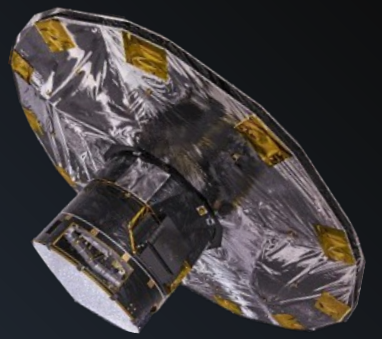
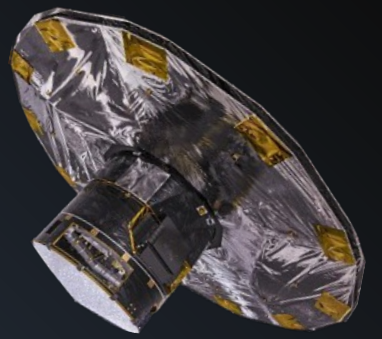


How Gaia Grounds Kepler, K2, TESS, and Direct Imaging

Jessie Christiansen
Caltech/IPAC-NASA Exoplanet Science Institute
Sagan Summer Workshop 2022

christia@ipac.caltech.edu @aussiastronomer



How Gaia Grounds Kepler, K2, TESS, ~~and Direct Imaging~~

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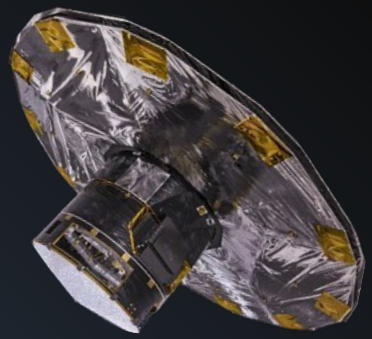
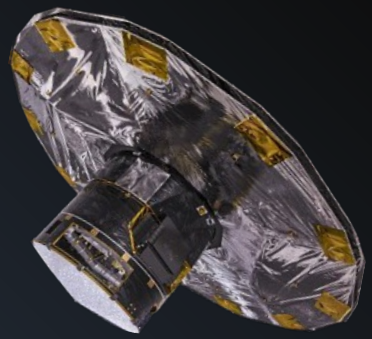
Overview



1. Planets! (Not from astrometry)
2. Improving our understanding of planets and planet populations with Gaia
3. Future open questions that Gaia will help tackle

Overview



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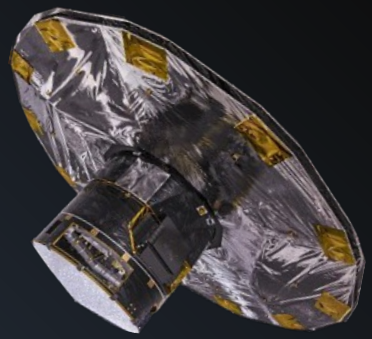
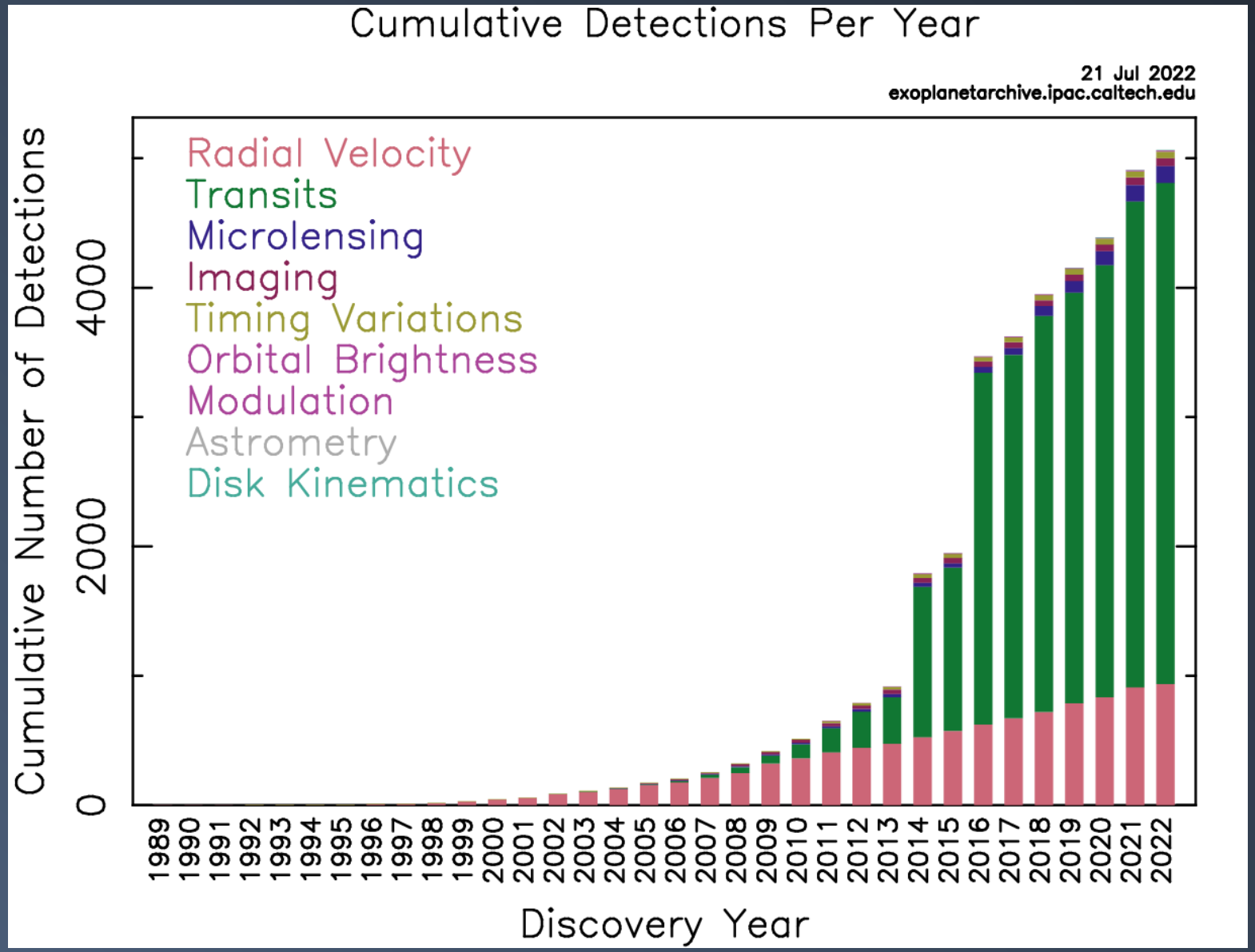




Transit: 3875 (inc 2 from Gaia!)

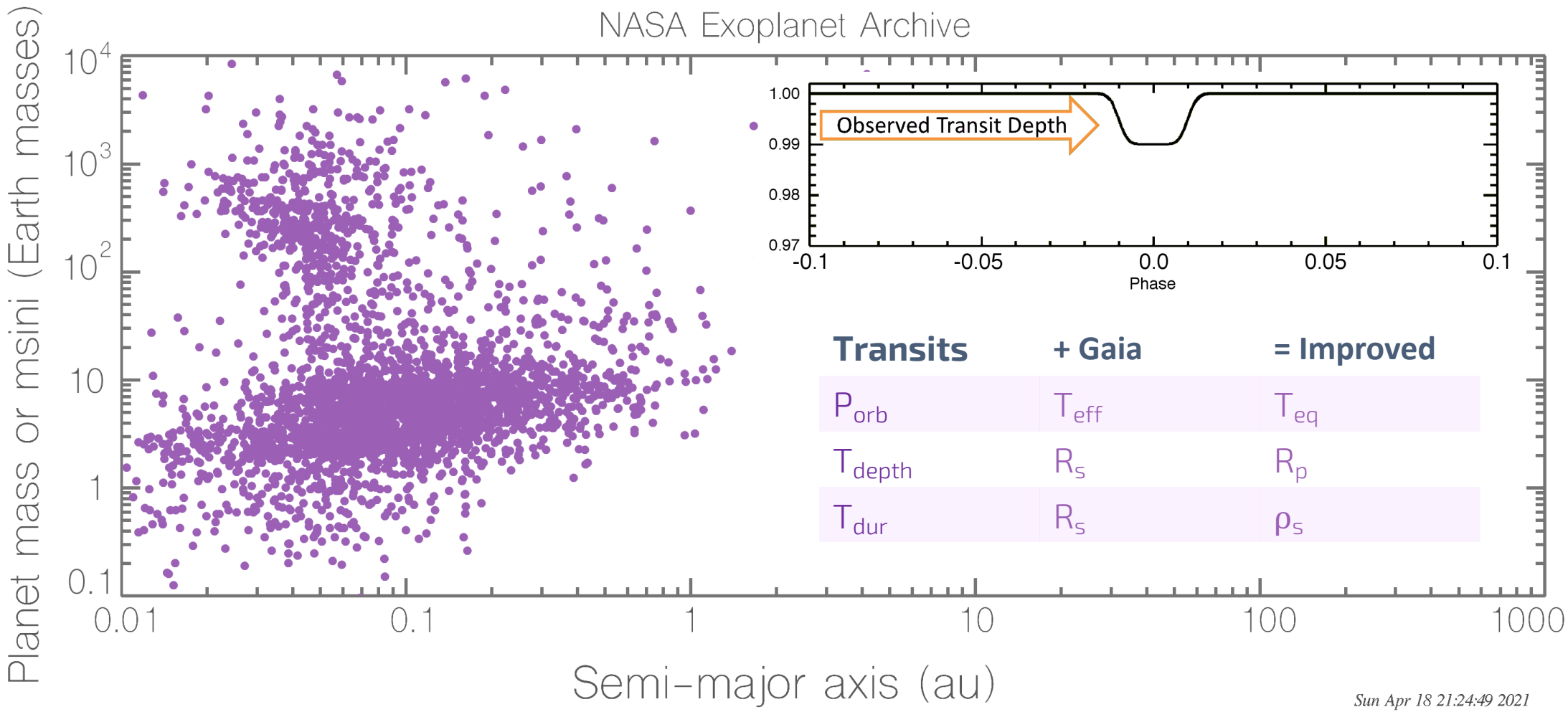
RV: 936

Microlensing: 130

Imaging: 61

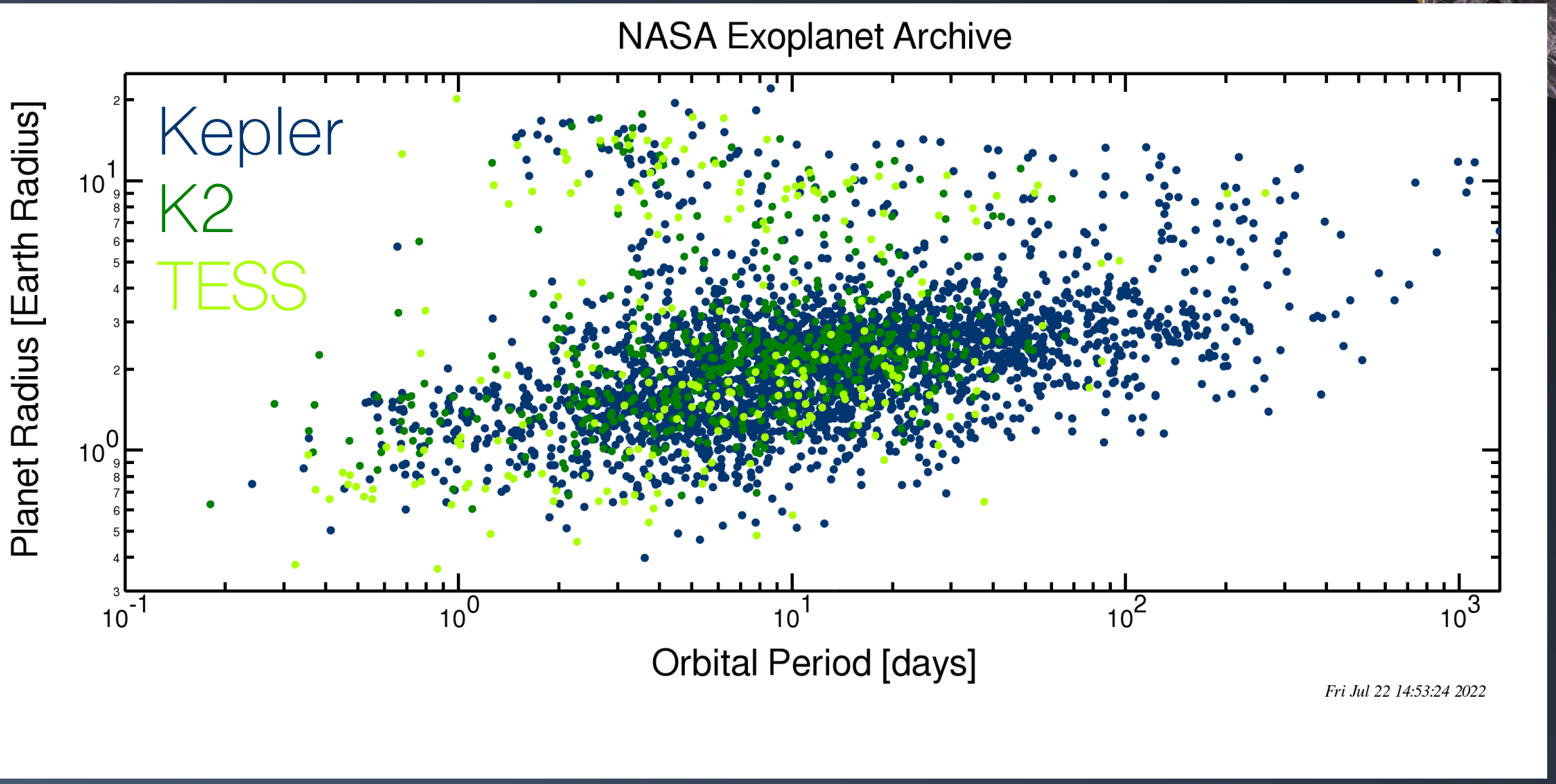
(Astrometry: 20,000?)

