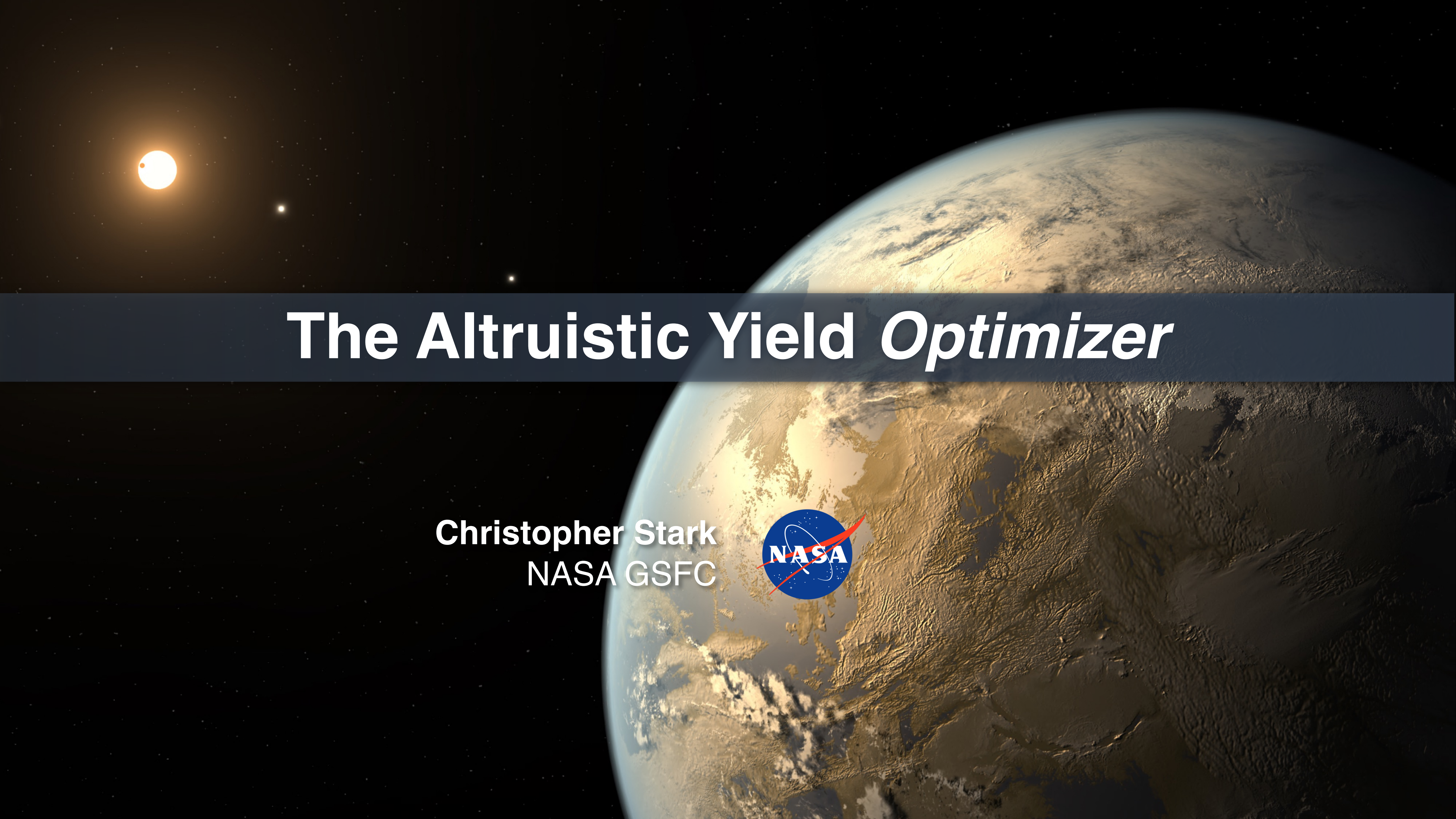
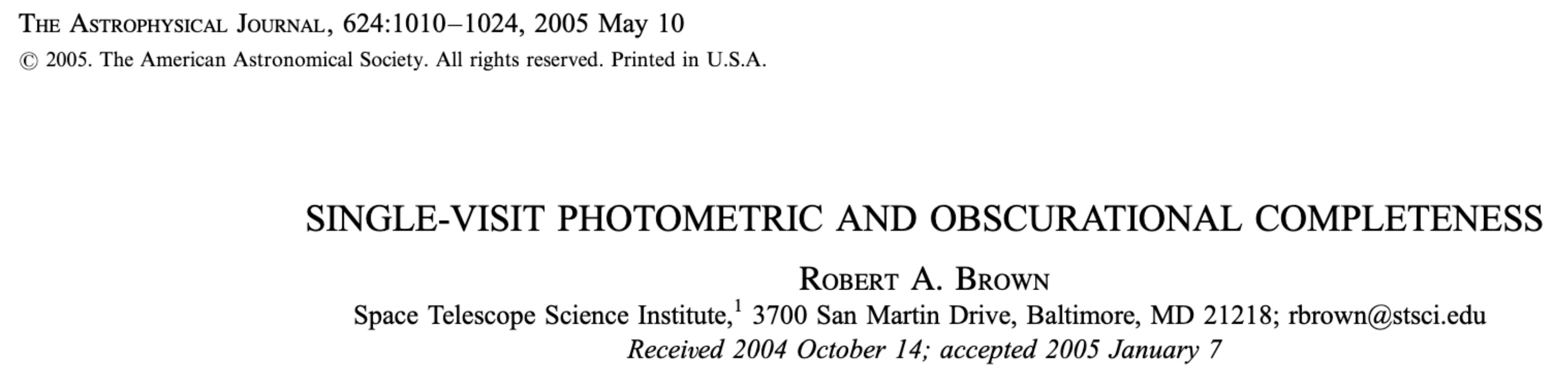


The Altruistic Yield *Optimizer*

Christopher Stark
NASA GSFC

Exoplanet imaging DRMs started with TPF



THE ASTROPHYSICAL JOURNAL, 624:1010–1024, 2005 May 10

SINGLE-VISIT PHOTOMETRIC AND OBSCURATIONAL COMPLETENESS

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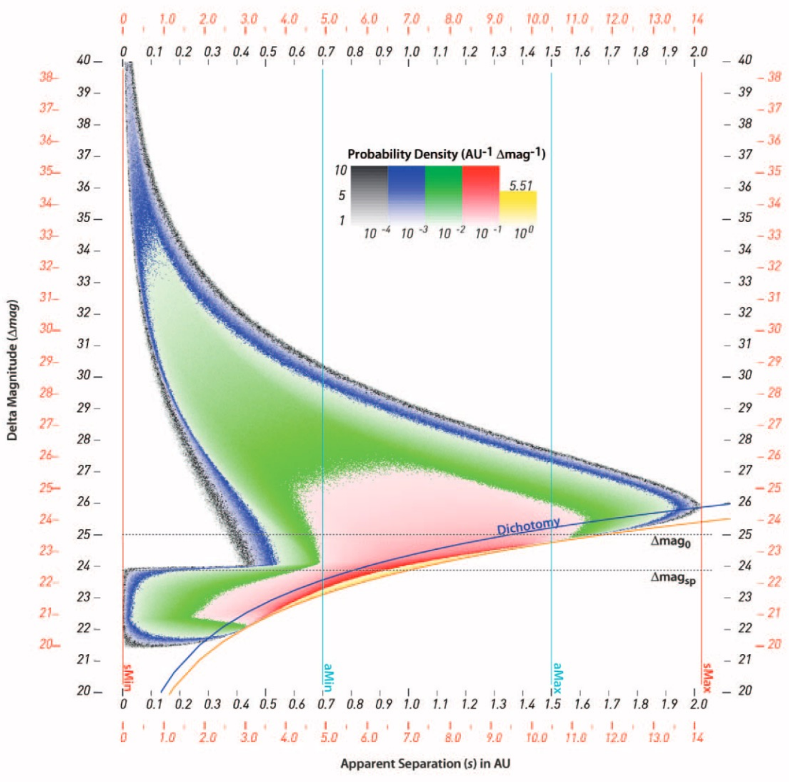
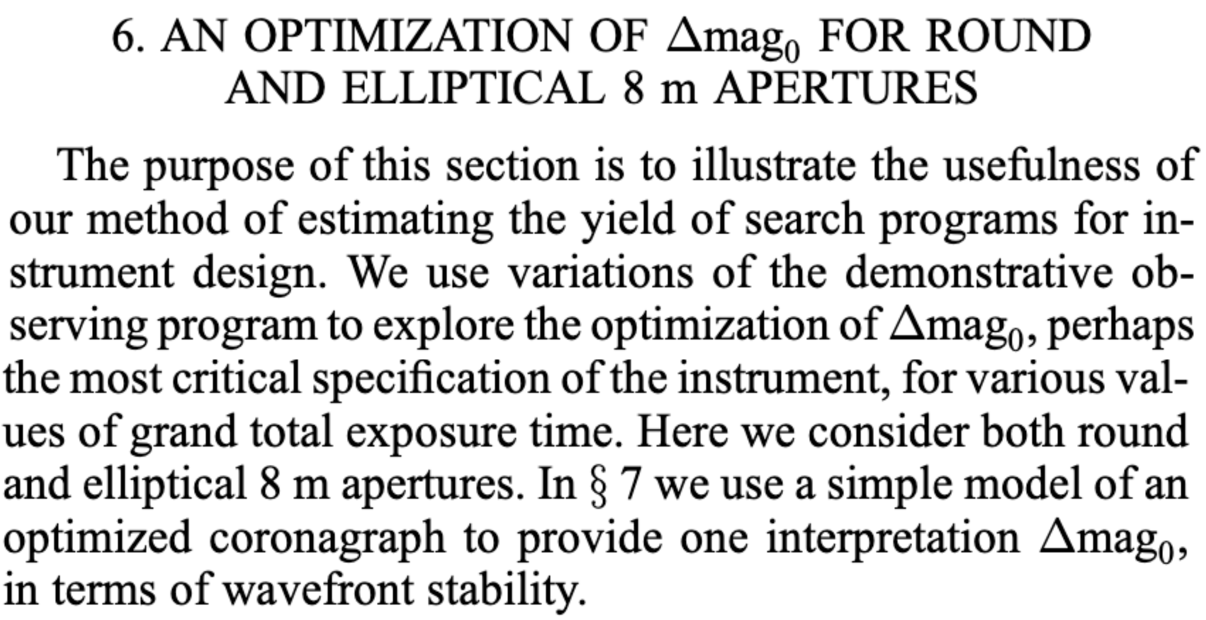


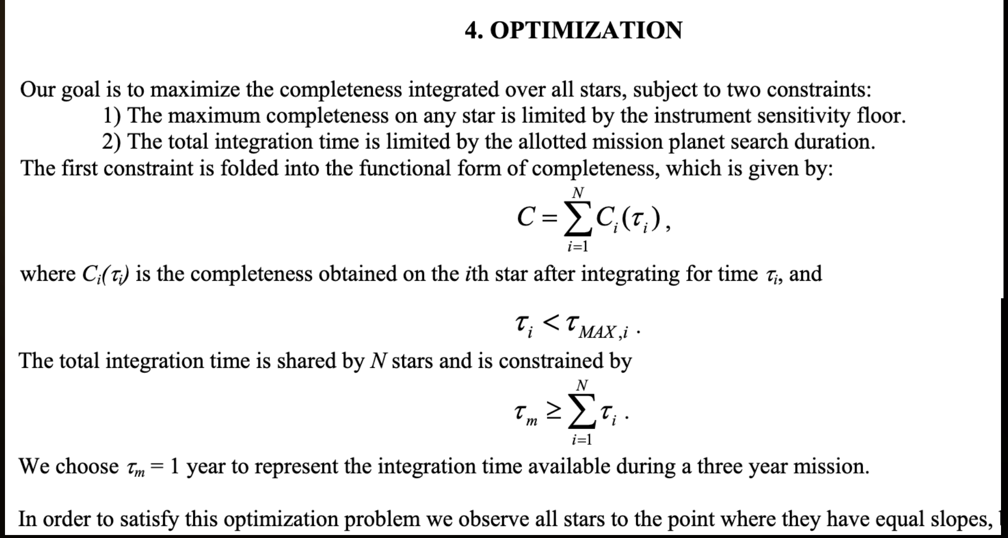
Brown (2005)



6. AN OPTIMIZATION OF $\Delta\mathrm{mag}_0$ FOR ROUND AND ELLIPTICAL 8 m APERTURES

The purpose of this section is to illustrate the usefulness of our method of estimating the yield of search programs for instrument design. We use variations of the demonstrative observing program to explore the optimization of $\Delta\mathrm{mag}_0$, perhaps the most critical specification of the instrument, for various values of grand total exposure time. Here we consider both round and elliptical 8 m apertures. In § 7 we use a simple model of an optimized coronagraph to provide one interpretation $\Delta\mathrm{mag}_0$, in terms of wavefront stability.

