ExoSpinAp

Jet Propulsion Laboratory
California Institute of Technology

An architecture for space-based exoplanet spectroscopy in the mid-infrared

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Jet Propulsion Laboratory
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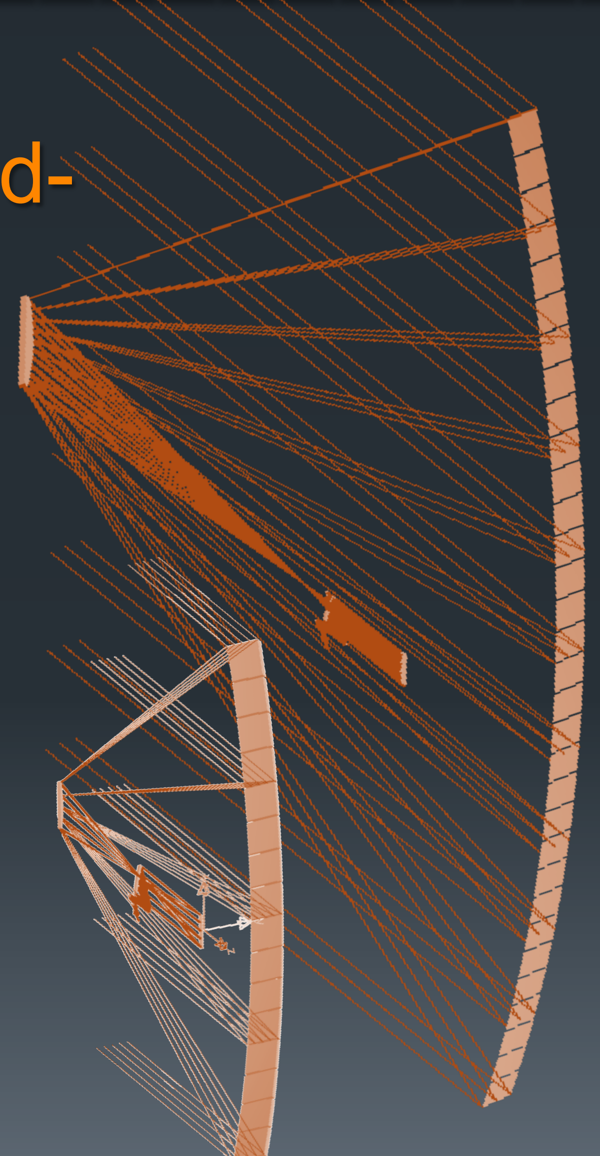

Government sponsorship acknowledged

Concept Objectives

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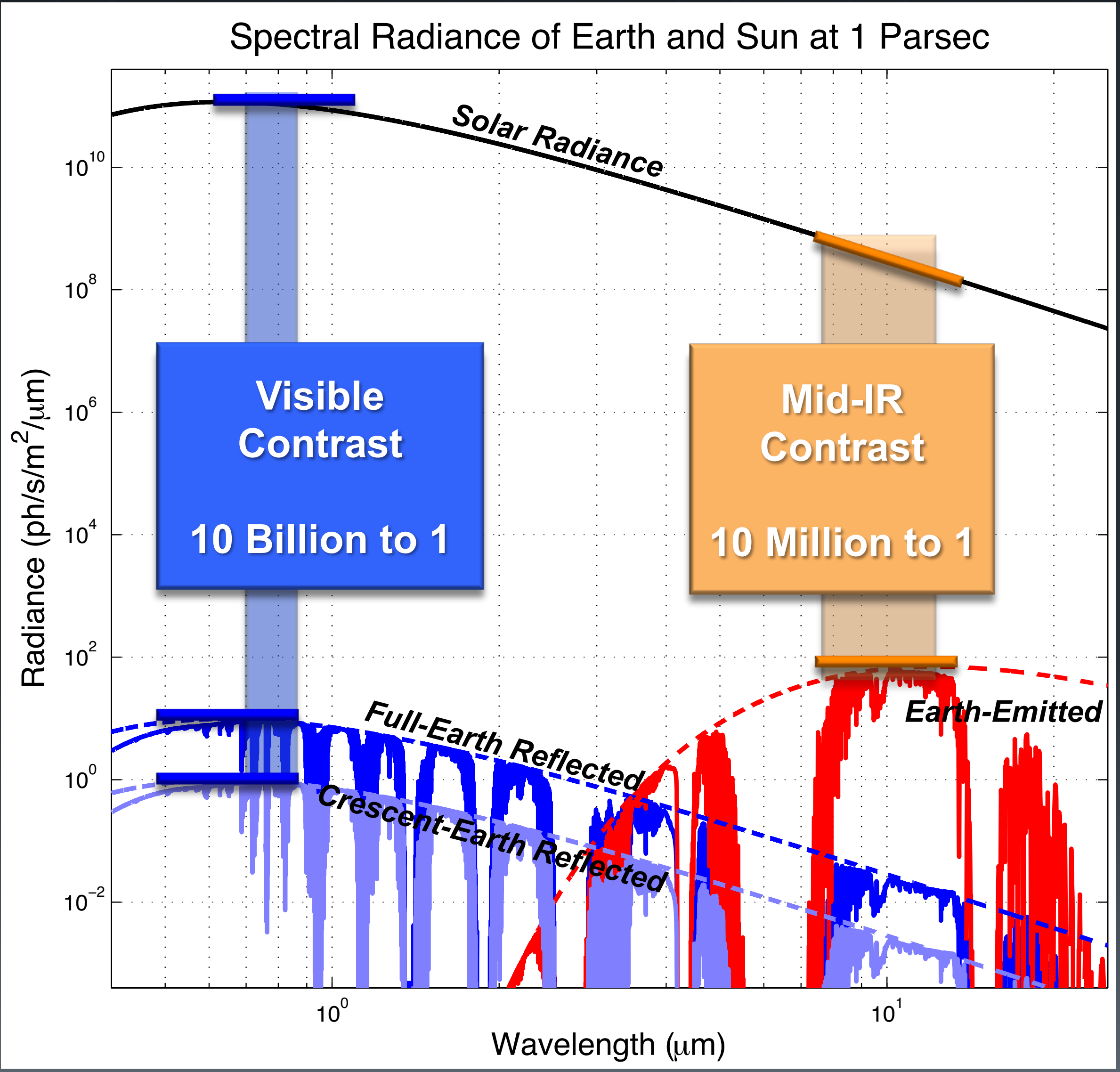
- **Science** *Direct imaging and spectroscopy of Earth-like exo-planets*
- **Engineering** *Maintain requirements with current class of technologies*
- **Scalability** *Offer compelling science even at designs that may fit into the NASA probe class*

