National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Technology for Future Exoplanet Missions

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International Astronautical Congress
Cape Town, South Africa, October 9, 2011

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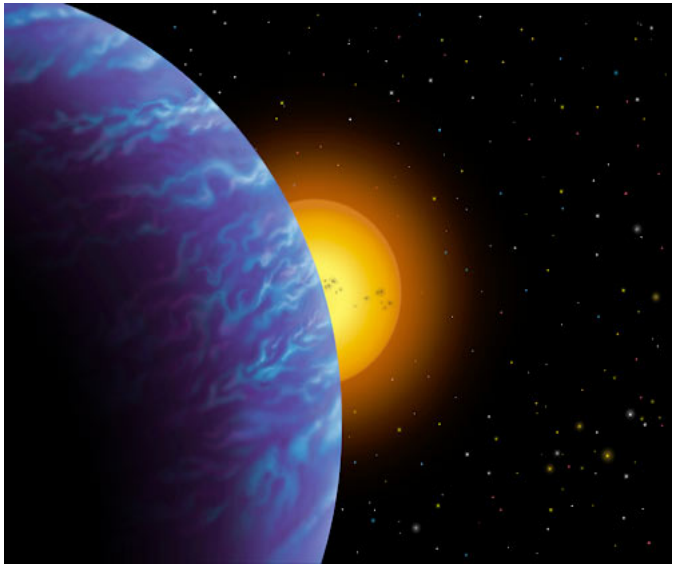
Program Science Goals of NASA's Exoplanet Exploration Program

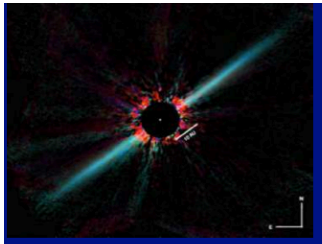
- Direct detection of terrestrial planets in the habitable zone around nearby stars
- Characterization of planetary atmospheres in search of the signatures of life
- Direct detection and characterization of other constituents of planetary systems



- ***Direct detection - must separate planet light from star light***
- ***Planet characterization - must determine type of planet, its gross physical properties and atmosphere constituents allowing assessment of likelihood of life***

Astrophysics 2010 Decadal Survey

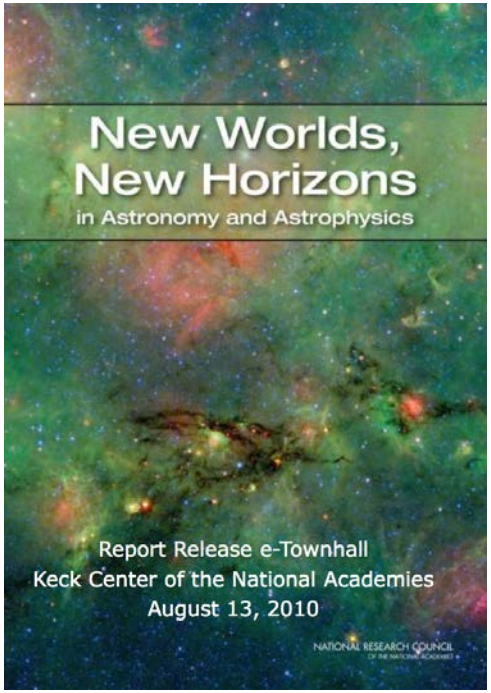
#1 Priority for Medium-scale space program



New Worlds Technology Development Program

- To achieve New Worlds objective – studying nearby, habitable exoplanets - need preliminary observations before choosing a flagship mission:
  - Planetary demography over wide range of conditions:
    - Kepler, WFIRST, integrated ground-based program
  - Measurement of zodiacal light:
    - Ground-based telescopes.
    - Sub-orbital and explorer mission opportunities.
- In parallel, need technology development for competing approaches to make informed choice in second half of decade
- **RECOMMEND $100-200M over decade**
- Planned integrated ground-space exoplanet program

New Worlds, New Horizons in Astronomy and Astrophysics NATIONAL RESEARCH COUNCIL OF THE NATIONAL ACADEMIES 30



National Research Council of the National Academies

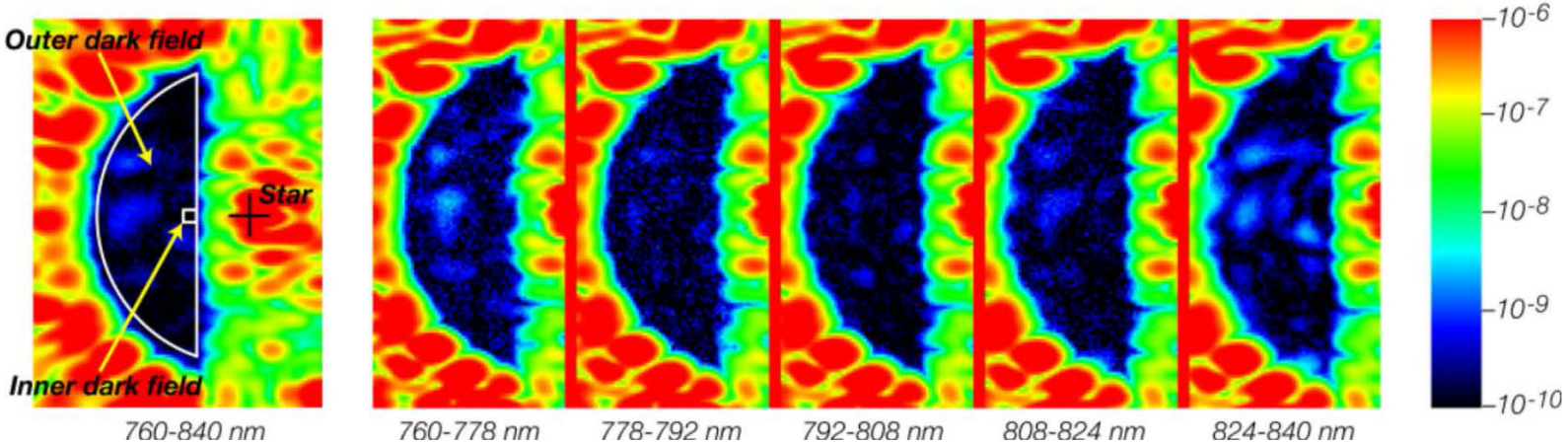
Approaches to Exoplanet Detection

- Combined-light methods
  - Radial velocity
  - Transit
  - Microlensing
  - Timing
  - Astrometry

- Starlight suppression methods
  - Coronagraph
  - Interferometer
  - Starshades

Technology for Future Missions

Progress in Exoplanet Science



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http://exoplanet.eu

The Extrasolar Planets Encyclopaedia

Established in February 1995

Home | Interactive Catalog | Bibliography | Searches | Meetings | Other Sites

Interactive Extra-solar Planets Catalog

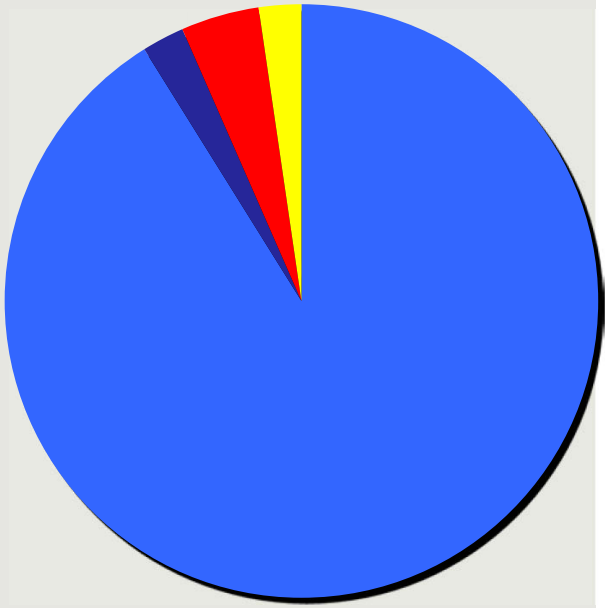
Version: 2.07 Maintained by © 2011 *Jean Schneider* *(CNRS-LUTH, Paris Observatory)*
Technical support : ***Renaud Savalle***

For the use of this catalog README first.

All Catalogs

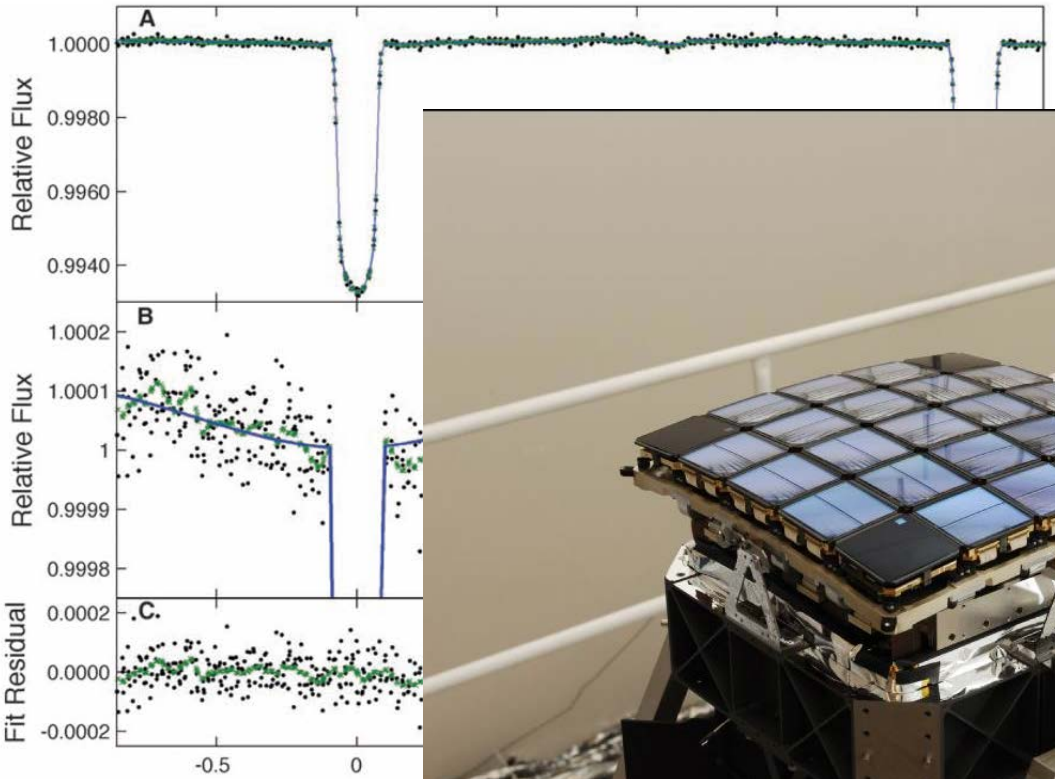
update : **16 September 2011**

All Candidates detected	**684 planets**
Candidates detected by radial velocity or astrometry *update : 15 September 2011*	520 planetary systems 633 planets 74 multiple planet systems
Transiting planets *update : 15 September 2011*	166 planetary systems 177 planets 13 multiple planet systems
Candidates detected by microlensing *update : 14 June 2011*	12 planetary systems 13 planets 1 multiple planet systems
Candidates detected by imaging *update : 11 August 2011*	21 planetary systems 24 planets 1 multiple planet systems
Candidates detected by timing *update : 31 August 2011*	9 planetary systems 14 planets 4 multiple planet systems



27% of radial velocity planets also detected by transits

Transit Photometry: Kepler (NASA)



