Dark Hole Digging Reference Star Vetting for the Roman-Coronagraph and Beyond

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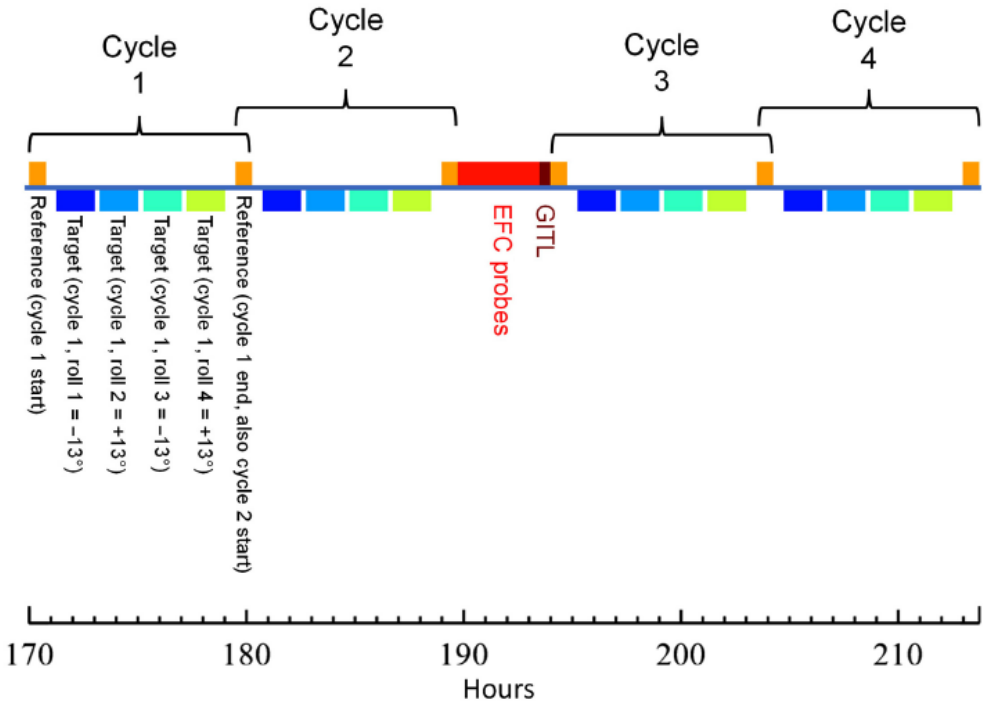
THE UNIVERSITY OF ARIZONA
COLLEGE OF SCIENCE
Astronomy
& Steward Observatory

UASAL
UArizona Space
Astrophysics Lab

Motivation

- Dark hole digging and touch-up on a nearby reference star is a required component of a typical science observation
- Science camera images of the reference star can serve as post-processing RDI references



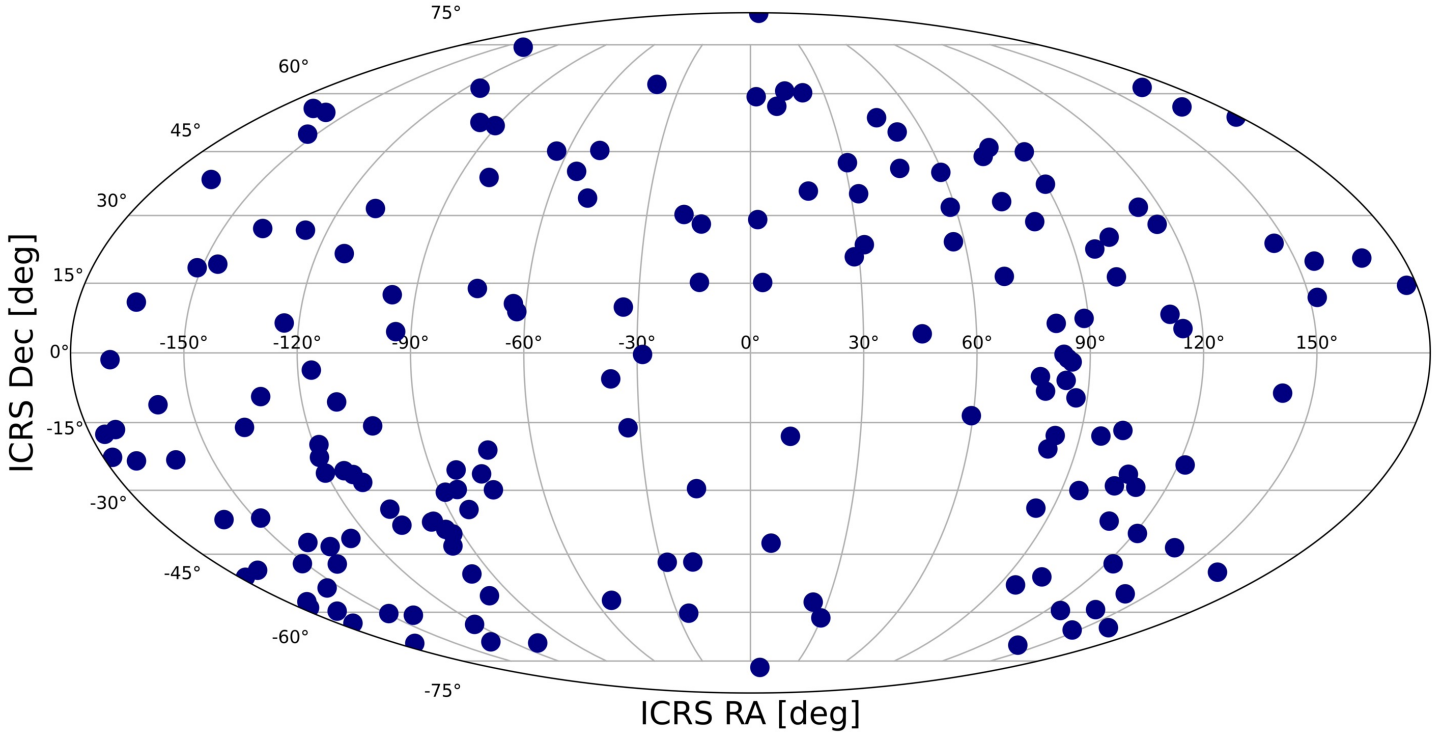
Credit: Krist et al. (2023)

Reference Star Criteria

- $V < 3$
- Resolved angular stellar diameter < 2 mas
- Cannot have any companions (bound and background) that may inhibit dark hole digging
  - Specifically, no off-axis sources where $\Delta mag \leq 17.5$ in the dark hole region (~100-450 mas HLC Band 1, ~400-1400 mas SPC-WFOV Band 4)
  - Bright companions interior to IWA severely impact observatory pointing stability
  - Other off-axis sources interior to IWA and exterior to OWA may still be problematic depending on brightness and separation
- Science targets must be within 5 degrees of observatory pitch angle from the reference star

