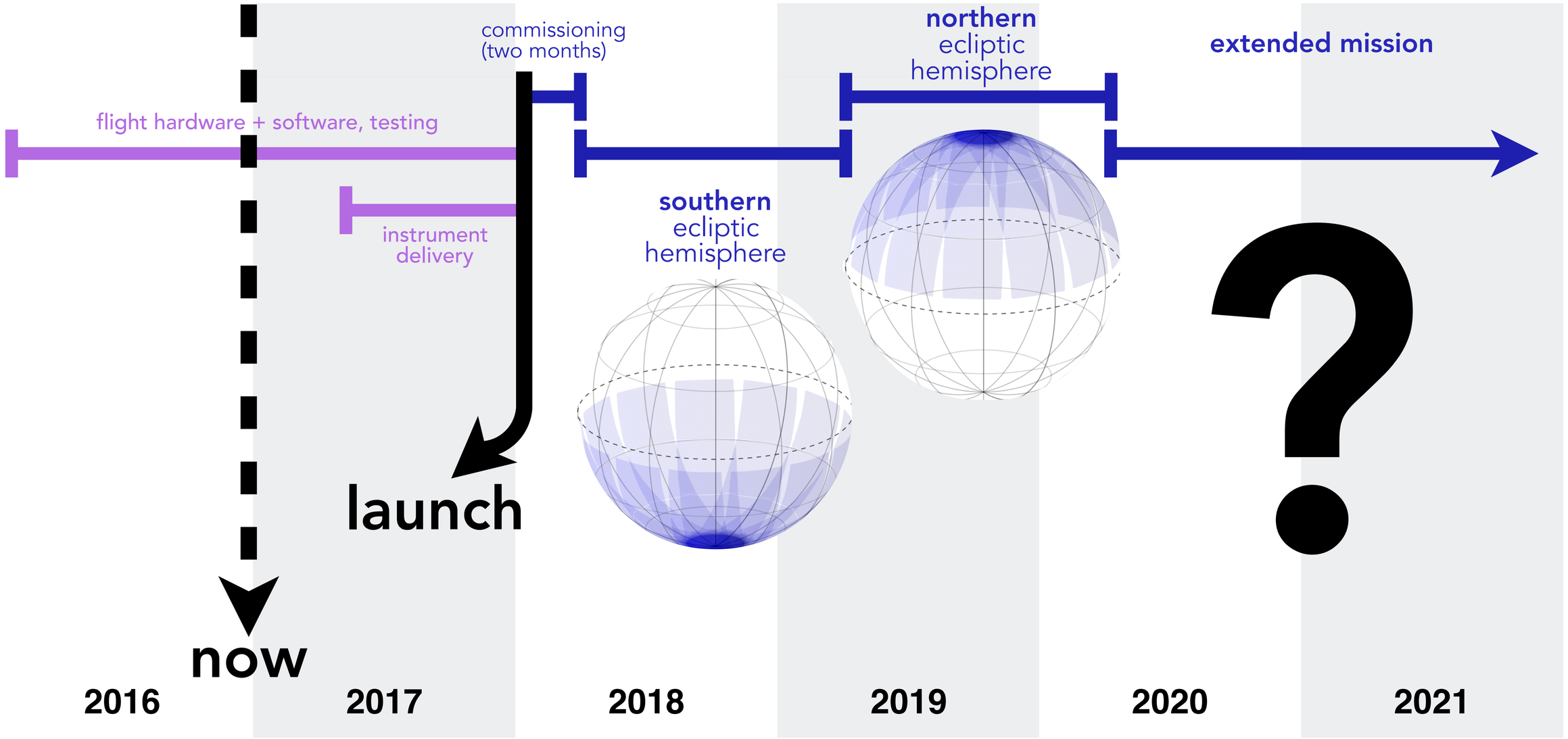
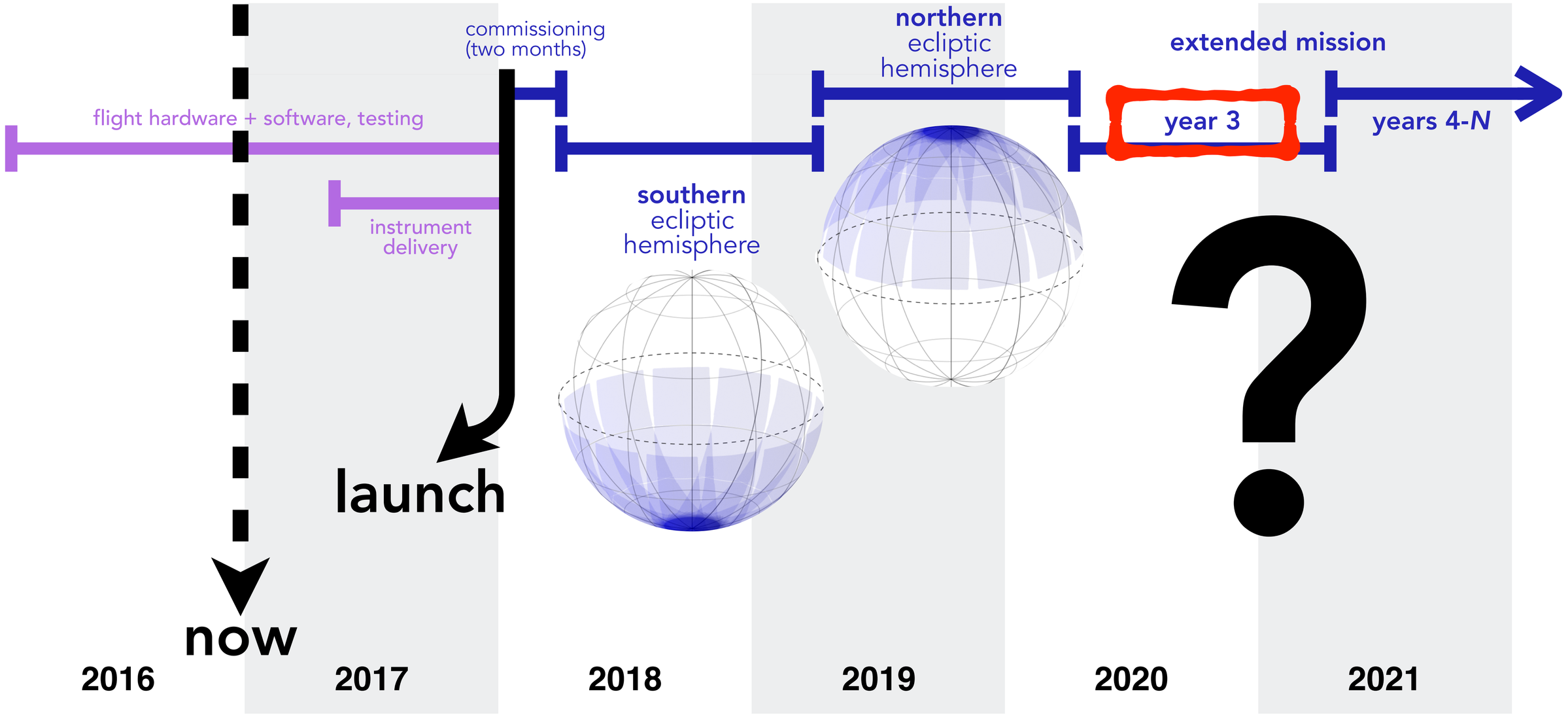
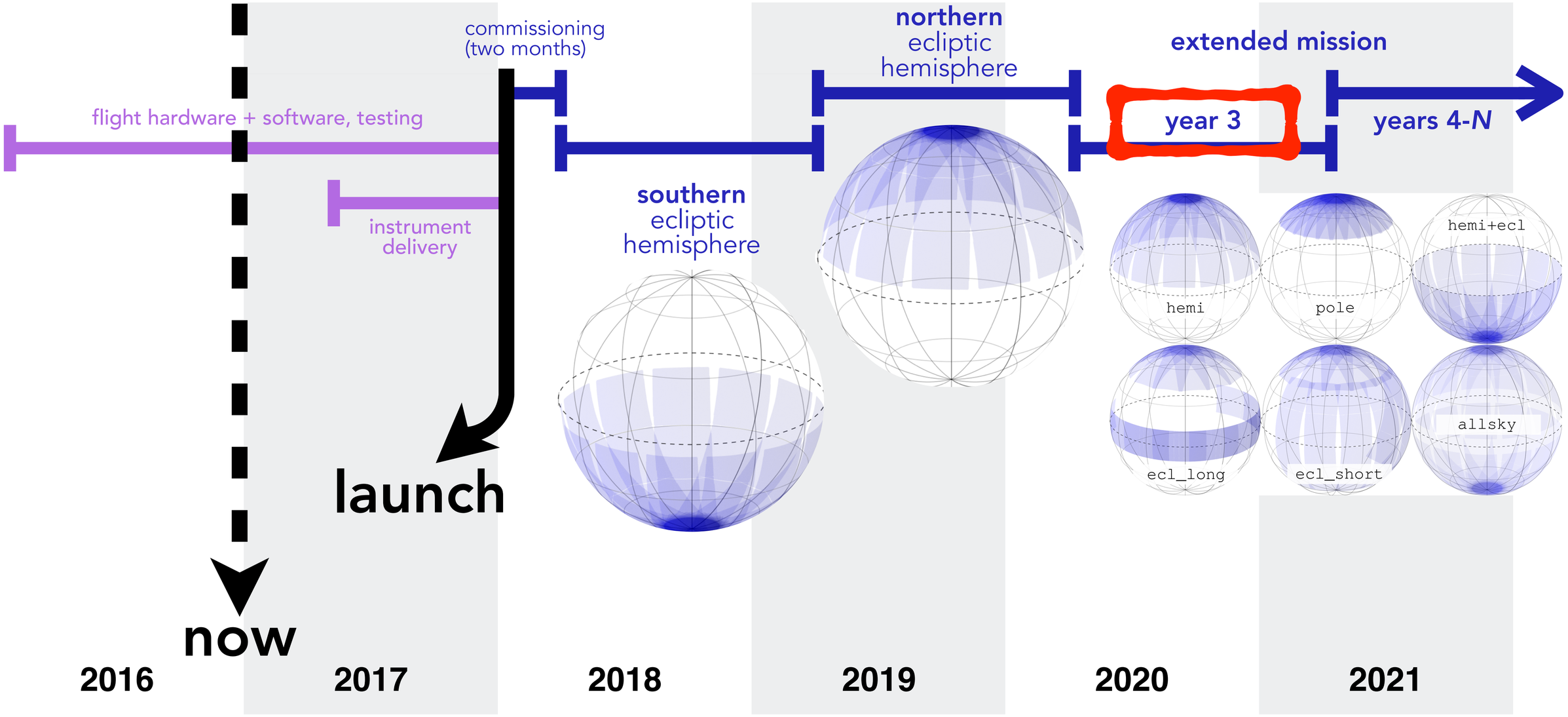



*adapted from Zach Berta-Thompson*




*adapted from Zach Berta-Thompson*




*adapted from Zach Berta-Thompson*

# *Planet Detection Simulations for Several Possible TESS Extended Missions*

*Luke Bouma, Josh Winn, Jacobi Kosiarek, Peter McCullough*

*TESS Science Team Meeting, Dec 8, 2016*

We wrote an Extended Mission white paper,
and invite you to read it & give us feedback.

We wrote an Extended Mission white paper,
and invite you to read it & give us feedback.

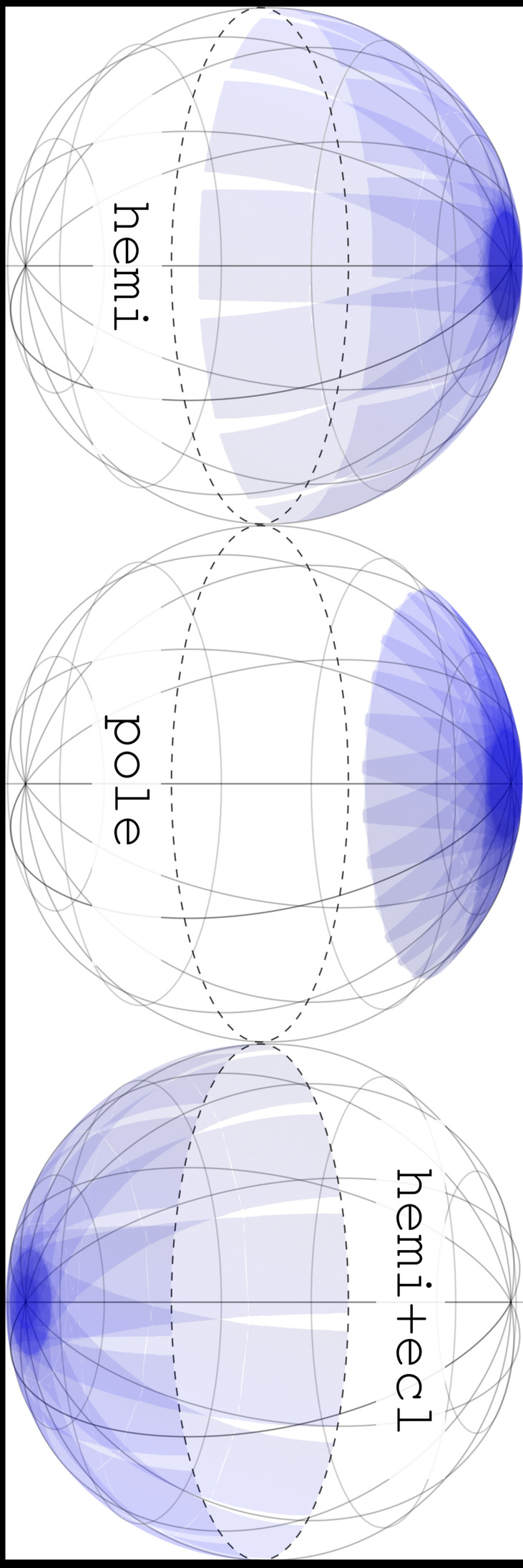
The paper has an accompanying Wiki document,
to which you can contribute.

The wiki is a repository for Extended Mission planning:

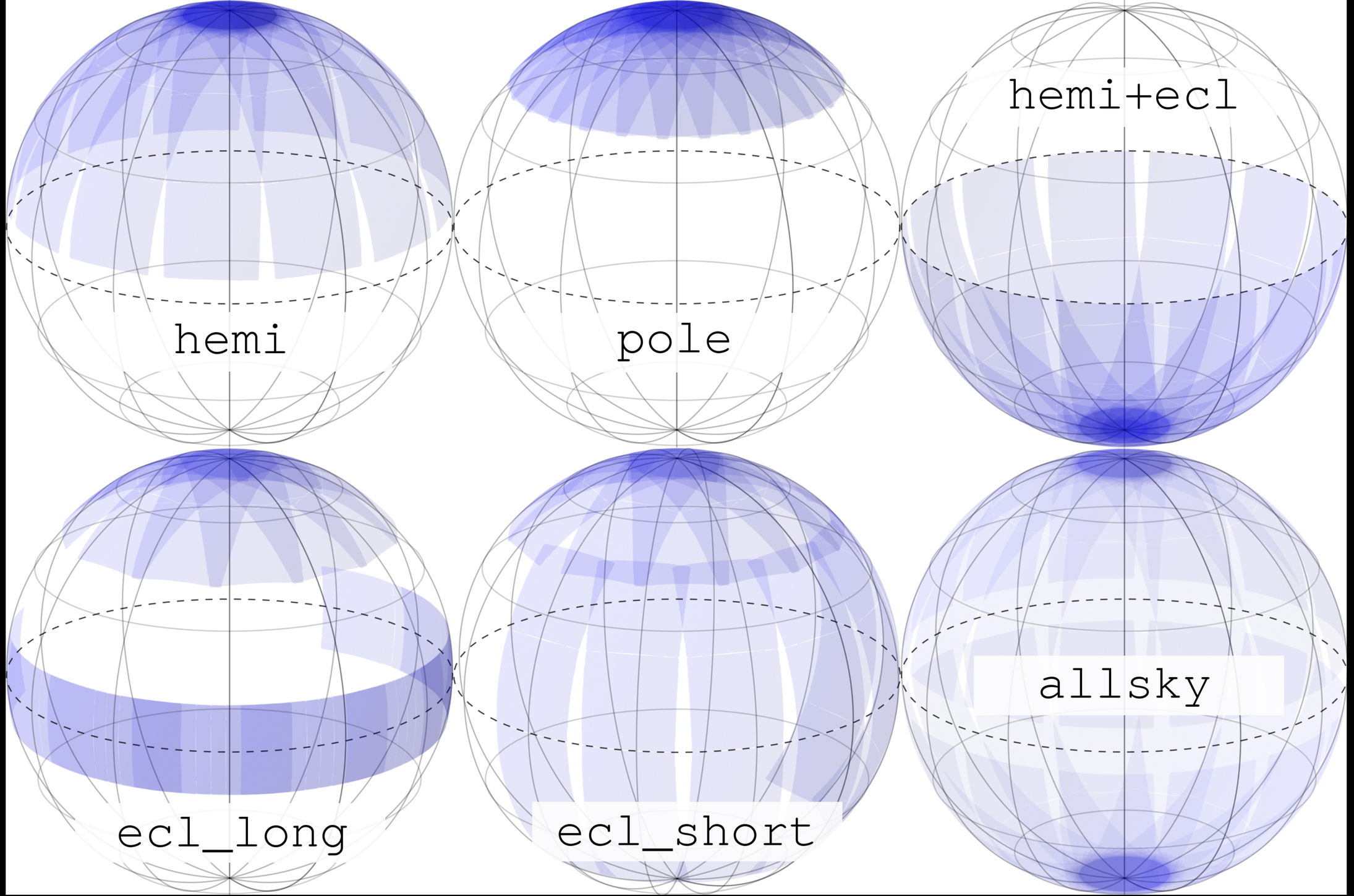
- Opportunities for exoplanets (TTVs, CBPs, …)
- Space-based followup (JWST, CHEOPS, K2, …)
- Fields outside of exoplanet science

spacebook.mit.edu/display/TESS/Considerations+for+Extended+Missions

# Proposed scenarios for Year 3



Proposed scenarios for Year 3



# We perform Monte Carlo simulations of TESS's planet detections for each scenario


Sullivan+ (2015), Bouma+ (2016)

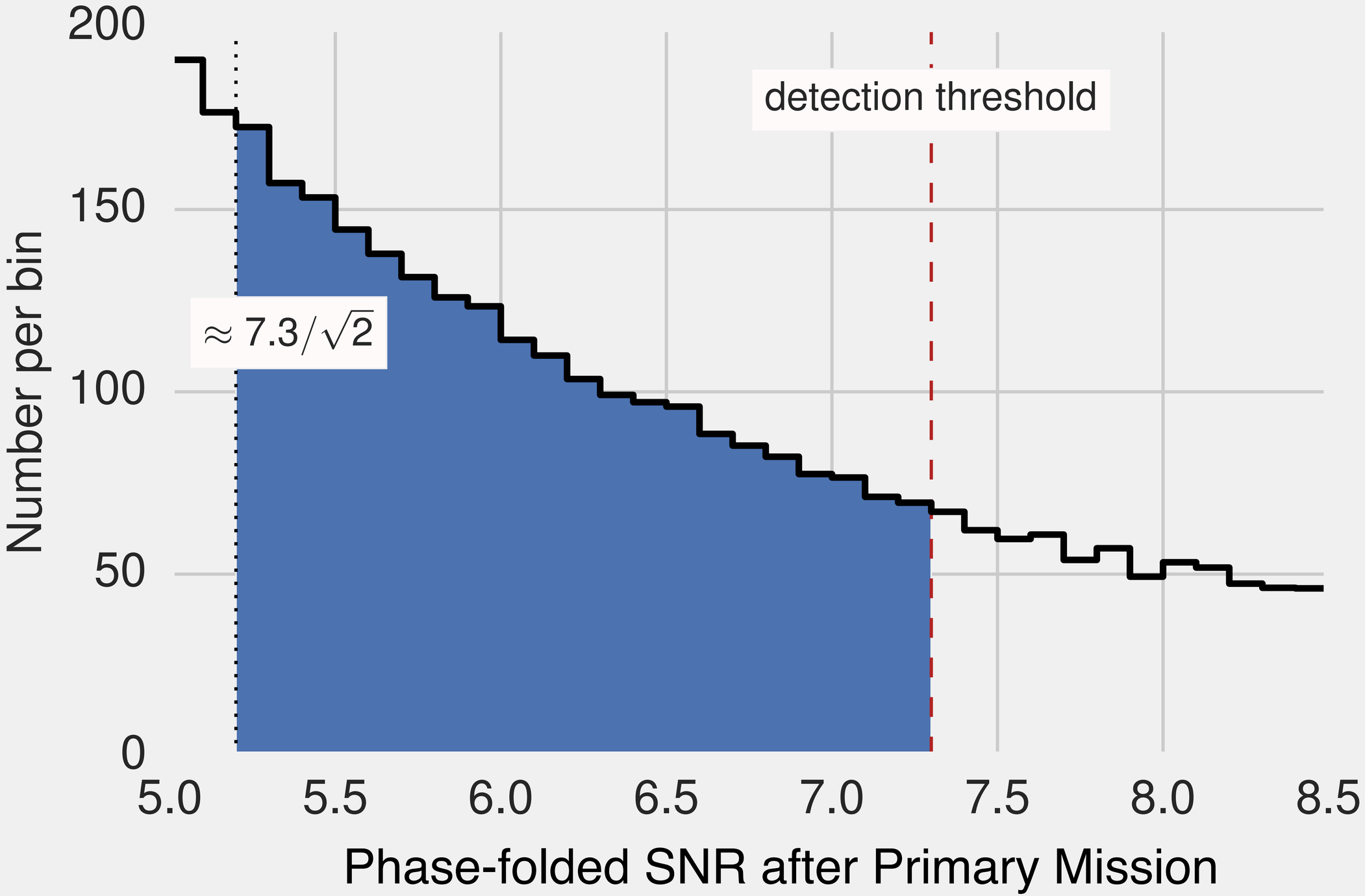
$$\mathrm{Prob(detection)} = \begin{cases} 1 & \text{if } \mathrm{SNR}_{\mathrm{phase-folded}} > 7.3 \text{ and } N_{\mathrm{tra}} \geq 2 \\ 0 & \text{otherwise,} \end{cases}$$

