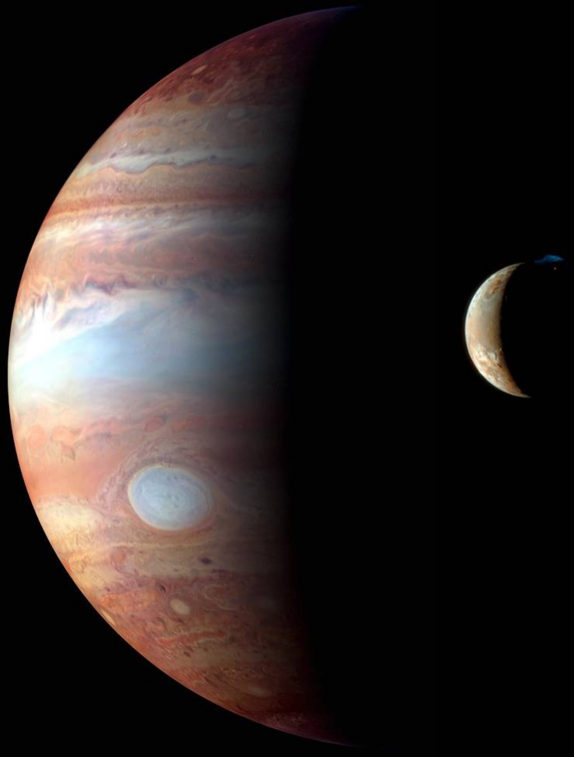


NASA/JPL

RV Measurements of Directly Imaged Brown Dwarf GQ Lup B to Search for Exomoons

Katelyn Horstman[1,4], JB Ruffio[2], Dimitri Mawet[1,3]

[1]Caltech Exoplanet Technology Lab, [2]UC San Diego, [3]JPL,

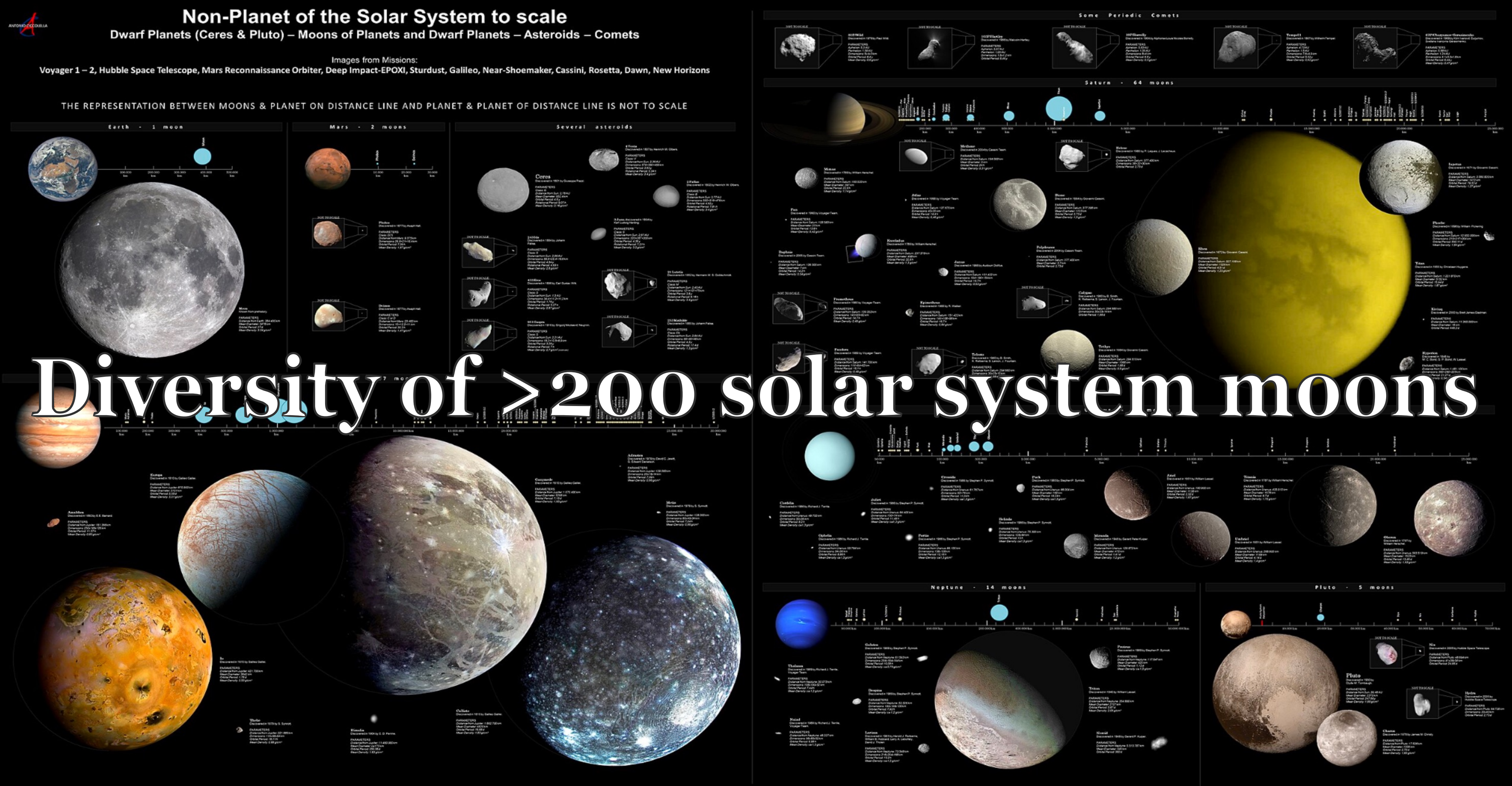
[4]NSF Graduate Research Fellow


NASA

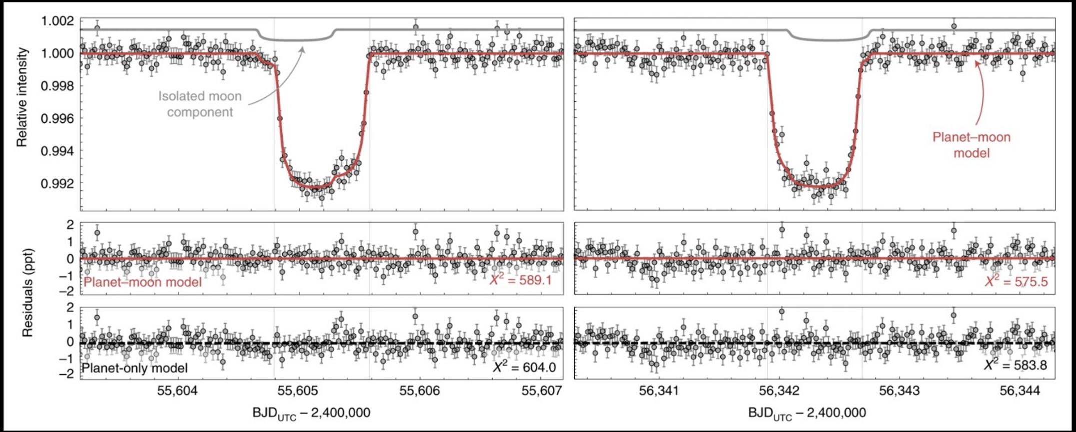
Why are moons important?

- Exoplanet formation
- Circumplanetary disks
- New places to search for habitability

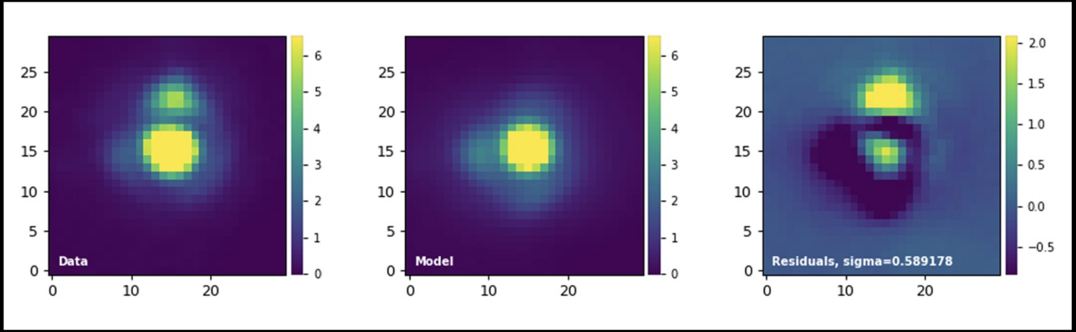
Diversity of >200 solar system moons



Few exomoon candidates, but none confirmed



Transits (Teachey et al. 2018; **Kipping et al. 2022**)



High contrast imaging **(Lazzoni et al. 2020)**

Exomoon Formation Pathways

- **Gravitational instabilities**
- **Capture**
- **Collisions**
- **Circumplanetary disk (CPD)**
    - CPD dust mass ~ 10^{-4}
    - Moonlets form from solids, but can also accrete gas
    - Larger planets may form even larger moons:

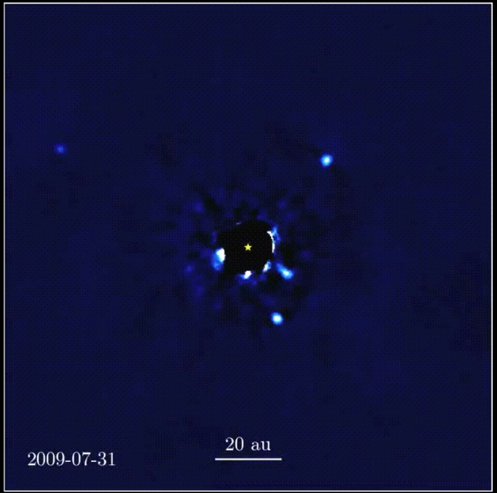
$$m \propto M^{3/2}$$

(Batygin, K., & Morbidelli, A. 2020)

