Examining the Multiplicity of the Galactic Halo through Lick A.O., Speckle Imaging, and More!

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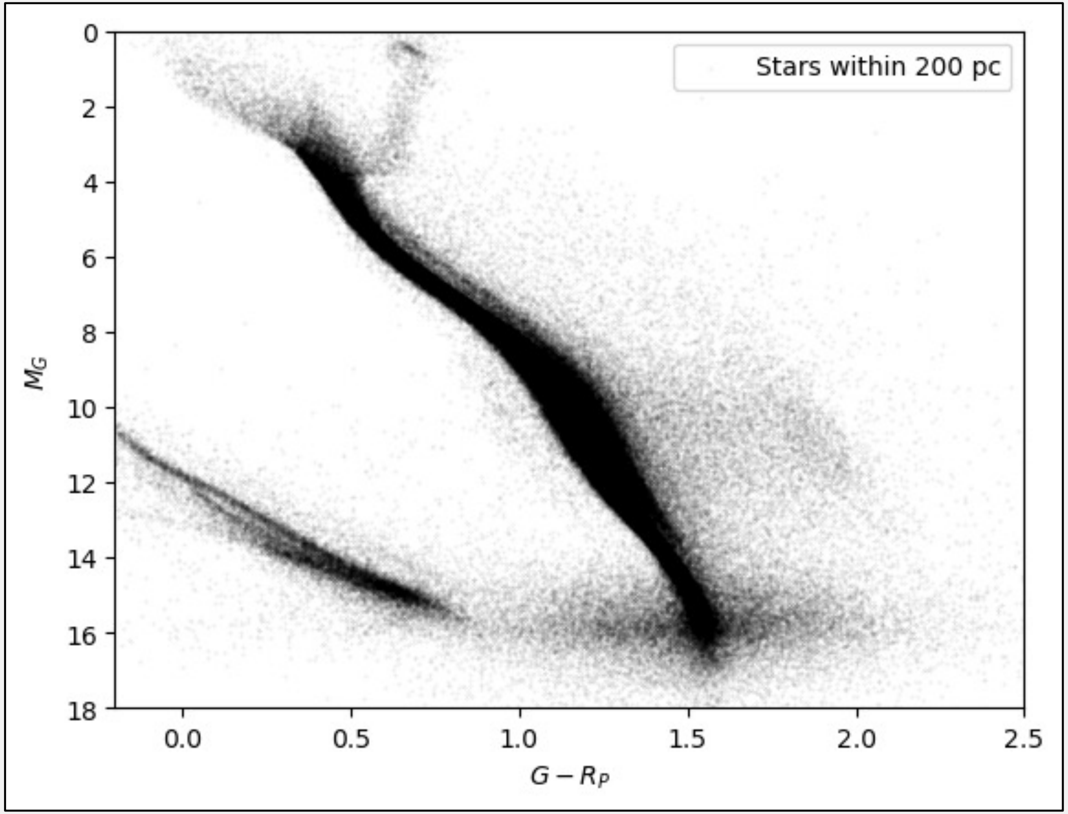
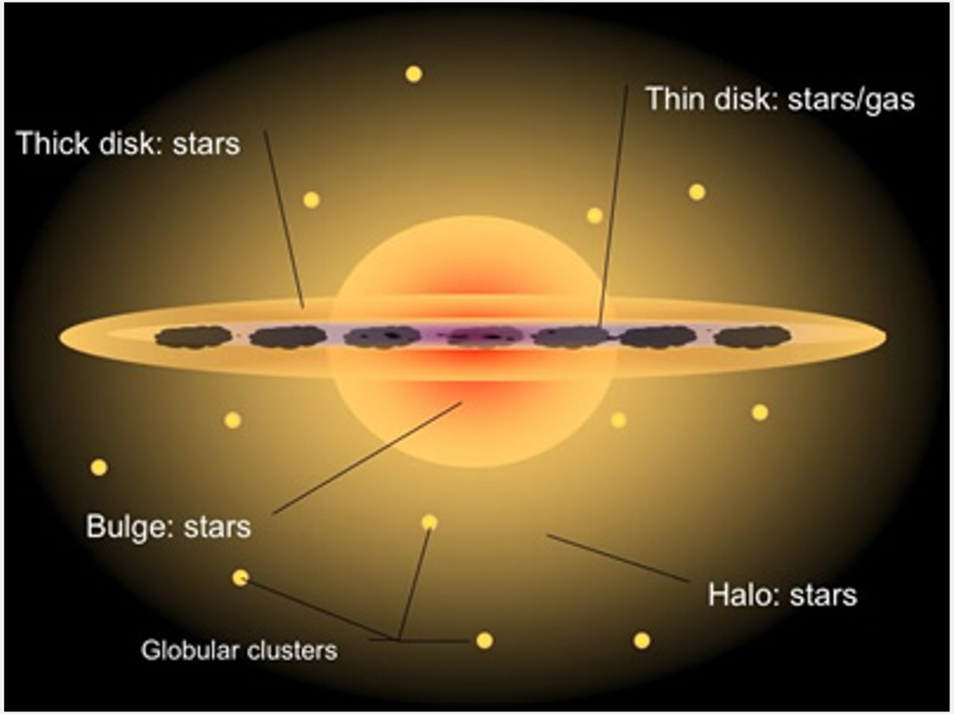
The Solar Neighborhood

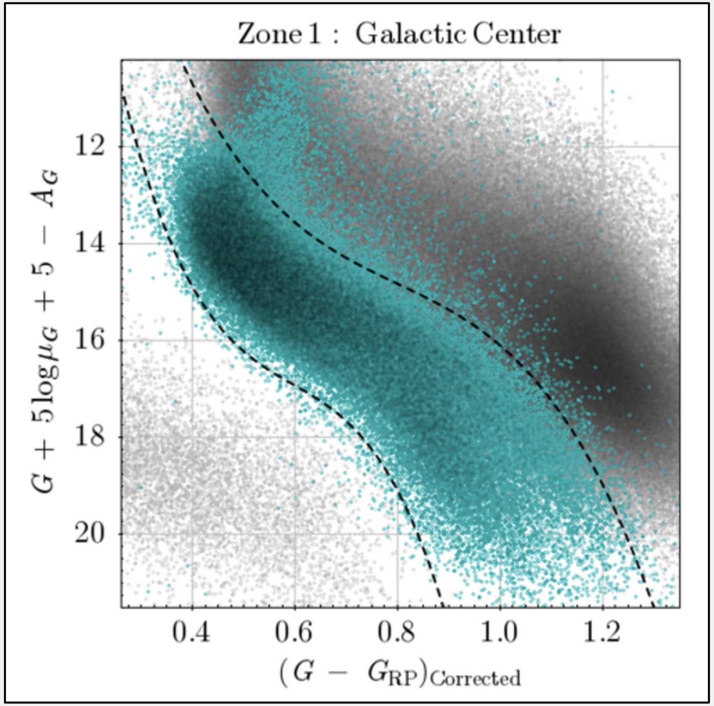


- 1,864,570 stars with proper motions larger than 20 mas/yr within 200 pc
- Large majority are low-mass stars

What is a Galactic Halo Star?



COSMOS - Swinburne University



Kim & Lépine 2022, Top left panel of Figure 2

Why should you care about Galactic Halo stars?

- From an Exoplanet perspective:
  - Exoplanets are supposed to be rare around them
    - Need metals to form planets and there are no planets
  - Boley et al. 2021, Yoshida et al. 2022
- From a dark matter perspective:
  - Using halo wide binaries to examine the separation distribution of these systems
    - Put constraints on dark matter candidates
    - Yoo et al. 2004

Period vs. Planet Radius	3.5 to 10 days	10 to 29 days	29 to 50 days
1.0 to 2.0 R_J	0.52%	2.96%	18.2%
	+0.01/-0.01%	$+0.18/-0.16\%$	+0.85/-1.99%
0.5 to 1.0 R_J	2.14%	27.7%	*undefined*
	+0.02/-0.02%	$+10.4/-4.63\%$	
0.1 to 0.5 R_J	*undefined*	*undefined*	*undefined*

Upper limits on Planet Occurrence around Galactic halo stars of potentially extragalactic origin. Table 1 from Yoshida et al. 2022

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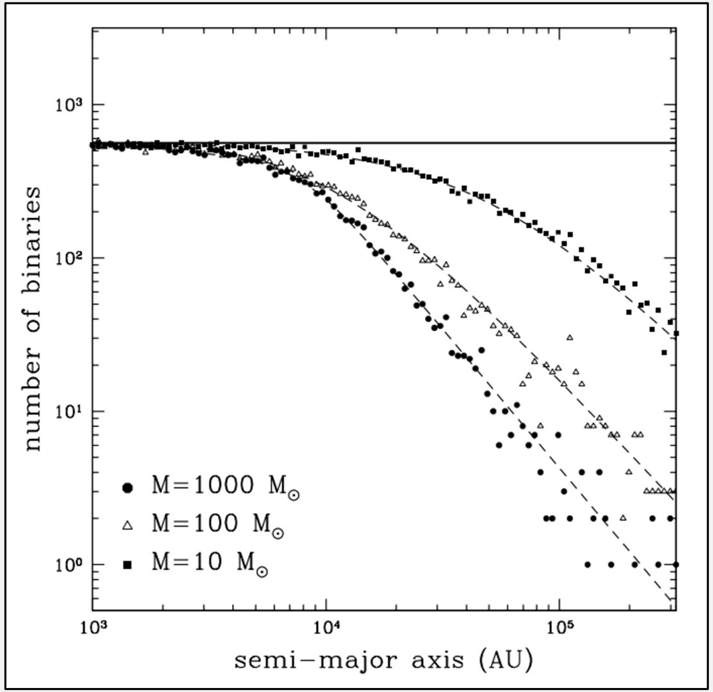
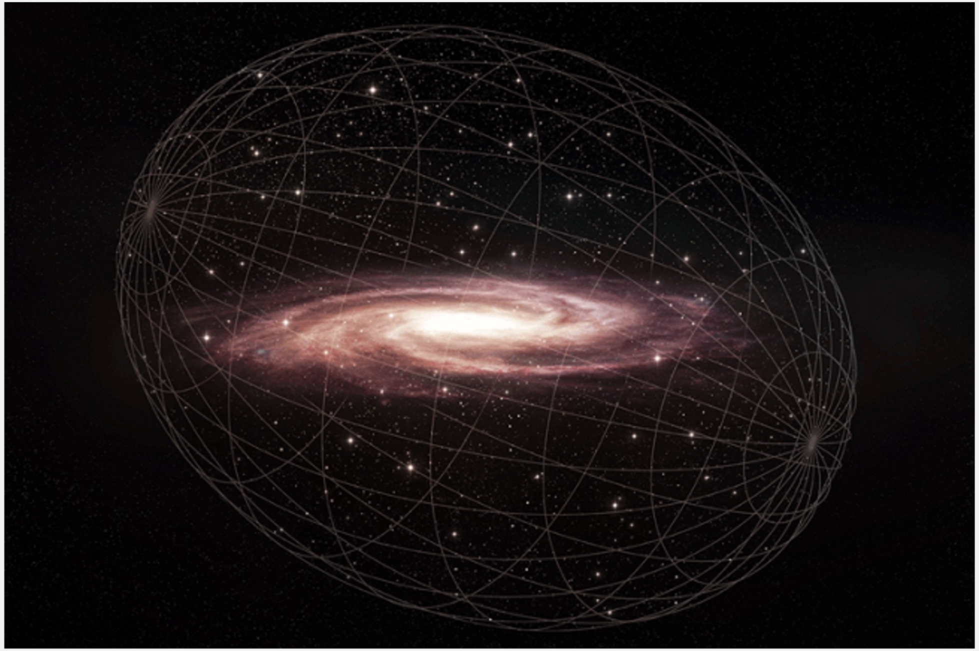


Yoo et al. 2004

Why should you care about Galactic Halo stars?

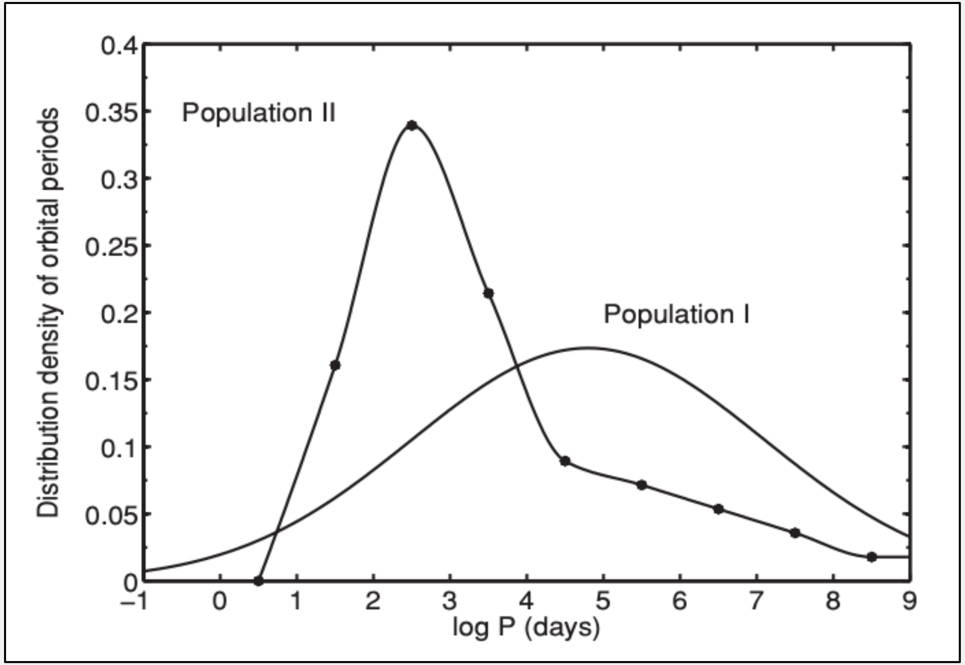


Melissa Weiss/ Center for Astrophysics Harvard & Smithsonian.

- Contains some of the oldest stars we know of
  - Tracer of dynamical history of the Galaxy
  - Han et al. 2022
- Contains some of the most metal-poor stars we know of
  - Tracer of chemical history of the Galaxy
  - Lépine et al. 2007

Why should you care about Galactic Halo stars?

- From a star formation standpoint:
  - They are still a puzzle
  - Even though our understanding of star formation as a function of metallicity is improving
    - Rastegaev 2010
    - Moe et al. 2019
- To better understand the formation of halo stars, we need more precisely determined parameters of the current halo population.



