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WFIRST Coronagraph

WFIRST Coronagraph Simulations and Performance Estimates

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Outline

I. Overview of the noise sources and their relation to planet yield

II. Sample results on known RV planets

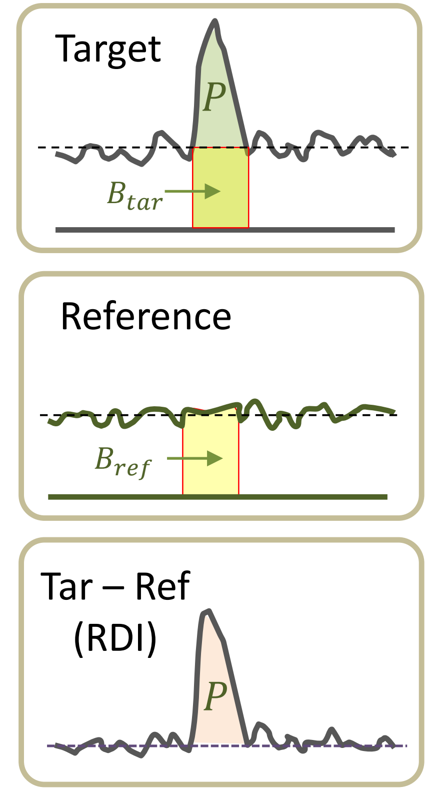
III. Choosing a reference case for requirements

IV. Initial look at sensitivities to key parameters

CALCULATING PLANET YIELD

A Simple Observing Scenario for Yield

- We seek a simple analytical model of planet yield, via calculating the time to reach a desired SNR
- We need to be explicit about the observing assumptions
- 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



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

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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:

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

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

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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, excludes meas. 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 $\quad F \equiv$ EMCCD excess noise factor $\sim \sqrt{2}$ $\quad \Phi_* = F_\lambda \cdot \Delta\lambda \quad \Phi_Z = F_\lambda^Z \cdot \Delta\lambda$

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.

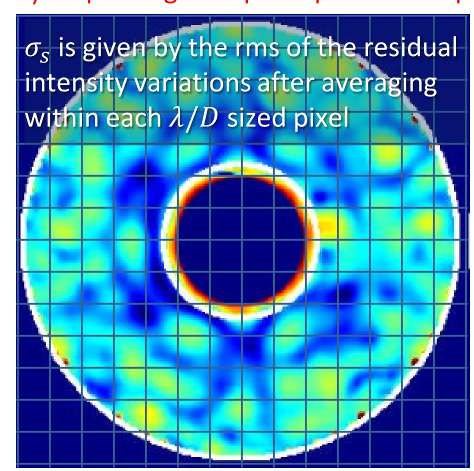
Looking a little more closely at σ_s

- The speckle subtraction term σ_s contains **only** the speckle instability effects.
  - Excludes noise in the subtracted images, and corresponds to the post processing error
- For a given level of speckle instability, different post processing schemes (e.g. PCA, KLIP) will have different dependencies on prior data.
- But, in the context of a *single observation*, taking a total integration time *t*, this error *grows at the same rate as the signal*, i.e., $\sigma_s = k\, t$
- A useful version of this parameterization defines a post-processing improvement factor, which can depend on many variables unstated here, that is calculated from the residual speckle scene according to:

$$f_{pp} \equiv \frac{\sigma_s}{r_{sp}\, t}$$

$r_{sp} \equiv$ mean raw speckle rate

residual speckle, excluding shot noise; λ/D spaced grid superimposed on top



- NB: The above definition shows how f_{pp} is measured, *not its dependencies*!
- From this definition, we have: $\sigma_s = f_{pp}\, r_{sp}\, t$

Putting it all together: time to reach SNR

Analytical expression for SNR:

$$S = \frac{r_{pl}\, t}{\sqrt{r_n t + \sigma_s^2}}$$

(planet rate: r_{pl}; noise rate: r_n)