20 years of optimization progress



4. OPTIMIZATION

Our goal is to maximize the completeness integrated over all stars, subject to two constraints:

1) The maximum completeness on any star is limited by the instrument sensitivity floor.
2) The total integration time is limited by the allotted mission planet search duration.

The first constraint is folded into the functional form of completeness, which is given by:

$$C = \sum_{i=1}^{N} C_i(\tau_i),$$

where $C_i(\tau_i)$ is the completeness obtained on the ith star after integrating for time τ_i, and

$$\tau_i < \tau_{MAX,i}.$$

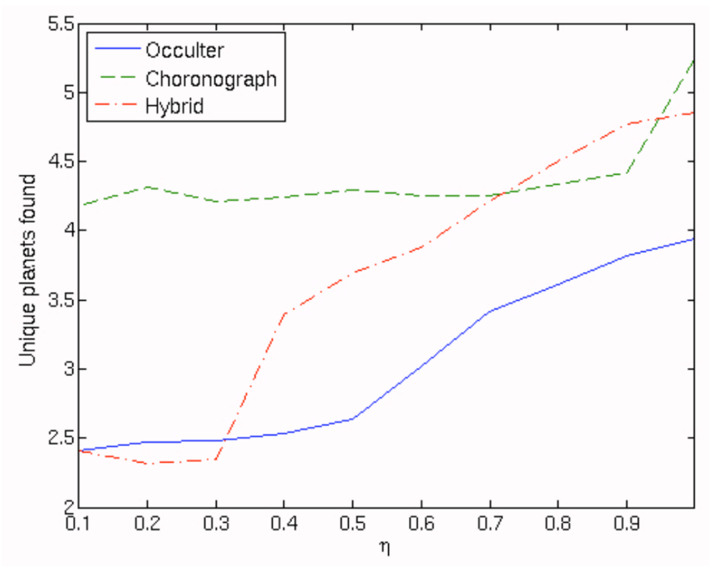
The total integration time is shared by N stars and is constrained by

$$\tau_m \ge \sum_{i=1}^{N} \tau_i.$$

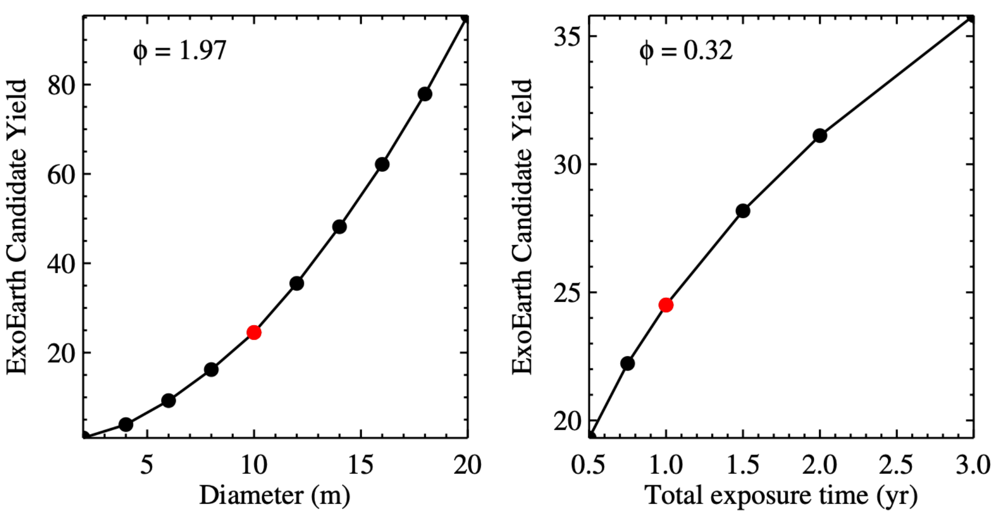
We choose τ_m = 1 year to represent the integration time available during a three year mission.

In order to satisfy this optimization problem we observe all stars to the point where they have equal slopes,

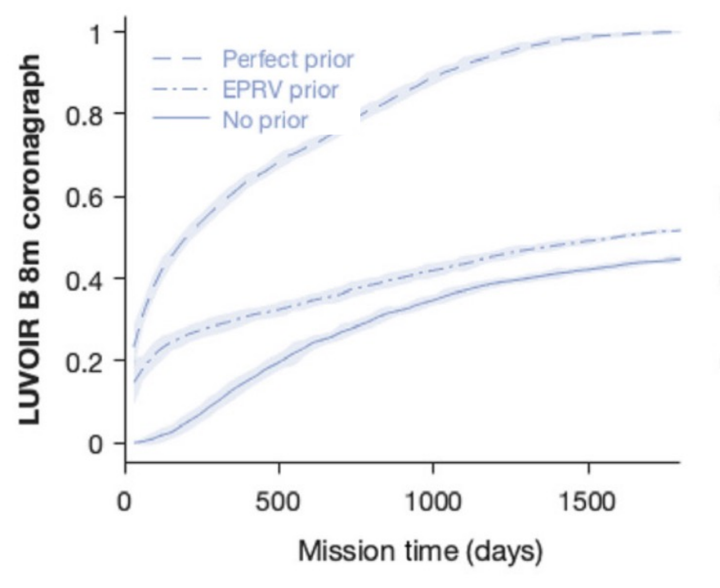
Hunyadi, Lo, & Shaklan (2007)



Savransky & Kasdin (2008)



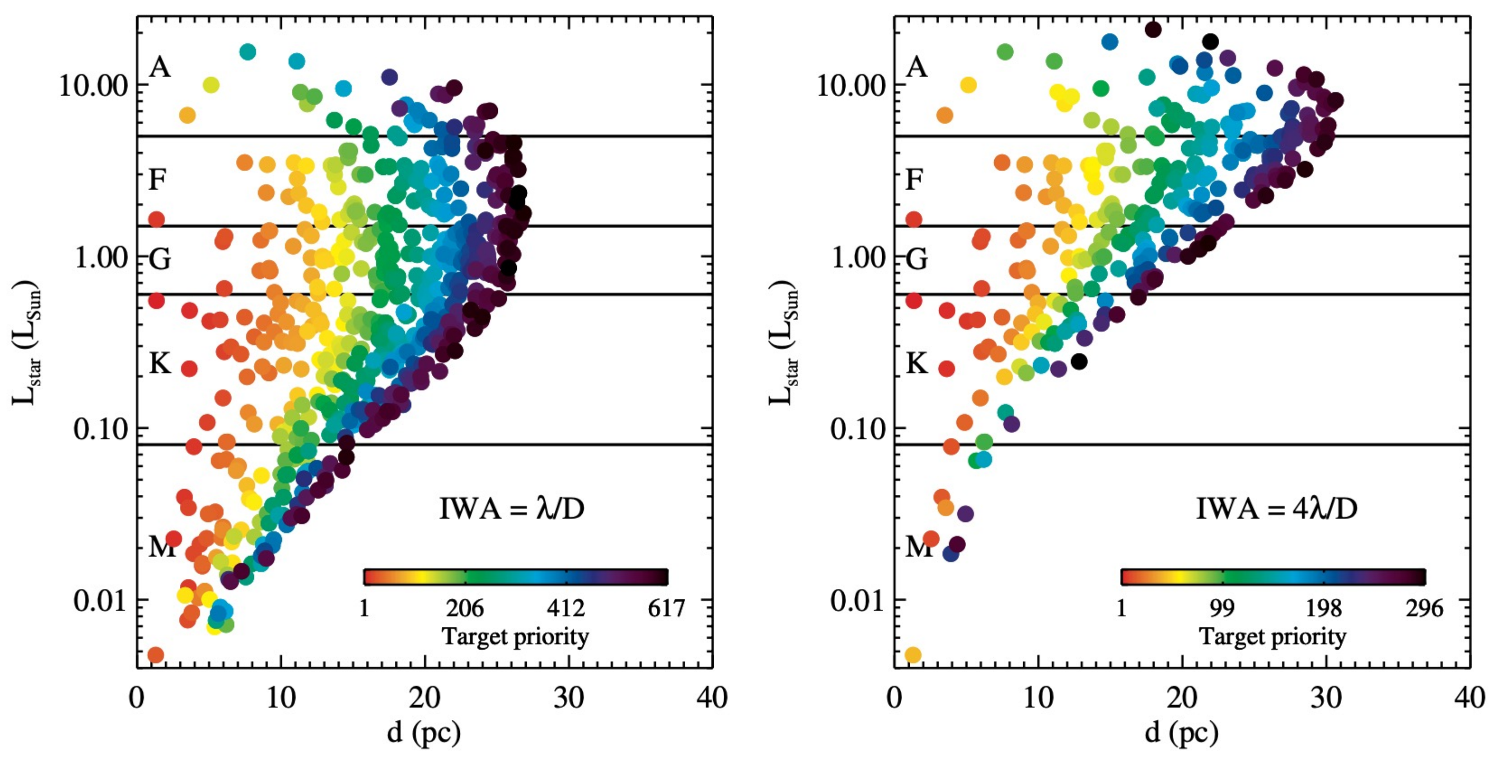
Stark et al. (2015)



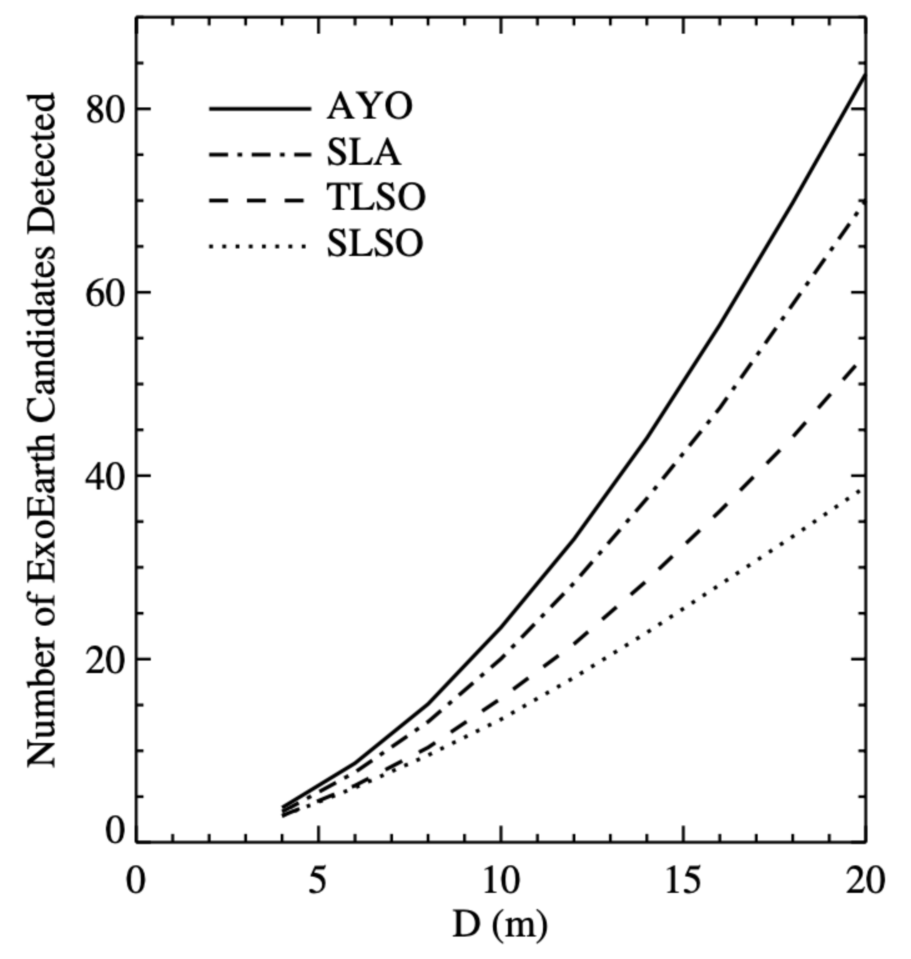
Morgan et al. (2021)

Yield calculations require choices: a chance for optimization!