Rastegaev 2010

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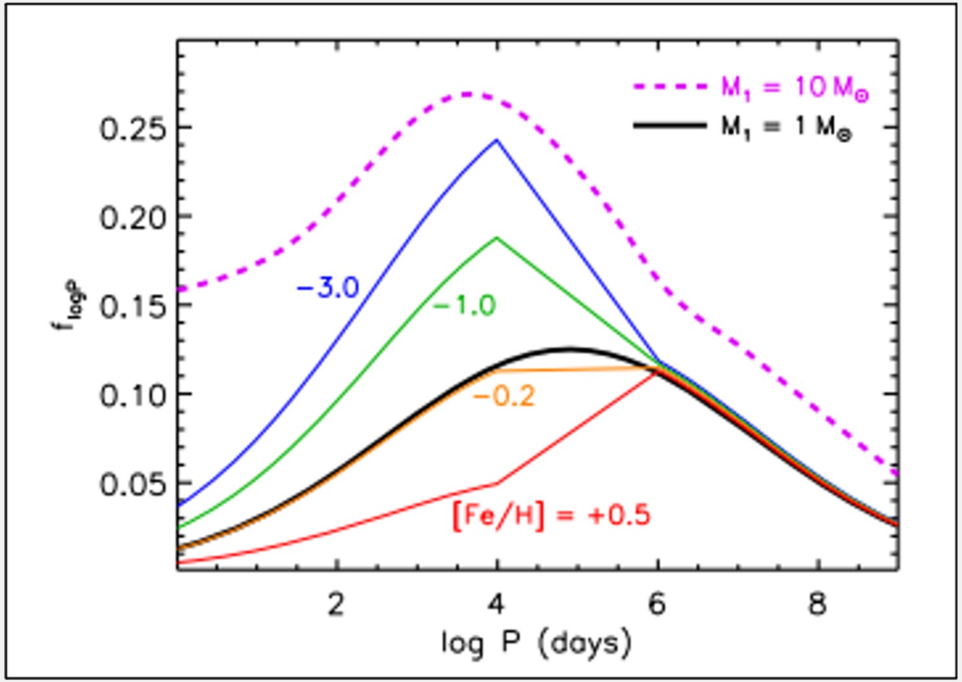
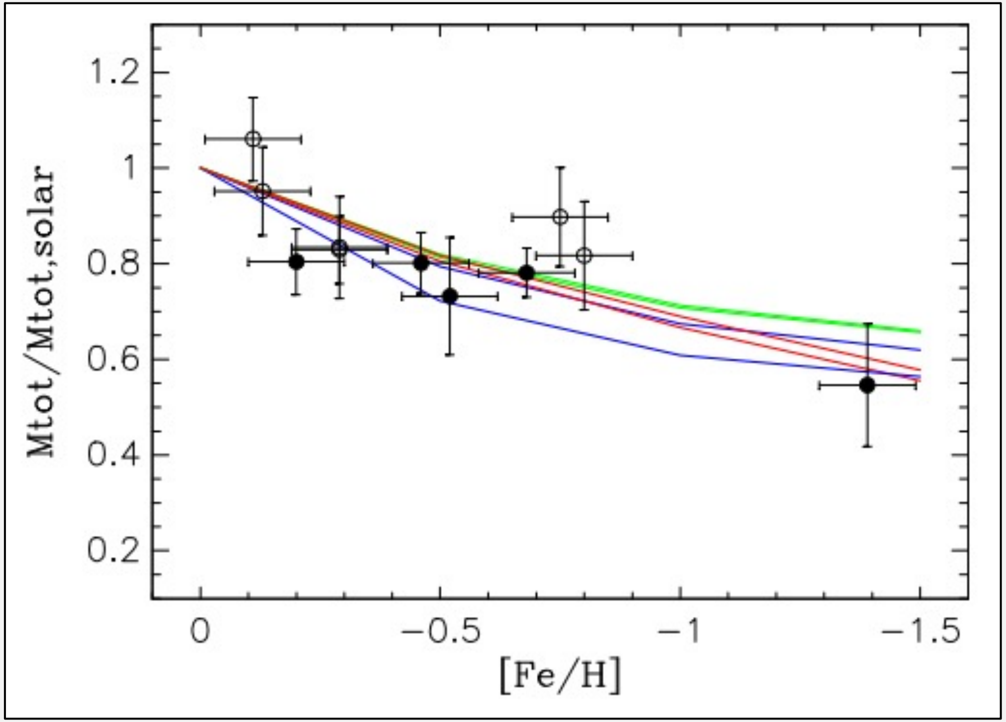


Moe et al. 2019

To better understand this, we need to find binaries!

- What parameters do we need?
  - "The dependency of the multiplicity frequency and their associated orbital parameters on primary mass should contain the imprint of the physical processes at play throughout the lifetime of stellar populations."
    - Duchene and Kraus 2013
  - Period/Separation Distribution
  - Eccentricity Distribution
  - Multiplicity fraction
- We need binaries where the mass can be determined
  - Mass-ratio Distribution
  - Mass-Luminosity relation
  - Luminosity function of the Galactic halo



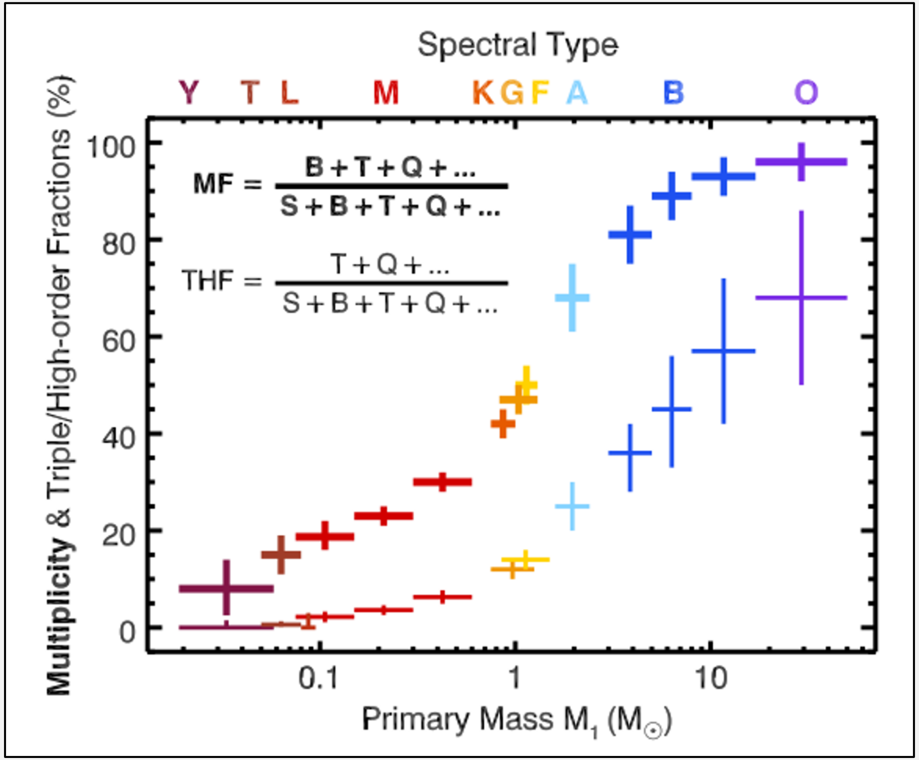
Horch et al. 2019

Disk Multicity Studies over the decades

- Over the past decade, a lot of work has been done to fill in our knowledge of the multiplicity fraction as a function of primary mass
  - Tokovinin - F-G Sample
  - RECONS - M-dwarfs

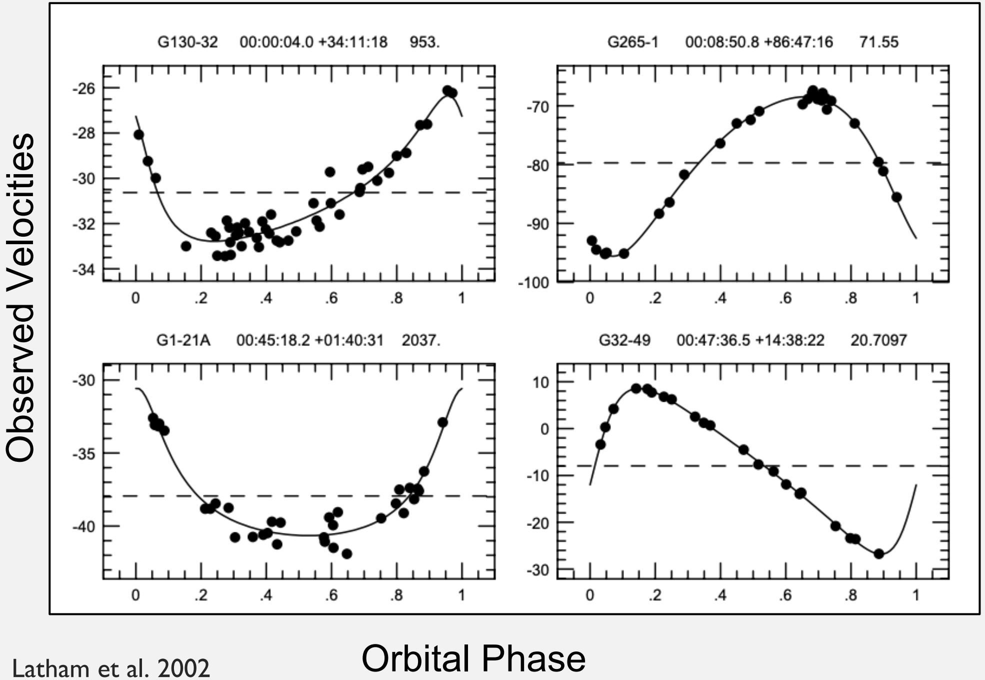
- ~50% of FGK stars in the disk are in binary systems.

- This fraction varies as a function of primary mass



Offner et al. 2023

History of Galactic Halo Multiplicity Studies

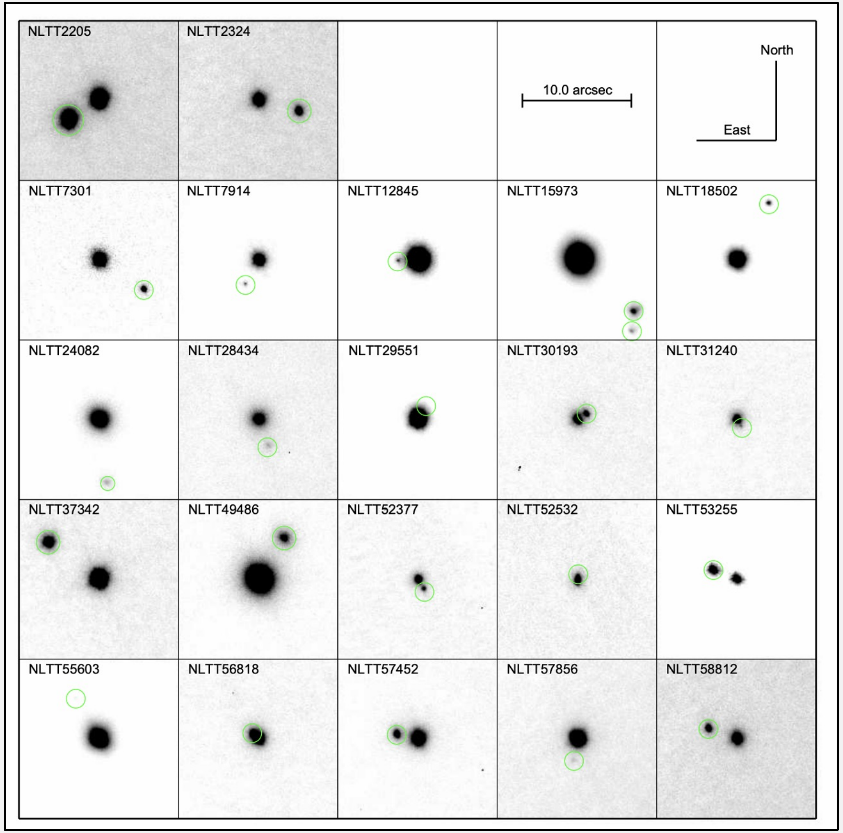


Latham et al. 2002

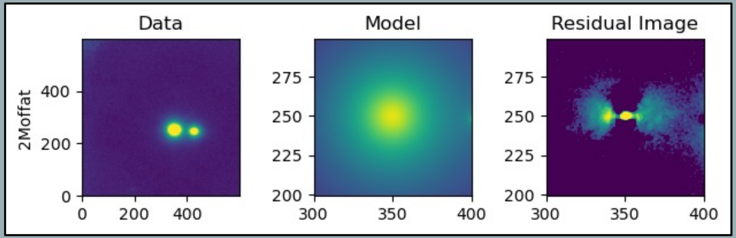
- Carney-Latham Spectroscopic Binary Survey
  - Carney & Latham 1987
- Observed 1464 FGK stars looking for spectroscopic binaries (SB)
- Found that the disk and halo populations had a similar SB fraction
- However, in a re-analysis of their results, Moe et al. 2019 found that the halo had a larger SB fraction than the disk.

