Simulations for Upcoming and Proposed Exoplanet Surveys as Pathfinders for Direct Imaging Missions

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Survey Simulations 1
Survey Simulations 2
Orbiting Photometric Lightsource

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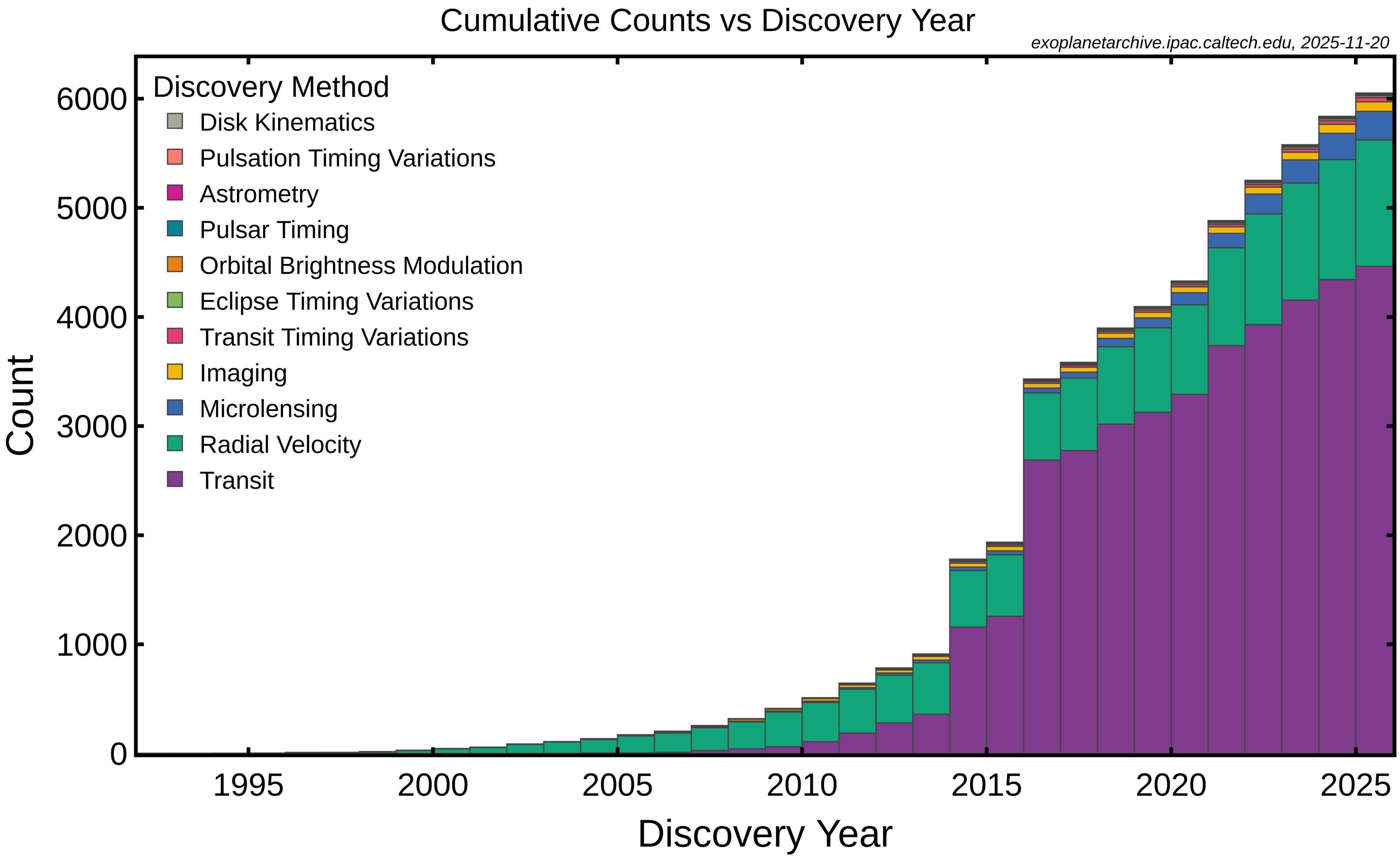


Radial Velocity Method

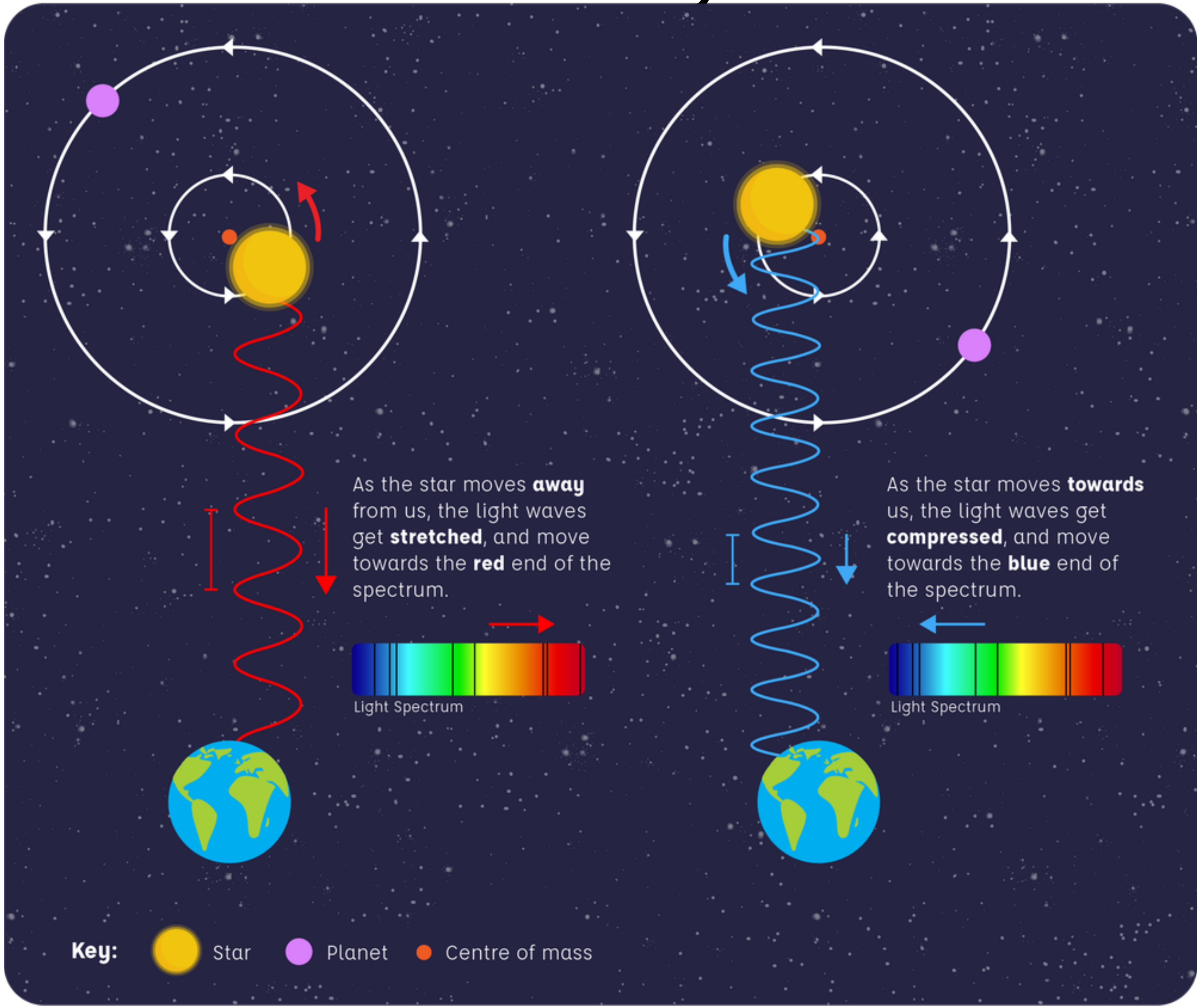


Image: Alice Hopkinson, LCO. Based on the Radial Velocity Method diagram by Jessica Barton, LCO

Radial Velocity Method

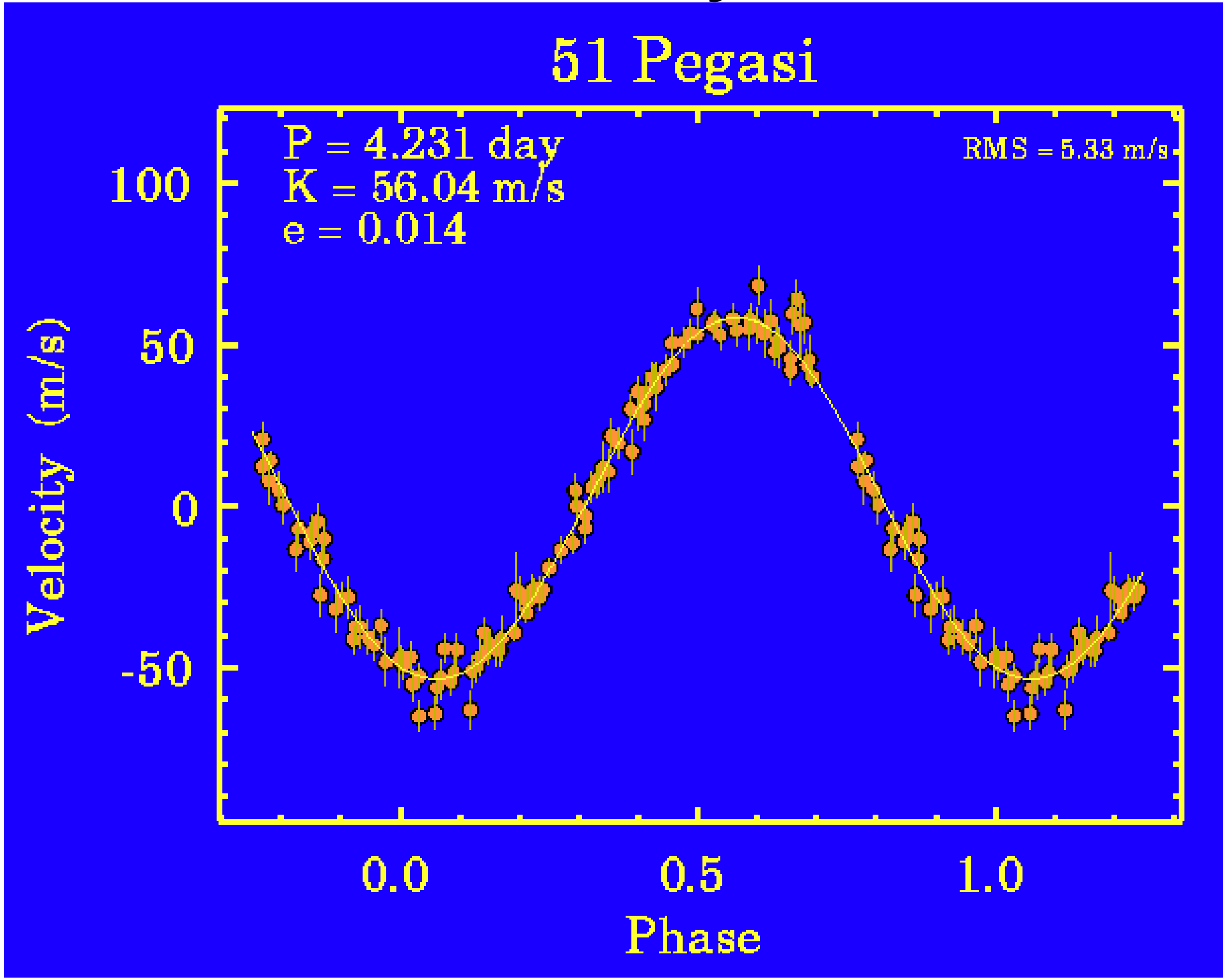


Image: exoplanets.org

Transit Method

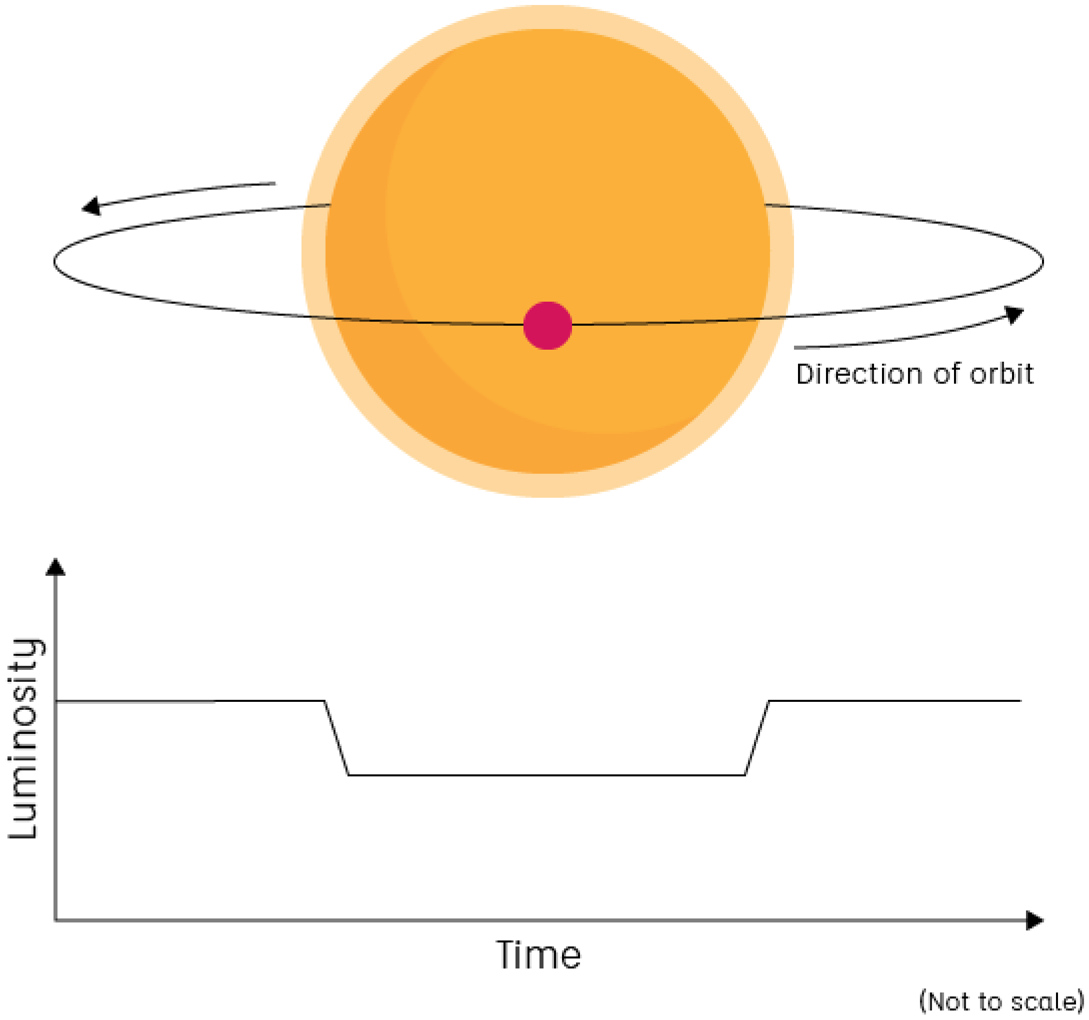
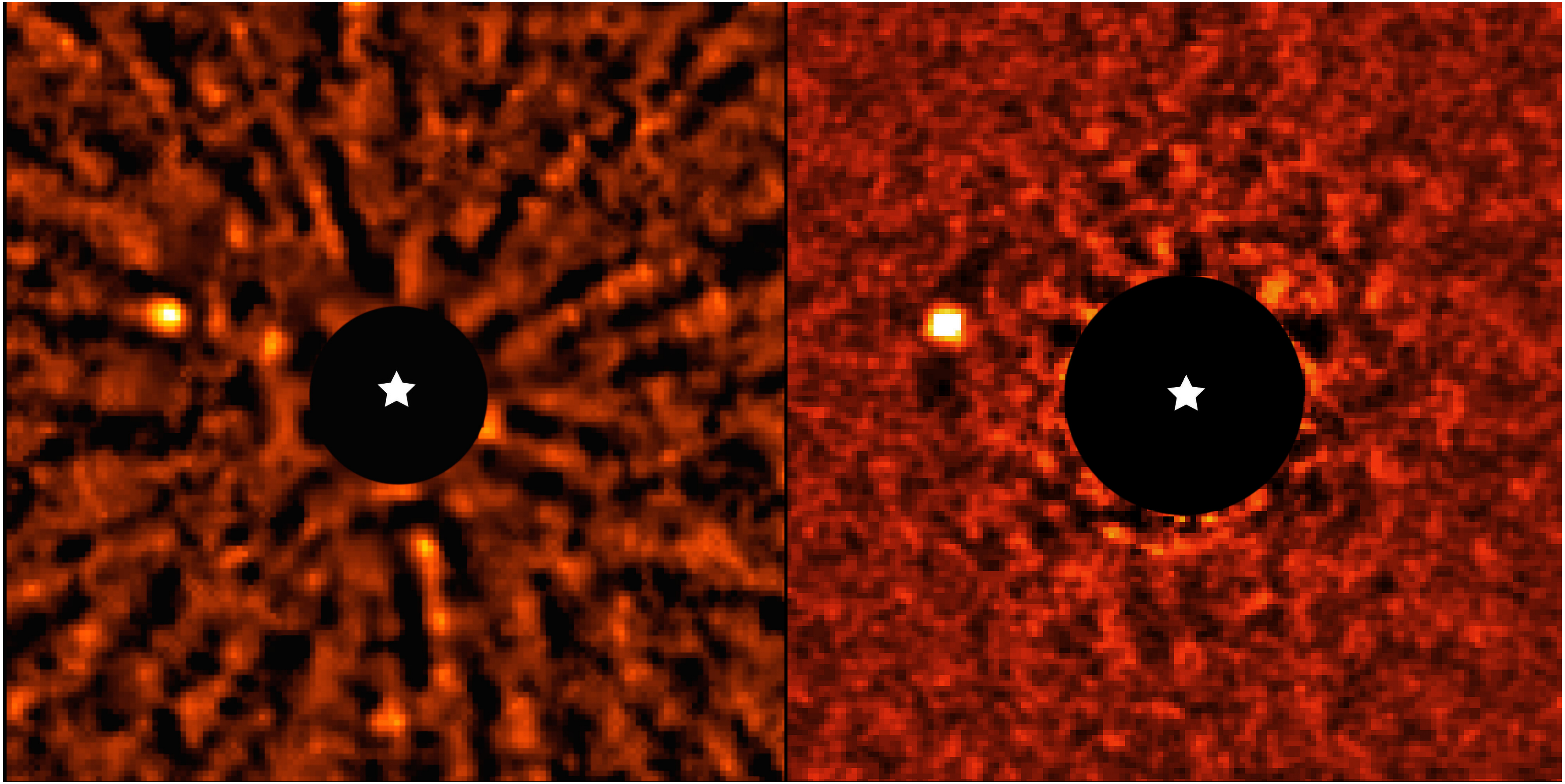


Image: LCO

Direct Imaging



AF Lep b. Image: ESO/Mesa, De Rosa et al.

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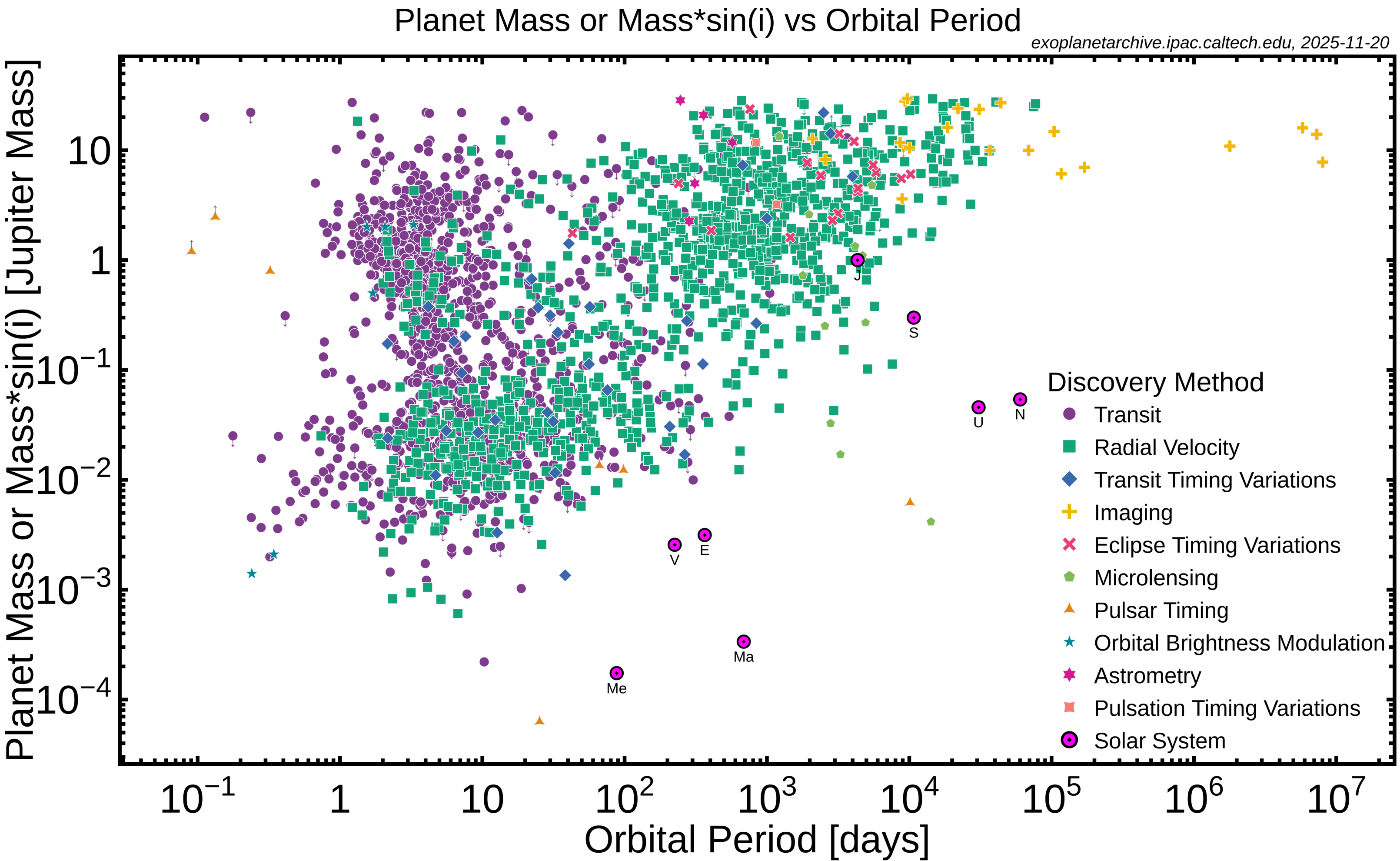


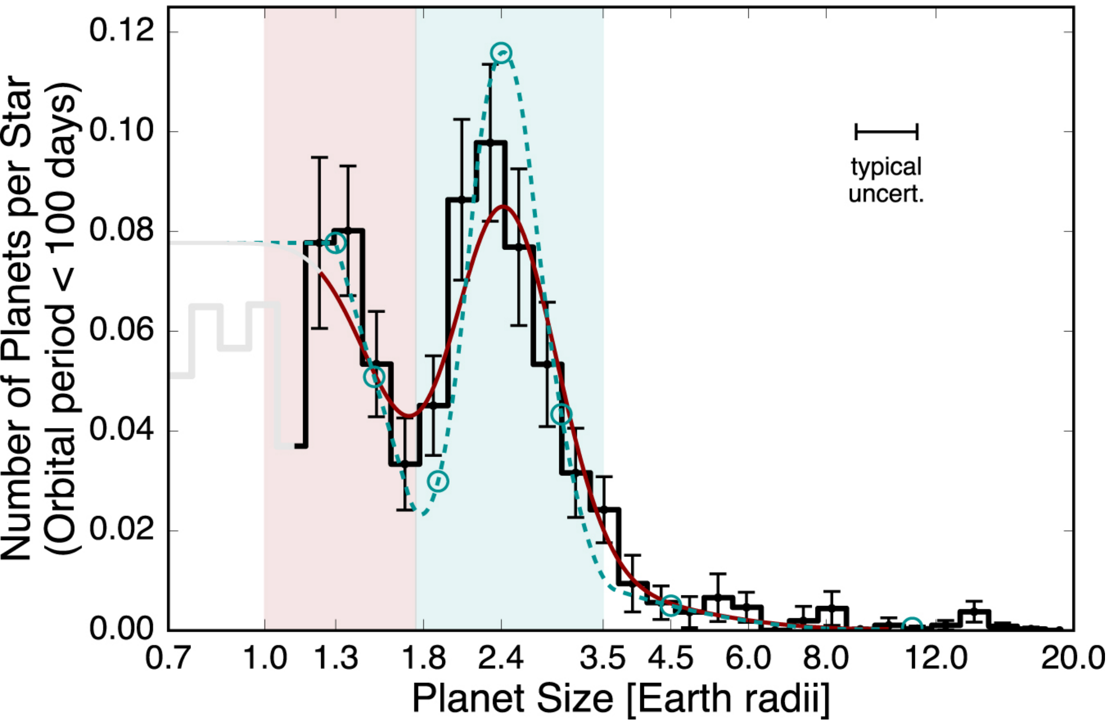
Carmenes – Terrestrial Planets around M-dwarfs

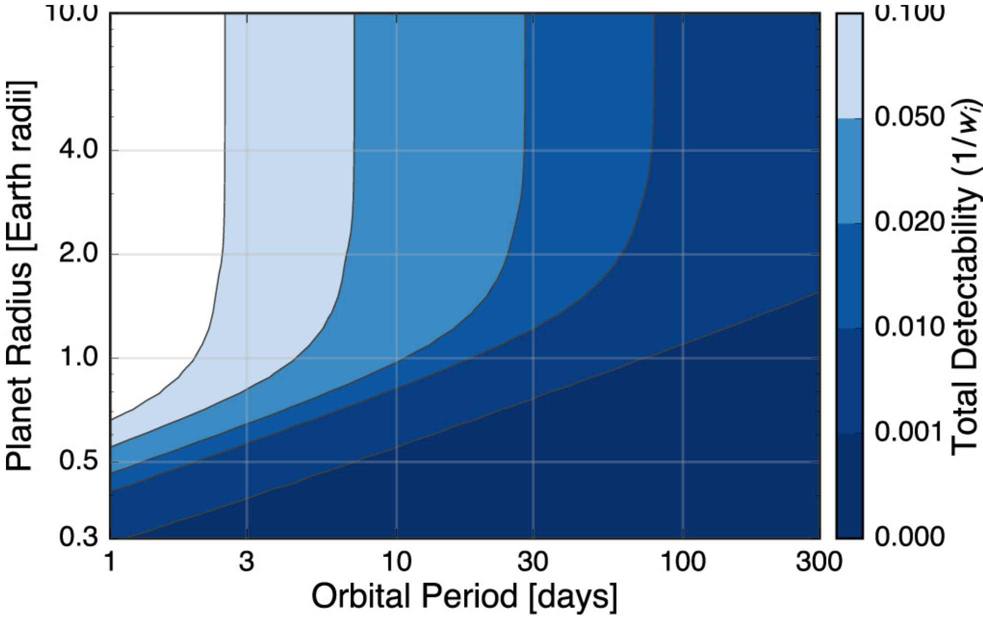
High resolution visible/near-IR spectrograph (520-1710 nm)

Has so far (late 2025) found 57 planets around M-dwarfs and 12 around earlier stars. Also confirmed another 27.

Some are Earth-mass, but M-dwarf planets are difficult to directly image and transiting ones need JWST to characterize atmospheres.

California-Kepler Survey and the Radius Gap





Visible spectrograph on Keck following up on transiting planets.
Lots of demographics, but iffy at smaller sizes and only for close-in planets.
(Fulton et al al 2017)

Survey Simulations 1

Direct Imaging characterization benefits from having planets with known orbits and masses.

RV probes a different parameter space than transits (or direct imaging).

What can current/near-future EPRV surveys do to find planets?

Survey Simulations 1 – Motivation

“NASA and NSF should establish a strategic initiative in extremely precise radial velocities (EPRVs) to develop methods and facilities for measuring the masses of temperate terrestrial planets orbiting Sun-like stars” – 2018 National Academies Exoplanet Science Strategy Report

Survey Simulations 1

Part of NASA-NSF Extreme Precision Radial Velocity Initiative

Gather community architectural designs.

Simulate surveys.

