High contrast technologies and methods for future large space-based telescopes

Habex/LUVOIR f2f meeting, Yale,
10 Nov 2016

Content

- Intro and executive summary (Dimitri Mawet, Caltech)
- SCDA-APLC update (Laurent Pueyo, STScI)
- SCDA-VC update (Garreth Ruane, Caltech)
- Spectral resolution vs contrast trade-off space
  (Ji Wang, Caltech)

Current status

- SCDA study found high-contrast coronagraph designs for segmented / obscured apertures (e.g. APLC, VC), waiting for PIAACMC and HLC designs

- We do have coronagraph solutions immune to low-order aberrations for unobscured telescopes:

  – Low-order aberrations (z2-z8, z11) are in the null space of the VC6, enabling stability requirement relaxation by ~1-2 orders of magnitude

  – APLC is very insensitive to tip-tilt errors and to low-order aberrations to some degree TBD (a $1B question)

  – Need to transpose/verify this immunity to obscured telescopes (work in progress for VC AND APLC)

  – <u>All coronagraphs still need to consider realistic aberrations => all yield estimations are upper limits (beamwalk will be an issue for all coronagraphs, see WFIRST)</u>

Habex is zeroing on a potential internal coronagraph architecture

- Charge 6 Vortex with off-axis 4-m monolith:
  - F/2.0-F/2.5 primary, polarization effects negligible
  - HST-like coatings (MgF_2/Al) on M1 and M2
  - Wavefront stability potentially relaxed to ~1 nm rms (z2-z8,z11)
  - Exo-Earth yield = 7 (V-band imaging)

Two instrument architectures

- Integral field spectrograph with R~70 (a la WFIRST):
  - Need to deal with speckle noise
- Imager + (fiber-fed?) spectrograph:
  - Classical imager for detection
  - R~1000 spectrograph for characterization:
    - Cross-correlation technique side-steps speckle noise, potentially relaxing raw contrast requirements by 1-2 orders of magnitude

Work in progress

Habex and LUVOIR: partial yield calculation for internal coronagraphs

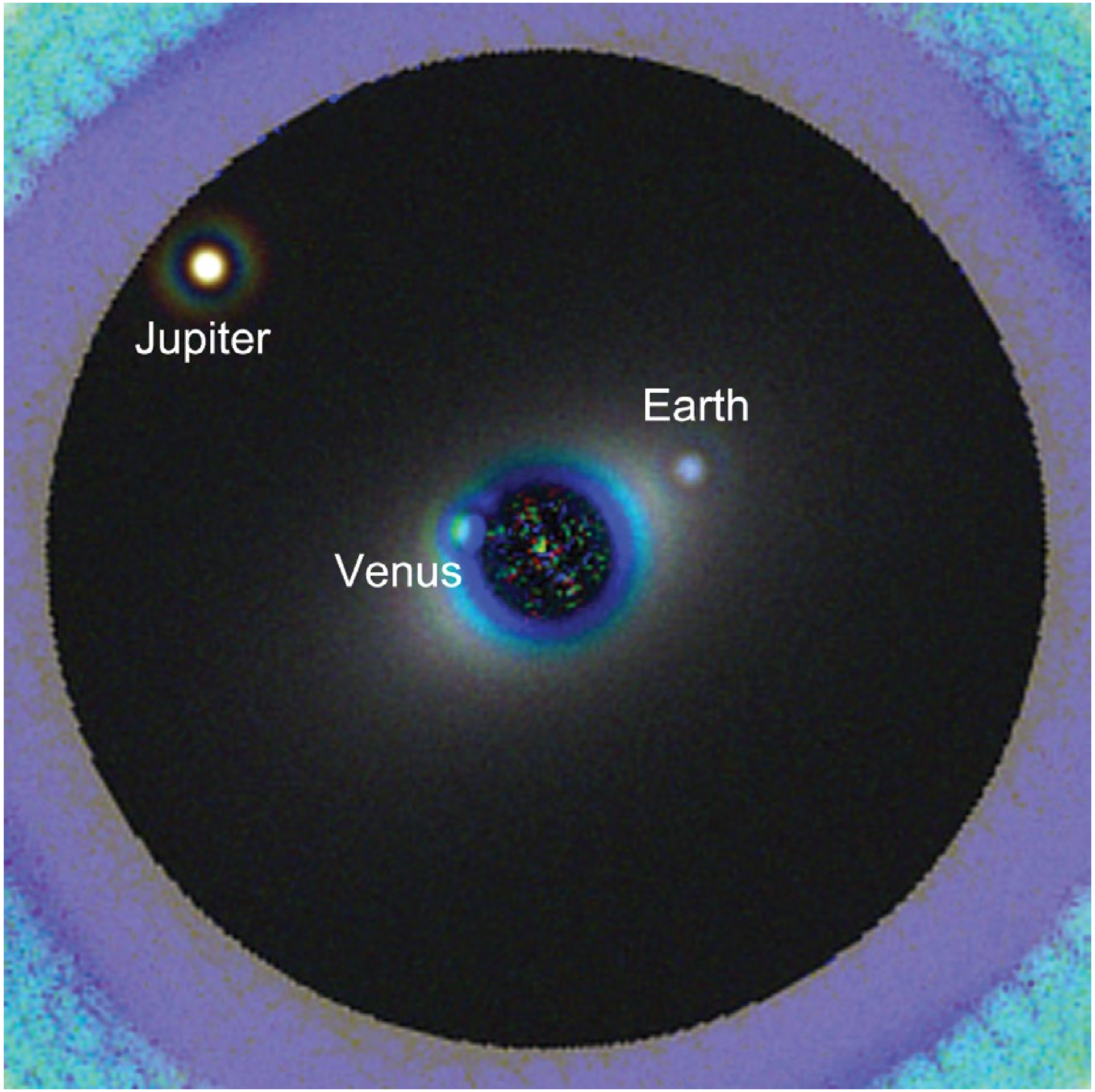
	4-m off-axis	**6.5-m on-axis**	**6.5-m off-axis**	**12-m on-axis**	**12-m off-axis**
Mission	Habex	Habex/LUVOIR	Habex/LUVOIR	LUVOIR	LUVOIR
Coronagraph	VC6	APLC	VC6	APLC	VC6
exo-Earth Yield	7	12	9-17	31	22-53
Stability C<1e-11: Z2->Z8, Z11	~1 nm	?	~1 nm	?	~1 nm
F#	f/2.0-f/2.5	?	f/2.0-f/2.5	?	f/2.0-f/2.5
Coating	MgF2/Al-Ag	?	MgF2/Al-Ag	?	MgF2/Al-Ag

Coronagraph designs for HabEx and LUVOIR

Joint LUVOIR & HabEx STDT meeting.
Nov 10 th 2016.

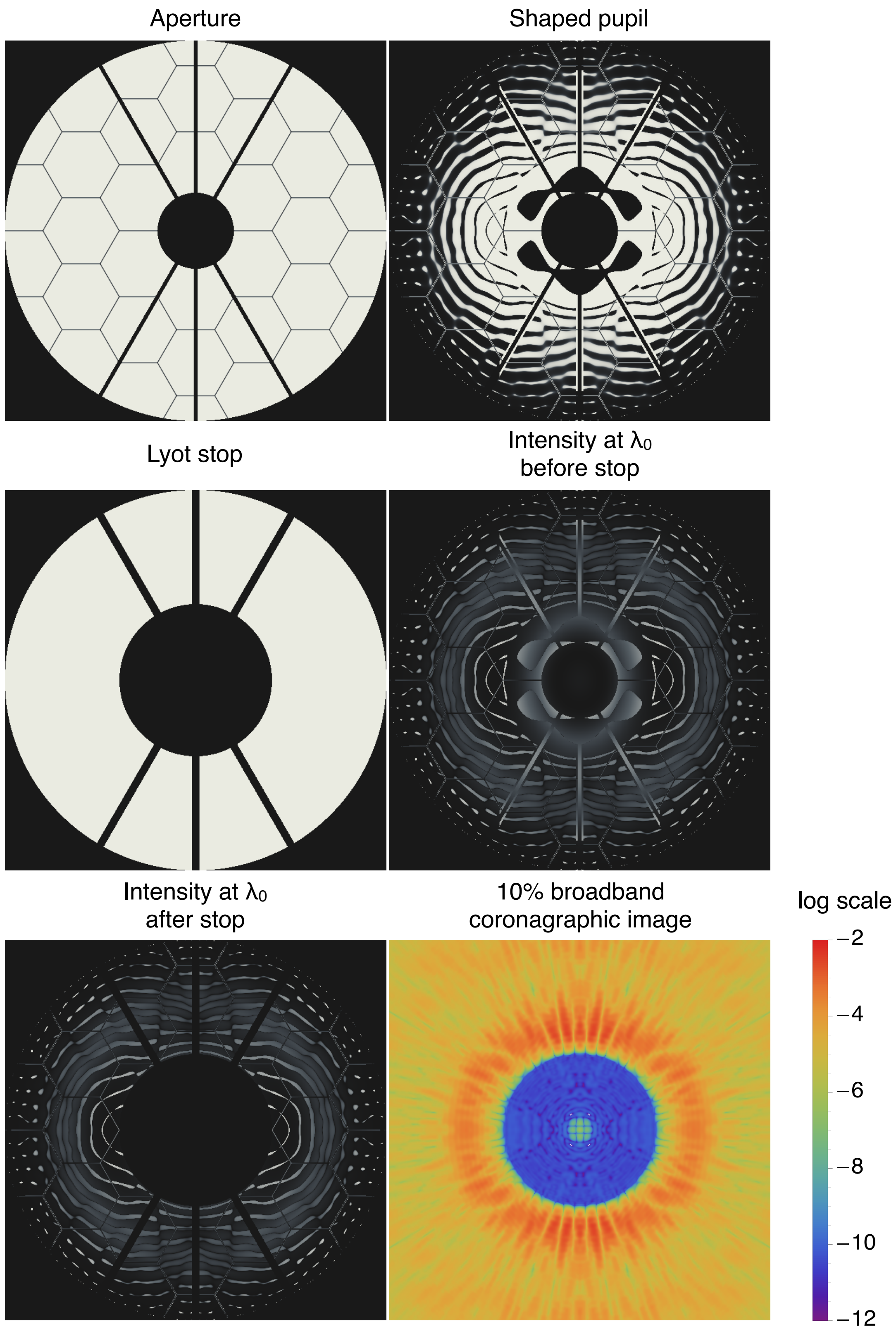
Laurent Pueyo

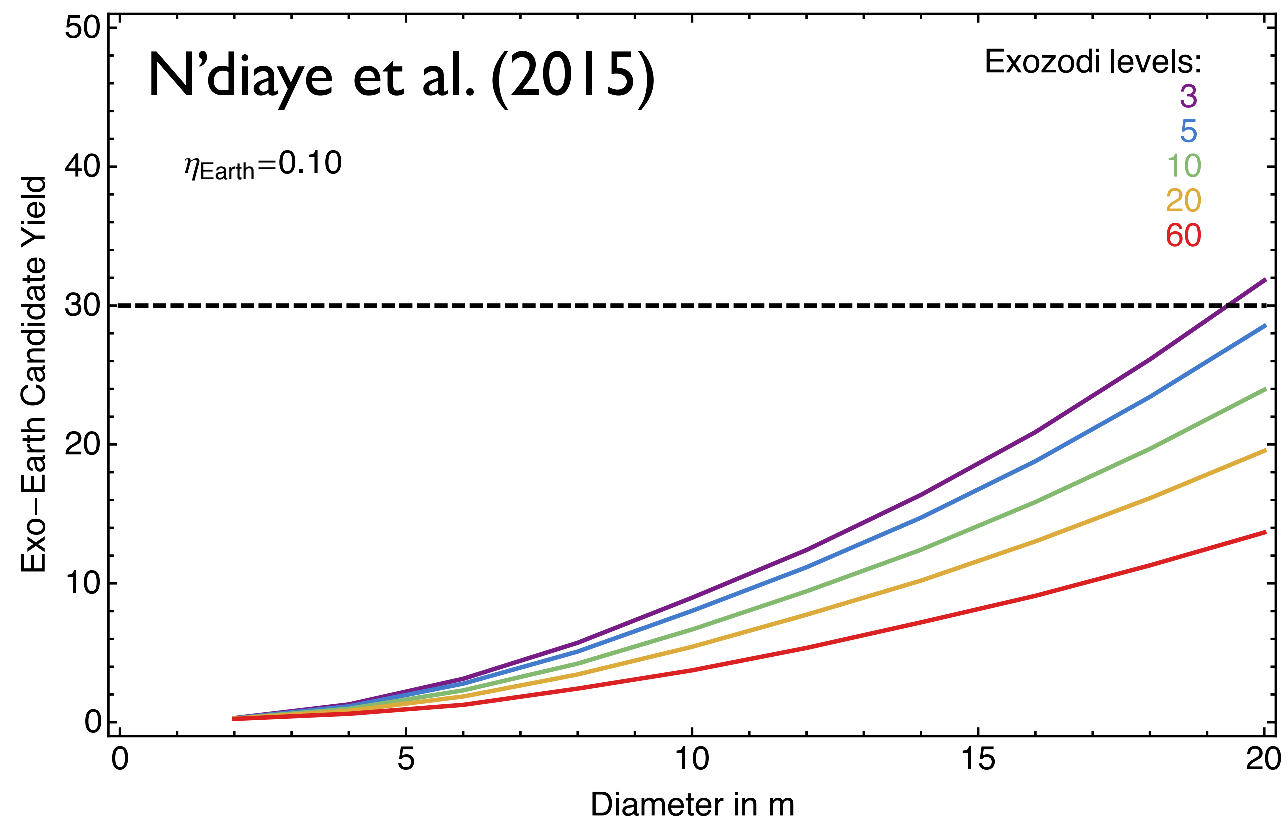
HDST image

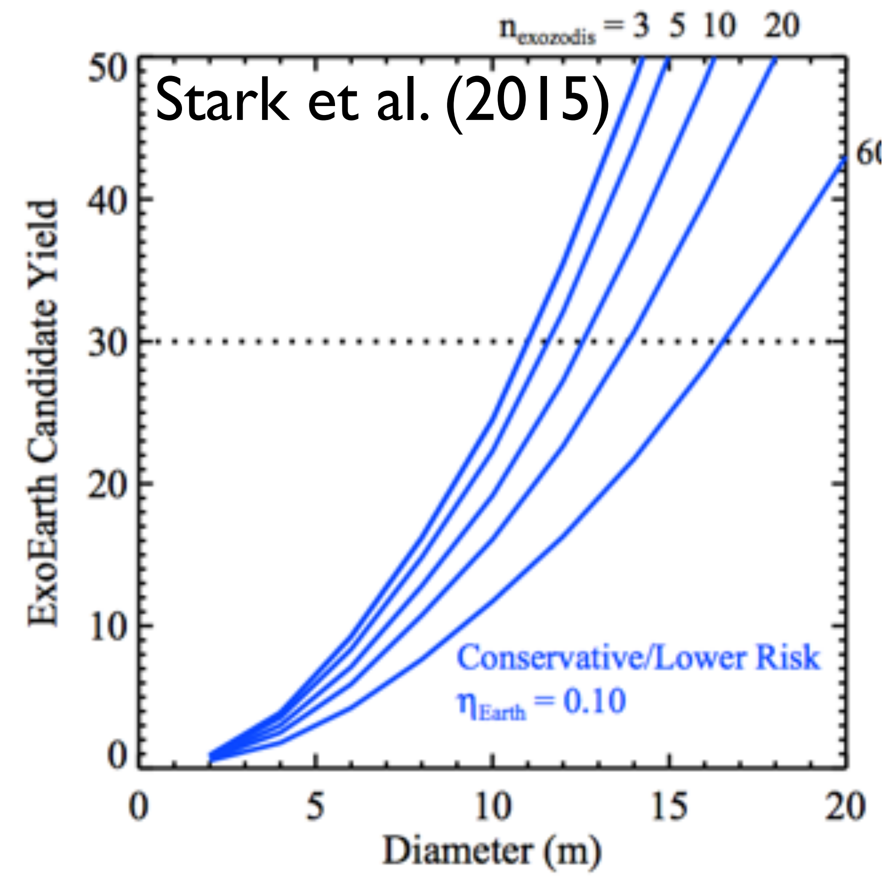


HDST report (2015)

Coronagraphs: starting point



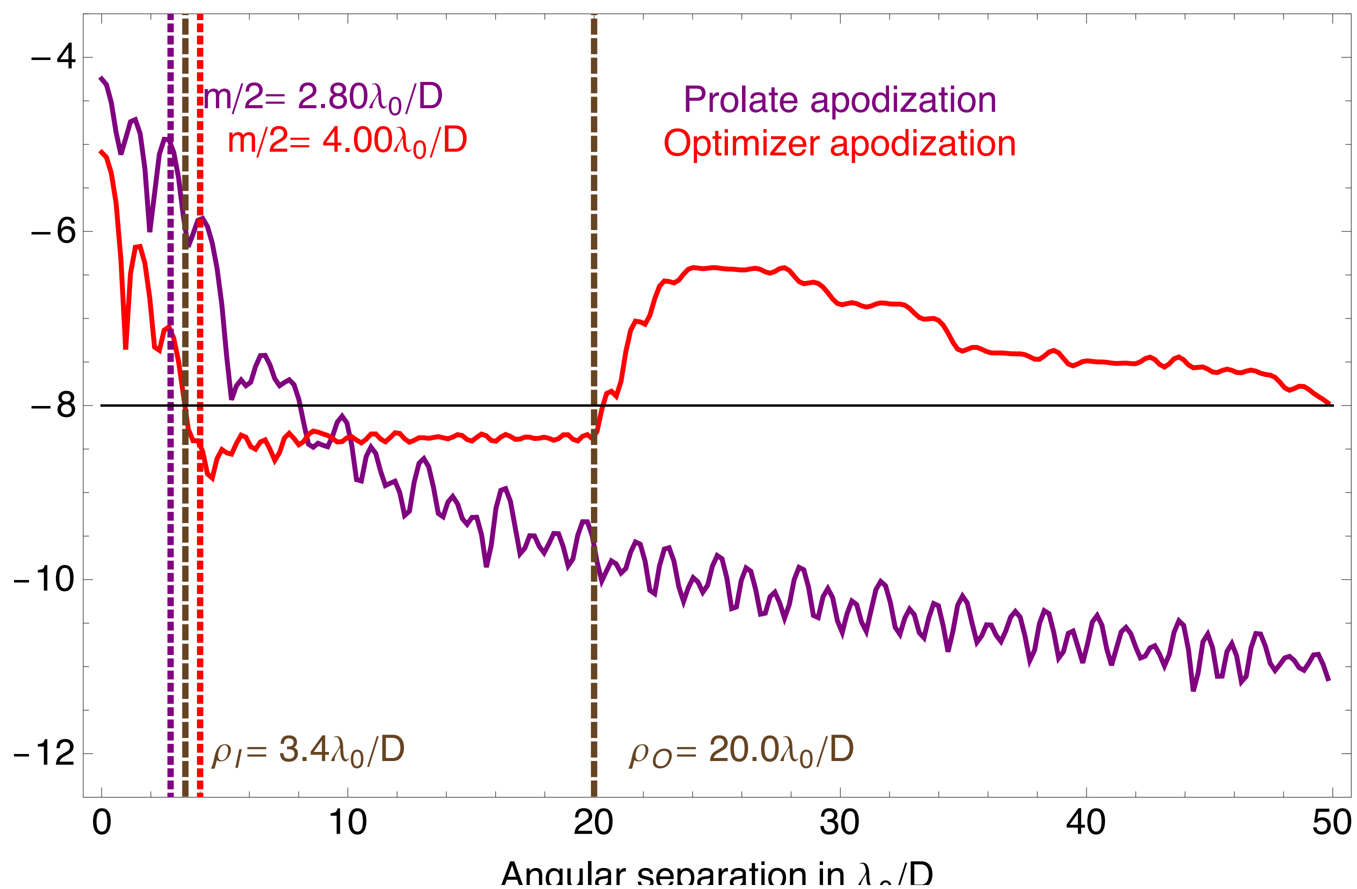


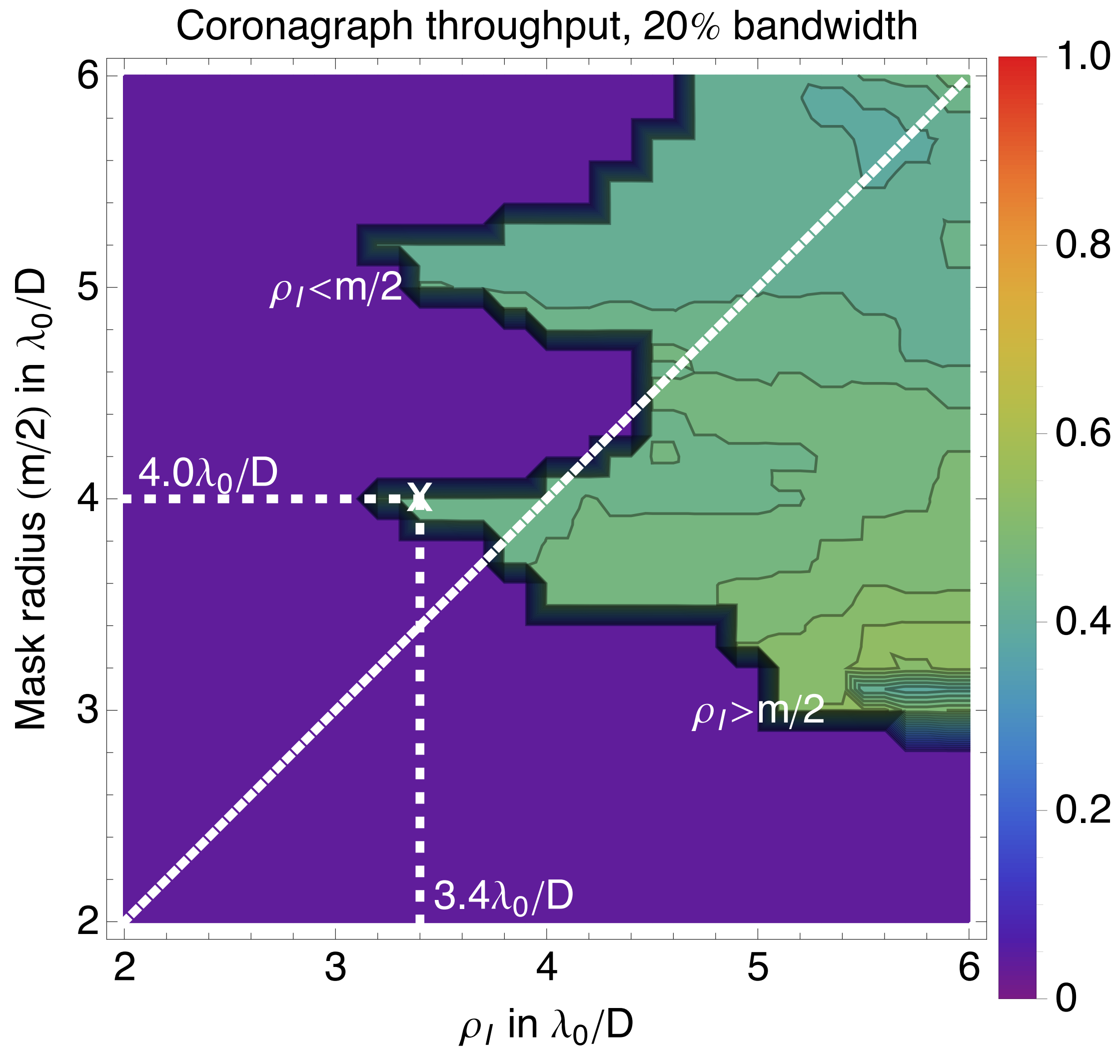


How to design higher performance coronagraphs?

Robustness to misalignments

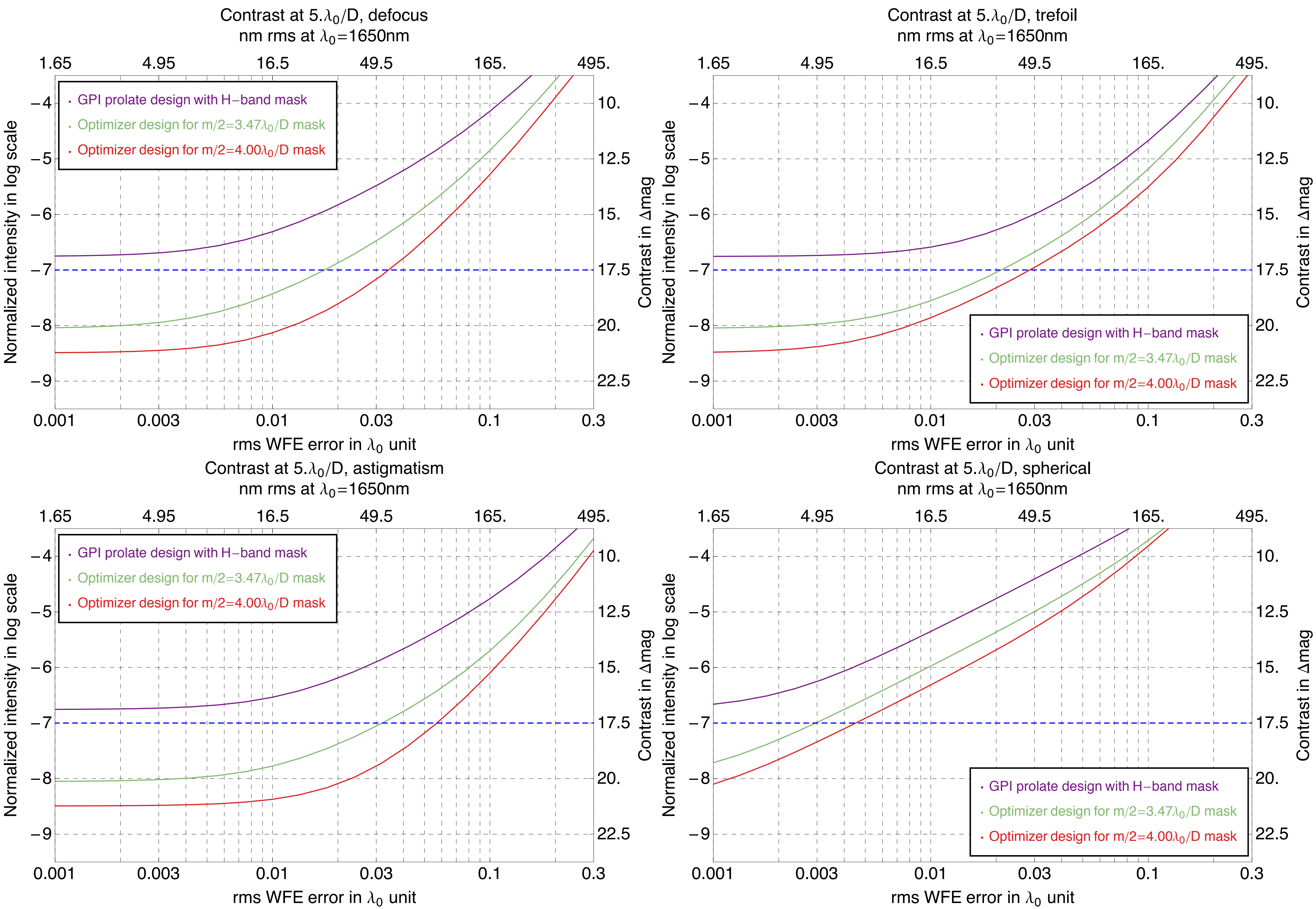
N'diaye et al. (2014)





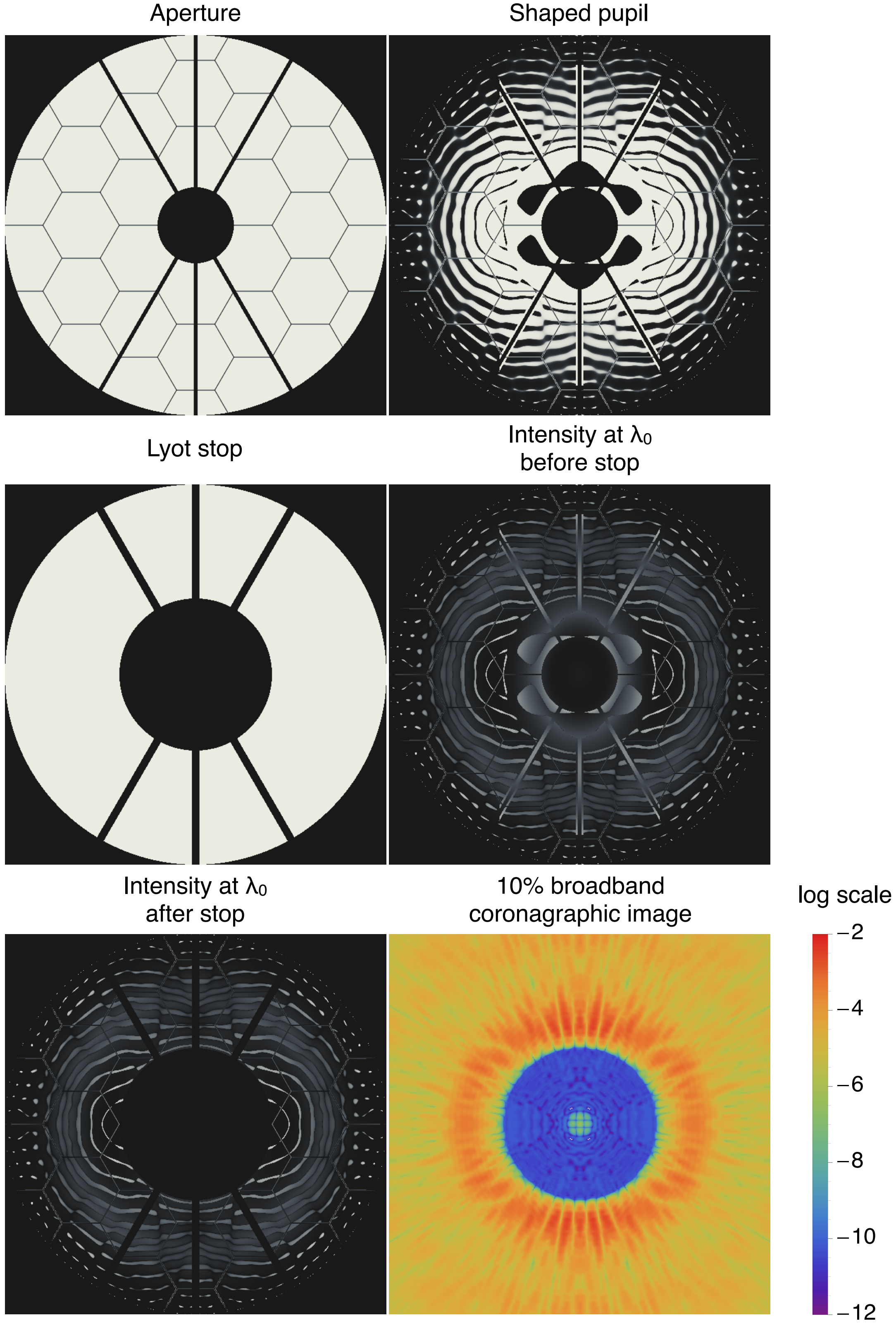
By forcing the "core of the PSF" to be smaller than the focal plane mask we are buying robustness to misalignments.

Robustness to misalignments

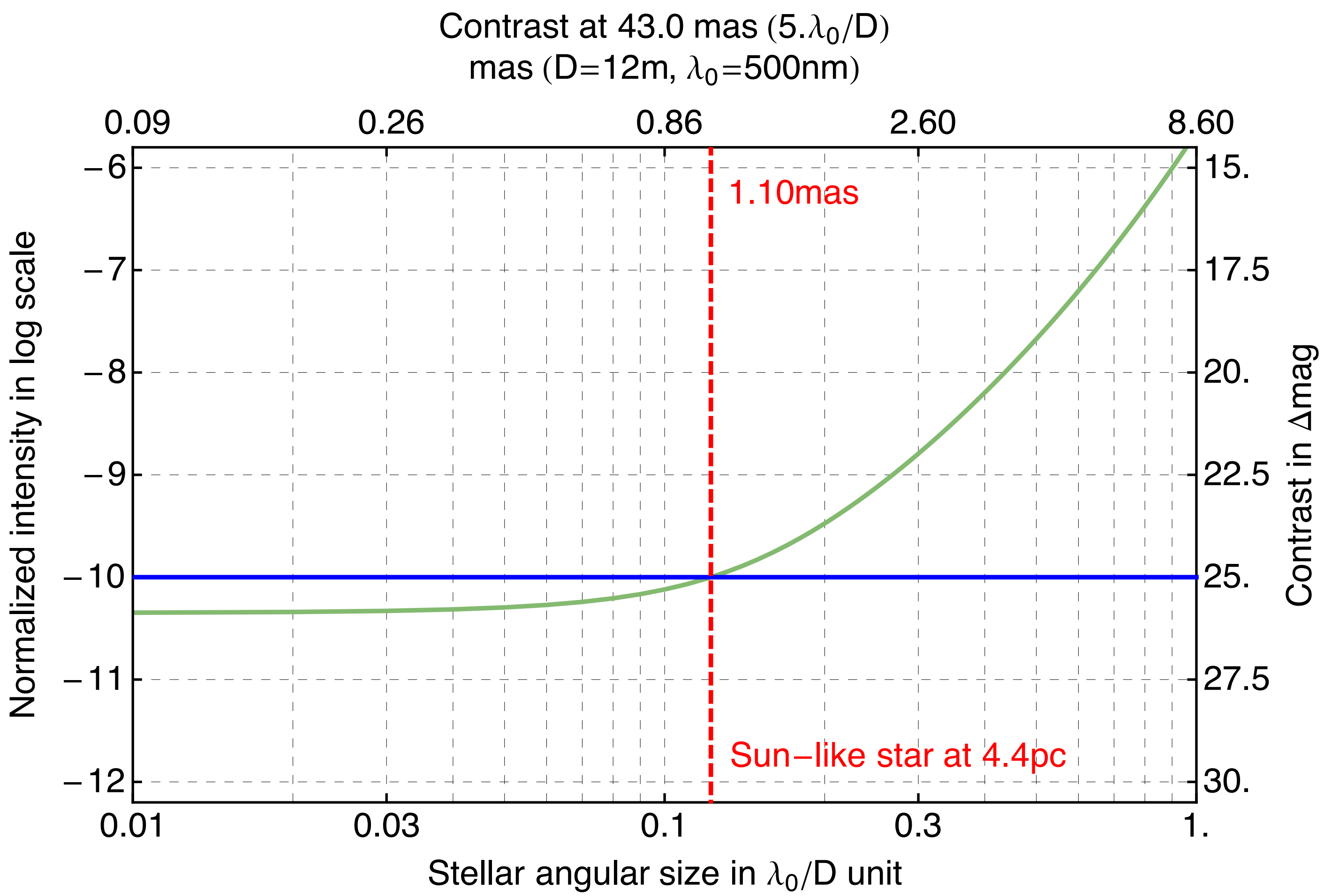


N'diaye et al. (2014)

Coronagraphs: starting point



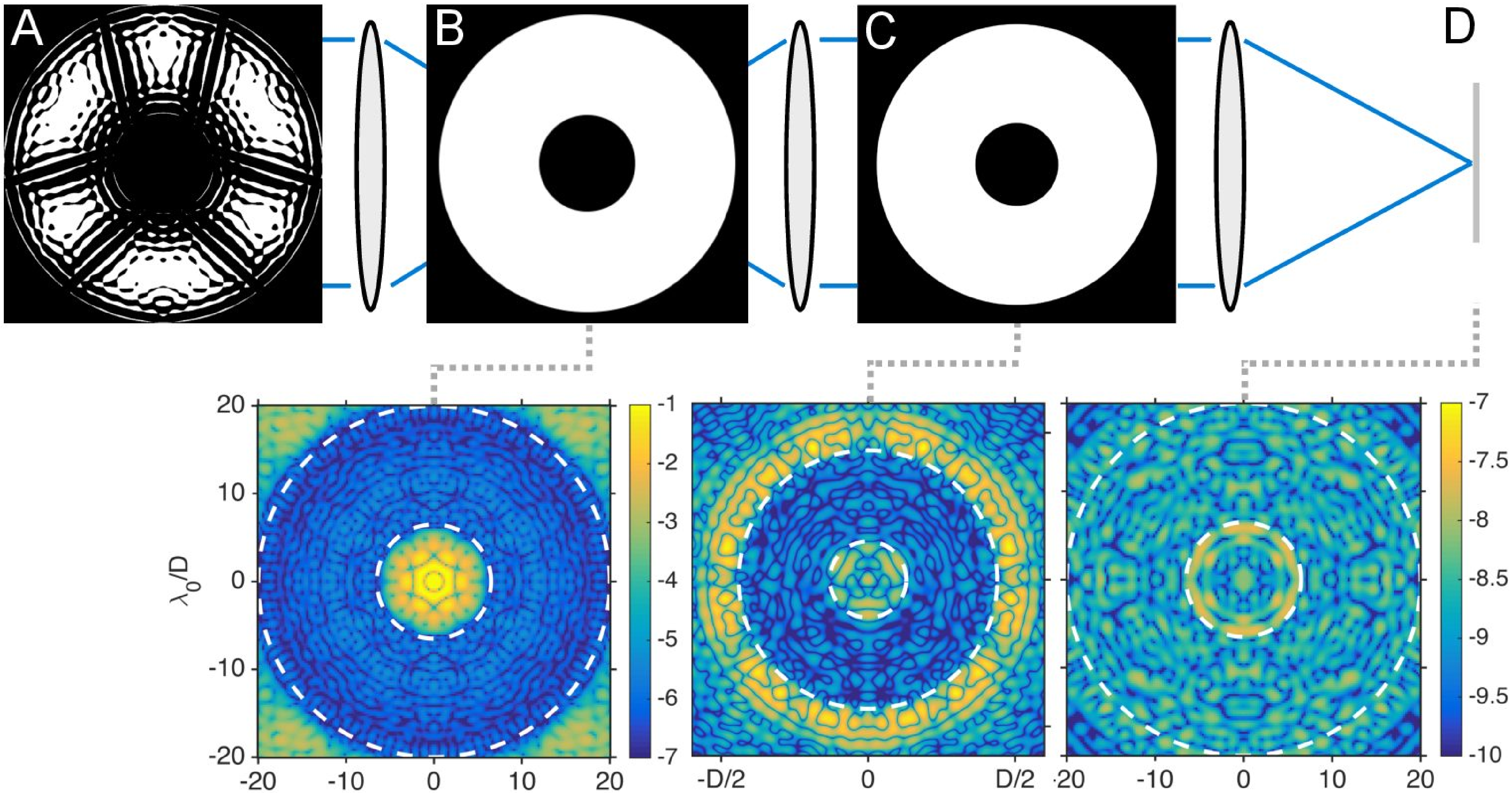
N'diaye et al. (2015)



As long as the target is farther than 4.4 pc, stellar angular size has no impact on contrast.

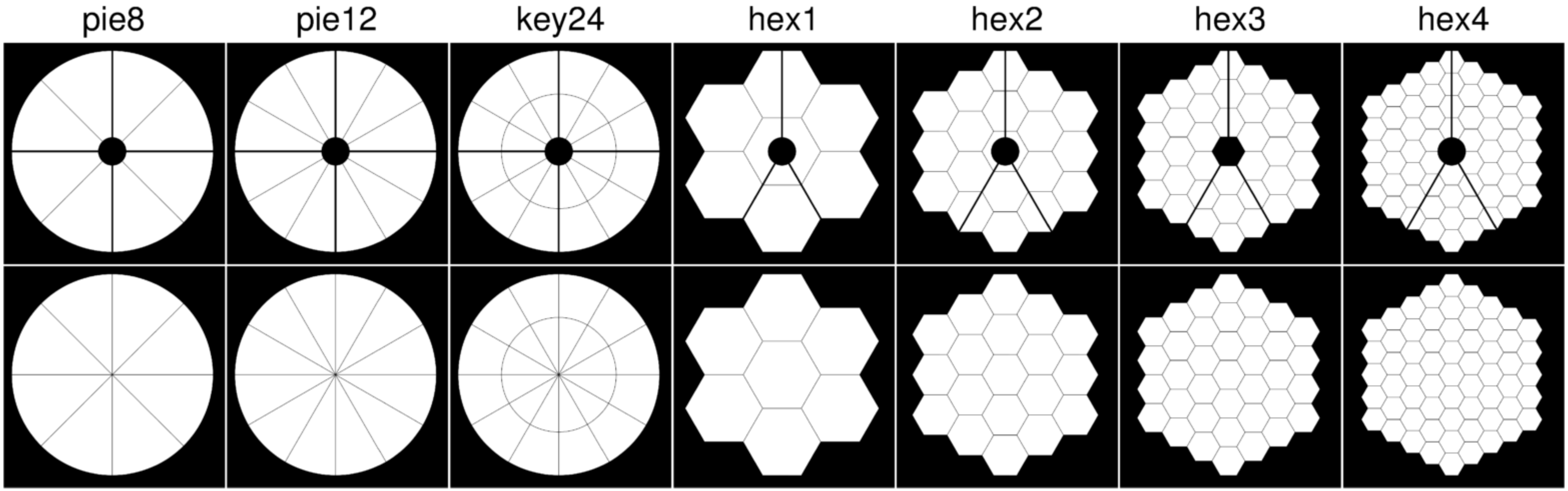
This will fly on WFIRST

Zimmerman et al. (2014)



This is the technology that will fly with WFIRST

Coronagraphs: SCDA study



- Telescope builders choose possible architectures.
- Coronagraph designers do their homework
- Coronagraph design propagated through PROPER code.
- Agreed upon metrics for yield calculations are estimated.
- Yield calculation.

SPC team: Remi Soummer, Neil Zimmerman, Kathryn St Laurent, Chris Stark, Robert Vanderbei, Jeremy Kasdin.

SCDA results SP/APLC

Courtesy of Neil Zimmerman

August-Sep 2016: New APLC design survey with expanded parameter range

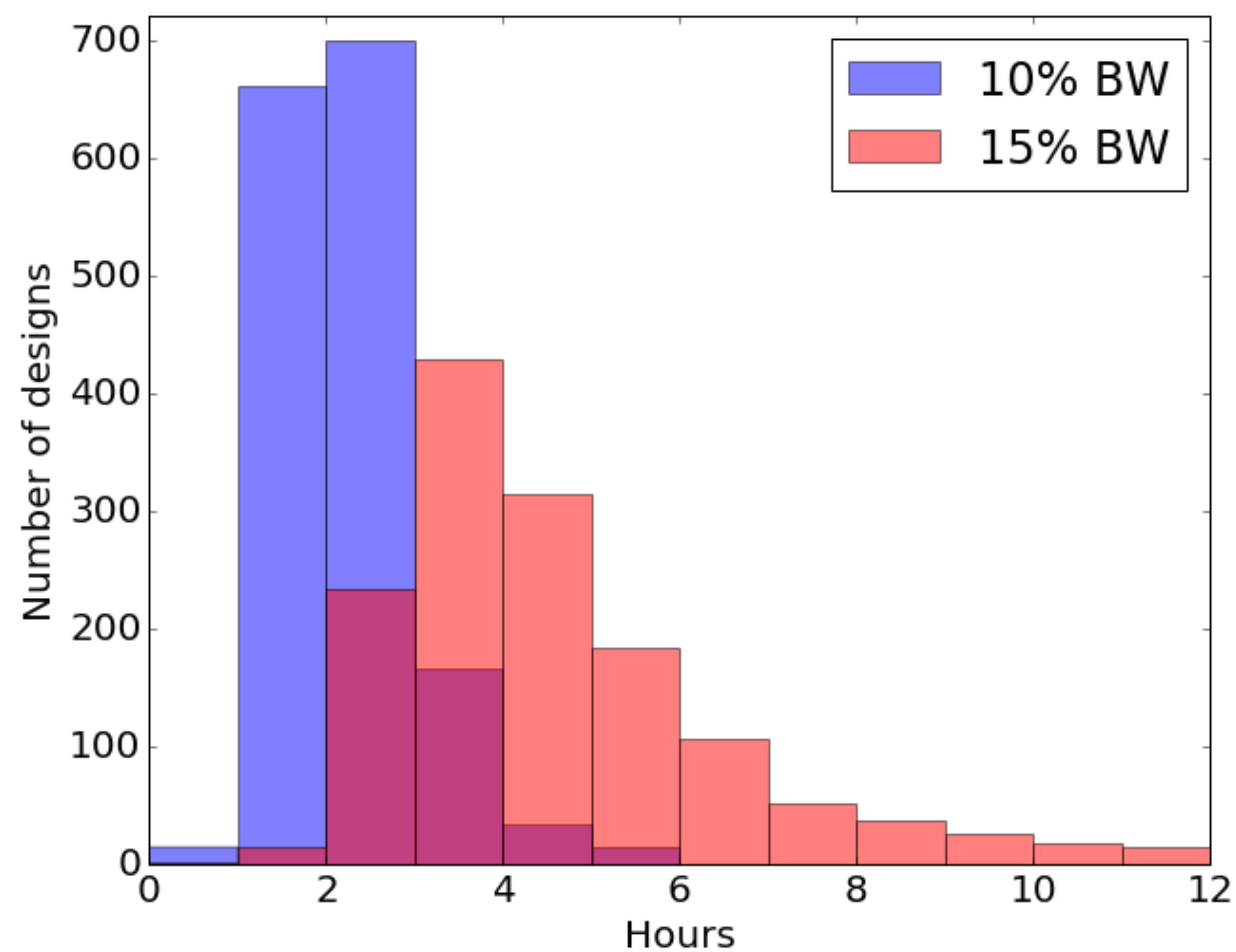
- 3100 new designs optimized on NCCS Discover supercomputer
- All SCDA reference apertures (hexagonal, pie, and keystone primaries)
- Inner working angles down to 2.5 λ/D
- With and without central obscuration (on-axis versus off-axis)
- Contrast fixed at 10^{-10} throughout

NCCS Discover is an efficient tool for running many linear optimization programs to survey the APLC design parameter space.