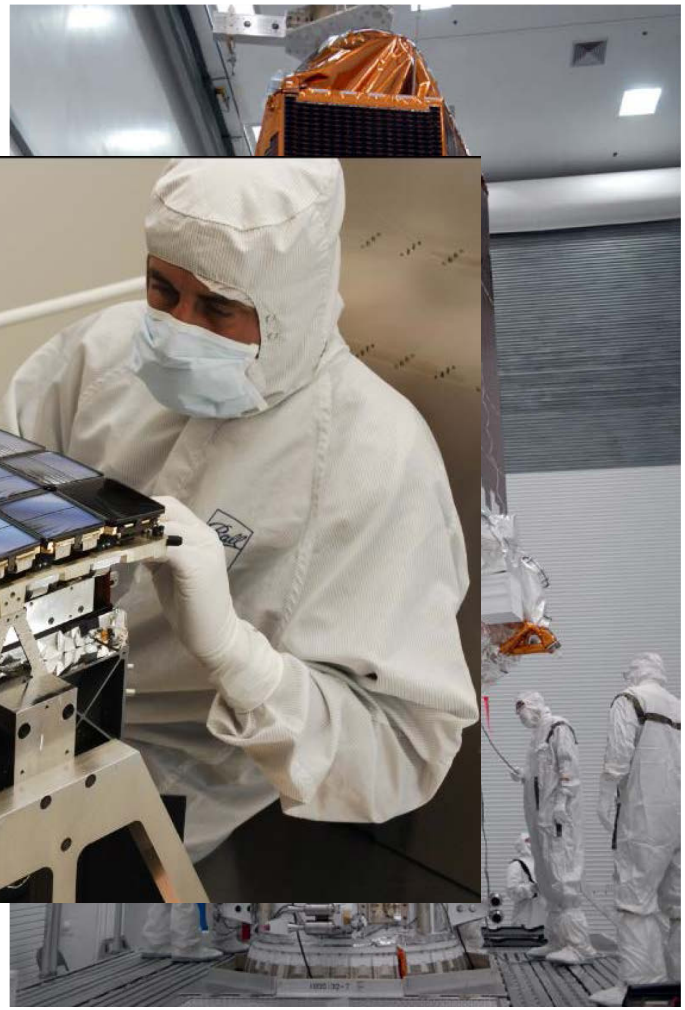
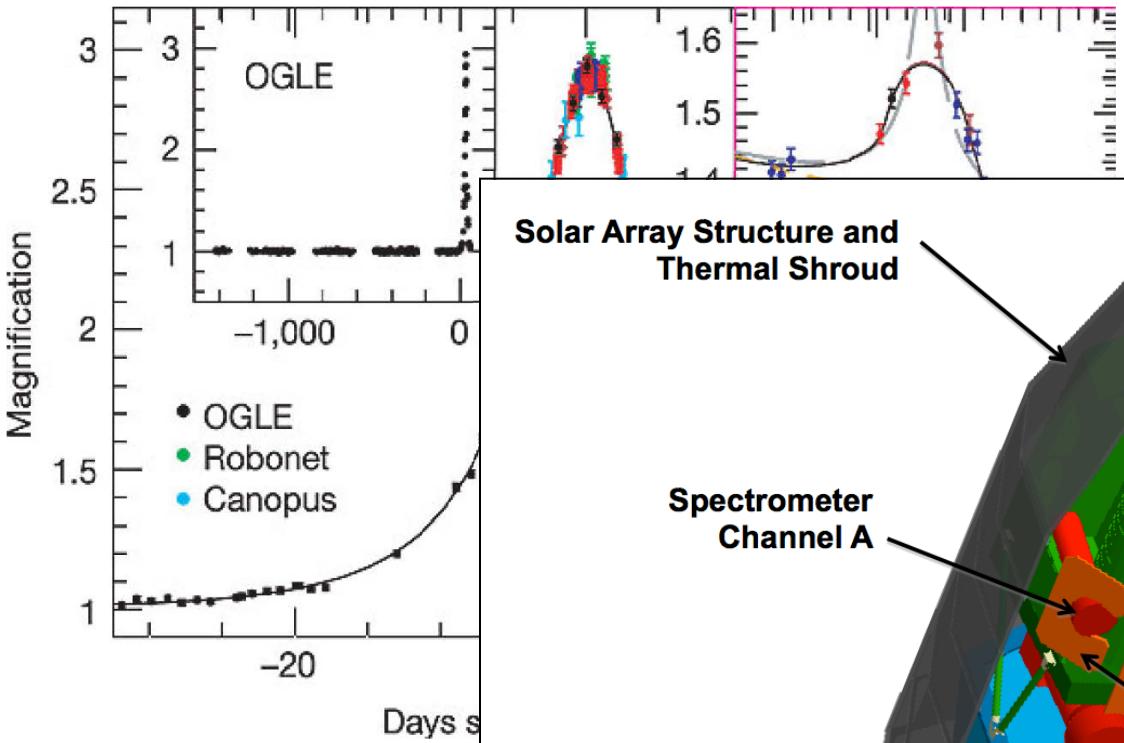
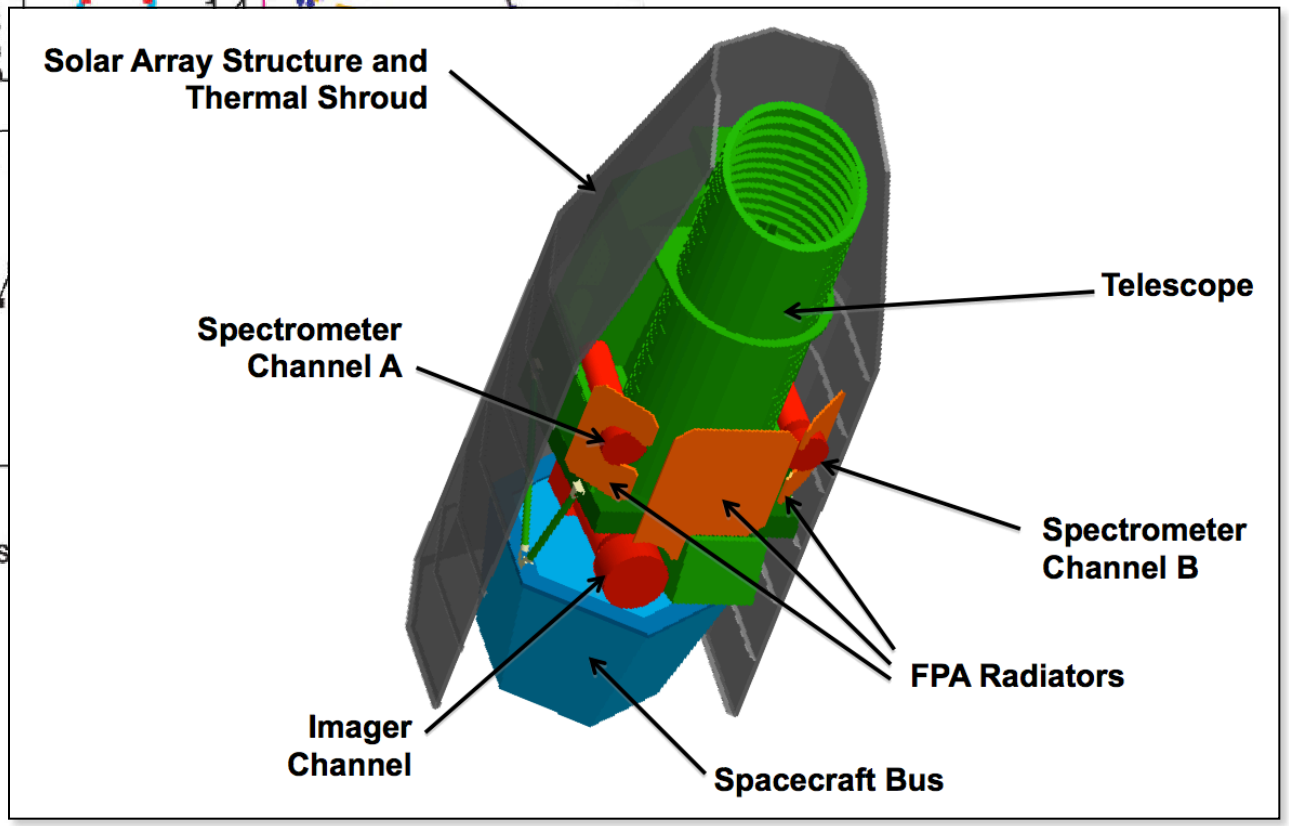


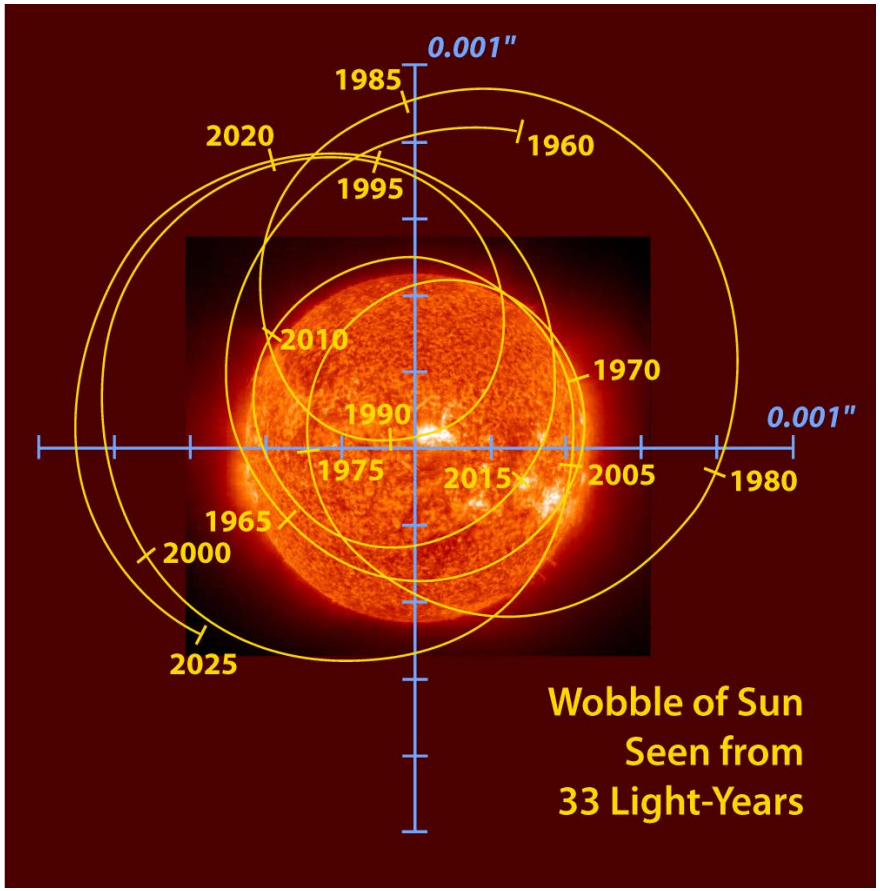
Fig. 1. Light curve for HAT-P-7b obtained by fo
measurements. The green × marks are 0.1-day moving averages over the data. The blue line is a simple fit. (**A**) Light curve showing full depth of transit. (**B**) Expanded view to show phase curve and occultation. (**C**) Residuals from fit.

