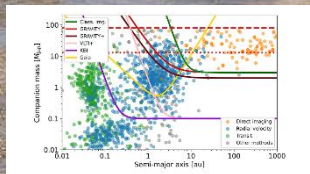
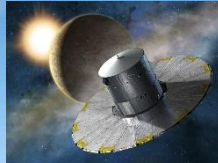
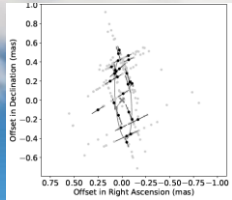


The Frontier of High-Precision Astrometry in the 21st Century

A. Sozzetti

INAF - Osservatorio Astrofisico di Torino

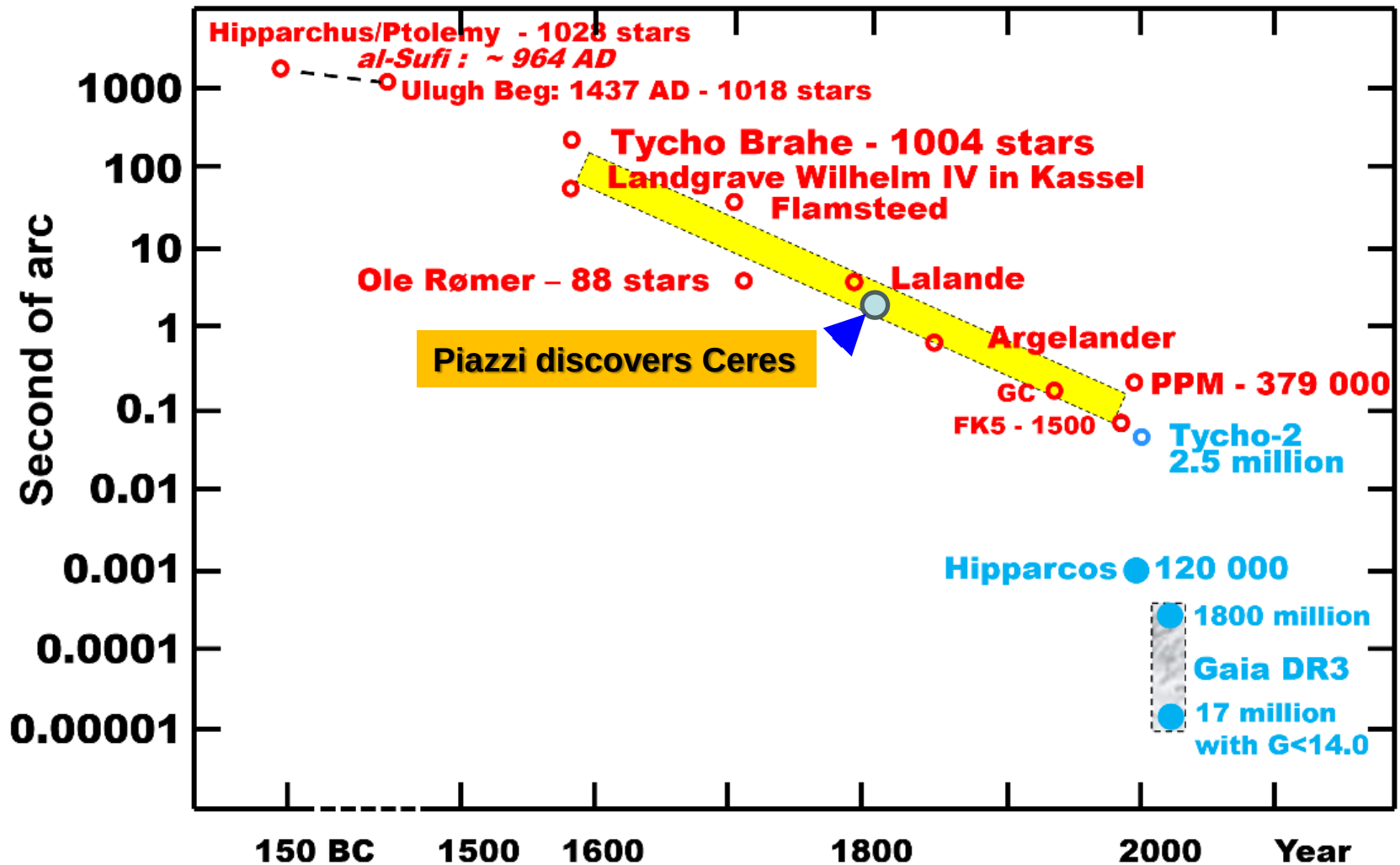




gaia



Astrometric Accuracy during 2000 Years



Erik Høg
1995/2024

Unfolding the box

We live in the middle of this box of space.
When opened out it gives a six-part framework
for a novel map, computed from Hipparcos
results, shown in **ESA SPACE ASTROMETRY**

Hipparcos

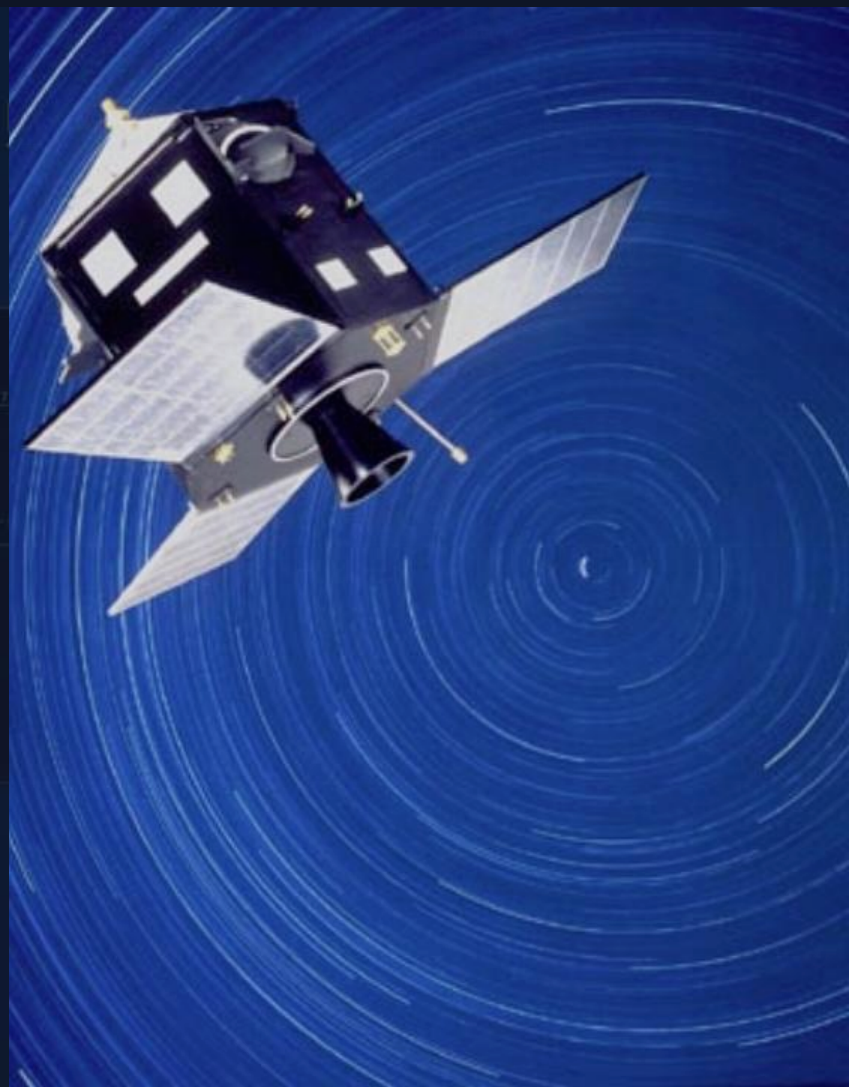
The first space mission dedicated to
absolute precision astrometry.

118,218

Stars mapped with
milliarcsecond precision.

2.5 Million

Stars located in the extended
Tycho-2 catalogue.





Cosmic Distance Scale



Recalibrated Cepheid variables to refine Hubble's constant

Feast & Catchpole 1997

- **Pre-Hipparcos Cepheid P-L Relation Zero-Point:**
- $M_V \approx -2.81 \log P - 1.23$
- **Post-Hipparcos Cepheid P-L Relation Zero-Point:**
- $M_V \approx -2.81 \log P - 1.43$ (0.2 magnitudes brighter)



- **Galaxies with Cepheids are further away:**
- e.g., M31 is at 2.4 Mly, not 2.0 Mly
- **Expansion rate of the Universe decreases:**
- $H_0 = 70-73$ km/s/Mpc (was 75-85 km/s/Mpc)



The Age Paradox



Proved the universe is older than its globular clusters

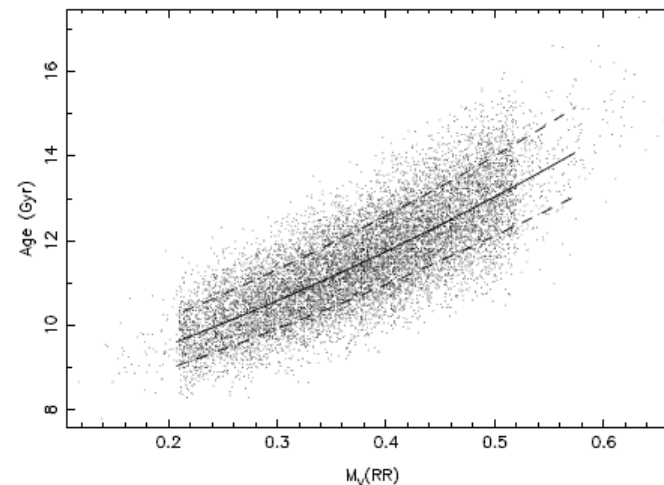
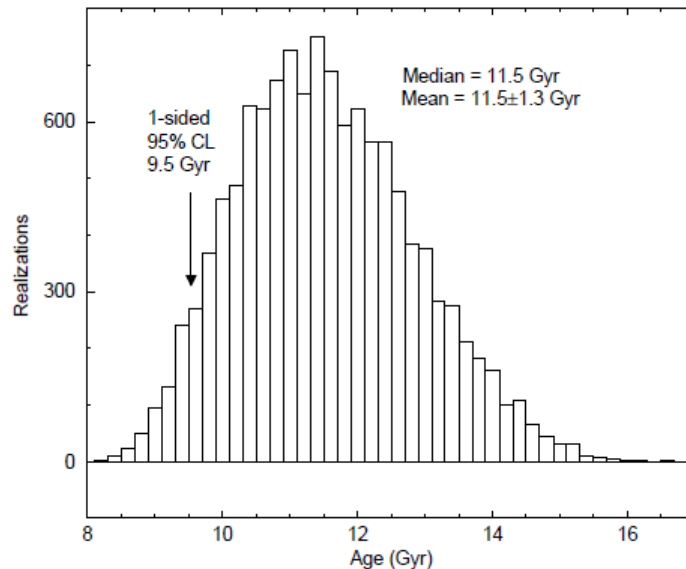
Chaboyer et al. 1998

Before Hipparcos:

- GCs ages at 15 Gyr, but age of the Universe 13 Gyr!

After Hipparcos:

- RR Lyrae stars in GCs are further away
- $M(RR) = 0.44 \rightarrow 0.39$



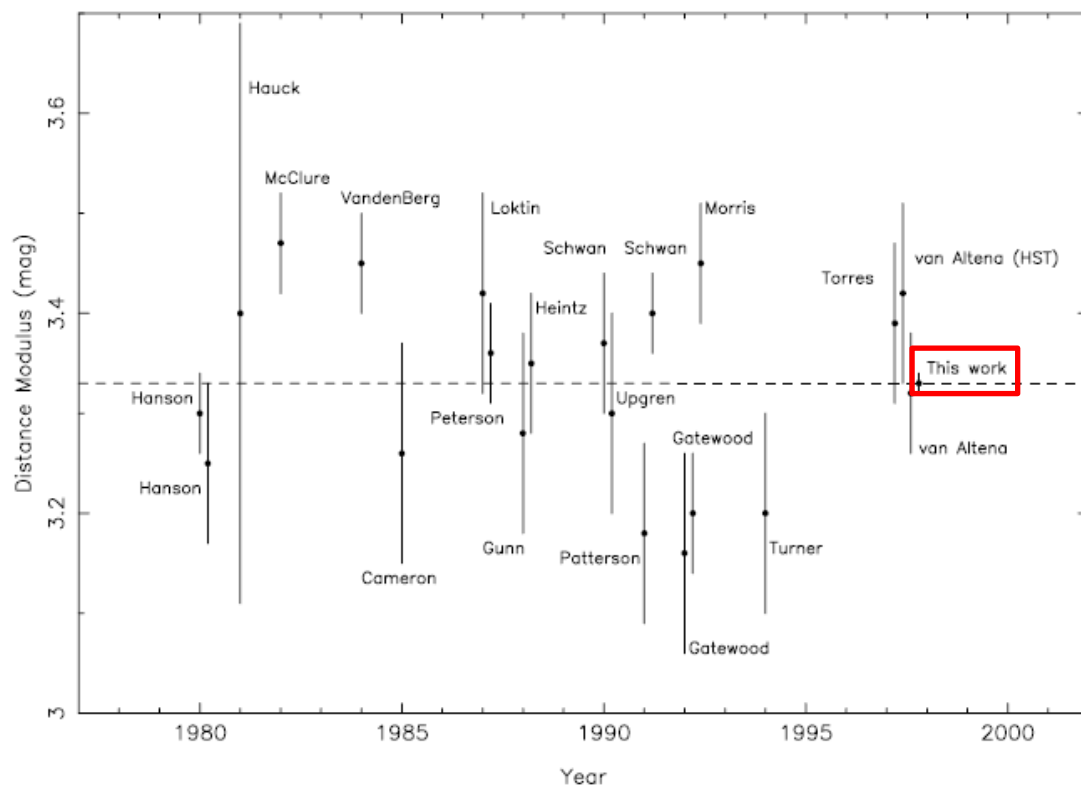


Galactic Dynamics



Reconstructed the 3D structure of the Hyades cluster

Perryman et al. 1998

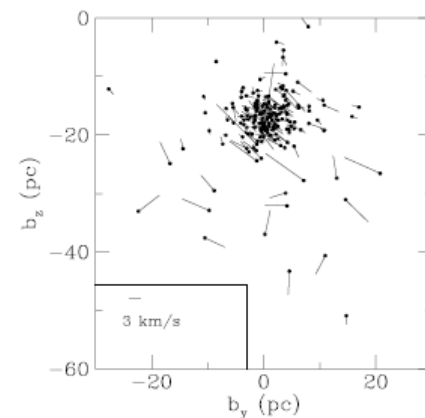


Before Hipparcos:

- Hyades are at $d=40-50$ pc

Before Hipparcos:

- Hyades are at $d=46 \pm 0.27$ pc





gaia



The Gaia Revolution

SKY-SCANNING COMPLETE FOR ESA'S MILKY WAY MAPPER GAIA

From 24 July 2014 to 15 January 2025, Gaia made more than three trillion observations of two billion stars and other objects, which revolutionised the view of our home galaxy and cosmic neighbourhood.