- Assumptions/prescriptions re how to observe can lead to unintended bias, or worse—**incorrect trade studies**
- Pick a metric, then get out of the way and let your code tell you how to use the mission



Target list adapts to changes in instrument

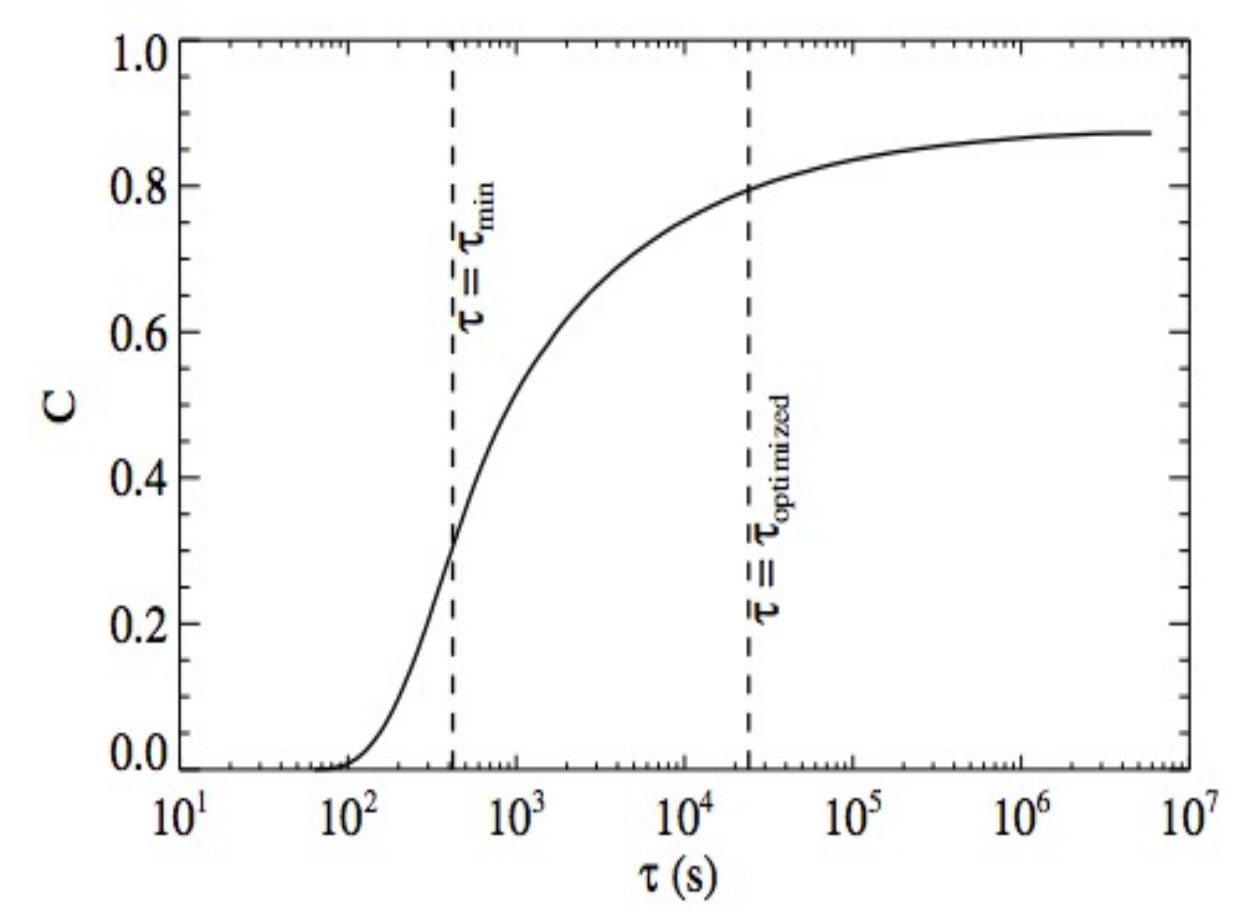


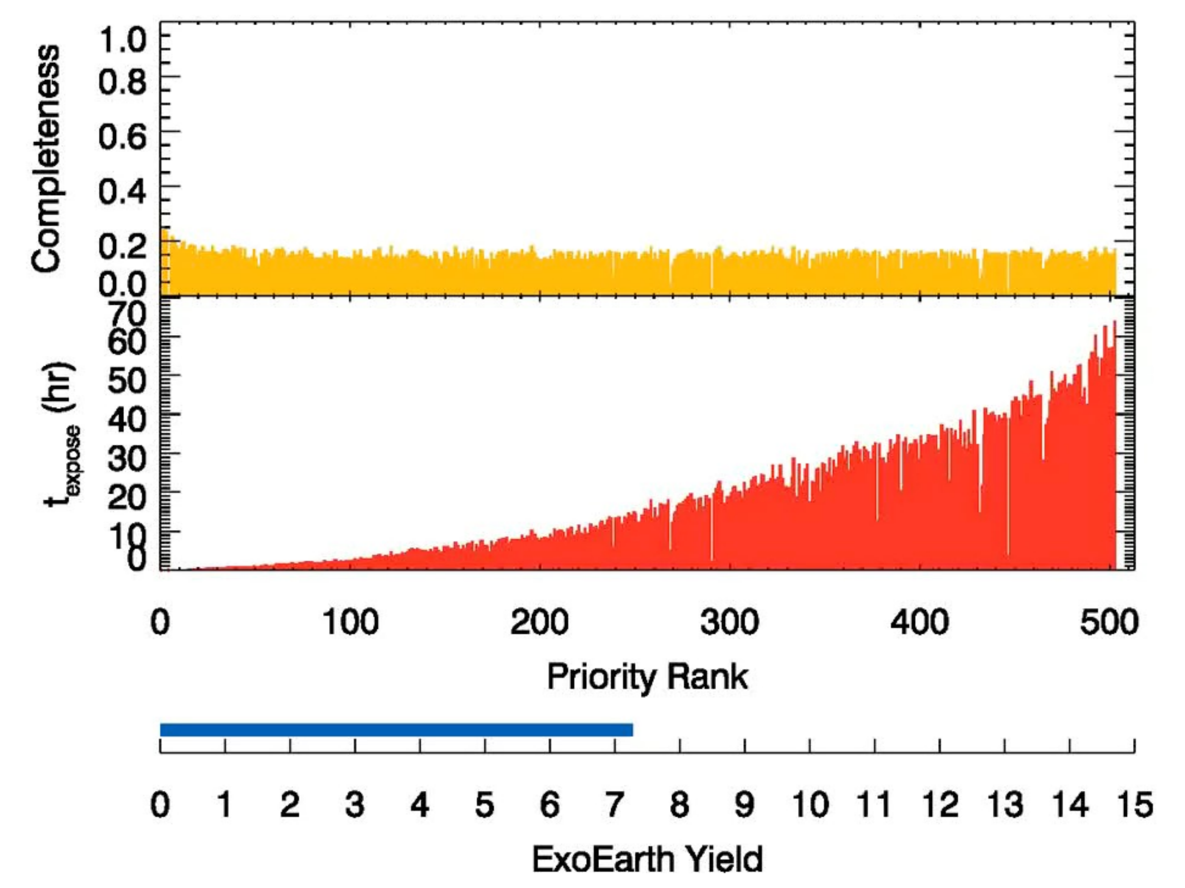
Stark et al. (2014)

Exoplanet yield & completeness

- Completeness, C = the chance of observing a given planet around a given star if that planet exists (Brown 2004)
- Yield = $\eta_{\text{Earth}} \Sigma C$
- Calculated using a large number of synthetic planets

