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RVs in the Greater Context of Exoplanet Science

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How Difficult is it to Detect Extrasolar Planets?

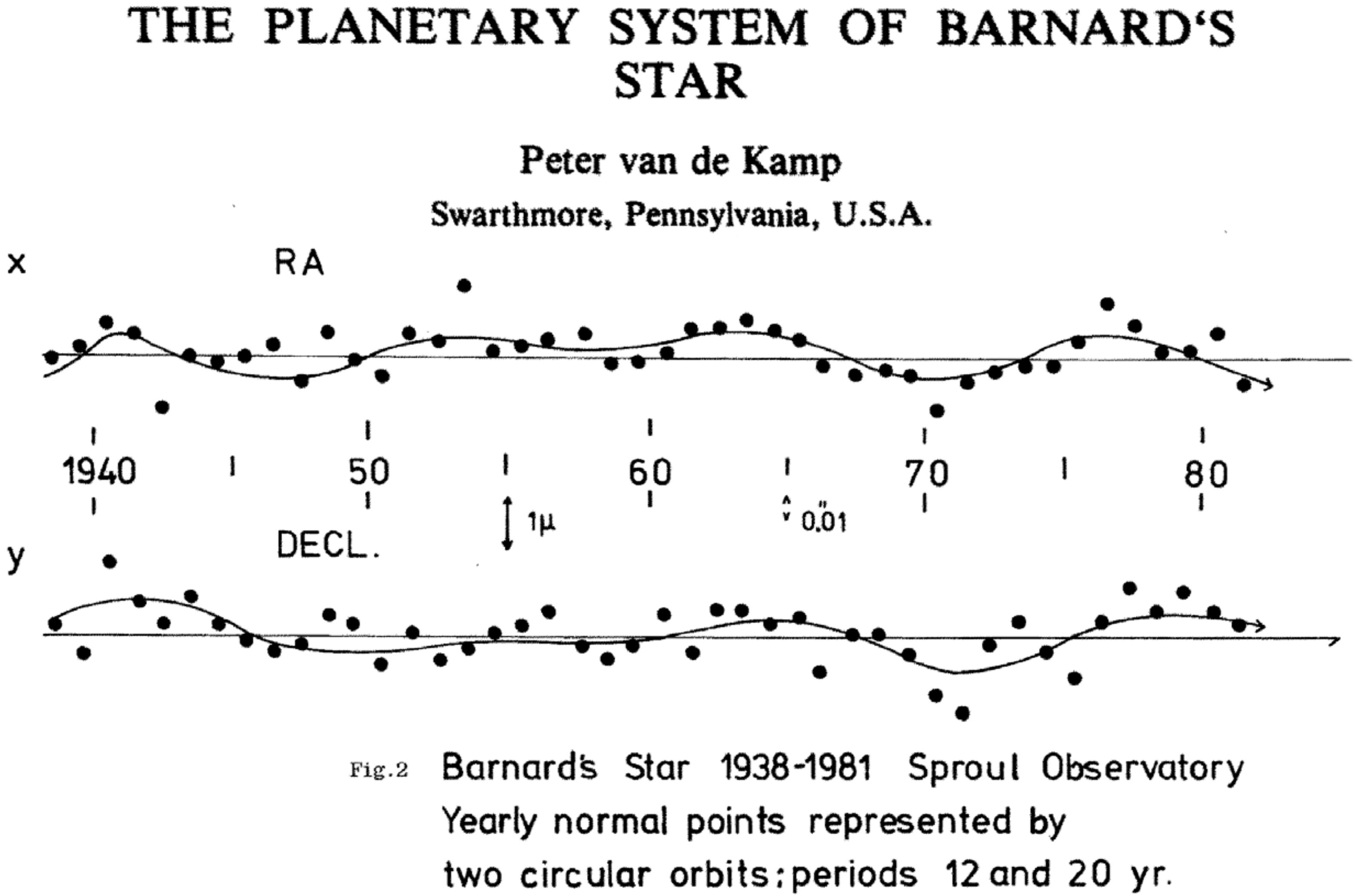
- Some rough numbers and scaling relations
- Radius: $R_\odot : R_\mathrm{Jup} : R_\oplus = 100 : 10 : 1$
- Density: $\rho_\odot : \rho_\mathrm{Jup} : \rho_\oplus = 1 : 1 : 3$
- Mass: $m_\odot : m_\mathrm{Jup} : m_\oplus = 300{,}000 : 300 : 1$
- Orbital velocity: $v_\oplus = 30\ \mathrm{km/s}$
- Scaling: $v \propto 1/\sqrt{a}$
- Definition: 1 AU at 1 pc is 1"
- Example Earth around G star at 10 pc:

$$v_* = v_\oplus m_\oplus / m_* = 10\ \mathrm{cm/s}\ ,\ \ a_* = 0.3\ \mu\mathrm{as}$$

Extrasolar Planets: Expectations from the Solar System

- Naïve expectation: other planetary systems have the same architecture as ours
  - Small inner planets, large outer planets
  - Orbital radii of a few AU
  - Orbits close to one common plane
  - Orbits with small eccentricities
- Jupiter is easiest to detect
  - RV accuracy: $\approx 10\ \mathrm{m/s}$
  - Astrometric accuracy at $10\ \mathrm{pc}$: $\approx 0.5\ \mathrm{mas}$
  - Orbital period: $\approx 10\ \mathrm{yr}$

Planets of Barnard’s Star??



