Astrometry and precision radial velocities

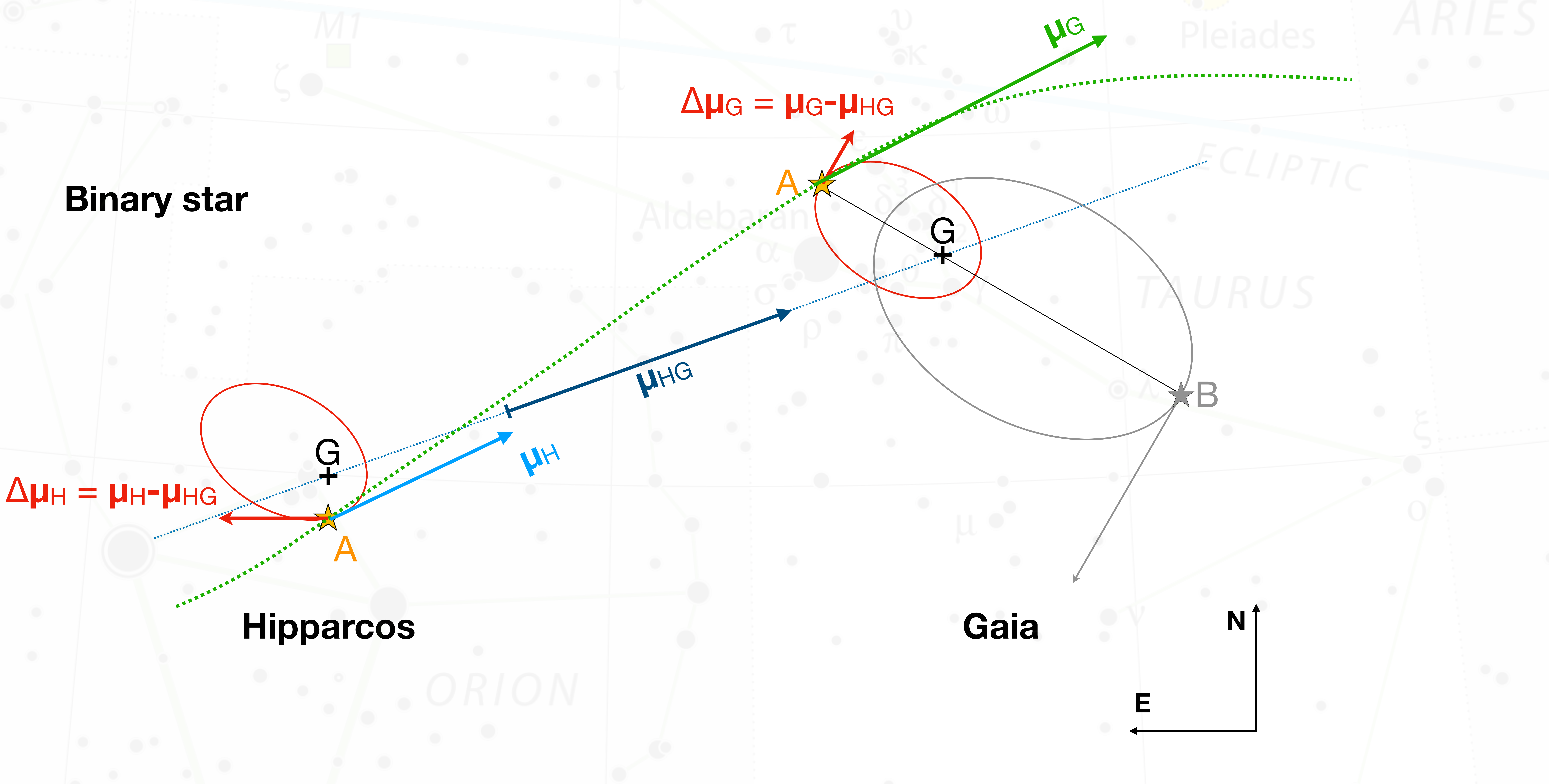
Pierre Kervella
LESIA, Paris Observatory

Overview

- Identification of stellar and substellar companions from Hipparcos - Gaia proper motion anomaly
- Proxima Centauri and other nearby stars: Gaia and radial velocity constraints on exoplanet properties
- GRAVITY astrometry and radial velocities: the β Pictoris system

Proper motion anomaly

Proper motion anomaly



- Sensitivity in companion mass:

$$\frac{m_2}{\sqrt{r}} = \sqrt{\frac{m_1}{G}}\, v_1 = \sqrt{\frac{m_1}{G}} \left(\frac{\Delta\mu[\mathrm{mas\,a^{-1}}]}{\varpi[\mathrm{mas\,au^{-1}}]} \times 4740.470 \right)$$

Gaia DR2

$$\sigma(\Delta\mu_{\mathrm{G2}}) = 234\ \mu\mathrm{as\,a^{-1}}$$

$$\sigma(\Delta v_{\mathrm{tan,G2}}) = 1.1\ \mathrm{m\,s^{-1}\,pc^{-1}}$$

$$\sigma(m_2^{5\,\mathrm{au}})_{m_1=M_\odot} = 40\ \mathrm{M_\oplus\,pc^{-1}}$$

Gaia (E)DR3

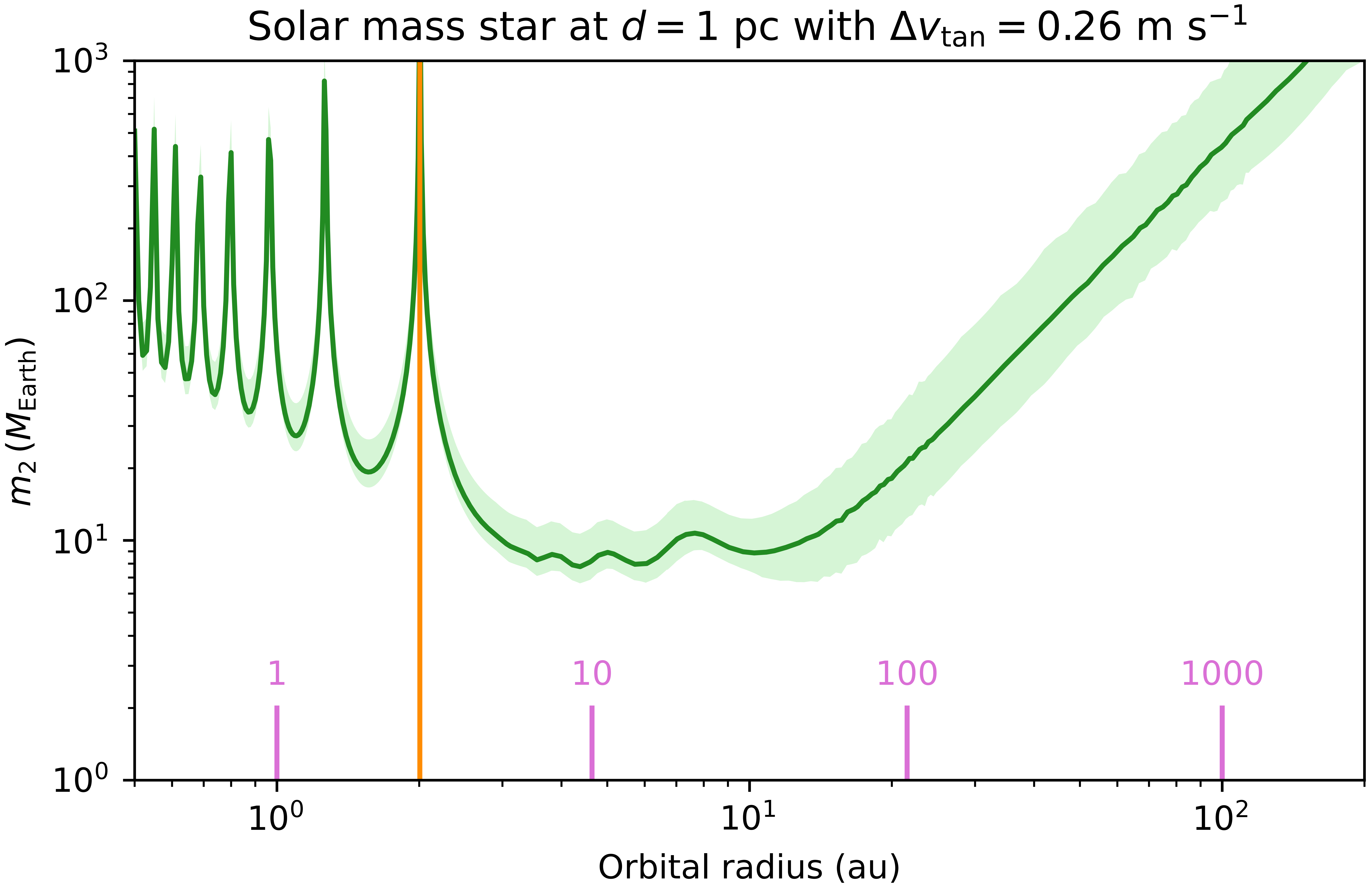
$$\sigma(\Delta\mu_{\mathrm{G3}}) = 56\ \mu\mathrm{as\,a^{-1}}$$

$$\sigma(\Delta v_{\mathrm{tan,G3}}) = 0.26\ \mathrm{m\,s^{-1}\,pc^{-1}}$$

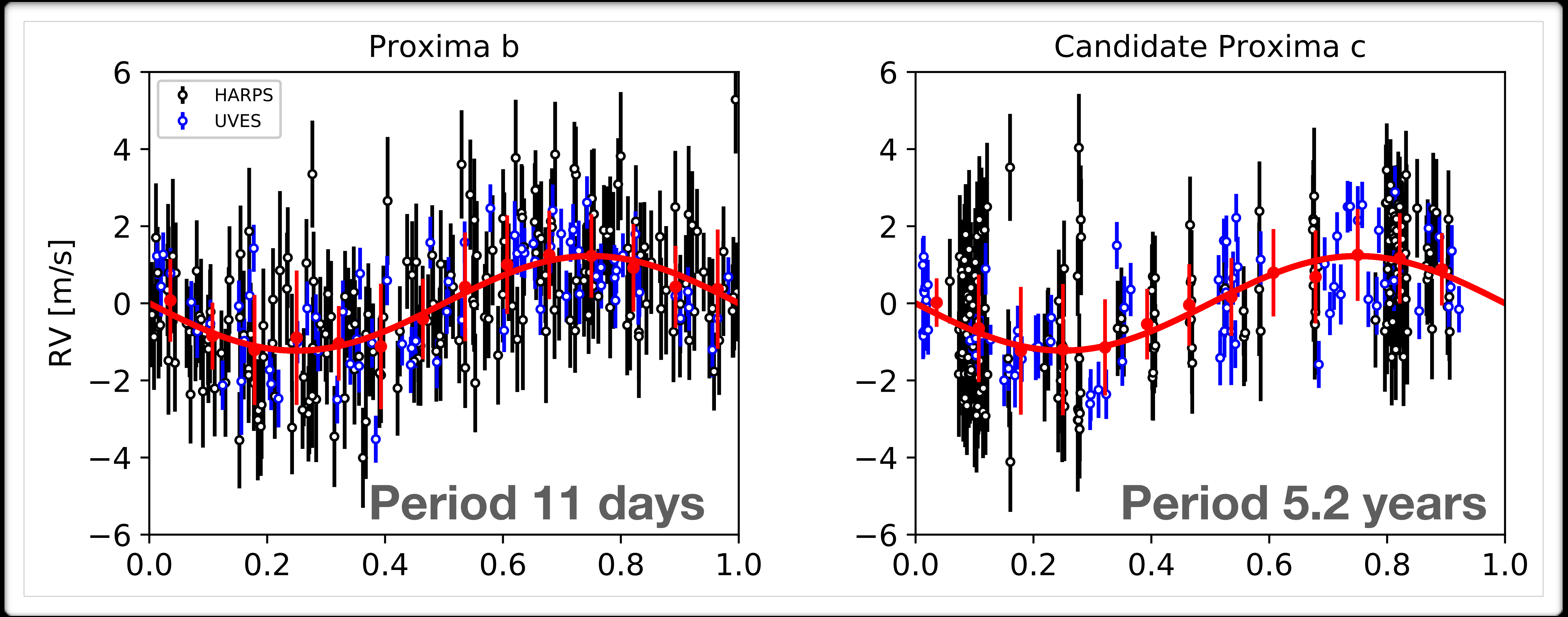
$$\sigma(m_2^{5\,\mathrm{au}})_{m_1=M_\odot} = 10\ \mathrm{M_\oplus\,pc^{-1}}$$

- The sensitivity of the PMa technique decreases with the distance to the target

PMa sensitivity curve



A long-period planet orbiting Proxima Centauri ?