Maximizing yield by optimizing observations



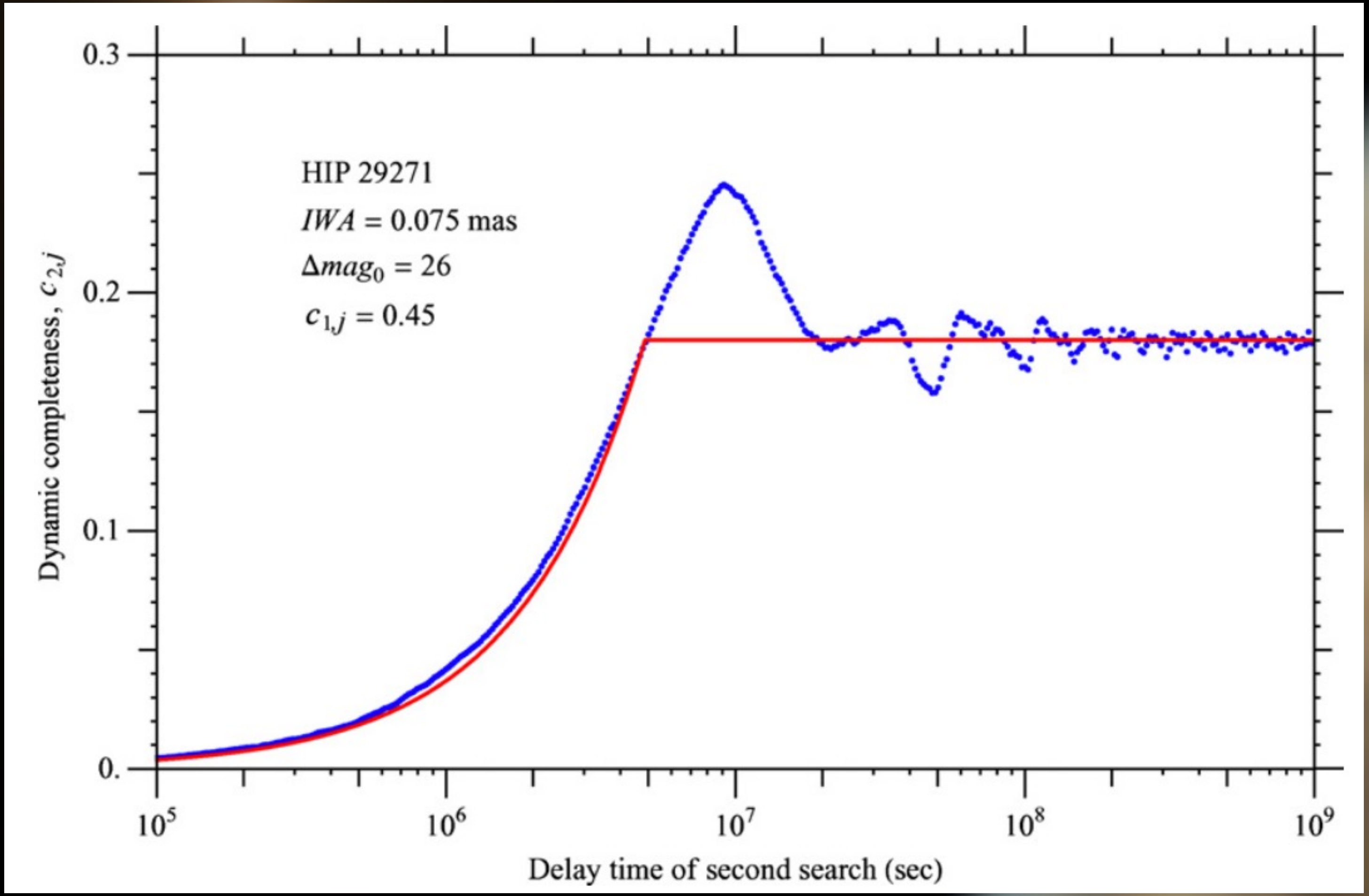


Optimally distributing exposure time can potentially double yield

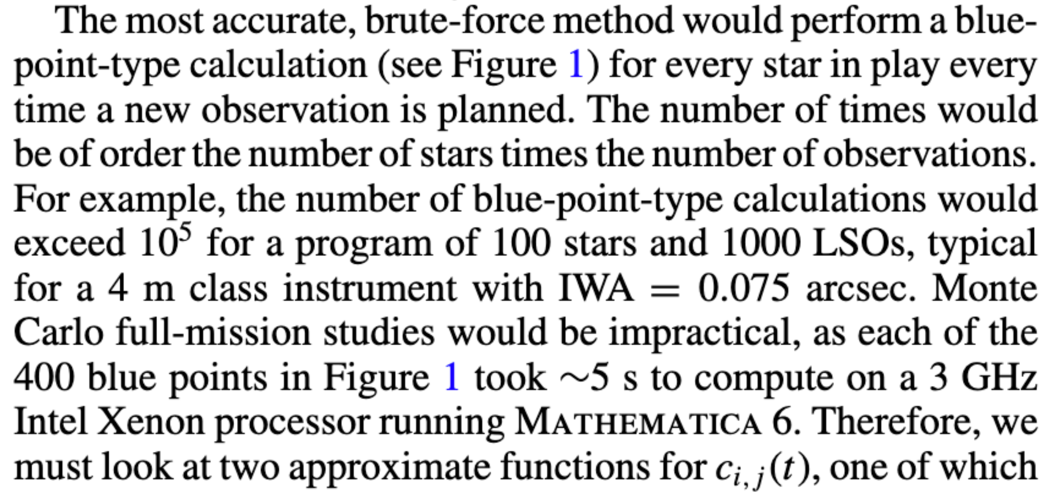
If once wasn't enough, look again

Revisiting same star multiple times can increase total completeness

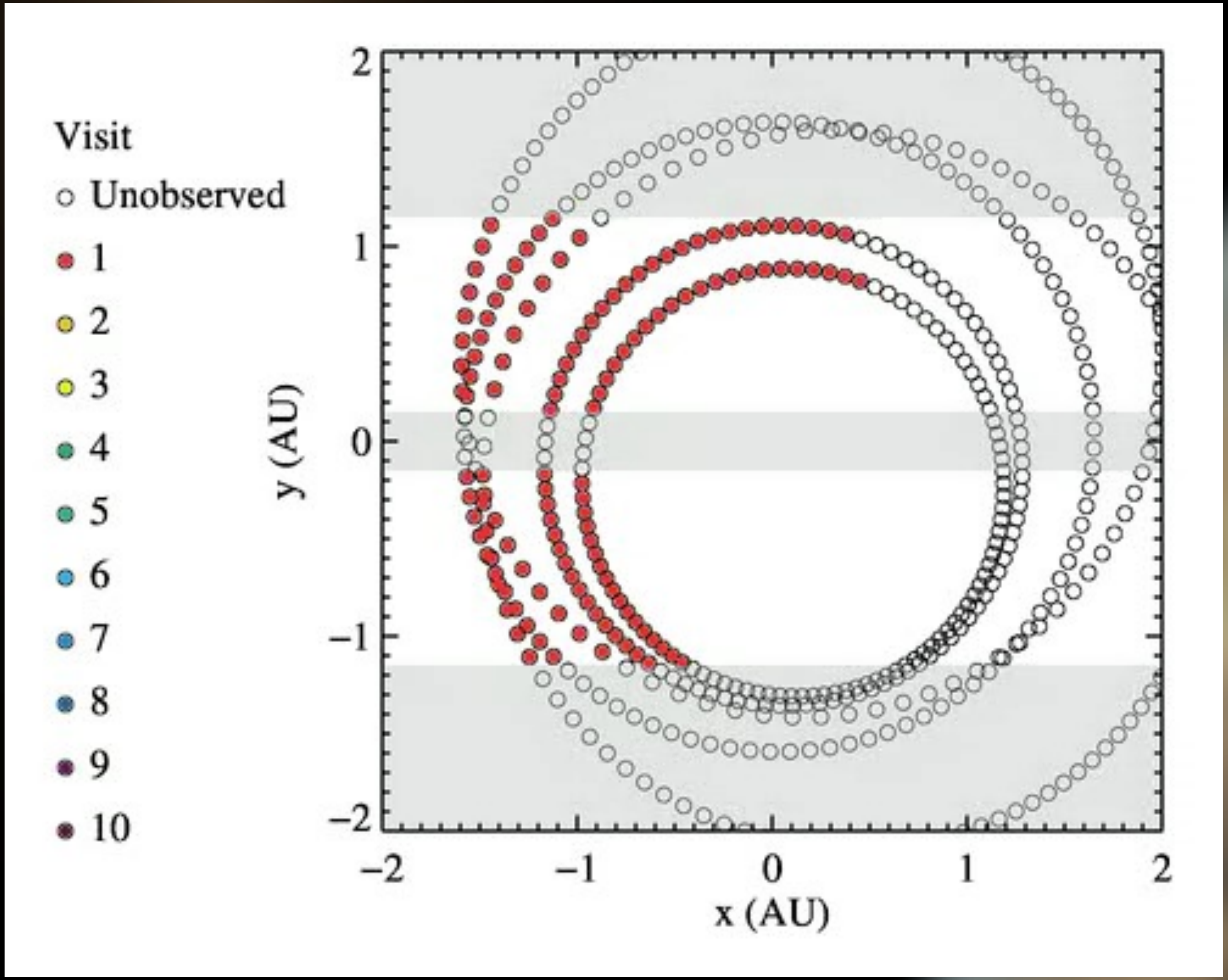
Optimizing revisits

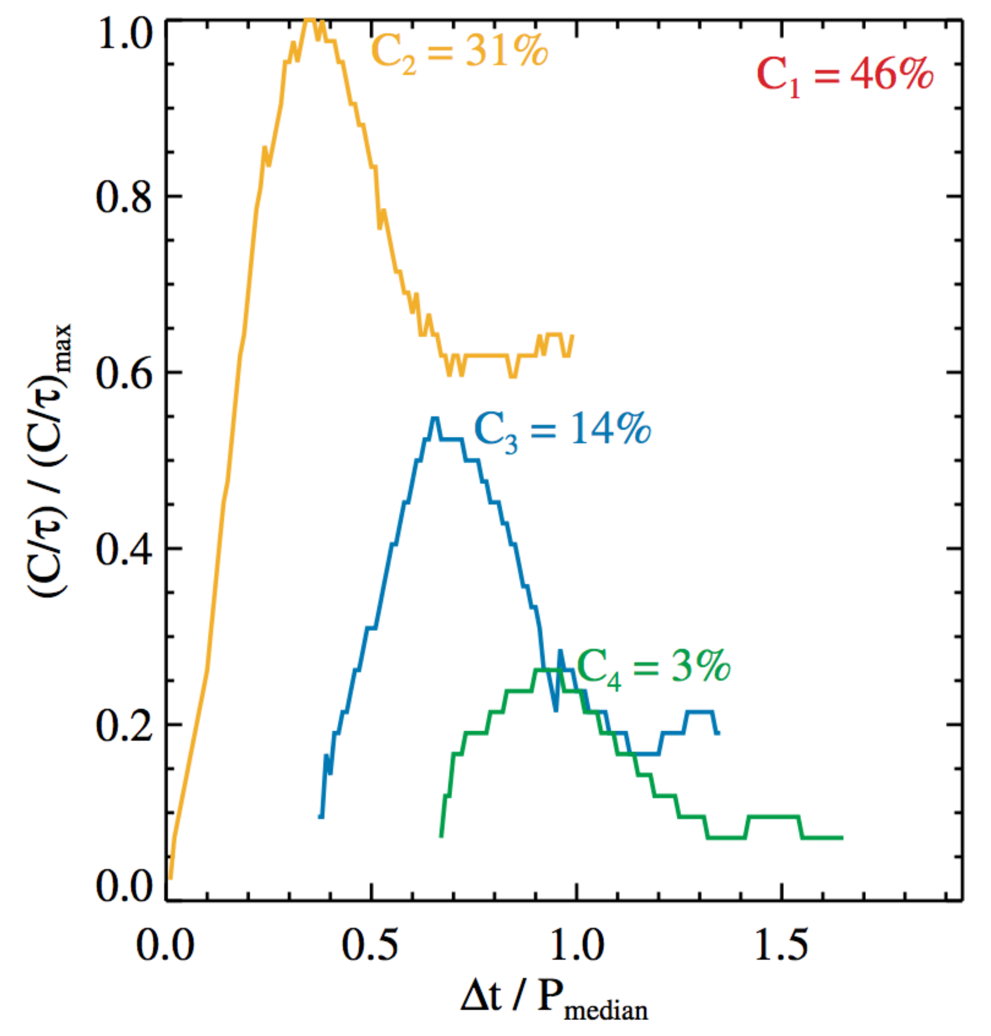


Brown & Soummer et al. (2010)


The most accurate, brute-force method would perform a blue-point-type calculation (see Figure 1) for every star in play every time a new observation is planned. The number of times would be of order the number of stars times the number of observations. For example, the number of blue-point-type calculations would exceed 10^5 for a program of 100 stars and 1000 LSOs, typical for a 4 m class instrument with IWA = 0.075 arcsec. Monte Carlo full-mission studies would be impractical, as each of the 400 blue points in Figure 1 took ∼5 s to compute on a 3 GHz Intel Xenon processor running MATHEMATICA 6. Therefore, we must look at two approximate functions for $c_{i,j}(t)$, one of which