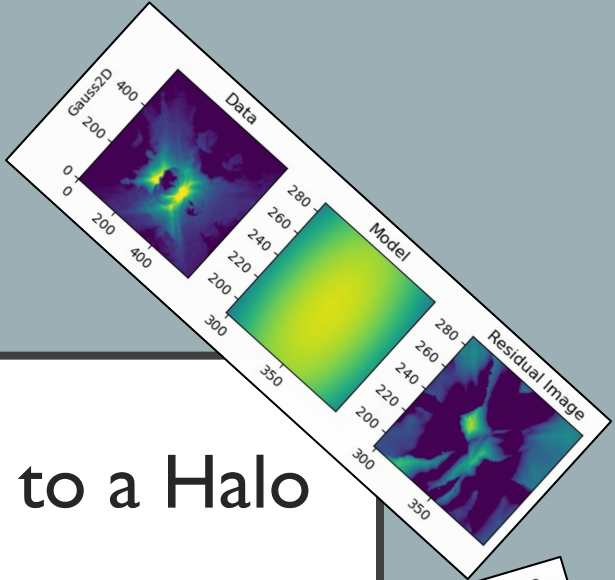
History of Galactic Halo Multiplicity Studies

- Different multiplicity fractions have been found over the past decade using high angular resolution imaging
- Jao et al. 2009 (speckle imaging)
  - 62 K/M subdwarfs
  - $26\% \pm 6\%$
- Rastegaev 2010 (combination of speckle and RV observations)
  - 233 metal-poor subdwarfs
  - $33\%^{+6\%}_{-7\%}$
- Ziegler et al. 2015 (Robo-AO)
  - 344 cool subdwarfs
  - $12.5\% \pm 1.9\%$

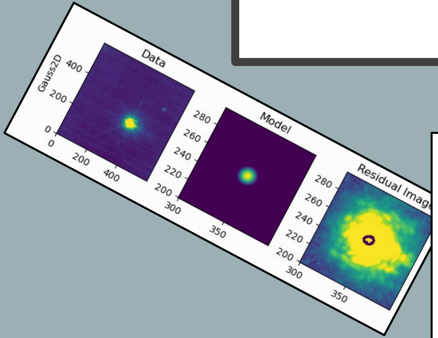


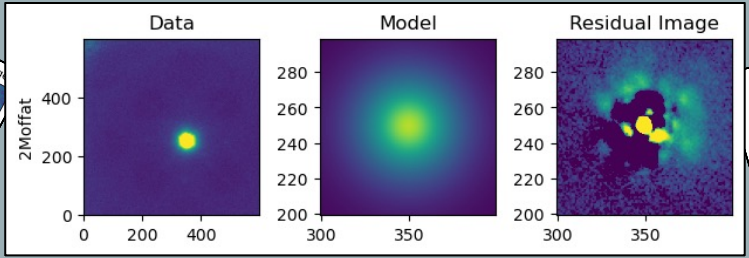
Ziegler et al. 2015

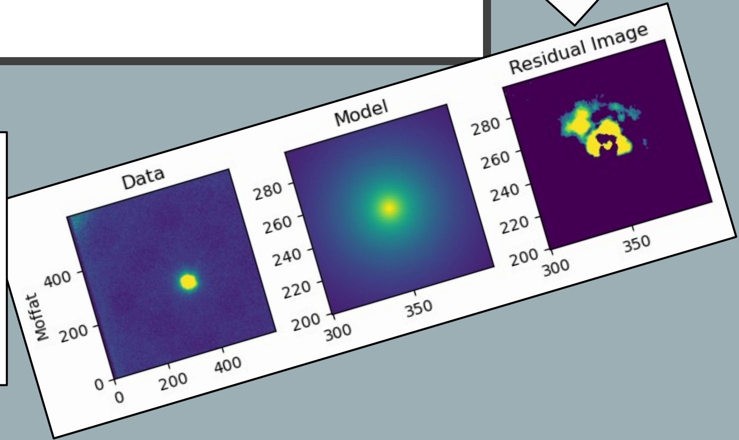




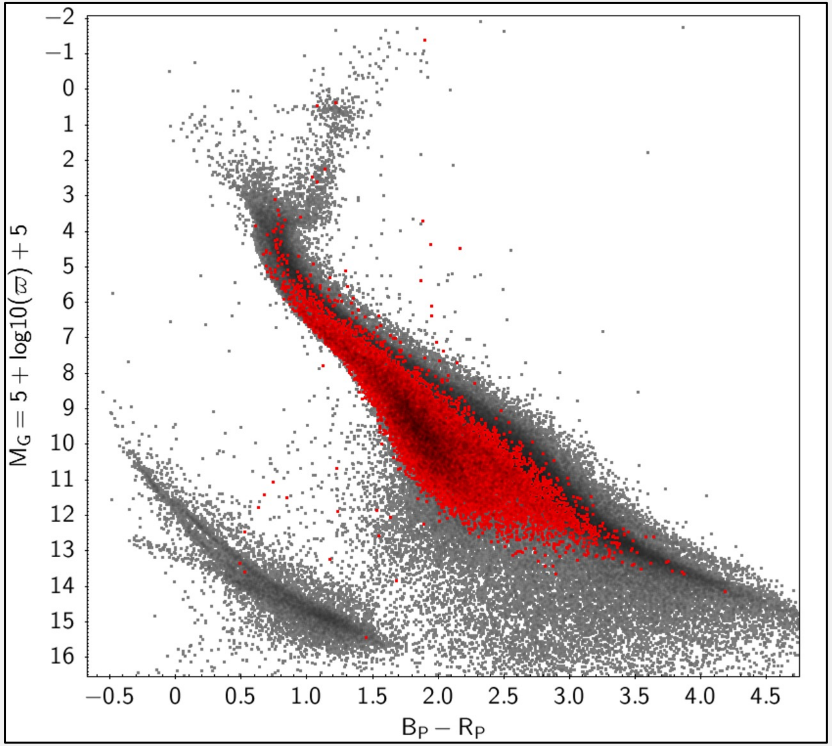
Searching for Some Light Next to a Halo

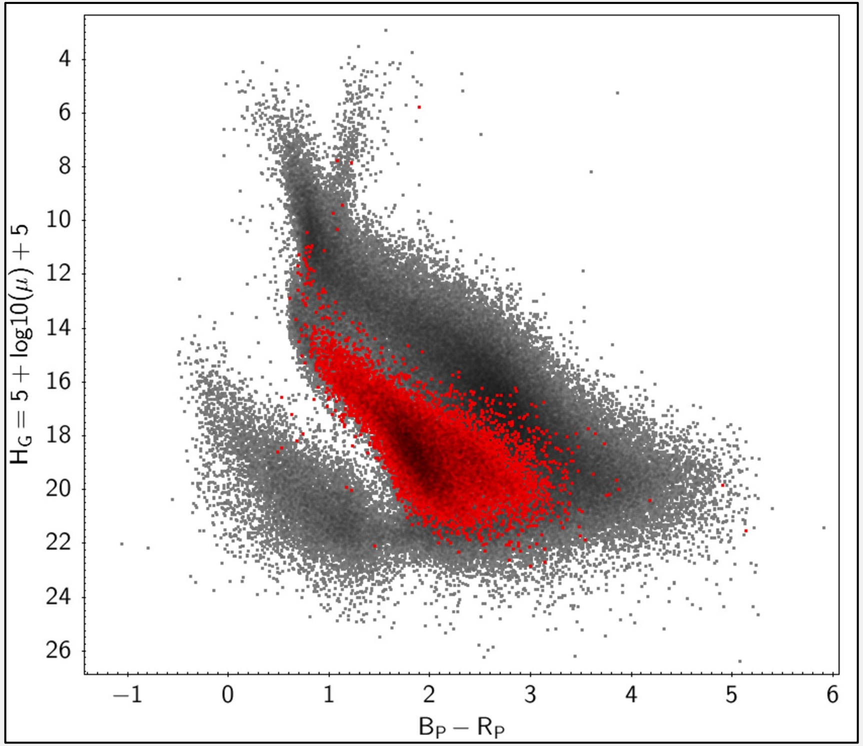






Galactic Halo Sample (Rich and Lépine Edition)

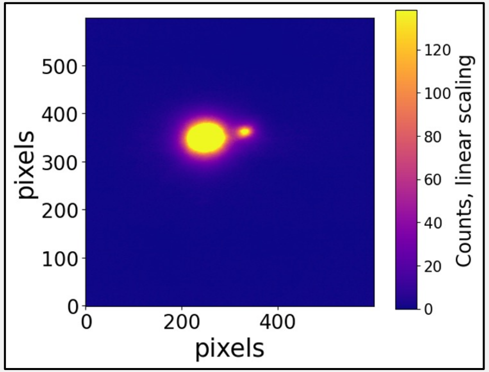


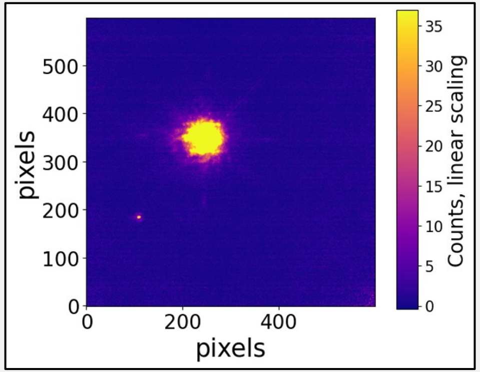


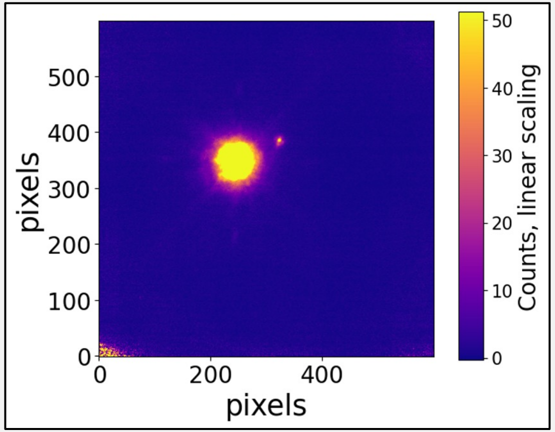
Proper motions > 150 mas/yr

Lick Adaptive Optics Reductions

- Began a survey of nearby high proper motion stars believed to be part of the Galactic halo.
- In total, ~800 stars have been observed
  - Almost none fully reduced and analyzed before 2023
- Currently reducing ShARCS data
  - Started in 2014
- Using the SImMER Reduction code
  - Savel et al. 2022

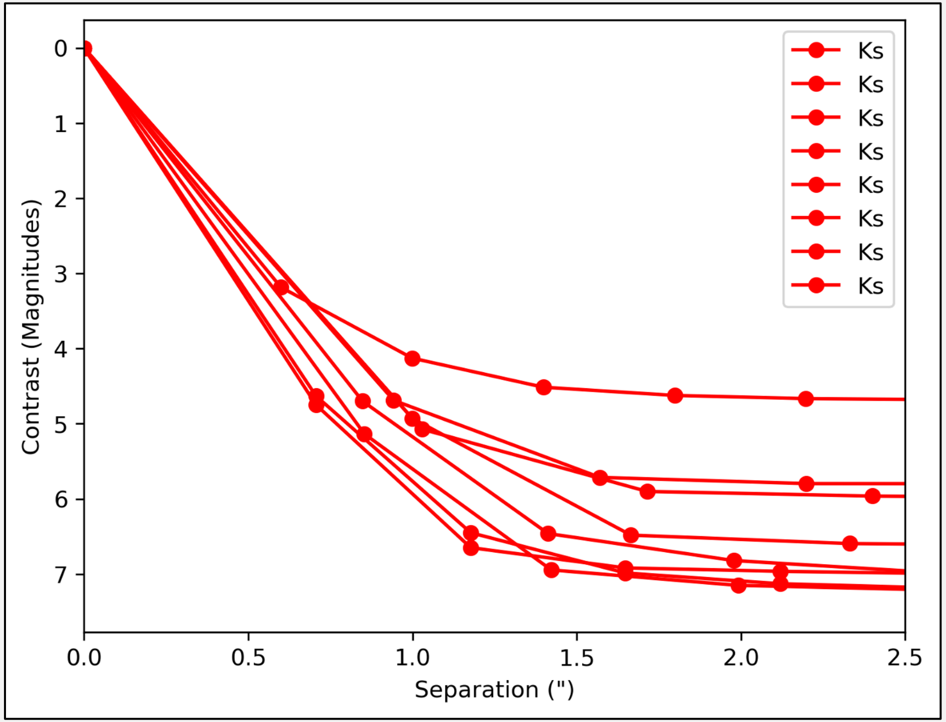




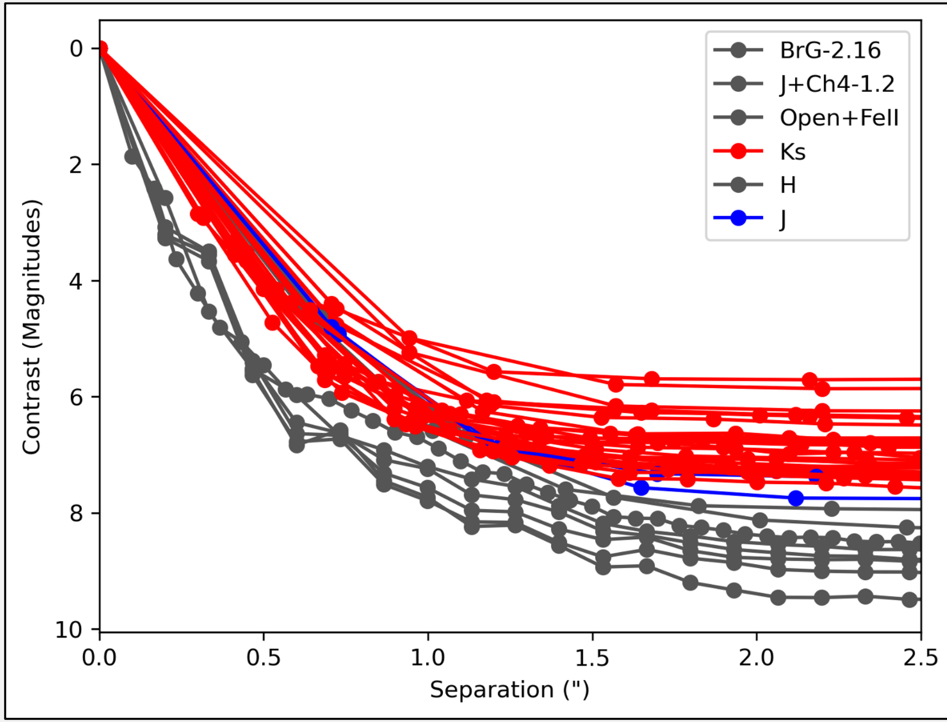


Lick Adaptive Optics Reductions

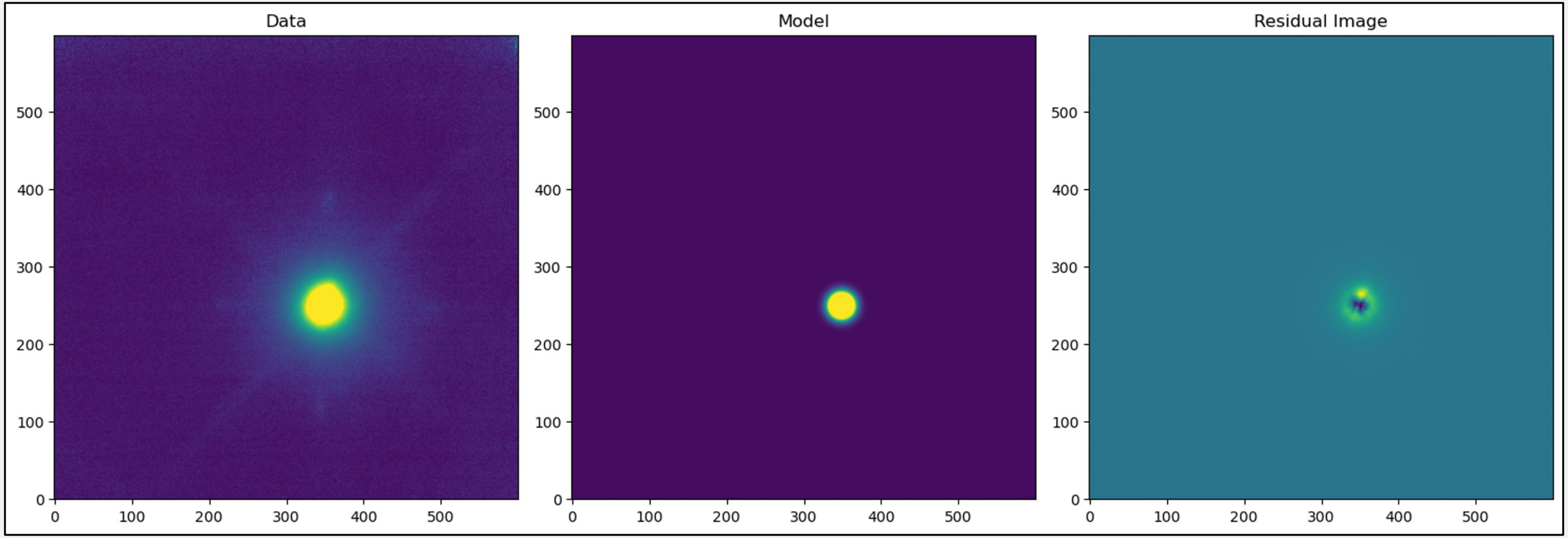
Bad night!