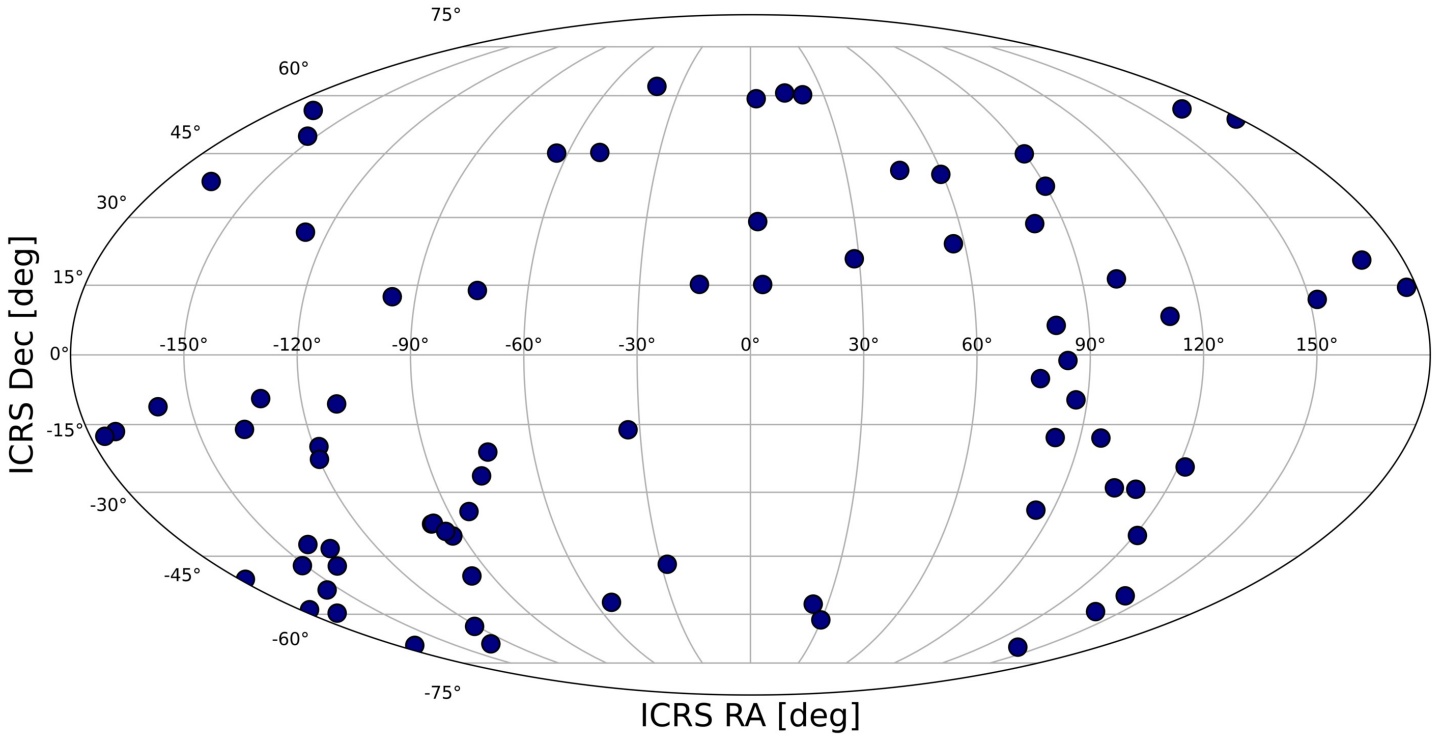
See Wolff et al. (2024), Proc. SPIE for more details

