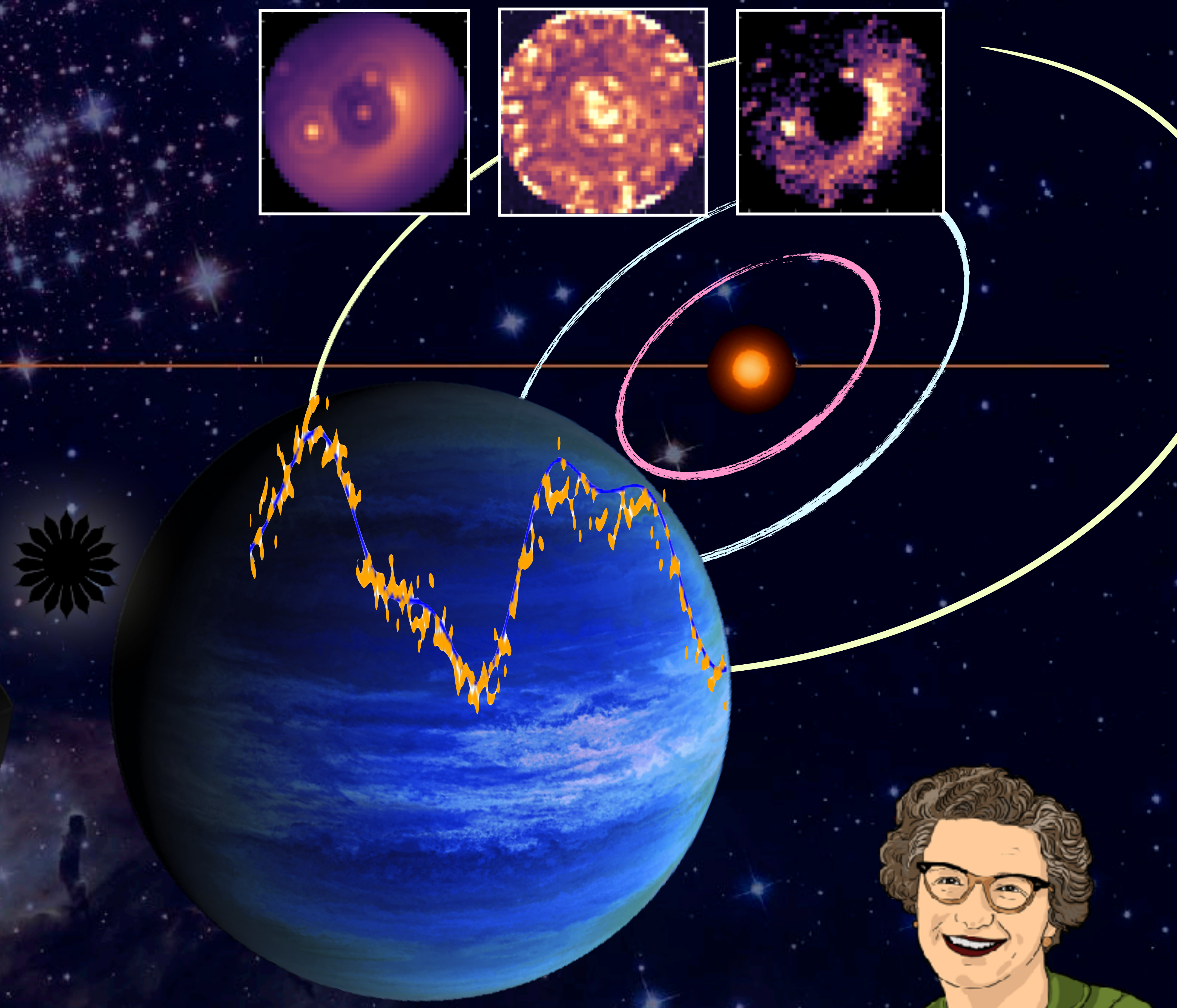
EXOPLANET IMAGING COMMUNITY DATA CHALLENGE

ROMAN SPACE TELESCOPE

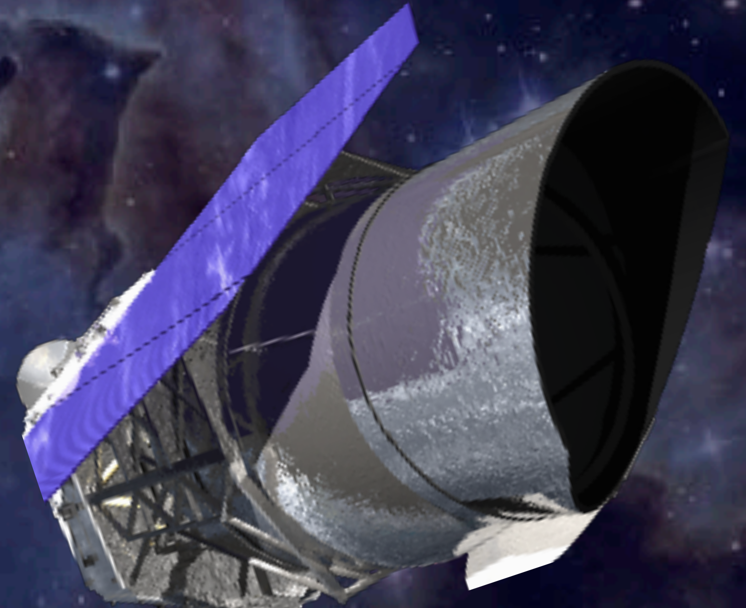
www.exoplanetdatachallenge.com



Julien Girard & Turnbull SIT

@djulik

STScI Liaison for the Coronagraph Instrument



Roman Coronagraph Instrument Information Sessions - October 26 & 28 2021 - IPAC/Virtual

Roman Exoplanet Imaging Community Data Challenge: Goals

To broaden and deepen our knowledge as exoplanet community

To get the community acquainted with the **Coronagraph Instrument** data's **new contrast regime** and astrophysics that will be enabled:

giant planets in reflected light

To develop, use and improve data simulation and analysis tools

To foster collaborations and train future exoplanet scientists!

www.exoplanetdatachallenge.com

Data Challenge **Team**, ∈ Turnbull SIT

M. Turnbull leads one of the 2 Science Investigation Teams (SIT) for the **Coronagraph Instrument** (form. CGI)


Margaret Turnbull


Neil Zimmerman


Ell Bogat


Julien Girard


Junellie Gonzalez


Sergi Hildebrandt


Avi Mandell


Stephen Kane


Chris Stark


Tiffany Meshkat


Zhexing Li

Roman Exoplanet Imaging Data Challenge: Organization

Ell Bogat (GSFC)

Julien Girard (STScI)

Junellie Gonzalez-Quiles (JHU)

Sergi Hildebrandt (JPL)

Stephen Kane (UCR)

Zhexing Li (UCR)

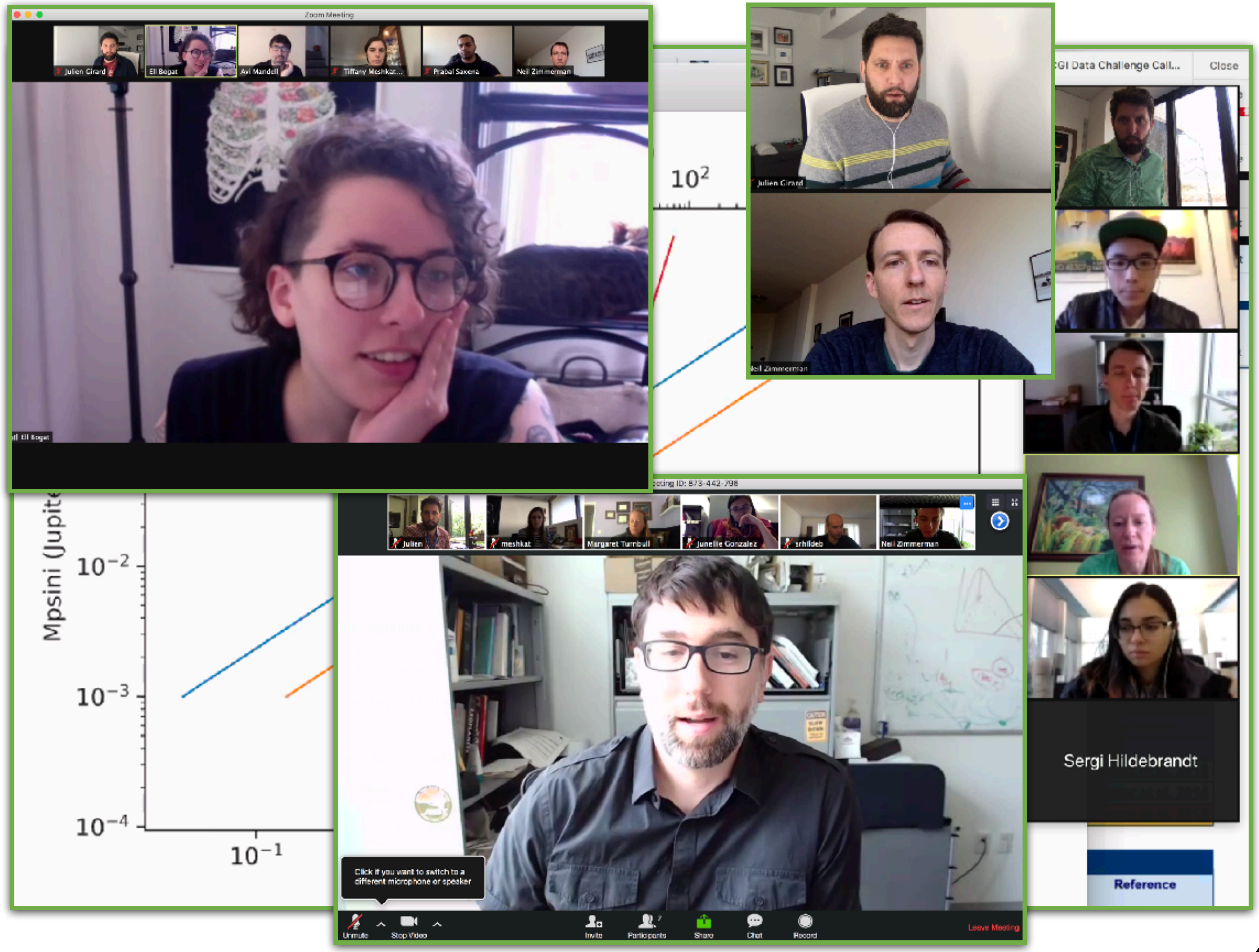
Avi Mandell (GSFC)

Tiffany Meshkat (IPAC)

Chris Stark (GSFC)

Maggie Turnbull (SETI, SIT PI)

Neil Zimmerman (GSFC)

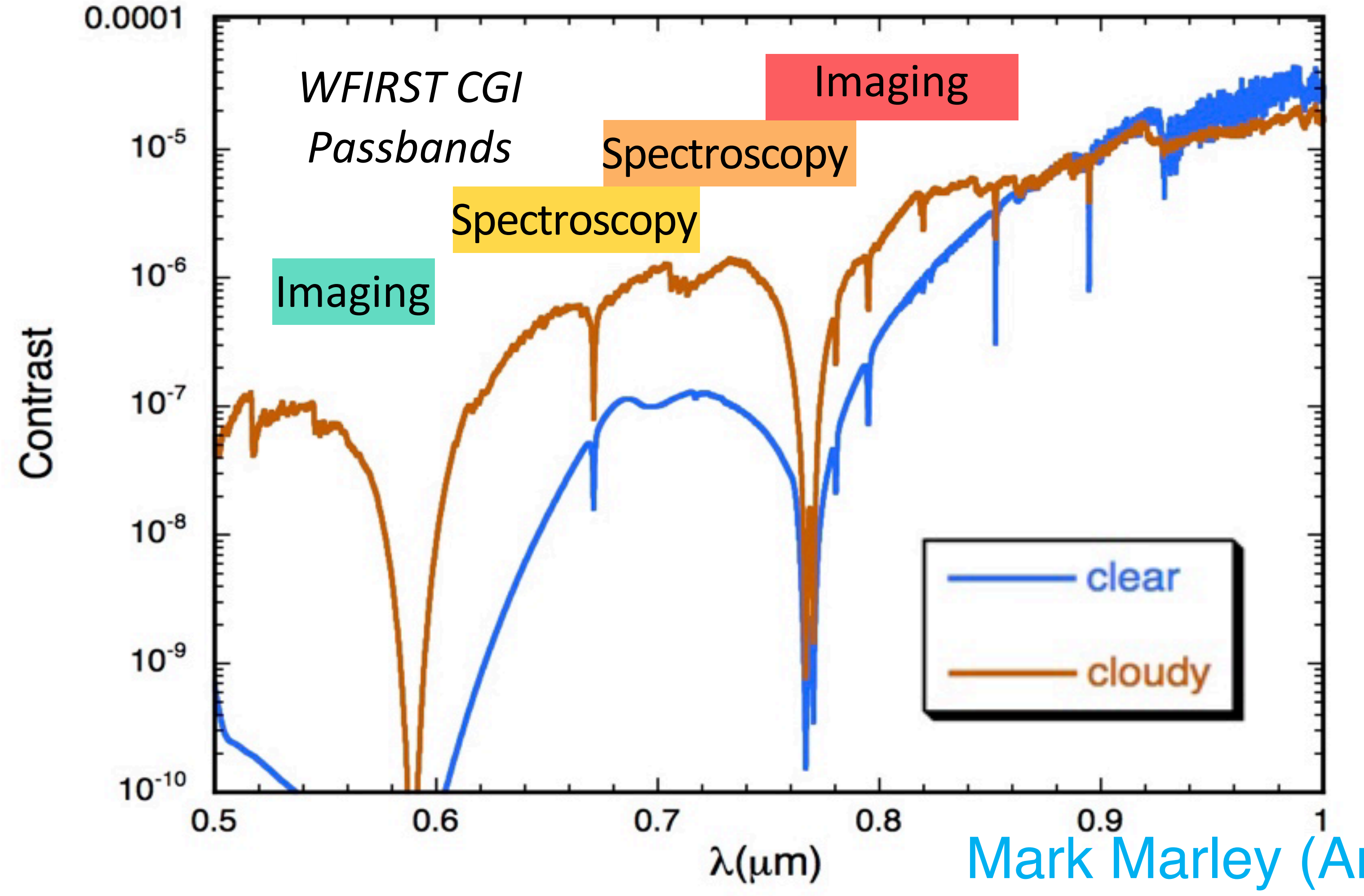


A NEW CONTRAST REGIME, A NEW TYPE OF SCIENCE

GIANT EXOPLANETS IN REFLECTED LIGHT!

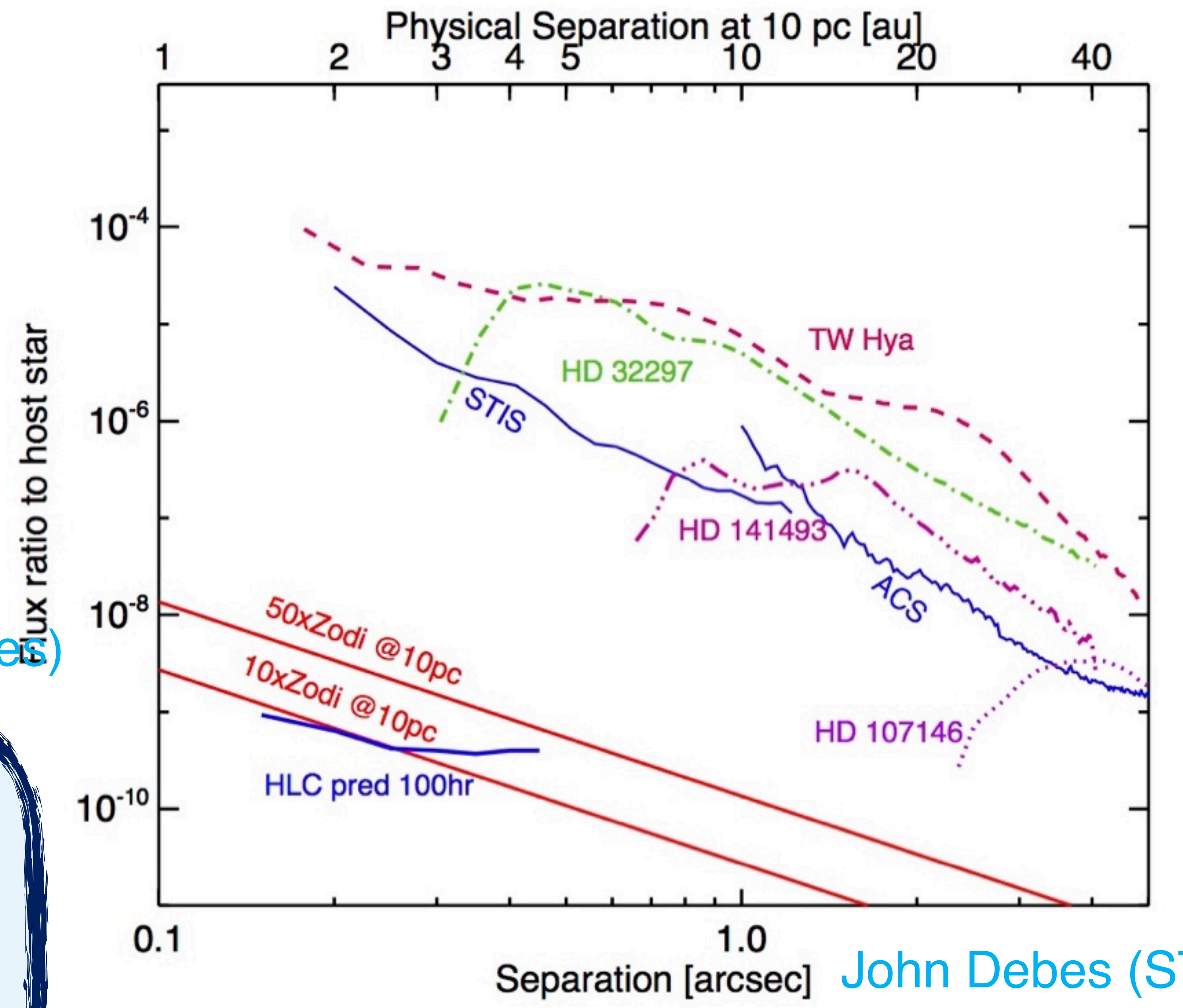
Roman Exoplanet Imaging DC & Coronagraph Science Cases

Self-luminous, Young Super Jupiters:
Atmospheric Properties

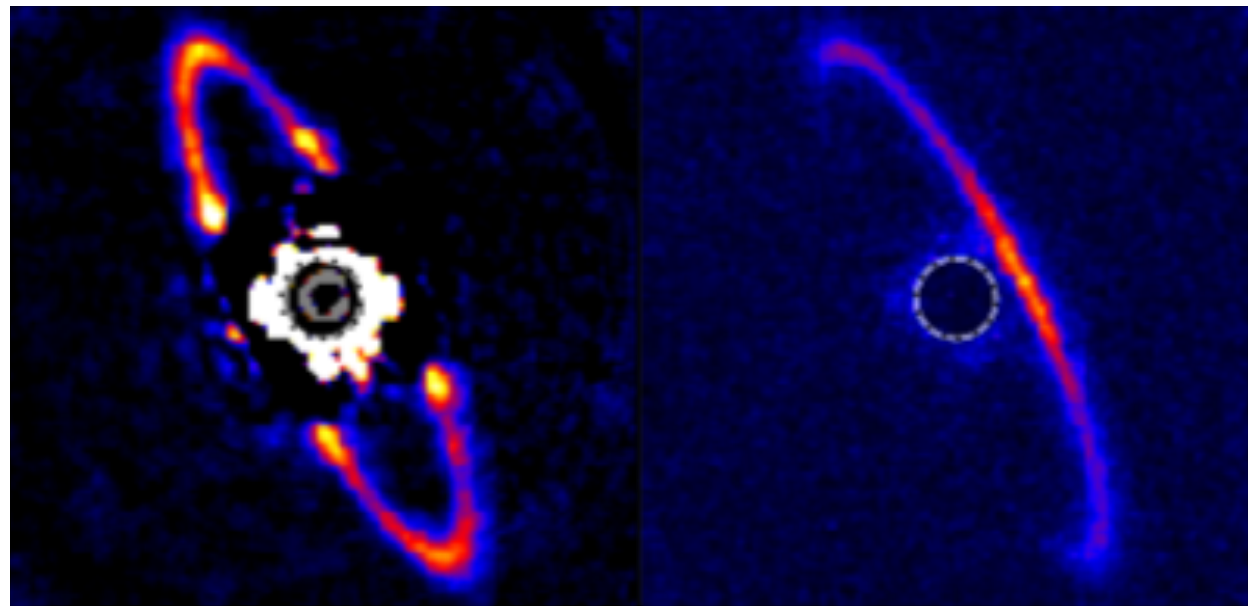


Mark Marley (Ames)

Circumstellar disks:
Protoplanetary (young)
Debris (mature)
Exozodi (mature, HZ)

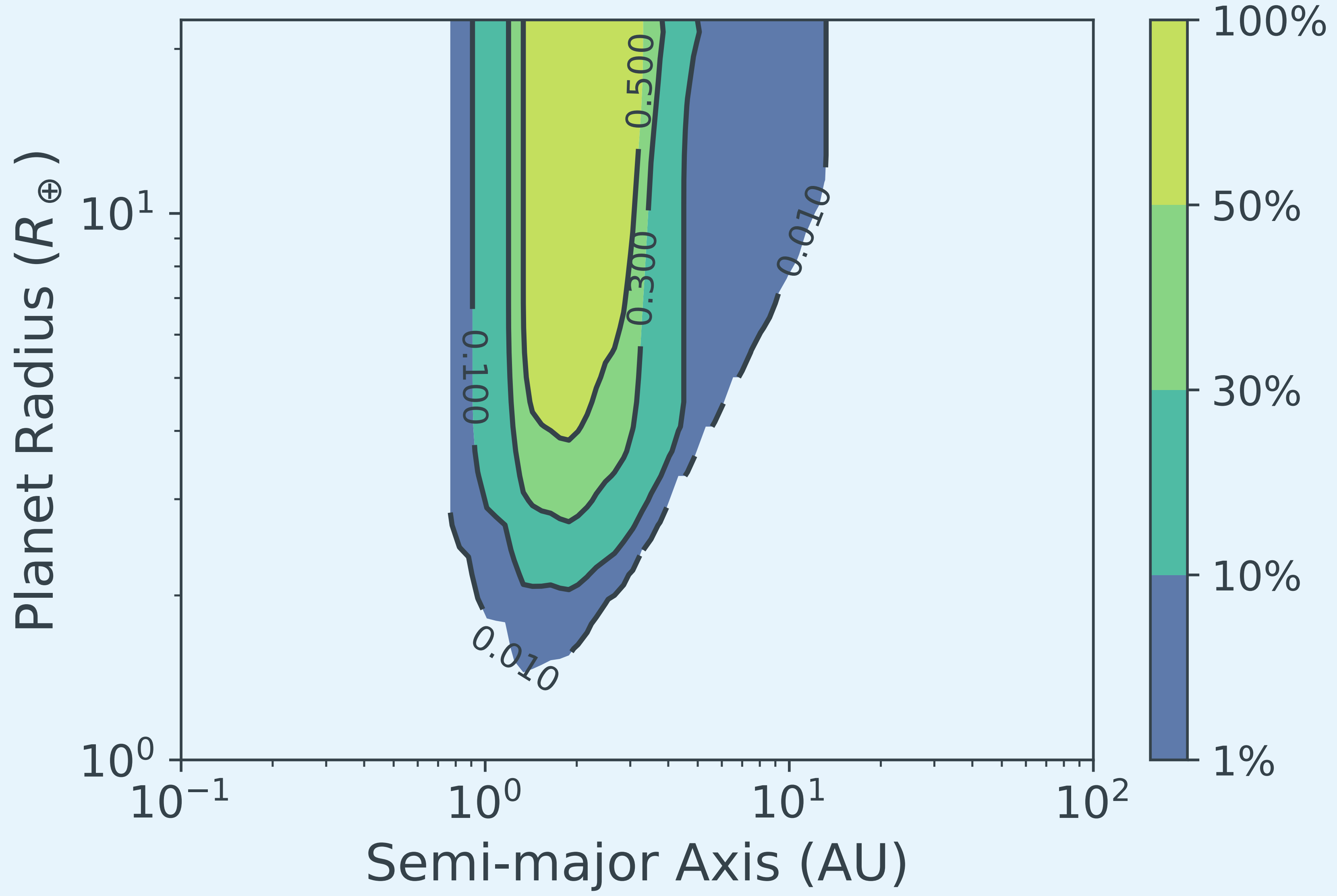


John Debes (STScI)



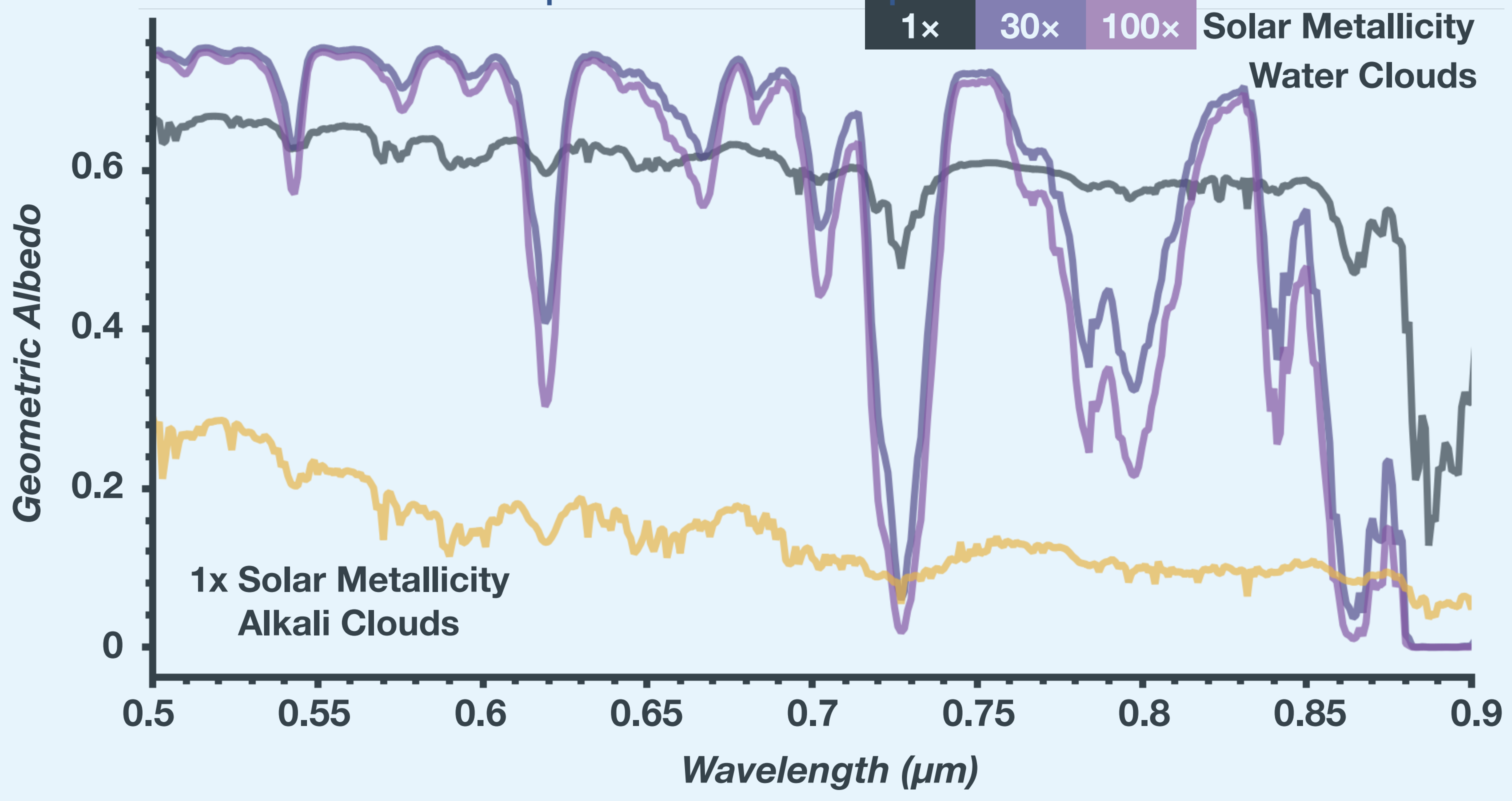
Marshall Perrin et a. 2015

Blind search for exoplanets



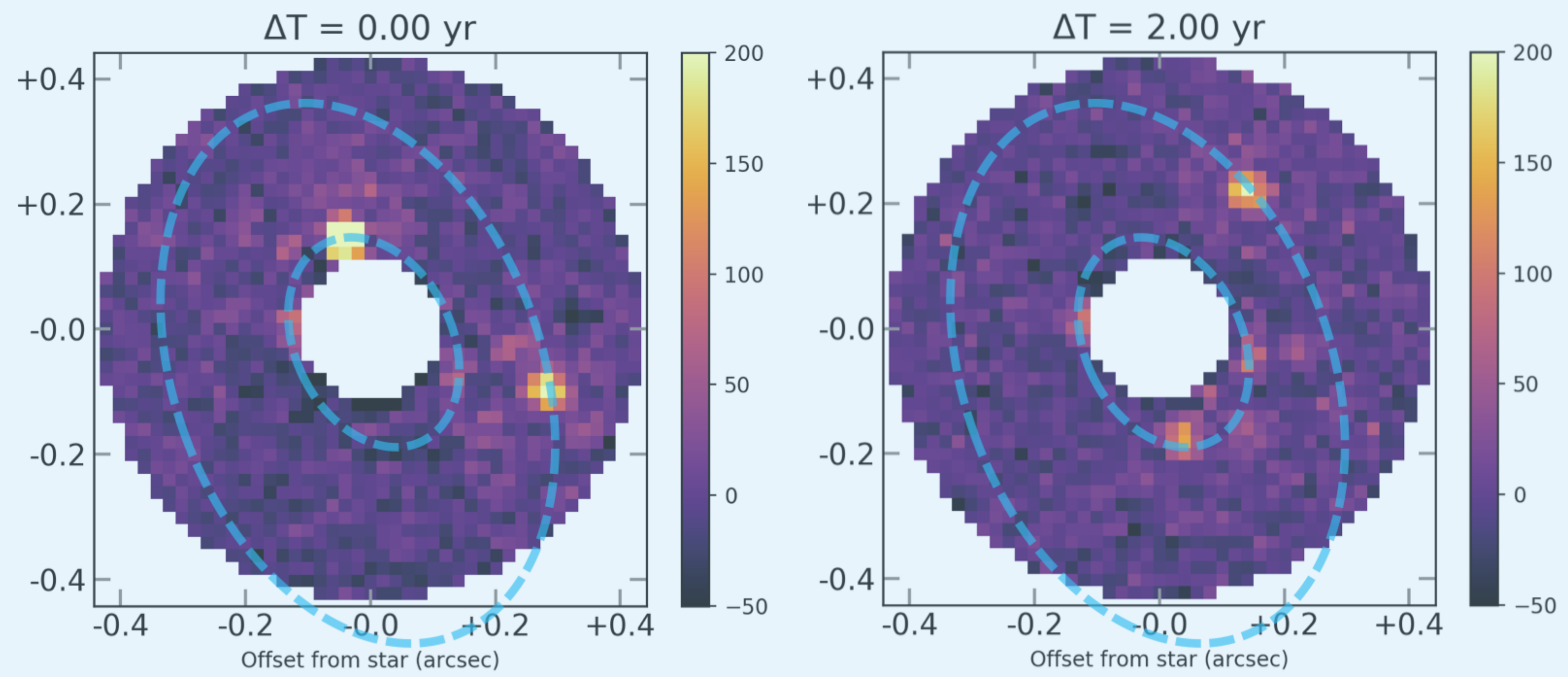
Garret, Savransky & Macintosh (2017)

Mature Jupiter Analogues in Reflected Light:
Atmospheric Properties



Natasha Batahla & Mark Marley (Ames)

