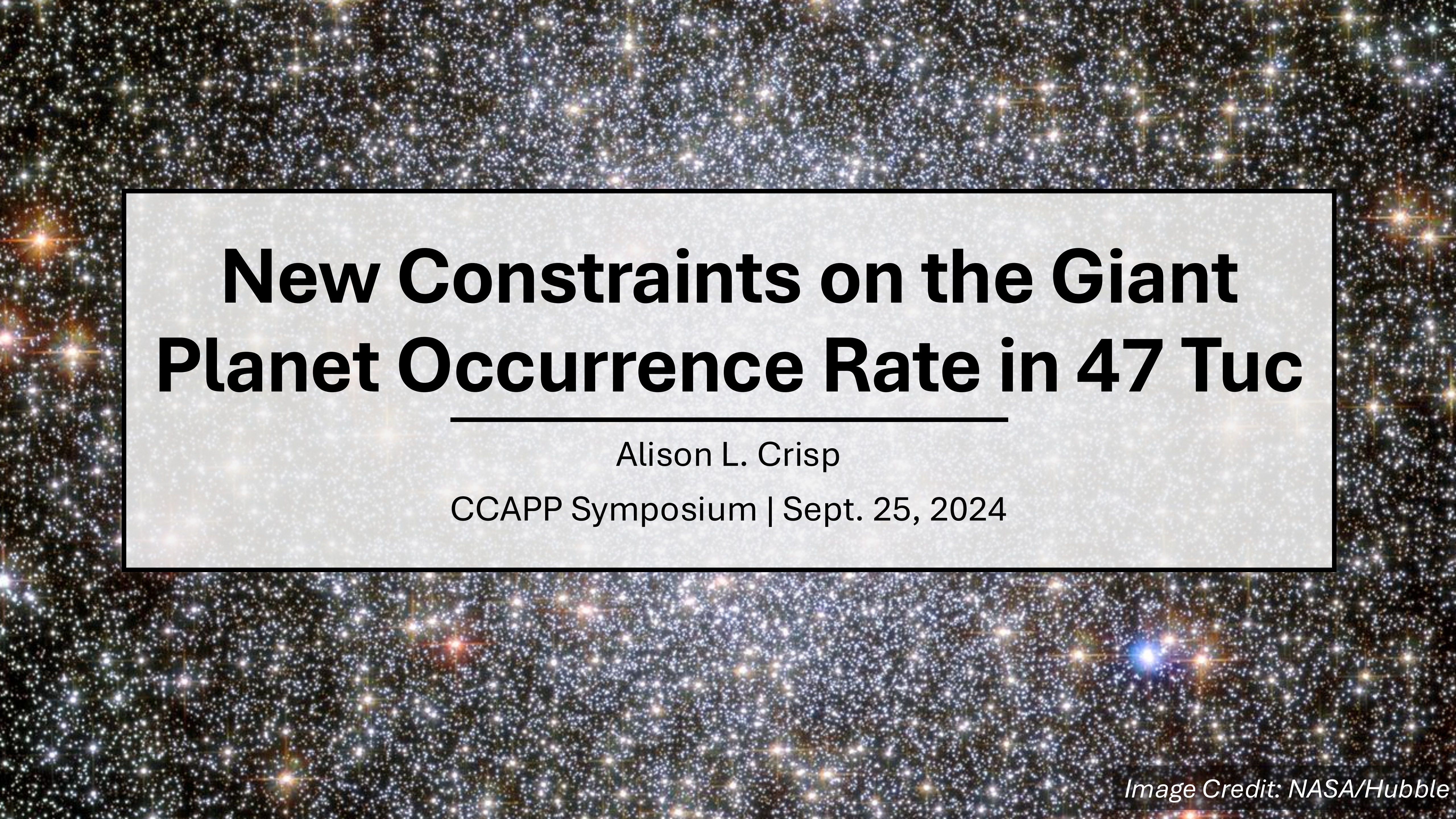


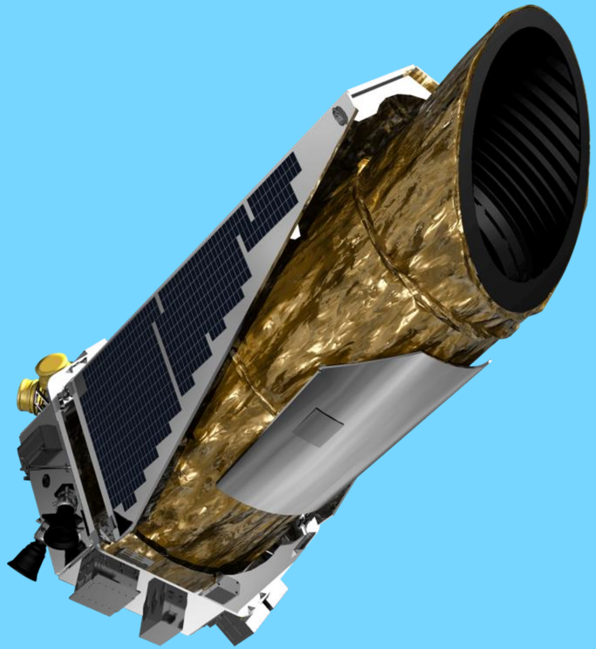
# New Constraints on the Giant Planet Occurrence Rate in 47 Tuc

Alison L. Crisp

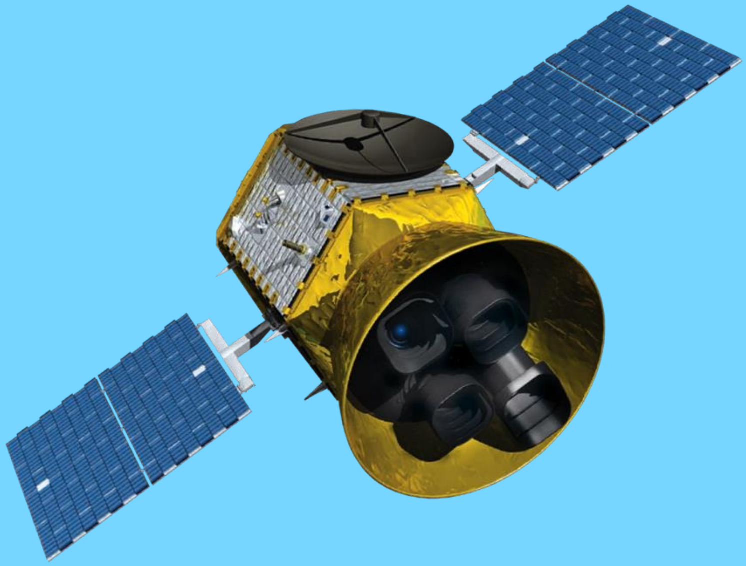
CCAPP Symposium | Sept. 25, 2024

*Image Credit: NASA/Hubble*

# 5,759 Exoplanets



3,321 *Kepler* + *K2*



557 *TESS*

*(NASA Exoplanet Archive 09/24/2024)*

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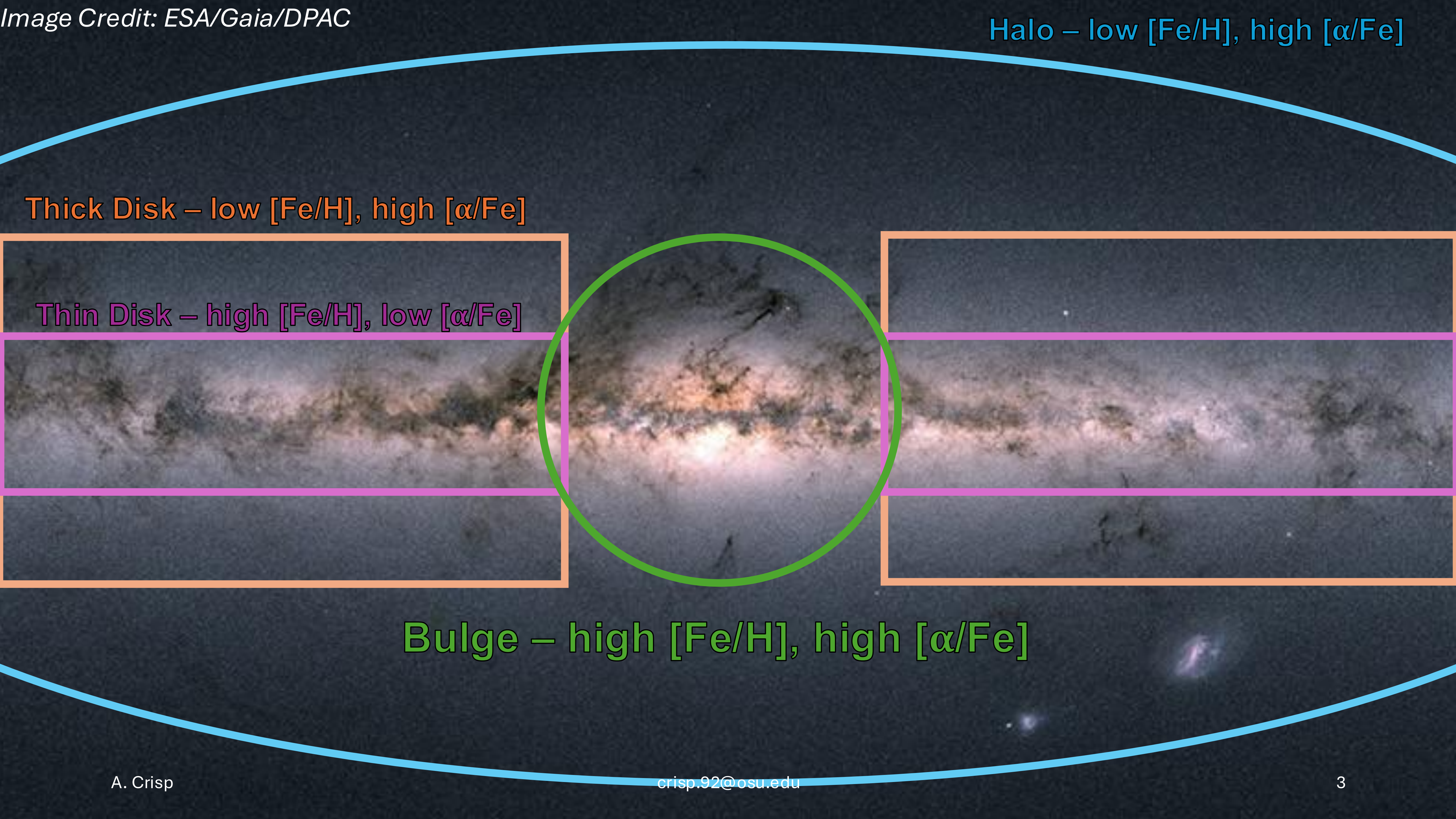

*Image Credit: ESA/Gaia/DPAC*

Halo – low [Fe/H], high [α/Fe]

Thick Disk – low [Fe/H], high [α/Fe]

Thin Disk – high [Fe/H], low [α/Fe]

Bulge – high [Fe/H], high [α/Fe]

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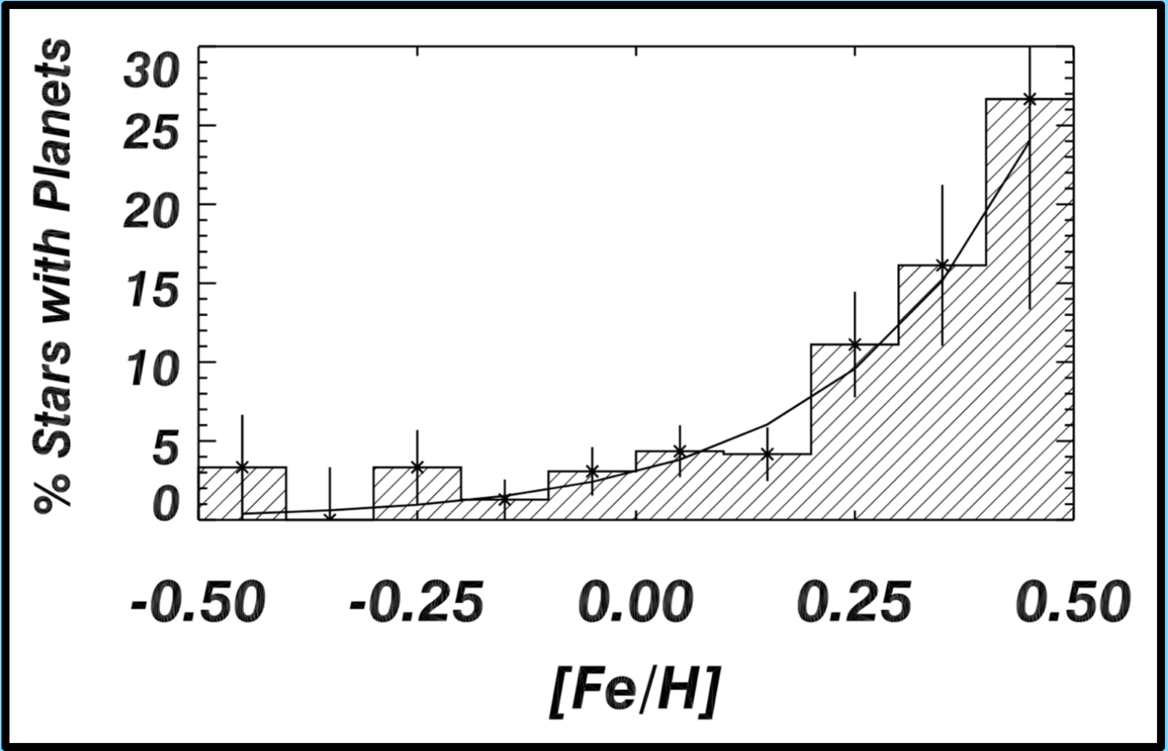
# Why disentangle abundances?

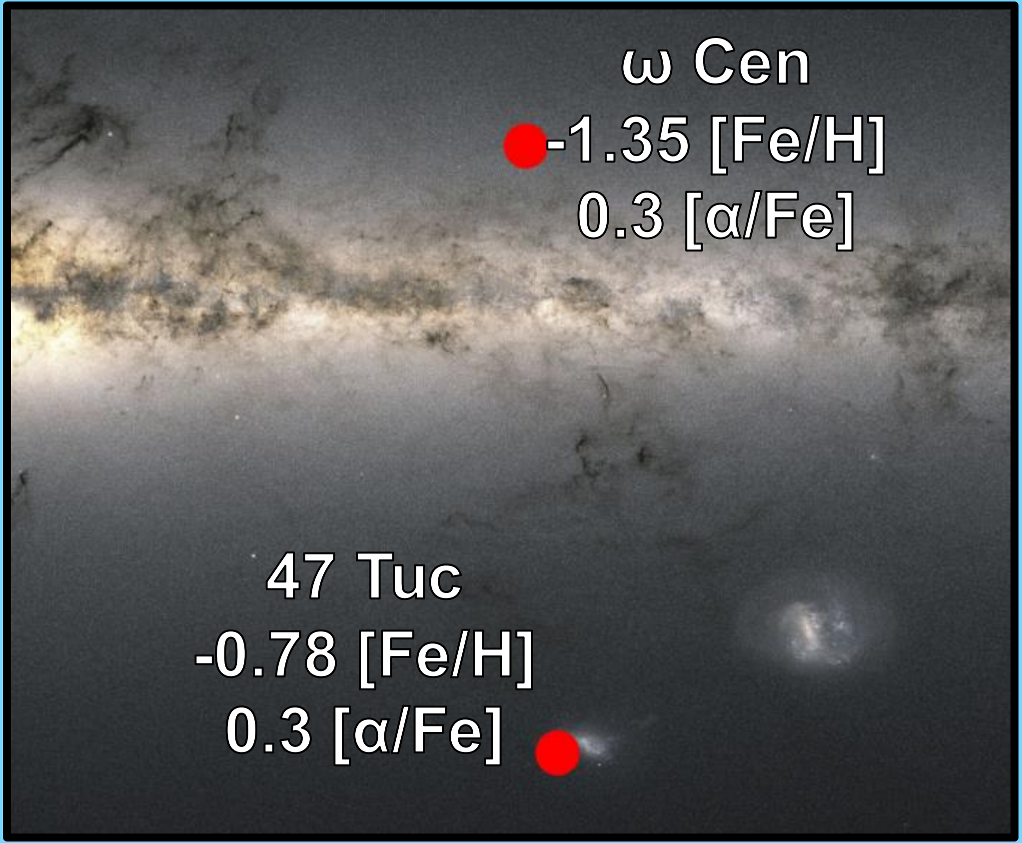
- Giant planet formation strongly correlated with metallicity.
  - $f_{GP} \propto 10^{2.0\,[\mathrm{Fe/H}]}$ (Fischer & Valenti, 2005)
  - $f_{GP} \propto 10^{1.2\,[\mathrm{Fe/H}]}$ (Johnson et al., 2010)
- Is [α/H]=[α/Fe]+[Fe/H] more important than [Fe/H] alone?
- [Fe/H] and [α/Fe] are strongly correlated in disk stars, so multiple populations need to be surveyed.