Characterization in Mid-IR is Easier



- Earths are brightest at 10um

10-30x Faster to Detect

- 10^{-7} contrast permits 10-nm tolerances **not** *picometers*

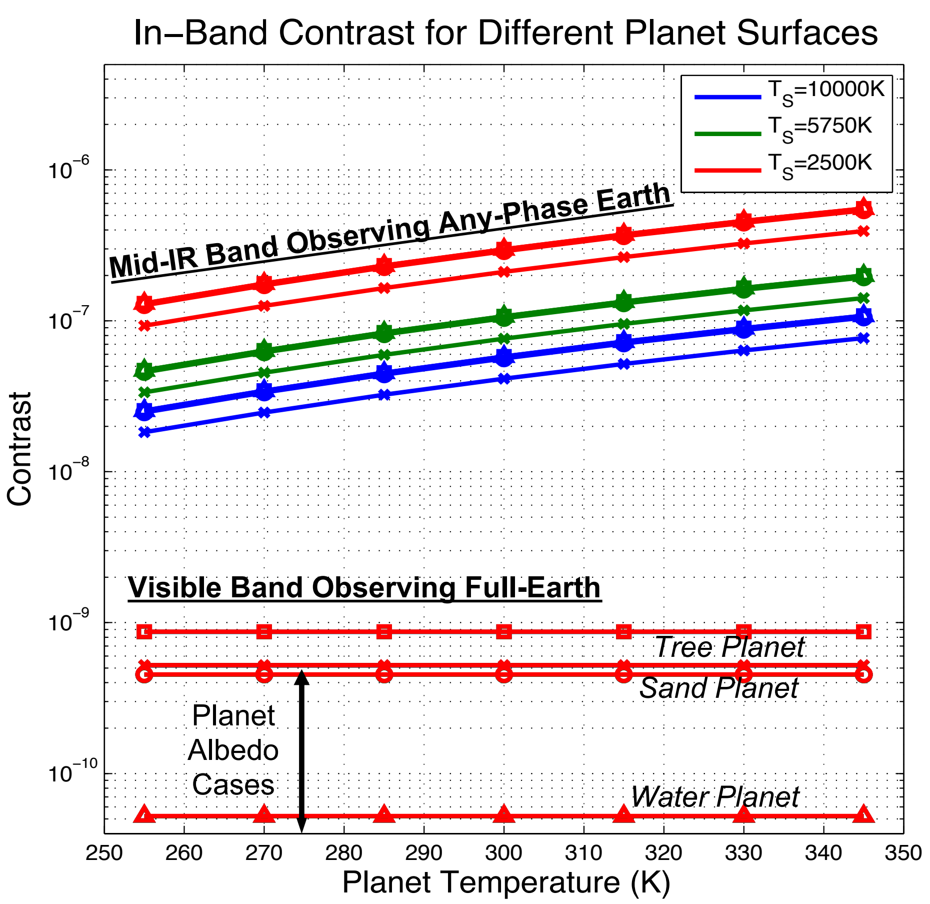
> 1000x relaxation

- Access to many important chemicals signatures

Water, Ozone, Ammonia, Methane, Silicates, NO_2, and CO_2

It just has to be big and cold…

Warm Planets Wanted



	B1 = 700-840nm B2 = 7.5-12.5um	Planet Temp (K)	Stellar Contrast		
			B1	B2	Ratio
5750K Star	**Average Earth** *Albedo: B1=30% B2=30%*	300	5.2E-10	7.6E-08	*146*
	Sand Planet *Albedo: B1=26% B2=4%*	300	4.5E-10	1.0E-07	*230*
	Water Planet *Albedo: B1=3% B2=1%*	300	5.2E-11	1.1E-07	*2050*
	Tree Planet *Albedo: B1=50% B2=1%*	300	8.7E-10	1.1E-07	*123*
	Snow Planet *Albedo: B1=90% B2=4%*	265	1.6E-09	5.6E-08	*36*

Mid-IR contrast benefits from cooler stars -but- habitable zone worsens

TRAPPIST-1 at 2511K has a habitable zone of ~ 0.03 to 0.05 AU

ExoSpinAp Approach

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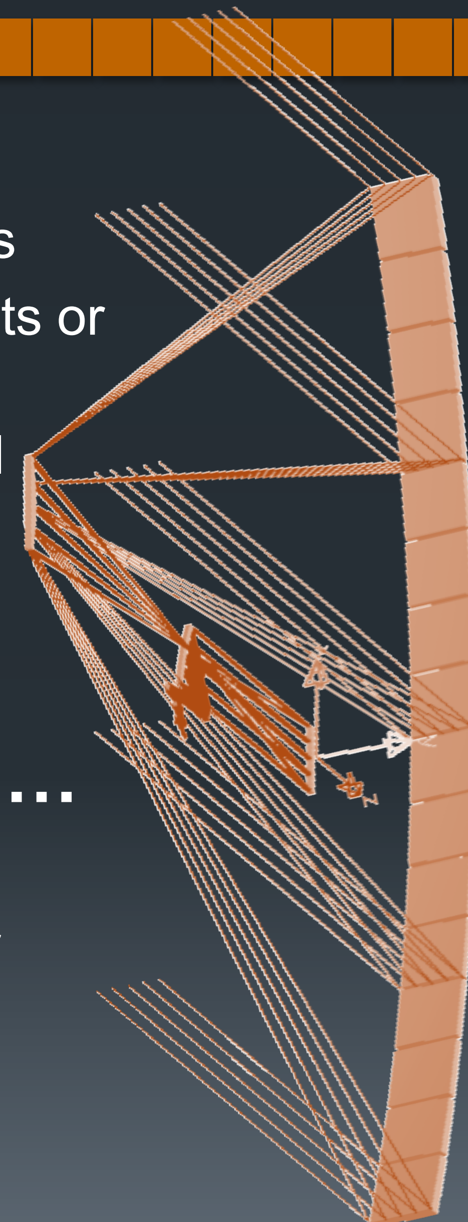
- **Synthesize the large aperture by…**
  - Linearize aperture to minimize fabrication requirements
  - Segment primary mirror to enable compact deployments or on-orbit assembly
  - Use laser metrology trusses to actively stabilize optical architecture
    - 5-10 nanometer tolerance needed



- **Puts resolution only where its needed…**
  - Collecting area maximally leveraged for resolution
  - Rotate aperture to map out discovery space about star
  - Upon full-rotation entire FOV is mapped out with 1 DM

