrandt/HTOF

- Automatic downloading of Hip1 and Hip2, Gaia raw data for on-sky positions (a.k.a the intermediate astrometry; IAD).
- Easy parsing of the IAD files/scanning law
- Fit 5,7,9 parameter skypaths, compute hip2 error inflations etc..

HTOF: M Brandt. et al. 2021, arxiv: 2109.06761 (developed by myself, Daniel Michalik, Tim Brandt & Gavin K. Hung)
REBOUND: Rein & Liu 2012, github.com/hannorein/rebound

Open-source software framework for masses+orbits

Orvara combines absolute astrometry with relative astrometry (also RVs and relative RVs).

orvara: An Efficient Code to Fit Orbits Using Radial Velocity, Absolute, and/or Relative Astrometry

Timothy D. Brandt[1], Trent J. Dupuy[2], Yiting Li[1], G. Mirek Brandt[7,1], Yunlin Zeng[3], Daniel Michalik[4], Daniella C. Bardalez Gagliuffi[5], and Virginia Raposo-Pulido[6]

github.com/t-brandt/orvara

Open-source software framework for masses+orbits

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HTOF inside!

orvara: An Efficient Code to Fit Orbits Using Radial Velocity, Absolute, and/or Relative Astrometry

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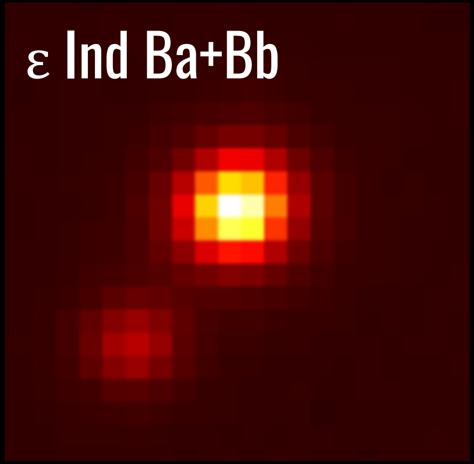
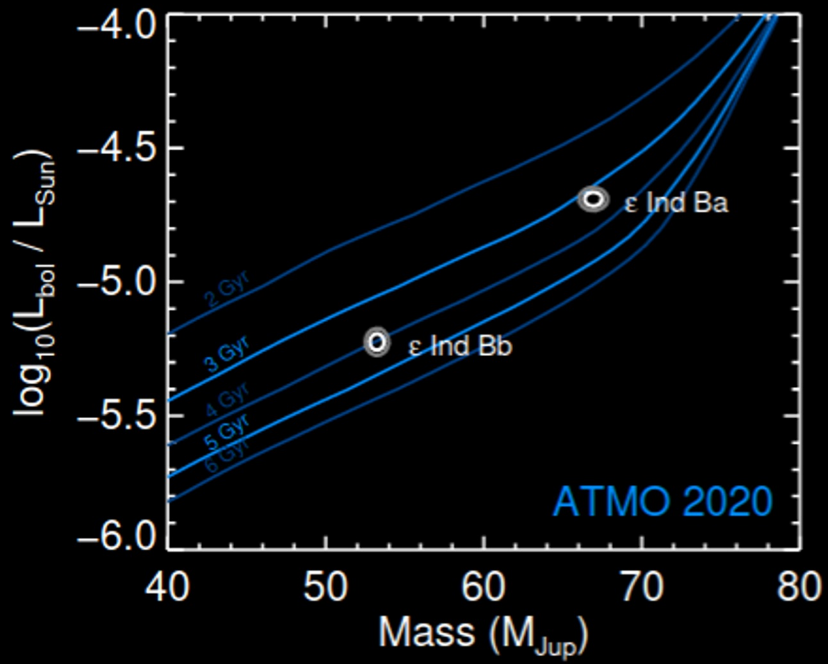
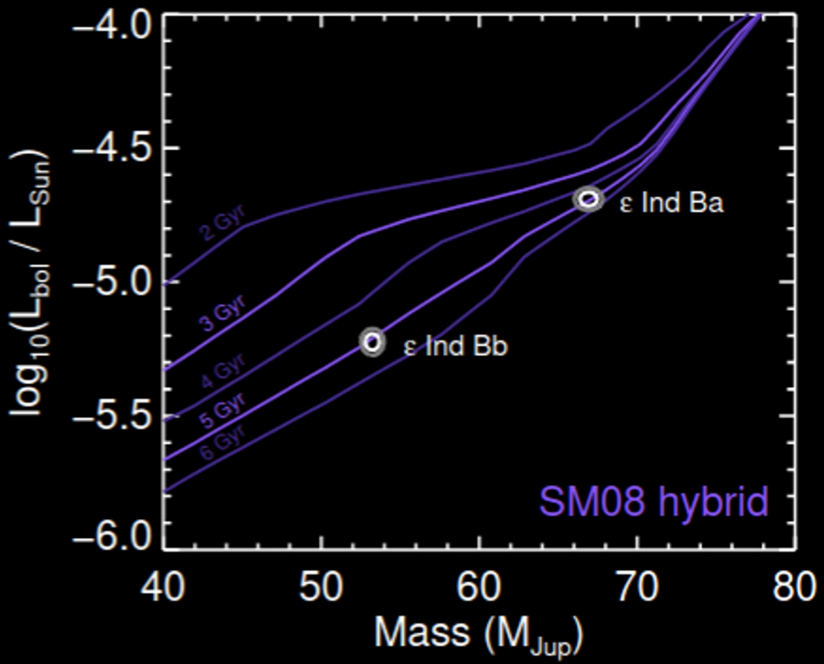
A fantastic example of constraining detailed attributes of Brown Dwarfs, not just the age



Empirically testing BD Model Isochrones





Using orvara ! Minghan Chen + Yiting Li et al. 2022, arxiv: 2205.08077

The common denominator of both examples:

Relative astrometry + absolute astrometry to arrive at the mass. No radial velocities were used in either case!

Masses give us so much!

But we have *so few* of them...

All known exoplanets

About 5000

Brown Dwarfs
(defined here as mass > 13 Mjup)

About 100

Imaged Brown Dwarfs with known mass*

About 20

*meaning the mass is independently measured, not inferred from a cooling model.

Masses give us so much!

But we have *so few* of them...

We need to build up this sample size!

All known exoplanets

About 5000

Brown Dwarfs

(defined here as mass > 13 Mjup)

About 100

Imaged Brown Dwarfs with known mass*

About 20

*meaning the mass is independently measured, not inferred from a cooling model.