3 TRILLION
Observations

2 BILLION
Stars & other objects observed

938 MILLION
Camera pixels on board

15 300
Spacecraft 'pirouettes'

55 KG
Cold nitrogen gas consumed

580 MILLION
Accesses of Gaia catalogue so far

3827
Days in science operations

>16000

Refereed scientific publications so far

2.8 MILLION
Commands sent to spacecraft

142 TB
Downlinked data (compressed)

500 TB
Volume of data release 4
(5.5 years of observations)

50 000 HOURS
Ground station time used





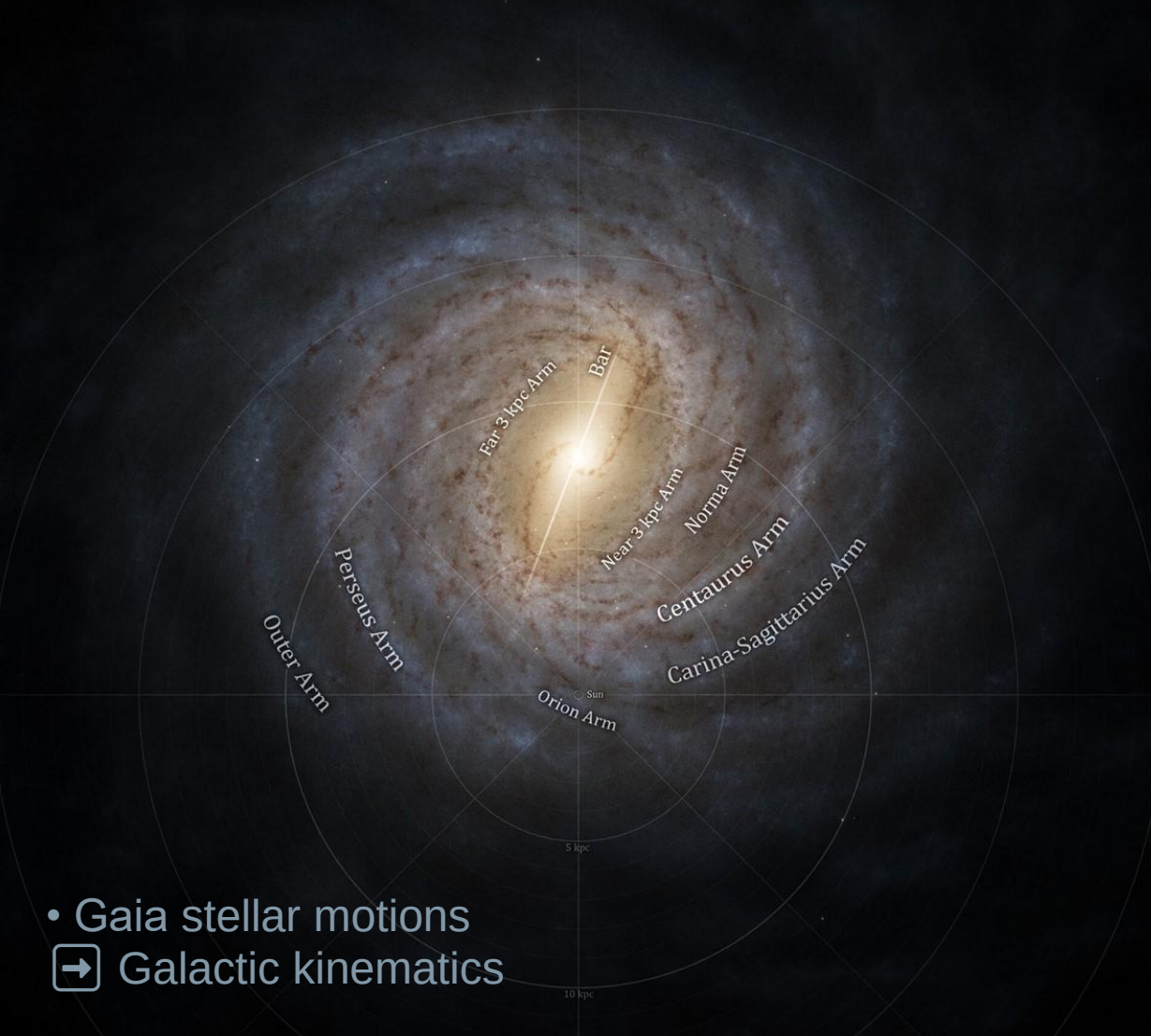
gaia



Galactic Archeology

* Gaia stellar positions and distances

→ Galactic structure



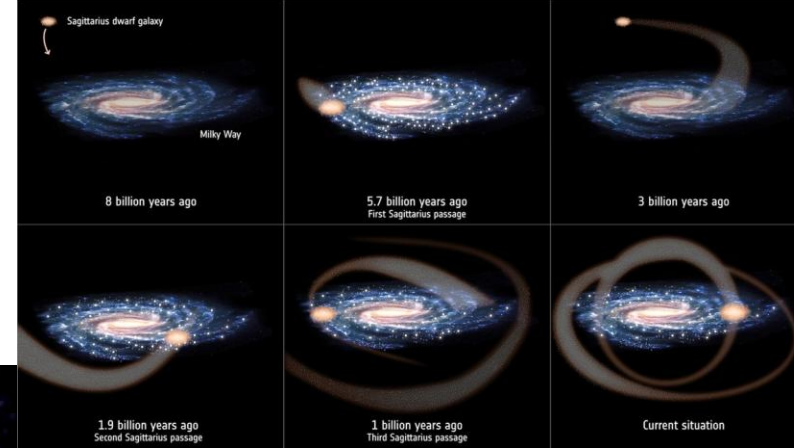
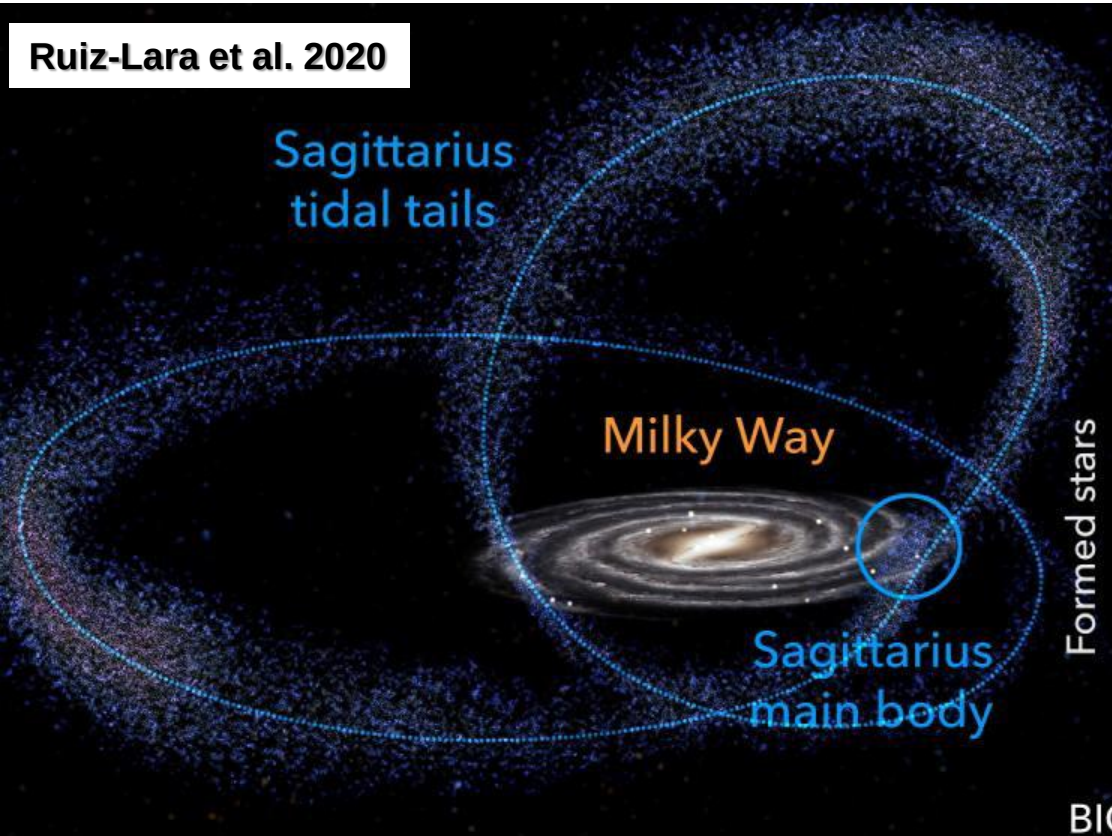
• Gaia stellar motions

→ Galactic kinematics

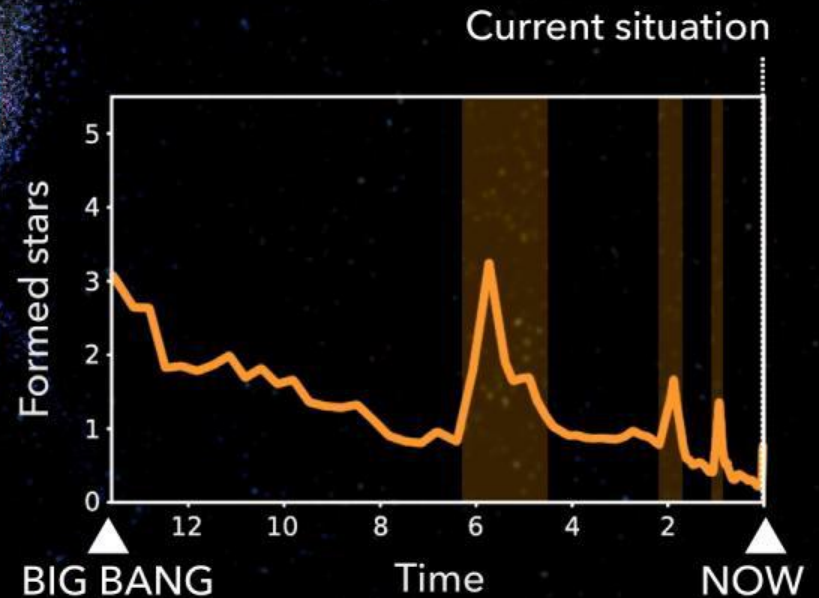
**Gaia reveals the
origin and evolution
of the Milky Way**

Milky Way Star Formation History

Ruiz-Lara et al. 2020



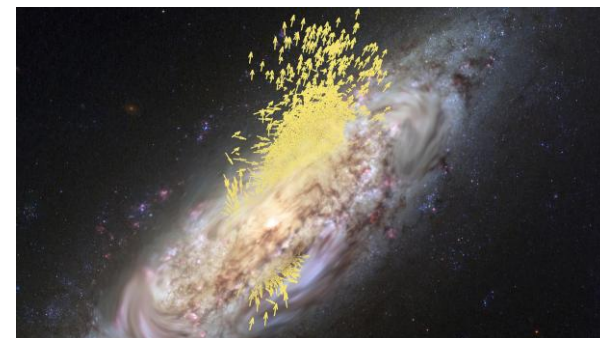
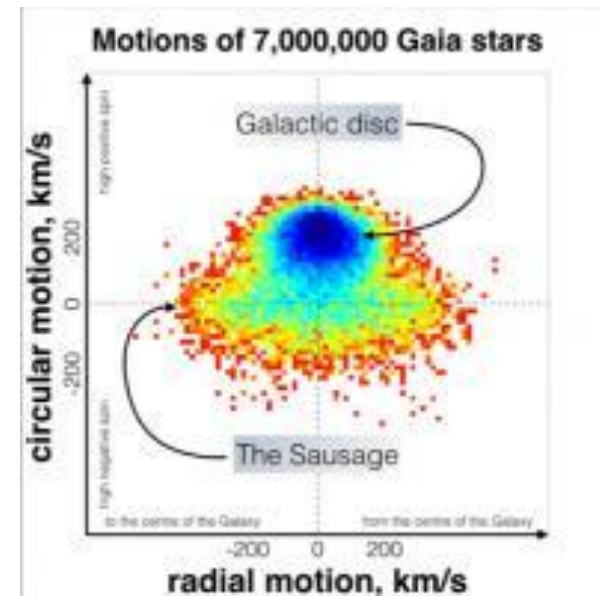
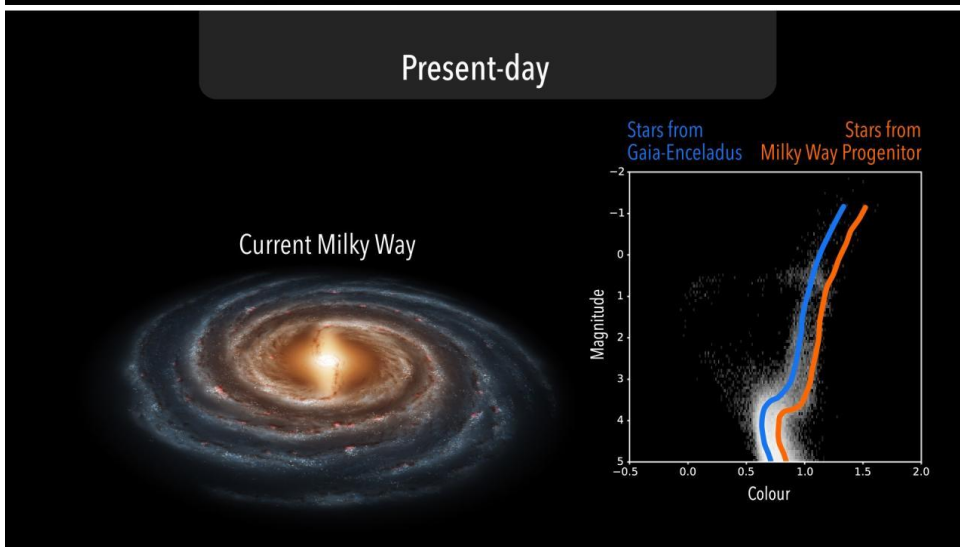
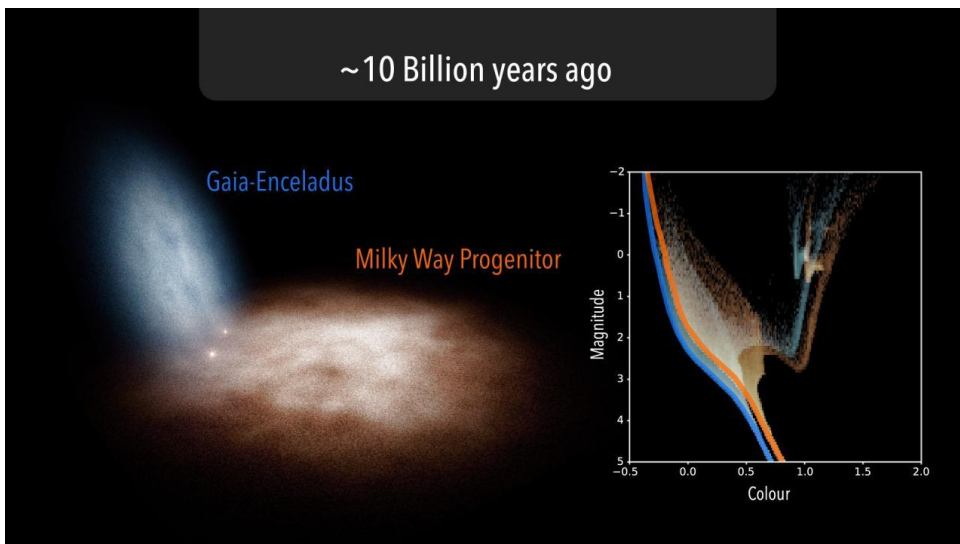
Gaia π $\rightarrow$ CMD



Three impacts of Sagittarius dwarf galaxy with the Milky Way trigger star formation

Maybe our Sun too...