A Strip Aperture Resurgence

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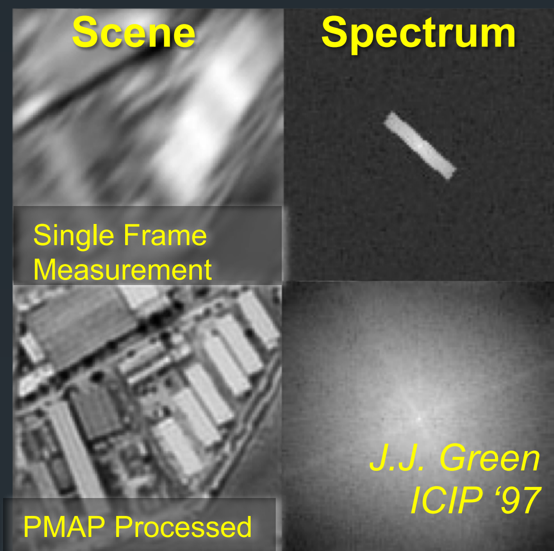
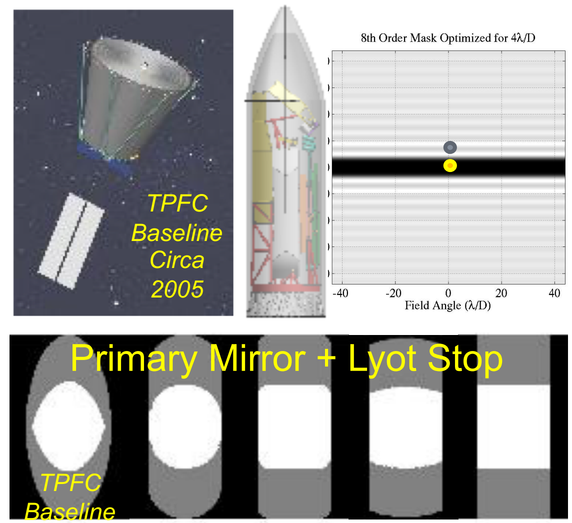
1997: Aperture Synthesis w/PMAP



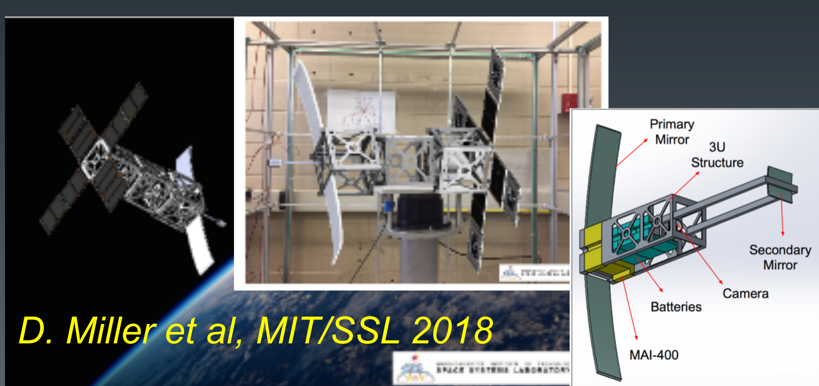
2005: TPF-C Was Becoming Linearized



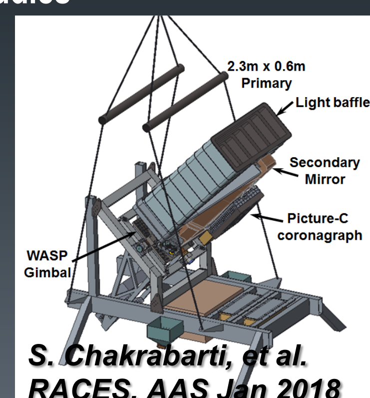
TPFC found that with Strip-Apertures

- 40% more collecting area for 8% more PM
- Planet PSF 50% more compact
- **2X** Science over the 8x3.5m baseline!

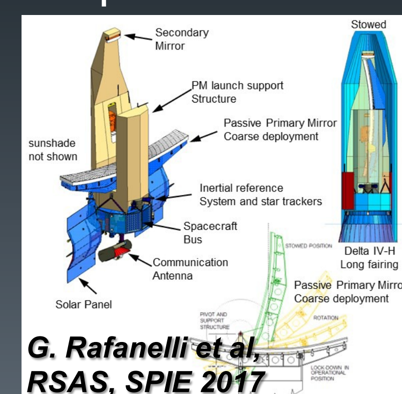
2018: REIF-Sat Cubesat Demo Concept



2018: Rotatable Aperture Coronagraph for Exoplanetary Studies

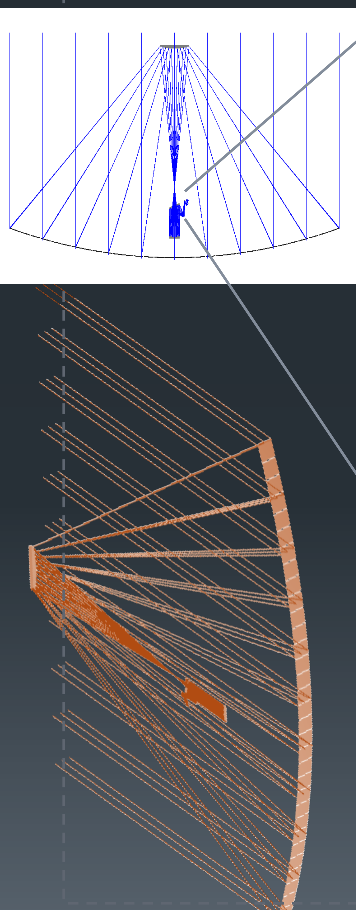


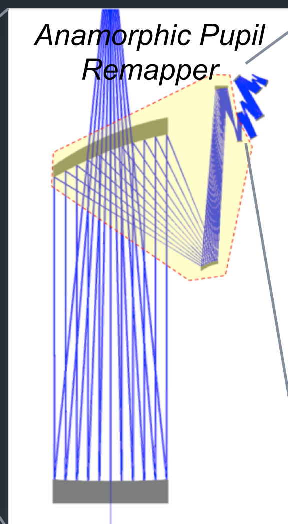
2017: Revolutionary Astrophysics using an Incoherent synthetic optical aperture