*Fischer & Valenti, 2005*

# Why globular clusters?

- Well-known characteristics.
- Generally consistent populations.
- Accessible low-[Fe/H], high-[α/Fe].
- Place important constraints either way.



*Values from Forbes 2010, Cordero 2014, & Pilachowski 2010*

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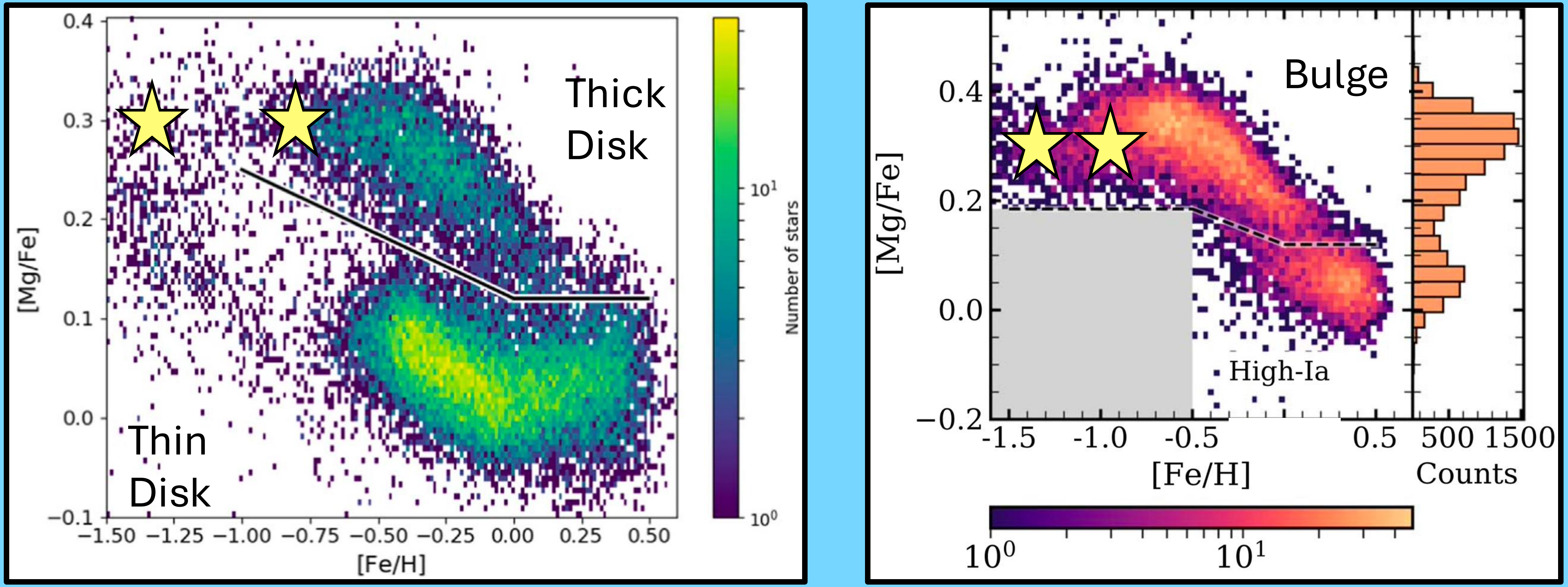
# Why globular clusters?



*APOGEE abundance data from Left: Weinberg et al., 2019; Right: Griffith et al., 2021*

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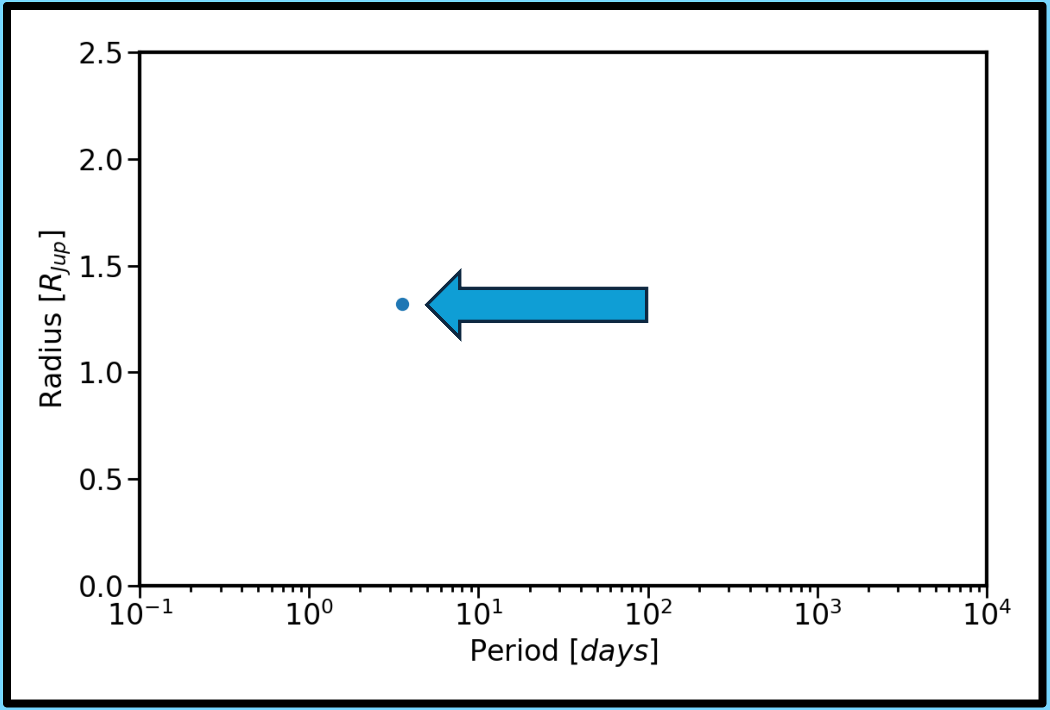
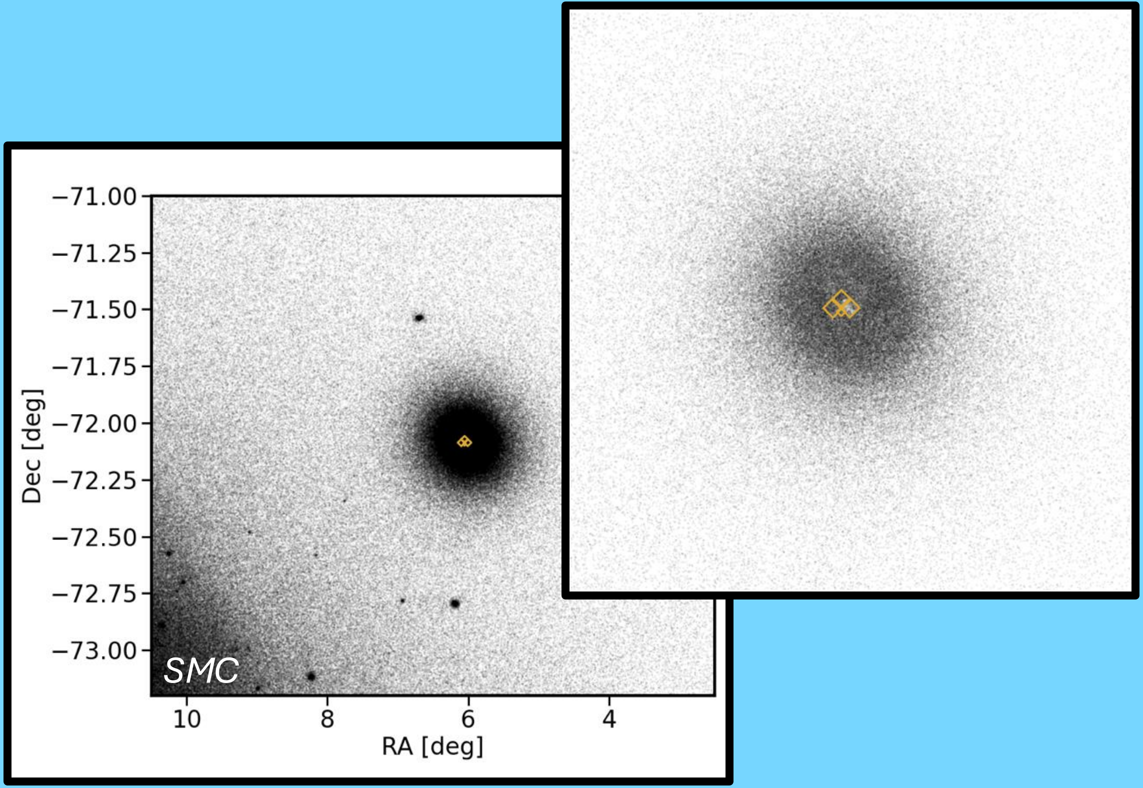
# Previous Searches

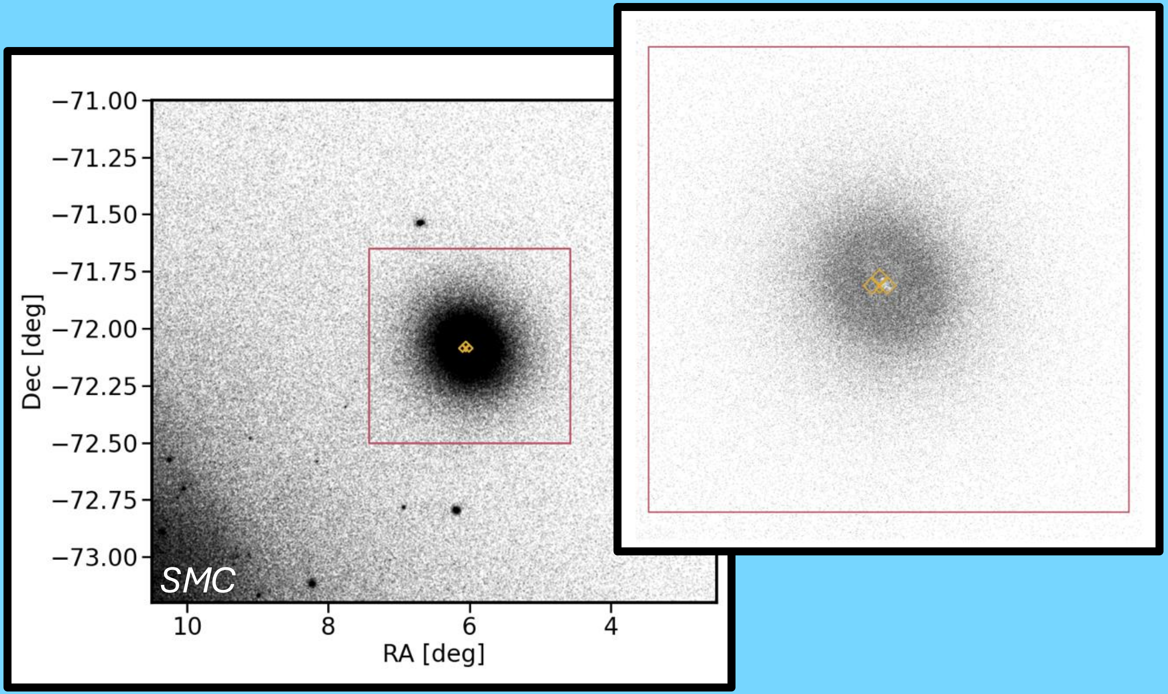
| Study | # Stars | Assumed Occ. | Exp. Plan. |
|---|---|---|---|
| Gilliland et al. 2000 | 34,091 | 0.8-1.0% | ~17 |

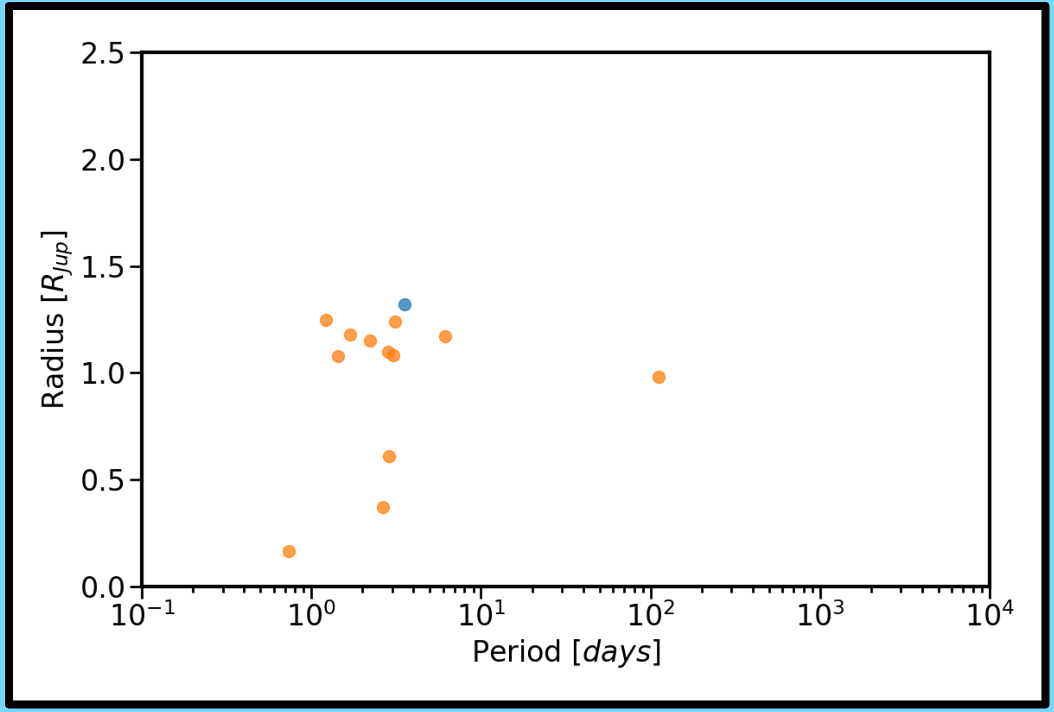




# Previous Searches

| Study | # Stars | Assumed Occ. | Exp. Plan. |
|---|---|---|---|
| Gilliland et al. 2000 | 34,091 | 0.8-1.0% | ~17 |
| Weldrake et al. 2005 | 21,190 | 0.8% | ~7 |

