



Jet Propulsion Laboratory
California Institute of Technology

Coronagraph

WFIRST Coronagraph Integrated Modeling



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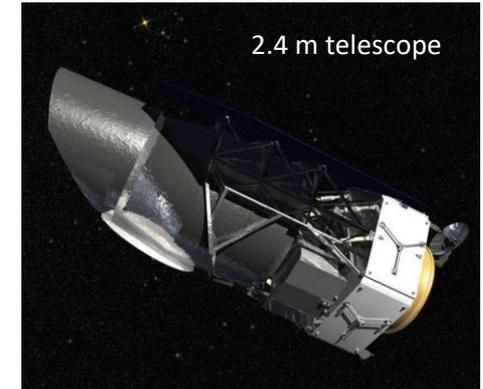
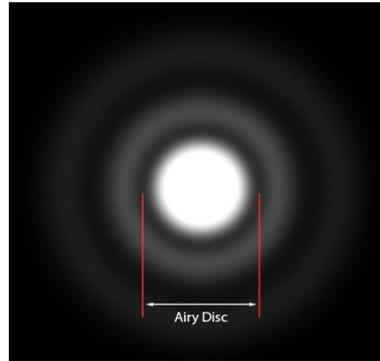
FSWG Meeting

2/8/2017

Exoplanet Direct Detection

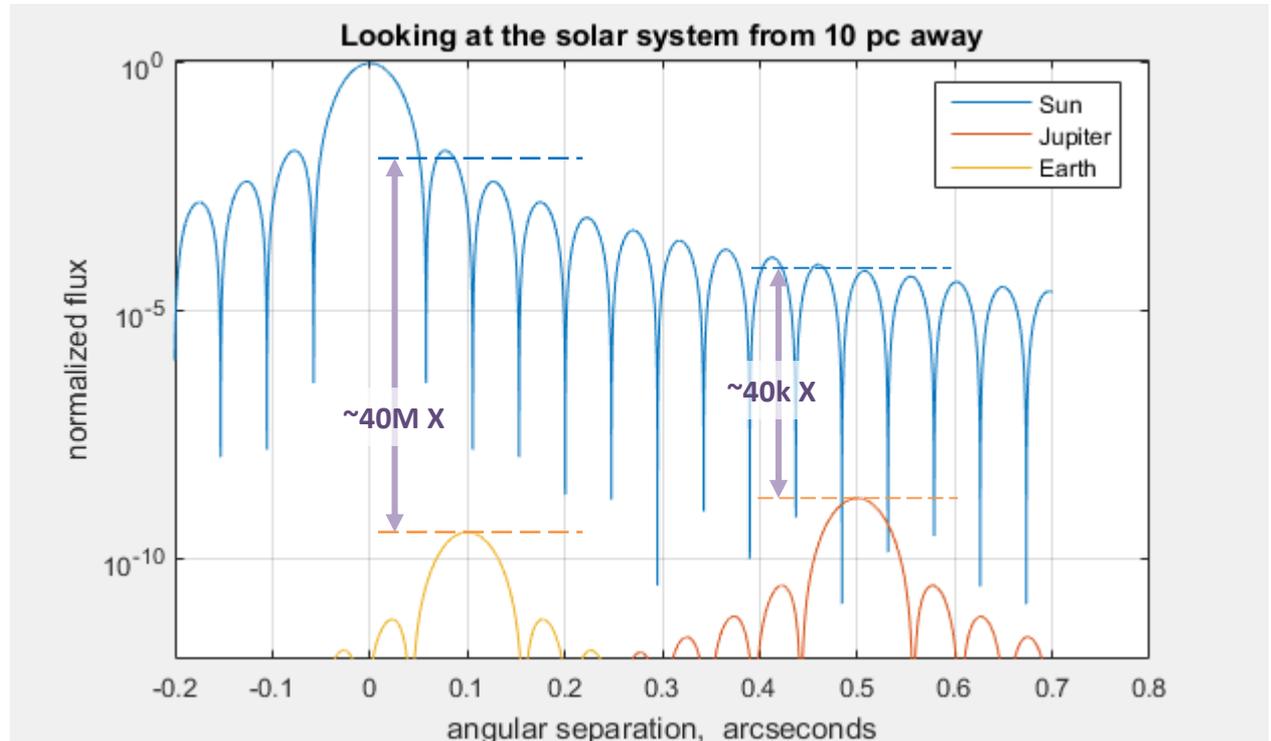
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- Diffraction of the star's light **buries** the planet light



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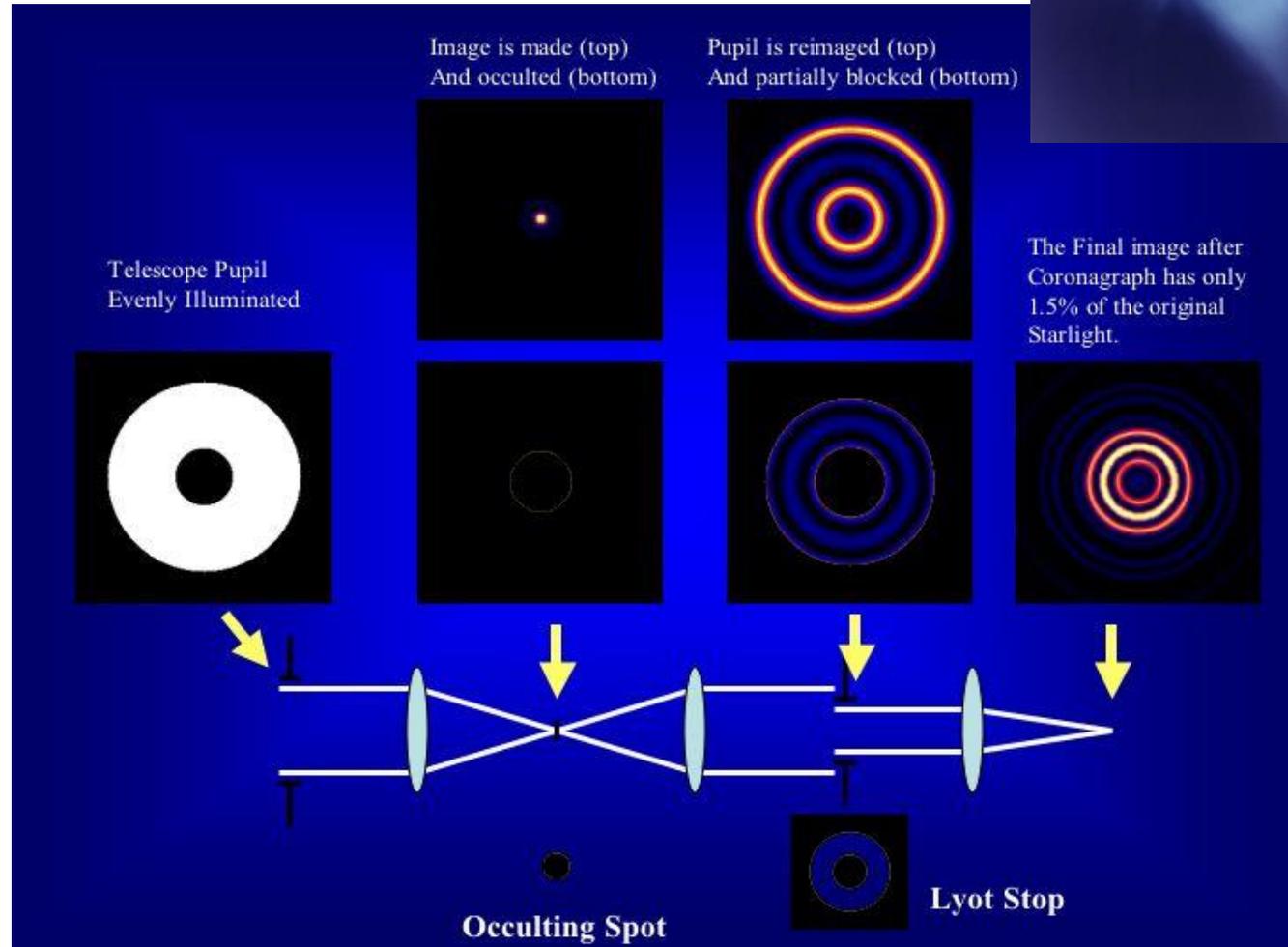
- Using a normal telescope, signal to noise ratio is very small!



