Atmospheric Characterization and Further Orbital Fitting of κ And b

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ATMOSPHERIC CHARACTERIZATION AND FURTHER ORBITAL MODELING OF κ AND B

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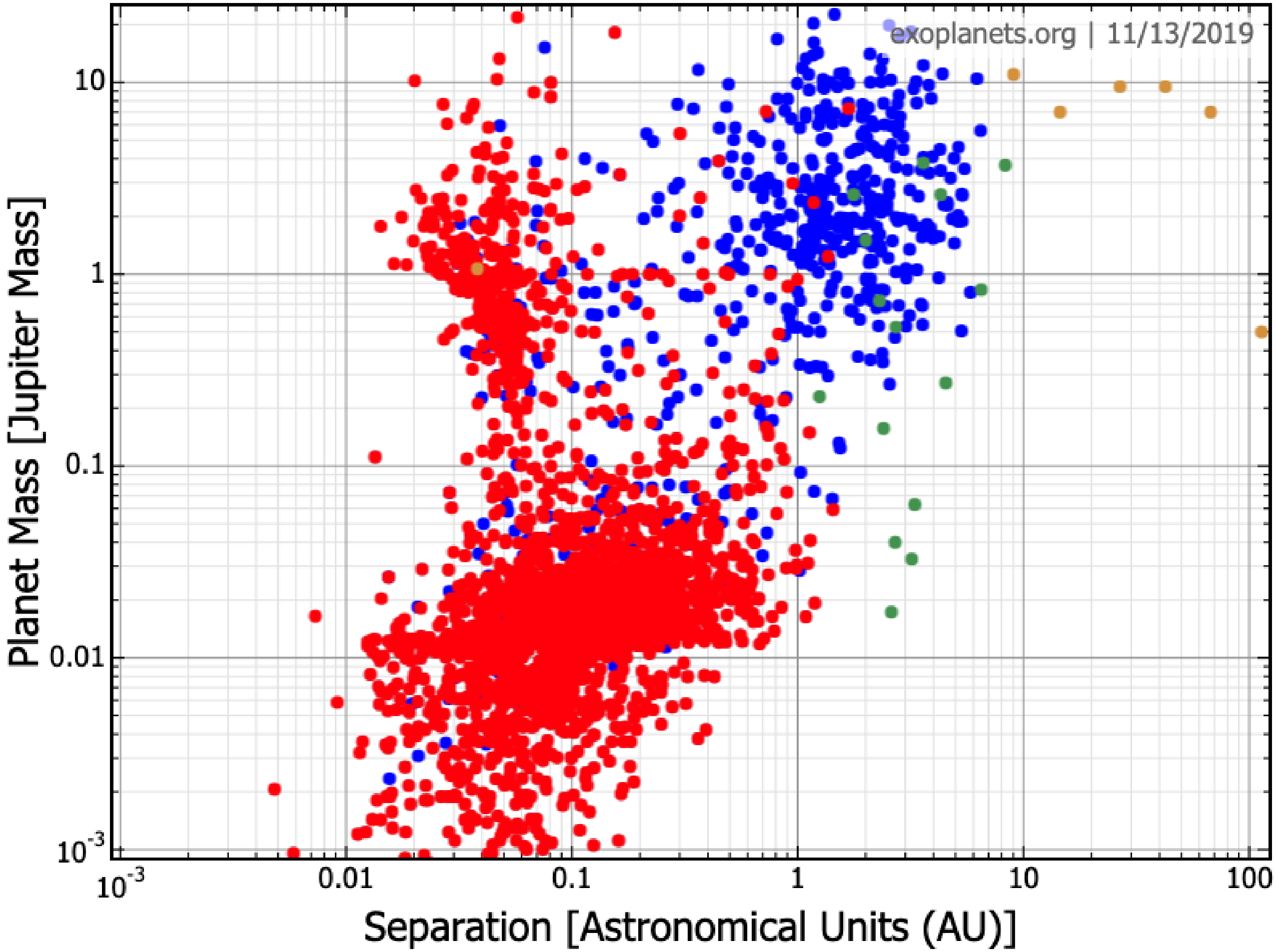
Direct Imaging of Exoplanets

other methods: transit, radial velocity, microlensing, etc.



- Direct imaging (High-contrast imaging)