Which ones work best/are highest yield?

Simulations for Upcoming and Proposed Exoplanet Surveys as Pathfinders for Direct Imaging Missions

- Survey Simulations 1

Survey Simulations 2

Orbiting Photometric Lightsource

Survey Simulations 1 – Code Outline

Inputs

- Telescope aperture
- Telescope location
- Telescope allocation
- Instrument design
- Desired RV precision and SNR
- Properties of target stars
- Historical weather data

Dynamic Scheduler

Outputs

- Exposure times
- Observing Logs
- Targets observed, date/time
- Resulting RV precision
- Weather losses

Survey Simulations 1 – Radial Velocities

Code from Beatty et al 2015

Simulated Stellar Spectra and their RV content (but not activity)

Effective Temperature, metallicity, surface gravity, rotational velocity, macroturbulence (if available)

Telescope size, spectrograph R, detector size and noise, system throughput/efficiency

Atmosphere model

Survey Simulations 1 – Exposure Time Calculation

Target either SNR or RV value

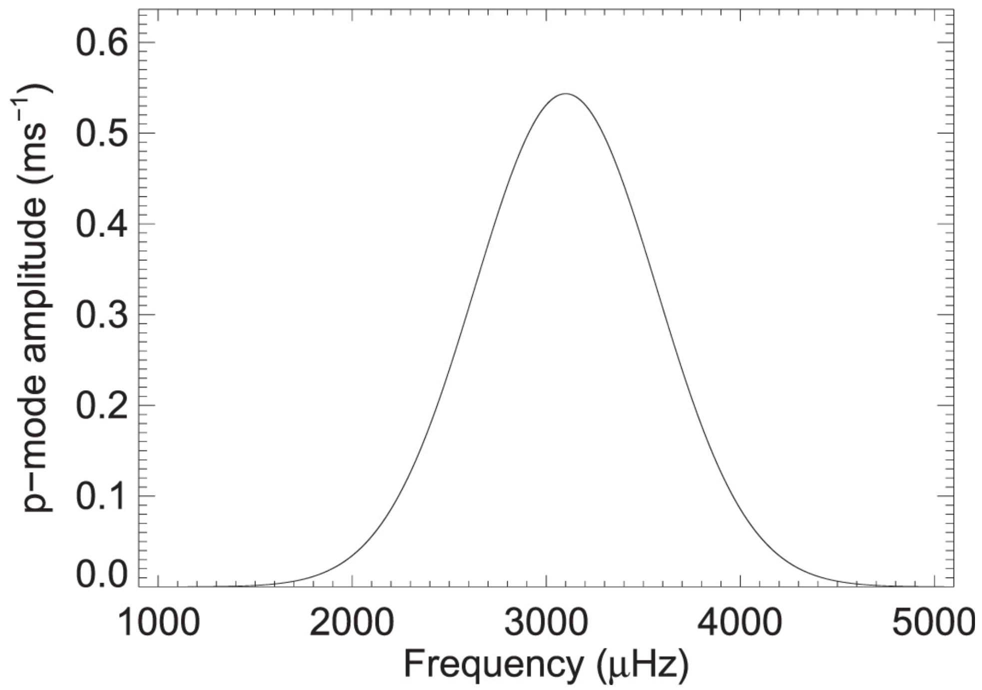
Find RV/SNR when the peak part of the detector is saturated (“guess RV” and “guess time”)

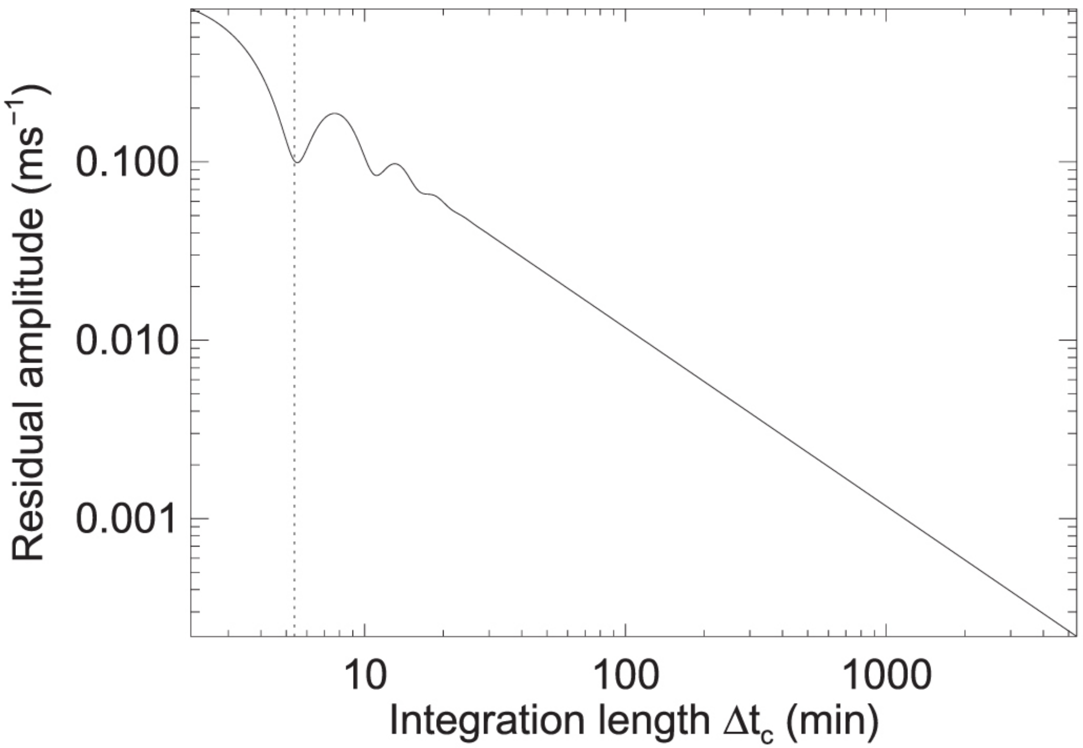
Scale by time = guess time*(target RV/guess RV)^2

This can be for multiple exposures (and readout times will be noted)

P-mode scaling

Survey Simulations 1 – P-modes





Stars wobble and oscillate. For sun-like stars, the pressure mode (p-mode) is the most important. This adds a periodic RV “signal” that we want to remove by exposing over the period of an oscillation. (Chaplin et al 2019)

Fixed 5 minute (and later 10 minute) minimums to cover typical and worst cases in the sample stars.

Survey Simulations 1 – Dispatch Scheduler

MINERVA Telescopes
Credit: CfA/Rick Peterson

Survey Simulations 1 – Dispatch Scheduler

Derived from MINERVA’s observation program

Picks targets “on the fly”

Slew time, sun angle, telescope lat/long/alt, pointing limits, moon avoidance, weather

Survey Simulations 1 – Dispatch Scheduler

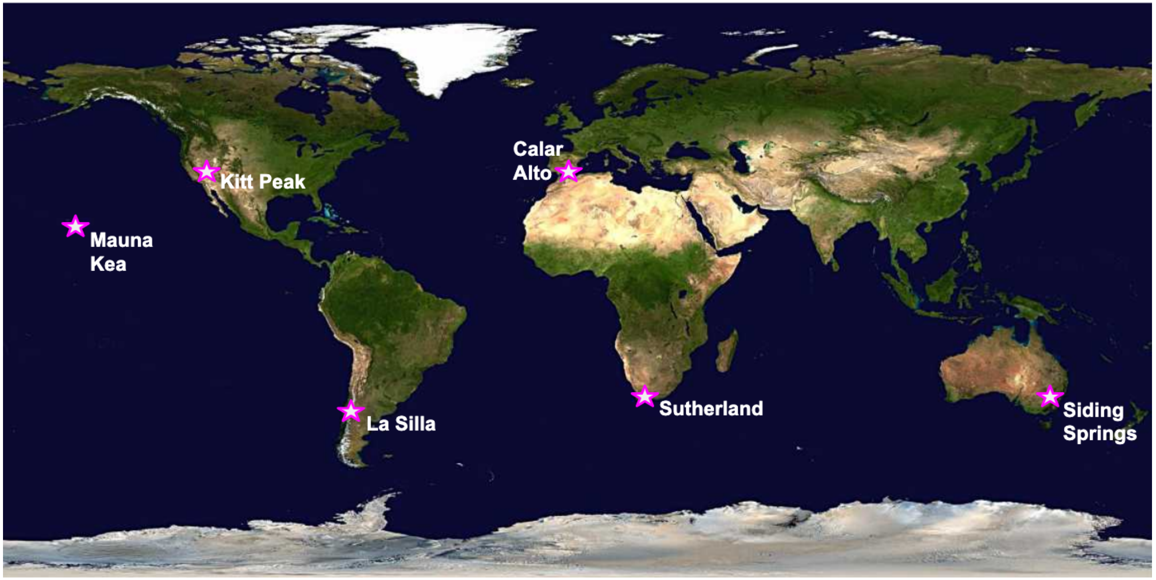
Typical night

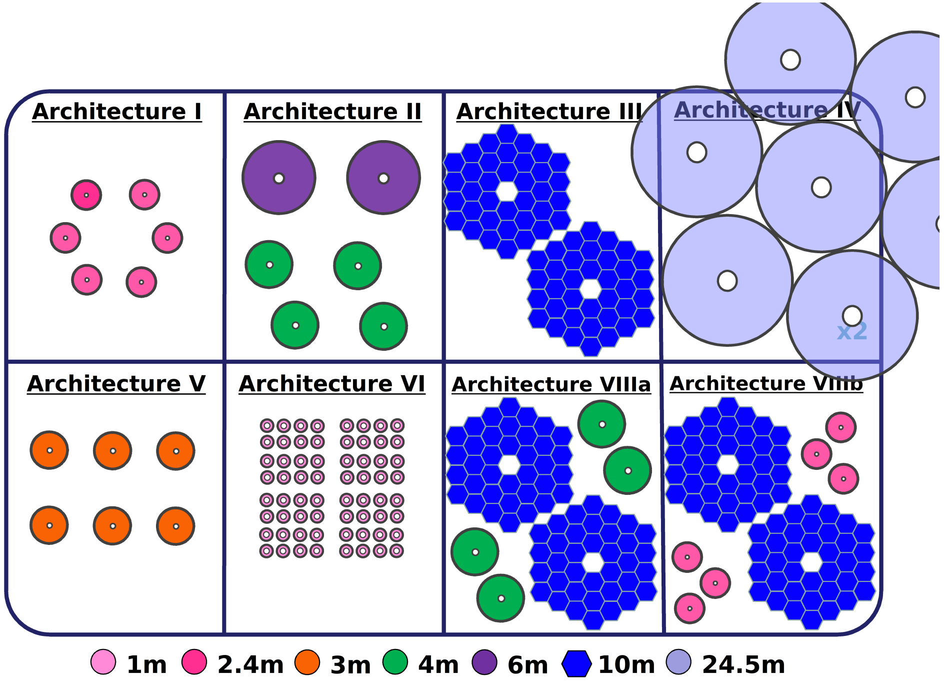
Advance time to “full dark” (default -12° altitude for Sun)
Check to see if the night is clear, or lost due to weather
If the night is cloudy, advance time to dawn
If the night is clear, prep target list (determining which stars are observable due to sufficient separation from the moon, and being above the horizon)
Begin observation loop

Observation loop

Generate weightings for the target stars
Pick highest weighted target
If the target has a positive weight, observe it for the duration specified
Wait five minutes (this is done whether or not a target is observed.)
Repeat until dawn

Survey Simulations 1 - Architectures

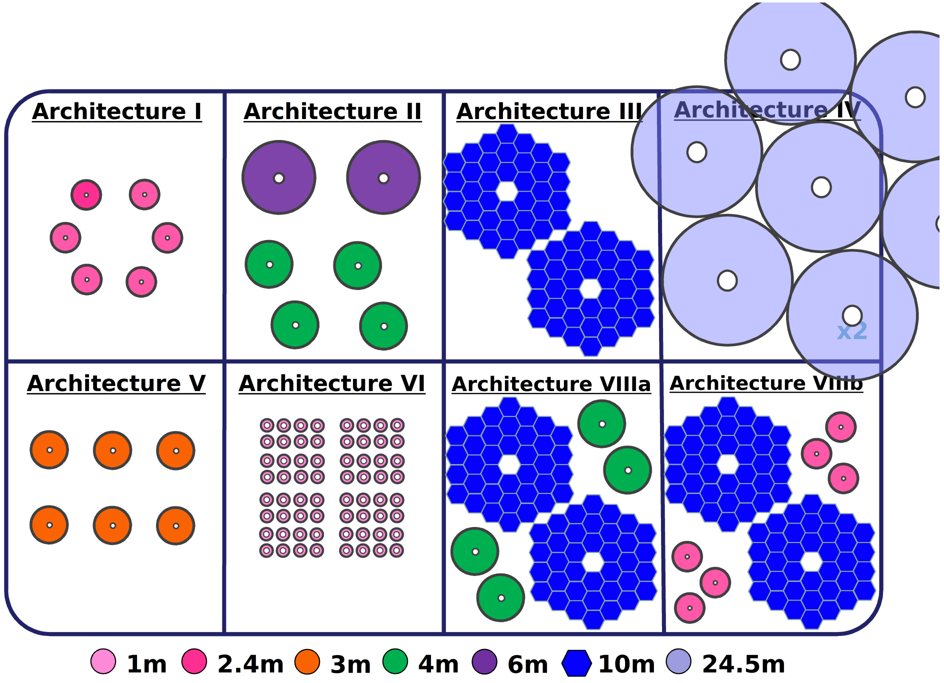




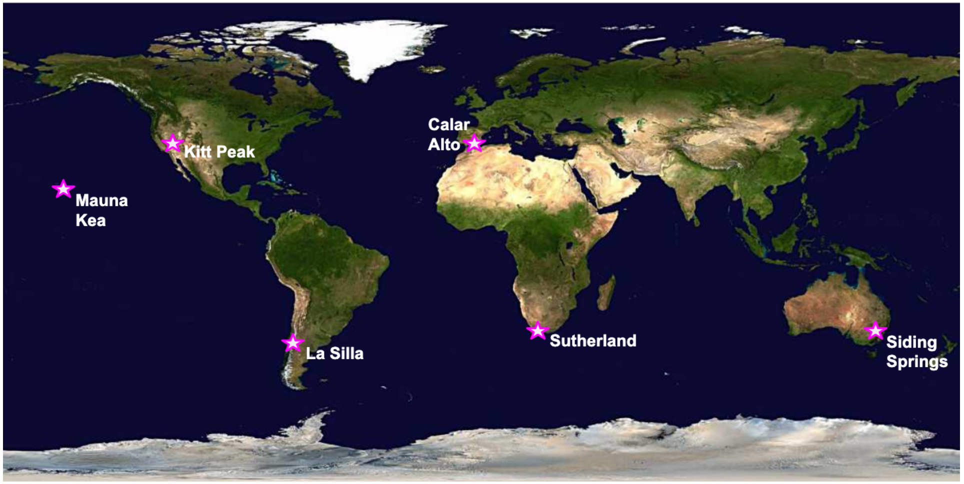
Survey Simulations 1 - Architectures

Differing telescope sizes and availability
Defined Instrument (NEID)
“Champion” Instrument (varies per-architecture)
Peak SNR vs single measurement RV precision

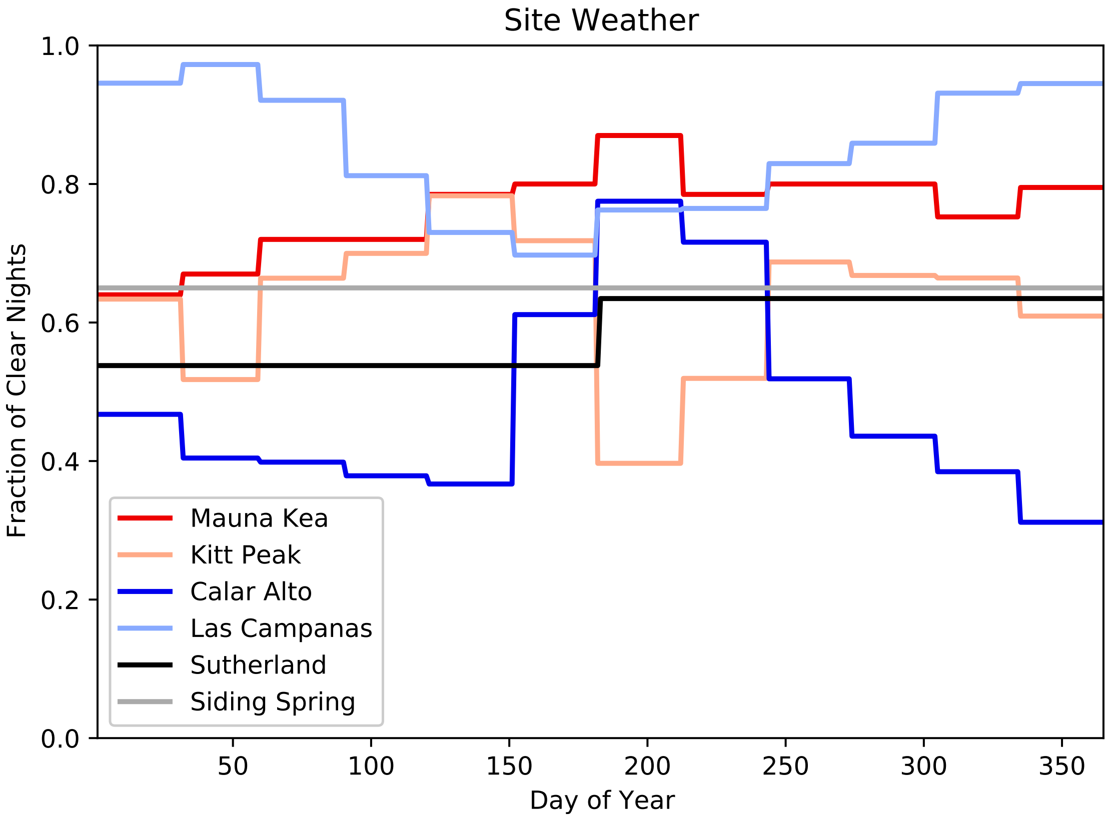
Final selection was 7 telescope/spectrograph combinations



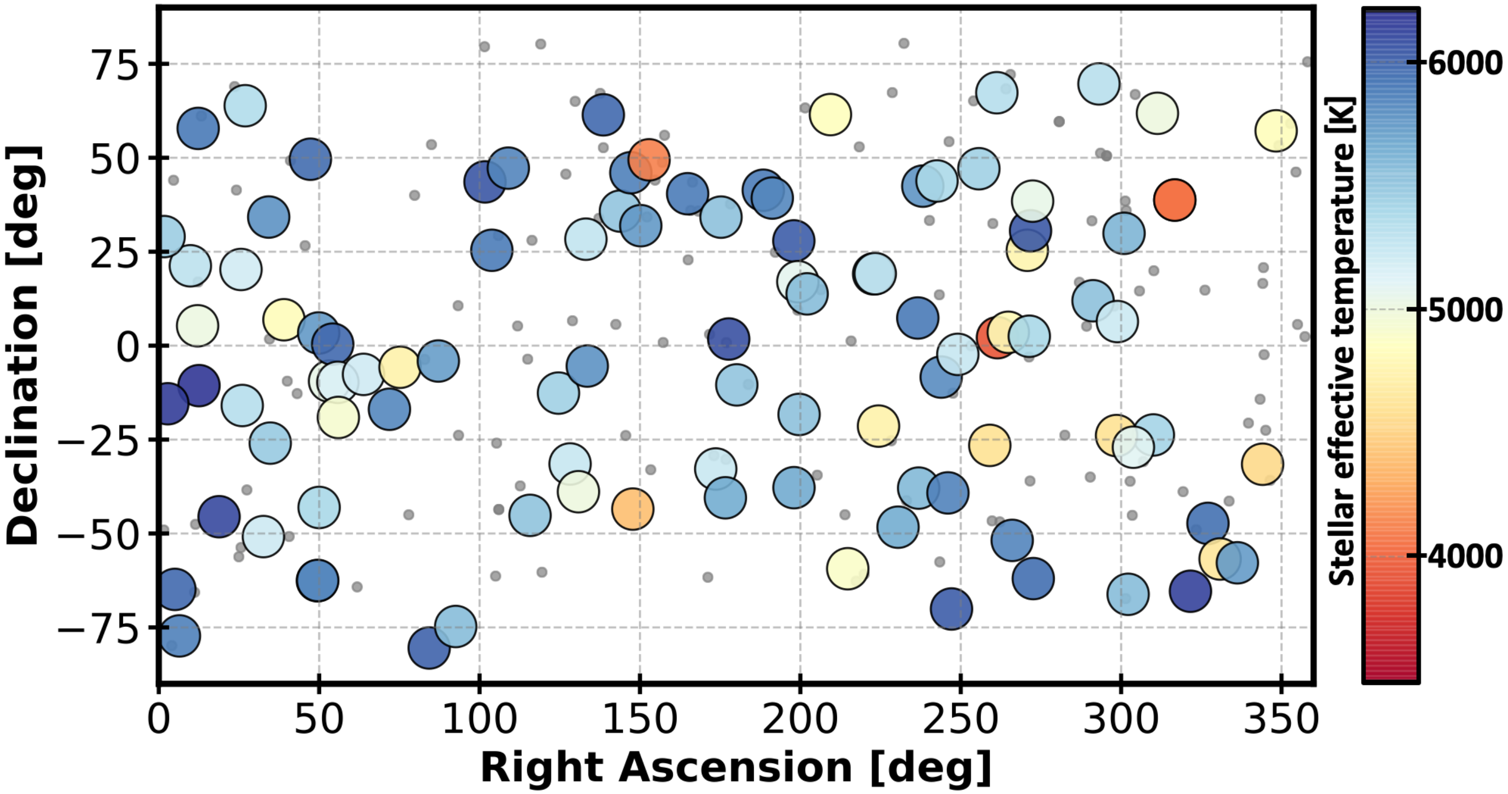
Survey Simulations 1 – Site Locations



“Typical” locations with existing observatories



Survey Simulations 1 - Green Prime Targets



101 FGK stars within 5 pc, low vsin(i), and low stellar activity.

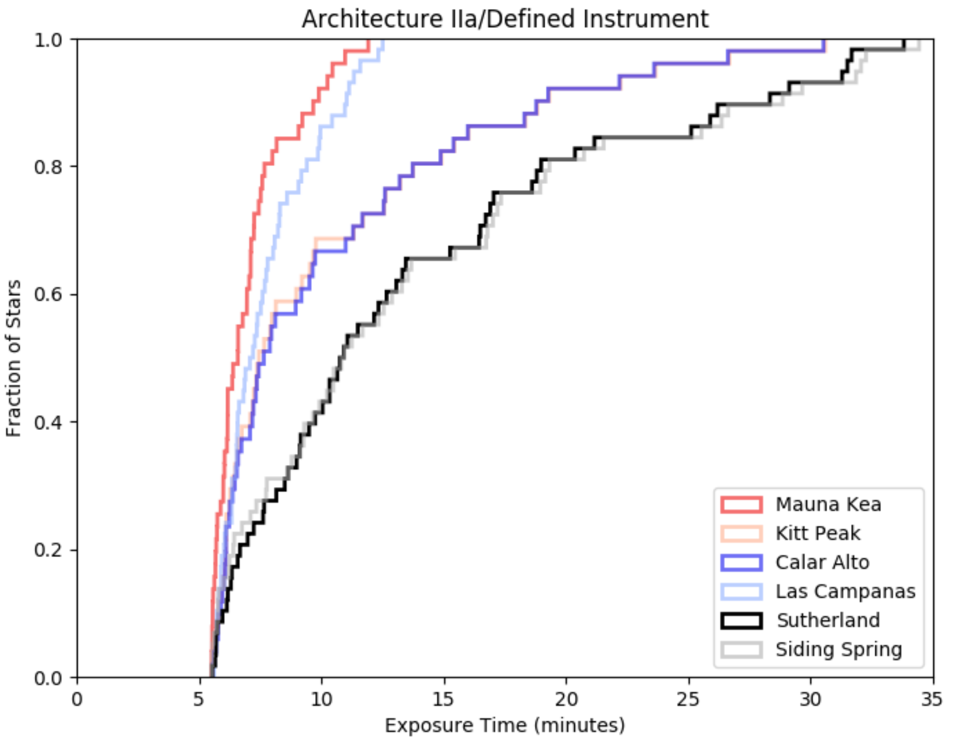
Two groups: 58 >-5° Dec, and 62 <+5° Dec (19 star overlap).

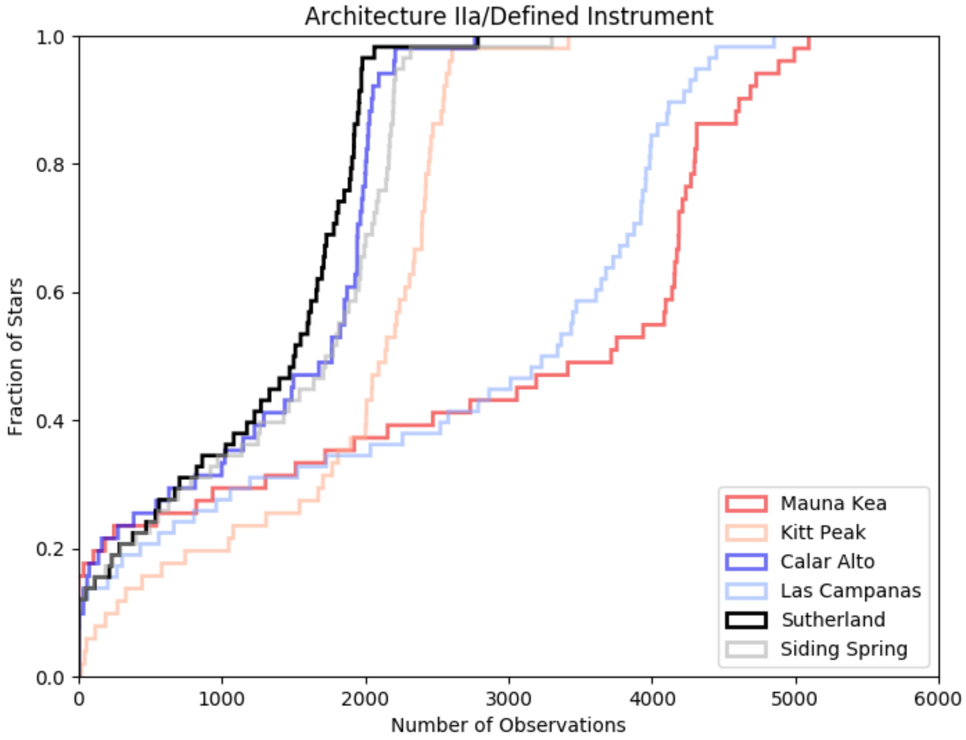
Survey Simulations 1 – Detection Heuristic

$$SNR = \frac{K}{\sigma}\sqrt{\frac{N_{obs}}{2}} \qquad K = SNR \cdot \sigma \sqrt{\frac{2}{N_{obs}}}$$

Computationally cheap (no injection/recovery tests). Can split up σ and observation counts, depending on what we're modeling.

