Using Orbital Phase and Atmospheric Composition to Discriminate Reflected Light Observations of Exoplanets

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ExoExplorers Science Series
6.13.2025

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Outline

Introduction

Part I: Leveraging Exoplanet Orbital Phase and Color for Deconfusion

Part 2: High Phase Angle Observations of Uranus

Summary

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Looking toward future direct imaging missions

Roman Space Telescope

Extremely Large Telescope(s)

Habitable Worlds Observatory

EAC1 – NASA/GSFC

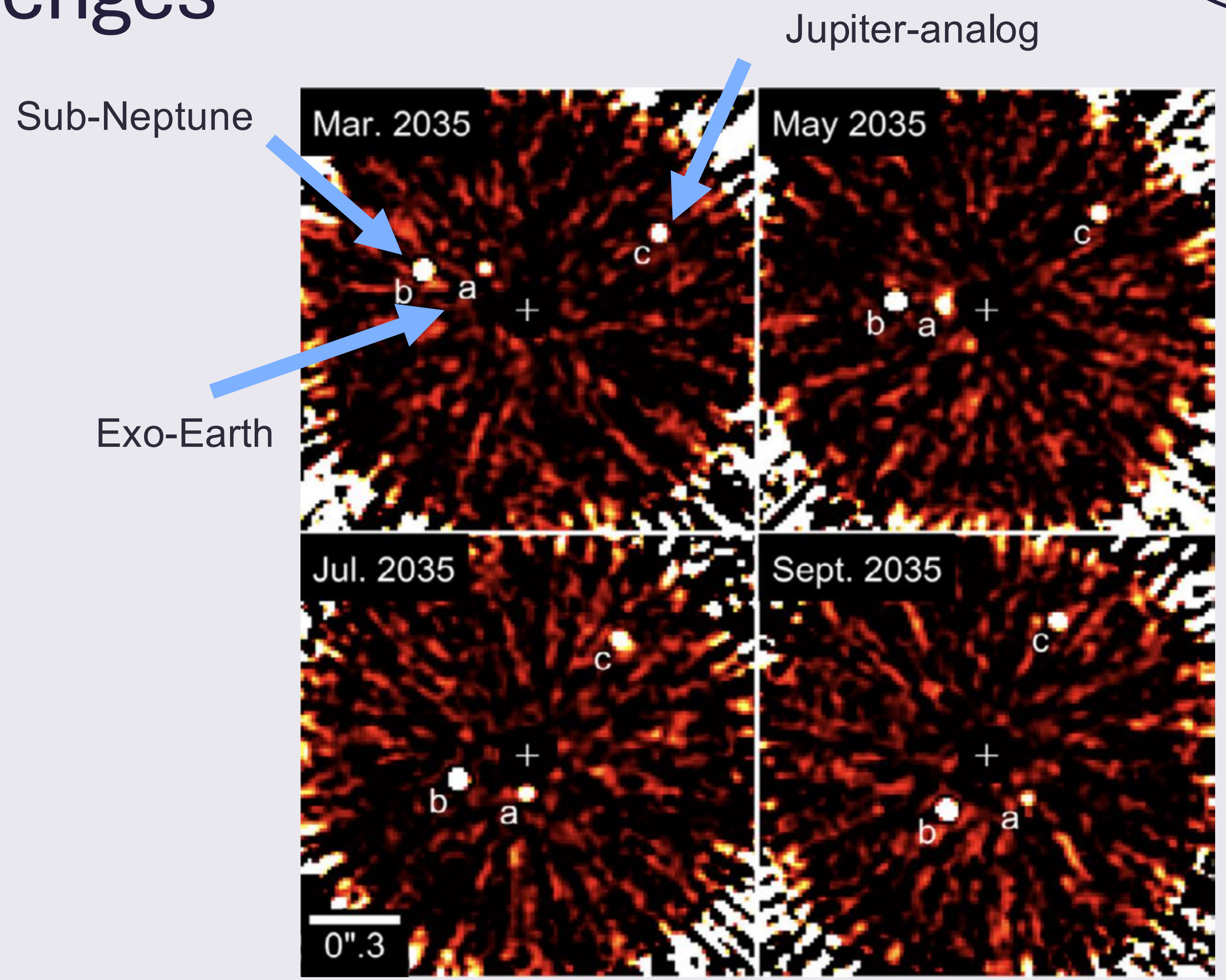
Object	Contrast	Angular separation @ 10 pc
Earth	~2x10^{-10}	0.1”
Jupiter	~1.4x10^{-9}	0.5”

Observing Instrument	Contrast	Inner Working Angle
*Gemini Planet Imager	10^{-7}	0.2” – 1.0”
Thirty Meter Telescope	10^{-8}	0.03”
Roman CGI	10^{-7}-10^{-9}	0.15”
HabEx CG	10^{-10}	0.062”

*For context; currently operational

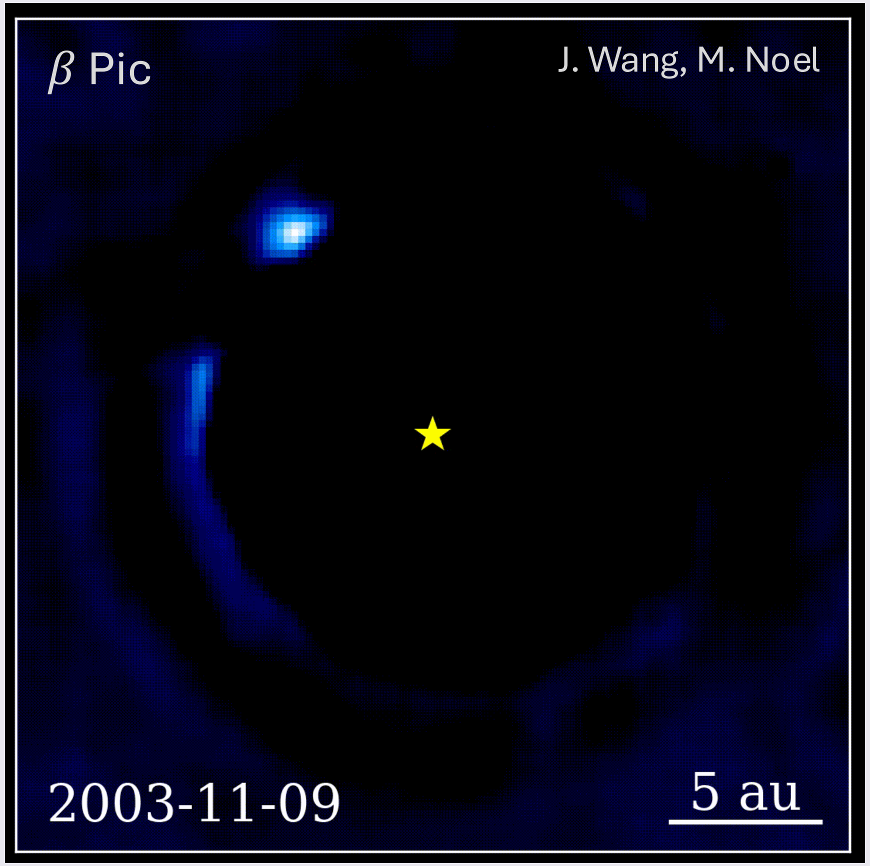
Future direct imaging missions will enable exciting science and face new challenges

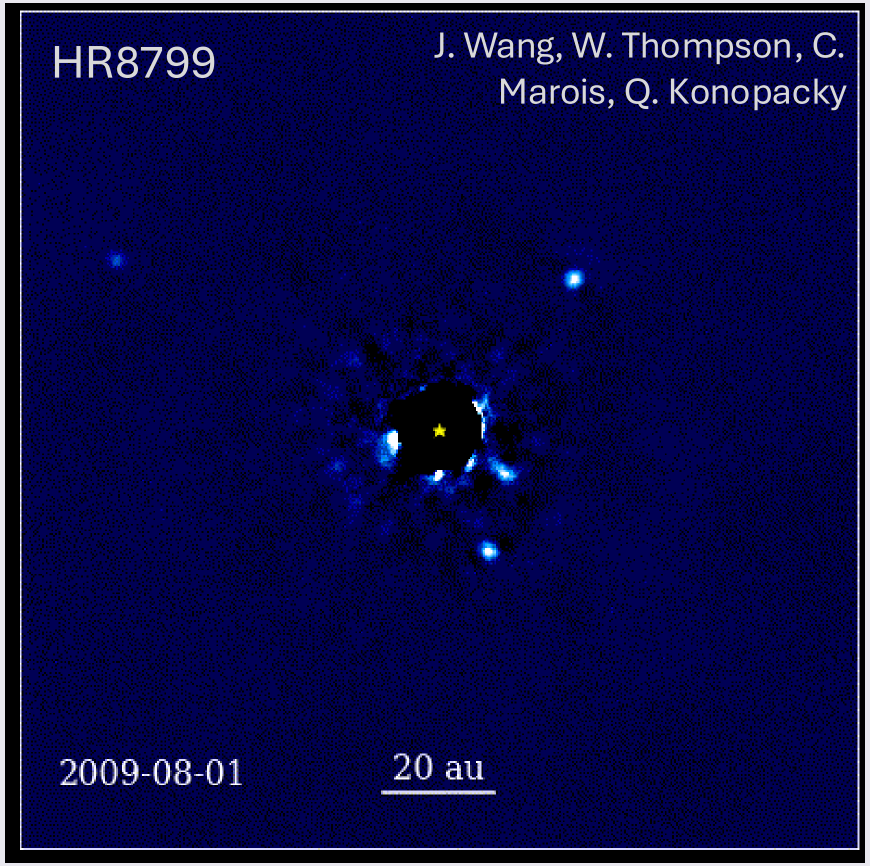
- ✶ Reach potentially habitable planets
- ✶ Shorter orbital periods
- ✶ May complicate observation scheduling
  - More planets
  - Missed detections
  - False positives
  - Lack of precursor observations



