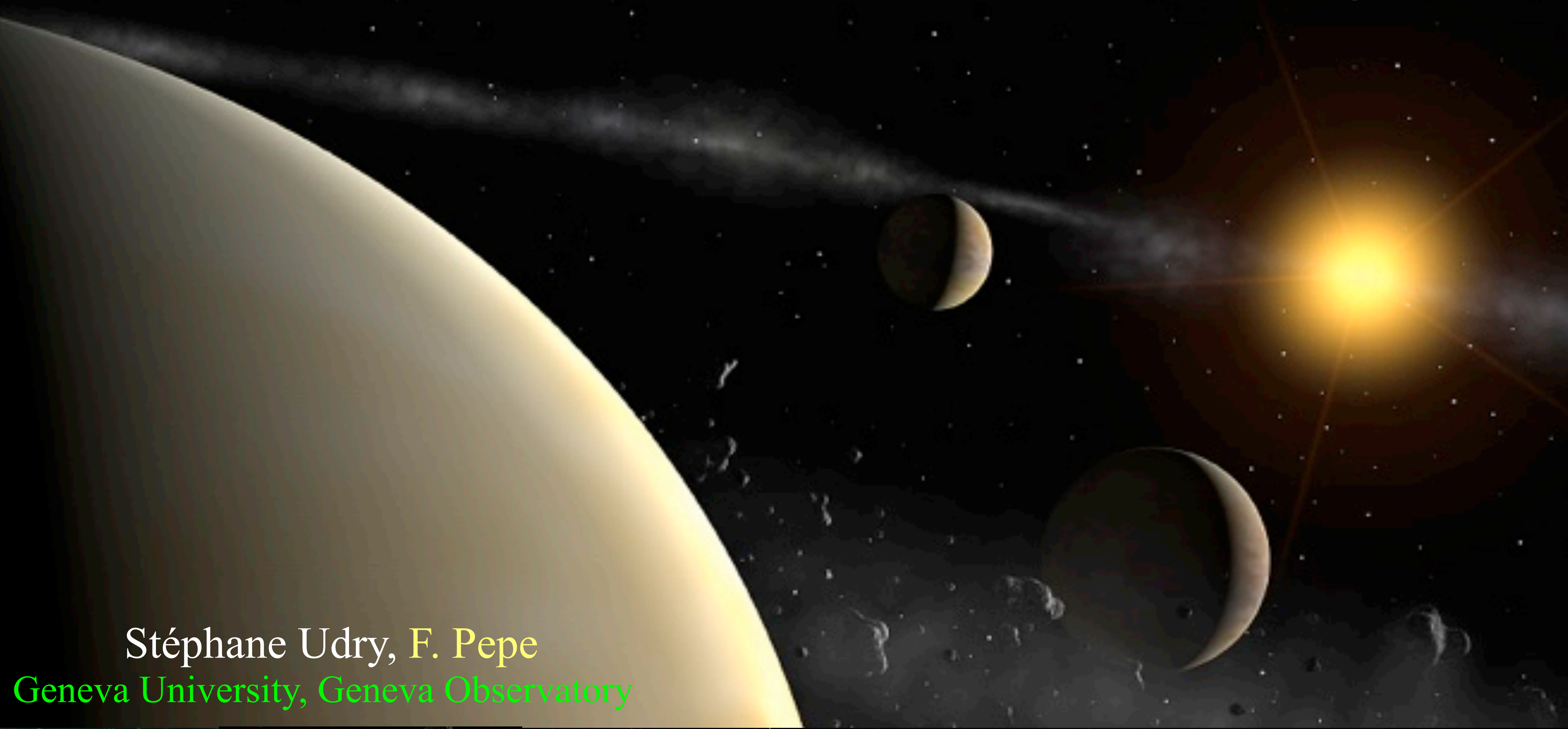
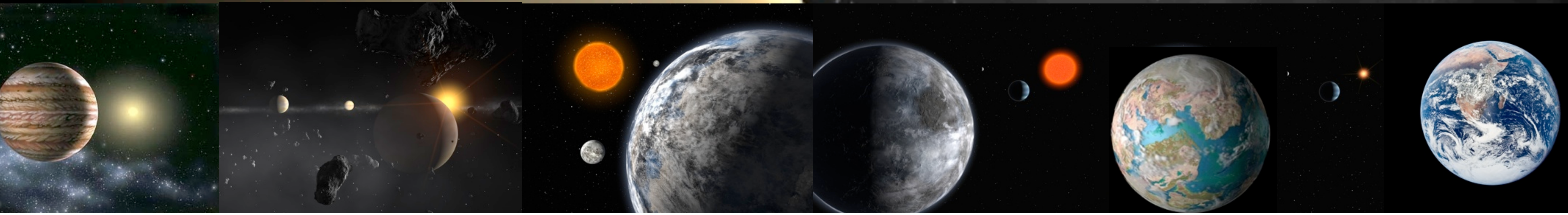
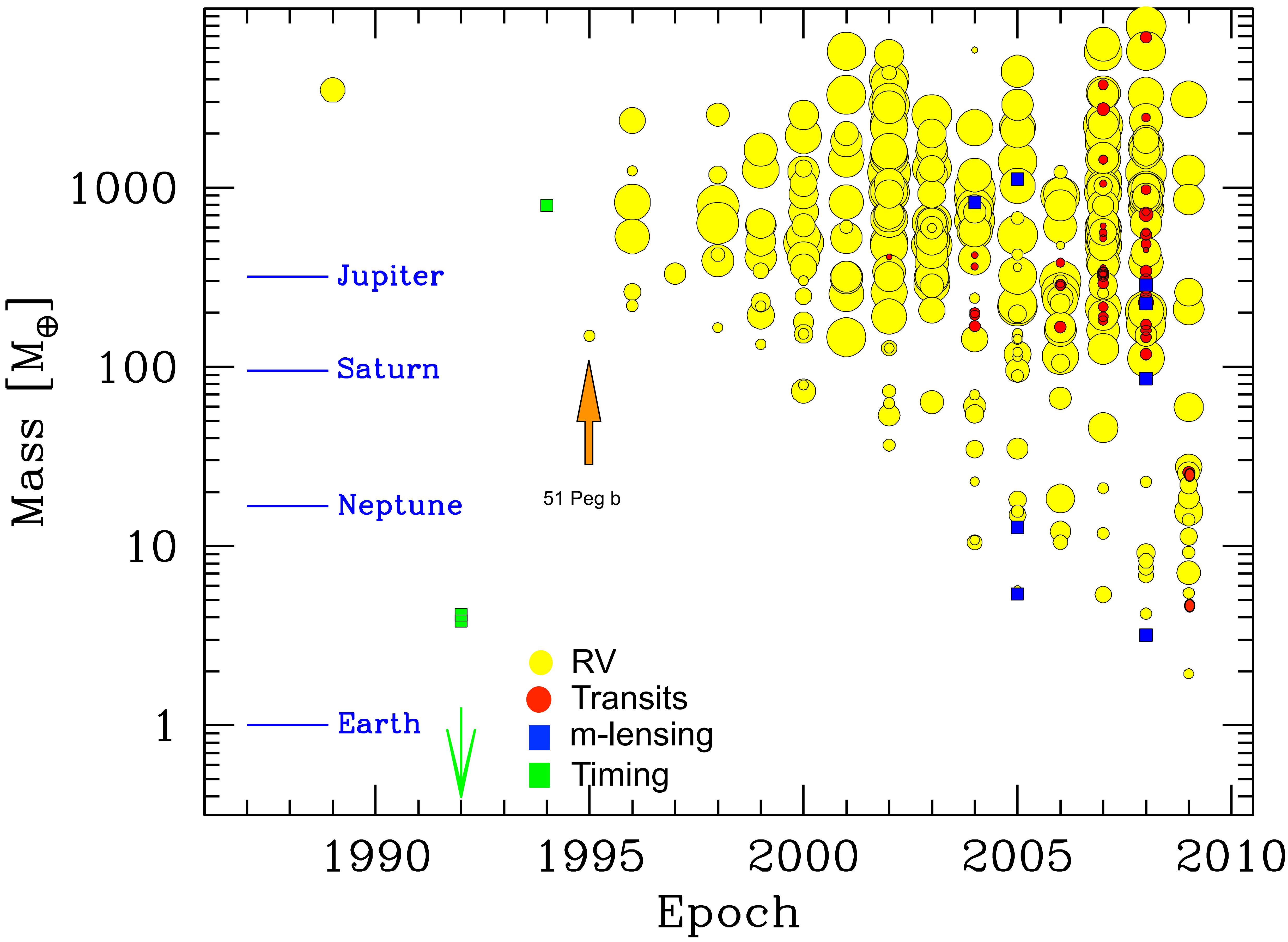
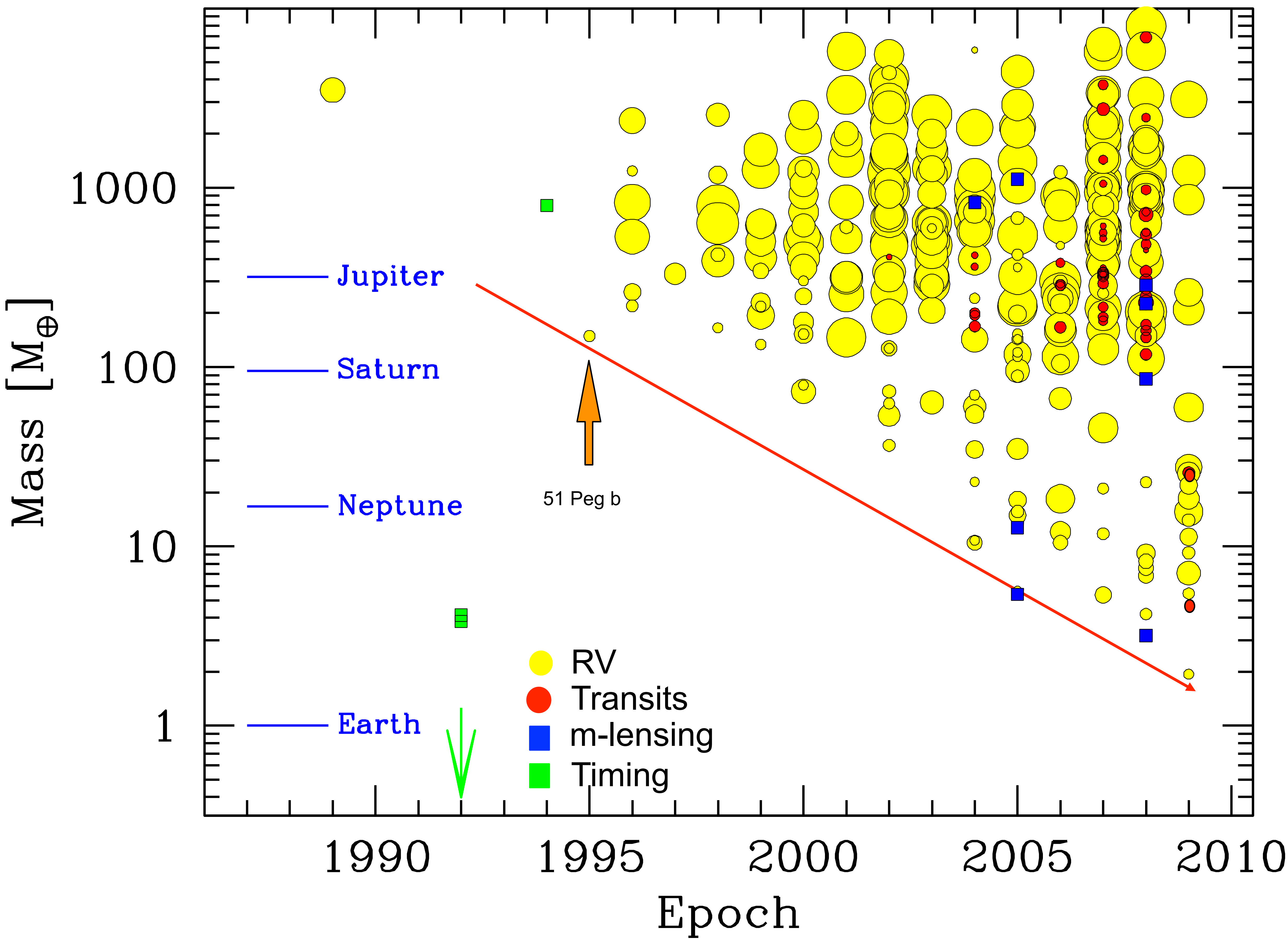
Exoplanets - An Overview



Stéphane Udry, F. Pepe
Geneva University, Geneva Observatory




Mass [M⊕]
1000
100
10
1
Jupiter
Saturn
Neptune
Earth
51 Peg b
RV
Transits
m-lensing
Timing
1990
1995
2000
2005
2010
Epoch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Jupiter
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Timing
1990
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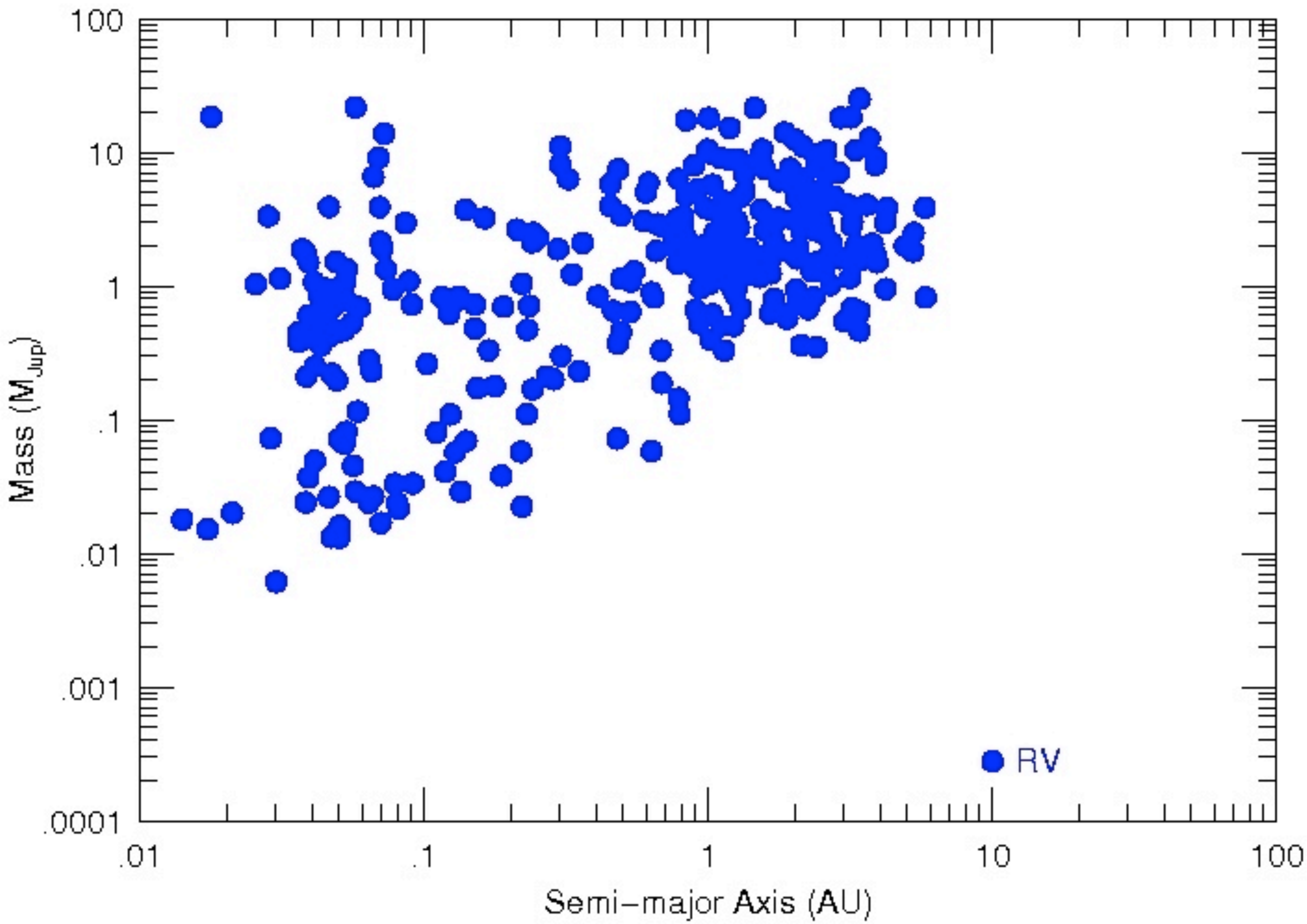
The Planet Discovery Space



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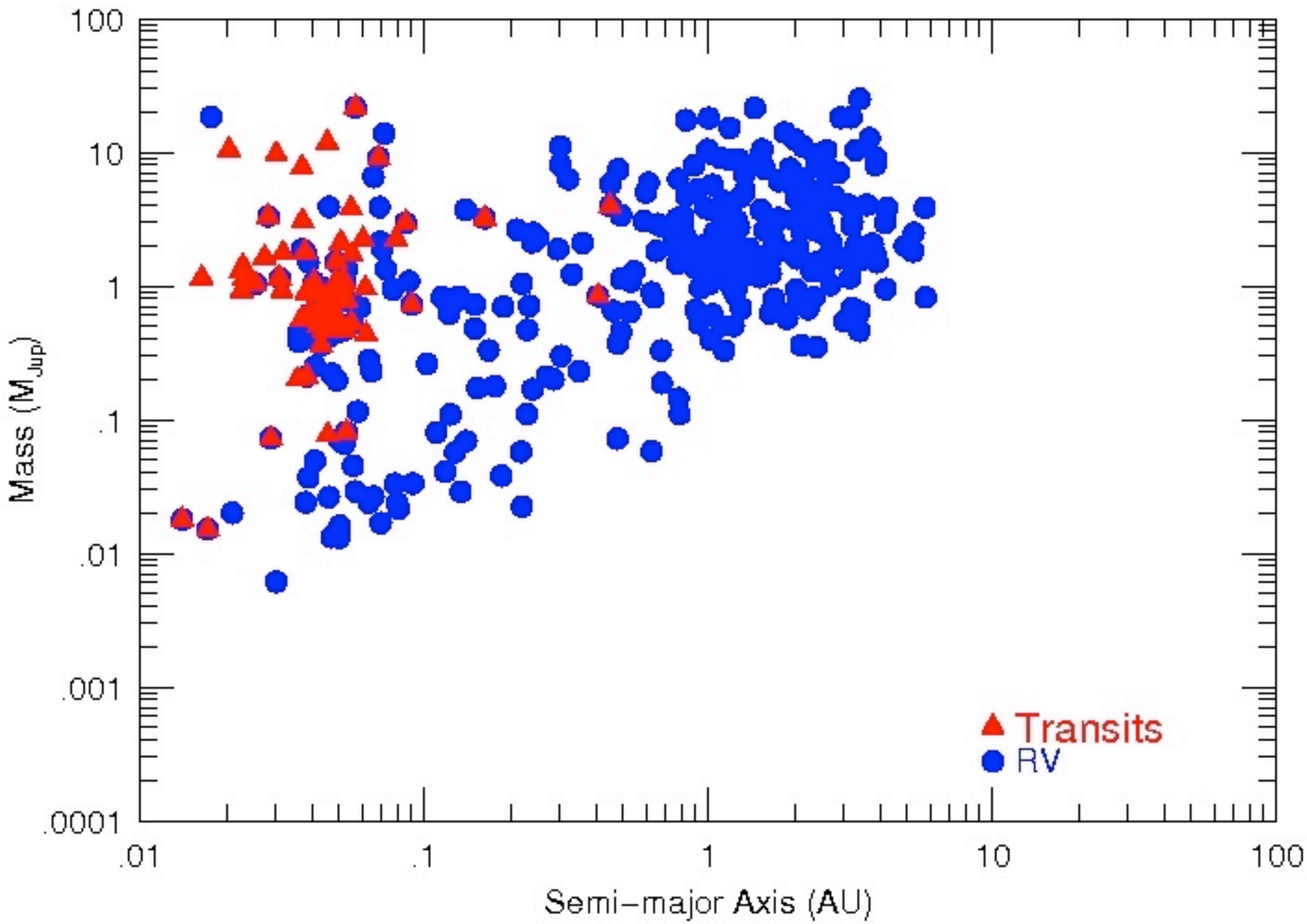

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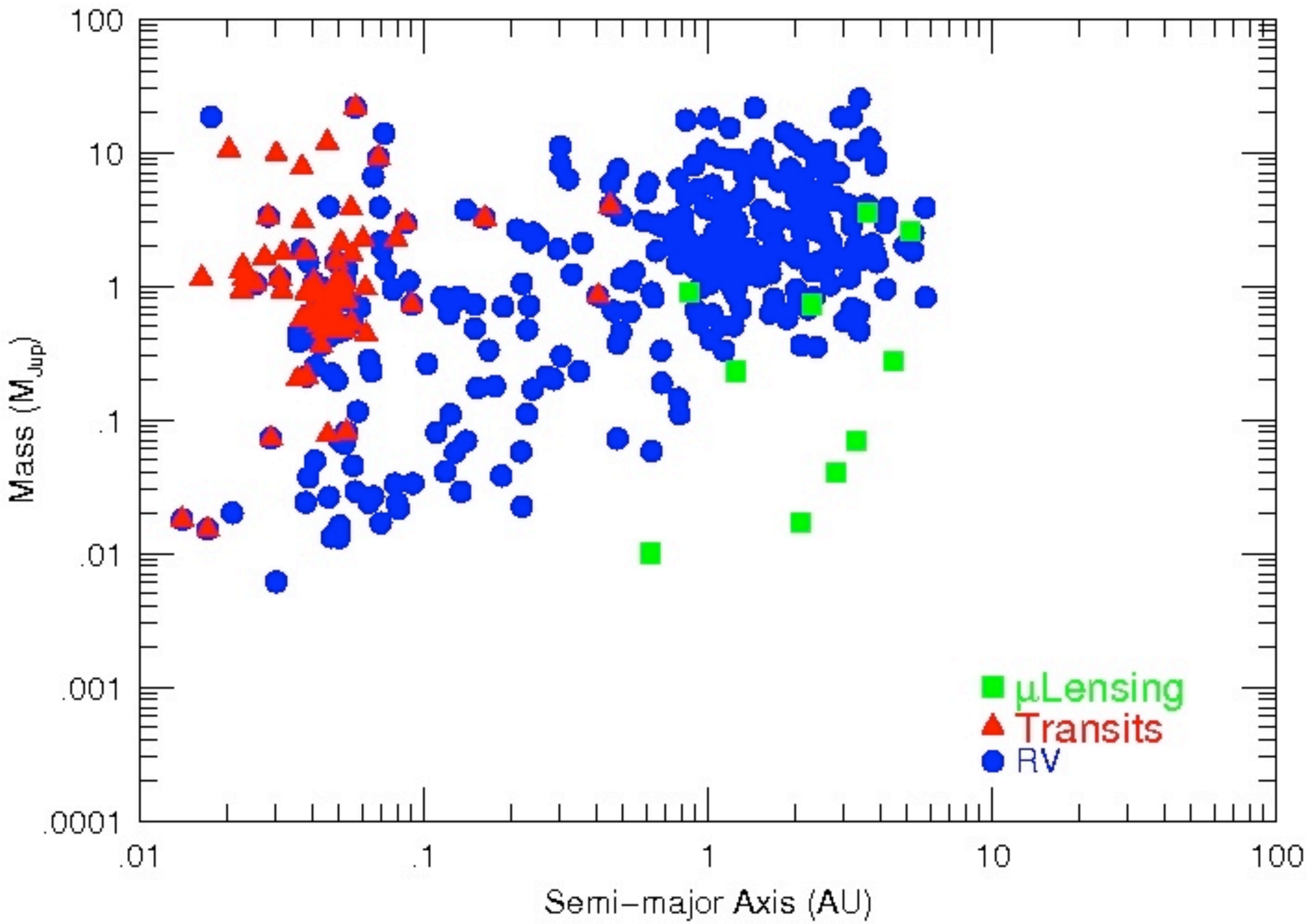

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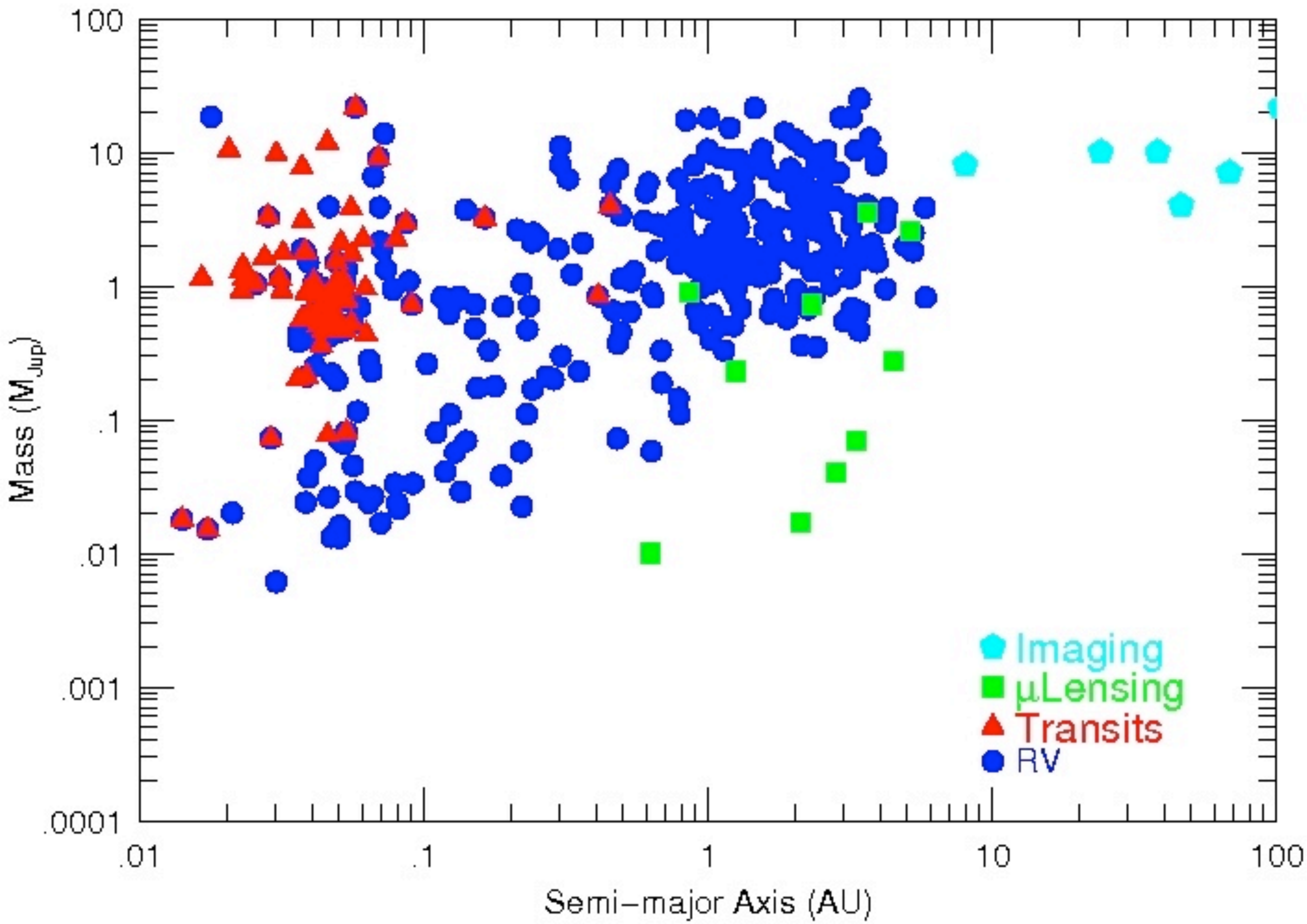
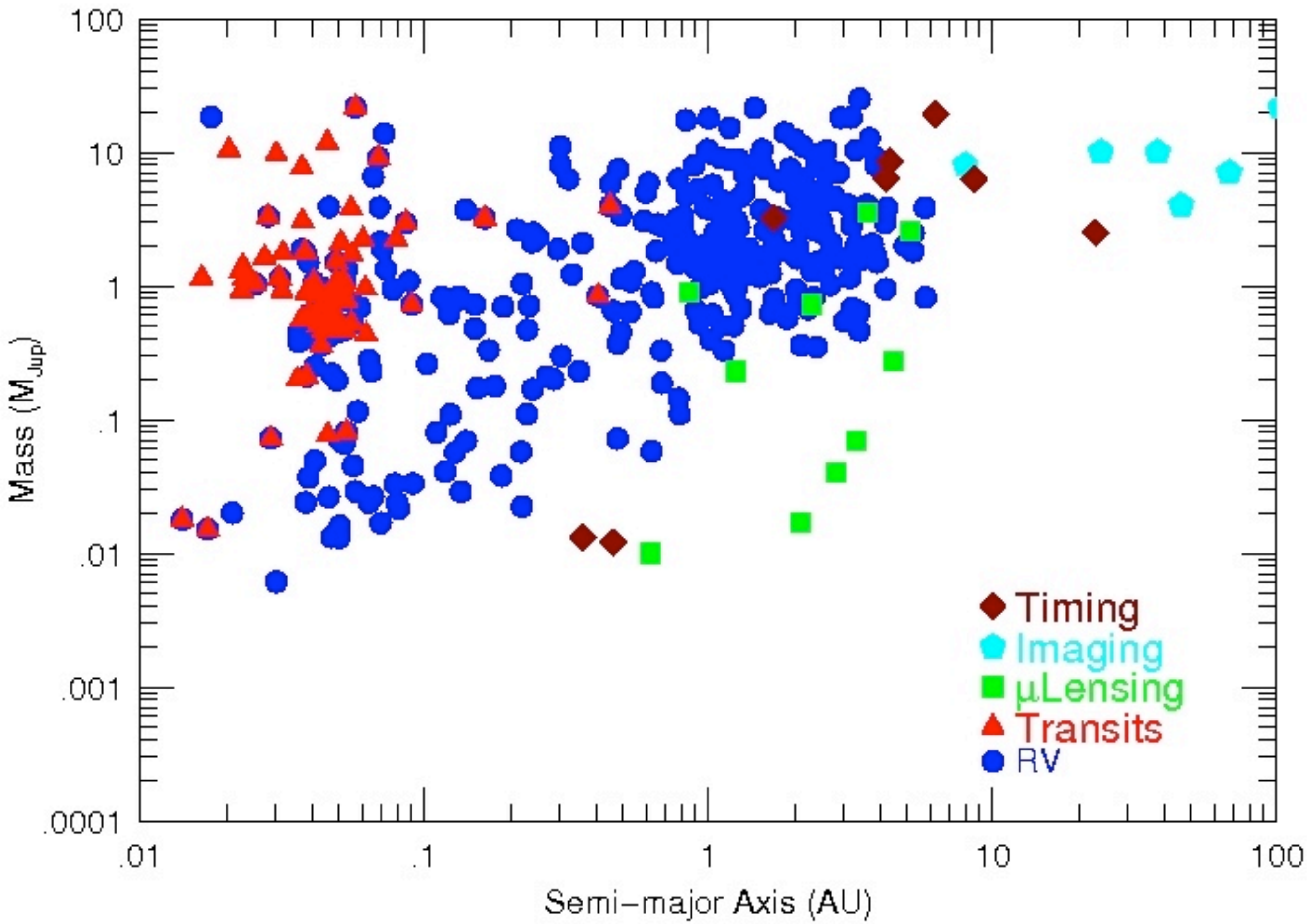
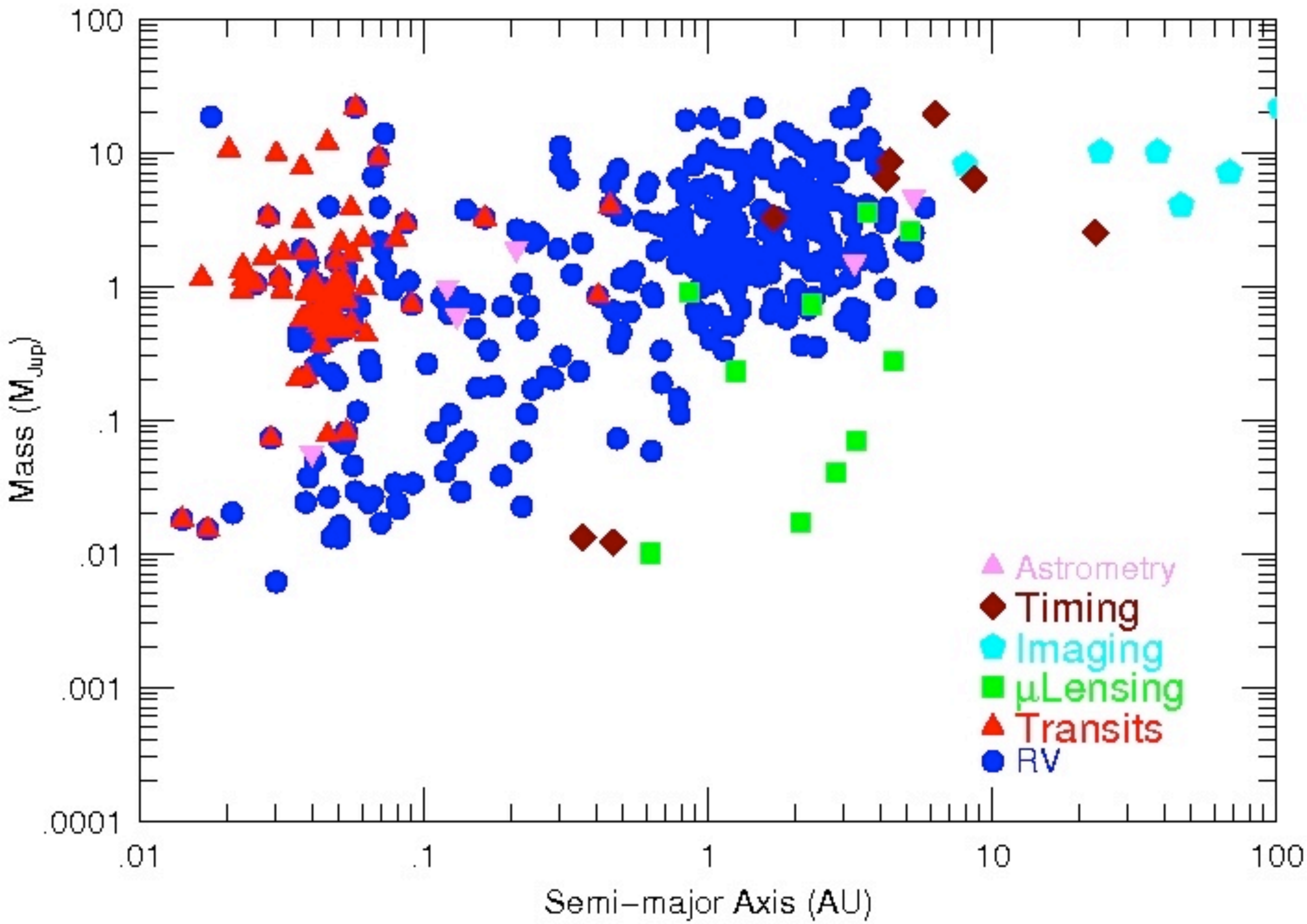


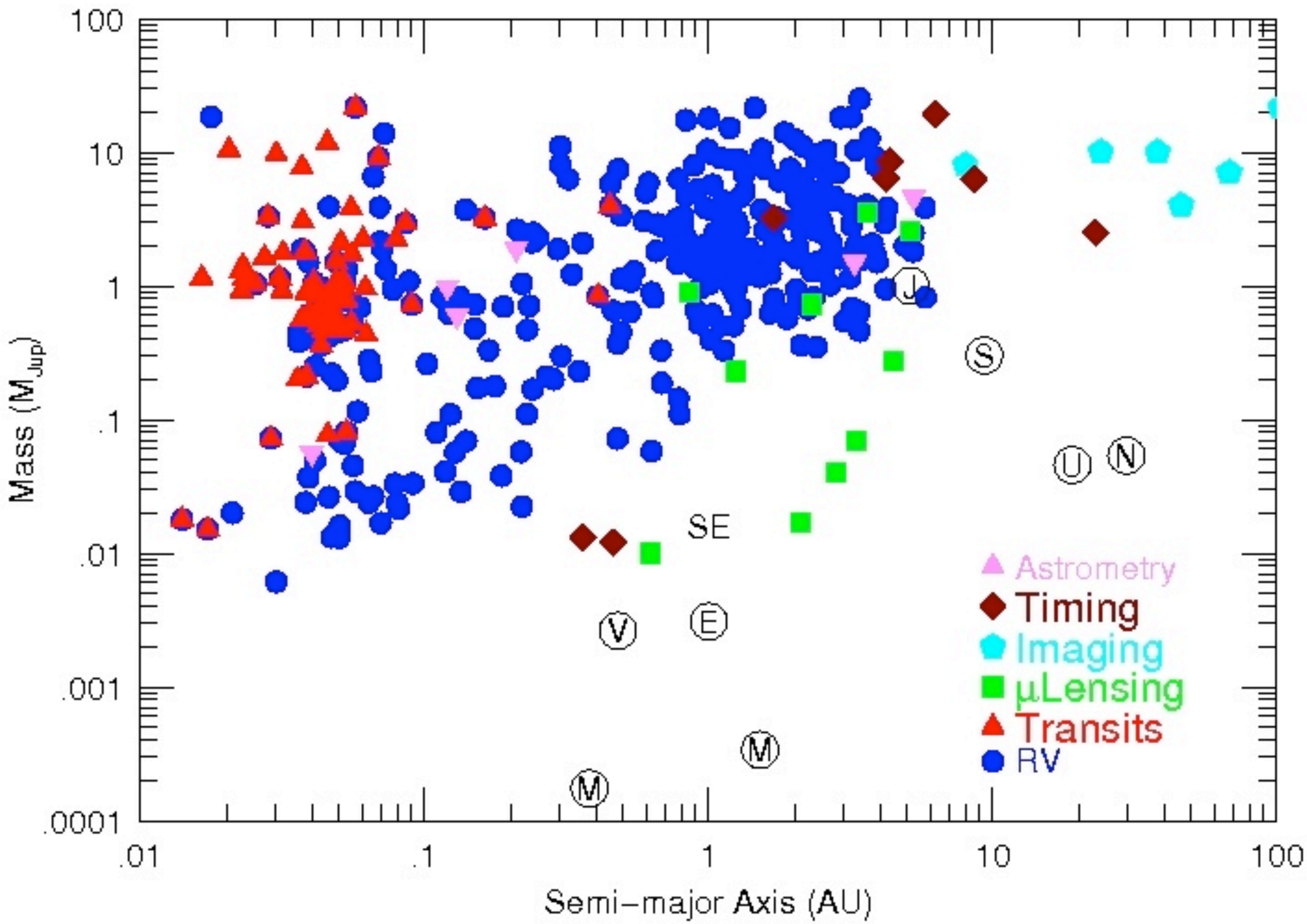
The Planet Discovery Space



The Planet Discovery Space



The Planet Discovery Space



Planet Detectability with radial velocities

$$k_1 = \frac{28.4\ \mathrm{m\ s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}}\right)^{-2/3} \left(\frac{P}{1\ \mathrm{yr}}\right)^{-1/3}$$

(M_1 = Sun)

Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

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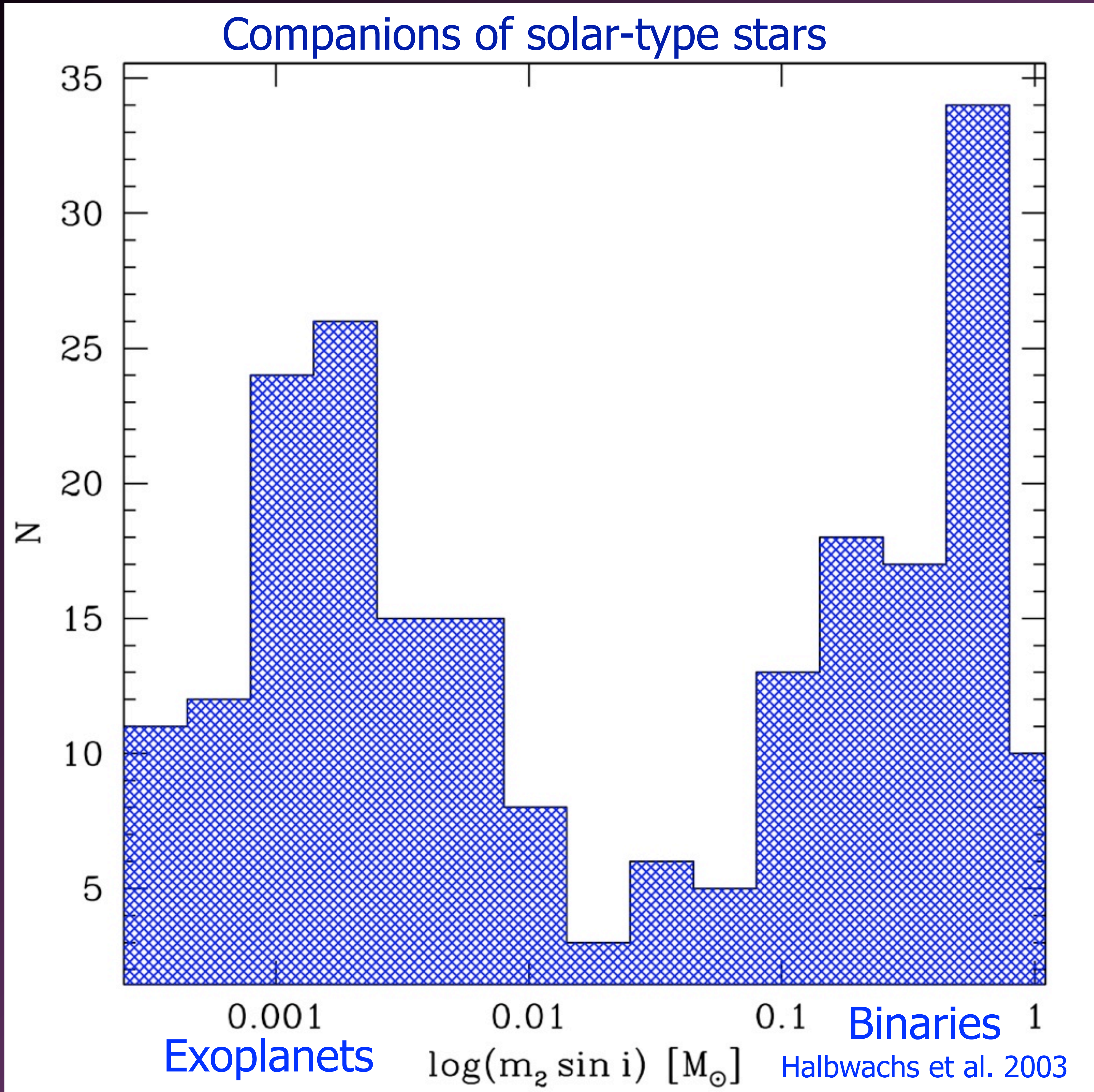
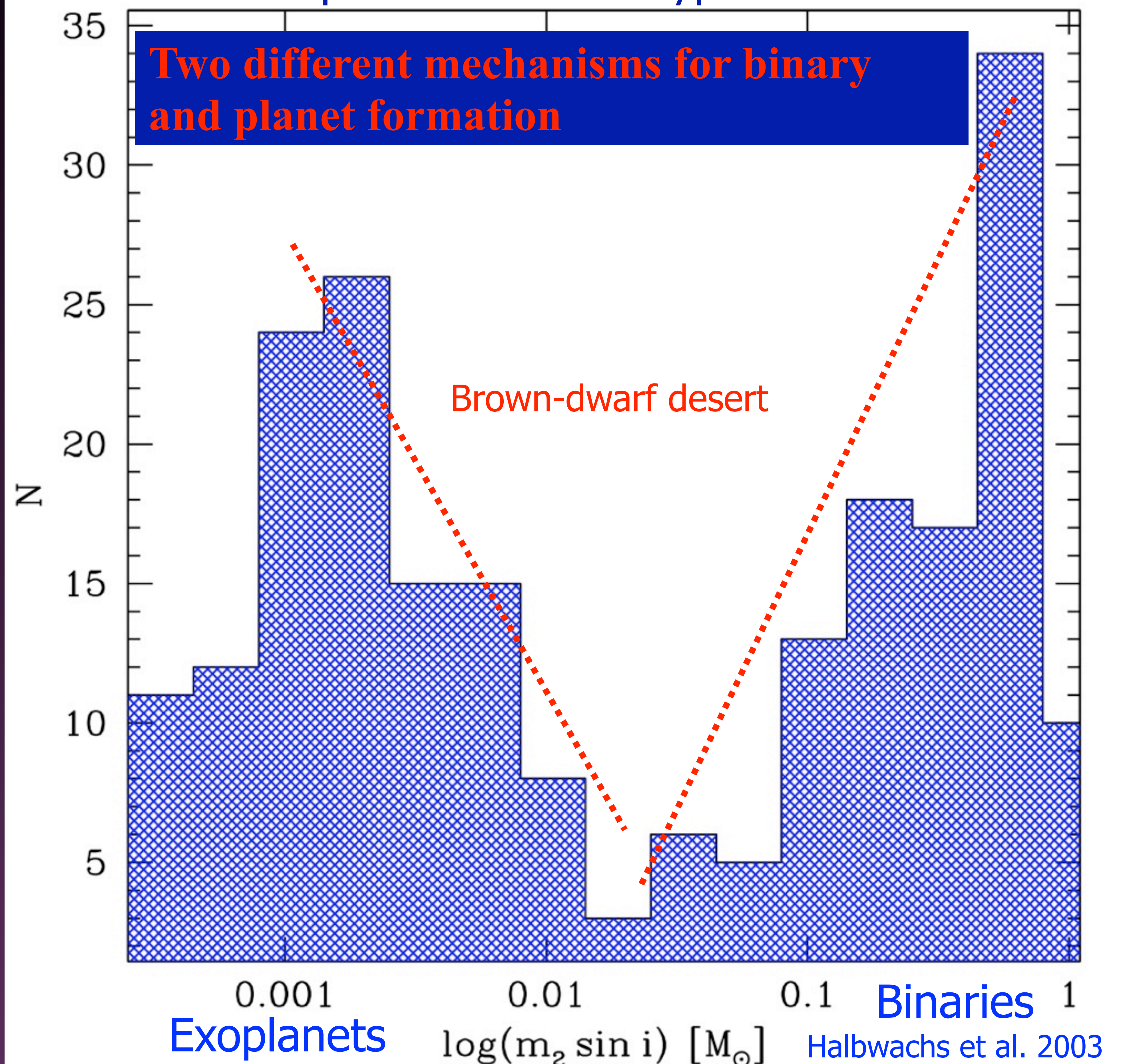
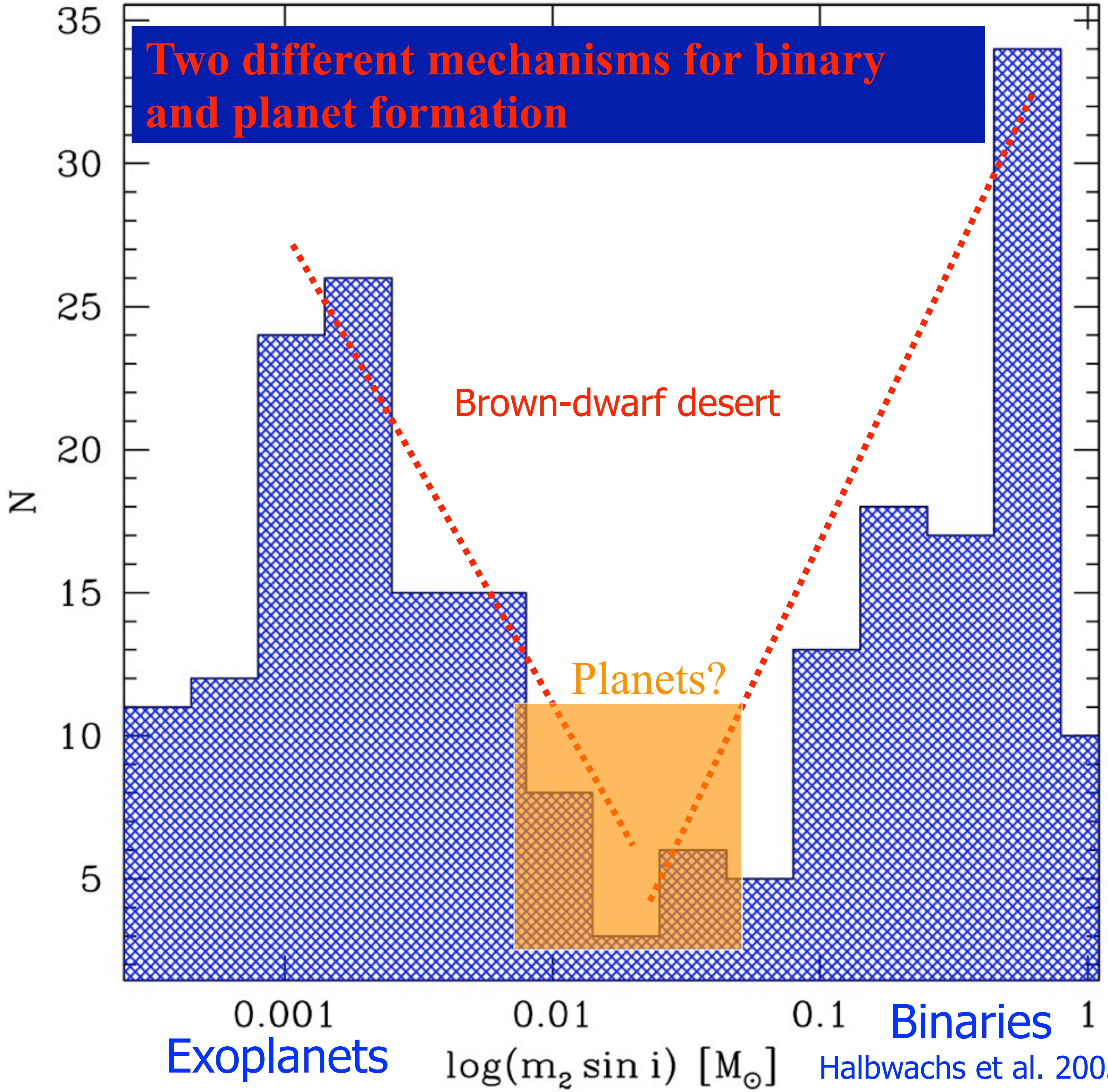
A few m/s precision OK for giant planets
e.g. Jupiters out to > 5 AU


Companions of solar-type stars
35
30
25
20
15
10
5
N
0.001
0.01
0.1
1
Exoplanets
Binaries
log(m₂ sin i) [M⊙]
Halbwachs et al. 2003

