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Coronagraph

WFIRST

WFIRST Coronagraph Integrated Modeling

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FSWG Meeting

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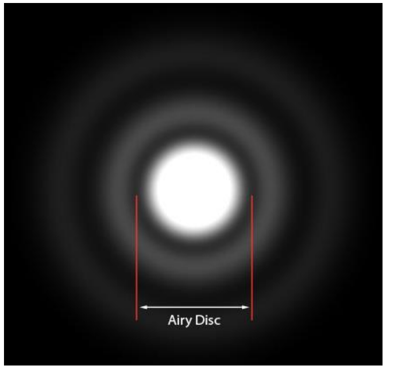
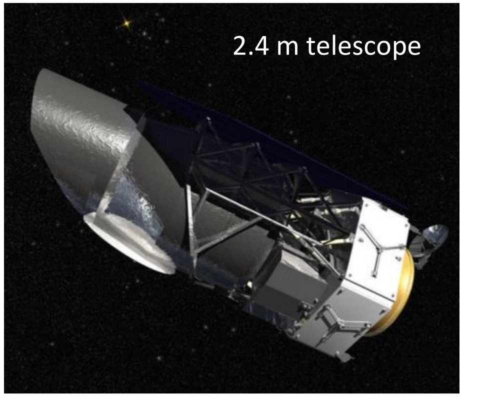
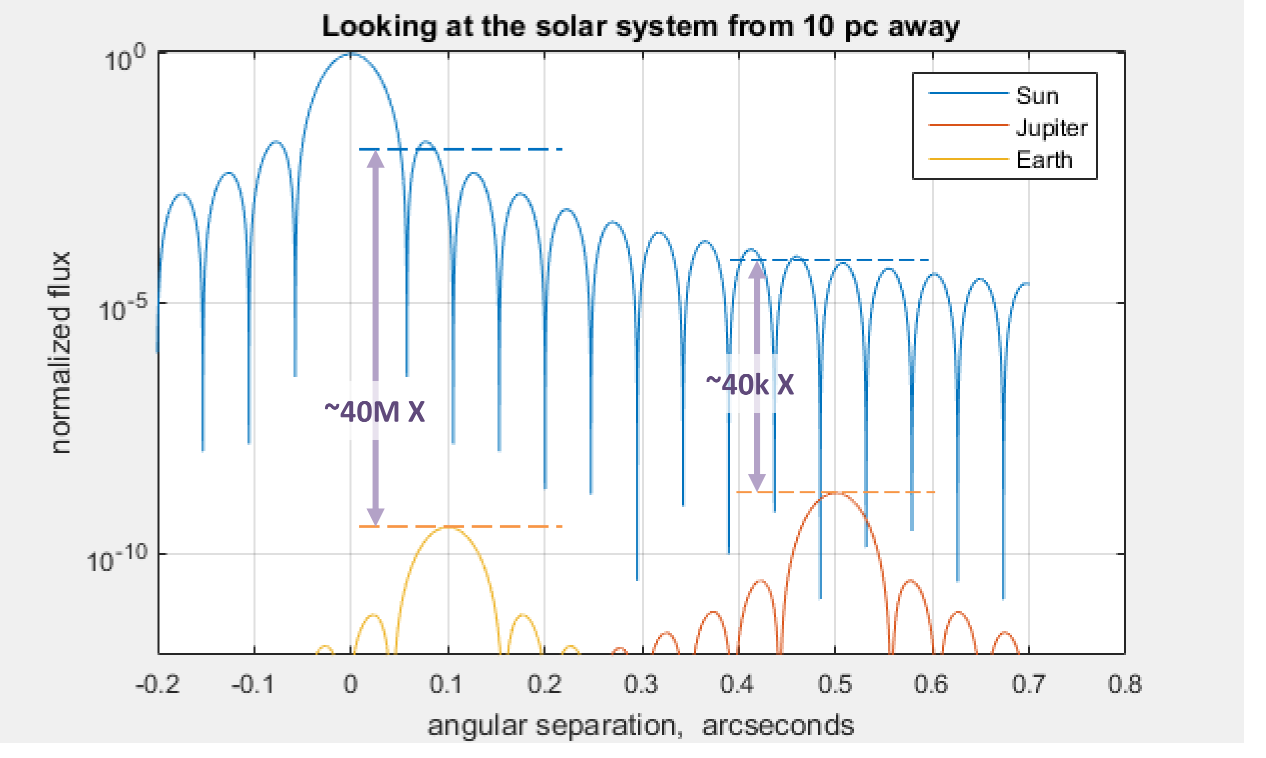
Exoplanet Direct Detection

- Diffraction of the star's light **buries** the planet light





- Using a normal telescope, signal to noise ratio is very small!

