Jet Propulsion Laboratory
California Institute of Technology

AFTA Coronagraph Working Group Recommendation to Astrophysics Division

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December 13, 2013

Outline of Presentation

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Executive Summary

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- Hardcopy Trade Matrix

Purpose and Approach

- **Objective:** Recommend a primary and backup coronagraph architecture to focus design and technology development to maximize readiness for new mission start in FY17
- Recommendation by ExEPO and ASO based on inputs from
  - **AFTA SDT:** Sets the science requirements
  - **ACWG:** Delivers technical FOMs and technology plans
    - > *Aim for the positive: a consensus product*
    - > SDT delivers science FOMs
  - **TAC:** Analysis of technical FOM, TRL readiness plans, and risks
- **ExEPO and ASO** recommendation to **APD Director** based on:
  - Technical and Programmatic criteria
  - Musts (Requirements), Wants (Goals), and Risks
  - Opportunities
- **APD Director** will make the decision

ACWG = AFTA Coronagraph Working Group: representatives of ExEPO, ASO, SDT, Community

Acronyms:
ExEPO: Exoplanet Expl. Prog. Office
ASO: AFTA Study Office
SDT: Science Definition Team
FOM: Figure of Merit
TRL: Technology Readiness Level

TAC: Technical Analysis Committee
Alan Boss (Carnegie Inst.)
Joe Pitman (EXSCI)
Steve Ridgway (NOAO)
Lisa Poyneer (LLNL)
Ben Oppenheimer (AMNH)

ACWG: Broad Membership Ensures Success

AMES RESEARCH CENTER

NASA Goddard

THE OHIO STATE UNIVERSITY

JPL

PRINCETON UNIVERSITY

Lawrence Livermore National Laboratory

NExScI NASA Exoplanet Science Institute

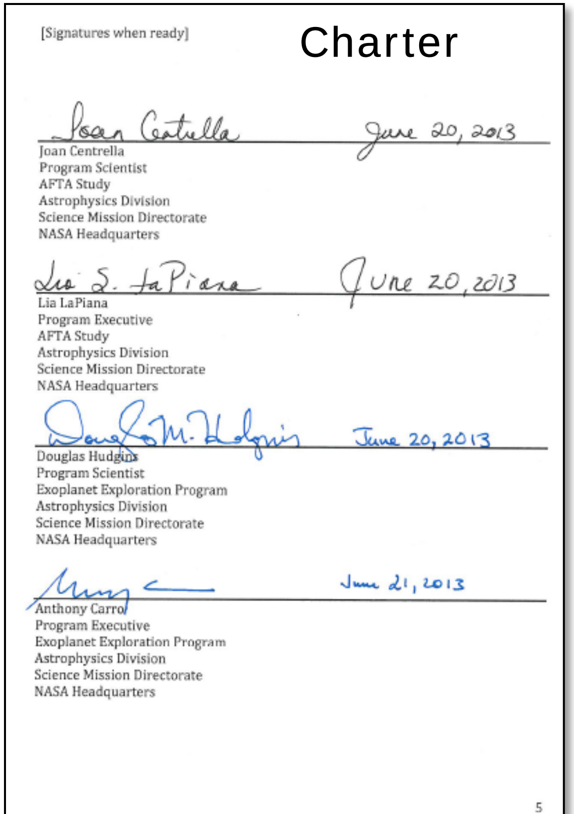
SPACE TELESCOPE SCIENCE INSTITUTE

The AFTA Coronagraph Working Group includes members from these organizations.

ACWG Membership

ExoPlanet Exploration Program

- These represent Program, Study Office, SDT, and Community: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Workshop Organizers:

Gary Blackwood (NASA JPL)
Kevin Grady (NASA GSFC)
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Steering Group:

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Neil Gehrels (NASA GSFC)
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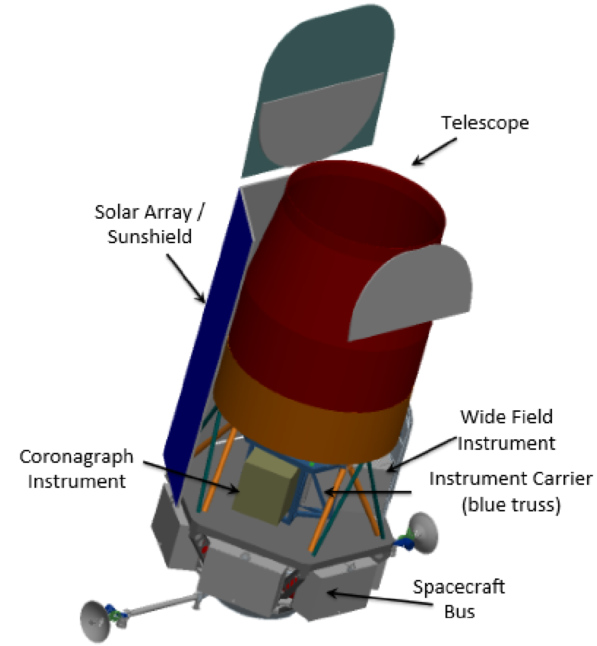
- Additional consultants participate at request of Steering Group; names listed in backup charts

Executive Summary

- **Intended Results of this Briefing:**
  - Provide Recommendation for Primary and Backup coronagraph architectures for AFTA
  - Request APD approval and announcement
- **Executive Summary:**
  - Community working group conducted an open, technical evaluation using public evaluation criteria in a series of workshops and telecons since July 2013
  - We reached a broad consensus on the basis for the recommendation
  - Three strong technologies emerged, spanning the risk/performance continuum
  - The independent Technical Analysis Committee (TAC) concurred with the basis and with findings of ACWG
  - Recommendation:
    - **Primary Architecture:** Occulting Mask Coronagraph (OMC) that includes masks for Shaped Pupil Coronagraph (SPC) and Hybrid Lyot Coronagraph (HLC)
    - **Backup Architecture:** Phase-Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)
  - Recommendation best minimizes risk, preserves options to protect the project schedule, advances technologies, and preserves possibilities of increased science yield
  - Plan for Recommendation to reach TRL 5 is feasible (technically) and credible within existing resources (schedule, cost)

AFTA-WFIRST

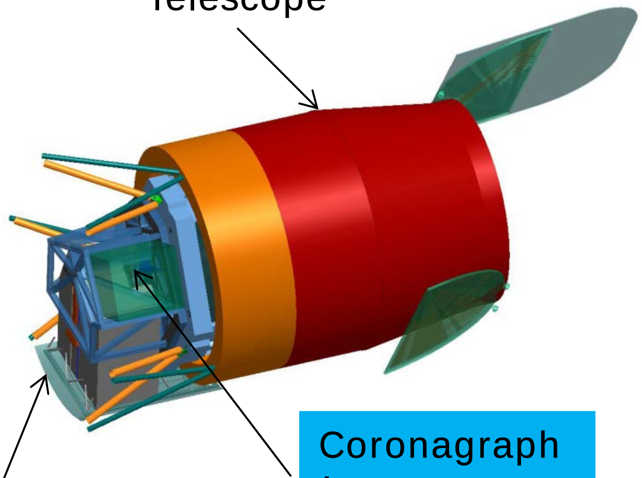
- 2.4m aperture on-axis obscured telescope, 270K
- 28.5 degree inclination geosynchronous orbit, Atlas V 541 launch vehicle
- Dedicated 18m Ka and S-band antenna in White Sands, NM. Ka-band downlink of 150 Mbps.
- Two-channel widefield instrument with IFU channel 0.6 to 2.0 um for Dark Energy, NIR Surveys, and Exoplanet Microlensing
  - FPA: 6x3 4kx4k HgCdTe detectors, 0.76 to 2.0 um
- Coronagraph instrument for Exoplanet Direct Imaging and Characterization
- The small PSF of the asset telescope enables coronagraphy
- Mission life 6 years with coronagraph



WFIRST final report May 23, 2013
http://wfirst.gsfc.nasa.gov/

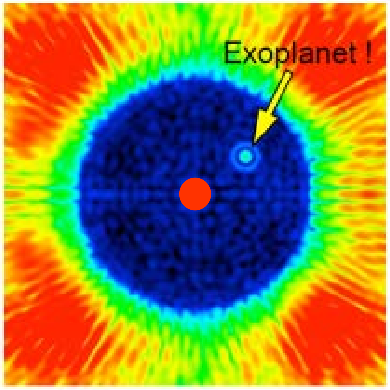
AFTA Coronagraph Instrument

Telescope

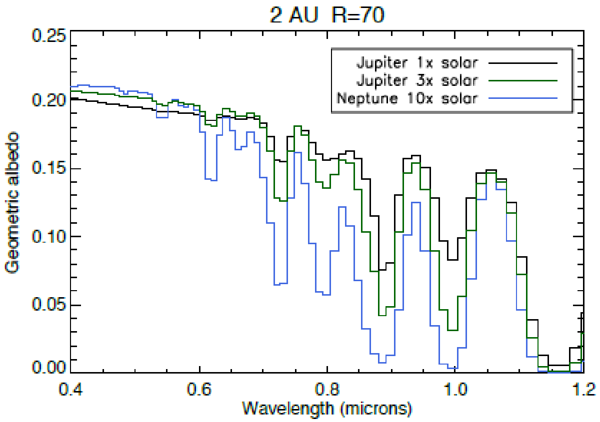


Wide field instrument

Coronagraph Instrument



Exoplanet Direct imaging



Exoplanet Spectroscopy

Bandpass	400-1000 nm	Measured sequentially in five 18% bands
Inner Working Angle	100 mas	at 400 nm, 3 λ/D driven by challenging pupil
	250 mas	at 1 um
Outer Working Angle	1 arcsec	at 400 nm, limited by 64x64 DM
	2.5 arcsec	at 1 um
Detection Limit	Contrast $=10^{-9}$	Cold Jupiters, not exo-earths. Deeper contrast looks unlikely due to pupil shape and extrememe stability requirements.
Spectral Resolution	70	With IFS, ~70 across the spectrum.
IFS Spatial Sampling	17 mas	This is Nyquist for λ400 nm.

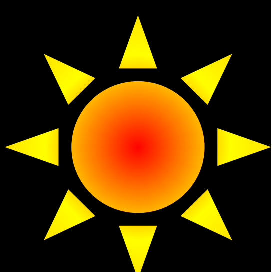
WFIRST final report May 23, 2013
http://wfirst.gsfc.nasa.gov/

AFTA Coronagraph Instrument will:

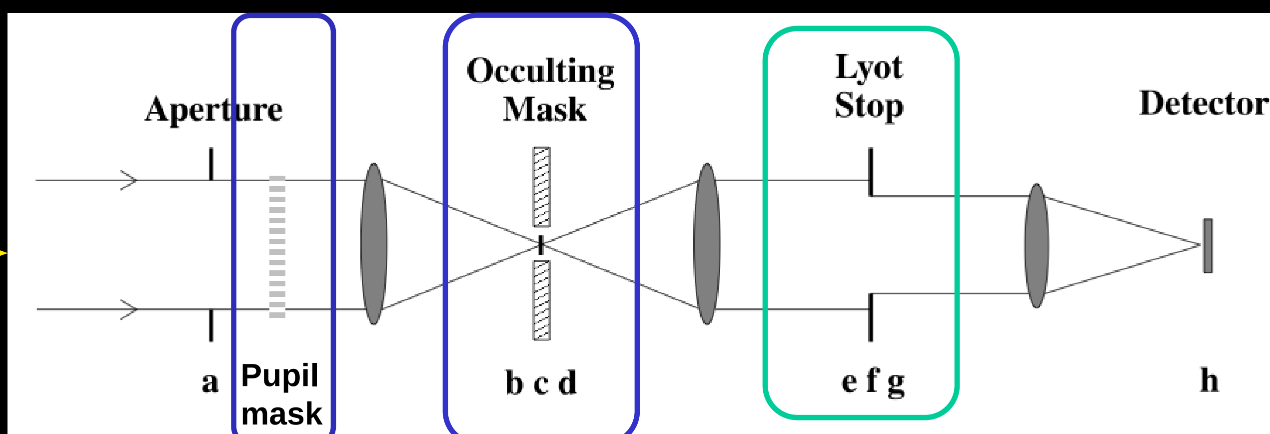
- Characterize the spectra of over a dozen radial velocity planets.
- Discover and characterize up to a dozen more ice and gas giants.
- Provide crucial information on the physics of planetary atmospheres and clues to planet formation.
- Respond to decadal survey to mature coronagraph technologies, leading to first images of a nearby Earth.

Diffraction control used to selectively reject starlight

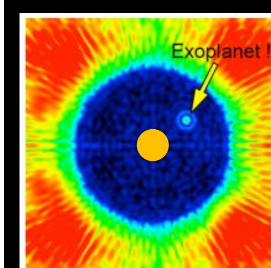
- A diffractive optic is used to remove star-light from the field of view, while allowing the planet light to be detected
  - A fixed optic (does not move)
    - e.g. an image plane mask in a coronagraph, or the occulter of an external coronagraph
  - Mathematically may have perfect performance
  - In practice may have subtle imperfections
  - Creates "dark hole" between Inner and Outer Working Angles (IWA, OWA)
- Concepts in Fourier Optics provide a wide variety of possible solutions



Diffraction Pattern Of Stellar Point Source



Sivaramakrishnan et al. ApJ 552, 397 (2001)



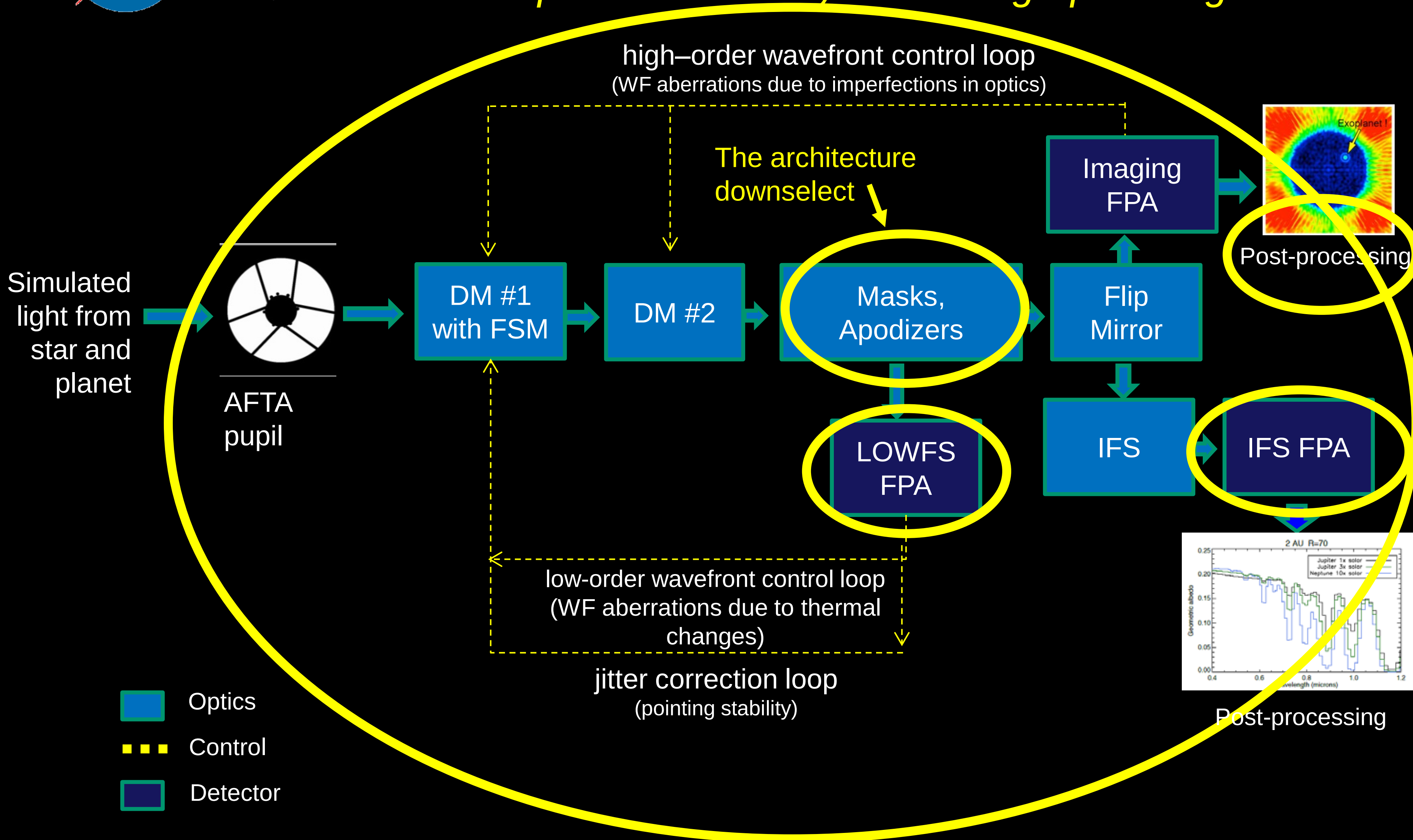
"Dark Hole" Between IWA and OWA

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Coronagraph Instrument: Several Technologies

Example: Classical Lyot Coronagraph Design



Trade Approach for ACWG

- Adapted from Kepner-Tregoe methods. The Rational Manager, Kepner and Trego, 1965
- A systematic approach for decision making

				Option 1		Option 2		Option 3	
Decision Statement									
Description	*Feature 1*								
	Feature 2								
	Feature 3								
Evaluation	**Musts**								
	M1			✓		✓		✓	
	M2			✓		?		?	
	M3			✓		✓		✗	
	Wants	*Weights*							
	W1	*w1%*		*Rel score*		*Rel score*			
	W2	*w2%*		*Rel score*		*Rel score*			
	W3	*w3%*		*Rel score*		*Rel score*			
		100%	Wt sum =>	*Score 1*		*Score 2*			
	Risks			C	L	C	L	C	L
	Risk 1			M	L	M	L		
	Risk 2			H	H	M	M		
Final Decision, Accounting for Risks									

C = Consequence, L = Likelihood

Trade Criteria: Defining a Successful Outcome

DECISION STATEMENT: Recommend a primary and backup coronagraph architecture (option) to focus design and technology investments

MUSTS (Requirements): ***Go/No_Go***

1. Science: Does the proposed architecture meet the threshold science drivers?
2. Interfaces: For the threshold science, does the architecture meet telescope and spacecraft requirements of the observatory as specified by the AFTA project (DCIL[1])
3. Technology Readiness Level (TRL) Gates: For threshold science, is there a credible plan to be at TRL5 at start of FY17 and at TRL6 at start of FY19 within available resources?
4. Is the option ready in time for this selection process?
5. Is the architecture applicable to future earth-characterization missions (no showstoppers)?