1. Planets! (Not from astrometry)



Transits	+ Gaia	= Improved
P_{orb}	T_{eff}	T_{eq}
T_{depth}	R_s	R_p
T_{dur}	R_s	ρ_s

1. Planets! (Not from astrometry)



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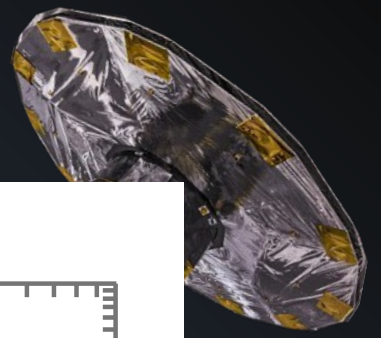

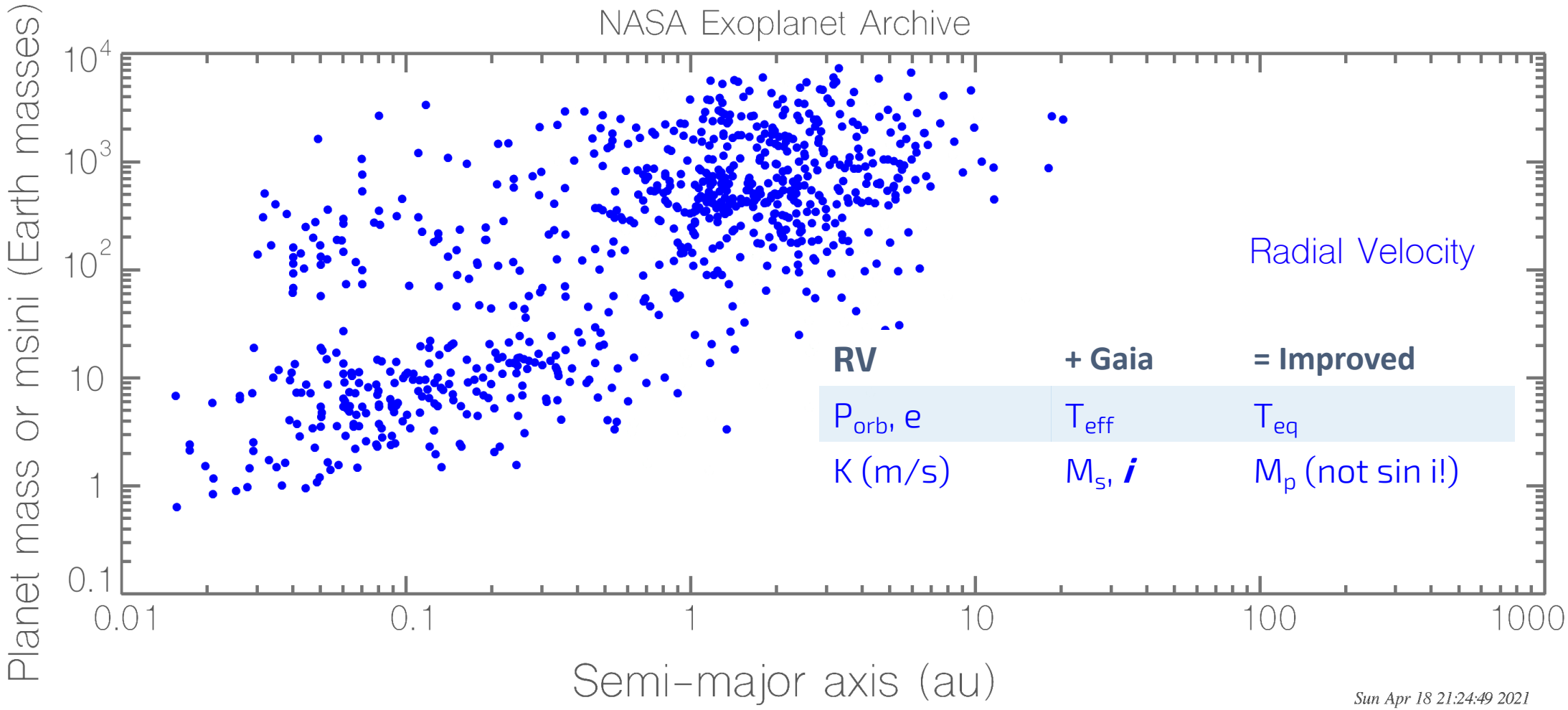

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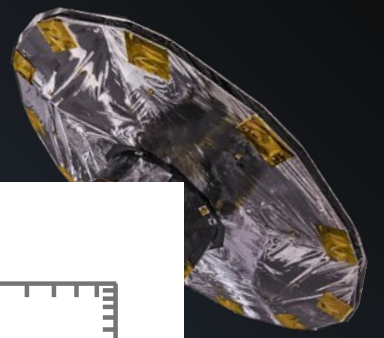

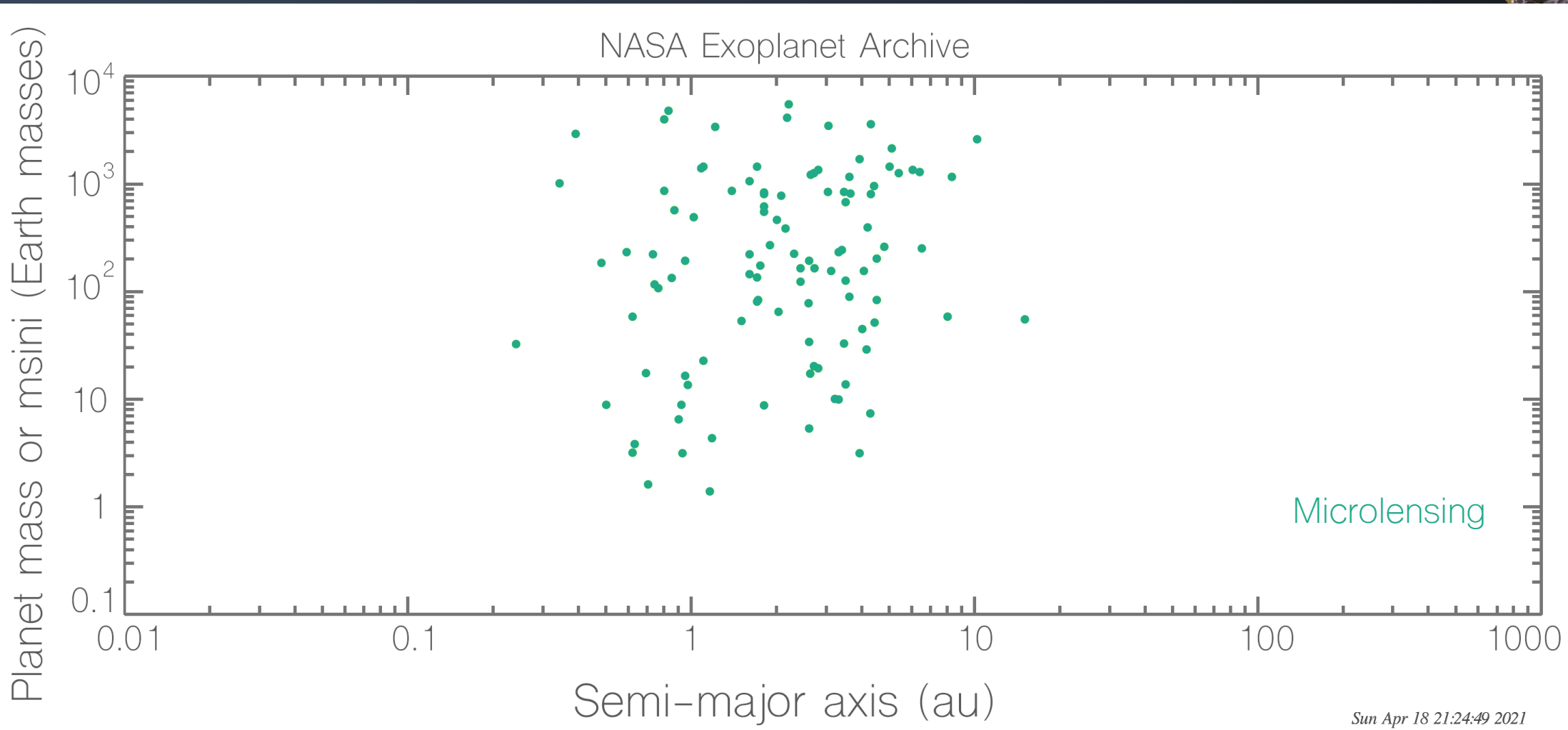

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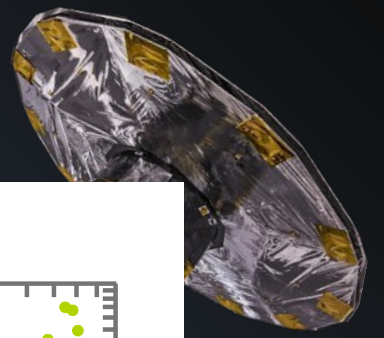

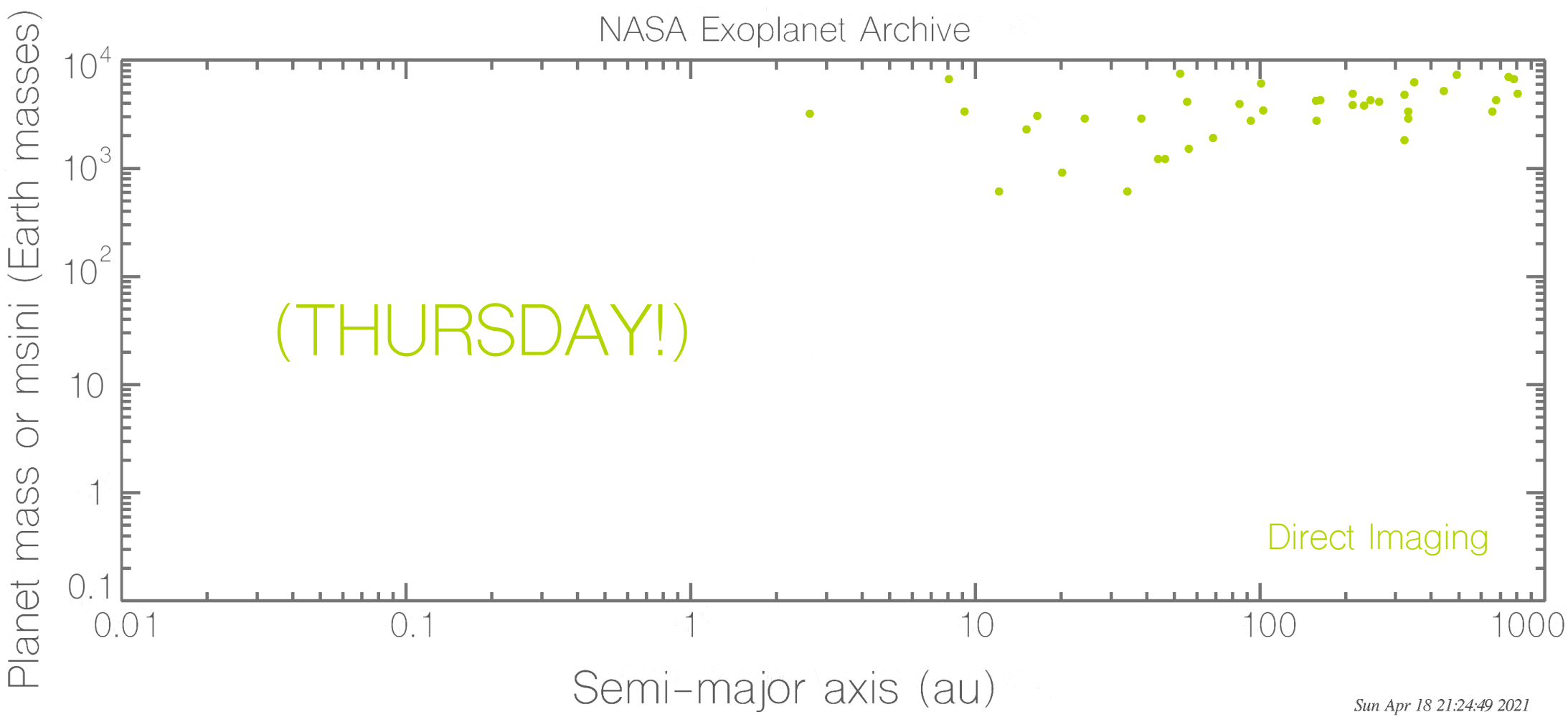

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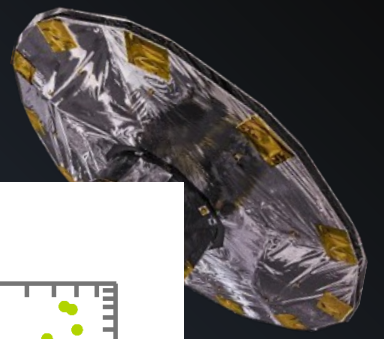
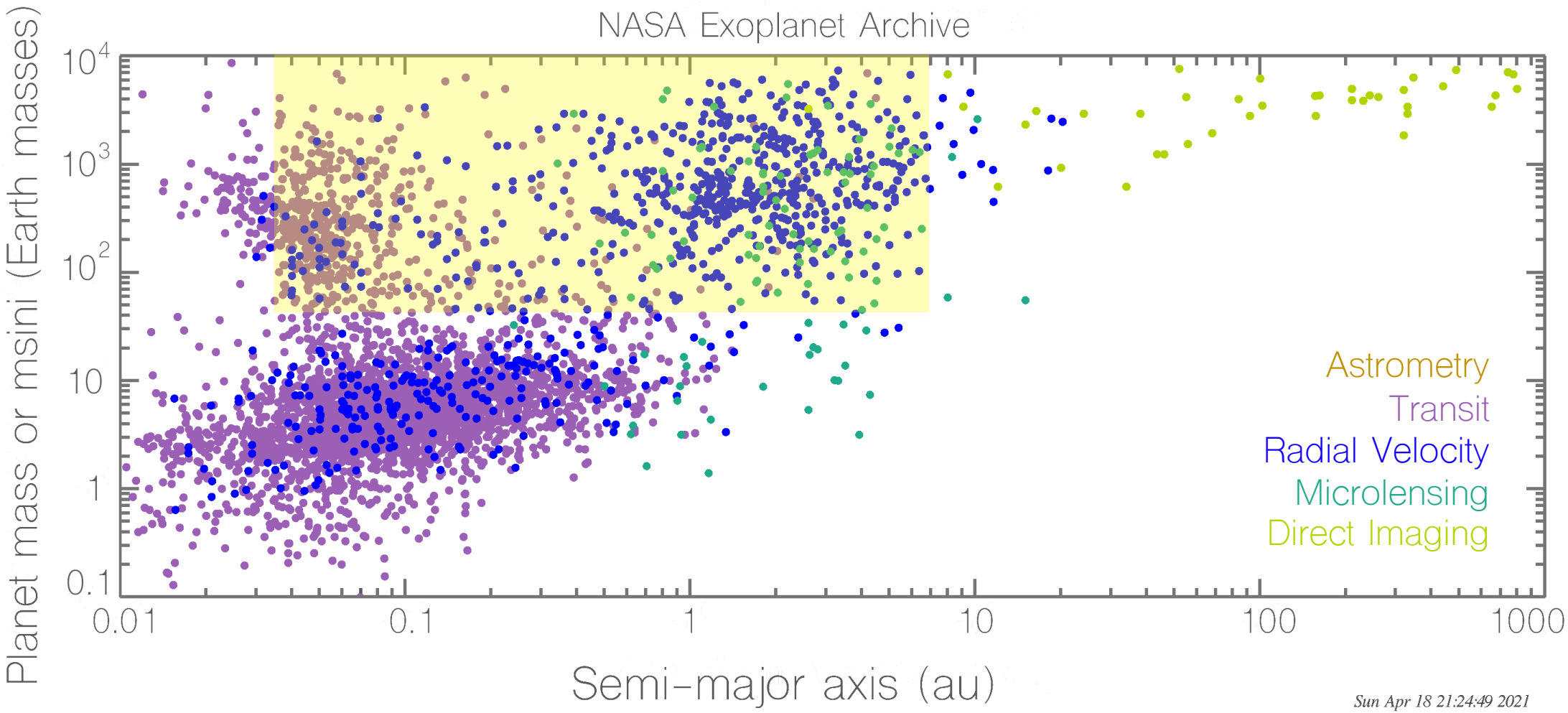
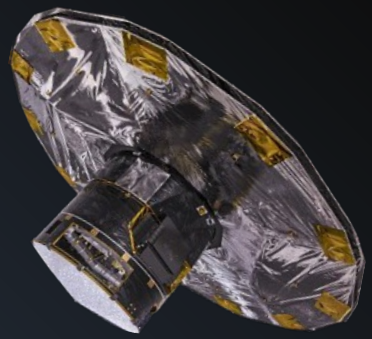