Companions of solar-type stars



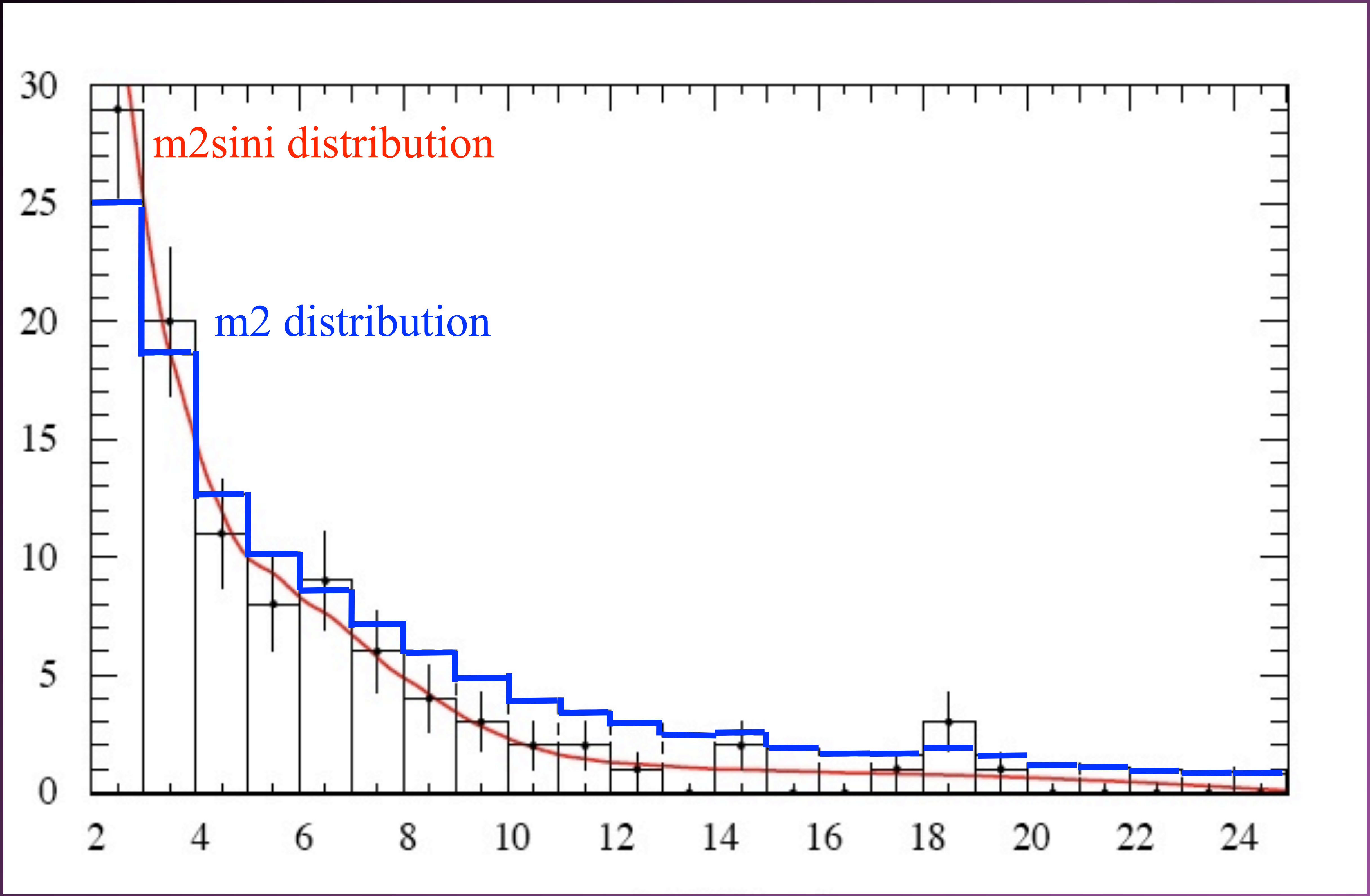
Companions of solar-type stars



Halbwachs et al. 2003

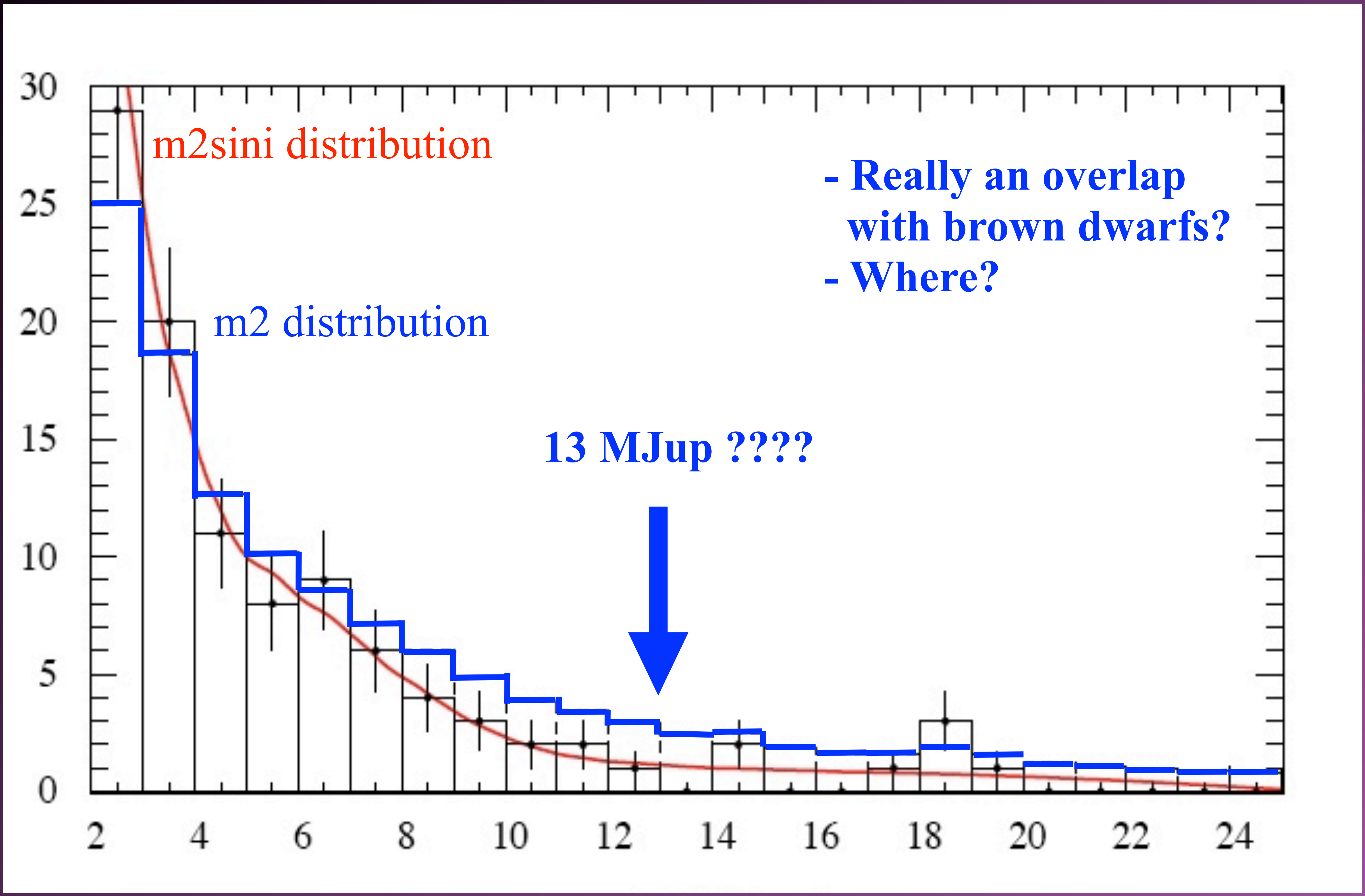
Planetary mass distribution

Segransan et al. 2009



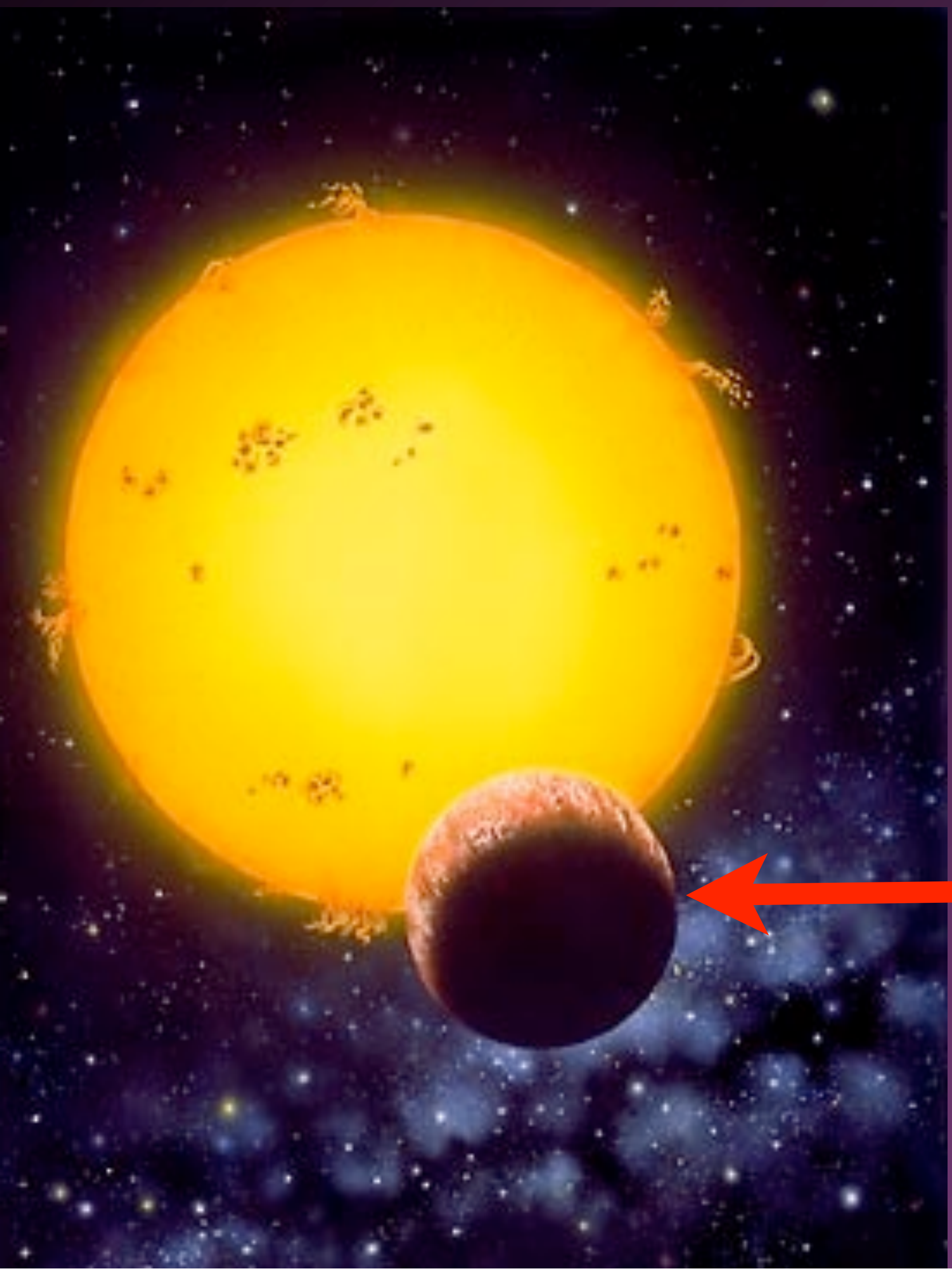
Planetary mass distribution

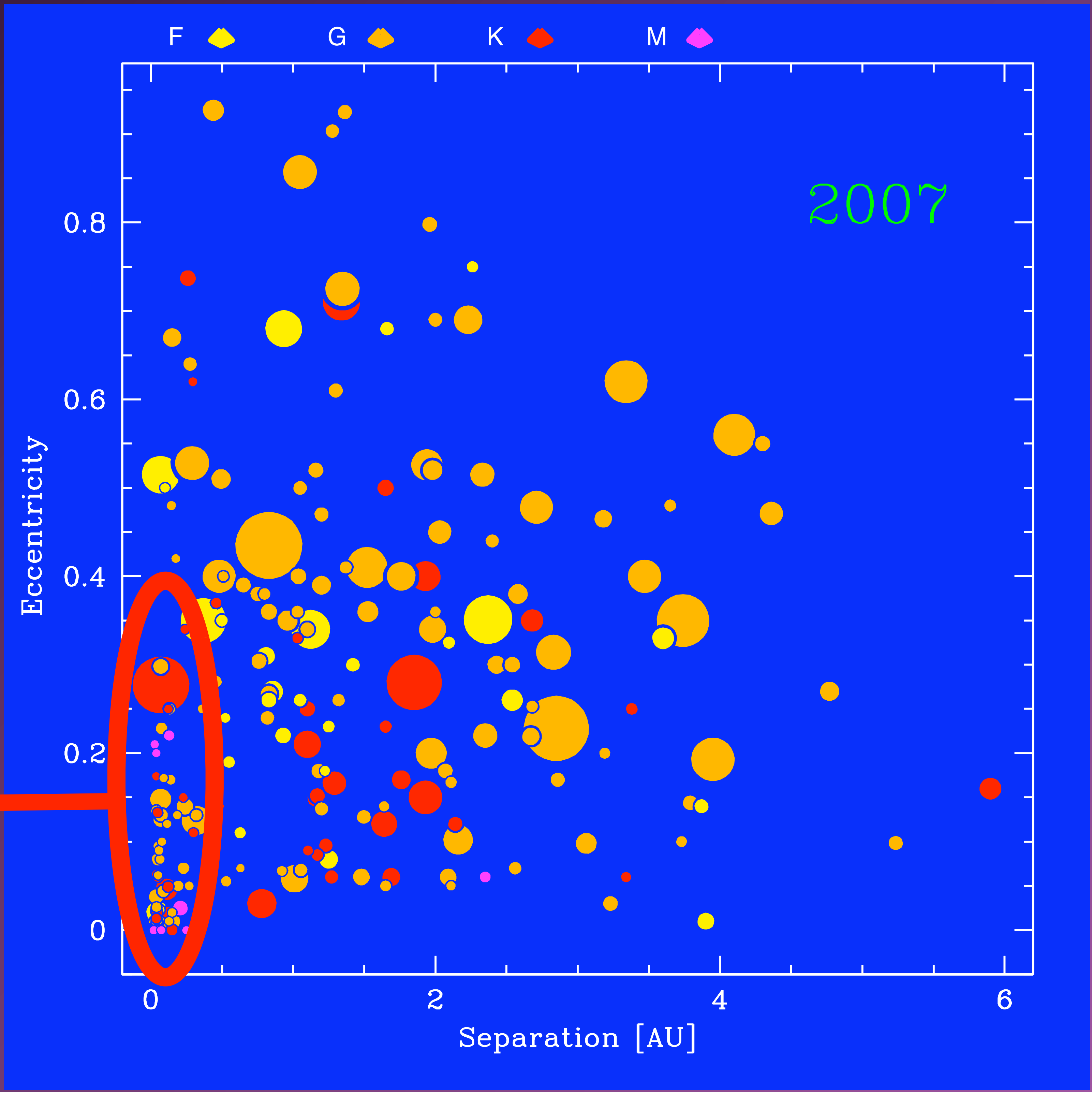
Segransan et al. 2009



(VII) Constraints from transit detections

2000-2010: ~100 transiting planets

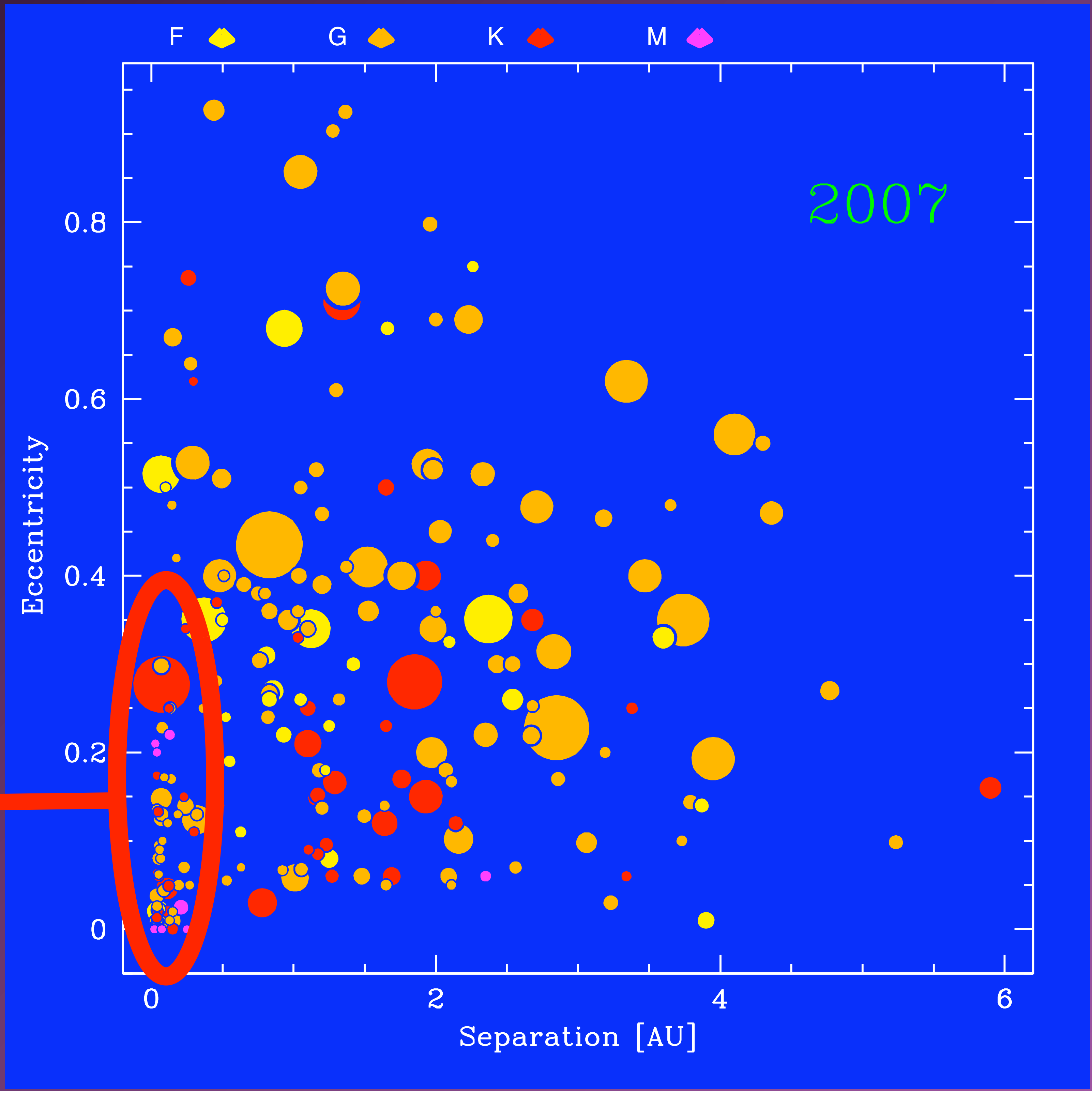


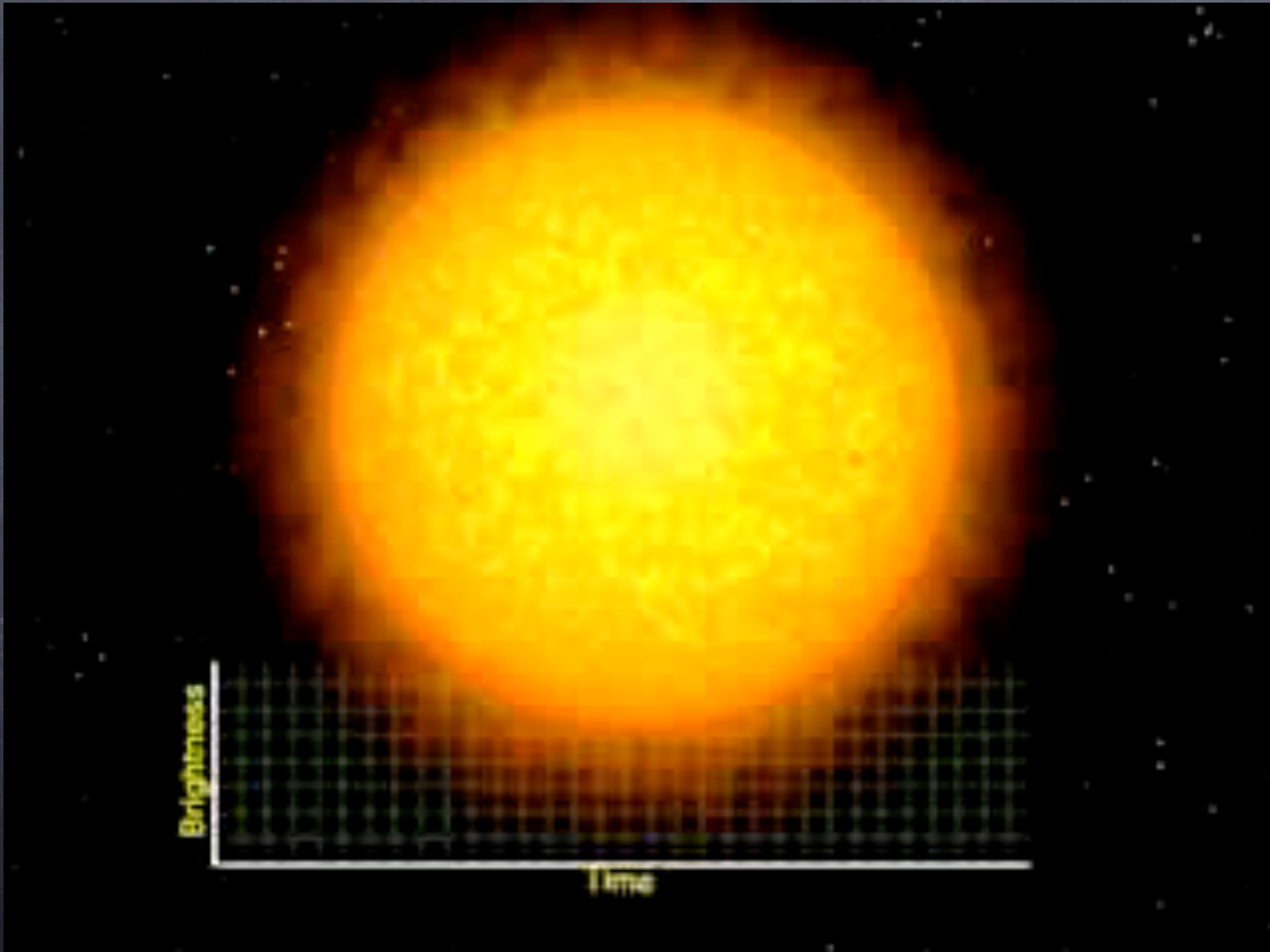


(VII) Constraints from transit detections

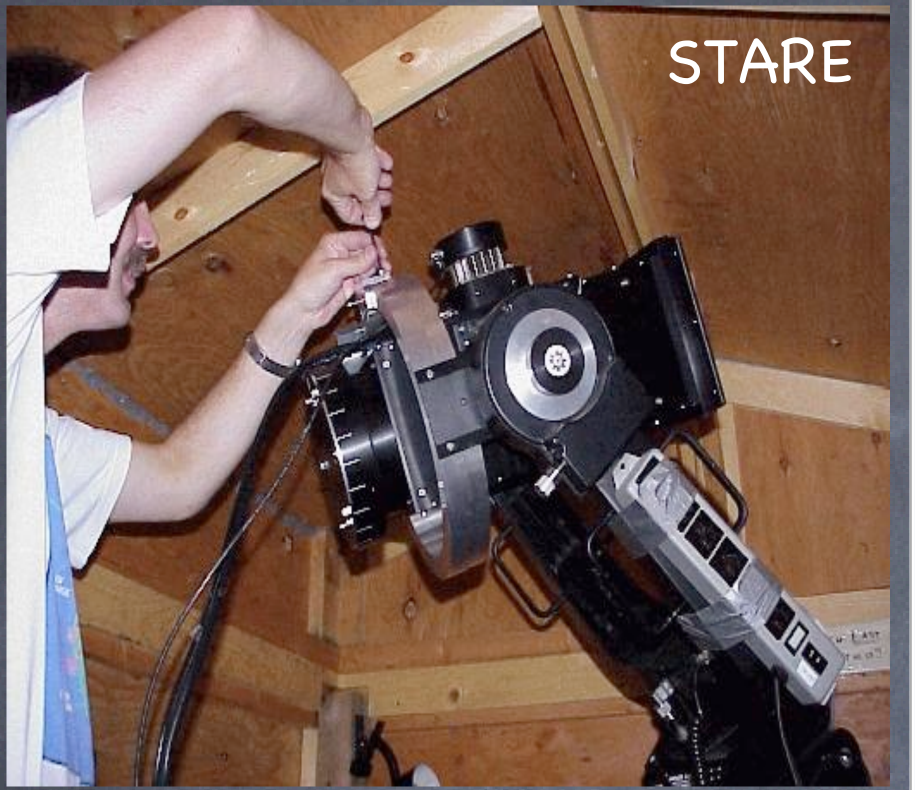
2000-2010: ~100 transiting planets

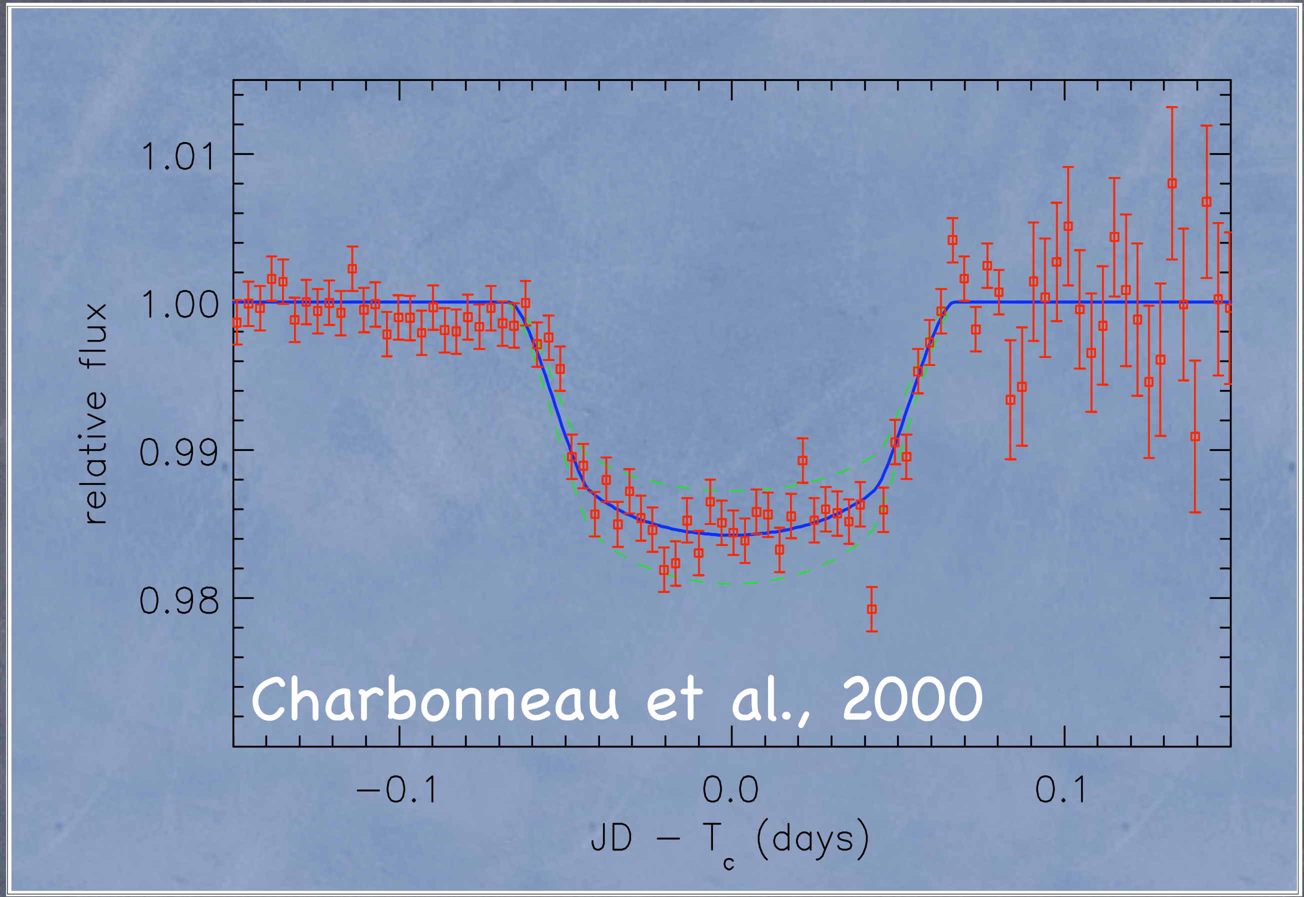
Short periods:
high probabilities of transit

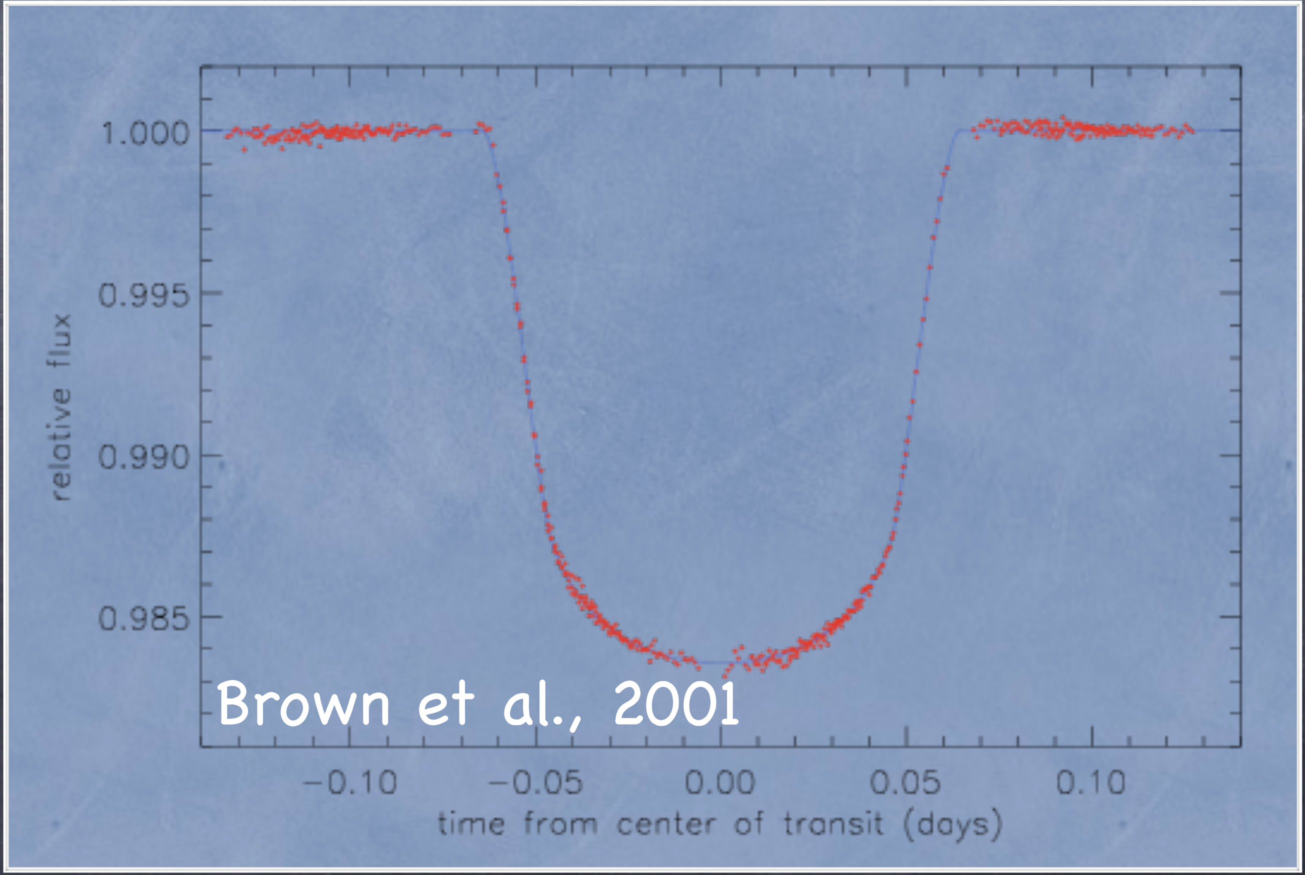



Brightness
Time

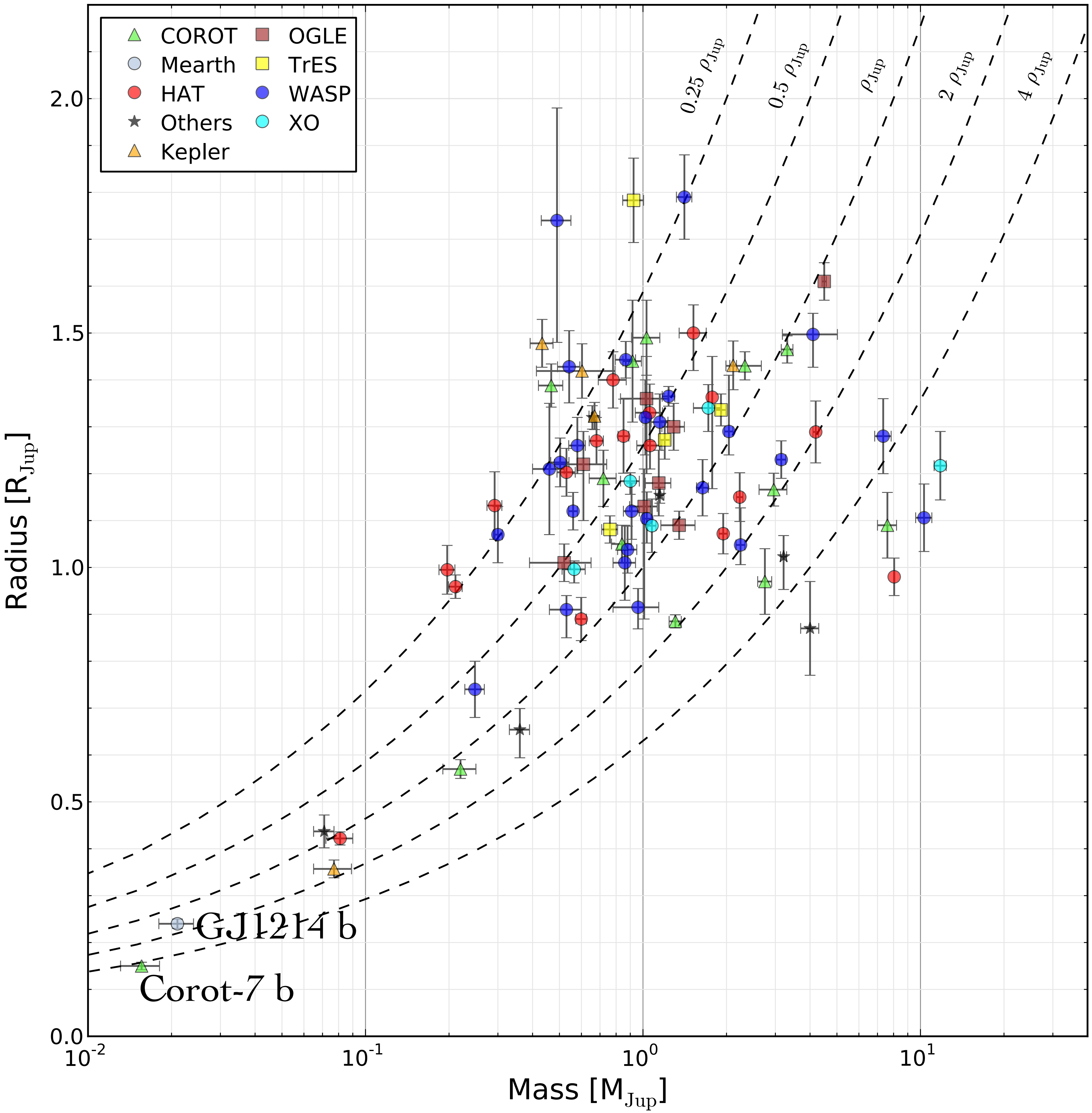
First transit: HD209485b







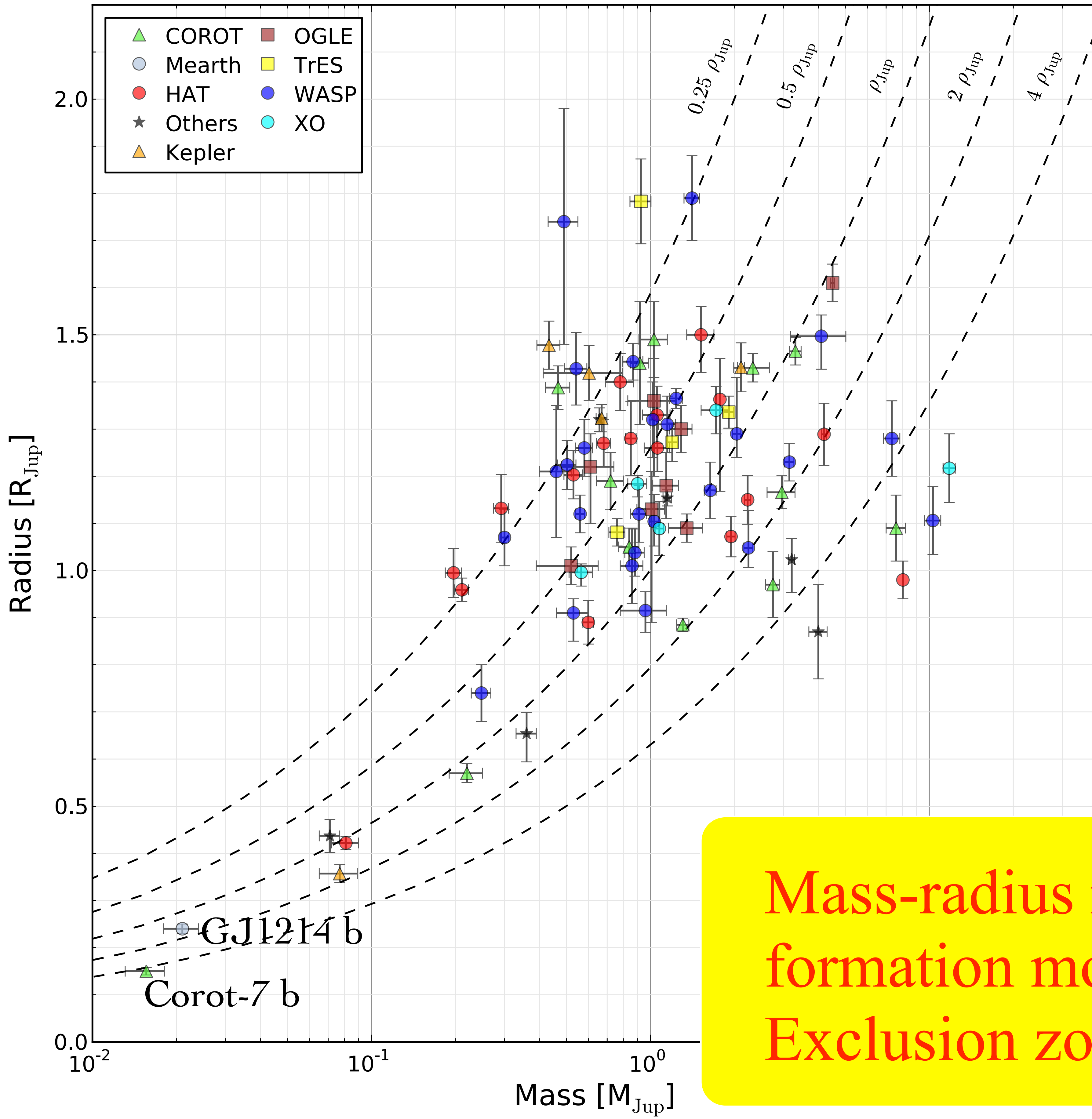
Mass-radius relation from planets to stars



85 before
OHP meeting
(Aug 2010)

+ ~20
during meeting
(SWASP, HAT,
Kepler)

Mass-radius relation from planets to stars



85 before
OHP meeting
(Aug 2010)

+ ~20
during meeting
(SWASP, HAT,
Kepler)

Mass-radius relation from formation models?
Exclusion zones?

Massive planets: true mass from astrometry

HD 33636 b (Bean et al. 2007)

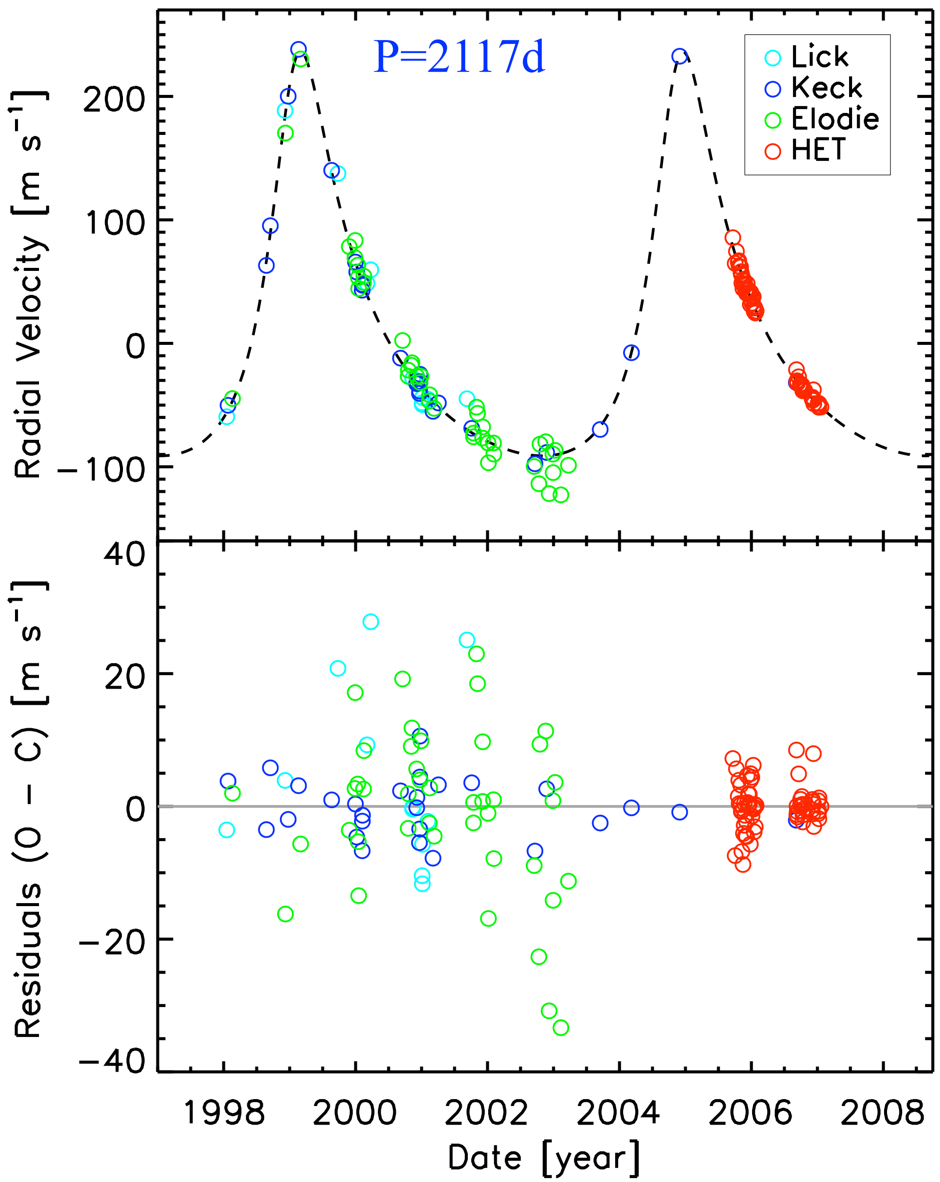
HST Fine Guidance Sensor

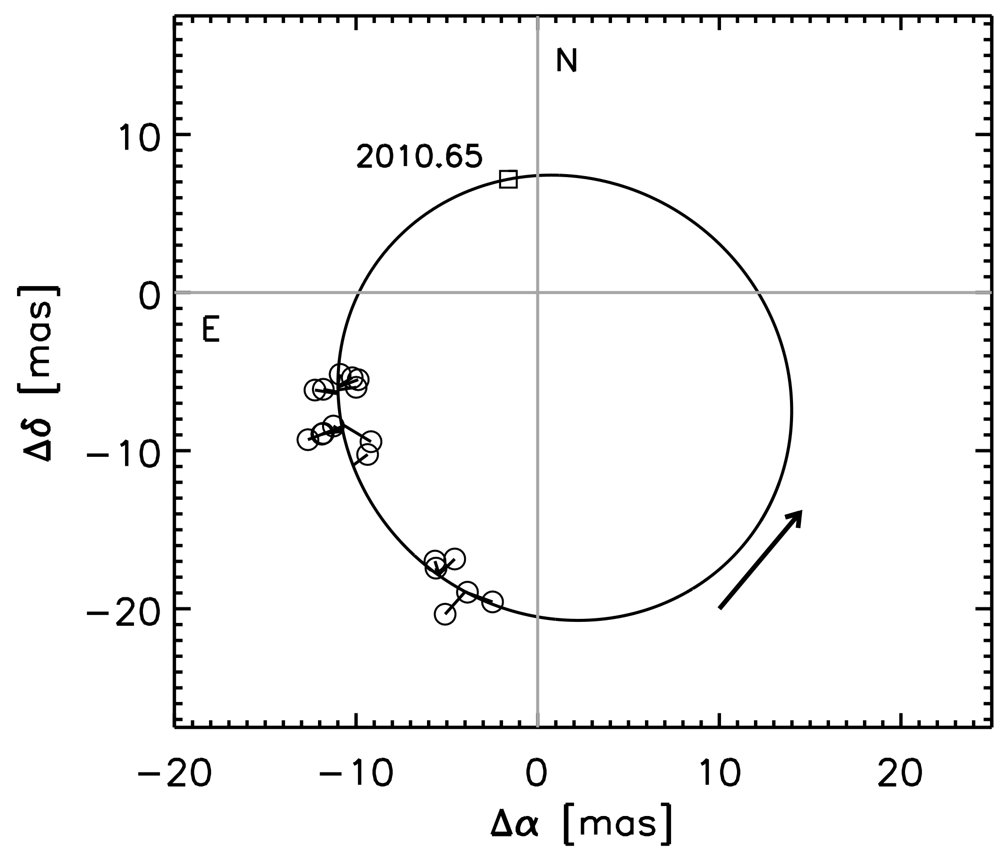
$m2 = 142 +/- 11 M_{Jup}$

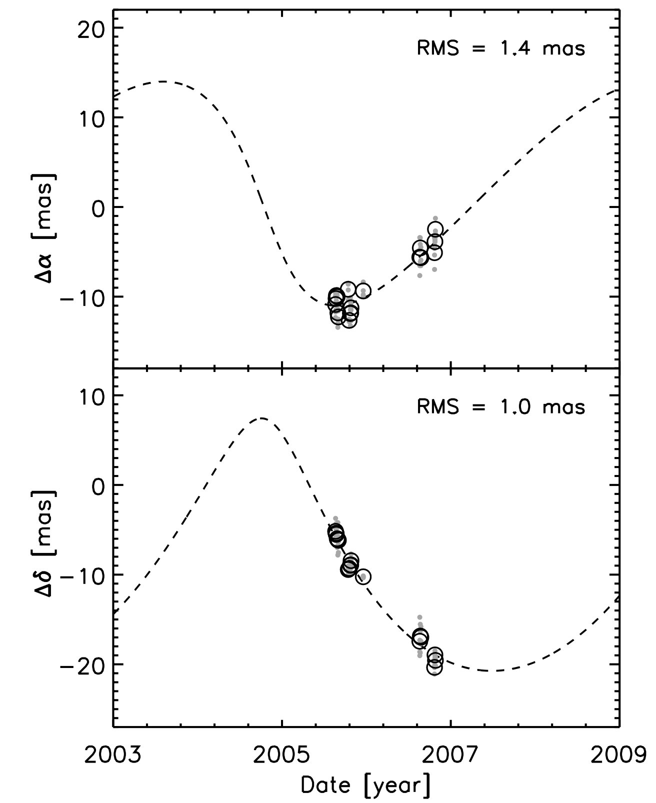
Radial velocities

$m2sini = 9.3 M_{Jup}$

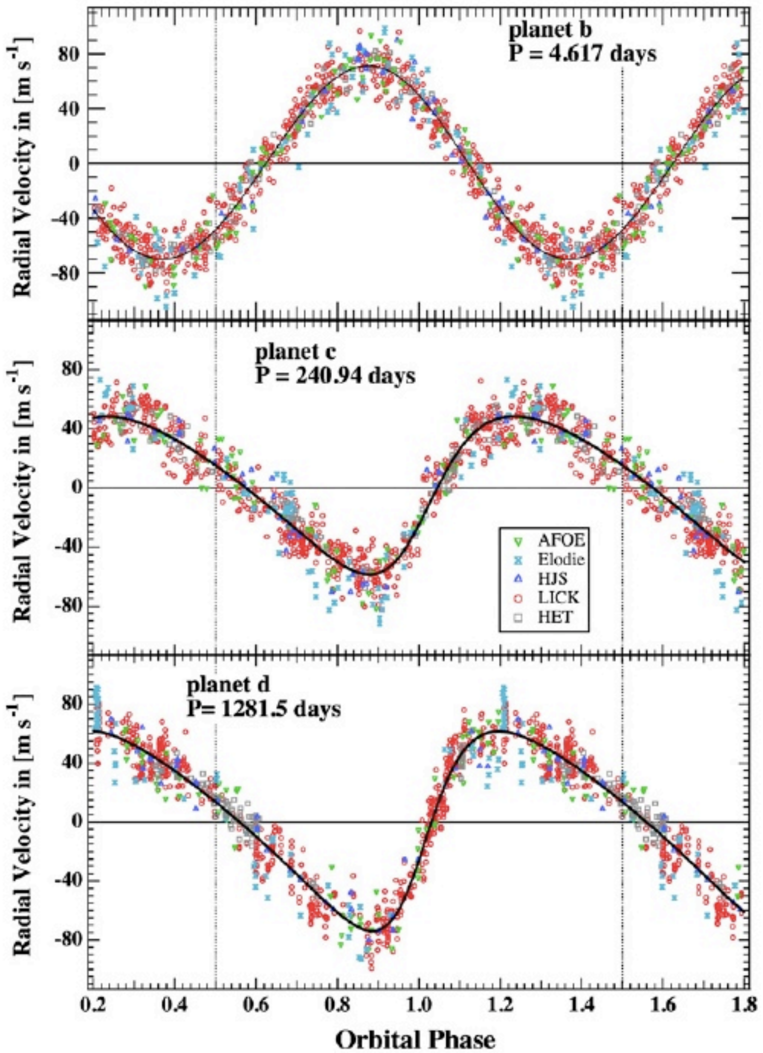
→ late M star companion







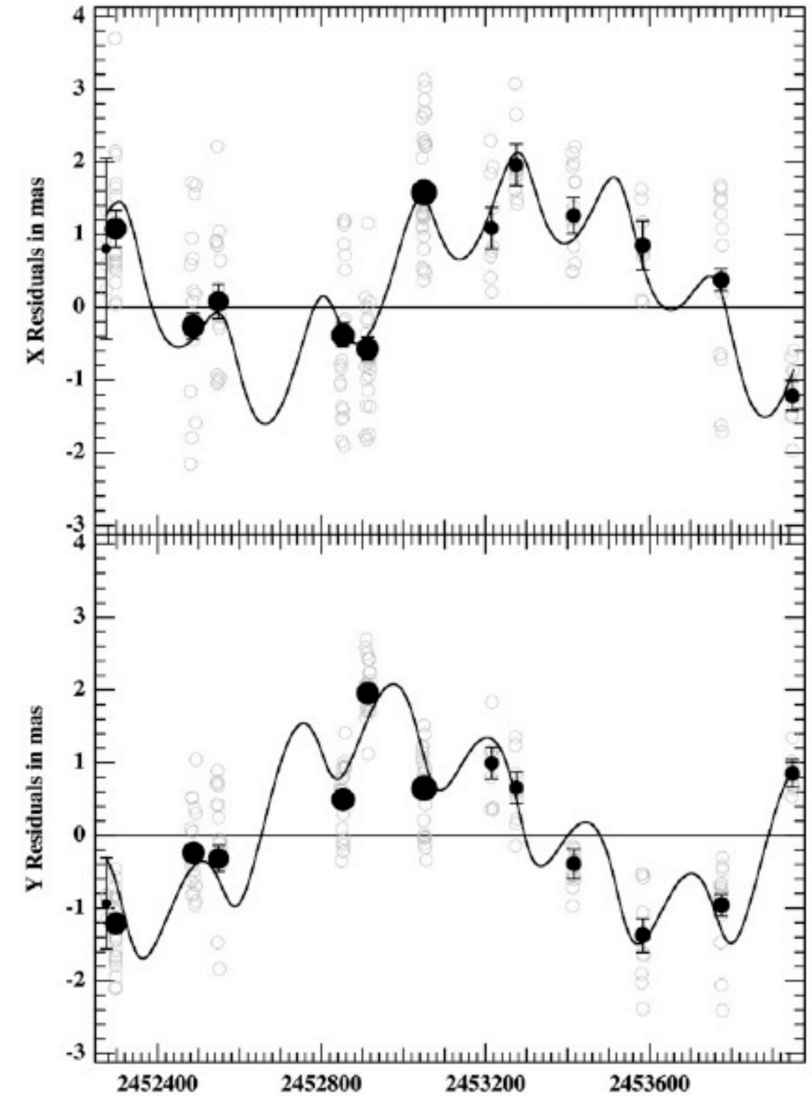
Massive planets: "true" mass from astrometry

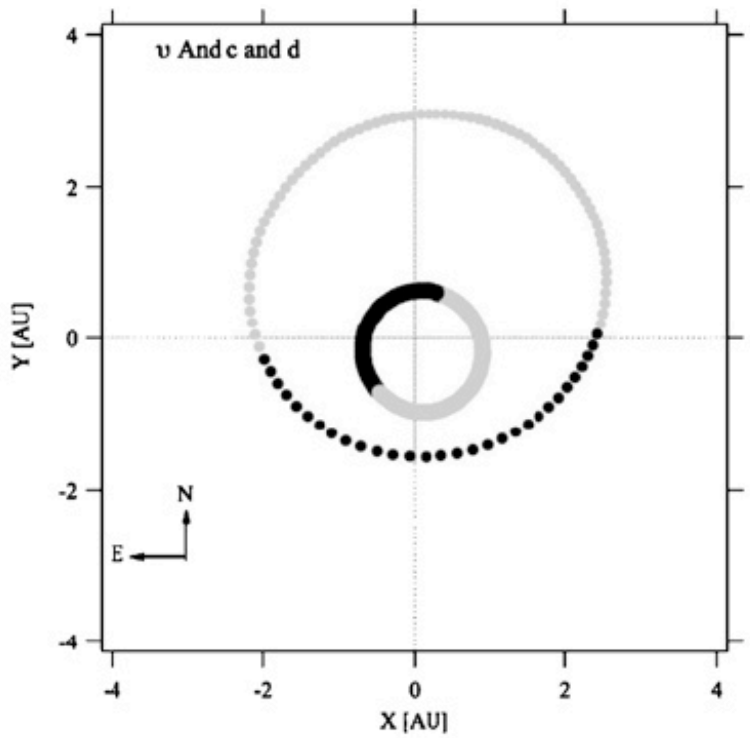


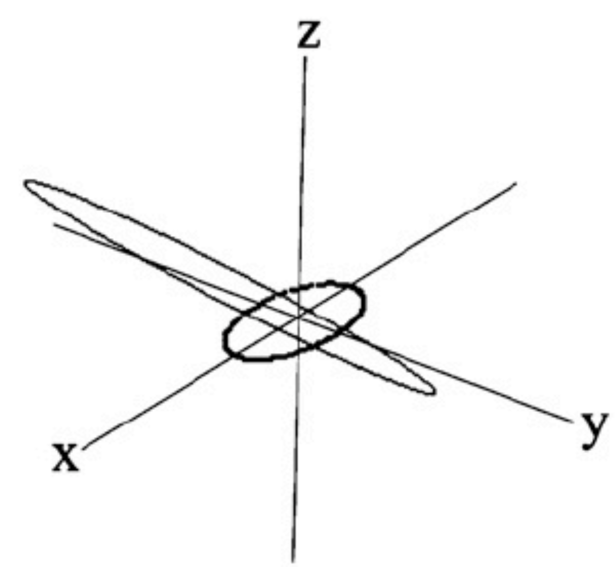
Ups And (McArthur et al. 2010)
HST Fine Guidance Sensor