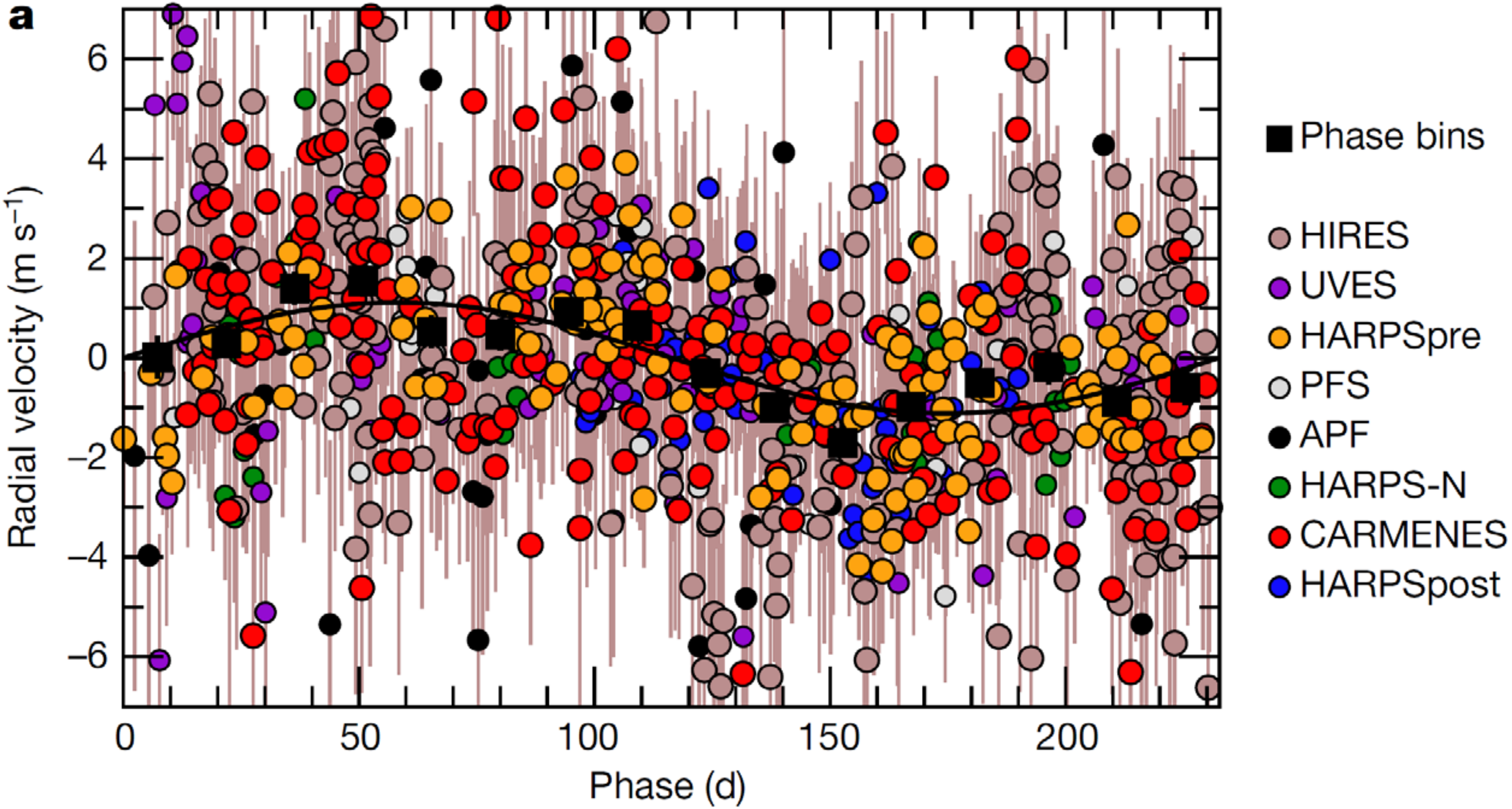
THE PLANETARY SYSTEM OF BARNARD‘S STAR

Peter van de Kamp

Swarthmore, Pennsylvania, U.S.A.

Fig.2 Barnard's Star 1938-1981 Sproul Observatory
Yearly normal points represented by
two circular orbits: periods 12 and 20 yr.

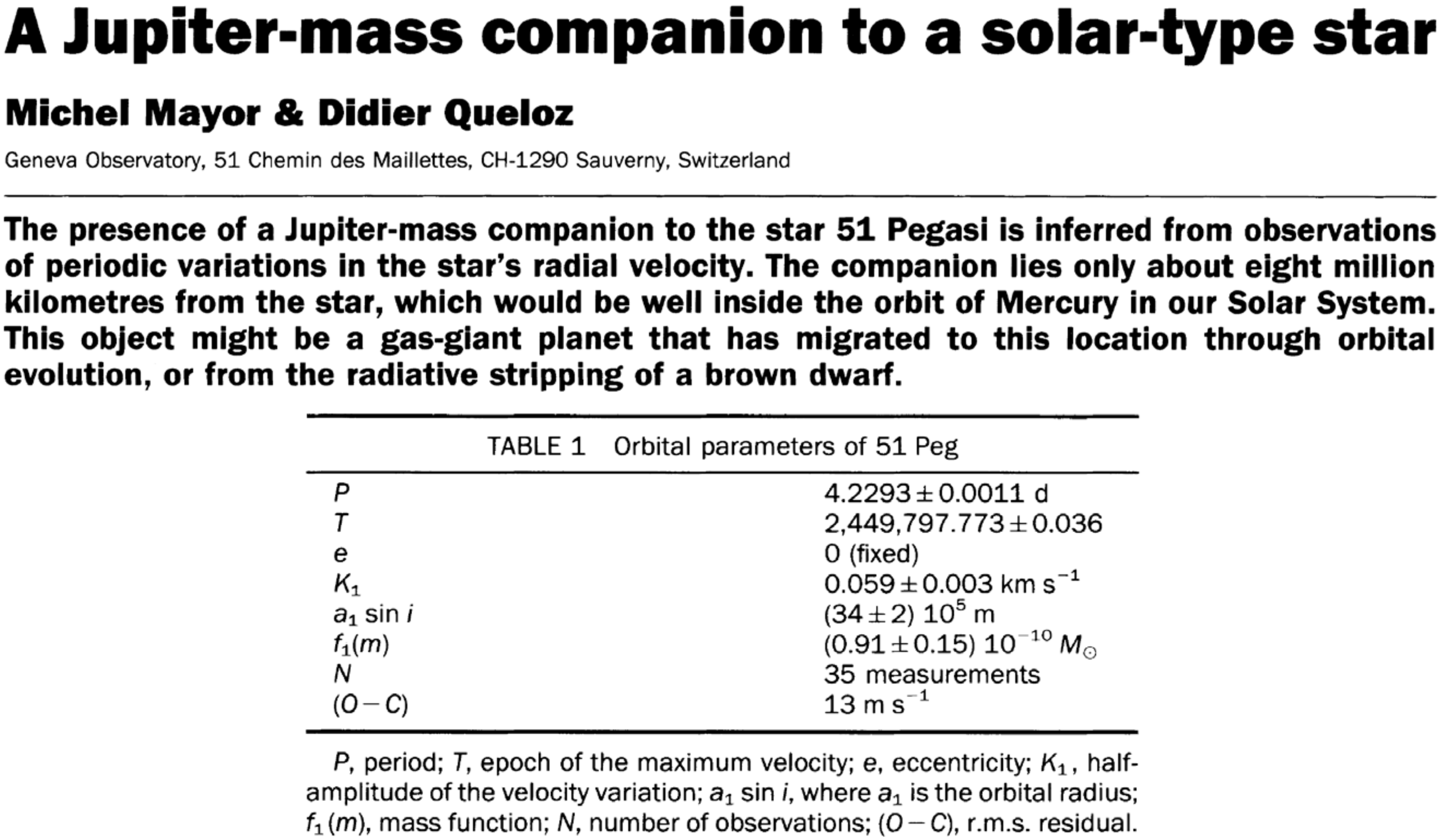
A Planet of Barnard's Star!



$$m \sin i = 3.2\, m_\oplus \quad P = 233\,\mathrm{d} \quad T_\mathrm{eq} = 105\,\mathrm{K}$$

Ribas et al.
(Nature 2018)

Nature 378, 355–359 (1995)



A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

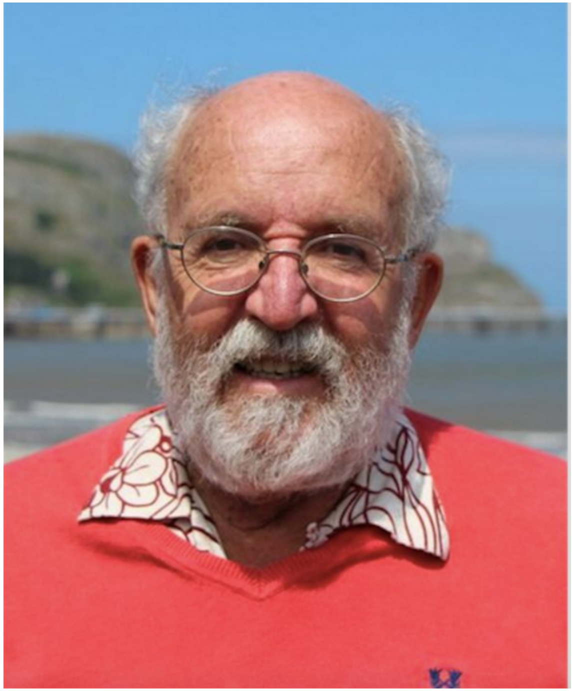
The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