Lyot Coronagraph



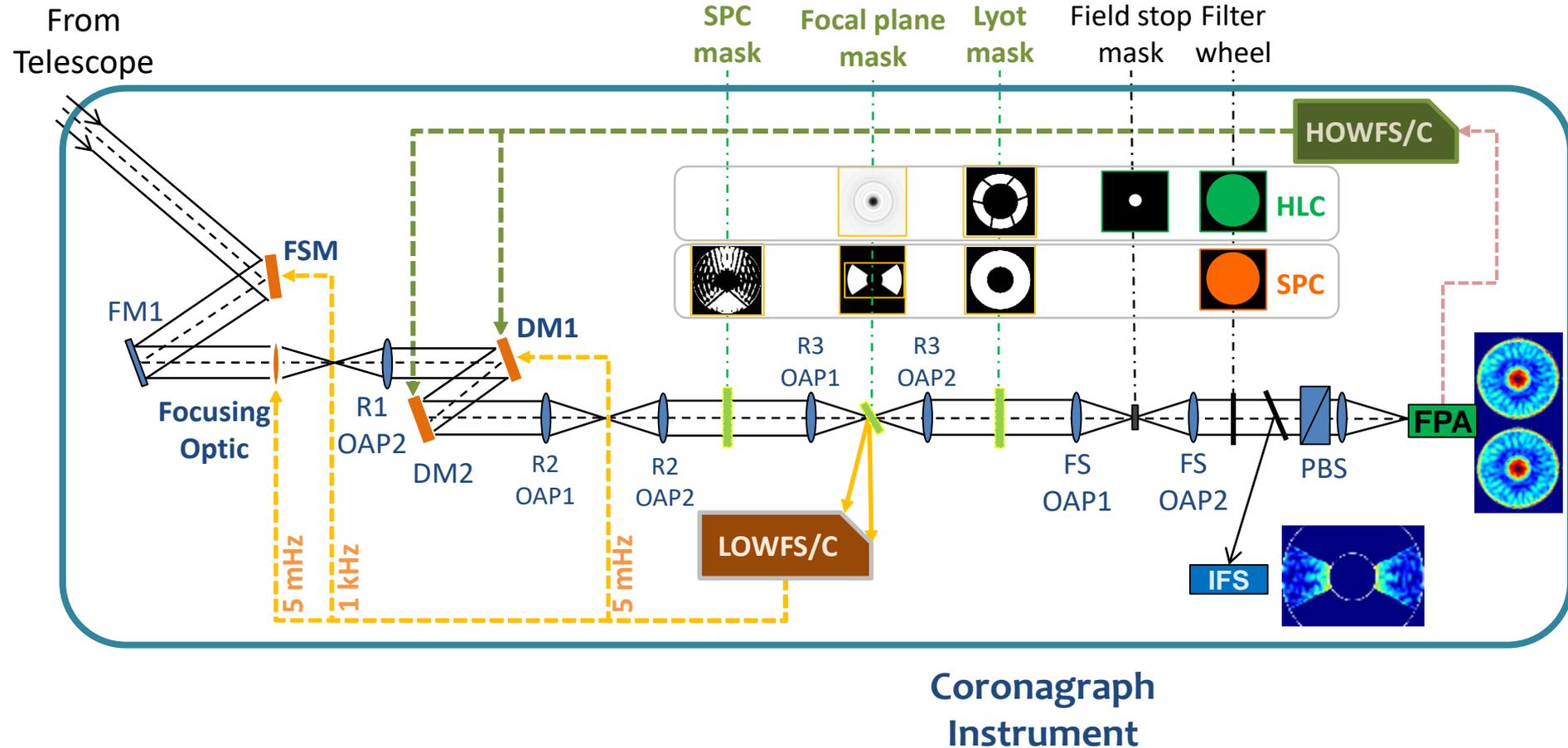
Bernard Lyot, 1939
 French Astronomer
 Inventor of the Coronagraph