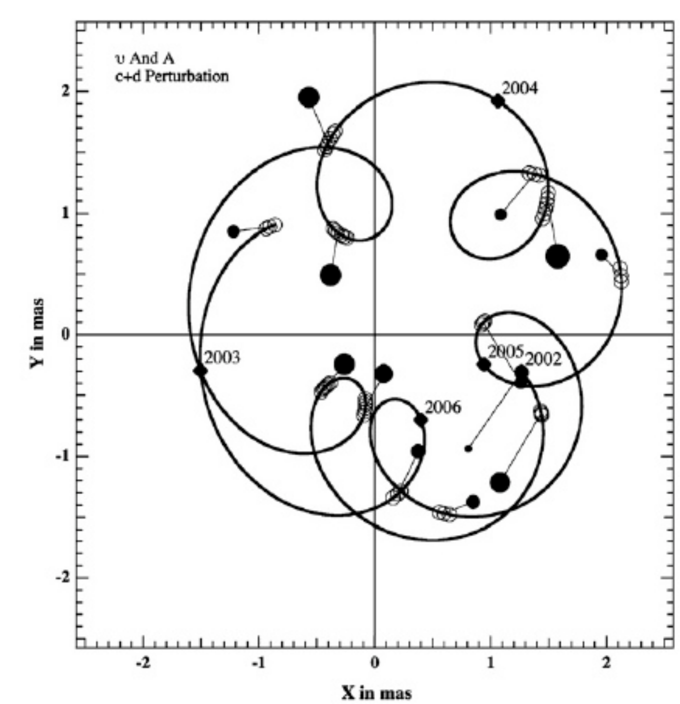
$P_b = 4.6$ d
$P_c = 240$ d
$P_d = 1281$ d

$m_b \sin i = 0.7\ M_{Jup}$
$i_c = 8^o$ $m_c = 12\ M_{Jup}$
$i_d = 24^o$ $m_d = 10\ M_{Jup}$

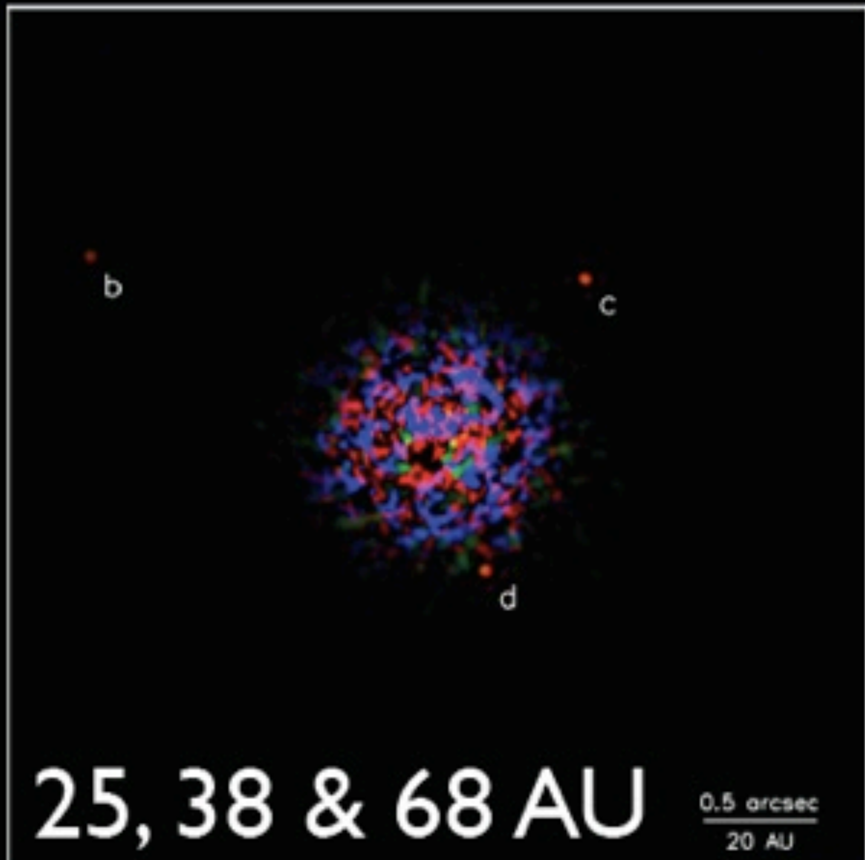




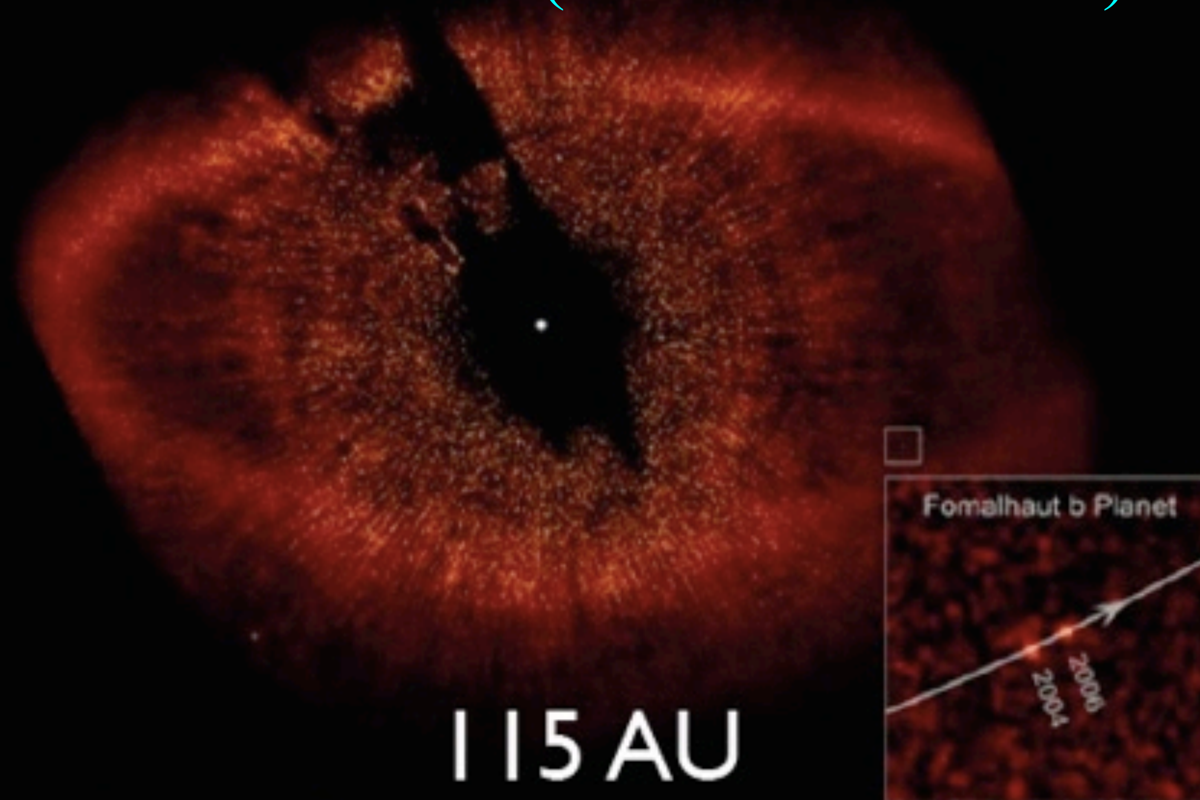


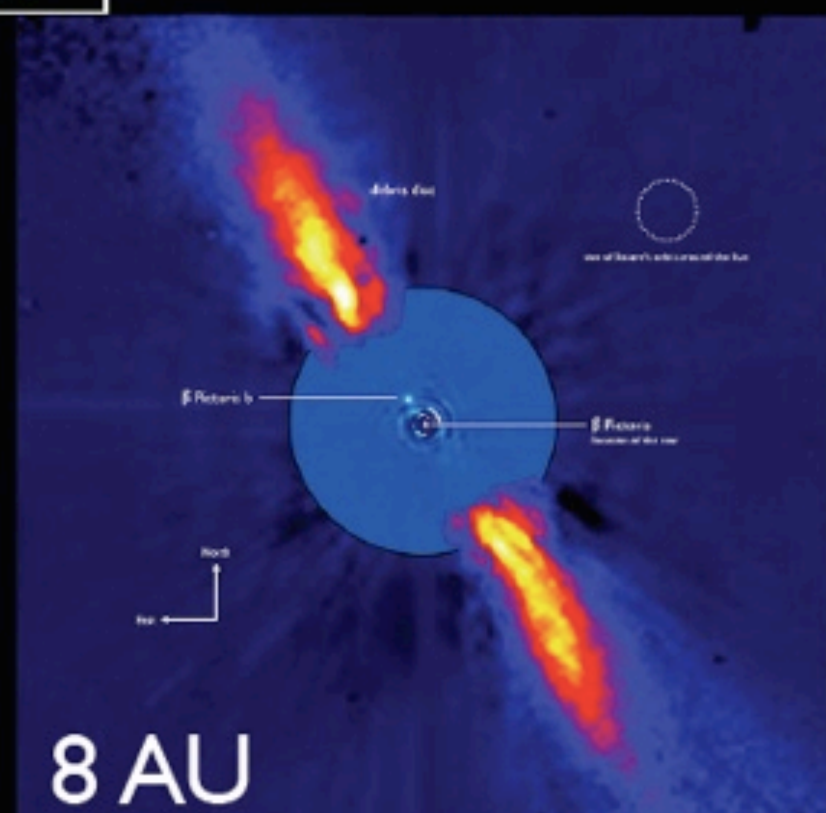


HR8799 b, c, d : 7, 10 & 10 M_{Jup}
(Marois et al. 2009)



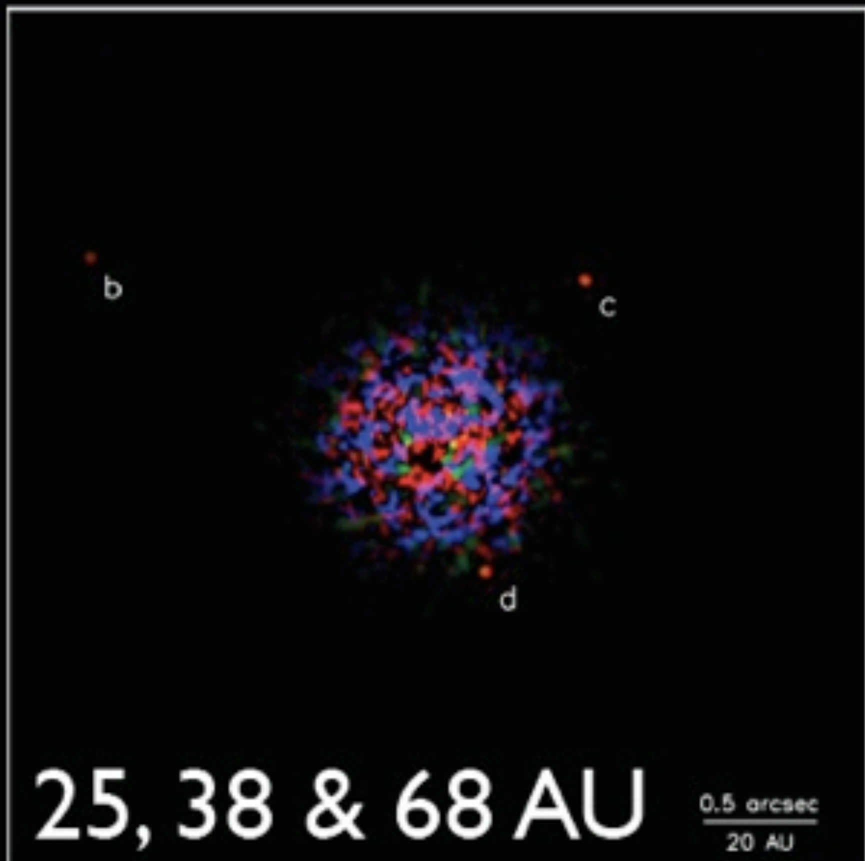
Formalhaut b : 3 M_{Jup}
HST
(Kalas et al. 2009)





Beta Pic b : 8 M_{Jup}
(Lagrange et al. 2009, 2010)

HR8799 b, c, d : 7, 10 & 10 M_{Jup}
(Marois et al. 2009)



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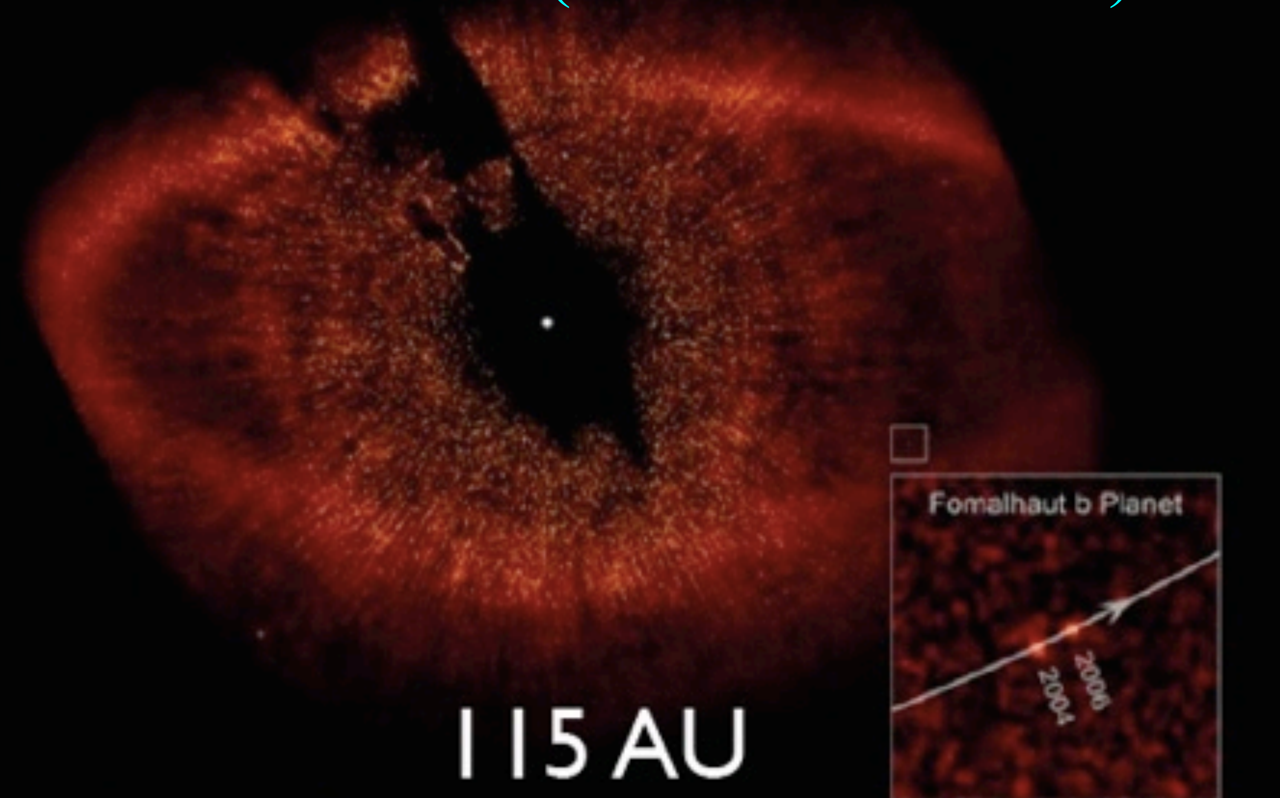
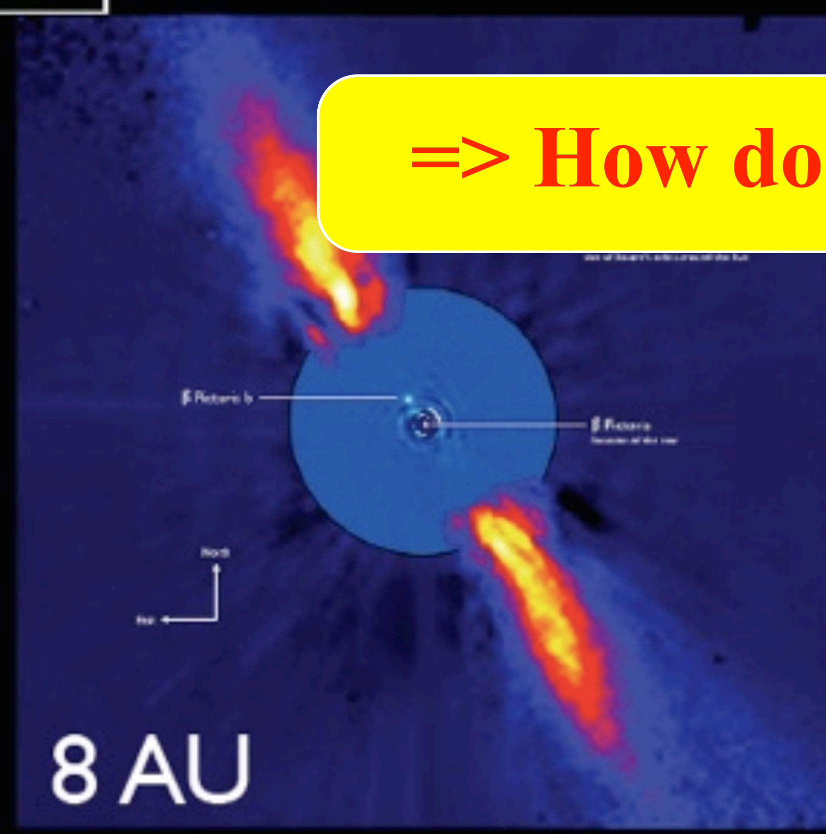
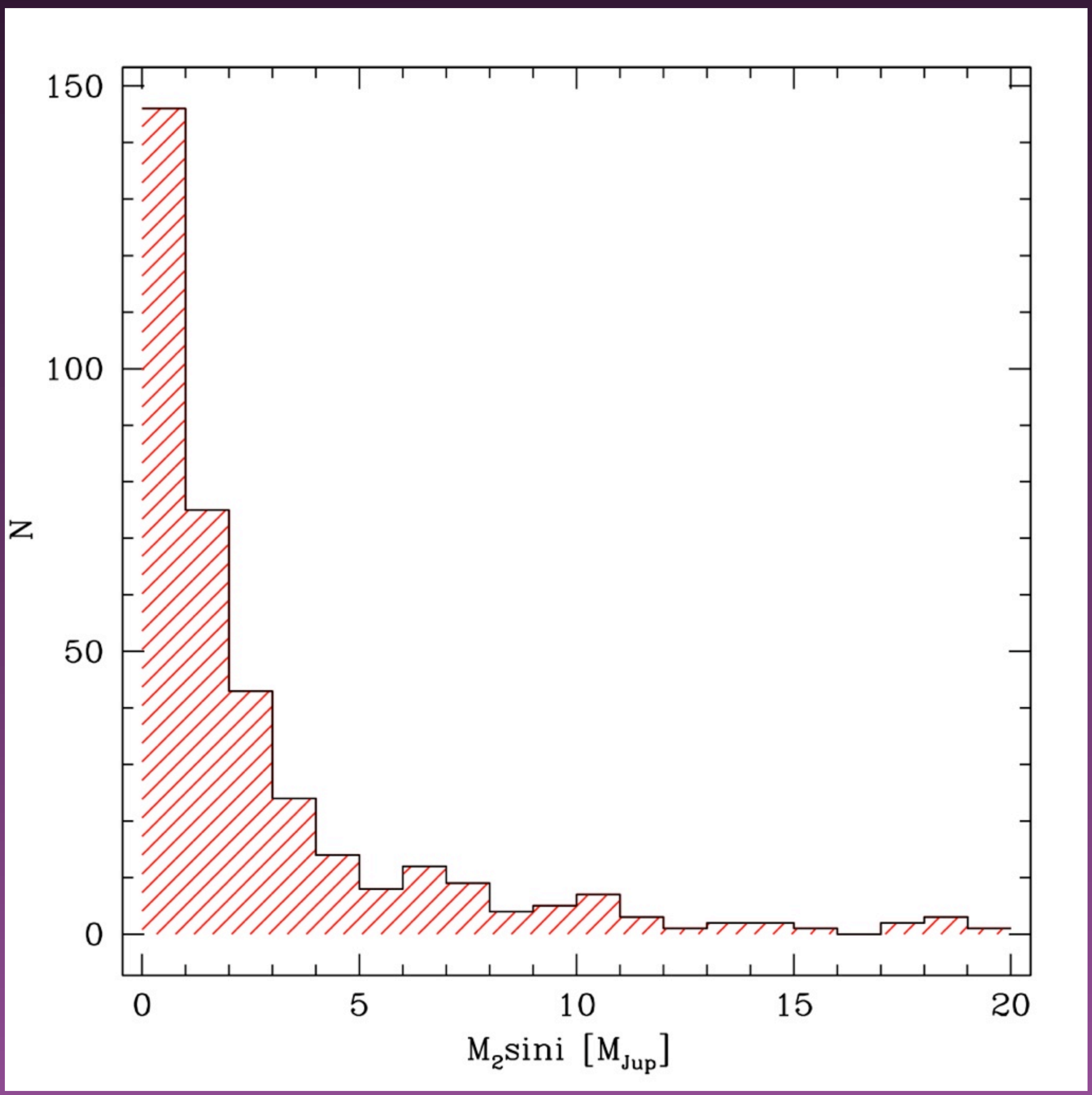


=> **How do these planets form?**

Beta Pic b : 8 M_{Jup}
(Lagrange et al. 2009, 2010)

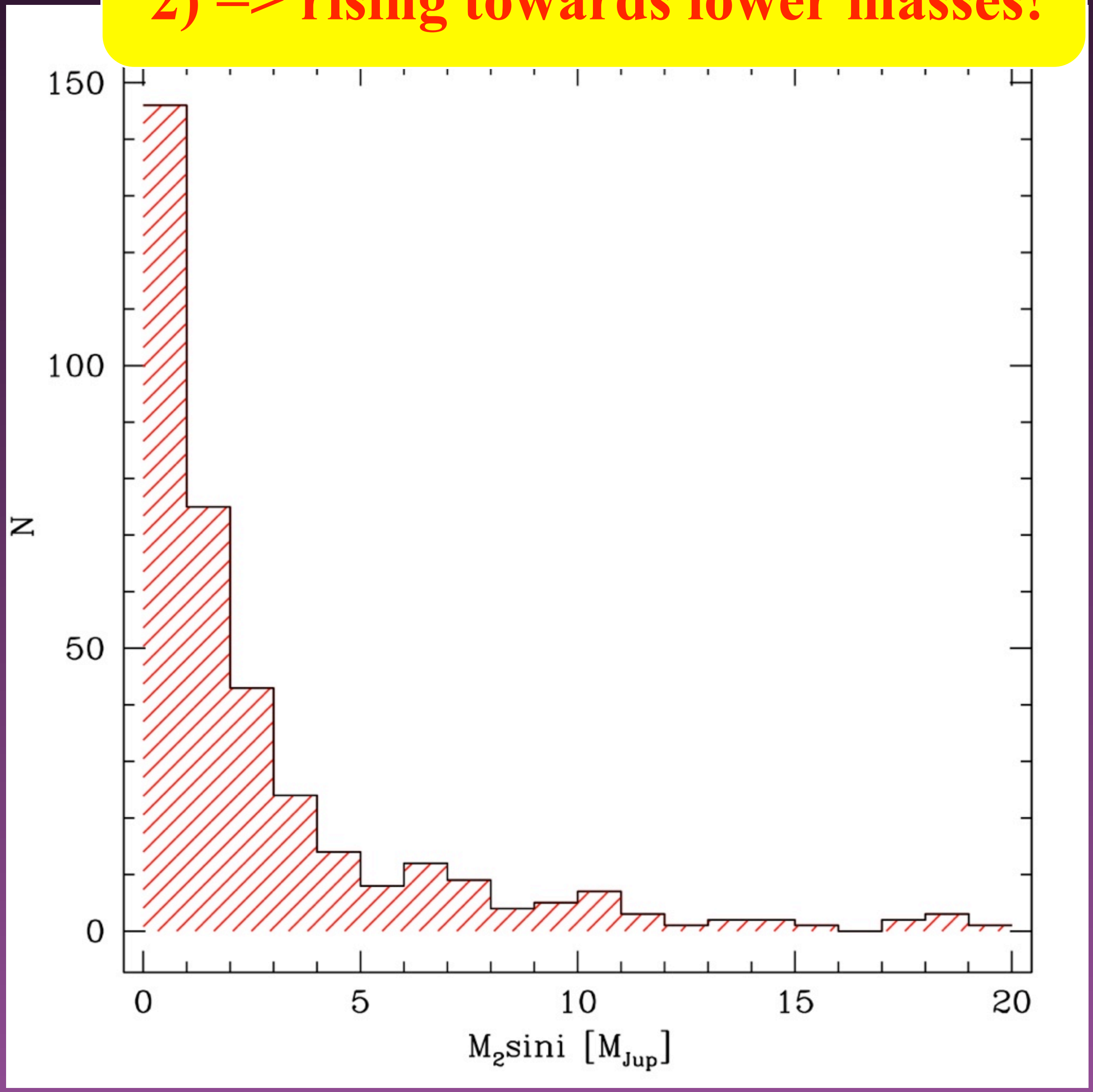


(I) Planetary mass distribution



(I) Planetary mass distribution

2) => rising towards lower masses!



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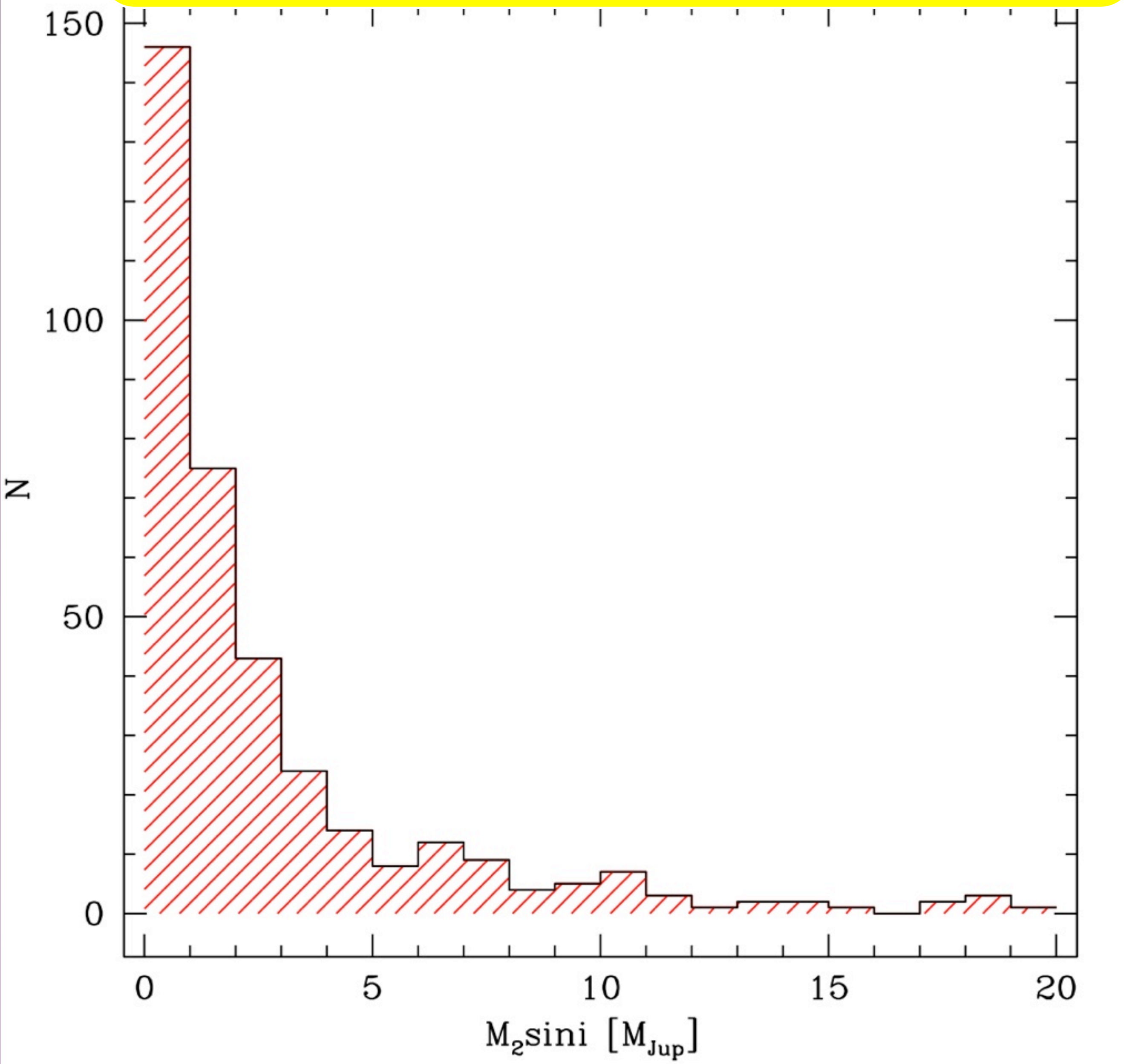

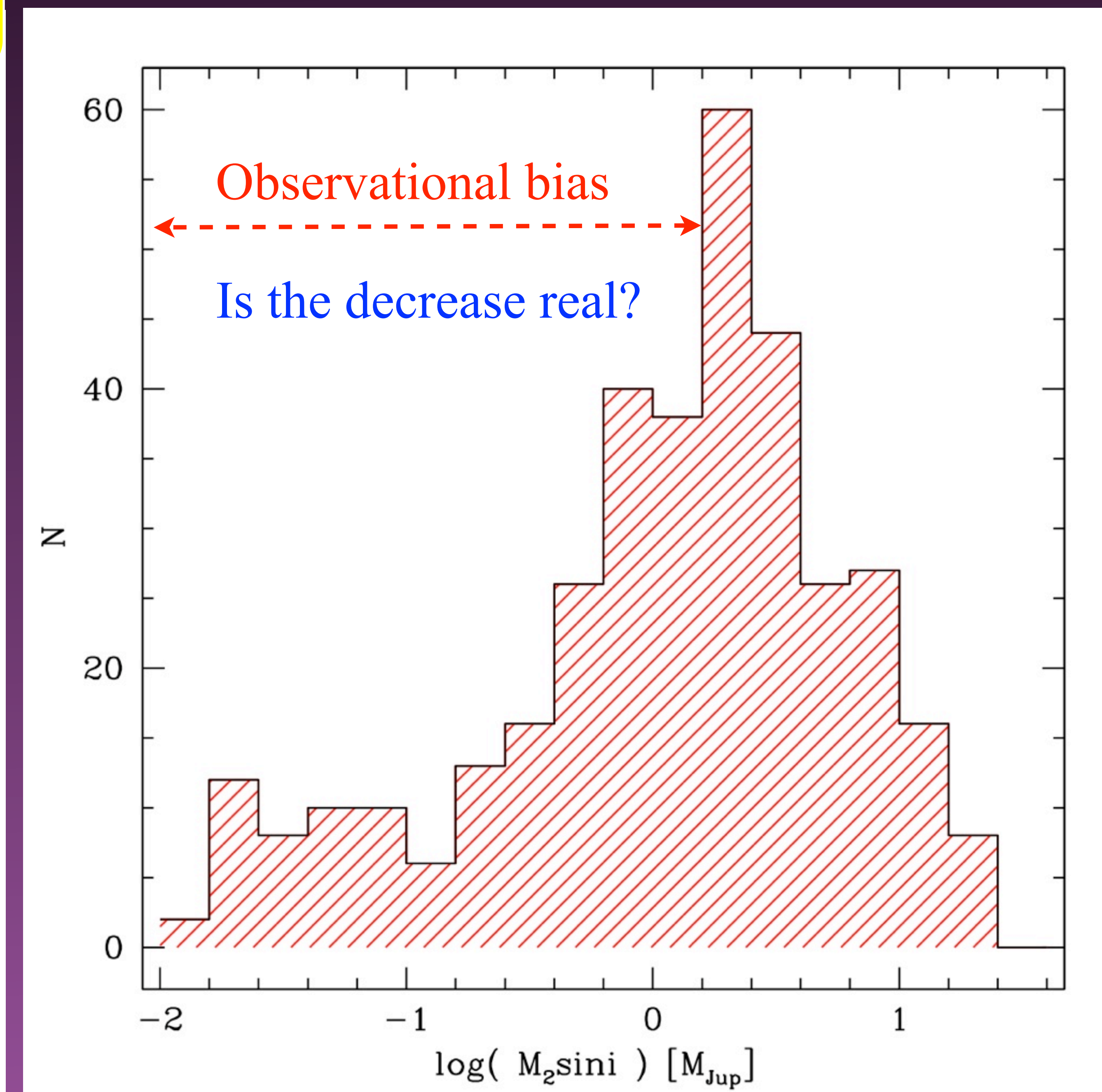

Planet Detectability with radial velocities

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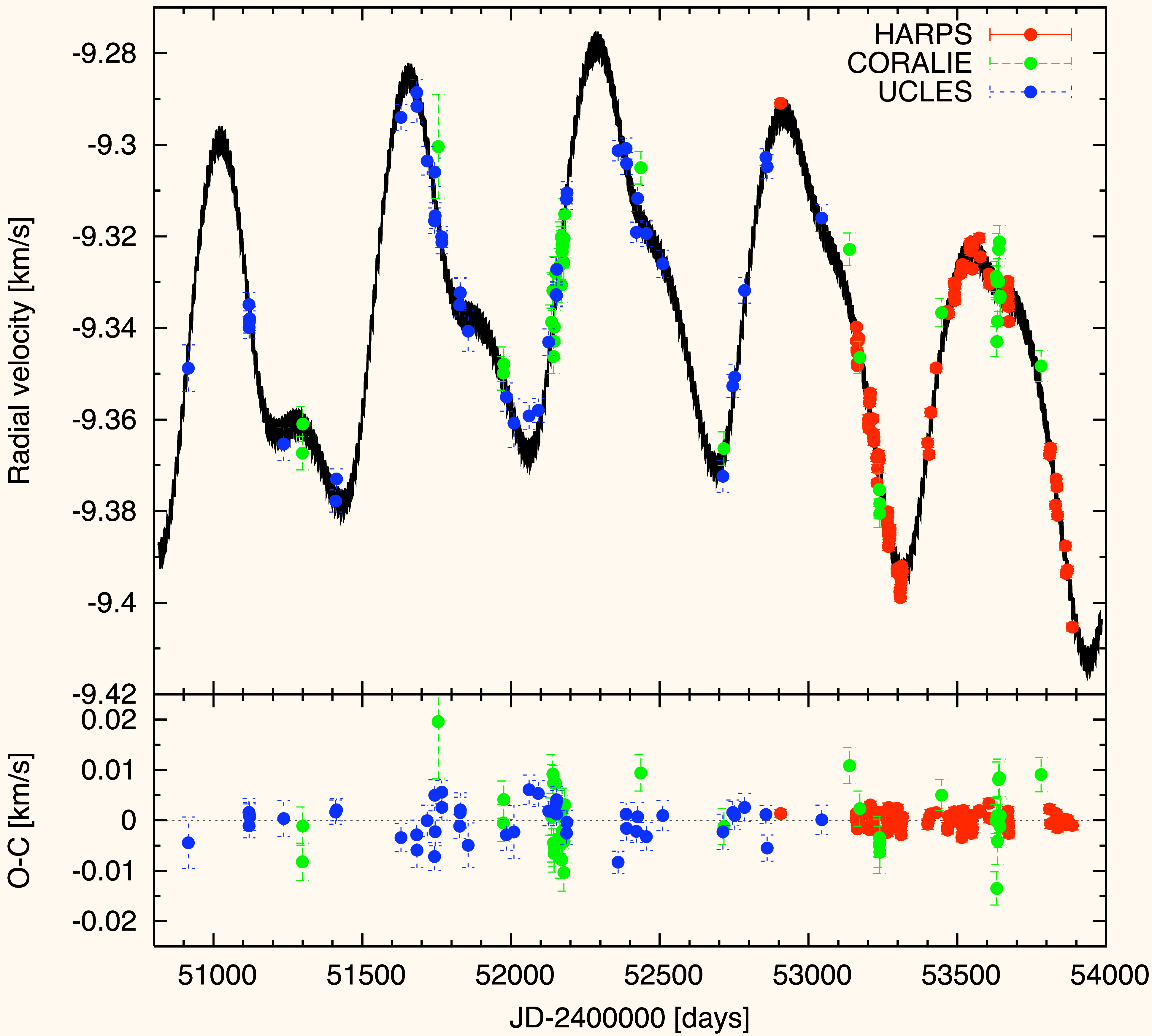
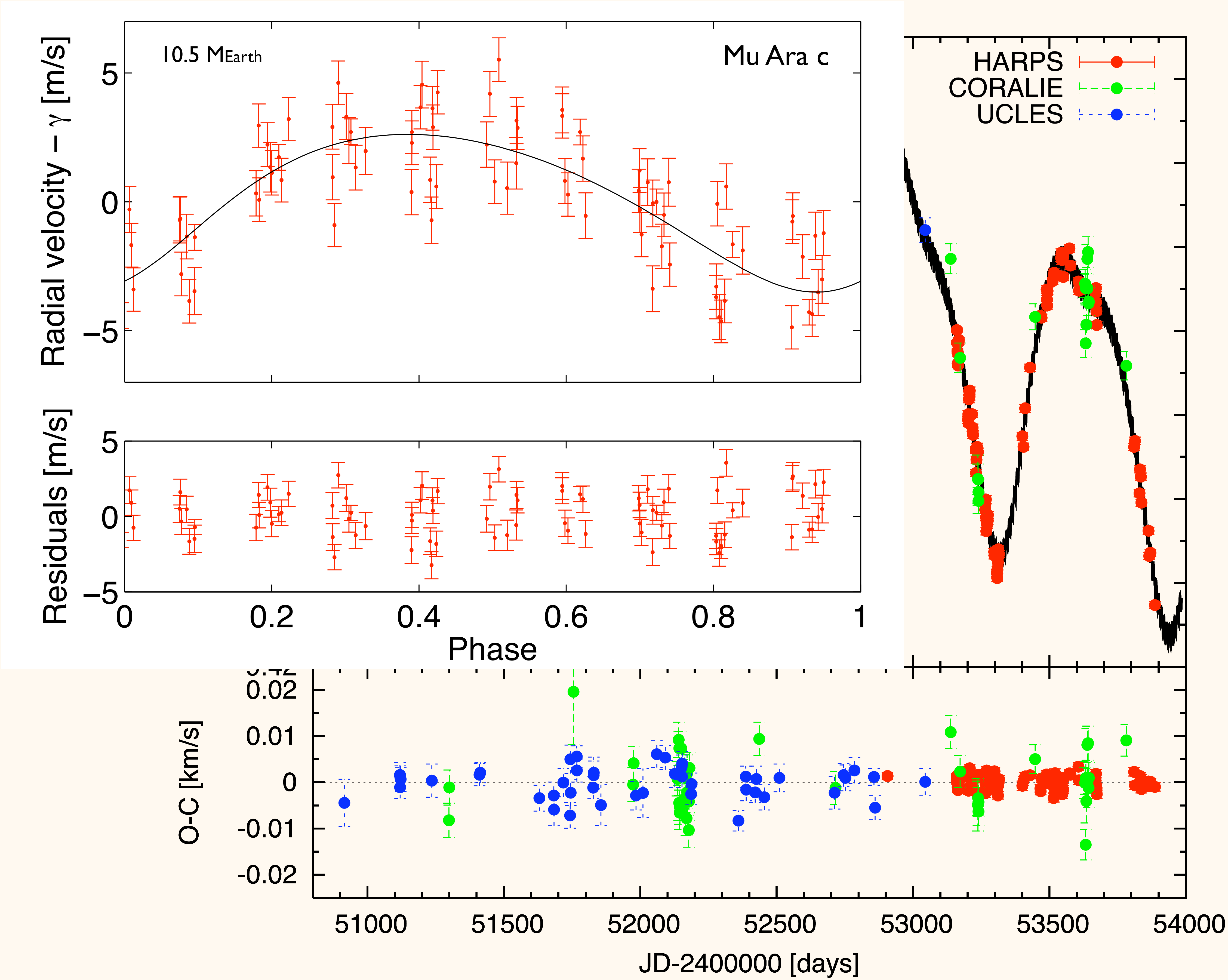
A few m/s precision OK
for giant planets
e.g. Jupiters out to > 5 AU

Need ~1 m/s
for close super-Earths!



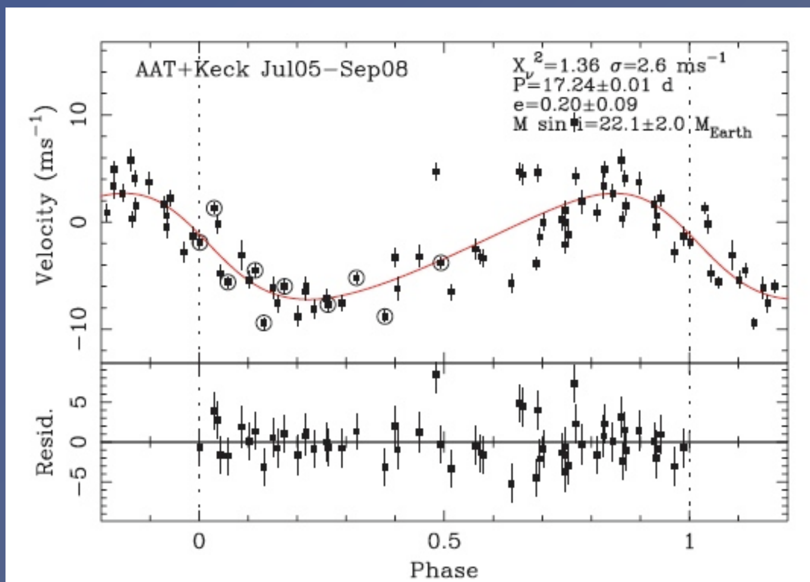
Mu Ara: 4 planets system (Pepe et al. 2006)



Mu Ara: 4 planets system (Pepe et al. 2006)

Encouraging results: Keck + AAT detections as well

HD16417 (O'Tool et al. 2009)

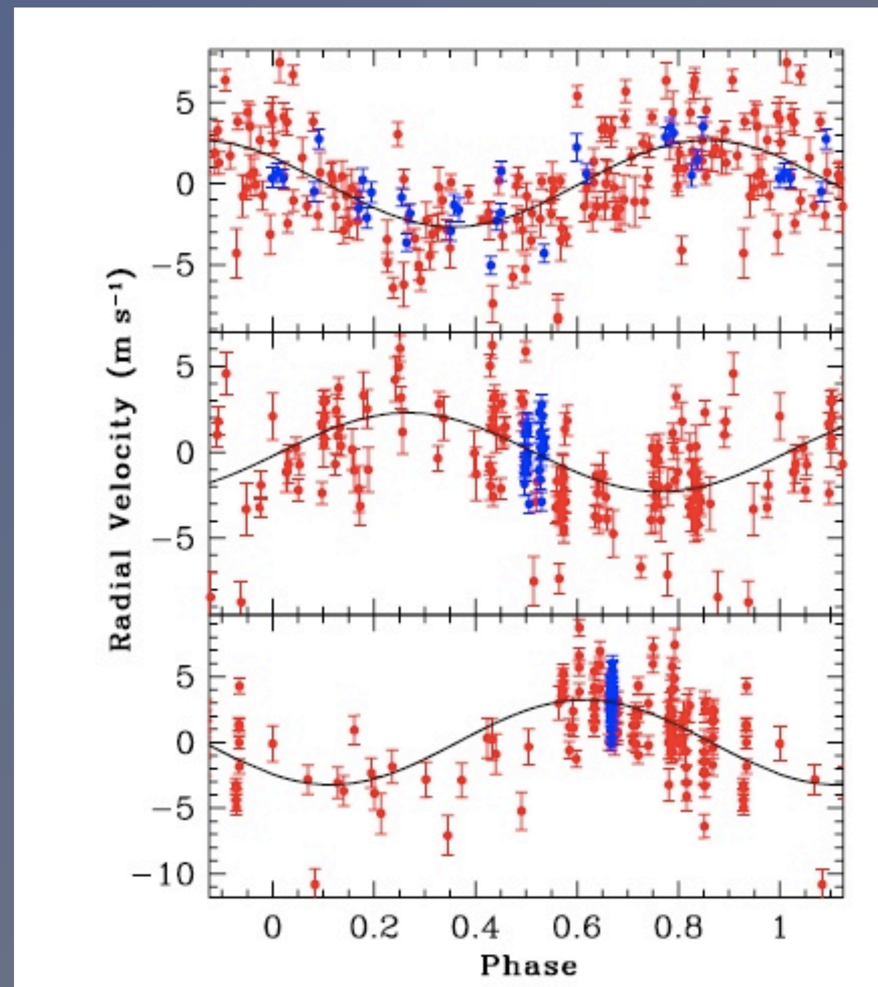


P_1 = 17.2 days

m_1 sini = 22 $M_\oplus$

O-C=2.7m/s

HD1461 (Rivera et al. 2010)



P_1 = 5.77 days

m_1 sini = 7.4 $M_\oplus$

P_2 = 446 days

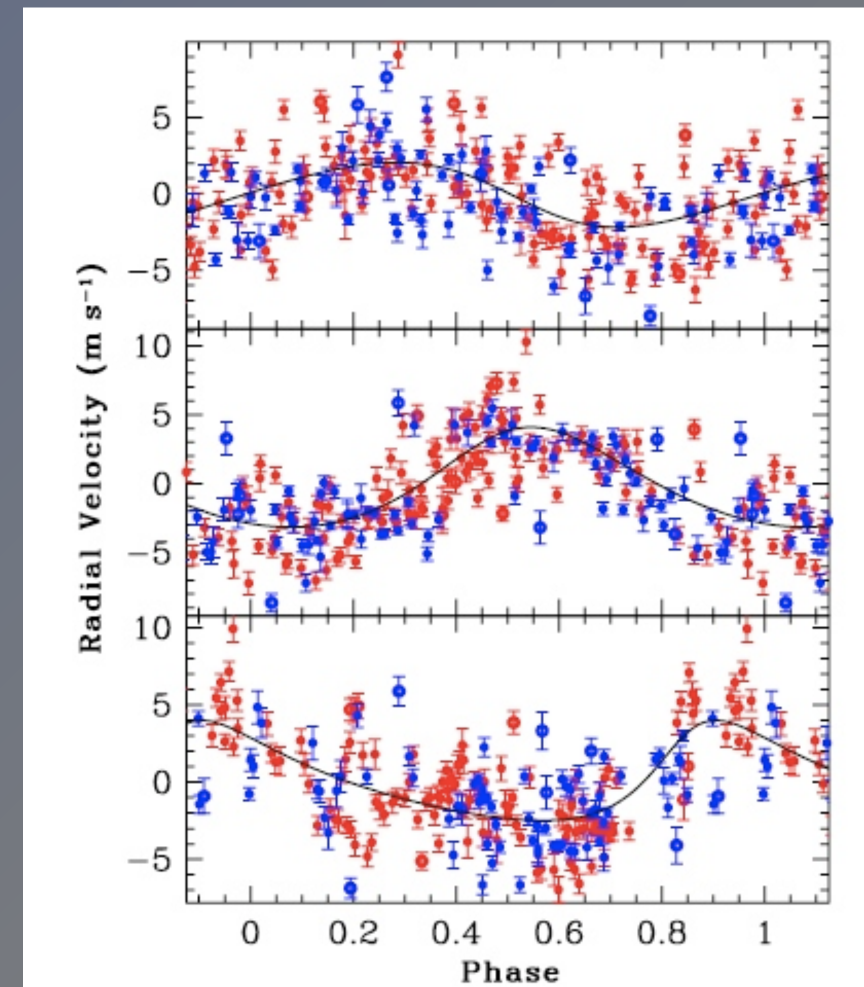
m_2 sini = 28 $M_\oplus$

P_3 = 5017 days

m_3 sini = 87 $M_\oplus$

O-C=2.3m/s

HD215617 (Vogt et al. 2010)



P_1 = 4.21 days

m_1 sini = 5.1 $M_\oplus$

P_2 = 38 days

m_2 sini = 18 $M_\oplus$

P_3 = 124 days

m_3 sini = 24 $M_\oplus$

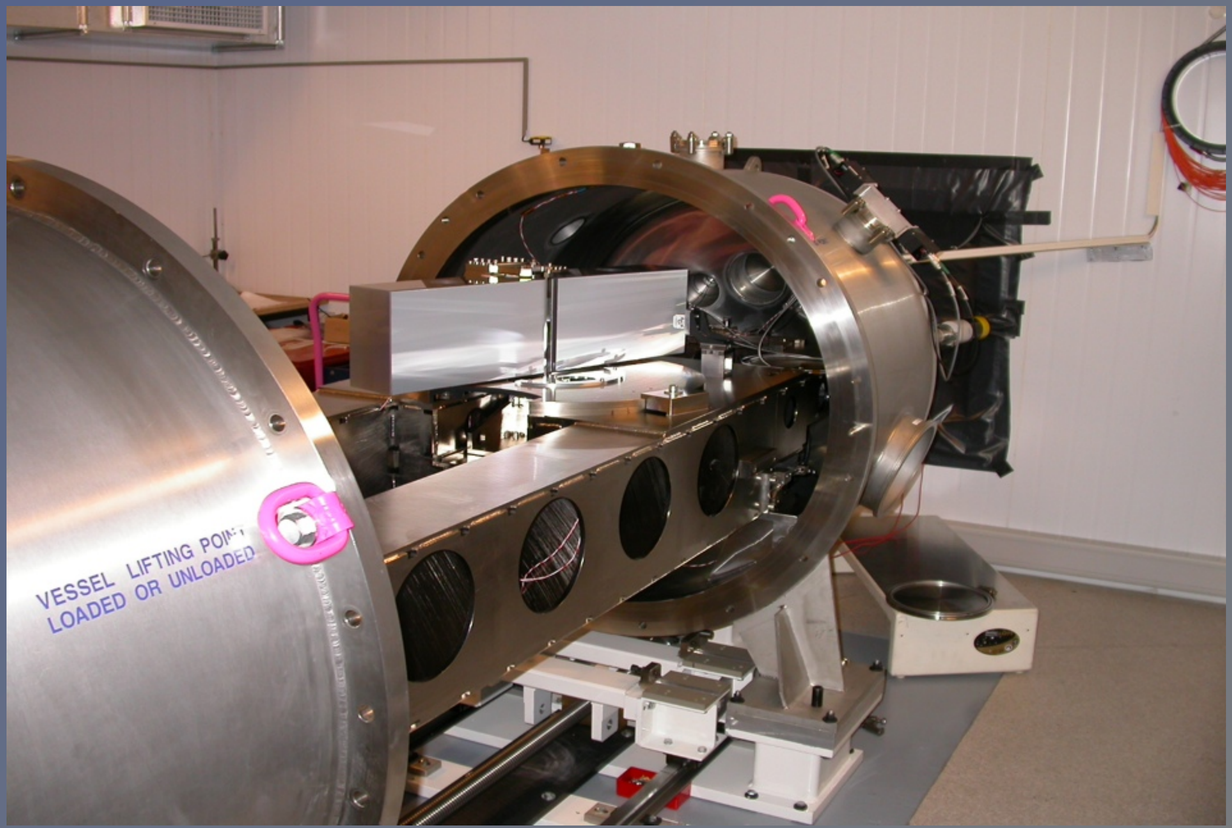
O-C=2m/s

The HARPS search for low-mass planets

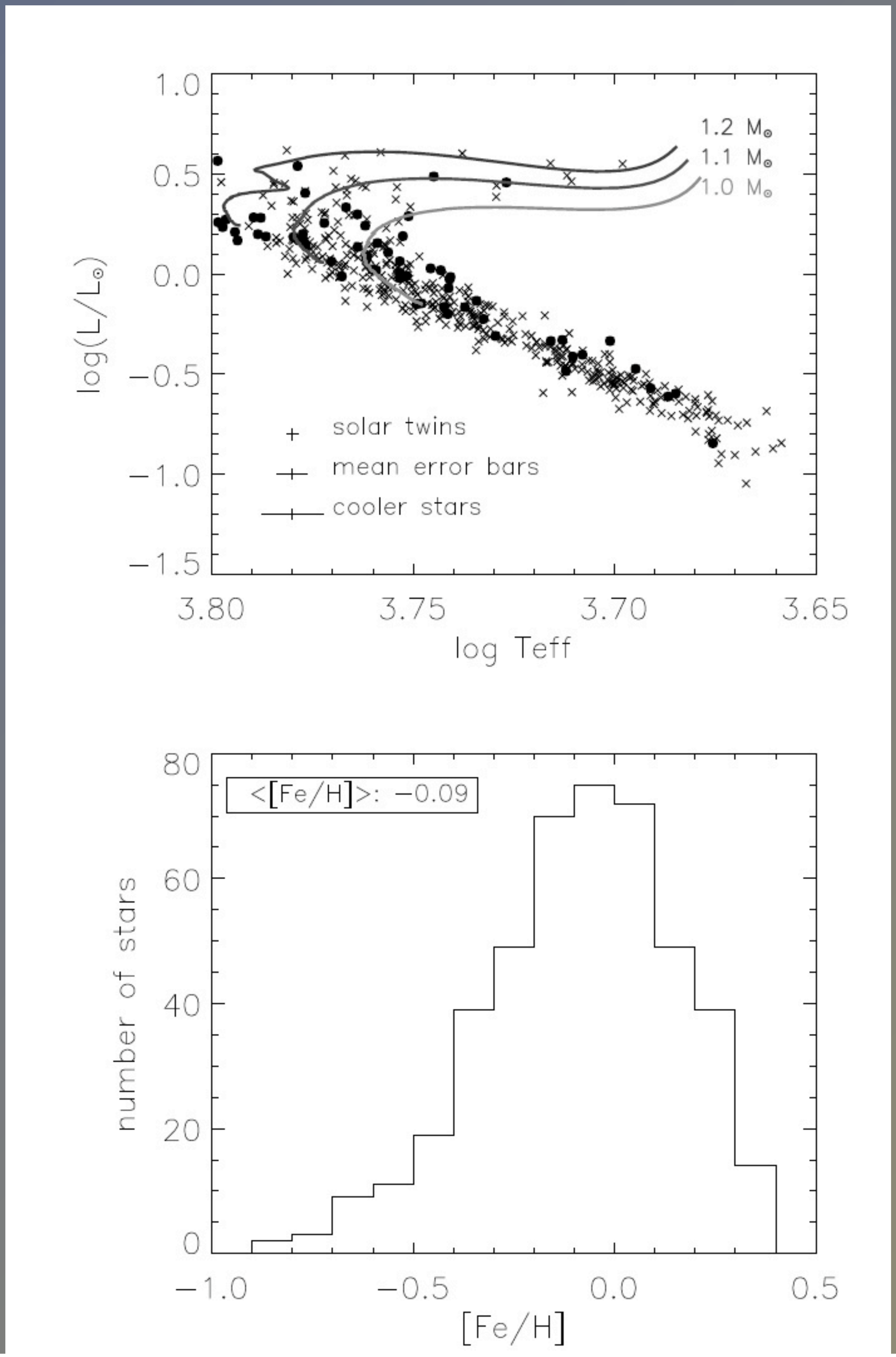
- Sample of ~400 slowly-rotating, nearby FGK dwarfs from the CORALIE planet-search survey + known planets
- HARPS log(R'_{HK})<-4.8 => ~280 good targets Non evolved (Sousa et al. 2009)
- Observations ongoing since 2004
- Focus on low-amplitude RV variations