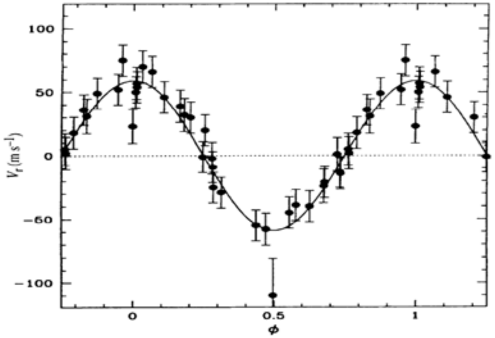
TABLE 1 Orbital parameters of 51 Peg

P	4.2293 ± 0.0011 d
T	$2{,}449{,}797.773 \pm 0.036$
e	0 (fixed)
K_1	0.059 ± 0.003 km s^{-1}
$a_1 \sin i$	$(34 \pm 2)\ 10^5$ m
$f_1(m)$	$(0.91 \pm 0.15)\ 10^{-10}\ M_{\odot}$
N	35 measurements
$(O-C)$	13 m s^{-1}

P, period; T, epoch of the maximum velocity; e, eccentricity; K_1, half-amplitude of the velocity variation; $a_1 \sin i$, where a_1 is the orbital radius; $f_1(m)$, mass function; N, number of observations; $(O-C)$, r.m.s. residual.