Overview



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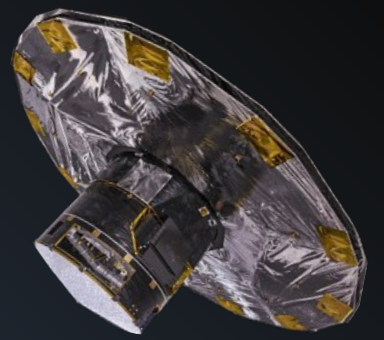
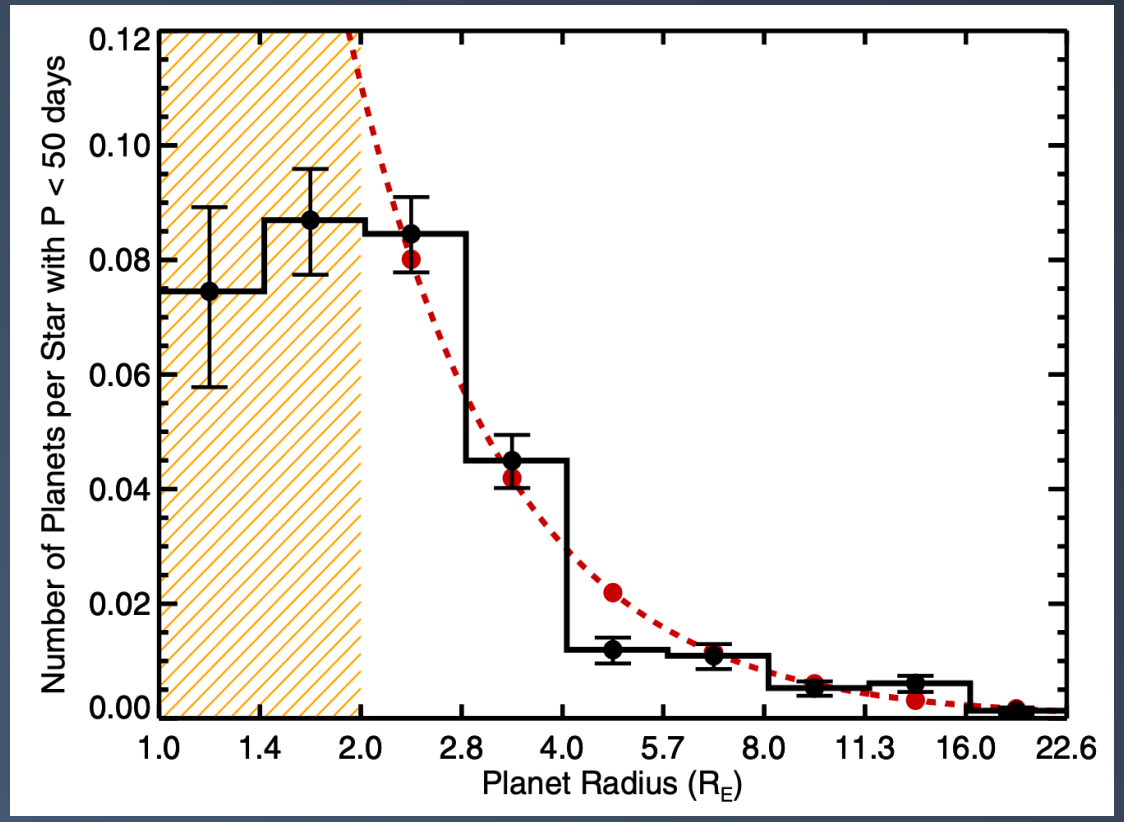
2. **Improving our understanding of planets and planet populations with Gaia**

3. Future open questions that Gaia will help tackle

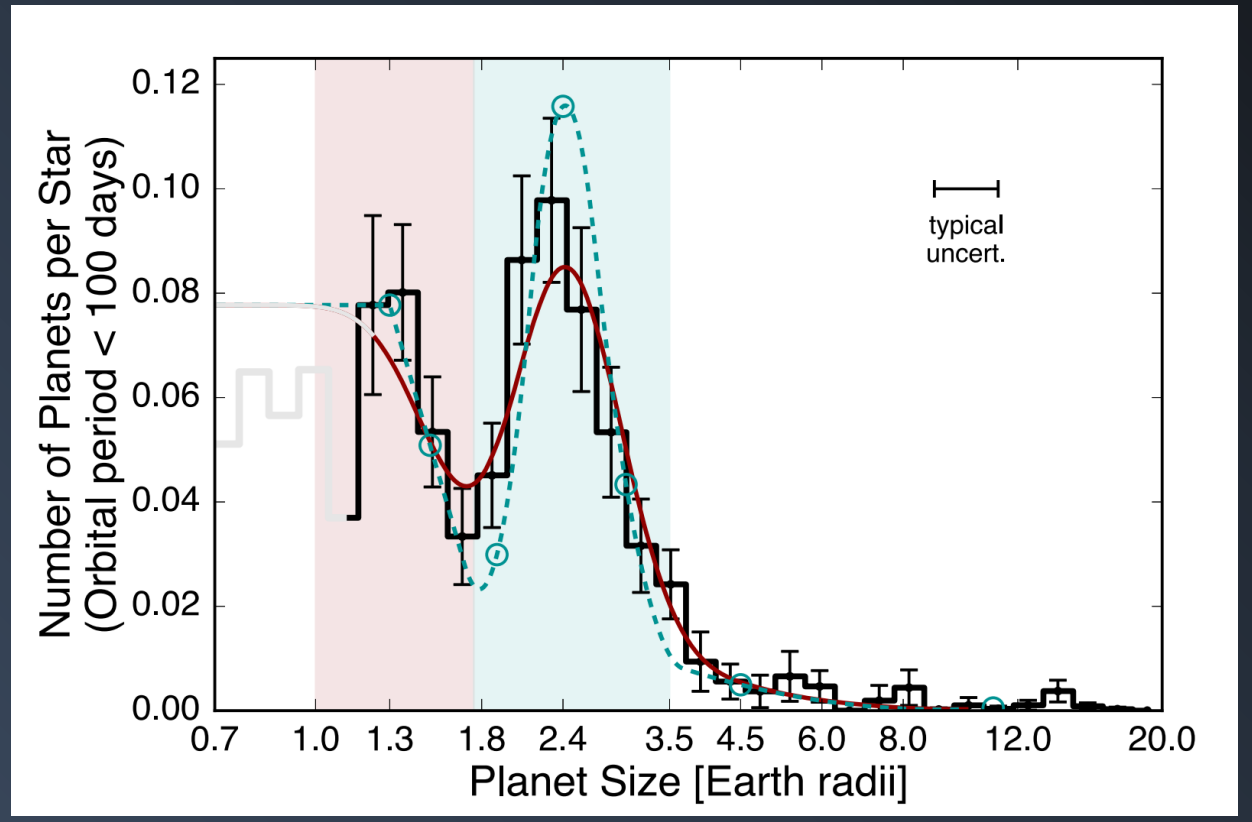
2. Improving our understanding



Pre-Gaia...