The Gaia-Enceladus Sausage



The merger led to the formation of the Milky Way's inner stellar halo and thick disk

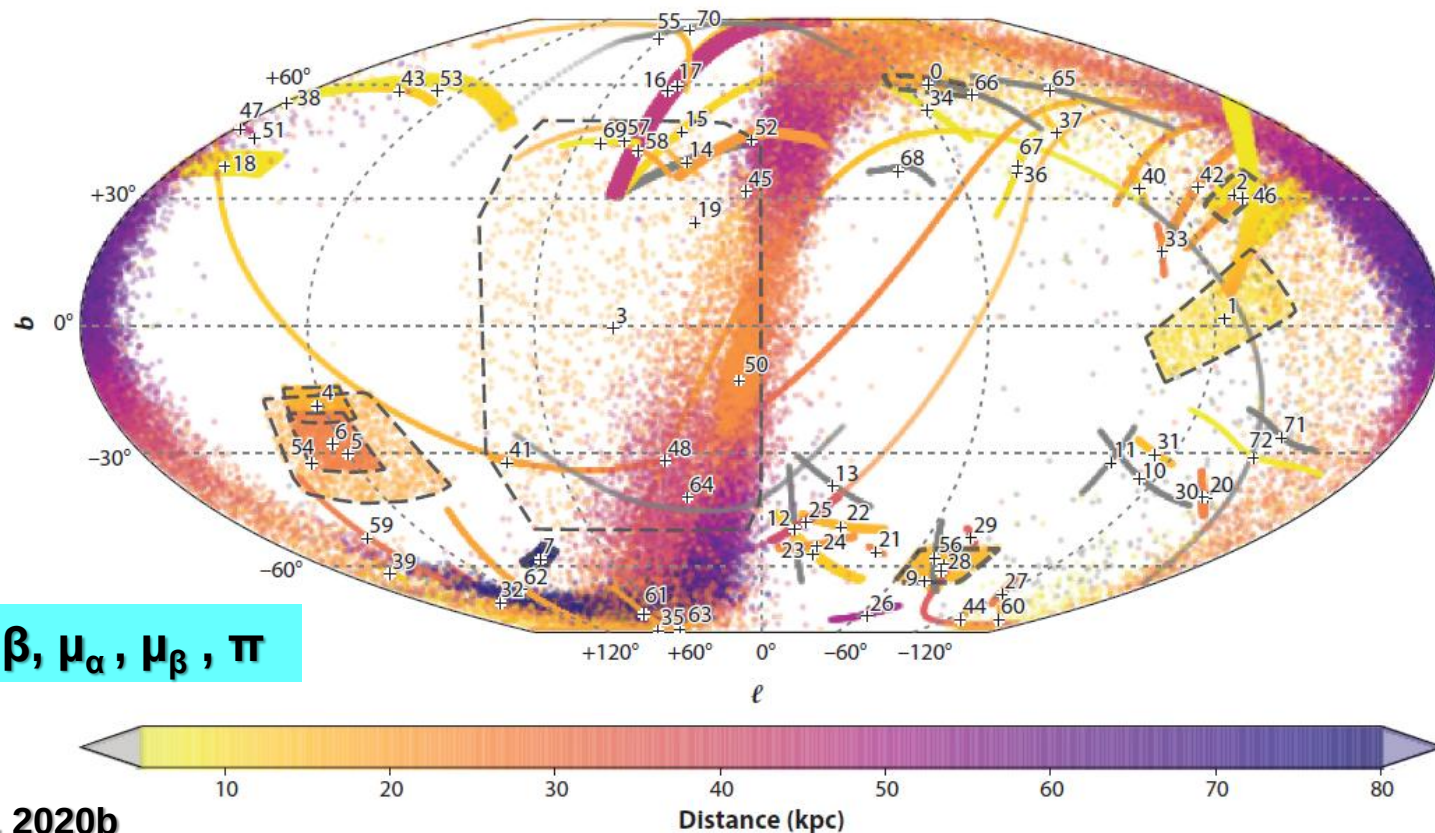


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A History of (Hierarchical) Accretion

0: VOD/VSS	1: Monoceros	2: EBS	3: Her-Aq	4: PAndAS	5: Tri-And	6: Tri-And2	7: PiscesOv	8: EriPhe
9: Phoenix	10: WG1	11: WG2	12: WG3	13: WG4	14: Acheron	15: Cocytos	16: Lethe	17: Styx
18: ACS	19: Pal15	20: Eridanus	21: Tucana III	22: Indus	23: Jhelum	24: Ravi	25: Chenab	26: Elqui
27: Aliqa Uma	28: Turbio	29: Wilka Yaku	30: Turránburra	31: Wambelong	32: Palca	33: Jet	34: Gaia-1	35: Gaia-2
36: Gaia-3	37: Gaia-4	38: Gaia-5	39: PS1-A	40: PS1-B	41: PS1-C	42: PS1-D	43: PS1-E	44: ATLAS
45: Ophiucus	46: Sangarius	47: Scamander	48: Corvus	50: Sgr-L10	51: Orphan	52: Pal5	53: GD-1	54: Tri/Pis
55: NGC5466	56: Alpheus	57: Hermus	58: Hyllus	59: Cetus	60: Kwando	61: Molonglo	62: Murrumbidgee	63: Orinoco
64: Phlegethon	65: Slidr	66: Sylgr	67: Ylgr	68: Fimbulthul	69: Svol	70: Fjorm	71: Gjoll	72: Leiptir



Sky distribution of spatially coherent Milky Way streams and overdensities

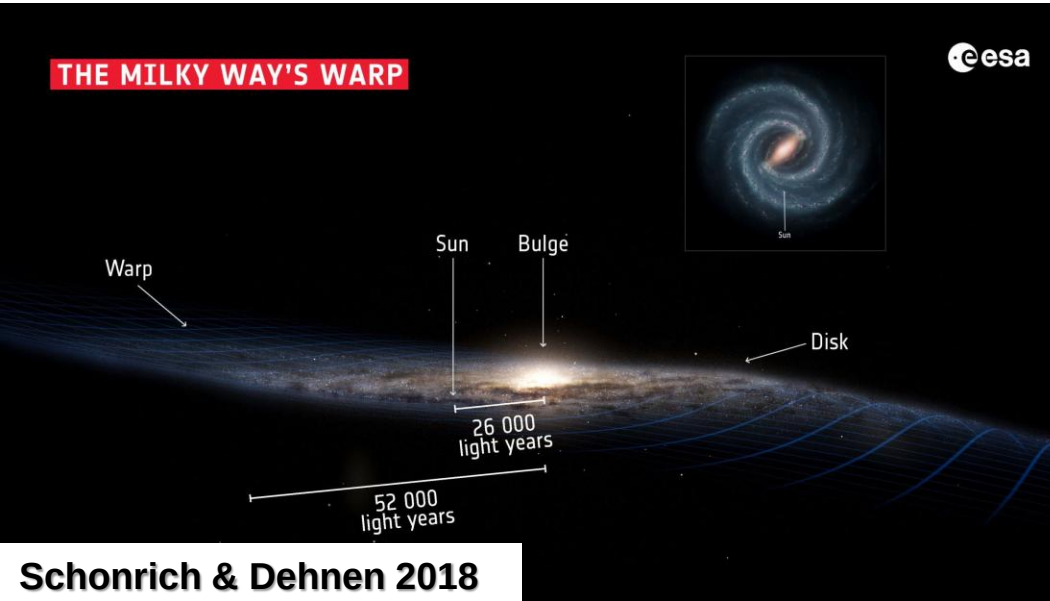


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Milky Way Warps and Corrugations

THE MILKY WAY'S WARP



Motion of key stellar tracers
(RGB, young giants)
reveals warps and waves in
the Milky Way disk

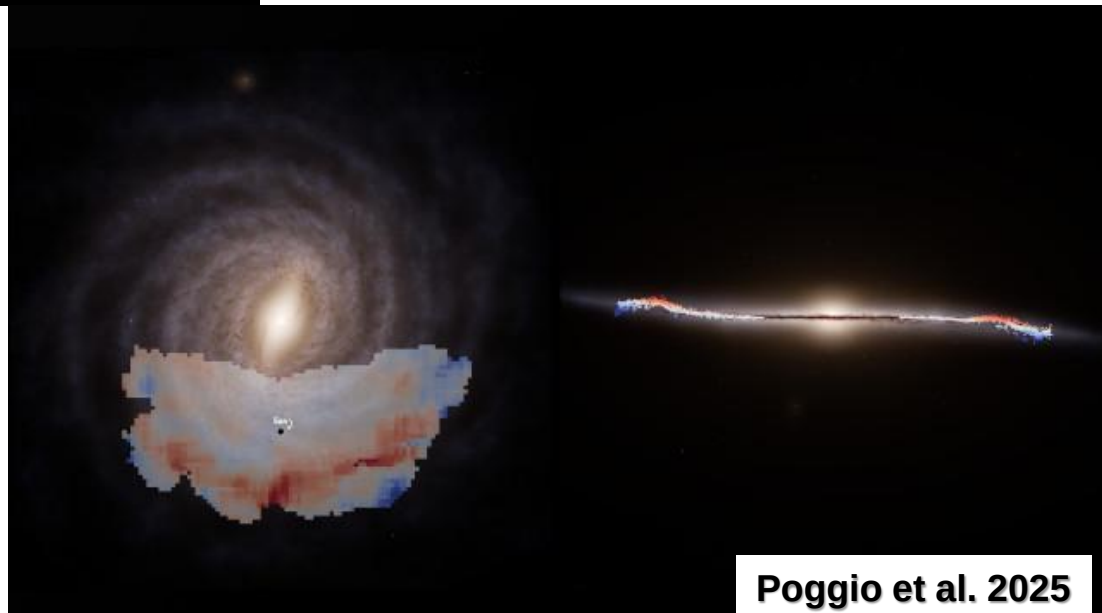


Evidence of past mergers?
Interaction with DM halo?

Fantastic Insights on the
Milky Way formation and
evolution history!

Gaia α , β , μ_α , μ_β , π

PIAZZI 200: NEW FRONTIERS IN ASTROMETRY



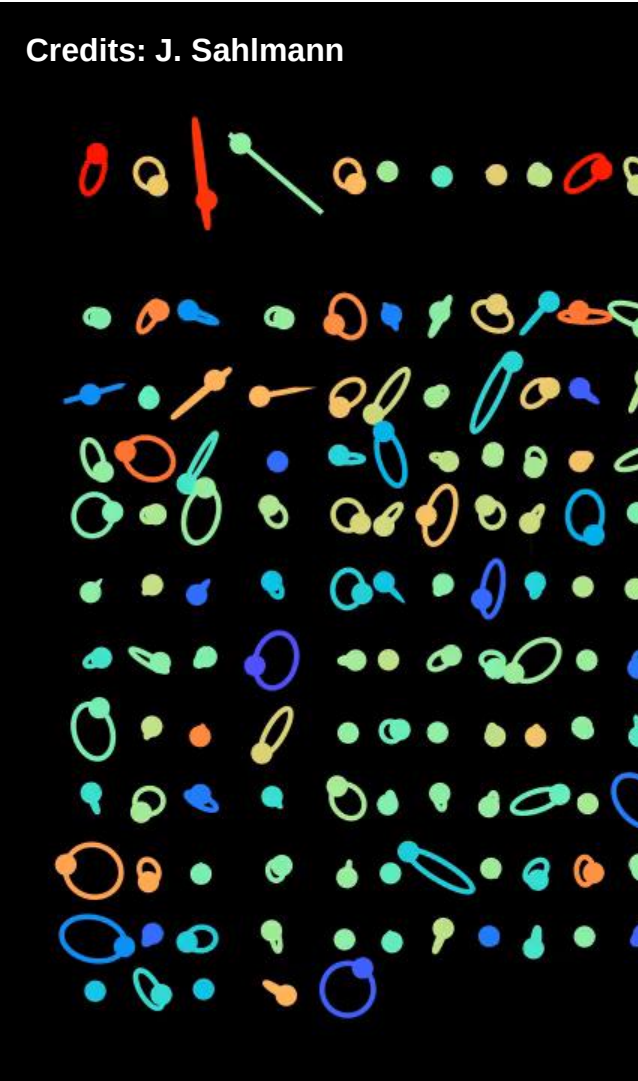


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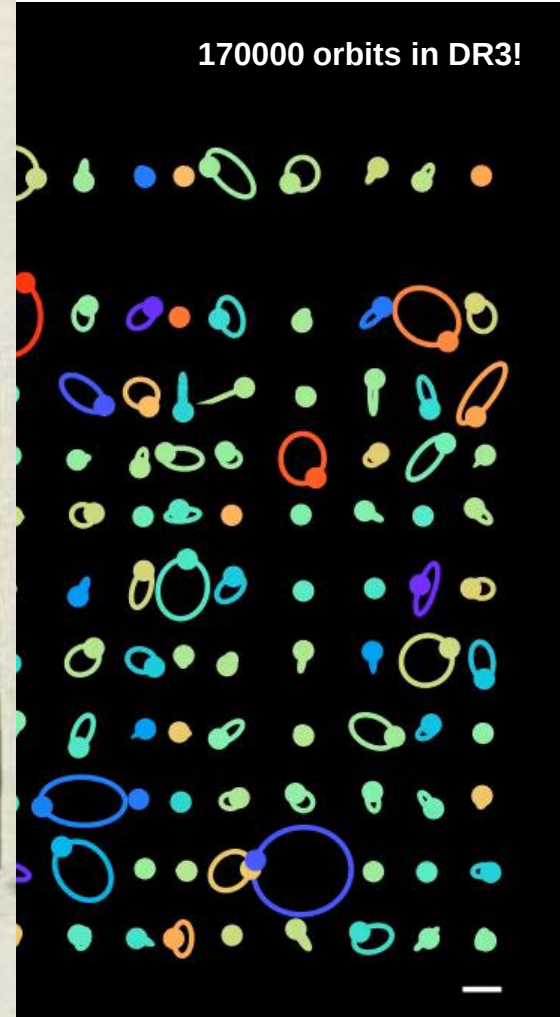
Piazzi Measured Orbits...



Credits: J. Sahlmann



170000 orbits in DR3!