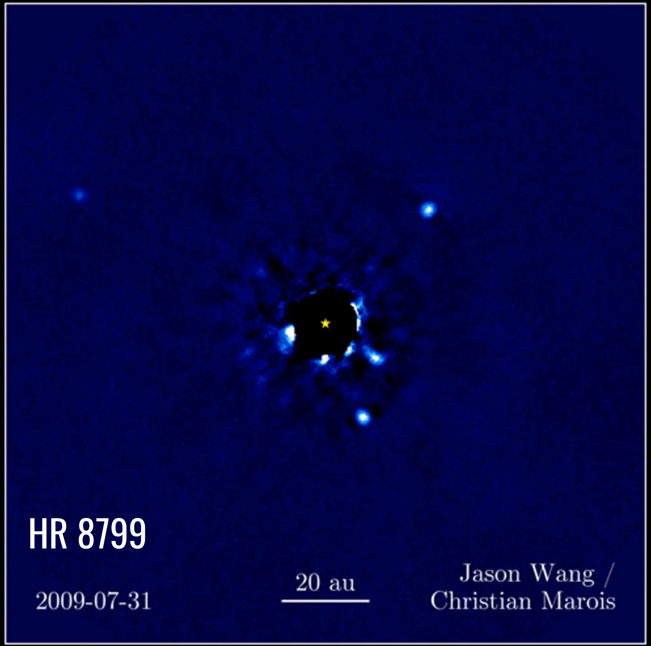
How to measure more masses

Combine relative astrometry + absolute astrometry (and RVs too).

For absolute astrometry: The standard is to use proper motion anomalies.

But with Gaia DR4 we will have the individual position measurements on-sky. (often called the epoch astrometry; or IAD for Hipparcos)

