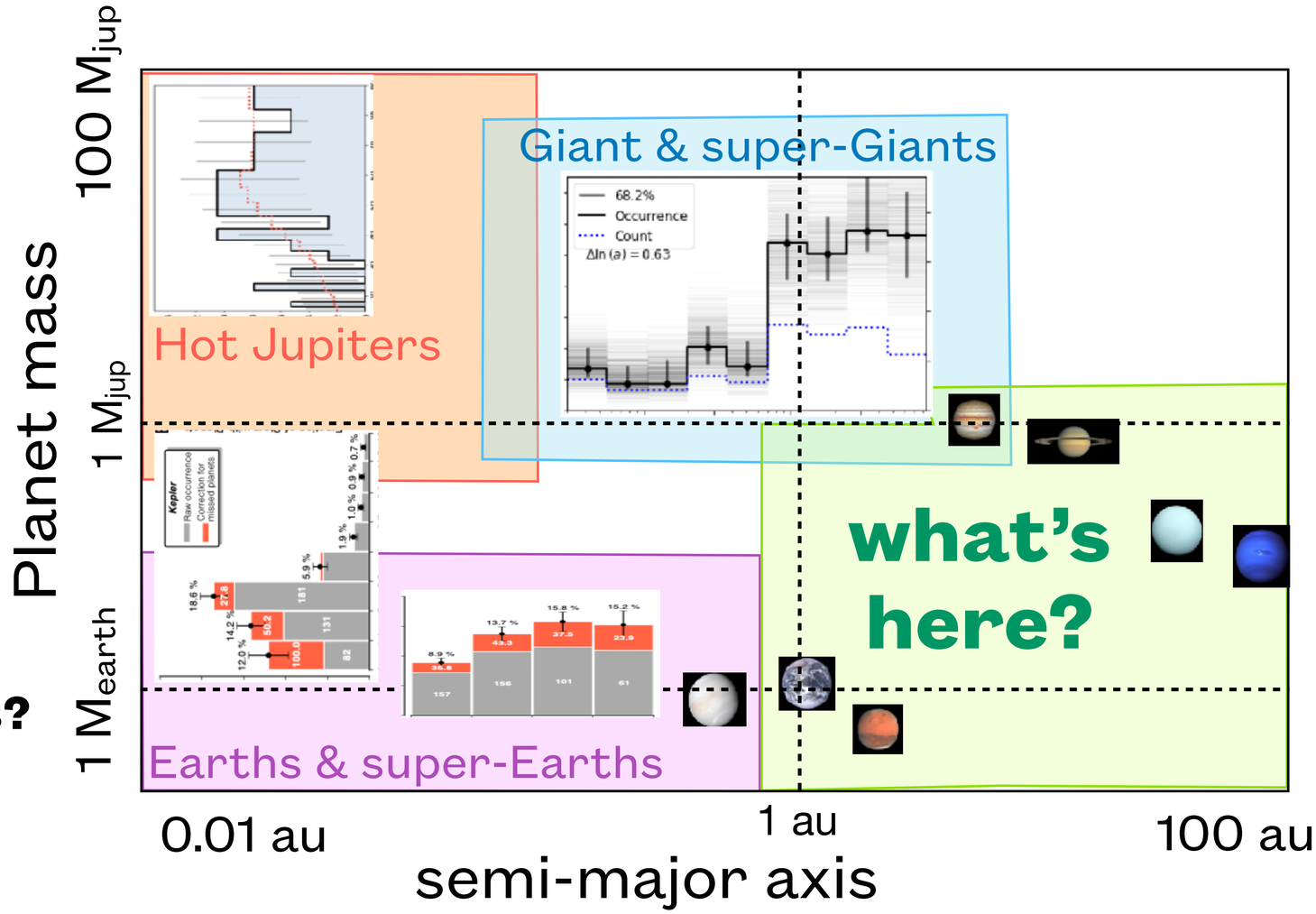
Characterization of Brown Dwarfs and Long-Period Giant Planets Observed by Radial Velocity with the Aid of Gaia Astrometry

F. KIEFER, A.-M. LAGRANGE, F. DESTRIEZ, G. HÉBRARD, P. RUBINI, F. PHILIPOT, E. BIANCHI, T. NOEL…

51 PEG B 30TH BIRTHDAY - 2025 - OHP - 9 OCTOBER

Main Objective: Statistics and Planet Formation History

- Some sub-populations of exoplanets described statistically
- How do they form? What's the history?
- Still pending:
  - **Long orbits under-represented**
  - **Distribution of giant exoplanets beyond 3—5 au uncertain**
  - **Planets as Solar system still missing**
  - **GP formation around low-mass stars?**



Kiefer et al. 2019
Lagrange et al. 2023
Fulton et al. 2017
Petigura et al. 2013

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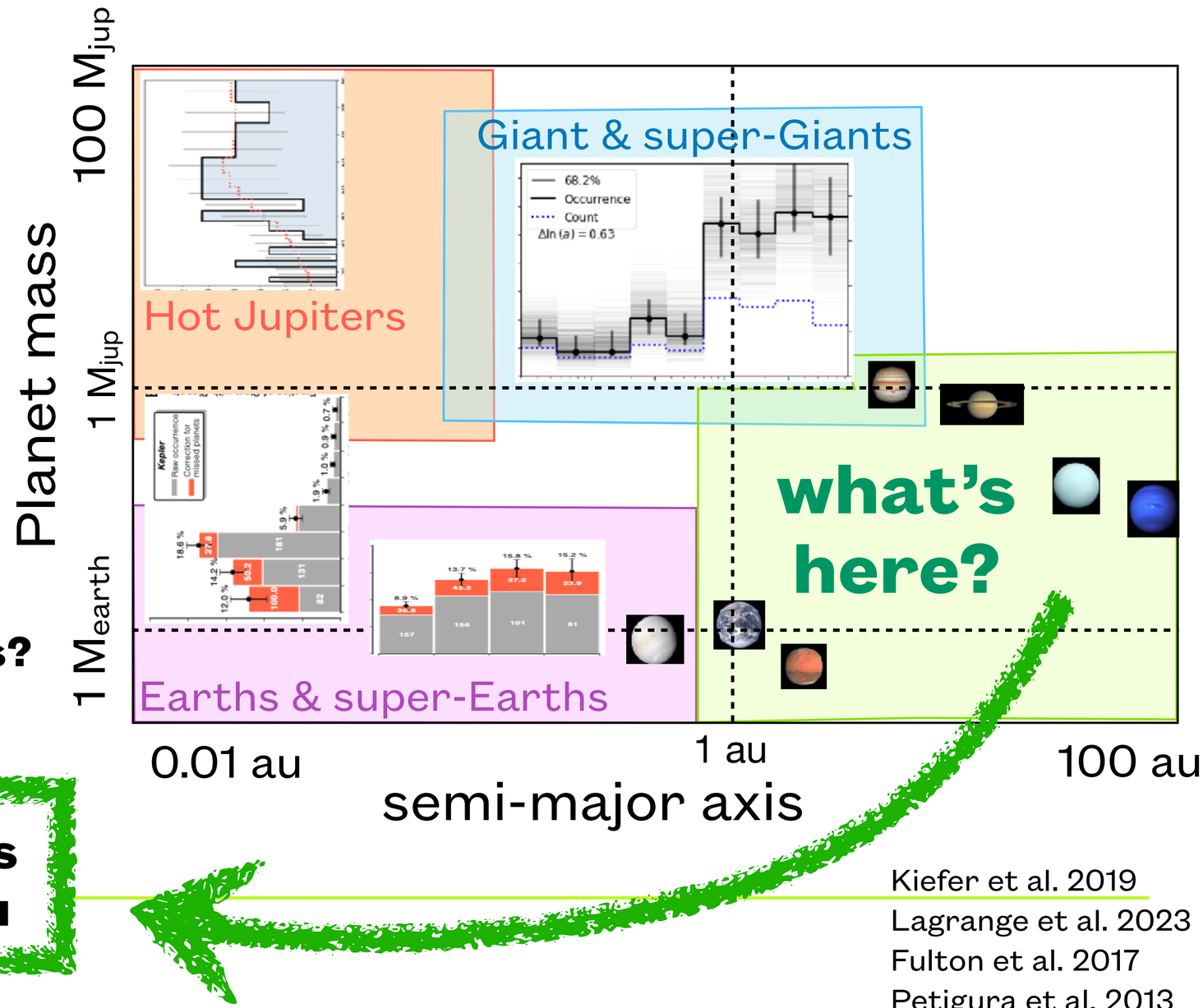

Gaia should detect thousands planets > 0.1 M_{Jup} beyond 1 au

Kiefer et al. 2019
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Brown dwarf populations and occurence rates

BD occurence rates < 5 au

Salhmann+ 2011: **1.3**%

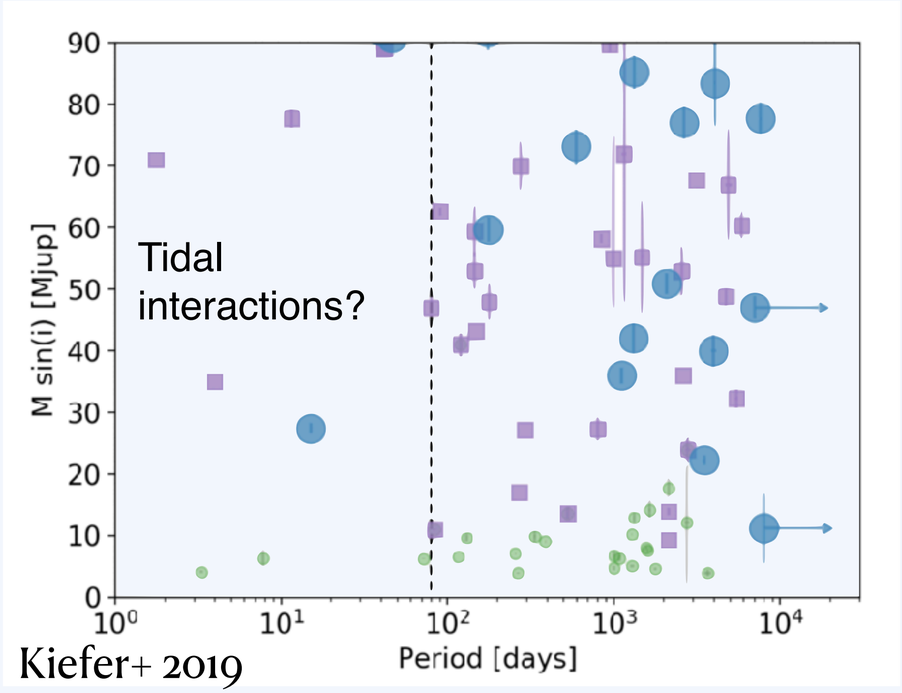
Santerne+ 2016: **0.29**±0.17%

Nielsen+ 2019: $\mathbf{0.8}^{+0.8}_{-0.5}$%

Kiefer+ 2019: **2.0**±0.5%

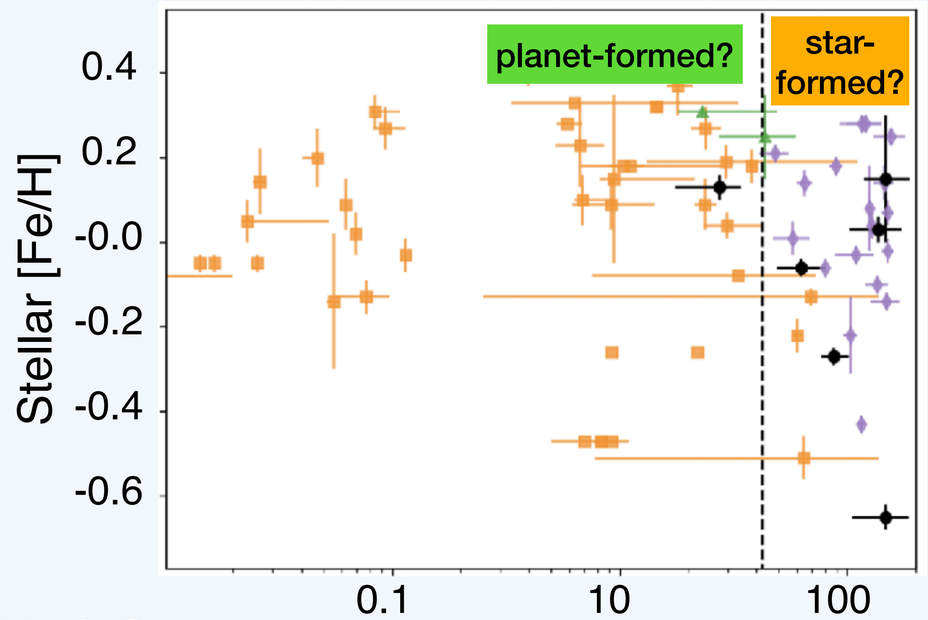
Unger+ 2023: $\mathbf{0.8}^{+0.3}_{-0.2}$%

A rich BD desert beyond 80 days



Kiefer+ 2019

Two populations of BD?

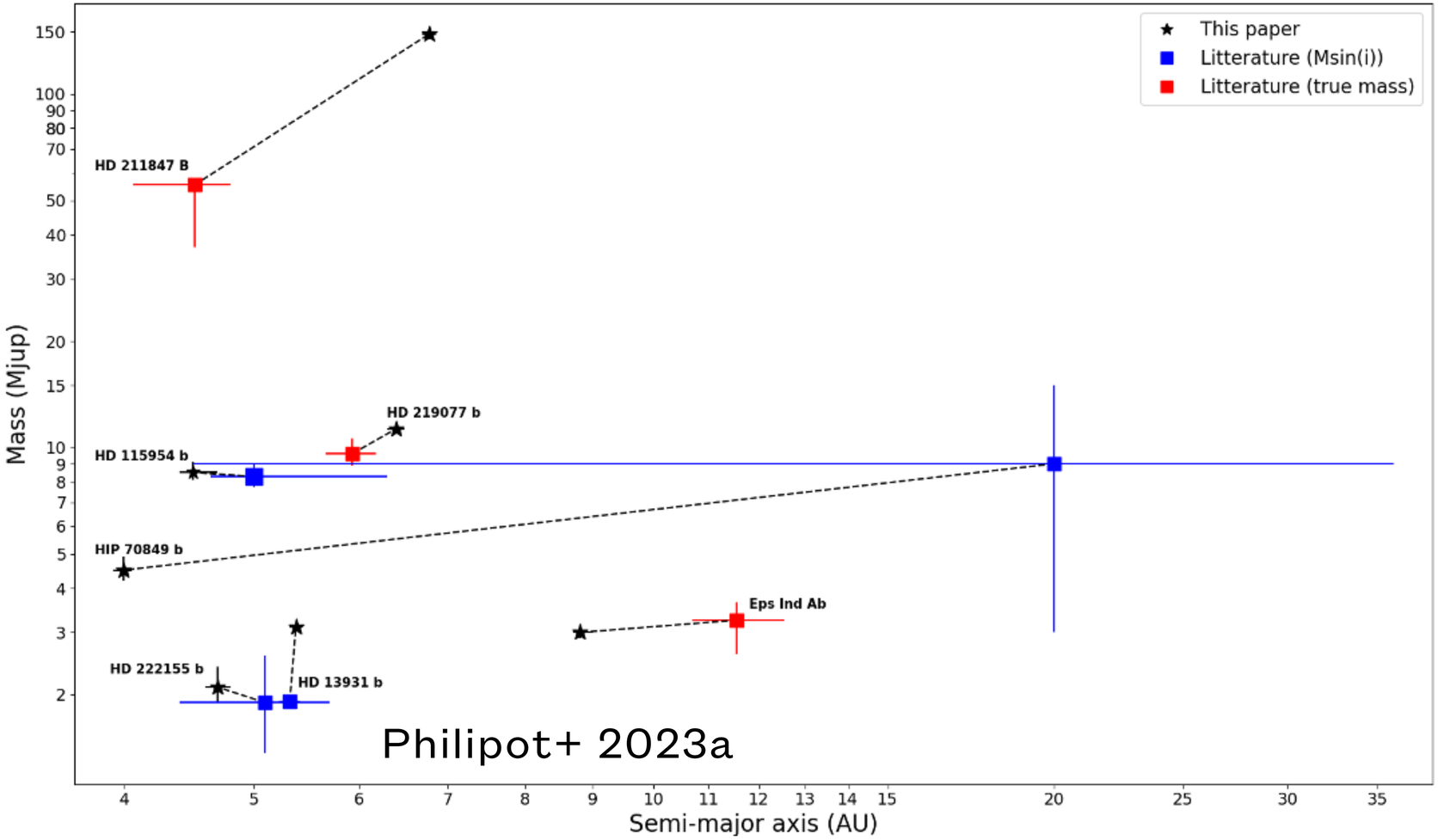


Ma & Ge 2014

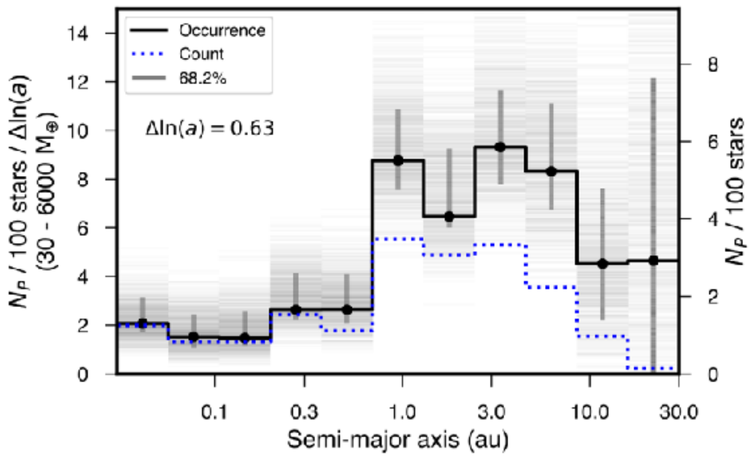
Kiefer+ 2021

Uncertainties on RV-derived orbits: the phase coverage

8 single systems with a > 5 au listed in exoplanet.eu



Philipot+ 2023a



Fulton+ 2021

Lagrange+ 2023

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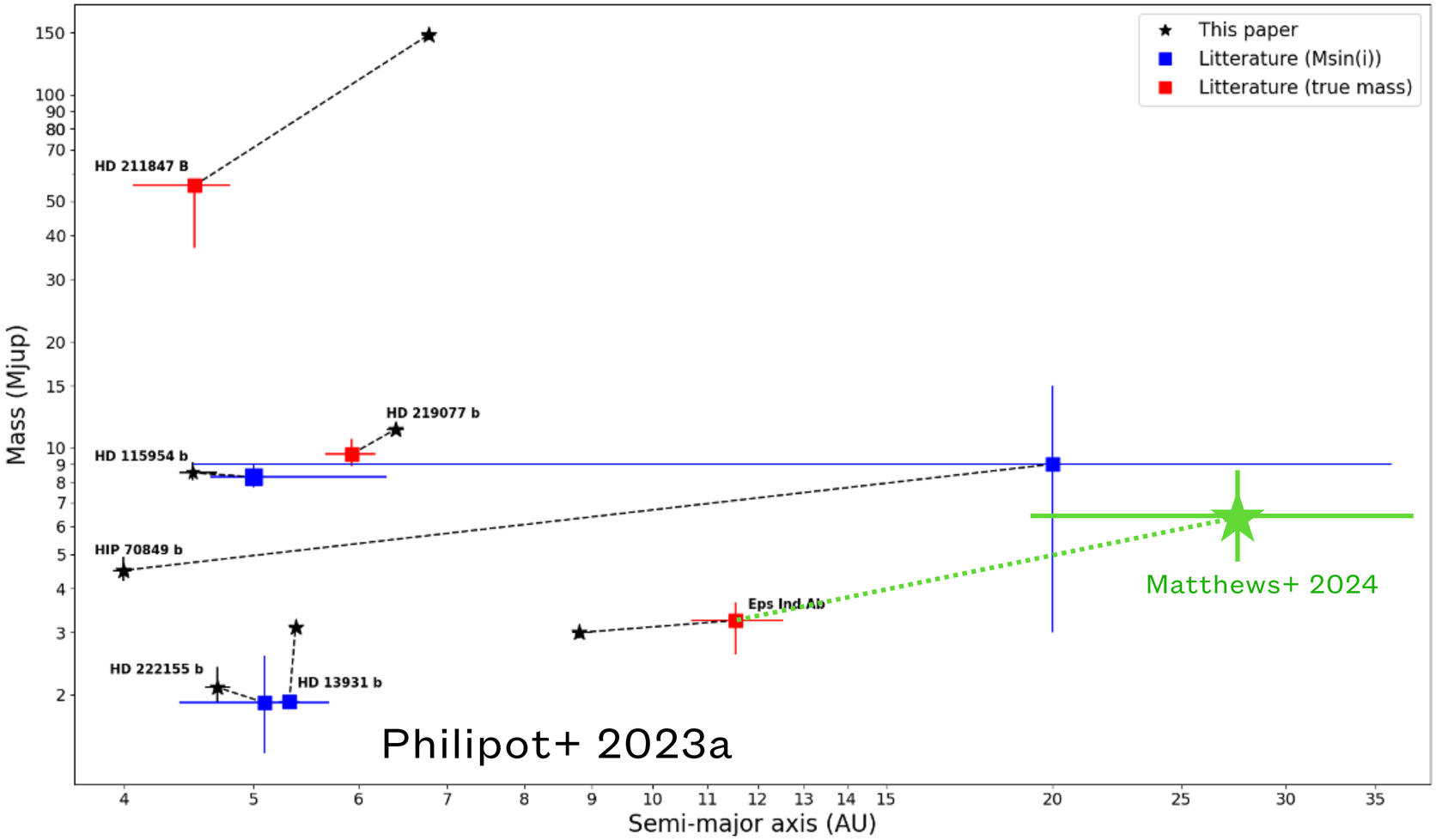
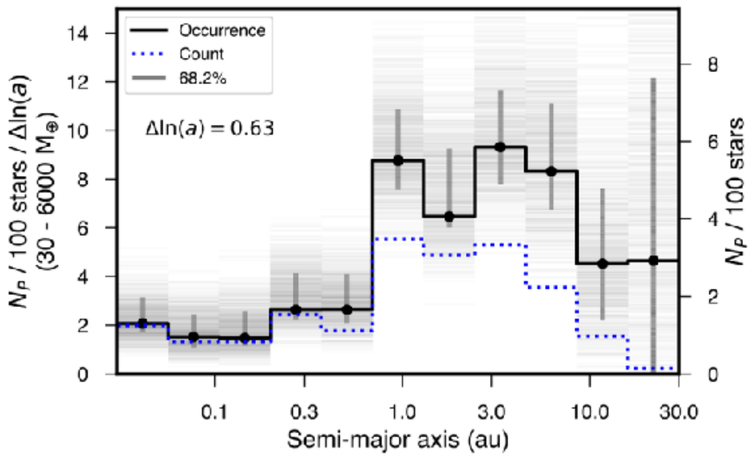