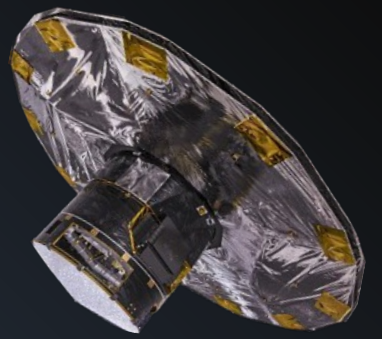


Howard+2012

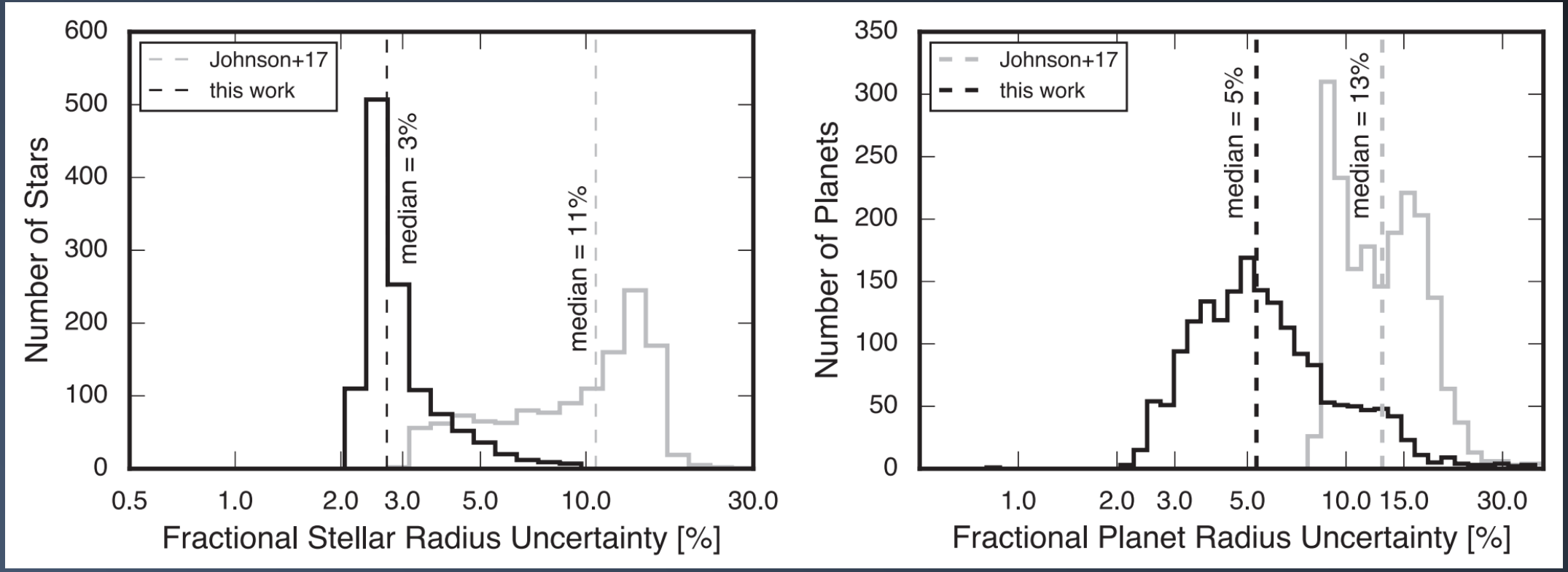


Fulton+2017

2. Improving our understanding

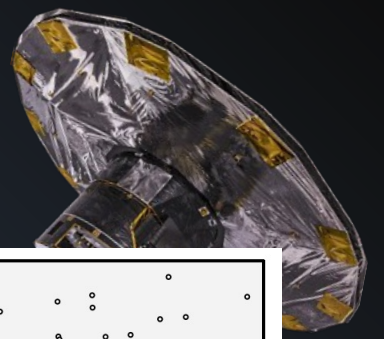


Gaia DR2 + Kepler



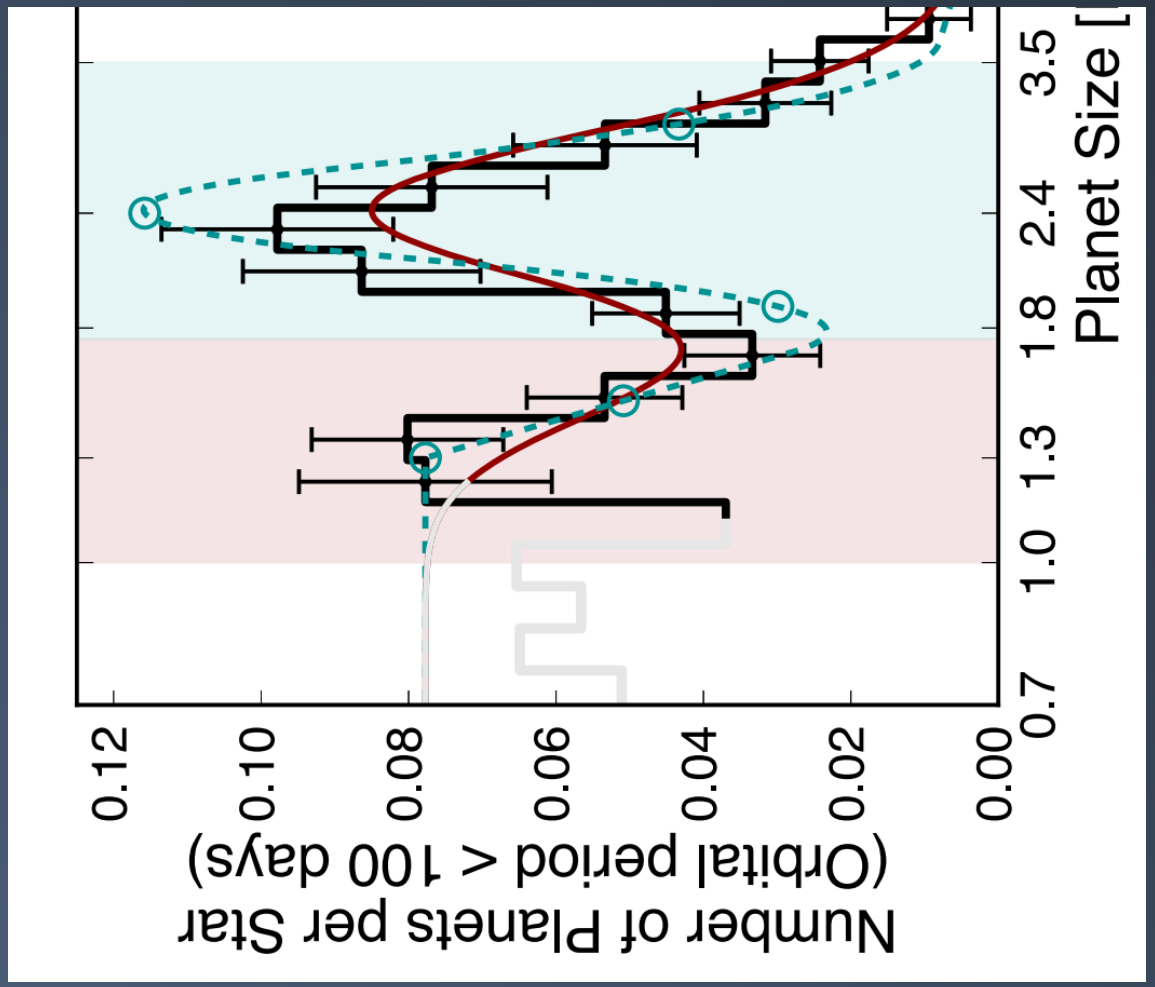
Fulton+2018

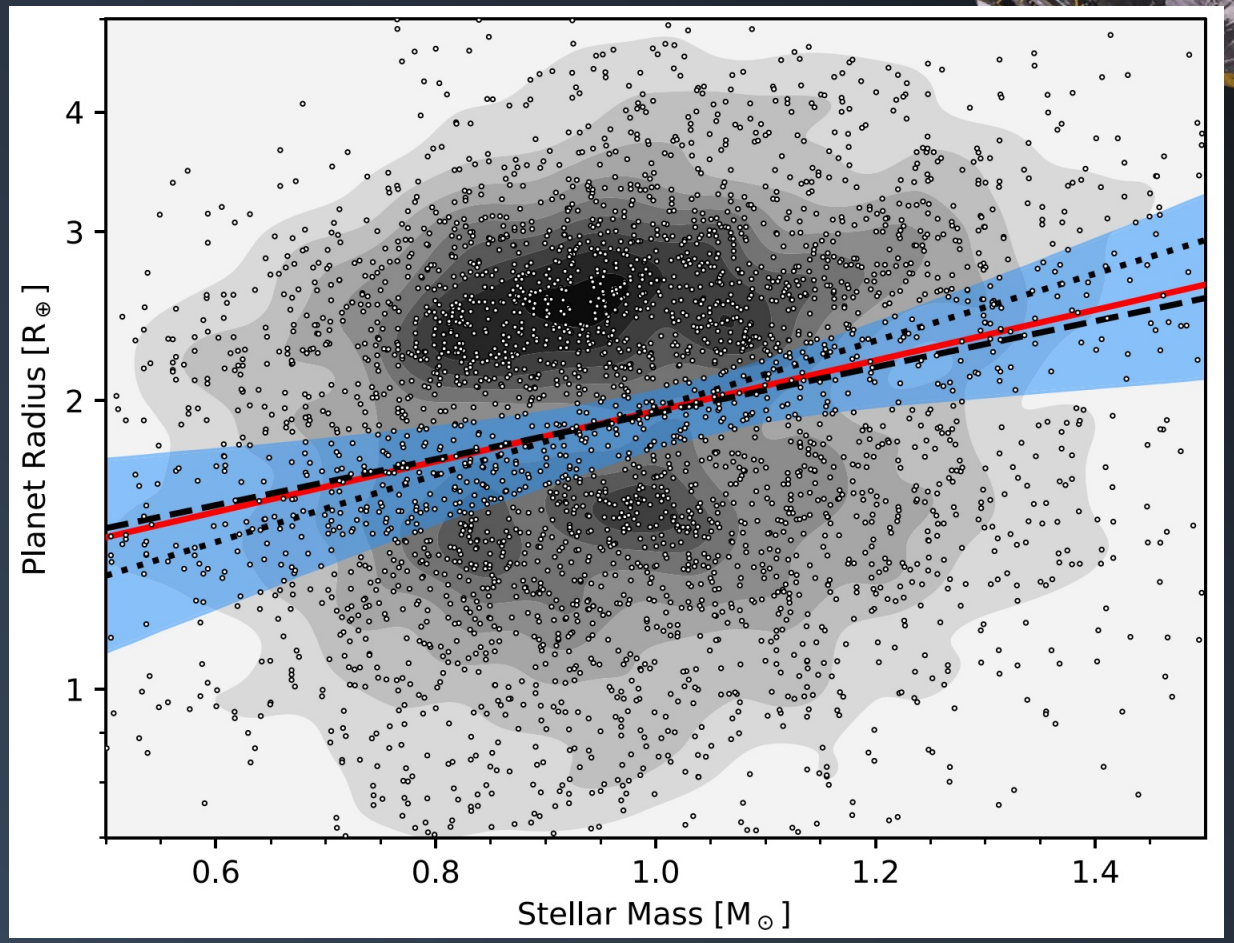
2. Improving our understanding



Gaia DR2 + Kepler

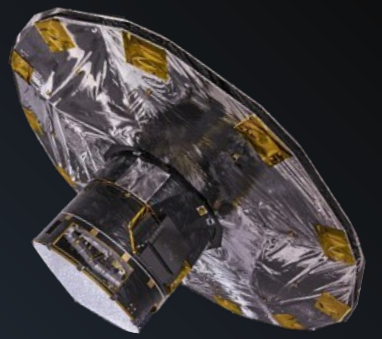
Fulton+2017





Berger+2020

2. Improving our understanding



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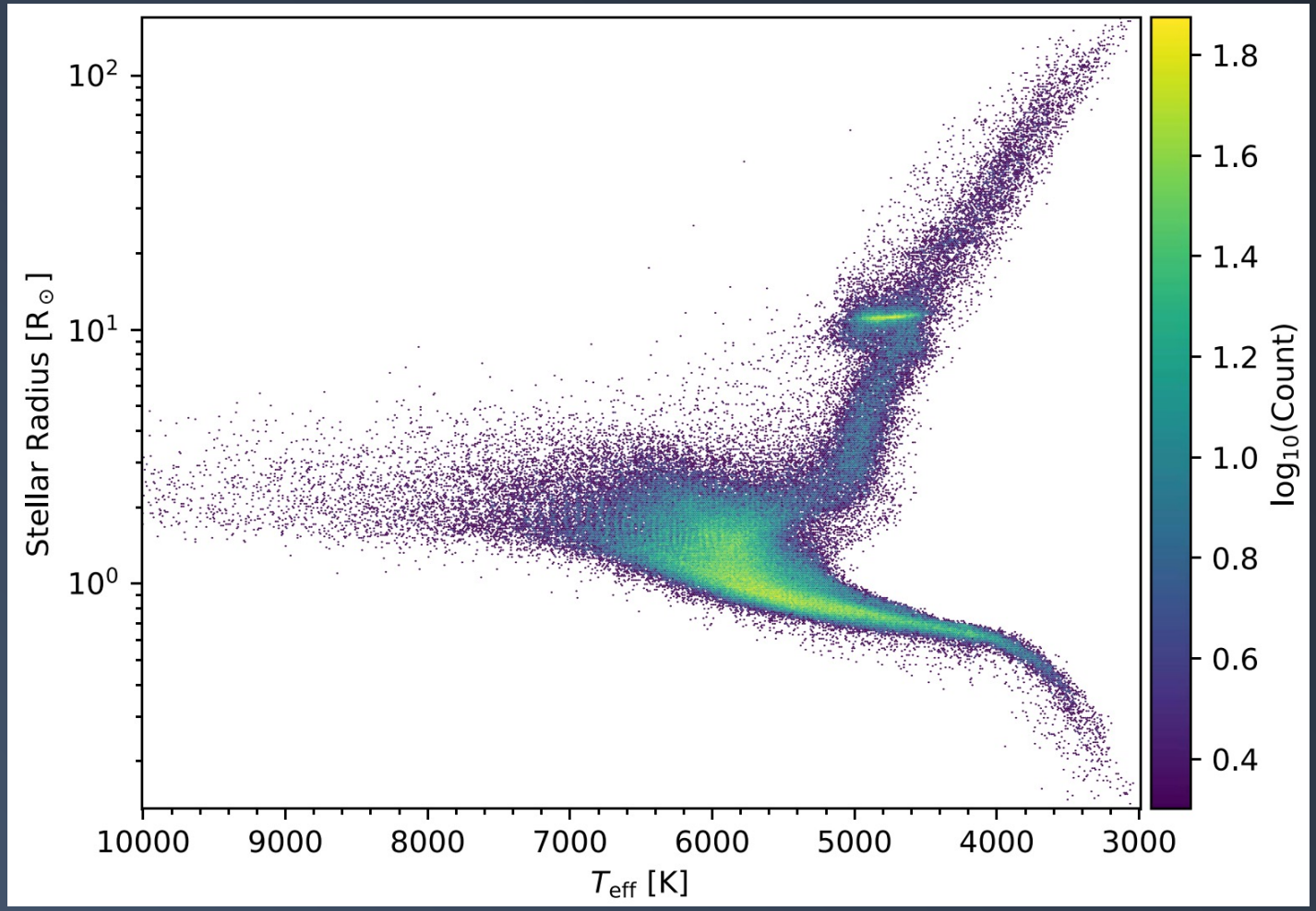
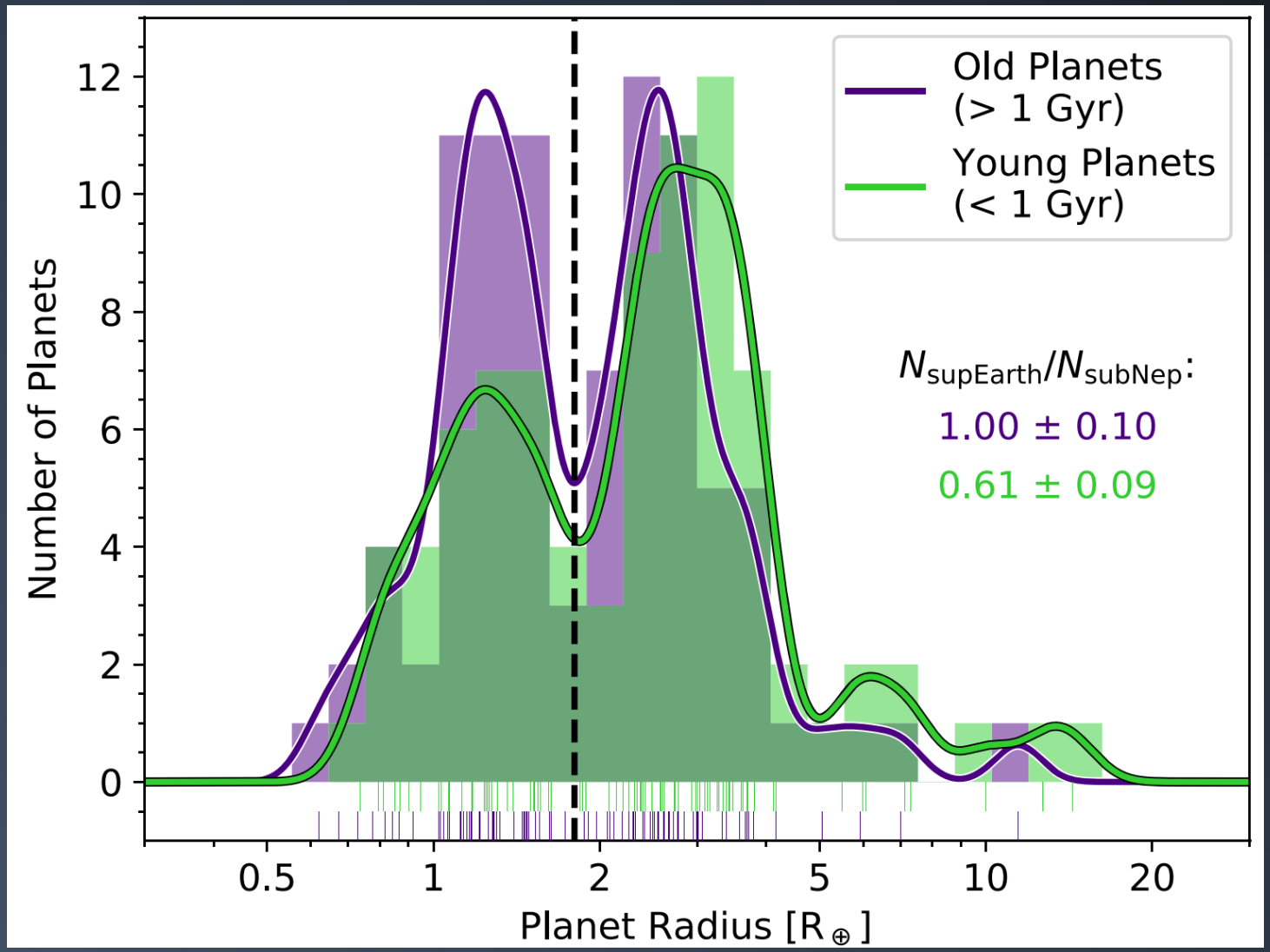


Berger+2020

2. Improving our understanding

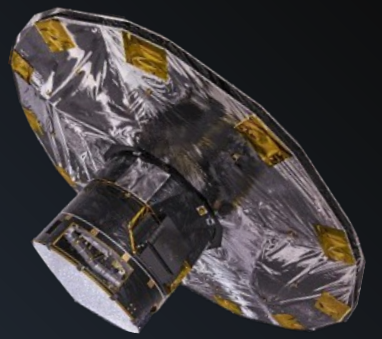
Gaia DR2 + Kepler

Confirming a ***stellar age*** dependence for the ratio of super-Earths to sub-Neptunes in the planet radius valley