Nobel Prize in Physics, 2019

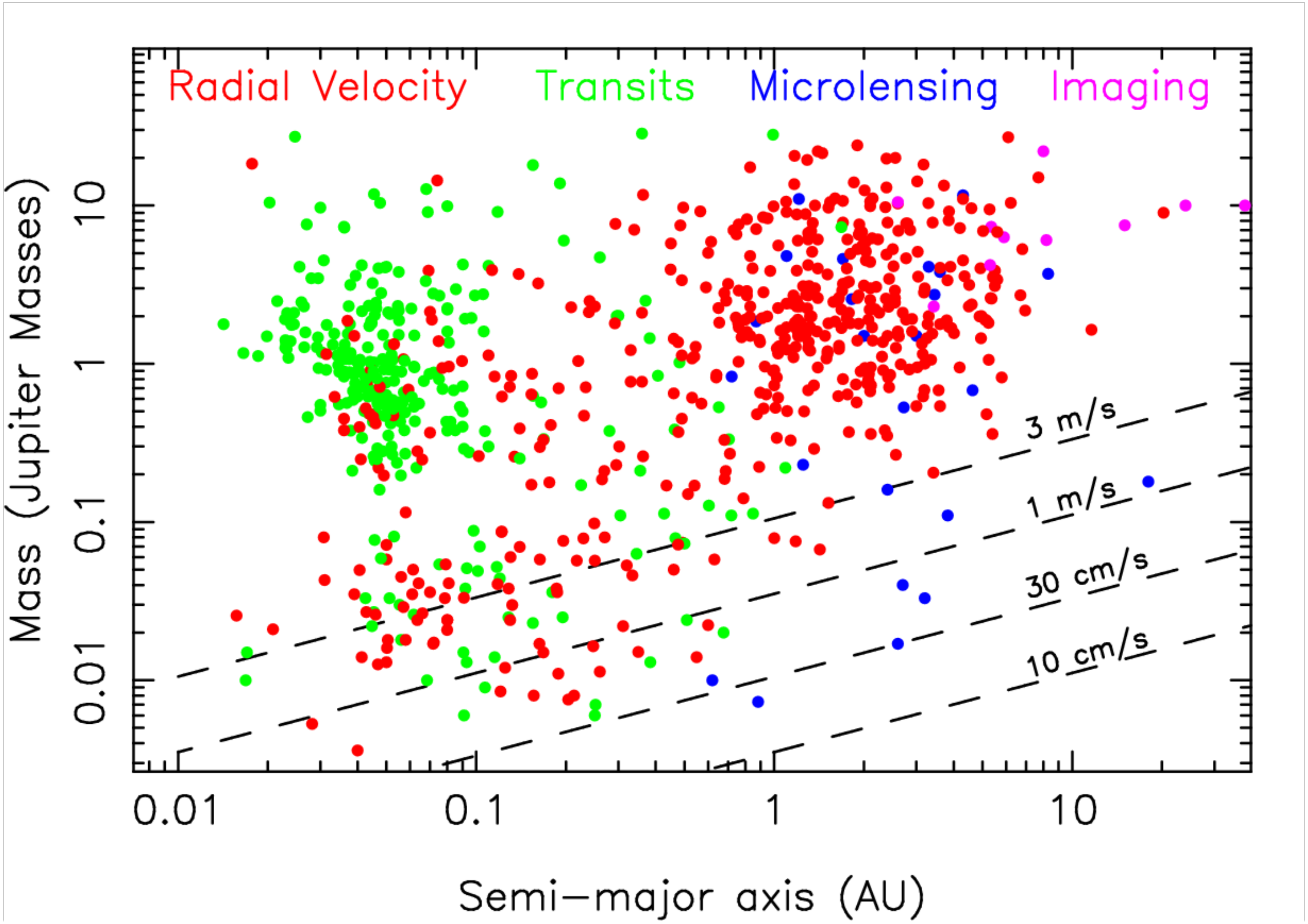




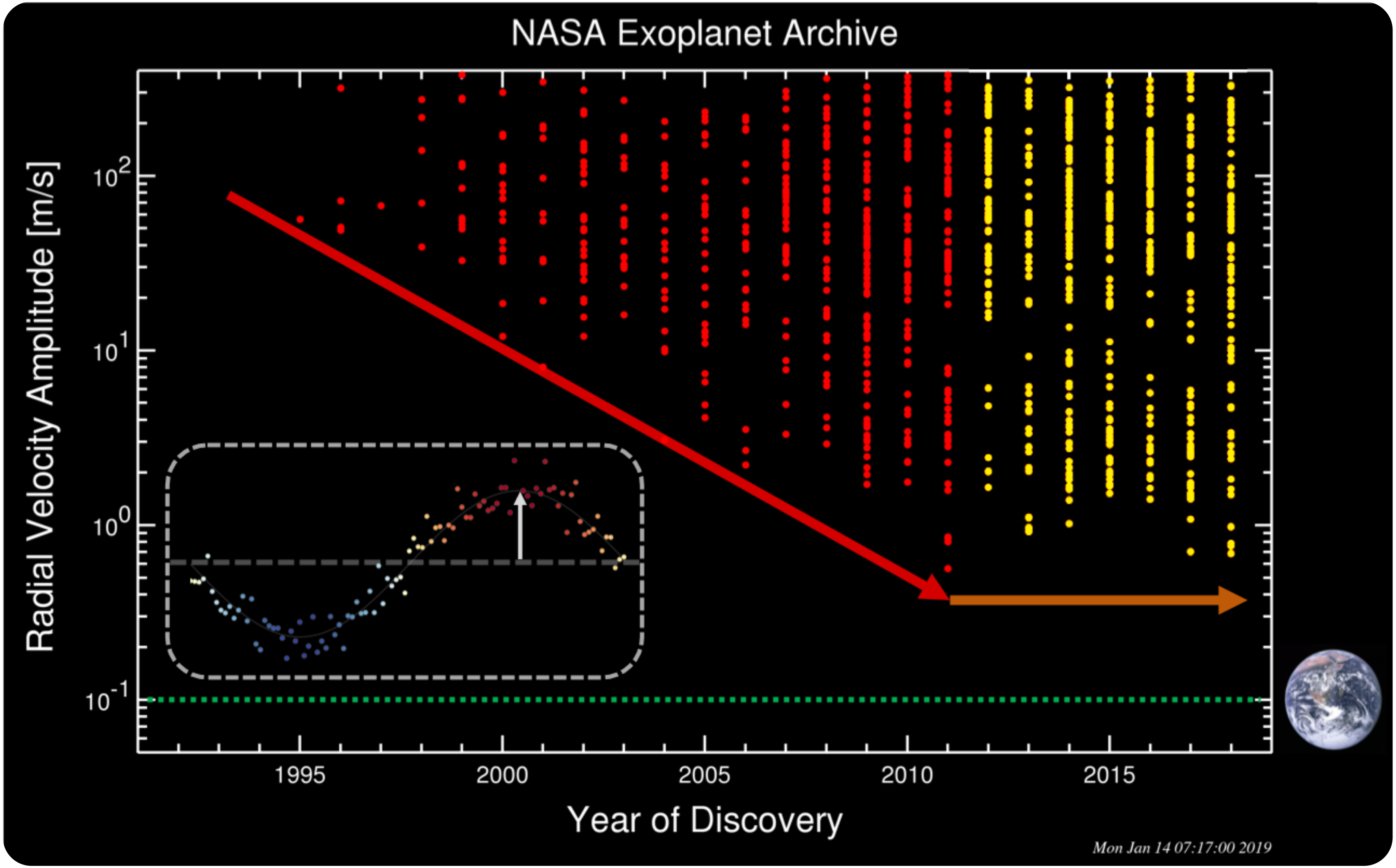
Early Surprises from RV Surveys

- There are hot Jupiters!
  - Types of planets that don’t exist in the Solar System
- Many planets have highly eccentric orbits
  - Different dynamical history than Solar System
- It is “easier” to find extrasolar planets than thought before.
- The diversity of planetary systems is larger than thought before.
- By observing extrasolar planets, we can learn about the origin of the Solar System.

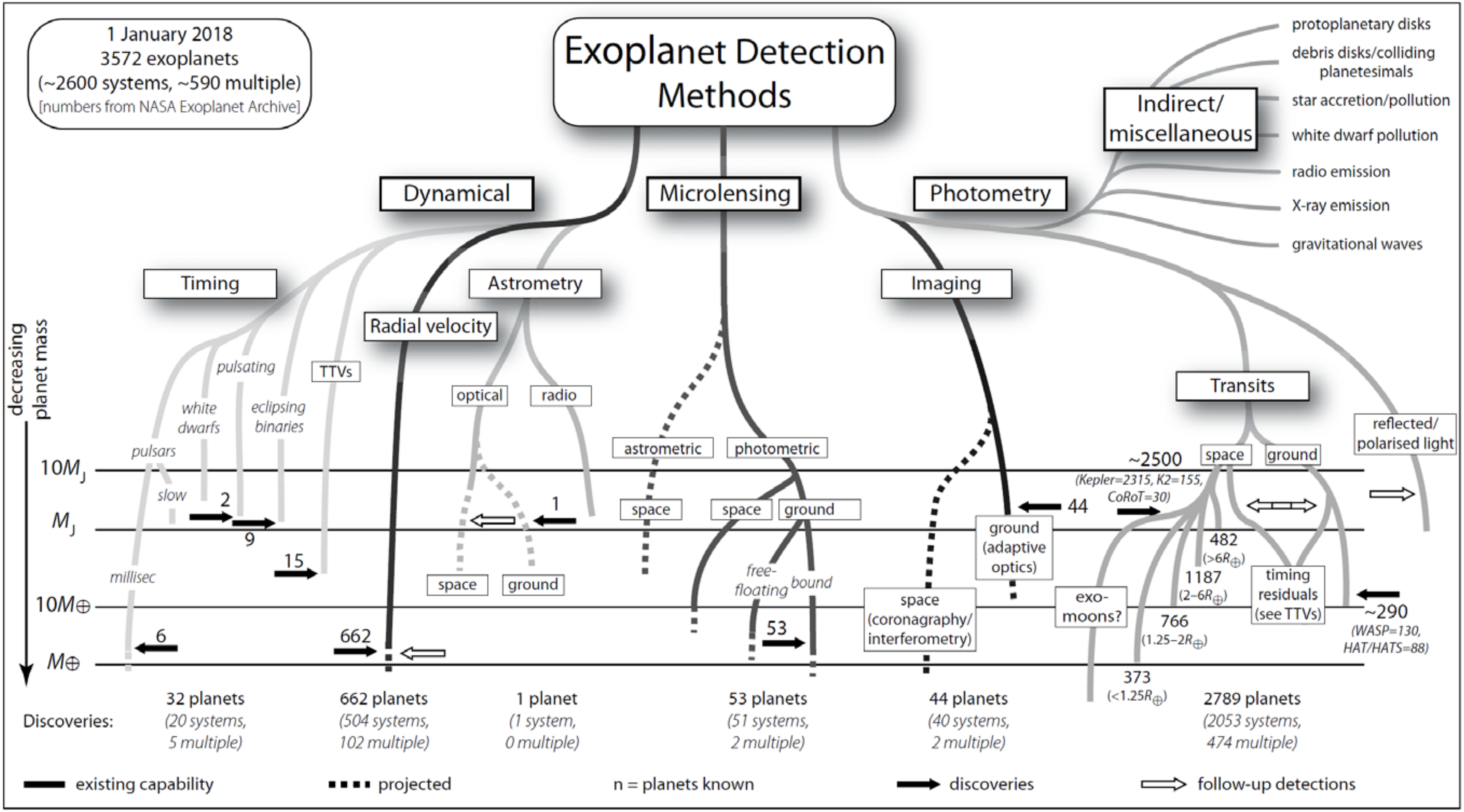
Exoplanet Demographics Prior to Kepler



Advances in RV Precision



Genealogy of Exoplanet Detection Methods



Perryman (2018)

Masses from Radial Velocities

- RVs yield minimum masses ($m \sin i$)
  - Note: $\langle \sin i \rangle = \frac{\pi}{4} = 0.79$, $p(\sin i > 0.5) = \frac{\sqrt{3}}{2} = 0.87$
  - "Typical" planet: $m = 1.27 \cdot m \sin i$
  - Only 13% of planets have $m > 2 \cdot m \sin i$
  - Ok for classification and statistics
- RVs for transiting planets yield masses
  - $i \approx 90°$, can frequently be measured precisely $\rightarrow m$
  - R also known → density → bulk composition