Up to 50 optimization jobs run concurrently, with typical completion times < 6 hours.

STScI team has submitted a proposal to renew the NCCS allocation in November (~25k run hours)

Optimization completion time per design



SCDA results SP/APLC

Courtesy of Neil Zimmerman

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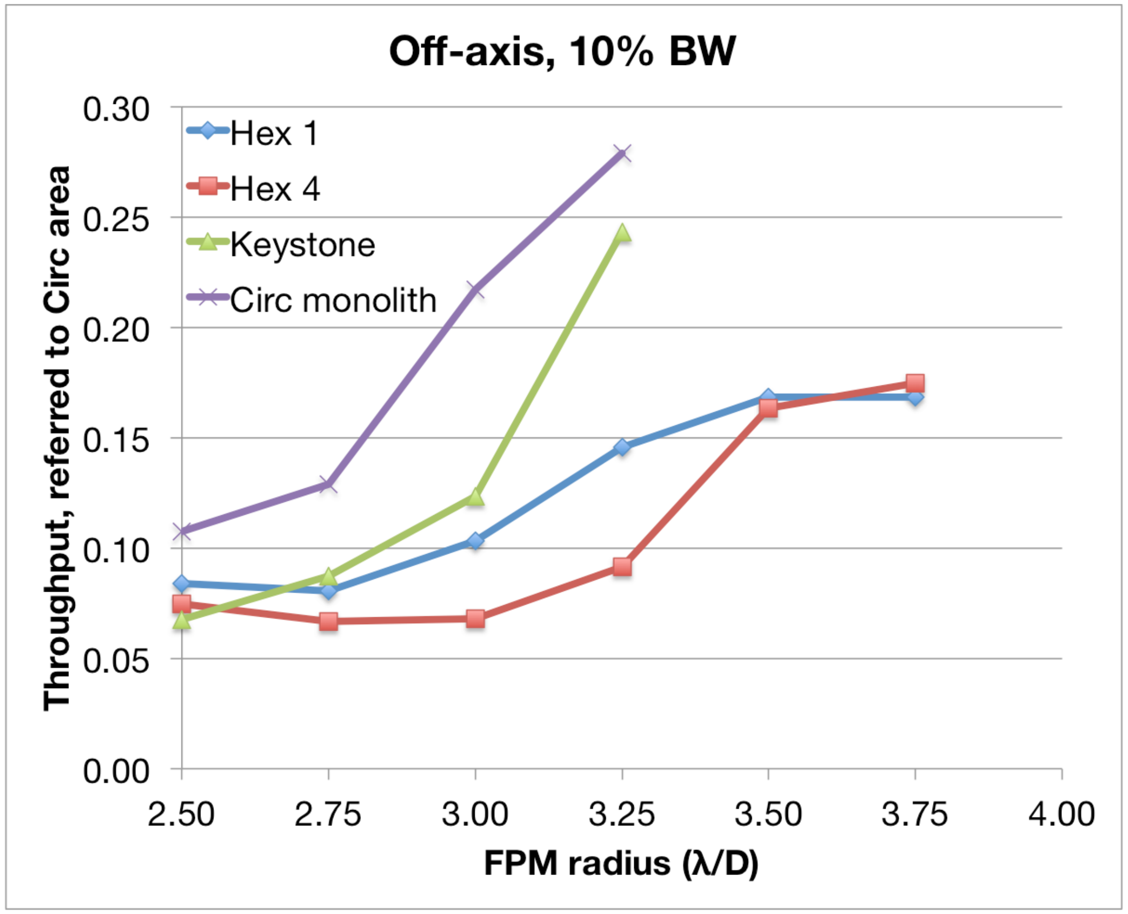
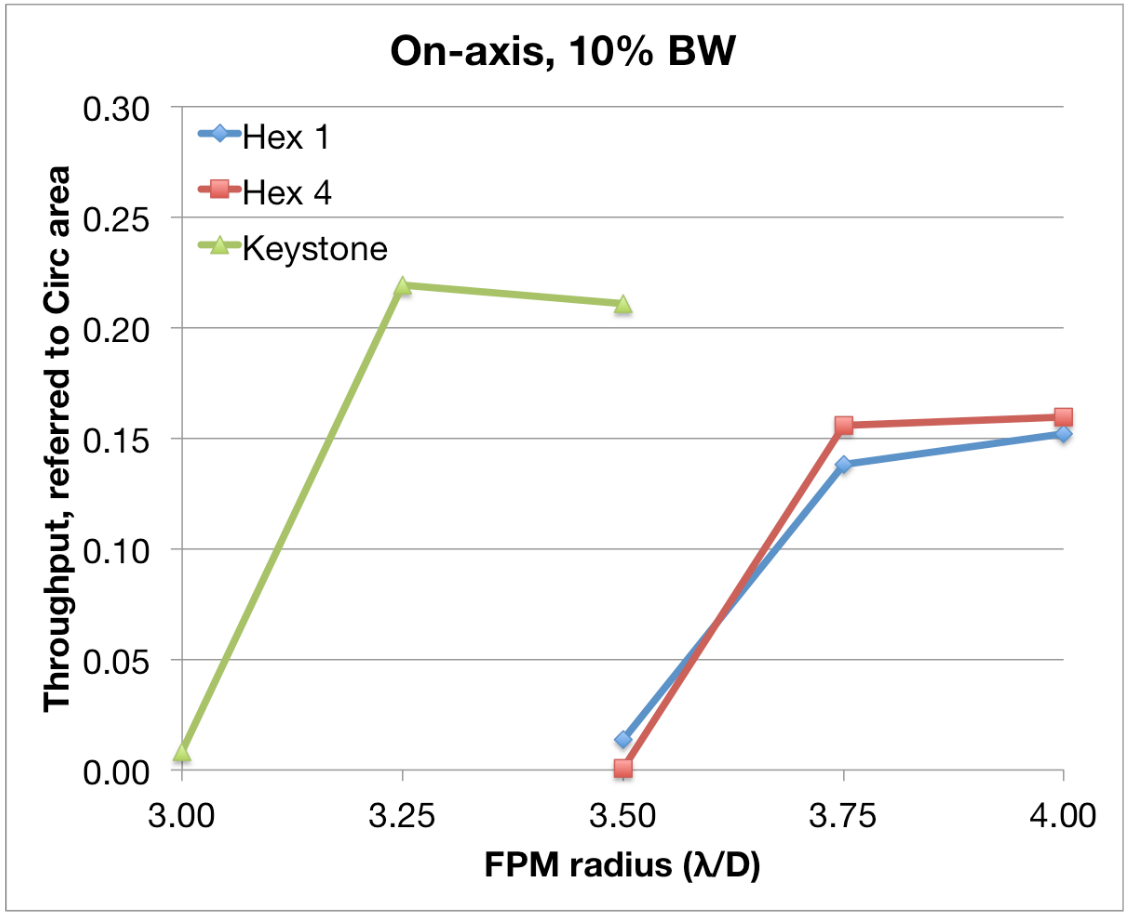
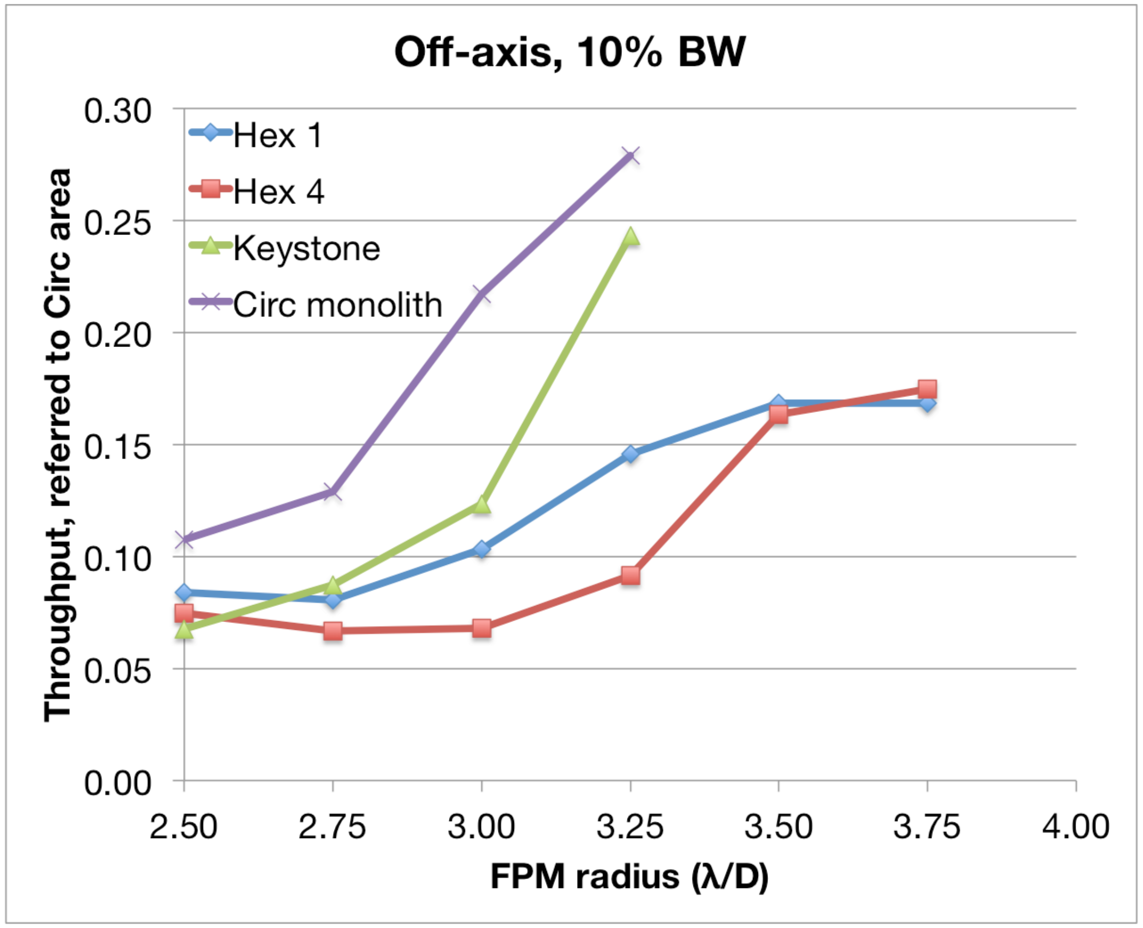
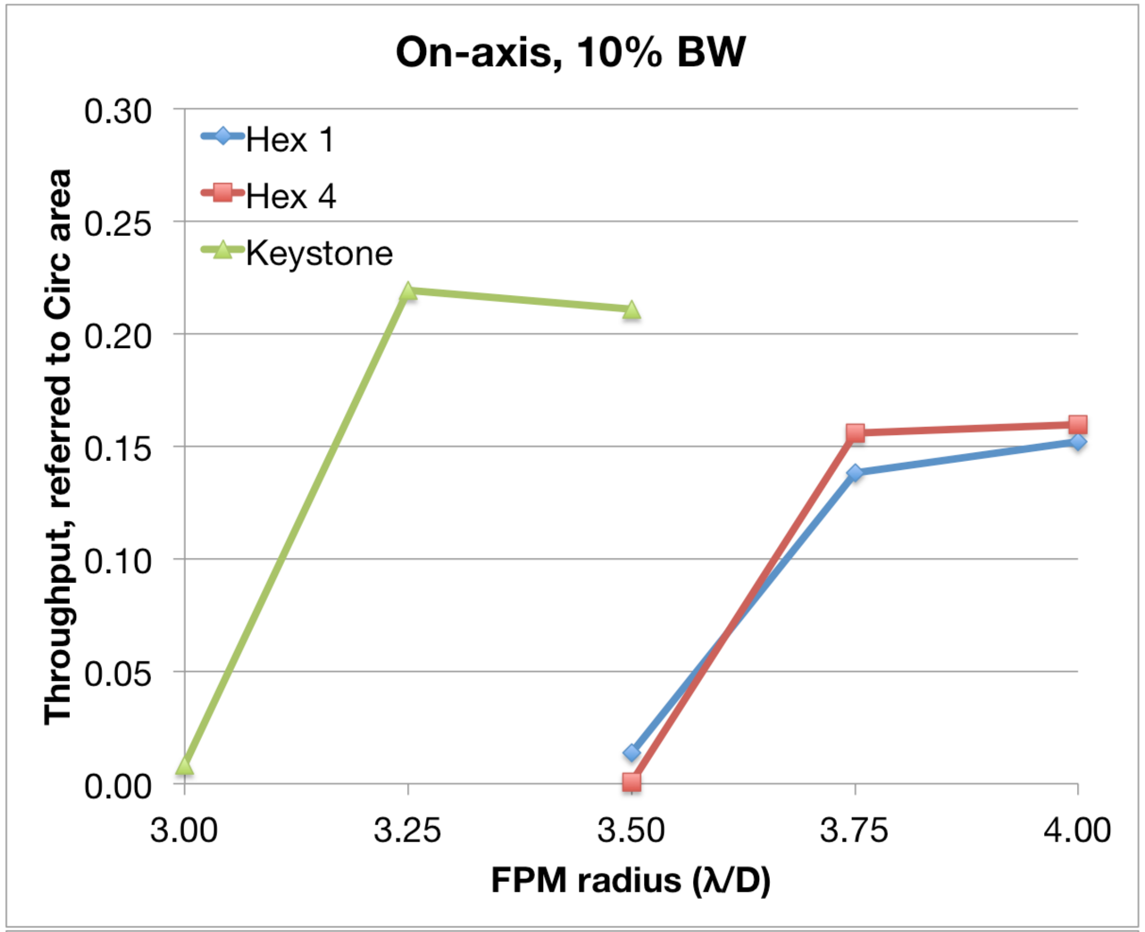
Throughput of best designs as a function of IWA

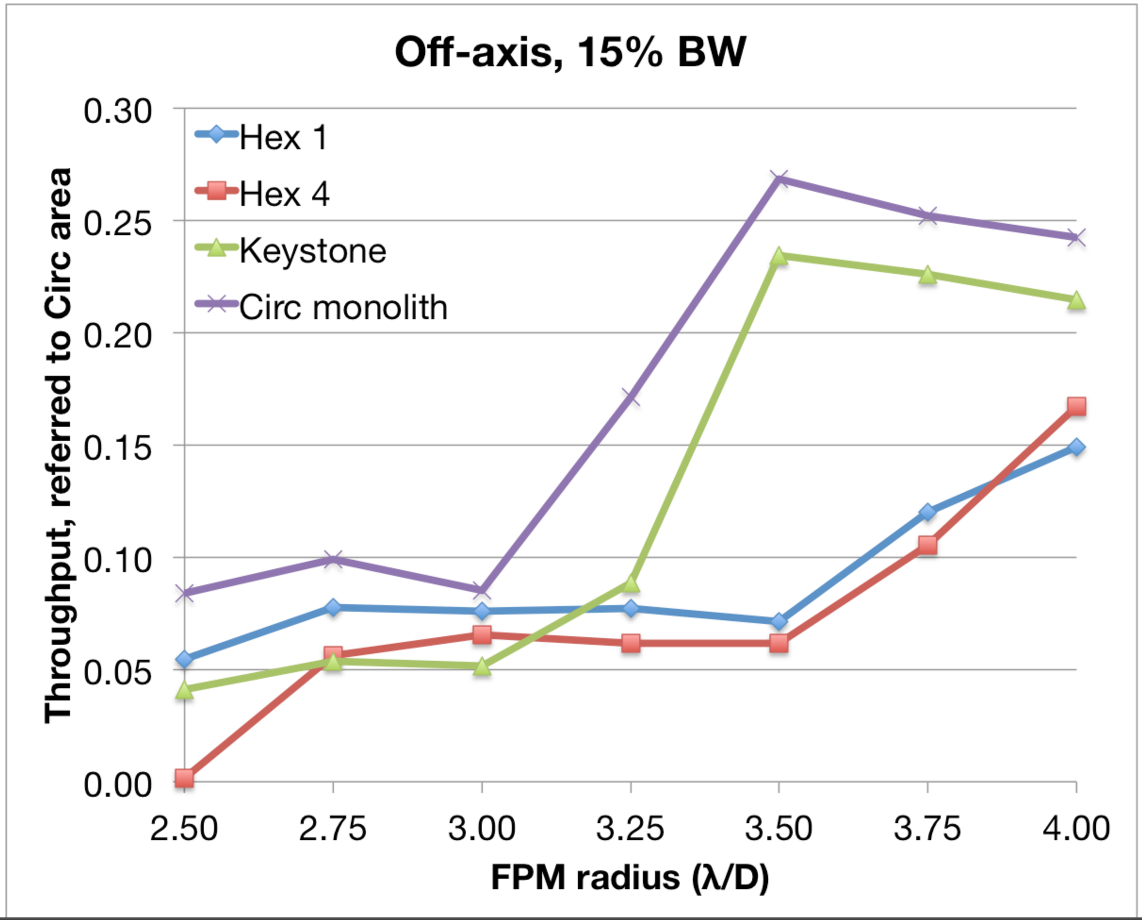


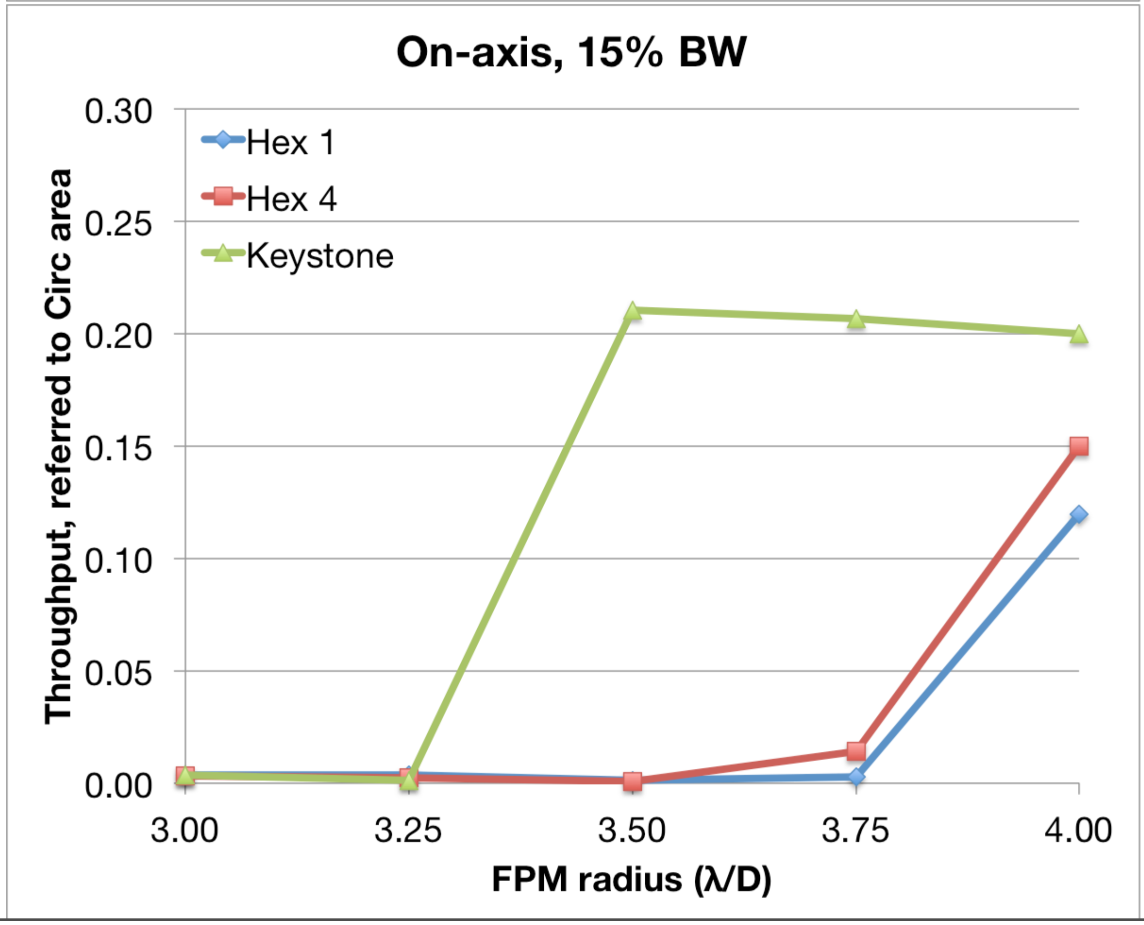


SCDA results SP/APLC

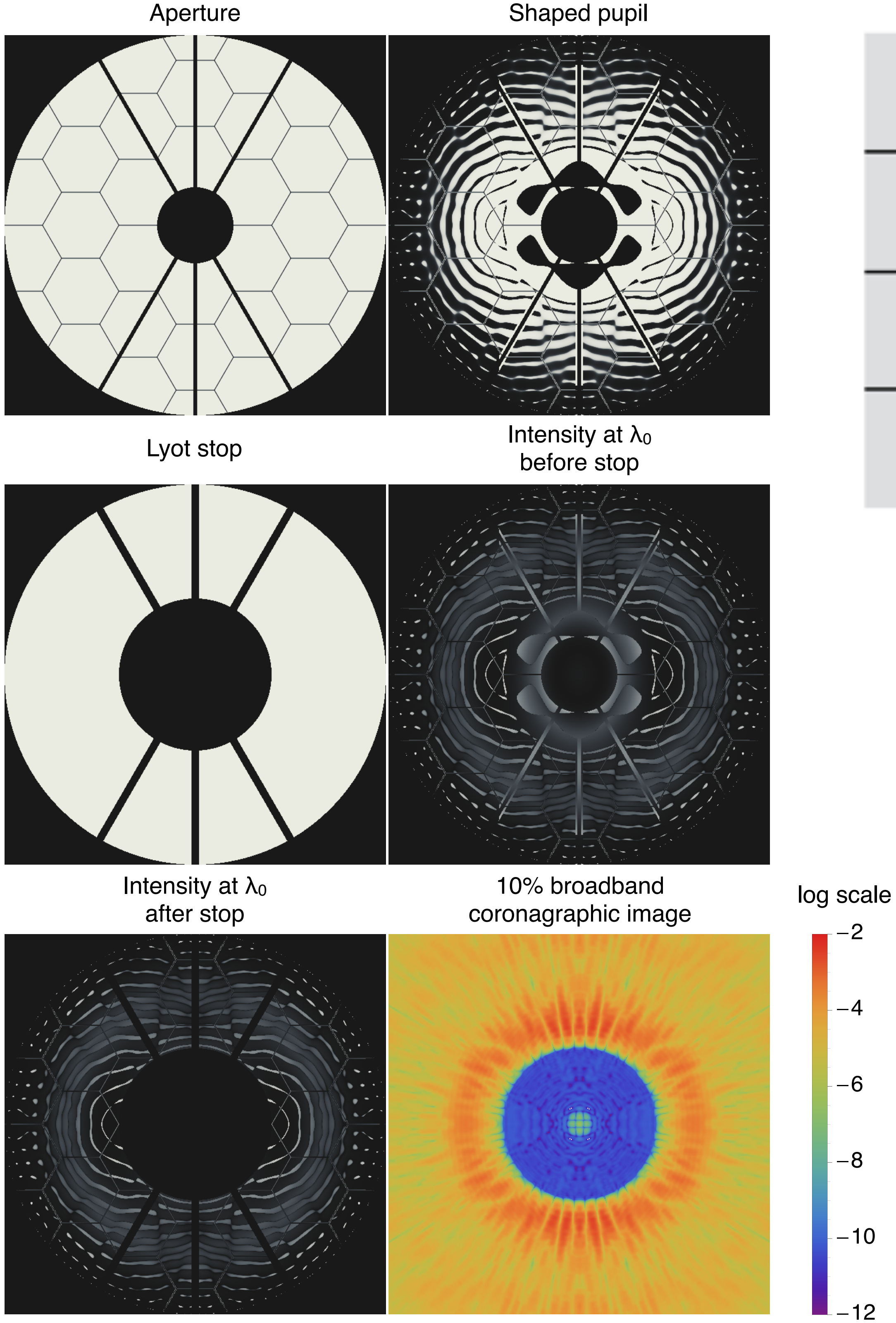






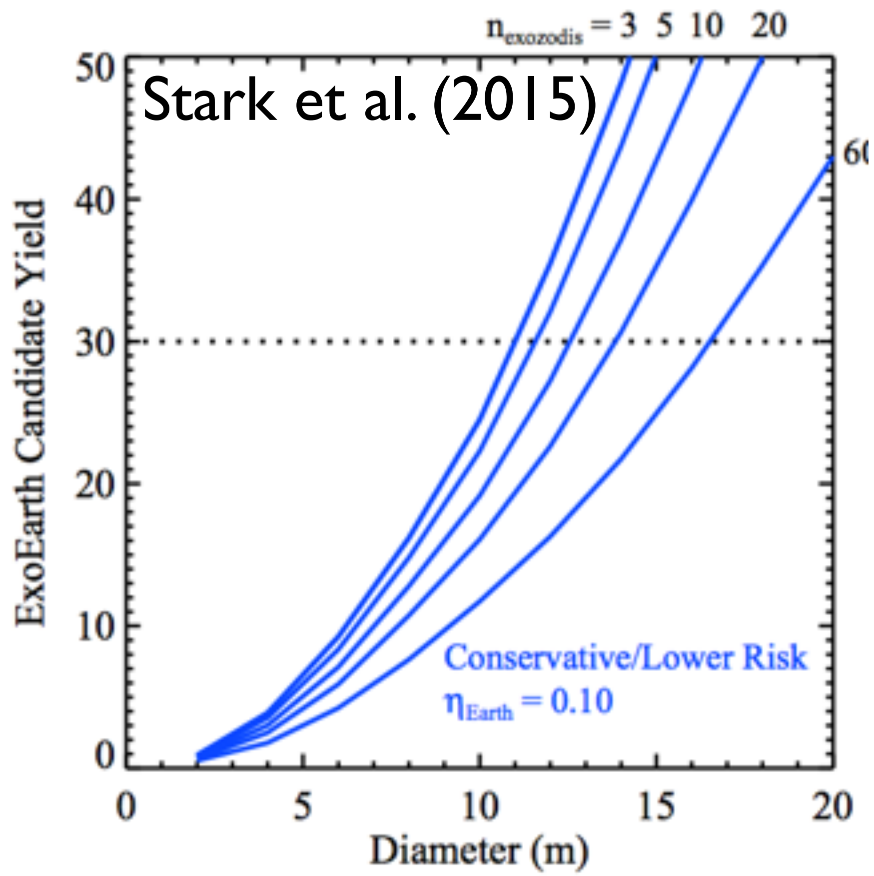


SCDA results SP/APLC



Aperture	Obscured	Unobscured
Hex 1	22	31
Hex 4	26	28
Keystone 24	31	36

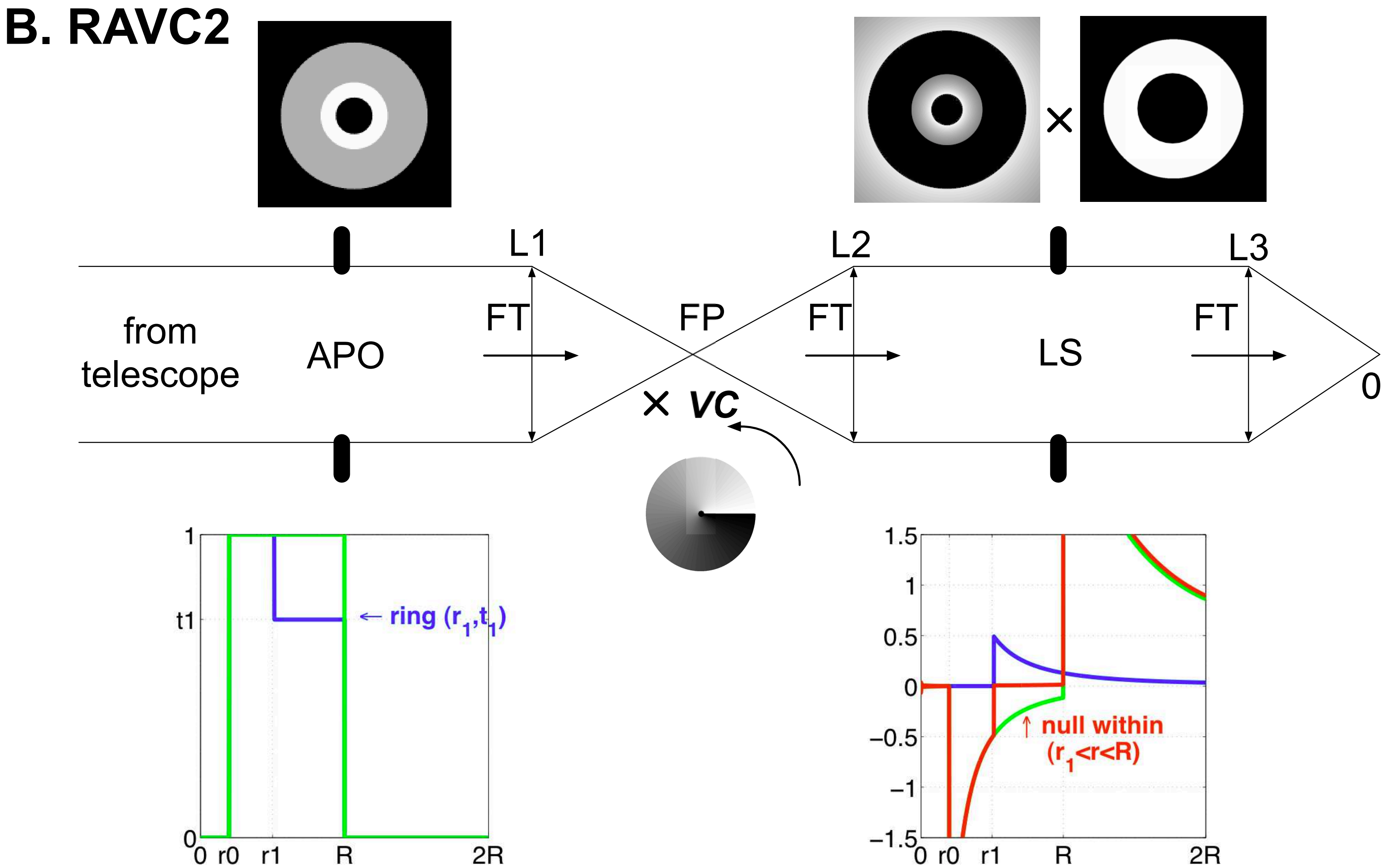
Courtesy of Neill Zimmerman

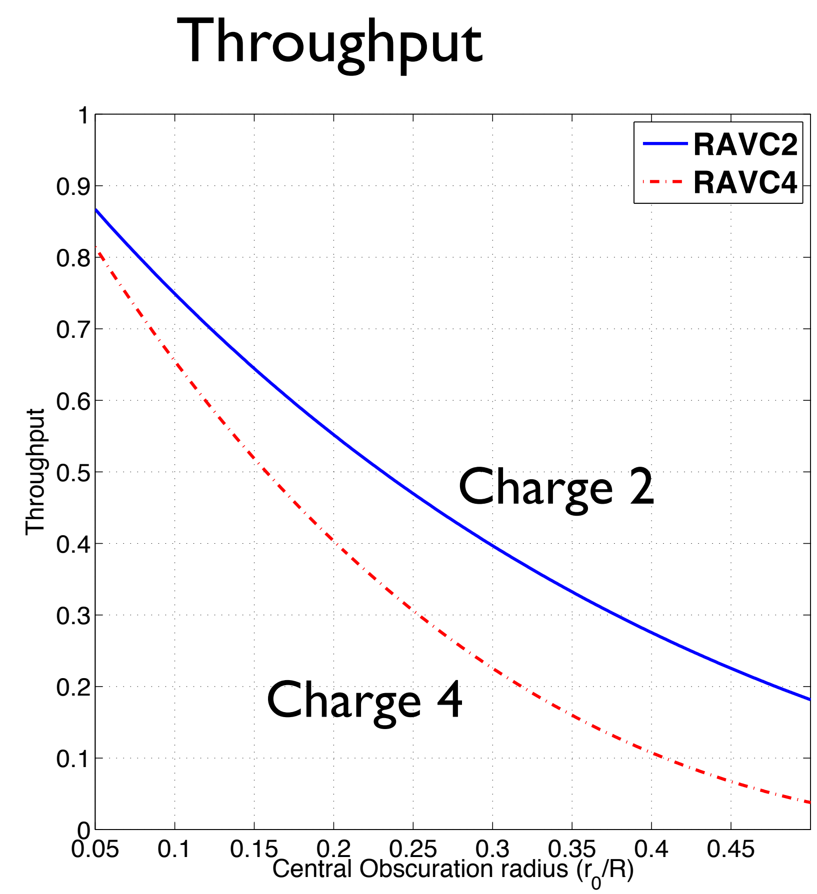


How to better design coronagraph.

Preliminary Results with Vortex

Mawet et al. (2013)

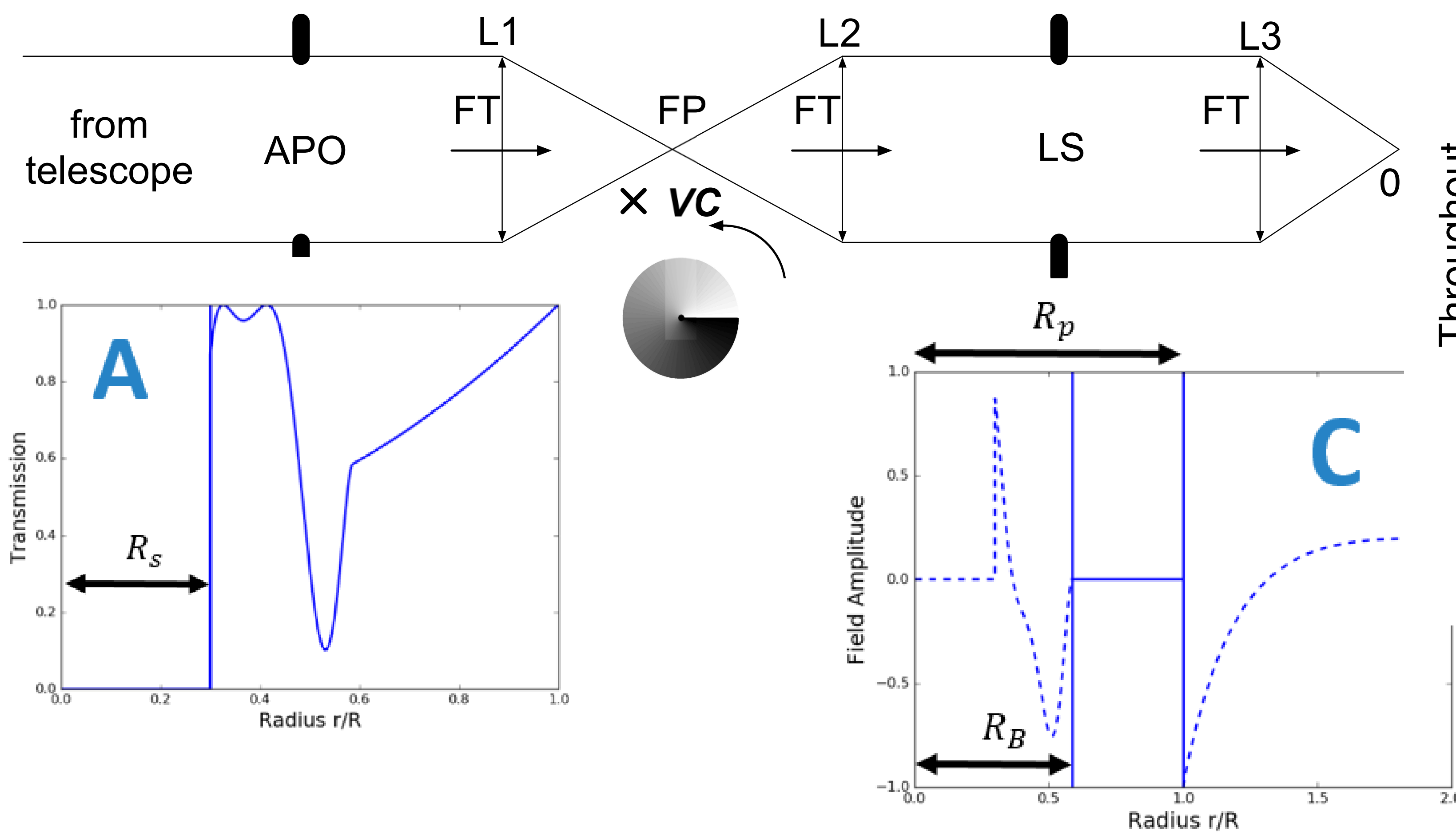




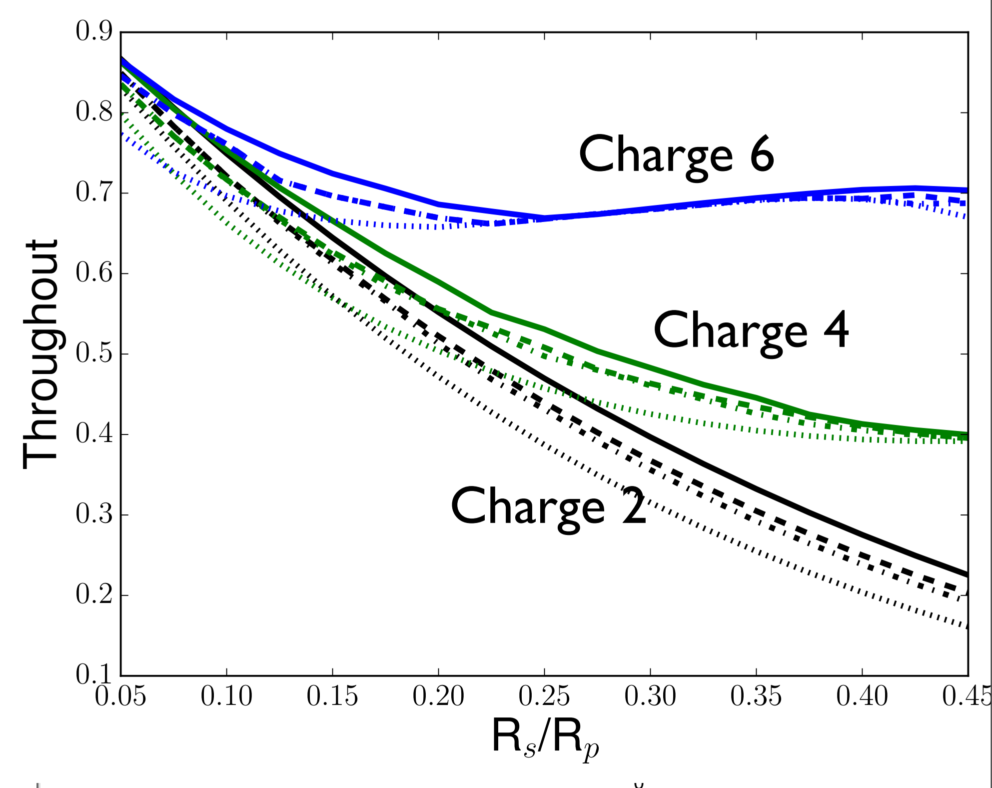
- Analytical solutions for pupil mask take care of the central obscuration

Preliminary Results with Vortex

Fogarty et al. (in prep)