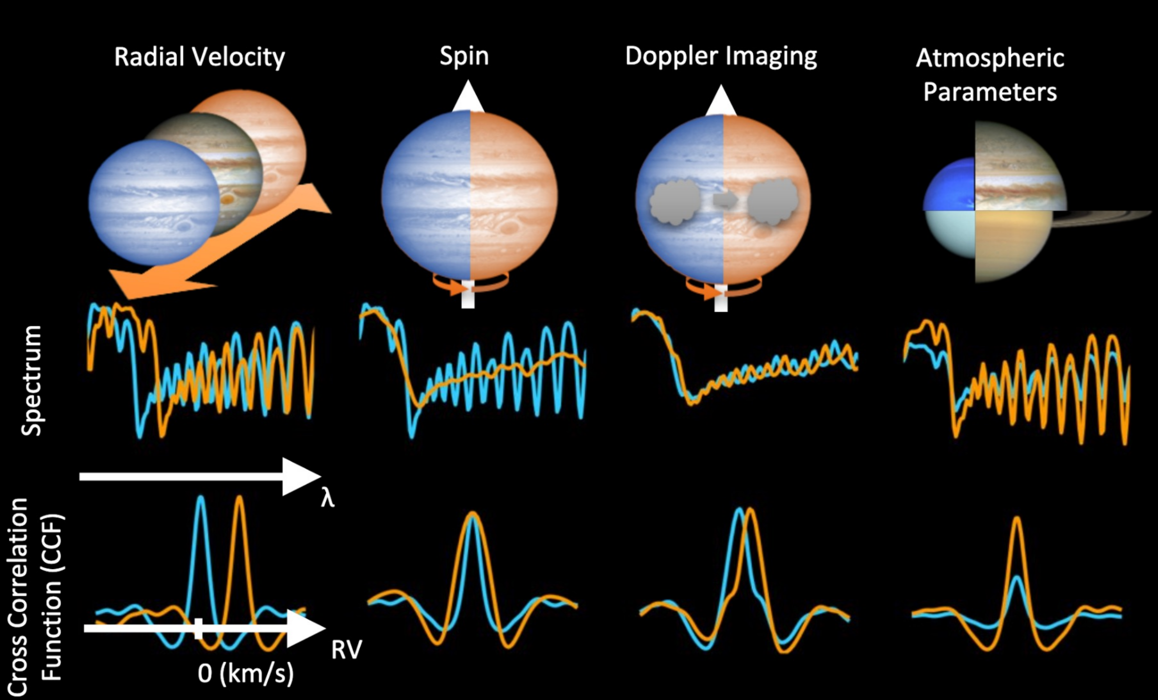
Benisity et. al 2021

RV Measurements of Directly Imaged Planets

KPIC



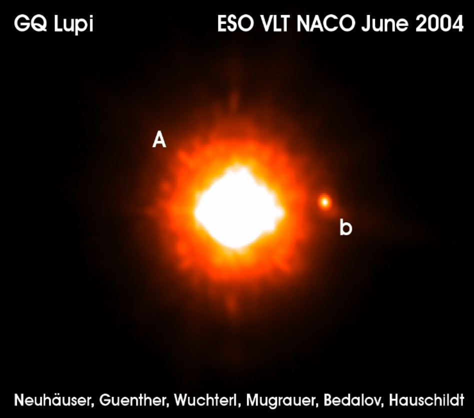
Jason Wang et al



JB Ruffio

RV Measurements of Directly Imaged Planets

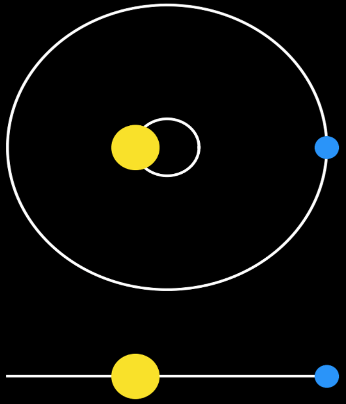
- Isolate the light of the planet
  - high contrast imaging
- High resolution spectrum
  - Derive planet RV



Neuhäuser, Guenther, Wuchterl, Mugrauer, Bedalov, Hauschildt

+

Alysa Obertas (@AstroAlysa)



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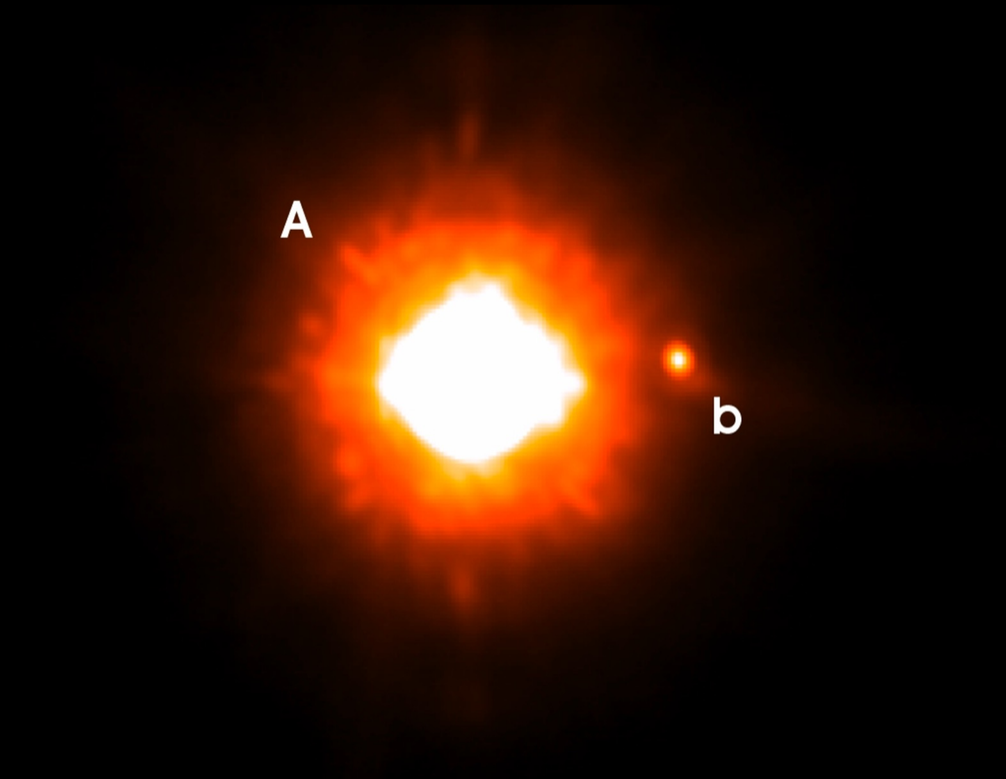
NASA/JPL

GQ Lupi B

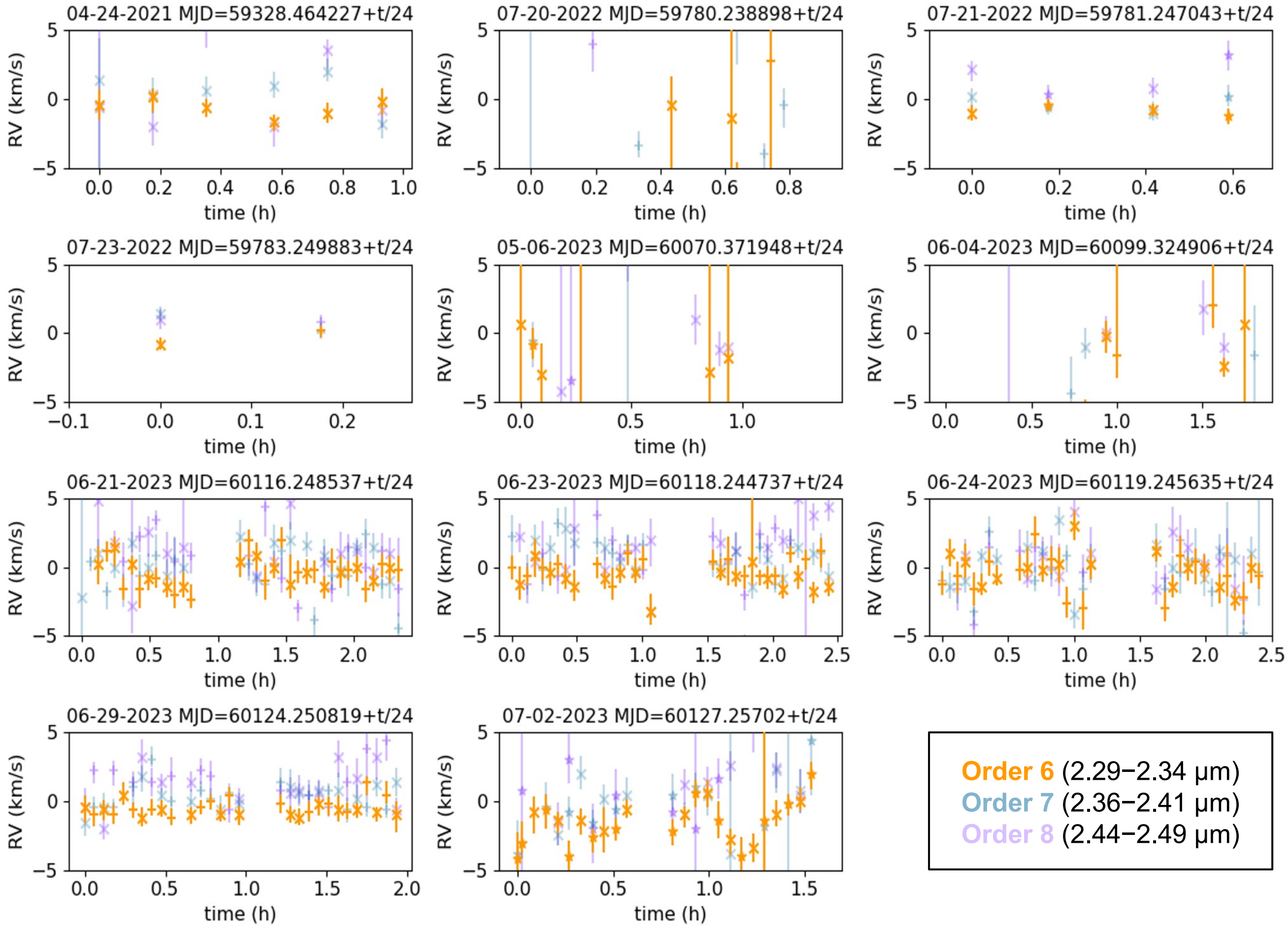


Neuhäuser, Guenther, Wuchterl, Mugrauer, Bedalov, Hauschildt
ESO VLT NACO June 2004