WANTS (Goals): ***Relative to each other, for those that pass the Musts:***

1. Science: Relative strength of science beyond the threshold
2. Technical: Relative technical criteria
   - See details
3. Programmatic: Relative cost of plan to meet TRL Gates

RISKS and OPPORTUNITIES – scored as H,M,L

[1]DCIL = Dave Content Interface List

Evaluation Criteria:
Defining a Successful Outcome for AFTA

ExoPlanet Exploration Program

Decision Statement: Recommend one Primary and one Backup coronagraph *architecture* (option) to focus design and technology development

Descr	Name			Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
				SPC	PIAACMC	HLC	VVC	VNC - DA	VNC - PO
Musts		Programmatic							
	M1 - T	Science: Meet Threshold requirements? (1.6, x10)							
	M2	Interfaces: Meets the DCIL**?							
	M3	TRL Gates: For baseline science is there a credible plan to meet TRL5 at start of FY17 and TRL6 at start of FY19 within available resources?							
	M4	Ready for 11/21 TAC briefing							
	M5	Architecture applicable to future earth-characterization missions							

Legend: ✓ yes, or expected likely; ? unknown; ✕ no, or expected showstopper

Evaluation		Wants	Weights	SPC	PIAACMC	HLC	VVC	VNC-DA	VNC - PO
	W1	Science	40						
	a	Relative Science yield (1.6, x10) beyond M1-T							
	W2	Technical	30						
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability							
	b	Relative sensitivities of post-processing to low order aberrations							
	c	Demonstrated Performance in 10% Light							
	d	Relative complexity of design							
	e	Relative difficulty in alignment, calibration, ops							
	W3	Programmatic	30						
	a	Relative Cost of plans to meet TRL gates							
		Wt. sum =>	100%						

Identify "Best" and others are:
-Wash
-Small Difference
-Significant Difference
-Very Large Difference

Risks		(all judged to be Hgh consequence)	SPC C	SPC L	PIAACMC C	PIAACMC L	HLC C	HLC L	VVC C	VVC L	VNC-DA C	VNC-DA L	VNC - PO C	VNC - PO L
	Risk 1	Technical risk in meeting TRL5 gate												
	Risk 2	Schedule or Cost risk in meeting TRL5 Gate												
	Risk 3	Schedule or Cost risk in meeting TRL6 Gate												
	Risk 4	Risk of not meeting at least threshold science												
	Risk 5	Risk of mnfr tolerances not meeting BL science												
	Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt												
	Risk 7	Risk that wrong architecture is chosen due to any assumption made for practicality/simplicity												
	Risk 8	Risk that ACWG simulations (by JK and BM) overestimate the science yield due to model fidelity												

Legend: H M L

Opportunities		(judged to be High benefit)	SPC B	SPC L	PIAACMC B	PIAACMC L	HLC B	HLC L	VVC B	VVC L	VNC-DA B	VNC-DA L	VNC - PO B	VNC - PO L
	Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30												

Legend: H M L

Final Decision, Accounting for Risks and Opportunities:

C = Consequence, L = Likelihood, B=Benefit
**DCIL = Dave C C = Consequence, L = Likelihood, B=Benefit

Indicates Sig. Discriminator

Science Threshold

Science Beyond Threshold

Where is Science Considered?

Where is Technology Plan and Risk Considered?

Risk of not meeting Threshold

Oppty: Science if Jitter lower, Speckle subtraction better

Criteria: Wants

Evaluation

Wants			Weights
	W1	**Science**	**40**
	a	Relative Science yield (1.6, x10) beyond M1-T	
	W2	**Technical**	**30**
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability	
	b	Relative sensitivities of post-processing to low order aberrations	
	c	Demonstrated Performance in 10% Light	
	d	Relative complexity of design	
	e	Relative difficulty in alignment, calibration, ops	
	W3	**Programmatic**	**30**
	a	Relative Cost of plans to meet TRL gates	
		Wt. sum =>	100%

- Relative Science yield beyond the threshold "Must"
- Post processing algorithms required to remove dark hole speckles, and degree of speckles sensitivity to optical low-order aberrations (static and dynamic). How sensitive are the dark holes of the technologies to these aberrations?
- Demonstrated performance in 10% light: what has been accomplished through investments to date?

Criteria: Risks and Opportunities

Risks	(all judged to be Hgh consequence)	
	Risk 1	Technical risk in meeting TRL5 gate
	Risk 2	Schedule or Cost risk in meeting TRL5 Gate
	Risk 3	Schedule or Cost risk in meeting TRL6 Gate
	Risk 4	Risk of not meeting at least threshold science
	Risk 5	Risk of mnfr tolerances not meeting BL science
	Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt
	Risk 7	Risk that wrong architecture is chosen due to any assumption made for practicality/simplicity
	Risk 8	Risk that ACWG simulations (by JK and BM) overestimate the science yield due to model fidelity
Opportunities	(judged to be High benefit)	
	Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30

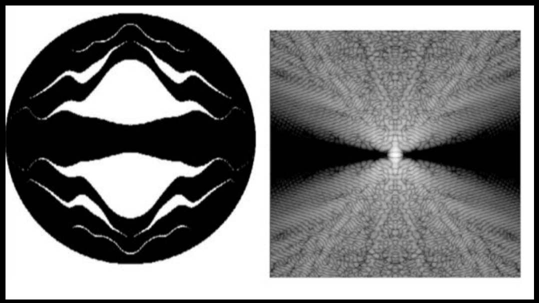
- Risks account for uncertainties in the prior evaluations:
  - In the Musts: credible plan, threshold science
  - In the Wants: the relative cost, the science beyond the Must)
- Also considered any parameters in the decision matrix to which the trade evaluations may be sensitive (e.g., jitter)
- Opportunity: considers improved science yield if the actual jitter is lower, and speckle subtraction is better

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Coronagraph Mask Architectures

SPC



Pupil Masking (Kasdin, Princeton University)

HLC

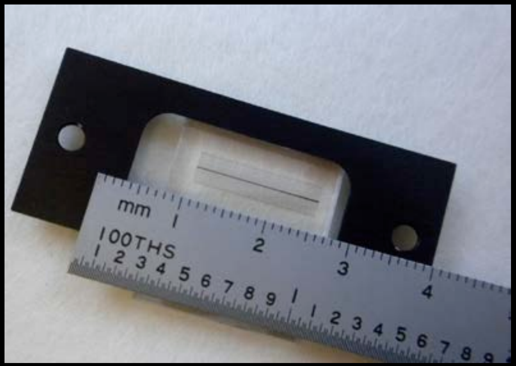
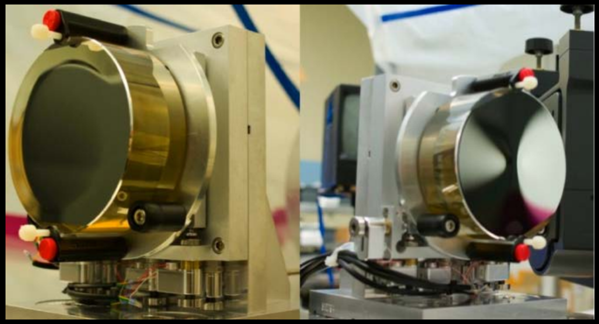


Image Plane Amplitude & Phase Mask (Trauger, JPL)

PIAACMC



Pupil Mapping
(Guyon, Univ. Arizona)

VVC

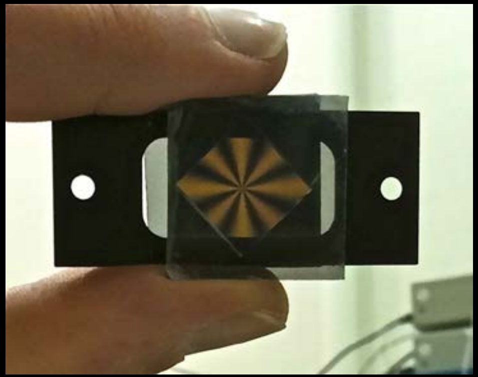
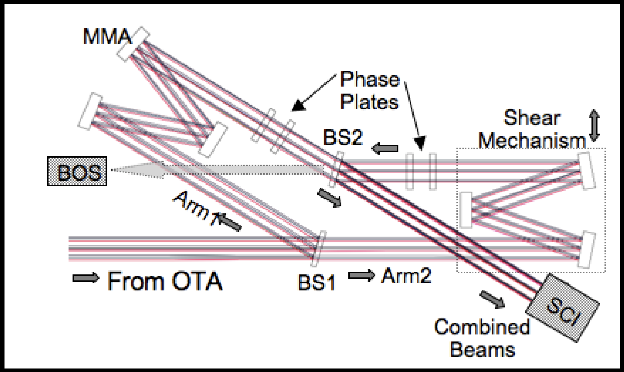


Image Plane
Phase Mask (Serabyn, JPL)

VNC(2) - DAVINCI

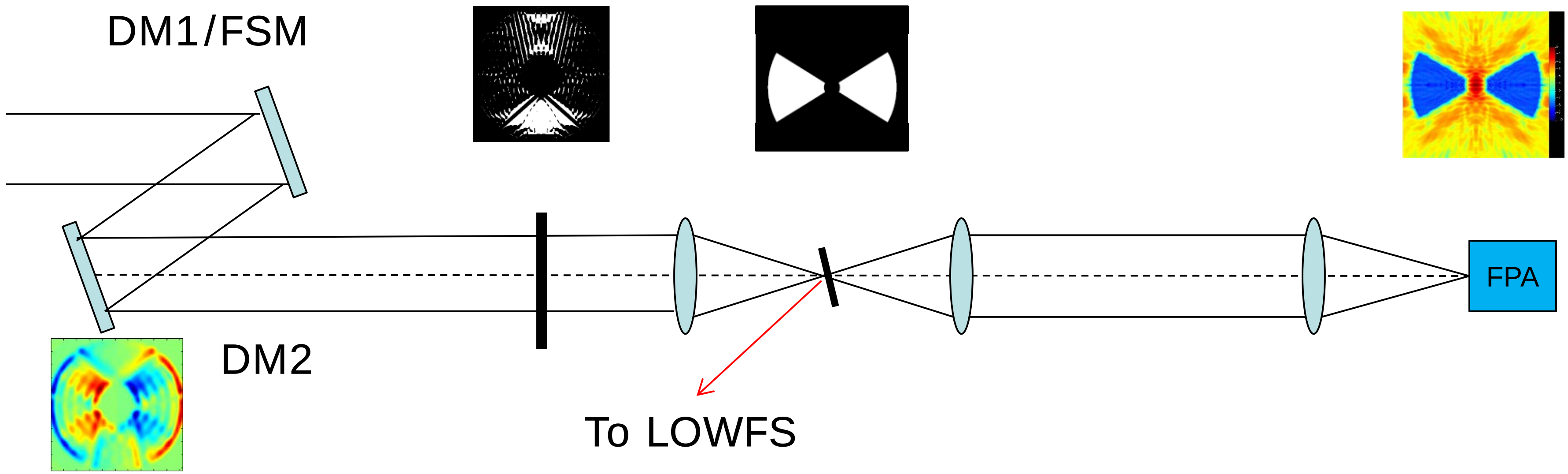
Visible Nulller - DAVINCI
(Shao, JPL)

VNC-PO



Visible Nuller – Phase Occulting
(Clampin, NASA GSFC)

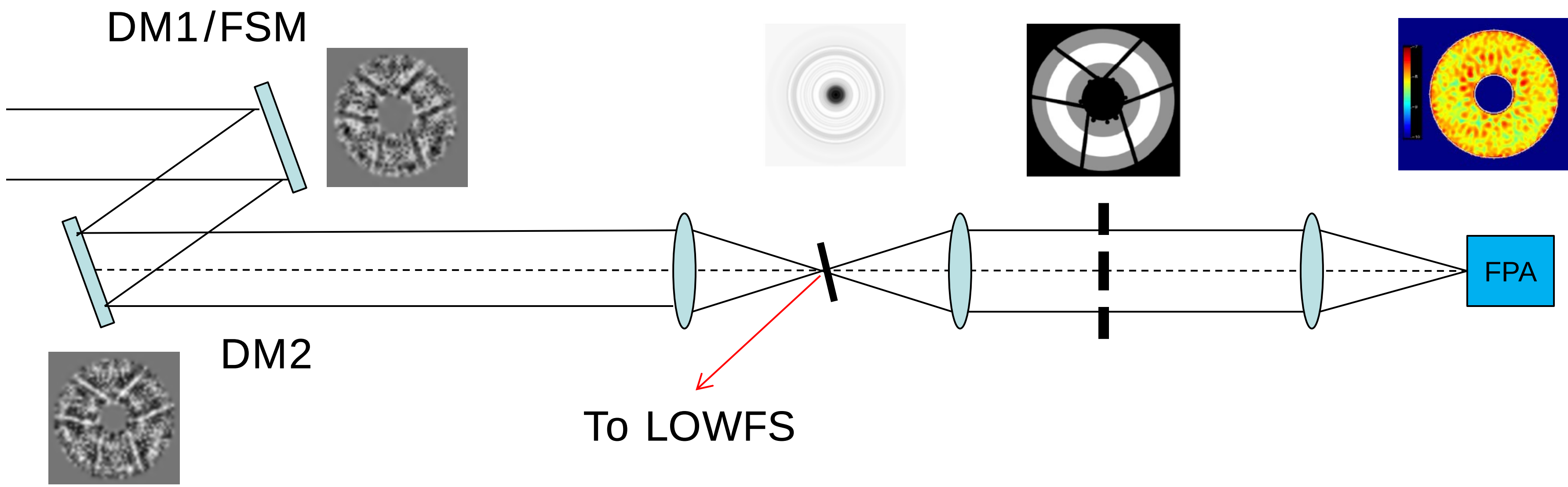
Shaped Pupil



DM1, DM2	Pupil mapping	Apodizer mask	Focal plane mask	Lyot stop	Inverse pupil mapping
Mild ACAD on both DMs		Binary reflection on filter wheels	Binary transmission, on filter wheel		

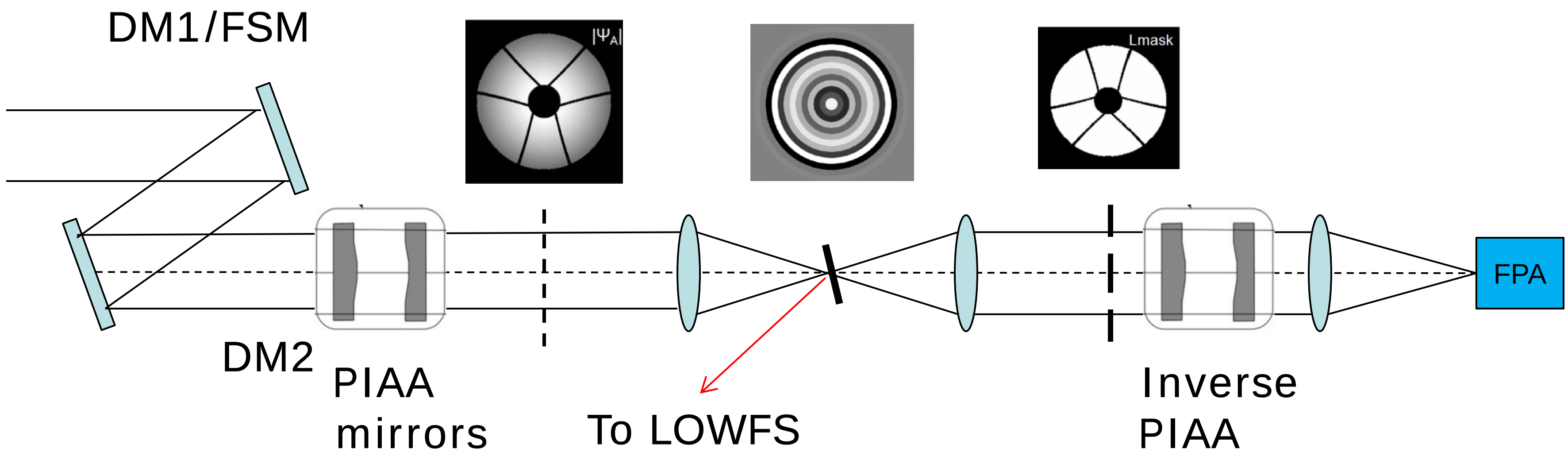
ACAD: Adaptive Correction of Aperture Discontinuities

Hybrid Lyot



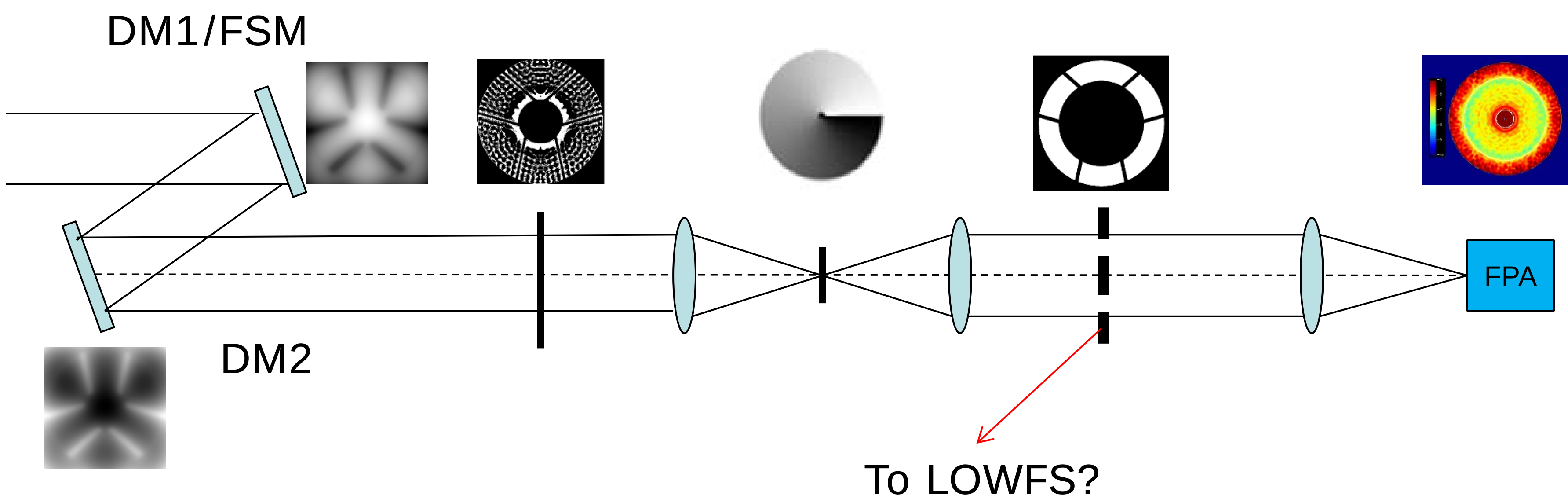
DM1, DM2	Pupil mapping	Apodizer mask	Occulting mask	Lyot stop	Inverse pupil mapping
Mild ACAD on both DMs	X	X	Complex transmission, on filter wheel	Transmission, grey, fixed	X