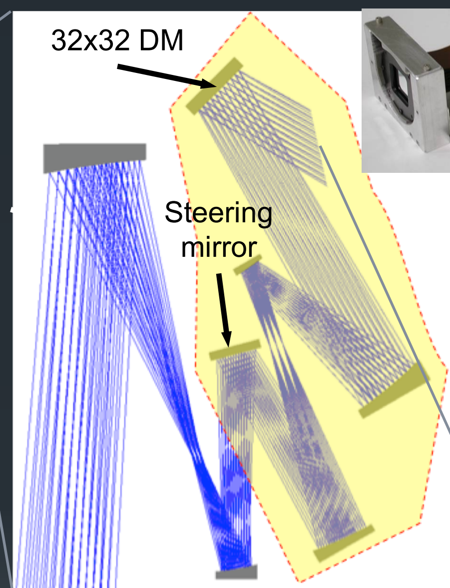
Architecture Overview

Strip Aperture Telescope → Asymmetric Pupil Relay → Pointing and WF Control → Starlight Suppression → 2-D Multiband Imager / Spectrometer

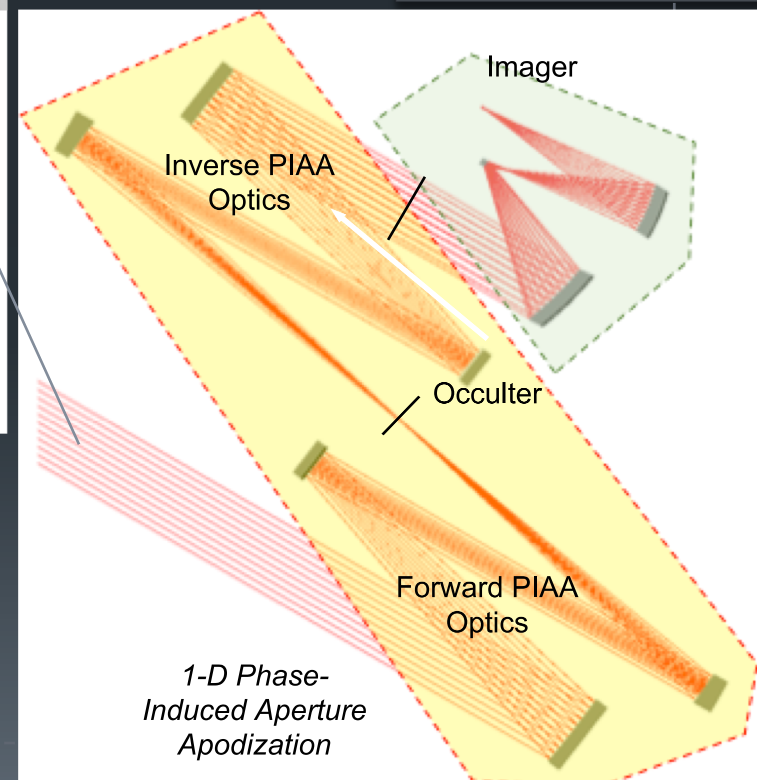




Remaps pupil into small square form factor



Relay for Steering and Deformable Mirrors



Linearized PIAA Approach

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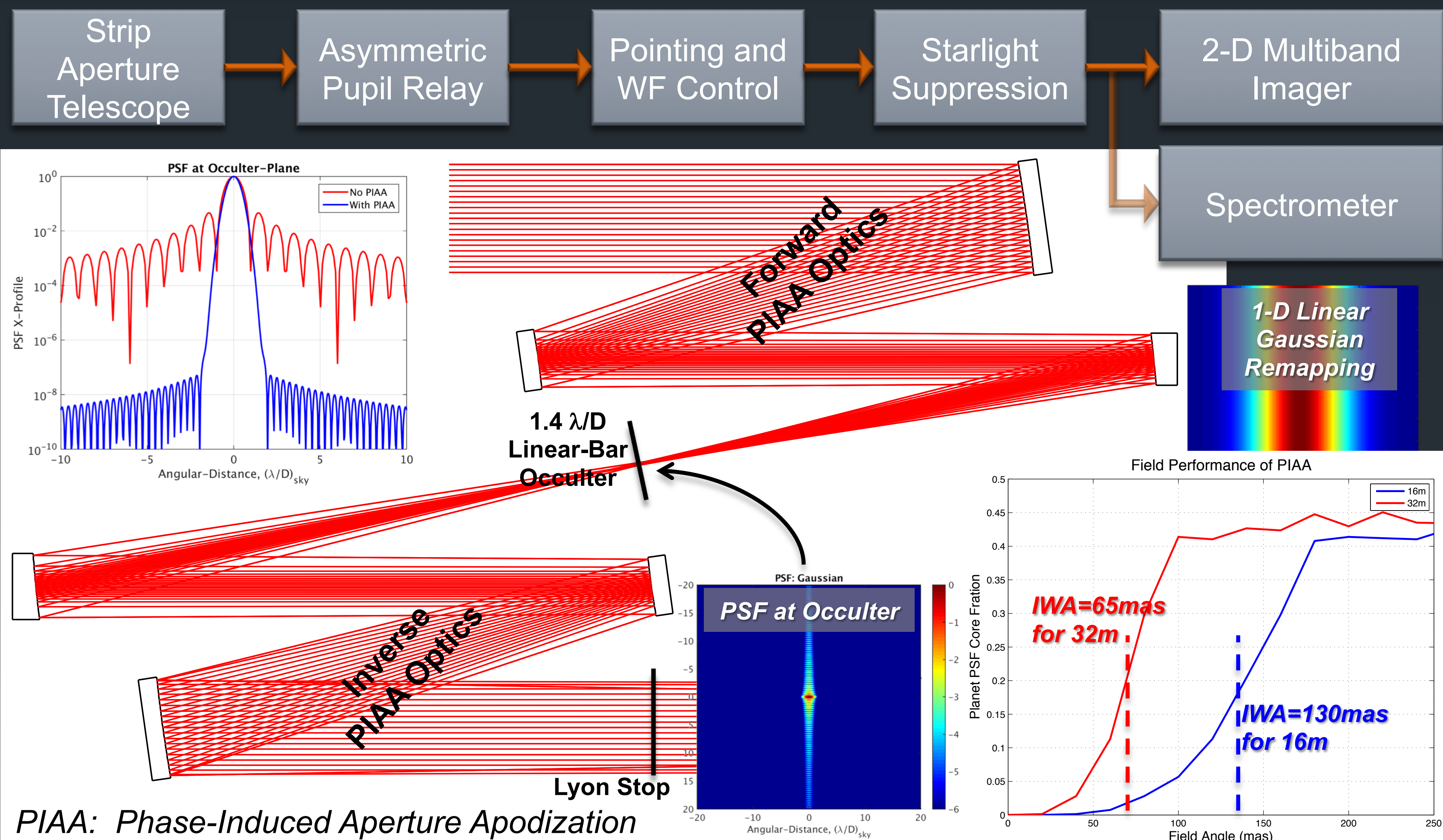