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

Coronagraph Optical Layout

Three Coronagraph configurations for a variety of science applications

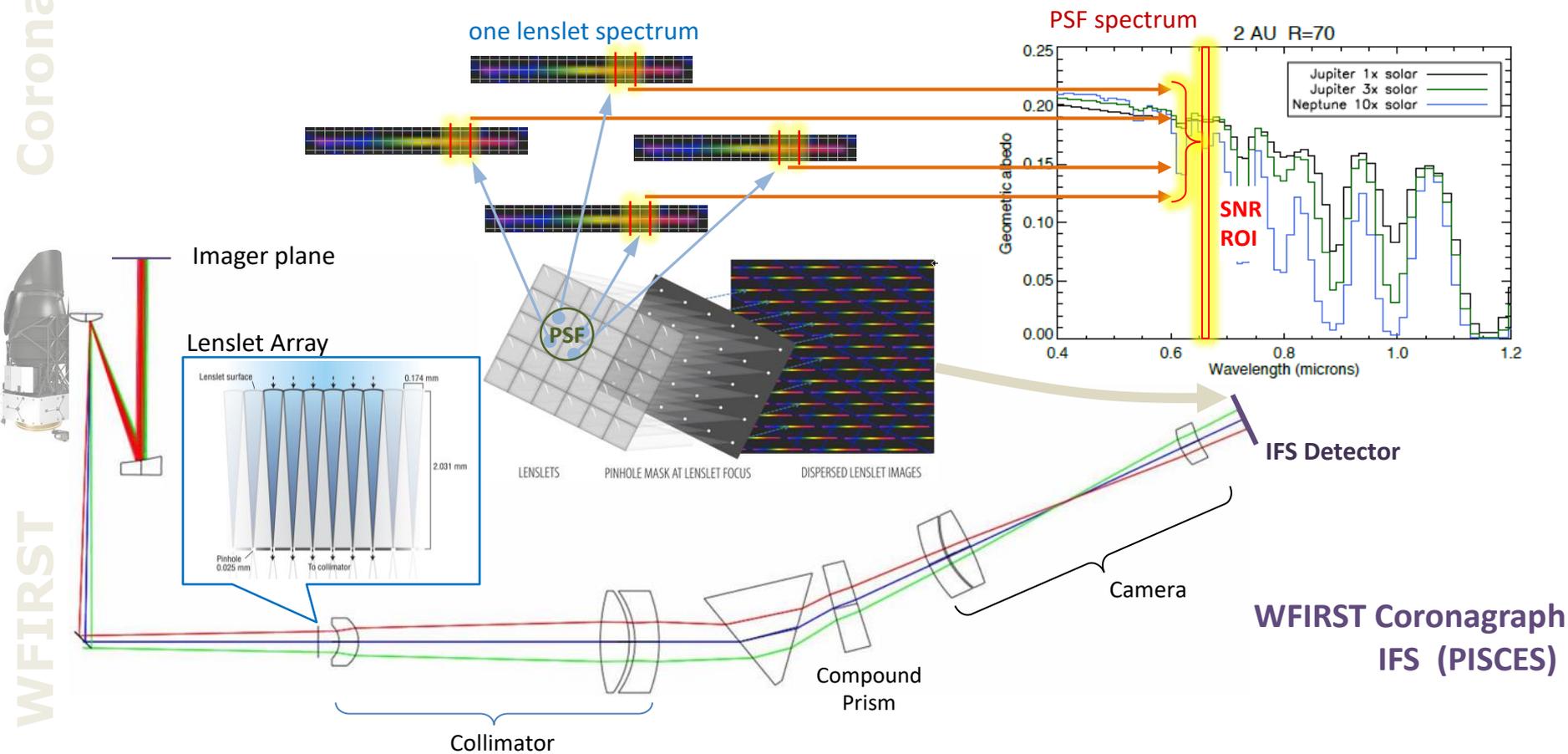


Spectroscopy with Integral Field Spectrograph (IFS)

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*

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Coronagraph Contrast

Coronagraph



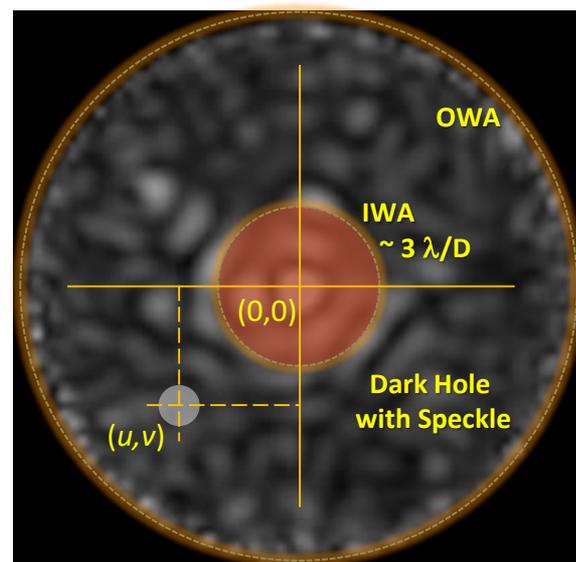
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- The Coronagraph contrast is computed on a per pixel basis.
- Steps to getting contrast at (u, v)
 1. Propagate a flat wavefront (corresponding to the star being at 0,0) through the optical system, from the primary all the way to the imager
 2. Obtain 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 $(u, v) \rightarrow$ this gives $I(u, v; u, v)$
 4. Divide the intensity distribution in step 2 by the PSF peak in step 3

evaluate

source

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





- 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

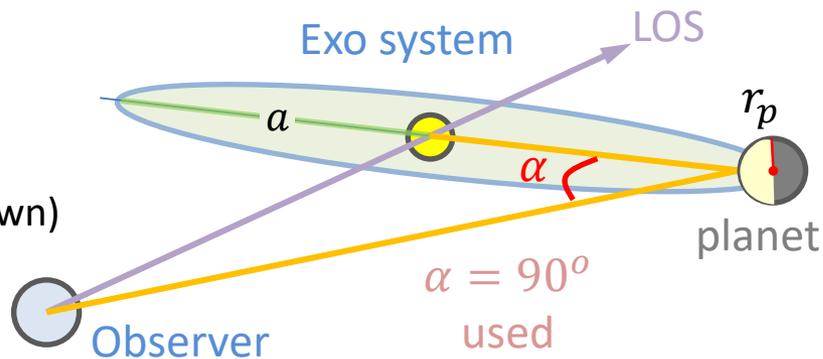
↘

↙

Phase law

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

(simple case of 90 deg inclination angle shown)



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

$$C_{vis} = p\phi(\alpha)\left(\frac{r_p}{a}\right)^2 \quad (14)$$

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

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

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.

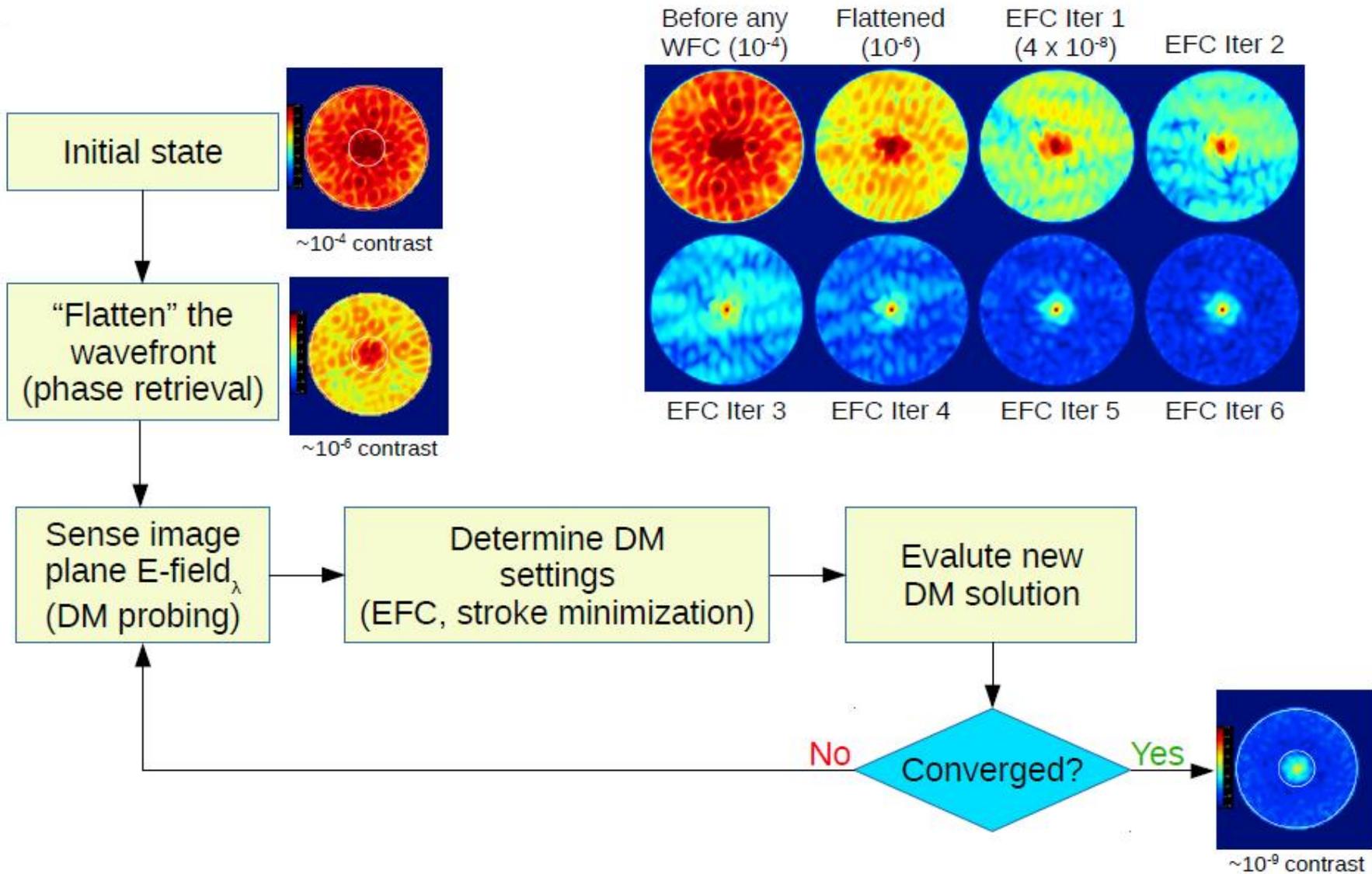
```
% Planet contrast C = albedo * phi(alpha) * (r_p / SMA)^2;
% phi(alpha) = (sin(alpha) + (pi-alpha)*cos(alpha)) / pi , where alpha = phase angle
```