Relative motion

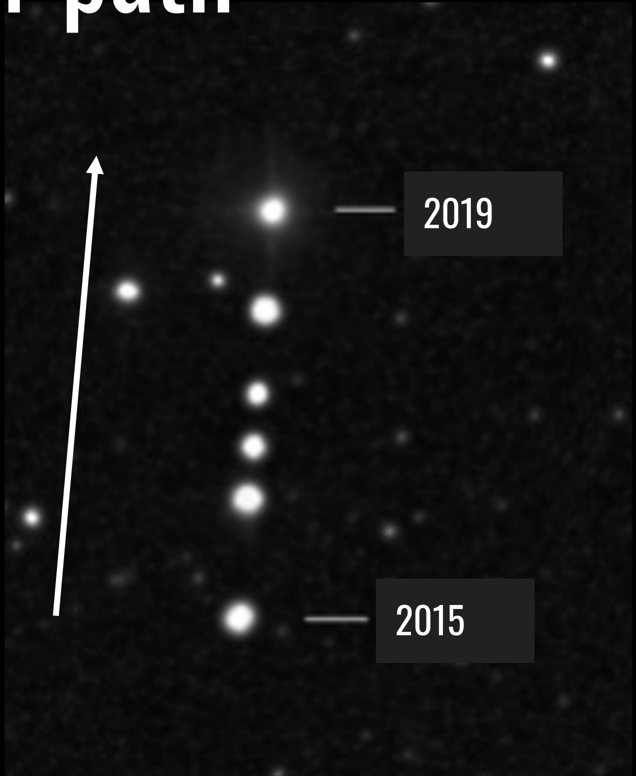


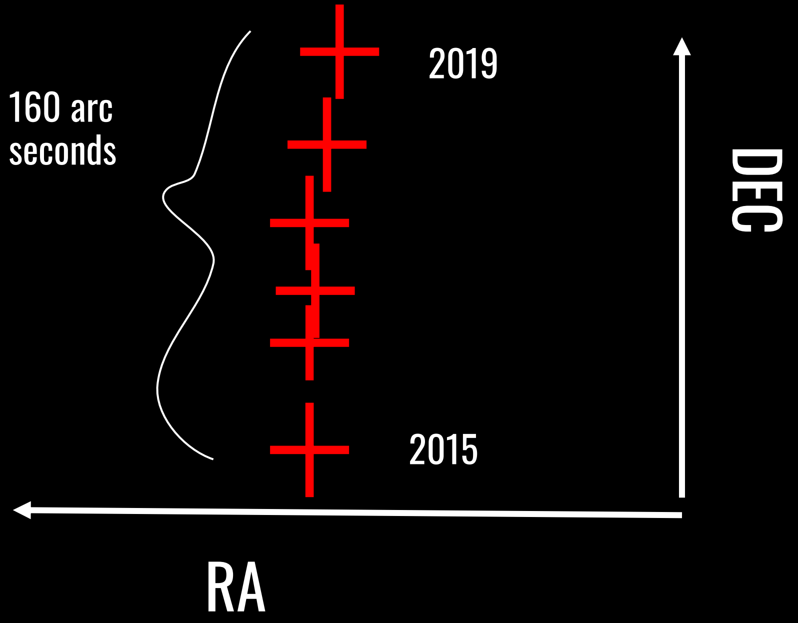
Absolute motion from Epoch Astrometry

+

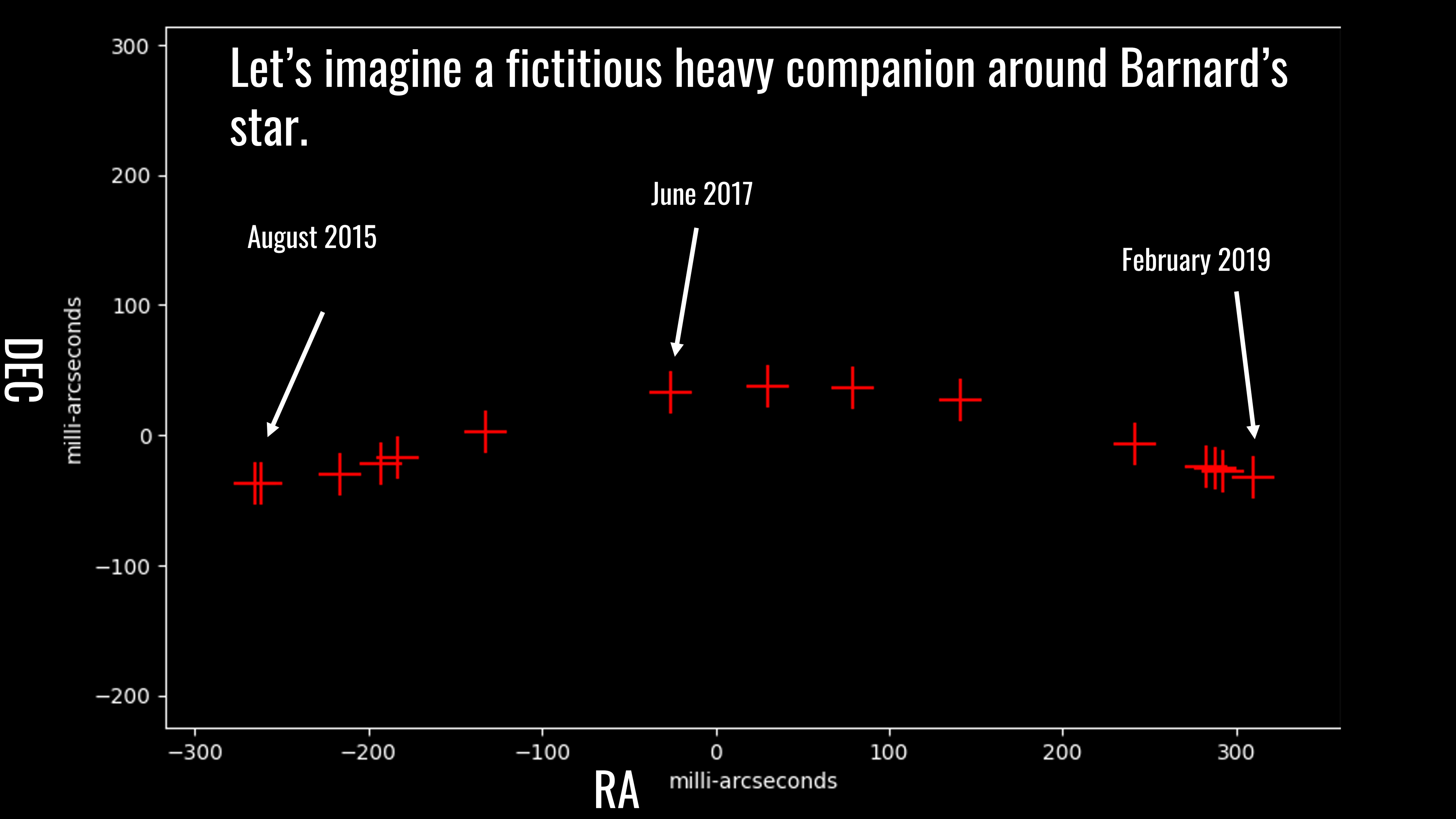
= the mass (and other orbital elements)