Damasso et al. 2020, Science Advances, 6, 3

Proxima Centauri

Radial velocities incl. grav. redshift and acceleration of +0.45 m/s/a:
RV measur. 2012.554 -22204 (32) m/s (Kervella+ 2017)

Parallaxes:

Hip2	1991.250	771.640 (2.600)	mas	(observed)
Hip2 calc	1991.250	767.757 (0.056)	mas	(derived from Gaia plx)
GDR2	2015.500	768.529 (0.220)	mas	(observed)
EDR3 ZP		-0.022	mas	Plx err inflation: 1.127
EDR3	2016.000	768.089 (0.056)	mas	(observed)

GDR3 to Hip light travel time correction = +0.670 d (115.9 au)

Measured PM vector in ICRS frame:

Hip2	1991.250	-3775.750 (1.630)	+765.540 (2.010)	mas/a	
GDR2	2015.500	-3781.411 (0.101)	+769.804 (0.208)	mas/a	
EDR3 spin		-0.036	+0.016	mas/a	
EDR3	2016.000	-3781.705 (0.031)	+769.449 (0.051)	mas/a	(spin corrected)

Computed (μalpha,μdelta) mean angular PM vector in ICRS frame:

H2G2	2015.500	-3781.629 (0.049)	+769.421 (0.054)	mas/a
H2G3	2016.000	-3781.683 (0.034)	+769.518 (0.046)	mas/a

Computed diff. PM vector in ICRS frame:

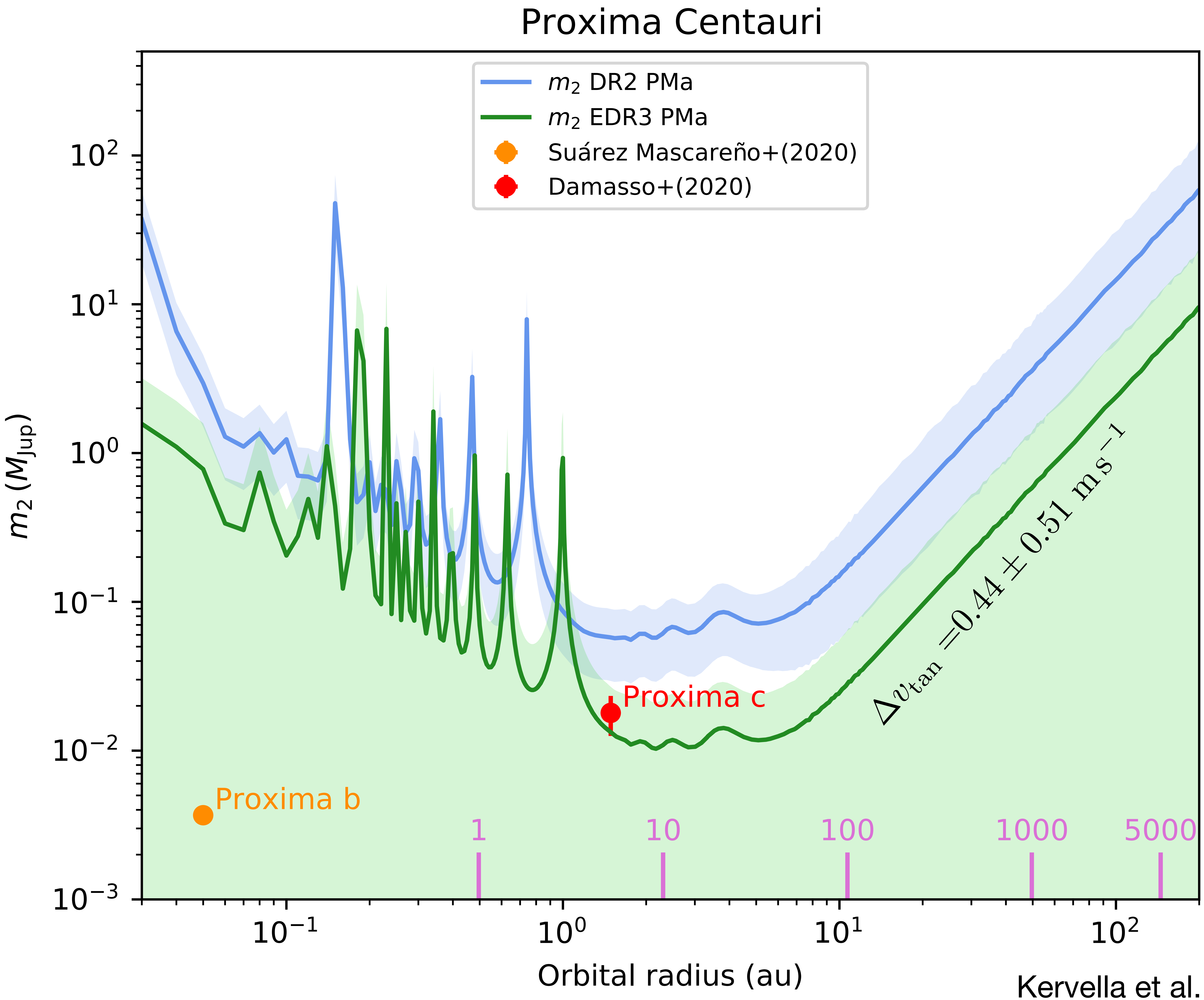
GDR2-H2G2	2015.500	+0.218 (0.112)	+0.384 (0.215)	mas/a	= (+1.9,+1.8) sig
GDR3-H2G3	2016.000	-0.022 (0.046)	-0.069 (0.069)	mas/a	= (-0.5,-1.0) sig

2D transverse velocity residual   G2-H2G2 :[+1.34 (0.69),   +2.37 (1.33)] m/s

Transverse velocity residual norm G2-H2G2 :   2.72 (1.50) m/s   SNR: 1.82

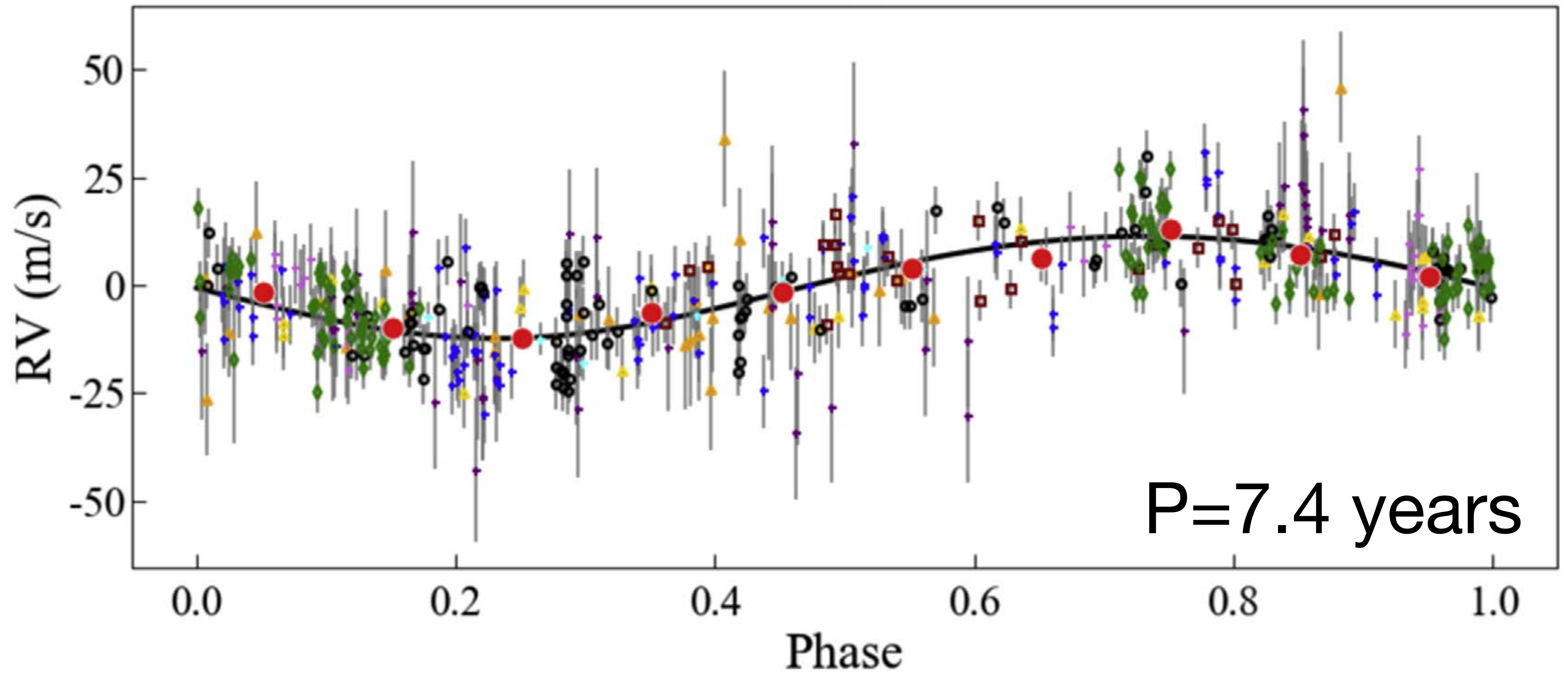
2D transverse velocity residual   G3-H2G3 :[-0.14 (0.28),   -0.42 (0.42)] m/s