Creating A Starlight “Dark Zone” To See Planets

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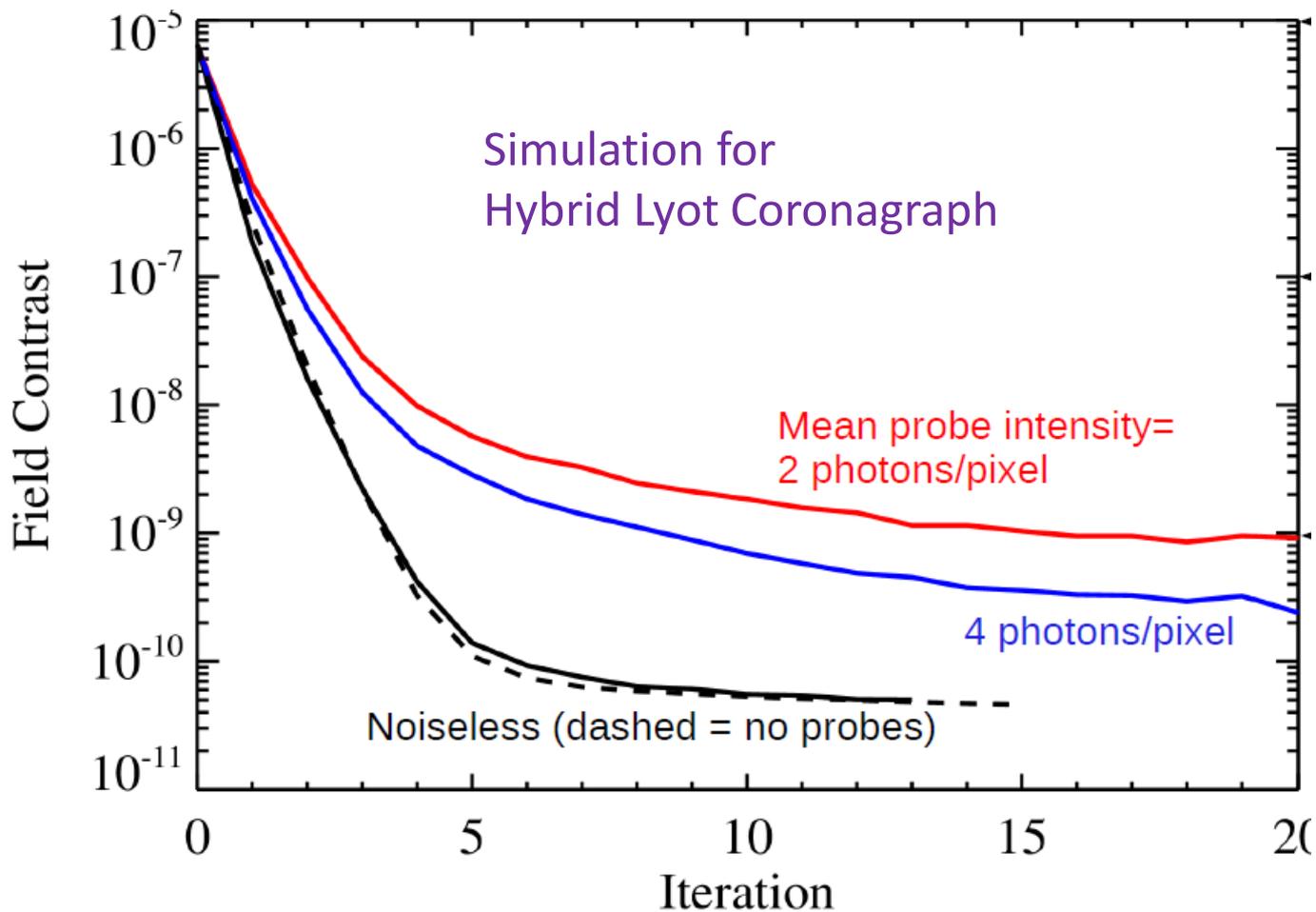


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Digging A Dark Hole: Contrast vs. Iteration

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



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What are typical Rates?

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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

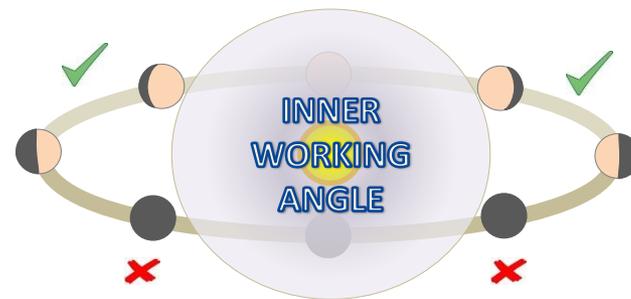
Planet Orbital Phase

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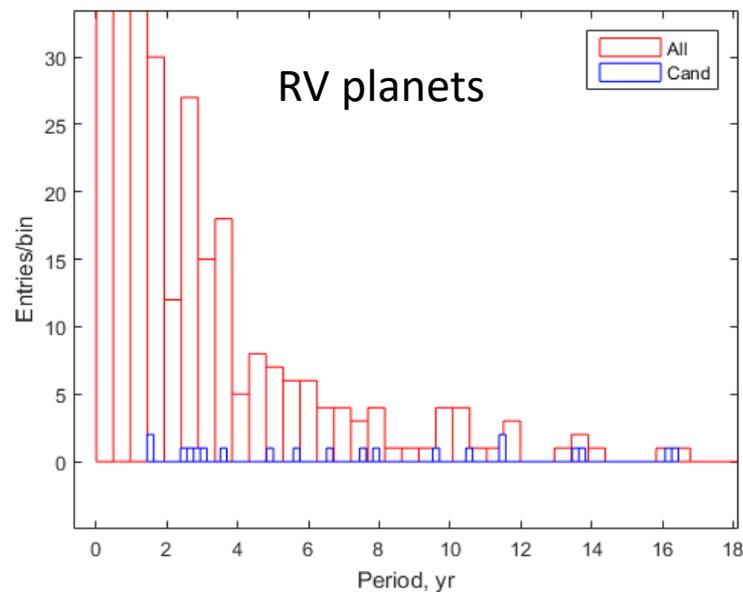