Reference Star Criteria



187 Stars where $V < 3$

Reference Star Criteria

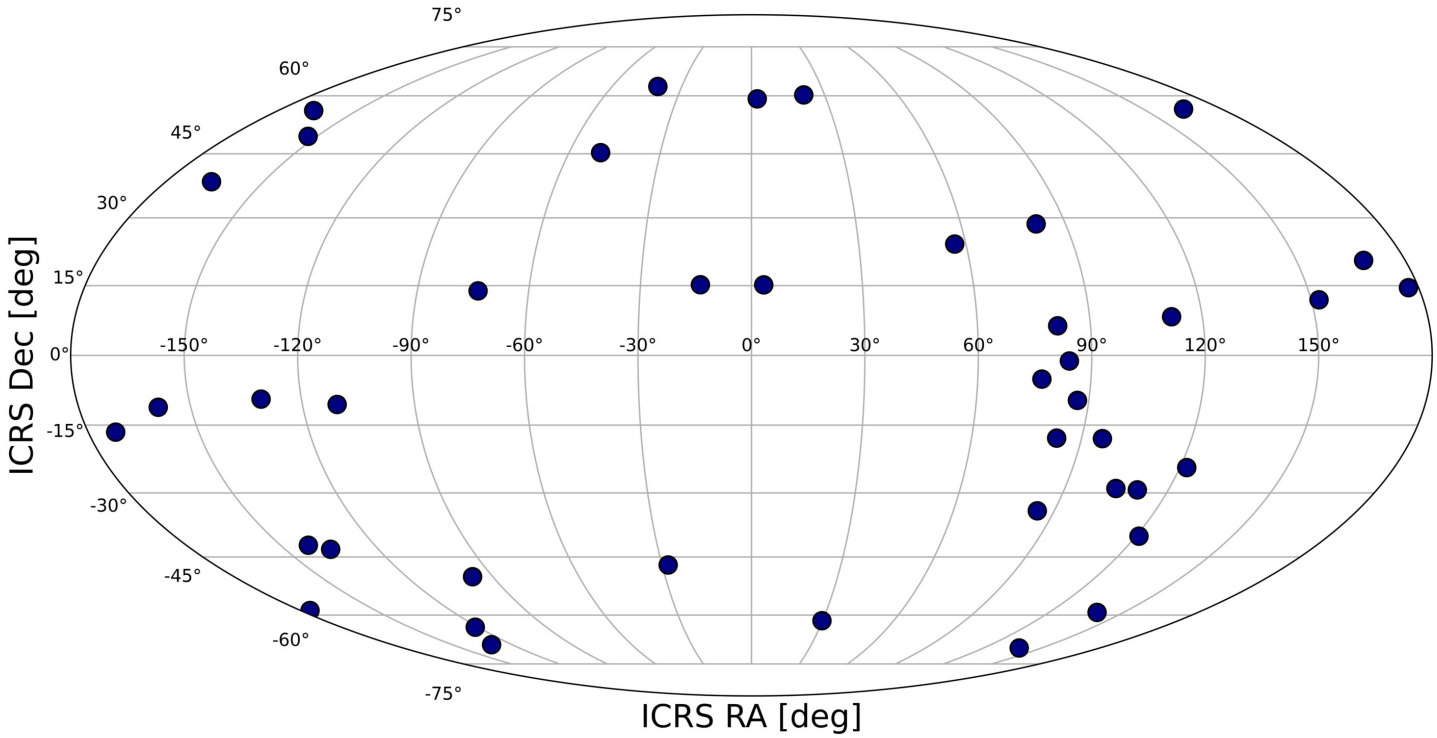


~70 Stars where $V < 3$ and $UDD_V \leq 2$ mas

The first three criteria are a perfect storm…

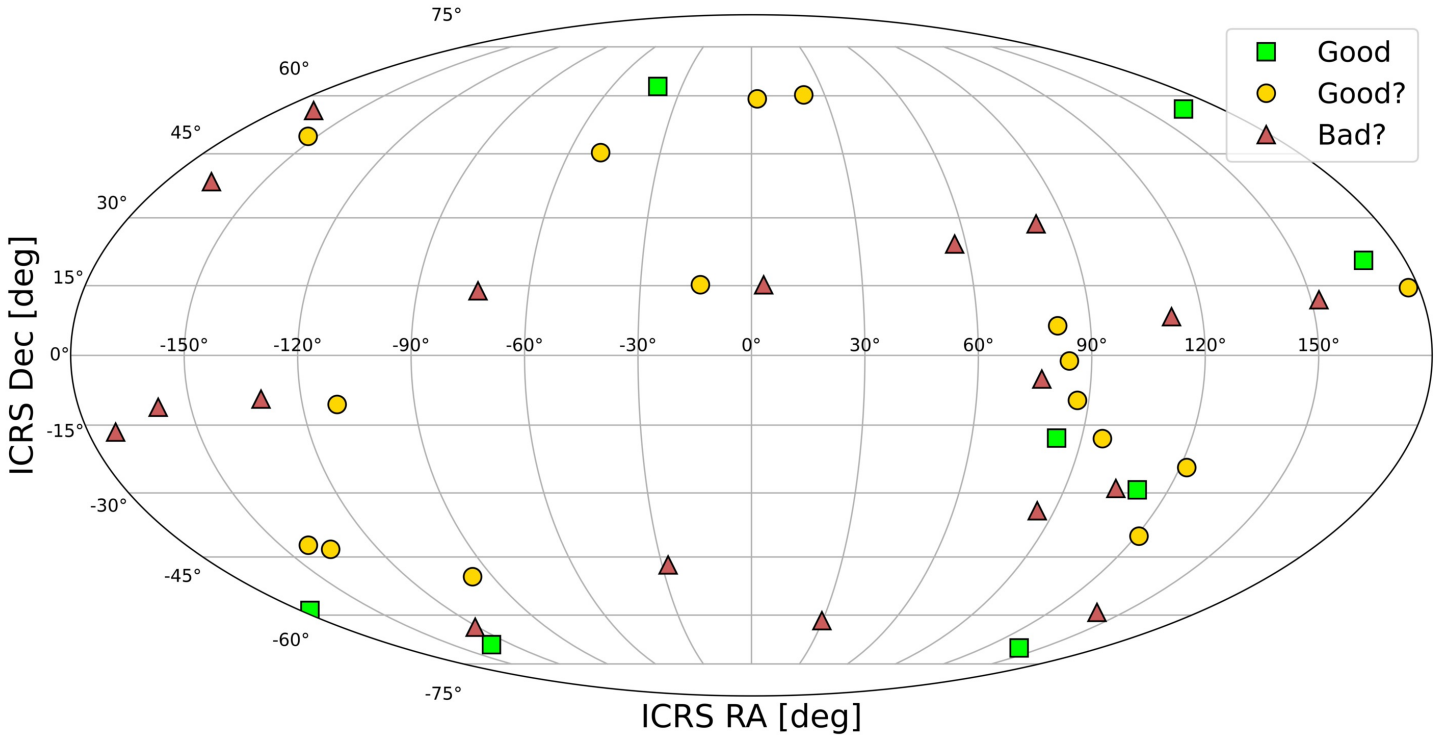
- From our magnitude and diameter criteria, all reference star candidates are massive stars: OBA main sequence, BAFGK post-main sequence
- Multiplicity occurrence rate is estimated at >50% and as high as ~80-90% for the highest mass stars
- Investigated WDS, spectroscopic and astrometric binary catalogs, and other literature and unpublished data sources

Reference Star Criteria



40 Stars remaining, no strong evidence of a problematic binary companion…yet

Reference Star Criteria



Current Candidates are not a Monolith!

Putting it all together

- If we pick a bad reference star for an observation, dark hole digging will fail and we will waste several hours of the guaranteed 90 day Observation Phase
- Availability of reference stars at a given time dictates when science targets can be observed
- We must verify that our reference star candidates are suitable well in advance of science operations
- A poor reference star choice for one observing mode may not be a poor choice for another observing mode
- If necessary, we may need to relax criteria to gain back sky coverage/scheduling flexibility at the cost of degraded performance

What will thorough vetting require?

- Extensive archival direct imaging data investigation
- New AO imaging, optical/IR interferometry, and high contrast imaging observing campaigns for all targets

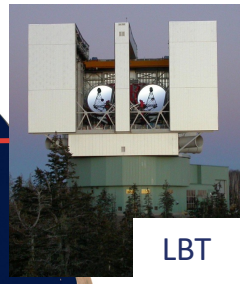
AO Imaging
Speckle Imaging
Interferometry
High Contrast

MIRC-X
MYSTIC
SPICA

CHARA

Hale

PHARO



LBT

SHARK-NIR
SHARK-VIS
LBTI/LMIRCam

NIRI
'Alopeke

Gemini-N

VLT

NACO
ERIS
SPHERE
PIONIER
GRAVITY

HiCIAO
CHARIS
VAMPIRES

Subaru

Magellan

MagAO-X

NIRC2
OSIRIS

Keck

Gemini-S

NICI
GPI
Zorro

The CPP Reference Stars Sub-WG

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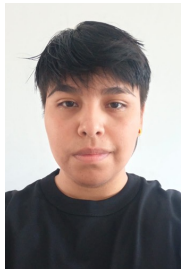
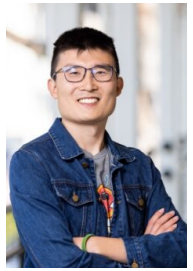


Macarena Vega Pallauta MPIA

Nicholas Schragal U. Arizona



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External Collaborators

- John Monnier
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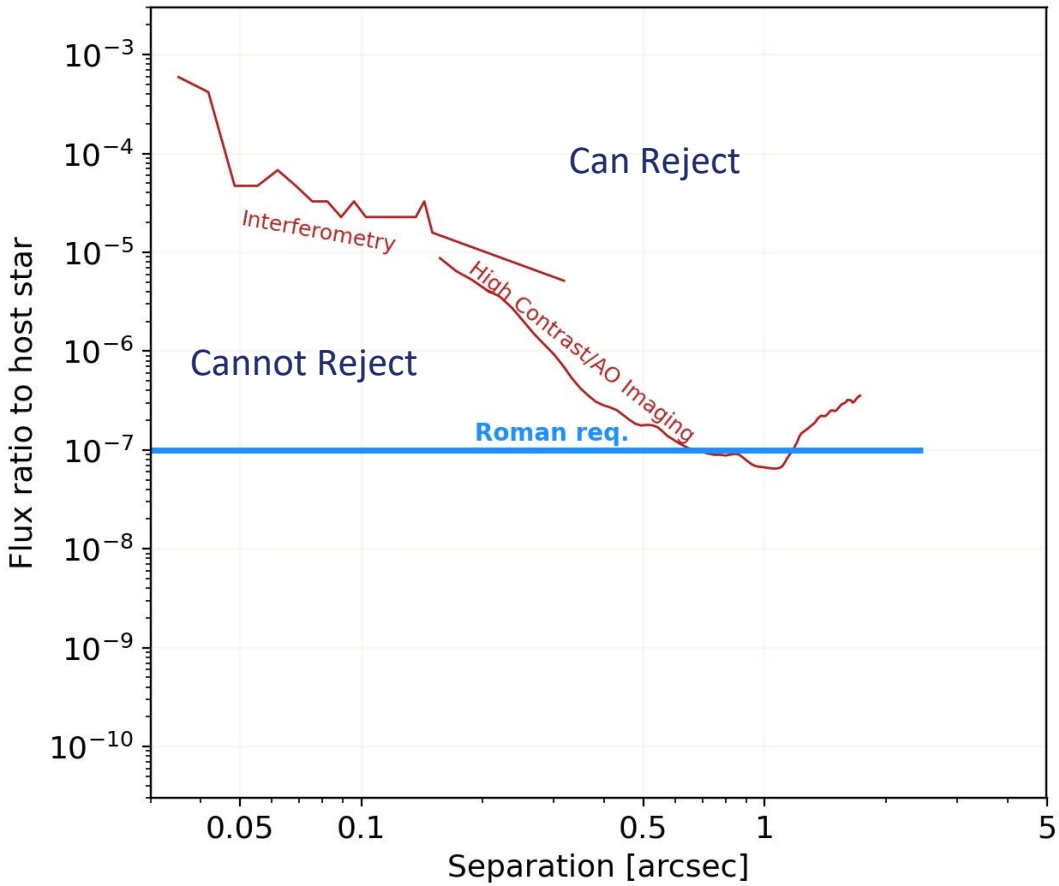
- Fernando Pedichini
- Simone Antoniucci
- Olivier Guyon
- Luci Lilley
- Miles Lucas
- Rebecca Zhang
- Barnaby Norris
- Sloane Wiktorowicz
- Jennifer Patience
- Jarron Leisenring
- Becky Flores