PIAA - CMC



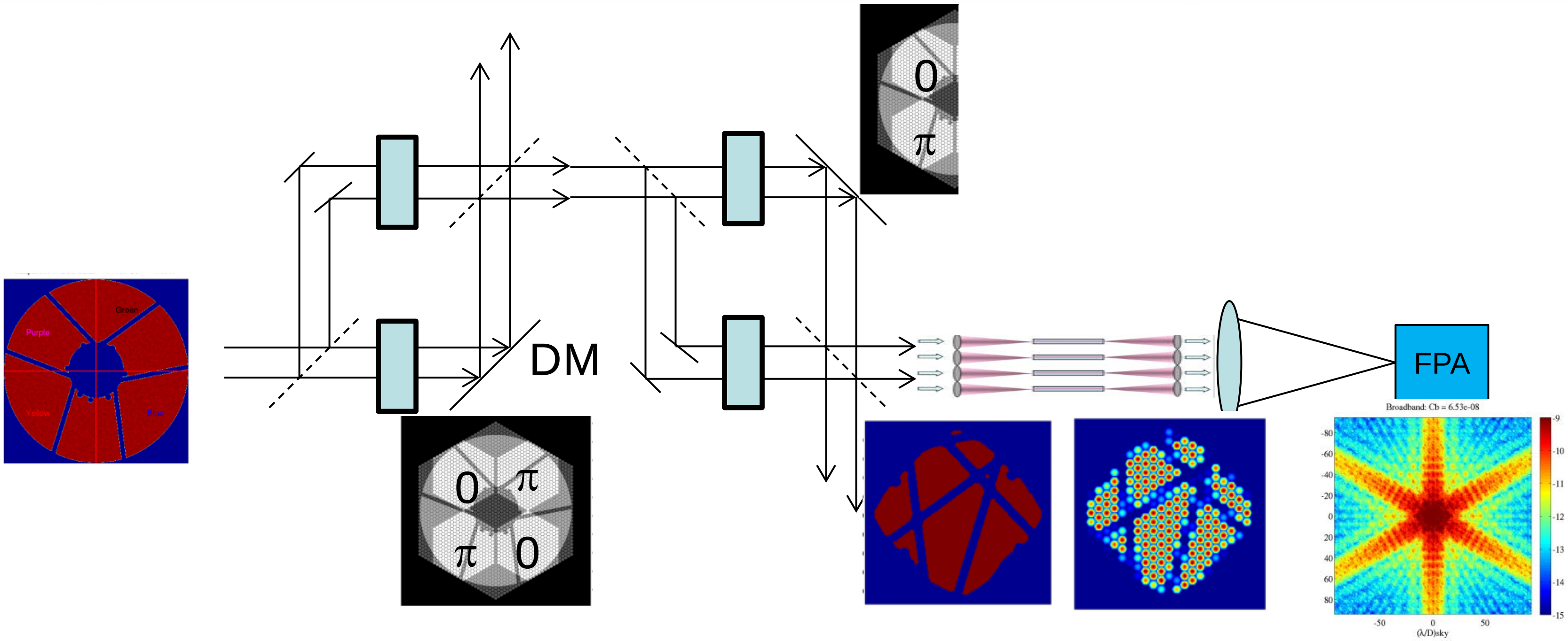
DM1, DM2	Pupil mapping	Apodizer mask	Occulting mask	Lyot stop	Inverse pupil mapping
Medium ACAD on both DMs	PIAA mirrors	Gray scale, filer wheels?	Phase transmission, on filter wheel	Transmission, binary, fixed?	Inverse PIAA mirrors

Vector Vortex



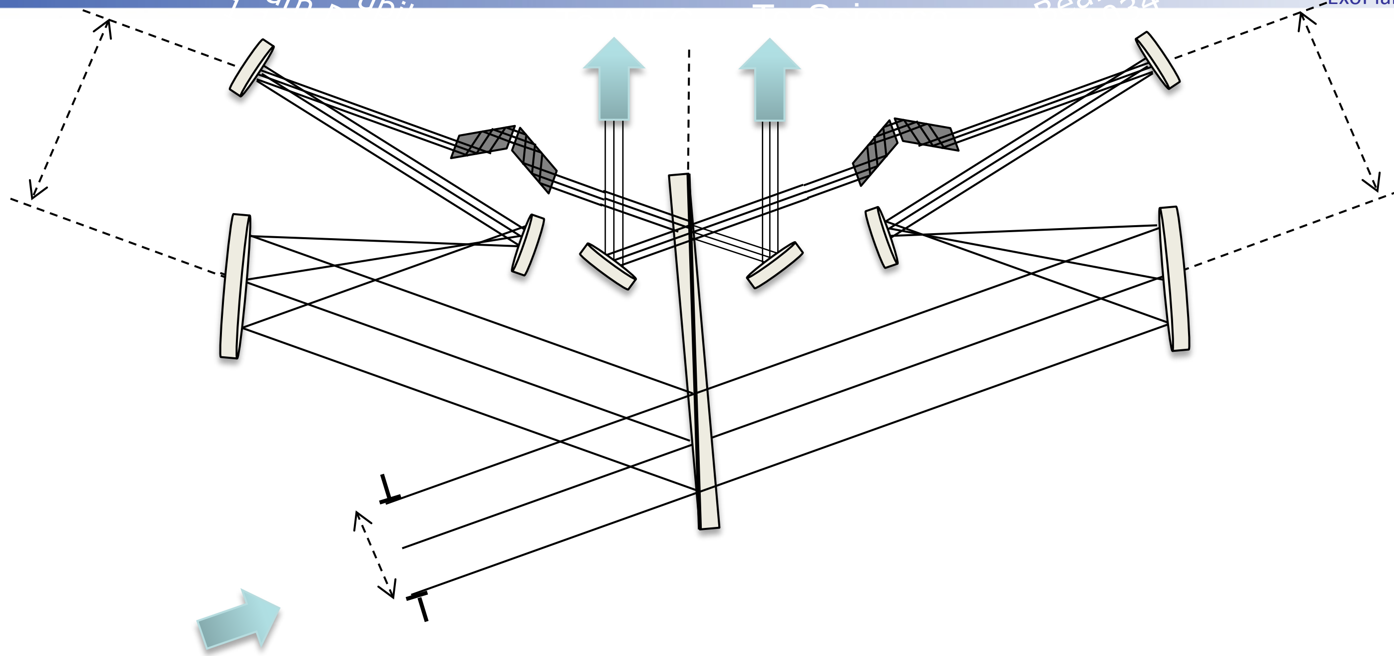
DM1, DM2	Pupil mapping	Apodizer mask	Focal plane mask	Lyot stop	Inverse pupil mapping
Strong ACAD on both DMs	X	Binary transmission, on filter wheel	Vortex transmission, on filter wheel	Transmission, binary, fixed	X

VNC-DaVinci



Interferometer	WFC
2 stage nulling interferometers	One DM (4 quadrants) for both phase and amplitude control
Diluted aperture (4X)	Lyot stop mask (binary, transmission, fixed)
Achromatic phase shifters	Fiber bundle spatial filters
Delay line to adjust OPD	

AFTA: Phase-Occulted VNC Nulling Schematic

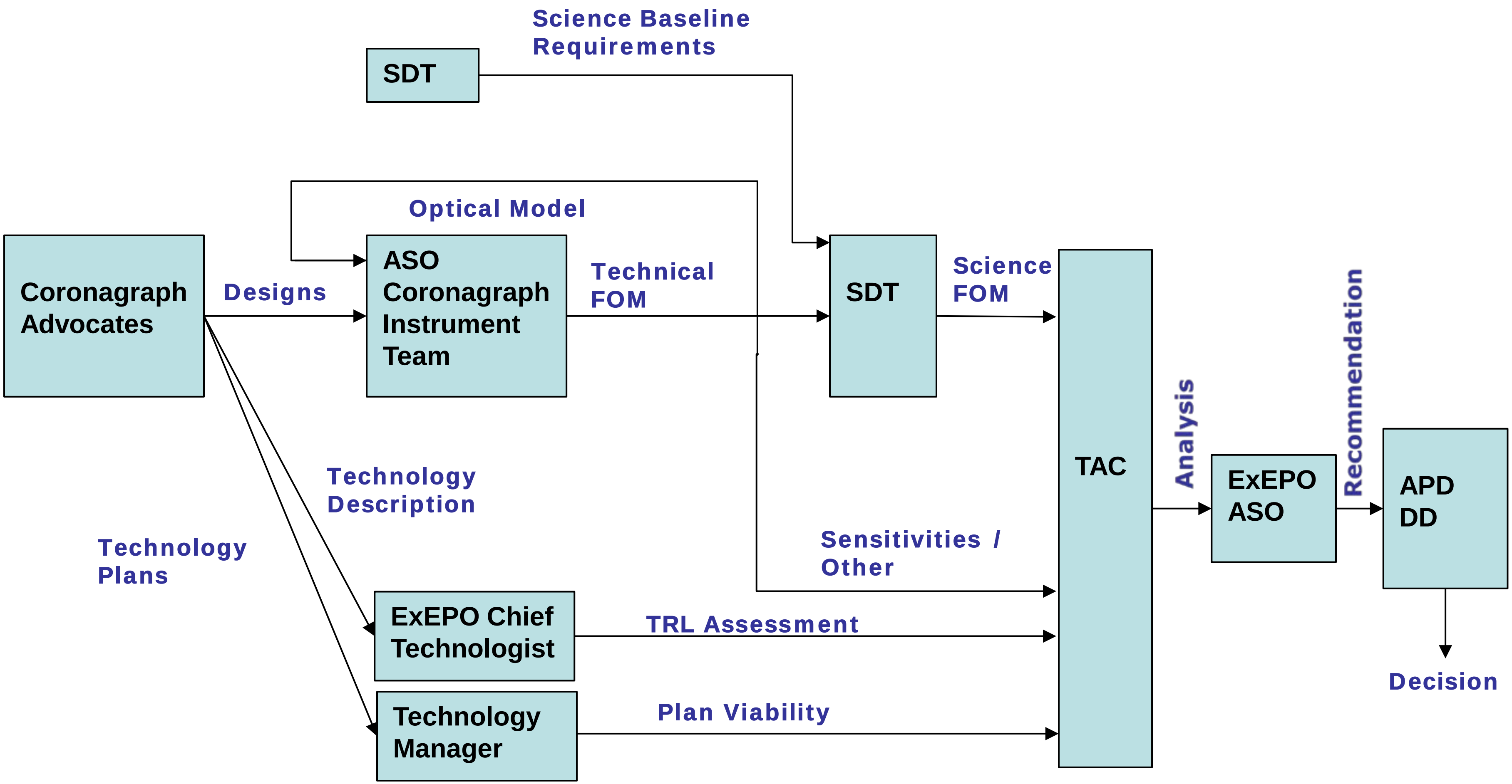


Interferometer	WFC
1 stage nulling interferometer	Two DMs for both phase and amp
Full aperture (radial shear)	Lyot stop?
Achromatic phase shifters*	
Delay line to adjust OPD	

Evaluation Method

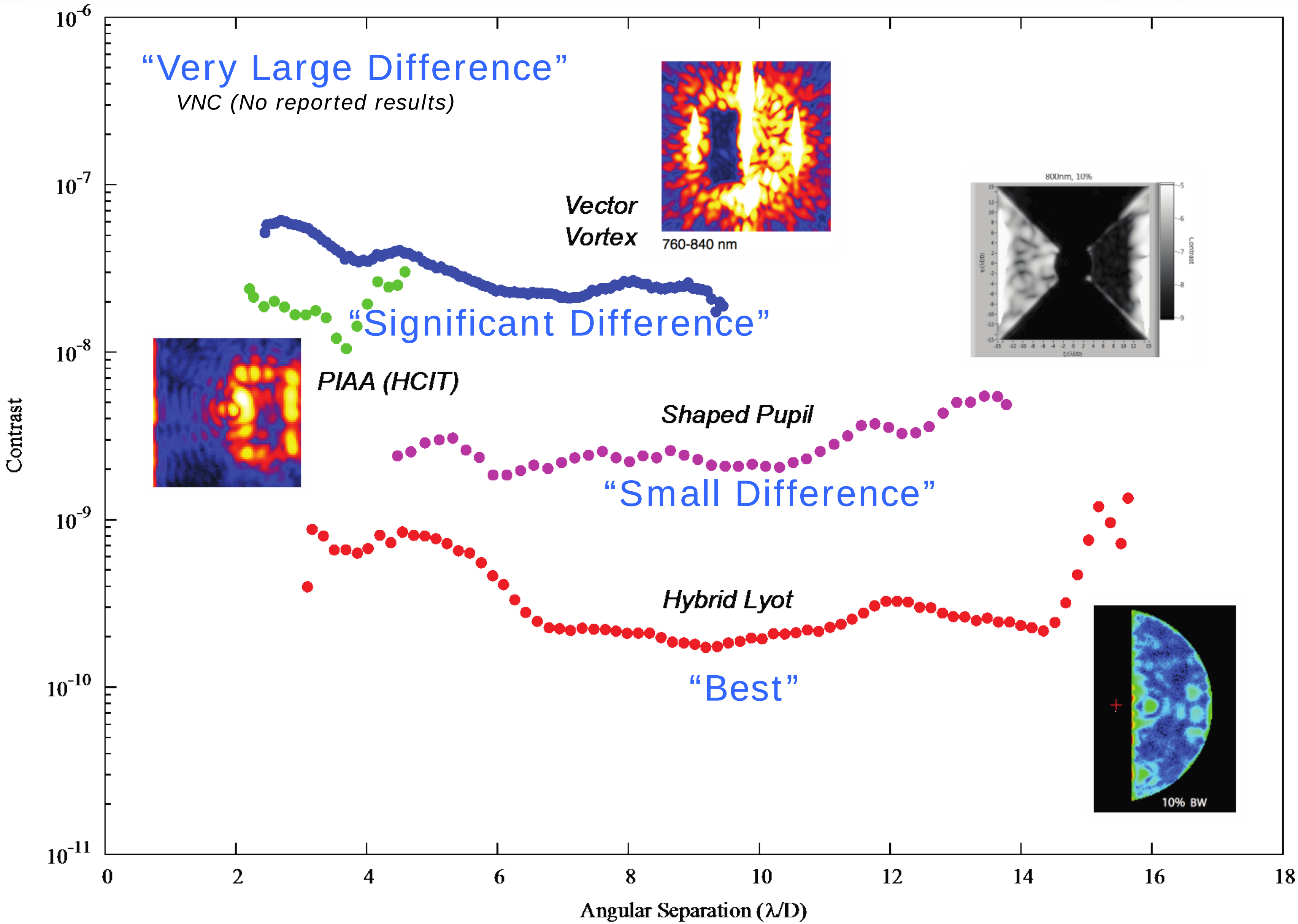
- Advocates asked to provide a mask design for AFTA pupil with certain assumptions, of which the residual jitter was primary discussion:
  - Telescope (DCIL) expected 14mas RMS per axis, > 2Hz
  - Low Order Wavefront Sensing and Control (LOWFSC) inside coronagraph intended to attenuate jitter; conservative value for residual jitter of 1.6mas adopted based on heritage demonstrations
    - Residual jitter limits the dark hole contrast (and hence science yield)
    - Coronagraphs prefer a lower number (~0.2 mas)
  - Designs submitted for 1.6mas assumption; science yield evaluated
  - A simple "opportunity" evaluation (d_science/d_jitter) was evaluated for 0.2mas jitter.
    - Time for downselect prohibited a second mask optimization cycle
    - The opportunity evaluation was considered suggestive of the gain in yield that could be obtained in later design cycles
- We checked constantly with the SDT for science guidance and with the AFTA study office for engineering realism.