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- Planet orbital phase affects the planet contrast.
- In general the planet is only viewable about 1/3 of the time
- The typical RV candidate will have an 8 year orbital period.
- We will want to optimize observation times to 'catch the planet' near 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

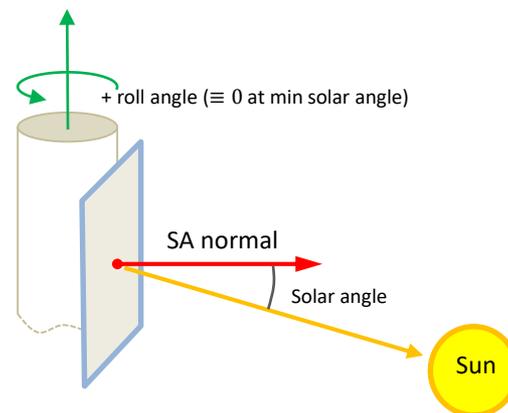
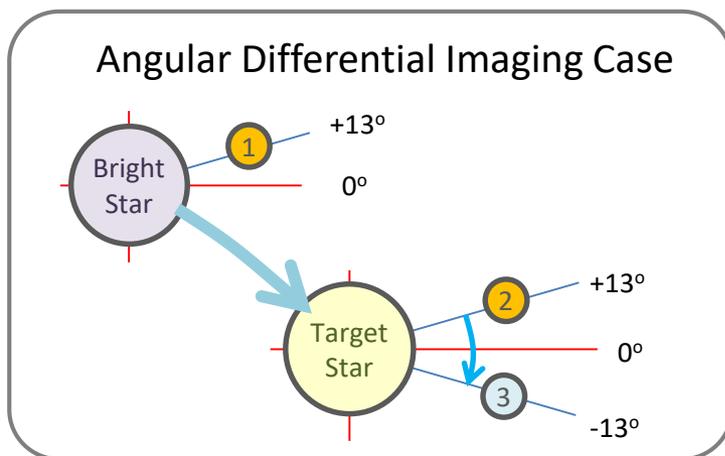
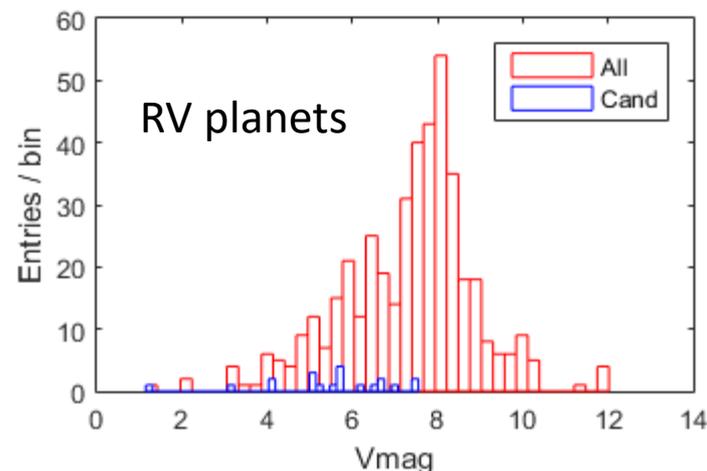
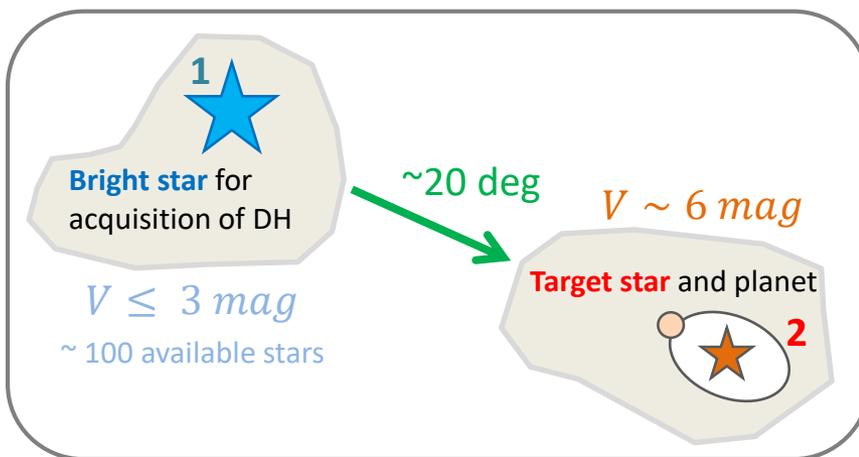


the planet will be observable only ~ 1/3 of the time



Typical Observing Sequence

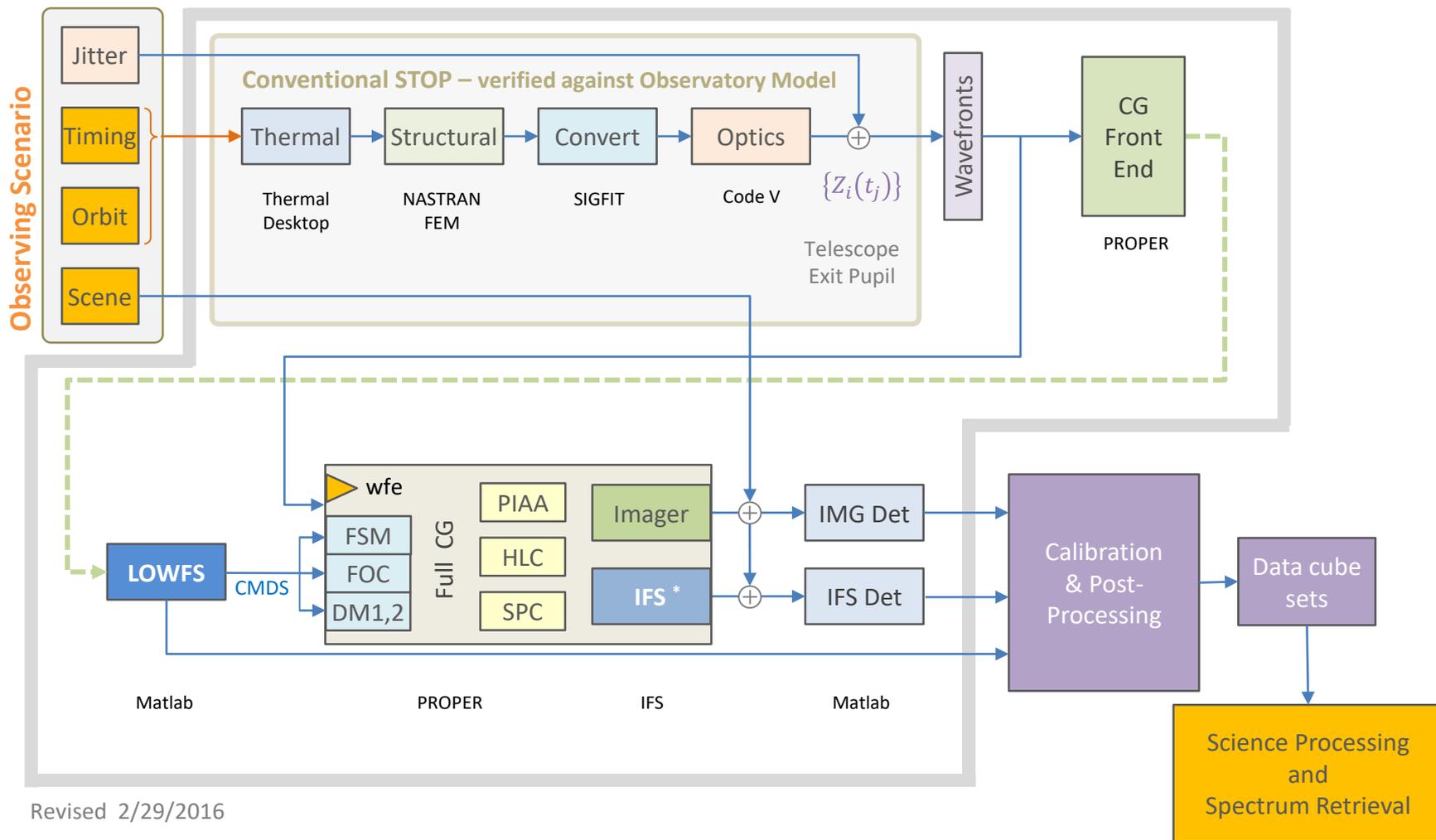
- The typical scenario involves two stars:
 - A nearby **bright star** for getting a dark hole (~ 3 Hrs)*
 - The planet host **target star** (~ 10 Hrs)*
- * numbers notional