Philipot+ 2023a

Matthews+ 2024



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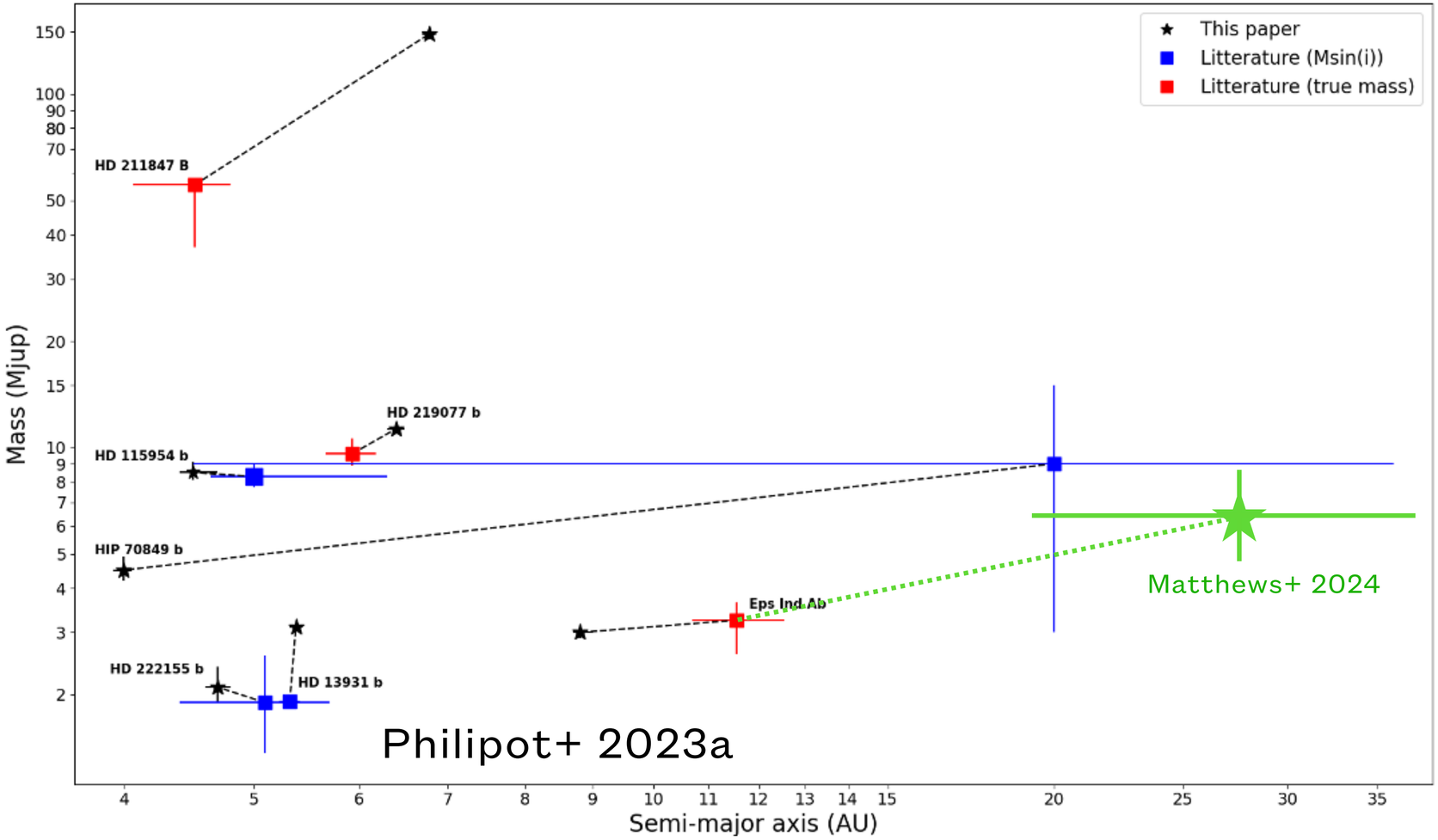
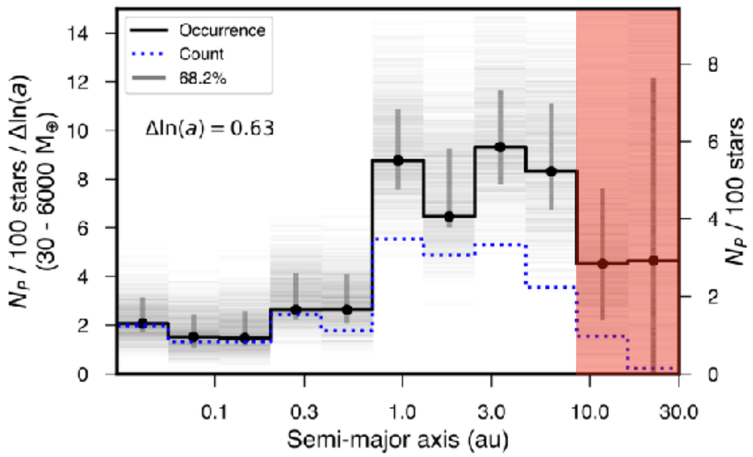
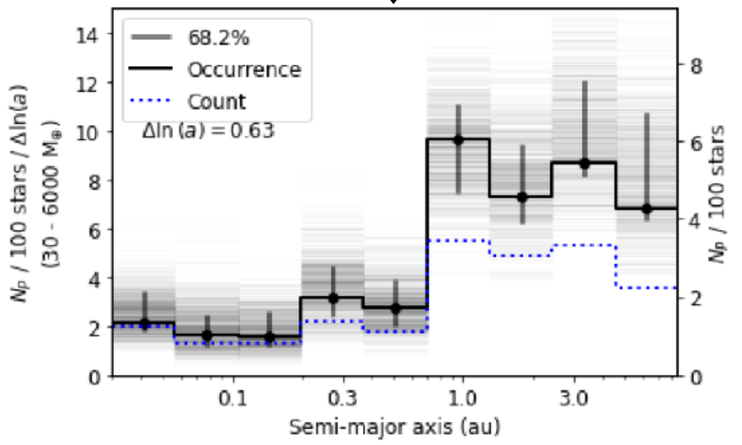
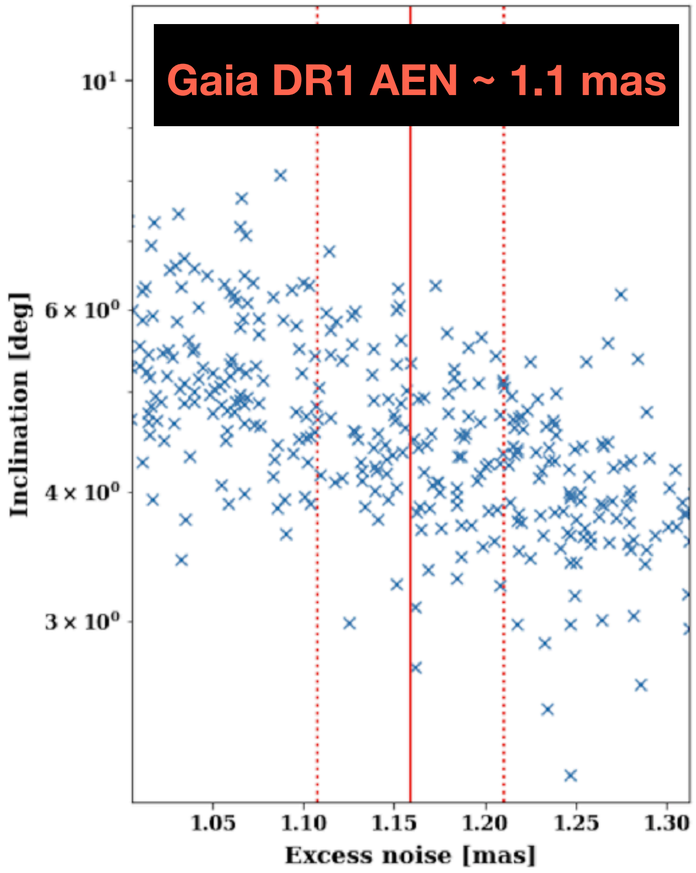


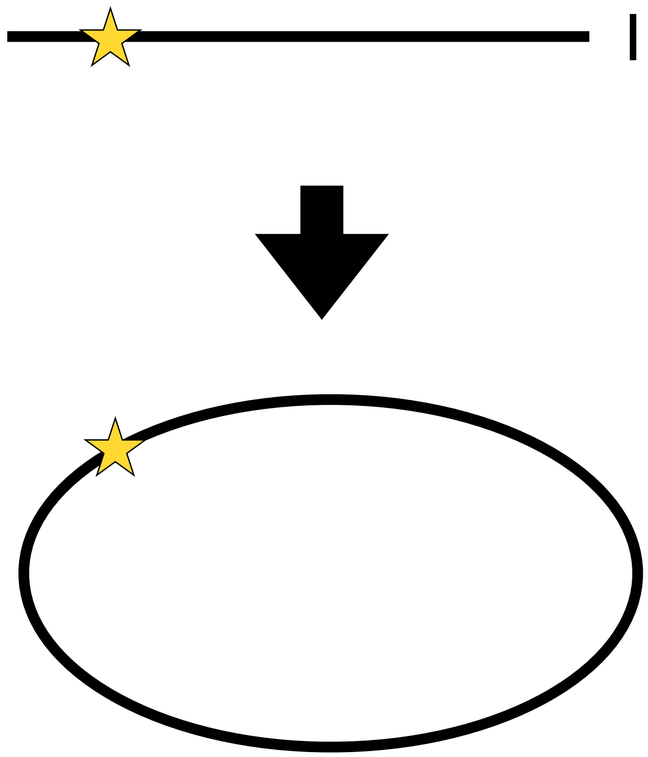


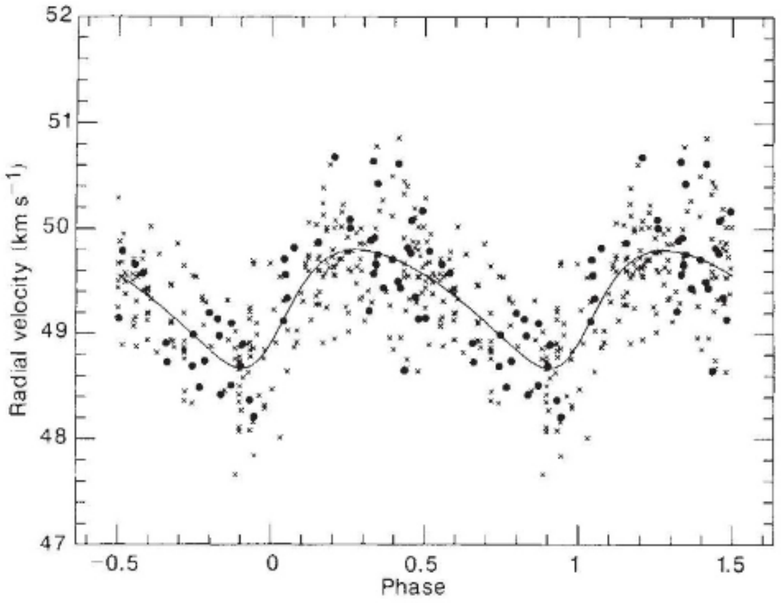


Uncertainties on RV-derived mass: the inclination

- HD 114762 RVs ➜ $M_b \sin(i) = 11\ M_{jup}$ (Latham+ 1989)







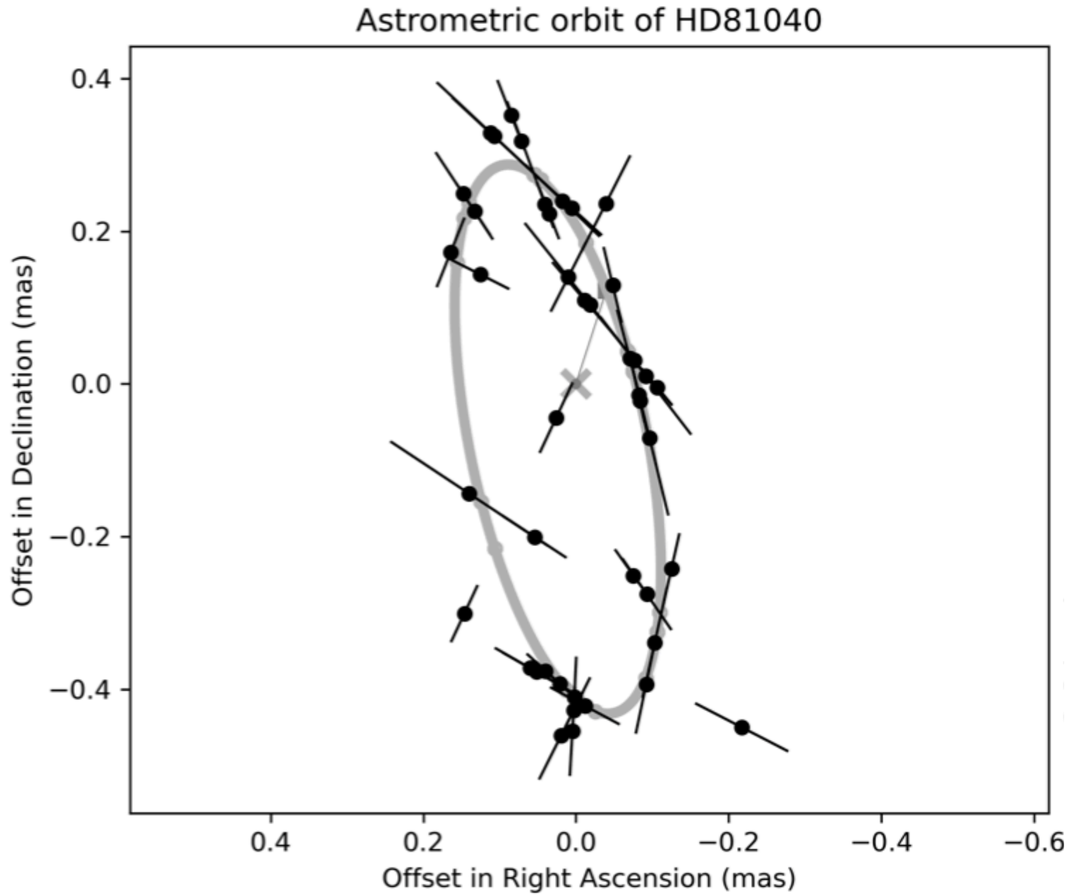
$$M_b = 107^{+31}_{-27} M_J$$

Confirmed (Arenou+ 2023)
>200 M_J with DR3 time series

Kiefer 2019

Use astrometry when possible (Gaia + Hipparcos)

But, no astrometric time series published in Gaia DR3…



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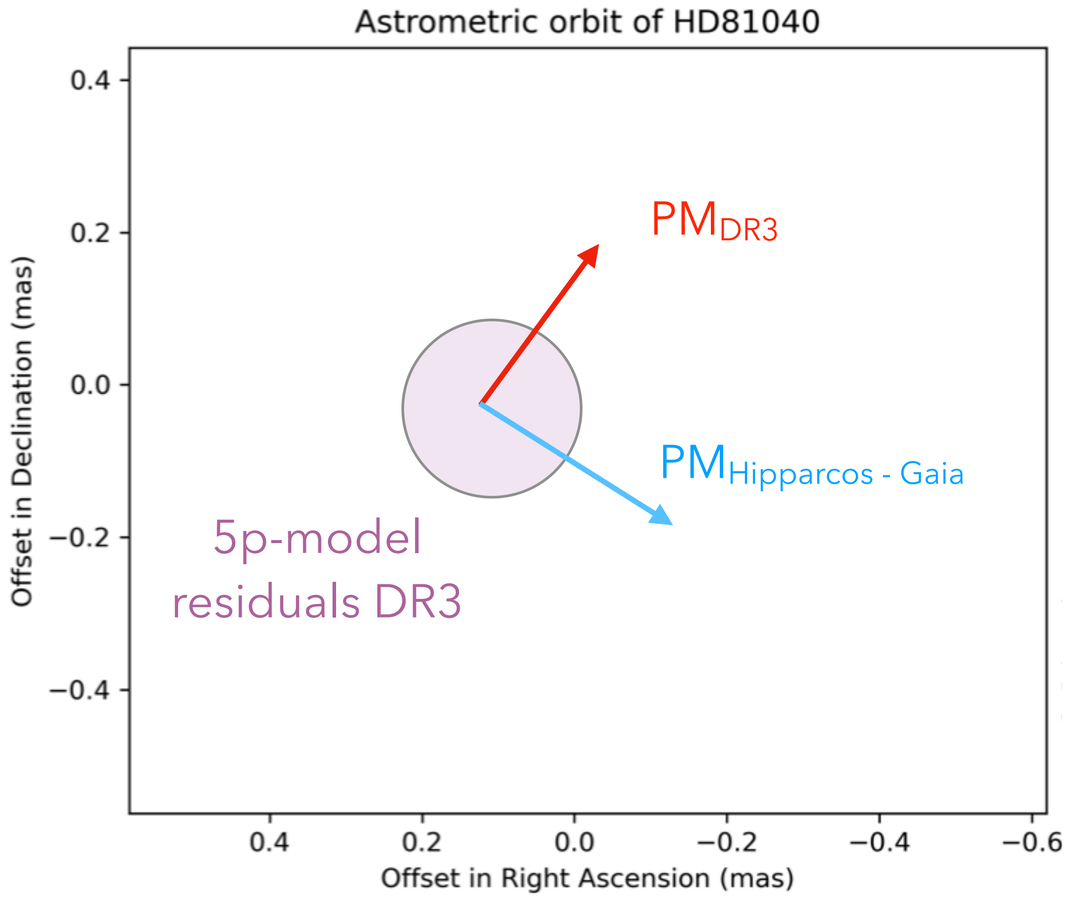
So, we need to innovate…



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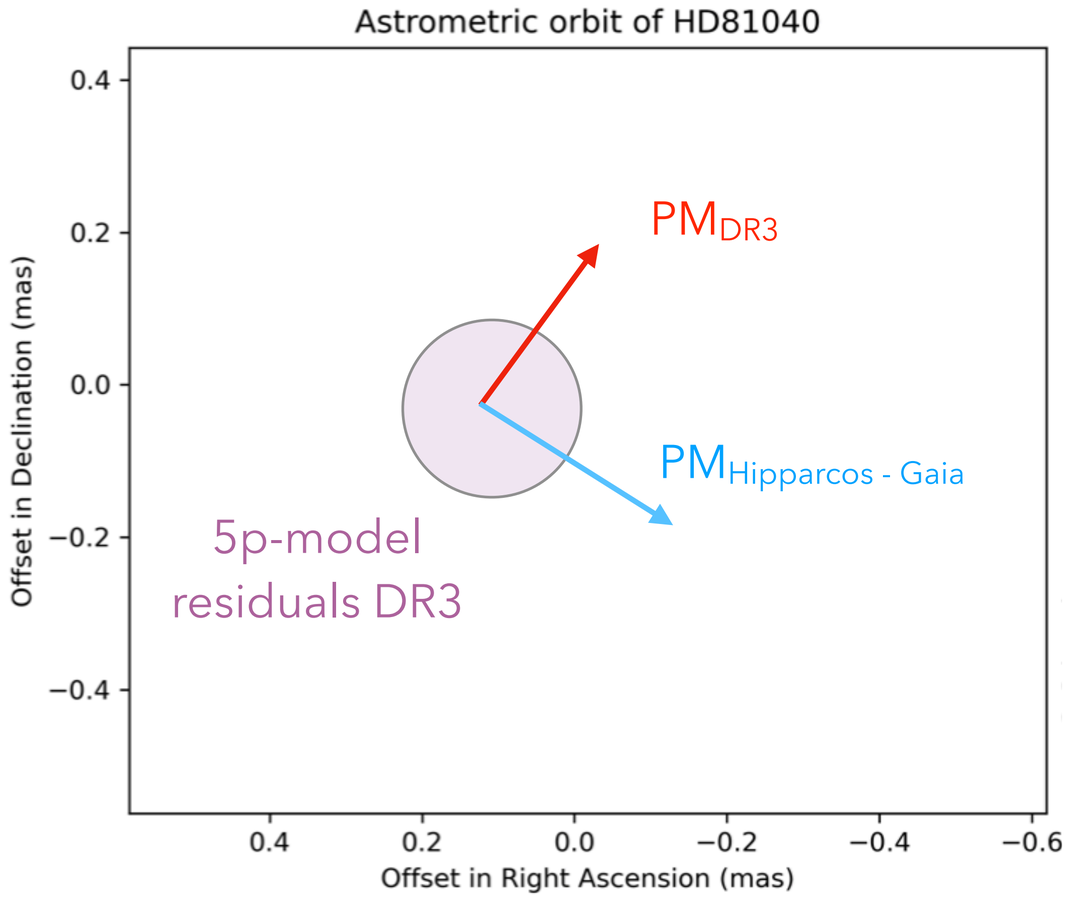

5p-model fitted including

- position in 2016.0
- proper motion (PM)
- parallax

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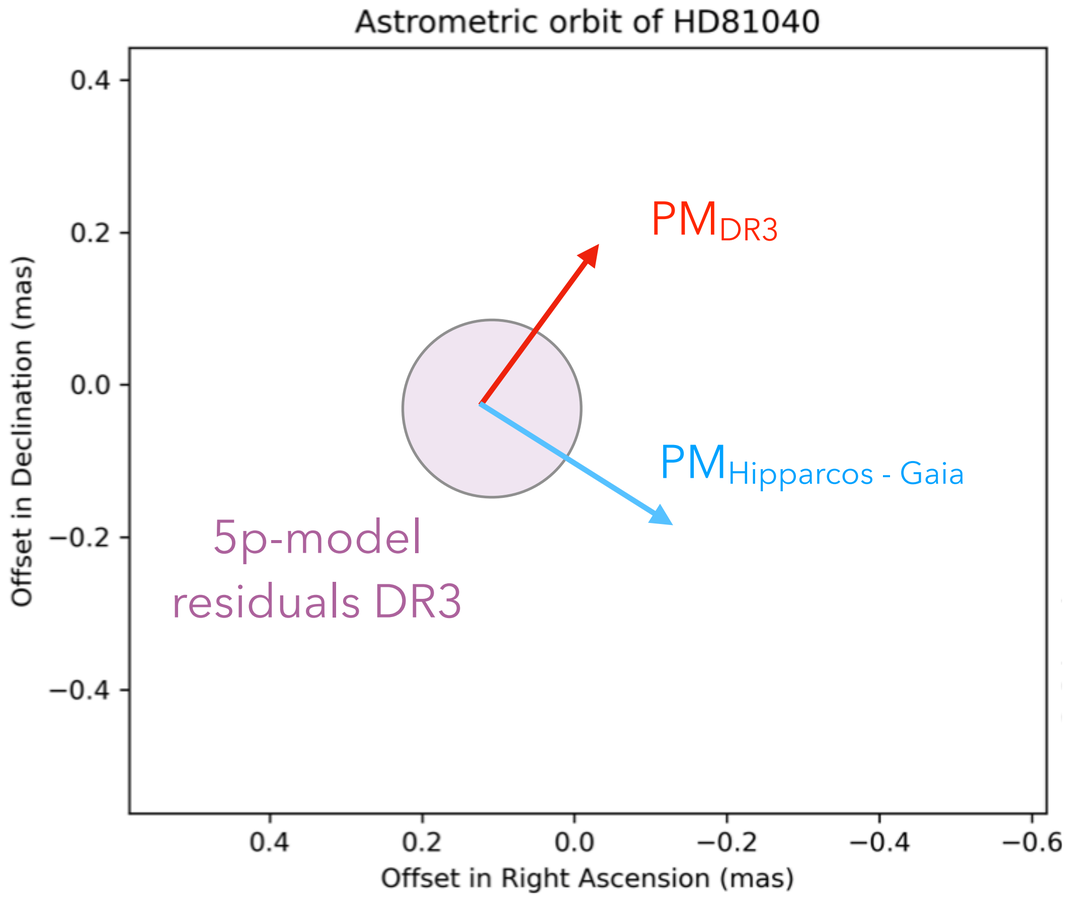

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5p-model residuals found in:

- RUWE: renormalised unit weight error
- AEN: astrometric excess noise

Kiefer+ 2019, 2021, 2024

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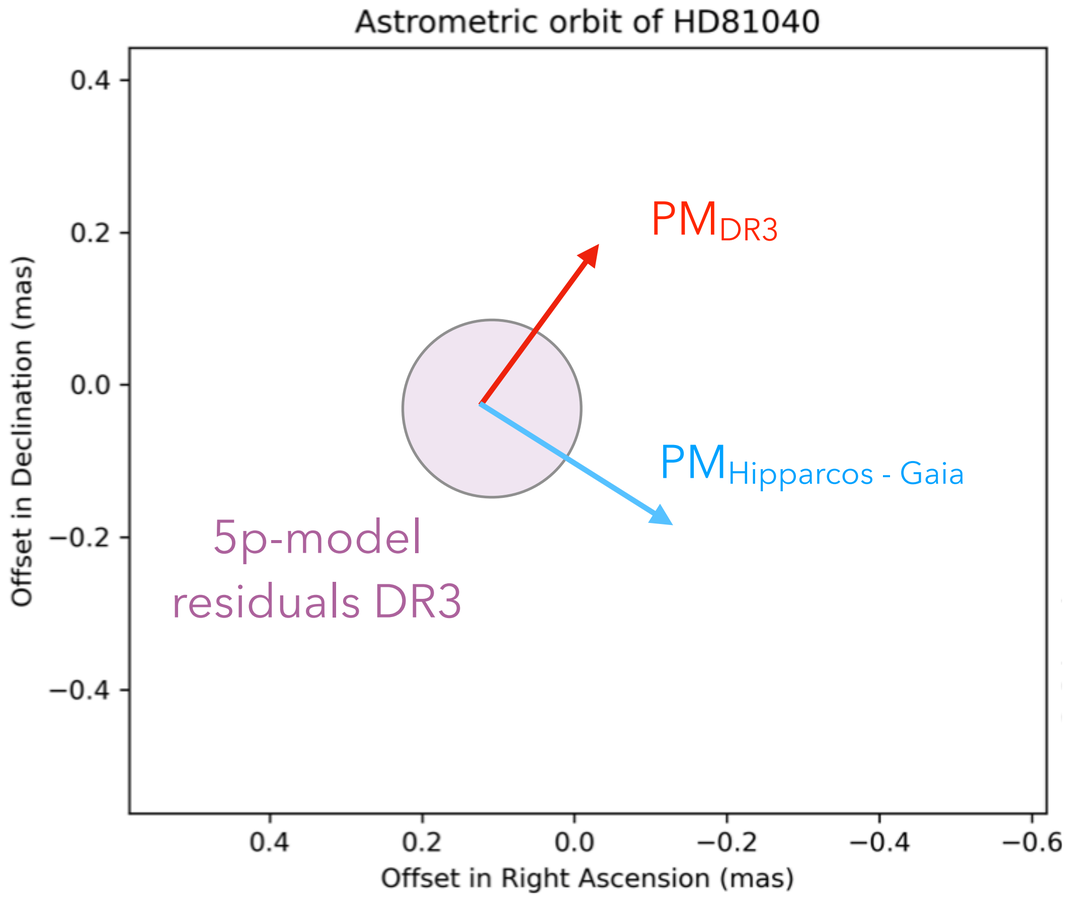