- Measured cavity in CPD (Stolker et al 2021)
- Likelihood to harbor proportionally more massive moons
- Properties = high precision RVs

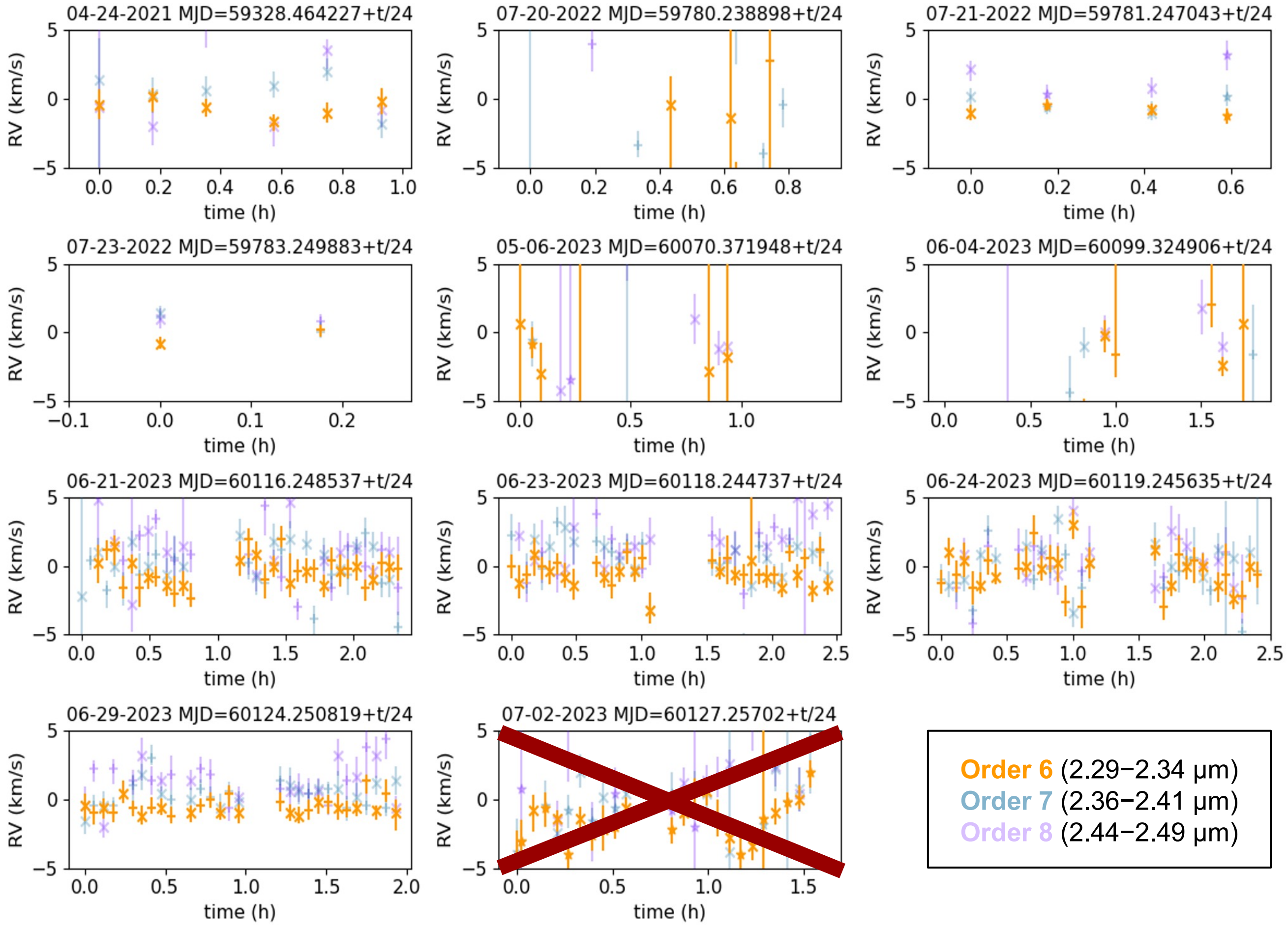
GQ Lup B
RV Time Series

- 180 s exposures
- 7 epochs
  (11 total)
- ~19.5 hours of monitoring
  (~22.25 total)
- RV precision
  400-1000 m/s
  (best/median)



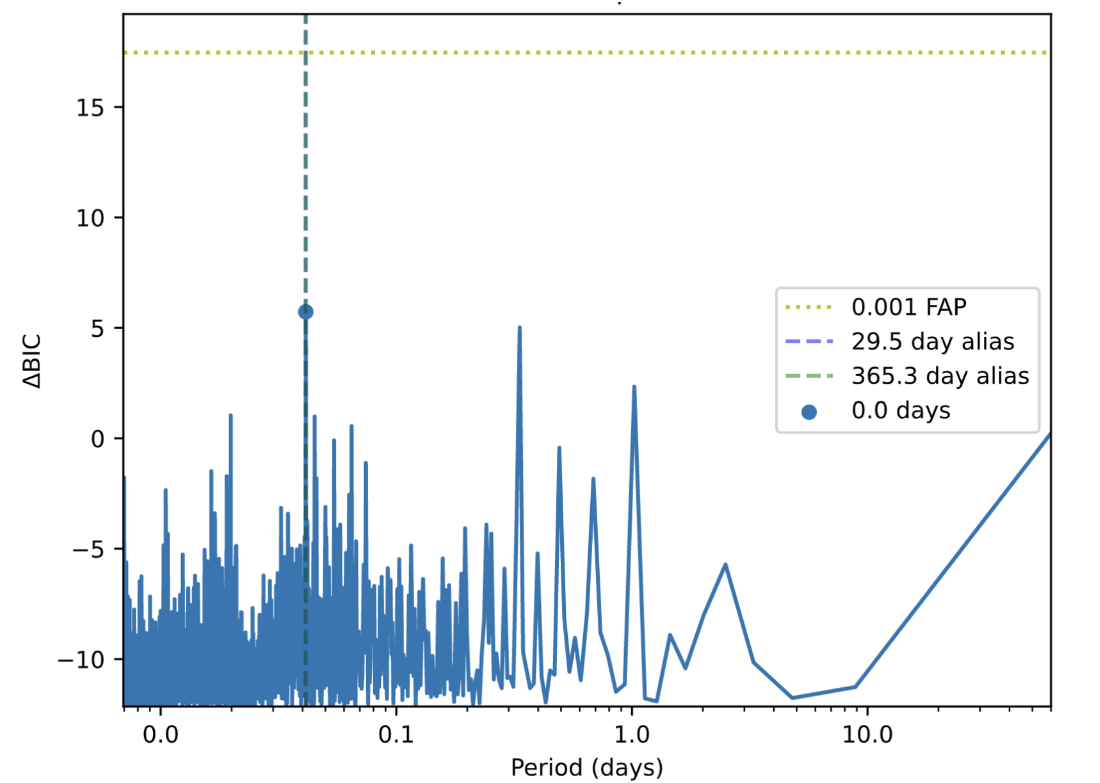
GQ Lup B
RV Time Series

- 180 s exposures
- **6 epochs (10 total)**
- **~18 hours of monitoring (~20.75 total)**
- RV precision 400-1000 m/s (best/median)