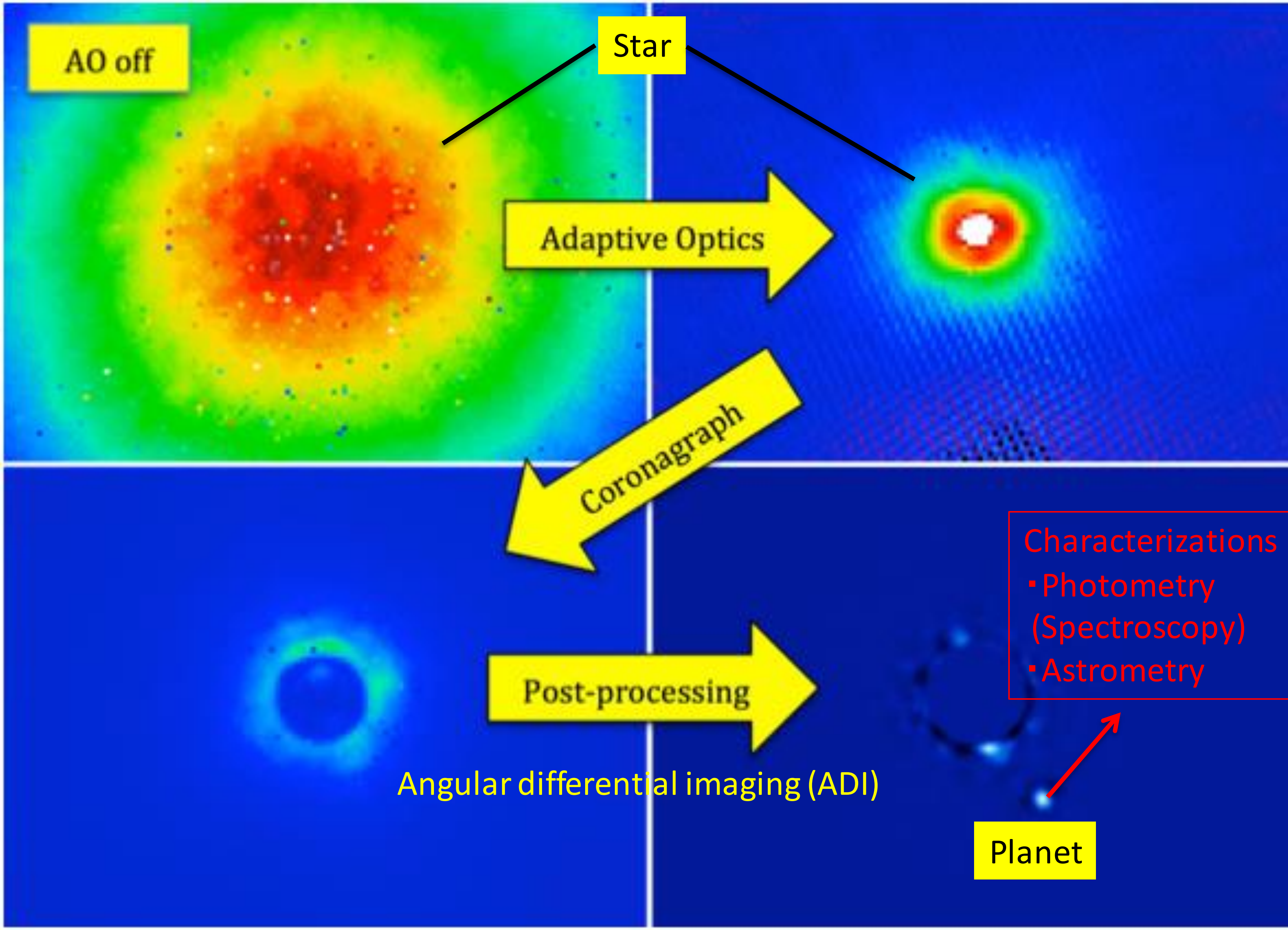
  - sensitive to young and wide-orbit Jovian planets

  -> useful information for planet formation and evolution mechanisms

  - smaller number of detections

  -> need more explorations and detailed characterizations

Flowchart of Direct Imaging



κ And system

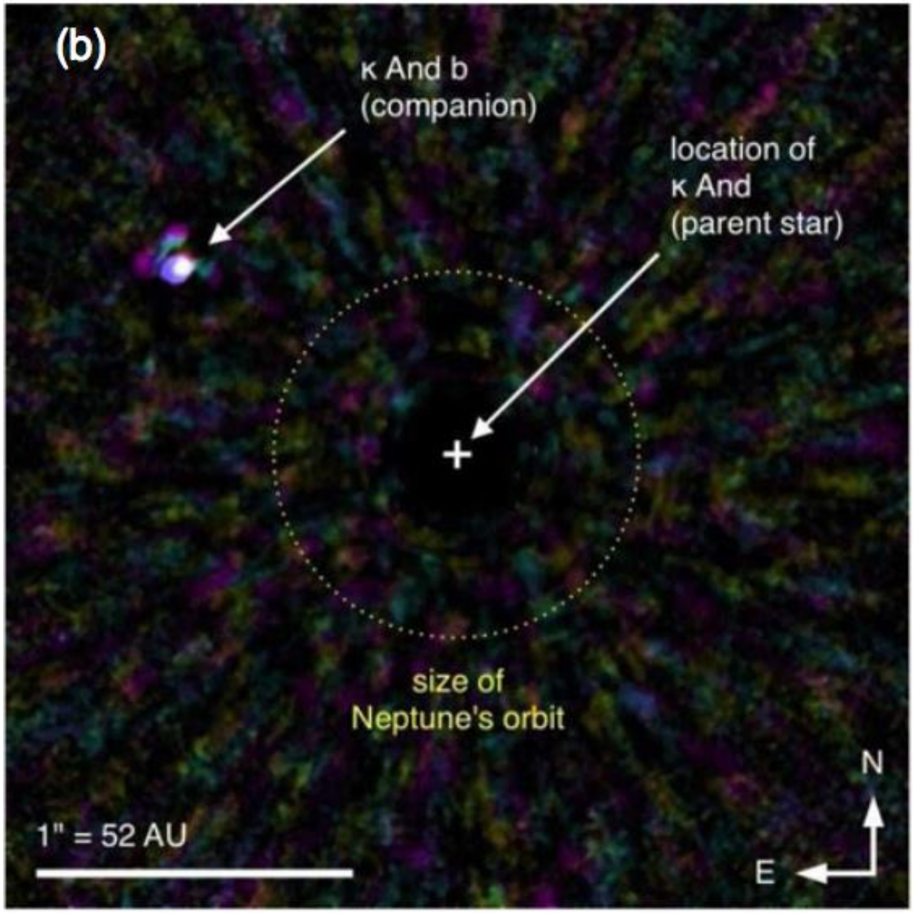
One of the first directly-imaged planets
(Discovered by SEEDS; Tamura2009)

age: ~40-50 Myr
distance: 50 pc
mass: ~13 M_J
Sp type: L0-L1
log (g): ~4.0-4.5?
T_{eff}: 1700-2000

- suggestions about formation mechanism
  - gravitational instability
  - similar separation to current location

- Little discussion of astrometry in the previous studies

references: Carson et al. (2013); Bonnefoy et al. (2014); Jones et al. (2016); Currie et al. (2018)



The first report of κ And b
(Carson et al., 2013)

