LEVERAGING THE ROMAN CORONAGRAPH APPROACH FOR THE HWO ERROR BUDGET

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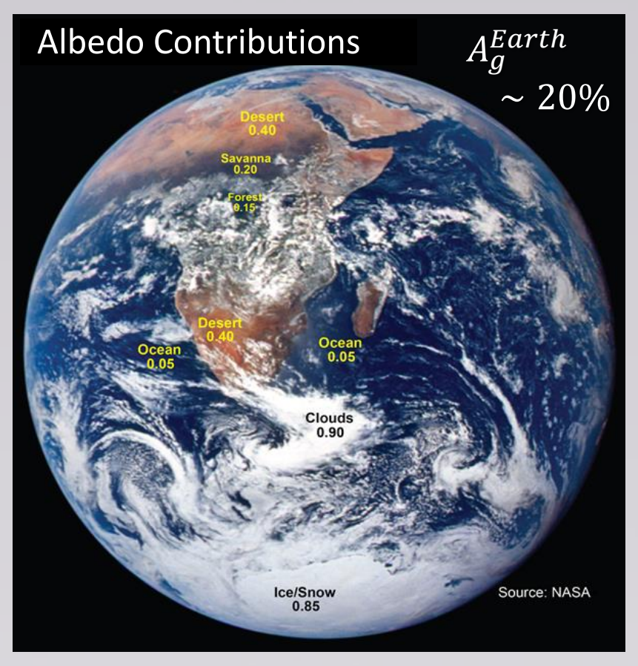
IMAGING AN EXO-EARTH IN REFLECTED LIGHT



The planet in reflected light needs to be observable against the speckle background

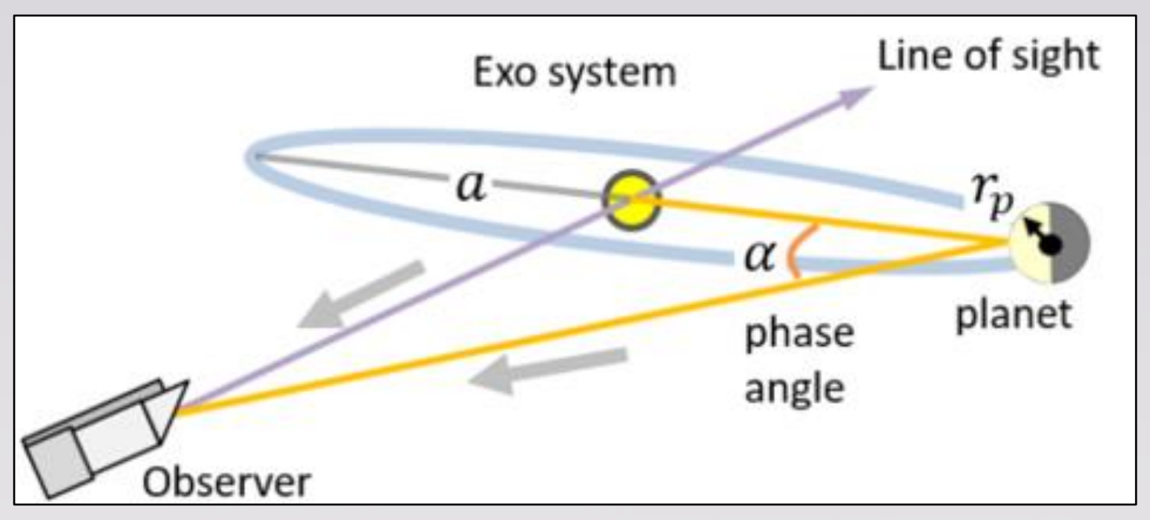
The measurement of interest is the flux ratio: flux from the planet / flux from the star

Let ξ represent the flux ratio:

$$\xi = A_g \, \phi(\alpha) \, r_p^2 \, a^{-2}$$

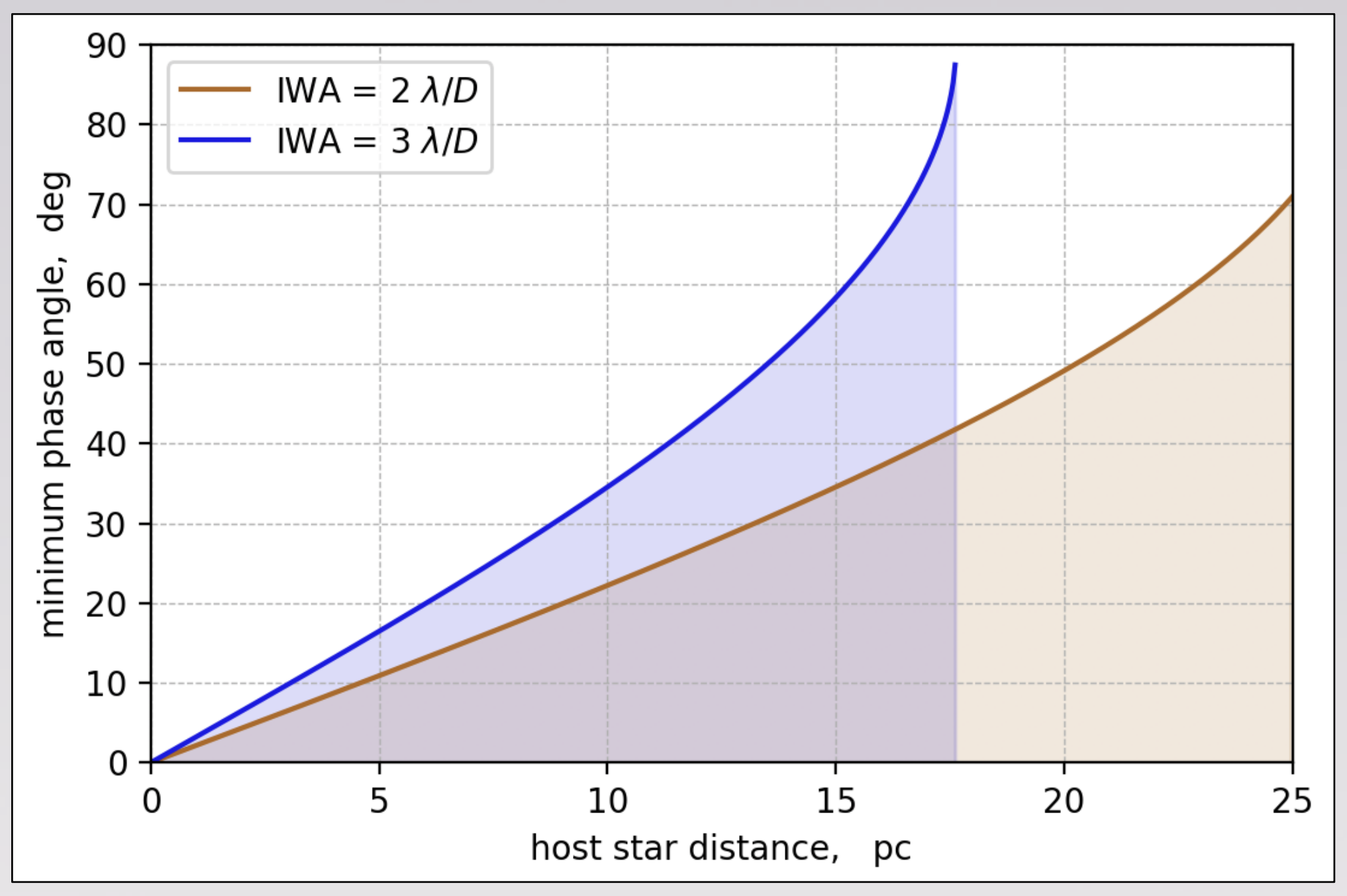
The phase angle for a Lambertian sphere is given by:

$$\phi(\alpha) = \frac{\sin(\alpha)+(\pi-\alpha)\cos(\alpha)}{\pi}$$



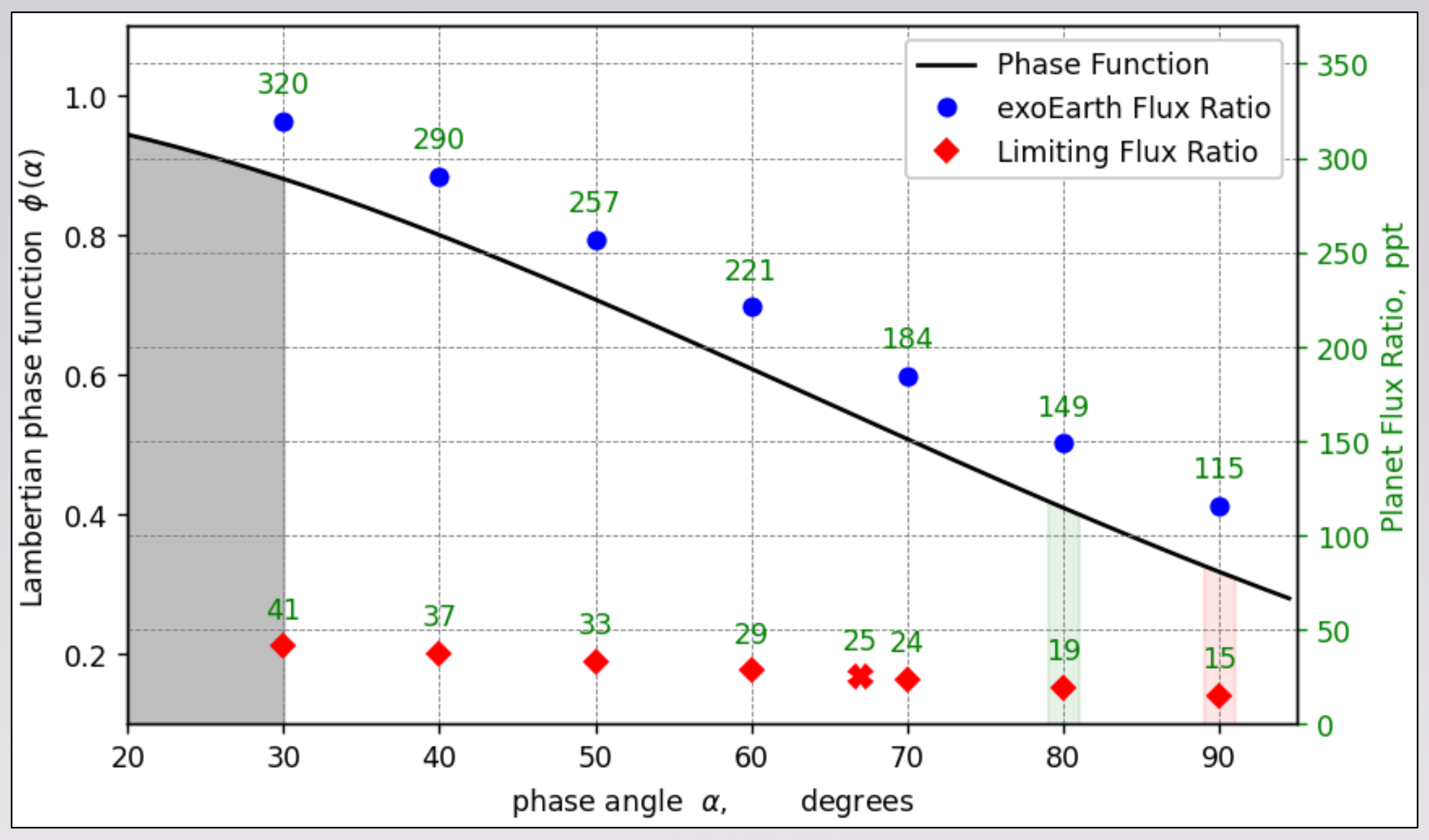
PHASE ANGLE CHOICE

For a coronagraph with a given minimum working angle, observing a planet at smaller working angles becomes less possible for farther targets. Two cases are shown, one with inner working angle (IWA) of 2 λ/D and 3 λ/D. Inaccessible phase angles are shaded.