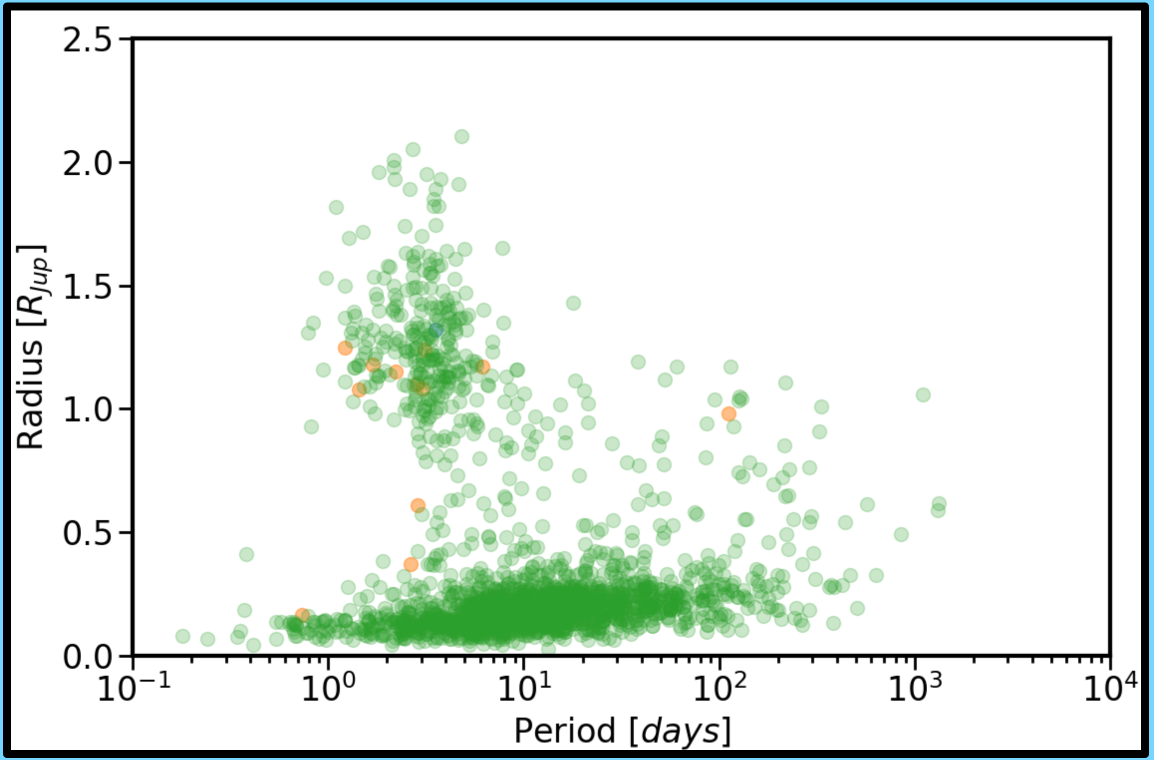




# But what if clusters match *Kepler* instead?

- Masuda & Winn (2017).
- Draws 34,091 stars matching G00's parameters from *Kepler sample*.
- Assumes two occurrence rates:
  - 0.43% (full sample).
  - 0.24% (low mass *Kepler,* 0.568–0.876 $M_\odot$).

⇒ Expect 4 planets for full, 2.2 planets for low mass.



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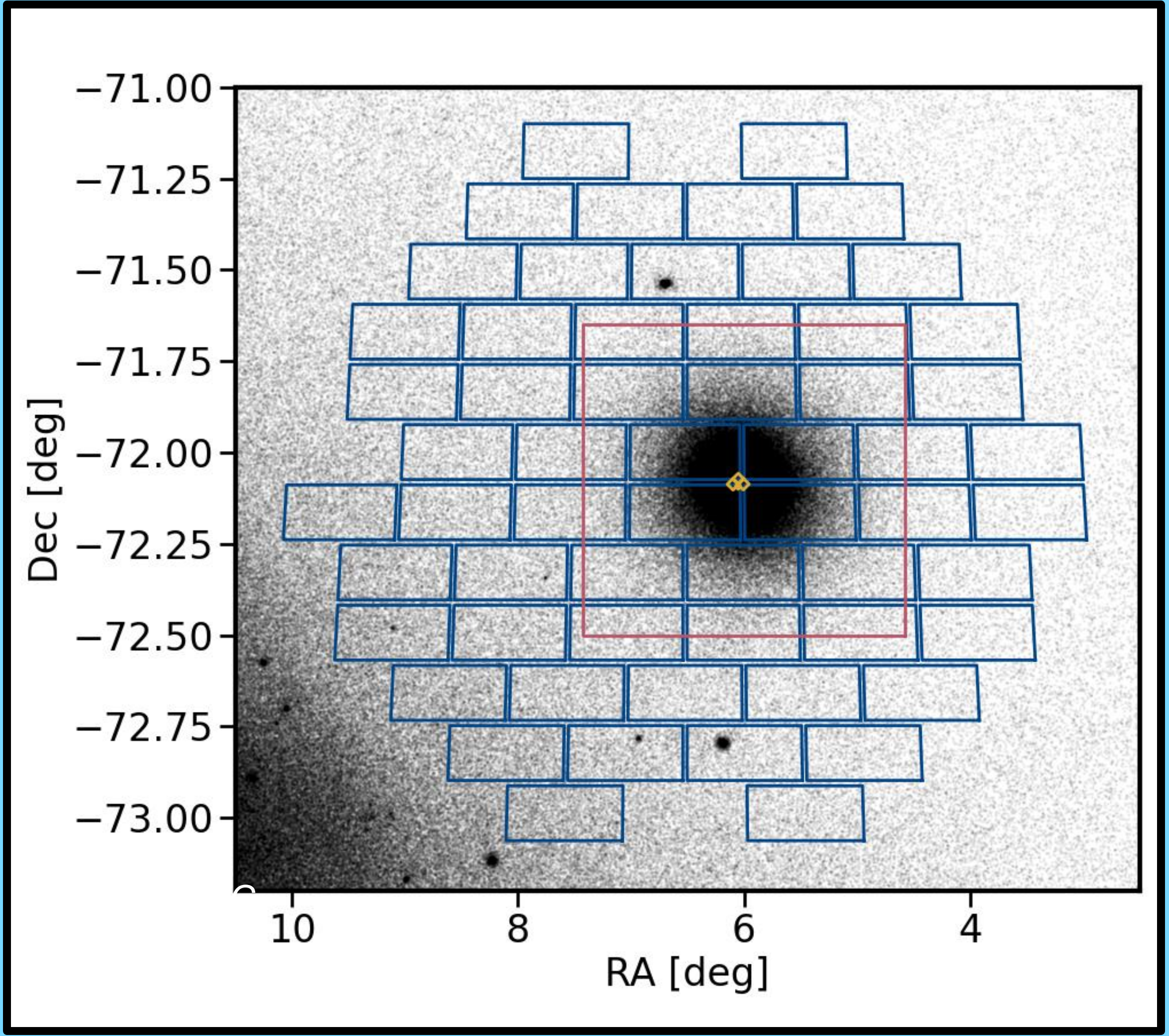
# MISHAPS: The Multiband Image Survey for High-Alpha PlanetS

- Performed with the Dark Energy Camera (DECam) at CTIO.
- Goal of measuring occurrence rates in different [α/Fe] population.
- Multiple filters used for false positive rejection.



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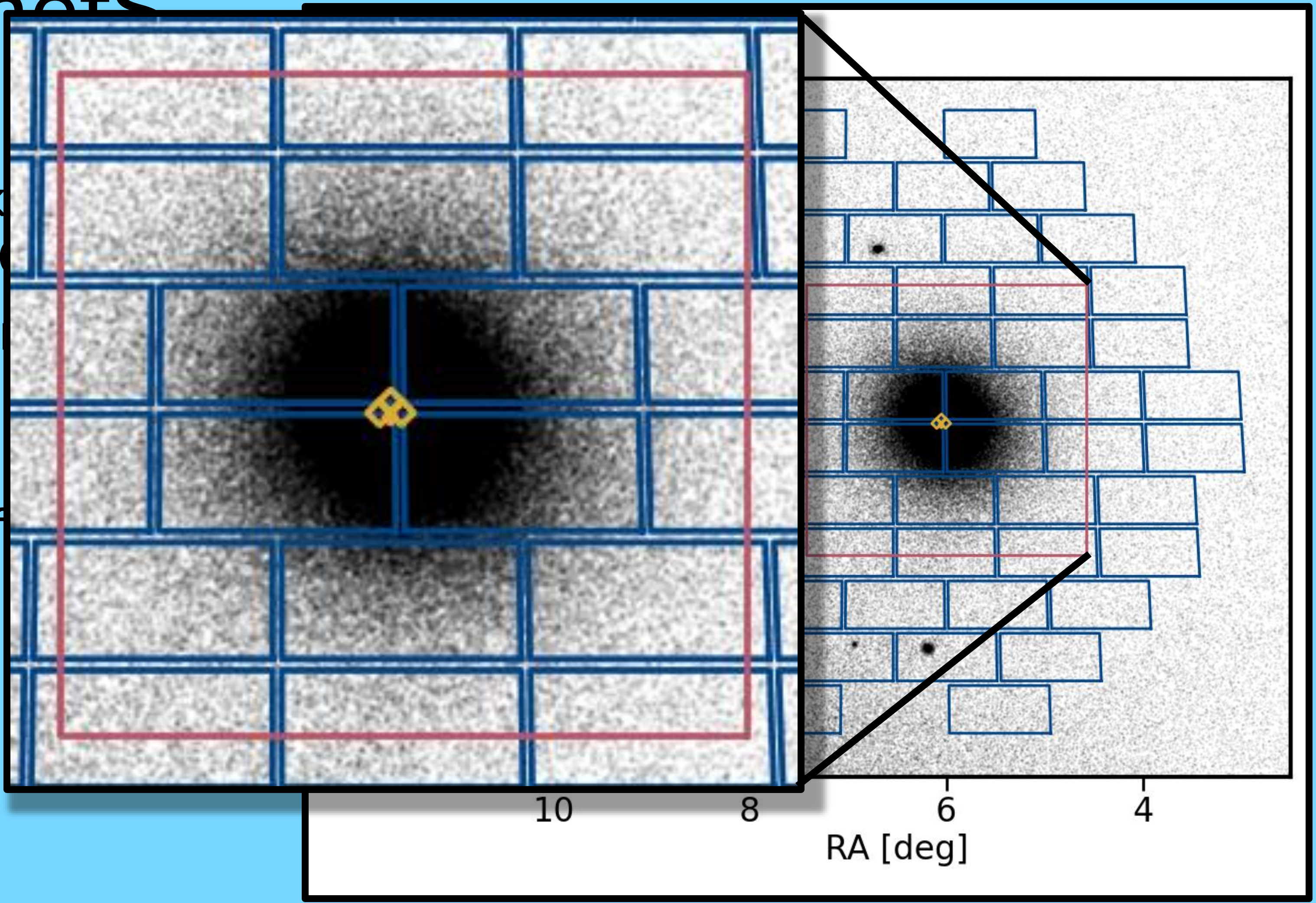
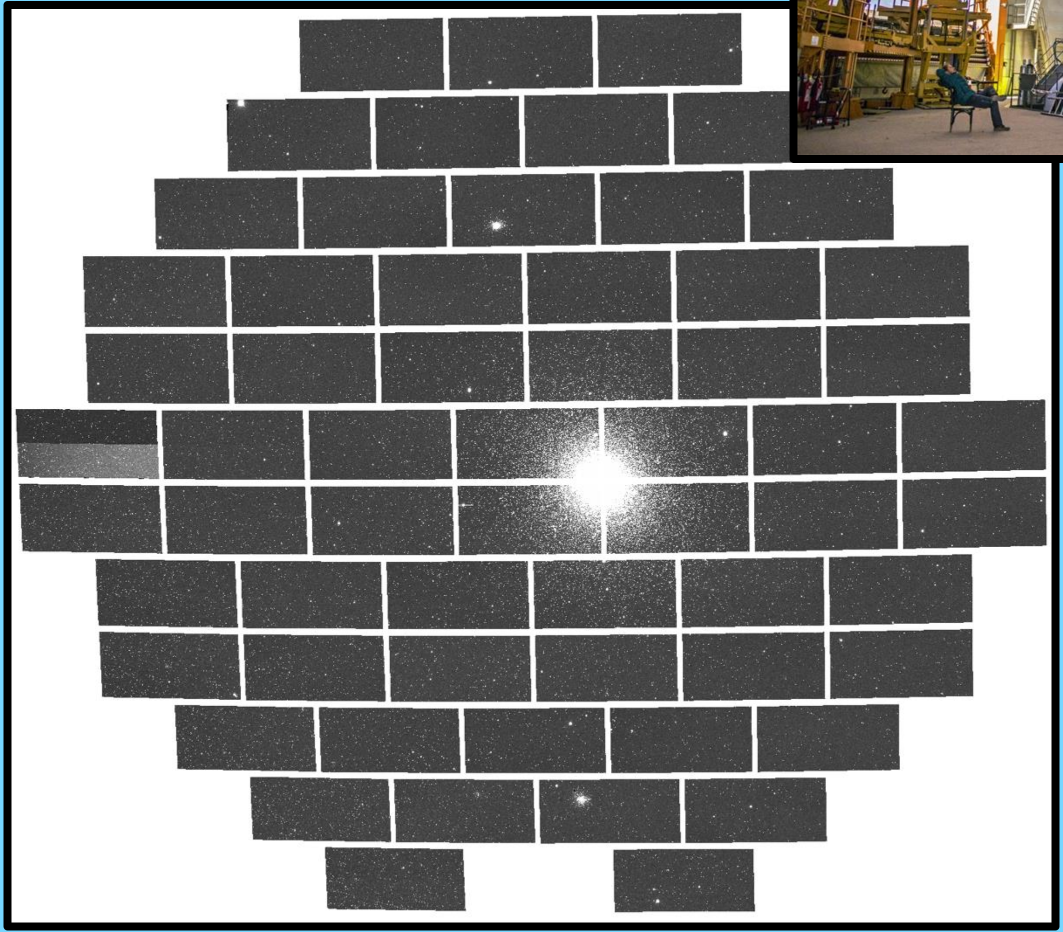


# 47 Tuc Observations

|  | 47 Tuc |
|---|---|
| **[Fe/H]*** | -0.78 |
| **[α/Fe]*** | 0.3 |
| **Hours Observed** | 126 |