PIAA: Phase-Induced Aperture Apodization

Aberration Control & Sensitivity

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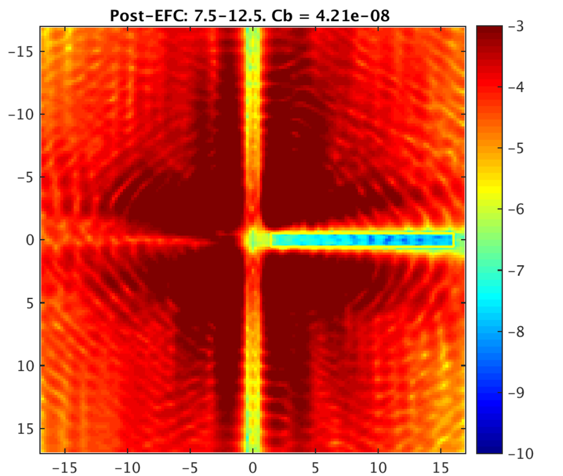
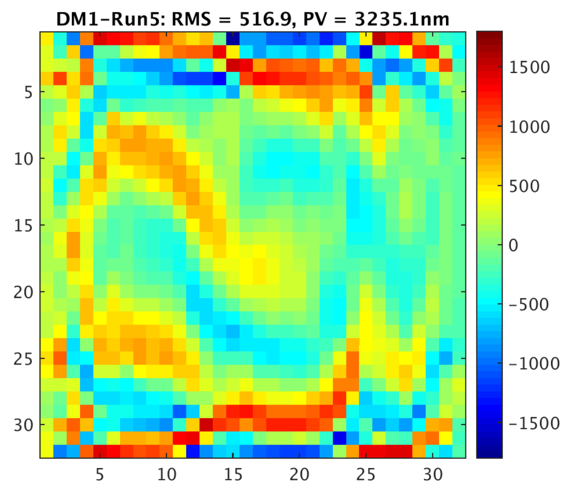
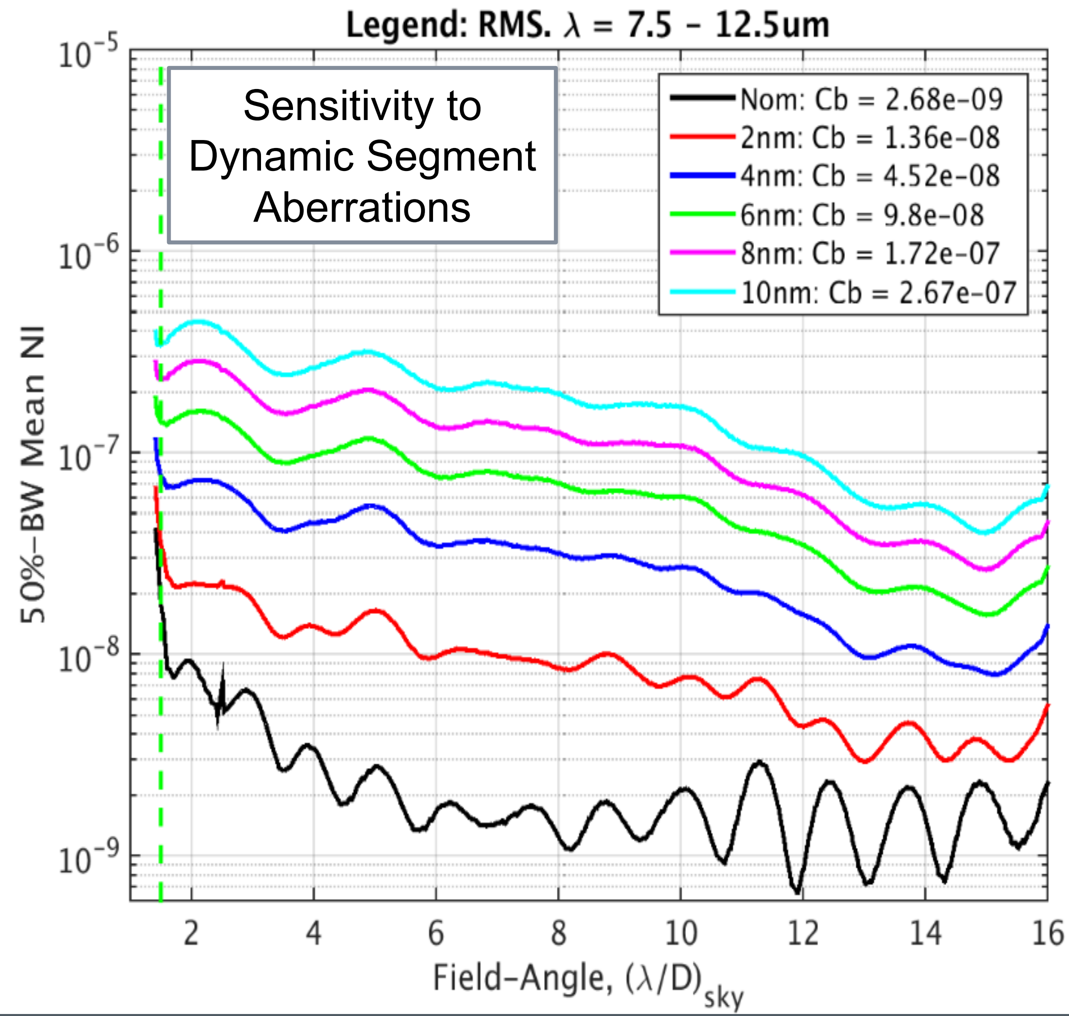
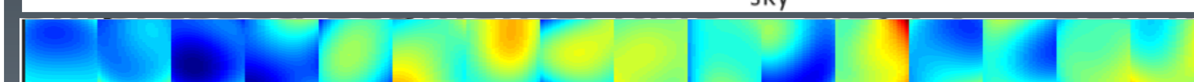
7.5-12.5 um Control of Static