=> about 50% of HARPS GTO time (250 nights)

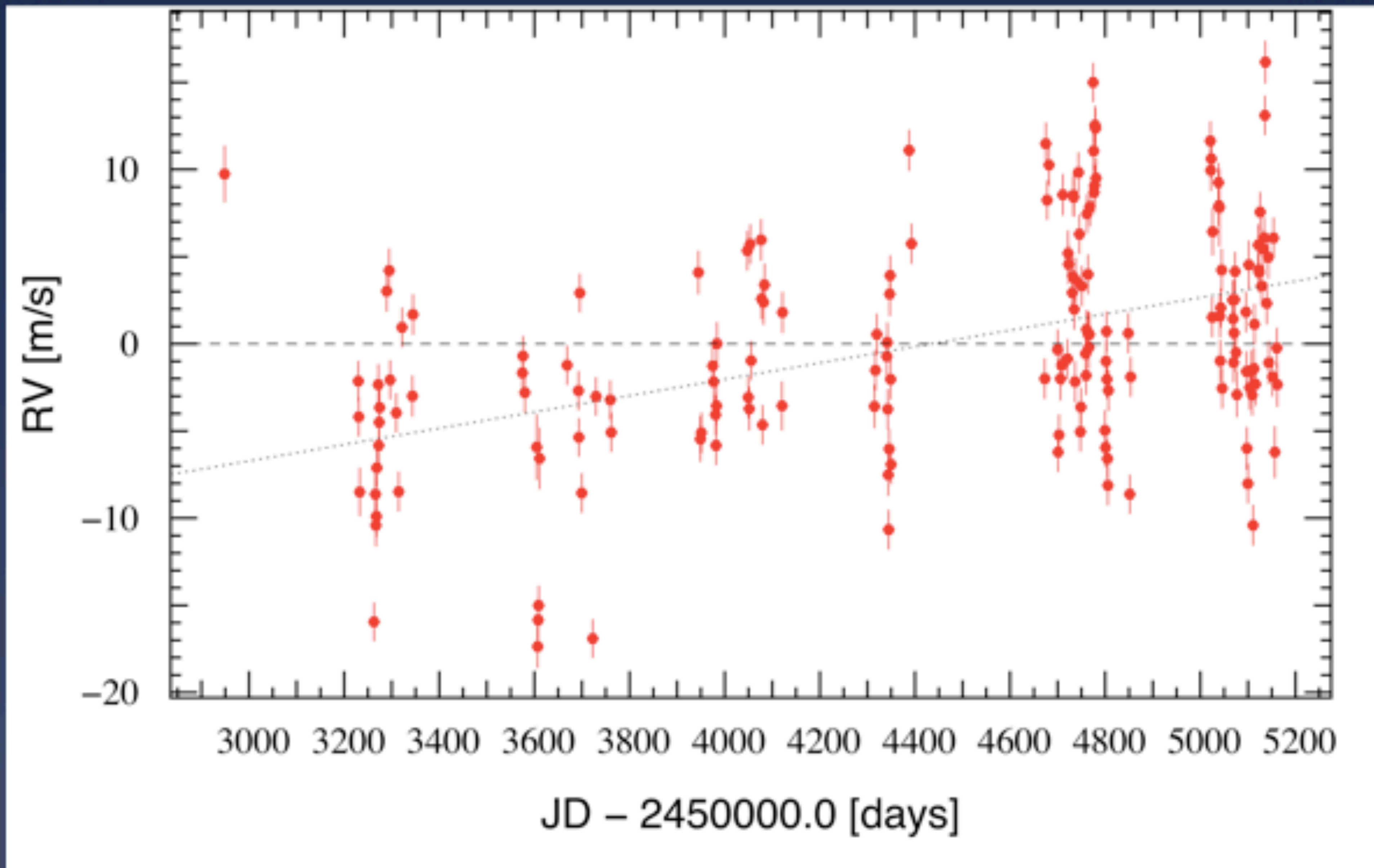
=> continuing with 280 nights over 4 years



HARPS



HD10180



175 HARPS precise radial velocities

HD10180 : 7-planet system

P_1 = 1.18 day
e_1 = 0
m_1 sini = 1.5 $M_\oplus$

P_2 = 5.76 days
e_2 = 0.07
m_2 sini = 13.2 $M_\oplus$

P_3 = 16.4 days
e_3 = 0.16
m_3 sini = 11.8 $M_\oplus$

P_4 = 49.7 days
e_4 = 0.06
m_4 sini = 24.8 $M_\oplus$

P_5 = 122.7 days
e_5 = 0.13
m_5 sini = 23.4 $M_\oplus$

P_6 = 595 days
e_6 = 0.0
m_6 sini = 22 $M_\oplus$

P_7 = 2150 days
e_7 = 0.15
m_7 sini = 67 $M_\oplus$

Lovis, Segransan, Udry, Mayor et al. 2010

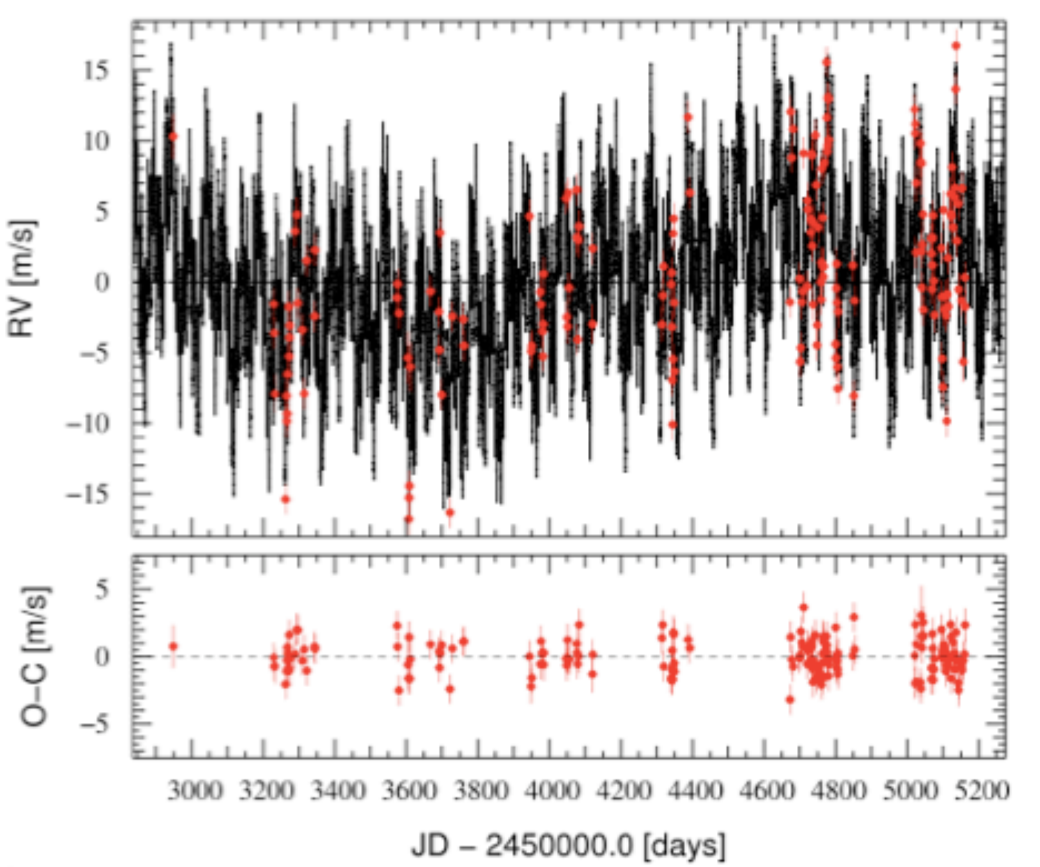
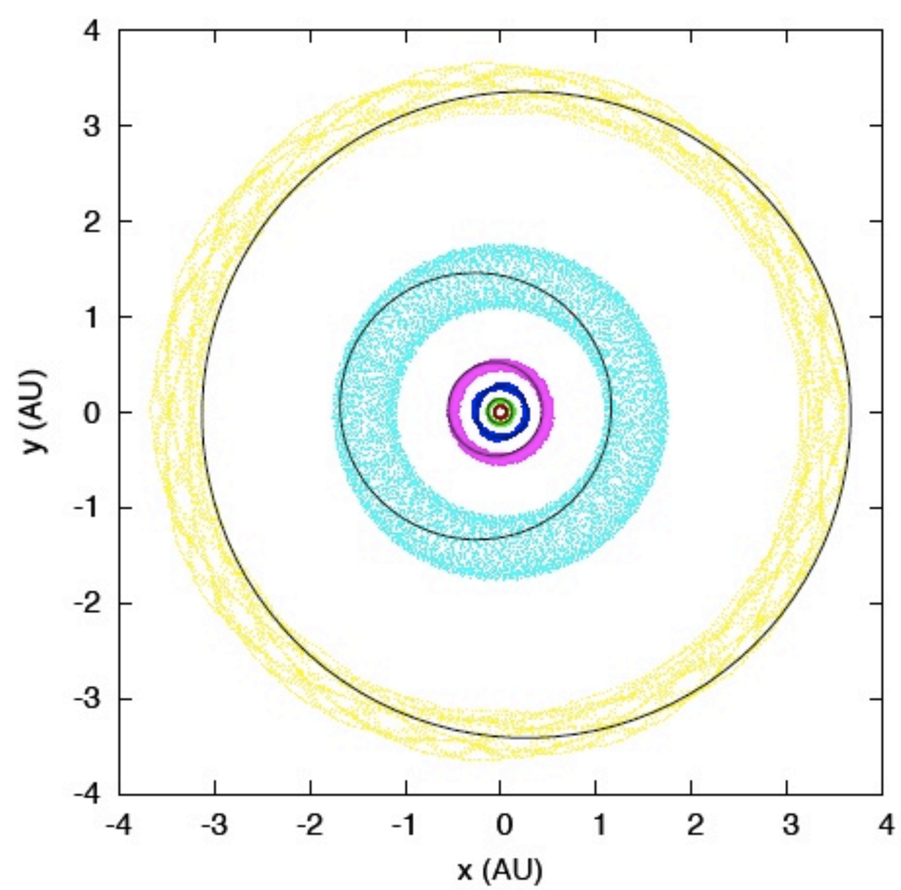
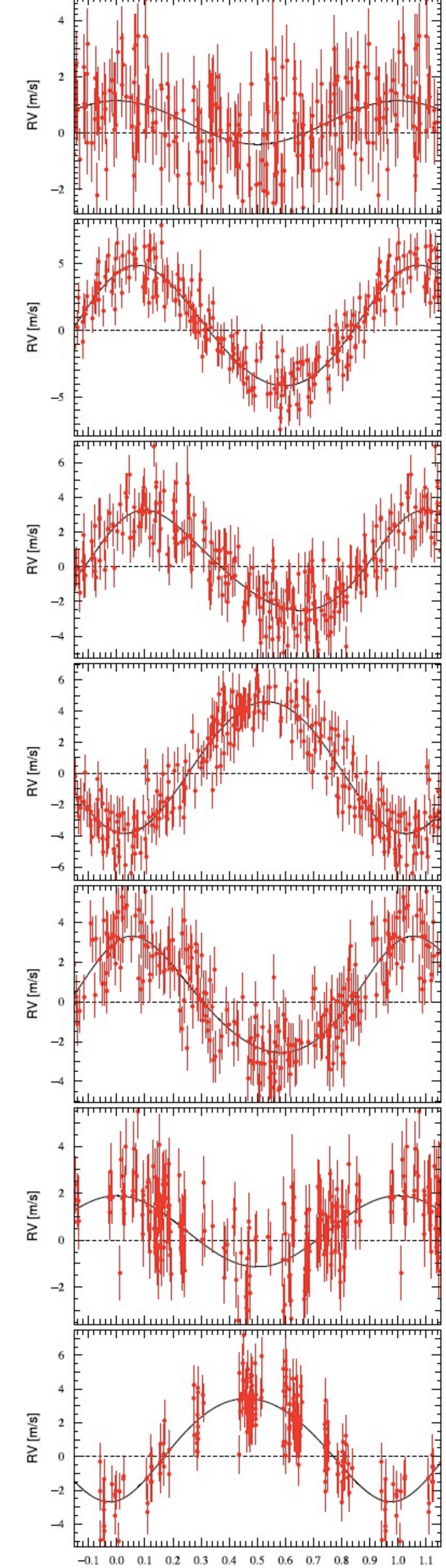
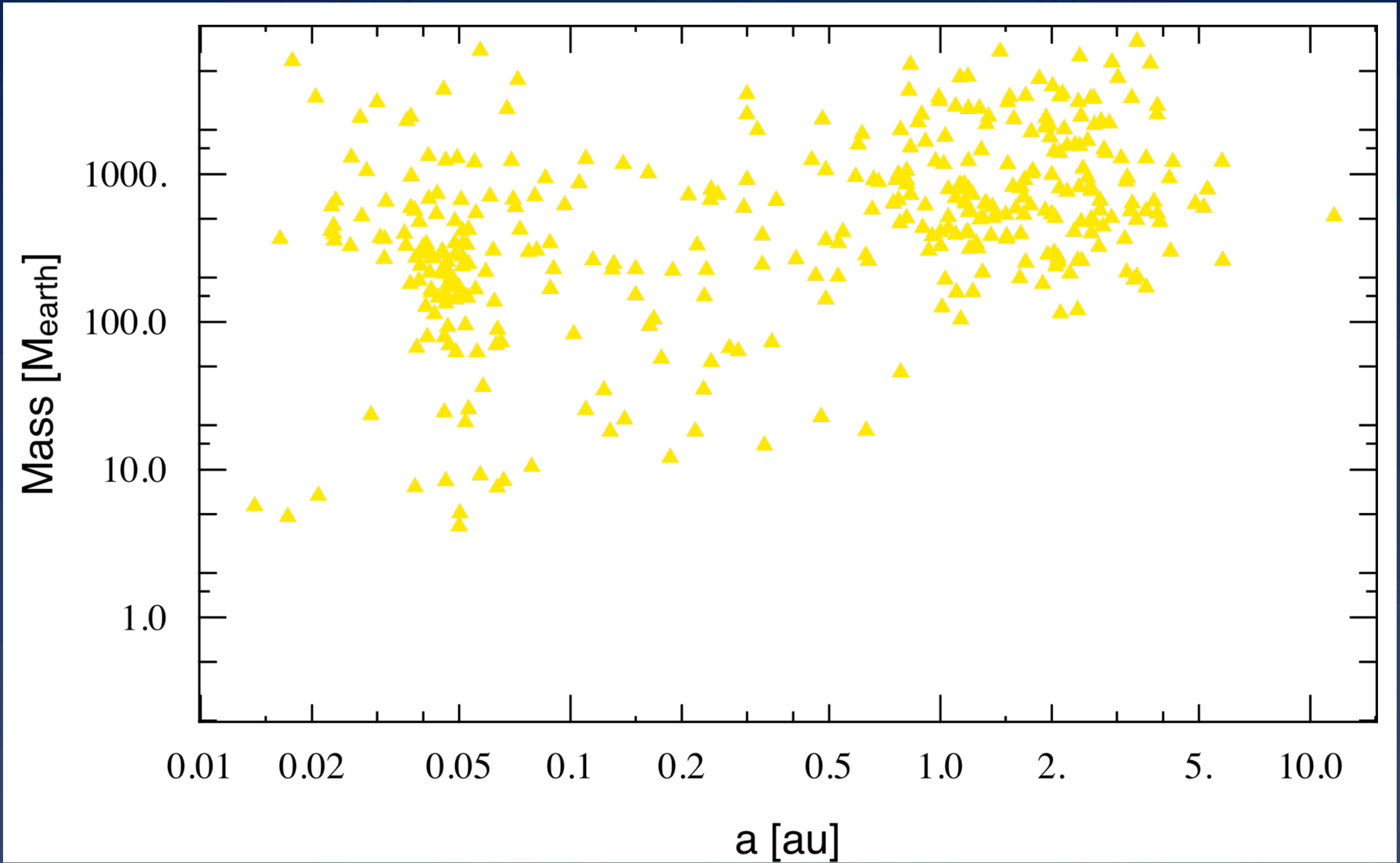


Fig. 5. Radial velocity time series with the 7-Keplerian model overplo





Published (and new) discoveries



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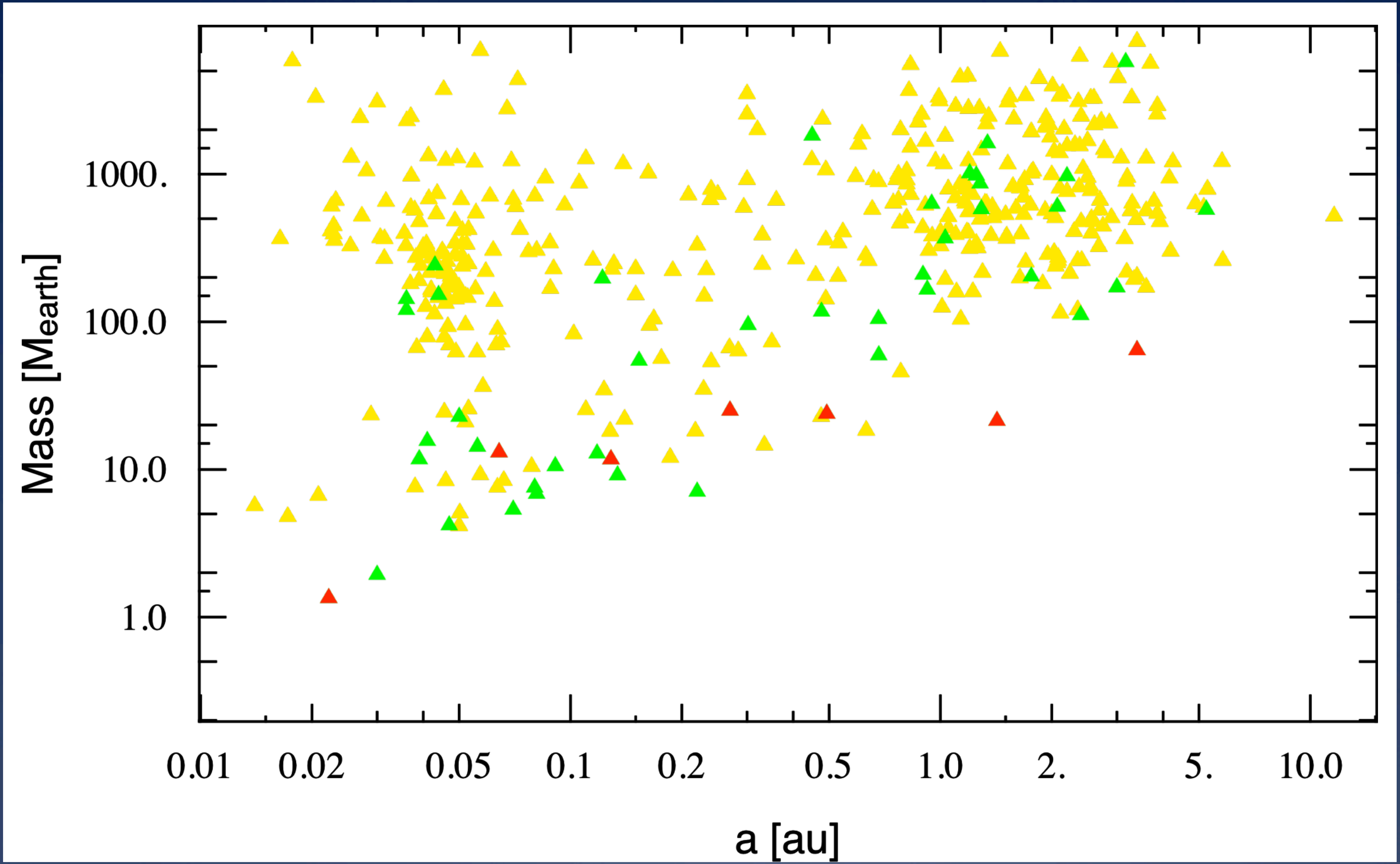

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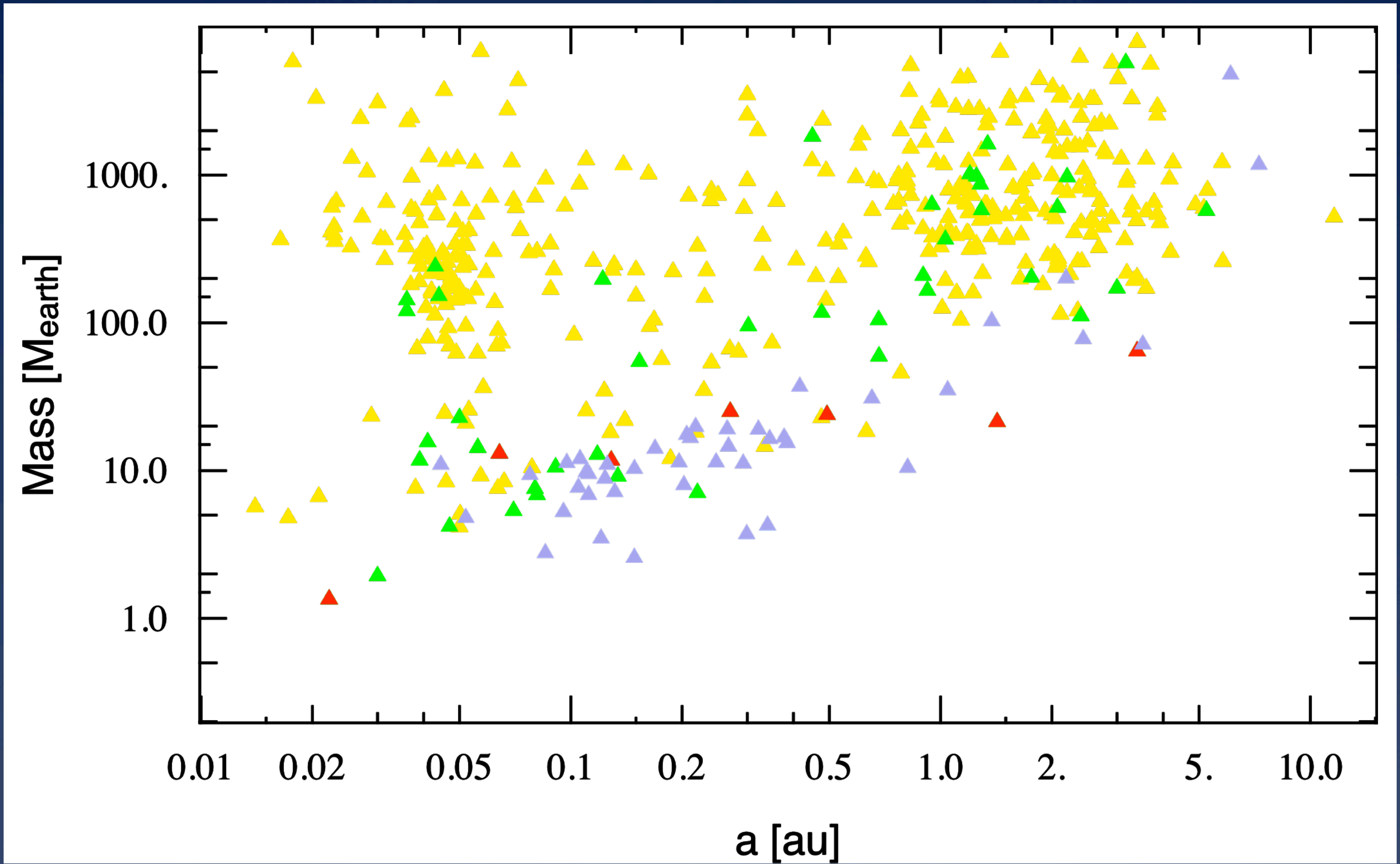

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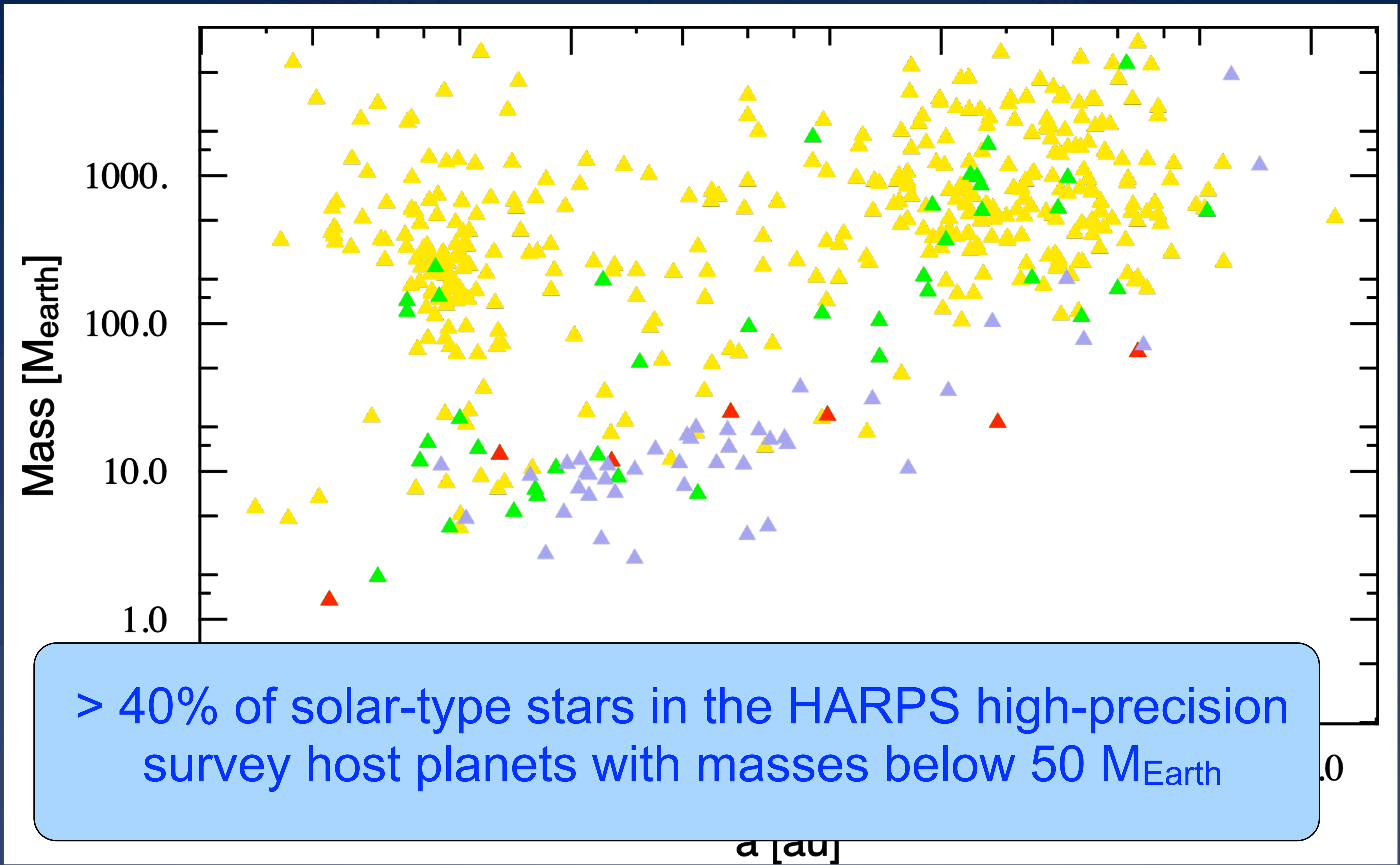
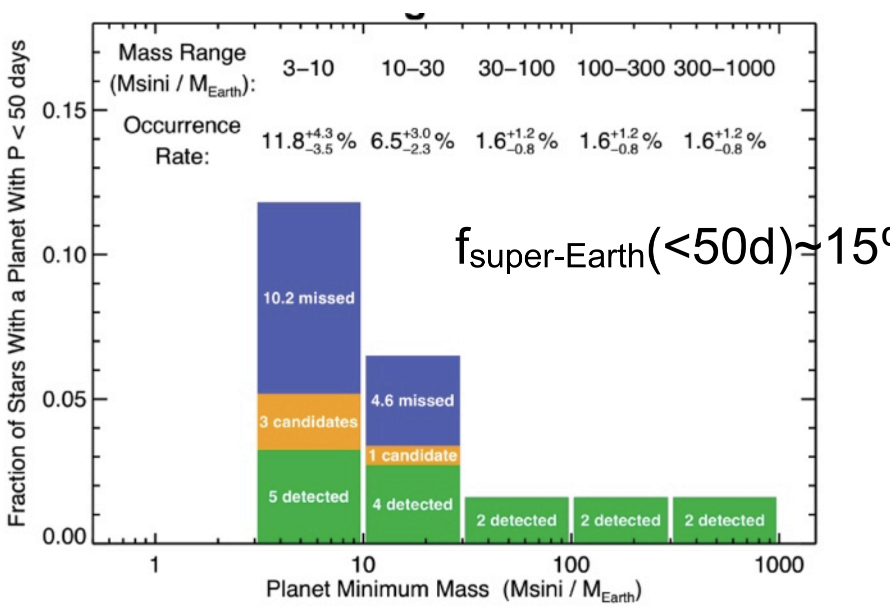


> 40% of solar-type stars in the HARPS high-precision survey host planets with masses below 50 M_{Earth}

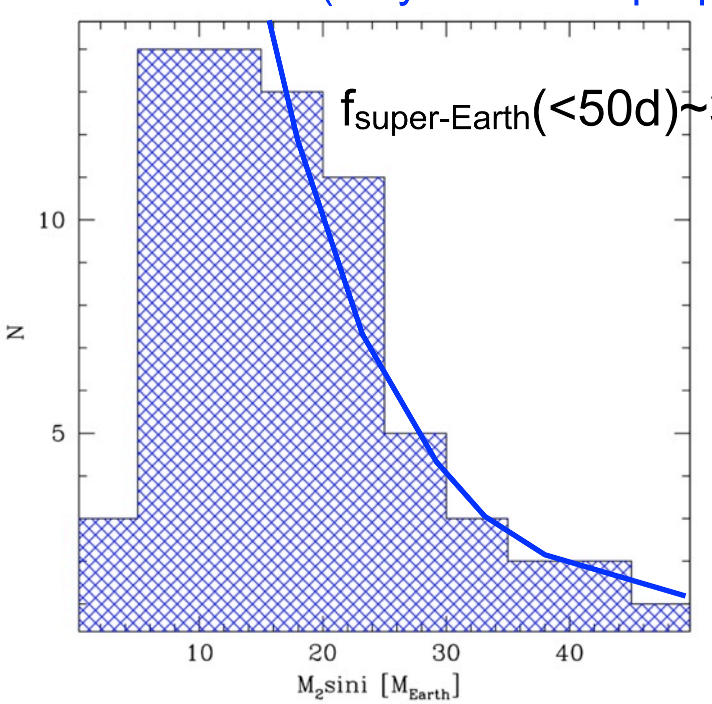
Low-mass planets...
Small-size planets...
....are numerous!

Keck (Howard et al. 2010, Science)



$f_{super\text{-}Earth}(<50d)\sim15\%$

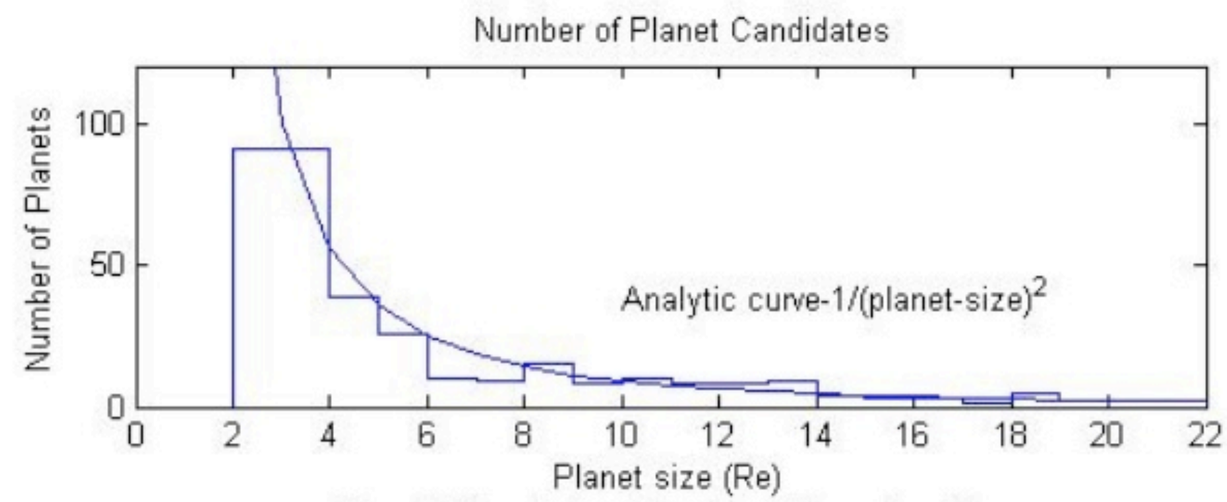
HARPS (Lovis et al. 2009) (Mayor et al. in prep)

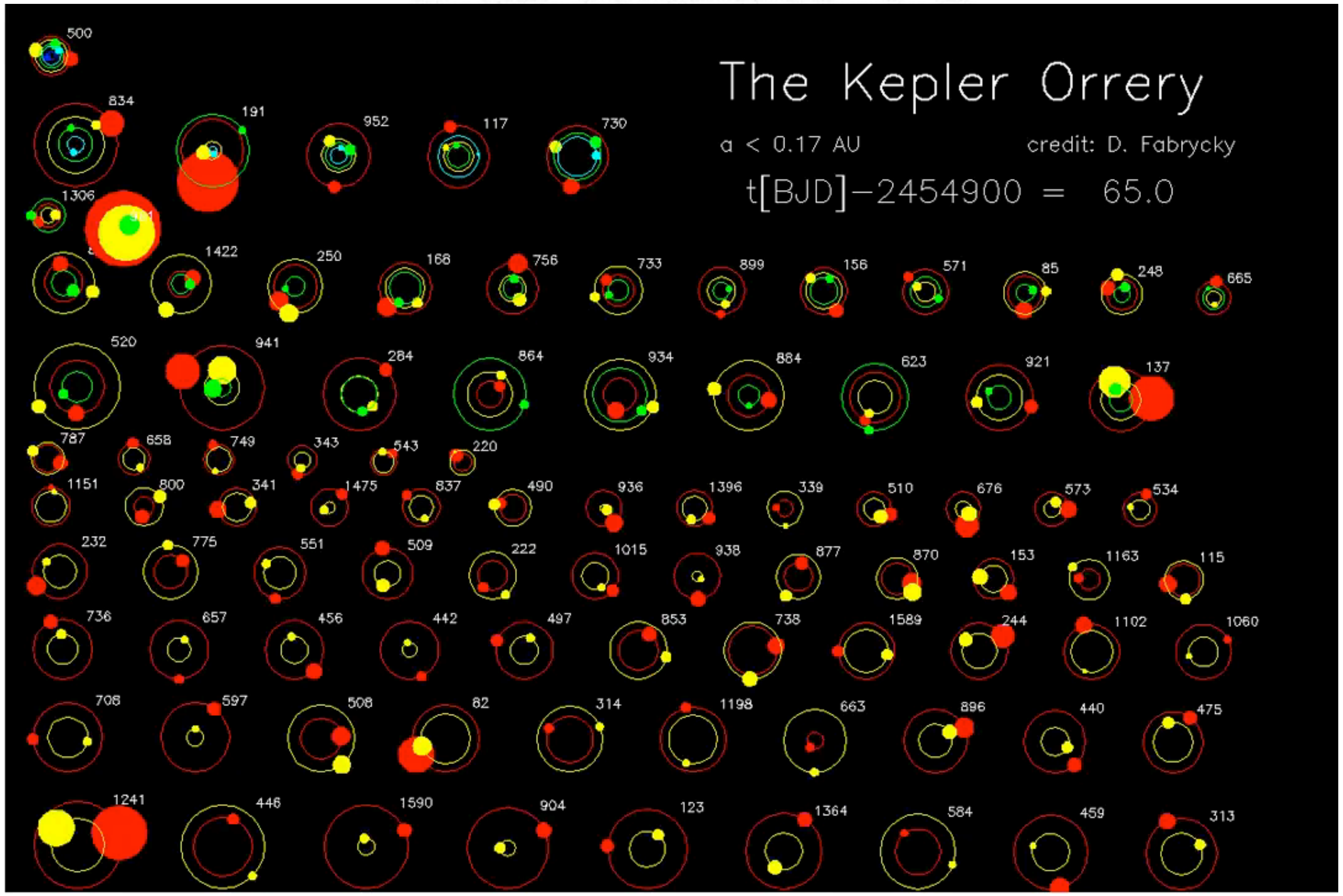


$f_{super\text{-}Earth}(<50d)\sim30\text{-}50\%$

Kepler (Borucki et al. 2010)

Abstract. On 1 February 2011 the *Kepler* Mission released data for 156,453 stars observed from the beginning of the science observations on 2 May through 16 September 2009. There are 1235 planetary candidates with transit like signatures detected in this period. These are associated with 997 host stars. Distributions of the characteristics of the planetary candidates are separated into five class-sizes; 68 candidates of approximately Earth-size ($R_p < 1.25\ R_\oplus$), 288 super-Earth size ($1.25\ R_\oplus < R_p < 2\ R_\oplus$), 662 Neptune-size ($2\ R_\oplus < R_p < 6\ R_\oplus$), 165 Jupiter-size ($6\ R_\oplus < R_p < 15\ R_\oplus$),





(III) Multi-planetary systems

- Present statistics

RV: 108 planets in 41 systems:

~ 25 % of known exoplanets

+ transit candidates

- Most of them with 2 planets
- HD10180: 7 planets
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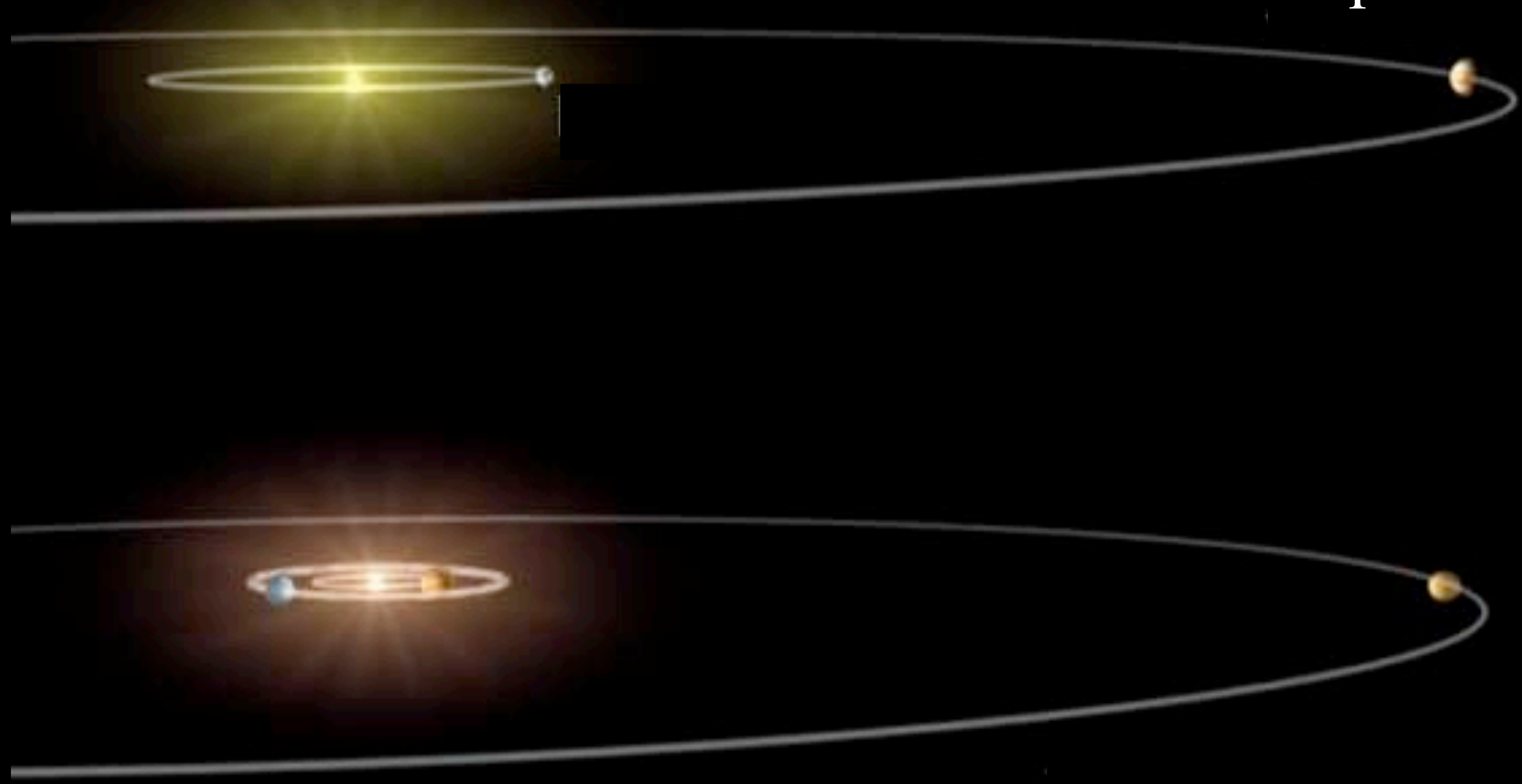

- longest-running programmes

--> largest fraction of multi-planet systems

Planets mainly form in multi-planet systems

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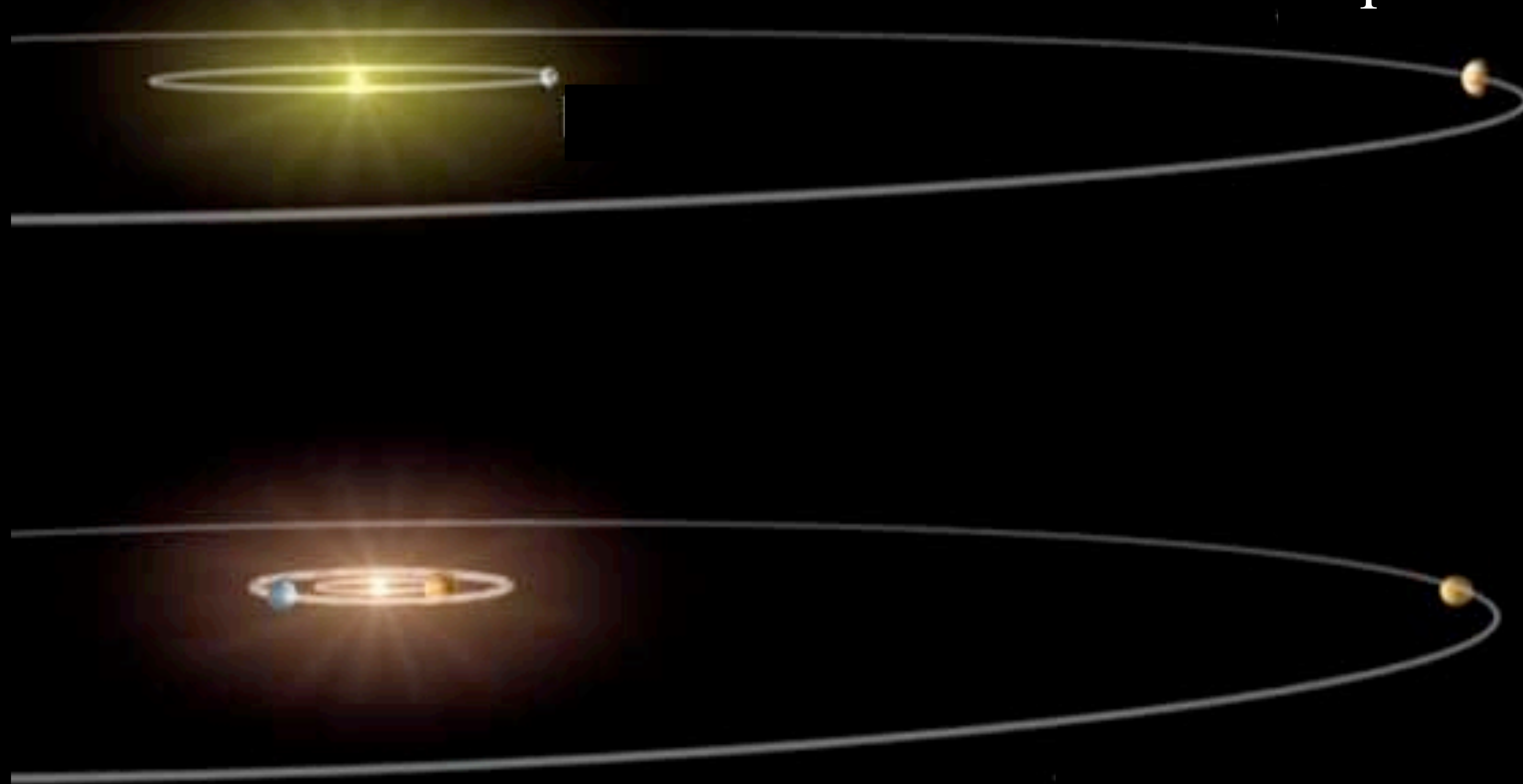

- longest-running programmes

--> largest fraction of multi-planet systems
Planets mainly form in multi-planet systems

Need for multi-planet formation models!

Planetary multiplicity (at least 1 Neptune or Super-Earth) in VR surveys only

R Super-Earths
N Neptune-type
G Gaseous giant planet

- G and K stars (multiple)

BD-08:2823	N + G	
HD 10180	R + 5N + G	
HD 11964	N + G	
HD 40307	3R	
HD 47186	N + G	
HD 69830	3N	
55 Cnc	N + 4G	(HD 75732)
HD115617	R + 2N	
HD 125612	N + 2G	
Mu Ara	N + 3G	(HD 160691)
HD 181433	R + 2G	
GJ 777A	N + G	(HD 190360)
HD 219828	N + G	
HD 215497	R + G	

- G and K stars (single)

HD 1461	R
HD 4308	N
HD 7924	R
HD 16417	N
HD 90156	N
HD 97658	R
HD 125595	N
HD 155668	R
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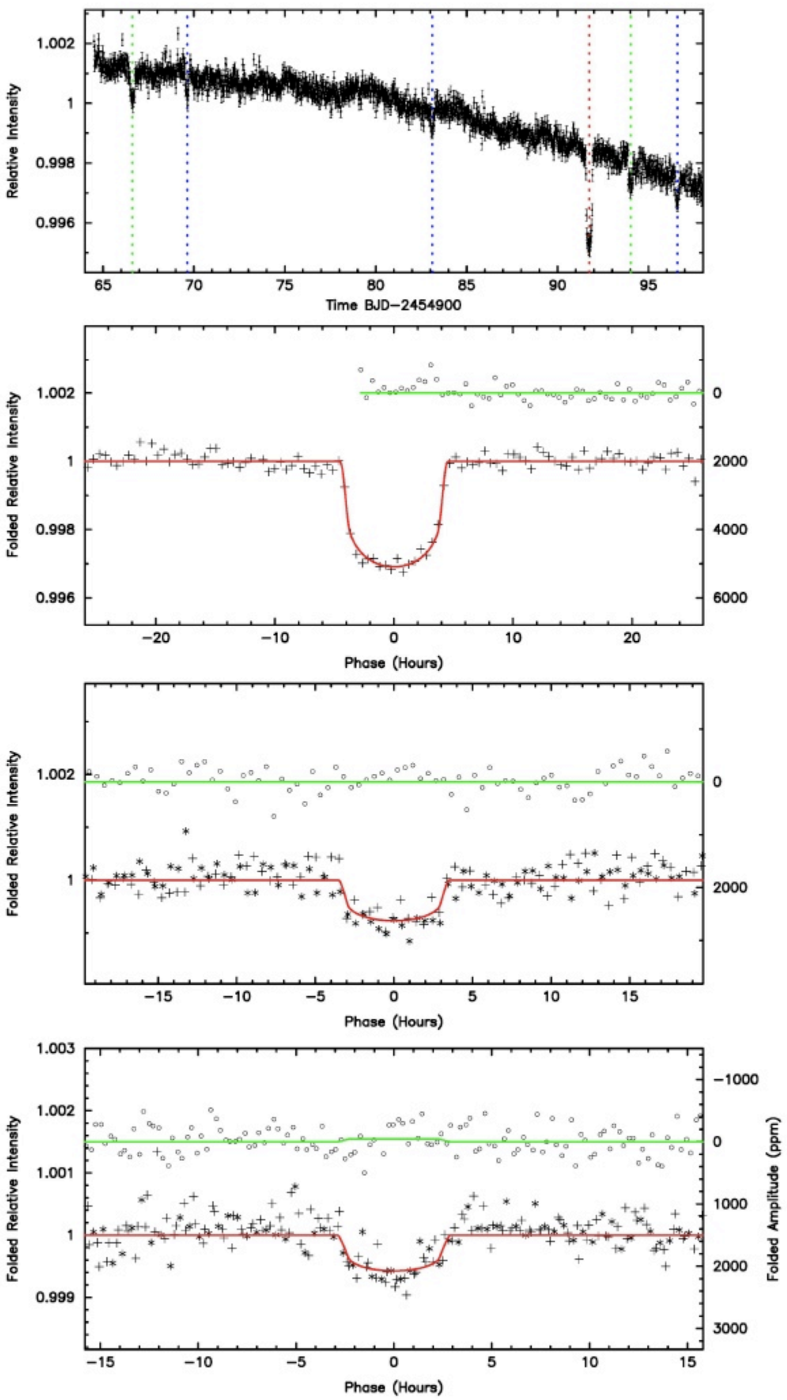
> 65% of
multi-planet systems
=> minimum value

Trend confirmed by unpublished candidates
(including curved drift)

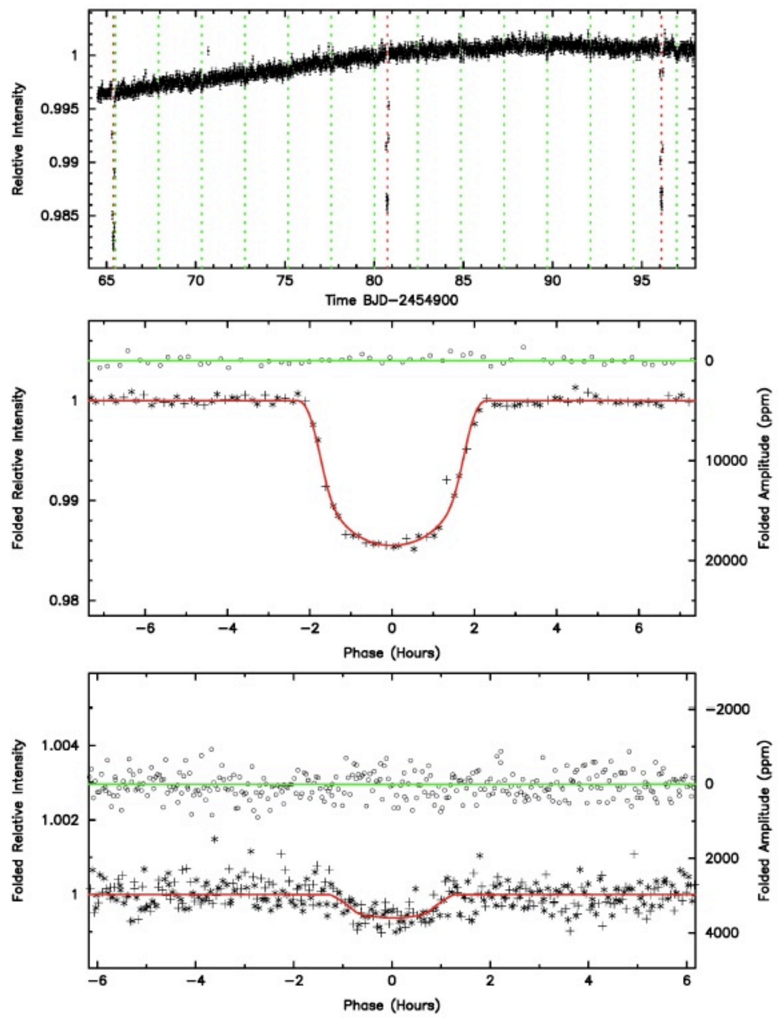
Mult-transiting systems

Kepler (Steffen et al. 2010)

KIO 152



KIO 191



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KIO 152

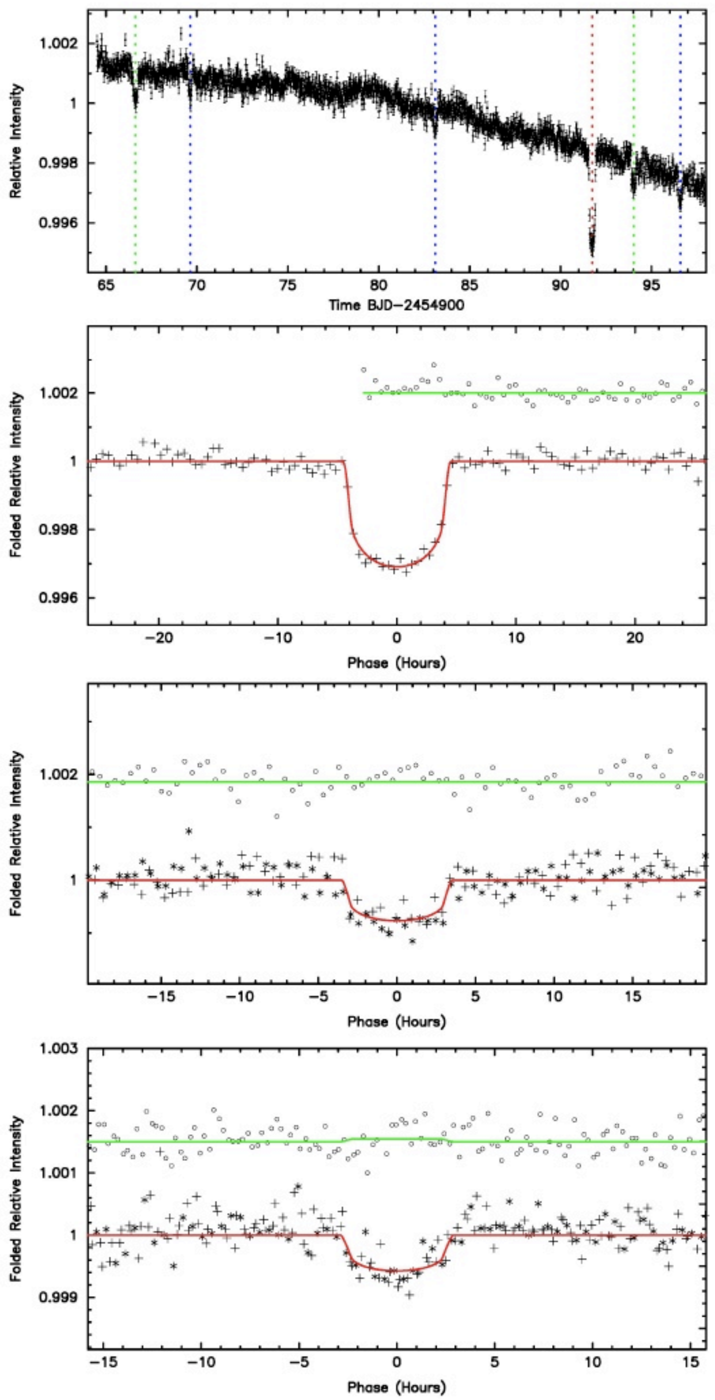

TABLE 3
ORBITAL PERIODS AND TRANSIT EPOCHS FOR THE CANDIDATE PLANETS.