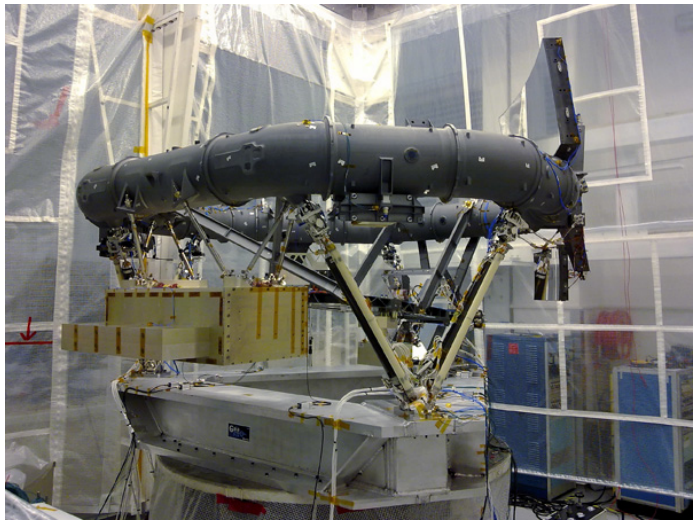
Gravitational Microlensing: WFIRST (NASA)

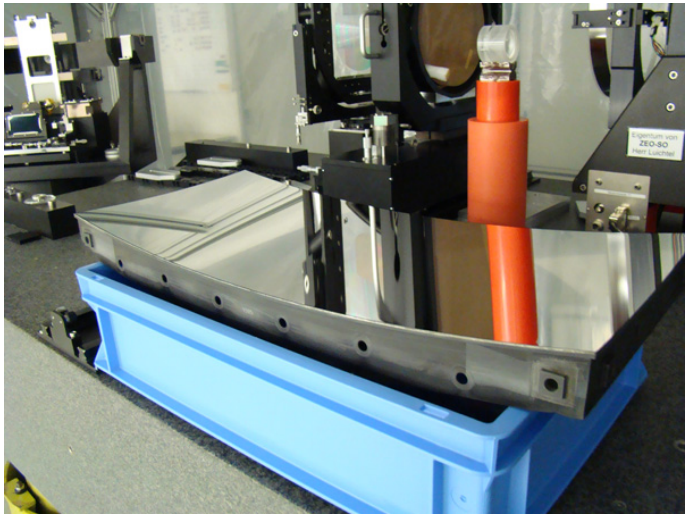




Astrometry: GAIA (ESA)

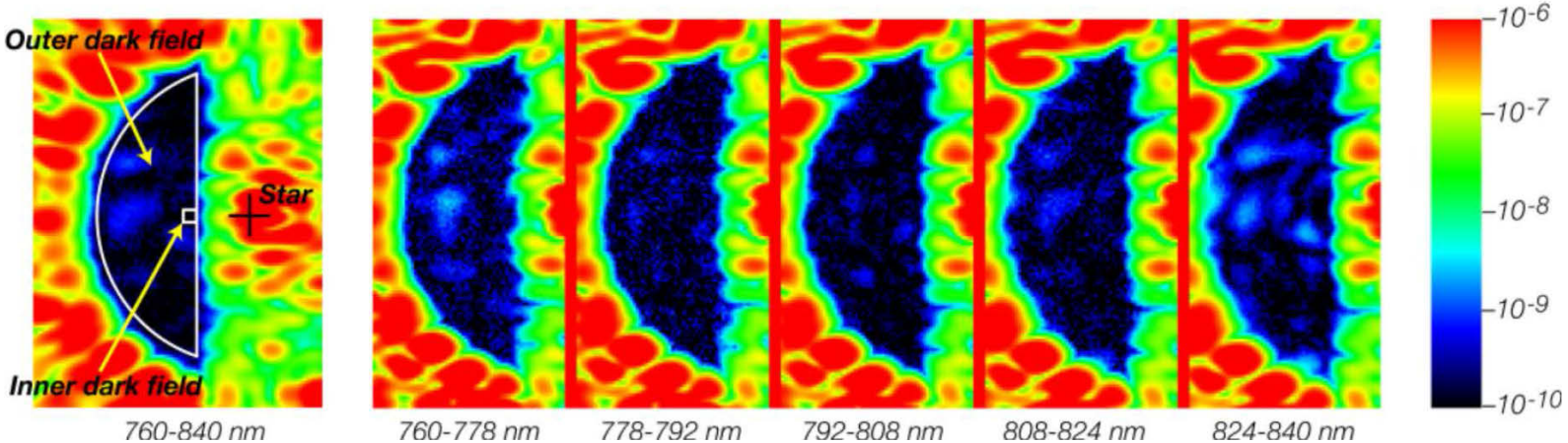




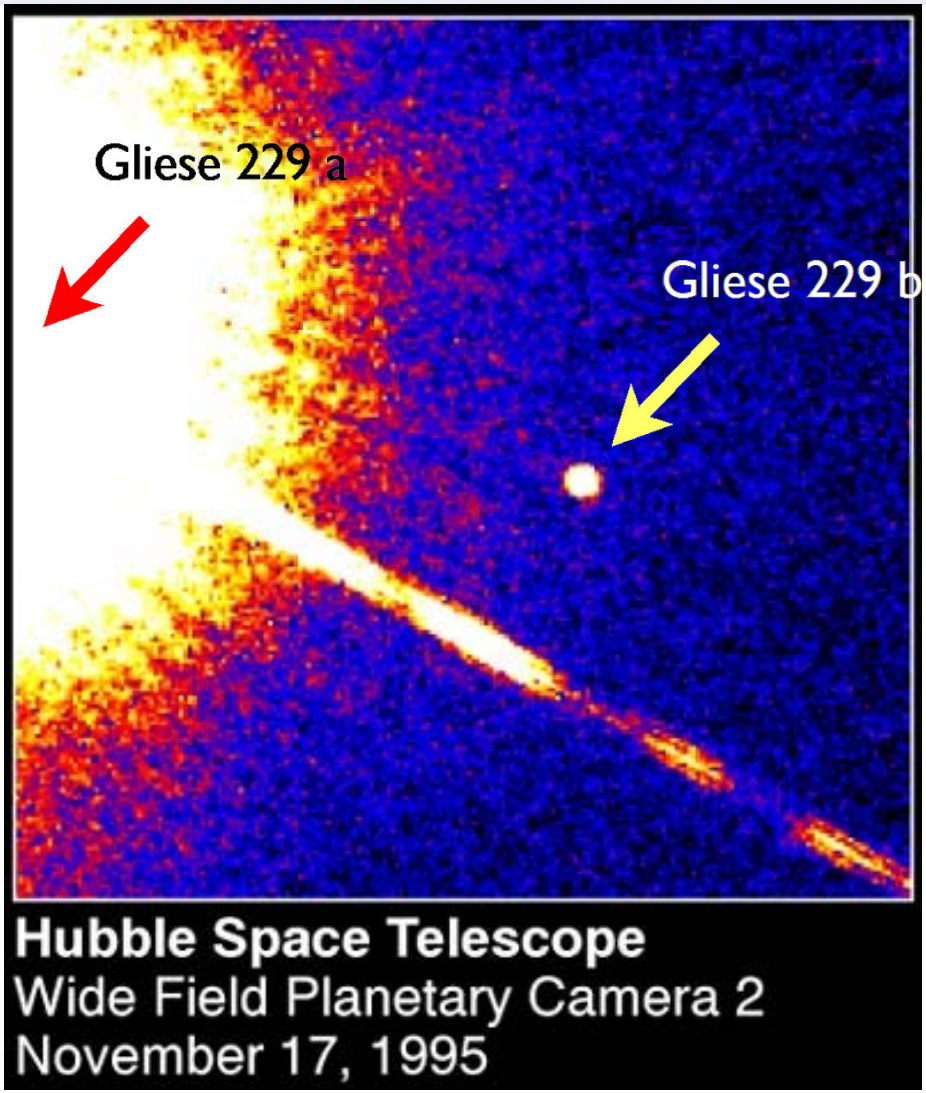


Technology for Future Missions

Angular Resolution
Dynamic Range



Diffraction and Angular Resolution



Brown Dwarf
44 AU
20-50 M_J

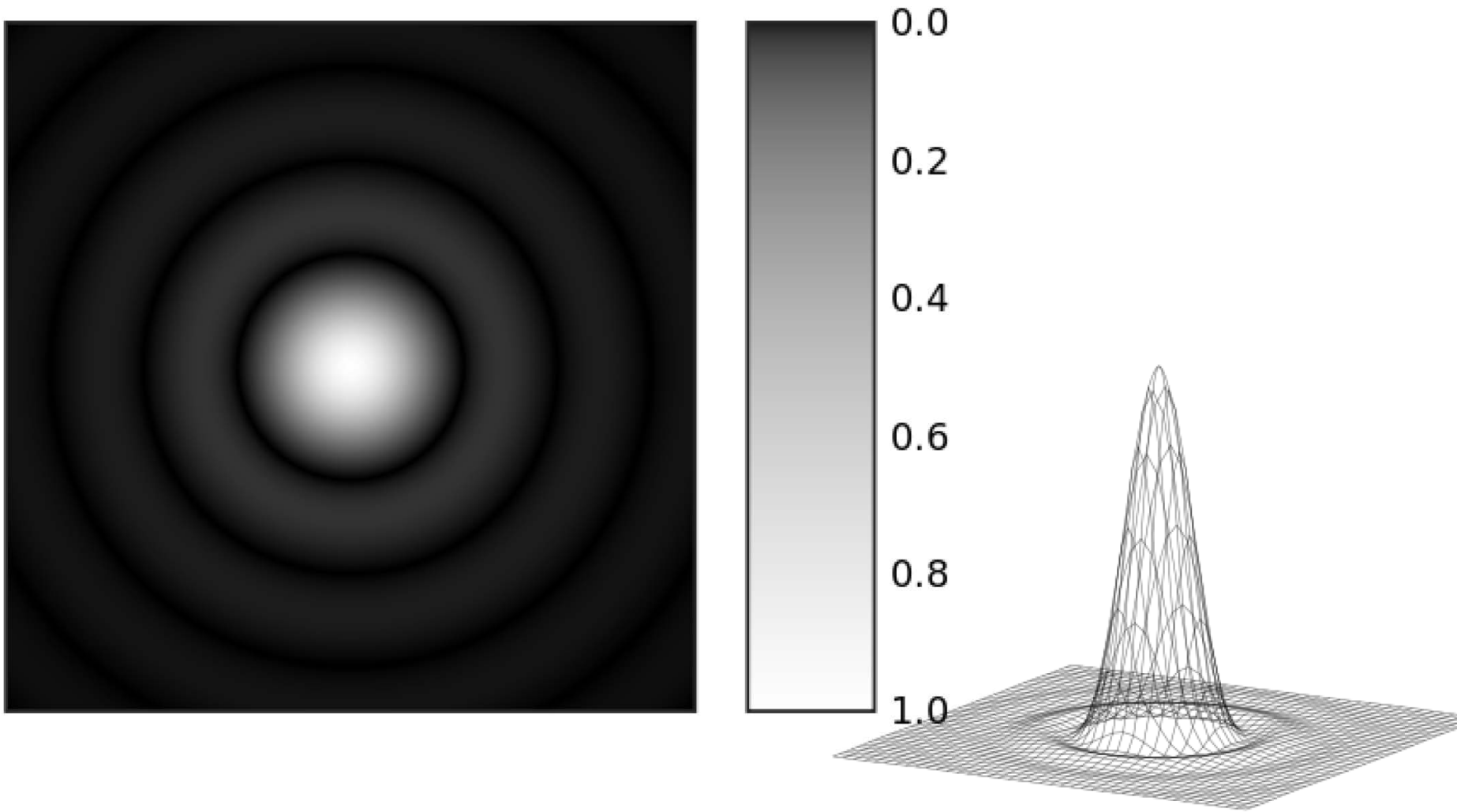
Discovered 1995

Starlight suppression allows the spectra of planets to be detected

2.4-m telescope

50 mas resolution

Airy Disk



High Dynamic Range

At mid-infrared wavelengths, exoplanets shine because they are warm

At visible wavelengths, exoplanets shine in reflected starlight

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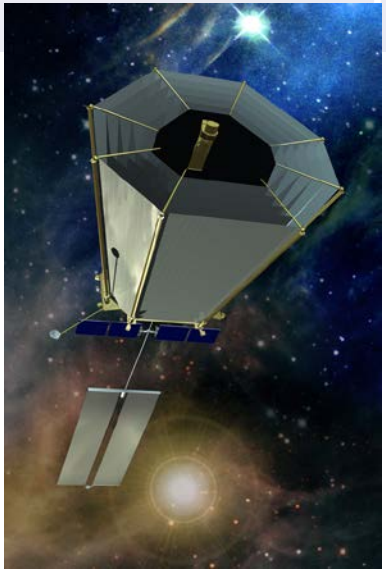
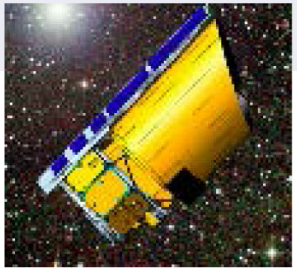
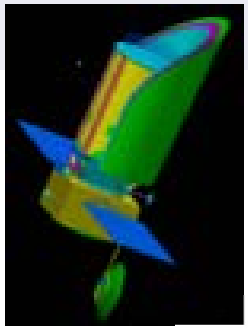
Gallery of Exoplanet Mission Concepts



