Mitigating Science Risks: Paths to Robust Exoplanet Yield Margin for HWO

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The Astro2020 Decadal Recommendation

Recommendation: After a successful mission and technology maturation program, NASA should embark on a program to realize a mission to search for biosignatures from a robust number of about ~25 habitable zone planets and to be a transformative facility for general astrophysics. If mission and technology maturation are successful, as determined by an independent review, implementation should start in the latter part of the decade, with a target launch in the first half of the 2040s.

The mission the survey puts forward will combine a large, stable telescope with an advanced coronagraph intended to block the light of bright stars. It will be capable of surveying a hundred or more nearby Sun-like stars to discover their planetary systems and determine their orbits and basic properties. Then for the most exciting ~25 planets, astronomers will use spectroscopy at ultraviolet, visible, and near-infrared wavelengths to identify multiple atmospheric components that could serve as biomarkers (see

scope, and with checks and course corrections along the way. Inspired by the vision of searching for signatures of life on planets outside of the solar system, and by the transformative capability such a telescope would have for a wide range of astrophysics, the survey recommends that the first mission to enter this program is a **large (~6 m aperture) infrared/optical/ultraviolet (IR/O/UV) space telescope.**

Inspired by the vision of searching for signatures of life on planets outside of our solar system, and by the transformative capability such a telescope would have for a wide range of astrophysics, the priority recommendation in the frontier category for space is a large (~6 m diameter) IR/O/UV telescope with high-contrast (10^{-10}) imaging and spectroscopy. This is an ambitious mission, of a scale comparable

Astro2020 Final Report

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meters provides an appropriate balance between scale and feasibility. Such a mission would yield a robust sample of ~25 atmospheric spectra of potentially habitable exoplanets, and it could launch by the first half of the 2040 decade. A sample this size provides robustness against the uncertainties in the occurrence rate of Earth-sized worlds, and against the vagaries associated with the particular systems near Earth. Analysis

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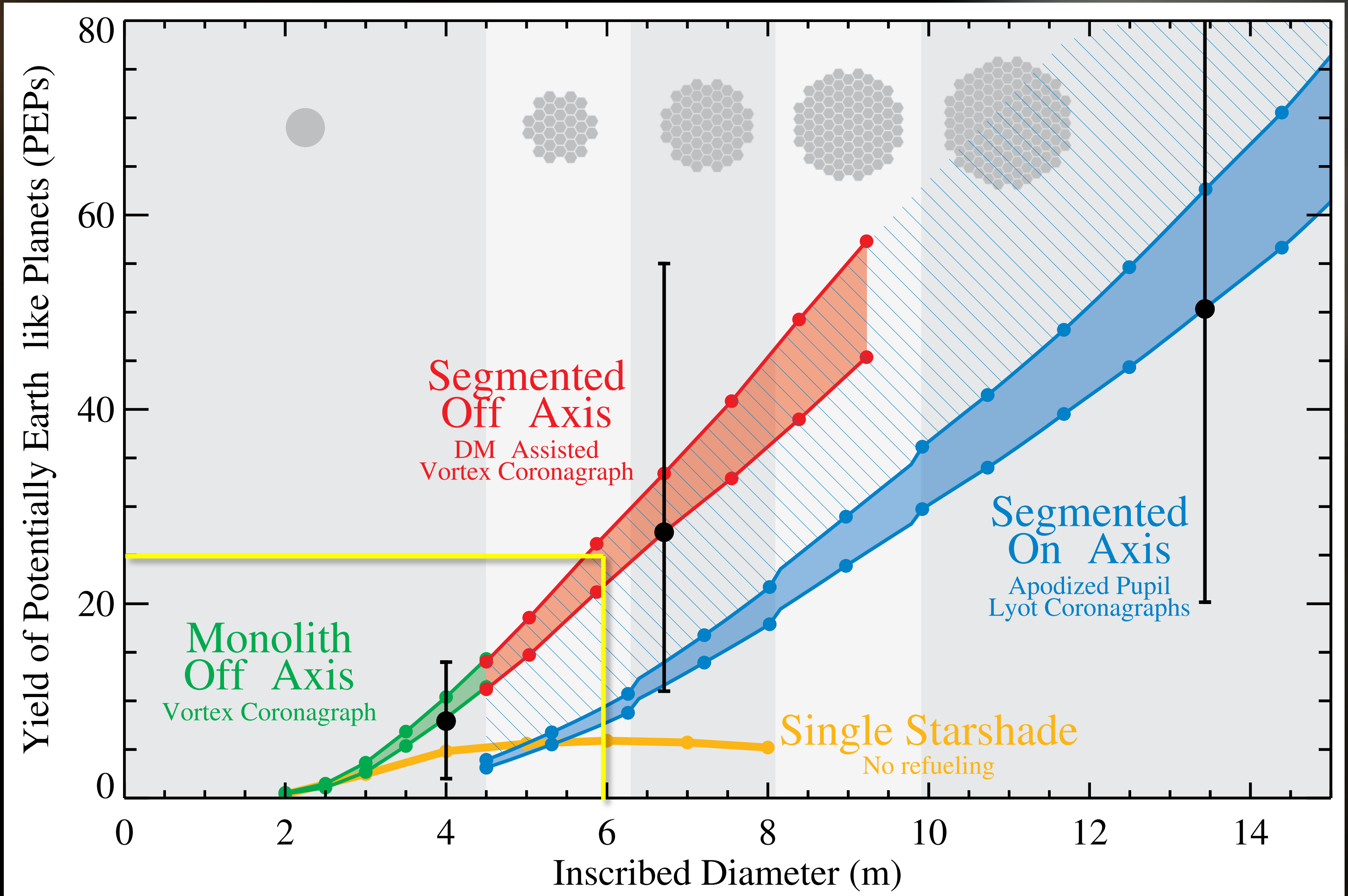
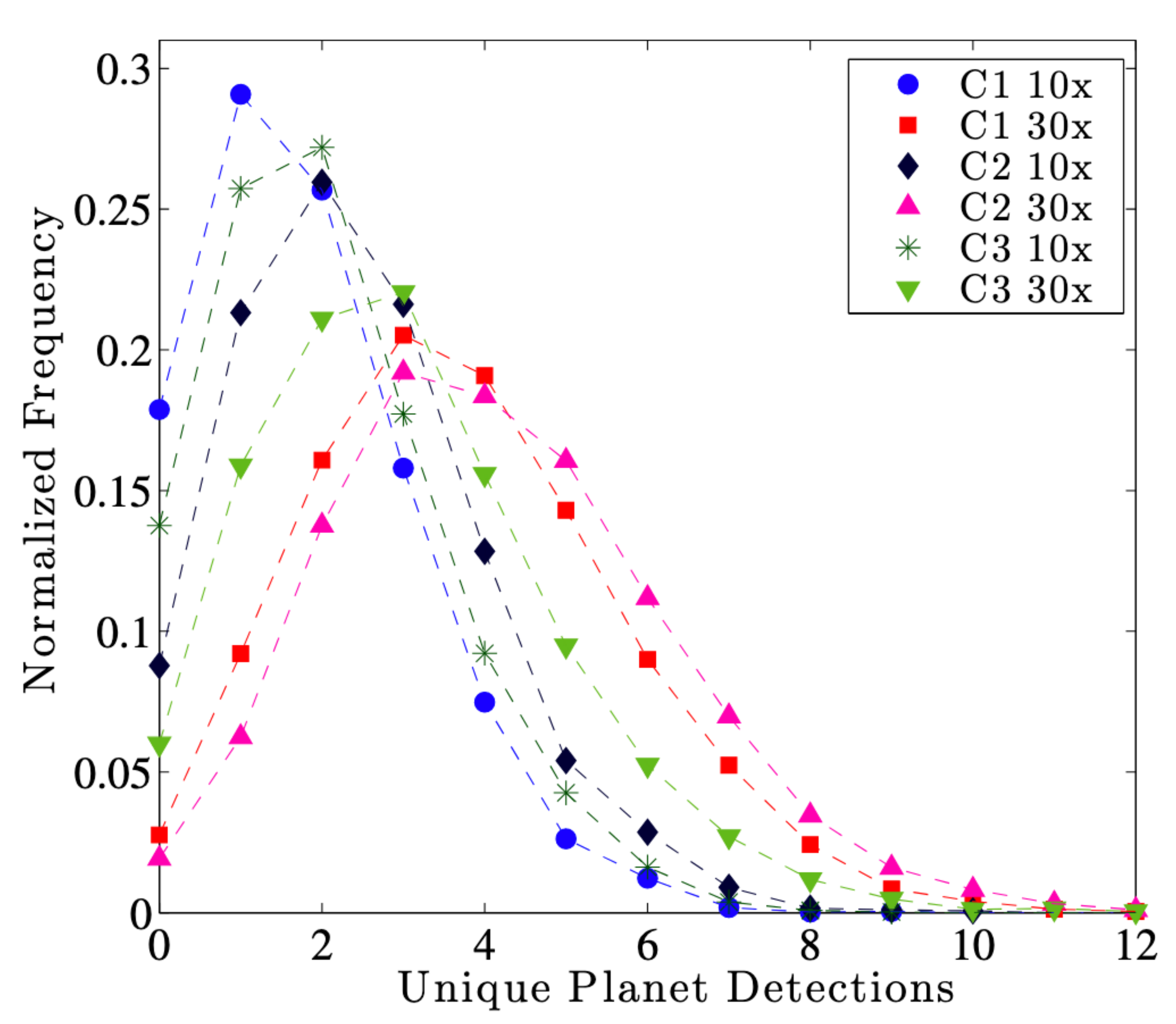
The ExoEarth Candidate Yield Landscape



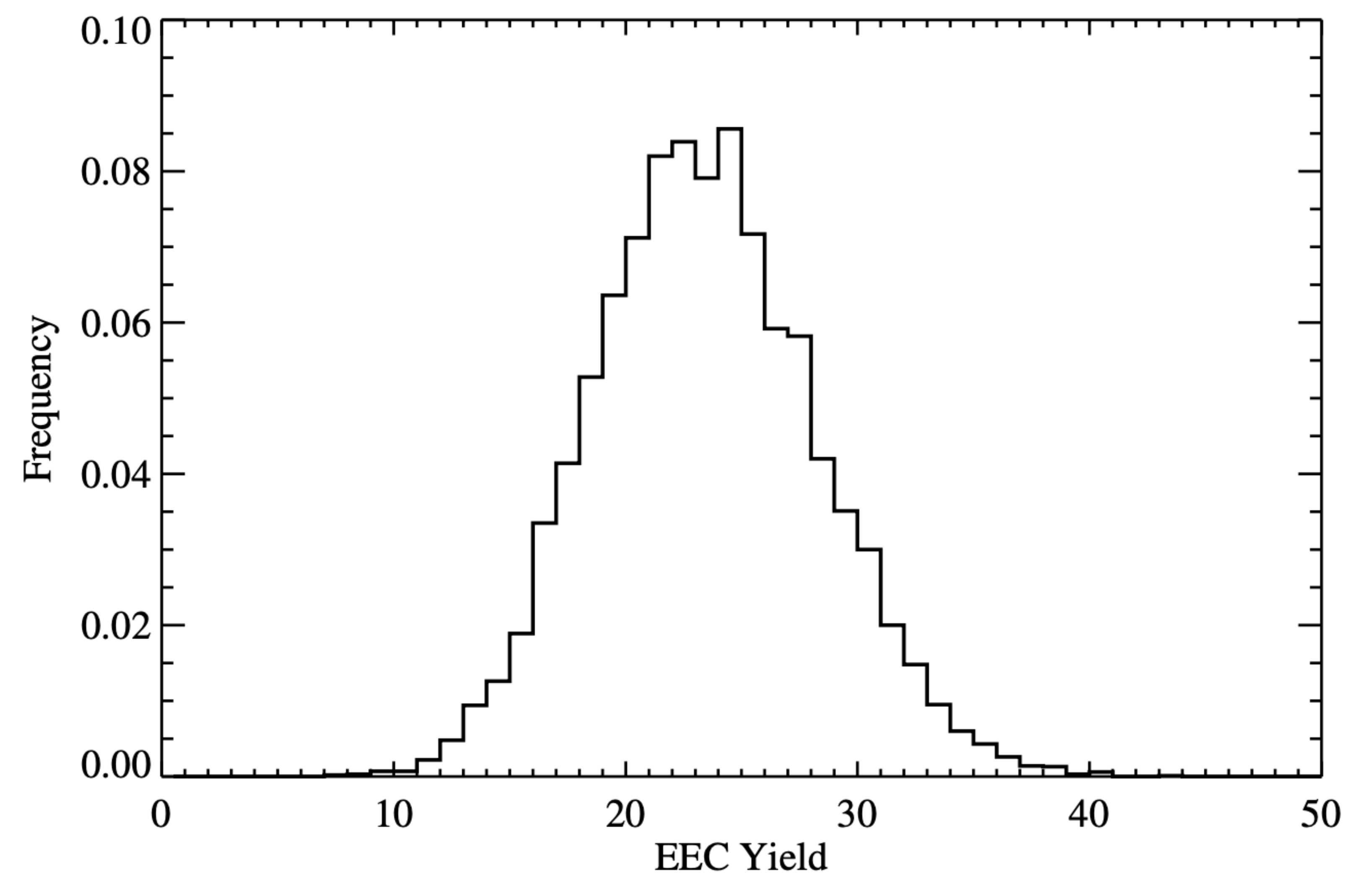
Stark et al. (2019)

Exoplanet yields are probabilistic



Savransky et al. (2016)

Sources of yield uncertainty: exoplanet sampling



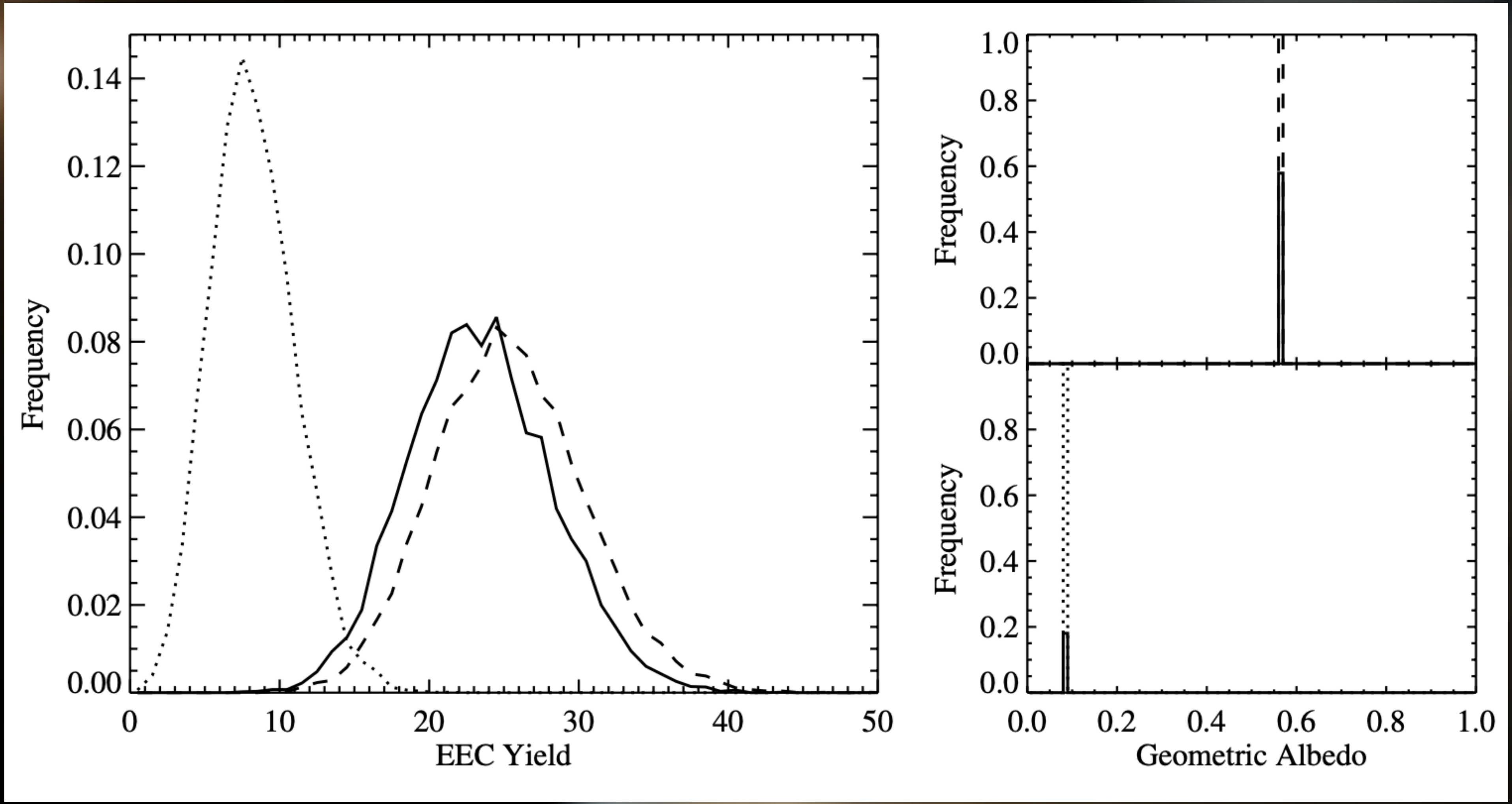
6 m ID version of LUVOIR-B

Uncertainties Included:

- **Exoplanet sampling**

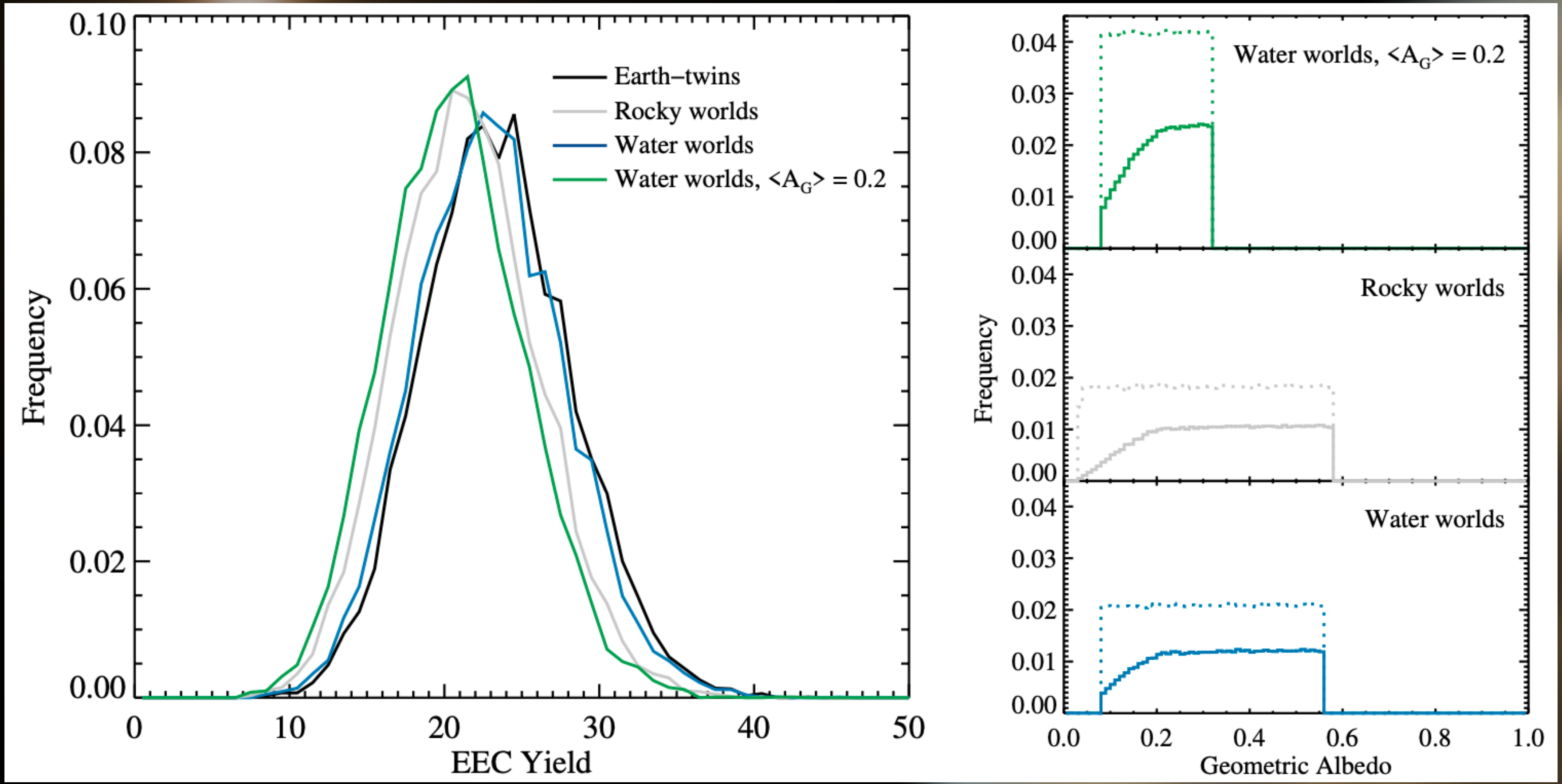
With *no* astrophysical uncertainties included, exoplanet sampling alone leads to < 50% confidence in achieving 25 exoEarth candidates (EECs)

Sources of yield uncertainty: exoplanet albedo



Albedo can dramatically reduce EEC yields.

Sources of yield uncertainty: exoplanet albedo

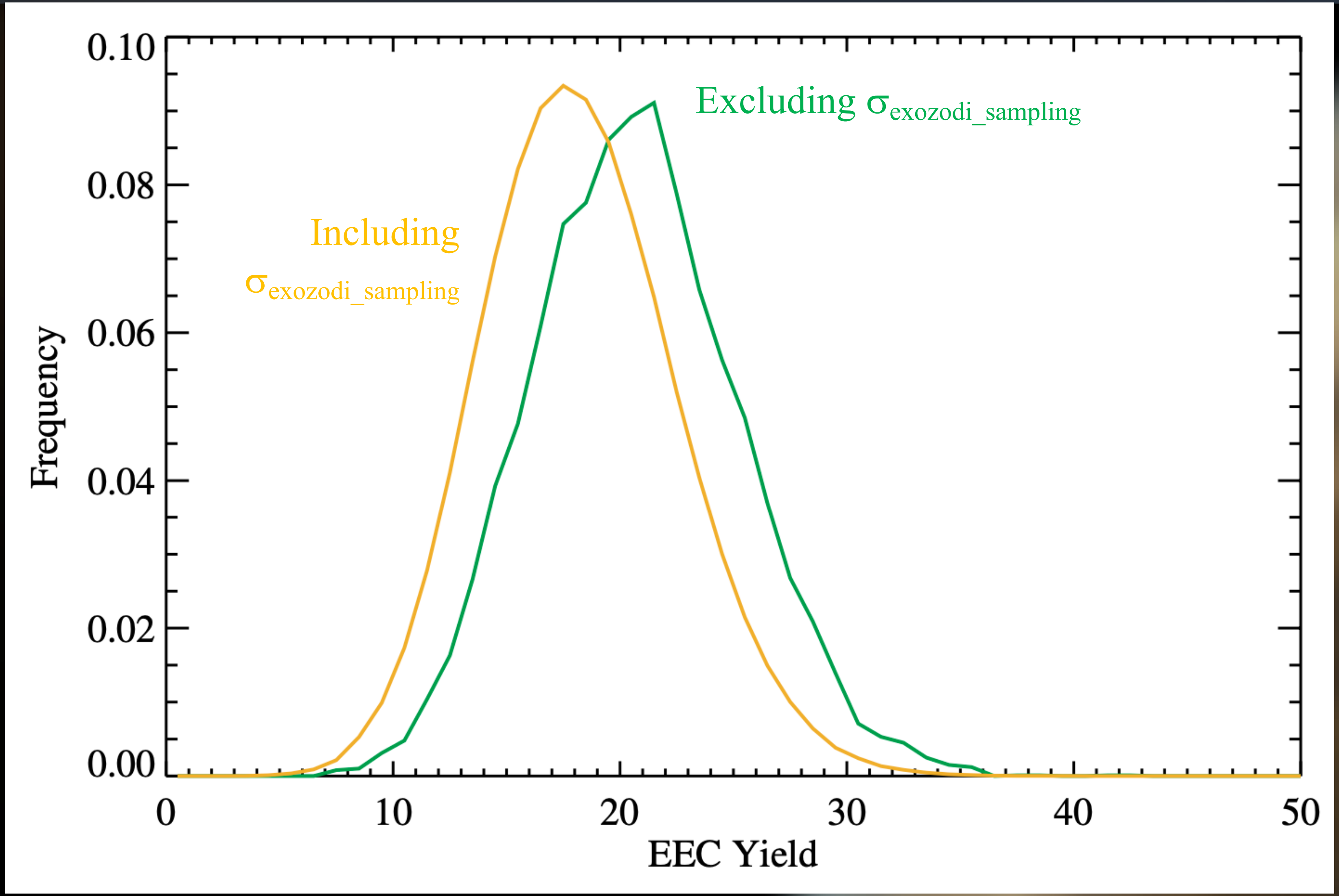


6 m ID version of LUVOIR-B

Uncertainties Included:
- Exoplanet sampling
- Albedo distribution

We can't know the albedo distribution ahead of time. We adopt the conservative green curve above, which assumes water worlds w/ mean albedo of Earth.

Sources of yield uncertainty: exozodi sampling



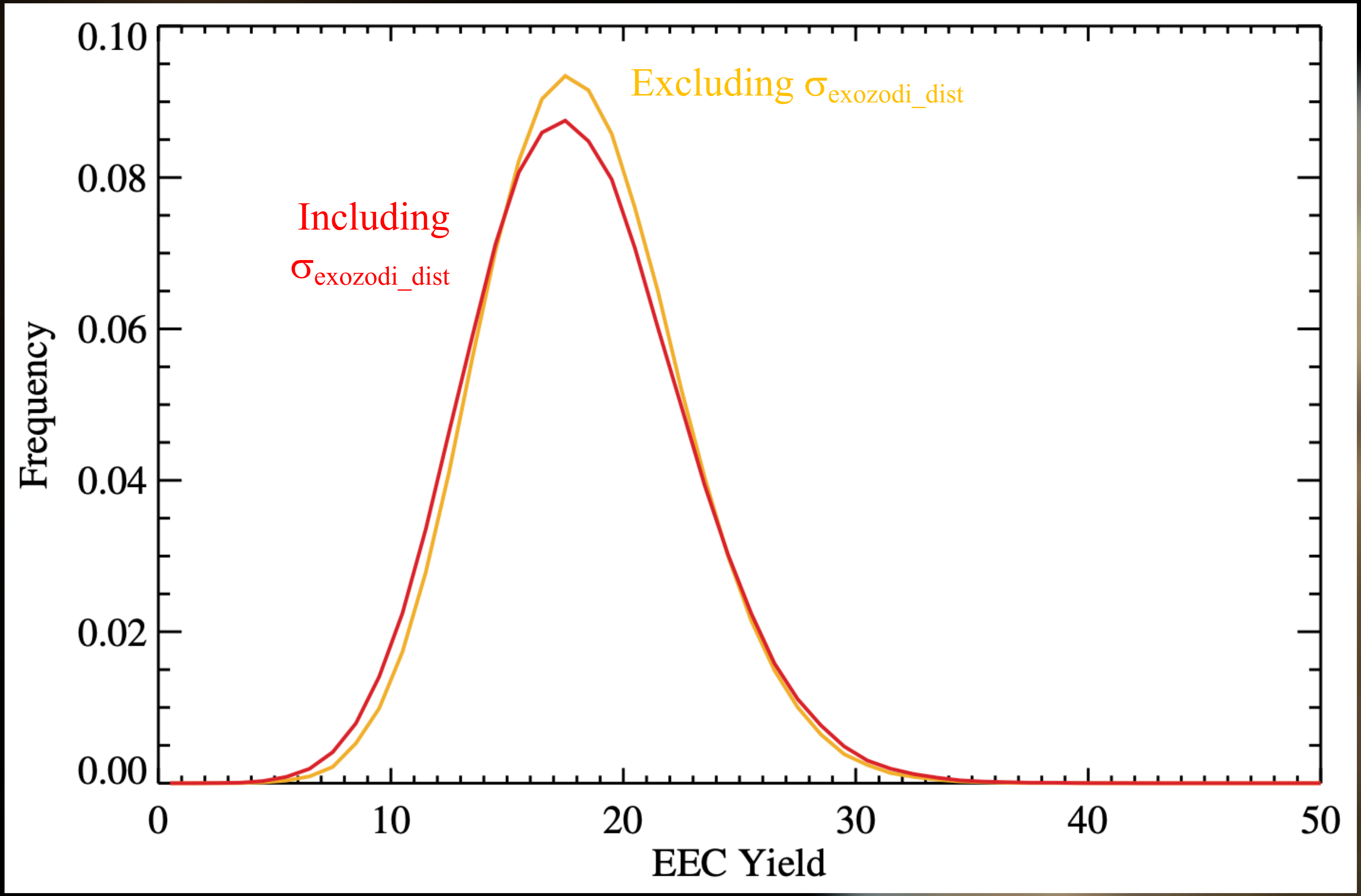
6 m ID version of LUVOIR-B

Uncertainties Included:

- Exoplanet sampling
- Albedo distribution
- Exozodi sampling

Exozodi sampling reduces yields, as it can assign high exozodi levels to high priority stars, which effectively removes them from the target list.

