Segmented Coronagraph Design and Analysis (SCDA)
A study by the Exoplanet Exploration Program

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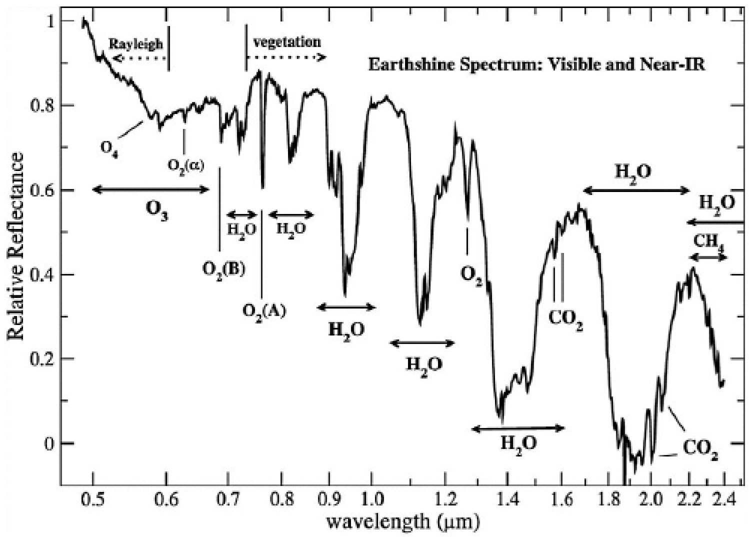
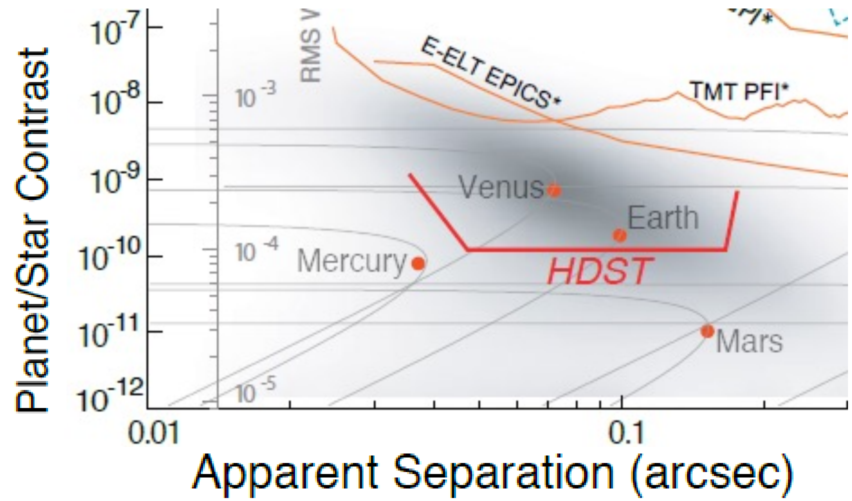
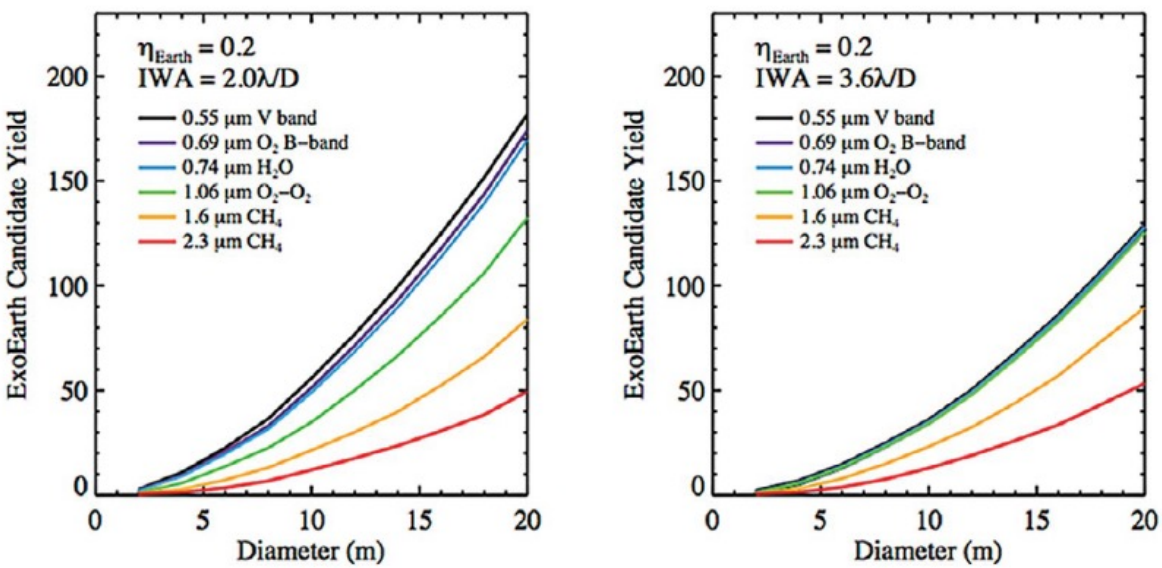
JPL