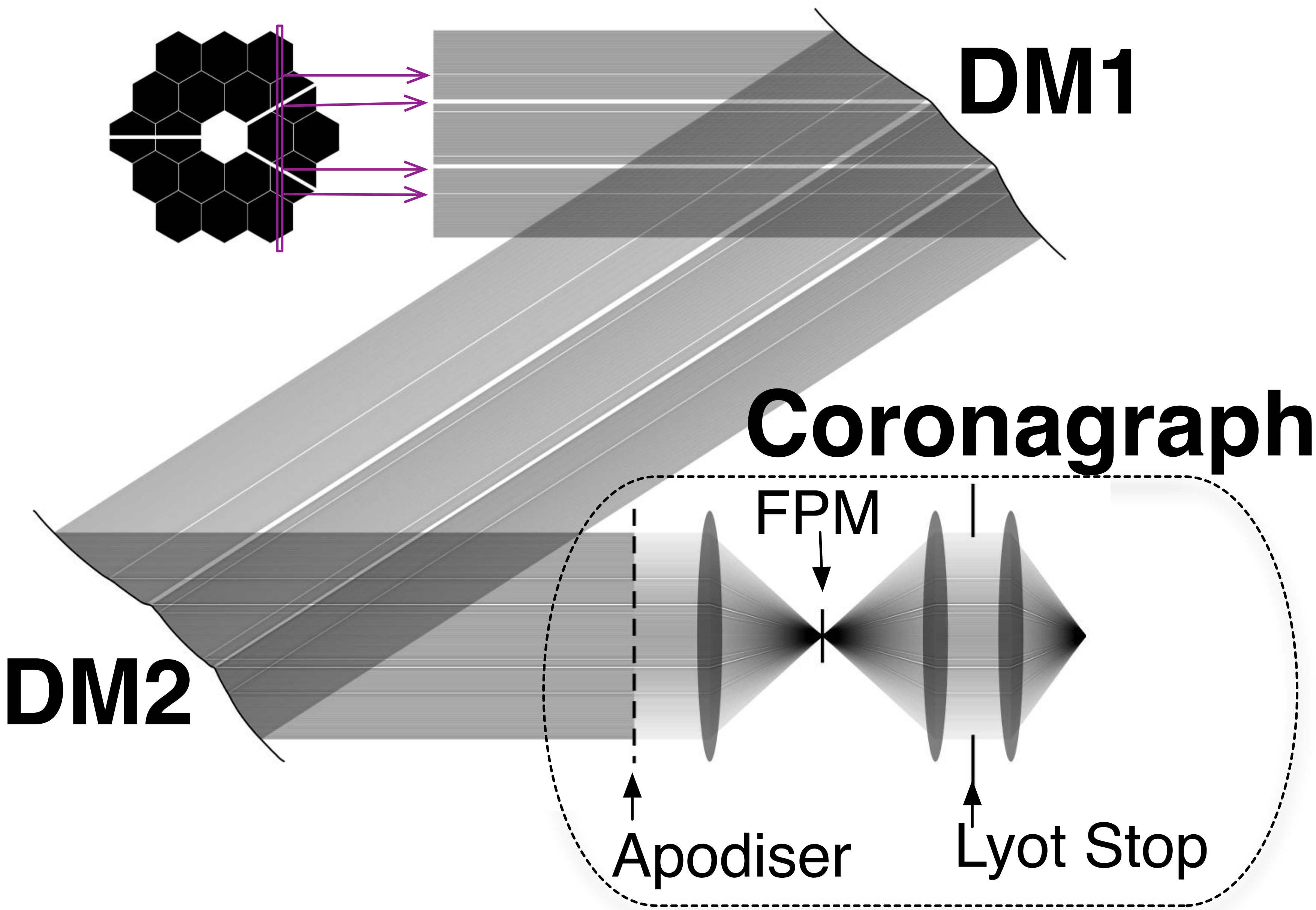
Throughput



• Analytical solutions for pupil mask take care of the central obscuration

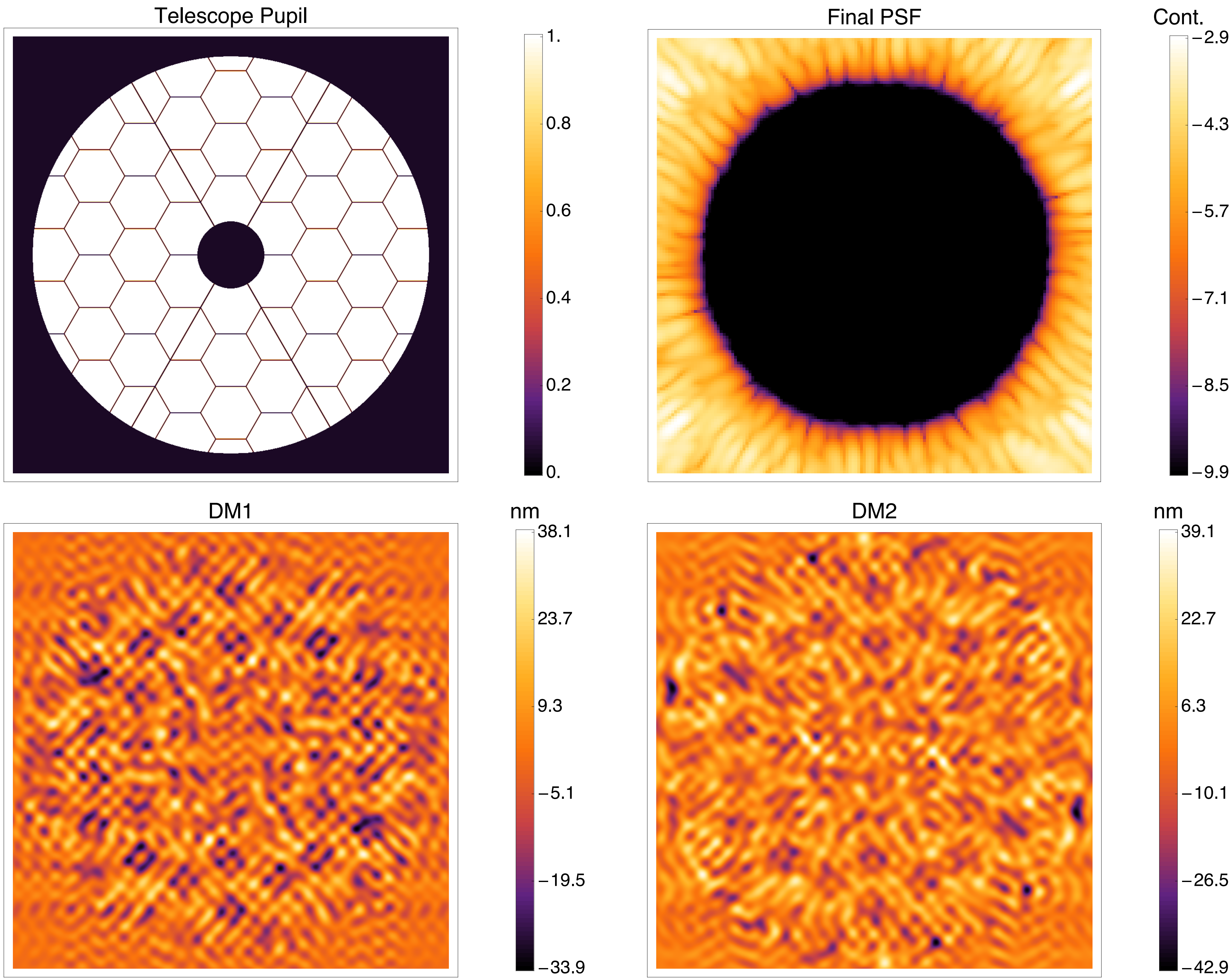
Preliminary Results with Vortex

Pueyo and Norman (2013)



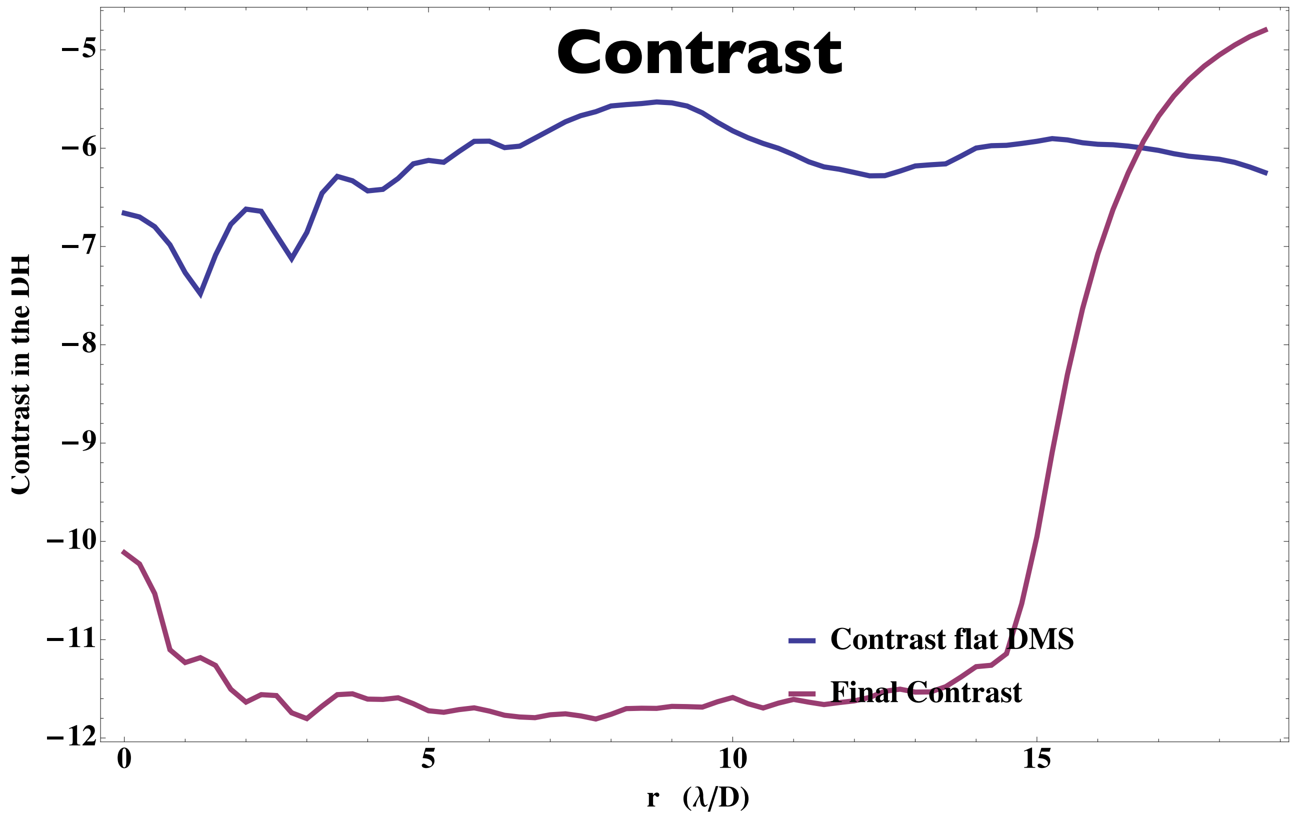
- Use Deformable Mirrors to take care spiders/segment gaps.

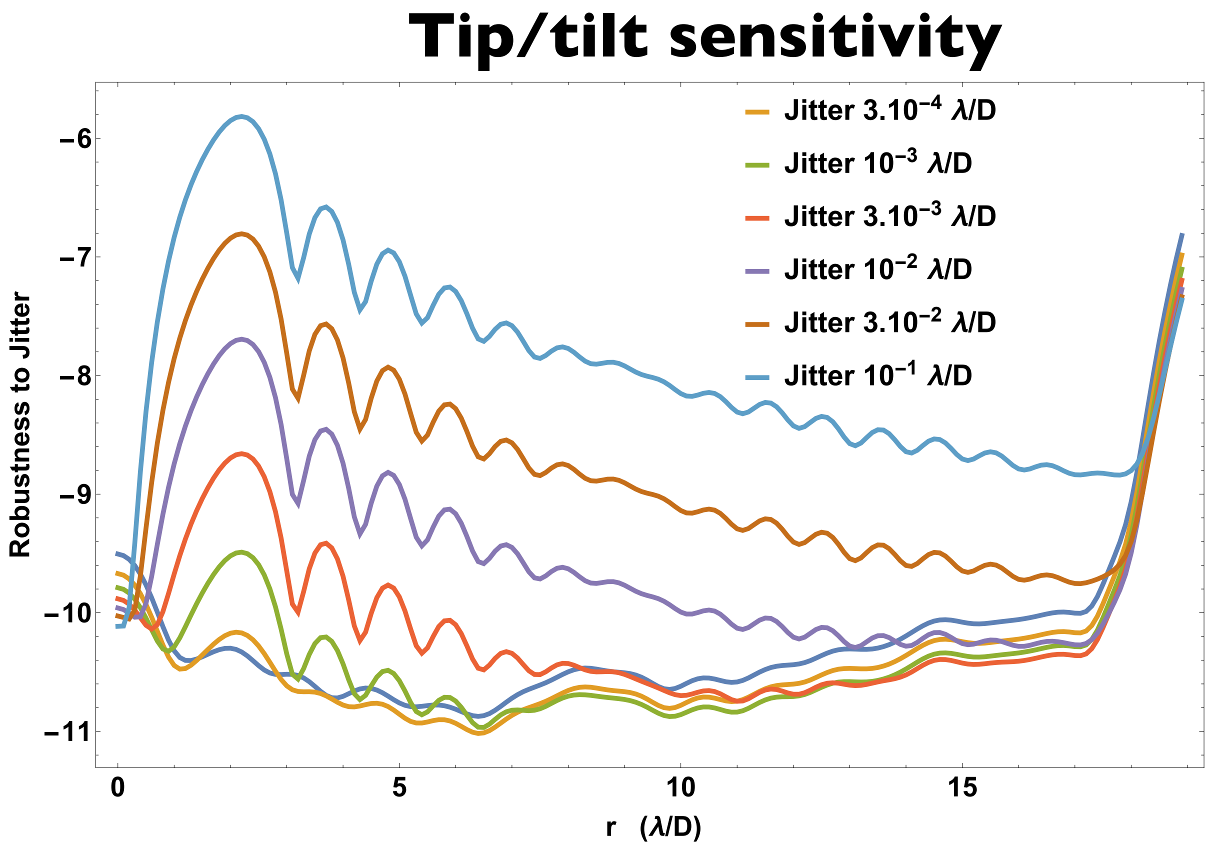
Preliminary Results with Vortex

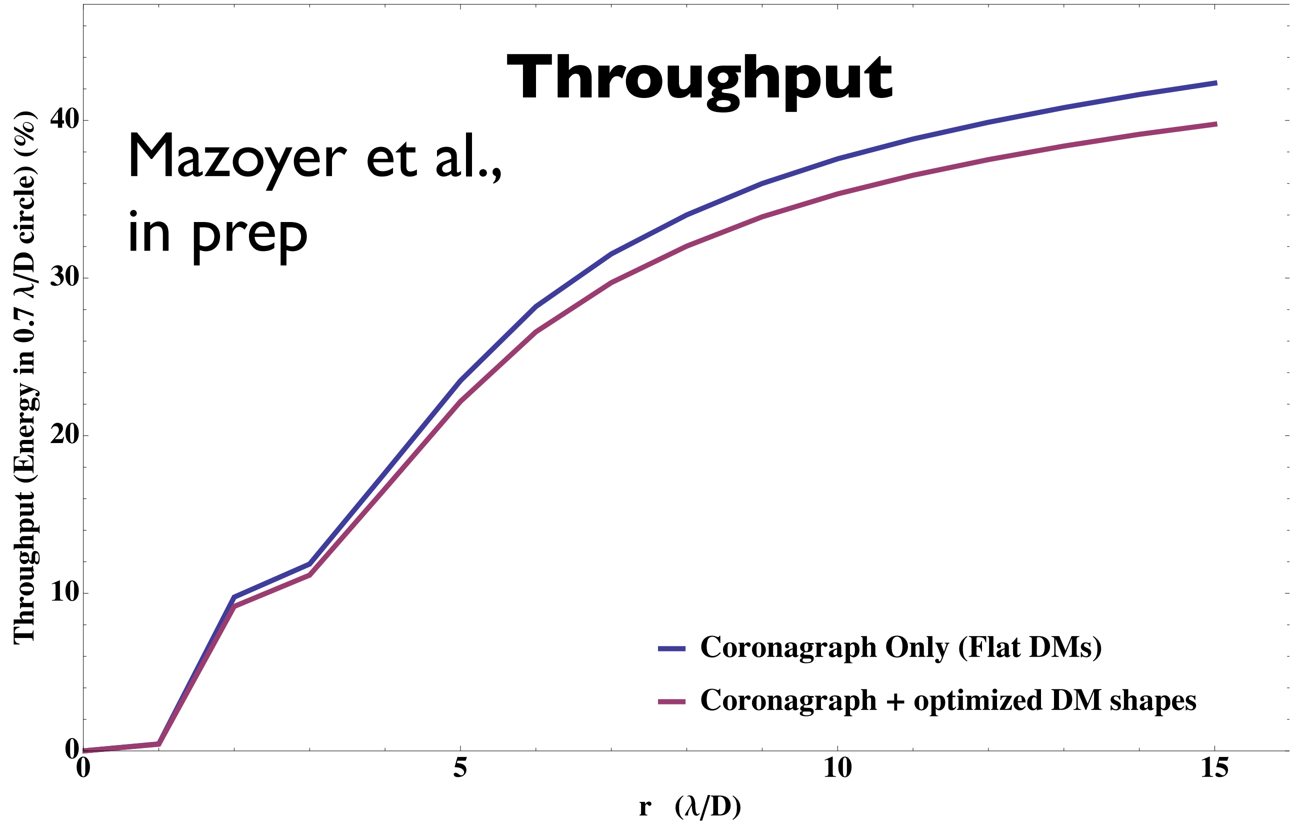


Mazoyer et al., in prep

Preliminary Results with Vortex







- Clear advantage in throughput as a function of separation.
- However more sensitive to jitter/finite stellar angular size.
- Yield calculations done yet with this specific design.

Garreth will tell you a lot more about this...

Vortex coronagraph performance

G. Ruane[1,*], J. Jewell[2], D. Mawet[1,2], S. Shaklan[2], C. Stark[3], K. Fogarty[3], J. Mazoyer[3], L. Pueyo[3], and J. Wang[1]

[1]California Institute of Technology

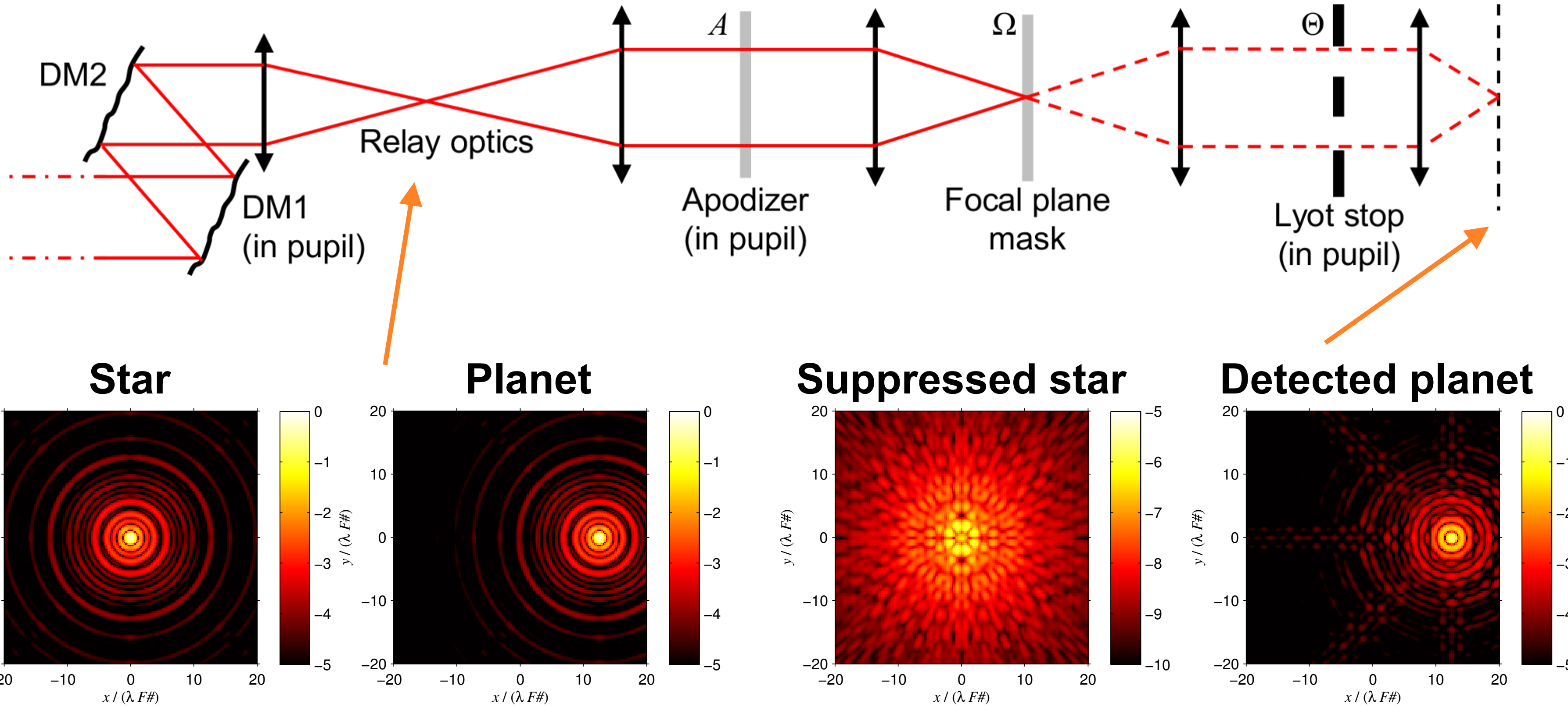
[2]Jet Propulsion Laboratory

[3]Space Telescope Science Institute / JHU

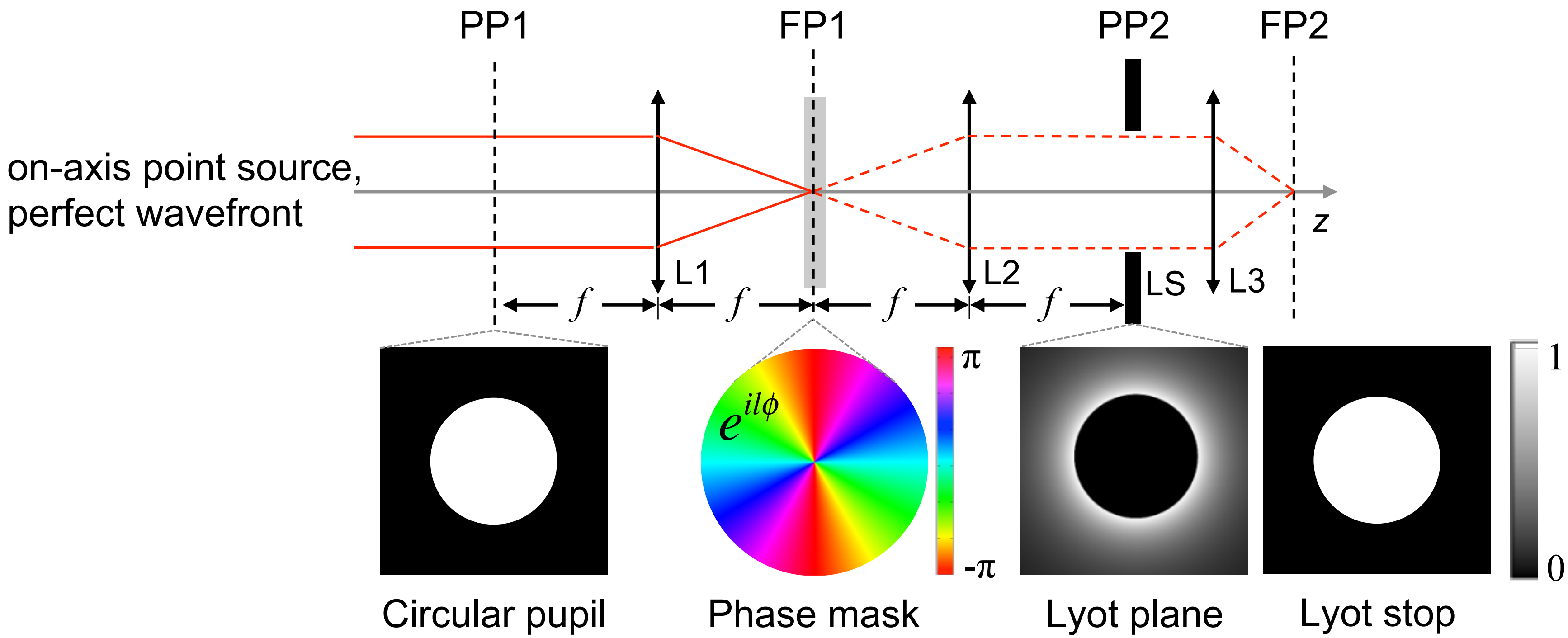
*NSF Astronomy and Astrophysics Postdoctoral Fellow

HabEx meeting | 11/7/2016

Three-mask coronagraph concept



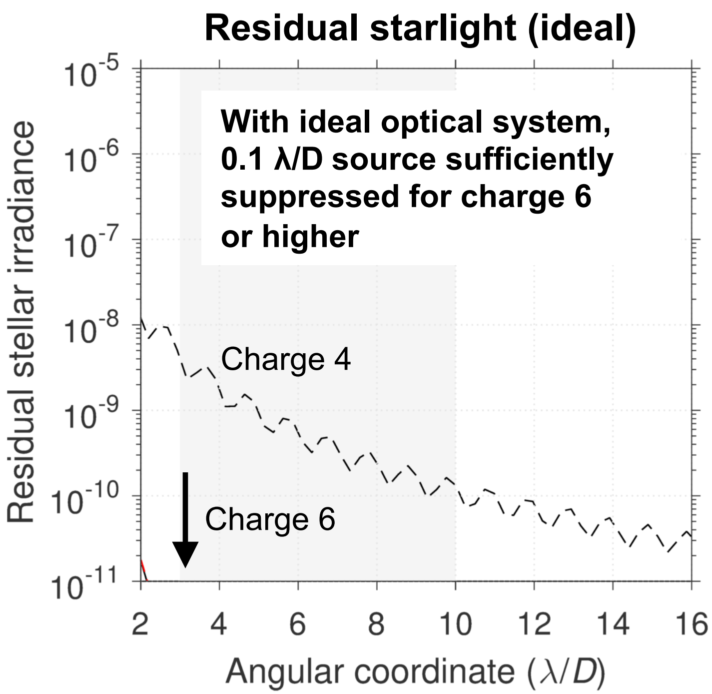
Vortex coronagraph

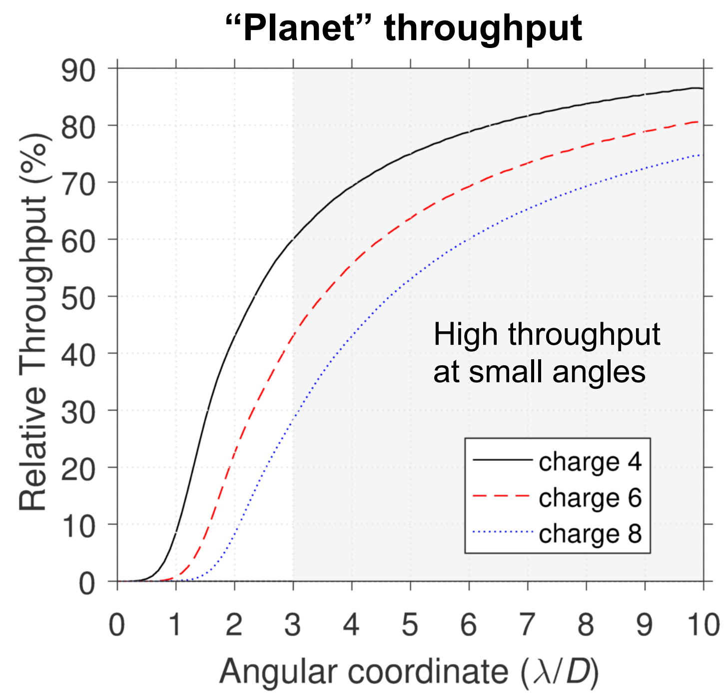


“Piston” rejected by Lyot stop for even (nonzero) charges.

Mawet et al., *ApJ* **633** 1191 (2005)

Performance with unobscured (off-axis) telescopes





Stellar irradiance is azimuthally averaged and normalized to the peak of the telescope PSF.

Throughput is defined as energy within 0.7 λ/D of the source position, normalized to that of the telescope.

Mawet et al., *Proc. SPIE* 773914 (2010)

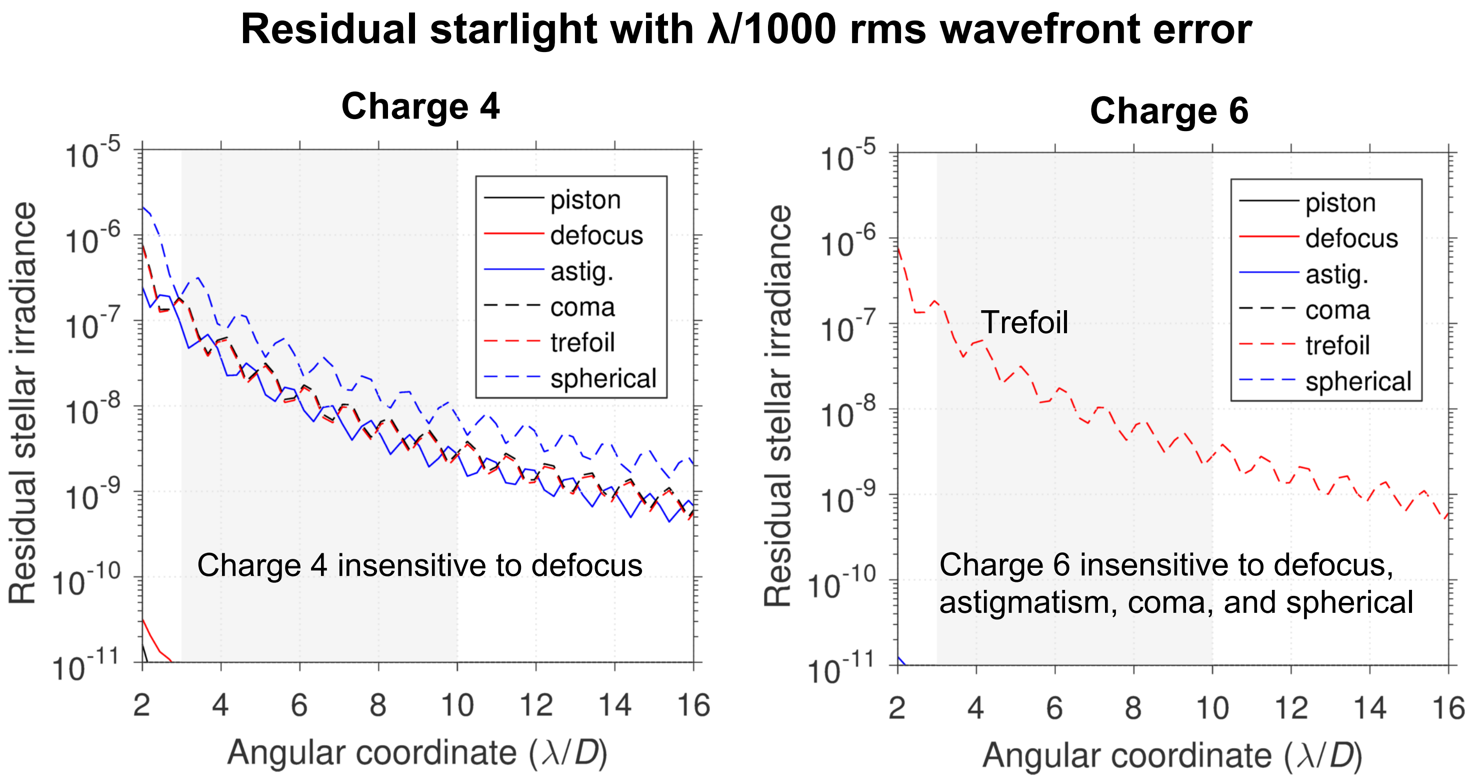
ExoEarth Candidate Yield Calculations

Diameter	VC4 Yield	VC6 Yield	VC8 Yield
4.0-m	8	7	5
6.5-m	19	17	14
12-m	55	53	45

- **Method outlined in Stark et al. (2014) and (2015)**
- Target list generated using Hipparcos catalog
  - Nearest main sequence and sub-giant stars w/o companions
- $\eta_{\oplus} = 0.1$
- 3 ‘zodis’ of dust
- V band detections with $S/N = 7$ (via classical imaging only)
  - No spectral characterization
  - Multiple visits allowed
- Total integration time = 1 year
- Detection limit: $S_{\mathrm{planet}} > 0.1 S_{\mathrm{star}}$
- **Coronagraph simulations include the finite size of star**
- **All other optical aberrations/imperfections ignored**

Stark et al., *ApJ* **795** 122 (2014)
Stark et al., *ApJ* **808** 149 (2015)

Performance with unobscured (off-axis) telescopes



Stellar irradiance is azimuthally averaged and normalized to the peak of the telescope PSF.

Mawet et al., *Proc. SPIE* 773914 (2010)

Zernike mode selection rules

For small phase aberration
i.e. $\Phi \ll 1$ rad

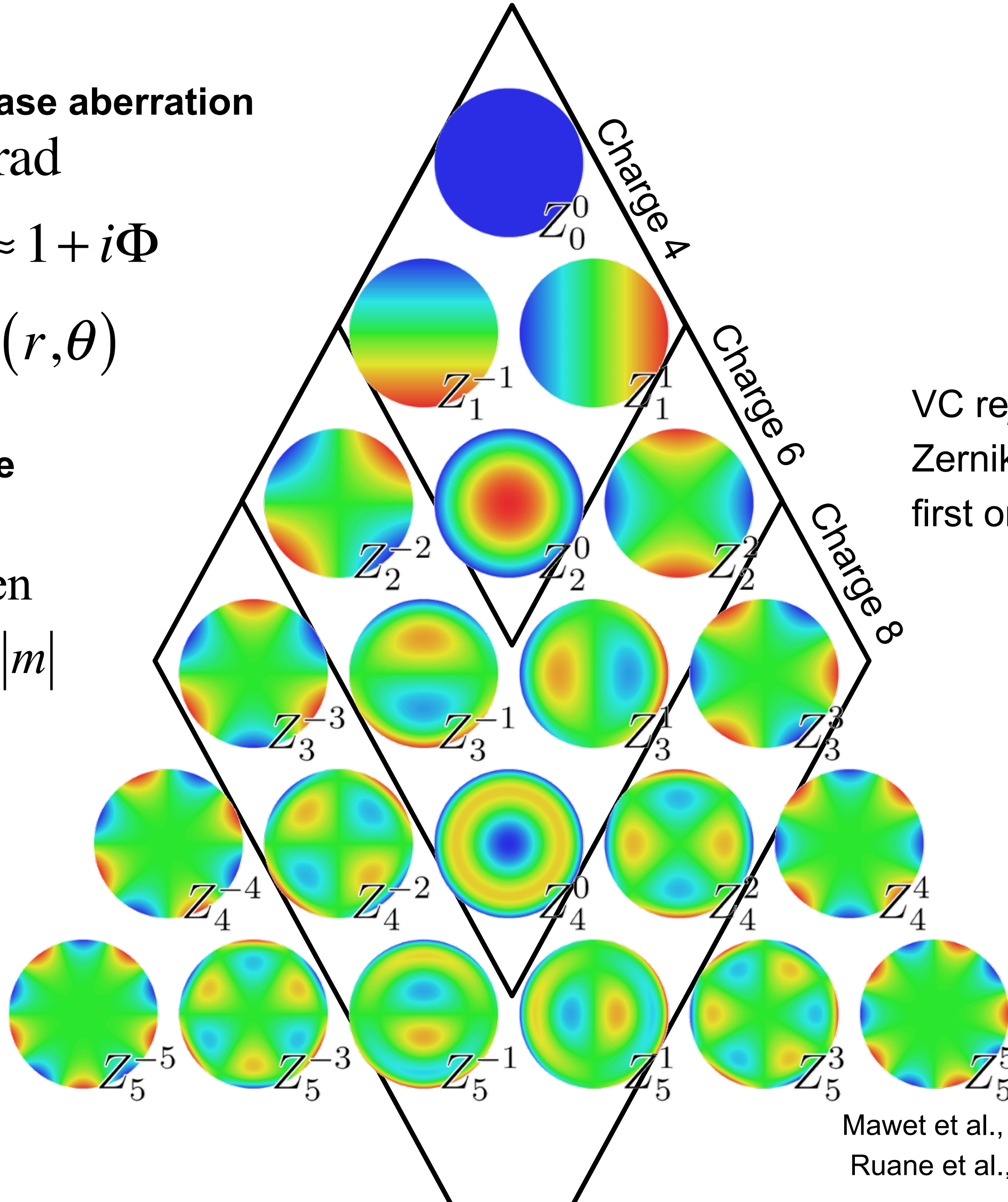
$$\exp(i\Phi) \approx 1 + i\Phi$$

$$\Phi = Z_n^m(r,\theta)$$

Zernike mode
is rejected if:

l is even

$|l| > n + |m|$

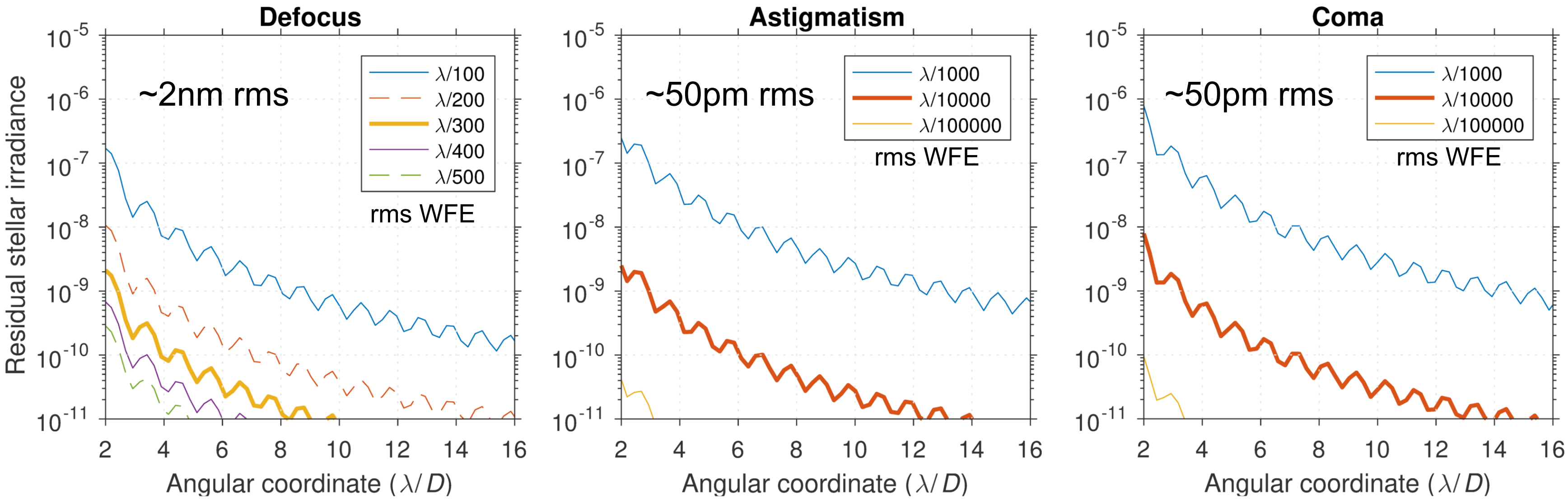


VC rejects $(l/2)^2$ Zernike modes to first order

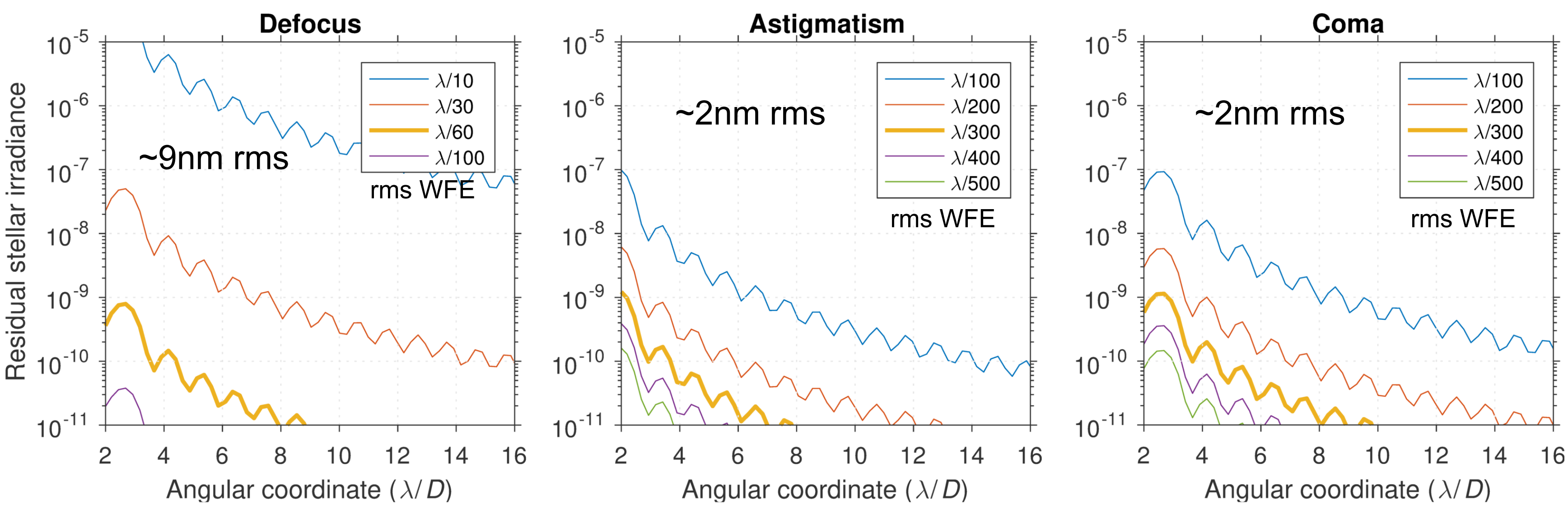
Mawet et al., *Proc. SPIE* 773914 (2010)
Ruane et al., *Proc. SPIE* 96051I (2015)

Low order aberration requirements for unobscured telescope

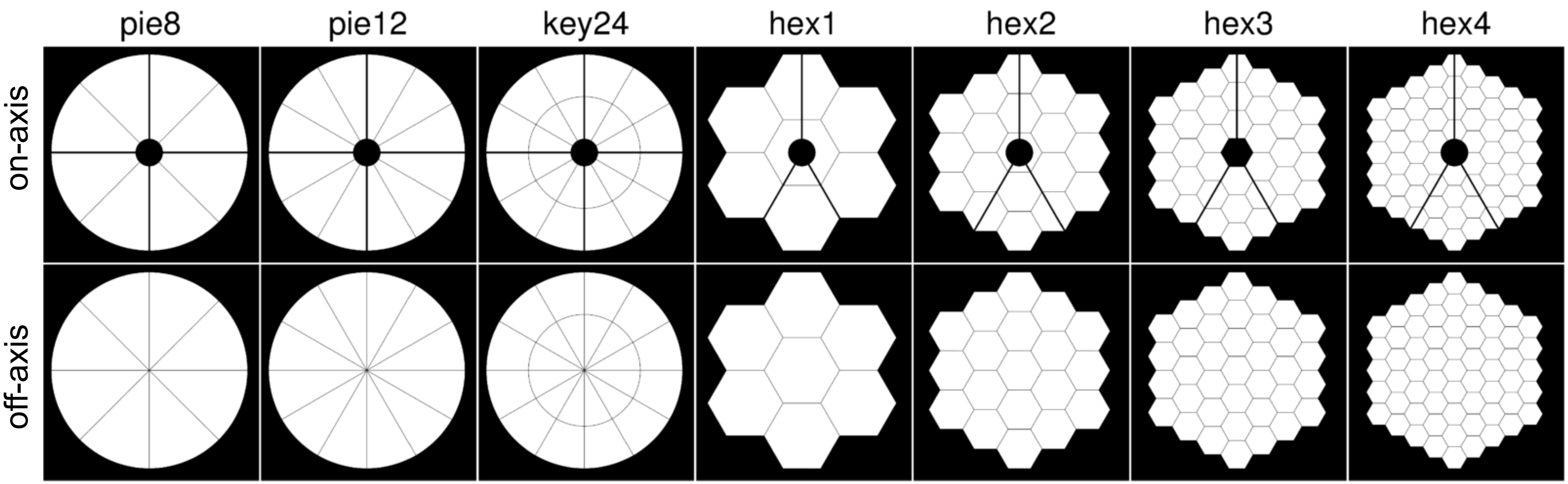
Charge 4



Charge 6



SCDA aperture designs

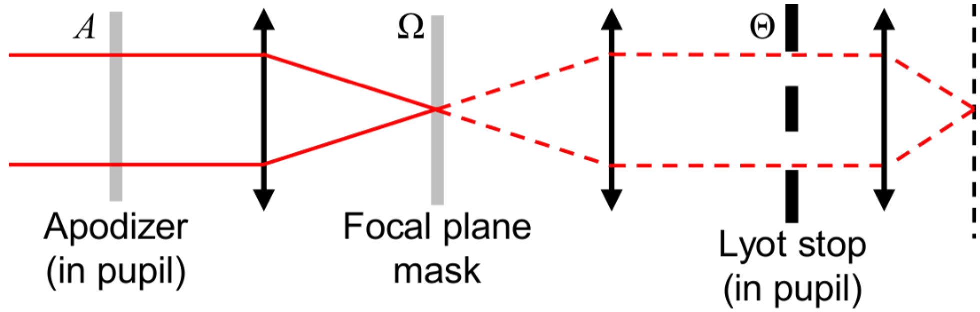


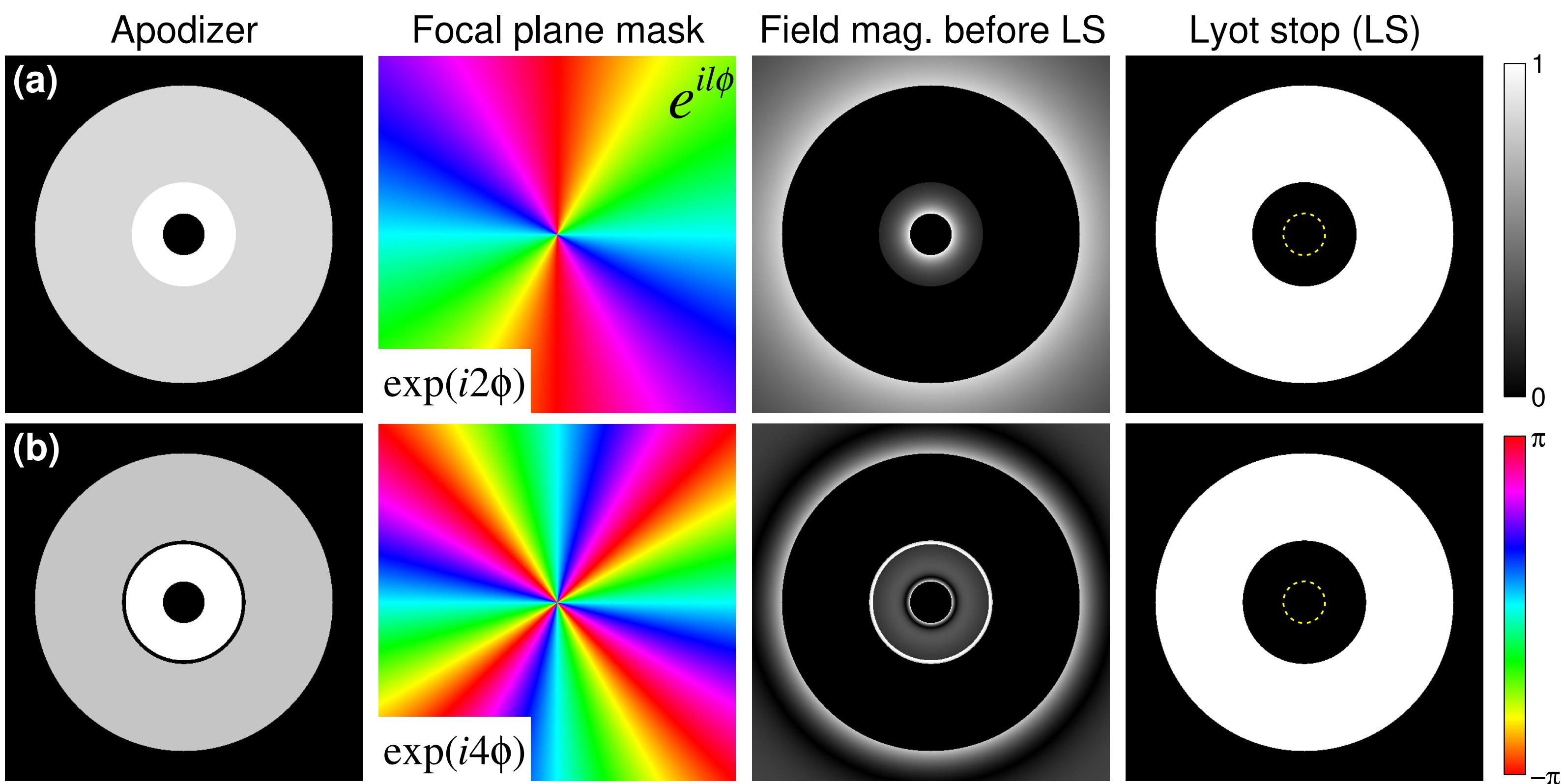
Can we take advantage of these benefits on segmented apertures?