Gaia DR3 Astrometric Orbit Orrery

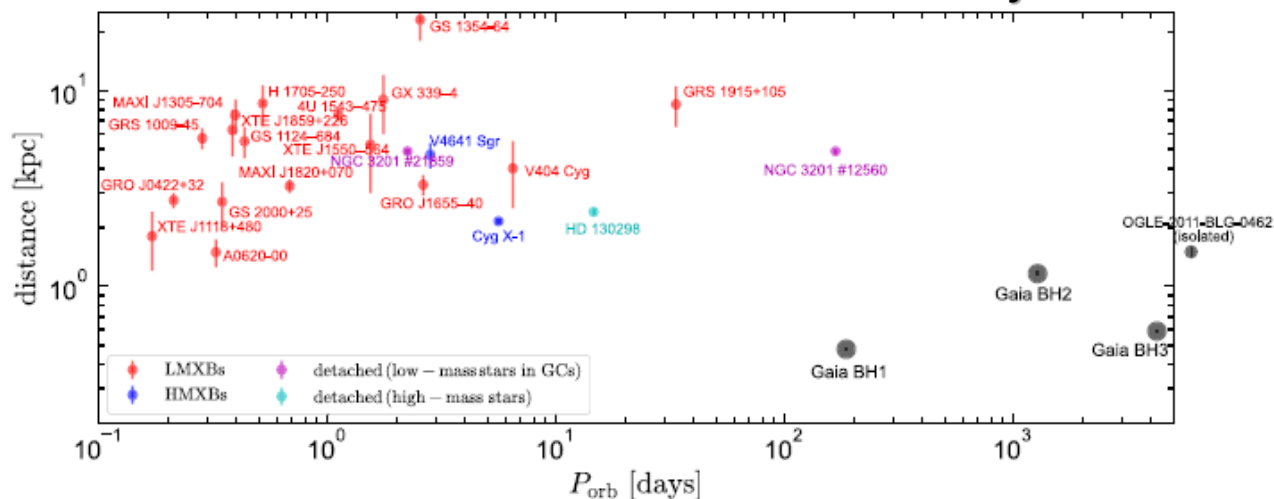
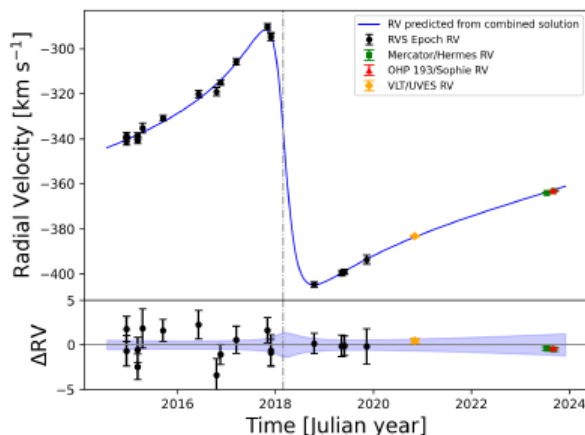


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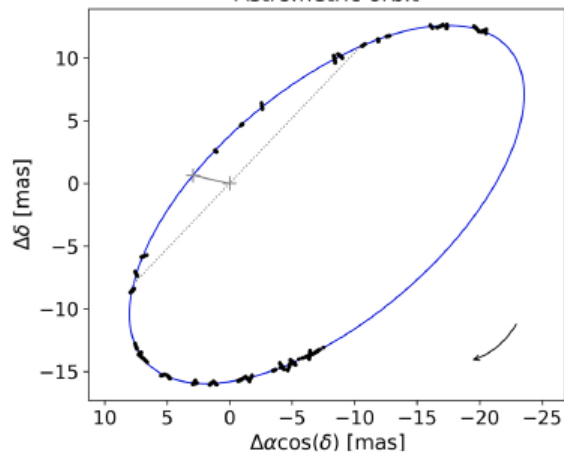


Dormant Black Holes

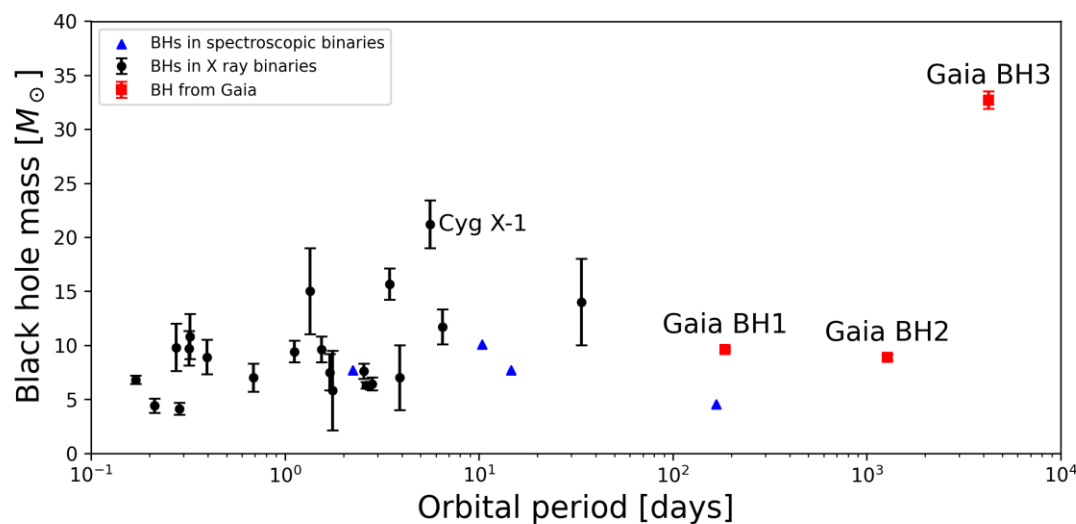
El Badry 2024



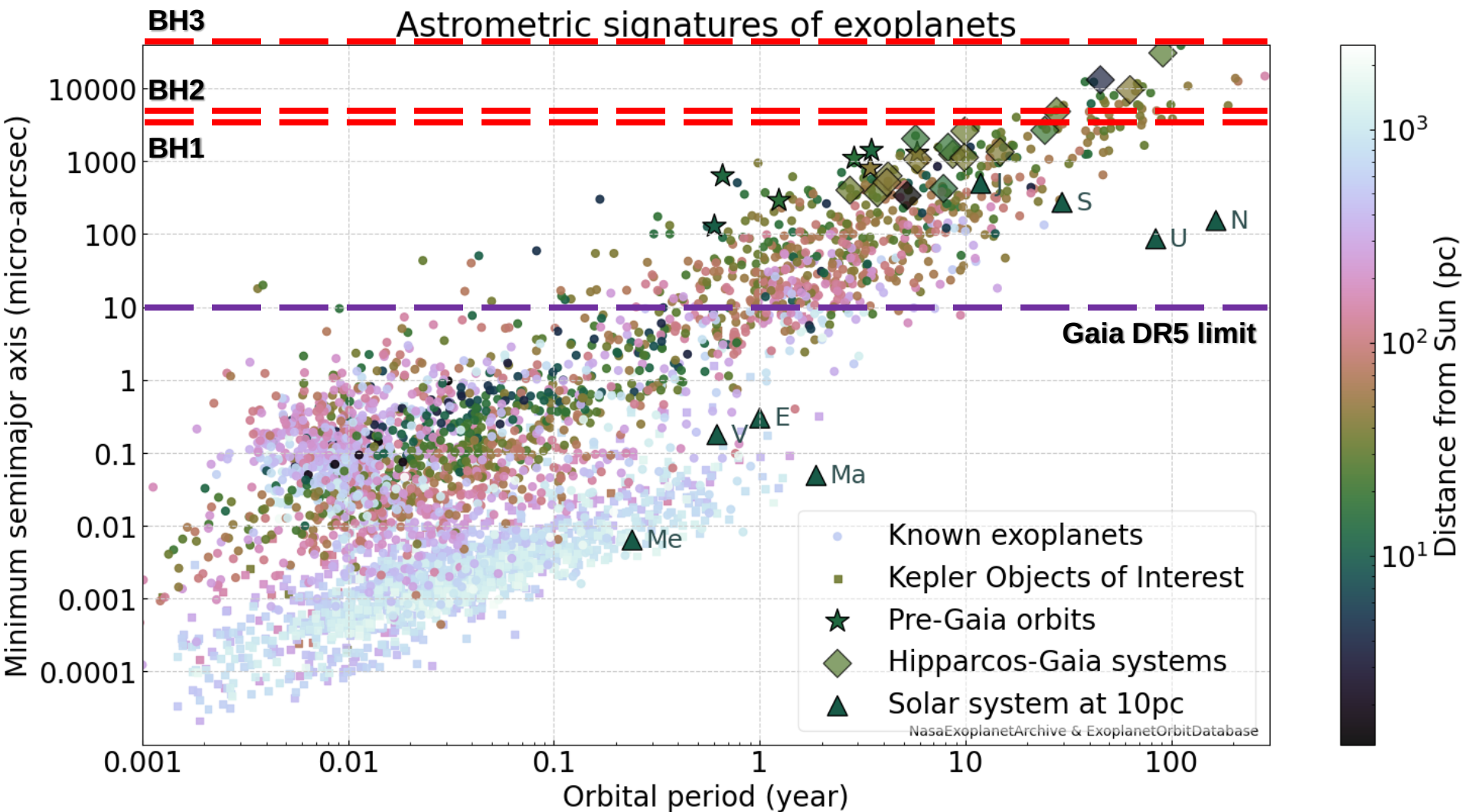
Astrometric orbit



Gaia Collaboration et al. 2024

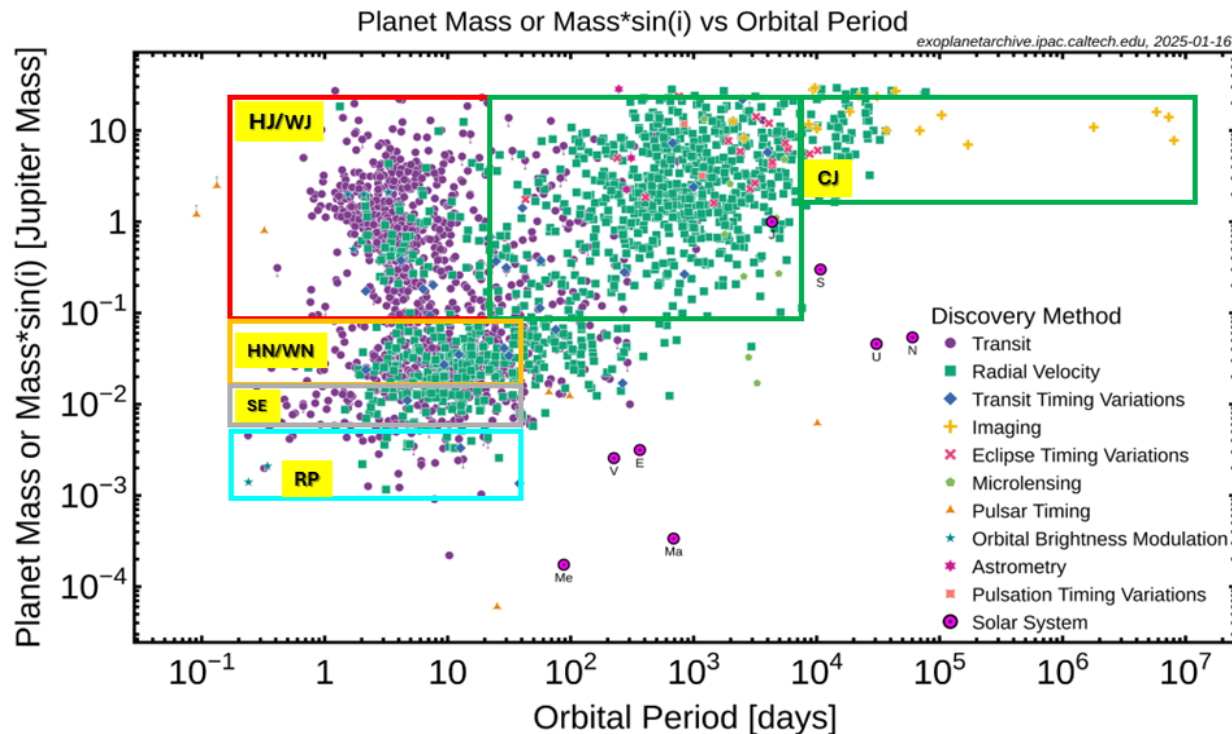


Exoplanet Signatures





Exoplanet Demographics



Today, our Solar System is unlike any others!

Key questions of Giant Exoplanet Demographics Gaia DR4/DR5 will address:

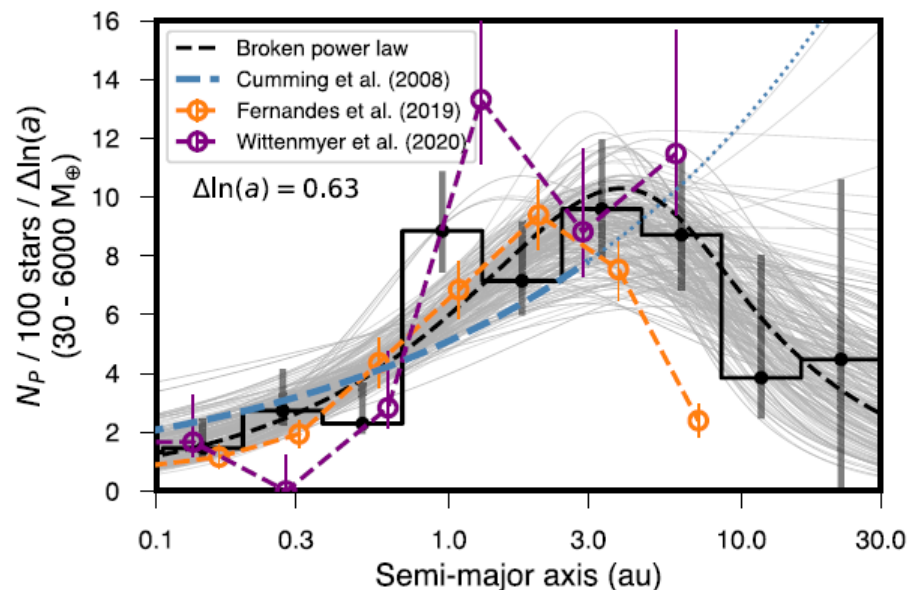
A) What is the dependence of their occurrence rates on orbital properties? **B)** How do their physical and architectural properties depend on stellar and environmental properties? **C)** How common are true Solar System analogs? **D)** What is the mass threshold of the GP-BD transition?



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Separation Distribution



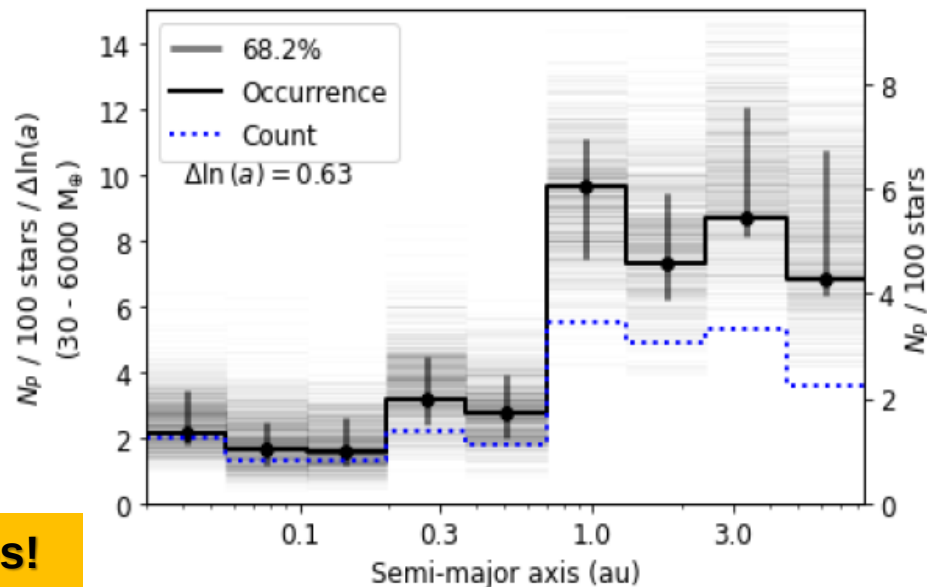
Fulton et al. 2021

Same (RV) technique,
different surveys:
Different answers!