Complementarity of RVs and Astrometry

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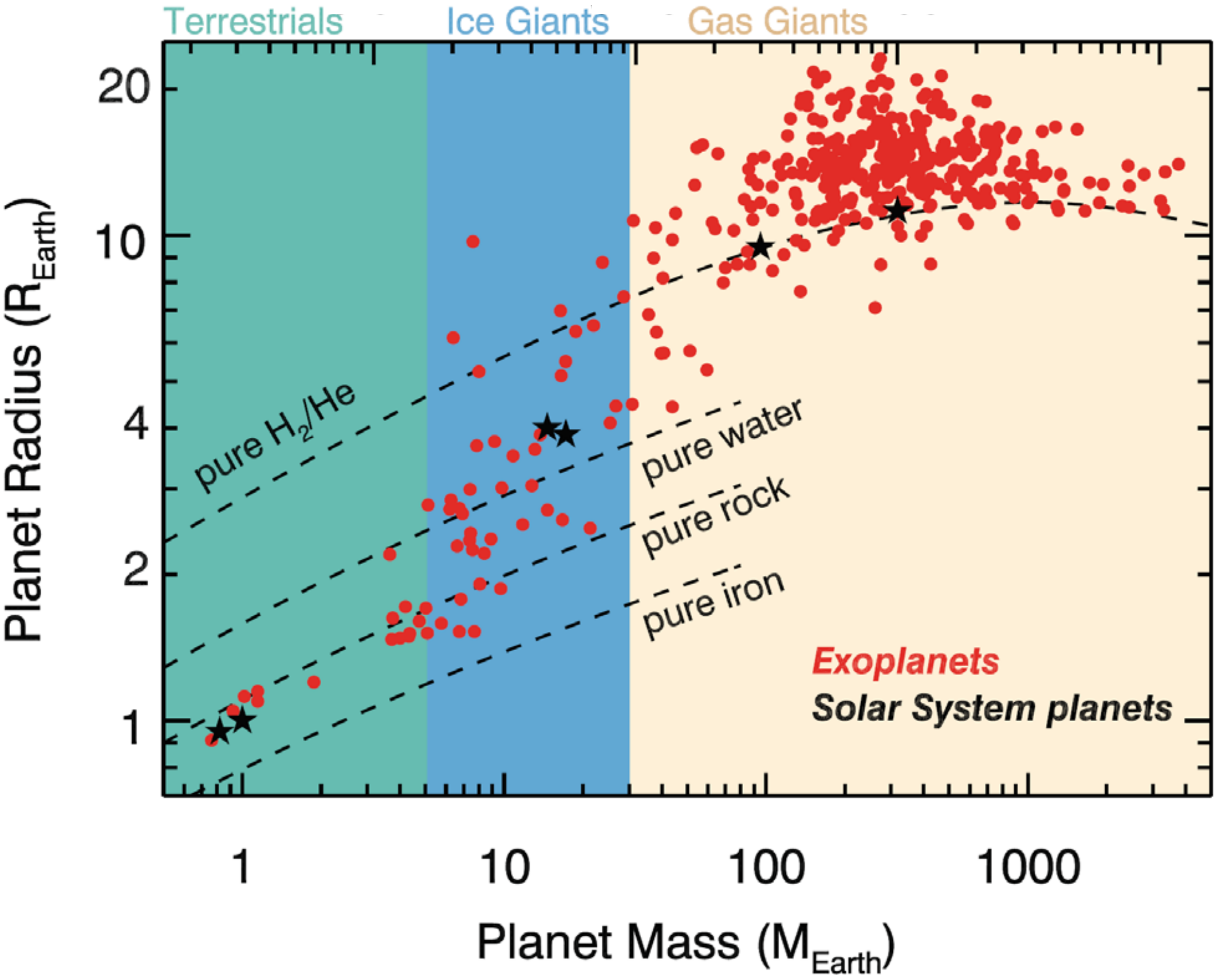
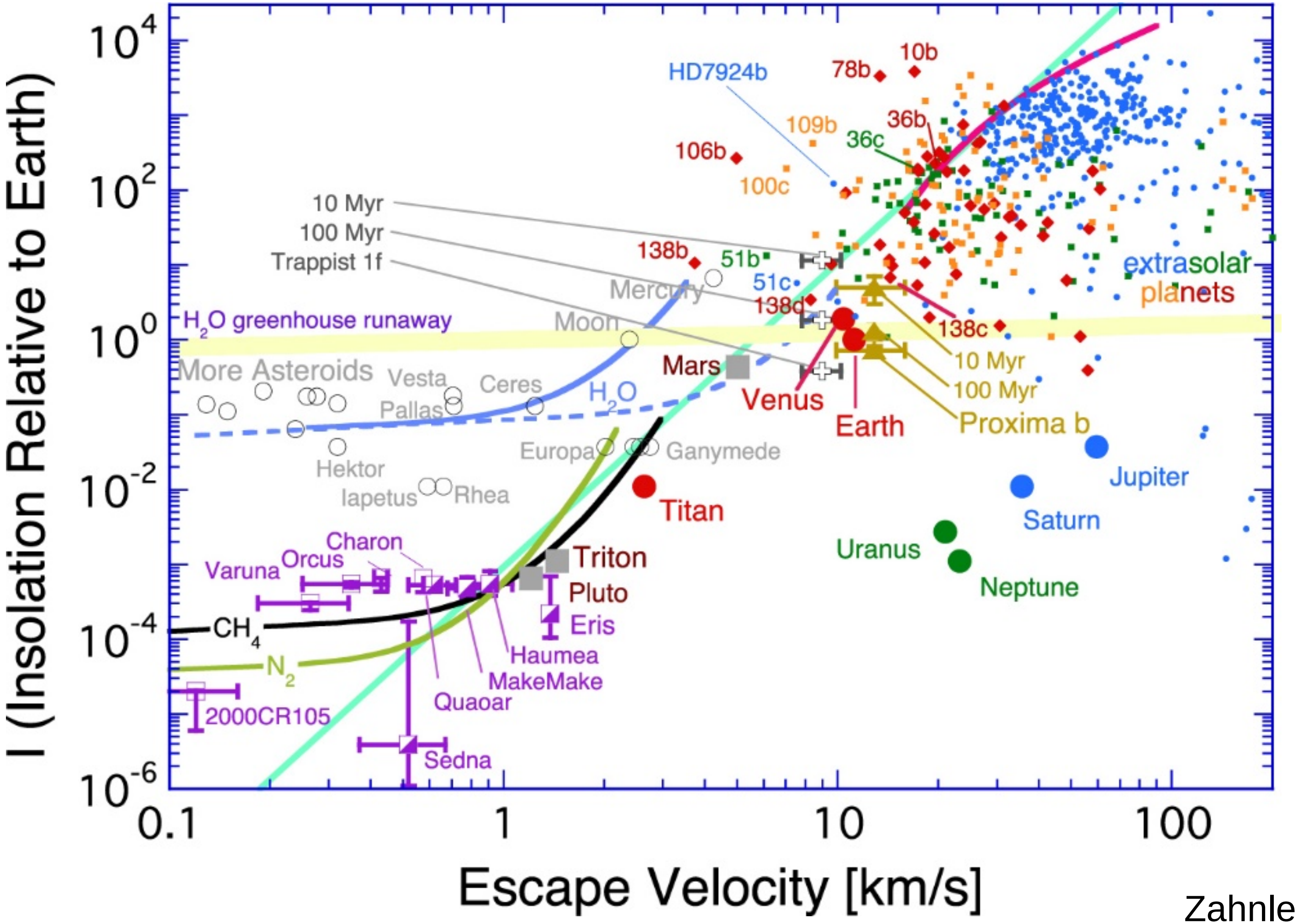
Radial Velocity	**Astrometry**
Provides $m \sin i$	Provides m
No mutual i for multiples	Mutual i for multiples
Best for close-in planets	Best for large planet orbits
Works for cool stars	Works for all stellar types
Very sensitive to activitiy	Less sensitive to activity
Signal independent of distance	Signal proportional to $1/d$
Works to 100s of pc	Works to 10s of pc
Works well from ground	Best done from space