Stars without heavy companions follow a linear path**



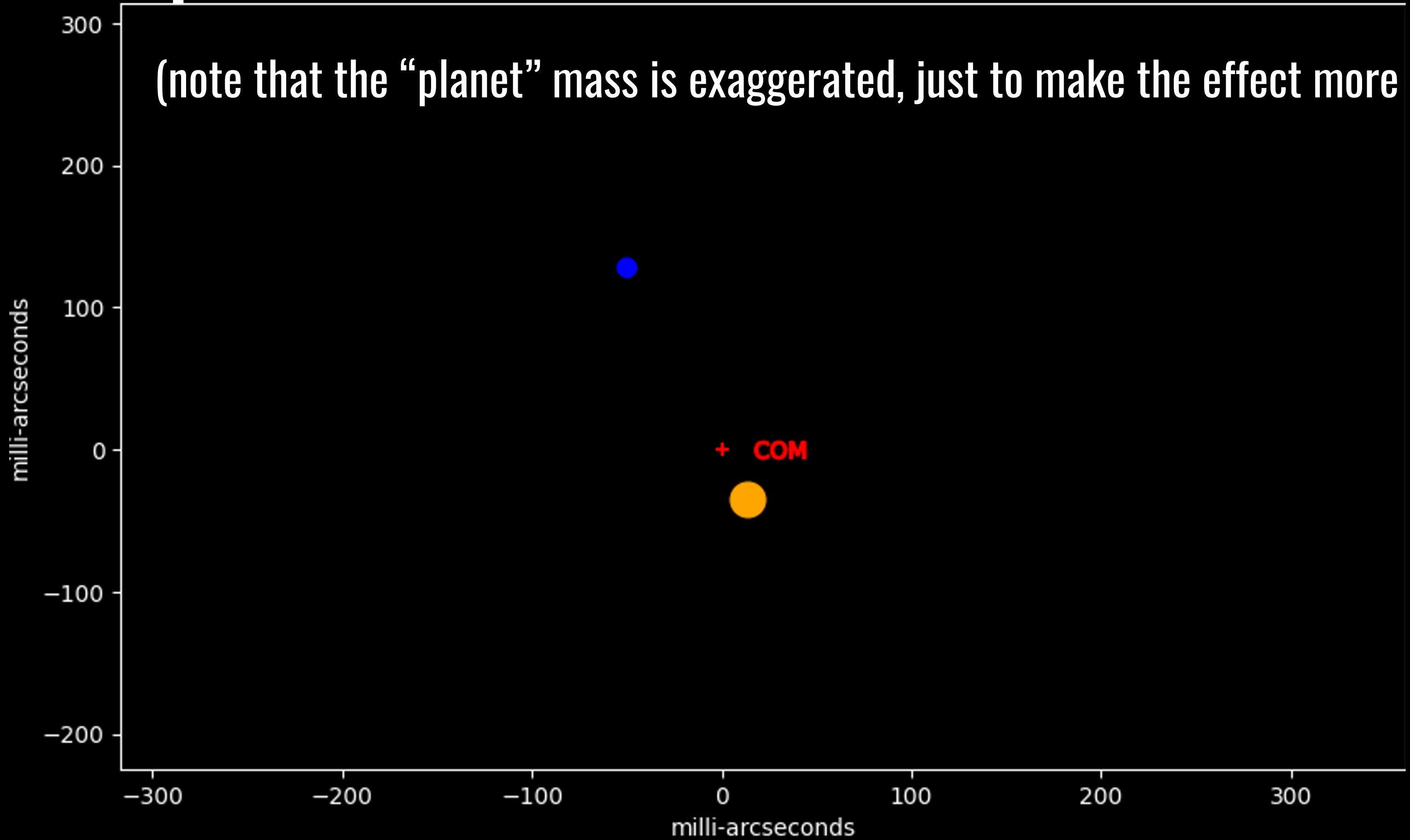


** after removing parallax motion

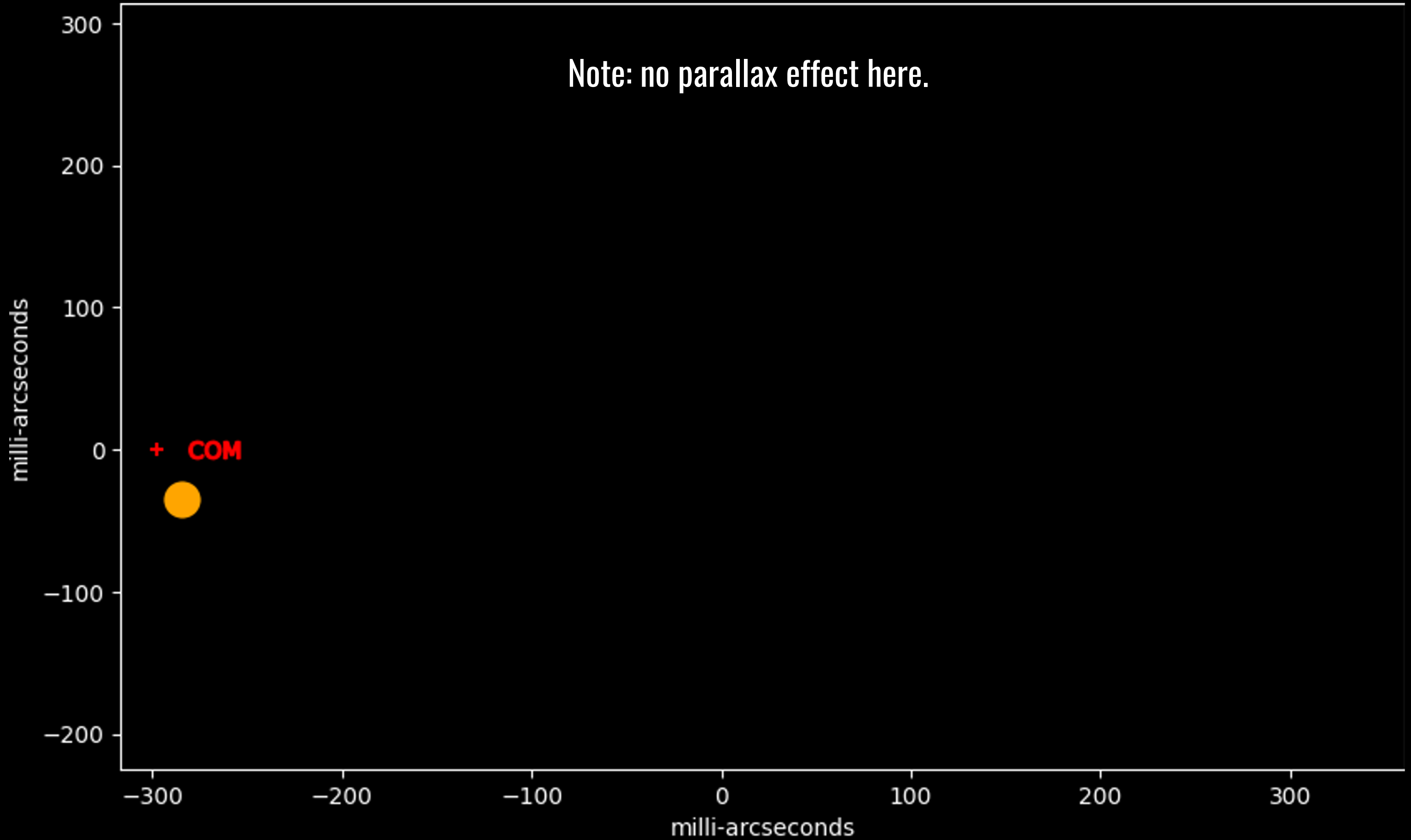

Let's imagine a fictitious heavy companion around Barnard's star.
August 2015
June 2017
February 2019
DEC
milli-arcseconds
RA
milli-arcseconds
300
200
100
0
−100
−200
−300
−200
−100
0
100
200
300

A star + planet in their own frame of reference

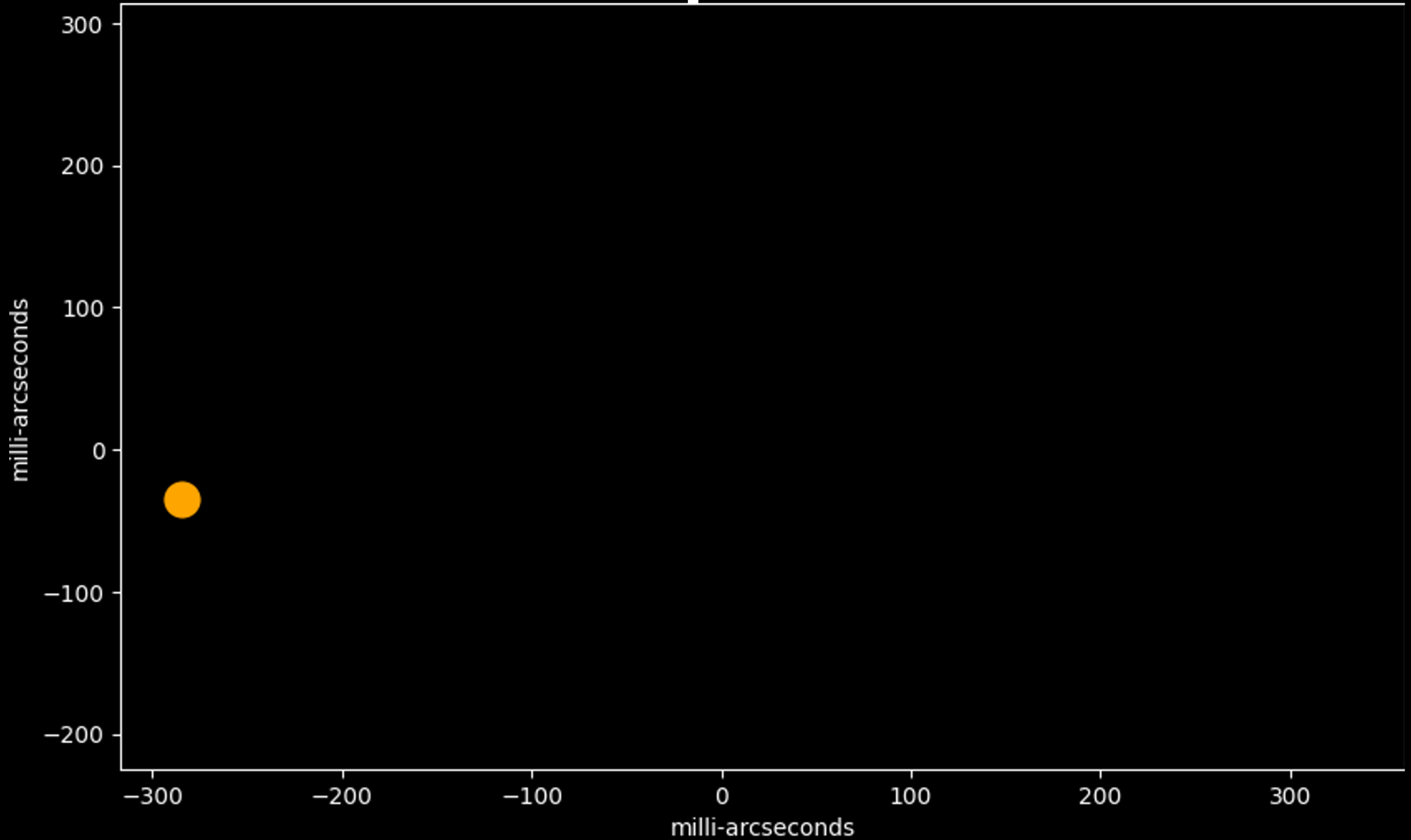
(note that the "planet" mass is exaggerated, just to make the effect more obvious)



From our Earthly frame of reference.