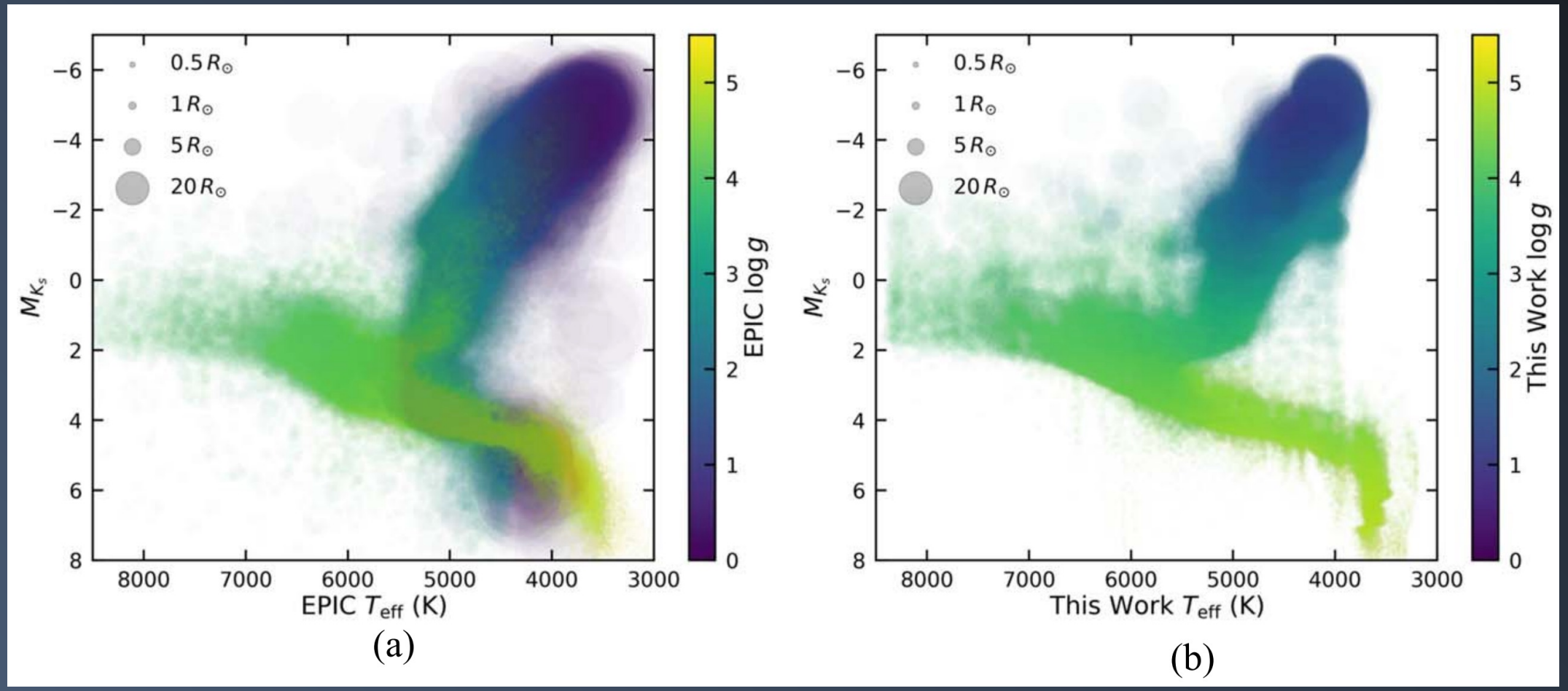


Berger+2020

2. Improving our understanding

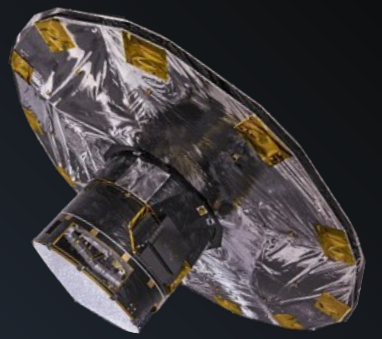


Gaia DR2 + K2



Hardegree-Ullman+2020

2. Improving our understanding

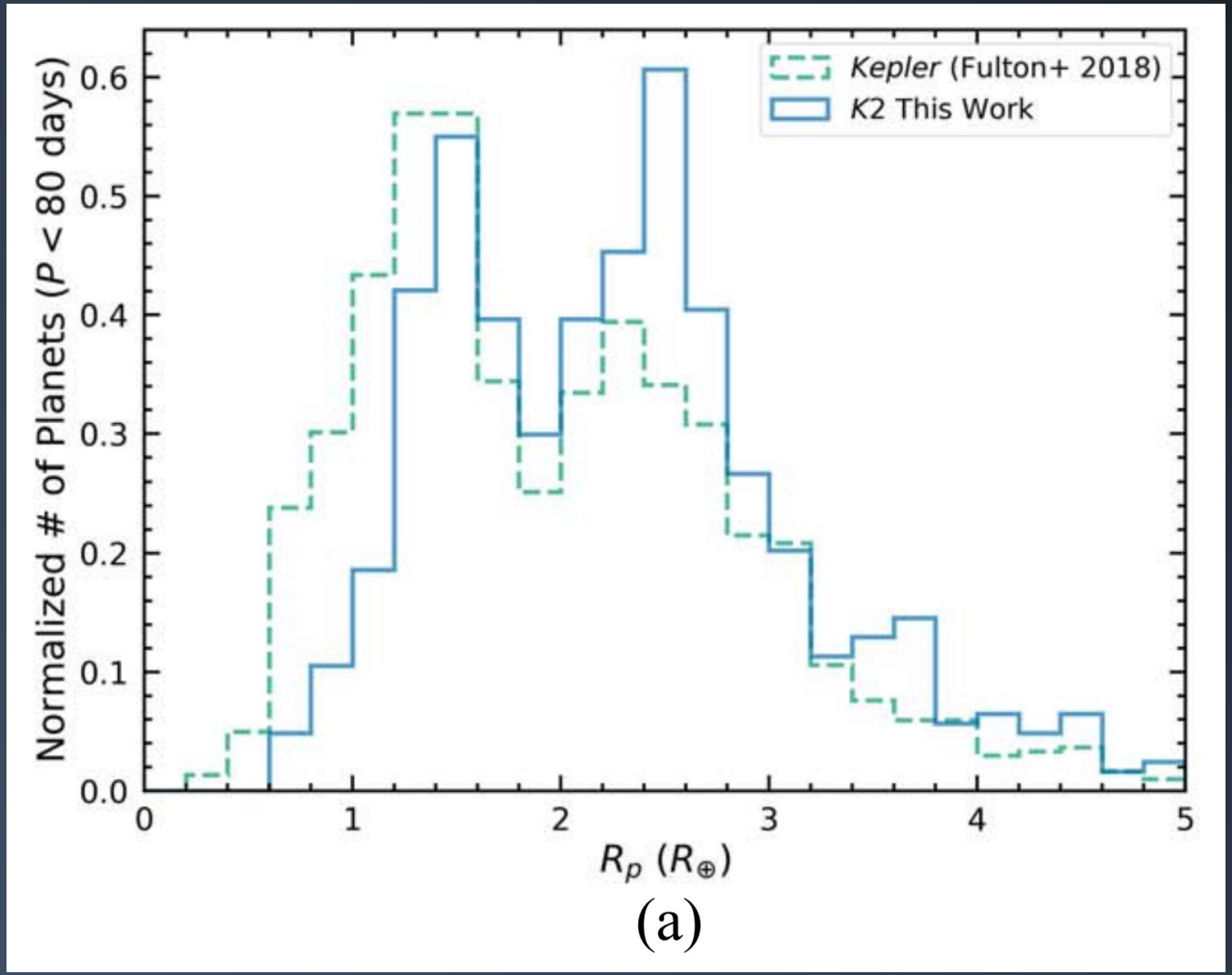


Gaia DR2 + K2

Confirming the planet radius valley in an independent* dataset

*sort of, mostly

Hardegree-Ullman+2020



2. Improving our understanding

Gaia + TESS

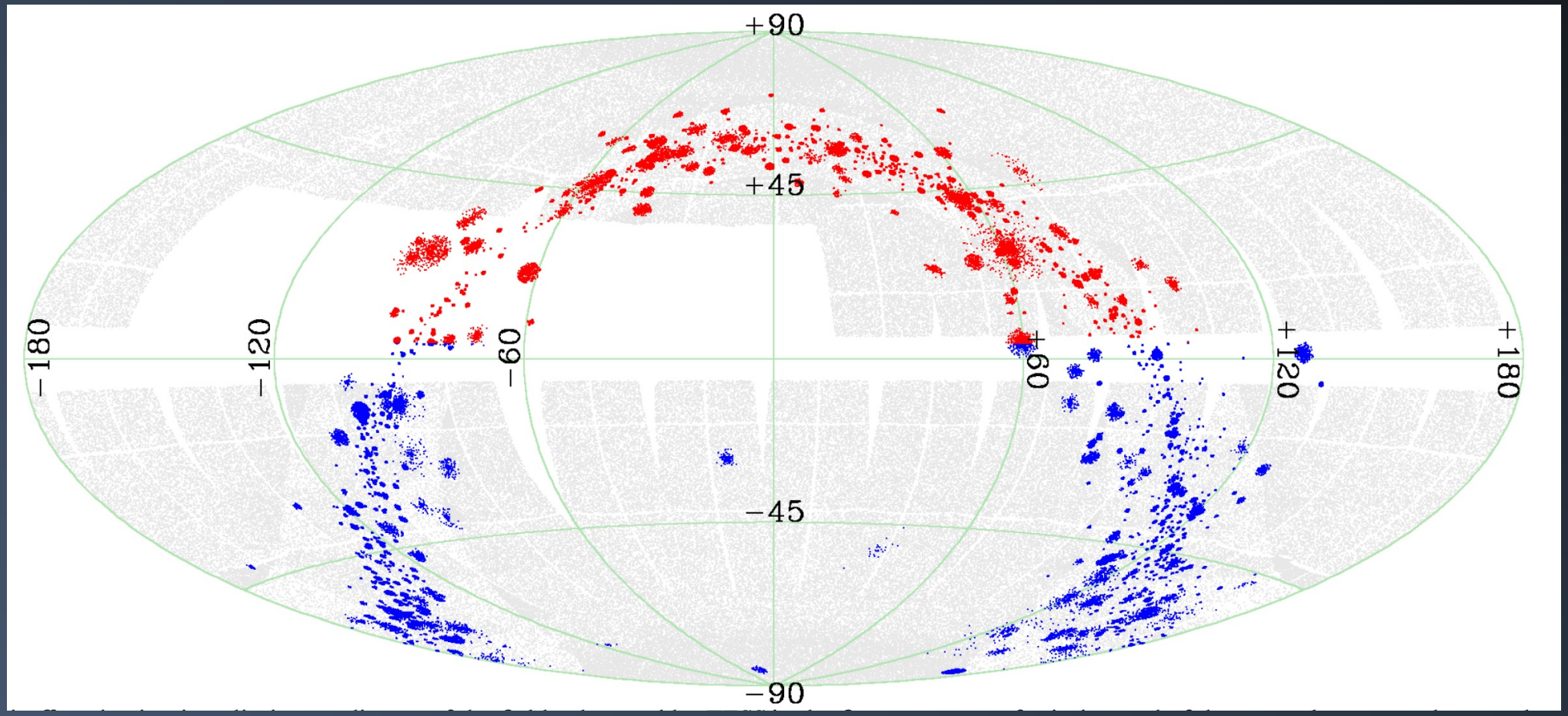
(TESS + Gaia = stellar astrophysics, solar system/asteroids, etc etc!)

Star clusters – astronomy's laboratory!

Age
Chemistry
Dynamical history

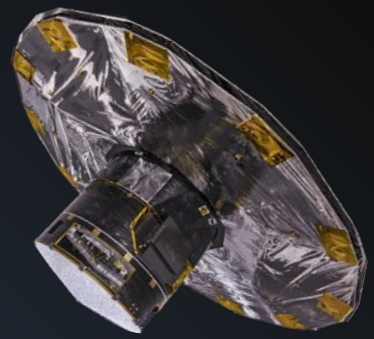
Constraining known clusters

Finding new clusters!



Nardiello+2020

2. Improving our understanding

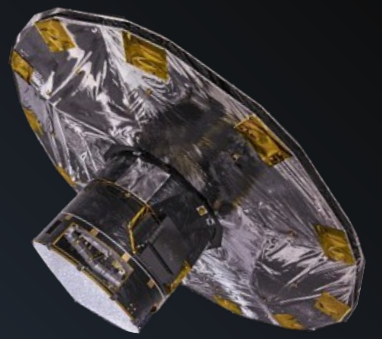


SNAP POLL:

Which name of a new star cluster found by Gaia is worse?

1. Gaia-Enceladus Sausage
2. Group X

2. Improving our understanding

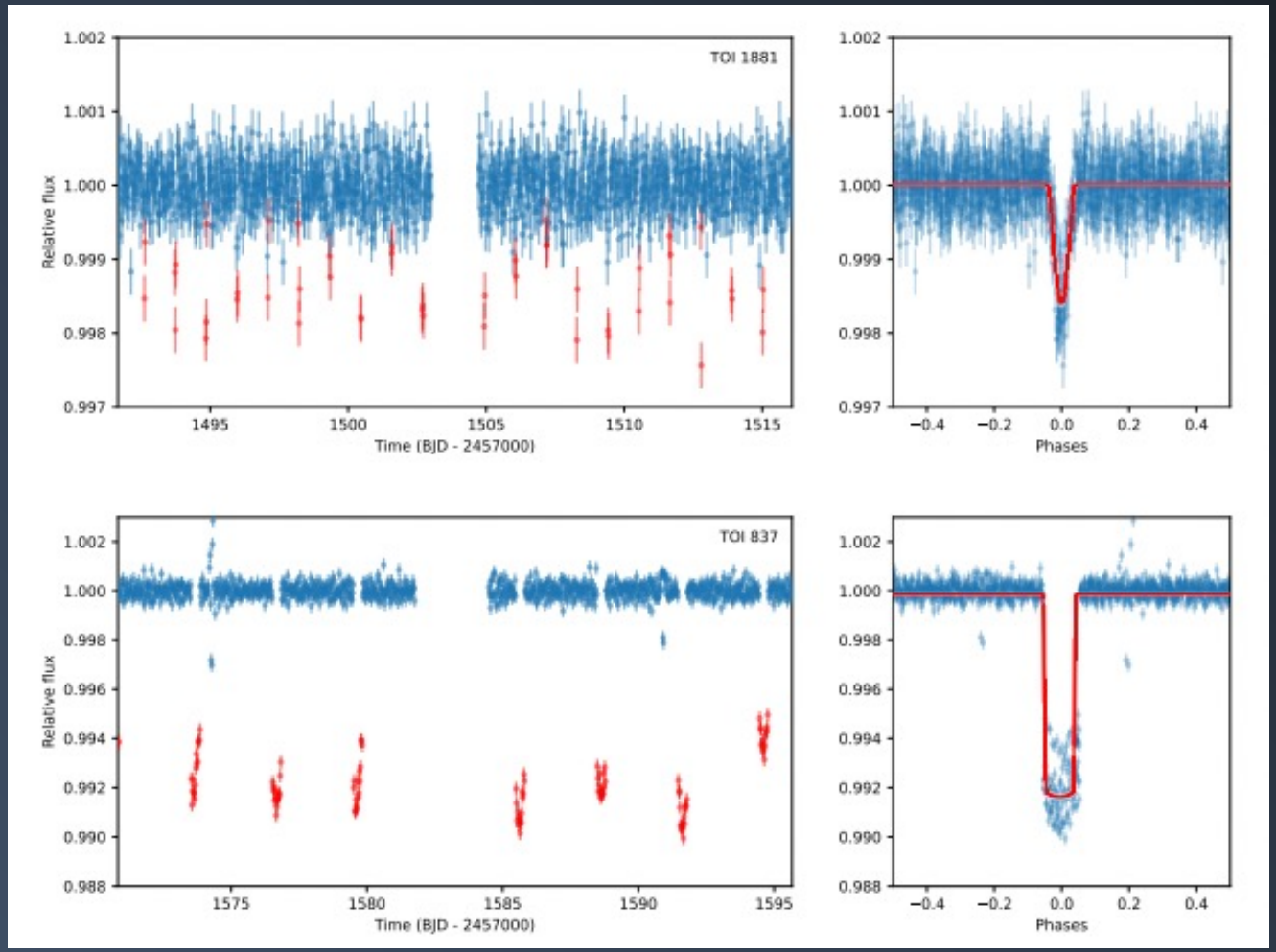


Gaia DR2 + TESS

Identifying planet candidates in open clusters

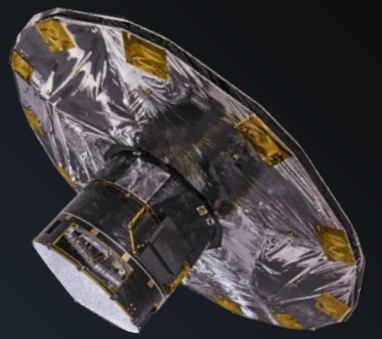
Gaia: positions and velocities

TESS: rotation periods



Sun+2022

2. Improving our understanding



Gaia DR2 + TESS

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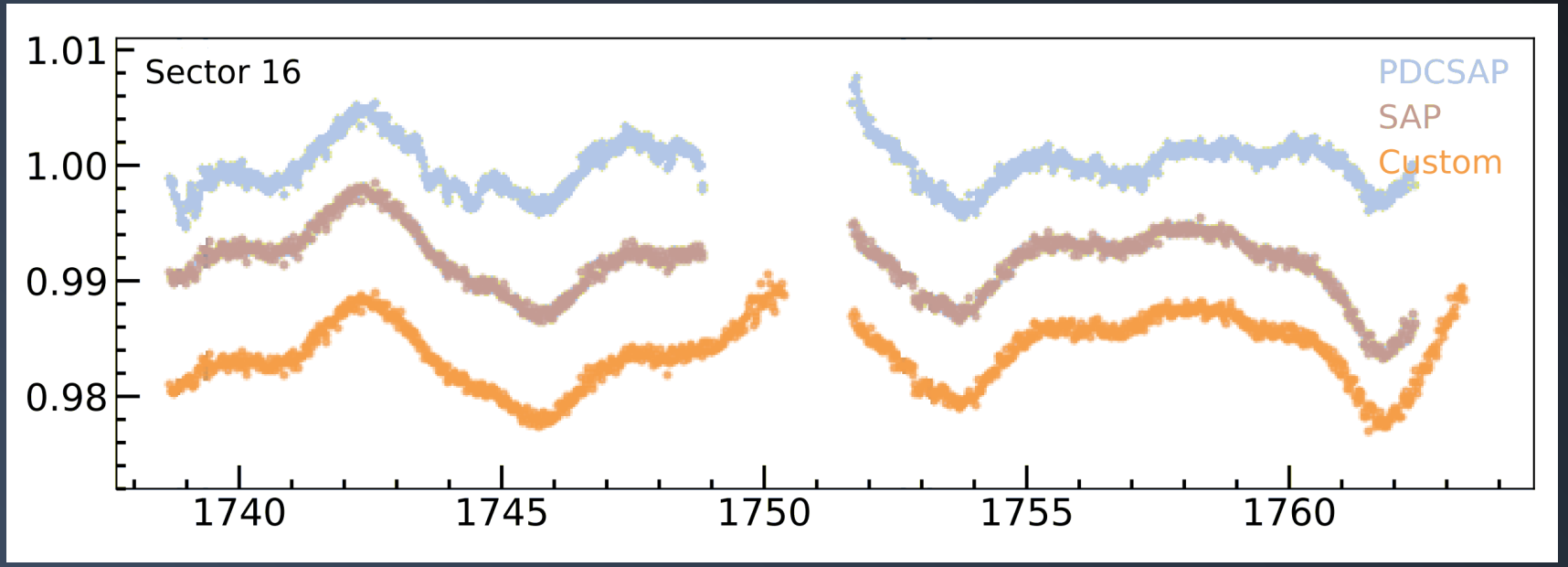
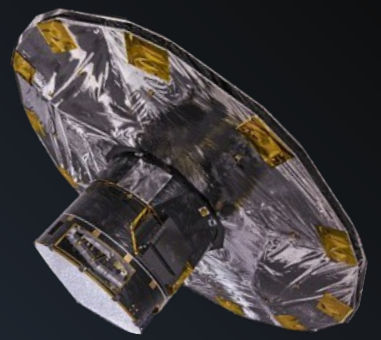