TPF-C *Terrestrial Planet Finder Coronagraph*

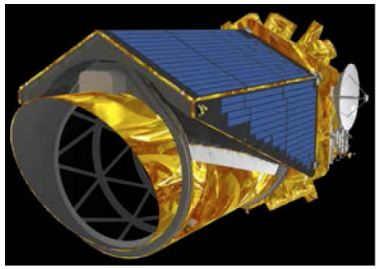


PECO *Pupil-Mapping Exoplanet Coronagraphic Observe*

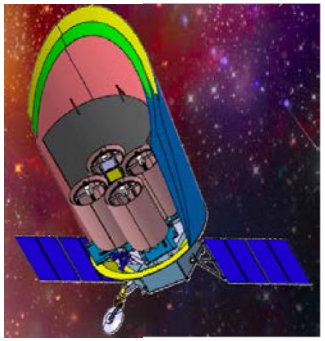


ACCESS *Actively-Corrected Coronagraph for Exoplanet System Studies*

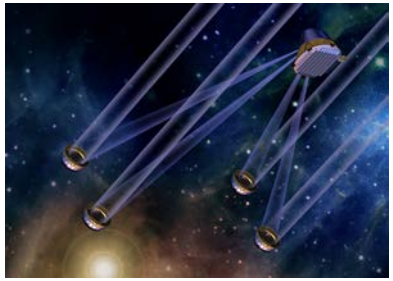
NWO
New Worlds Observer



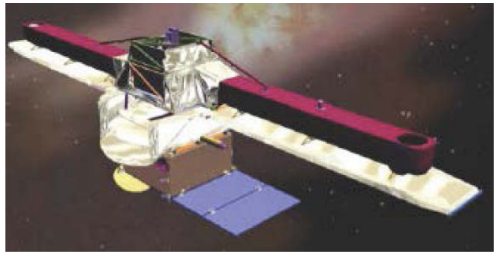
EPIC *Extrasolar Planetary Imaging Coronagraph*



O3
Occulting Ozone Observatory

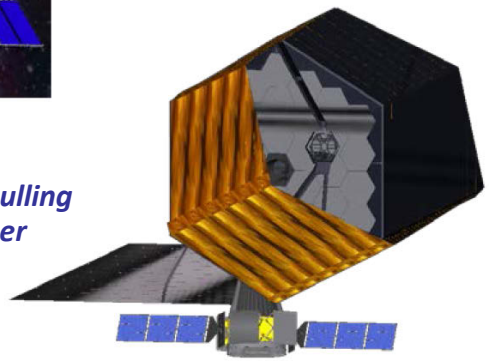


TPF-I *Terrestrial Planet Finder Interferometer*



FKSI *Fourrier-Kelvin Stellar Interferometer*

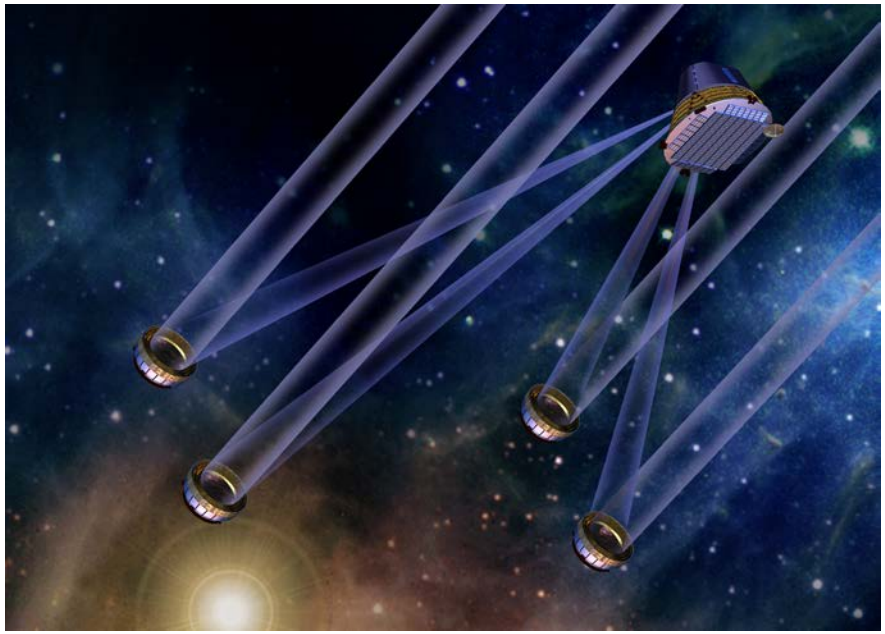
DAViNCI *Dilute Aperture Visible Nulling Coronagraph Imager*



ATLAST *Advanced Technology Large-Aperture Space Telescope*

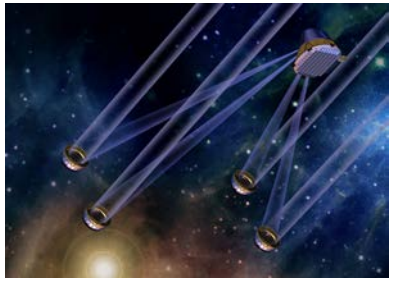
Technology for Future Missions

Interferometers



Infrared **Interferometer** Concepts

- Wavelength range: 3-8 microns, 6-18 microns
- Cryogenic optics, diffraction limited
- Primary mirrors (0.5–2-m diameter) of beryllium or silicon carbide
- Cryogenic deformable mirrors for wave-front correction
- Cryogenic delay-lines and fine-steering mirrors
- Mid-infrared single-mode fiber optics
- Cryocoolers for detectors
- Passive cooling of optics to 35–40 K
- Formation flying



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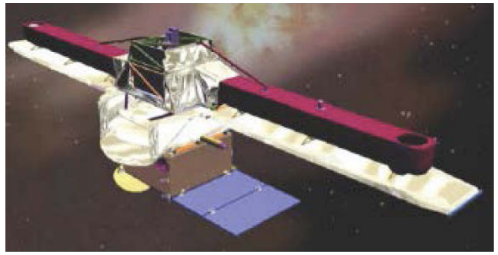
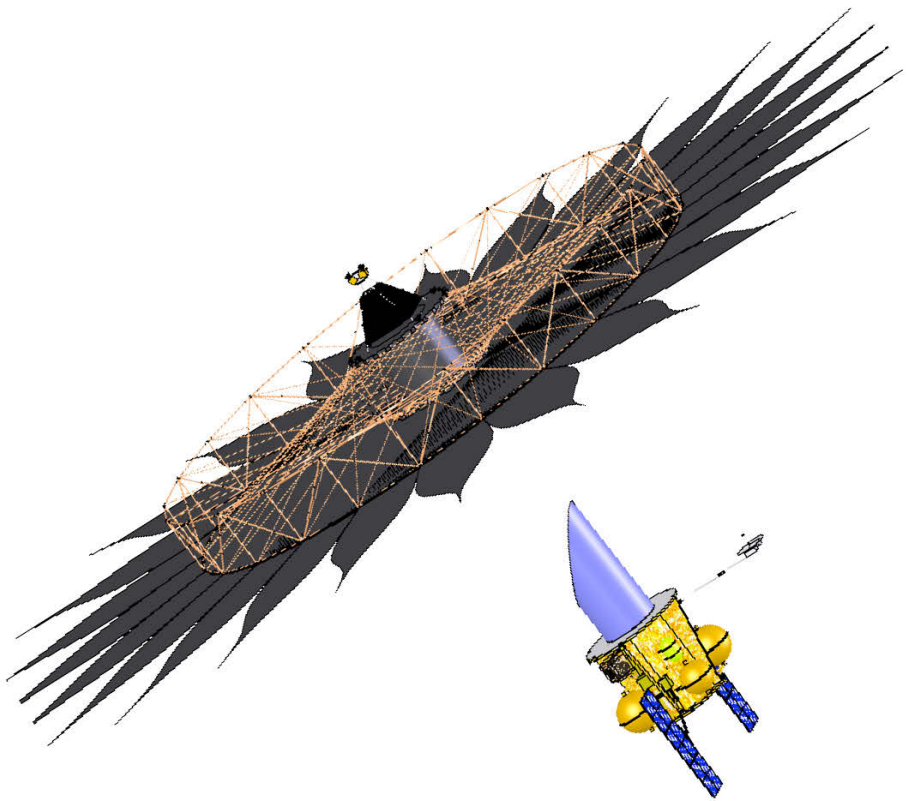


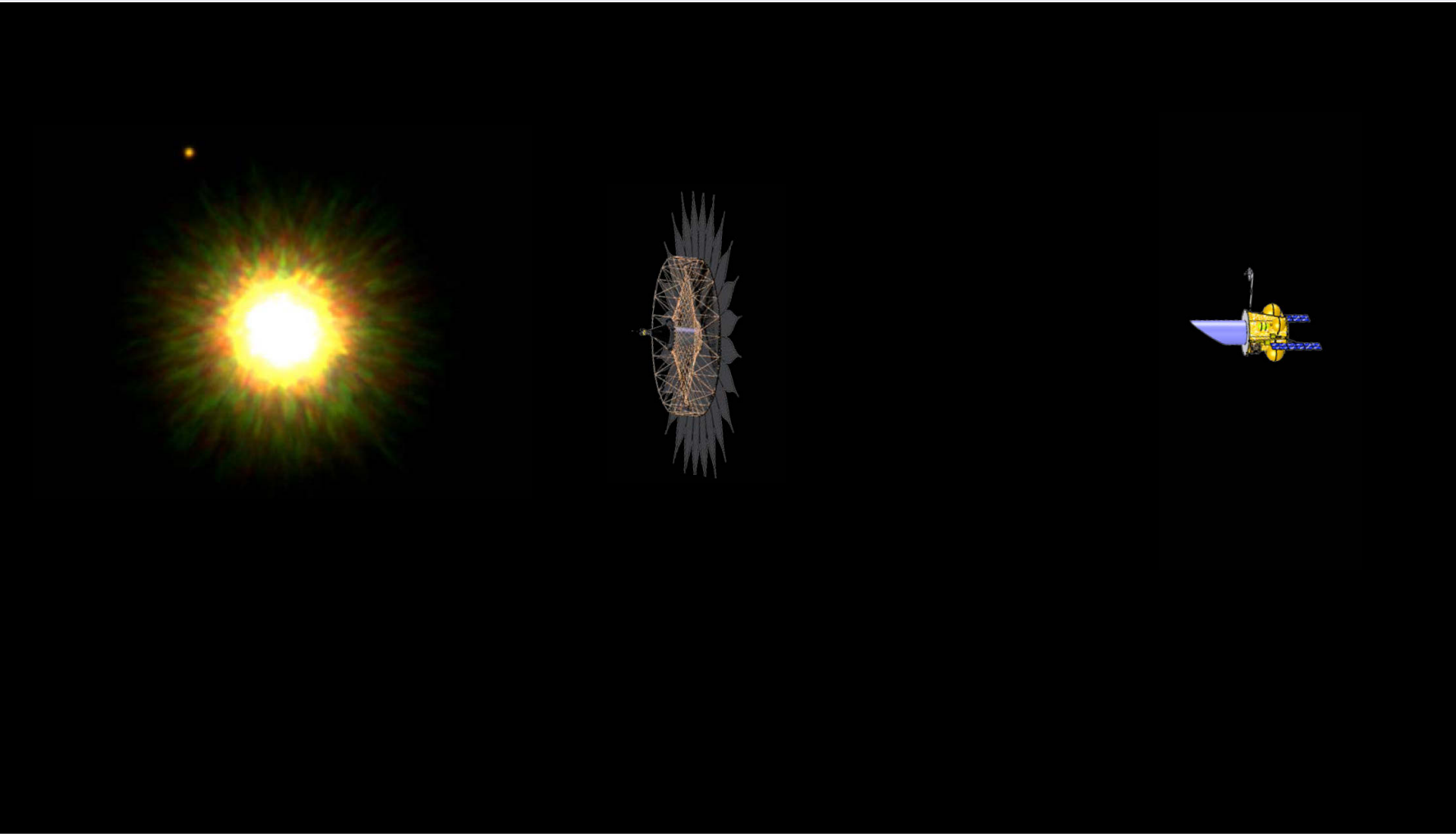
***FKSI** Fourier-Kelvin Stellar Interferometer*