Survey Simulations 1 – Example Results





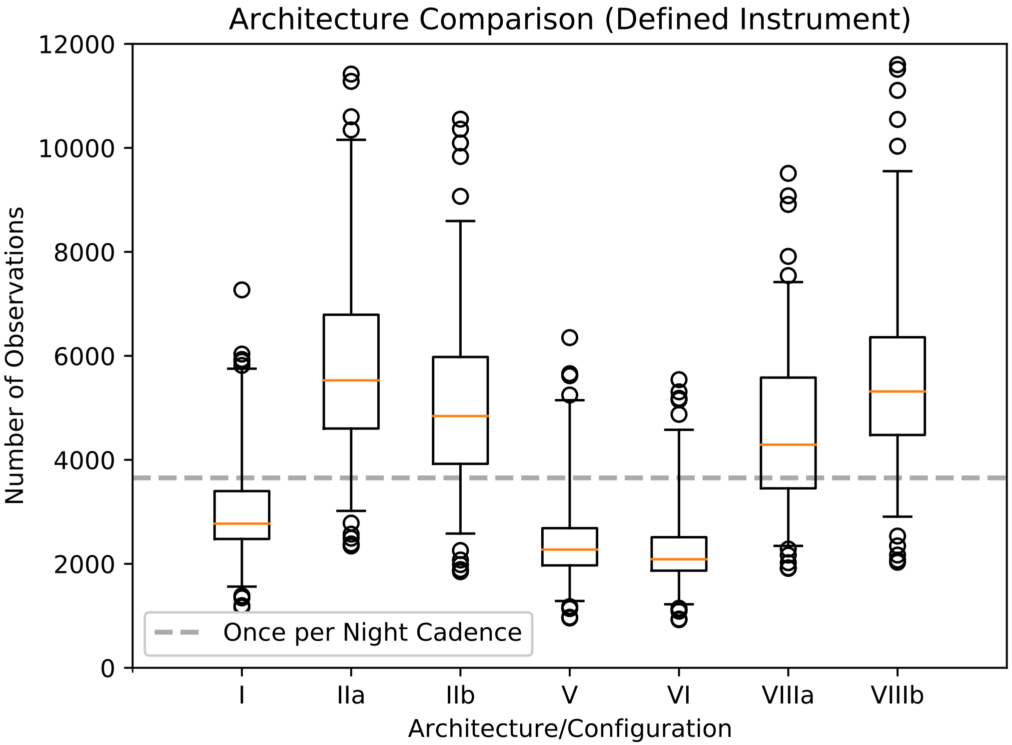
Survey Simulations 1 – Results

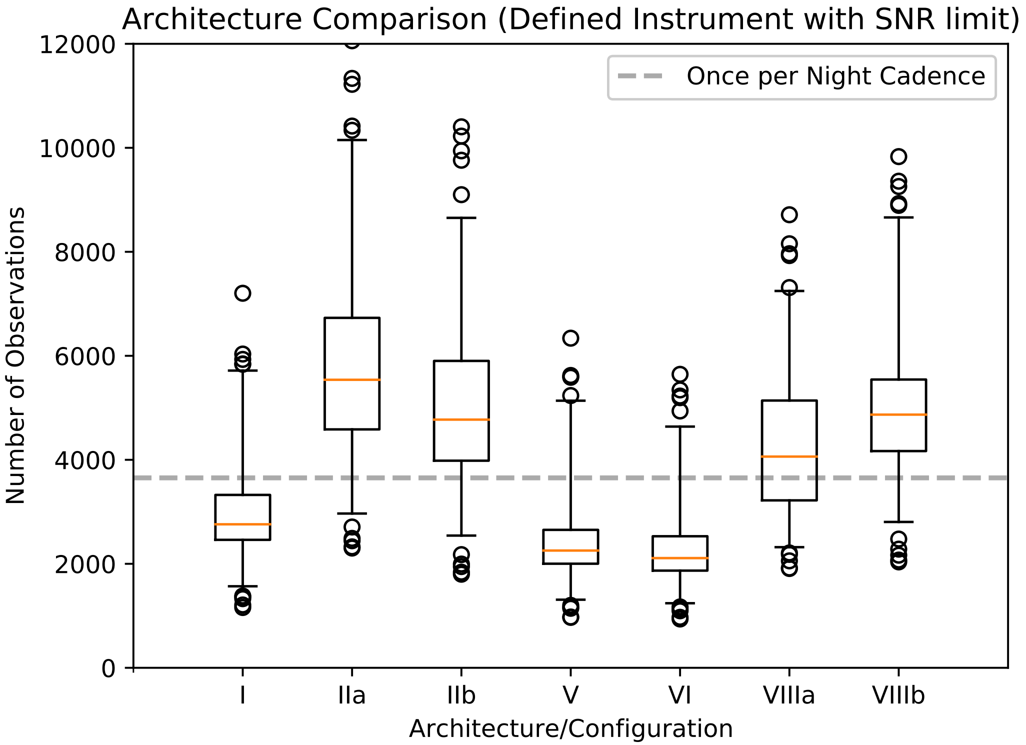
How often was a star observed?

How well was a telescope used?

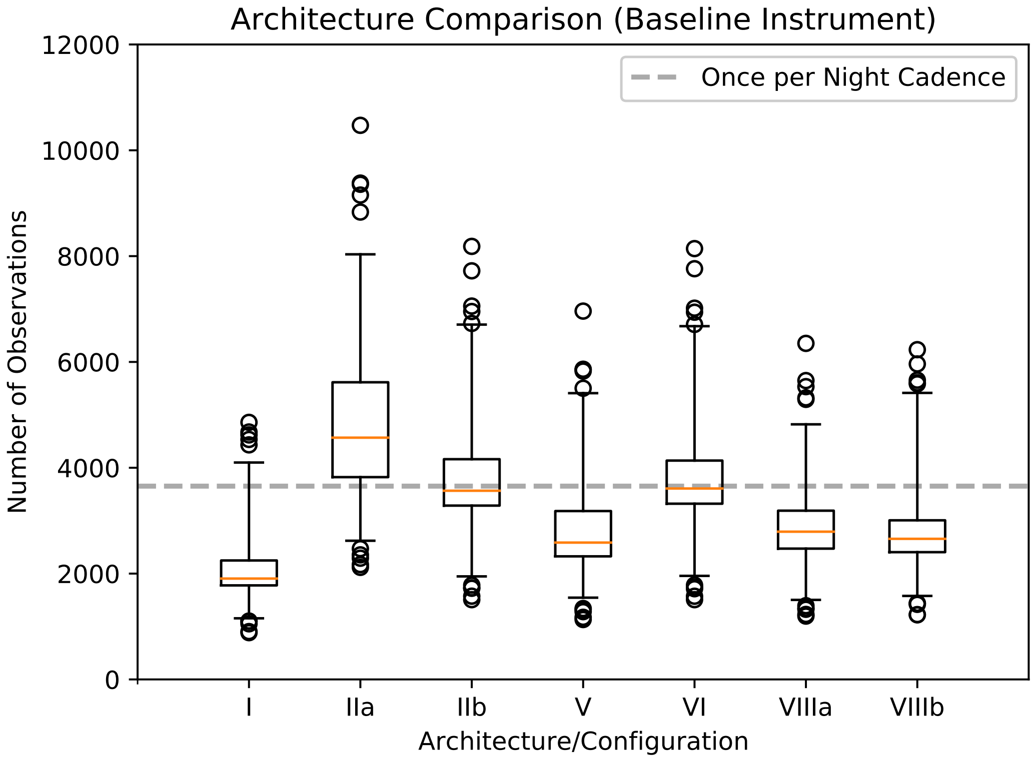
How small of a planet could we find?

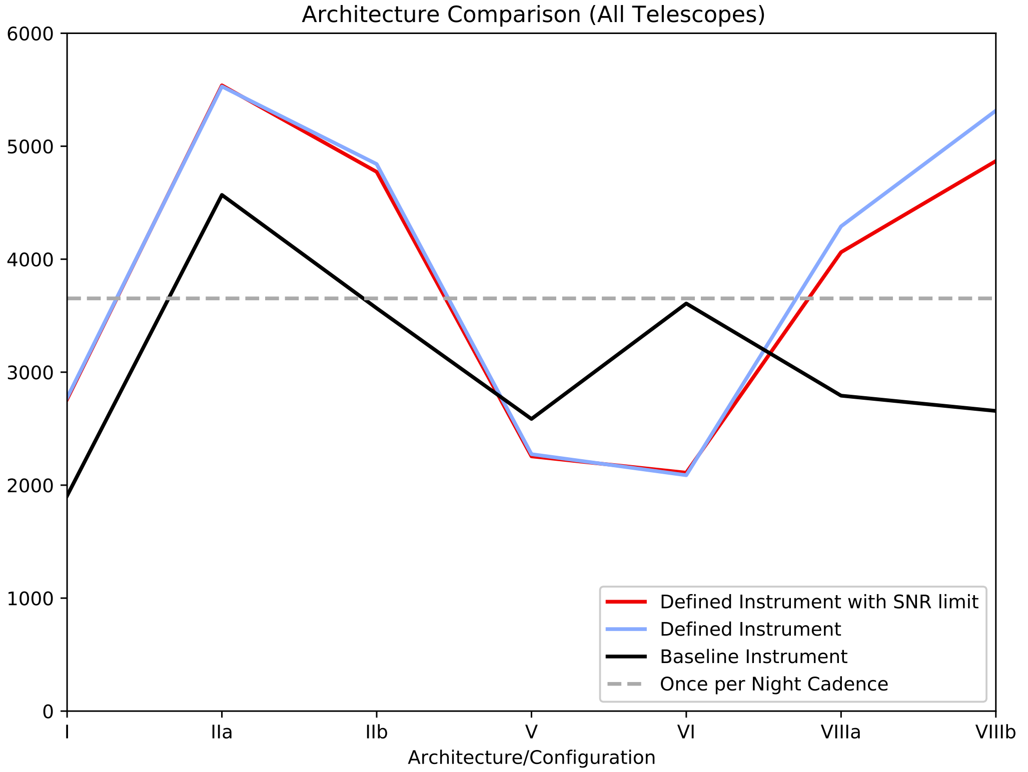
Survey Simulations 1 - observations



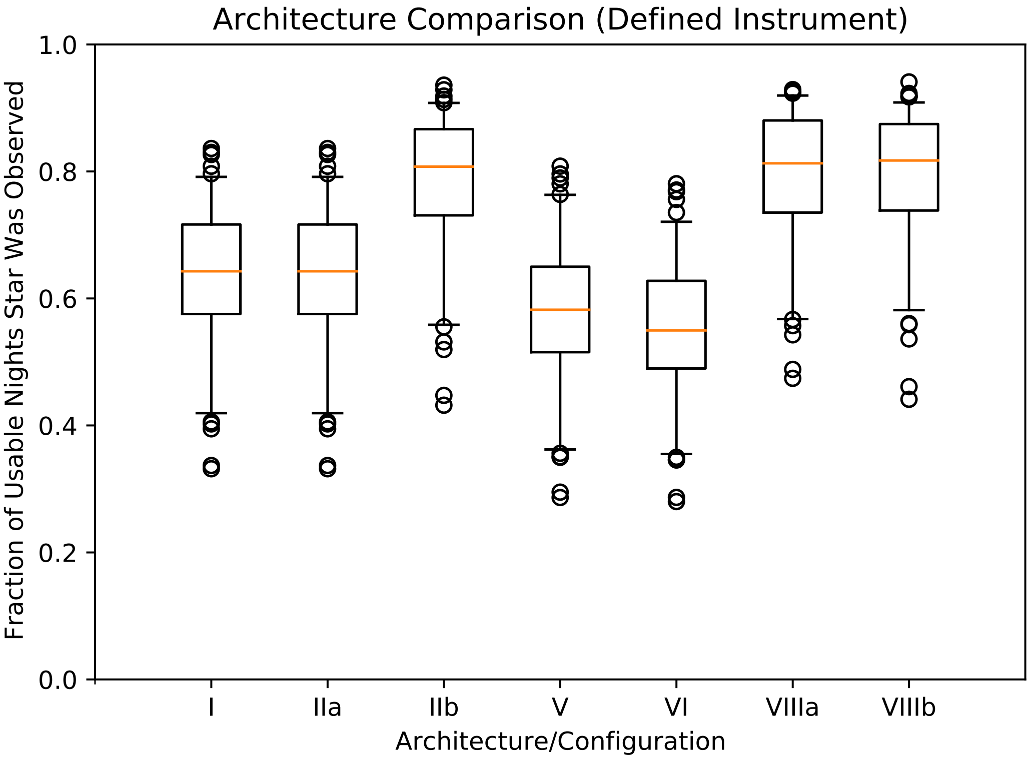


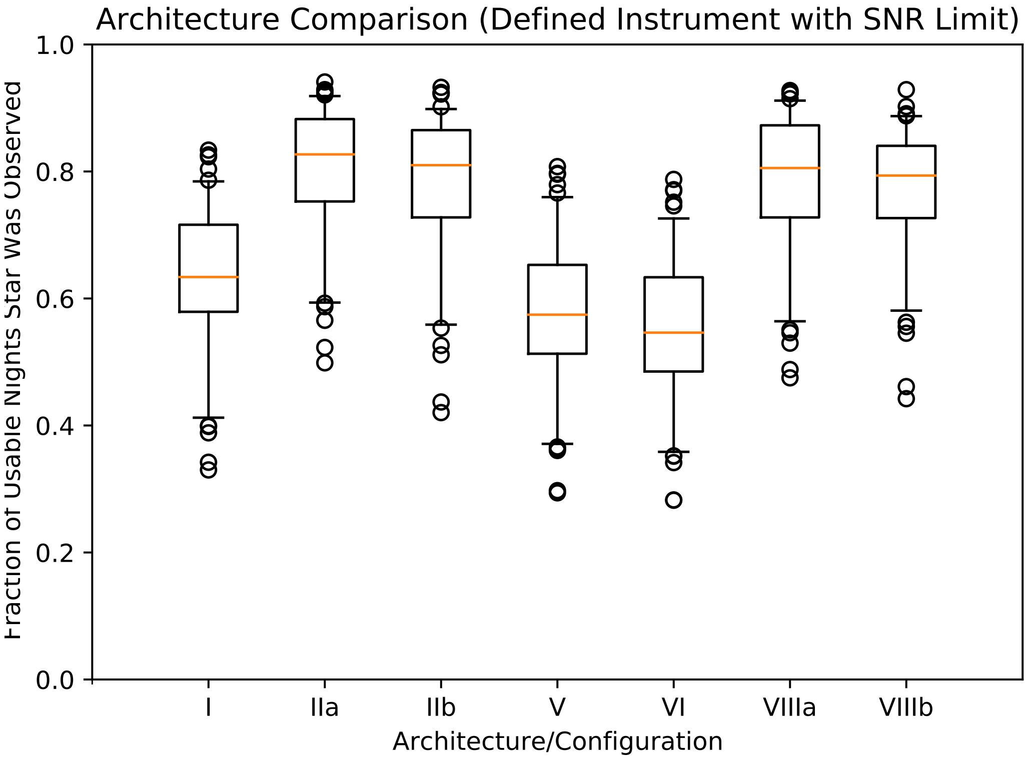
Survey Simulations 1 - observations



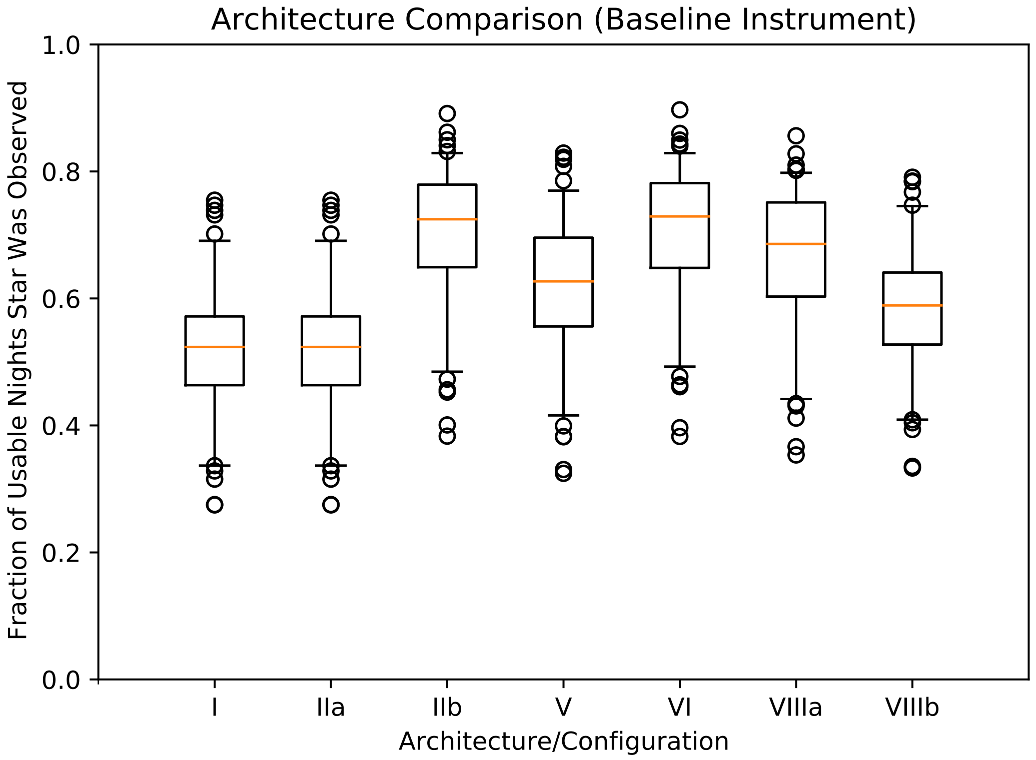


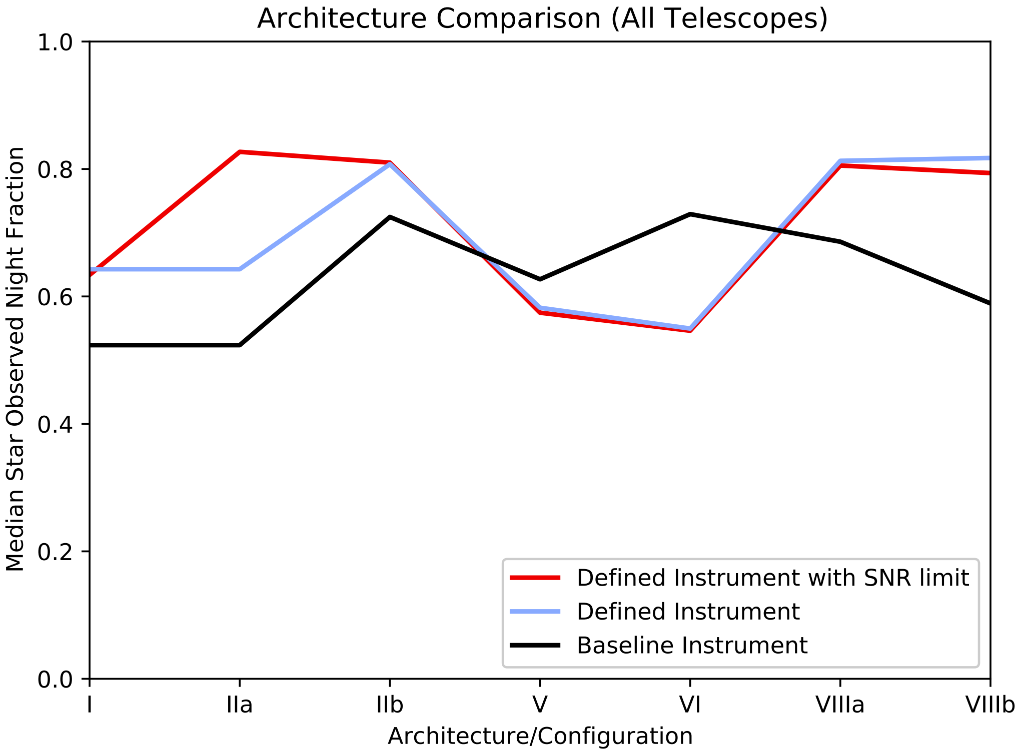
Survey Simulations 1 - utilization



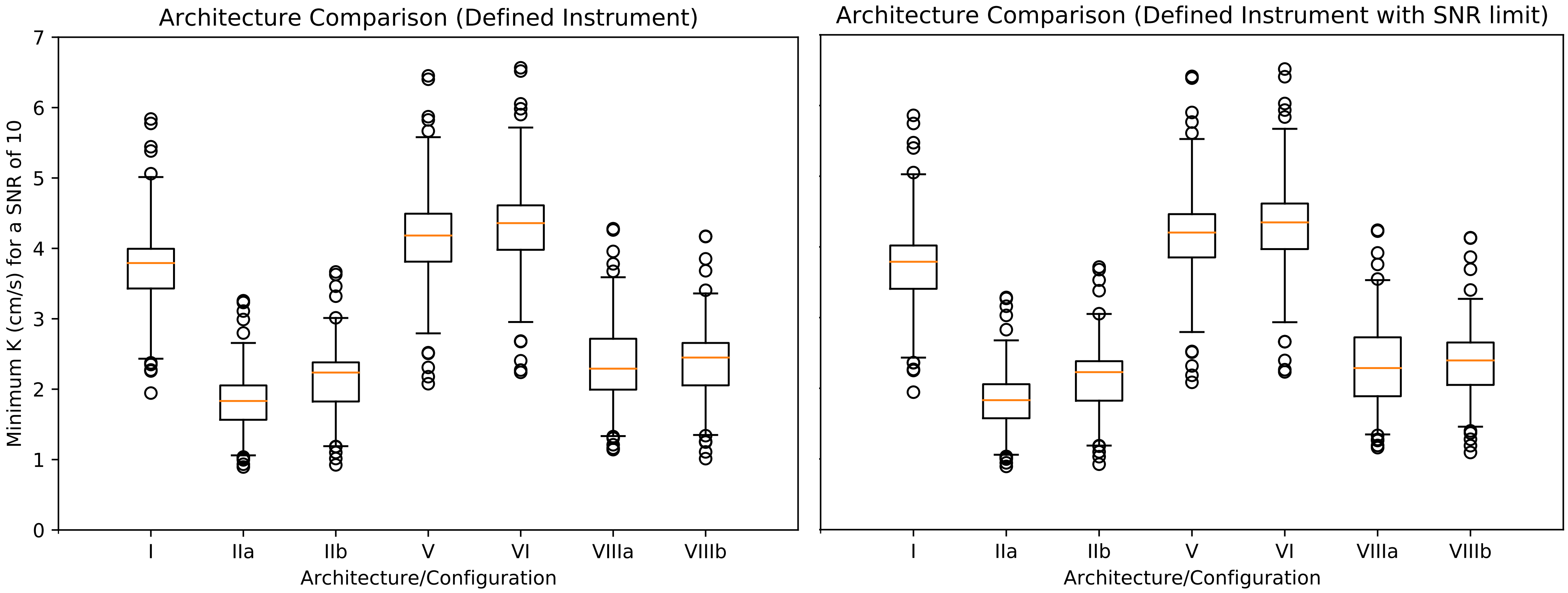


Survey Simulations 1 - utilization

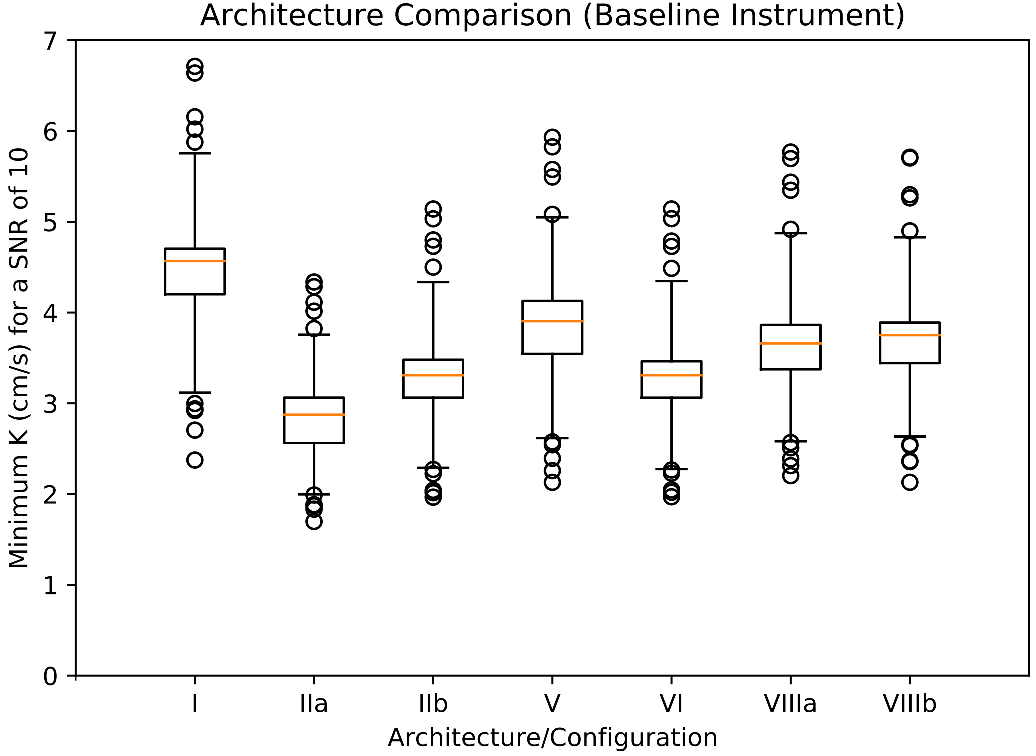


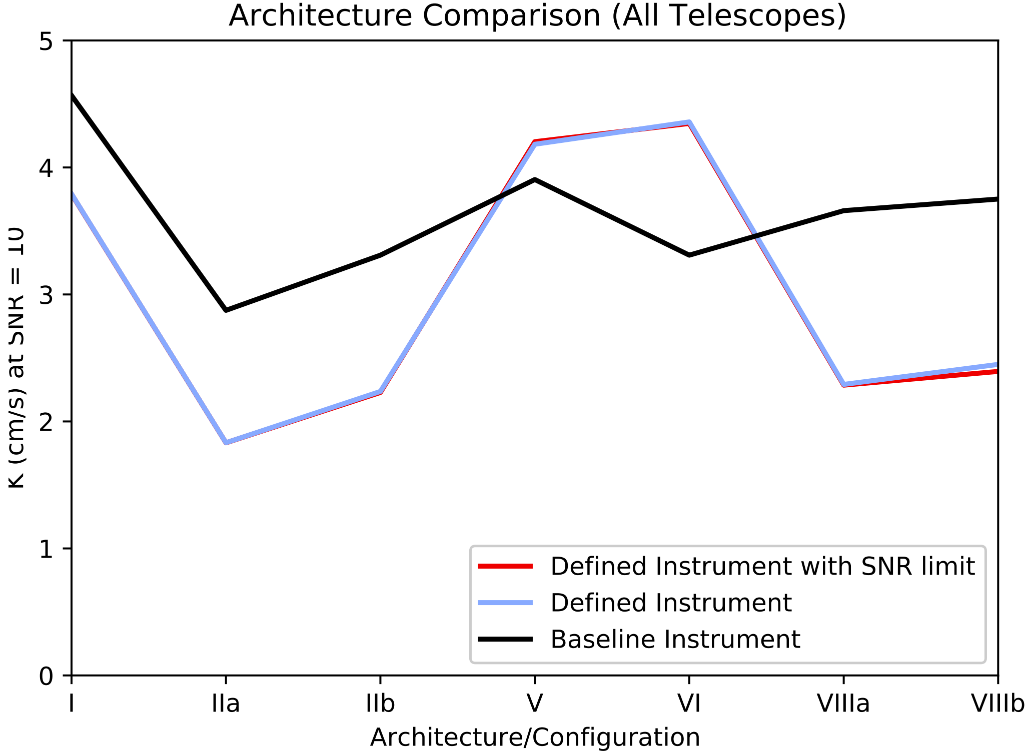


Survey Simulations 1 – detected semi-amplitude

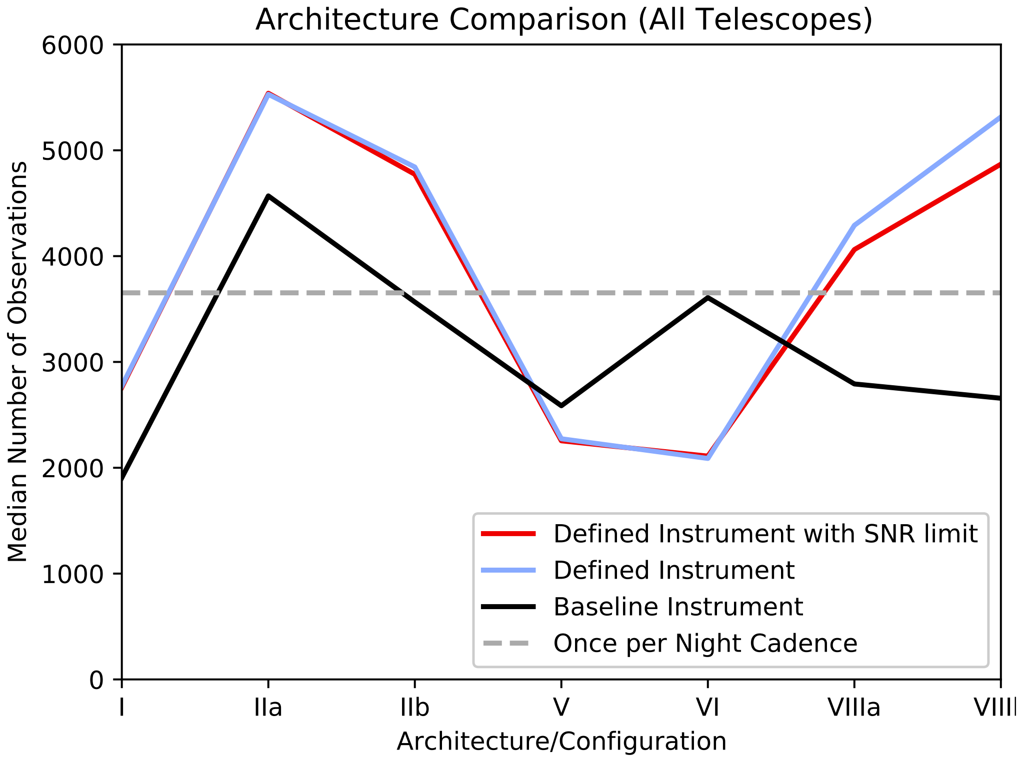


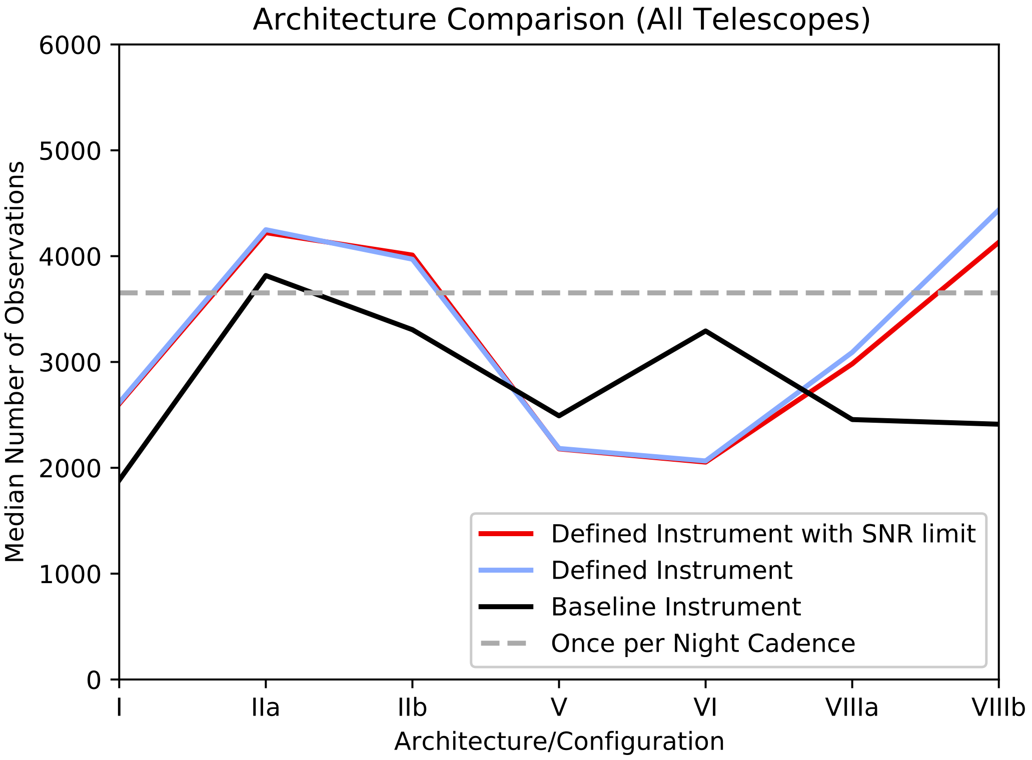
Survey Simulations 1 – detected semi-amplitude