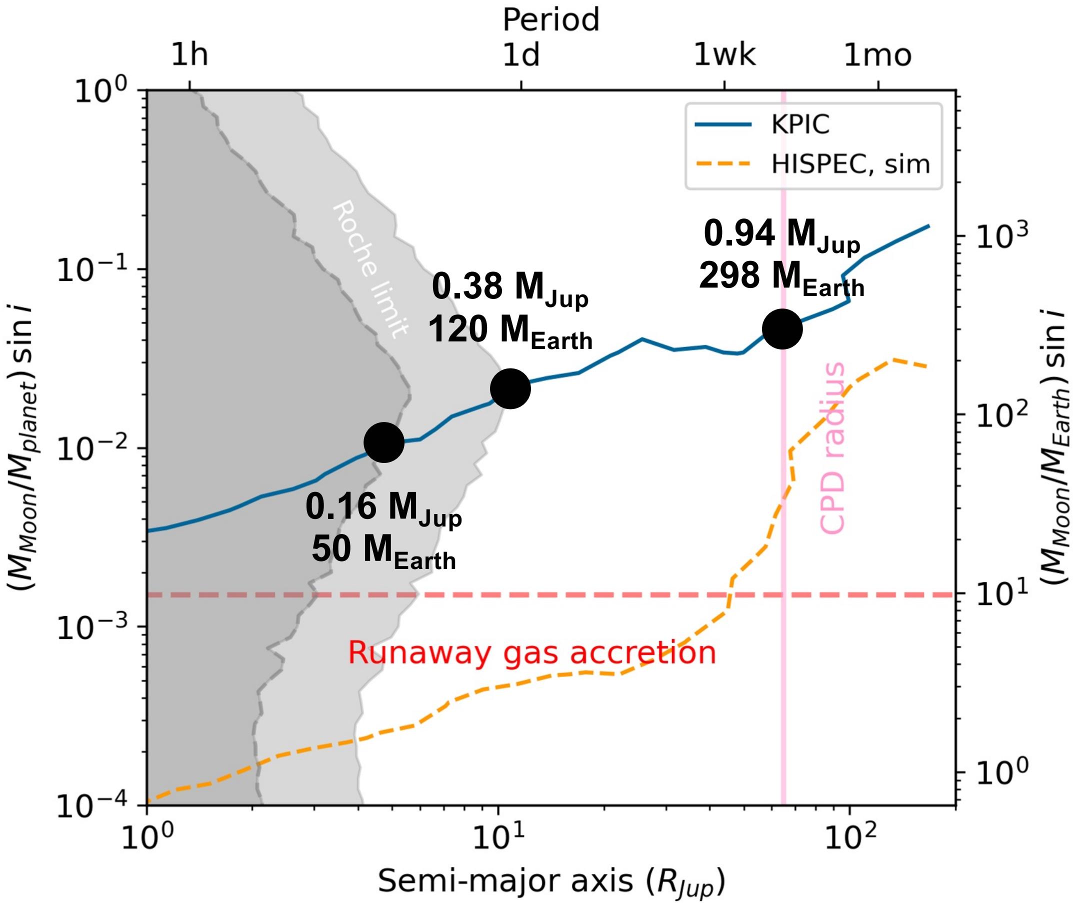
GQ Lup B
exomoon detection threshold

- No companion detected



GQ Lup B
exomoon recovery curve

- ~0.8-1.9% between ridgid/fluid Roche limits
- ~4.7% at a separation of $65R_{Jup}$
- Less massive/multiple moons?



NASA/JPL/University of Arizona

Questions?

Contact me: khorstma@astro.caltech.edu
khorstman.github.io

Summary:

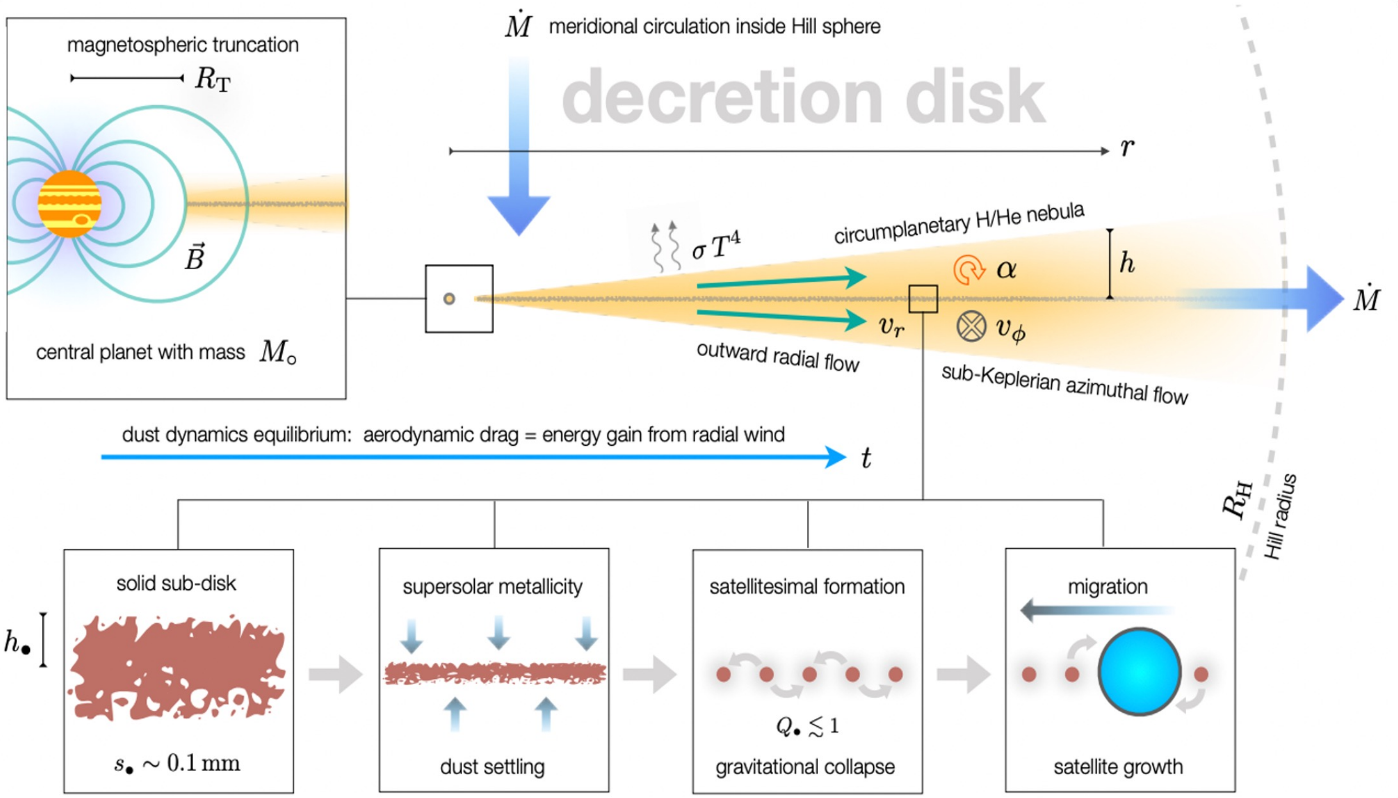
- First dedicated RV campaign to look for exomoons
- KPIC sensitive to 0.8-4.7% mass ratios within the cavity
  - No exomoons with mass ratio > ~10^{-2}

Future and current work:

  - Ongoing exomoon survey
  - Simulations of CPD cavity
  - Develop code to extend to other instruments (HISPEC/MODHIS)

Additional Slides

Exomoon Formation in the CPD



(Batygin, K., & Morbidelli, A. 2020)

Moon Mass Scaling Relation

- Equate the accretion and migration timescales
  - Non-trivial and non-linear dependence on mass

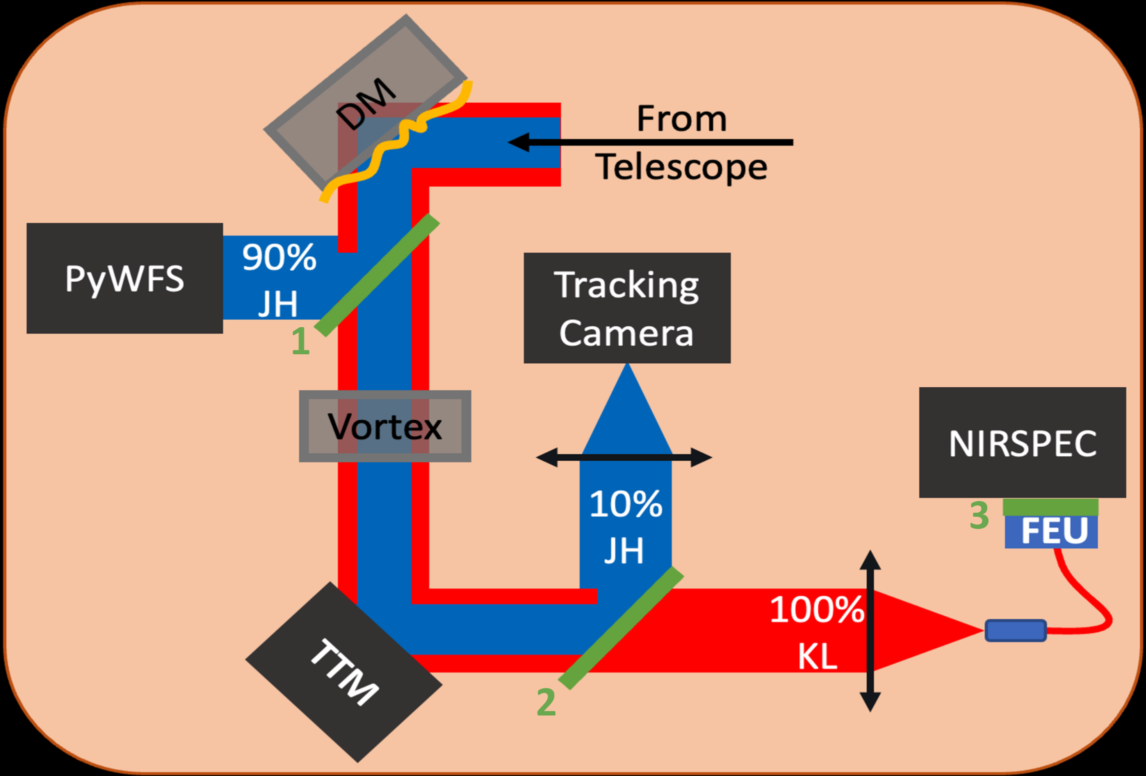
$$\mathcal{T}_{\rm accr} = \frac{4\,\bar{\rho}\,(\mathcal{R}-\mathcal{R}_0)}{\kappa\,\Lambda\,\mathcal{Z}\,(1+\Theta)\,\Sigma\,\Omega}. \qquad (41)$$

$$\mathcal{T}_{\rm mig} = \frac{\gamma}{\Omega}\,\frac{M_\circ}{\mathcal{M}}\,\frac{M_\circ}{\Sigma\,r^2}\left(\frac{h}{r}\right)^2, \qquad (42)$$

$$\boxed{\mathcal{R}^3\,(\mathcal{R}-\mathcal{R}_0) \sim \frac{3\,\kappa\,\gamma}{16\,\pi}\left(\frac{h\,M_\circ}{\bar{\rho}\,r^2}\right)^2 \mathcal{Z}\,\Lambda\,(1+\Theta).} \qquad (43)$$