Optimizing revisits

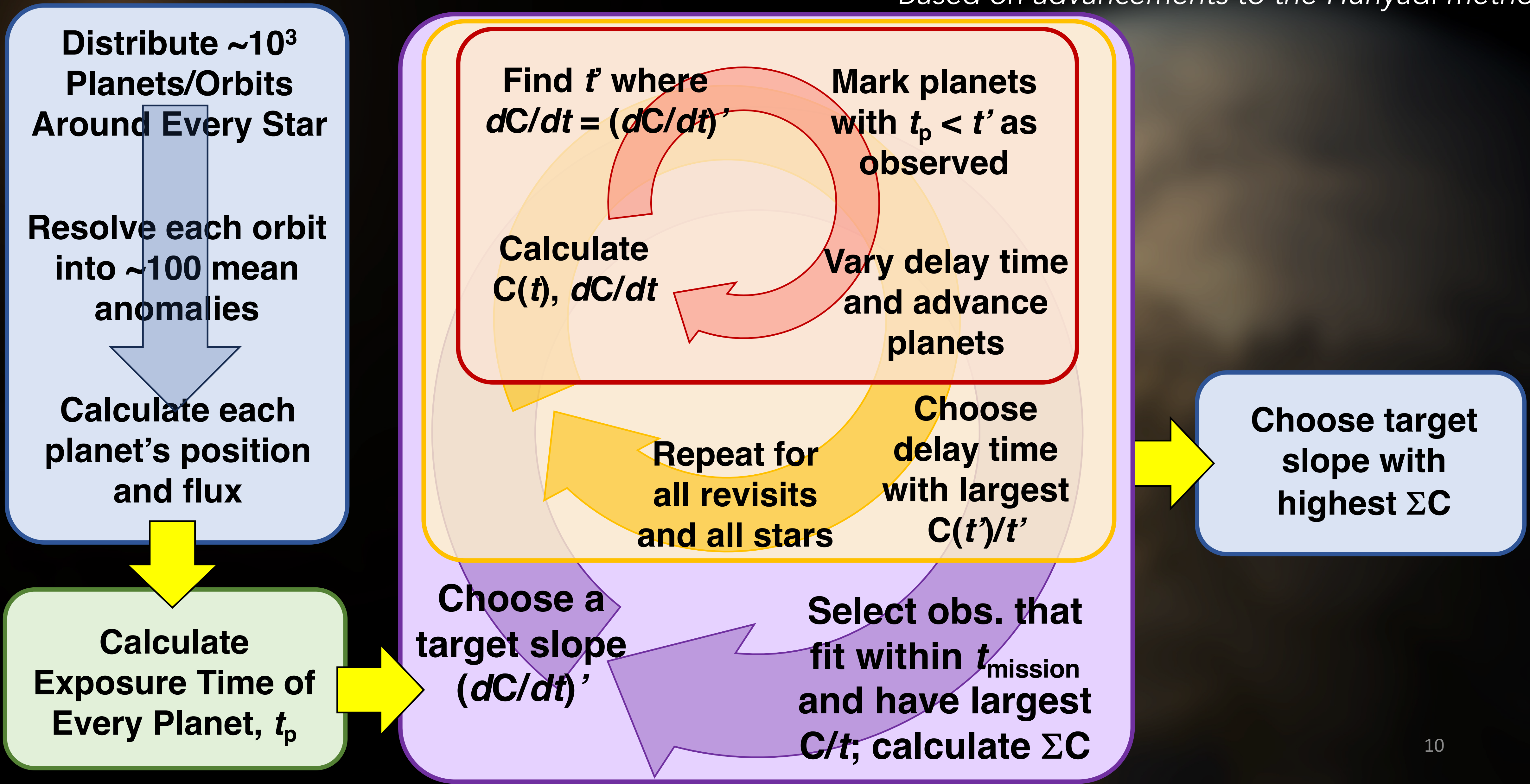




Optimized revisits can increase yield by additional 35-75%

Method used by AYO

Based on advancements to the Hunyadi method



Distribute ~10^3 Planets/Orbits Around Every Star

Resolve each orbit into ~100 mean anomalies

Calculate each planet's position and flux

Calculate Exposure Time of Every Planet, t_p

Choose a target slope $(dC/dt)'$

Find t' where $dC/dt = (dC/dt)'$

Mark planets with $t_p < t'$ as observed

Vary delay time and advance planets

Calculate $C(t)$, dC/dt

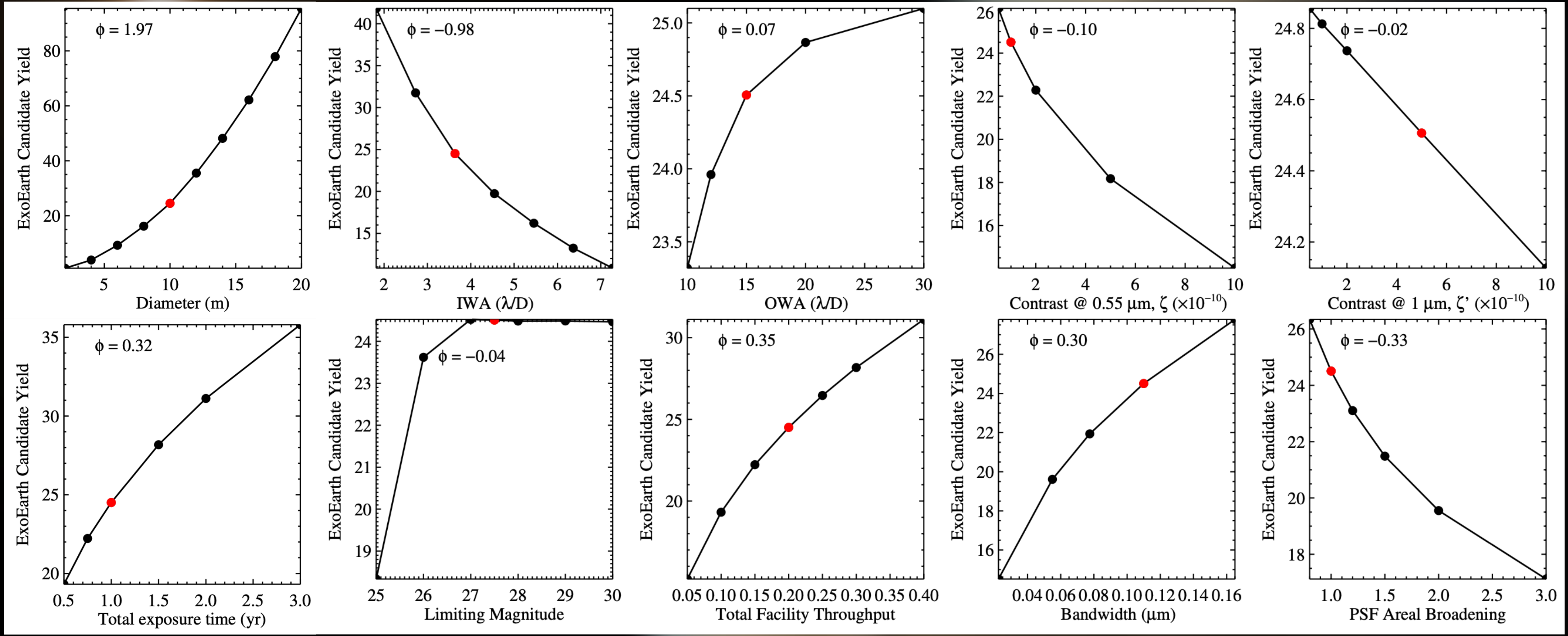
Choose delay time with largest $C(t')/t'$

Repeat for all revisits and all stars

Select obs. that fit within $t_{mission}$ and have largest C/t; calculate ΣC

Choose target slope with highest ΣC

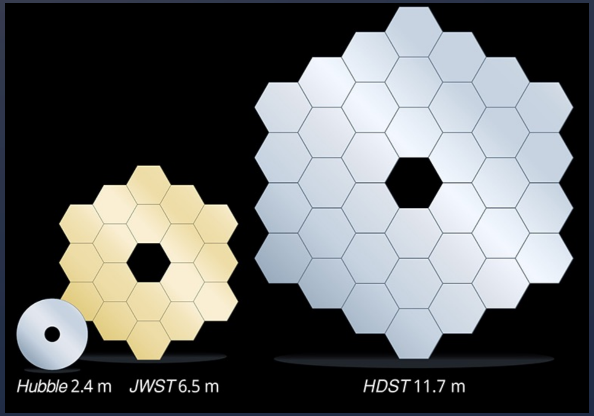
Mapping out yield sensitivities



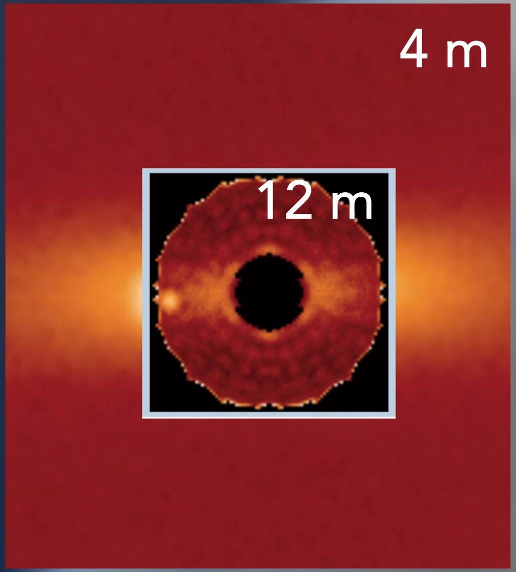
Stark et al. (2015)

Why coronagraph yield is controlled by *D*

Larger photon bucket



Sharper PSF

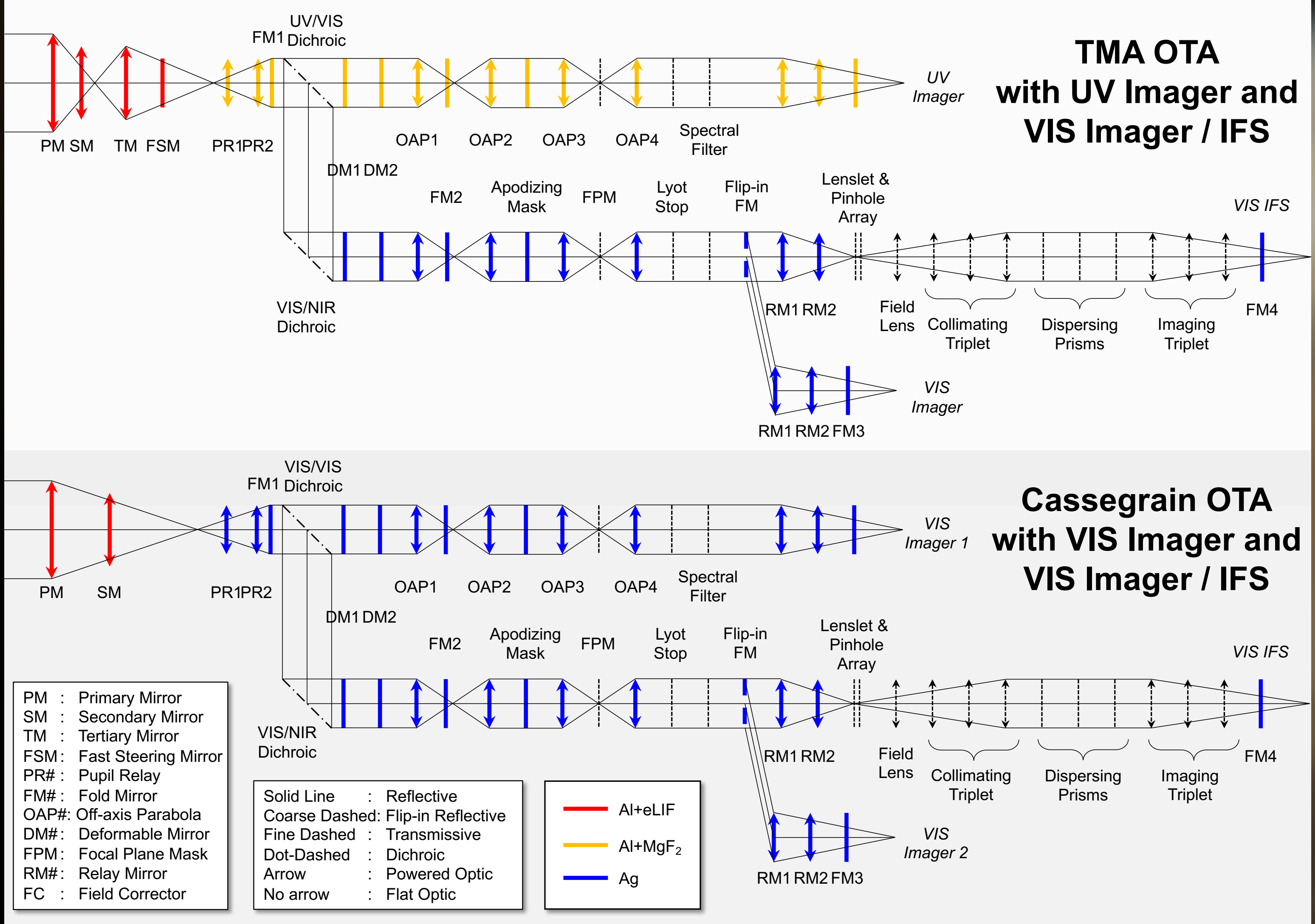


Smaller IWA

$\sim \lambda/D$

Exposure time scales as D^{-4}

AYO models realistic mission concepts



PM	Primary Mirror
SM	Secondary Mirror
TM	Tertiary Mirror
FSM	Fast Steering Mirror
PR#	Pupil Relay
FM#	Fold Mirror
OAP#	Off-axis Parabola
DM#	Deformable Mirror
FPM	Focal Plane Mask
RM#	Relay Mirror
FC	Field Corrector