Duties and Goals of the WG

- Reduce and analyze archival and newly obtained direct imaging data to determine the presence of companions around reference stars (<- we are here!)
- Set deep rejection limits for reference stars to grade suitability for science operations
- Catalog properties of reference stars necessary for simulations, scheduling, and exposure time calculations
- Determine a metric for selecting reference stars for a given science observation
- Release the results of our investigation in publications and as an online resource

Towards Deep Rejection Limits for all Reference Stars

We already have over 200 hours of approved visible/NIR observing time from Fall 2024-end of Spring 2025 to vet candidates



Made with https://github.com/nasavbailey/DI-flux-ratio-plot/

*Curves are optimal NIR rejection limits

Lessons Learned/Being Learned for HWO

- The outlook for dark hole digging stars may seriously impact survey campaigns for HWO IF:
  - An HWO coronagraph follows a similar observing procedure as the Roman-Coronagraph
  - Reference stars have similarly strict criteria:
    - Brightness (going fainter provides more options but increases exposure times)
    - Stellar diameters (tolerance to diameters depends on coronagraph architecture)
    - Pitch angle change (dark holes would need to be more robust against thermal variations)
    - Color restrictions (no reference stars are FGK main sequence)
  - Can we make dark holes stable for longer periods of time?
  - Roman-Coronagraph may be able to survey/vet HWO calibration/reference targets during an extended mission, but the criteria for these targets must be determined

Summary

- Reference stars are a critical component of Roman-Coronagraph science operations, but have extremely strict criteria
- To maximize the success and efficiency of the mission, these sources must be thoroughly investigated and characterized
- This is a significant effort that requires a large team to investigate the 100+ datasets available
- The results of our investigation may have a significant impact on HWO observation planning
- The reference star rabbit hole only gets deeper…
- Have any feedback or knowledge of any of our reference stars? See Wolff et al. (2024), Proc. SPIE Volume 13092, id. 1309255
- Want to get involved? Contact me: jrhom@arizona.edu

^See the list of reference stars and desired new observations here https://tinyurl.com/CorGIRefStars

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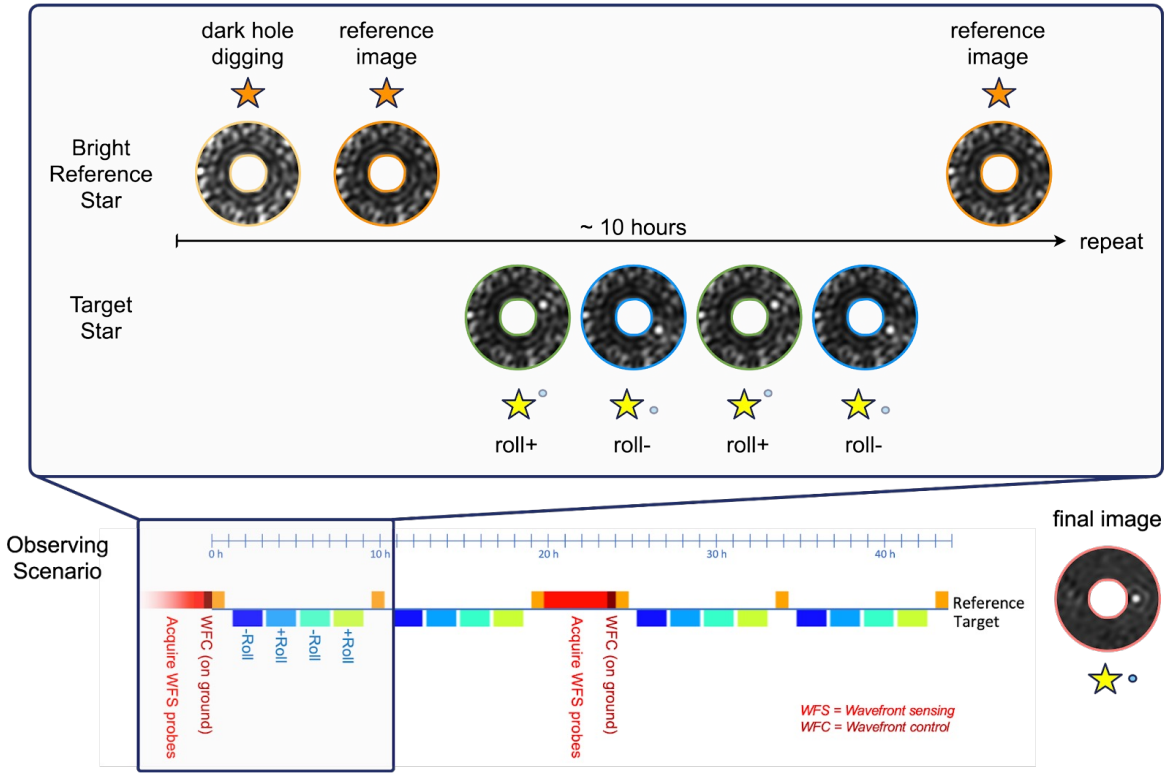
Backup Slides

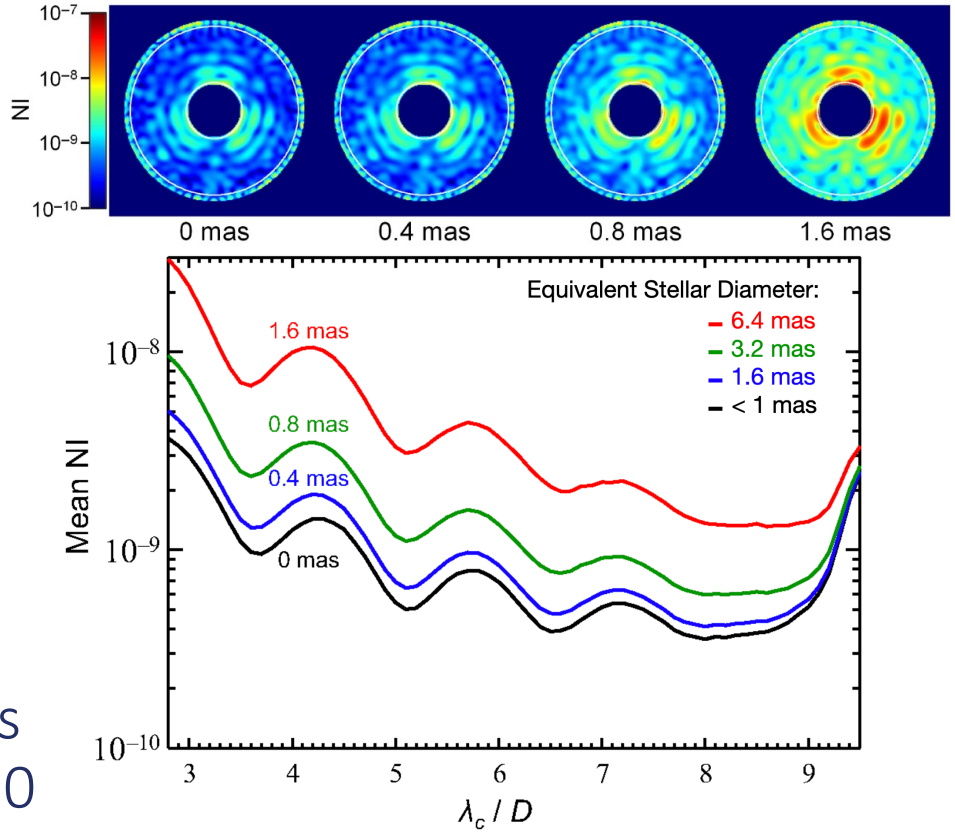
Roman-Coronagraph Observing Sequence



Credit: Julien Girard; Note that sequence time varies and scales with ref. star magnitude