**Values from Forbes 2010, Cordero 2014,*
*& Pilachowski 2010*



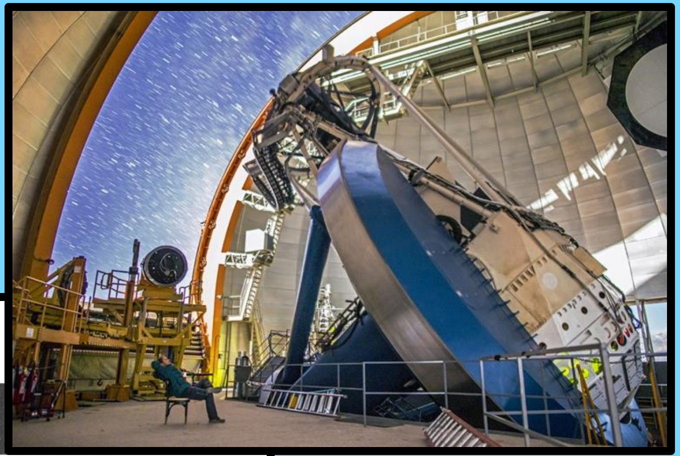


*Image: DES*

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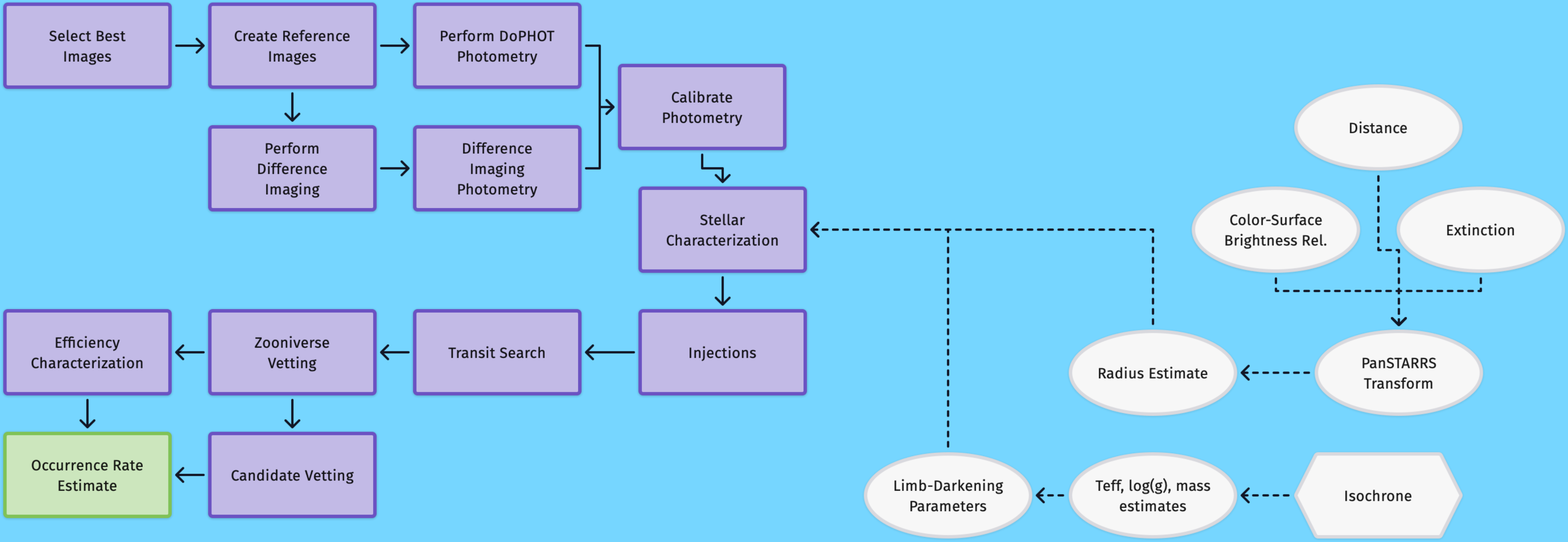

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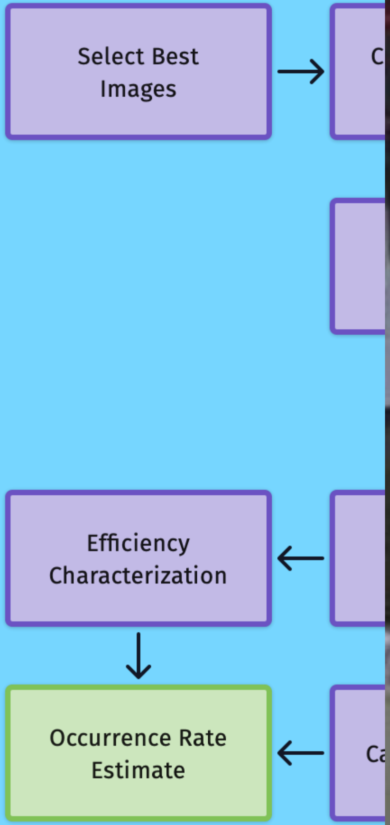

Select Best Images
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Efficiency Characterization
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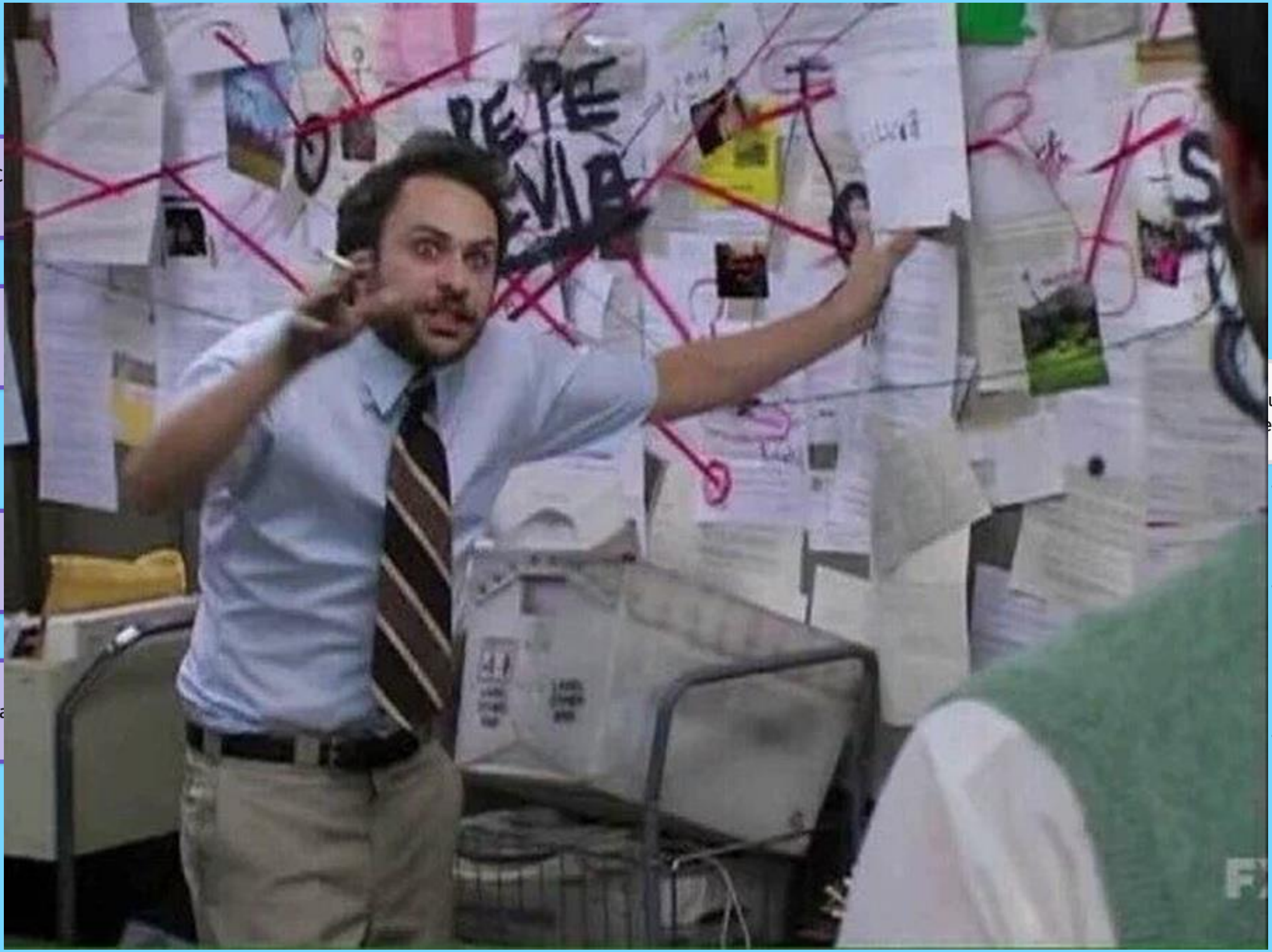

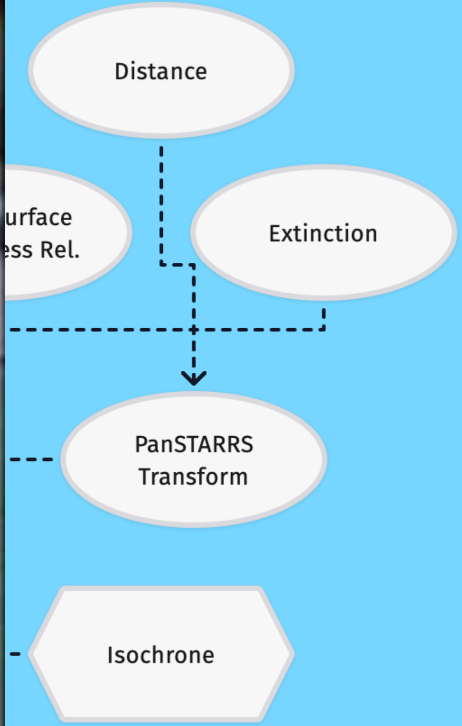

Distance
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ess Rel.
Extinction
PanSTARRS Transform
Isochrone

# The MISHAPS Pipeline

## Process Images

- Create Reference Images
- Perform Difference Imaging

## Calibrate Photometry

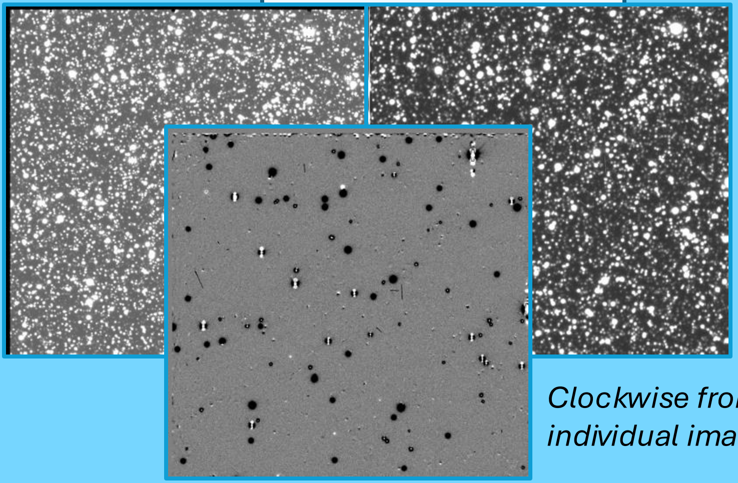
- De-trend with Vartools

## Perform Transit Search

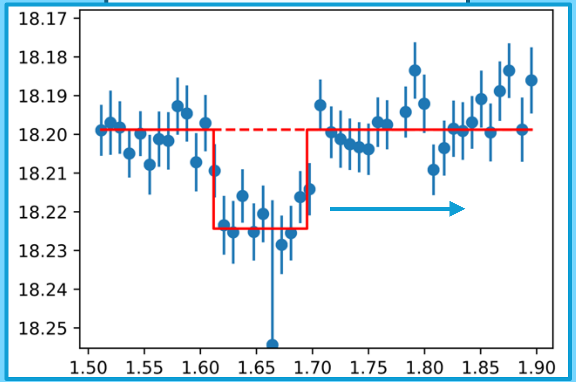
- Search over grid of transit centers and durations with sliding "Boxcar"

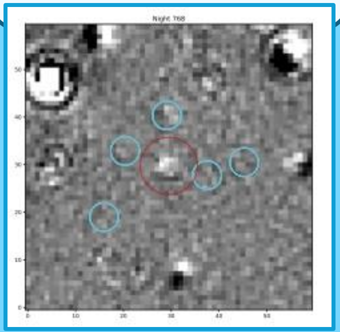
## Vet Candidates

- Lightcurves
- CMD
- Stacked Difference Images
- Periodograms & Folded Lightcurves



*Clockwise from top left: reference image, individual image, difference image*





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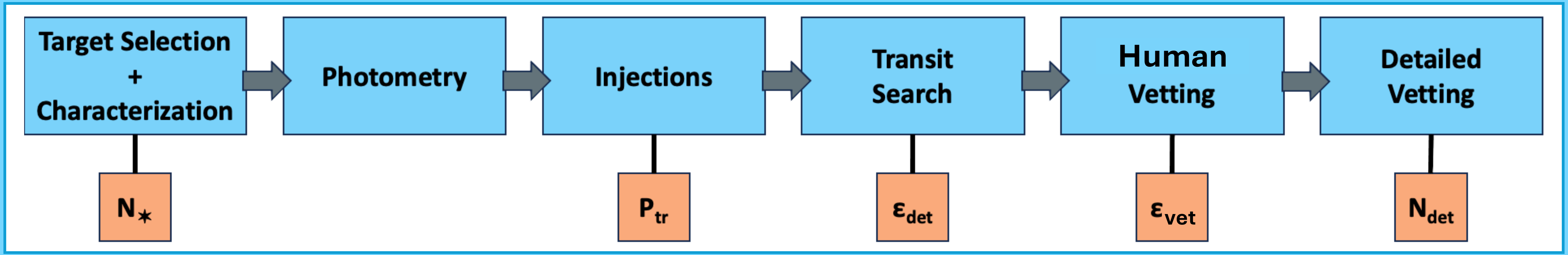
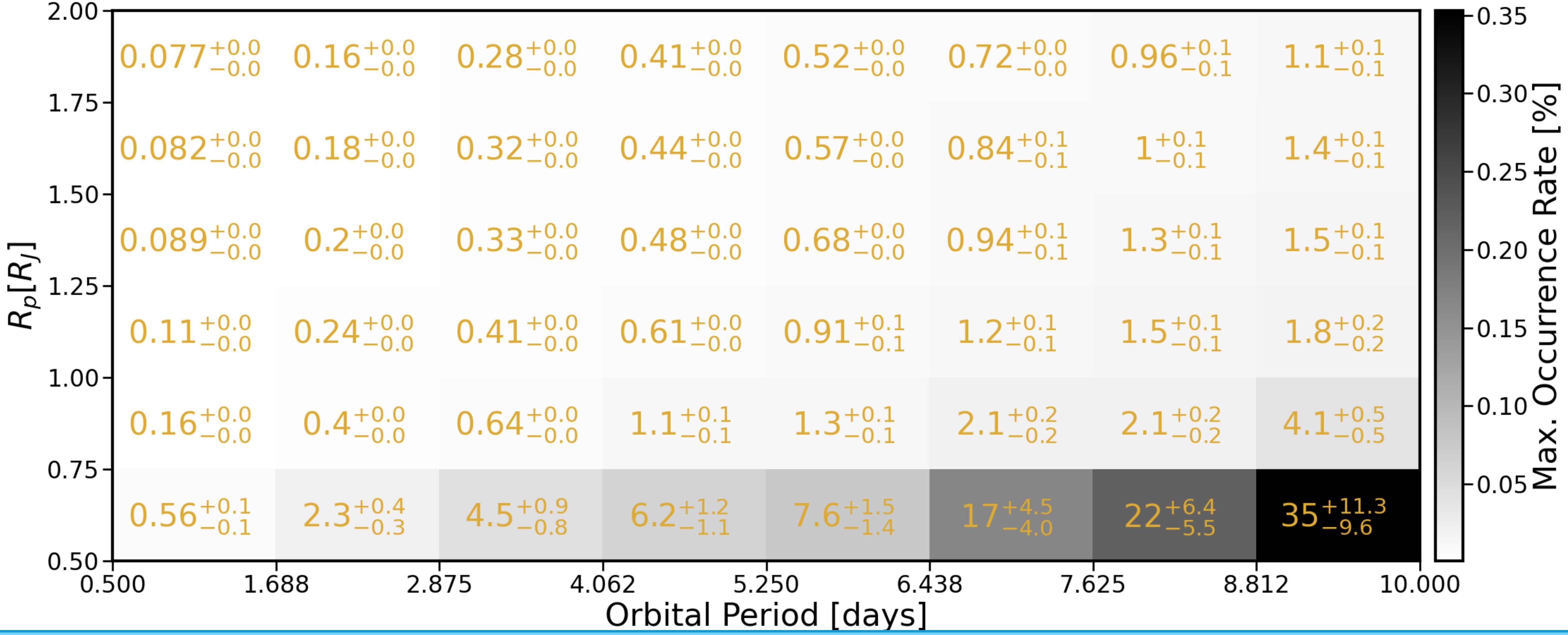
# Occurrence Rate and Limits

$$f_{HJ} = \frac{N_{det}}{\varepsilon_{det} P_{tr} N_{*}} \Rightarrow Occurrence\ rate = \frac{Number\ of\ planets\ detected}{Detection\ Efficiency\ x\ Transit\ Probability\ x\ Number\ of\ Stars}$$



95% confidence ⇒ up to 3 planets could be present while we still observe none.