Transverse velocity residual norm G3-H2G3 :   0.44 (0.51) m/s   SNR: 0.87

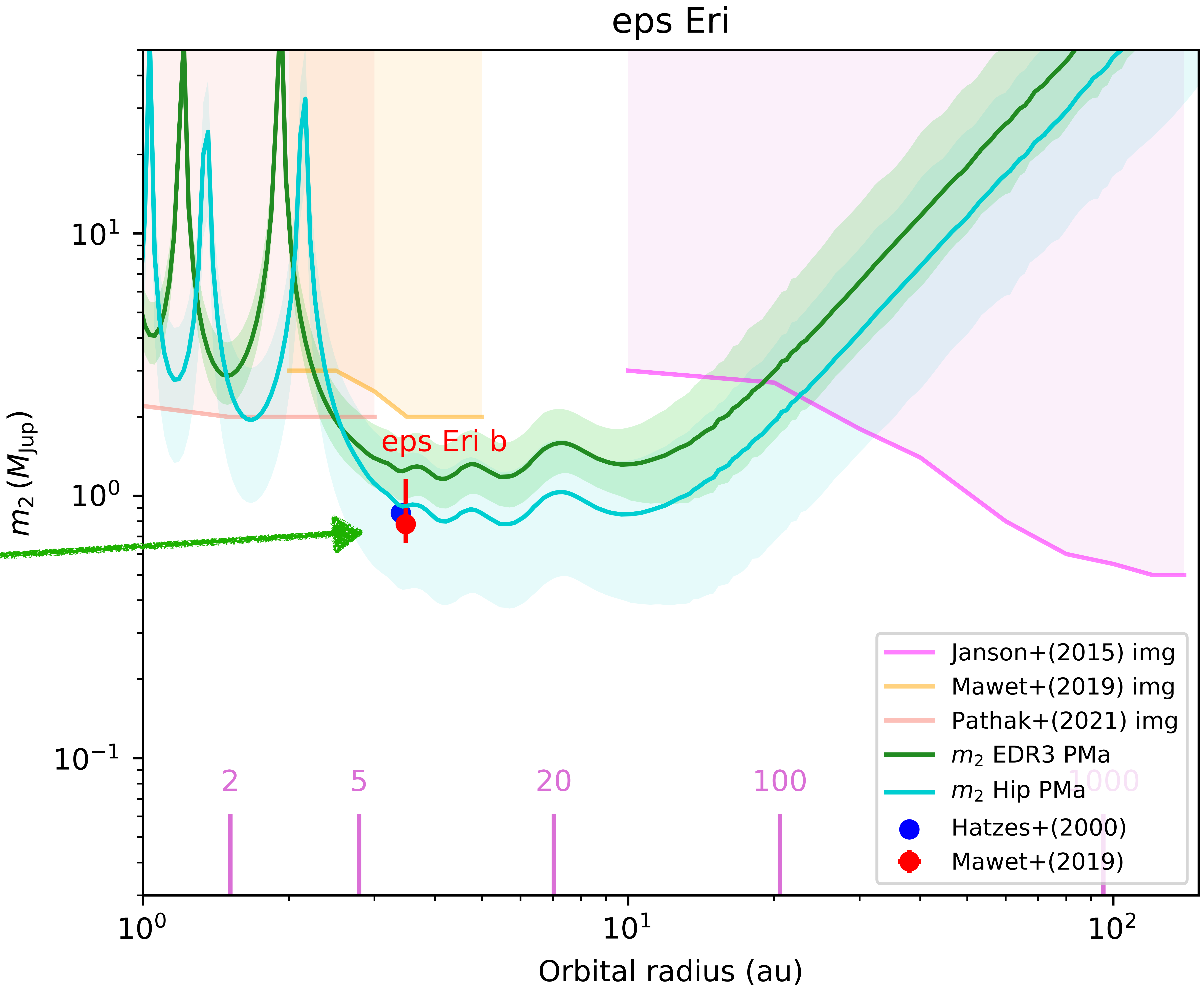


Kervella et al. 2022, A&A, 657, A7

ε Eridani

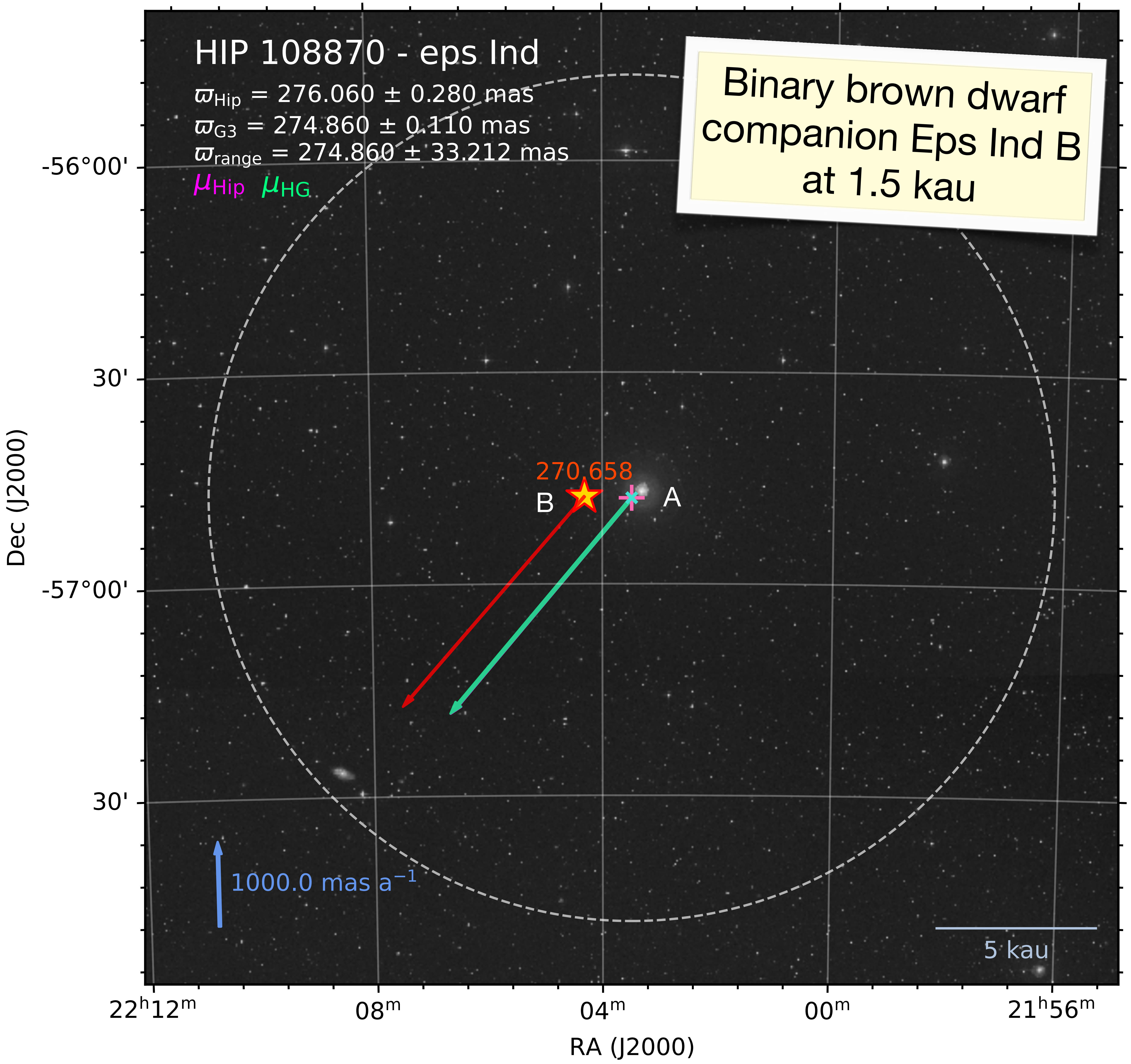


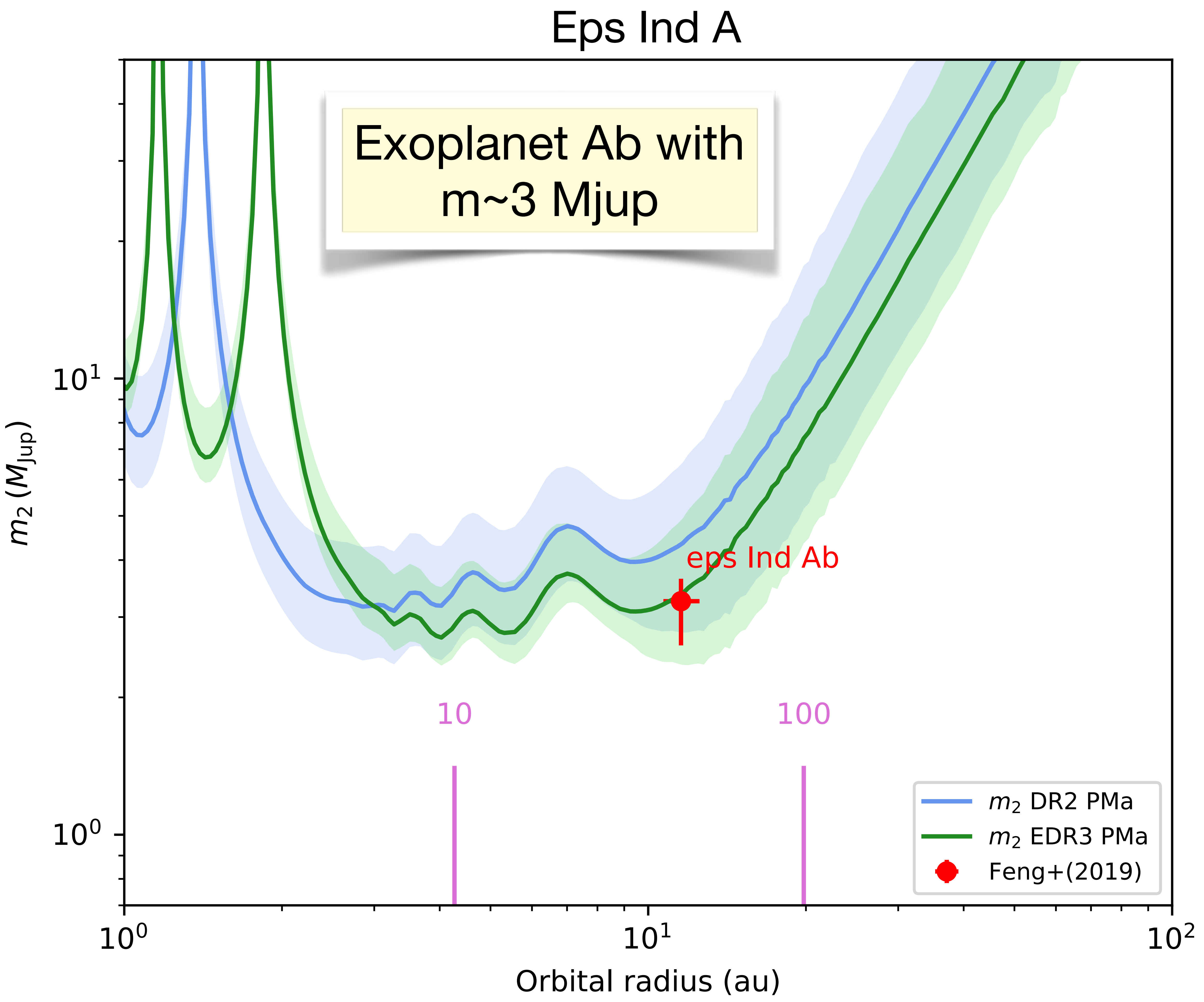
Mawet et al. 2019, AJ, 157, 33



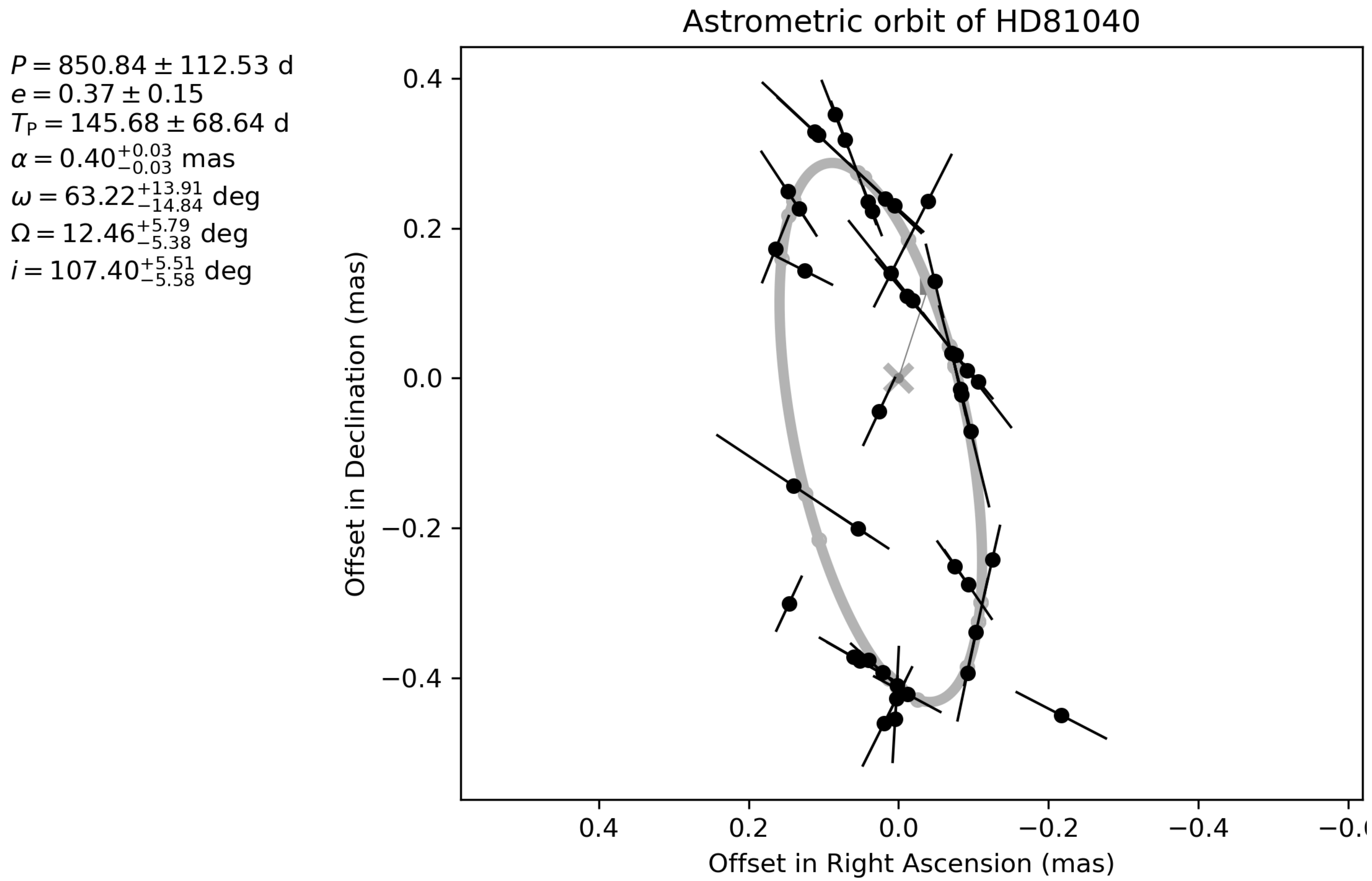
Kervella et al. 2022, A&A, 657, A7

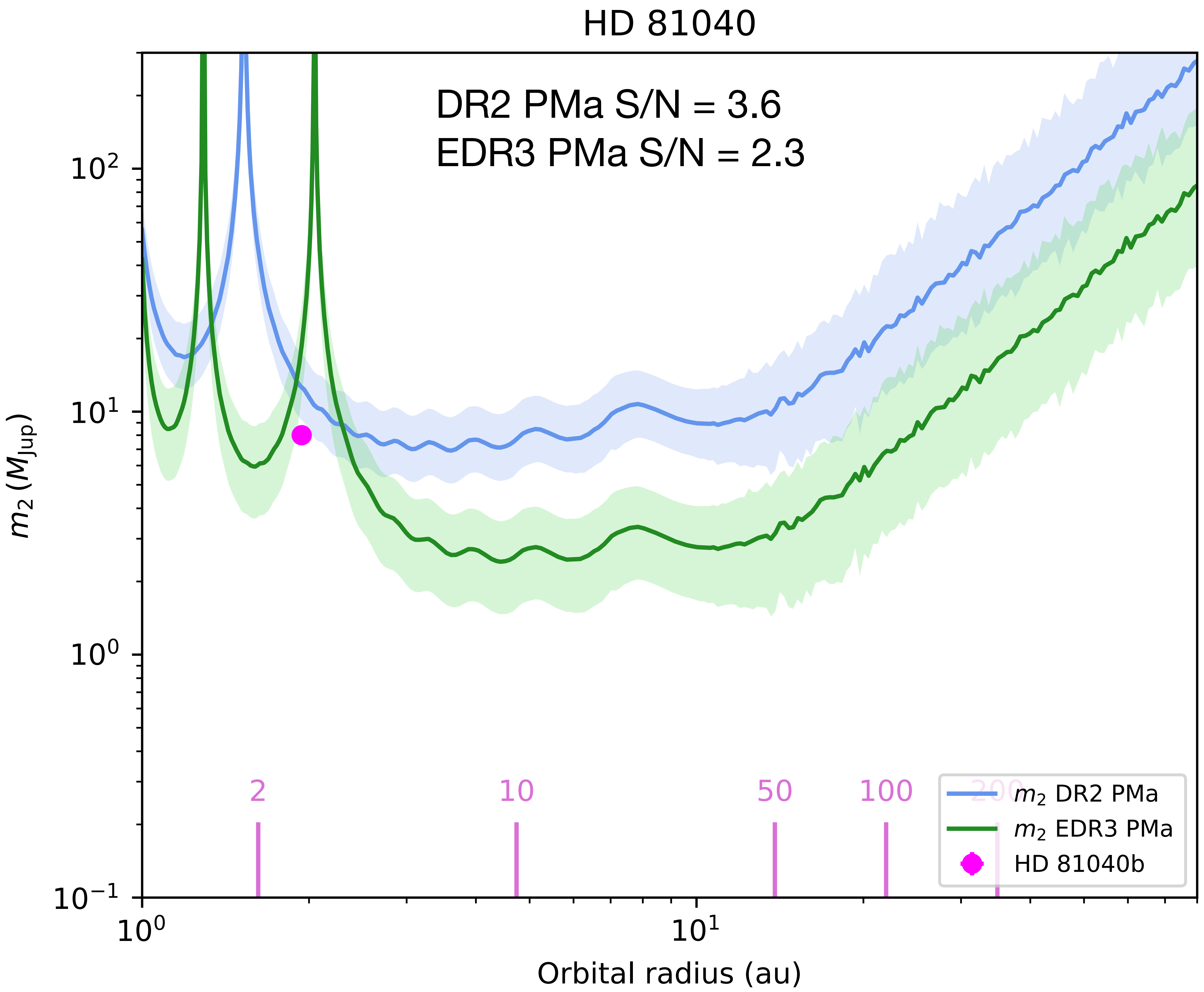
Epsilon Ind


HIP 108870 - eps Ind
ϖ_{Hip} = 276.060 ± 0.280 mas
ϖ_{G3} = 274.860 ± 0.110 mas
ϖ_{range} = 274.860 ± 33.212 mas
μ_{Hip} μ_{HG}
Binary brown dwarf companion Eps Ind B at 1.5 kau
270.658
B
A
1000.0 mas a^{-1}
5 kau
-56°00'
30'
-57°00'
30'
Dec (J2000)
22h12m
08m
04m
00m
21h56m
RA (J2000)