EXO-EARTHS VS. EARTH-LIKE

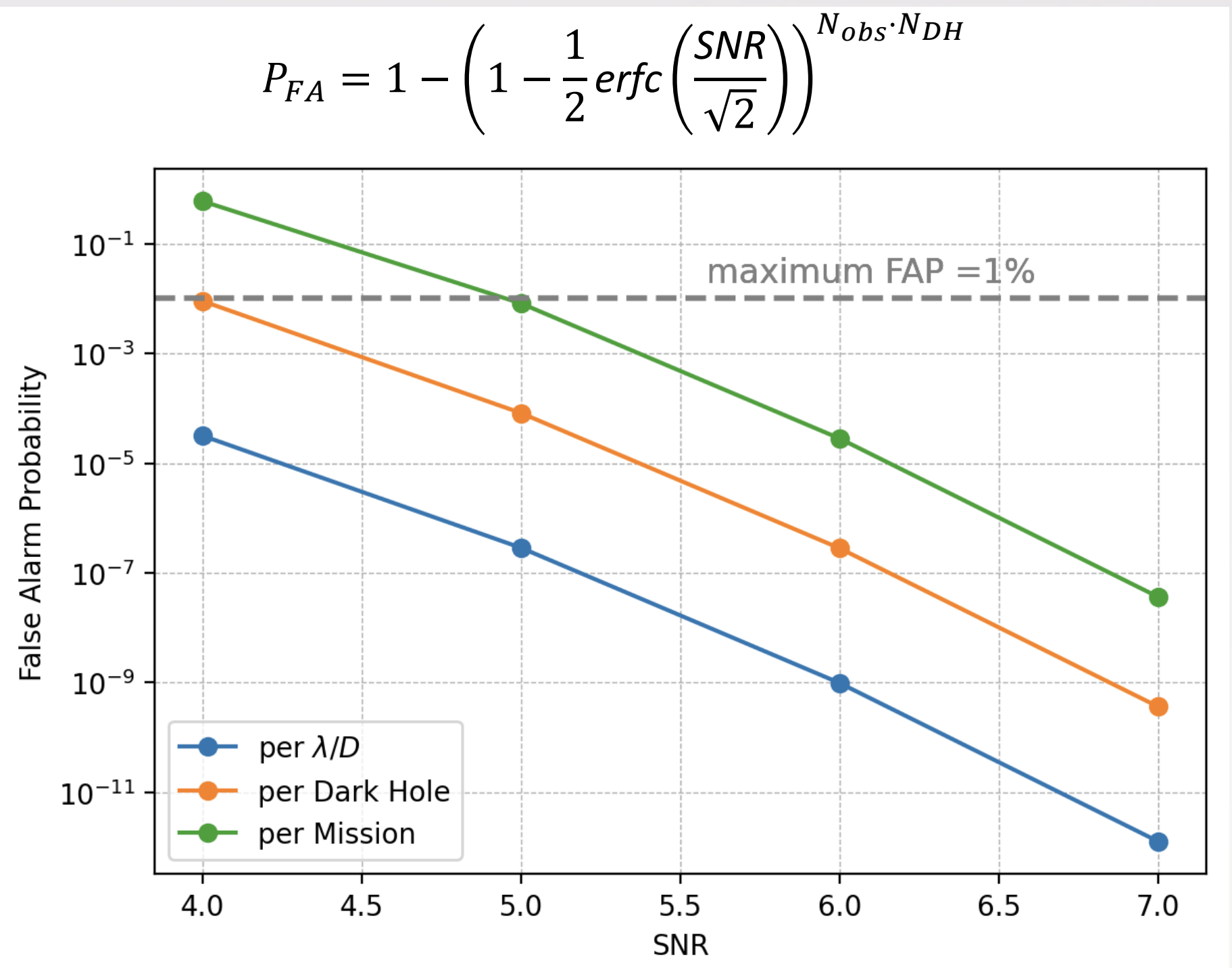
Earth has measured geometric albedo of $A_g = 0.2$. We show an exo-Earth flux ratio vs. that of planet that is merely Earth-like at the outer edge of the optimistic habitable zone, at 1.67 AU. For the exo-Earth we see that at 80 degrees we have 150 ppt. For the 0.6-$R_\oplus$ target at 1.67 AU, the flux ratios are 7.75X lower.