Reference Star Criteria - Detailed

- Small resolved stellar diameters
- A resolved stellar diameter introduces speckles in a similar manner as jitter
- D_* ~0.25 effect in jitter
- Bigger stars, greater contrast degradation
- Our threshold: $D_* < 2$ mas
- Our original threshold was < 1 mas but this was too restrictive (only 20 total candidates)

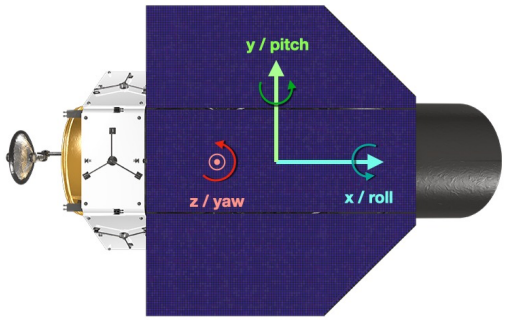


Credit: Krist et al. (2023)

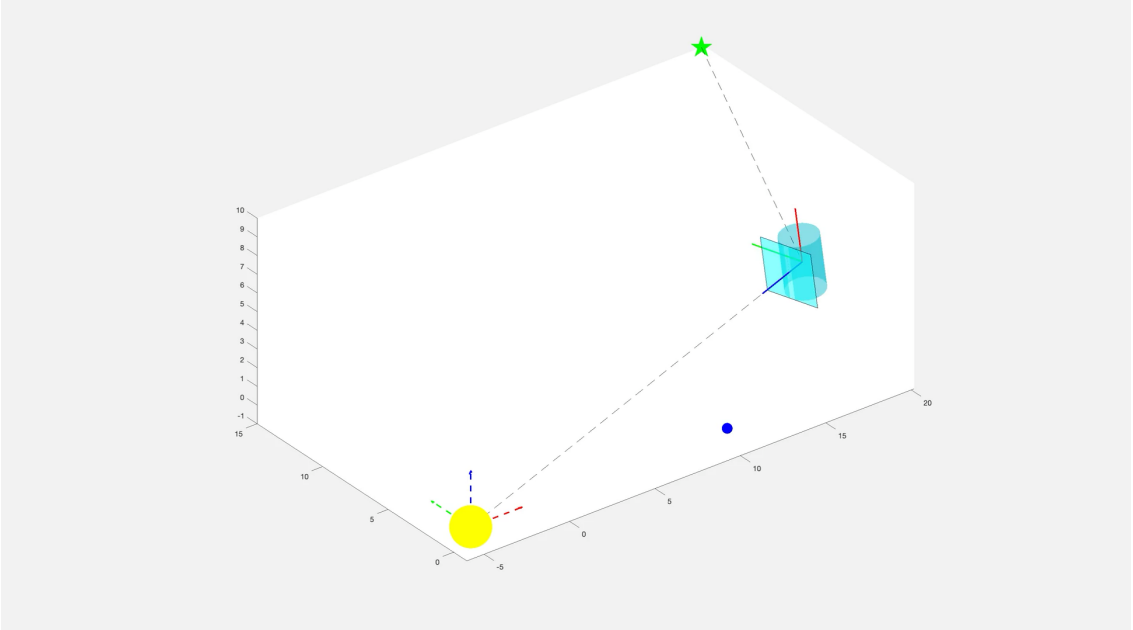
Reference Star Criteria - Detailed

- No companions (visual or bound) brighter than 10^{-7} contrast within the dark hole
- No companions brighter than target *V*+3 within 1.3”
- Companions inside the IWA can affect stable pointing (i.e., more jitter)
- Companions outside the OWA can introduce their own speckles
- All of these effects can significantly degrade the dark hole contrast
- Best case: reference star is a poor RDI match to science
- Worst case: dark hole digging fails outright
- If the worst case, we will have wasted several hours from our allocated 90 days

Reference Star Criteria - Detailed



Credit: IPAC



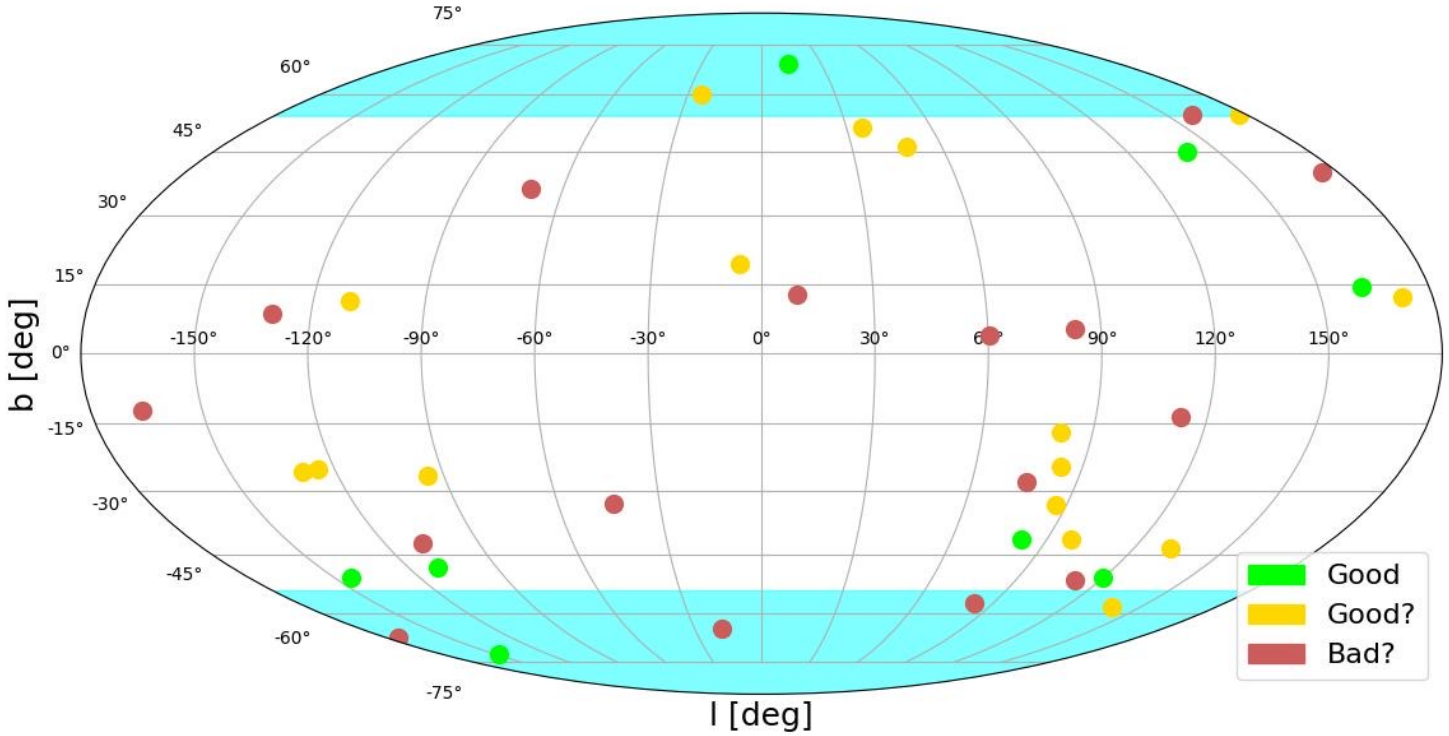
Credit: Dmitry Savransky

Instrument data currently being investigated

Instrument	Data Type
CHARA/MIRC(-X)/MYSTIC	Interferometry
CHARA/SPICA	Interferometry
Gemini/'Alopeke/Zorro	Speckle imaging
Gemini/GPI	HCI
Gemini/NIRI	AO imaging
Gemini/NICI	HCI
Keck/NIRC2	HCI
Keck/OSIRIS	AO imaging
LBTI/LMIRCam	AO imaging/HCI
LBT/SHARK-NIR	HCI
LBT/SHARK-VIS	HCI