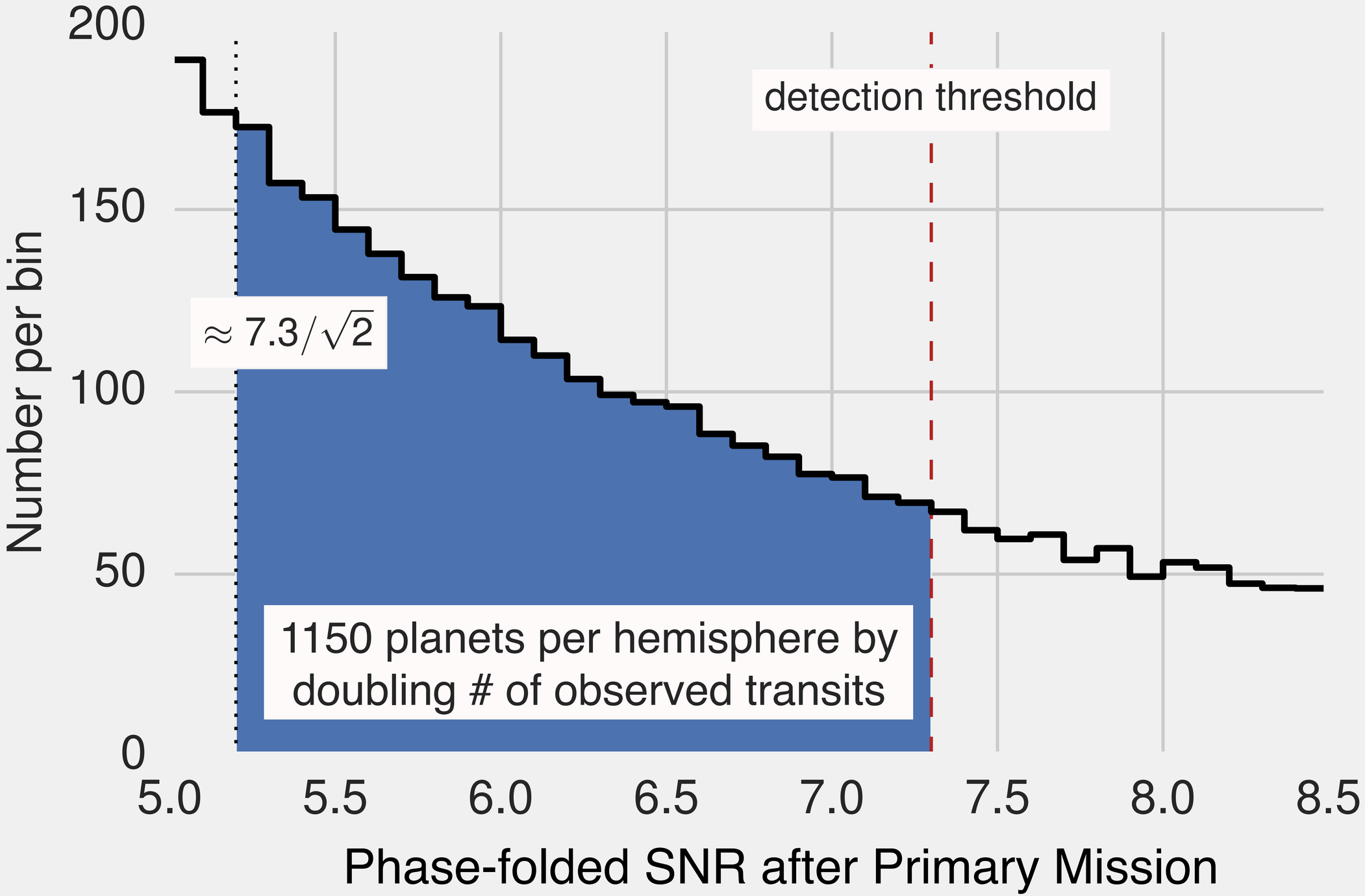
Sullivan+ (2015), Bouma+ (2016)

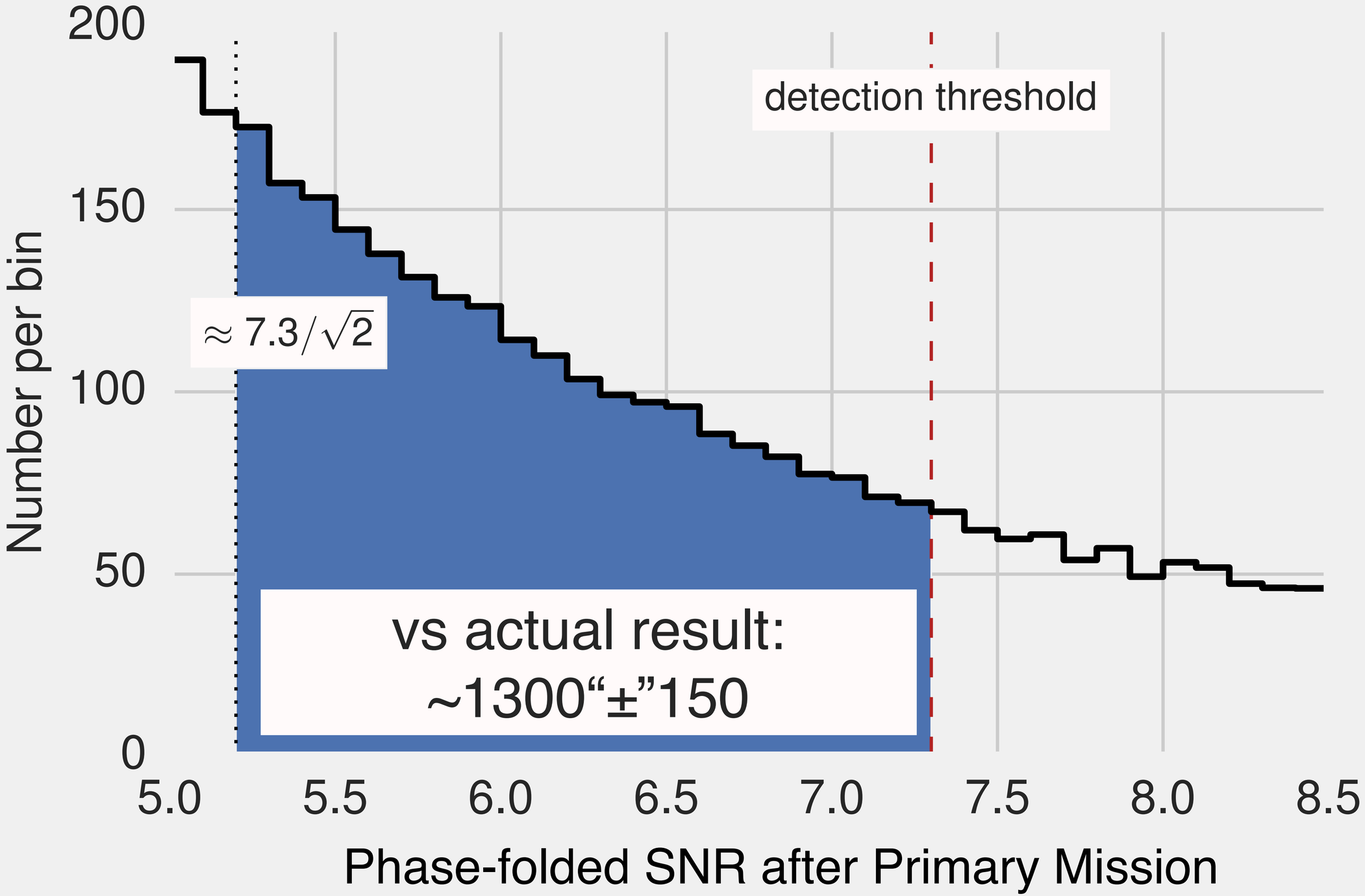
We detect ~1300“±”150 new $R_p<4R_\oplus$ planets.

We detect ~1300“±”150 new $R_p<4R_\oplus$ planets.

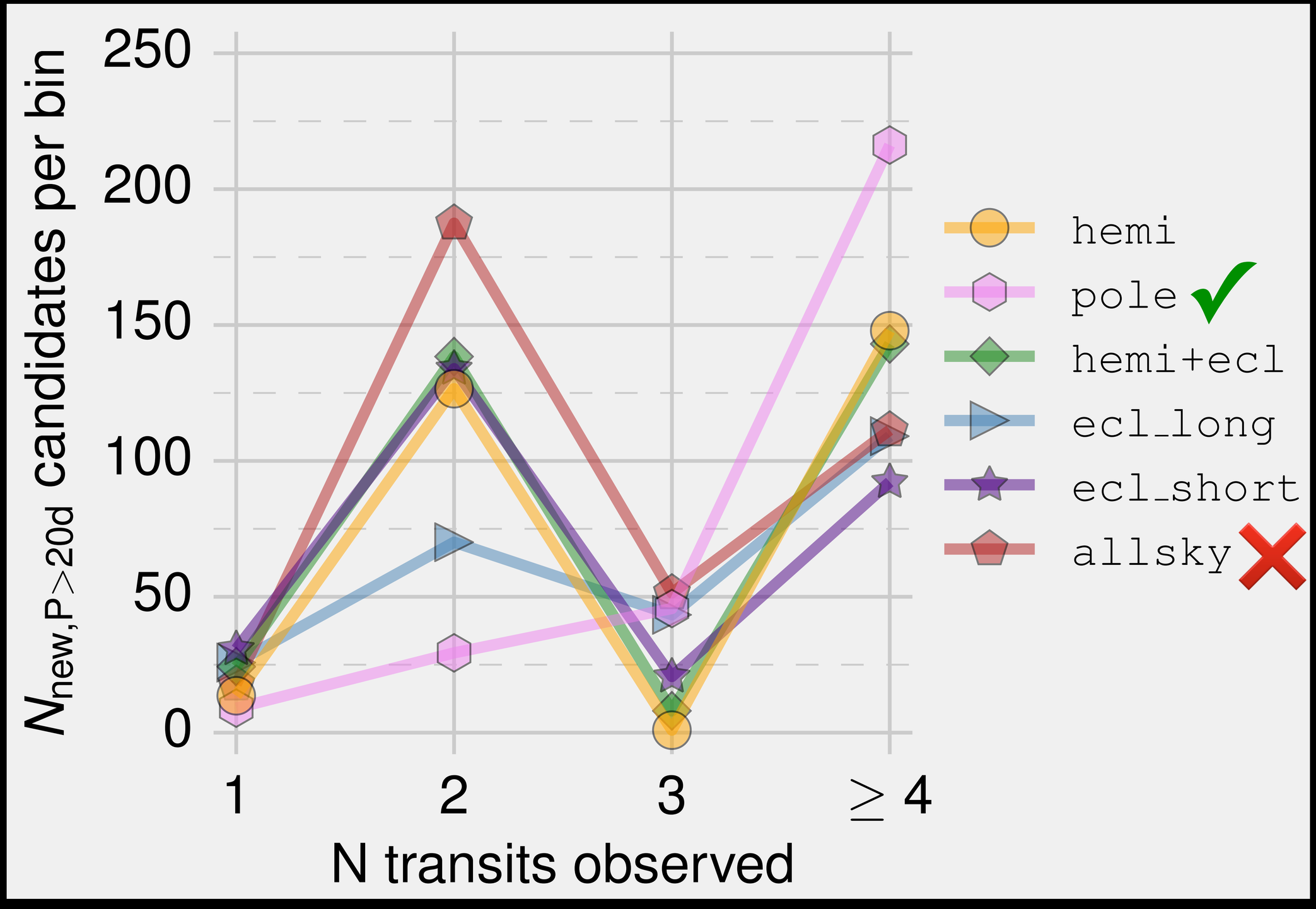
(The number of newly detected $R_p<4R_\oplus$ planets varies by at most 25% between our six scenarios).


200
150
100
50
0
Number per bin
$\approx 7.3/\sqrt{2}$
detection threshold
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
Phase-folded SNR after Primary Mission


200
150
100
50
0
Number per bin
detection threshold
$\approx 7.3/\sqrt{2}$
1150 planets per hemisphere by
doubling # of observed transits
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
Phase-folded SNR after Primary Mission


200
150
100
50
0
Number per bin
detection threshold
$\approx 7.3/\sqrt{2}$
vs actual result:
~1300“±”150
5.0
5.5
6.0
6.5
7.0
7.5
8.0
8.5
Phase-folded SNR after Primary Mission

| **Combined** | hemi | pole | hemi+ecl | ecl_long | ecl_short | allsky |
|---|---|---|---|---|---|---|
| $N_{uniq}$ | 3767 | 3901 | 3831 | 3672 | 3701 | 3907 |
| $N_{new}$ | 1284 | 1419 | 1355 | 1169 | 1216 | 1433 |
| $N_{pri}$ | 2483 | 2482 | 2476 | 2504 | 2485 | 2474 |
| $N_{new,P>20d}$ | | | ~250-300 per year | | (≥ 2 transits) | |
| $N_{pri,P>20d}$ | | | ~150 per year | | | |
| $N_{new,HZ}$ | 122 | 124 | 122 | 107 | 120 | 146 |
| $N_{pri,HZ}$ | 205 | 210 | 212 | 217 | 210 | 208 |
| $N_{sys,extra\ planets}$ | 71 | 65 | 70 | 44 | 61 | 92 |
| $N_{new,atm}$ | 14 | 8 | 19 | 21 | 23 | 22 |
| $N_{pri,atm}$ | 104 | 108 | 108 | 106 | 112 | 104 |
| $N_{new,new\ stars}$ | 63 | 92 | 114 | 366 | 171 | 42 |
| $N_{new,SNR\vee N_{tra}}$ | 1220 | 1327 | 1241 | 803 | 1045 | 1390 |


250
200
150
100
50
0
$N_{new,P>20d}$ candidates per bin
1
2
3
≥ 4
N transits observed
hemi
pole
hemi+ecl
ecl_long
ecl_short
allsky

| **Combined** | hemi | pole | hemi+ecl | ecl_long | ecl_short | allsky |
|---|---|---|---|---|---|---|
| $N_{uniq}$ | 3767 | 3901 | 3831 | 3672 | 3701 | 3907 |
| $N_{new}$ | 1284 | 1419 | 1355 | 1169 | 1216 | 1433 |
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| $N_{new,SNR\vee N_{tra}}$ | 1220 | 1327 | 1241 | 803 | 1045 | 1390 |

| **Combined** | hemi | pole | hemi+ecl | ecl_long | ecl_short | allsky |
|---|---|---|---|---|---|---|
| $N_{uniq}$ | 3767 | 3901 | 3831 | 3672 | 3701 | 3907 |
| $N_{new}$ | 1284 | 1419 | 1355 | 1169 | 1216 | 1433 |
| $N_{pri}$ | 2483 | 2482 | 2476 | 2504 | 2485 | 2474 |
| $N_{new,P>20d}$ | | | ~110-250 per year | | (≥ 3 transits) | |
| $N_{pri,P>20d}$ | | | ~110 per year | | | |
| $N_{new,HZ}$ | 122 | 124 | 122 | 107 | 120 | 146 |
| $N_{pri,HZ}$ | 205 | 210 | 212 | 217 | 210 | 208 |
| $N_{sys,extra\ planets}$ | 71 | 65 | 70 | 44 | 61 | 92 |
| $N_{new,atm}$ | 14 | 8 | 19 | 21 | 23 | 22 |
| $N_{pri,atm}$ | 104 | 108 | 108 | 106 | 112 | 104 |
| $N_{new,new\ stars}$ | 63 | 92 | 114 | 366 | 171 | 42 |
| $N_{new,SNR\sqrt{N_{tra}}}$ | 1220 | 1327 | 1241 | 803 | 1045 | 1390 |

| **Combined** | hemi | pole | hemi+ecl | ecl_long | ecl_short | allsky |
|---|---|---|---|---|---|---|
| $N_{uniq}$ | 3767 | 3901 | 3831 | 3672 | 3701 | 3907 |
| $N_{new}$ | 1284 | 1419 | 1355 | 1169 | 1216 | 1433 |
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| $N_{new,P>20d}$ | 253 | 275 | 248 | 207 | 218 | 304 |
| $N_{pri,P>20d}$ | 294 | 292 | 295 | 296 | 298 | 296 |
| $N_{new,HZ}$ | | | ~110 per year | | | |
| $N_{pri,HZ}$ | | | ~100 per year | | | |
| $N_{sys,extra\ planets}$ | 71 | 65 | 70 | 44 | 61 | 92 |
| $N_{new,atm}$ | 14 | 8 | 19 | 21 | 23 | 22 |
| $N_{pri,atm}$ | 104 | 108 | 108 | 106 | 112 | 104 |
| $N_{new,new\ stars}$ | 63 | 92 | 114 | 366 | 171 | 42 |
| $N_{new,SNR \vee N_{tra}}$ | 1220 | 1327 | 1241 | 803 | 1045 | 1390 |

Beyond the quantitative metrics,
**what are the important qualitative differences?**

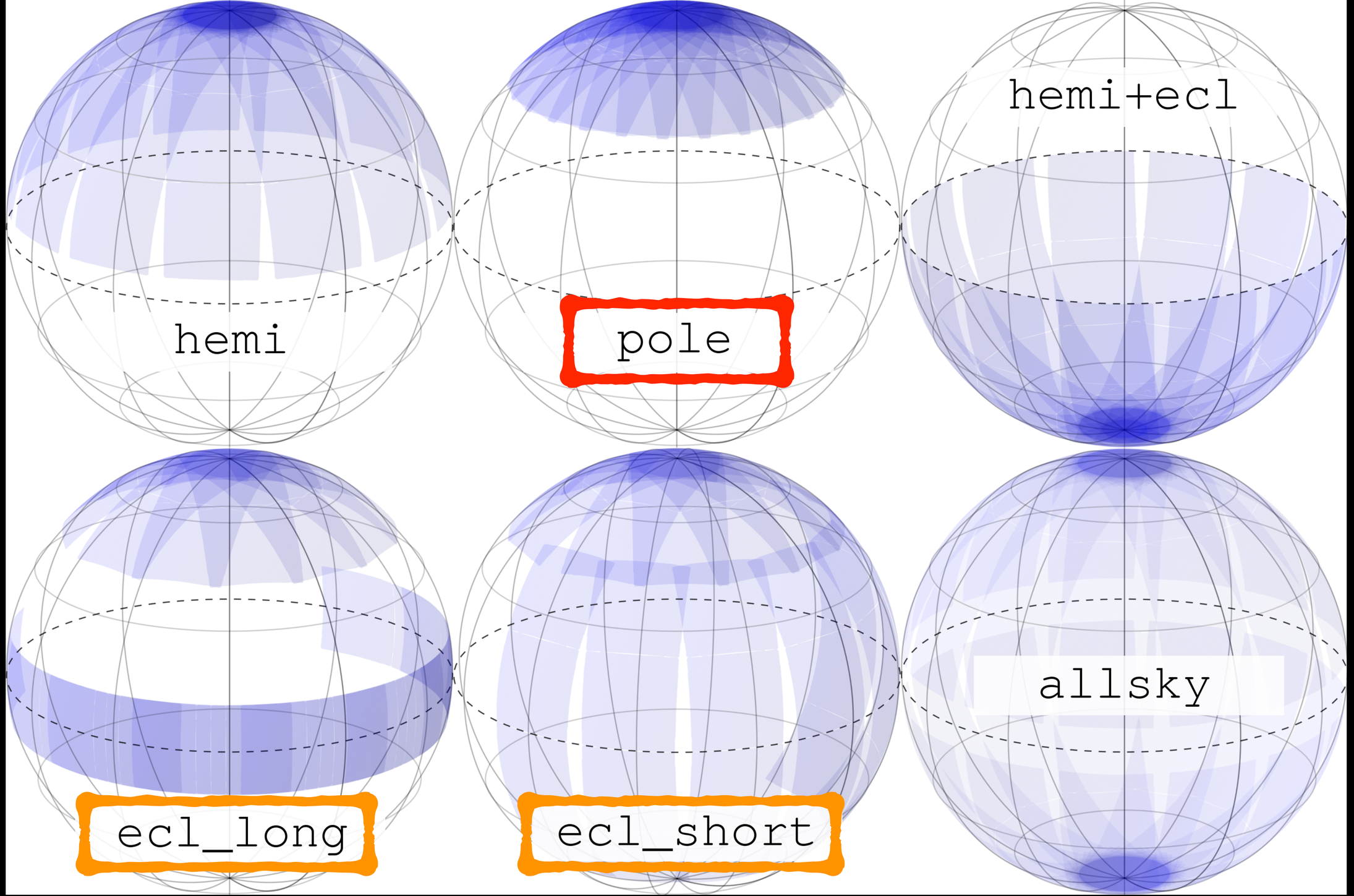
Qualitative differences include:

- mitigating scattered light
- continuing in years 4-*N*
- improving ephemerides

Qualitative differences include:

- **mitigating scattered light**
  - continuing in years 4-*N*
  - improving ephemerides