But we cannot see the planet, so:

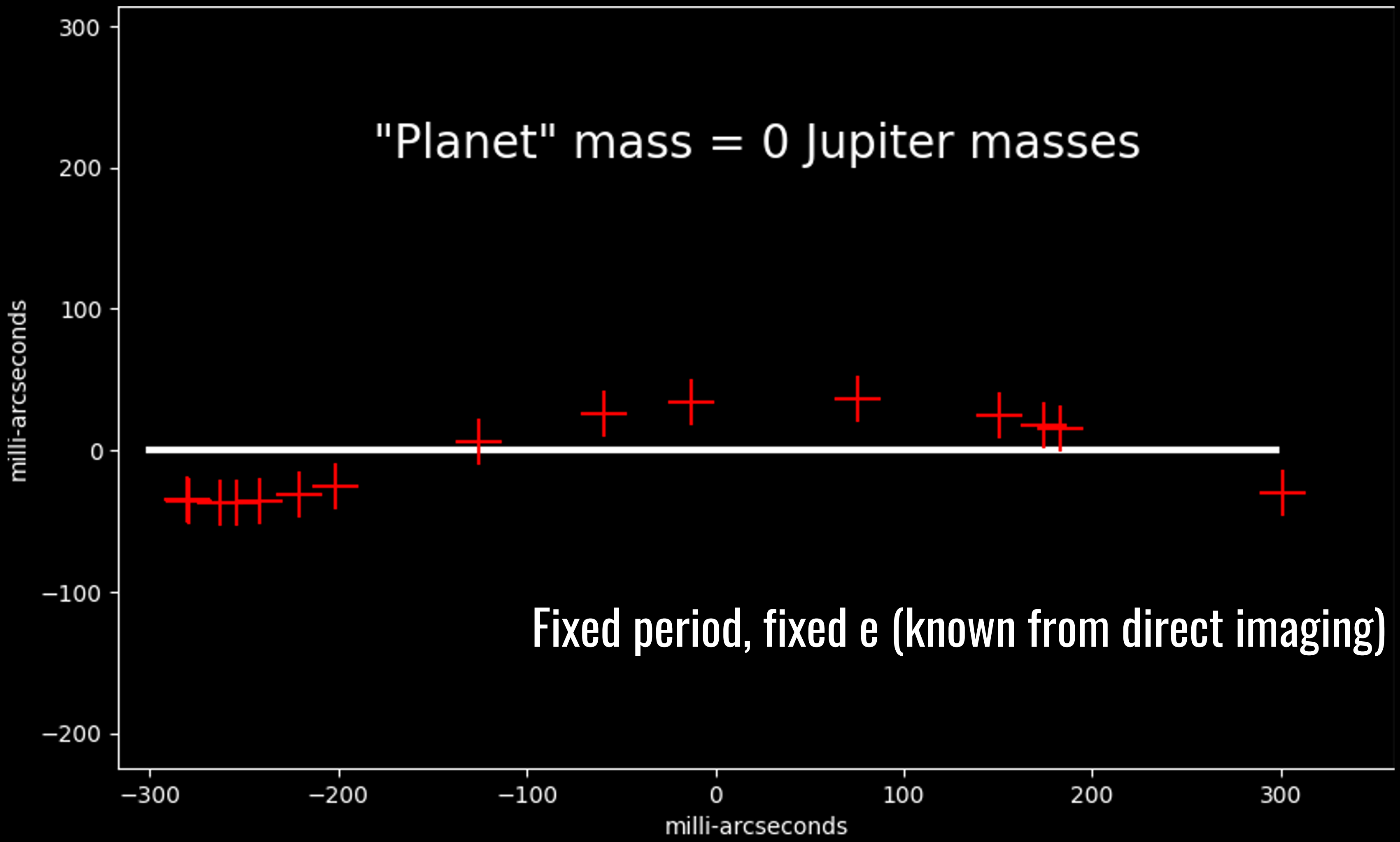


How do we solve for the mass?

if we have direct imaging over a long enough baseline, we *already* have strong constraints on:

- the eccentricity e
- the inclination i
- the semi-major axis

We can combine those with absolute astrometry to get the mass.

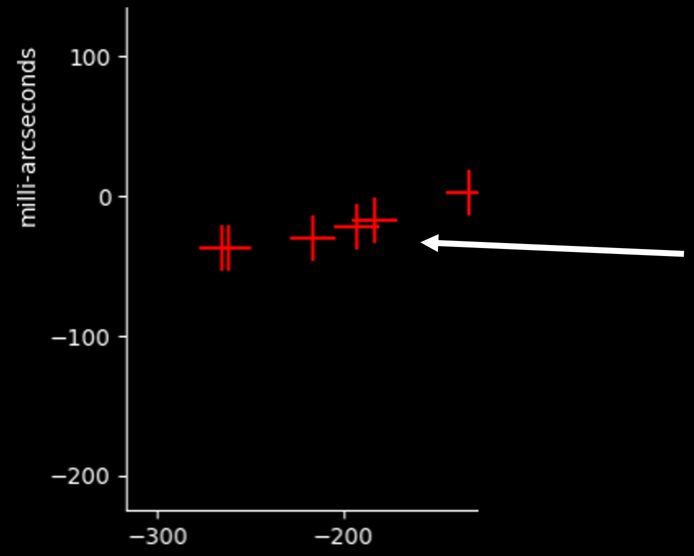


"Planet" mass = 0 Jupiter masses
Fixed period, fixed e (known from direct imaging)
milli-arcseconds
milli-arcseconds
300
200
100
0
−100
−200
−300
−200
−100
0
100
200
300

For a face-on circular orbit, the host star will exhibit sky-plane motion with an amplitude of

$$\text{astrometric semiamplitude} = \varpi \left(\frac{M_{\text{planet}}}{M_{\text{planet}} + M_{\text{star}}} \right) \left(\frac{a}{\text{A.U.}} \right)$$

But using the on-sky positions can be tricky.



These 2d measurements were not exactly like real Gaia observations...

Why one should interpret Hipparcos/Gaia on-sky positions carefully

For some systems, we know the companion orbits so well* that we can predict what Gaia DR3 would have reported for accelerations.