SCDA study, led by Stuart Shaklan (JPL), supported by the Exoplanet Exploration Program (ExEP).

Grayscale apodized vortex coronagraph

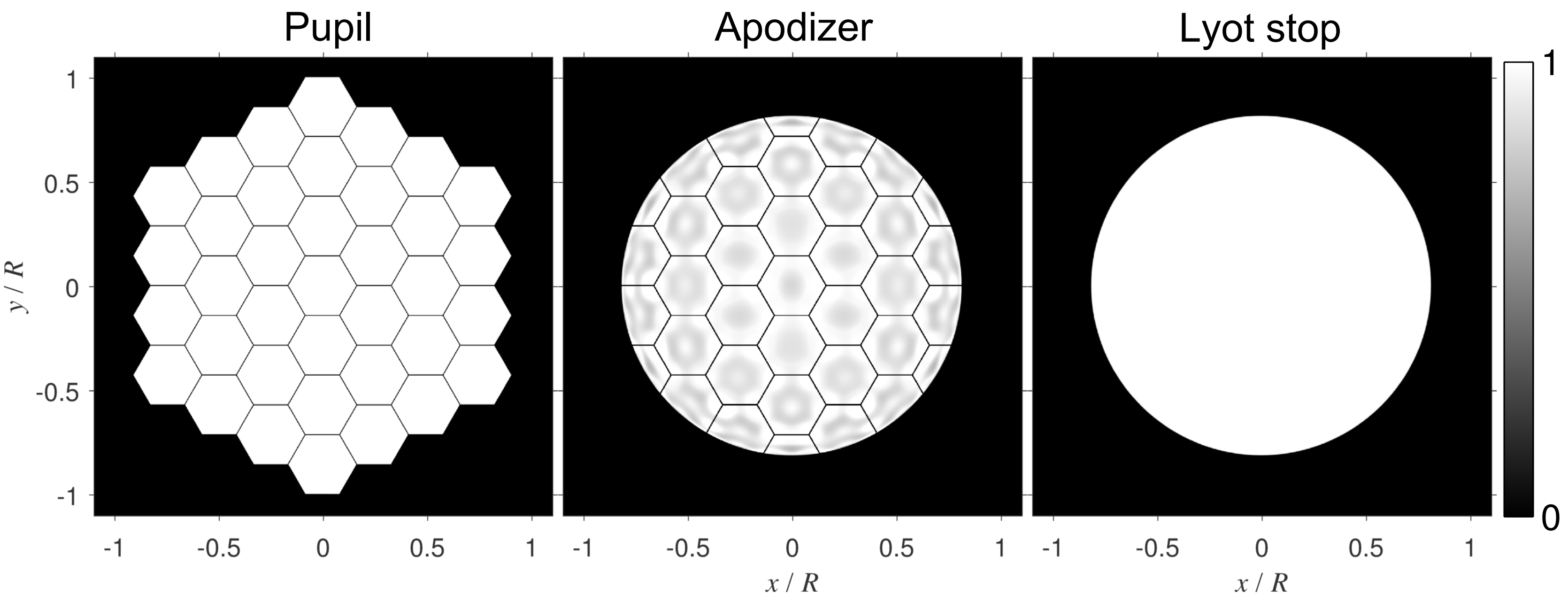
on-axis point source,
perfect wavefront

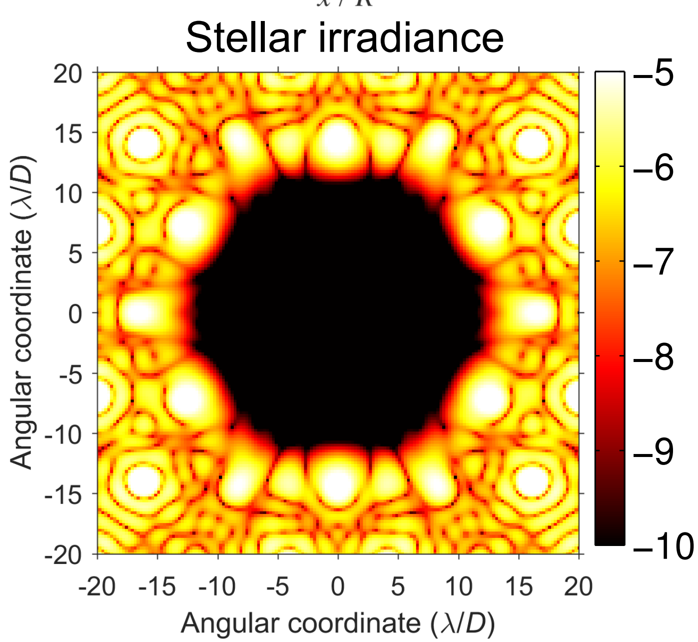




Mawet et al., *ApJS* **209** 7 (2013)

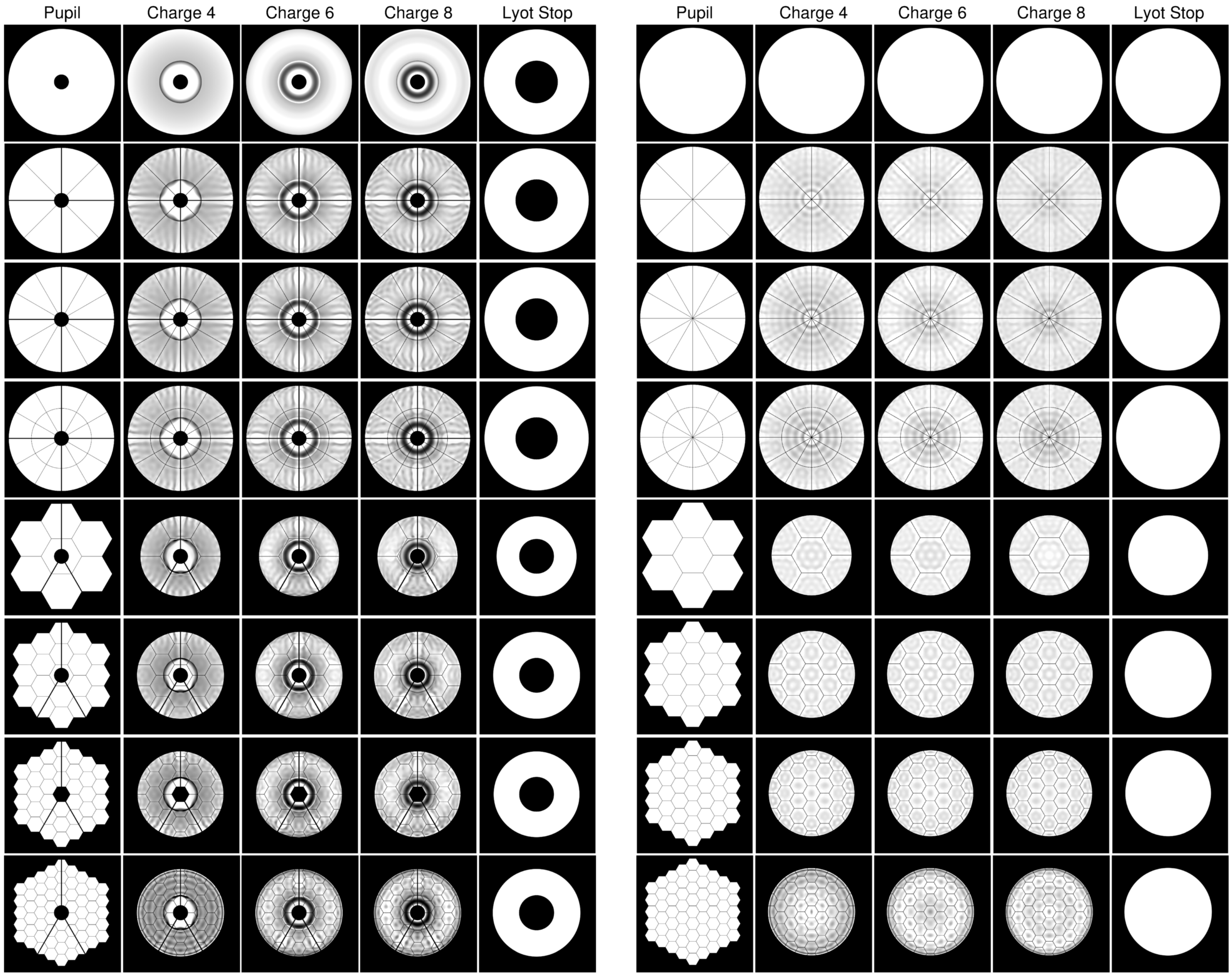
Grayscale apodized vortex coronagraph





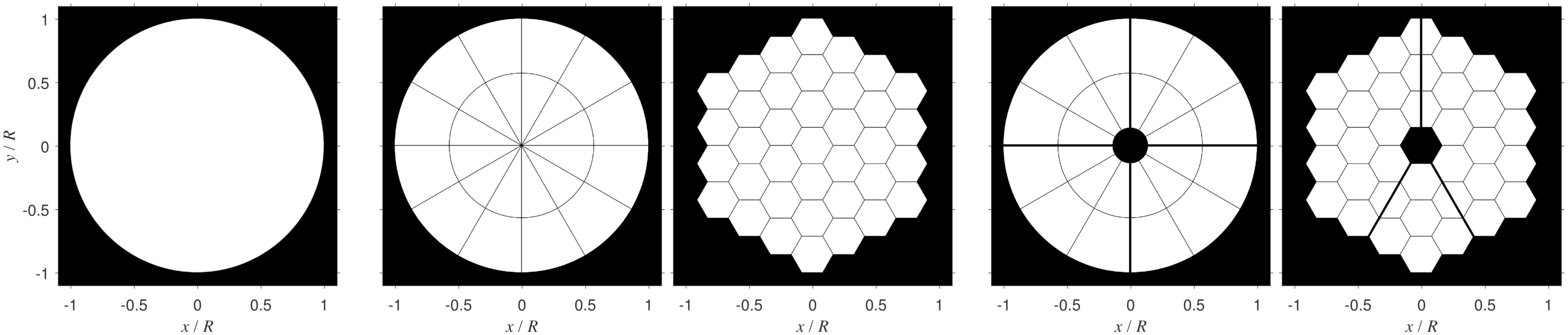
Ruane et al., *Proc. SPIE* 99122L (2016)

A family portrait of apodizer designs



ExoEarth Candidate Yield Calculations

Off-axis monolith **Off-axis segmented** **On-axis segmented**



Telescope	**ExoEarth Yield**
4.0-m off-axis monolith	***7***
6.5-m off-axis monolith	17
12-m off-axis monolith	53
4.0-m off-axis segmented	3-4
6.5-m off-axis segmented	***8-11***
12-m off-axis segmented	22-30
12-m on-axis segmented	work in progress

Yield maintained in the presence of nm level low order aberrations in off-axis cases

Improving designs for on-axis telescopes

- **Goal: Reach performance achieved with an off-axis monolith (>50 exoEarths for 12m) on segmented telescopes.**

- **Compounding issues with current on-axis designs:**
  1. Decreased throughput.
  2. More sensitivity to the finite size of the star.
  3. Large *D* means λ/D is smaller with respect to the star.
  4. More sensitivity to low order aberrations.

- **Updating optimization procedure to combat these effects.**

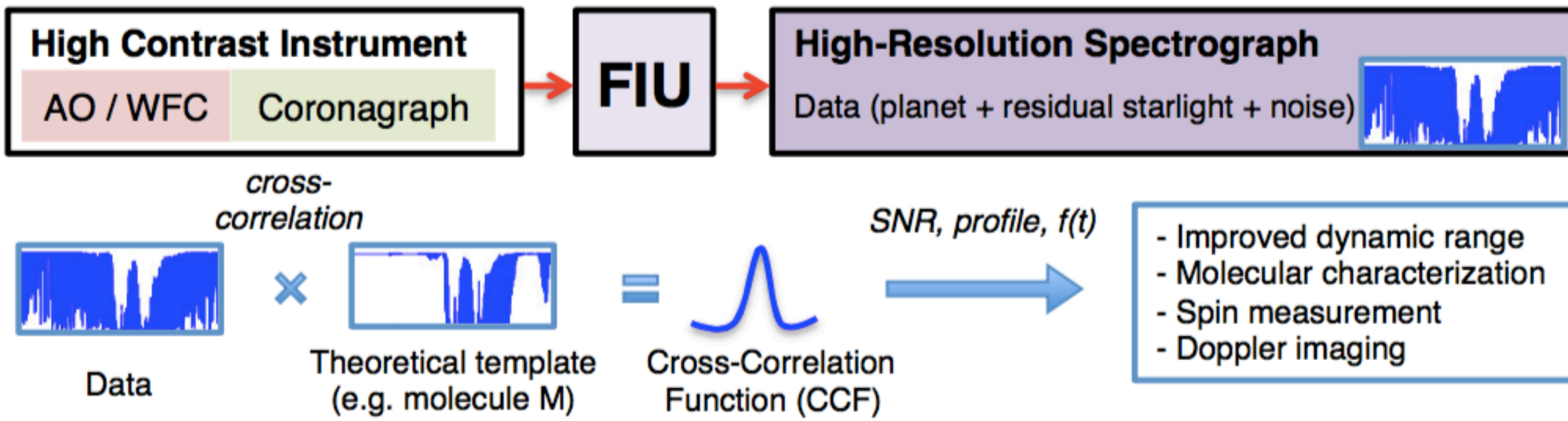
- **Several approaches have yet to be considered:**
  - Gray-scale apodizers with updated metrics
  - Lyot stop optimization
  - Focal plane mask optimization

High Dispersion Coronagraphy (HDC)

Caltech: Ji Wang, Dimitri Mawet, Garreth Ruane, Bjorn Benneke,

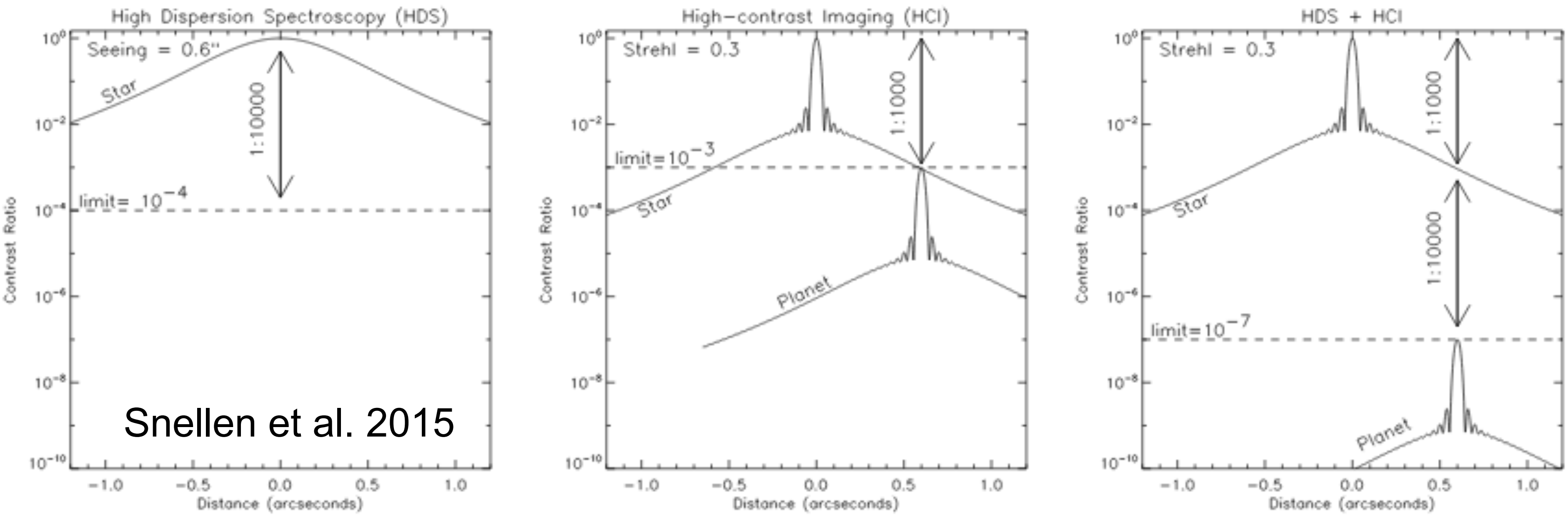
JPL: Renyu Hu

High Dispersion Coronagraphy (HDC) and Template Matching



Mawet et al. 2016

High Dispersion Coronagraphy (HDC)



- Notional for ground-based telescopes:
  - High dispersion -> 10^4
  - Coronagraph -> 10^3 – 10^4
  - HDC -> 10^7 – 10^8 (the planet-star contrast of Proxima Cen b)

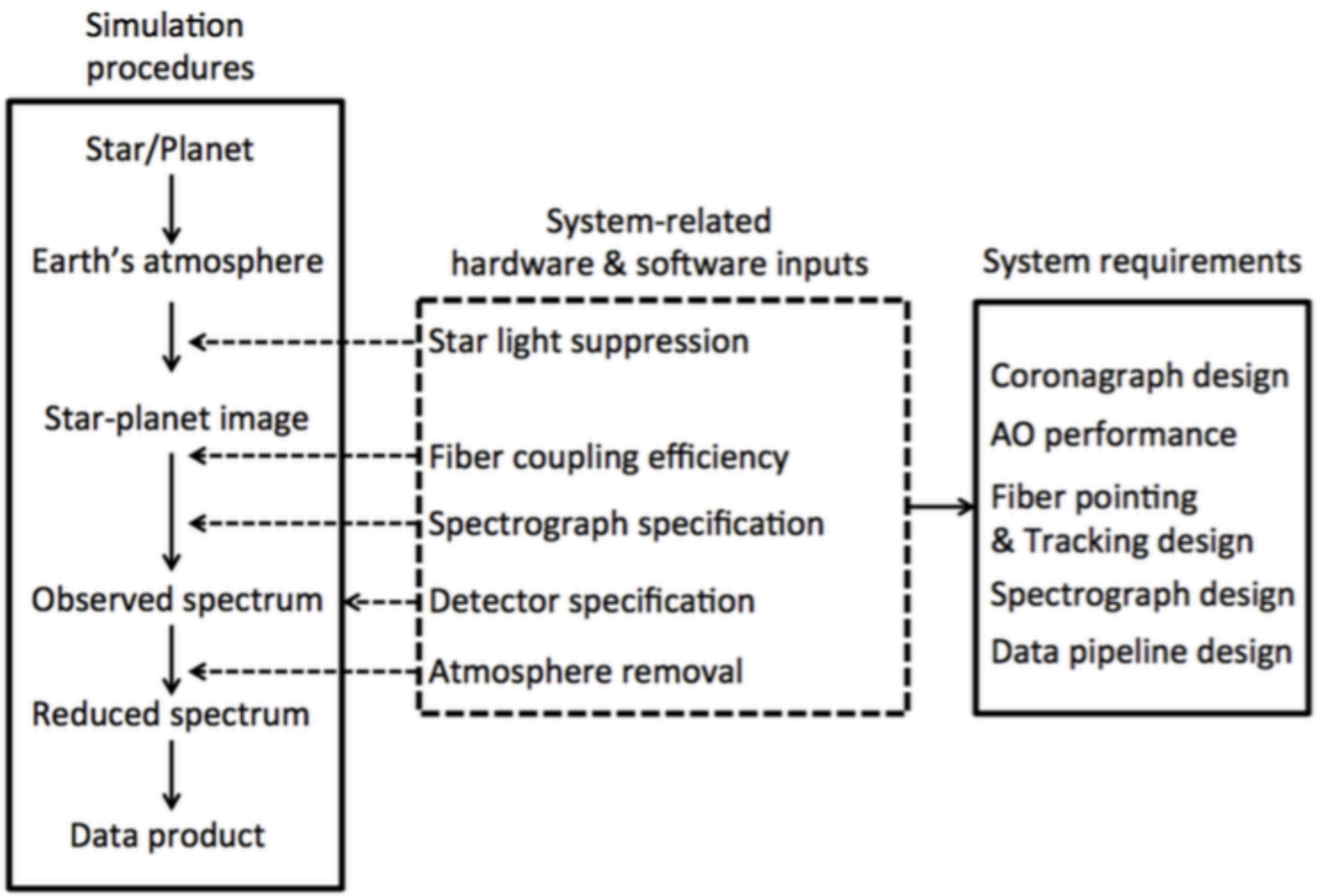
HDC Instruments

- CRIRES
- SPHERE + ESPRESSO
- SCExAO + IRD
- MagAO-X + RHEA
- Keck Planet Imager and Characterizer (KPIC)
- Space? (LUVOIR/HabEx)

Science cases and challenges for HDC

- Planet detection and confirmation at moderate star suppression levels (how much gain by high dispersion?)
- Detecting molecular species in planet atmospheres (mismatched template?)
- Measuring planet rotation (spectral resolution requirement?)
- Mapping surfaces/atmospheres of exoplanets (SNR requirement?)

HDC Simulator



LUVOIR

Telescope and instrument parameters for LUVOIR or HabEx.

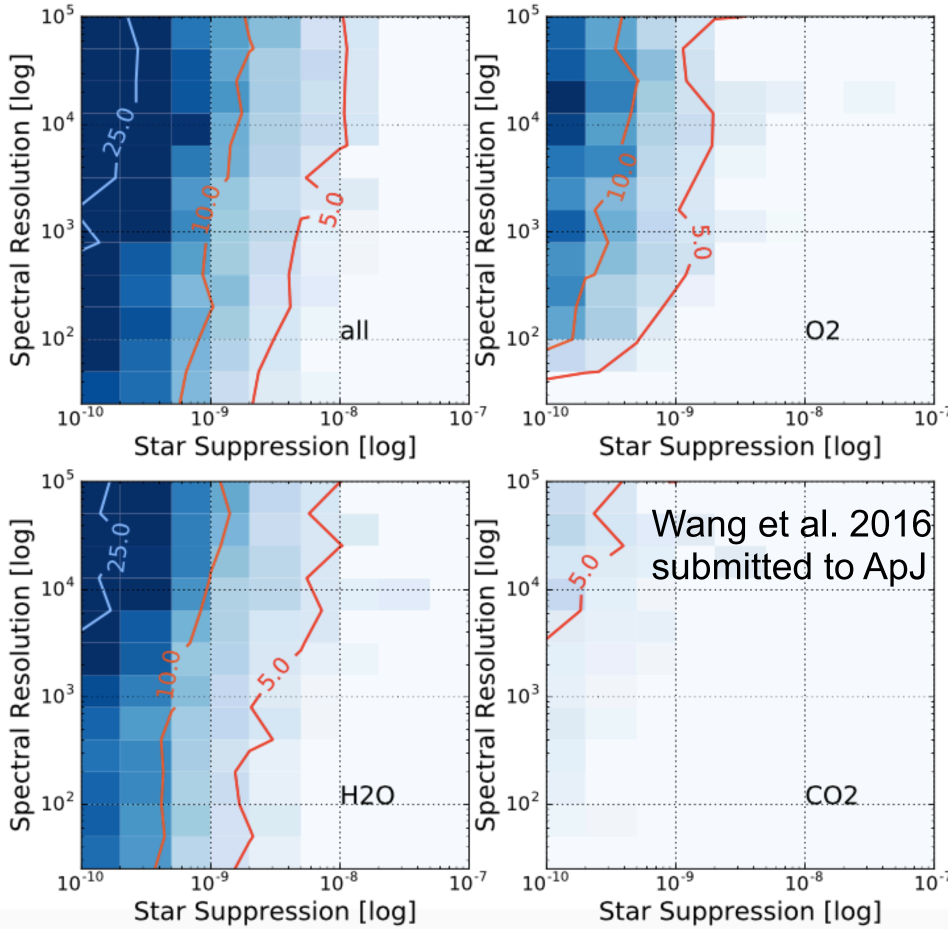
Parameter	Value	Unit
Telescope aperture	4.0 or $\boxed{12.0}$	m
Telescope+instrument throughput	10%	⋯
Wavefront correction error floor	5	nm
Spectral resolution	varied	⋯
Spectral range	$\boxed{0.5 - 1.7}$	μm
Exposure time	400 or $\boxed{100}$	hour
Fiber angular diameter	1.0	λ/D
Readout noise	0.0 or $\boxed{2.0^*}$	e^{-*}
Dark current	0.0 or $\boxed{0.002}$ or $5.5 \times 10^{-6**}$	$e^- s^{-1}$

Note. — $*$: Based on H2RG detector specification (Blank et al. 2012) and e2v CCD specification. $**$: Used for O_2 detection.

LUVOIR

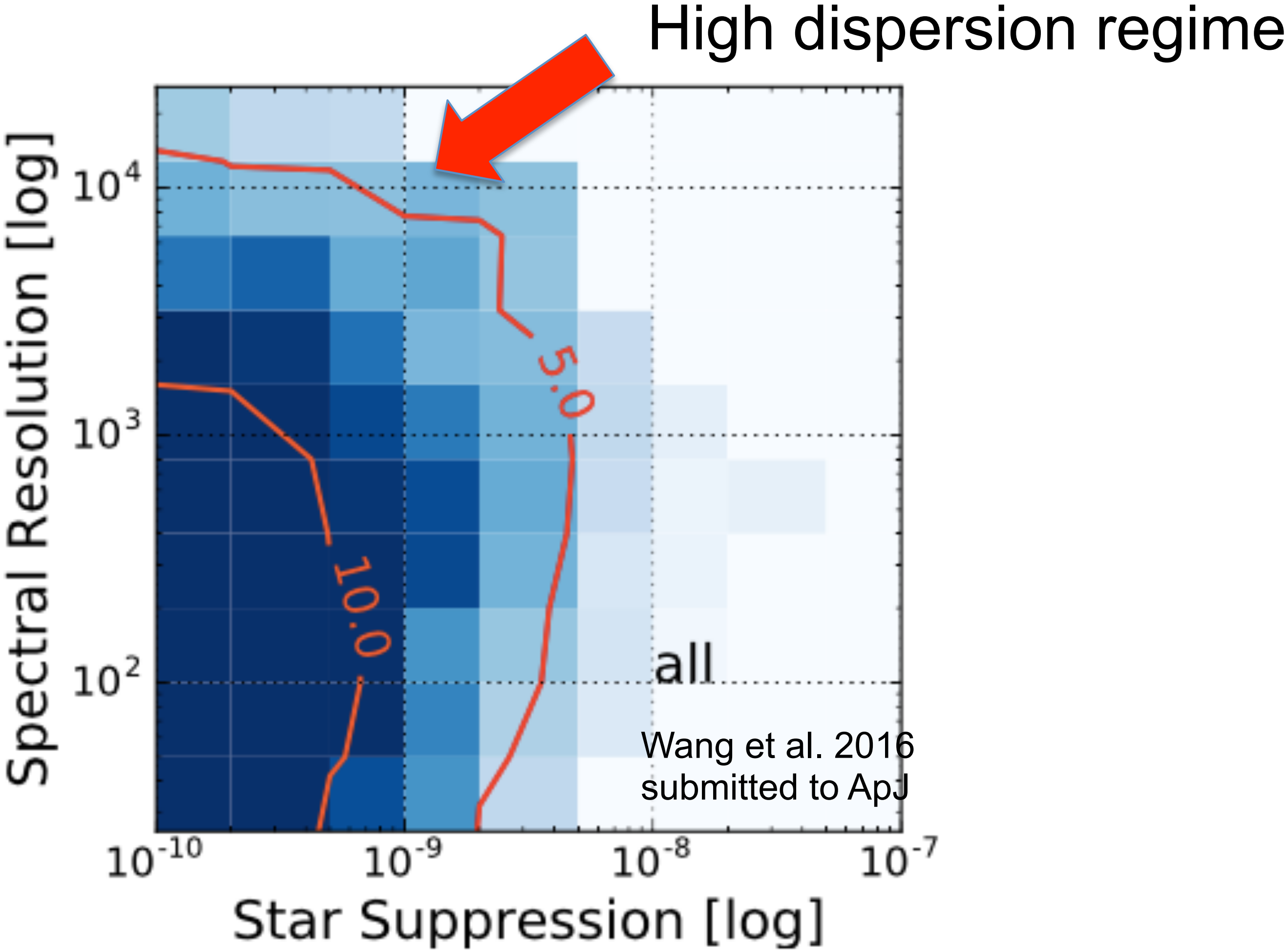
Parameter	Value	Unit
Star		
Effective temperature (T_{eff})	5800	K
Mass	1.0	$M_\odot$
Radius	1.0	$R_\odot$
Surface gravity ($\log g$)	4.5	cgs
Metallicity ([M/H])	0.0	dex
Distance	5.0	pc
Rotational velocity	2.0	km s^{-1}
Inclination (i)	50	degree
Radial velocity	0,0	km s^{-1}
Planet		
Vsin i***	0.5	km s^{-1}
Inclination (i)	50	degree
Semi-major axis (a)	1.0	AU
Radius	1.0	$R_\oplus$
Radial velocity	20.4	km s^{-1}
Illuminated Area	0.5	...
Planet/Star Contrast	$\boxed{6.1 \times 10^{-11}}$	...
Angular separation	200.0	mas
Angular separation at 1 μm for 12-m aperture	11.6	λ/D
Angular separation at 1 μm for 4-m aperture	3.9	λ/D

LUVOIR – photon-noise only

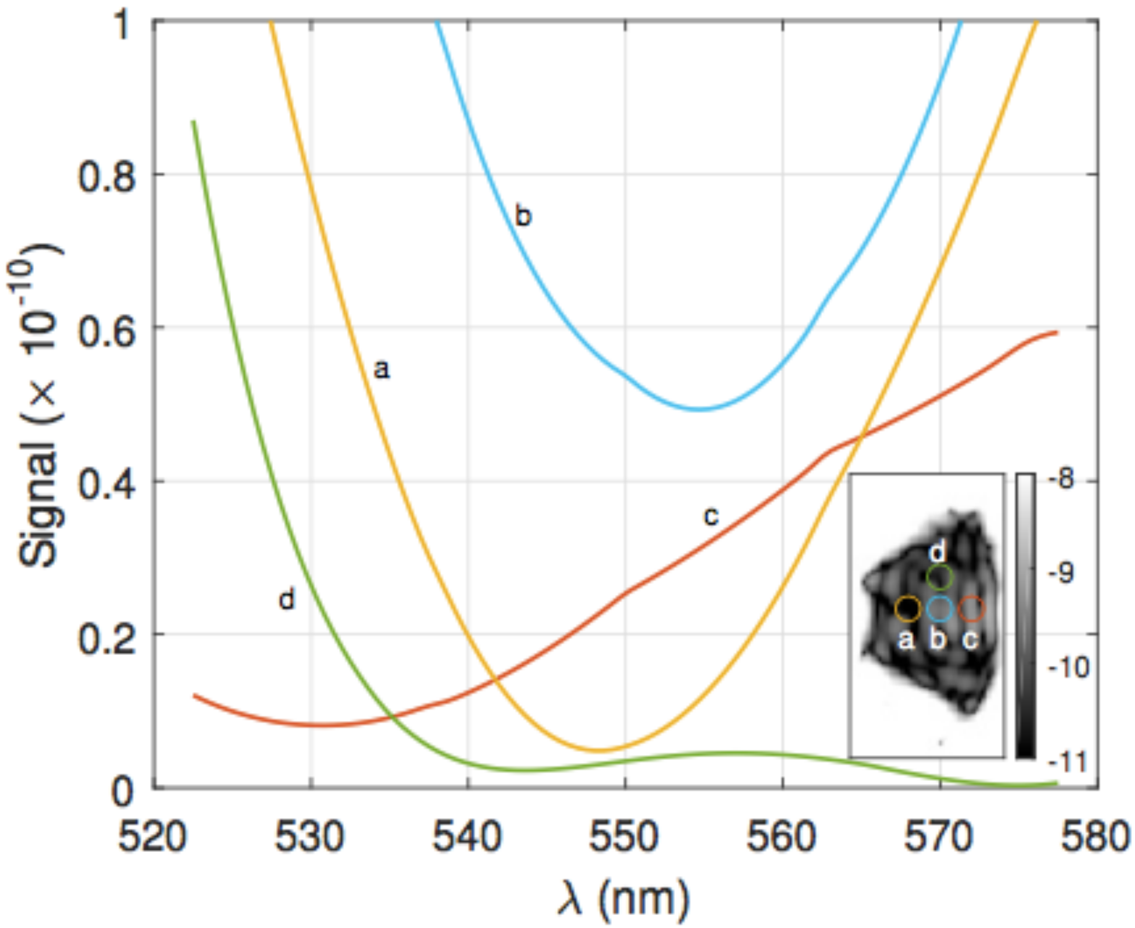


- A spectrograph can relax the star light suppression requirement by 1-2 orders of magnitude for planet detection.
- High dispersion is required for CO2 detection

Adding Detector Noise

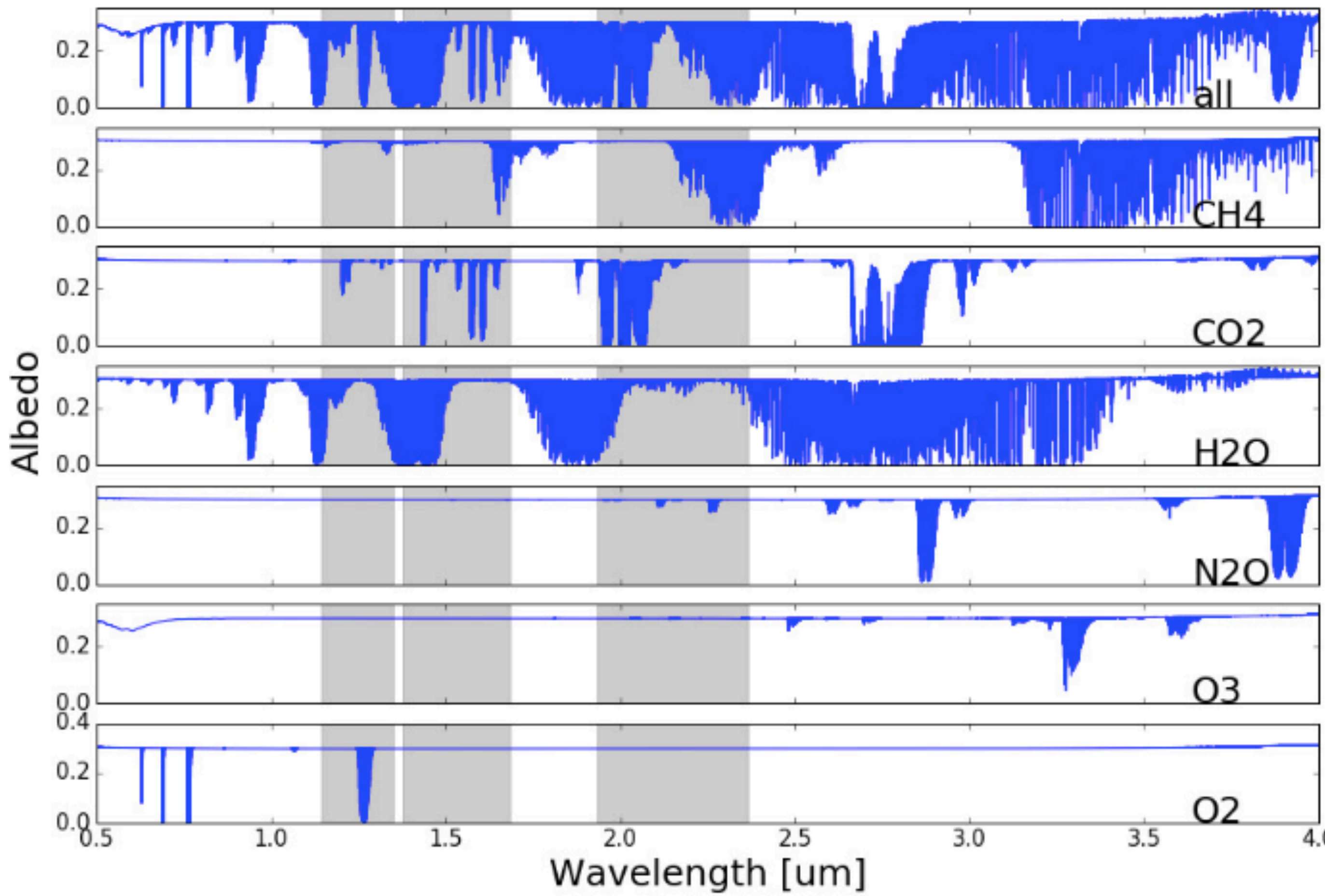


Speckle Chromatic Noise



Simulation by Garreth Ruane
see also Krist et al. 2008

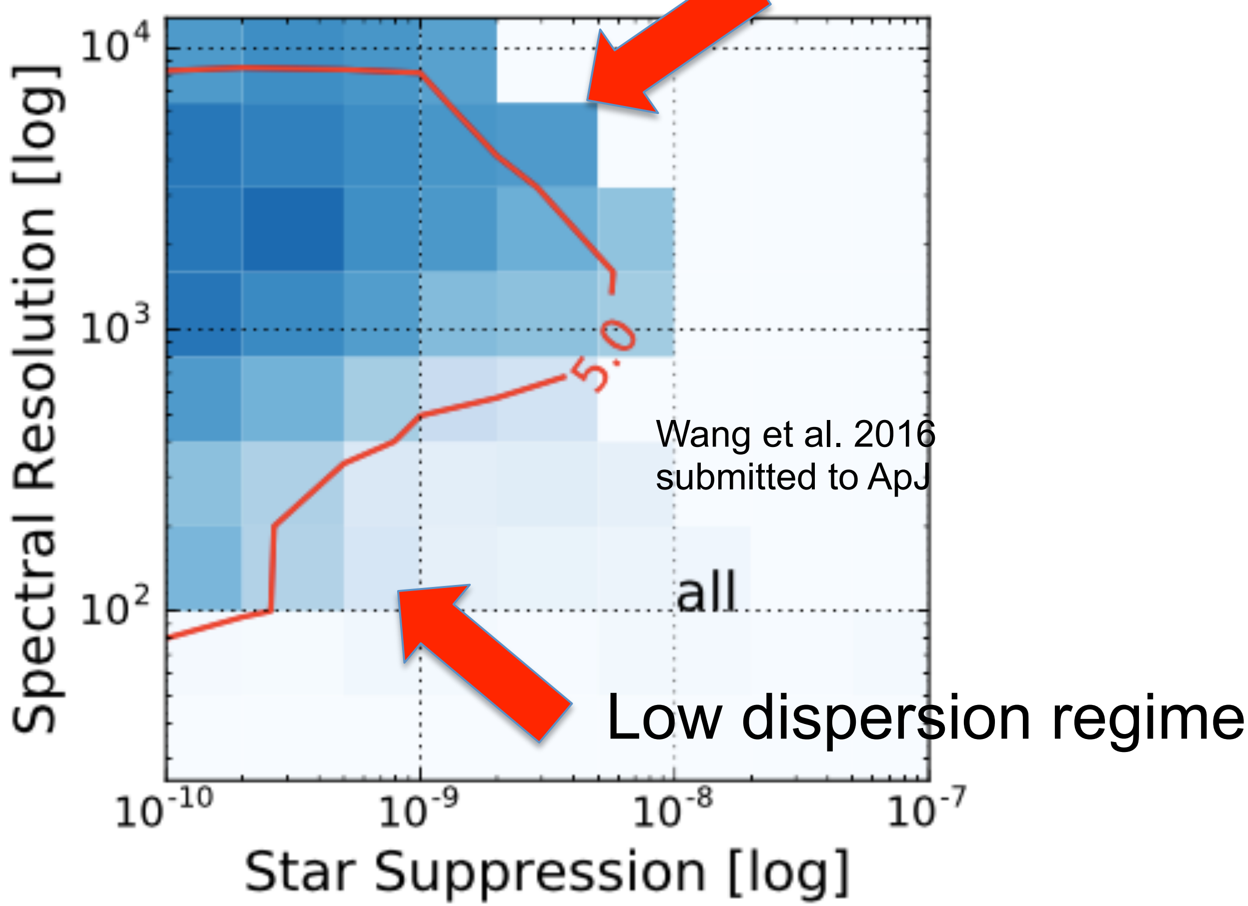
Absorption bands vs. lines



Adding Spectral Chromatic Noise

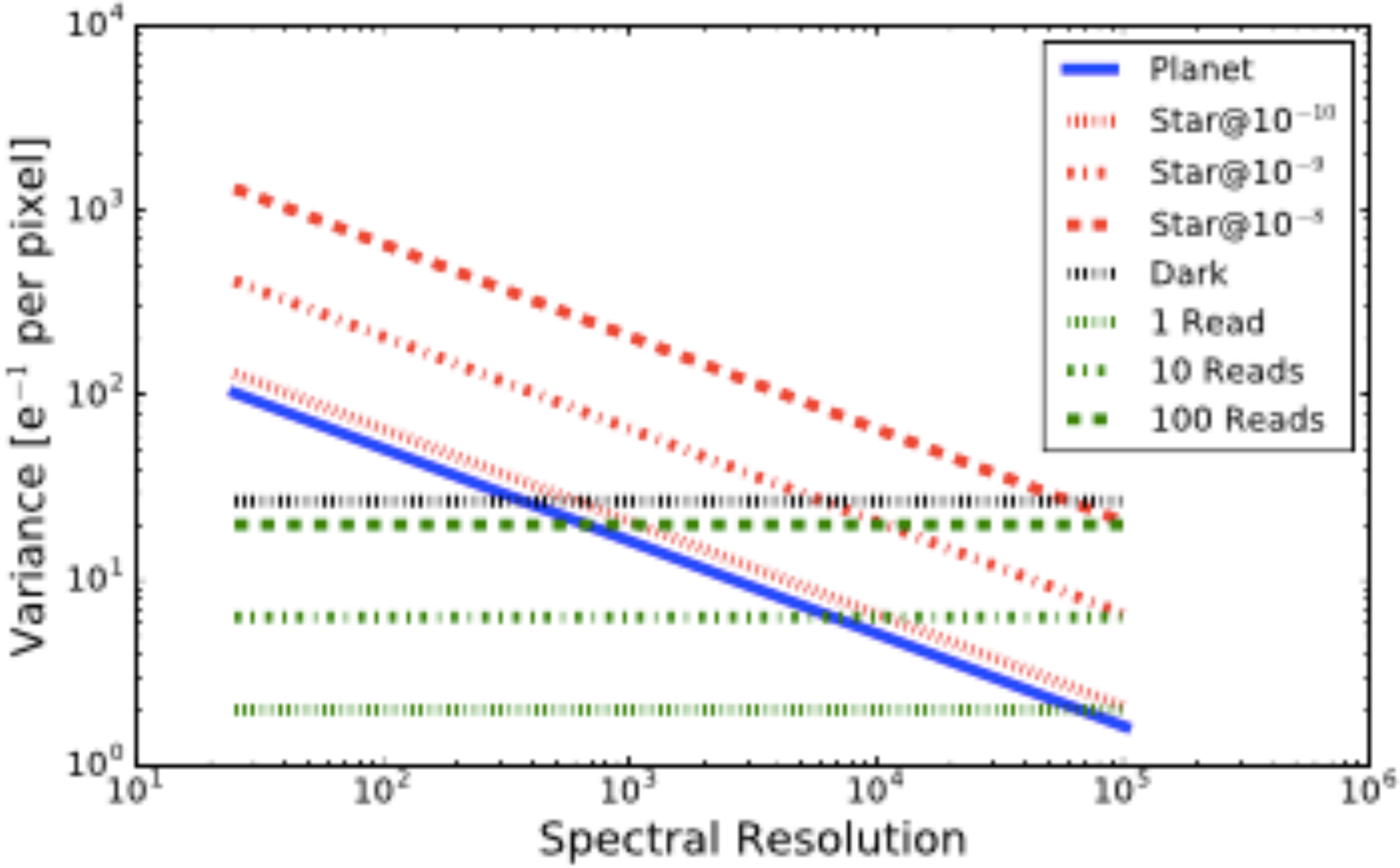
Planet to star contrast = 6.1×10^{-11}

High dispersion regime



- R = 1600 and star suppression = 5×10^{-8} is an optimal combination to relax the requirement for star light suppression and maintain high sensitivity to planet detection
- H_2O and O_2 can still be detected at >3-sigmal level, CO_2 no longer detectable

Source of Noise



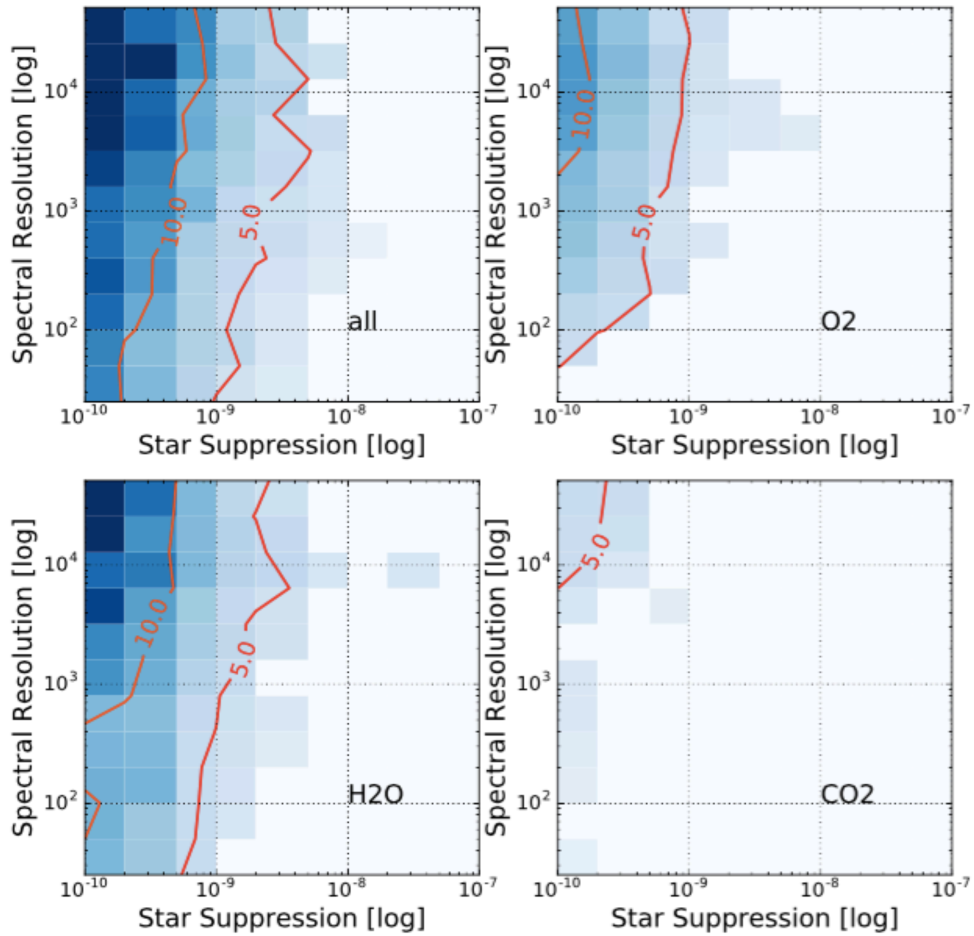
HabEx

Telescope and instrument parameters for LUVOIR or HabEx.