Planet Mass-Radius Diagram

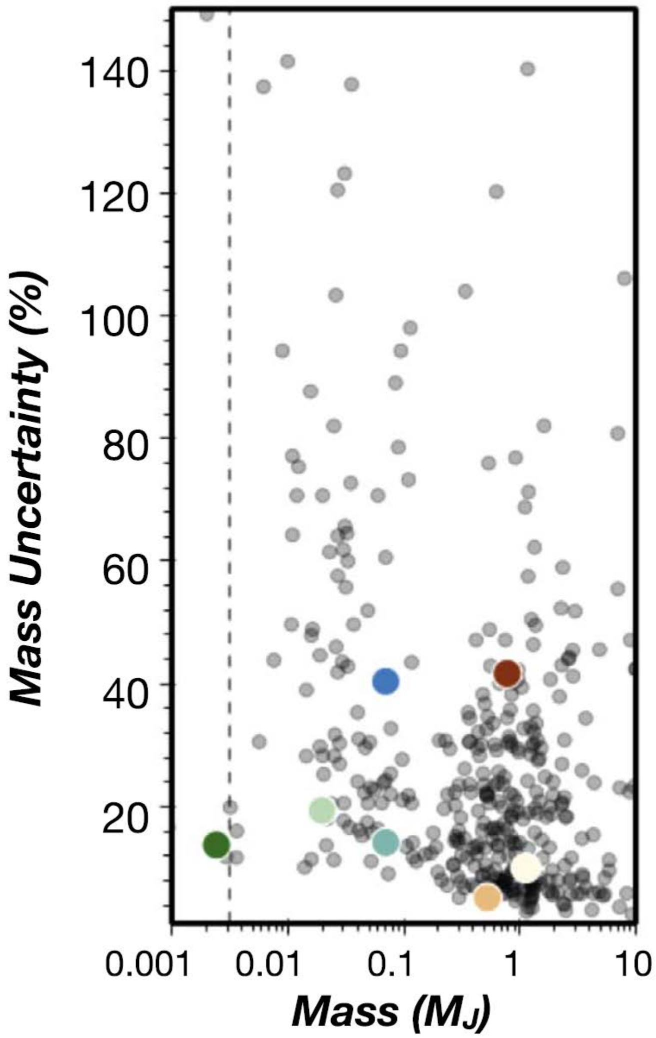


The “Cosmic Shoreline”



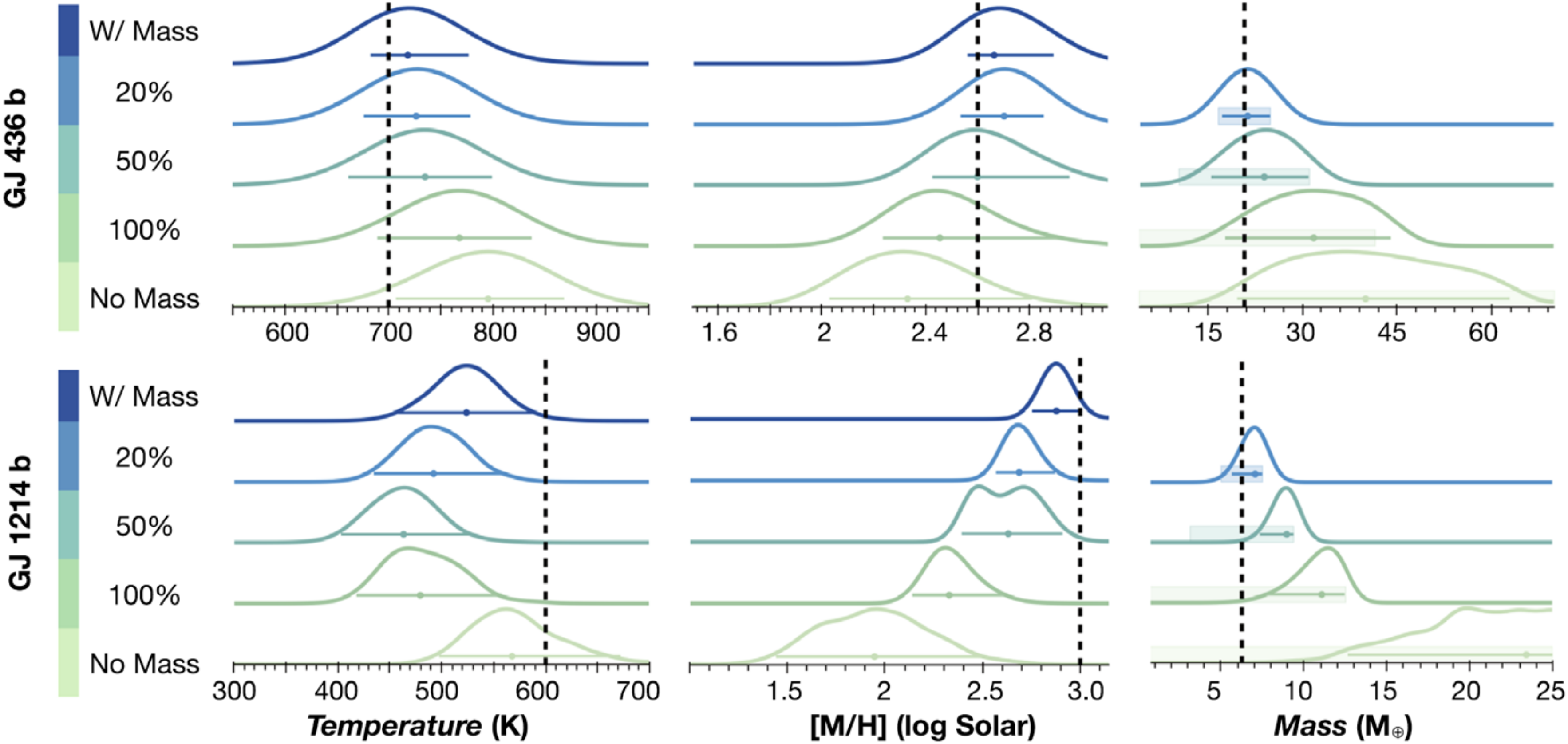
Zahnle & Catling (2017)

Precision of Measured Masses



Batalha et al. (2019)