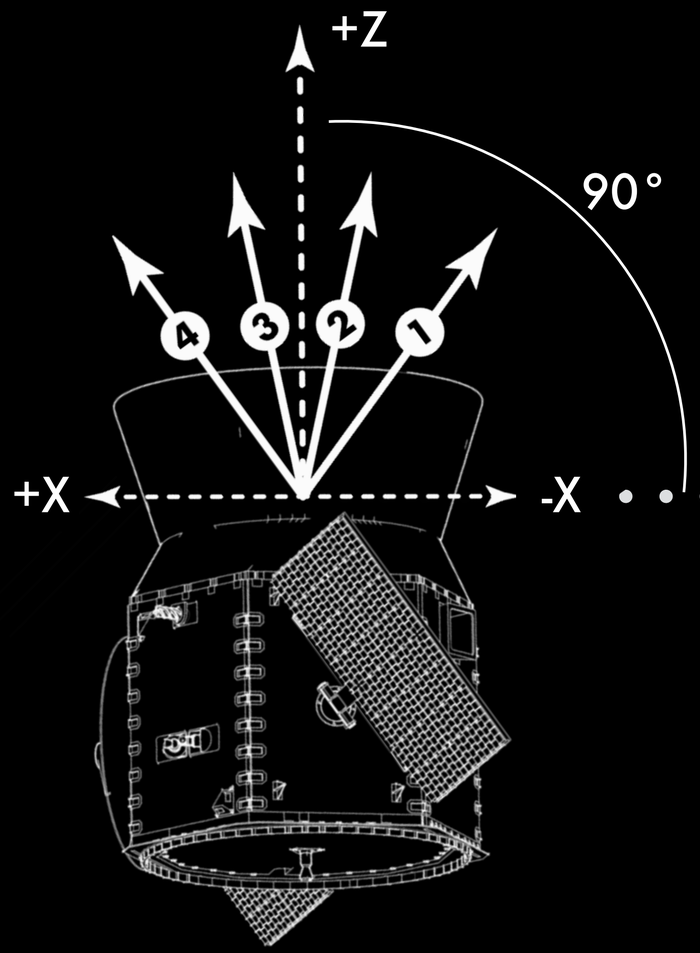
Proposed scenarios for Year 3



*adapted from Orbital ATK design document*

Incoming sunlight

Ecliptic pole



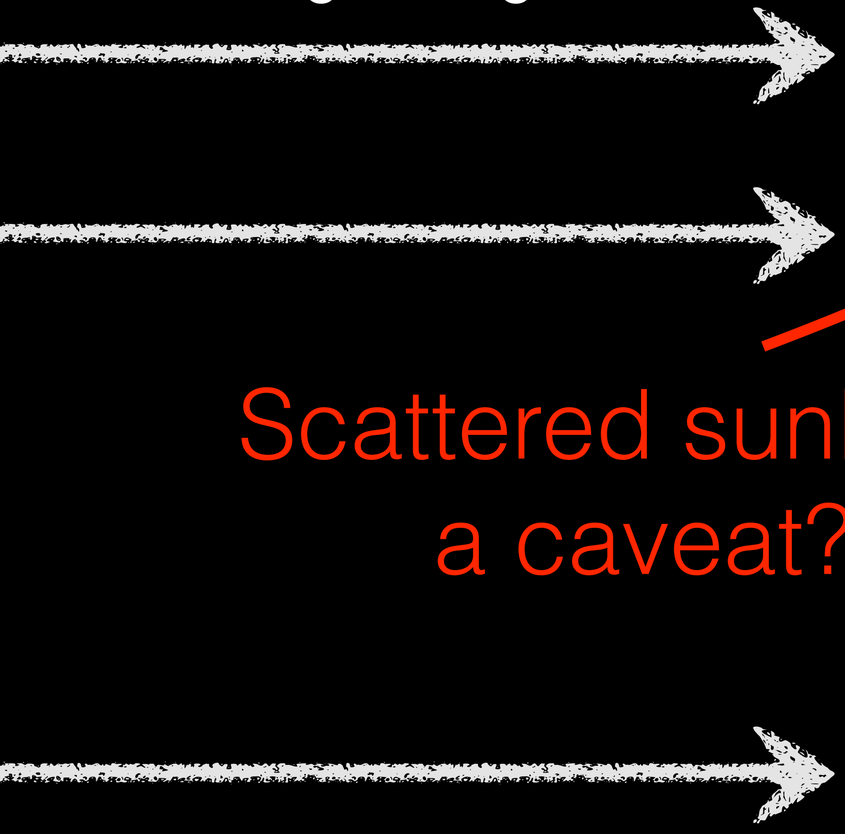

Ecliptic plane

Year 3 of Extended Mission

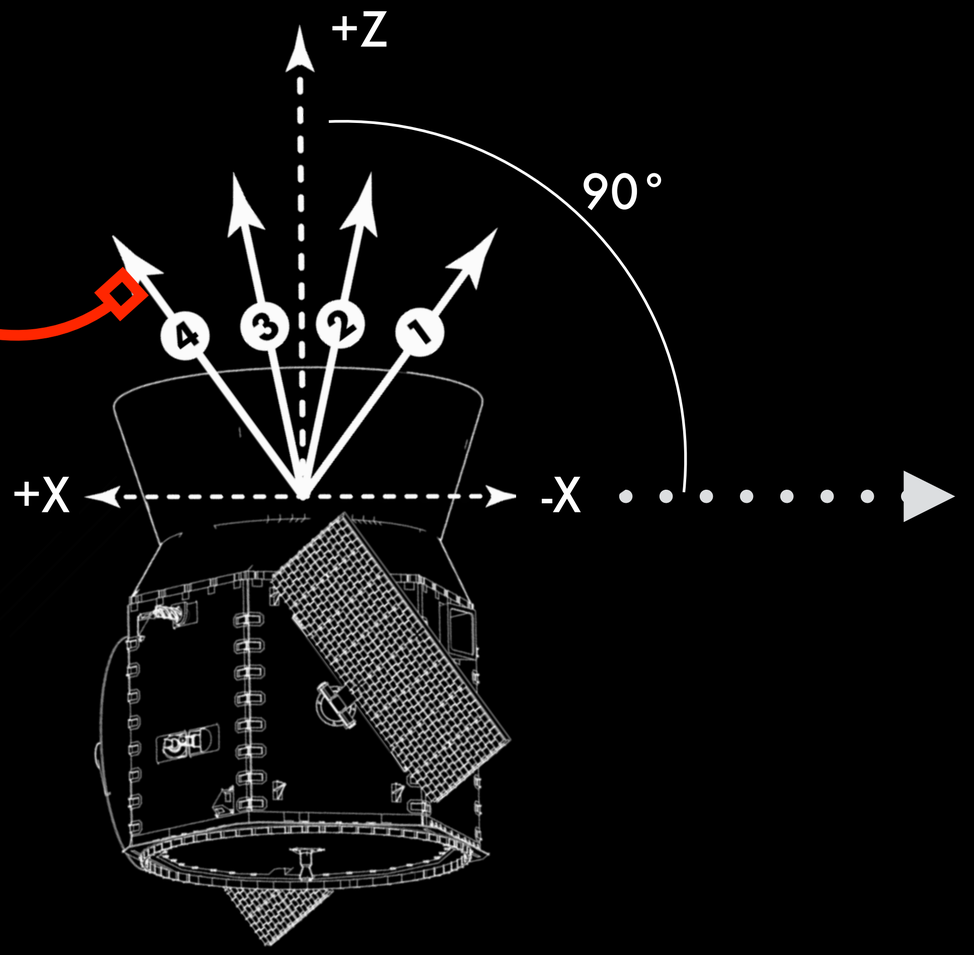
*adapted from Orbital ATK design document*

Ecliptic pole

Incoming sunlight



Scattered sunlight:
a caveat?



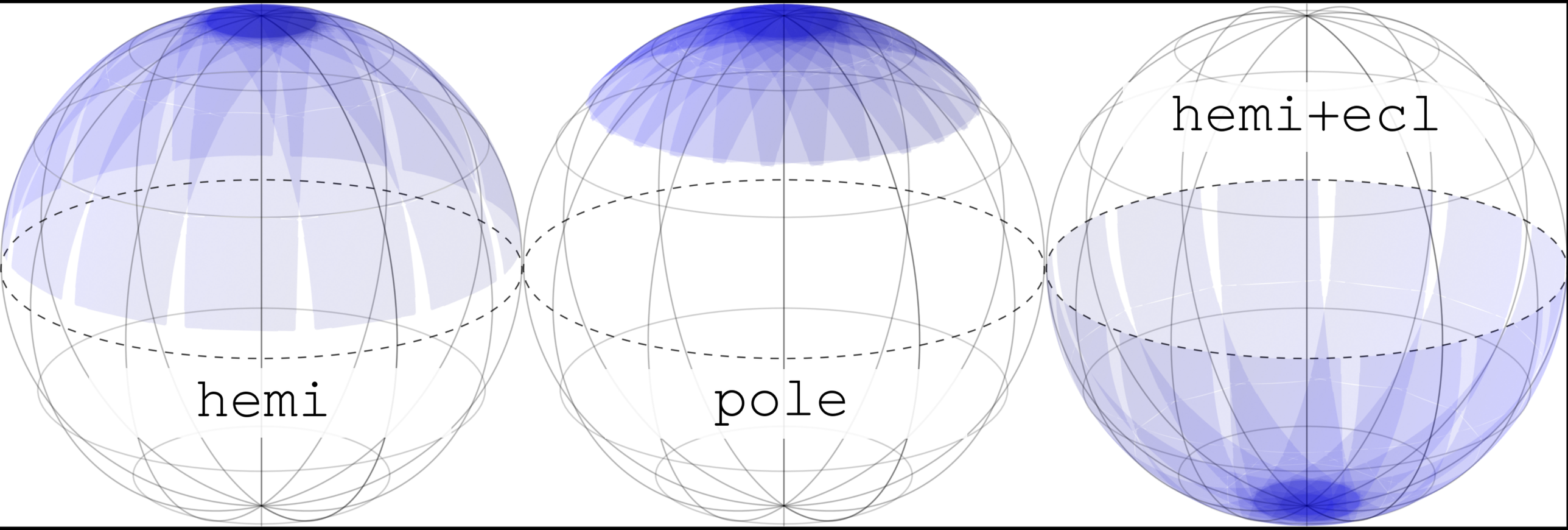

Ecliptic plane

Year 3 of Extended Mission

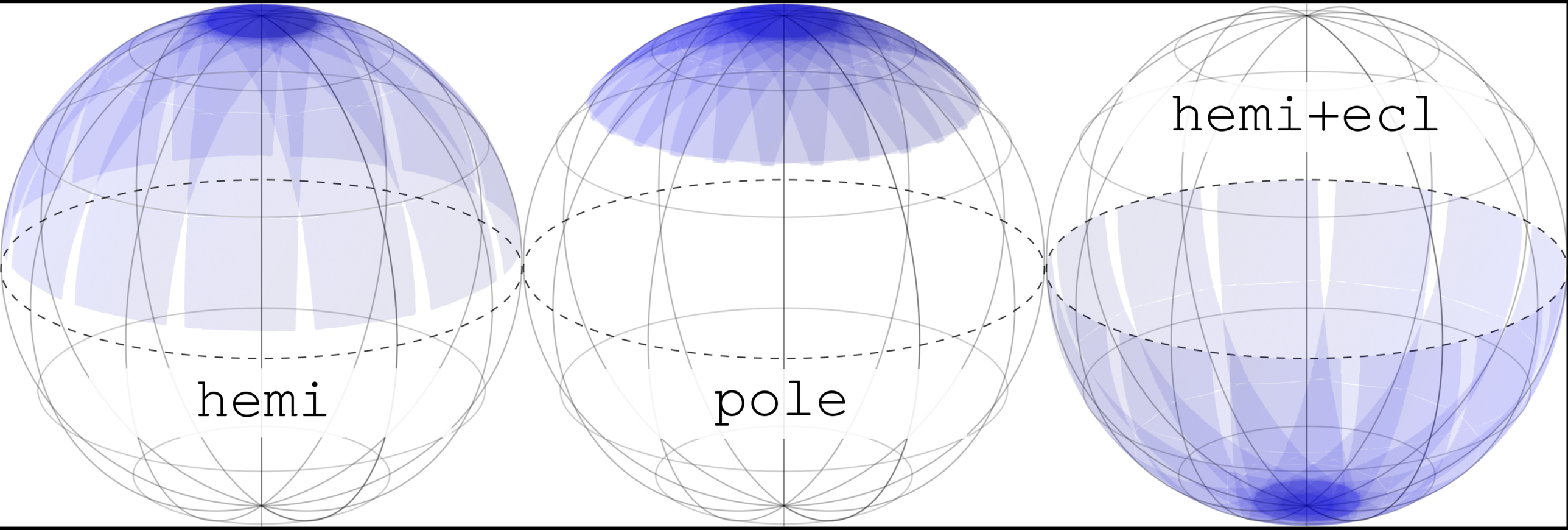
Qualitative differences include:

- mitigating scattered light
- **continuing in years 4-*N***
- improving ephemerides

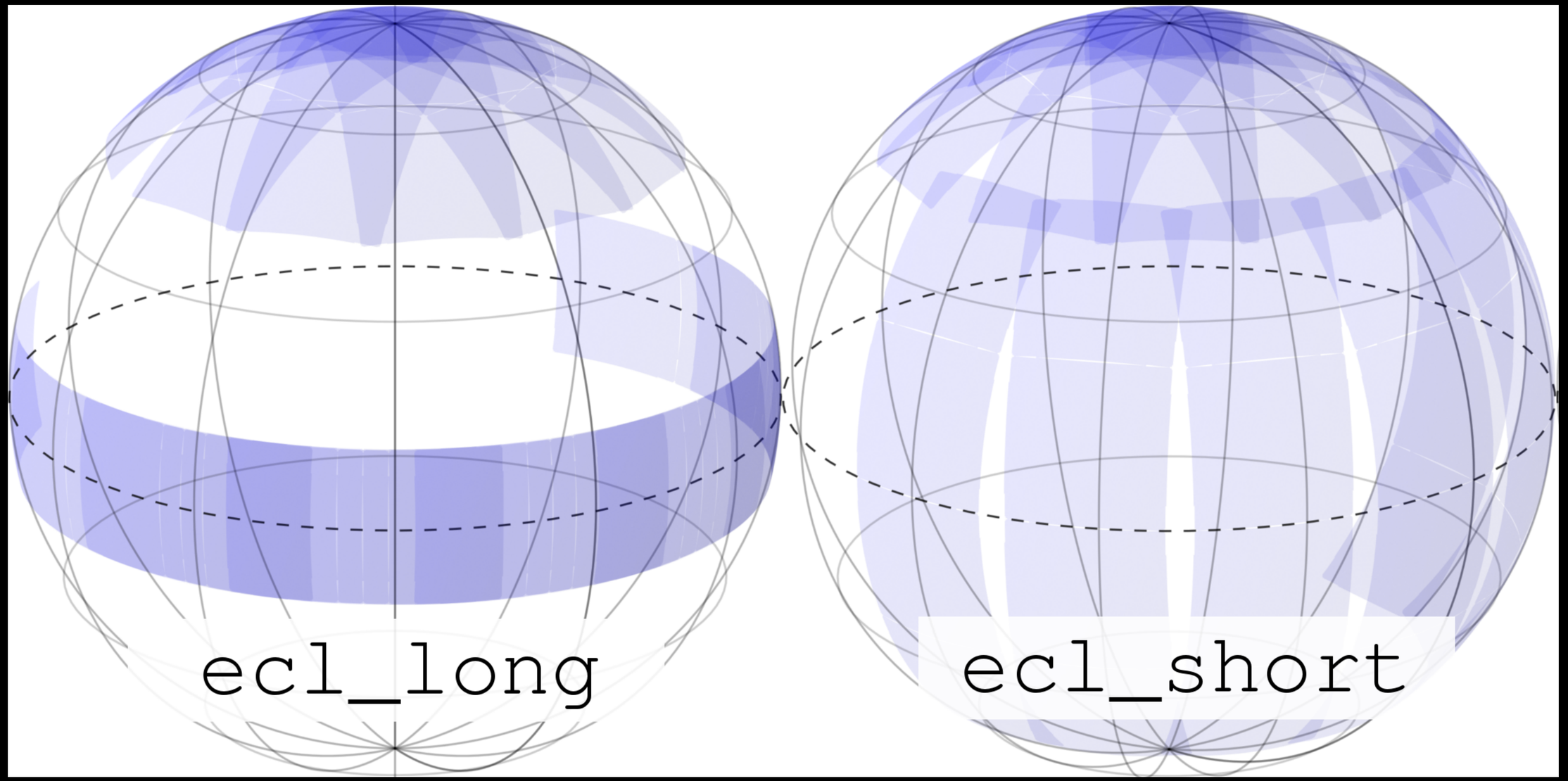
# These scenarios can be extended by observing the opposite hemisphere during Year 4



# These scenarios can be extended by observing the opposite hemisphere during Year 4

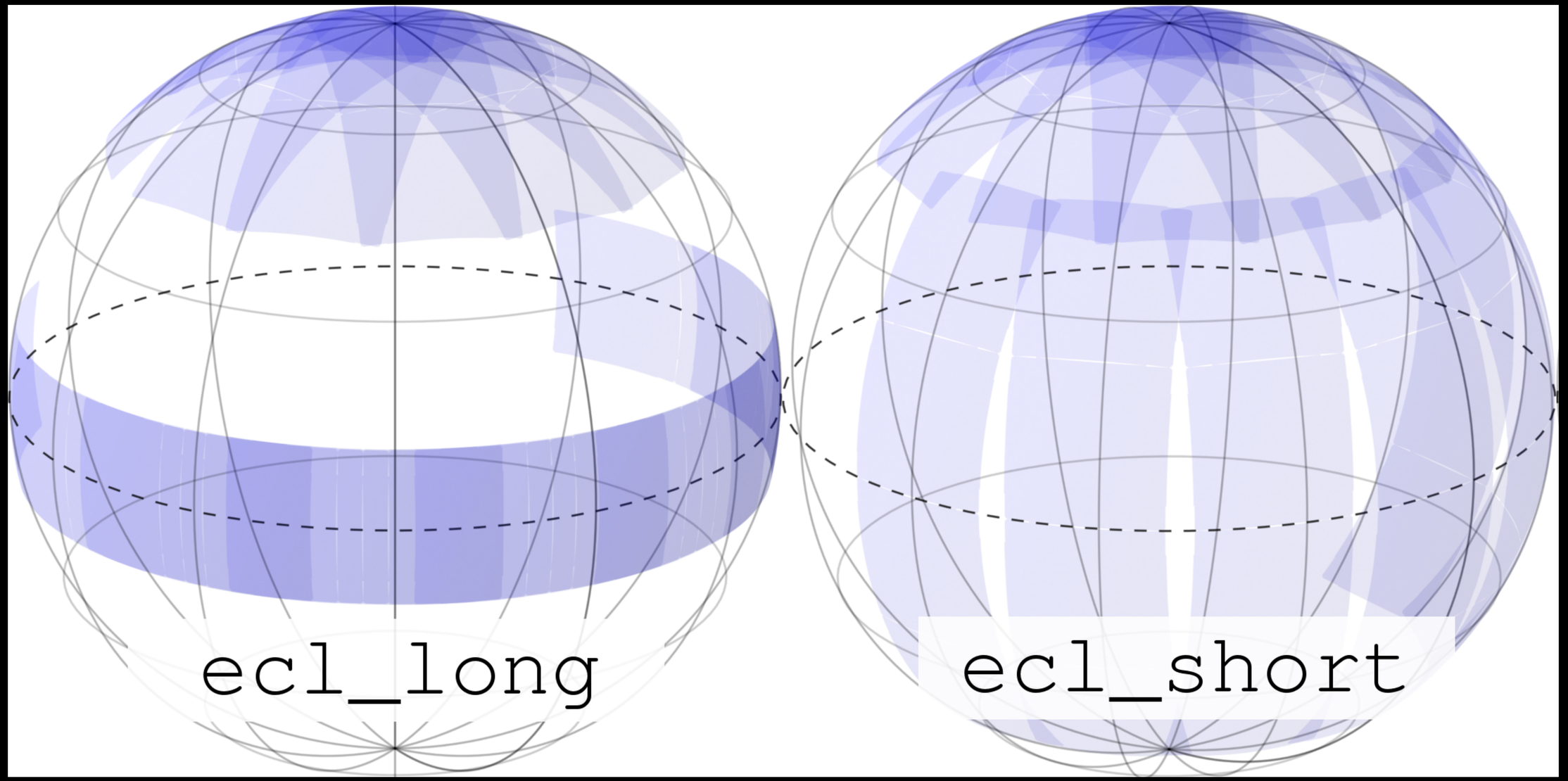


# These scenarios “extend” easily only if Moon & Earth are in right locations

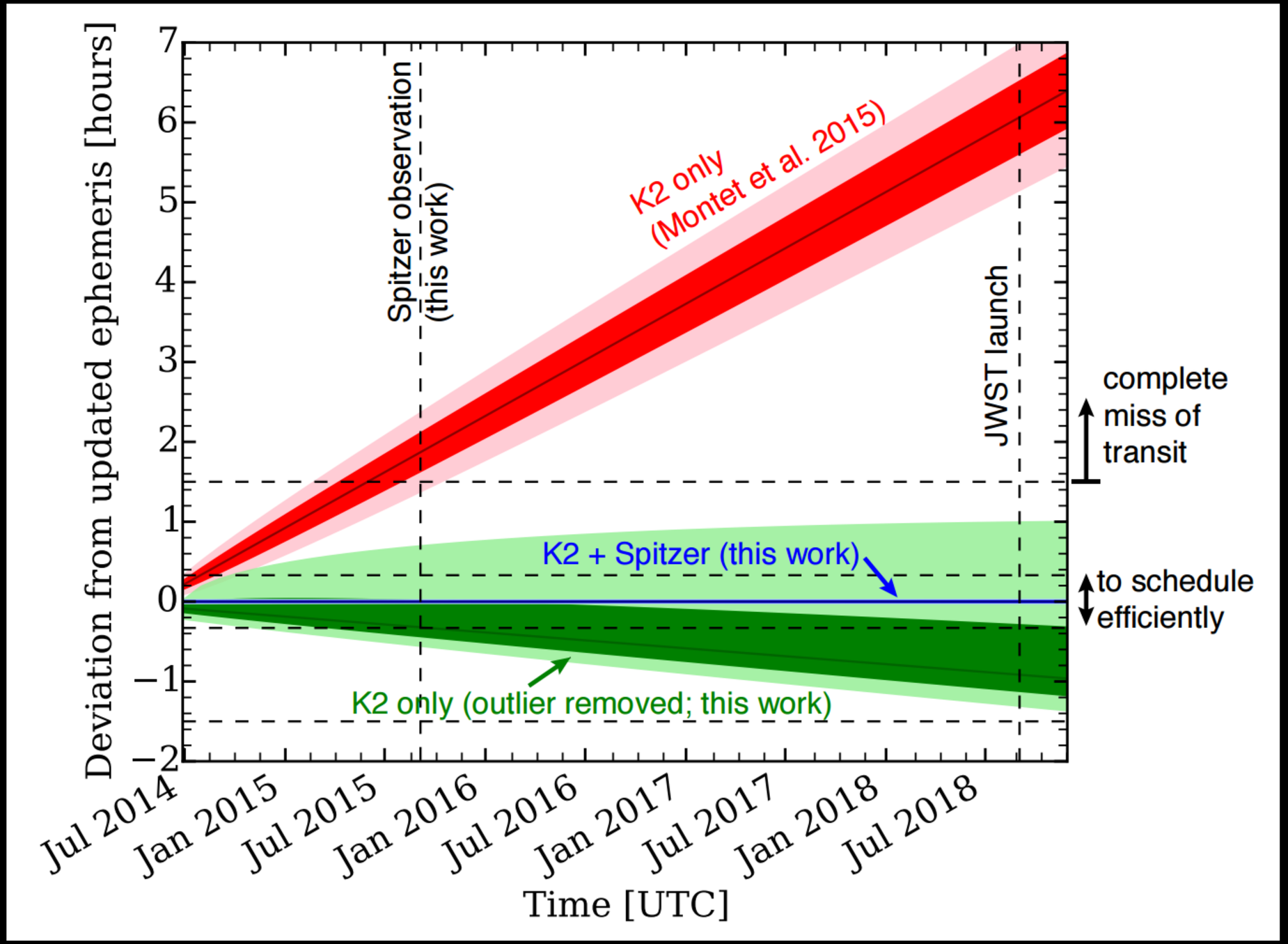


# These scenarios “extend” easily only if Moon & Earth are in right locations

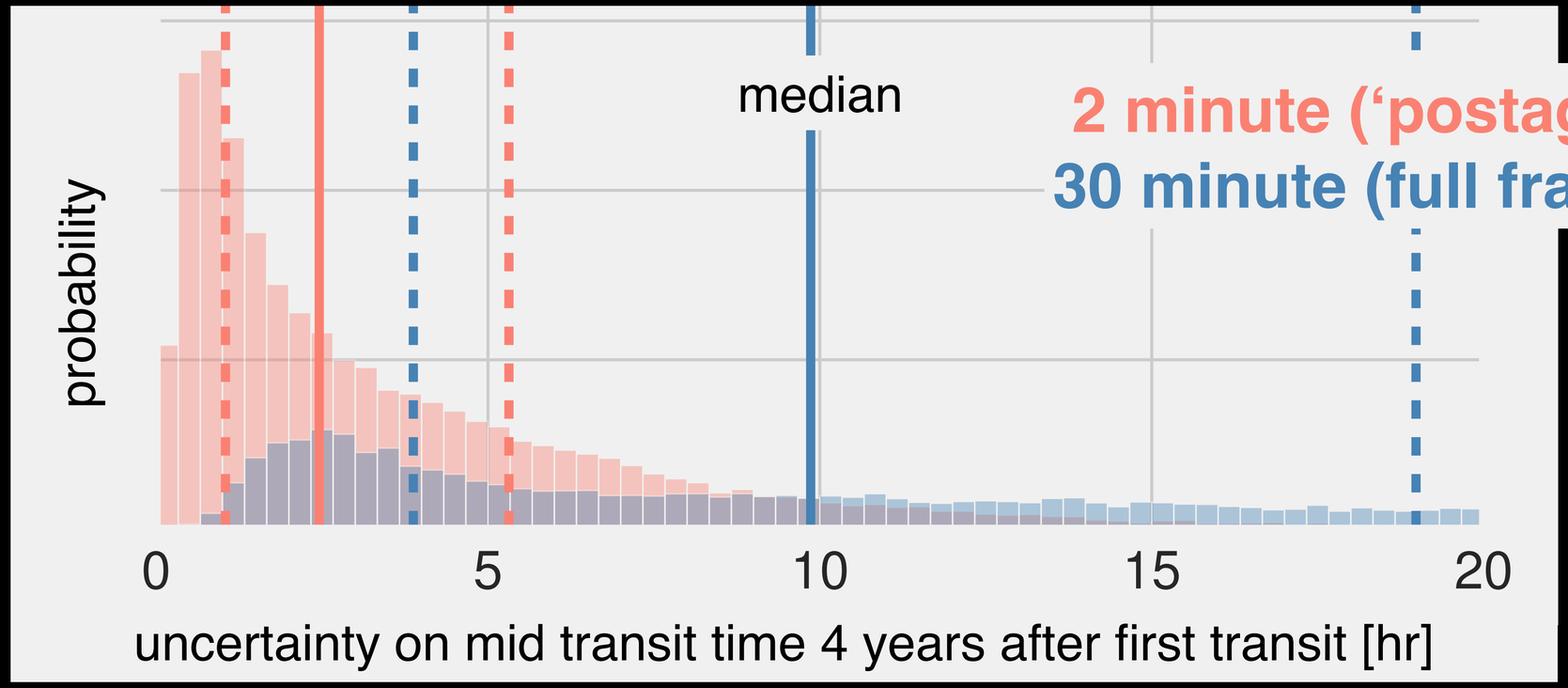
?