Habitable Exoplanet Observatory Final Report 2019, G. Ruane

Exoplanets can only ever be imaged at partial phase angles





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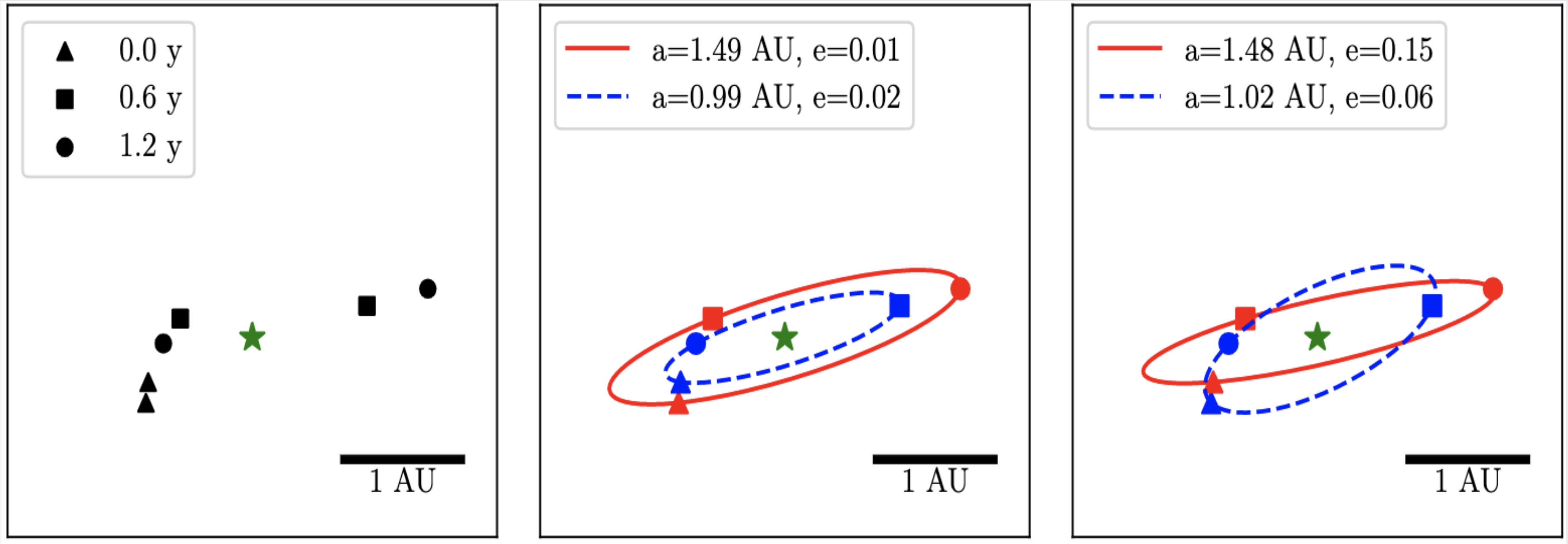
The confusion problem

Detections of 2 planets, each shape corresponds to time of detection

Possible orbits #1

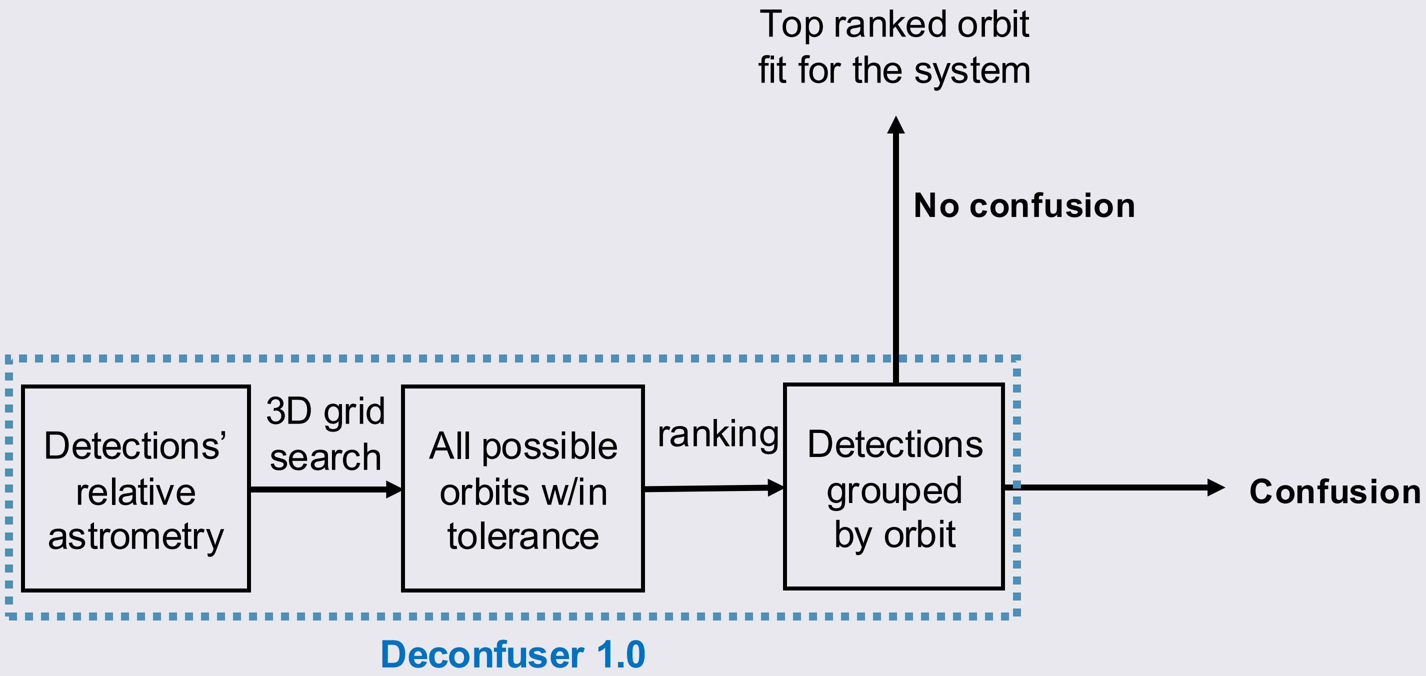
Possible orbits #2



Pogorelyuk et al. 2022

Which detection corresponds to which planet?

Assisting deconfusion with photometry



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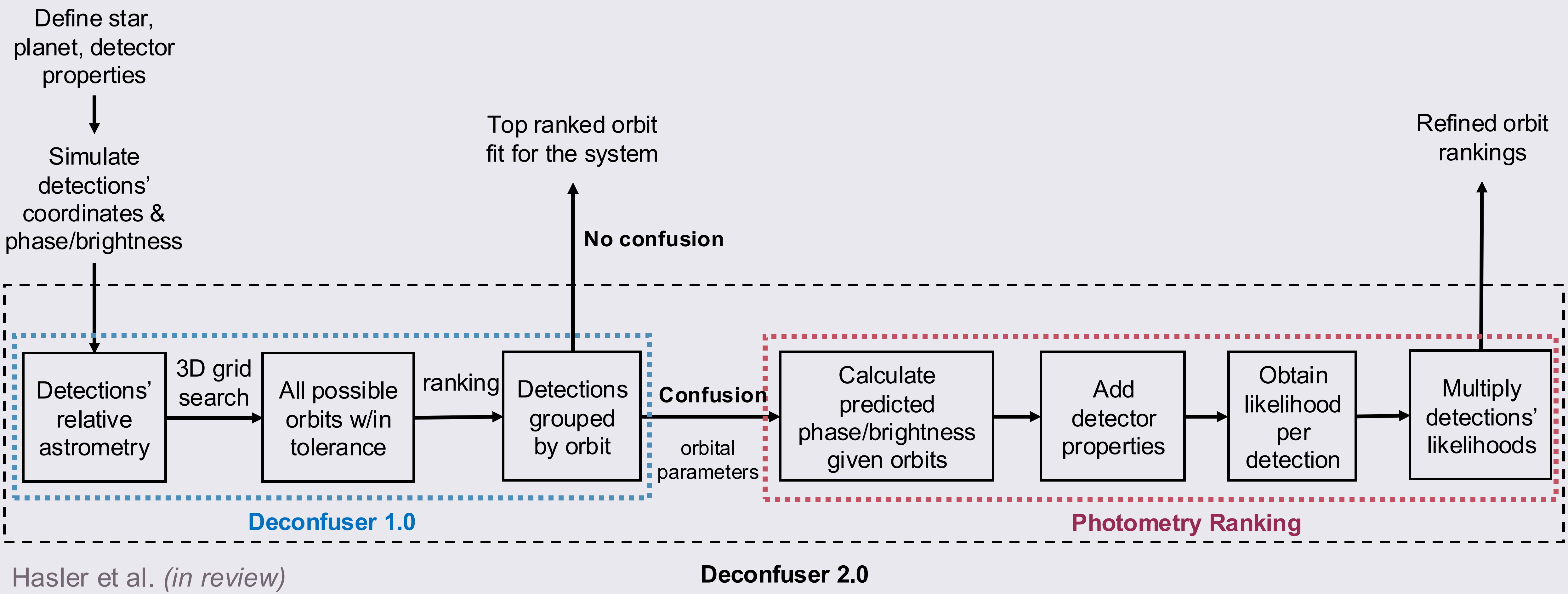
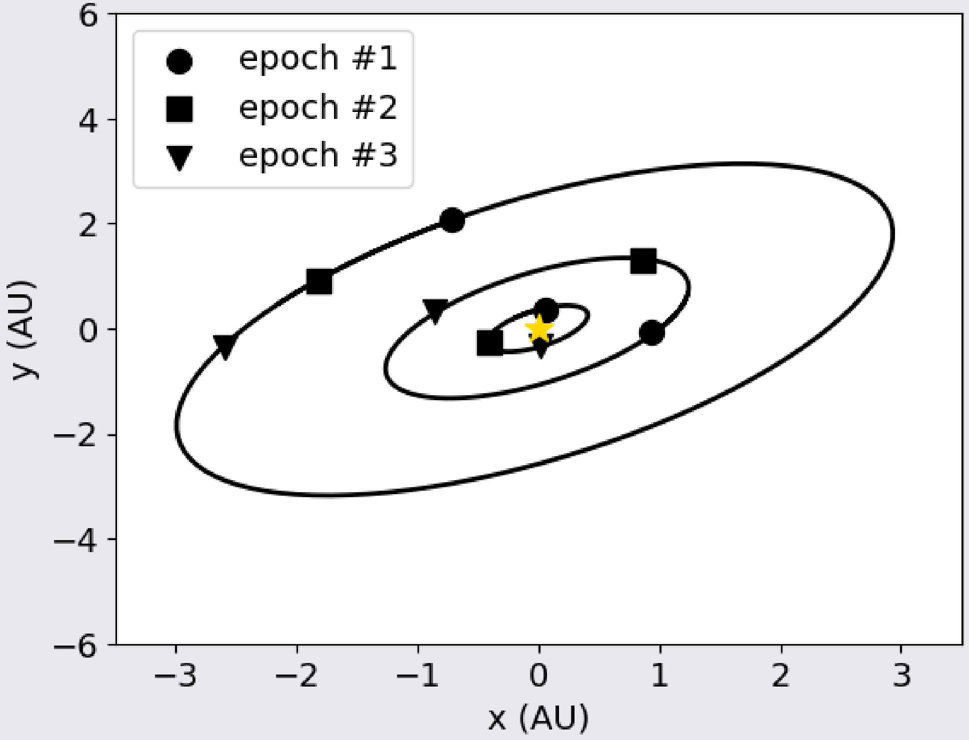
Assisting deconfusion with photometry



