Exoplanetary Astrophysics

Professor Giampaolo Piotto

Adriana Barbieri
Master Degree in Astrophysics and Cosmology
University of Padova
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Università degli Studi di Padova
Dipartimento di Fisica e Astronomia Galileo Galilei

A RICH POPULATION OF FREE-FLOATING PLANETS IN THE UPPER SCORPIUS YOUNG STELLAR ASSOCIATION

- Miret-Roig, N., Bouy, H., Raymond, S.N. *et al.*
- https://arxiv.org/abs/2112.11999
- arXiv.org>astro-ph.EP
- Submitted on 22 December 2021
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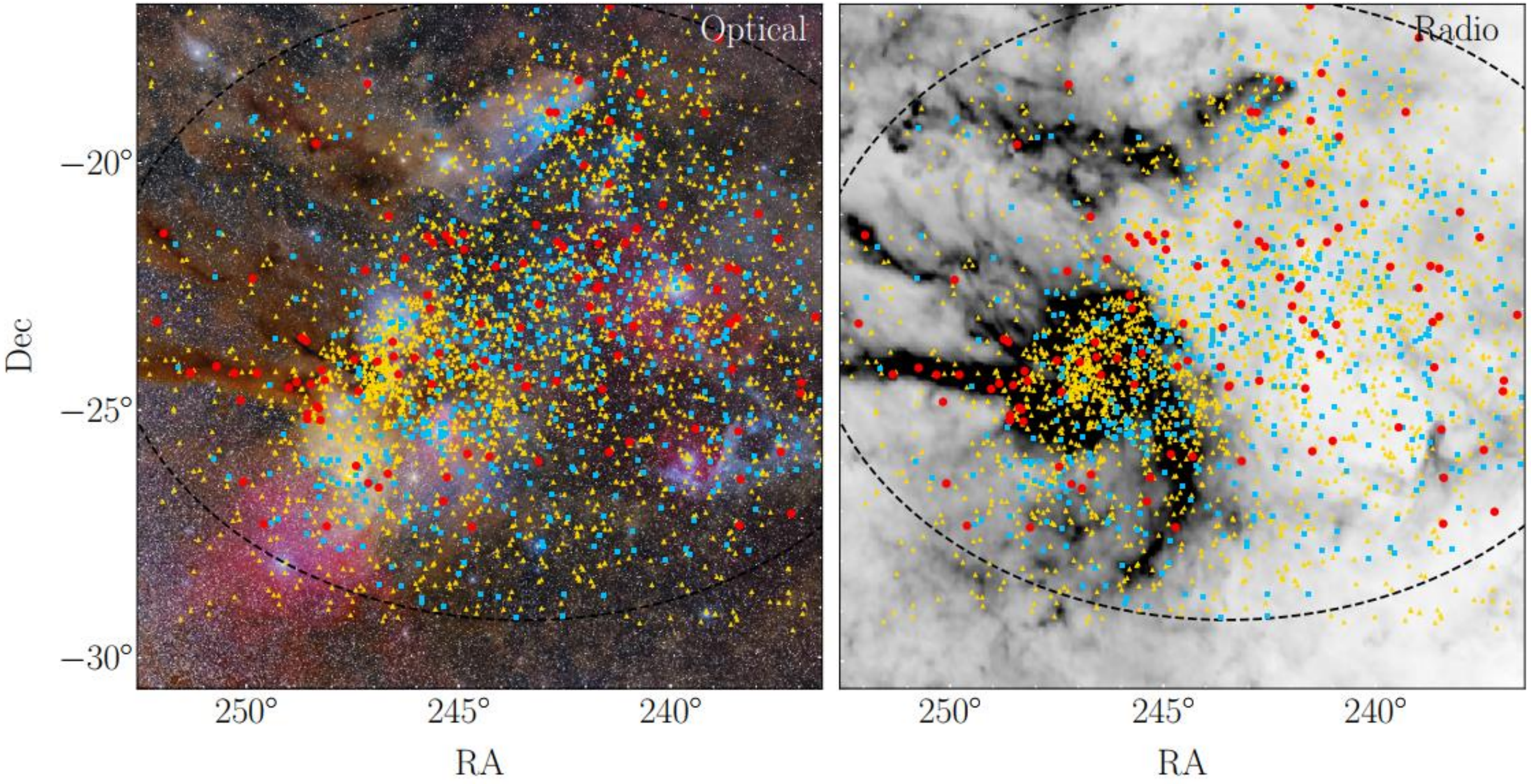
INTRODUCTION