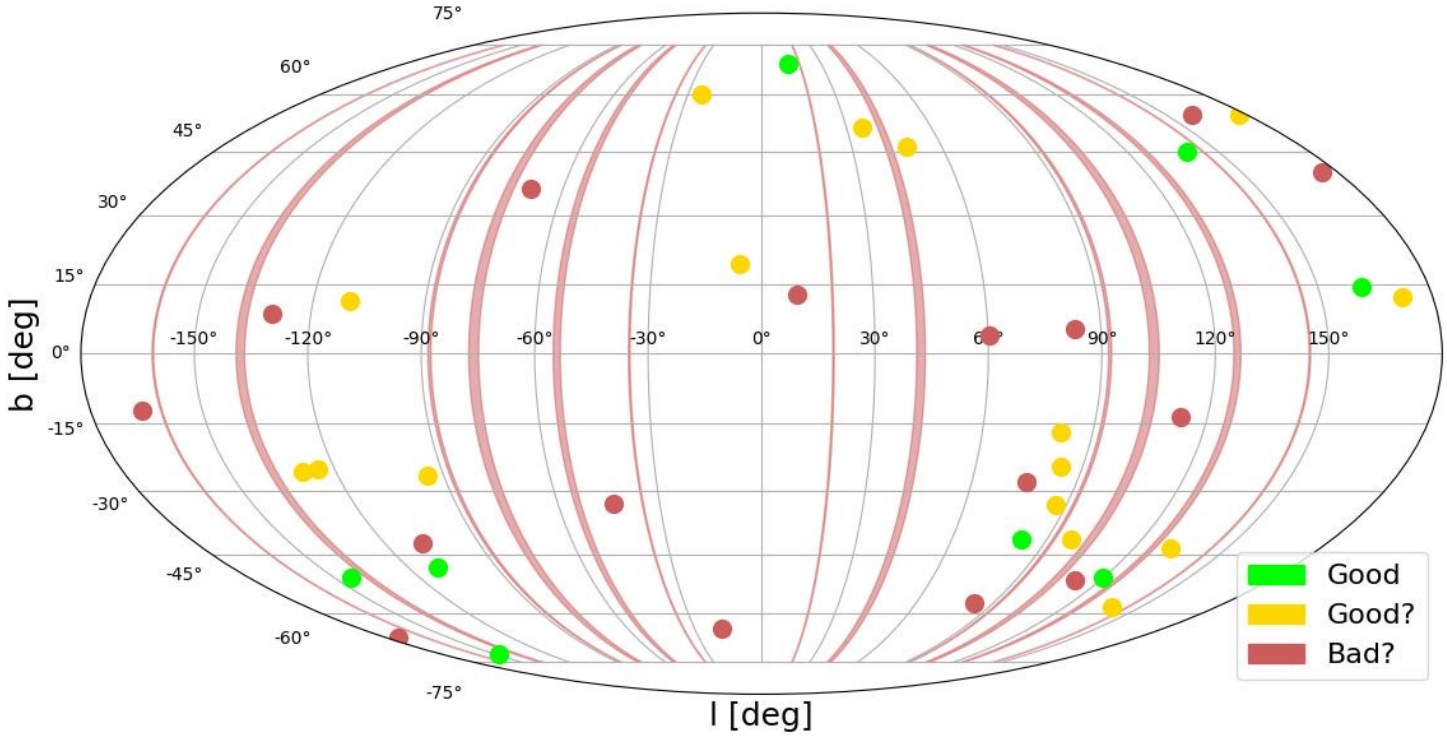
Instrument	Data Type
Magellan/MagAO-X	HCI
Palomar/PHARO-AO	AO imaging
Subaru/CHARIS	HCI
Subaru/HiCIAO	HCI
Subaru/VAMPIRES	HCI
VLT/ERIS	AO imaging/HCI
VLTI/GRAVITY	Interferometry
VLT/NACO	HCI
VLTI/PIONIER	Interferometry
VLT/SPHERE	HCI

Continuous Viewing Zone Availability



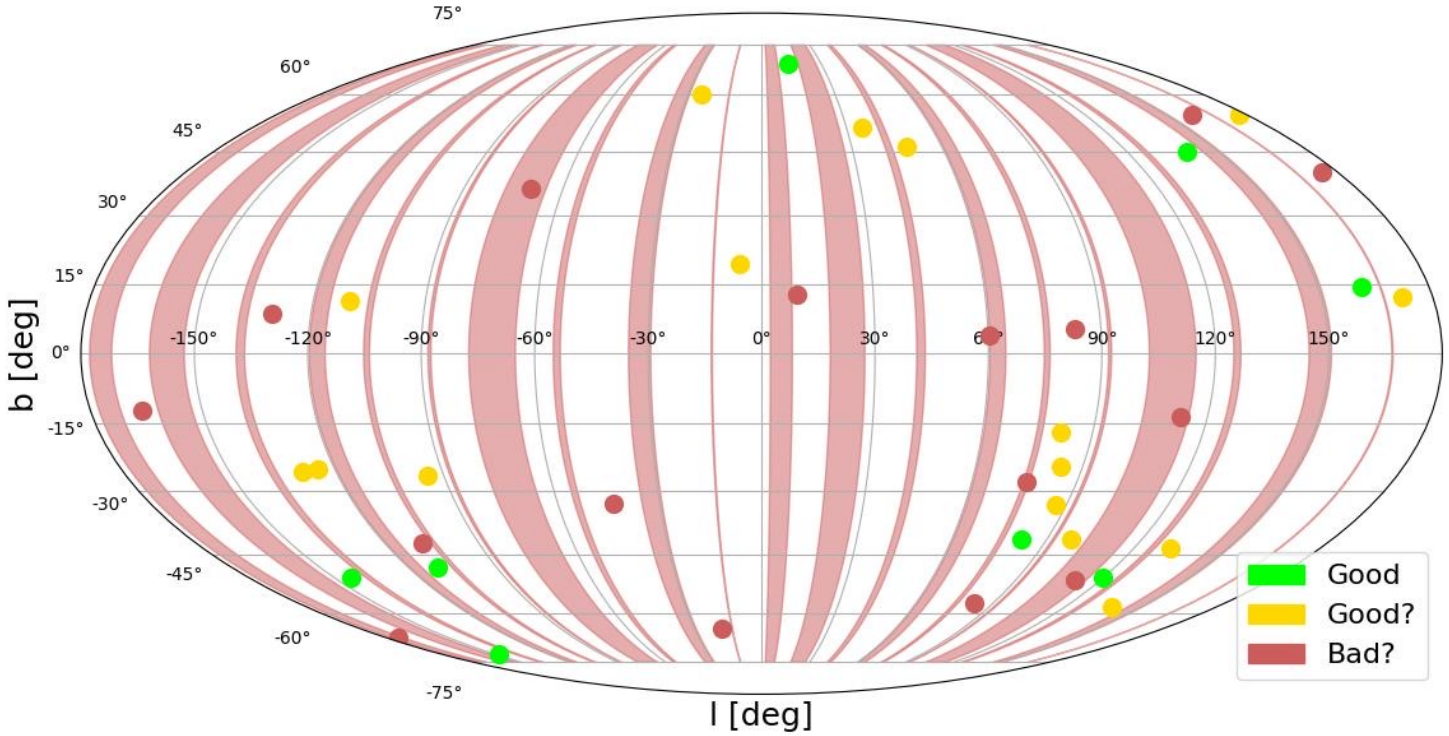
A modest sample of reference star candidates are in the continuous viewing zone