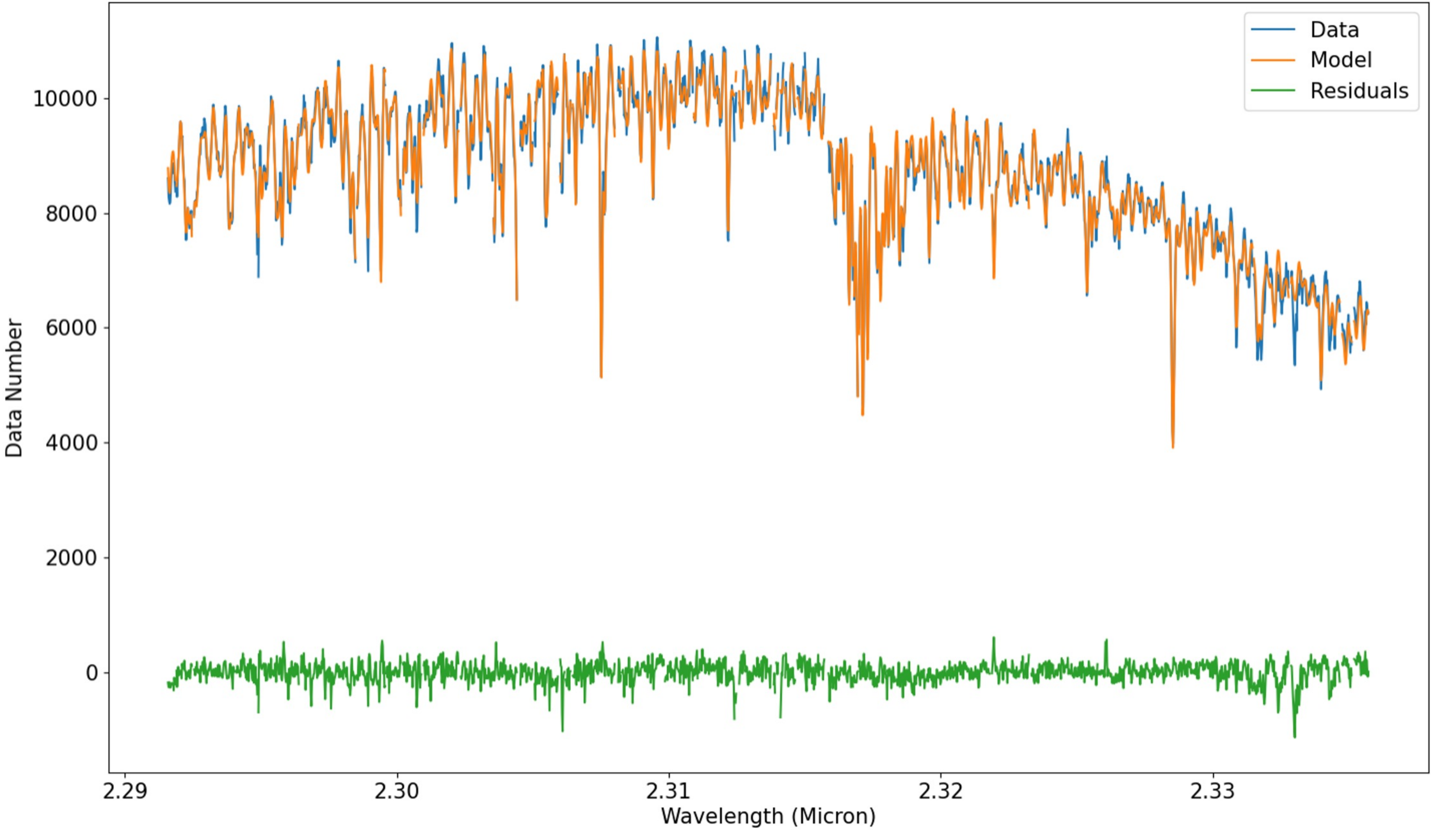
Transmissive optics can cause light interference

1. PyWVS Pickoff Dichroic
1. TC Pickoff Dichroic
1. NIRSPEC Entrance Window

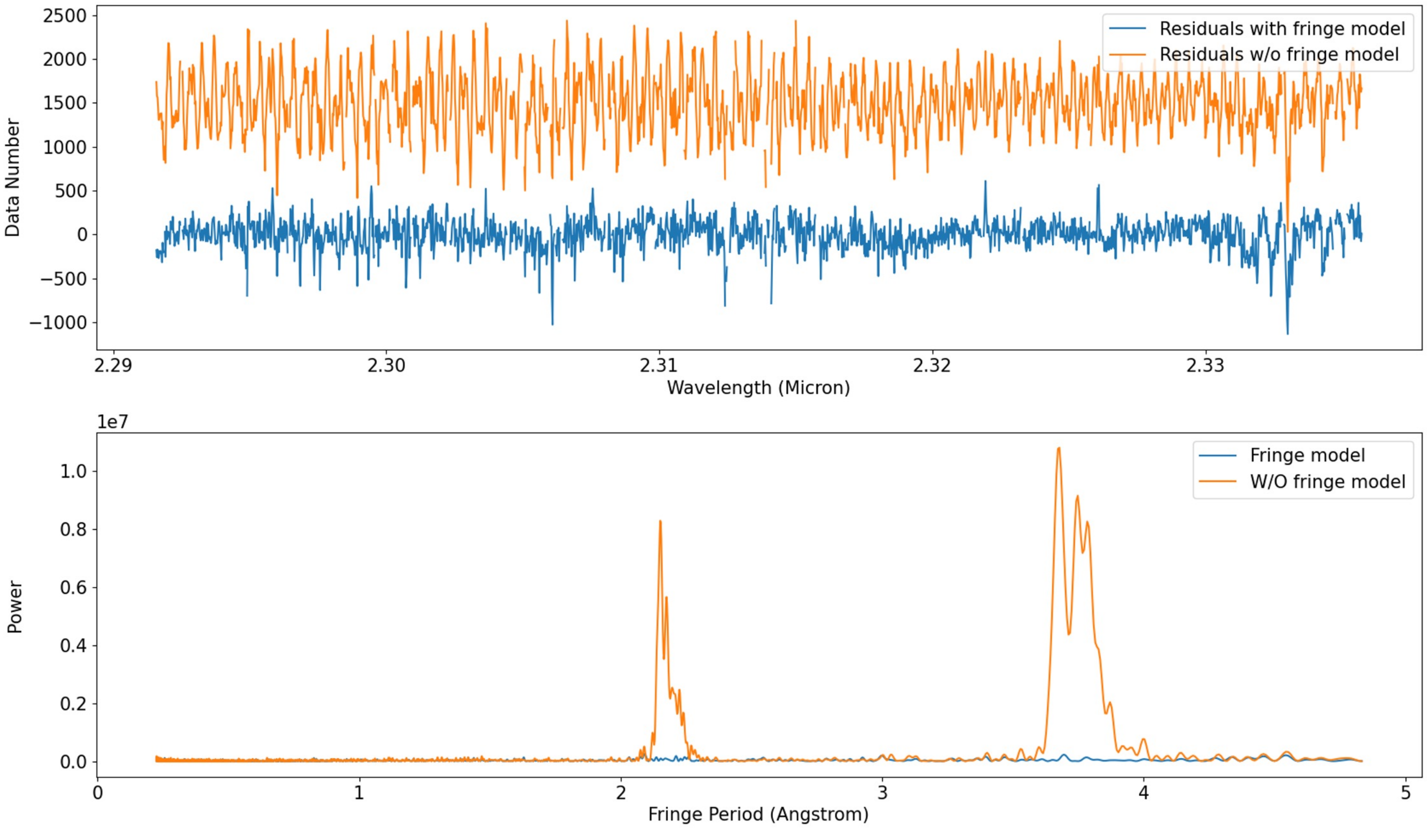


Dan Echeverri and KPIC Team

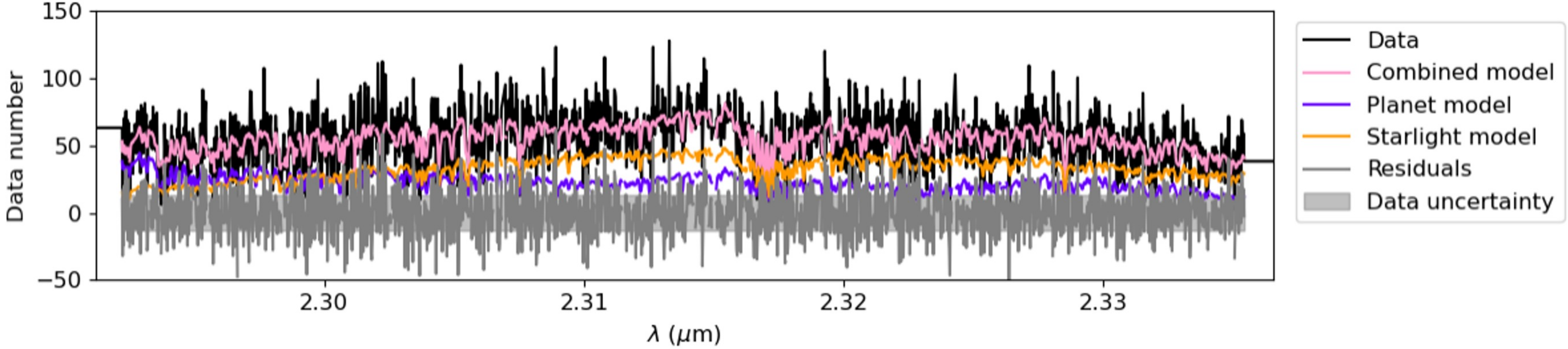
Model fit to AO stellar spectrum and telluric spectrum