Eps Ind A
Exoplanet Ab with m~3 Mjup
eps Ind Ab
10
100
m_2 DR2 PMa
m_2 EDR3 PMa
Feng+(2019)
m_2 (M_{Jup})
10^1
10^0
10^0
10^1
10^2
Orbital radius (au)

Gaia DR3 NSS exoplanet detection



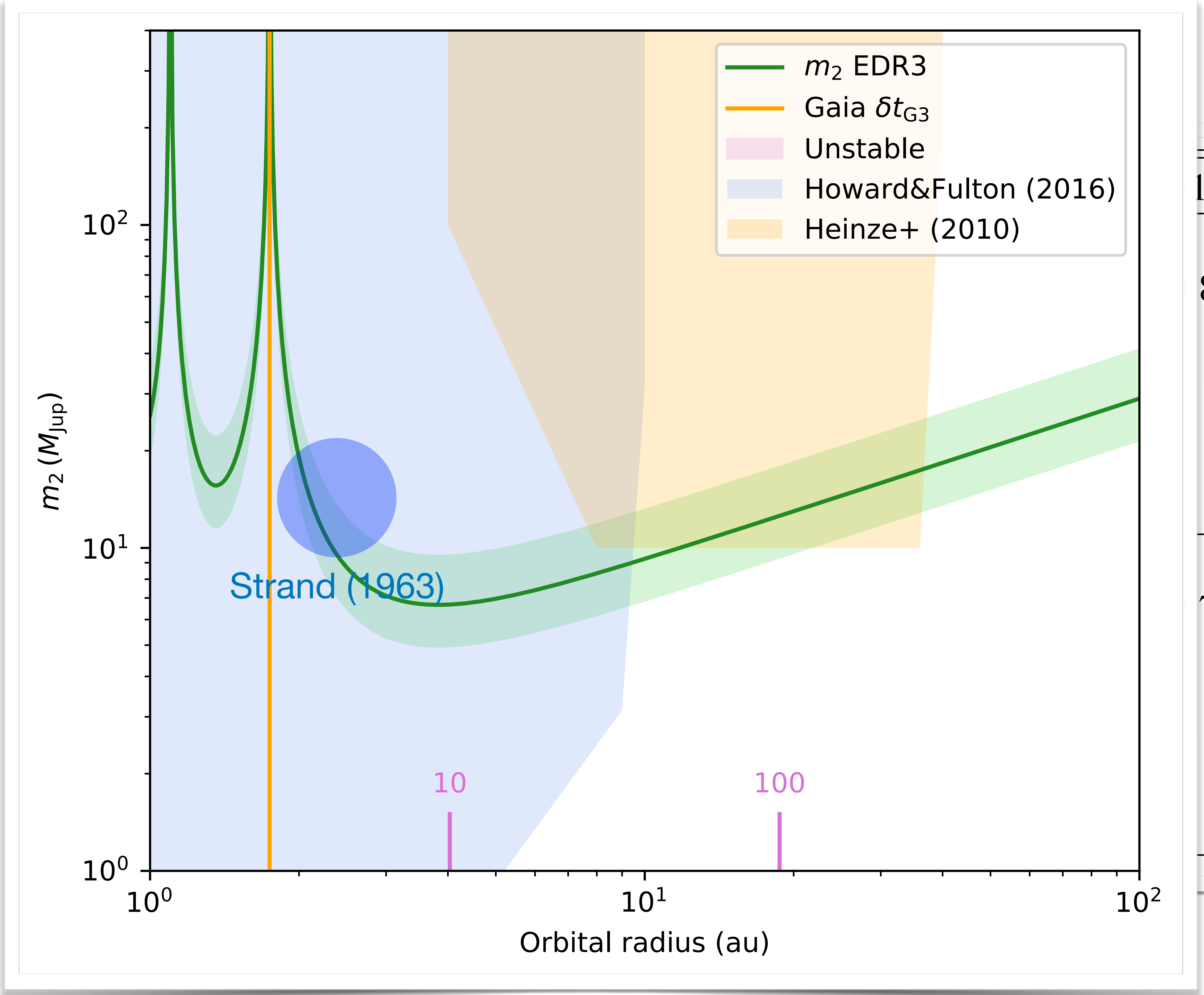


- Astrometric wobble of the star due to its ~ 8 M_J companion (Sozzetti et al. 2006; Stassun et al. 2017; Li et al. 2021) on a ~ 1000 days orbit.

https://www.cosmos.esa.int/web/gaia/iow_20220131

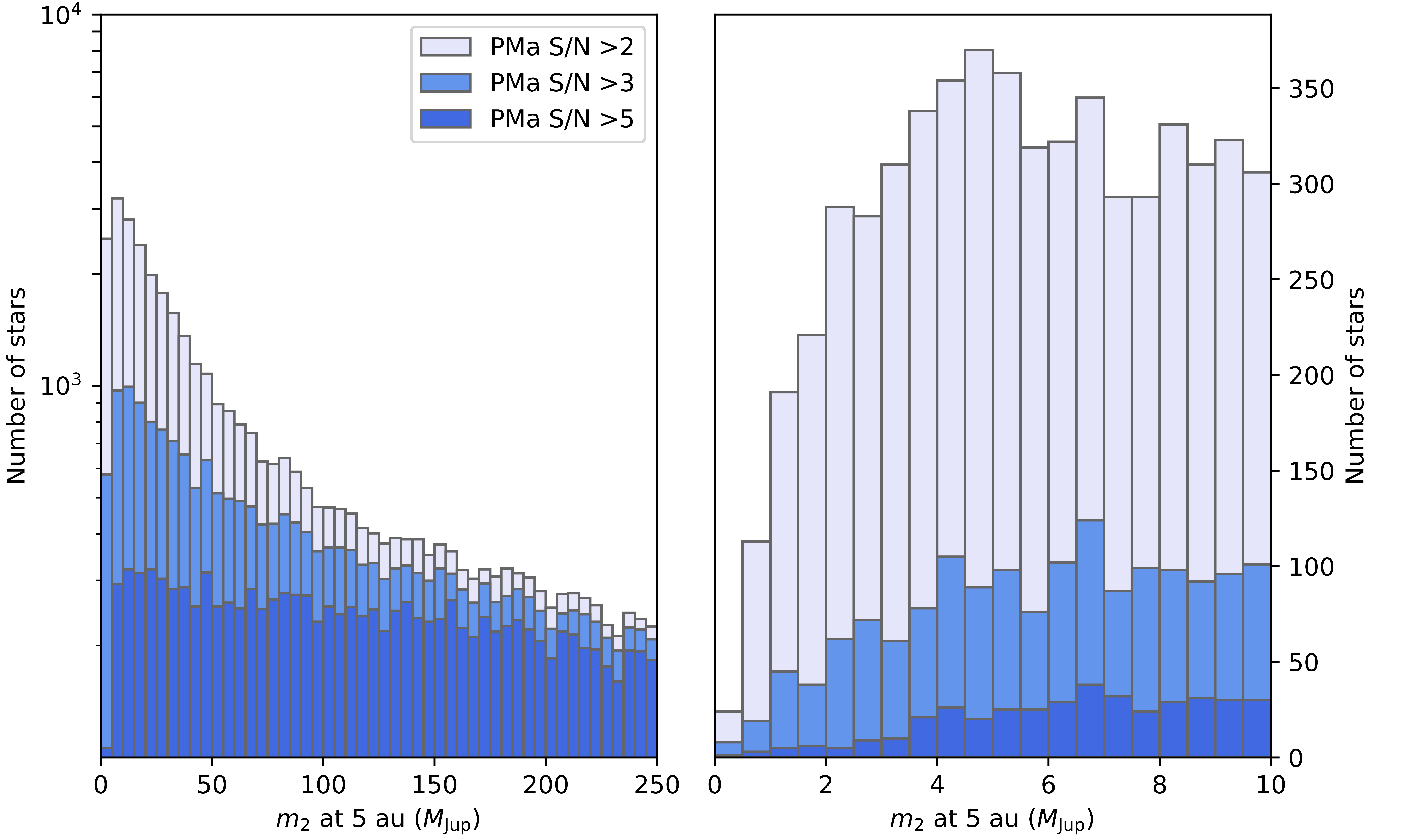
Binary orbital velocity anomaly: example of 61 Cyg AB

Orbital velocity anomaly: example of 61 Cyg AB



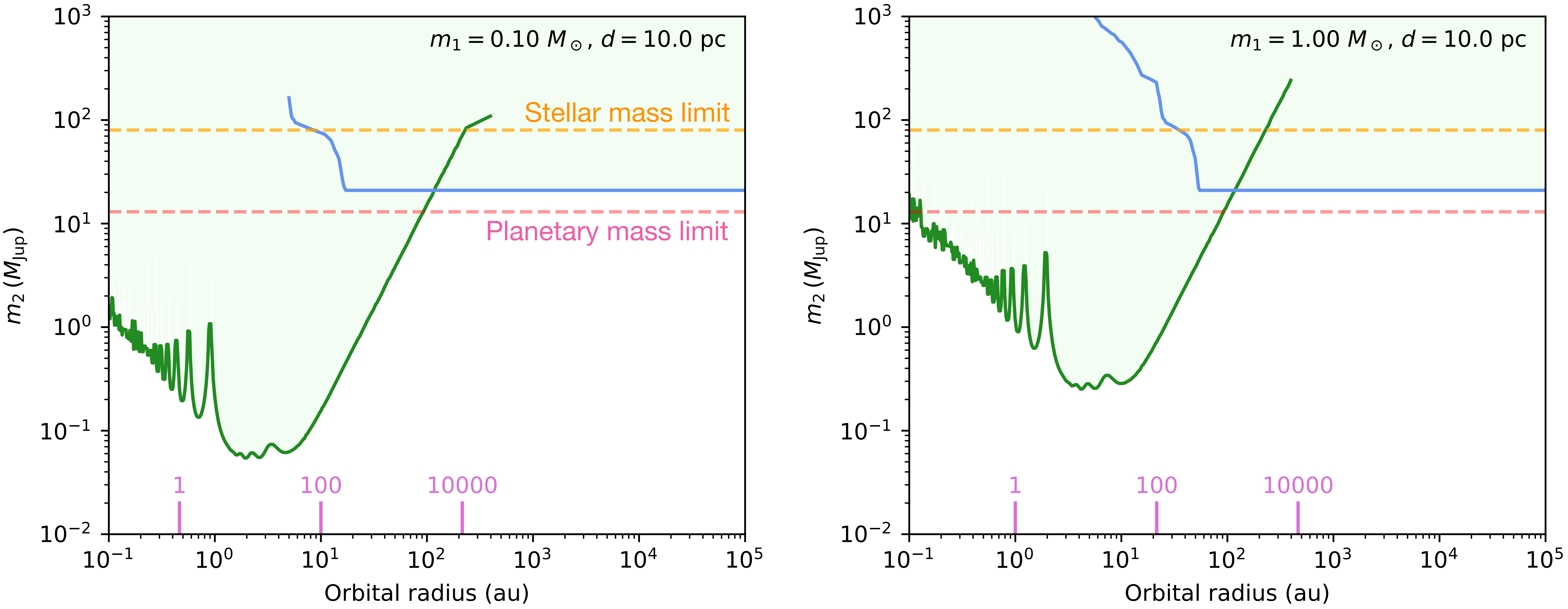
1 Cyg A	61 Cyg B
81, +47.95 ± 0.32)	(−26.85 ± 0.79, −46.28 ± 0.20)
± 0.69 deg	210.12 ± 0.75 deg
3.21 ± 1.01 deg	
(+4.69 ± 1.13, +1.67 ± 0.38) mas a^{-1}	
(+77.7 ± 18.7, +27.7 ± 6.3) m s^{-1}	
87.1 ± 21.2 m s^{-1}, +74.6 ± 6.3 deg	
77, +47.74 ± 0.17)	(−26.74 ± 0.76, −45.93 ± 0.17)
± 0.66 deg	210.21 ± 0.70 deg
3.20 ± 0.96 deg	
(+4.75 ± 1.08, +1.81 ± 0.24) mas a^{-1}	
(+78.7 ± 17.9, +30.0 ± 4.0) m s^{-1}	
88.5 ± 19.8 m s^{-1}, +73.5 ± 5.4 deg	