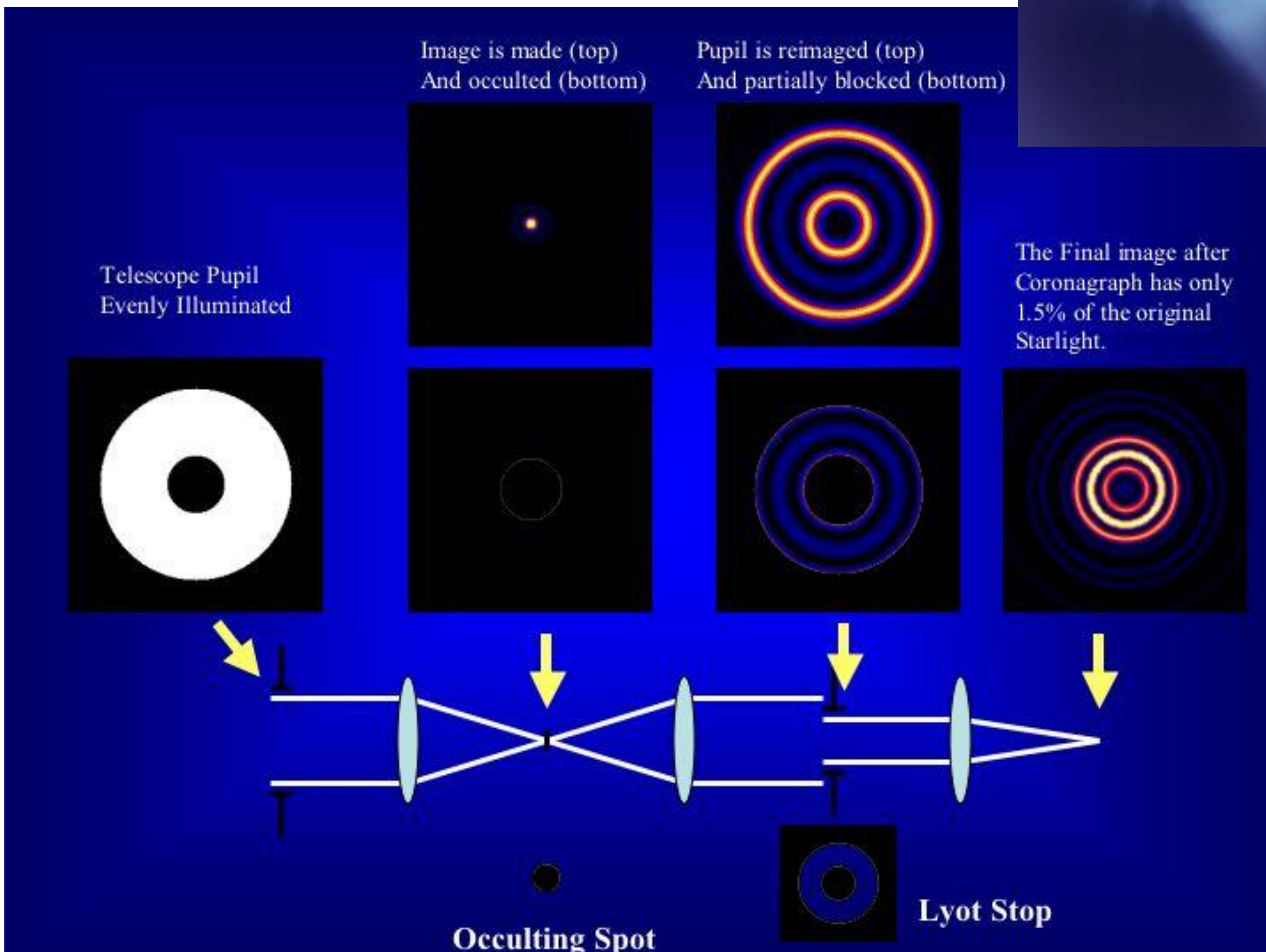


Lyot Coronagraph

Bernard Lyot, 1939

French Astronomer

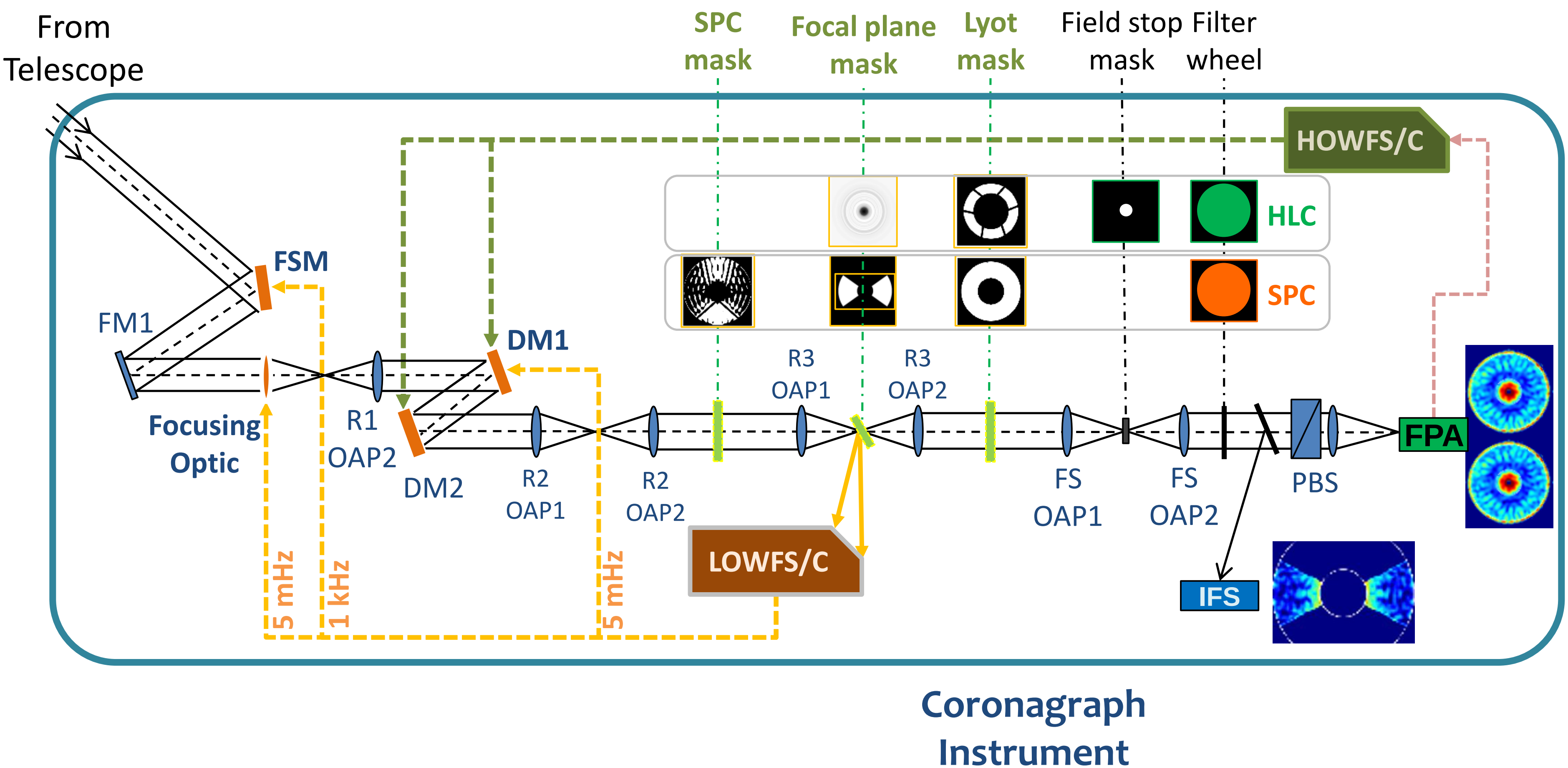
Inventor of the Coronagraph



http://lyot.org/background/coronagraphy.html

Coronagraph Optical Layout

Three Coronagraph configurations for a variety of science applications



Spectroscopy with Integral Field Spectrograph (IFS)

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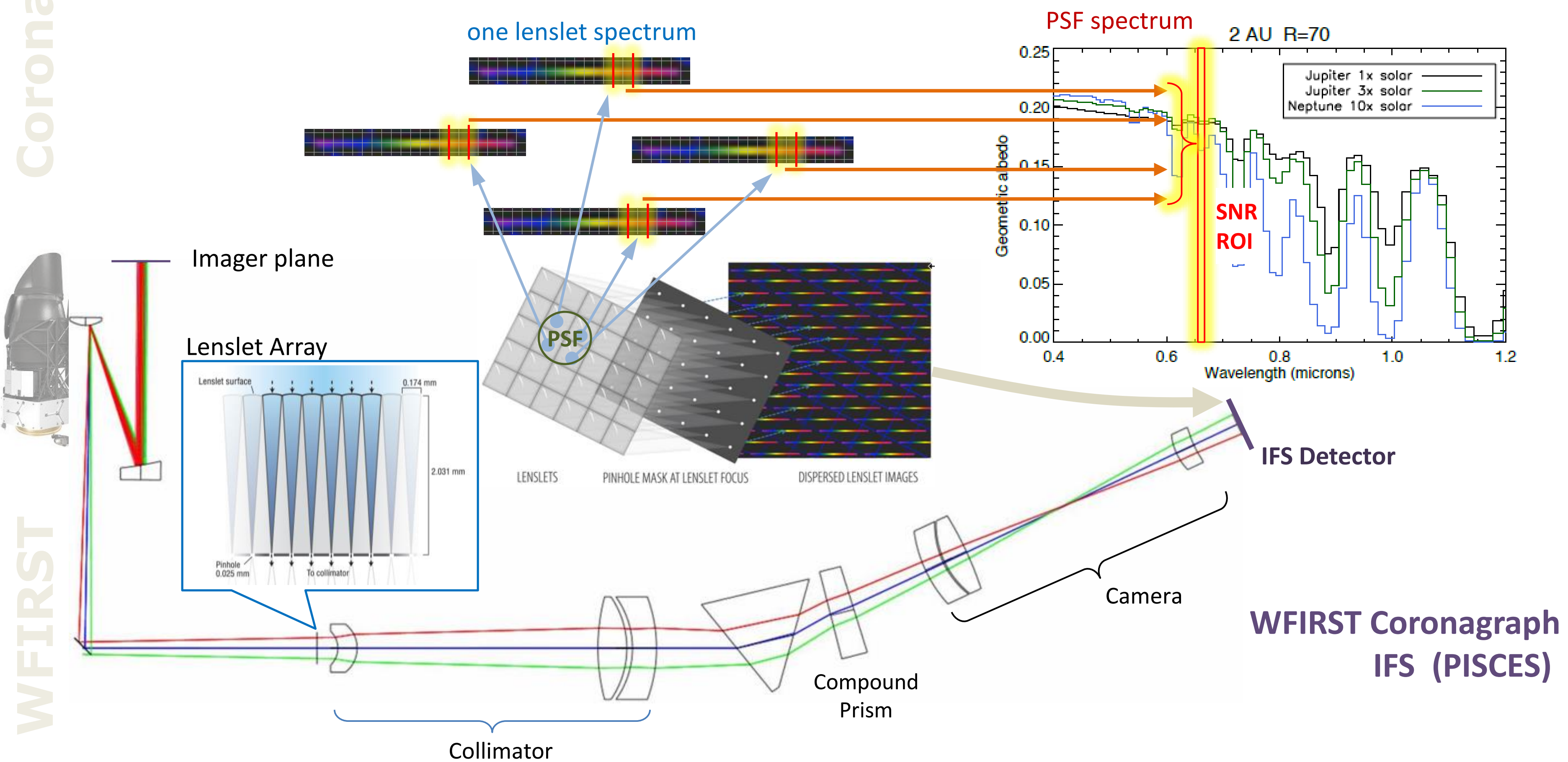
For the IFS, the SNR region of interest (ROI) comprises the collection of pixels that altogether are involved in the photometry of a *single spectral element*