Overview

- Motivation
- Defining the SCDA task
- Selection of apertures, comparison of their relative merits
- Funded Teams
- Progress on Apodized Pupil Lyot Coronagraph (APLC)
- New Optimization approach: Auxiliary Field Optimization (AFO)
- Progress on Vortex and Lyot Coronagraphs (VC, LC)
- Progress on Phase Induced Amplitude Apodization Coronagraphs
- Science Yield Modeling
- Plans for the coming year



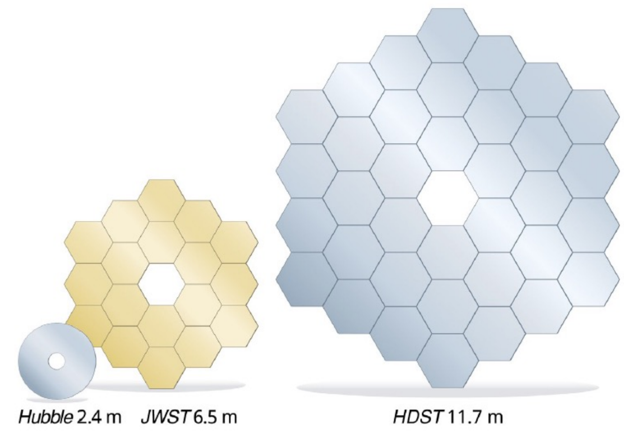




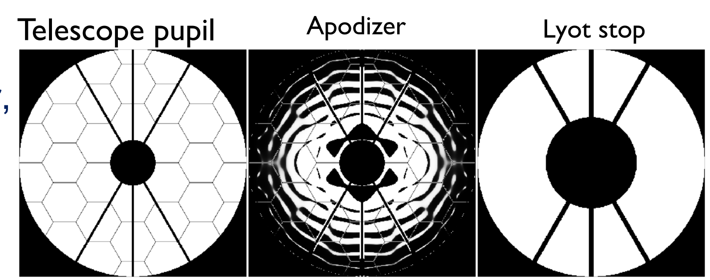
- 12 m telescope
- 10^10 suppression
- IWA = 2 λ/D or 3.6 λ/D
- IFU R=70-100
- Band 400 – 2000 nm
- Goal: characterize dozens of exo-Earths

Defining the SCDA Task

- Find coronagraph designs that enable direct imaging of exo-earths with large, segmented-aperture, partially obscured telescopes.
- Identify attributes of reference apertures that impact performance: central obscuration, spiders, gaps, aperture perimeter
- Optimize for science return