PMa secondary mass @5au histogram

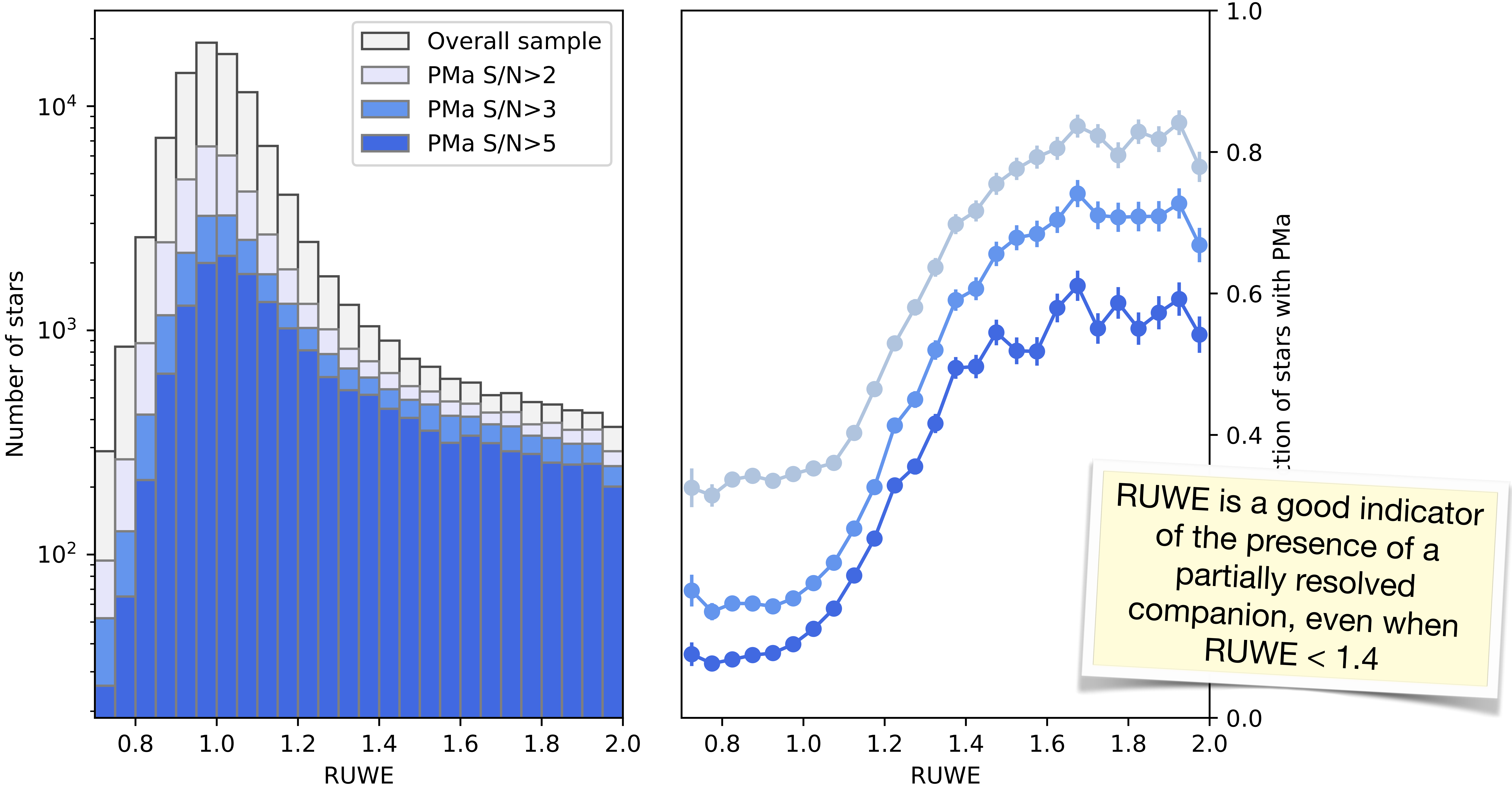


Kervella et al. 2022, A&A, 657, A7

Combined PMa + common proper motion limits



RUWE as an indicator of binarity



Kervella et al. 2022, A&A, 657, A7

Overall statistics for Hipparcos stars

Method	Number of stars	Fraction
Full catalog	117 955	100%
PMa $S/N > 3$	37 347	32%
CPM bound candidates	12 914	11%
RUWE > 1.4	25 067	21%
PMa or CPM	37 347	32%
PMa or CPM or RUWE	50 720	43%

And many other results !

Determining the true mass of radial-velocity exoplanets with Gai

9 planet candidates in the brown-dwarf/stellar regime and 27 confirmed planets

F. Kiefer[1,2], G. Hébrard[1,3], A. Lecavelier des Etangs[1], E. Martioli[1,4], S. Dalal[1], and A. Vidal-Madjar[1]

[1] Institut d'Astrophysique de Paris, Sorbonne Université, CNRS, UMR 7095, 98 bis bd Arago, 75014 Paris, France
[2] LESIA, Observatoire de Paris, Université PSL, CNRS, Sorbonne Université, Université de Paris, 5 place Jules Janssen, 92195 Meudon, France*
[3] Observatoire de Haute-Provence, CNRS, Universiteé d'Aix-Marseille, 04870 Saint-Michel-l'Observatoire, France
[4] Laboratório Nacional de Astrofísica, Rua Estados Unidos 154, 37504-364, Itajubá - MG, Brazil

Submitted on 2020/08/20 ; Accepted for publication on 2020/09/24

Kiefer et al. 2020, arXiv :2009.14164

A Dynamical Mass of 70 ± 5 M_{Jup} for Gliese 229B, the First T Dwarf

Timothy D. Brandt[1], Trent J. Dupuy[2,3], Brendan P. Bowler[4], Daniella C. Bardalez Gagliuffi[5], Jacqueline Faherty[6], G. Mirek Brandt[1], and Daniel Michalik[6]

[1] Department of Physics, University of California, Santa Barbara, Santa Barbara, CA 93106, USA
[2] Gemini Observatory, Northern Operations Center, 670 N. Aohoku Place, Hilo, HI 96720, USA
[3] Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
[4] Department of Astronomy, The University of Texas at Austin, Austin, TX 78712, USA
[5] American Museum of Natural History, NY, USA
[6] Science Support Office, Directorate of Science, European Space Research and Technology Centre (ESA/ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands

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Brandt et al. 2020, AJ, 160:196

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

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

[1] Department of Physics, University of California, Santa Barbara, Santa Barbara, CA 93106, USA
[2] Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh, EH9 3HJ, UK
[3] European Space Agency (ESA), European Space Research and Technology Centre (ESTEC), Keplerlaan 1, 2201 AZ Noordwijk, The Netherland

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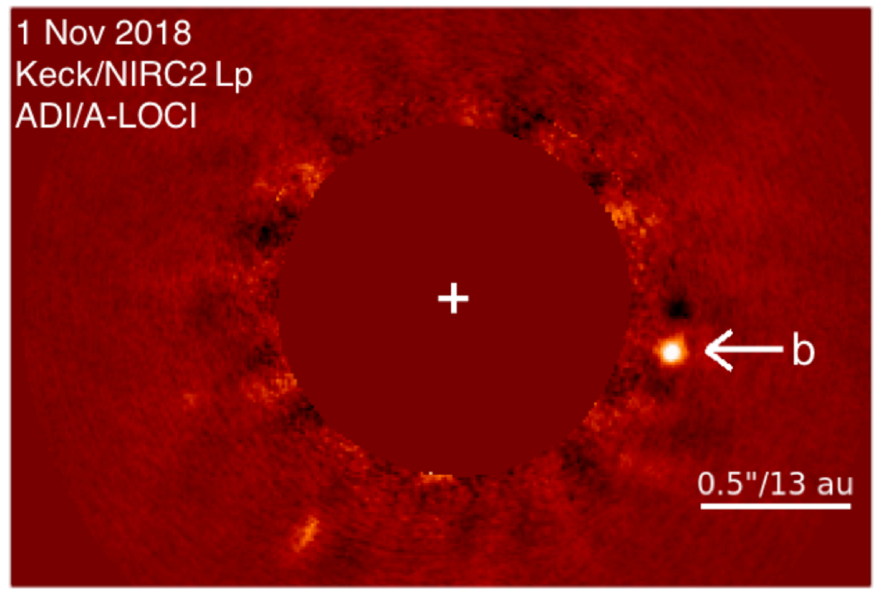
Brandt et al. 2021, AJ, 161:179

SCExAO/CHARIS Direct Imaging Discovery of a 20 au Separation, Low-Mass Ratio Brown Dwarf Companion to an Accelerating Sun-like Star*

Thayne Currie,[1,2,3] Timothy D. Brandt,[4] Masayuki Kuzuhara,[5,6] Jeffrey Chilcote,[7] Olivier Guyon,[1,5,8,9]
Christian Marois,[10,11] Tyler D. Groff,[12] Julien Lozi,[1] Sebastien Vievard,[1] Ananya Sahoo,[1] Vincent Deo,[1]
Nemanja Jovanovic,[13] Frantz Martinache,[14] Kevin Wagner,[8,15] Trent Dupuy,[16] M
Michael Letawsky,[1] Yiting Li,[4] Yunlin Zeng,[17] G. Mirek Brandt,[4] Daniel Michalik
Markus Janson,[19] Gillian R. Knapp,[20] Jungmi Kwon,[21] Kellen Lawson,[22] Michael
Taichi Uyama,[23] John Wi