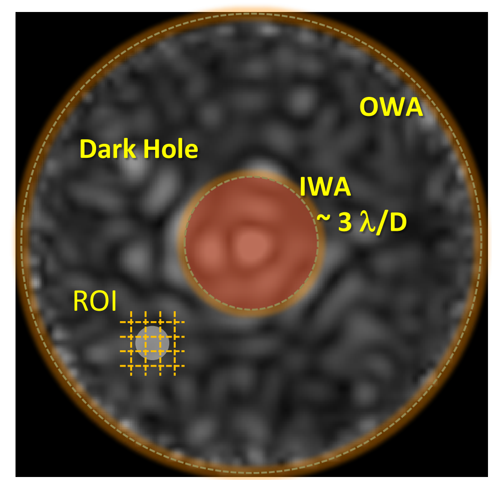
Speckle Subtraction Error:

$$\sigma_s = f_{pp}\, r_{sp}\, t$$

(mean speckle rate: r_{sp})

Time to reach desired SNR:

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



Estimated Integration Times, Imaging 2

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Imaging 2 in order of increasing integration time										
Rank	S/N	Planet		Vmag		WA		Hrs	Days	Cum Days
	gamma	30	3.21		2.85		1.61	30		0.00
1	1	beta Gem b	1	1.15	1	3.45	1	0.02	0.00	0.00
2	5	upsilon And d	5	4.1	5	3.81	5	0.75	0.03	0.03
3	9	47 UMa c	9	5.03	9	5.17	9	0.88	0.04	0.07
4	6	epsilon Eri b	6	3.72	6	9.30	6	1.28	0.05	0.12
5	7	47 UMa b	7	5.03	7	3.04	7	1.57	0.07	0.19
6	2	gamma Cep b	2	3.21	2	2.85	2	1.61	0.07	0.26
7	13	Gliese 777 b	13	5.73	13	5.09	13	3.41	0.14	0.40
8	11	HD 114613 b	11	4.85	11	5.23	11	4.18	0.17	0.57
9	14	mu Ara e	14	5.12	14	7.00	14	4.20	0.17	0.75
10	33	psi Dra B b	33	5.81	33	4.09	33	6.49	0.27	1.02
11	15	14 Her b	15	6.61	15	3.40	15	14.08	0.59	1.60
12	19	HD 217107 c	19	6.17	19	5.46	19	19.84	0.83	2.43
13	4	HD 192310 c	4	5.73	4	2.70	4	20.62	0.86	3.29
14	20	HD 154345 b	20	6.76	20	4.61	20	25.58	1.07	4.35
15	22	HD 134987 c	22	6.47	22	4.52	22	60.91	2.54	6.89
16	31	HD 142 c	31	5.7	31	6.71	31	63.40	2.64	9.53
17	17	55 Cnc d	17	5.96	17	9.02	17	74.83	3.12	12.65
18	10	HD 39091 b	10	5.65	10	3.72	10	76.97	3.21	15.86
19	23	HD 87883 b	23	7.57	23	4.00	23	411.15	17.13	32.99
20	29	GJ 832 b	29	8.66	29	9.30	29	4019.91	167.50	200.49

565 nm, 10% BW

SCENARIO PARAMETER SELECTIONS	
Observation Mode	Img 2comp
SNR Target	5
Detector Type	PC EMCCD
Coronagraph Type	HLC
RV System	2
Frame Time	30
Post-proc Factor	3.3%
Planet phase angle	65
Exo-Zodi Set	1
Contrast Floor	2E-09

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OPTIMIZING PLANET YIELD

The Goal In Optimization

- We could frame the discussion as:
  - **A. Want to maximize planet yield**
  - **B. Want to minimize planet equivalent contrast**

- Option A:
  1. Set a maximum total time, then add up all the easiest planets until the time is exhausted. Report the number of planets.
  2. Proxy: minimize the time-to-SNR for the dimmest viable planets (total time is dominated by the dimmest planet)

- Option B:
  - Used in the error budget (a.k.a. contrast sensitivity budget):
  - Define a nominal case, e.g. dimmest viable planet; report smallest planet flux ratio that can be observed in given time t_0

Noise Equivalent Contrast (NEC): ξ_{eq}

- What is the minimum planet contrast that can be seen with SNR ≥ 5 under our observing scenario?
- Equivalent Contrast 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