Hasler et al. *(in review)*

Incorporating photometry from orbit fits

Example simulated planet detections



$$\alpha = \frac{\vec{r}_{planet-star} \cdot \vec{r}_{planet-observer}}{|\vec{r}_{planet-star}||\vec{r}_{planet-observer}|}$$

Phase angle

$$\Phi(\alpha) = \frac{\sin\alpha + (\pi - \alpha)\cos\alpha}{\pi}$$

Lambertian phase function

$$F_{planet} = A_g \Phi(\alpha) \left(\frac{R_p}{r}\right)^2 F_{star}$$

Planet's flux density

$$c_{planet} = \pi q f_{pa} \mathrm{T} \left(\frac{\lambda}{hc}\right) F_{planet} \Delta\lambda \left(\frac{D}{2}\right)^2$$

Planet count rate at detector

Hasler et al. *(in review)*

Orbit-ranking with photometry

Photon distribution

$$P(N = k) = \frac{n_p^k e^{-n_p}}{k!}$$

Expected number of photons

$$n_p(a, e, i, \Omega, \omega, M_0) = \phi_p(a, e, i, \Omega, \omega, M_0) \cdot \Delta t + d$$

Probability of measuring n_p photons

$$f(y | n_p(a, e, i, \Omega, \omega, M_0)))$$

Likelihood of measuring all detections

$$\prod_{j=1}^{Z} f(y_j | n_{p,j}(a_j, e_j, i_j, \Omega_j, \omega_j, M_{0,j})))$$

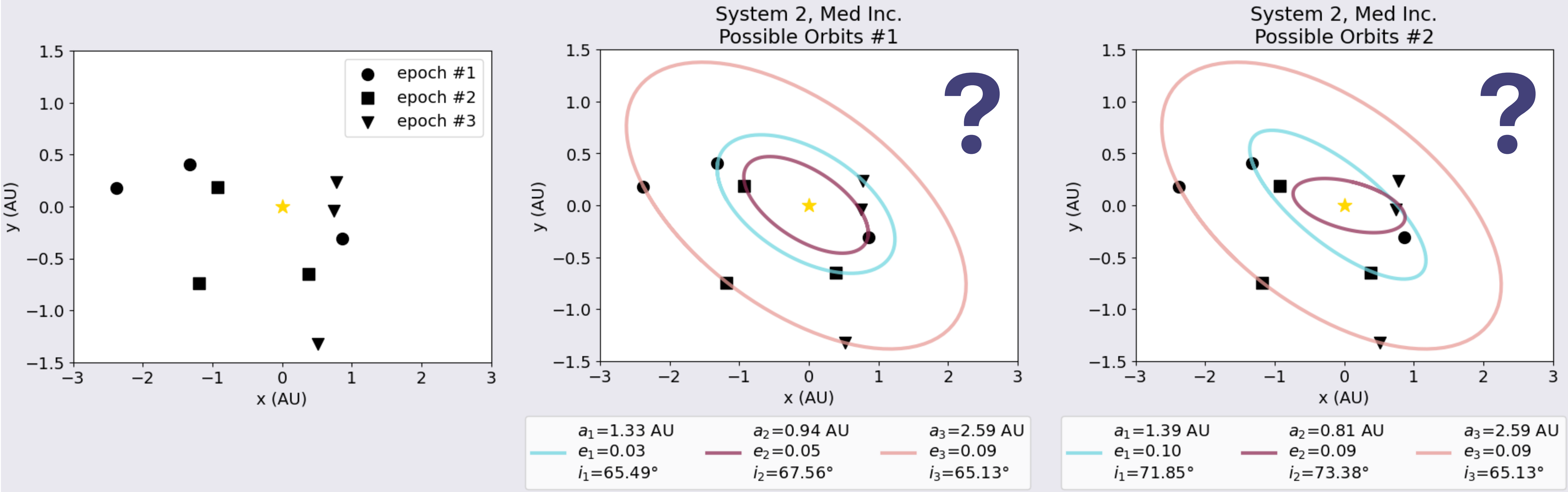
Variables
N = number of photons measured
k = number of occurrences
n_p = expected number of photons
$(a, e, i, \Omega, \omega, M_0)$ = orbital parameters
ϕ_p= photon flux
Δt = observation time
d = background
y = measured photon count
Z = number of measurements

Log Likelihood Function

$$\sum_{j=1}^{N} [\, y_j \cdot \ln\left(n_{p,j}(a_j, e_j, i_j, \Omega_j\,, \omega_j, M_{0,j})\right) - n_{p,j}(a_j, e_j, i_j, \Omega_j, \omega_j, M_{0,j}) - \ln(y_j!) \,]$$

Hasler et al. *(in review)*

Example of deconfusion with photometry



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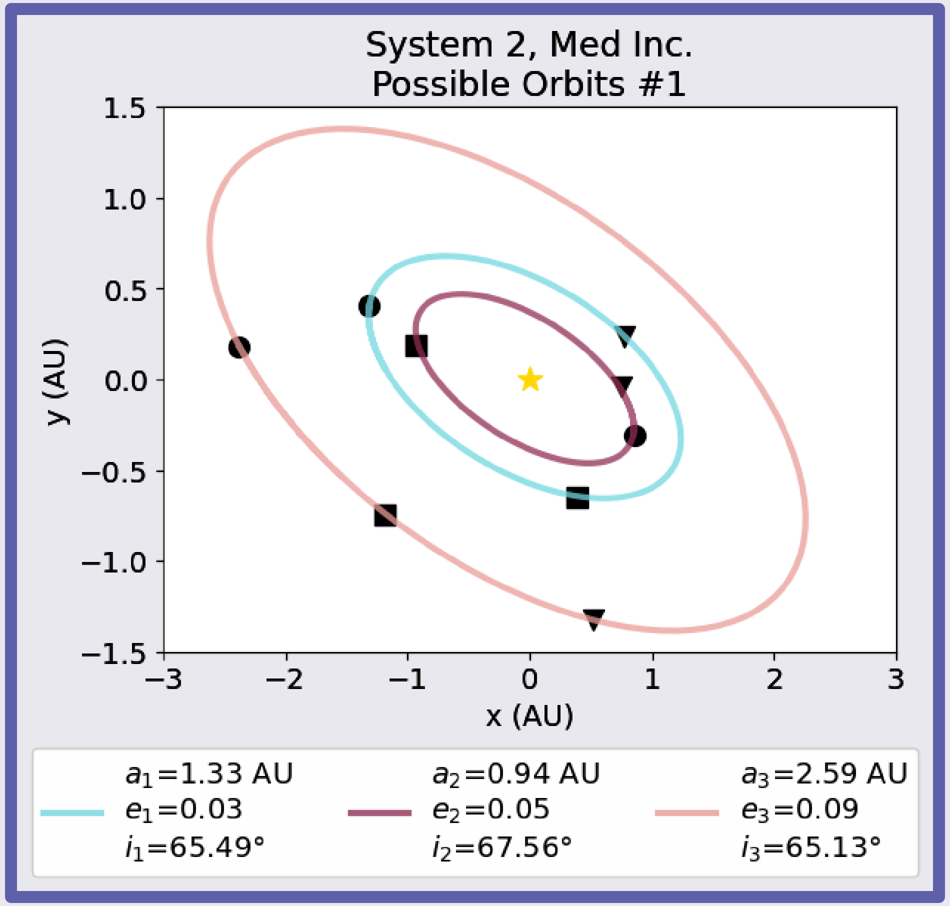
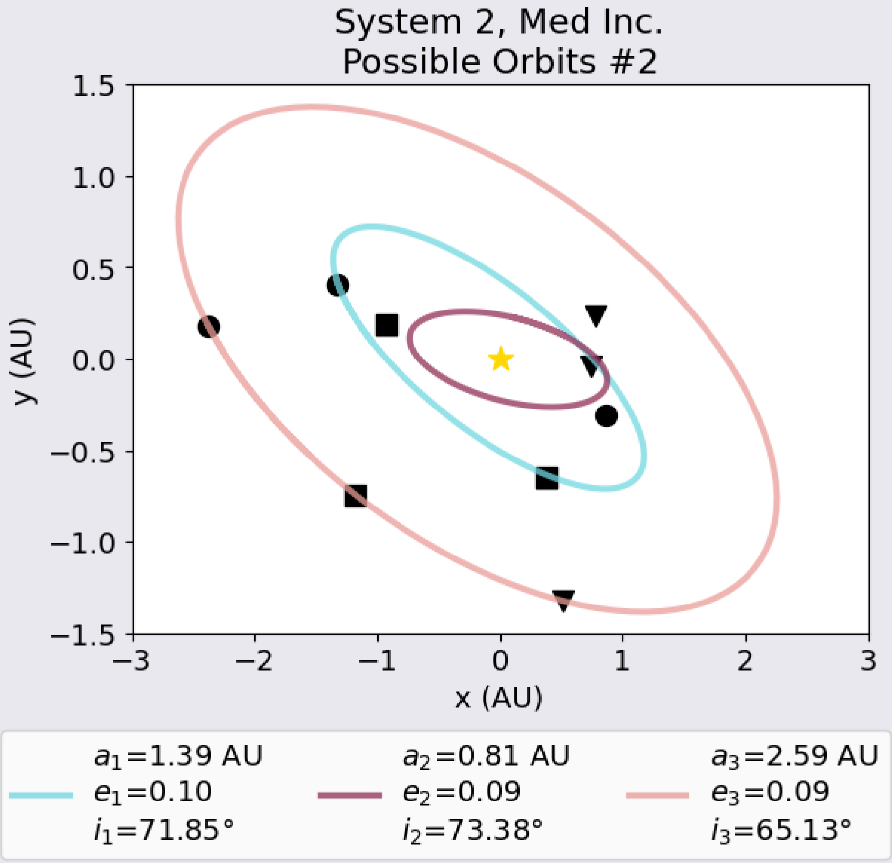
Example of deconfusion with photometry





L(#1 | detections) ? > L(#2 | detections) ?