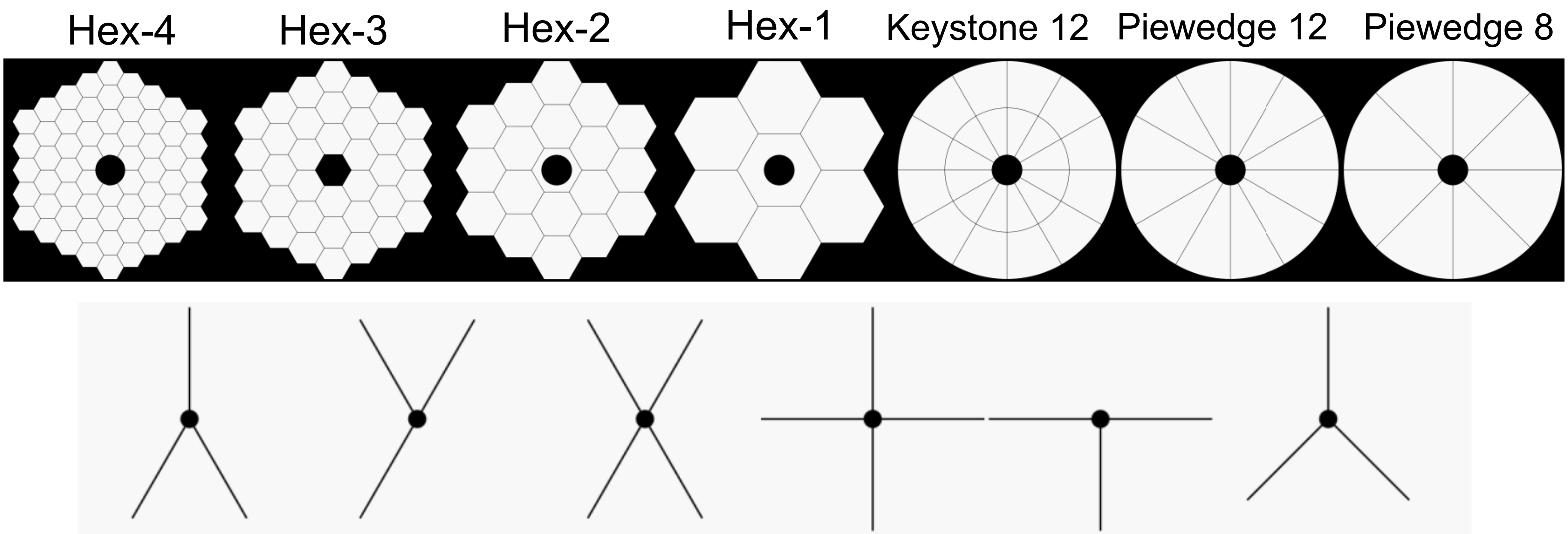
- Consider the fundamental limit set by finite stellar diameter;.
  – Assume pointing errors are small compared to stellar diameter, e.g. sub-mas
- Ignore polarization since that is a function of f/#, on- or off-axis, coating, bandpass, and bandwidth.



"ATLAST" APLC
N'Diaye et al. ApJ 818, 2 (2016)
10^{-10} contrast over **10% BW**
Working angle 4 – 10 λ/D
$T_{0.7/circ}$ = **7.0%**

- Initial design investigation
- Collaboration/ Cross-fertilization encouraged
- Will inform technology gap and future technology investments.

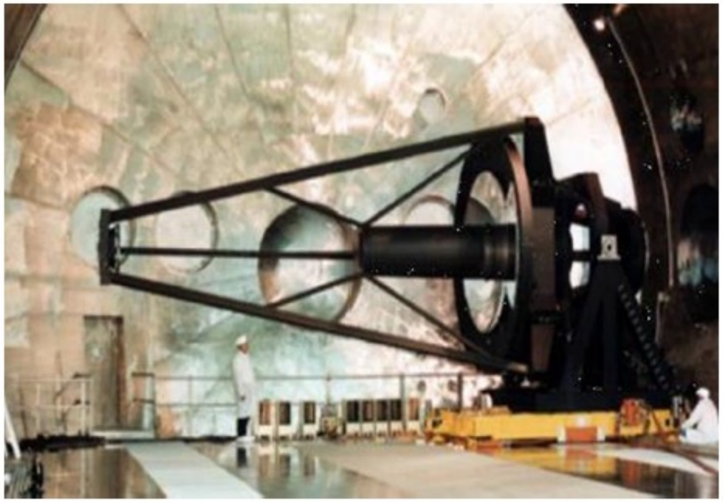
Selection of Apertures

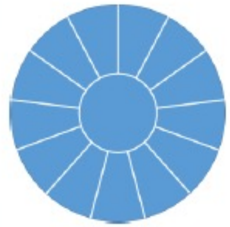


- This set of apertures and secondary mirror supports represents the likely range of segmented apertures that could be manufactured and launched without on-orbit assembly.
- An SLS is assumed.
- The optical prescription for all telescopes is the same: f/1.25 12-m diameter primary, nearly parabolic, with secondary mirror 13.1 m in front of primary. Secondary obscuration is 14%. Cassegrain field is 10 arcsec diameter.
- Gaps: 20 mm (6 mm spacing, 7 mm edge roll-off). Spiders 25 mm wide.

