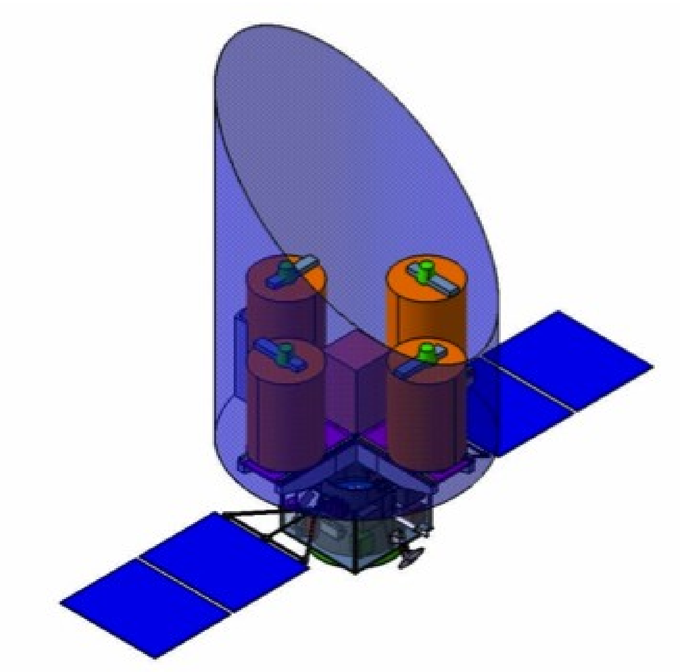
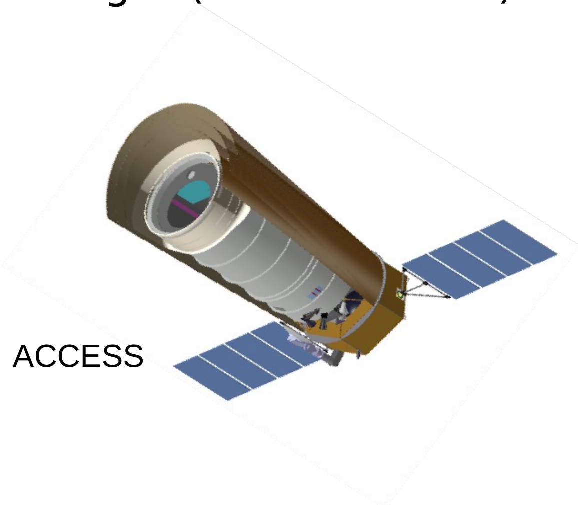
Probe class missions – internal coronagraphs

Olivier Guyon *(University of Arizona / Subaru Telescope)*
With major contributions from:

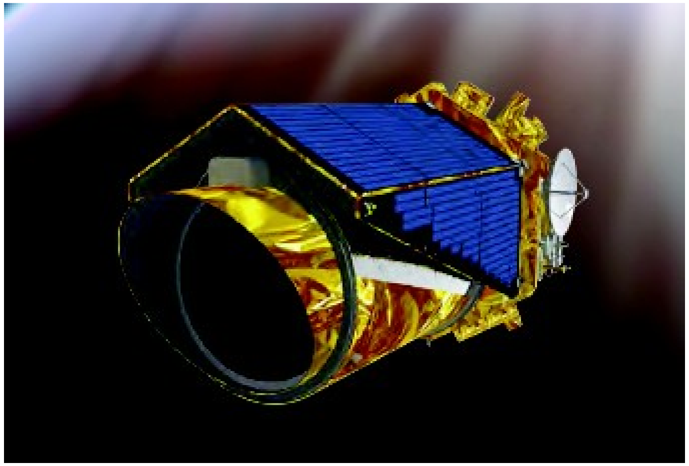
- Michael Shao (DAViNCI team)
- Mark Clampin / Rick Lyon (EPIC / VNC team)
- John Trauger (ACCESS team)



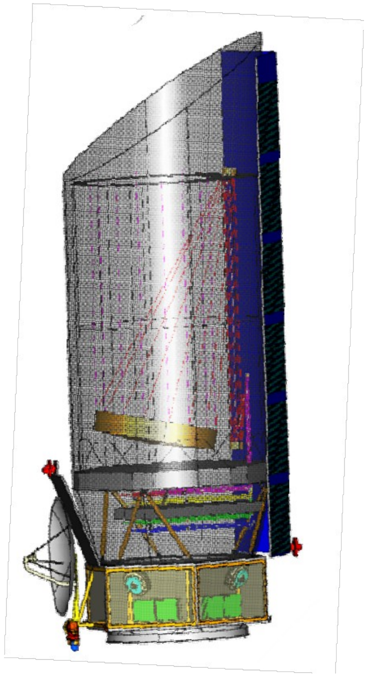
DAViNCI



ACCESS



EPIC



PECO

Science Goals

Probe-class mission <u>"secure" science goals</u> include:

(1) discovery and spectroscopic characterization of ~hundred **giant planets**
(2) mapping **exozodi clouds**, to better understand planetary systems achitectures, and prepare future flagship mission aimed at imaging Earth-like planets
(3) direct **mass measurement** for both planet and star when planet is also detected by RV
(4) **technology and science precursor** to flagship life-finder mission

(2)+(4) make a probe-class mission highly desirable to minimize risk and cost of future flagship.

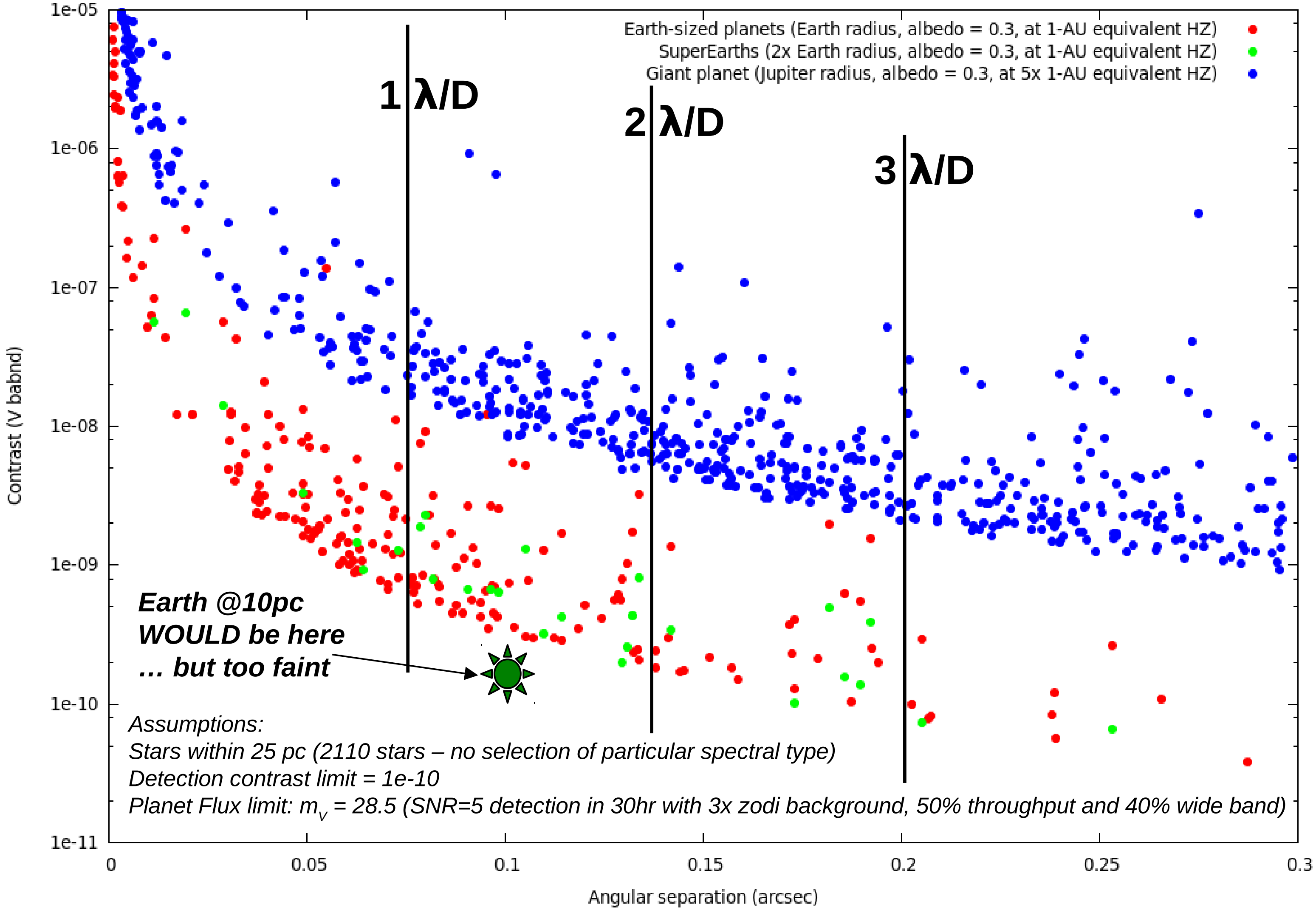
Billion $ question is:
Will potentially habitable planets (Earths or SuperEarths) be imaged and characterized (spectroscopy) with a probe-class mission ?
… maybe is the current answer (see next slides).