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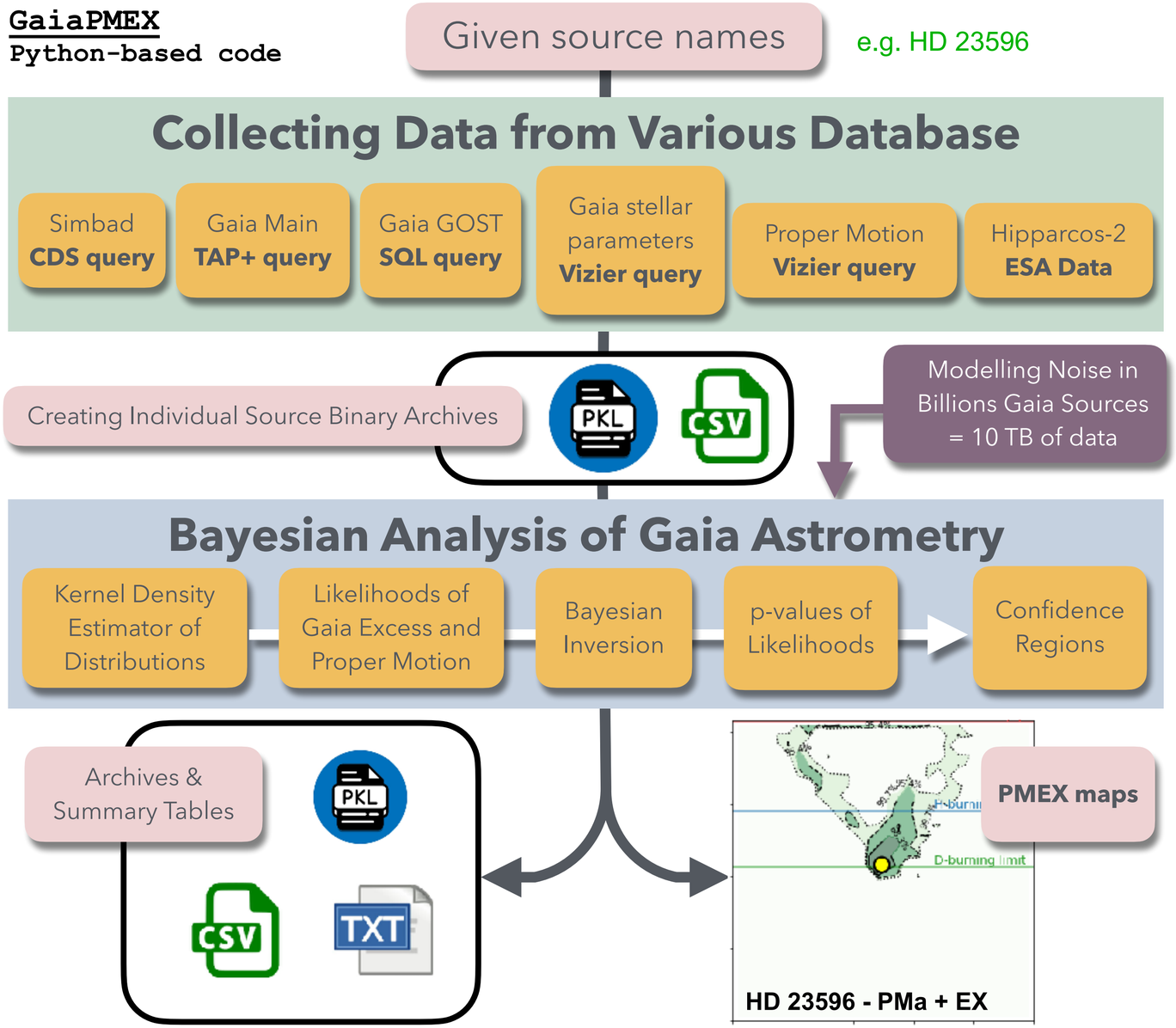
Kiefer+ 2019, 2021, 2024

$PM_{Hipparcos\text{-}Gaia}$ and PM_{DR3} lead to PM anomaly:

$|PMa|>0$ → non-zero acceleration

Kervella+ 2019, Brandt+ 2019

GaiaPMEX: Orbit and Mass Predictions



Kiefer+ 2024 Paper I

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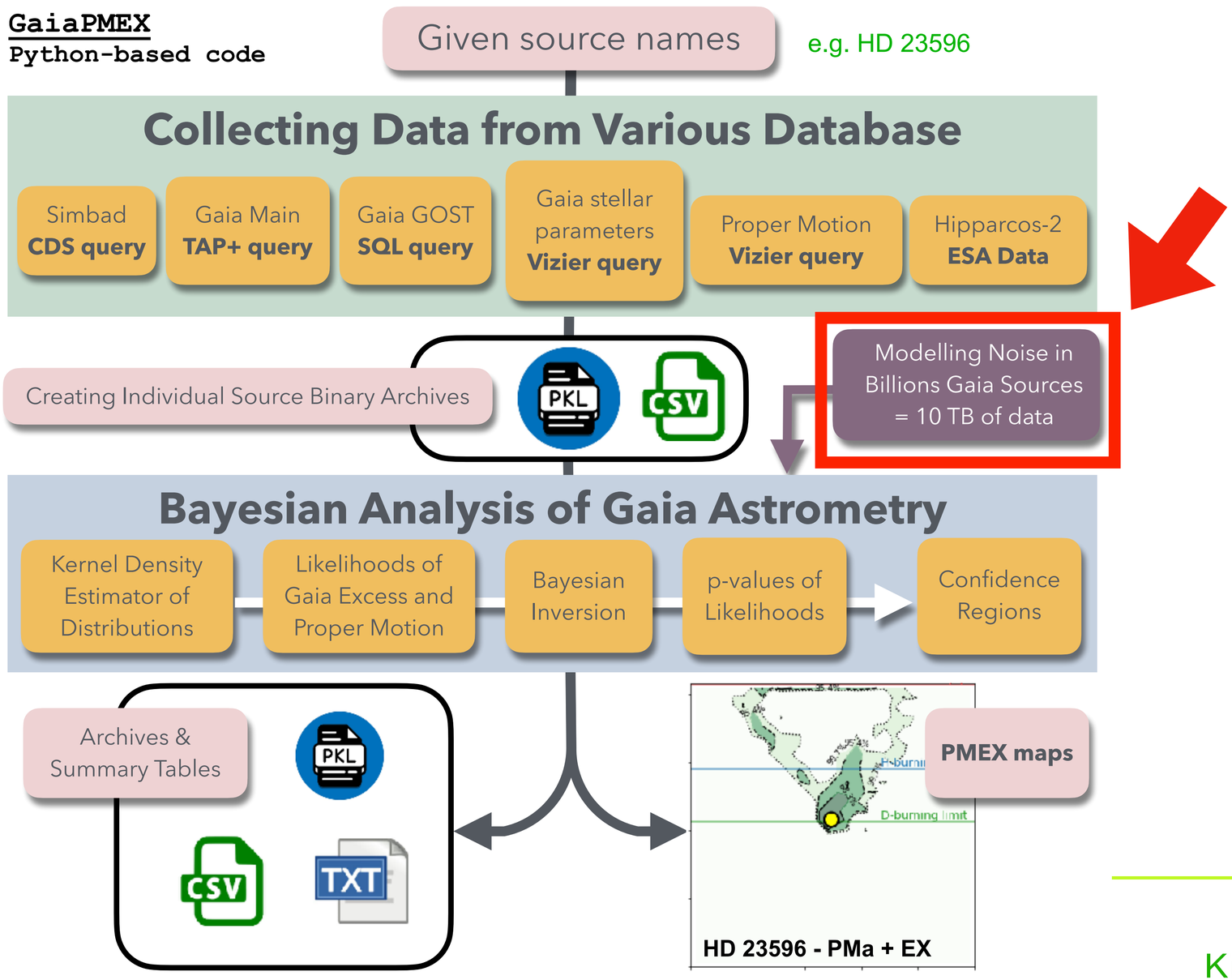
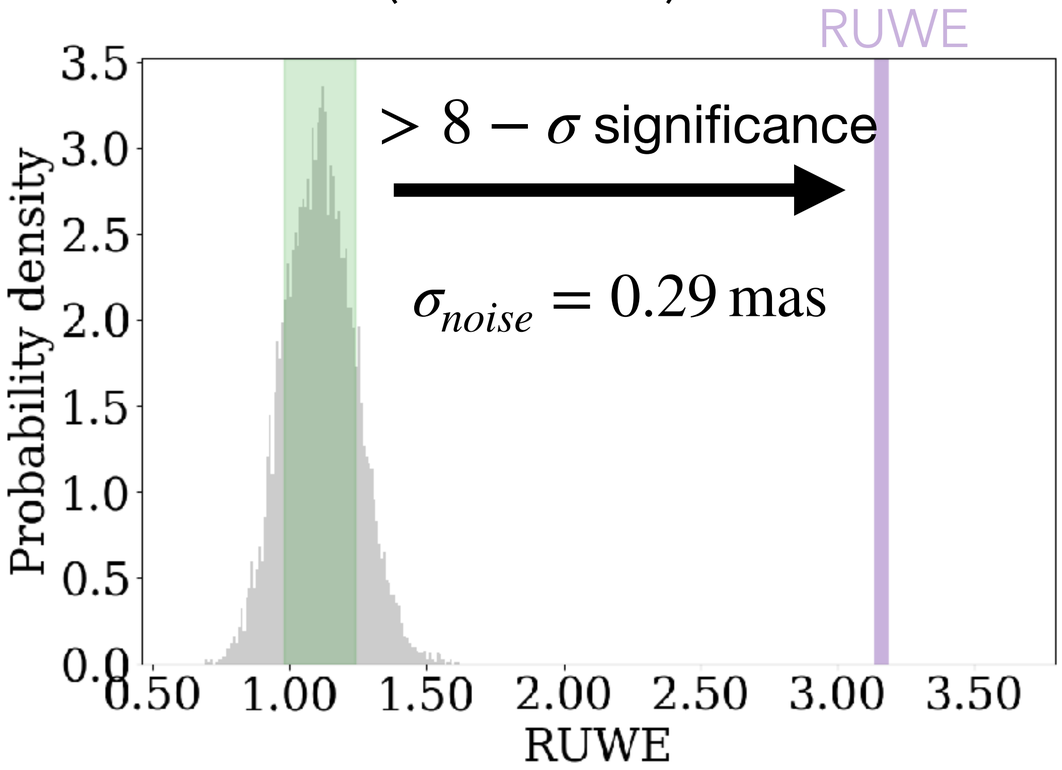


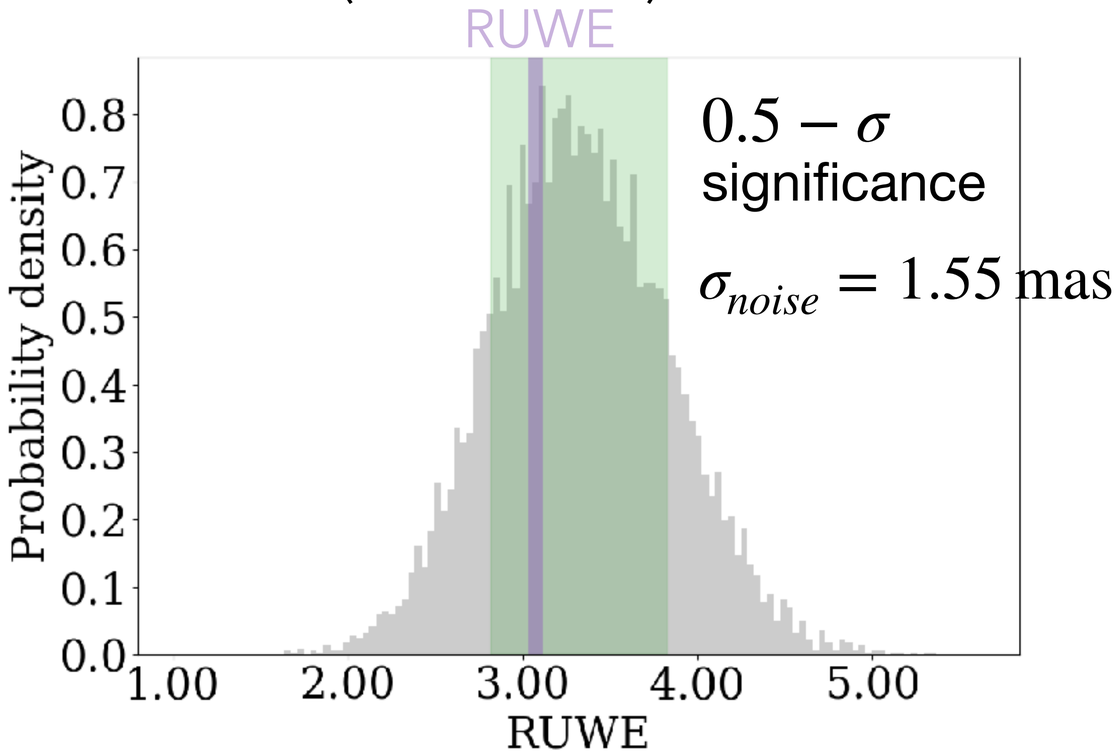
Kiefer+ 2024 Paper I

RUWE & single star null hypothesis: importance of estimating noise

HD 114762 (RUWE=3.1)



Beta Pic (RUWE = 3.0)



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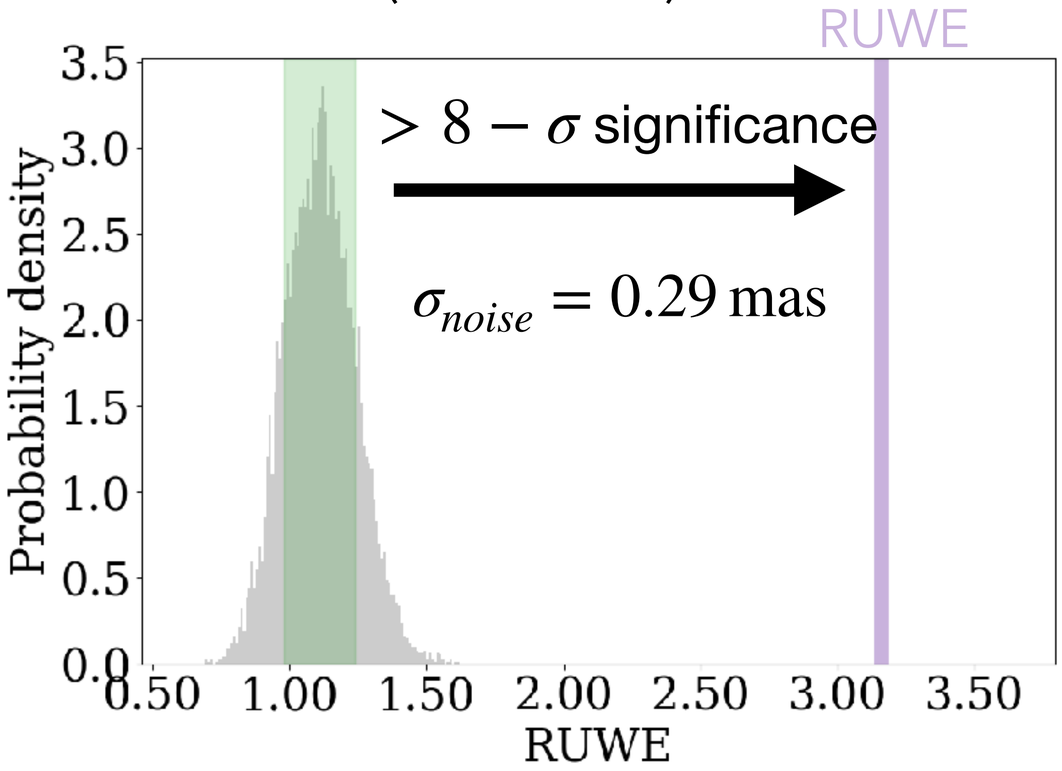

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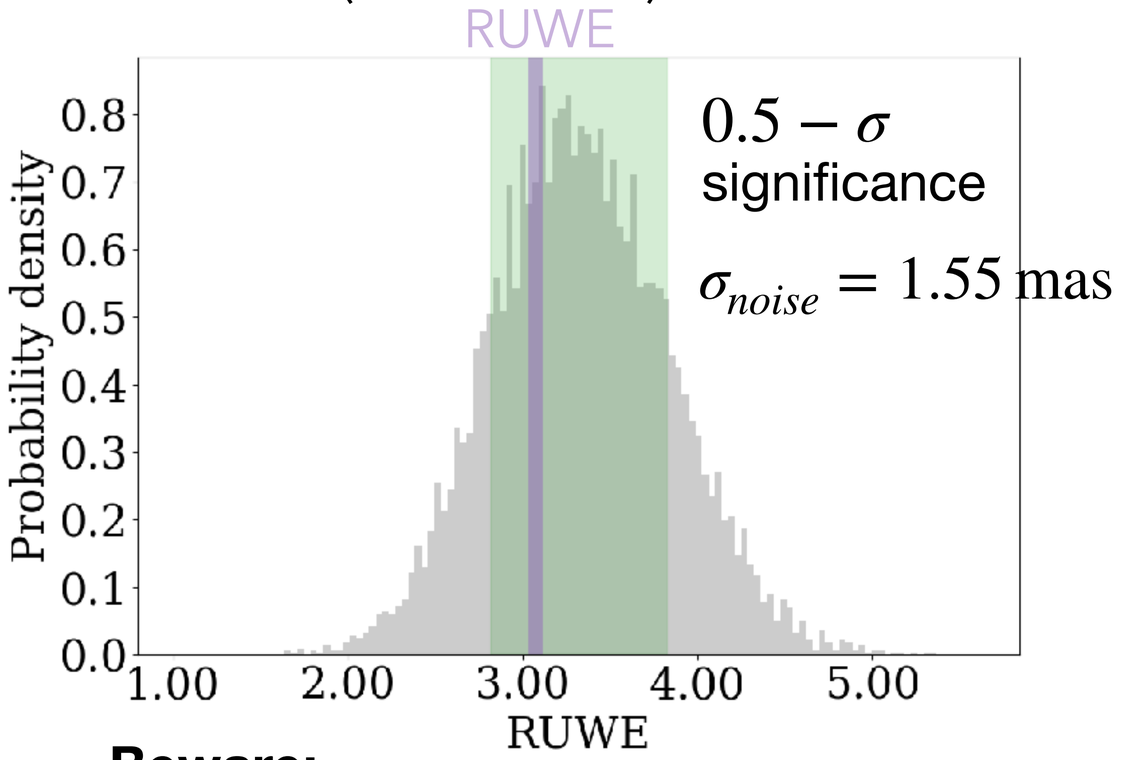


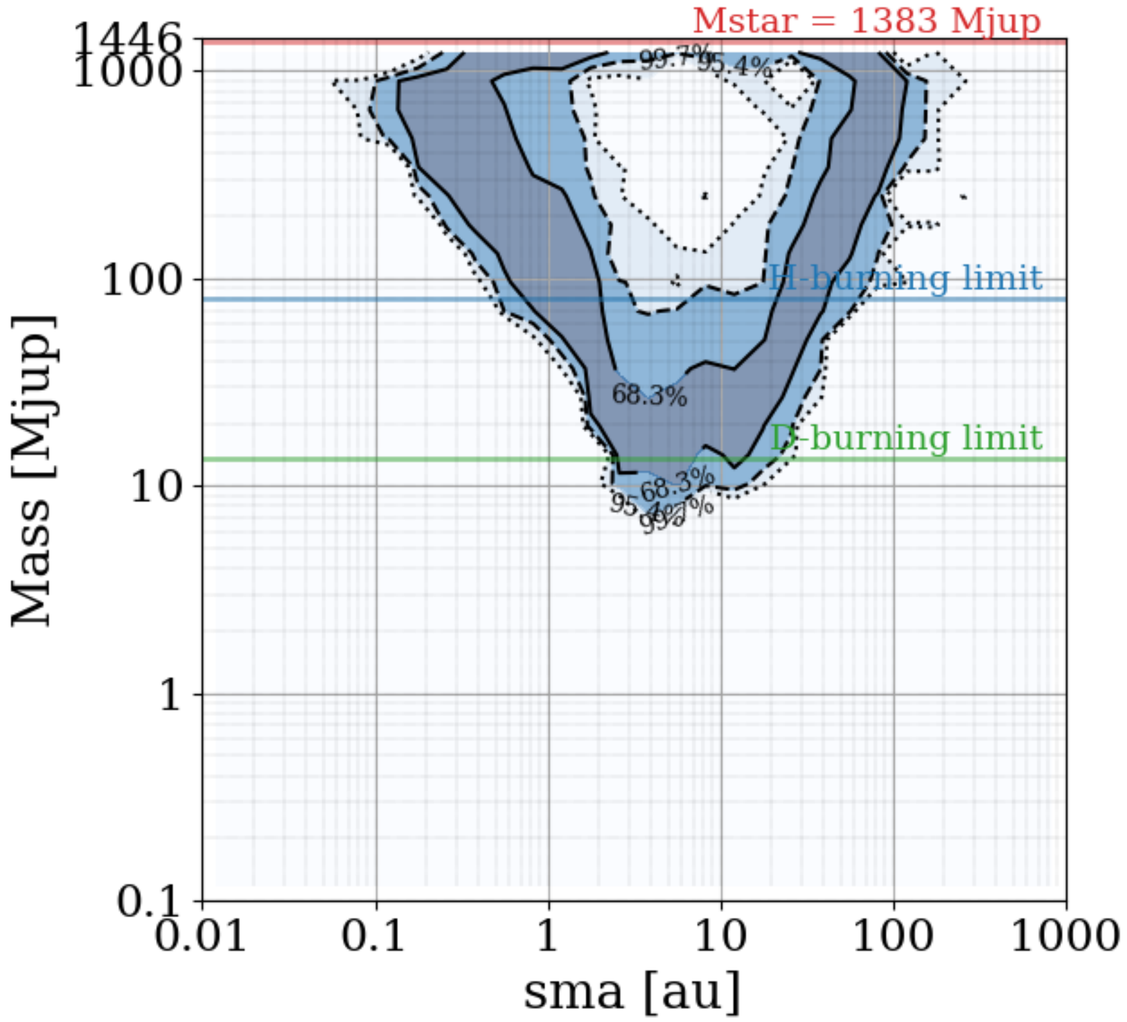
Beware:

- Higher instrumental astrometric noise!
- RUWE cannot be interpreted without knowledge of instrumental noise

Kiefer+ 2024 Paper I

GaiaPMEX: the power of combining

Gaia-Hipparcos **PMa** only



Kiefer+ 2024 Paper I

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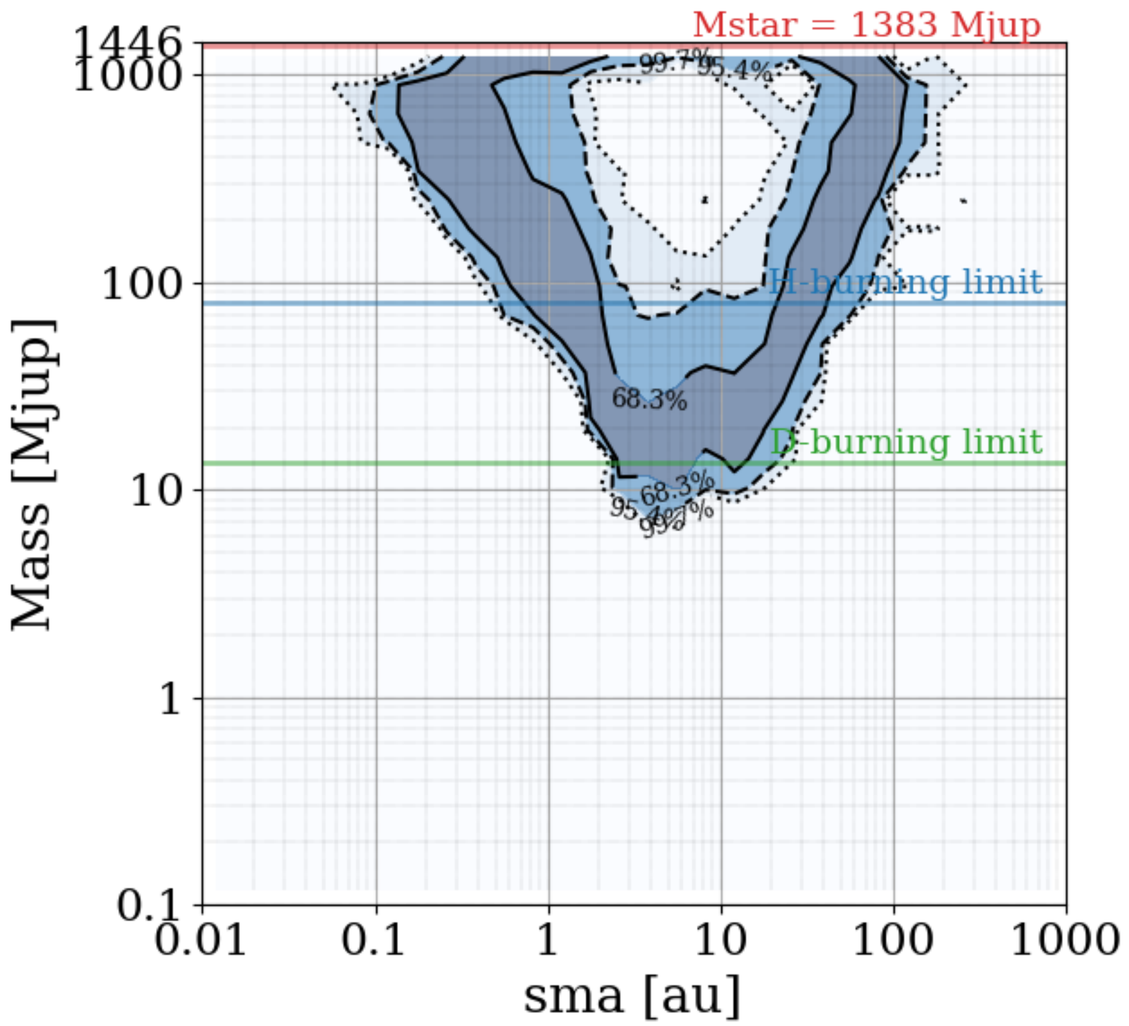
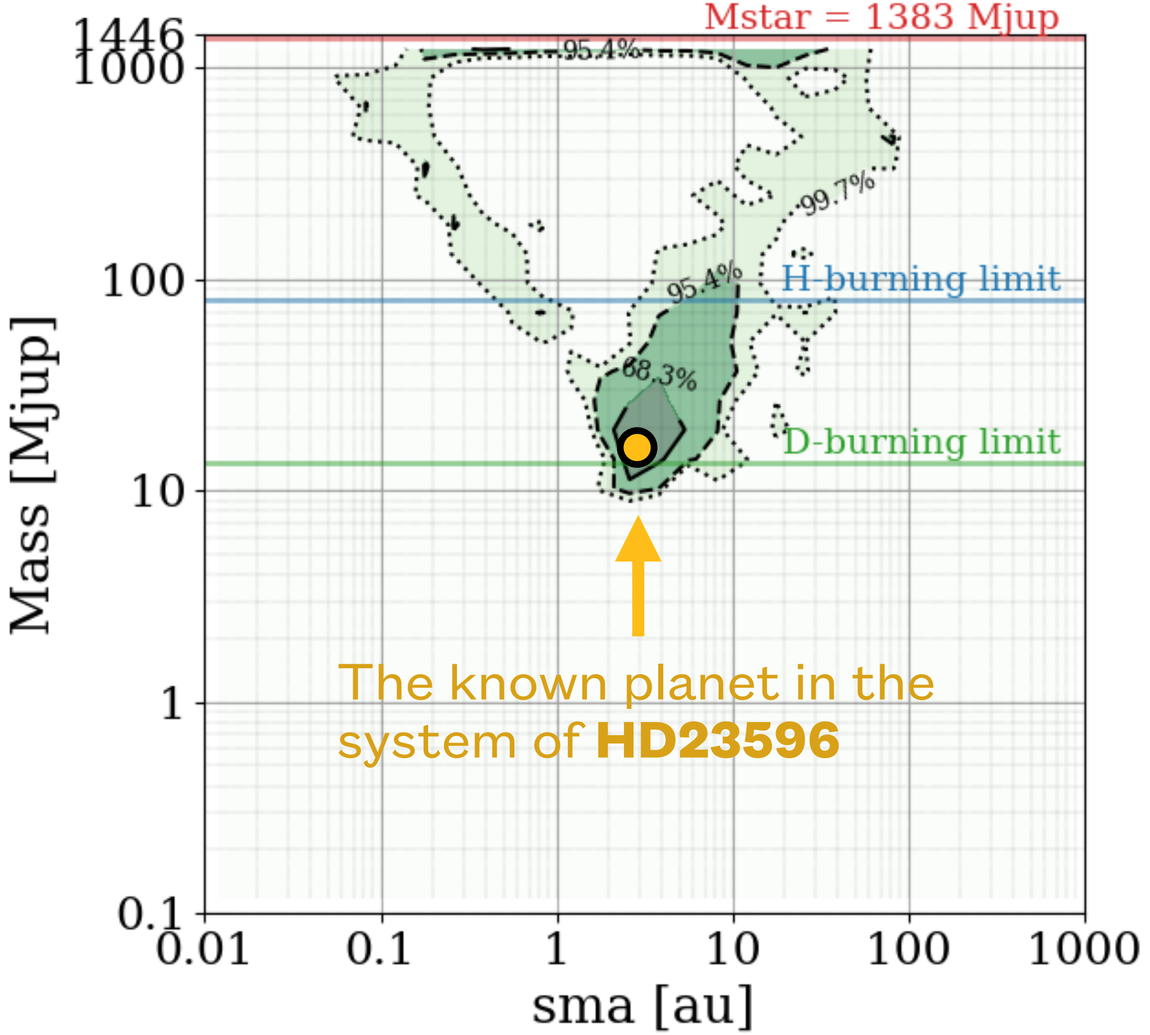
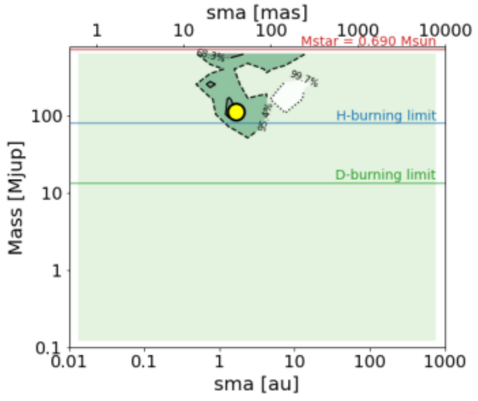