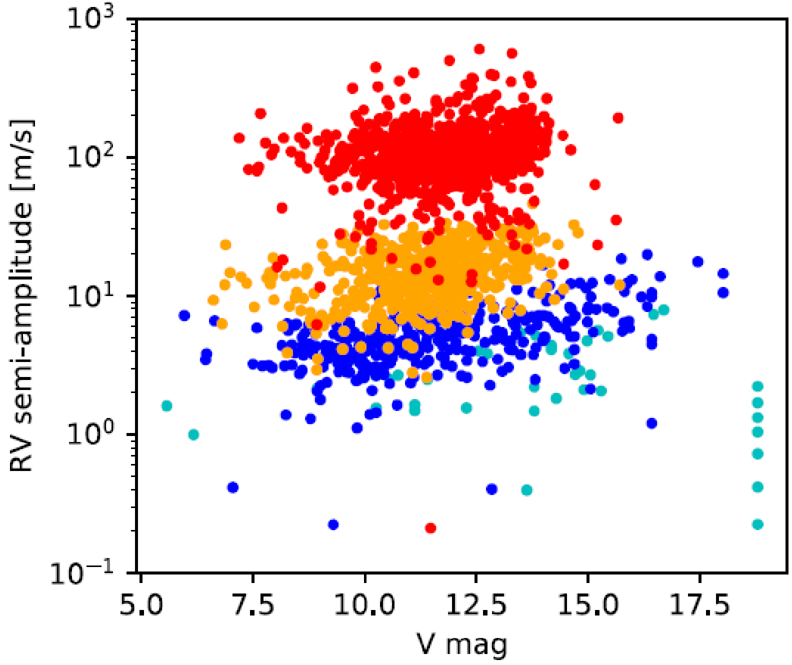
Retrievals from Transit Spectroscopy



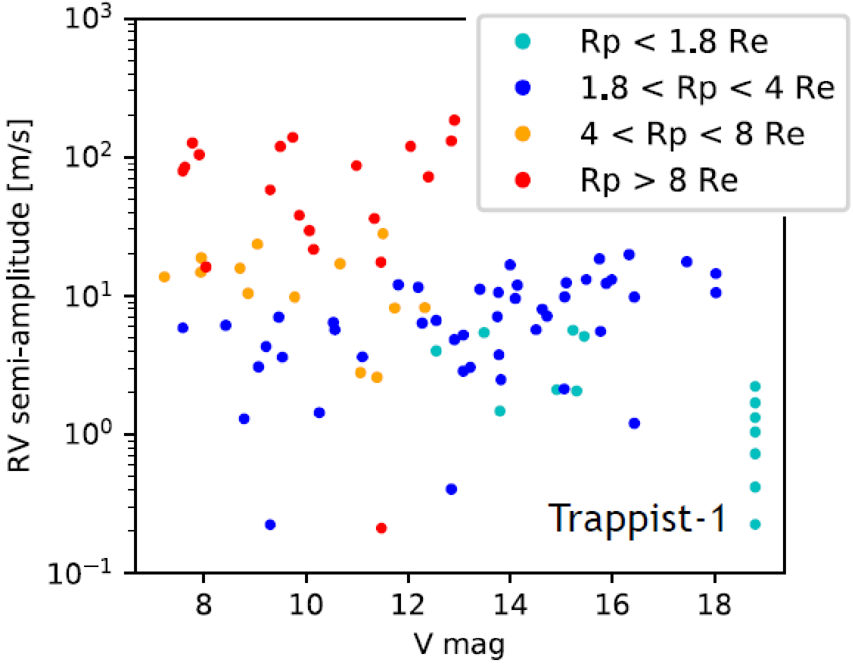
Batalha et al. (2019)

Transit Spectroscopy Needs Mass Determination

Full ARIEL sample



Expected JWST targets
(includes known planets and expected TESS discoveries)



We need to know the masses of all these planets to better than 20% precision!!

L. Kreidberg

Distribution of Orbital Eccentricities

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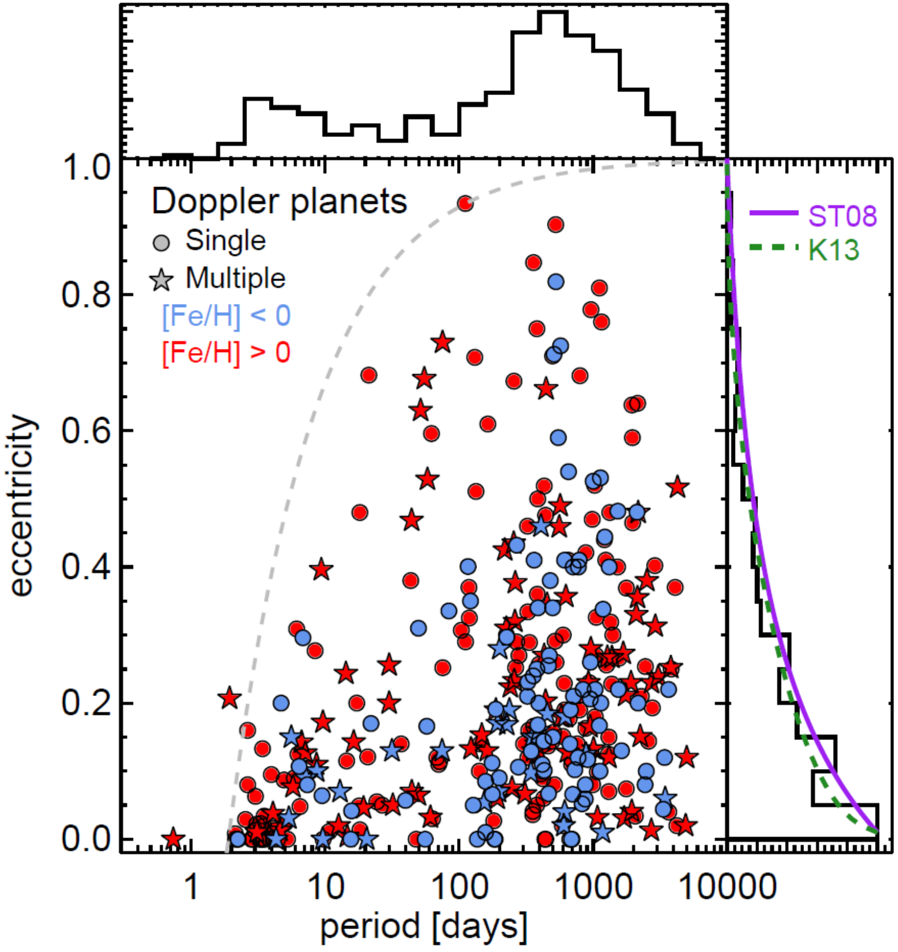
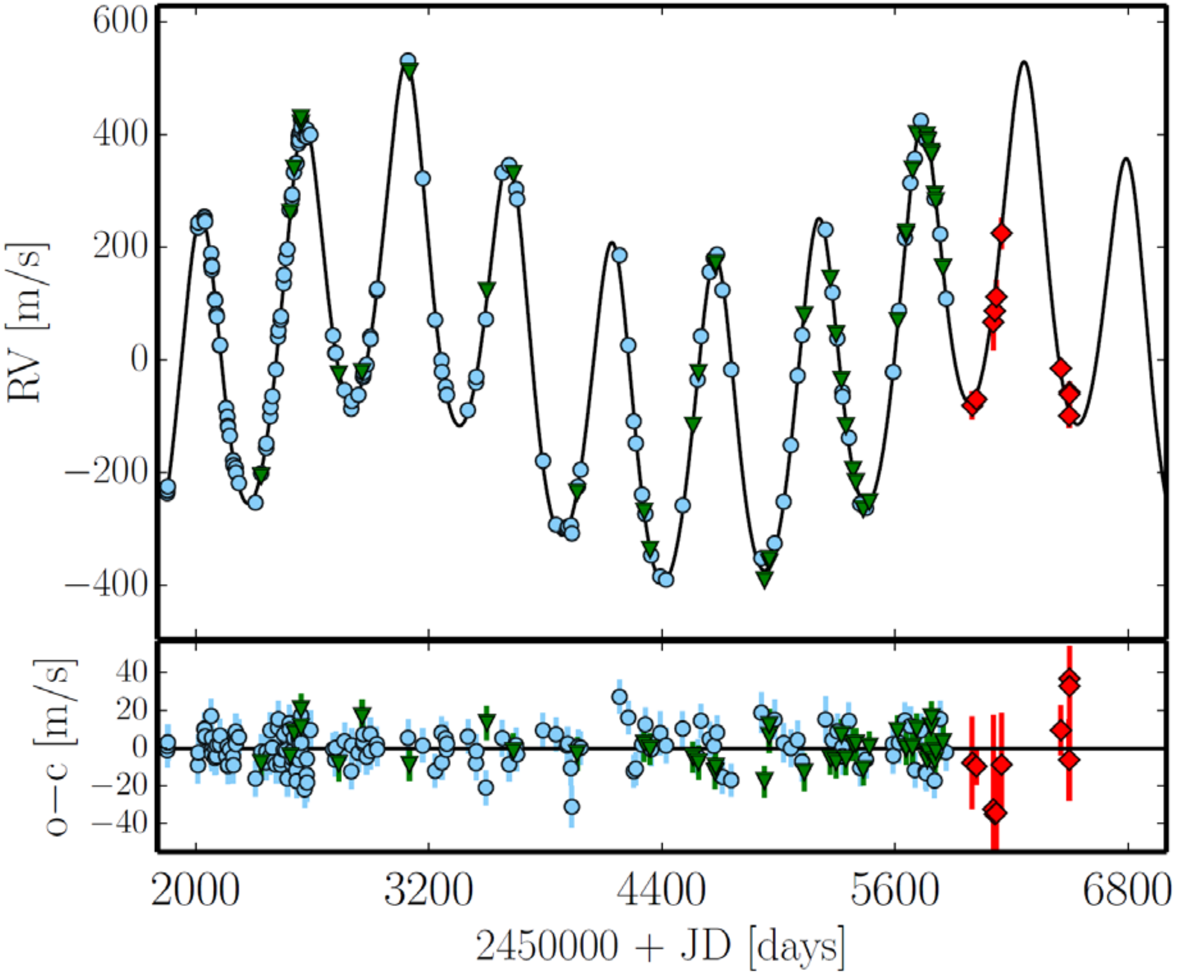