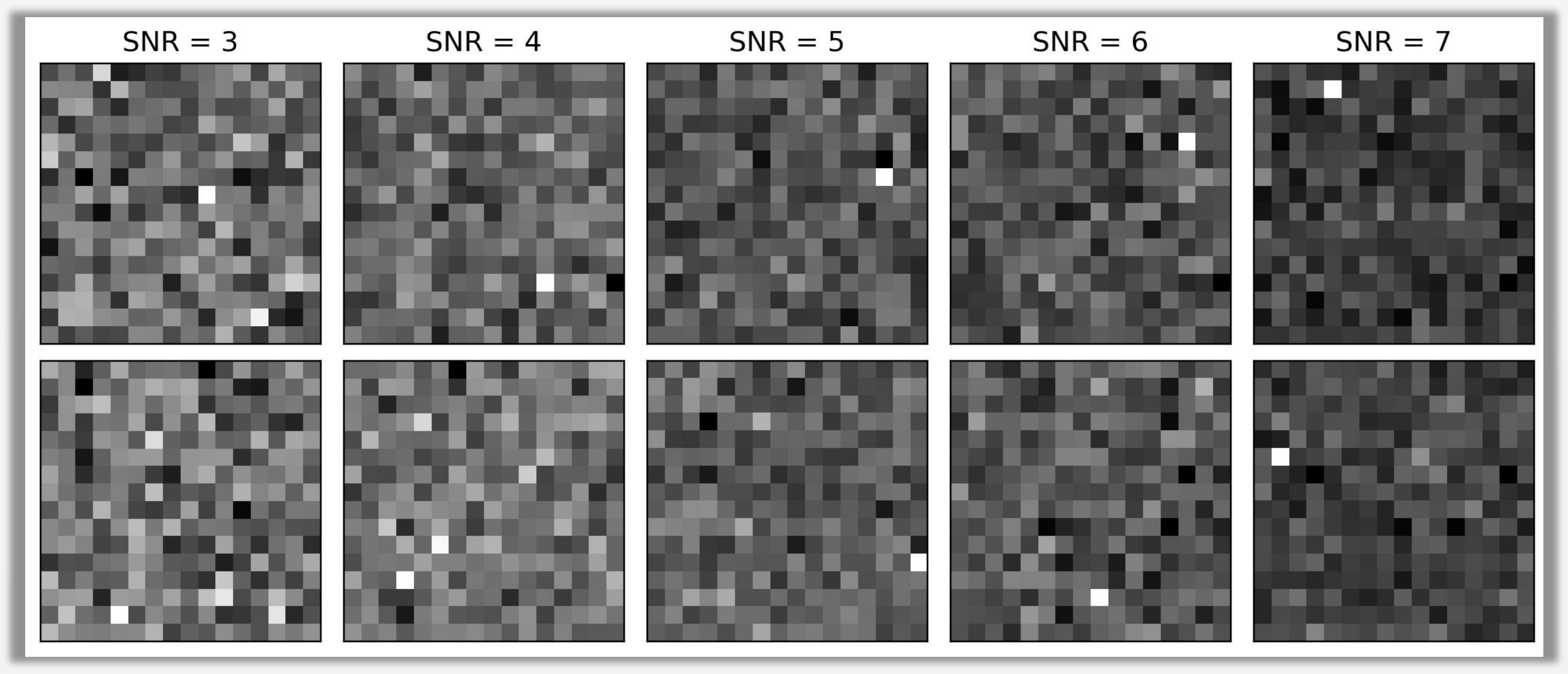


SNR AND FALSE POSITIVE REJECTION

Calculating false alarm/positive probability vs. SNR:

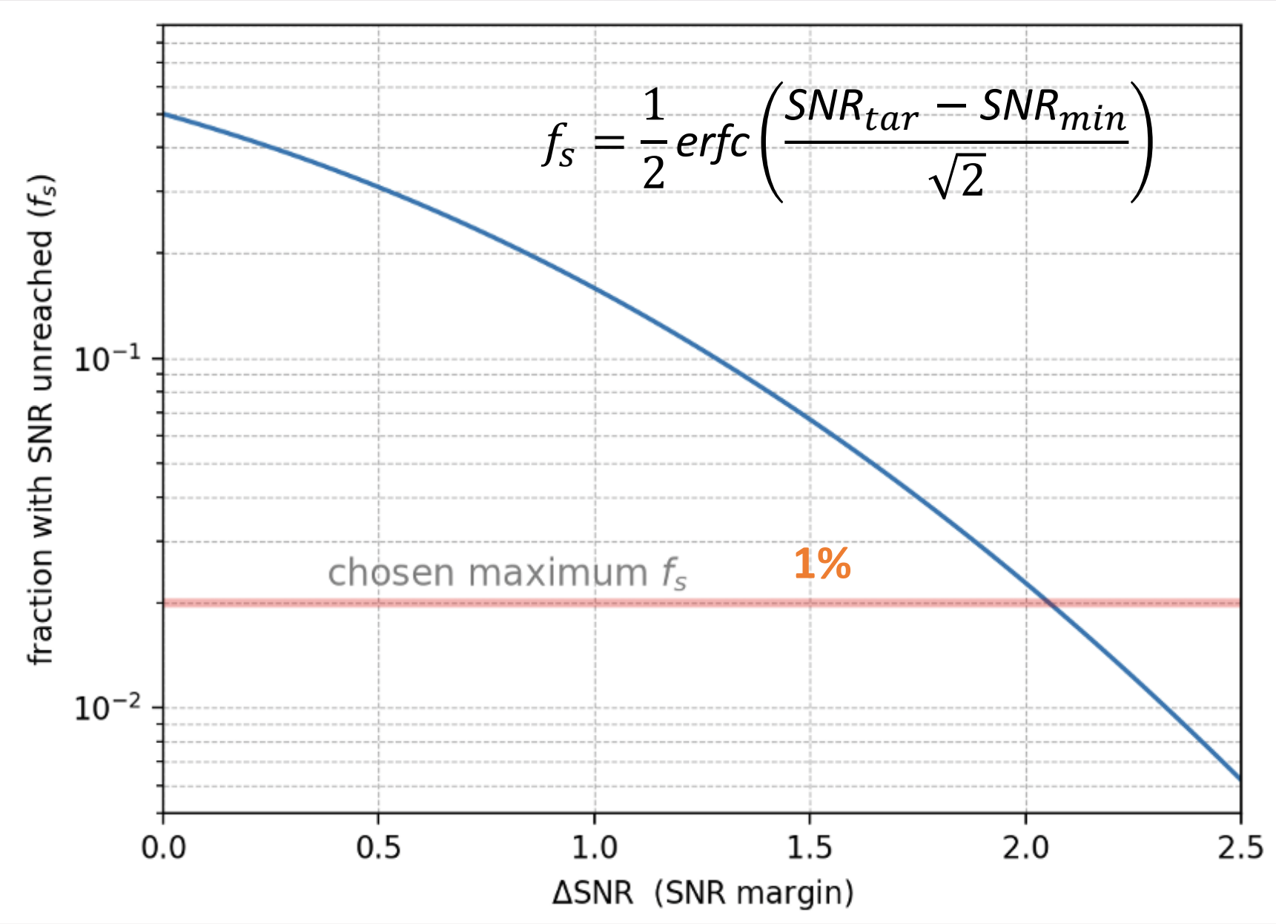
Can you spot the signal pixel?
Each has as many pixels as a dark hole has speckles. One of these is a signal ("planet"). At low SNR's there are false positives.