Performance Requirements (D=1.5m)

Inner Working Angle, Contrast and Sensitivity

	1 λ/D (0.069")	1.5 λ/D (0.103")	2 λ/D (0.137")	2.5 λ/D (0.172")	3 λ/D (0.206")	3.5 λ/D (0.241")	4 λ/D (0.275")
1e-8	2 152	94	52	29	26	20	11
1e-9	4 35 574	1 10 514	4 435	3 348	1 287	1 219	1 160
1e-10	22 102 778	15 49 718	8 26 639	7 18 552	2 7 491	2 5 423	2 3 364

D = 1.5m, λ = 500nm



Earth-like planet
Albedo = 0.3
1 Earth radius
At 1AU-scaled HZ

SuperEarth
Same as above
2 Earth radius

Giant planet
Jupiter size
Albedo = 0.3
At 5x HZ

Observatory Concepts & Strategies

Previous probe-class mission concepts studies illustrate different strategies :

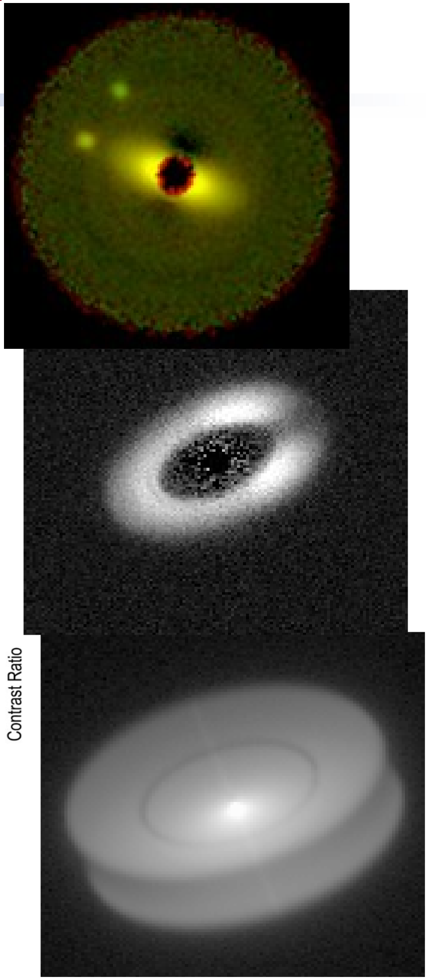
ACCESS & EPIC tend to focus on secure science goals, while allowing direct imaging of habitable planets when within reach of instrument performance
→ aimed at lower risk, cost, higher maturity

PECO makes direct imaging and characterization of habitable planets a core science goal.
→ allocates major fraction of observing time to few targets
→ requires 2 λ/D coronagraphy at nearly full efficiency

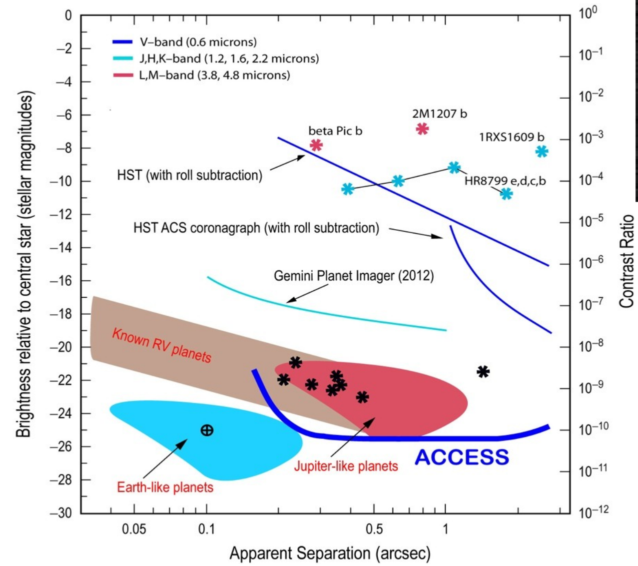
DAViNCI makes direct imaging and characterization of habitable planets its primary science goal, by boldly adopting a diluted aperture configuration.
→ highest cost of the four Probe-class missions, but larger scientific payoff