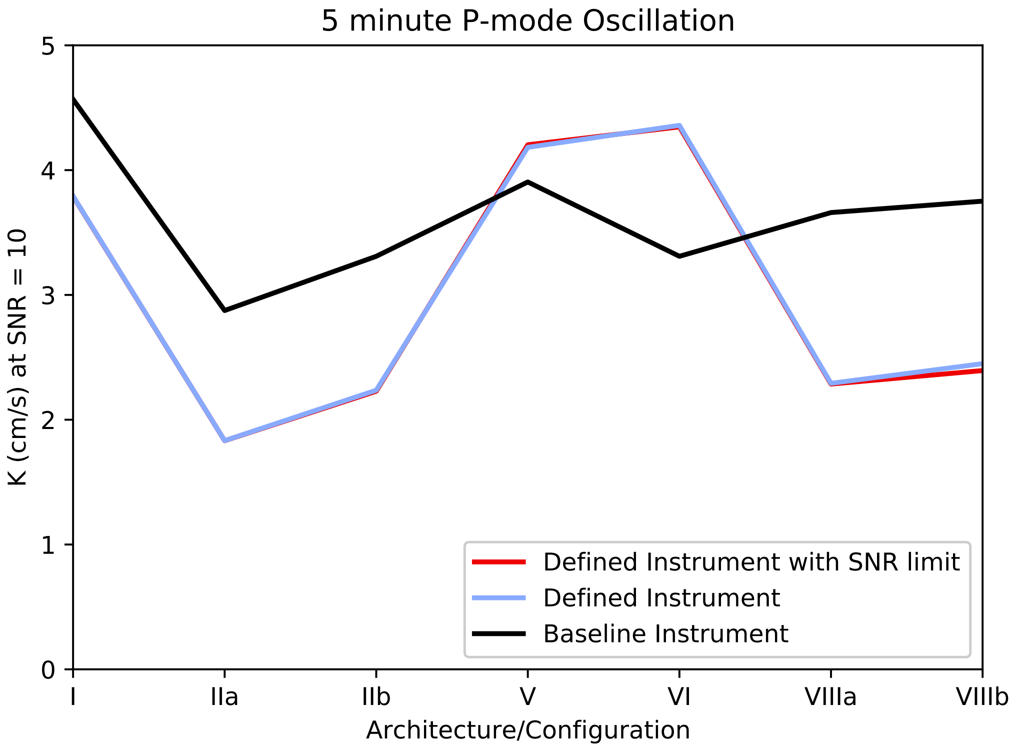


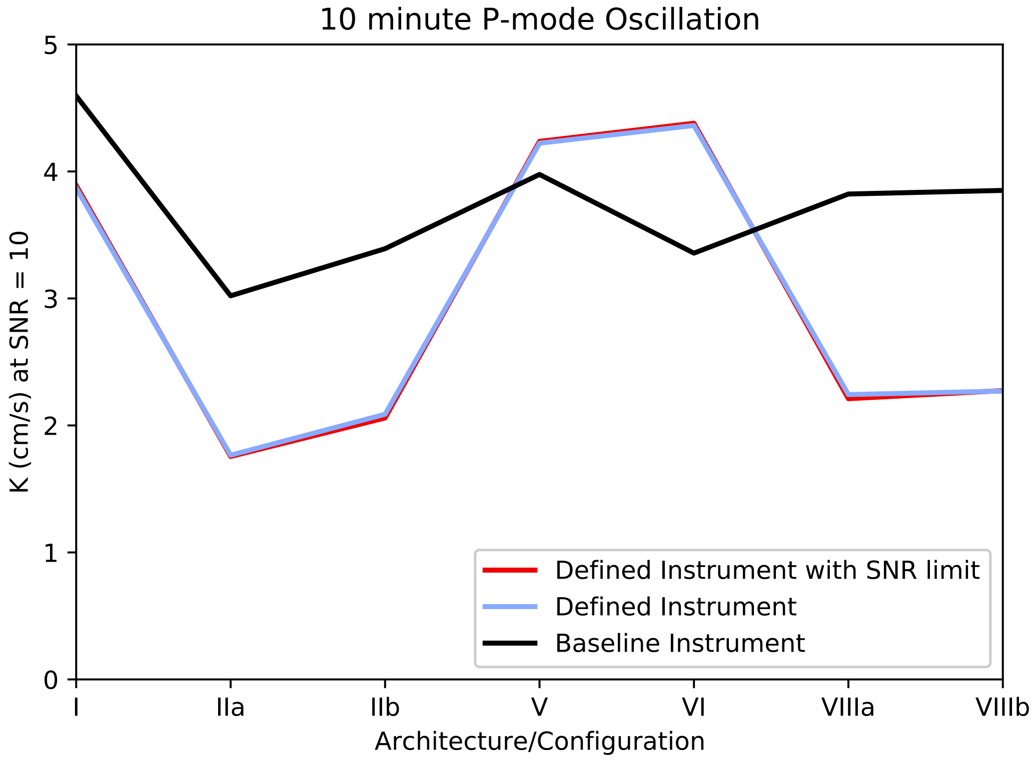
Survey Simulations 1 – p-mode aside





Survey Simulations 1 – p-mode aside





Survey Simulations 1 – Conclusions

- Most architectures can work okay, though fully dedicated 4+ m telescopes are best.
- More telescopes at more locations solve everything. (but fewer might work)
- Exposure times based on single measurement RV precision and on target SNR give similar results.
- Going from 5 to 10 minute p-modes changes observation count but not survey sensitivity!

Simulations for Upcoming and Proposed Exoplanet Surveys as Pathfinders for Direct Imaging Missions

Survey Simulations 1
- Survey Simulations 2

Orbiting Photometric Lightsource

Survey Simulations 2

Are the exposure time and dispatch scheduler assumptions good?

Atmosphere/How much do microtellurics matter?

Stellar activity/Laying p-mode oscillations to rest.

How much does target selection matter?

Survey Simulations 2 – Architectures

Spectrographs:
NEID (the existing one)
NIRS (a nominal near infrared spectrograph)

Telescopes:
WIYN (3.5 m), LBT (8.4 m, 11.8 m)

Target precisions:
40 cm/s, 27 cm/s, 9 cm/s, 3 cm/s

Survey Simulations 2 – Architectures

Canonical:
NEID/WIYN 27 cm/s
NEID/WIYN 3 cm/s
NEID/LBT 3 cm/s
NIRS/LBT 40 cm/s
NIRS/LBT 3 cm/s

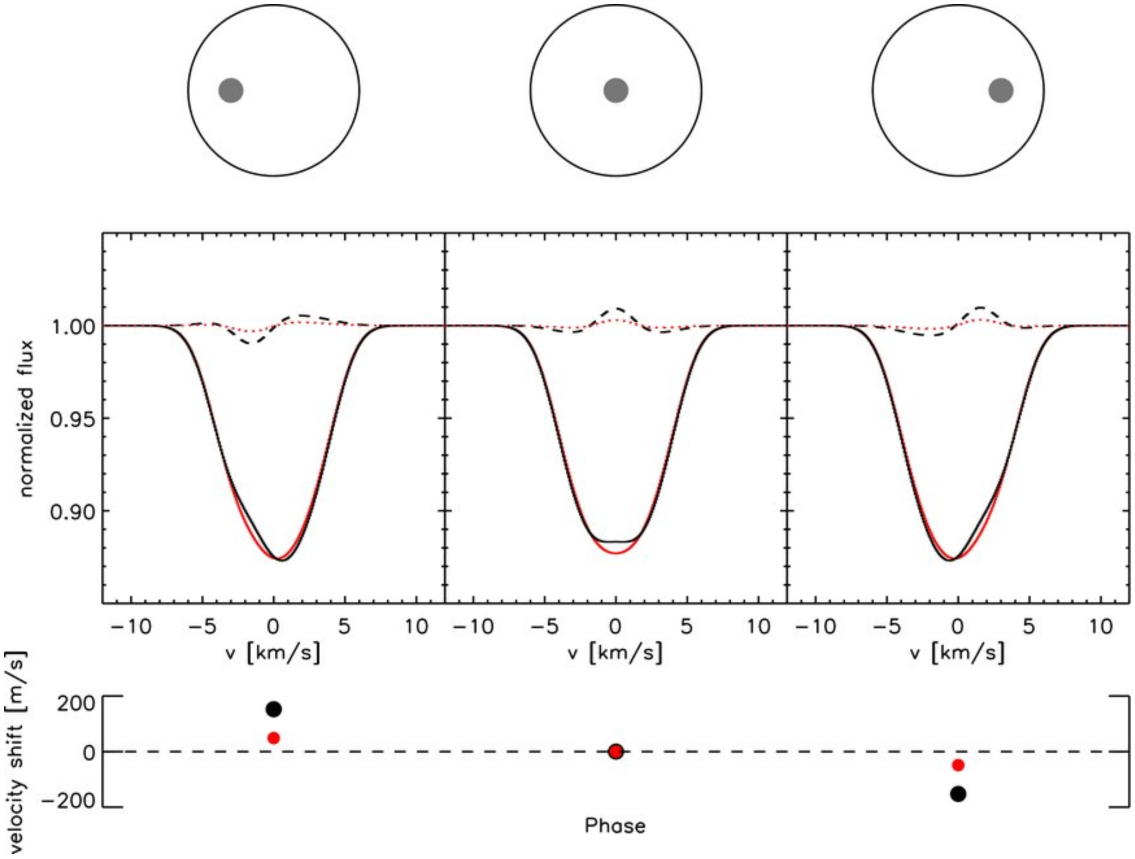
Non-canonical: every combination (40/27/9/3 cm/s)

Survey Simulations 2 – Target Lists

Stapelfedt and Mamajek 2023 (HWO)
Green Prime (EPRV)
A previous list (HabEx)

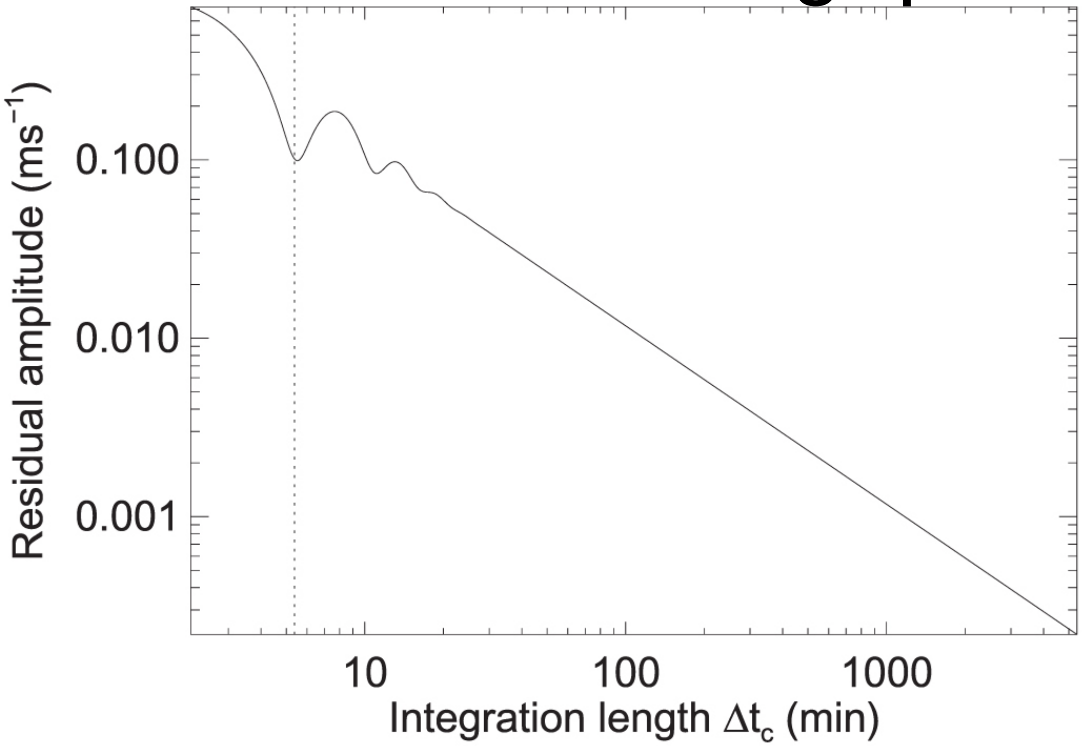
Different but related requirements.

Survey Simulations 2 – Unsimulated Stellar Activity



Starspots introduce a (potentially very large) periodic RV signal as they cross the stellar disk. This effect is smaller in NIR than visible (Reiners et al 2010). We do not directly compensate for this.

Survey Simulations 2 – “Solving” p-mode oscillations



Solar-type oscillations introduce additional noise, and there’s a minimum observation time to minimize the effect (Chaplin et al 2019). The mismatch from an approximate value significantly reduces the effectiveness of this sort of compensation (Luhn et al 2023).

Survey Simulations 2 – “Solving” p-mode oscillations

$$T = 300\,s$$

$$T = 600\,s$$

Nominal times

$$T = 300\,s\sqrt{\frac{(R/R_{\odot})^{3}}{M/M_{\odot}}}$$

Dynamical timescale

$$\nu = 3100\,\mu Hz\left(\frac{g}{g_{\odot}}\right)^{1}\left(\frac{T_{eff}}{T_{eff,\odot}}\right)^{-0.5}$$

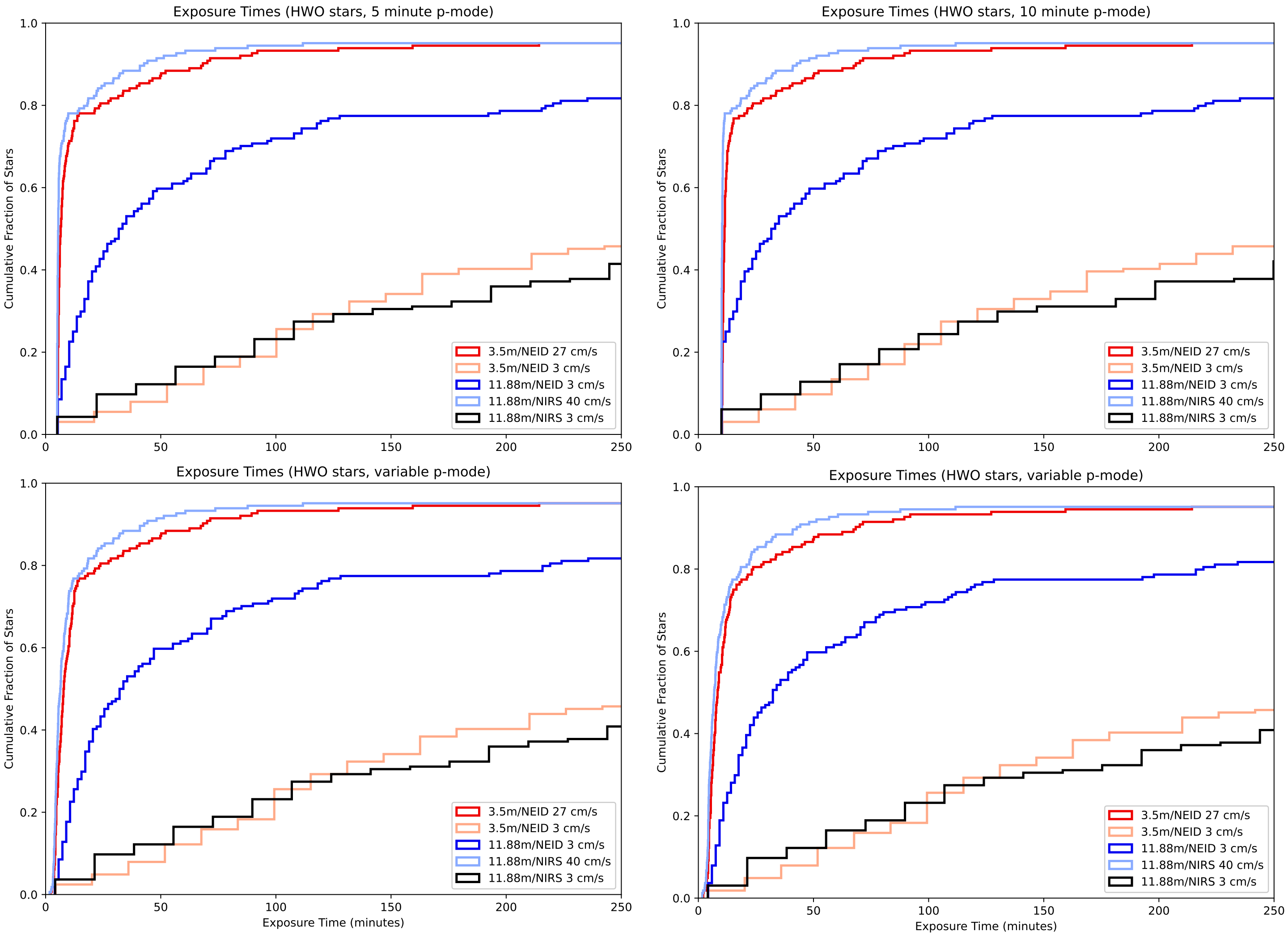
Chaplin 2019 et al, etc

Survey Simulations 2 – “Solving” p-mode oscillations

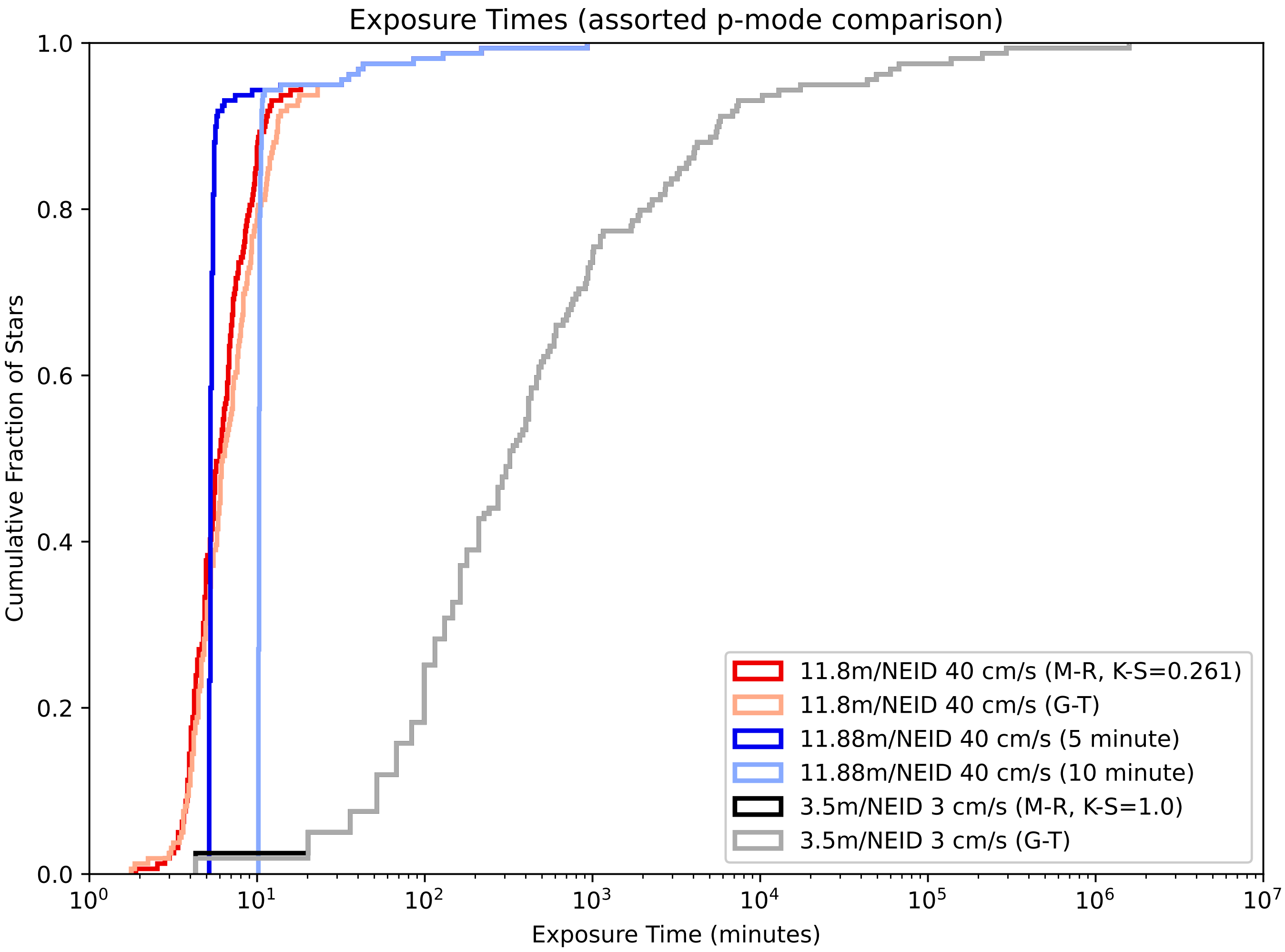
Only the short exposures change

Those exposure times are still short with observing for a full p-mode (the HWO list doesn’t have much in the way of subgiants).

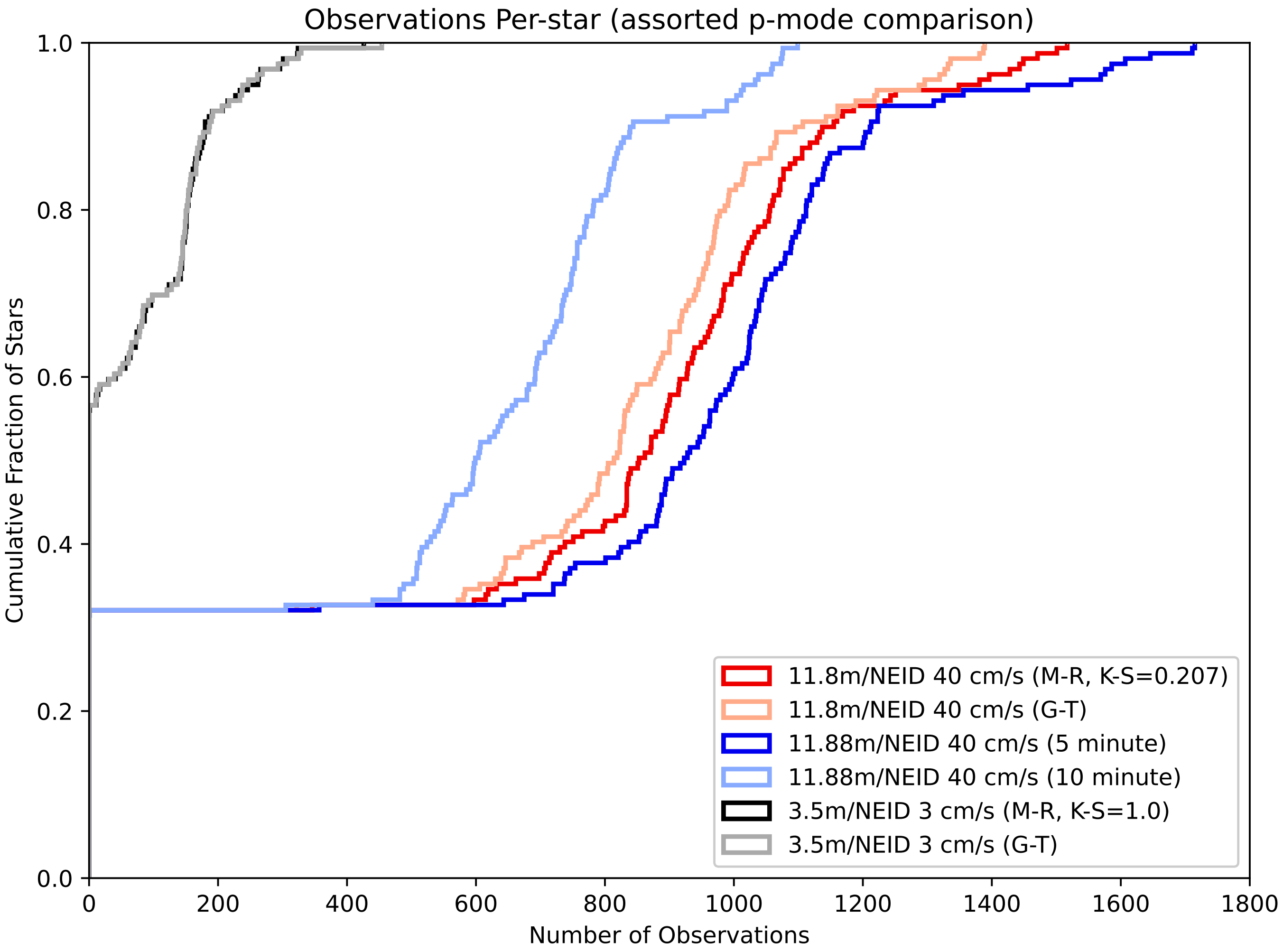
So probably no penalty for accurately accounting for this noise source.