Combining PMa + RUWE



Kiefer+ 2024 Paper I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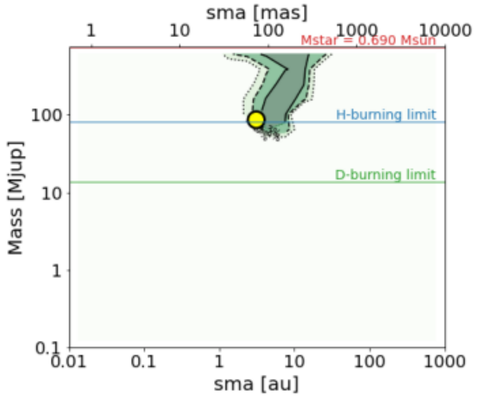
D-burning limit
Mass [Mjup]
sma [au]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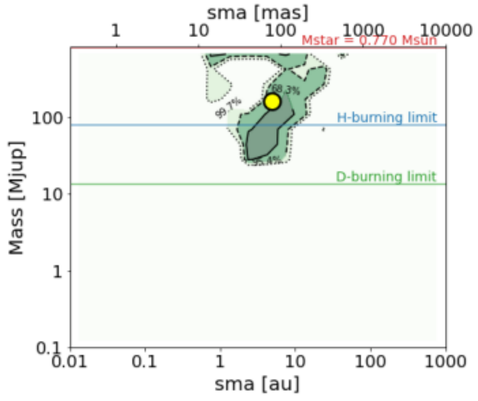
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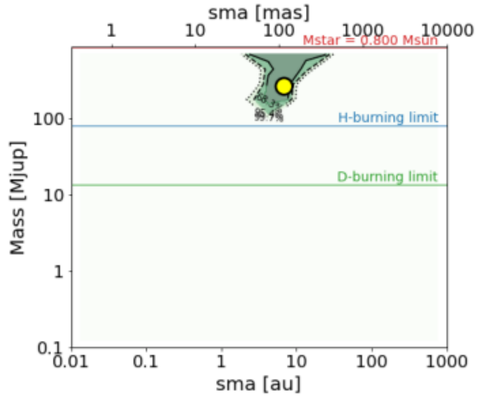
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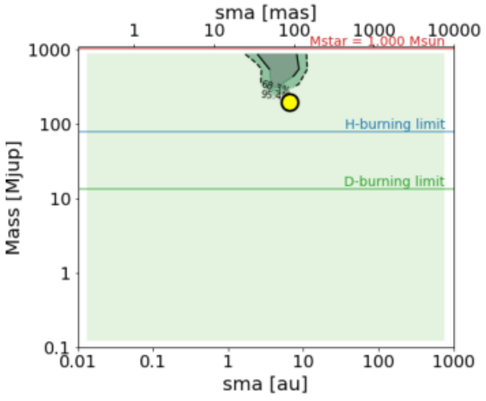
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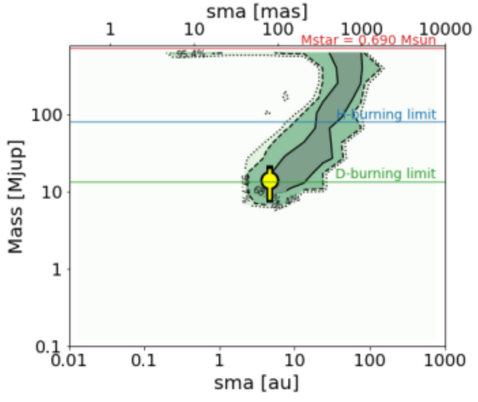
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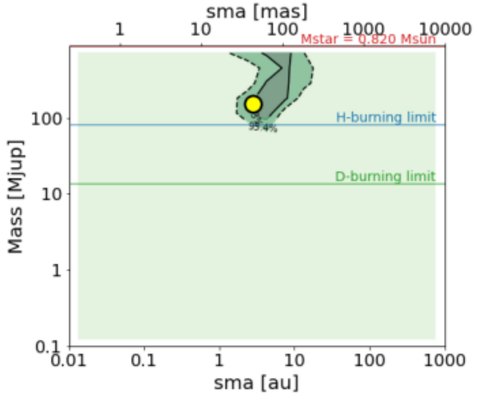
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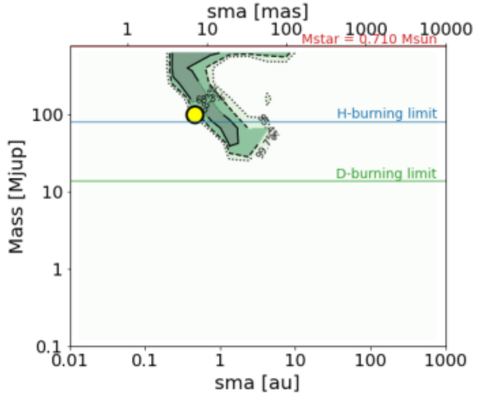
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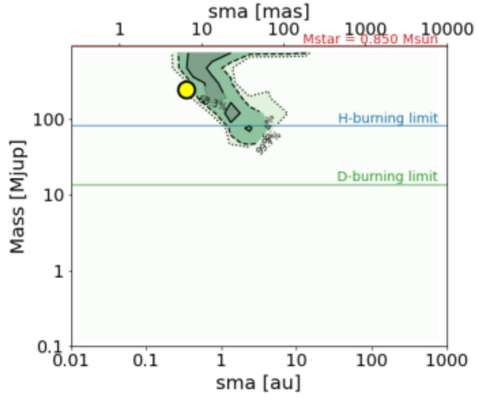
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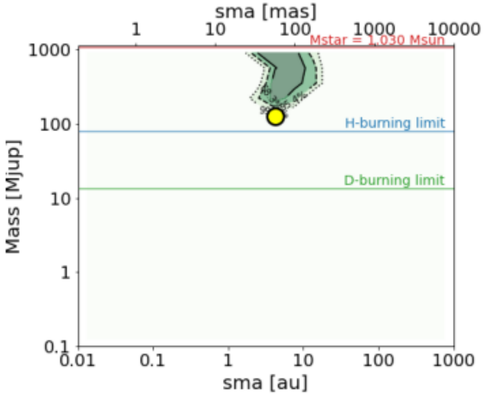
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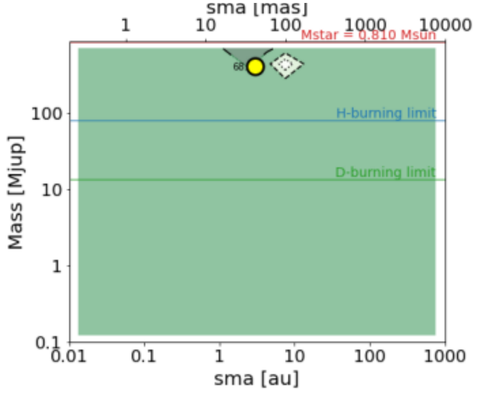
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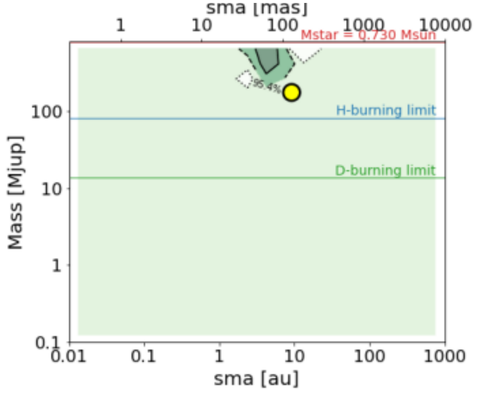
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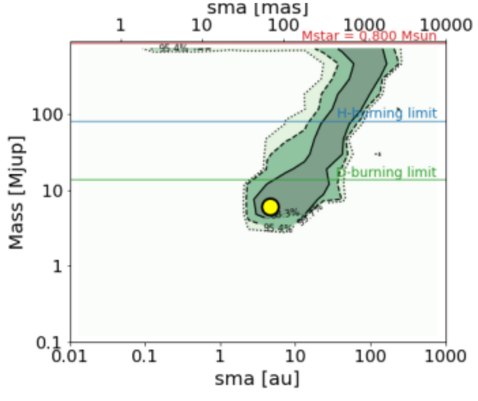
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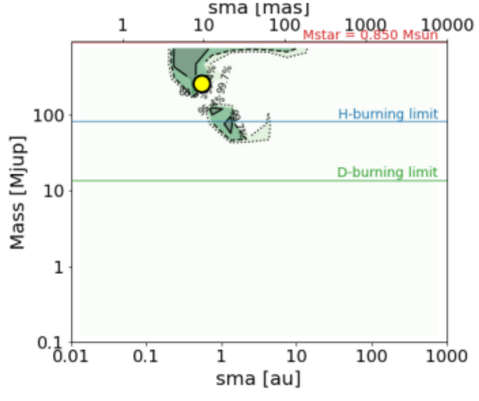
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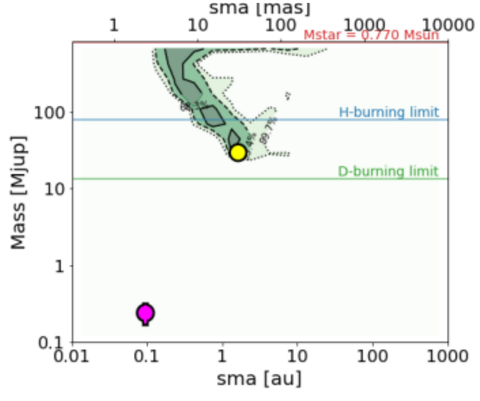
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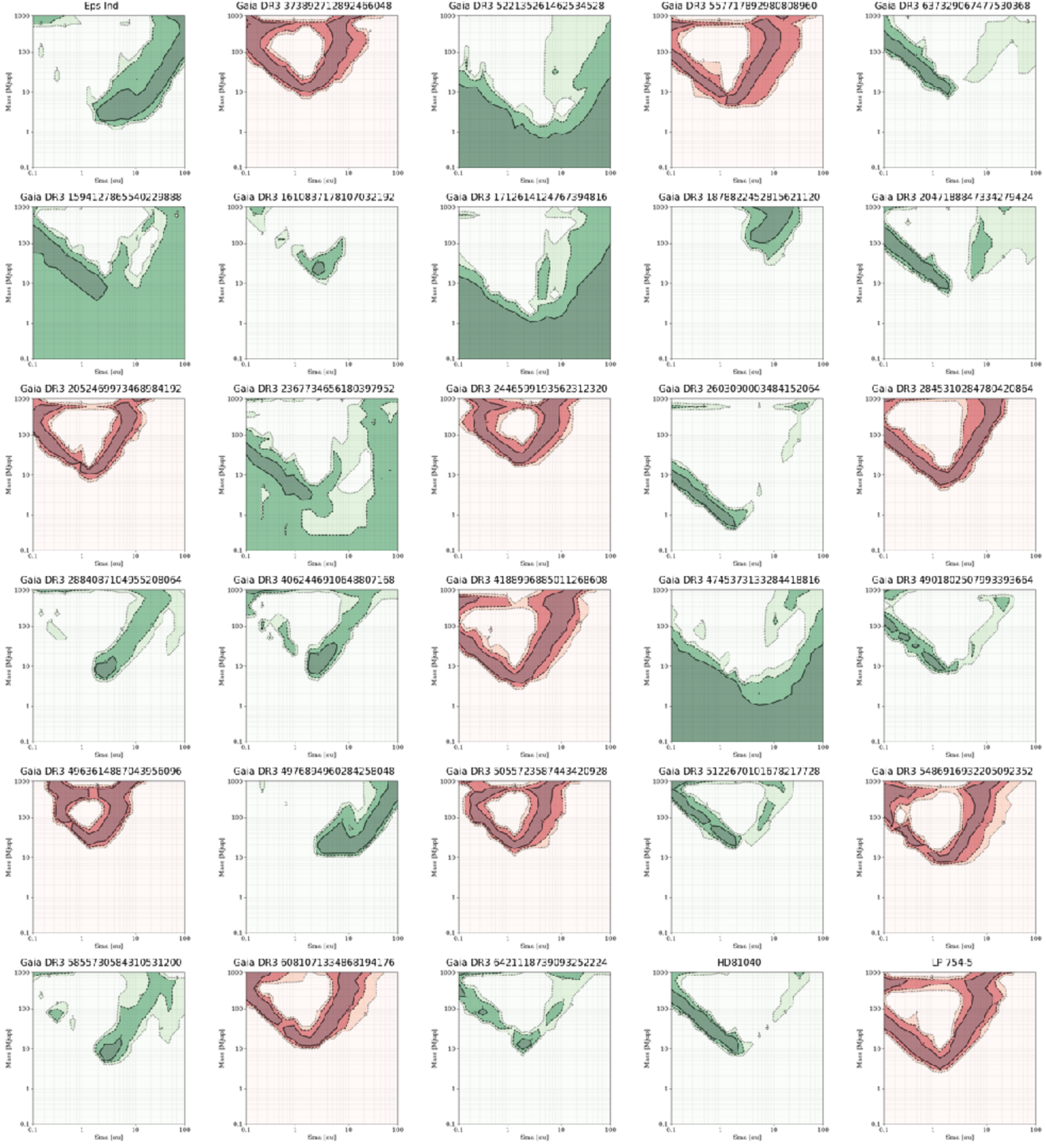
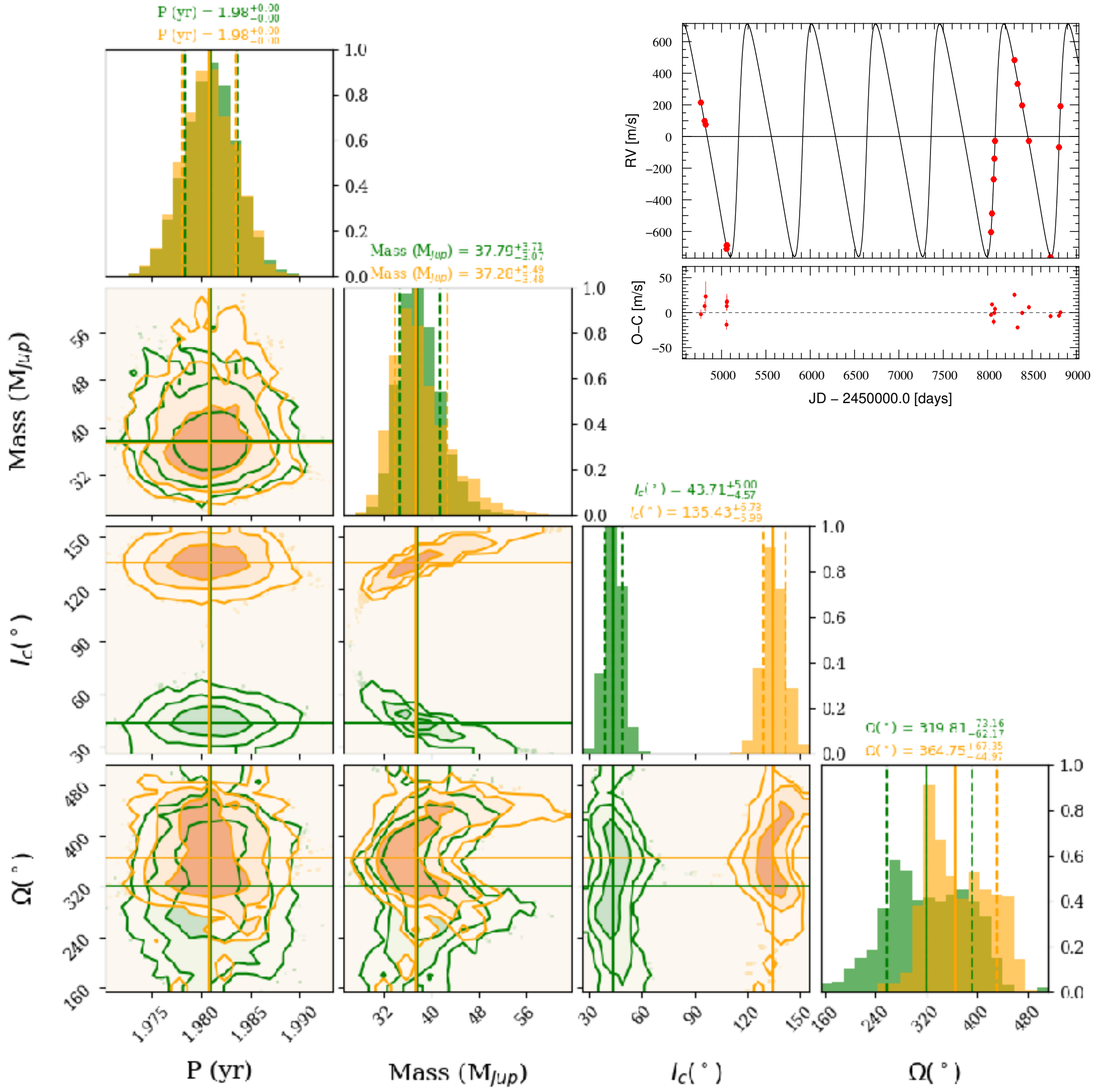
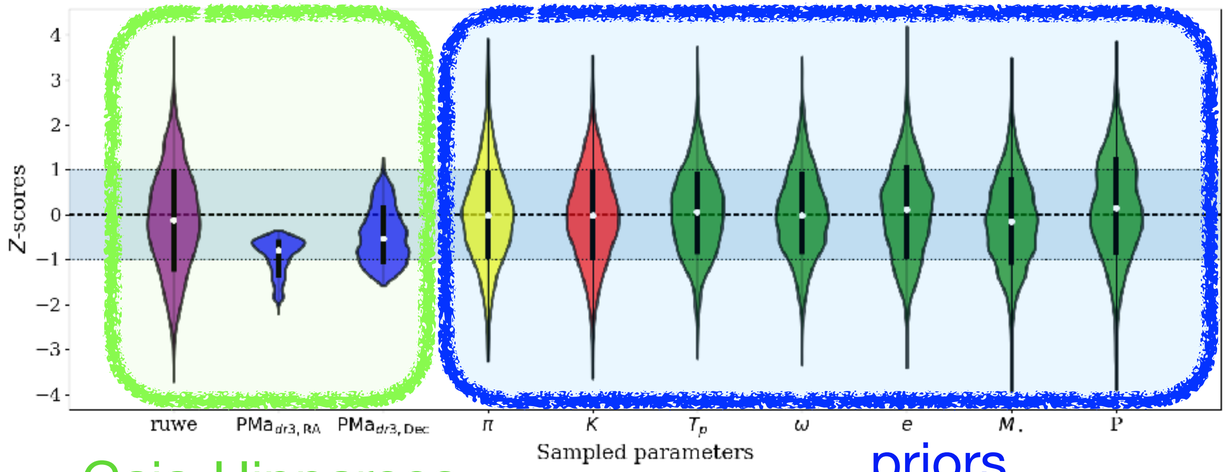
Gaia DR3 ASOI