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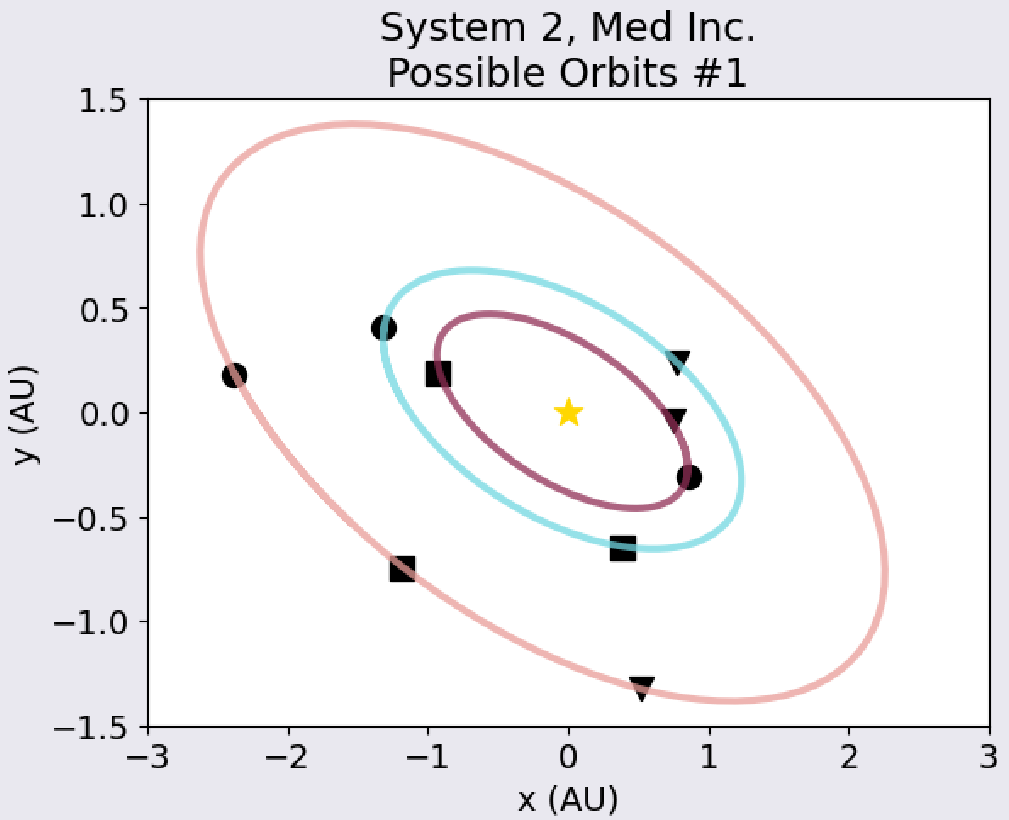
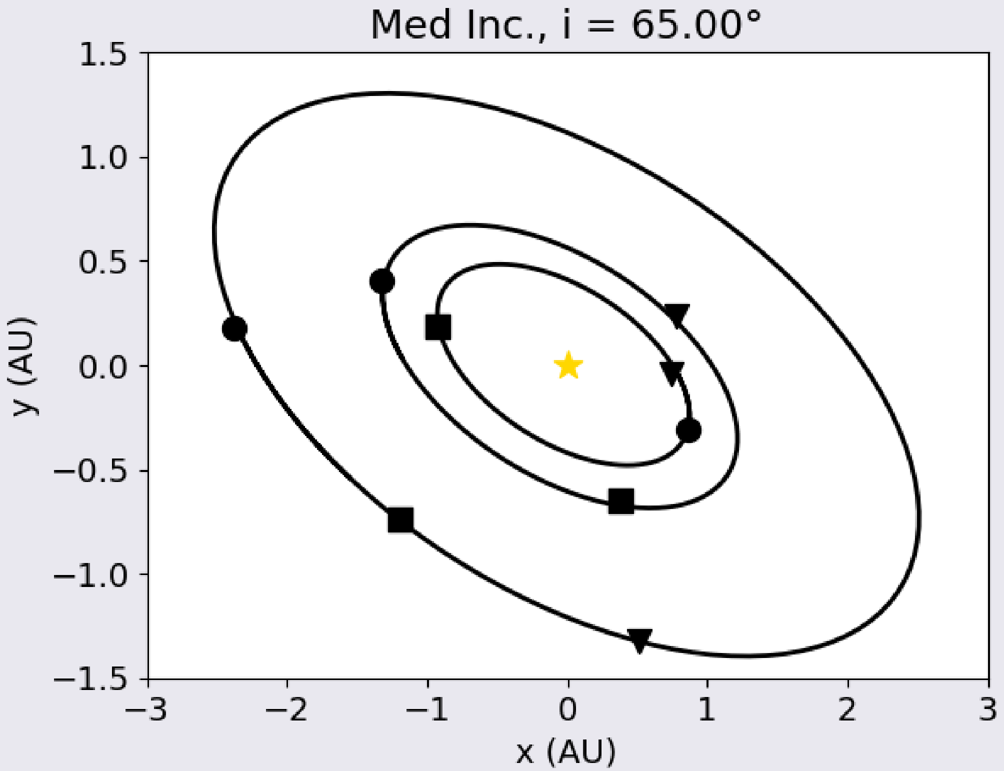
Example of deconfusion with photometry

Option #1



True System



Hasler et al. *(in review)*

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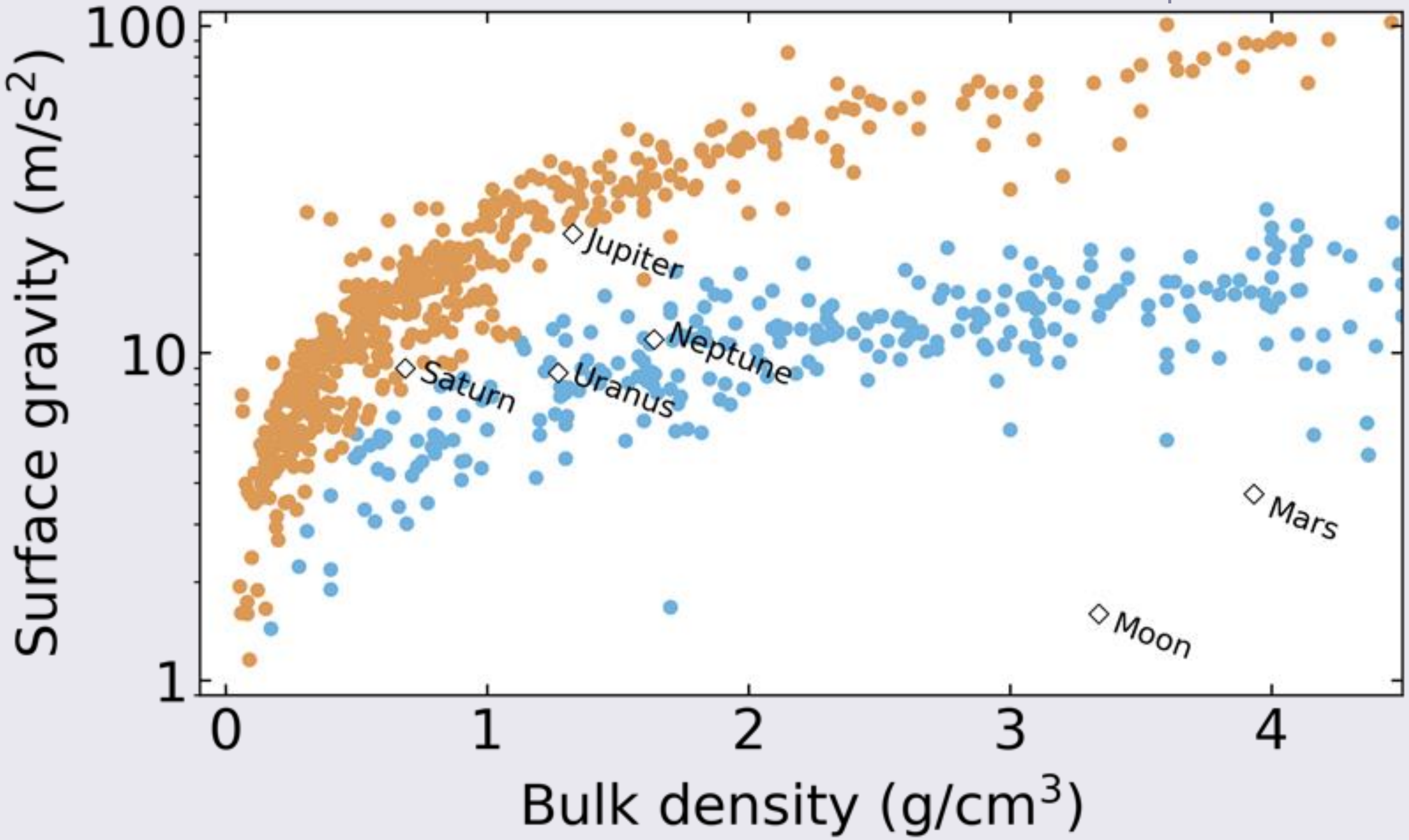
Motivation: Ice-giants are not well understood, and exoplanets of similar size are common