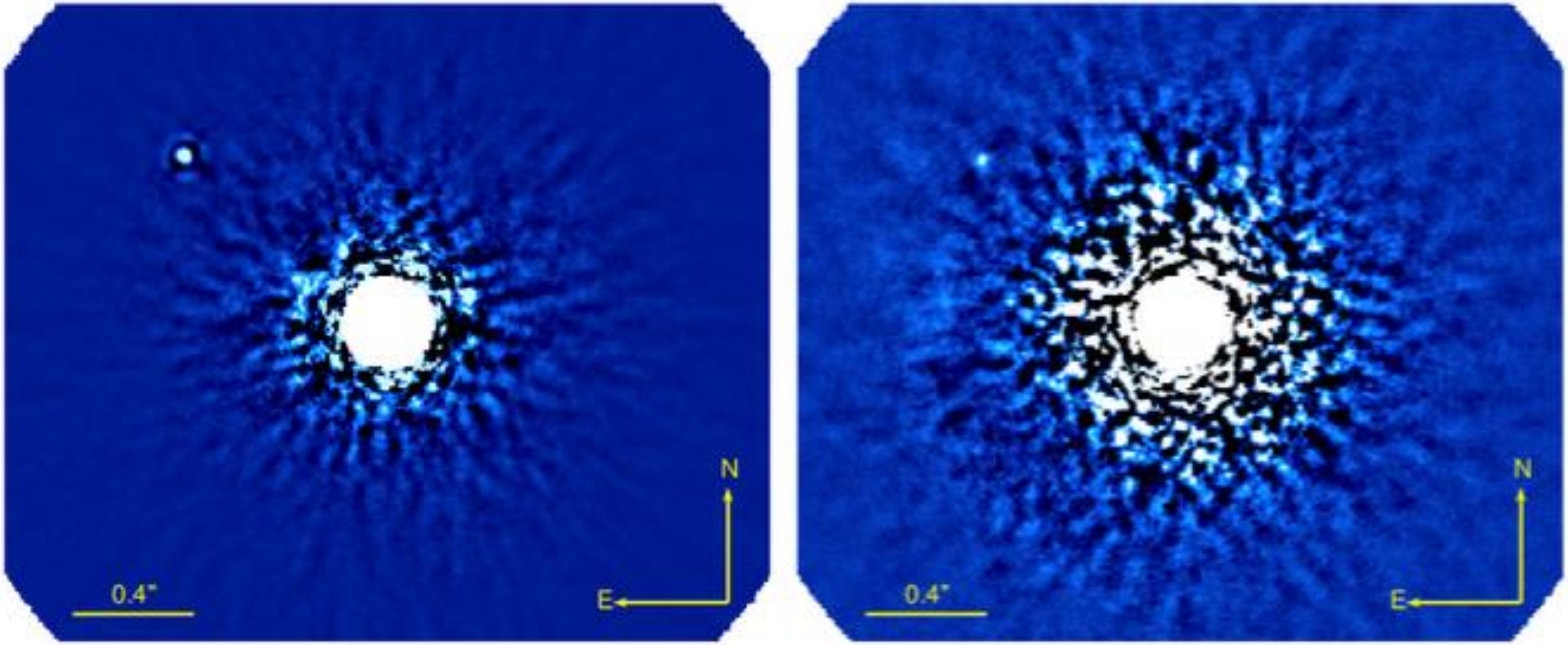
Observations and Results

- ADI reduction conducted

Date (*HST*)	instrument	Band	$T_{\rm exp}$ [min]	Rotation Angle [deg]	remarks
2015-08-02	Subaru/HiCIAO+SCExAO	*H*	35.0	27.70	SCExAO engineering obs
2016-07-18	Subaru/HiCIAO+SCExAO	*H*	25.0	41.70	science obs
2016-07-18	Subaru/HiCIAO+SCExAO	*Y*	30.5	41.31	science obs for photometry
2018-11-01	Keck/NIRC2	$K_{\rm s}$	10	3.70	science obs for astrometry

band	κ And A [mag]	κ And b [mag]
H	...	15.18±0.56 [a]
Y	4.28±0.09	16.60±0.15

a: bad *H*-band photometric references in both epochs



H-band (SNR~130) *Y*-band (SNR~10)

Photometry and Astrometry

Photometry

band	κ And A	κ And b	Ref.
Y [mag]	4.28±0.09	17.04±0.15	a
J [mag]	4.26±0.04	15.84±0.09	b
H [mag]	4.31±0.05	15.01±0.07	b
K_s [mag]	4.32±0.05	14.37±0.07	b
L' [mag]	4.32±0.05	13.12±0.1	c,d
$NB\_4.05$ [mag]	4.32±0.05	13.0±0.2	d
M' [mag]	4.30±0.06	13.3±0.3	d

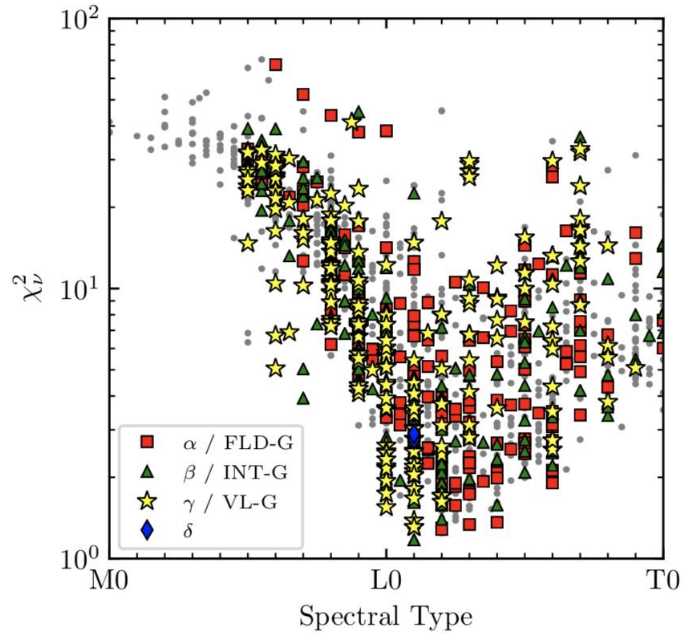
a. This work
b. Currie, Brandt, Uyama, et al. (2018)
c. Carson et al. (2013)
d. Bonnefoy et al. (2014)