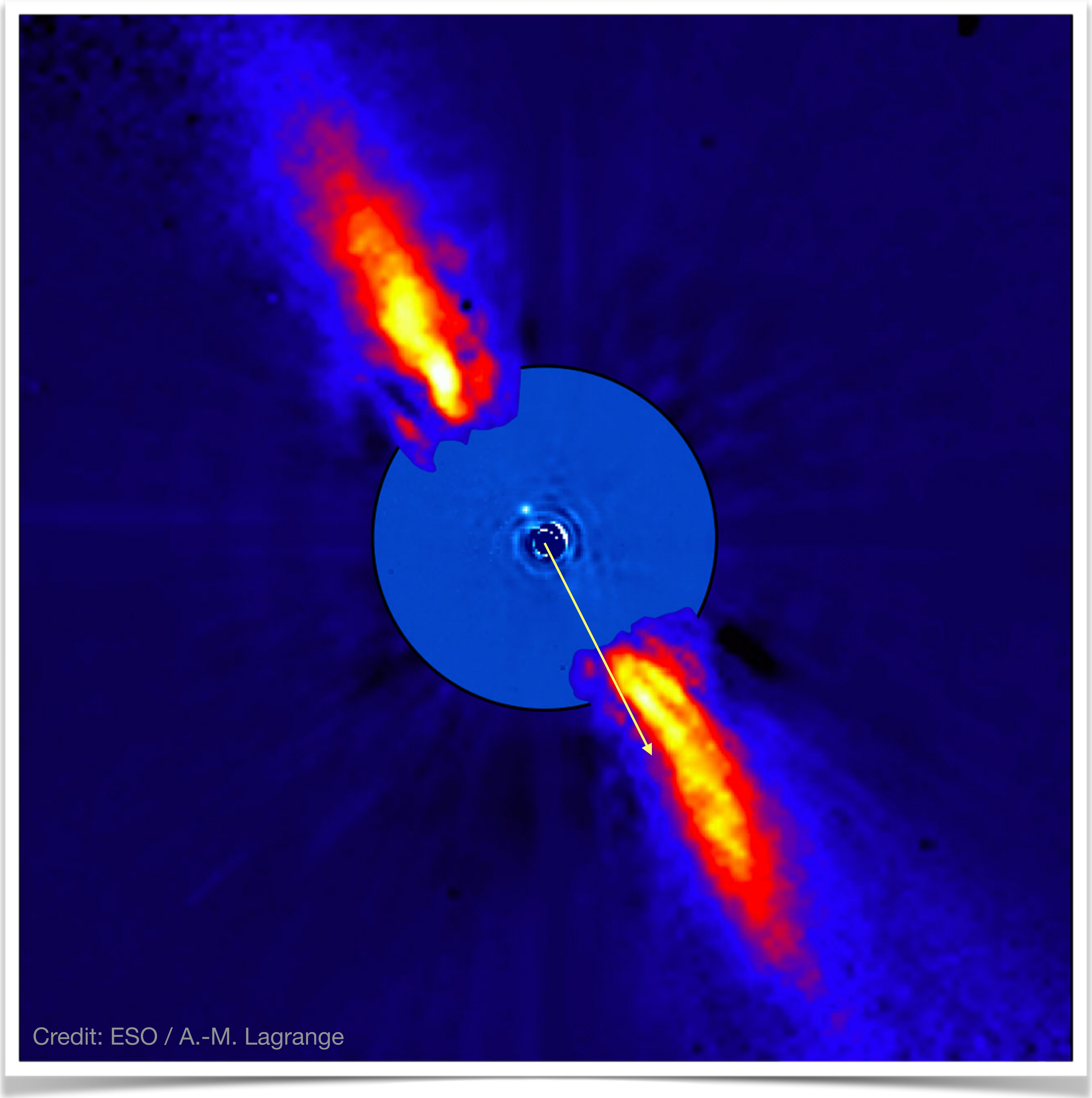
Currie et al. 2020, ApJL 904, 25

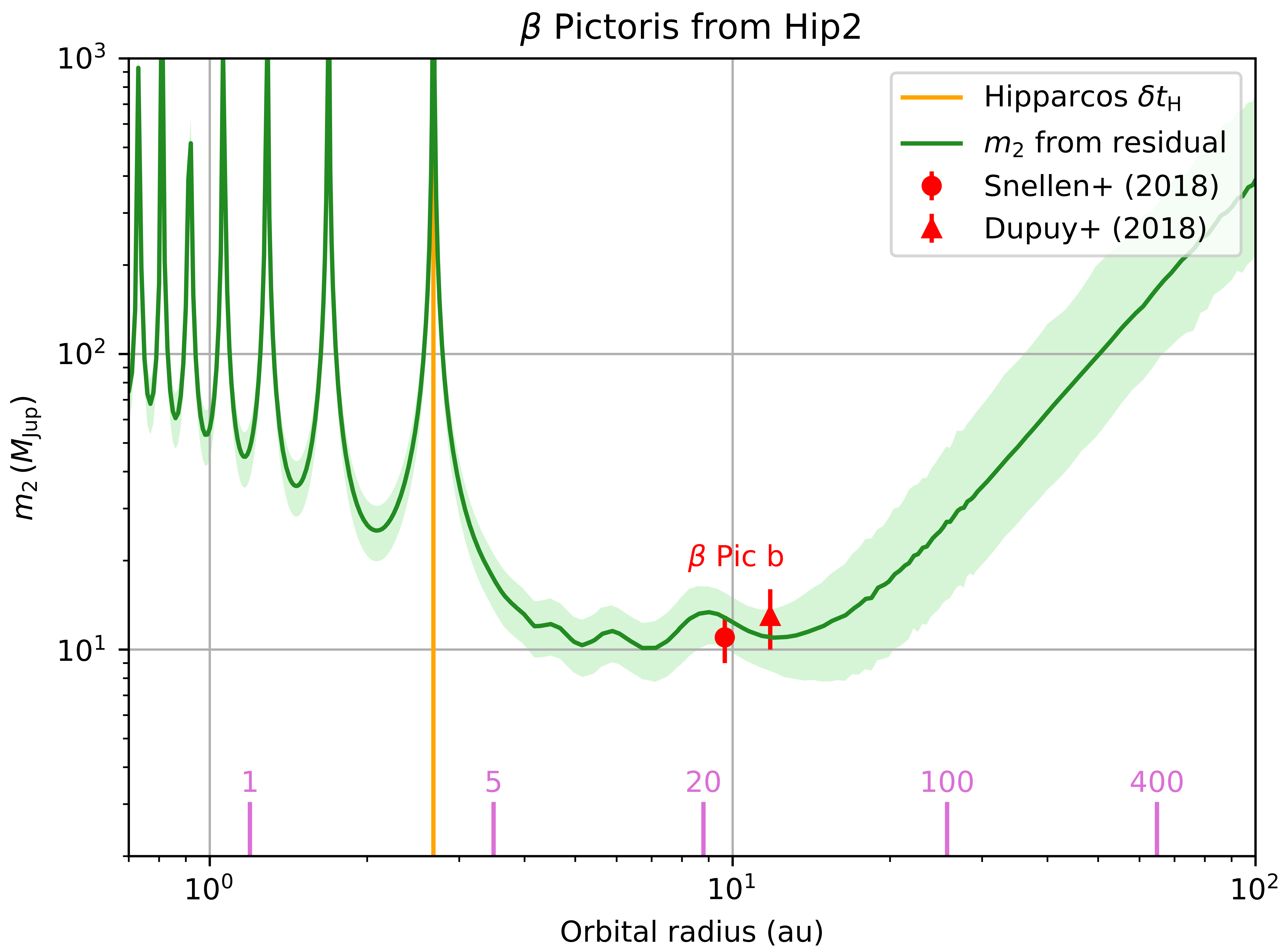
Constraining masses and separations of unseen companions to five accelerating nearby stars*

D. Mesa[1], M. Bonavita[1,2], S. Benatti[3], R. Gratton[1], S. Marino[4,5], P. Kervella[6], V. D'Orazi[1], S.Desidera[1], T. Henning[7], M. Janson[8], M. Langlois[9,10], E. Rickman[11,12], A. Vigan[9], A. Zurlo[13,14,9], J.-L. Baudino[6], B. Biller[7,15,16], A. Boccaletti[6], M. Bonnefoy[17], W. Brandner[7], E. Buenzli[7], F. Cantalloube[9], D. Fantinel[1], C. Fontanive[18,1], R. Galicher[6], C. Ginski[19], J. Girard[20,17], J. Hagelberg[21], T. Kopytova[7], C. Lazzoni[1], H. Le Coroller[9], R. Ligi[22], M. Llored[9], A.-L. Maire[23,7], D. Mouillet[17], C. Perrot[6], S. Rochat[17], C. Romero[17,24], D. Rouan[6], M. Samland[7,8], T.O.B. Schmidt[6,25], E. Sissa[1], F. Wildi[11]

Mesa et al. 2022, A&A, accepted

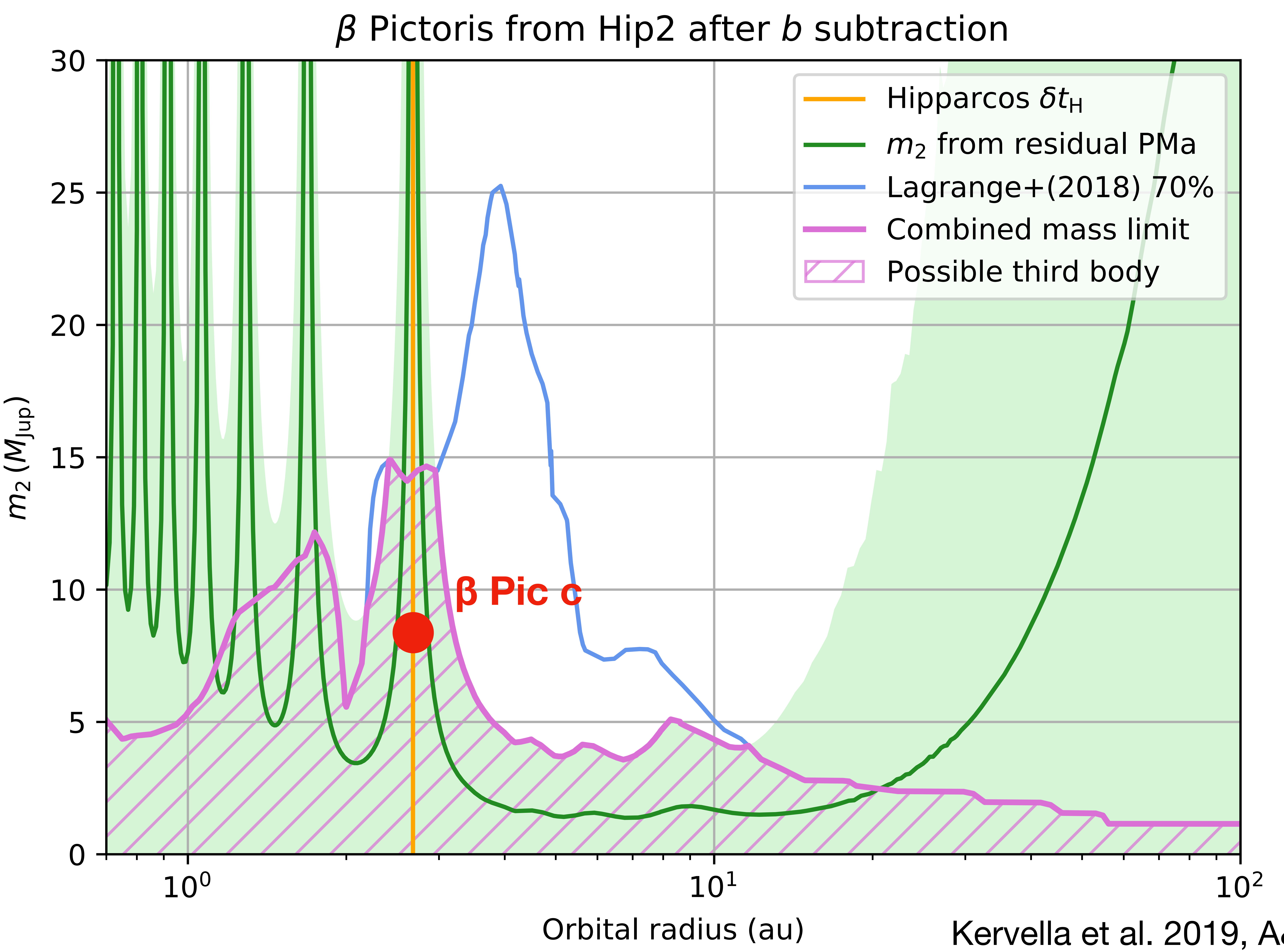
β Pictoris b





Kervella et al. 2019, A&A, 623, A72

Snellen & Brown 2018, Nat. Astronomy, 2, 883



Kervella et al. 2019, A&A, 623, A72
Nowak et al. 2020, A&A, 642, L2

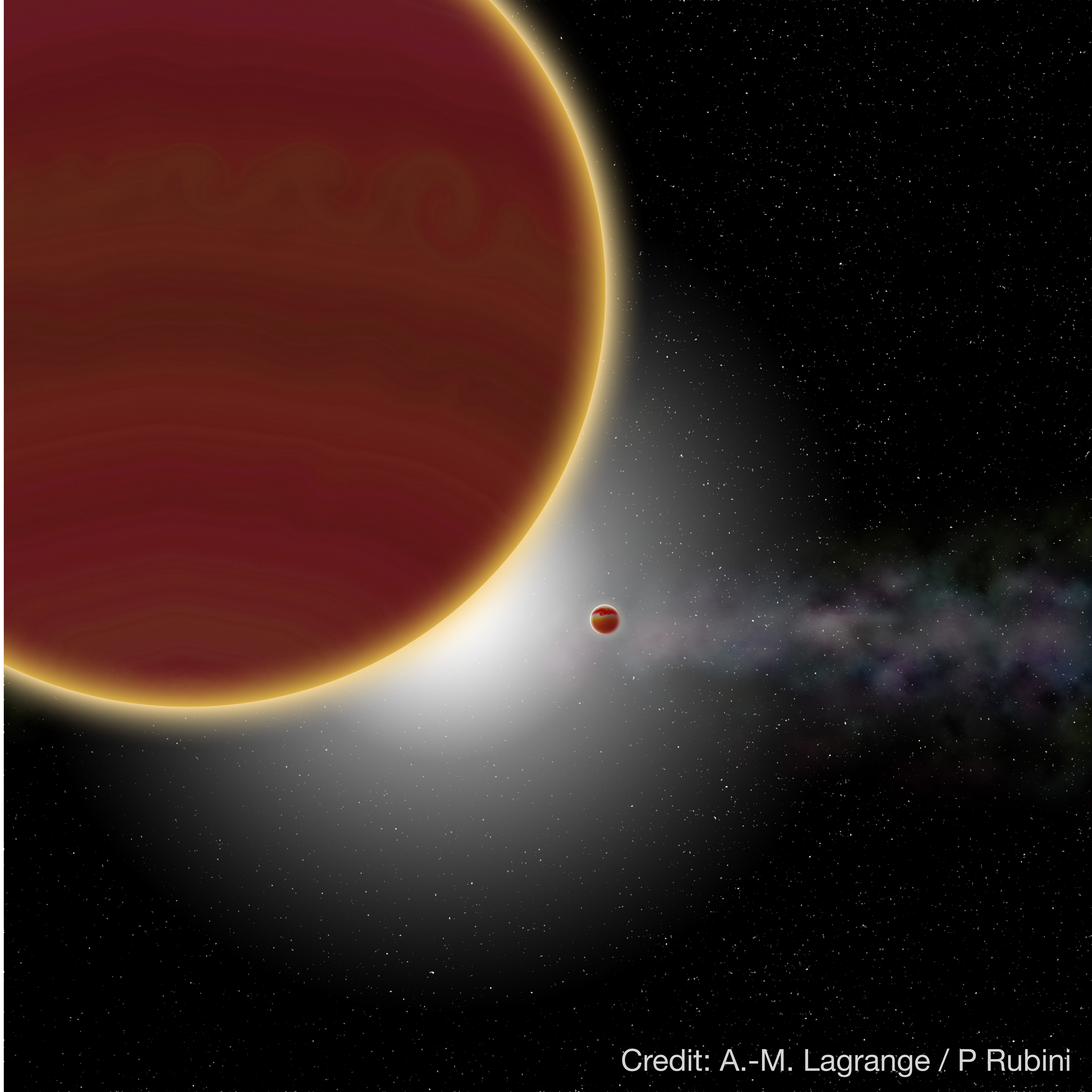
β Pictoris and GRAVITY

- **<u>Discovery:</u> β Pictoris b** by direct imaging (Lagrange et al. 2008, A&A, 493, L21) and **β Pictoris c** by radial velocity (Lagrange et al. 2019, Nature Astronomy, 3, 1135).