Observation Concept

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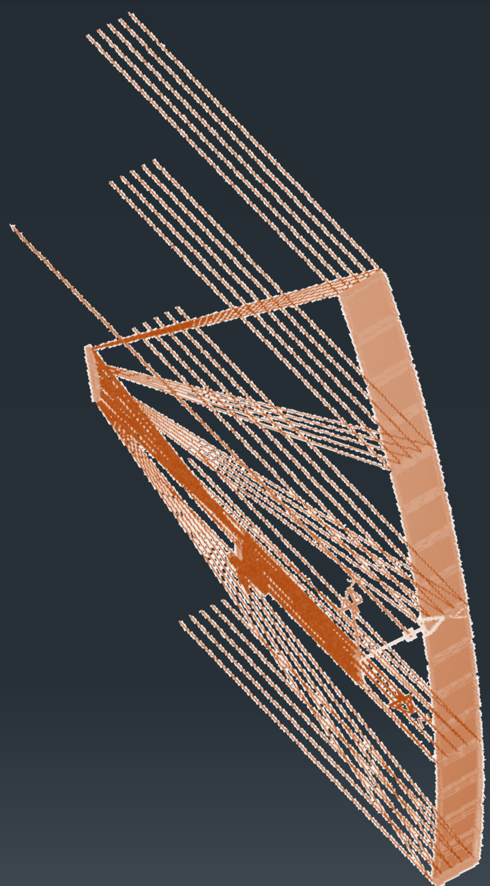
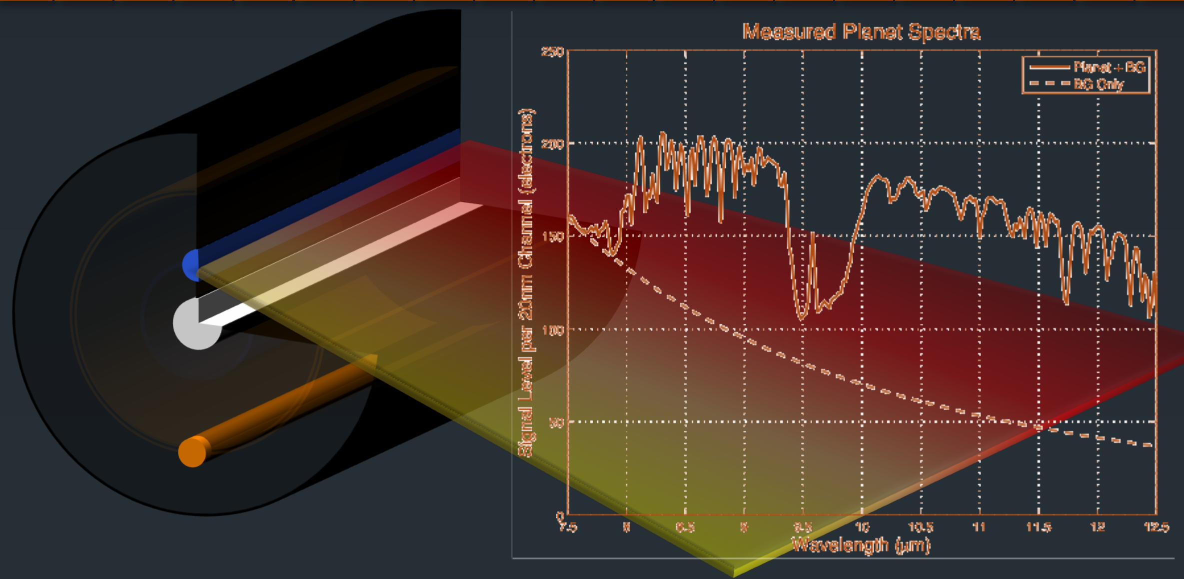
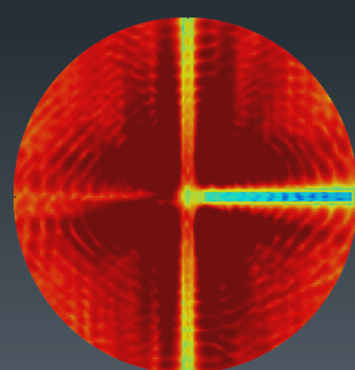
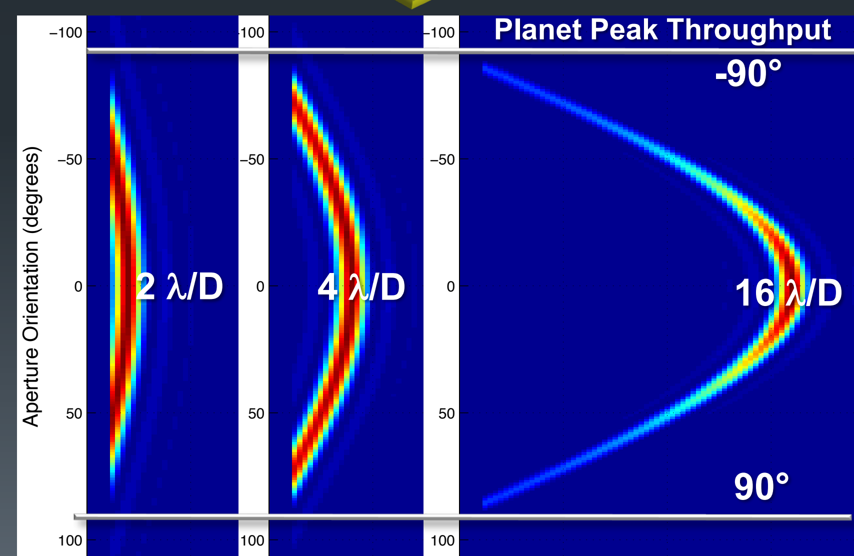