Technology for Future Missions

Starshades

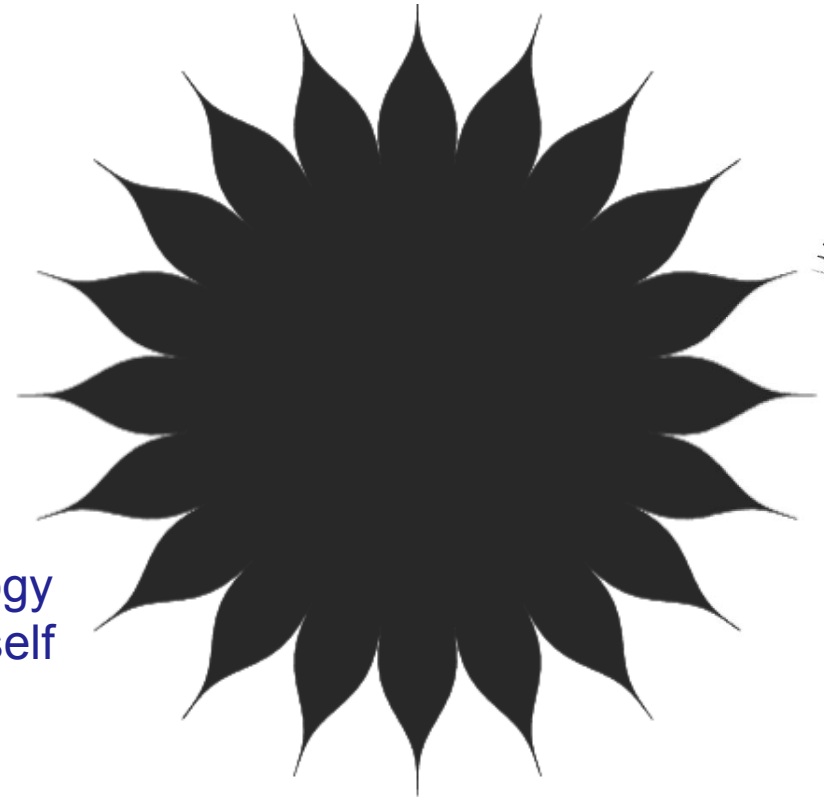


Starshade principle of operation



Starshade Concepts

- Nominally 4-m diffraction-limited primary mirror
- Mirror technology is not a driving concern
- Challenging technology is in the starshade itself and alignment



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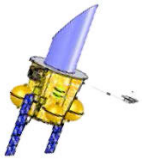
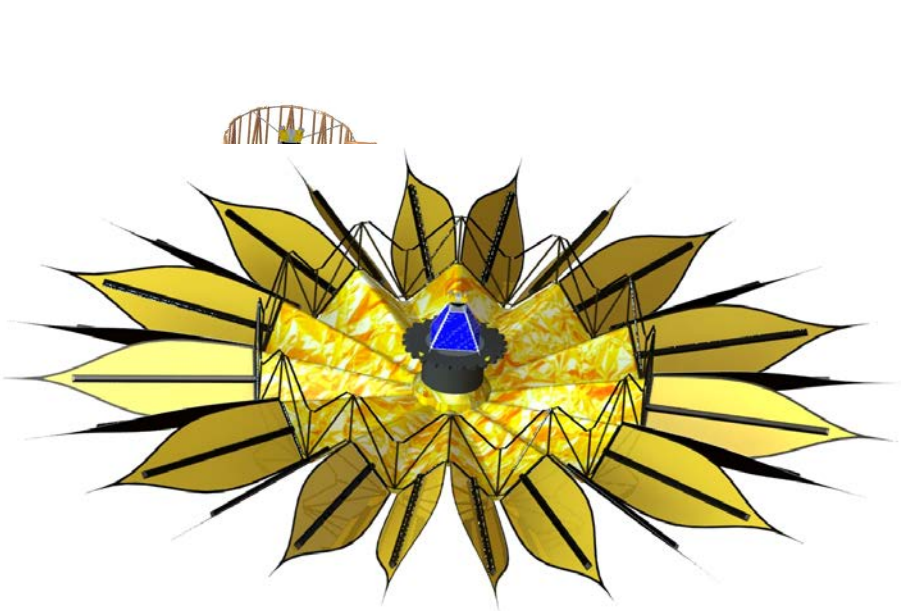
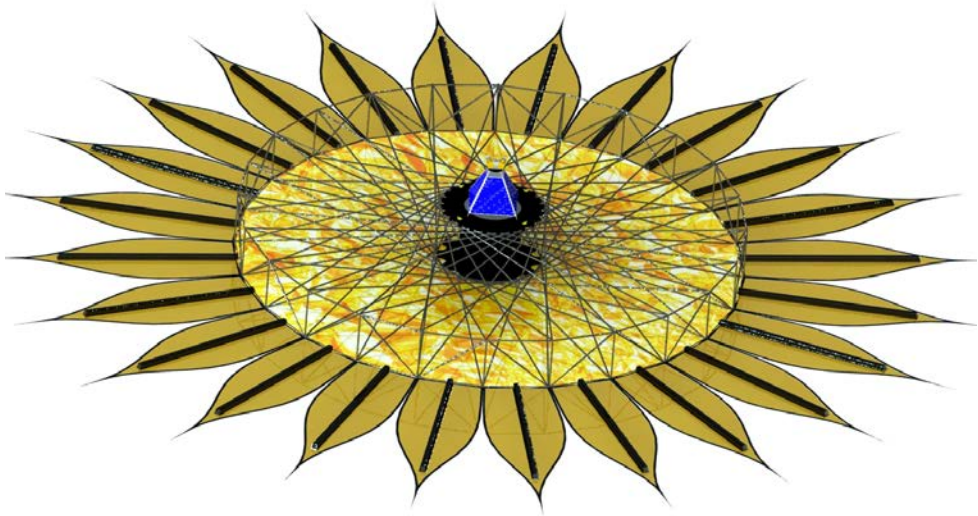


O3

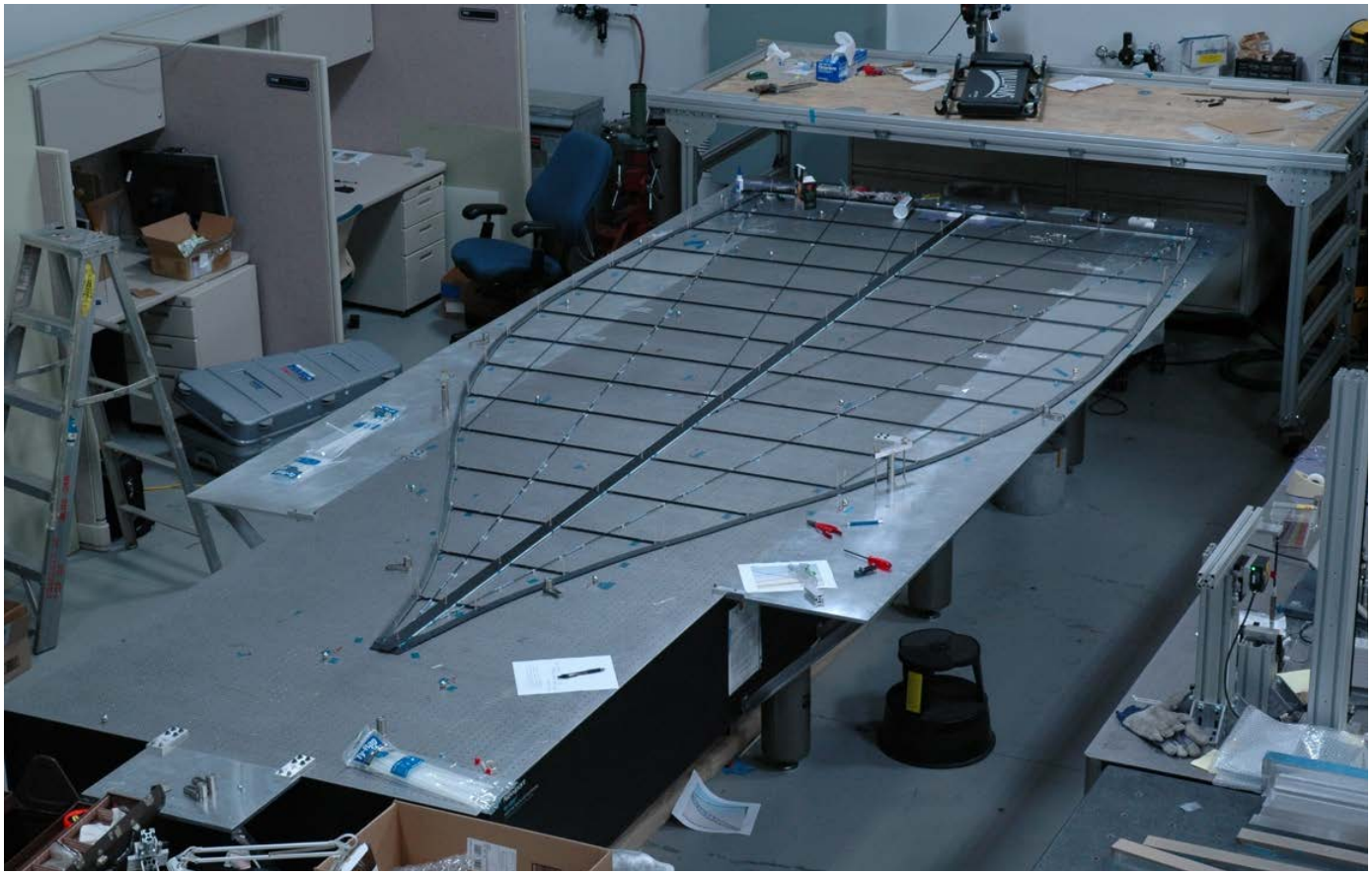
Occulting Ozone Observatory

Deployment Concept for Starshade





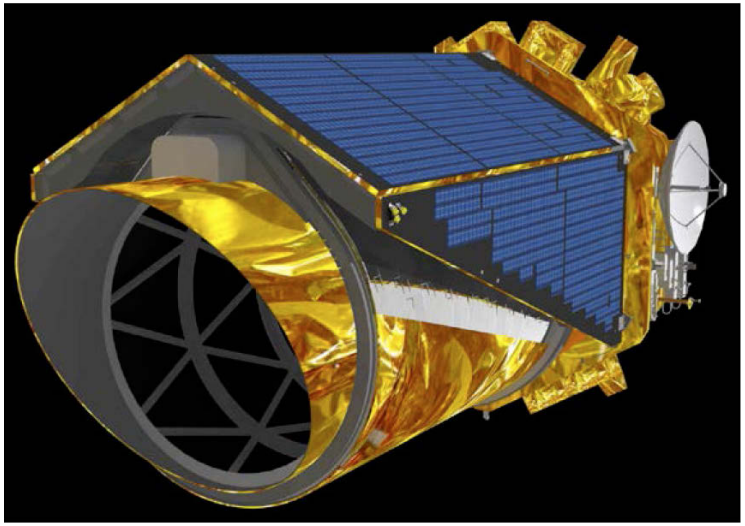
Starshade Development
N. J. Kasdin (Princeton University)



1 of 7 awards in 2009-2011: Technology Demonstrations for Exoplanet Missions 2009