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.



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Thermal → Structural Mapping

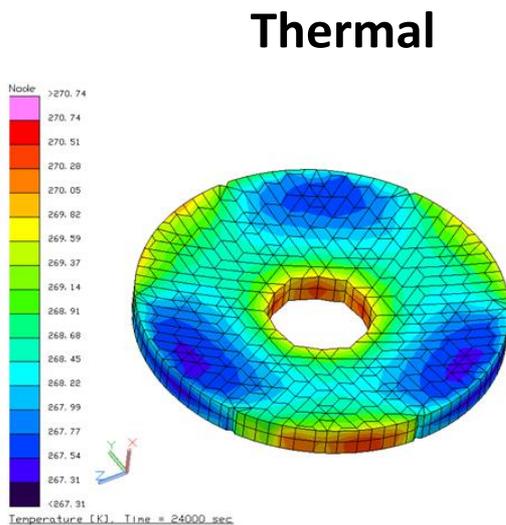
- Example at $t = 24000$ sec

Coronagraph



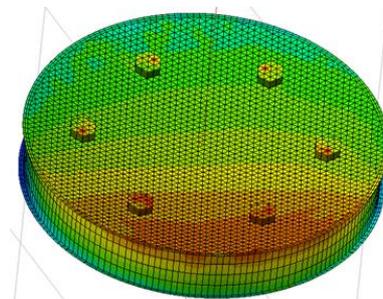
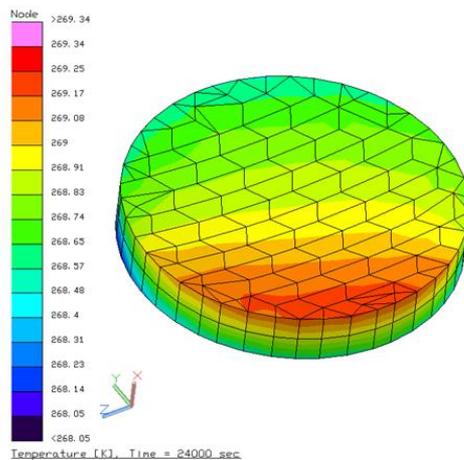
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PM



Structural

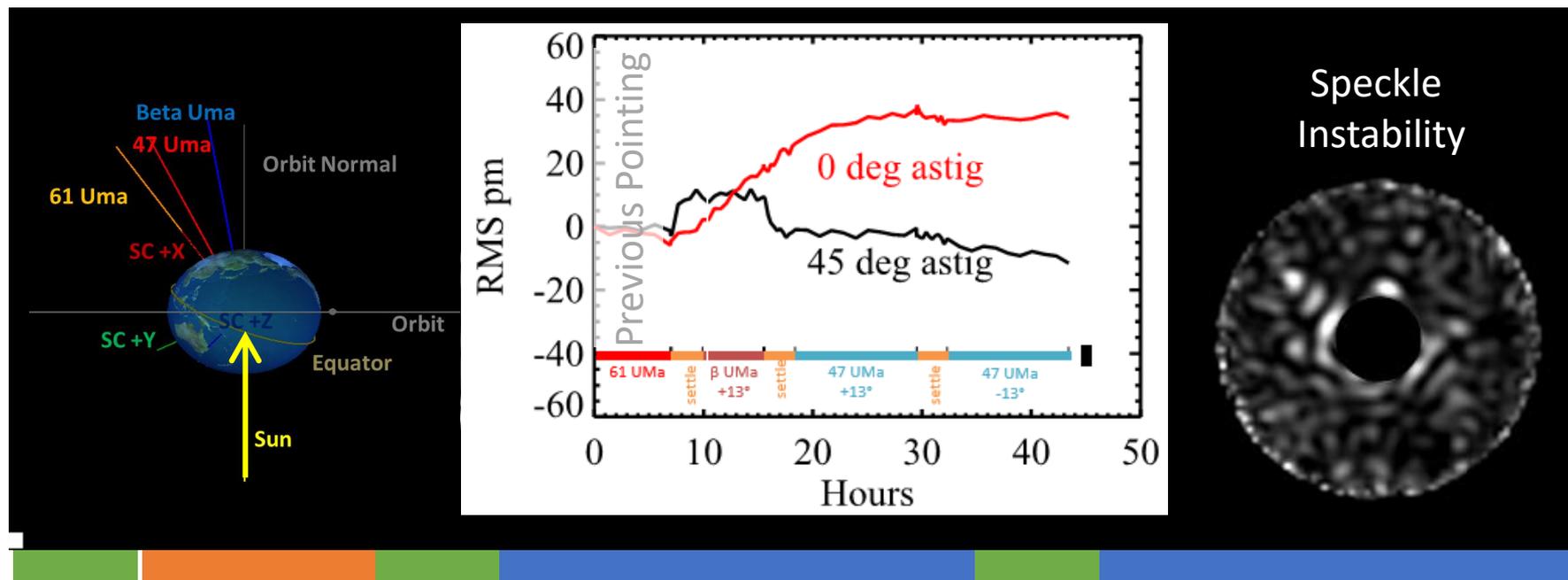
SM



Observing Scenario Speckle Movie

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



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

Reference and Angular Differential Imaging

Are the Speckles Stable Enough to Allow Differential Imaging?