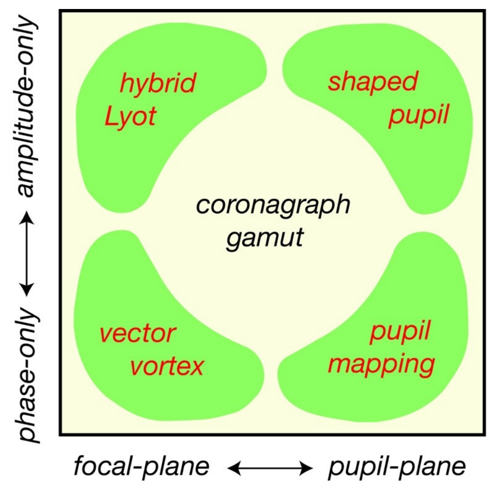
The approach to this core question is the main driver to cost, complexity and technology readiness of probe-class exoplanet missions:
Direct imaging and characterization of habitable planets with probe scale mission requires significant technology development effort

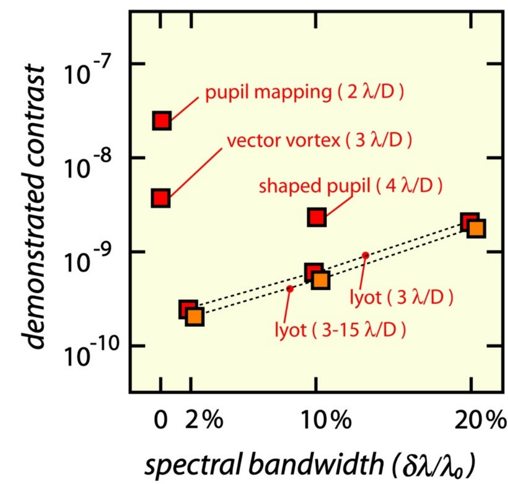
Actively-corrected Coronagraph Concept for Exoplanet System Studies (ACCESS)



- *ACCESS is one of four medium-class exoplanet concepts selected by NASA for ASMCS studies*
- *Coronagraphic imaging and spectroscopy of exoplanetary systems in reflected starlight at visible wavelengths (450-900 nm) with a 1.5 meter unobscured telescope*
- *Study compared performance and readiness of four major coronagraph architectures*
- *Defined a conceptual space observatory platform as the "level playing field" for comparisons among coronagraph types*
- *Also used laboratory coronagraph performance demonstrations on JPL's HCIT as another "level playing field" for coronagraph hardware readiness*
- *Evaluated science reach of a medium-class coronagraph mission*
- *Identified a class of scientifically compelling exoplanet mission concepts at high TRL.*



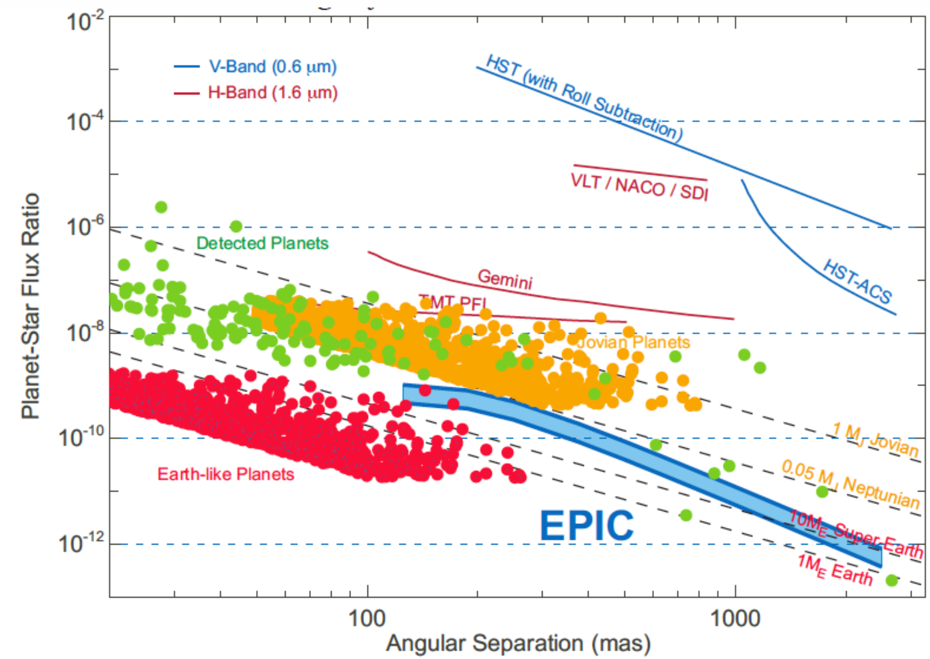


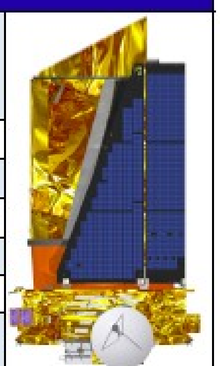


Extrasolar Planetary Imaging Coronagraph (EPIC)