- **<u>GRAVITY observations :</u>**

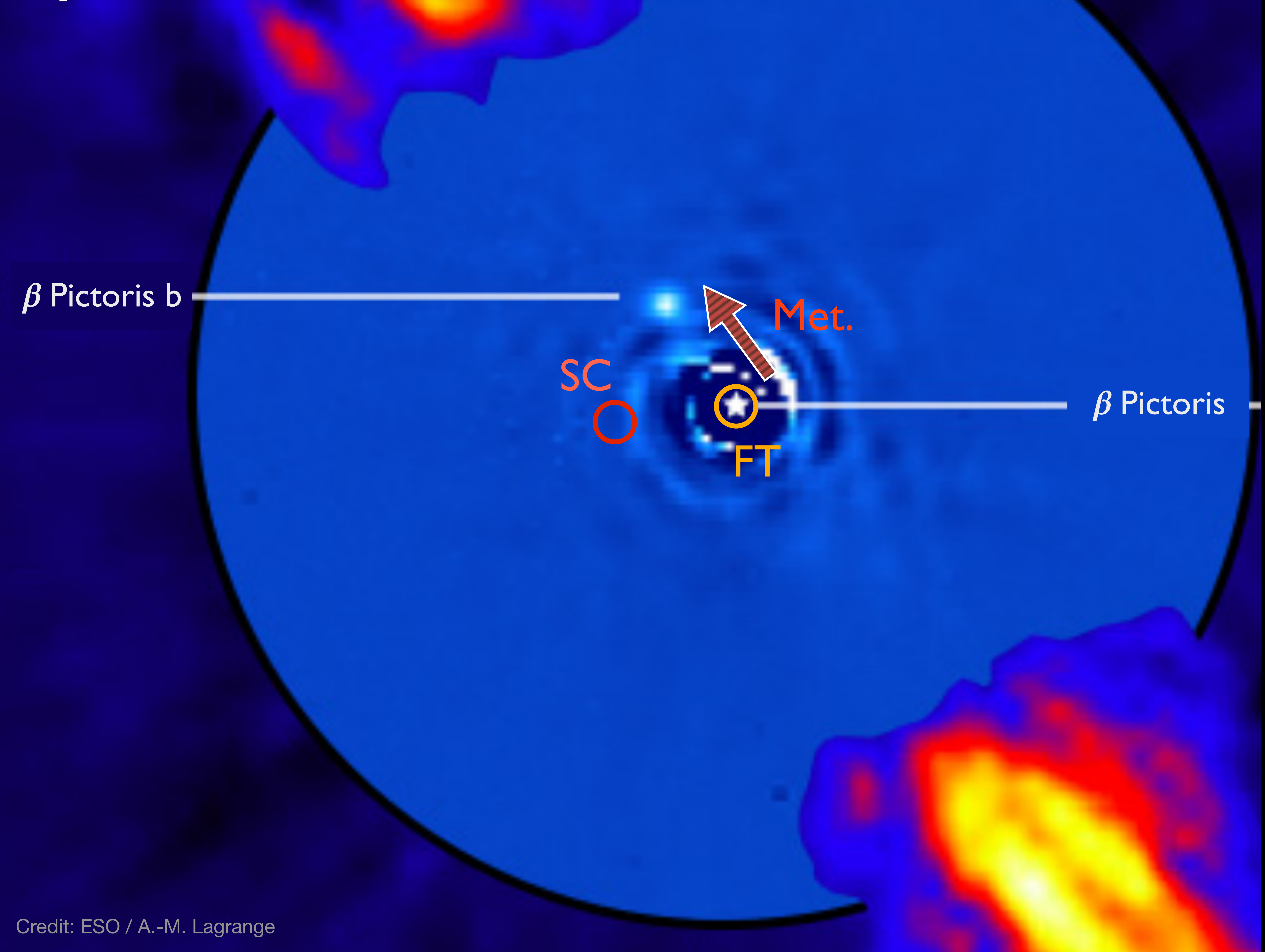
  - **β Pictoris b** was directly detected (GRAVITY Collaboration, Nowak et al. 2020, A&A 633, A110).

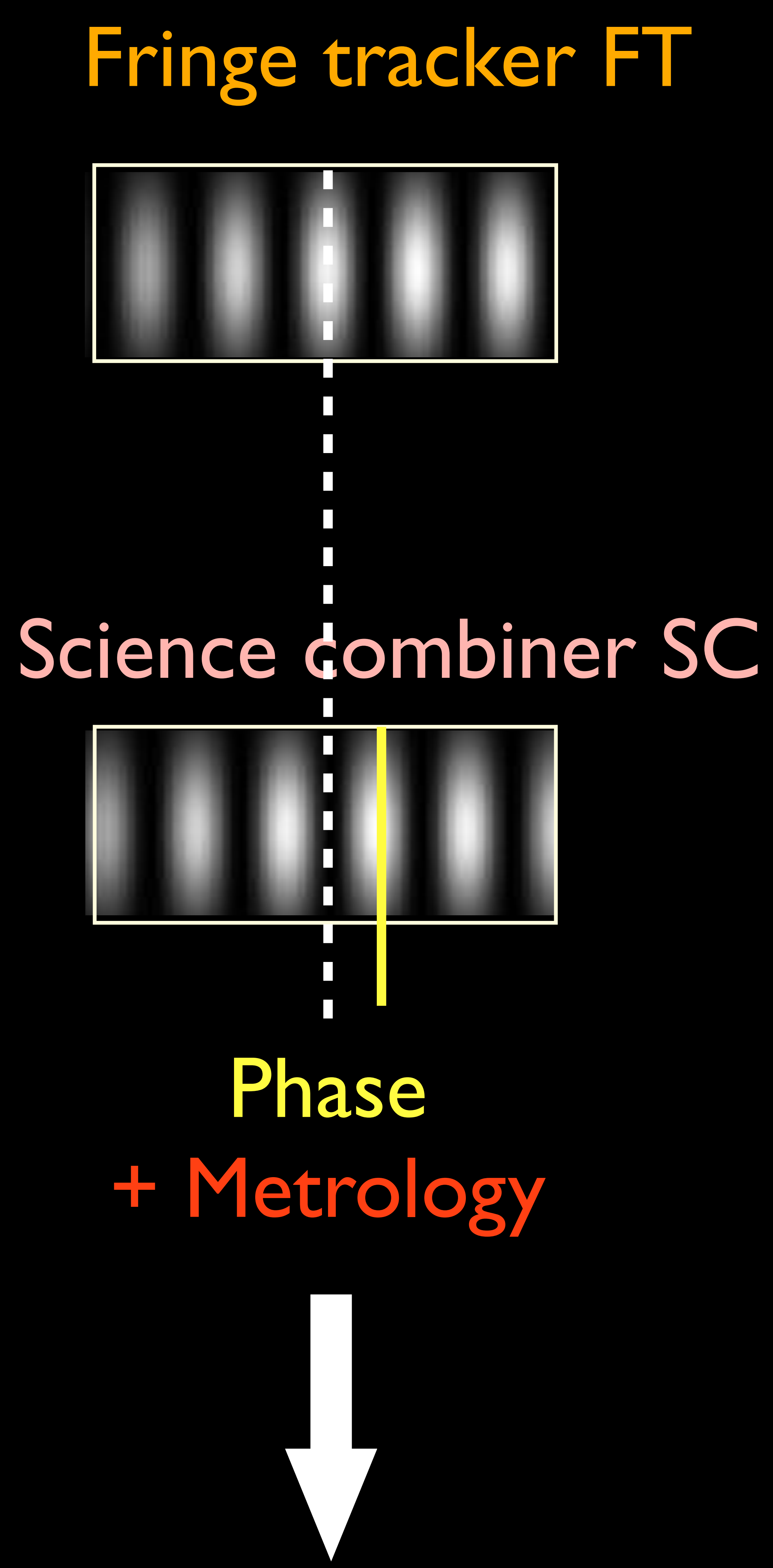
  - **β Pictoris c** was directly detected with GRAVITY (Nowak et al. 2020, A&A, 642, L2) and from its perturbation to the astrometric orbit of planet b (Lacour et al. 2021, A&A 654, L2).


Credit: A.-M. Lagrange / P Rubini


Object A
Object B
GRAVITY @ Paranal observatory
Credit: ESO/G. Hudepohl

β Pictoris and GRAVITY

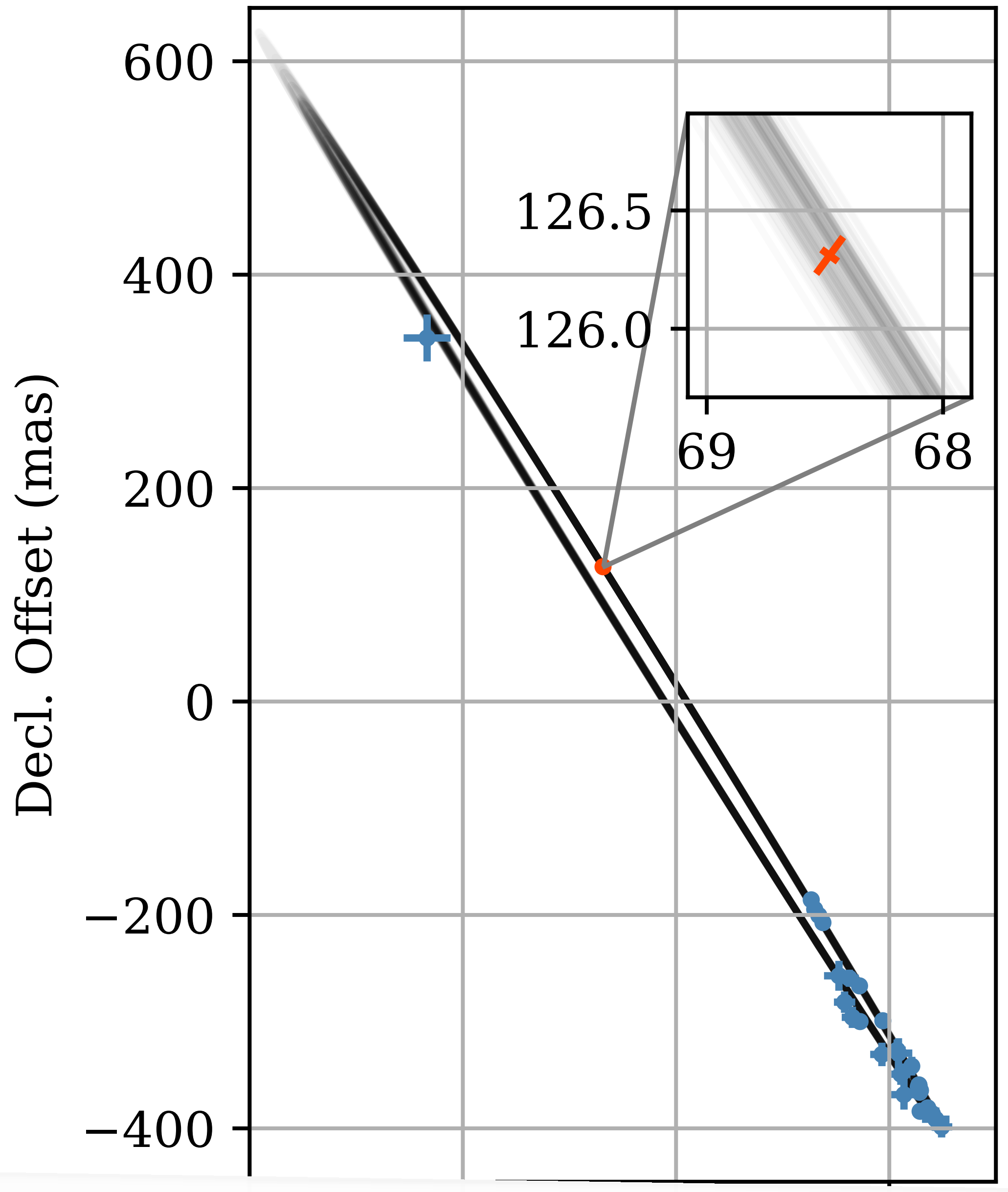




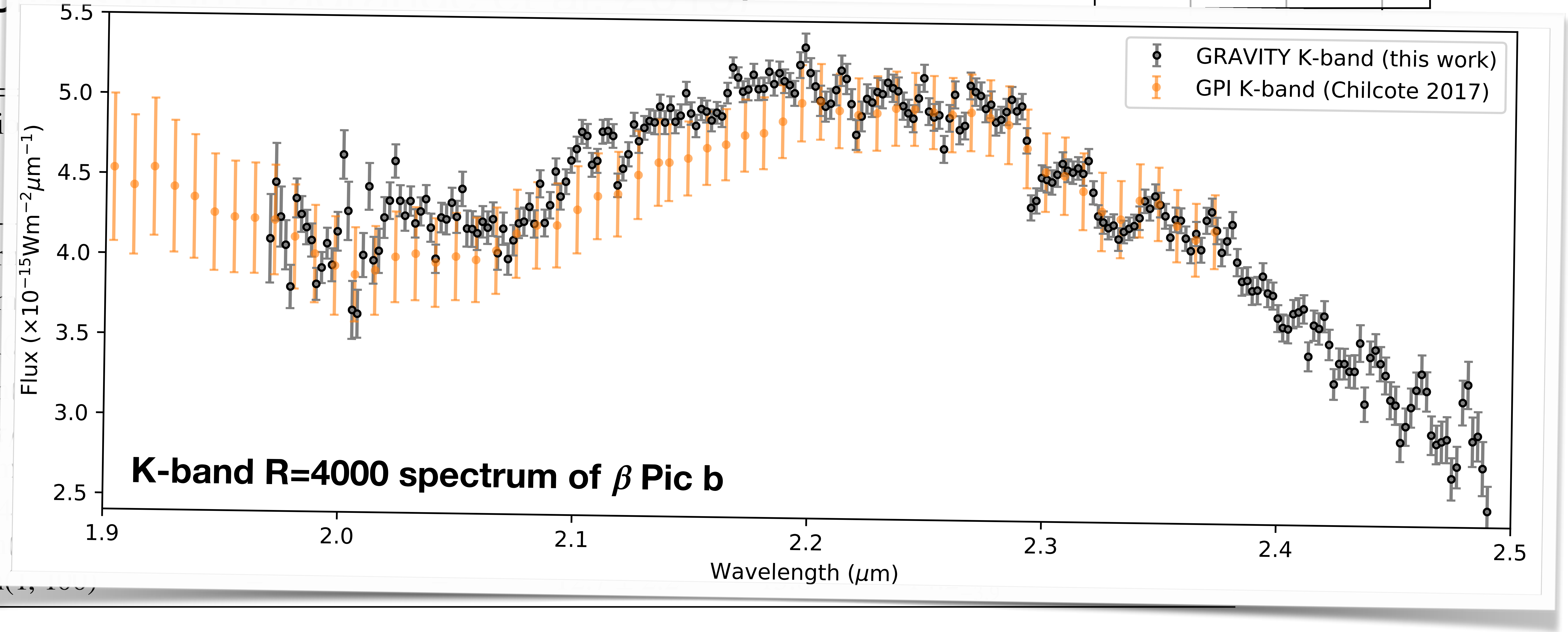
- Astrometry
- Spectro-imaging

β Pictoris b

- Astrometric accuracy of GRAVITY position ~ 70 µas from 1.5 hour of VLTI with 4 UTs
- Parameters constrained by relative astrometry, Hipparcos epoch astrometry + Gaia DR2, HGCA and stellar radial velocities (from Lagrange et al. 2019)