ACWG Work Flow Leading to Recommendation



FOM = Figure of Merit
ASO = AFTA Study Office
ExEPO = Exoplanet Exploration Program Office

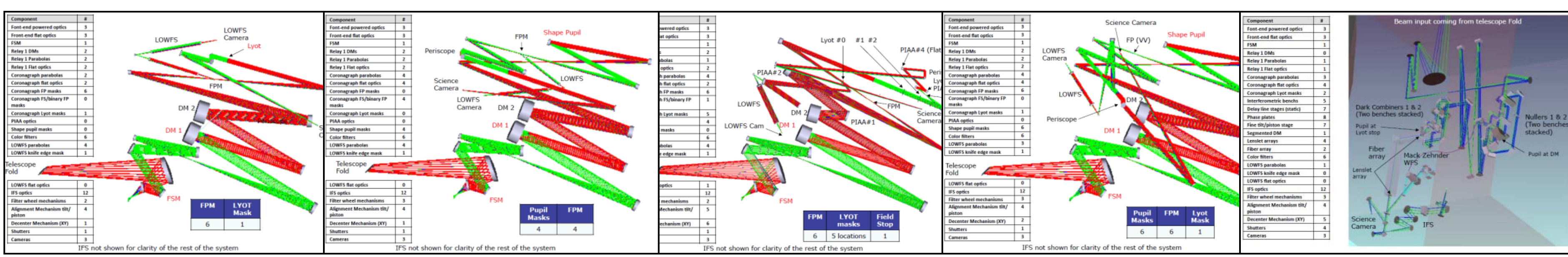
10% Bandwidth Results and Relative Assessment using an un-obscured pupil



TFOM (Technical Figures of Merit): Engineering

ExoPlanet Exploration Program

- Evaluated optical design (CODE V, ZEMAX)
  - Common: Tertiary and front end , IFS, Sci camera
  - Masks, FSM/DMs, LOWFS, Interferometers
- Evaluated alignment complexity
  - Optical alignment
  - Other engineering issues that are important
- Evaluated mechanical complexity
  - Mechanism to be used for changing masks/filters (to cover 0.4 – 1.0um band)



Results: Full Trade Matrix

ExoPlanet Exploration Program

Decision Statement: Recommend one Primary and one Backup coronagraph *architecture* (option) to focus design and technology development

Descr	Name		Option 1 SPC	Option 2 PIAACMC	Option 3 HLC	Option 4 VVC	Option 5 VNC - DA	Option 6 VNC - PO	Notes
Musts	**Programmatic**								
M1 - T	Science: Meet Threshold requirements? (1.6, x10)		Yes	Yes	Yes	No	No	U	
M2	Interfaces: Meets the DCIL**?		Yes	Yes	Yes	Yes	Yes	U	
M3	TRL Gates: For baseline science is there a credible plan to meet TRL5 at start of FY17 and TRL6 at start of FY19 within available resources?		Yes	Yes	Yes	U	No	U	
M4	Ready for 11/21 TAC briefing		Yes	Yes	Yes	Yes	Yes	No	
M5	Architecture applicable to future earth-characterization missions		Yes	Yes	Yes	Yes	Yes	U	

Legend: yes, or expected likely / unknown / no, or expected showstopper

Evaluation		Weights	SPC	PIAACMC	HLC	VVC	VNC-DA	VNC - PO	Notes
Wants									
W1	**Science**	40							
a	Relative Science yield (1.6, x10) beyond M1-T		Sm/Sig	Best	Sm/Sig	VL	VL		Range of opinions between "significant and small". For SPC and VNC2 the search area is ~3 times less than 360deg, and that was taken into acct in comparisons
W2	**Technical**	30							
a	Relative demands on observatory (DCIL), except for jitter and thermal stability		Best	Best	Best	Best	Small		
b	Relative sensitivities of post-processing to low order aberrations		Best	Sig	Sig	VL	U		For n-lambda over D or different amplitudes the designs will have the same relative ranking
c	Demonstrated Performance in 10% Light		Small	Sig	Best	Sig	VL		Demonstrated Performance (10%) and Prediction
d	Relative complexity of design		Best	Small	Best	Small	Sig		
e	Relative difficulty in alignment, calibration, ops		Best	Small	Best	Small	Sig/Sm		
W3	**Programmatic**	30							
a	Relative Cost of plans to meet TRL gates		Best	Small	Best	Sig	Sig		
	Wt. sum =>	100%							

Identify "Best" and others are:
- Wash
- Small Difference
- Significant Difference
- Very Large Difference

Risks	(all judged to be Hgh consequence)	SPC C	SPC L	PIAACMC C	PIAACMC L	HLC C	HLC L	VVC C	VVC L	VNC-DA C	VNC-DA L	VNC - PO C	VNC - PO L	Notes
Risk 1	Technical risk in meeting TRL5 gate		L		M		M/L		M/H		H			PIAA trend over the last three working days lower, but recommendation to keep M
Risk 2	Schedule or Cost risk in meeting TRL5 Gate		L		M		M/L		M/H		H			
Risk 3	Schedule or Cost risk in meeting TRL6 Gate		L		L		L		M		M			
Risk 4	Risk of not meeting at least threshold science		L		L		L		H		H			
Risk 5	Risk of mnfr tolerances not meeting BL science		L		L		L		M/L		H			One dissent, previous TDEM performance track record and Bala's assessment should be taken into account.
Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt		L		M/H		M		M/H		M			
Risk 7	Risk that wrong architecture is chosen due to any assumption made for practicality/simplicity	open ended question, spawned evaluations on Risk 5, Risk 6, Risk 8, and Oppty 1												
Risk 8	Risk that ACWG simulations (by JK and BM) overestimate the science yield due to model fidelity	discussed; not enough understanding at this time to make an evaluation.												Model validation is a risk that needs to be evaluated in the future

Opportunities	(judged to be High benefit)	SPC B	SPC L	PIAACMC B	PIAACMC L	HLC B	HLC L	VVC B	VVC L	VNC-DA B	VNC-DA L	VNC - PO B	VNC - PO L
Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30		L		M/H		M		L		H		

Final Decision, Accounting for Risks and Opportunities:

- Scores entered as group
- Consensus sought but not required; no dissent received
- Consensus reached after ~24 hours of group discussion on all points but those indicated in yellow
- Other colors for evaluation added afterwards for presentation clarity

C = Consequence, L = Likelihood, B=Benefit

**DCIL = Observatory-Coronagraph Interface List

Indicates Sig. Discriminator in ACWG discussion

indicates those few areas where consensus was not achieved

consensus achieved on balance of matrix

Results (Musts)

Descr				Option 1	Option 2	Option 3	Option 4	Option 5	Option 6
		Name		SPC	PIAACMC	HLC	VVC	VNC - DA	VNC - PO
	Musts		Programmatic						
		M1 - T	Science: Meet Threshold requirements? (1.6, x10)	Yes	Yes	Yes	No	No	U
		M2	Interfaces: Meets the DCIL**?	Yes	Yes	Yes	Yes	Yes	U
		M3	TRL Gates: For baseline science is there a credible plan to meet TRL5 at start of FY17 and TRL6 at start of FY19 within available	Yes	Yes	Yes	U	No	U
		M4	Ready for 11/21 TAC briefing	Yes	Yes	Yes	Yes	Yes	No
		M5	Architecture applicable to future earth-characterization missions	Yes	Yes	Yes	Yes	Yes	U

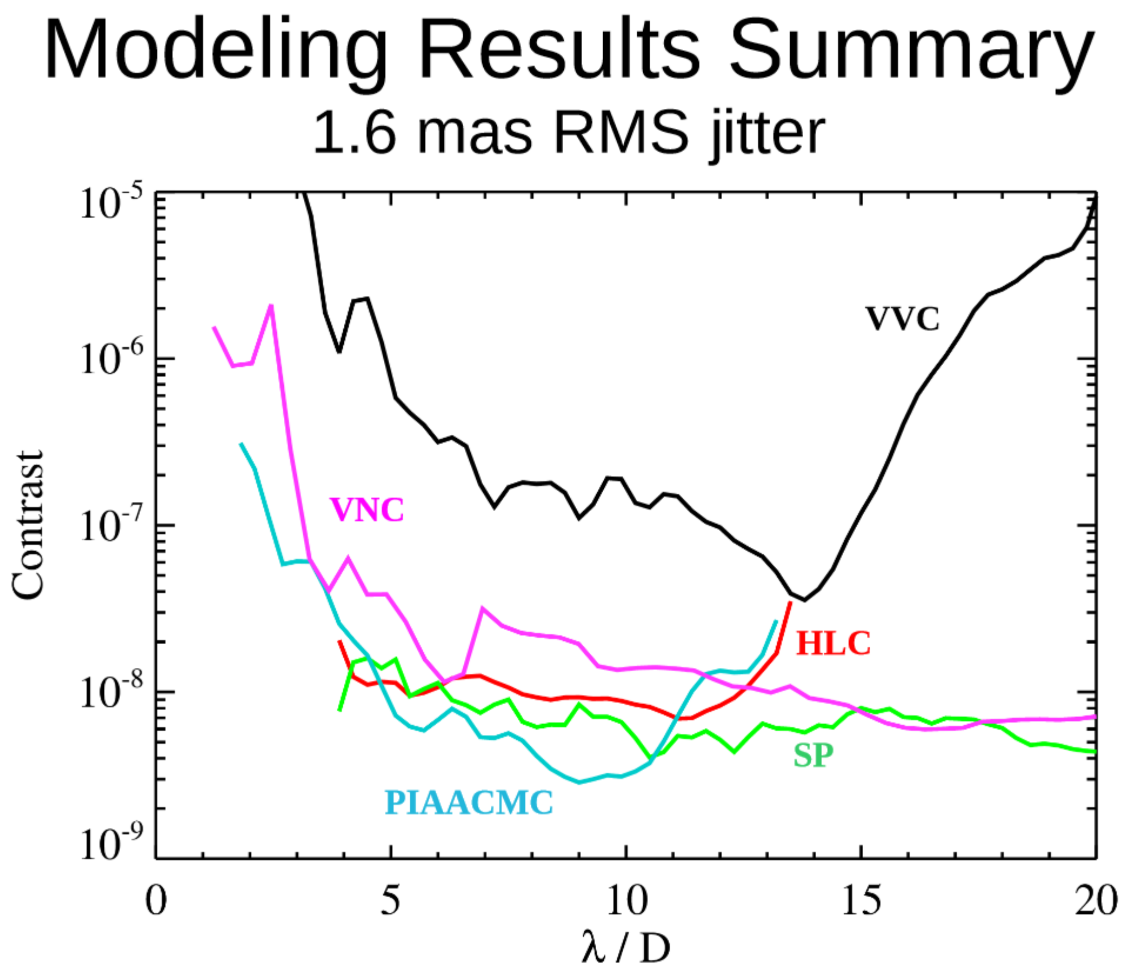
- Three options past all the Musts
- Vector Vortex design does not meet the threshold science, and requires more stroke than the deformable mirrors can provide to compensate for pupil
- VNC-DAVINCI does not meet threshold science at design-point levels of jitter, and does not have a plan for TRL5 by FY17 that the ACWG judged to be credible
  - VVC and VNC-DA evaluated further for Wants/Risks/Opportunities with the others
- A design was not submitted by VNC-PO, and was not evaluated further

Results (Must): Suitability for Future Missions

Consensus view of ACWG:

- Any of the coronagraphs studied for AFTA may be suitable for future Astrophysics missions, including Earth-like planet imaging
  - Visible nullers handle segmented and obstructed pupils well naturally, but mask coronagraphs may also provide high contrast via ACAD
- All studied AFTA coronagraph and wavefront control technologies are applicable to future high contrast missions
  - Deformable mirrors, coatings, masks, detectors, algorithms, modeling
- None of these technologies is a dead end!
- Future mission design must progress and coronagraph performance needs to be advanced farther before a quantitative evaluation can be made.

Intermediate Result: Contrast vs Angle from Star



Each coronagraph's performance scales differently depending on jitter.

Results (Must) – Threshold Science

- Simulation by Coronagraph Team
- Science Reqts and Metrics by SDT

Colors indicate pass / fail vs Threshold

Values indicate the Science Want "Beyond the Must" for Design Point (1.6mas, x10)

M1-T

Threshold	@1.6mas, x10	Value	SPC	PIAA	HLC	VVC	VNC2-DA
1	**Wavelength:** 430-980 nm, 10% bandpass, pol.		yes	yes	yes	yes	yes
2	**Outer Disk:** 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	6 (E-9)	5	6	5	50	10
3	**Gas Giant Detection:** Depth>10 for 4-14 RE	10	10	11	12	0	2
	550 nm photometry of doppler planets		1	3	0	0	0

- What is "Depth"? Parameter SDT calculates to indicate the degree of detection possible given instrument contrast, throughput, angular coverage, relative to hypothetical planets around known stars of given planet radius R_earth
  - Depth of ~10 likely to produce one giant planet from current RV catalog (more for future catalogs expected by 2023)
  - Many more planets when Depth >10; not linear function

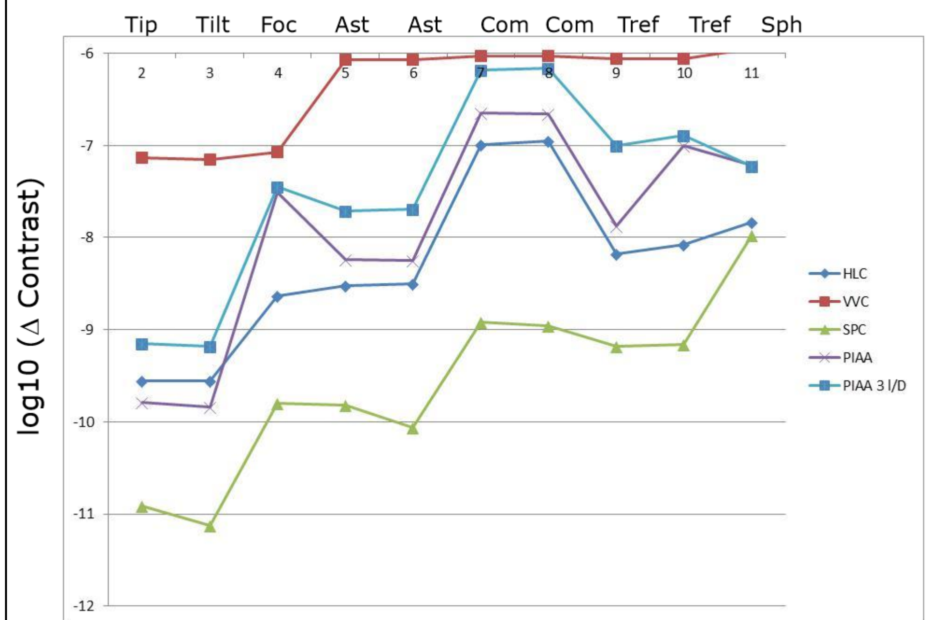
Results (Want): Sensitivity to Low Order Aberrations

Conclusions

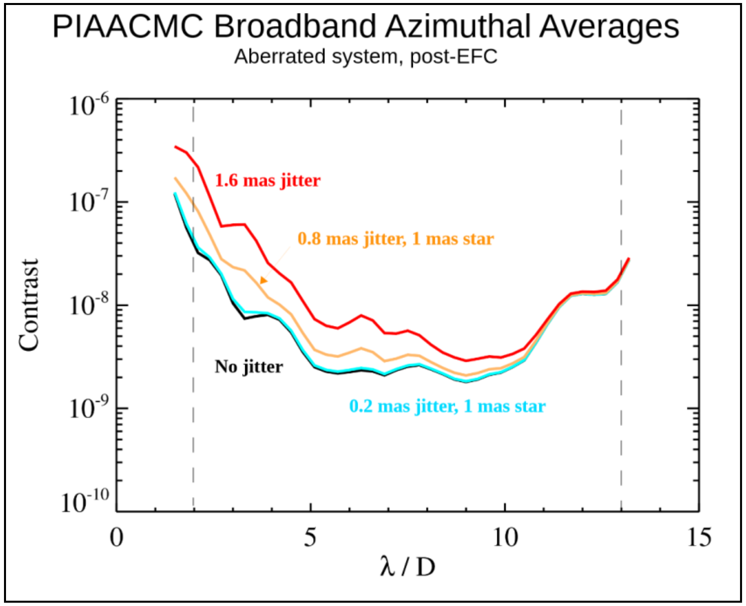
- SPC is least sensitive to aberrations.
- HLC is 10-100x more sensitive.
- PIAA is is 2 times less sensitive to tip-tilt than HLC. It is more sensitive to other aberrations, in particular it has an azimuthal component due to focus that is 13x more sensitive than HLC.
  - The radial components for focus are identical.
- VVC is 1000x more sensitive than HLC.
- All show contrast scaling as aberration^2.
- Most sensitive terms are coma for HLC, and spherical for SPC.
  - Spherical contributes an annular ring to HLC but does not by itself masquerade as a planet.

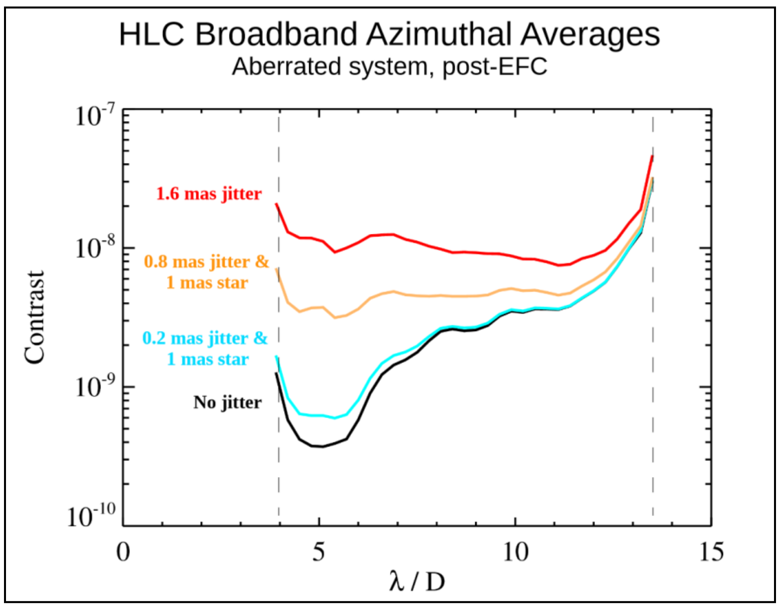
Spatial Standard Deviation of Intensity

3 and 4 λ/D, 1 nm rms wavefront error



Intermediate Result: Performance Sensitivity to Jitter (examples)





- Dark Hole contrast improves with decreasing jitter
- Technologies have different sensitivities:
  - Strong sensitivity to jitter:
    - PIAACMC (shown)
    - HLC (shown)
    - VVC
    - VNC
  - Insensitive to jitter:
    - SPC (not shown)
- Results shown are for simple “opportunity” evaluation
- To fully realize yield of lower jitter, masks must undergo another design cycle at the lower jitter number

Results (Opportunity): Greater Science Yield for Lower Jitter, Greater Speckle Suppression

Colors indicate pass/fail vs Threshold

Values indicate the Science Want "Beyond the Must" for Design Point (1.6mas, x10)

M1-T

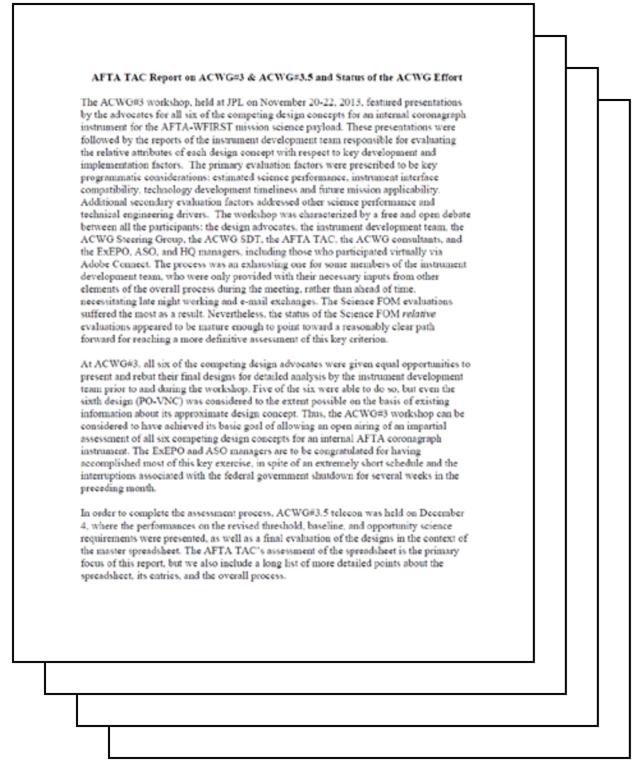
Threshold	@1.6mas, x10	Value	SPC	PIAA	HLC	VVC	VNC2-DA
1	Wavelength: 430-980 nm, 10% bandpass, pol.		yes	yes	yes	yes	yes
2	Outer Disk: 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	6 (E-9)	5	6	5	50	10
3	Gas Giant Detection: Depth>10 for 4-14 RE	10	10	11	12	0	2
	550 nm photometry of doppler planets		1	3	0	0	0
Oppty	@ 0.2mas, x30	**Value**	**SPC**	**PIAA**	**HLC**	**VVC**	**VNC2-DA**
2	Outer Disk: 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	<6 (E-9)	2	0.4	0.6	100	0.3
5	HZ Disk: 10 zodi@1AU = 10e-9@ 130mas @450 nm	< 10 (E-9)	n/a	10	10	100	2
3	Gas Giant Detection: Depth>10 for 4-14 RE	>10	23	43	14	0	28
	550 nm photometry of doppler planets		8	31	15	0	30
4	Gas Giant Spectrum: Doppler planets at 550nm, 2 months	Max	1	12	5	0	19
6	Ice Giant Detection: Depth >2 for < 4RE	>2	0.4	3	3.6	0	6.1

Colors indicate degree of Science Benefit for Oppty (0.2mas, x30)

- Calculations of exoplanet yields based on current catalogs of radial velocity exoplanets were adequate for comparing architectures.
- Yields are low due to conservative assumptions on spacecraft jitter and limitation of the current sample size
- We anticipate exceeding the SDT requirement of 6 exoplanet images with the AFTA coronagraph based on upcoming engineering studies and estimates of exoplanet population knowledge by 2023.