Sources of yield uncertainty: exozodi distribution



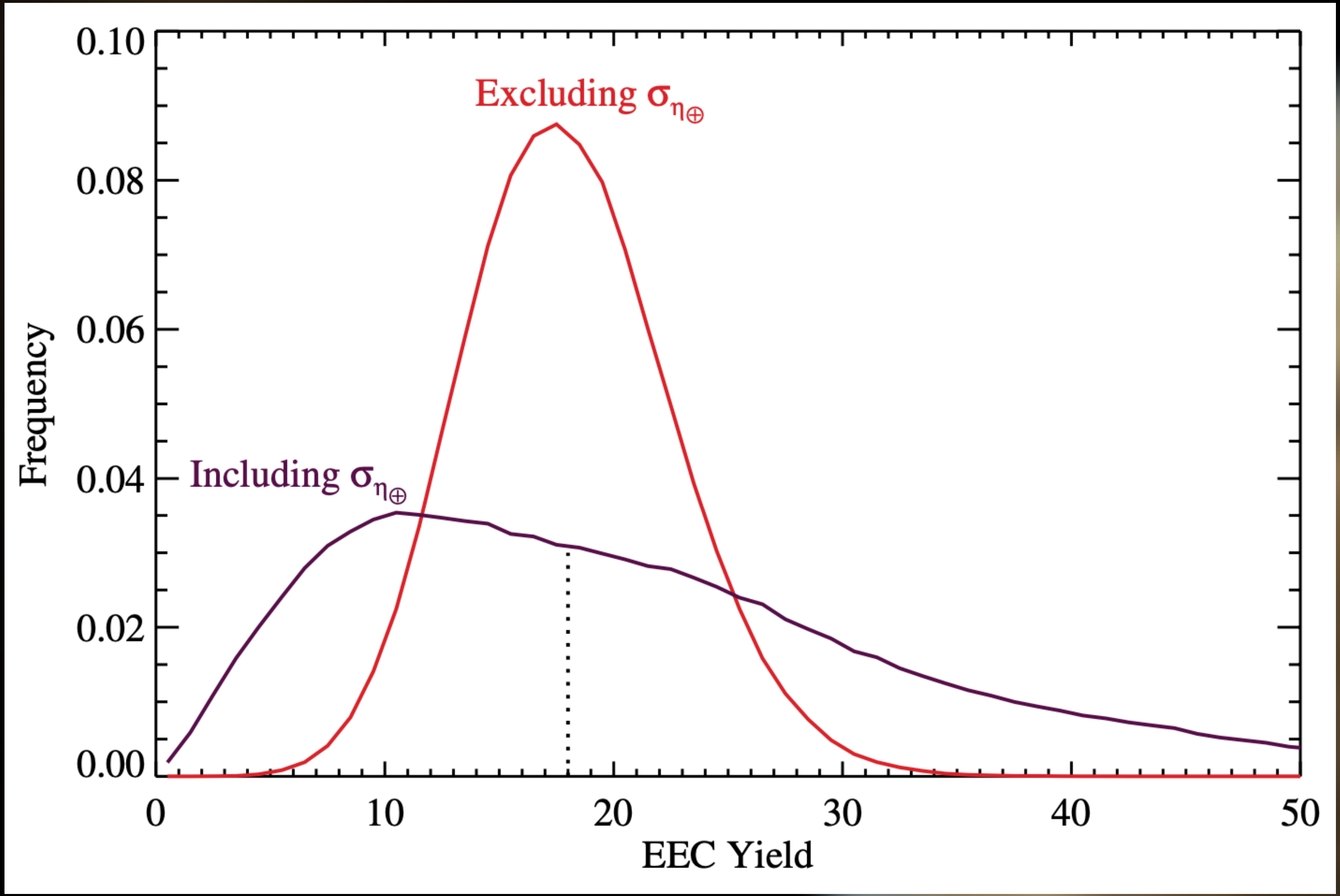
6 m ID version of LUVOIR-B

Uncertainties Included:

- Exoplanet sampling
- Albedo distribution
- Exozodi sampling
- Exozodi distribution

The uncertainty in the exozodi distribution from LBTI constraints appears to have minimal impact. This is tentative--TBR in the near future.

Sources of yield uncertainty: $\eta_\oplus$



Uncertainty in $\eta_\oplus$ is large.

6 m ID version of LUVOIR-B

Uncertainties Included:

- Exoplanet sampling
- Albedo distribution
- Exozodi sampling
- Exozodi distribution
- $\eta_\oplus$ uncertainty

Summary so far...

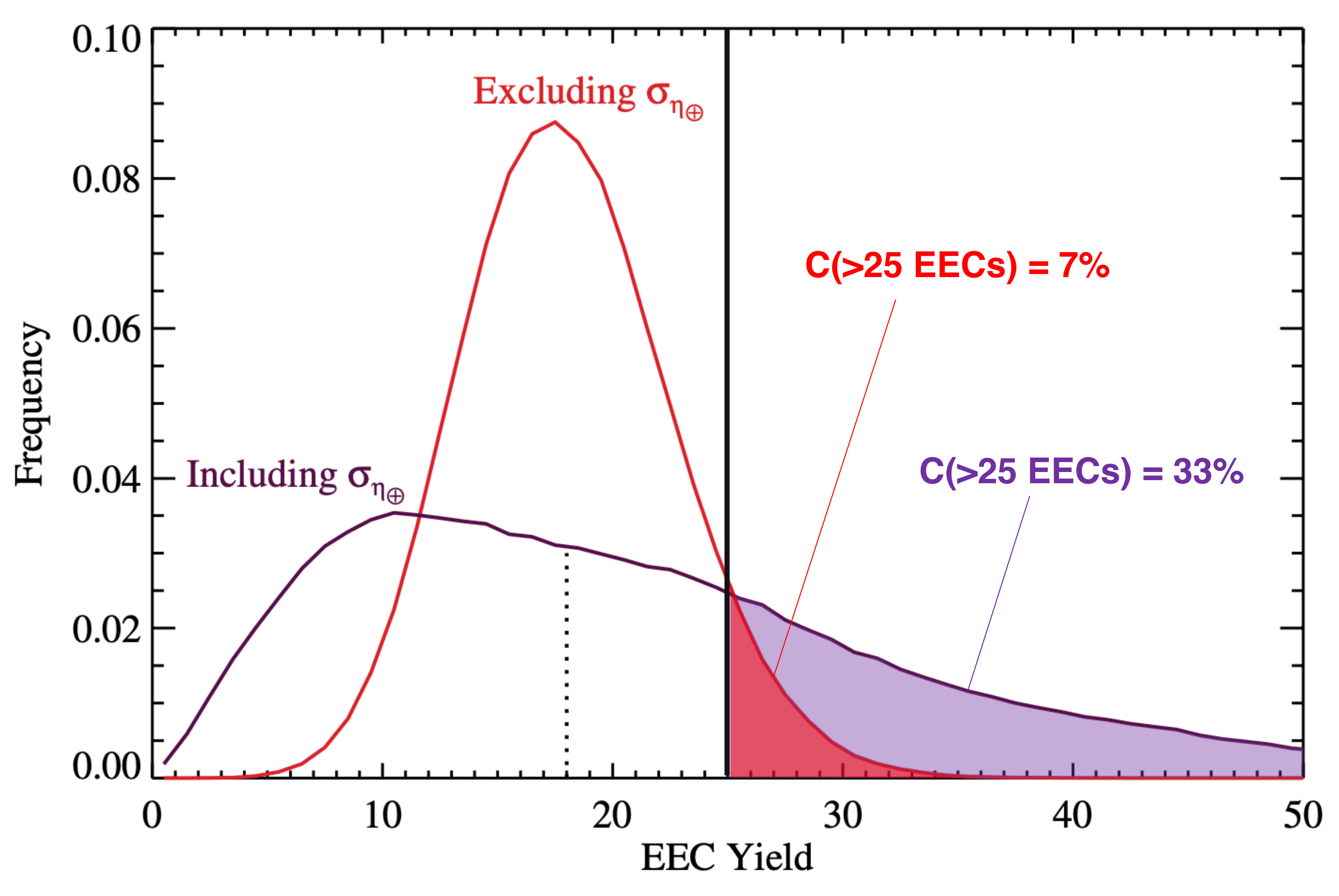
Conclusions from astrophysical uncertainty analysis:

- **$\eta_\oplus$ uncertainty dominates**
- **Second dominant term is exoplanet sampling, *which is intrinsic to a blind survey***
- **Many uncertainties shift yield distribution to lower values due to observational biases**
- **If one interpreted the Astro2020 goal as "100 cumulative HZs," *both* dominant sources of uncertainty would be ignored**

We proceed with two goals:

- **25 EECs including all sources of uncertainty**
- **25 EECs excluding $\eta_\oplus$ uncertainty, but including all others**

Confidence in achieving our goals w/ 6 m ID LUVOIR-B is low



How do we improve confidence?

1. Reduce uncertainties

- $\eta_\oplus$: Bryson's precursor science work?
- Exoplanet sampling: precursor knowledge could partially mitigate, but possibly not in time to inform design

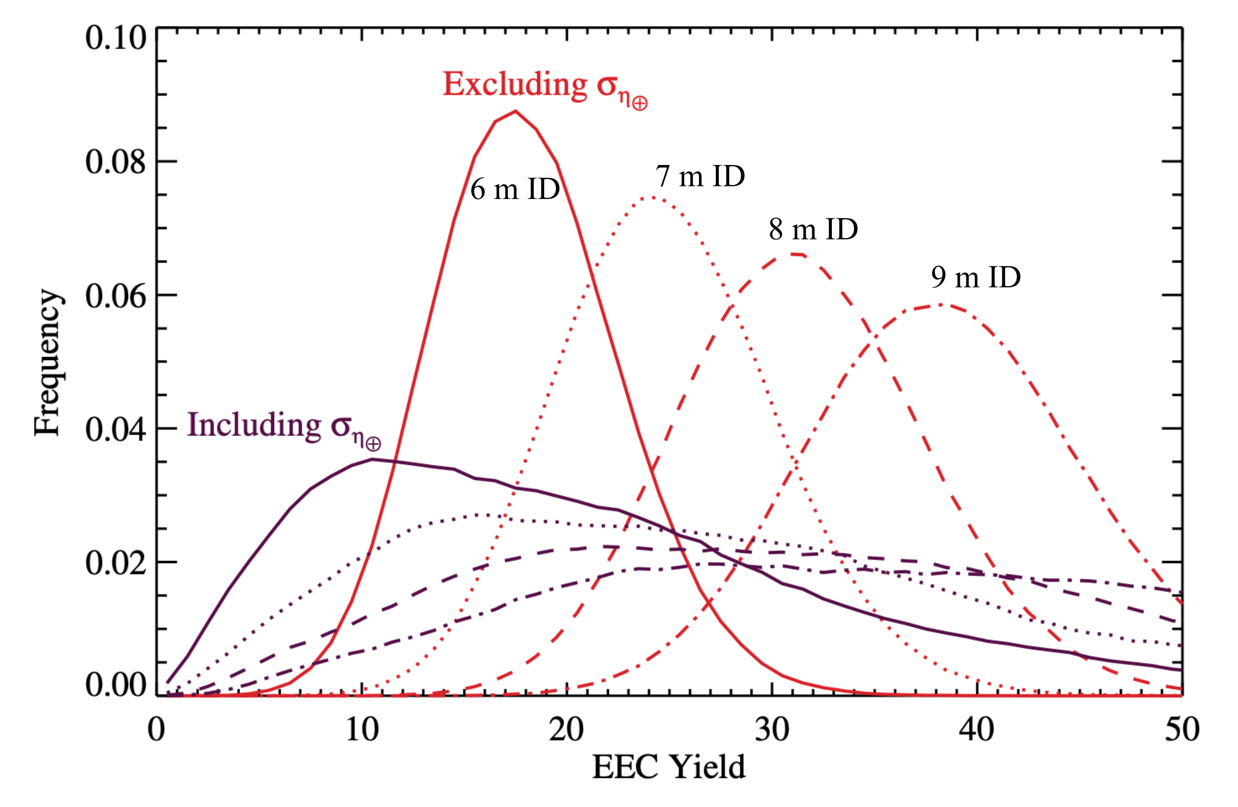
2. Build a bigger telescope

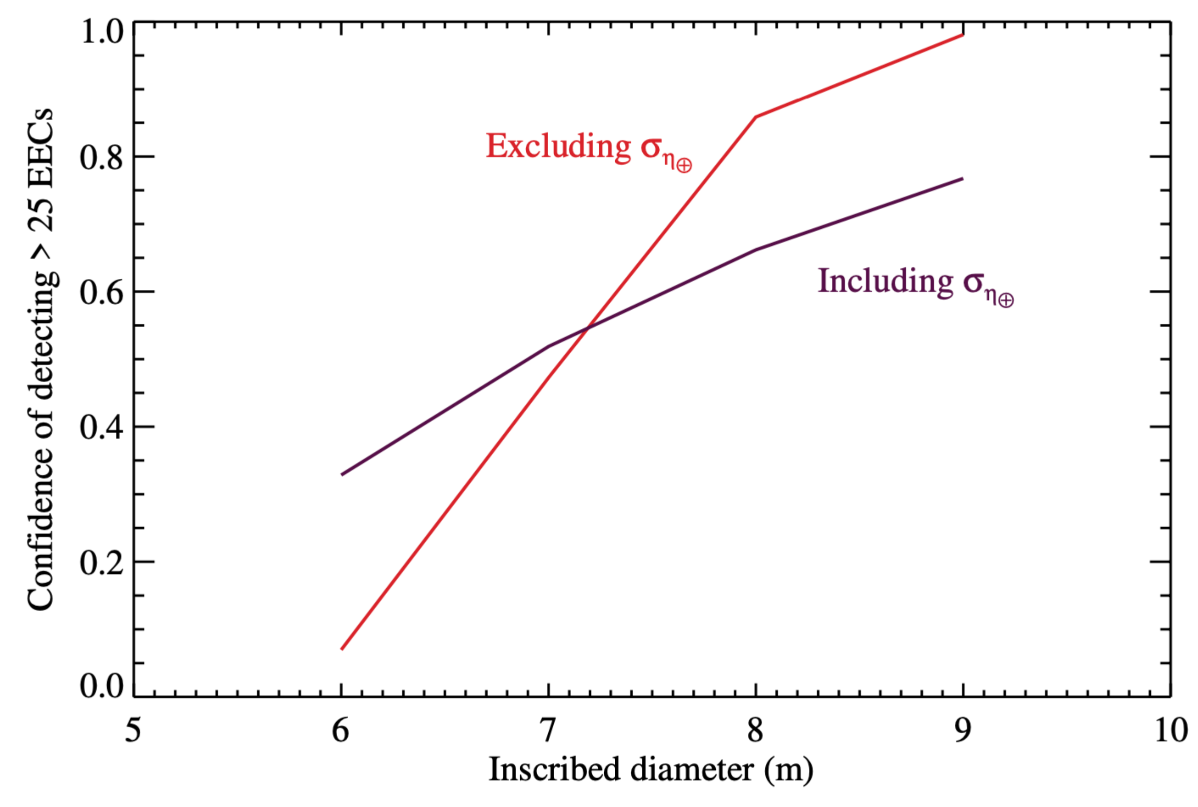
- Yield is most sensitive to D

3. Improve system design

Option 2: Build a Bigger Telescope

Larger telescopes can provide higher yields and greater confidence in achieving goals

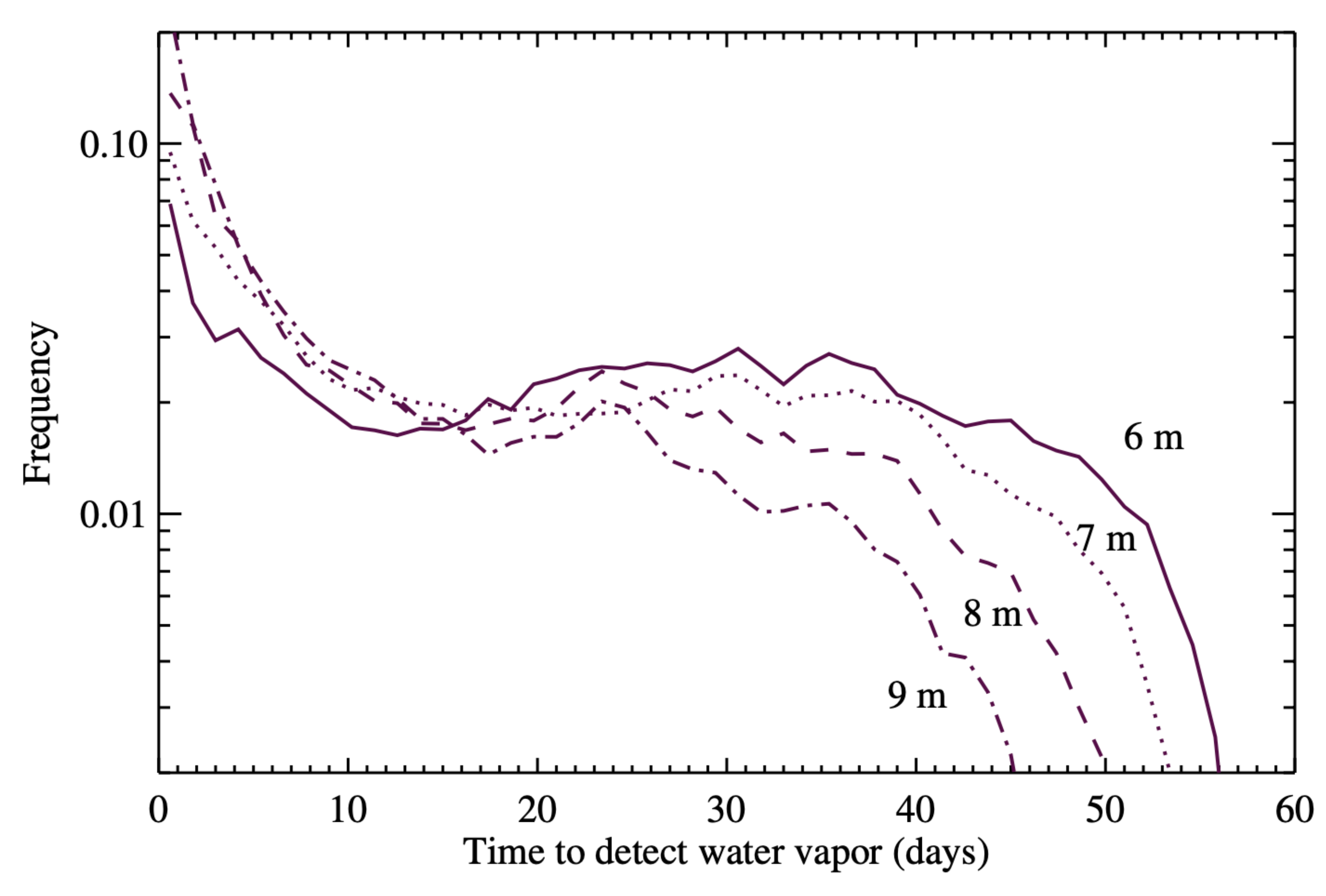




Larger D can achieve compelling confidence levels, but requires >8 m ID.