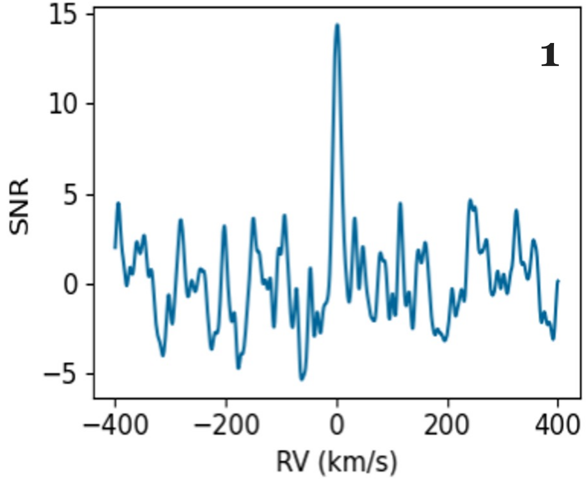


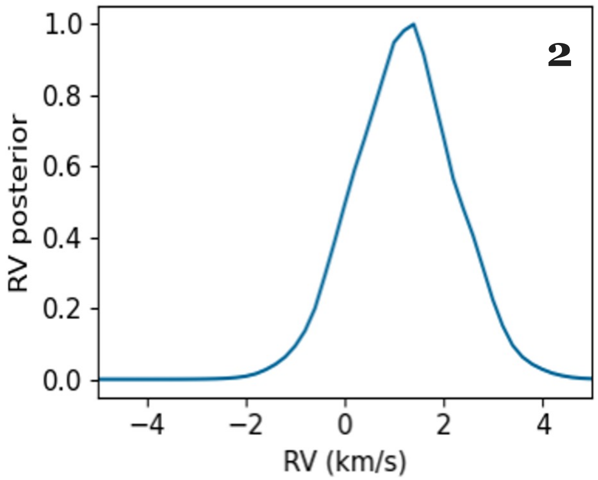
Model fit to AO stellar spectrum and telluric spectrum



GQ Lup B Spectrum



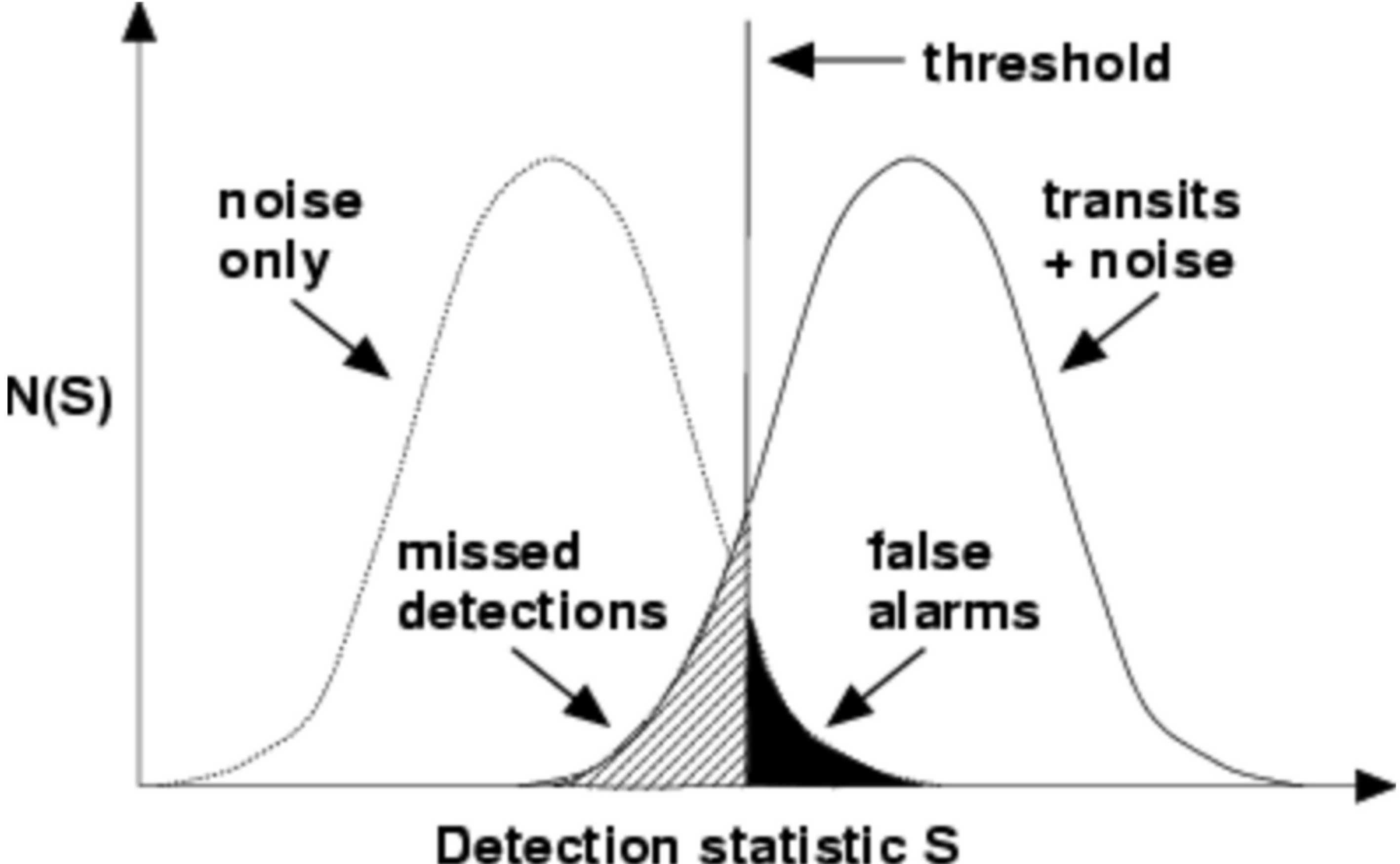




1. SNR CCF

2. Most likely RV

FAP: False Alarm Probability



Delta(BIC): Bayesian Information Criterion

$$\mathrm{BIC} = \ln(n)k - 2\ln(\hat{L}).$$

$\hat{L}$ is the maximized value of the likelihood function of the model

n is the number of data points

k is the number of free parameters to be estimated

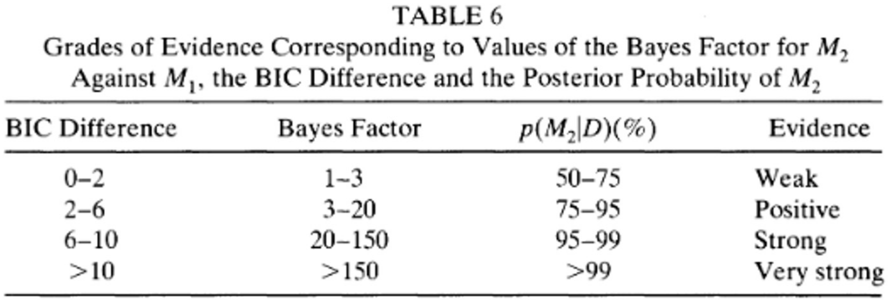
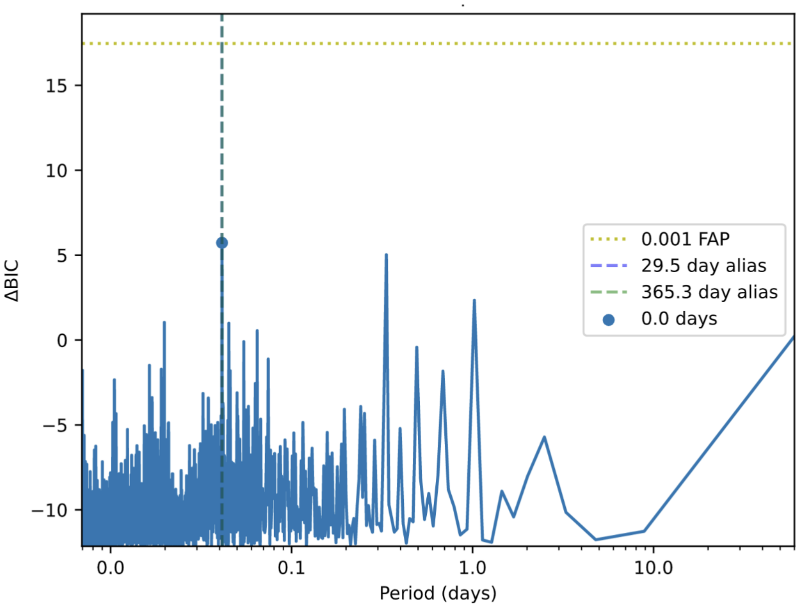