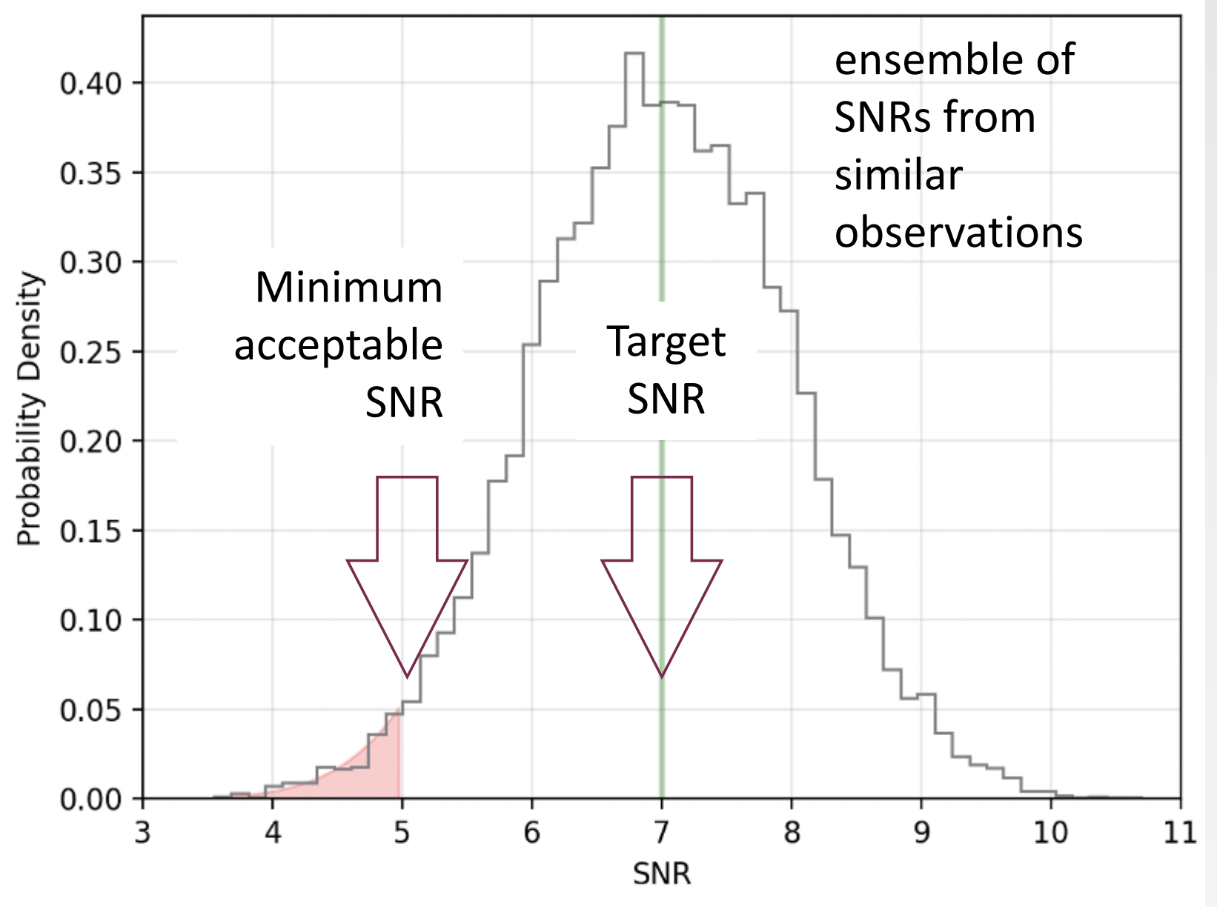

$$P_{FA} = 1 - \left(1 - \frac{1}{2} erfc\left(\frac{SNR}{\sqrt{2}}\right)\right)^{N_{obs} \cdot N_{DH}}$$