Some Space Telescope concepts

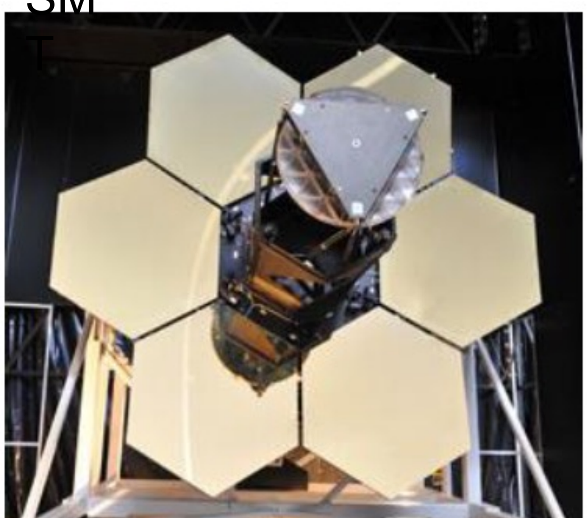
Large Optical Segment Project



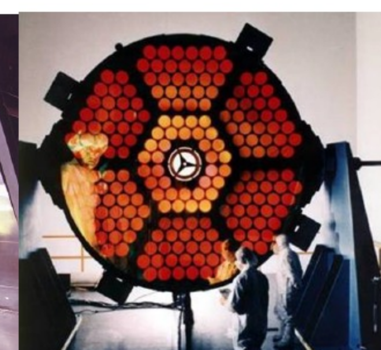


AOSD

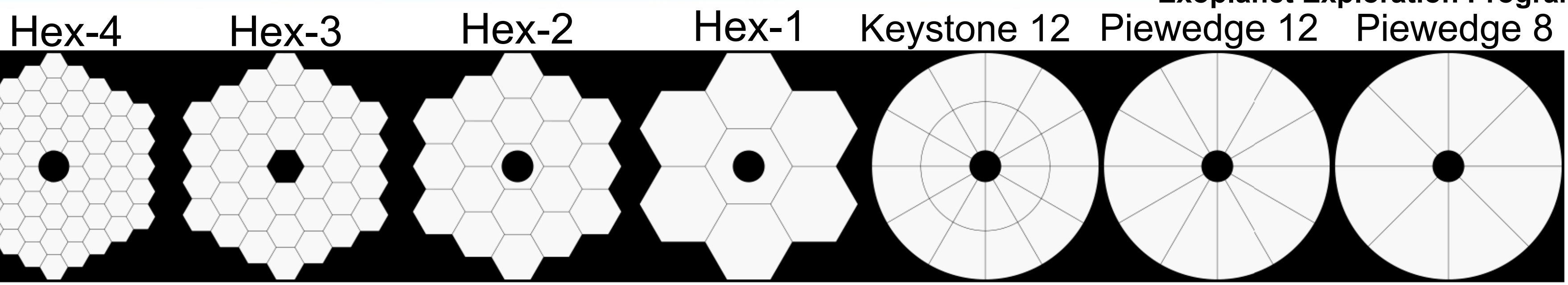
SM
T



LAMP telescope



Comments on the Apertures



- 4-ring: stiffer, lighter, HST size.
  - Requires the most actuators
- 3-, 2-, 1-ring as segments grow, the system sees increasing…
  - Challenges to segment stiffness
  - Gravity sag
  - Testing difficulty including gravity offloading, model fidelity, GSE
- 1-ring – >4 m tip-to-tip
  - Closed back ULE demonstrated. Open back Zerodur possible but risky due to depth.
- Keystone, piewedge
  - Asymmetry complicates mounting and control. Warping harness?
  - Also impacts metrology needs.
- Piewedges have 5-m long sides.
- Thermal stability is dominated by front-to-back gradients.
  - Wavefront varies as radius^2.
  - Gradients decrease with thermal time constant (want more thermal mass).
  - 1-2 pm stability possible with 1 mK control on 1.5 m ULE mirrors. Could be 10x worse on 5 m segments.