Technology for Future Missions

Coronagraphs



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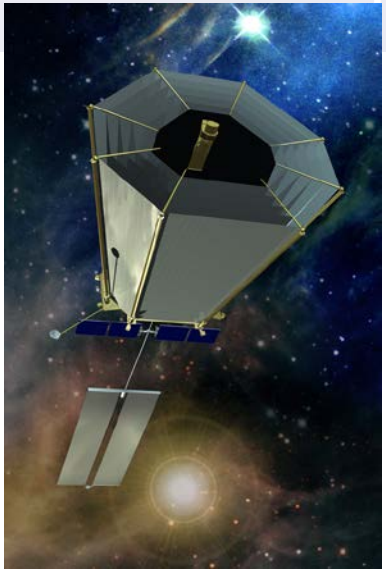
Coronagraph Concepts



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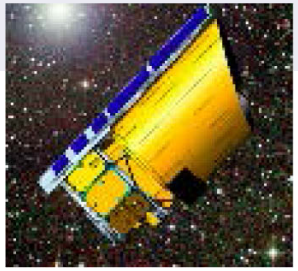
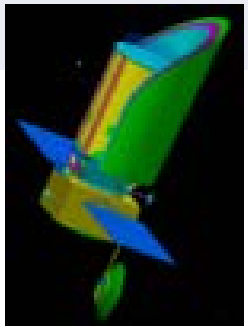
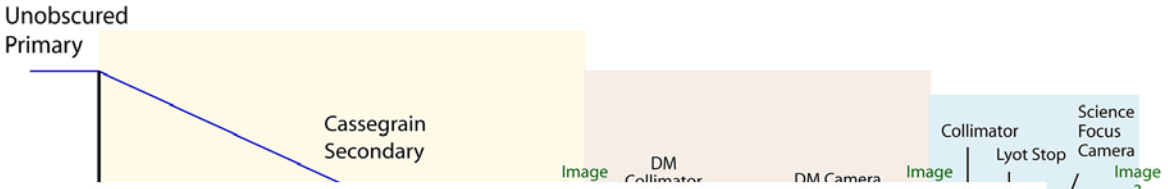


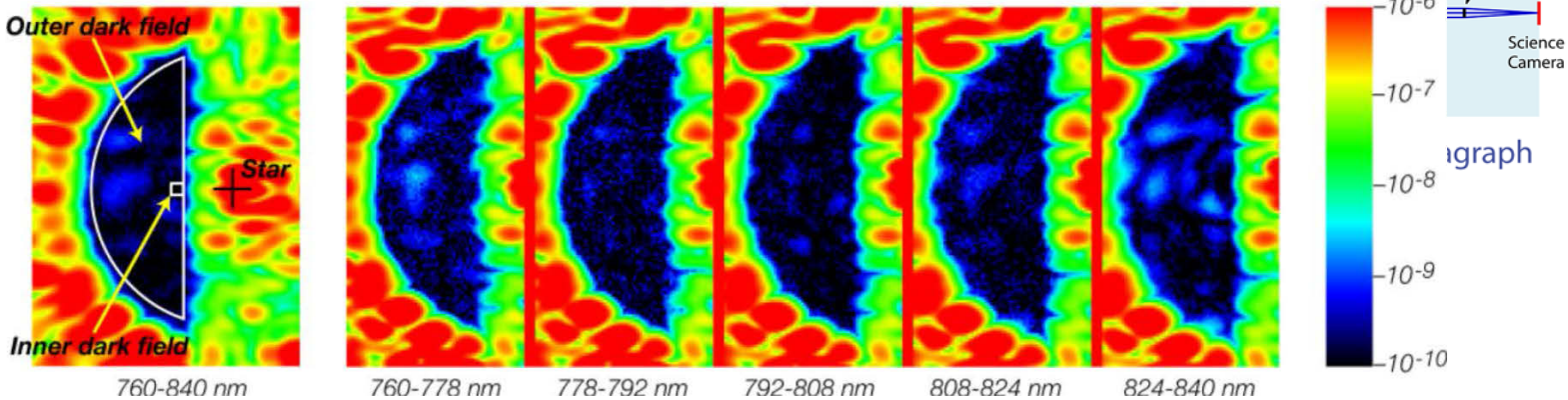
PECO ***Pupil-Mapping Exoplanet Coronagraphic Observe***



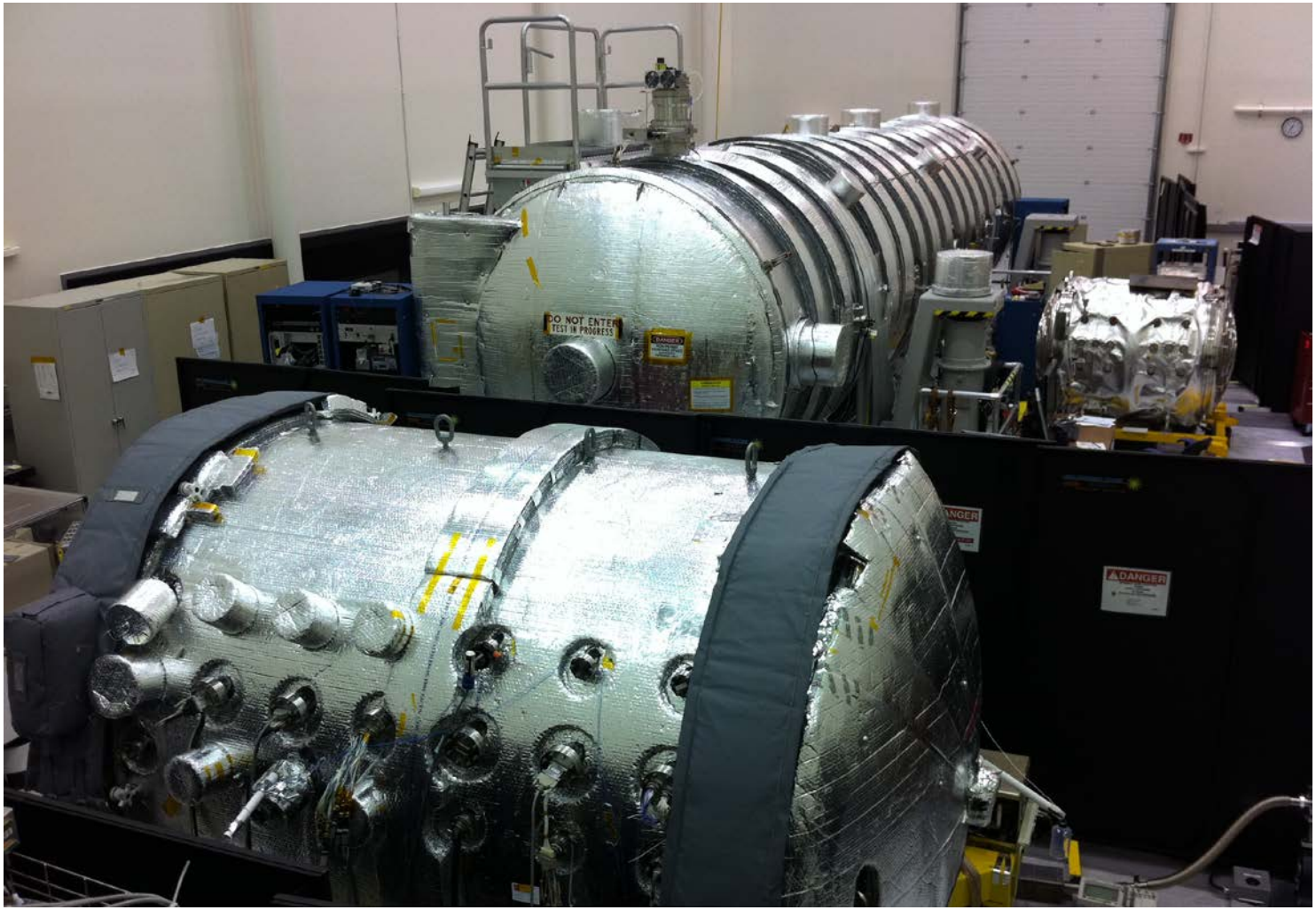
ACCESS ***Actively-Corrected Coronagraph for Exoplanet System Studies***

Xinetics Inc (NGAS)

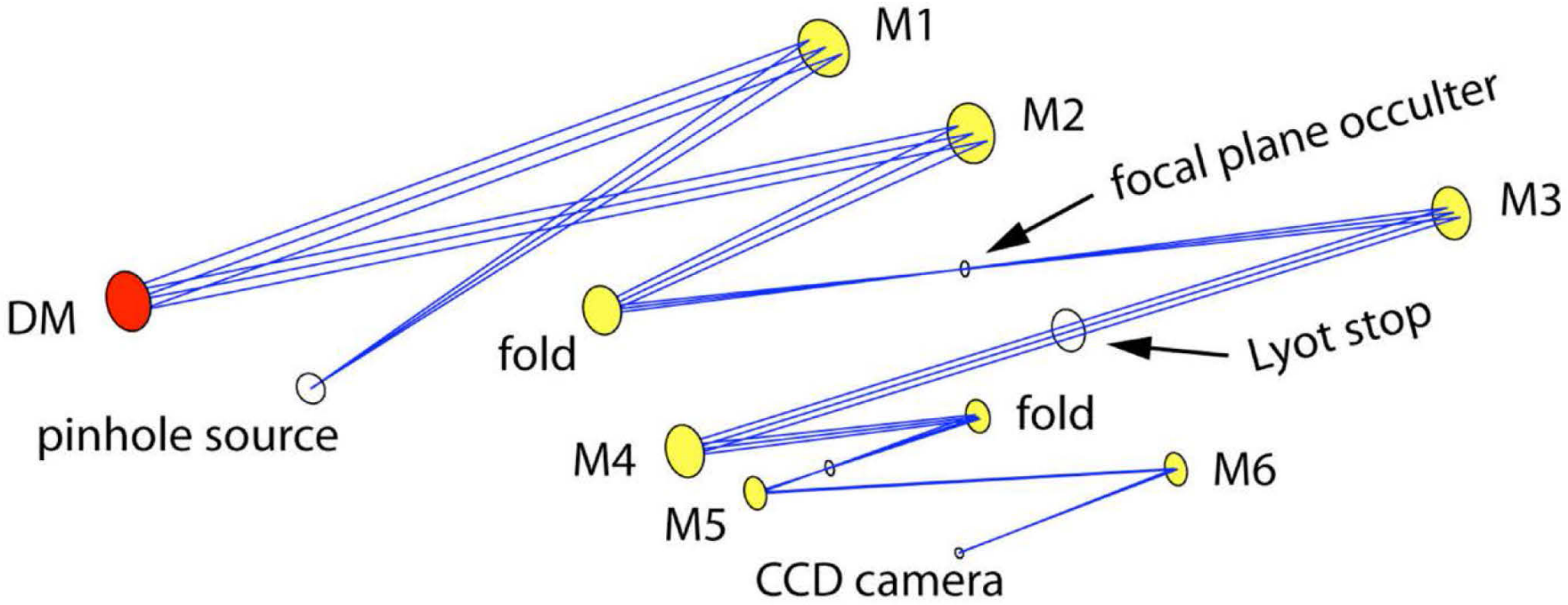




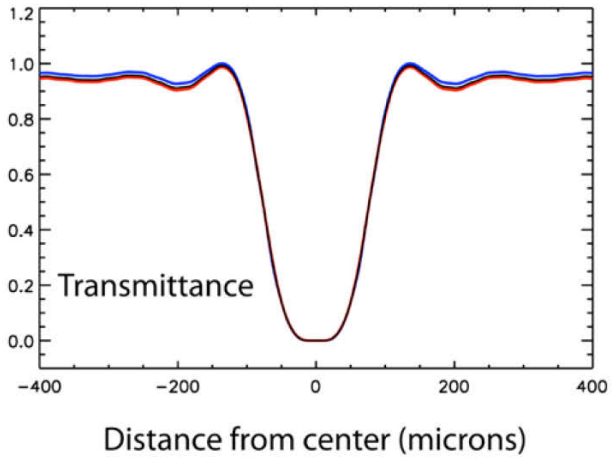
High Contrast Imaging Testbeds (JPL/Caltech)