# Occurrence Rate Limit



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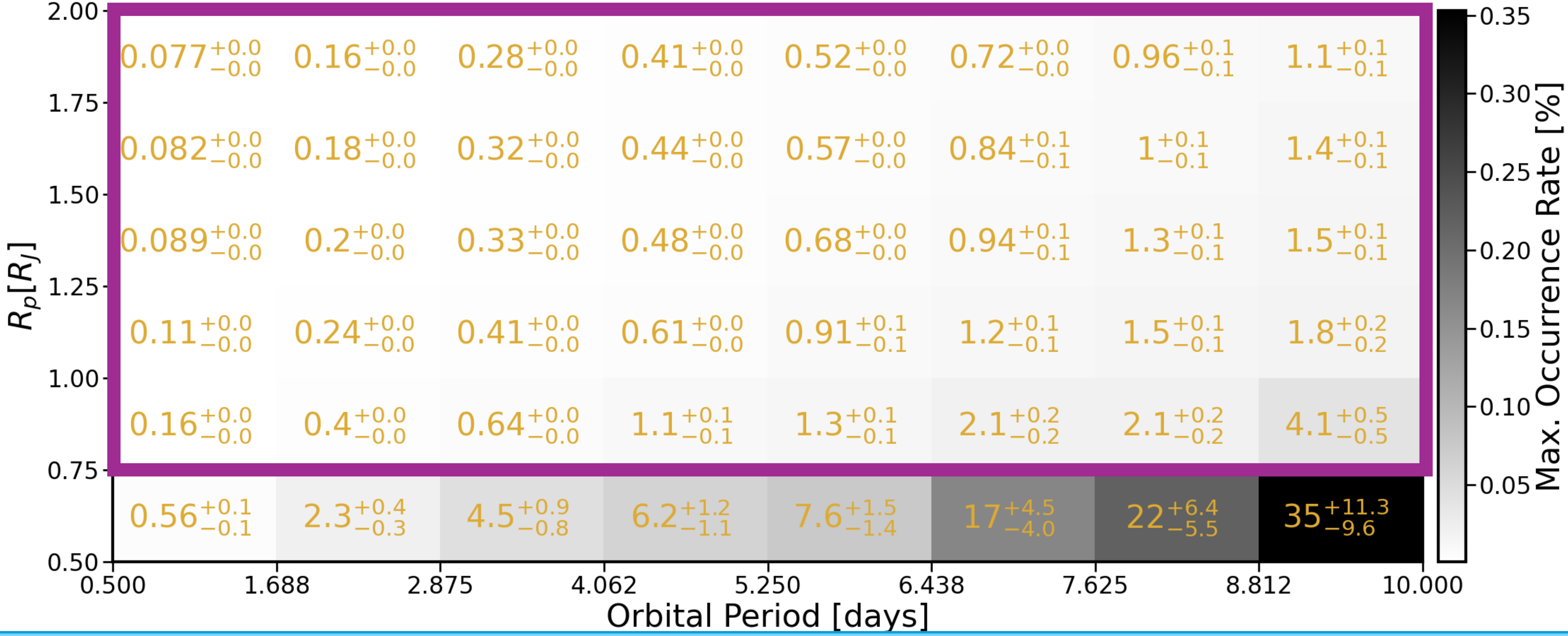
# Occurrence Rate Limit

**$f_{HJ} < 0.43\%$**



| | | | | | | | |
|---|---|---|---|---|---|---|---|
| $0.077^{+0.0}_{-0.0}$ | $0.16^{+0.0}_{-0.0}$ | $0.28^{+0.0}_{-0.0}$ | $0.41^{+0.0}_{-0.0}$ | $0.52^{+0.0}_{-0.0}$ | $0.72^{+0.0}_{-0.0}$ | $0.96^{+0.1}_{-0.1}$ | $1.1^{+0.1}_{-0.1}$ |
| $0.082^{+0.0}_{-0.0}$ | $0.18^{+0.0}_{-0.0}$ | $0.32^{+0.0}_{-0.0}$ | $0.44^{+0.0}_{-0.0}$ | $0.57^{+0.0}_{-0.0}$ | $0.84^{+0.1}_{-0.1}$ | $1^{+0.1}_{-0.1}$ | $1.4^{+0.1}_{-0.1}$ |
| $0.089^{+0.0}_{-0.0}$ | $0.2^{+0.0}_{-0.0}$ | $0.33^{+0.0}_{-0.0}$ | $0.48^{+0.0}_{-0.0}$ | $0.68^{+0.0}_{-0.0}$ | $0.94^{+0.1}_{-0.1}$ | $1.3^{+0.1}_{-0.1}$ | $1.5^{+0.1}_{-0.1}$ |
| $0.11^{+0.0}_{-0.0}$ | $0.24^{+0.0}_{-0.0}$ | $0.41^{+0.0}_{-0.0}$ | $0.61^{+0.0}_{-0.0}$ | $0.91^{+0.1}_{-0.1}$ | $1.2^{+0.1}_{-0.1}$ | $1.5^{+0.1}_{-0.1}$ | $1.8^{+0.2}_{-0.2}$ |
| $0.16^{+0.0}_{-0.0}$ | $0.4^{+0.0}_{-0.0}$ | $0.64^{+0.0}_{-0.0}$ | $1.1^{+0.1}_{-0.1}$ | $1.3^{+0.1}_{-0.1}$ | $2.1^{+0.2}_{-0.2}$ | $2.1^{+0.2}_{-0.2}$ | $4.1^{+0.5}_{-0.5}$ |
| $0.56^{+0.1}_{-0.1}$ | $2.3^{+0.4}_{-0.3}$ | $4.5^{+0.9}_{-0.8}$ | $6.2^{+1.2}_{-1.1}$ | $7.6^{+1.5}_{-1.4}$ | $17^{+4.5}_{-4.0}$ | $22^{+6.4}_{-5.5}$ | $35^{+11.3}_{-9.6}$ |

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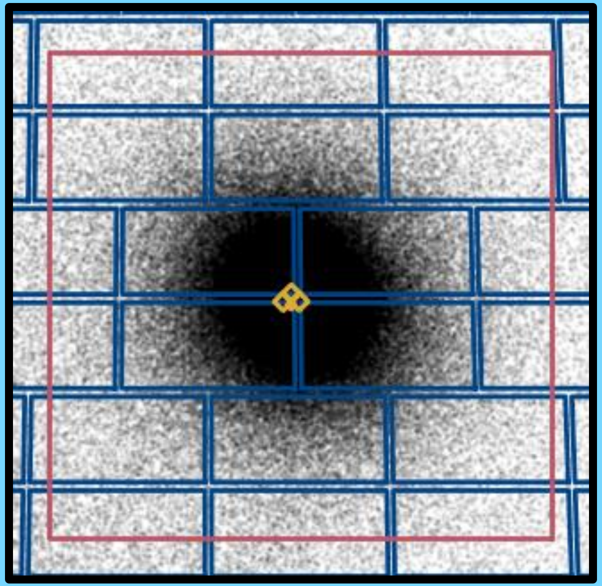
# Occurrence Rate Comparisons

We can combine our data with Gilliland et al., yielding $f_{HJ} < 0.11\%$, the **strongest constraint** on 47 Tuc's HJ population so far.



# Occurrence Rate Comparisons

We can combine our data with Gilliland et al., yielding **$f_{HJ} < 0.11\%$**, the **strongest constraint** on 47 Tuc's HJ population so far.

This rate also rules out Masuda & Winn's estimated low-mass *Kepler* host rate of 0.24%.

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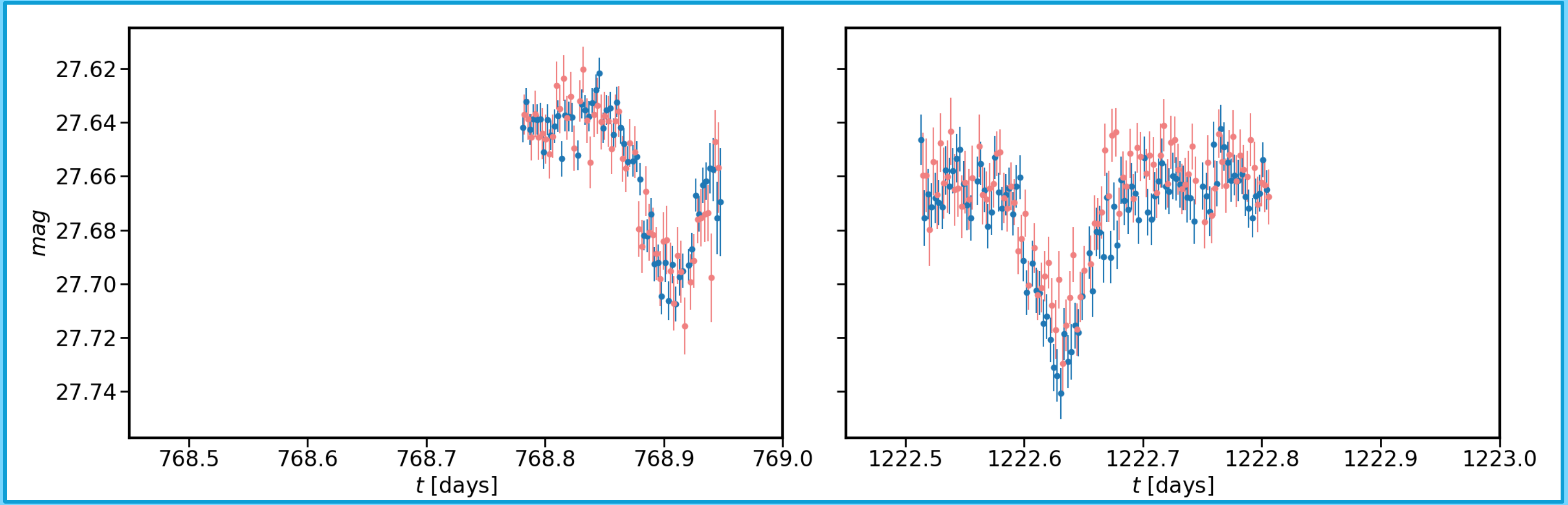
# A planet candidate?

The lightcurve itself looks reasonable…



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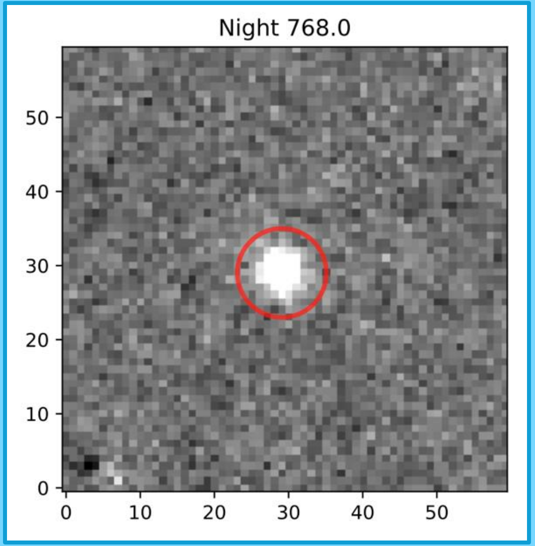
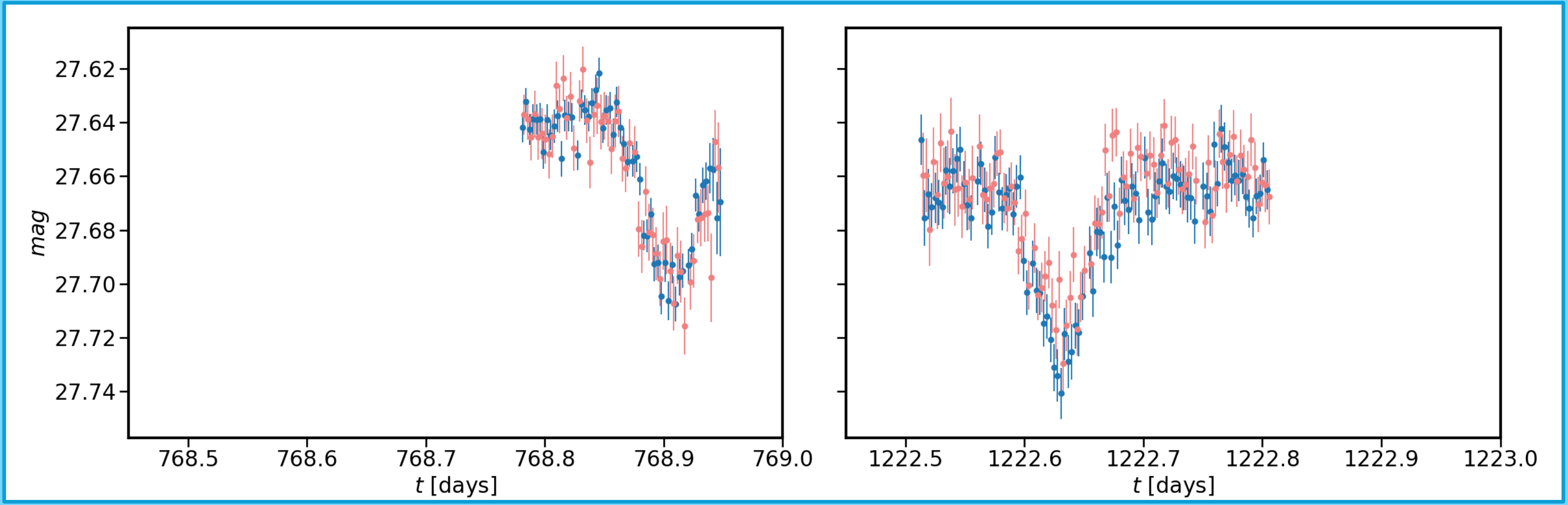
# A planet candidate?