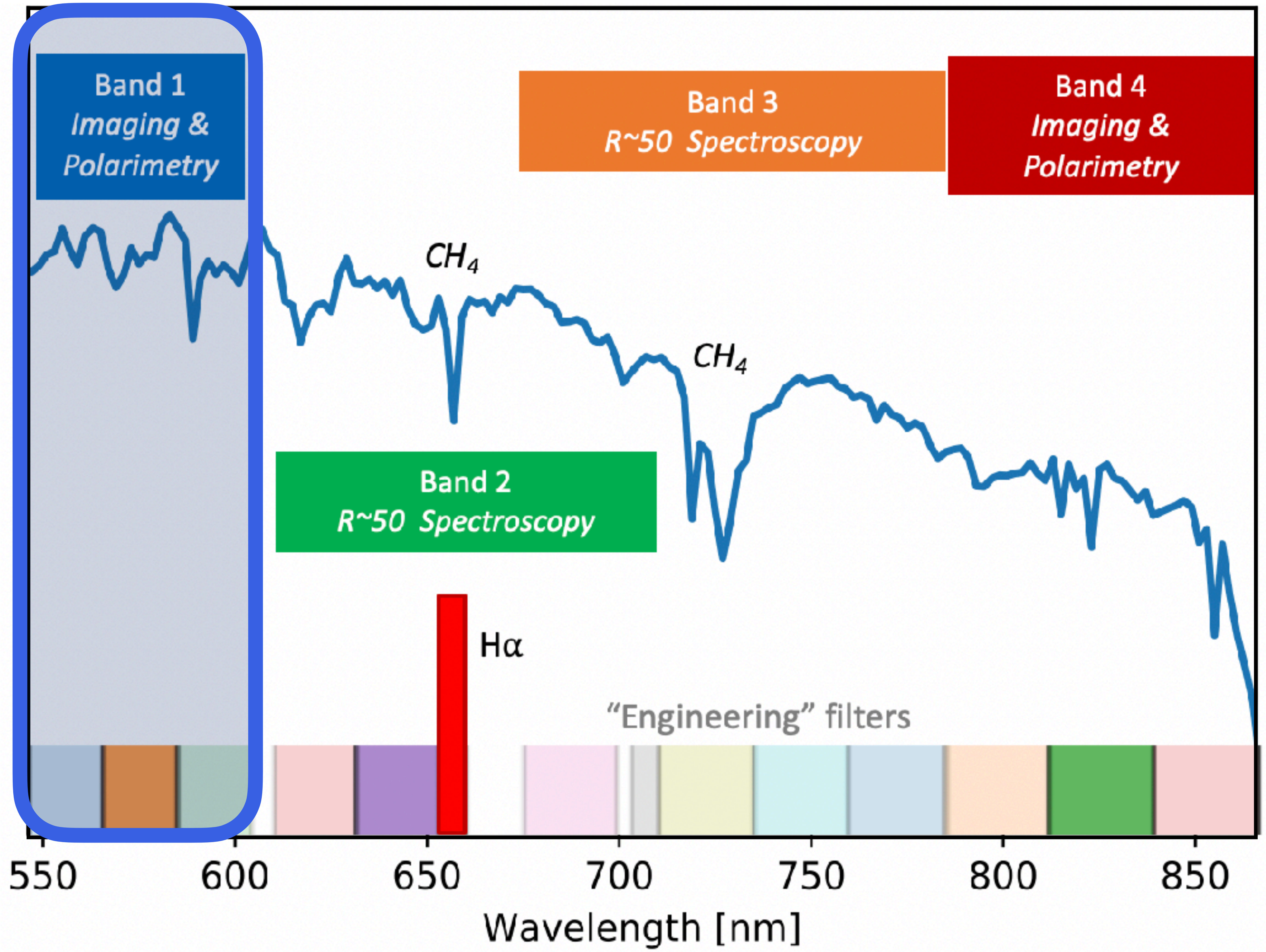
Orbital Solution and Mass Measurement

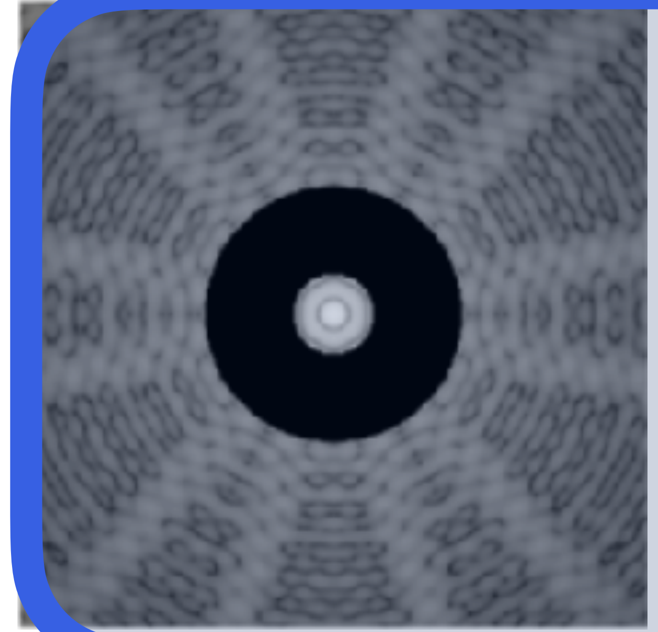


Natasha Batahla & Mark Marley (Ames)

Credit: JPL ROMAN Project Science Team

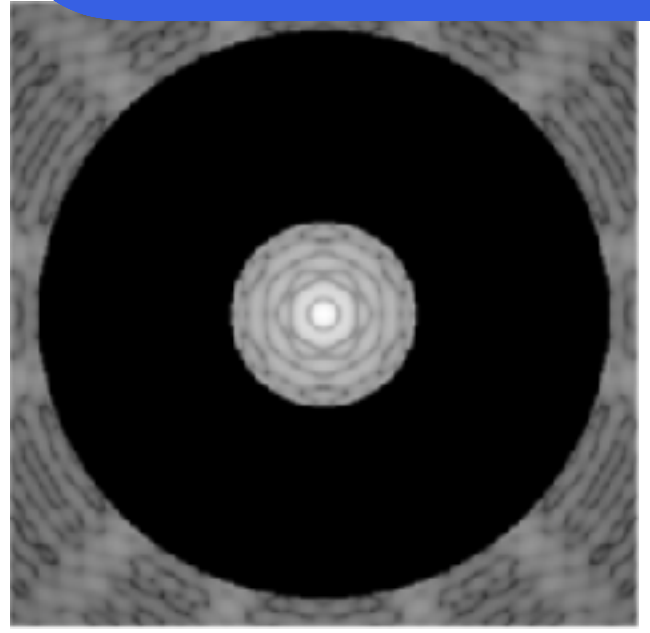
Roman Exoplanet Imaging DC: Coronagraph Modes





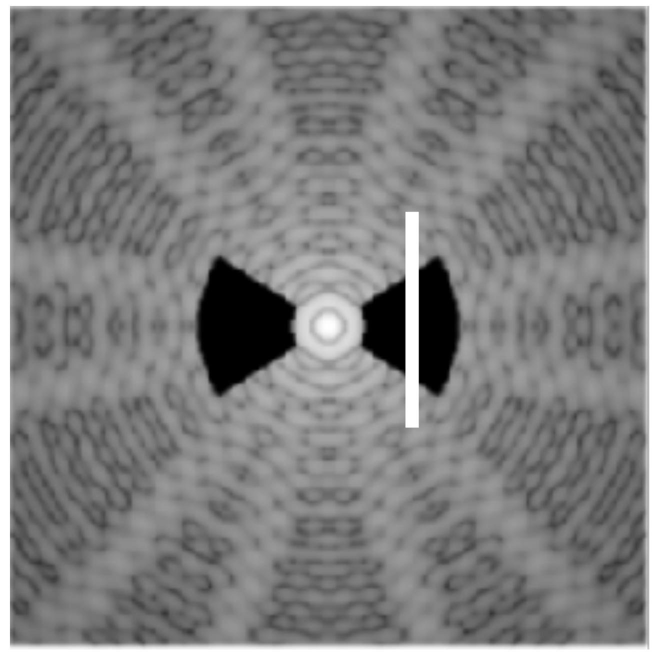
Narrow field of view mode
Full 360 deg
- Inner working angle (IWA): 3 lambda/D (0.15")
- Outer working angle (OWA): 9 lambda/D (0.45")

Band 1: 575 nm, 10.1% bandwidth



Wide field of view mode
Full 360 deg
- IWA: 6.5 lambda/D (0.43")
- OWA: 20 lambda/D (1.45")

Band 4: 825 nm, 9.9% bandwidth



Spectroscopy mode
Prism+ slit

Band 3: 730 nm, 16.7% bandwidth

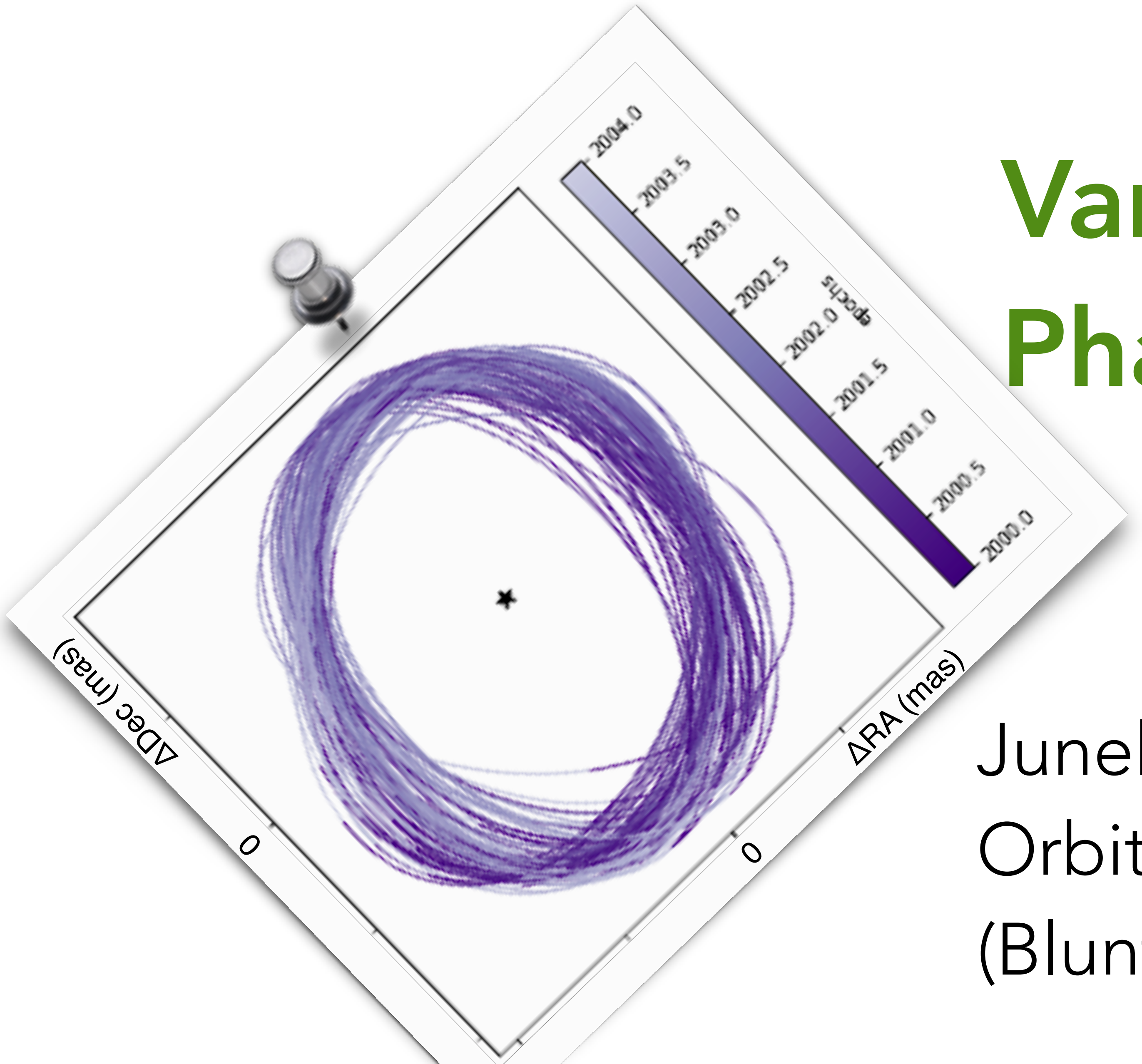
+ Starshade 360° large FoV @425-552nm (assuming a rendezvous)

Credit: JPL / 2020


An original Data Challenge

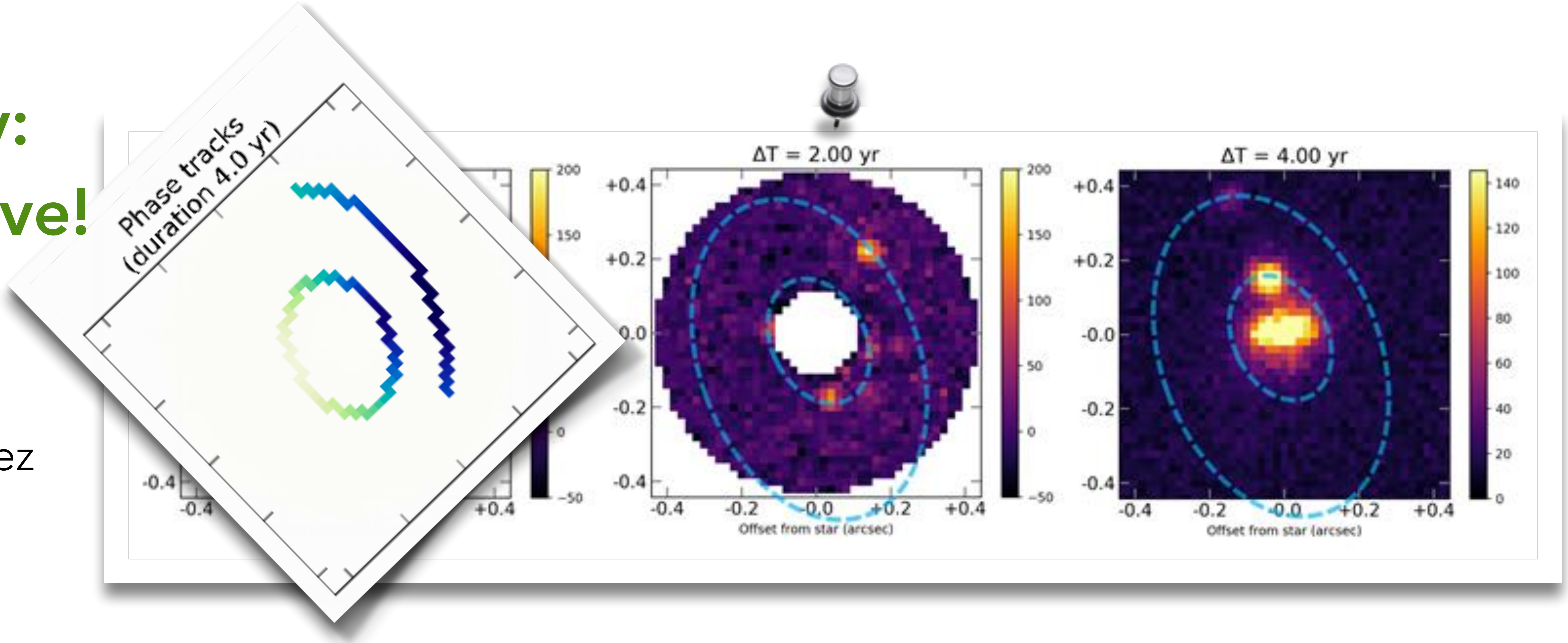
ROMAN Exoplanet Imaging DC: focus on Astrometry

- **6 imaging epoch**s of the same target throughout mission: 47 UMa
- 3 planet with matching and realistic **radial velocity data**
- Extract sources, compute relative photometry & astrometry, disentangle from background sources, exozodiacal light
- Compute orbital solution using all the information available

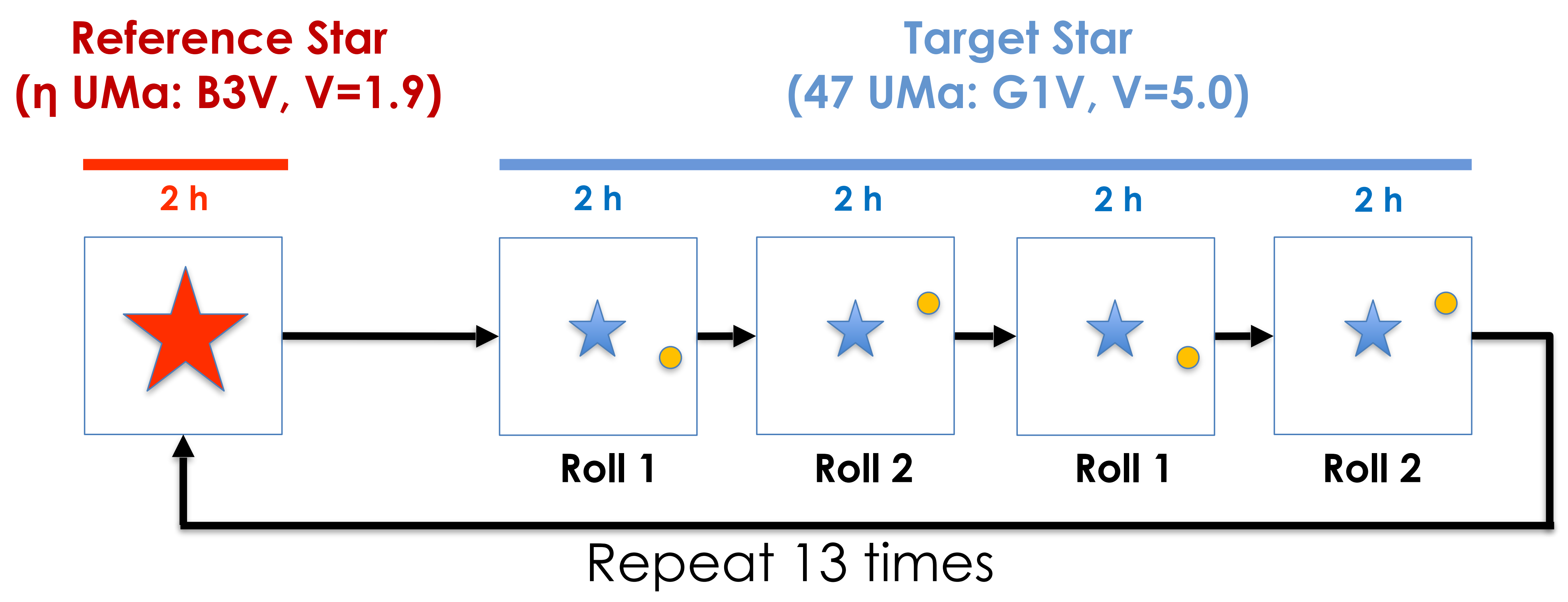


Junellie Gonzalez
Orbitize/OFTI
(Blunt 2017)

Variability:
Phase curve!



Roman Exoplanet Imaging DC: HLC & Precursor RV data

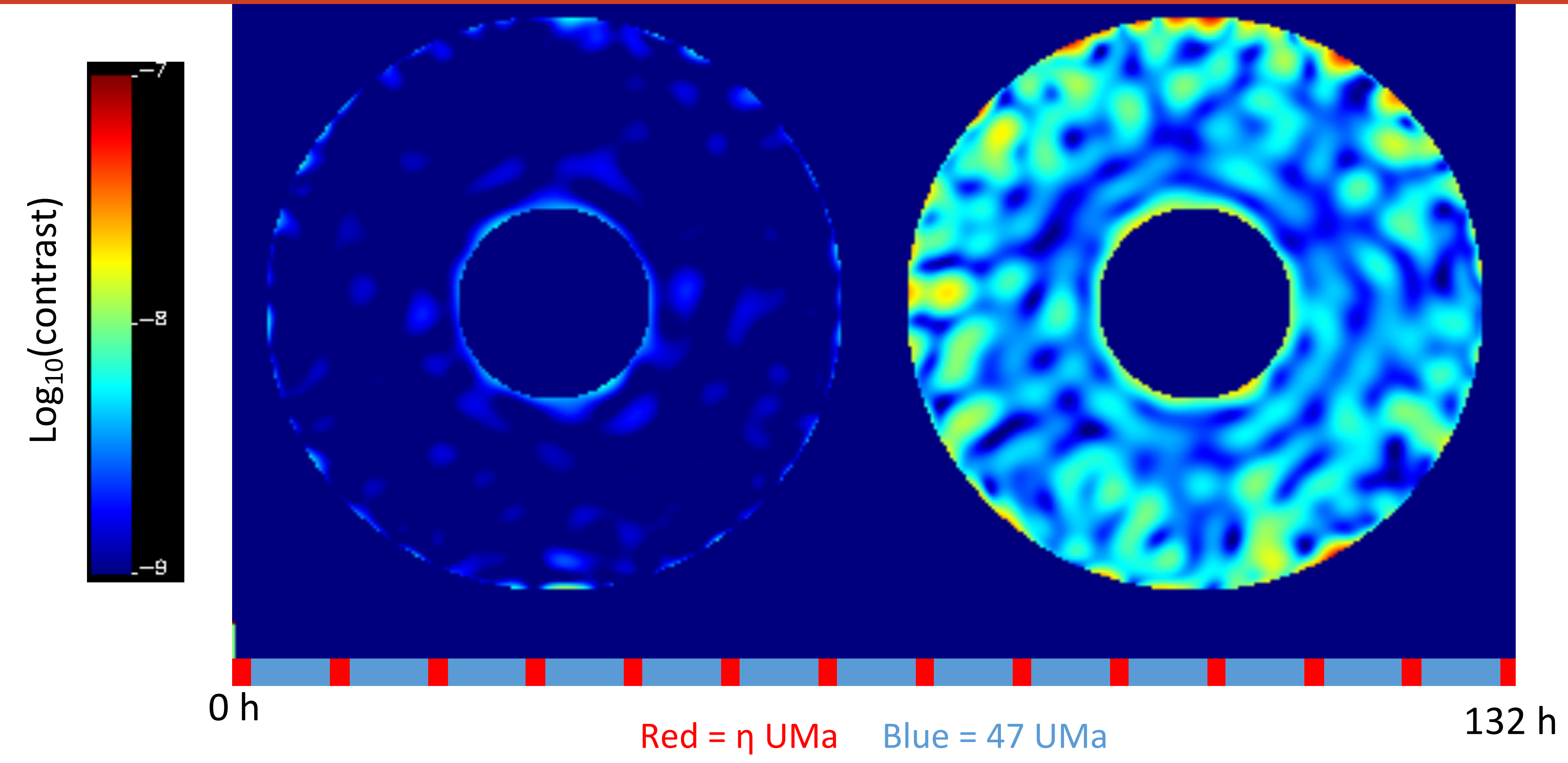


CGI DATA OS6

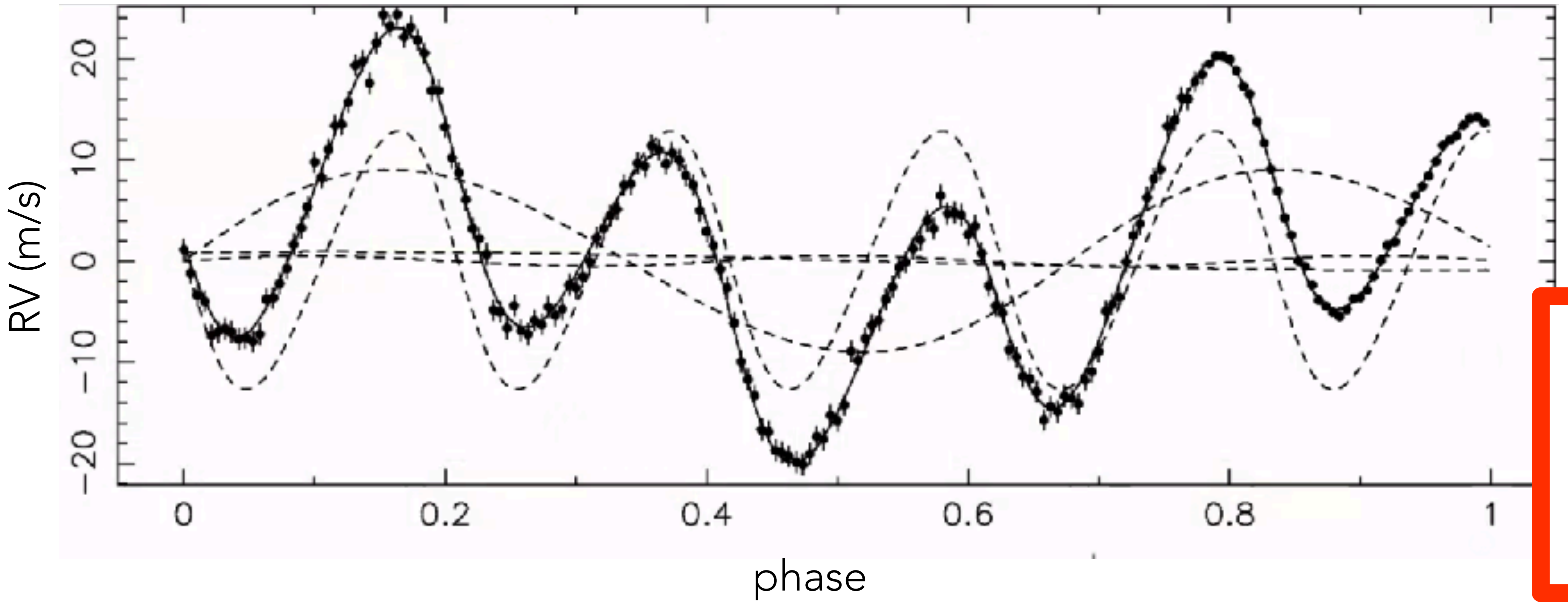
+

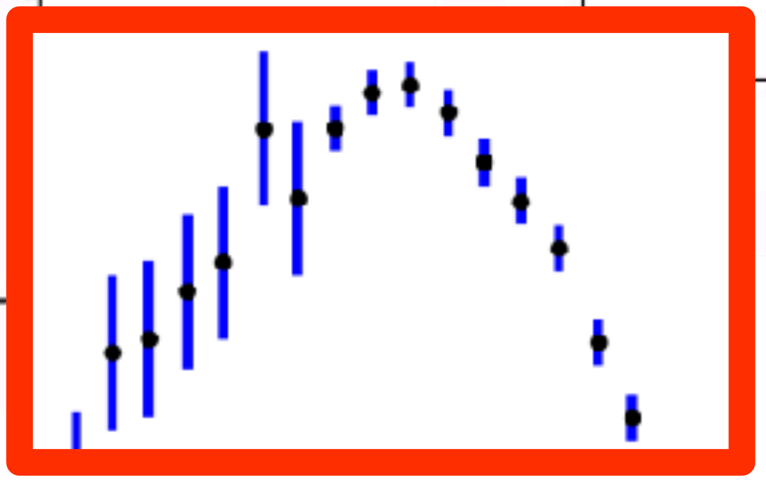
RV

Talk by John Krist on Observing Scenarios

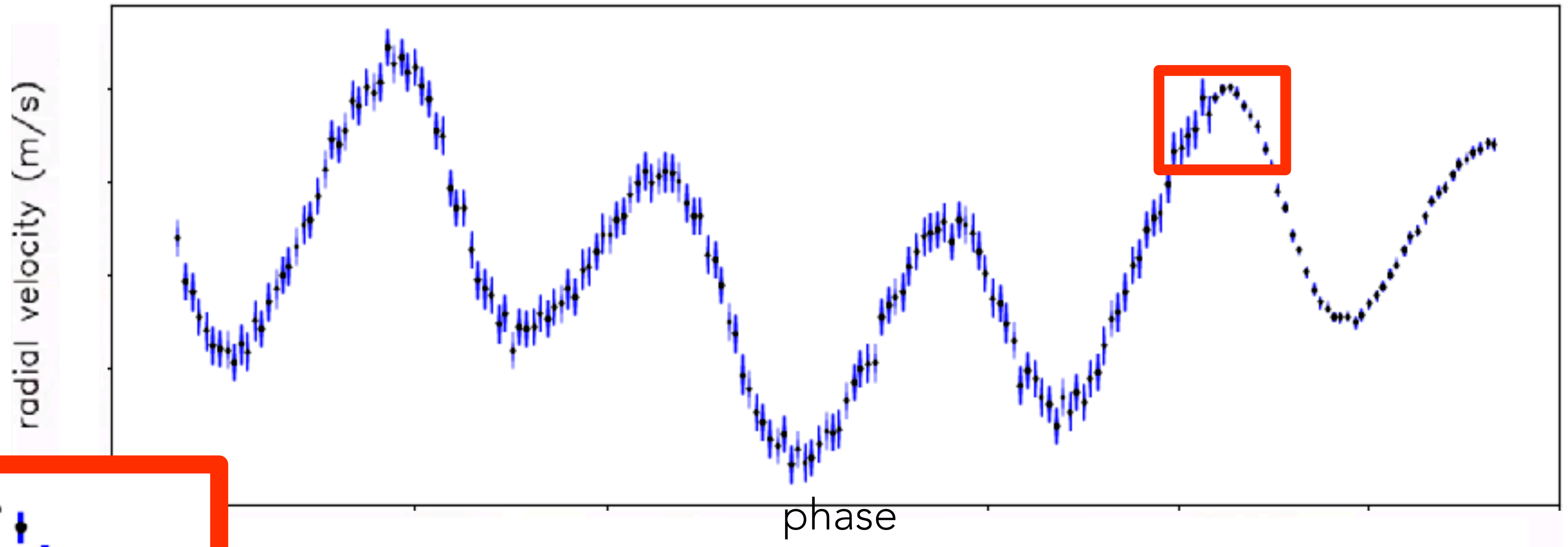


"Truth" (hackathon n°2)
4 planets, 2 detectable with RV





Precursor RV Data provided (hackathon n°2)



2006 - 2020 ~1 m/s accuracy (e.g. Keck)

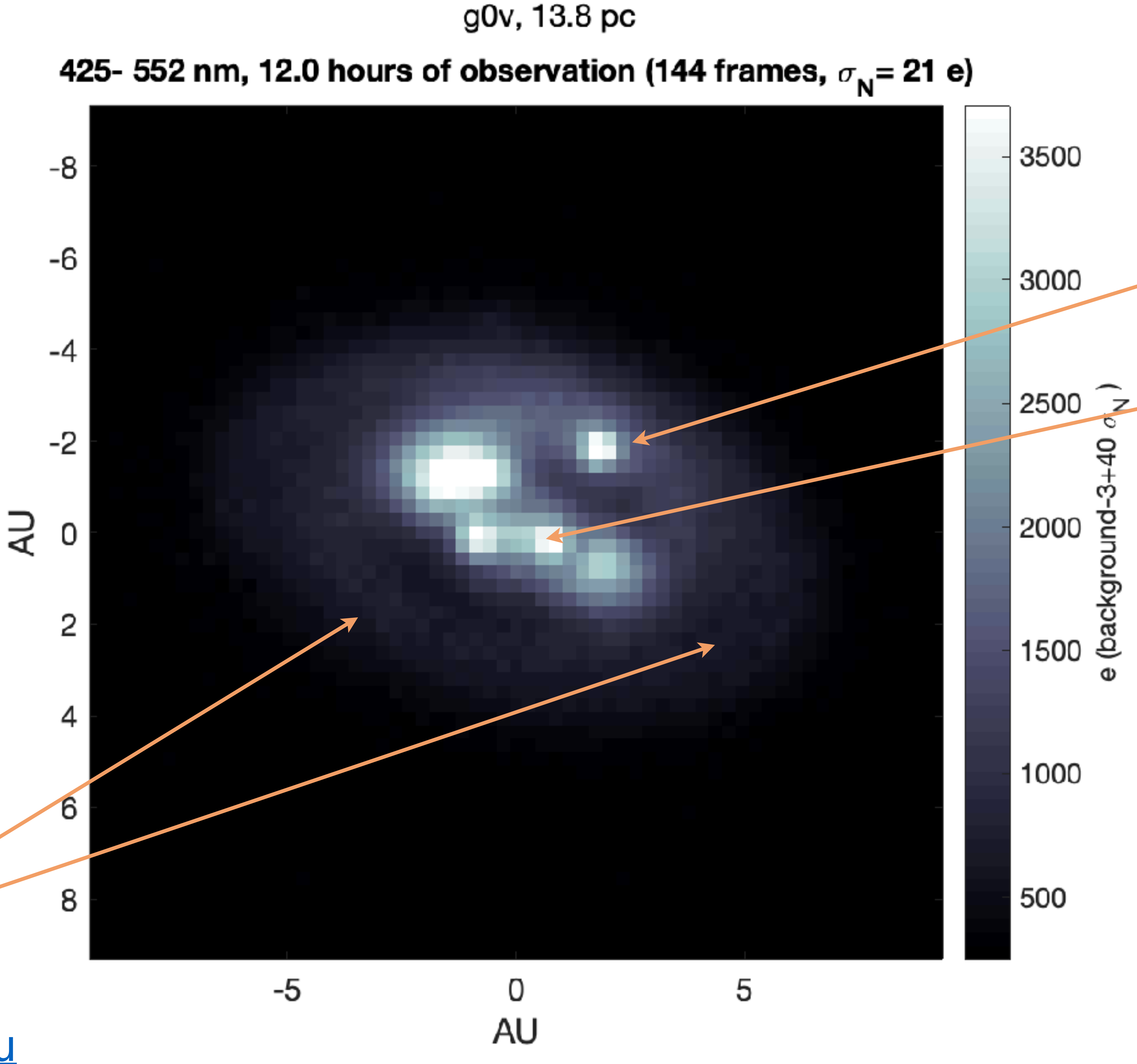
2020 - 2024* ~0.3 m/s accuracy (e.g. NEID)