Some Deployment Approaches

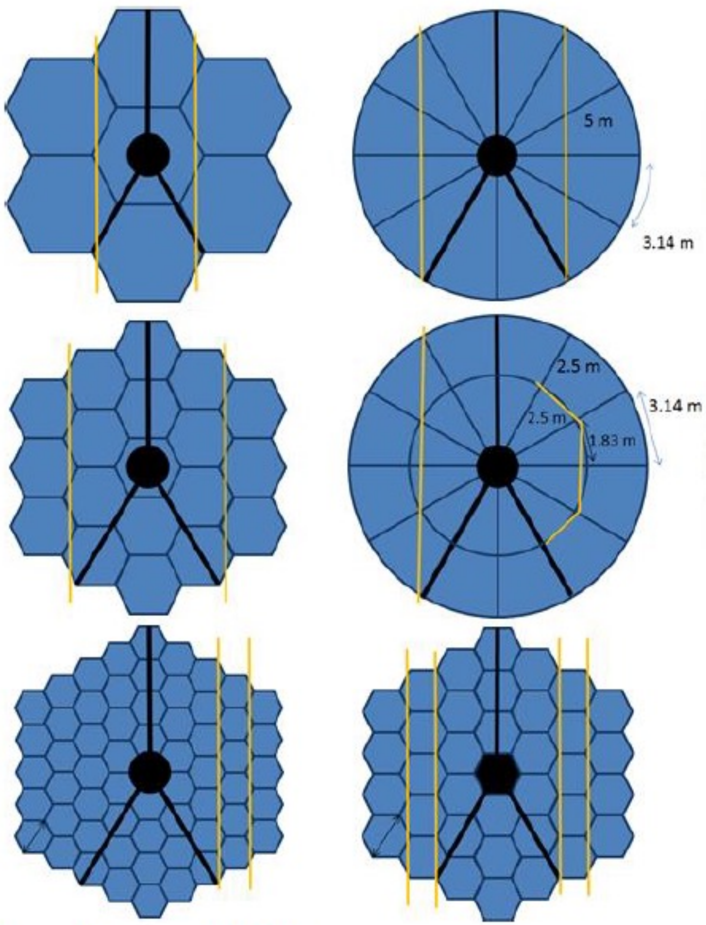
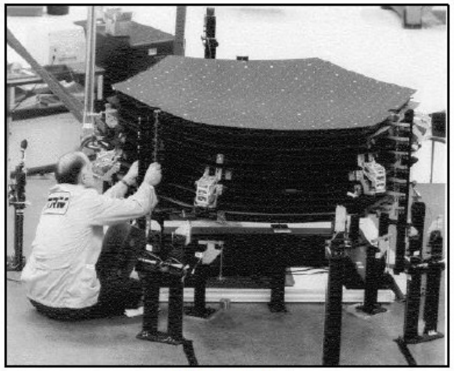
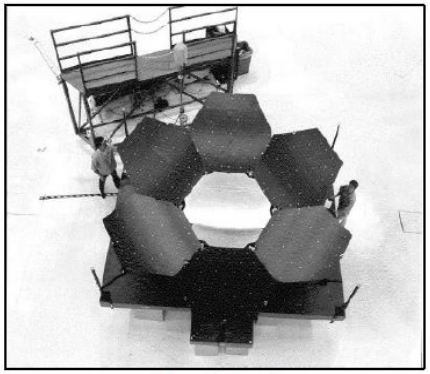


Figure 2 Some possible fold lines.

HARD Reflector



Stowed



Deployed

Comparison of Aperture Relative Merits

Table 1 Relative challenges of designs under consideration. Green to red designates least to most challenging. No absolute scale of difficulty is implied.

	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							

A document detailing the trades is available at:
*https://**exoplanets**.nasa.gov/system/.../211_**SCDA**ApertureDocument050416.pdf*

Authors: Feinberg, Hull, Knight, Krist, Lightsey, Matthews, Stahl, Shaklan

Funded Teams

- Apodized Pupil Lyot Coronagraph (APLC)
  - Led by R. Soummer, with N. Zimmerman, M. Ndiaye (Post-doc), J. Mazoyer (Post-doc), C. Stark
- Vortex Coronagraph (VC) and Lyot Coronagraph (LC)
  - Led by D. Mawet, with G. Ruane (Post-doc), and J. Jewell (JPL)
- Phase Induced Amplitude Apodization Complex Mask Coronagraph (PIAACMC)
  - Led by O. Guyon, with J. Codona, R. Belikov, students.
- Optimization approaches
  - R. Vanderbei working with the teams

- Teams began work early in CY16.

- Presently the Visible Nuller team is not funded through SCDA as they are focused on TDEM activities.

- Now for the presentations from the teams:
- Neil Zimmerman APLC
- Garreth Ruane VC
- Olivier Guyon PIAACMC

Science Yield Modeling

- APLC and VC have submitted designs to Chris Stark.
- Chris runs them through his DRM tool and evaluates the observational completeness for a number of designs.

- Method outlined in Stark et al (2014, 2015)
- Target list generated using Hipparcos catalog
  - Nearest stars < 50 pc
  - Main sequence and sub-giant stars without companions.
  - Model-based angular size
- Eta_earth = 0.1
- Exozodi density ~ solar system density (so 3 ‘zodis’ of dust)
- Telescope throughput = 0.56 (without coronagraph losses).
- Total integration time = 1 year
- V band photometric detection limit S/N=7
- Systematic limit: Planet flux > 0.1 Stellar leakage flux
- Multiple visits allowed.
- Finite stellar diameter included, aberrations / pointing / imperfections not included.