The lightcurve itself looks reasonable…
In-transit image stacking doesn't indicate any centroid shifts…





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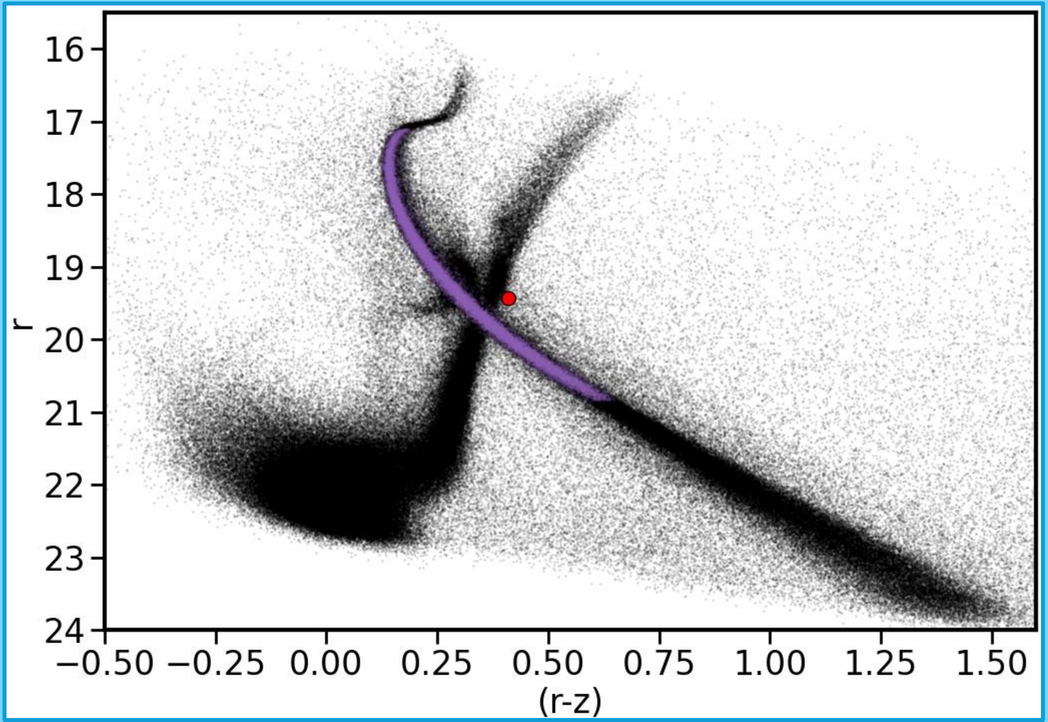
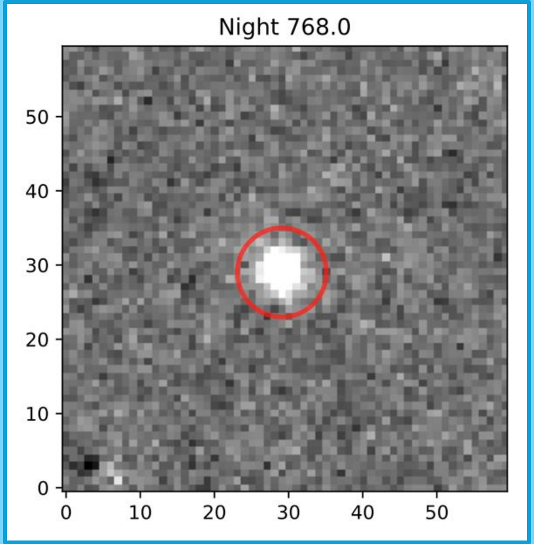
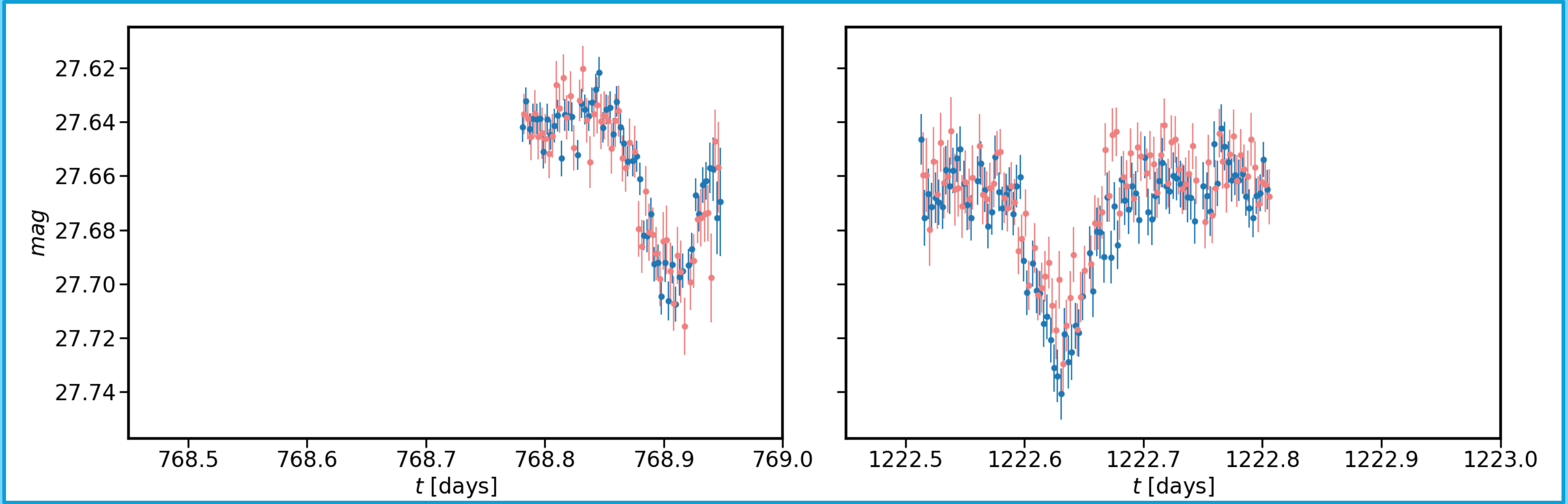
# Another eclipsing binary…

The lightcurve itself looks reasonable…
In-transit image stacking doesn't indicate any centroid shifts…

But it's on 47 Tuc's binary sequence :-(







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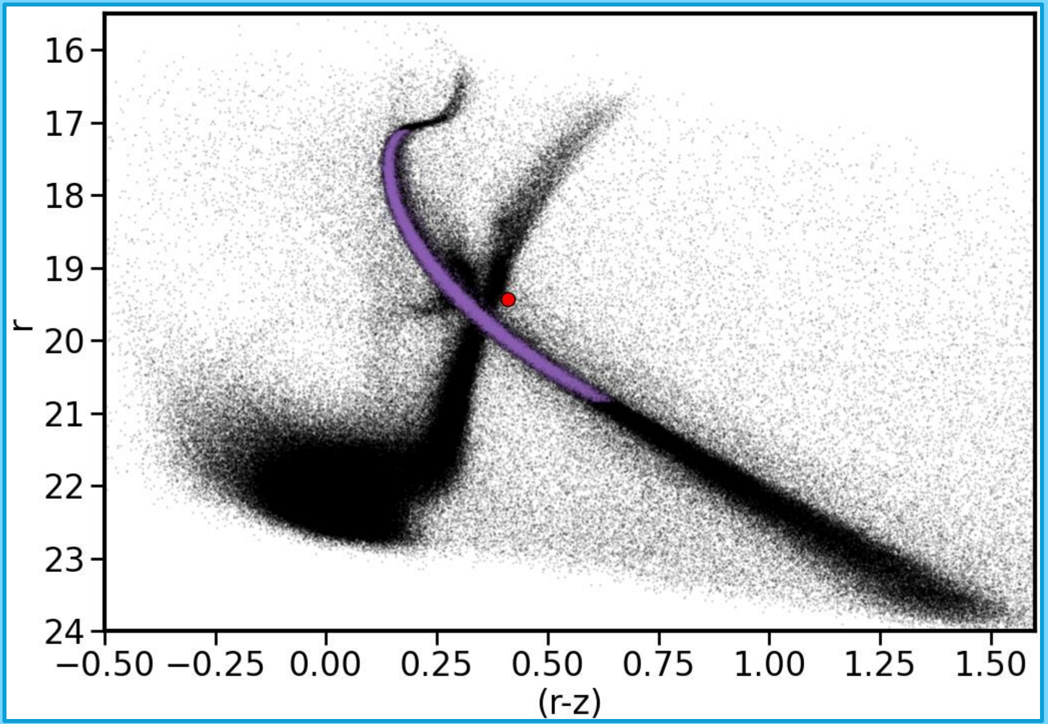
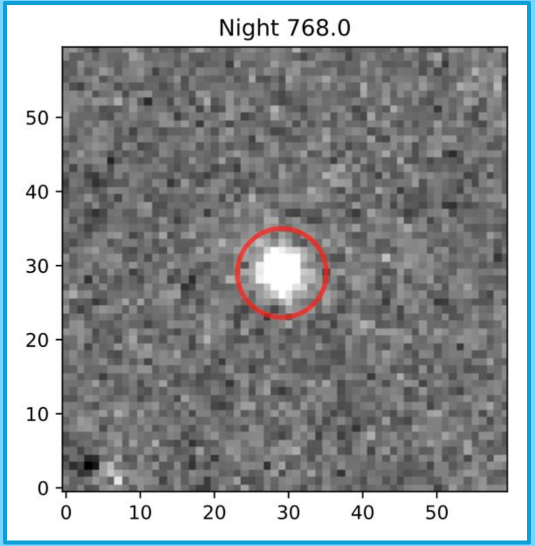
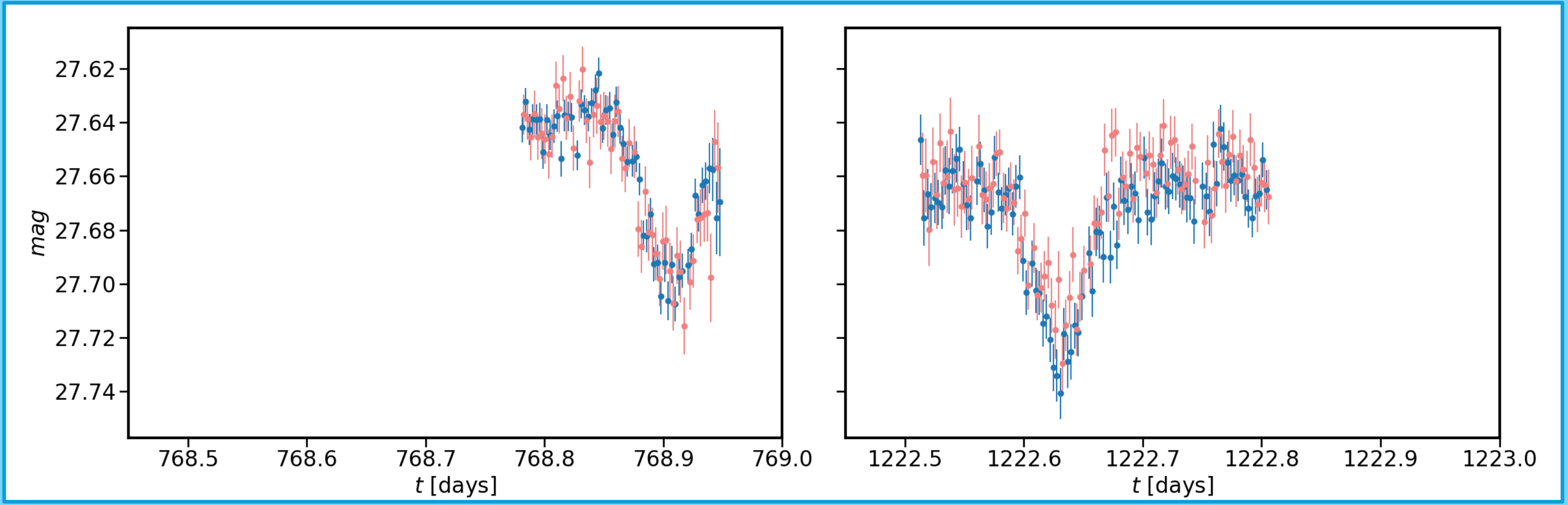
# New eclipsing binary?

It’s not included in the Weldrake 2004 or the OGLE catalog, but we still need to investigate more.







# Summary

1. When combined with G00, we place the strongest constraint on 47 Tuc's $f_{HJ}$ so far ($f_{HJ} < 0.11\%$).
2. We also rule out an $f_{HJ}$ similar to the *Kepler* field rate for the first time.
3. We still find no planets in 47 Tuc, but there is interesting science to be done with our data, and with the other MISHAPS fields.

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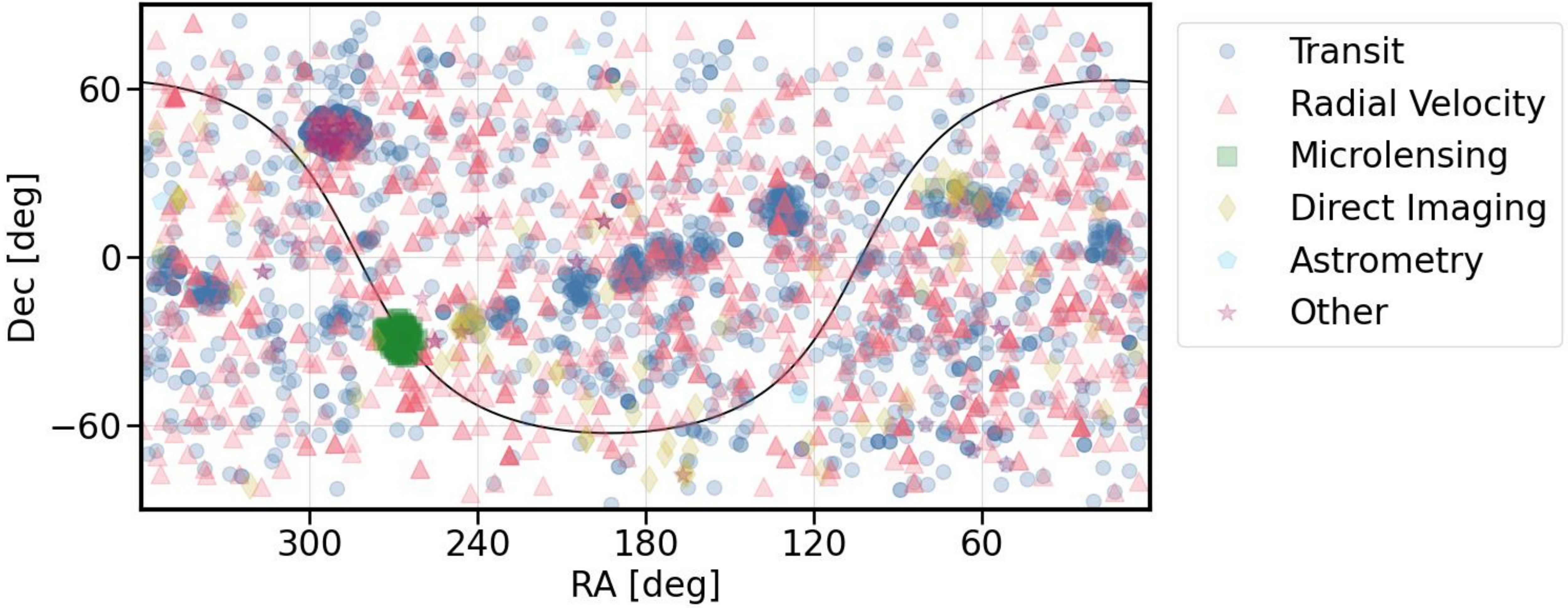
# Back-up



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# Occurrence Rate Comparisons

We can combine our data with Gilliland et al., yielding **$f_{HJ} < 0.11\%$**, the **strongest constraint** on 47 Tuc's HJ population so far.

This rate also rules out Masuda & Winn's estimated low-mass *Kepler* host rate of 0.24%.

But how does that compare to our expectations for the [Fe/H] and [α/Fe]-dependent scenarios?

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# Occurrence Rate Comparisons

We scale the low-mass *Kepler* occurrence rate from MW17 to the average abundances of 47 Tuc & the *Kepler* field, Johnson et al. 2010

$$f_{HJ,47\,Tuc} = f_{HJ,LMK}\,\frac{10^{1.2[{}^{Fe}/_{H}]47T}}{10^{1.2[{}^{Fe}/_{H}]LMK}}$$

Using [Fe/H] gives $f_{HJ} \approx 0.028\%$

Using [α/H] = [Fe/H] + [α/Fe] gives $f_{HJ} \approx 0.055\%$

Adding our stars from the central chip may allow us to reach the [α/H] range, but a different survey will be required to distinguish between the two scenarios.