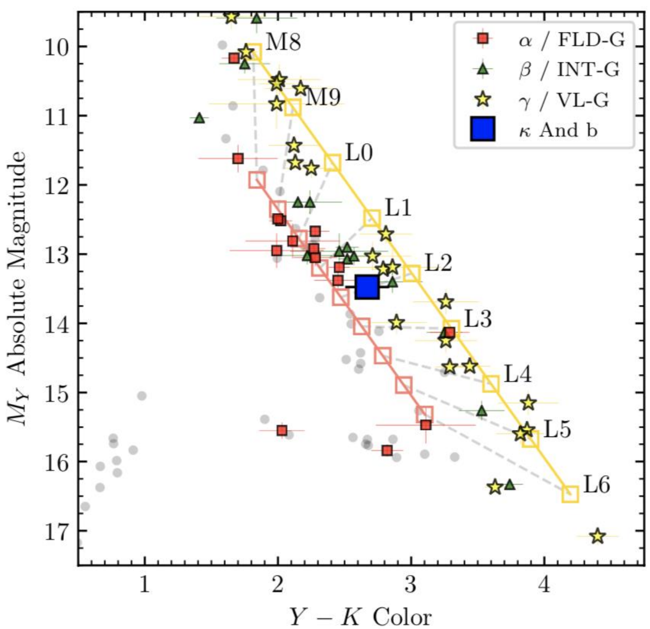
Astrometry

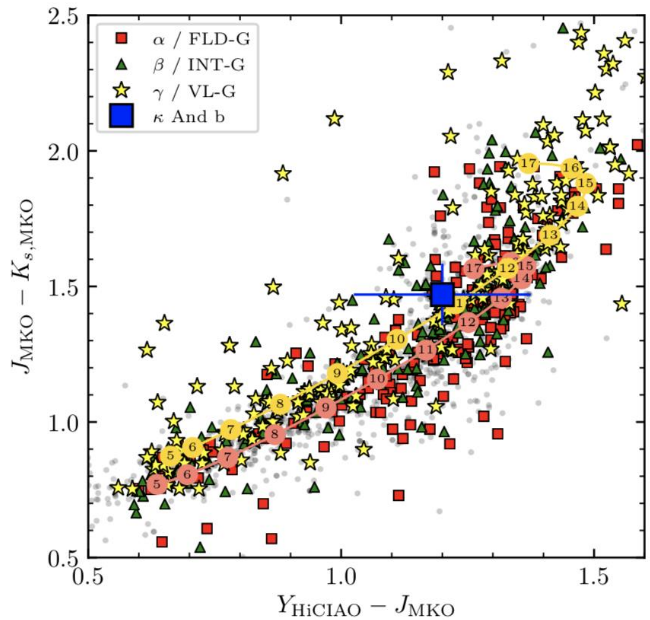
Date (UT)	instrument	ΔRA [″]	ΔDec [″]	Ref.
2011-01-01	Subaru/AO188+HiCIAO	0.884±0.010	0.603±0.011	c
2011-07-08	Subaru/AO188+HiCIAO	0.877±0.007	0.592± 0.007	c
2012-11-03	Keck/NIRC2	0.846±0.010	0.584±0.010	b, d
2013-08-18	Keck/NIRC2	0.829±0.010	0.585±0.010	b
2016-07-18	Subaru/SCExAO+HiCIAO	0.734±0.008	0.599±0.007	a
2017-09-05	Subaru/SCExAO+CHARIS	0.710±0.016	0.576±0.012	b
2017-12-09	Keck/NIRC2	0.699±0.010	0.581±0.010	b
2018-11-01	Keck/NIRC2	0.656±0.006	0.580±0.006	a

Empirical Comparisons with Spectral Libraries

- *Y*(HiCIAO) and *JHK*(CHARIS)-bands are used
- Empirical comparisons with spectral libraries: κ And b likely has a low surface-gravity
- Some best-fit objects (field-gravity objects) may have lower gravity than previously classified

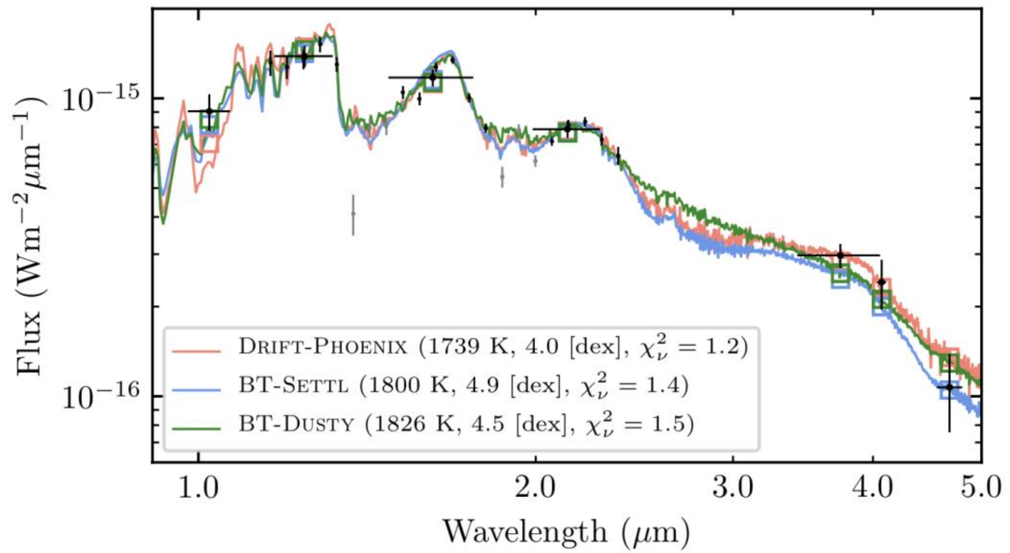






Atmospheric Modeling

- spectrophotometric results between *Y*-*M'* bands
- A variety of models used for comparison
- The best-fit 3 models: DRIFT-PHOENIX, BT-SETTL, BT-DUSTY