Preliminary Yield Modeling Results
Detection in Visible Light

- NOTE: These results will change as designs evolve. The results below are for 'non-robust' designs that assume an ideal telescope, perfect alignment of the masks, and no polarization losses.
  - Yields will go up with improved designs.
  - Yields will come down when robustness and aberrations are included.
  - Characterization yields will be much smaller.

	APLC		VC	
	On-Axis	Off-Axis	On-Axis	Off-Axis
12 m				
Hex 1	22	31	3	27
Hex 4	26	28	4	8
Keystone 24	31	36	7	31
Circular	31	39	8	55
6.5 m				
Hex 1	8	11	1	10
Hex 4	9	10	2	3
Keystone 24	11	12	3	11
Circular	10	13	3	19
4 m				
Hex 1	3	5	0	4
Hex 4	3	4	1	1
Keystone 24	4	5	1	4
Circular	4	5	1	8

FY16 Results Summary

- Generated white paper on segmented coronagraph aperture
- *Powerful new optimization approaches* employed for Vortex and PIAA coronagraphs.
- Significant advances have been made in *coronagraph throughput* for on-axis segmented mirrors.
  - Throughput of APLC has doubled, and bandwidth increased by 50% compared to 2015.
- Significant advances in *coronagraph robustness*.
  - APLC designs allow ~0.6% scale errors, and wavefront control allows an additional 0.2% margin.
- Significant progress *in coronagraph contrast*
  - Broadband (10%) contrast of 1e-10 for both APLC and VC.
  - Viable VC designs did not exist for segmented apertures in 2015.
- *Inner working angles* of >3 lambda/D for APLC and VC.
- *Supercomputers* employed to explore thousands of designs (APLC).
- *Powerful new optimization approach* opens design space for VC.
  - Viable solutions with amplitude-only masks (DMs not needed).
- Pie-wedge and Keystone emerging as significantly higher throughput than Hex segment apertures.
  - On-axis APLC designs approach off-axis (unobscured) in coronagraph performance.
  - With VC, off-axis design has double the throughput of on-axis.