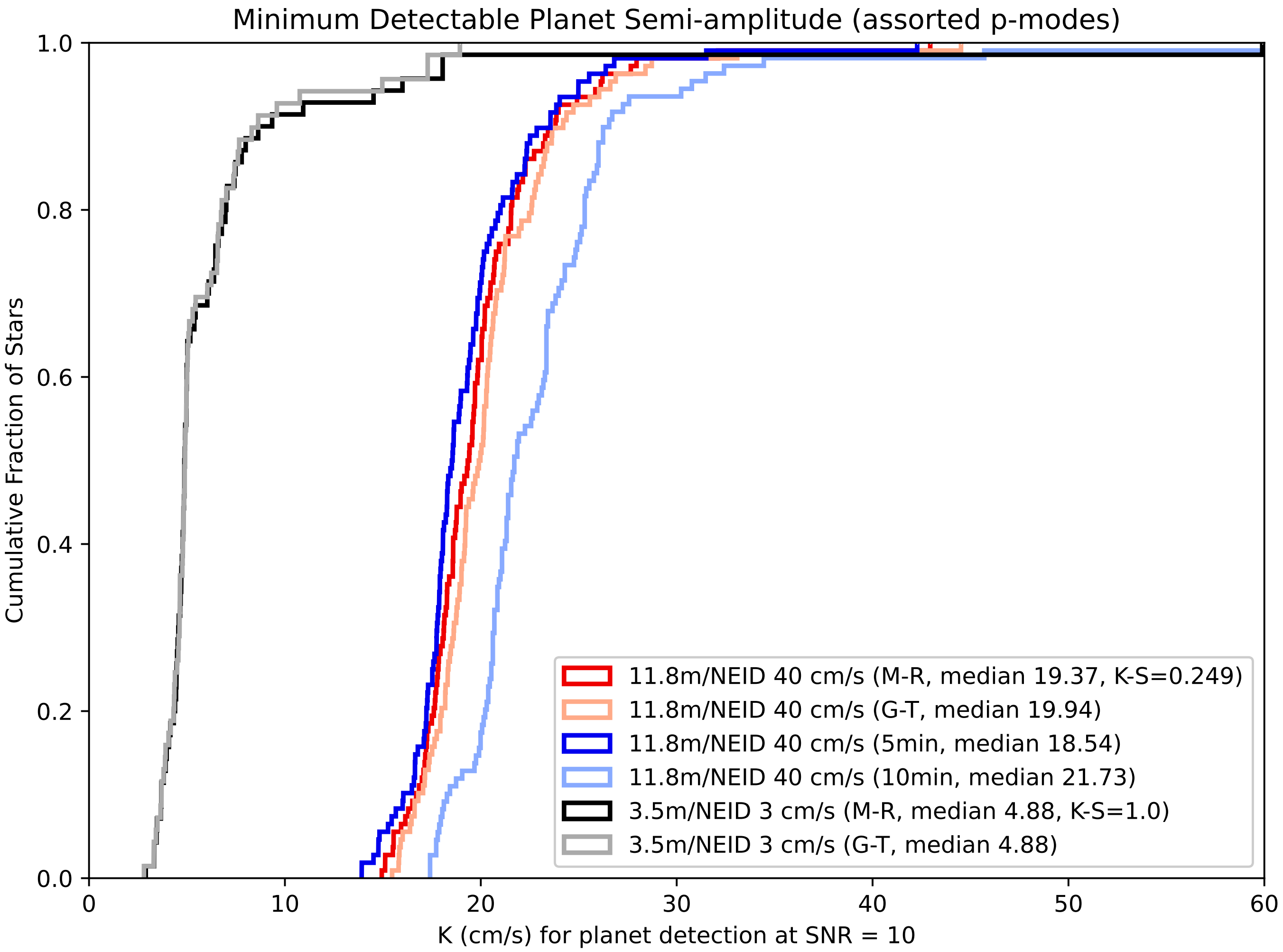
Survey Simulations 2 – “Solving” p-mode oscillations



Survey Simulations 2 – “Solving” p-mode oscillations



Survey Simulations 2 – “Solving” p-mode oscillations

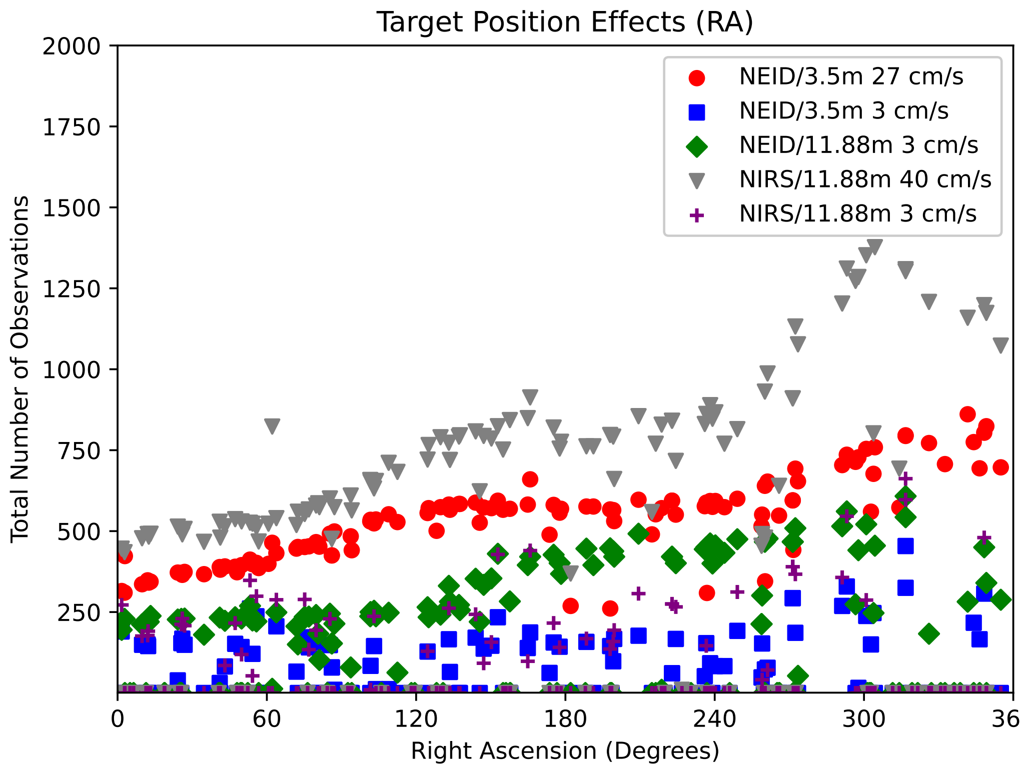


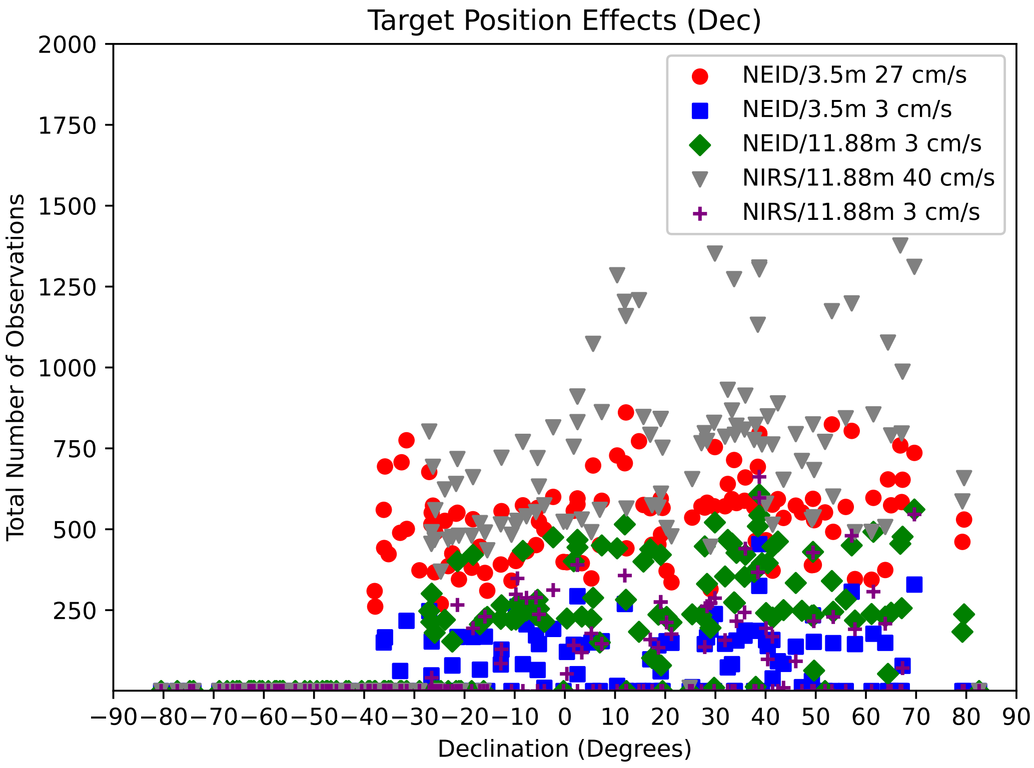
Survey Simulations 2 – “Solving” p-mode oscillations

This part of stellar activity is easy to compensate for.

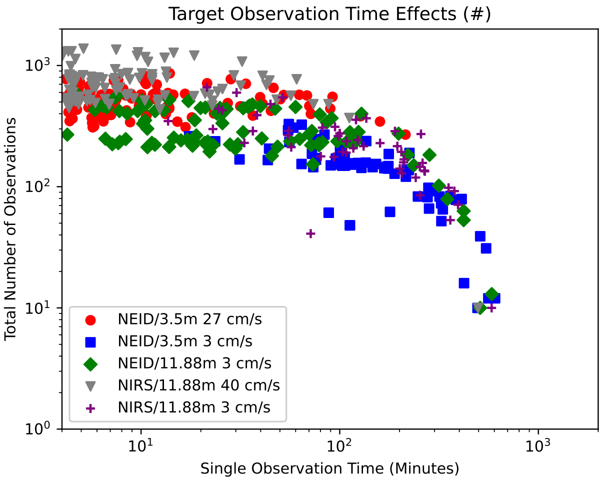
Outside of unlikely cases, exposure times are minimally affected.

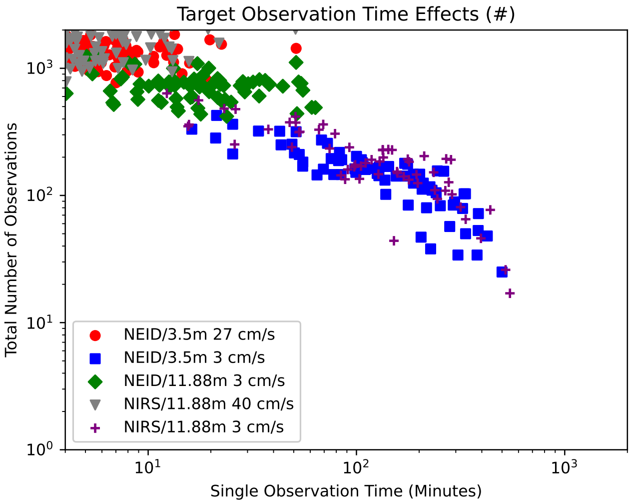
Survey Simulations 2 – Target Star Properties (HWO)

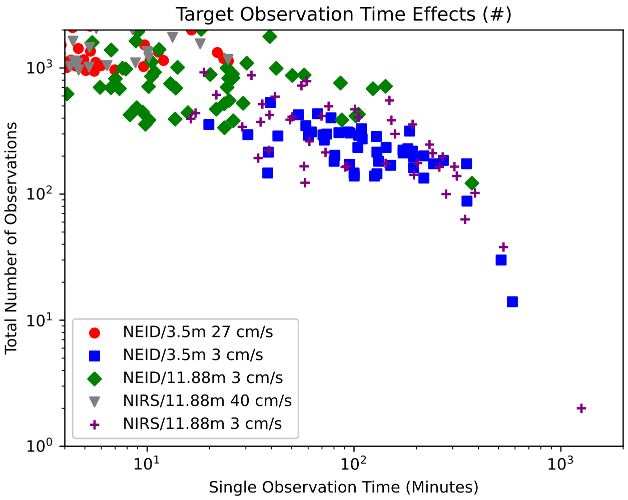




Survey Simulations 2 – Target Star Properties (HWO, EPRV, HabEx)







Selecting for targets that are EPRV friendly may be needed, regardless of direct imaging wants

Survey Simulations 2 - Microtellurics

My atmospheric model lacks line absorption (as losses), and assumes that noise from telluric lines can be fully corrected.

How much do microtellurics matter?

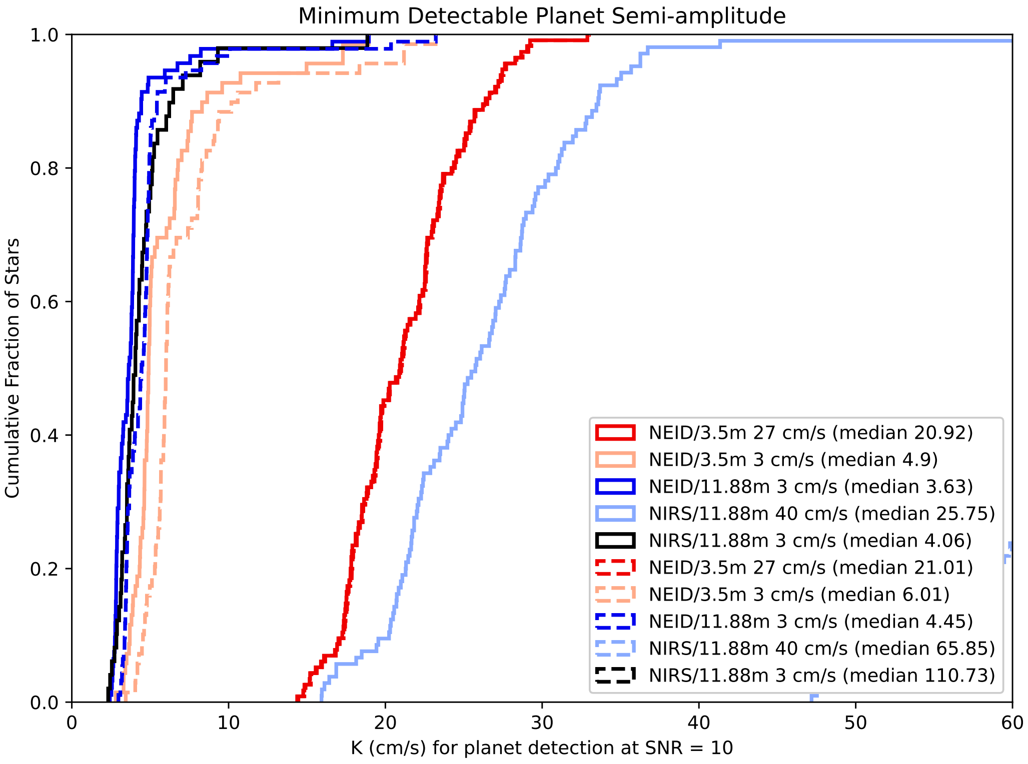
Survey Simulations 2 - Microtellurics

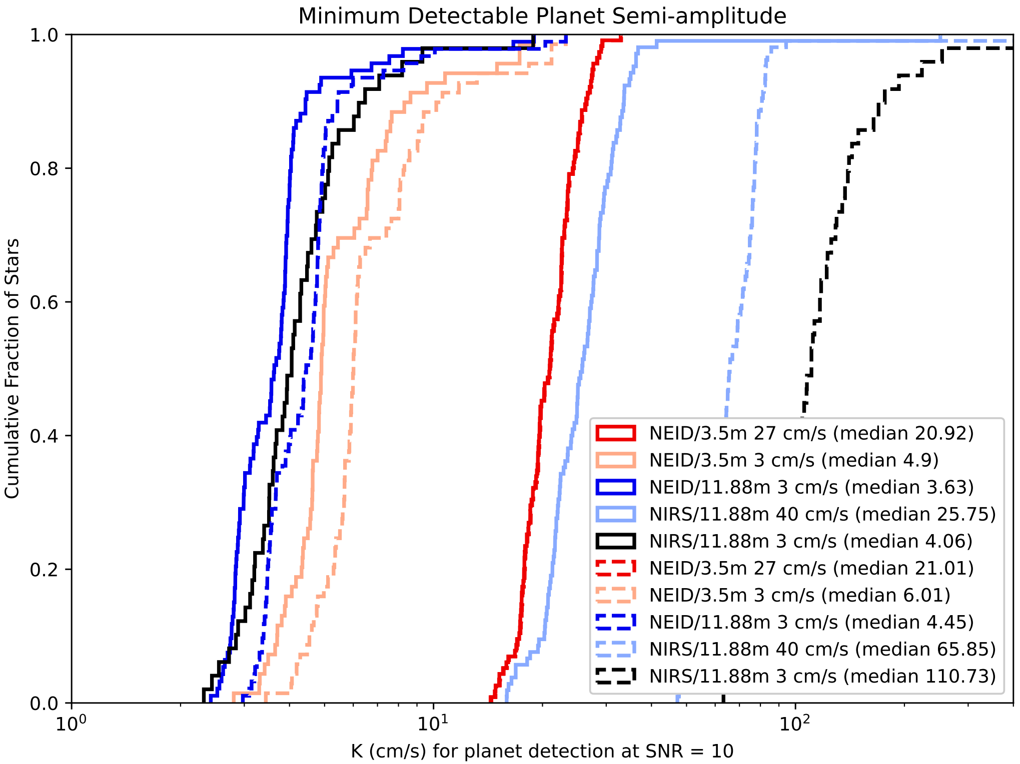
We can add in a noise term to approximate uncorrected microtellurics.

$$K = SNR \cdot \sqrt{\left(\sigma^2_{instrument} + \sigma^2_{photon} + \sigma^2_{atmosphere}\right)\frac{2}{N_{obs}}}$$

Using $\sigma_{atmosphere}$ of 3 cm/s visible, 115 cm/s NIR (S. X. Wang et al. 2022)

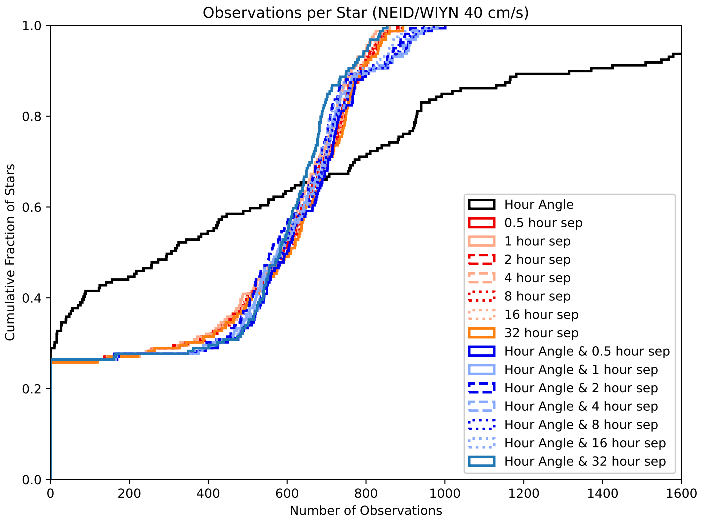
Survey Simulations 2 – Microtellurics

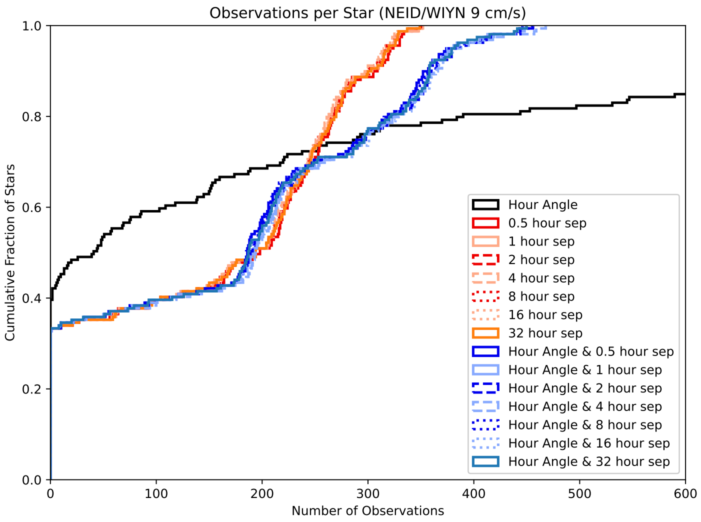




Acceptable in visible (3 cm/s), but a showstopper (115 cm/s) if we need to use NIR.

Survey Simulations 2 – Justifying the Weighting



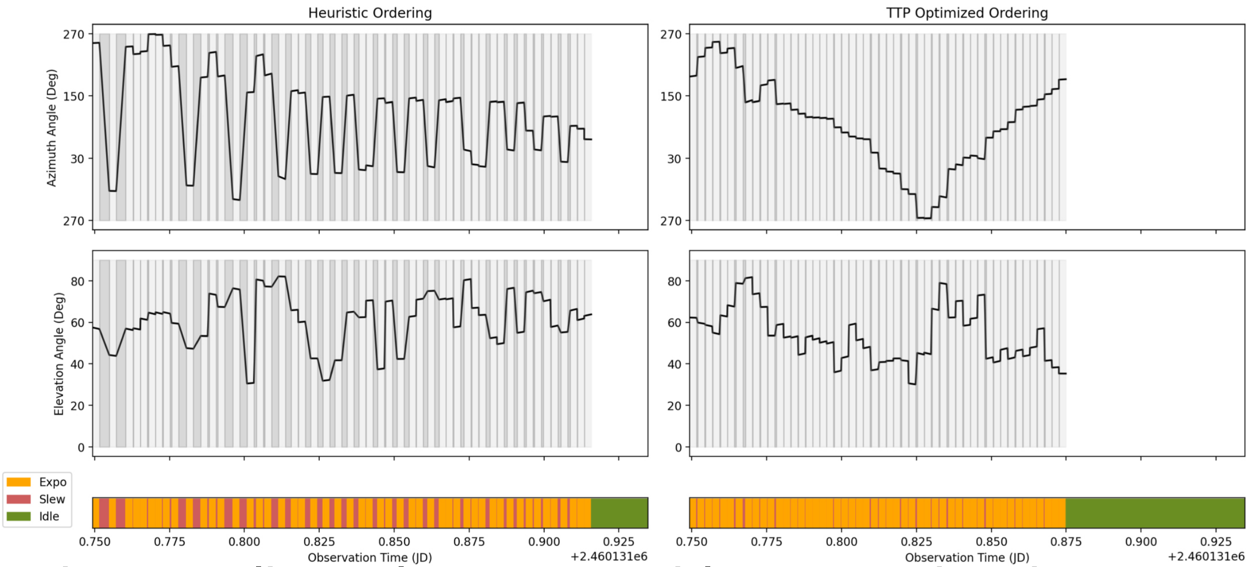


Very easy to calculate and approximates real world usage numbers.

“Best” isn’t always Hour Angle & 2 hour separation.

Don’t want to solve the traveling telescope problem. (Garcia-Piquer et al 2017, Handley et al 2024 A&B look at observation programs more generally but more constrained exptimes and/or target lists)

Survey Simulations 2 – Is the Weighting Justified?



Don’t want to solve the traveling telescope problem. Garcia-Piquer et al 2017 use 3 nested schedulers (long, medium, and short term).

Handley et al 2024 A&B look at observation programs more generally but more constrained exptimes and/or target lists. Compared with heuristics, they list going from minutes of slew to seconds.

Lubin et al 2025 may have found a computationally cheap, if currently site-specific way to deal with it.

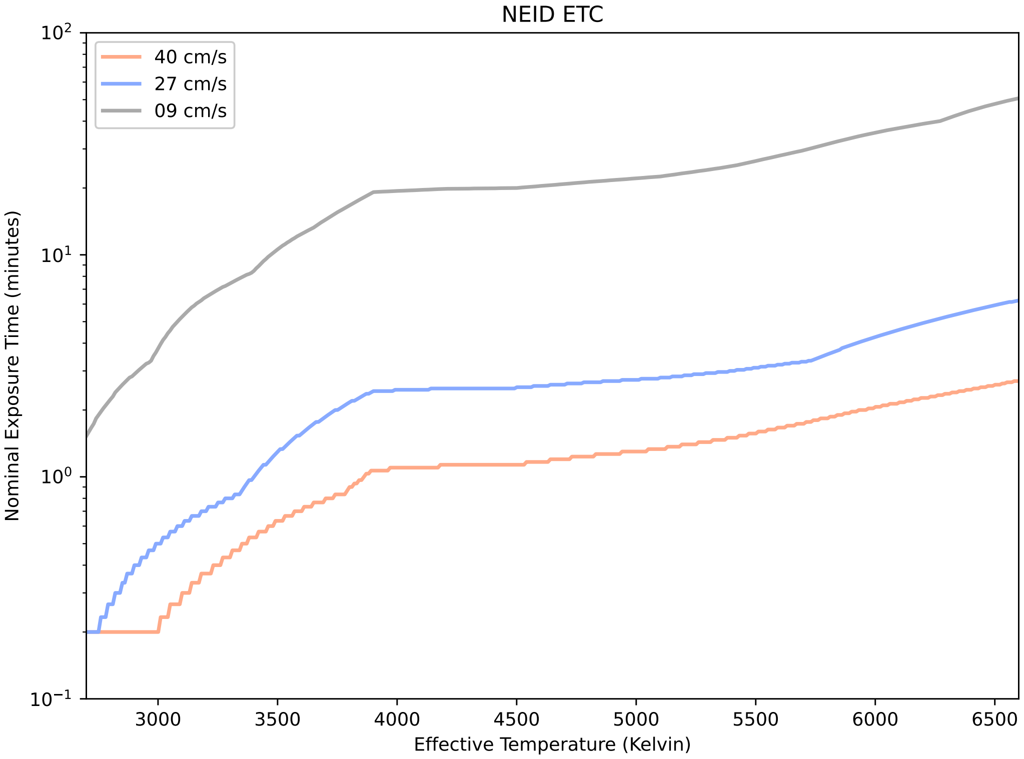
Survey Simulations 2 – Justifying the ETC

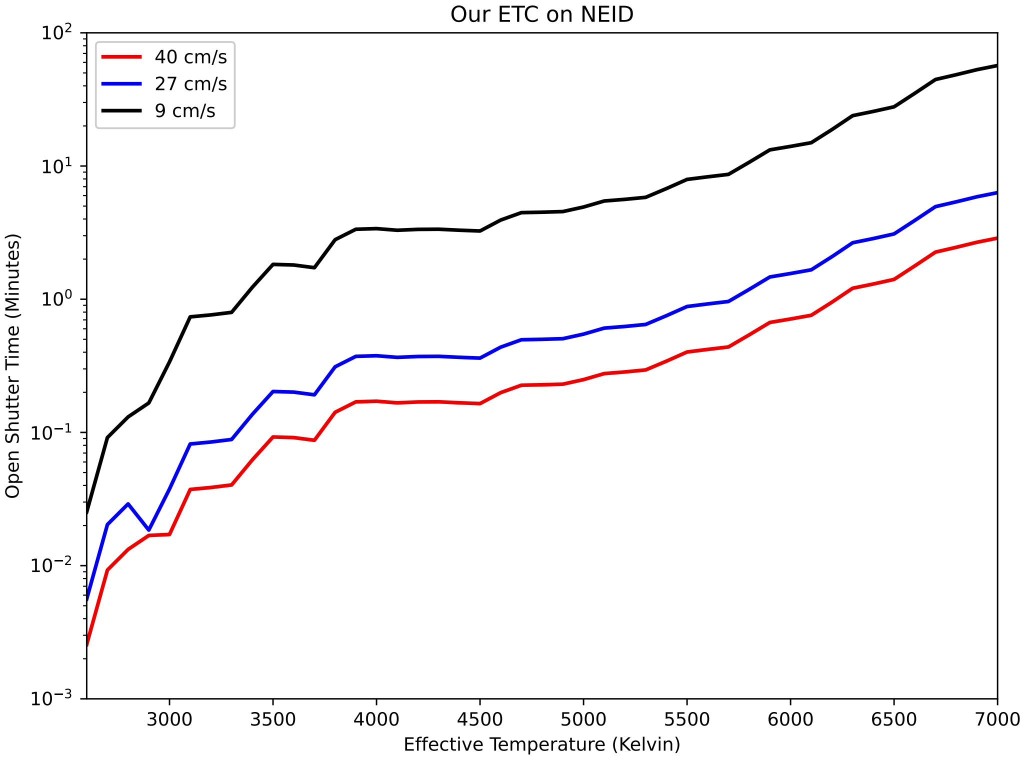
Exposure Time Calculators (ETCs) are mission-specific.

NEID ETC uses Teff and V-mag only.

ESPRESSO uses more but is primarily for extragalactic surveys and/or few targets.