NASA Exoplanet Archive



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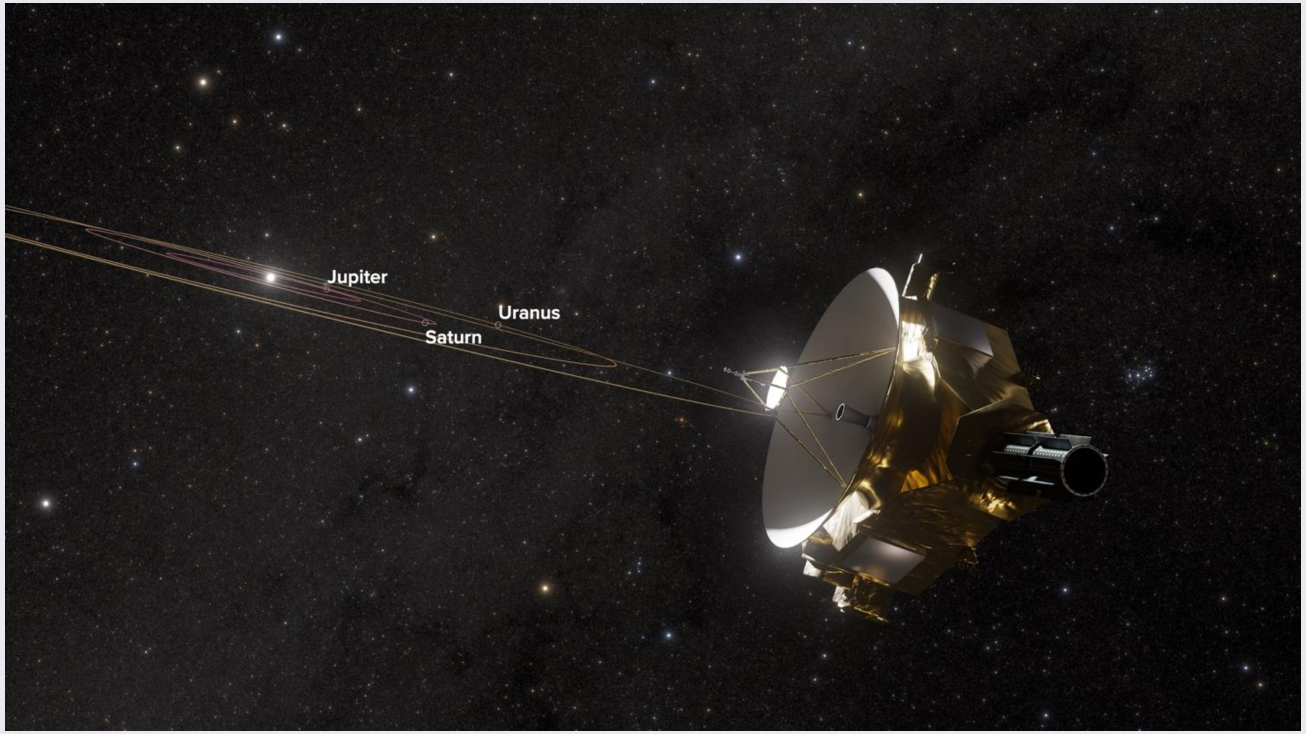
High phase angle observations of the giant planets are inaccessible from Earth

- Previous observations of Uranus and Neptune from Voyager 2 flyby in 1986 and 1989
  - Left major questions about differences between the ice giants

- New Horizons spacecraft currently > 61 AU from Sun
  - Launched 2006
  - Pluto flyby in 2015
  - Unique vantage point for high phase observations

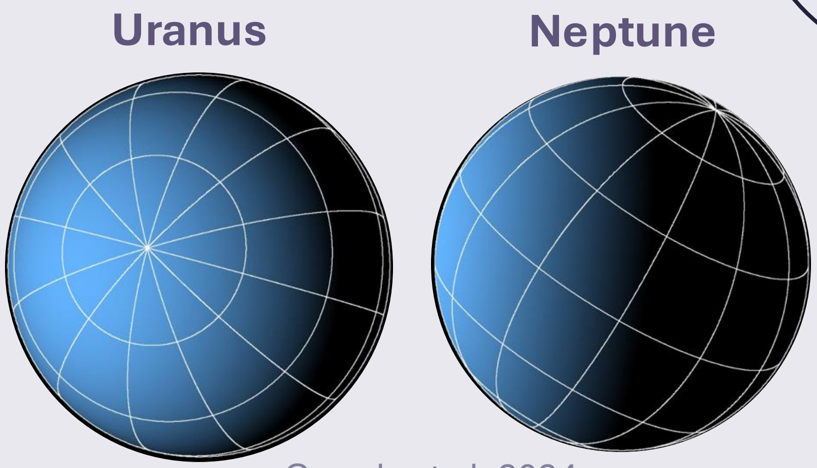


NASA, ESA, C. Nieves (STScI), R. Crawford (STScI), G. Bacon (STScI)

New Horizons/MVIC Observations of Uranus & Neptune

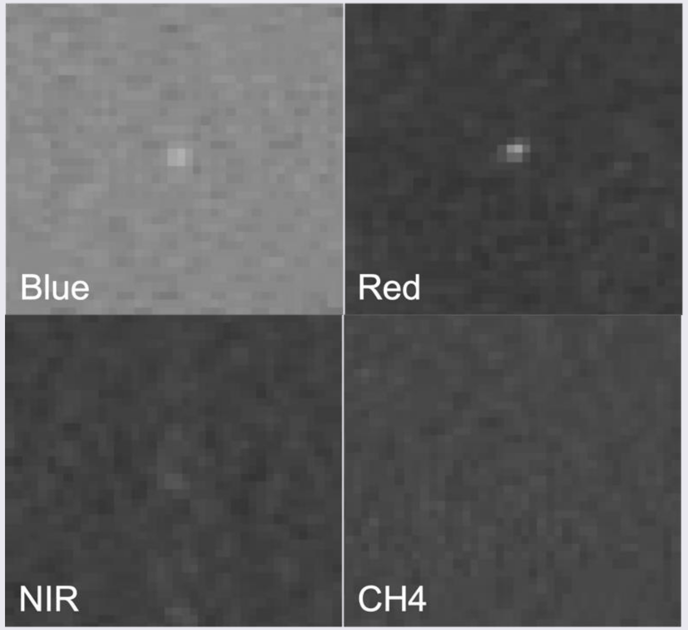
Observation Details

Planet	Date	Phase angle (°)	Planet-Sun distance (AU)	Planet-NH distance (AU)	No. of scans
Uranus	2023 Sep 16	43.9	19.6	69.5	6
	2019 Sep 2	52.4	19.8	54.5	1
	2010 Jun 23	44.0	20.1	24.2	1
Neptune	2023 Sep 23	80.6	29.9	53.7	36
	2019 Sep 03	78.9	29.9	40.2	1
	2010 Jun 23	34.4	30.0	23.2	1



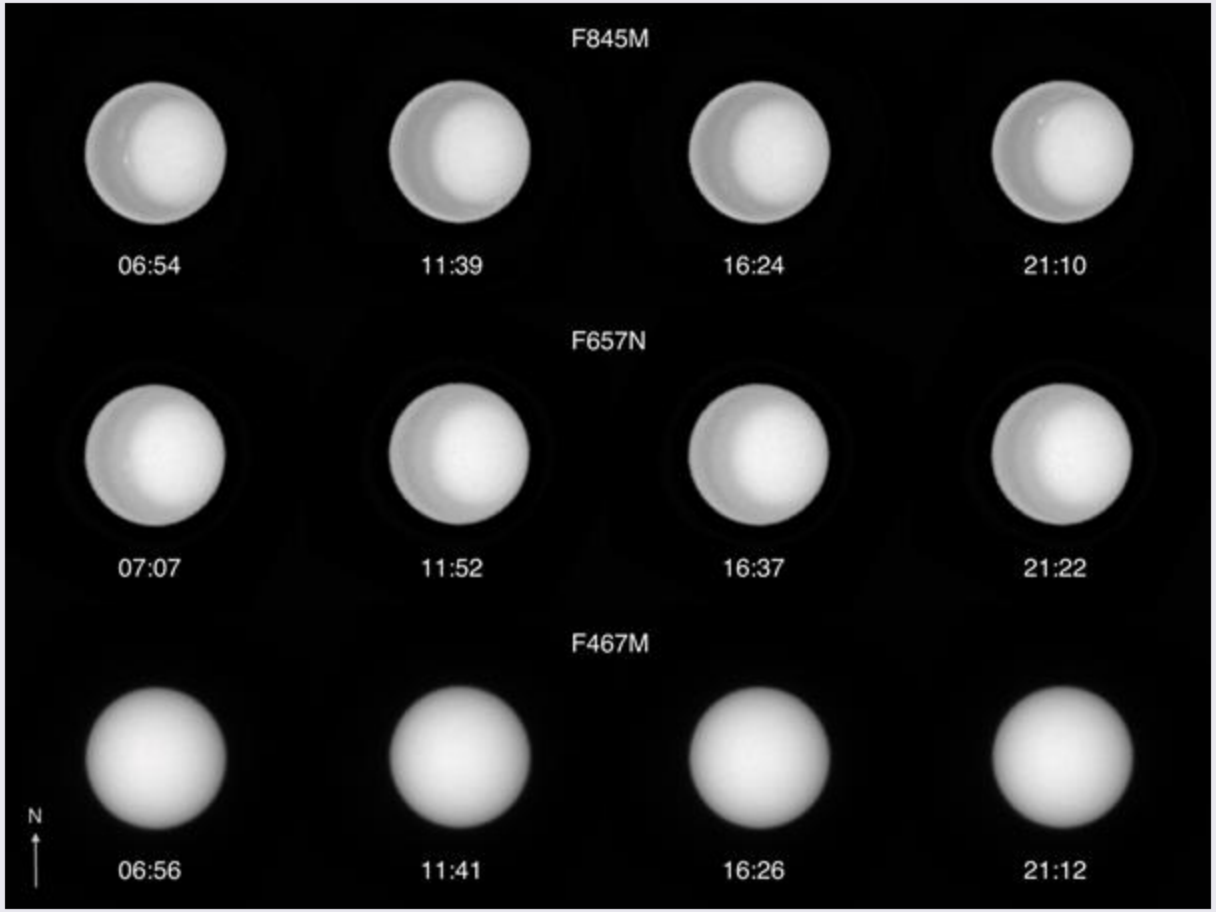
Grundy et al. 2024

MVIC observations of Uranus



Simultaneous observations with HST/WFC3

HST OPAL (Thanks to Amy Simon!)