EPIC Science Goals

- Determine the properties of RV selected gas giant planets
- Characterize their atmospheres
- Investigate the diversity of planetary system architectures



Science Payload	Performance	
Telescope Optics	1.65 meter aperture off-axis primary	
Coronagraph Design	Visible Nulling Coronagraph - Instrument throughput: 18% - Instantaneous Bandpass: >20%	
Science modes - Discovery - Discovery - Characterization	 $\geq 10^9$ contrast @ 2λ/D: 4.5"x4.5" FOV $\geq 10^7$ contrast @ 2λ/D: 10"x10" FOV (w/o SFA) R=20 – 50 spectroscopy	
- Discovery mode	Photon counting, 512x512 CCD detectors Readnoise: zero in photon counting mode Quantum Efficiency: 85% @ 700 nm	
Spacecraft	**Performance**	
Pointing - Via Spacecraft & fast steering mirror	Pointing Stability: 4 mas (3 σ) Coarse Pointing: 2.5" (3 σ) Abs. Pointing Knowledge: 5"	
Power	785 W	
Mass	1356 kg wet mass	
Orbit	Heliocentric, trailing Earth's orbit	
Launcher	EELV	
Mission Lifetime	5 years	
Communications	Ka-Band via HGA, <0.5 Gb/Day X-Band via Omni	

Probe Class Mission Profile

Visible nulling coronagraph: differential WFSC minimizes stressing requirements (i.e. thermal/mechanical stability) on telescope & spacecraft

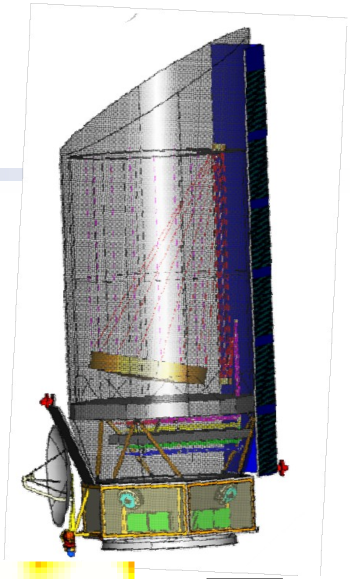
Five-year mission on drift-away orbit

Compatible with multiple launch vehicles

Deep Impact/Kepler spacecraft bus

Pointing Requirement: 4 mas (3σ) jitter

Pupil Mapping Exoplanet Coronagraph Observer (PECO)

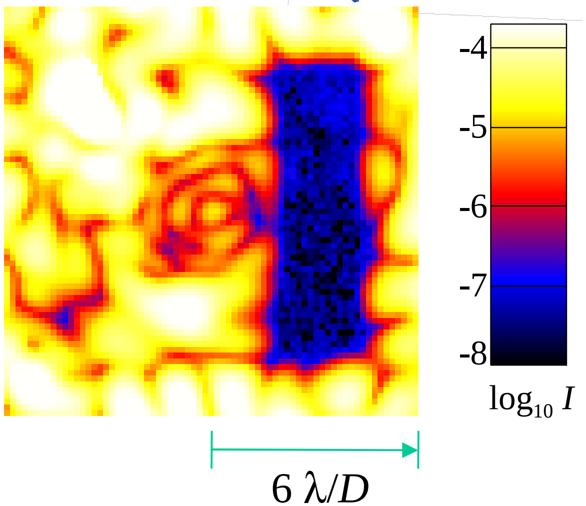


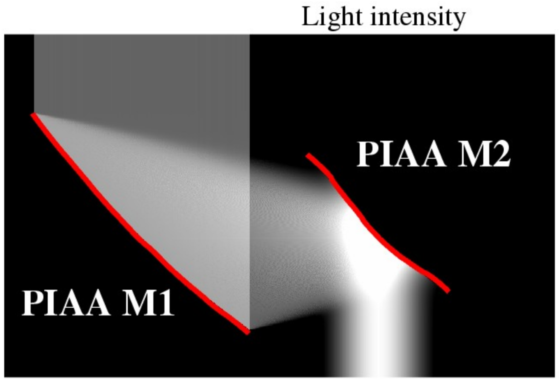
PECO Pupil mapping Exoplanet Coronagraph Observer