Option 2: Build a Bigger Telescope

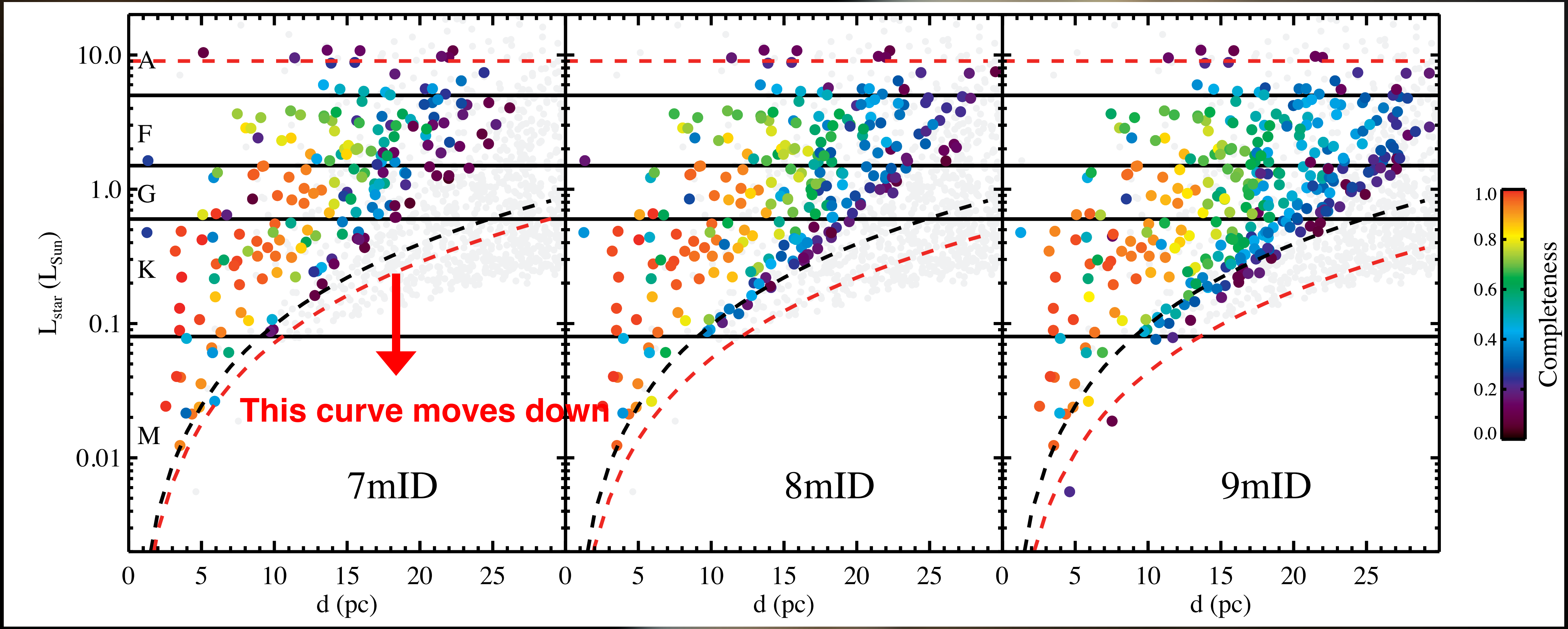
Larger telescopes can provide better data quality via shorter exposure times



Mean spec. char. time reduced from 22 days for 6 m ID to 3.3 days for 9 m ID.

Option 2: Build a Bigger Telescope

Larger telescopes can *expand the range of accessible targets* and improve spatial resolution of observed targets

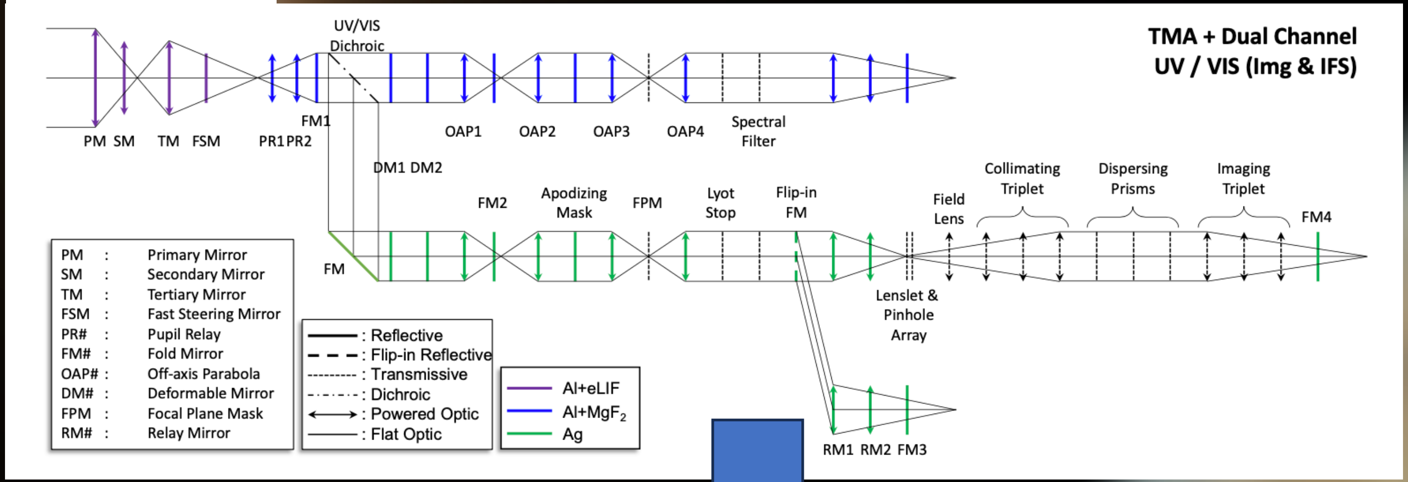


Option 3: Improve System Design

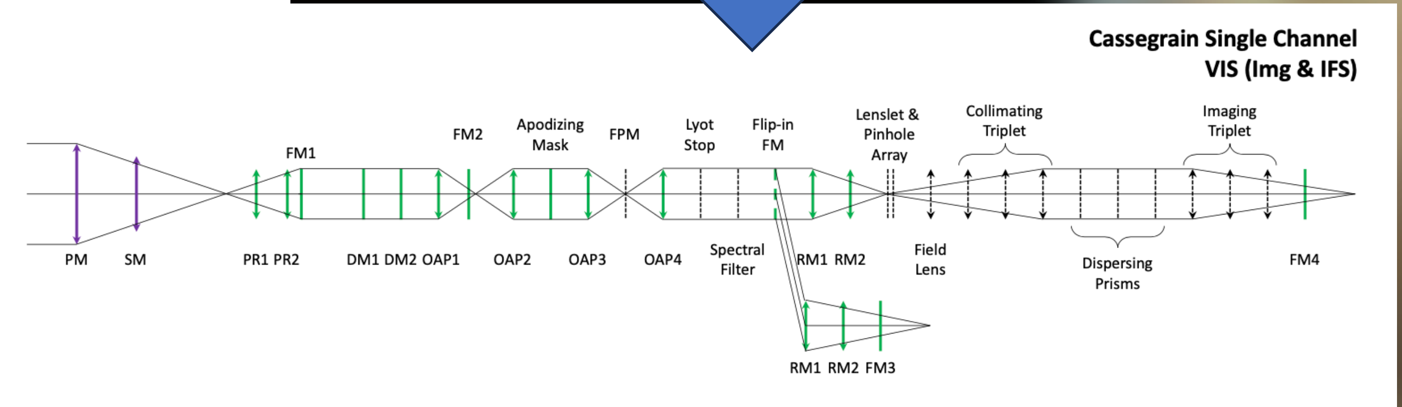
- LUVOIR design was not fully optimized for yield
- Many new ideas have arisen since the LUVOIR study
- There are a lot of levers to pull
- We consider 6 possible design changes (many others exist)
  - Each change results in a modest incremental improvement
  - Improvements will compile “synergistically”
  - Some will require technological investment; some may not pan out

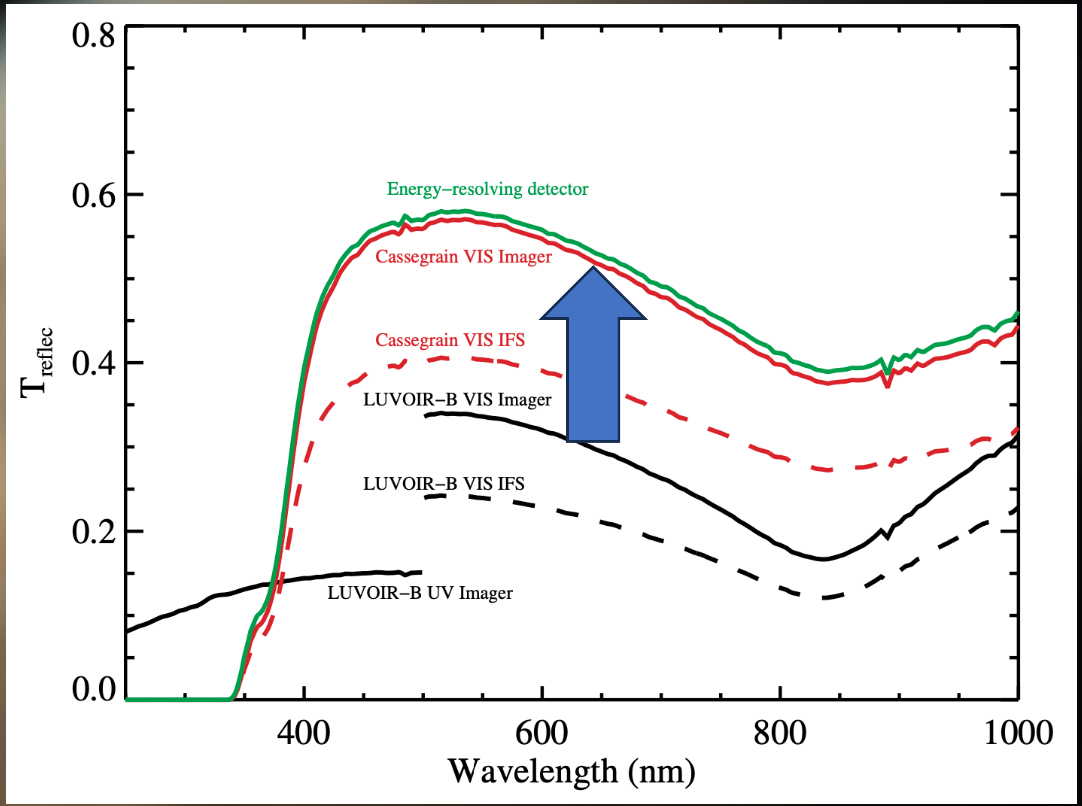
Scenario A: Minimize Aluminum Reflections