RDI

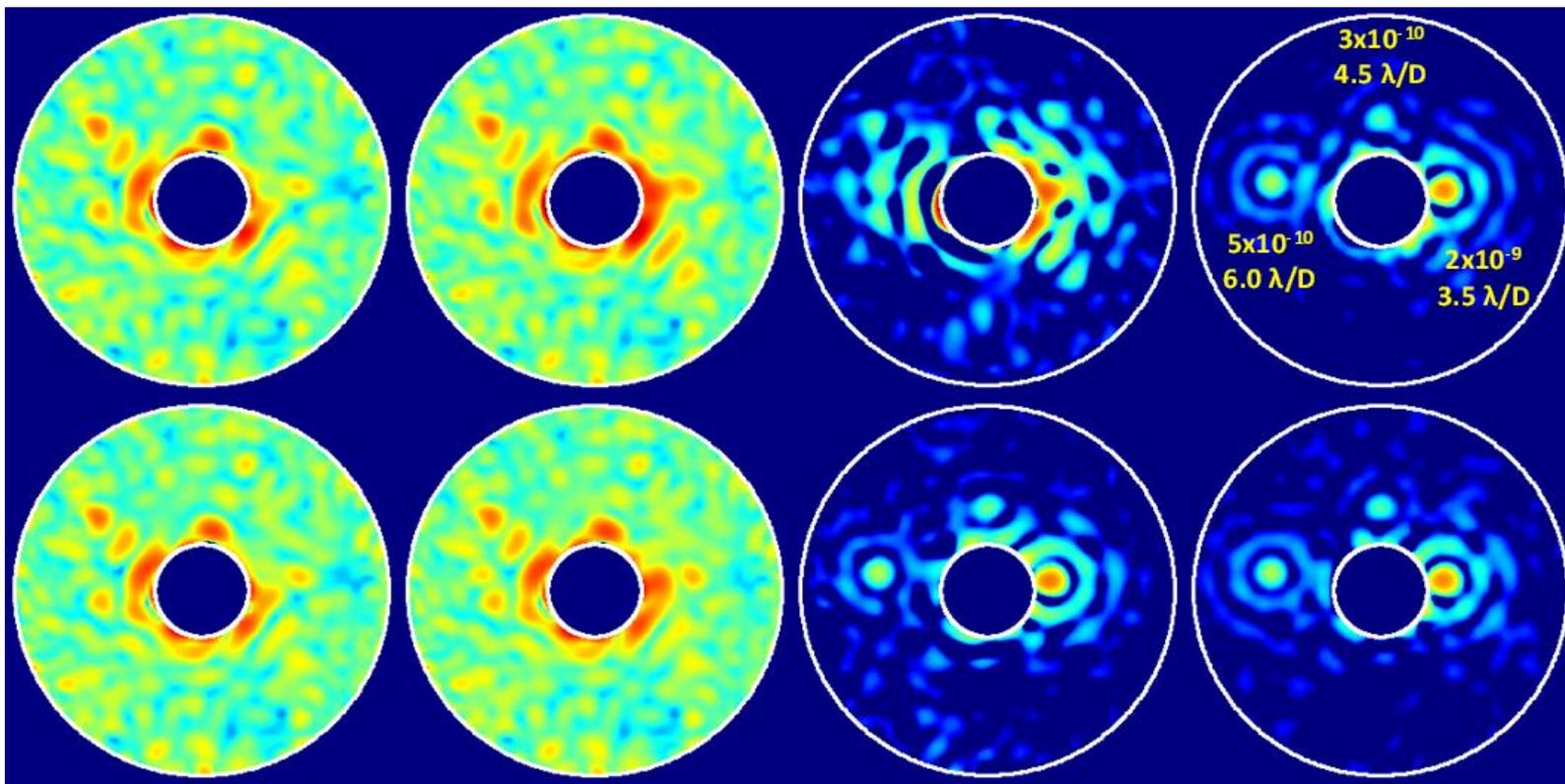
ADI

β UMa

47 UMa_{+13°}

47 UMa_{+13°} - β UMa

47 UMa iterative roll subtraction*



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

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

$$P = r_{pl} t \quad \text{planet signal}$$

- We write the total noise as:

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

random, uncorrelated, reduces with t
Speckle subtraction error, excluding measurement noise

- The uncorrelated, random noise is given by:

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

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

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

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

$\Phi_* = F_\lambda \cdot \Delta\lambda$

$\Phi_Z = F_\lambda^Z \cdot \Delta\lambda$

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.

Putting it all together: time to reach SNR

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Analytical expression for SNR:
$$S = \frac{\overset{\text{planet rate}}{r_{pl} t}}{\underset{\text{noise rate}}{\sqrt{r_n t + \sigma_s^2}}}$$

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

Speckle Subtraction Error:

$$\sigma_s = \underset{\text{mean speckle rate}}{f_{pp} r_{sp} t}$$

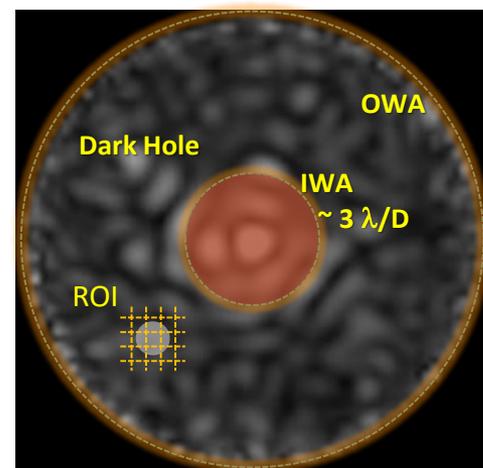
$$r_{sp} = f_{SR} \Phi_* C_{CG} I_{pk} m_{pix} \tau_{sp} A_{PM} \eta$$



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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}

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- 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 S after integrating for time t is one which has a planet-contrast equal to the S - σ equivalent contrast, after post processing:



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Planet signal in the core region after t seconds

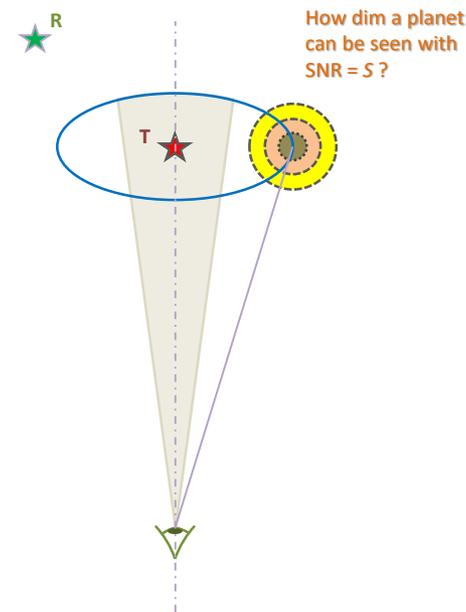
$$f_{SR} \cdot \Phi_* \xi_{eq} A \tau_{pl} \eta t = S \cdot \sigma_{tot}$$

signal fraction
area
QE
flux
thruput
time

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

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

This conversion factor is set by the scenario parameters





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

WFIRST Coronagraph Brightness Depend Errors

B. Nemati - rev. 1/26/2017

Instrument Mode	Imaging 2 Thresh.	Target System	9	47R/Mpc	HLC
Planet Contrast	1.73 ppb				
SNR range	5.00	Time to SNR	1.8 hr		
SNR Total Alloc.	1.58 ppb				
Non-det errors	0.33 ppb	Time Margin	98%		
Detector budget	1.51 ppb				

Planets Observable in the Selected Mode

Mode	CG Contrast	1 cm	30 cm	SNR	L gap	Mission Life	img hrs
Imaging 2 Thresh	HLC	565	56.5	5	18%	0%	34

Noise Equivalent Contrast (NEC) Parameters

Conversion factor for equivalent contrast

Kepler like FPS	6.00E-02	Conversion	For noise image time
ppb/ppb	0.0093	ppb/ppb	For noise image time