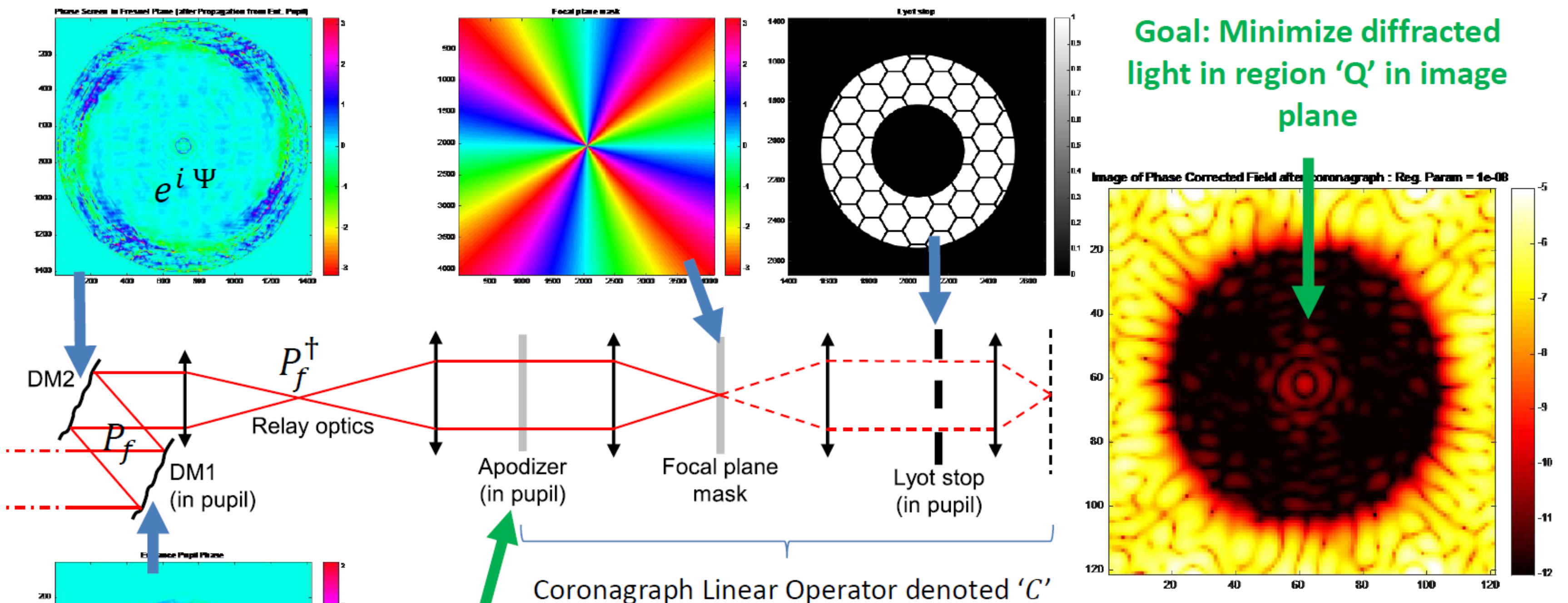
FY17 Plans

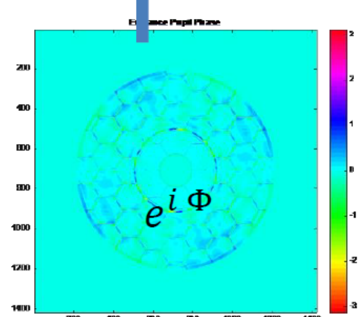
- Continue design of HLC and VC coronagraphs (Mawet, CIT)
  - Battery of designs, robustness, science return, supercomputers
  - Explore mask optimization for HLC
  - Gray-scale mask studies (in collaboration with STScI and JPL)
  - Laboratory demo of high contrast solution (1e-7 or better)
- Continue design of APLC coronagraphs (Soummer, STScI)
  - Battery of designs, add DoFs in focal plane, combine with WFC, robustness, science return
  - Gray-scale mask studies (in collaboration with CIT and JPL)
  - Laboratory demo of high contrast solution (1e-7 or better)
- Continue design of PIAACMC (Guyon and Belikov)
  - Explore design space
  - Battery of designs, robustness, science return
- Continue development of Auxiliary Field Optimization (Jewell, JPL)
- Evaluation of designs (JPL)
- Dynamics error budget for one of the designs (JPL)

Backup Material

Auxiliary Field Optimization: Powerful New Approach to Optimizing the DM shapes and Pupil Amplitude Profile

Iterative Solution of Phase Control with an Auxiliary Field (Jeff Jewell, JPL)





Aux Field, denoted 'W', lives in this plane!

Iteration to solve for phase control D.o.F:

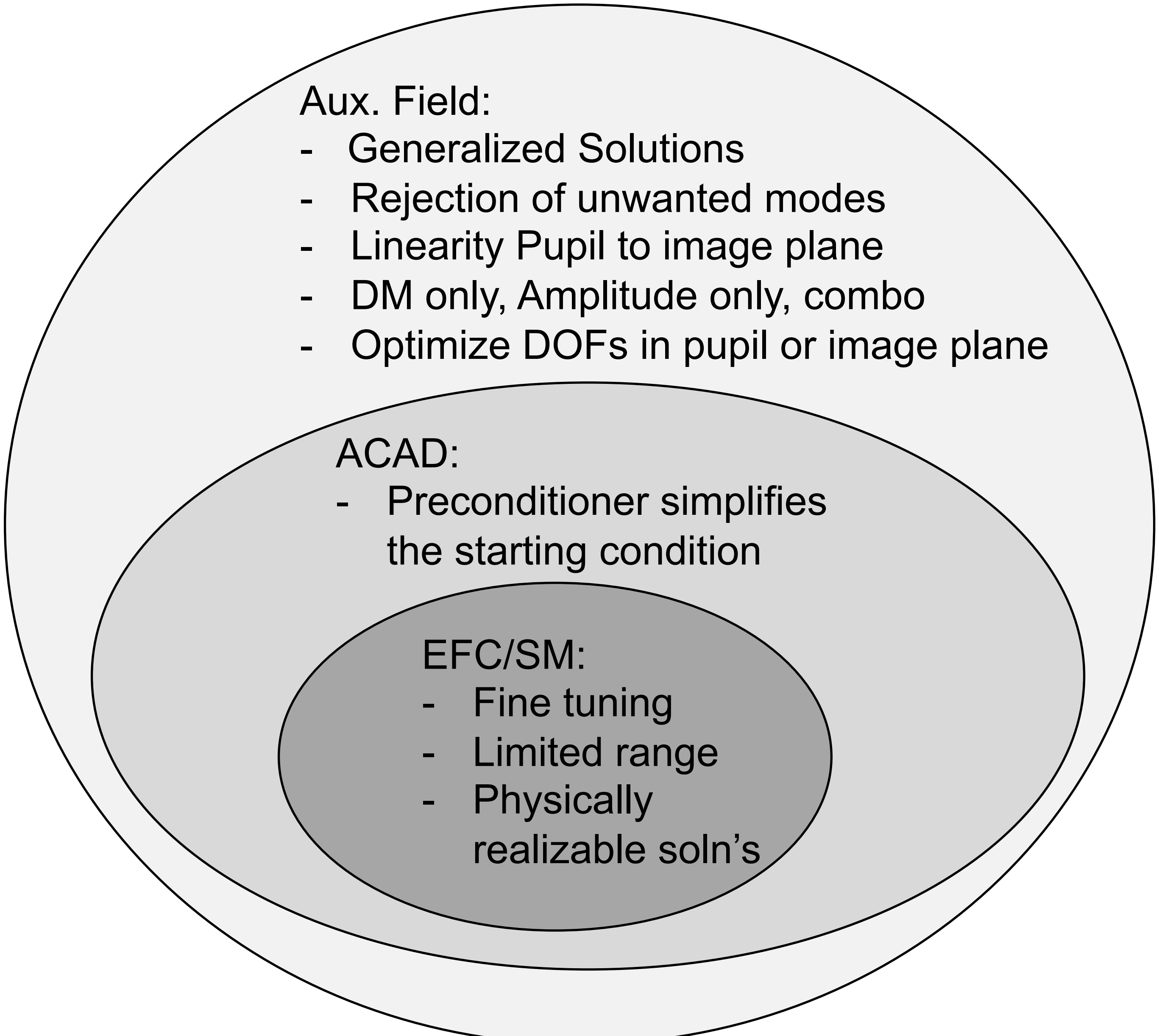
$$1)\ \min_{W}\left(\|QCW\|^2 + \lambda\left\|W - P_f^\dagger e^{i\Psi} P_f e^{i\Phi} A\right\|^2\right)$$