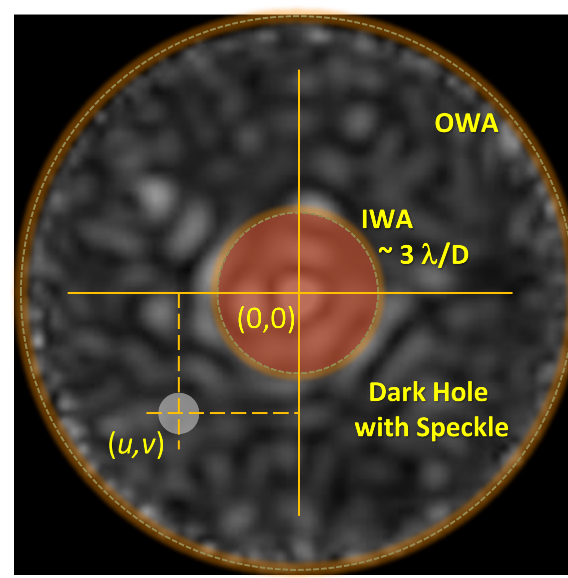


Coronagraph Contrast

- The Coronagraph contrast is computed on a per pixel basis.
- Steps to getting contrast at (u, v)
  1. Propagate a flat wavefront (corresponding to the star being at 0,0) through the optical system, from the primary all the way to the imager
  2. Obtain the intensity distribution $I(u, v; 0{,}0)$ in the focal plane
     - Normalize the intensity distribution to the total incident power (photons/second) incident on the unobscured parts of the primary.
  3. Repeat with a tilt applied to the incoming wavefront so that the star is effectively at (u, v) → this gives $I(u, v; u, v)$
  4. Divide the intensity distribution in step 2 by the PSF peak in step 3

evaluate | source

$$C_{CG}(u, v) \equiv \frac{I_{star}(u, v; 0, 0)}{I_{star}(u, v; u, v)}$$



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Planet Flux Ratio

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- Planet flux ratio (aka planet contrast) is independent of the instrument. It is simply the ratio of the flux arriving at the instrument aperture from the planet divided by the same from the star.

albedo

$$\xi_{pl} = P \cdot \phi(\alpha) \cdot \left(\frac{r_p}{a}\right)^2$$

Phase law

Traub & Oppenheimer

The *geometric albedo* p of a planet is defined to be the ratio of planet brightness at $\alpha = 0$ to the brightness of a perfectly diffusing disk with the same position and apparent size as the planet. In other words, p is the ratio of the flux reflected toward an observer at zero phase angle to the flux from the star that is incident on the planet. The geometric albedo will in general be wavelength dependent. Numerical values of p_V, for the visible band, are listed in Table 3.

The reflected-light contrast of a planet can be written as

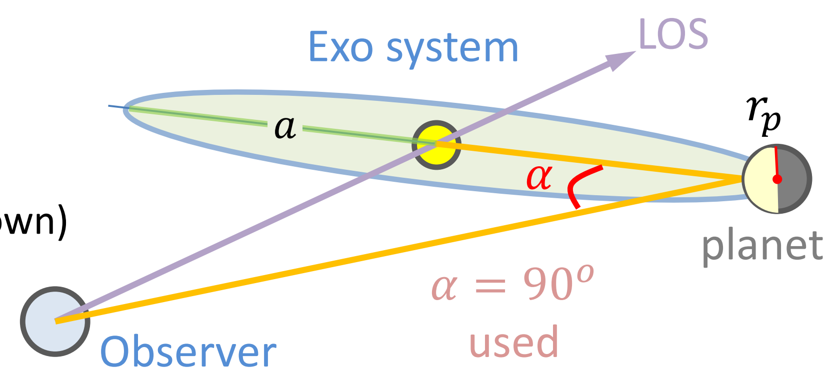
$$C_{vis} = p\phi(\alpha)(r_p/a)^2 \qquad (14)$$

where $\phi(\alpha)$ is the phase law, sometimes called the integral phase function, at phase angle α, r_p is the planet radius, and a is the distance from planet to star, here simply written as the semimajor axis. For a Lambert sphere the phase law is

$$\phi(\alpha) = [\sin(\alpha) + (\pi - \alpha)\cos(\alpha)]/\pi \qquad (15)$$

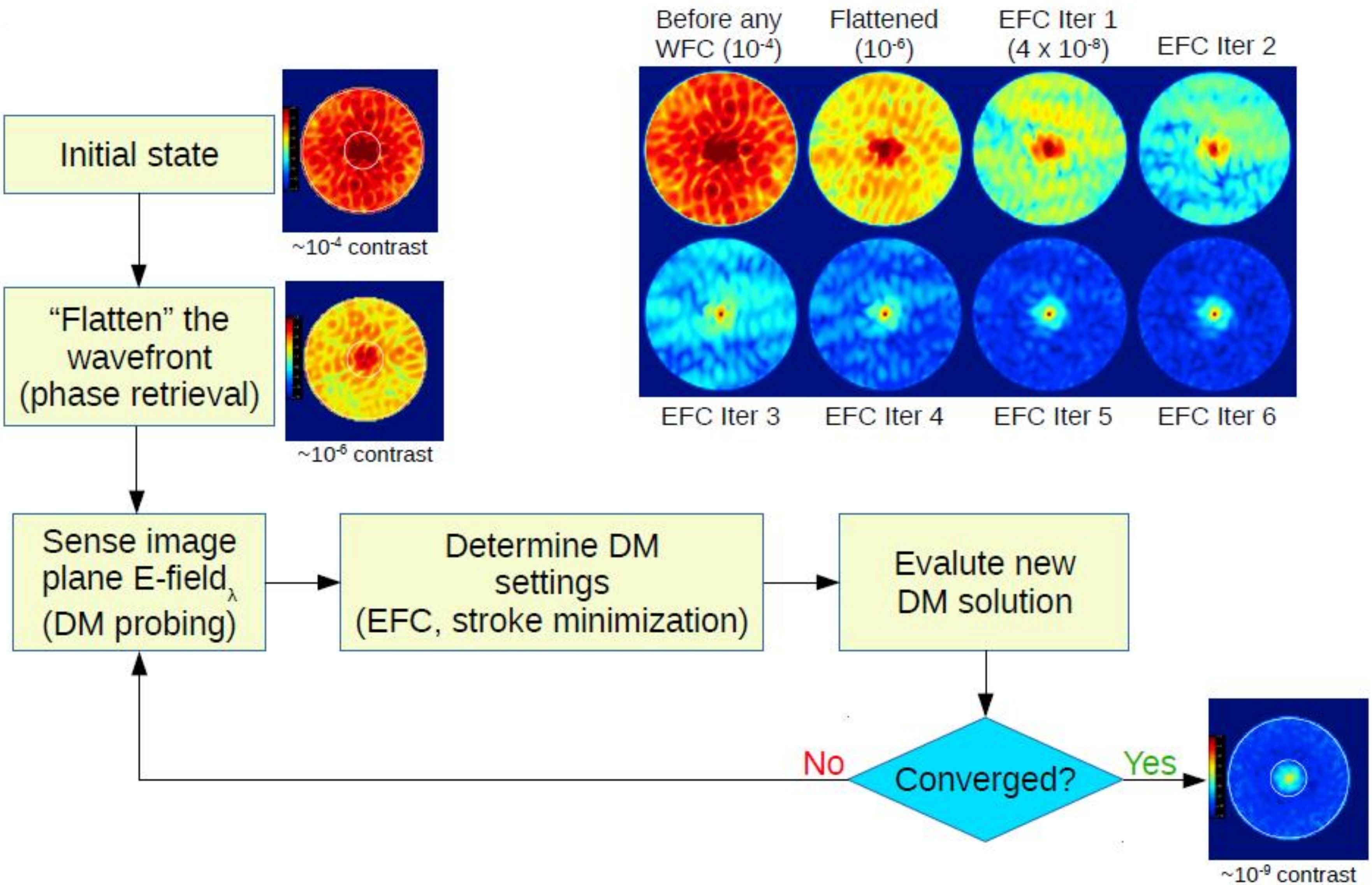
For example, in an edge-on system $\phi(0) = 1$ at superior conjunction, $\phi(\pi/2) = 1/\pi$ at maximum elongation, and $\phi(\pi) = 0$ at inferior conjunction.