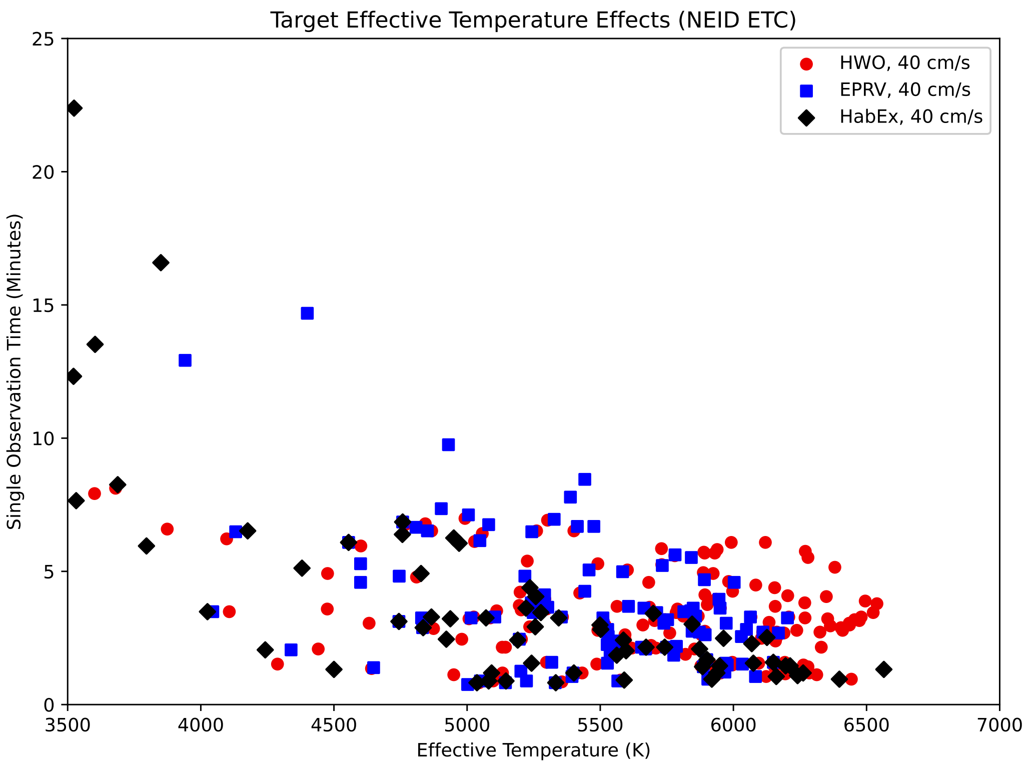
Survey Simulations 2 – Justifying the ETC

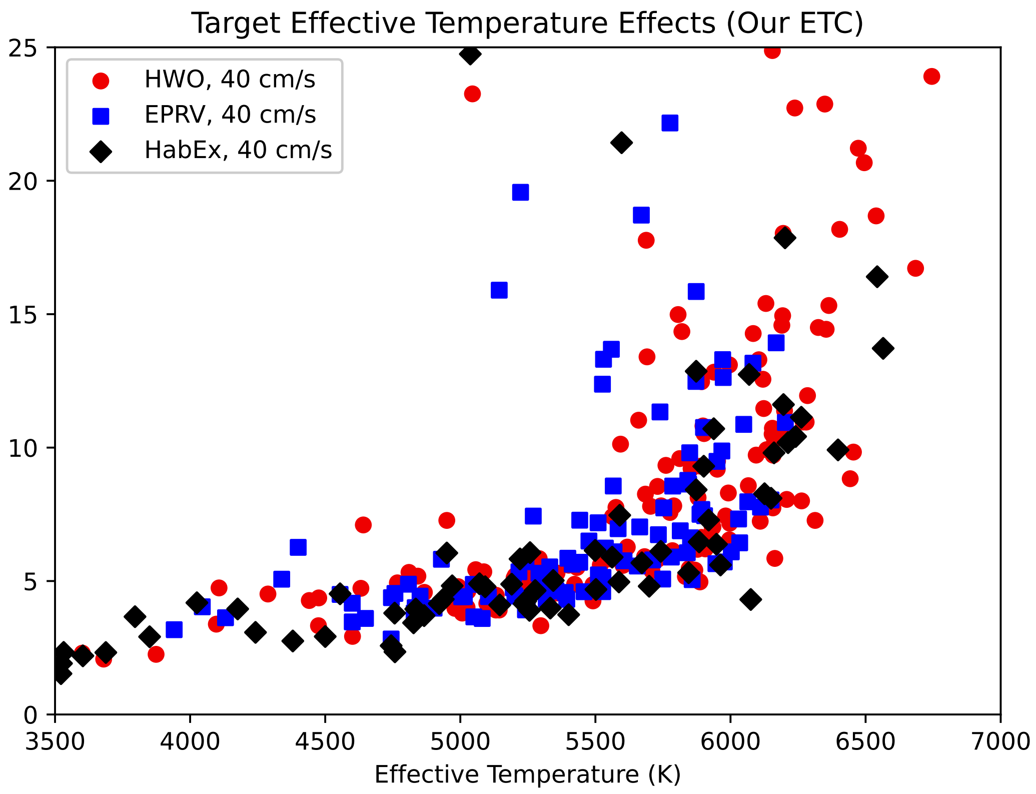




General agreement with NEID ETC on Teff trends

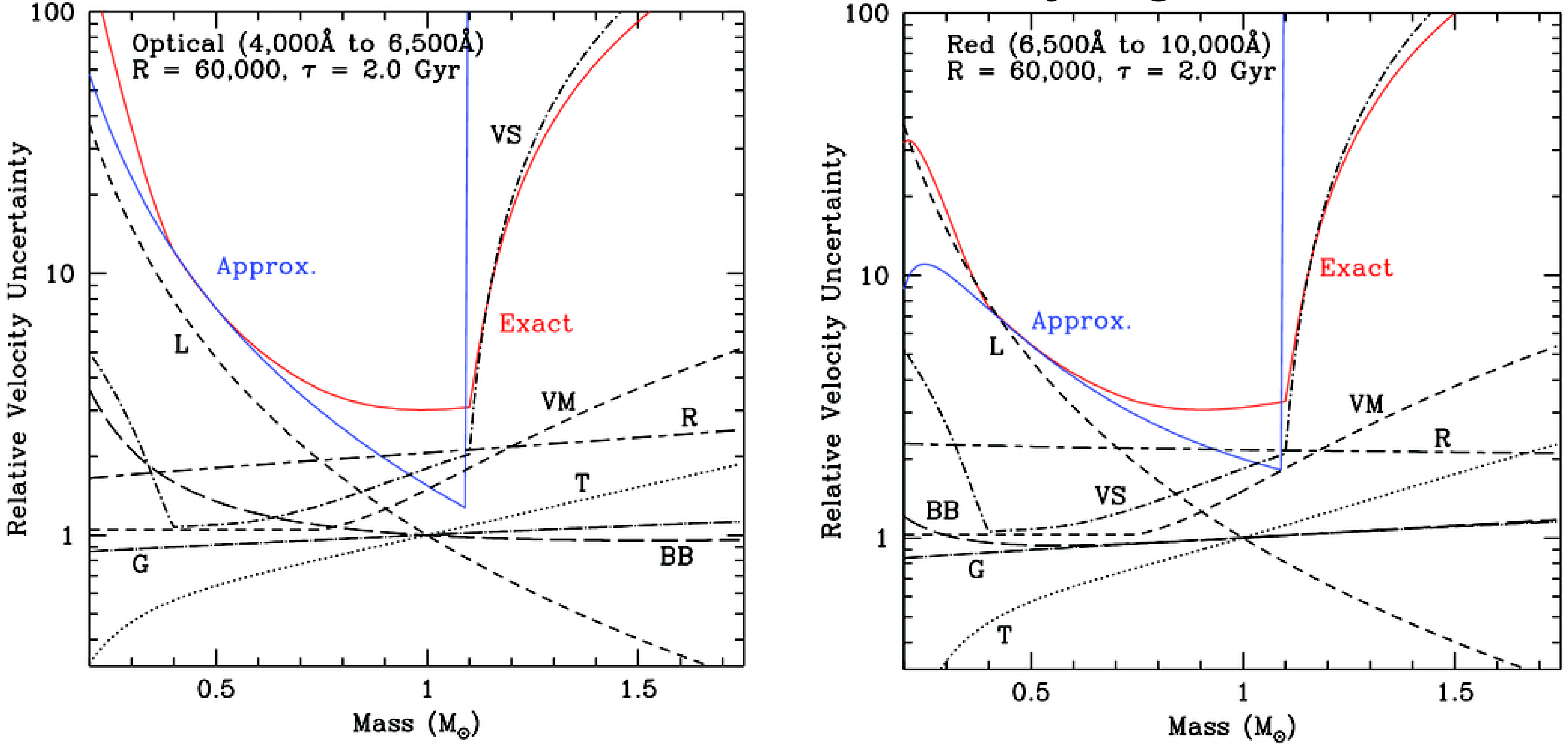
Survey Simulations 2 – Justifying the ETC





But including radius, vsin(i), log(g), metallicity, and p-modes changes everything.

Survey Simulations 2 – Justifying the ETC



Uncertainty sources: lines from effective temperature (T), overall luminosity (L), luminosity from blackbody peak vs bandpass (BB), rotation (VS), macroturbulence (VM), surface gravity (G), and spectral resolution (R). (Beatty et al 2015)

Survey Simulations 2 - Conclusions

- Target list size and exposure times matter a lot.
- Declination matters a moderate amount.
- Right Ascension technically matters.
- If we need/want NIR, we need better telluric corrections.
- We can “solve” p-modes entirely (though other stellar noise sources remain).
- There’s a case to be made for better weighting, but that would be a whole paper (or multiple papers) into itself.
- My exposure times are probably trustworthy, but there could be large missing systematics.

Simulations for Upcoming and Proposed Exoplanet Surveys as Pathfinders for Direct Imaging Missions

Survey Simulations 1

Survey Simulations 2

- Orbiting Photometric Lightsource

Orbiting Photometric Lightsource – Why?

Good relative photometric precision

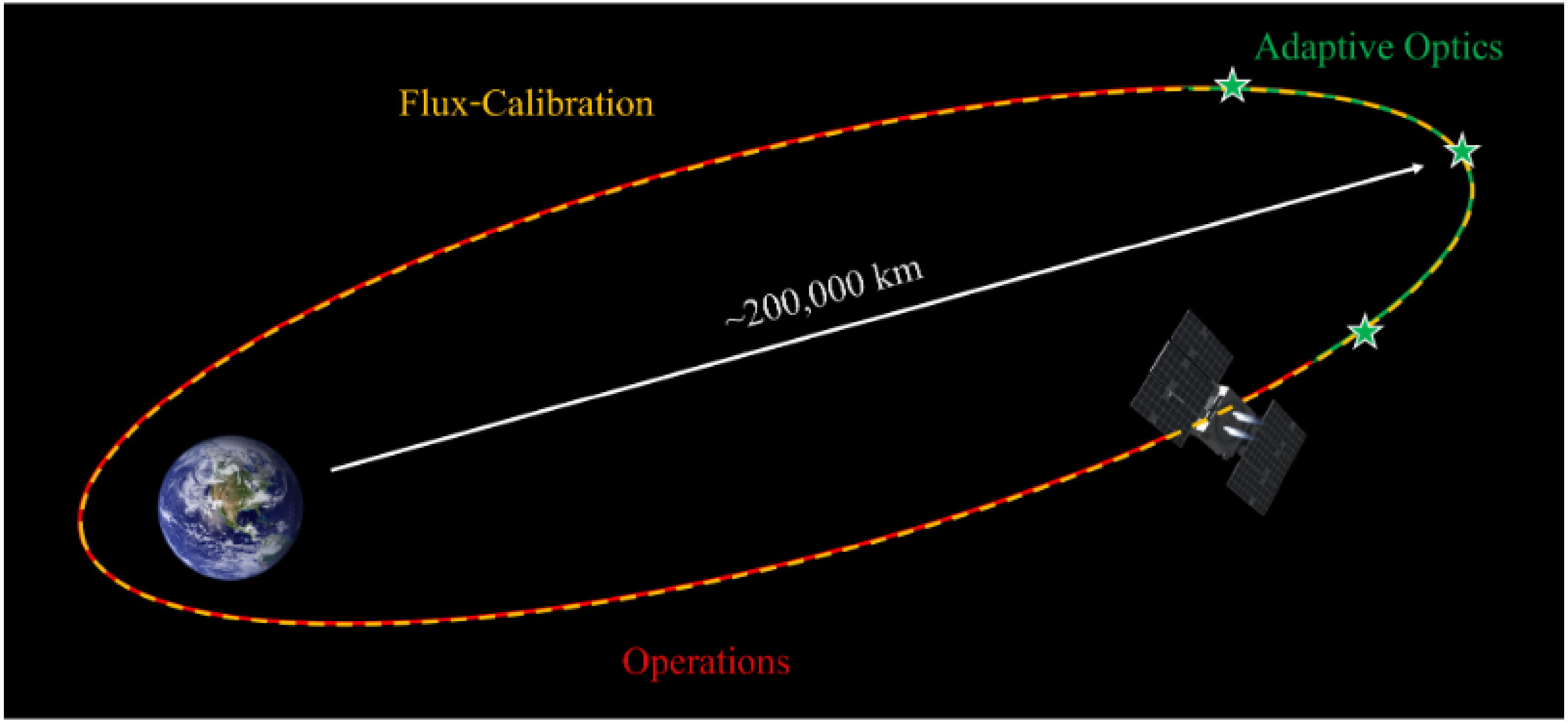
Bad absolute photometric precision

HST calibration based on 3 DA stars

Good physically understood calibrators in labs, but are not end-to-end for telescopes (atmosphere and stellar properties)

Can also tune brightness and use as AO target

Orbiting Photometric Lightsource – Why?



Albert 2012 used 532 nm laser on CALIPSO to calibrate extinction. This was an Earth observation platform, with an orbit not designed for ease observing the satellite.

ORCAS (Peretz et al 2021) looks into orbits that can do more.

Orbiting Photometric Lightsource – Why/How?

ORCASat 2022

“Artificial star”/satellite in orbit – known properties

What light-sources are best, and where should it go?

Orbiting Photometric Lightsource – How?

Simulate sources – how bright at what distance

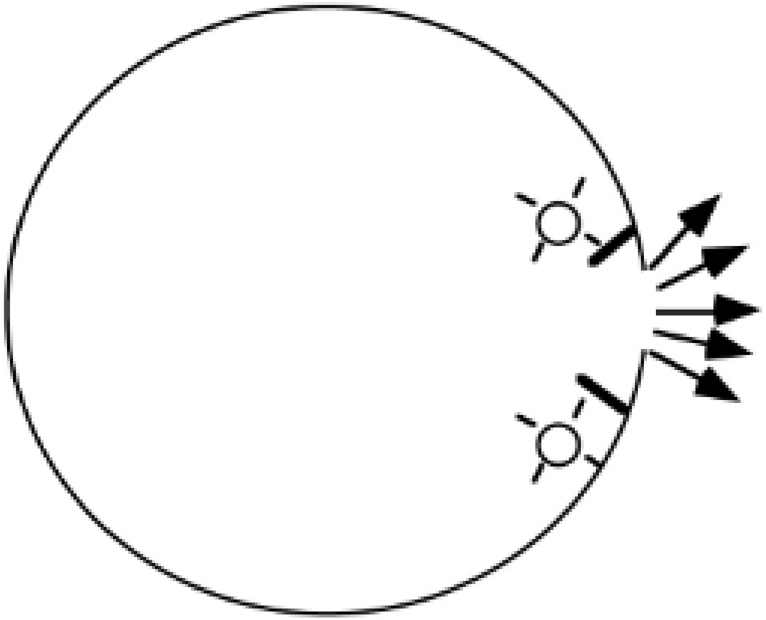
Blackbody and LED

Detectors at many photometric bands

Many source dispersions (though not profile details)

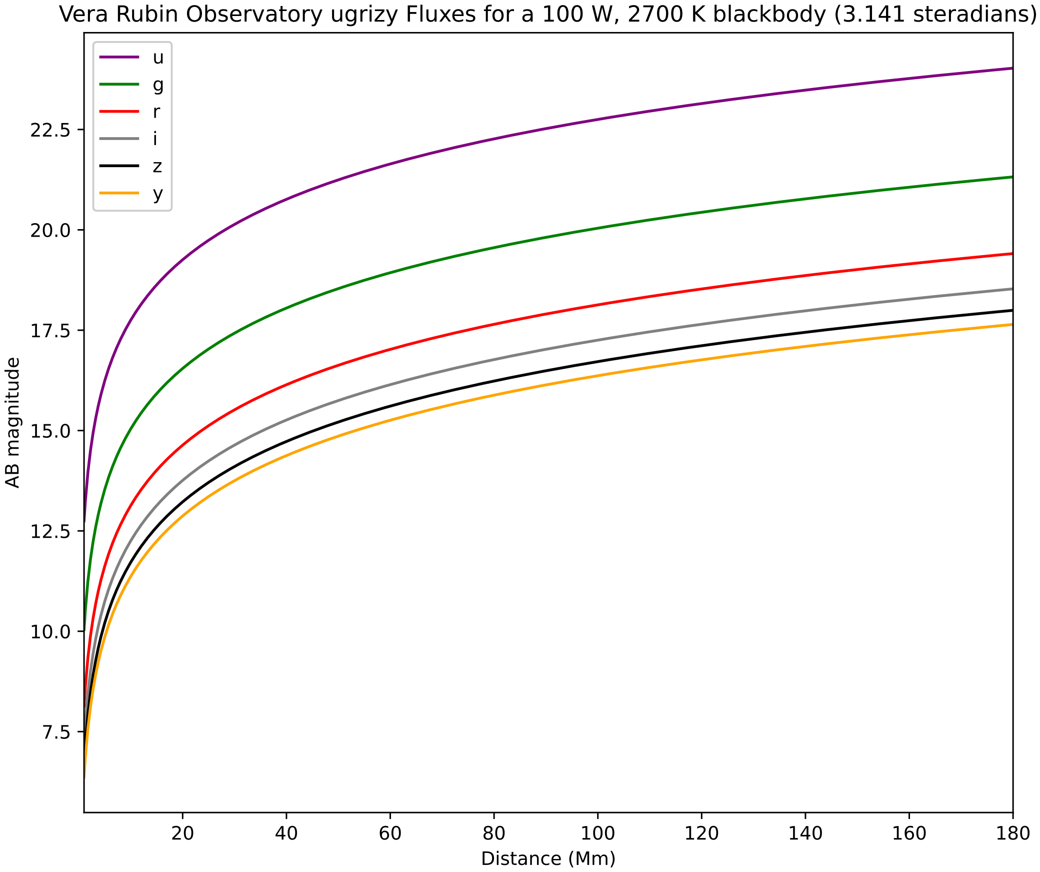
No atmosphere

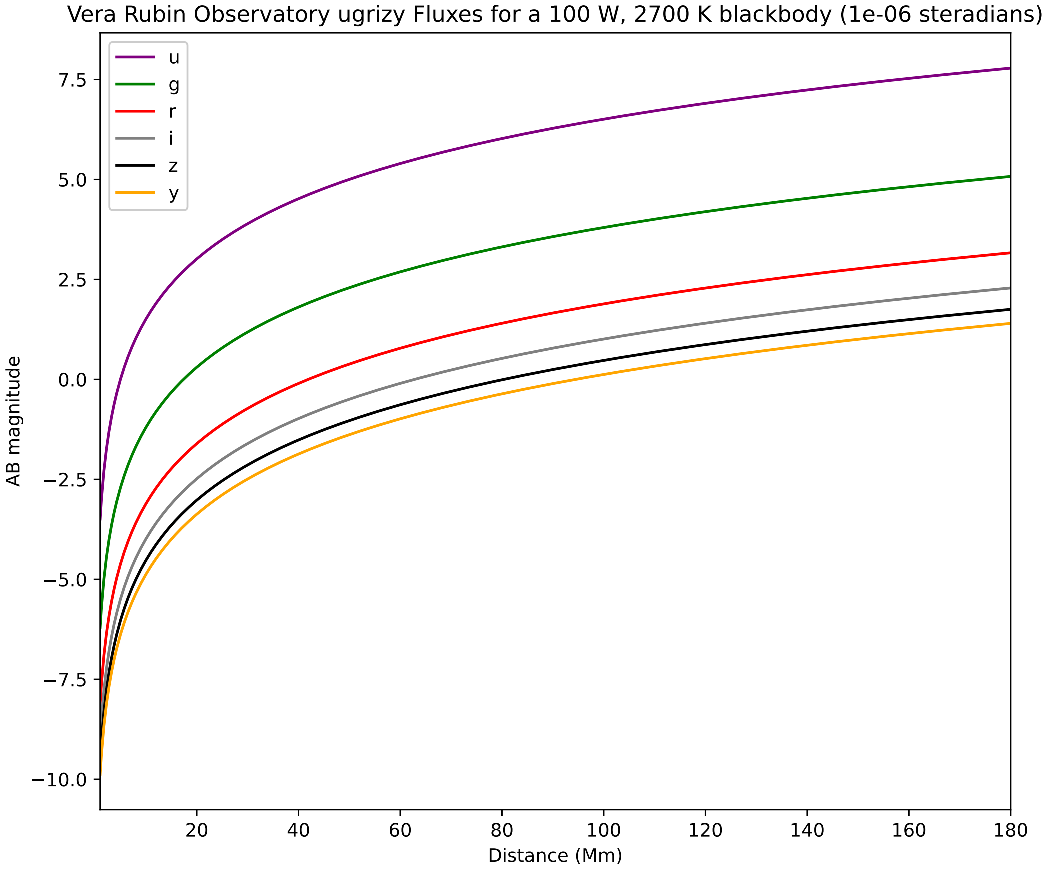
Orbiting Photometric Lightsource – How?



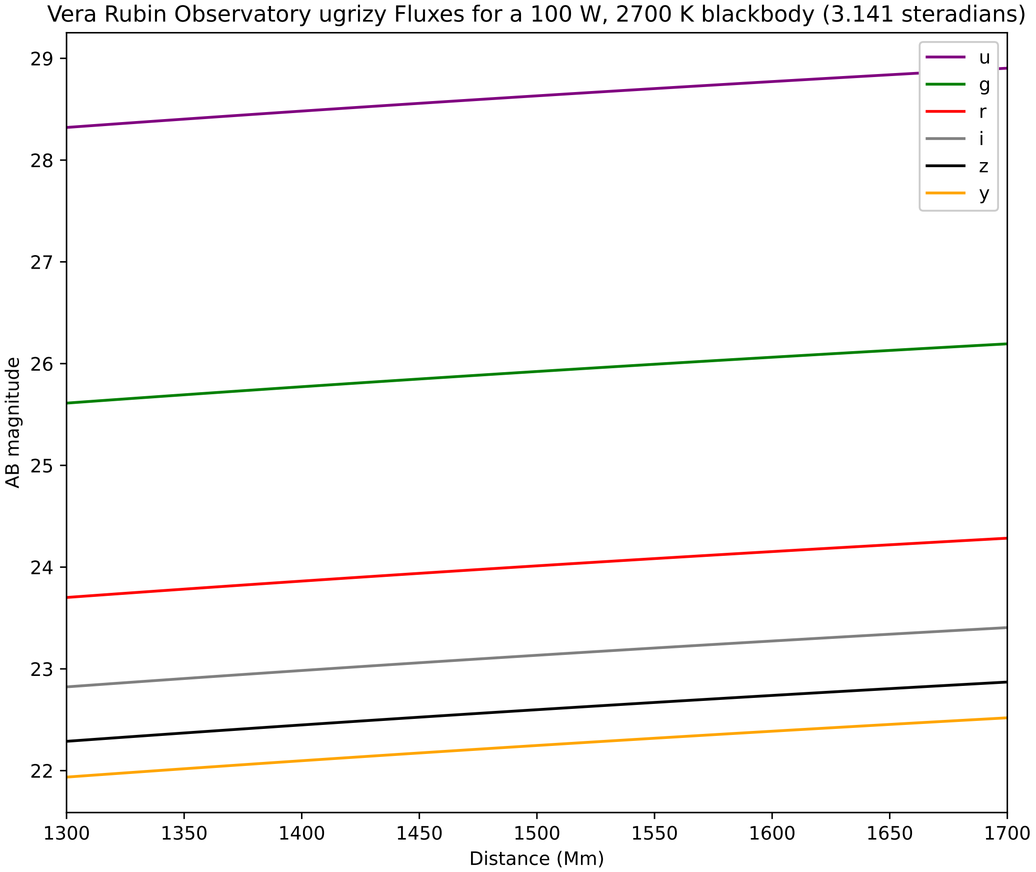
Integrating sphere is lambertian, but has large dispersion.
Collimated optics can be (almost) arbitrarily focused, but need to consider gaussian beam profile and aiming.
Bare fibres as an ‘intermediate’ (and simple) option.