Model Properties							Best fit			
Name	Ref.	Special Remark	$T_{\rm eff}$ (K)	$\log g$ [dex]	$\Delta T_{\rm eff}$ (K)	$\Delta \log g$ [dex]	$T_{\rm eff}$ (K)	$\log g$ [dex]	R ($R_{\rm Jup}$)	χ^2_ν
Clear models										
AMES-COND	a	...	1000–2400	2.5–6.0	100	0.5	2400	4.0	0.74	29.7
BT-COND	b	...	1000–2200	4.0–5.5	100	0.5	2200	4.0	0.85	20.4
Burrows	c	...	1000–2000	4.5–5.5	100	0.5	2000	4.5	0.90	53.9
Cloudy models										
AMES-DUSTY	a	...	1000–2500	3.5–6.0	100	0.5	1800	5.0	1.19	3.62
BT-DUSTY	b	...	1000–2400	4.5–5.5	100	0.5	1800	4.5	1.64	1.81
BT-SETTL	b	Asplund et al. (2009) abundances	1000–2400	3.0–5.5	100	0.5	1900	4.5	1.23	2.80
BT-SETTL	b	Caffau et al. (2011) abundances	1000–2400	3.5–5.5	50	0.5	1800	5.0	1.34	1.70
BT-SETTL-2015	b	...	1200–2400	3.0–5.5	50	0.5	1750	5.5	1.37	3.49
BT-SETTL-bc	b	...	1100–2400	3.0–5.5	100	0.5	1800	4.0	1.30	2.99
DRIFT-PHOENIX	d	...	1000–2400	3.0–6.0	100	0.5	1700	4.0	1.57	1.66
Burrows	c	Nominal cloud model, 100μm modal size (E100)	1000–2000	4.5–5.5	50	0.1	1800	4.6	1.25	7.08
Burrows	e	Thick clouds, 4μm modal size (A4)	1800–2200	3.5–4.0	25–100	0.25	1900	4.0	1.23	6.39
Burrows	e	Thick clouds, 10μm modal size (A10)	1800–2200	3.6–4.0	100	0.1	2000	4.0	1.09	3.24

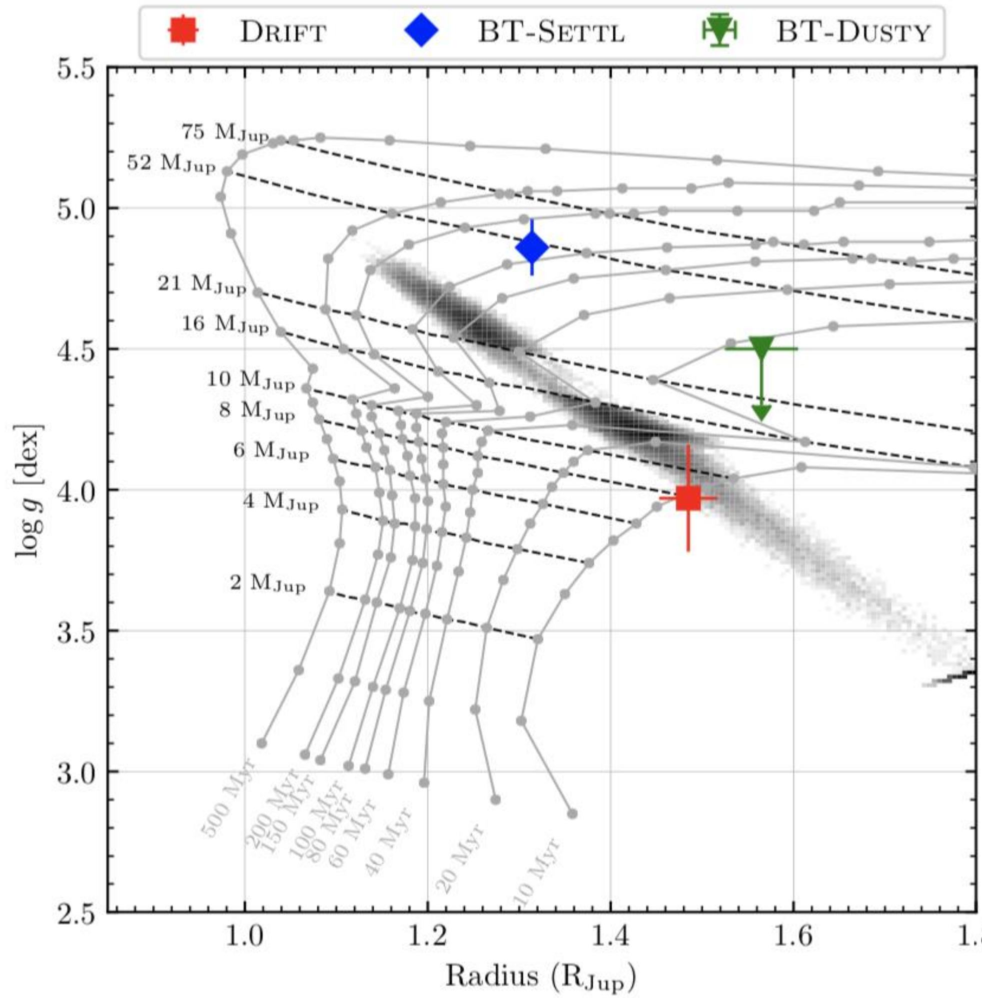
a: Allerd et al. (2001), b: Allard et al. (2012), c: Burrows et al. (2006), d: Write et al. (2011), e: Currie et al. (2014)

Comparison with an Evolutionary Model (COND03)

・The best-fit three models are compared with isochrones in terms of radius and surface gravity.