* assuming cross-instrument calibrations are ok

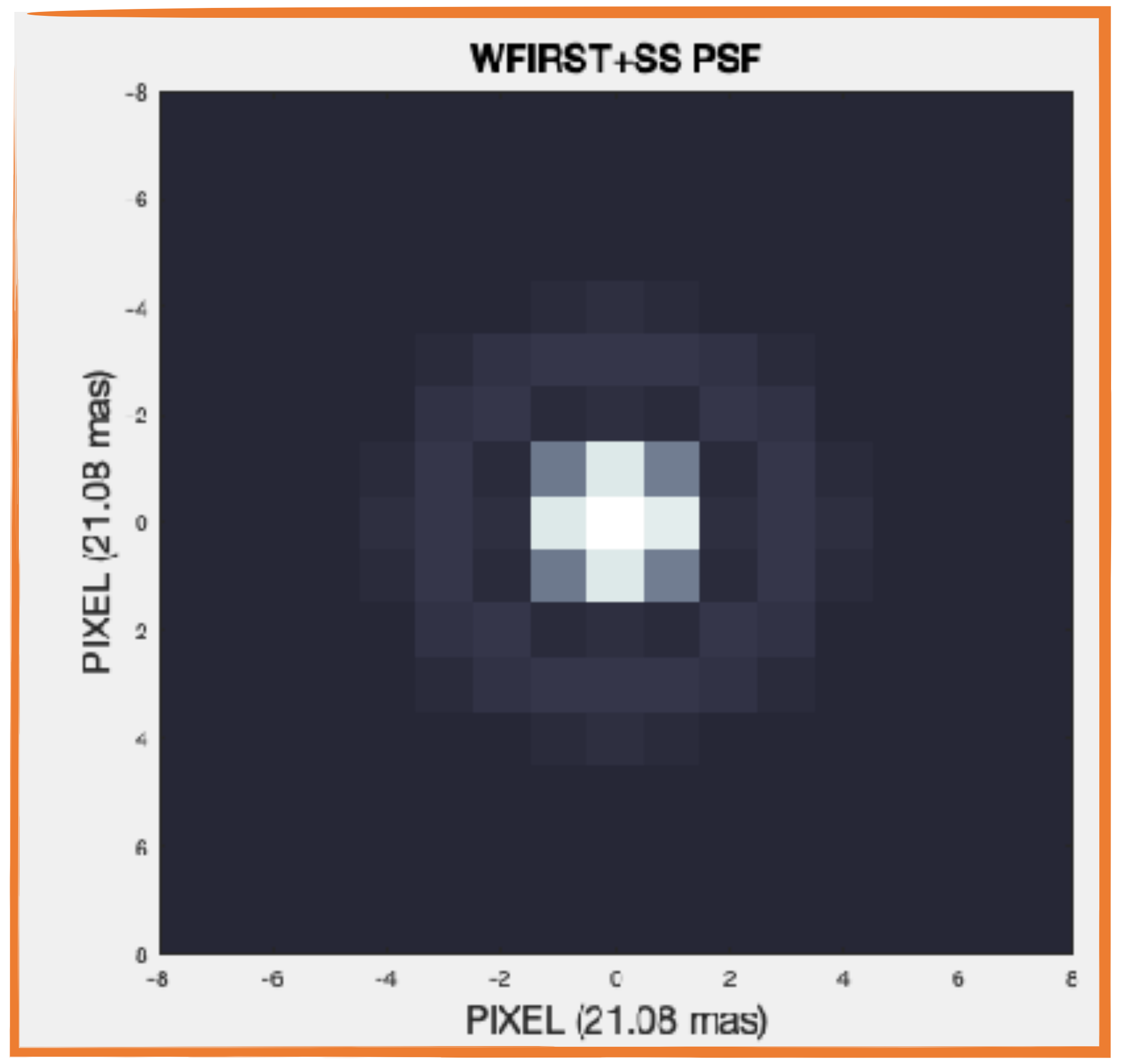
Talk by Stephen Kane & Zhexing Li on RV precursor work

ROMAN Exoplanet Imaging DC: Starshade Rendezvous Simulations

Sergi Hildebrandt (JPL)

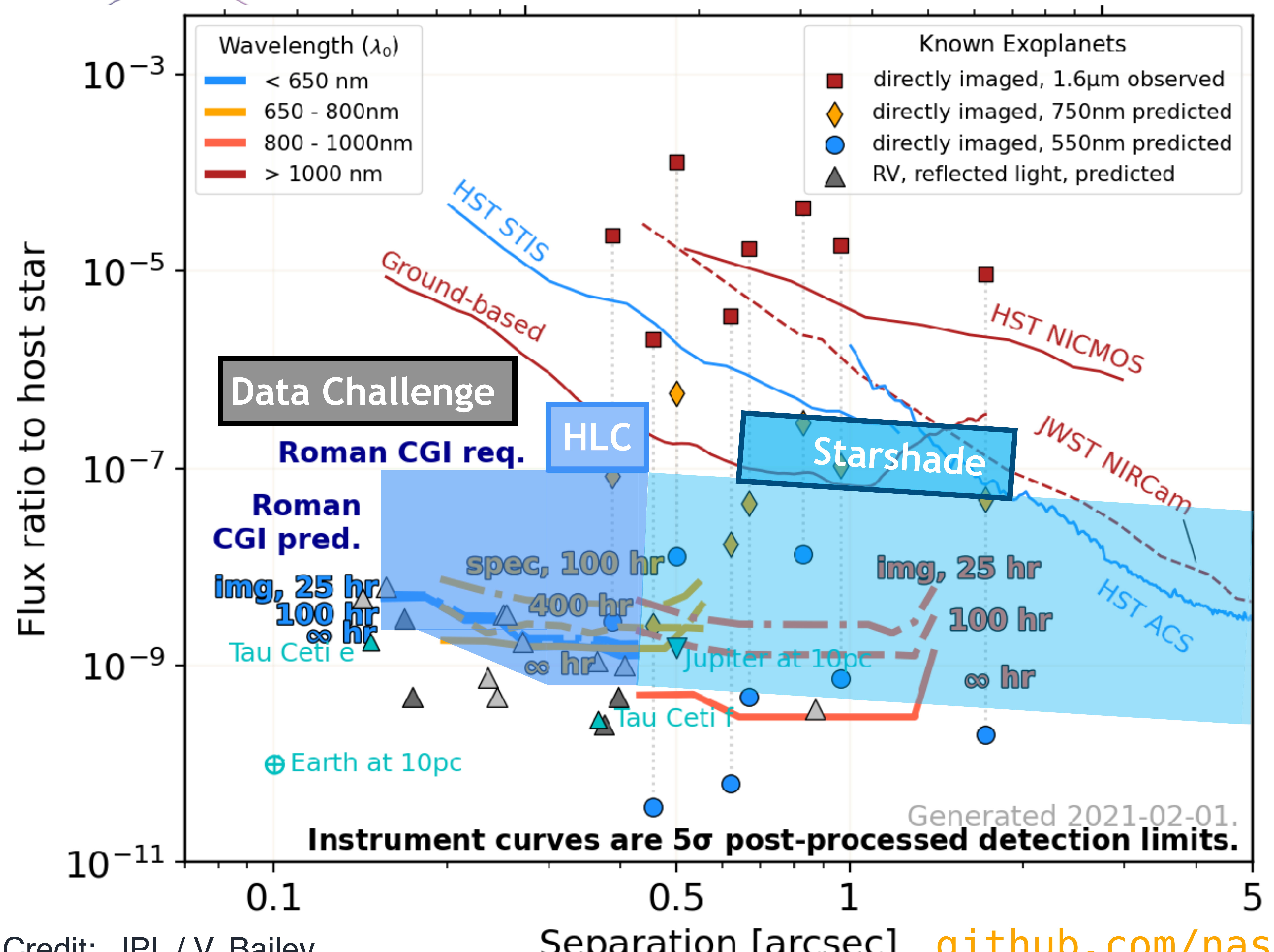


PSF Reference



www.sister.caltech.edu

Roman Exoplanet Imaging DC: Contrast Regime (OS6-OS9)



Credit: JPL / V. Bailey

github.com/nasavbailey/DI-flux-ratio-plot

For 5 < V <6 stars

The expected contrast is

< 10^{-7} (required)

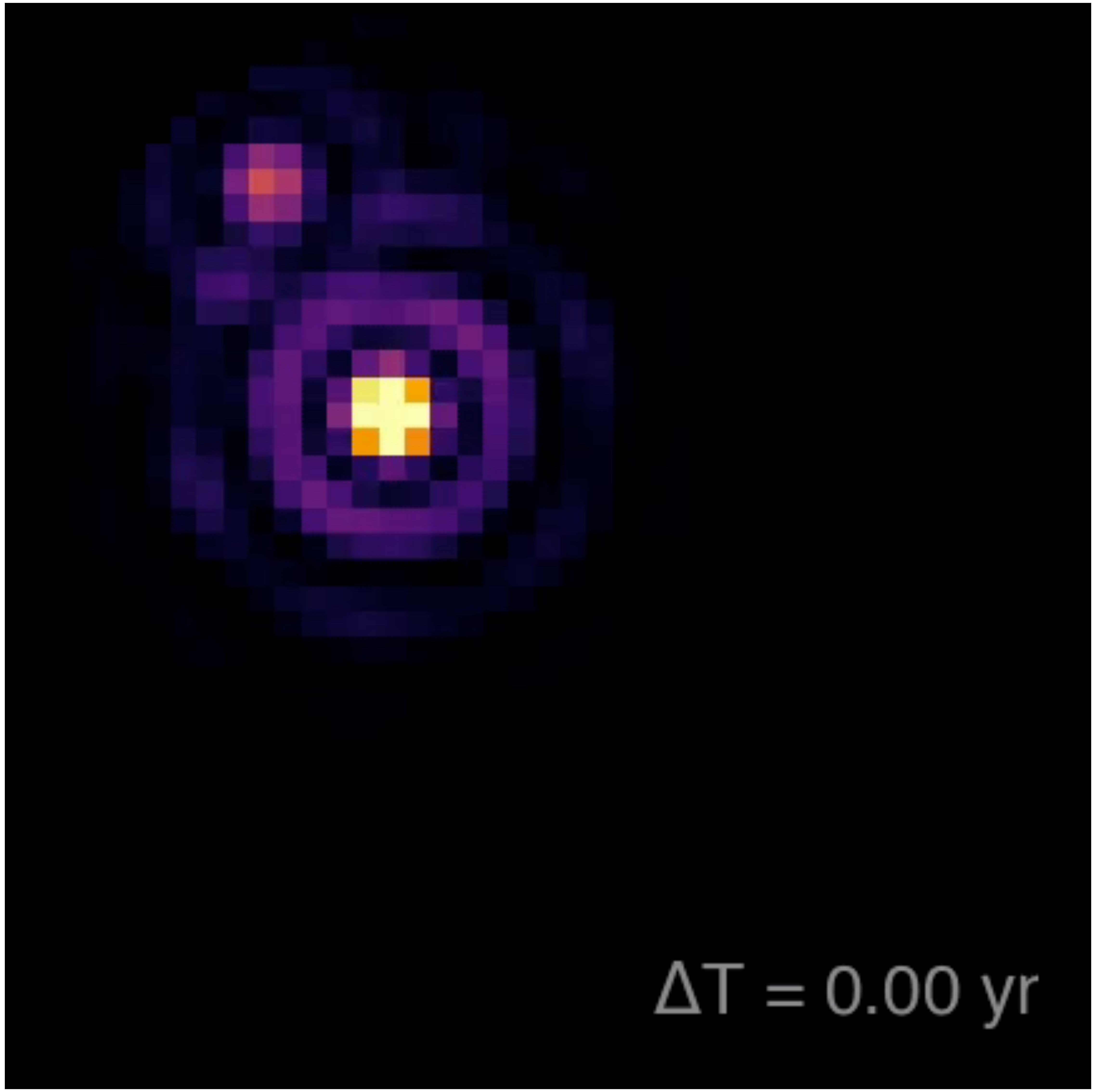
~ 10^{-9} (predicted)

100 to 1,000 times better than current facilities. Optimistically, image

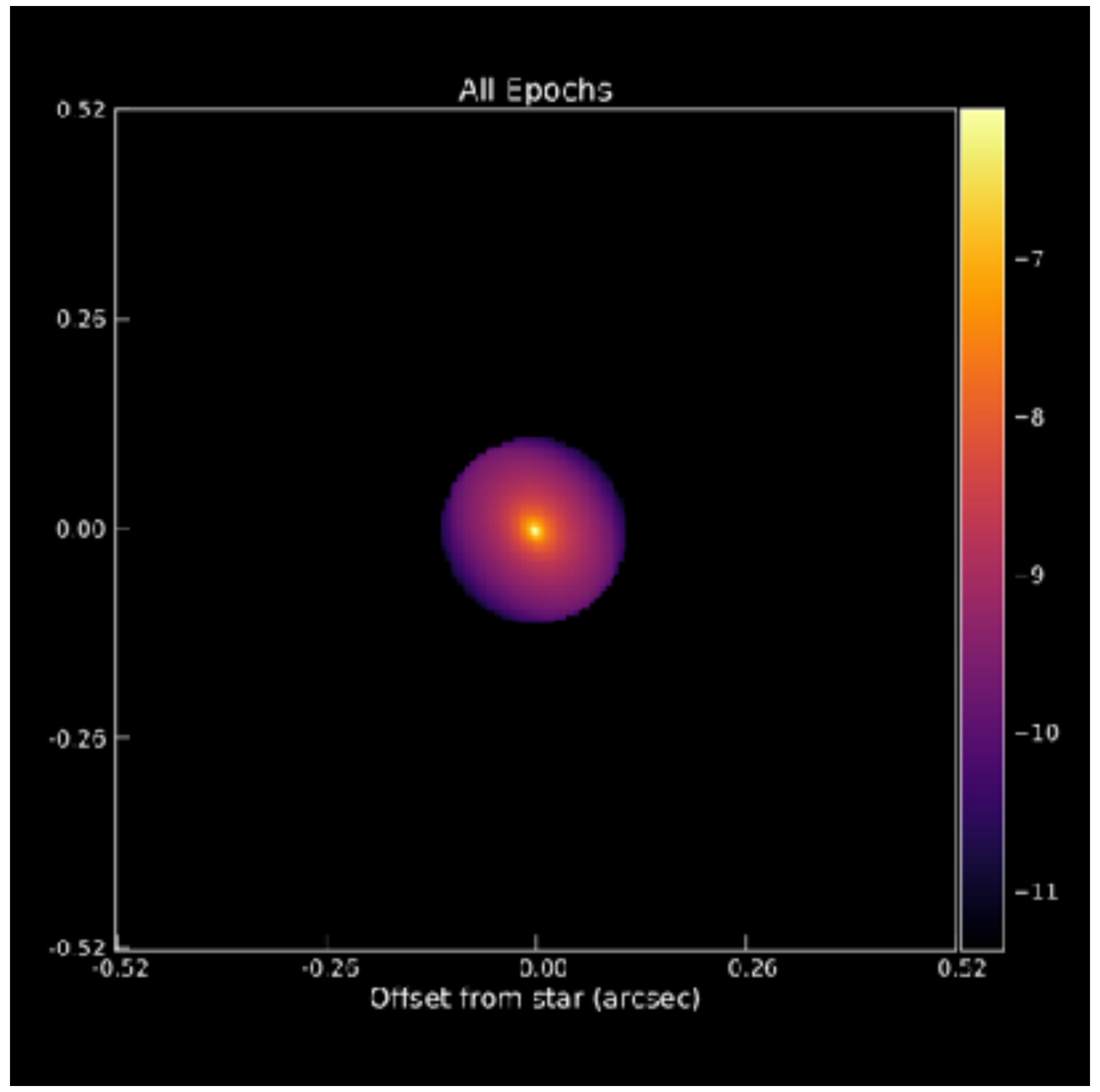
"Jupiters" to "Neptunes"

@50pc in reflected light!

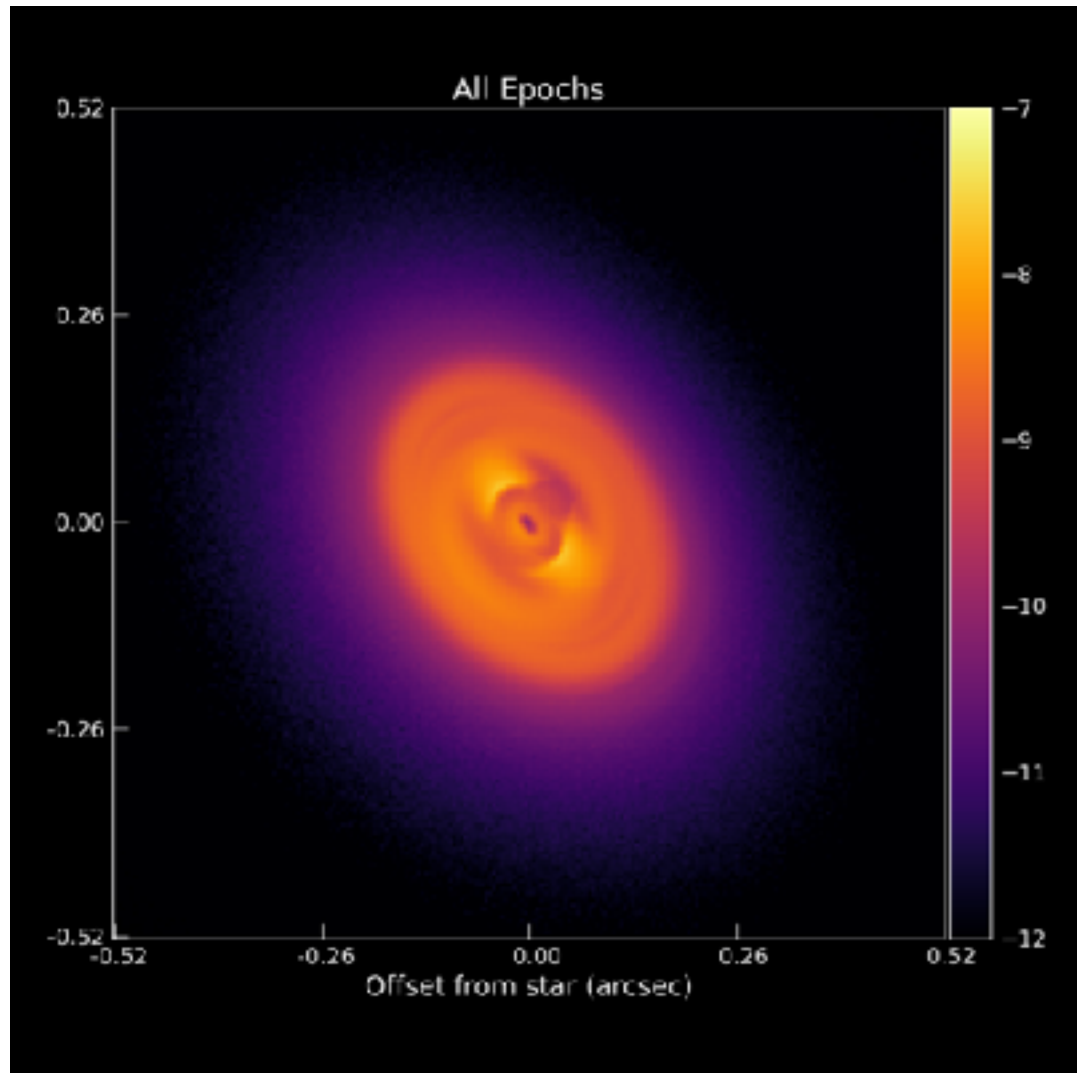
Data Challenge Design: 3-Jupiter analogs + disk



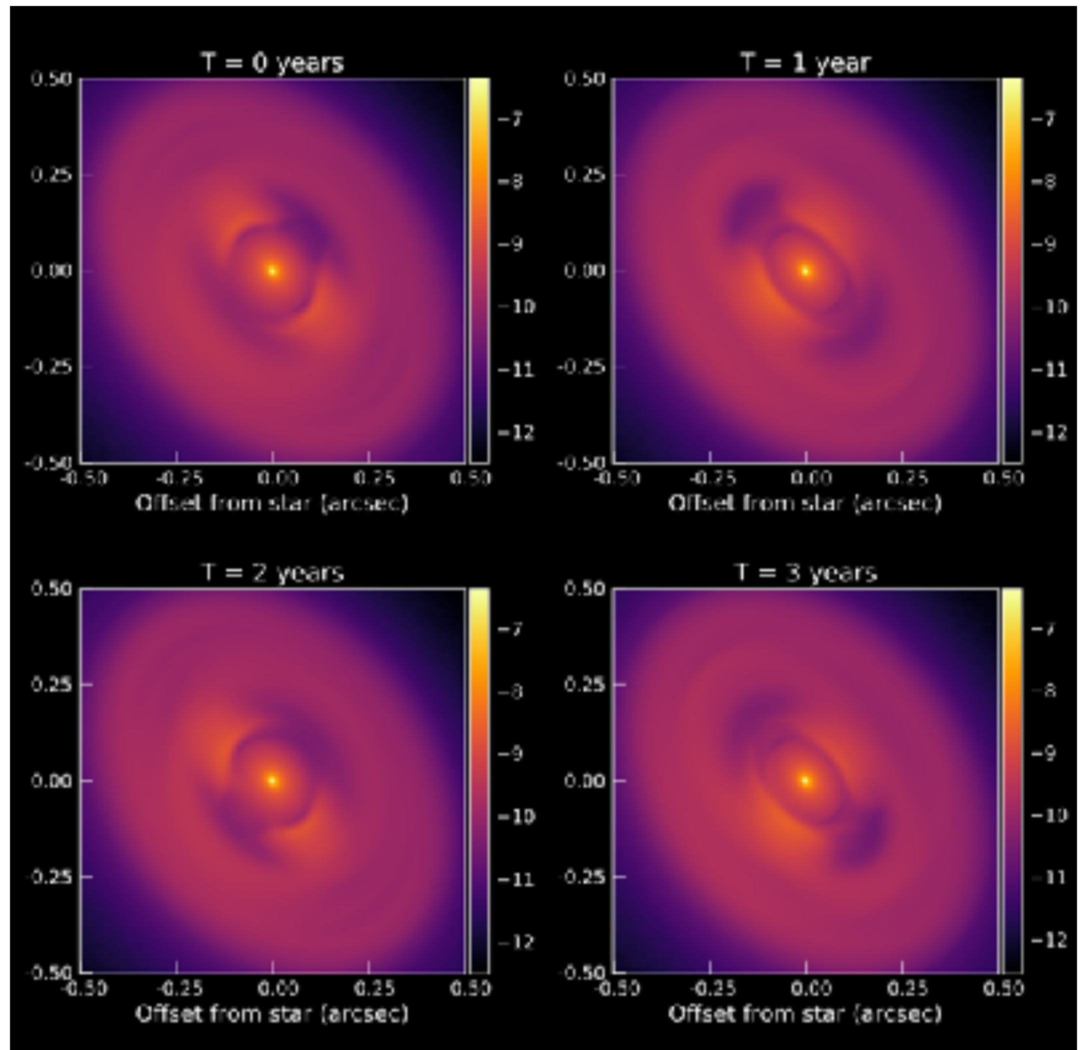
Exozodiacal Cloud



Dynamical Simulations



Exozodiacal Debris Disk Model



Stark & Kuchner et al. 2008, 2009

ZIMMERMAN+ (IN PREP)

Junellie Gonzalez-Quiles (GSFC)

Chris Stark (STScI)

Neil Zimmerman (GSFC)

Sergi Hildebrandt (JPL)

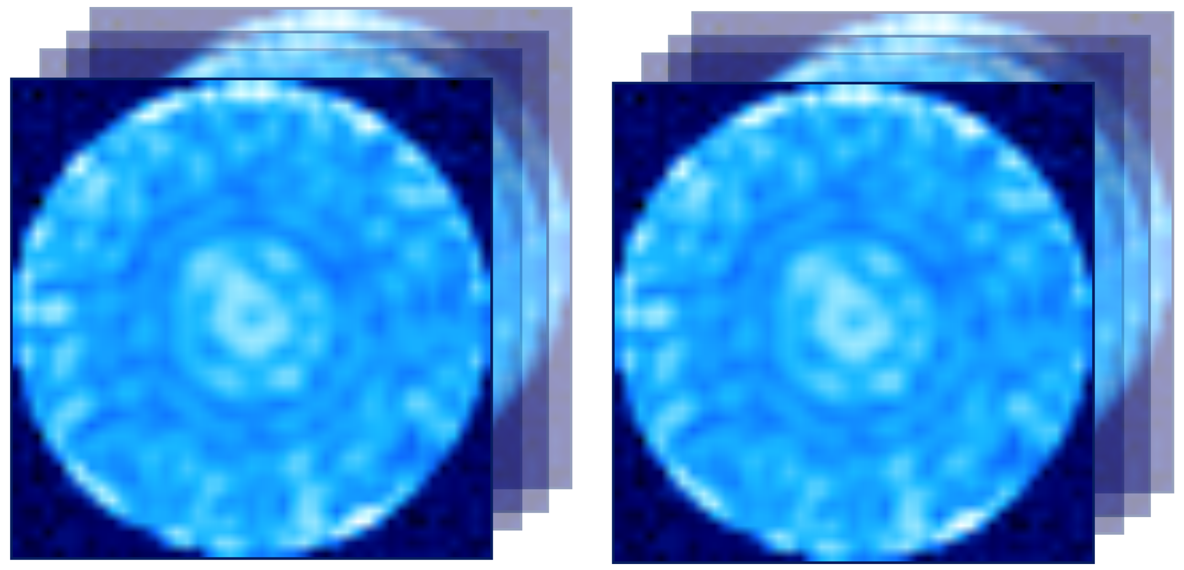
In-house Analysis

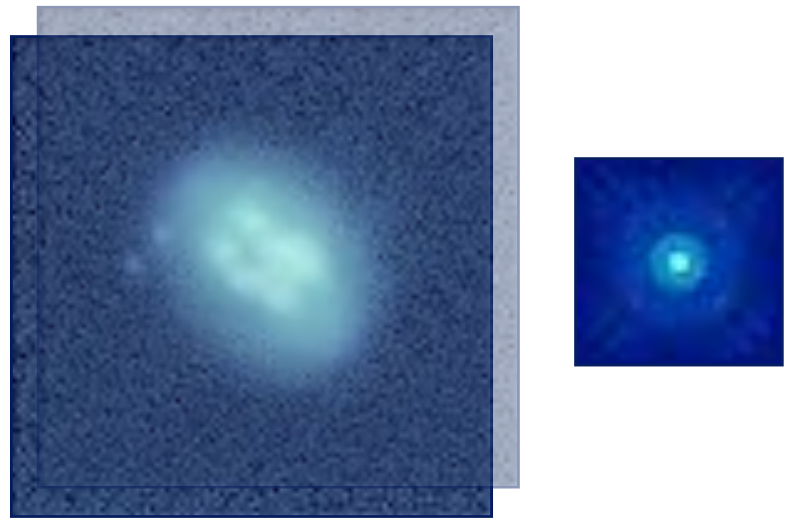
The Roman Exoplanet Imaging DC: 4 Steps

DATA

6 imaging epochs throughout the mission

Realistic simulations:OS6 Speckle field time series, detector model, background contamination sources, exozodiacal light

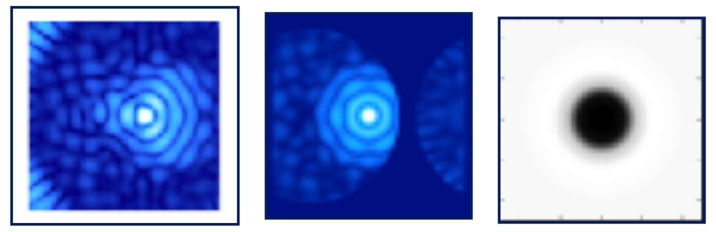




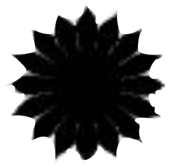
Hybrid Lyot Coronagraph

4 epochs, 2 rolls

+ Calibrations



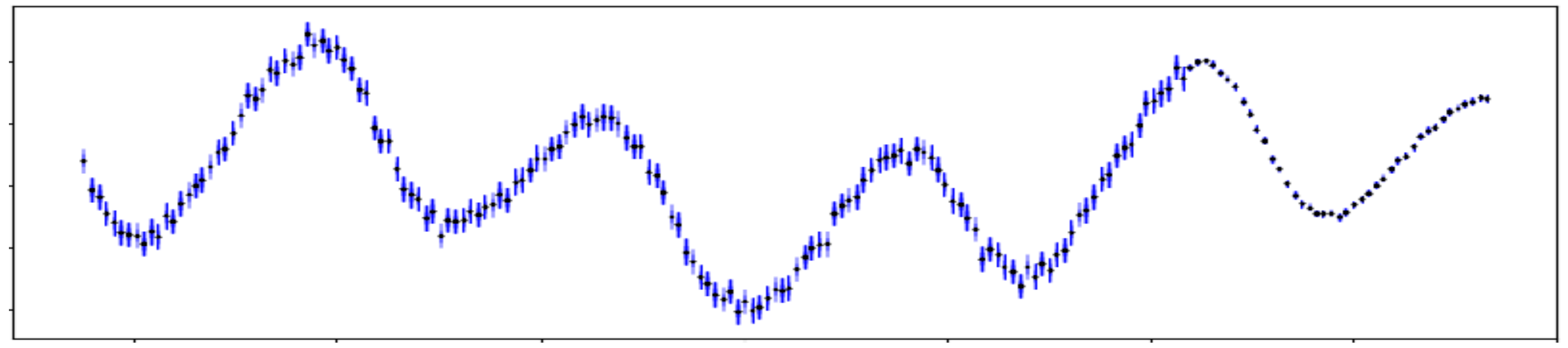
Star Shade



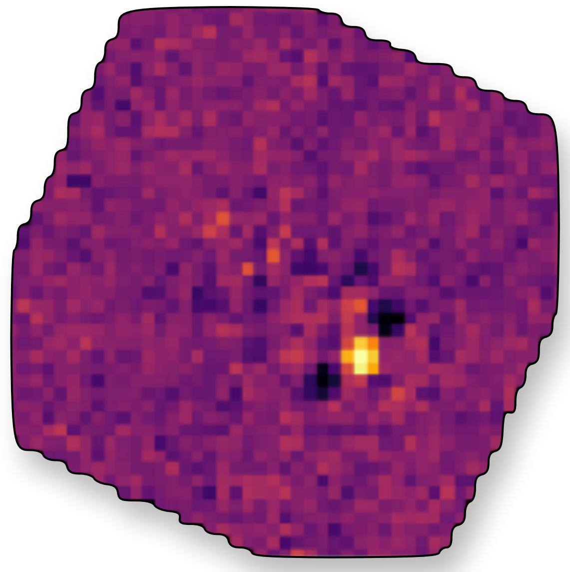
2 epochs

+ Calibrations

& **15 years** of **precursor RV data**

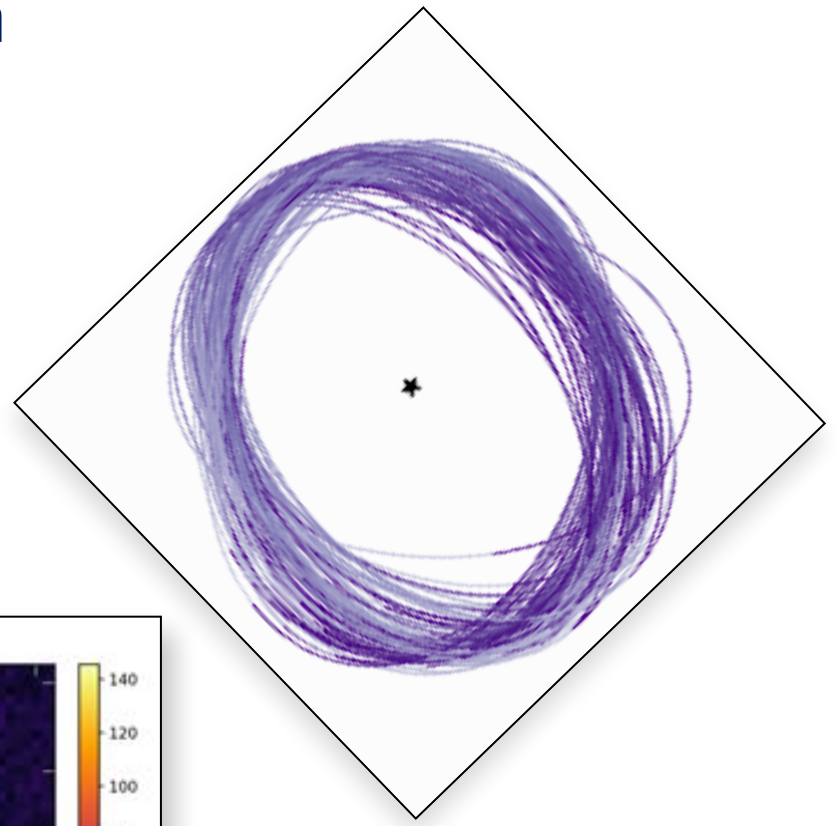


CHALLENGE

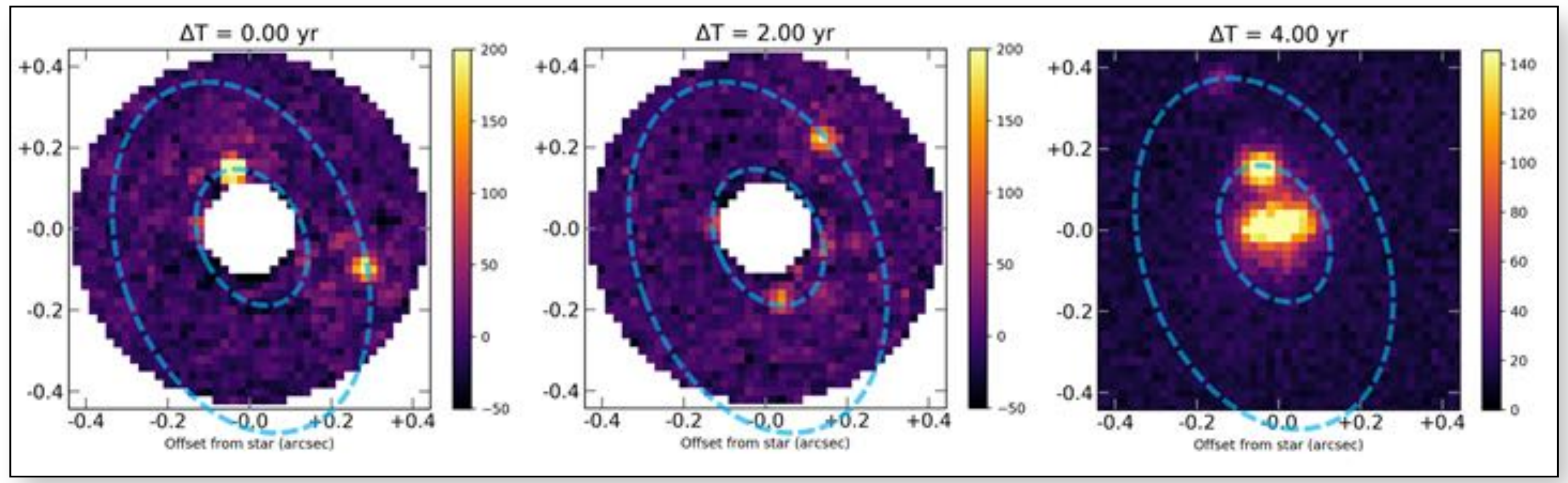


1. **Extract & identify point sources** in 4 HLC **epochs**, disentangle from background sources, provide **census and rough astrometry**