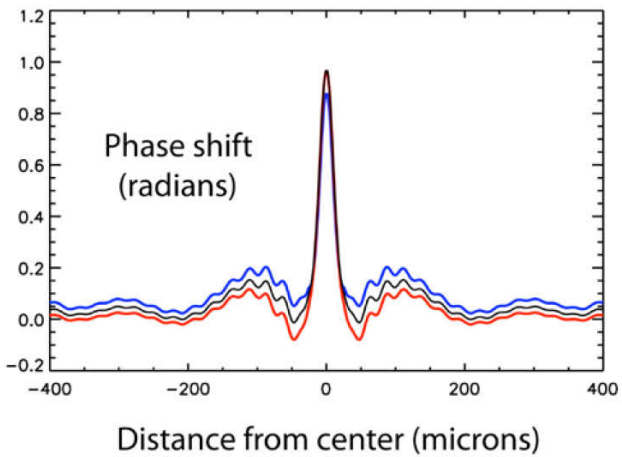


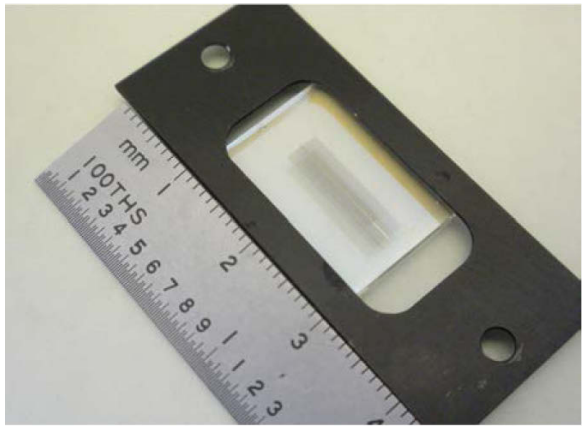
High Contrast Imaging Testbed



Hybrid Lyot Masks
John Trauger (JPL/Caltech)







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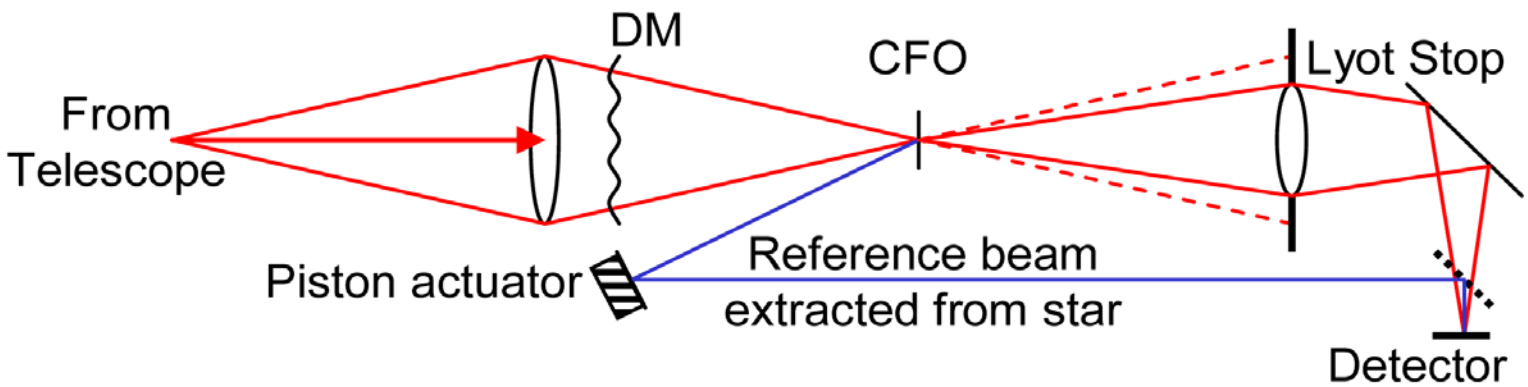
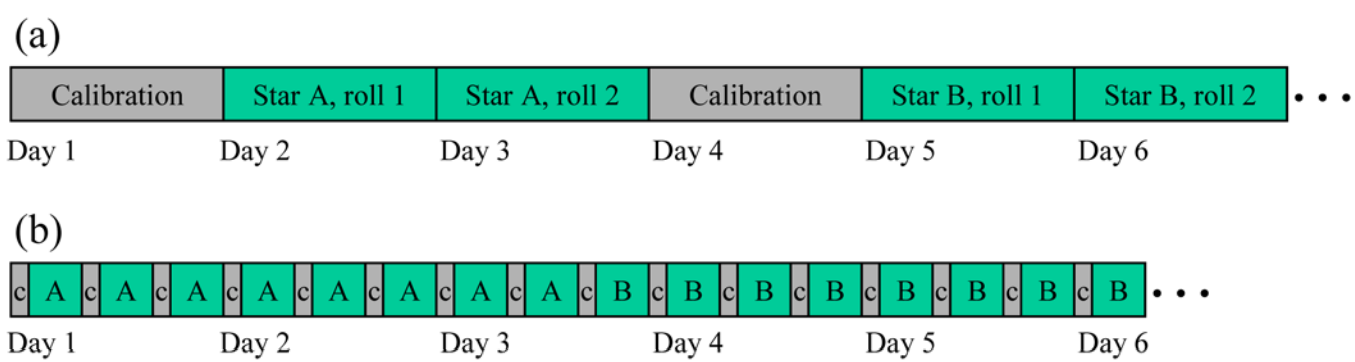
Advanced Speckle Detection Methods
M. C. Noecker (Ball Aerospace Tech Systems)





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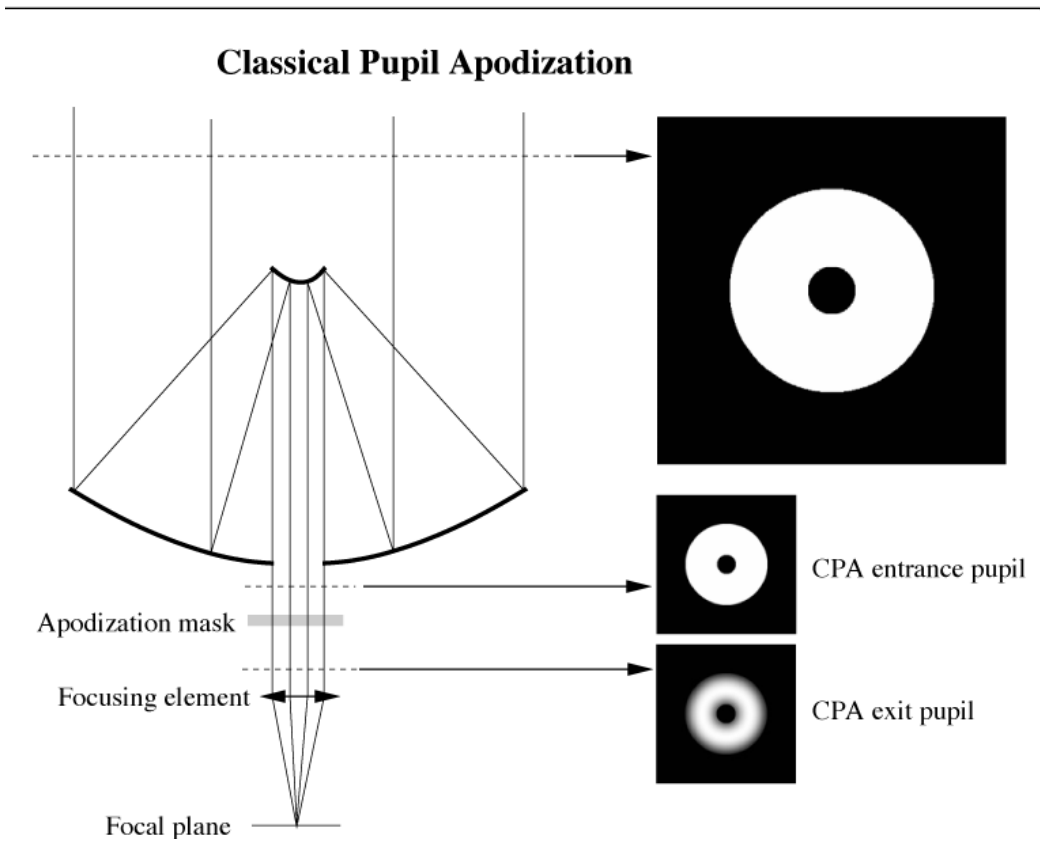
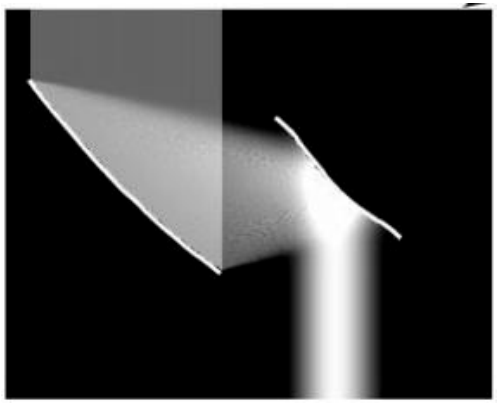
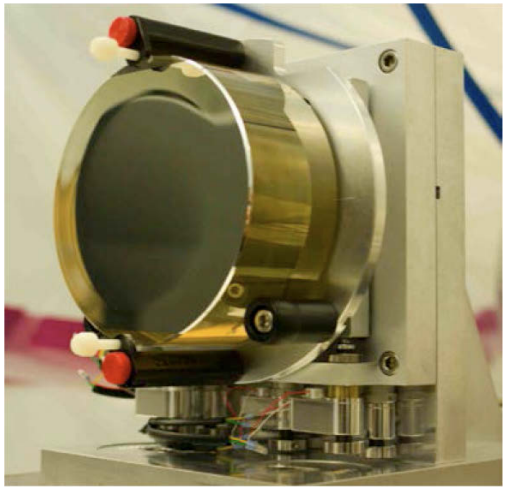
Phase-Induced Amplitude Apodization
Olivier Guyon (University of Arizona)