TAC Assessment - Summary

- Report of the AFTA TAC:



AFTA TAC Report on ACWG#3 & ACWG#3.5 and Status of the ACWG Effort

The ACWG#3 workshop, held at JPL on November 20-22, 2013, featured presentations by the advocates for all six of the competing design concepts for an internal coronagraph instrument for the AFTA-WFIRST mission science payload. These presentations were followed by the reports of the instrument development team responsible for evaluating the relative attributes of each design concept with respect to key development and implementation factors. The primary evaluation factors were prescribed to be key programmatic considerations: estimated science performance, instrument interface compatibility, technology development timeliness and future mission applicability. Additional secondary evaluation factors addressed other science performance and technical engineering drivers. The workshop was characterized by a free and open debate between all the participants: the design advocates, the instrument development team, the ACWG Steering Group, the ACWG SDT, the AFTA TAC, the ACWG consultants, and the ExEPO, ASO, and HQ managers, including those who participated virtually via Adobe Connect. The process was an exhausting one for some members of the instrument development team, who were only provided with their necessary inputs from other elements of the overall process during the meeting, rather than ahead of time, necessitating late night working and e-mail exchanges. The Science FOM evaluations suffered the most as a result. Nevertheless, the status of the Science FOM *relative* evaluations appeared to be mature enough to point toward a reasonably clear path forward for reaching a more definitive assessment of this key criterion.

At ACWG#3, all six of the competing design advocates were given equal opportunities to present and rebut their final designs for detailed analysis by the instrument development team prior to and during the workshop. Five of the six were able to do so, but even the sixth design (PO-VNC) was considered to the extent possible on the basis of existing information about its approximate design concept. Thus, the ACWG#3 workshop can be considered to have achieved its basic goal of allowing an open airing of an impartial assessment of all six competing design concepts for an internal AFTA coronagraph instrument. The ExEPO and ASO managers are to be congratulated for having accomplished most of this key exercise, in spite of an extremely short schedule and the interruptions associated with the federal government shutdown for several weeks in the preceding month.

In order to complete the assessment process, ACWG#3.5 telecon was held on December 4, where the performances on the revised threshold, baseline, and opportunity science requirements were presented, as well as a final evaluation of the designs in the context of the master spreadsheet. The AFTA TAC's assessment of the spreadsheet is the primary focus of this report, but we also include a long list of more detailed points about the spreadsheet, its entries, and the overall process.

AFTA TAC Report Conclusions:

* All three occulting mask designs (SPC, HLC, PIAA-CMC) should continue to be studied and developed – not enough is known at present to choose a primary and a backup design.

* Congratulations to the entire ACWG team for working together to perform this assessment on a tight schedule.

* We need to maintain this productive, collegial approach as we move forward with AFTA.

AFTA TAC Members

Alan P. Boss (chair), Carnegie Institution
Ben R. Oppenheimer, American Museum of Natural History
Joe Pitman, Exploration Science
Lisa Poyneer, Lawrence Livermore National Laboratory
Steve T. Ridgway, National Optical Astronomy Observatory

Focus of Trade: 3 strongest options

Decision Statement: Recommend one Primary and one Backup coronagraph *architecture* (option) to focus design

Descr		Name		Weights	Option 1	Option 2	Option 3
					SPC	PIAACMC	HLC
	Musts		Programmatic		Yes	Yes	Yes
	Wants			Weights	SPC	PIAACMC	HLC
Evaluation		W1	Science	40			
		a	Relative Science yield (1.6, x10) beyond M1-T		Sm/Sig	Best	Sm/Sig
		W2	Technical	30			
		a	Relative demands on observatory (DCIL), except for jitter and thermal stability		Best	Best	Best
		b	Relative sensitivities of post-processing to low order aberrations		Best	Sig	Sig
		c	Demonstrated Performance in 10% Light		Small	Sig	Best
		d	Relative complexity of design		Best	Small	Best
		e	Relative difficulty in alignment, calibration, ops		Best	Small	Best
		W3	Programmatic	30			
		a	Relative Cost of plans to meet TRL gates		Best	Small	Best
			Wt. sum =>	100%			

Risks	(all judged to be Hgh consequence)	SPC C	SPC L	PIAACMC C	PIAACMC L	HLC C	HLC L
Risk 1	Technical risk in meeting TRL5 gate		L		M		M/L
Risk 2	Schedule or Cost risk in meeting TRL5 Gate		L		M		M/L
Risk 3	Schedule or Cost risk in meeting TRL6 Gate		L		L		L
Risk 4	Risk of not meeting at least threshold science		L		L		L
Risk 5	Risk of mnfr tolerances not meeting BL science		L		L		L
Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt		L		M/H		M

Opportunities	(judged to be High benefit)	SPC B	SPC L	PIAACMC B	PIAACMC L	HLC B	HLC L
Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30		L		M/H		M

- Focus on primary discriminators from ACWG discussion (most common rows hidden)

<u>Findings:</u>

- SPC most robust to jitter, lower nominal or potential science yield, low risk overall
- PIACMC best potential additional science, sensitive to jitter, least mature of three leaders
- HLC falls somewhere in between on potential science yield for lower jitter, also sensitive to jitter, mature technology demonstrations

<u>Assignment remains:</u> choose a primary and backup architecture

Results (Opportunity): Greater Science Yield for Lower Jitter, Greater Speckle Suppression

- Revisit Opportunity Science:

Colors indicate pass/fail vs Threshold

Values indicate the Science Want "Beyond the Must" for Design Point (1.6mas, x10)

M1-T

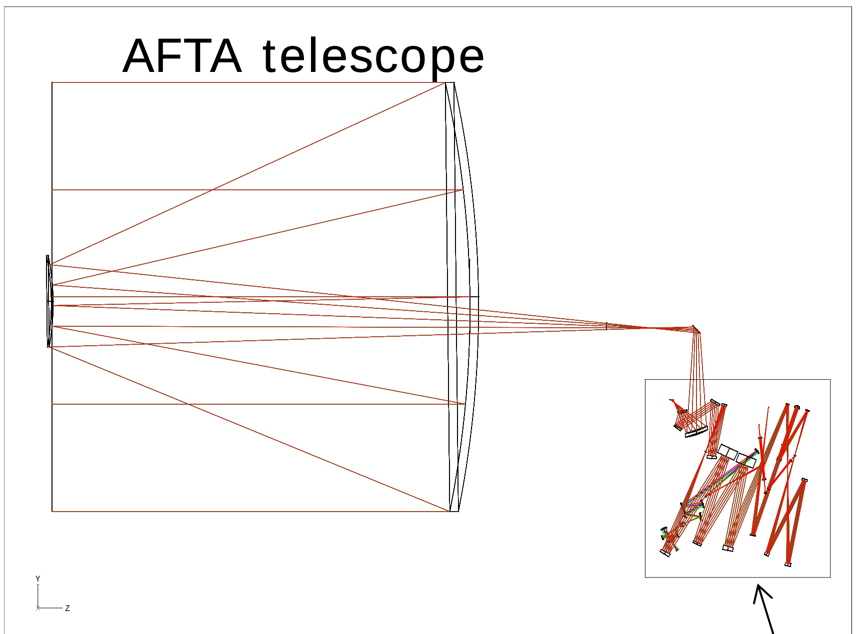
Threshold	@1.6mas, x10	Value	SPC	PIAA	HLC
1	**Wavelength:** 430-980 nm, 10% bandpass, pol.		yes	yes	yes
2	**Outer Disk:** 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	6 (E-9)	5	6	5
3	**Gas Giant Detection:** Depth>10 for 4-14 RE	10	10	11	12
	550 nm photometry of doppler planets		1	3	0
Oppty	@ 0.2mas, x30	**Value**	**SPC**	**PIAA**	**HLC**
2	**Outer Disk:** 100 zodi@2AU = 6e-9 at 250 mas @ 550 nm	<6 (E-9)	2	0.4	0.6
5	**HZ Disk:** 10 zodi@1AU = 10e-9@ 130mas @450 nm	< 10 (E-9)	n/a	10	10
3	**Gas Giant Detection:** Depth>10 for 4-14 RE	>10	23	43	14
	550 nm photometry of doppler planets		8	31	15
4	**Gas Giant Spectrum:** Doppler planets at 550nm, 2 months	Max	1	12	5
6	**Ice Giant Detection:** Depth >2 for < 4RE	>2	0.4	3	3.6

3 leaders have different science strengths

Can we choose a primary architecture that plays to combined strengths?

Colors indicate degree of Science Benefit for Oppty (0.2mas, x30)

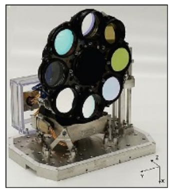
Define a new Option 7: Occulting Mask Coronagraph with SPC and HLC Masks

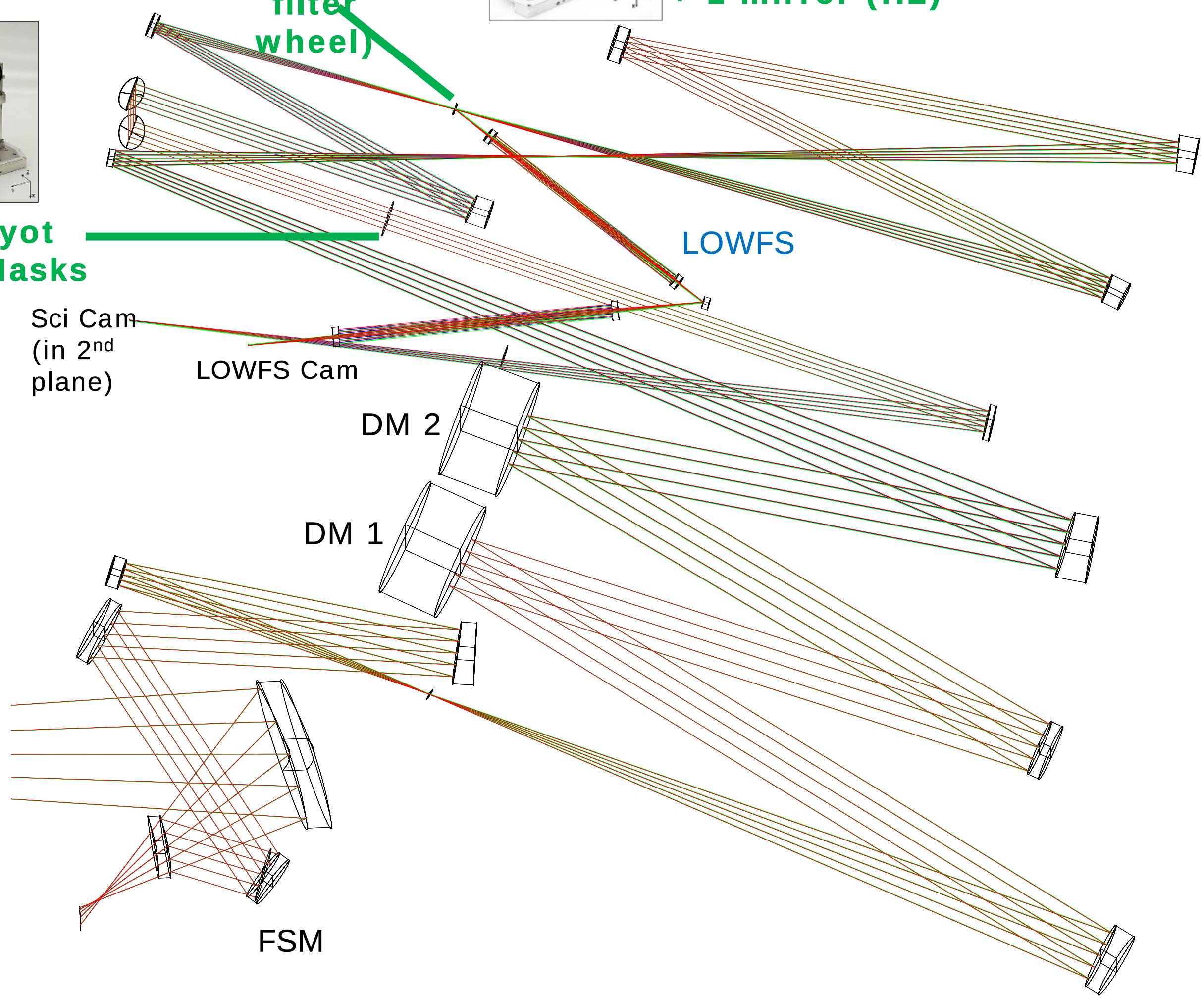


Coronagraph instrument with two types of masks

- Recognize that both SPC and HLC masks share very similar optical layouts
- OMC with two types of masks (SPC and HLC) fits instrument envelope defined in Cycle #4 AFTA-WFIRST DRM
- Small increase in over all complexity compared with single mask implementation

OMC:
SPC + HLC Instrument Layout





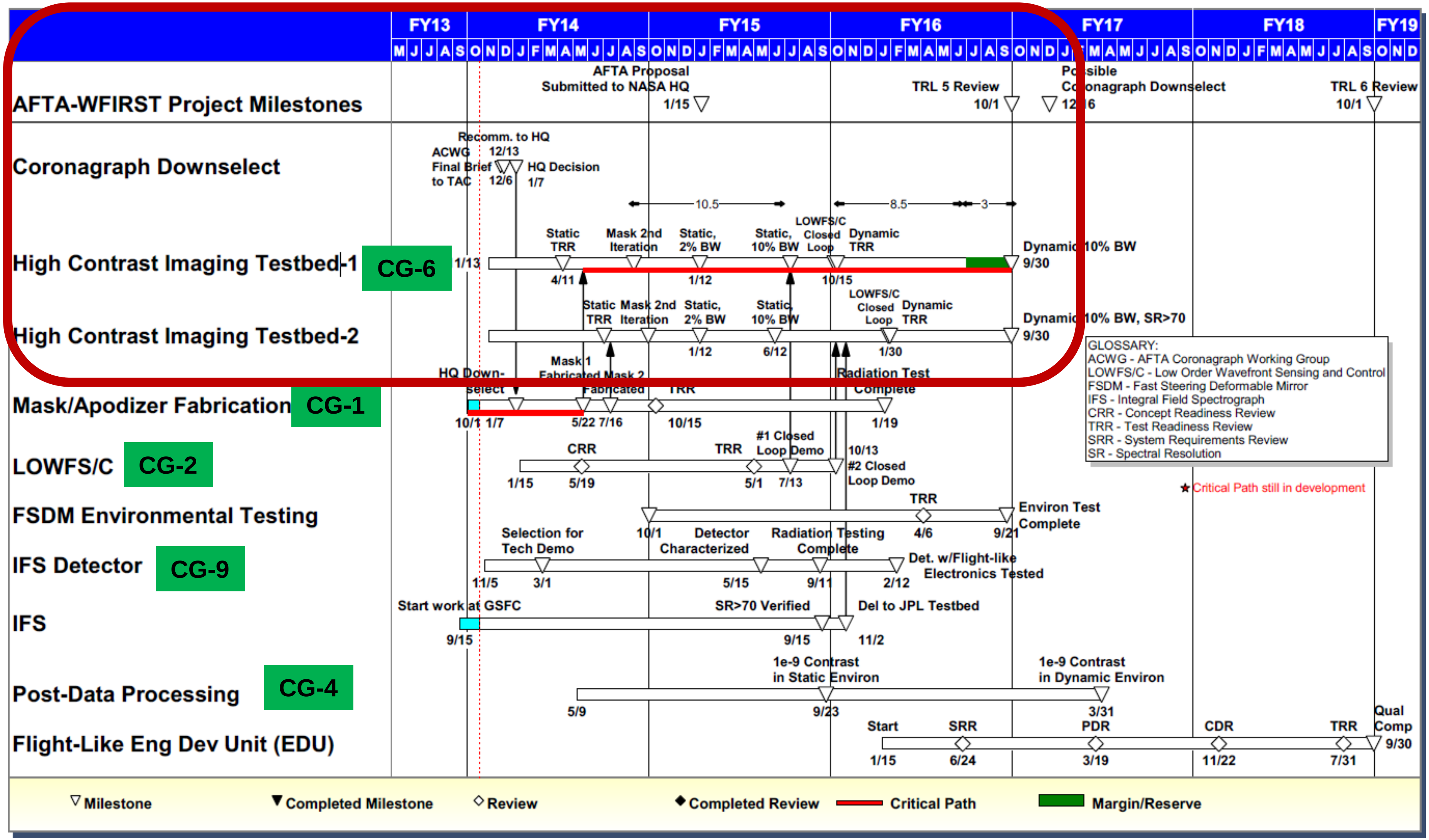
Components	SP C+ HL C	HL C	SP C
Coronagraph parabolas	4	2	4
Coronagraph flat optics	4	2	4
Coronagraph FP masks (SP: 19, HL: 6)	25	6	19
Coronagraph Lyot masks (HL: 6, SP: 1 - open)	7	6	0
Shaped pupil masks (SP: 4, HL: 1-mirror)	5	0	4
Filter wheel mechanisms	4	3	3