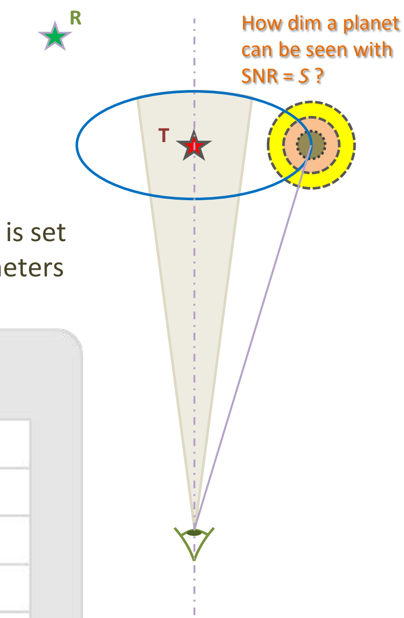
$$f_{SR} \cdot \Phi_* \xi_{eq} A \, \tau_{pl} \, \eta \, t = S \cdot \sigma_{tot}$$

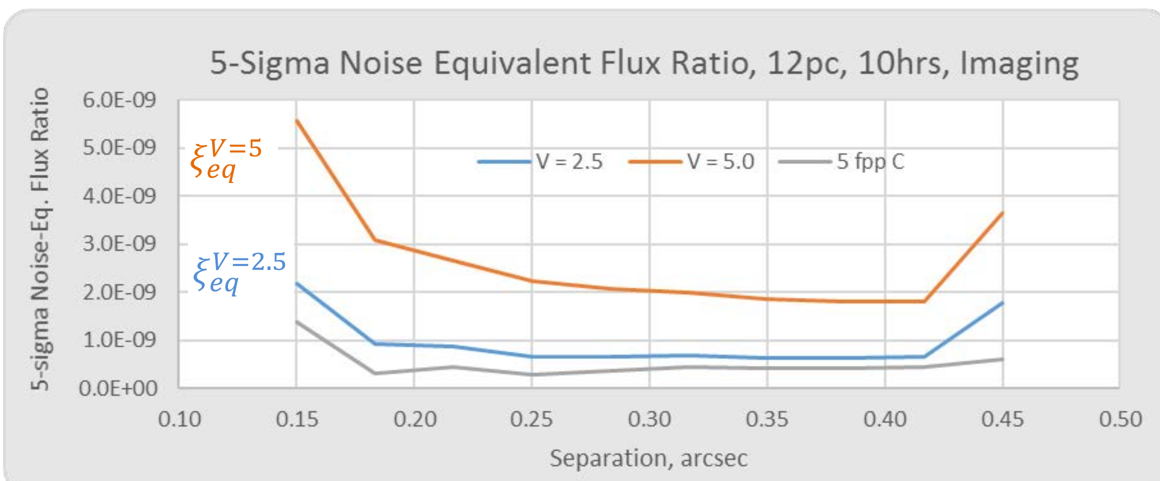
(f_{SR}: signal fraction; Φ_*: flux; A: area; τ_{pl}: thruput; η: QE; t: time)

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

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

This conversion factor is set by the scenario parameters





Asymptotic Behavior of ξ_{eq}

- How does the NEC depend on post processing and integration time?

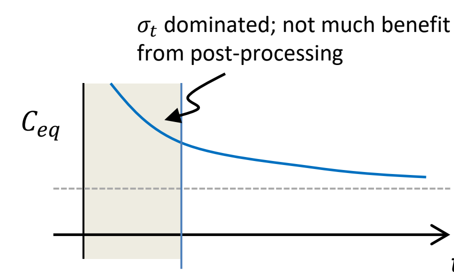
Our definitions of NEC:

$$\Phi_* \xi_{eq} A\, \tau_{pl}\, \eta\, t = S \underbrace{\sqrt{r_n t + f_{pp}^2 r_{sp}^2 t^2}}_{\sigma_{tot}}$$

- For imaging, $f_{SR} = 1$, so for simplicity we drop this factor, and we have:

$$\xi_{eq} = S \sqrt{\frac{r_n}{\Phi_*^2 A^2 \tau_{pl}^2 \eta^2\, t} + f_{pp}^2 \frac{C_{CG}^2 I_{pk}^2 m_{pix}^2}{\tau_{core}^2}}$$

- For very short times the first term dominates and there is no benefit from post-processing



- At large times, the first term under the radical drops out, so that we arrive at:

$$\xi_{eq} \xrightarrow{t\to\infty} S\, f_{pp}(t) \frac{C_{CG} I_{pk} m_{pix}}{\tau_{core}}$$

Which System to Evaluate On?