LUVOIR B



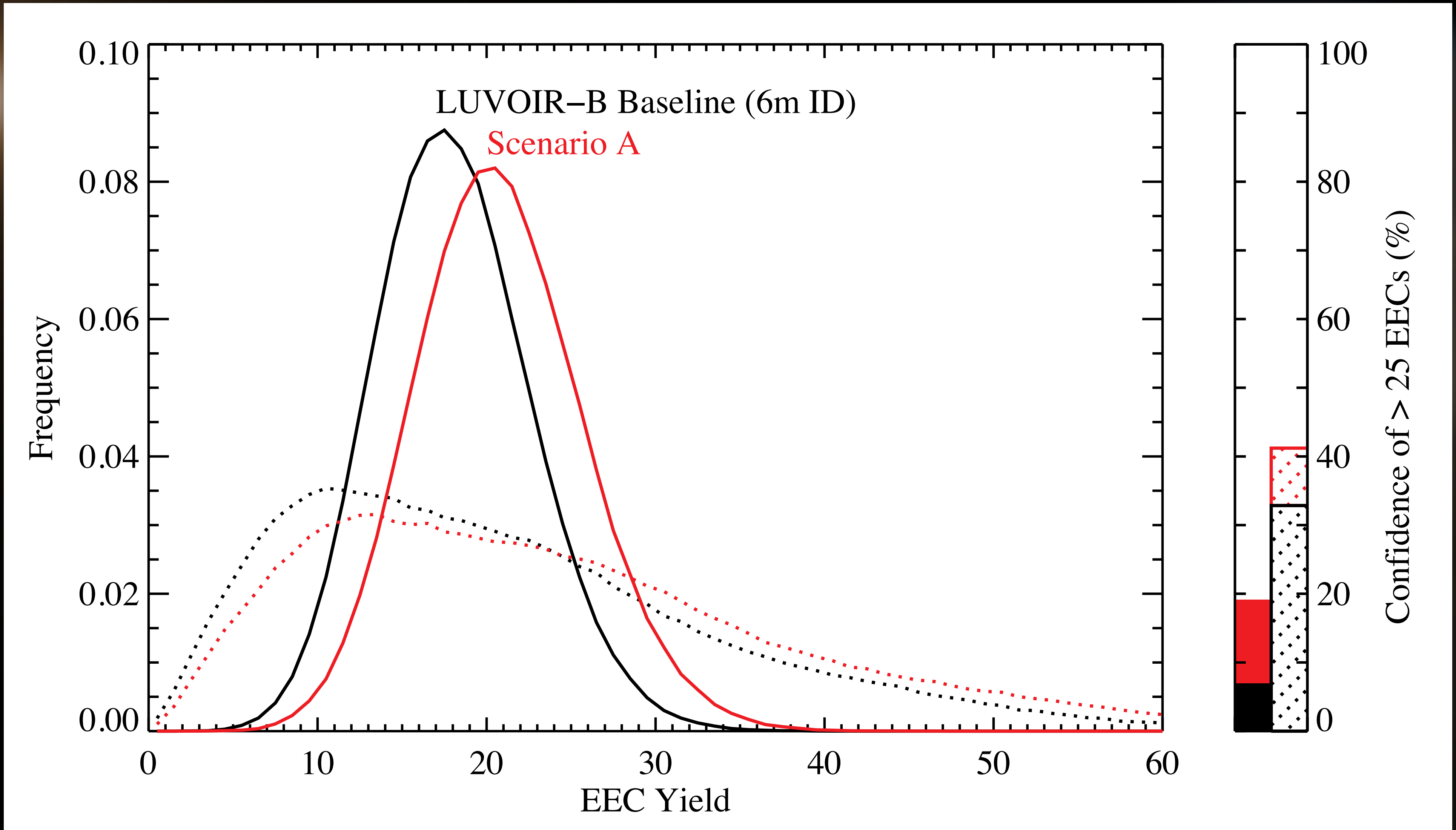
Scenario A





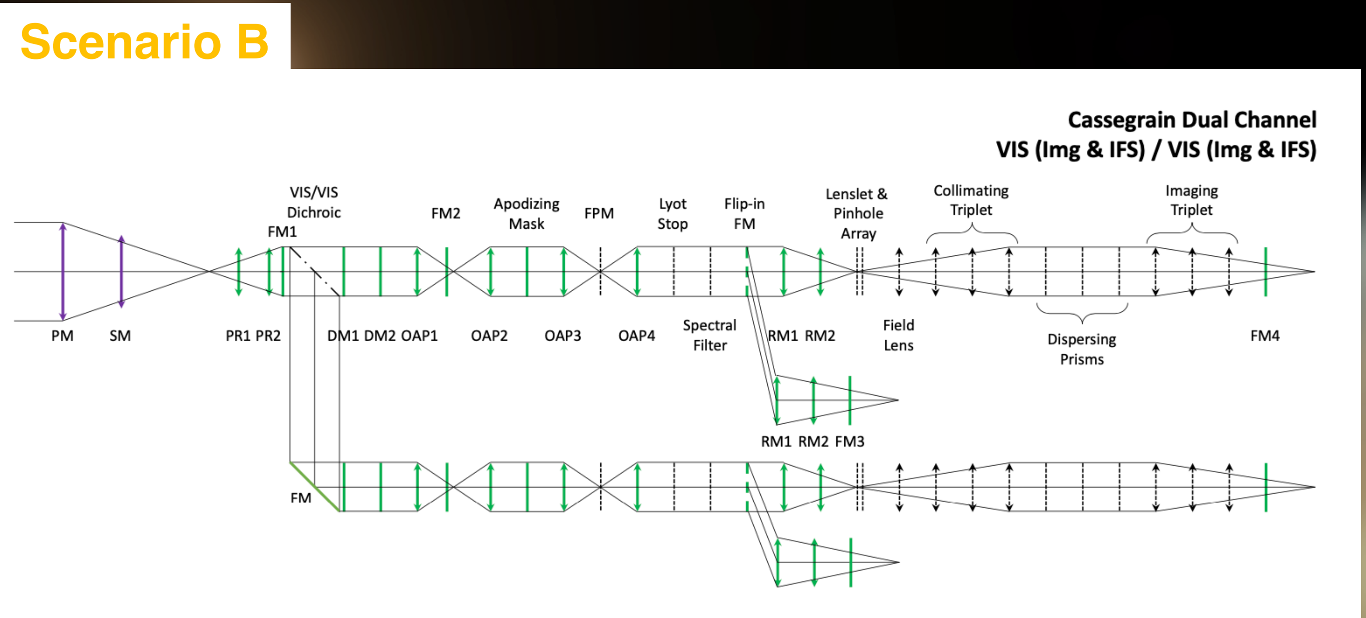
Can boost end-to-end throughput by 50% at 1 micron, more than enough to make up for loss of parallel UV channel.

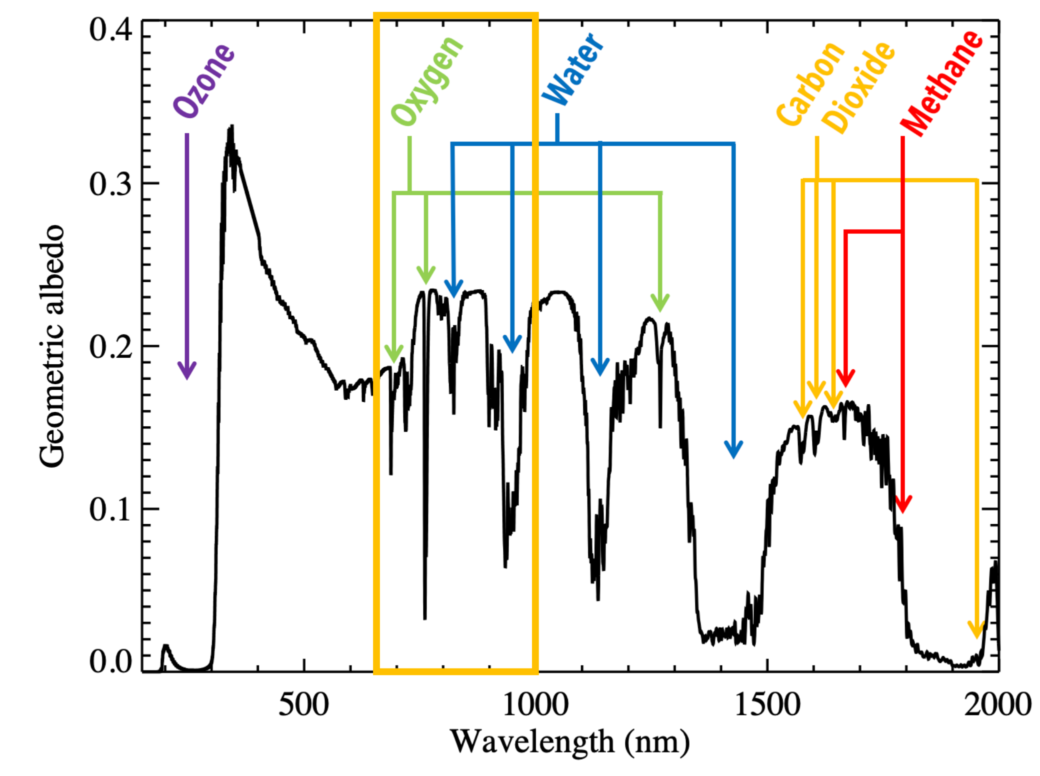
Scenario A: Minimize Aluminum Reflections



A Cassegrain design w/ only a single VIS channel could increase yields by 16% and reduce spec char exposure times by 1.4x.

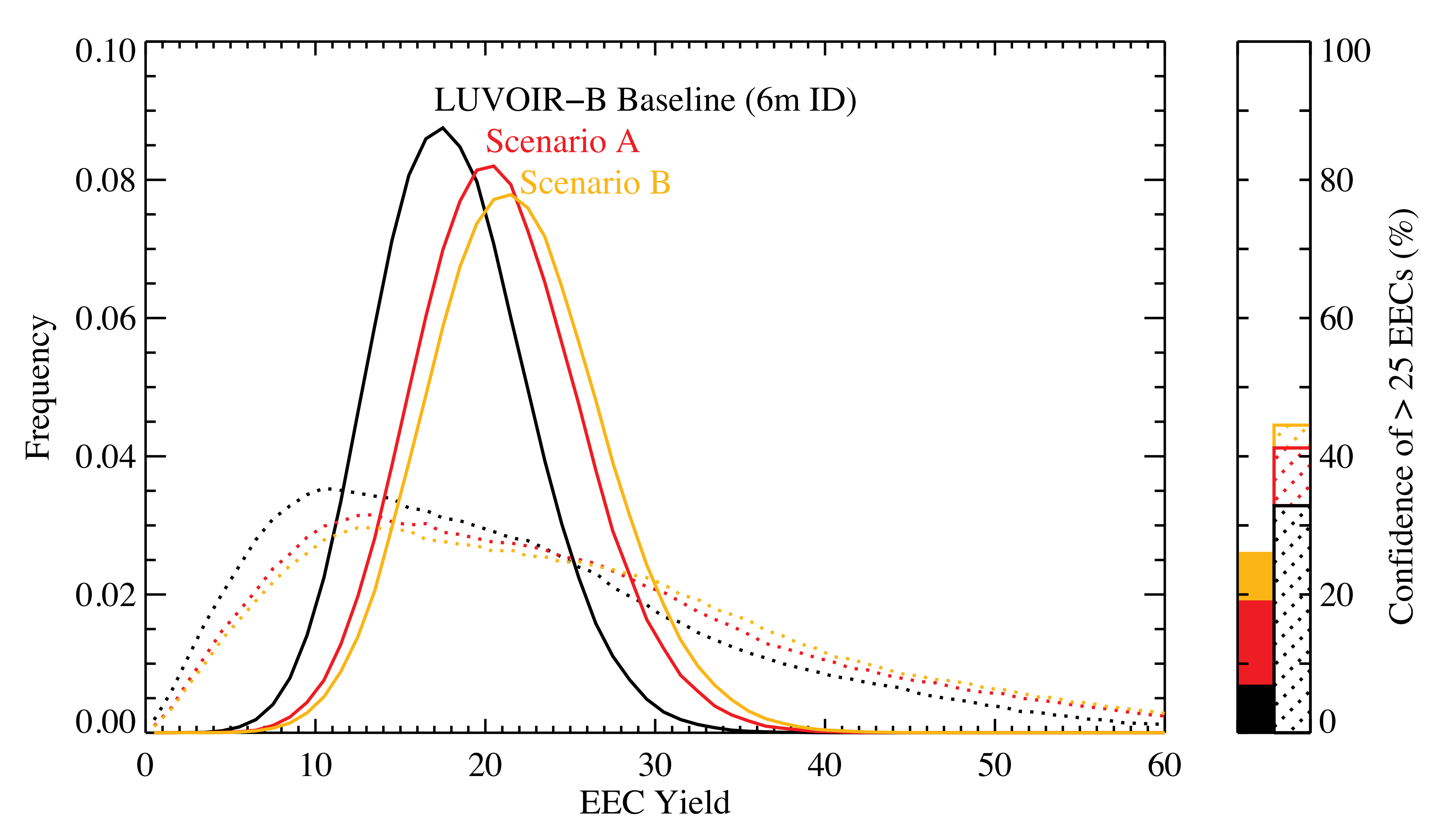
Scenario B: Add a parallel VIS channel





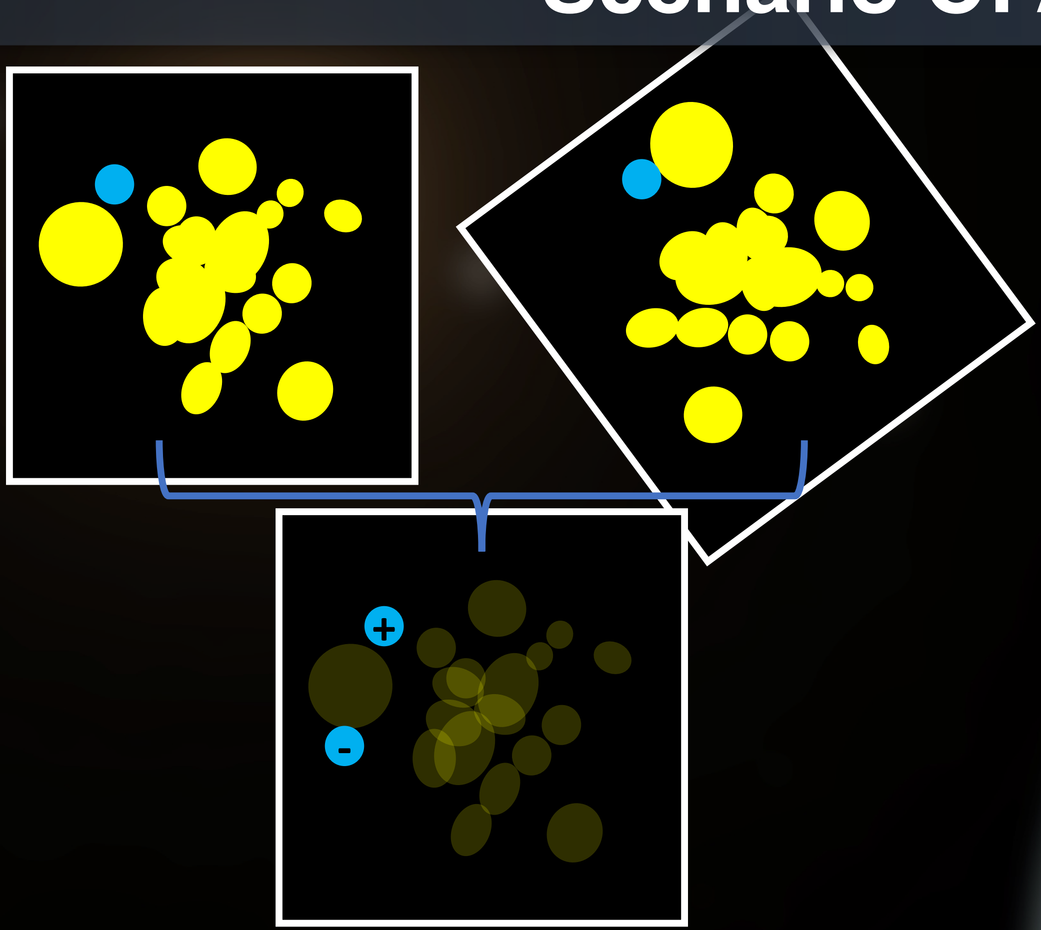
- Split VIS channels w/ selectable dichroic to shift both channels anywhere is VIS spectrum
- Doubles bandwidth for detections, reducing exposure times
- Doubles bandwidth for spectra, significantly improving data quality and covering O2 and H2O simultaneously
- Provides redundancy for prime science instrument

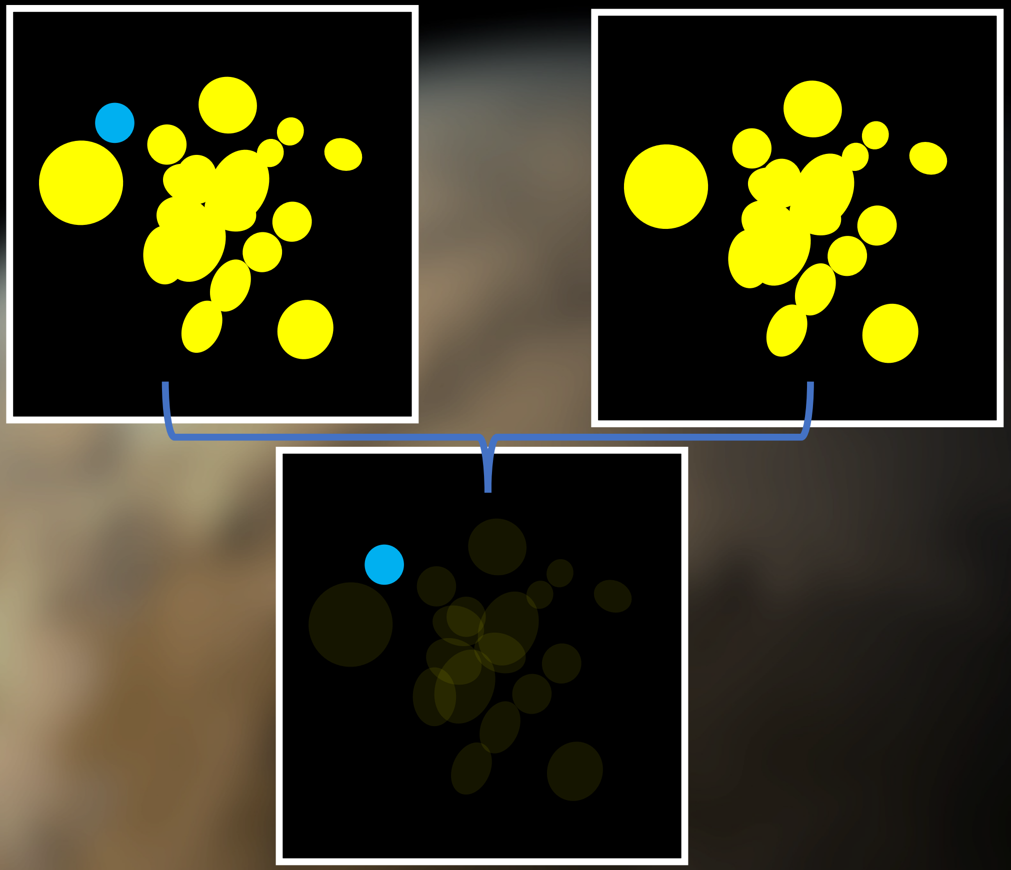
Scenario B: Add a parallel VIS channel



Adding a second parallel VIS channel could increase yields by 5%, double the bandwidth of all spectra, and provide critically important redundancy.