Low increase in overall complexity to include both SPC and HLC masks

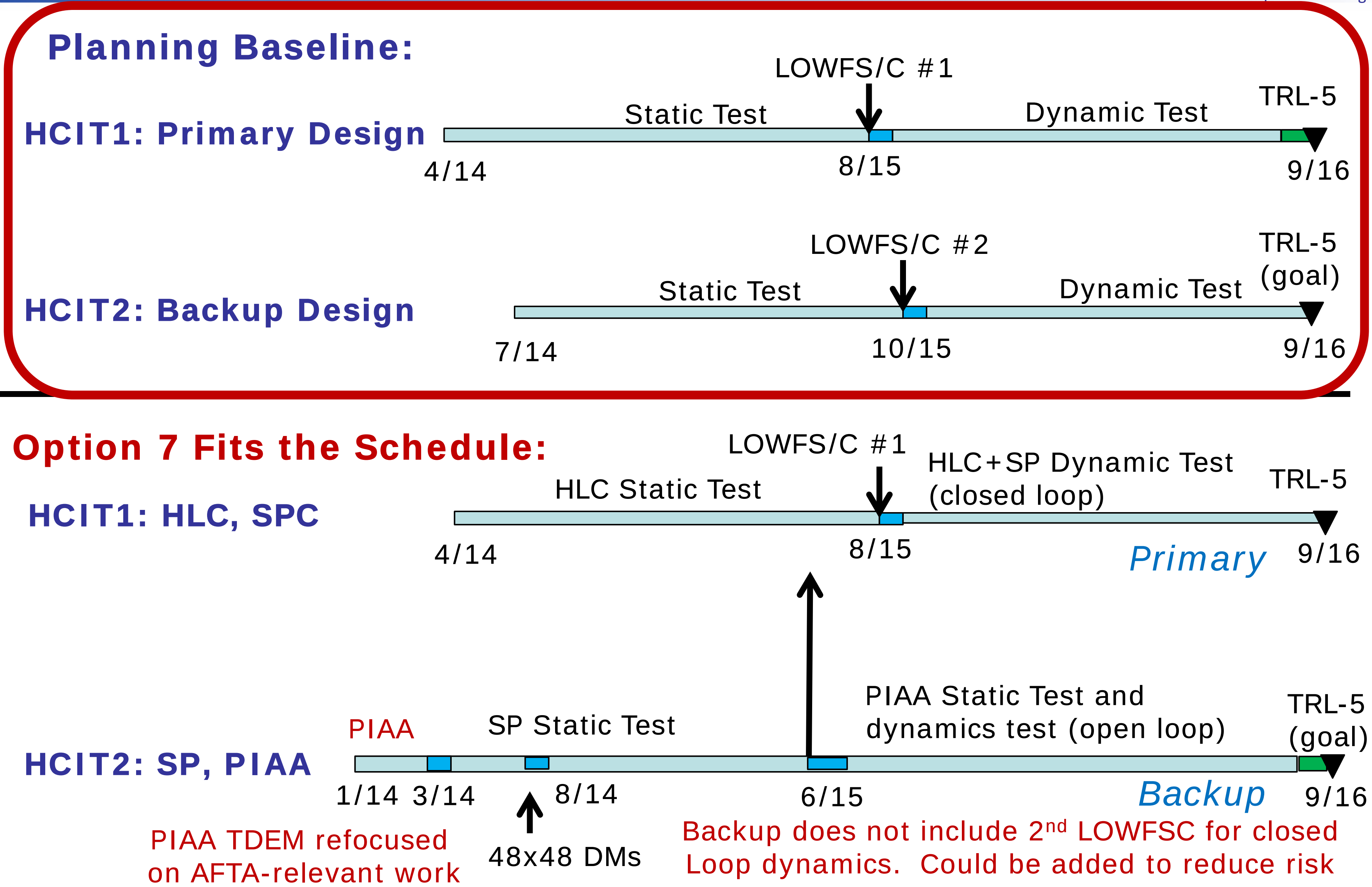
Option 7 Cost and Schedule Impacts

- **No expected cost impact compared to planning baseline:**
  - Manufacturing 3 (not 2) sets of coronagraph optics and masks: +$0.6M
  - Making 1 (not 2) LOWFS/C: -$0.6M
- **Primary architecture: Intended plan matures all technologies to TRL 5 by beginning of FY17**
  - Confidence in at least one mask completing closed-loop dynamic testing.
- **Backup architecture: Intended to mature technology through open-loop dynamic testing**

AFTA-WFIRST Coronagraph Technology Development Top-Level Schedule



Technology Plan Overview (Preliminary)



Final Trade Evaluation considering OMC=Option 7

Decision Statement: Recommend one Primary and one Backup coronagraph *architecture* (option) to focus design

Descr		Name	Weight	Option 7 OMC	Option 1 SPC	Option 2 PIAACMC	Option 3 HLC
Musts		Programmatic		Yes	Yes	Yes	Yes
Wants			Weight	ABC	SPC	PIAACMC	HLC
	W1	Science	40				
	a	Relative Science yield (1.6, x10) beyond M1-T		Sm/Sig	Sm/Sig	Best	Sm/Sig
	W2	Technical	30				
	a	Relative demands on observatory (DCIL), except for jitter and thermal stability		Wash	Best	Best	Best
	b	Relative sensitivities of post-processing to low order aberrations		Best	Best	Sig	Sig
	c	Demonstrated Performance in 10% Light		Best	Small	Sig	Best
	d	Relative complexity of design		Best	Best	Small	Best
	e	Relative difficulty in alignment, calibration, ops		Best	Best	Small	Best
	W3	Programmatic	30				
	a	Relative Cost of plans to meet TRL gates		Small	Best	Small	Best
		Wt. sum =>	100%				

Risks	(all judged to be Hgh consequence)	ABC C	ABC L	SPC C	SPC L	PIAACMC C	PIAACMC L	HLC C	HLC L
Risk 1	Technical risk in meeting TRL5 gate		L		L		M		M/L
Risk 2	Schedule or Cost risk in meeting TRL5 Gate		L		L		M		M/L
Risk 3	Schedule or Cost risk in meeting TRL6 Gate		L		L		L		L
Risk 4	Risk of not meeting at least threshold science		L		L		L		L
Risk 5	Risk of mnfr tolerances not meeting BL science		L		L		L		L
Risk 6	Risk that wrong architecture is chosen due to assumption that all jitter >2Hz is only tip/tilt		L		L		M/H		M

Opportunities	(judged to be High benefit)	ABC B	ABC L	SPC B	SPC L	PIAACMC B	PIAACMC L	HLC B	HLC L
Oppty 1	Possibility of Science gain for 0.2marcsec jitter, x30		M		L		M/H		M

Primary (Option 7 OMC) **Backup** (Option 2 PIAACMC)

- Define OMC = Occulting Mask Coronagraph
- Includes SPC+HL masks on different filter wheels
- OMC emerges as strongest candidate for Primary Architecture
- PIAACMC emerges as the candidate for the Backup Architecture

Recommendation

- Summary Observation:
  - *Three leading technologies, all with different strengths and weaknesses, all will benefit from further design optimization cycles and high contrast lab testing.*
- Recommendation: Primary Architecture - **Occulting Mask Coronagraph (OMC)** and Back-up Architecture – **PIAACMC**
- Assumptions:
  - Plan is to mature both Primary and Backup architecture technologies. The OMC primary includes both HL and SP masks in a single optical design, and the current thinking is that we would fly both masks.
  - If programmatic, technical or scientific factors suggest off-ramping of one approach is appropriate (either part of the primary or the backup), the project will implement that, to maximize performance and minimize risk going forward.
  - HCIT testbeds will be utilized to exploit their maximum utilization based on the availability of hardware and the benefit to the project.
- Benefits:
  - OMC in its “SP mode” provides the simplest design, lowest risk, easiest technology maturation, most benign set of requirements on the spacecraft and “use-as-is” telescope. This translates to low cost/schedule risk and a design that has a high probability to pass thru the CATE process.
  - In its “HL mode”, the OMC affords the potential for greater science, however the increased risk is mitigated by the SP safety net.
  - PIAACMC offers the possibility of even greater science and at greater complexity. Hardware demonstrations and more detailed analyses are necessary to substantiate projected performance.
  - Taken together, the primary & backup architectures afford numerous “built-in descopes” and/or opportunities to accept greater risk due to the diversity of the approach.

Summary and Next Steps

- The ExEPO and ASO Recommend and Request:

1. Approval of recommended Primary and Backup architectures for AFTA Coronagraph
2. Early APD announcement of decision. Will help protect the critical path and allow community to focus on facts for upcoming design cycles (now), ExoPAG (1/4), AAS (1/6-10), SDT (1/9-10)
3. Permission to proceed with detailed planning of this recommendation with return of:
   - Milestone Plan to APD by end of January 2014.
   - Cost/implementation plan to APD prior to PPBE cycle (State of the Program, February 2014)

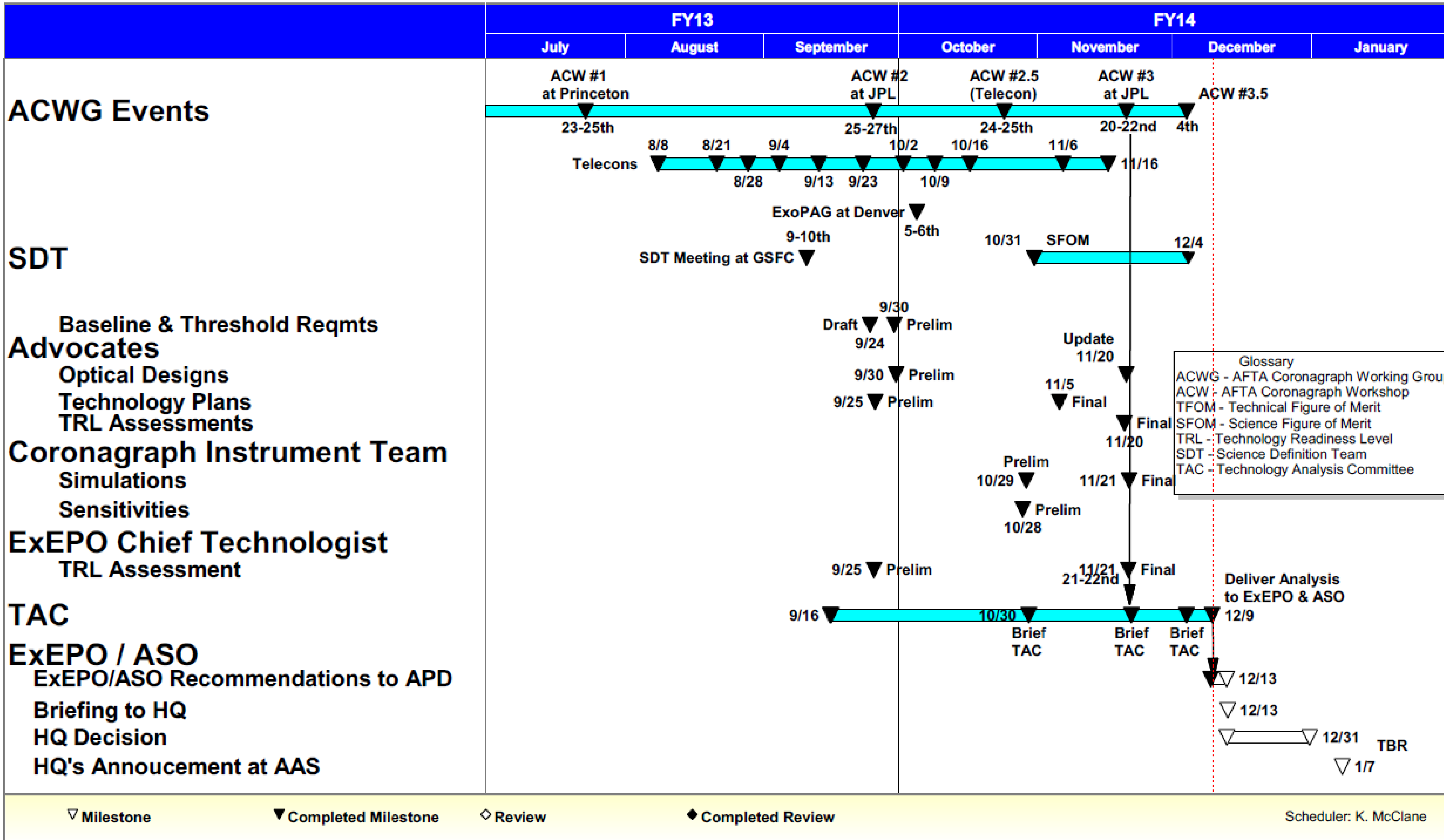
BACKUP

ACWG Schedule

ExoPlanet Exploration Program

Coronagraph Architecture Prioritization Top Level Schedule

Rev. 12/9/2013



AFTA Coronagraph Working Group: Background

- **September 2012:** WFIRST/AFTA study begins for coronagraph on 2.4m telescope
- **April 2013:** Final report completed by AFTA Study Office
- **May 2013:** AFTA Coronagraph Steering Group formed to anticipate possible follow-up
- **May 30:** NASA Administrator gives permission for AFTA pre-formulation activities including a coronagraph

- **June 20:** AFTA Coronagraph Working Group (ACWG) Charter signed by Astrophysics Division
- **July 23-25:** AFTA Coronagraph Workshop ACW#1 held at Princeton University
- **September 9-10:** Reconvened AFTA Science Definition Team (SDT) meeting
- **September 16:** Initial briefing to Technology Analysis Committee (TAC)
- **September 25-27:** ACW#2 held at JPL – initial science requirements
- **October 5:** Briefing to ExoPAG#8 on AFTA Coronagraph by Program Office
- **October 24-25:** ACW#2.5 Two-day telecon – preliminary technical assessments

- **October 30:** Deep technical Briefing to TAC
- **November 15:** Briefing to STMD
- **November 20-22:** ACW#3 held at JPL
- **December 5**: ACW#3.5 Telecon held
- **December 9:** Outbrief by TAC to full ACWG
- **December 13:** Recommendation by ExEPO and ASO to Astrophysics Division

AFTA Coronagraph Workshop (ACW) Series Charter

AFTA Coronagraph Workshop (ACW) Series – Charter

6/17/2013

A. Background

At the request of the NASA Administrator, the Astrophysics Directorate (APD) has been studying the use of the 2.4-meter telescopes obtained by NASA as a basis for accomplishing the science of WFIRST, Astro2010's highest-ranked Large Space Mission. A recent study[1] termed the Astrophysics Focused Telescope Assets (AFTA) included an analysis of the possibility of augmenting such a mission with a coronagraphic instrument for direct imaging of exoplanetary systems in our solar neighborhood. The Astrophysics Implementation Plan[2] calls for continued mission concept study and technology development for AFTA to be prepared for the NRC mid-decadal review in FY2015-16 and a potential new start within this decade. A prioritization and selection of a primary and backup coronagraph technology is needed to support a possible new mission start in FY17, specifically, to support the completion of an updated mission concept report by January 31, 2015 and to enable the prioritization of technology investments. A final point design for the coronagraph is not required until entering Phase A in FY17.

The Exoplanet Exploration Program Office (ExEPO) and AFTA Study Office (ASO) are directed by APD at NASA Headquarters to engage the community in developing and delivering to the NASA Astrophysics Director a recommendation for the AFTA coronagraph technology (primary and backup) by November 2013 . The recommendation will best satisfy the threshold and baseline science drivers provided by the AFTA Science Definition Team (SDT), constraints imposed by the ASO and other programmatic criteria including risk and cost.

The following groups will participate in the study:

1. A Working Group (representatives of coronagraph technologists, ASO from GSFC and JPL, and the AFTA SDT)
2. A Steering Committee (a subset of the Working Group responsible for setting agendas and ensuring community representation)
3. Consultants as needed and approved by the Steering Committee
4. An independent Technical Analysis Committee (TAC) approved by APD

[1] http://wfirst.gsfc.nasa.gov
[2] http://science.nasa.gov/astrophysics/documents/

A. Structure of the Work: The process leading to a recommendation to APD will be:

1. The Working Group will provide to the TAC the coronagraph technology descriptions, model predictions and any comparisons to metrics by September 30, 2013. The Working Group will start with the current science drivers in the WFIRST-AFTA final report[3] until the SDT update.
2. Updates to science drivers (requirement and threshold) will be provided by the AFTA SDT by September 30, 2013 to the TAC, ExEPO, ASO and AD.
3. The TAC will assess both the ability of the technologies to meet the updated science drivers and other technical requirements and to meet the required TRL gates for project formulation. Analysis will be delivered to ExEPO and ASO by October 31, 2013.
4. ExEPO and ASO will develop and deliver a joint recommendation to APD on which 2 coronagraph technologies should be down-selected for continued development by December 2, 2013 using the analysis above as input.

The ACW Series is expected to consist of 2-3 face-to-face workshops and supporting telecons that enable virtual participation for all participants. The ExEPO and ASO may convene a Red Team for vetting of concepts prior to final delivery to the TAC or to ExEPO and ASO.

B. Participants

Steering Committee:

Gary Blackwood (JPL)	ExEPO Manager, ACW Series organizer
Kevin Grady (GSFC)	AFTA Study Manager
Jeremy Kasdin (Princeton)	AFTA SDT Member, Workshop#1 organizer
Scott Gaudi (Ohio State)	ExoPAG EC Chair, member APS
Peter Lawson (JPL)	ExEP Chief Technologist
Tom Greene (ARC)	ExoPAG EC Member, AFTA SDT Member
Wes Traub (JPL)	ExEP Chief Scientist, AFTA SDT Member
Chas Beichman (NExScI)	Director, NExScI
Karl Stapelfeldt (GSFC)	Chair, Exoplanet Probe STDT for Coronagraph
Jeff Kruk (GSFC)	AFTA Scientist

Working Group: Consistent with the AFTA SDT charter, these members will be US Persons. Steering Committee members are also member of the Working Group. Working group members are expected to participate (in person or virtually) in all working group events.