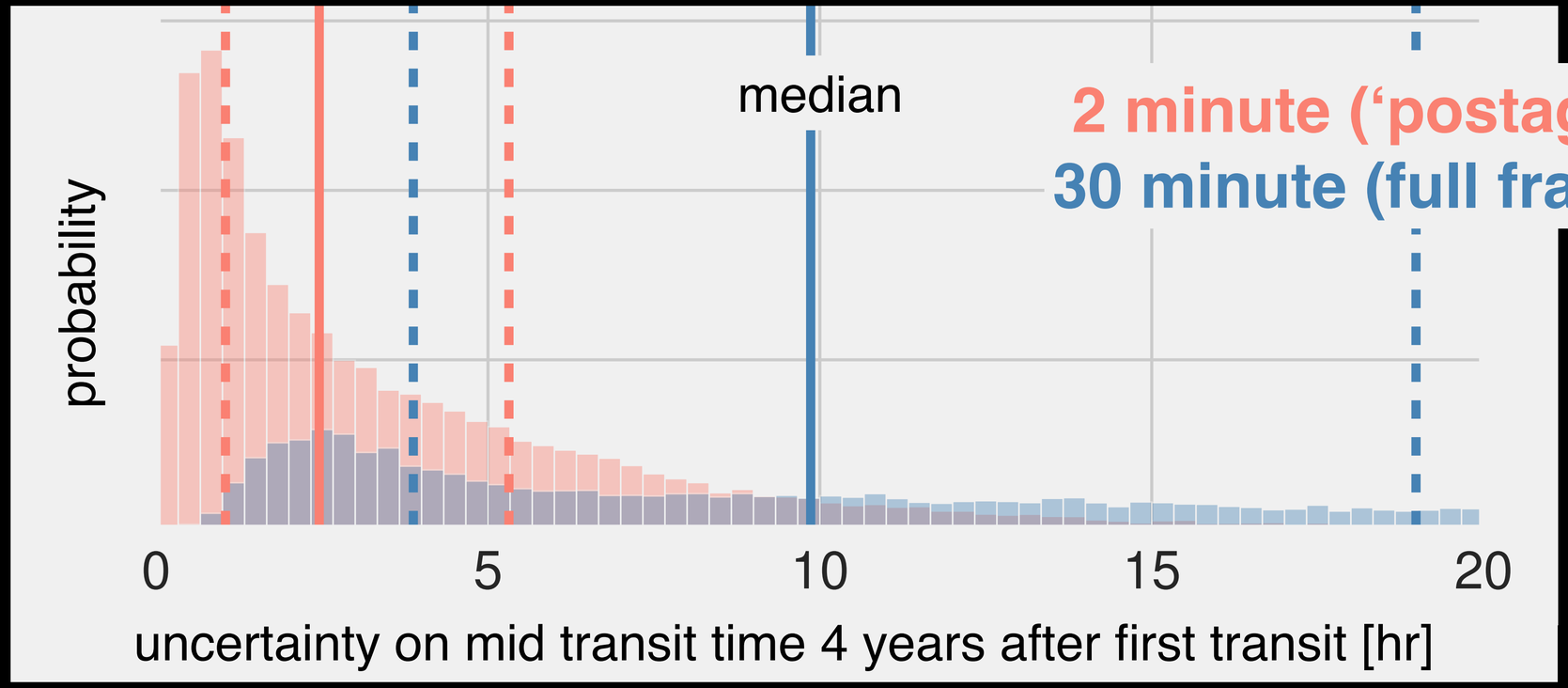


We want to avoid the stale ephemeris problem

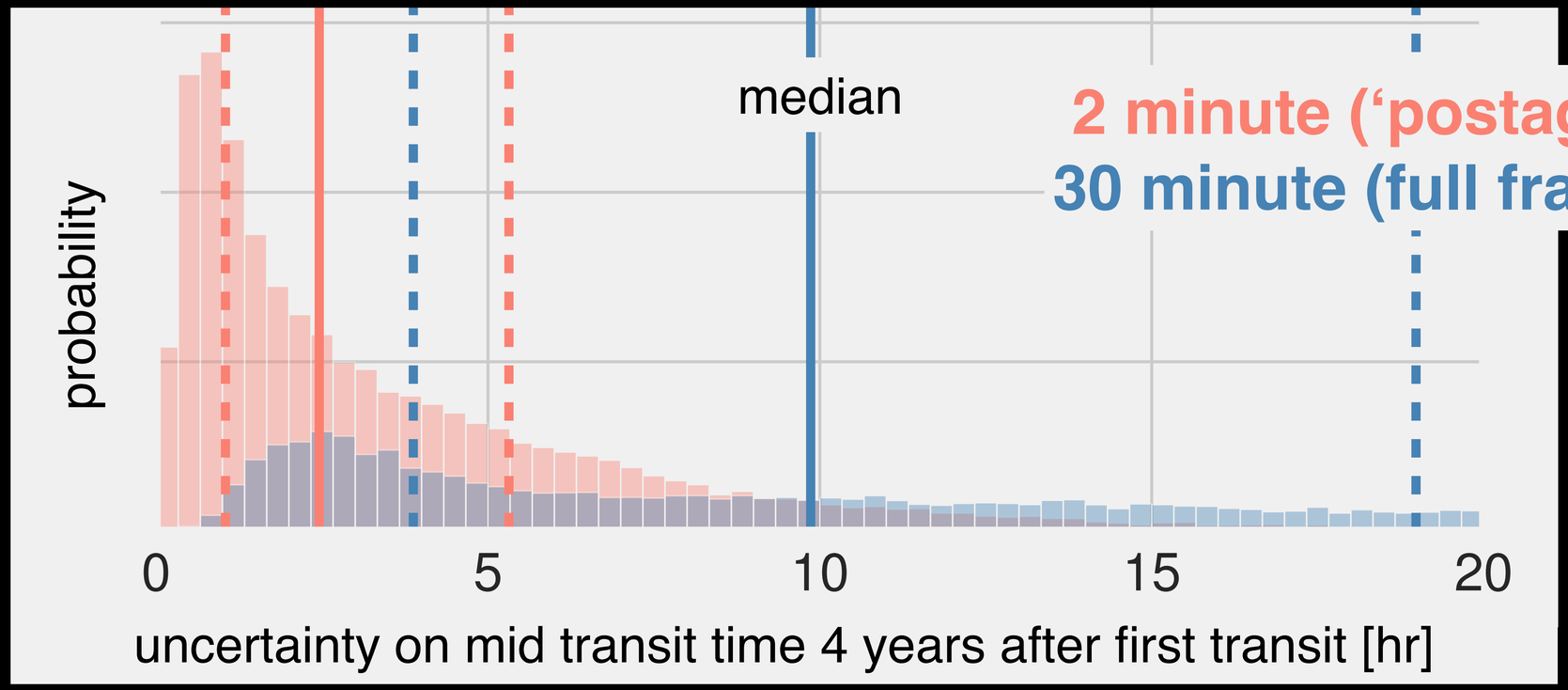



Benneke+ 2016 (K2 18b)

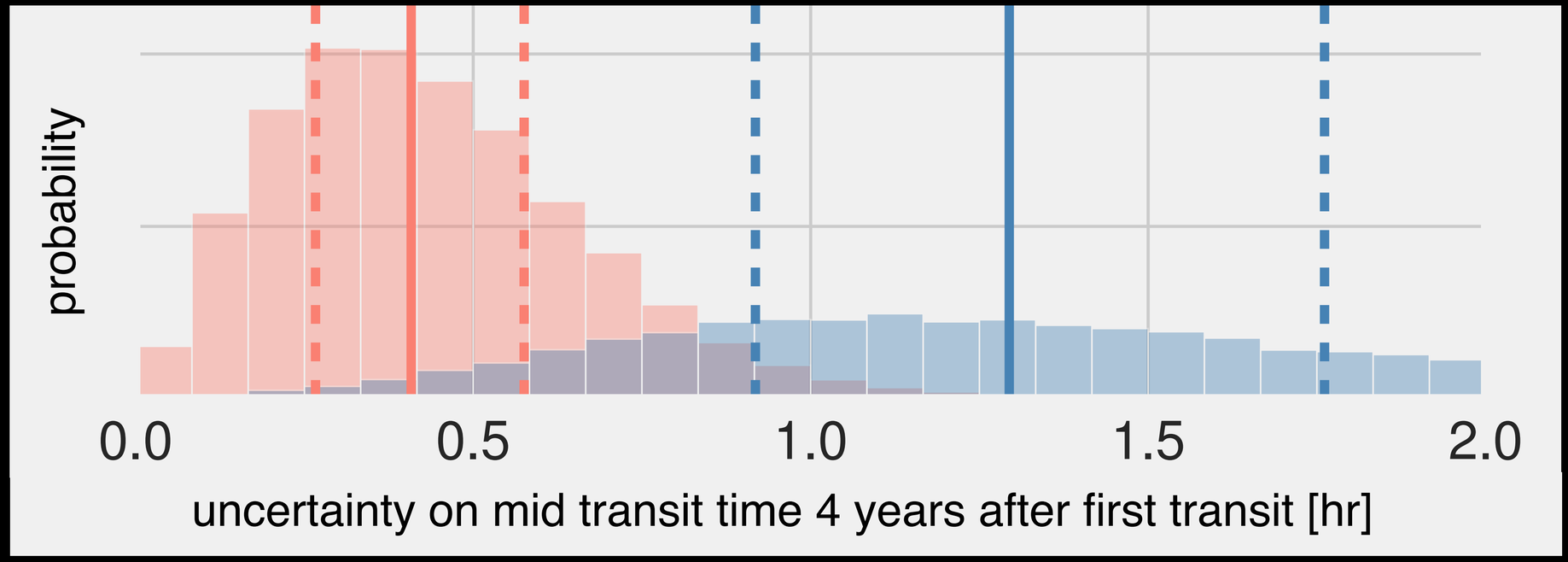

median
2 minute (‘postage stamp’)
30 minute (full frame image)
probability
0
5
10
15
20
uncertainty on mid transit time 4 years after first transit [hr]

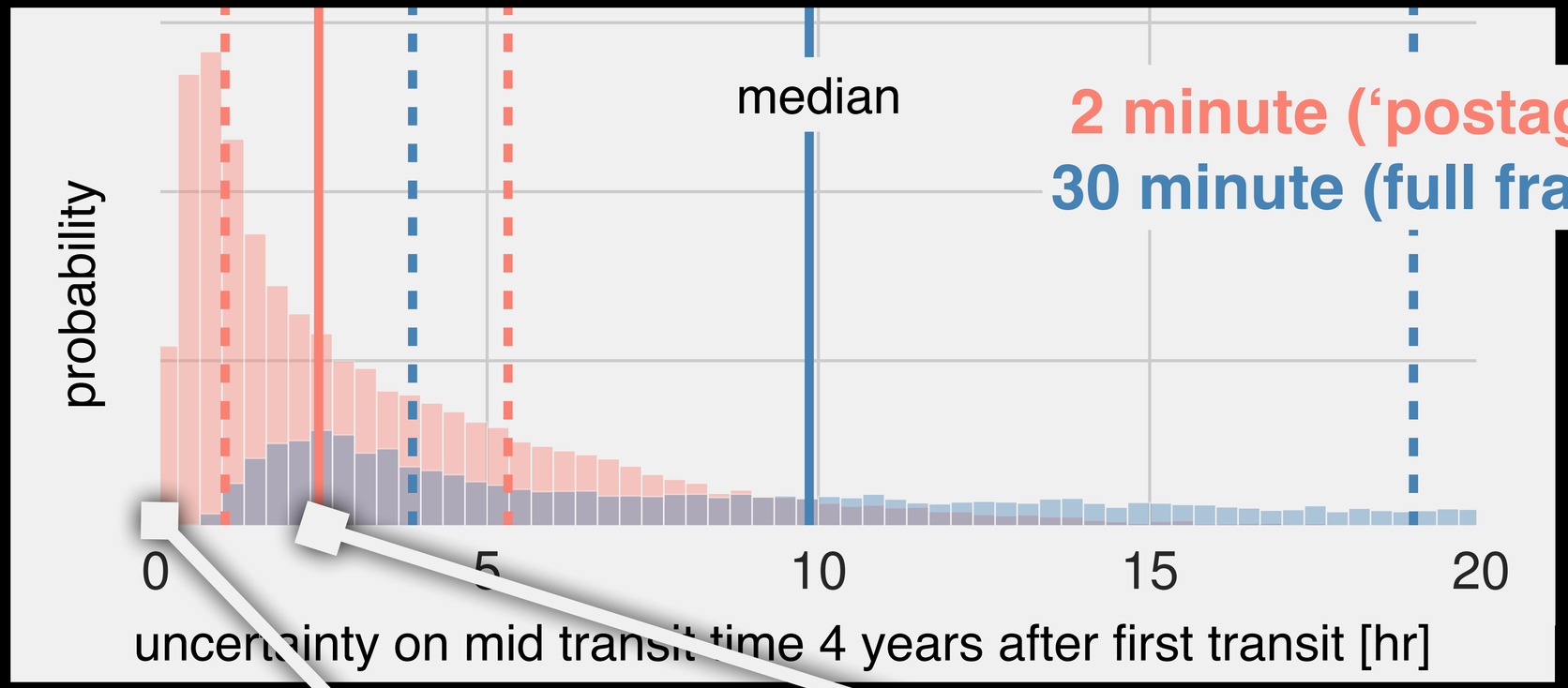



one extra transit,
one year later

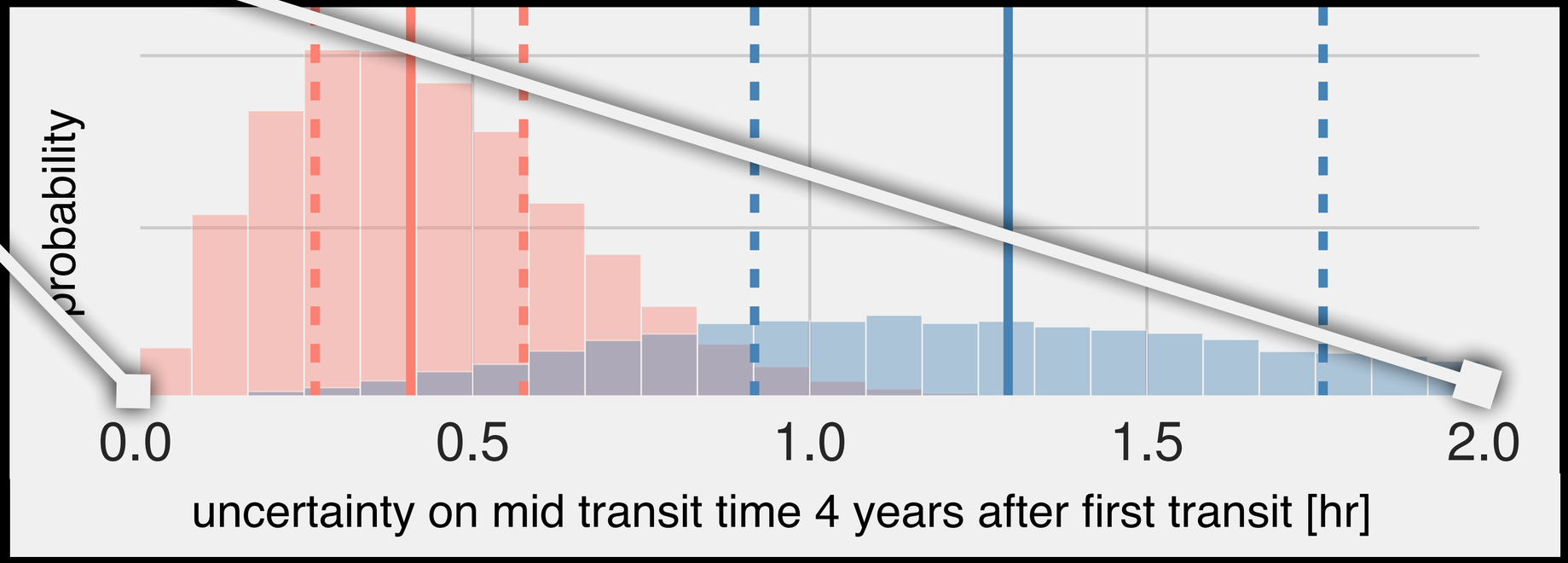



one extra transit,
one year later






one extra transit,
one year later



1. Please read and comment on our Extended Mission white paper

2. There are quantitative differences between the scenarios. However, qualitative differences could be more important. (Mitigating scattered light, being extensible, improving ephemerides)

# bonus slides

Analyze target prioritization problem

Figure out false alarm + astrophysical false positive rates

Optimize cadence

Take steps to address ‘upgrading cadence’ problem

GI Office / TSO: solicit advice for Extended Missions

Decide on weights between qua[nt](l)itative metrics

Simulate combining TESS & K2 for `ecl_long` & `ecl_short`

Quantify `pole`’s tradeoff between scattered light & incident solar flux

| hemi | pole | hemi+ecl | ecl_long | ecl_short | allsky |
|---|---|---|---|---|---|
| 162 | 154 | 188 | 167 | 183 | 198 |

Table 2: Number of new, $I_c < 10$, $R_p < 4R_\oplus$ planets from each Extended Mission (average of 50 Monte Carlo realizations of our code; showing sum of PSs & FFIs). `pole` detects the fewest new planets orbiting bright stars.