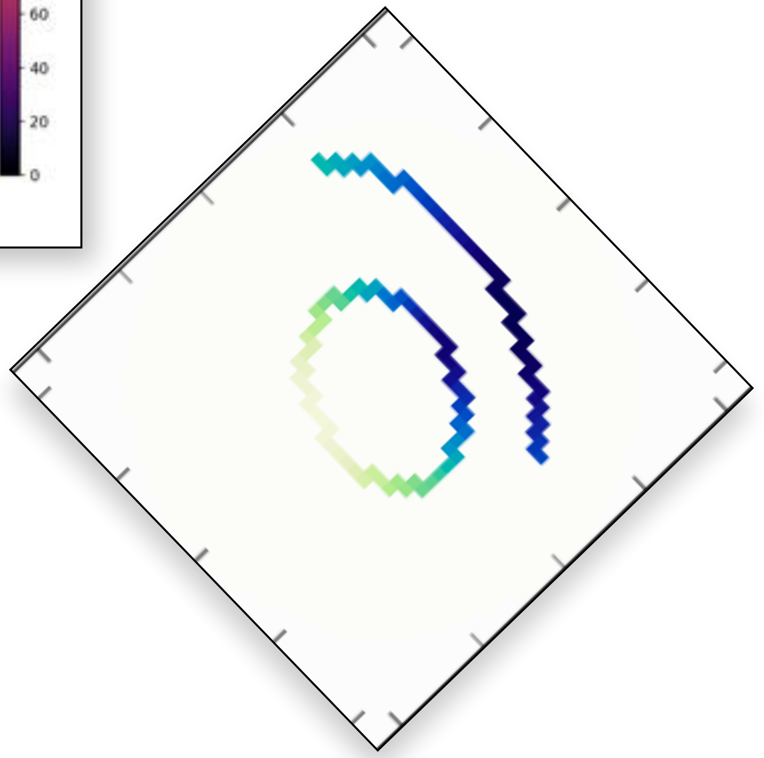
2. **Compute orbital parameters** & masses with those **4 epochs**, use **priors from RV data**



3. **Refine orbital parameters & masses** using additional **2 SS epochs**, all the information available



4. For a given planet, measure the **phase curve** assuming it is Lambertian, provide **radius & albedo** given mass-radius relationship



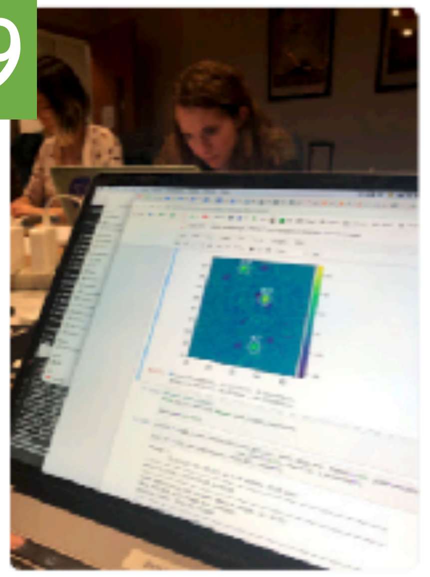
www.exoplanetdatachallenge.com

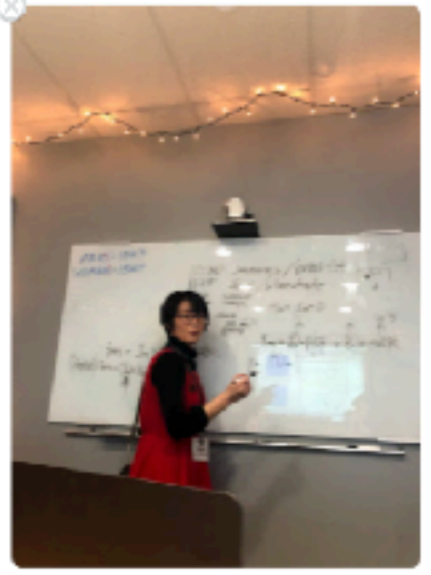
4 Tutorial Events: a Young & Diverse Crowd

Tokyo
OCTOBER ‘19

CALTECH/IPAC
JUNE ‘19

STScI
MARCH’19





NY FLATIRON
OCTOBER’19

www.exoplanetdatachallenge.com

ROMAN Exoplanet Imaging DC: key numbers

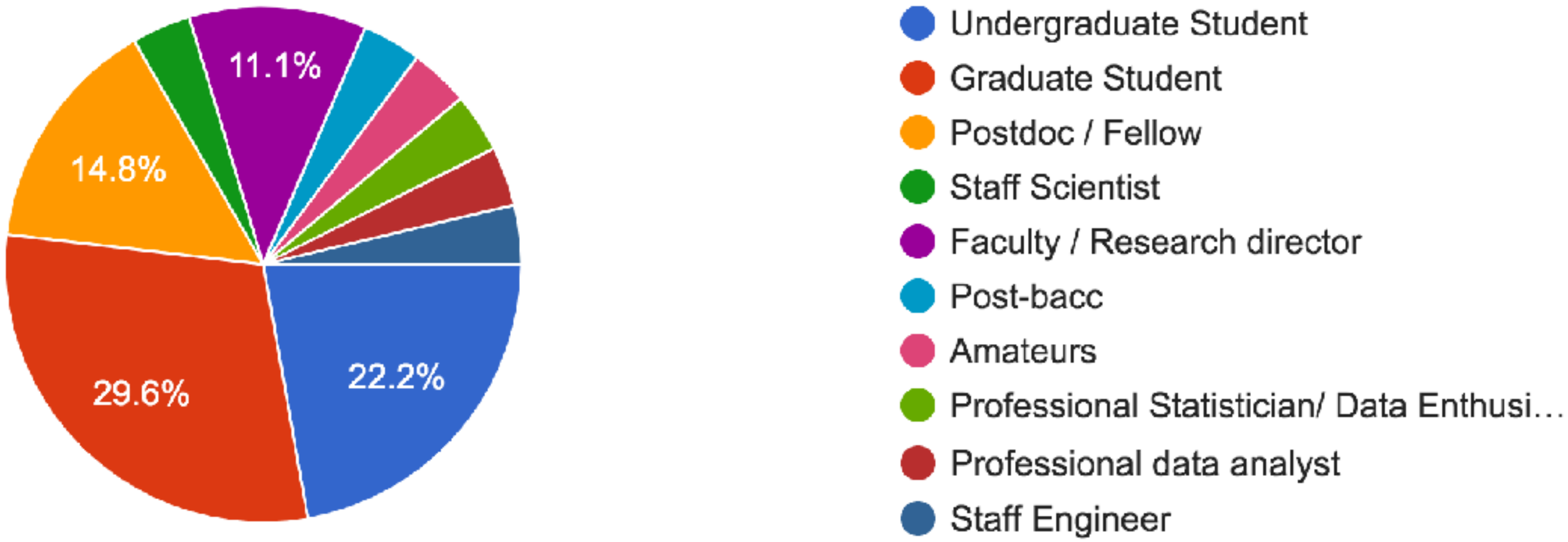
~ **70 people** participated in person to our four "hack events"

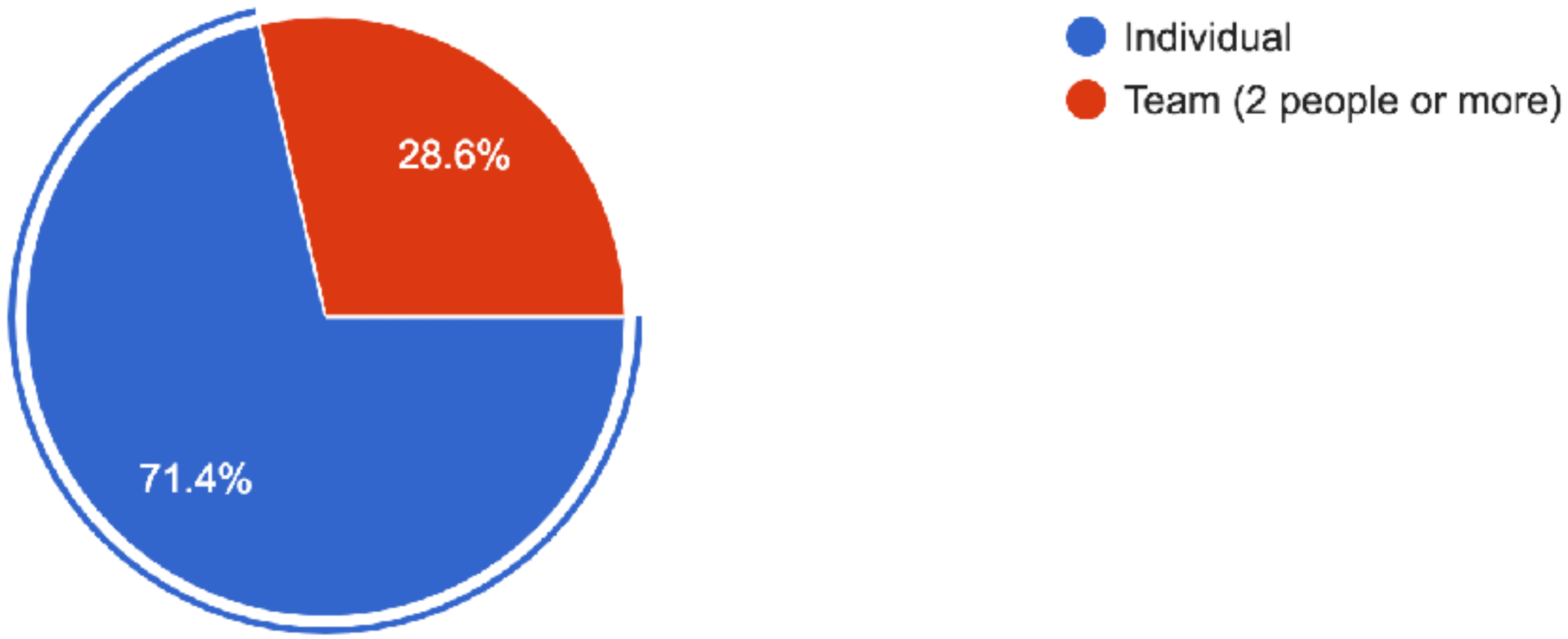
Diverse crowd in age, seniority, gender and country of origin / workplace

8 teams (1 to 4 persons) entered the competition

4 of them have completed the step 3 and have access to the star shade data

One of these "top" participants did not attend our events





DC: HLC PSF Subtraction / Processing

Neil Zimmerman

ZIMMERMAN+ IN PREP
(DC DESIGN, IN HOUSE ANALYSIS FOR PLANET C & CODE)

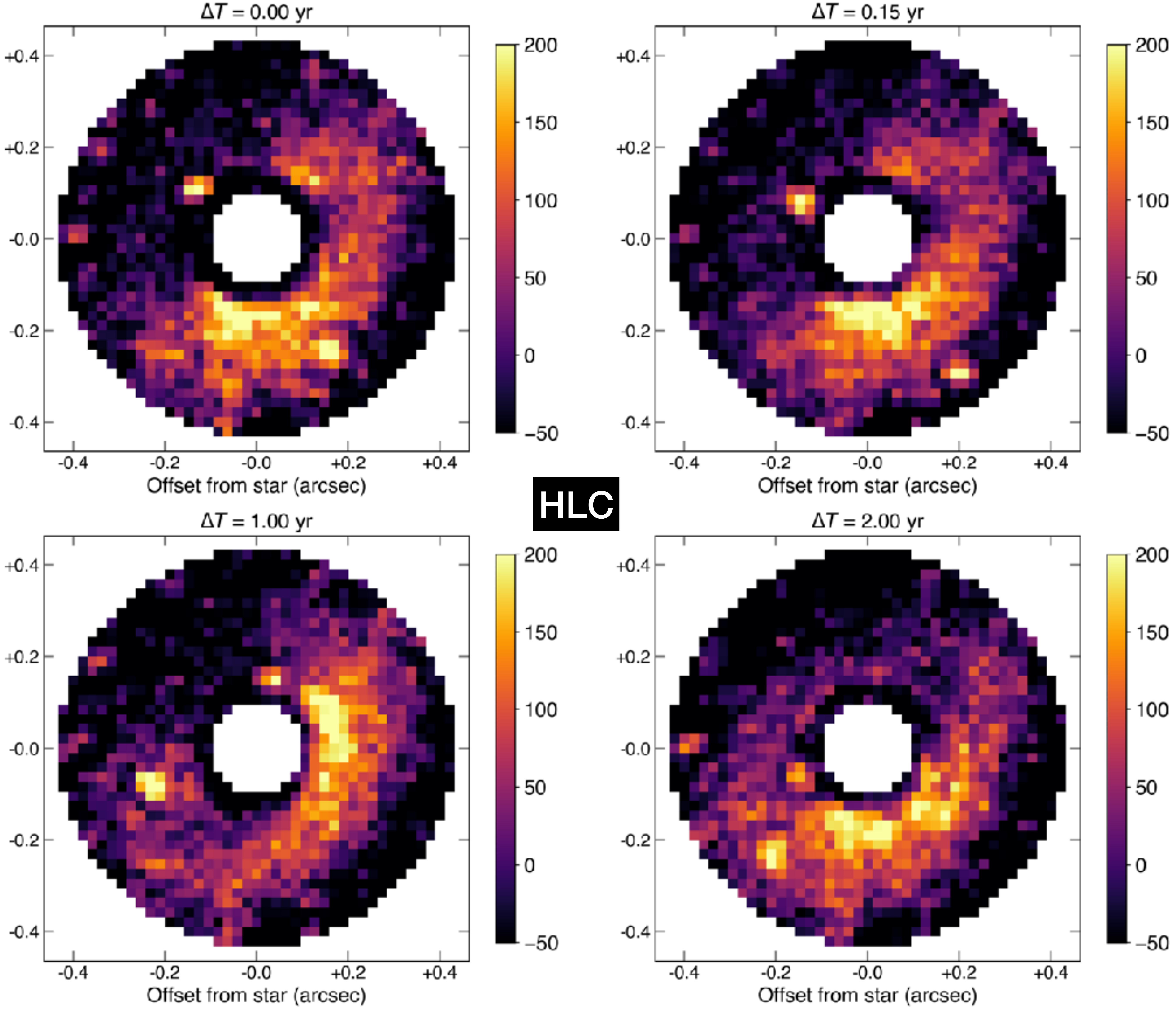
4 HLC epochs

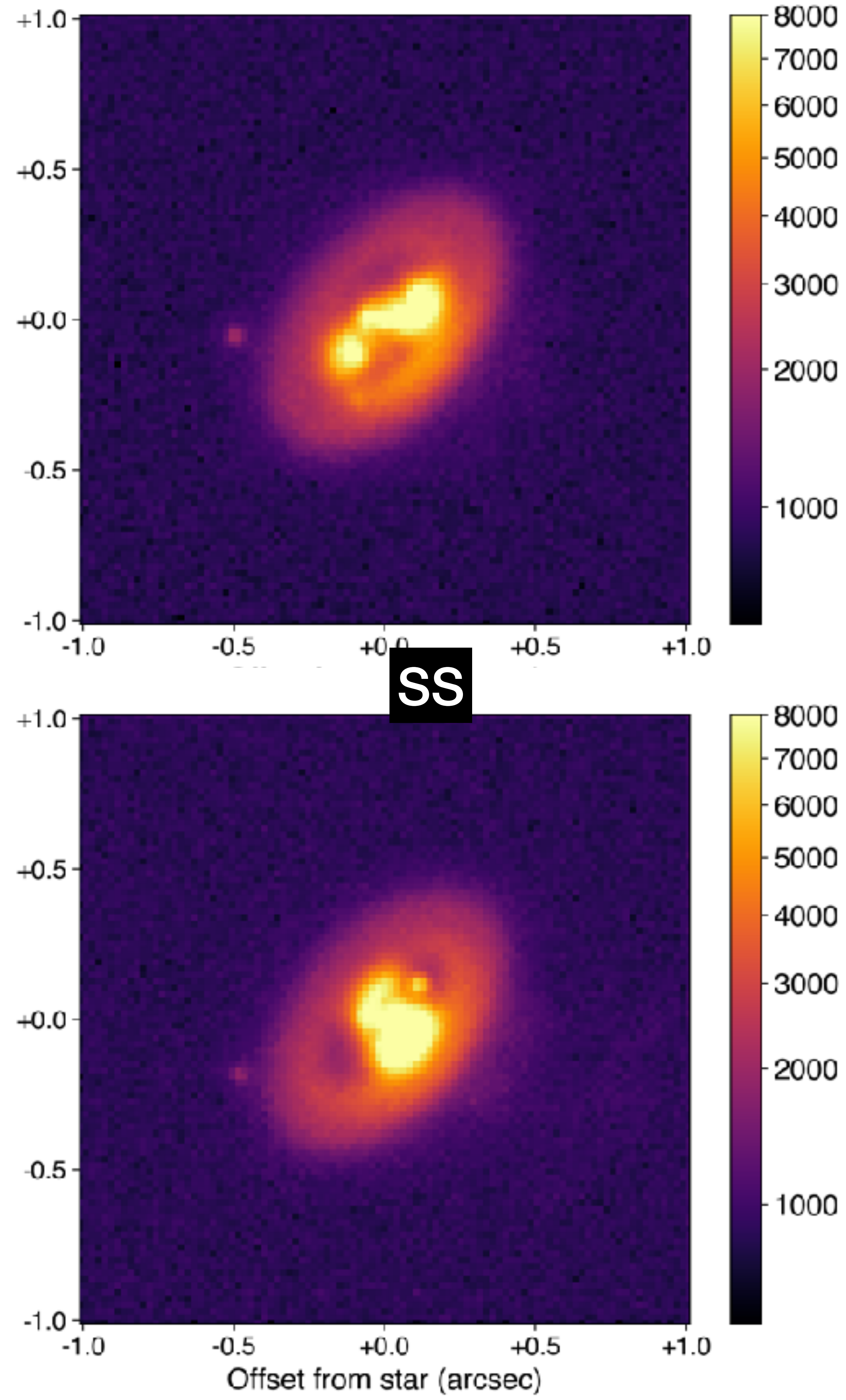
Noiseless "truth"

With OS6 Speckle Field
(co-added frames)

PSF subtracted / processed
The "science grade data product"
We have to work with

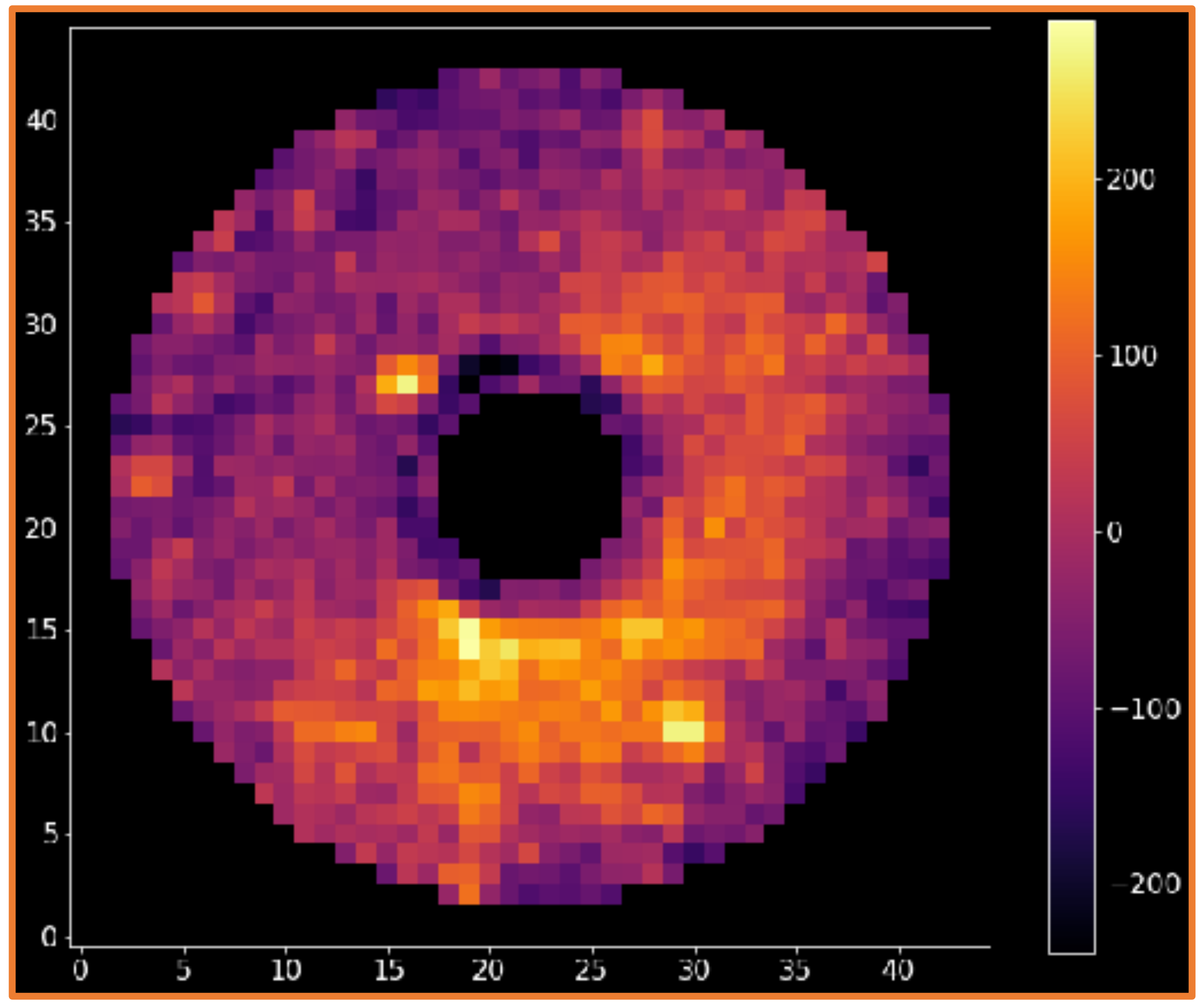
In-house Analysis: PSF Subtracted Images

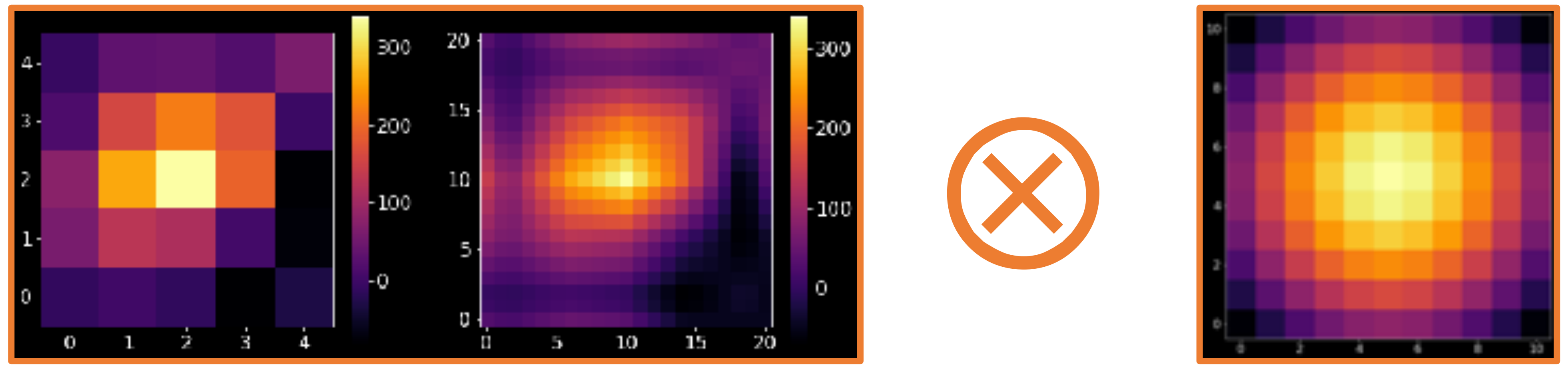


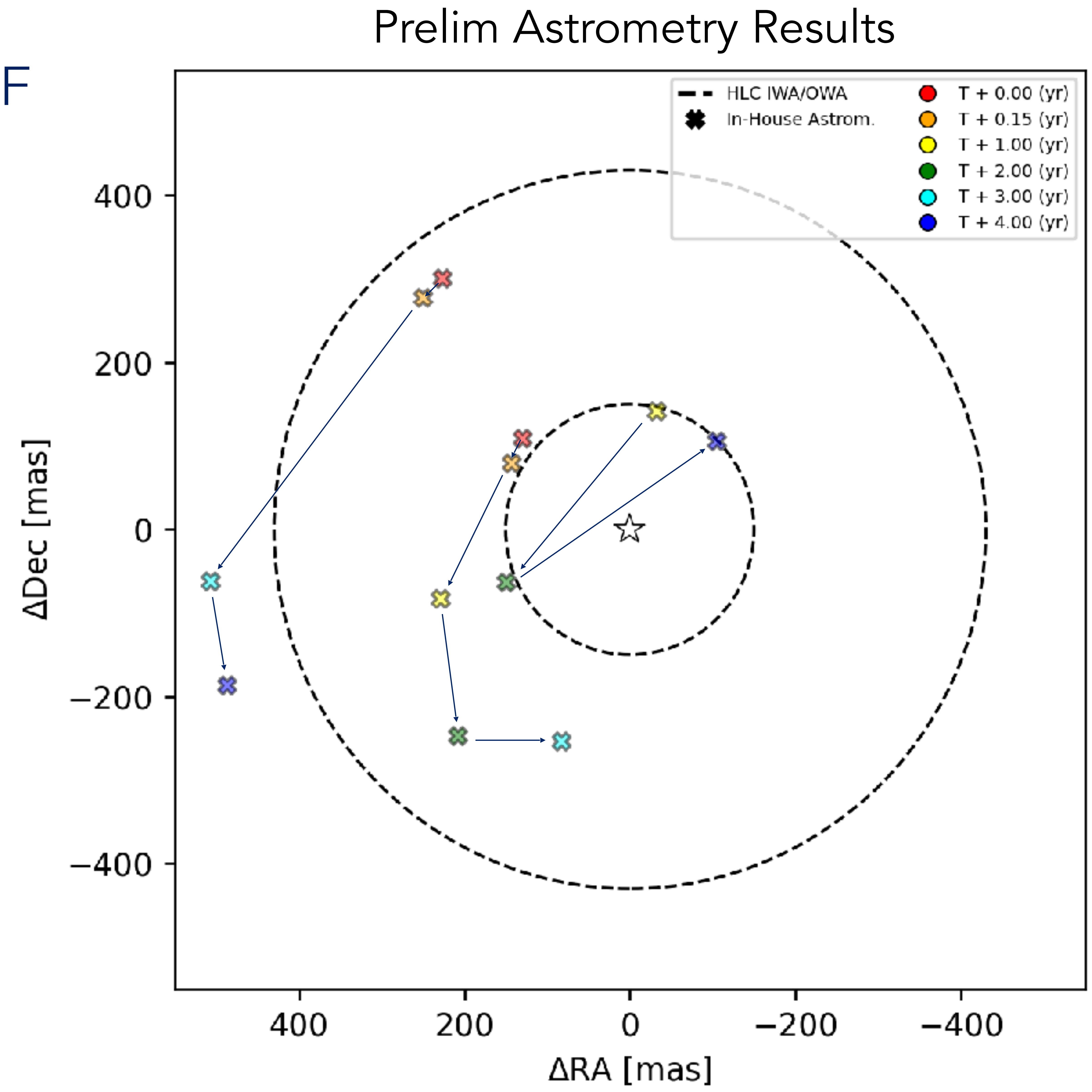


In-house Analysis: Preliminary Astrometry

Uses cross-correlation to a high resolution PSF to obtain accurate astrometry for each signal