Scenario C: Adopt model-based PSF subtraction



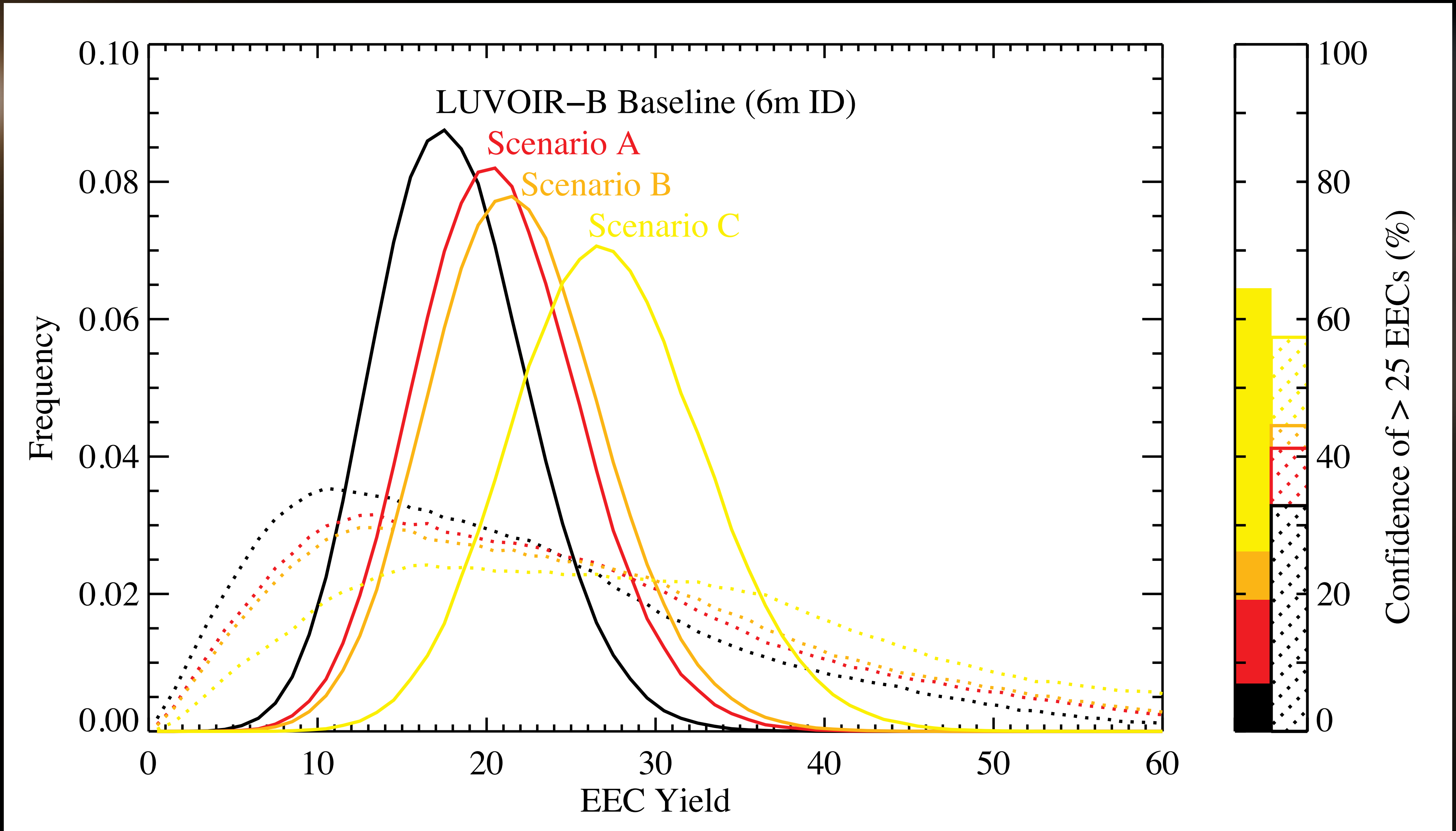


$$\tau = (\mathrm{S/N})^2 \left(\frac{\mathrm{CR_p} + 2\,\mathrm{CR_b}}{\mathrm{CR_p}^2} \right)$$

$$\tau = (\mathrm{S/N})^2 \left(\frac{\mathrm{CR_p} + \cancel{2}\,\mathrm{CR_b}}{\mathrm{CR_p}^2} \right)$$

Most yield calculations have adopted ADI, leading to a factor of 2 on all background count rates in the exposure time equation. Model-based PSF subtraction removes this.

Scenario C: Adopt model-based PSF subtraction



Model-based PSF subtraction could increase yields by 25% and reduce spec char exposure times by 1.7x.

Scenario D: Improve the detector

Parameter	Units	EMCCD	Skipper
QE		0.9*	See Fig. 21
dQE		0.75	1.0
DC	counts pix^{-1} s^{-1}	3×10^{-5}	6.8×10^{-9}
CIC	counts pix^{-1} $frame^{-1}$	1.3×10^{-3}*	1.5×10^{-4}
RN	counts pix^{-1} $read^{-1}$	0	0
Scenarios		0, A, B, C	D

*Parameters assume future improvements.

Courtesy B. Rauscher (see LUVOIR Final Report, Morrissey 2023, Bebek 2015, Barak 2022)

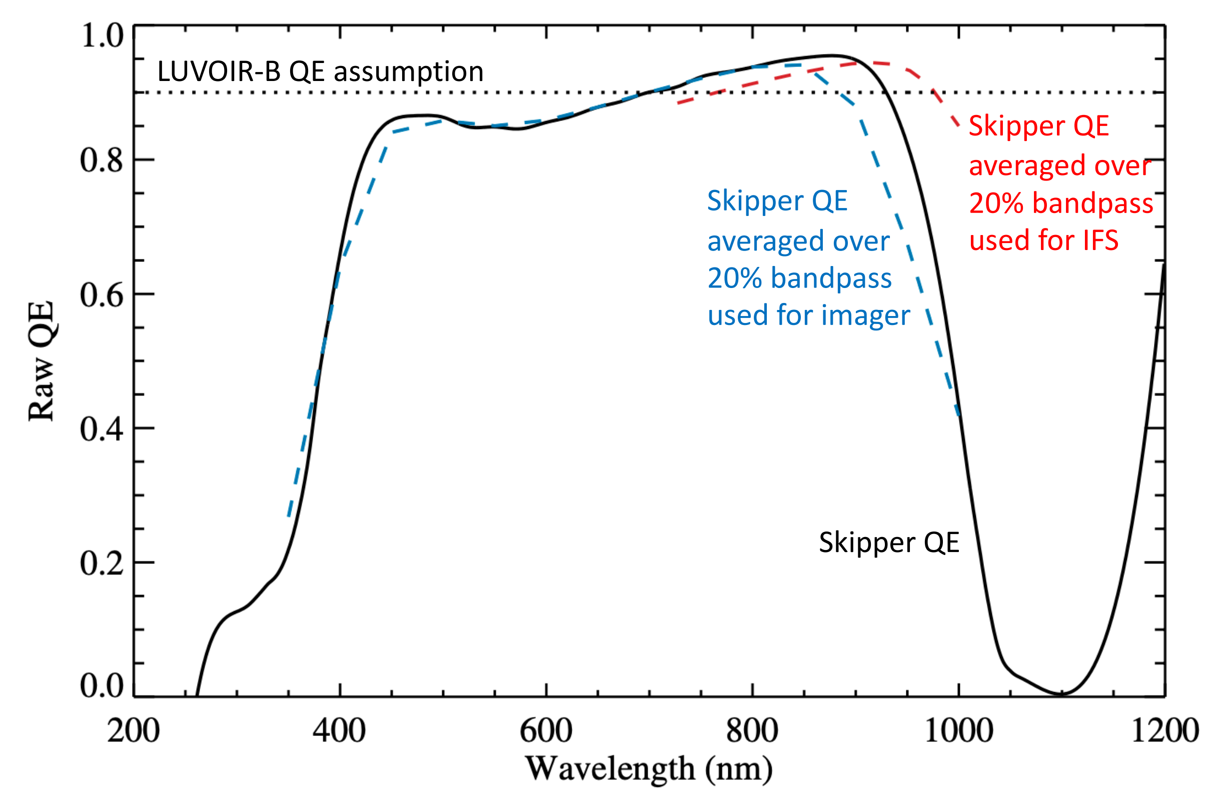
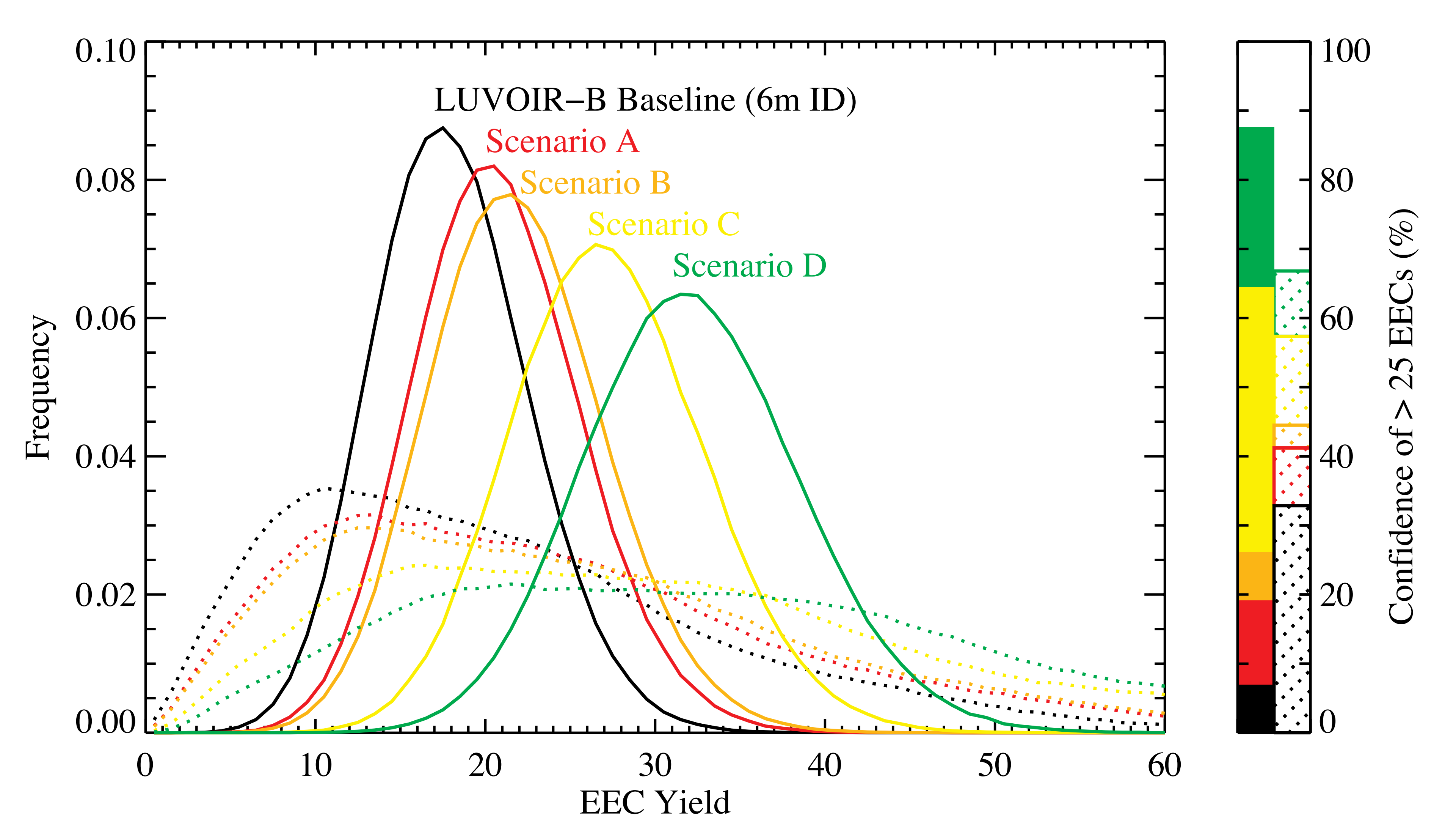


Fig 21. Adopted QE for a Skipper CCD (Tiffenberg et al .2017)

Scenario D: Improve the detector



A detector similar to a Skipper CCD could increase yield by 19% and reduce spec char exposure times by 1.6x.

Scenario E: Adopt an energy-resolving detector

Parameter	Units	EMCCD	Skipper	ERD
QE		0.9*	See Fig. 21	0.9
dQE		0.75	1.0	1.0
DC	counts pix^{-1} s^{-1}	3×10^{-5}	6.8×10^{-9}	0
CIC	counts pix^{-1} $frame^{-1}$	$1.3 \times 10^{-3*}$	1.5×10^{-4}	0
RN	counts pix^{-1} $read^{-1}$	0	0	0
Scenarios		0, A, B, C	D	E, F

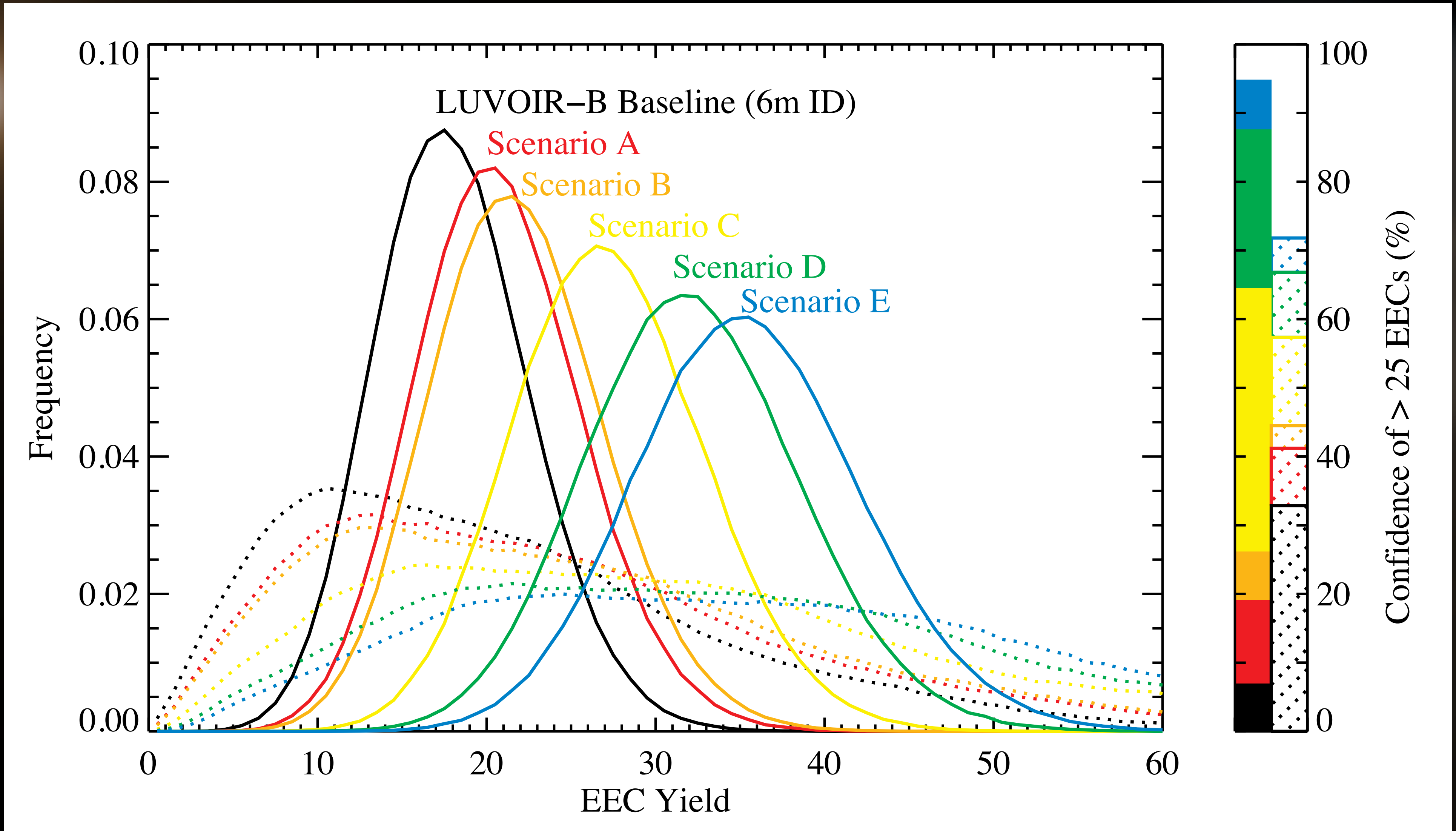
*Parameters assume future improvements.