Solid Line	Reflective
Coarse Dashed	Flip-in Reflective
Fine Dashed	Transmissive
Dot-Dashed	Dichroic
Arrow	Powered Optic
No arrow	Flat Optic

🟥 Al+eLIF
🟨 Al+MgF$_2$
🟦 Ag

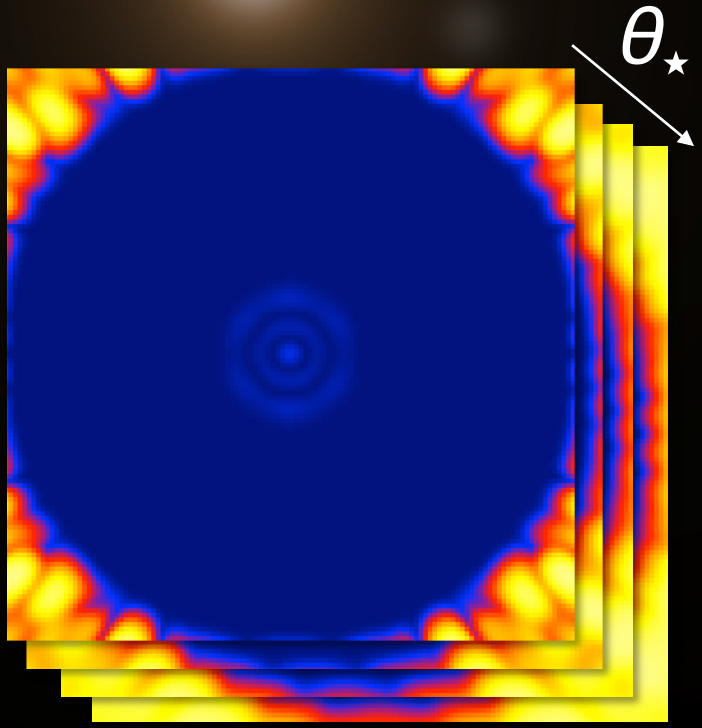
Stark et al. (2019)

Key points:

- The reflectivity of coatings matters a lot!
  i.e., 0.95^12 = 0.5
- We will likely have to trade bandwidth for throughput. UV coronagraphy reduces throughput at all wavelengths by up to ~0.5
- Efficiently parallelizing coronagraphs may be essential for wavelength coverage

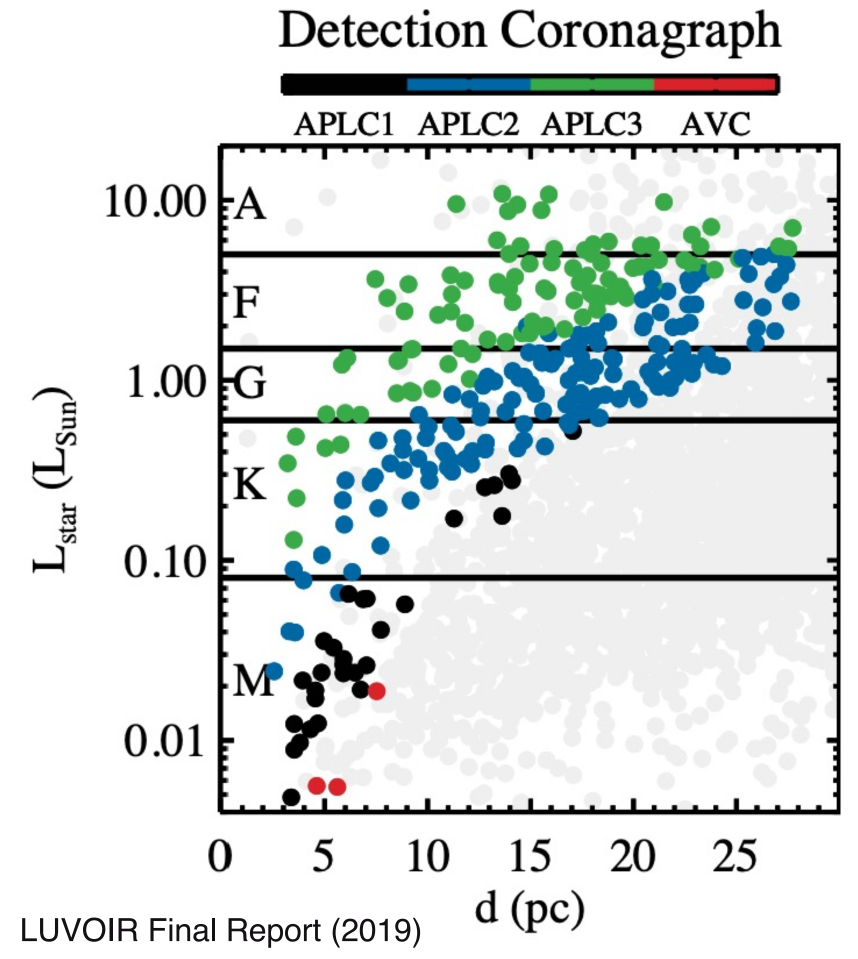
AYO uses detailed coronagraph simulations

DRMs can teach us about mission design



Zimmerman/Soummer/St. Laurent

- Assign simulated 2D leaked starlight to each star as a function of stellar diameter
- Use 2D off-axis simulated PSFs to calculate planet's flux



LUVOIR Final Report (2019)

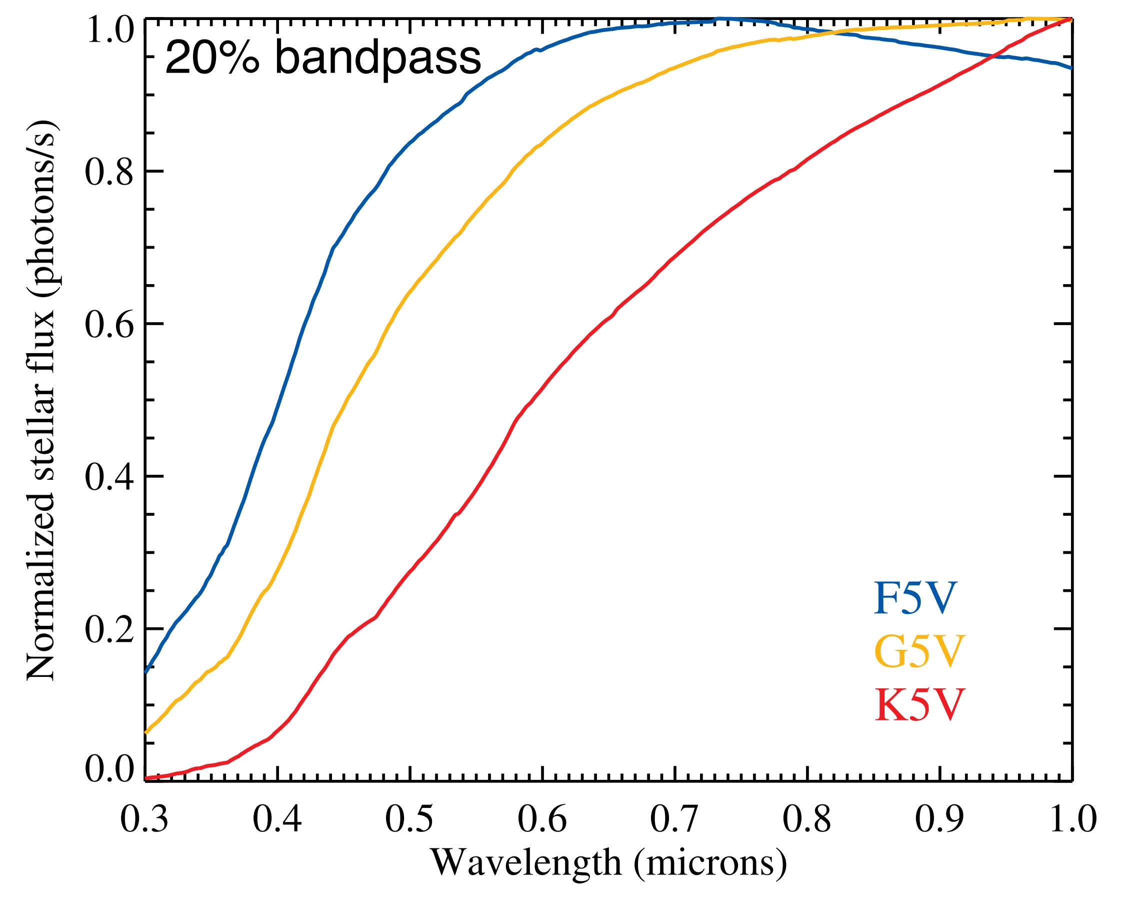
DRM optimally assigned LUVOIR-A's four coronagraph masks to each star.

To optimally assign N_c coronagraphs:

- Create a for loop in the exposure time calculator
- Calculate exposure times for each of the N_c coronagraphs
- Once all planet exposure times calculated, determine the peak of C/t
- Choose the coronagraph with the largest peak C/t

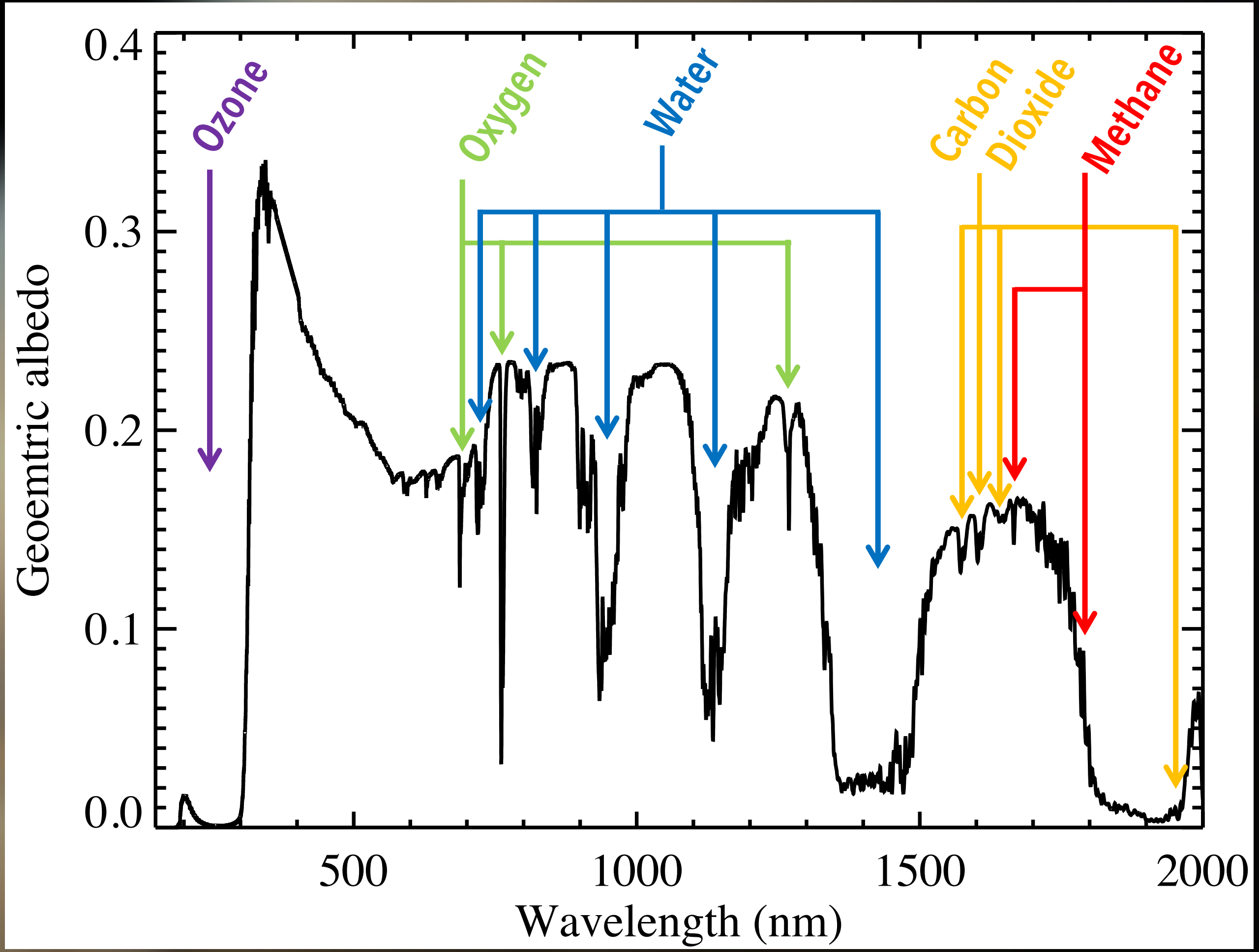
At what wavelength should we observe?