Candidate	T_{ec} BJD −2454900	Period (Days)	Period Ratio (vs. inner)	Duration (Days)	ξ (obs.)	ξ_{MC} (predicted)
152.03	69.622 ± 0.0053	13.478 ± 0.0098	-	0.2071 ± 0.0022	–	–
02	66.630 ± 0.0079	27.406 ± 0.0150	2.03	0.2823 ± 0.0060	0.9291	$1.10^{+0.46}_{-0.09}$
01	91.747 ± 0.0026	> 27 (51.9)	(3.85)	0.3432 ± 0.0013	1.0188	$1.08^{+0.36}_{-0.07}$
191.02	65.50 ± 0.16	2.420 ± 0.0006	-	0.0948 ± 0.0016	–	–
01	$65.3847 \pm 4 \times 10^{-4}$	15.359 ± 0.0004	6.347	0.1494 ± 0.0002	1.1751	$1.15^{+0.60}_{-0.13}$
209.02	78.822 ± 0.0046	18.801 ± 0.0087	-	0.2884 ± 0.0018	–	–
01	68.635 ± 0.0036	> 29 (49.3)	(2.62)	0.4252 ± 0.0007	0.9429	$1.12^{+0.68}_{-0.11}$
877.01	103.952 ± 0.0028	5.952 ± 0.0024	-	0.0962 ± 0.0012	–	–
02	114.227 ± 0.0051	12.039 ± 0.0077	2.023	0.1192 ± 0.0021	1.0204	$1.08^{+0.47}_{-0.07}$
896.02	107.051 ± 0.0028	6.311 ± 0.0024	-	0.1278 ± 0.0016	–	–
01	108.568 ± 0.0024	16.242 ± 0.0075	2.574	0.1916 ± 0.0017	0.9144	$1.11^{+0.55}_{-0.10}$

Very coplanar?

TABLE 4
PLANETARY RADII AND LIKELY RANGE OF MASSES.

Candidate	Planet Radius	Mass Range
152.03	$0.30\ R_J$	$9 - 30\ M_E$
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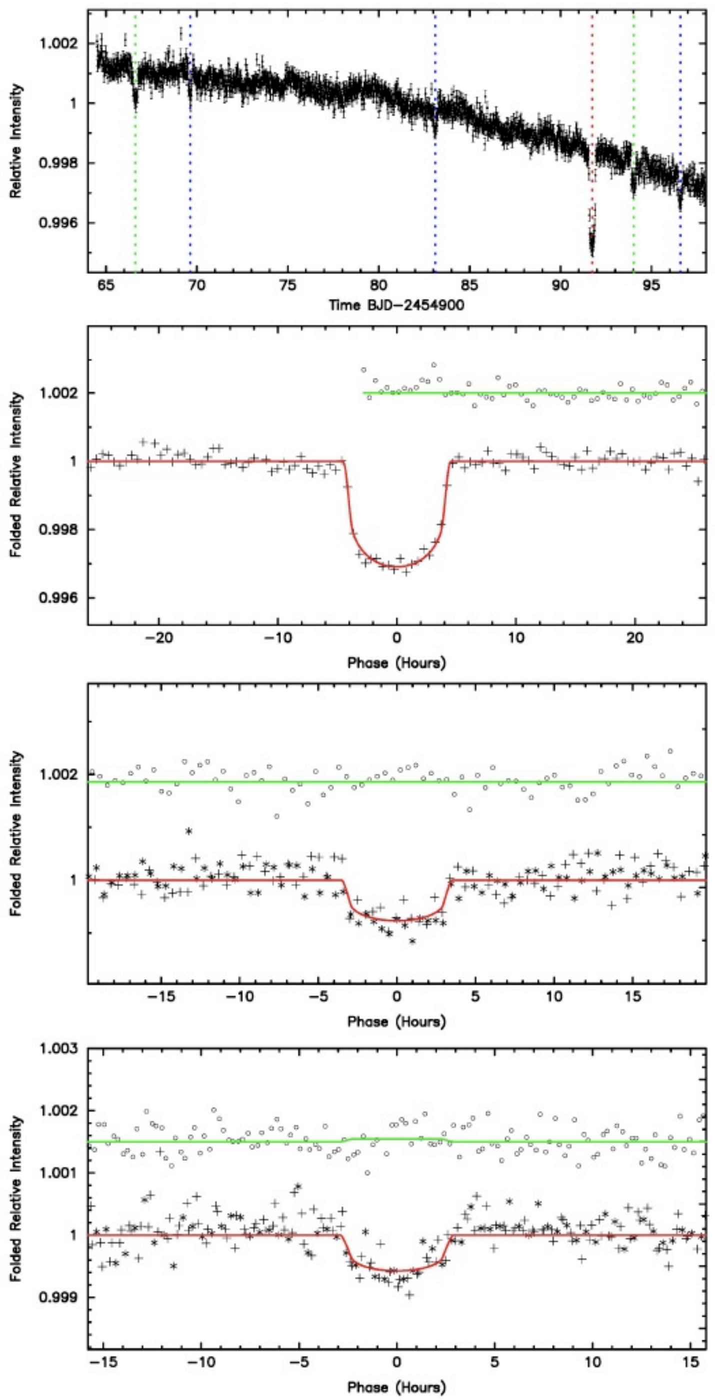
Kepler (Steffen et al. 2010)

KIO 152



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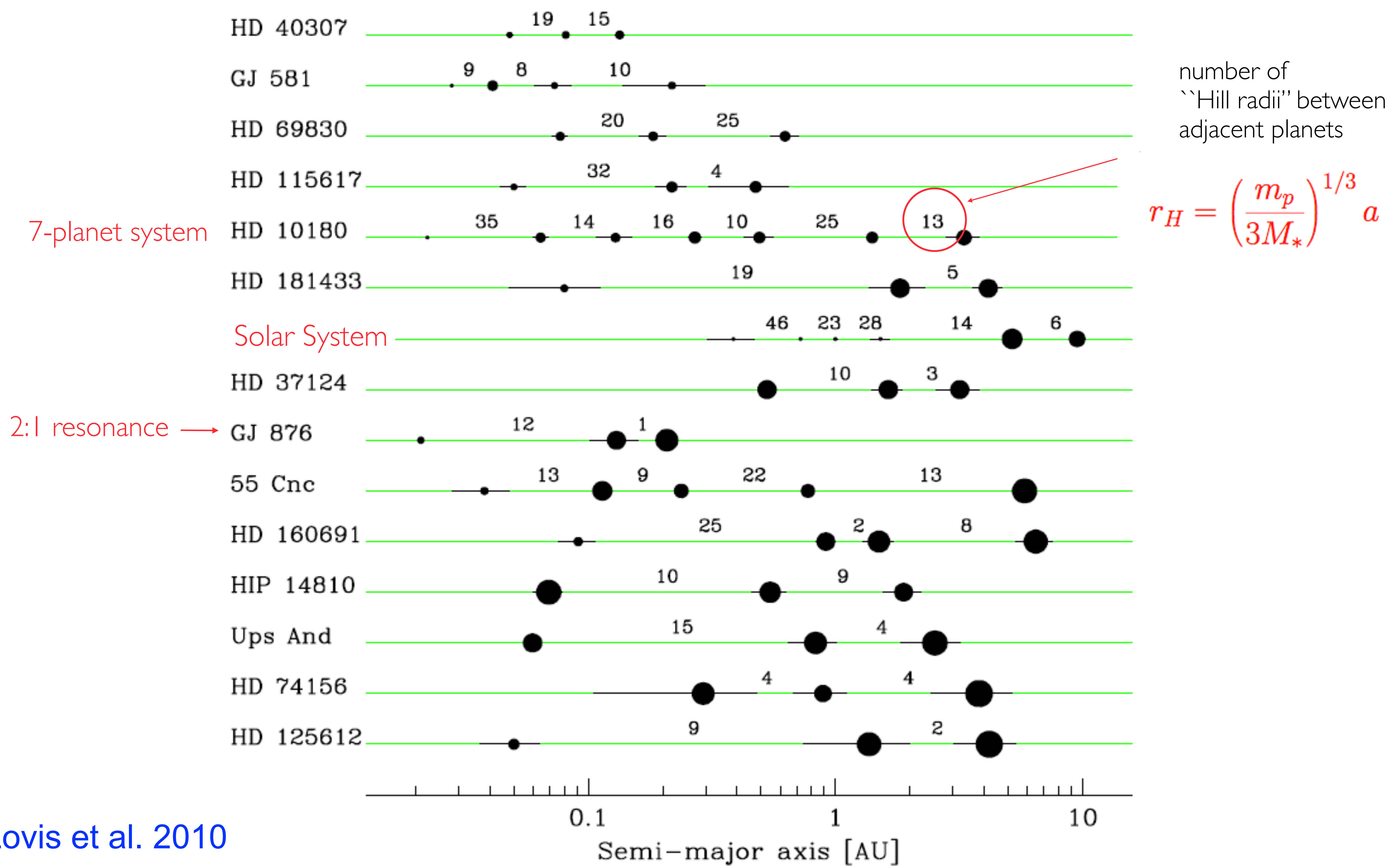
Dynamical effects?
- between planets?
- with disk?

=> Need
- masses (RV)
- inclination (RM effect)

=> Need bright stars

Systems with n>2 planets

multi-planet systems: many are almost optimally ``packed'' (no room for more stability-wise)



$$r_H = \left(\frac{m_p}{3M_*}\right)^{1/3} a$$

Lovis et al. 2010

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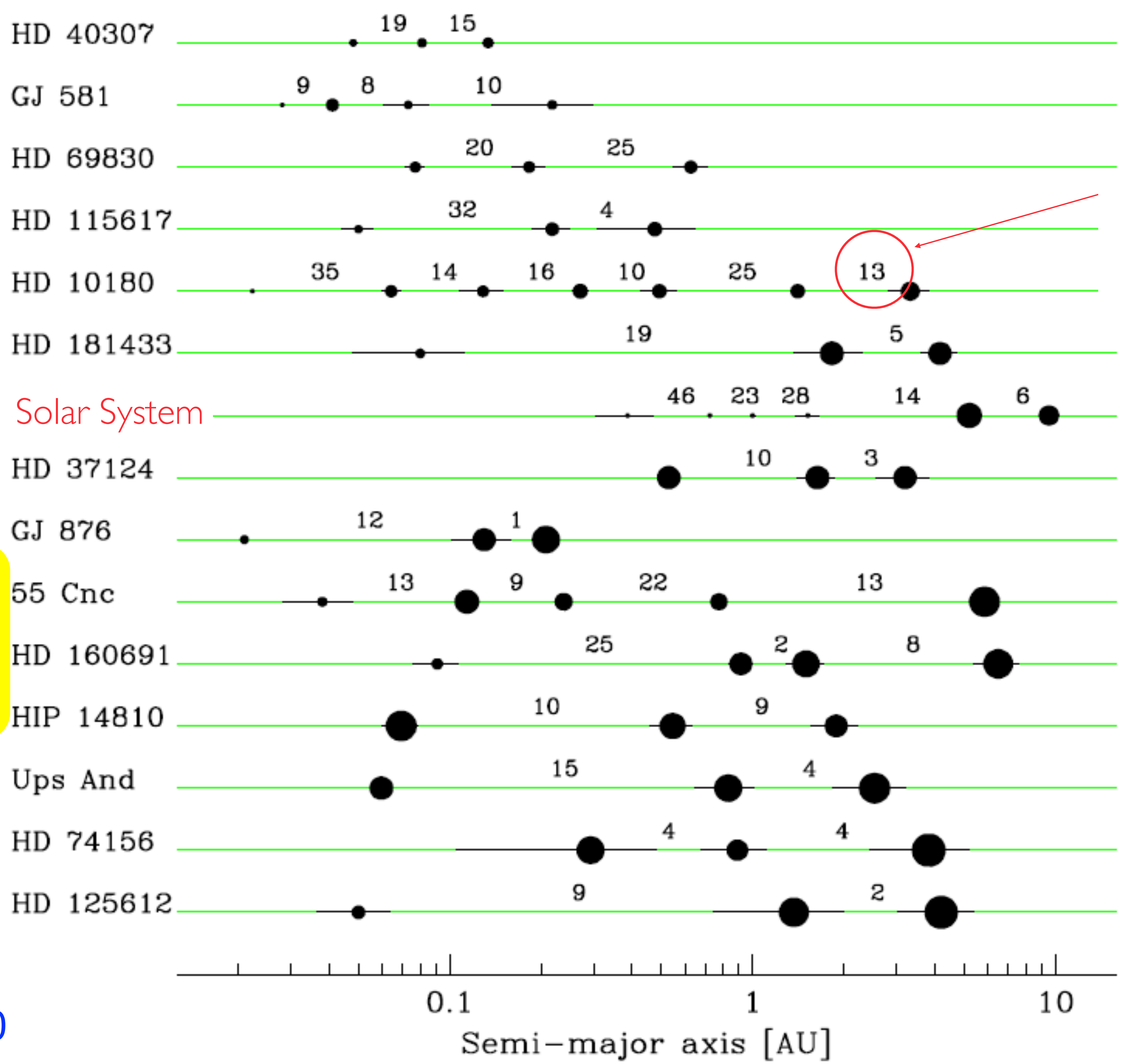

7-planet system

2:1 resonance →

number of ``Hill radii'' between adjacent planets

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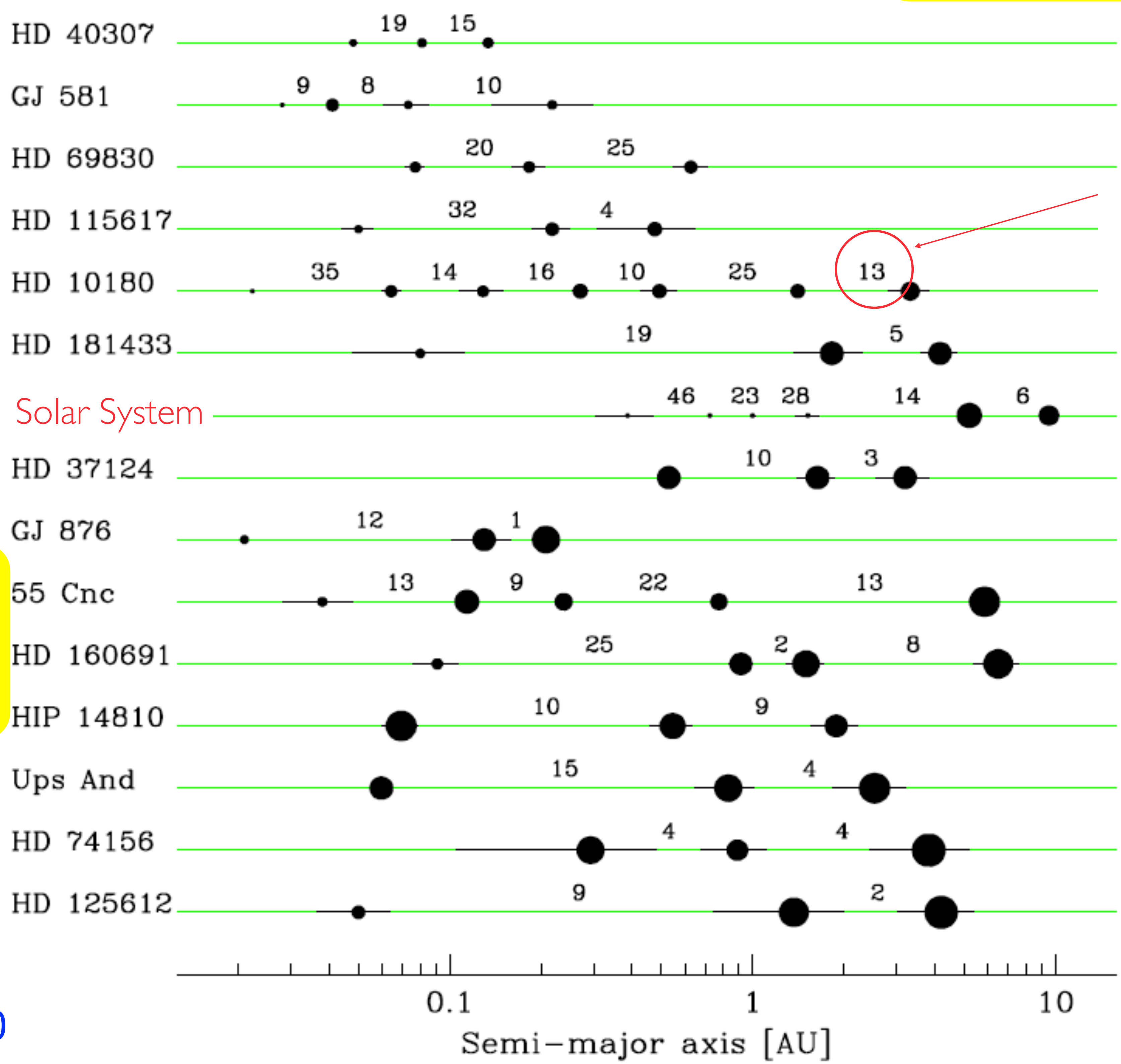
Resonances
2:1, 3:1, 3:2, ...

Lovis et al. 2010

Systems with n>2 planets

multi-planet systems: many are almost optimally ``packed''

Also a constraint for planet formation models!



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Lovis et al. 2010

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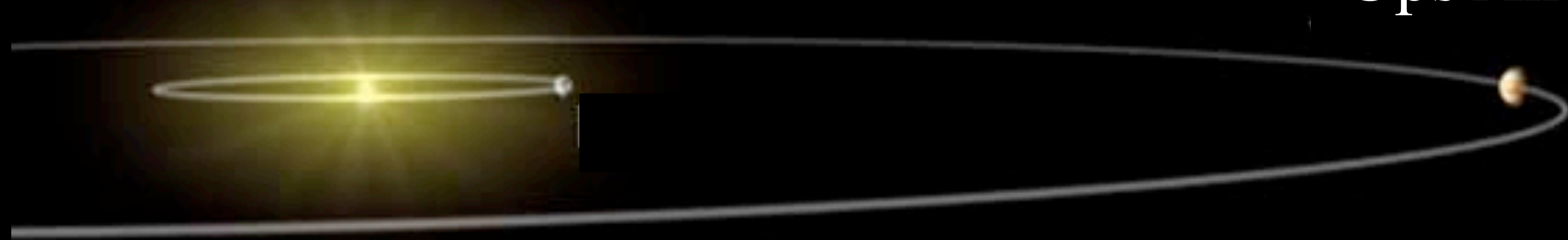

- longest-running programmes

--> largest fraction of multi-planet systems

Planets mainly form in multi-planet systems

Need for multi-planet formation models!

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Structure helps us to understand/ constrain planet-formation scenarios

=> Importance of dynamics (stability, Inner structure,...)

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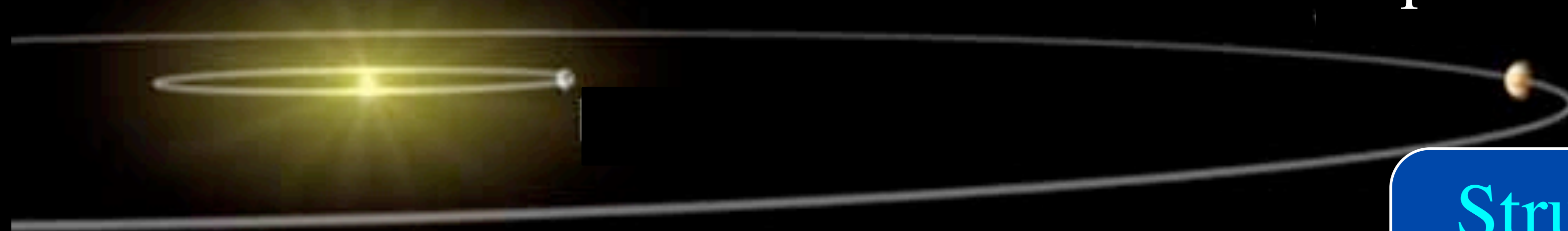

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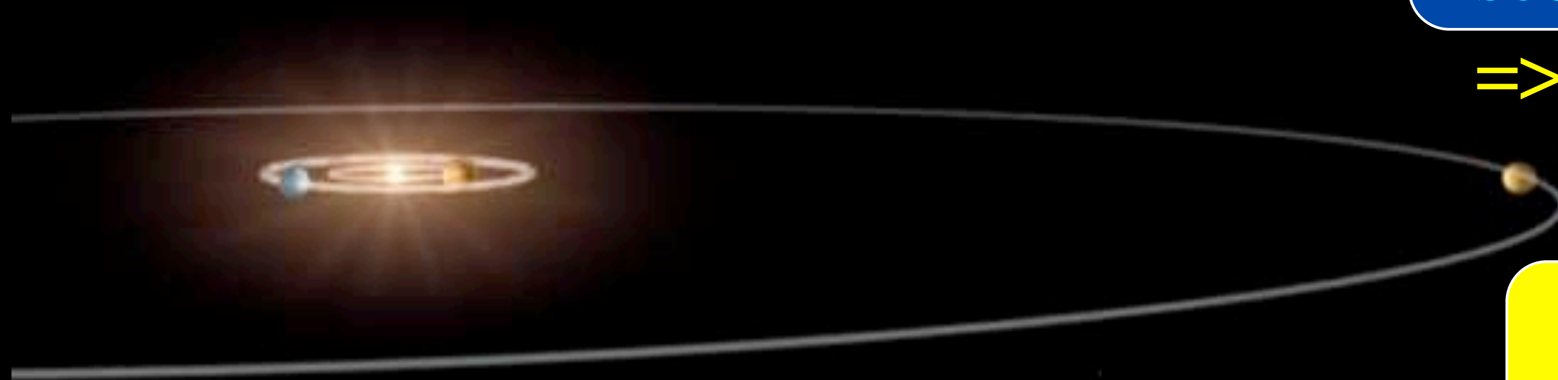


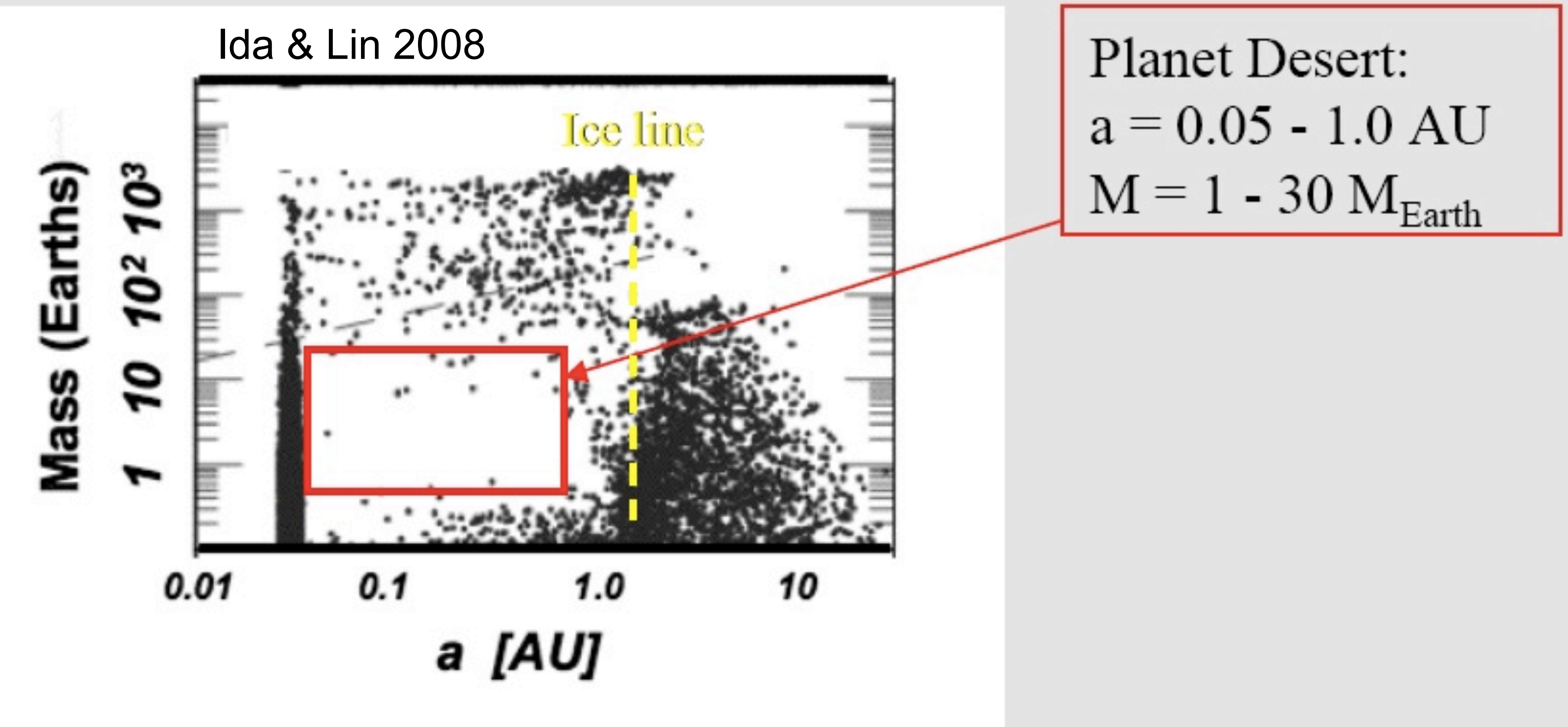
=> Importance of dynamics
(stability, Inner structure,...)

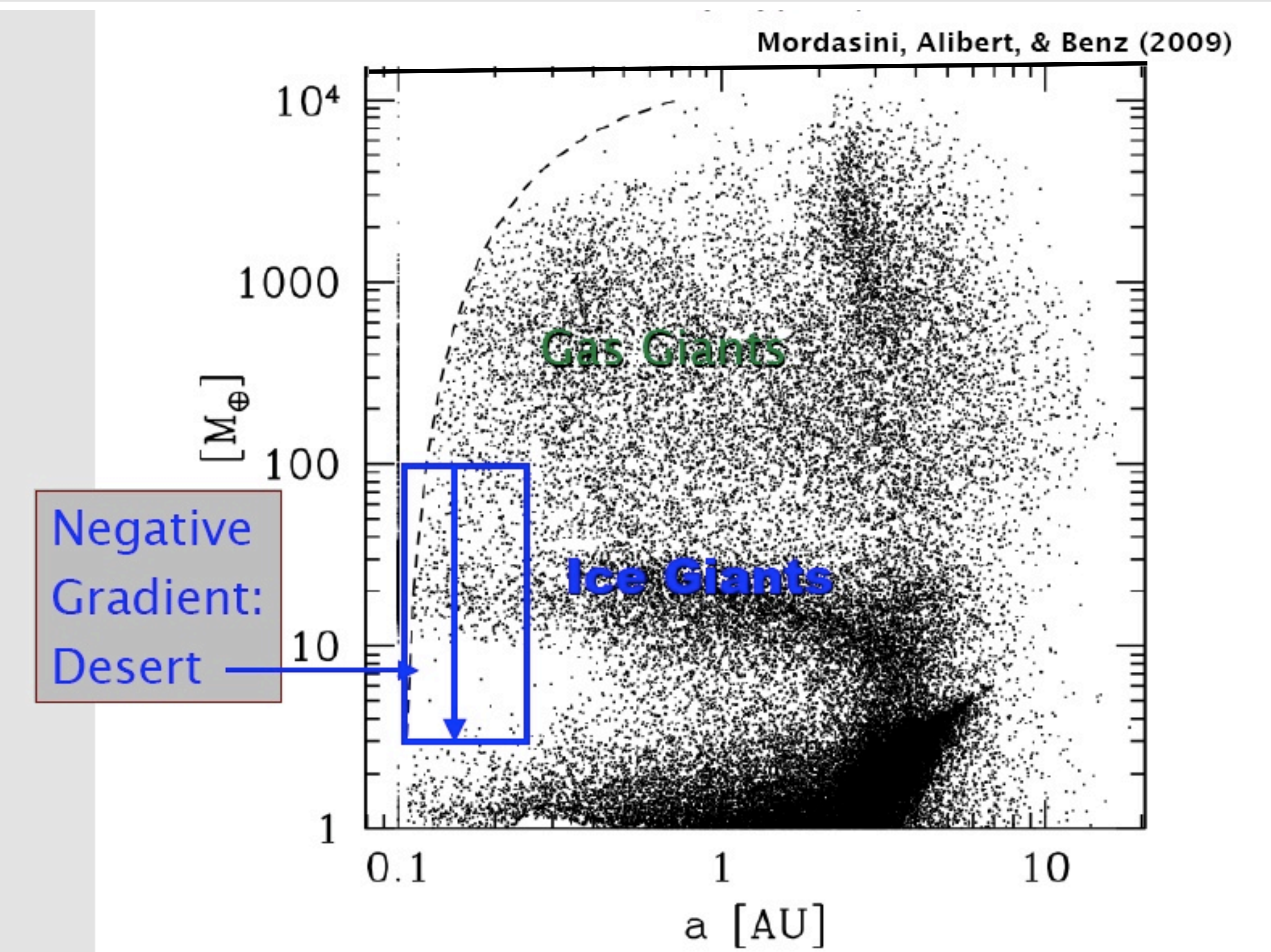
Need for good modeling of evolution processes!

- longest-running programmes

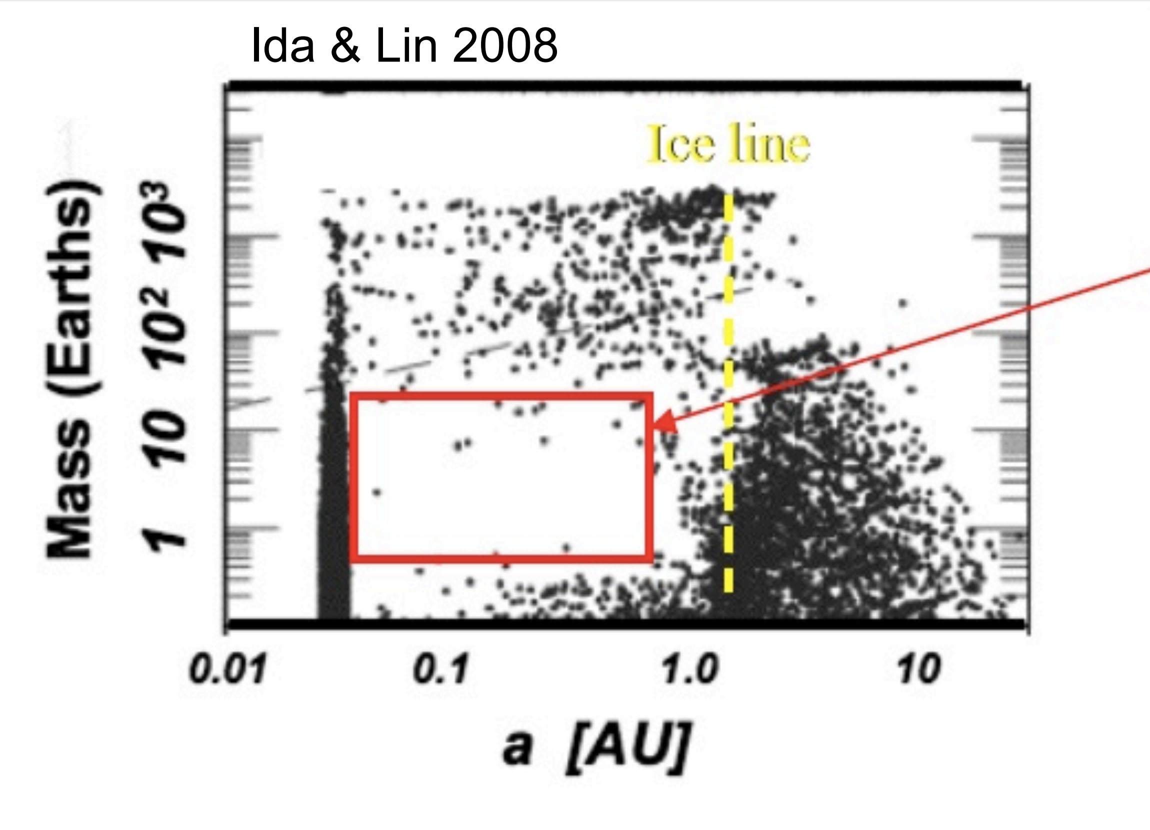
--> largest fraction of multi-planet systems
Planets mainly form in multi-planet systems

Need for multi-planet formation models!

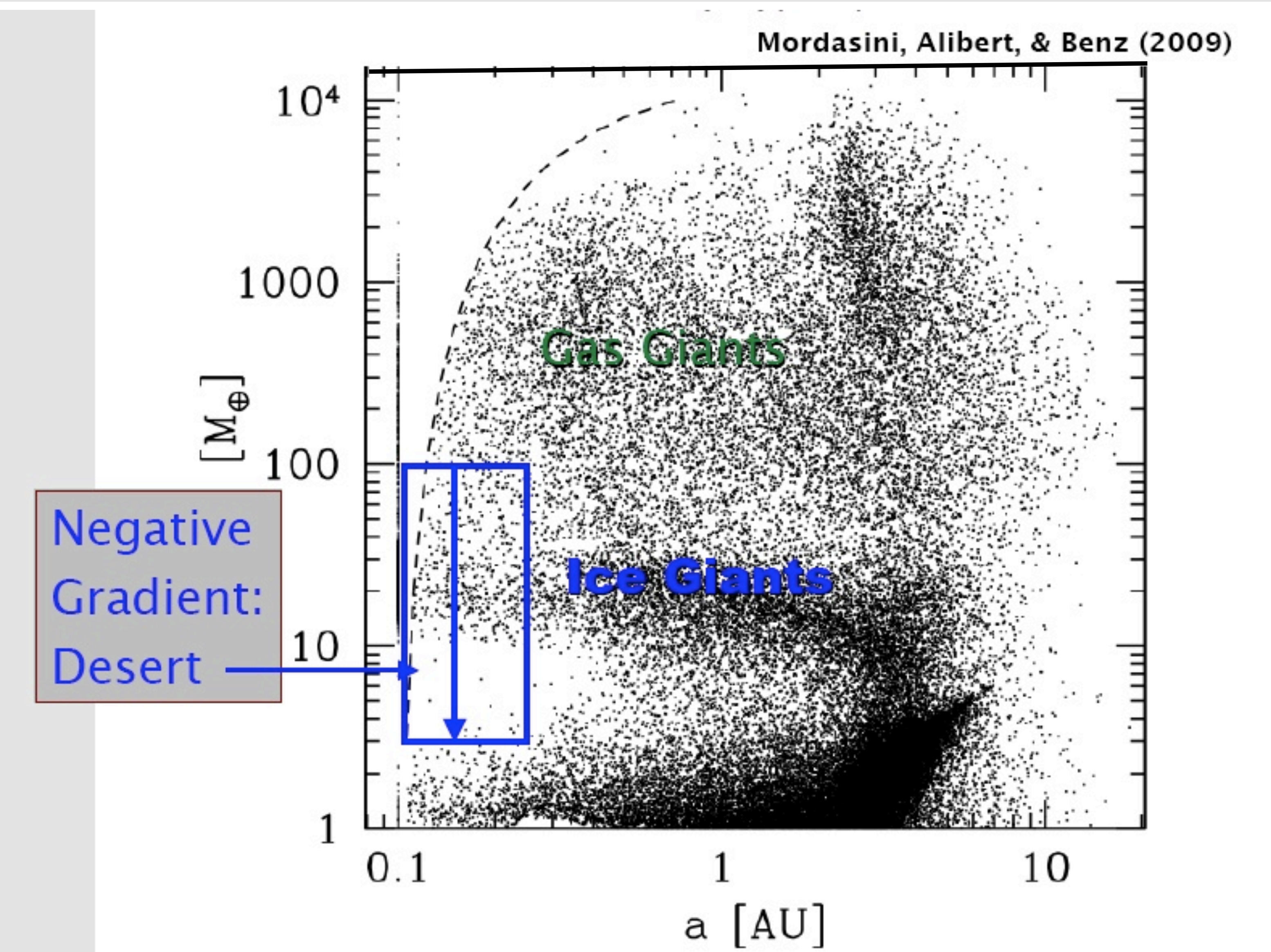




(From G. Marcy, IAU 276)



Planet Desert:
a = 0.05 - 1.0 AU
M = 1 - 30 M_{Earth}



Prediction of planet formation models in the sep-mass plane

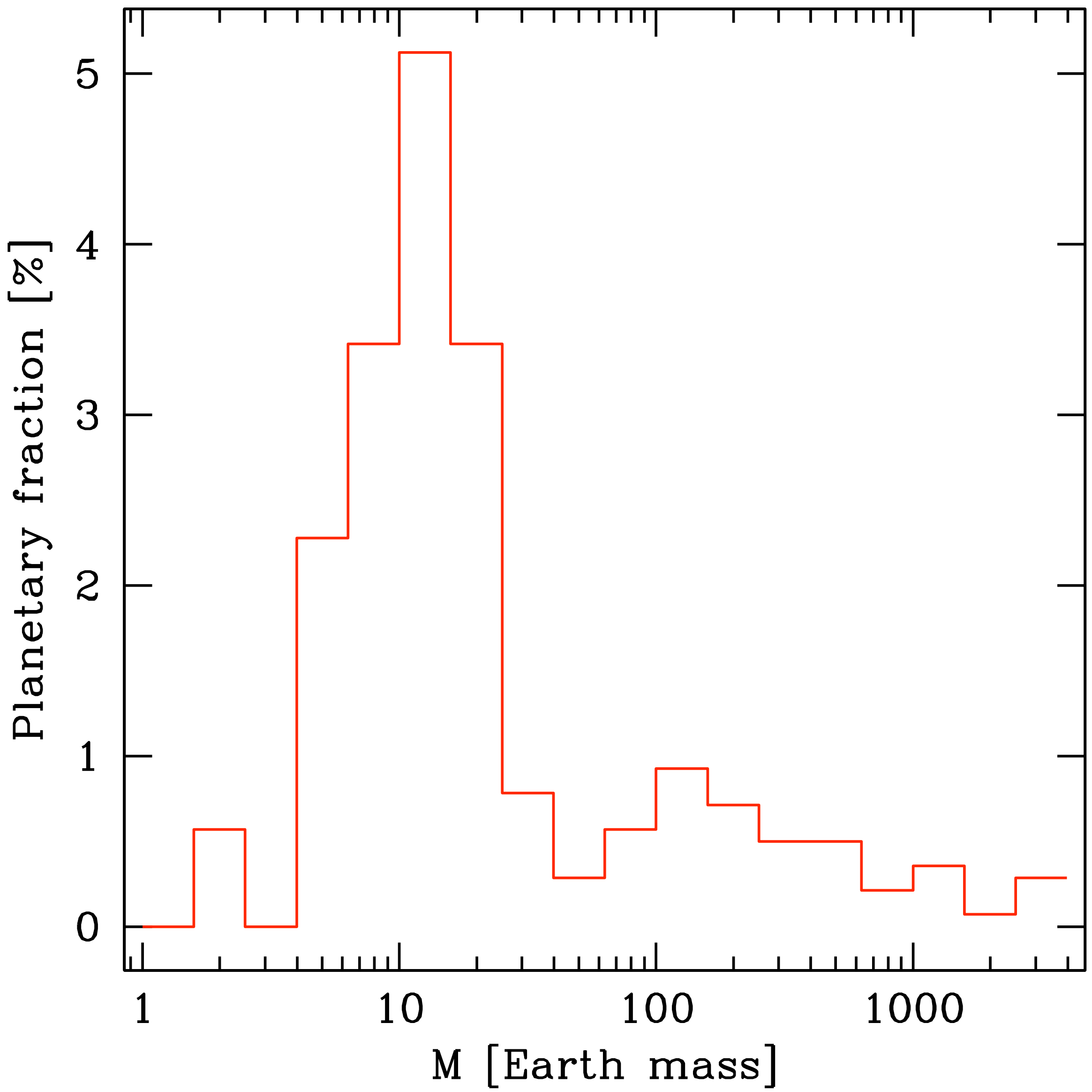
=> Constraints for planet-formation models: Type I migration?

(From G. Marcy, IAU 276)

Some properties of close-in low-mass planets

1) Mass distribution

Observations
(normalized distribution)



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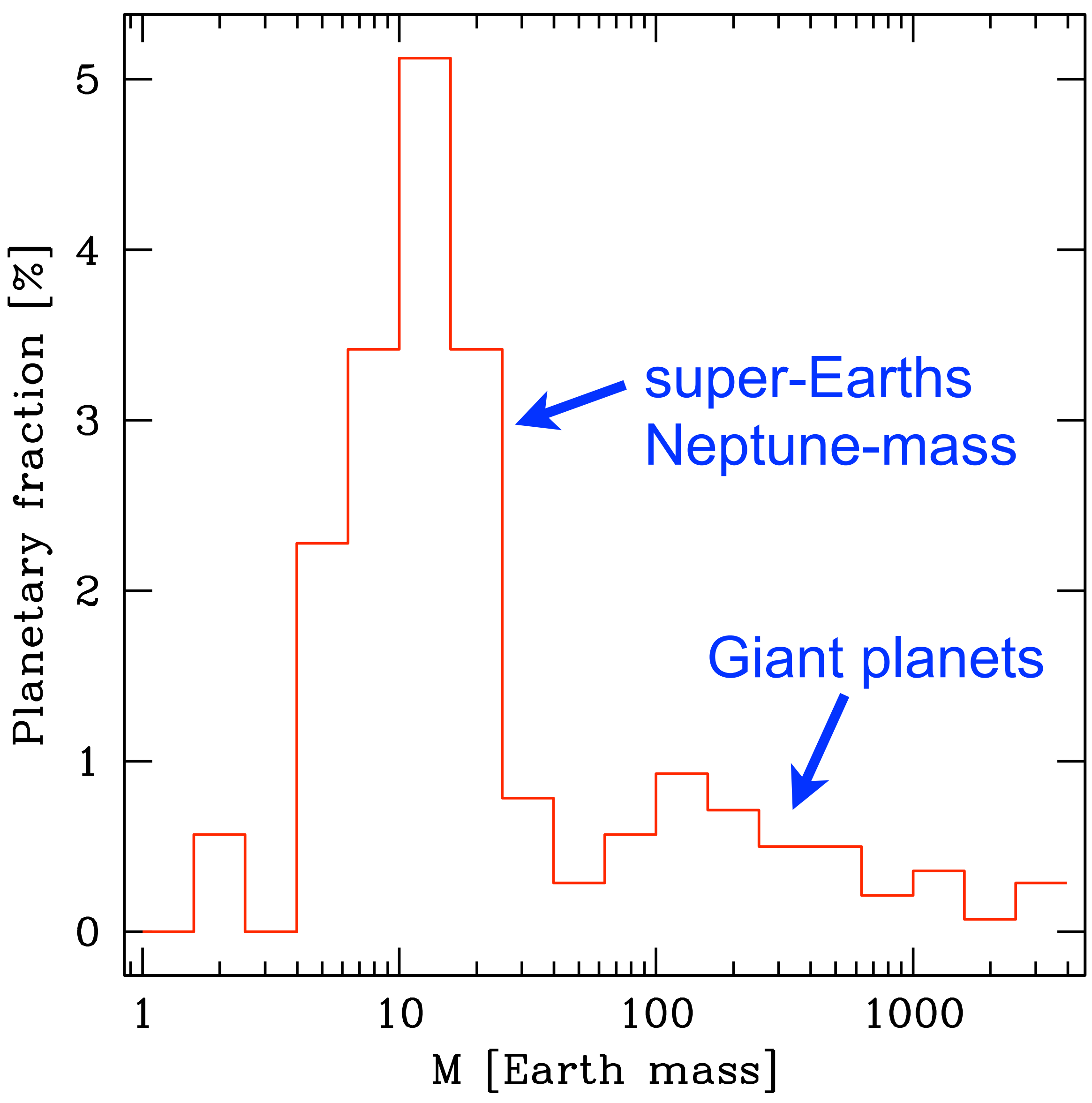

Bimodal distribution
"solid" & gaseous planets

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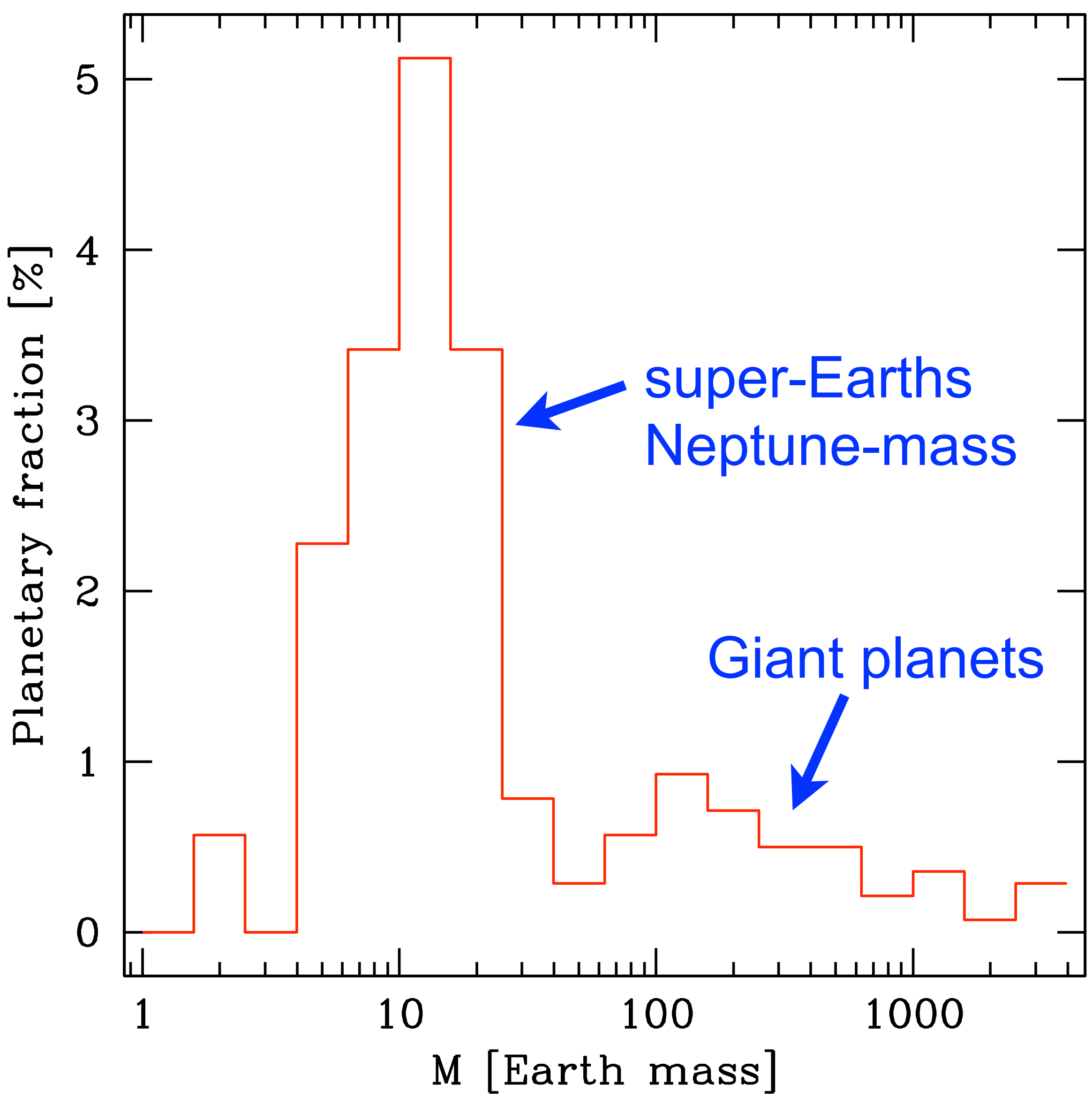

Bimodal distribution
"solid" & gaseous planets

Relative frequency ?
Coralie+HARPS analysis
to come soon...

=> Important constraint
for
planet-formation models!