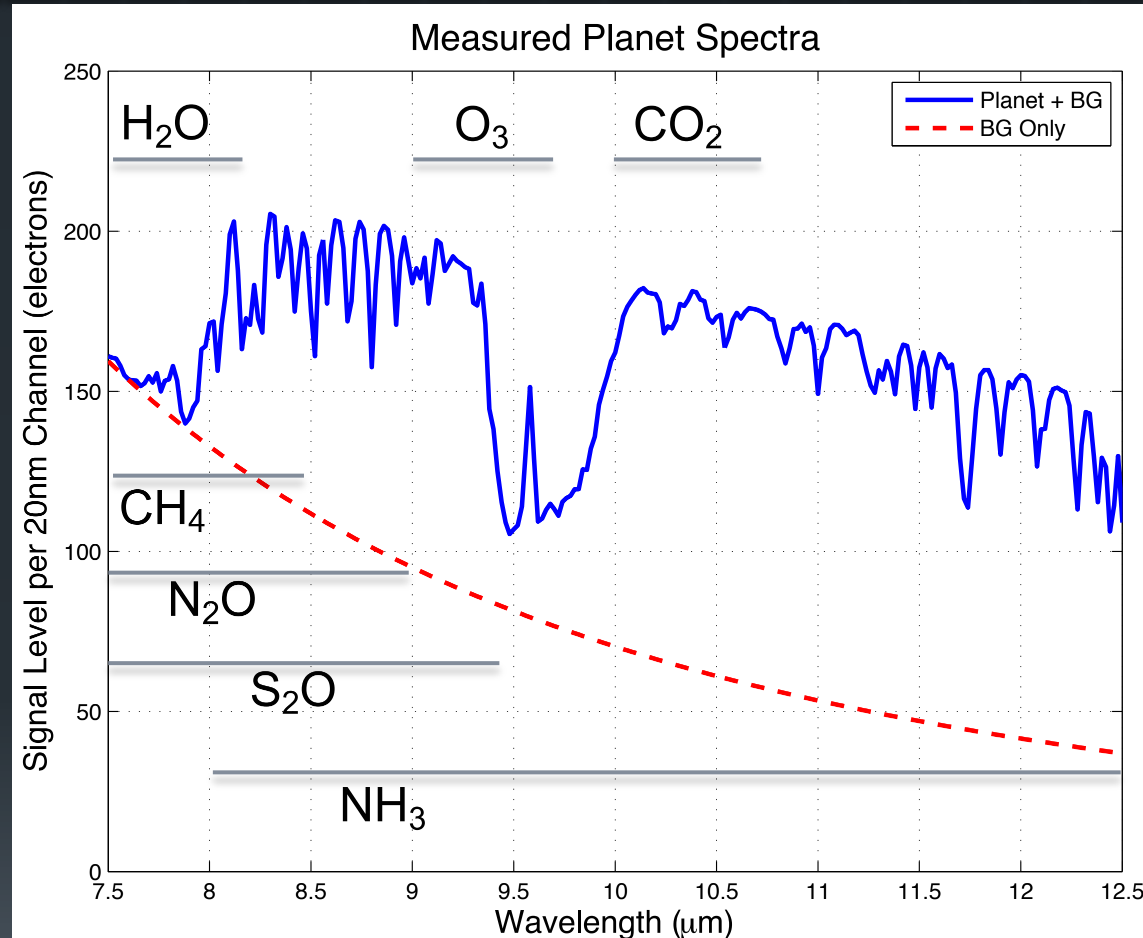




16-meter Example

Characterization Potential

- **Atmospheric Retrieval**
  - Water Vapor, Methane, Ozone, Ammonia, Hydrogen Sulfide, Sulfur Dioxide
- **Surface Temperature Emissivity Separation**
- **Surface Mineralogy**
  - Silicates, Oxides, Sulfates and Hydroxides
- **Temporal and Rotational Characteristics**
  - Scan Repeat every 60-90min
  - Observe spectral evolution as water, land and clouds vary.



16m Aperture with 20nm/channel
60 min/scan and 36 second/frame
Earth-Sun Analogy at 1 Parsec

Catalog Performance

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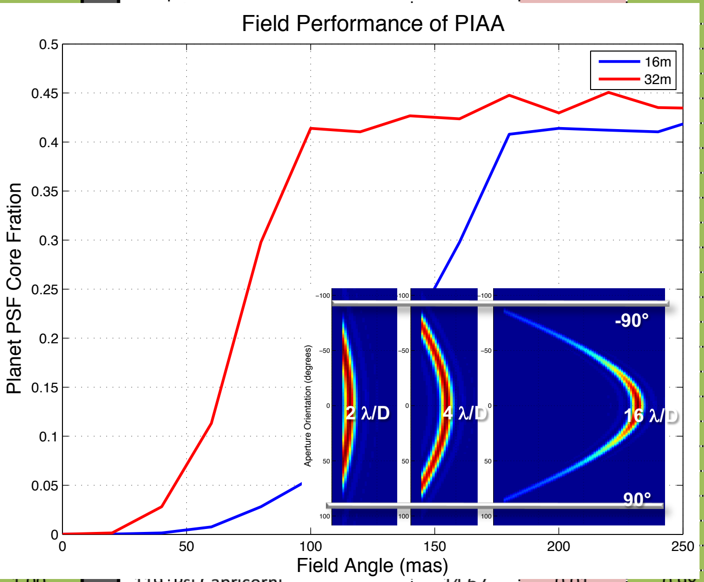
	Star	Parsecs	P-Throughput 16m	32m
1	Alpha Centauri	1.35	1.00	1.00
2	Alpha Canis Majoris	2.64	1.00	1.00
3	Epsilon Eridani	3.22	1.00	1.00
4	Alpha Canis Minoris	3.50	1.00	1.00
5	61 Cygni	3.50	1.00	1.00
6	Epsilon Indi	3.63	1.00	1.00
7	Tau Ceti	3.65	1.00	1.00
8	Omicron¬≤ Eridani	5.04	1.00	1.00
9	70 Ophiuchi	5.09	1.00	1.00
10	Alpha Aquilae	5.14	1.00	1.00
11	Sigma Draconis	5.77	1.00	1.00
12	HR5568	5.91	1.00	1.00
13	Eta Cassiopeiae	5.95	1.00	1.00
14	36 Ophiuchi	5.98	1.00	1.00
15	HR7703	6.05	1.00	1.00
16	82 Eridani	6.06	1.00	1.00
17	Delta Pavonis	6.11	1.00	1.00
18	HR8832	6.52	1.00	1.00
19	Xi Bov∂tis	6.70	1.00	1.00
20	HR753	7.21	0.99	1.00
21	HR6426	7.24	0.99	1.00
22	HR222	7.46	0.98	1.00
23	107 Piscium	7.47	0.98	1.00
24	Beta Hydri	7.47	0.98	1.00
25	Mu Cassiopeiae	7.55	0.97	1.00
26	HR8721	7.64	0.97	1.00
27	Alpha Piscis Austrini	7.69	0.96	1.00
28	Alpha Lyrae	7.76	0.95	1.00
29	Pi¬≥ Orionis	8.03	0.91	1.00
30	Chi Draconis	8.06	0.91	1.00
31	p Eridani	8.15	0.89	1.00
32	Xi Ursae Majoris	8.34	0.84	1.00
33	Beta Canum Venaticorum	8.37	0.83	1.00
34	Mu Herculis	8.40	0.82	1.00
35	61 Virginis	8.53	0.78	1.00
36	Zeta Tucanae	8.59	0.75	1.00
37	Chi¬π Orionis	8.66	0.72	1.00
38	HR6416	8.79	0.67	1.00
39	HR1614	8.81	0.66	1.00
40	HR7722	8.82	0.66	1.00