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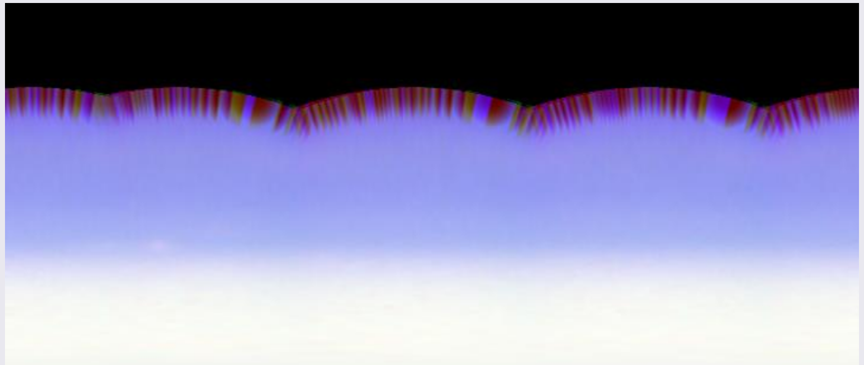
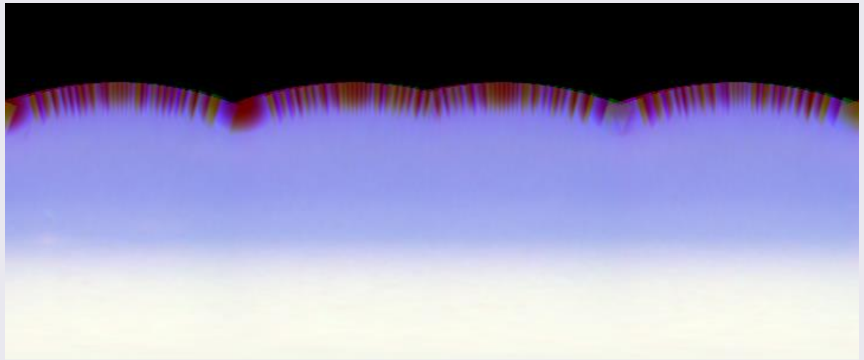
3-color maps of Uranus

Rotation 1

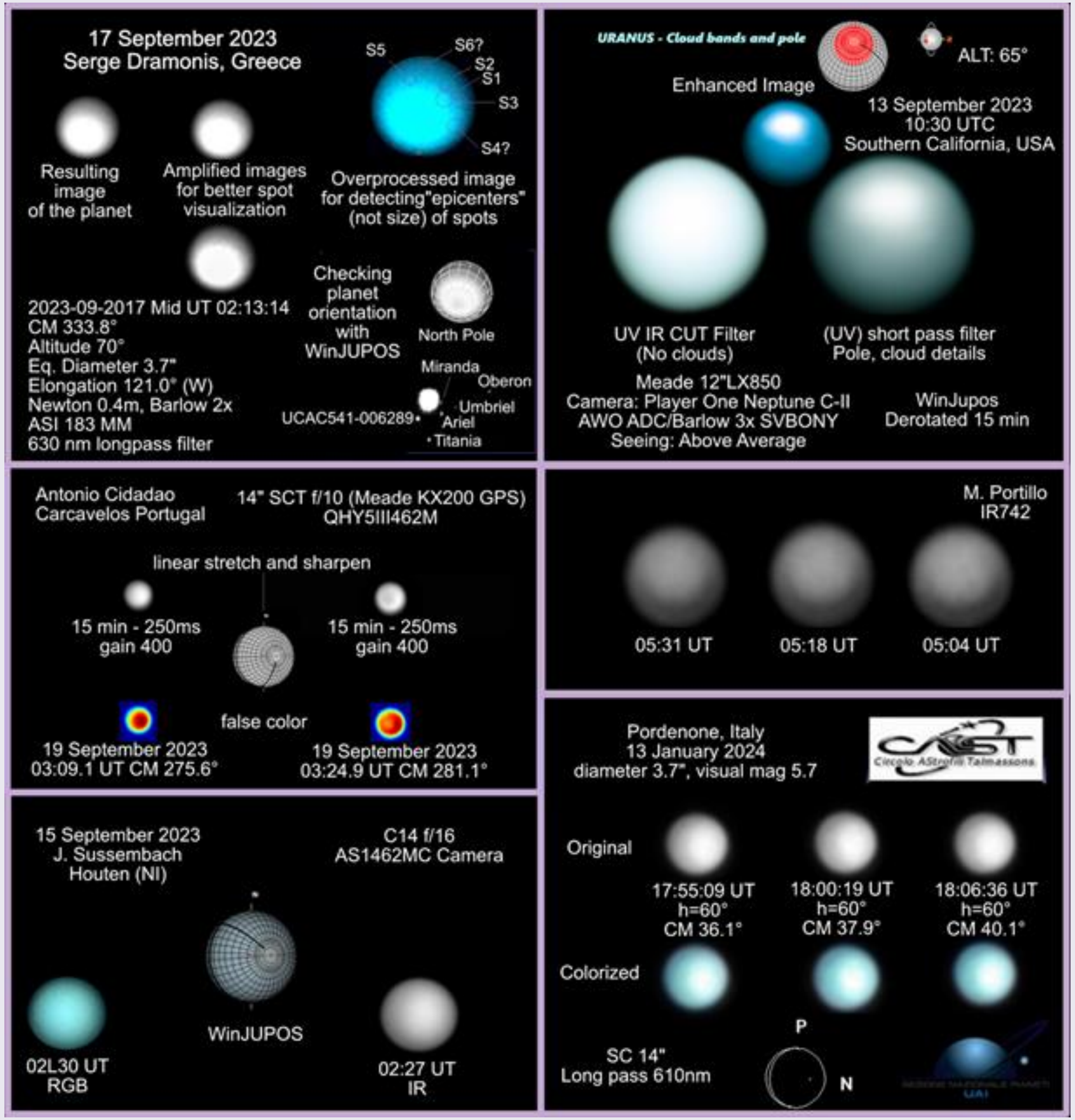


Rotation 2



Complementary observations from ground-based community observers

Thanks to Susan Benecchi!



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Methods: Data reduction and photometry

De-stripe images & identify planet location → Perform aperture photometry → Convert DN to I/F

$$d = D * \frac{P}{L}$$

$$R_{pix} = \frac{R_T}{d}$$

$$A_{pix} = \pi R_{pix}^2$$

$$F_{\mathrm{fil}} = \frac{c}{R_{\mathrm{T,fil}}}$$

$$I_{\mathrm{fil}} = \frac{F_{\mathrm{fil}}}{A_{pix}}$$

$$\frac{I}{F} = \frac{\pi I_{\mathrm{fil}} r^2}{F_{\odot}}$$

<u>Variables</u>

d = spatial scale of observations
D = target-observer distance
P = pixel scale of MVIC
L = focal length
R_T = radius of target (km)
R_{pix} = radius of target in pixels
A_{pix} = area of target in pixels
F_{fil} = target flux per filter
c = count rate
$R_{\mathrm{U,fil}}$ = calibration-dependent keyword
$F_{\odot}$ = solar flux at 1 AU
r = target's heliocentric distance (AU)
$\frac{I}{F}$ = radiance factor

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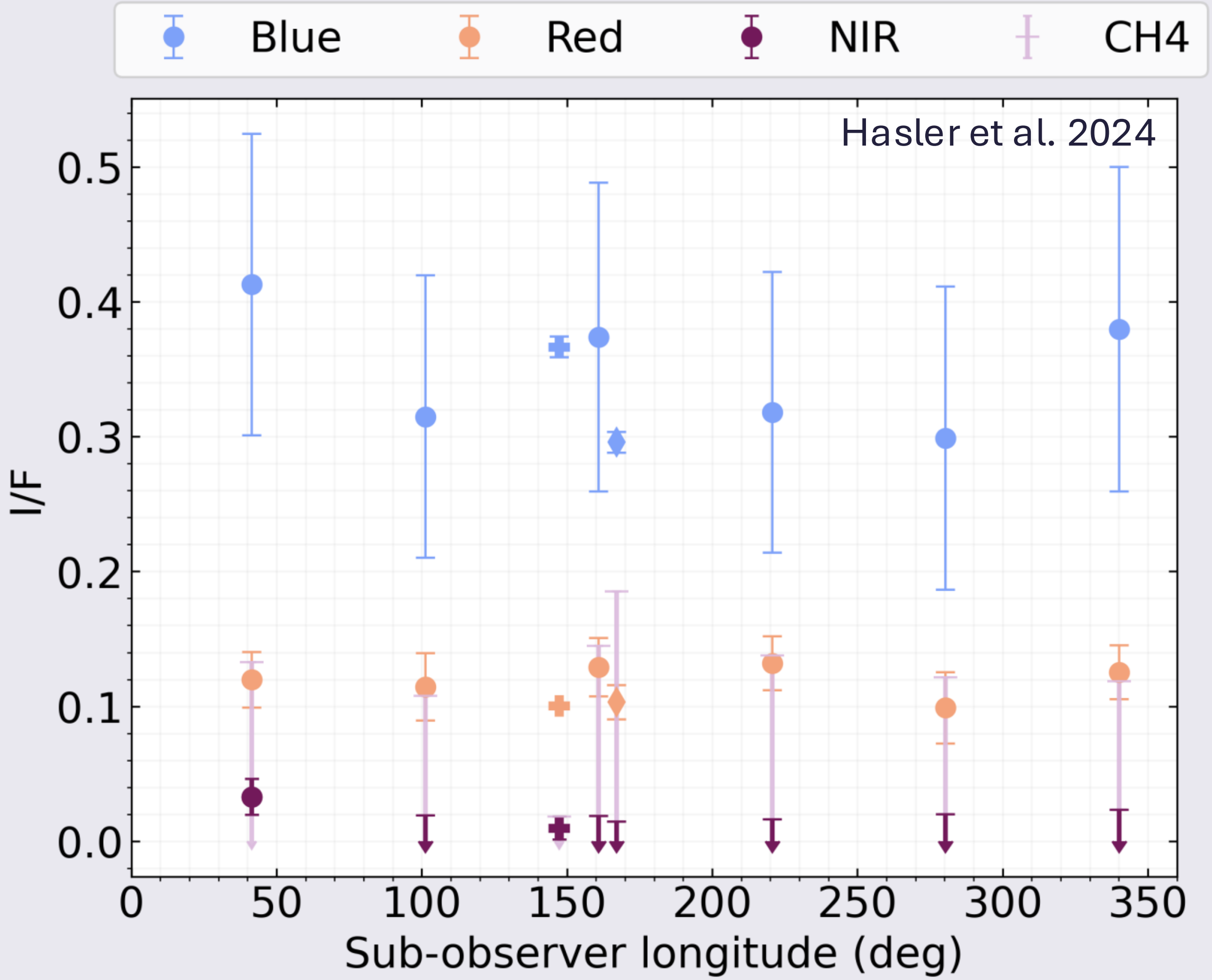
Uranus I/F vs. sub-spacecraft longitude