- Free-floating planets (FFPs) are compact planetary-mass objects (M < 13 MJ) that are not bound to host stars.
- Ultra-faint objects incapable of sustaining nuclear fusion and steadily fading in time: easier to observe at a young age.
- 171 deg^2 area encompassing Upper Scorpius OB stellar association and Ophiucus region
- Selected region ≈ 120–145 pc away from Earth (≈420 light-years) and 1–10 Myr old
- 80,000 wide-field images collected over 20 years of observations.
- At least 70 (up to 170 candidates) new rogue planets in our galaxy: largest homogeneous sample of nearly coeval FFPs discovered to date using direct images.

REGION OF INTEREST



- Sky distribution of stars (gold triangles), brown dwarfs (blue squares), and FFPs (red dots/circles) discovered in this study and classified assuming an age of 5 Myr

UNCERTAINTIES

- Planetary-mass members are several thousand times fainter than stars and can only be detected with large aperture telescopes and sensitive detectors.

- The rare planetary-mass members must be identified within the overwhelming multitude of field stars and background galaxies.

- The uncertainty in the number of discovered FFPs comes from the lack of precise ages:
  - Objects with 13 < M < 80 M_J are called brown dwarf or failed stars and must be excluded from the count
  - An upper limit on the mass of the objects was inferred from their brightness (not direct measurement)
  - The brightness is age-dependent
  - The age of the selected stellar association is known only to a given certainty
  - As a result, it is easy to confuse a young low-mass planet with a slightly older and more massive one.

- Our analysis is expected to miss the objects most affected by extinction (A_V> 3 mag), as well as those displaying a large ΔNIR related to the presence of circumstellar material.
  - The completeness of our census is expected to be better in USc than in Oph given the more advanced age and timescale for disc decay.

DETECTION METHODS

- Microlensing surveys
  - Indirect method, successful down to a few Earth masses
  - Ephemeral nature of micro-lensing events prevents any follow-up observations and individual characterisation of FFPs

- Astro-photometric surveys
  - Positions + proper motions + multi-wavelenght photometry
  - In this study ground-based observations in the optical and IR were combined with wide-field images available in various public archives, for a total of 80818 analysed images acquired over 20 years.

GROUND-BASED FACILITIES

- ESO's VLT, VISTA, VST, MPG/ESO 2.2m
- NSF's NOIRLab
- the CHFT
- the Subaru Telescope
- the Isaac Newton Telescope

CATALOGUES FROM SPACE AND GROUND SURVEYS

- Gaia Data Release 2 (Gaia DR2)