(simple case of 90 deg inclination angle shown)




```
% Planet contrast C = albedo * phi(alpha) * (r_p / SMA)^2;
% phi(alpha) = (sin(alpha) + (pi-alpha)*cos(alpha)) / pi , where alpha = phase angle
```

Creating A Starlight "Dark Zone" To See Planets



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Digging A Dark Hole: Contrast vs. Iteration

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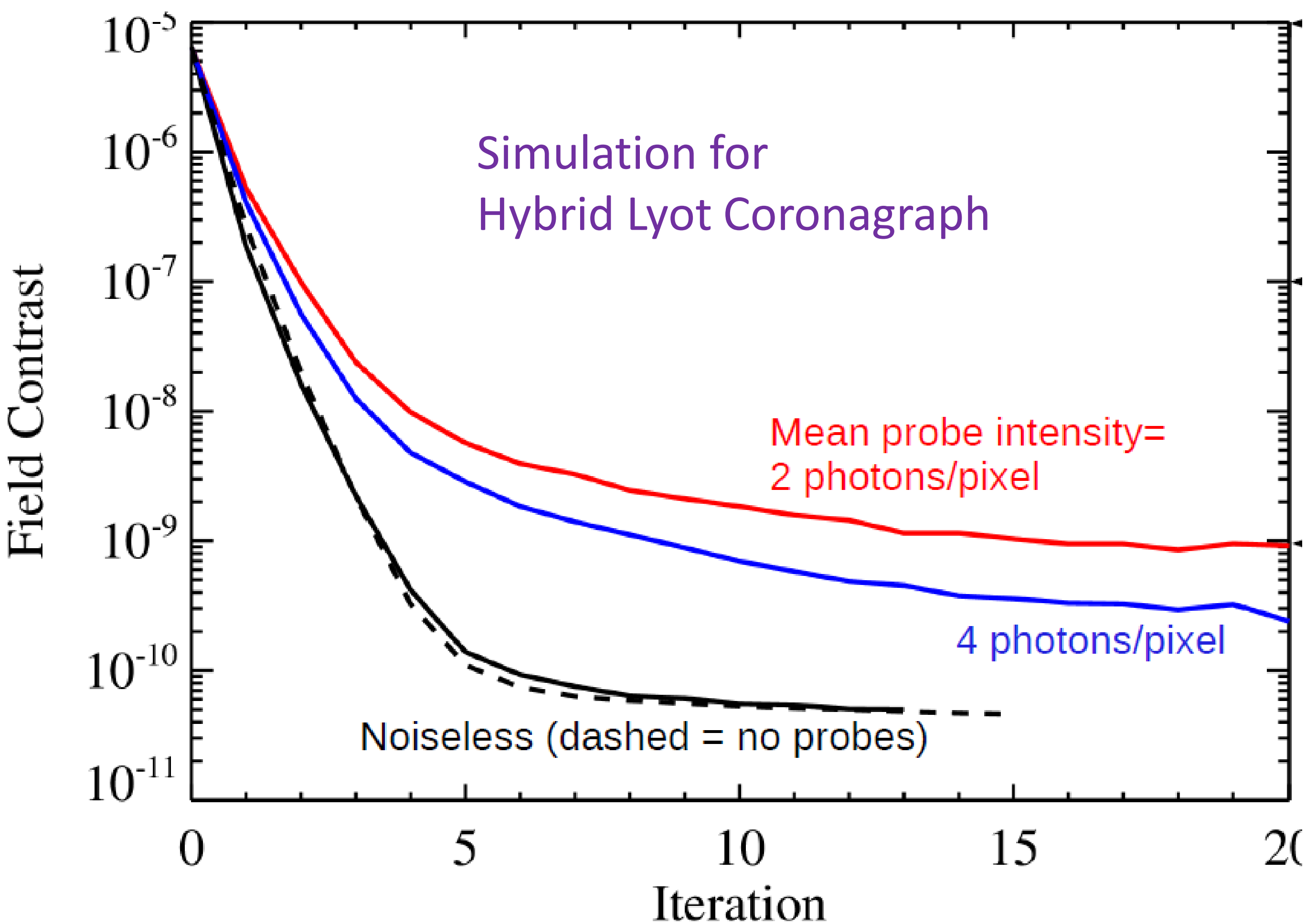
WFIRST requirement is C < 1e-8 before post-processing

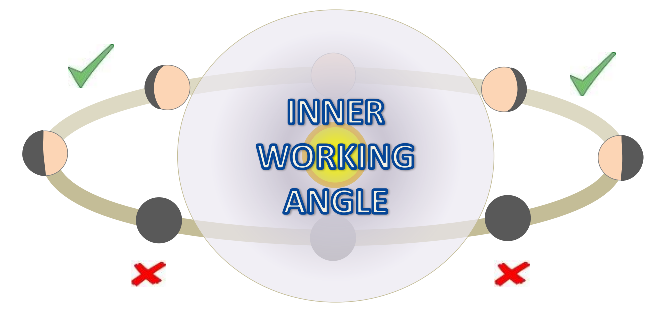


What are typical Rates?

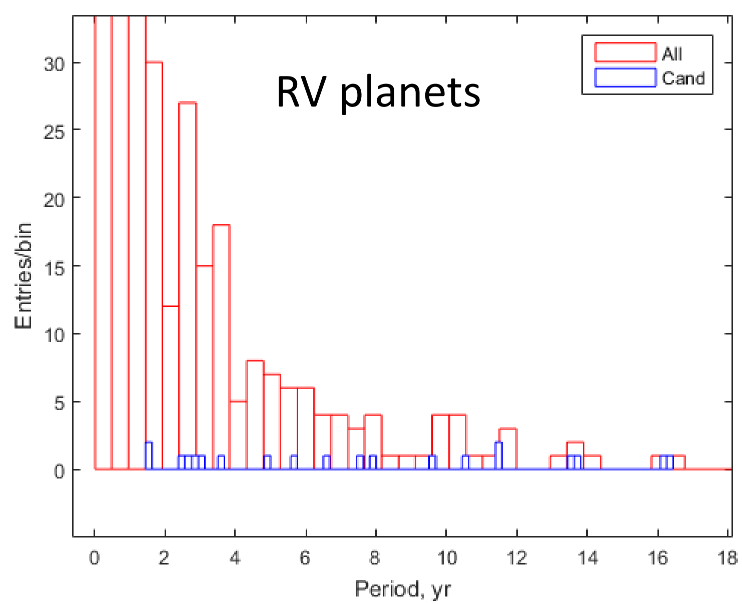
47 UMa c, V = 5, FR = 8e-9		
Central and strut obscurations	85%	
Reflections, filter, polarizer	26%	
Core throughput	3.9%	
Planet Photons entering telescope	2	ph/s
Photons into image plane airy disk	0.017	ph/s
Imager photons per pixel	0.0035	ph/s
IFS photons per pixel	0.00012	ph/s

Planet Orbital Phase

- Planet orbital phase affects the planet contrast.
- In general the planet is only viewable about 1/3 of the time
- The typical RV candidate will have an 8 year orbital period.
- We will want to optimize observation times to ‘catch the planet’ near a favorable phase.
- Our selected systems will be ones with orbital phase and inclination information available
- One consequence is that planet observations will necessarily be interspersed throughout the mission lifetime.
  - Early ones will see a new detector
  - Last ones will see a detector with traps