・These models suggest different age and mass for κ And b

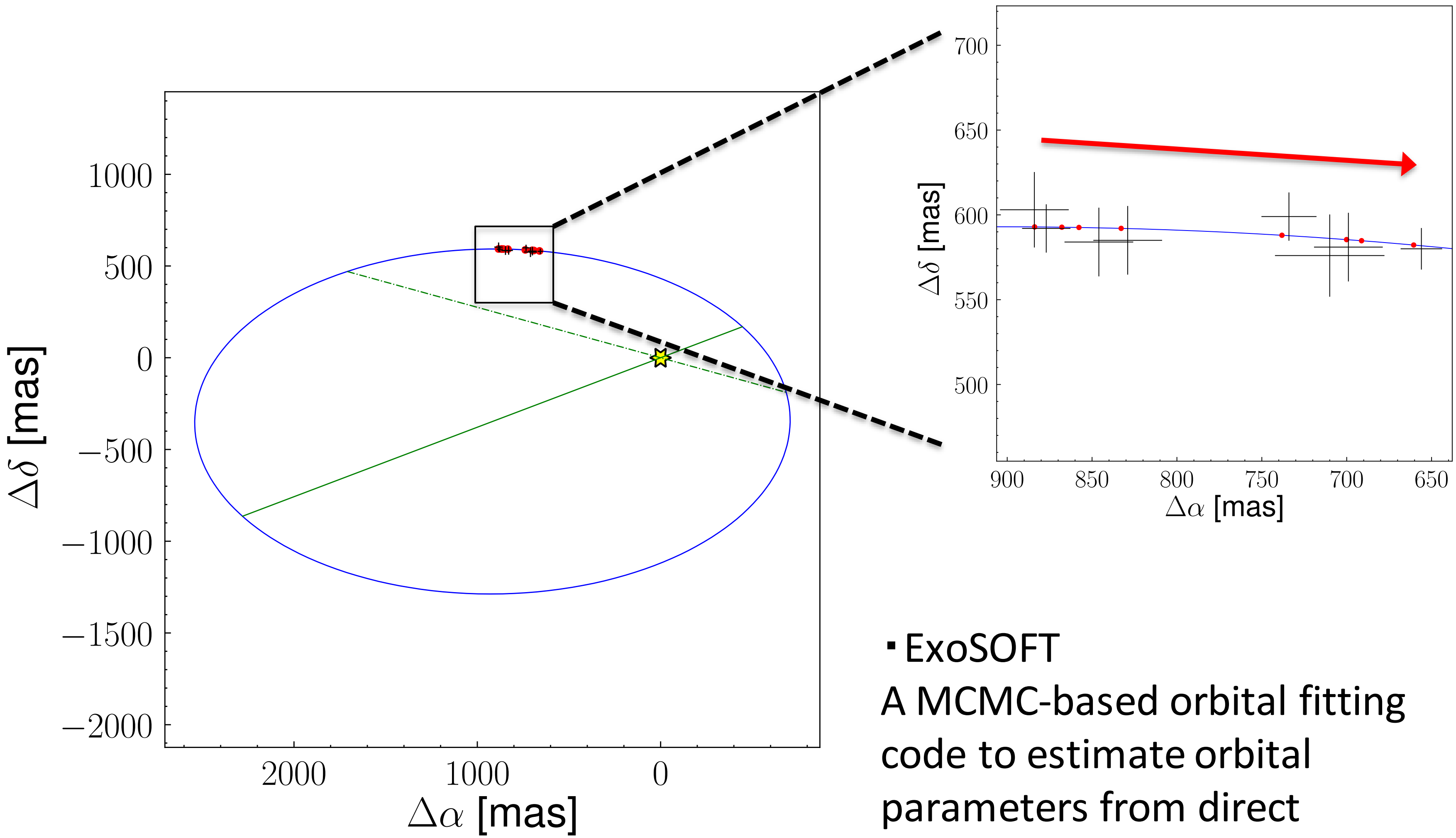
・The DTIFT-PHOENIX model (the best-fit one) implies a radius and gravity consistent with evolutionary model predictions of the age (t < 40 Myr)



・Gray lines: Isochrones (COND 03; Baraffe et al. 2003)

・Black Contours: Measured luminosity of κ And b (Currie et al. 2018)

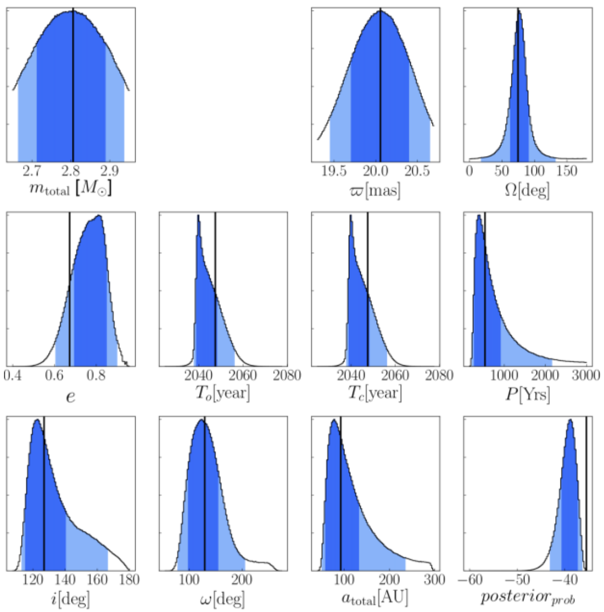
Orbital Fitting with ExoSOFT



- ExoSOFT

A MCMC-based orbital fitting code to estimate orbital parameters from direct imaging and/or radial velocity (Mede & Brandt; 2017)