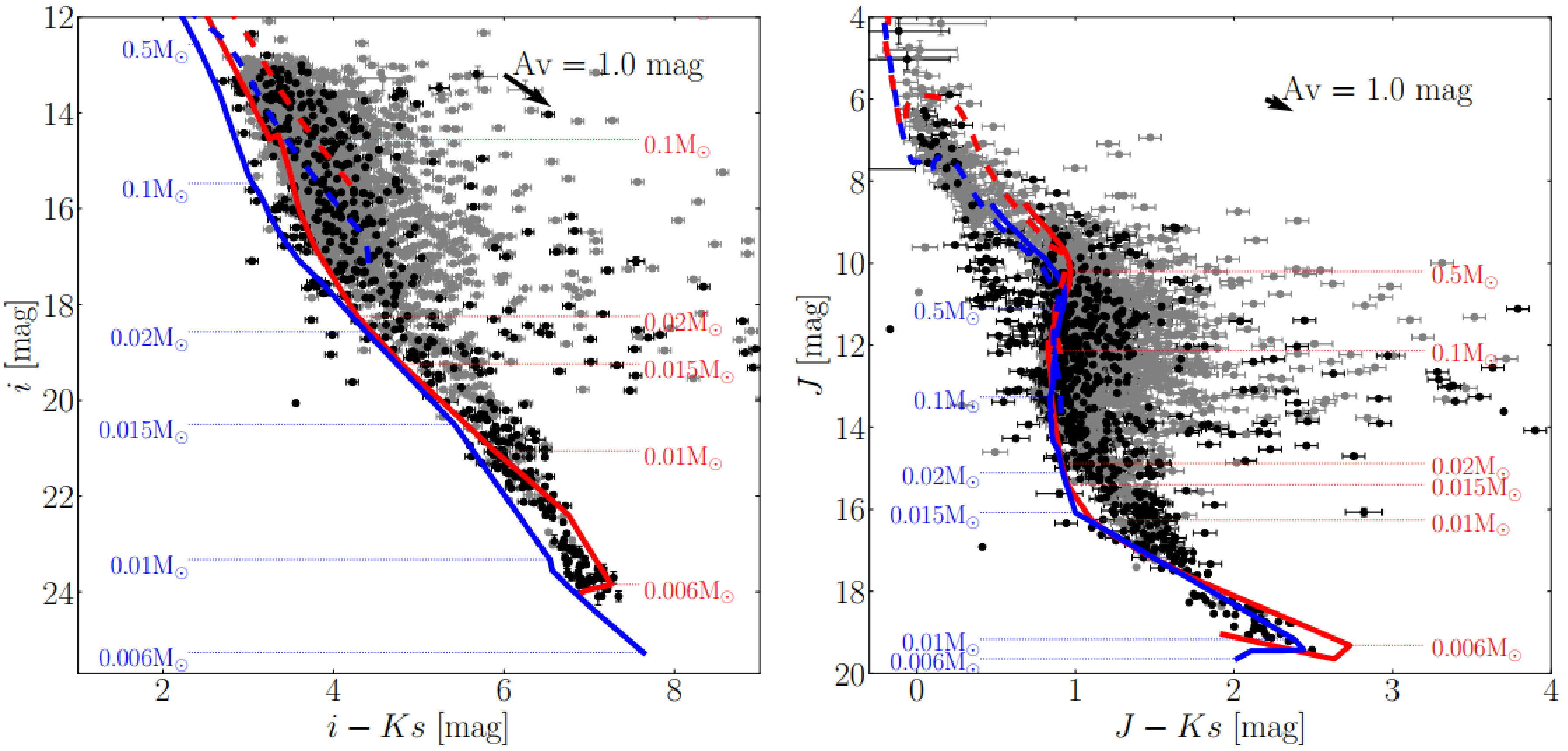
- Hipparcos catalogue

- COSMIC DANCe (Dynamical Analysis of Nearby ClustErs) project
  - Automated astrometry from the ground and precise proper motions over wide field

ANALYSIS

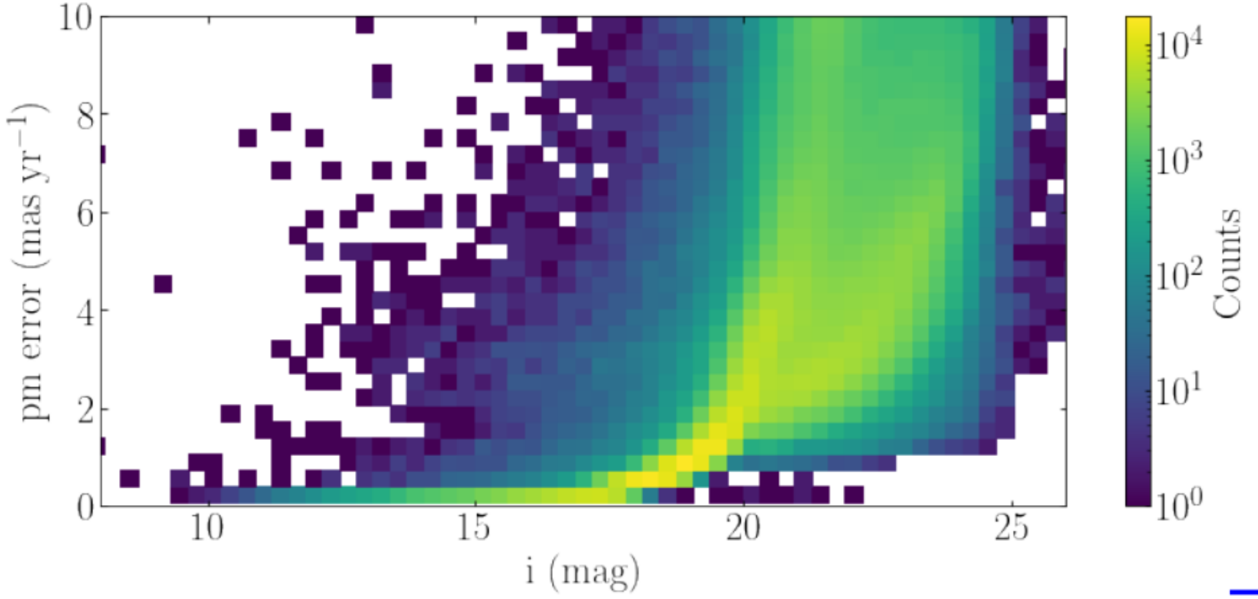
- The DANCe catalogue was complemented with the astrometry and photometry of Gaia DR2 and Hipparcos catalogue
- Probabilistic model of the observables' distribution (parallaxes, proper motions and photometry) applied to the cluster and background field populations: maximum likelihood approach and Bayesian analysis
- Chosen parameter space containing the largest amount of parameters and sources with complete information, namely proper motions and *iJHK* photometry
- De-contamination from members of globular cluster NGC 6121, background reddened giant stars and background Galaxies
- Field and cluster modelled by a Gaussian mixture model (GMM) selected with a Bayesian information criterion (BIC)