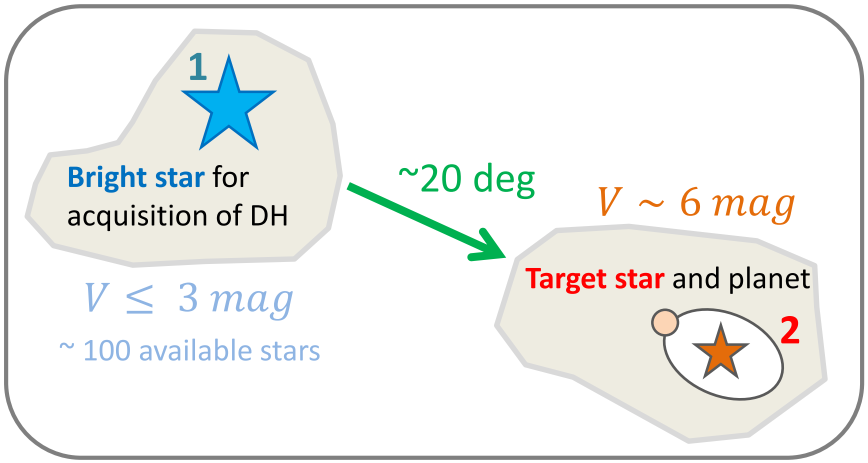
the planet will be observable only ~ 1/3 of the time

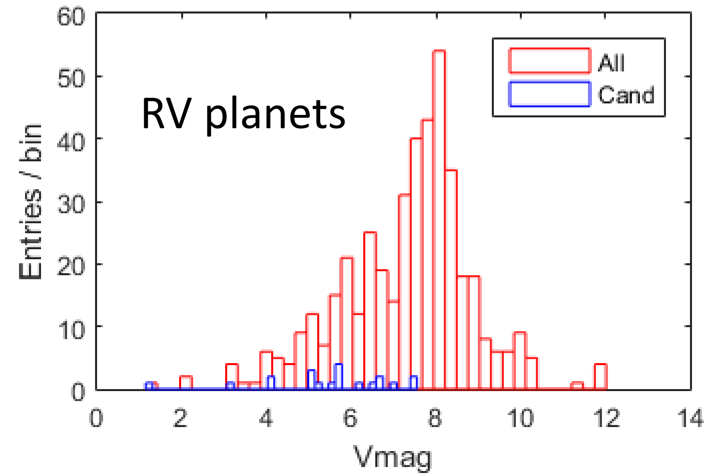


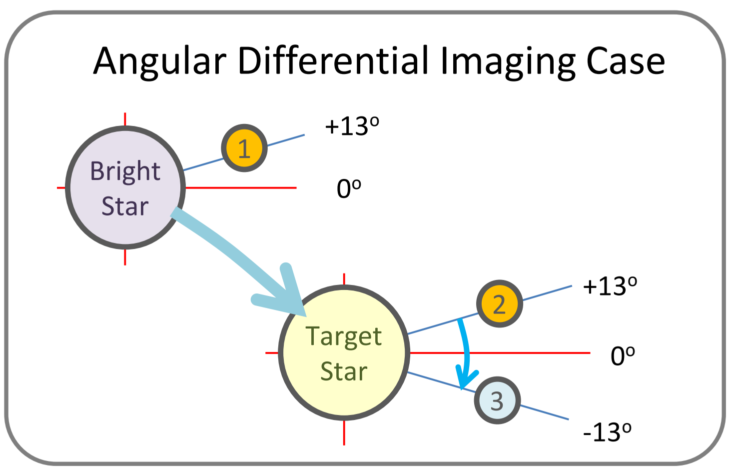
Typical Observing Sequence

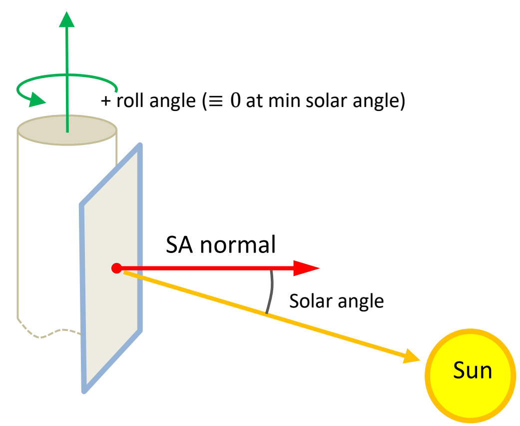
- The typical scenario involves two stars:
  1. A nearby **bright star** for getting a dark hole (~ 3 Hrs)*
  2. The planet host **target star** (~10 Hrs)*