Gaps in Sky Coverage (Overly Pessimistic)



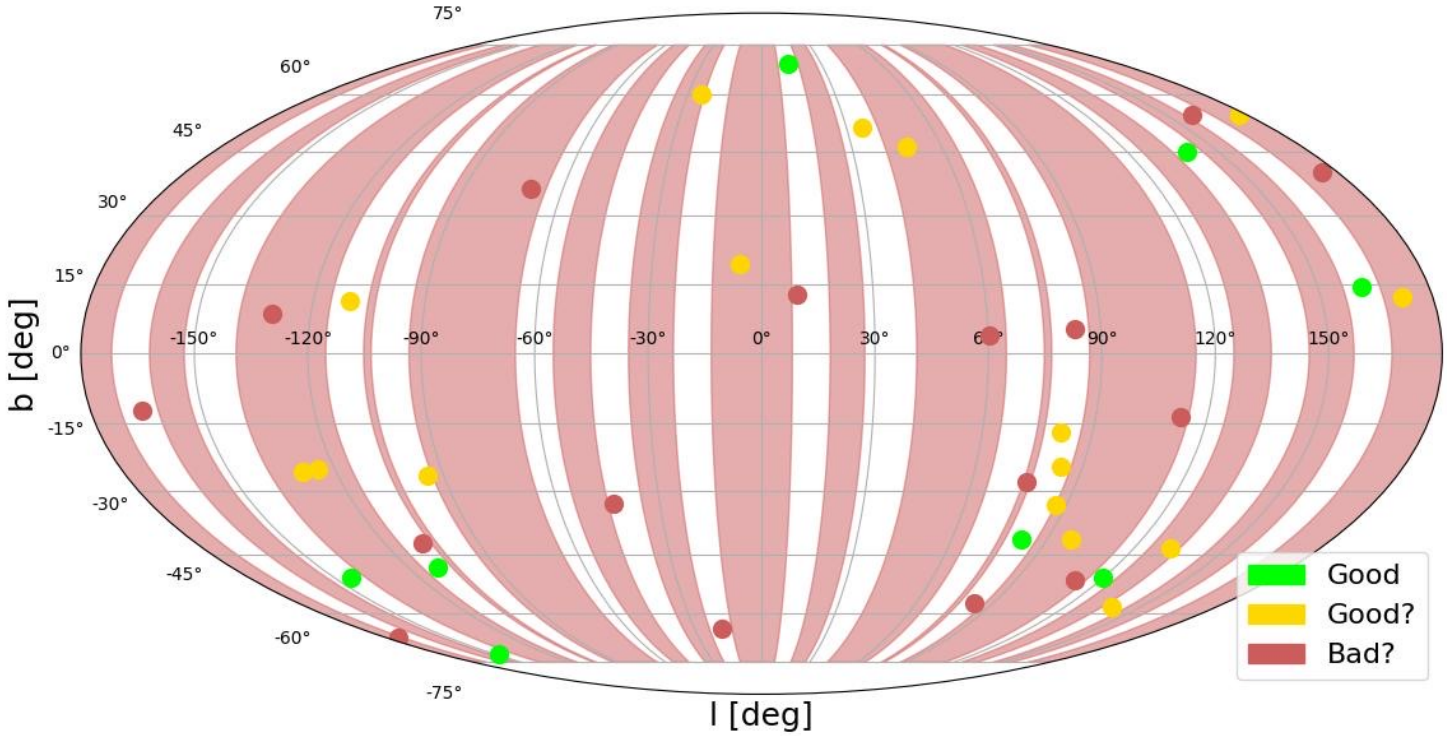
Assuming all candidates are suitable

Gaps in Sky Coverage (Overly Pessimistic)



Assuming all “Good” and “Good?” are suitable

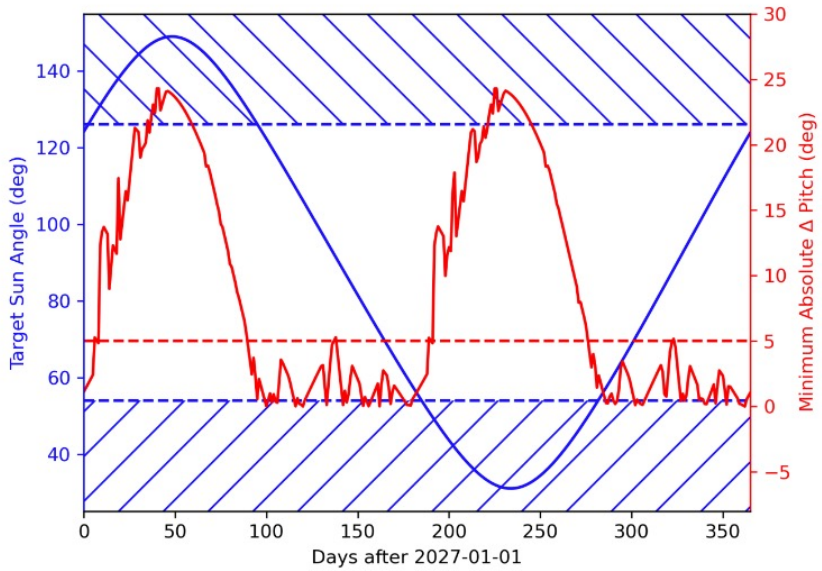
Gaps in Sky Coverage (Overly Pessimistic)



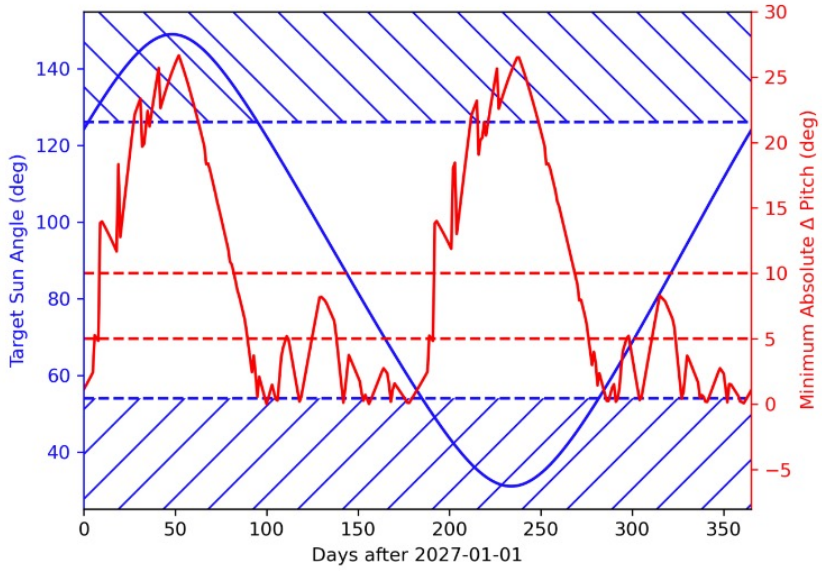
Assuming only “Good” candidates are suitable