Mass, inclination and orientation using RV + Gaia + Hipparcos



Sophie RV solution as informative priors



Gaia-Hipparcos data

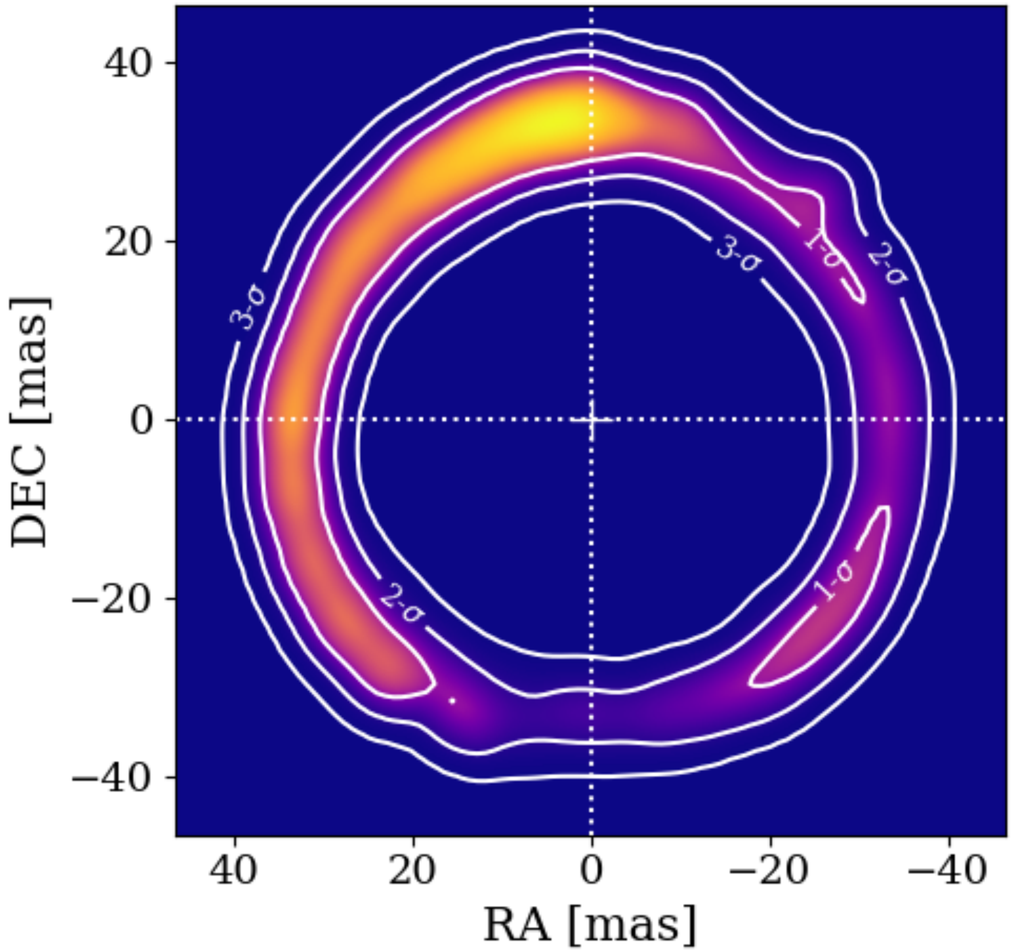
priors

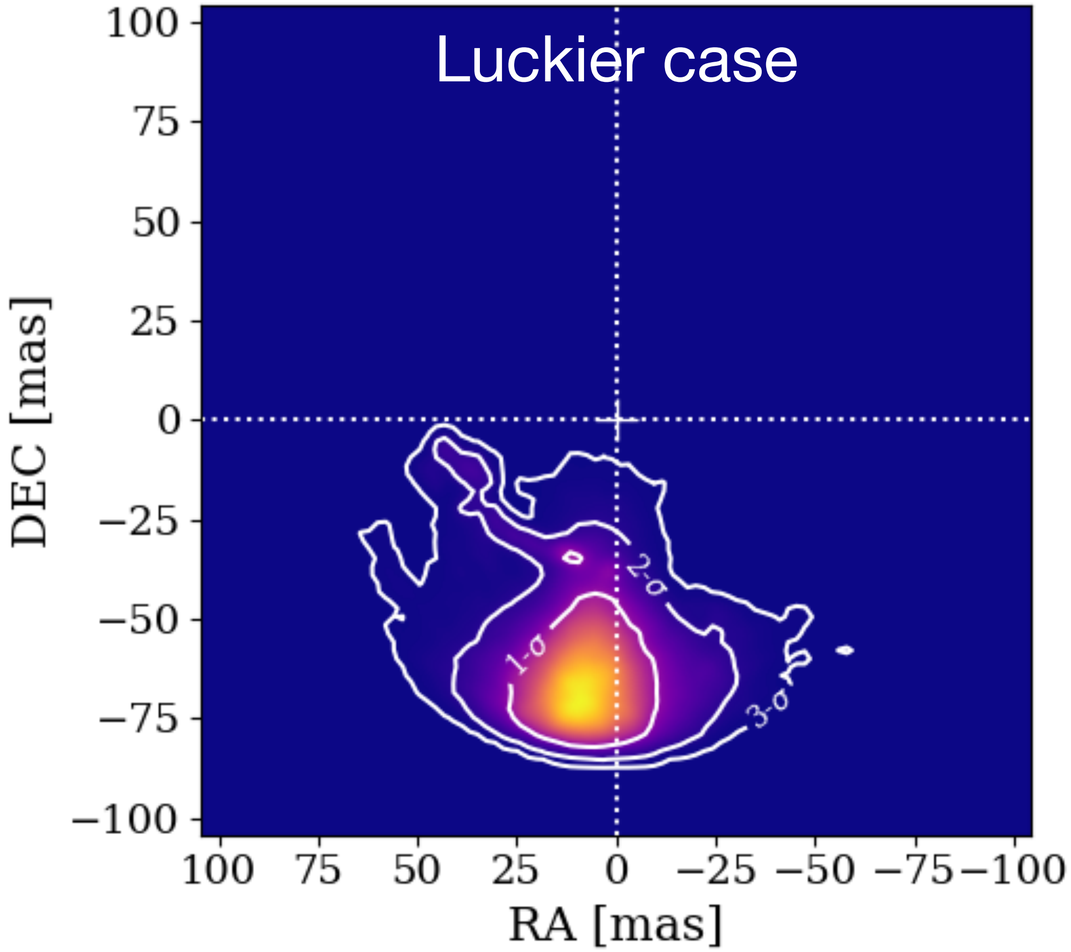
- Prograde / retrograde solutions
- Degenerate ➜ need time series (DR4)
- But tight mass constraint ➜ 37 ± 3 M_{Jup}

Kiefer+ 2025, in prep

Predict the location of the planet for DI characterisation

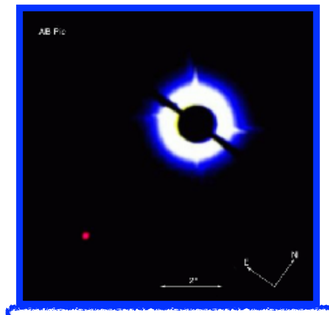
not so predictive (pro/retro)





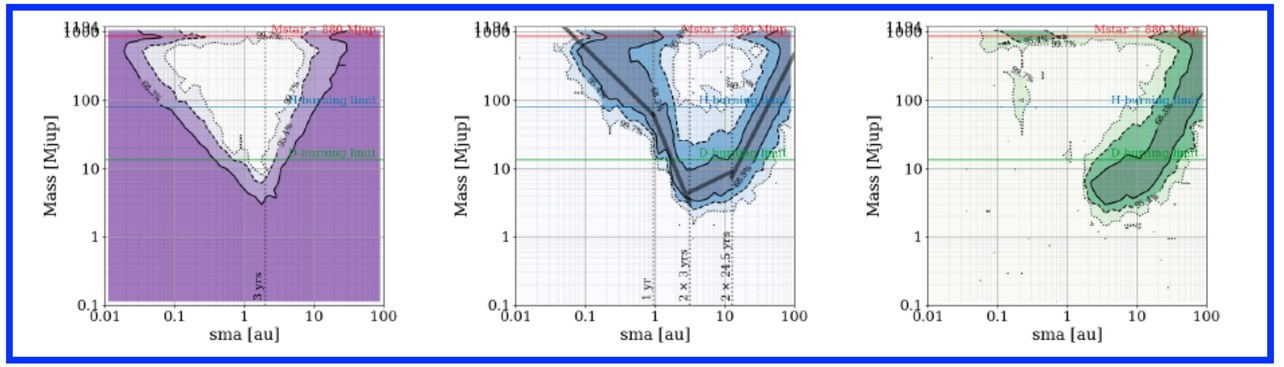
Kiefer+ 2025, in prep

Coupling Gaia, HIP, RV & HCI to characterize LPGPs in young associations



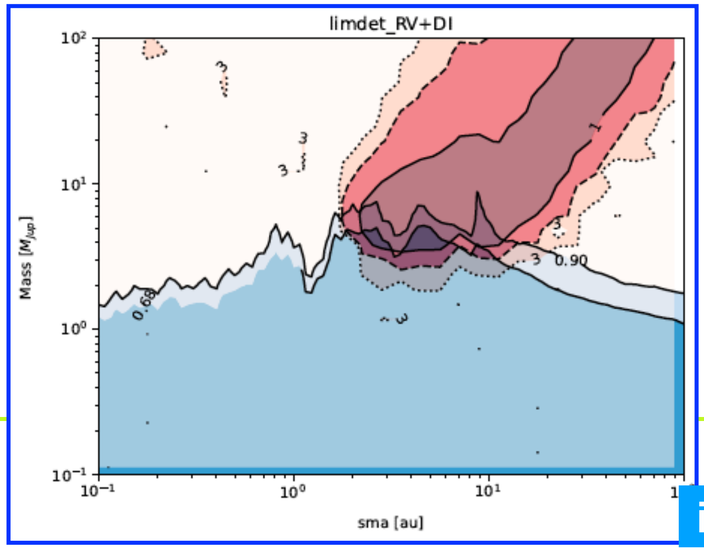
AB Pic

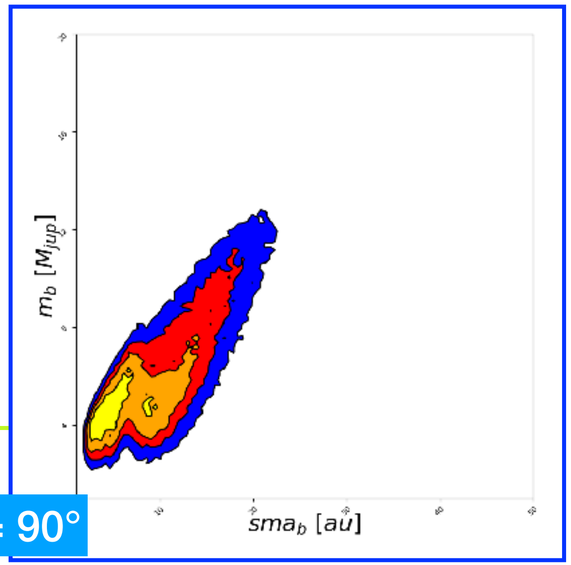
AB Pic b
- Sep = 260 AU (proj.)
- M ~ 13 M_{jup} (Chauvin+, 2005)
- M ~10 M_{jup} (Booth+, 2021)
- Eccentric orbit (Palma-Bifani+, 2023)



Gaia/PMa => additional companion

Adding RV and HCI





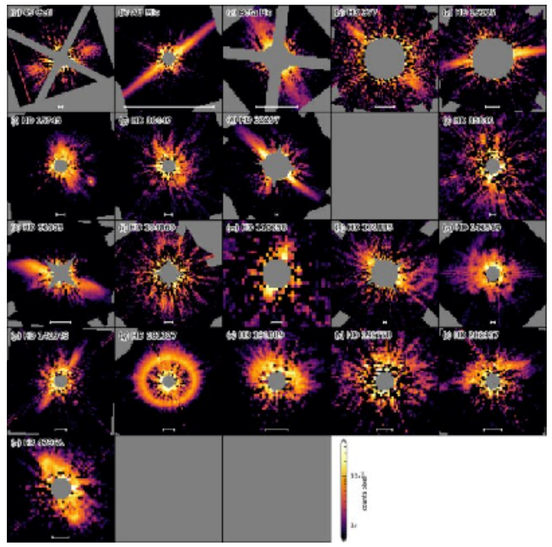
i = 90°

1-10 au & 2-6 MJup
System dynamical history ?
Direct detection with Gravity? ELT

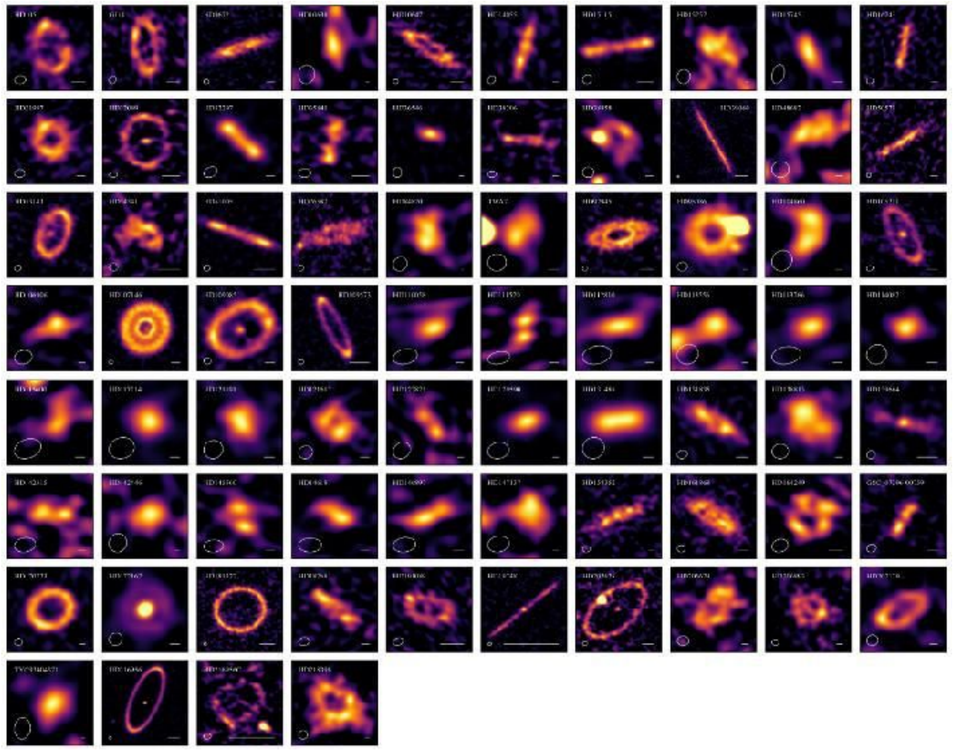
Lagrange+ 2025 Paper III

Gaia-informed HCI to search for Giant Planets in young debris disks

A few VLT/SPHERE images



NICMOS. Ren et al. 2023



ALMA. Matra et al. 2025

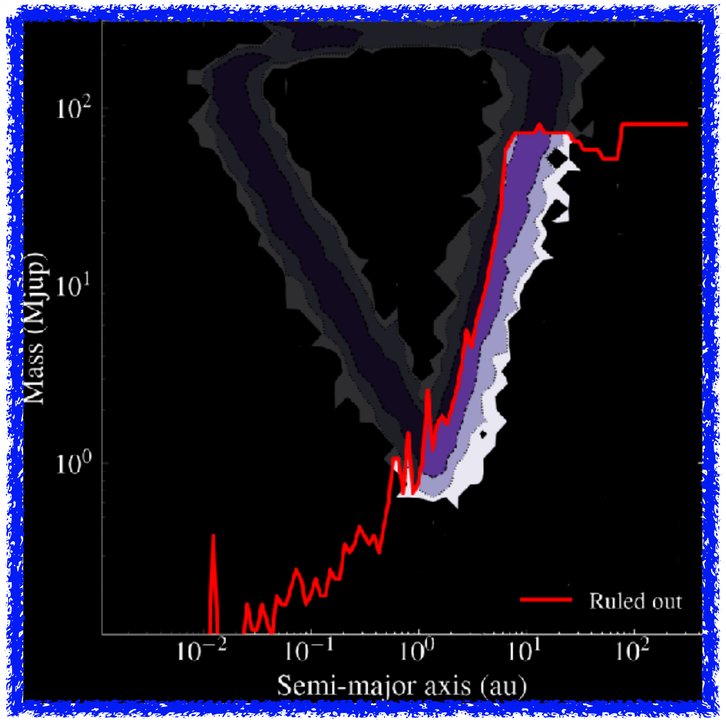
- 94 debris disks spatially resolved (ALMA)
- 4 new companions found
- Some systems already have outer companions

Lagrange+ to be submitted

Gaia-informed HCI + RV to search for Giant Planets around M stars

cf F. Destriez talk

M15 survey



Sample

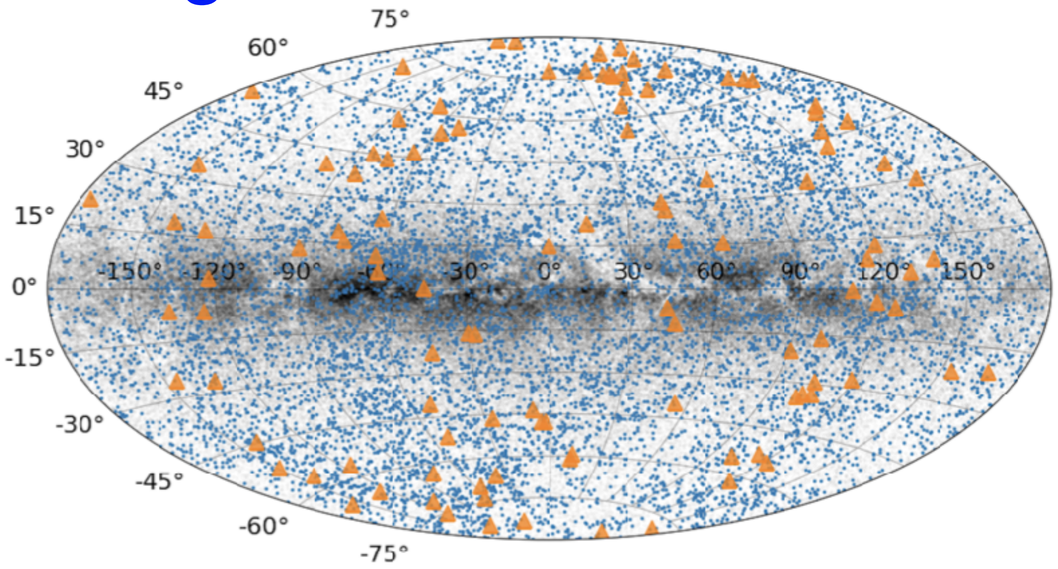
- $d < 15\ pc$
- $m_G < 16$
- 706 M-dwarfs

- **New stellar binaries**
- **Several planets & BDs**

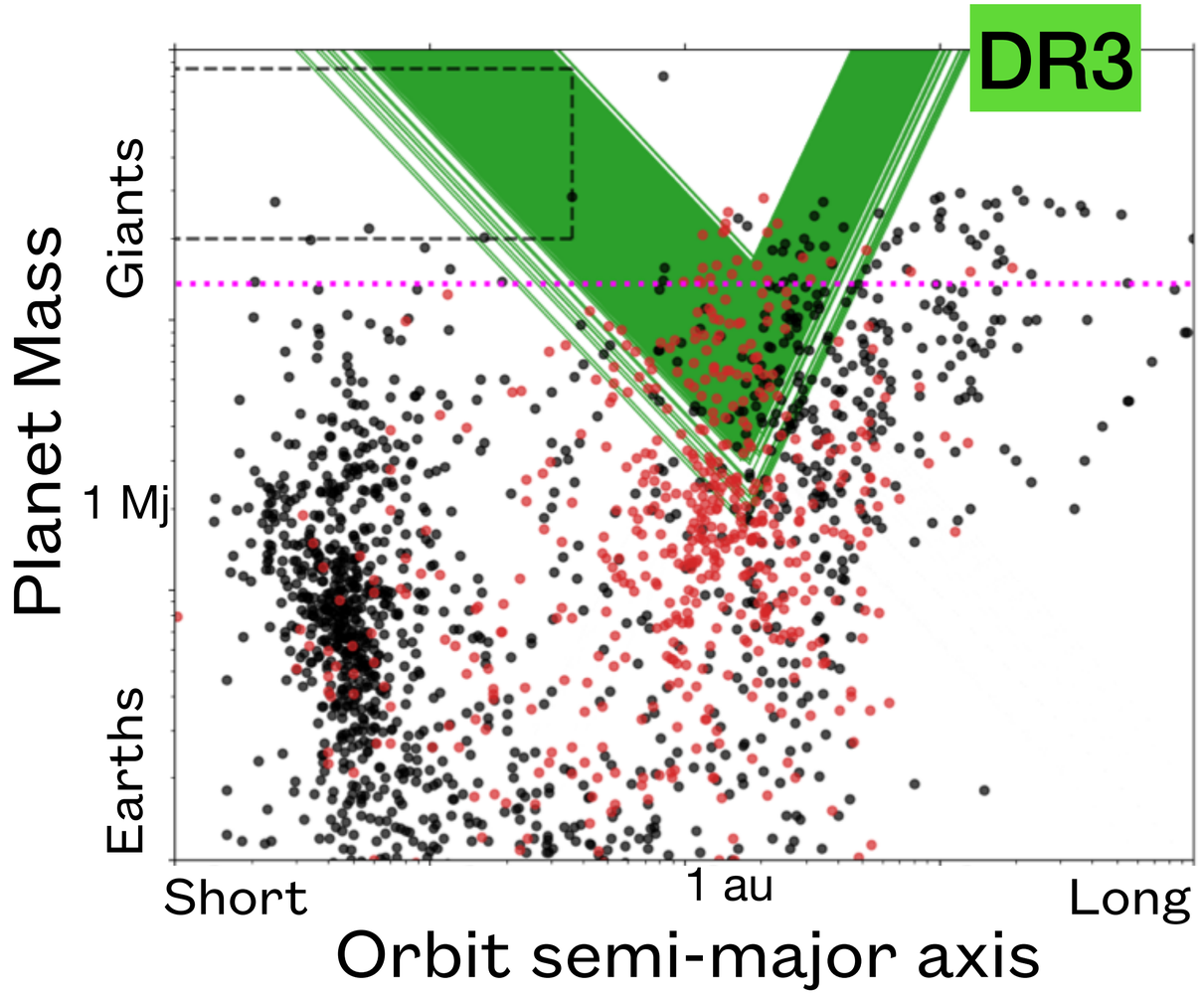
(known from RV & new ones)

Destriez+ in prep

80M “bright” Gaia sources ➜ the 9,698 Exoplanet Candidates Catalog

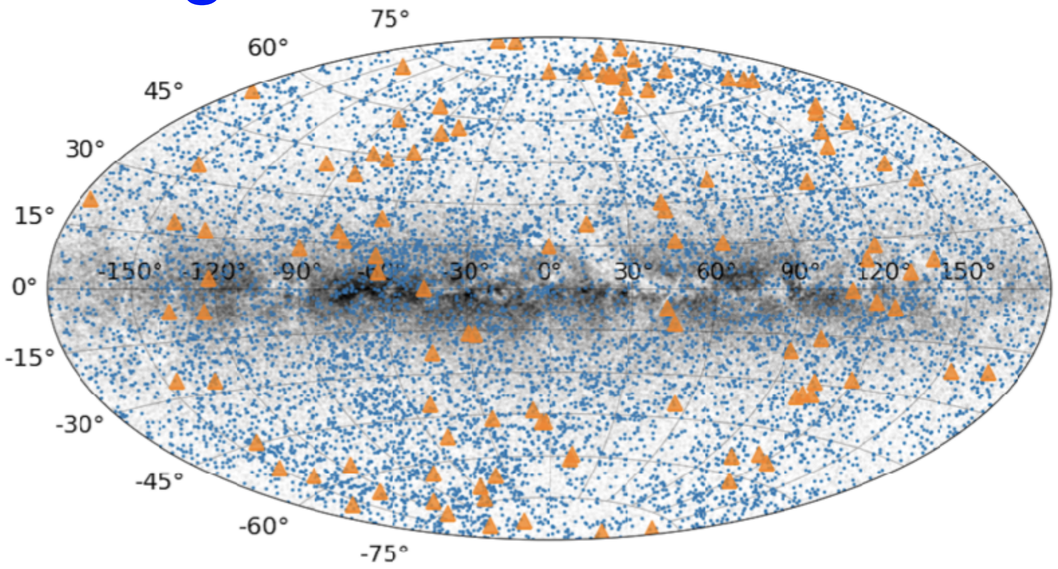


- mostly 50–500 pc + G<16
- RUWE significance > 2.7-σ
- 0.5 - 1.5 Msun (mostly <0.8)
- candidate (unknown) planets
  - ➡ sma in 0.3 - 4 a.u.
  - ➡ mass > 1 M_{Jup}



Kiefer+ 2024 Paper II

80M “bright” Gaia sources ➜ the 9,698 Exoplanet Candidates Catalog



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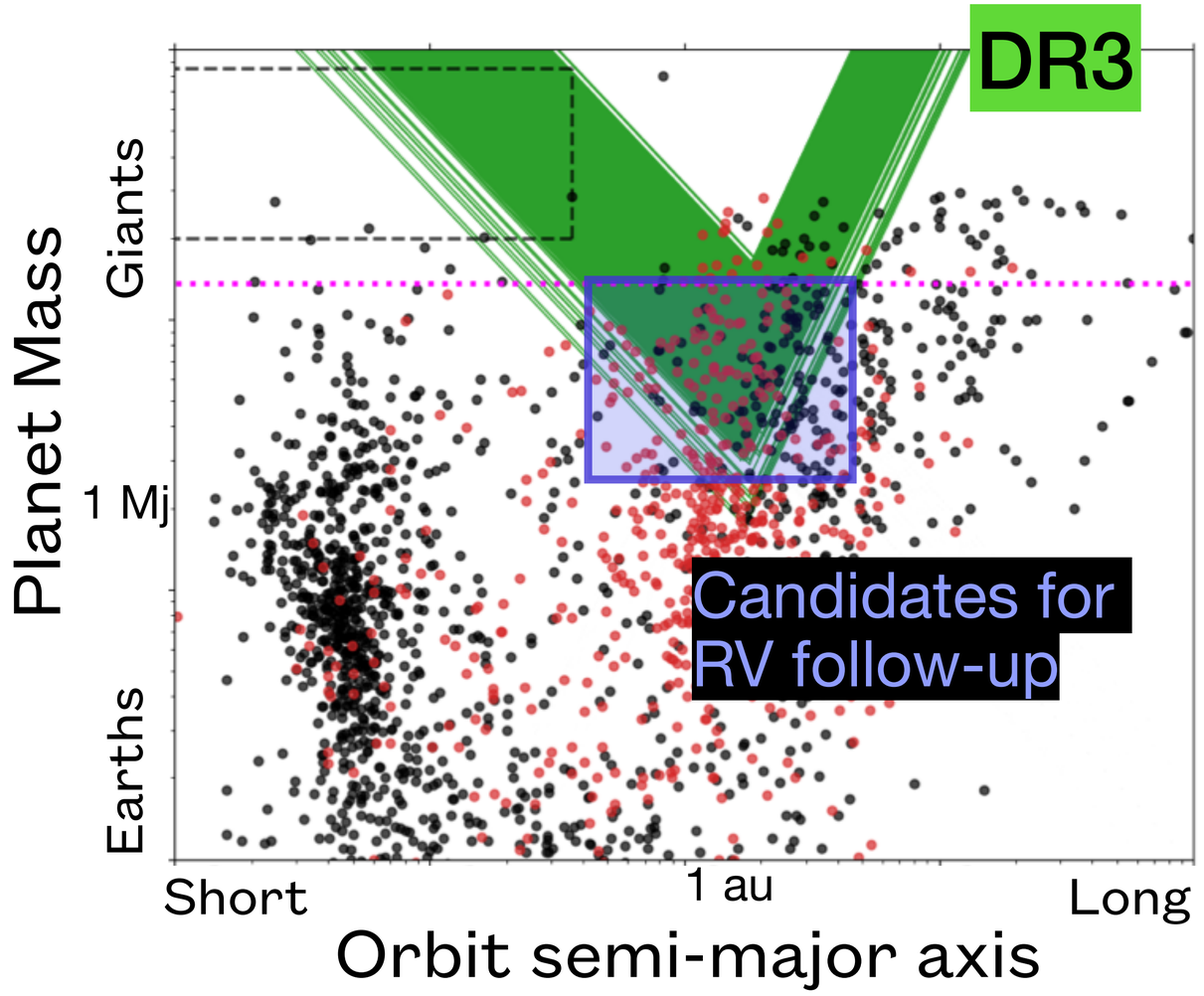
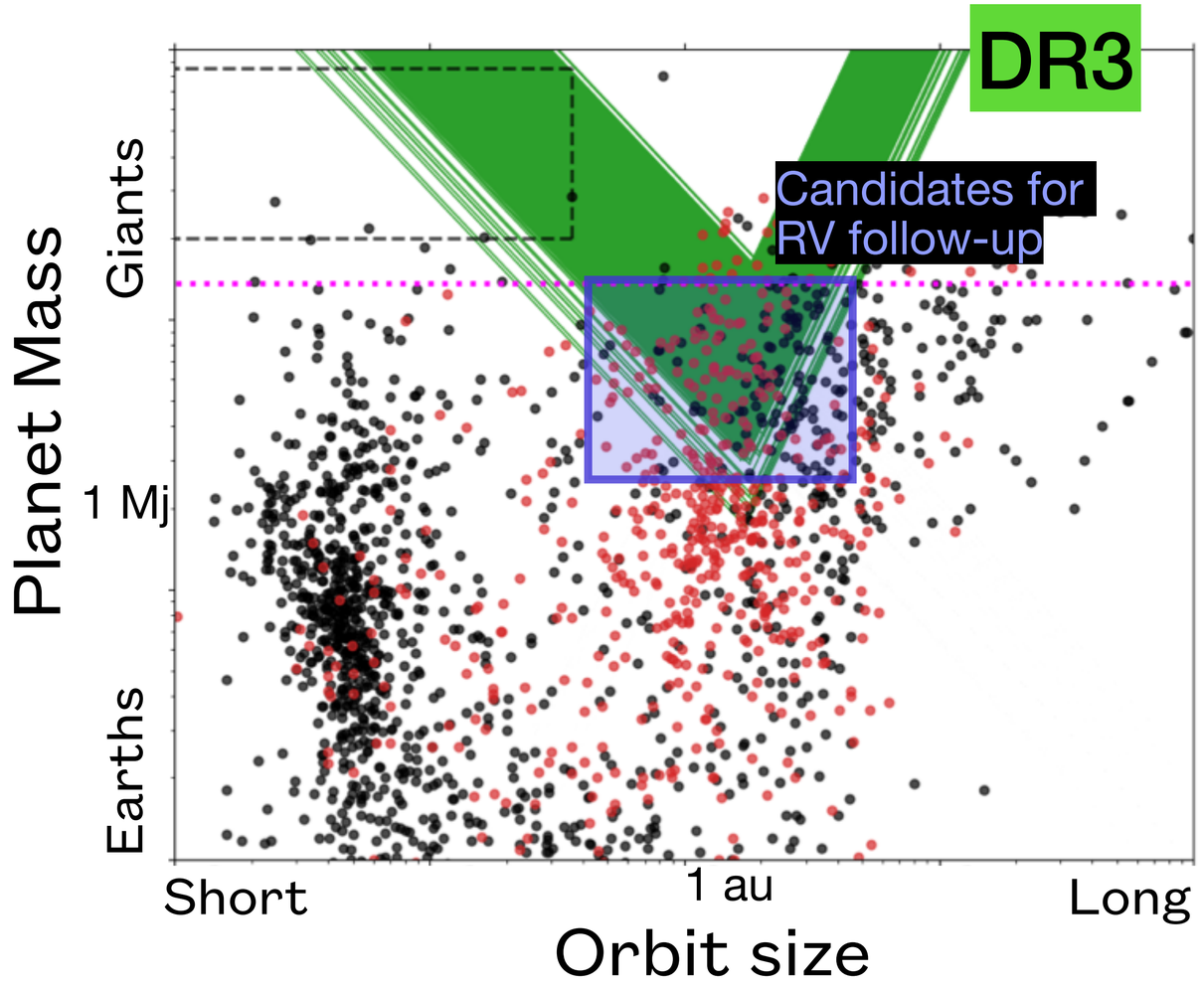