Primary Mission:
~195 per year

| **Combined** | hemi | pole | hemi+ecl | ecl_long | ecl_short | allsky |
|---|---|---|---|---|---|---|
| $N_{uniq}$ | 3767 | 3901 | 3831 | 3672 | 3701 | 3907 |
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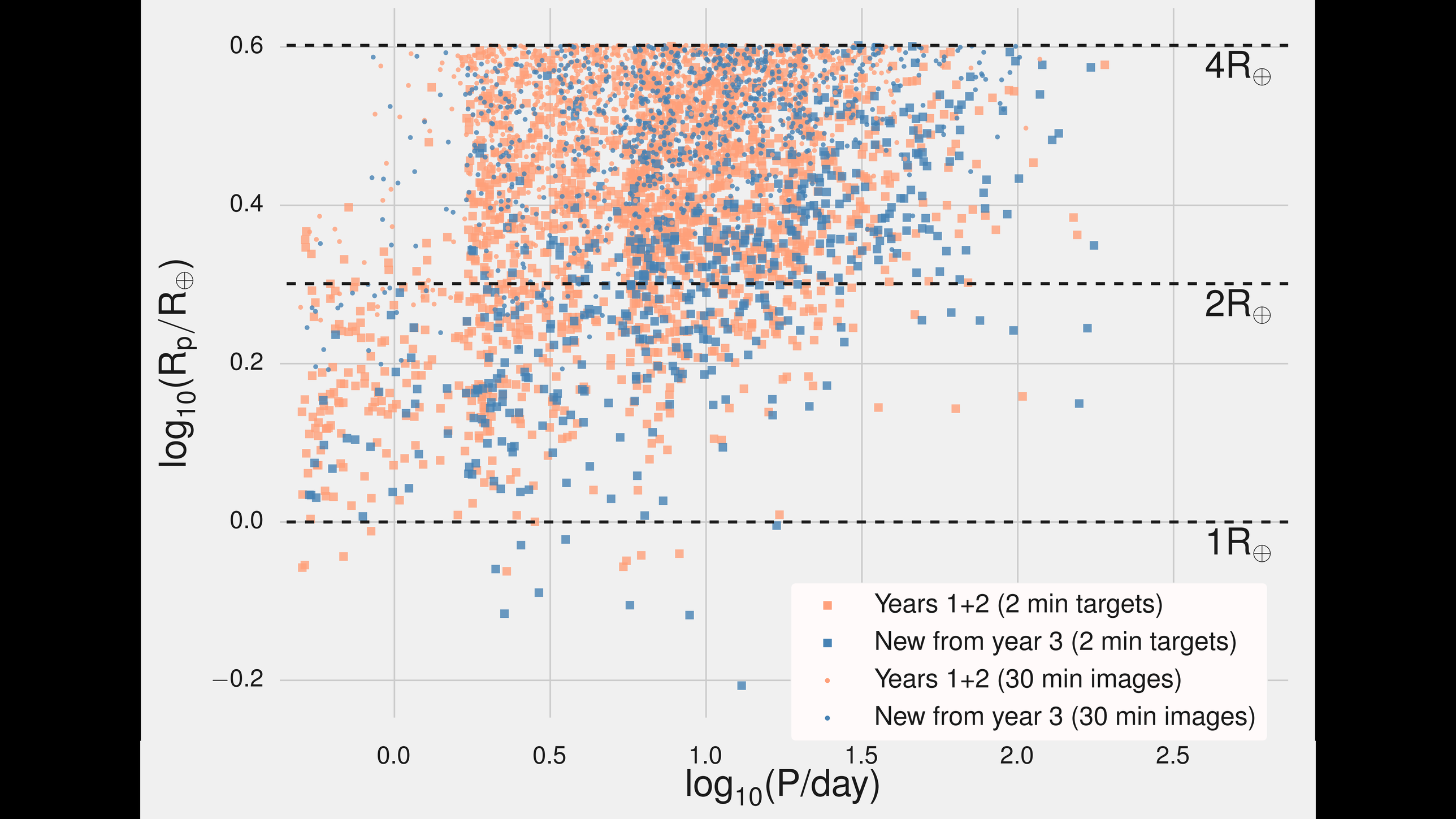
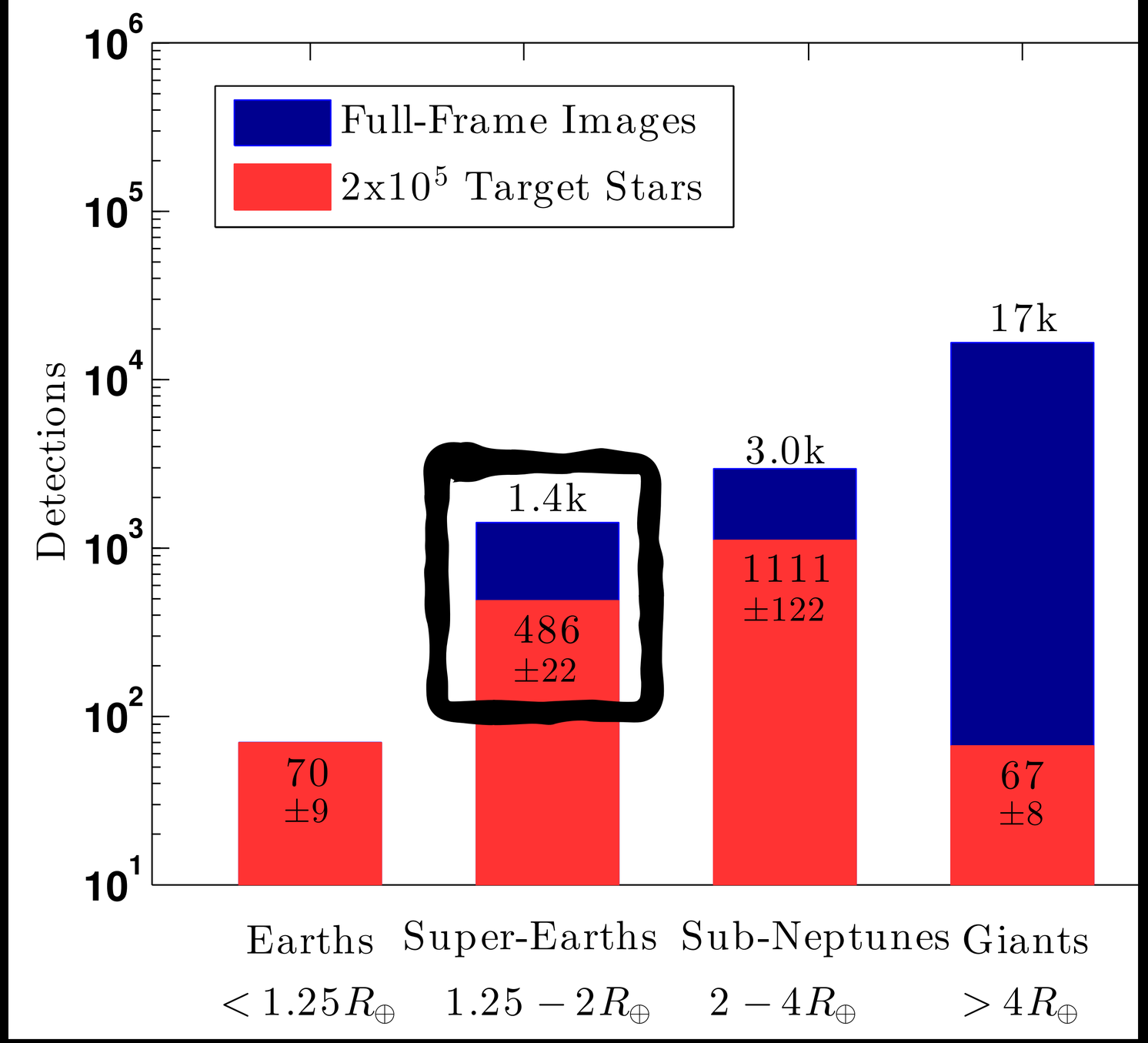
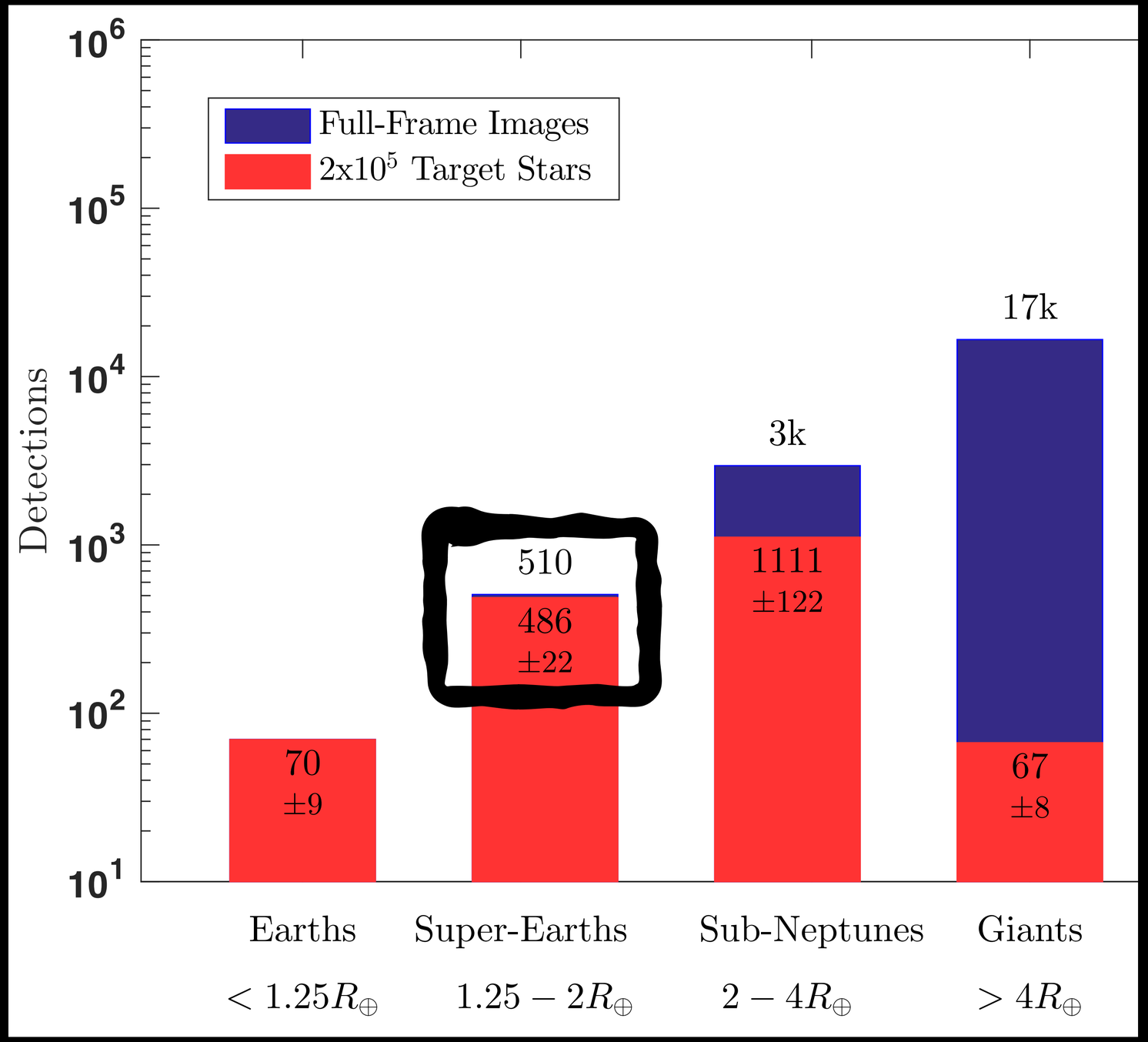
| $N_{new,HZ}$ | 122 | 124 | 122 | 107 | 120 | 146 |
| $N_{pri,HZ}$ | 205 | 210 | 212 | 217 | 210 | 208 |
| $N_{sys,extra\ planets}$ | 71 | 65 | 70 | 44 | 61 | 92 |
| $N_{new,atm}$ | | | ~10-20 per year | | | |
| $N_{pri,atm}$ | | | ~50 per year | | | |
| $N_{new,new\ stars}$ | 63 | 92 | 114 | 366 | 171 | 42 |
| $N_{new,SNR \vee N_{tra}}$ | 1220 | 1327 | 1241 | 803 | 1045 | 1390 |

# Extended Missions find smaller planets at longer orbital periods

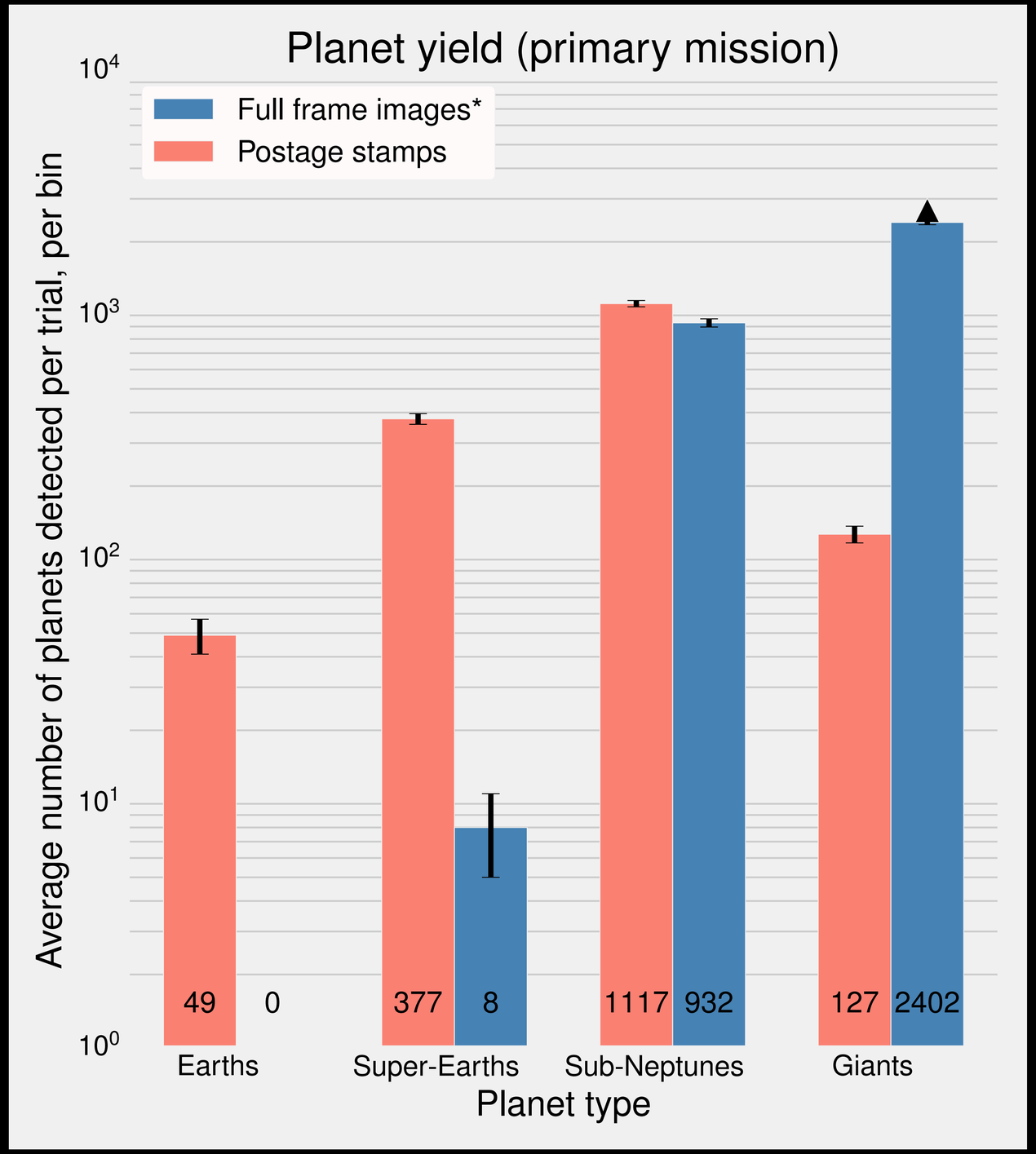

0.6
0.4
0.2
0.0
−0.2
4R⊕
2R⊕
1R⊕
log10(Rp/R⊕)
0.0
0.5
1.0
1.5
2.0
2.5
log10(P/day)
Years 1+2 (2 min targets)
New from year 3 (2 min targets)
Years 1+2 (30 min images)
New from year 3 (30 min images)

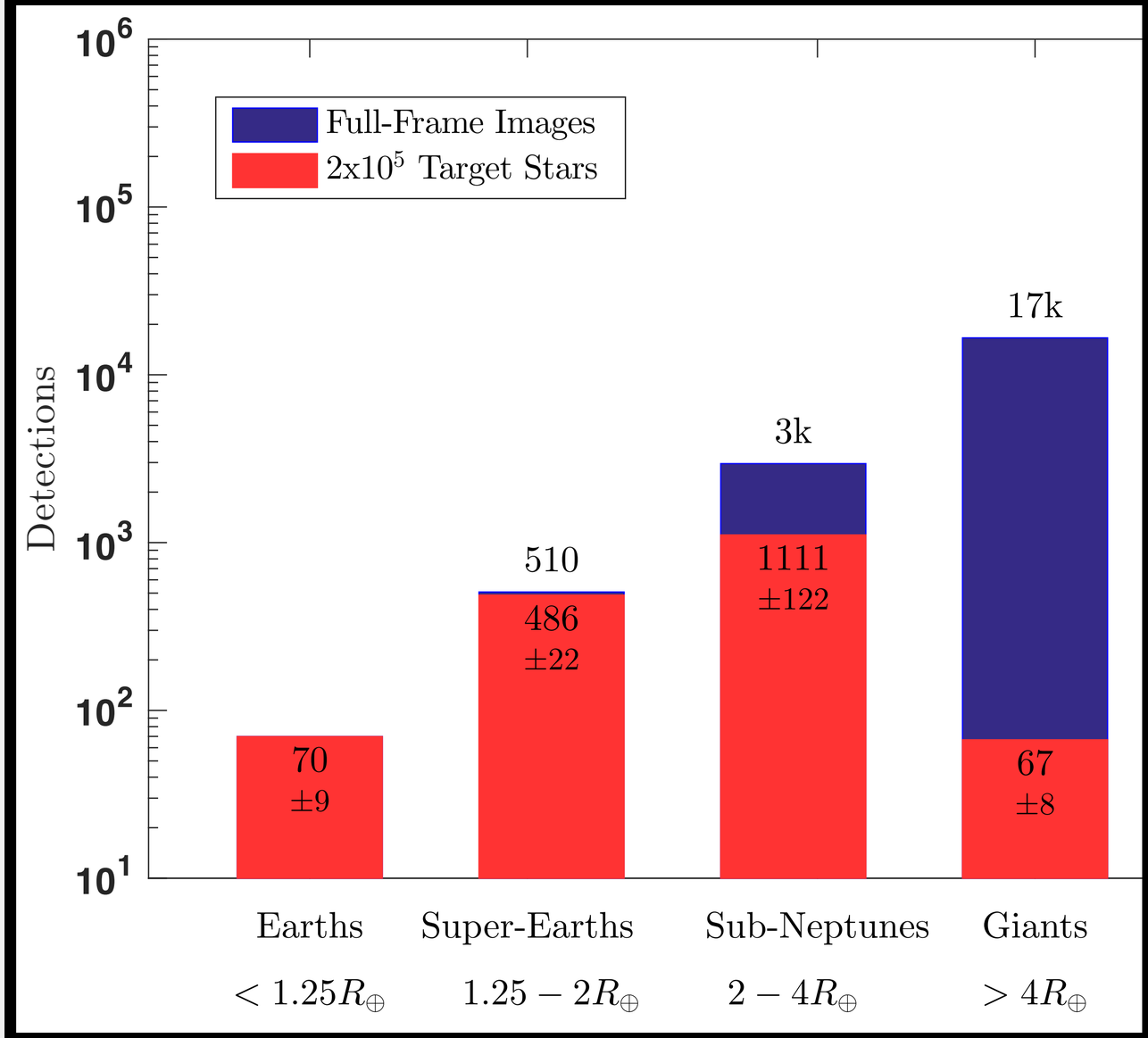



Sullivan+ (2015)




Sullivan+ (2015) erratum in prep.

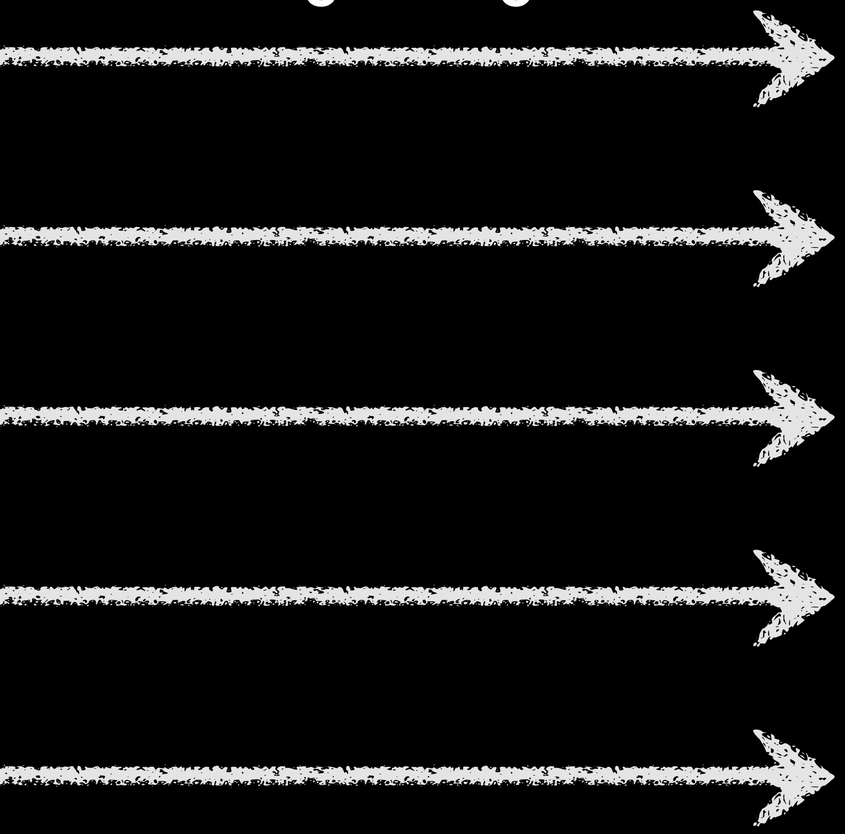

Planet yield (primary mission)
Full frame images*
Postage stamps
Average number of planets detected per trial, per bin
$10^4$
$10^3$
$10^2$
$10^1$
$10^0$
49
0
377
8
1117
932
127
2402
Earths
Super-Earths
Sub-Neptunes
Giants
Planet type

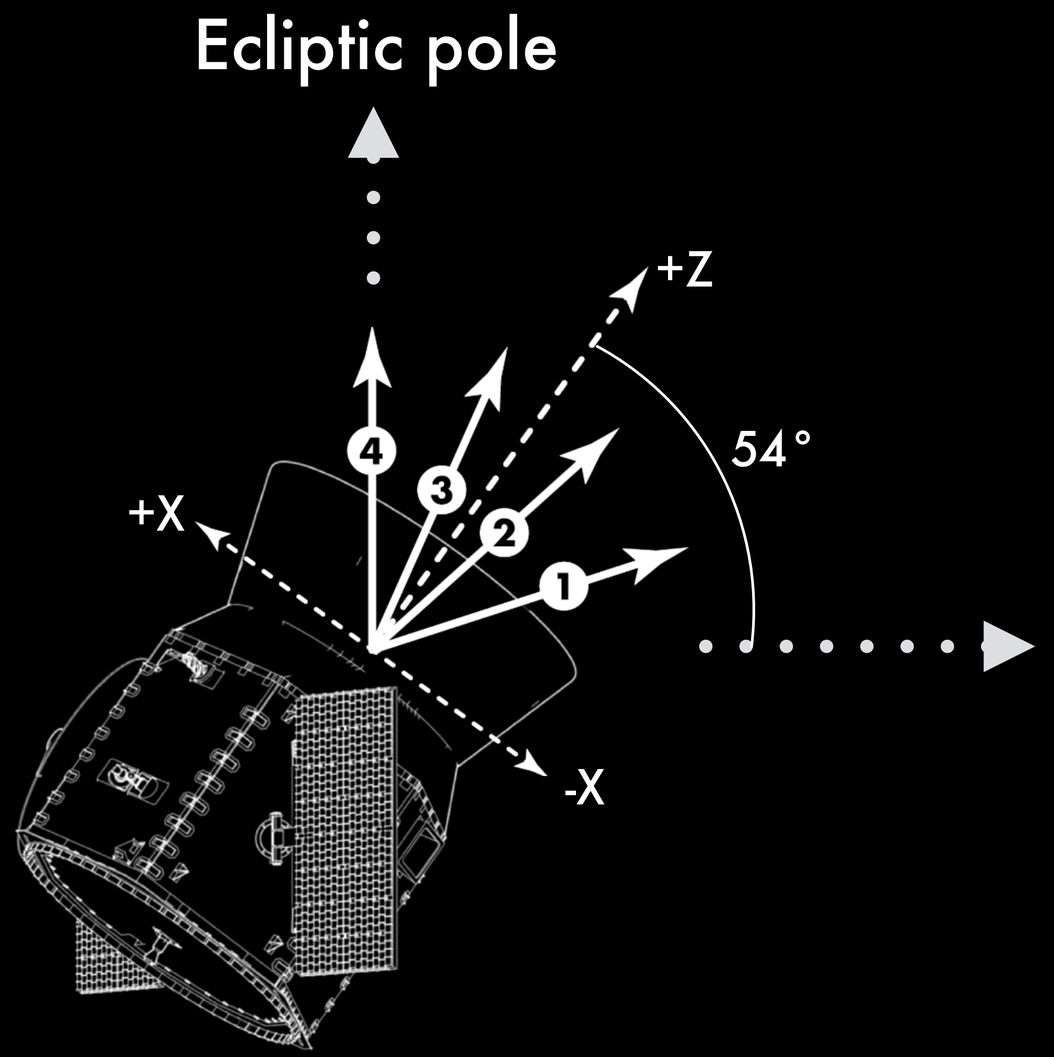

Full-Frame Images
2x10$^5$ Target Stars
Detections
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
70
±9
510
486
±22
3k
1111
±122
17k
67
±8
Earths
$< 1.25R_\oplus$
Super-Earths
$1.25 - 2R_\oplus$
Sub-Neptunes
$2 - 4R_\oplus$
Giants
$> 4R_\oplus$

We integrated nominal Earth/Moon/TESS orbits to estimate the fraction of TESS data ruined by Earth & Moon crossings.