Courtesy B. Rauscher (see LUVOIR Final Report, Morrissey 2023, Bebek 2015, Barak 2022)

Energy-resolving detectors:

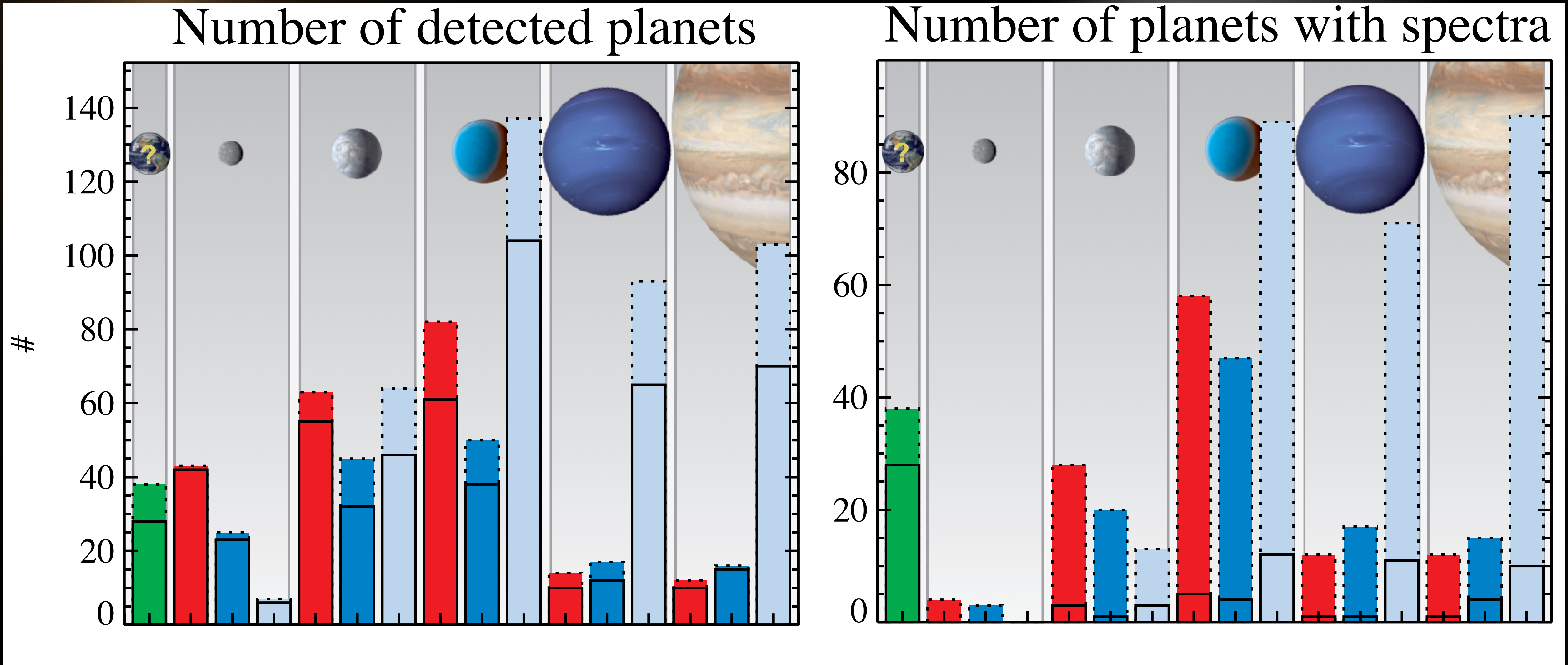
- **Remove the need for IFS optics, increasing throughput**
- **Can be noiseless**
- **Can have very high QE over a broad bandpass**
- **Can take spectra all the time penalty-free**
- **Can be rad-hard**
- **Require cooling to ~mK**

Scenario E: Adopt an energy-resolving detector



An energy-resolving detector could increase yields by 11% and reduce exposure time by 1.4x compared to a Skipper, and provide hundreds of additional spectra ”for free”.

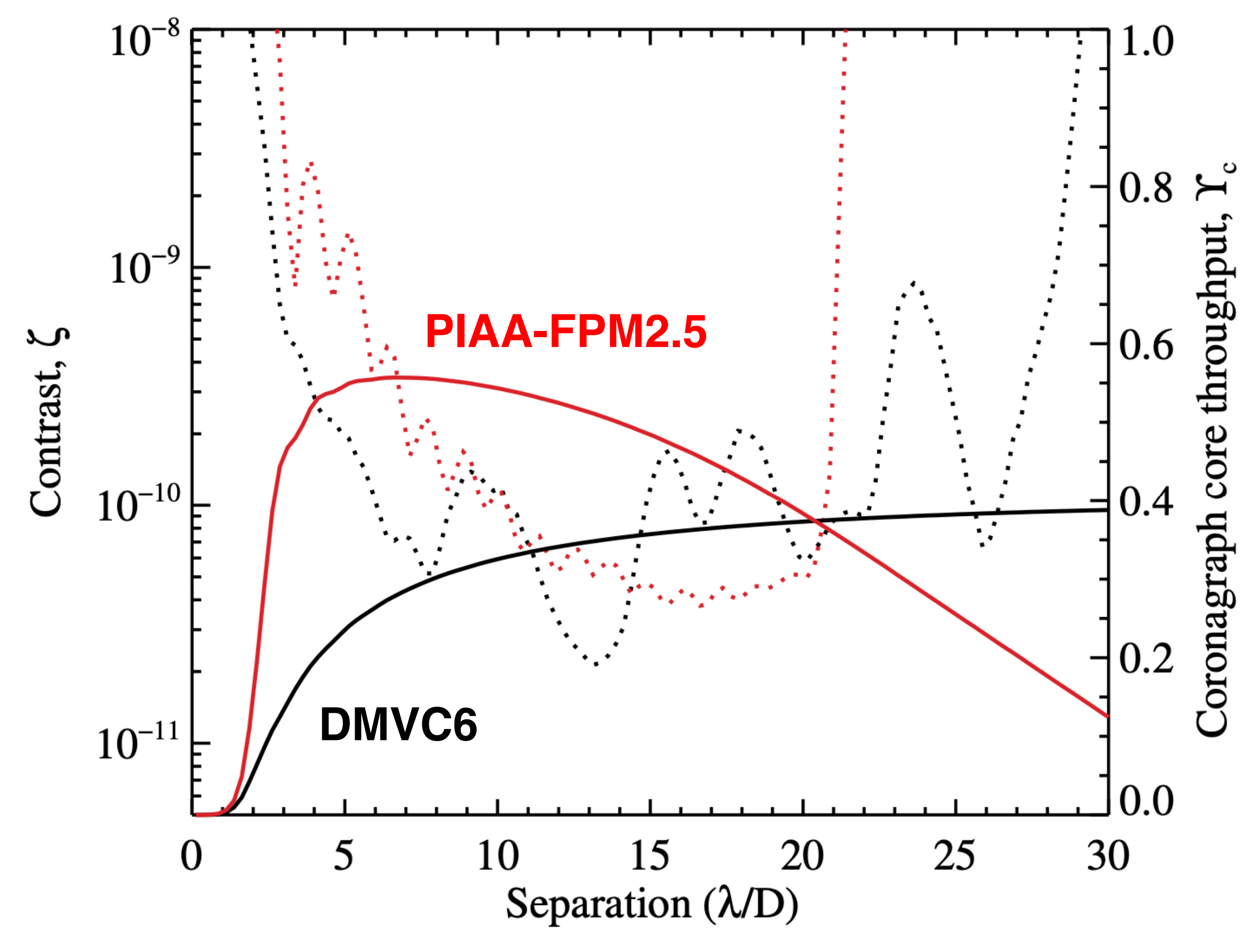
Scenario E: Adopt an energy-resolving detector



Howe, Stark, & Sadleir (submitted)

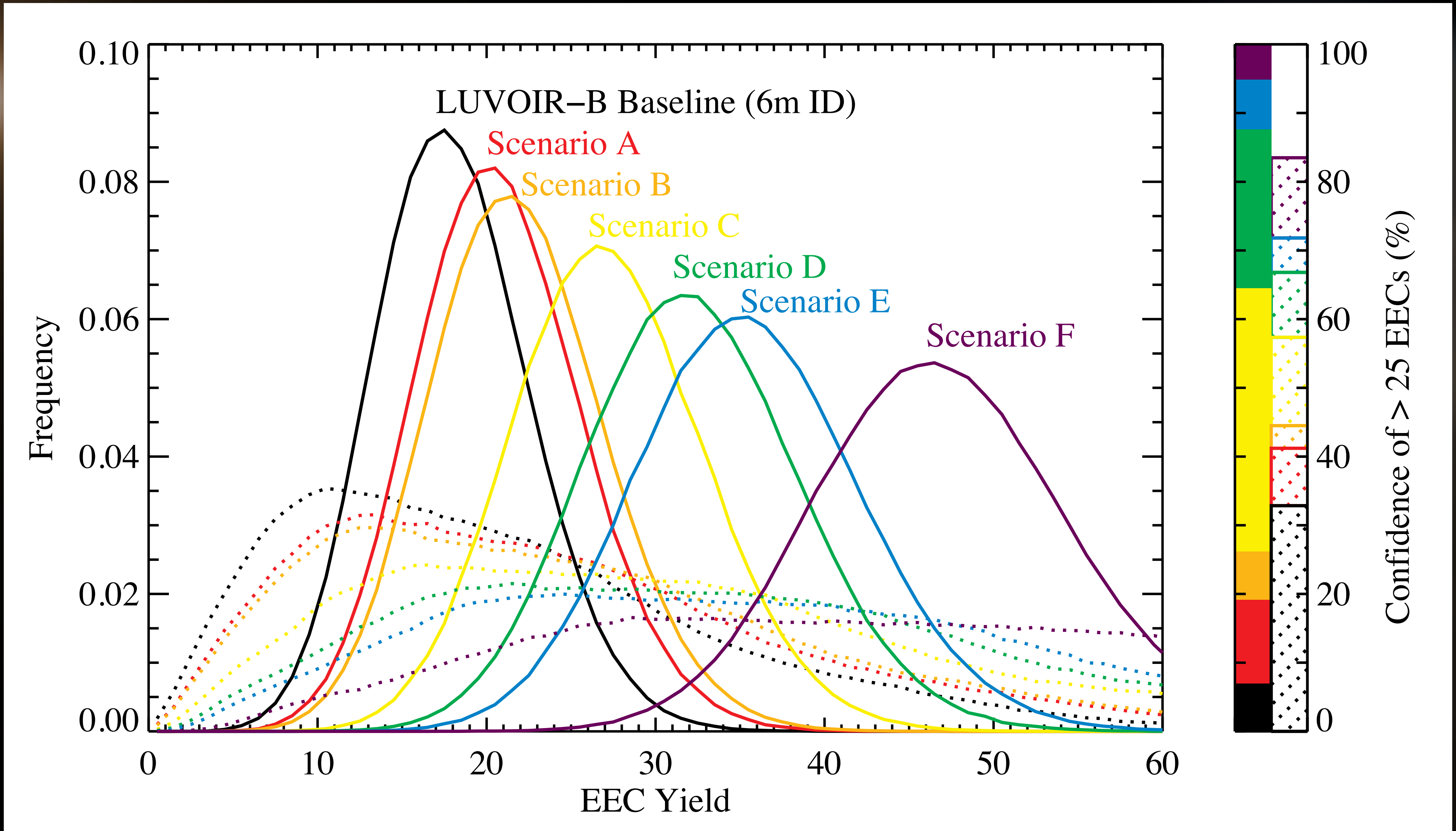
ERDs can observe spectra of hundreds of additional exoplanets "for free."

Scenario F: Adopt a high-throughput coronagraph



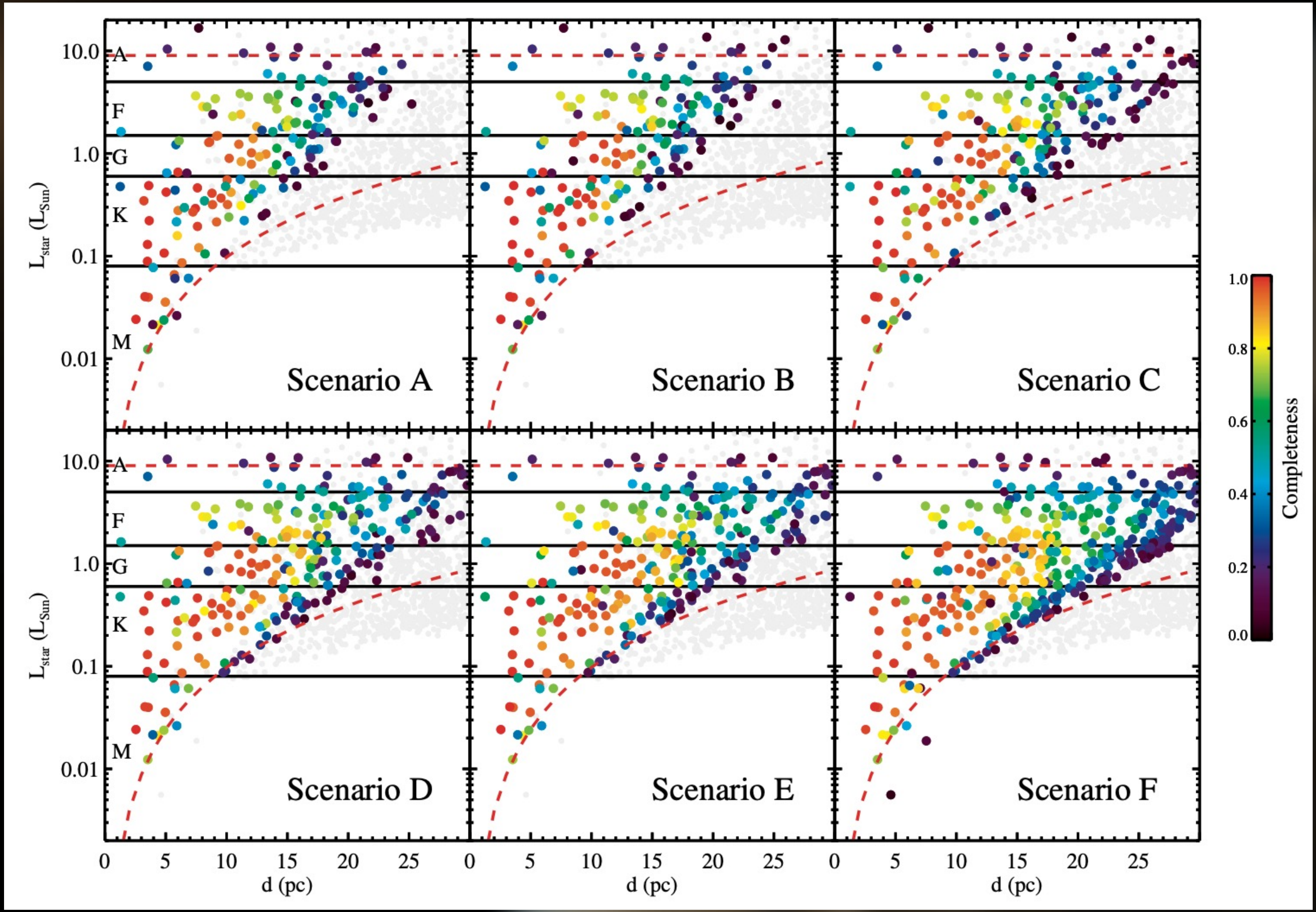
PIAA-FPM2.5 offers very high throughput at small WA, but degraded contrast. Turns out this is a good trade if the noise floor is decoupled from raw contrast.