MUST SHOOT FOR A HIGHER SNR

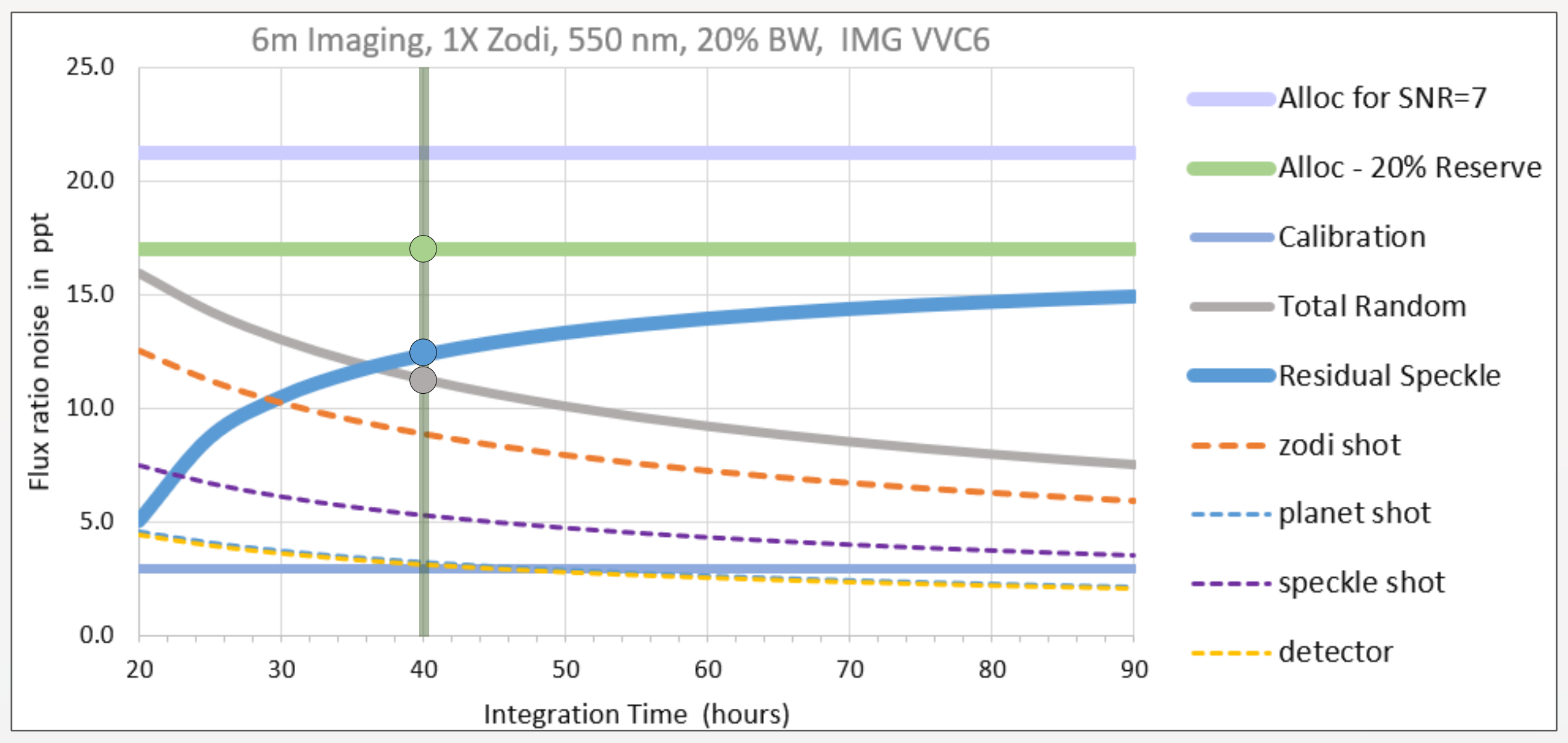
Calculations of SNR for a given integration time, etc. actually give the **50th percentile** SNR: ½ the time we would not get that SNR. Remedy: calculate the time for a higher SNR such that the probability of reaching the desired SNR is high.


$$f_s = \frac{1}{2} erfc\left(\frac{SNR_{tar} - SNR_{min}}{\sqrt{2}}\right)$$



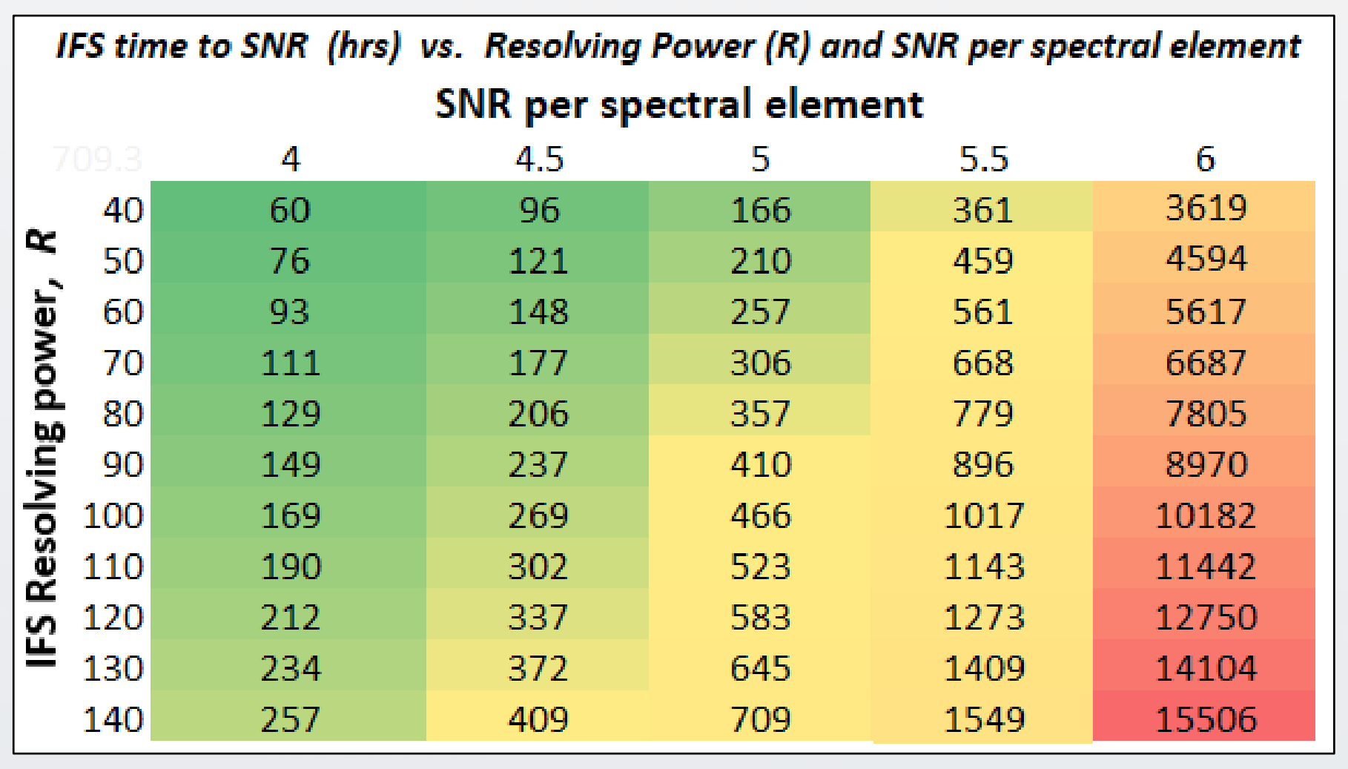
DERIVING FLUX RATIO NOISE BUDGET ALLOCATIONS

Start with the flux ratio that must be detected, and the SNR with which it must be detected. Then forward model the photometric errors for the given instrument assumptions. Select a workable integration time. Read off the remaining error that can be allocated to residual speckle.