TABLE 6

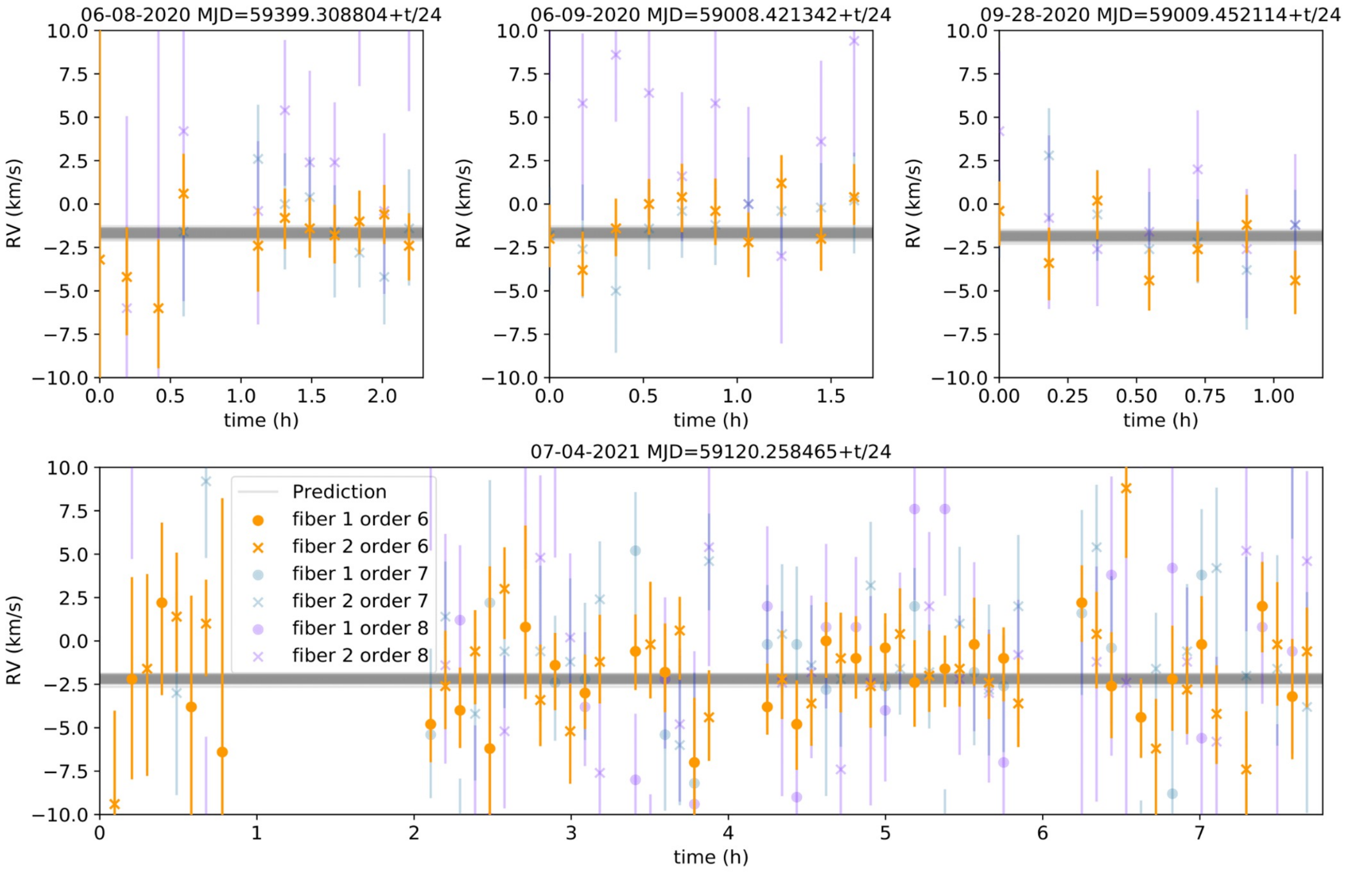
Grades of Evidence Corresponding to Values of the Bayes Factor for M_2 Against M_1, the BIC Difference and the Posterior Probability of M_2

BIC Difference	Bayes Factor	$p(M_2\|D)(\%)$	Evidence
0–2	1–3	50–75	Weak
2–6	3–20	75–95	Positive
6–10	20–150	95–99	Strong
>10	>150	>99	Very strong



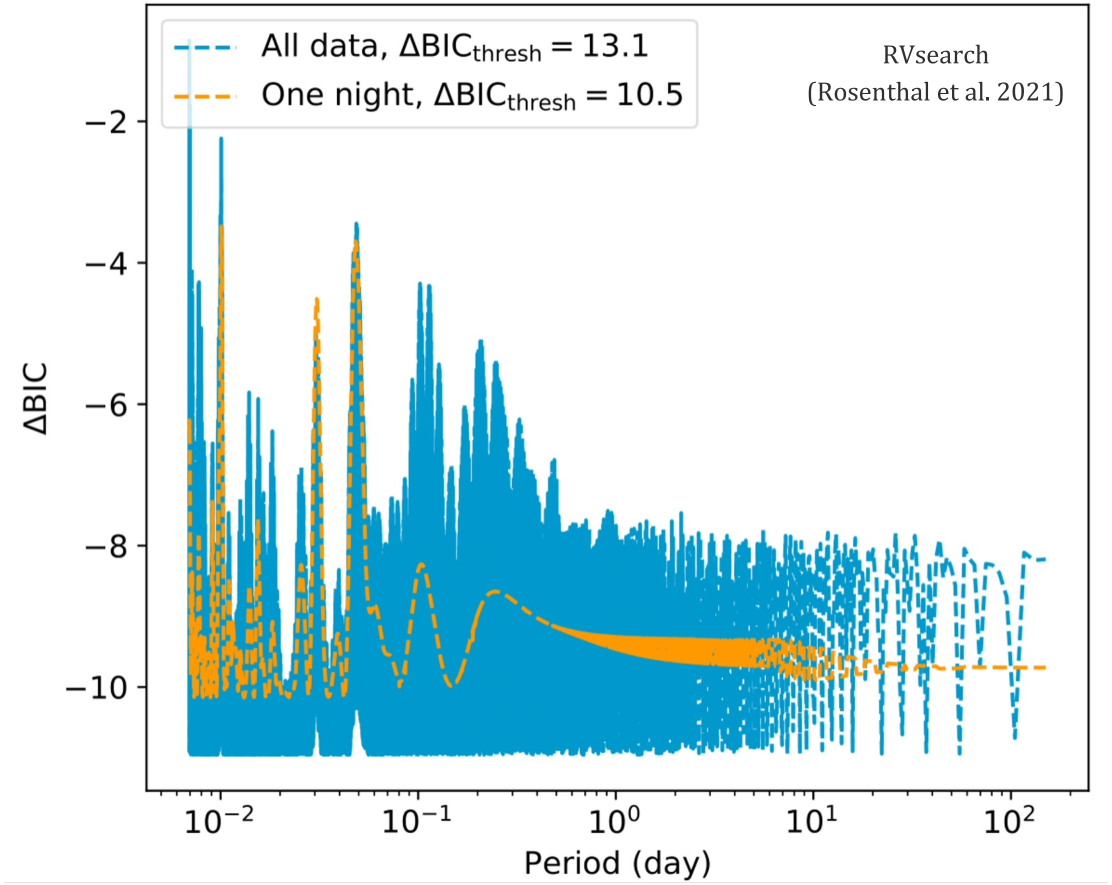
HR 7672B

RV time series for HR 7672 B using KPIC data



Ruffio, **Horstman,** Mawet et. al submitted

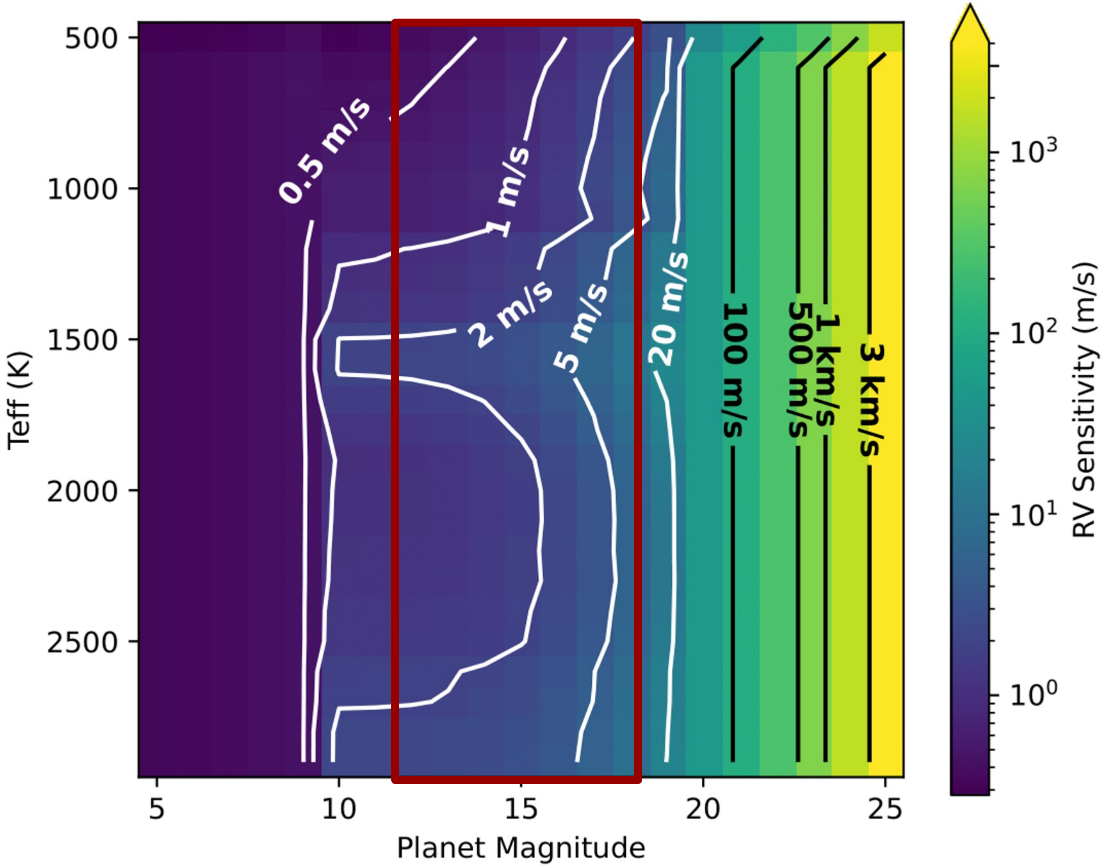
Existing code already developed to analyze HR 7672 RV time series