Parameter	Value	Unit
Telescope aperture	$\boxed{4.0}$ or 12.0	m
Telescope+instrument throughput	10%	···
Wavefront correction error floor	5	nm
Spectral resolution	varied	···
Spectral range	0.5 - 1.7	μm
Exposure time	$\boxed{400}$ or 100	hour
Fiber angular diameter	1.0	λ/D
Readout noise	0.0 or 2.0*	e^{-*}
Dark current	0.0 or 0.002 or $5.5 \times 10^{-6**}$	$e^{-}s^{-1}$

Note. — *: Based on H2RG detector specification (Blank et al. 2012) and e2v CCD specification. **: Used for O_2 detection.

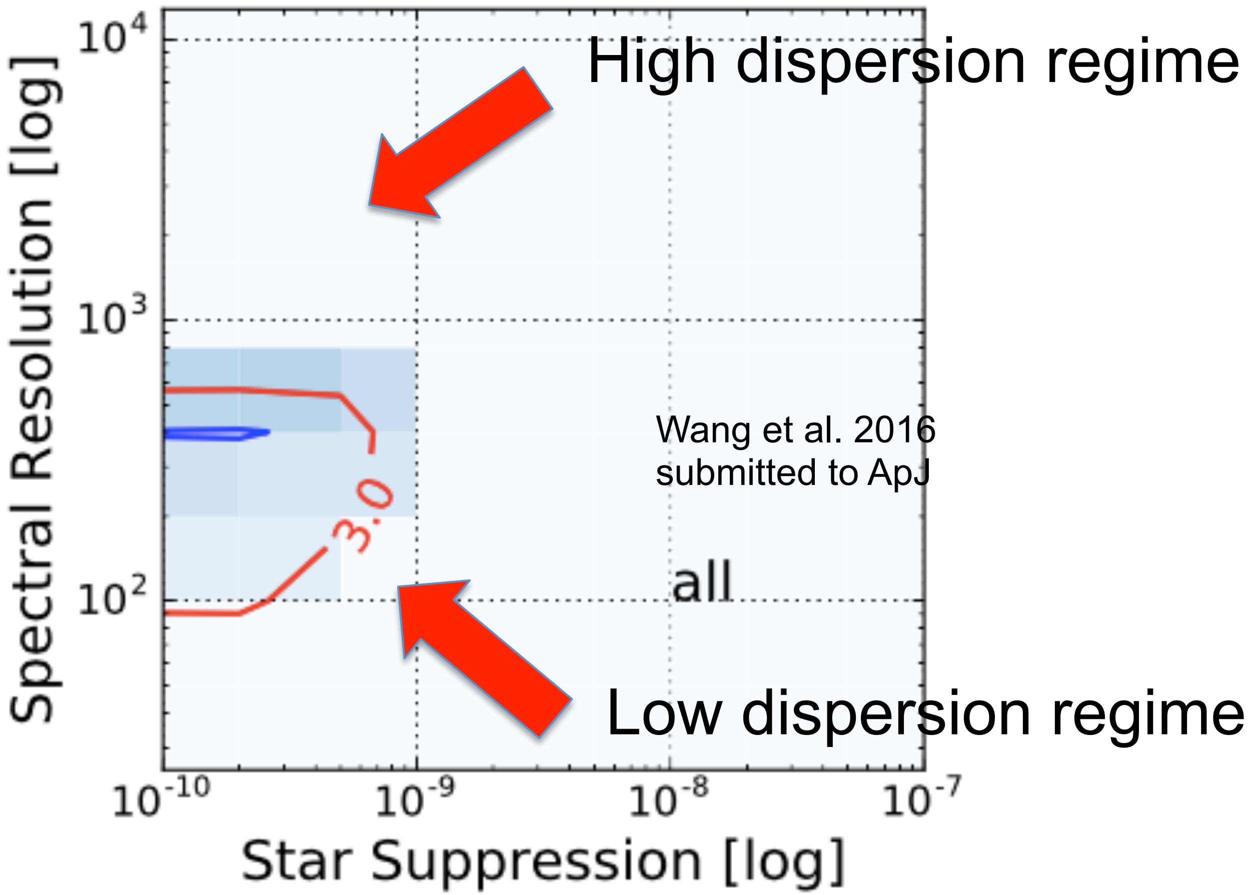
HabEx– photon-noise only



Wang et al. 2016
submitted to ApJ

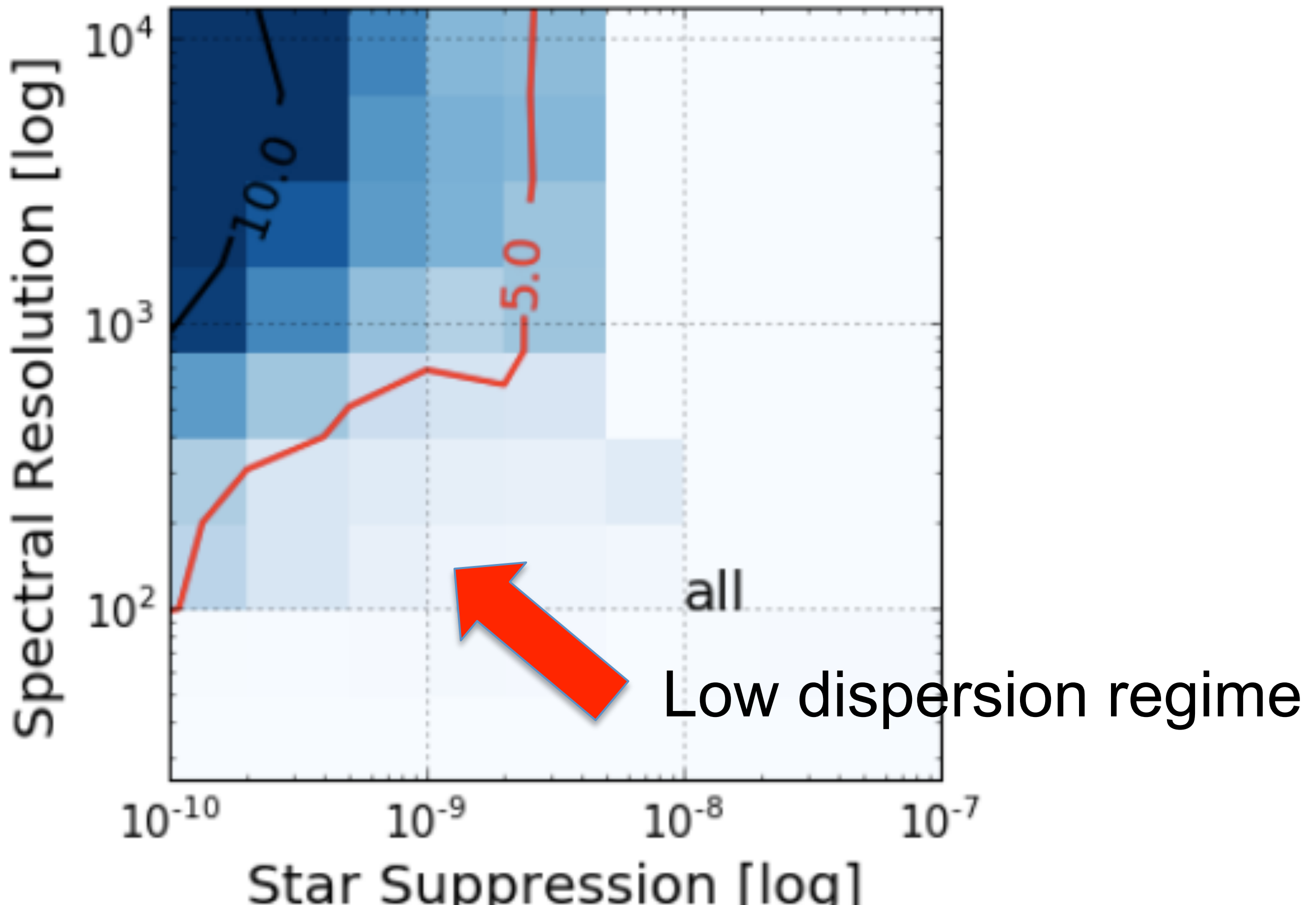
Adding Spectral Chromatic Noise and detector noise

Planet to star contrast = 6.1×10^{-11}



- R = 400 and star suppression = 5×10^{-9} is an optimal combination to relax the requirement for star light suppression and maintain high sensitivity to planet detection
- H_2O and O_2 can still be detected at >3-sigmal level, CO_2 no longer detectable

Only Spectral Chromatic Noise
No detector noise (HabEx)



- R = 1000 and star suppression ~10^{-9} is an optimal combination to relax the requirement for star light suppression and maintain high sensitivity to planet detection

Summary

- We develop a framework to simulate performance of an HDC instrument.
- HDC relaxes star suppression level by 1-2 orders of magnitude for space-based mission to detect an Earth-like planet around a solar-type star.
- Detector noise is a major factor that limits the performance of a space-based HDC instrument.
- Speckle chromatic noise limits the performance at low spectral resolution regime. R>1000 is preferred to remove the speckle chromatic effect.

Take home messages

- SCDA study found coronagraph designs for segmented / obscured apertures (e.g. APLC, VC)
- We do have coronagraph solutions immune to low-order aberrations for unobscured telescopes
  - low-order aberrations (z2-z8, z11) are in the null space of the VC6, enabling stability requirement relaxation by ~1-2 orders of magnitude
  - not clear if this immunity is valid for obscured telescopes, (work in progress for VC AND APLC)
  - all options still need to consider realistic aberrations => all yield estimations are upper limits

Habex is zeroing on a potential internal coronagraph architecture

- Charge 6 Vortex with off-axis 4-m monolith:
  - F/2.0-F/2.5 primary, polarization effects negligible
  - HST-like UV Al-Ag coatings on M1 and M2
  - Wavefront stability relaxed to ~1 nm rms (z2-z8,z11)
  - Exo-Earth yield = 7 (V-band imaging)

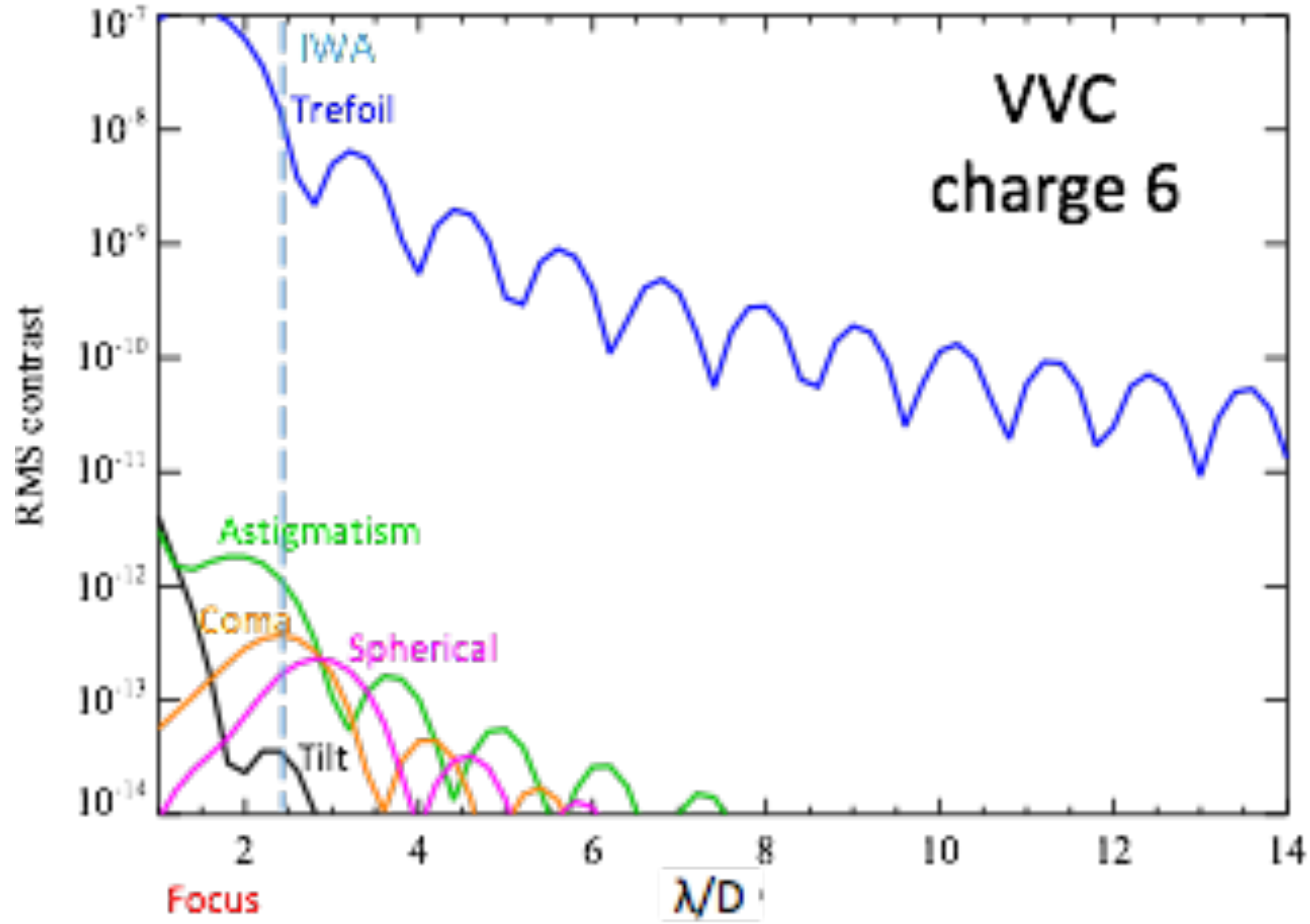
Two instrument architectures

- Integral field spectrograph with R~70 (a la WFIRST)
- Imager + diffraction-limited spectrograph
  - Classical imager for detection
  - R~1000 spectrograph for characterization:
    - Cross-correlation technique side-steps speckle noise, potentially relaxing raw contrast requirements by 1-2 orders of magnitude

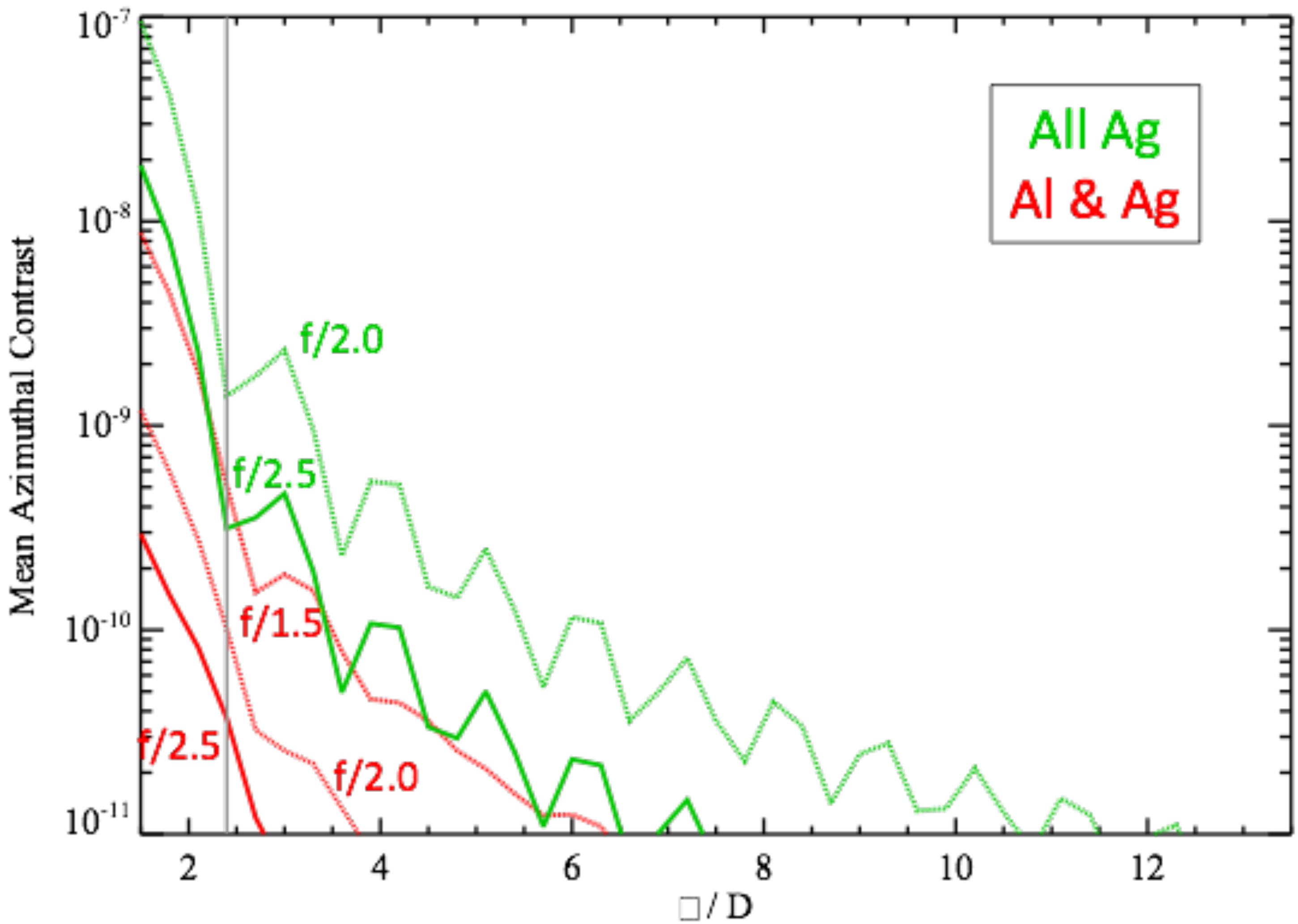
Habex and LUVOIR: partial yield calculation for internal coronagraphs

	4-m off-axis	6.5-m on-axis	6.5-m off-axis	12-m on-axis	12-M off-axis
Mission	Habex	Habex/LUVOIR	Habex/LUVOIR	LUVOIR	LUVOIR
Coronagraph	VC6	APLC	vc6	APLC	VC6
exo-Earth Yield	7	12	9-17	31	22-53
Stability C<1e-11: Z2->z8, Z11	1 nm	?	1 nm	?	1 nm
F#	f/2.0-F/2.5	?	f/2.0-F/2.5	?	f/2.0-F/2.5
Coating	Al-Ag	?	Al-Ag	?	Al-Ag

Extra slides



John Krist (JPL)



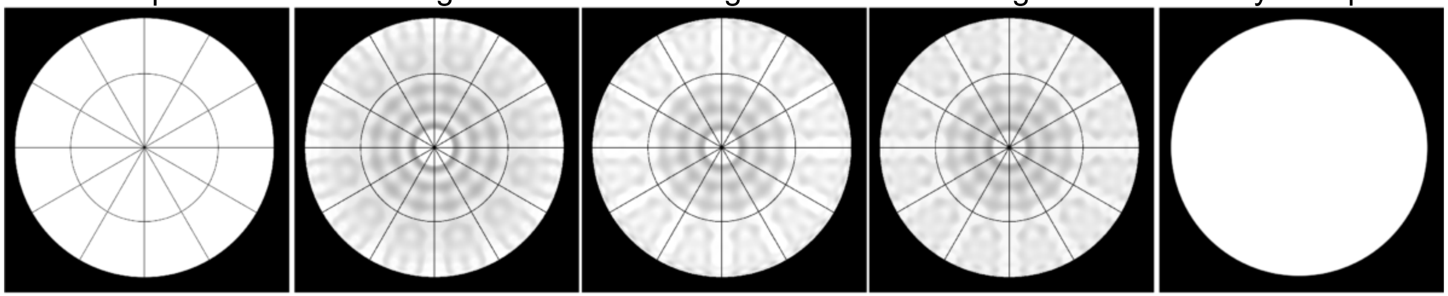
John Krist (JPL)

Notes to self

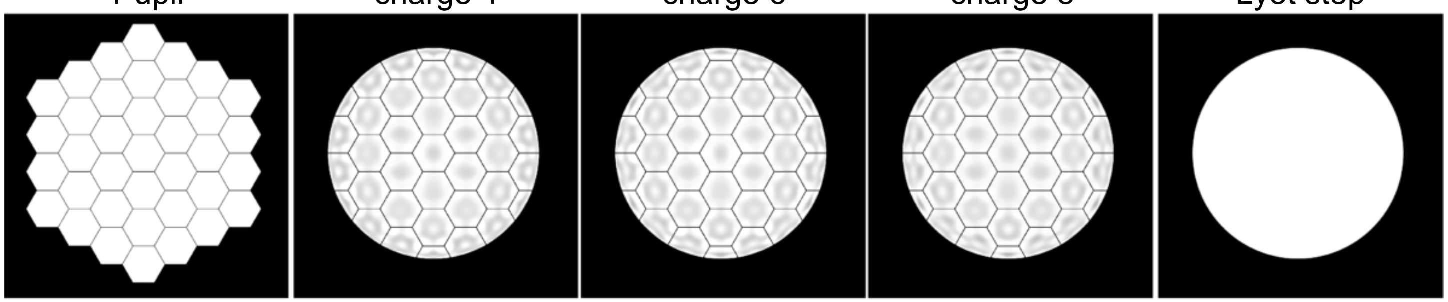
- For the VC on a circular unobscured pupil, the light is diffracted outside the pupil.
- For the VC, when there is any feature inside the pupil, light is diffracted inside the pupil.
    - The apodizer distributes the light s.t. it self-cancels, inside the pupil, but the field strength in the pupil is strong
    - The tip-tilt, or any aberrations destroys the self-cancellation, so overcomes the natural rejection of the pure mask
- The APLC removes most of the light before it reaches the LS
- Can we try that with the vortex? E.g. put a central dot on the mask?

Designs for off-axis segmented telescopes

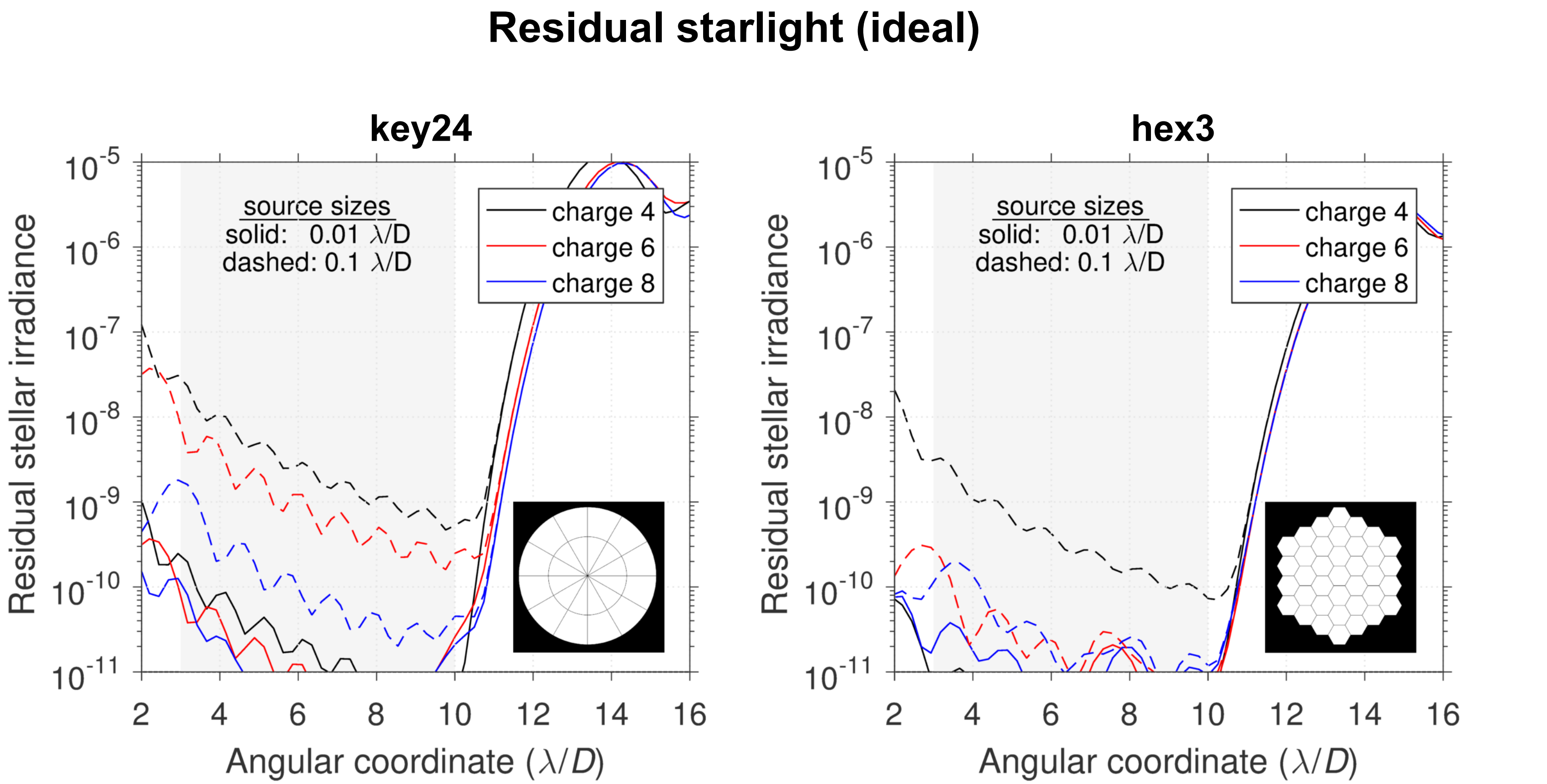
key24: 2-ring Keystone/Piewedge (24 segments)



hex3: 3-ring Hex (37 segments)



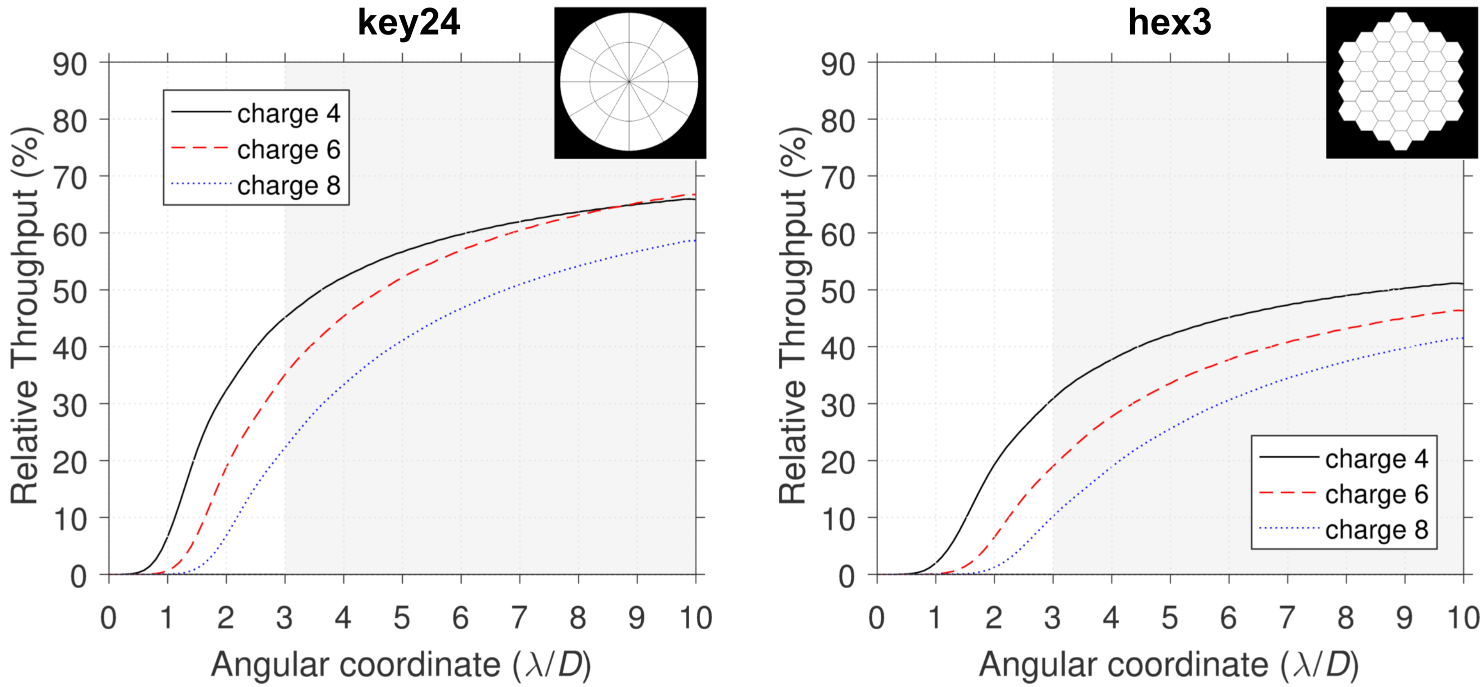
Performance for off-axis segmented telescopes



Stellar irradiance is azimuthally averaged and normalized to the peak of the telescope PSF.

Performance for off-axis segmented telescopes

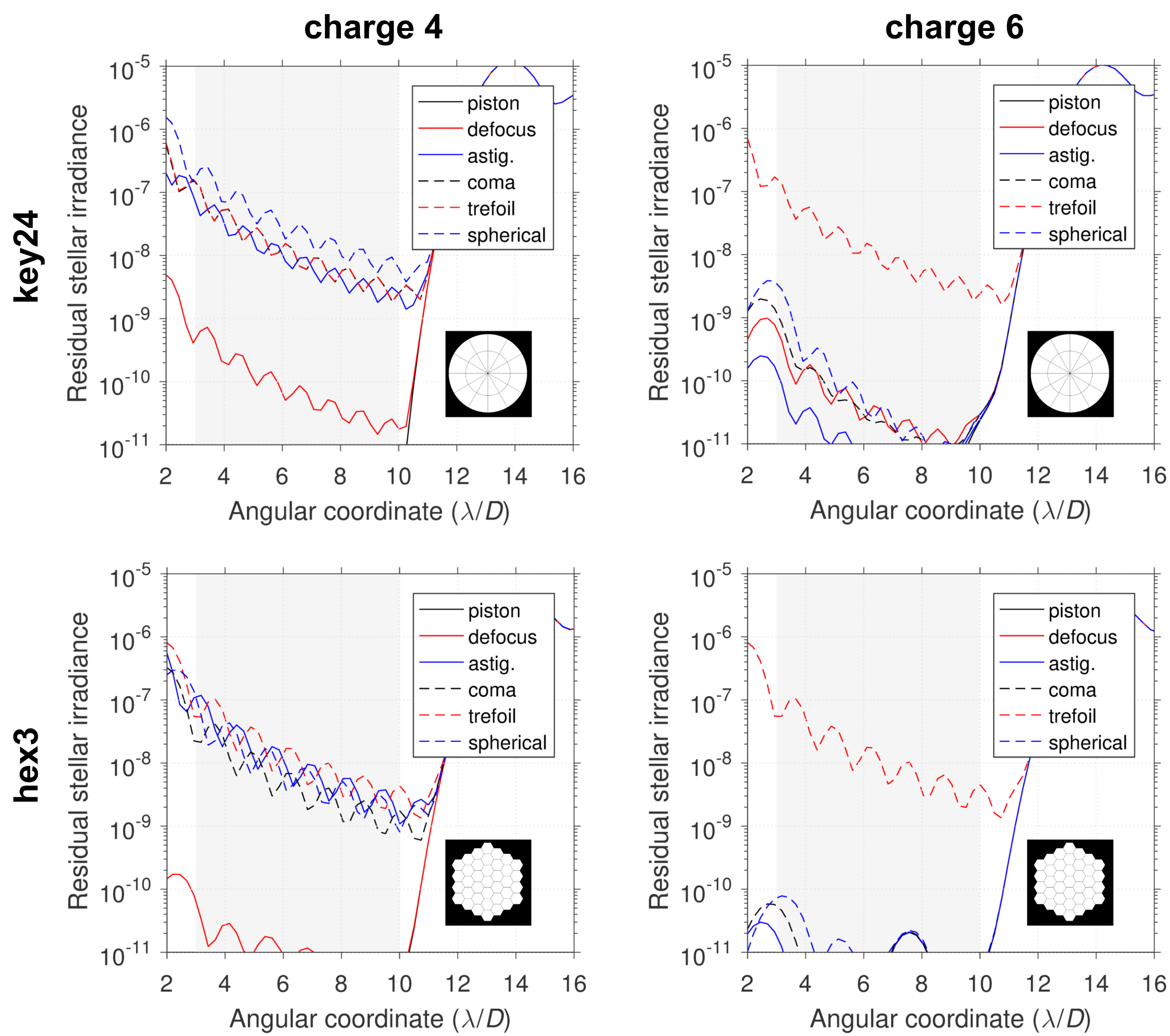
“Planet” throughput



Throughput is defined as energy within 0.7 λ/D of the source position, normalized to that of the telescope.