Comparison with planet population synthesis models

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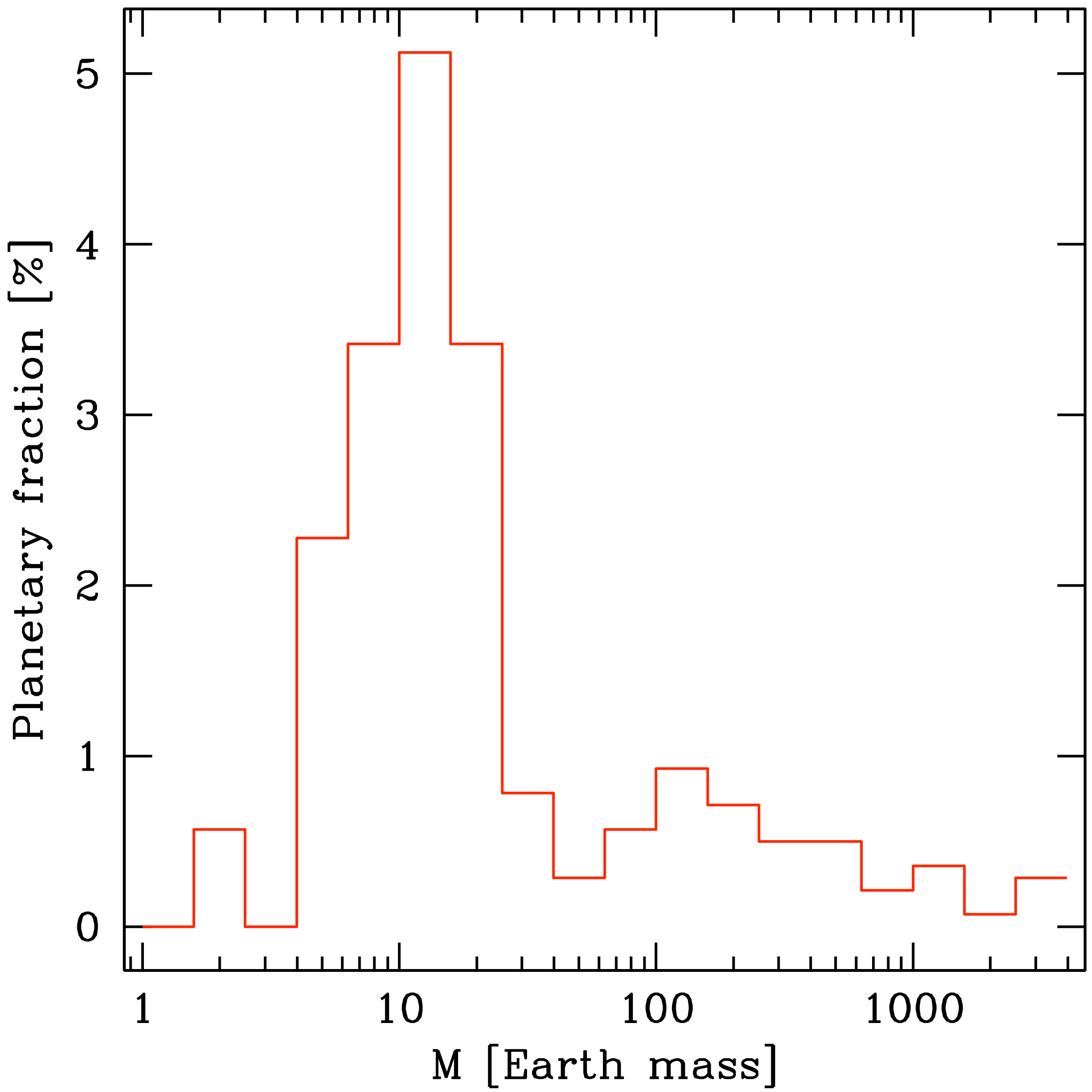
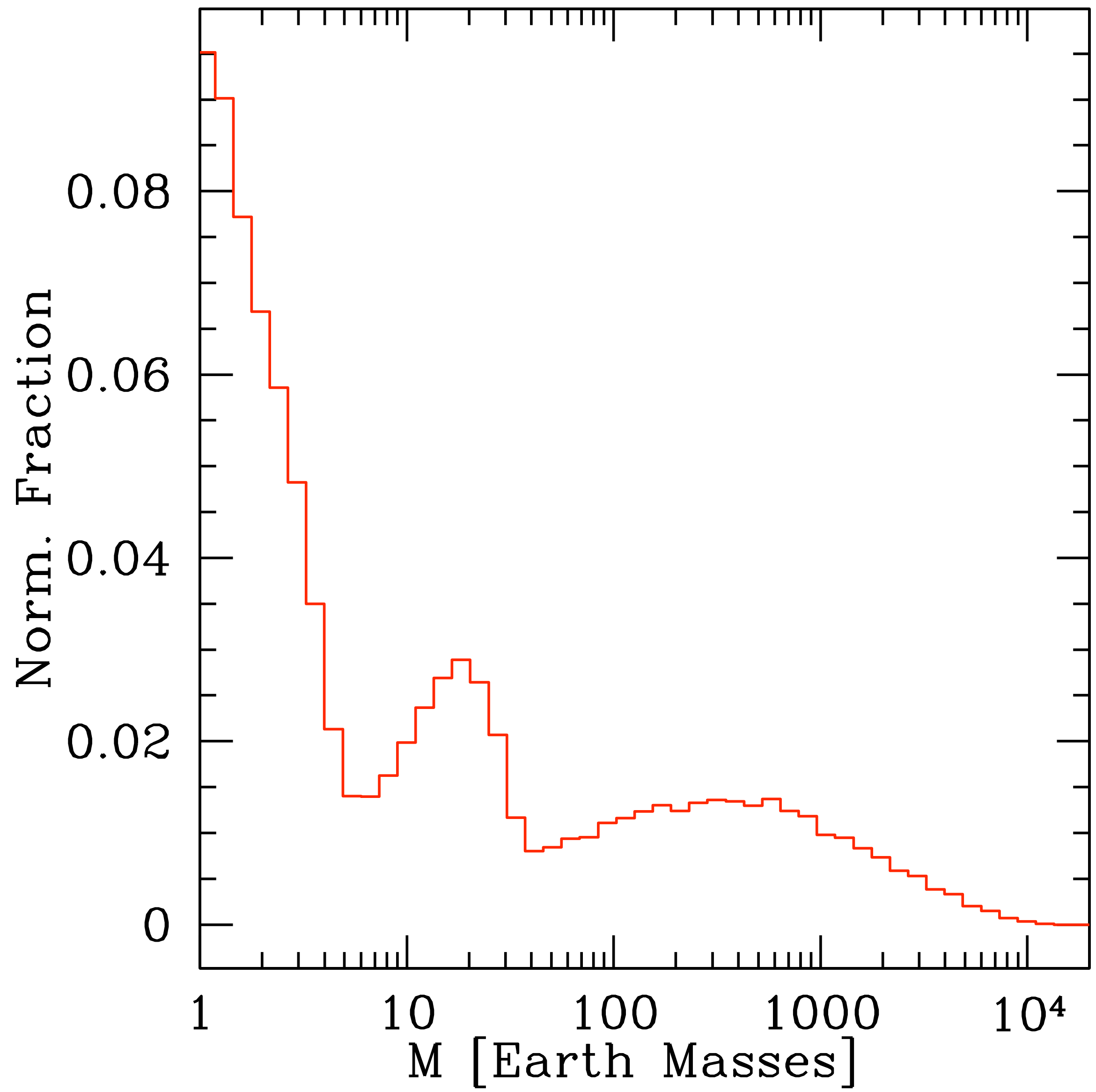
Observations
(normalized distribution)



Models
(Mordasini et al. 2009)



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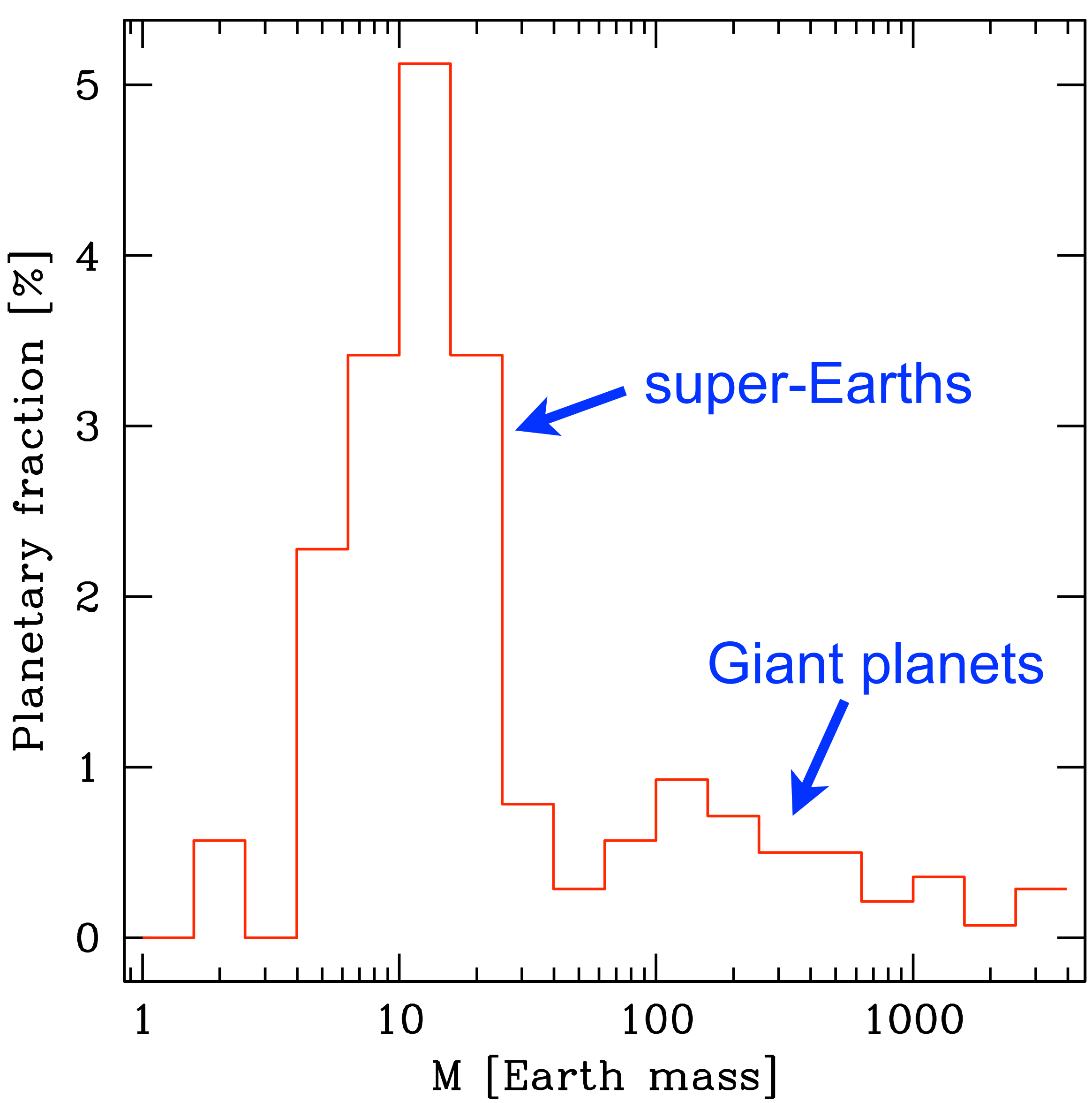

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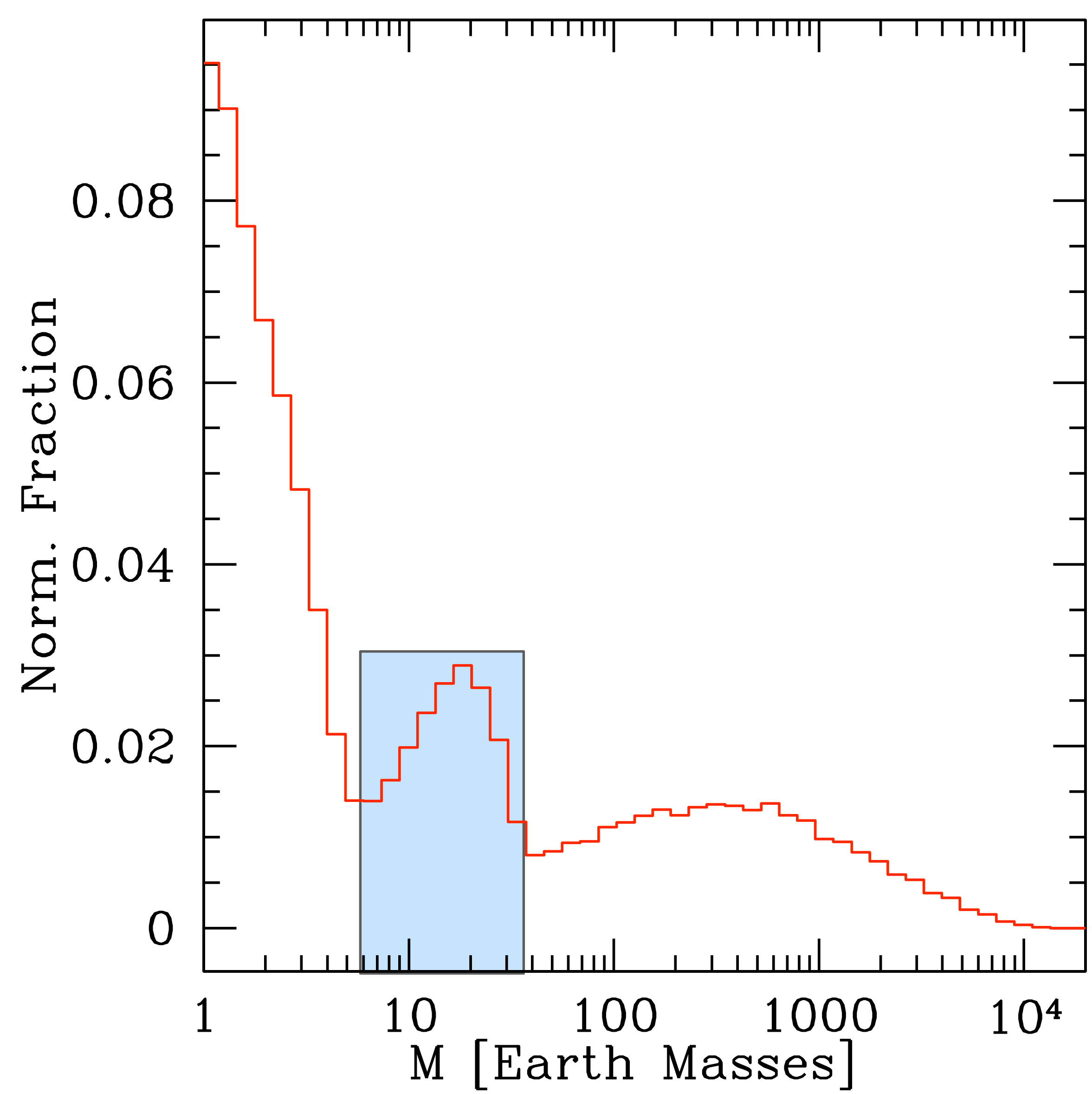

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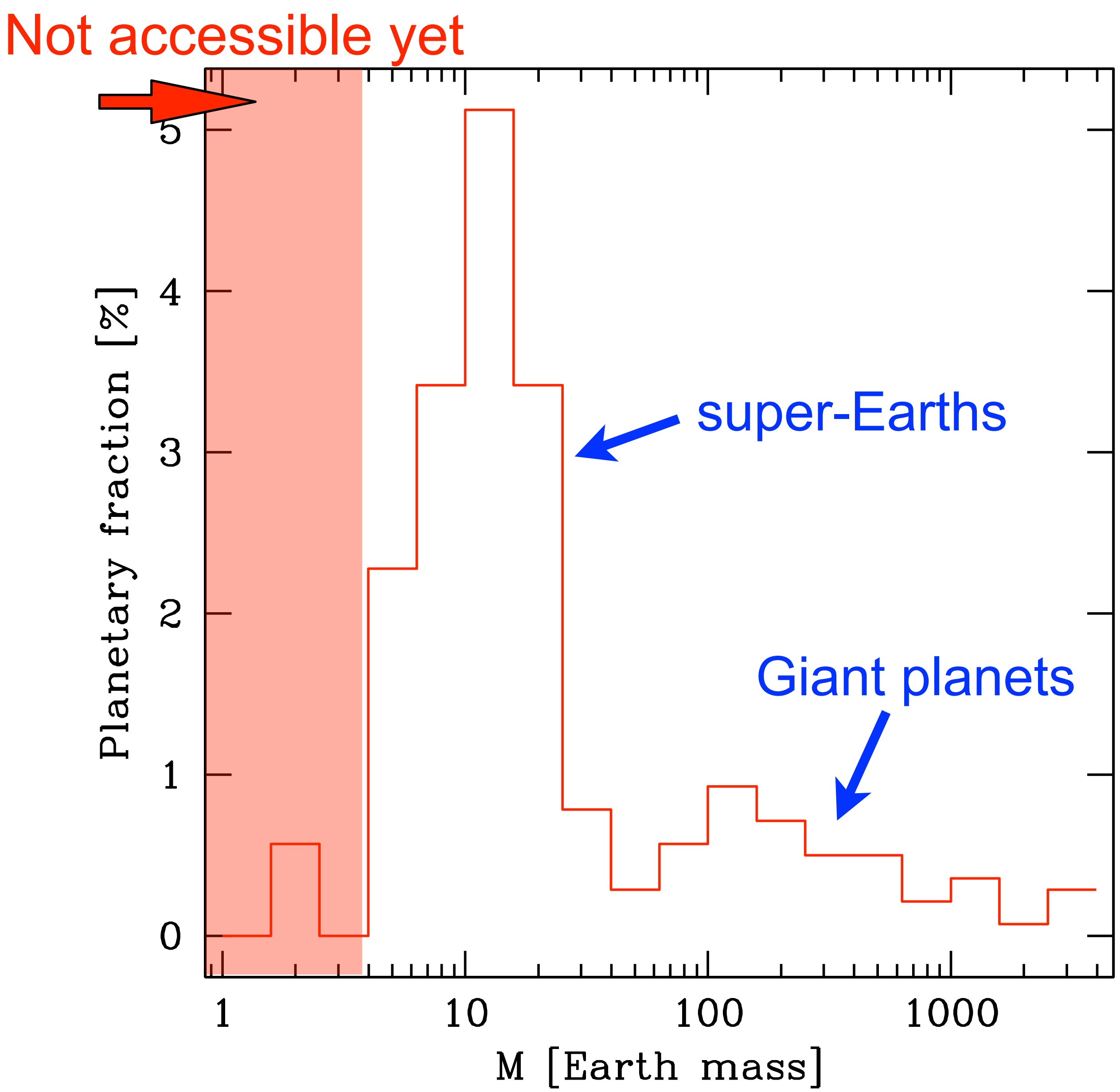

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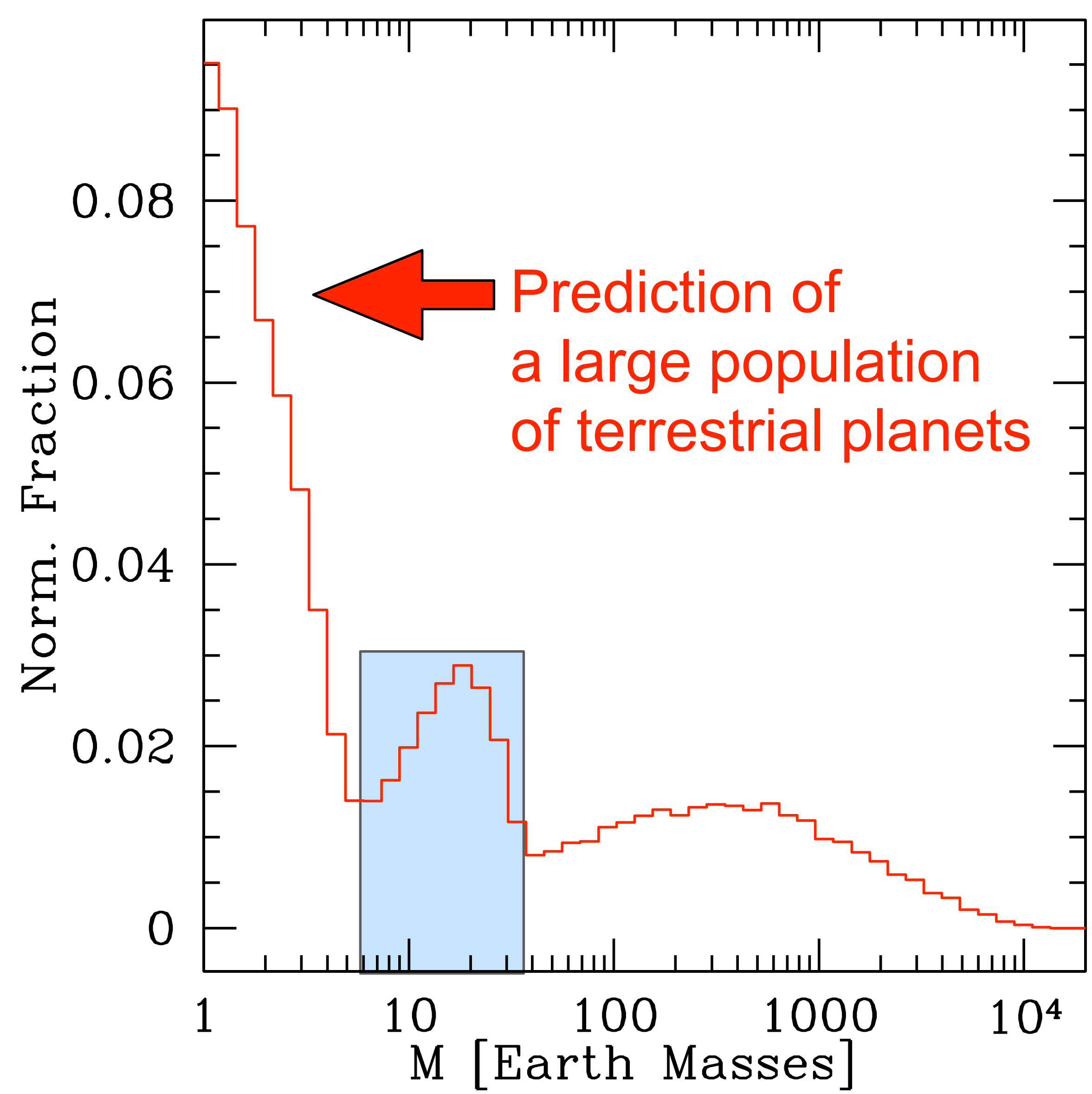
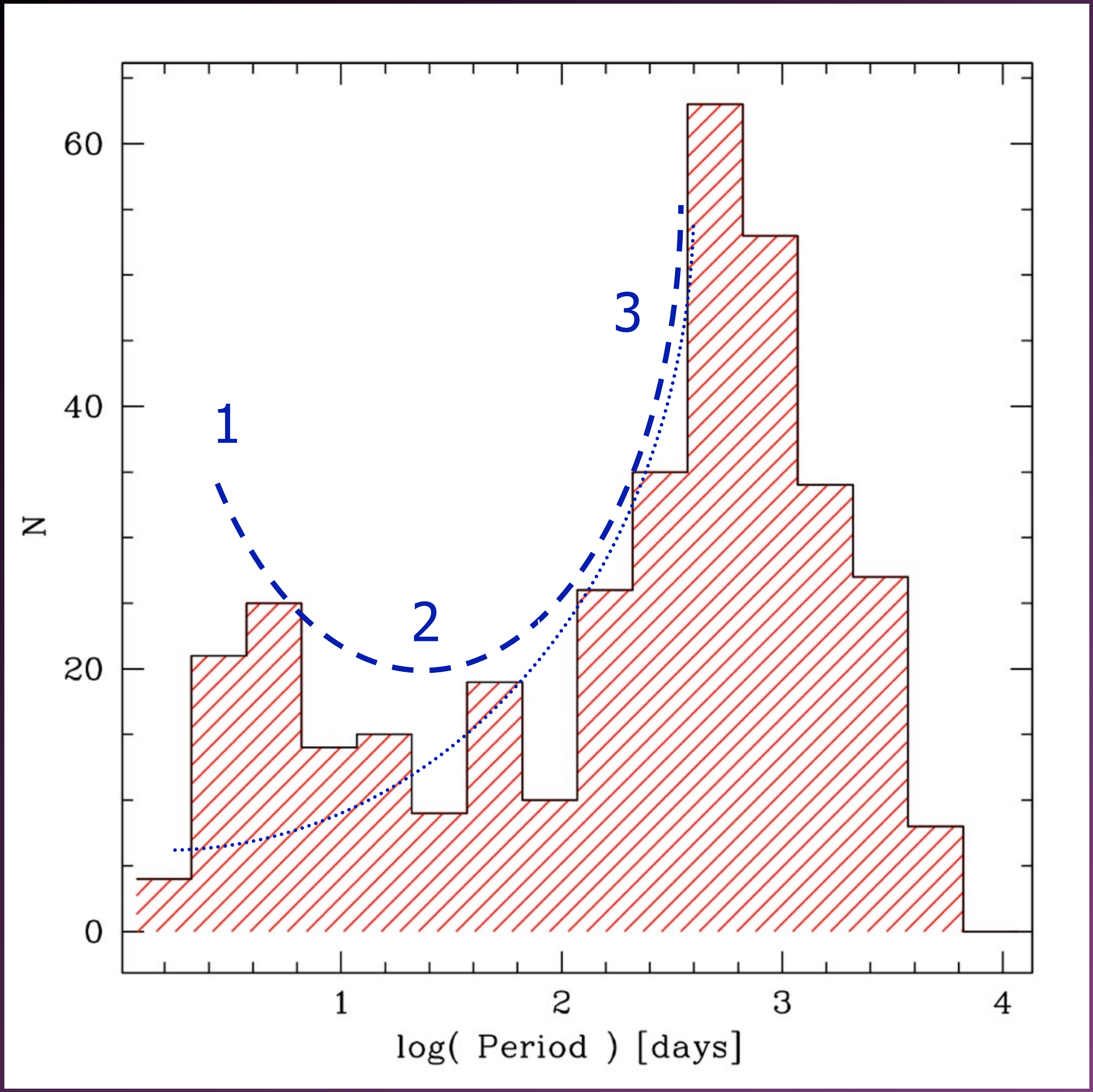


(II) Orbital period distribution (giants)



1. Peak at short periods
   -> migration stop

2. Shortage
   for 10 d < P < 100 d

3. N(log P) is rising

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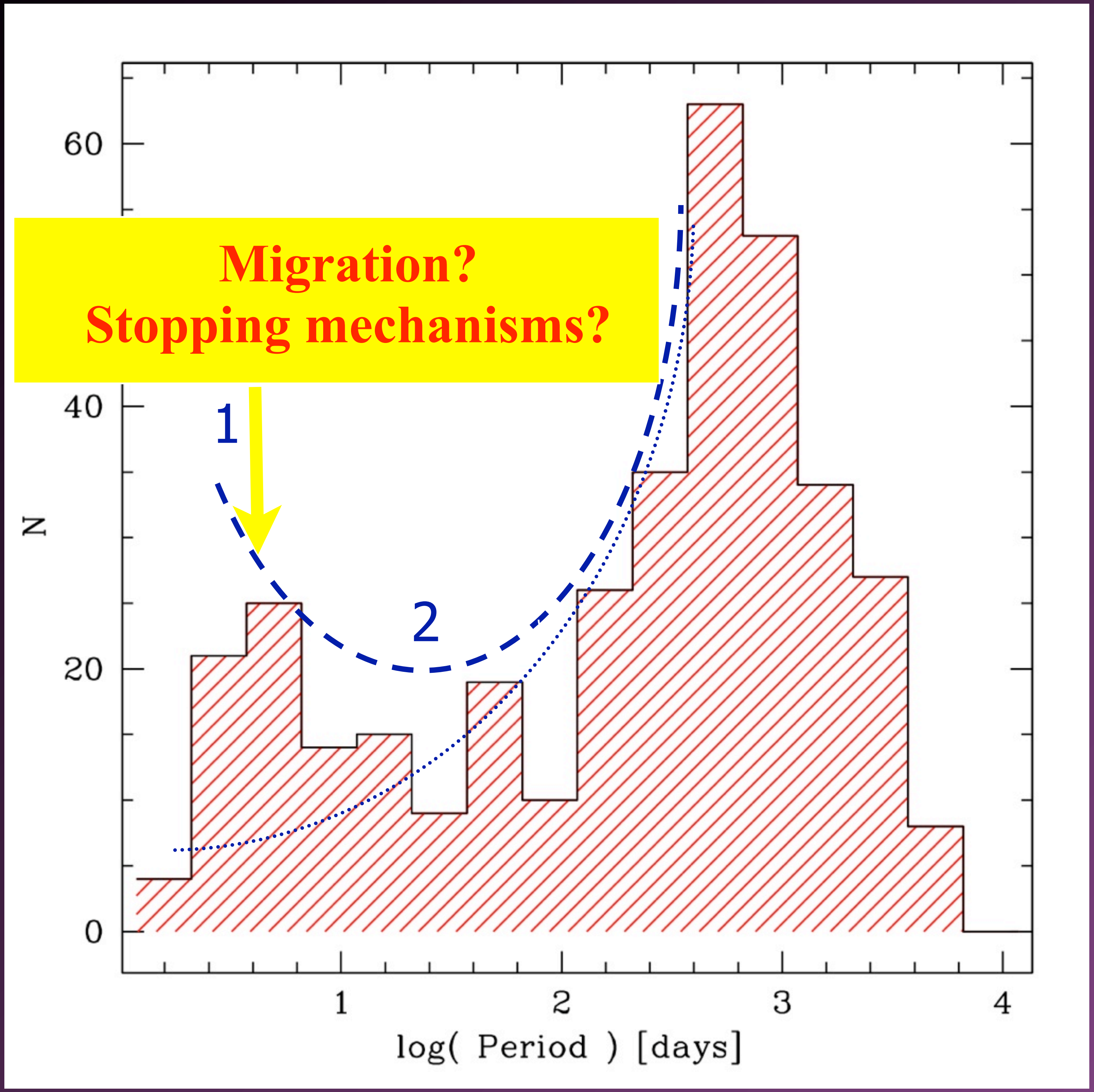

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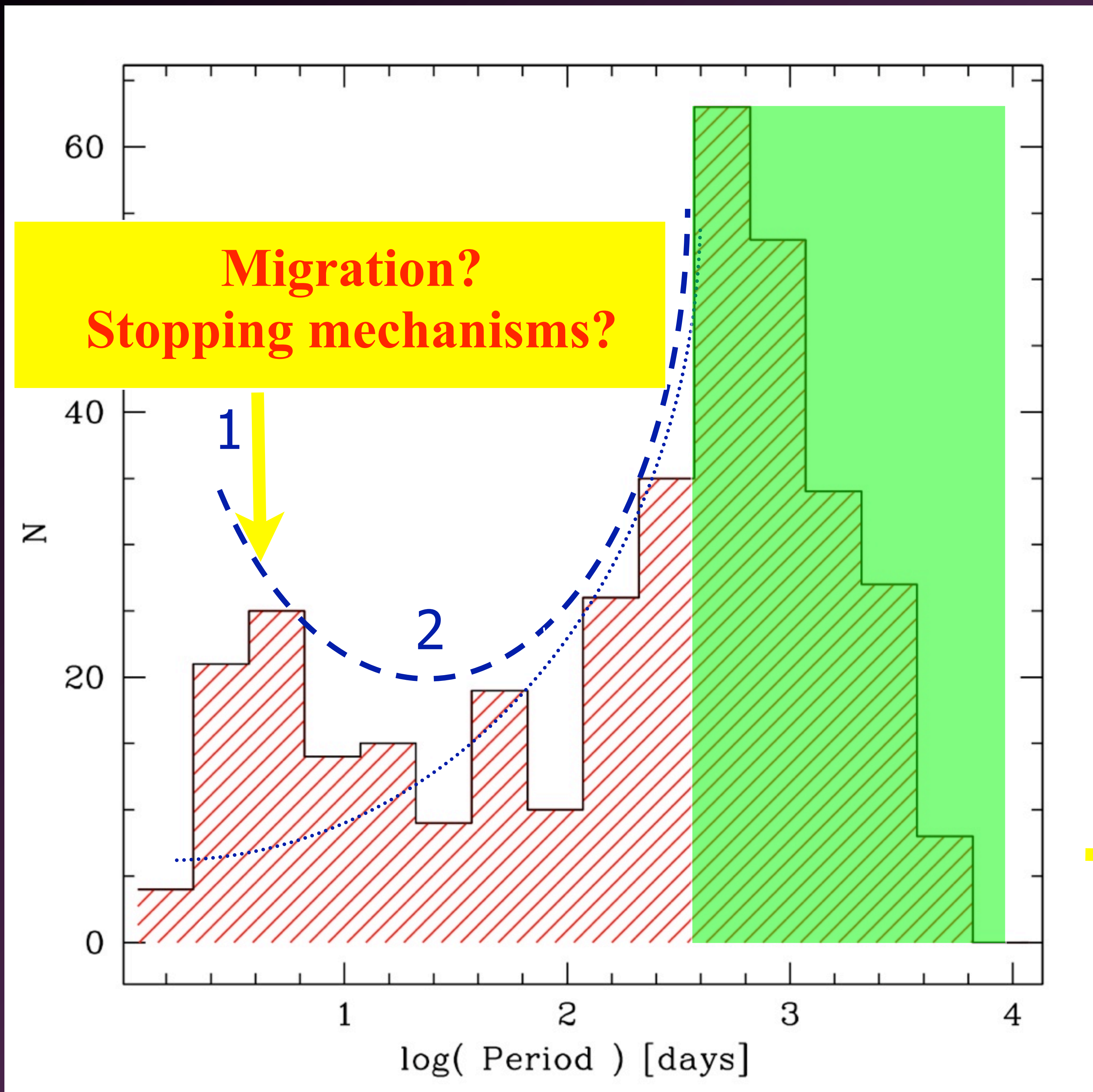

1. Peak at short periods
   -> migration stop
2. Shortage
   for 10 d < P < 100 d
3. N(log P) is rising

Planet reservoir at large separations

> 20 -25% of planets
between
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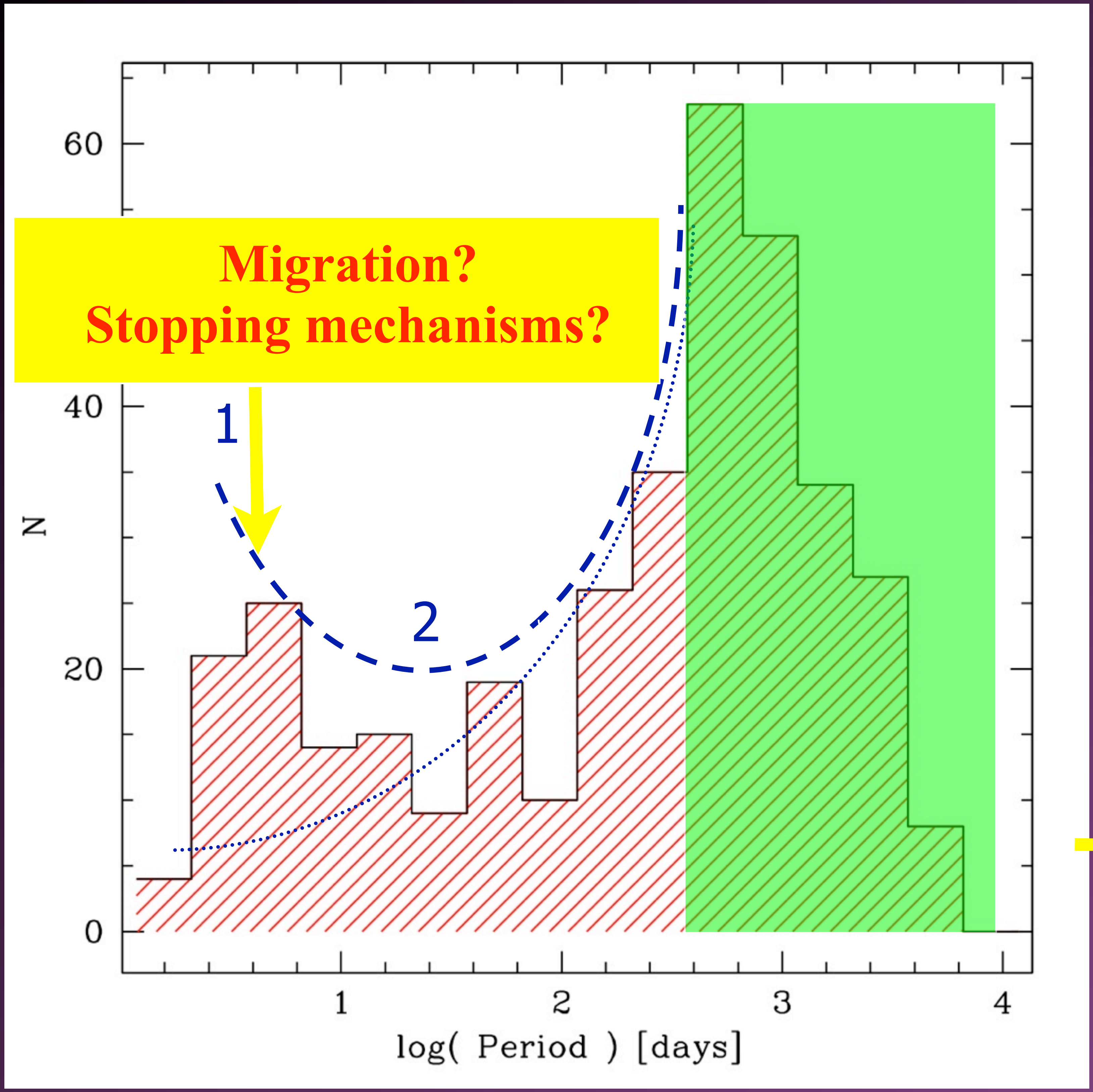

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Max distance for formation?
Link with disk properties?

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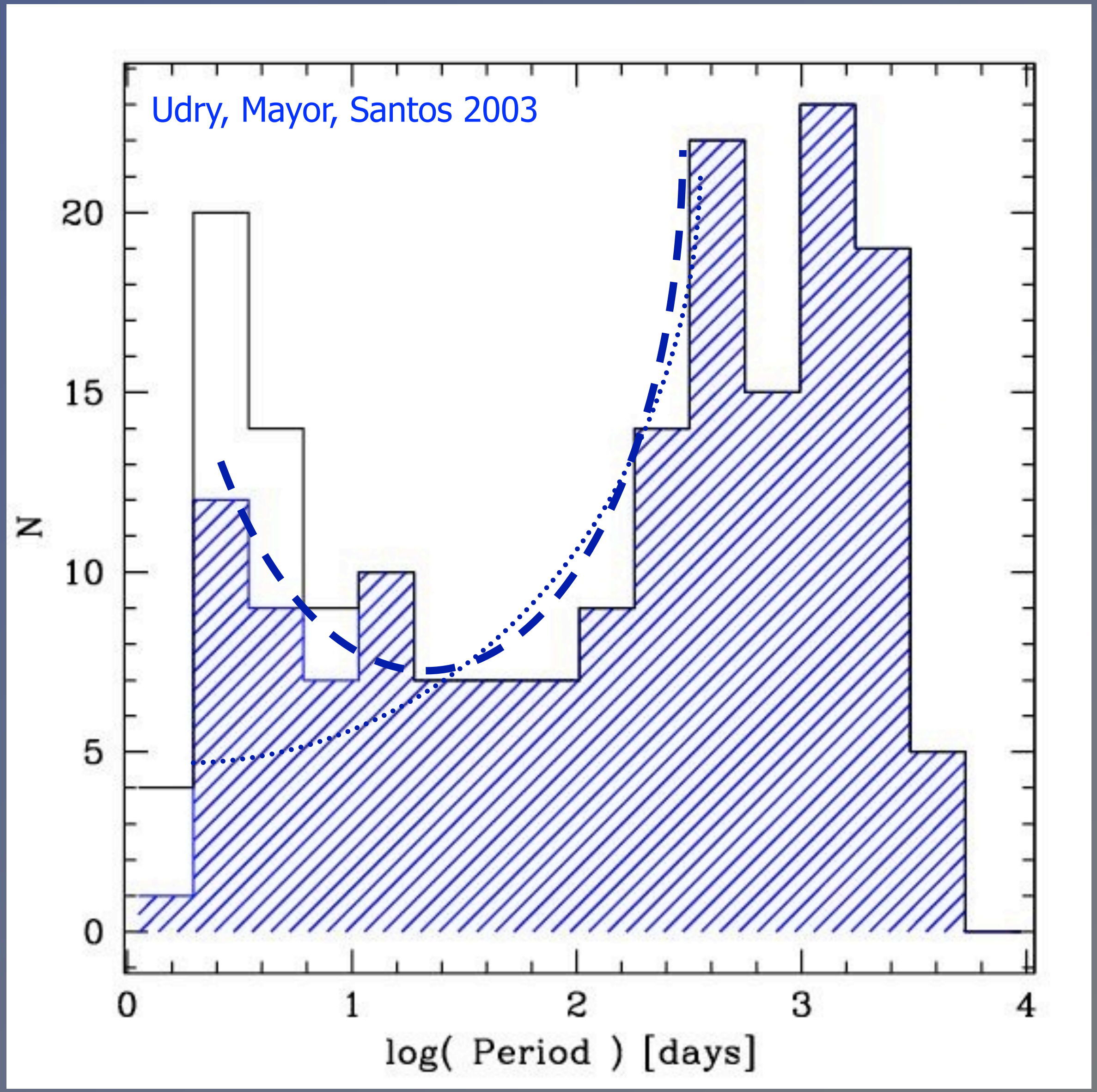
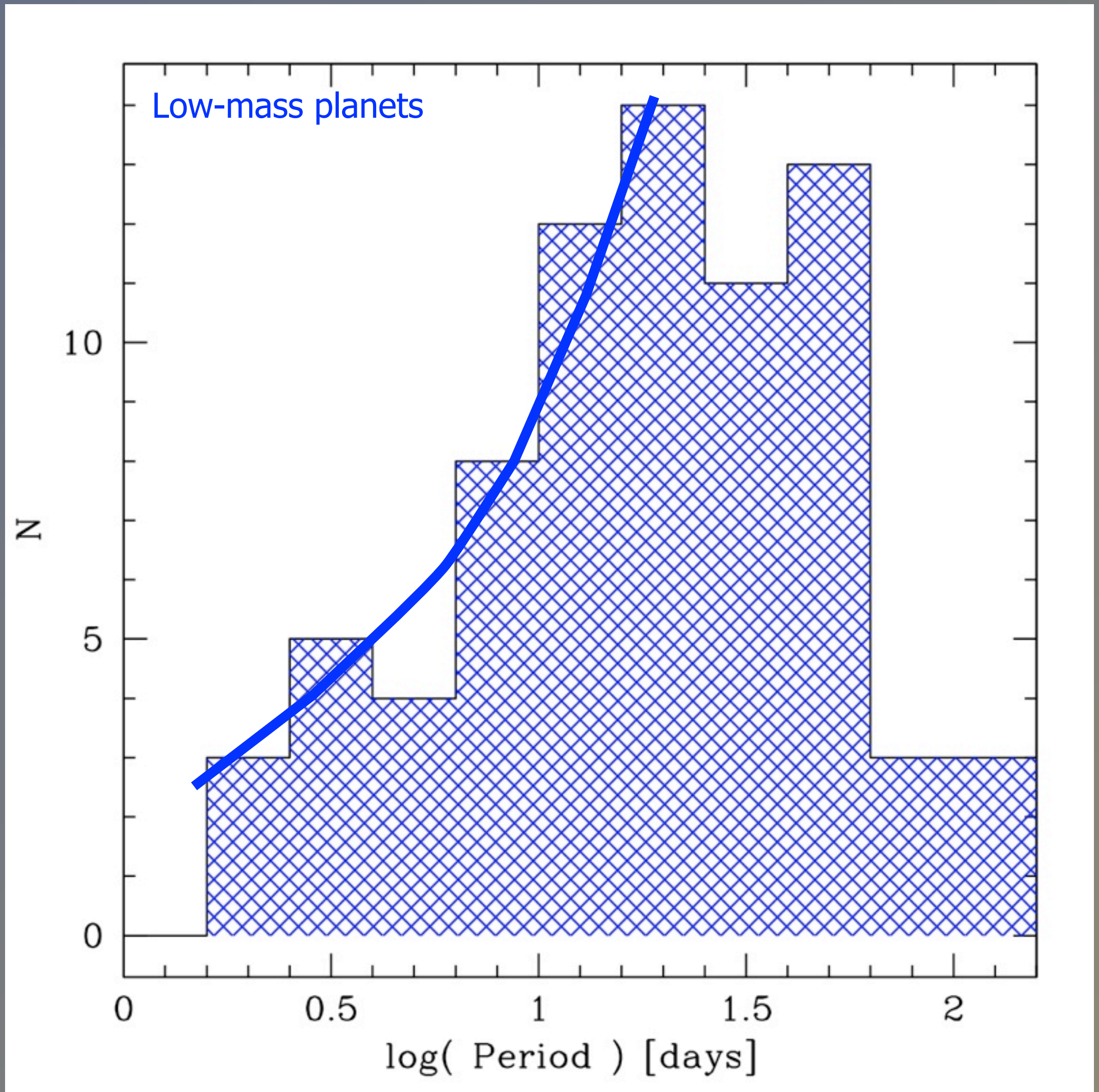
- For small-mass planets, no peak at ~3 days. Rise to >15-20 days. farther -> bias. -> migration stops earlier than for gas giants ? No stopping mechanism? Type I ?





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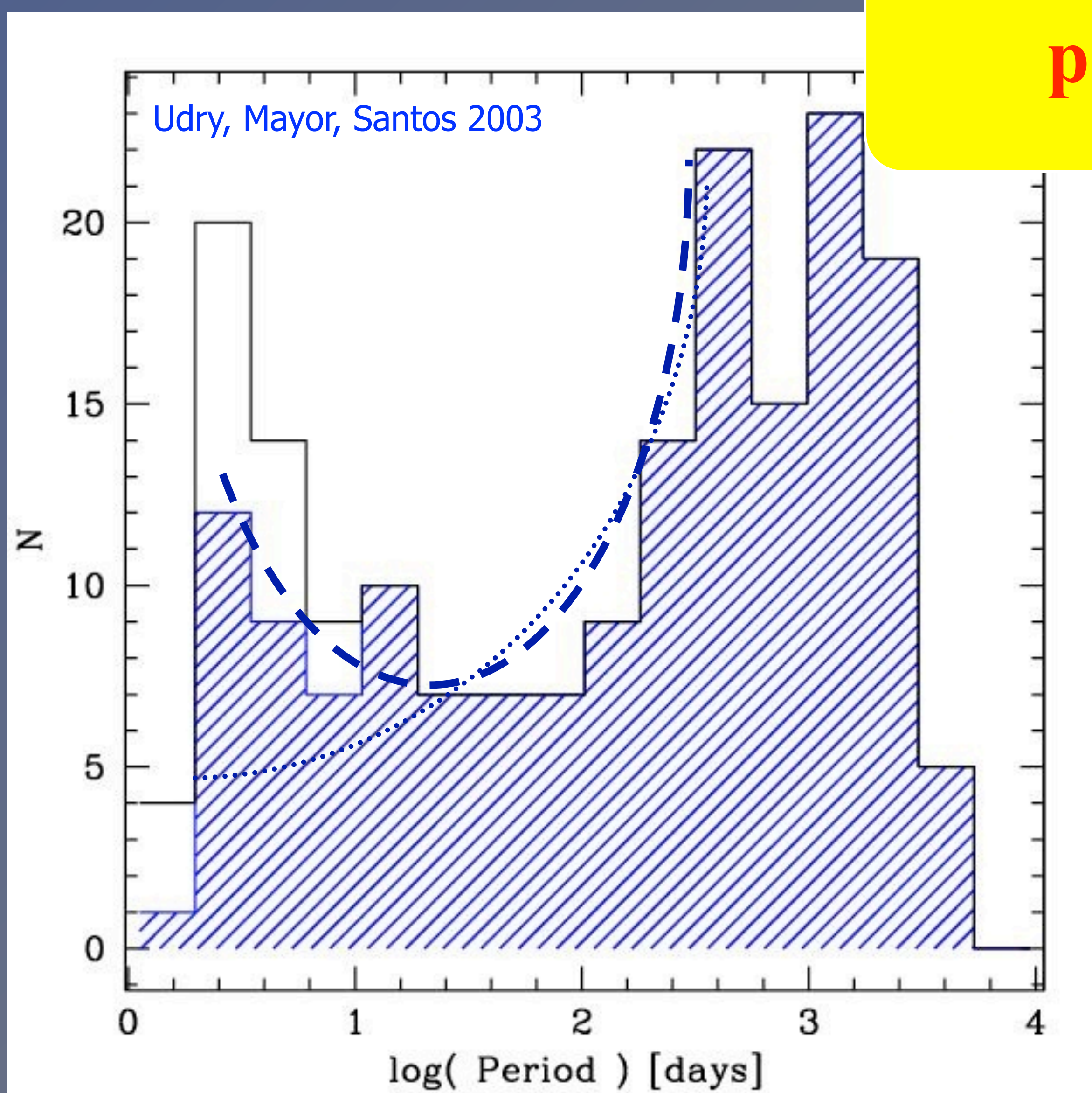
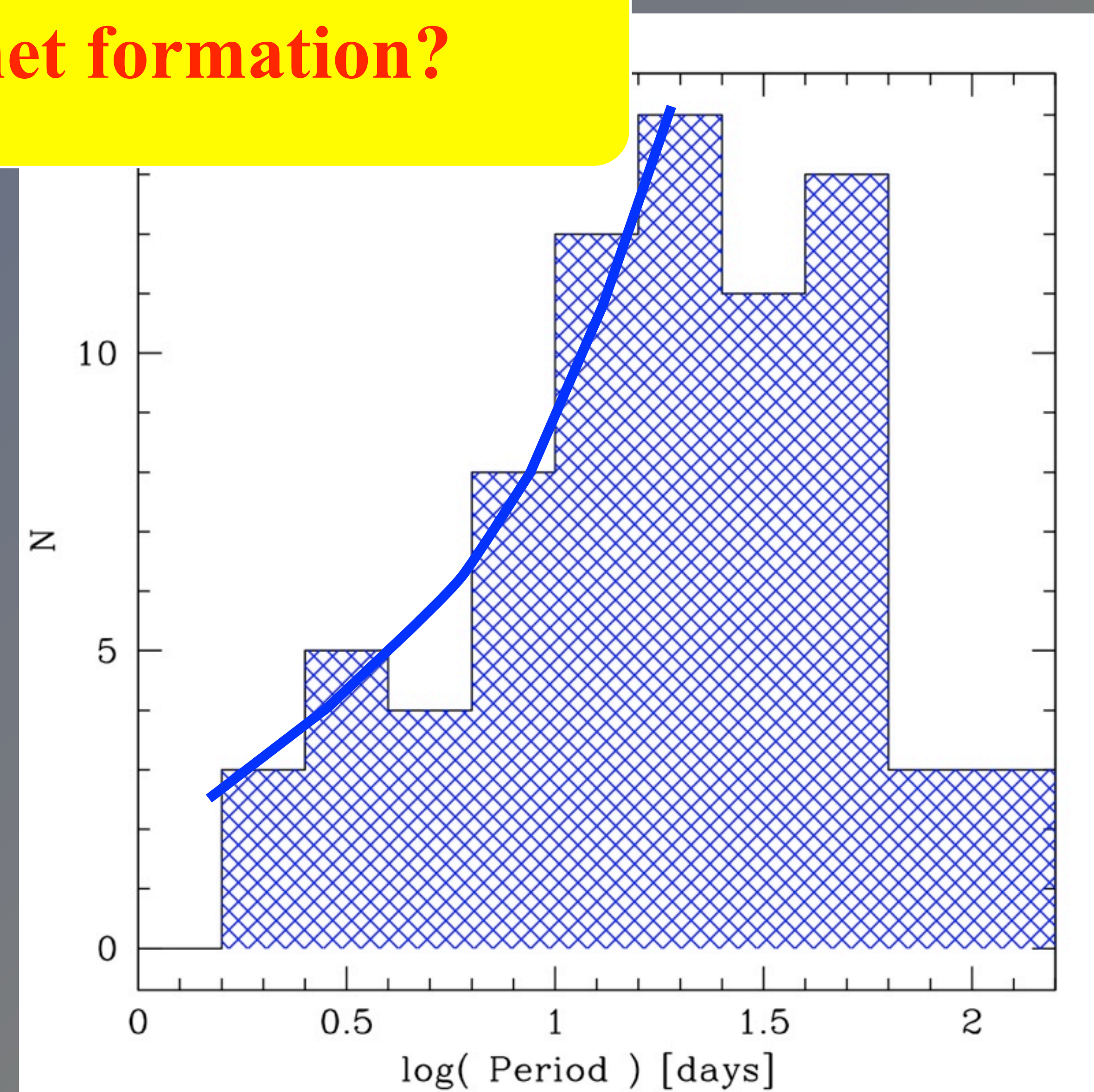
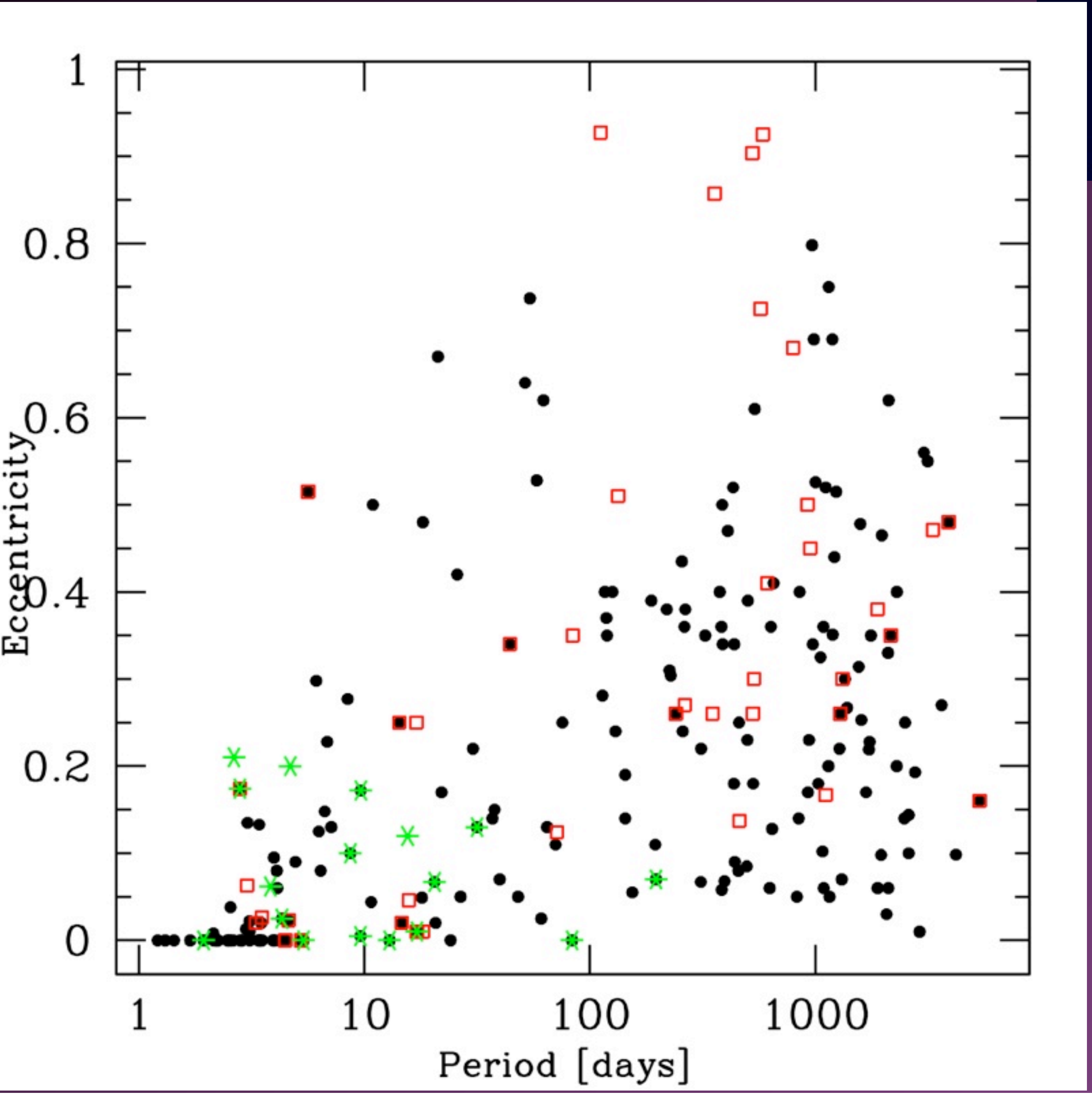




(IV) Exoplanet eccentricities

- High observed eccentricities
  - <e> = 0.28 > any planet of the SS



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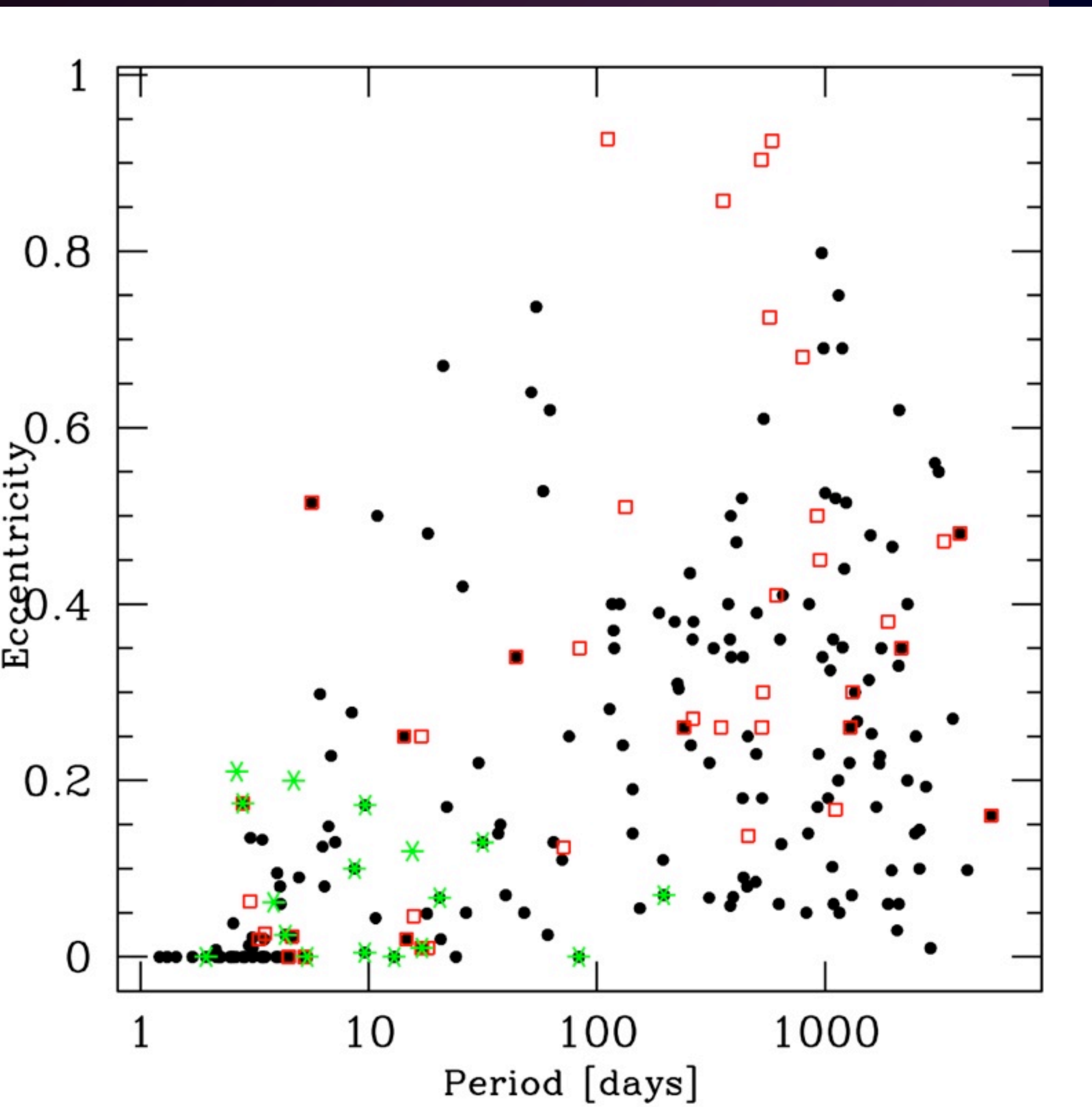
Origin?
Formation - evolution?