Kiefer+ 2024 Paper II

Conclusions & Perspectives

- A publically available (CDS) catalog of close to **10,000 planet-hosting candidates**,
- All potential candidates for follow-up!
- Many more to come (lower M_{star}, DR4 …),
- RUWE and PMa (combined) are powerful data to detect companions in the DR3,
- But requires a **careful treatment** of Gaia noises
- Identification of LP giants around young stars w/ or w/o, debris disk
- Also around close-by late-type stars,
- Full characterisation using also RV + HCI.



Kiefer, Lagrange+ 2024 Paper II
Lagrange, Kiefer+ 2024 Paper III

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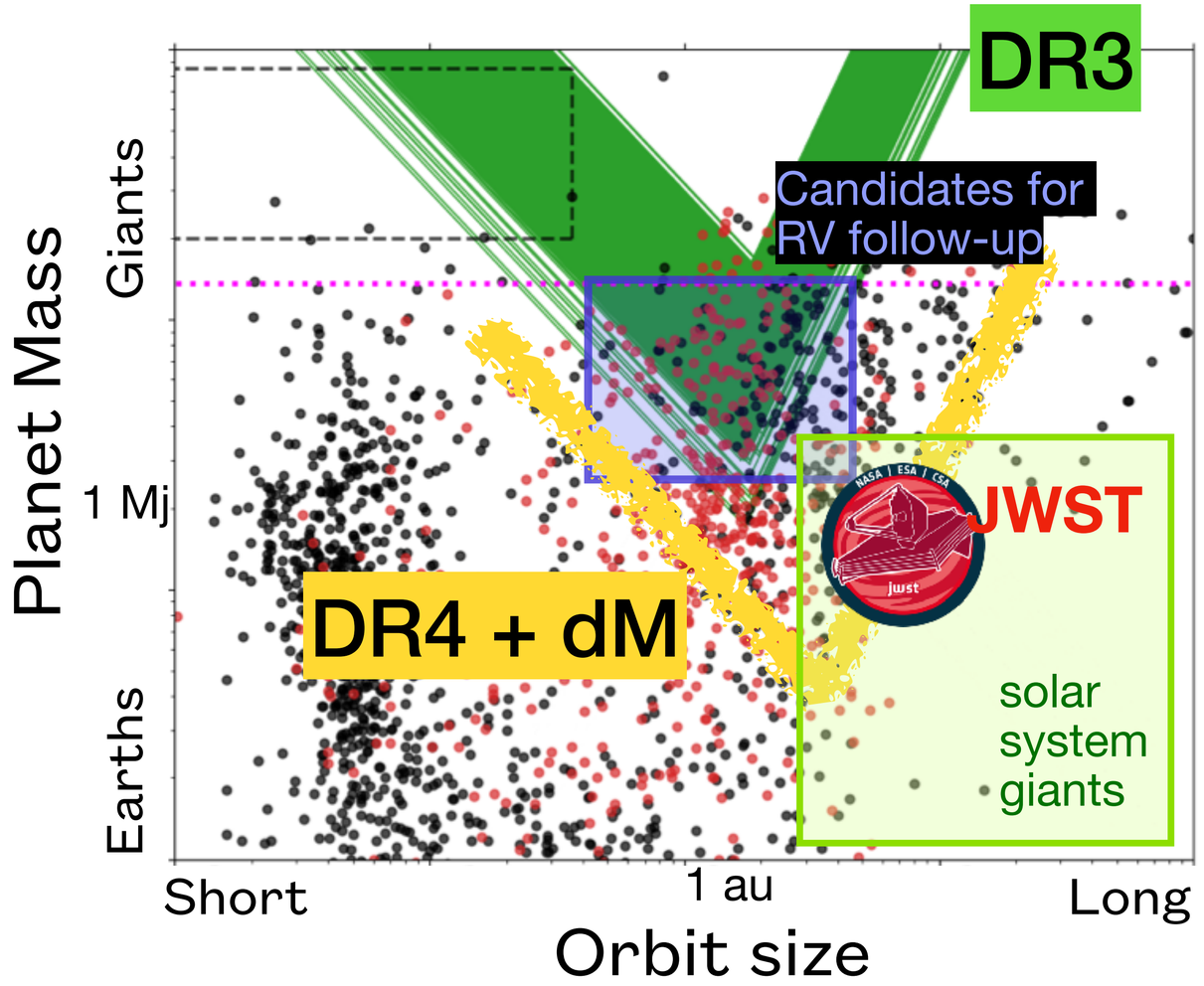

Kiefer, Lagrange+ 2024 Paper II

Lagrange, Kiefer+ 2024 Paper III

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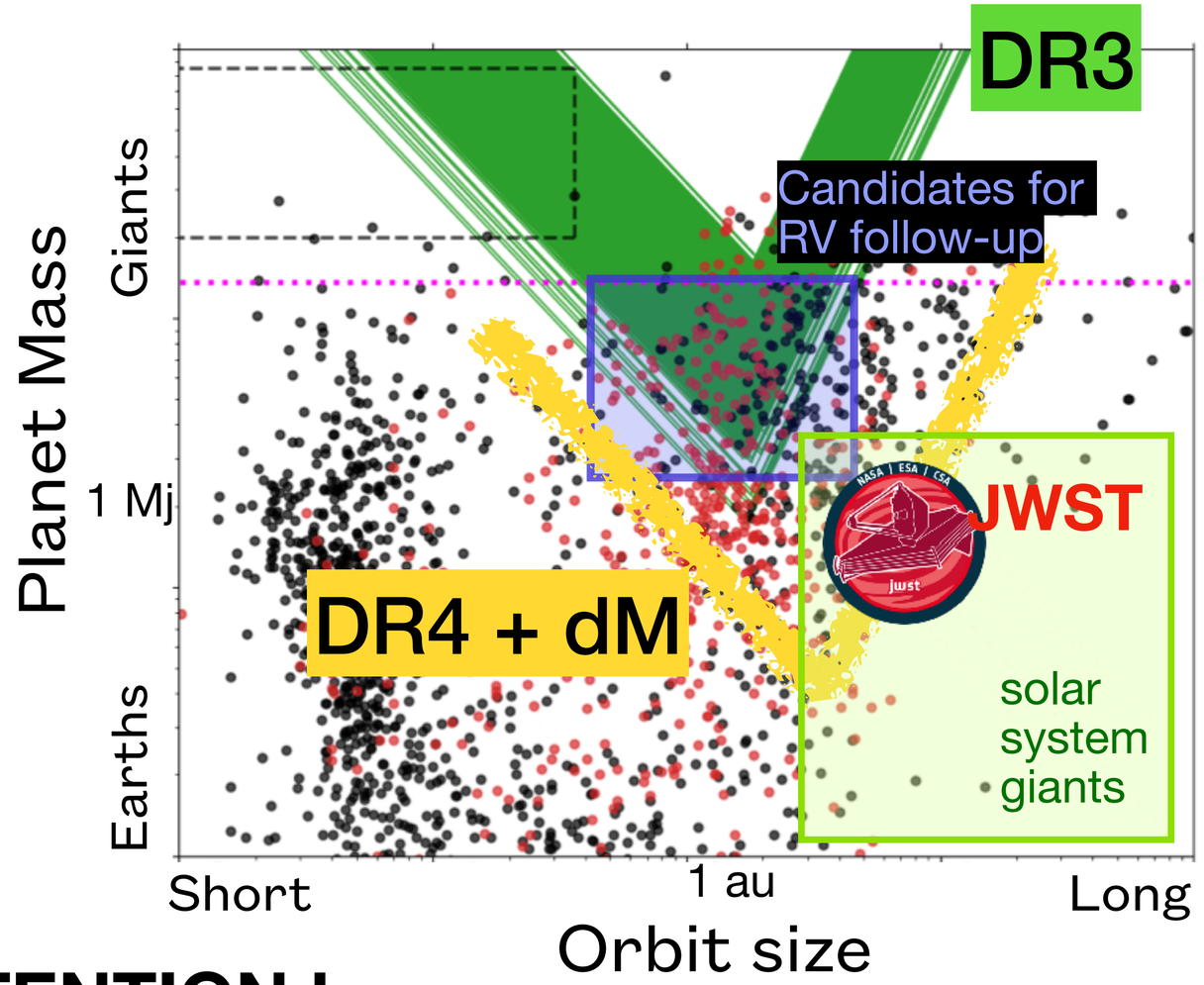


THANKS FOR YOUR ATTENTION !

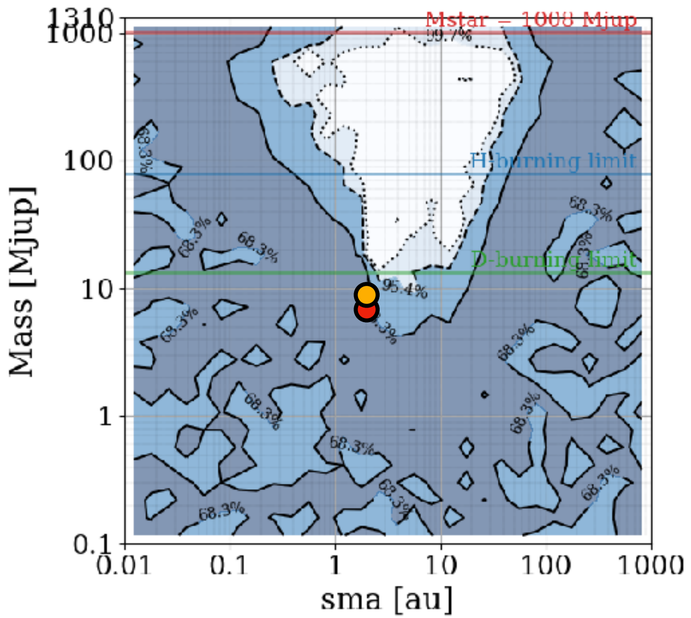
Kiefer, Lagrange+ 2024 Paper II

Lagrange, Kiefer+ 2024 Paper III

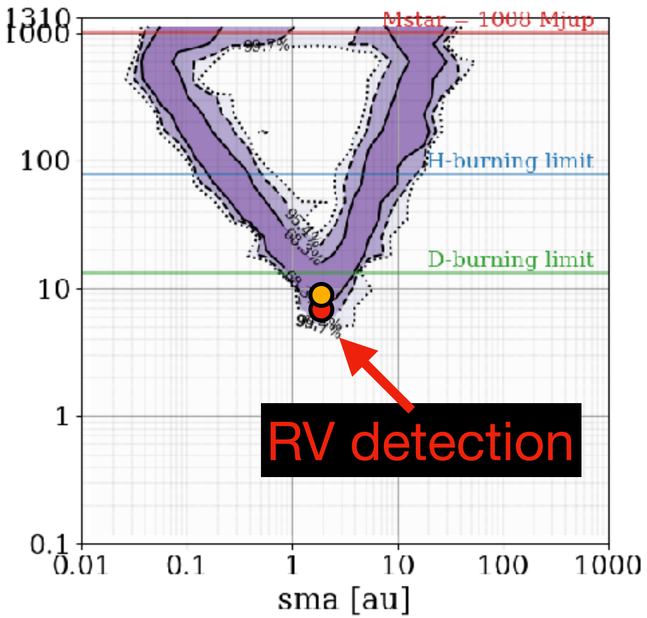
Backup slides…

Characterising the mass, inclination and orientation using astrometry

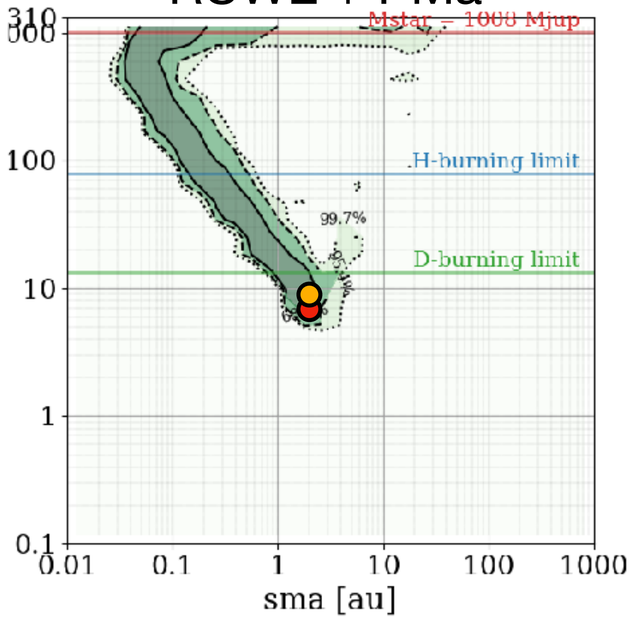
Gaia-Hipparcos PMa



Gaia - RUWE

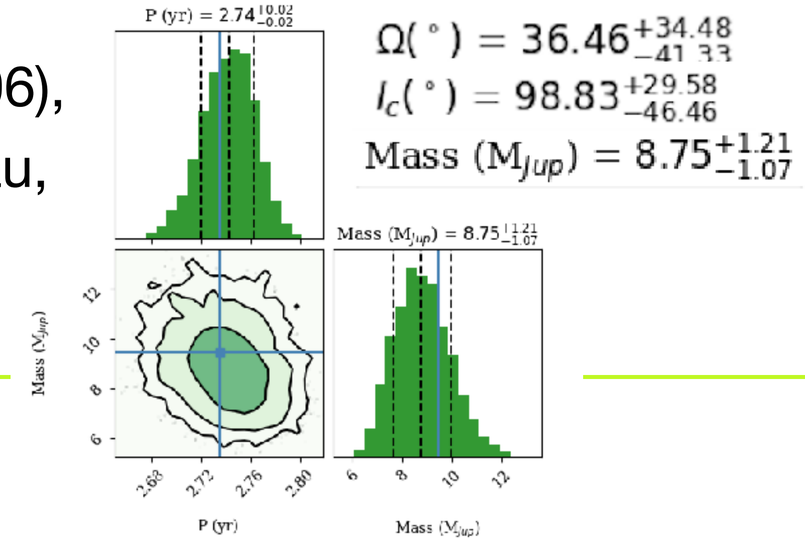


RUWE + PMa



HD 81040

- RV-planet at 6.9 M_{Jup} and 2 au (Sozetti+ 2006),
- 95% confidence prediction: 6-20 M_{Jup} at 2 au,
- **MCMC** compatible with Gaia-NSS solution.

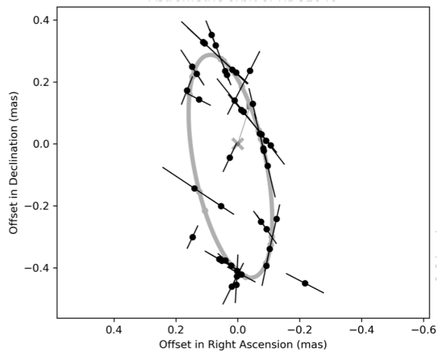


Gaia-NSS

$\Omega = 12.46^{+5.79}_{-5.38}$ deg

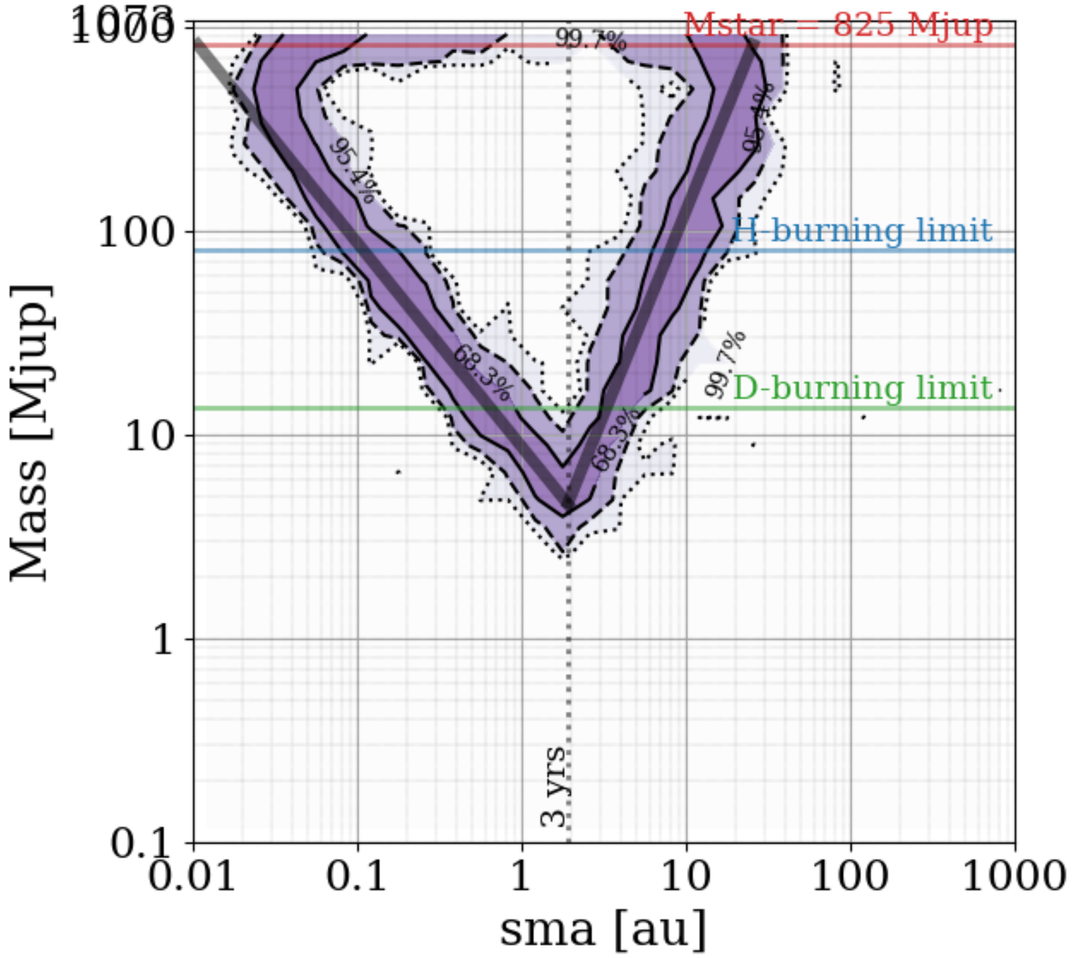
$i = 107.40^{+5.51}_{-5.58}$ deg

M_p ~8.0±0.5 M_{jup}



Kiefer+ 2024 Paper II

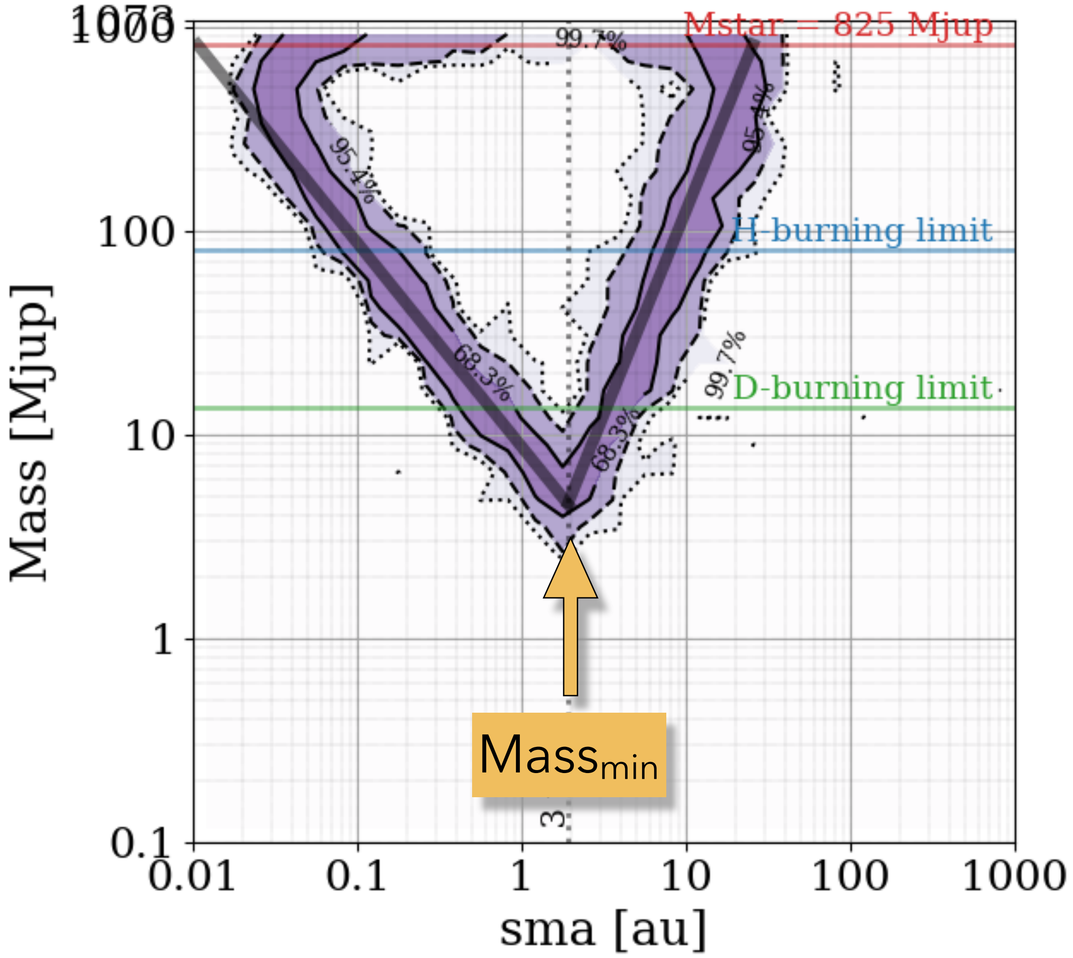
Using the RUWE for searching exoplanet candidates in Gaia DR3



- Many sources w/o Hipparcos data
- Need use Gaia RUWE only
- min mass at the bottom of the V