$$W = \left(\lambda I + C^\dagger Q C\right)^{-1} \lambda P_f^\dagger e^{i\Psi} P_f e^{i\Phi} A$$

$$2)\ \min_{\{\Psi,\Phi\}}\left\|W - P_f^\dagger e^{i\Psi} P_f e^{i\Phi} A\right\|^2$$

- Fresnel Propagators denoted P_f and (backwards) $P_f^\dagger$
- Goal is to find phase solutions in the entrance pupil $e^{i\Phi}$ and out of plane $e^{i\Psi}$ for any aperture in order to directly minimize on-axis source light in the image plane "dark hole"

Domains of AFO, EFC/SM, and ACAD



Powerful New Optimization Approaches: Auxiliary Field, and Linear Coronagraph Theory

- Two new approaches, Auxiliary Field Optimization (AFO) and Linear Coronagraph Theory (LCT) have been developed under SCDA funding.
  - These complement the approaches used to date: Electric Field Conjugation (EFC) and its close cousin Stroke Minimization (SM), and Active Correction of Amplitude Discontinuities (ACAD)
- A quick summary of the approaches, with EFC and ACAD discussed as reference points:
- **AFO: for generalized solutions with segmented pupils**
  - New algorithm finds the complex pupil field that best minimizes the dark hole, subject to physical limitations of DMs. Developed in conjunction with the vortex coronagraph design effort.
  - Linear between pupil and image plane.
  - Proven useful for addressing pupil discontinuities in a wide range of conditions: DMs only, amplitude masks only, combinations of both.
  - So far used only to address the pupils and wavefronts, not the design of the coronagraph masks or Lyot Stop.
- **LCT: for design of focal plane masks given an apodization function**
  - New algorithm for optimizing the focal plane mask given a pupil apodization .Developed as part of the PIAA design effort.
  - Linear approach based on expressing arbitrary apodized pupil complex max coronagraph as a series of linear matrix operations.
  - Linear operators provide a means of projecting out undesired modes, e.g. rejecting leakage from tip-tilt or finite star diameter.
- EFC/SM: for ‘fine-tuning’ the broadband dark hole.
  - Use DMs to minimize scatter in the dark hole. EFC sets the contrast goal to C=0. SM minimizes the stroke subject to an iteratively decreasing contrast goal.
  - This algorithm maps DM phase to image plane electric field, which is a non-linear mapping. It requires recalculation of large Jacobian matrices as the DM shapes evolve.
- ACAD: for pre-conditioning the pupil to account for obscuring struts and segment gaps
  - Use ray optics to compute DM shapes that flatten the pupil, effectively filling in segment gaps.
  - Use EFC/SM to account for diffraction and optimize the dark hole.
  - Tends to lead to large DM strokes. Recent developments show that a patient application of SM (thousands of iterations, careful control of convergence) leads to better solutions with smaller DM strokes.