Good night!



Lick Adaptive Optics Reductions



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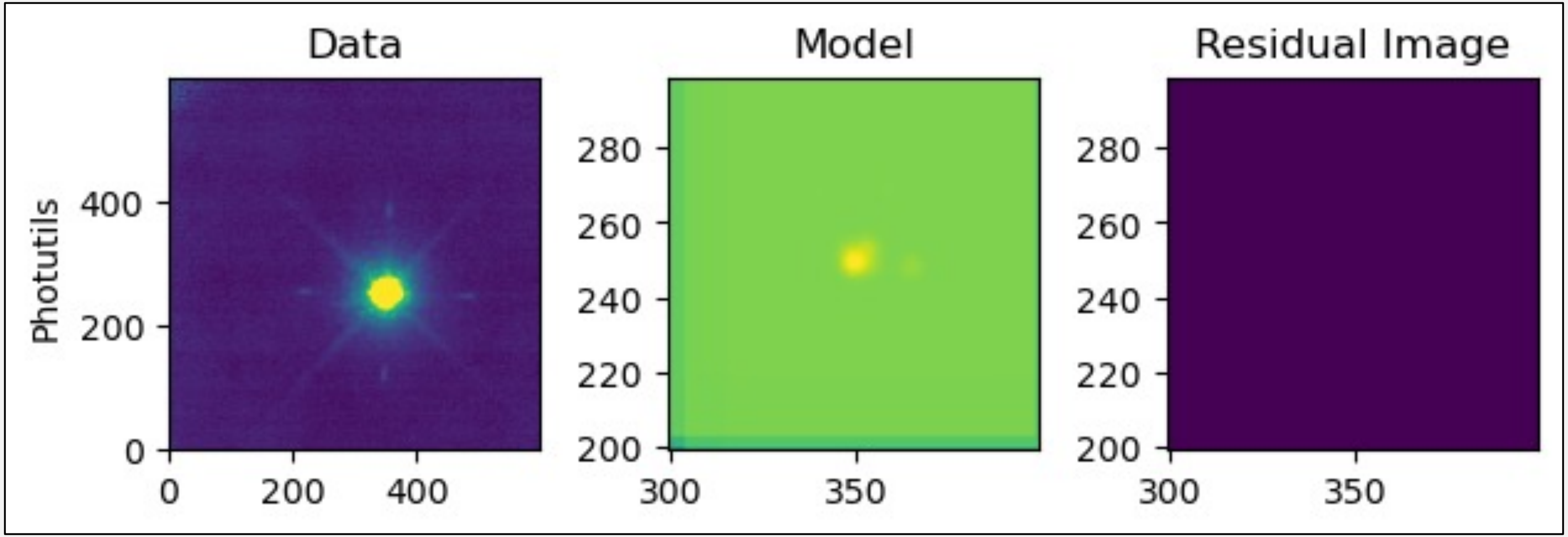

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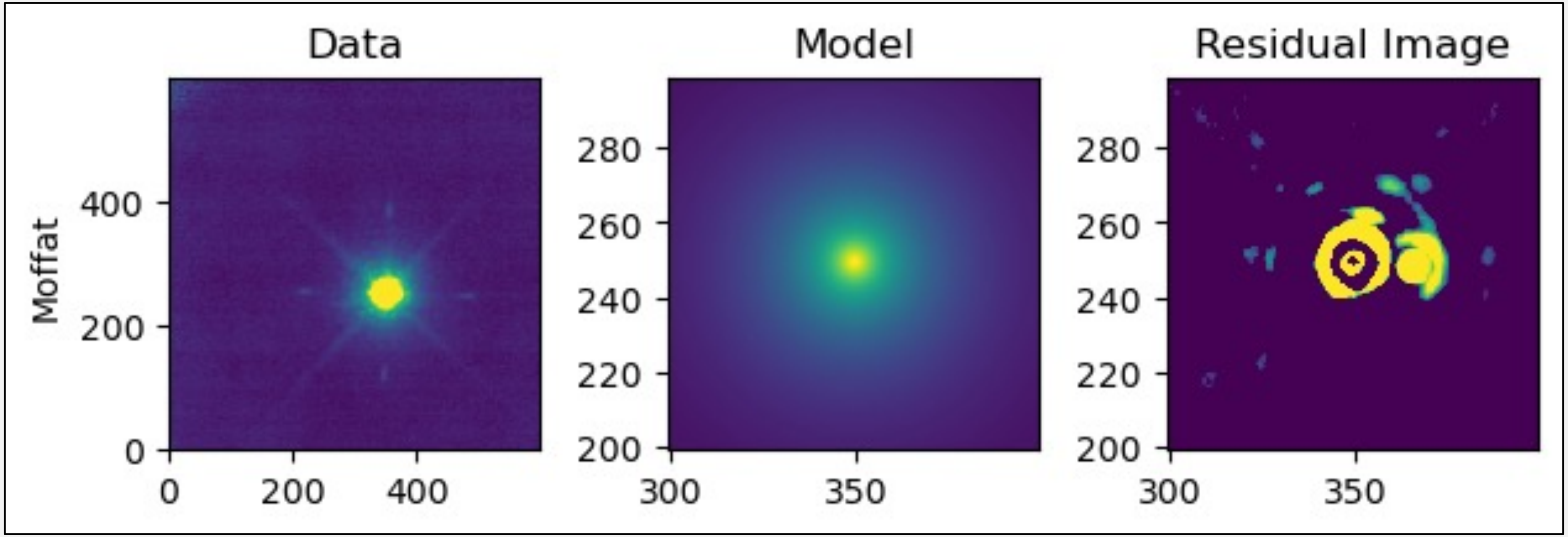

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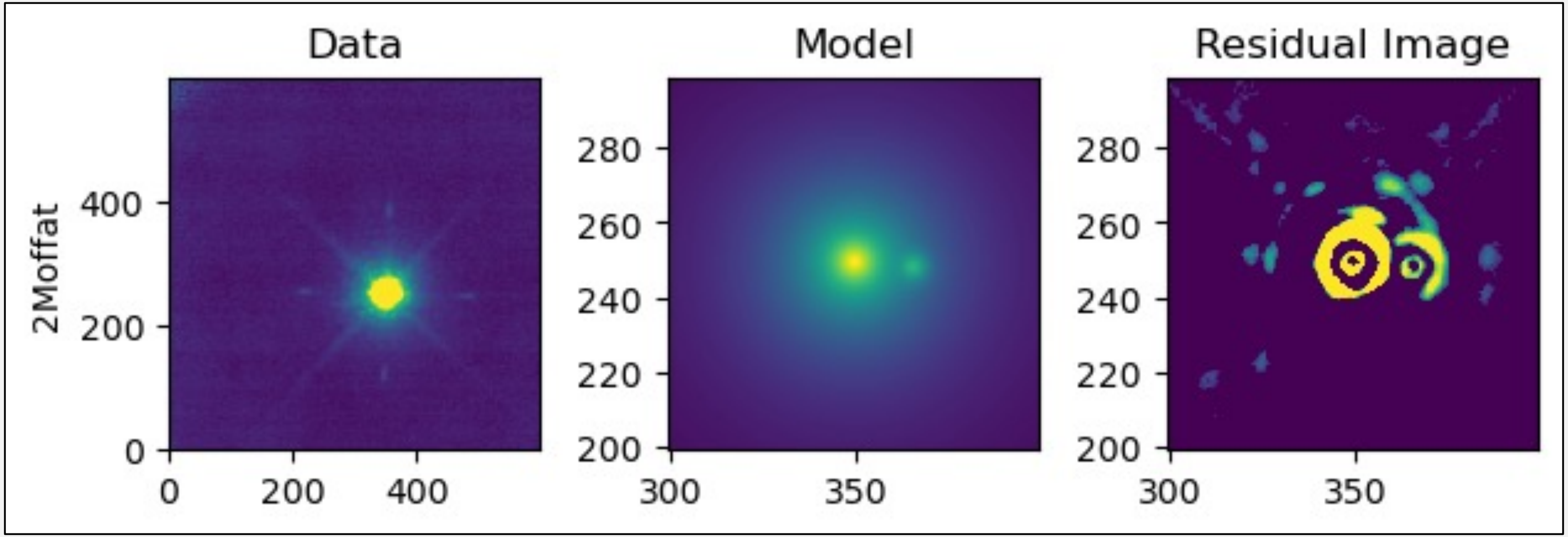
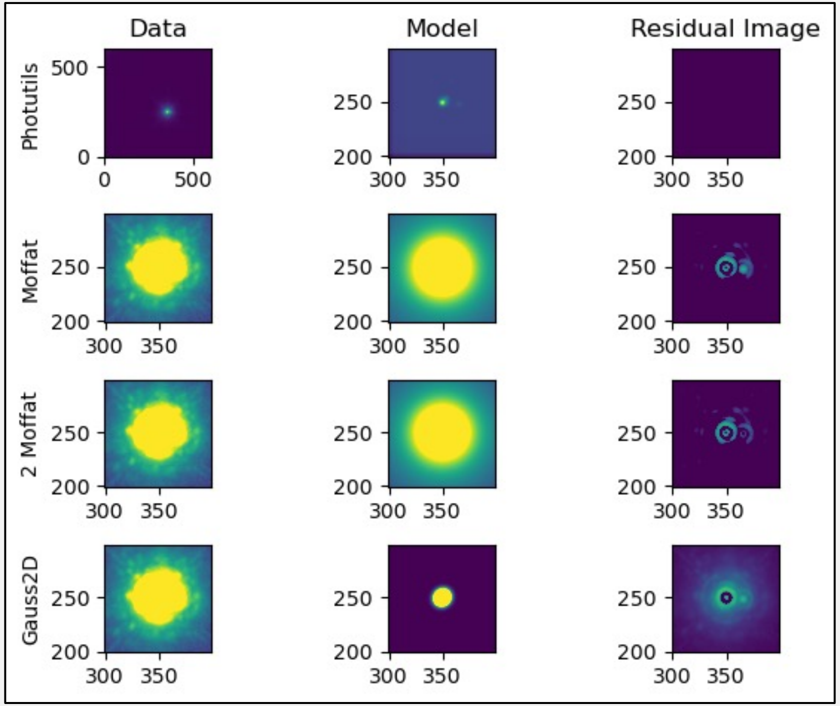
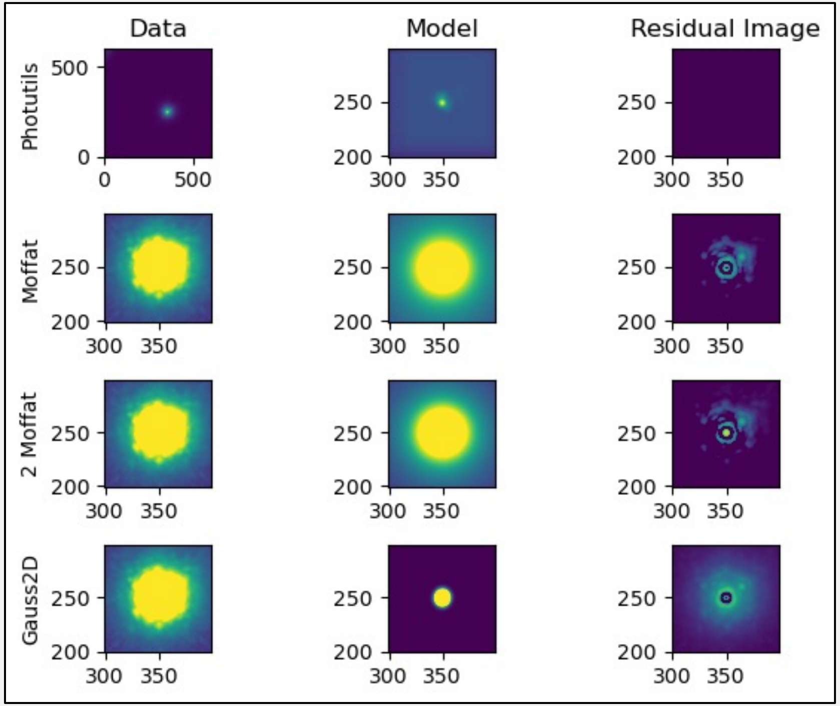