Kiefer, Lagrange+ 2024 Paper I

Using the RUWE for searching exoplanet candidates in Gaia DR3



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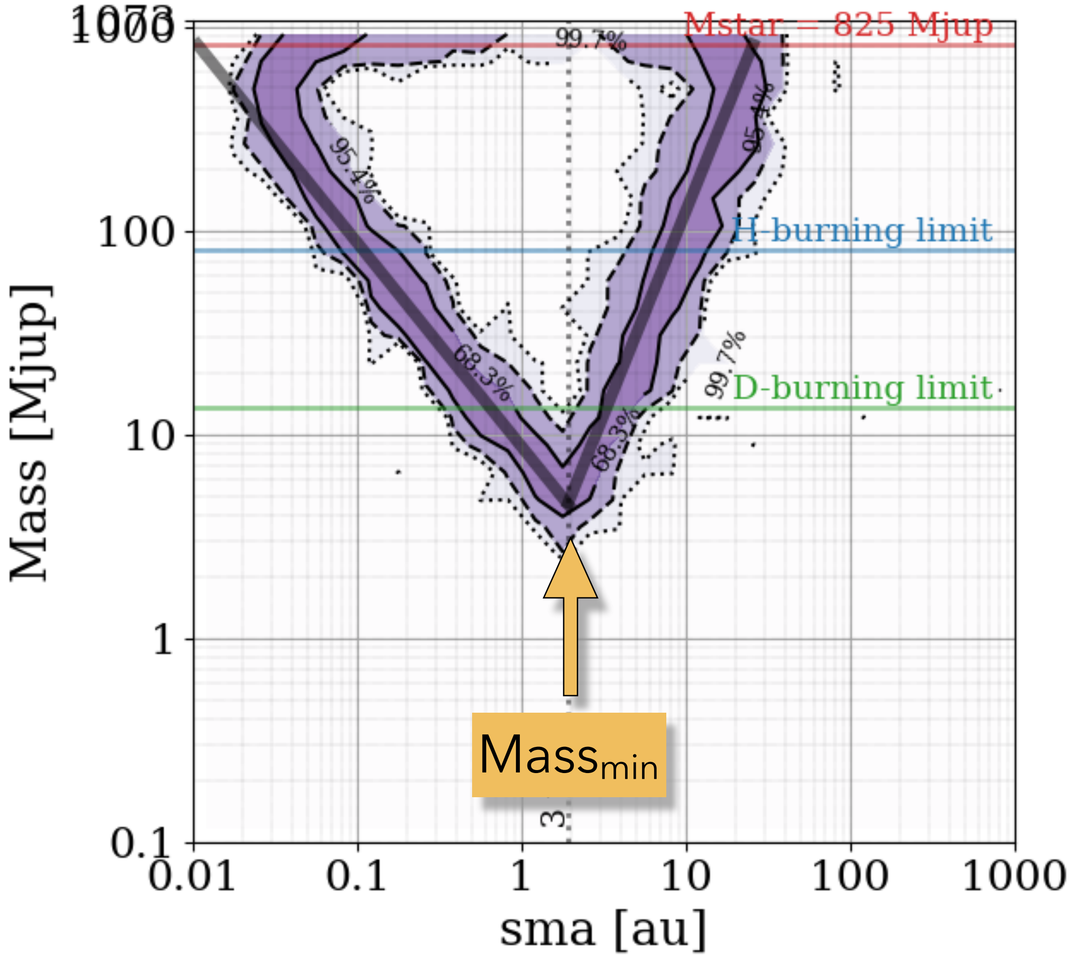


- Many sources w/o Hipparcos data
- Need use Gaia RUWE only
- min mass at the bottom of the V

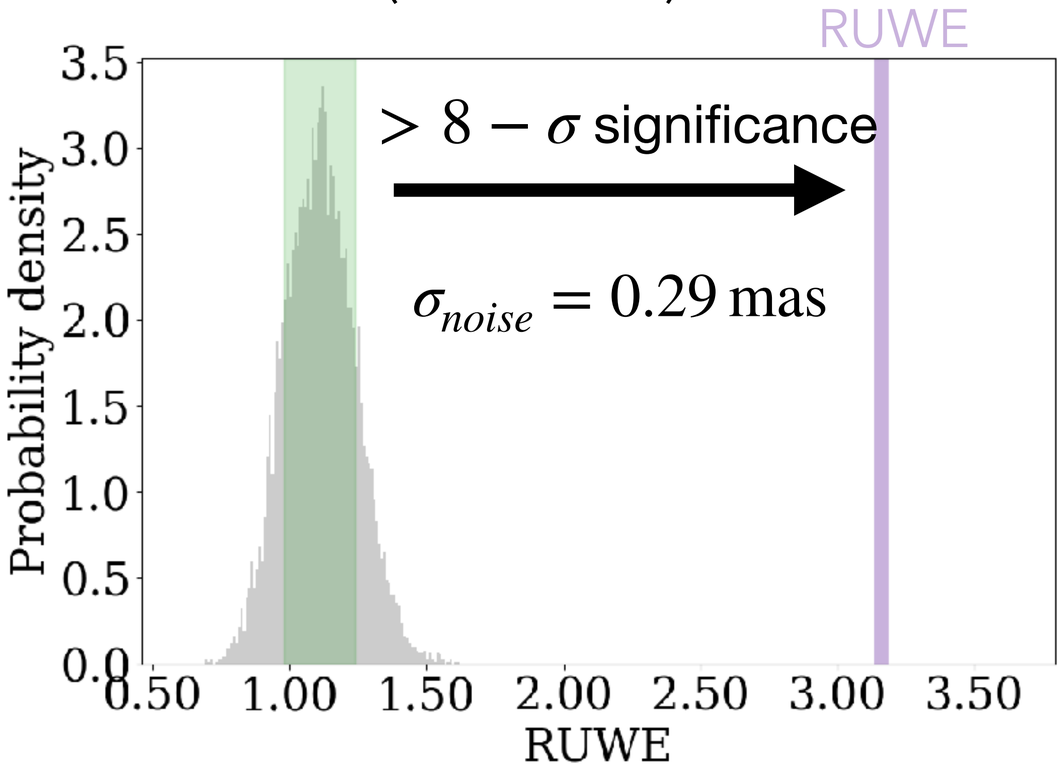
If smaller than the limit for fusion of Deuterium <13.5 M_{Jup}

planet candidate

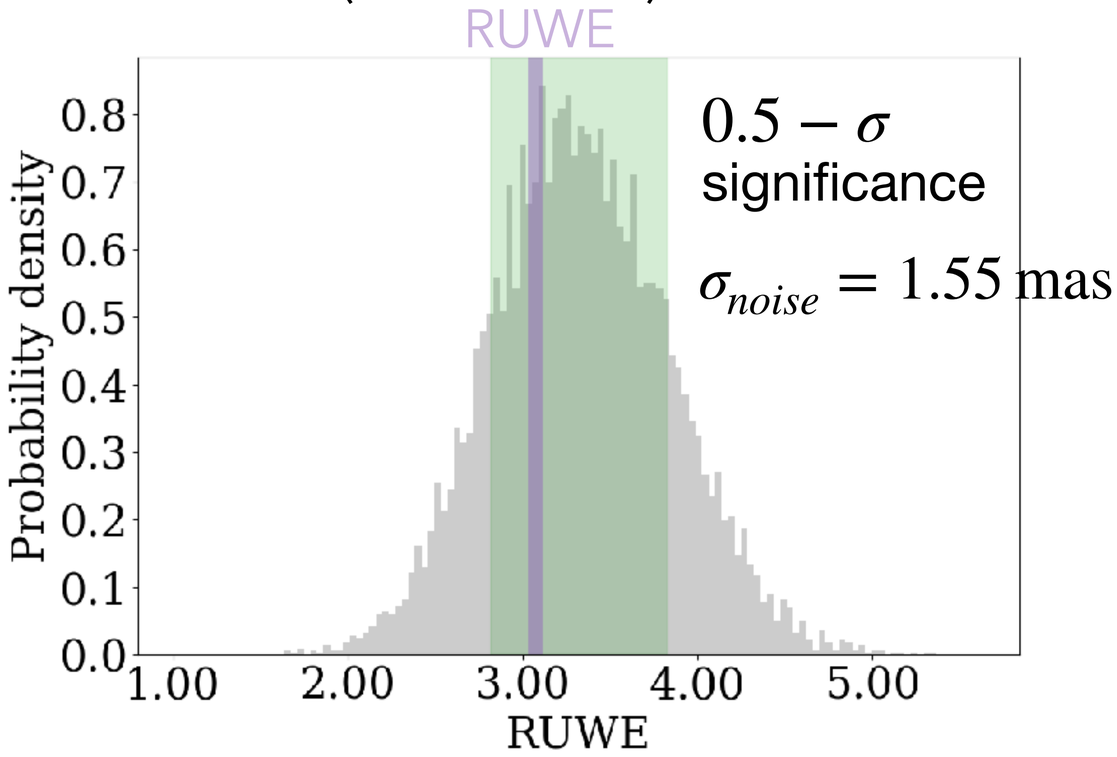
Kiefer, Lagrange+ 2024 Paper I

The significance: RUWE vs. the single stars hypothesis

HD 114762 (RUWE=3.1)



Beta Pic (RUWE = 3.0)



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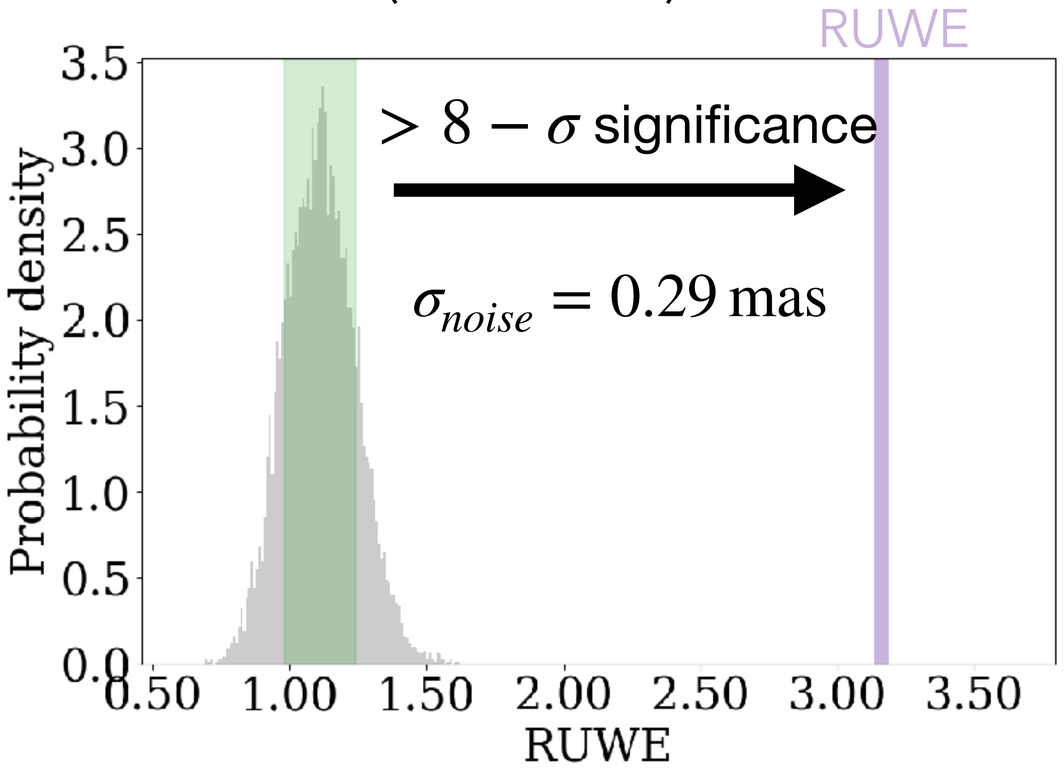

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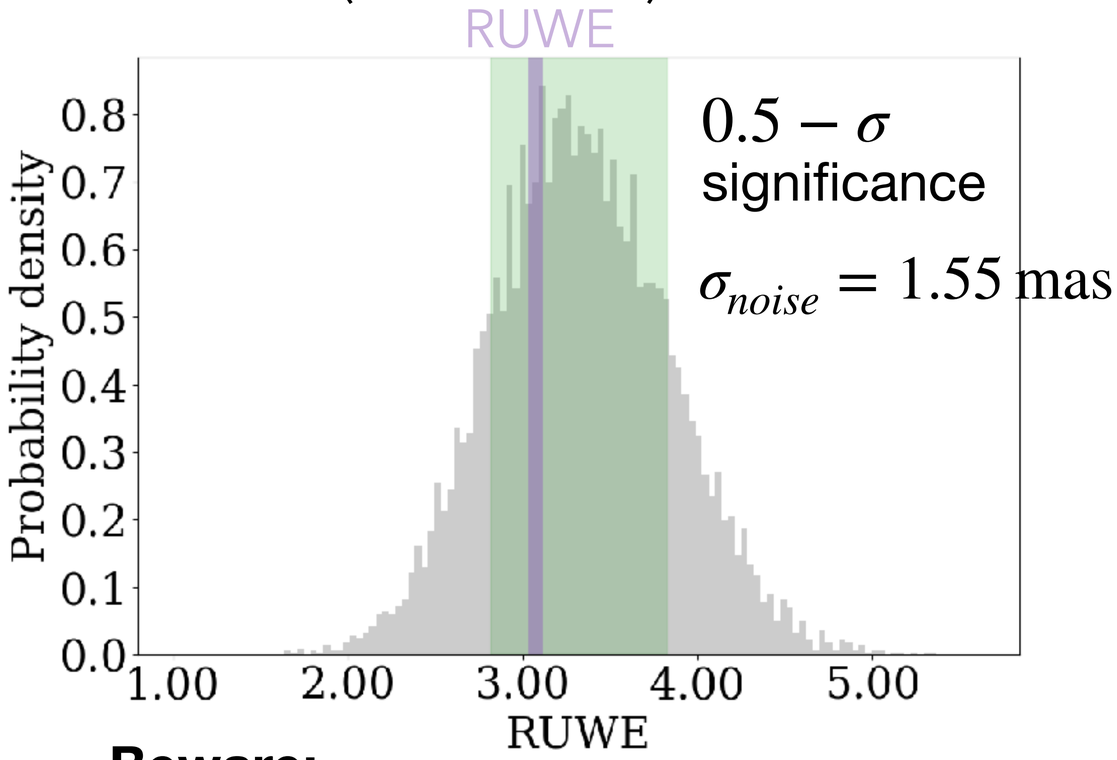
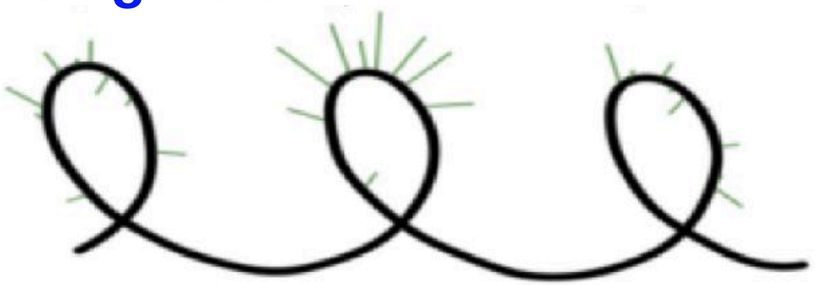


Beware:

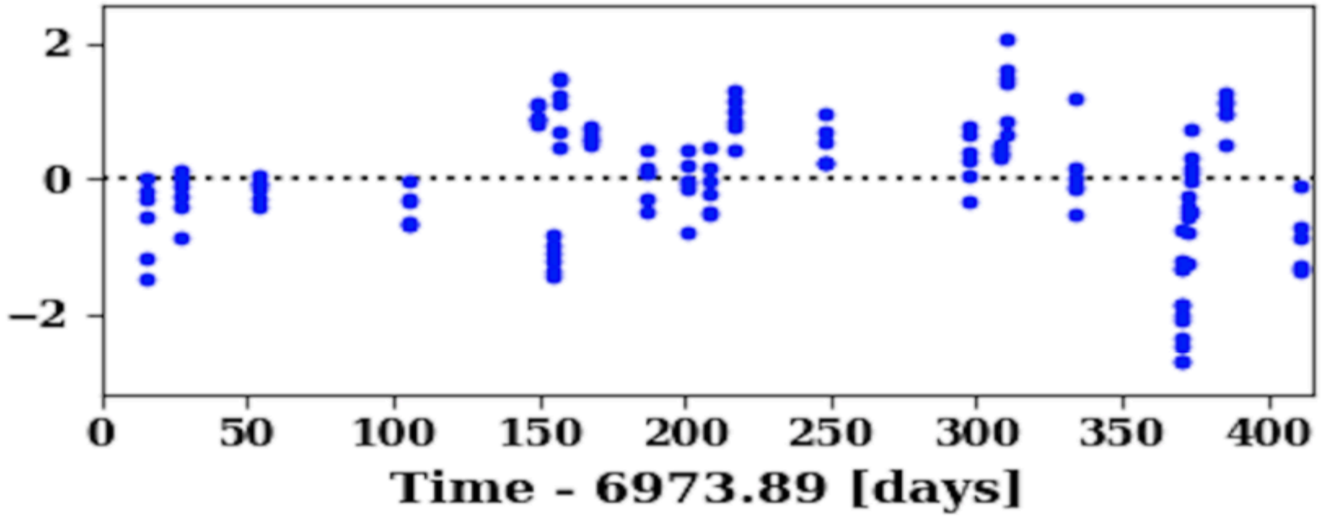
- Higher instrumental astrometric noise!
- RUWE cannot be interpreted without knowkedge of instrumental noise

Astrometric signature and the RUWE

Single star



5p fit residuals difference



$$\mathrm{V(residuals)} = \sigma^2_{noise}$$

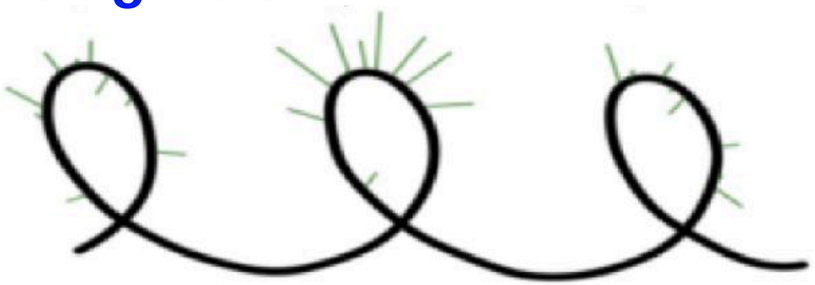
Kiefer+ 2019, 2021

Kiefer+ 2024

Lagrange+ 2024

Astrometric signature and the RUWE

Single star



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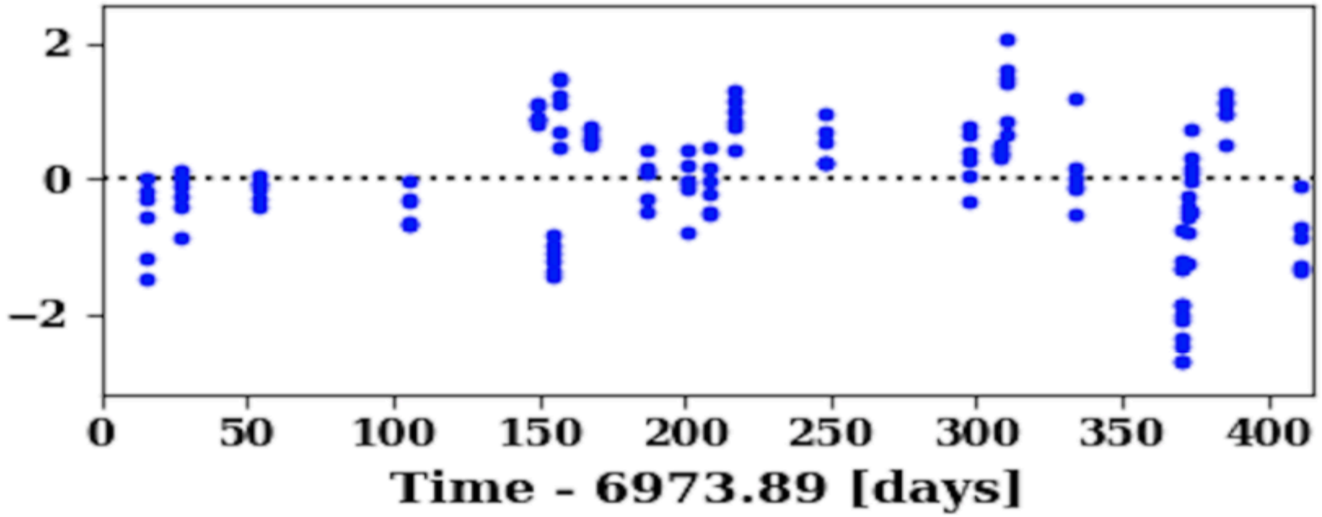


$$\mathrm{V(residuals)} = \sigma^2_{noise}$$

$$\mathrm{RUWE} = \sqrt{\chi^2_r} \approx 1$$

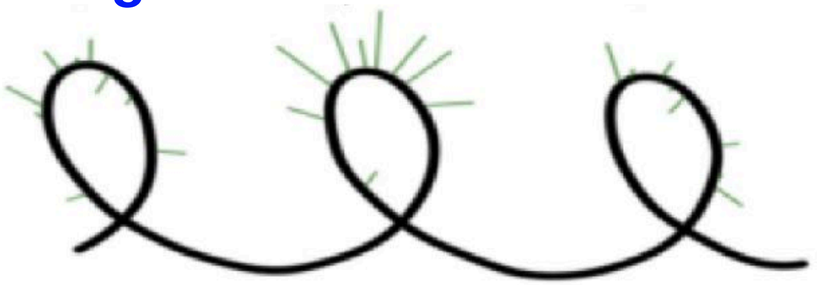
Kiefer+ 2019, 2021

Kiefer+ 2024

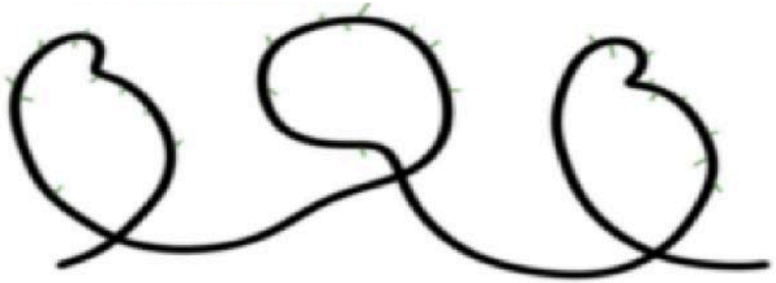
Lagrange+ 2024

Astrometric signature and the RUWE

Single star

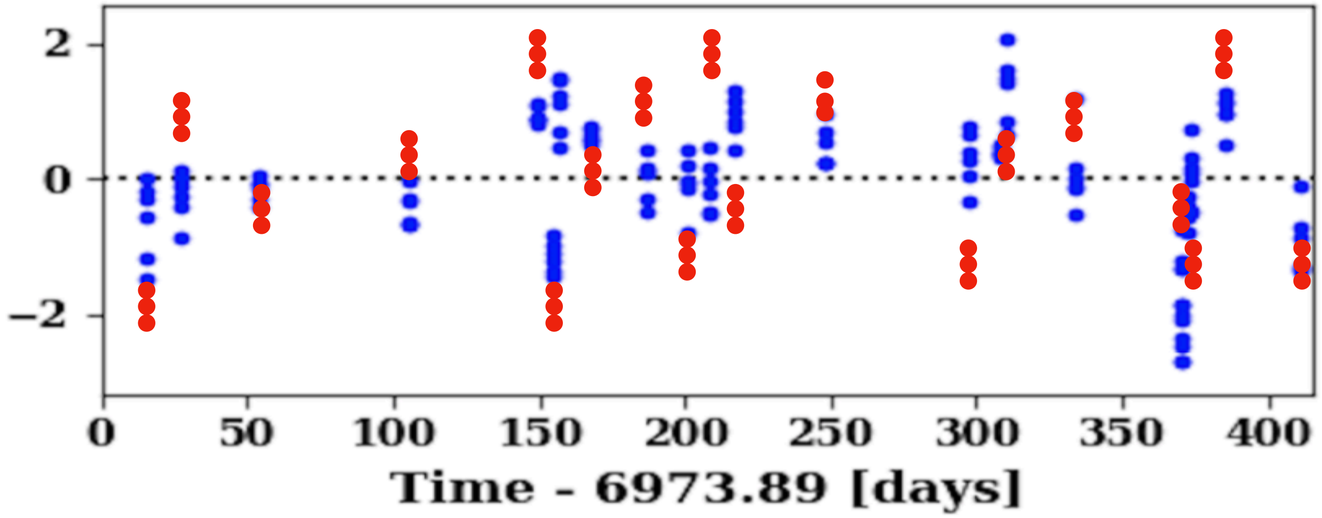


Star w/ companion



Kiefer+ 2019, 2021
Kiefer+ 2024
Lagrange+ 2024

5p fit residuals difference



$$\mathrm{RUWE} = \sqrt{\chi_r^2} \approx 1$$

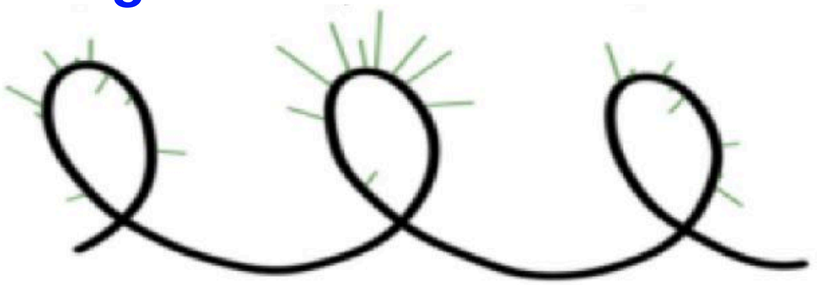
> 1

$$\mathrm{V(residuals)} = \sigma_{noise}^2 + \alpha_{astro}^2$$

Astrometric signature

Astrometric signature and the RUWE

Single star



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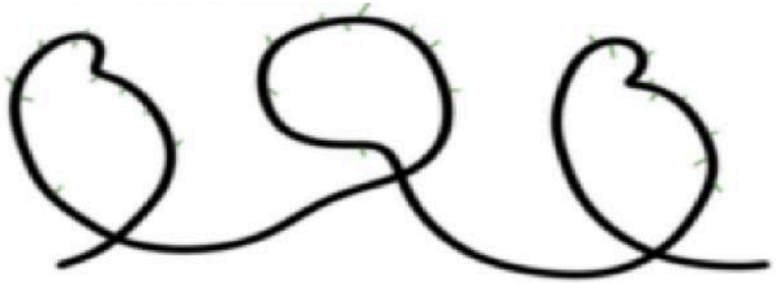