Need well-measured orbits and true masses!

**Giant planet frequency
declines beyond the
snowline
*Or does it?***

Lagrange et al. 2023



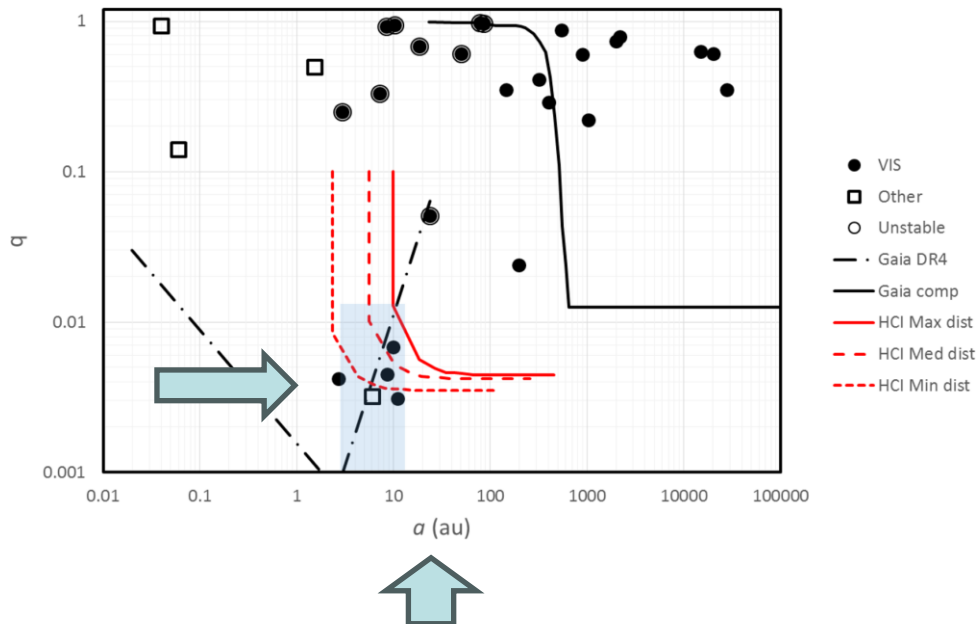


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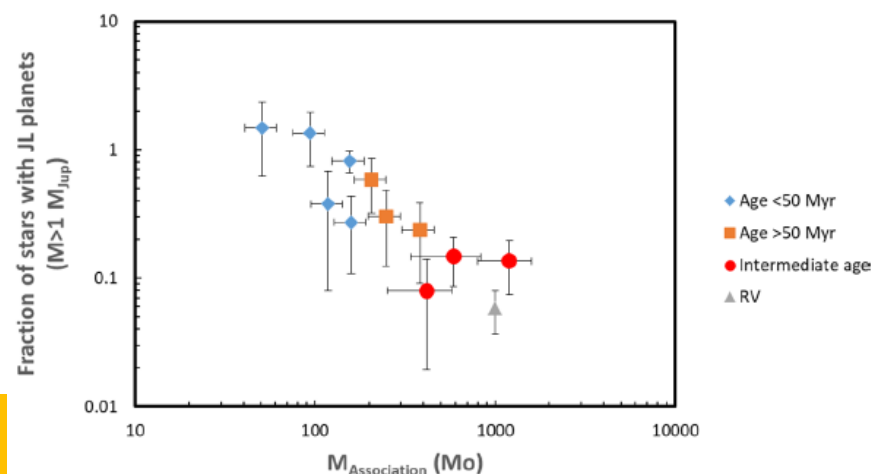
Occurrence Rate of true Jupiters

Gratton et al. 2023



True Jupiters occurrence declines with mass and age of associations

Gratton et al. 2025



Jupiter-like planet occurrence in β Pic moving group 2-3 times higher than for FGK stars in the solar neighbourhood from RV surveys

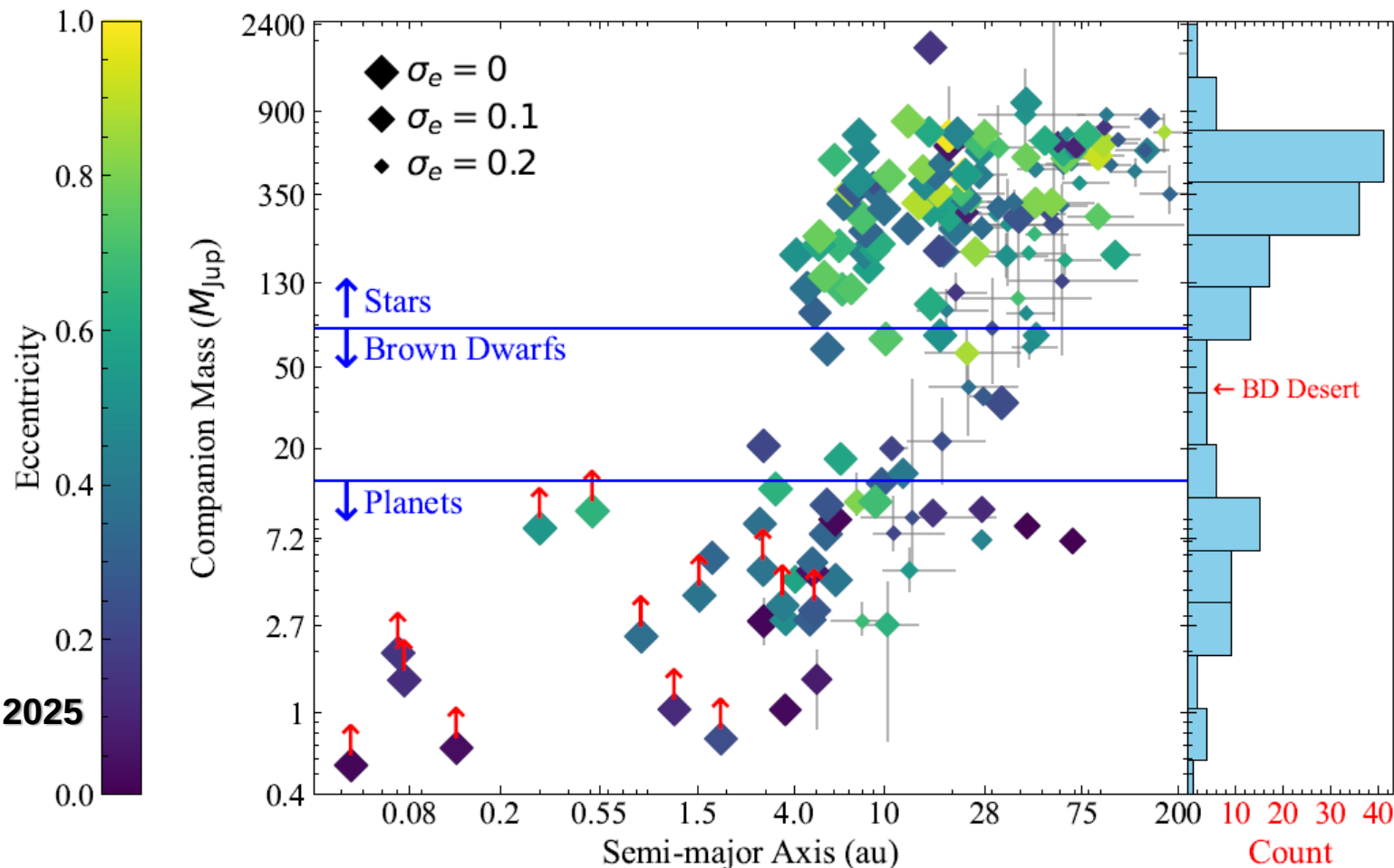
**Key test of formation and evolution models:
It requires well-determined orbits and masses**



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The GP-BD Transition



**Where does the planet mass function really end?
It requires well-determined orbits and true masses**

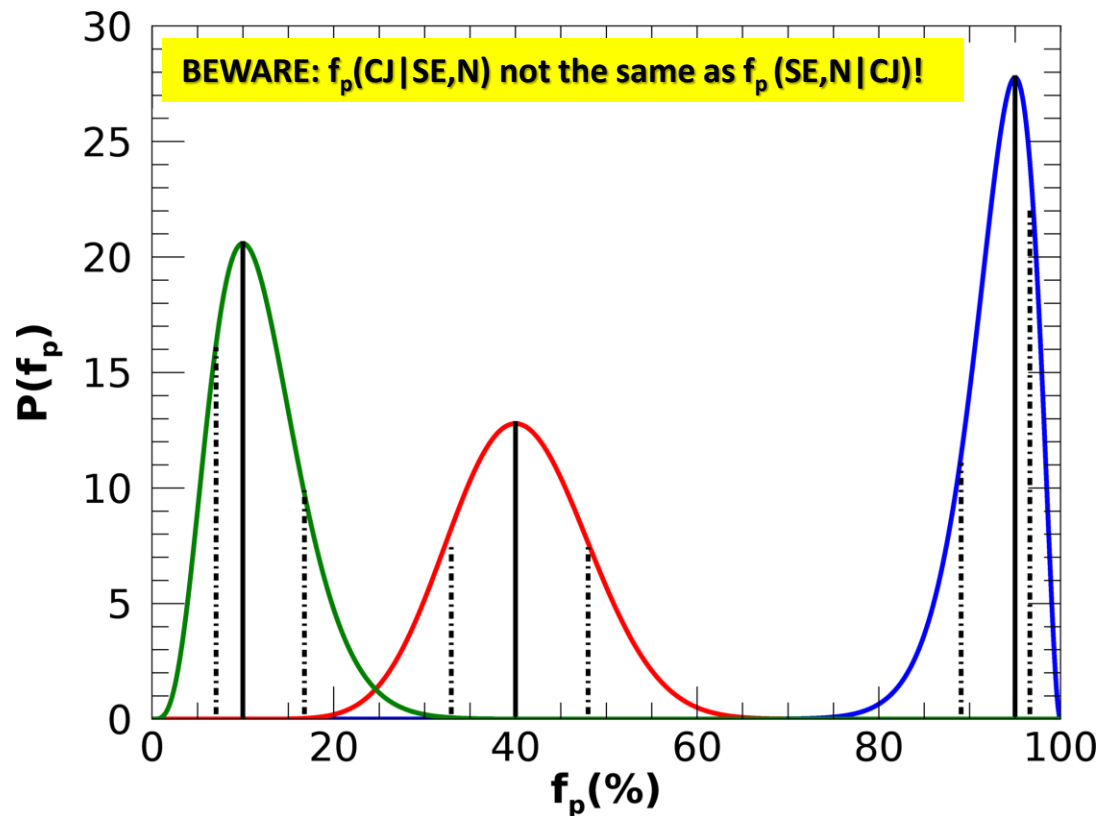


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'Ordered' Architectures: Occurrence

Solar-System-type: *inner Super-Earths (SE) & SubNeptunes (SN), outer Jupiters (CJ)*



Barbato et al. 2018
Zhu & Wu 2018
Bryan et al. 2019
Rosenthal et al. 2022
Pinamonti et al. 2023
Bonomo et al. 2023
Bryan & Lee 2024
Zu 2024
Bryan & Lee 2025
Bonomo et al. 2025
Delisle et al. 2025
Liu et al. 2026

Differences might be due to: sample definitions, survey sensitivities, etc...

High-precision orbits and true masses necessary



Gaia DR3 Astrometry & Exoplanets

- **Astrometric accelerations: true masses of companions**
- **Astrometric accelerations: new detections**

$$w^{(\text{model})} = w_{\text{ss}} = (\Delta\alpha^\star + \mu_{\alpha^\star} t) \sin \psi + (\Delta\delta + \mu_\delta t) \cos \psi + \varpi f_\varpi$$

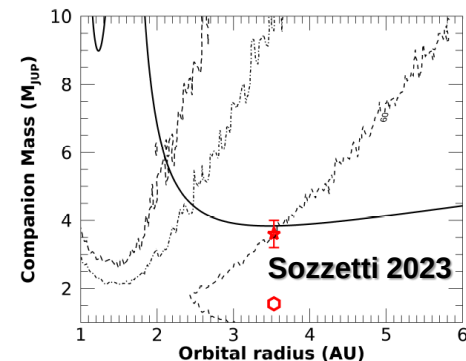
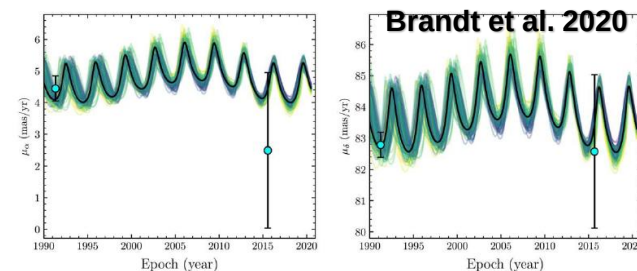
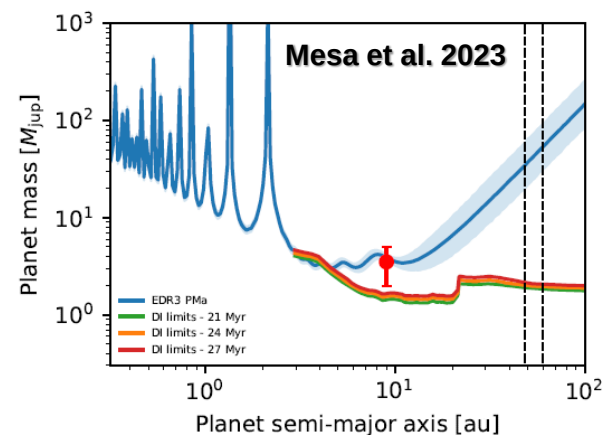
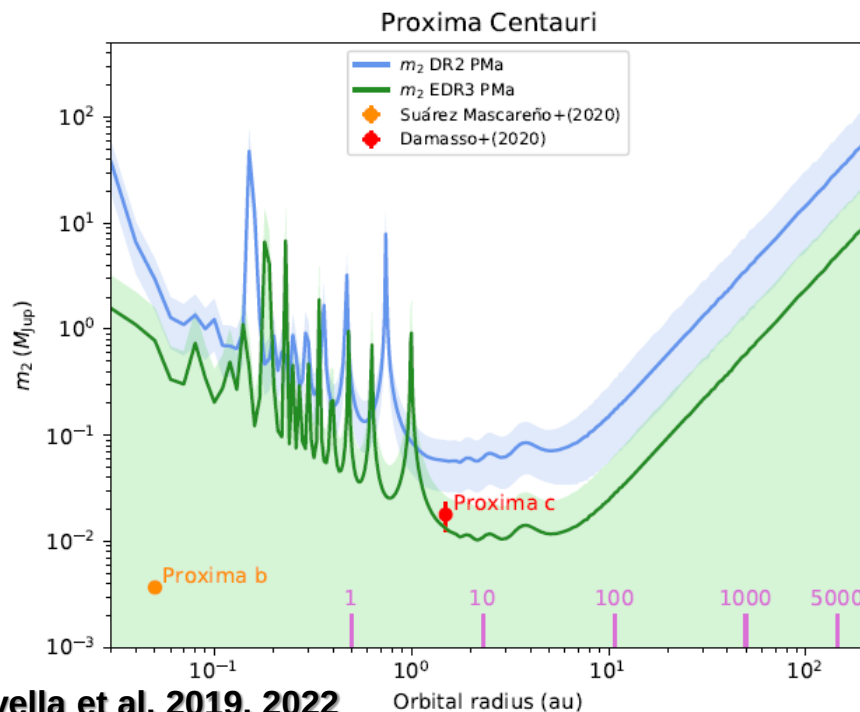
- **Astrometric orbits: Doppler-detected planets**
- **Astrometric orbits: new detections**

$$\begin{aligned} w^{(\text{model})} &= w_{\text{ss}} + w_{\text{k1}} \\ &= (\Delta\alpha^\star + \mu_{\alpha^\star} t) \sin \psi + (\Delta\delta + \mu_\delta t) \cos \psi + \varpi f_\varpi \\ &\quad + (B X + G Y) \sin \psi + (A X + F Y) \cos \psi. \end{aligned}$$