Lick Adaptive Optics Reductions

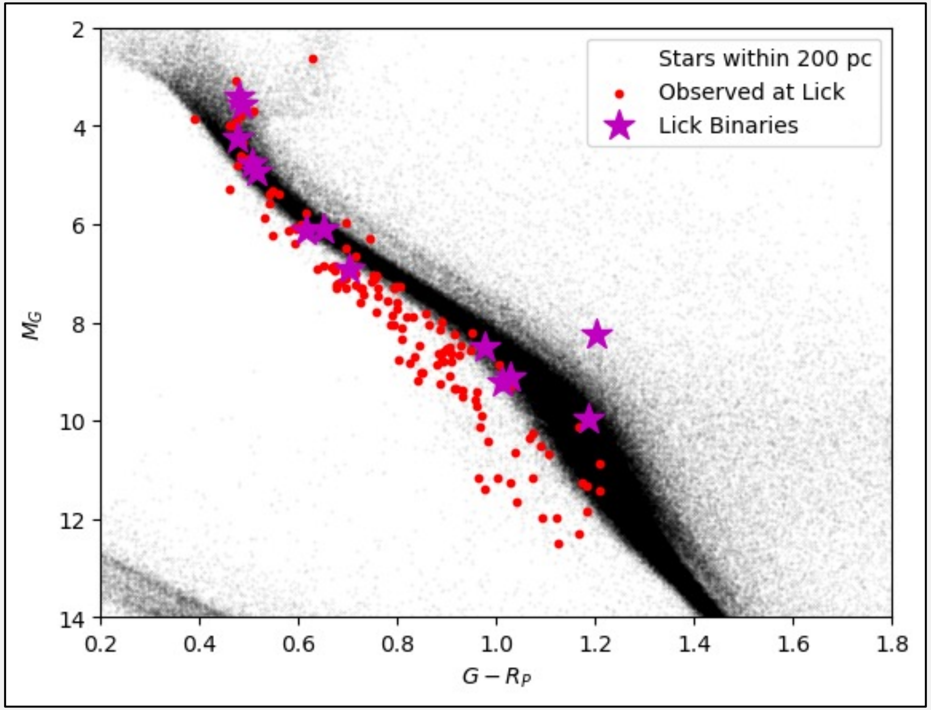


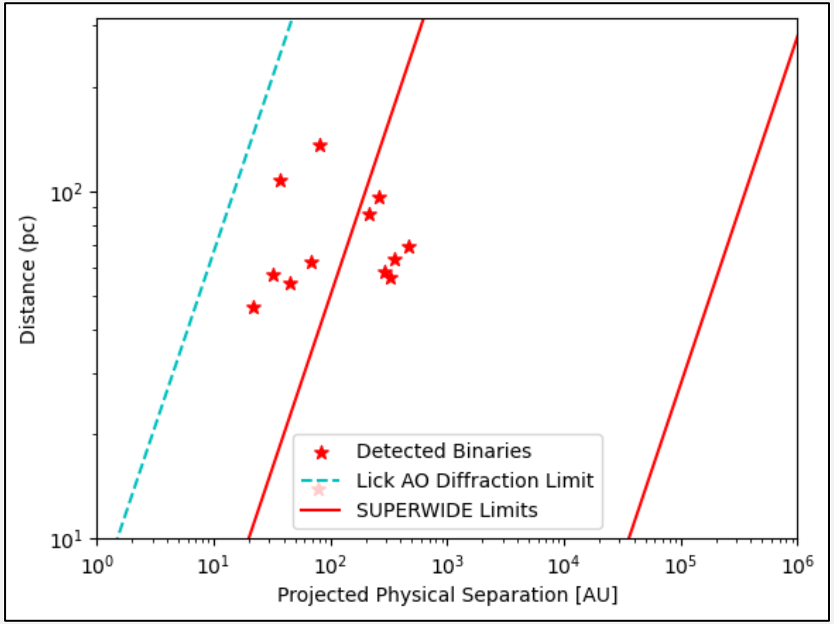
0.47” Binary Candidate



0.56” Binary Candidate

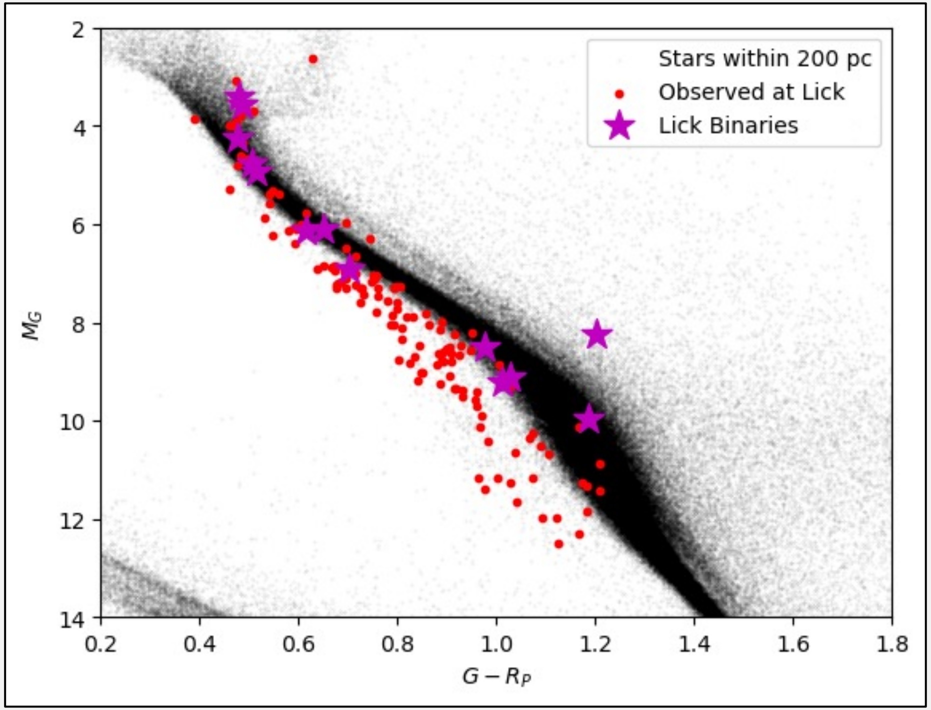
Lick Adaptive Optics Survey

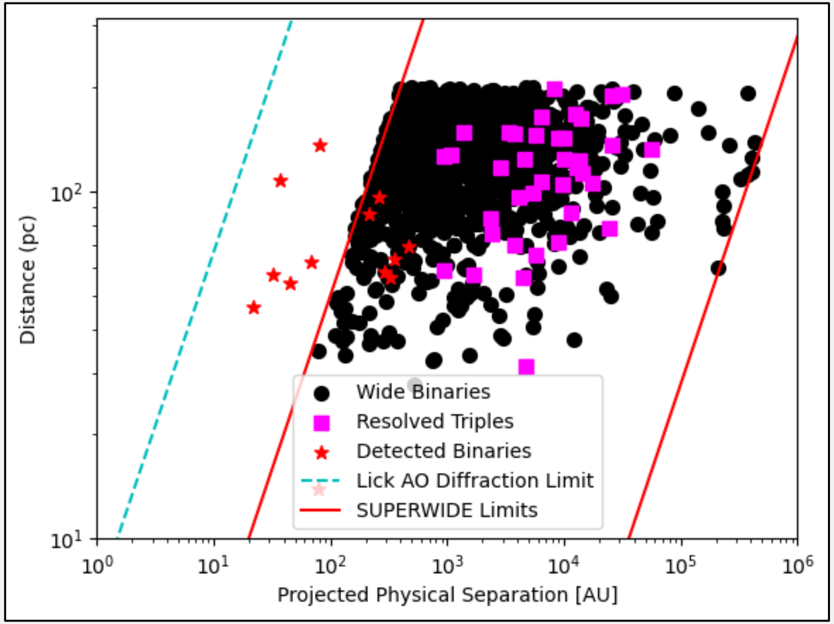




147 stars have been reduced from 2014 to Summer 2019

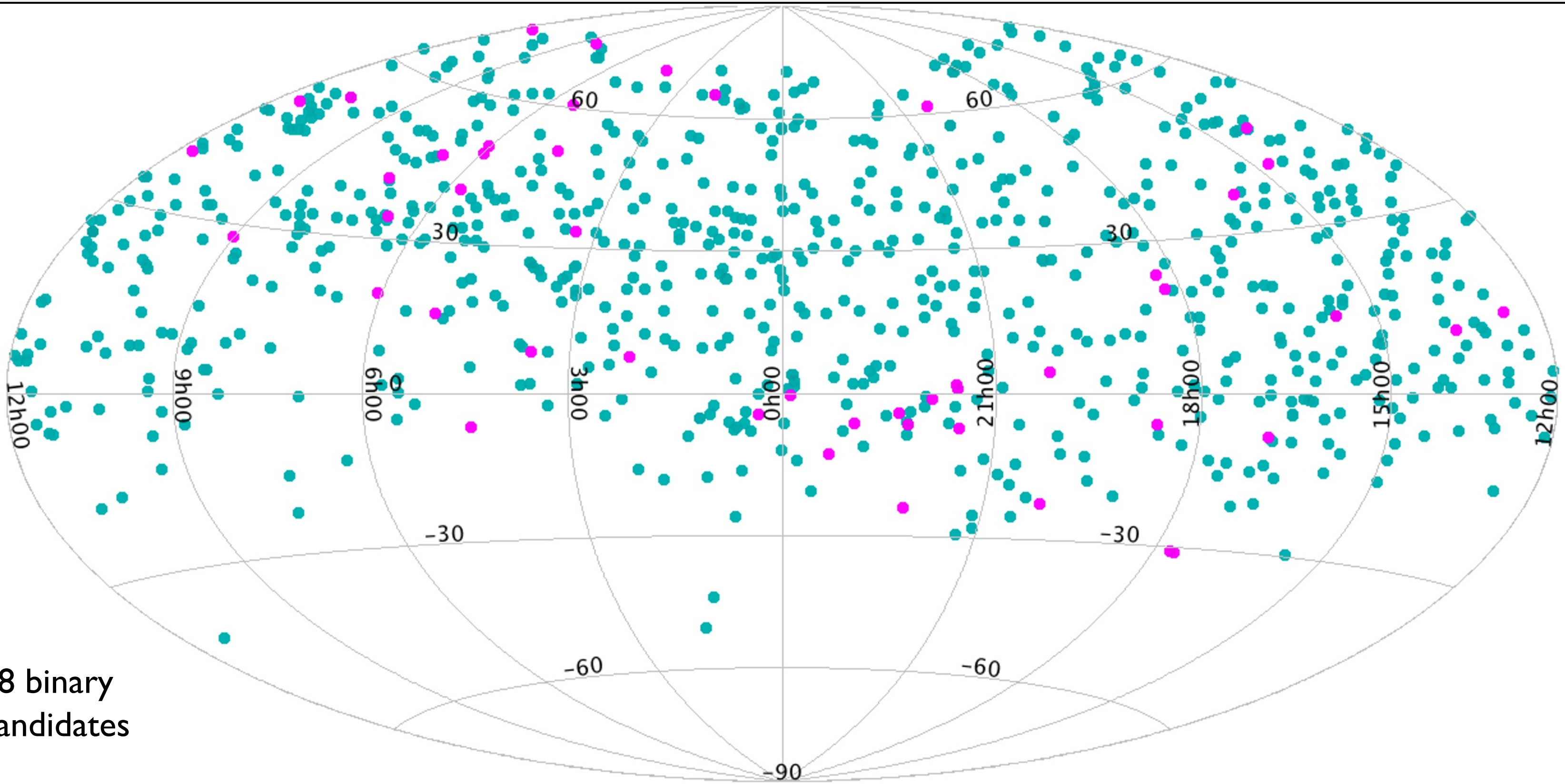
Lick Adaptive Optics Survey



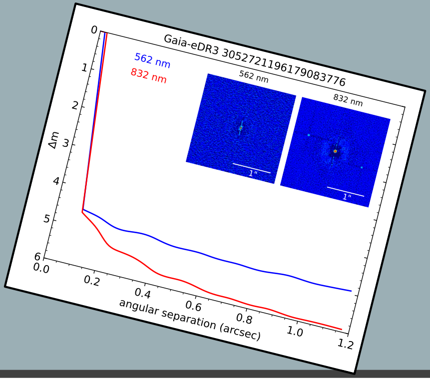


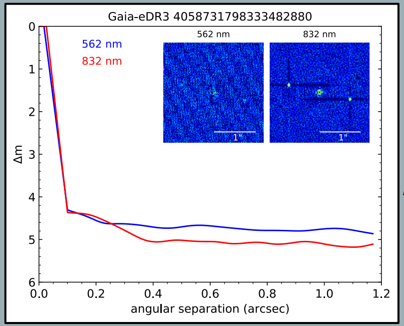
Multiplicity fraction for only Lick observed stars: $17\% \pm 3.7\%$

Current Status of Lick Observations (with some additional targets included)