PHOTOMETRIC MEASUREMENTS



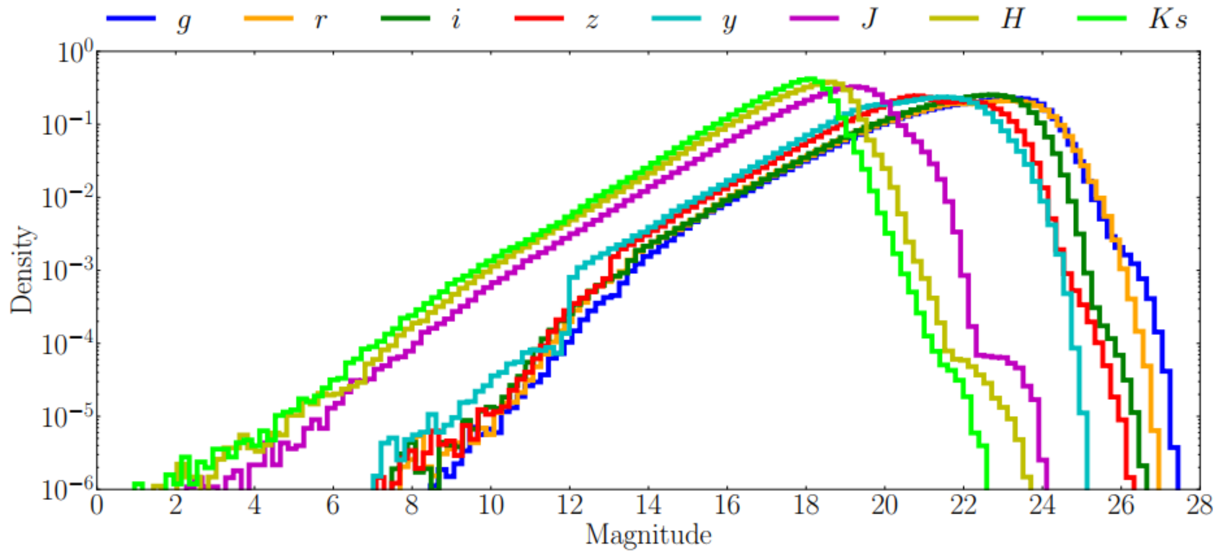
- Color-magnitude diagram of the members of USC and Oph identified in this work: previously known members (gray) and new members (black)