Newton+2021

2. Improving our understanding



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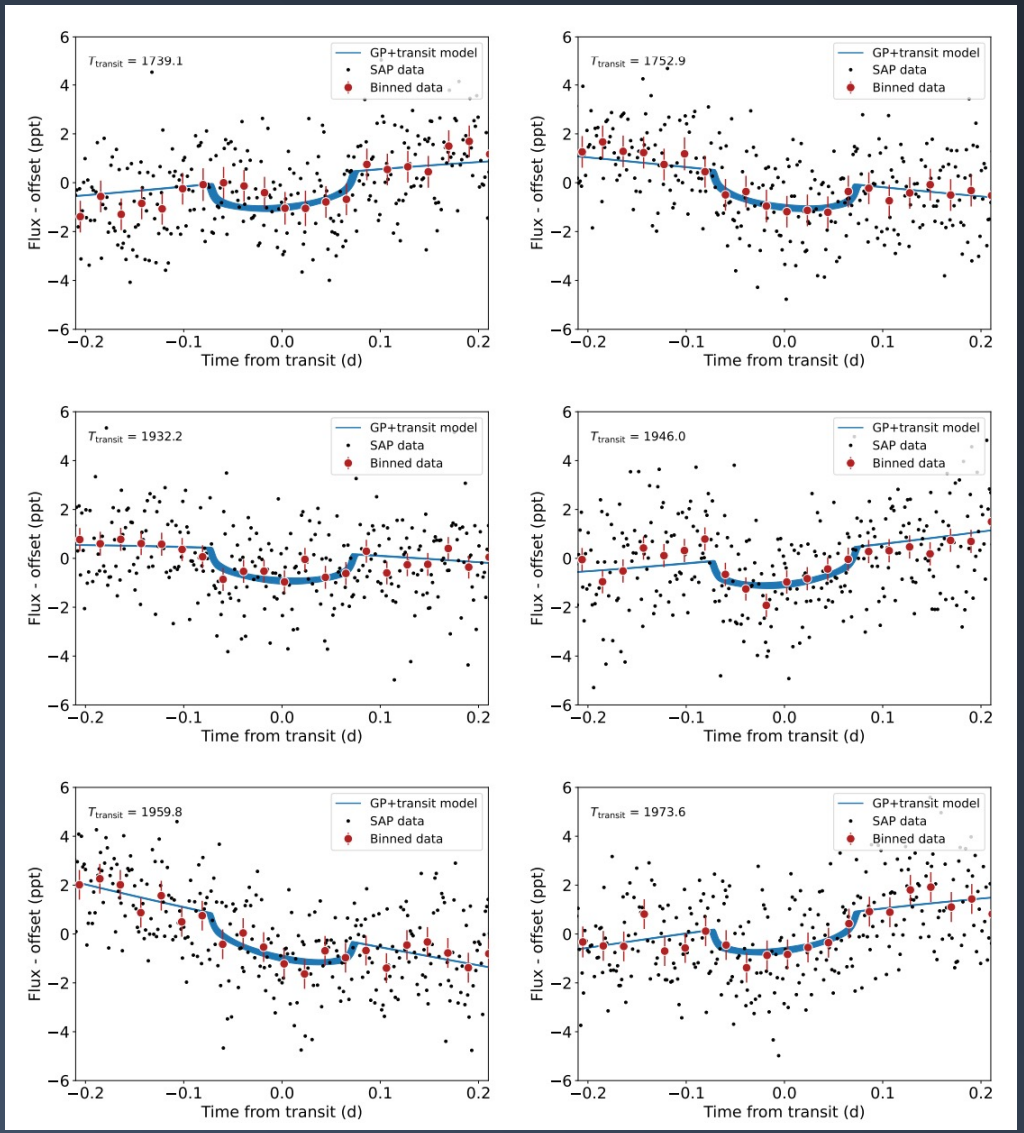

Newton+2021

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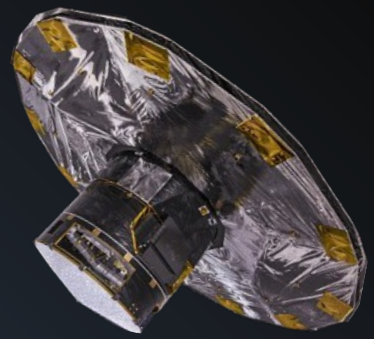
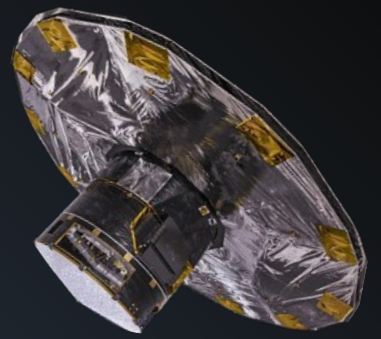


Gaia clusters

Planet Name	Cluster	Age (Myr)	Planet radius $R_\oplus$	Orbital period d	Provenance
AU Mic b	Beta Pictoris	22	4.20	8.463	Plavchan et al. (2020)
AU Mic c	Beta Pictoris	22	2.79	18.859	Gilbert et al. (2022)
DS Tuc A b	Tucana–Horologium	40	5.70	8.138	Newton et al. (2019)
EPIC 211822797 b	Praesepe	700	2.20	21.170	Mann et al. (2017)
HD 110082 b	MELANGE-1	250	3.20	10.183	Tofflemire et al. (2021)
HD 63433 b	Ursa Major	414	2.15	7.108	Mann et al. (2020)
HD 63433 c	Ursa Major	414	2.67	20.545	Mann et al. (2020)
HIP 67522 b	Sco-Cen OB	17	10.07	6.960	Rizzuto et al. (2020)
K2-100 b	Praesepe	700	3.88	1.674	Barragán et al. (2019)
K2-101 b	Praesepe	700	2.00	14.677	Mann et al. (2017)
K2-102 b	Praesepe	700	1.30	9.916	Mann et al. (2017)
K2-104 b	Praesepe	700	1.90	1.974	Mann et al. (2017)
K2-136 b	Hyades	700	0.99	7.975	Mann et al. (2018)
K2-136 c	Hyades	700	2.91	17.307	Mann et al. (2018)
K2-136 d	Hyades	700	1.45	25.575	Mann et al. (2018)
K2-25 b	Hyades	700	3.44	3.485	Stefansson et al. (2020)
K2-264 b	Praesepe	700	2.27	5.840	Rizzuto et al. (2018)
K2-264 c	Praesepe	700	2.77	19.663	Rizzuto et al. (2018)
K2-33 b	Upper Sco	9	5.04	5.425	Mann et al. (2016b)
K2-95 b	Praesepe	700	3.47	10.134	Obermeier et al. (2016)
Kepler-1627 b	Delta Lyra	38	3.82	7.203	Bouma et al. (2022)
TOI-1227 b	Epsilon Cha	11	9.57	27.364	Mann et al. (2022)
TOI-451 b	Pisces–Eridanus	120	1.91	1.859	Newton et al. (2021)
TOI-451 c	Pisces–Eridanus	120	3.10	9.193	Newton et al. (2021)
TOI-451 d	Pisces–Eridanus	120	4.07	16.365	Newton et al. (2021)
TOI-837 b	IC 2602	35	8.63	8.325	Bouma et al. (2020)
V1298 Tau b	Taurus	23	10.27	24.140	David et al. (2019b)
V1298 Tau c	Taurus	23	5.59	8.250	David et al. (2019a)
V1298 Tau d	Taurus	23	6.41	12.403	David et al. (2019a)
V1298 Tau e	Taurus	23	8.74	60.000	David et al. (2019a)

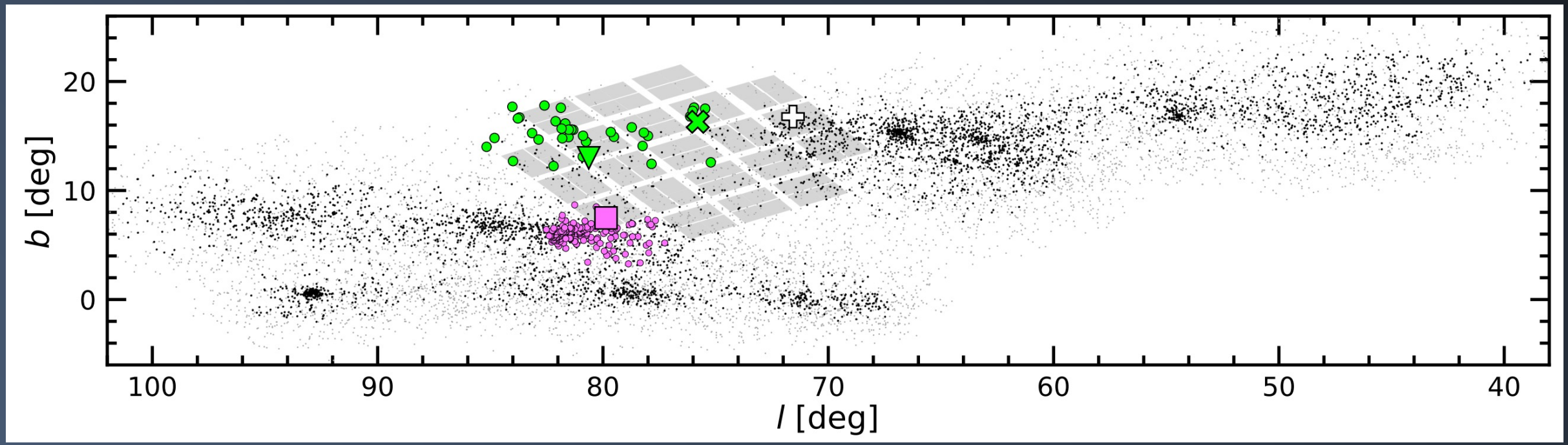
Newton+2021

2. Improving our understanding



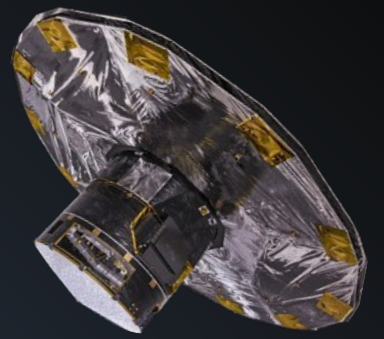
Gaia clusters

Bouma+2022 arXiv:02205.01112

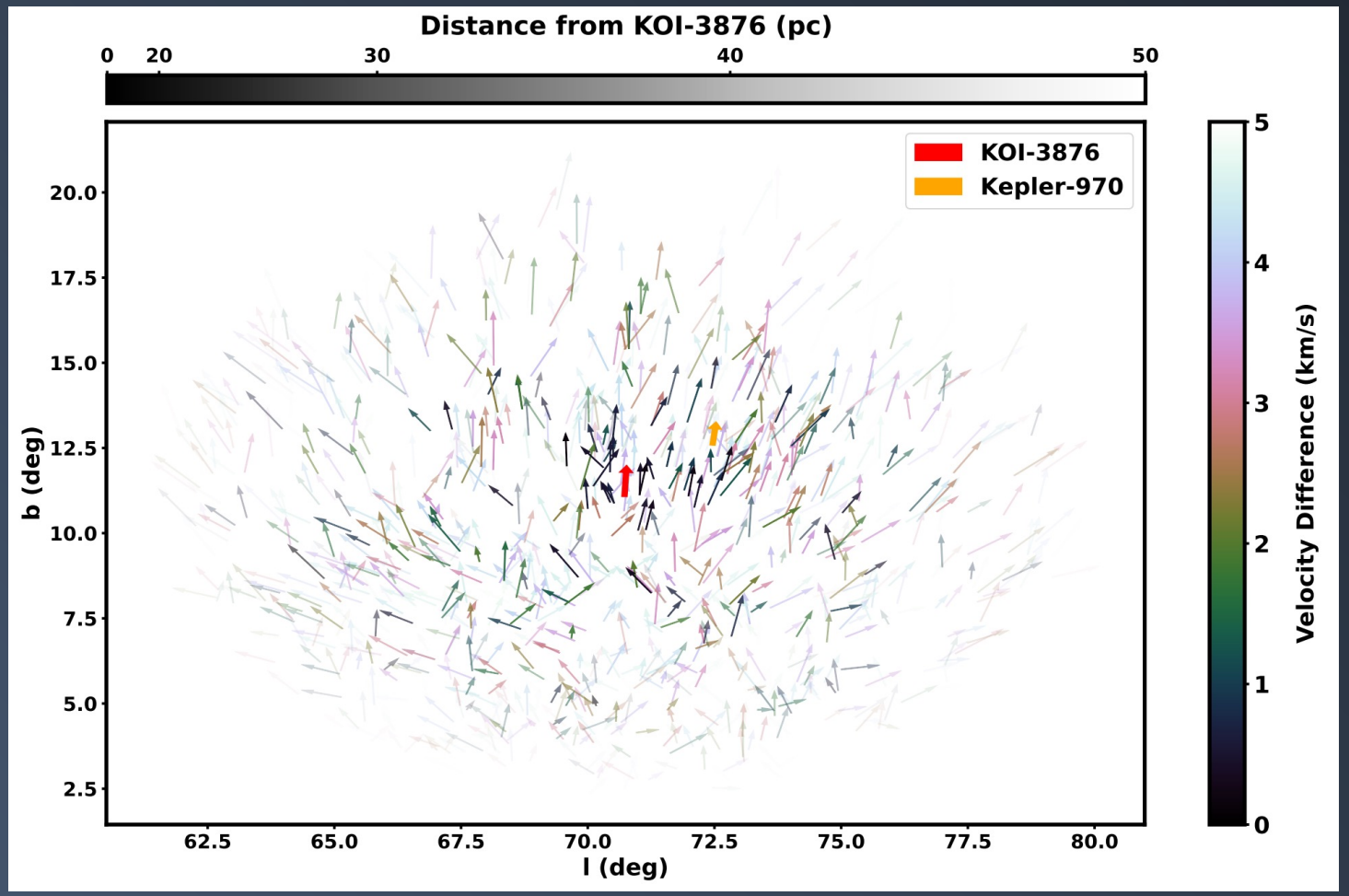


()Identifying EXTRAGALACTIC planets (e.g. Yoshida+2022)