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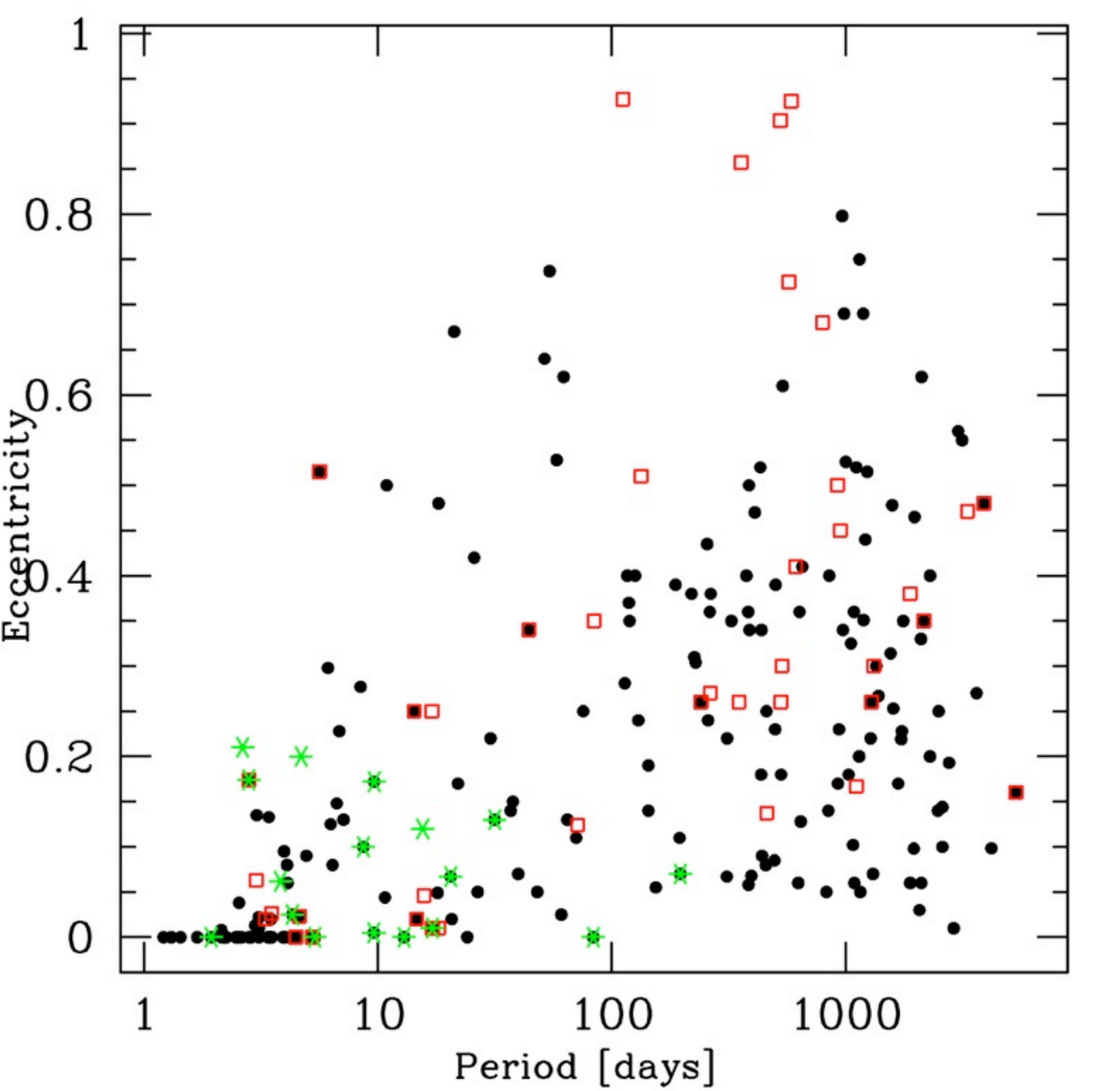

- Possible explanations
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  - Planet-planetesimal interaction
  - Influence of stellar or planet companion (Kozai effect)
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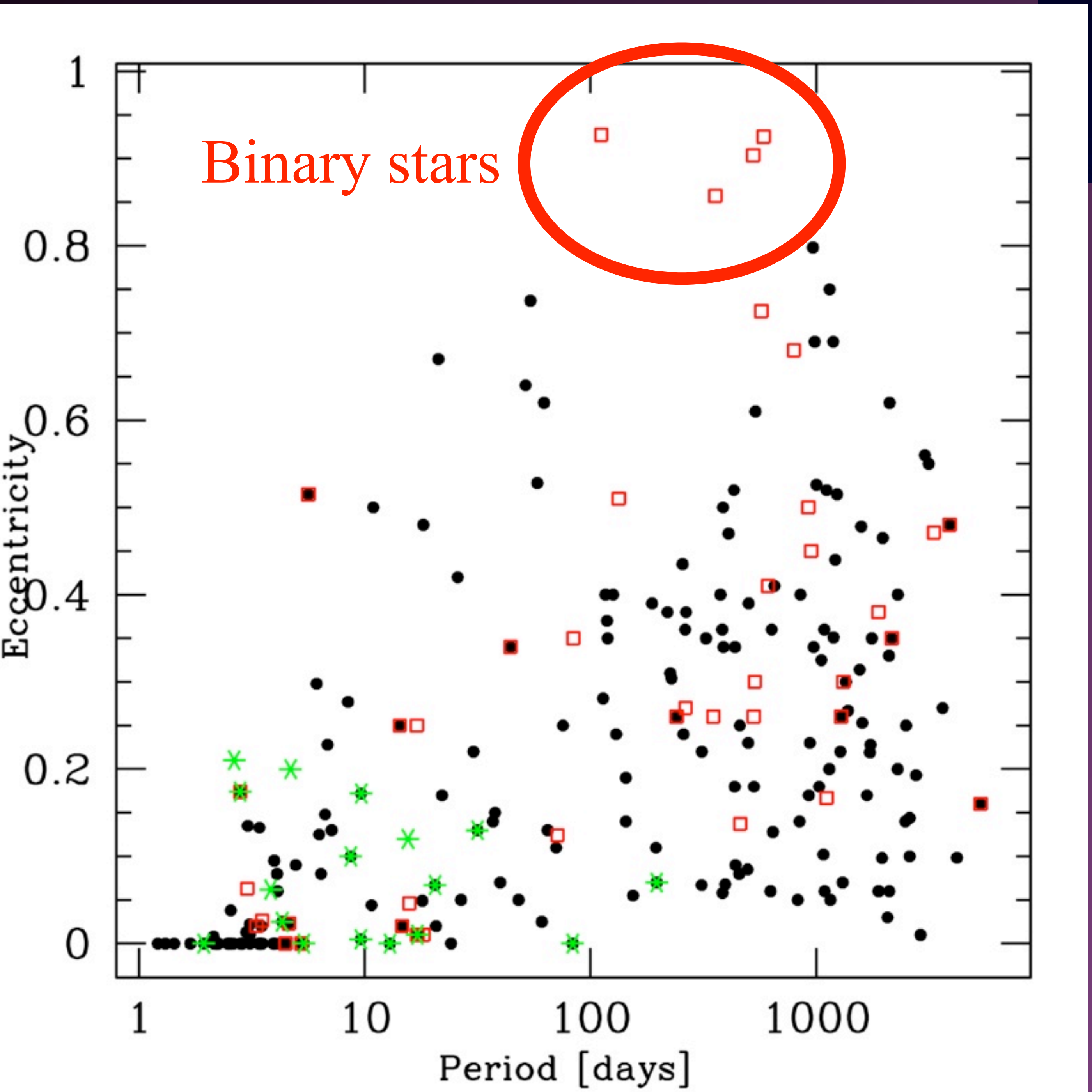

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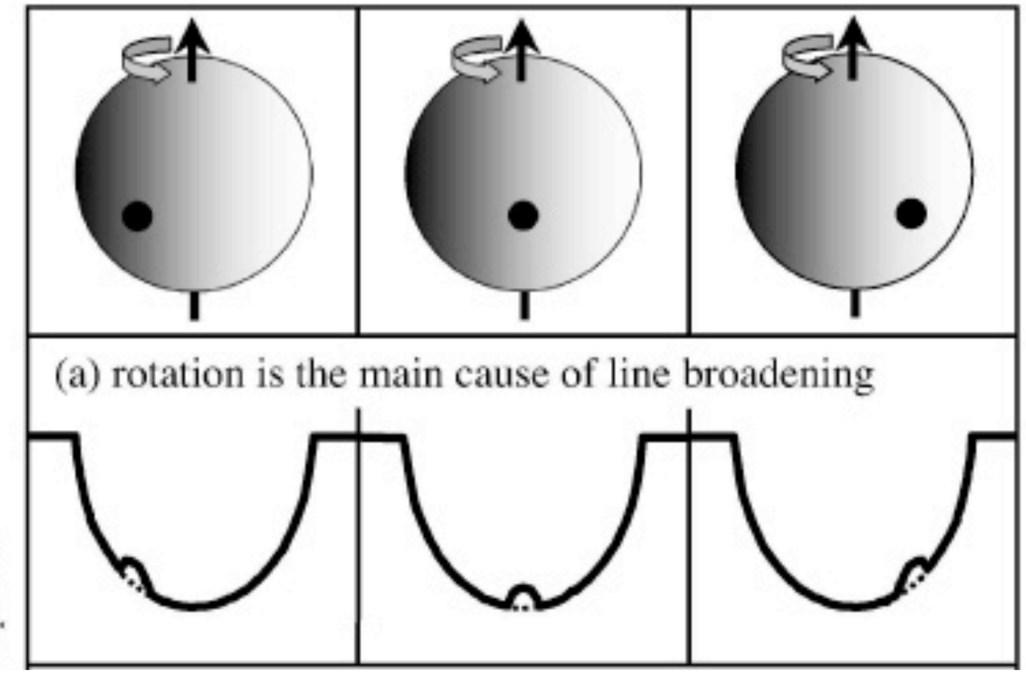
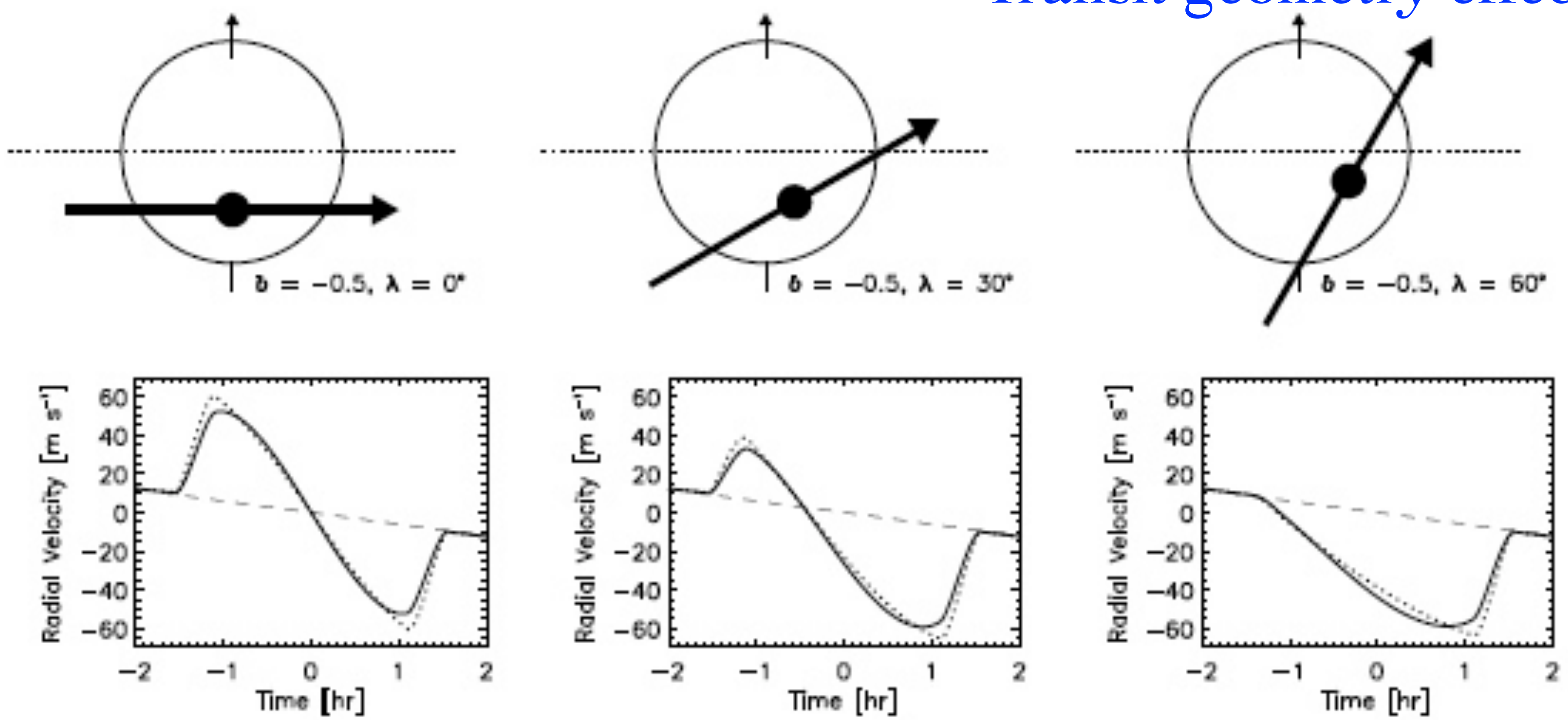
(VII) Rossiter-McLaughlin effect

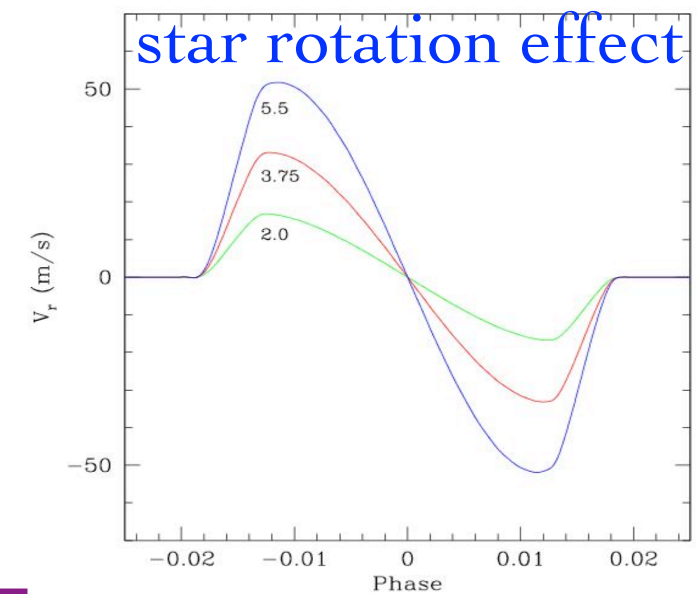


Measure of
the orbital and stellar spin-axis
(mis)alignment

Transit geometry effect



star rotation effect



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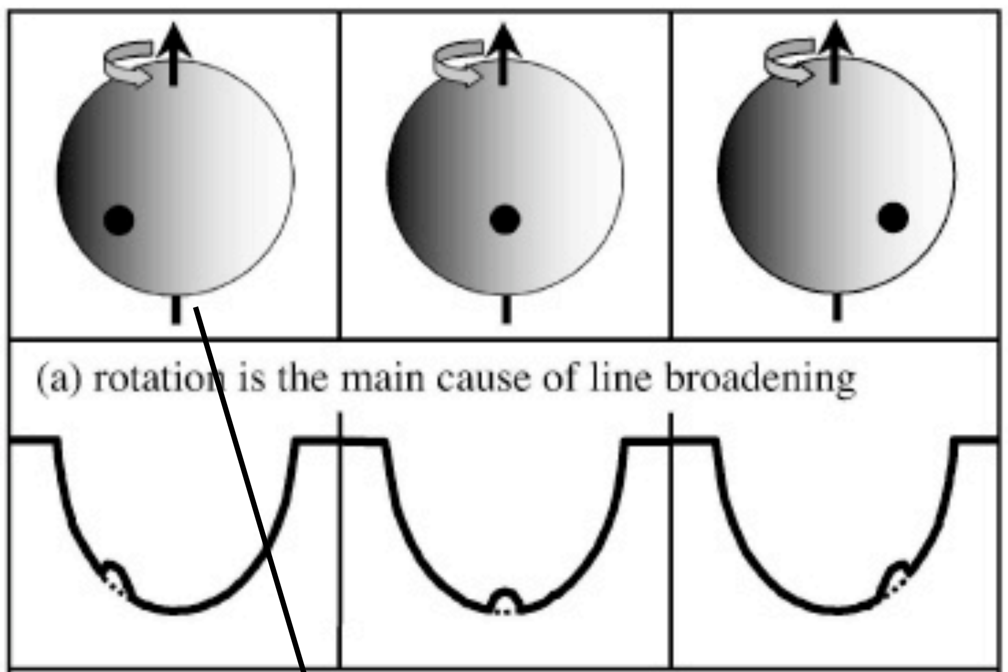

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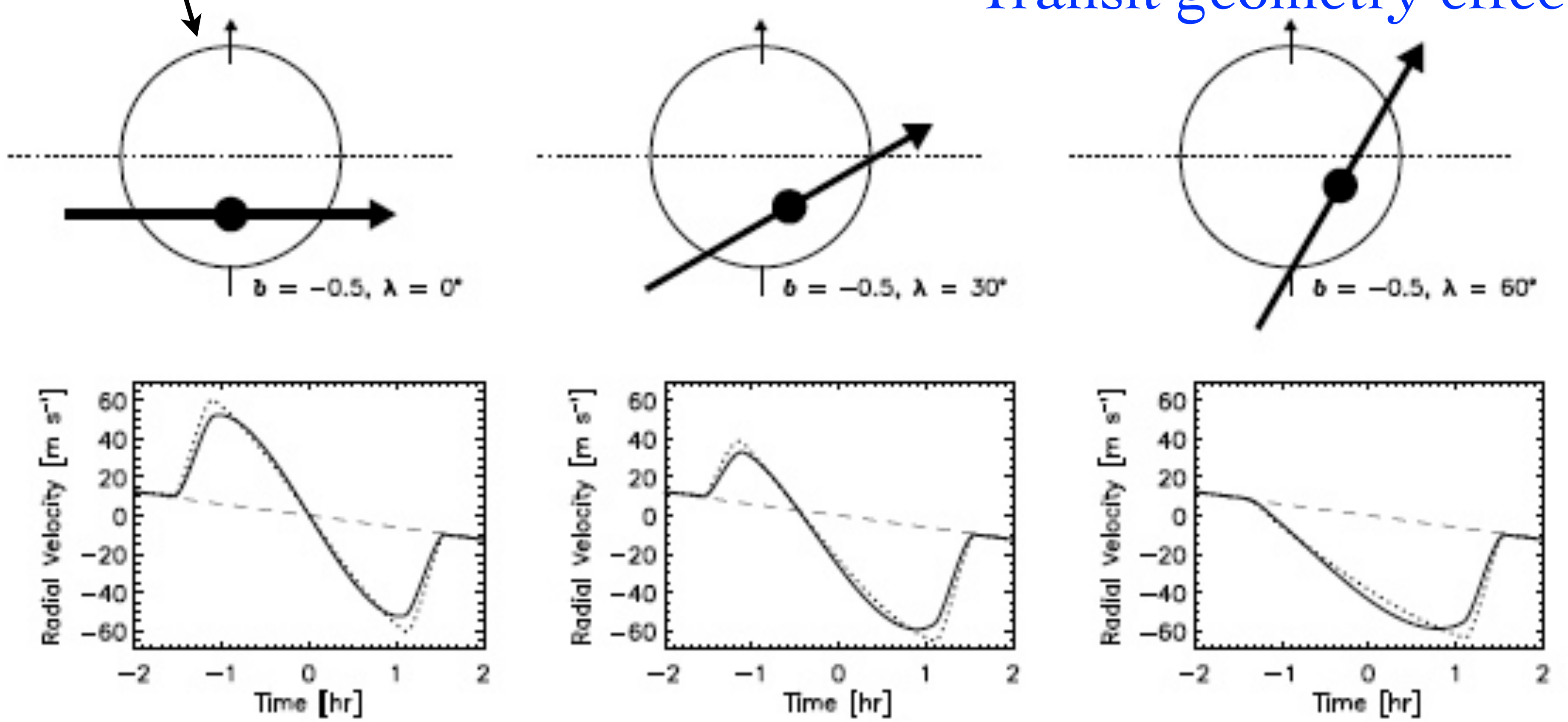

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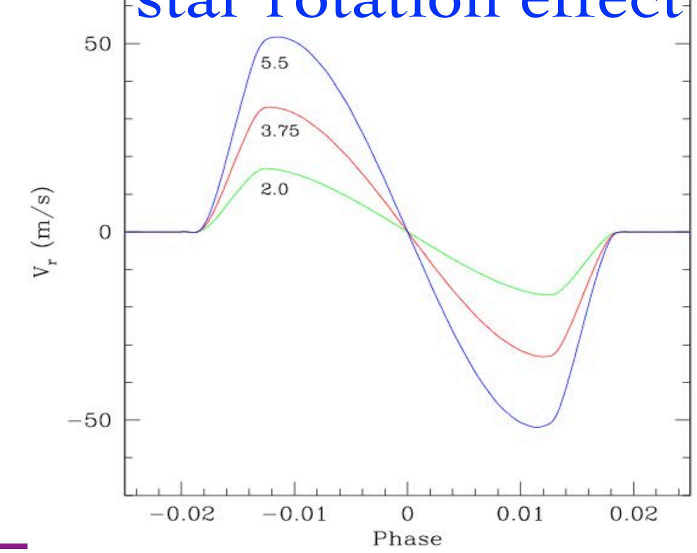
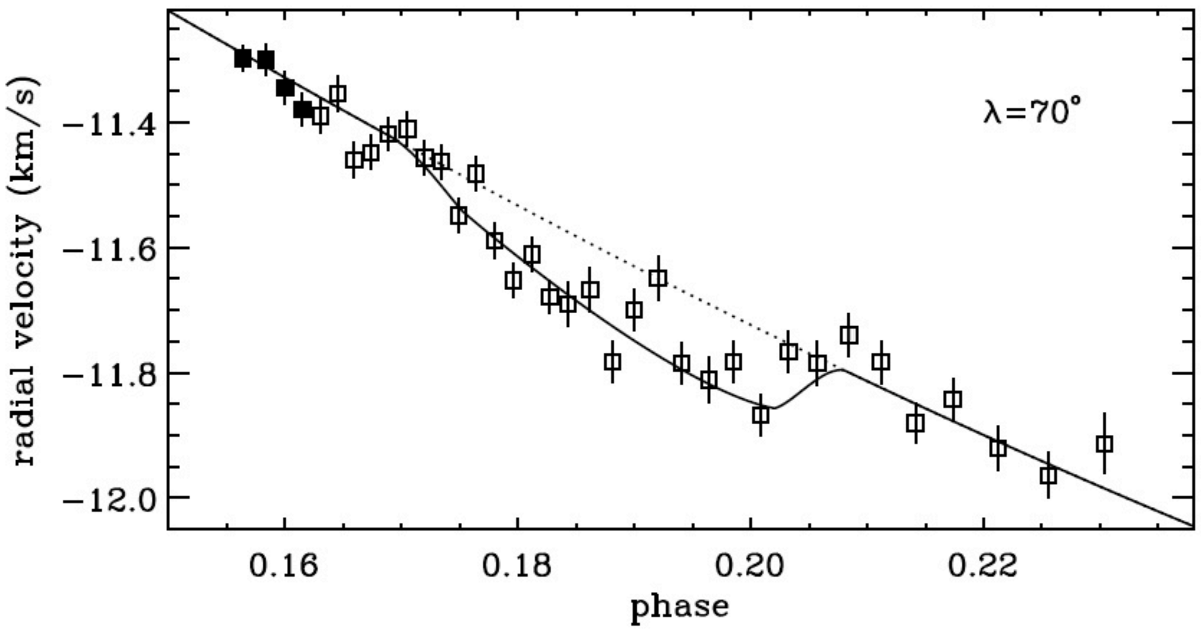
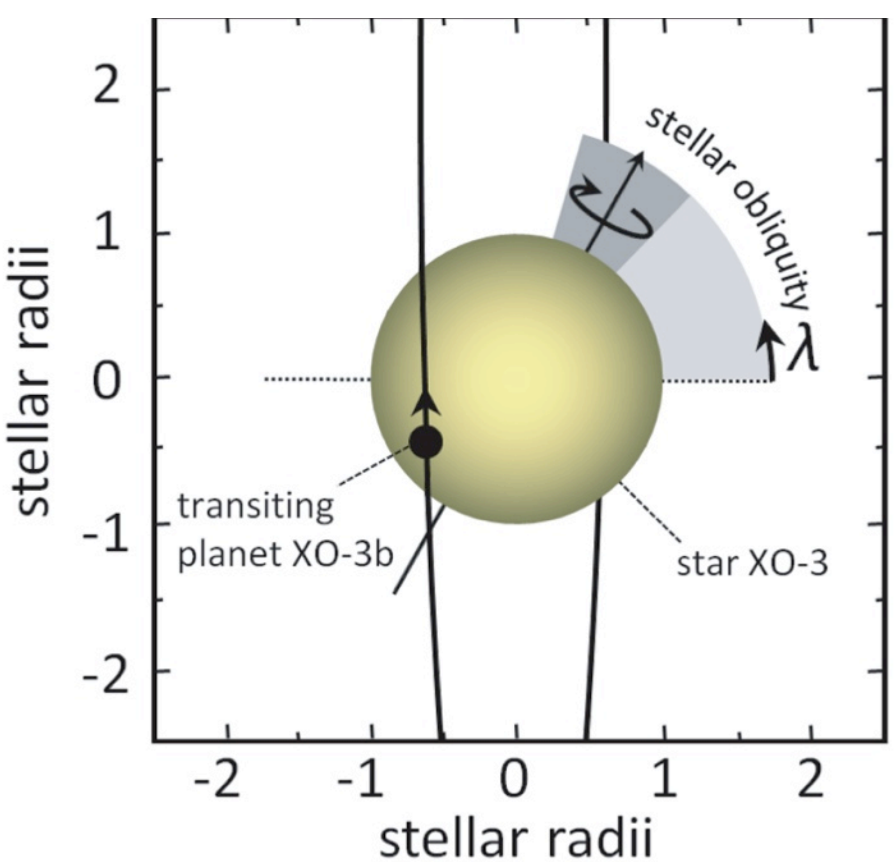
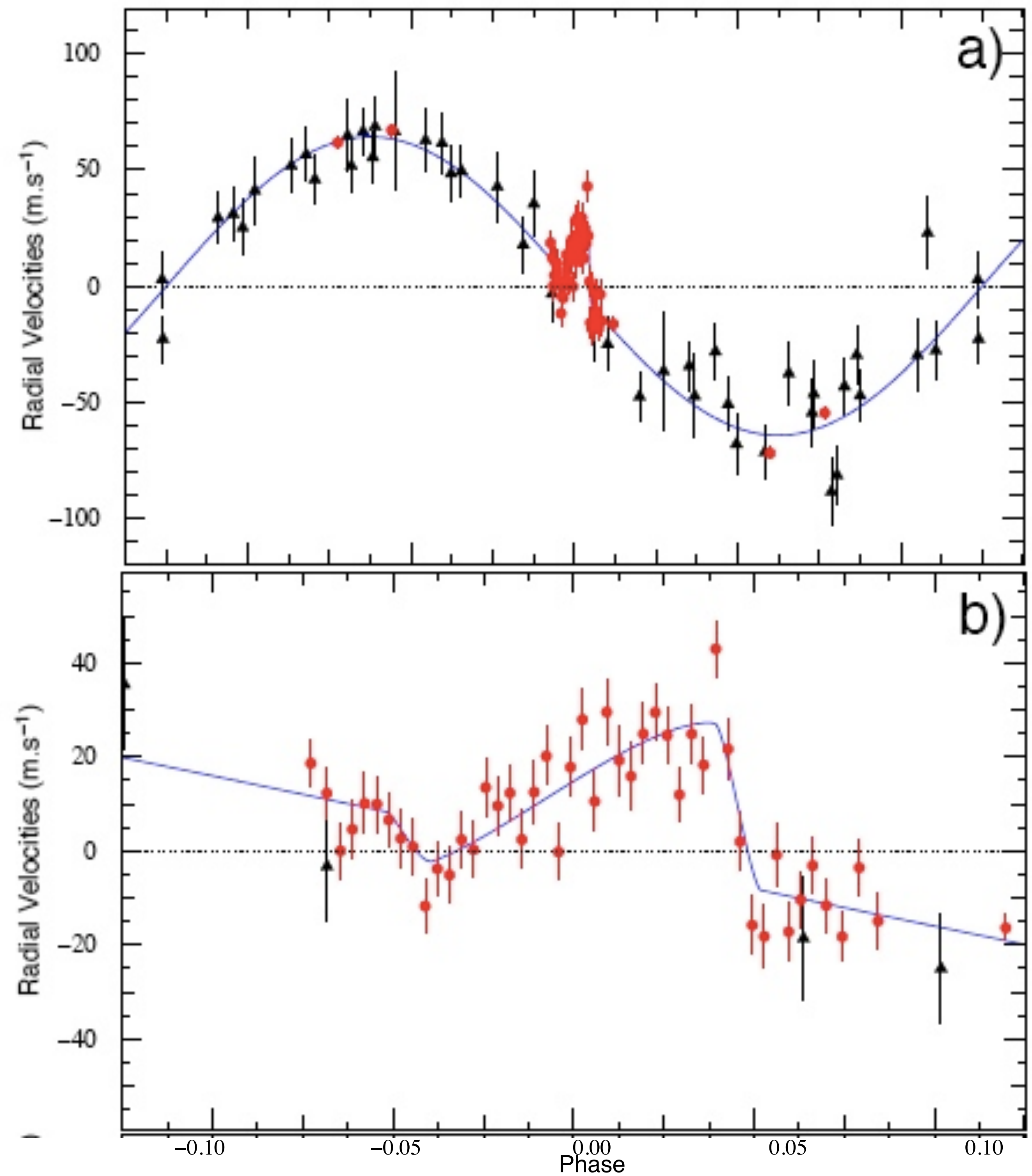


XO-3 misaligned candidate
(Hébrard et al. 2009)





Retrograde candidates
(Triaud et al. 2010)



Monday, June 6, 2011

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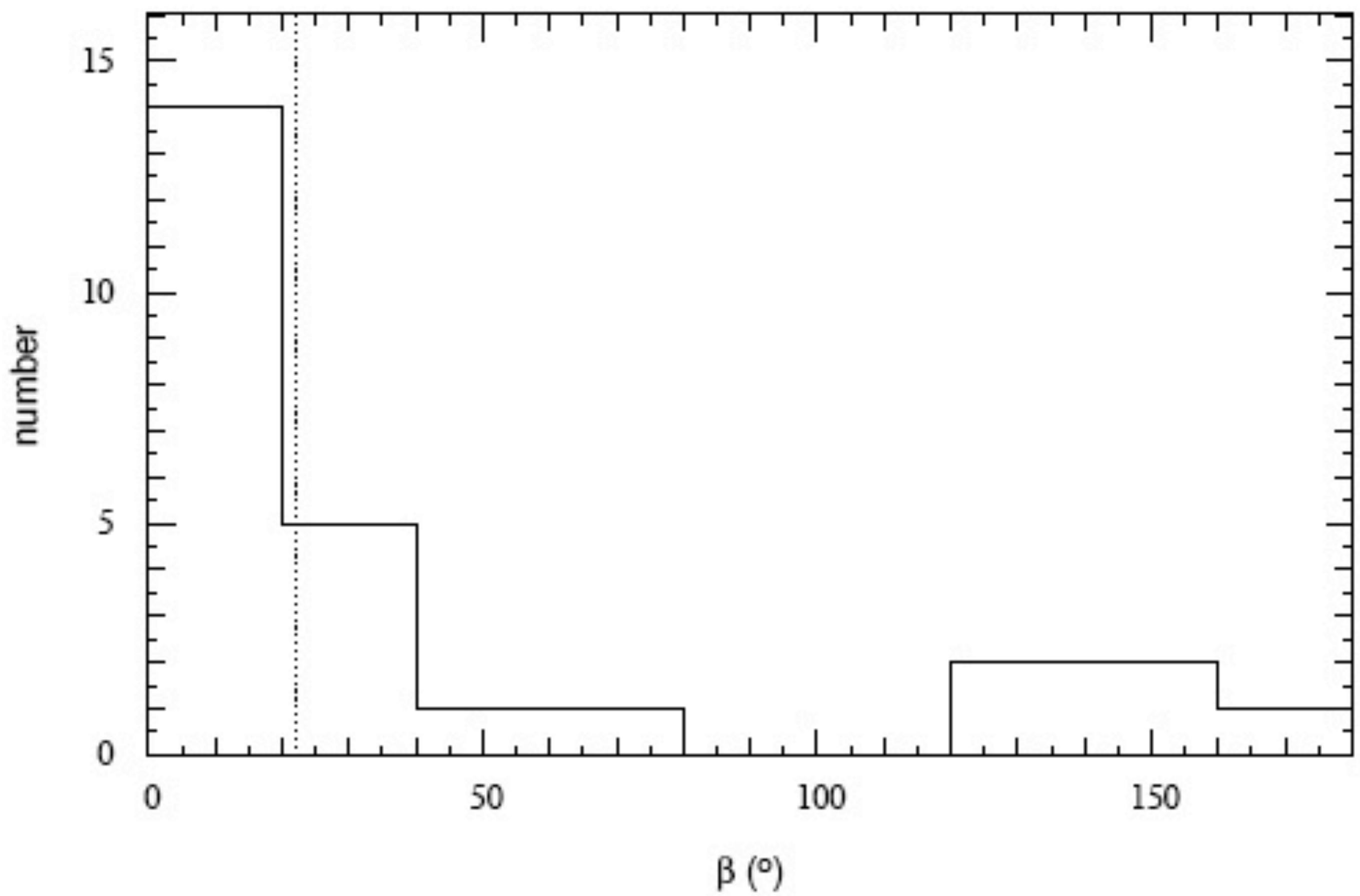

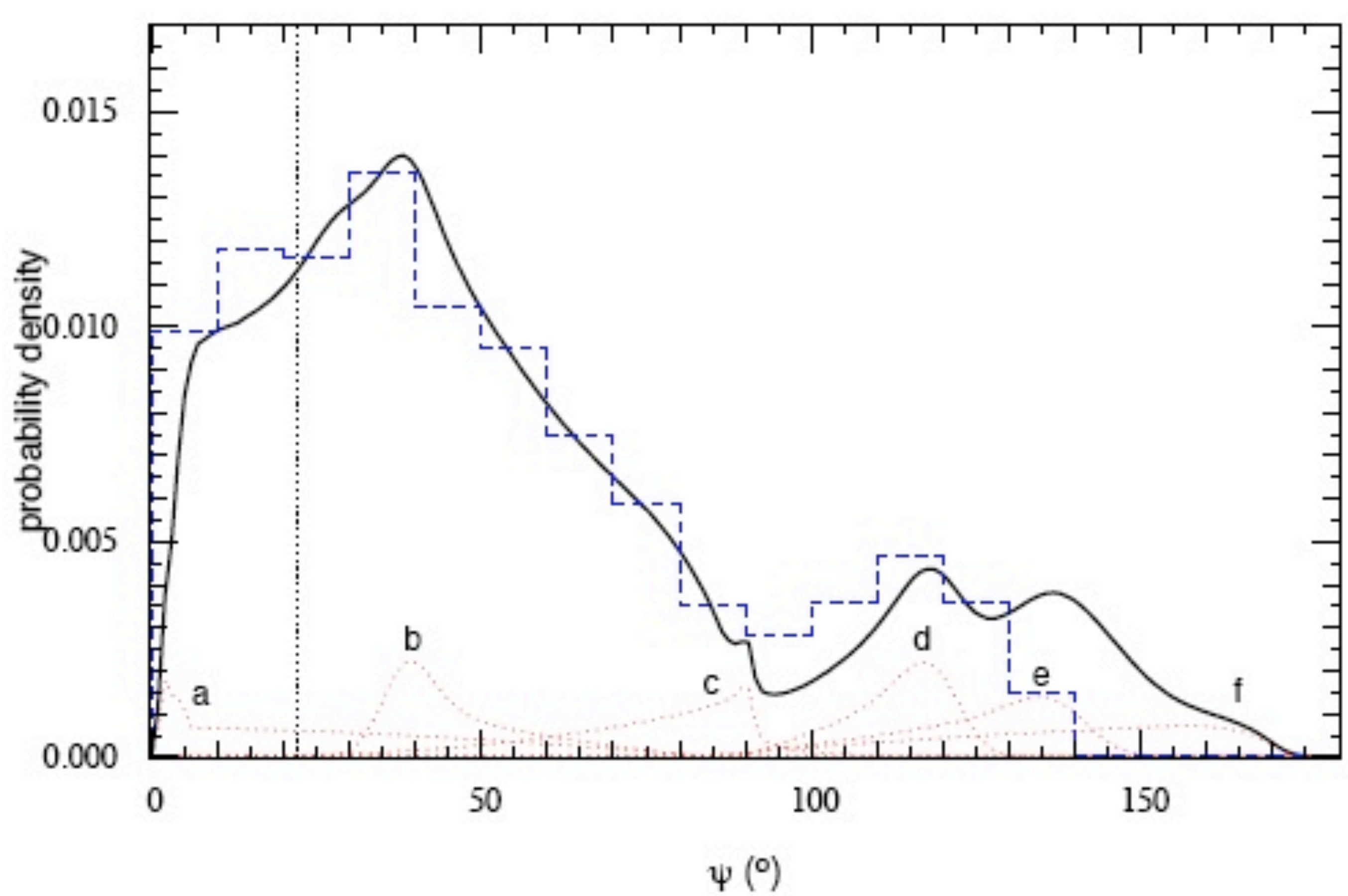

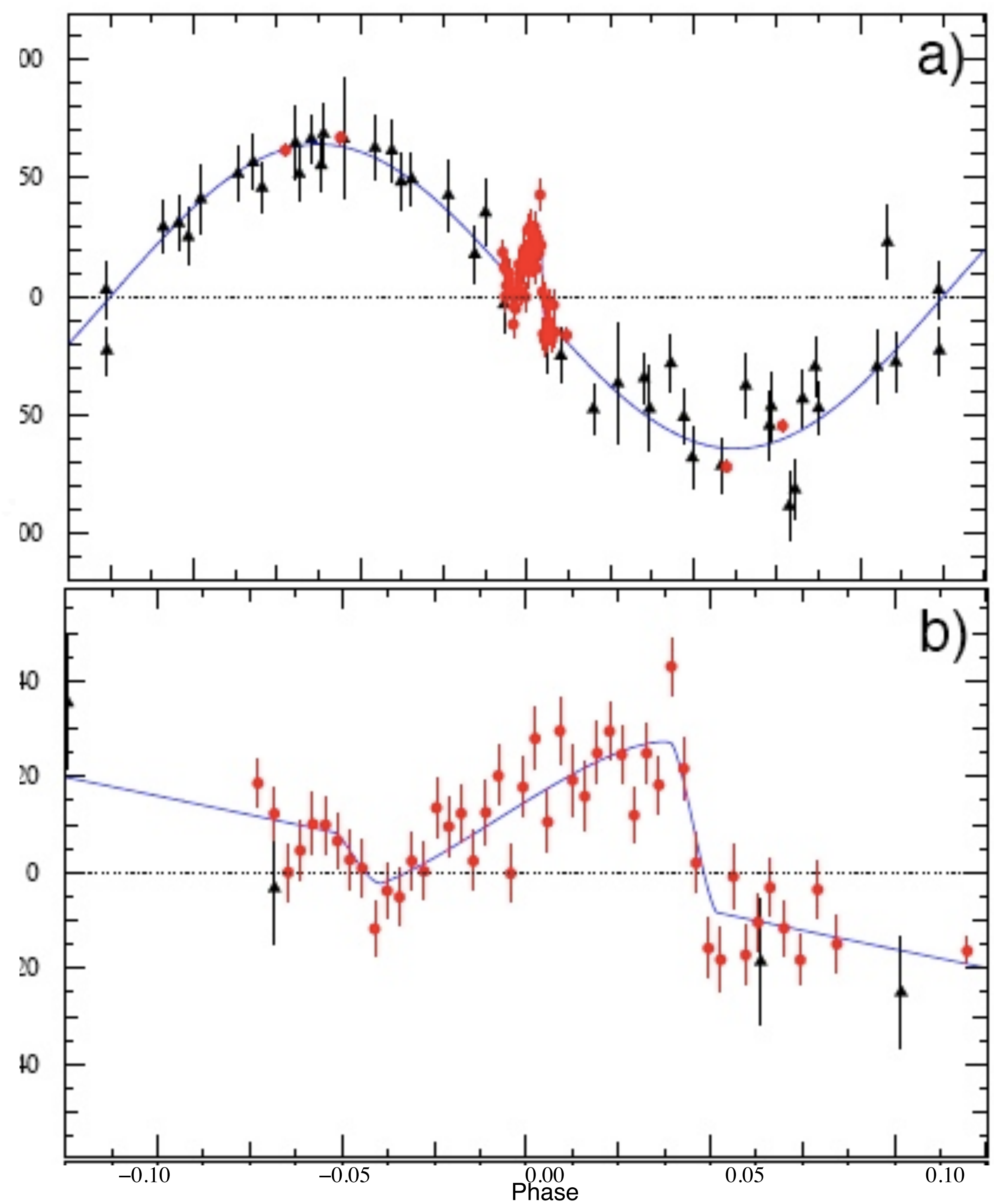

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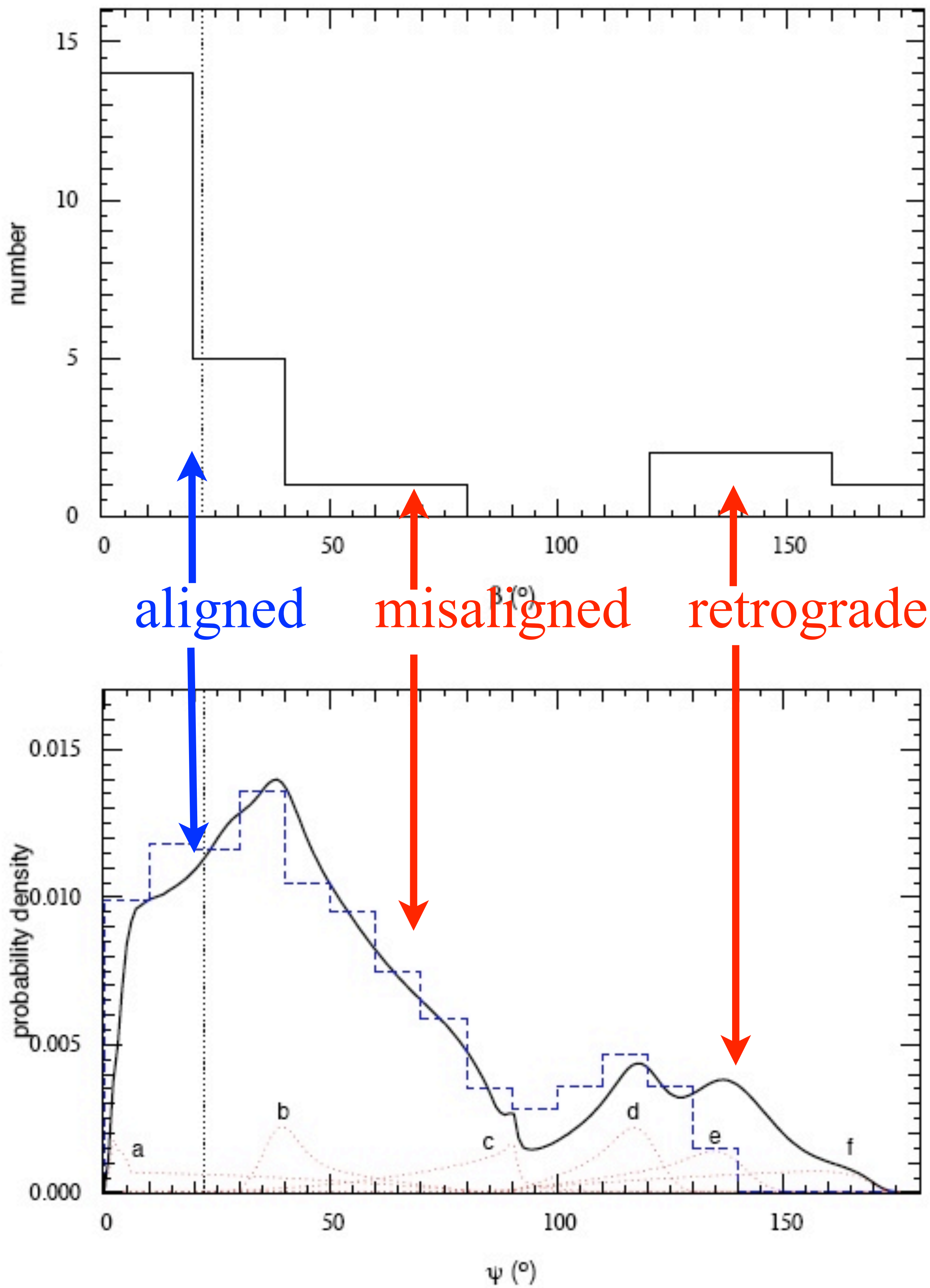
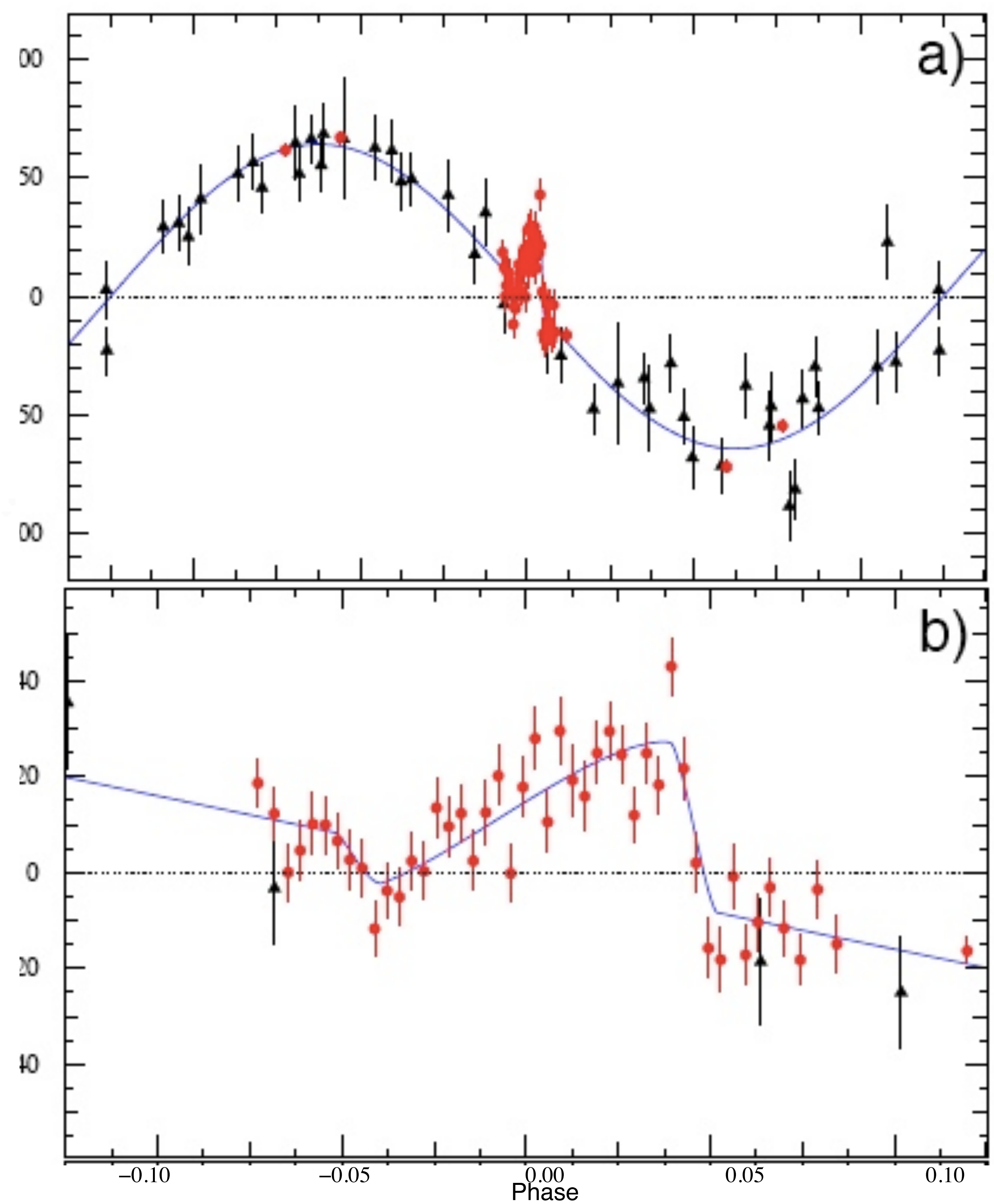


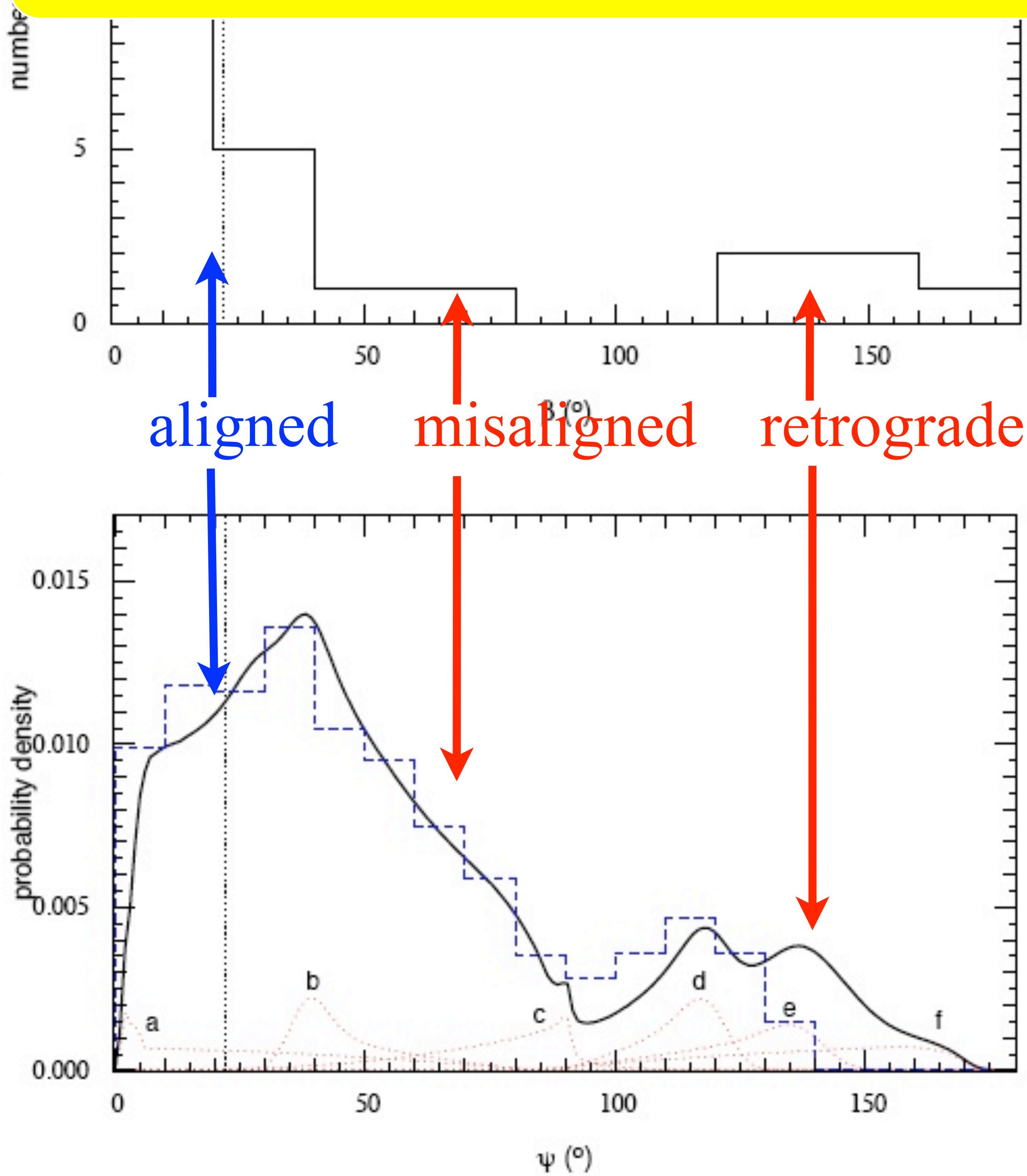


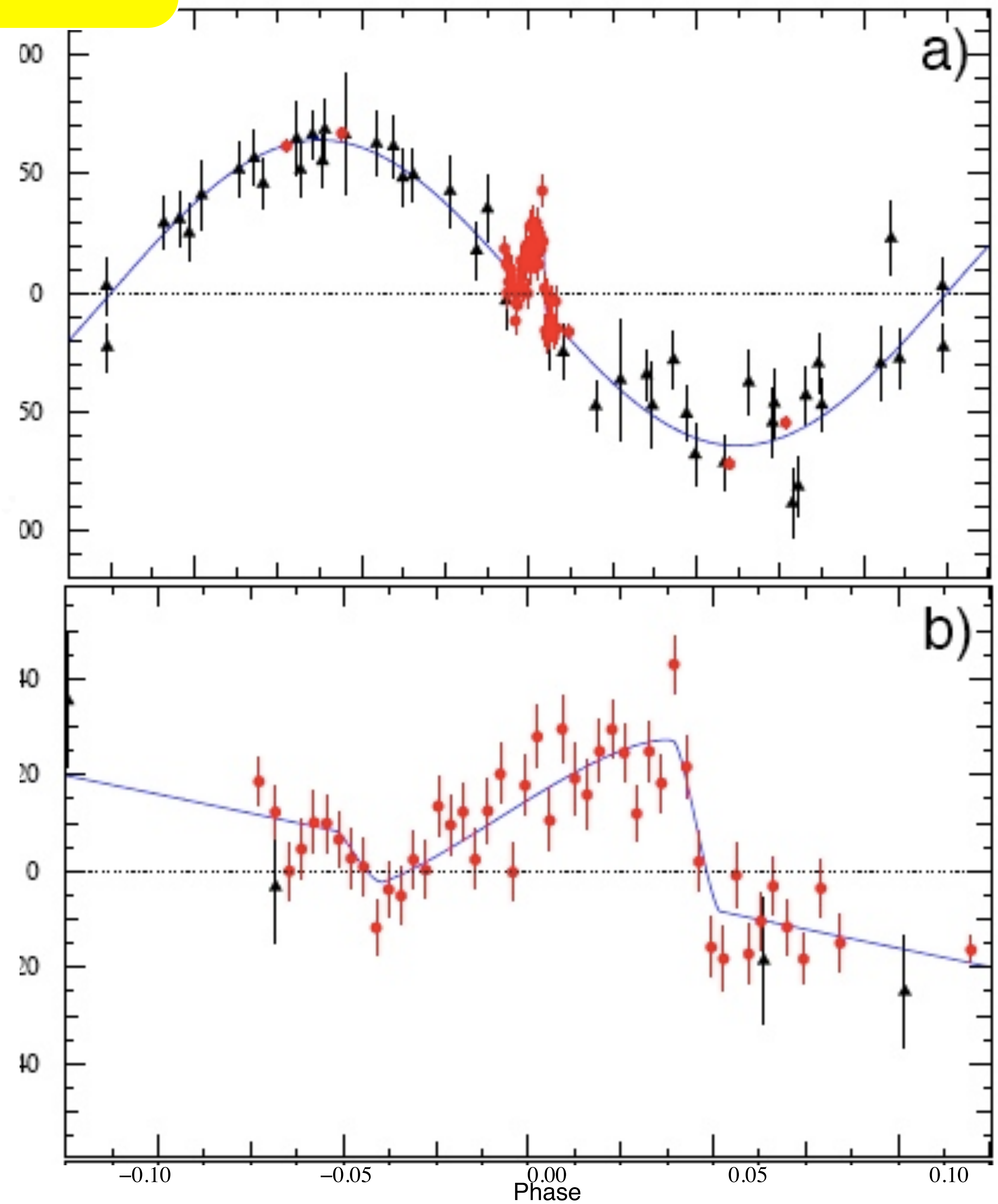
Formation-evolution mechanisms?