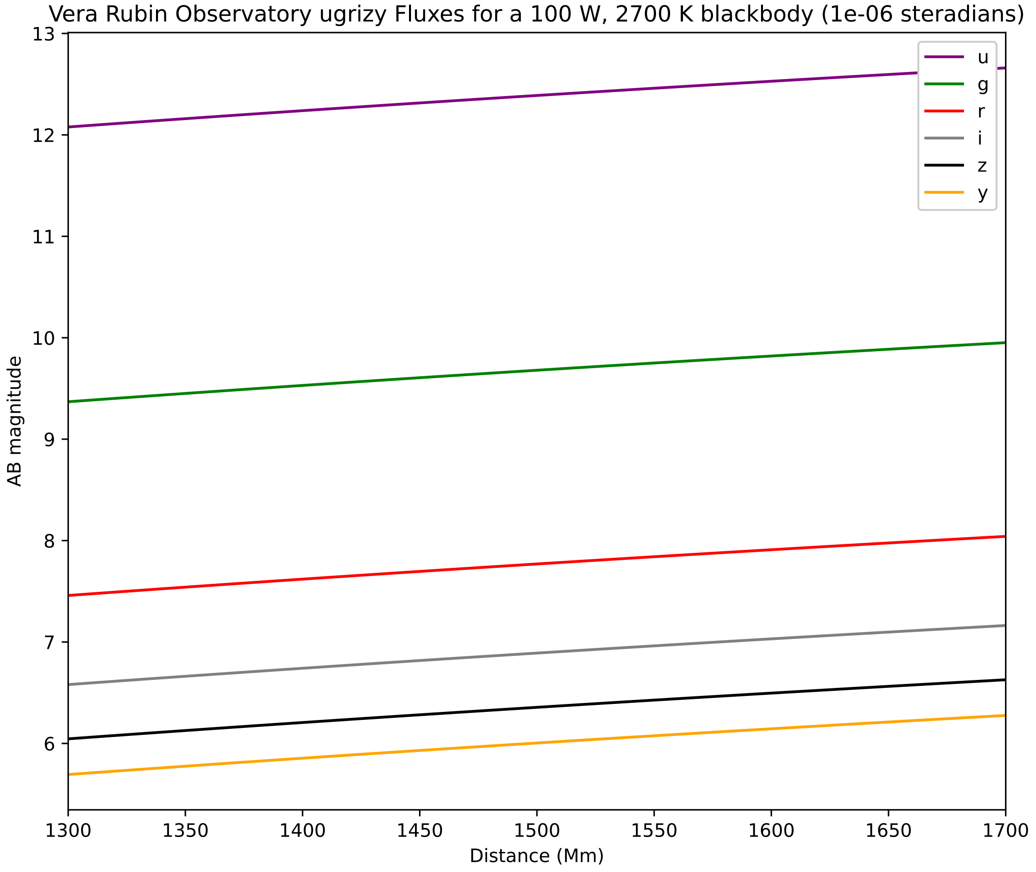
Orbiting Photometric Lightsource – Black Body (GEO)



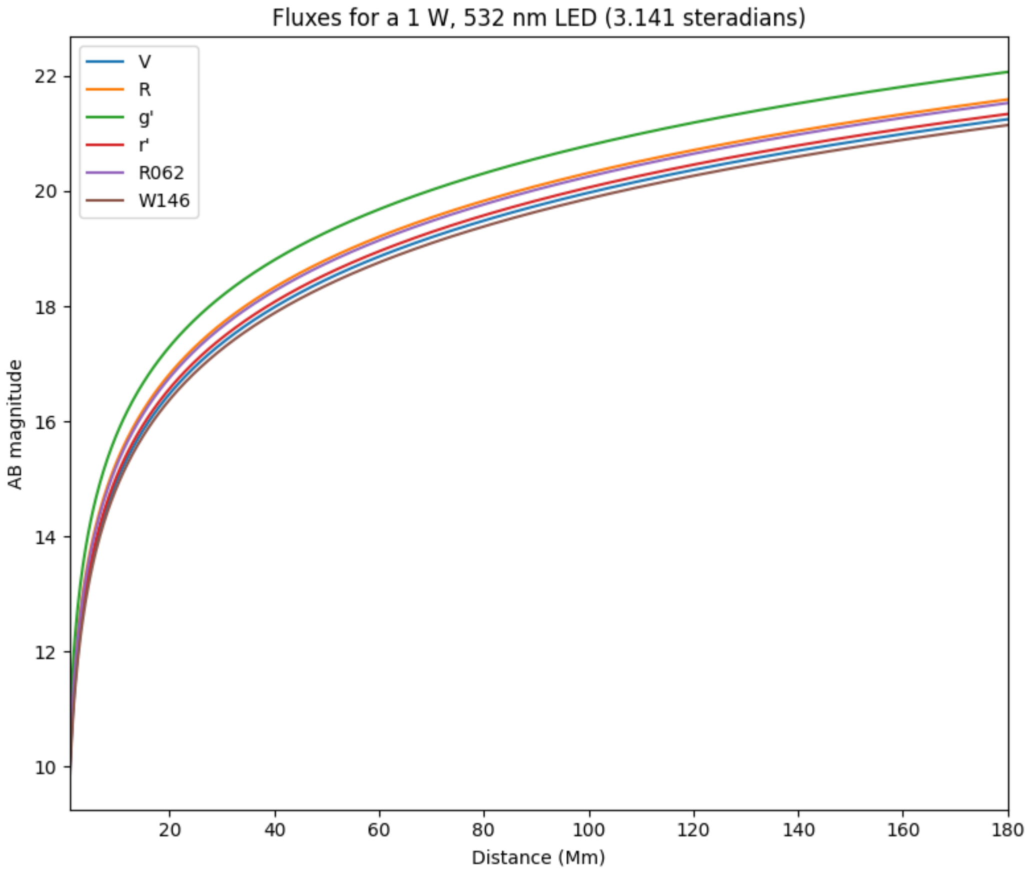


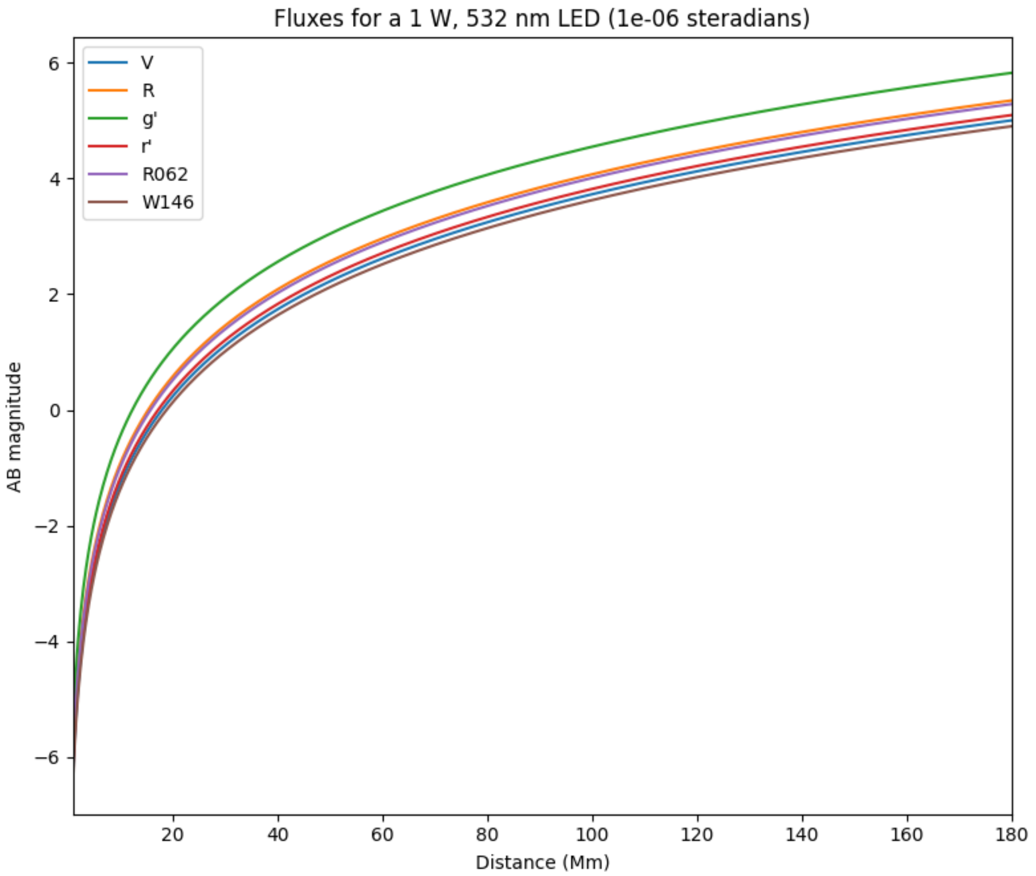
Orbiting Photometric Lightsource – Black Body (L2)



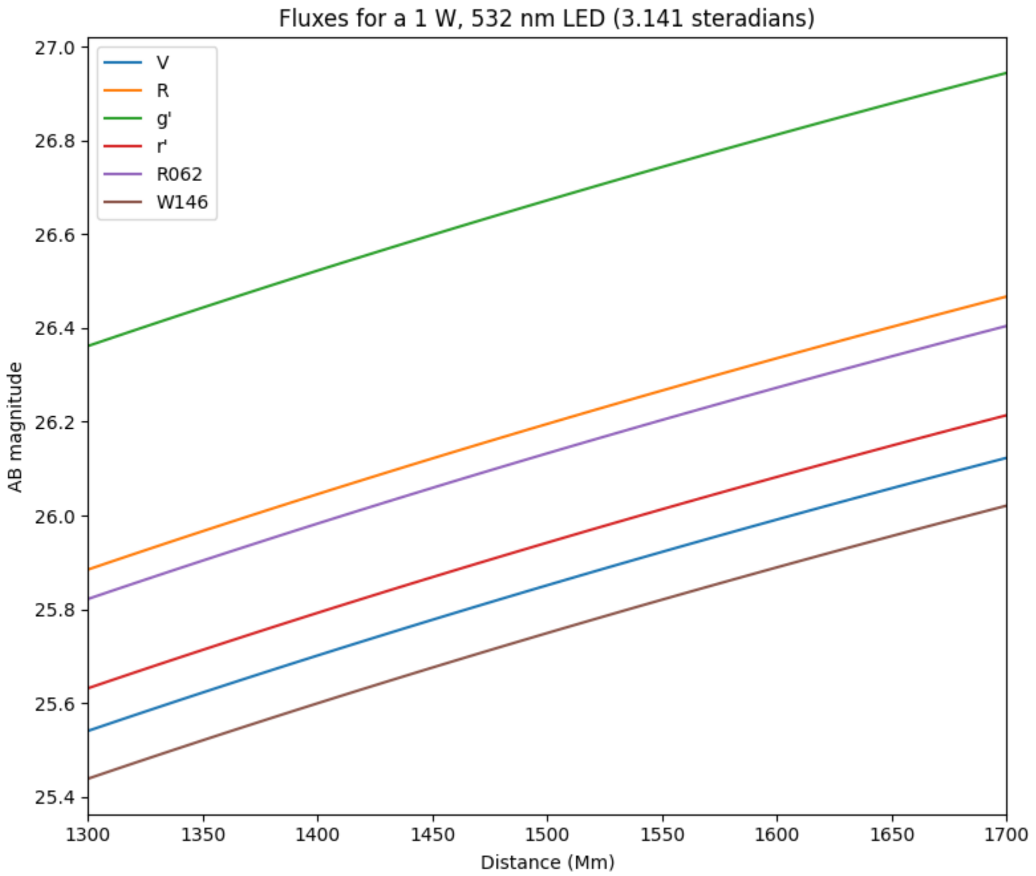


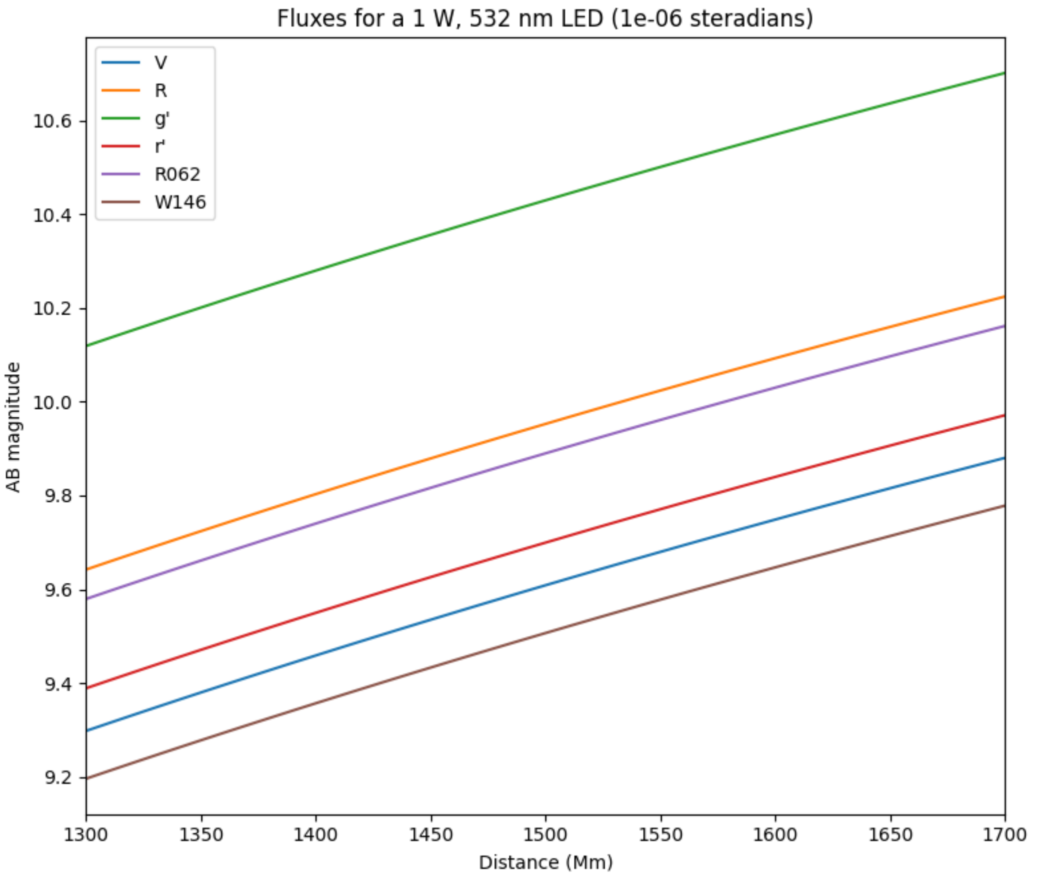
Orbiting Photometric Lightsource – LED (GEO)





Orbiting Photometric Lightsource – LED (L2)





Orbiting Photometric Lightsource – Results

- Need LEDs to keep power in line
- Want LEDs anyway for covering lots of bands
- Need some degree of collimation (unless you launch a cubesat from the ISS)
- Difficult to use distant orbits

Summary of Thesis Findings

Survey Simulations 1:

- Most architectures can work okay, though fully dedicated 4+ m telescopes are best.
- More telescopes at more locations solve everything. (but fewer might work)
- Exposure times based on single measurement RV precision and on target SNR give similar results.
- Going from 5 to 10 minute p-modes changes observation count but not survey sensitivity!

Survey Simulations 2:

- Target list size and exposure times matter a lot.
- Declination matters a moderate amount.
- Right Ascension technically matters.
- If we need/want NIR, we need better telluric corrections.
- We can “solve” p-modes entirely (though other stellar noise sources remain).
- There’s a case to be made for better weighting, but that would be a whole paper (or multiple papers) into itself.
- My exposure times are probably trustworthy, but there could be large missing systematics.

Orbiting Photometric Lightsource:

- Need LEDs to keep power in line
- Want LEDs anyway for covering lots of bands
- Need some degree of collimation
- Difficult to use distant orbits

Bonus Slide(s)

Bonus Slide(s)

Exposure time calculations assumed 10° Zenith angle

There are lots of text files (including CSVs) as output if wanted

(Simulations 1 had some sims pull double duty)

(Simulations 2 has many “non-canonical” sims)

Weighting includes MINERVA’s 3 obs/night attempt (sort of)

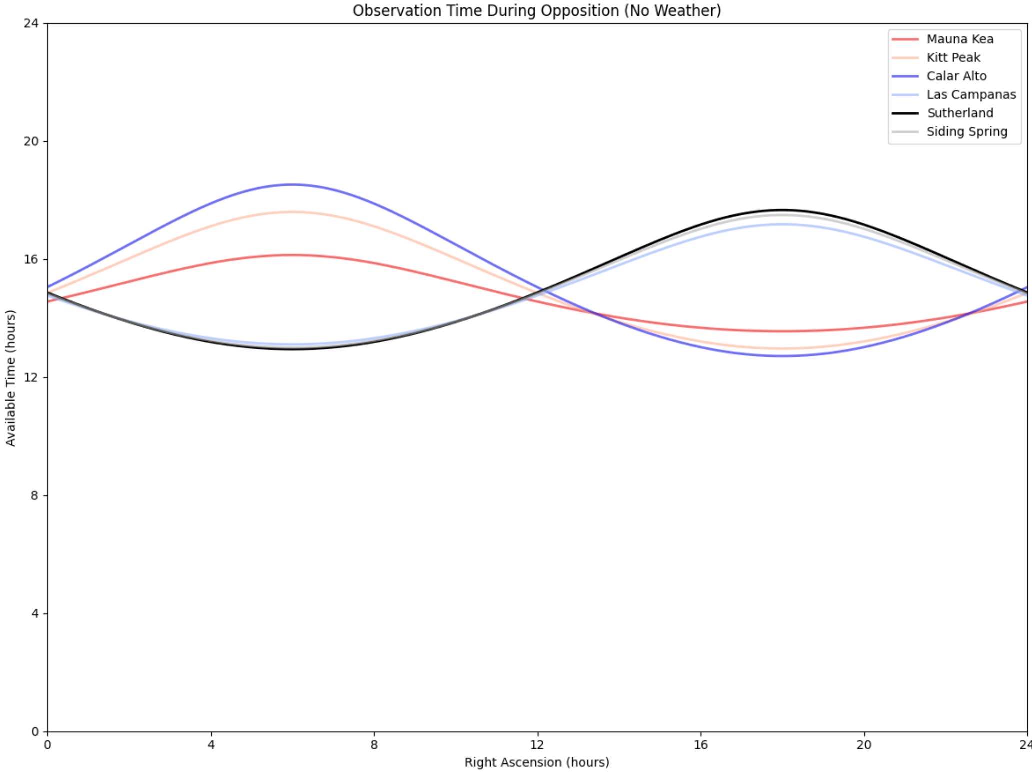
Weighting does not include our 2016-2017 attempts

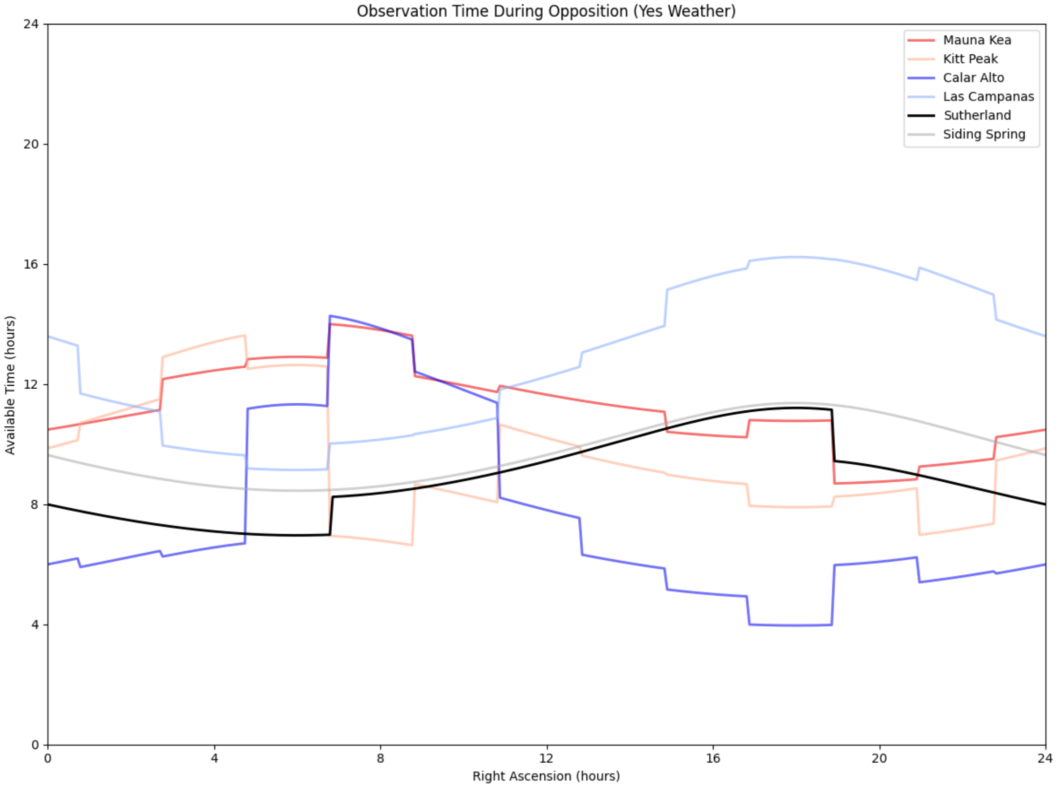
Bonus Slide(s) – atmosphere model

2 component continuum model.
Rayleigh and gray haze, both have the same scale height (8400 m by default).
Slab, no refraction.

$$\tau = 0.09 + \left(\frac{3080\, Angstroms}{\lambda}\right)^4$$

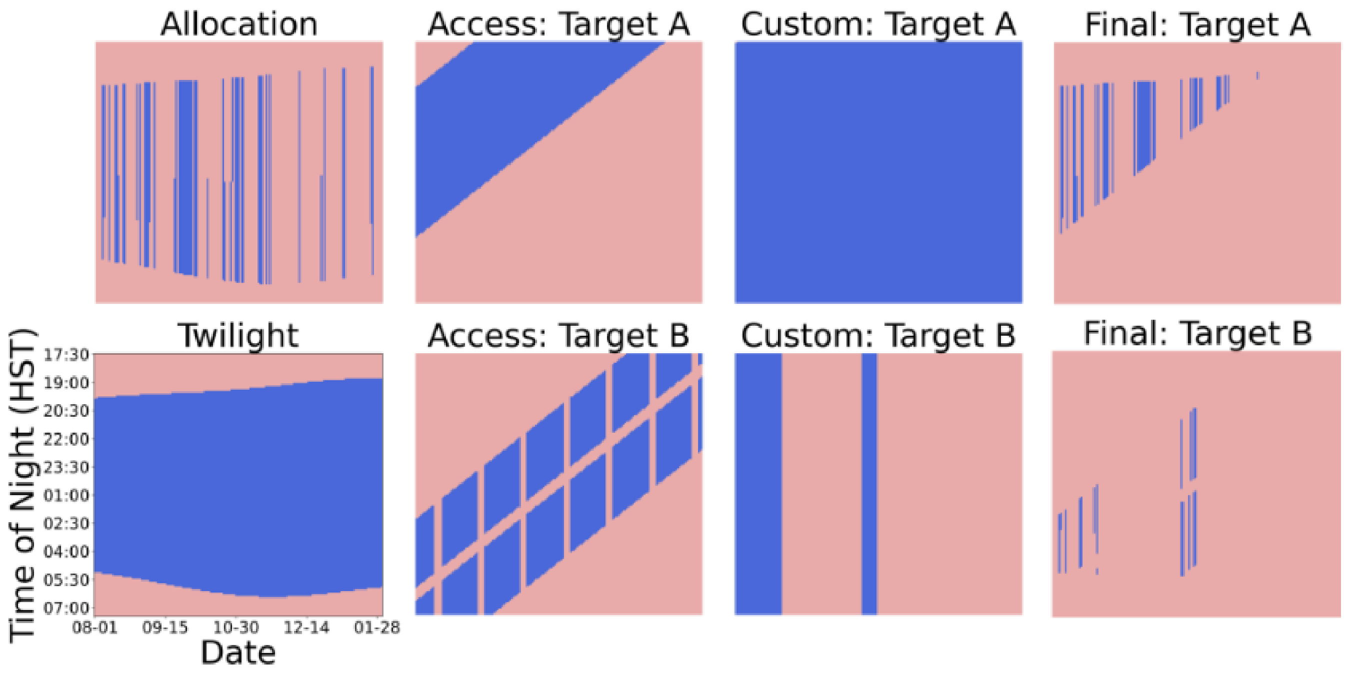
Bonus Slide(s) – Sites/Weather/Time

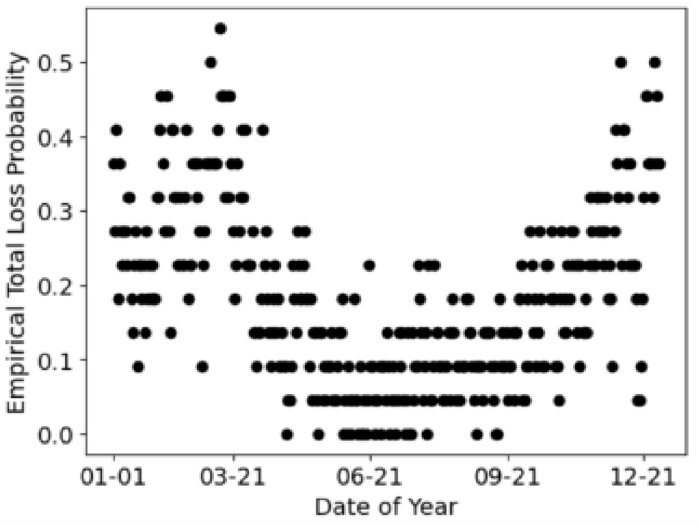




Target properties and per-site list optimization (RA/Dec/Time) could be studied more formally.

Bonus Slide(s) – Sites/Targets/Weather/Time





Lubin et al 2025 do that, though specifically for Keck

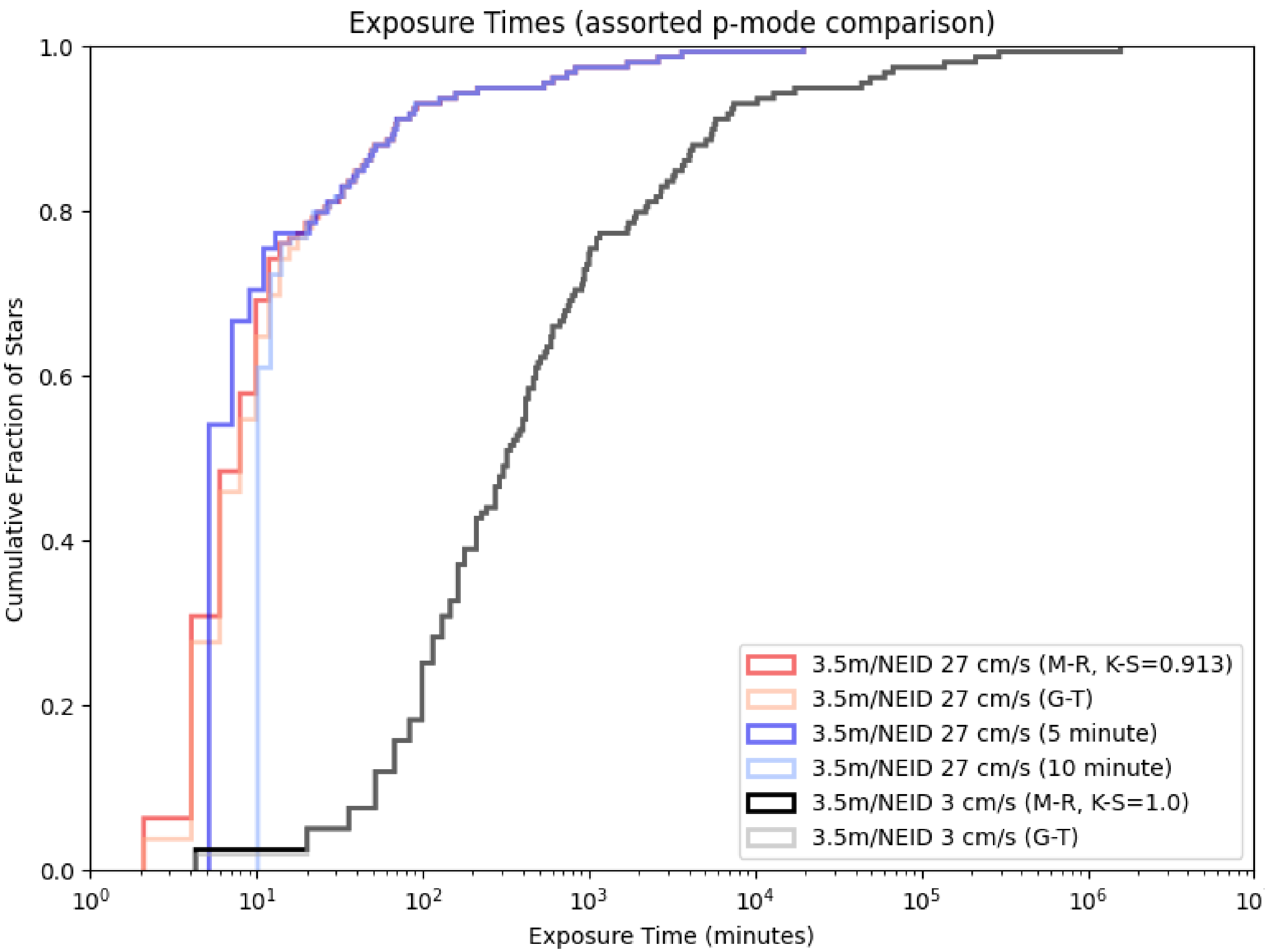
Bonus Slide(s) – Champion Architectures

Architecture	I	IIa	IIb
Telescopes	6x2.4 m	2x6 m and 4x4 m	6x4 m
Collecting area by aperture	2.4 m = 4.2 m^2	4 m = 9.5 m^2; 6 m = 27 m^2	4 m = 9.5 m^2
Time allocation	100%	100%	100%
Wavelength coverage	380-930 nm	380 - 930 nm	380 - 930 nm
Spectral resolution	180 000	180 000	180 000
Total system efficiency	6%	6%	6%
instrument noise floor	10 cm/s	5 cm/s	5 cm/s
Required (peak) SNR/pix	300	300	300
Required RV precision	10 cm/s	10 cm/s	10 cm/s
Observation cadence per star	1 / night	3 / night	3 / night