2. Improving our understanding



Gaia clusters

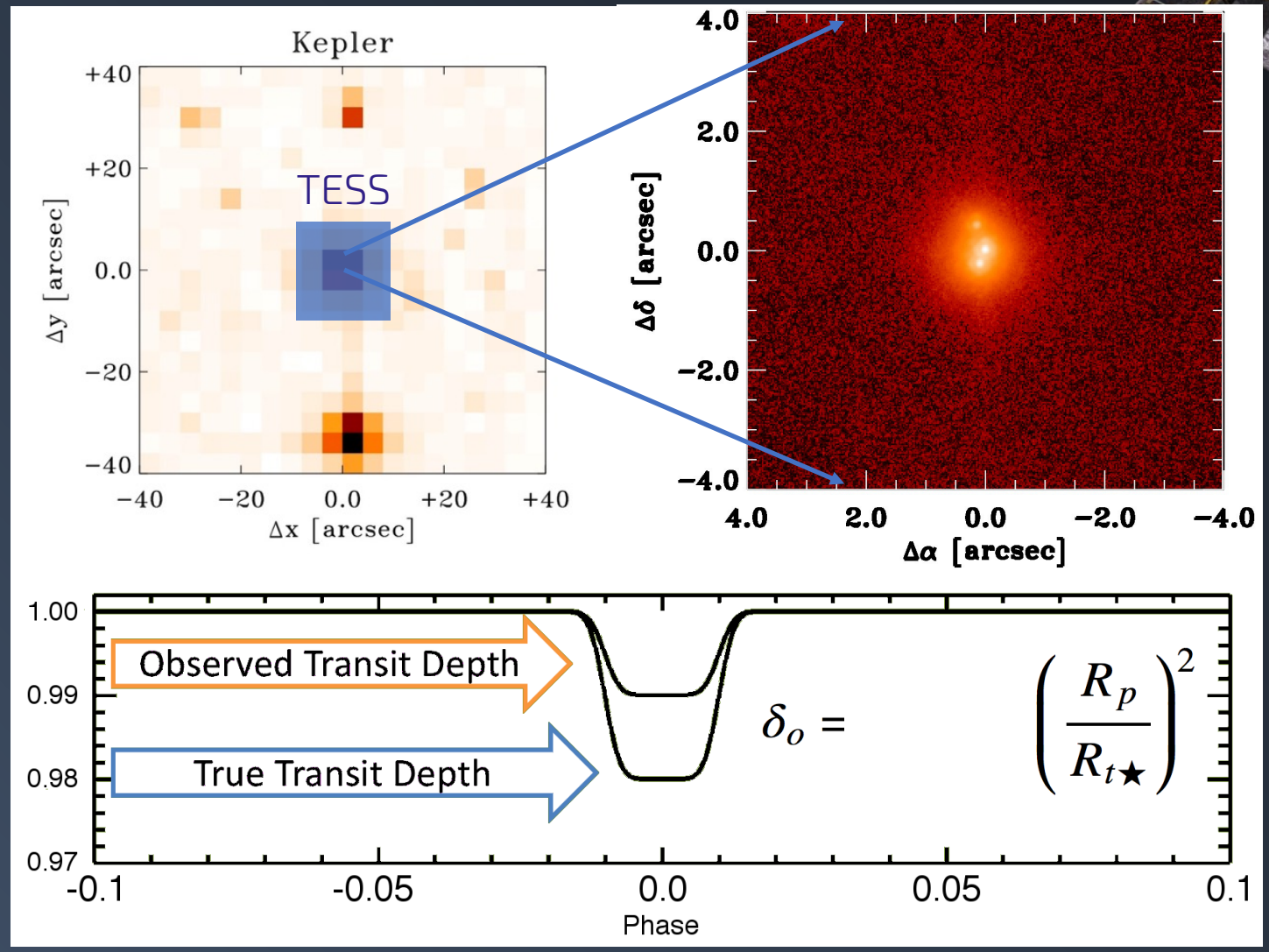


MELANGE-3

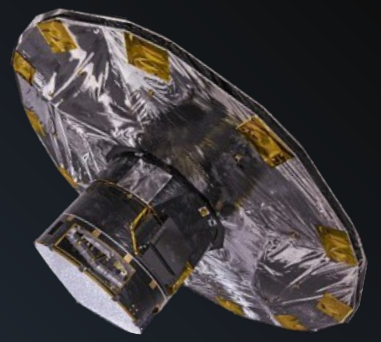
Barber+2022

2. Improving our understanding

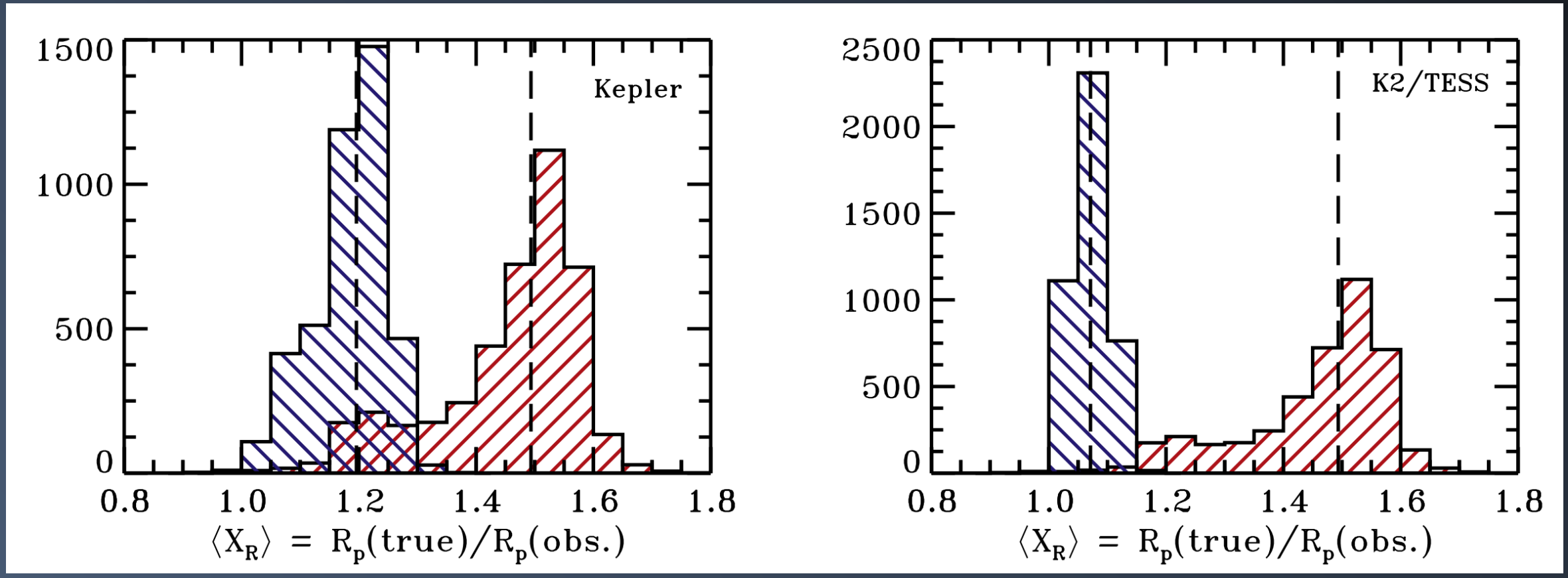
Stellar multiplicity



2. Improving our understanding

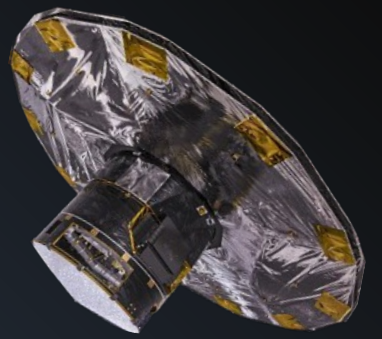


Stellar multiplicity



Ciardi+2015

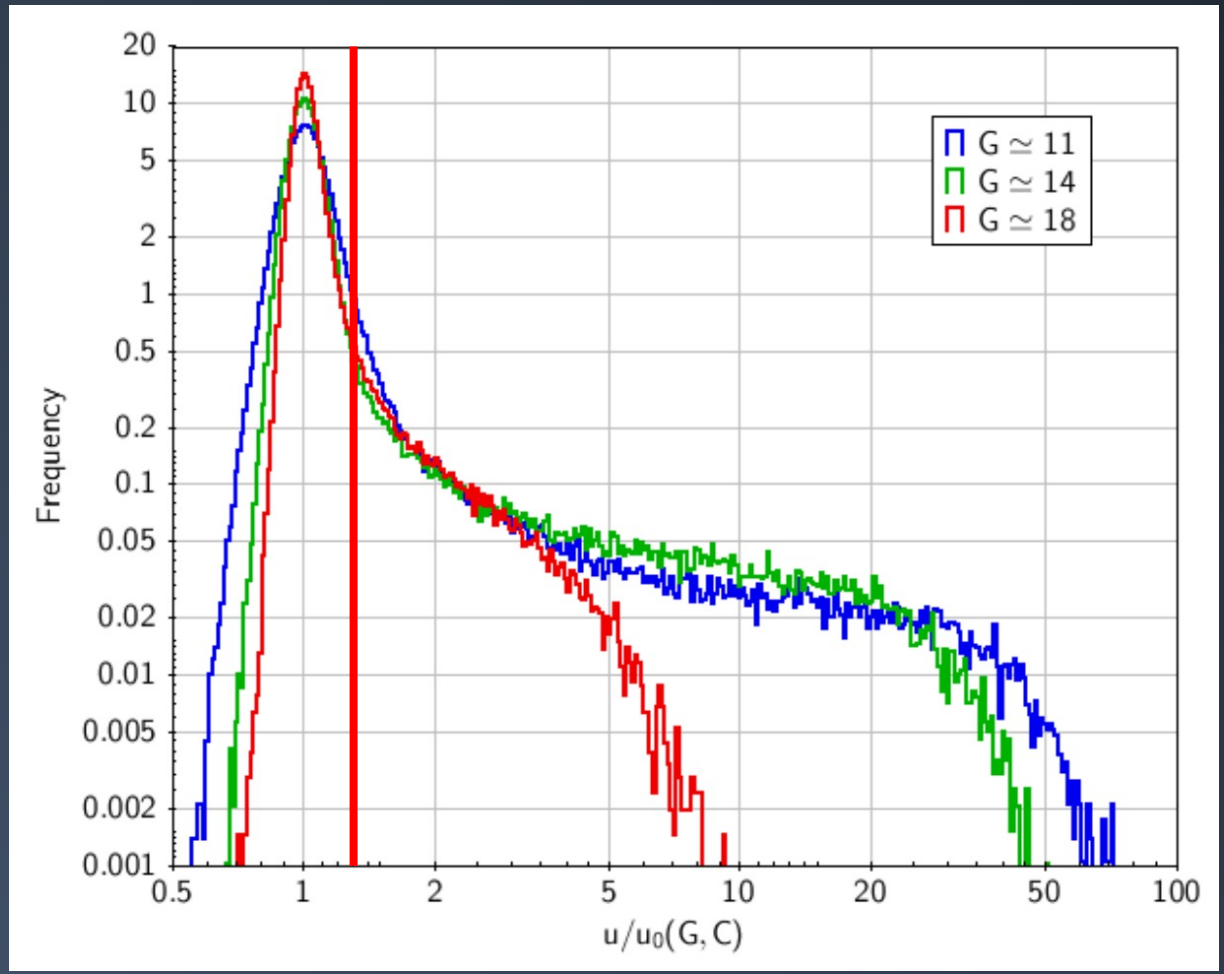
2. Improving our understanding



Gaia identifies stellar binaries to within ~0.7"

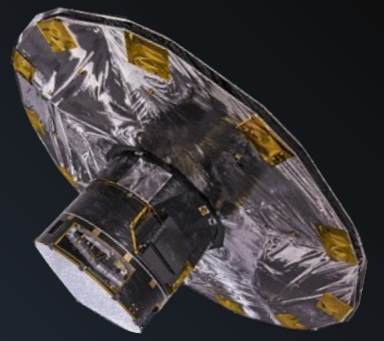
Astrometric noise = "Renormalized Unit Weight Error (RUWE)"

"The median RUWE value for resolved close binaries (<0."75) is 5.56, compared to 1.04 for wider binaries (>0."75) and 1.03 for single targets." (Ziegler+2018)



Lindegren+2018

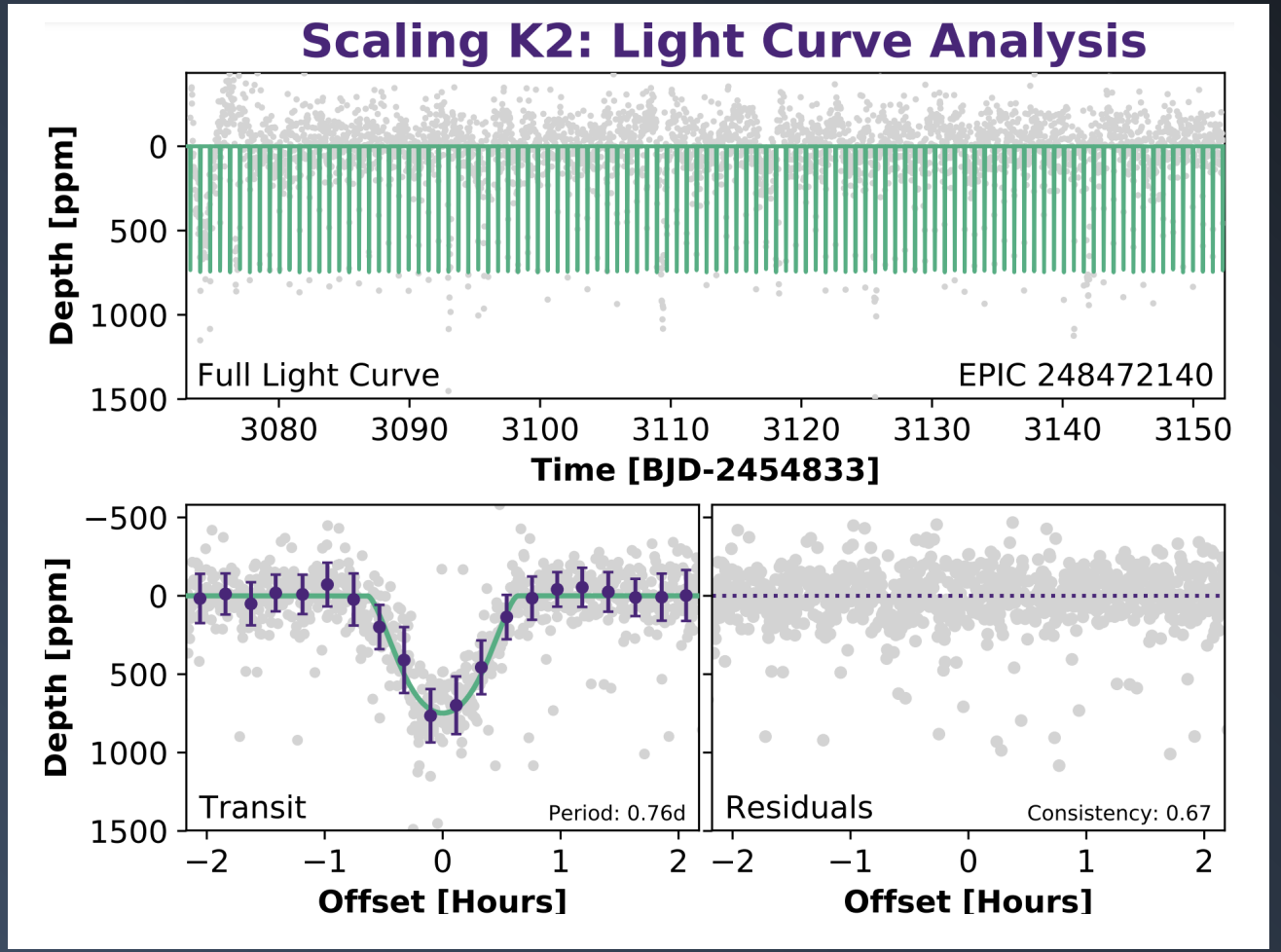
2. Improving our understanding



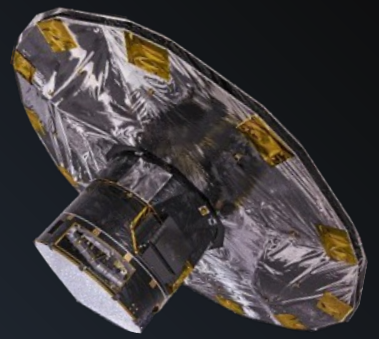
Gaia helps vet planet candidates

K2 candidate with a RUWE of 4.89

(credit: my spreadsheet of retired candidates and lost dreams)