Alternative models:

- migration by 3-body dynamics (Kozai?)
- evolution of 3 interacting planets?

Retrograde candidates
(Triaud et al. 2010)



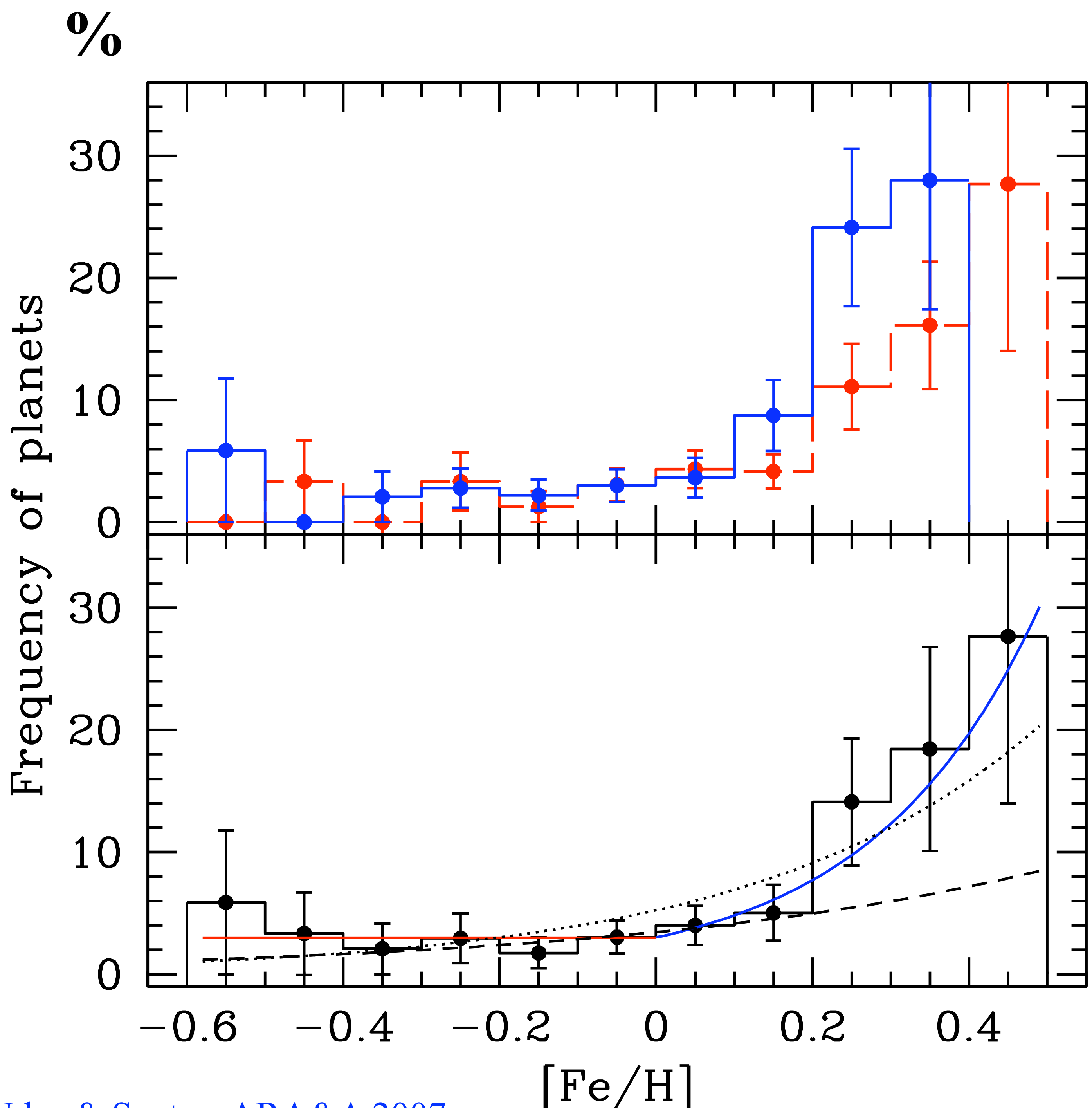


(V) Properties of planet-host stars: metallicity

Giant gaseous planets

Stars with planets are more metal rich?

(Gonzalez 1997, 1998, 1999)



Udry & Santos, ARA&A 2007

Santos et al. 2001-2006

Fischer & Valenti 2002-2005

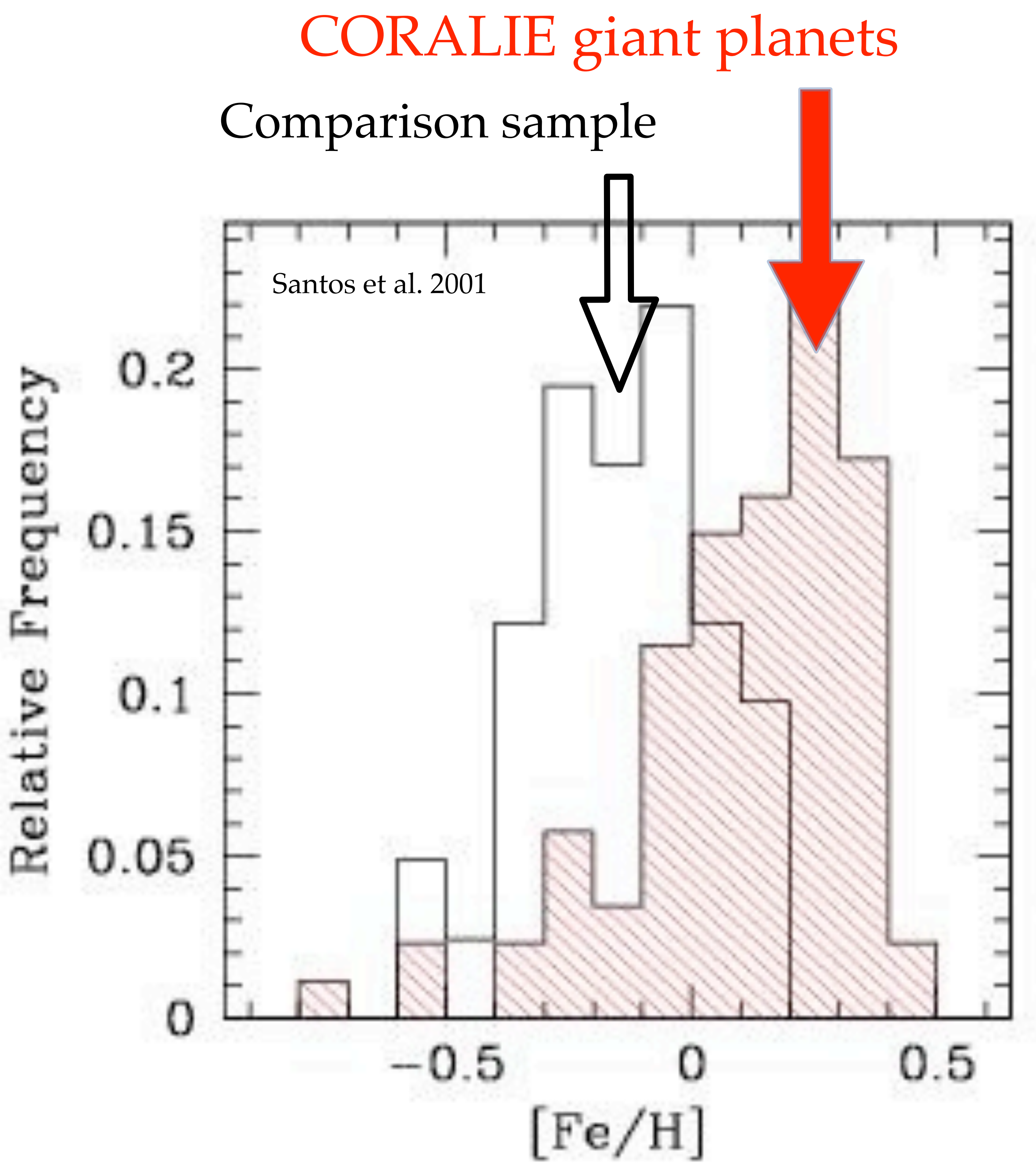
- Well-defined samples with and without planets
- Uniform analyses
- Large number of stars

Average: 2 regimes

flat + power law

Constant probability at low metallicities ?

No metallicity correlation for low-mass planets ?



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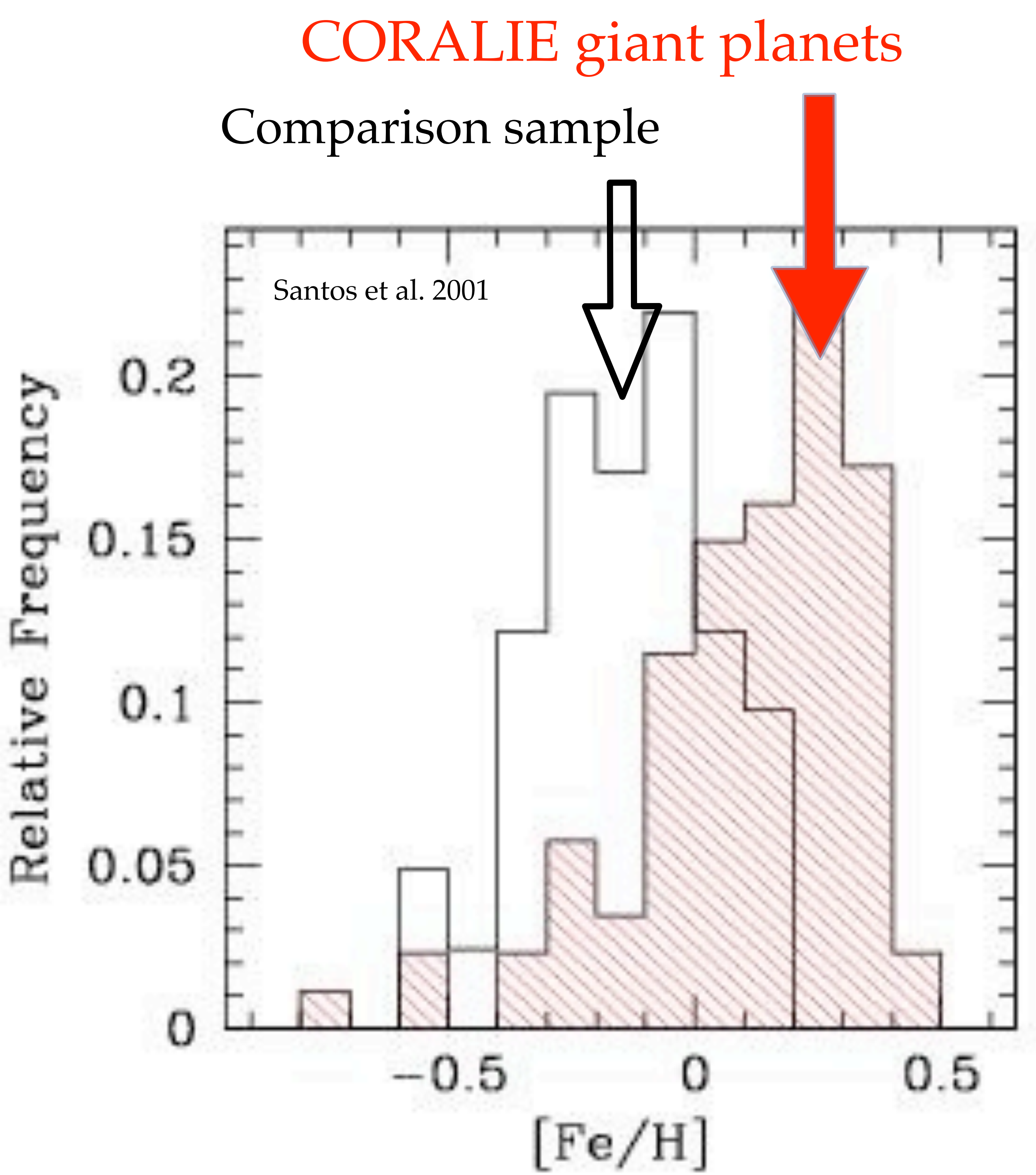

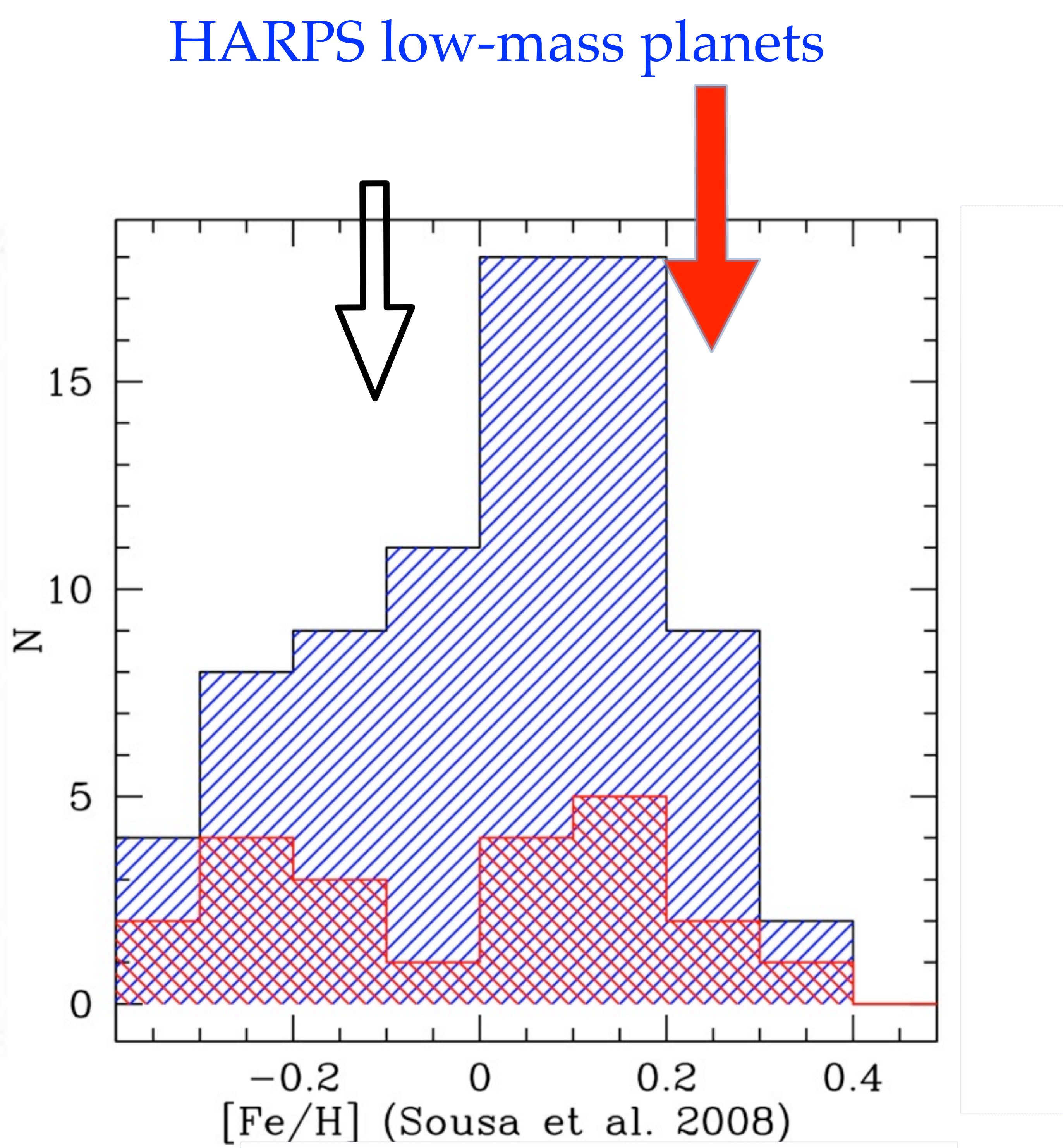

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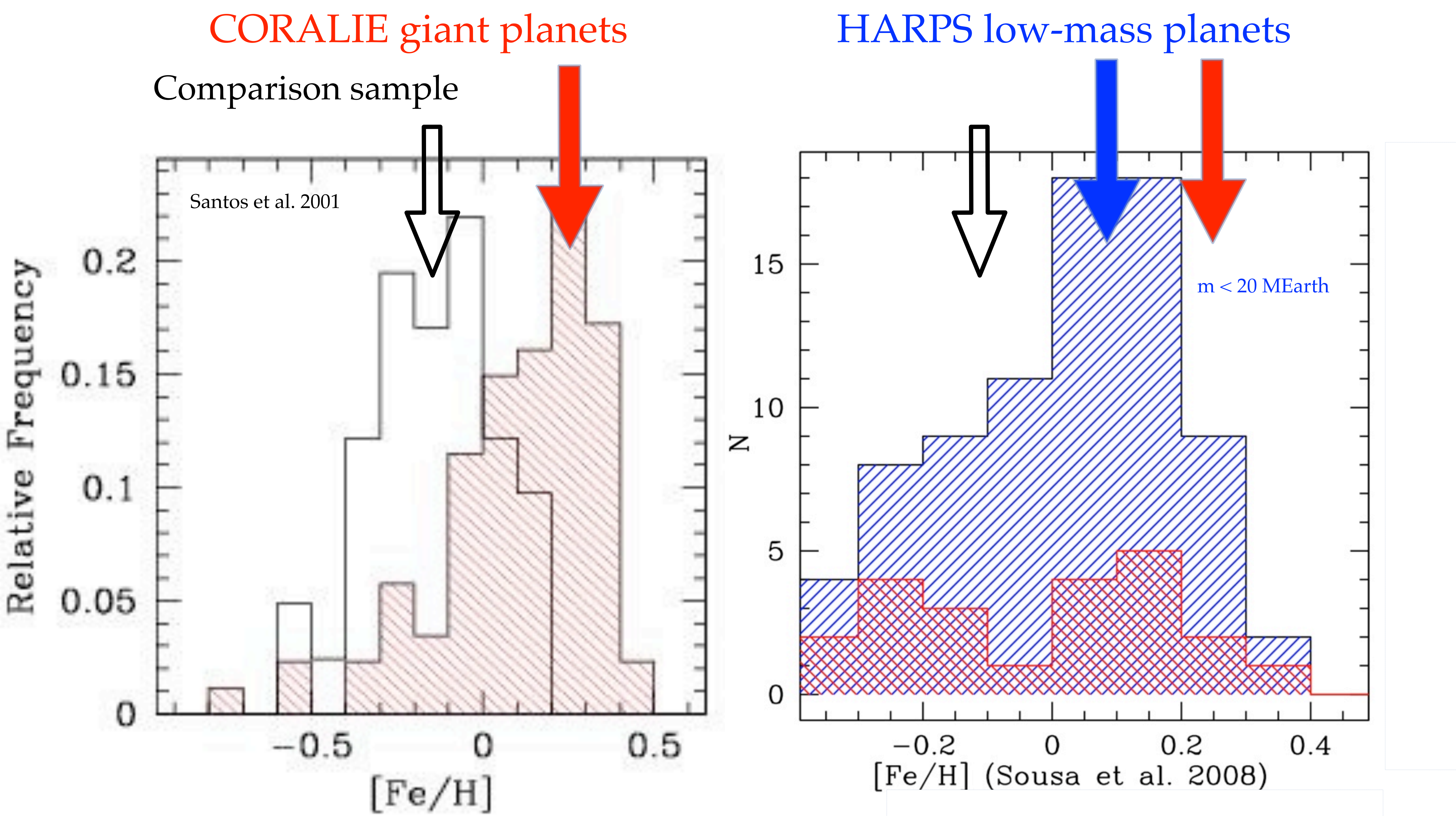

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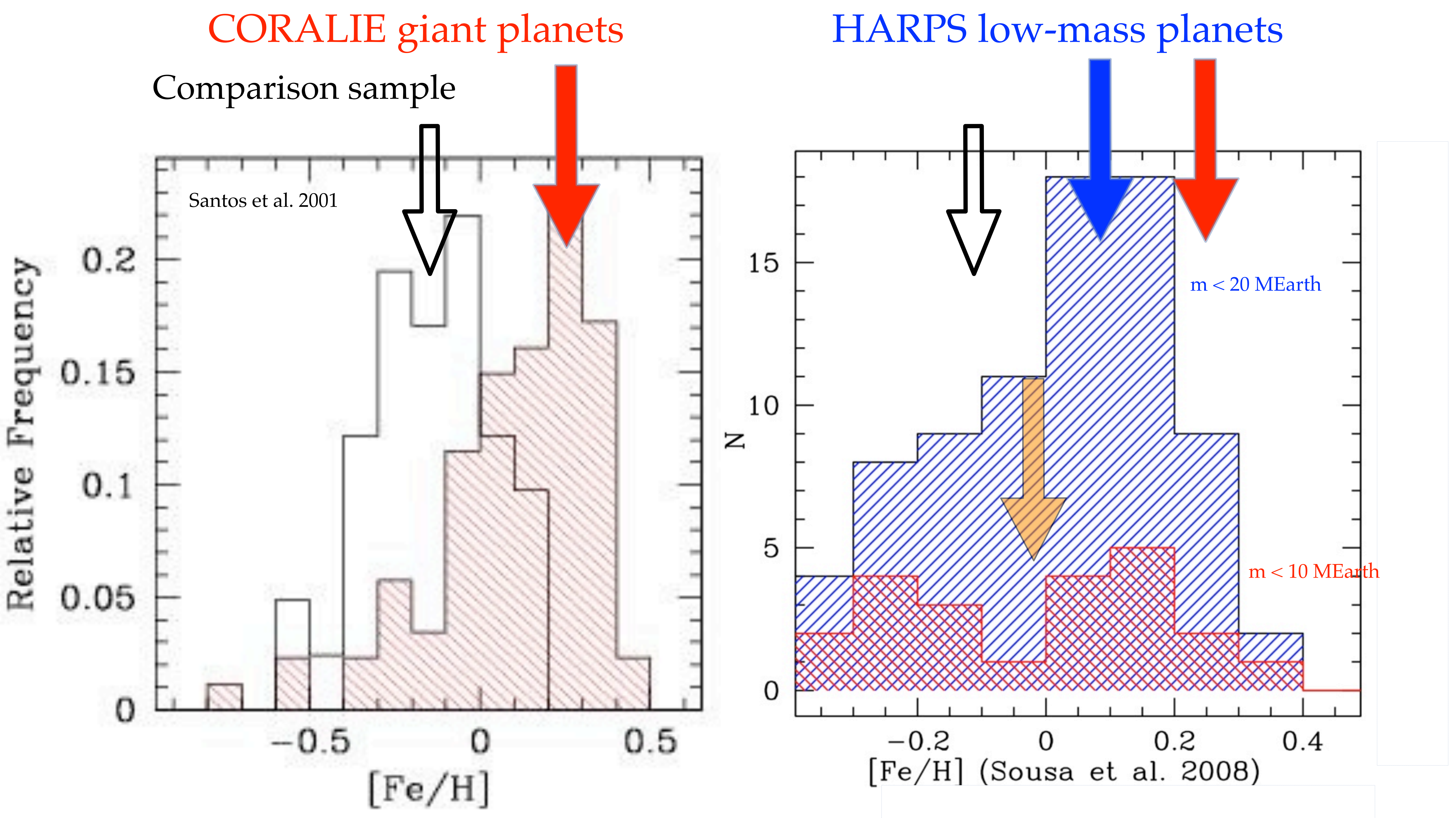
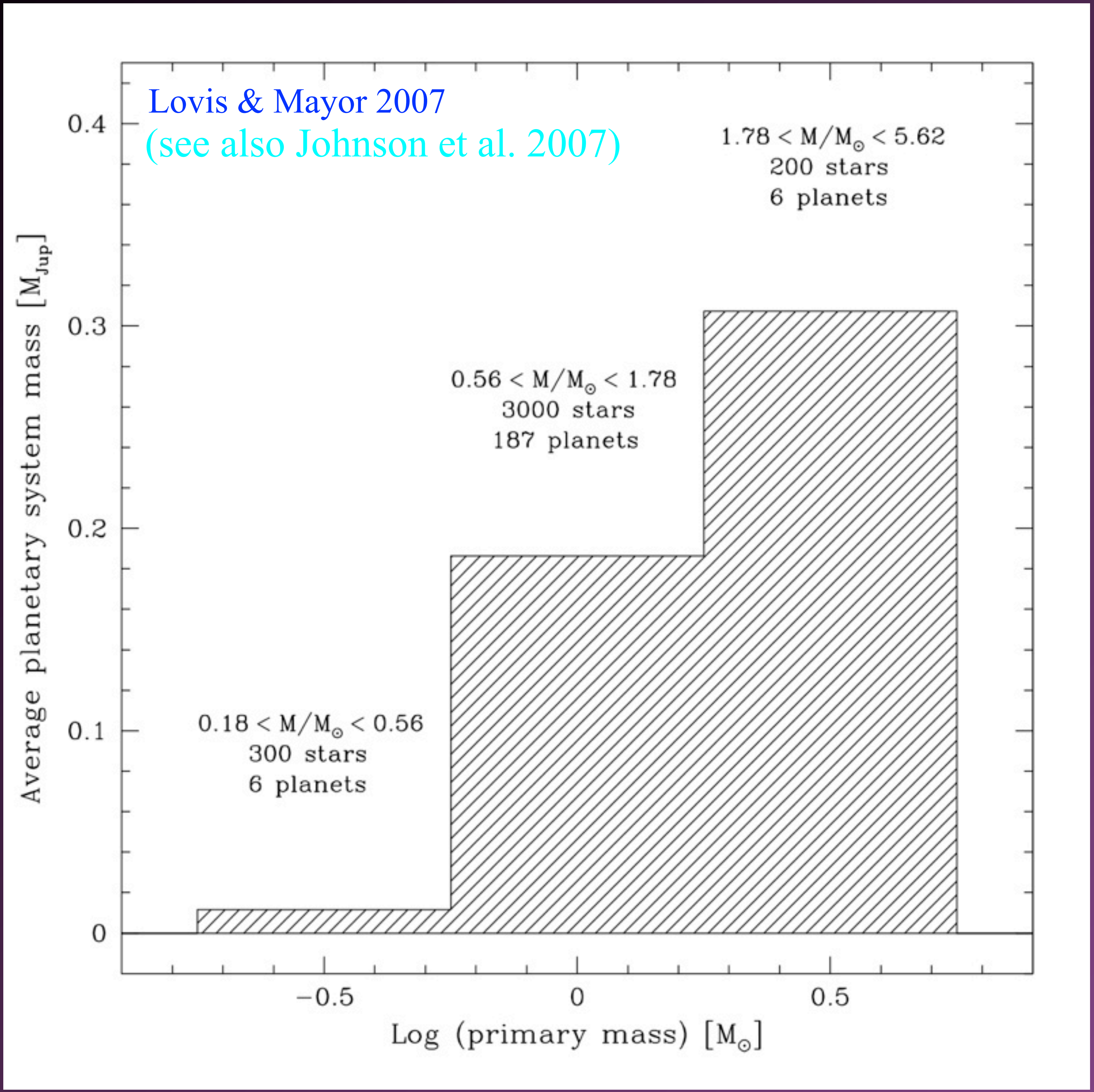


(VI) Properties of planet-host stars: primary mass



Equal bin in log(M_{star})

- M dwarfs
- solar stars
- intermediate masses

Planetary system mass

planet masses/star number

=> mass of planetary material scales with M_{star}

RV bias

underestimate the last bin

Planet Detectability with radial velocities

$$k_1 = \frac{28.4\ \mathrm{m\ s^{-1}}}{\sqrt{1-e^2}} \frac{m_2 \sin i}{M_{\mathrm{Jup}}} \left(\frac{m_1 + m_2}{M_{\mathrm{Sun}}} \right)^{-2/3} \left(\frac{P}{1\ \mathrm{yr}} \right)^{-1/3}$$

Jupiter	@ 1 AU	: 28.4 m s^{-1}
Jupiter	@ 5 AU	: 12.7 m s^{-1}
Neptune	@ 0.1 AU	: 4.8 m s^{-1}
Neptune	@ 1 AU	: 1.5 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 0.1 AU	: 1.4 m s^{-1}
Super-Earth (5 $M_\oplus$)	@ 1 AU	: 0.45 m s^{-1}
Earth	@ 1 AU	: 9 cm s^{-1}

A few m/s precision OK
for giant planets
e.g. Jupiters out to > 5 AU

Need to go below 1 m/s
for close super-Earths!

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Need to go below 1 m/s
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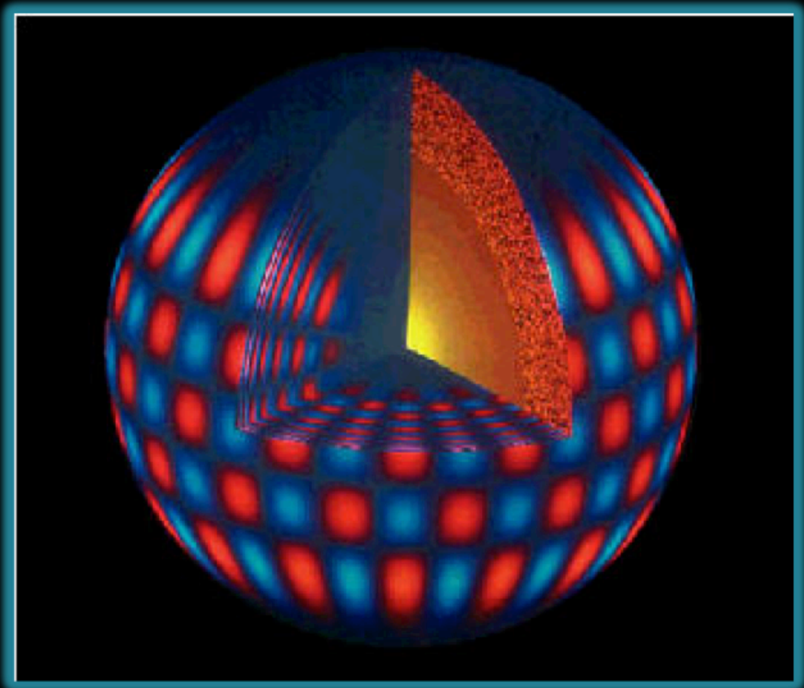
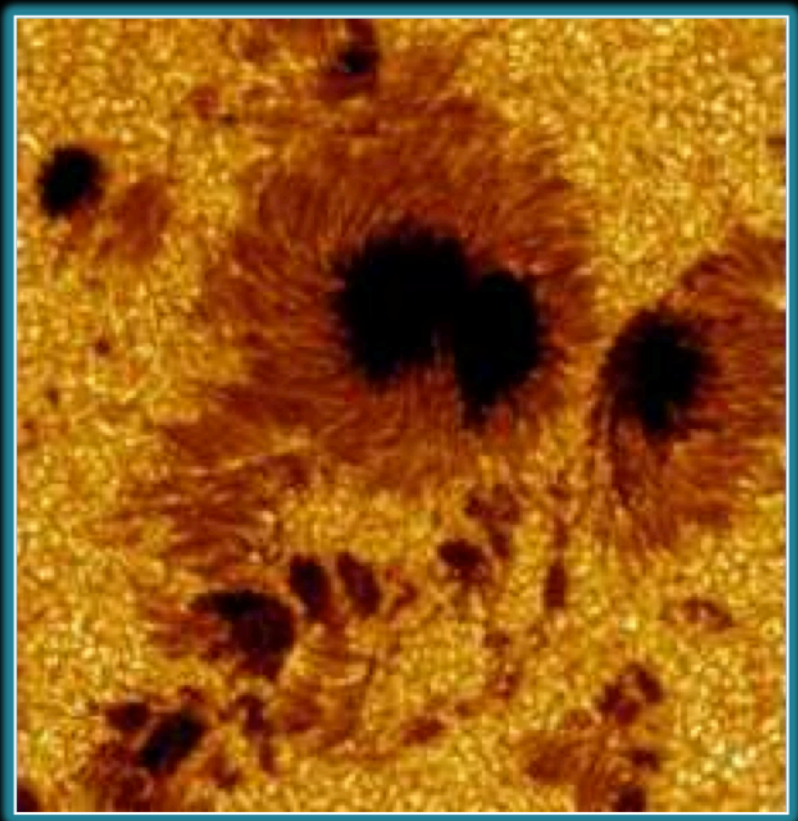
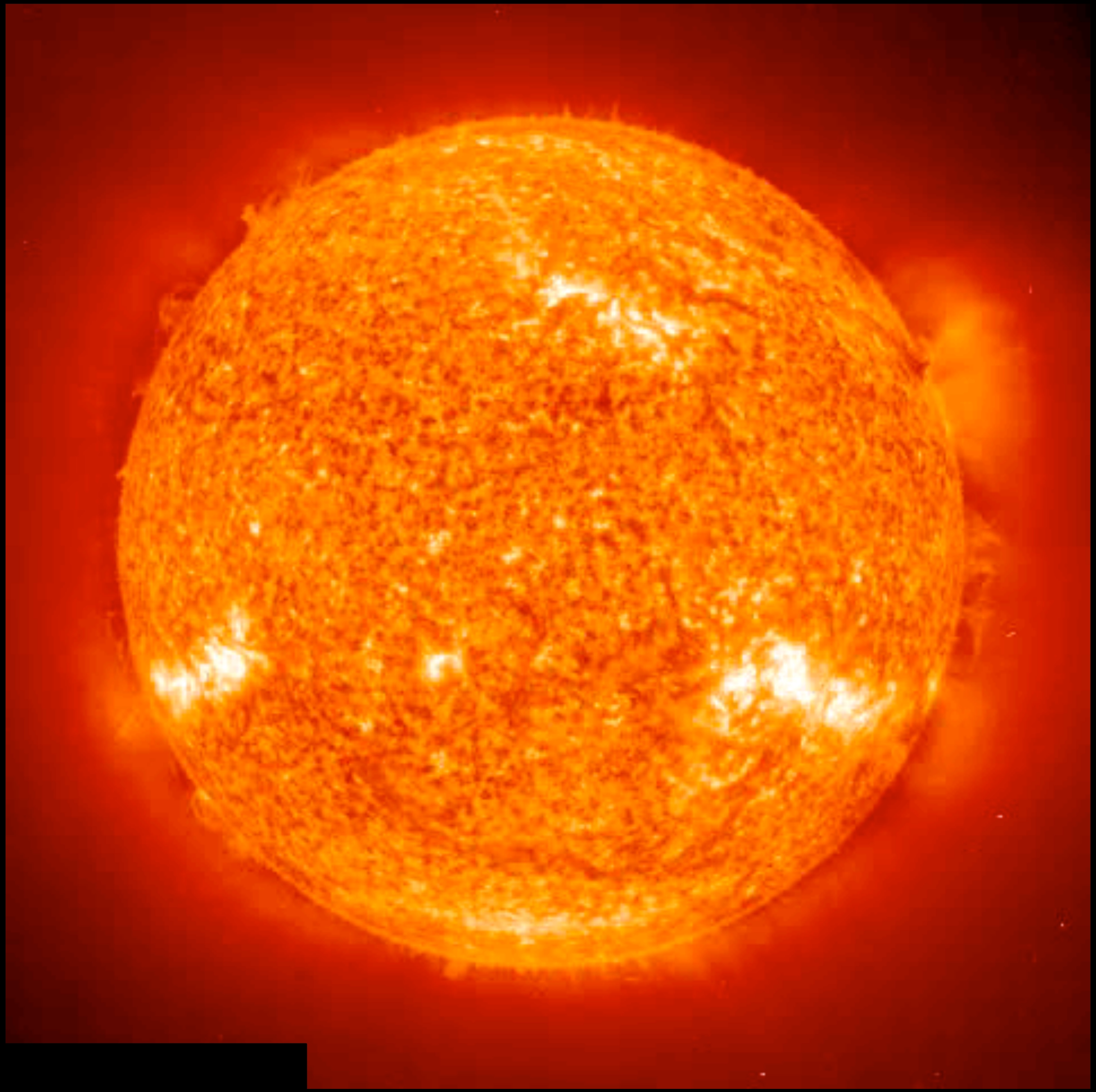
Required an order of
magnitude improvement

Possibly in the habitable zone ;-)

Stellar intrinsic limitations



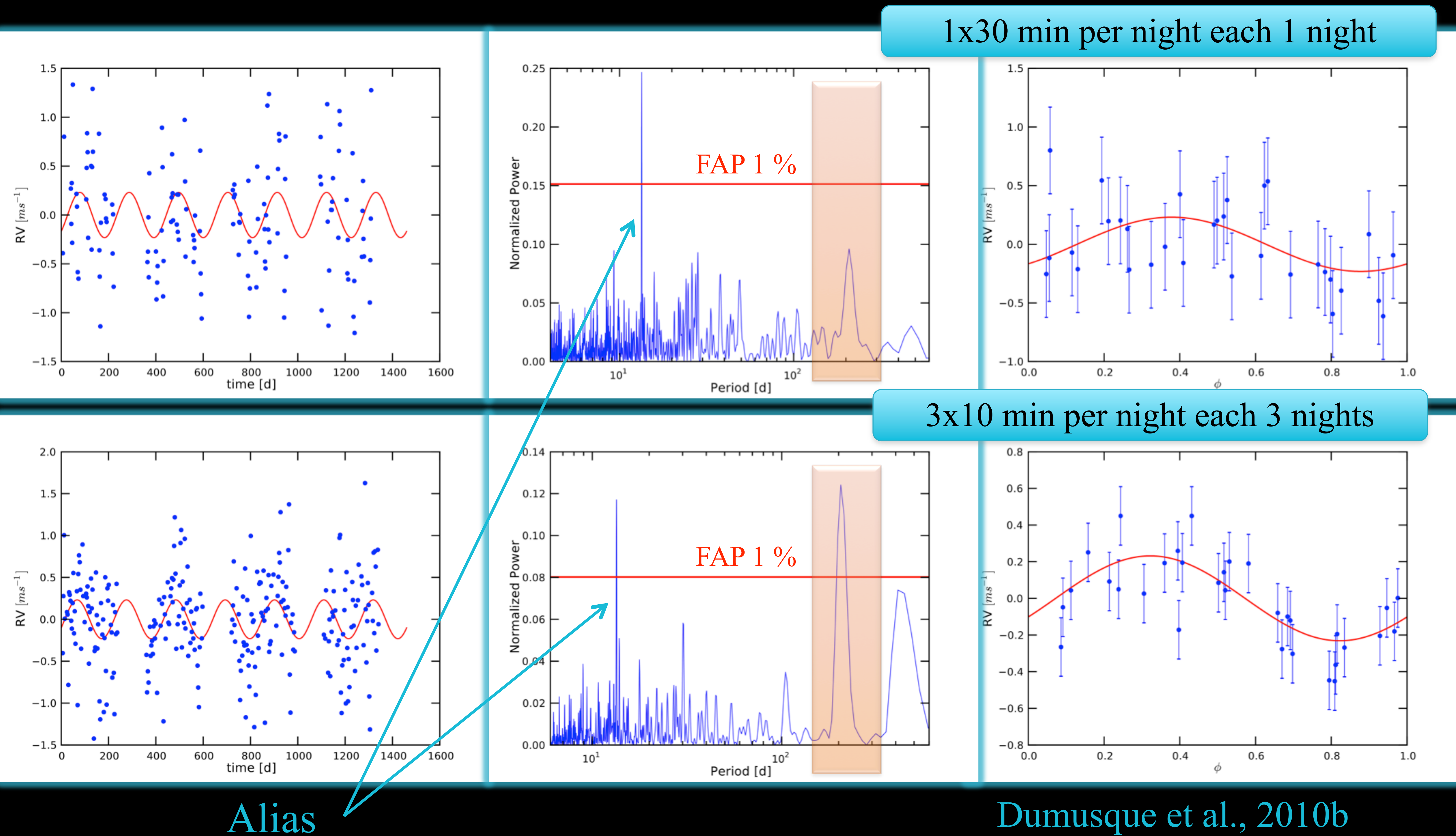




SIMULATIONS OF STELLAR NOISE APPLIED TO ...

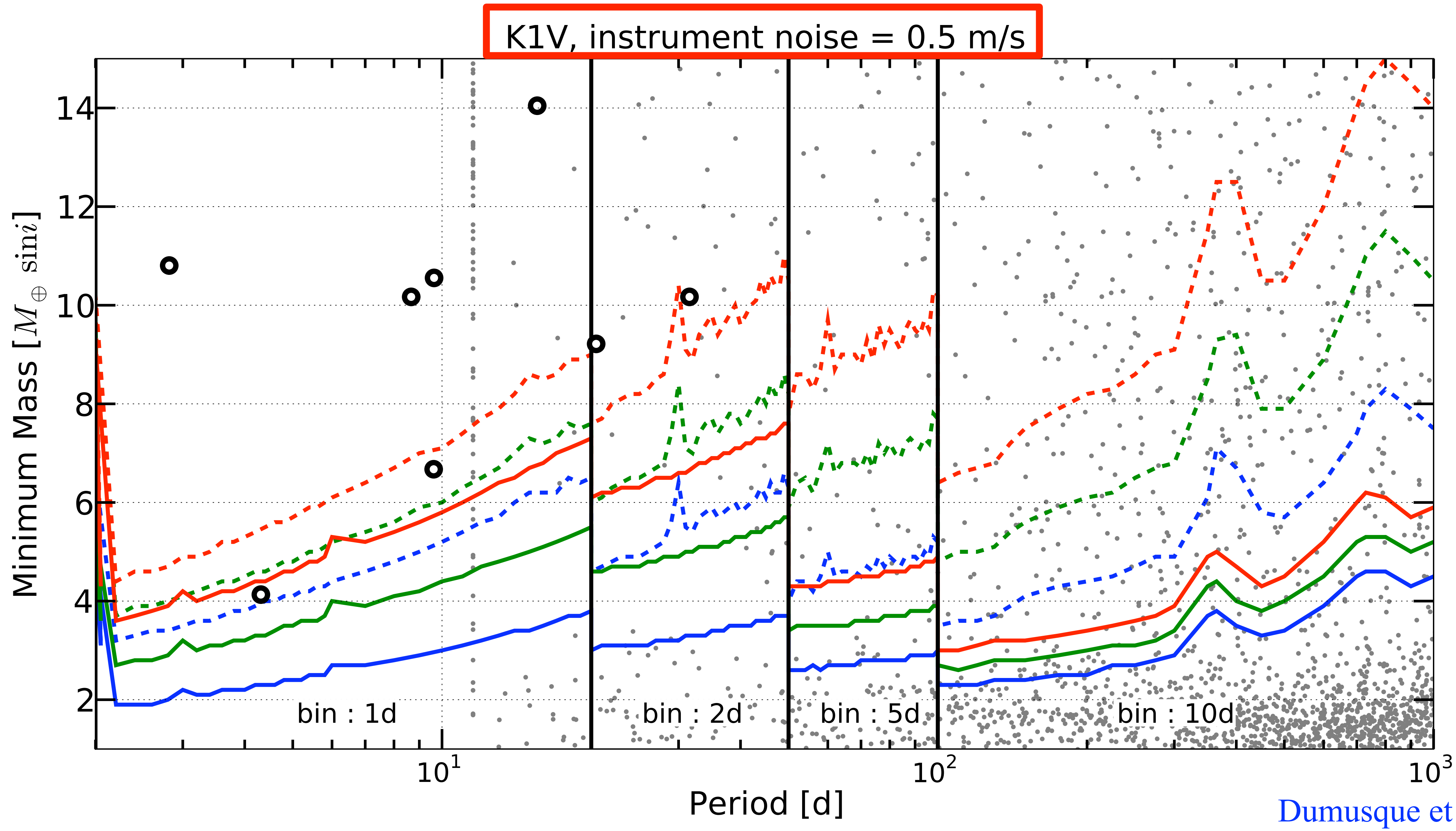
...ESPRESSO @ VLT

A 2 Earth-mass planet in the habitable zone of a quiet K star (P=200 days), Log(R'_{HK}) = -4.9



Dumusque et al., 2010b

From RV rms to detection limits through Monte Carlo simulations



Dumusque et al. 2010 b

Longer periods => larger possible bins for average
=> small effect of the period on detection capability

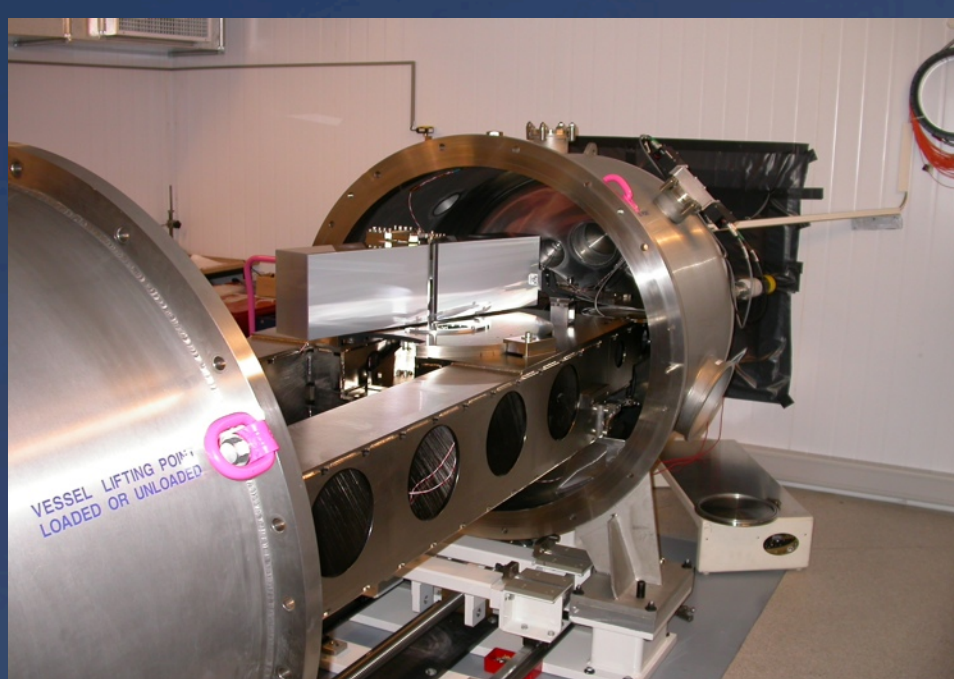
Future searches ...

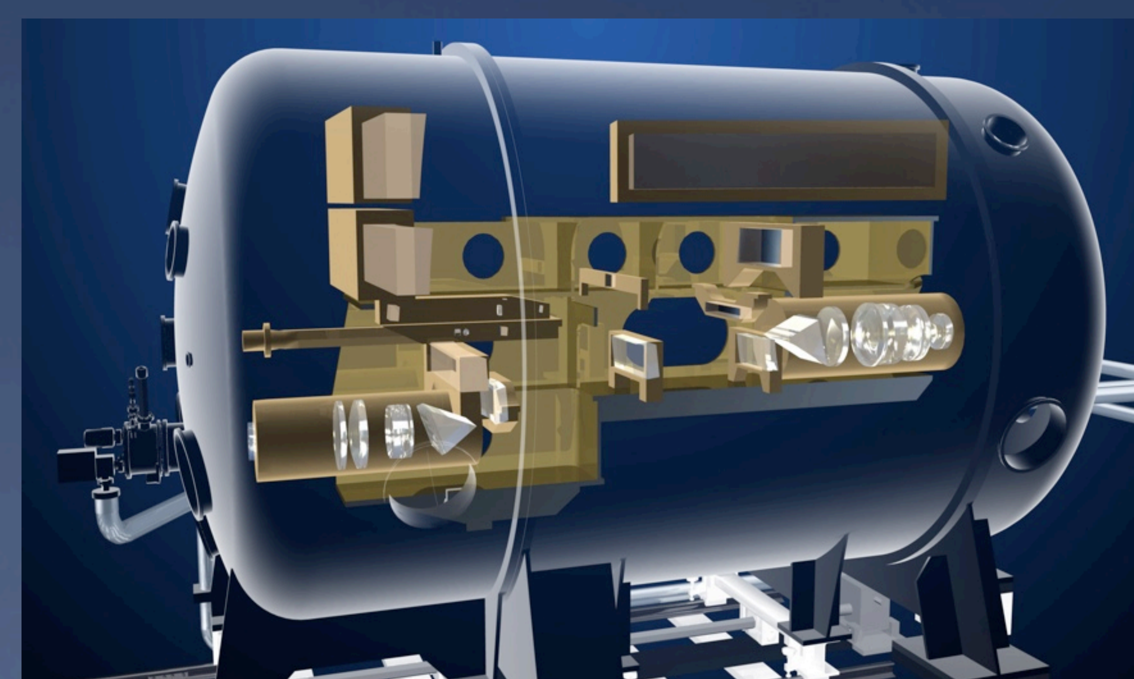
HARPS-N

* HARPS copy for northern hemisphere
* Follow-up of KEPLER candidates
* Search for Earth analogs
* Etc.

ESPRESSO@VLT

* Better precision on larger telescope
* Aim: 10 cm/s instrumental and photon noise
* Search for Rocky planets in habitable zone & variability of fundamental constants, etc.
* Up to 4 UTs incoherently





Summary of constraints/questions for theoretical approaches

- Mass distribution
  - Long tail towards high masses => Maximum mass of planets = ~25 M_{Jup}
  - Bimodal distribution: gaseous giants vs "solid" planets => occurrence frequency ratio
  - Increase towards lower masses
- Period distribution
  - Increasing distribution (in logP) => reservoir at large sep => Dmax for formation?
  - Giant planets: peak at 3 days, "Solid" planets: no pile-up => migration?
- Multi-planet systems
  - All kinds: only small masses or giants, mixed
  - Systems seem to be packed => planet spacing?
- Eccentricity distribution
  - Large range of observed values => origin? Importance of dynamics!
- Primary star properties
  - Metallicity - frequency correlation for gaseous giants, not for small-mass planets
  - Mass of planetary material scales with primary mass
- Constraints from transits
  - Variety in M-R relation (size, density)
  - System geometry (large fraction of misaligned systems) => formation processes?
  - Multi-transiting systems => formation? Importance of dynamics
- Atmospheres
- Habitability