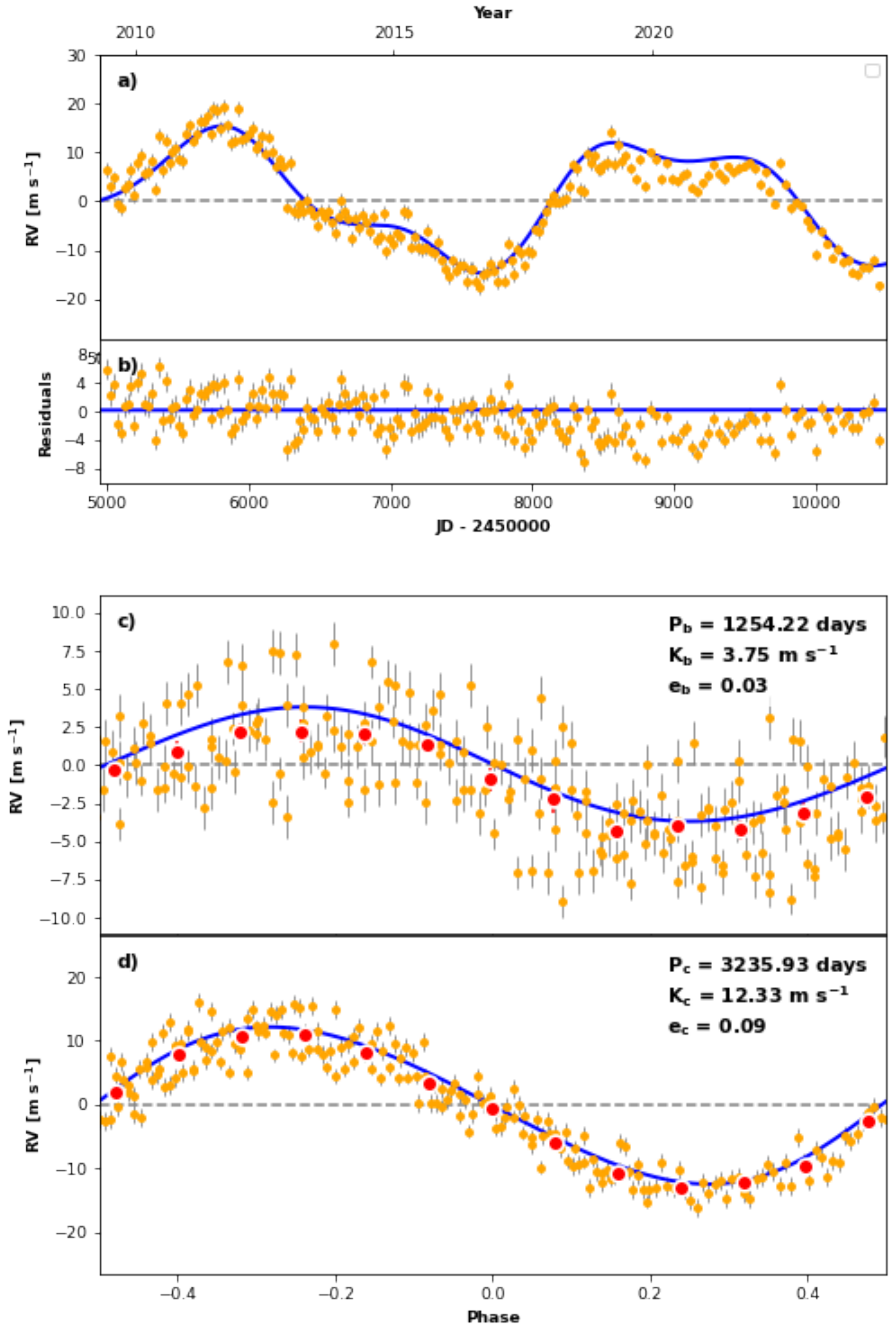


In-house Analysis: Final Orbital Fit

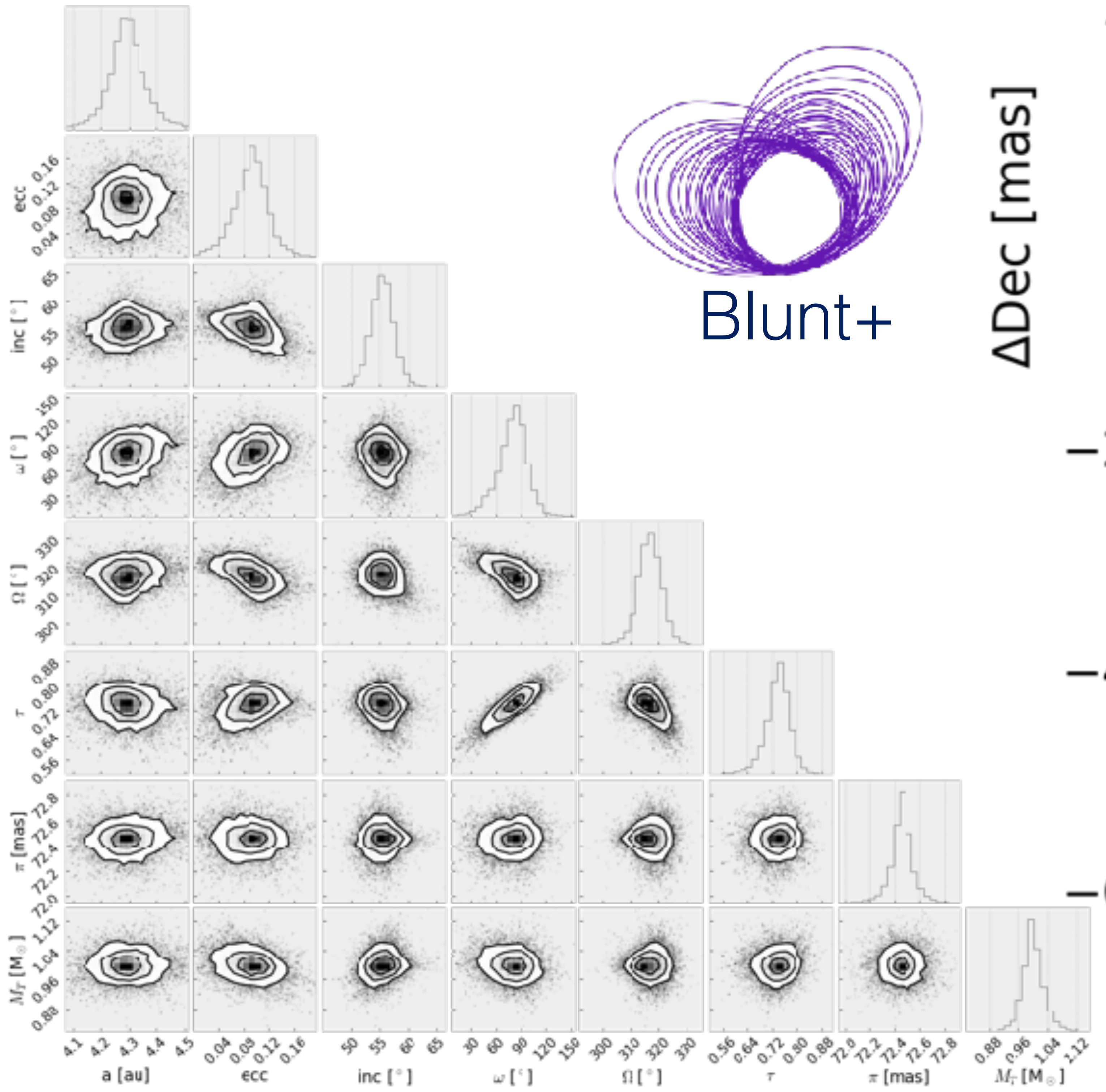
Ell Bogat & Neil Zimmerman

Finds initial orbital constraints from radial velocity data using RadVel

Fulton+

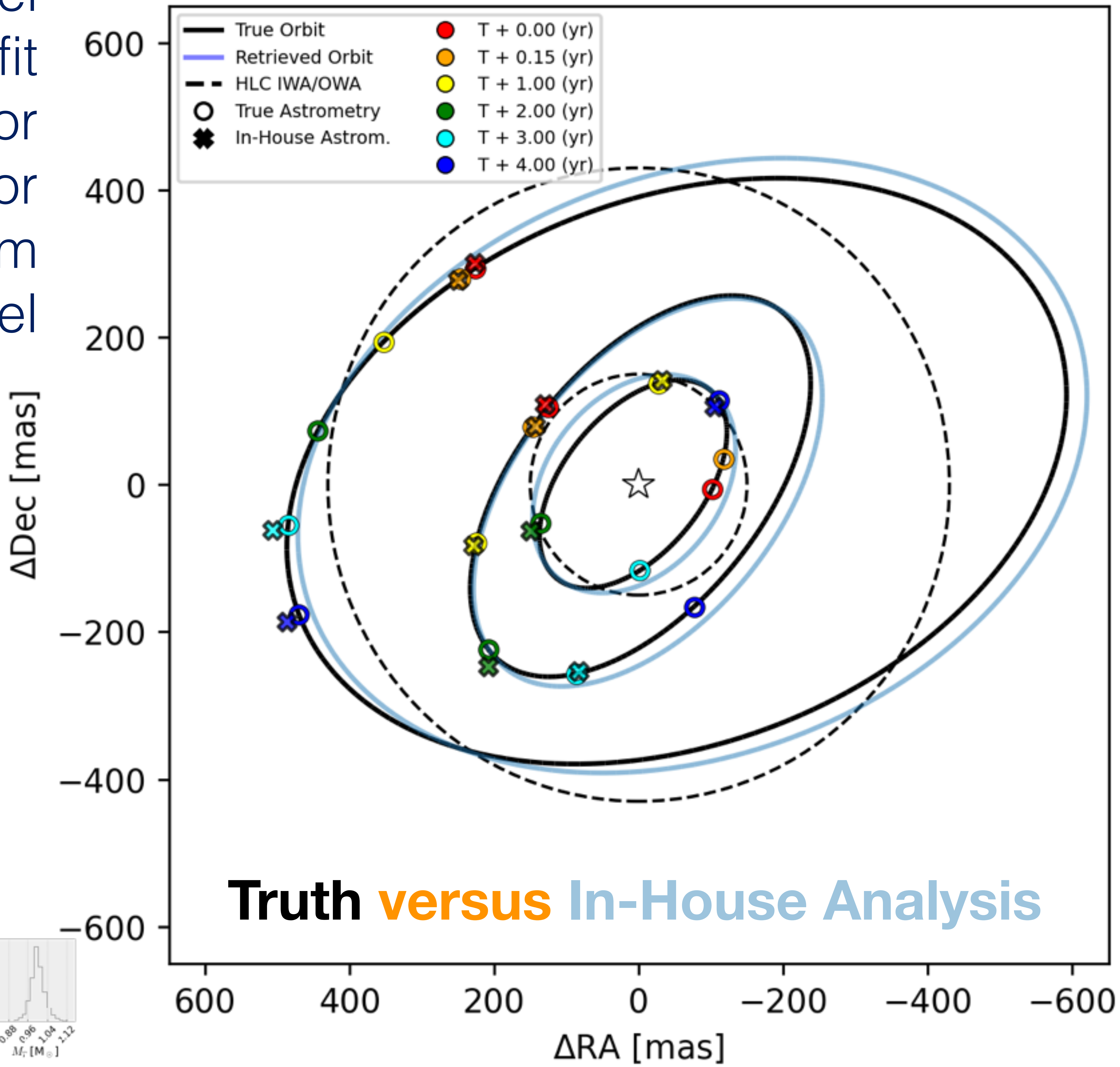


Uses **orbitize!** (parallel MCMC chain fit) to fit astrometry data for each planet with prior constraints from RadVel



Blunt+

Orbit + Astrometry Results

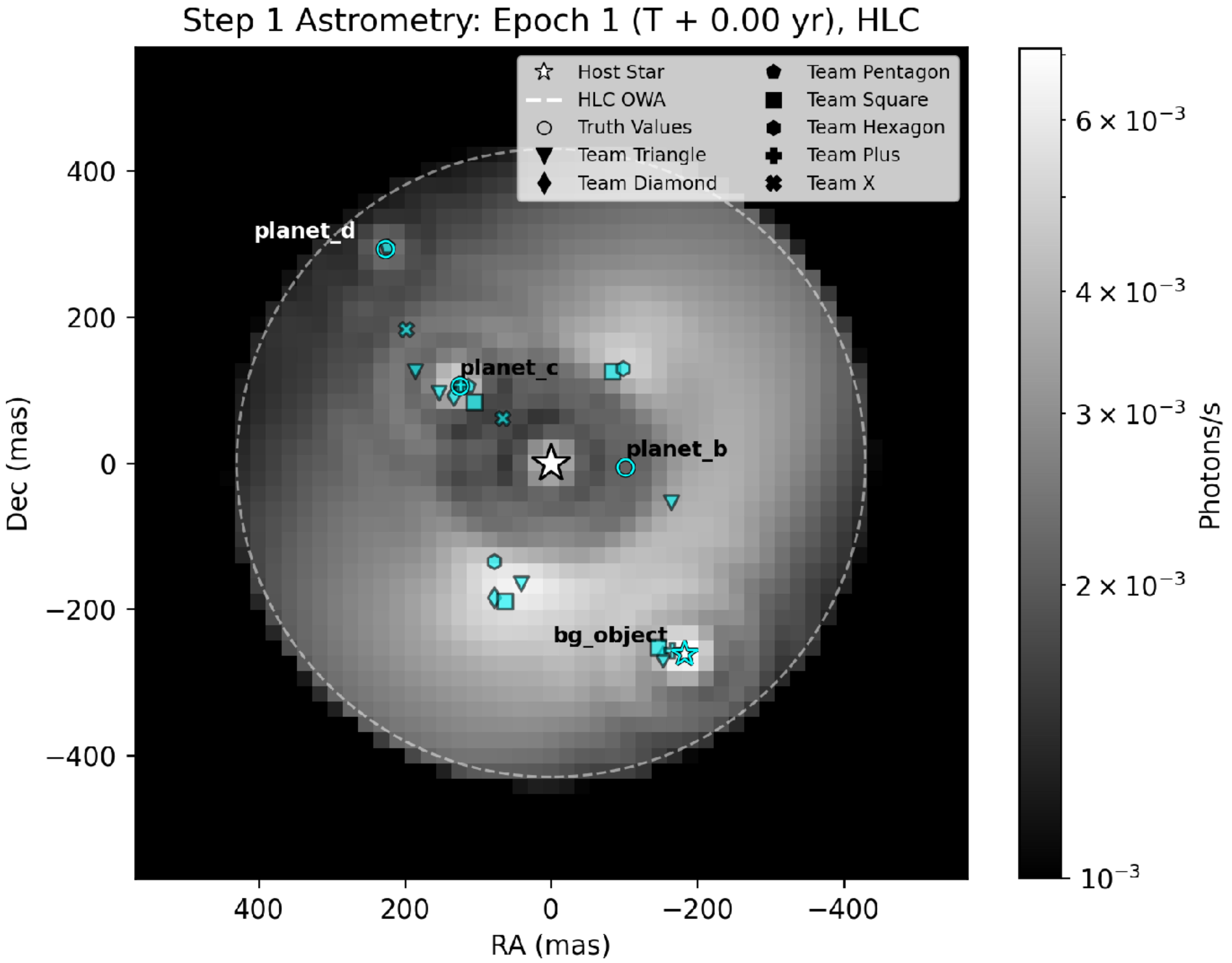


Metrics, Results & Prize

Step 1 results: quick astrometry / identification

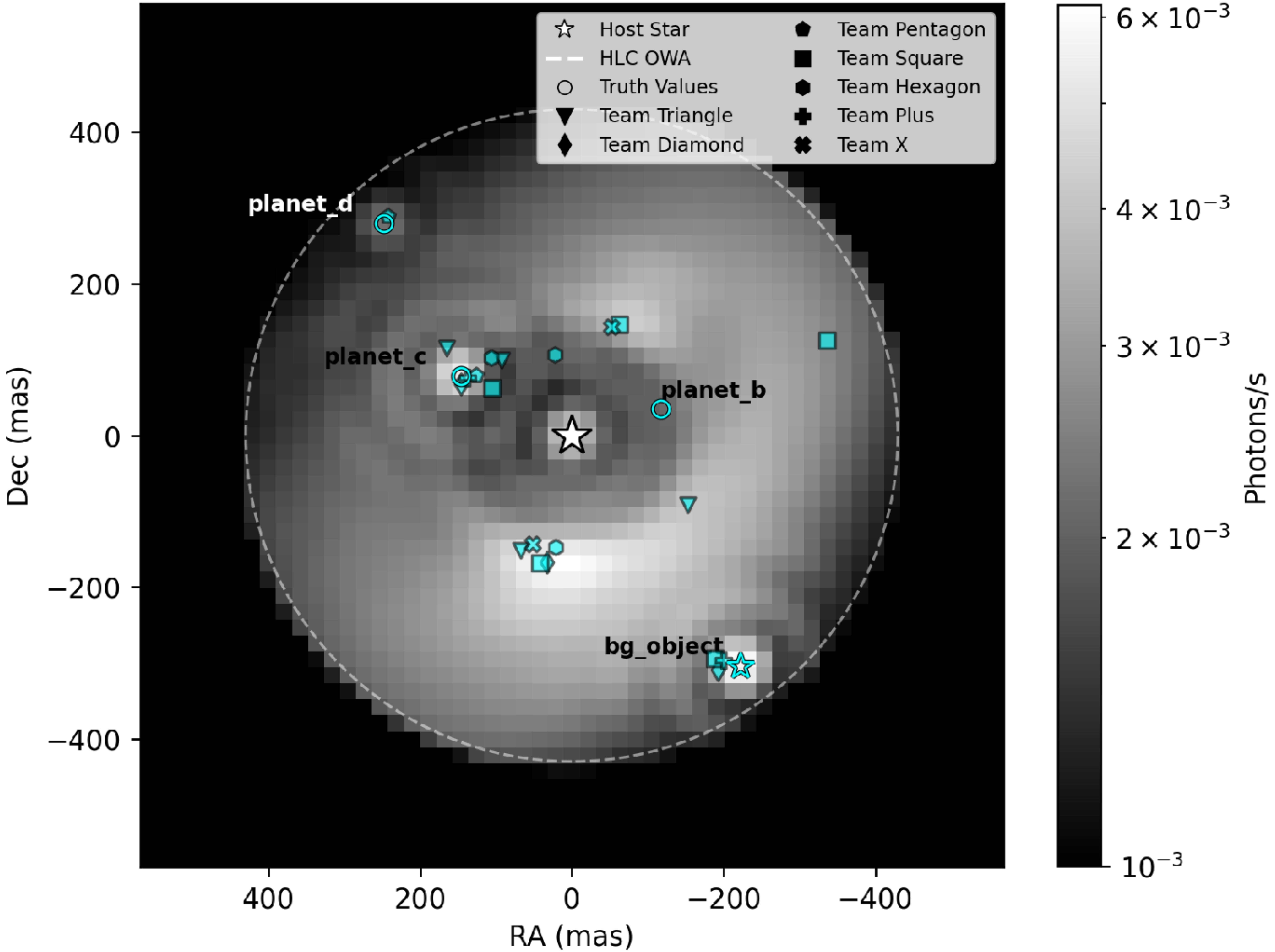
Ell Bogat

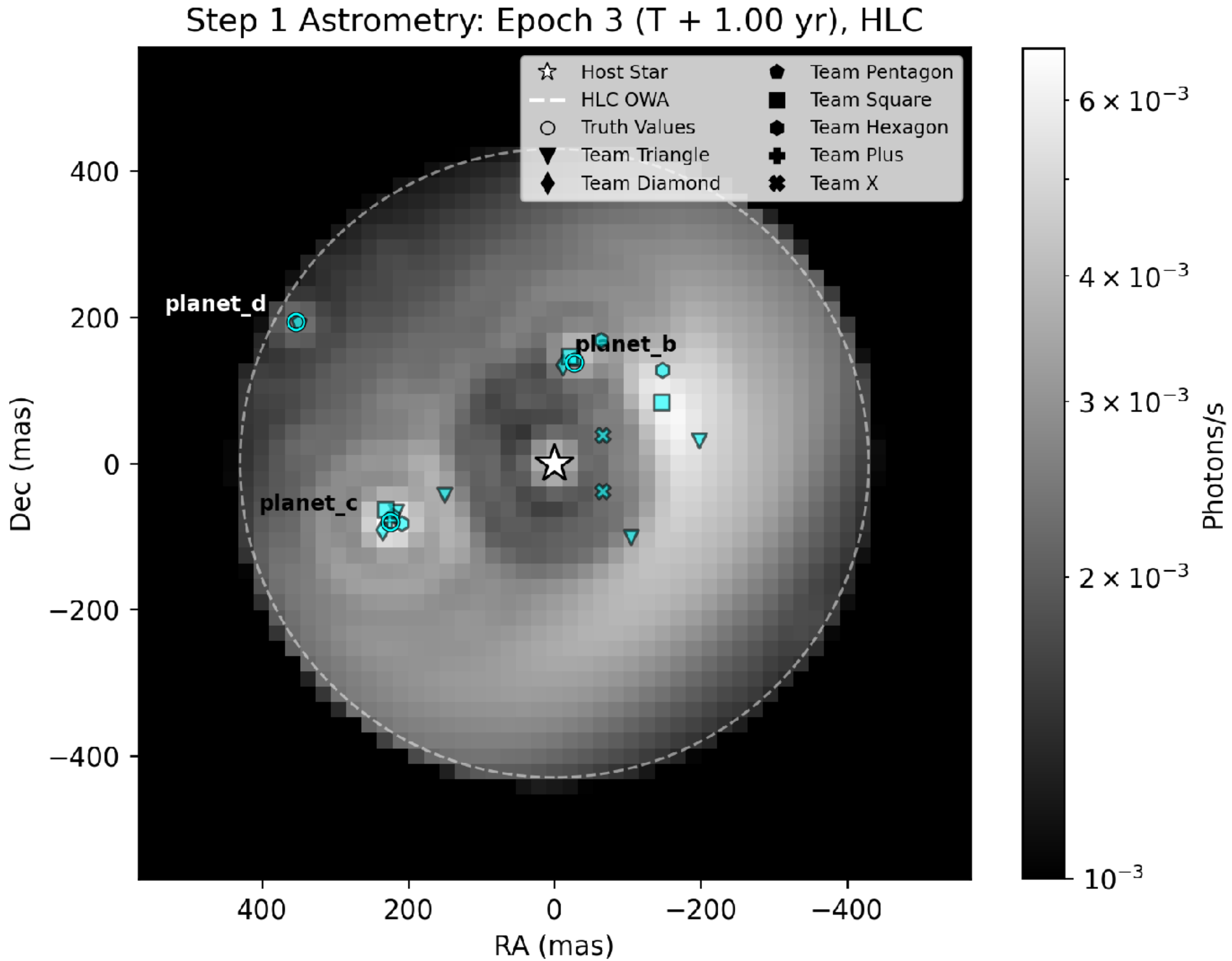
7 Teams



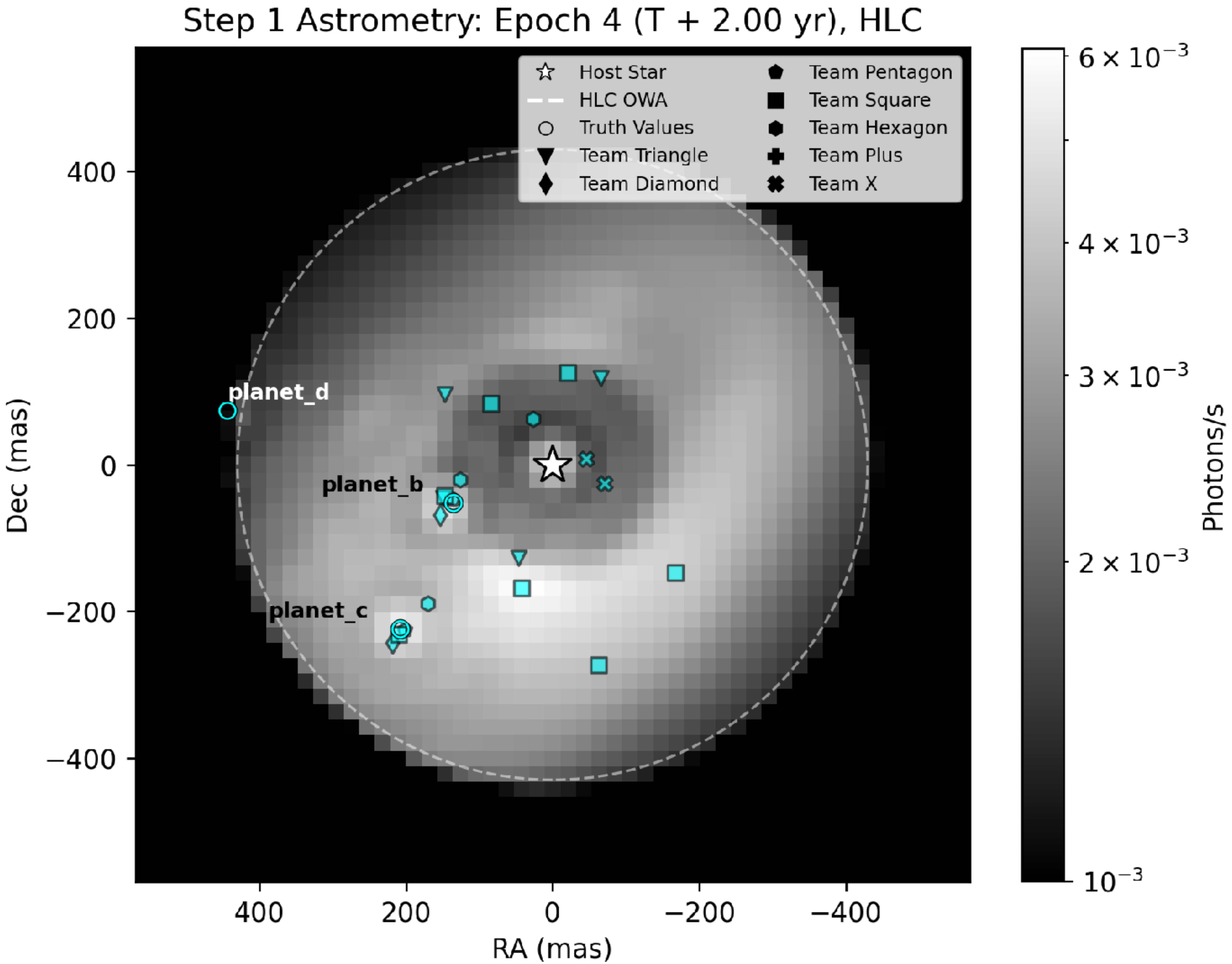
Step 1 Astrometry: Epoch 1 (T + 0.00 yr), HLC
Host Star
HLC OWA
Truth Values
Team Triangle
Team Diamond
Team Pentagon
Team Square
Team Hexagon
Team Plus
Team X
planet_d
planet_c
planet_b
bg_object
400
200
0
−200
−400
Dec (mas)
RA (mas)
6×10^{-3}
4×10^{-3}
3×10^{-3}
2×10^{-3}
10^{-3}
Photons/s

Step 1 Astrometry: Epoch 2 (T + 0.15 yr), HLC





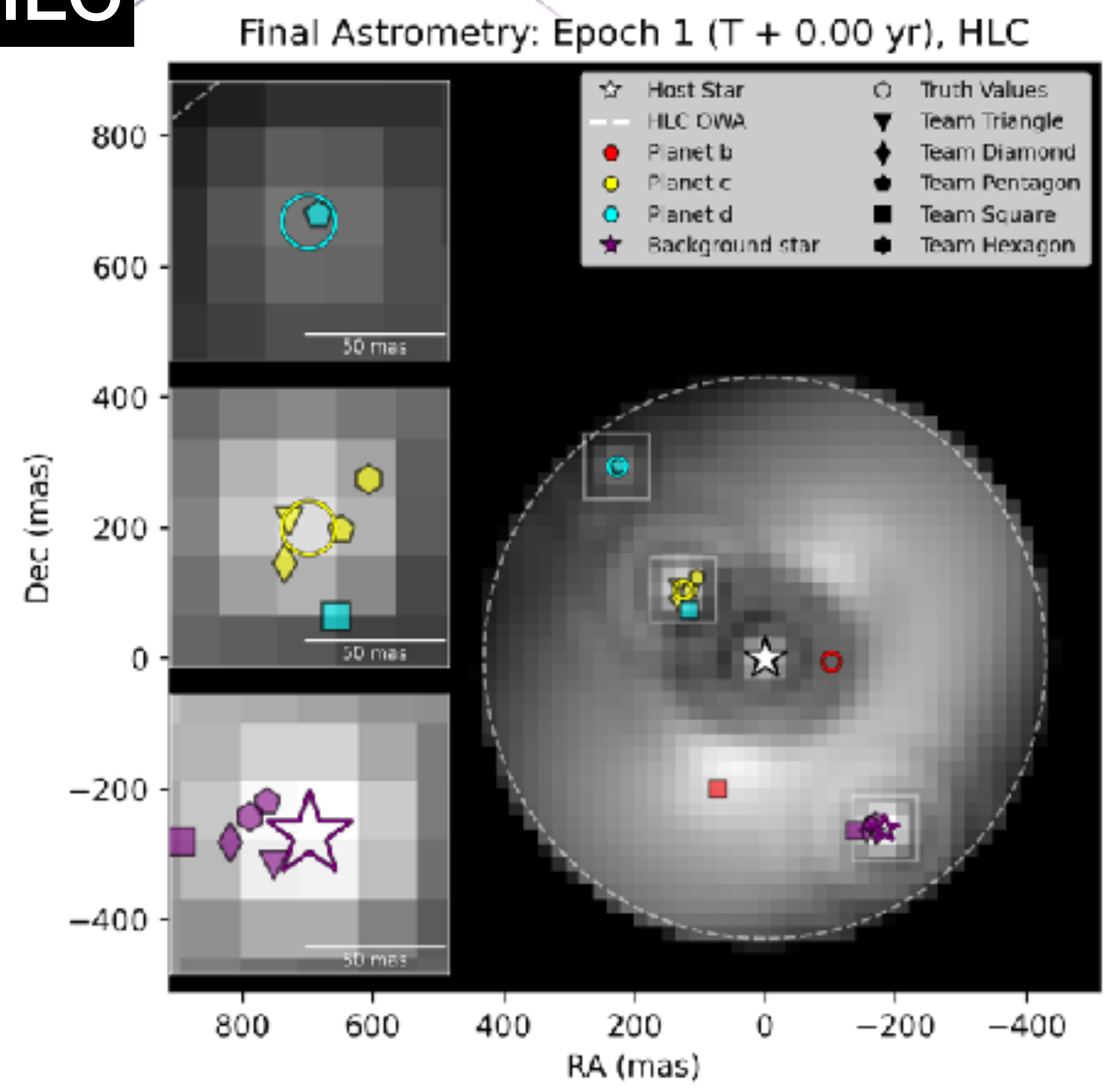
Step 1 Astrometry: Epoch 3 (T + 1.00 yr), HLC
Host Star
HLC OWA
Truth Values
Team Triangle
Team Diamond
Team Pentagon
Team Square
Team Hexagon
Team Plus
Team X
planet_d
planet_b
planet_c
Dec (mas)
RA (mas)
Photons/s
400
200
0
−200
−400
6×10^{-3}
4×10^{-3}
3×10^{-3}
2×10^{-3}
10^{-3}