*adapted from Orbital ATK design document*

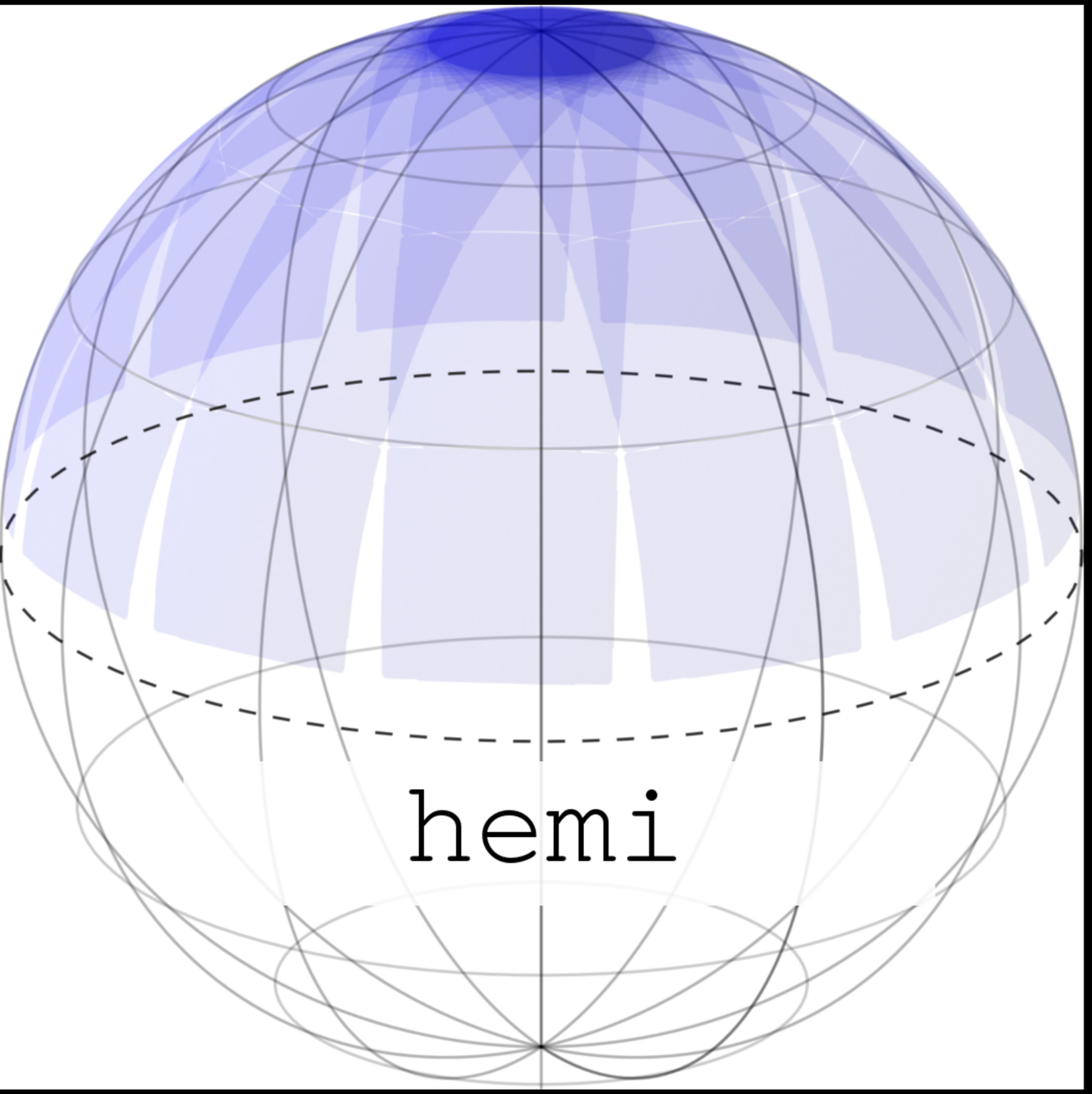
Incoming sunlight

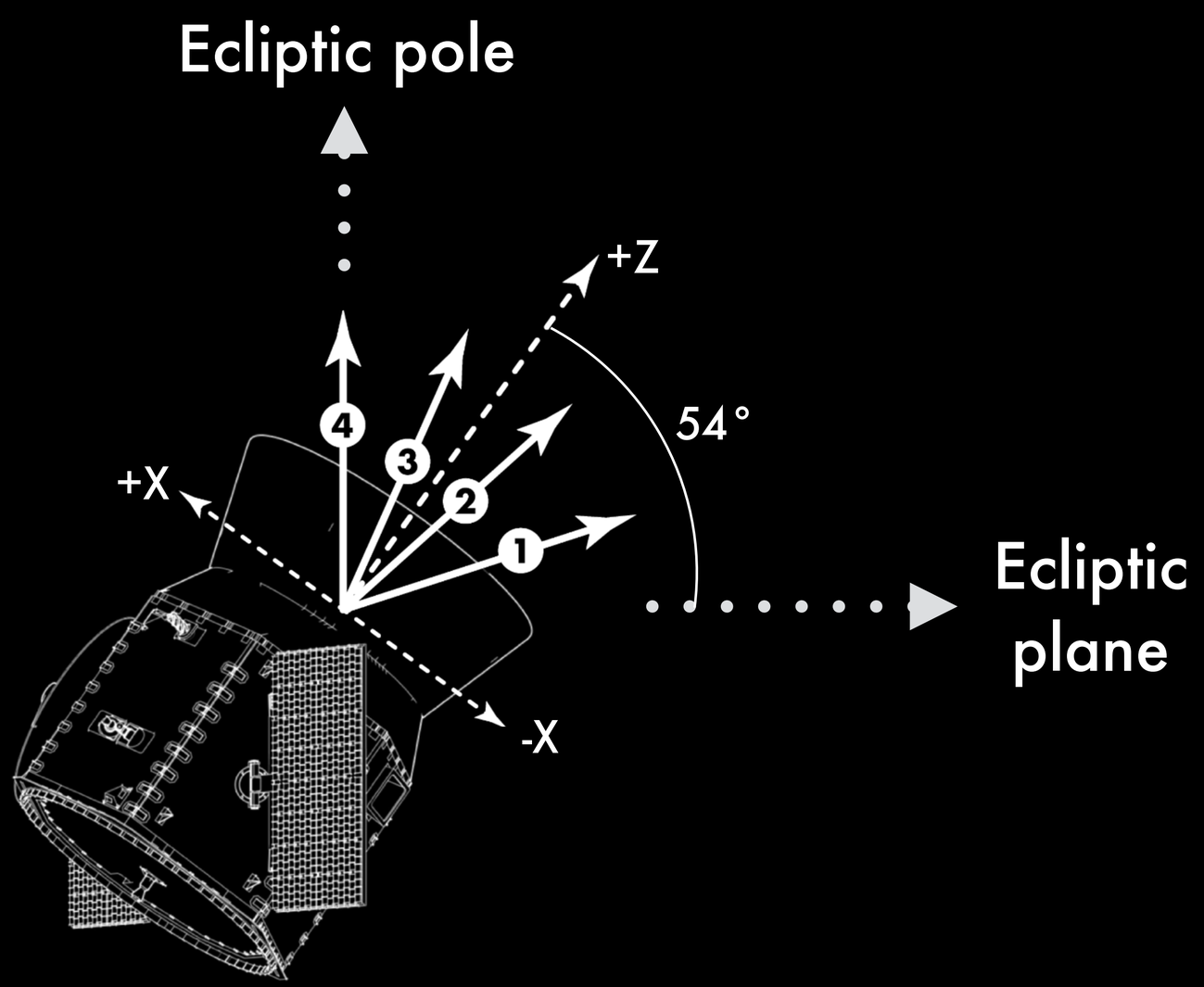





Year 2 of Primary Mission

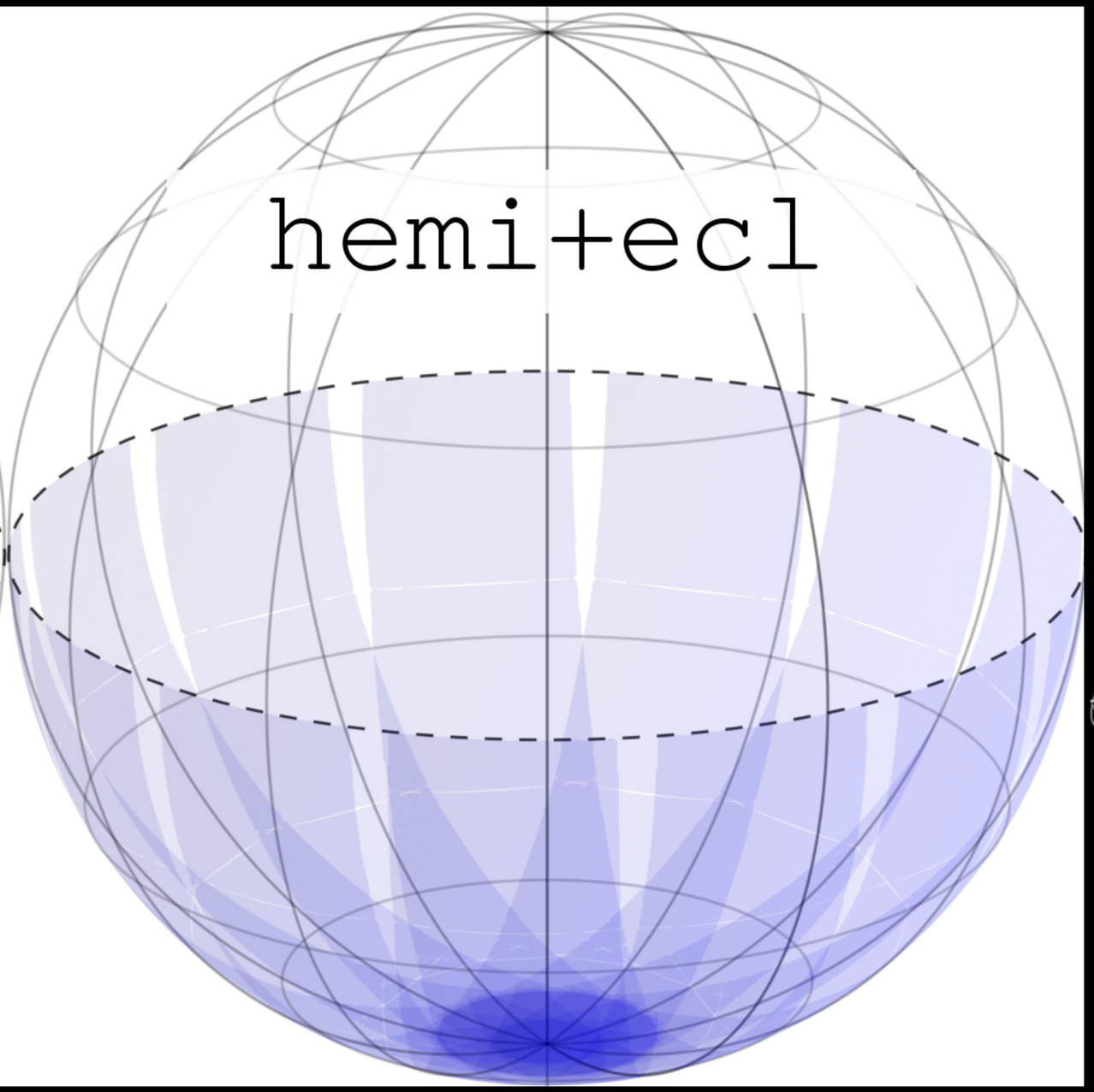
*adapted from Orbital ATK design document*

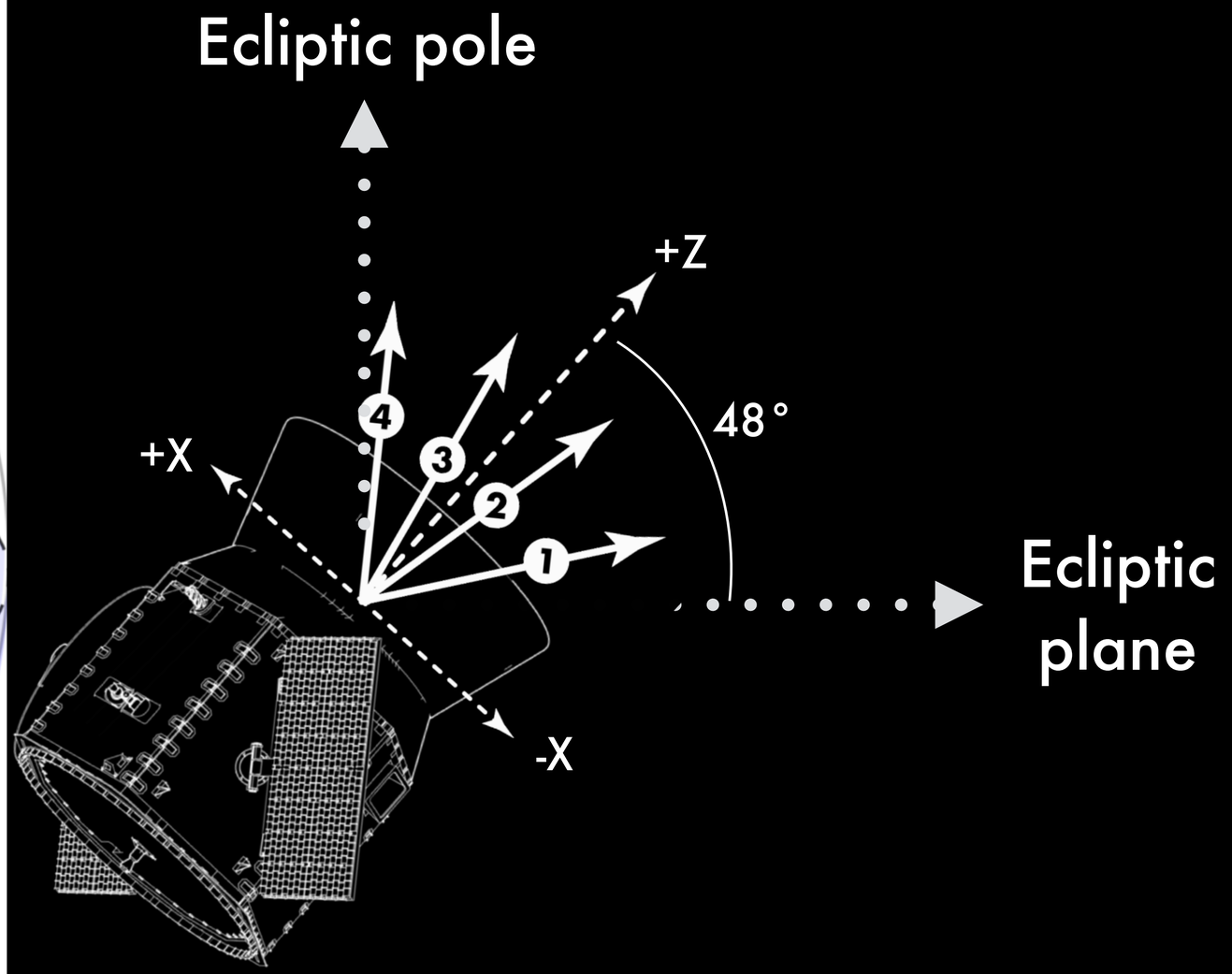



Year 3 of Extended Mission

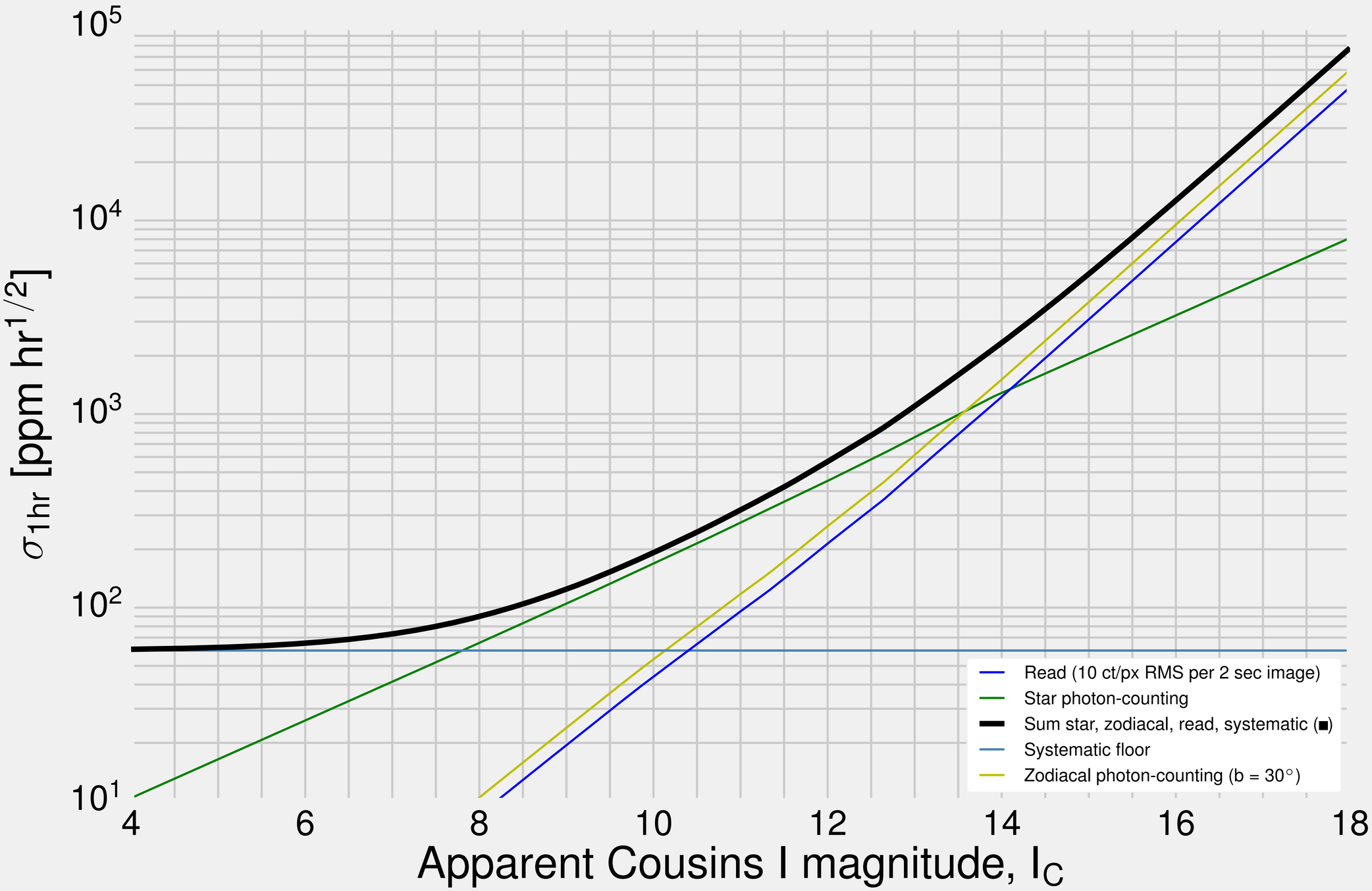
*adapted from Orbital ATK design document*