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- The sensitivity is most important on the hardest viable target
- Consider a realistic IFS case, and compare integration time
- Comparison suggests
  - HD 190360 b
  - aka **Gliese 777 b** (easier to remember?)

Observation Mode	IFS 1comp		
SNR Target	15		
Detector Type	PC EMCCD		
Coronagraph Type	SPC	mag	Star
RV System	1	1.15	HD62509
Frame Time	30	s	single frame
Post-proc Factor	7.0%	f_pp	resid. speckle str.
Planet phase angle	45	deg	not used
Exo-Zodi Set	1	1 or 0	mulitiplies exoZodi
Contrast Floor	2E-09	5E-09	knowledge errors

IFS 1 in order of increasing integration time

Rank	No.	Planet	Vmag	WA	Hrs	Days	Cum Days
	Gliese 7	30	30	30	30		0.00
1	1	beta Gem b	1.15	2.95	1.58	0.07	0.07
2	9	47 UMa c	5.03	4.42	29.00	1.21	1.27
3	5	upsilon And d	4.1	3.26	138.34	5.76	7.04
4	13	Gliese 777 b	5.73	4.36	126.29	5.26	12.30
5	33	psi Dra B b	5.81	3.50	660.63	27.53	39.83
6	11	HD 114613 b	4.85	4.47	707.62	29.48	69.31
7	20	HD 154345 b	6.76	3.95	1382.64	57.61	126.92
8	19	HD 217107 c	6.17	4.68	1625.24	67.72	194.64

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Detector and IFS Design Settings

Detector Architecture

Item	Value	Units	Comments
Dark current	3E-05	e/pix/s	Leon Harding, 10/6/2016
Clock Ind. Charge	2E-03	e/pix/fr	Leon Harding, 10/6/2016
Read noise	0	e	eff. Read noise below
EM gain	1000	X	0
Quantum Eff.	74%	QE	Includes Ph. Ctg. Eff. Loss
Pixel Size	13	μm	
f_SR	0.111		frac. Of core light in SNR ROI
Desired mpix	16.0		pixels in SNR ROI
Excess Noise Fac.	1.00	ENF	
Frame Rate	0.0333	Hz	Wes used 300s

Focal Plane Architecture

Item	Value	Units	Comments
Imager Critical λ	450	nm	Nyquist sampled
Imager Sampling	0.341	(λ/D) / pix	
IFS Critical λ	660	nm	Nyquist sampled
IFS Lensl per PSF	2	lenslets	across PSF core
IFS Spatial Samp	2	rows	pixels in spatial dir.
IFS Spectral Samp	2	cols	pixels / spect. Elem.
IFS sampling on sky	0.029	arcsec	/ lenslet @ crit. λ
		10.5mas	

Rates of signal and background into the SNR region of interest

Stellar Flux

Item	Value	Units	Comments
Local Zodi	22	mag/as^2	brightness density
Exo Zodi	23	mag/as^2	brightness density

What are the dominant errors for Gliese 777 b?