Orbital Parameters of κ And b



- Eccentricity – the first eccentric and wide-orbit planet
- orbital migration via planet-planet scattering?
- previous studies assumed on-site formation

This work

Parameter	Median	68% confidence level	95% confidence level
$a_{\rm tot}$ [au]	103.6	[57.4, 133.4]	[50.3, 236.0]
P [yr]	631.1	[242.4, 900.4]	[198.6, 2148.9]
e	0.77	[0.69, 0.85]	[0.60, 0.90]
i [deg]	130.0	[114.9, 140.0]	[112.6, 166.6]
ω [deg]	130.7	[96.6, 155.4]	[77.0, 205.0]
Ω [deg]	76.5	[61.3, 90.5]	[16.4, 132.1]
T_0 [yr]	2044.1	[2038.4, 2047.9]	[2037.5, 2056.3]

c.f.

	Bonnefoy et al. (2018)	Wang et al. (2018)[a]			
Parameter	GJ 504 b	HR 8799 b	HR 8799 c	HR 8799 d	HR 8799 e
$a_{\rm tot}$ [AU]	44 ± 11	$69.5^{+9.3}_{-7.0}$	$37.6^{+2.2}_{-1.7}$	$27.7^{+2.2}_{-1.7}$	$15.3^{+1.4}_{-1.1}$
e	0.31 ± 0.15	0.15 ± 0.05	0.09 ± 0.04	0.15 ± 0.11	$0.13^{+0.06}_{-0.05}$
i [deg]	$137.8^{+12.9}_{-4.6}$	29^{+7}_{-8}	20^{+4}_{-5}	33 ± 4	31 ± 5

a: unconstrained model

Constraints on Planet-Planet Scattering

▪ Assumptions

1) three planets with coplanar and circular orbits
2) one of them was ejected previously
3) the ejected one has smaller mass than κ And b
4) these three objects have similar diameters

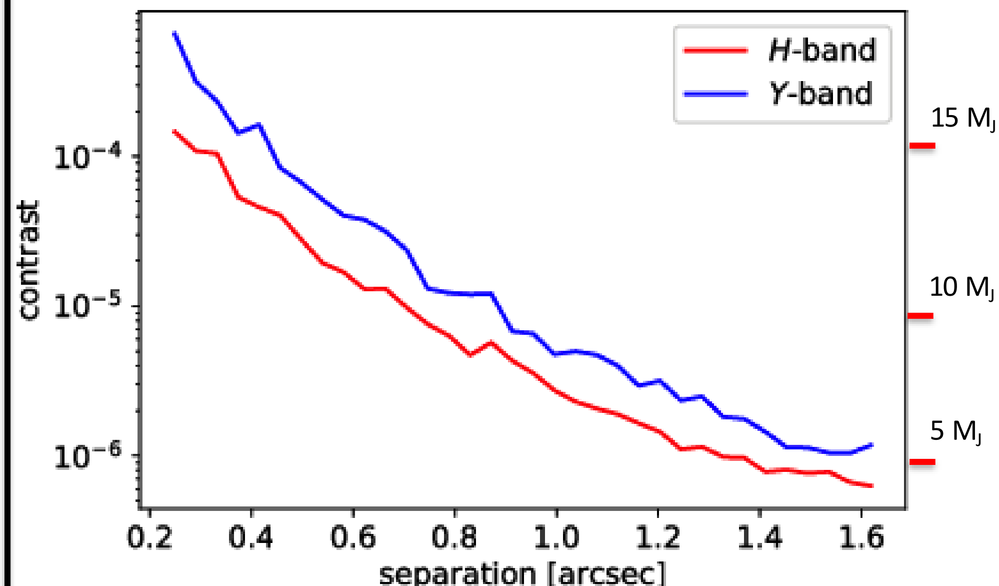
$$e_{\rm out} \simeq \frac{m_{\rm in}}{m_{\rm out}} \times \sqrt{\frac{m_{\rm out}+m_{\rm eje}}{m_{\rm out}+m_{\rm in}}}$$

Ida et al. (2013)

assuming m_{out}=13 M_J, e_{out}=0.77±0.08

ejected object $[M_{\rm Jup}]$	inner object $[M_{\rm Jup}]$
2	$13.2^{+1.9}_{-1.7}$
4	$12.2^{+1.7}_{-1.6}$
6	$11.3^{+1.6}_{-1.5}$
8	10.6 ± 1.4
10	$10.0^{+1.4}_{-1.3}$

▪ 5σ contrast limits



▪ Mass limits

- 15 M_J, 12 M_J, 7 M_J at 12.5, 25, and 50 AU
- 15 M_J, 8-10 M_J, 3-5 M_J (converted mass limit from Currie et al. 2018)

(assuming COND03 model and 47 Myr)

-> a potential inner planet is located at 25 AU or less

How to Detect/Constrain the Potential Inner Planet?

- Radial velocity

- $\sigma_{RV} \geqq$ 1km/s (Hinkley et al., 2013; Becker et al., 2015)
  -> κ And is not a suitable target for accurate radial velocity measurement

- Host-star astrometry

- a combination of *Gaia* and *Hipparcos*
- κ And is too bright for accurate acceleration estimation

- Future high-contrast imaging

- TMT enables better contrast
- better orbital fitting with more plots of κ And b over next 10 years

↓

Continuing high-contrast imaging is better to constrain migration scenarios of κ And b.