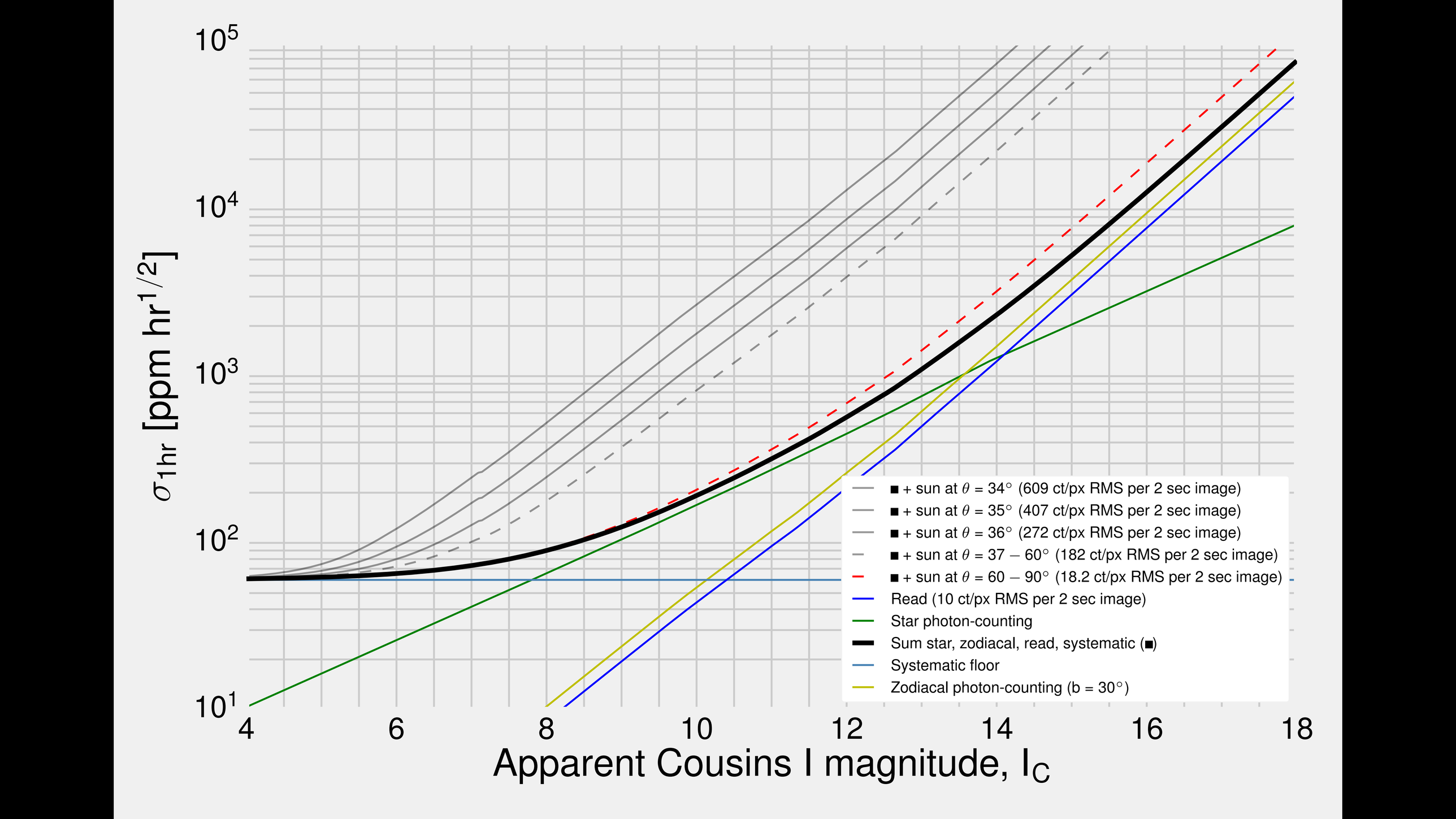


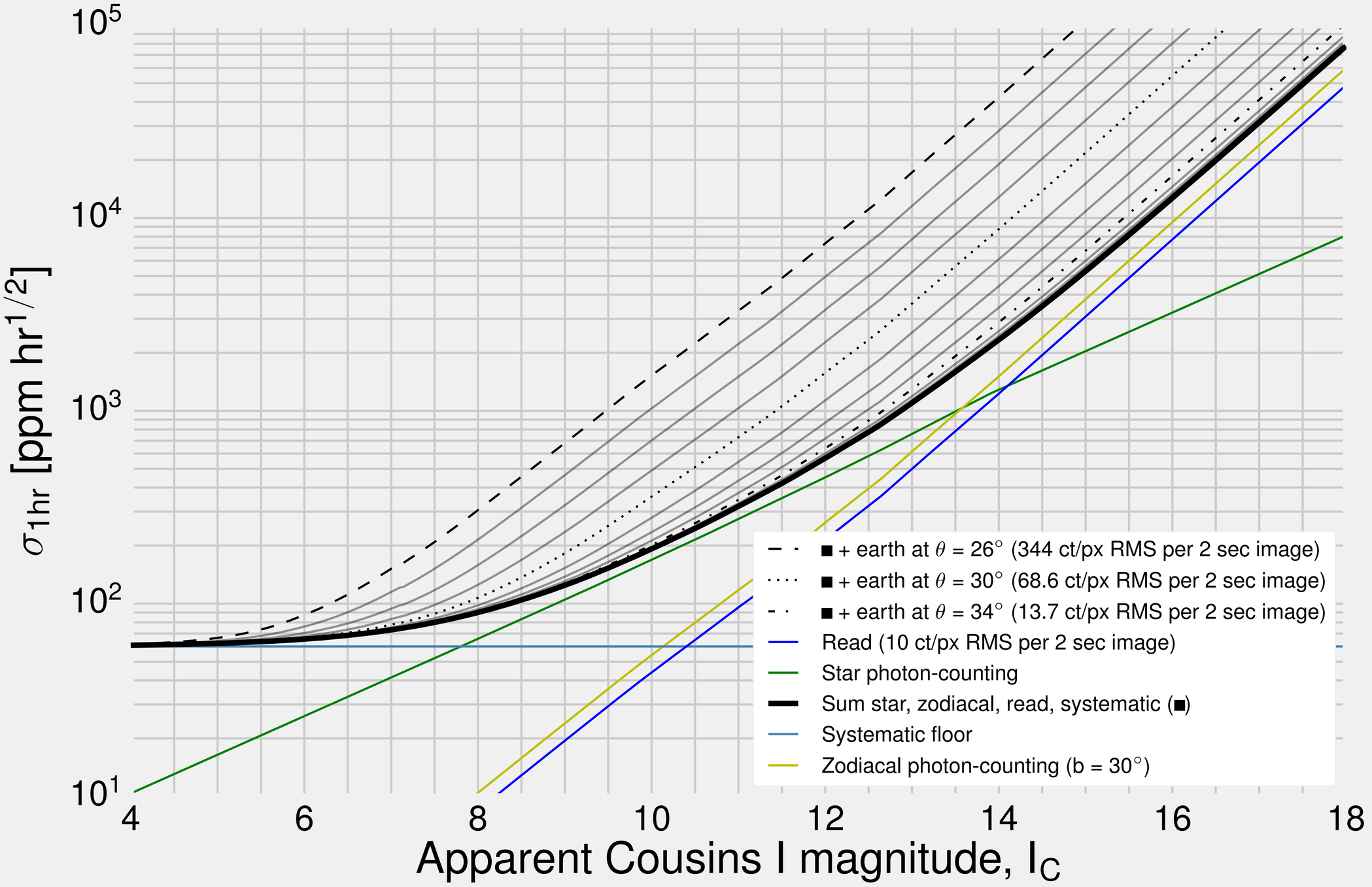



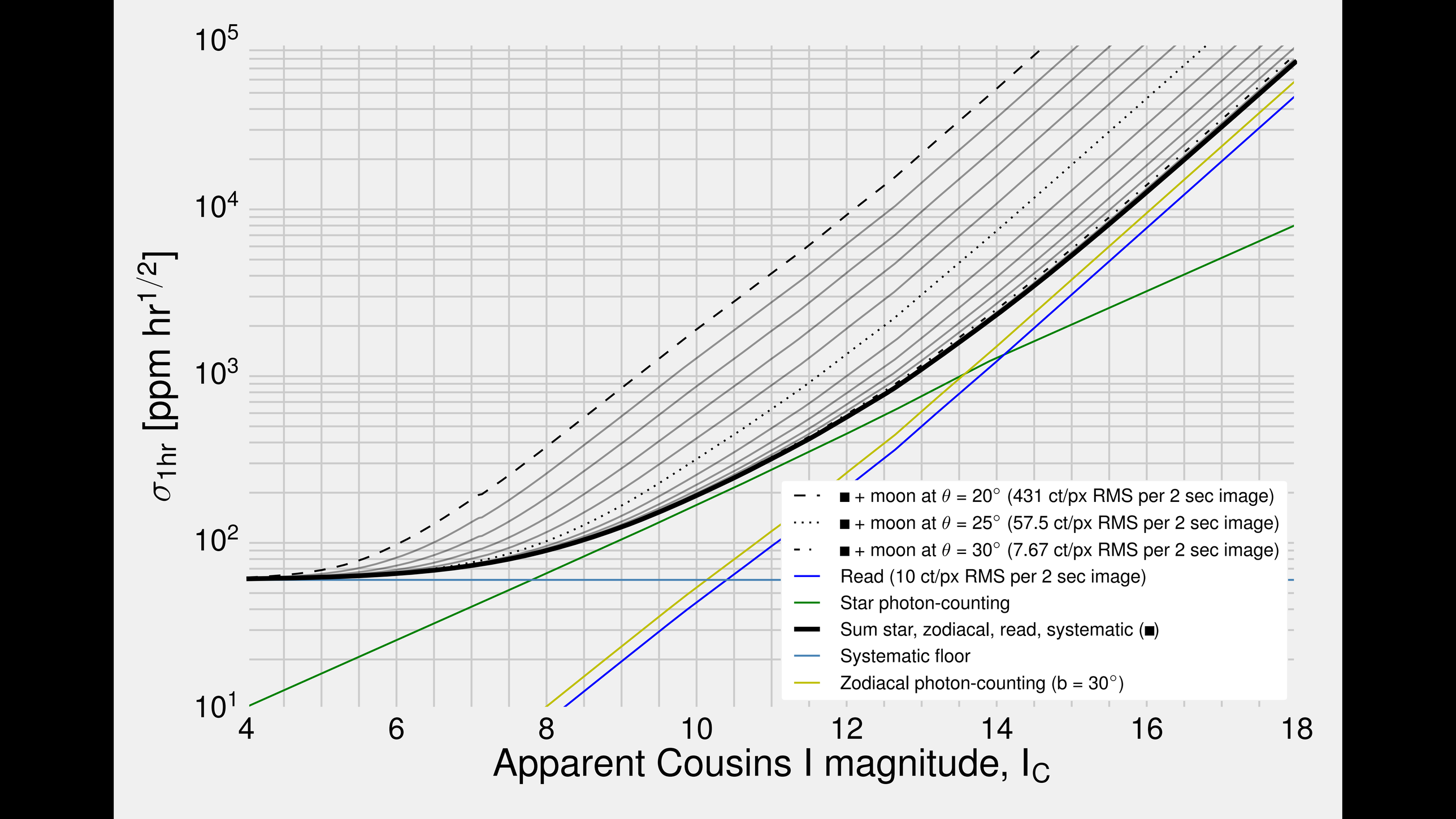

Year 3 of Extended Mission

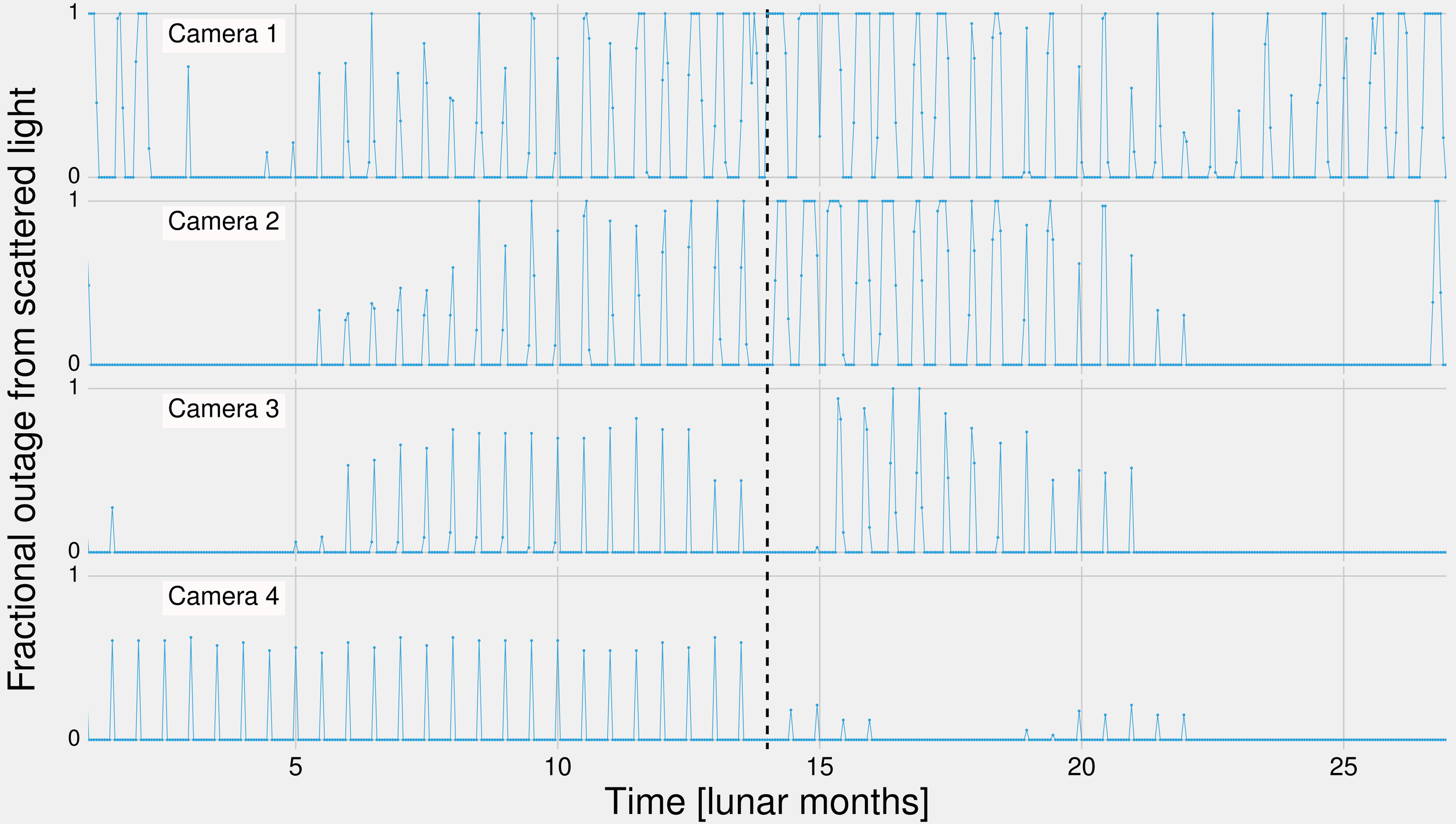
$$\begin{aligned}\mathrm{SNR}_{\mathrm{phase-folded}} &\approx \sqrt{N_{\mathrm{tra}}} \times \mathrm{SNR}_{\mathrm{per-transit}} \\ &= \sqrt{N_{\mathrm{tra}}} \times \frac{\delta \cdot D}{\left( \frac{\sigma_{\mathrm{1hr}}^2}{T_{\mathrm{dur}}} + \sigma_v^2 \right)^{1/2}}\end{aligned}$$

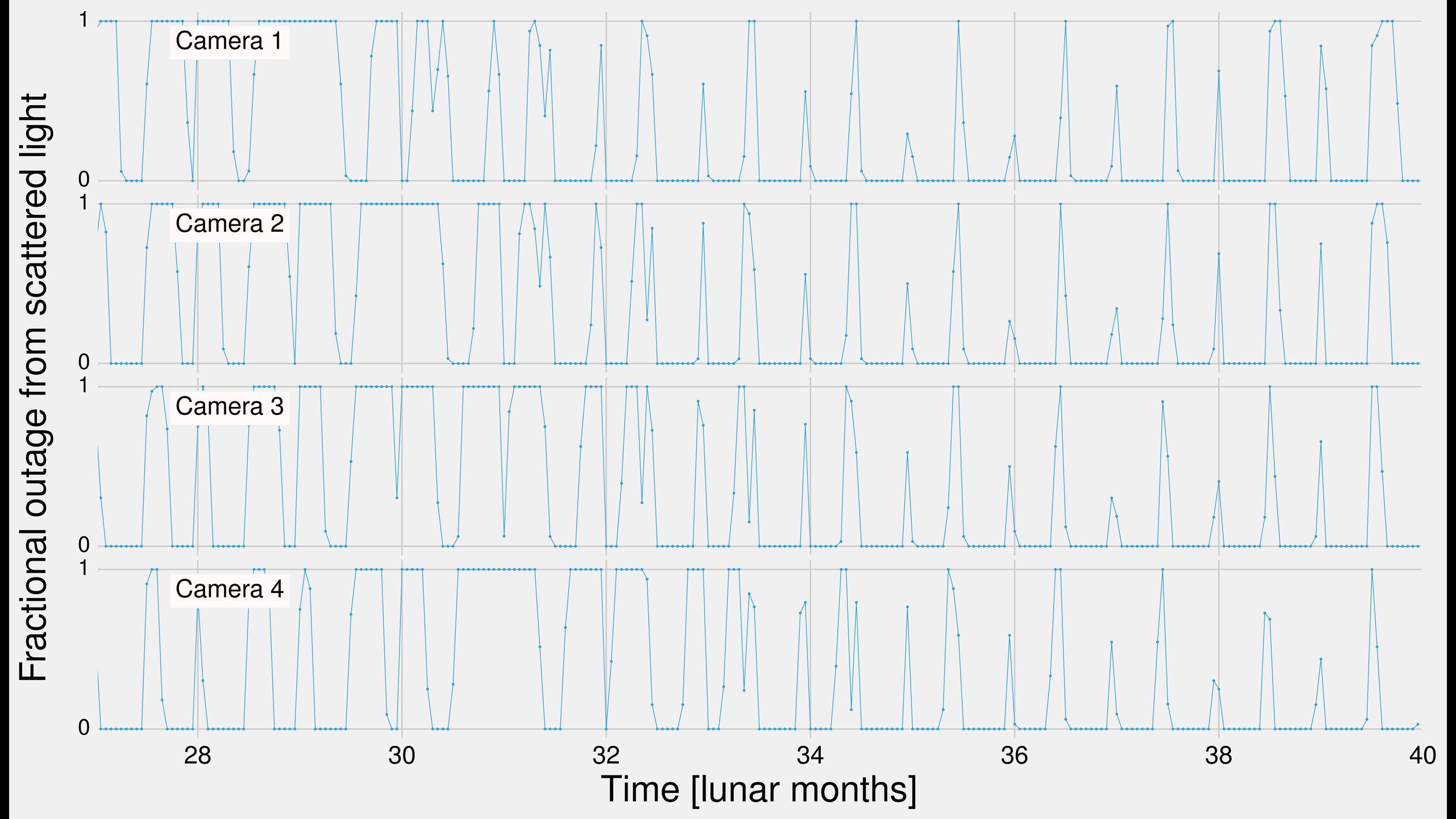

$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$\sigma_{1hr}$ [ppm hr$^{1/2}$]
4
6
8
10
12
14
16
18
Apparent Cousins I magnitude, $I_C$
Read (10 ct/px RMS per 2 sec image)
Star photon-counting
Sum star, zodiacal, read, systematic (■)
Systematic floor
Zodiacal photon-counting (b = 30°)

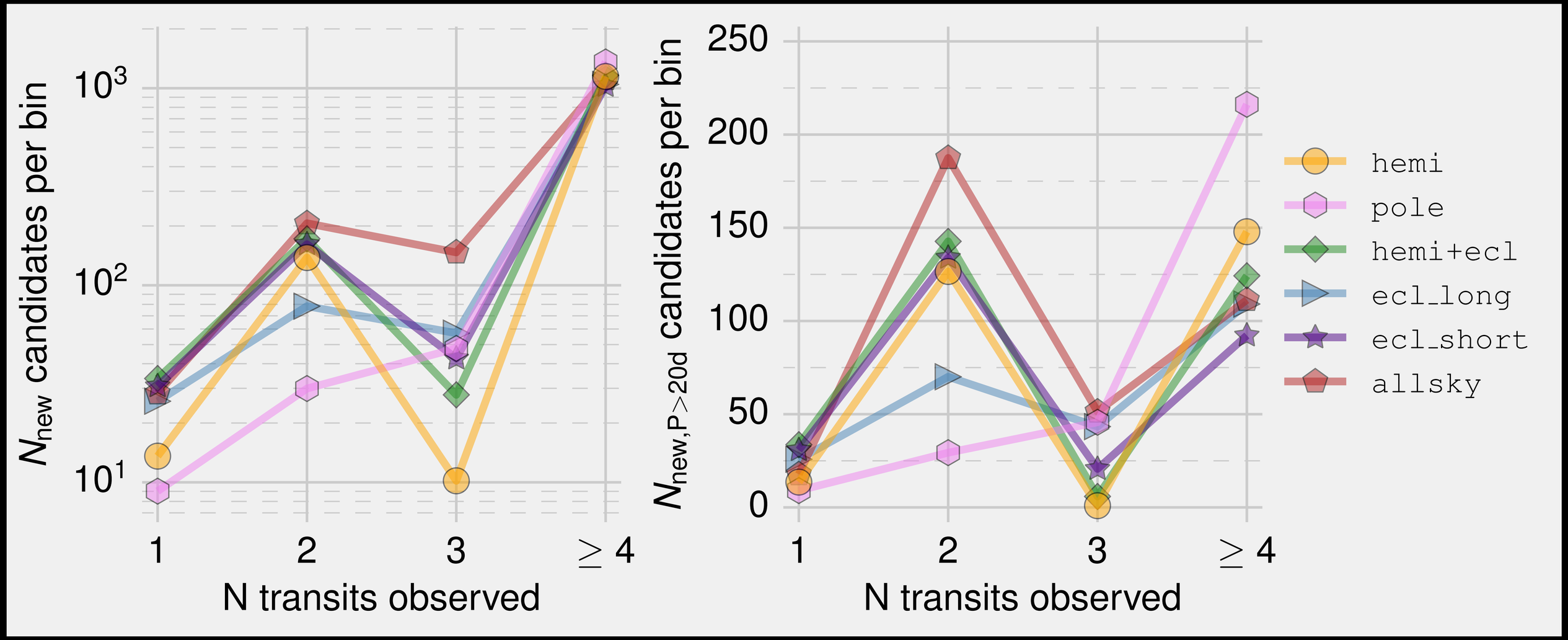

$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$\sigma_{1hr}$ [ppm hr$^{1/2}$]
4
6
8
10
12
14
16
18
Apparent Cousins I magnitude, $I_C$
■ + sun at $\theta$ = 34° (609 ct/px RMS per 2 sec image)
■ + sun at $\theta$ = 35° (407 ct/px RMS per 2 sec image)
■ + sun at $\theta$ = 36° (272 ct/px RMS per 2 sec image)
■ + sun at $\theta$ = 37 – 60° (182 ct/px RMS per 2 sec image)
■ + sun at $\theta$ = 60 – 90° (18.2 ct/px RMS per 2 sec image)
Read (10 ct/px RMS per 2 sec image)
Star photon-counting
Sum star, zodiacal, read, systematic (■)
Systematic floor
Zodiacal photon-counting (b = 30°)

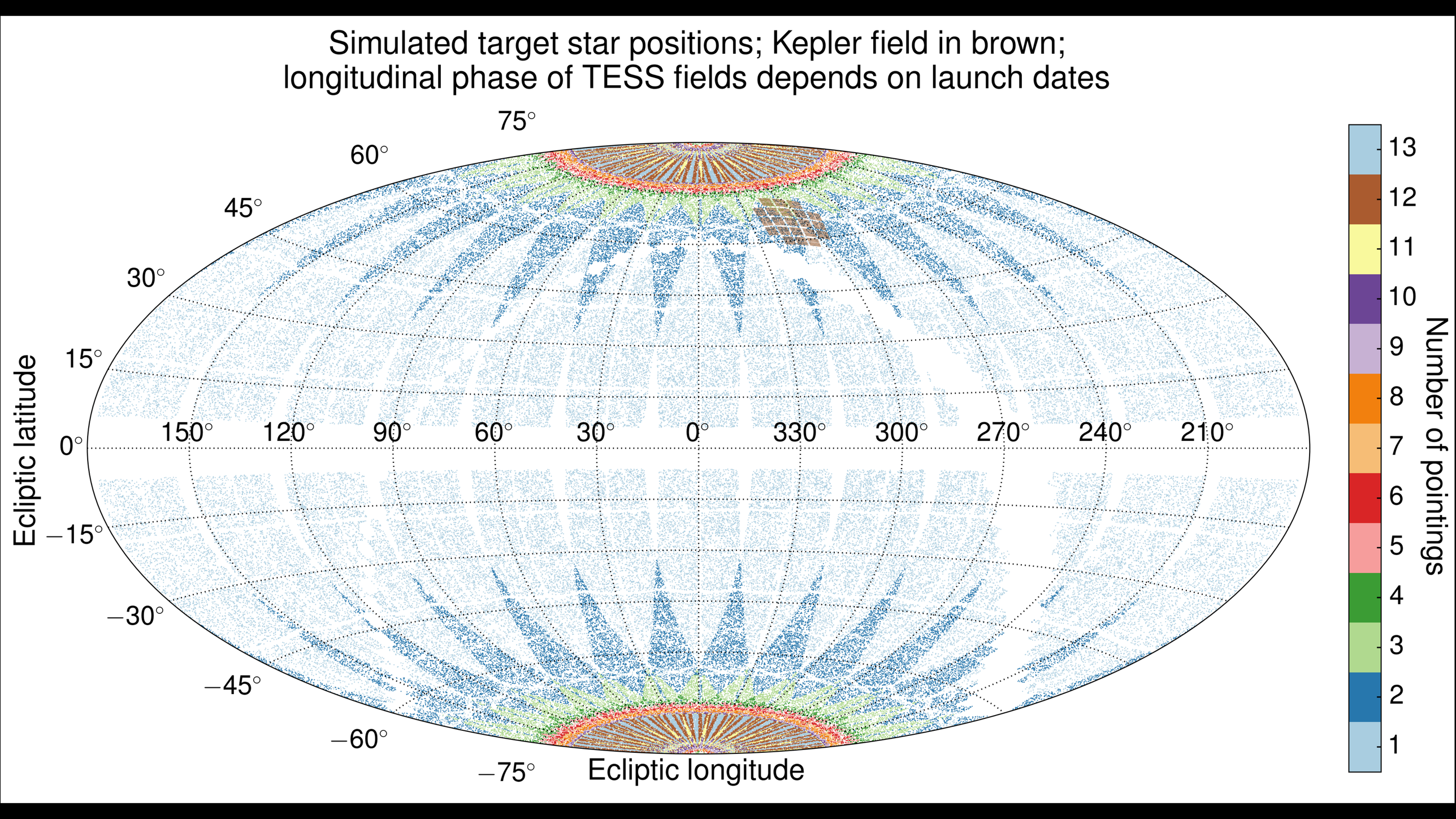

$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$\sigma_{1hr}$ [ppm hr$^{1/2}$]
4
6
8
10
12
14
16
18
Apparent Cousins I magnitude, $I_C$
■ + earth at $\theta$ = 26° (344 ct/px RMS per 2 sec image)
■ + earth at $\theta$ = 30° (68.6 ct/px RMS per 2 sec image)
■ + earth at $\theta$ = 34° (13.7 ct/px RMS per 2 sec image)
Read (10 ct/px RMS per 2 sec image)
Star photon-counting
Sum star, zodiacal, read, systematic (■)
Systematic floor
Zodiacal photon-counting (b = 30°)