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SCENARIO PARAMETER SELECTIONS

Observation Mode	IFS 1comp		
SNR Target	15		
Detector Type	PC EMCCD		
Coronagraph Type	SPC	mag	Star
RV System	13	5.73	HD190360
Frame Time	30	s	single frame
Post-proc Factor	7.0%	f_pp	resid. speckle str.
Planet phase angle	45	deg	not used
Exo-Zodi Set	1	1 or 0	mulitiplies exoZodi
Raw Contrast Floor	2E-09	5E-09	knowledge errors

Scene Signal and Background (per Frame)

Core electrons per frame

Item	Value	Units	Comments
Planet Electrons	0.057	e-/fr	PSF core (photon)
Speckle Electrons	0.022	e-/fr	PSF core
Zodi Electrons	0.058	e-/fr	PSF core

Pixel electrons per frame

Item	Value	Units	Comments
Planet Electrons	0.0036	e-/fr	per pixel (in core)
Speckle Electrons	0.00	e-/fr	per pixel
Zodi Electrons	0.0	e-/fr	per pixel

Core electrons per frame

Item	Value	Units	Comments
Planet in Core	0.06	e-/fr	PSF core (elec.)
Speckle in Core	0.02	e-/fr	PSF core
Zodi in Core	0.1	e-/fr	PSF core

Scene Rates (per second)

Core photons per second

Item	Value	Units	Comments
Planet Phot Rate	2.57E-03	phot/s	PSF core (photon)
Speckle Phot Rate	1.0E-03	phot/s	PSF core

Scenario Summary

Science Instrument	IFS		
Center lambda	6.60E-07	m	V-band ctr.
Bandwidth	18%	--	V-band is 16.18%
Spec Resolution	50	R	

Filter

Item	Value	Units	Comments
WL Beginning	6.01E-07	m	Wavelength min
WL Ending	7.19E-07	m	Wavelength max
$\Delta\lambda$	1.00E-09	m	For calc. integral

SNR

Time to SNR

Item	Value	Units	Comments
Time Required to Reach SNR	4.55E+05	sec	This is integration time only
	126.290	hrs	
	5.262	days	

Final SNR

Item	Value	Units	Comments
SNR Check	15.00	SNR	
Signal	868.9	e	Total Signal
Noise	57.9	e	Total Noise
Frames Needed	15,154.8	frames	for SNR target

Final Noise Contributions

Item	Value	Units	Comments
Shot	29.477	e	signal shot noise
Speckle	18.442	e	<sp> shot noise
Zodi	29.608	e	zodi shot
Dark Current	14.773	e	
CIC	22.022	e	
Read	0.000	e	
Speckle Structure	23.808	e	residual Speckle

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Which Parameters to Investigate?

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- Initial Set:
  - τ_{core}
  - C_{CG}
  - $\Delta\Omega_{PSF}$
  - q_{CIC}
  - t_{fr}
  - f_{pp}

Final Noise Contributions

Item	Value	Units	Comments
Shot	37.860	e	signal shot noise
Speckle	23.686	e	<sp> shot noise
Zodi	56.372	e	zodi shot
Dark Current	27.386	e	
CIC	40.824	e	
Read	0.000	e	
Speckle Structure	39.273	e	residual Speckle

Set to IFS1 Comp and planet = 13 (Gliese 777 b)						
	tau Core	C_CG	dOmega	qCIC	t_fr	fpp
nominal	3.64E-02	2.31E-09	5.23E-03	2.00E-03	3.00E+01	7.00E-02
nom + 10%	4.01E-02	2.54E-09	5.75E-03	2.20E-03	3.30E+01	7.70E-02
tNom	126.29	126.29	126.29	126.29	126.29	126.29
tDelta	103.96	133.70	130.30	128.50	124.30	131.90
delta tSNR	22.3	7.4	4.0	2.2	2.0	5.6
Sensitivity	177%	59%	32%	18%	16%	44%

Sensitivity is defined here as the ratio of fractional increase in tSNR over fractional change in the given parameter

NB: Another important attribute to consider is the inner working angle.
A study of inner working angle has to be done somewhat differently, since there we are looking for the number of additional planets available as IWA becomes smaller.