Scenario F: Adopt a high-throughput coronagraph



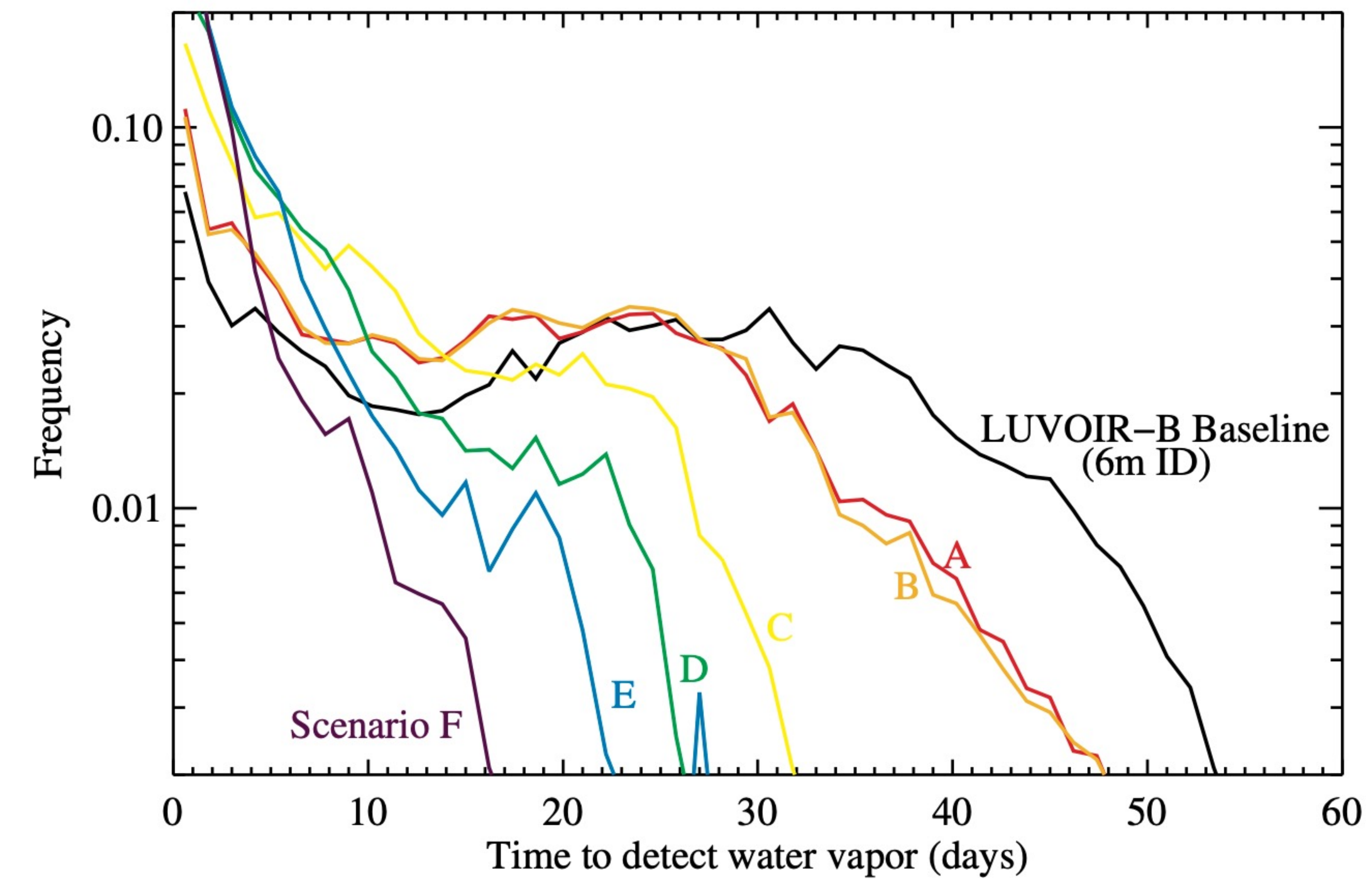
A high throughput coronagraph could increase yields by 32% and reduce spec char exposure times by 2x.

Design changes probe deeper into the target list



Yield isn't everything: Exposure times matter

A month is too long to search for water vapor



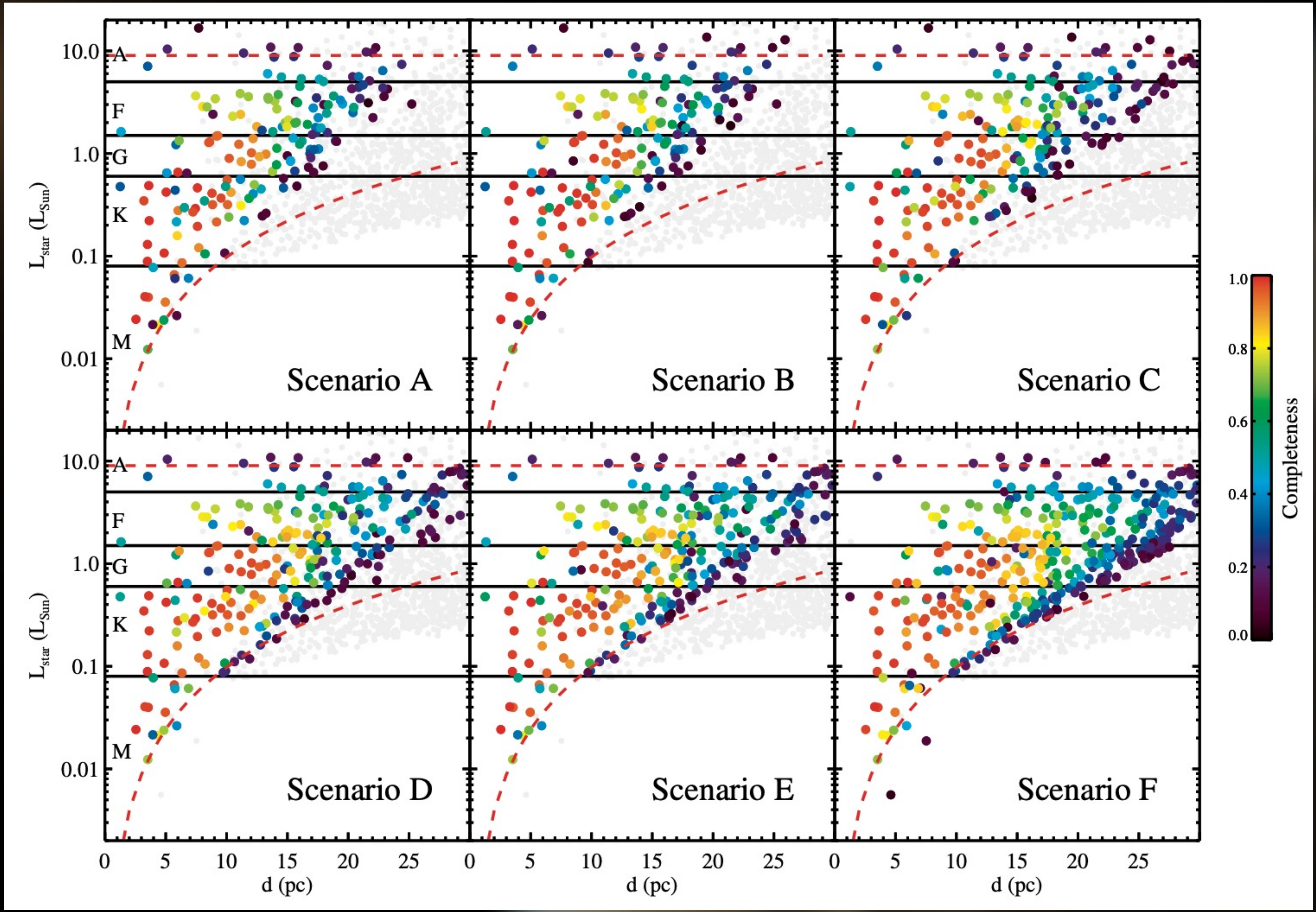
Stark et al. (in prep)

These six changes reduce mean spec. char. times of high priority targets by >10x, from 22 days to ~ 2 days while doubling bandwidth, all without increasing D.

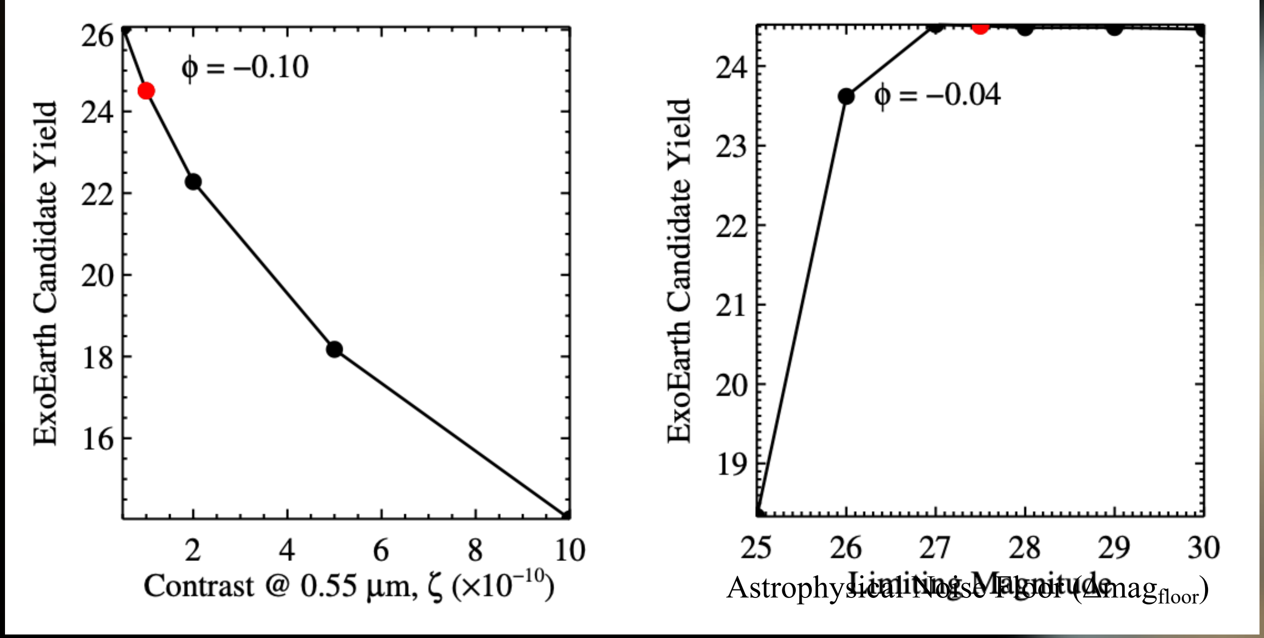
Conclusion

A combination of a modest increase in telescope diameter and system design changes could provide robust exoplanet science margins for HWO.

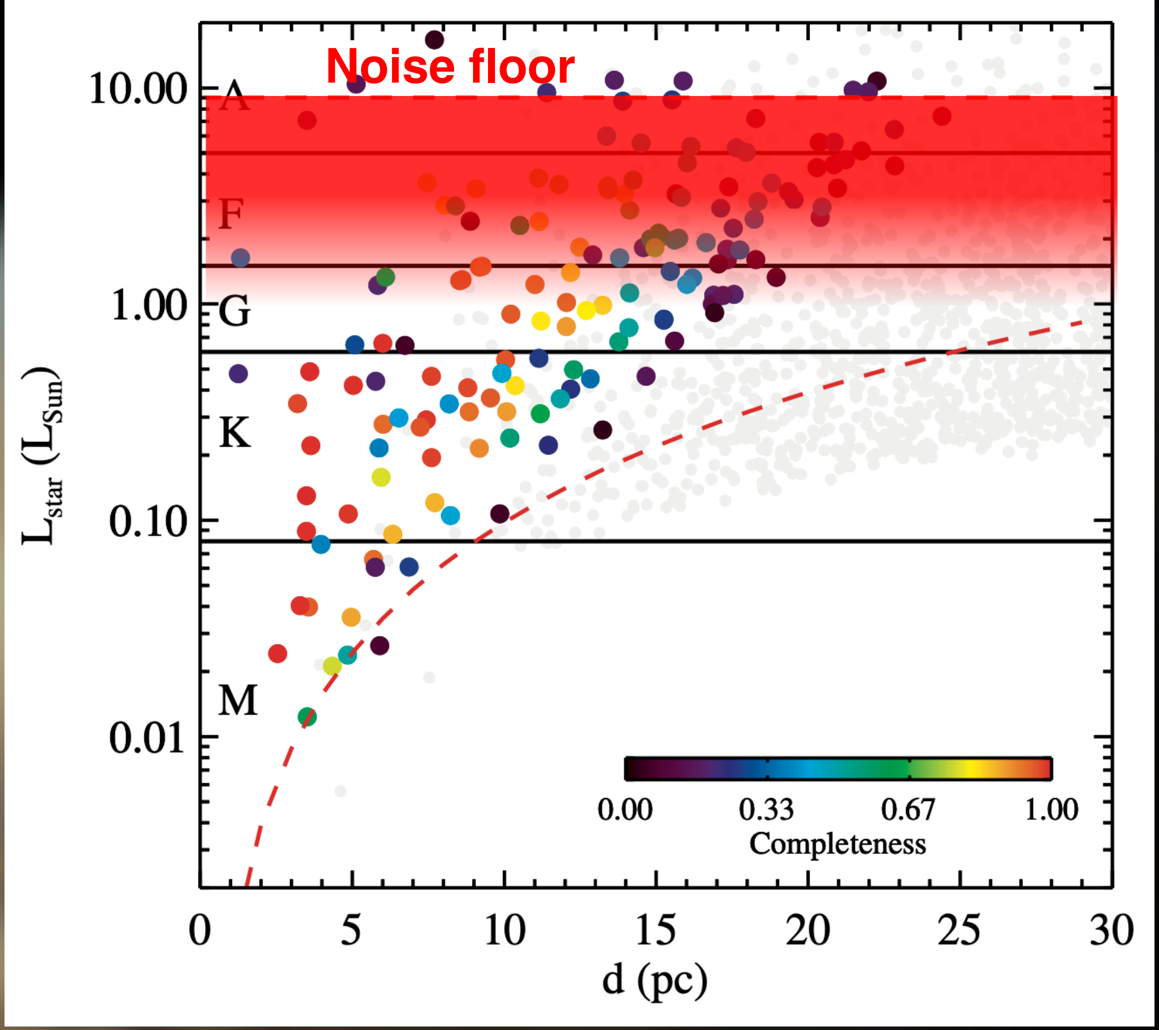
Mitigating Performance Risk



Noise floor may be the highest risk



Stark et al. (2015)



Yield is relatively insensitive to raw contrast because of exozodi. But the *contrast floor after PSF subtraction is a critical* parameter.

The noise floor directly limits the range of accessible targets

How to mitigate noise floor risk? Reduce IWA

Larger telescopes can expand the range of accessible targets to later type stars, helping to mitigate risk of noise floor removing early type stars