CONVENTIONAL IFS SPECTROSCOPY OF EXO-EARTHS TAKES A LONG TIME

Depending on the required SNR per spectral element, the integration time per target is large. For an exo-Earth, and assuming a very low SNR of 5.5 per spectral element, and R = 140, the integration time is approximately 1550 hours, dominated by exo-Zodi, if we assume ultra-low dark current (< 0.1 e/pix/hr.) This means that obtaining 24 spectra will take ~4.2 years of pure spectroscopy integration time.

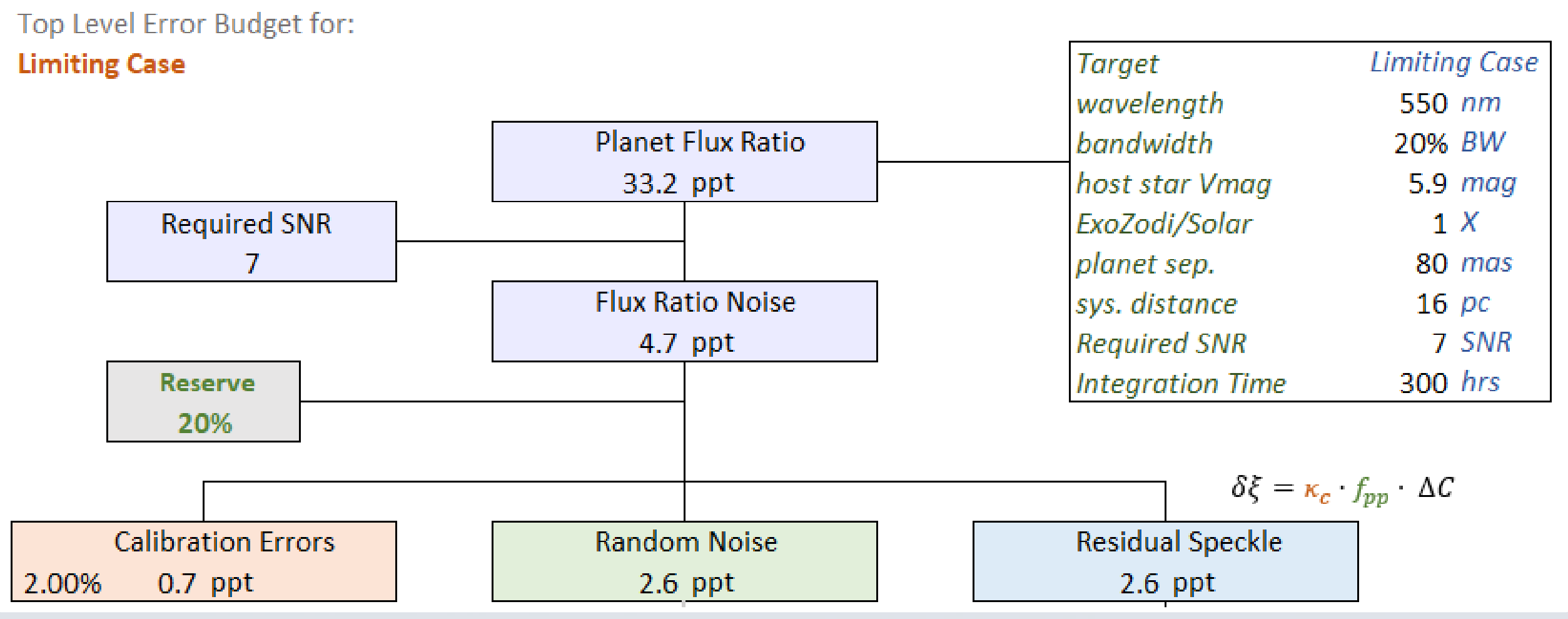

IFS time to SNR (hrs) vs. Resolving Power (R) and SNR per spectral element

SNR per spectral element

IFS Resolving power, R 709.3	4	4.5	5	5.5	6
40	60	96	166	361	3619
50	76	121	210	459	4594
60	93	148	257	561	5617
70	111	177	306	668	6687
80	129	206	357	779	7805
90	149	237	410	896	8970
100	169	269	466	1017	10182
110	190	302	523	1143	11442
120	212	337	583	1273	12750
130	234	372	645	1409	14104
140	257	409	709	1549	15506

TOP LEVEL ERROR BUDGET FOR A WIDER (DEEPER) SEARCH

Wider searches need to emphasize smaller rocky planets farther out due to the expected population statistics. However, these will experience severe photometric challenges.
For the limiting target, even at an aggressive phase angle of 50 degrees, the flux ratio is only 33 ppt. SNR =7 means total allocation is < 4.7 ppt.
Need **300 hrs of integration** time to reduce random noise enough to allow 2.6 ppt for residual speckle. This would be a very tight tolerance.