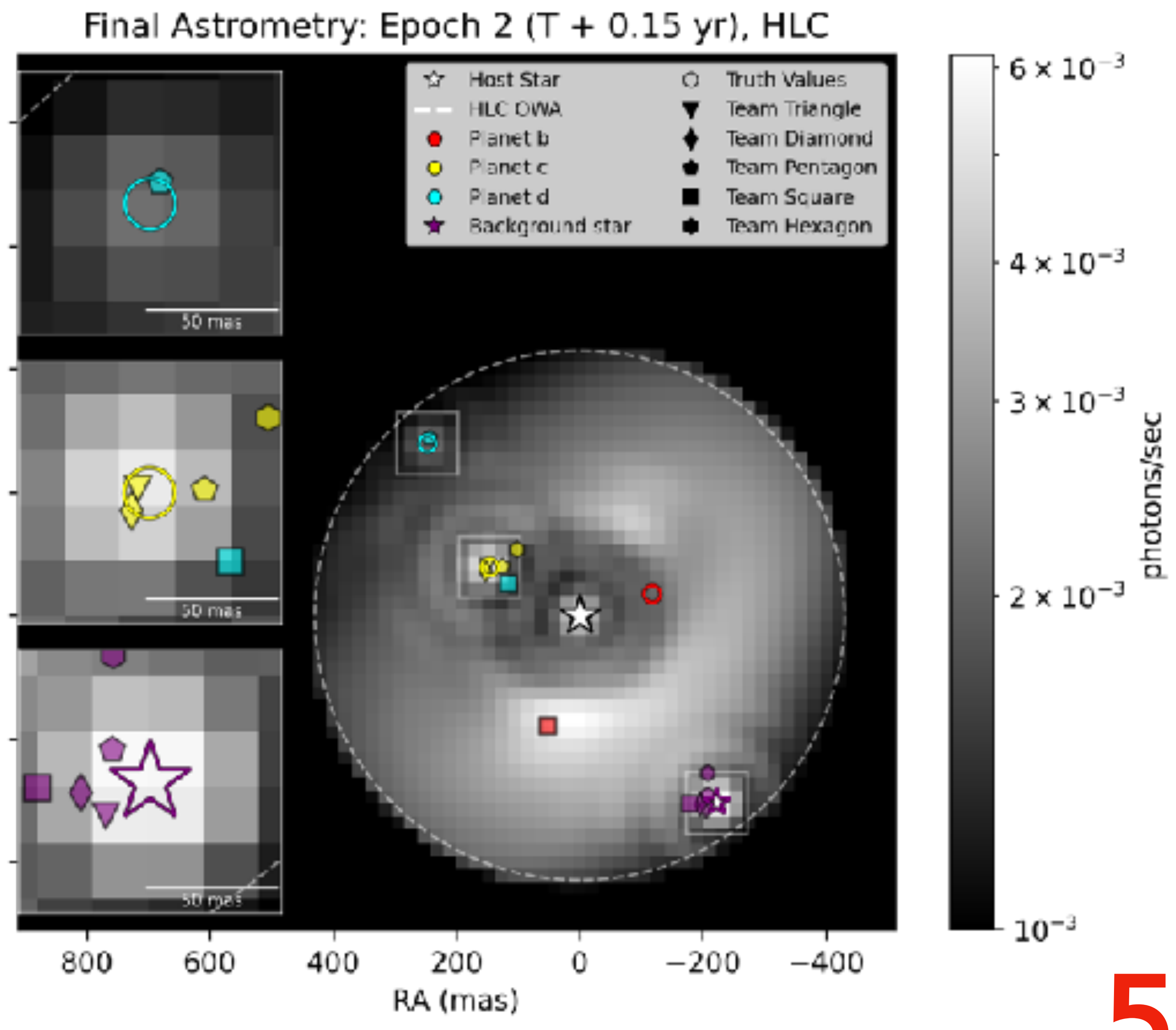

Step 1 Astrometry: Epoch 4 (T + 2.00 yr), HLC
Host Star
HLC OWA
Truth Values
Team Triangle
Team Diamond
Team Pentagon
Team Square
Team Hexagon
Team Plus
Team X
planet_d
planet_b
planet_c
400
200
0
−200
−400
Dec (mas)
RA (mas)
6 × 10−3
4 × 10−3
3 × 10−3
2 × 10−3
10−3
Photons/s

Final astrometry / identification by epoch

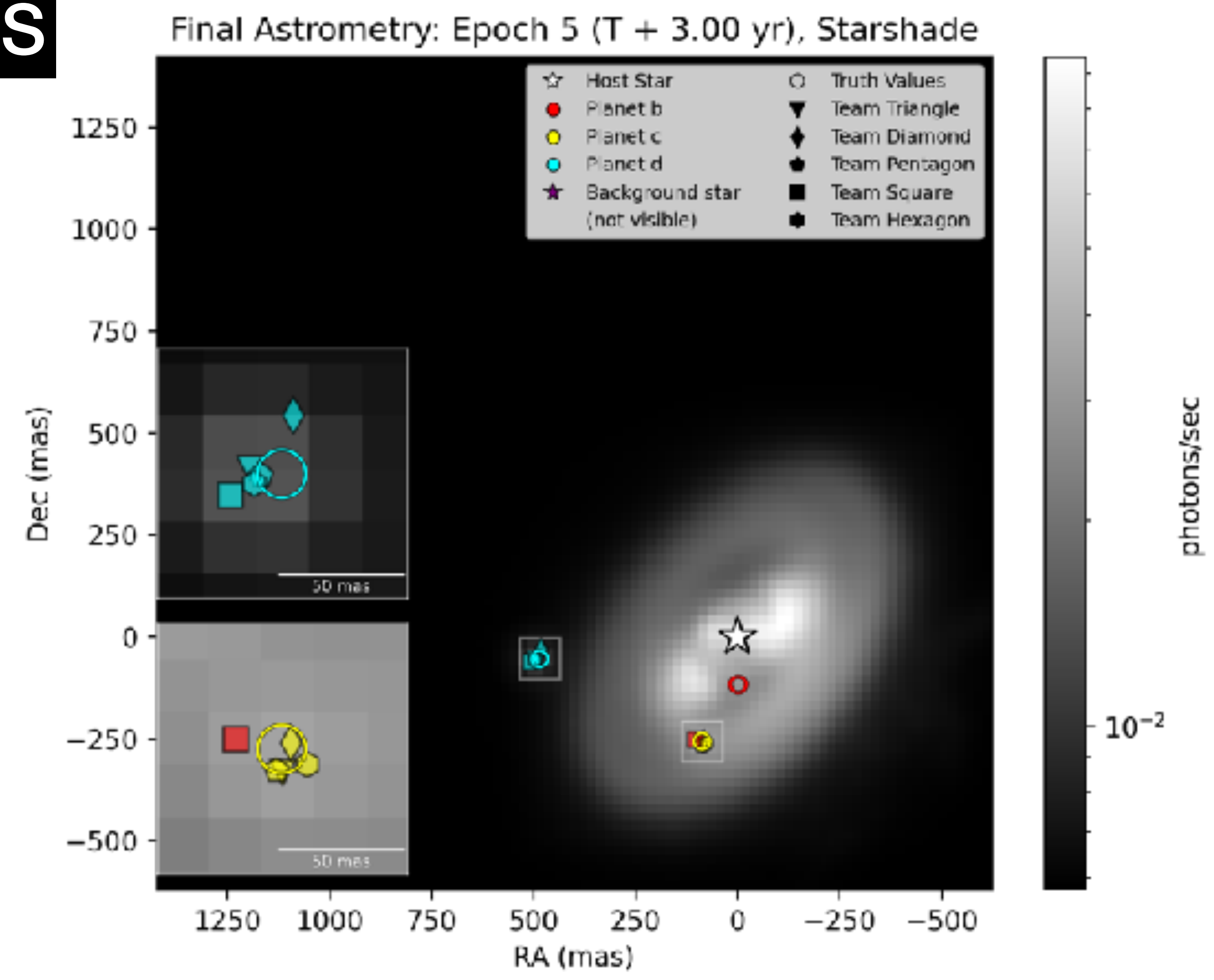
Ell Bogat

HLC

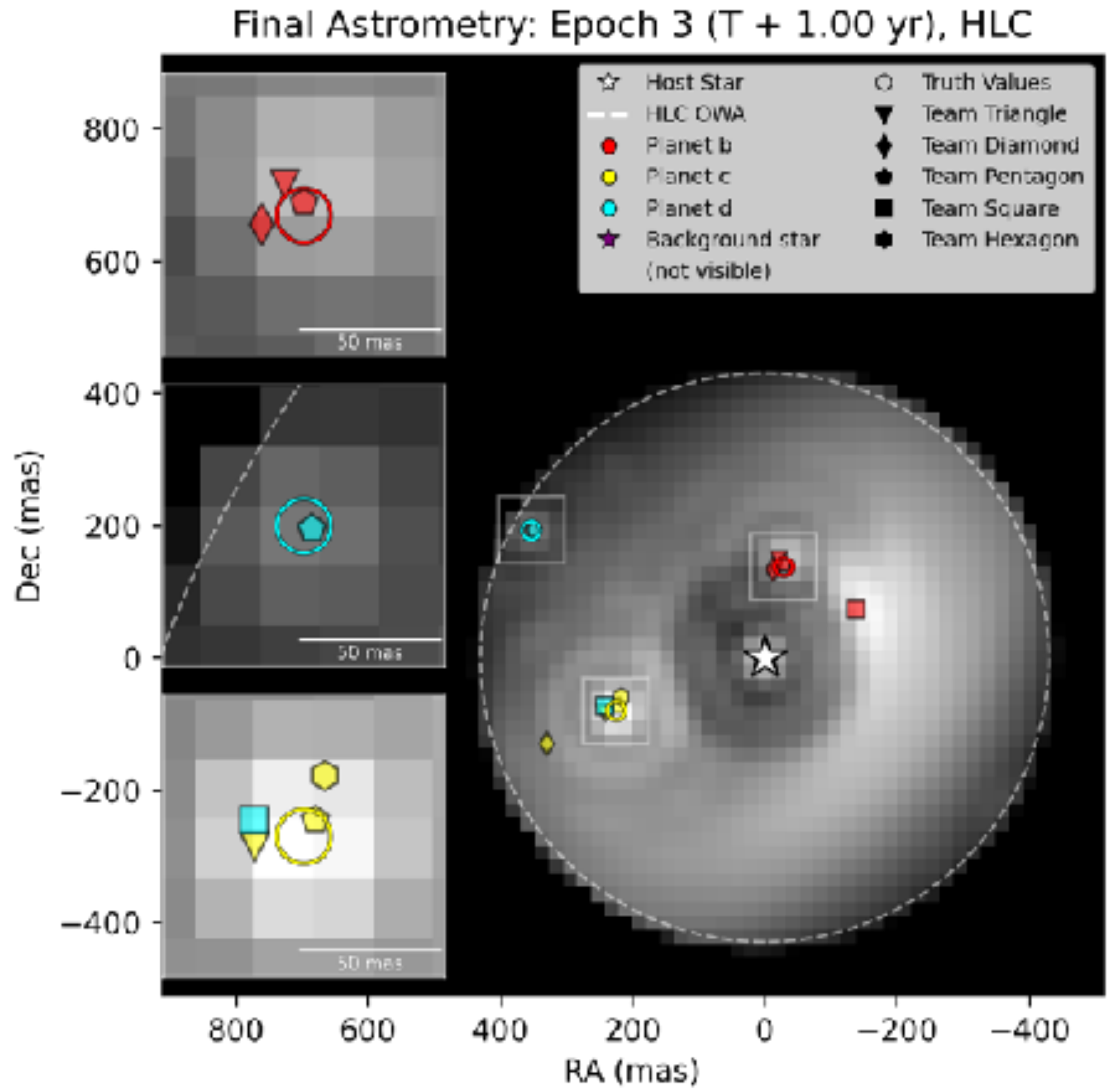


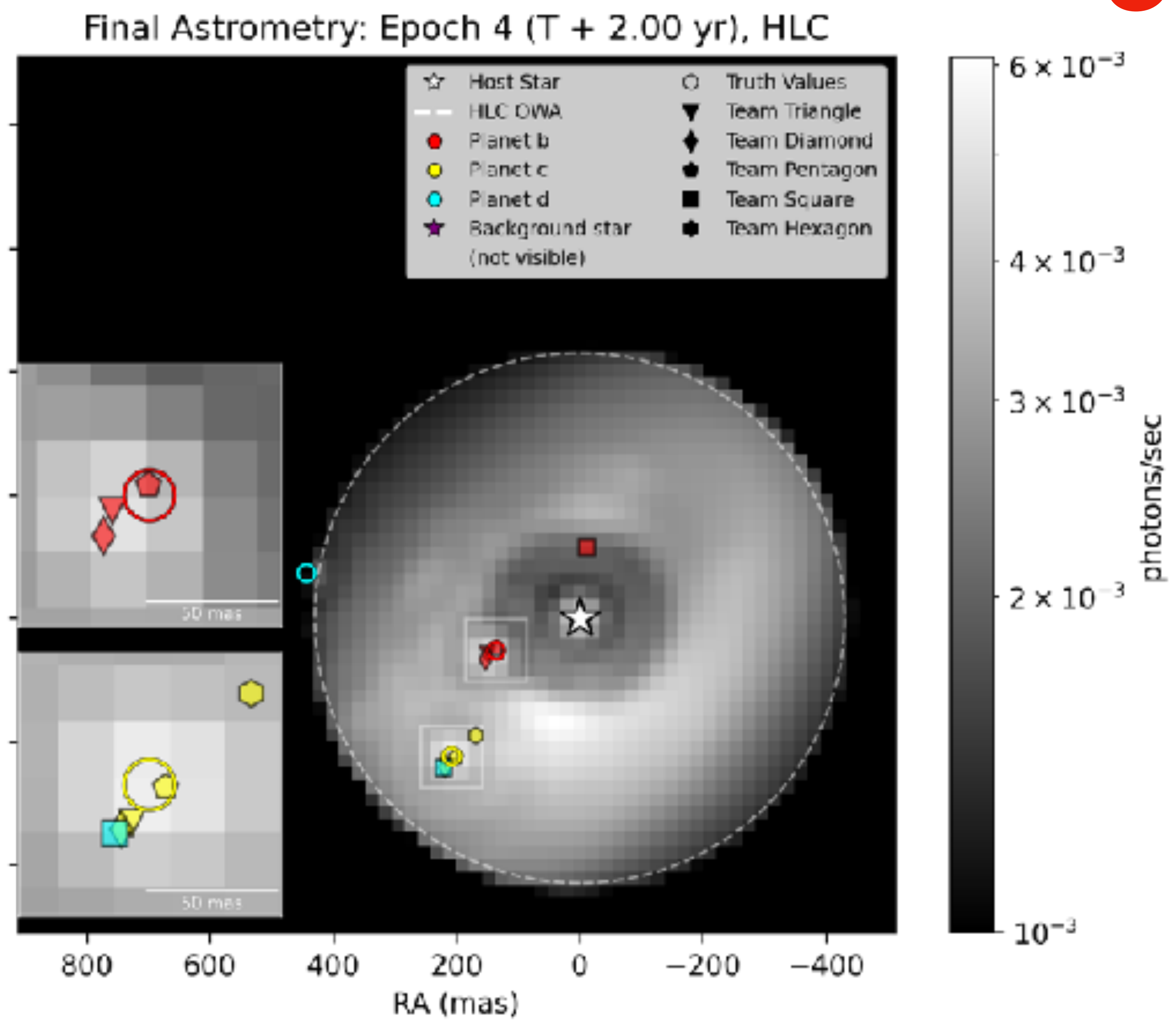


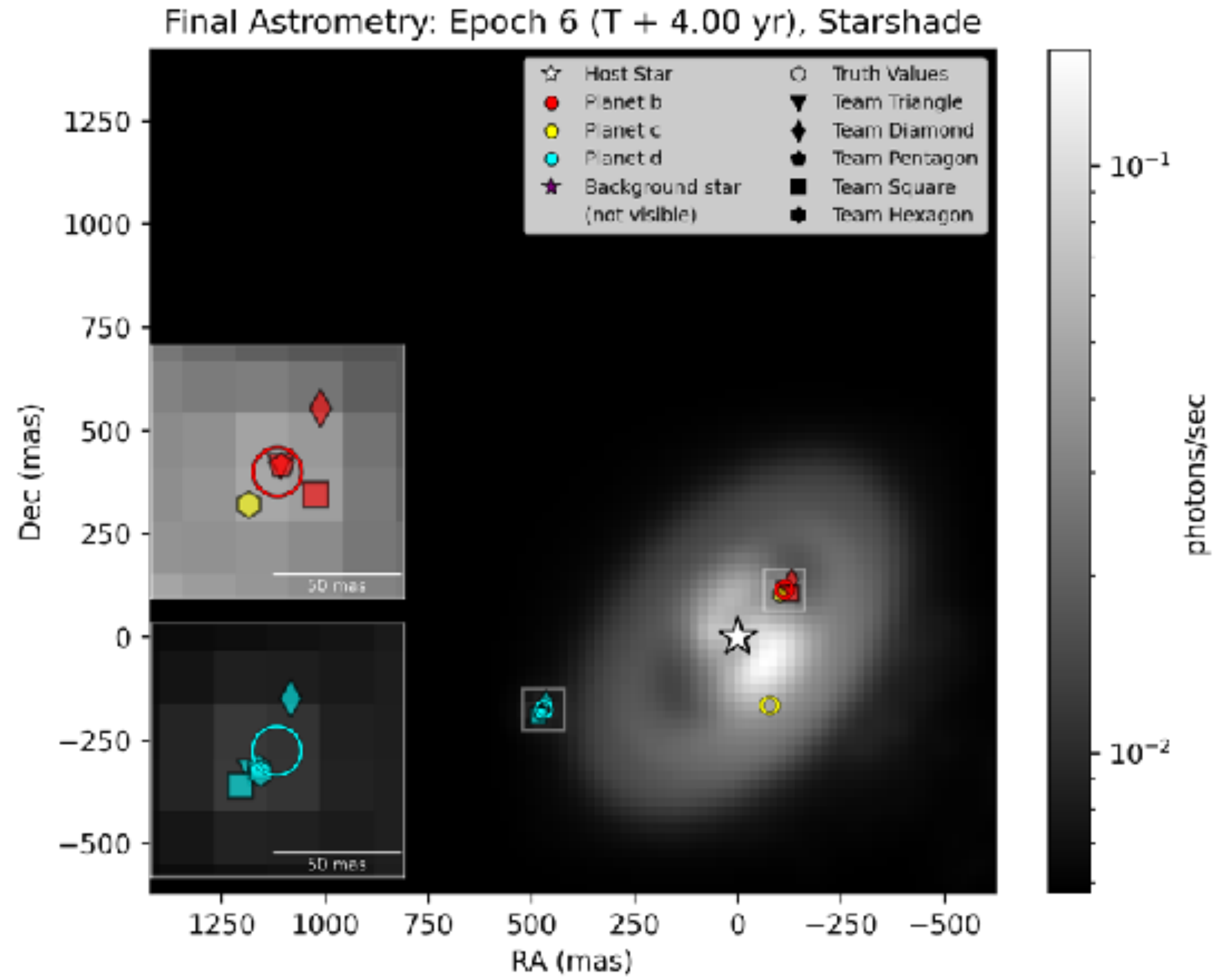
SS

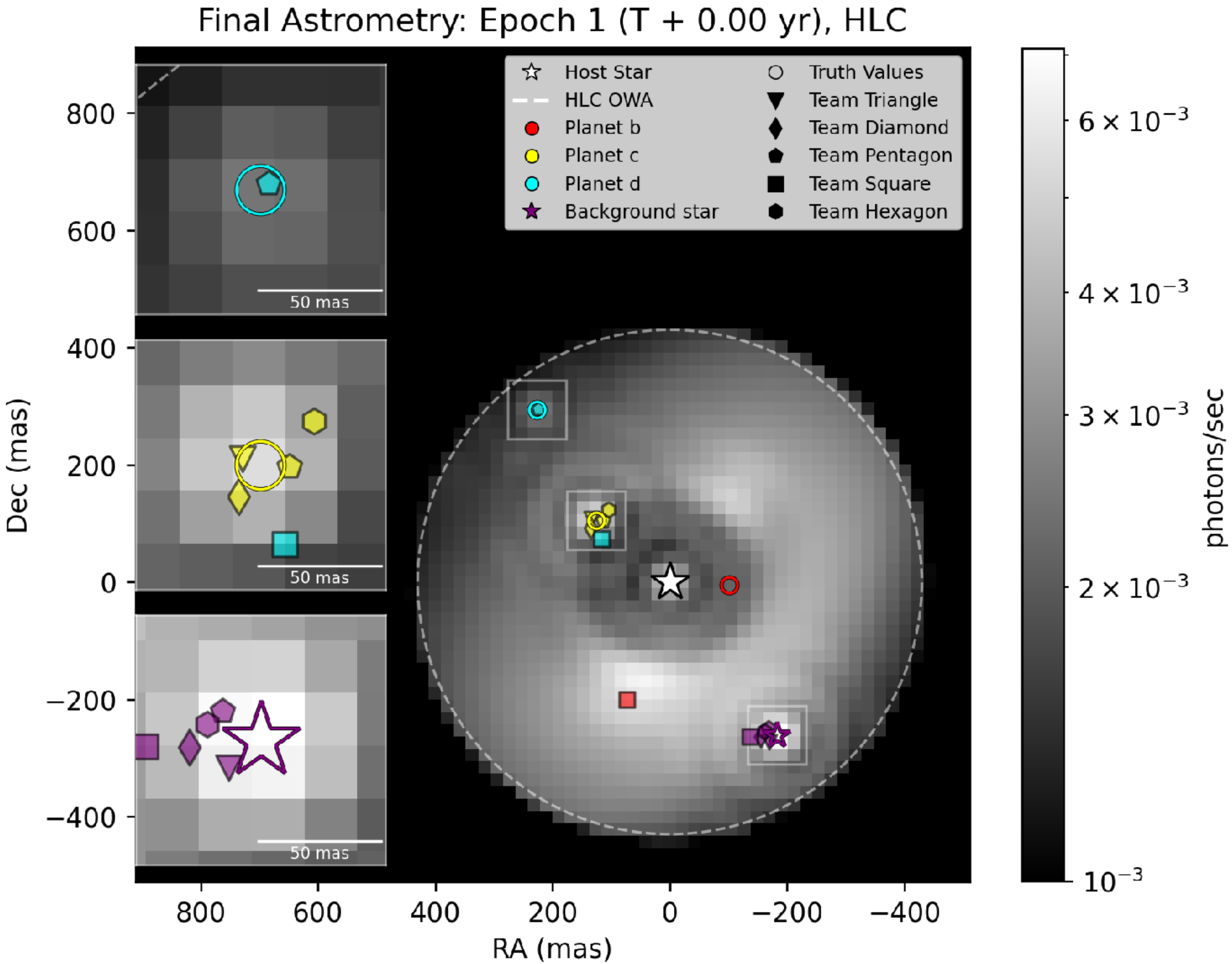


5 Teams

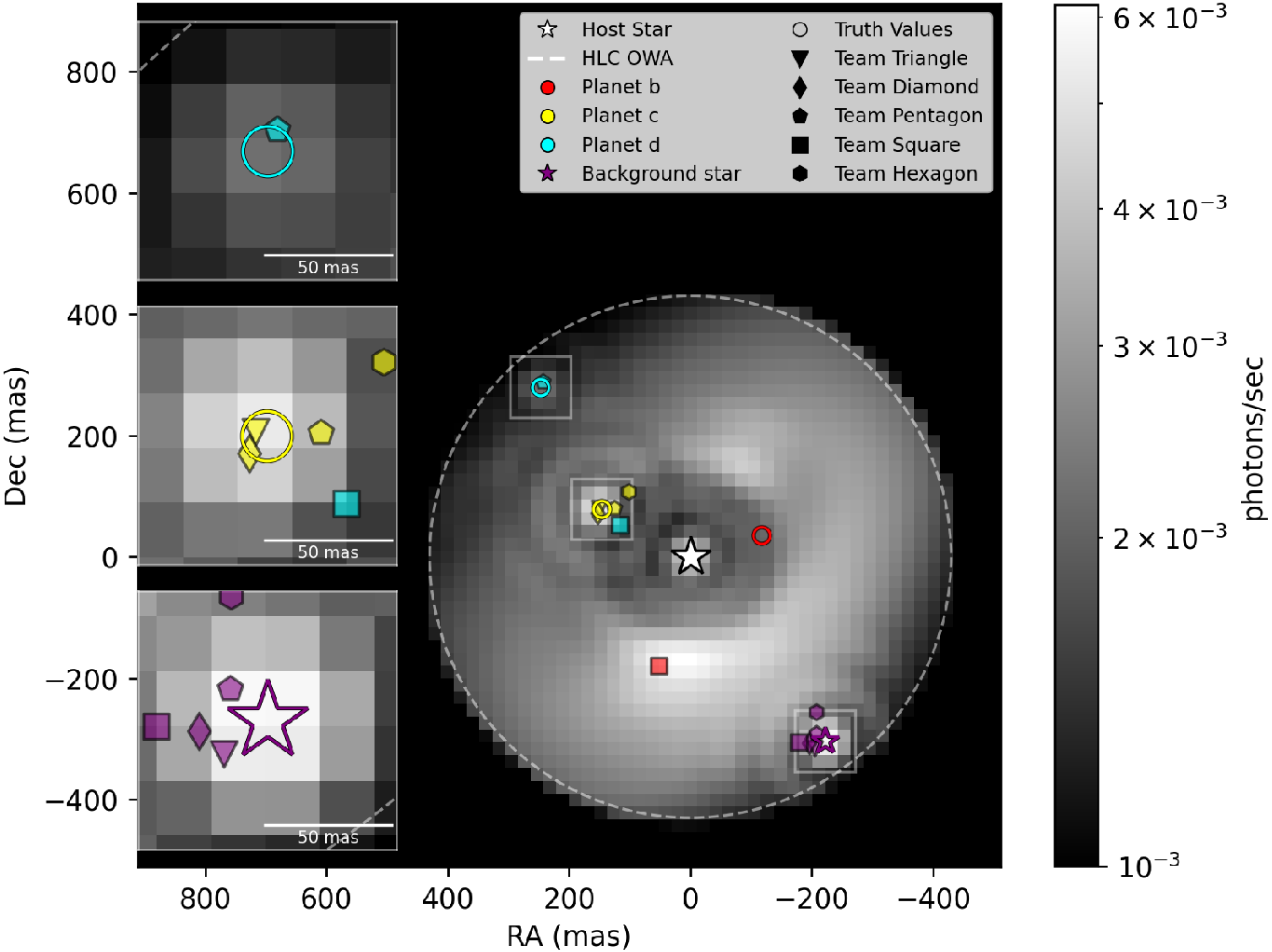


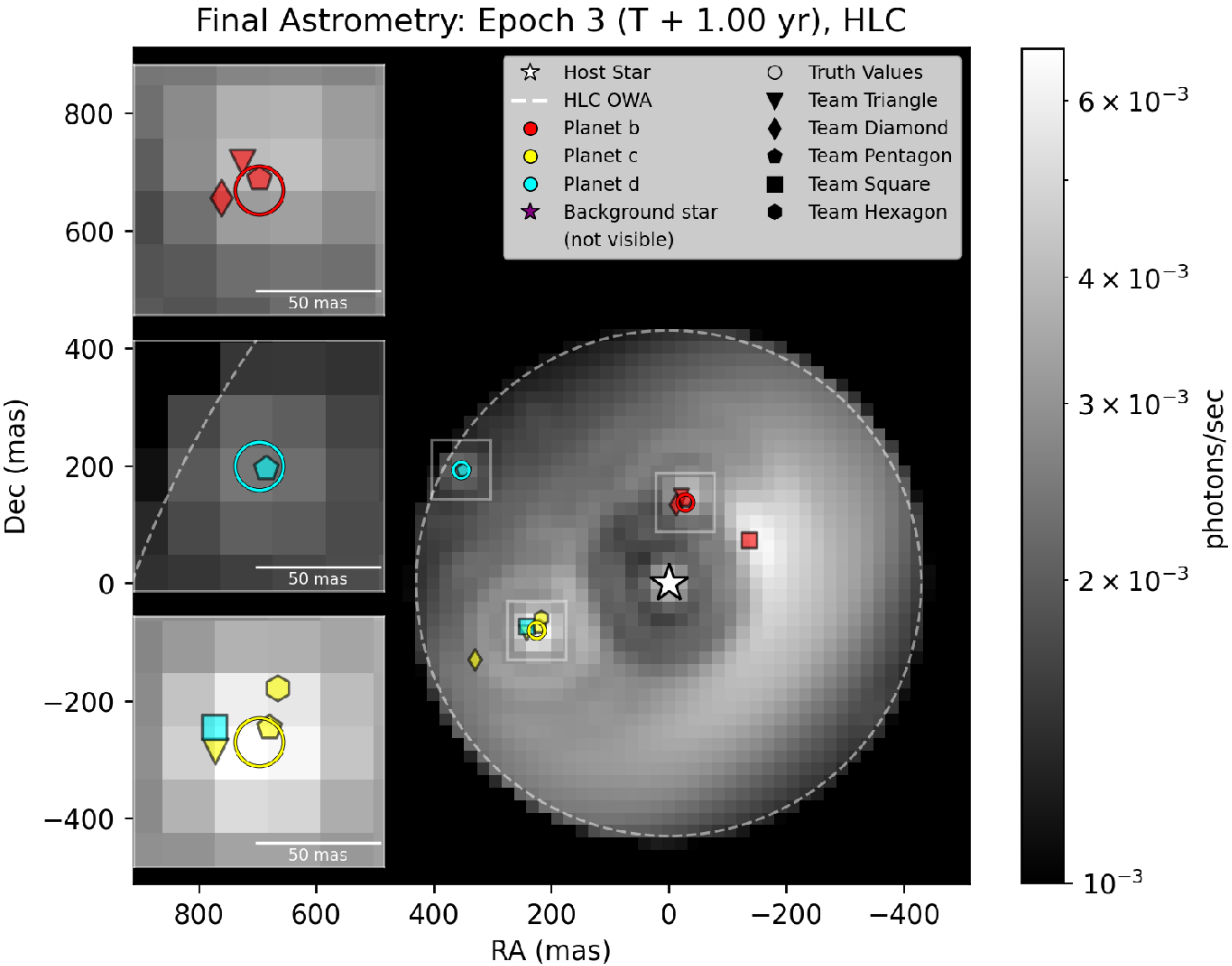


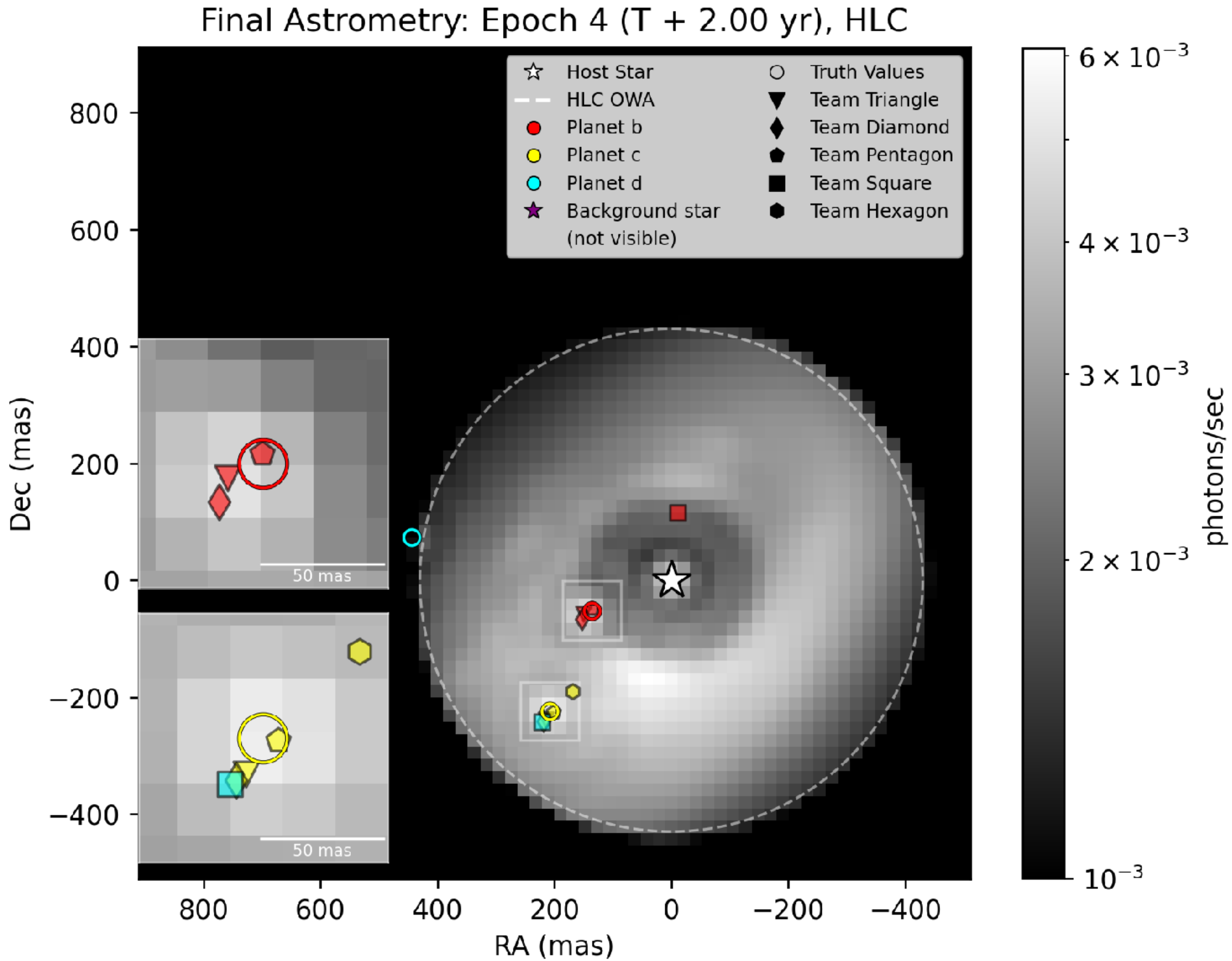



Final Astrometry: Epoch 1 (T + 0.00 yr), HLC
Host Star
HLC OWA
Planet b
Planet c
Planet d
Background star
Truth Values
Team Triangle
Team Diamond
Team Pentagon
Team Square
Team Hexagon
50 mas
50 mas
50 mas
Dec (mas)
RA (mas)
800
600
400
200
0
−200
−400
6×10^{-3}
4×10^{-3}
3×10^{-3}
2×10^{-3}
10^{-3}
photons/sec