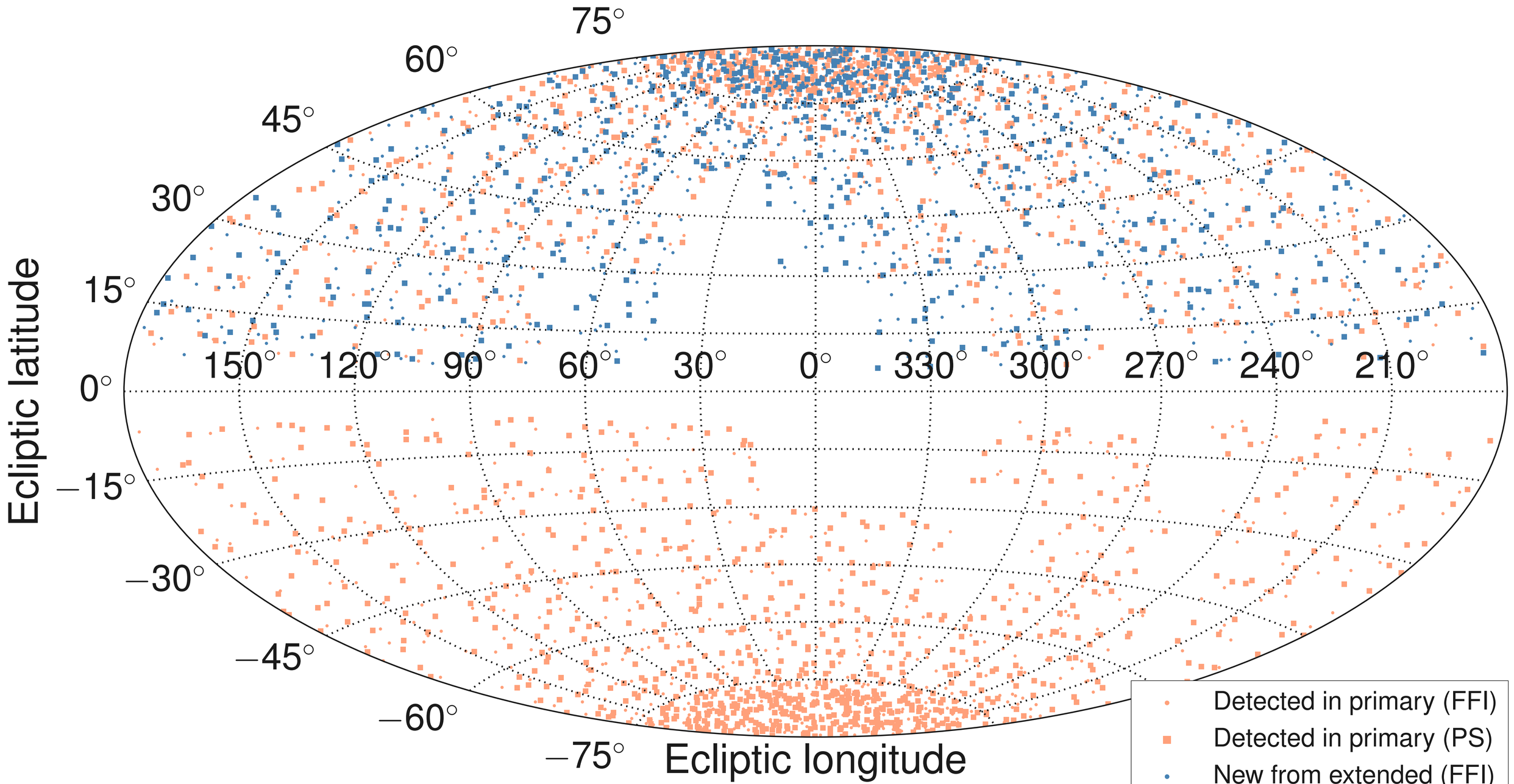

$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$\sigma_{1hr}$ [ppm hr$^{1/2}$]
4
6
8
10
12
14
16
18
Apparent Cousins I magnitude, $I_C$
■ + moon at $\theta$ = 20° (431 ct/px RMS per 2 sec image)
■ + moon at $\theta$ = 25° (57.5 ct/px RMS per 2 sec image)
■ + moon at $\theta$ = 30° (7.67 ct/px RMS per 2 sec image)
Read (10 ct/px RMS per 2 sec image)
Star photon-counting
Sum star, zodiacal, read, systematic (■)
Systematic floor
Zodiacal photon-counting (b = 30°)

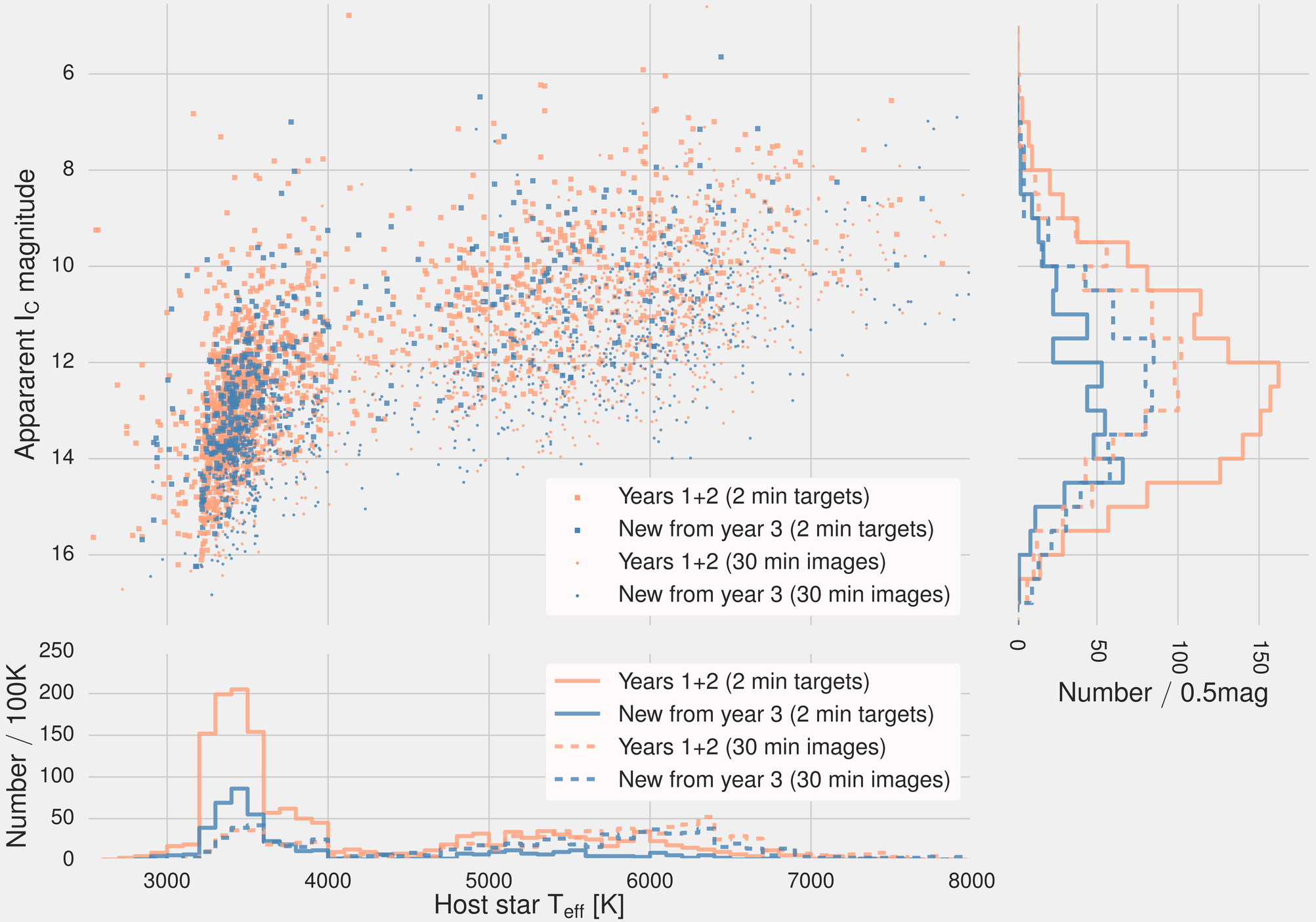

Camera 1
Camera 2
Camera 3
Camera 4
1
0
Fractional outage from scattered light
5
10
15
20
25
Time [lunar months]

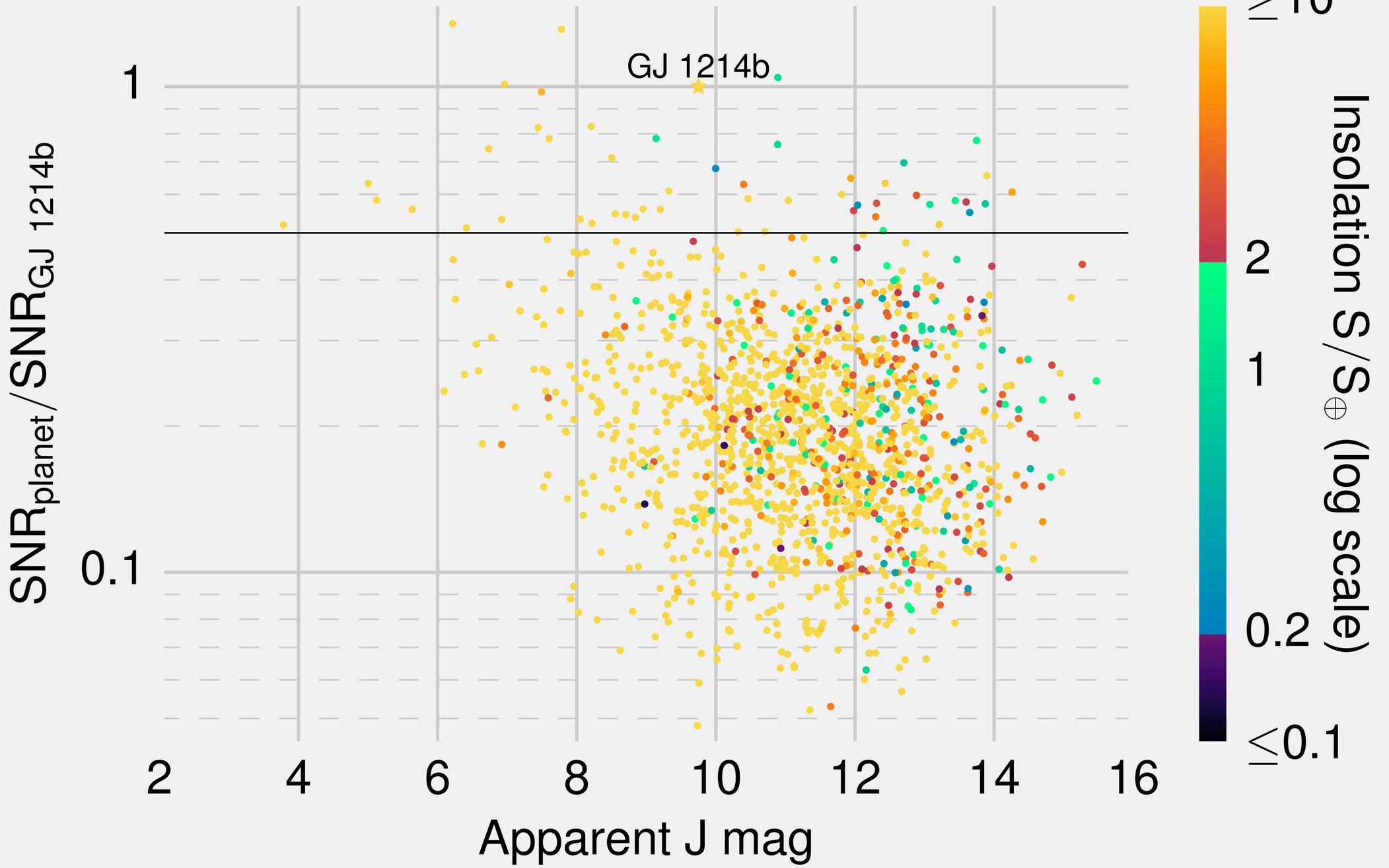

Camera 1
Camera 2
Camera 3
Camera 4
1
0
Fractional outage from scattered light
28
30
32
34
36
38
40
Time [lunar months]

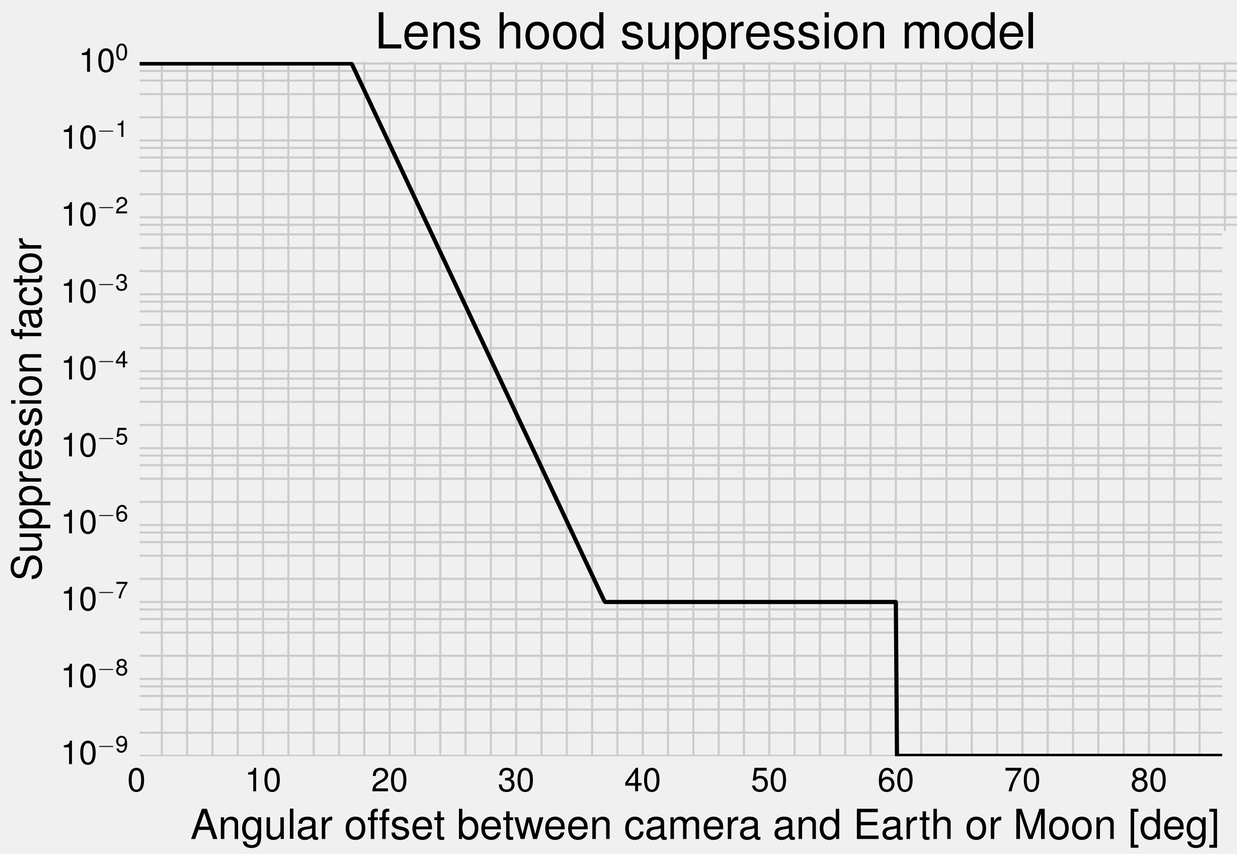

$N_{new}$ candidates per bin
$10^3$
$10^2$
$10^1$
1
2
3
$\geq 4$
N transits observed
$N_{new,P>20d}$ candidates per bin
250
200
150
100
50
0
1
2
3
$\geq 4$
N transits observed
hemi
pole
hemi+ecl
ecl_long
ecl_short
allsky

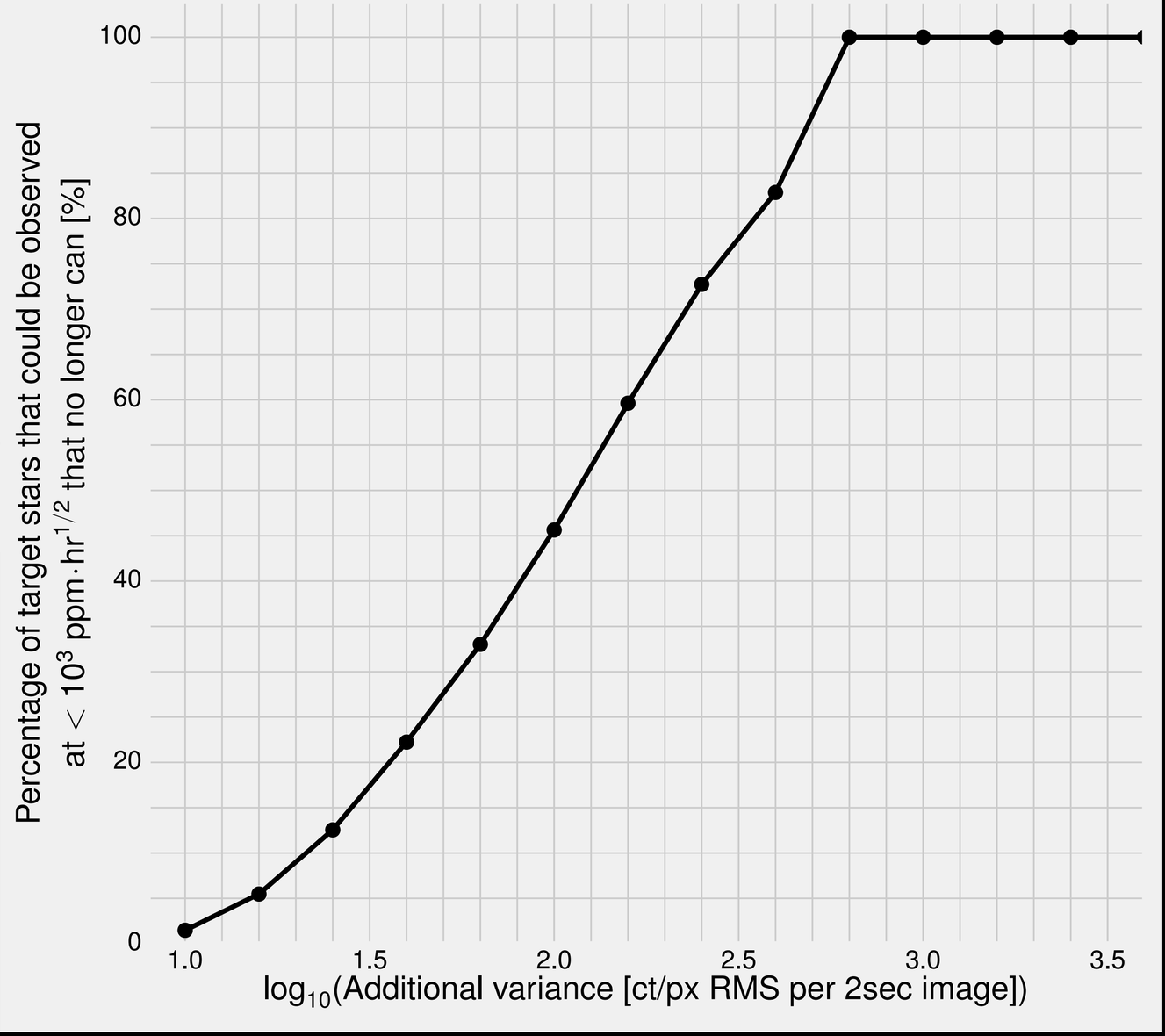

Simulated target star positions; Kepler field in brown;
longitudinal phase of TESS fields depends on launch dates
75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
Ecliptic latitude
Ecliptic longitude
Number of pointings
13
12
11
10
9
8
7
6
5
4
3
2
1


75°
60°
45°
30°
15°
0°
−15°
−30°
−45°
−60°
−75°
150°
120°
90°
60°
30°
0°
330°
300°
270°
240°
210°
Ecliptic latitude
Ecliptic longitude
Detected in primary (FFI)
Detected in primary (PS)
New from extended (FFI)
New from extended (PS)


Apparent $I_C$ magnitude
6
8
10
12
14
16
Years 1+2 (2 min targets)
New from year 3 (2 min targets)
Years 1+2 (30 min images)
New from year 3 (30 min images)
0
50
100
150
Number / 0.5mag
Number / 100K
250
200
150
100
50
0
Years 1+2 (2 min targets)
New from year 3 (2 min targets)
Years 1+2 (30 min images)
New from year 3 (30 min images)
3000
4000
5000
6000
7000
8000
Host star $T_{eff}$ [K]


GJ 1214b
1
0.1
$SNR_{planet}/SNR_{GJ\ 1214b}$
2
4
6
8
10
12
14
16
Apparent J mag
≥10
2
1
0.2
≤0.1
Insolation $S/S_\oplus$ (log scale)


Lens hood suppression model
Suppression factor
$10^{0}$
$10^{-1}$
$10^{-2}$
$10^{-3}$
$10^{-4}$
$10^{-5}$
$10^{-6}$
$10^{-7}$
$10^{-8}$
$10^{-9}$
0
10
20
30
40
50
60
70
80
Angular offset between camera and Earth or Moon [deg]


Percentage of target stars that could be observed at $< 10^{3}$ ppm·hr$^{1/2}$ that no longer can [%]
100
80
60
40
20
0
1.0
1.5
2.0
2.5
3.0
3.5
$\log_{10}$(Additional variance [ct/px RMS per 2sec image])