* numbers notional



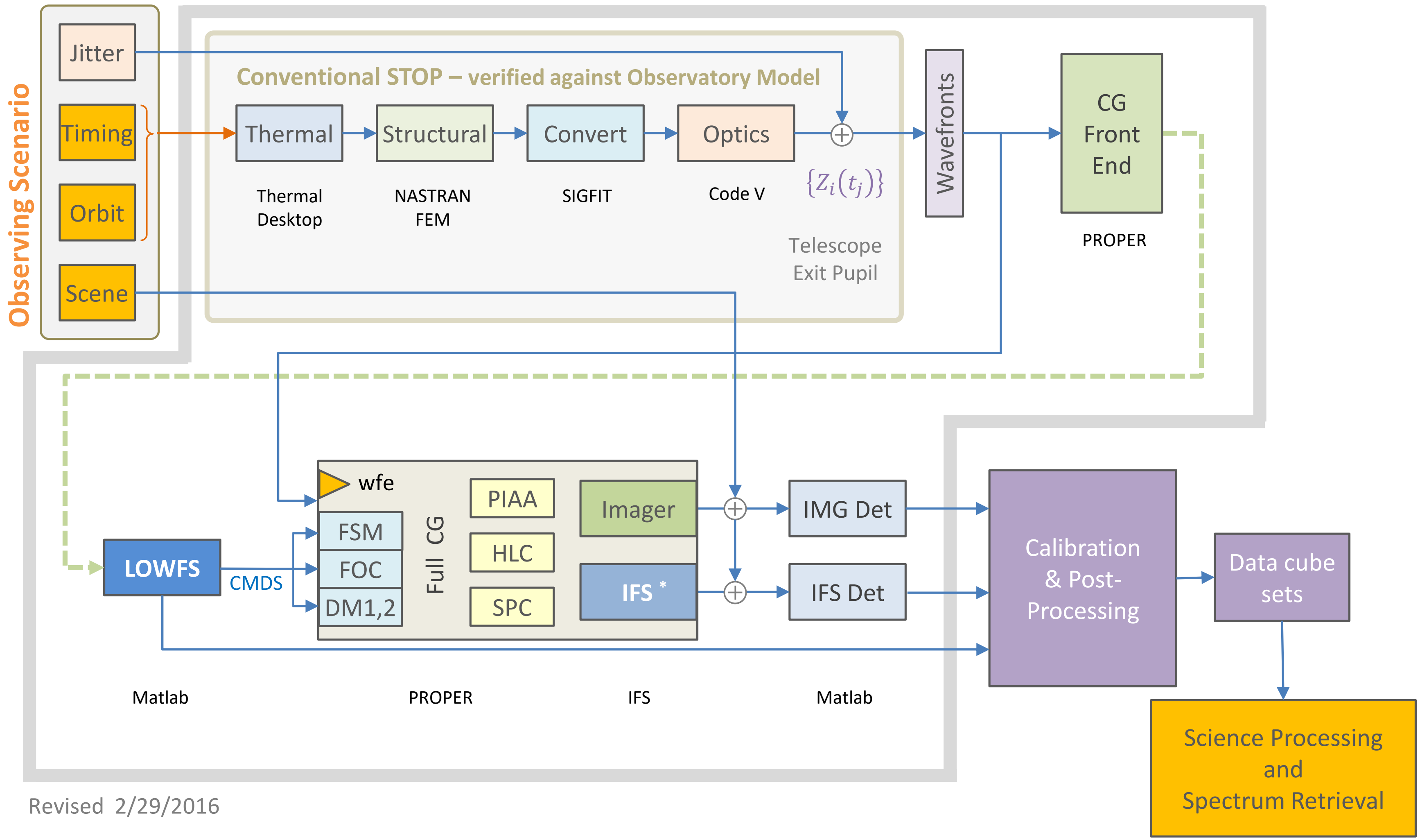






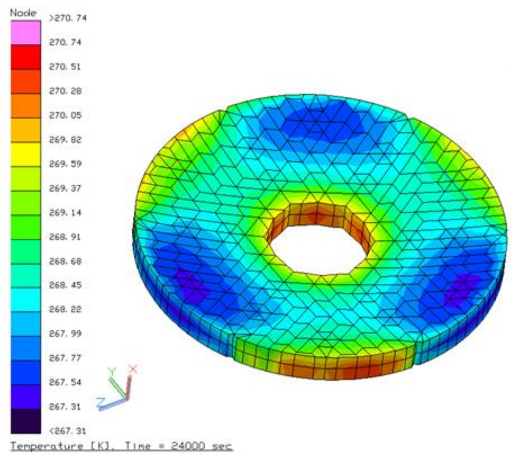
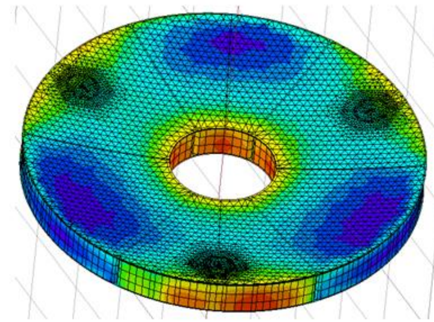
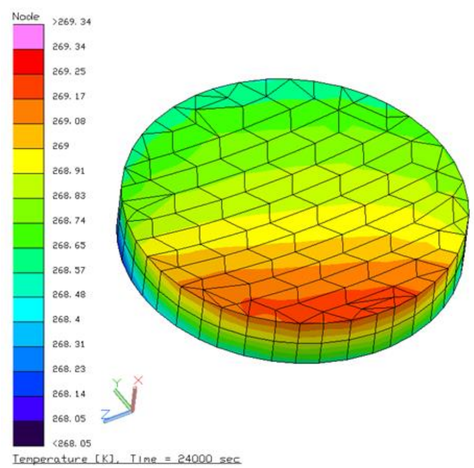
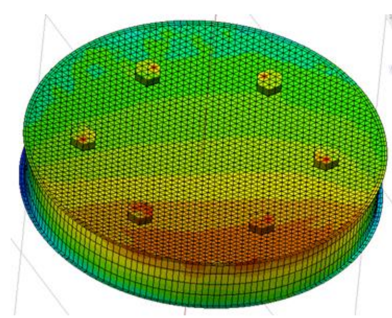
Coronagraph Integrated Model in Context

The Observatory STOP model is the official reference for design evaluations – the CGI STOP steps as shown are slightly different.



Thermal → Structural Mapping

- Example at t = 24000 sec

	Thermal	Structural
PM		
SM		

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Observing Scenario Speckle Movie

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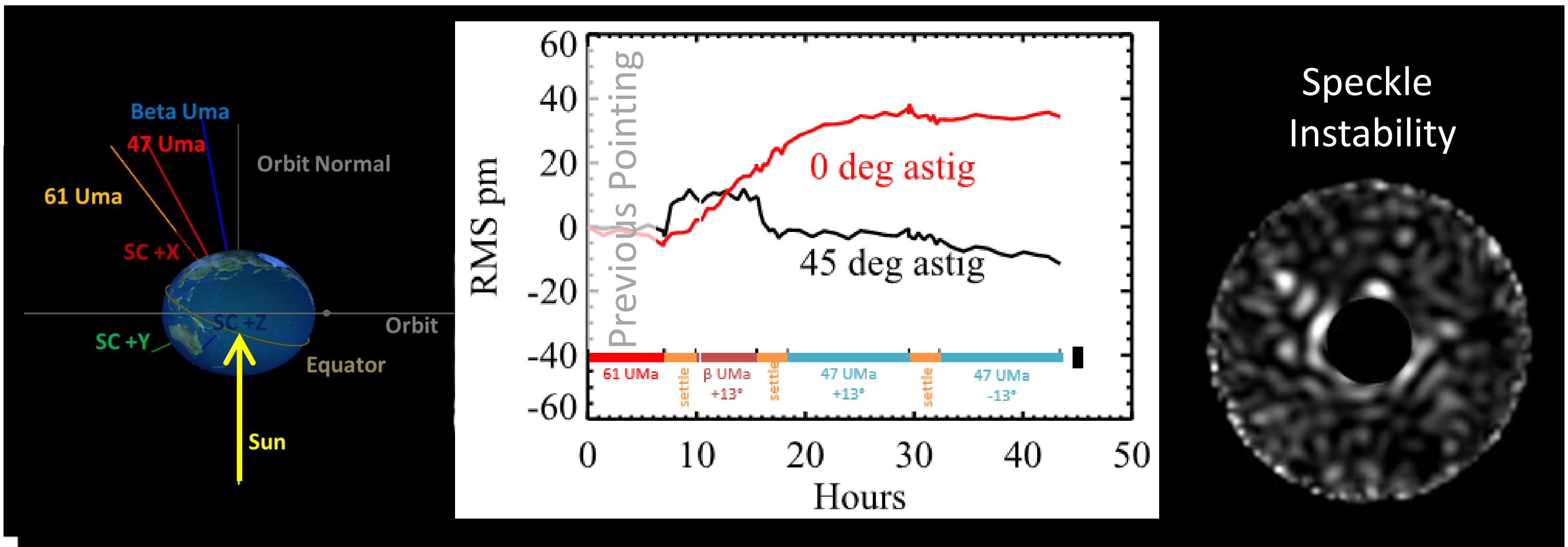
Simulate the entire observing sequence for a 'typical' target, and assess speckle stability



settle	β UMa +13°	settle	47 UMa +13°	settle	47 UMa -13°

Reference and Angular Differential Imaging

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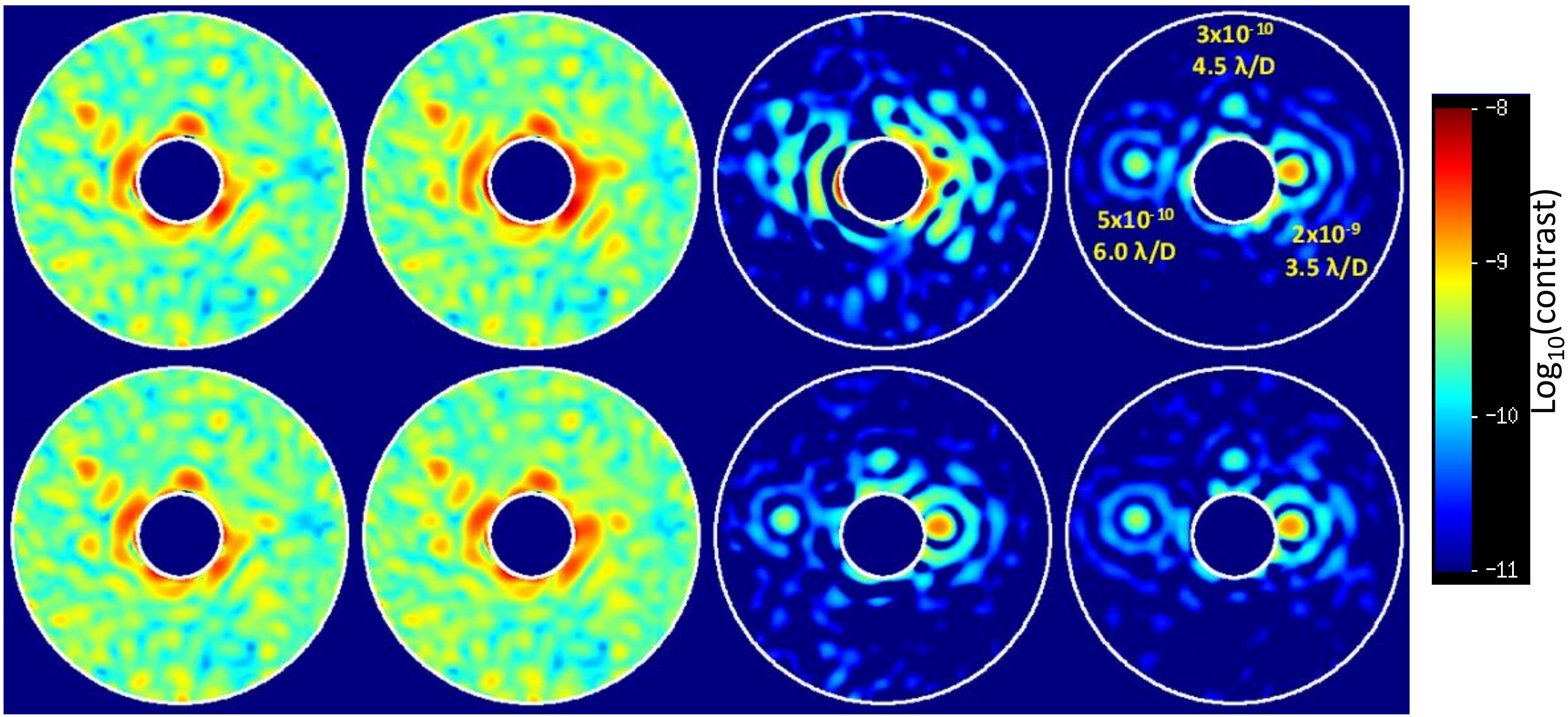
Are the Speckles Stable Enough to Allow Differential Imaging?