Final Astrometry: Epoch 2 (T + 0.15 yr), HLC

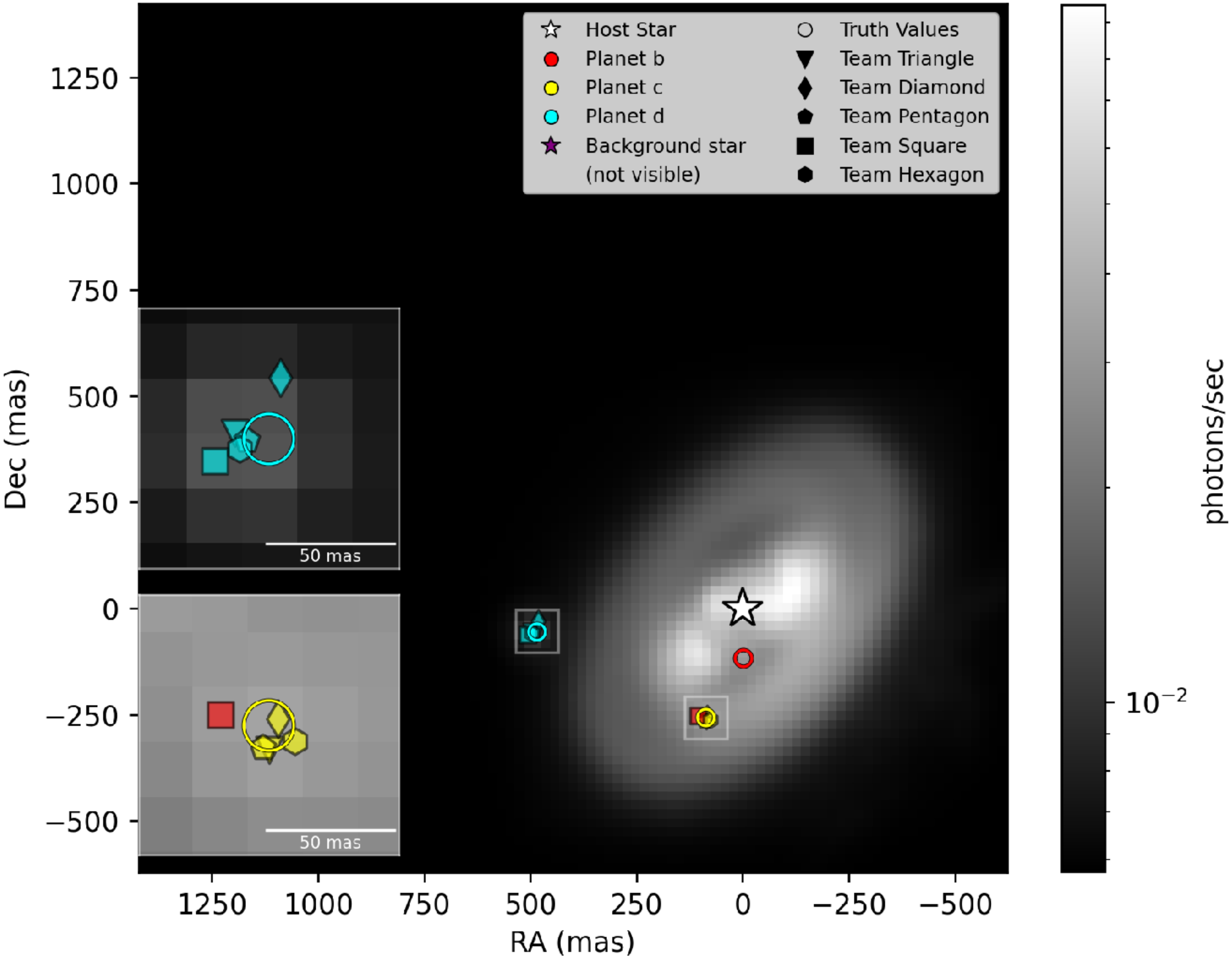


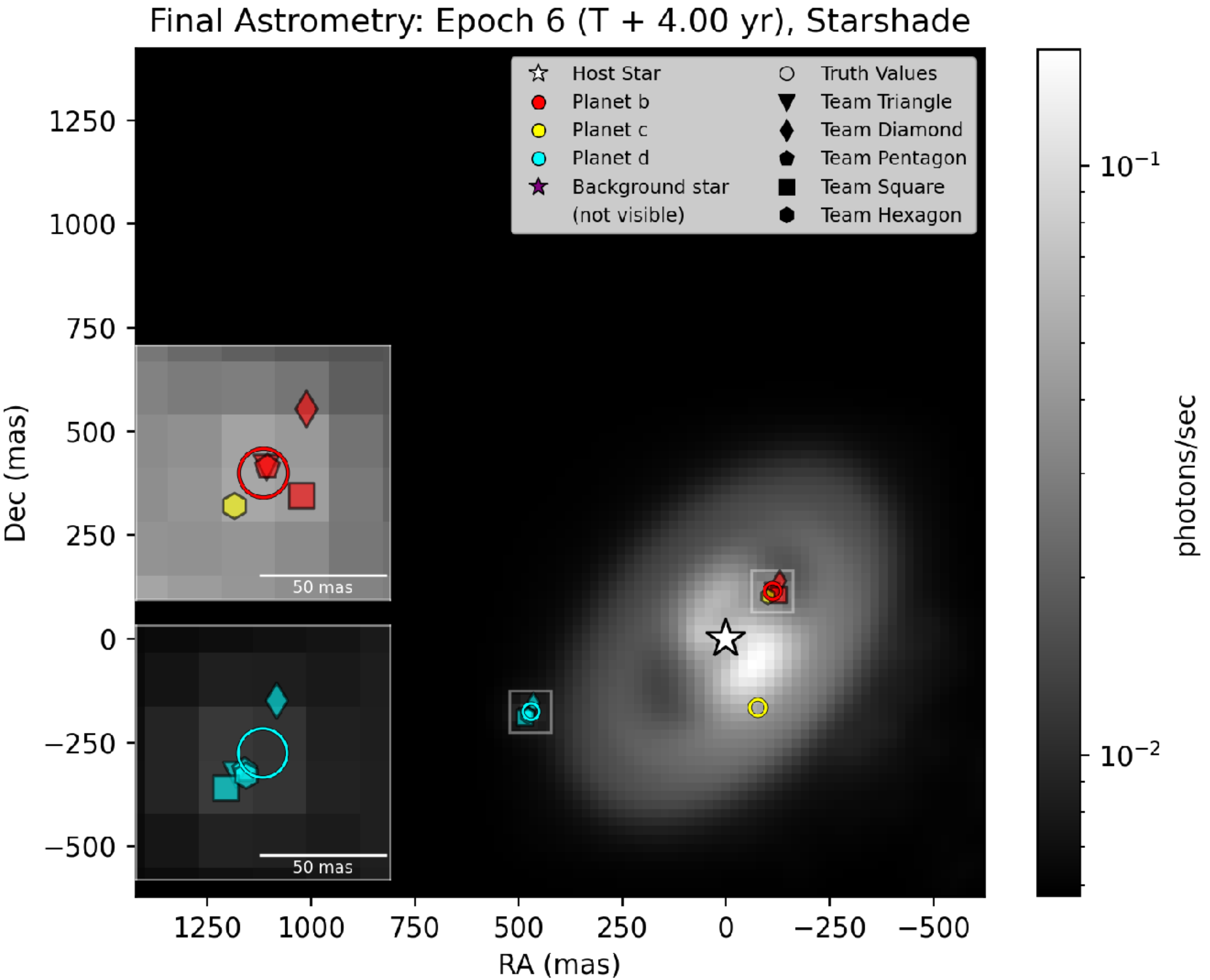

Final Astrometry: Epoch 3 (T + 1.00 yr), HLC
Host Star
HLC OWA
Planet b
Planet c
Planet d
Background star
(not visible)
Truth Values
Team Triangle
Team Diamond
Team Pentagon
Team Square
Team Hexagon
50 mas
50 mas
50 mas
Dec (mas)
RA (mas)
photons/sec
800
600
400
200
0
−200
−400
800
600
400
200
0
−200
−400
6×10^{-3}
4×10^{-3}
3×10^{-3}
2×10^{-3}
10^{-3}



Final Astrometry: Epoch 4 (T + 2.00 yr), HLC
Host Star
HLC OWA
Planet b
Planet c
Planet d
Background star
(not visible)
Truth Values
Team Triangle
Team Diamond
Team Pentagon
Team Square
Team Hexagon
50 mas
50 mas
Dec (mas)
800
600
400
200
0
−200
−400
RA (mas)
800
600
400
200
0
−200
−400
6×10^{-3}
4×10^{-3}
3×10^{-3}
2×10^{-3}
10^{-3}
photons/sec

Final Astrometry: Epoch 5 (T + 3.00 yr), Starshade



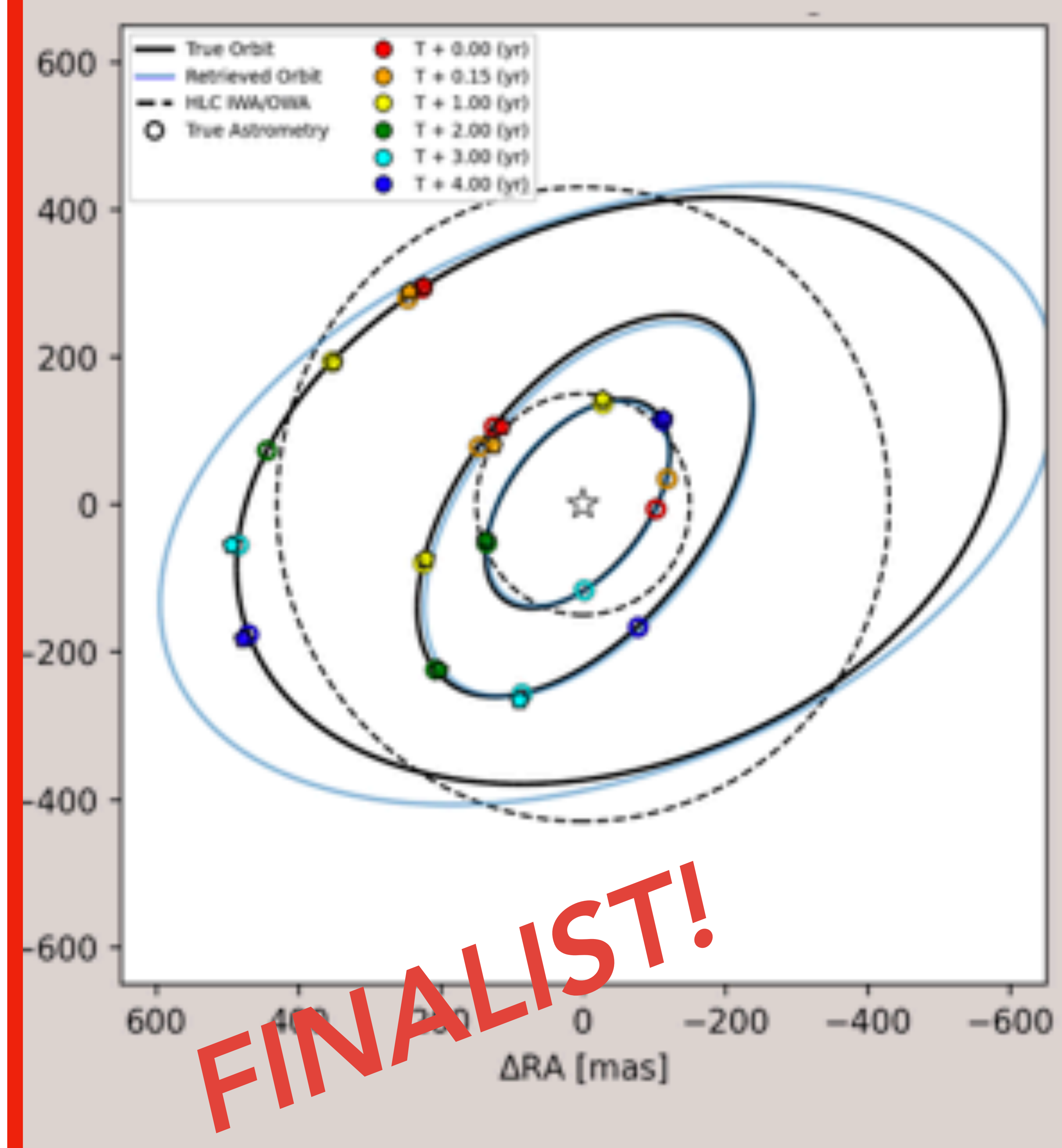


Final Astrometry: Epoch 6 (T + 4.00 yr), Starshade
Host Star
Planet b
Planet c
Planet d
Background star
(not visible)
Truth Values
Team Triangle
Team Diamond
Team Pentagon
Team Square
Team Hexagon
50 mas
50 mas
Dec (mas)
RA (mas)
1250
1000
750
500
250
0
−250
−500
1250
1000
750
500
250
0
−250
−500
10^{-1}
10^{-2}
photons/sec

Final Planet Count for the 3 Best Teams

TEAM PENTAGON

13/18 detections — 0 false positives

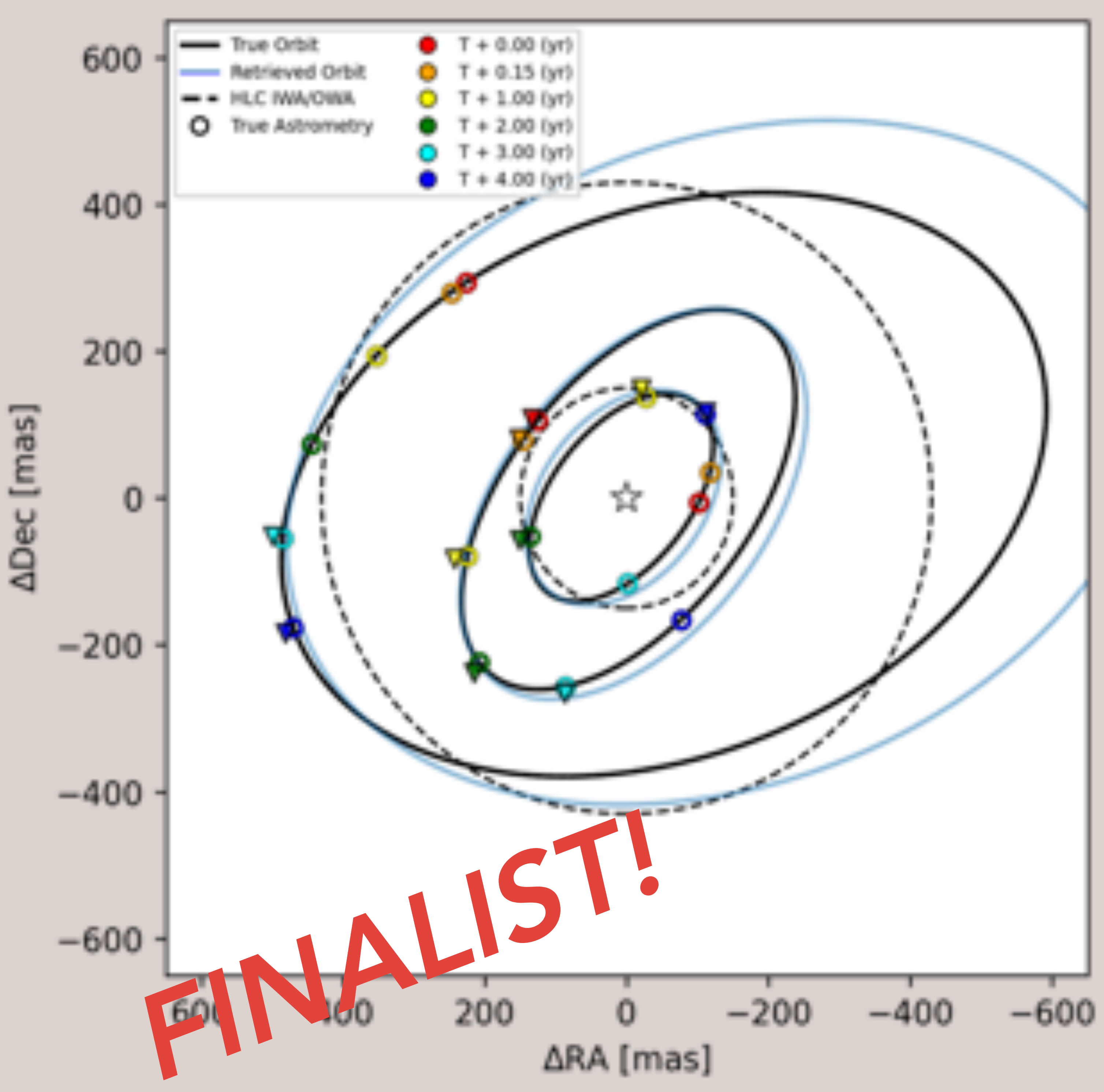


Mass: 0.3% error

Radius/Albedo: No estimate

TEAM TRIANGLE

10/18 detections — 0 false positives

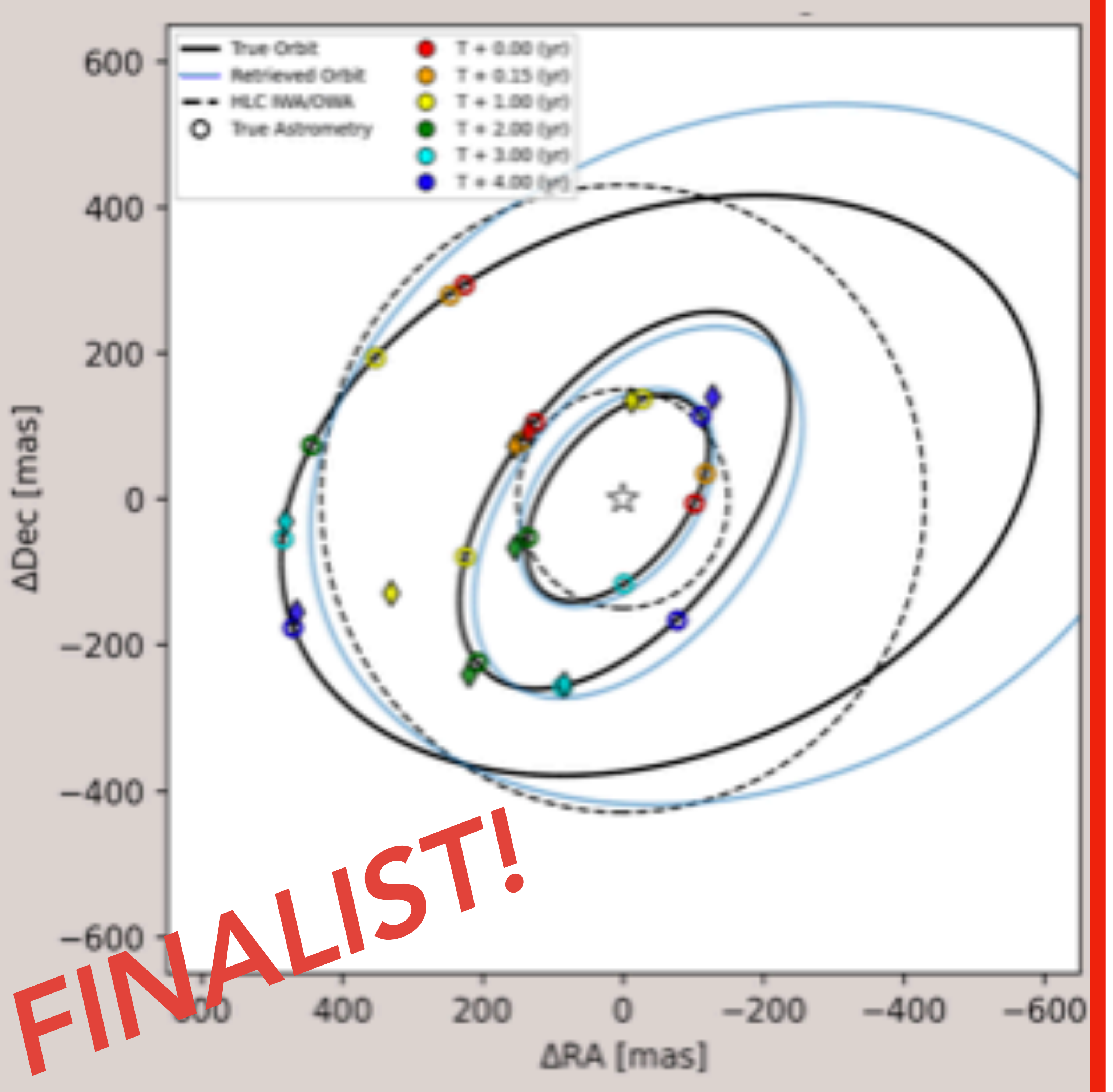


Mass: 0.5% error

Radius/Albedo: 21% error

TEAM DIAMOND

10/18 detections — 1 false positive

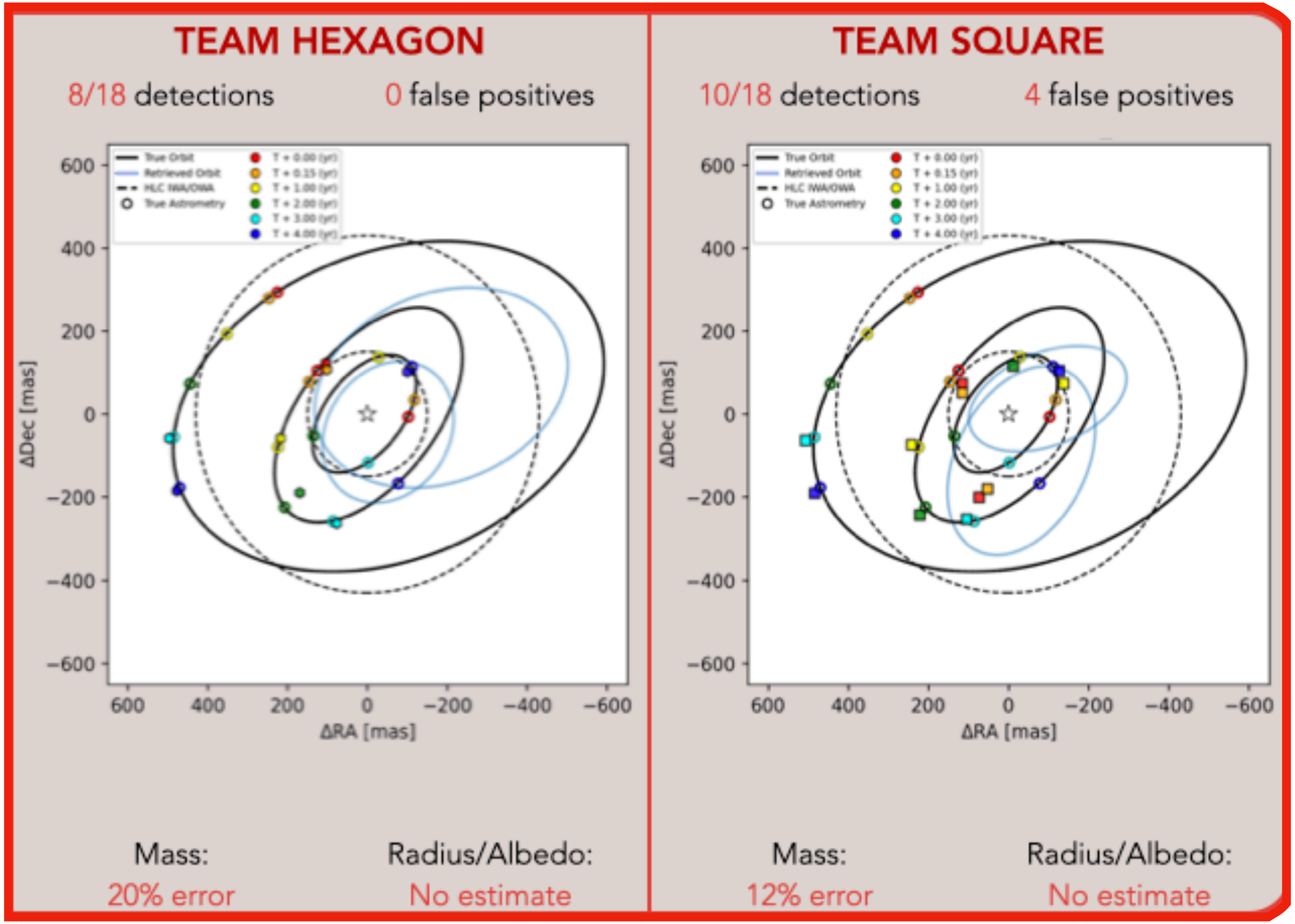


Mass: 11% error

Radius/Albedo: 49% error

Final Planet Count for the 2 Next Teams (4th-5th)

Mis-matching of the planets caused significant errors



False positives and mis-matching of the planets caused significant errors

Challenge Results: Planet detection matrix

Ell Bogat

Epoch	Time Elapsed (years)	Flux Ratio		
		Planet b	Planet c	Planet d
1	(HLC) 0.00	3.58e-10 ⬠▽◇⬡□	4.54e-09 ⬟▼◆⬢■	1.01e-09 ⬟▽◇⬡□
2	(HLC) 0.15	6.9e-10 ⬠▽◇⬡□	4.52e-09 ⬟▼◆⬢■	1.01e-09 ⬟▽◇⬡□
3	(HLC) 1.00	5.19e-09 ⬟▼◆⬡■	3.61e-09 ⬟▼◆⬢■	9.84e-10 ⬟▽◇⬡□
4	(HLC) 2.00	4.82e-09 ⬟▼◆⬡■	1.83e-09 ⬟▼◆⬢■	8.69e-10 ⬠▽◇⬡□
5	(Starshade) 3.00	4.96e-10 ⬠▽◇⬡□	5.6e-10 ⬟▼◆⬢■	6.85e-10 ⬟▼◆⬢■
6	(Starshade) 4.00	2.4e-09 ⬟▼◆⬢■	1.21e-10 ⬠▽◇⬡□	4.77e-10 ⬟▼◆⬢■

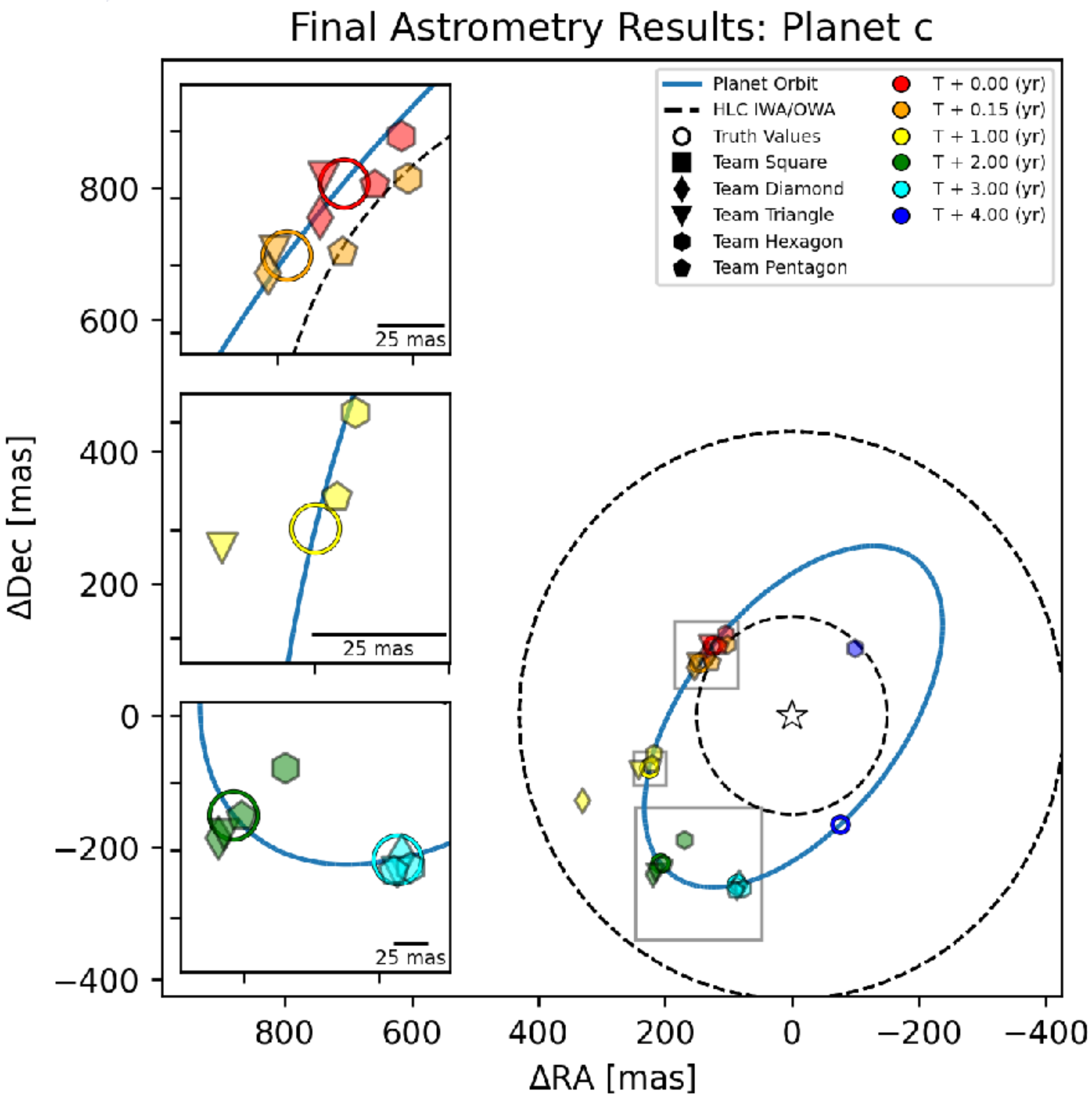
Working angle →

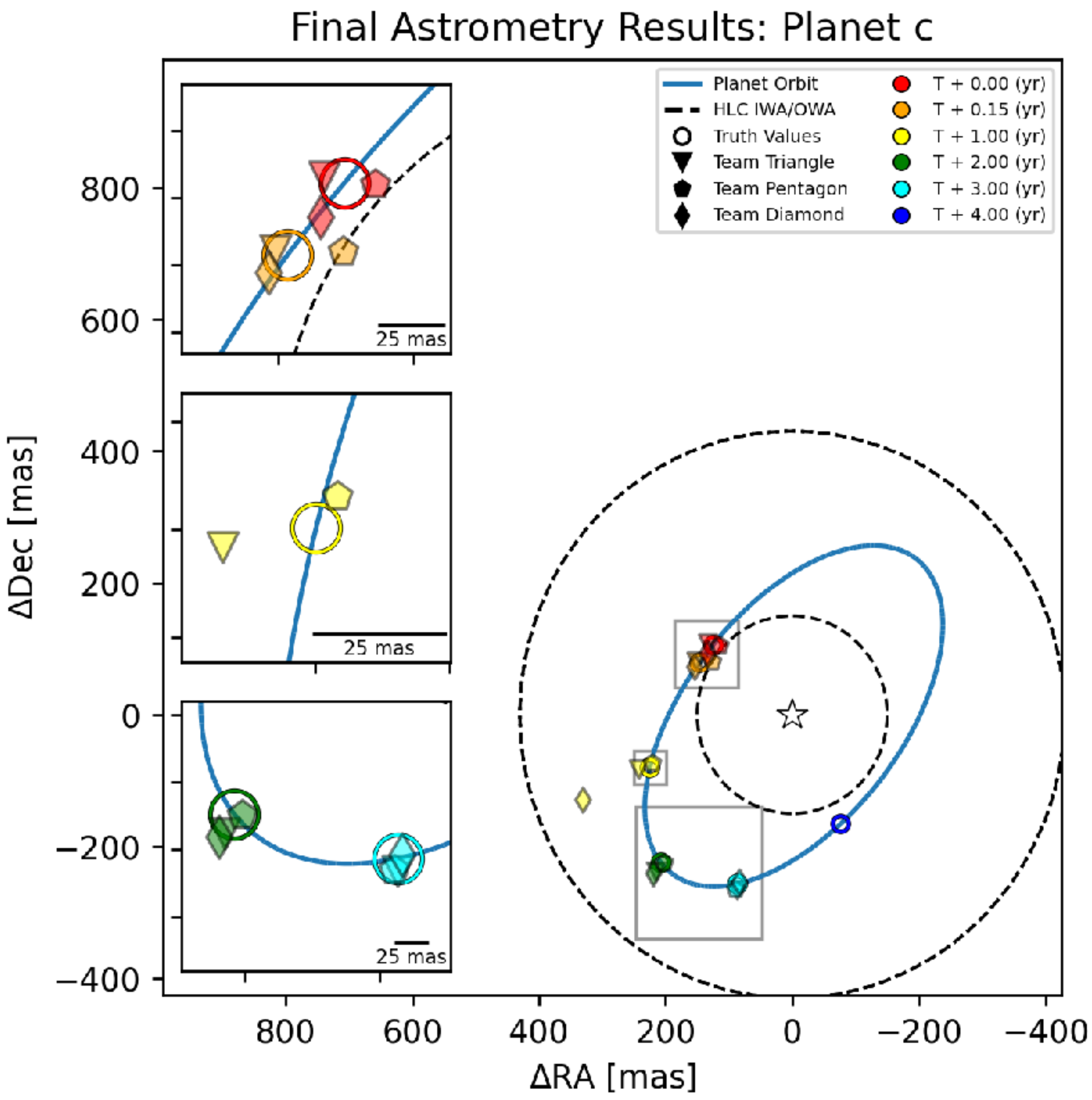
Legend	
●	Detection
○	Non-Detection
(green)	Easy
(yellow)	Medium
(red)	Difficult