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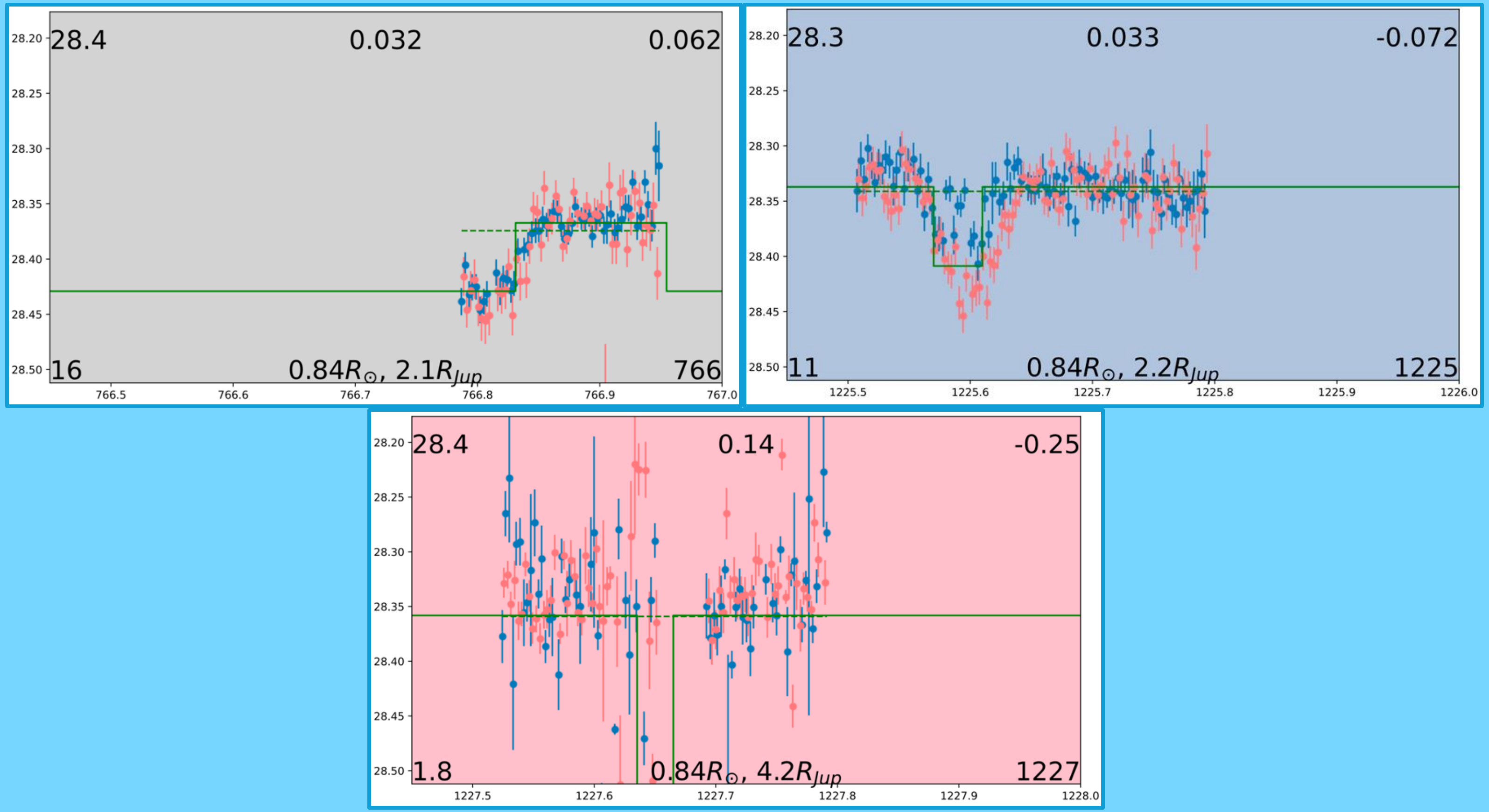
# Vetting

- Plot lightcurve



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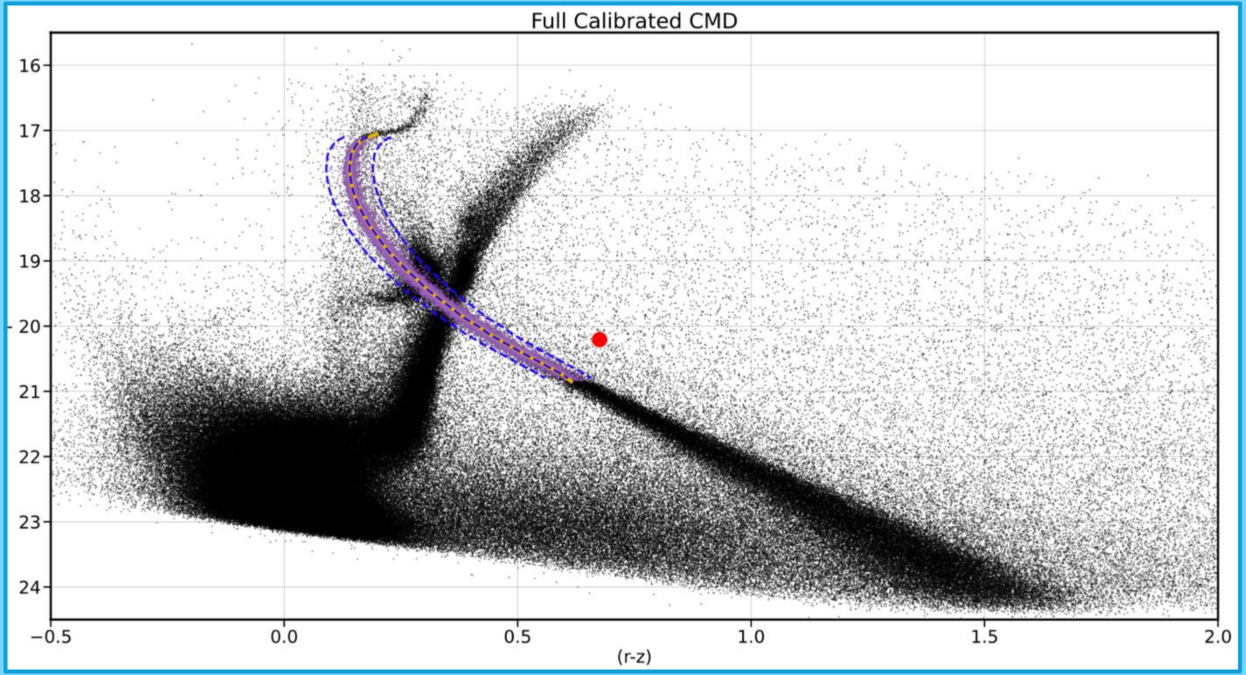
# Vetting

- Plot lightcurve
- Plot color-magnitude diagram



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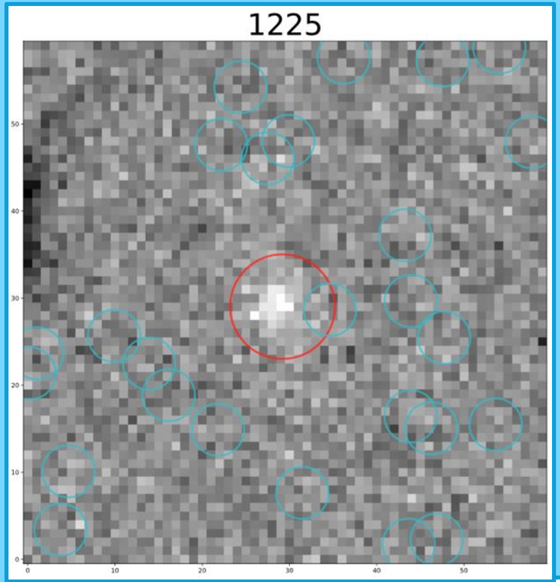
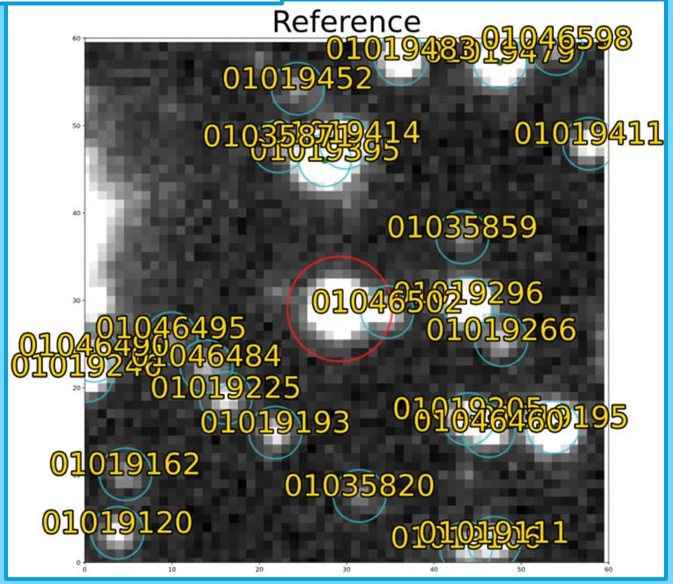
# Vetting

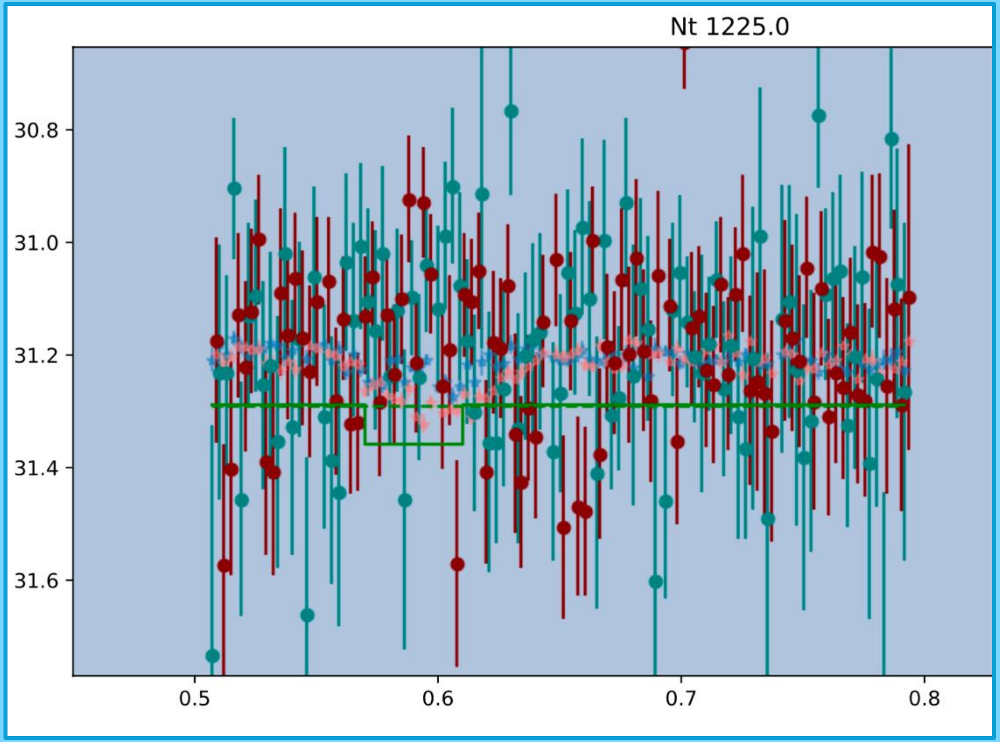
- Plot lightcurve
- Plot color-magnitude diagram
- Plot stacked in-transit images





# Vetting

- Plot lightcurve
- Plot color-magnitude diagram
- Plot stacked in-transit images
- Plot nearby lightcurves



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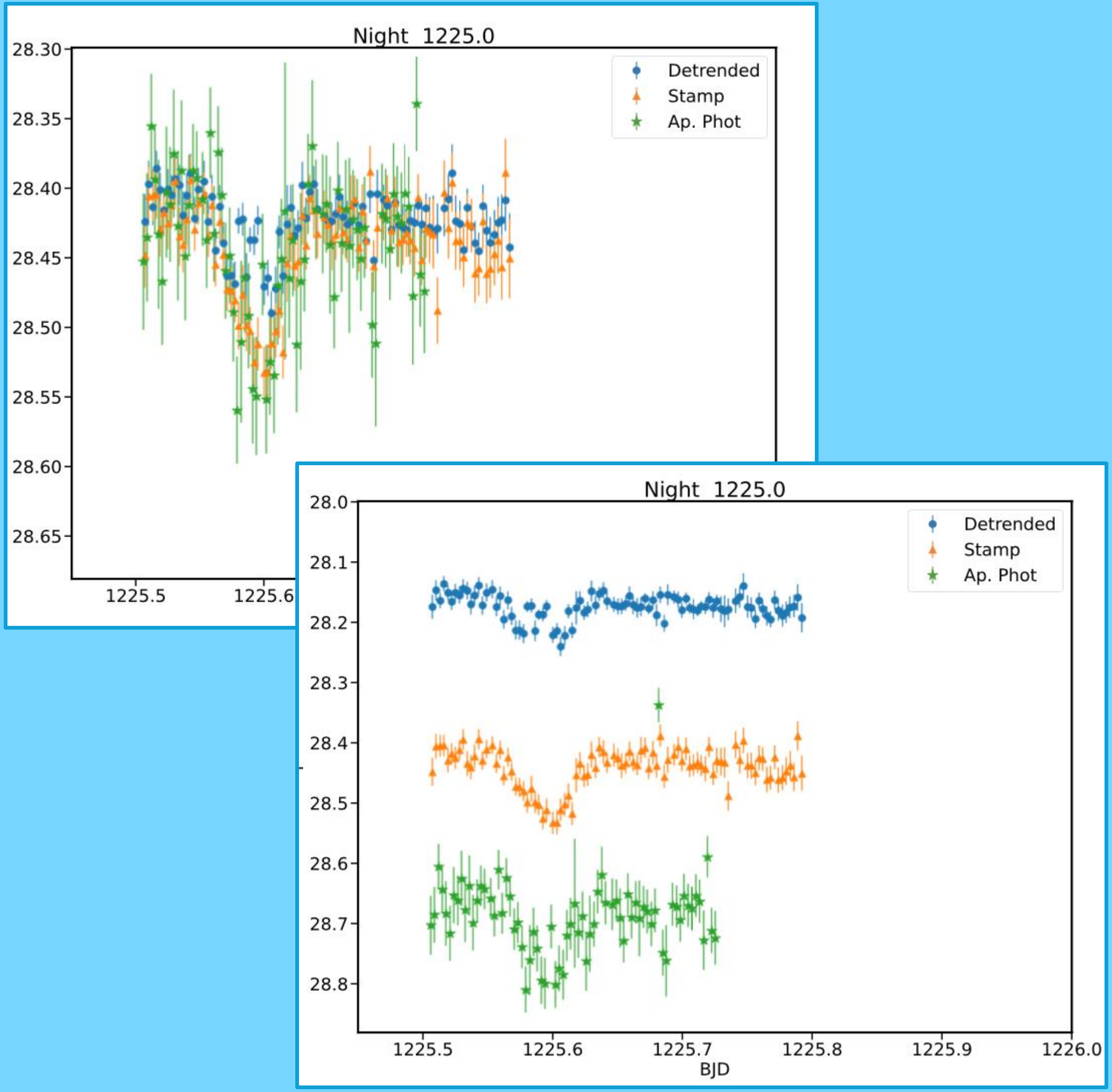
# Vetting