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Gaia DR3: Astrometric Accelerations



Dynamical Beacons:

- Young: HIP 99770 b, AF Lep b, HIP 54515

Dynamical Masses:

- Young: Pic b,c (RV+HCI+PMA)
- Mature: over 100 known planets (RV+PMA)

See talk by G. Piccinini



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Gaia DR3 astrometry: substellar companion orbits

Gaia Collaboration et al. 2023

≈ 1800 orbits



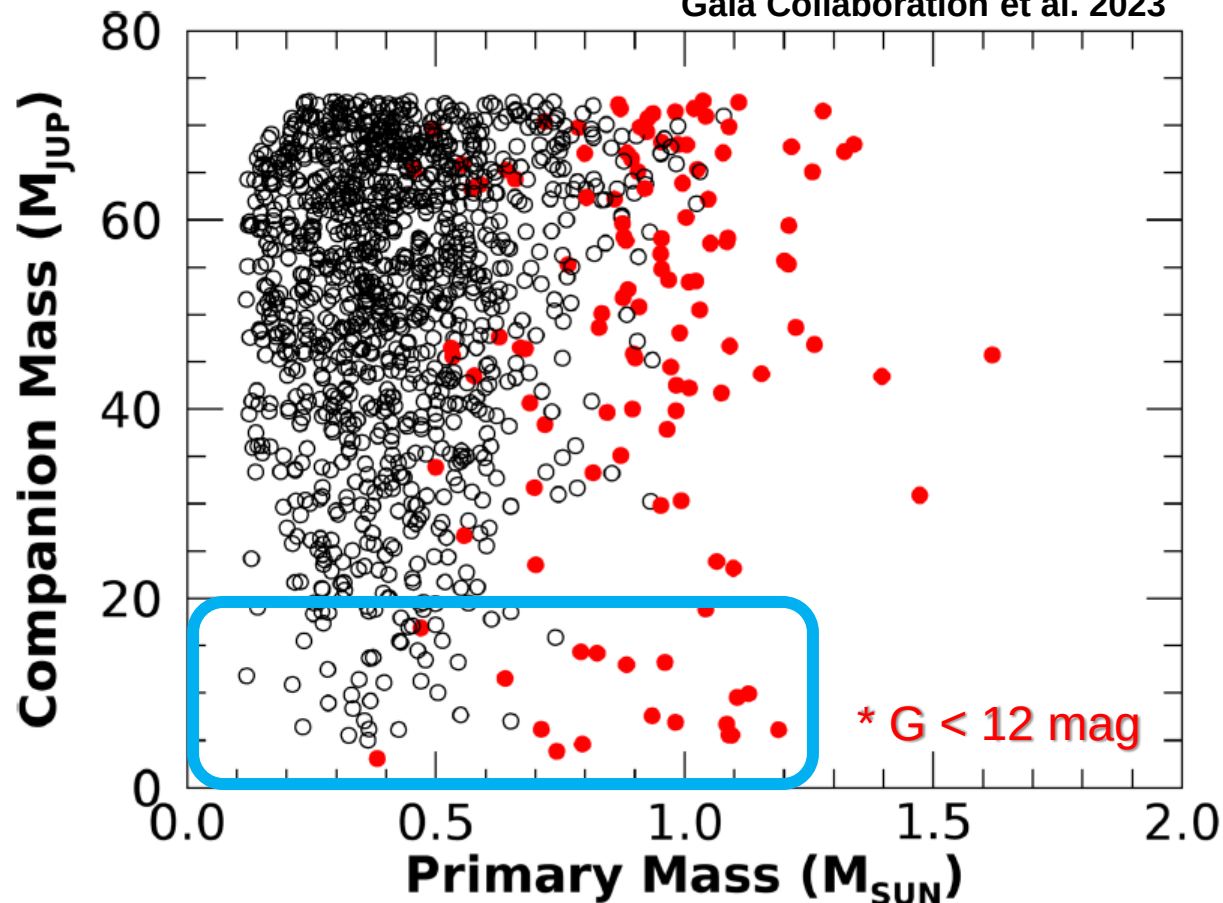
$\approx 5\%$ with $M_2 < 20 M_{\text{Jup}}$



$\approx 30\%$ with $G < 12$ mag

Typically:

- $P < 1000$ days
- $a_0 \approx 100\text{-}400 \mu\text{as}$
- M dwarf hosts



72(9) DR3 solutions corresponding to a planet candidate(known planet)

...BUT... meet masquerading SB2s, astrometry's astrophysical false positives



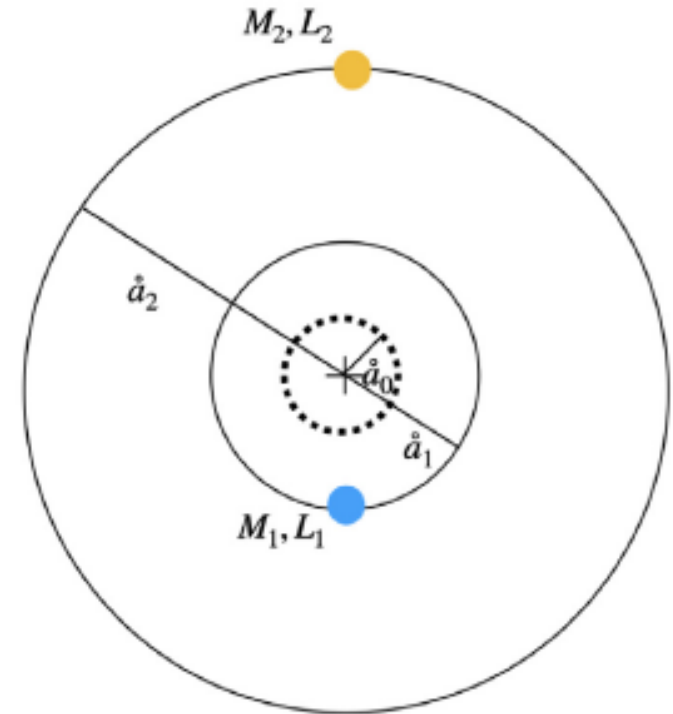
Lurking impostors...

- Masses from $f(M)$:

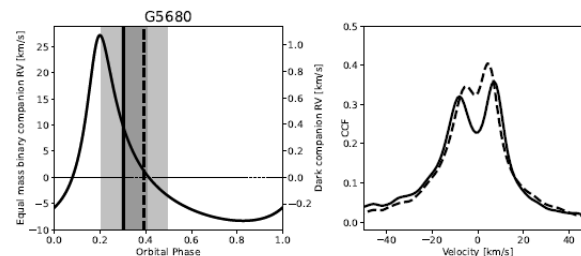
$$(\mathcal{M}_1 + \mathcal{M}_2) \left(\frac{\mathcal{M}_2}{\mathcal{M}_1 + \mathcal{M}_2} - \frac{F_2/F_1}{1 + F_2/F_1} \right)^3 = \frac{(a_0/\varpi)^3}{(P/365.25)^2}$$

- Small $f(M)$ $\rightarrow$ Small M_2 ?
- False positives: $M_2/M_1 \approx F_2/F_1$

El Badry 2024



Unveiled by:
double-peaked CCFs
in high-res spectra



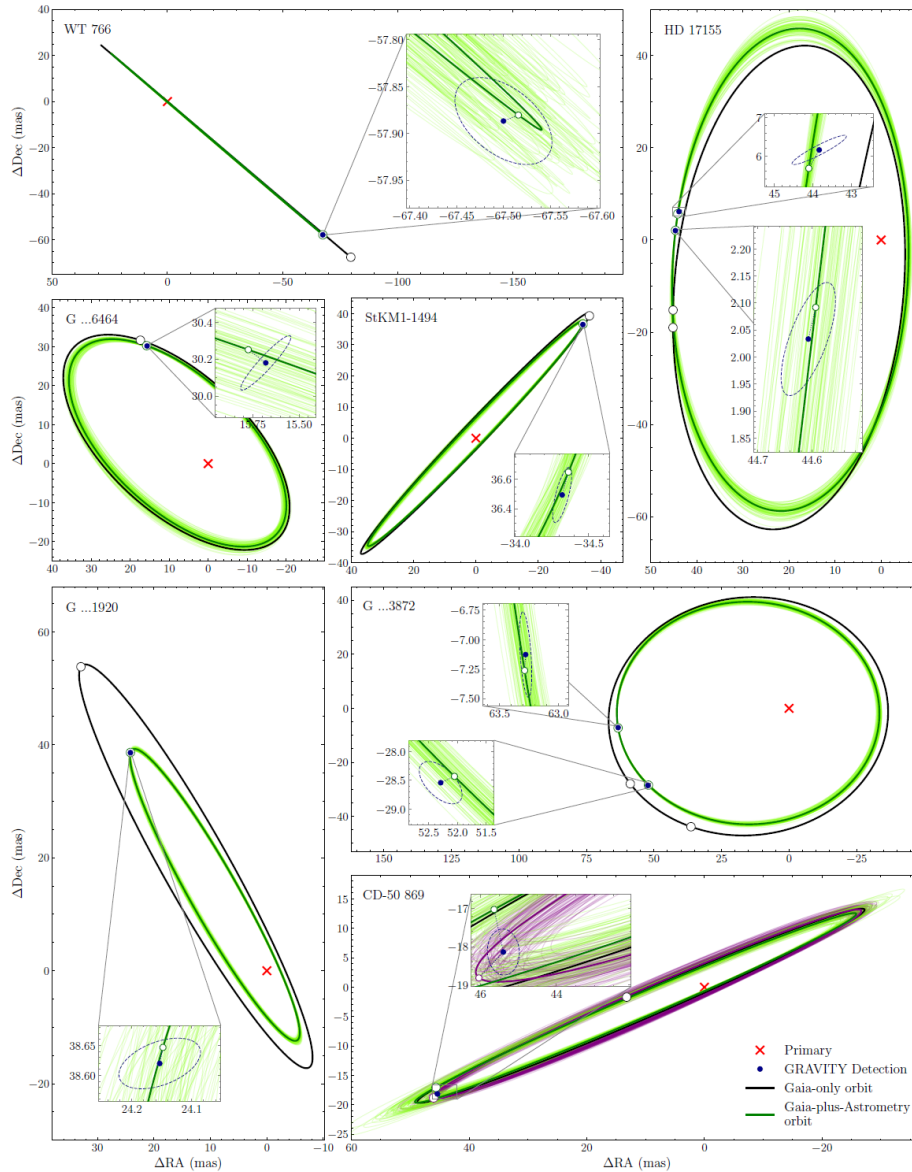
Marcussen & Albrecht 2023



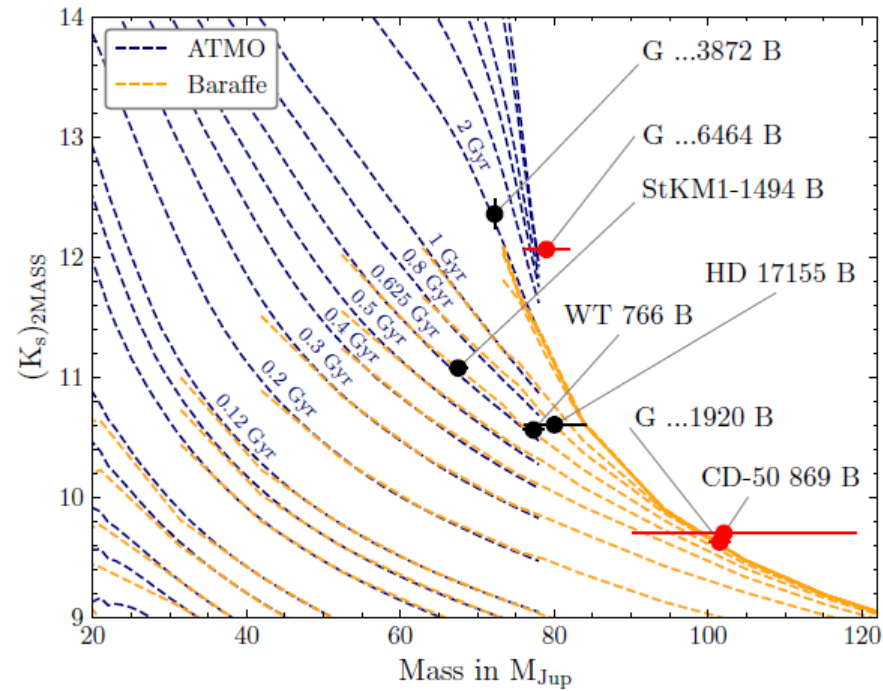
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High-Contrast Imaging Follow-up



BDs, for the time being



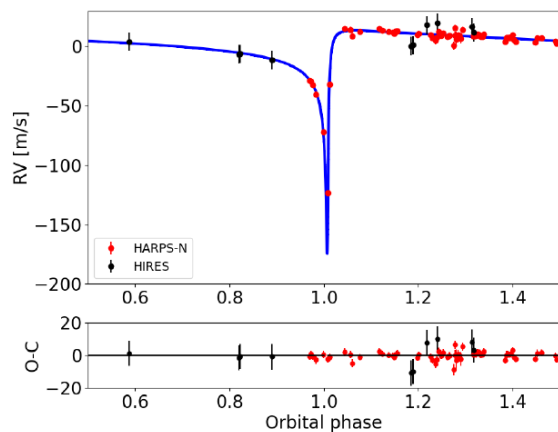
Winterhalder et al. 2024; Pourrè et al. 2024