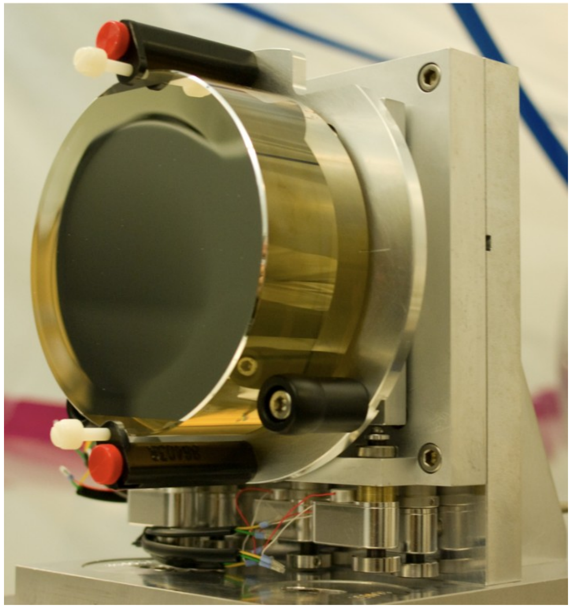
Characterization of planets (including Earths & SuperEarths) and dust in habitable zone

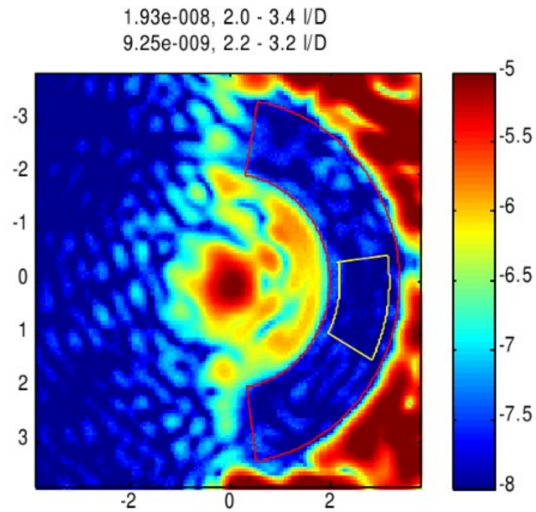
Around 7 stars, Earth-analog can be detected and characterized at R=20

1.4m diameter off-axis telescope, 3 yr mission
Uses high efficiency low IWA (2 λ/D) PIAA coronagraph
0.4 – 0.9 micron spectral coverage / R~20, polarimetric imaging
Active technology development program includes NASA JPL, NASA Ames, Subaru Telescope, Lockheed Martin







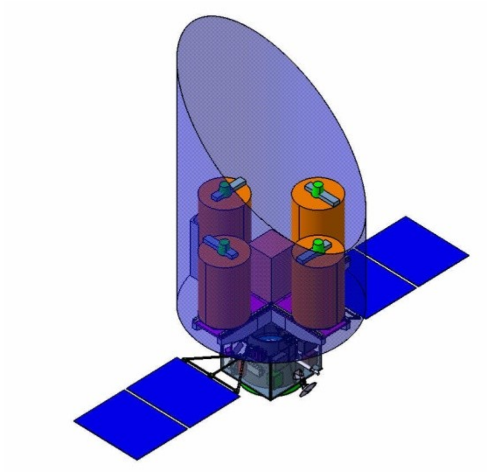


Dilute Aperture Visible Nulling Coronagraphic Imager (DAViNCI)

IWA = 38mas @800nm,   0.5um to 1.7um converage (25%BW)
Science of an 8m telescope at the cost of a 2.5m telescope

Four 1.1m diameter telescopes inside of a 4.5m fairing. Nulling coronagraph.

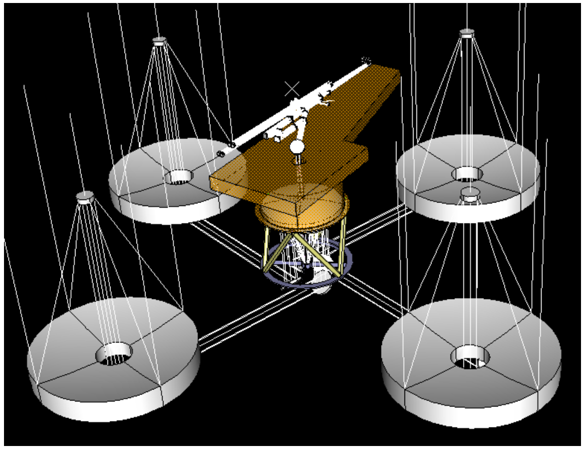
Equal collecting area to a 2.2m telescope, but telescope costs much lower than a filled aperture on axis 2.2m telescope