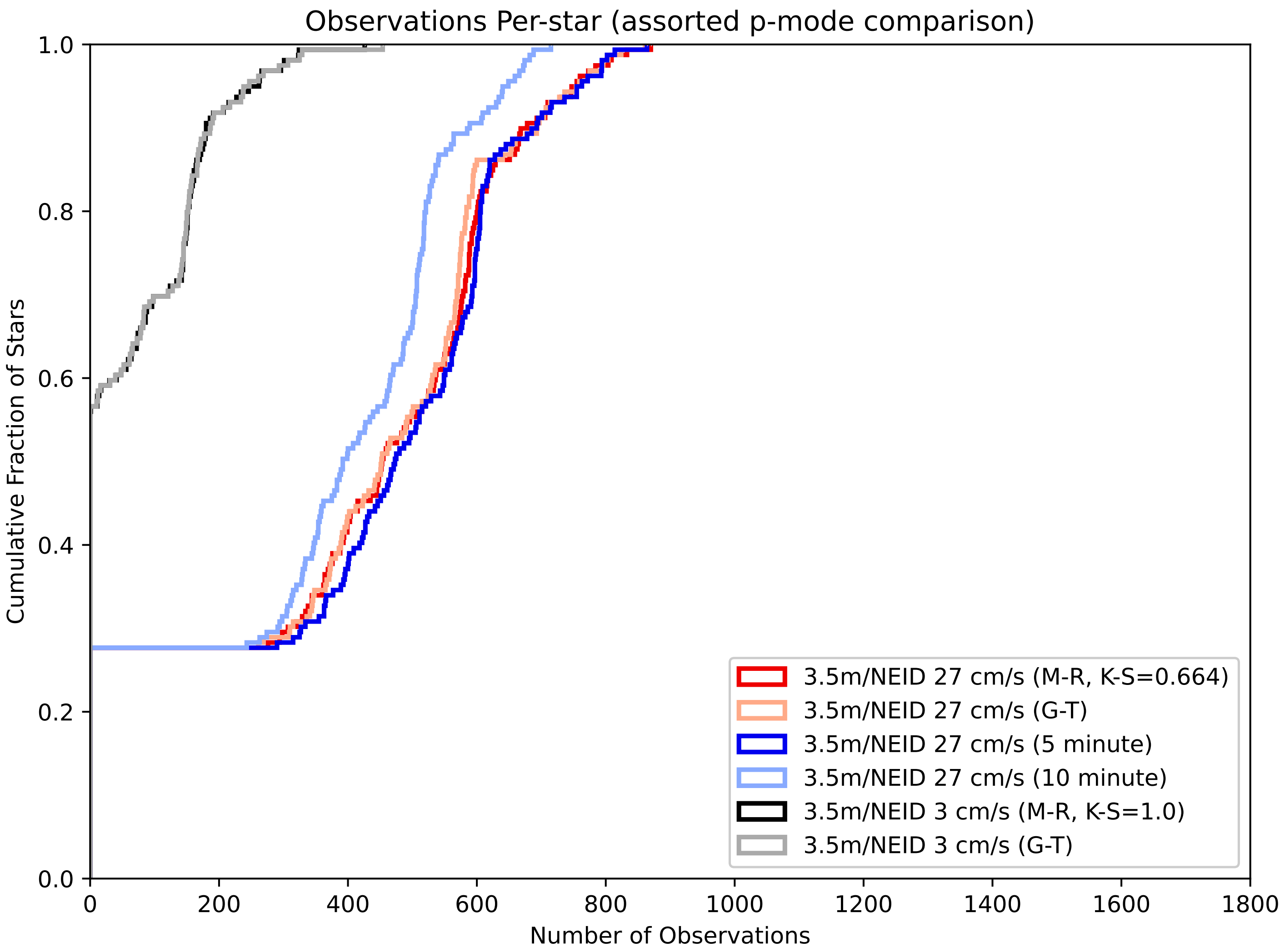
Architecture	V	VI
Telescopes	6x3 m	6x arrays of 1 m
Collecting area by aperture	3 m = 6.3 m^2	0.61m^2 each; array is 9.5 m^2
Time allocation	100%	100%
Wavelength coverage	500-1700 nm	500-800 nm
Spectral resolution	180 000	150 000
Total system efficiency	7%	6%
instrument noise floor	10 cm/s	10 cm/s
Required (peak) SNR/pix	300	300
Required RV precision	10 cm/s	10 cm/s
Observation cadence per star	2 / telescope / night	1/night

Architecture	VIIIa	VIIIb
Telescopes	2x10 m and 4x 3.5 m	2x10 m and 6x2.4 m
Collecting area by aperture	10 m = 75 m^2; 3.5 m = 9.5 m^2	10 m = 75 m^2; 2.4 m = 4.2 m^2
Time allocation	25% of 10 m; 100% of 3.5m	25% of 10 m; 100% of 2.4 m
Wavelength coverage	380-930 nm	380-930 nm
Spectral resolution	180 000	180 000
Total system efficiency	6%	6%
instrument noise floor	5 cm/s	5cm/s
Required (peak) SNR/pix	1000 for the 10 m; 300 for 3.5 m	1000 for the 10 m; 300 for 2.4 m
Required RV precision	15 cm/s on 3.5 m; 5 cm/s on 10 m	15 cm/s on 2.4 m; 5 cm/s on 10 m
Observation cadence per star	1/week on 10 m; 1/night on 3.5 m	1/week on 10 m; 1/night on 2.4 m

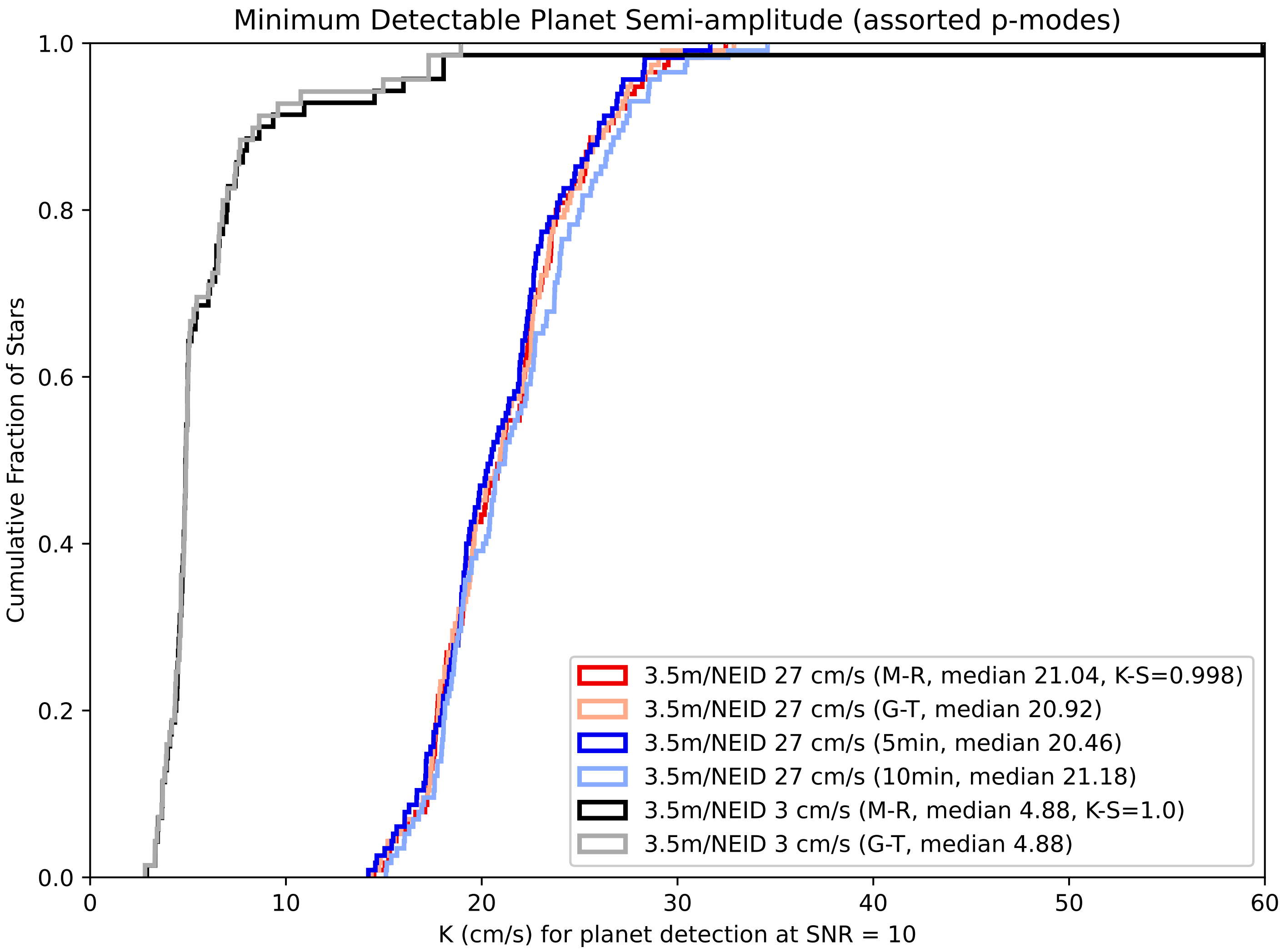
Bonus Slide(s) – p-mode oscillations (canonical)



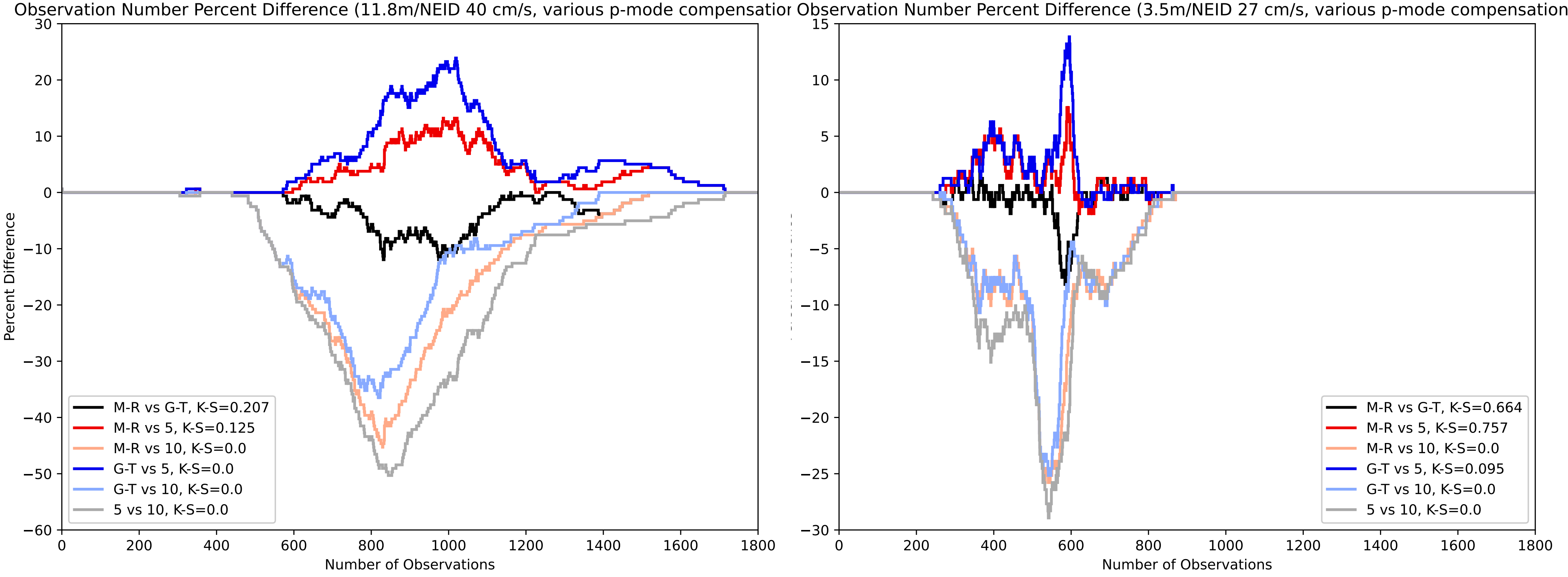
Bonus Slide(s) – p-mode oscillations (canonical)



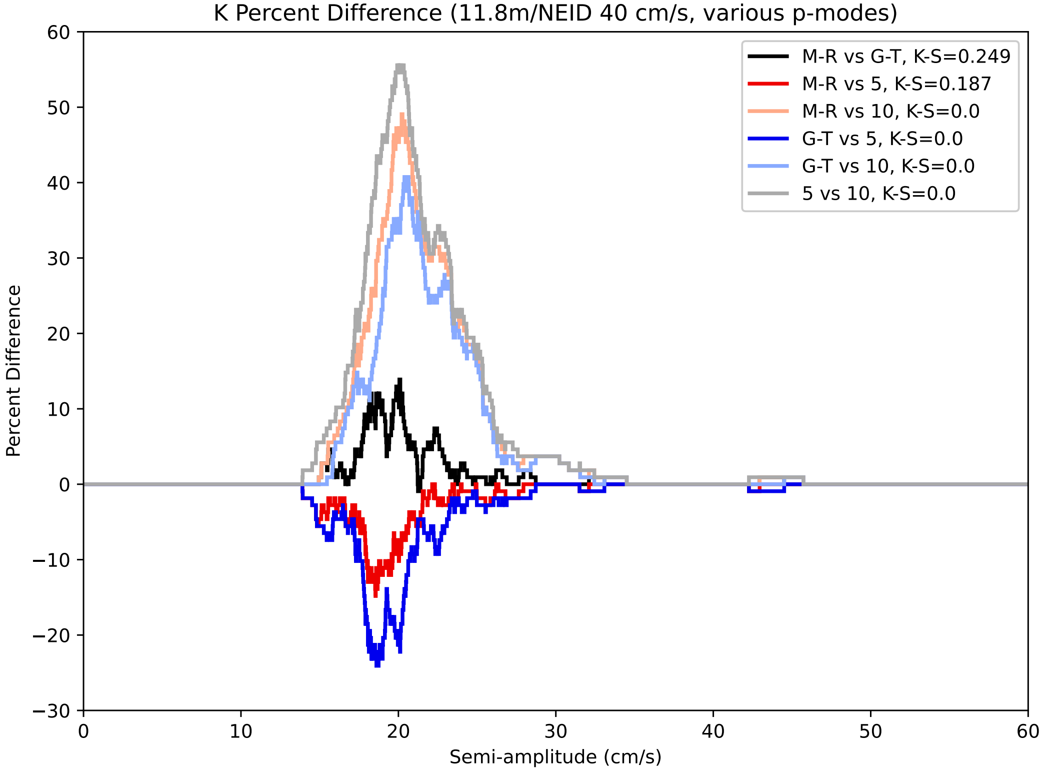
Bonus Slide(s) – p-mode oscillations (canonical)

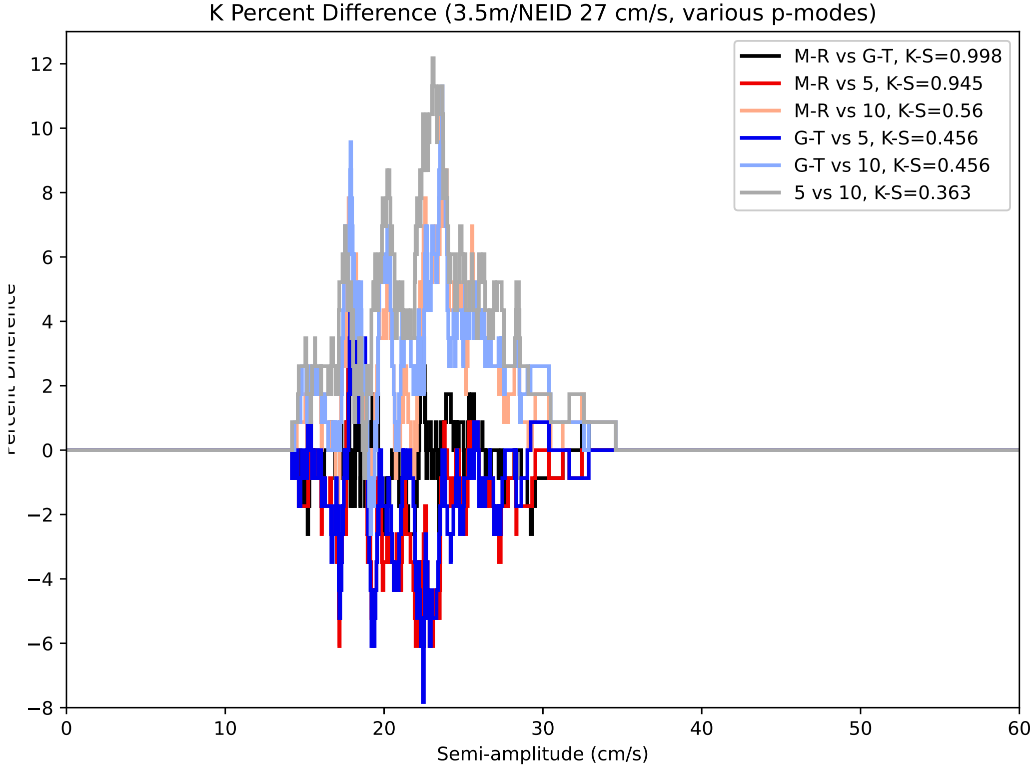


Bonus Slide(s) – p-mode oscillations (all obs)

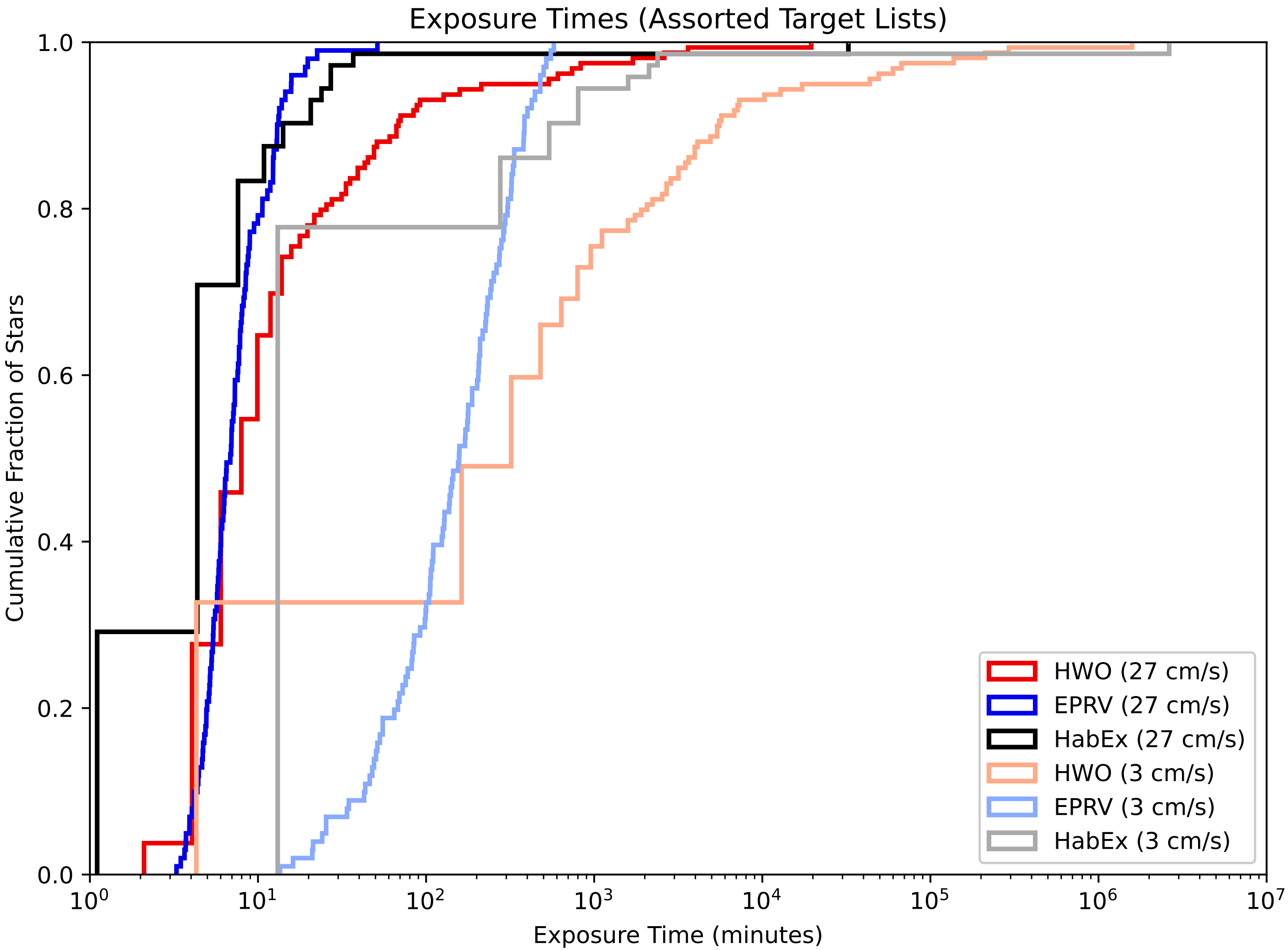


Bonus Slide(s) – p-mode oscillations (all K)

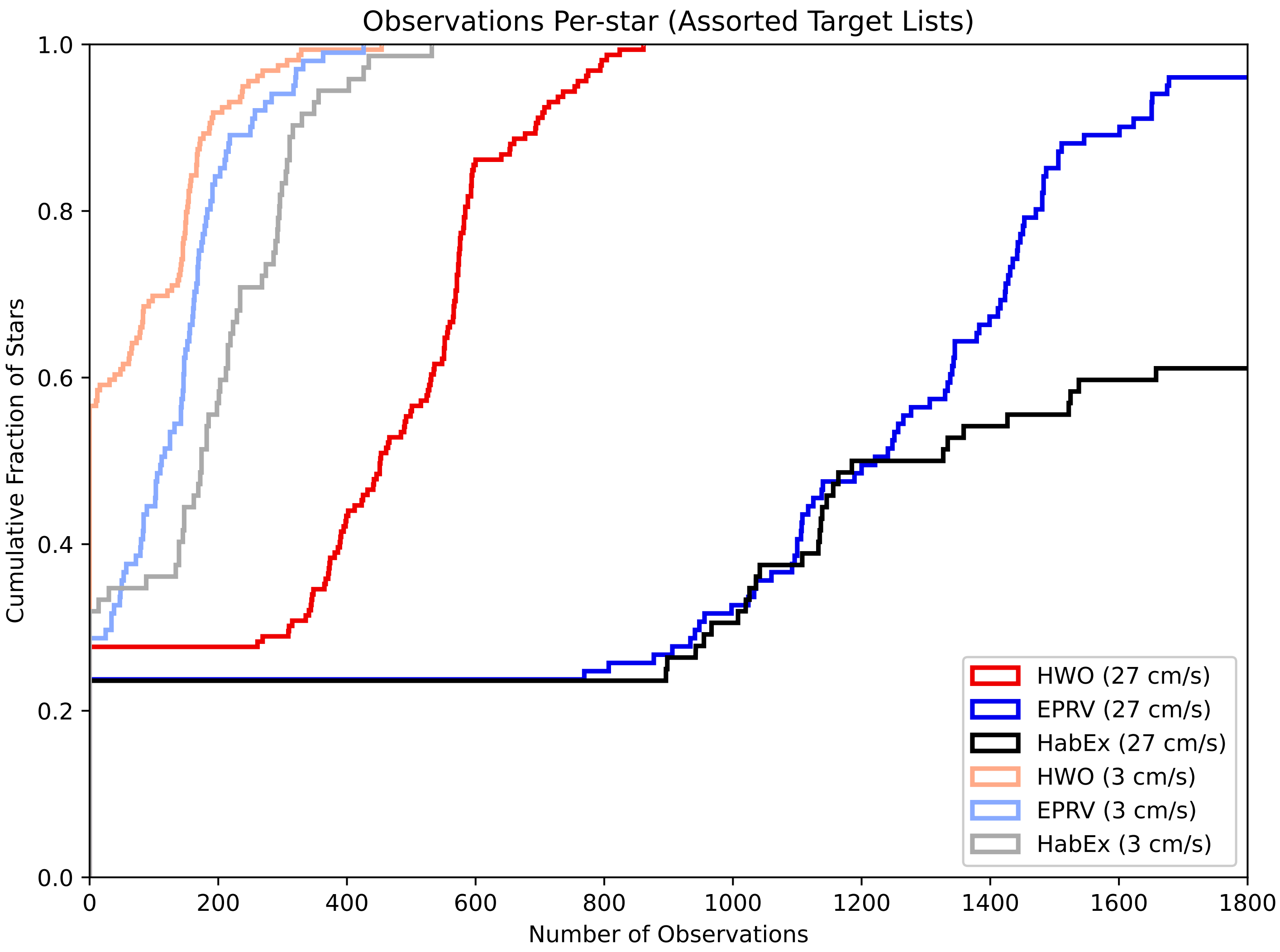




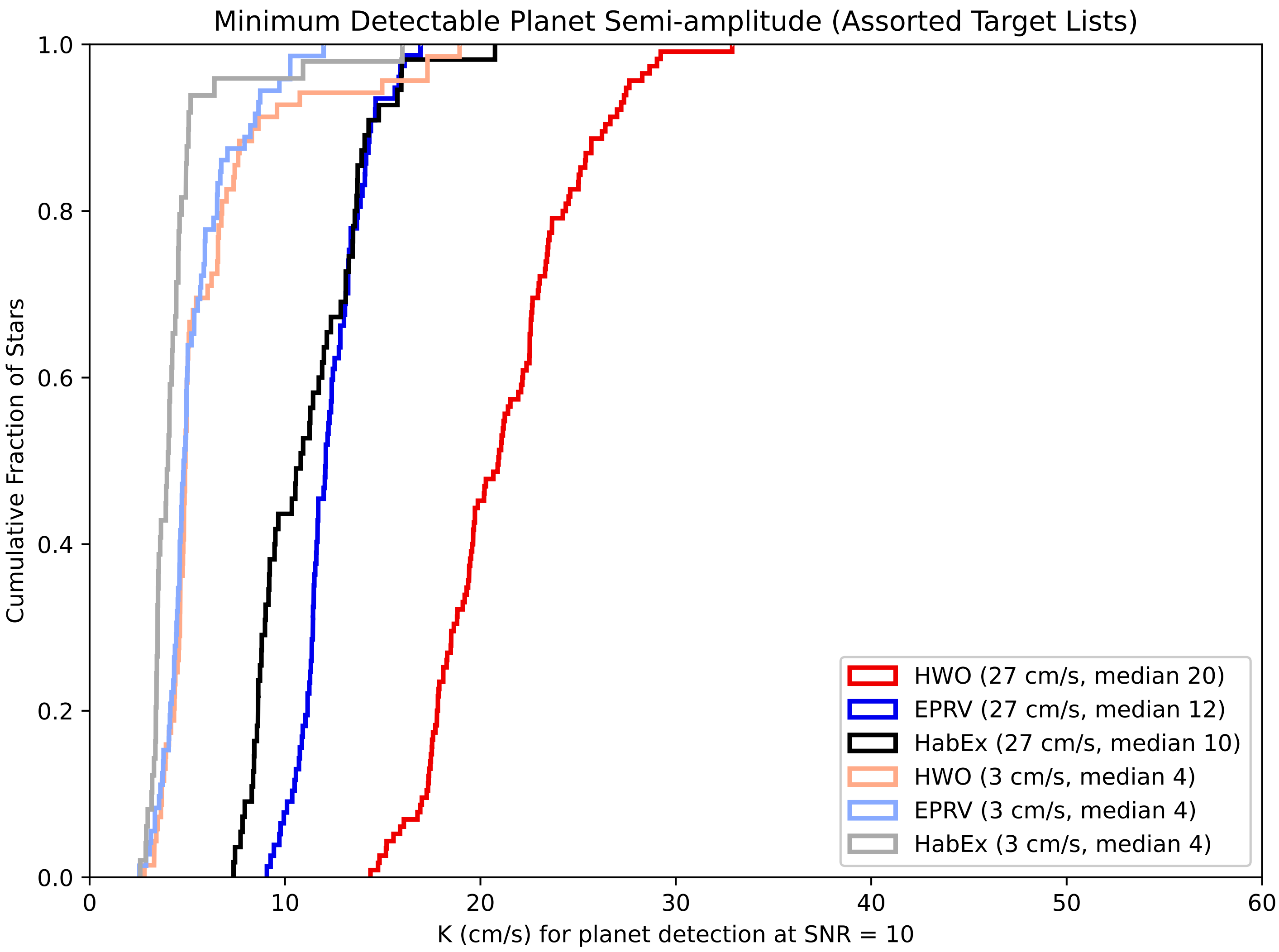
Bonus Slide(s) – Target List Comparisons (exptime)



Bonus Slide(s) – Target List Comparisons (obs)



Bonus Slide(s) – Target List Comparisons (K)



Survey Simulations 1 – Overview (bonus?)

6 architectures
6 sites
10 year baseline
101 stars
Want relative performance in detecting exoplanets, what features matter most?

Survey Simulations 2 – “Solving” p-mode oscillations

2 different fixed, and 2 different stellar property versions
All are computationally cheap, and can easily be adjusted if we get better data on the host stars that requires tweaking them.
Compare survey results: the observing time penalties are small!

Survey Simulations 2 – Outline (bonus?)

Previously: the weighting is “good enough” and very cheap computationally.
Other methods exist, but are tightly bound to a specific telescope (Garcia-Piquer et al 2017), very computationally intense (Handley et al 2024), or both.
We don’t want to solve the traveling telescope problem.
Already re-weight list after every observation

Our exposure times are physically motivated and plausible, but should be better confirmed.

Some of the survey landscape

CPS/CKS, HARPS, CARMENES, Terra Hunting Experiment

California Planet Survey and the mass-radius gap. (and other occurrence rates)

CARMENES pushing into NIR for finding planets around M-dwarfs in the solar neighborhood

HARPS as a gold standard for PRVs

Survey Simulations 2 – Justifying the Weighting

Very easy to calculate and approximates real world usage numbers.

“Best” isn’t always Hour Angle & 2 hour separation.

Don’t want to solve the traveling telescope problem. (Garcia-Piquer et al 2017, Handley et al 2024 A&B look at observation programs more generally but more constrained exptimes and/or target lists)