Top Level Error Budget for:
Limiting Case

Planet Flux Ratio
33.2 ppt

Required SNR
7

Flux Ratio Noise
4.7 ppt

Reserve
20%

Calibration Errors
2.00% 0.7 ppt

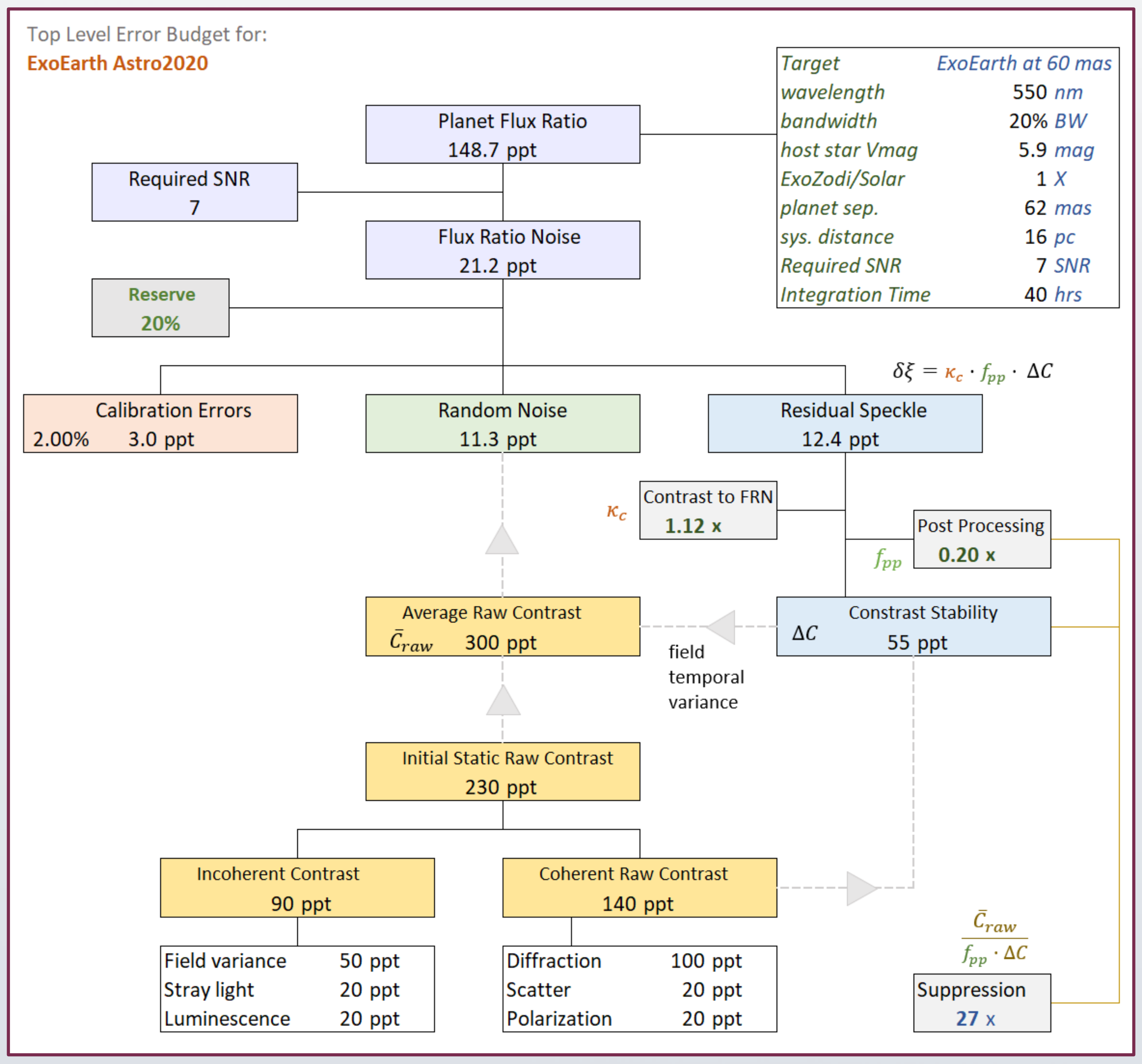
Random Noise
2.6 ppt

Residual Speckle
2.6 ppt

$\delta\xi = \kappa_c \cdot f_{pp} \cdot \Delta C$

Target	Limiting Case
wavelength	550 nm
bandwidth	20% BW
host star Vmag	5.9 mag
ExoZodi/Solar	1 X
planet sep.	80 mas
sys. distance	16 pc
Required SNR	7 SNR
Integration Time	300 hrs

ERROR BUDGET FOR EXO-EARTH IMAGING


Top Level Error Budget for:
ExoEarth Astro2020

Planet Flux Ratio
148.7 ppt

Required SNR
7

Flux Ratio Noise
21.2 ppt

Reserve
20%

Calibration Errors
2.00% 3.0 ppt

Random Noise
11.3 ppt

Residual Speckle
12.4 ppt

$\delta\xi = \kappa_c \cdot f_{pp} \cdot \Delta C$

κ_c Contrast to FRN
1.12 x

f_{pp} Post Processing
0.20 x

Average Raw Contrast
$\bar{C}_{raw}$ 300 ppt

field temporal variance

ΔC Constrast Stability
55 ppt

Initial Static Raw Contrast
230 ppt

Incoherent Contrast
90 ppt

Coherent Raw Contrast
140 ppt

Field variance	50 ppt
Stray light	20 ppt
Luminescence	20 ppt

Diffraction	100 ppt
Scatter	20 ppt
Polarization	20 ppt

$\frac{\bar{C}_{raw}}{f_{pp} \cdot \Delta C}$

Suppression
27 x

Target	ExoEarth at 60 mas
wavelength	550 nm
bandwidth	20% BW
host star Vmag	5.9 mag
ExoZodi/Solar	1 X
planet sep.	62 mas
sys. distance	16 pc
Required SNR	7 SNR
Integration Time	40 hrs

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