* from orvara fits to RV + proper motion anomalies + direct imaging (e.g, Y.Li + ‘21, Brandt+21, Qier An et al. ‘22)

Two examples from Qier An et al. (2022, in prep)

Gaia DR3 accel_ra	accel_ra prediction (i.e., ground truth)	Gaussian sigma discrepancy
17.8 ± 0.3 mas/yr^2	12.7 ± 0.2 mas/yr^2	14σ
-1.0 ± 0.1 mas/yr^2	-1.6 ± 0.1 mas/yr^2	4σ

Complications with real Gaia/Hipparcos

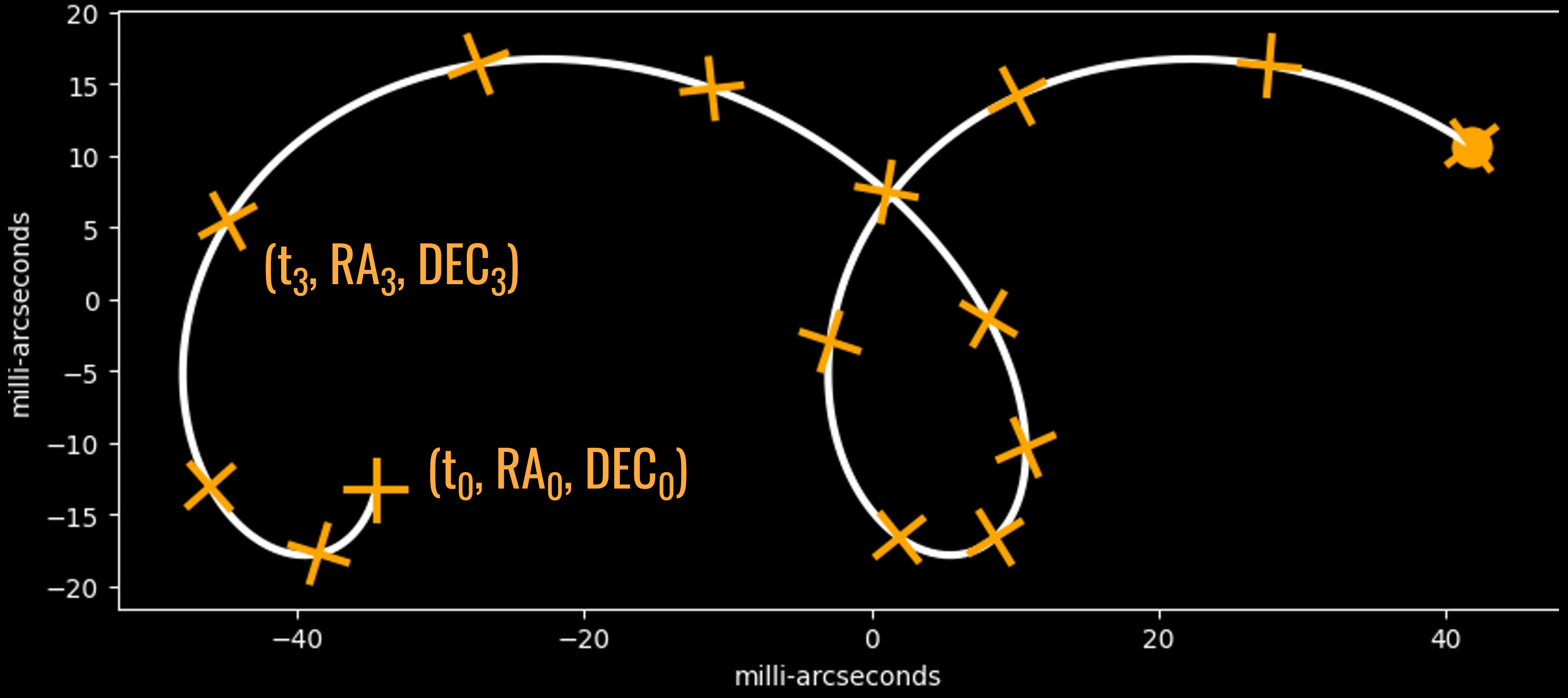
- 1-dimensional measurements.
- Potential systematics in the raw positions

Simple example

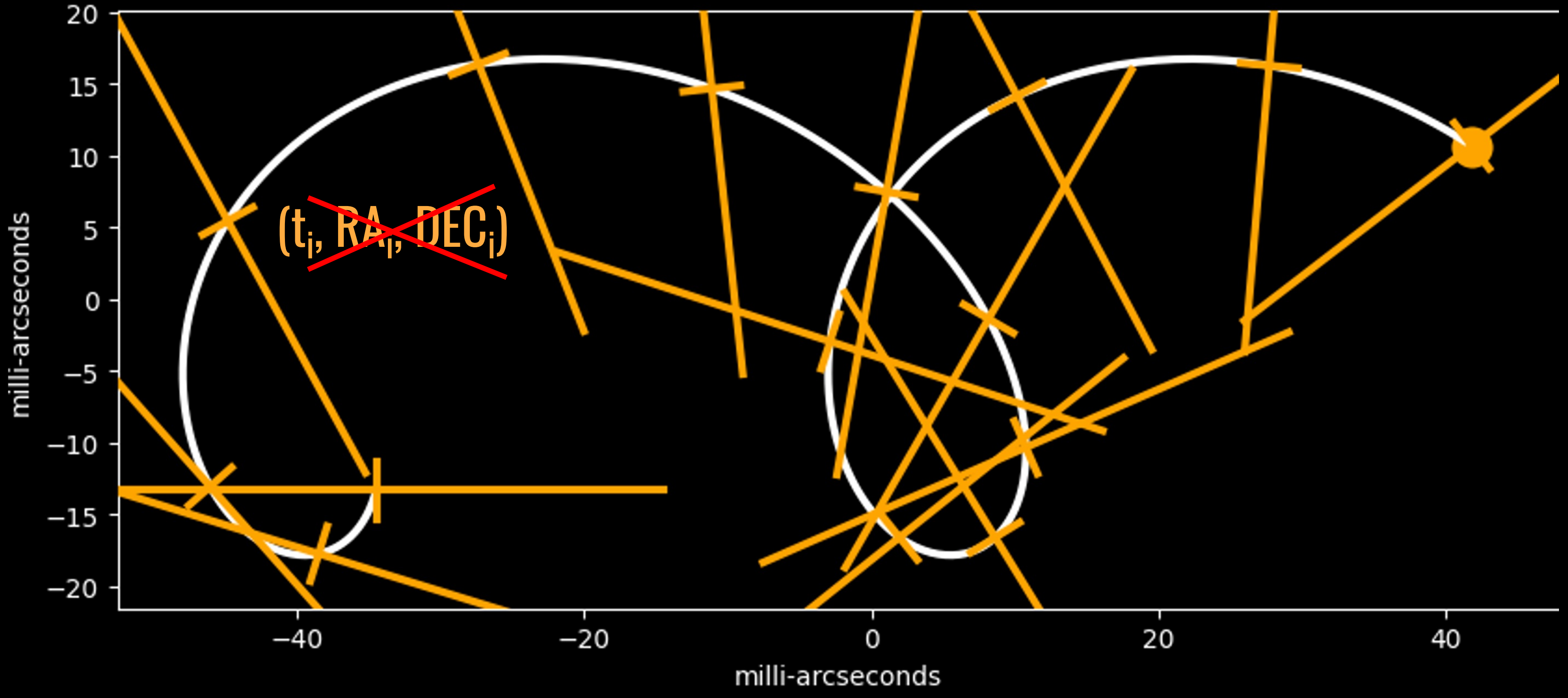
skypath with proper motion + orbital motion from an unseen companion.