ASTROMETRIC MEASUREMENTS

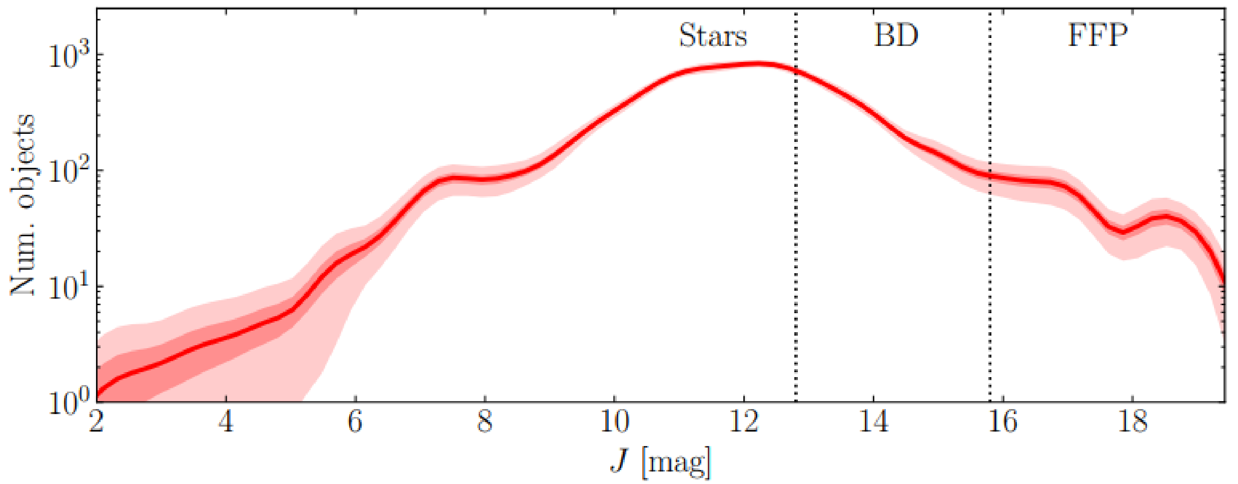


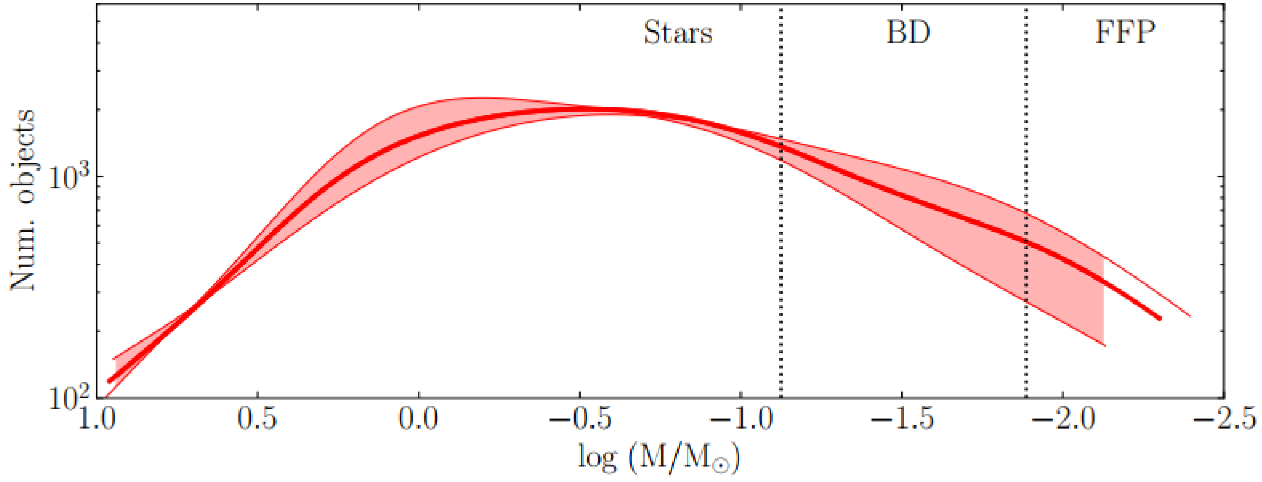
- Estimated proper motion error as a function of *i* magnitude for the DANCe catalogue.