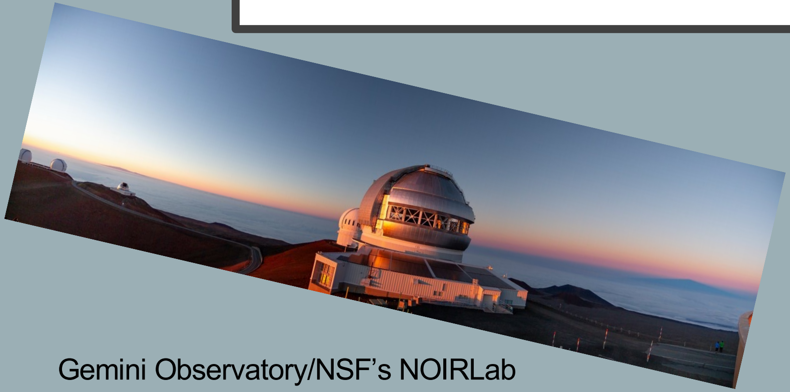
48 binary candidates



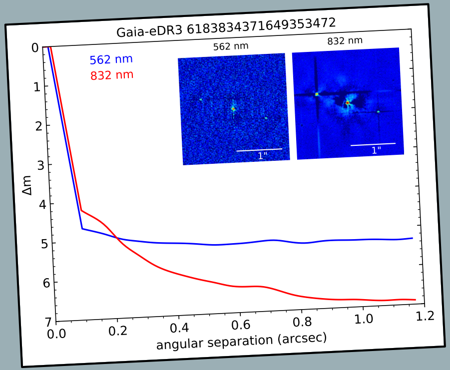


Gemini Observatory/NSF's NOIRLab Kwon O Chul

Getting Some Help from the Geminis

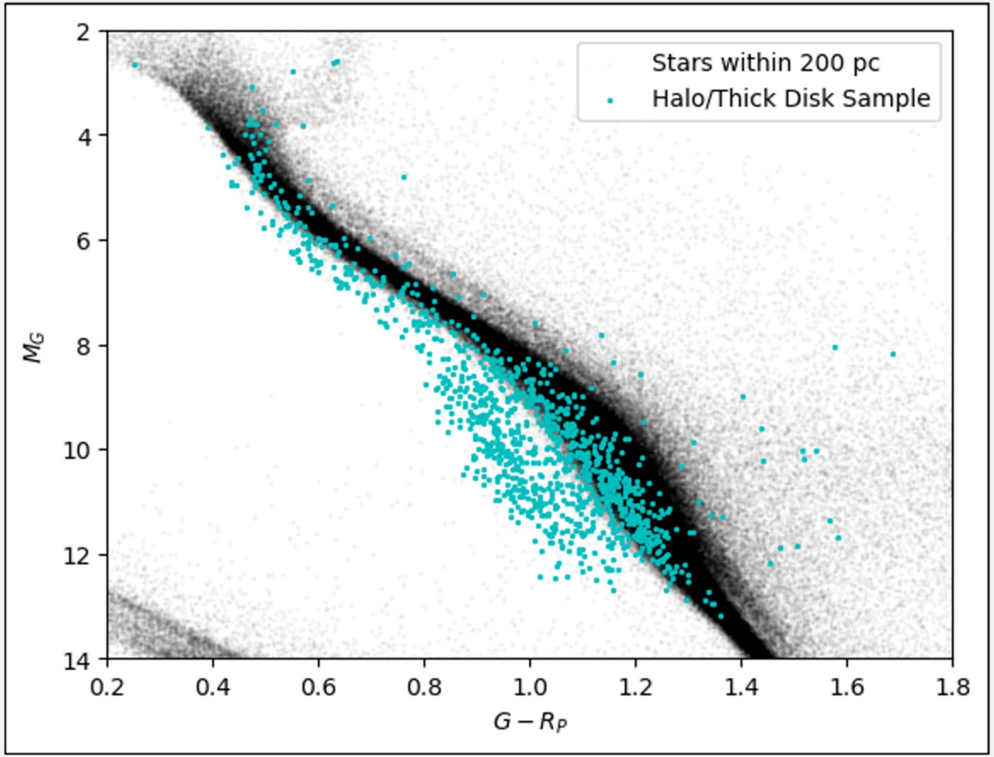


Gemini Observatory/NSF's NOIRLab
J. Pollard



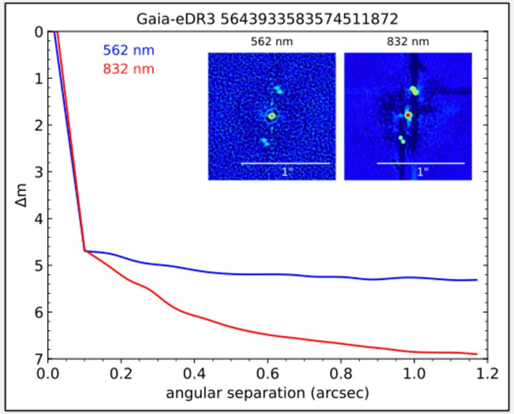
ALOPEKE • ZORRO

“Expanding” the Search to Closer Separations and *Gaia*



- Using Gaia DR3, we have selected a sample of neary halo/thick dick stars.
  - Tangential Velocities > 150 km/s
  - Distances < 100 pc
  - V < 18
  - No white dwarfs
- In total, we find 1149 stars.
- Applying for Speckle time on Gemini
  - Through Gemini proposals and data on the Gemini Archive, we have observed or have data on 174 stars in our sample.

Results of Speckle Imaging Campaign (So far…)

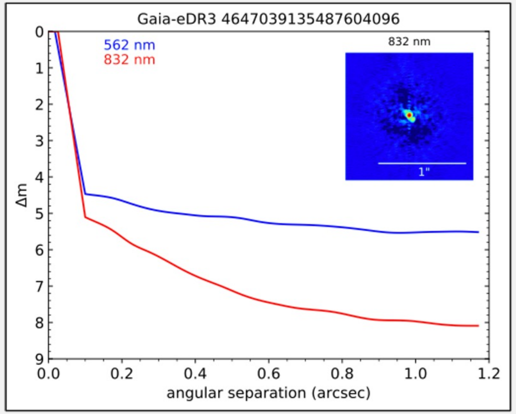


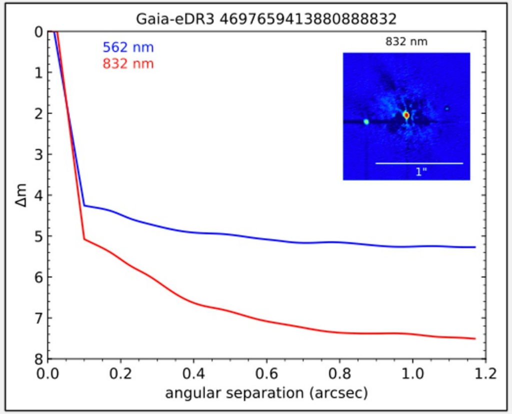
ρ = 0.307”
Δm_{red} = 1.42
Δm_{blue} = 2.31

ρ = 0.316”
Δm_{red} = 1.42
Δm_{blue} = 2.33

ρ = 0.06”

Δm_{red} = 2.83



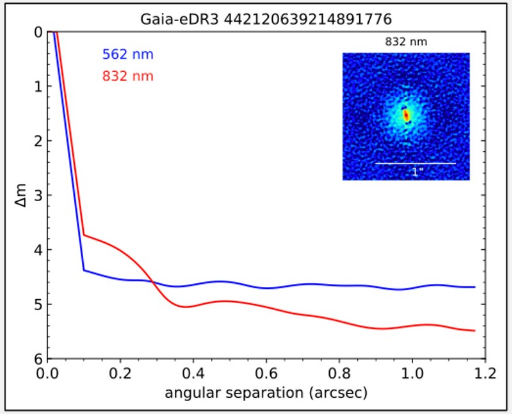


ρ = 0.473”

Δm_{red} = 3.0

ρ = 0.048”

Δm_{red} = 0.77



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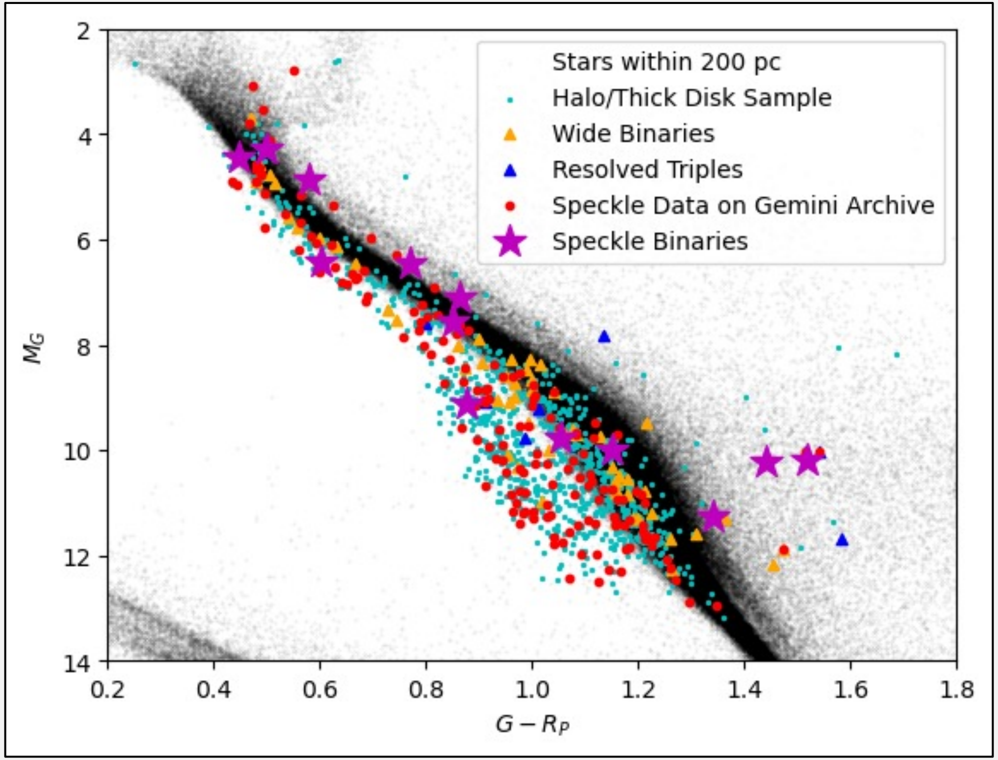
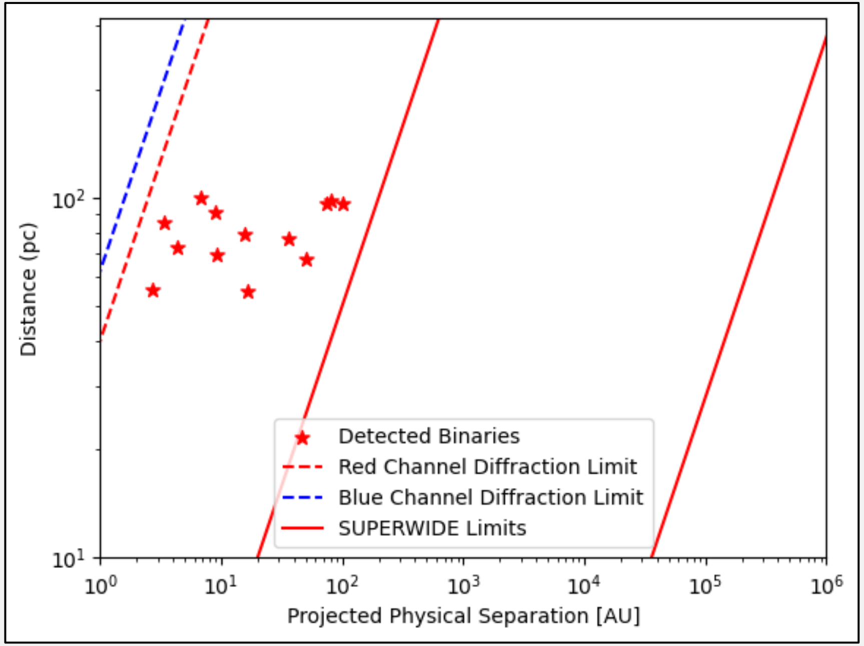
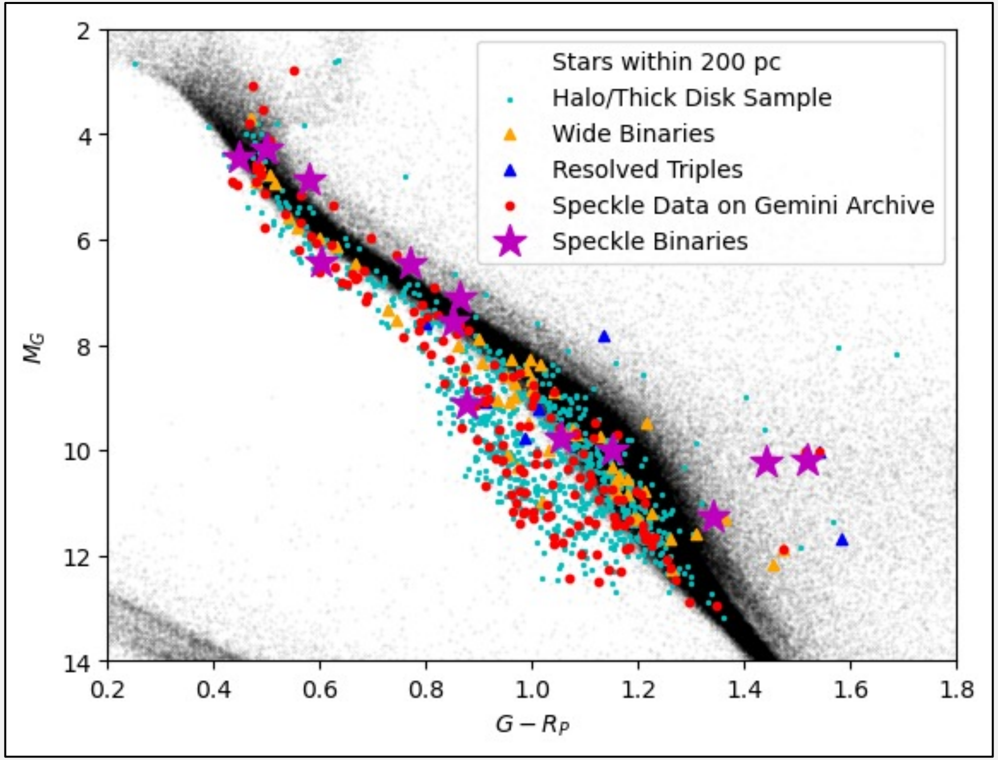
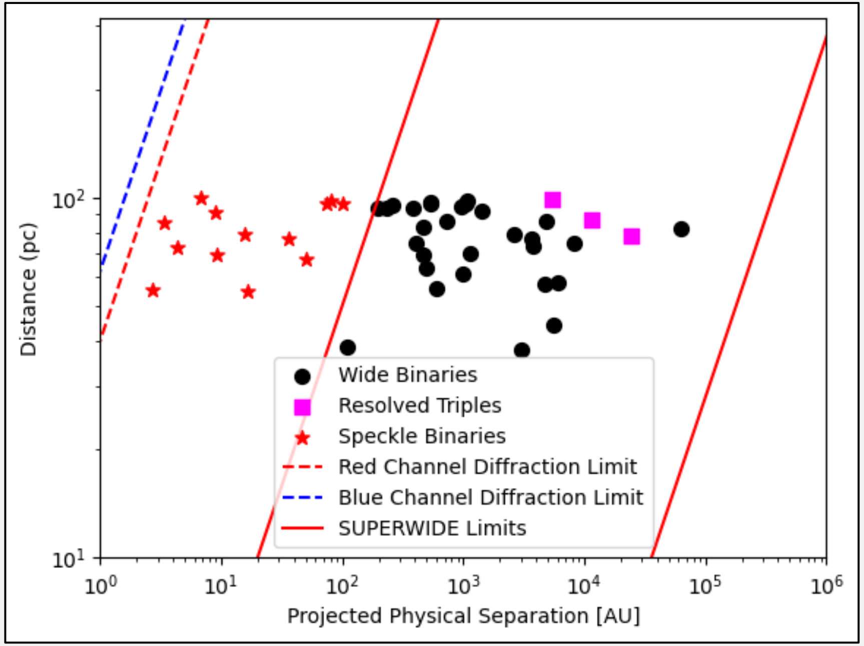




- We have found 13 binaries with speckle imaging.