RDI | ADI

β UMa | 47 UMa$_{+13°}$ | 47 UMa $_{+13°}$ - β UMa | 47 UMa iterative roll subtraction*

Control Off

Low Order Control



Using LOWFC improves stability at IWA and between stars

*Described in Krist et al., "HST and Spitzer Observations of the HD 207129 Debris Ring", Astron. J., 140, 1051 (2010).

Analytical Expression for SNR

- Photometric SNR means we include planet shot noise
  - Keep in mind that we are considering the post speckle-subtraction SNR

$$SNR \equiv S = \frac{P}{\sigma_{tot}}$$

$$P = r_{pl}\, t$$ planet signal

- We write the total noise as:

$$\sigma_{tot}^2 = \sigma_r^2 + \sigma_s^2$$

σ_r^2: random, uncorrelated, reduces with t

σ_s^2: Speckle subtraction error, excluding measurement noise

- The uncorrelated, random noise is given by:

planet — speckle — zodi — dark — clk. Ind. Chg. — read noise

$$\frac{\sigma_r^2}{t} = r_n = f_{SR}\, F^2 \left[\Phi_*\, C_{pl}\, \tau_{pl} + \Phi_* C_{CG} I_{pk} m_{pix} \tau_{sp} + \left(\frac{d\Phi_Z}{d\Omega}\, \Delta\Omega_{PSF} \right) \tau_Z \right] A_{PM}\, \eta + F^2 \left[i_d m_{pix} + q_{CIC} \frac{m_{pix}}{t_{fr}} \right] + \frac{m_{pix}}{t_{fr}} \left(\frac{\sigma_{rd}}{G_{EM}} \right)^2$$

photonic (shot noise) terms — electronic terms

$f_{SR} \equiv$ fraction of core light in region of interest for SNR

$F \equiv$ EMCCD excess noise factor $\sim \sqrt{2}$

$\Phi_* = F_\lambda \cdot \Delta\lambda$ $\quad \Phi_Z = F_\lambda^Z \cdot \Delta\lambda$

Note: This is the post-subtraction error, and should in principle reflect noise contributions for both the *target* and *reference* images. However, consistent with our assumption that the reference is significantly brighter than the target, we consider the error being dominated by the target star image only.

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Putting it all together: time to reach SNR

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Analytical expression for SNR: $S = \dfrac{r_{pl}\, t}{\sqrt{r_n t + \sigma_s^2}}$

planet rate

noise rate

$r_{pl} = f_{SR}\, \Phi_*\, C_{pl}\, \tau_{pl}\, A_{PM}\, \eta$

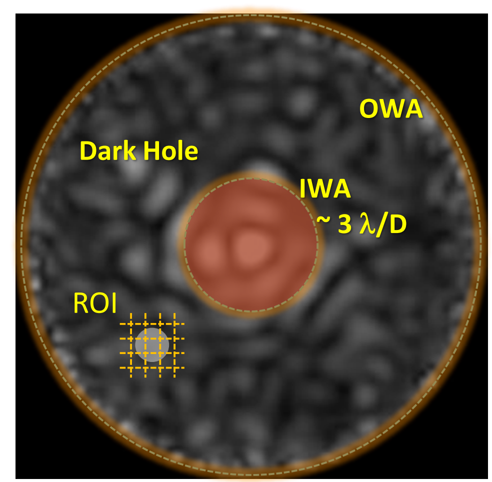
Speckle Subtraction Error: $\sigma_s = f_{pp}\, r_{sp}\, t$

mean speckle rate

$r_{sp} = f_{SR}\, \Phi_* C_{CG} I_{pk} m_{pix} \tau_{sp}\, A_{PM}\, \eta$

Time to reach desired SNR:

$$t = \frac{S^2\, r_n}{r_{pl}^2 - S^2\, f_{pp}^2\, r_{sp}^2}$$



Noise Equivalent Flux Ratio (NEFR): ξ_{eq}

- What is the minimum planet contrast that can be seen with SNR $\geq S$ under our observing scenario?
- Equivalent Flux Ratio Definition:
  - The planet that will be detected with SNR of $\boldsymbol{S}$ after integrating for time t is one which has a planet-contrast equal to the S-$\boldsymbol{\sigma}$ equivalent contrast, after post processing:

Planet signal in the core region after t seconds

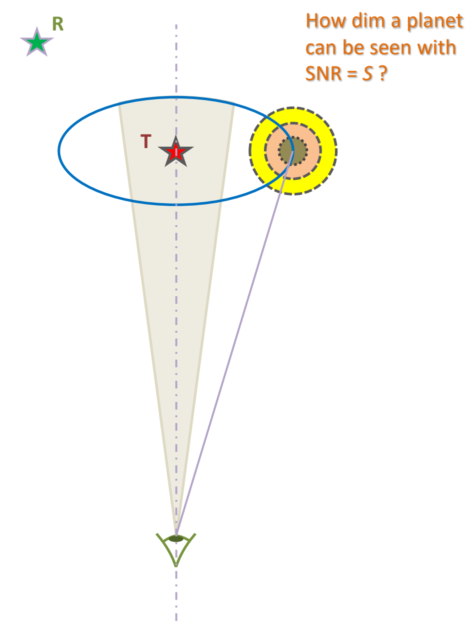
signal fraction · flux · area · thruput · QE · time

$$f_{SR} \cdot \Phi_* \xi_{eq} A \, \tau_{pl} \, \eta \, t = S \cdot \sigma_{tot}$$