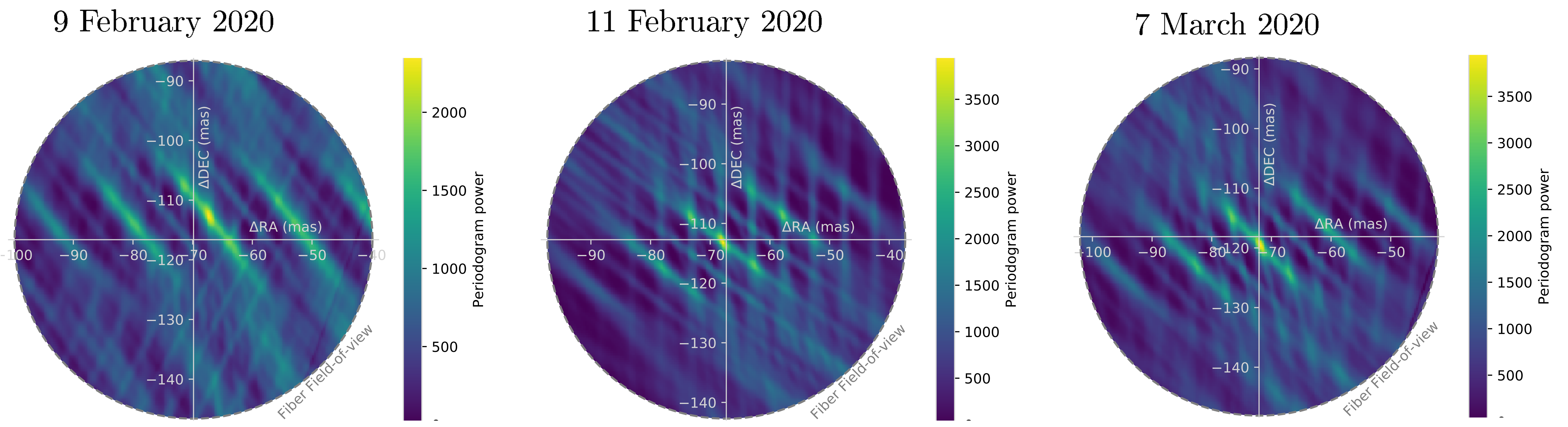


Orbital element	Pri…
a (au)	LogUnifor…
e	Uniforr…
i (°)	sin…
ω (°)	Uniform…
Ω (°)	Uniform(π…
τ	Unifor…
Parallax (mas)	$\mathcal{N}$(51.4…
M_{tot} ($M_\odot$)	Uniform…
M_b (M_{Jup})	Uniform(1, 100)



GRAVITY Collaboration, Nowak et al. 2020, A&A 633, A110

β Pictoris c

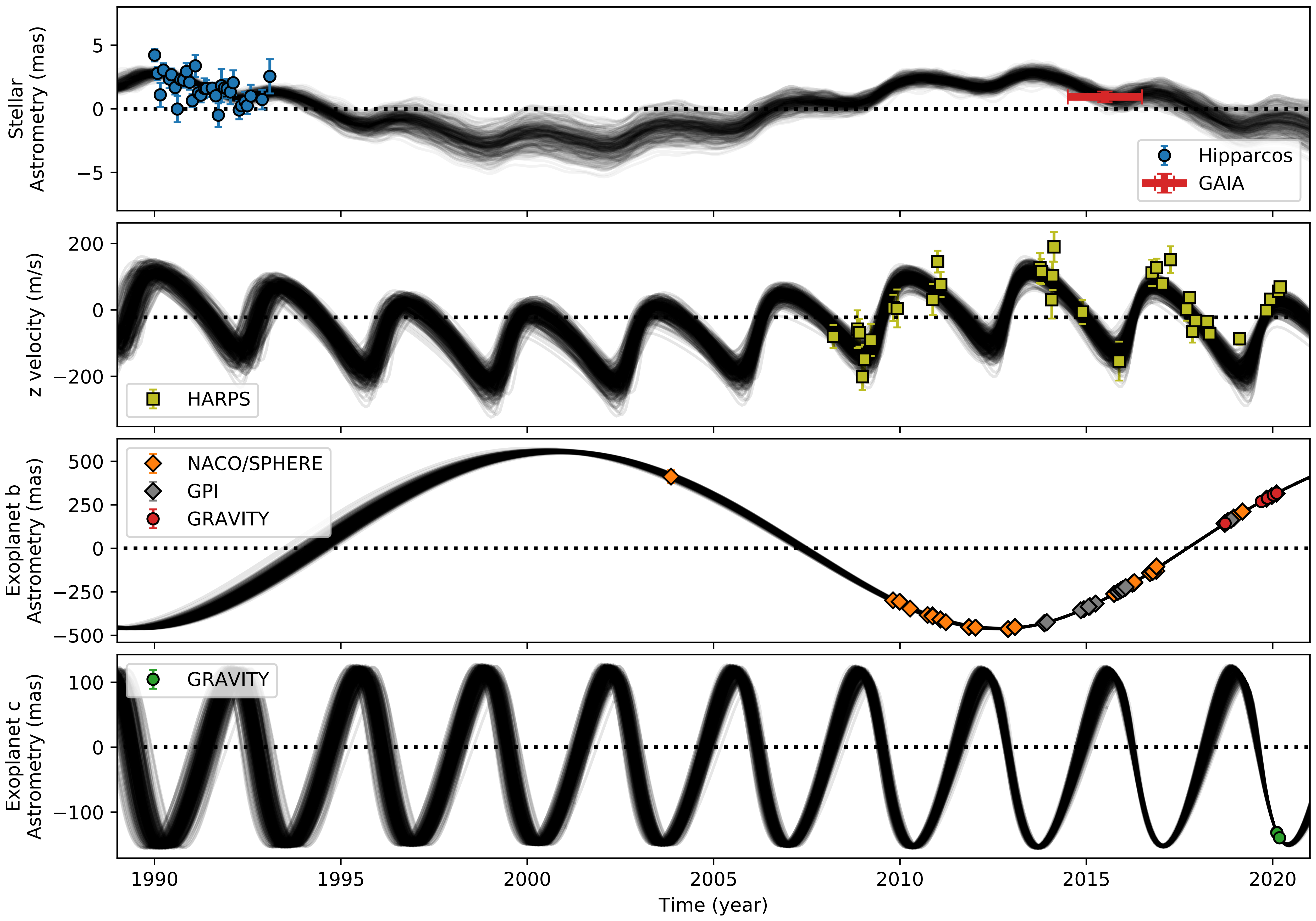


- First direct interferometric detection of a radial velocity planet

- Relative astrometry at ~200 µas

- Orbital fit using *orbitize!* (Blunt et al. 2020) including Hipparcos epoch astrometry, Gaia DR2 and relative astrometry

Nowak et al. 2020, A&A, 642, L2

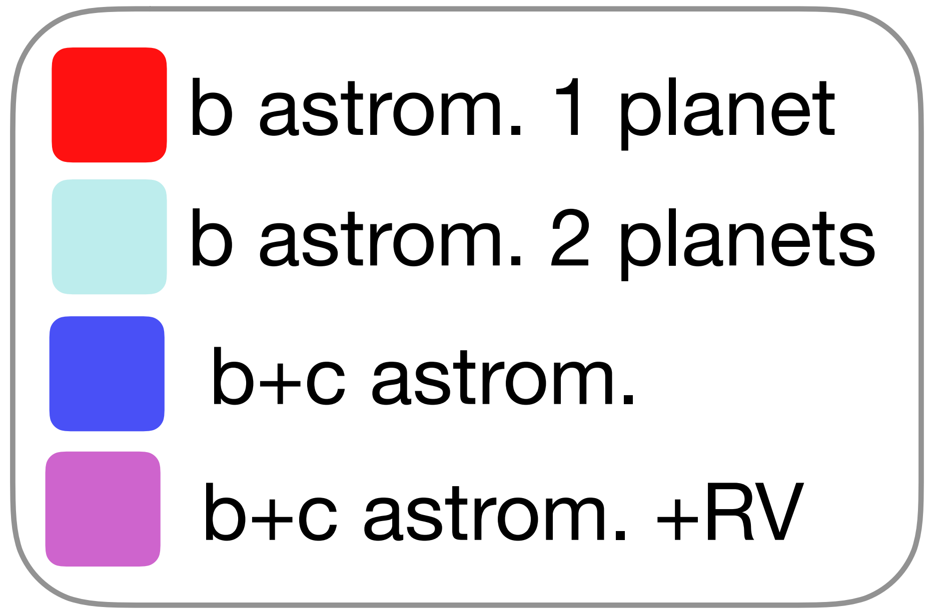


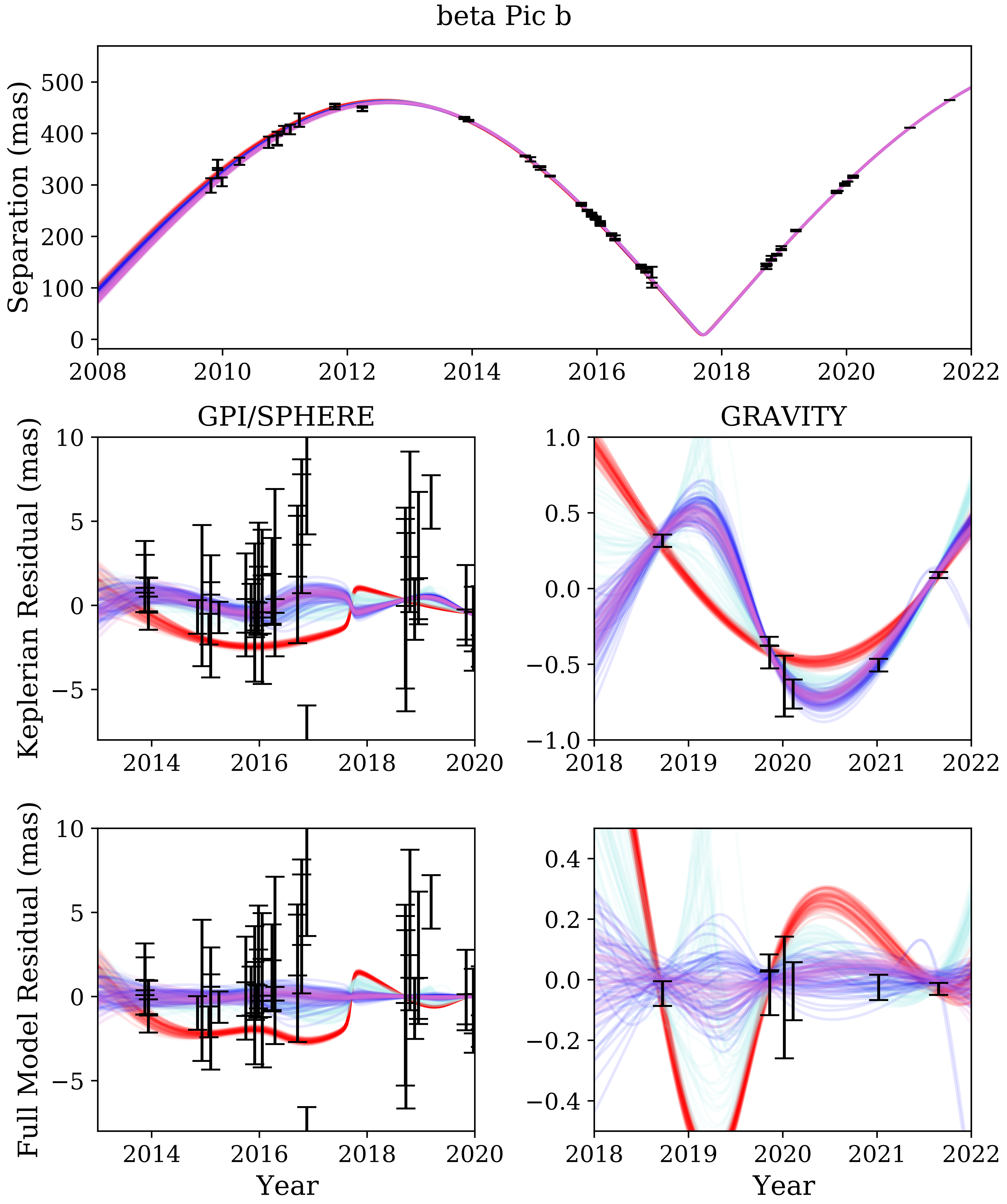
Perturbation of β Pic b by planet c

- The orbital trajectory of β Pic b is affected by the presence of planet c

- This perturbation at a level of only ~1 mas is detected from the GRAVITY astrometry of planet b

- The mass of c (8.9 ± 0.8 Mjup) is better constrained than that of b (11.9 ± 3.0 Mjup).





Lacour et al. 2021, A&A 654, L2

Summary

- **43%** of the 117,000 Hipparcos stars exhibit at least one signature of binarity (PMa, RUWE, CPM), with many **low mass companion** signatures. Tangential velocity anomaly accuracy: **Δv_{tan} ~ 0.26 m/s/pc** with the (E)DR3.
- Catalogs of Hipparcos-Gaia EDR3 proper motion anomalies for all Hipparcos stars are available (Kervella et al. 2022, A&A, 657 A7; Brandt 2021, ApJS, 254, 42)
- Efficient computing tools exist to include Hipparcos and Gaia astrometry in orbital fits, such as **orbitize!** (Blunt et al. 2019) and **orvara** (Brandt et al. 2021).
- The PMa approach is very complementary of the **DR3 non-single star (NSS) catalog** for long orbital periods (> 1000 days).
- **GRAVITY** (soon **GRAVITY+**) enable high precision differential astrometry and spectroscopy of exoplanets.