No parallax motion.

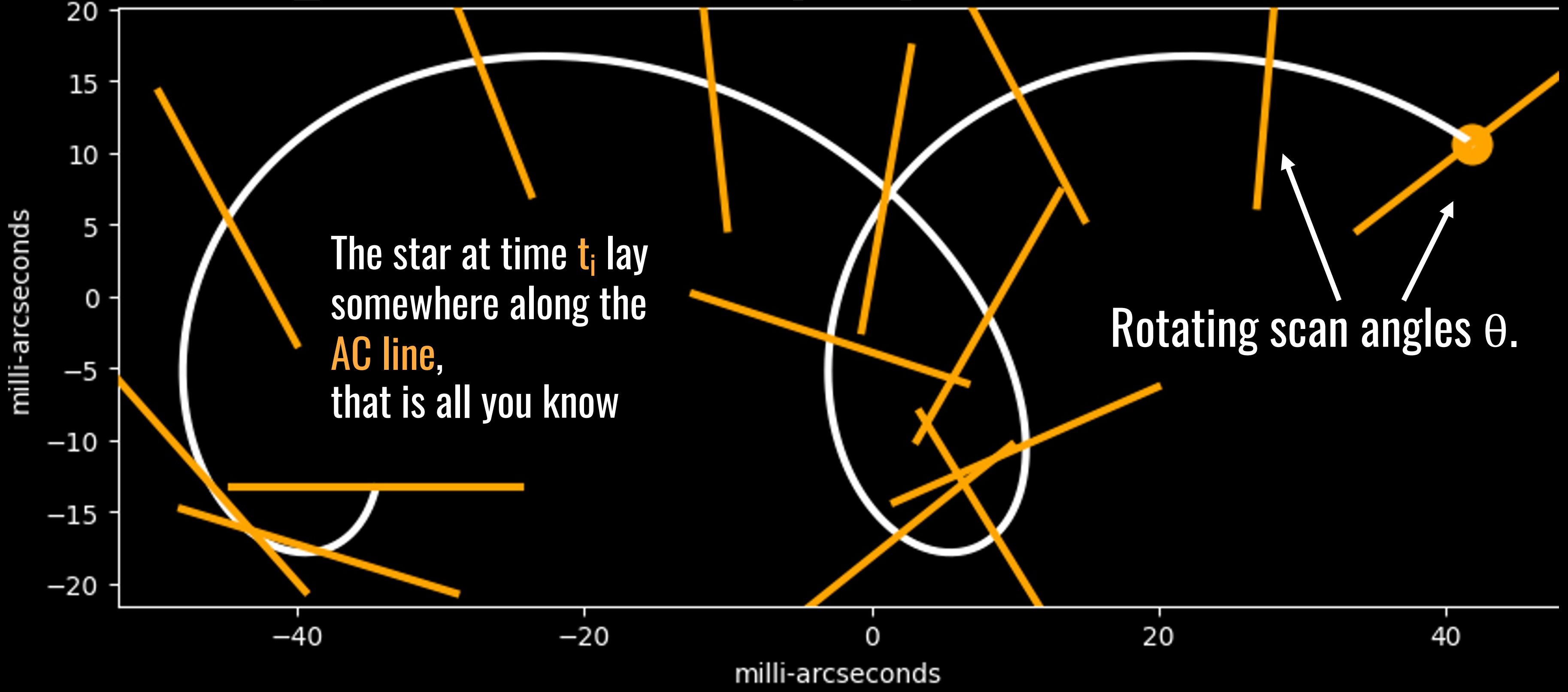
2d measurements



Gaia/Hipparcos: One axis has *much larger* uncertainty → "1d measurement"