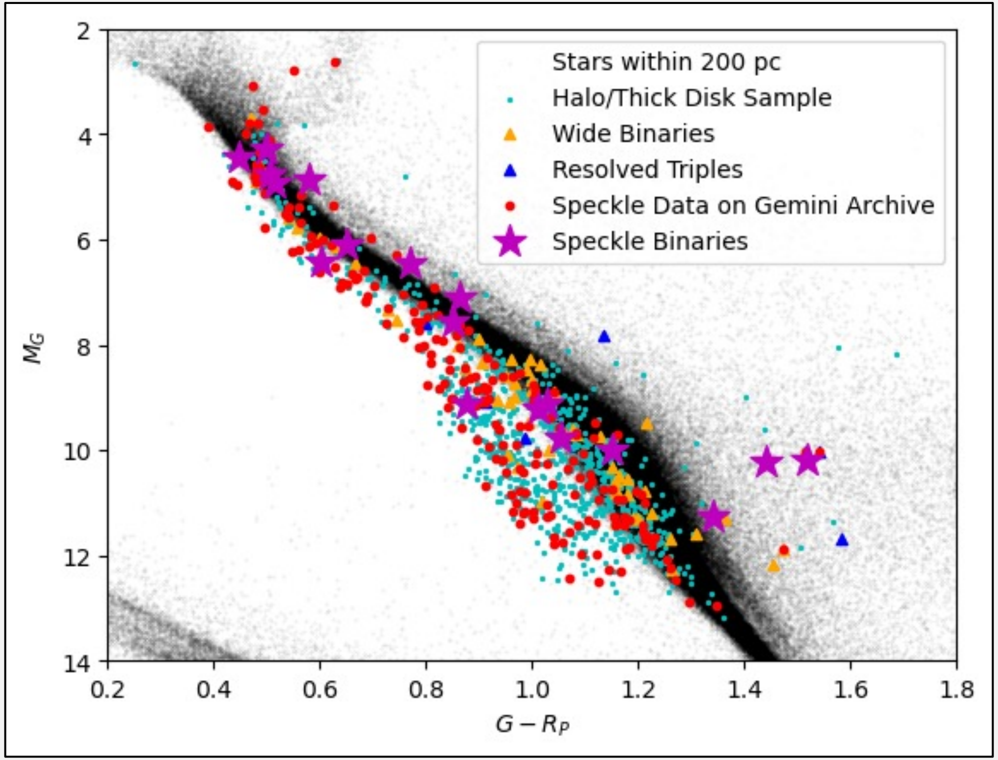
Results of Speckle Imaging Campaign (So far…)

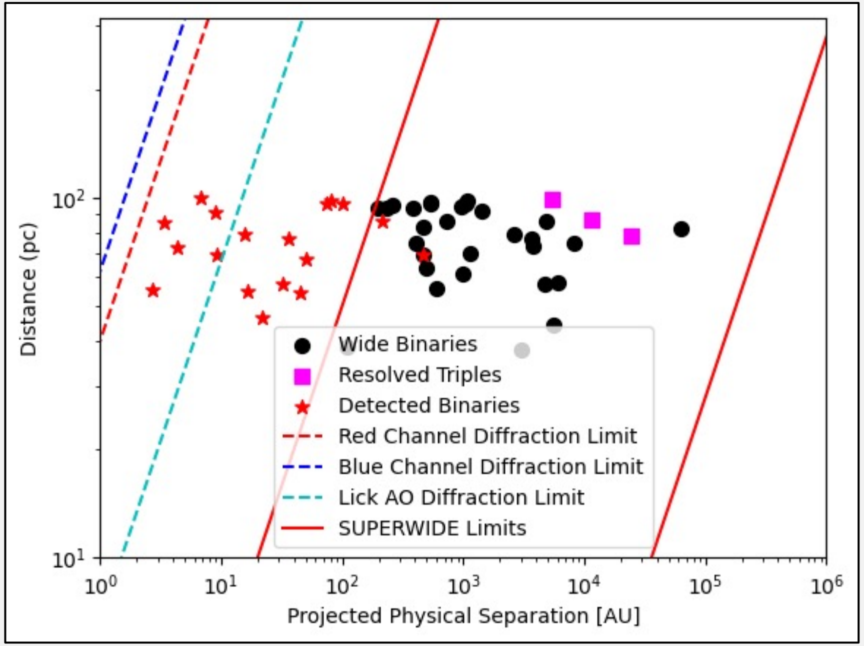




- Multiplicity fraction for speckle observed sample: $10.3\% \pm 2.6\%$

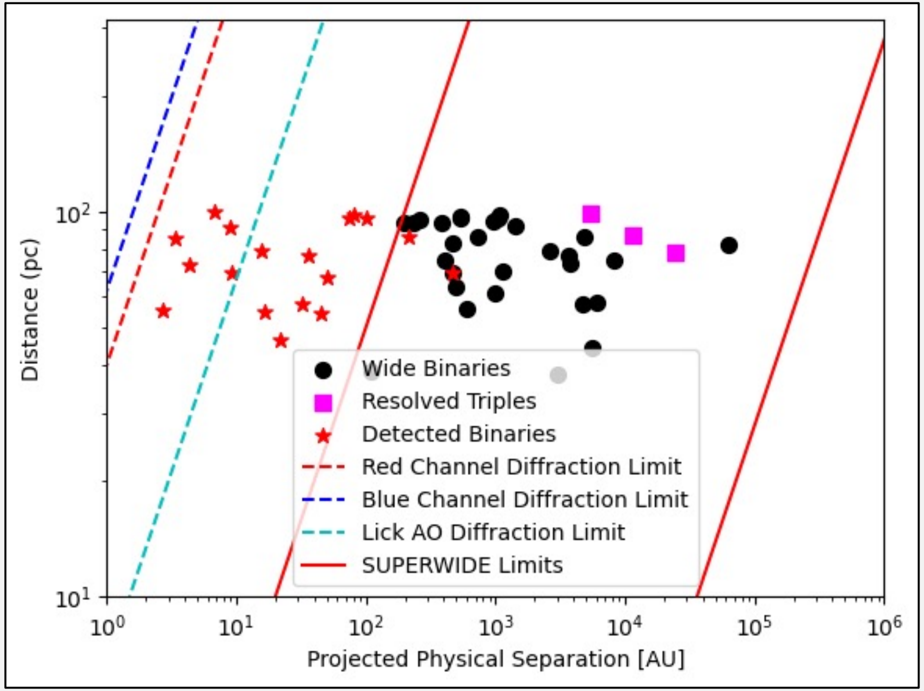
Combined Results between the Speckle and Lick AO Data



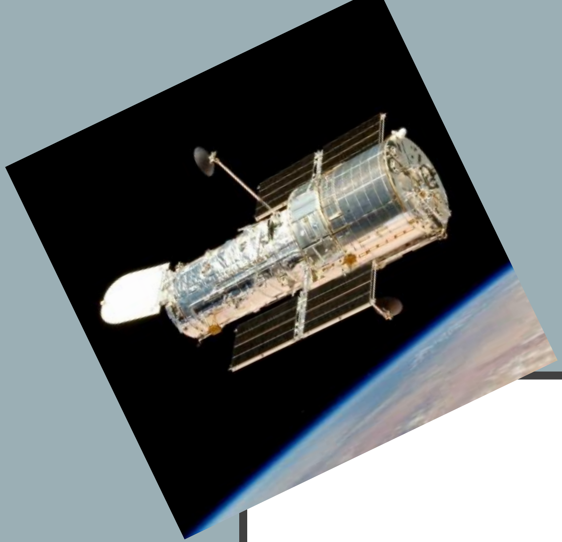


- Multiplicity fraction for the combined observed sample: $11.8\% \pm 2.4\%$

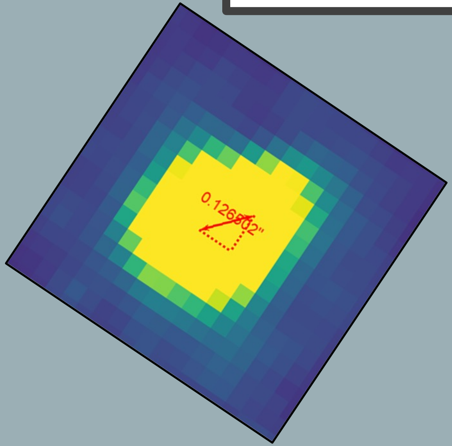
What about RUWE, IPD_MF, and *Gaia* NSS?

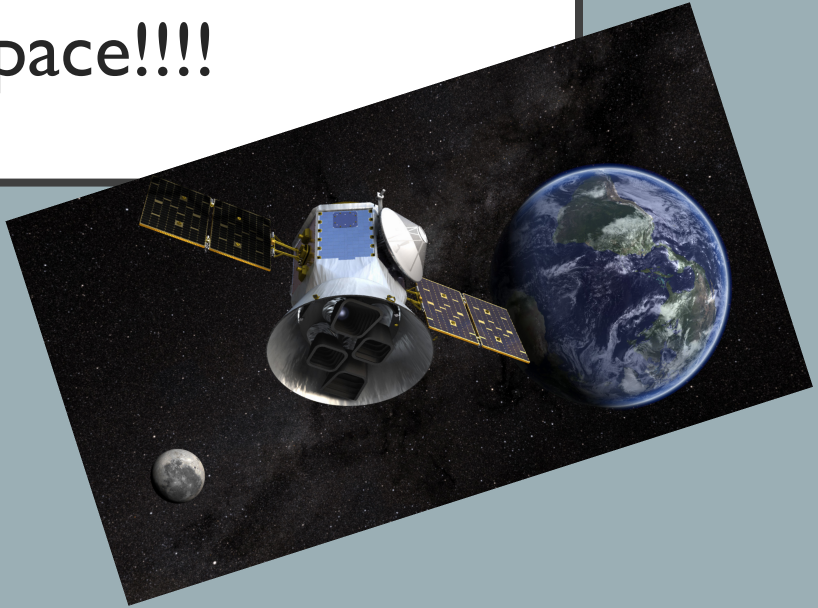


- We find 18 speckle or AO detected binaries in our survey so far…
- We checked our results against known *Gaia* parameters which might indicate binarity
  - RUWE
    - Observed sample – 22
    - Binary – 13
  - IPD_MF
    - Observed Sample – 9
    - Binary – 3
  - NSS
    - Observed Sample— 4
    - Binary – 0

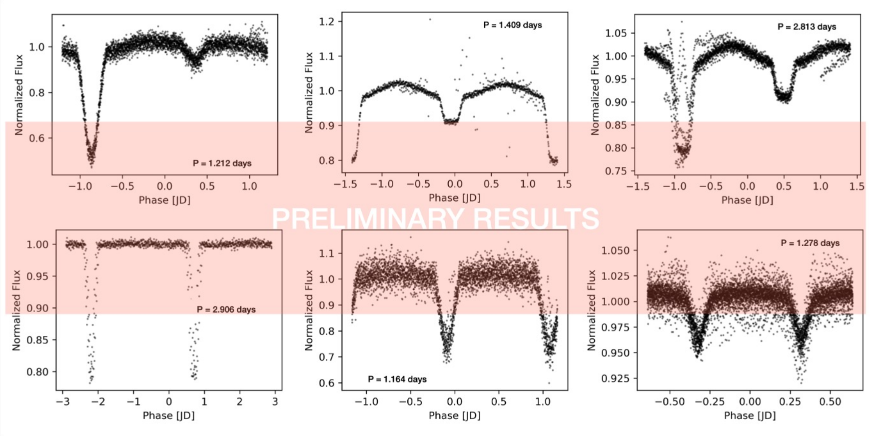


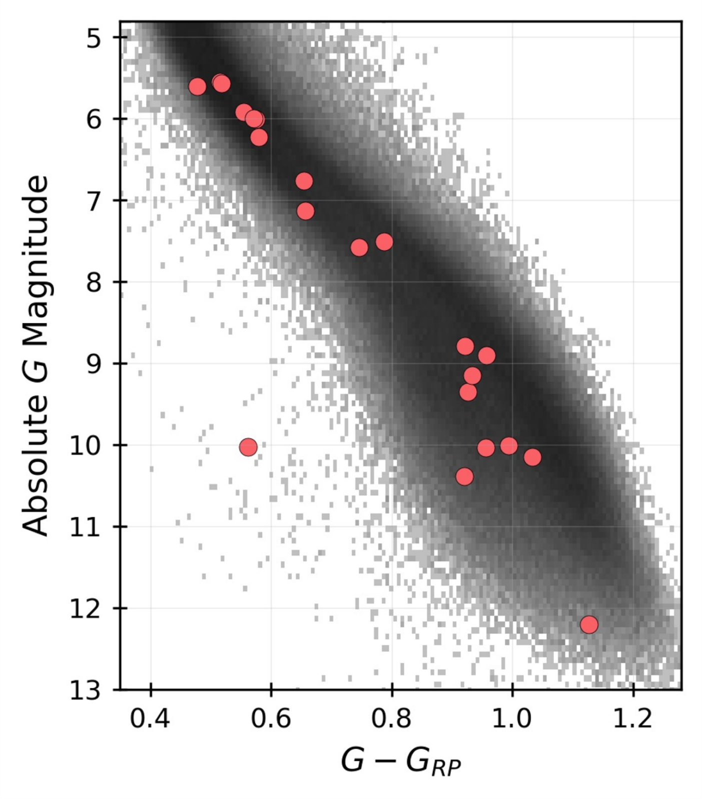
Expanding to Space!!!!





Low-mass, metal-poor eclipsing binaries from TESS light curves (B. Kim)

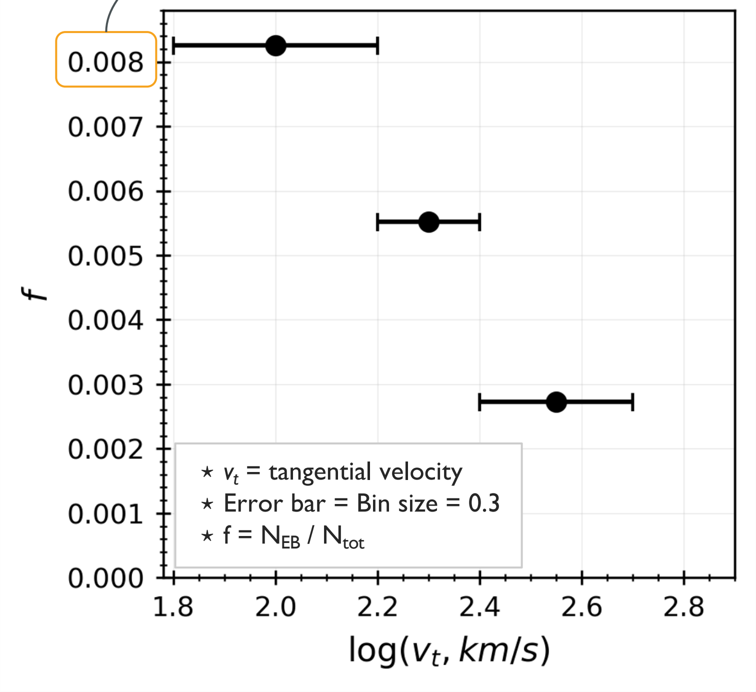


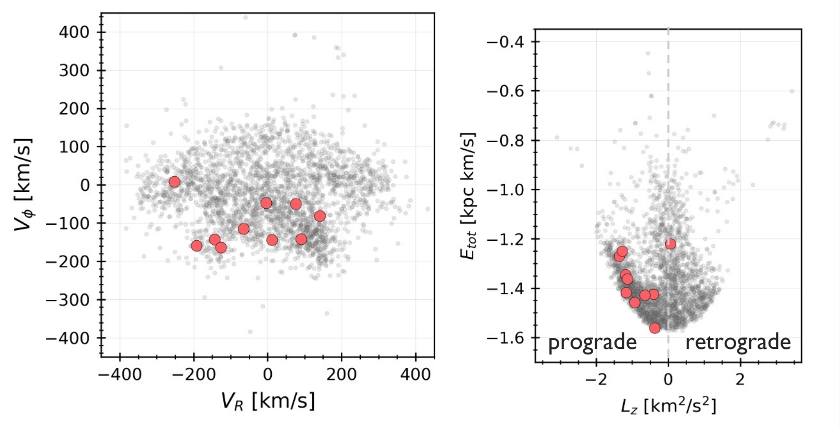


- From Kim & Lépine (2022), we obtain 207164 K and M dwarfs with TIC IDs under the following criteria:
  - $[Fe/H]_{grid} < -1.0$
  - Absolute G magnitude > 5.5 mag
- Among 4476 stars with TESS light curve files, we found 20 eclipsing binary candidates (red-filled circles).
  - The total EB Fraction ~ 0.45 % (20/4476)

Low-mass, metal-poor eclipsing binaries from TESS light curves (B. Kim)

Too high compared to Hwang et al. (2020)
→ due to the total number of stars with TESS light curve files in each bin?