[3] http://wfirst.gsfc.nasa.gov/

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AFTA Coronagraph Workshop (ACW) Series Charter

ExoPlanet Exploration Program

1. Gary Blackwood (ExEPO)
2. Kevin Grady (GSFC)
3. Jeremy Kasdin (Princeton)
4. Scott Gaudi (Ohio State)
5. Peter Lawson (ExEPO)
6. Tom Greene (ARC)
7. Wes Traub (ExEPO)
8. Chas Beichman (NExScI)
9. Karl Stapelfeldt (GSFC)
10. Jeff Kruk (GSFC)
11. Mark Marley (ARC)
12. Marc Clampin (GSFC)
13. Olivier Guyon (UofA)
14. Bruce Macintosh (LLNL)
15. Gene Serabyn (JPL)
16. Stuart Shaklan (JPL)
17. Remi Soummer (STScI)
18. John Trauger (JPL)
19. Aki Roberge (GSFC)
20. Marshall Perrin (STScI)
21. Marie Levine (JPL)
22. Rick Lyon (GSFC)
23. Dave Content (GSFC)
24. Mark Melton (GSFC)
25. Cliff Jackson (GSFC)
26. John Ruffa (GSFC)
27. Jennifer Dooley (JPL)

The SDT Co-Chairs, David Spergel and Neil Gehrels, will be invited to attend the working group events.

Consultants: may be identified and invited as needed by the Steering Committee. Non-US Persons may be considered on an exception basis for invitations to portions of meetings. Consultants are not expected to attend all events or all durations of meetings, except at invitation of Steering Committee.

Technical Analysis Committee (TAC): Membership to be recommended later by ExEPO and ASO to AD for approval.

C. Miscellaneous

1. Information will be disseminated via ExEPO website, AFTA website, quarterly newsletter, the SPIE evening session (August 2013), and ExoPAG (October 5-6 2013) and winter AAS (January 2014)
2. Headquarter APD Program Executives and Program Scientists will be invited as appropriate.

[Signatures when ready]

June 20, 2013

Joan Centrella
Program Scientist
AFTA Study
Astrophysics Division
Science Mission Directorate
NASA Headquarters

June 20, 2013

Lia LaPiana
Program Executive
AFTA Study
Astrophysics Division
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June 20, 2013

Douglas Hudgins
Program Scientist
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NASA Headquarters

June 21, 2013

Anthony Carro
Program Executive
Exoplanet Exploration Program
Astrophysics Division
Science Mission Directorate
NASA Headquarters

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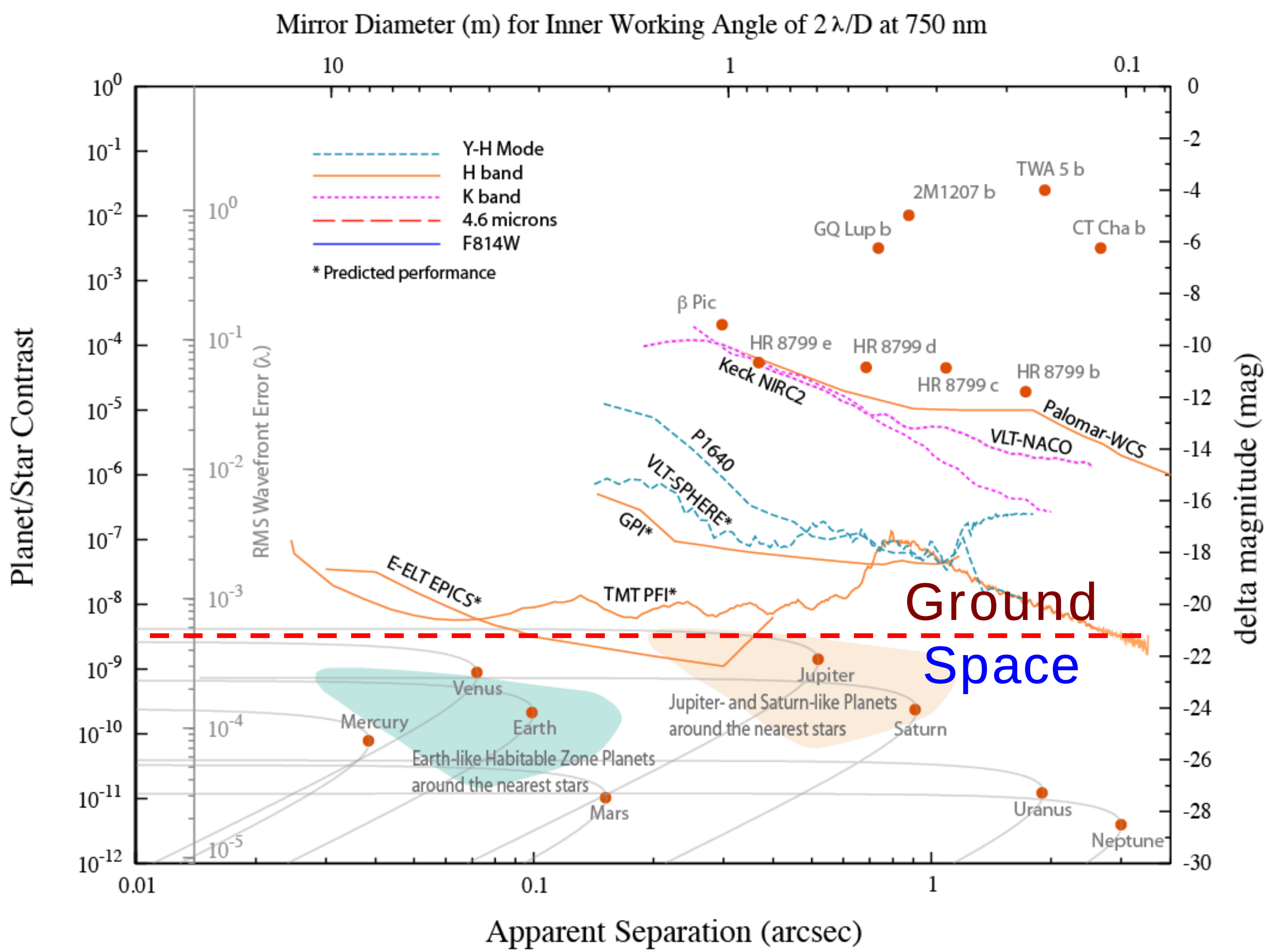
Future Science Improvements

- Current estimates of exoplanet yield are based on only the known RV planets.
- Current RV catalog is incomplete, particularly for long-period large planets
- The RV discovery program between now and 2023 will increase the AFTA exoplanet yield.
- Estimates of the expected yield will be done in time for the April report
- The coronagraph target list could also be expanded with an AFTA astrometric survey supplemented by Gaia as proposed by D. Spergel. Such a survey lasting 2 months could identify giant planets of all stars in the local neighborhood.

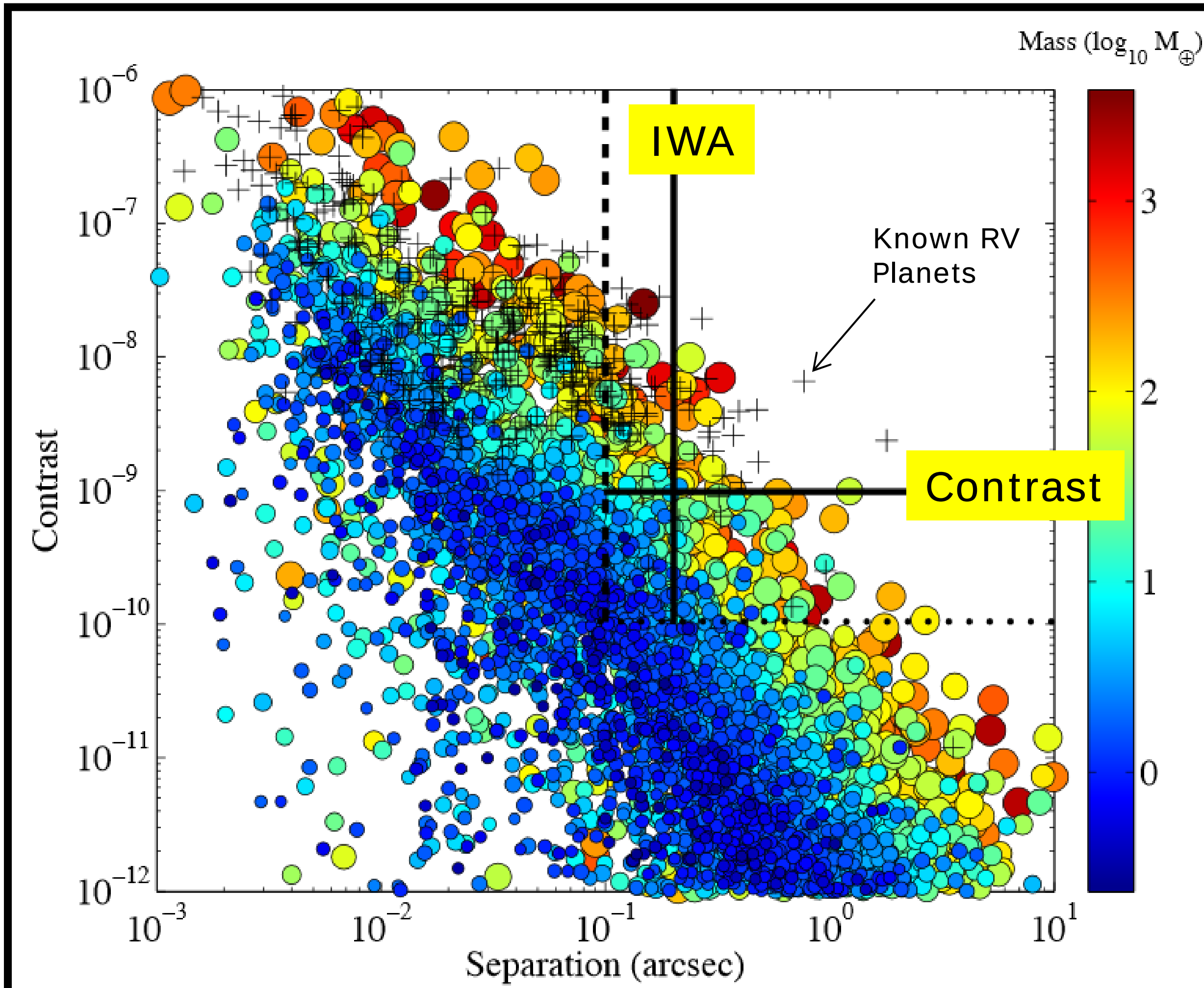
Discovery Space of Extremely Large Telescopes

ExoPlanet Exploration Program



Sensitivity of AFTA Coronagraph for Imaging Exoplanets

- Survey of ~200 nearest stars within 30 pc
- Model assumes 4 planets per star with size distribution consistent with Kepler results, extrapolated to larger semimajor axis and lower mass
- Crosses: known RV planets



Consultants and Guests

ExoPlanet Exploration Program

Last Name	First Name
BELIKOV	RUSLAN
CADY	ERIC
CAHOY	KERRI
GOULLIOUD	RENAUD
GROFF	TYLER
KRIST	JOHN
MATTHEWS	GARY
MCELWAIN	MICHAEL
MENNESSON	BERTRAND
MOODY	DWIGHT
NOECKER	CHARLEY
PEDDIE	CATHERINE
POBEREZHSKIY	ILYA
RUDD	MICHAEL
SANDHU	JAGMIT
SAVRANSKY	DMITRY
SIDICK	ERKIN
TANG	HONG
VANDERBEI	ROBERT
WALLACE	J KENT
Balasubramanian	Bala

Last Name	First Name
BENFORD	DOMINIC
BRENNER	MICHAEL
CARRO	ANTHONY
GRIFFITHS	RICHARD
HEINRICHSEN	INGOLF
HERTZ	PAUL
HUDGINS	DOUGLAS
HYDE	TRISTAM (TUPPER)
LAPIANA	LIA
LIGHTSEY	WILLIAM
PANANYAN	OZHEN
PODOLSKI	DENISE
REUTHER	JAMES
SHEEY	JEFFREY

Relative TRL Assessment for AFTA Components

TRL Hybrid Lyot
- 2-3 – **Hybrid Lyot mask**
- 5 – Xinetics DMs
- 3-4 – Low order sensor

“Best”

TRL PIAA
- 4 – **PIAA mirrors**
- 4 – Post apodizer
- 5 – Xin
- 2-3 – **Complex focal-plane mask**
- 3-4 – Low order wavefront sensor

“Significant Difference”

TRL Shaped Pupil
- 5 – Xineti
- 2-3 – **Shaped Pupil mask**
- 5 – Focal plane mask
- 3-4 – Low order wavefront sensor

“Small Difference”

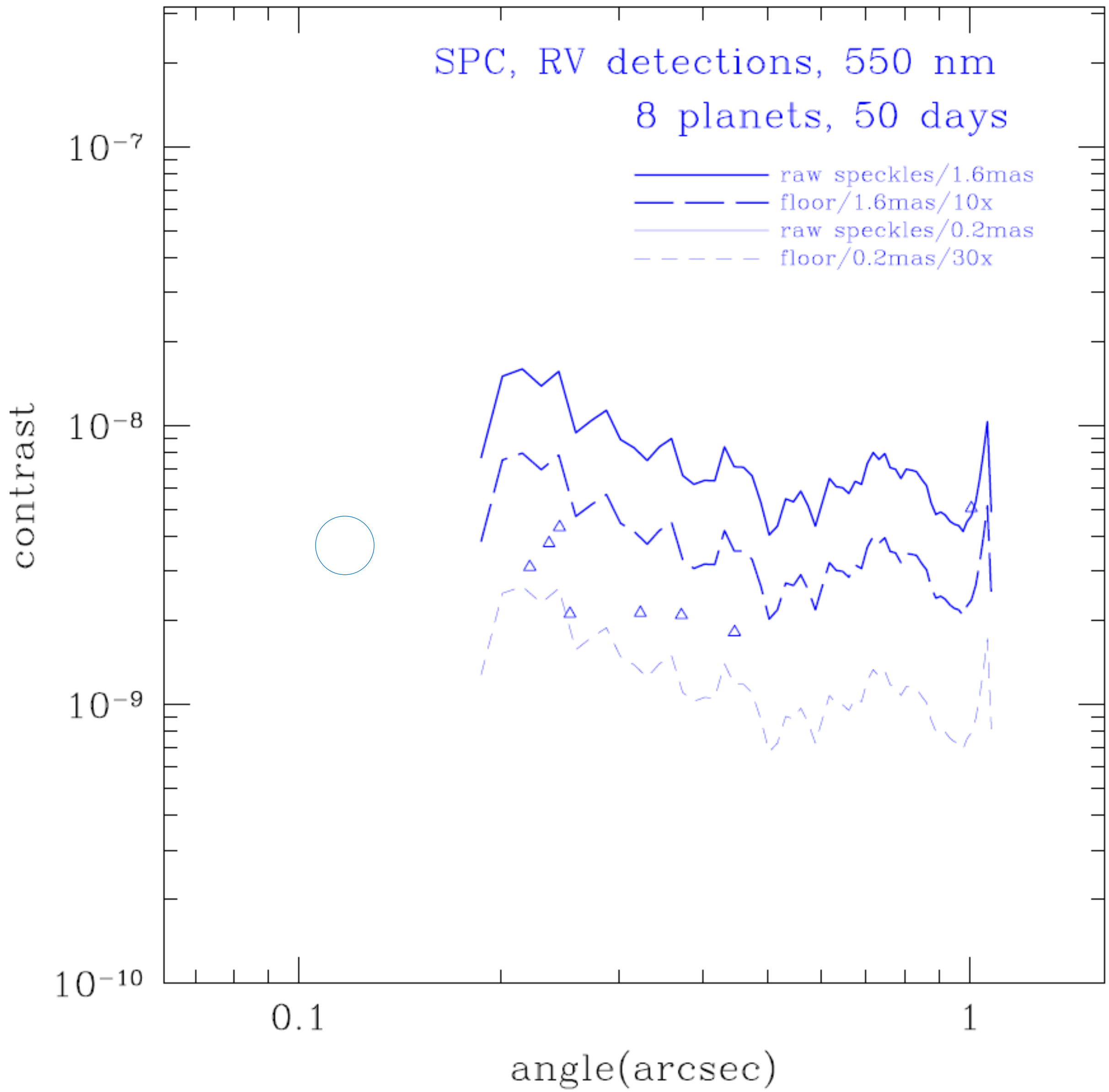
TRL Vector Vortex
- 5 – Xinetics DMs
- 4 – Polarizers (?)
- 4 –
- 2-3 – **Ring apodizer**
- 4 – **Vector Vortex mask**
- 3-4 – Low order wavefront sensor

“Significant Difference”

TRL Visible Nuller (s)
- 2-3 – **331-segment IRIS AO DM; or 2000 segment BMC DM**
- 4 –
- 2-3 – **Coherent fiber bundle with lenslet arrays**
- 3 – Low order wavefront sensor