Kiefer+ 2019, 2021
Kiefer+ 2024
Lagrange+ 2024

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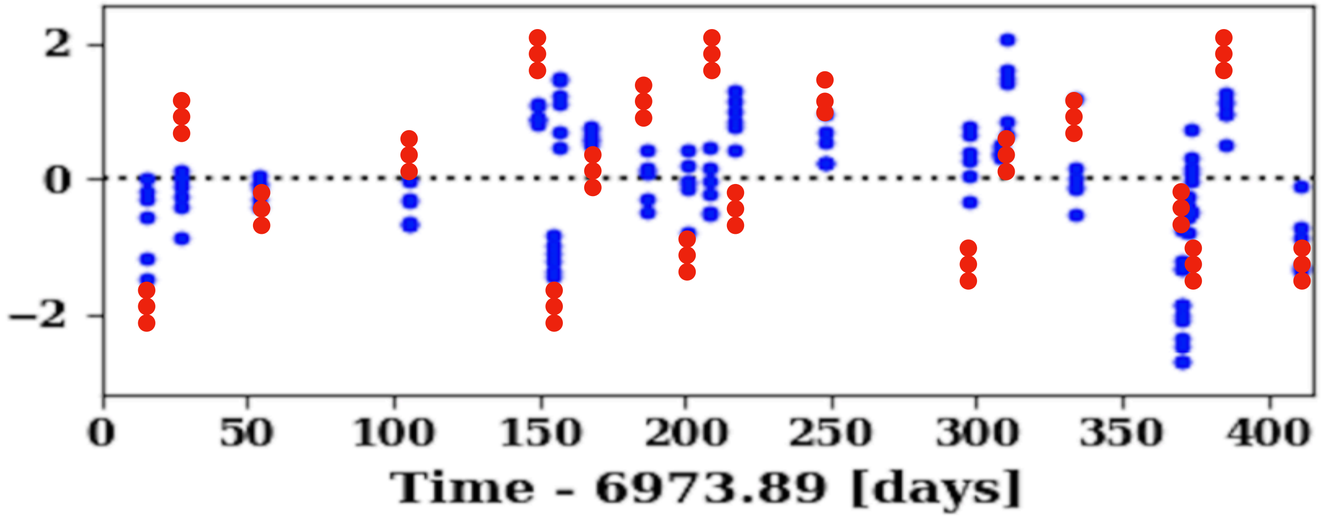

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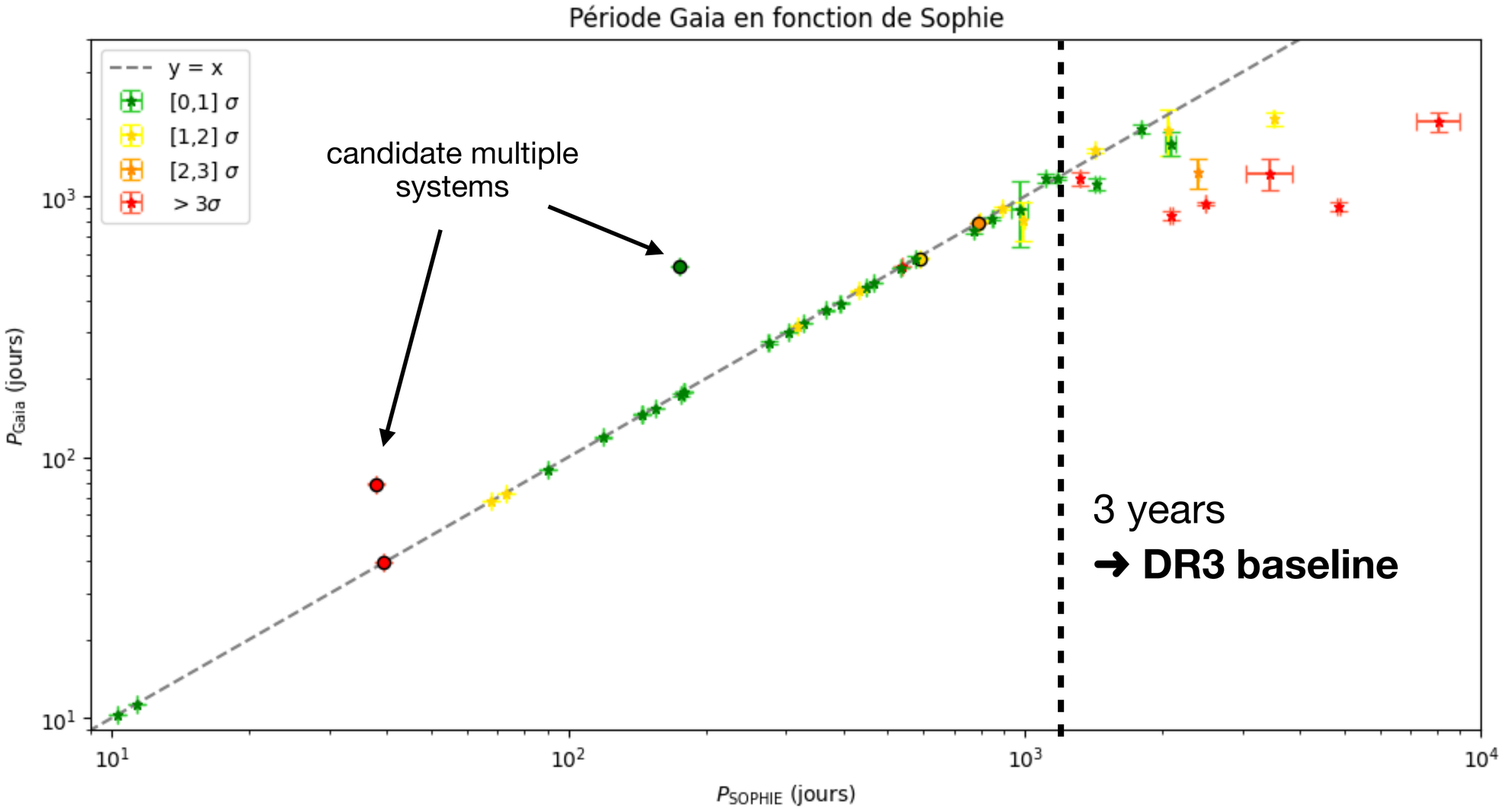
modeled for any star at
G<16 and -1 < *Bp* - *Rp* < 8
using AEN & RUWE
~ 0.07-1 mas

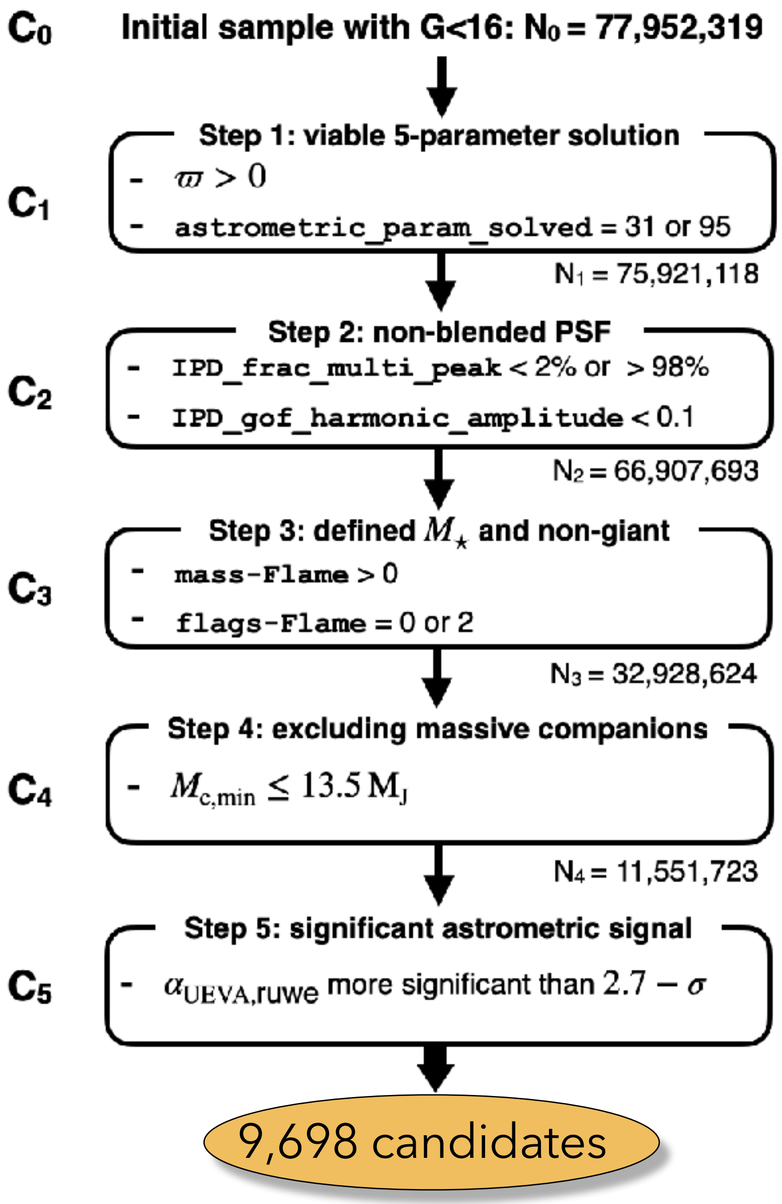
Astrometric signature

Comparing SOPHIE to Gaia-NSS results

M1 student: Eva Bianchi



A step by step selection of planet-candidate hosting systems



Removing 2p solutions

Issue with PSF blending
e.g. Holl et al. 2023

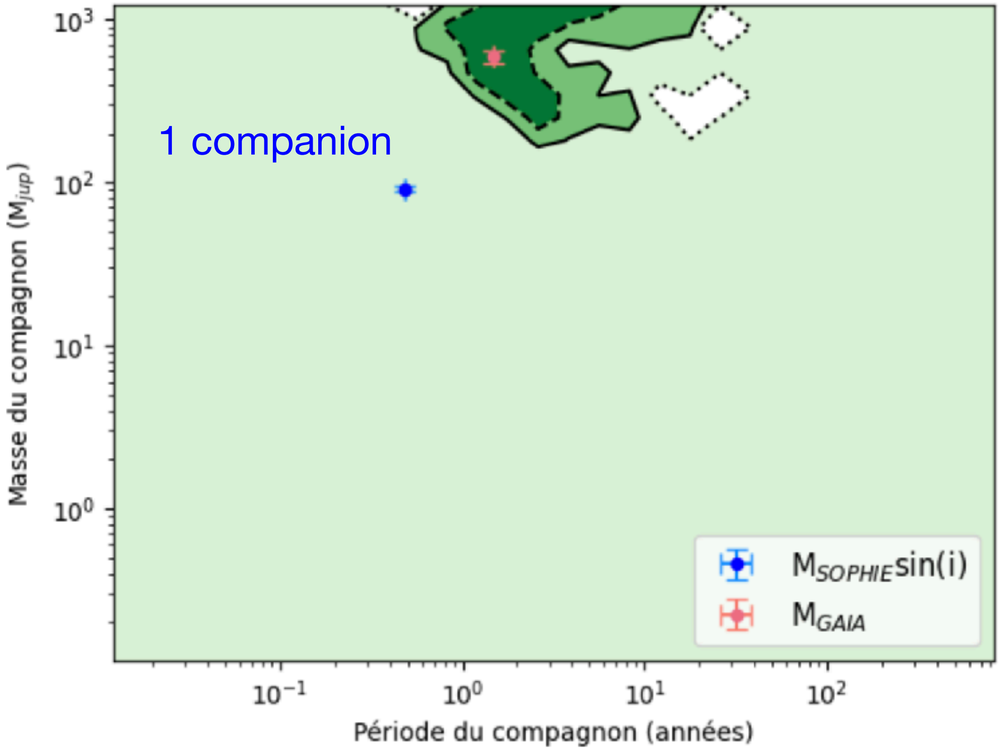
Using Gaia $M_\star > 0.5\,M_\odot$
(Gaia coll.), Creevey et al. 2023

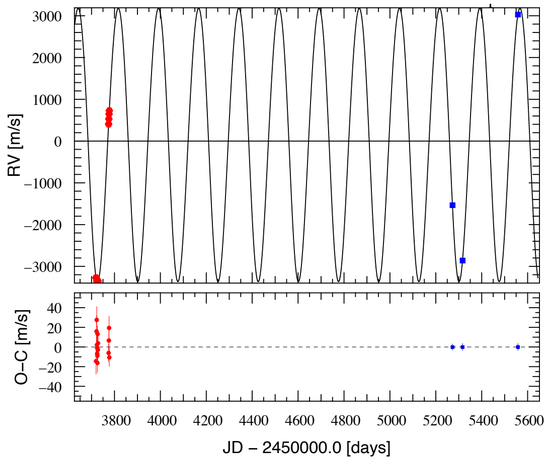
Keep level of false-positive < 10%

Kiefer, Lagrange+ 2024, paper II

Impact of Gaia on identifying multiple systems

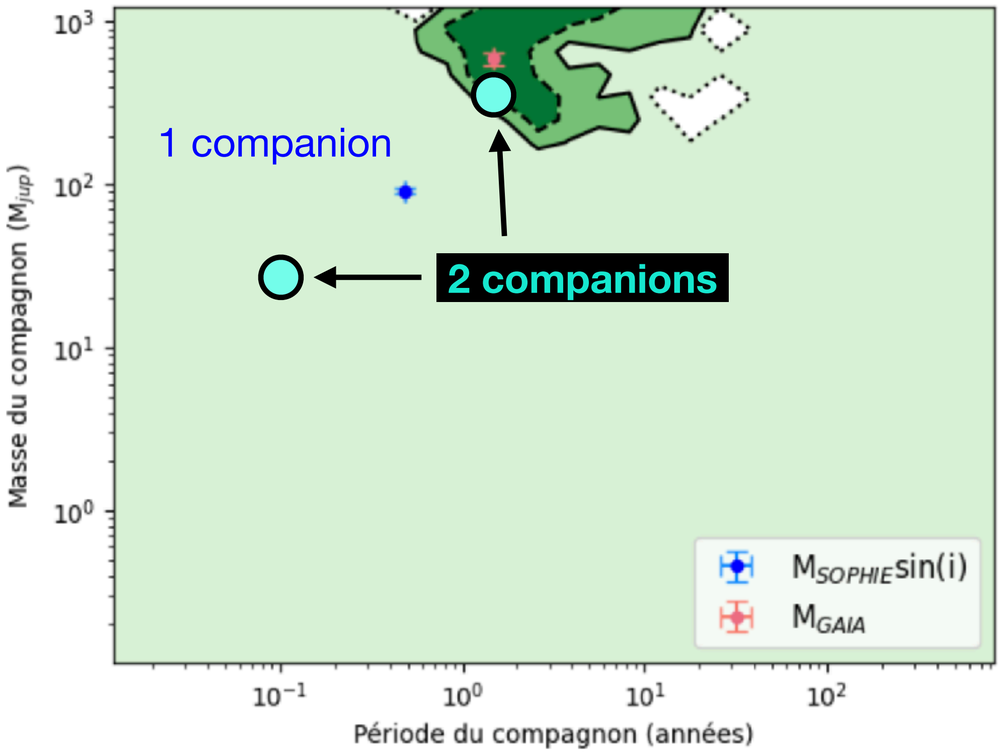
M1 student
E. Bianchi

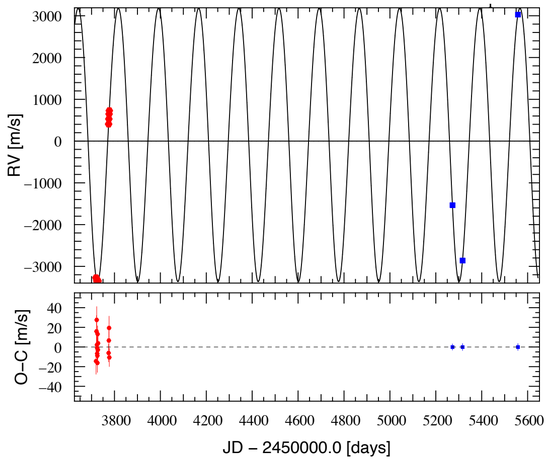


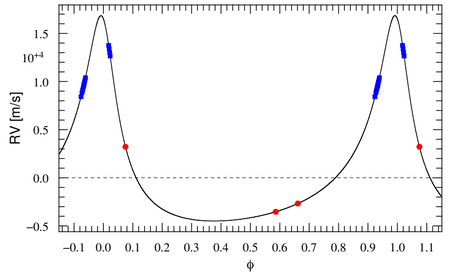


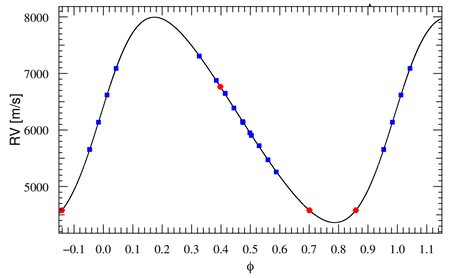
Kiefer+ *in prep.*

Impact of Gaia on identifying multiple systems



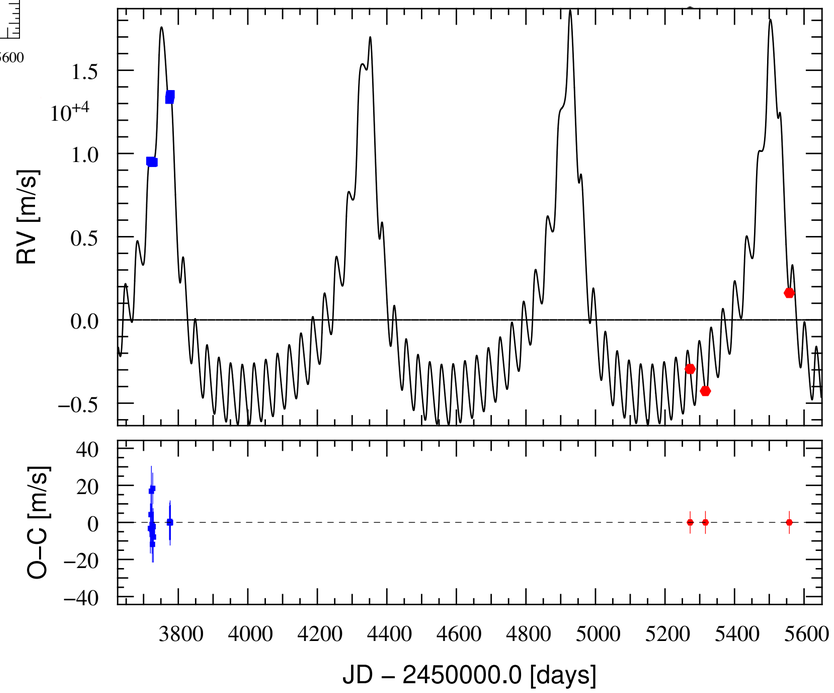






No RV solution at P_{Gaia}:

considering 2 companions



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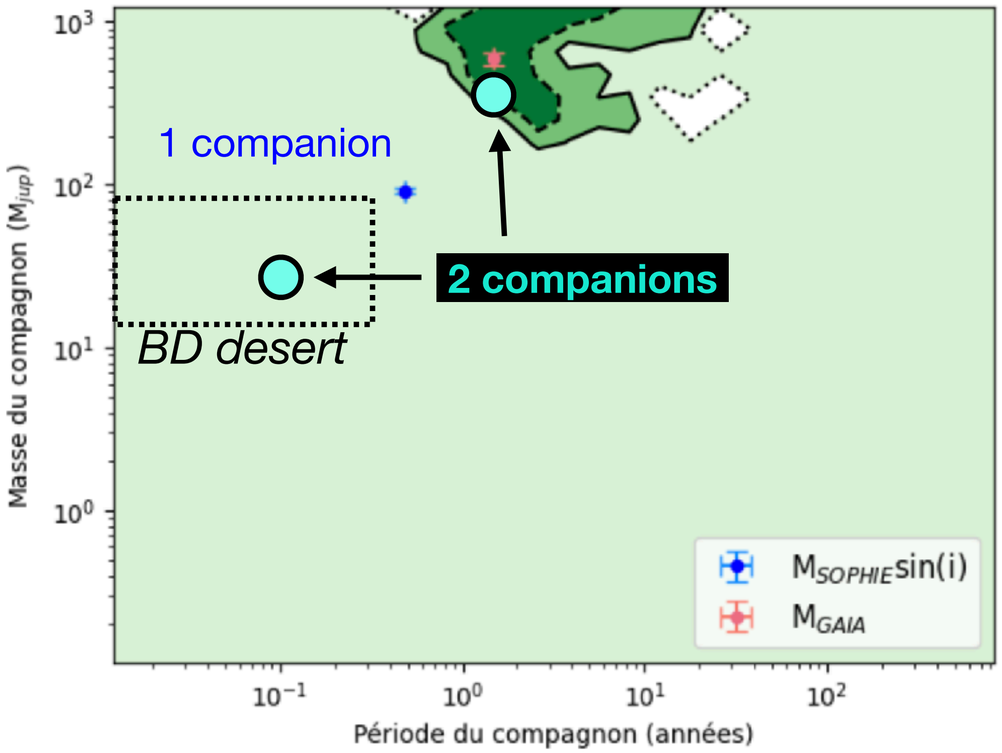
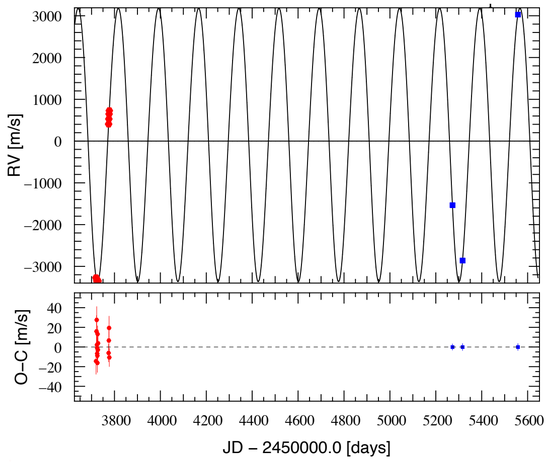
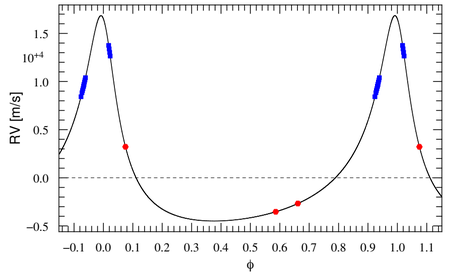
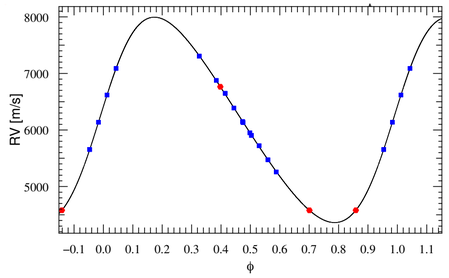
Impact of Gaia on identifying multiple systems



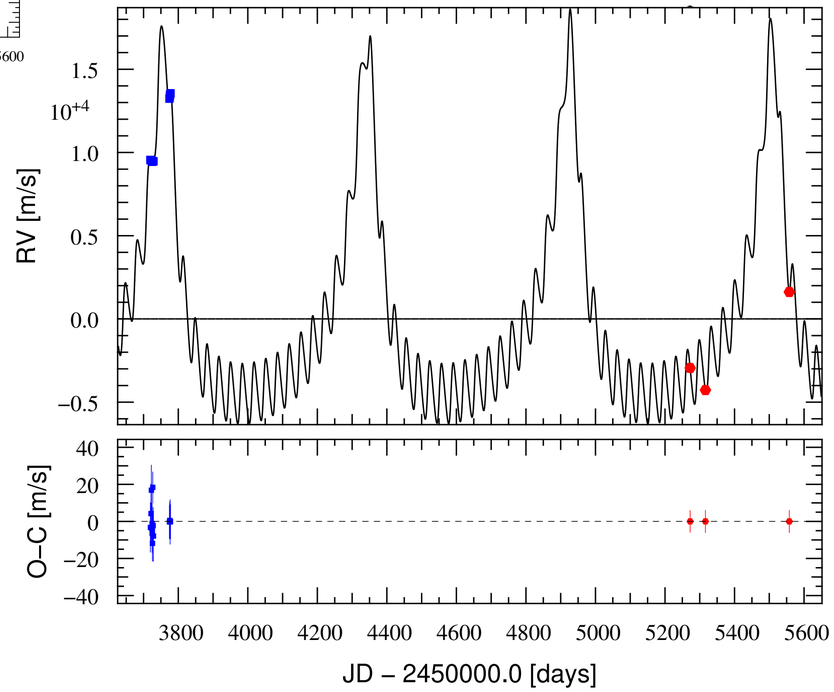






No RV solution at P_{Gaia}:

considering 2 companions



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