Performance for off-axis segmented telescopes

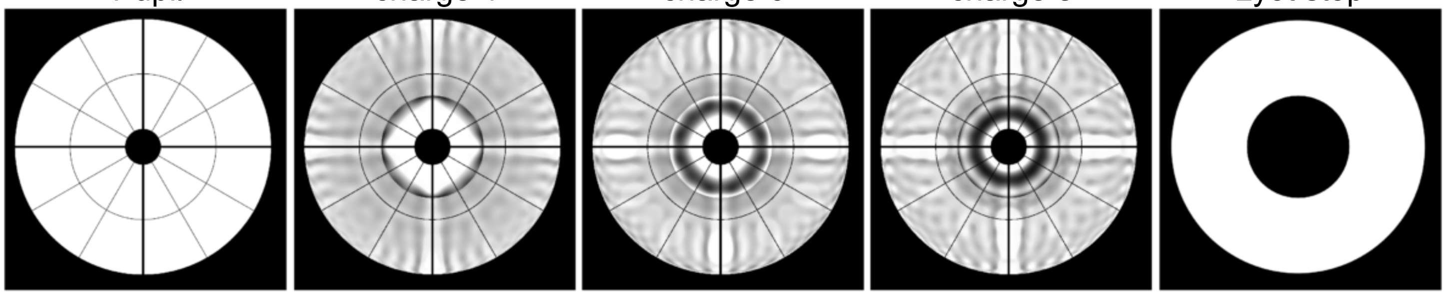
Residual starlight with λ/1000 rms wavefront error



Designs for on-axis segmented telescopes

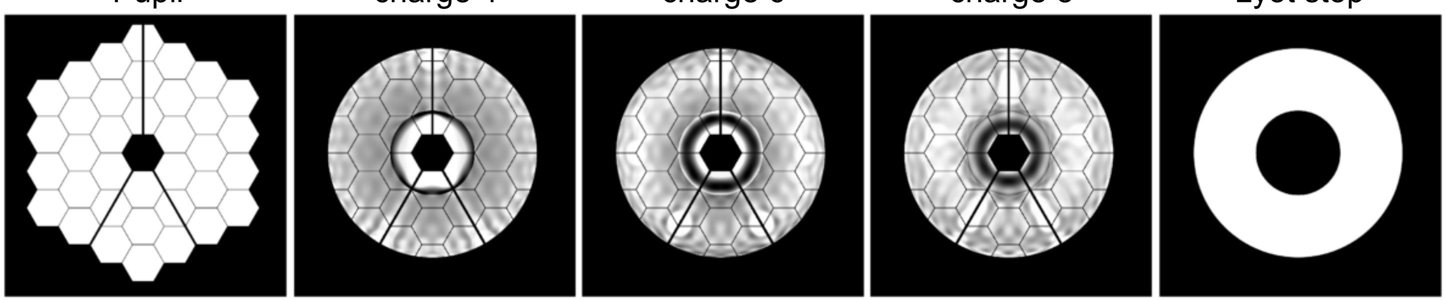
key24: 2-ring Keystone (24 segments) w/ cross spiders (10cm/12m)

Pupil | charge 4 | charge 6 | charge 8 | Lyot stop



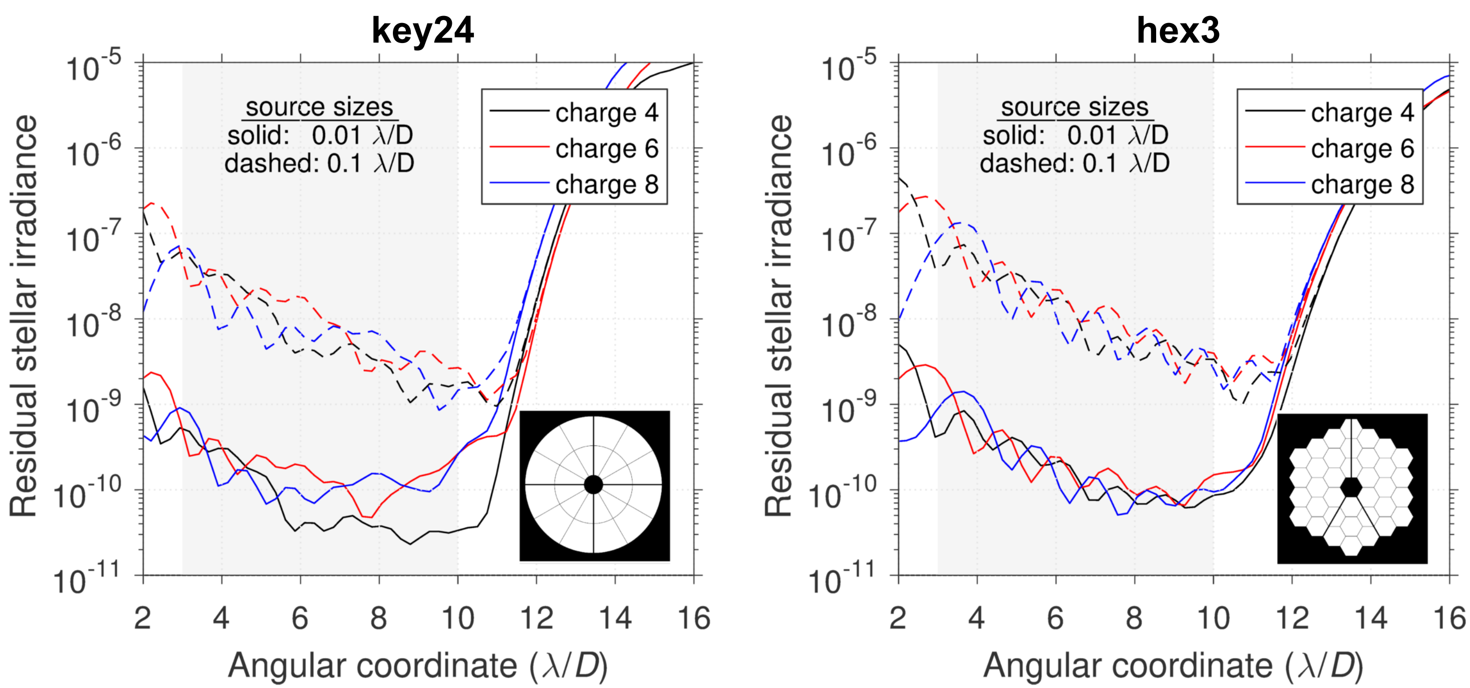
hex3: 3-ring Hex (36 segments) w/ 60° y-spiders (10cm/12m)

Pupil | charge 4 | charge 6 | charge 8 | Lyot stop



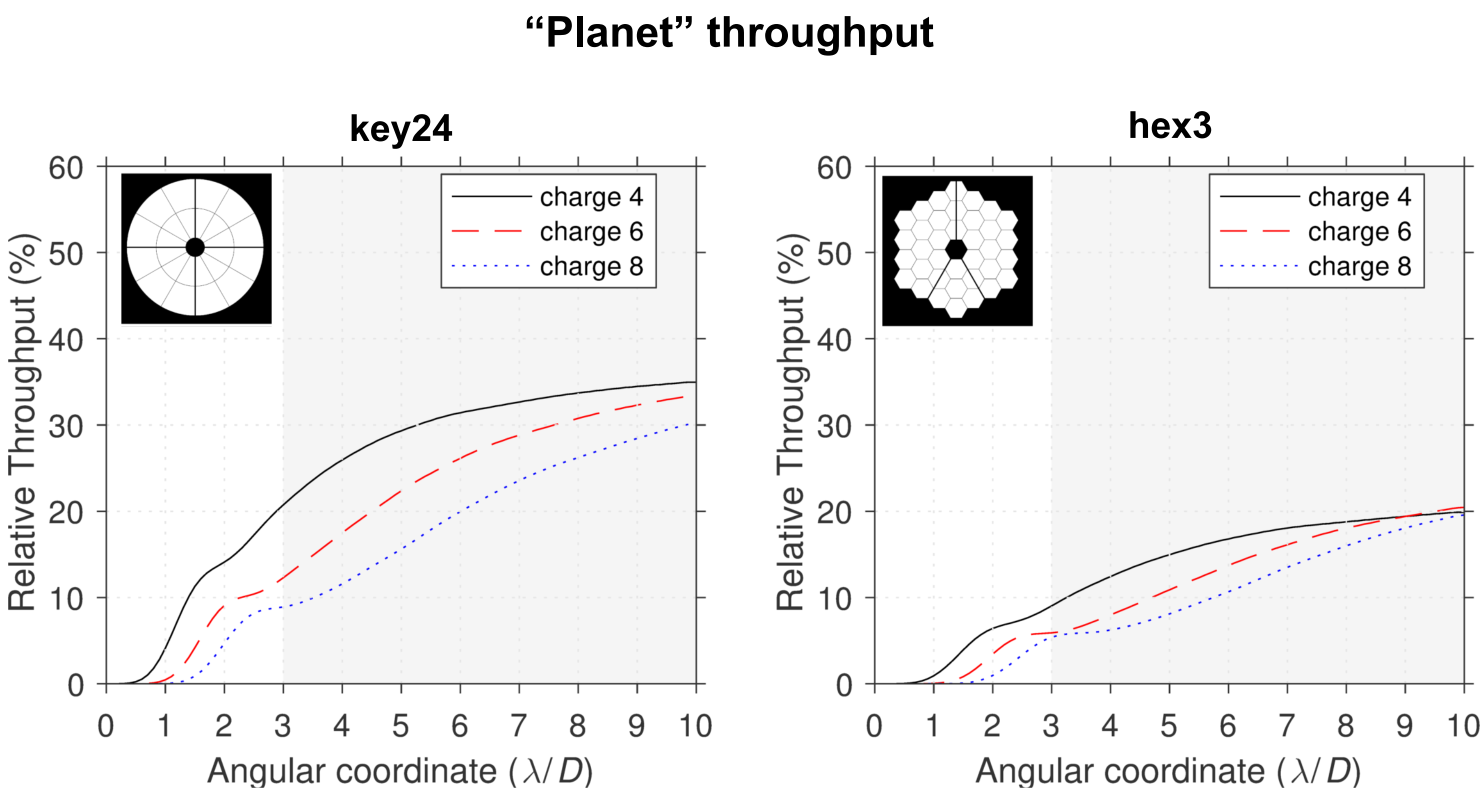
Performance for off-axis segmented telescopes

Residual starlight (ideal)



Stellar irradiance is azimuthally averaged and normalized to the peak of the telescope PSF.

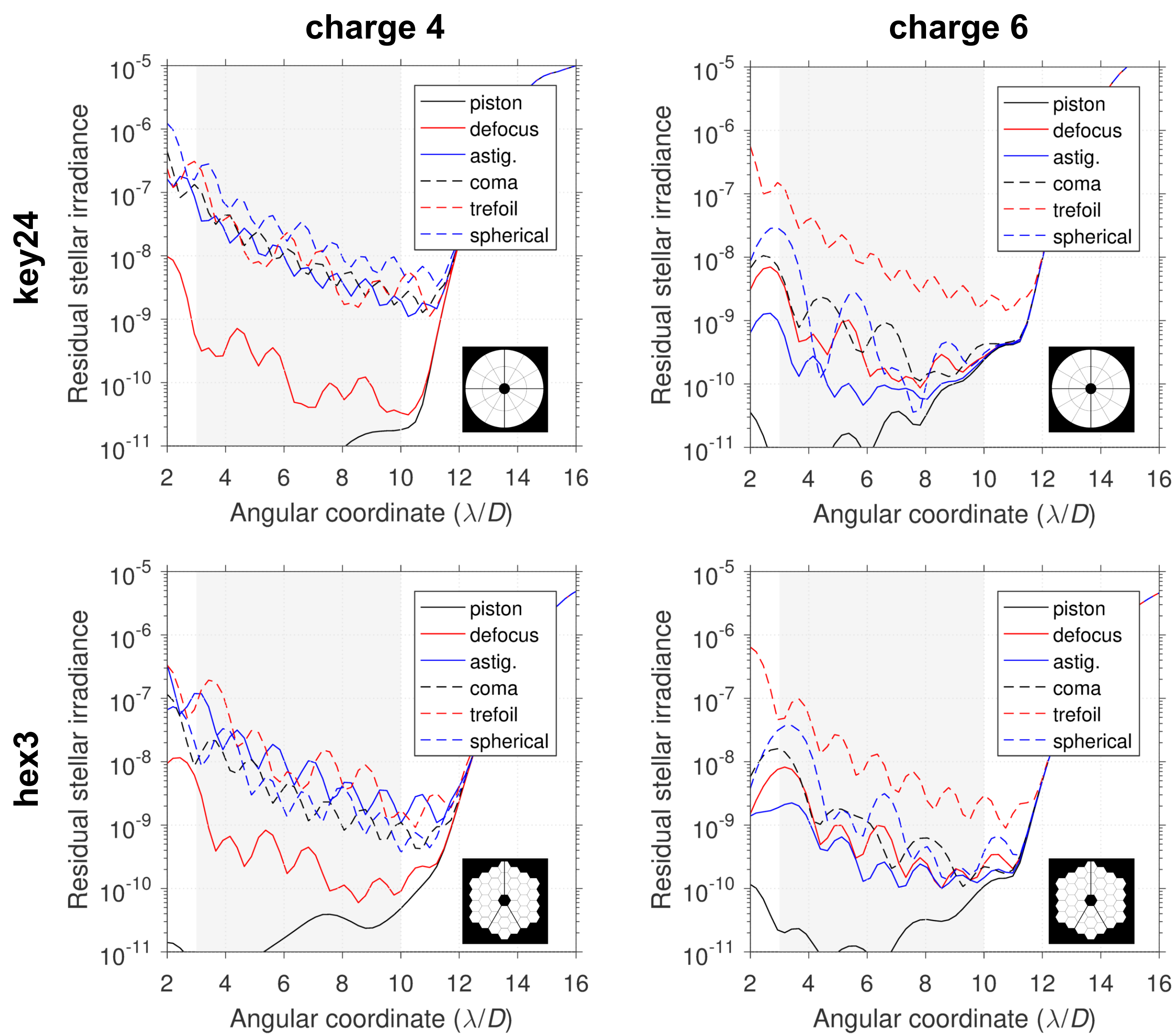
Performance for off-axis segmented telescopes



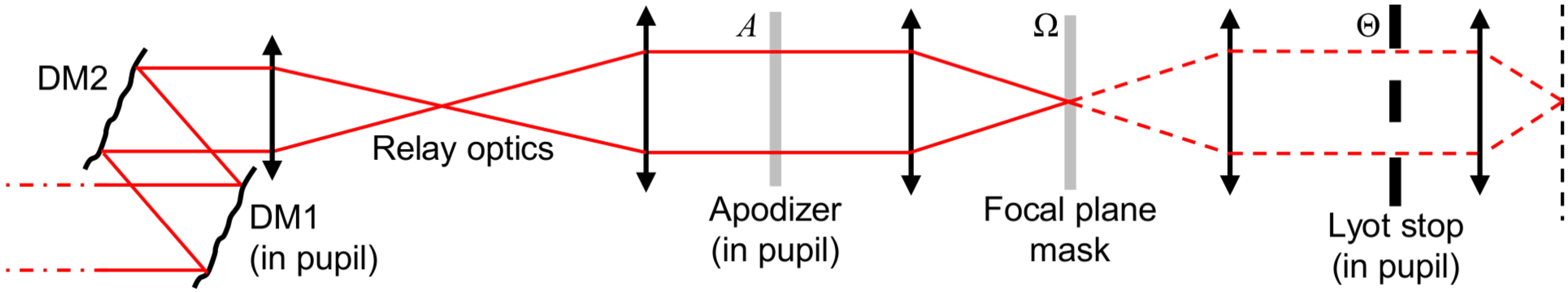
Throughput is defined as energy within 0.7 λ/D of the source position, normalized to that of the telescope.

Performance for off-axis segmented telescopes

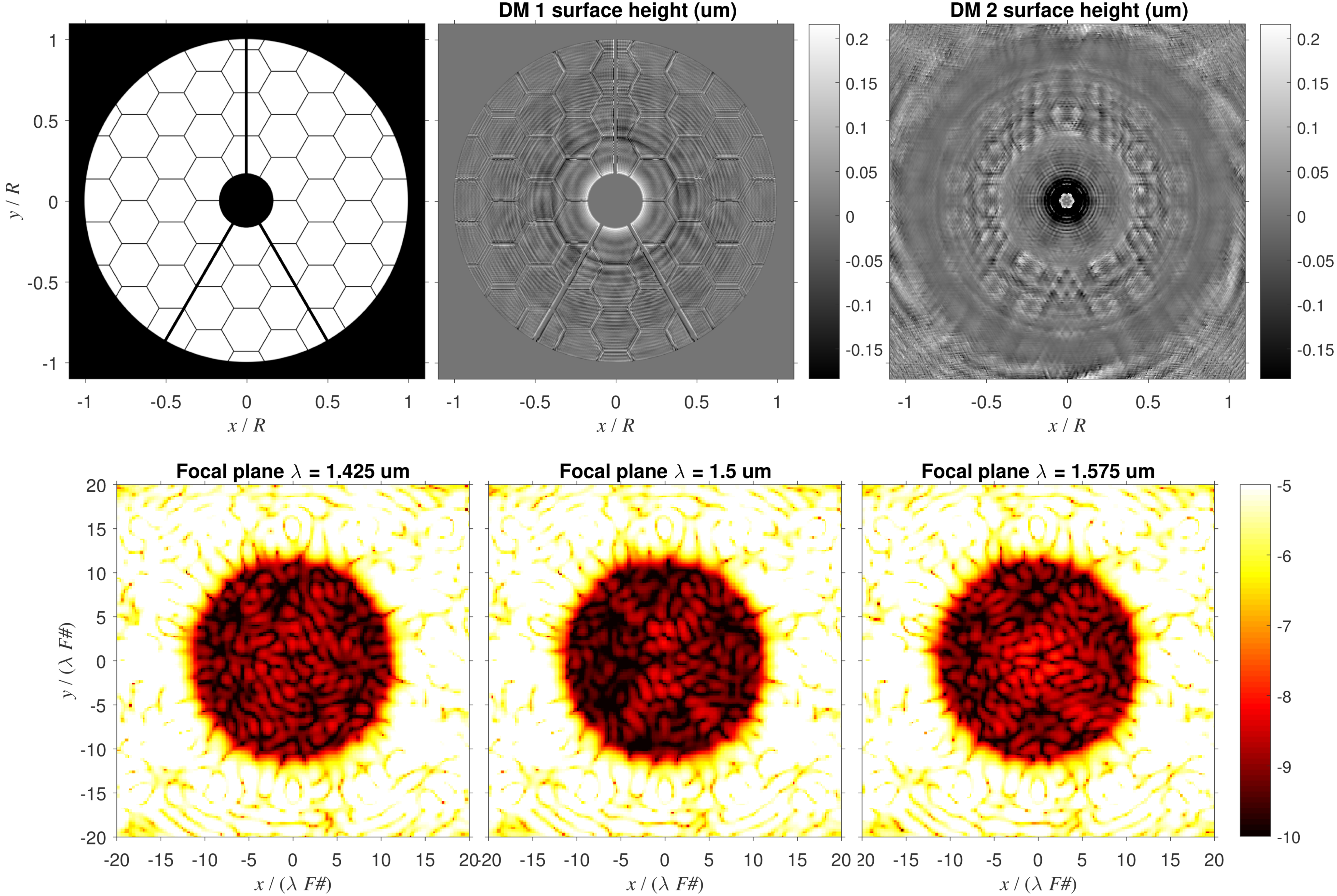
Residual starlight with λ/1000 rms wavefront error



Beam shaping used in lieu of an apodizer can improve throughput

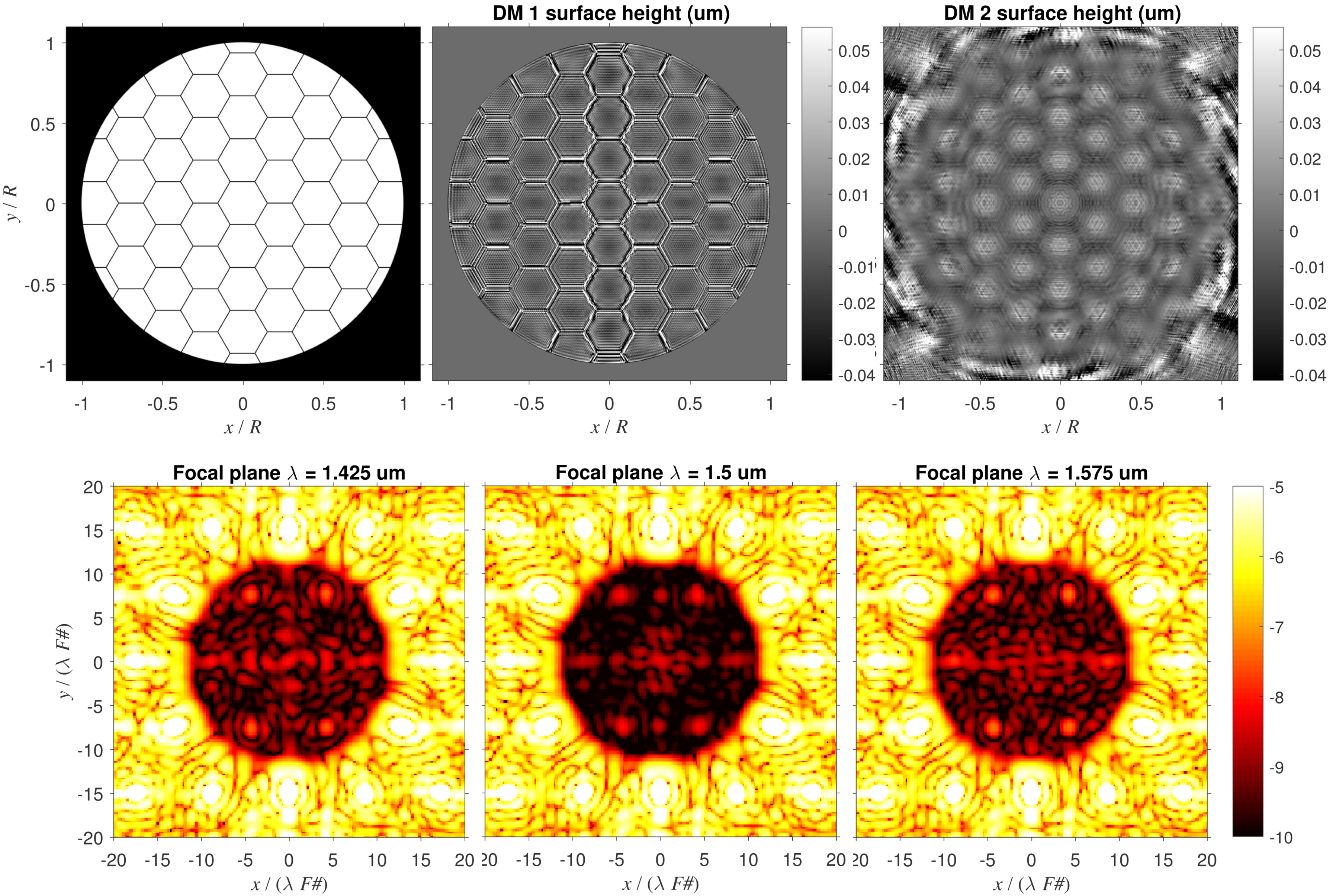


Beam shaping with central obscuration



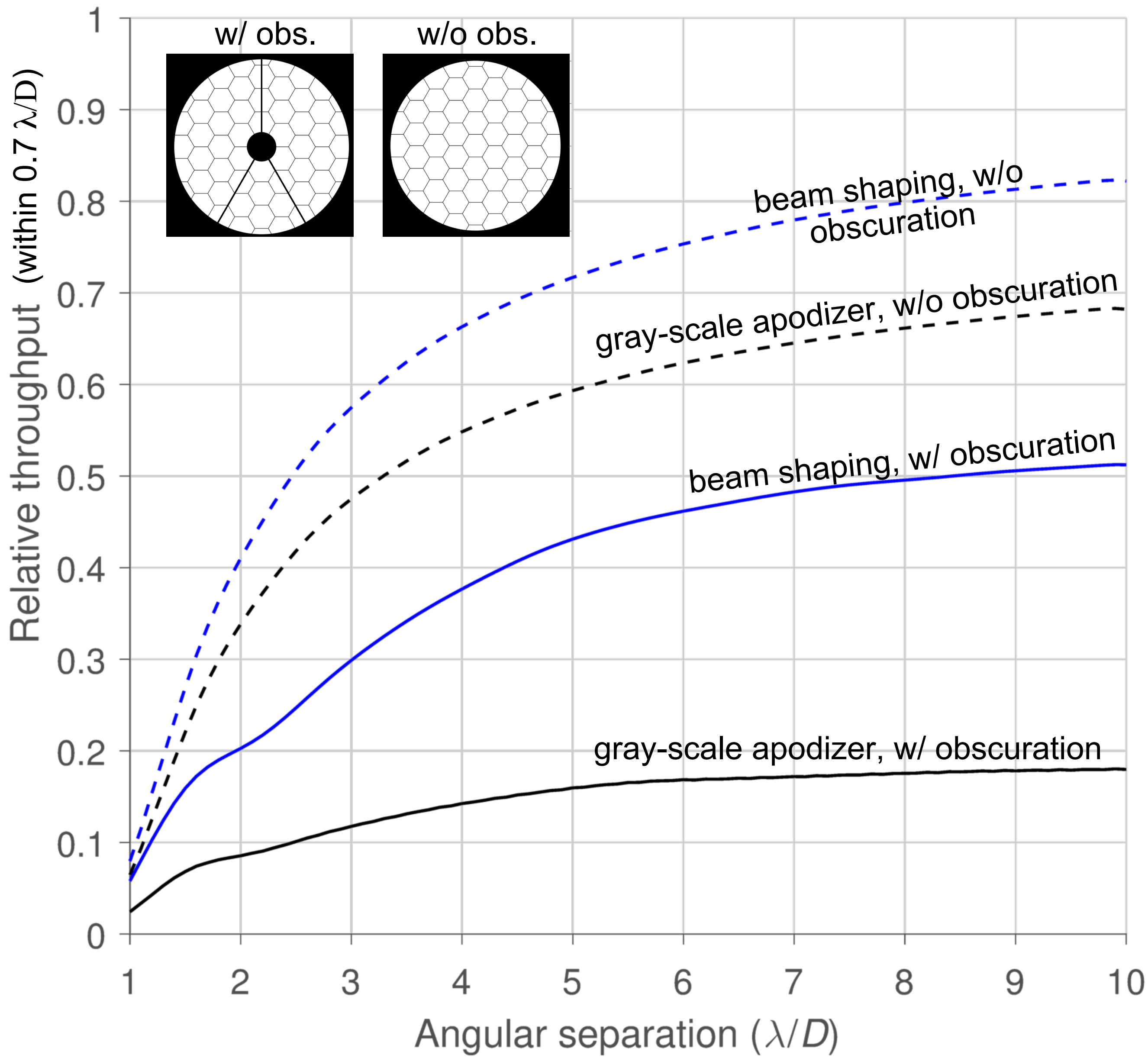
Solution obtained via “Auxiliary Field Optimization” (Jewell et al., in prep.)

Beam shaping without central obscuration

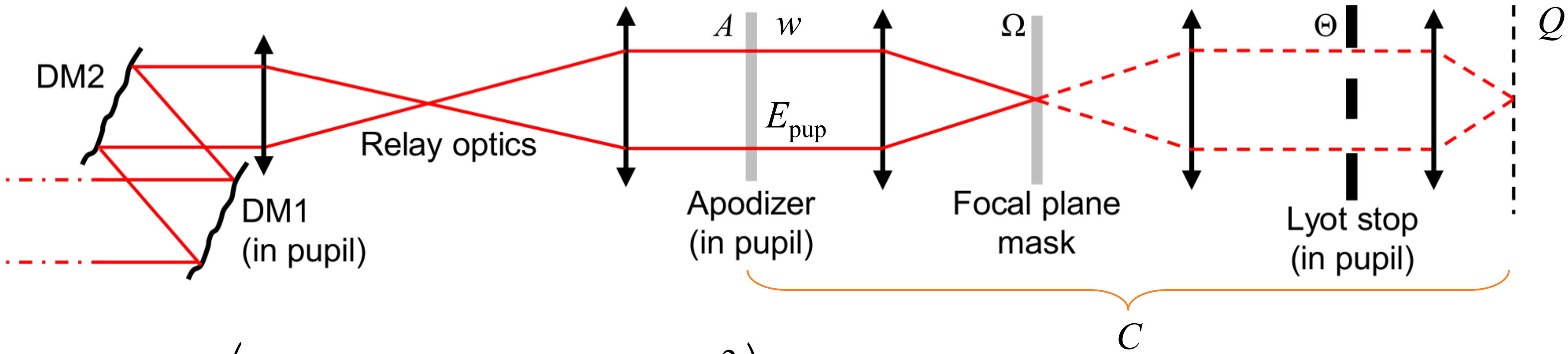


Solution obtained via “Auxiliary Field Optimization” (Jewell et al., in prep.)

Throughput comparison



Optimization procedure



$$\min_{w}\left(\left\|QCw\right\|^2 + b\left\|w - E_{\text{pup}}\right\|^2\right)$$

Algorithm: 1. Solve for pupil field that will create the specified dark hole:

$$w = \left(bI + C^{\dagger}QC\right)^{-1} bE_{\text{pup}}$$

2. Apply constraints set by optical system to $A = |w|$:

$$0 \leq A \leq 1$$

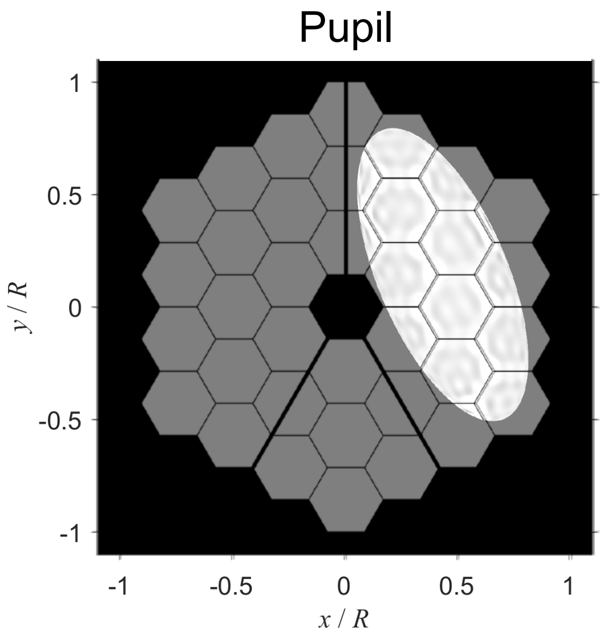
$$\text{supp}\{A\} = \text{supp}\{P\}$$

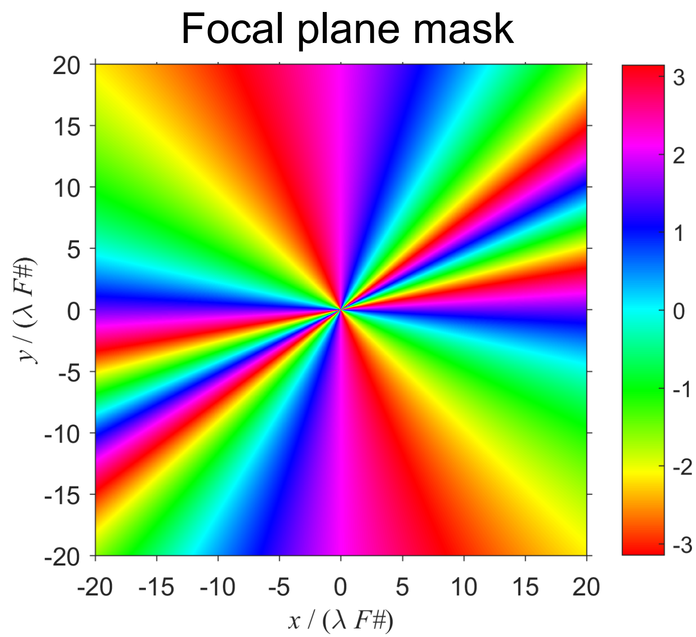
3. Set $E_{\text{pup}} = PA$, and repeat

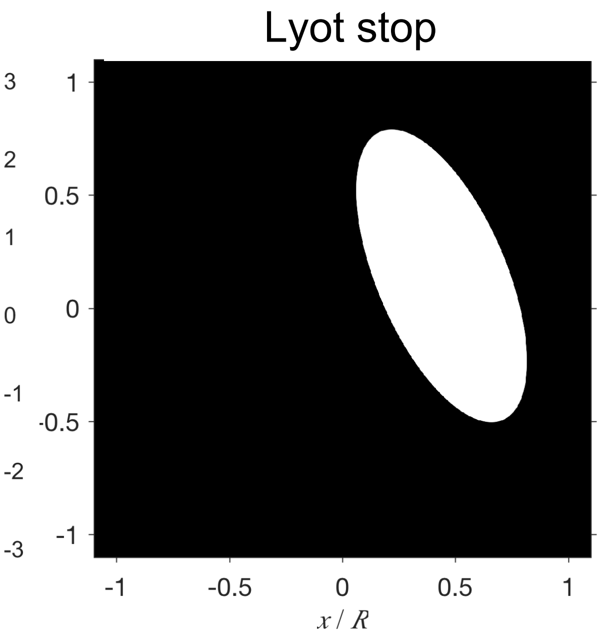
C – coronagraph propagation operator
Q – dark hole region
w – auxiliary field
b – regularization parameter
E_{pup} – current pupil field
A – gray-scale apodizer
P – original pupil field

Aux. field optimization algorithm developed by Jeff Jewell, JPL

Elliptical sub-aperture apodizers

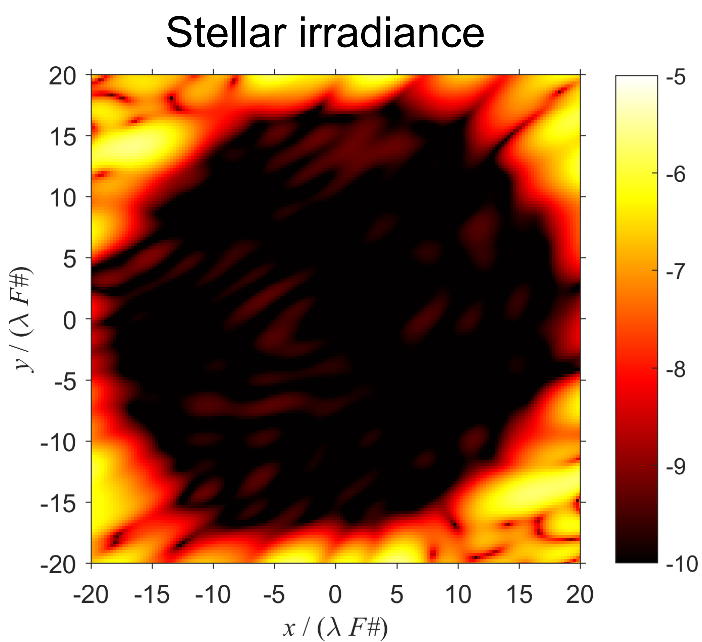






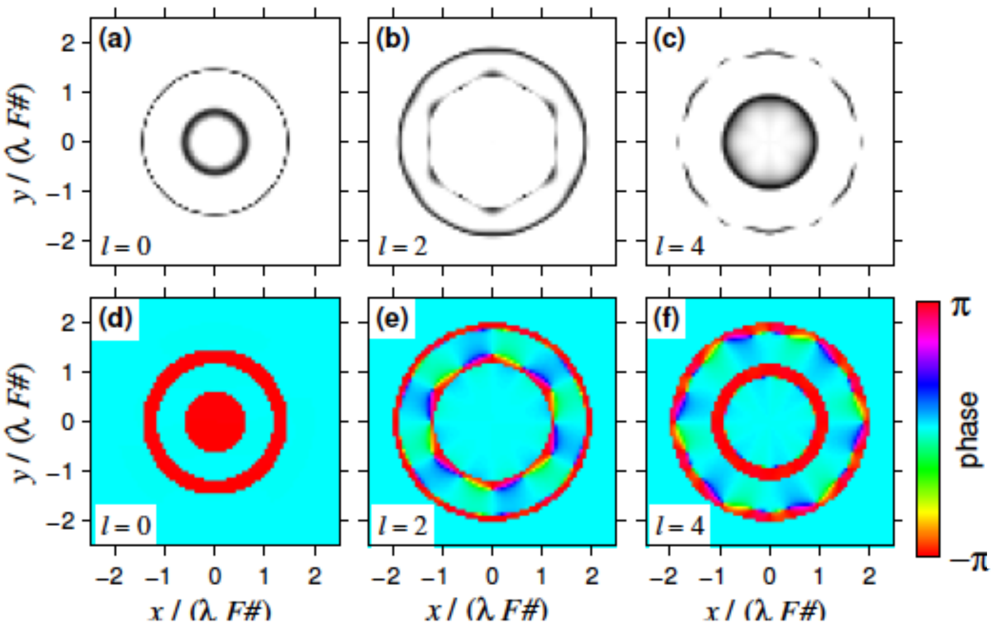
An elliptical sub-aperture on LUVOIR has more collecting area than a 4-m monolith (20% vs. 14%)

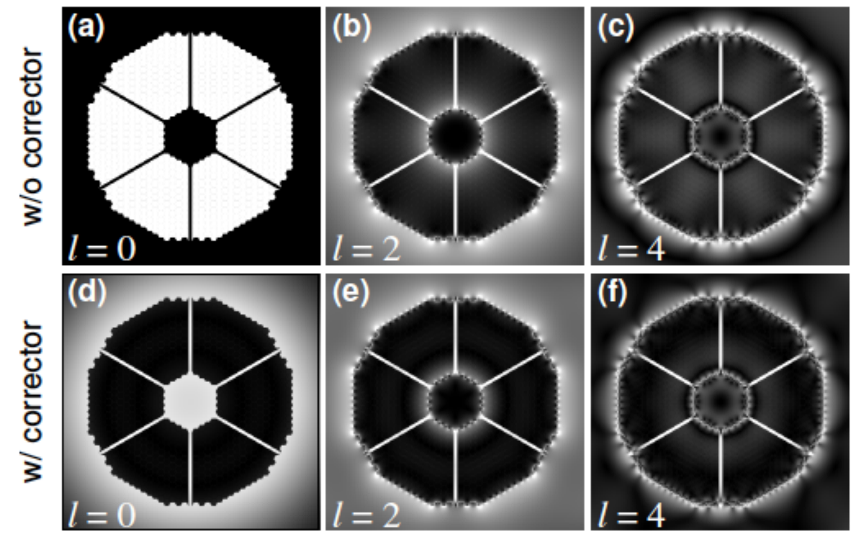
…and its possible to use more than one!



Ruane et al., *Appl. Opt.* **52**, 171 (2013)
Ruane et al., *Optica* 2, 147 (2015)

Focal plane mask optimization: complex correctors

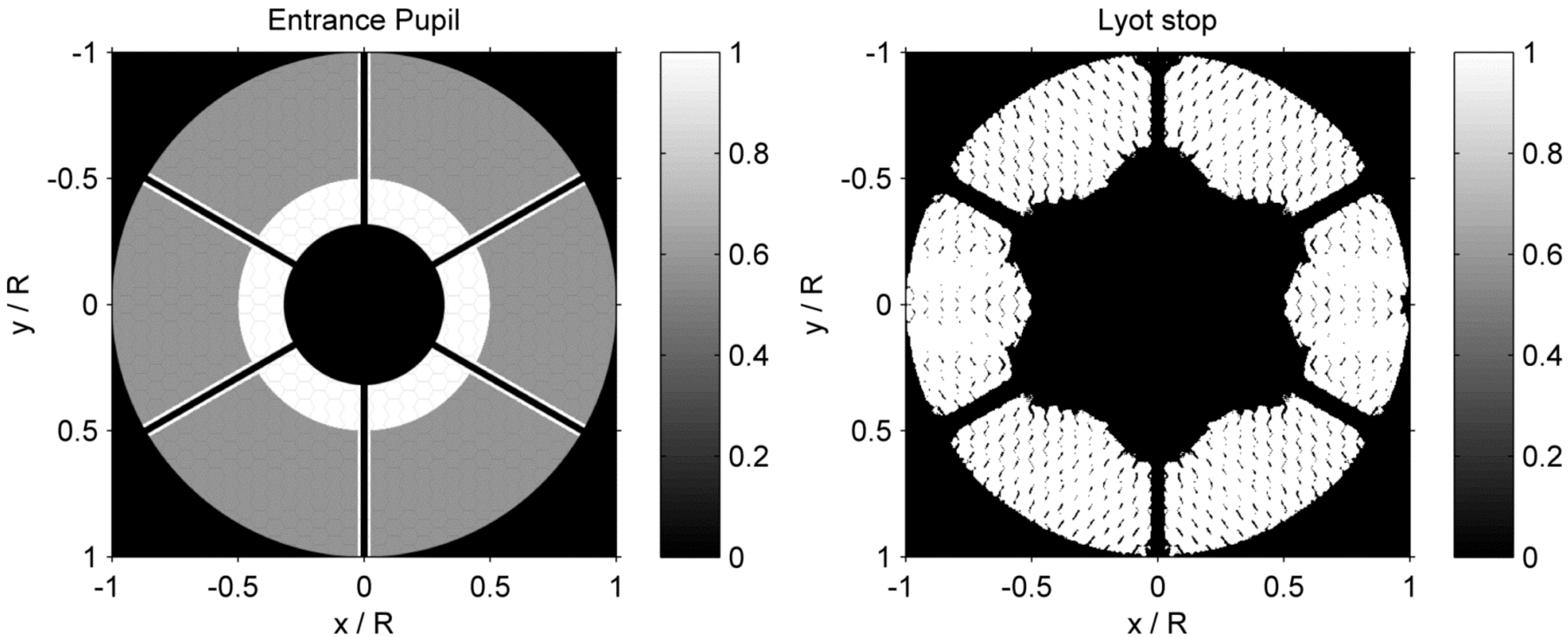




Complex corrections to the focal plane mask may help relocate more light outside of the Lyot stop.

Ruane et al., *Proc. SPIE* 96051I (2015)

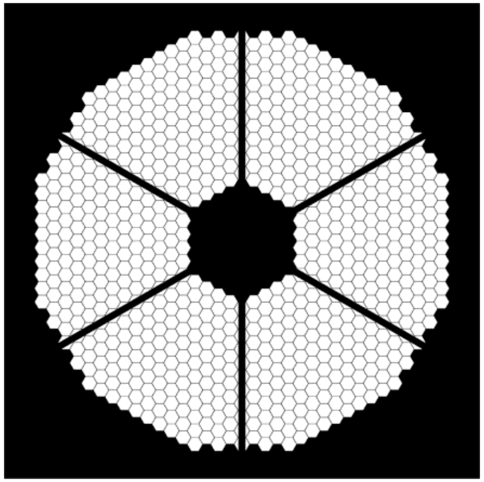
Lyot stop optimization: binary mask



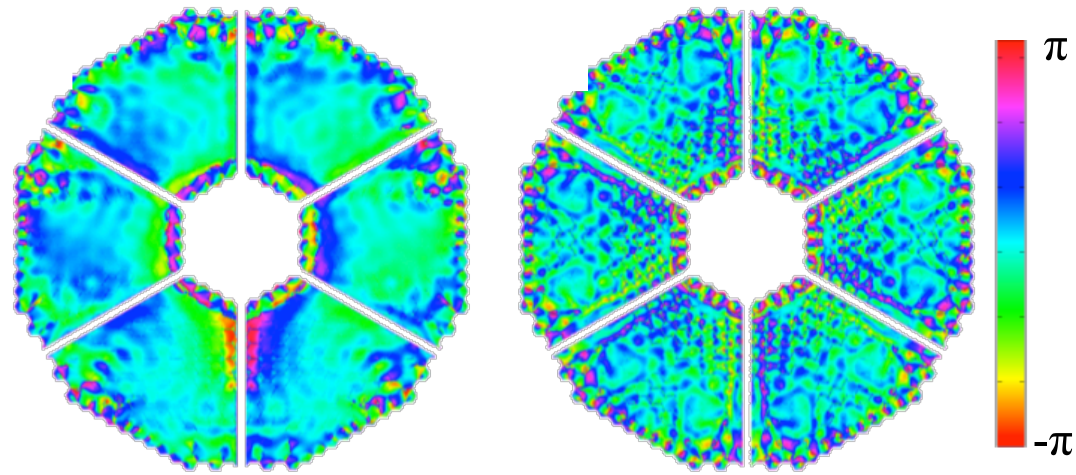
"Raw" Lyot stop

Lyot stop optimization: apodizer

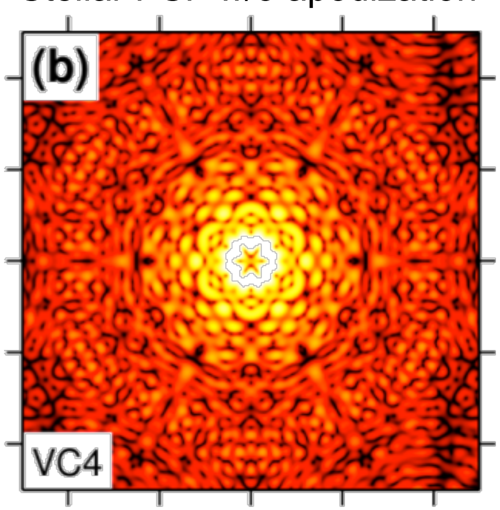
Entrance pupil (E-ELT)