Showing Across-Scan (AC) only

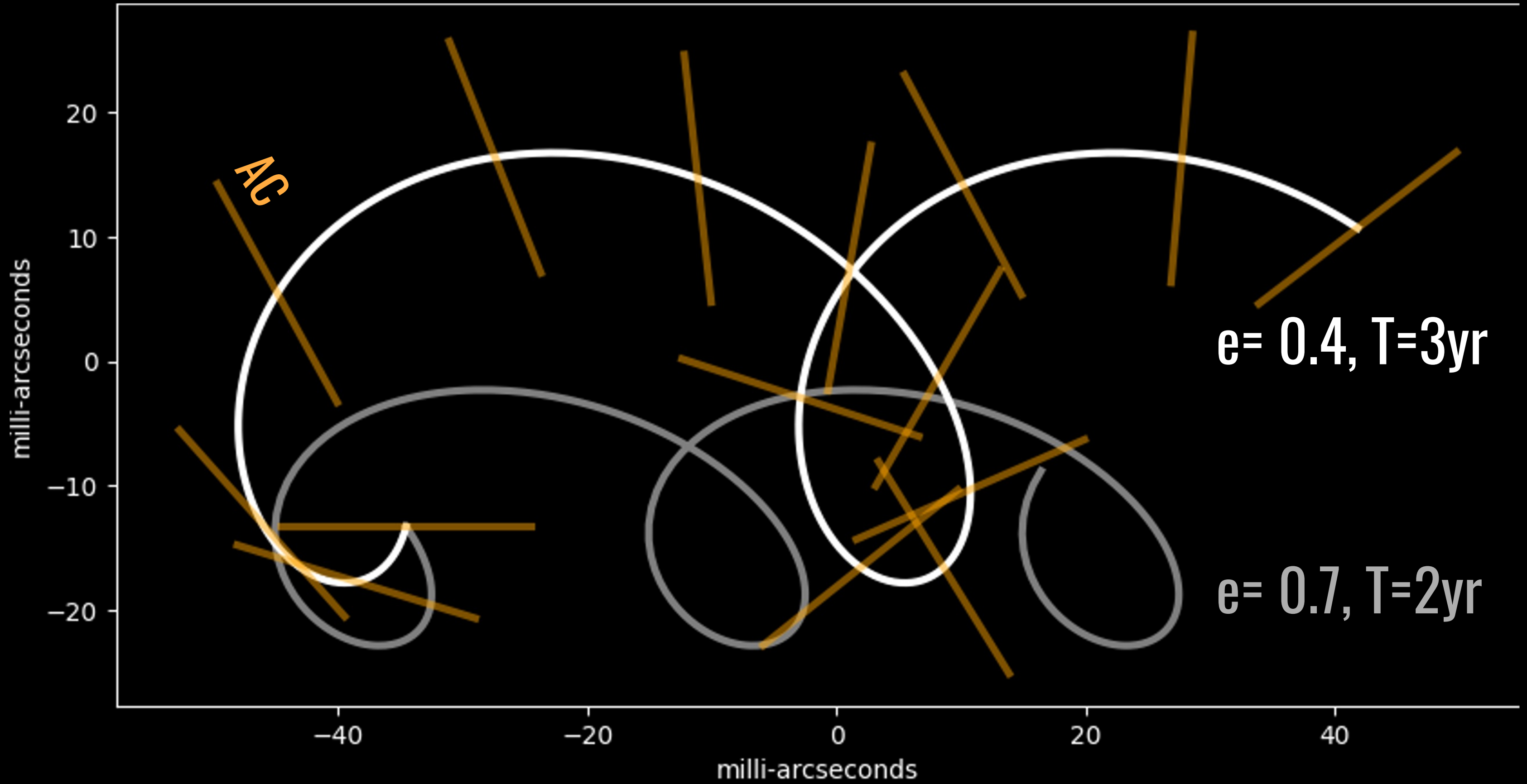


Fitting orbits to epoch astrometry

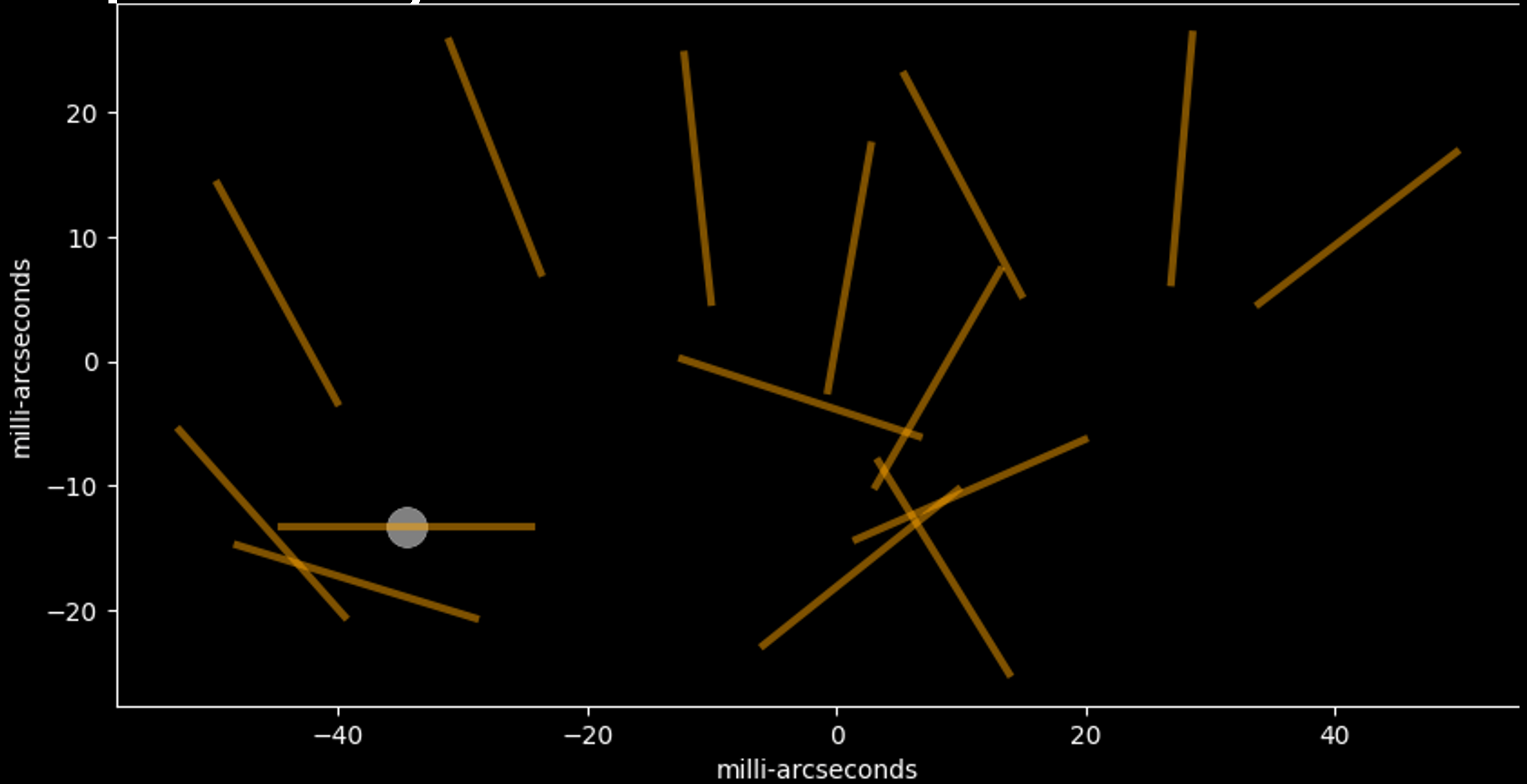
You can have multiple solutions that fit the data nearly equally as well but have very different orbital parameters.

To help illustrate that, next is an over-exaggerated example.

Is the gray orbit an OK fit to the data too?



Both orbits give the same projected positions! (at the sampled times)



So two **very different** orbits can fit a single absolute astrometric path.
The last example was contrived but..

In the hands-on session today

You'll generate real examples of families of modestly different orbits that all fit simulated Gaia epoch astrometry.

Confidence intervals on e&T in these cases are difficult to define.

The complications

- 1-dimensional measurements.
- Potential systematics in the raw positions

Look out for G.M. Brandt et al. 2022 – discussion of systematics in Hipparcos epoch astrometry in great detail.

The big takeaways

- direct imaging + absolute astrometry (+ RVs) is powerful & now is a golden age of open-source software (e.g., htof, orvara, orbitize*)
- Orbit fitting to absolute astrometry 1d scans can be tricky.

*S Blunt et al. 2019, arxiv: 1910.01756 , github.com/sblunt/orbitize

Thank you!

Questions?

"An oil painting of the telescopes atop Maunakea", created by the DallE neural net