No significant rotational variation

No significant variation in brightness from 2010 - 2023



● = 2023 observations
♦ = 2019 observations
+ = 2010 observations

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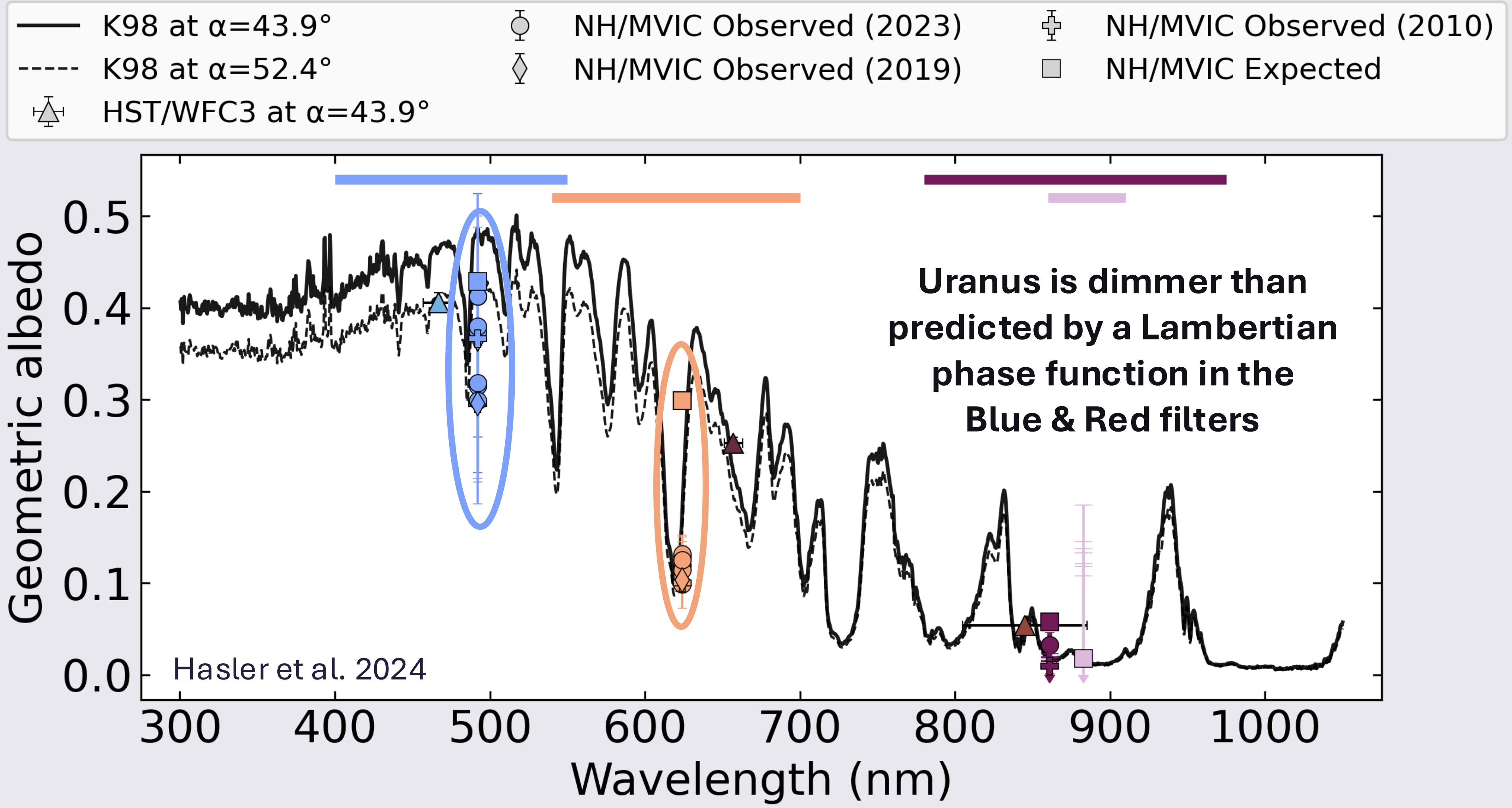
NH/MVIC observations compared to Uranus' spectrum



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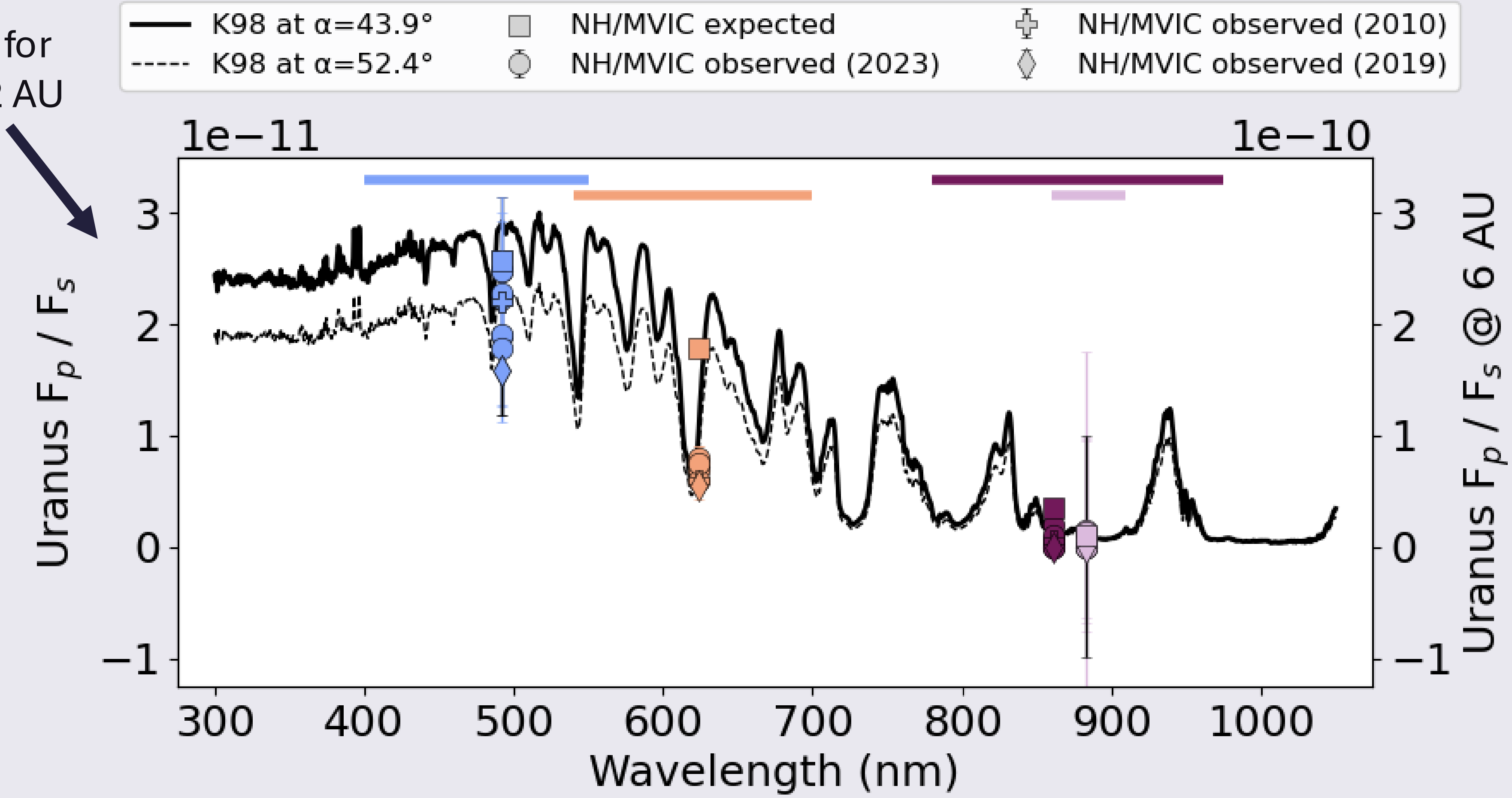
What does this mean for exoplanet observations?