	Star	Parsecs	P-Throughput 16m	32m
41	Gamma Leporis	8.97	0.60	1.00
42	Delta Eridani	9.04	0.56	1.00
43	Beta Comae Berenices	9.16	0.52	1.00
44	HR4550	9.16	0.52	1.00
45	Kappa¬π Ceti	9.16	0.52	1.00
46	Gamma Pavonis	9.22	0.49	1.00
47	HR4523	9.24	0.48	1.00
48	HR4458	9.54	0.37	1.00
49	61 Ursae Majoris	9.54	0.37	1.00
50	12 Ophiuchi	9.78	0.30	1.00
51	HR511	9.98	0.25	1.00
52	HR5256	10.11	0.22	1.00
53	Alpha Mensae	10.15	0.21	1.00
54	Beta Geminorum	10.34	0.18	1.00
55	HR857	10.38	0.17	1.00
56	Iota Persei	10.53	0.15	
57	HR9038	10.79	0.12	
58	Zeta Herculis	10.80	0.12	
59	Delta Trianguli	10.85	0.11	
60	Beta Virginis	10.90	0.11	
61	HR637	10.91	0.10	
62	Beta Leonis	11.09	0.09	
63	HR6806	11.10	0.09	
64	54 Piscium	11.11	0.09	
65	Gamma Serpentis	11.12	0.09	
66	11 Leonis Minoris	11.18	0.08	
67	Gamma Leporis	11.53	0.06	
68	Delta Eridani	11.63	0.06	
69	Beta Comae Berenices	11.73	0.05	
70	HR4551	11.84	0.05	
71	Kappa¬π Ceti	11.94	0.04	
72	Gamma Pavonis	12.04	0.04	
73	HR4393	12.14	0.04	
74	HR4328	12.24	0.03	
75	62 Ursae Majoris	12.34	0.03	
76	13 Ophiuchi	12.45	0.03	
77	HR10001	12.55	0.03	
78	HR14746	12.65	0.02	
79	Alpha Mensae	12.75	0.02	1.00
80	Beta Geminorum	12.85	0.02	1.00

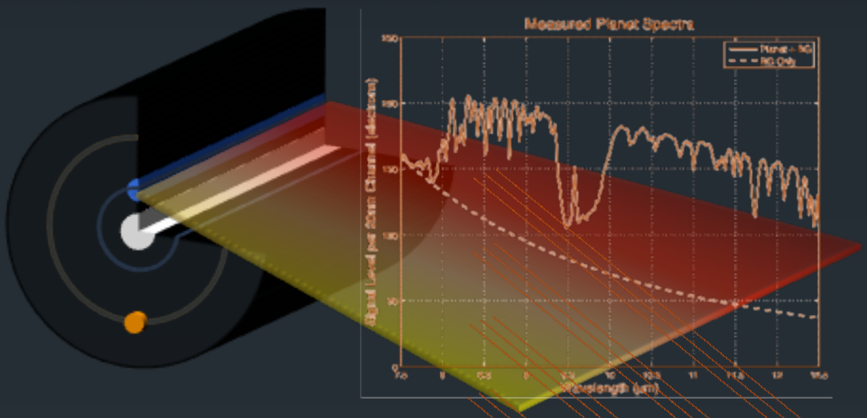
	Star	Parsecs	P-Throughput 16m	32m
81	85 Pegasi	12.40	0.03	1.00
82	Rho¬π Cancri	12.53	0.03	1.00
83	HR3259	12.58	0.03	1.00
84	HR483	12.64	0.02	1.00
85	Lambda Aurigae	12.64	0.02	1.00
86	HR683	12.68	0.02	1.00
87	44 Bov∂tis	12.76	0.02	1.00
88	HR6518	12.80	0.02	1.00
89	36 Ursae Majoris	12.85	0.02	1.00
90	HR6094	12.87	0.02	1.00
91	HR4587	12.91	0.02	1.00
92	Alpha Aurigae	12.94	0.02	1.00
93	HR6998	12.98	0.02	1.00
94	58 Eridani	13.32	0.01	1.00
95	Upsilon Andromedae	13.47	0.01	1.00
119	Psi Capricorni	14.67	0.01	0.98
120	Alpha Corvi	14.77	0.01	0.98



1-AU Planets Characterized out to 30-60 Light-Years

Remarks

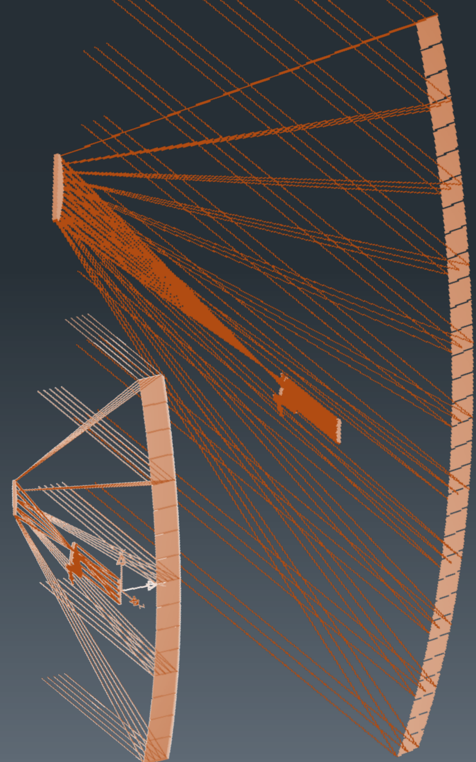
- **Mid-IR is best place for exo-planet characterization**
  - Rich in spectral features
  - Good intensity and contrast



- **Mid-IR permits practical designs over visible approaches**
  - 1000x Contrast Relaxation *nano –not- pico meters*
  - 30x Time Relaxation

- **Linearize Telescope and Starlight Suppression**

Maximize Performance with Minimum Hardware



Key Enabling Technologies

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- **Telescope**
  - 1x1m Segment Fabrication (15-30 nm class) — JWST Size / Quality
  - Segment/SM RB actuations (mm - 10nm) — Demonstrated by JWST
  - Segment Control (10-20nm class) — Demonstrated by JWST
  - Deployable/ Assemble (meters to < mm) — Follows aspects of OpTIIX concept
  - Laser Metrology Trusses — Demonstrated bySIM and other Testbeds
- **Thermal Control**
  - Conformal Deployable Shade (maintain OTA at ~55K)
- **Pointing and Wavefront Control**
  - Pointing-Mirror (0.1 urad rms in hi-res axis for 32m concept)
  - High Density Deformable Mirror — HCIT, Starfire, Palomar (but cold…)
- **Starlight Suppression and Control**
  - Linearized PIAA Optics for 10μm — Potential for relaxed fabrication specs

8m Probe Concept

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