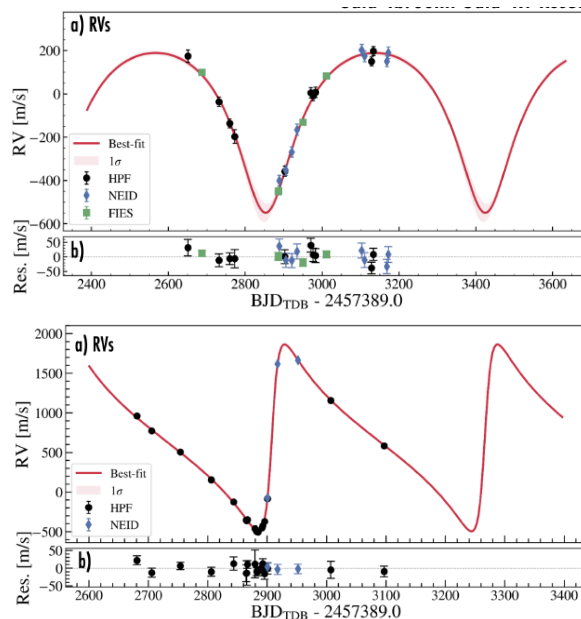
gaia



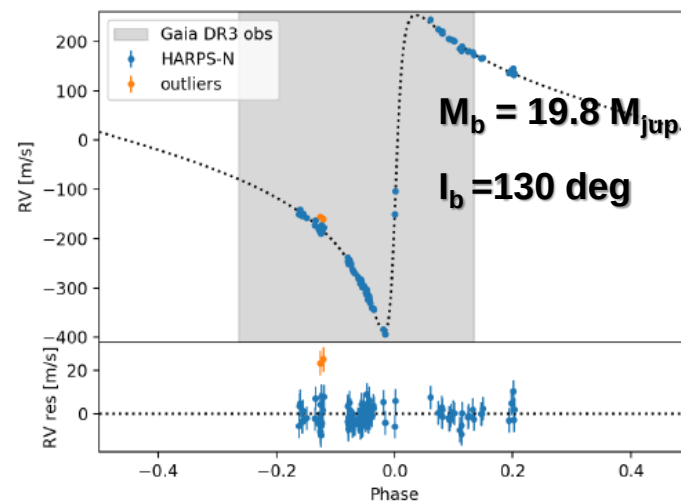
Spectroscopic Follow-up



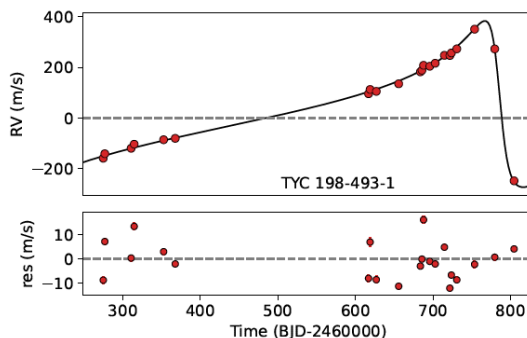
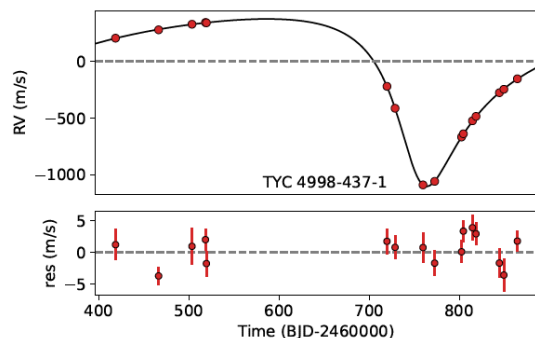
Gaia-3b (Sozzetti et al. 2023)



Gaia-4b/Gaia-5b (Stefansson et al. 2025)



Gaia-6b (Pinamonti et al. 2026)



Six new confirmed Brown Dwarfs
(Barbato et al., A&A)

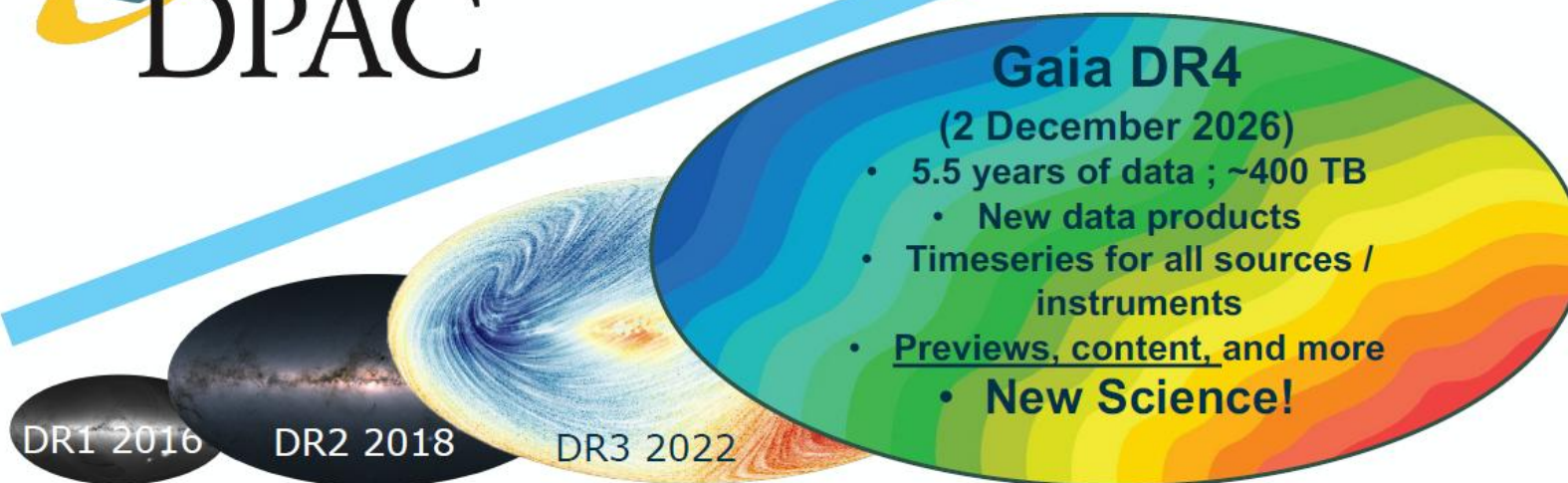
Maybe 50% of candidates (around M dwarfs) are astrophysical false positives

Gaia DR4 Is Coming!

- **Gaia DR4 is the first principal data release**
- **High quality data releases:** science-ready, calibrated, and validated data products; extensive documentation



Courtesy: J. Sahlmann



7

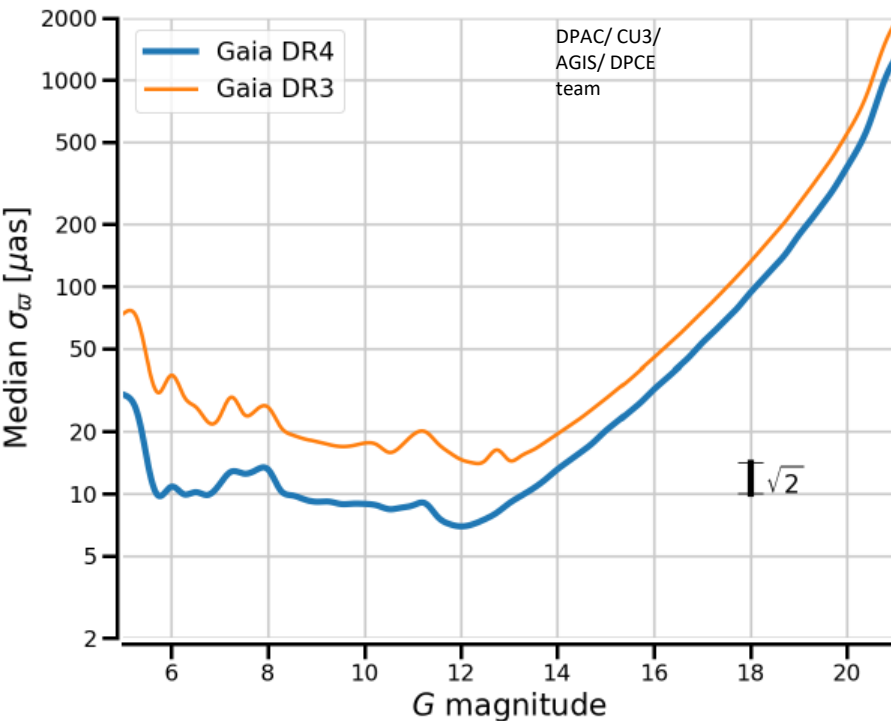


→ THE EUROPEAN SPACE AGENCY

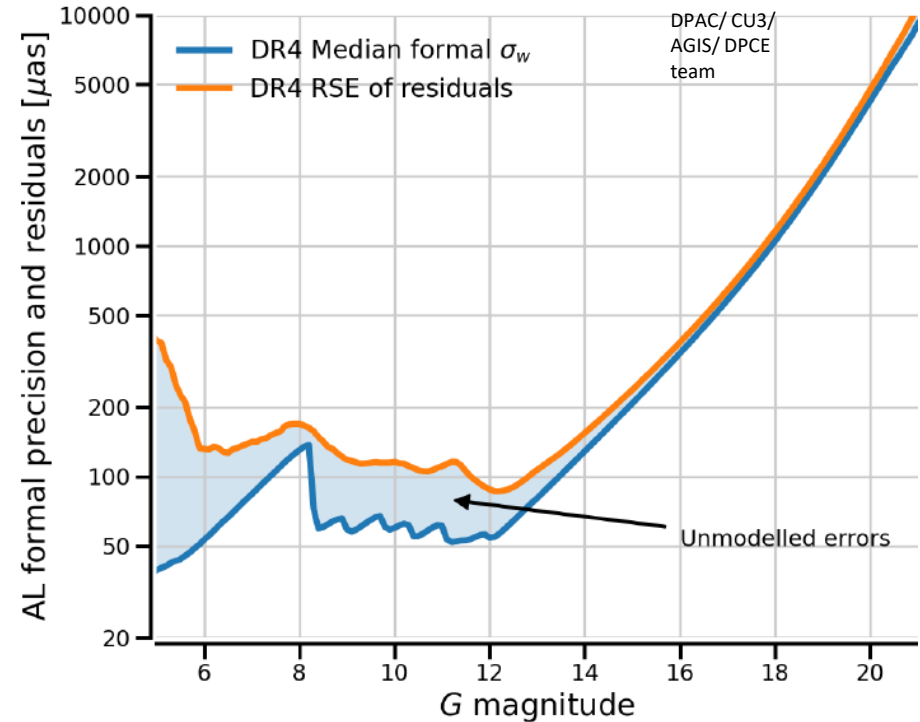


DR4: Astrometry

Courtesy: A. Brown



Expected improvement surpassed for $G < 13$



- Gaia DR4 formal per CCD astrometric uncertainties $\sim 50 \mu\text{as}$ at $G \lesssim 13$ ($\sim 15 \mu\text{as}$ averaged over 9 CCDs)
- But: total uncertainties limited by calibration errors to $\sim 80\text{--}150 \mu\text{as}$ ($30\text{--}50 \mu\text{as}$ averaged over 9 CCDs)



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Gaia (Expected) Discovery Space

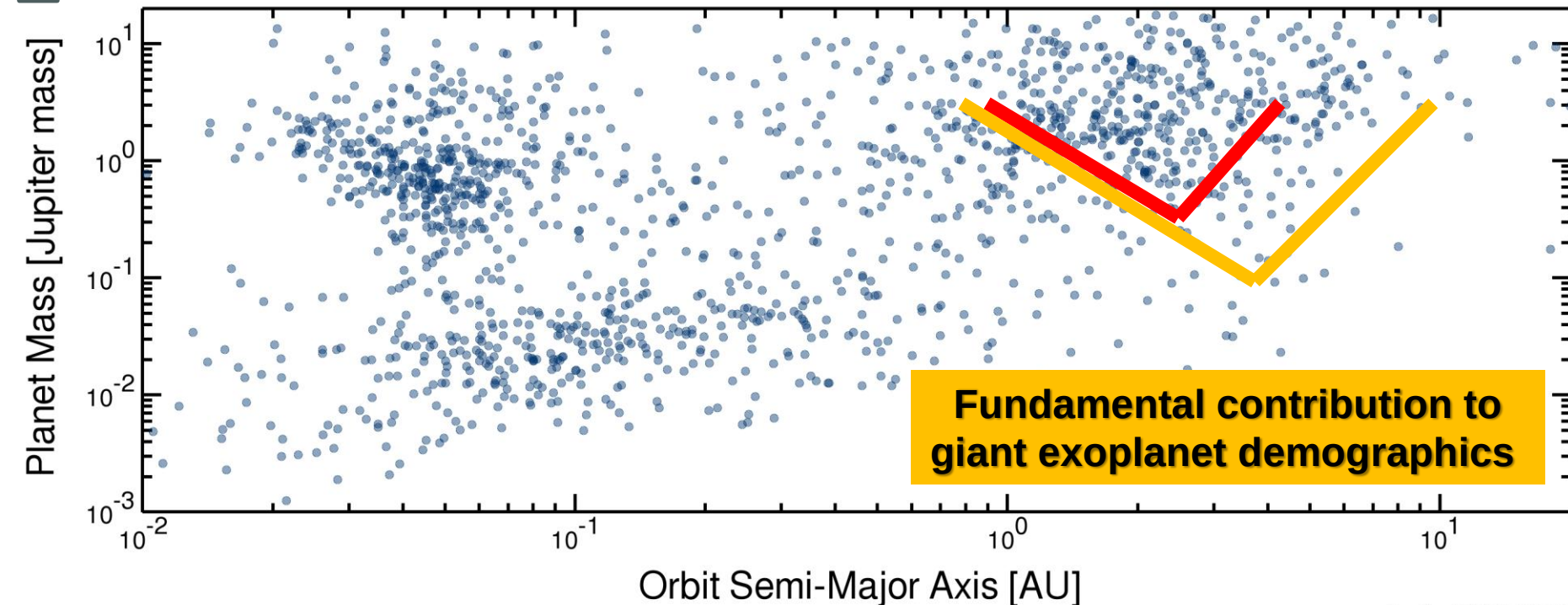


DR4

DR5



Between 1000s and 10000s around A-F-G-K-M hosts



Sun Nov 16 01:41:46 2025

$$\alpha \approx 95.4 \mu\text{as} \left(\frac{m_p}{M_J} \right) \left(\frac{a}{\text{AU}} \right) \left(\frac{M_\star}{M_\odot} \right)^{-1} \left(\frac{r}{10 \text{ pc}} \right)^{-1}$$

The challenge:
detecting robustly signals around 50-100 μas

A word of caution:

large samples of near-threshold candidates might be hard to discern from systematics, biasing occurrence rate calculations



The BIG Questions

A) What is the diversity of planets and planetary system architectures?

B) How do the physical and architectural properties depend on stellar and environmental properties?

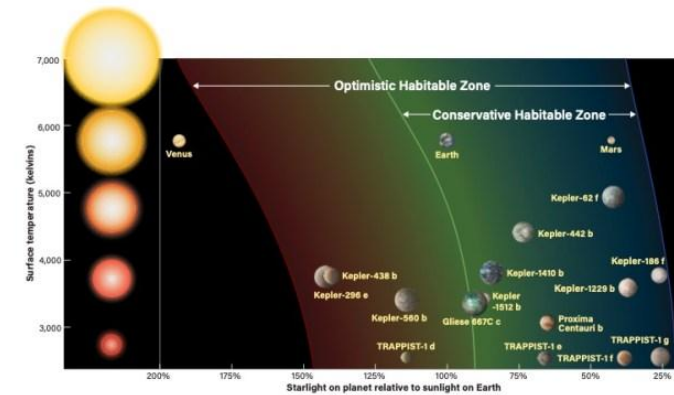
C) How common are true Solar System analogs?