Baseline = 2.2m (side of square), 4.2m tip to tip

Team X cost ~1.15 B total cost, includes launch vehicle and 5 years of mission operations. Cost roughly equal to a ~2.5m coronagraph

Science Case



38 mas IWA @ 800nm (Inner Working angle ~25mas @ 500nm)

Exo-Earth science equal to **~8m 2λ/D coronagraph ,** or 76m occulter (vs 50m) at 166,000 vs 72,000 km.

Science instrument **R~80** spectrometer **0.5um to 1.7um**, 25%BW at a time.

Technology Status (1/2)

Starlight suppression system (more in 2 slides)

Goal: demonstrate contrast / IWA / throughput / spectral bandwidth performance in lab (see next slide)

- **Wavefront control**
  - **Deformable mirror technologies**
    - Two technologies available: PMN+flexible membrane, or MEMS
    - Never flown before, but no major fundamental problem foreseen
  - **Wavefront control algorithms**
    - Under active development
    - Fundamental principles validated in labs, better than 1e-9 contrast validated at 4 l/D
    - Has never flown before (on-board computing, automated operation ?)
- **Coronagraph**
  - **Optics manufacturing**
    - Relaxed by wavefront control
    - Currently available high quality optics suitable
    - Specific components (PIAA mirrors, focal plane masks, beam combiners, fibers) demonstrated at or close to required performance
  - **Polychromatic design**
  - **Polarization**

Detectors

Need near zero photon noise detector with high QE
Technology exists in visible light (EMCCDs offer <e- RON with > 90% QE)
But: further maturation required for flight validation

Technology Status (2/2)

Telescope Pointing

Requirements:
~mas RMS pointing error (= stellar angular size)
~0.1 to 0.3 mas calibration

OK with dedicated sensor free of non-common path error
0.1 mas closed loop demonstrated in PIAA air testbed @ Subaru, soon to be deployed at JPL

Telescope WF stability

Requirement:
(@500nm, C=1e-9 speckle = 1.8pm pupil sine wave in phase)
Requirement per mode is the same for low order or high order mode, except within IWA (relaxed)
… but relaxed requirement for large IWA is a lure, as coronagraph then cannot sense the mode(s) !!!
For 25 actuators across DM (490 modes) → 34 pm RMS within controlled frequencies