Star’s Aren’t “Brightest” at V Band

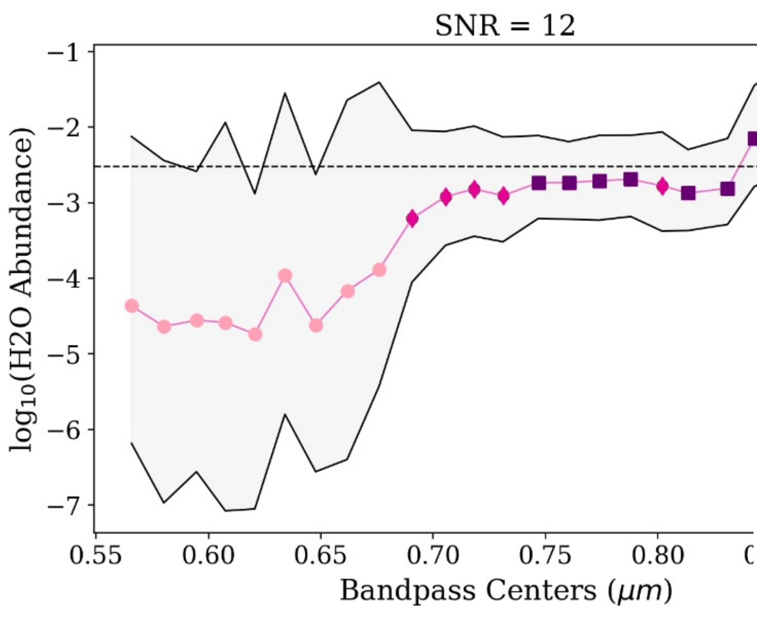


Stark et al. (submitted)

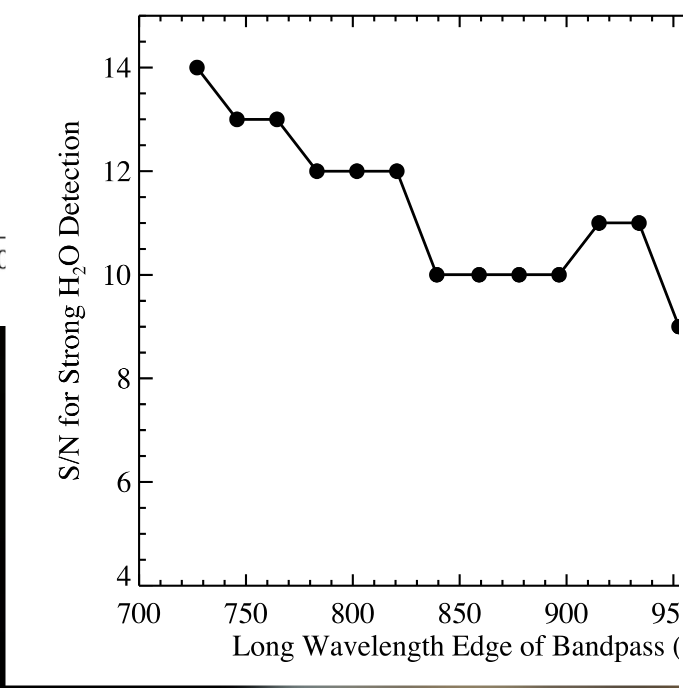
Which H_2O Feature Do We Pick?



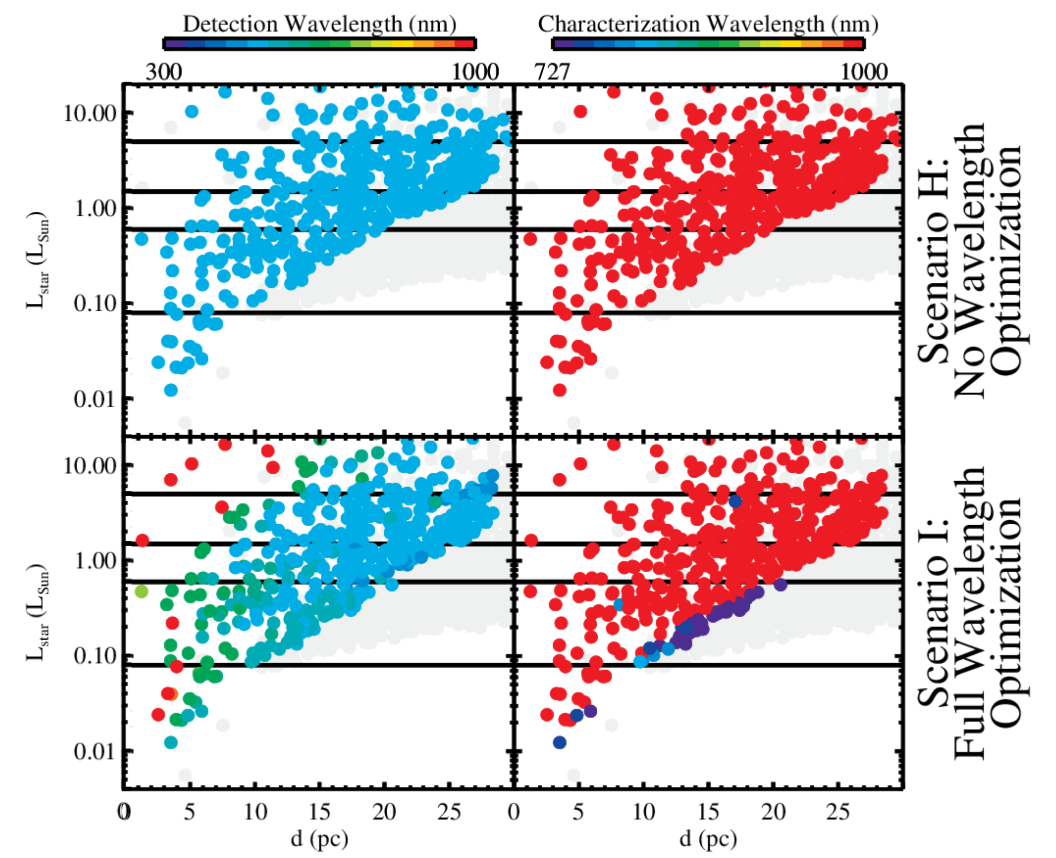
AYO now includes bandpass optimization



Latouf et al. (2023)