Error Category Allocation

Category	Allocation	NEC	Capability	NEC	Requirement	Capability	Units	Comments
Detector Noise	0.04	ppb	0.04	ppb	1.00E-03	5.00E-02	ppb/hrs	0% for EDC
Dark current	0.02	ppb	0.02	ppb	3.00E-05	3.00E-05	ppb/hrs	effective read noise
clock indig	0.02	ppb	0.02	ppb	2.00E-03	2.00E-03	ppb/hrs	

Observational Scenario Parameters

Parameter	Value	Units	Comments
Star distance	34.1	pc	The one system is Sun + Jupiter
Star apparent mag	3.63	mag	How far the system is from us
Planet SMA	3.6	AU	Line apparent magnitude as reported
Planet Abdo	0.28	g @ 50 pc	Comments: Abdo is phase function
Planet Radius	1.27	R _{Jup}	
Local Zodi	23	mag/arc ²	background density
Exo Zodi at 1AU	22	mag/arc ²	background density

Coronagraph Parameters

Parameter	Value	Units	Comments
Selected Contrast Type	Achieved		
Inner I/O	3.45E-01	arcsec	
Outer I/O	3.45E-01	arcsec	
Innerity	1.61E-10		Standard innerity at 1 normalized to 1
Contrast per design	5.34E-03	185E-03	Innerity/FPS
Cost Throughput	3.92E-02		Peak gain resolution on primary in FWHM of PSF normalized to 1
PSF Peak Intensity	6.17E-03	183E-03	Peak gain peak pixel of PSF normalized to 1 & normalized to 1
PSF Area on Sky	2.00E-02	5.76E-03	Area of FWHM of PSF normalized to 1

Planet Yield

Scenario	Center Line	EW	R	Coronagraph	Mission Life	Lpp	FP type	1 integ. hrs	SNR	Contrast
Custom	770	10%	50	HLC	0%	10%	IFS	100	5	Achieved
Imaging 1	850	10%	0	HLC	10%	10%	Imaging	24	5	Design
Imaging 2	565	10%	0	HLC	10%	10%	Imaging	24	5	Design
Imaging 2 Thresh	565	10%	0	HLC	0%	10%	Imaging	24	5	Achieved
IFS 1 Threshold	660	10%	50	HLC	10%	10%	IFS	100	5	Achieved
IFS 2 Threshold	770	10%	50	HLC	0%	10%	IFS	100	5	Achieved
IFS 3	660	10%	50	HLC	0%	10%	IFS	200	5	Design
IFS 2 Thresh	770	10%	50	HLC	0%	10%	IFS	200	5	Design
IFS 3	660	10%	50	HLC	10%	10%	IFS	200	15	Design

Relative QE vs Signal in each Frame

How do we deal with this in the context of getting spectra?

Scenario - Exo and Local Zodi - Derived

Parameter	Value	Units	Comments
Exo Zodi	1.29	ppb/arcsec ²	as 1AU/30pc
Local Zodi	3.97	ppb/arcsec ²	
Zodi per SA into Apert	23.21	ppb/arcsec ²	
Exo Zodi rate	3.3E-03	ppb/hrs	
Local Zodi rate	3.3E-03	ppb/hrs	

Detector total noise in 100 frame

Parameter	Value	Units	Comments
read noise	5.00E-02	ppb/hrs	
Dark current	0.02	ppb/hrs	
clock indig	0.02	ppb/hrs	

Scenario - Specifics and Post Proc

Parameter	Value	Units	Comments
Coronagraph Contrast	7.4E-10	Achieved	
Coronagraph Lpr	6.2E-03		

Scenario - Observation Parameters

Parameter	Value	Units	Comments
Photon Flux	1.000	ENP	at 1 AU wavelength
ENP	1.000	ENP	Photon Counting has No ENP
Local Zodi	3.97	ppb/arcsec ²	at the primary
Star apparent mag	4.29	mag	Star absolute magnitude (M _{bol}) = 3.74
Star separation	0.166	arcsec	Star apparent separation from the distance
Star-planet Separation	254	mas	separation as observed from here

Planet Yield

Scenario	Center Line	EW	R	Coronagraph	Mission Life	Lpp	FP type	1 integ. hrs	SNR	Contrast
Custom	770	10%	50	HLC	0%	10%	IFS	100	5	Achieved
Imaging 1	850	10%	0	HLC	10%	10%	Imaging	24	5	Design
Imaging 2	565	10%	0	HLC	10%	10%	Imaging	24	5	Design
Imaging 2 Thresh	565	10%	0	HLC	0%	10%	Imaging	24	5	Achieved
IFS 1 Threshold	660	10%	50	HLC	10%	10%	IFS	100	5	Achieved
IFS 2 Threshold	770	10%	50	HLC	0%	10%	IFS	100	5	Achieved
IFS 3	660	10%	50	HLC	0%	10%	IFS	200	5	Design
IFS 2 Thresh	770	10%	50	HLC	0%	10%	IFS	200	5	Design
IFS 3	660	10%	50	HLC	10%	10%	IFS	200	15	Design

Focus Plane Attributes

Attribute	Value	Units	Comments
L _{int}	-100	10	ppb/arcsec
mpa	11.7	4.95	ppb/arcsec
Cones/1	6.85E-07	1	ppb/arcsec
Focus Plane Sampling	0.564	0.338	1/0.166

Photos produce electrons in pixels

The signal rates that are used to estimate shot noise should only have the photo-conversion rate which is traditional QE. This quantity we call simple QE.

In computing detected signal ONLY, should we consider the other two factors, namely photon counting efficiency and charge transfer efficiency. This quantity which has the two other factors we call 'signal'.

Detected signal is what concerns computation of Kappa, as well as the computation of time-to-SNR



Basic Observing Modes and Sample Results

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
	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-



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BACKUP

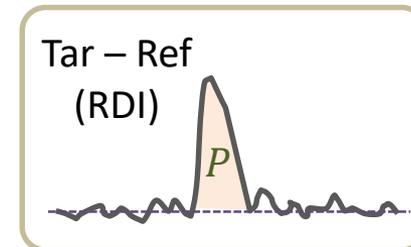
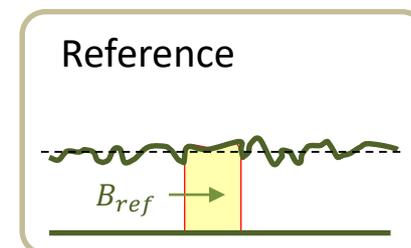
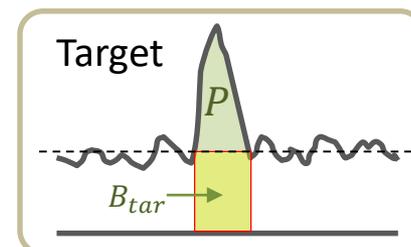
A Simple Observing Scenario

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- 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 $\gg \lambda m/D$



$$\begin{aligned}
 Sig &= I_{tar} - I_{ref} \\
 &= (P + B_{tar}) - B_{ref} \\
 &= P + (B_{tar} - B_{ref})
 \end{aligned}$$

Aside: Distinguishing types of SNR

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Detection and spectroscopy are different statistical questions.

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

$$S_{phot} = \frac{\overset{\text{planet signal}}{P}}{\sqrt{P + B}} \quad \text{background}$$

- For planet **detection**, with the imager, we would be interested in **detection SNR**:

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

- 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



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