D) Where are the nearest Earth-like planets?

This figure is a log-log plot showing the detection limits for various exoplanet discovery methods as a function of planet mass (M_E) and semi-major axis (AU). The y-axis represents Planet Mass (M_E) from 10^0 to 10^4 . The x-axis represents Semi-major Axis (AU) from 0.01 to 100. The plot includes several detection limit curves: Gaia (solid purple), Gaia+GaiaNIR (dashed purple), μ -lensing today (dotted black), μ -lensing - ROMAN (dotted black), Kepler, PLATO (dash-dotted red), Sub- μ as astrometry (blue dash-dot-dot), 1 m/s PRV (red dashed), Sub-10 cm/s EPRV (red dotted), Transits from the ground (green dashed), and Direct imaging in space (green shaded region). Planets J, S, U, N, V, and E are plotted as green pentagons.

Planet type (planet-radius range in $R_{\oplus}$)	$\eta_{\oplus}$ (planets per star)	Reference	Notes
0.5 – 1.5	$0.37^{+0.48}_{-0.21} - 0.60^{+0.90}_{-0.36}$	Bryson et al. (2021)	F G K dwarfs ^(a)
0.5 – 1.5	$0.58^{+0.73}_{-0.33} - 0.88^{+1.28}_{-0.51}$	Bryson et al. (2021)	F G K dwarfs ^(b)
0.75 – 1.5	$0.13^{+0.09}_{-0.06} - 0.11^{+0.07}_{-0.05}$	Kunimoto & Matthews (2020)	G dwarfs ^(a,b)
0.5 – 1.5	$0.302^{+0.181}_{-0.113}$	Bryson et al. (2020a)	G K dwarfs ^(a,c)
0.5 – 1.5	$0.126^{+0.095}_{-0.055}$	Bryson et al. (2020a)	G K dwarfs ^(a,d)
0.7 – 1.5	$0.11^{+0.06}_{-0.04}$	Pascucci et al. (2019)	F G K dwarfs ^(a,f)
0.7 – 1.5	$0.05^{+0.07}_{-0.03}$	Pascucci et al. (2019)	F G K dwarfs ^(a,g)
0.75 – 1.5	$0.33^{+0.10}_{-0.12}$	Hsu et al. (2020)	M dwarfs ^(a)
0.75 – 1.5	0.04 – 0.40	Hsu et al. (2019)	G K dwarfs ^(e)
0.85 – 1.4	0.33	Hsu et al. (2019)	G K dwarfs ^(a)
0.72 – 1.7	0.34 ± 0.02	Zink & Hansen (2019)	G dwarfs ^(a)
1.0 – 1.5	$0.41^{+0.29}_{-0.12}$	Hsu et al. (2018)	G K dwarfs ^(h)
1.0 – 1.5	$0.31^{+0.02}_{-0.03}$	Garrett et al. (2018)	G dwarfs ^(a)
0.5 – 1.5	$0.88^{+0.04}_{-0.03}$	Garrett et al. (2018)	G dwarfs ^(a)
0.5 – 1.0	$0.215^{+0.148}_{-0.099}$	Kopparapu et al. (2018)	G dwarfs ⁽ⁱ⁾
1.0 – 1.75	$0.145^{+0.071}_{-0.061}$	Kopparapu et al. (2018)	G dwarfs ^(j)
0.7 – 1.5	0.36 ± 0.14	Mulders et al. (2018)	G stars ^(a)
1.0 – 1.5	$0.16^{+0.17}_{-0.07}$	Dressing & Charbonneau (2015)	M dwarfs ^(a)
1.5 – 2.0	$0.12^{+0.10}_{-0.05}$	Dressing & Charbonneau (2015)	M dwarfs ^(a)
1.0 – 1.5	$0.21^{+0.08}_{-0.08}$	Burke et al. (2015)	G dwarfs ^(k)
0.5 – 1.5	$0.50^{+0.40}_{-0.20}$	Burke et al. (2015)	G dwarfs ^(k)
1.0 – 2.0	$0.064^{+0.034}_{-0.011}$	Silburt et al. (2015)	F G K dwarfs ^(l)
0.6 – 1.7	$0.017^{+0.018}_{-0.009}$	Foreman-Mackey et al. (2014)	G dwarfs ^(a)
1.0 – 2.0	0.00059	Schlaufman (2014)	G stars ^(m,n)
1.0 – 2.0	$0.057^{+0.022}_{-0.017}$	Petigura et al. (2013b)	G stars ^(m)
0.5 – 1.4	$0.15^{+0.13}_{-0.06}$	Dressing & Charbonneau (2013)	M dwarfs ^(a)
0.5 – 1.4	$0.48^{+0.12}_{-0.24}$	Kopparapu (2013)	M dwarfs ^(a)
0.5 – 2.0	0.34 ± 0.14	Traub (2012)	F G K dwarfs ^(o)
0.8 – 2.0	$0.028^{+0.019}_{-0.009}$	Catanzarite & Shao (2011)	F G K dwarfs ^(p)
0.5 – 3.0	2.75 ± 0.33	Youdin (2011)	G dwarfs ^(q)

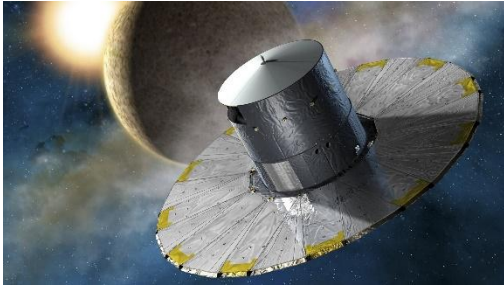
Earth Twins: Occurrence Rates



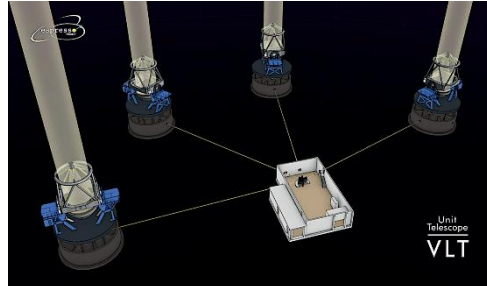
**Within 1-2 sigma:
 $\eta_{\oplus}$ may be 9%, or 90%...
...and just an extrapolation!**



The Gaia-RV-PLATO Synergy



+



+



Take 2×10^4 P1 PLATO targets (bright, nearby FGK dwarfs):

- Achieve homogeneous sensitivity to Earth-like transiting planets
- EPRV follow-up for mass confirmation for all of them
- Gaia DR4 & DR5 deliver homogeneous sensitivity to gas giants on Jupiter-like orbits

Determine $\eta_{\oplus}$ and η_{ss} for the first time without extrapolations!



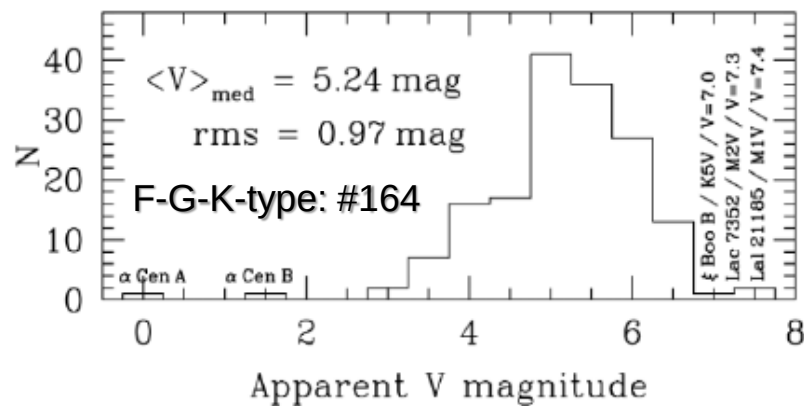
gaia



Earth-Like Planets: The Ultimate Frontier

Habitability and atmospheric biosignatures of temperate terrestrial exoplanets around the nearest solar-type stars

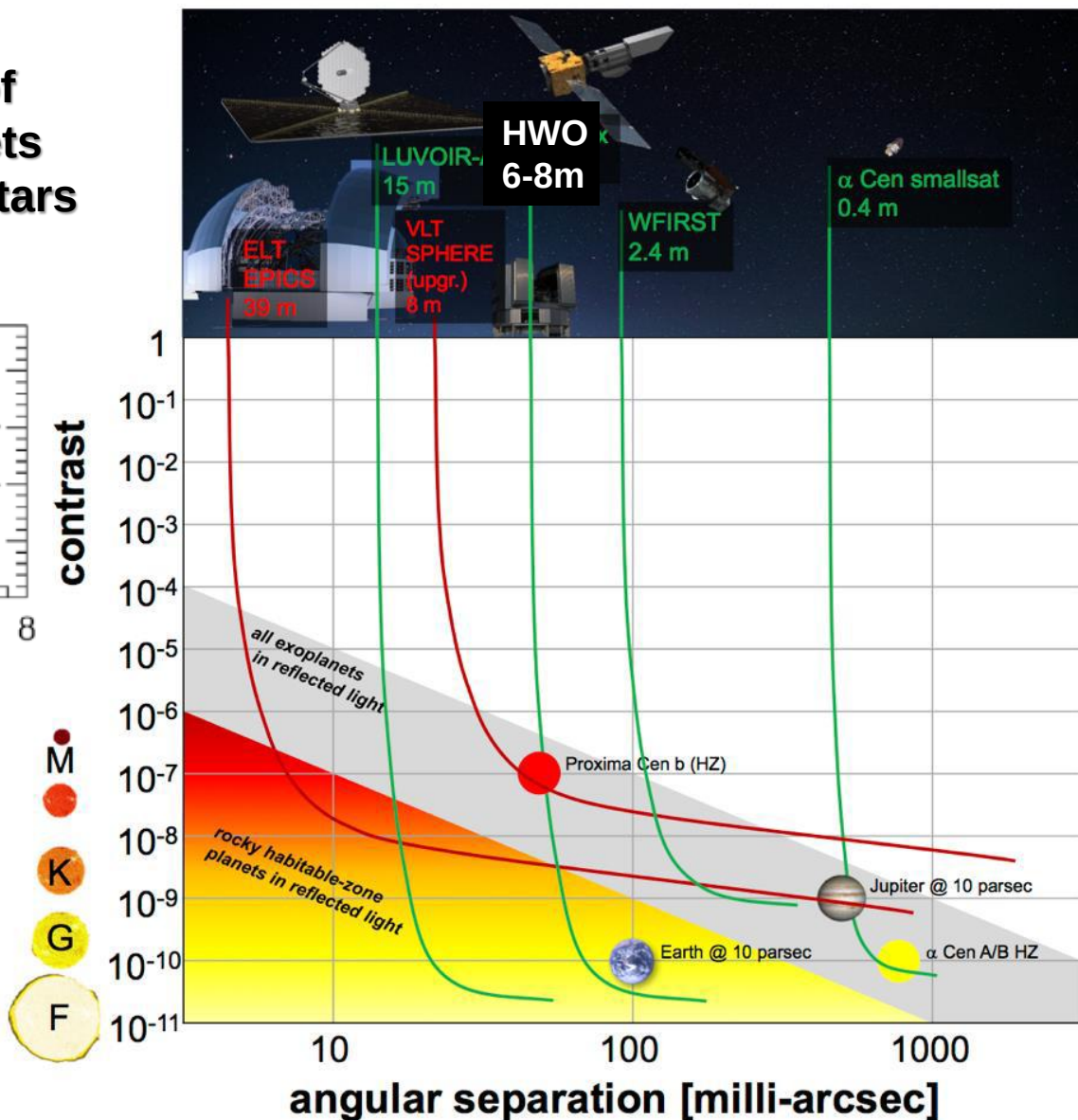
Mamajek & Stapelfeldt 2024



Knowledge of orbits and masses is mandatory in order to maximize science return

True Earth twin:
 $K = 9 \text{ cm/s}$, $\alpha@10\text{pc} = 0.3 \mu\text{as}$

PIAZZI 200: NEW FRONTIERS IN ASTROMETRY





Astrometry: Post-Gaia Outlook

GaiaNIR (2045-2050)

- NIR global astrometry
- Gaia-like precision

Exoplanet demographics

Census of Jupiter+Saturn-like systems
around stars of varied M, age, [Fe/H]



Frequency of true Solar-System analogs

Theia (2040+)

- Visible differential astrometry
- Precision 30x better than Gaia's

Exoplanet demographics

Census of temperate terrestrial planets
around the nearest solar-type stars



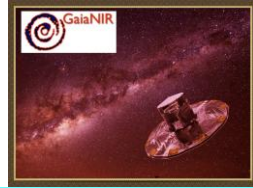
*Precursor science for HWO and LIFE to search
for atmospheric biomarkers*



Or, using HWO itself, or both



GaiaNIR Astrometry

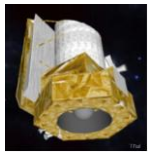


See talk by L. Prisinzano

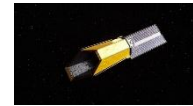
- *Cold giant planets around* stars Gaia can hardly see (*heavily reddened young stars within 200-300 pc*) or cannot see at all (*L, T and Y dwarfs within 20-30 pc*)
- Detection of *gas giants at Saturn-like distances*, combined with Gaia: the *demographics of exoplanets at 5-10 au around solar-type stars* is still vastly *unexplored/uncertain*
- First-ever estimate of the *frequency of planetary systems* with *BOTH Jupiters AND Saturns*
- *Cold Neptunes and Super Earths beyond the snowline around* the *nearest* low-mass *M dwarfs* (proper motion anomaly)



gaia



Theia/HWO Astrometry



- Determine the *true mass function of temperate $1-5 M_{\oplus}$ rocky planets around solar-type stars*, which is today *completely unknown*
- Measure *the true masses and 3-d architecture in multiple systems* to allow for the first time full *demographics studies* of planetary systems in the presence of *temperate telluric planets* around the nearest Sunlike stars, in high *synergy* with *Gaia* and *Doppler surveys*

Stellar type	Number of stars	Number of B comp.
F	16	2
G	17	1
K	22	9

- Revised estimates of Theia sensitivity indicate that the median detectable mass across the full HZ for this stellar sample is $\simeq 1.1 M_{\oplus}$.

- Very low impact of stellar activity

Meunier & Lagrange 2022

A Final Comment

- **225 years** since the G. Piazzi's discovery of the **dwarf planet Ceres**
based on 1 arcsec astrometric precision
- **High-precision astrometry** is revolutionizing today our *understanding* of the Milky Way Galaxy, boosting improvement in countless topics of Astronomy and Astrophysics
- **10 μ as astrometry** (10^5 better than available to Piazzi) is enabling fundamental contributions to **giant exoplanet demographics**
- Breaking the **1 μ as** barrier will not allow to identify Ceres analogues in other planetary systems, but will open the door to detection of **True Earth analogues**

The legacy of fundamental stellar position measurements lives on