Ruffio, **Horstman,** Mawet et. al submitted

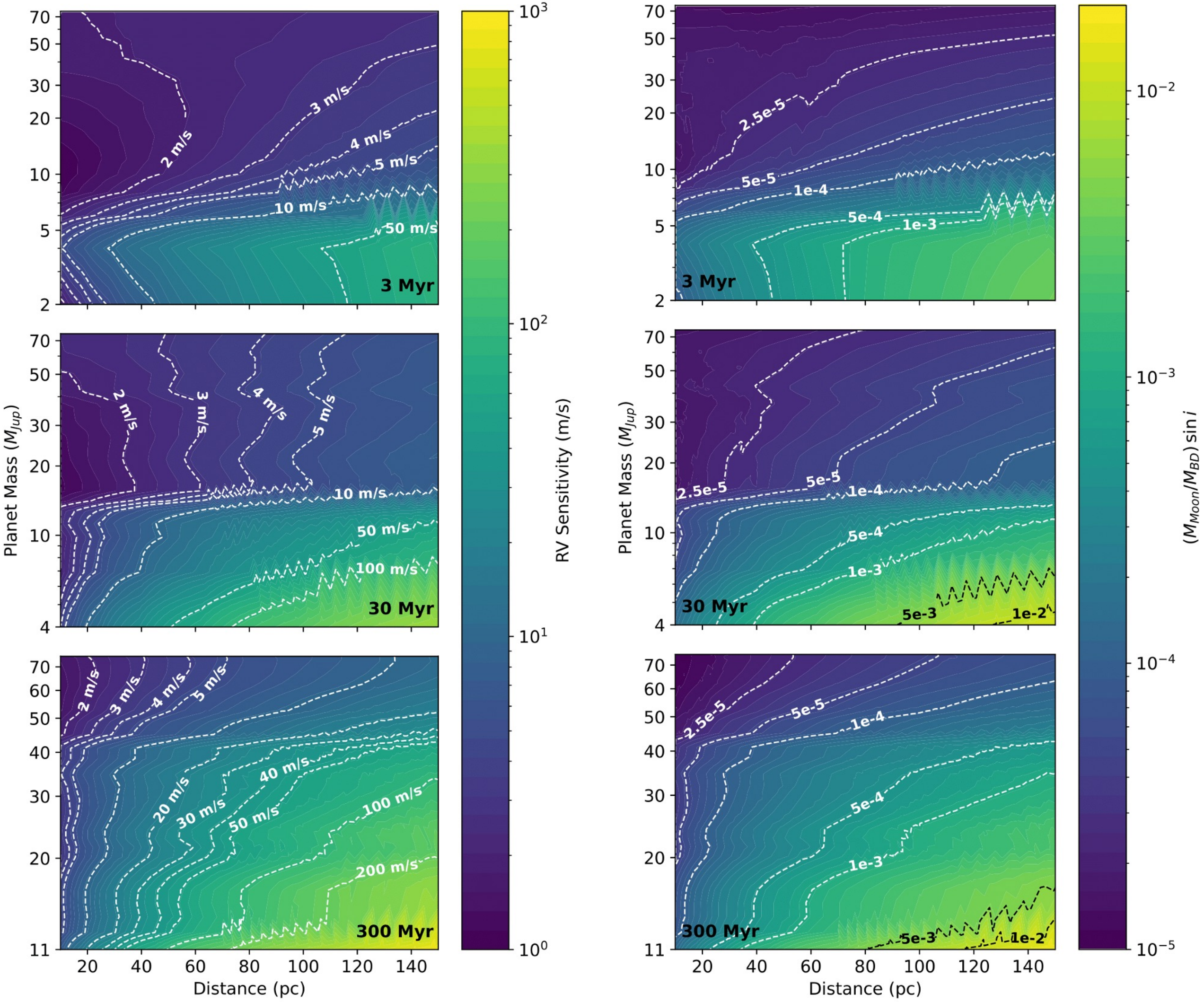
MODHIS/TMT Simulations

With a single two hour exposure, can reach sensitivity of 1-10 m/s



Current directly imaged planet magnitudes

Ruffio, **Horstman,** Mawet et. al submitted

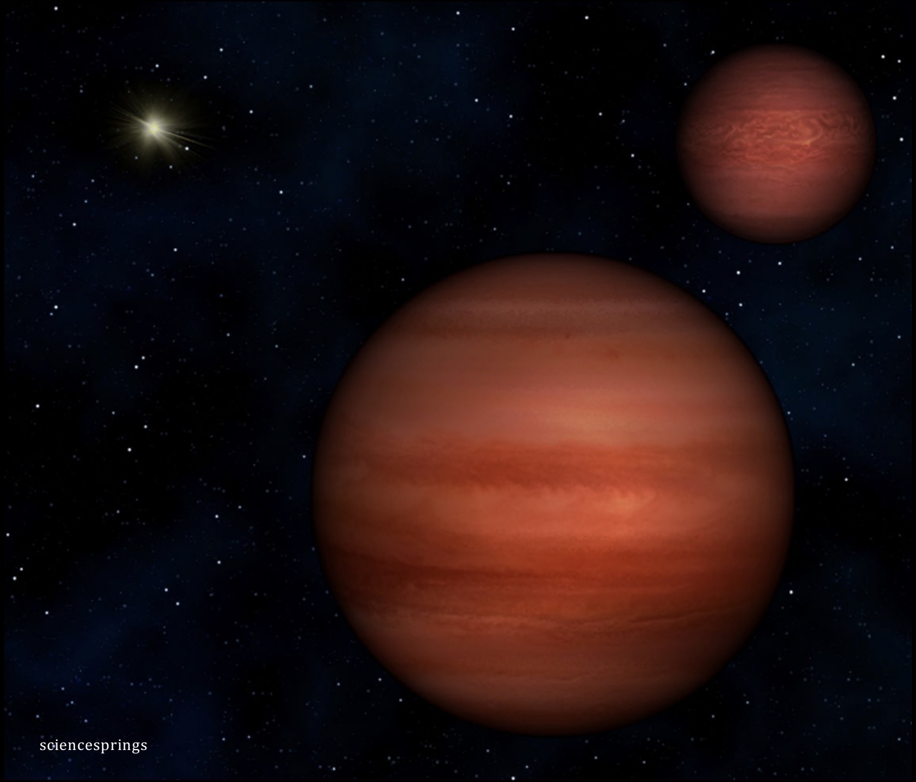


For more massive planets and brown dwarfs, RV sensitivity reached to look for solar system-like exomoons

Holds for all young systems

Background & Context

Exomoon Formation Pathways

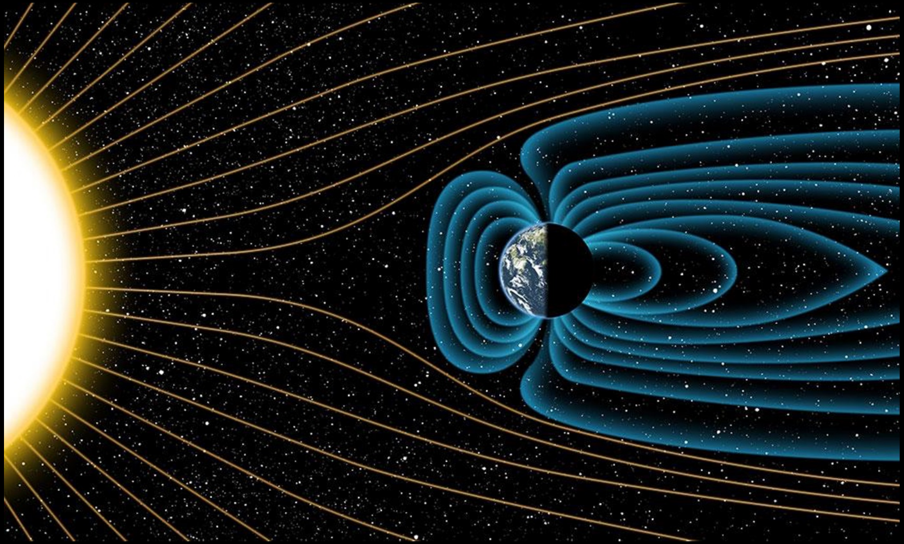

sciencesprings

- **Disk instabilities**
    - Mass ratios ~1
    - Thought to form in bound systems as often as ~45% when orbiting a host star (Burgasser, et al., 2005)

Potentially Habitable Exomoons

- Atmosphere retention
  - Flux received by the exomoon from planet/star
  - Tidal heating of the exomoon
  - Possible protection by the planet's magnetosphere

- Satellites on the order of 0.1-0.5 Mass Earth formed in CPD/captured could have a surface temperature compatible with liquid water Heller et al. (2014)
  - Larger planets may provide more protection (Heller & Zuluaga 2013).
  - Planetary illumination from Super Jupiters on exomoons with smaller separations and eccentric orbits can drive a 174 runaway greenhouse effect (Heller & Barnes 2015)



University of Rochester

Brown Dwarf RV Jitter

- $\Delta_{\mathrm{RV}} \approx F_{\mathrm{spot}} \times v \sin i$ (Vanderburg 2018)
- Typical planet vsini ~10-25 km/s (Snellen et al. 2014)
- Error on order of ~100 m/s
- Should be able to filter out signal (Vanderburg et al. 2016, 2018) and still obtain moon signal
- Look for slower rotating planets/planets with less clouds

RVsearch

- Likelihood periodograms to iteratively detect planet candidates (Rosenthal et al. 2021)
- Fits a detection threshold to the likelihood periodogram
  - Power law noise model (Howard & Fulton 2016)
- Injection-recovery tests

Relevant Physics/Math

- Kepler’s 3rd Law: $$P^2 = \frac{4\pi^2 a^3}{GM}.$$
- RV semi-amplitude: $$\frac{K}{\mathrm{ms}^{-1}} = 203 \left(\frac{P}{\mathrm{days}}\right)^{-1/3} \cdot \frac{(M_\mathrm{p}/M_\mathrm{Jup}) \sin i}{\left((M_*/M_\odot) + 9.548\times10^{-4}(M_\mathrm{p}/M_\mathrm{Jup})\right)^{2/3}} \cdot \frac{1}{\sqrt{1-e^2}},$$
- Roche limit: $$d = R_m \left(2\frac{M_M}{M_m}\right)^{\frac{1}{3}}$$
- Hill sphere: $$r_\mathrm{H} \approx a\sqrt[3]{\frac{m}{3M}}.$$

Relevant Physics/Math

- Doppler formula: $\frac{\Delta\lambda}{\lambda} = v_r/c$

- Resolution of KPIC: 1 km/s

- Astrometric signal: $\theta = \frac{m_S}{M_P}\frac{a_S}{d} arcsec$

- RV err = max(resolution,vsini)/CCF_SNR