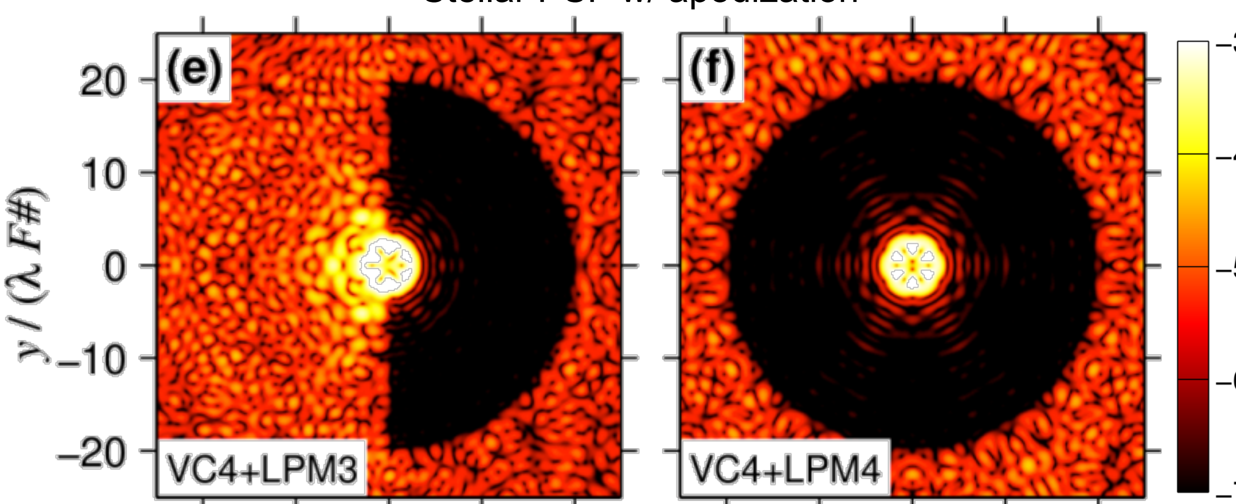
Phase masks for Lyot Stop



Stellar PSF w/o apodization



Stellar PSF w/ apodization

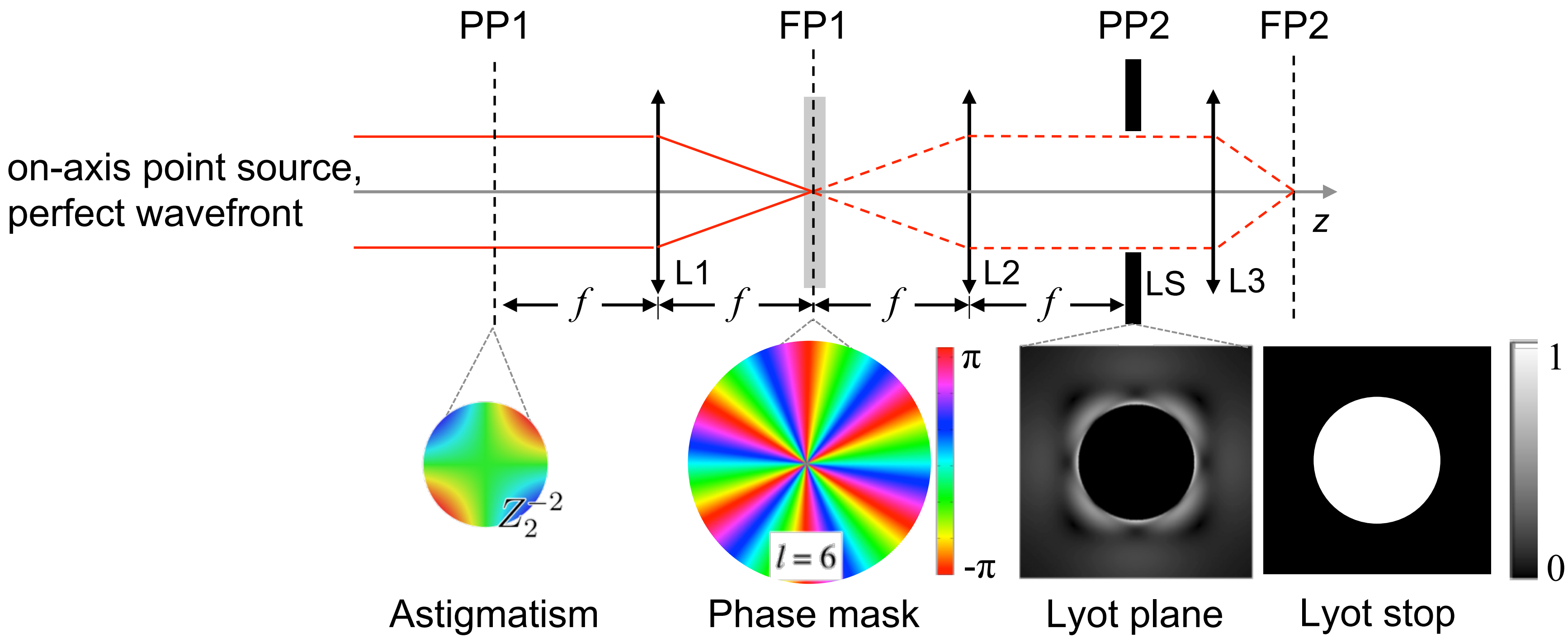


~50% throughput

~30% throughput

Ruane et al., *A&A* 583, A81 (2015)
Ruane et al., *Proc. SPIE* 96051I (2015)

e.g. Charge 6 rejects astigmatism

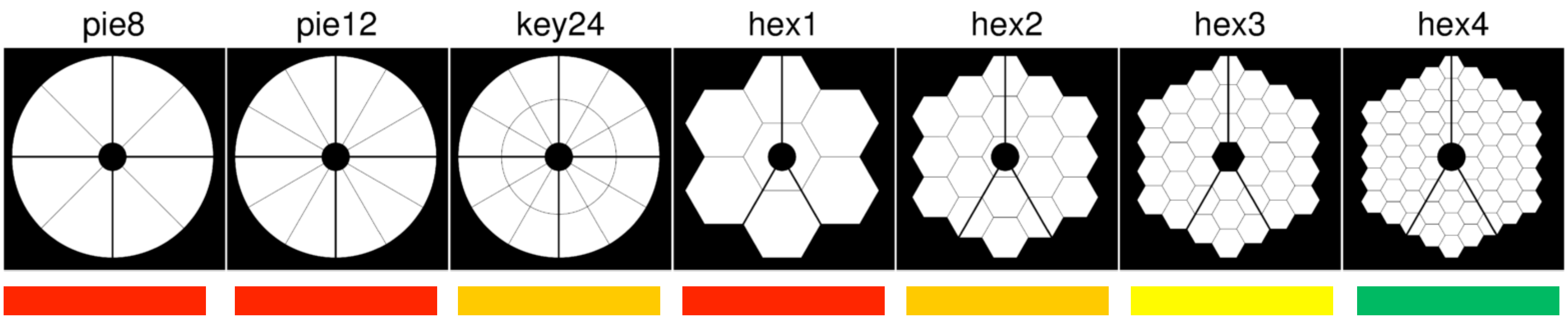


For small phase aberration

i.e. $\exp\left(i\Phi\right) \approx 1 + i\Phi$

Mawet et al., *Proc. SPIE* 773914 (2010)
Ruane et al., *Proc. SPIE* 96051I (2015)

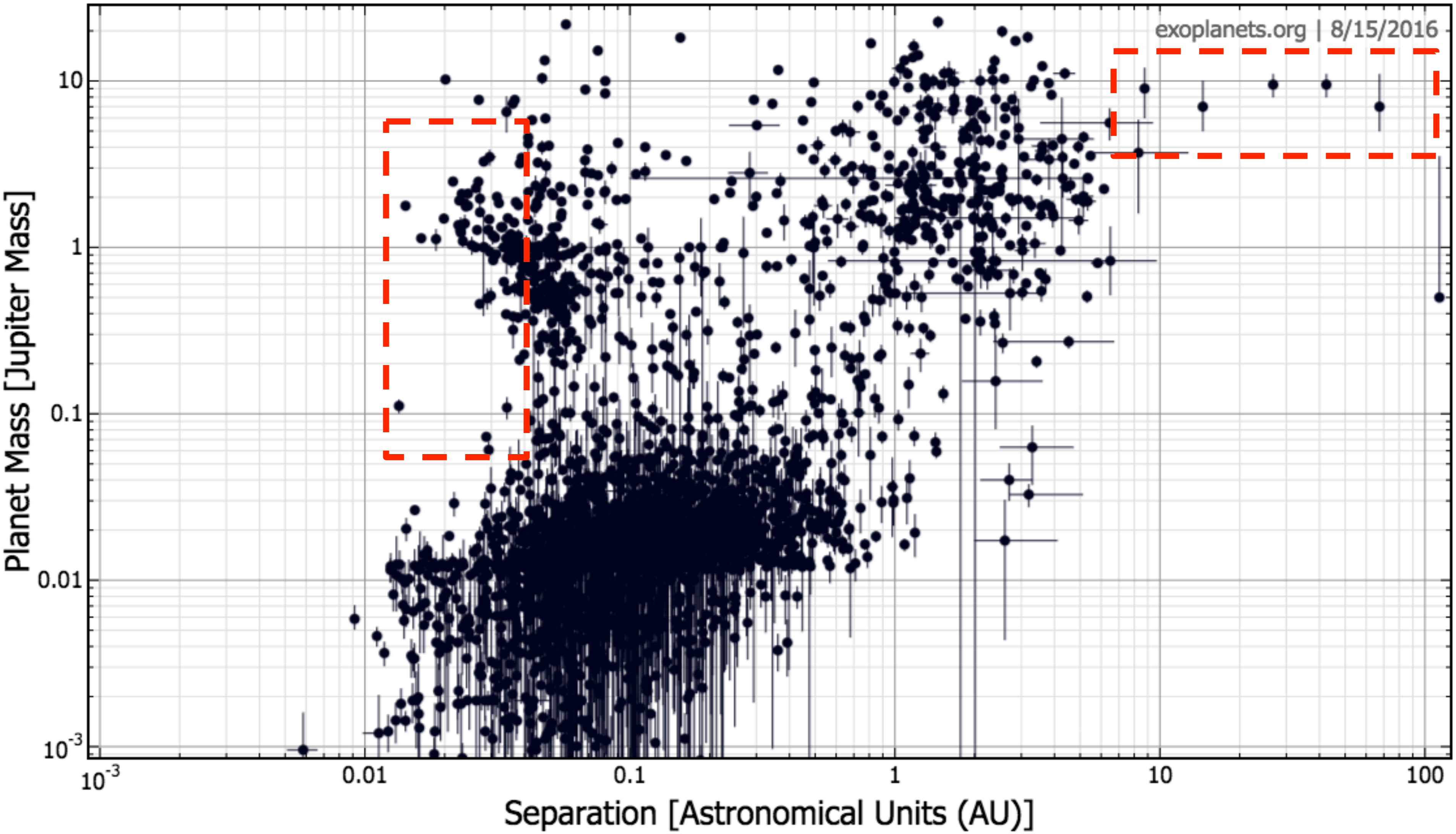
SCDA: How challenging are these apertures?



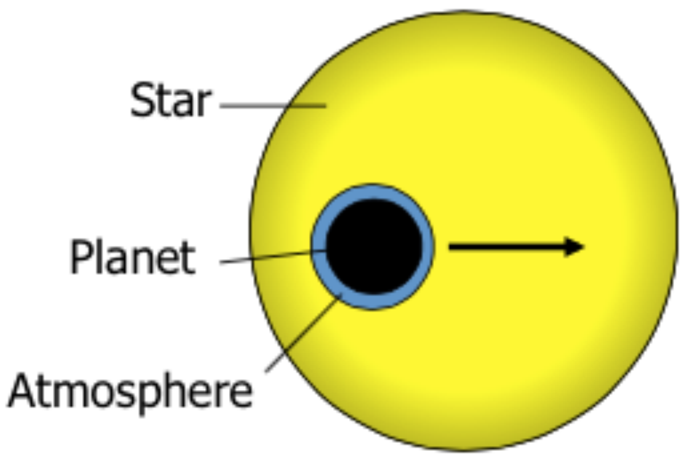
Relative challenge for 12-m telescope

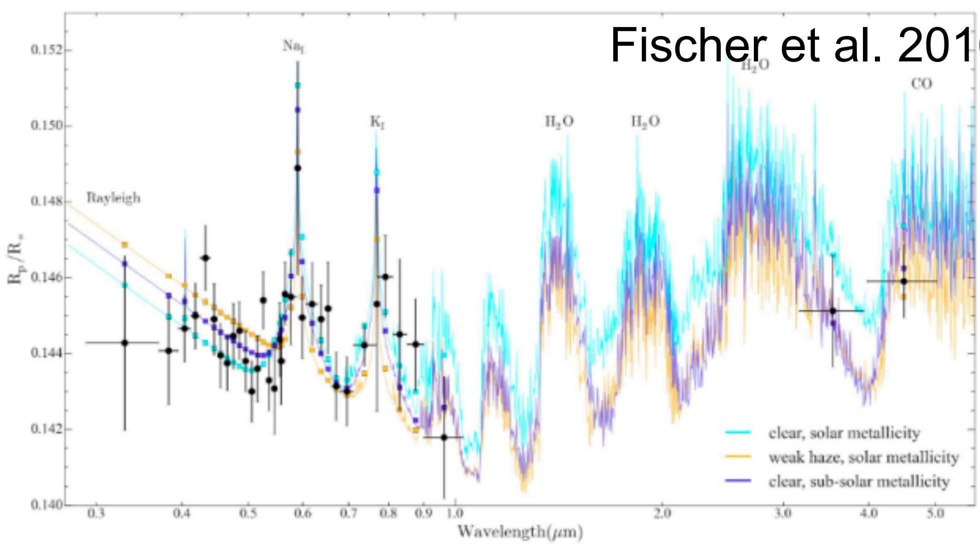
	APERTURES						
	4 ring	3 ring	2 ring	1 ring	Keystone 24	Pie wedge 12	Pie wedge 8
Segment Shape	Hex	Hex	Hex	Hex	Keystone	Pie wedge	Pie wedge
Max Segm. Dimension	1.54 m	1.98 m	2.77 m	4.62 m	2.5 m x 3.14 m	5 m x 3.14 m	5 m x 4.71 m
Segments							
Backplane							
Stability							
Launch Configuration							
SM Support							
Overall Ranking							

With input from:
L. Feinberg, T. Hull,
J. Scott Knight, J. Krist,
P. Lightsey, G. Matthews,
S. Shaklan, and
H. Philip Stahl

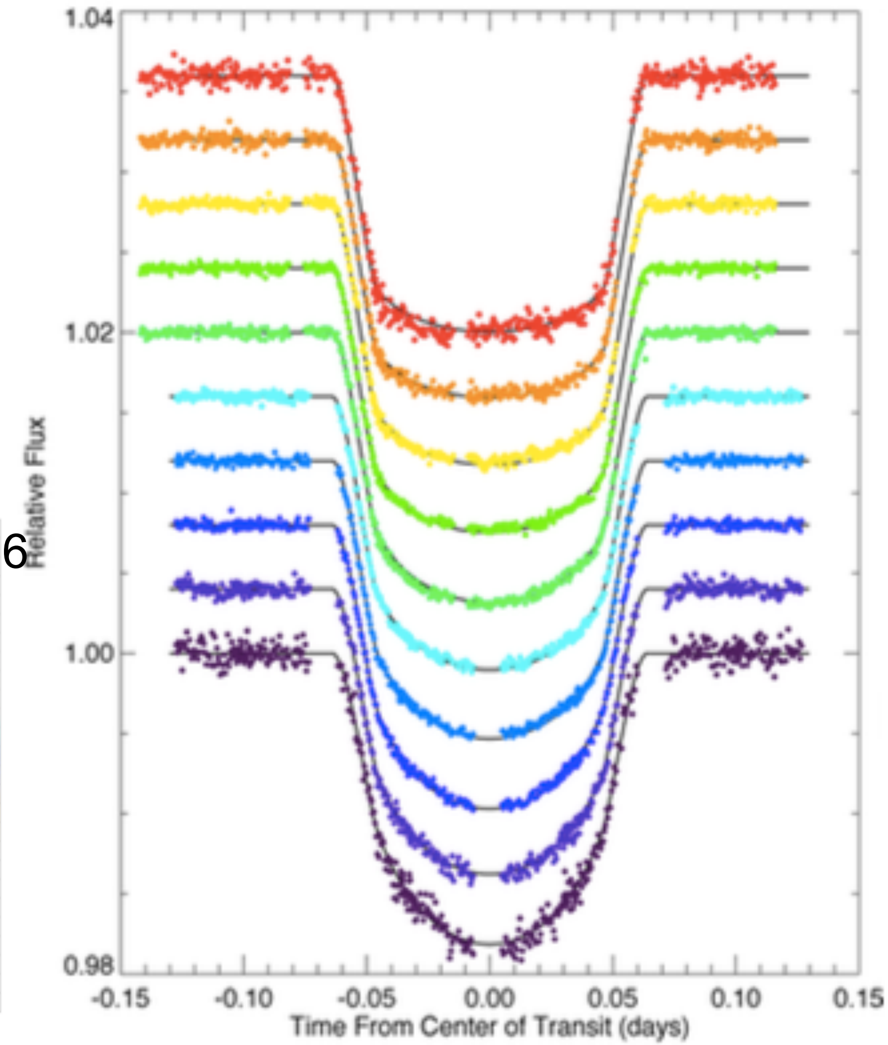

exoplanets.org | 8/15/2016
Planet Mass [Jupiter Mass]
10
1
0.1
0.01
10^{-3}
10^{-3}
0.01
0.1
1
10
100
Separation [Astronomical Units (AU)]

Transmission Spectroscopy



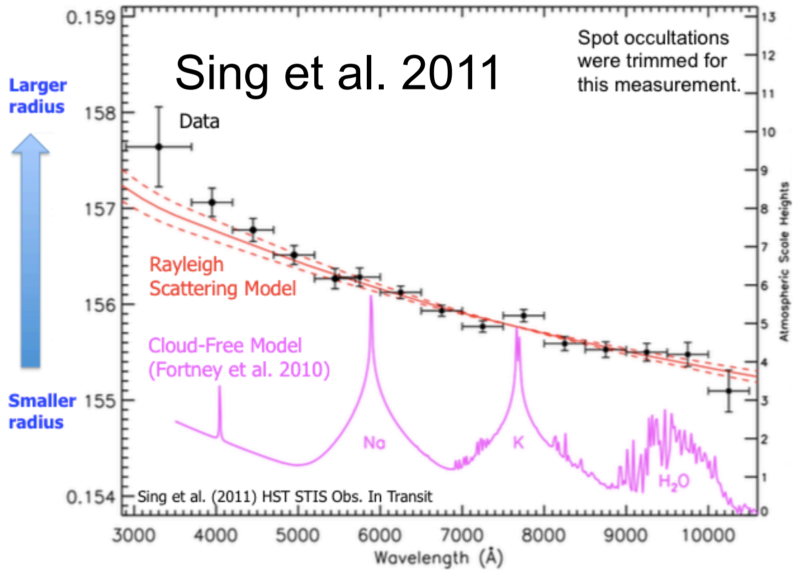


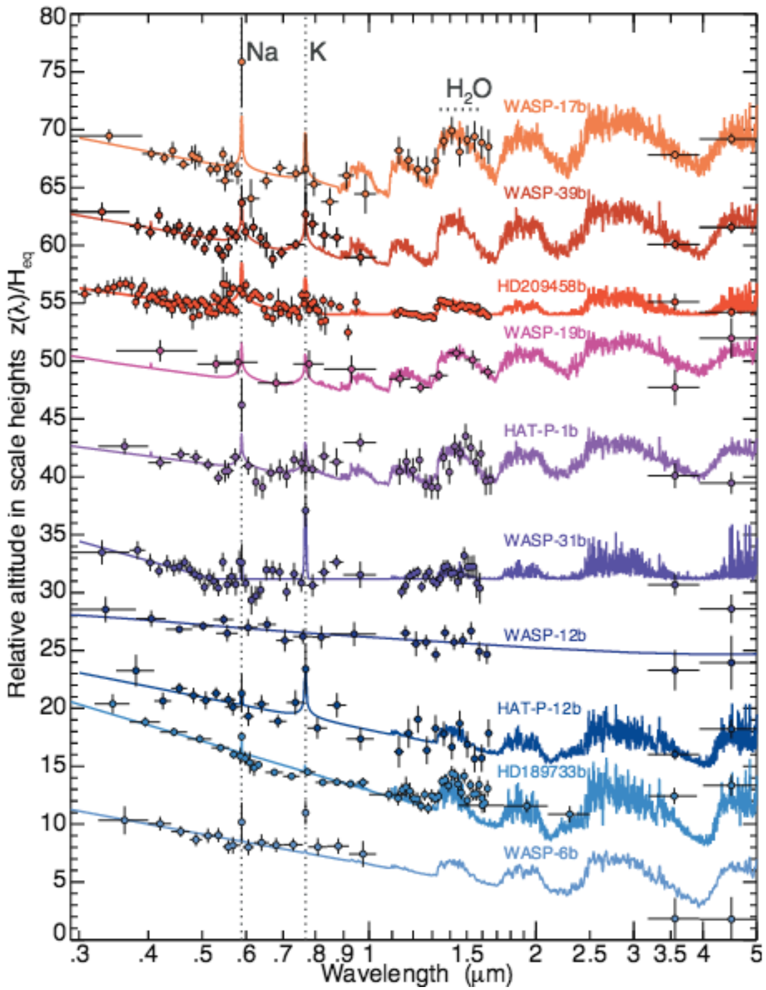
Fischer et al. 2016

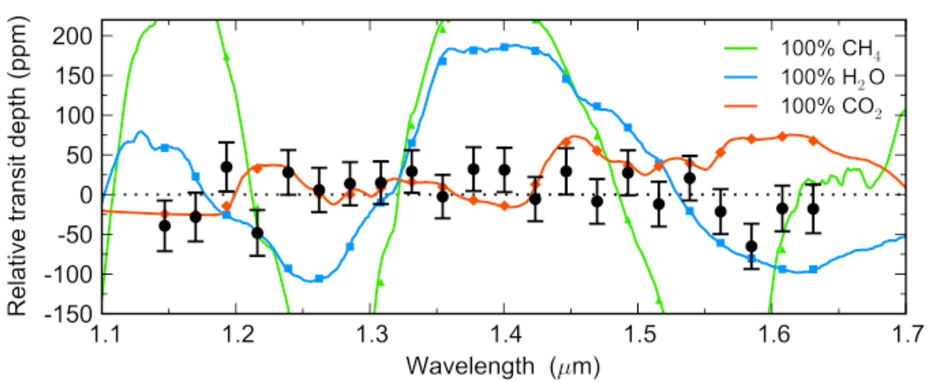


Knutson et al. 2007

Cloud and Haze



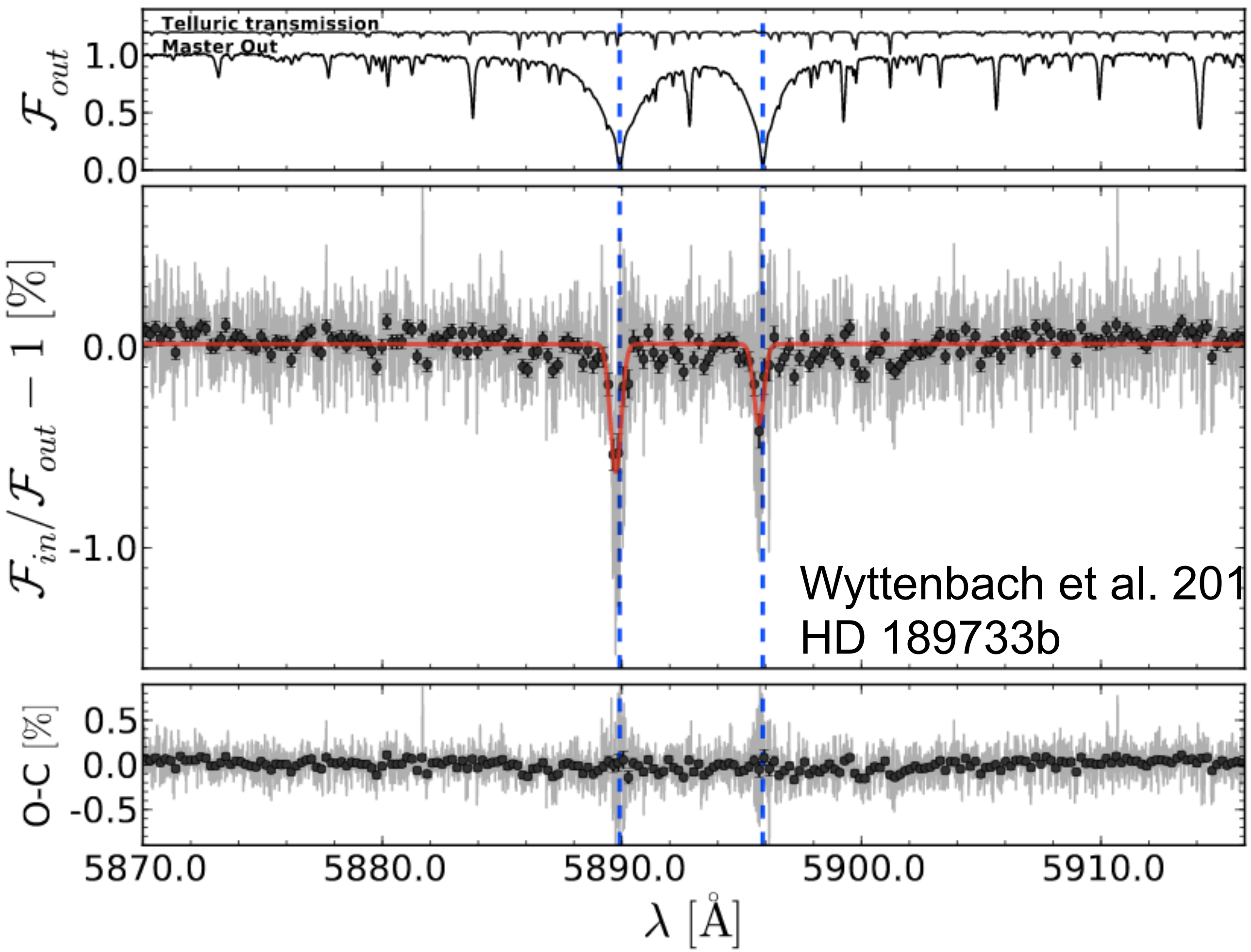




Kreidberg et al. 2014

Sing et al. 2016

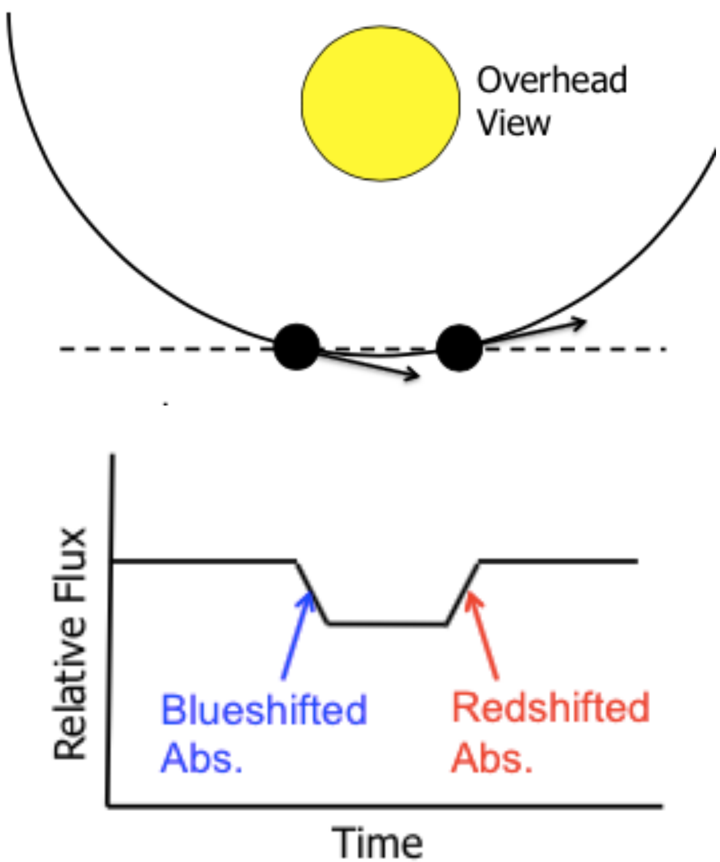
High Resolution Spectroscopy

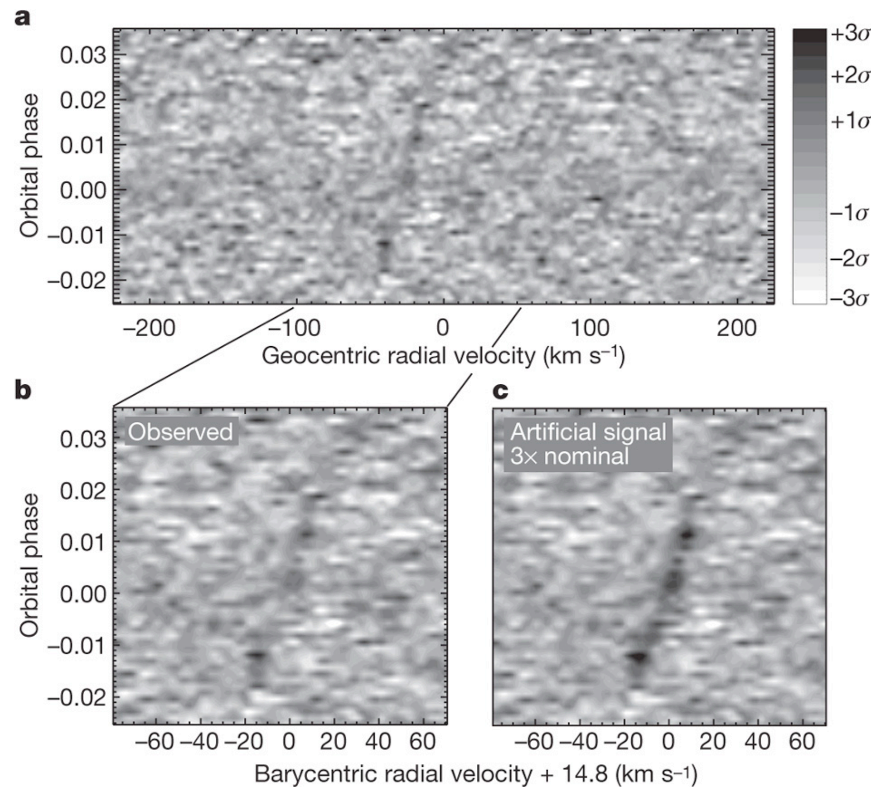


Wyttenbach et al. 2015
HD 189733b

See also Khalafinejad et al. 20

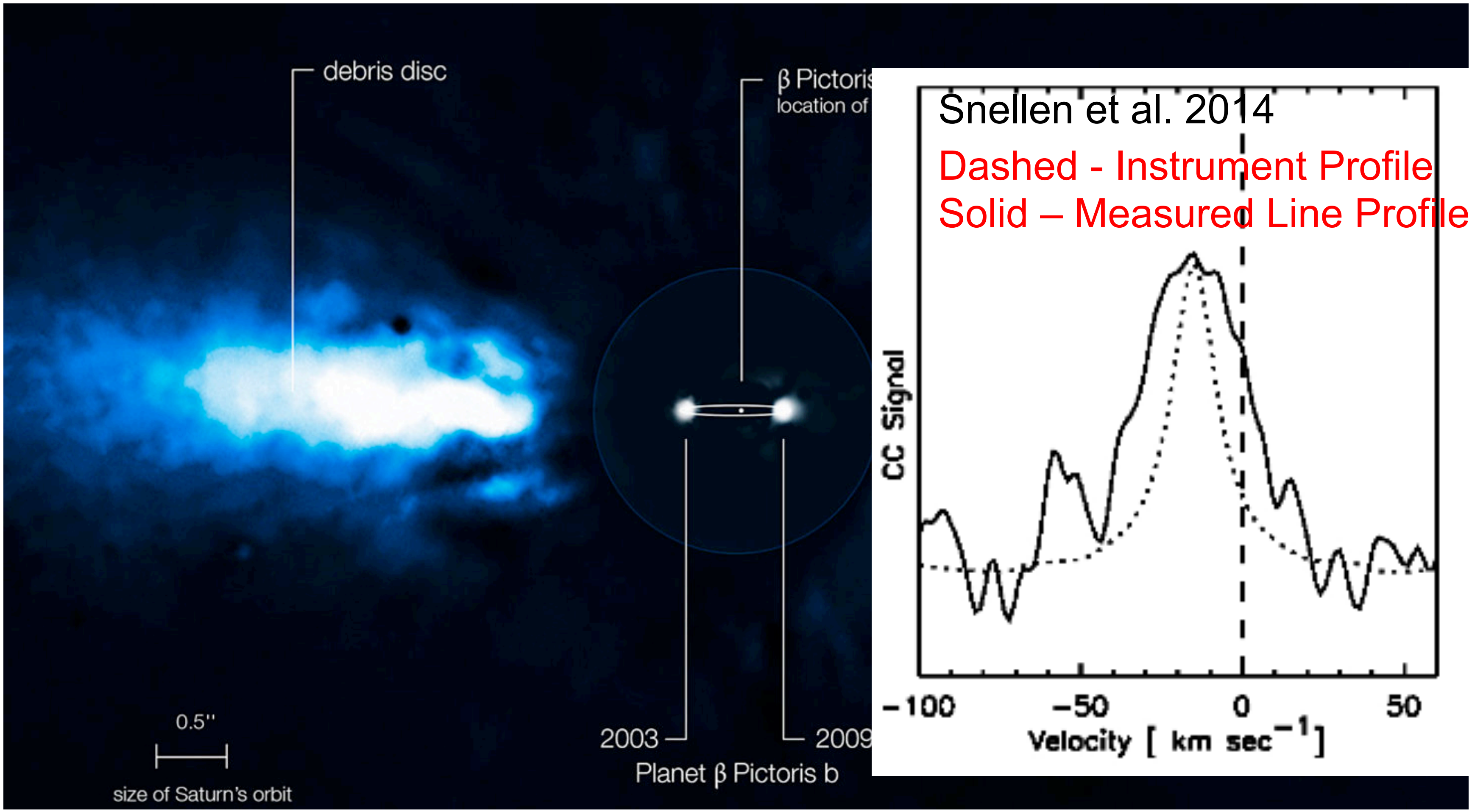
Atmospheric Composition From High-Resolution Spectroscopy



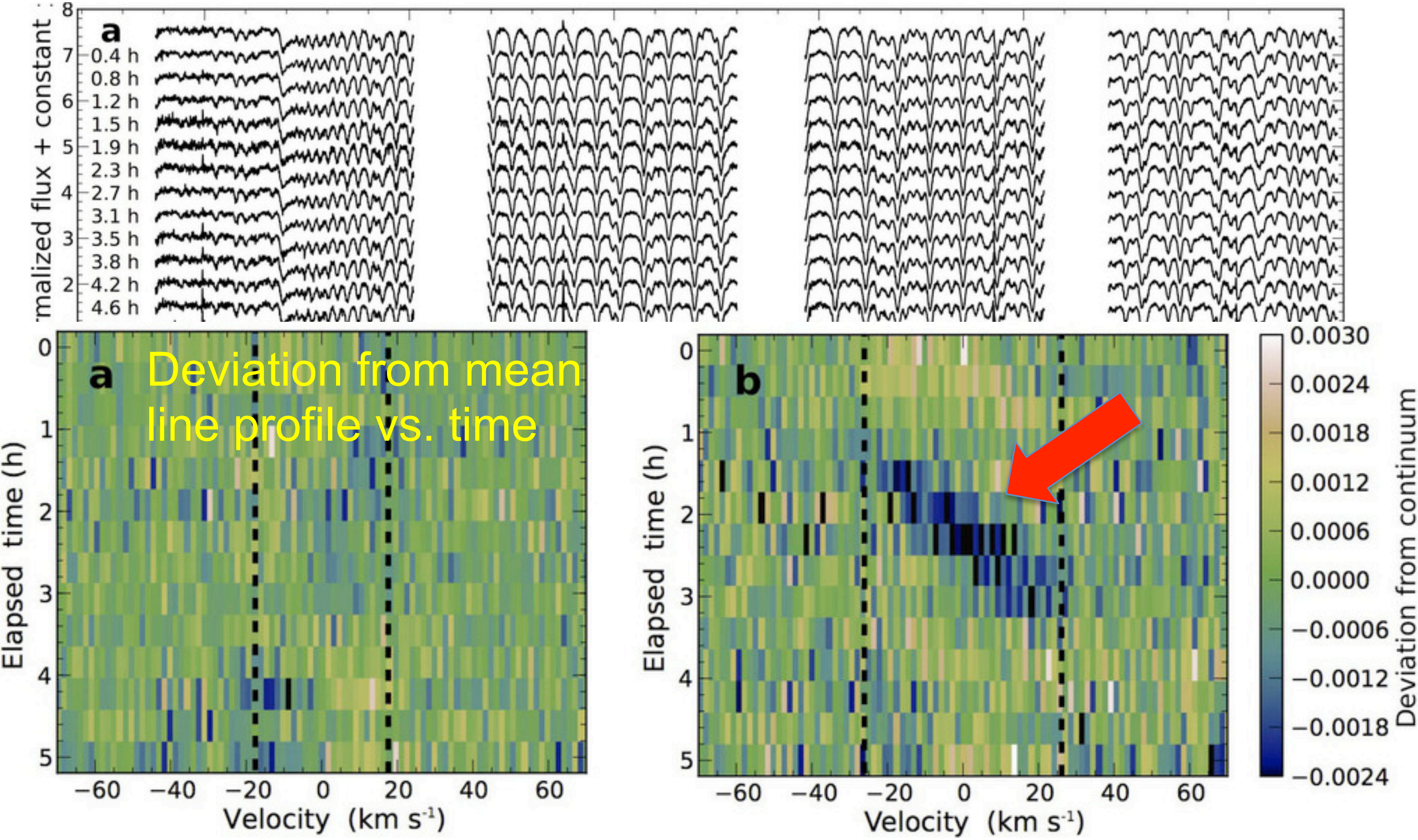


HD 209458, Snellen et al. 2010

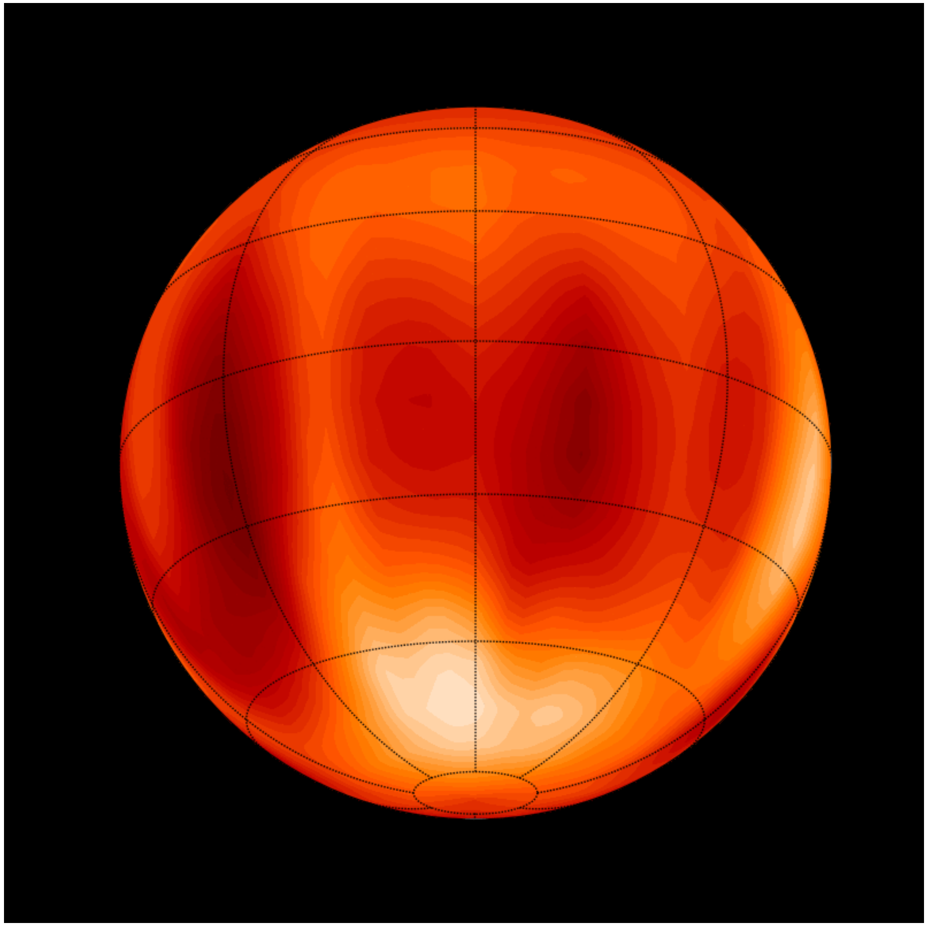
Planet Rotation – Beta Pic b



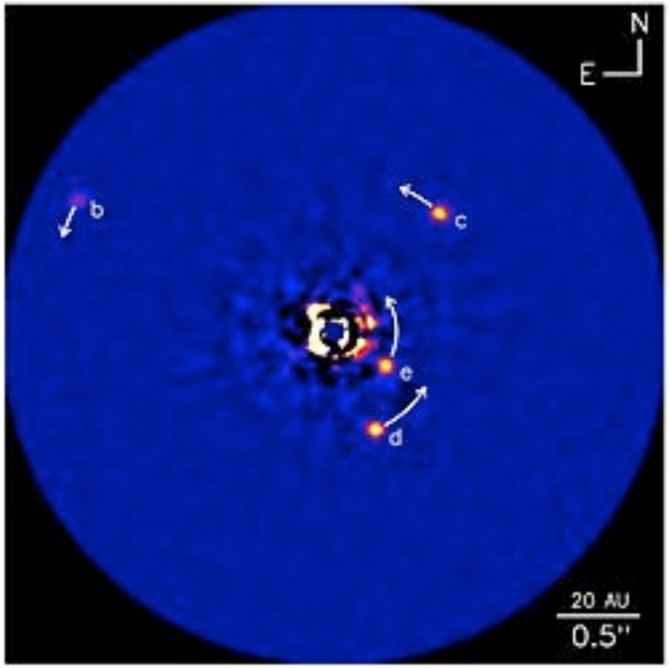
Doppler Imaging – Luhman 16 A & B

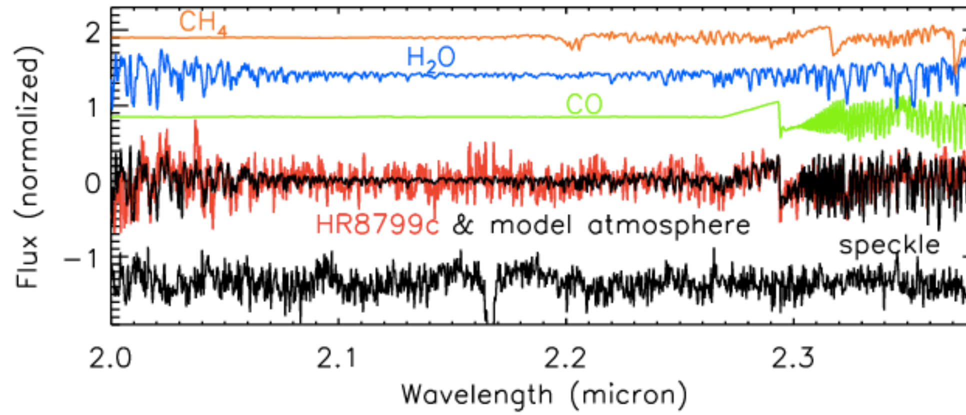


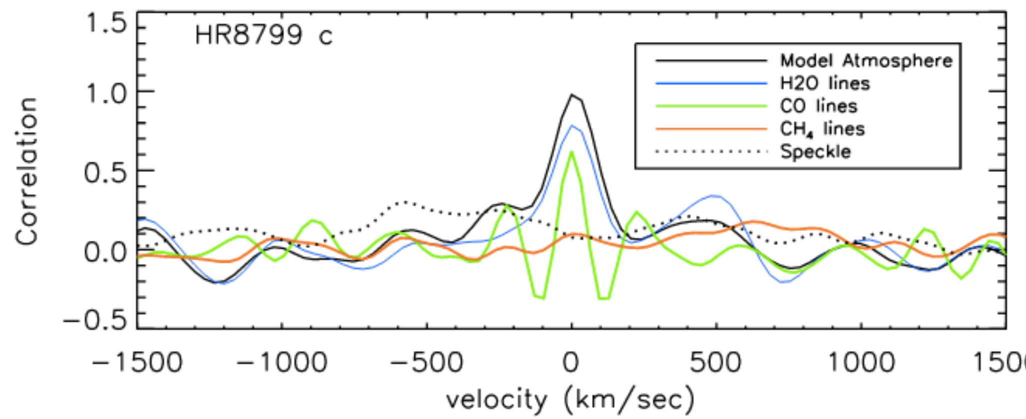
C



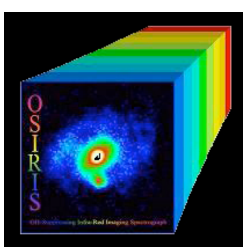
Detection of H_2O and CO on HR 8799 c





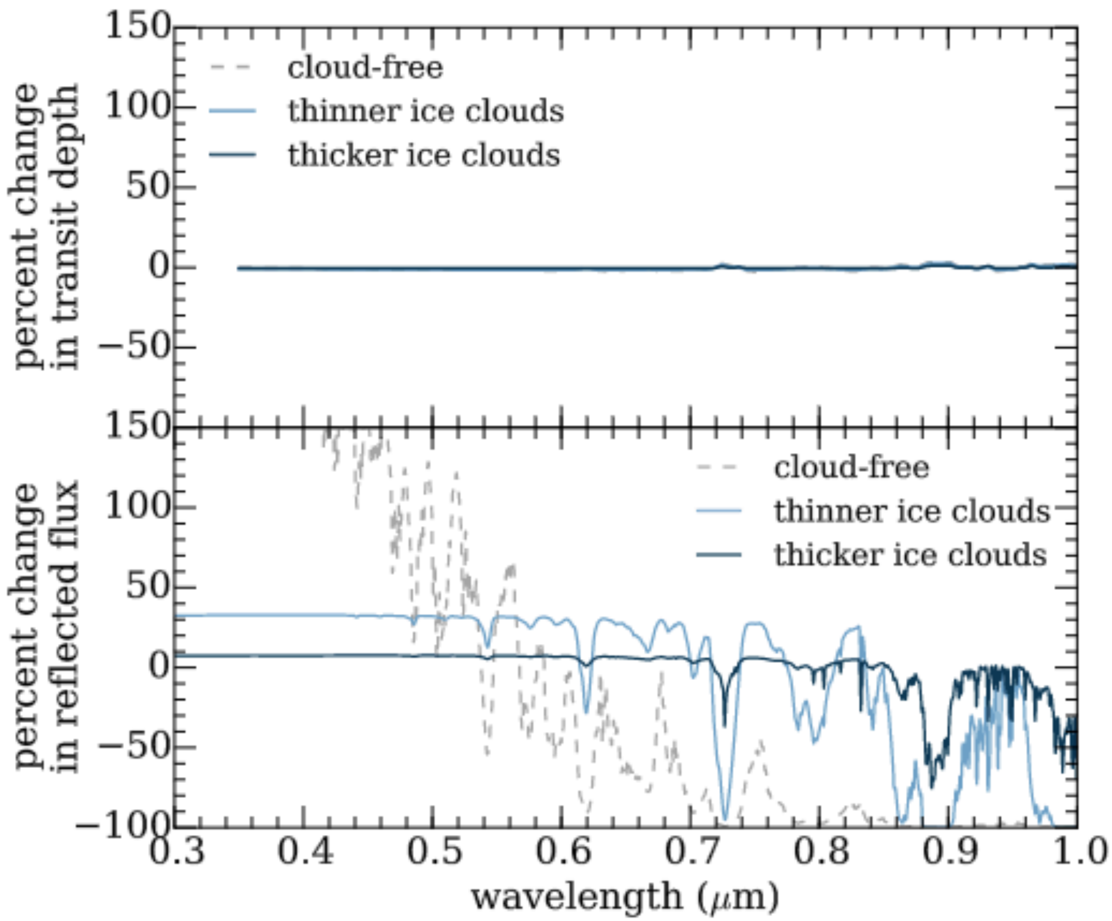


Keck OSIRIS



Konopacky et al. 2013

Reflection Spectrocopy



Morley et al. 2014

Keck Planet Imager and Characterizer

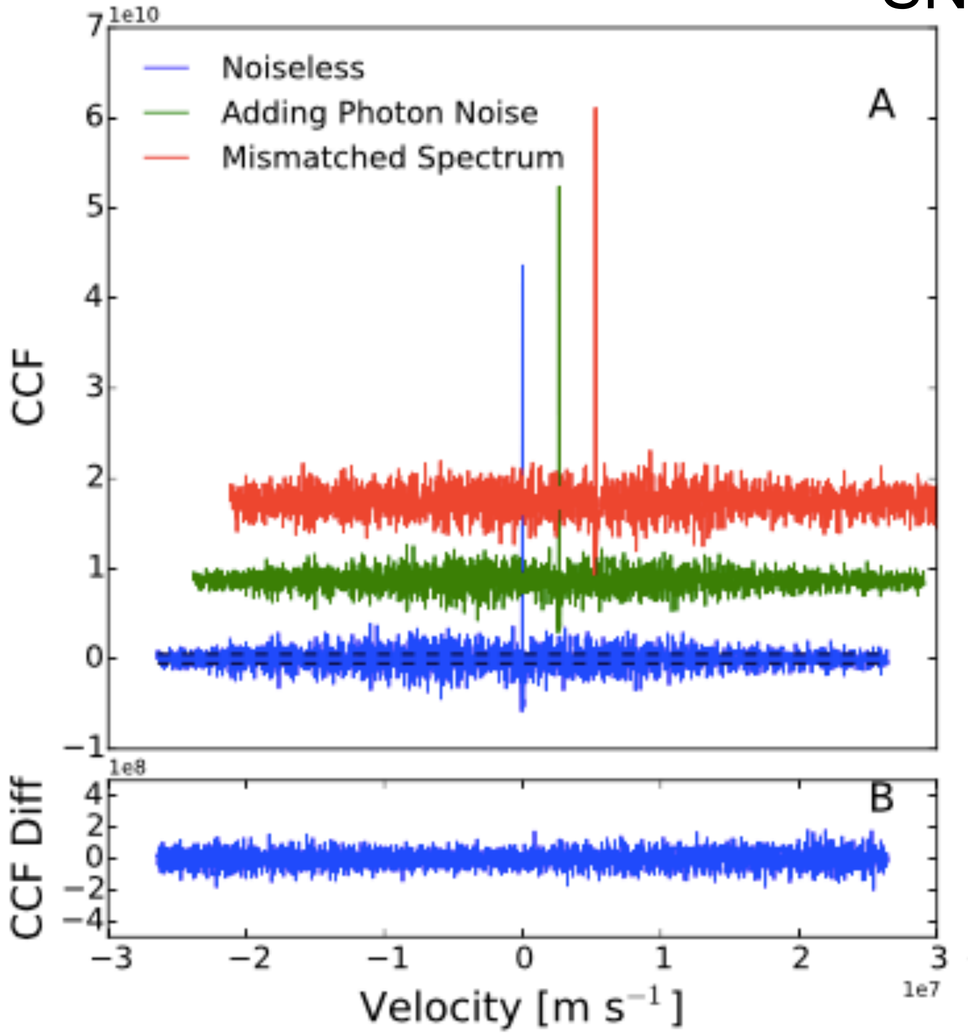
PI: D. Mawet (Caltech)