$$\xi_{eq} = \kappa \cdot \sigma_{tot}$$

$$\kappa \equiv \frac{S}{f_{SR} \Phi_* A \, \tau_{pl} \, \eta \, t}$$

This conversion factor is set by the scenario parameters



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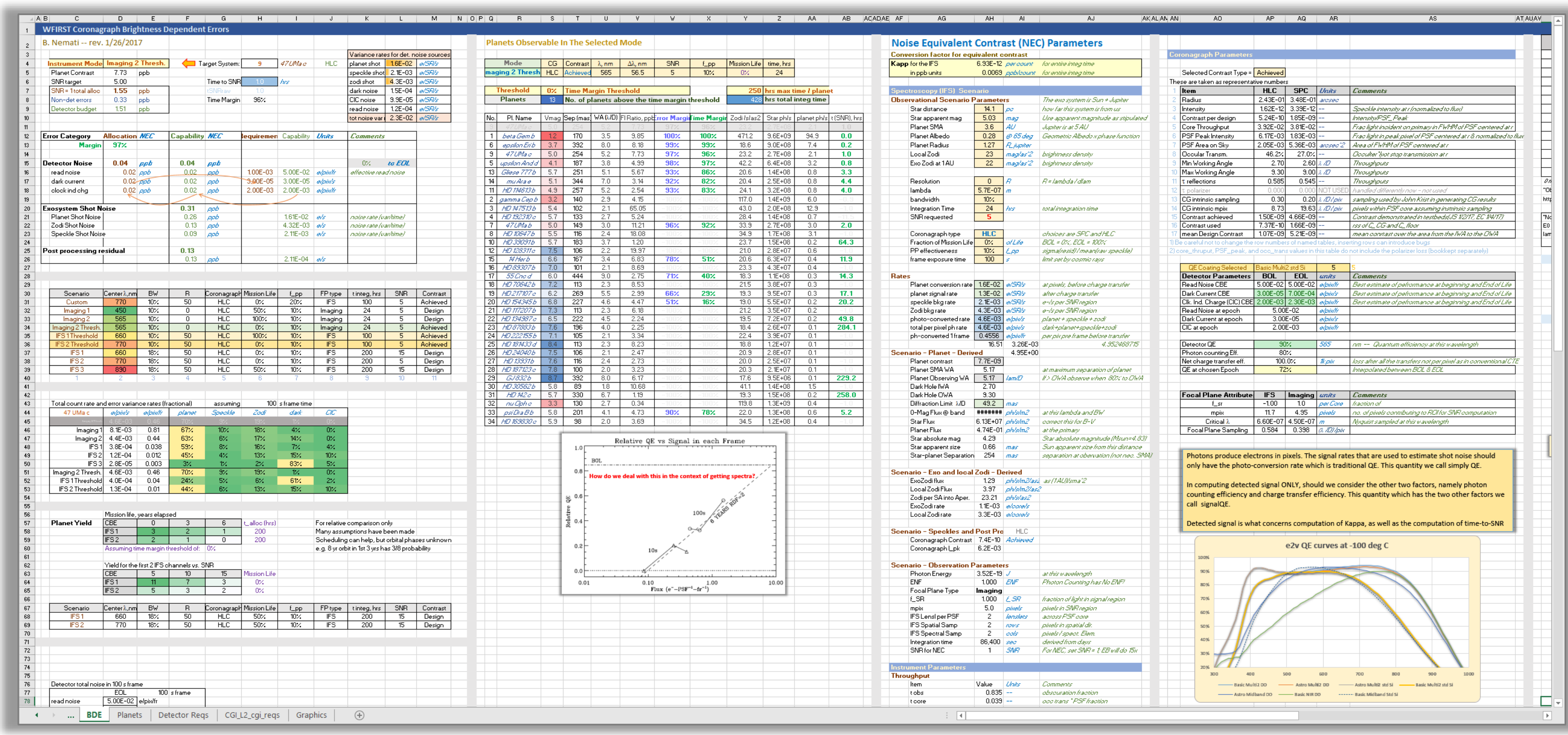
Performance Calculator

- Incorporating the coronagraph performance results, estimates of post processing effectiveness, and estimated detector performance, we can make a top-level science yield model



Basic Observing Modes and Sample Results

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Scenario	Center λ,nm	BW	R	Coronagraph	Mission Life	f_pp	FP type	t integ, hrs	SNR	Contrast
Custom	770	10%	50	HLC	0%	20%	IFS	100	5	Achieved
Imaging 1	450	10%	0	HLC	25%	10%	Imaging	24	5	Design
Imaging 2	565	10%	0	HLC	25%	10%	Imaging	24	5	Design
Imaging 2 Thresh.	565	10%	0	HLC	100%	20%	Imaging	24	5	Achieved
IFS 1 Threshold	660	10%	50	HLC	100%	20%	IFS	100	5	Achieved
IFS 2 Threshold	770	10%	50	HLC	100%	20%	IFS	100	5	Achieved
IFS 1	660	18%	50	SPC	25%	10%	IFS	200	15	Design
IFS 2	770	18%	50	SPC	25%	10%	IFS	200	15	Design
IFS 3	890	18%	50	SPC	25%	10%	IFS	200	15	Design

Total count rate and error variance rates (fractional)				assuming		100 s frame time		
47 UMa c	e/pix/s	e/pix/fr	planet	Speckle	Zodi	dark	CIC
IFS1	3.6E-04	0.04	40%	5%	17%	34%	4%
Imaging 1	8.1E-03	0.81	68%	11%	18%	2%	0%
Imaging 2	4.4E-03	0.44	70%	7%	19%	4%	0%
IFS 1	3.6E-04	0.036	40%	5%	17%	34%	4%
IFS 2	1.2E-04	0.012	21%	6%	8%	59%	6%
IFS 3	3.0E-05	0.003	7%	3%	2%	79%	8%

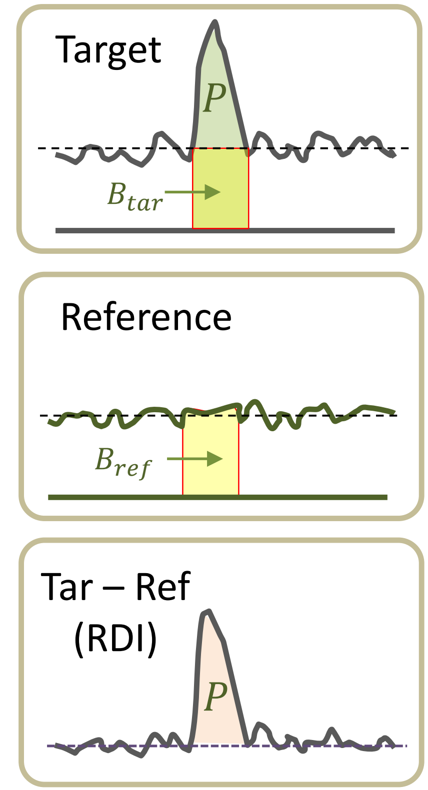
Summary of the contributions to SNR		
47 UMa c	<- example system	
Imaging 2	settings, with	
integ Time	1.1	hrs
	4.9525	pix/SR
SNR =	5	
Signal	46.8	e-
All Noise	9.4	e-
Shot noise	9.1	e-
Elec Noise	2.0	e-
resid. Speckle	0.6	e-

Summary of the contributions to SNR		
47 UMa c	<- example system	
IFS 1	settings, with	
integ Time	107	hrs
	16	pix/SR
SNR =	15	
Signal	944.5	e-
All Noise	63.0	e-
Shot noise	47.3	e-
Elec Noise	36.6	e-
resid. Speckle	19.7	e-

BACKUP

A Simple Observing Scenario

- We seek a simple analytical model of planet yield, via calculating the time to reach a desired SNR
- We choose these assumptions:
  1. We are after a **photometric measurement**
     - Though note that in *detection*, we would not be doing photometry. The SNR is different in that case.
  2. We are doing **differential imaging**.
     - The SNR is the post-differential imaging SNR.
     - For simplicity we assume we are doing **Reference Differential Imaging (RDI)**.
  3. The reference star is brighter than the target star
     - If $\Delta M > 3$ between target and reference then $B_T > 16\ B_R$
     - Shot noise of reference speckles is small compared with shot noise of target speckles
     - There is a normalization step also
  4. Exo-zodi is smooth and extended for both stars
     - Brightness distribution structures are >> lam/D



$$Sig = I_{tar} - I_{ref}$$
$$= (P + B_{tar}) - B_{ref}$$
$$= P + (B_{tar} - B_{ref})$$

Aside: Distinguishing types of SNR

Detection and spectroscopy are different statistical questions.

- For spectrometry, with the IFS, we are interested in the photometric SNR:

planet signal

$$S_{phot} = \frac{P}{\sqrt{P + B}}$$

background

- For planet detection, with the imager, we would be interested in detection SNR:
  - The noise of interest in this case does *not* include the signal's shot noise
  - We are instead interested in the background's false positive probability

$$S_{detec} = \frac{P}{\sqrt{B}}$$