Summary

This study shows a good example about
how we characterize a directly-imaged planet

▪New Data:
SCExAO+HiCIAO *YH*-band and Keck/NIRC2 Ks-band results of κ And b

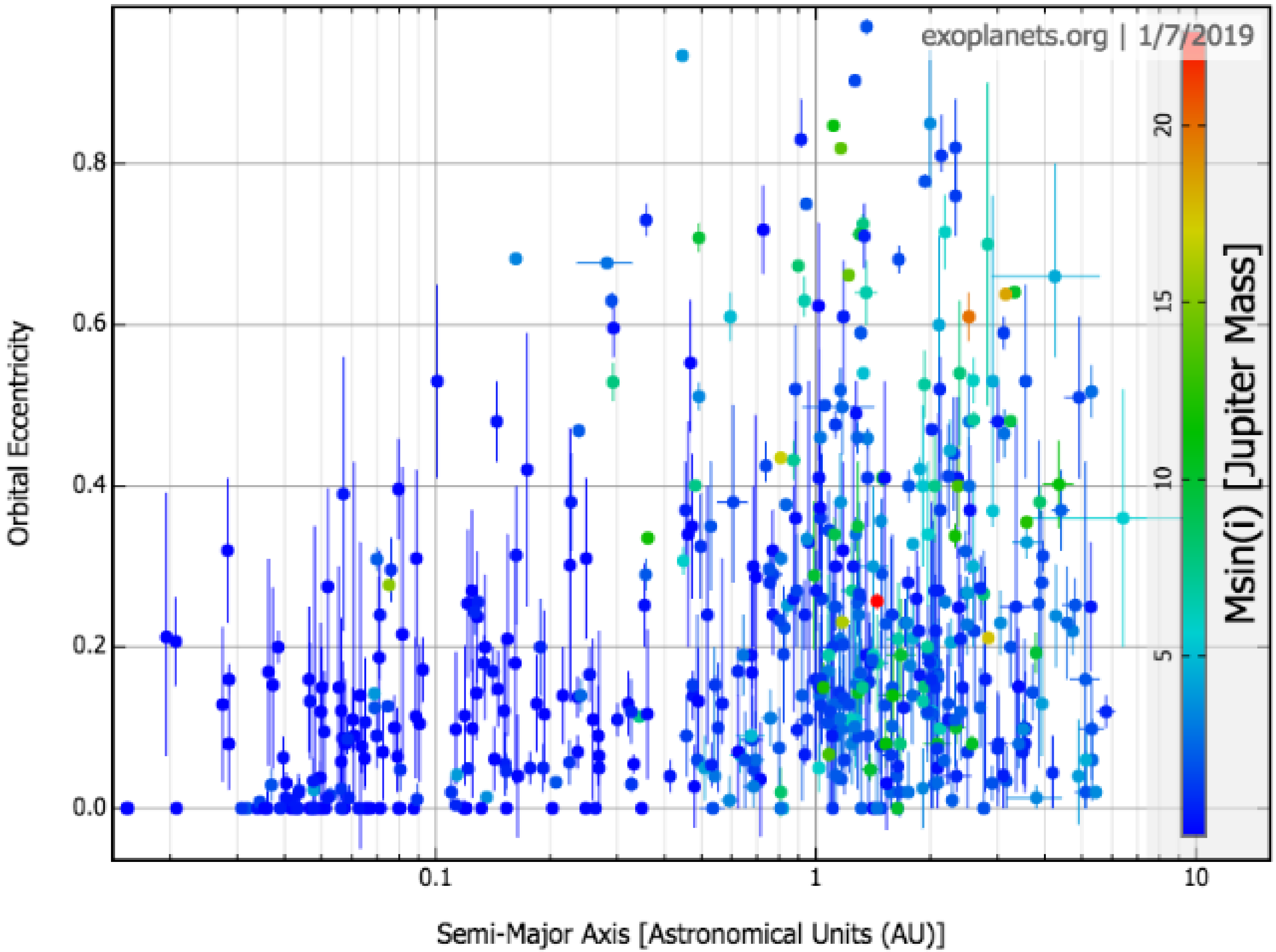
▪Empirical comparisons with spectral libraries
- suggestion of low surface gravity

▪Atmospheric modeling
- the DRIFT-PHOENIX matches κ And b's SED between *Y* and *M′* bands
- the model implies a radius and gravity consistent with predictions of the system age (t < 40 Myr)

▪Astrometry
- orbital fitting suggested a large eccentricity
- suggestion of planet-planet scattering?
-> further exploration with TMT!

Auxiliary slides

Eccentricity Distributions of Reported Exoplanets



Used Relationships in ExoSOFT

Define parameters of A, B, F, and G as follows:

$$A = a_{\text{tot}}[\cos(\Omega_2)\cos(\omega_2) - \sin(\Omega_2)\sin(\omega_2)\cos(i)]$$
$$B = a_{\text{tot}}[\sin(\Omega_2)\cos(\omega_2) + \cos(\Omega_2)\sin(\omega_2)\cos(i)]$$
$$F = a_{\text{tot}}[-\cos(\Omega_2)\sin(\omega_2) - \sin(\Omega_2)\cos(\omega_2)\cos(i)]$$
$$G = a_{\text{tot}}[-\sin(\Omega_2)\sin(\omega_2) + \cos(\Omega_2)\cos(\omega_2)\cos(i)],$$

as well as X(t) and Y(t)

$$X(t) = \cos(E(t)) - e$$
$$Y(t) = \sqrt{1-e^2}\sin(E(t)),$$

where E(t) is given by

$$M(t) \equiv \frac{2\pi}{P}(t - T_0)$$
$$M(t) = E(t) - e \times \sin(E(t)).$$

Finally relative positions of Δδ and Δα are provided

$$\Delta\delta = AX(t) + FY(t)$$
$$\Delta\alpha = BX(t) + GY(t)$$