Planet c is the easiest

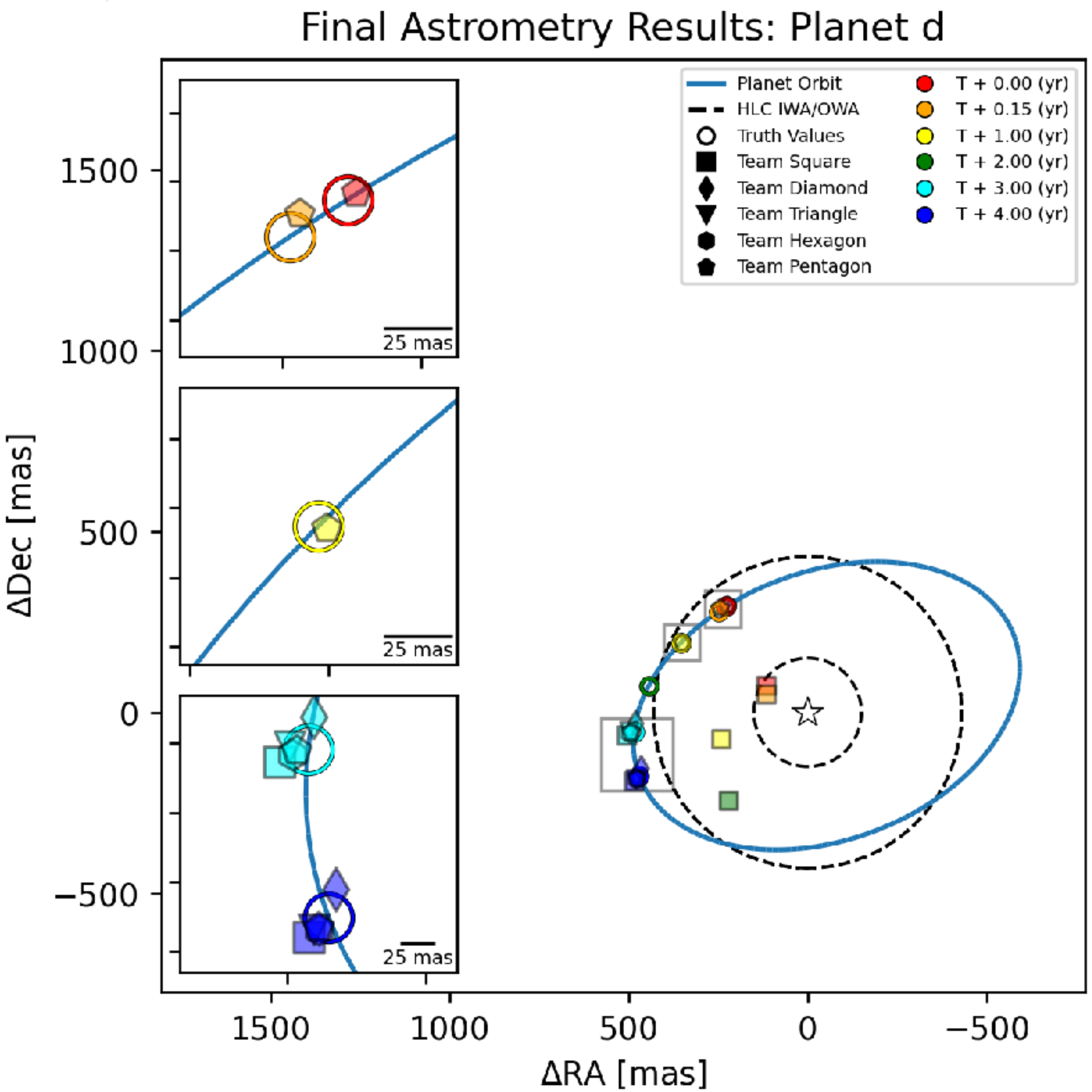
Team ⬟ detected Planet d for very challenging epochs (experience & post-processing skills)

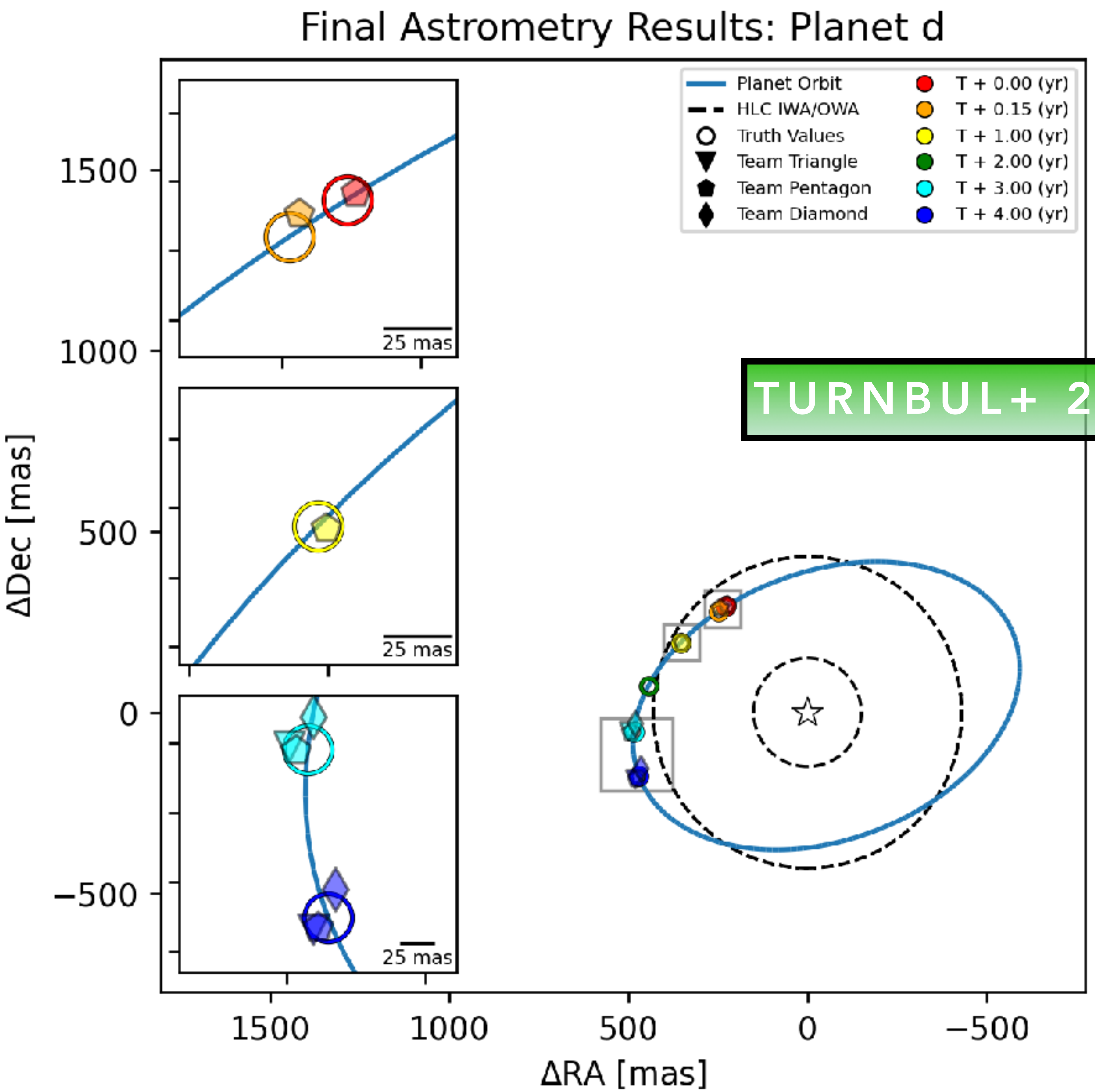
Step 2 & 3: Refined Astrometry / orbital fit - Nominal Planet c





Step 2 & 3: Refined Astrometry / orbital fit - Outer Planet d





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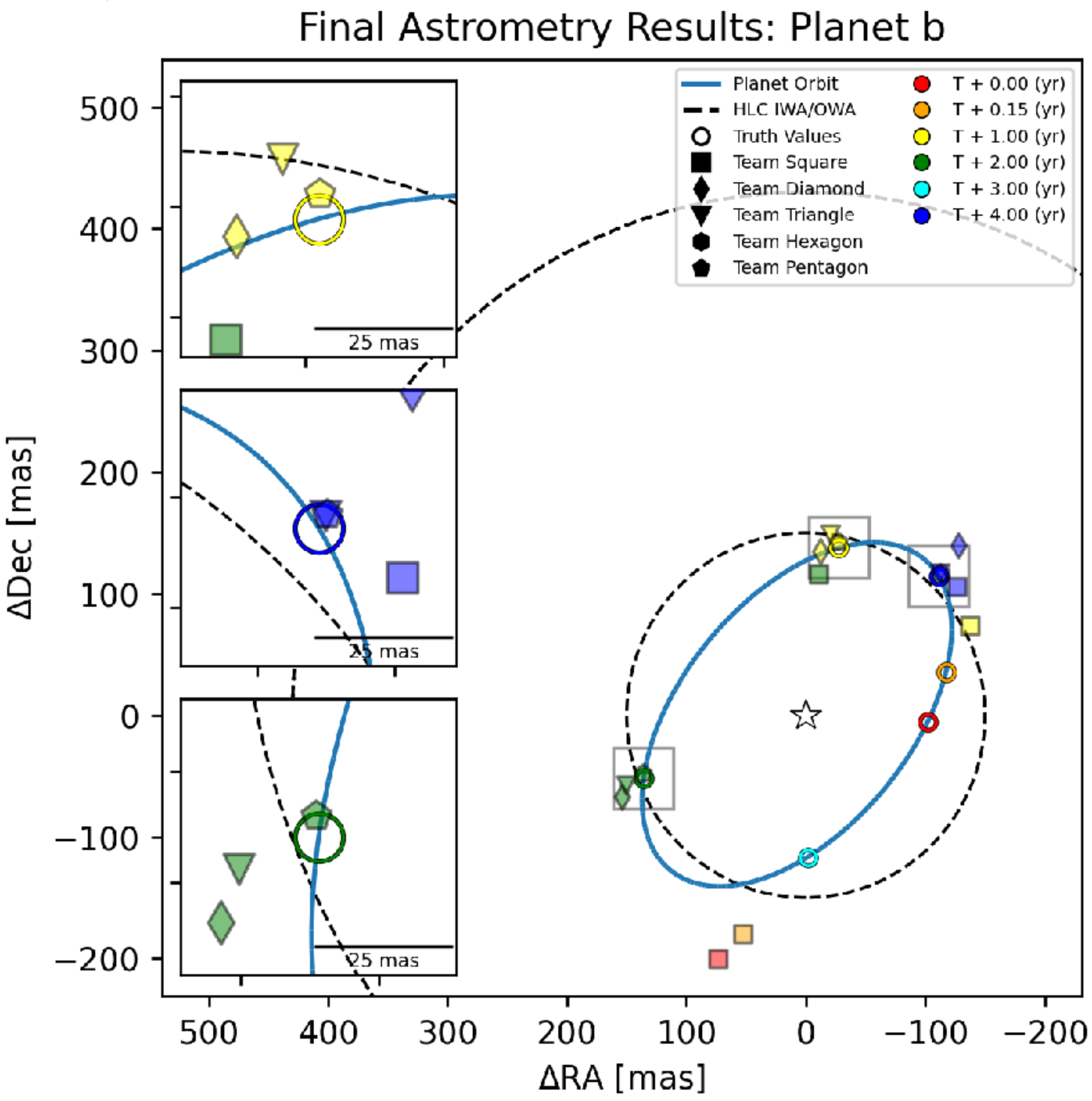
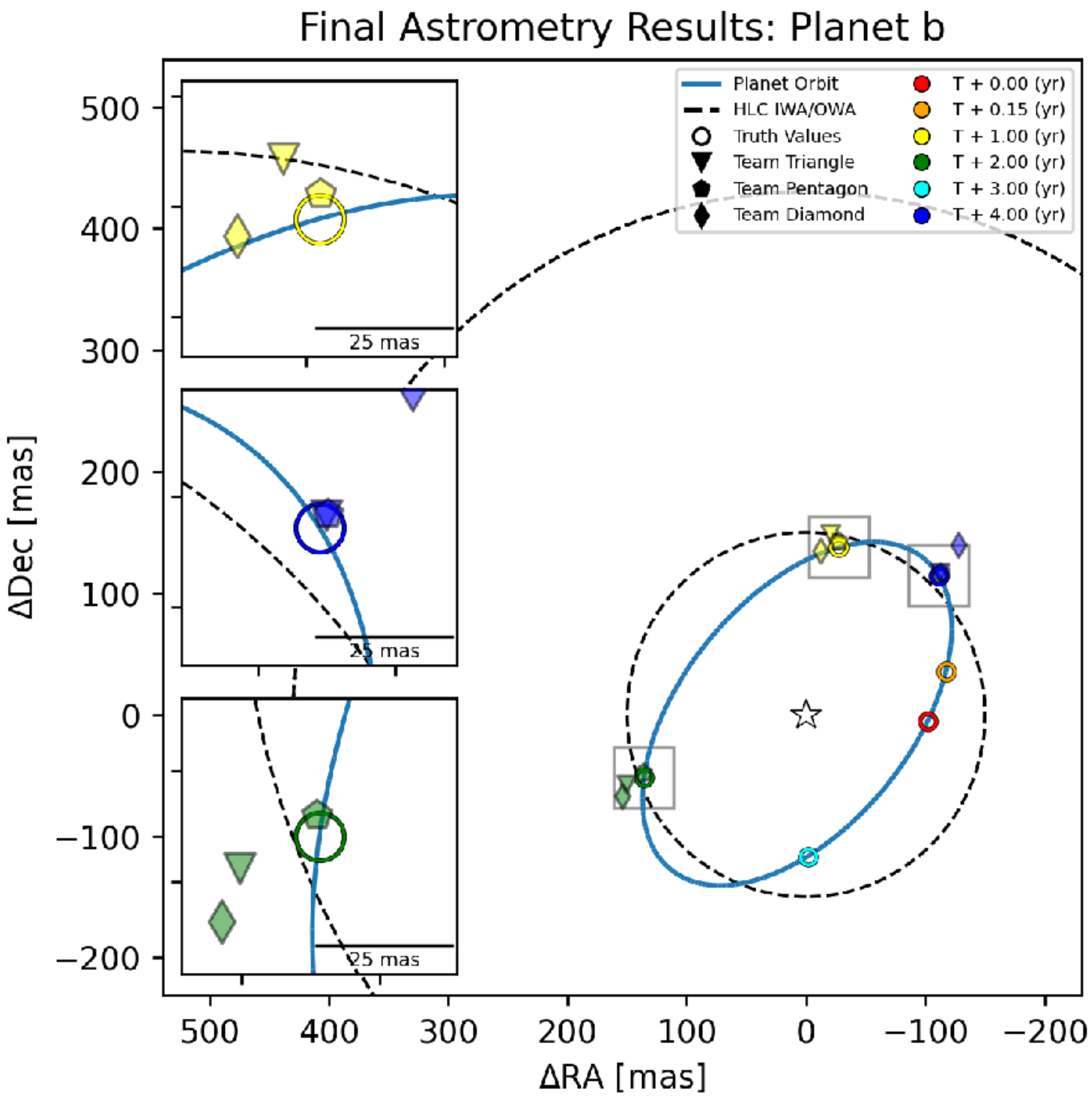
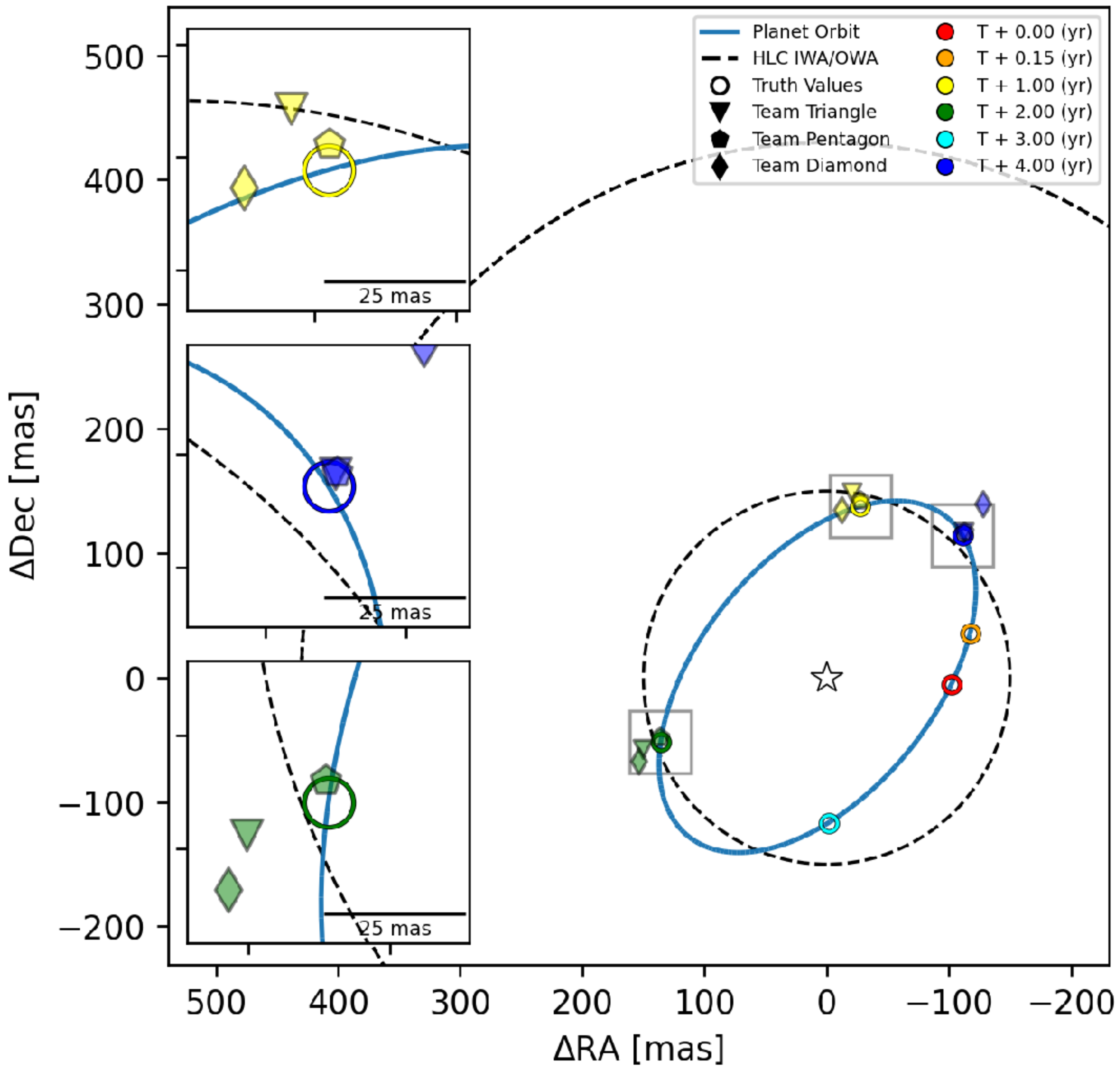
Step 2 & 3: Refined Astrometry / orbital fit - Inner Planet b





Final Astrometry Results: Planet b



Merit-based Ranking

SAT style scoring:

- 1 point awarded for a planet detection
- 0.25 points subtracted for a false positive
- etc.

Symbol	Step 1	Astrometry	Photometry	Orbit	Mass	Step 4	Total	Ranking
⬟	15	75	40	50	50	0	230	
▼	4.29	60	30	40	40	25	199.29	W
◆	12.86	45	50	30	10	12.5	160.36	
⬢	10.71	30	10	20	20	0	90.71	C
■	8.57	15	20	10	30	0	83.57	
✚	6.43	0	0	0	0	0	6.43	-
✖	2.14	0	0	0	0	0	2.14	

Team Identities: Who’s Who?

Check the jamboree page presentations from 3 finalists!

exoplanetdatachallenge.com/home/jamboree

Team	Symbol		Ranking	Prize
Wang	⬟	**Jason Wang**	W	
Princeton	▼	**Leonid Pogorelyuk & Brianna Lacy**	W	
Wagner	◆	**Kevin Wagner**	W	
Tanner	⬢	Angelle Tanner	C	
Planet Hunters	■	Mia Hu, Jonathan Brande, Tomás Silva, Taichi Uyama	C	
Milou	✚	Julien Milli	-	-
Agrawal	✕	Shubham Agrawal	-	-

Metrics, Results & Prizes

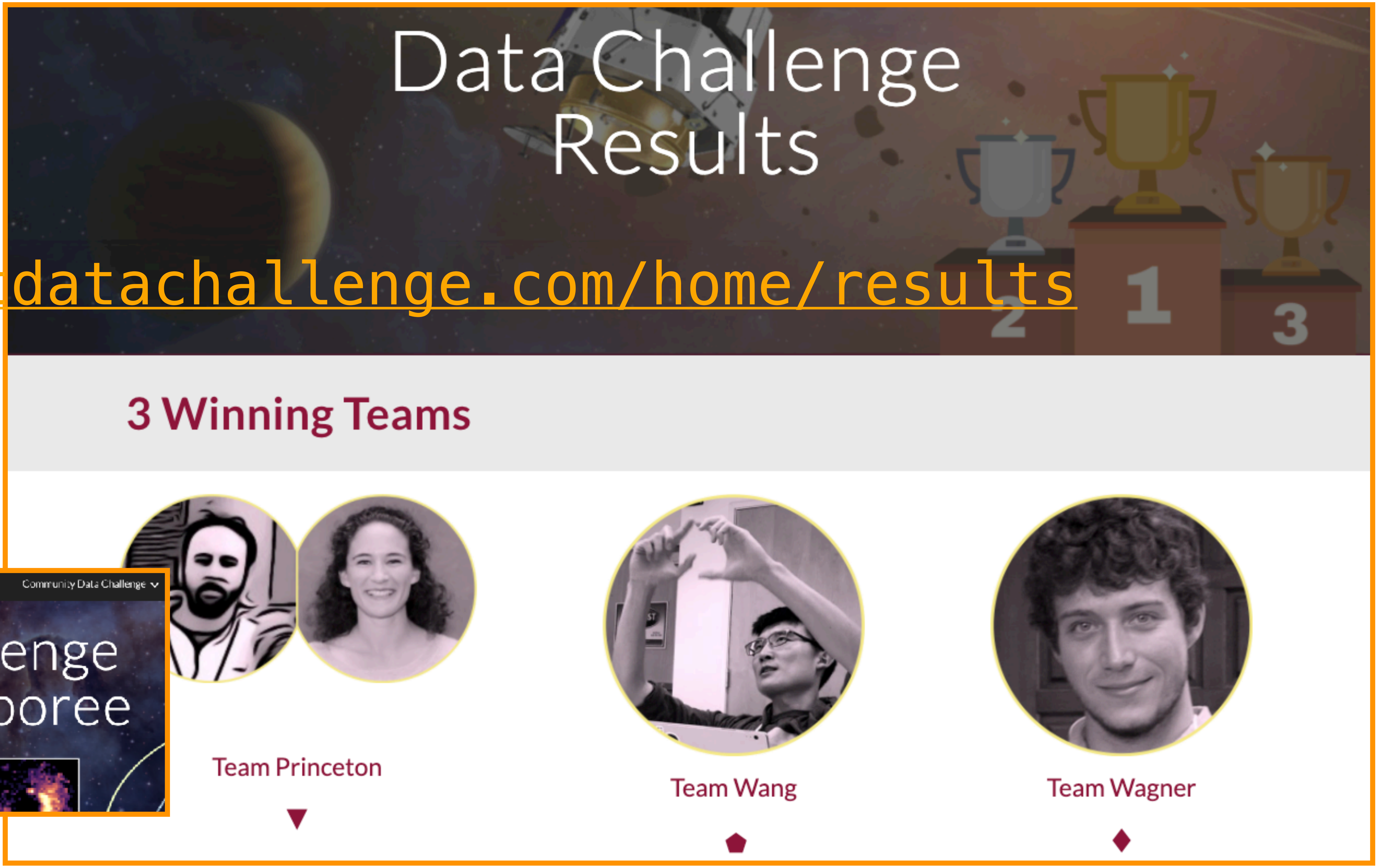
3 winning teams

2 challenger Teams

2 other teams

Data Challenge: Winners

exoplanetdatachallenge.com/home/results



Lessons Learned

Roman Exoplanet Imaging DC: What have we learned?

The CGI contrast regime and capabilities offers exciting science demonstration prospects in addition to the technological pathways: imaging **giant planets in reflected light.**

We are **better prepared** to **exploit the real Roman Coronagraph data** even if the DC data (OS6) was quite optimistic.

We are able **to perform orbital retrieval on HLC simulations (> 2-3 epochs) using real exoplanetary systems with RV trends** (not yet Gaia).

Talk by Ell Bogat on Simulations of Orbits

Talk by Dmitry Savransky on the Imaging Mission Database (plandb)

Roman Exoplanet Imaging DC: What have we learned?

Engaging the community is not too difficult but getting (young) people to commit and submit (results) is not easy as they are already pressured with paper writing, graduate school applications, etc. It could be a good idea to involve their supervisors early on. We encouraged people to **team up** and it has given some positive results in the engagement.

Several teams have found **decent astrometric solutions** for at least one planet with or without the priors from RV precursor data.

All participants **struggled** with **calibrating photometry**: we improved our tutorial on this matter.

Roman Exoplanet Imaging DC: What have we learned?

One team (Wang) has been able to **recover a challenging planet** in some epochs for which we thought it was not possible! Post-processing and experience on precursor data helps! It might be determinant for OS9, **OS11 and the real data**

Talk by John Krist on Observing Scenarios

Talk by Marie Ygouf on Simulation/Data Processing

Some participants preferred to **develop their own tools** rather than use the publicly available packages (potential added value).

A few bugs have been found and it has been **rewarding for the public package developers** (e.g for orbitize!) which suddenly **get many avid testers**.

Publications

Legacy Tutorial

Papers on the Data Challenge itself

GIRARD+

Online (2020)

SPIE Proceedings

- General paper on the Data Challenge

TURNBUL+

Online (2021)

JATIS Special issue on Star Shades

- Focus on star shade
- Focus on planet d

ZIMMERMAN+

In prep (2021)

Astronomical Journal

- Challenge design
- & HLC simulations
- In-house analysis
- & code for planet c

GIRARD+

In prep (2021)

Astronomical Journal

- Challenge organization
- In-house analysis for all 3 planets
- Lessons learned
- Participating teams feedback

Papers from SIT members related to the DC

HILDEBRANDT+

Online (2020)

AAS Proceedings

- SISTER, Starshade Imaging Simulation Toolkit

LI (ZHEXING)+

Online (2021), on **arxiv/ADS**

Astronomical Journal

“Direct Imaging of Exoplanets Beyond the Radial Velocity Limit”

- Compares Roman Coronagraph + Star shade rendezvous with HabEx

SAXENA+

Online (2021), on **arxiv/ADS**

Astronomical Journal

"Simulating Reflected Light Exoplanet Spectra of the Promising Direct Imaging Target, υ Andromedae d, with a New, Fast Sampling Method Using the Planetary Spectrum Generator”

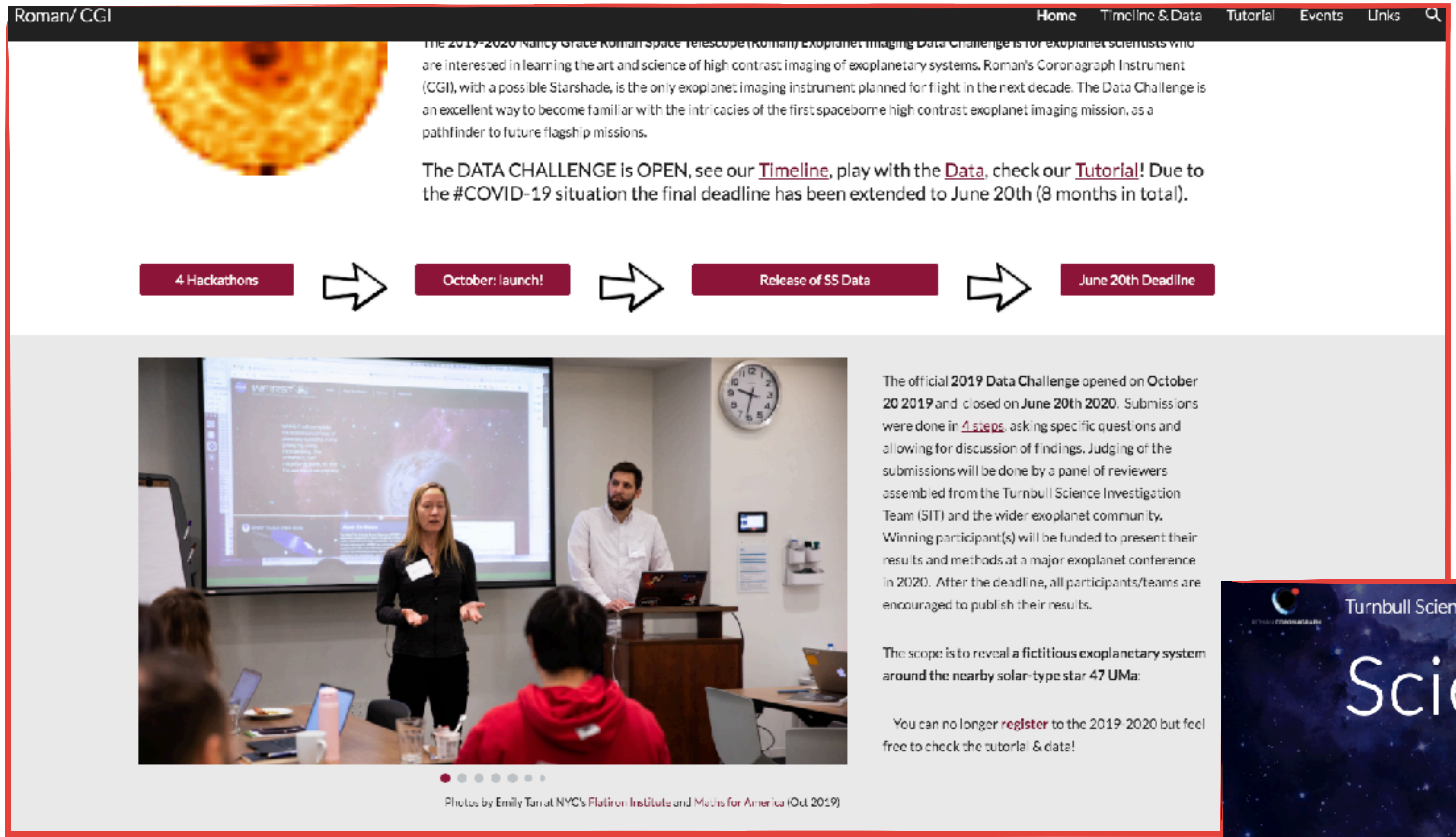
Legacy Tutorial suite (Jupyter notebooks)

Neil Zimmerman & team

ZIMMERMAN+ (IN PREP)

www.exoplanetdatachallenge.com/tutorial

Roman Exoplanet Imaging Data Challenge: Website



Data Challenge

Team, Jamboree/Results, Timeline, Events

Turnbull SIT

Final Report, Publications, etc.

Data & Tutorial

Legacy Tutorial, older versions

Links & Ressources

New section for the SIT

www.exoplanetdatachallenge.com