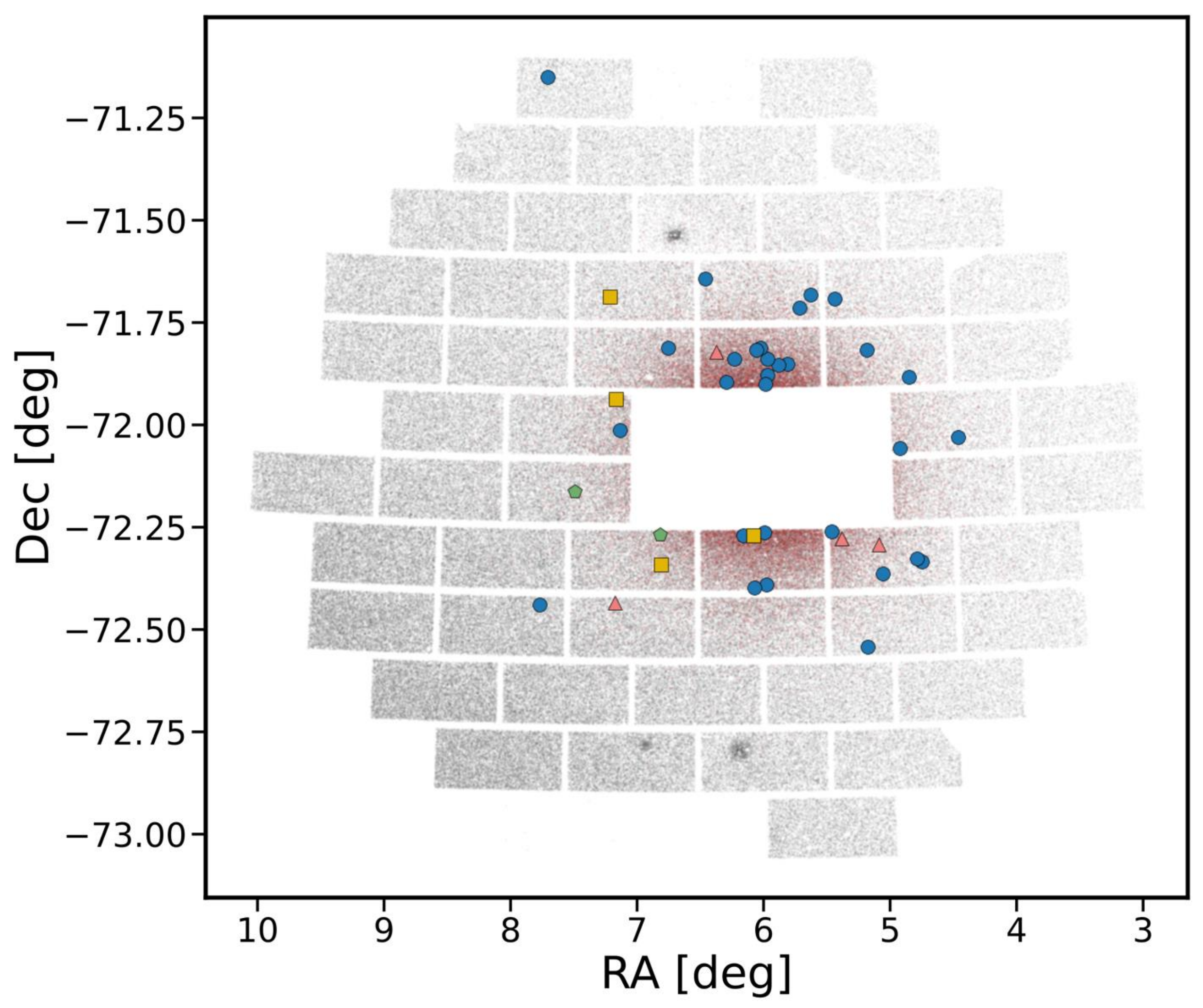
- Plot lightcurve
- Plot color-magnitude diagram
- Plot stacked in-transit images
- Plot nearby lightcurves
- Perform target-centered difference imaging and photometry



# Candidate Rejection

The initial Zooniverse vetting leaves us with 40 planet candidates.

Our in-depth vetting process allows us to reject all but 2 as eclipsing binaries and other false positives.



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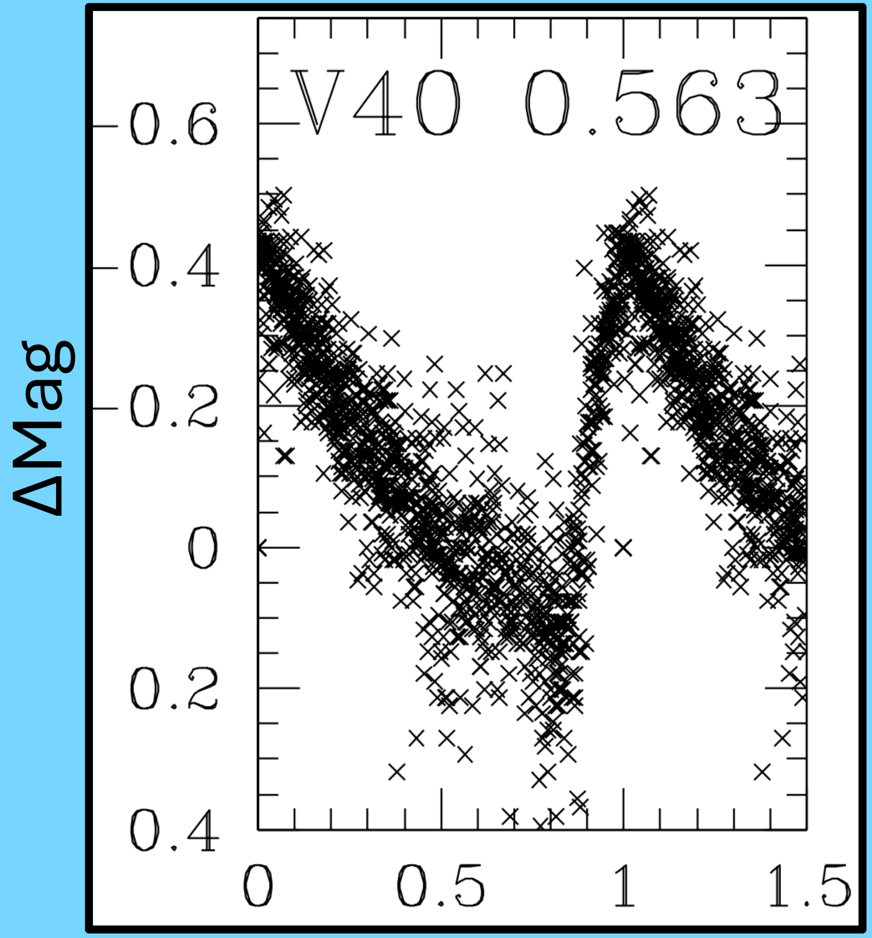
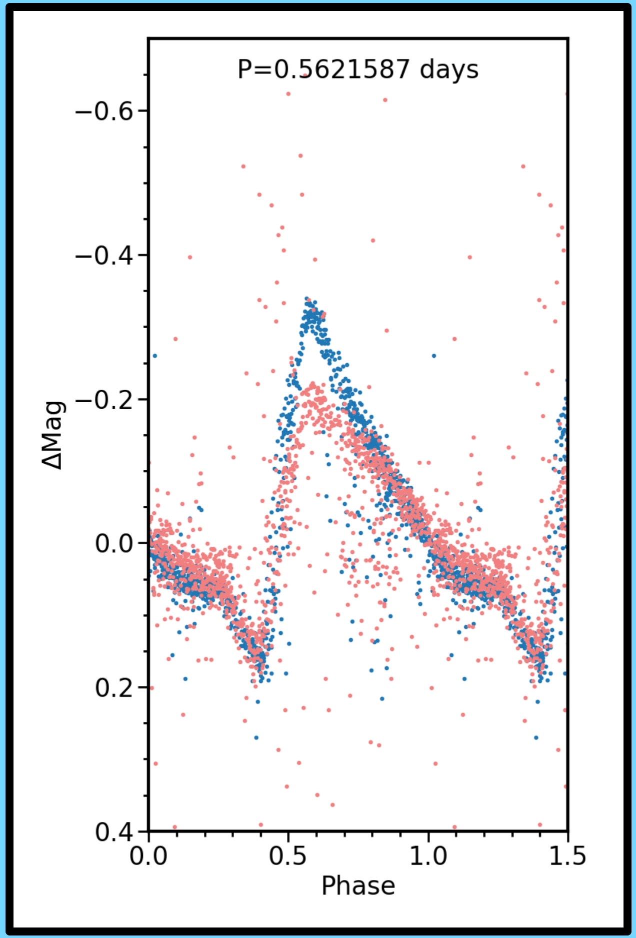
# Comparison Variable





*Left:*
*Weldrake et al., 2004*

*Right:*
*This work*

# Improvements

1. Add 3 more nights of data that can potentially be used to confirm/reject transit-like signals.
2. Improve difference imaging in core chips.
3. Improve target selection.
4. Improve transit search algorithm.

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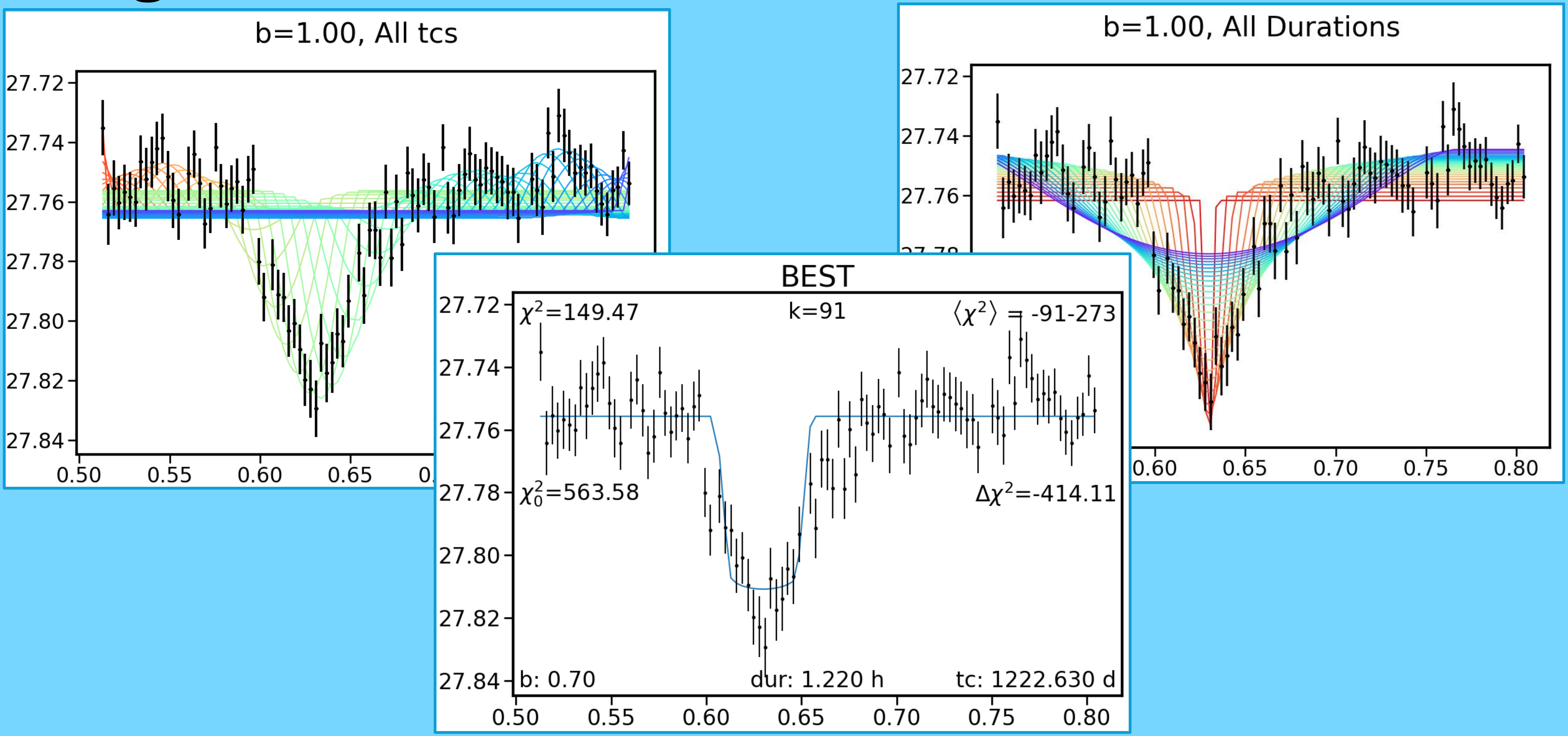
# Progress – Search Transit Models



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# Progress – New Color Cut

Extending our color selection from 20.8 to 22.0 increases our sample by ~9,400 stars.

Once the central chips have been added, together with the extended cut, our sample will increase by ~69,389 (87,499 total).

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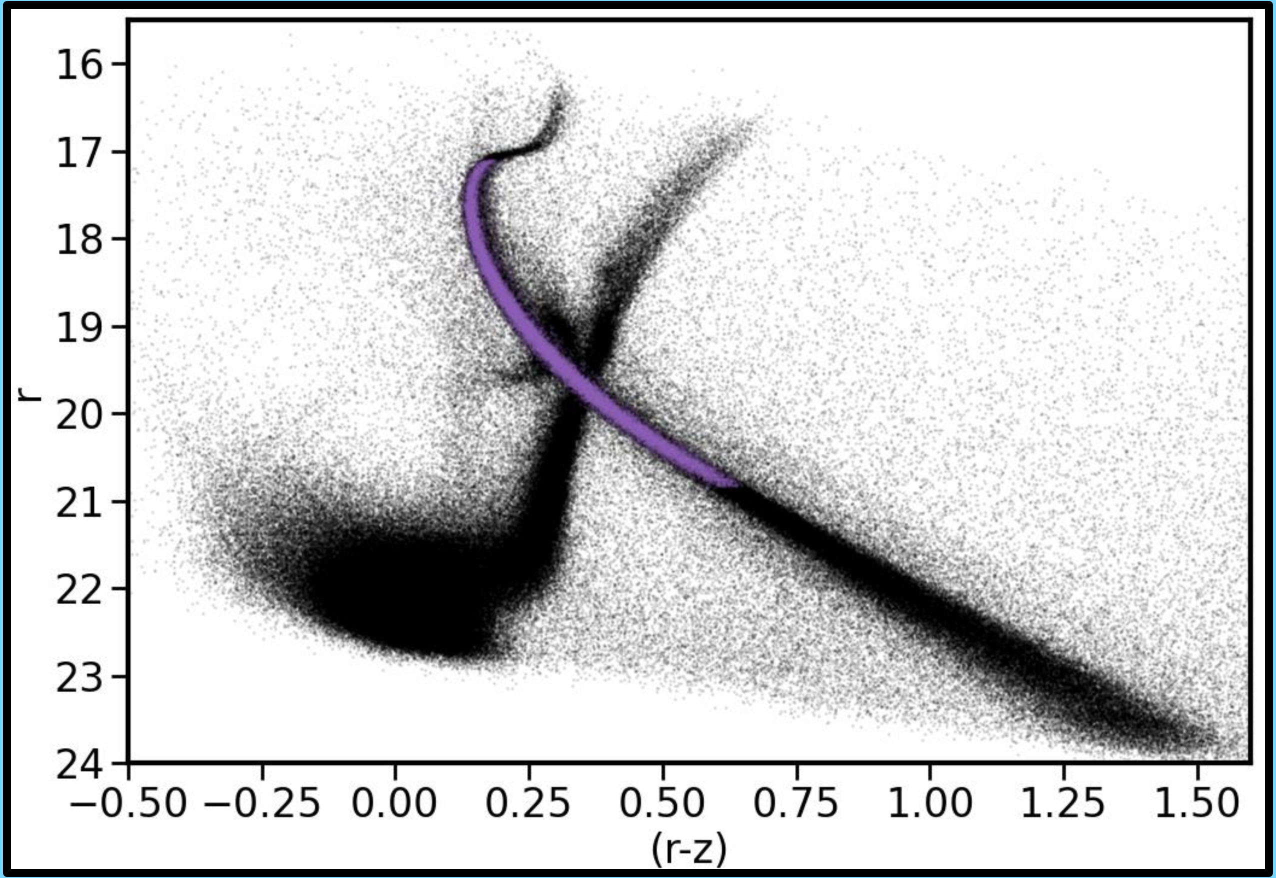
# Improvements

- Improve difference imaging in core chips.
- Improve target selection.
- Improve transit search algorithm.
- Add 4 more nights of data that can potentially be used to confirm transit-like signals.



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