Scheduling Flexibility Example: 47 UMa

All Reference Stars Usable

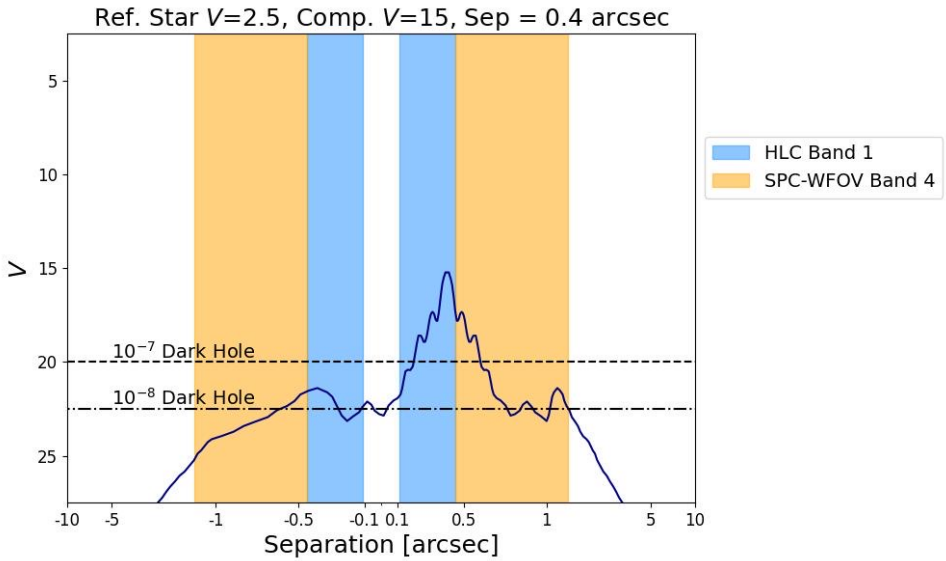


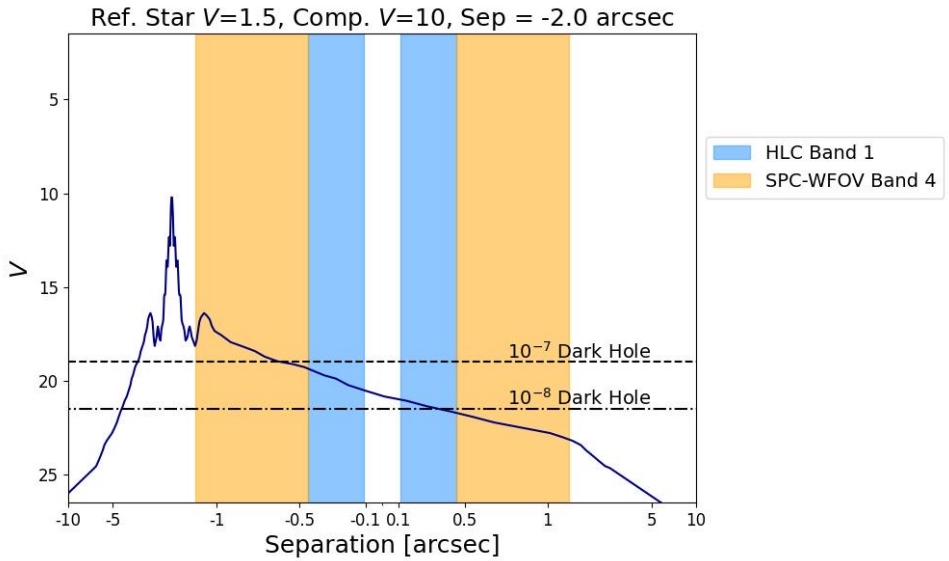
Only Good/Good? Usable



Credit: Dmitry Savransky

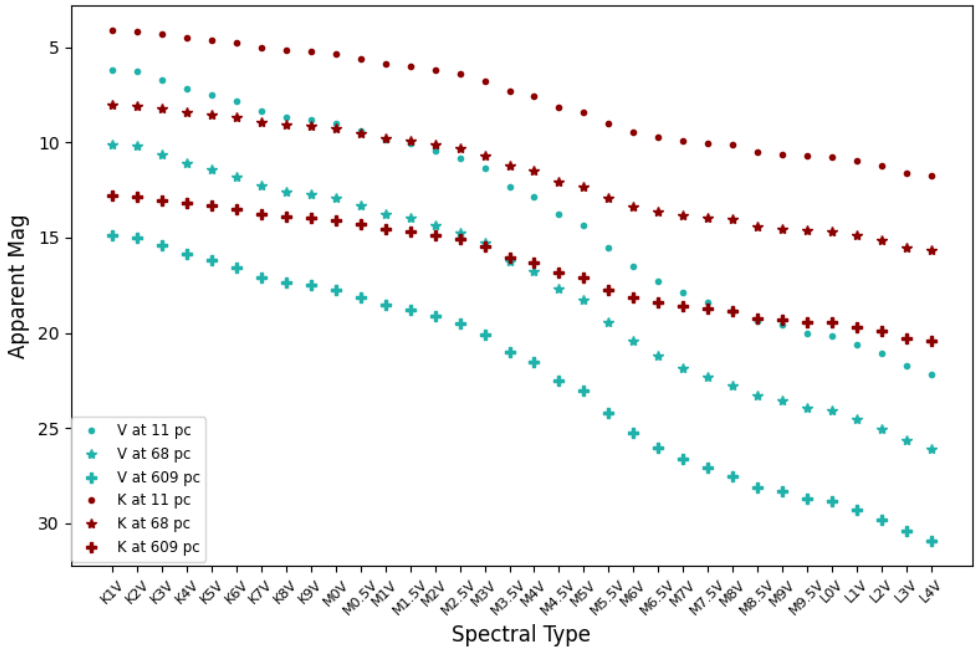
How Off-Axis Companions Impact DH Contrast

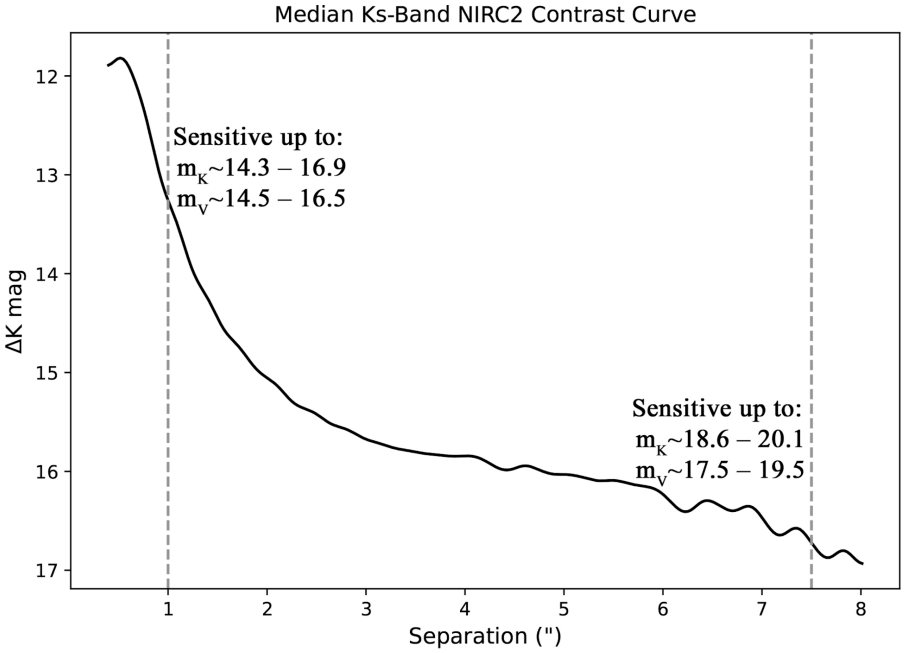




*Unocculted HLC PSF profile is sourced from: https://roman.ipac.caltech.edu/

Pushing how far we can reject companions





Credit: Marah Brinjikji