- Number density as a function of magnitude for all the sources in the DANCe catalogue



MAGNITUDE/MASS DISTRIBUTION





- J apparent magnitude distribution:
  - high density of very faint objects
  - dip at J ~ 17.8 mag, corresponding to M_J ~ 12 mag and masses 7–13 M_J
  - the young ages of USC and Oph (1–10 Myr) suggests that it must be the result of the formation and/or early evolution of these objects
- Mass function of the region (number density of members as a function of their masses) constitutes a fundamental constraint for formation theories because different mechanisms predict different relative abundances of stellar, sub-stellar and planetary mass objects

FORMATION MECHANISMS

- Core-collapse model
- Core accretion or gravitational fragmentation of massive extended discs
- Ejection from planetary systems due to dynamical instabilities (p-p scattering)
- Aborted stellar embryos ejected from a stellar nursery
- Photoerosion of a prestellar core by 0-B stellar winds

$$
\begin{aligned}
f_{\text{FFP observed}} &= f_{\text{FFP ejected}} + f_{\text{FFP core collapse}} + f_{\text{FFP other}} \\
&= f_{\text{giant}} \cdot f_{\text{unstable}} \cdot n_{\text{ejected}} + \int_{4\ \mathrm{M}_{Jup}}^{13\ \mathrm{M}_{Jup}} \xi_{\text{core collapse}}(m)\, dm + f_{\text{FFP other}}
\end{aligned}
$$

RESULTS

- We found an excess of FFPs by a factor of up to seven compared to core-collapse models predictions:
  - other formation mechanisms may be at work.
- Ejection from planetary systems might have a contribution comparable to that of core-collapse in the formation of FFPs.
  - Ejections due to dynamical instabilities in giant exoplanet systems must be frequent within the first 10 Myr of a system's life.
  - At least 10% of FFPs must have formed by ejection from a disc.
  - The number of ejected planets per unstable system scales with the number of planets involved in the instability
- A fraction of the FFPs formed like low-mass stars and another in planetary systems. Both mechanisms are needed to explain the large fraction of discovered planets.
  - The combined contributions of FFPs from core-collapse (13–118%) and ejection from planetary systems (10–130%) derived from our analysis can explain the formation of the majority of FFPs.

CONCLUSIONS

- Largest sample of FFPs (planets that wander through space without a parent star) ever discovered in a single group in our galaxy, which almost doubles the number of free-floating planets known to date over the entire sky.

- Huge success for the collaboration of ground- and space-based telescopes in the exploration and understanding of our Universe.

- There could be several billions of free-floating giant planets roaming freely in the Milky Way and even more of Earth-mass planets since they are known to be more common than massive planets.

- Follow up:
  1. Our sample of FFPs includes excellent targets for the study of planetary atmospheres in the absence of a blinding host star
  2. Studying the presence of gas and dust around their circumplanetary discs will shed more light on their formation process.

REFERENCES

- https://arxiv.org/abs/2112.11999
- https://www.nature.com/articles/s41550-021-01513-x
- https://astronomycommunity.nature.com/posts/the-largest-family-of-free-floating-planets-roaming-in-the-milky-way
- https://www.eso.org/public/news/eso2120/
- https://www.cosmos.esa.int
- https://www.ing.iac.es/PR/press/rogue.html
- https://subarutelescope.org/en/results/2021/12/22/3014.html
- M. Perryman, *The Exoplanet Handbook*, 2018, Cambridge University Press

APPENDIX
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ASTROMETRY

- The motion of a star projected onto the plane of sky is the combination of three types of apparent motion: parallax, proper motion and astrometric reflex motion due to the presence of planets.

- The astrometric perturbation consists of an oscillation of the position of the star around the common star-planet barycenter.

- The expected astrometric signal (displacement in μas) is directly proportional to the semi-major orbit axis, to the planetary mass and inversely proportional to the stellar mass and to the distance.

$$\alpha = \frac{M_p}{M_\star + M_p} a \simeq \frac{M_p}{M_\star} a$$

$$\equiv \left(\frac{M_p}{M_\star}\right)\left(\frac{a}{1\text{ au}}\right)\left(\frac{d}{1\text{ pc}}\right)^{-1} \text{ arcsec}$$

Type	d (pc)	M_p	a (au)	α (μas)
Jupiter	10	$1M_J$	5	500.
"	100	"	"	50.
Hot Jupiter	10	$1M_J$	0.01	1.
"	100	"	"	0.1
Earth	10	$1M_\oplus$	1	0.3
"	100	"	"	0.03

- Selection bias: large planets in long period orbits around nearby low-mass stars.