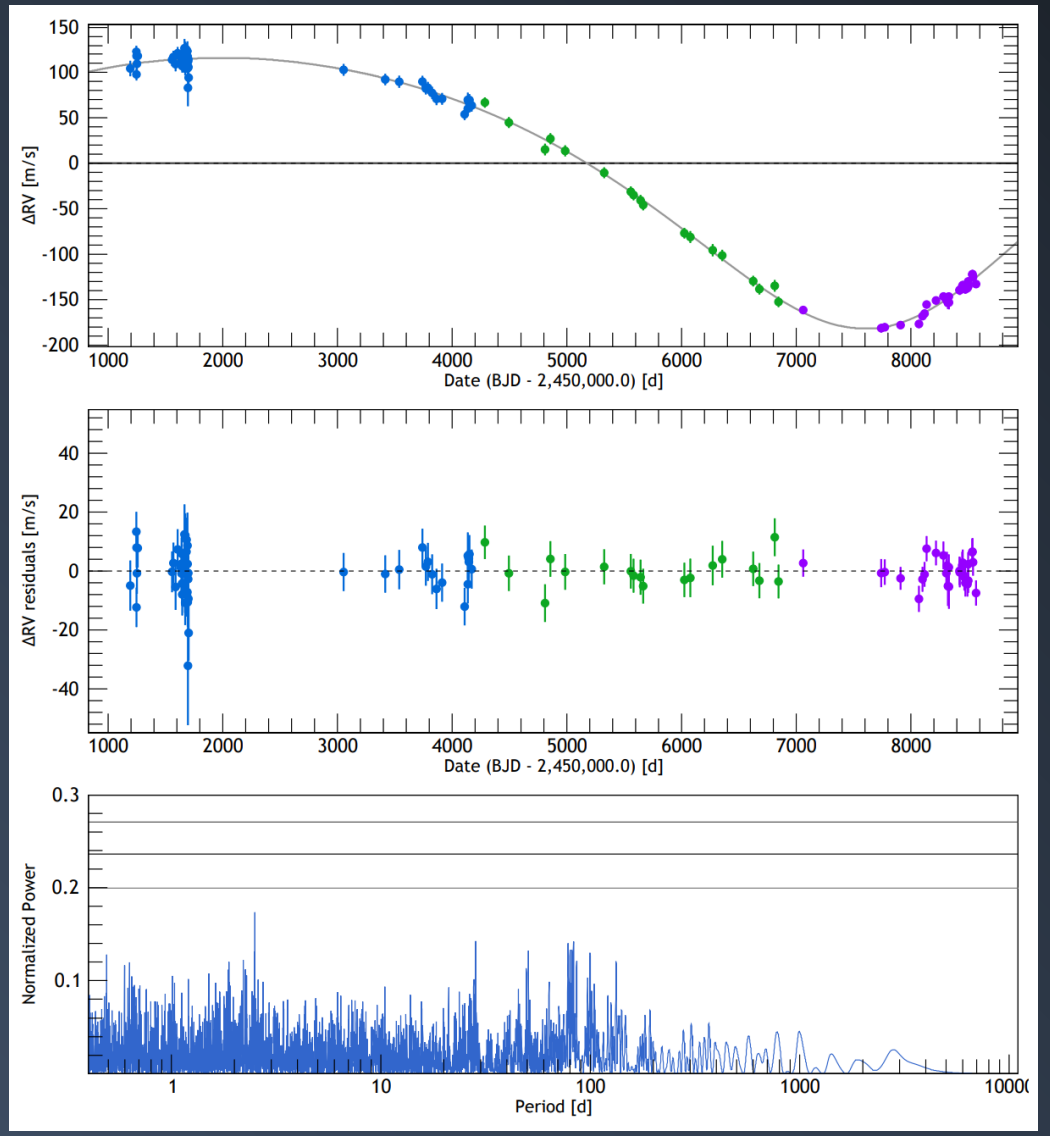
2. Improving our understanding



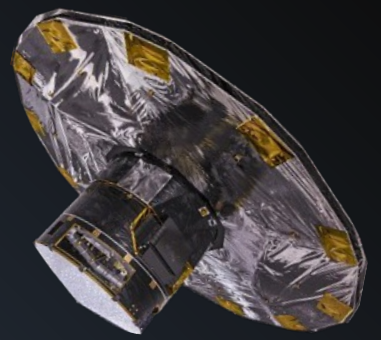
Gaia helps refute planets

HD 92987 b

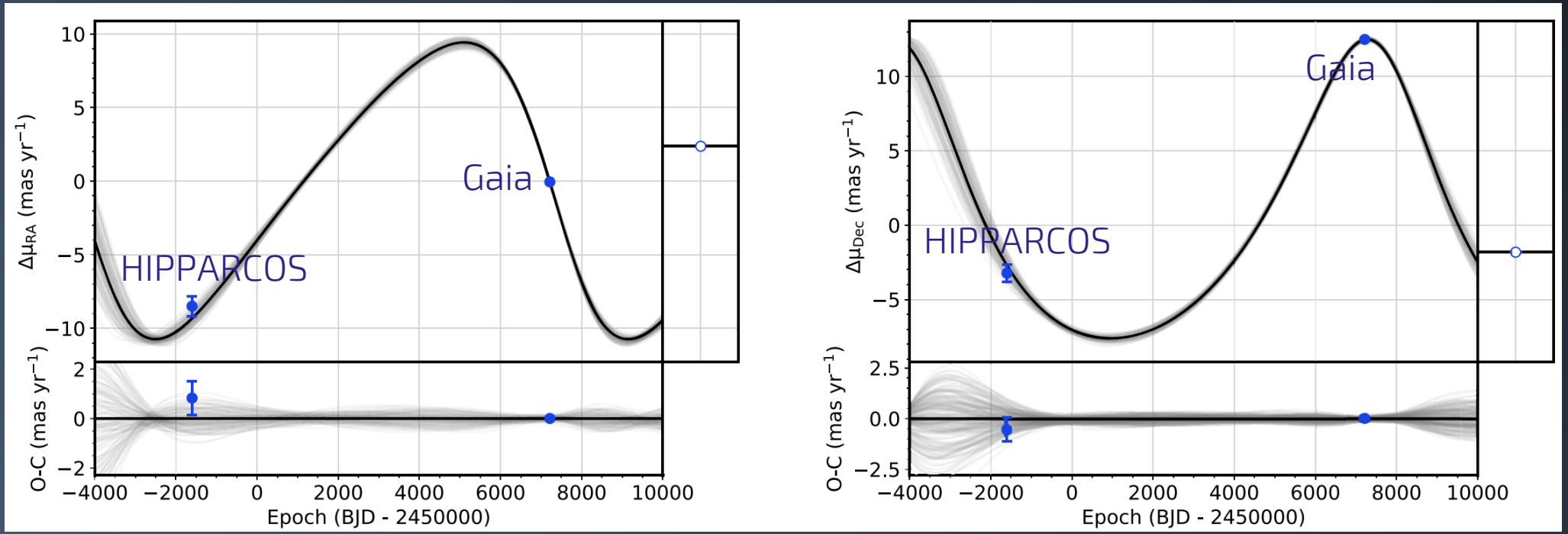
Mp sin ***i*** ~ 17 Jupiter masses (Rickman+2019)



2. Improving our understanding



HIPPARCOS-Gaia astrometry

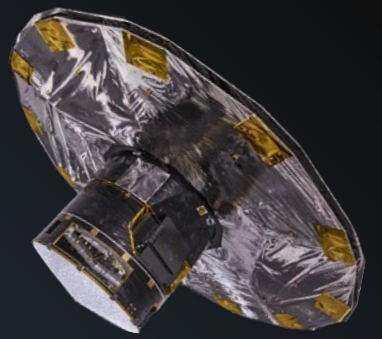


Venner+2021

i = 175 degrees (nearly pole-on)

Mp = 270 Jupiter masses

2. Improving our understanding

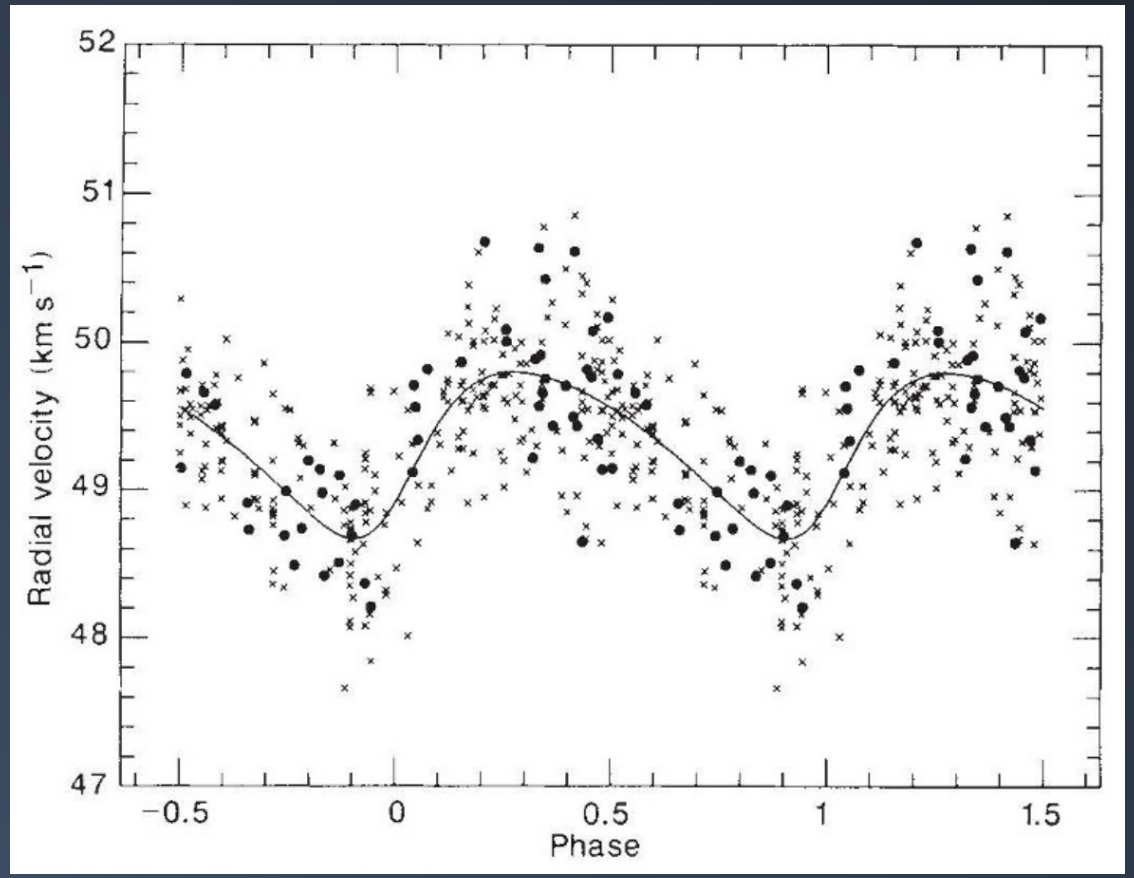


HIPPARCOS-Gaia astrometry

HD 114762 b
The (real) (not) first planet

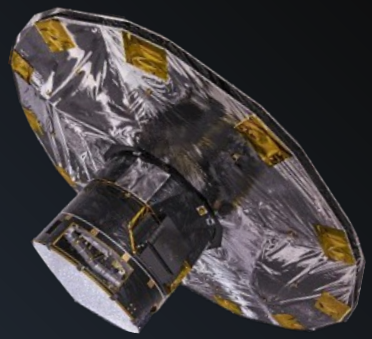
Mp sin ***i*** ~ 11 MJup (Latham+1989)

220 MJup (Gaia collaboration, 2022)



Many more improvements to RV planets pending…

Overview

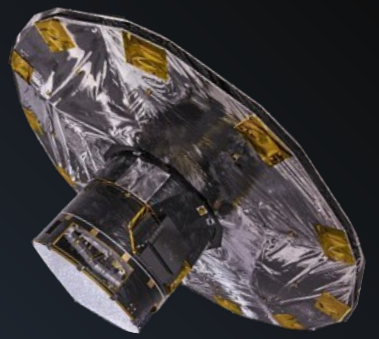


1. Planets! (Not from astrometry)

2. Improving our understanding of planets and planet populations with Gaia

3. Future open questions that Gaia will help tackle

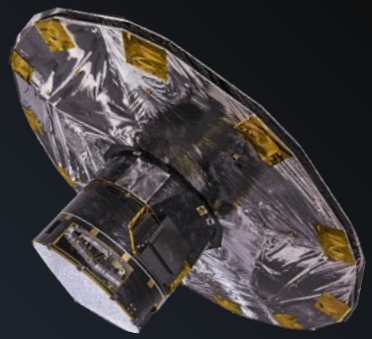
3. Future questions



DR3

- Full astrometric solution (inc. RUWE) for 1.46 billion objects
  - Higher fidelity discrimination between single and binary/higher order multiplicity planetary systems
  - Deeper exploration of planet demographics as a function of single vs. multiple stellar hosts
  - Exploring demographics as a function of Galactic sub-components
- Uniform stellar parameters for 470 million objects, including spectral type
  - Ability to explore Kepler/K2/TESS demographics more finely, along more stellar parameter axes
- 12 elemental abundances for 5.5 (2.5?) million objects
  - Exploring demographics as a function of planetary building blocks on an unprecedented scale

3. Future questions



DR4

- Full astrometric, photometric, and RV solutions for 1.46 billion objects
  - Full orbits (!)
  - Acceleration of future direct imaging mission targets (anything that's accelerating too fast wouldn't be a good target!) (see Tim's talk tomorrow!)
- Exoplanets!
  - Exploring the demographics of solar-system-like Jupiter systems (see Alessandro's talk tomorrow!)