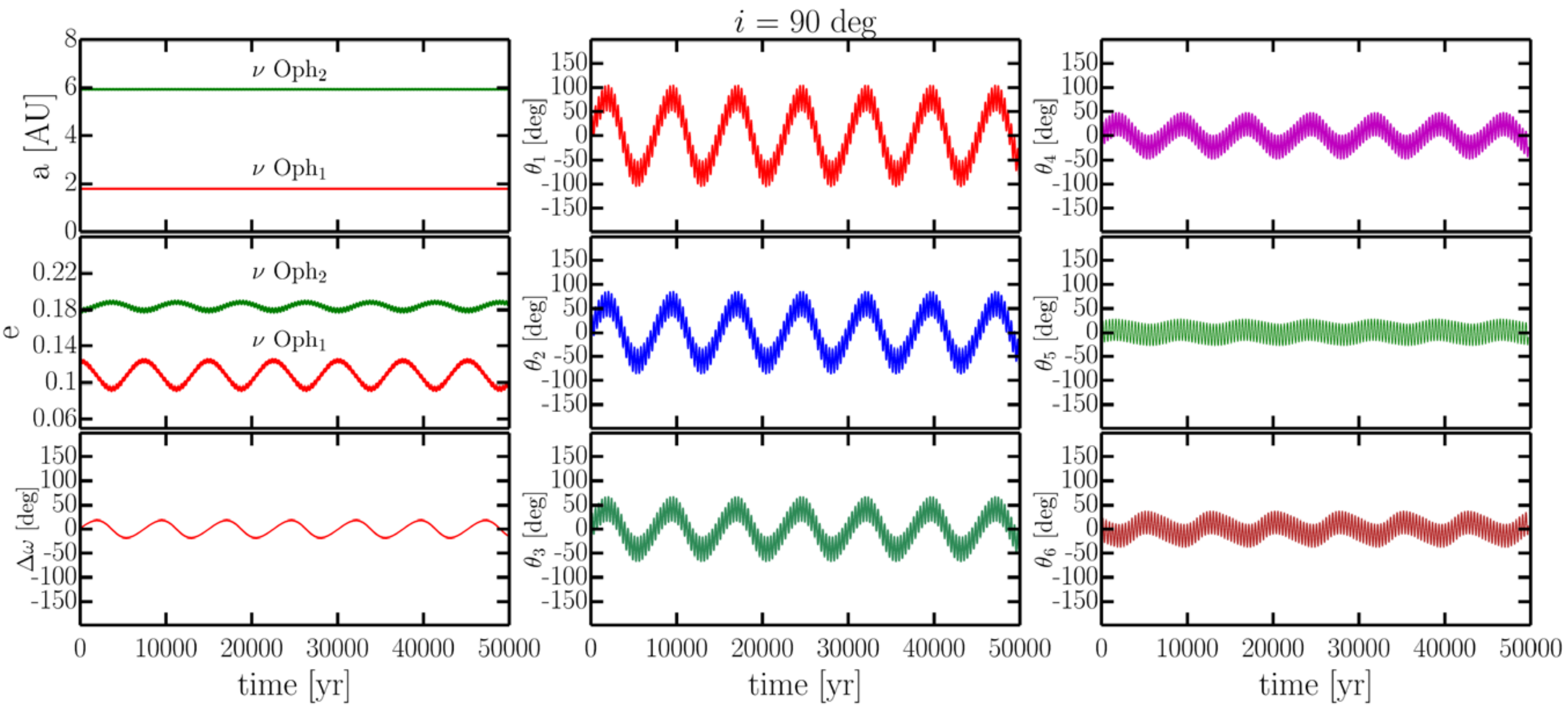
Winn & Farbrycky (2015)

ν Oph: Two Brown Dwarfs in a 6:1 Resonance



Quirrenbach et al. (2019)

Orbital Evolution of the ν Oph System



Quirrenbach et al. (2019)

Summary

- The field of exoplanet research started with RVs.
- RVs are important for planet statistics.
  - Very few transits with $P \gtrsim 1\,\mathrm{yr}$
- $m \sin i$ is a good proxy for m in population studies.
- Transits + RVs give $\rho \to$ bulk composition
- m is important for analyses of atmospheres.
- e and multiple systems $\to$ dynamics
- RVs and Gaia astrometry are complementary.