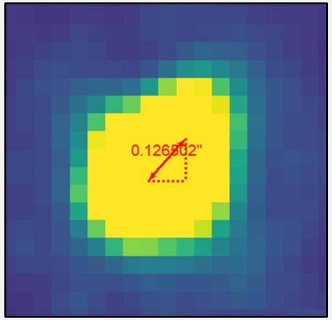


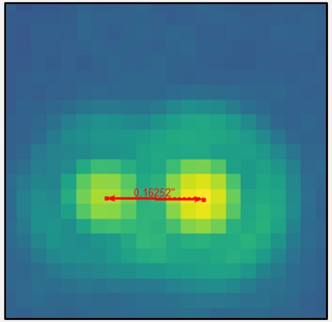


○ Gray points: 2769 K & M dwarfs with Gaia DR3 RVs and TESS light curve files
○ Red-filled circles: 10 eclipsing binary candidates

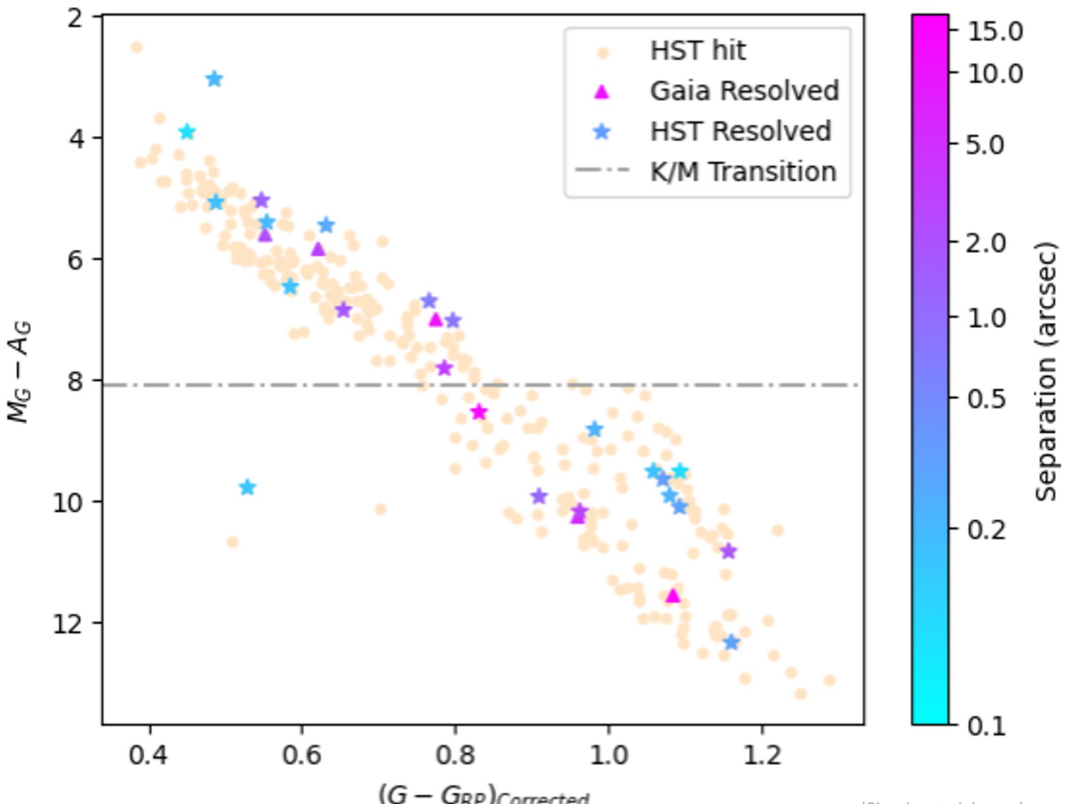
- Among those candidates, 10 systems have radial velocities from Gaia DR3.
- The majority of these systems follow the thick disk kinematics.

Hubble Halo Survey (M. Sloneker)



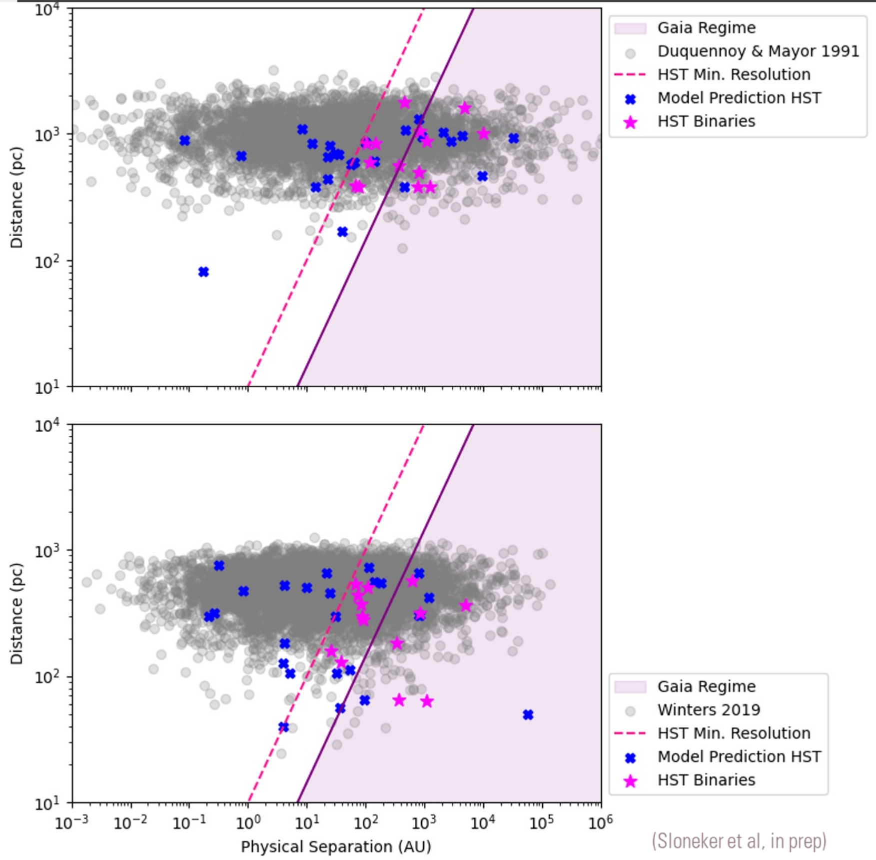


- Search through archival HST data for other programs and find halo stars in the background
- Able to search for fainter companions
- Found 26 binaries out of 284 systems
  - Multiplicity fraction = ~9%



(Sloneker et al, in prep)

Examining the HST Results (M. Sloneker)



(Sloneker et al, in prep)

Simulation Multiplicity Fractions:

FGK - 23%

M - 16%

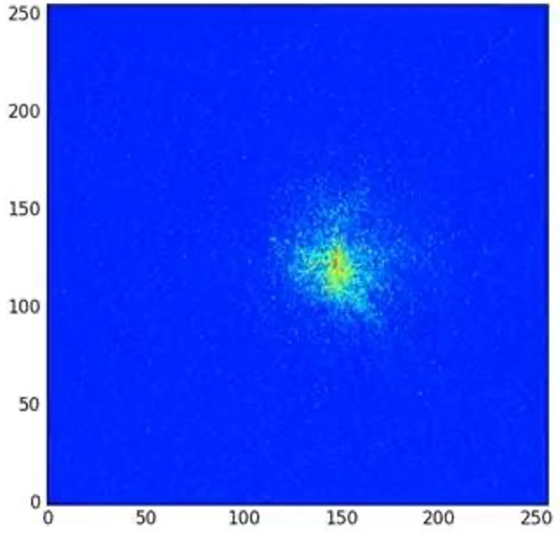
Conclusions

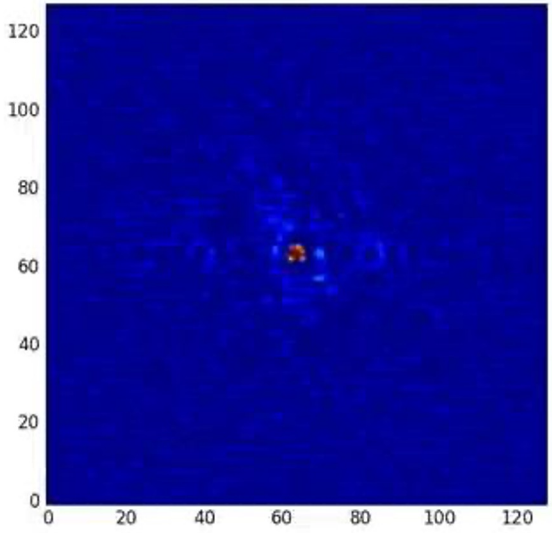
- Determining precise parameters for the nearby Galactic halo population will improve our understanding of how these old, metal-poor stars formed.

- We are conducting a multi-telescope, multi-high angular resolution method search for close companions
  - Combining the capabilities of ground-based adaptive optics and speckle imaging with that of space-based telescopes.

- We are finding a multiplicity fraction that is discrepant with results from other studies.
- Time for a spectroscopic survey!

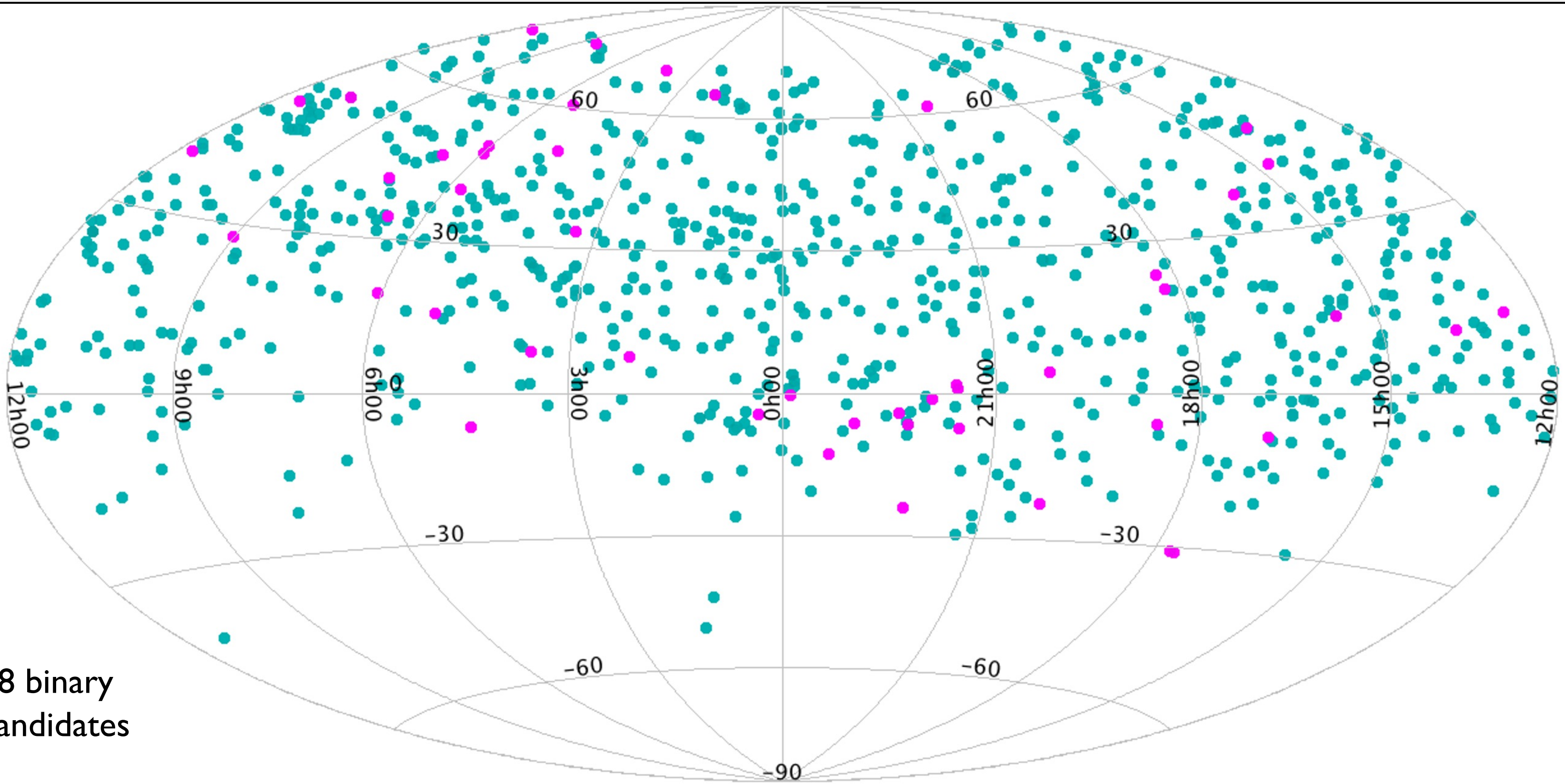
Speckle Imaging





Videos from Nic Scott, CHARA

Current Status of Lick Observations (with some additional targets included)



48 binary candidates