- Upgrade to Keck II AO and instrument suite:
  - L-band vortex coronagraph in NIRC2 - deployed
  - IR PyWFS – funded (NSF)
  - <u>SMF link to upgraded NIRSPEC (FIU) - funded (HSF & NSF)</u>
  - High contrast FIU – seeking funding
  - MODIUS: New fiber-fed, Multi-Object Diffraction limited IR Ultra-high resolution (R~150k-200k) Spectrograph – design study encouraged by KSSC

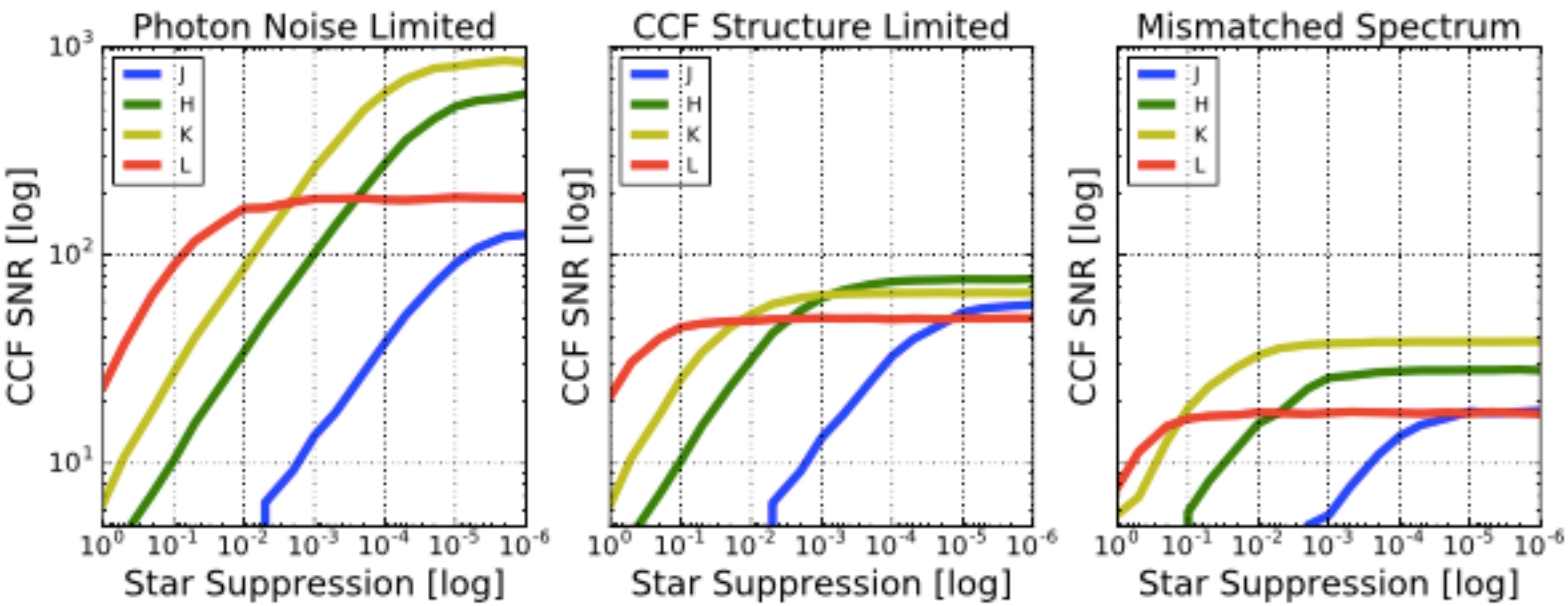
- Pathfinder to ELT planet imager exploring new high contrast imaging/spectroscopy instrument paradigms:
  - Decouple search and discovery from characterization: specialized module/strategy for each task
  - New hybrid coronagraph designs: e.g. apodized vortex
  - Wavefront control: e.g. speckle nulling on SMF

CCF SNR

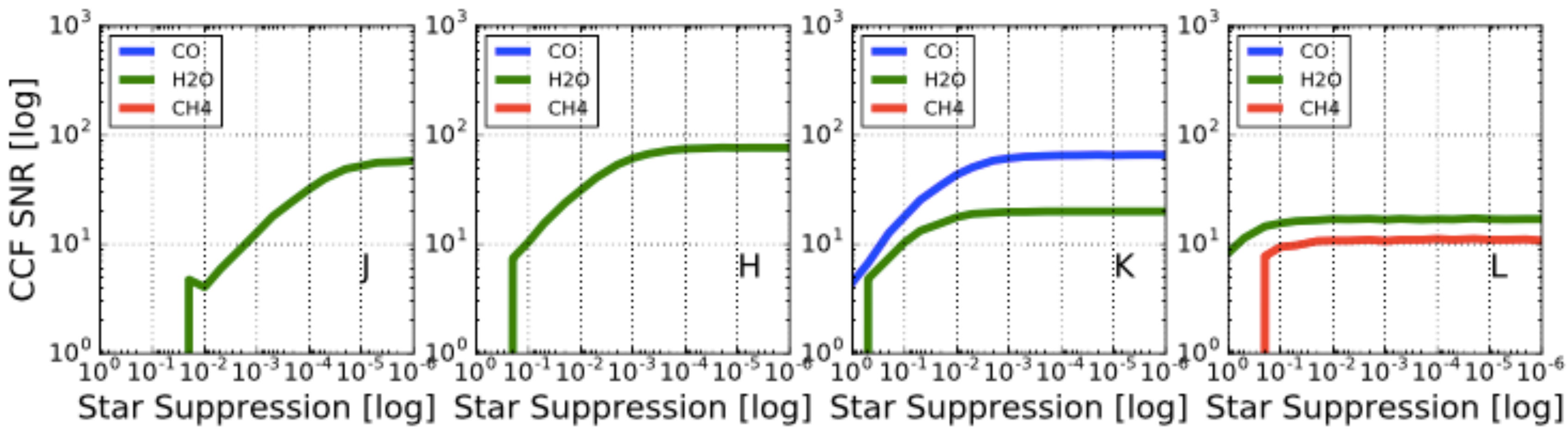
SNR = Peak / Fluctuation



Limiting Factors of CCF SNR for HR 8799e Observation



Detecting Molecular Species



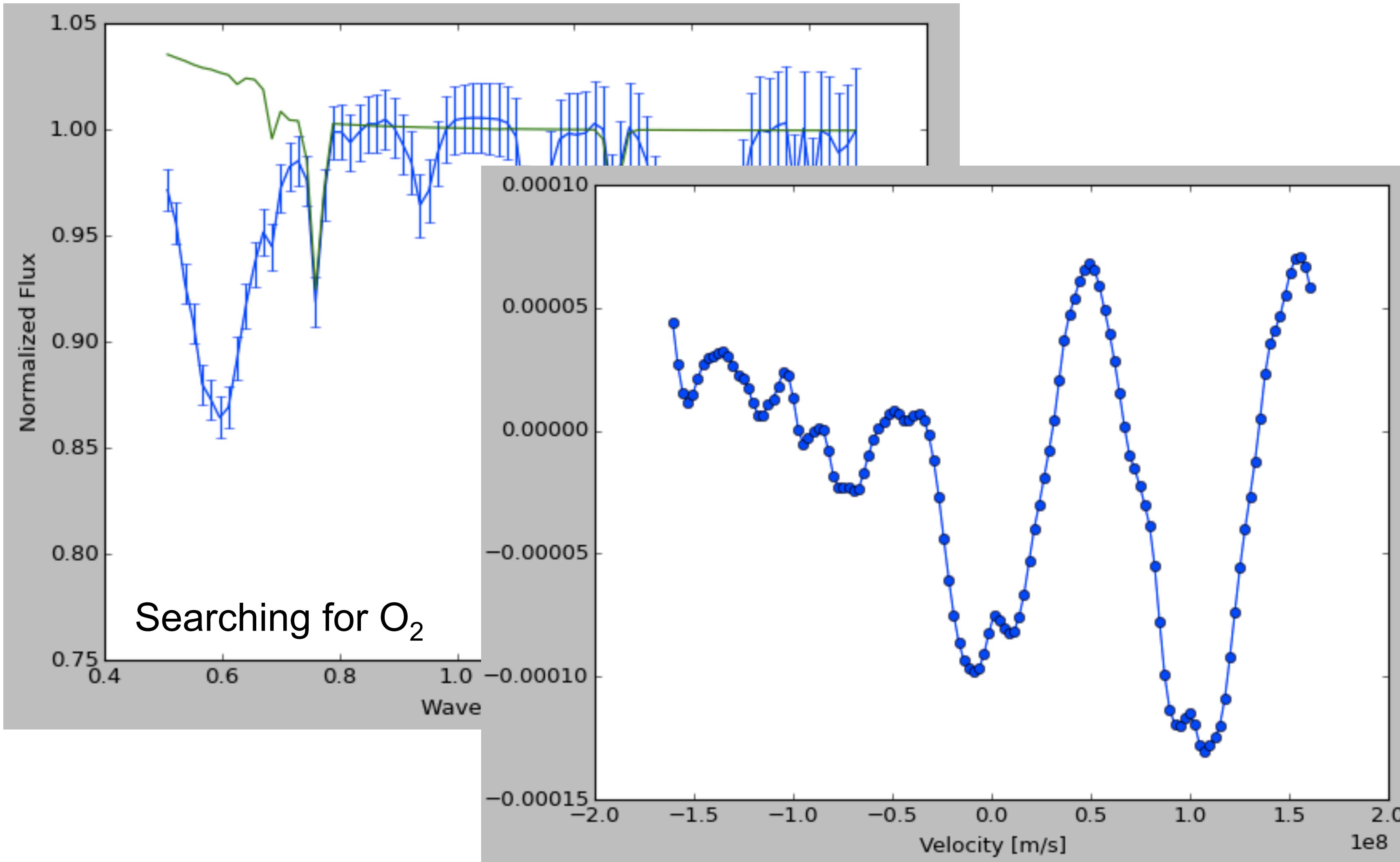
Space-based vs. Ground-based

- Non-cryogenic vs. cryogenic
- Atmosphere-free vs. atmosphere
- Absorption bands vs. lines
- Starlight suppression
- Inner working angle
- *Sun-Earth vs. M dwarf planet*

Redefining CCF SNR for Space-based Observation

- CCF does not work well in low spectral resolution (few data points)

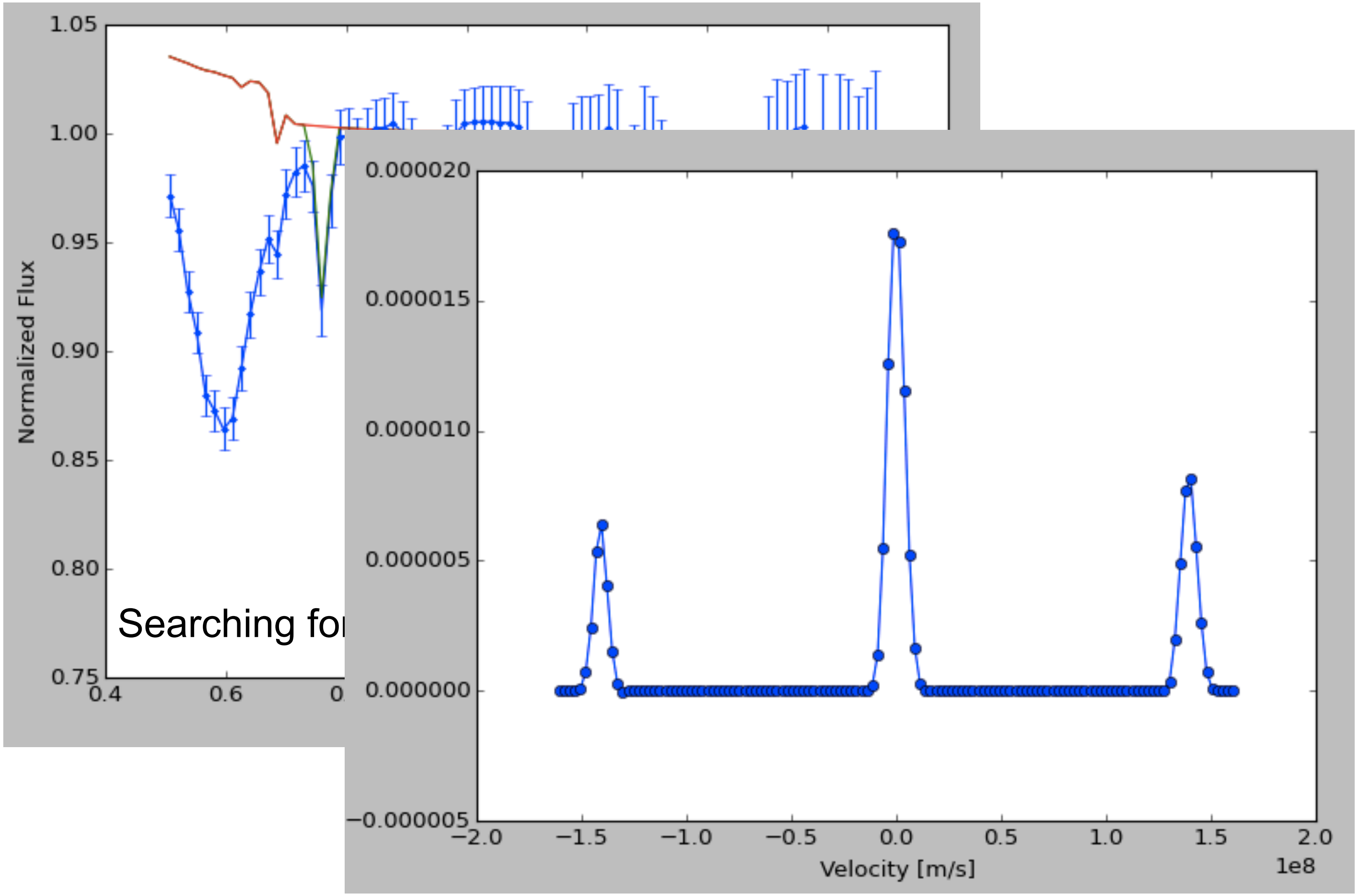
CCF at Low Resolutions



Redefining CCF SNR for Space-based Observation

- CCF does not work well in low spectral resolution (few data points)
- Masked cross correlation function

Masked Cross Correlation



Redefining CCF SNR for Space-based Observation

- CCF does not work well in low spectral resolution (few data points and speckle chromatic noise)
- Masked cross correlation function
- Photon-noise changes a factor of a few at two ends of spectrum (0.5 – 1.7 um)

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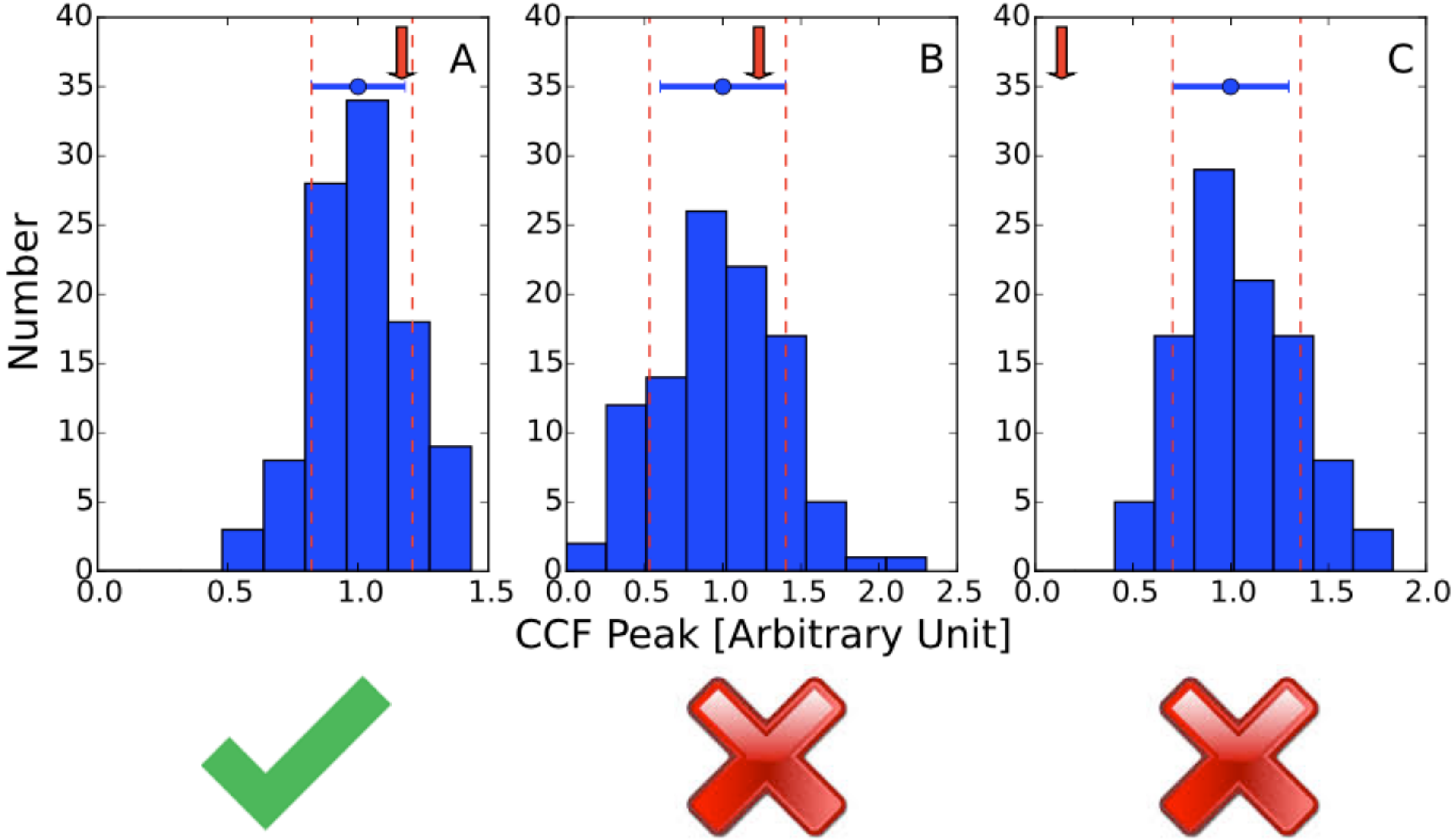
- Speckle chromatic noise

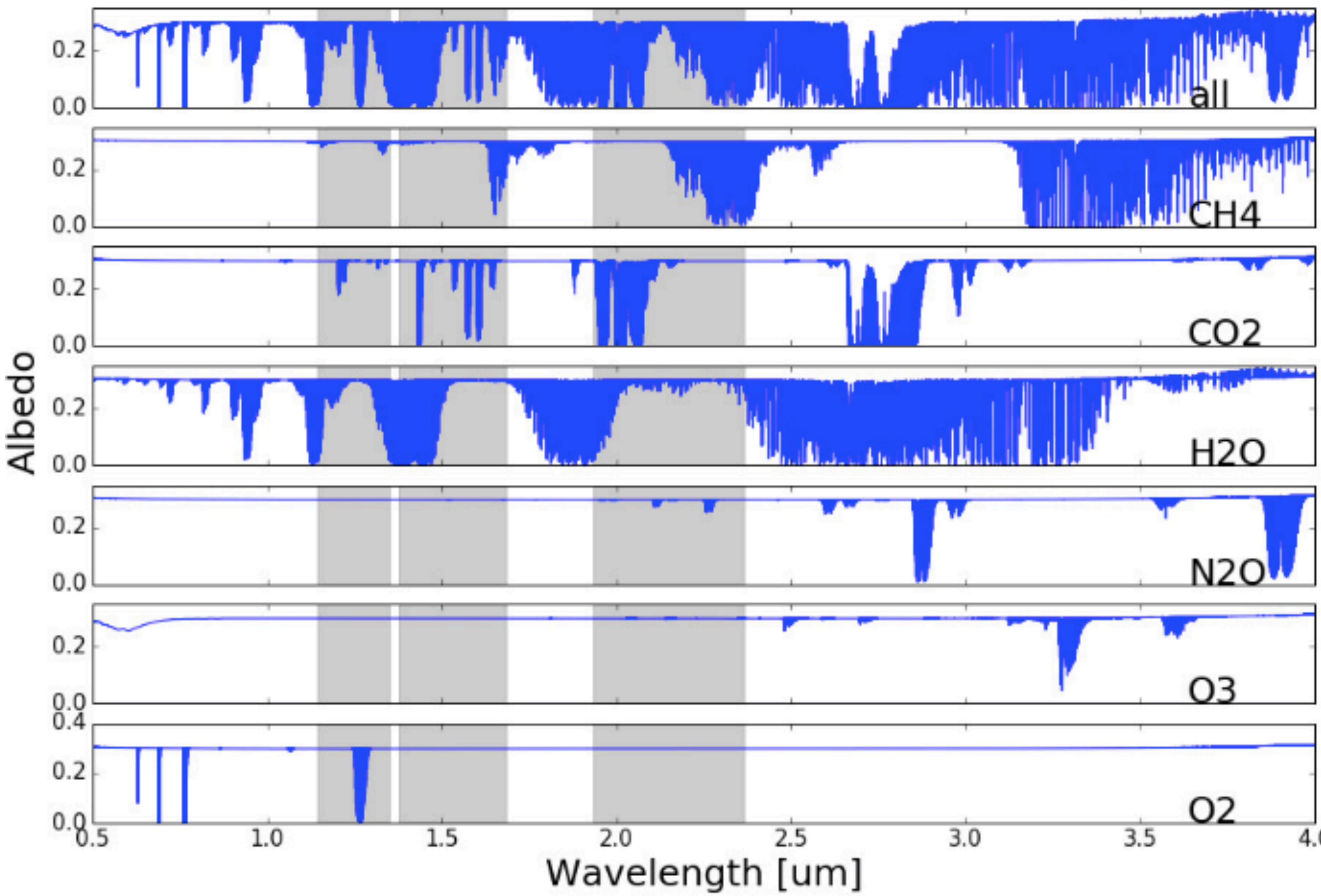
New Definition of CCF SNR

Red arrow – noiseless CCF peak

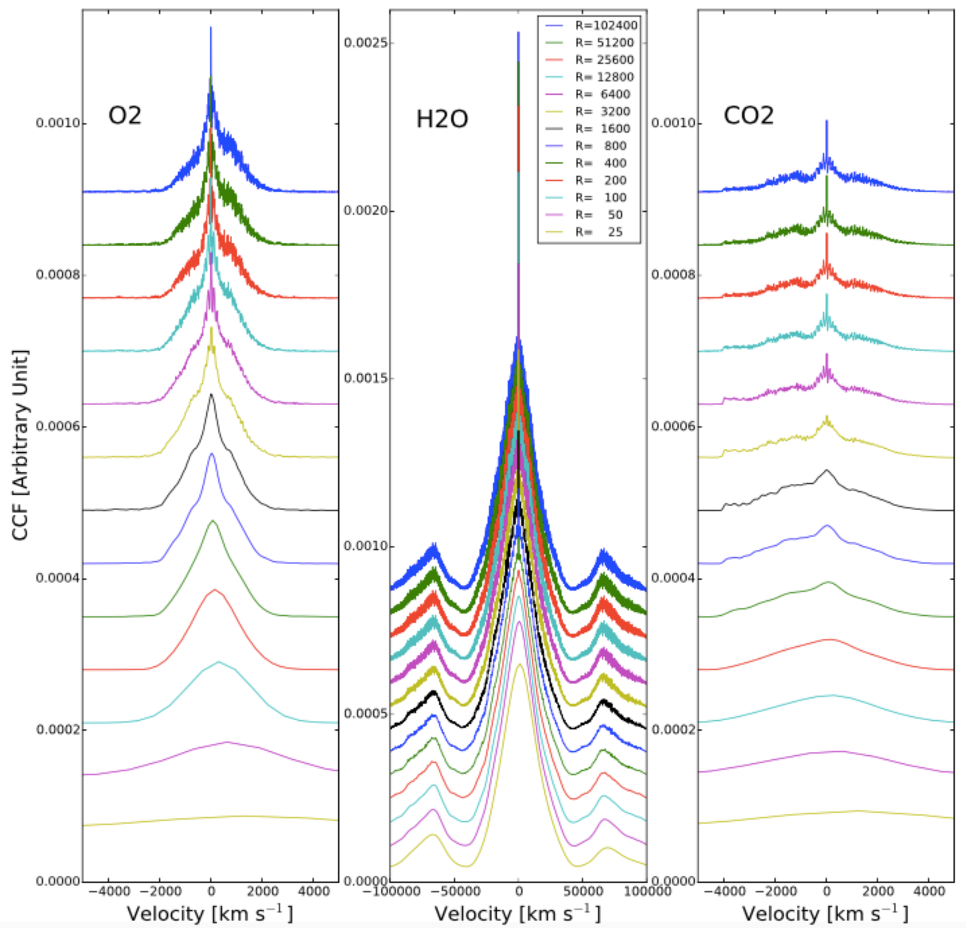
Blue error bar – median and 1-sigma range of simulated CCF peak distribution



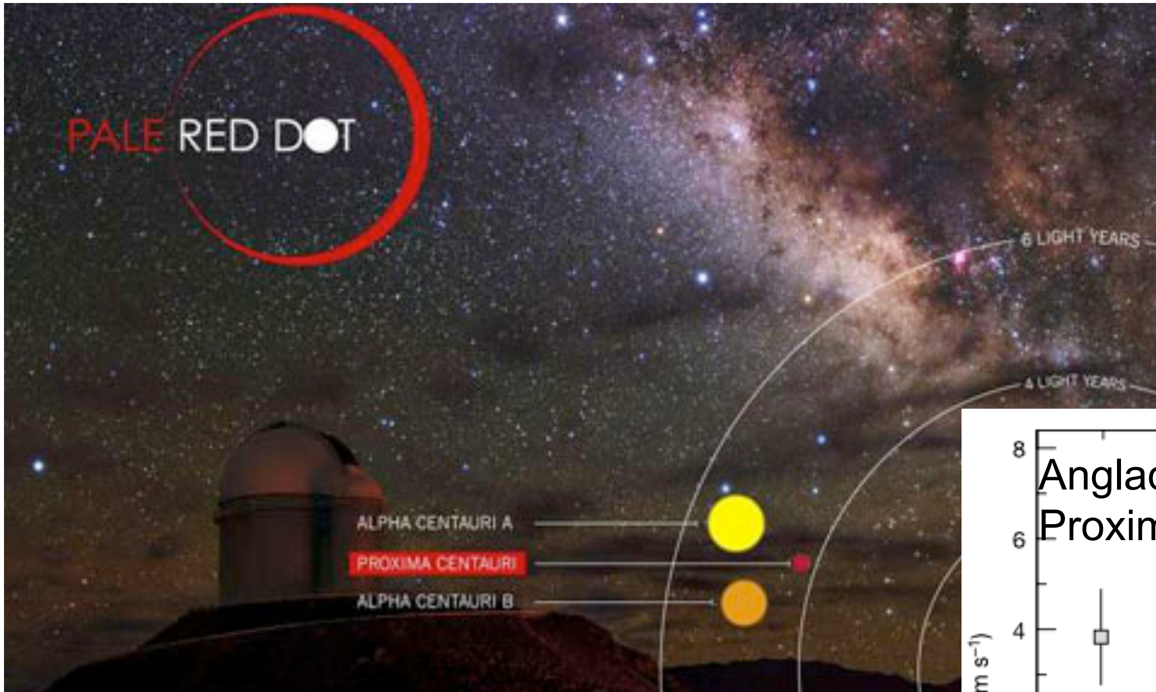
Absorption bands vs. lines

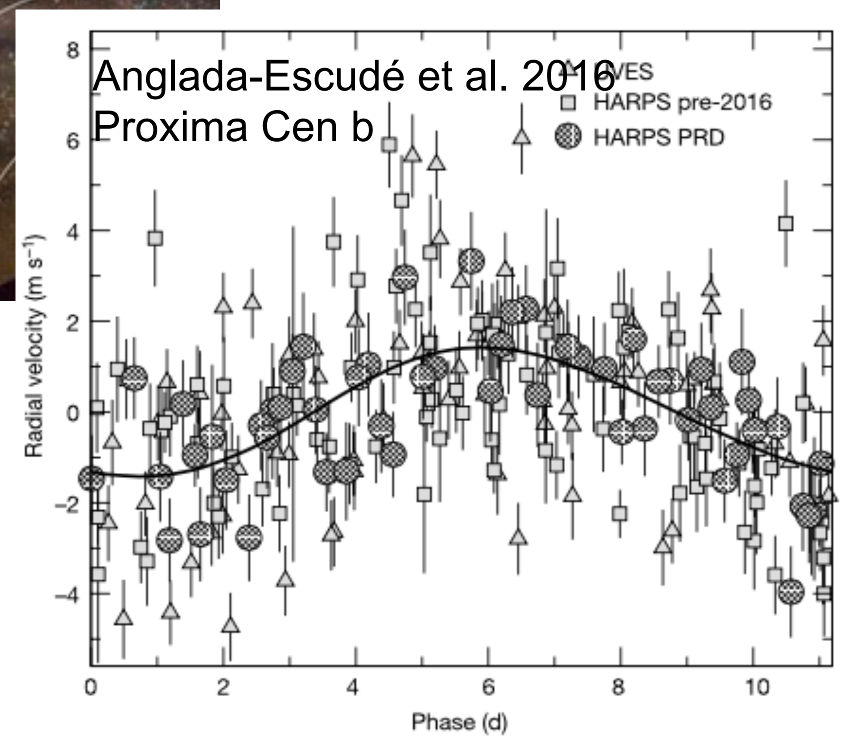


Absorption bands vs. lines



M Dwarf Planet “Frenzy”





Anglada-Escudé et al. 2016
Proxima Cen b

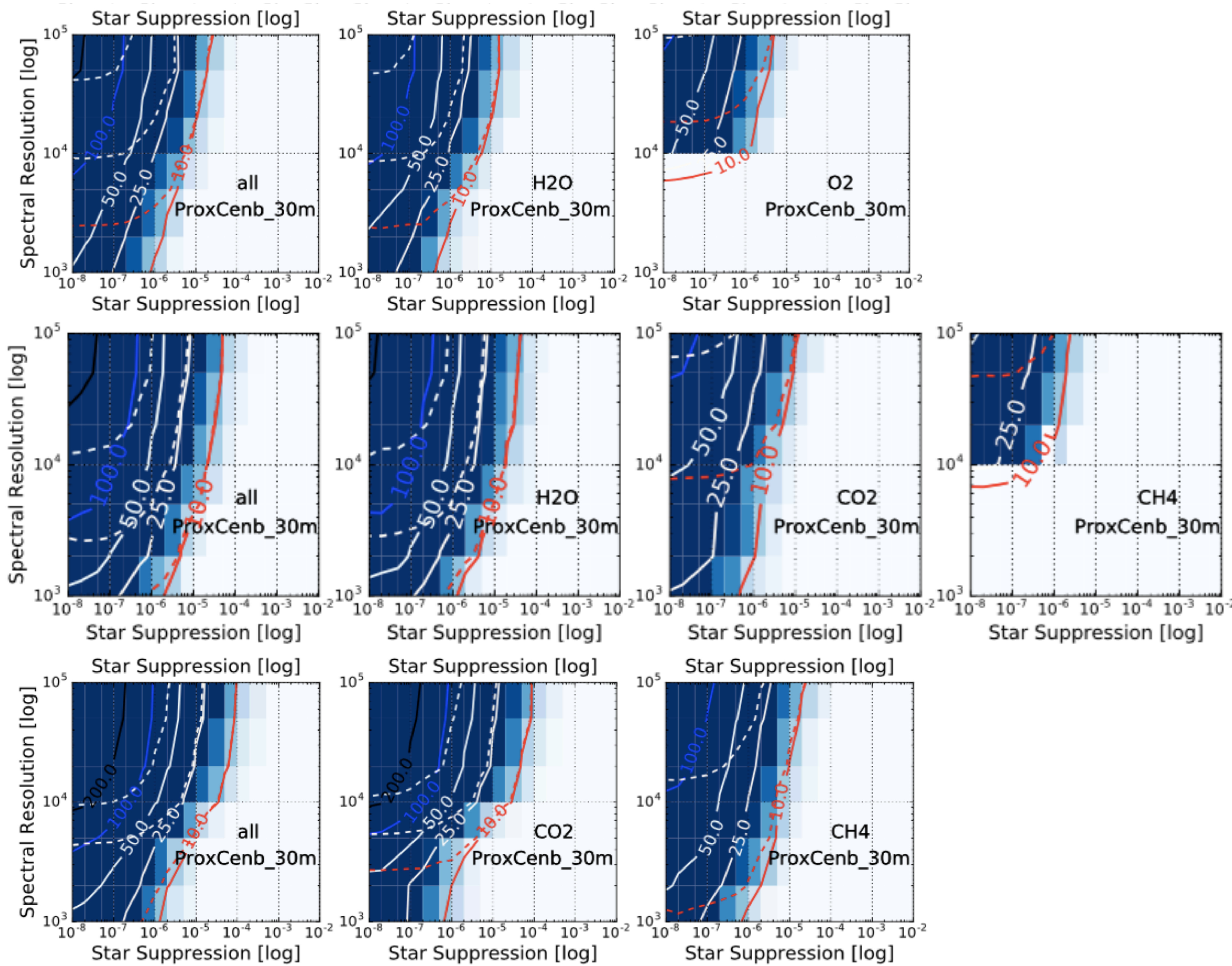
NIR HDC Observation of Prox Cen b with 30-m Class Telescopes

Parameter	Value	Unit
Telescope aperture	10.0 or 30.0	m
Telescope+instrument throughput	10%	...
Wavefront correction error floor	200	nm
Spectral resolution	varied	...
J band spectral range	1.143 - 1.375	μm
H band spectral range	1.413 - 1.808	μm
K band spectral range	1.996 - 2.382	μm
Exposure time	100	hour
Fiber angular diameter	1.0	λ/D
Readout noise	0.0 or 2.0	e^{-1*}
Dark current	0.0 or 0.002	e^{-1} s^{-1*}

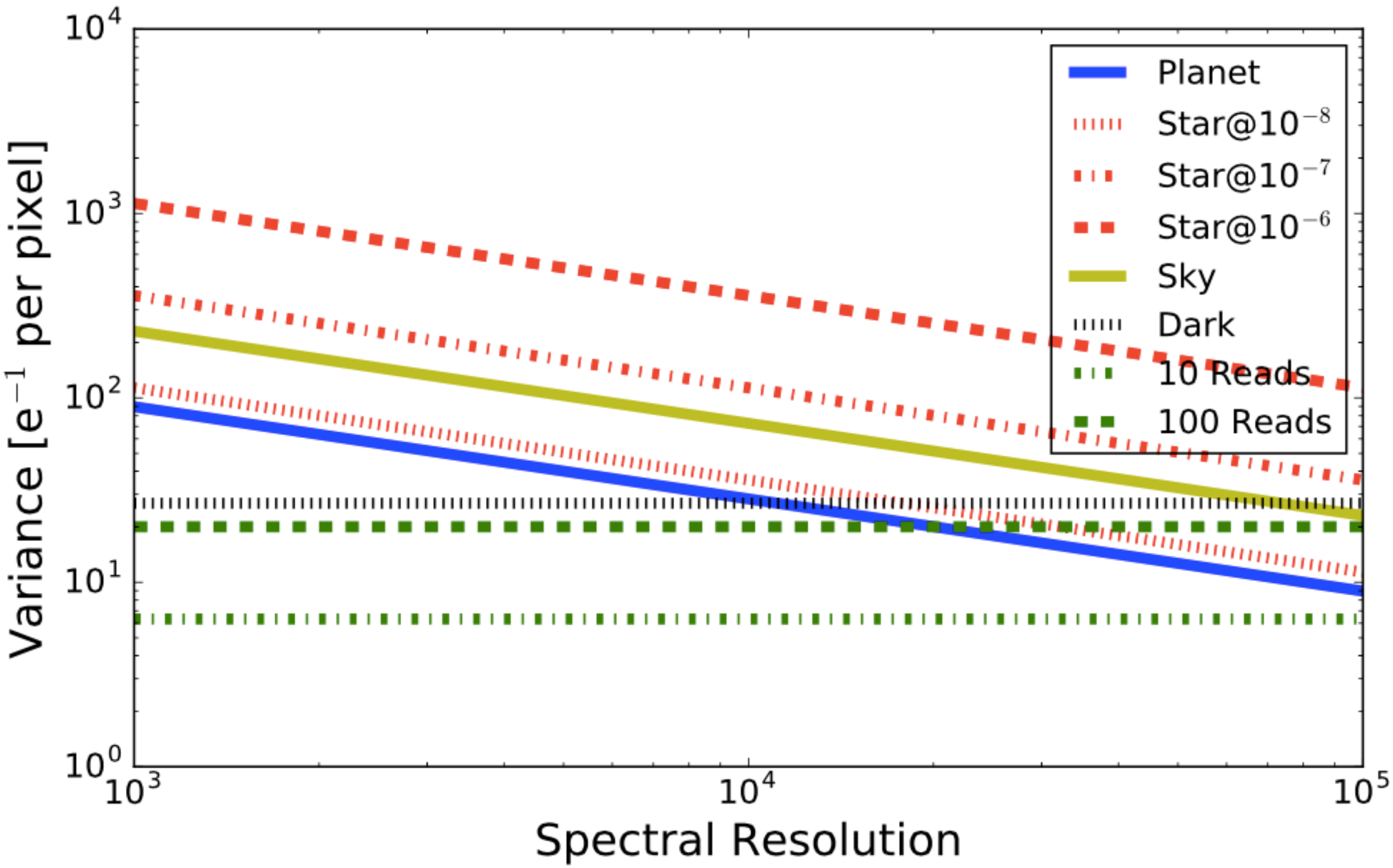
Note. — $*$: Based on H2RG detector specification (Blank et al. 2012)

Parameter	Value	Unit
Star		
Effective temperature** (T_{eff})	3050	K
Mass	0.12	$M_\odot$
Radius	0.14	$R_\odot$
Surface gravity ($\log g$)	5.0	cgs
Metallicity ([M/H])	0.0	dex
Distance	1.295	pc
Vsin i	<1	km s^{-1}
Inclination (i)	20	degree
Radial velocity	-22.4	km s^{-1}
Planet		
Effective temperature (T_{eff})	234	K
Vsin i**	0.014	km s^{-1}
Inclination (i)	20	degree
Semi-major axis (a)	0.05	AU
Radial velocity	22.2	km s^{-1}
Illuminated Area	0.5	...
Planet/Star Contrast	1.6×10^{-7}	...

Note. — $*$: All values are from Anglada-Escudé et al. (2016). We use 3000 K in simulation. $**$: We assume that the planet is tidally locked.


Star Suppression [log]
Spectral Resolution [log]
all
ProxCenb_30m
100.0
50.0
25.0
10.0
H2O
ProxCenb_30m
O2
ProxCenb_30m
CO2
ProxCenb_30m
CH4
ProxCenb_30m
200.0

Sources of Noise



Our order

- Small Red pie w/ Mozzarella
  - buffalo chicken, onion, garlic, green pepper
- Small Red pie w/ Mozzarella
  - shrimp, onion, garlic, broccoli, basil
- White pie w/ Mozzarella
  - mashed potato, bacon, onion