BACKUP

Detector Pixels in the IFS Configuration

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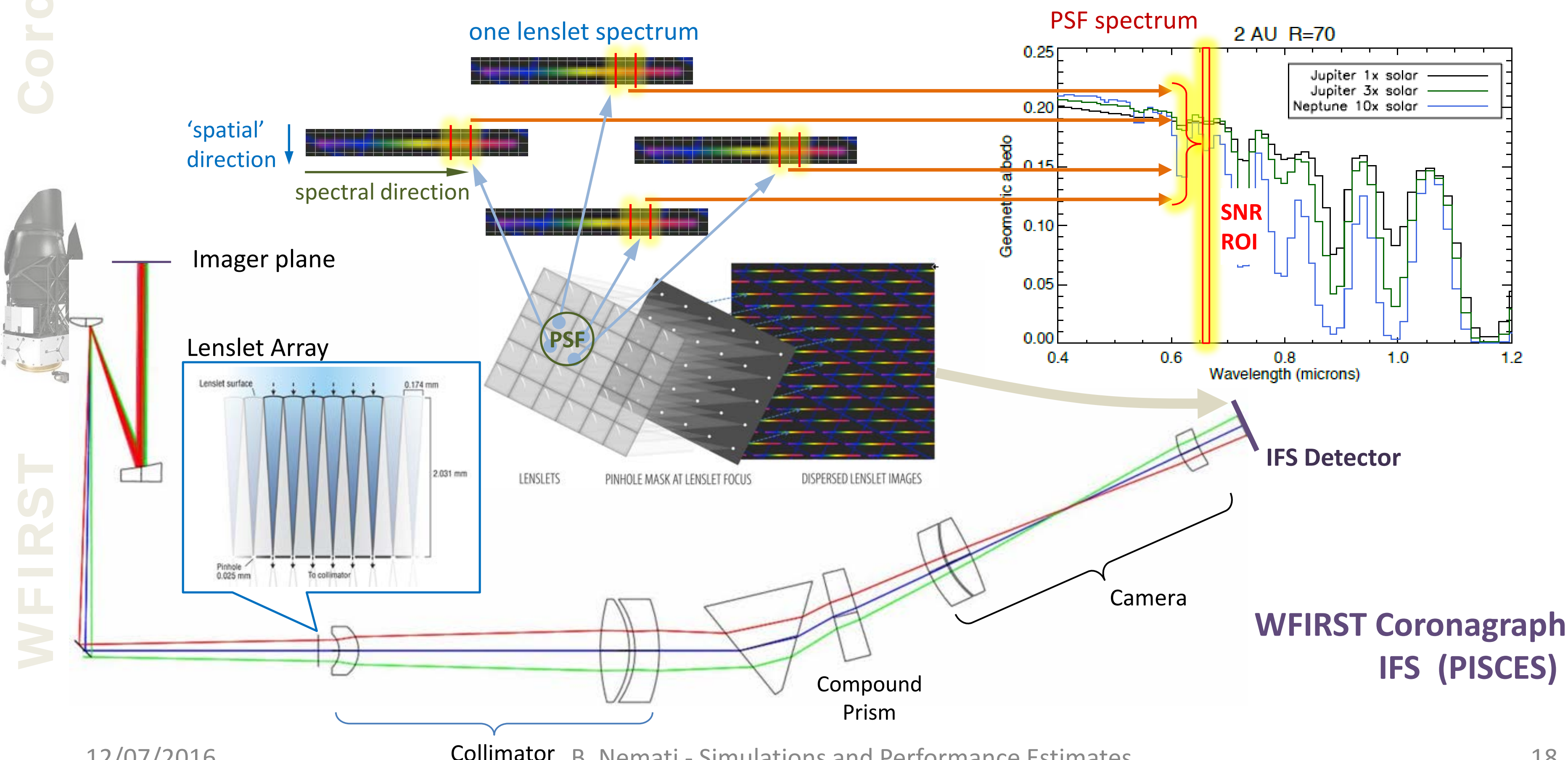
For the IFS, the SNR region of interest (ROI) comprises the collection of pixels that altogether are involved in the photometry of a *single spectral element*

The system is constant-dispersion, therefore the sampling in the spectral dimension is set, and not wavelength dependent. However, the spatial sampling does depend on wavelength.

$$m_{pix} = \left(N_{lens}\frac{\lambda_i}{\lambda_{min}}\right)^2 \cdot 2_{spec} \cdot N_{spat} \left(\frac{\lambda_i}{\lambda_{min}}\right)$$

neglect for realistic Wavefront errors



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