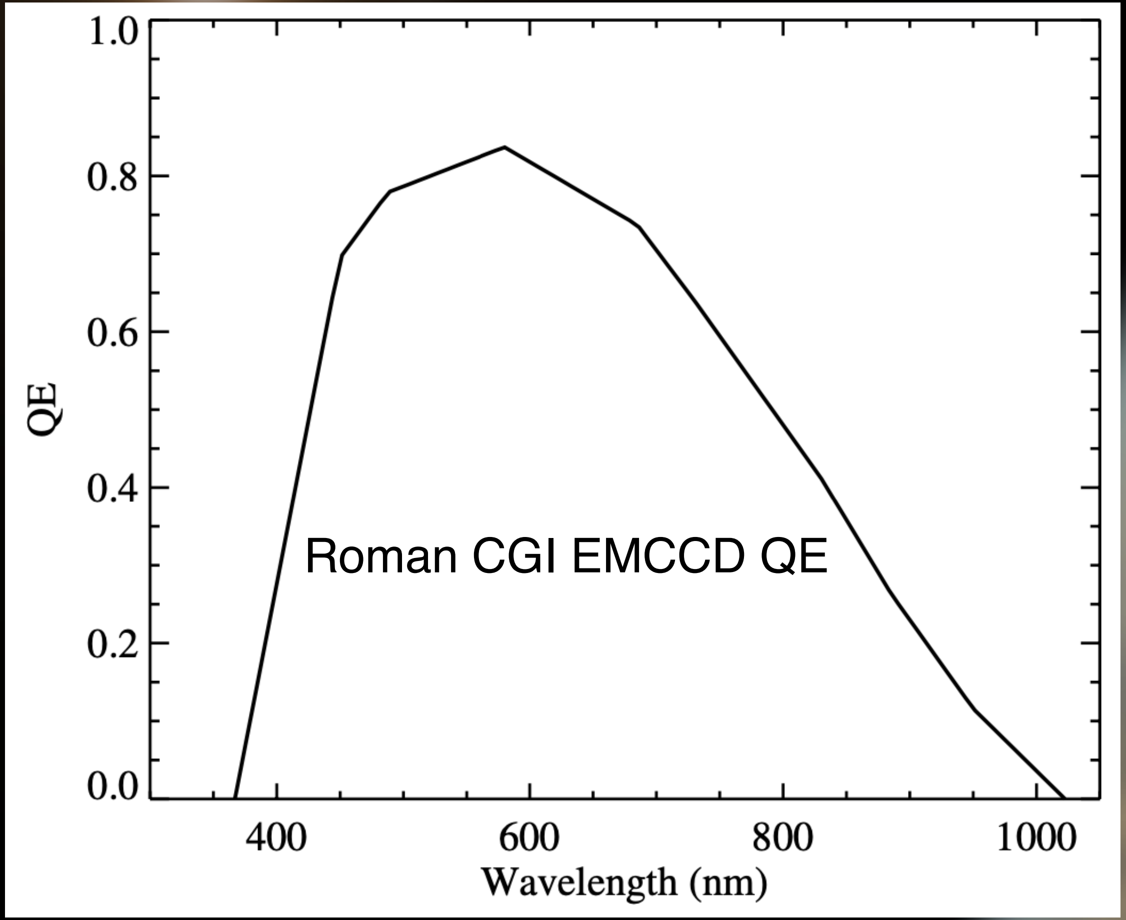


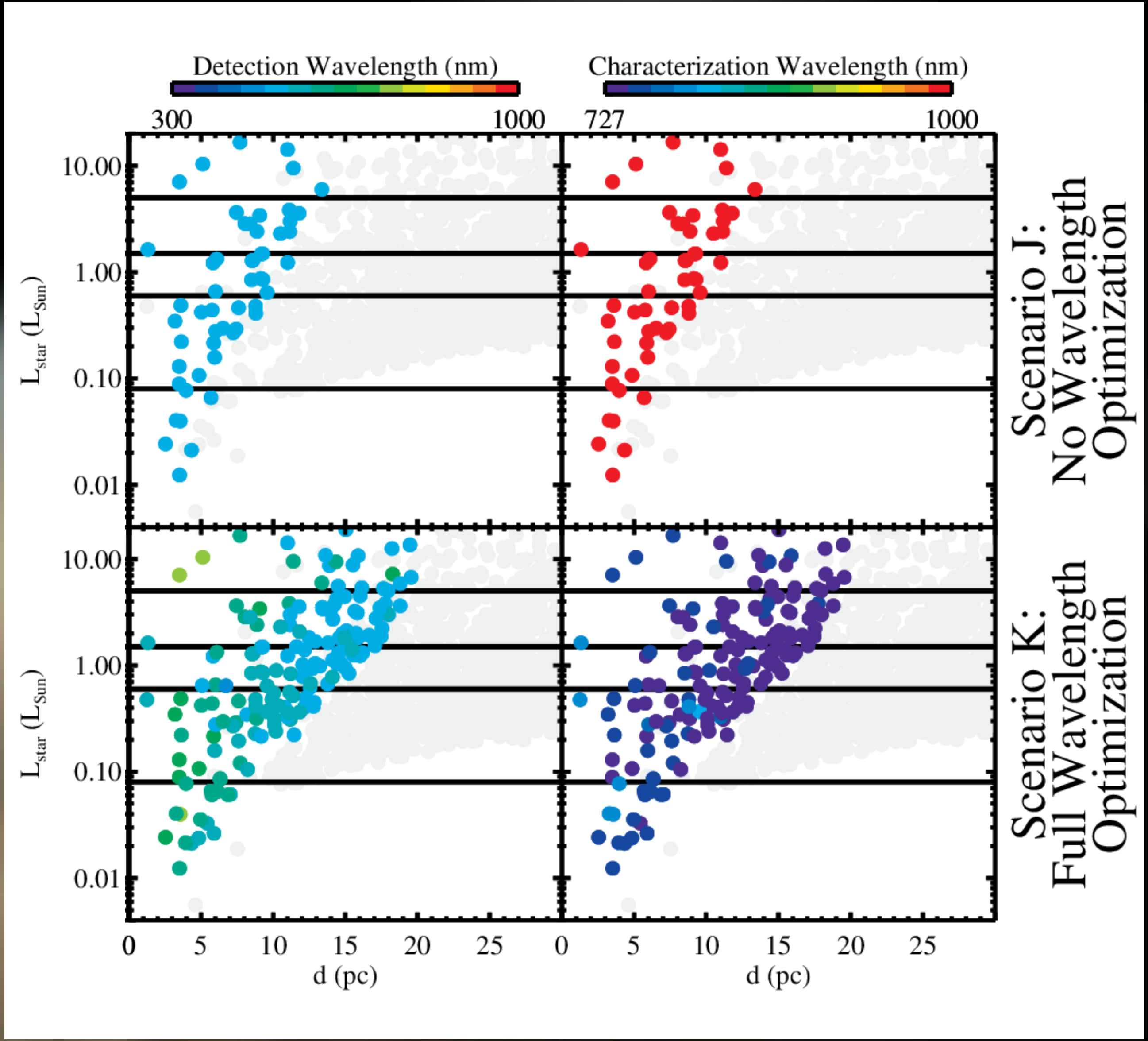
Stark et al. (submitt



AYO now includes bandpass optimization

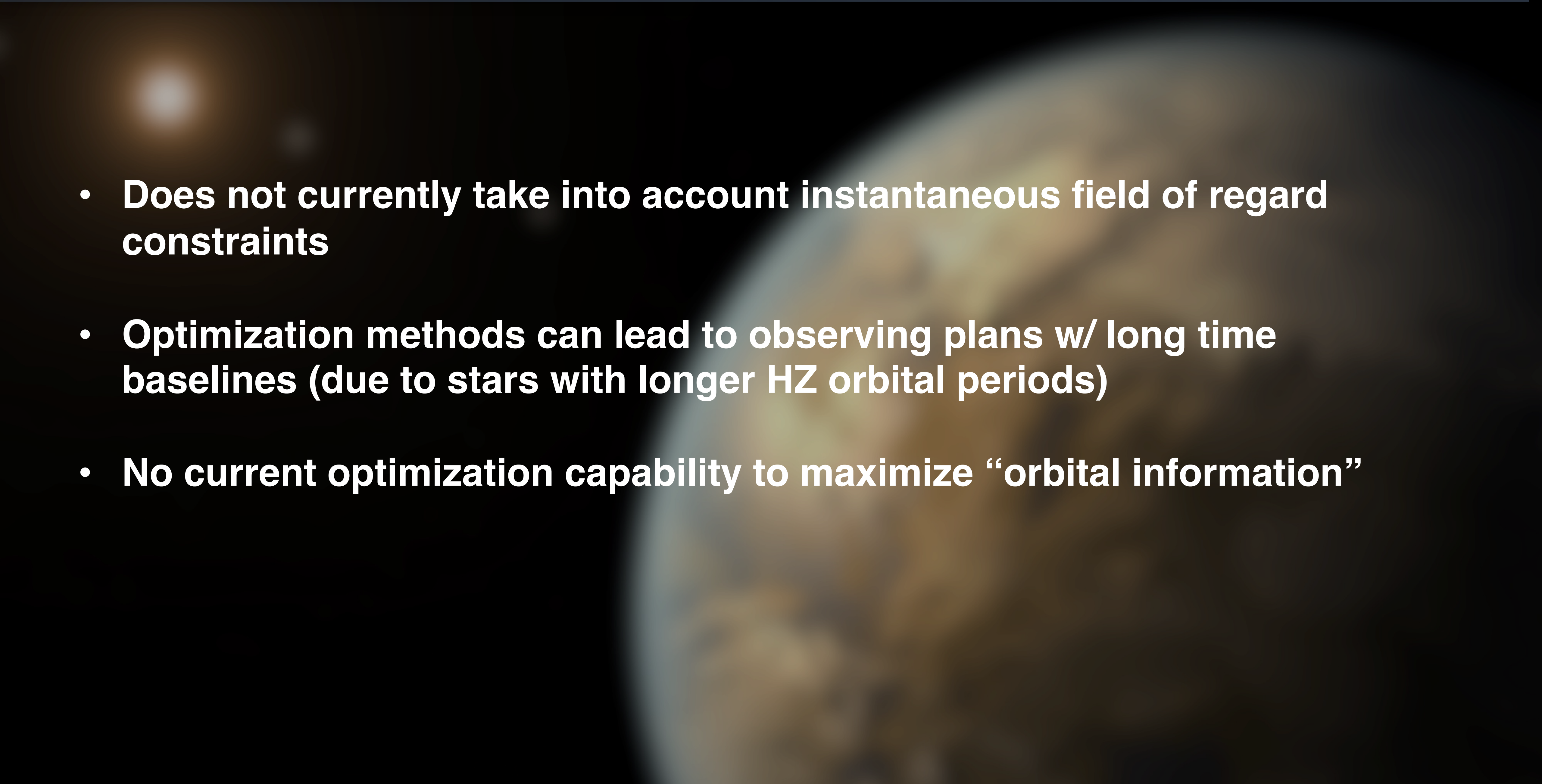
What Happens if Our QE Isn't Ideal?





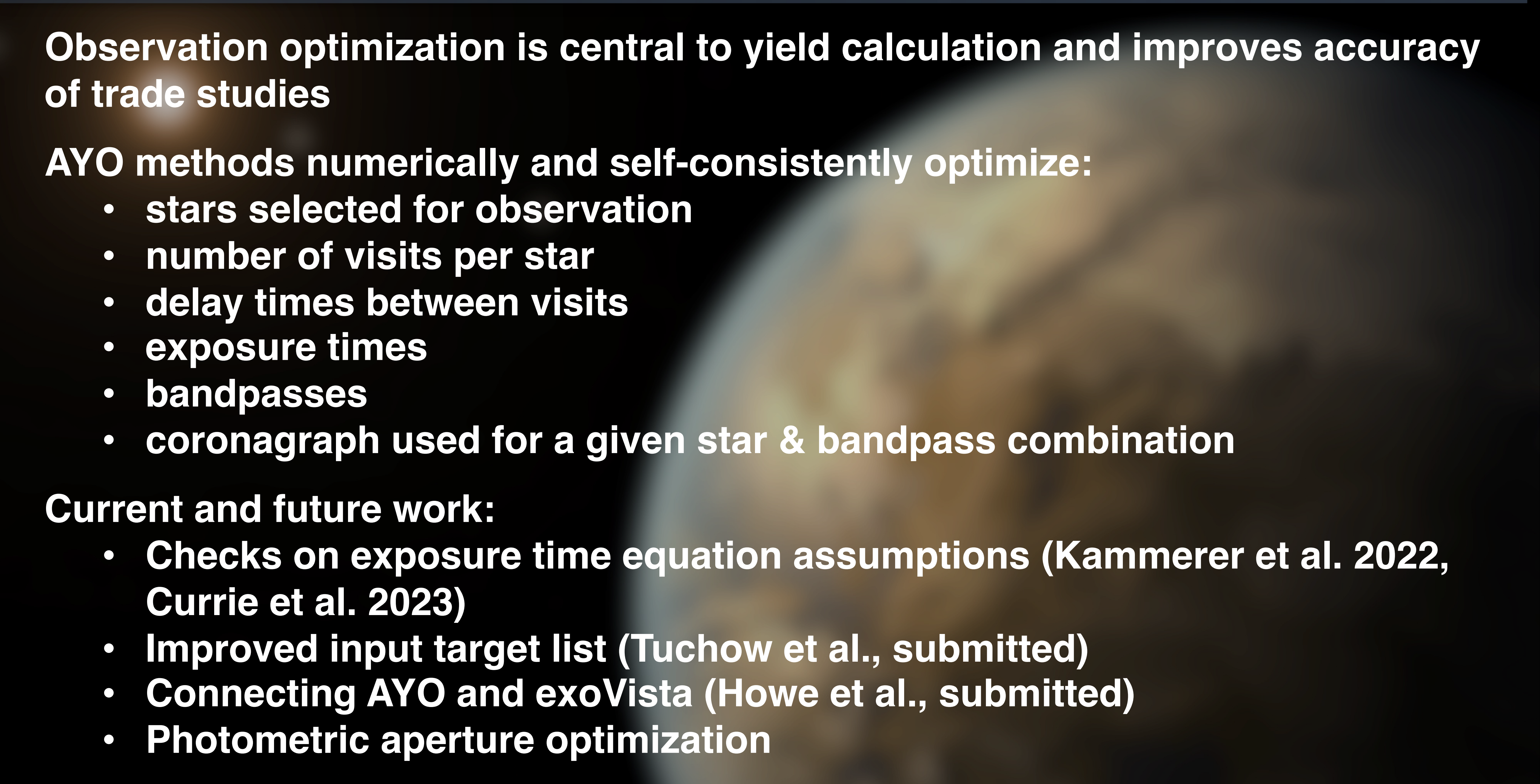
Stark et al. (submitted)

Major limitations of AYO



- Does not currently take into account instantaneous field of regard constraints
- Optimization methods can lead to observing plans w/ long time baselines (due to stars with longer HZ orbital periods)
- No current optimization capability to maximize “orbital information”

Summary



Observation optimization is central to yield calculation and improves accuracy of trade studies

AYO methods numerically and self-consistently optimize:

- **stars selected for observation**
- **number of visits per star**
- **delay times between visits**
- **exposure times**
- **bandpasses**
- **coronagraph used for a given star & bandpass combination**

Current and future work:

- **Checks on exposure time equation assumptions (Kammerer et al. 2022, Currie et al. 2023)**
- **Improved input target list (Tuchow et al., submitted)**
- **Connecting AYO and exoVista (Howe et al., submitted)**
- **Photometric aperture optimization**