Planet-star contrast ratio for Uranus at 19.2 AU

Planet-star contrast ratio for Uranus at 6 AU



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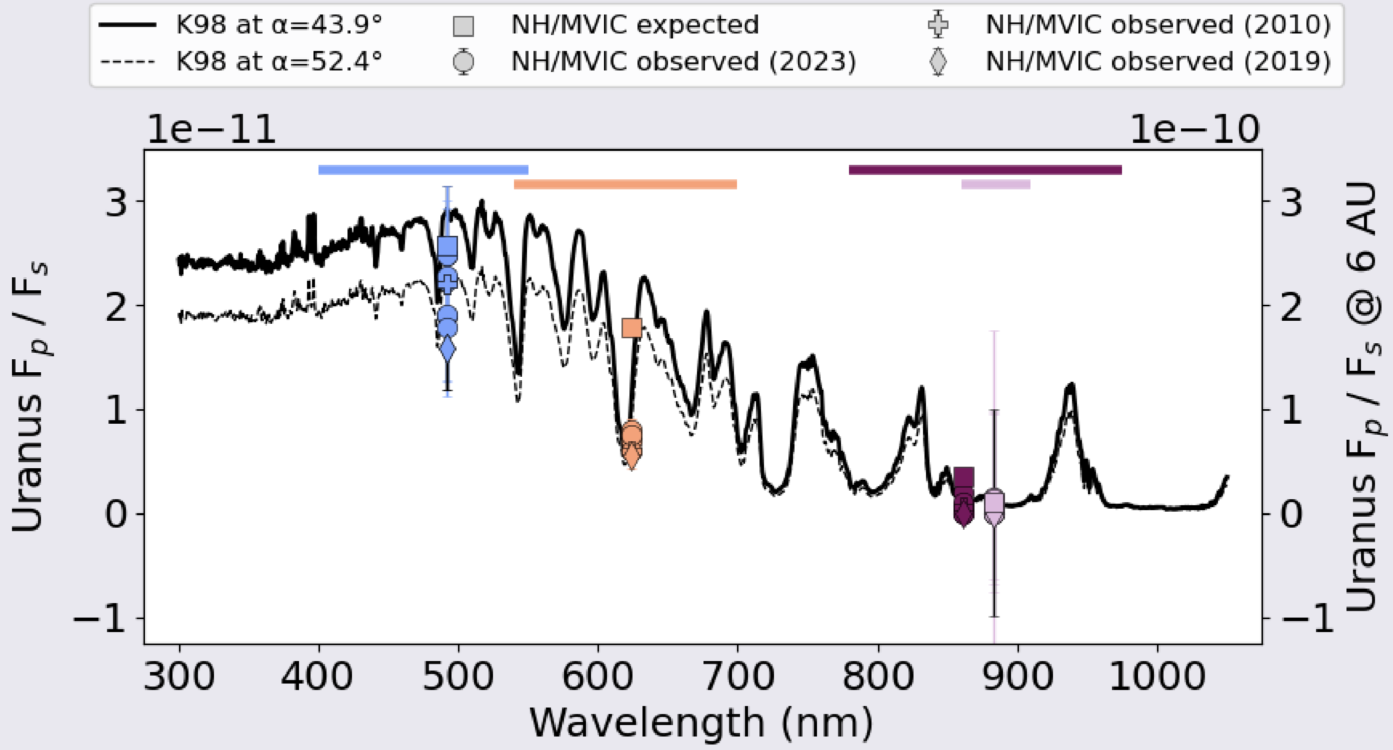
What does this mean for exoplanet observations?



We need to understand atmospheric scattering in these near-quadrature phase angle regimes

Interpretation of our observations will require sophisticated modeling

Fainter exoplanets will require more sensitive instruments/longer integration times for detection and characterization

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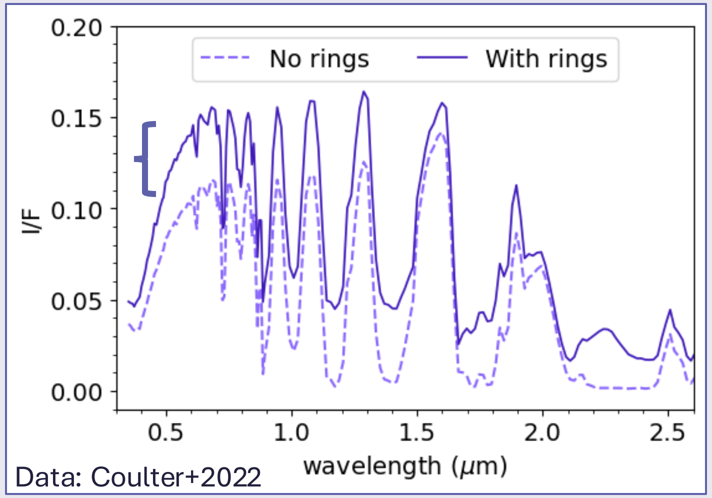
*Ringed exoplanets and bonus science!

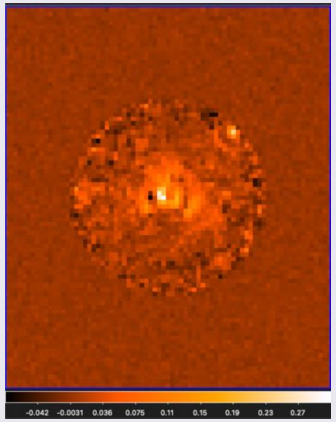
Feasibility of imaging a ringed exoplanet with Roman

Saturn at α = 90°, rings inclined by 20°

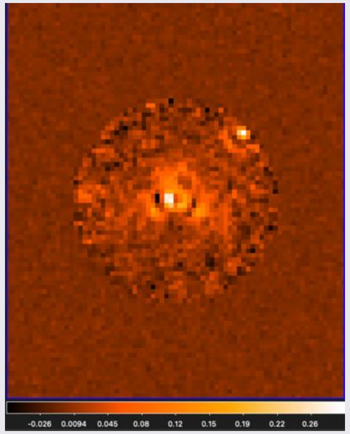


> 30% increase in reflectance with rings

5.2 AU Jupiter @ 15 pc



+ 30% reflectivity



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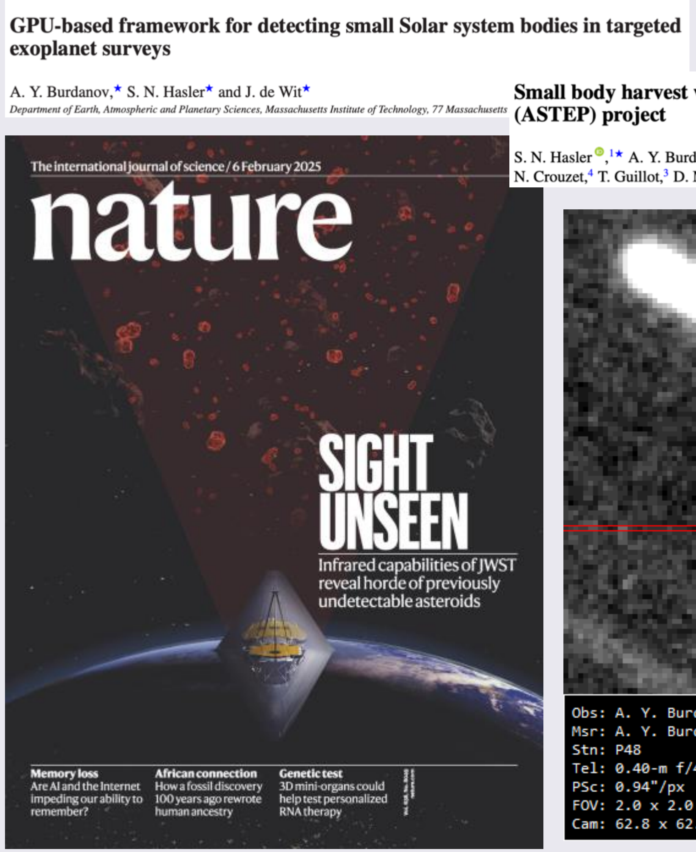
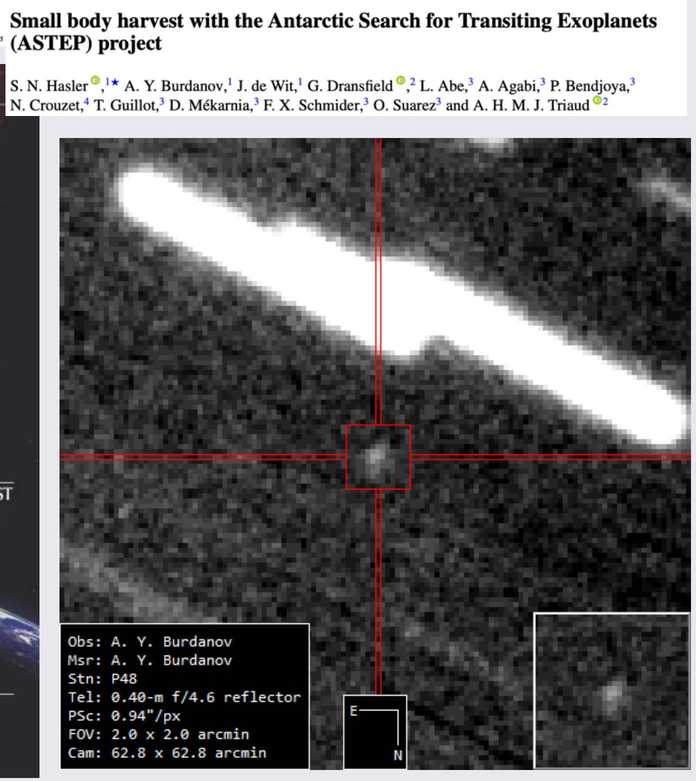
Uncovering unknown minor solar system bodies



Burdanov, de Wit, et al. 2025



Hasler et al. 2023

Summary

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Part 1: Deconfusion

The deconfuser:
- Quickly fits orbits to astrometric detections of planets in 2D images
- Decides which assignment of detection-to-planet fits the data best

Developed a photometry model and ranking scheme to augment the deconfuser

Analysis shows photometry to be useful for deconfusion (Hasler+ *under review*)

Part 2: Uranus at High Phase by New Horizons

We must use Solar System planets as “ground-truth” observations for exoplanet direct imaging

Uranus is dimmer than predicted by a Lambertian phase function at high phase

*Interested in exoplanet phase studies, direct imaging, or Solar System analogs for exoplanet research? Please reach out!

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