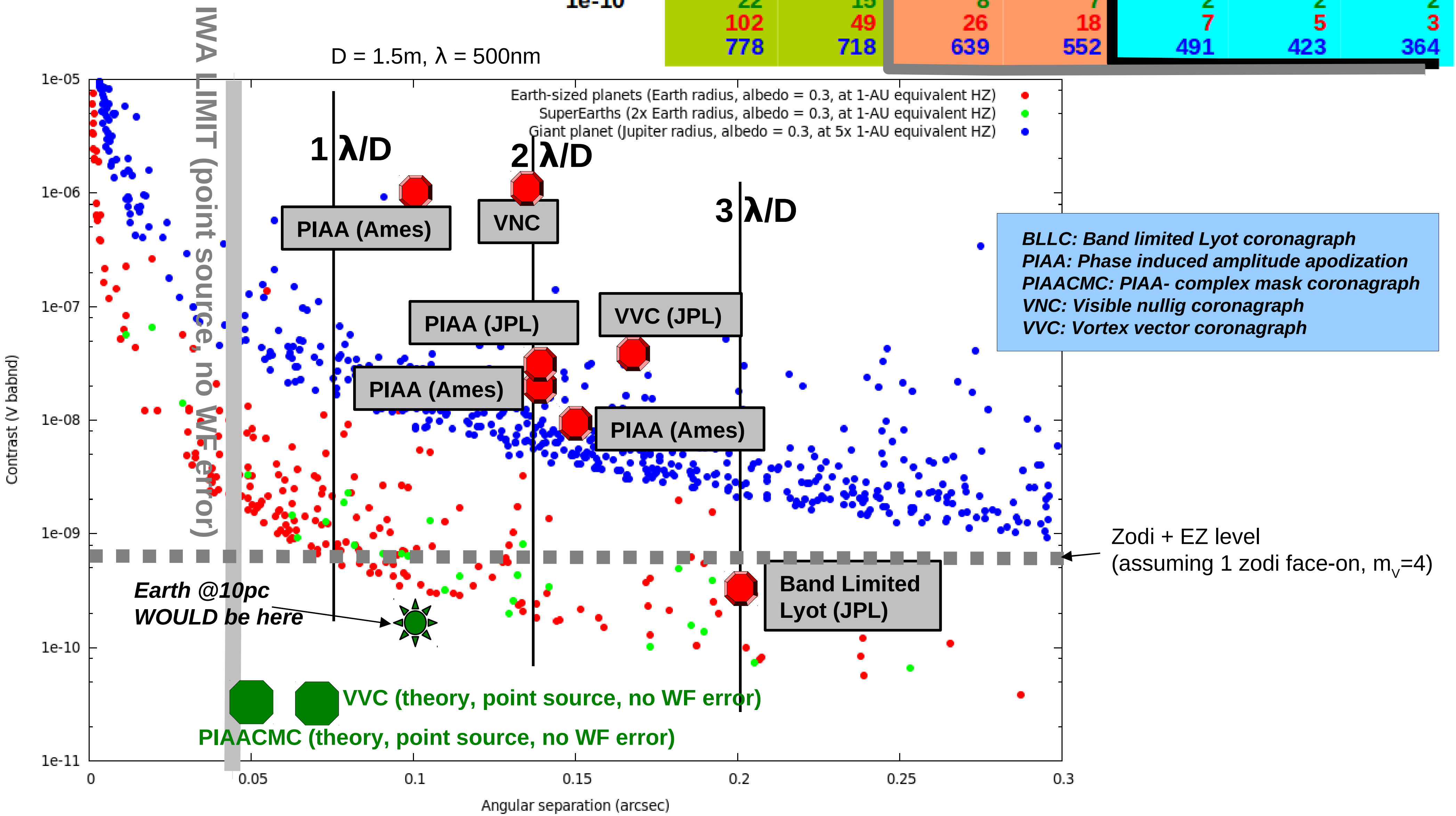
PASSIVE SYSTEM (or "Freeze & Forget" strategy adopted for TPF-C) → hopelessly difficult
Cannot maintain WF over hrs with "normal" telescope

Active system, with continuous WF control (similar to ground-based AO) → much easier
WF can be measured to required accuracy every few sec / min
Need technology dev and tests (lots of experience in ground-based AO)
Takes care of drifts but **VIBRATIONS NEED TO BE SMALL**

Technology Status

Contrast & IWA

	1 λ/D (0.069")	1.5 λ/D (0.103")	2 λ/D (0.137")	2.5 λ/D (0.172")	3 λ/D (0.206")	3.5 λ/D (0.241")	4 λ/D (0.275")
1e-8	2 152	94	52	29	26	20	11
1e-9	4 35 574	1 10 514	4 435	3 348	1 287	1 219	1 160
1e-10	22 102 778	15 49 718	8 26 639	7 18 552	2 7 491	2 5 423	2 3 364



Conclusions

Current starlight suppression lab performance already enables imaging and low R spectroscopy of giant planets and exozodi with Probe-class mission.

Direct imaging and low resolution spectroscopy of potentially habitable planets is conceptually within reach of a probe-class mission, but requires further technology development.

Ultimate limit is due to limited collecting area (no need to go much below 1e-9 contrast on probe)

Habitable planet imaging probe requires combination of performance characteristics that have been reached or approached individually on separate experiments/concepts:

- 1e-9 raw contrast (achieved with BLLC), better than 1e-10 calibration
- ~10% or more bandwidth (achieved with BLLC) → workable # of // channels

Perf required at > 3 λ/D has been reached

- < 2 λ/D IWA (achieved with PIAA, VNC & VVC get to below 2 λ/D, PIAACMC gets to 0.64 λ/D)
- Nearly 100% throughput at small IWA (PIAA[CMC] and VVC offer this)
- Better than 1mas pointing calibration (achieved at Subaru testbed, and soon at JPL)

BUT, regardless of science goals, exoplanet imaging probe class mission includes never flown before hardware & techniques:

- DMs (several of them)
- Wavefront control with coronagraph (onboard)
- Polychromatic high contrast wavefront control
- High stability telescope
- High precision pointing with coronagraph

→ System-level testbed and precursor(s) to probes could mitigate cost & risk

BLLC: Band limited Lyot coronagraph
PIAA: Phase induced amplitude apodization
PIAACMC: PIAA- complex mask coronagraph
VNC: Visible nullig coronagraph
VVC: Vortex vector coronagraph

Probe scale mission would considerably mitigate cost & risk of flagship