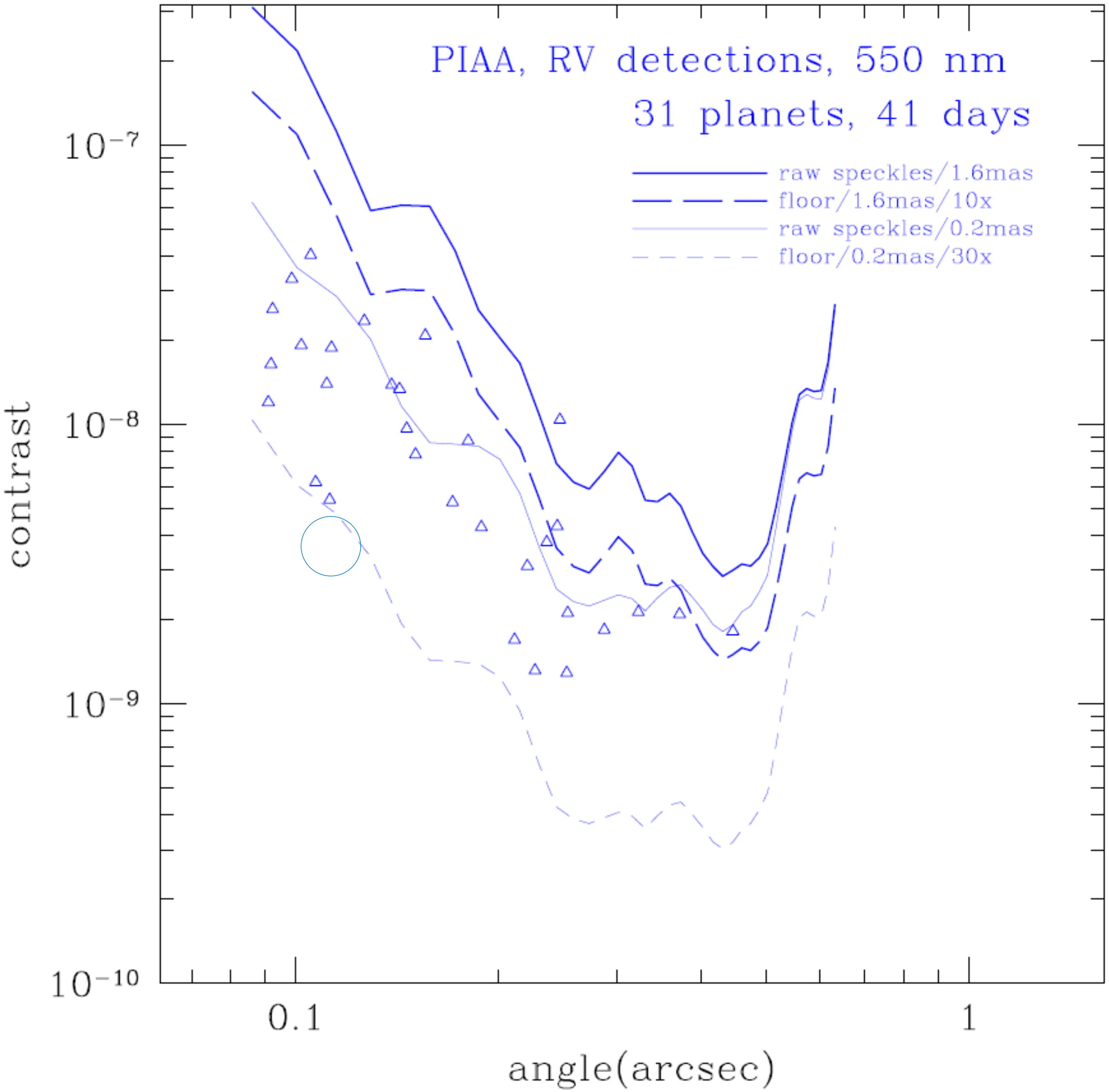
“Very Large Difference”

Shaped Pupil Coronagraph

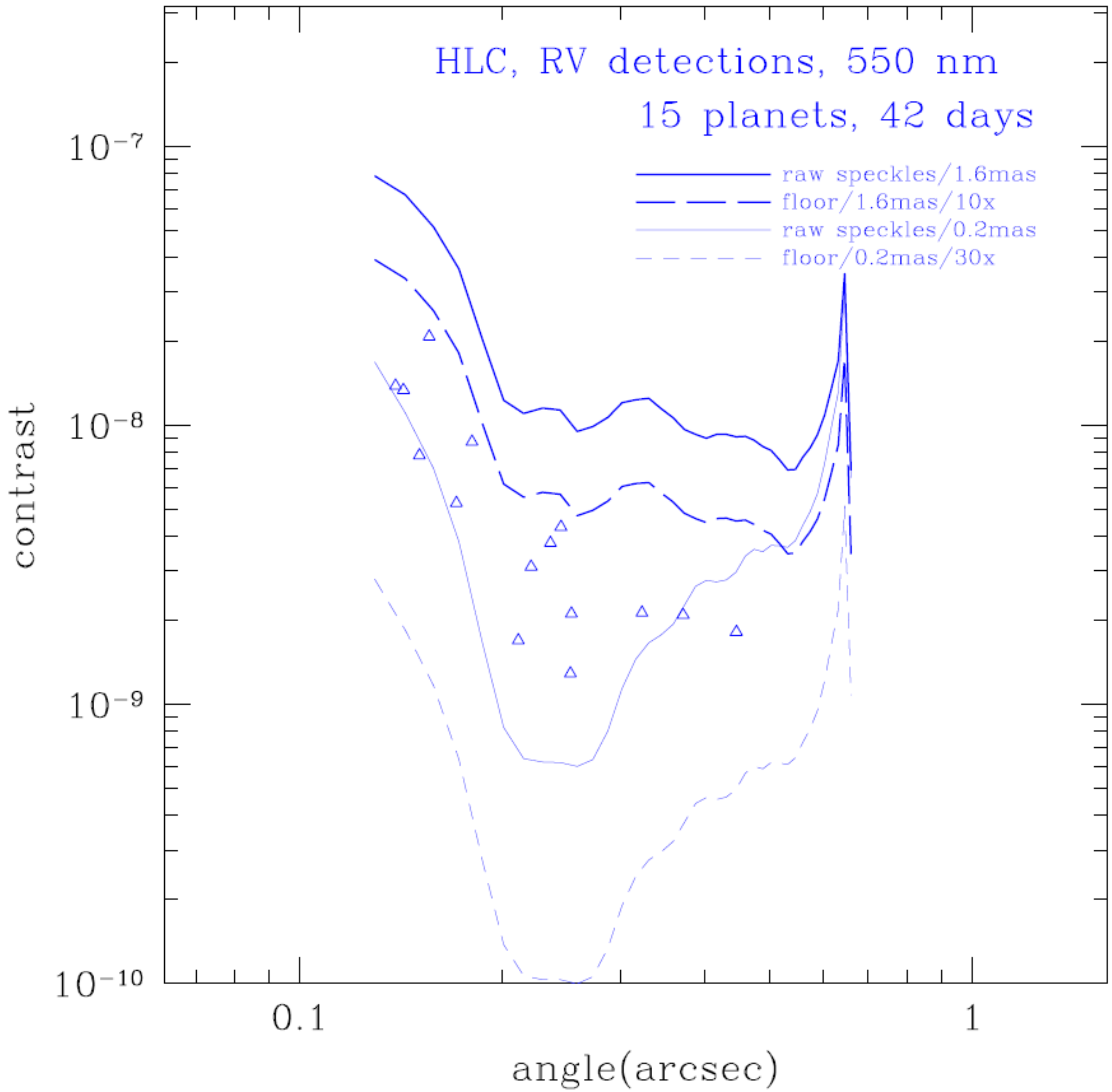


PIAA Coronagraph

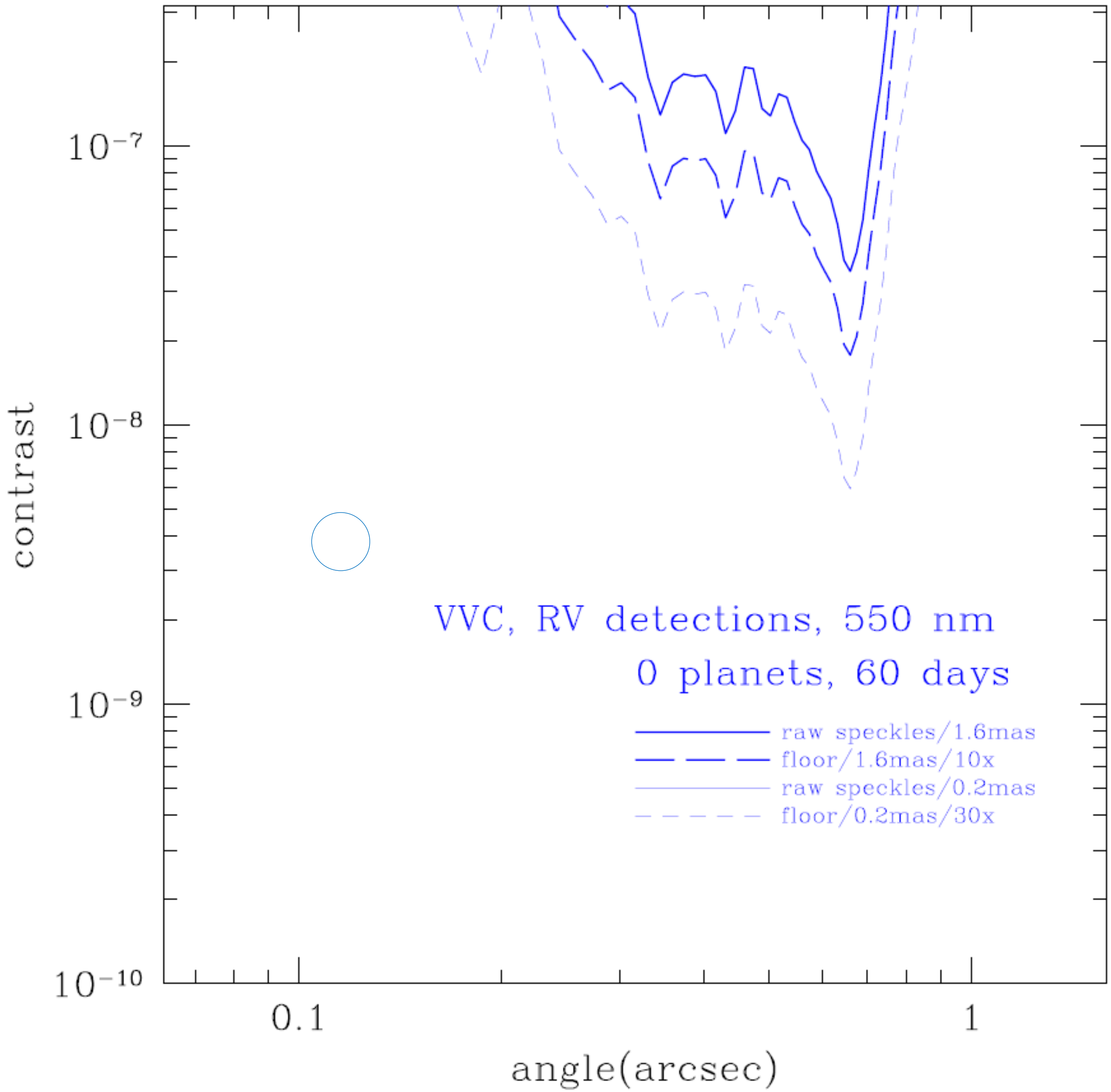
ExoPlanet Exploration Program



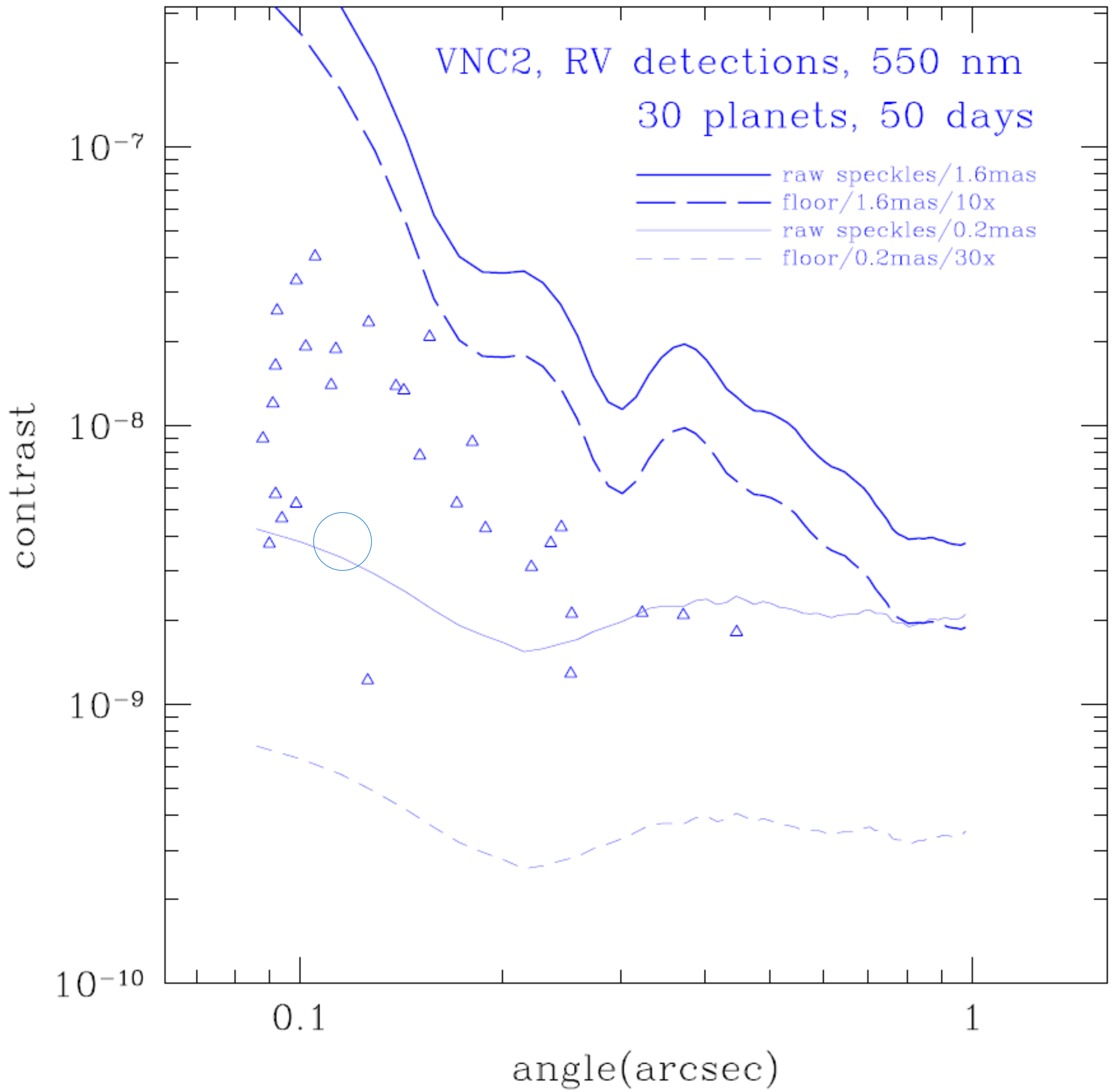
Hybrid Lyot Coronagraph



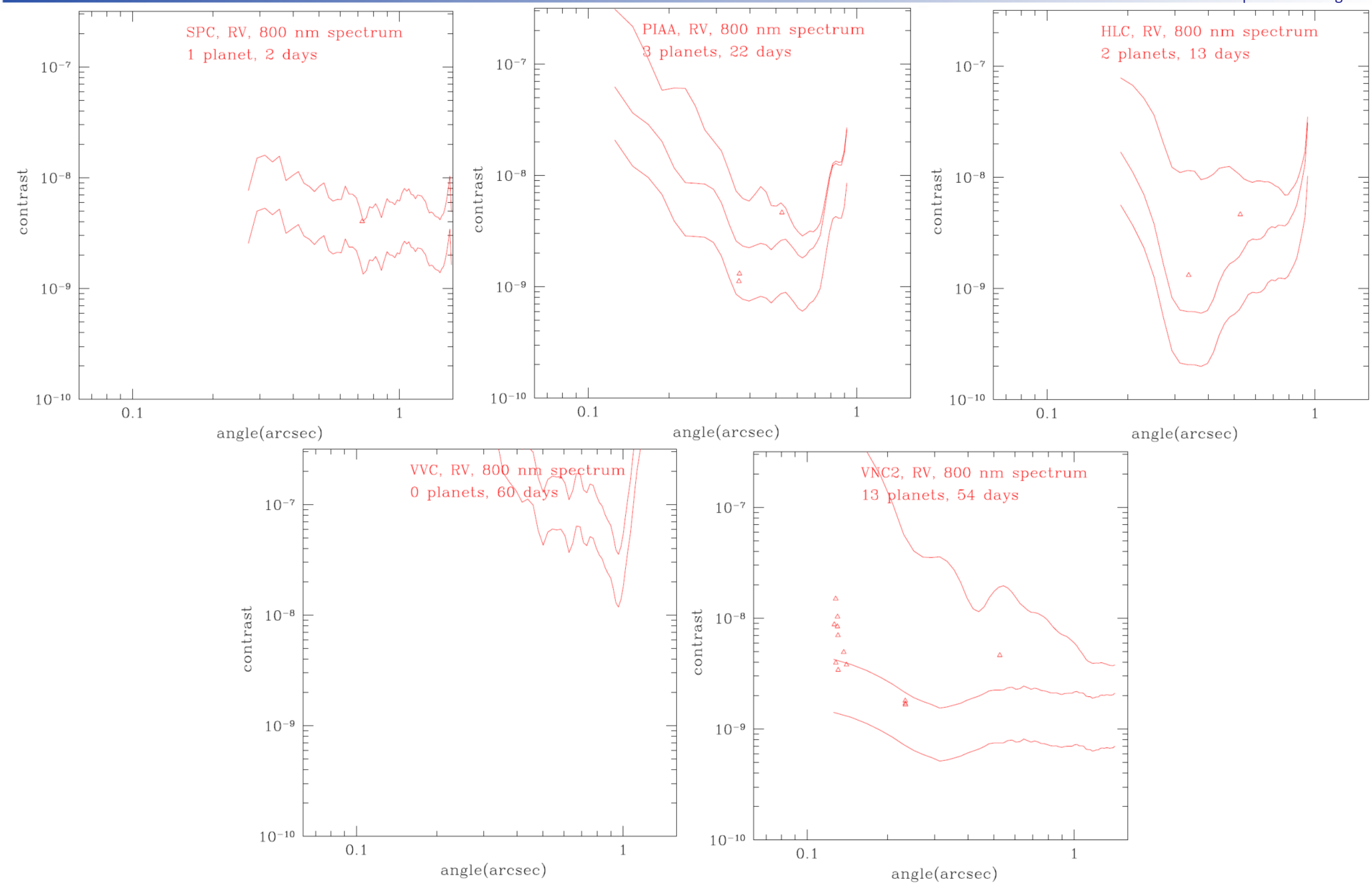
Vector Vortex Coronagraph



Visible Nuller Coronagraph 2



Spectra, 800 nm band, resolution = 70



Acknowledgements

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  - NASA Goddard Space Flight Center
  - NASA Ames Research Center
  - Lawrence Livermore National Laboratory
  - Space Telescope Science Institute

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