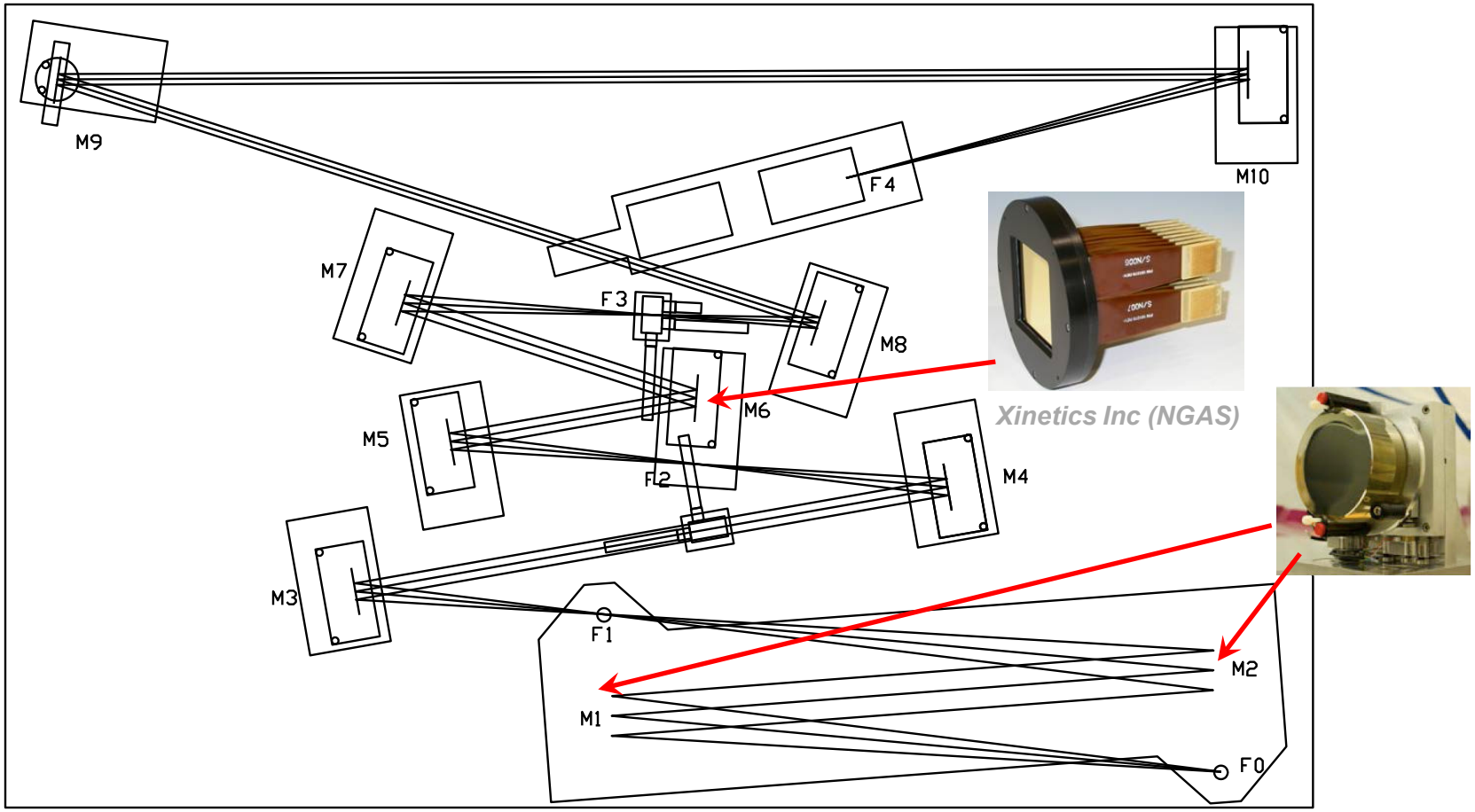




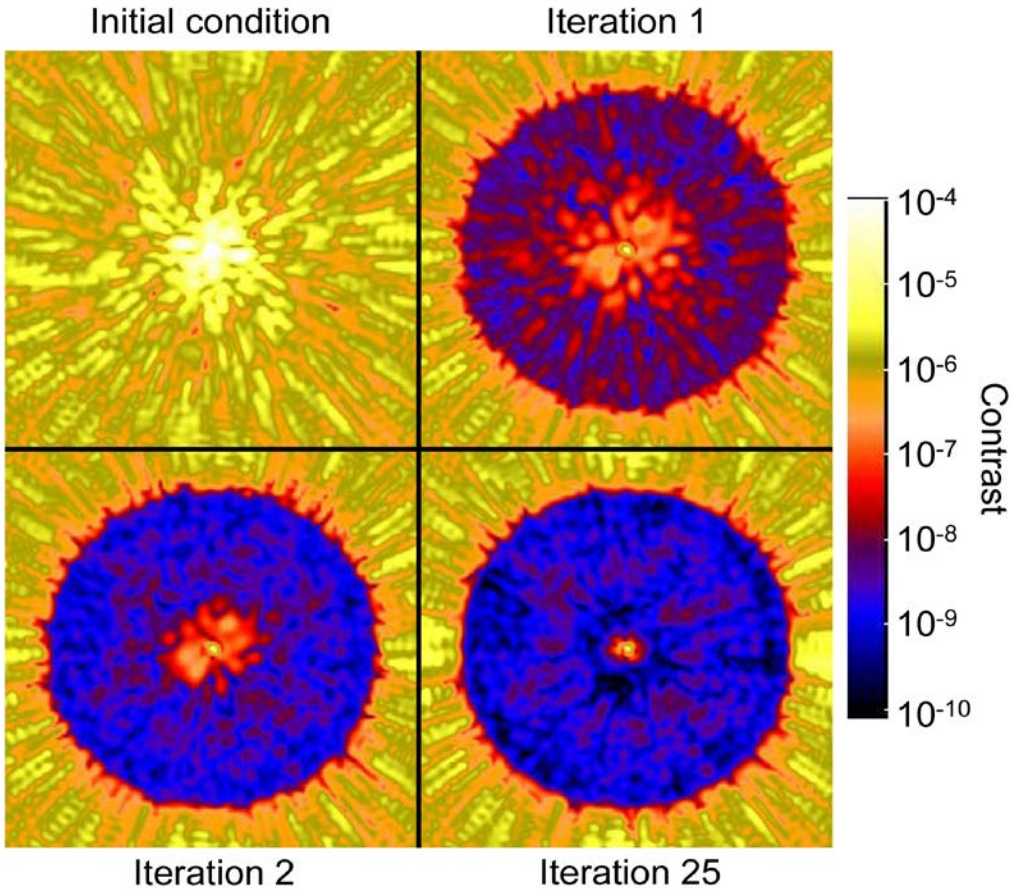
Tinsley Laboratories

4 of 7 awards in 2009-2011: Technology Demonstrations for Exoplanet Missions 2009

Phase-Induced Amplitude Apodization vacuum experiment

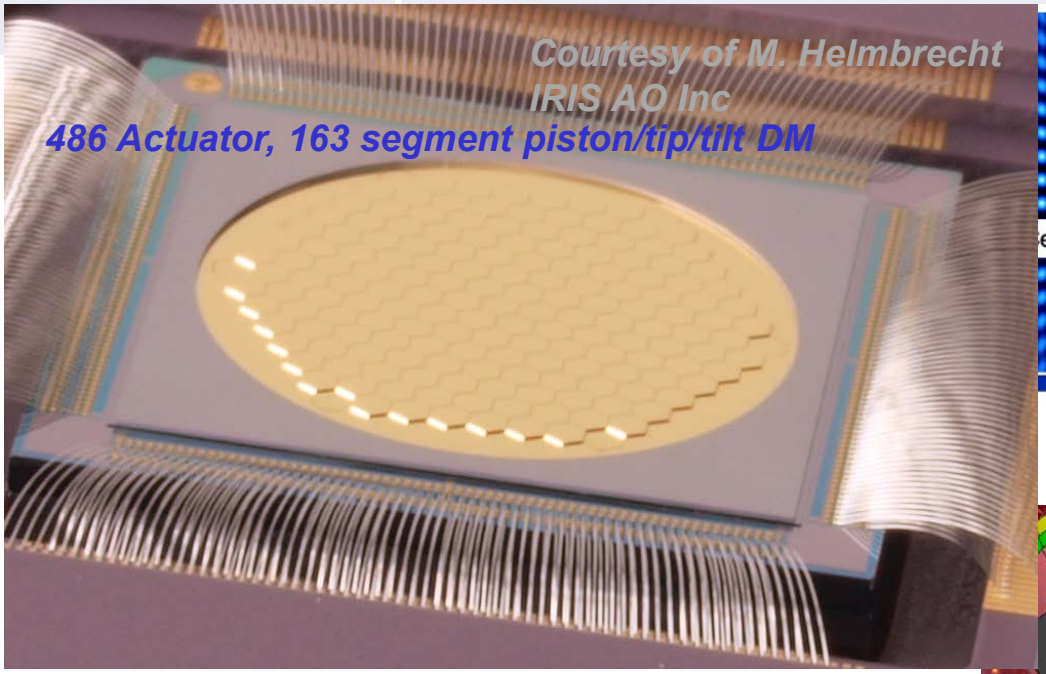


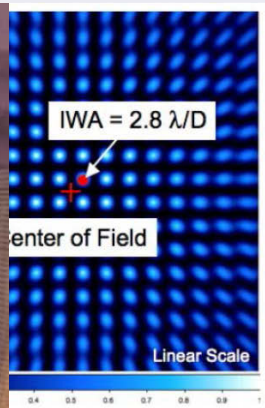
End-to-End Coronagraph Modeling
J. Krist (JPL/Caltech)

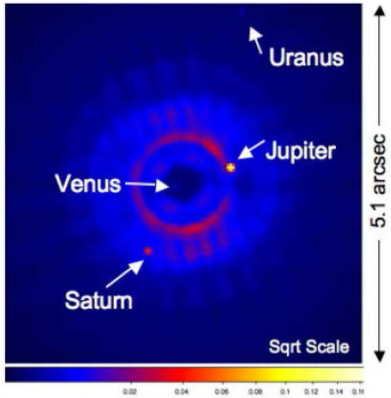


5 of 7 awards in 2009-2011: Technology Demonstrations for Exoplanet Missions 2009

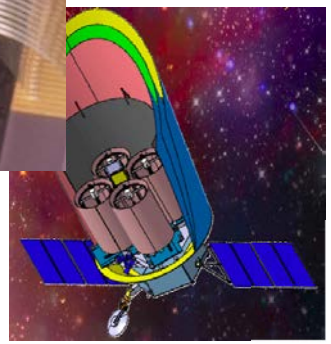
Visible Nulling Coronagraphs

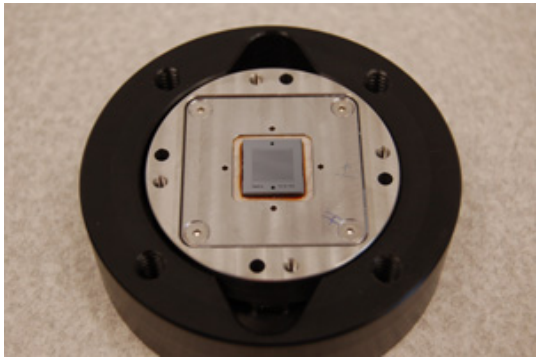




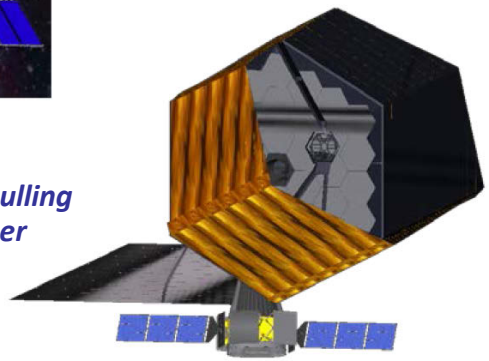


EPIC ***Extrasolar Planetary Imaging Coronagraph***





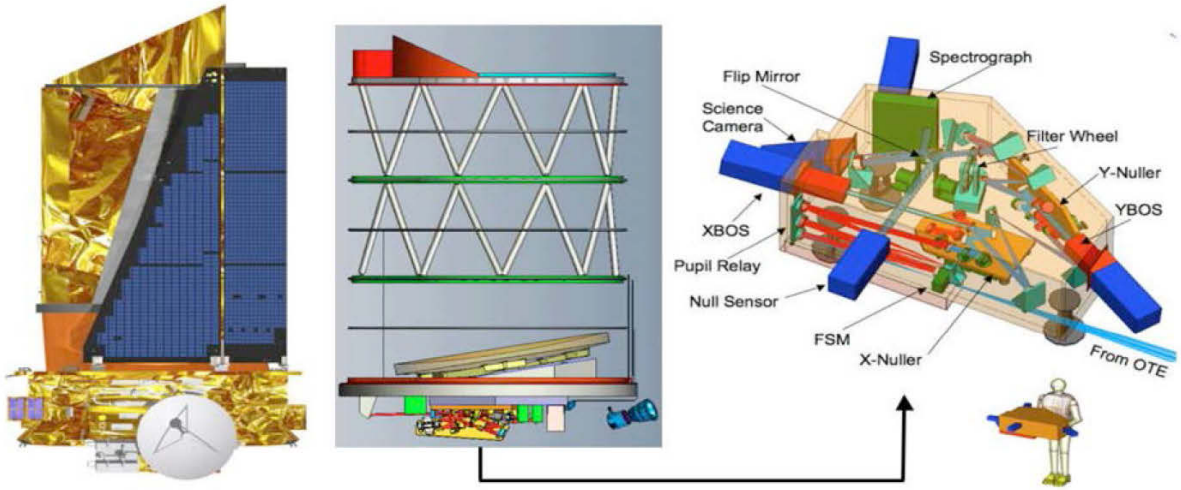
DAViNCI ***Dilute Aperture Visible Nulling Coronagraph Imager***

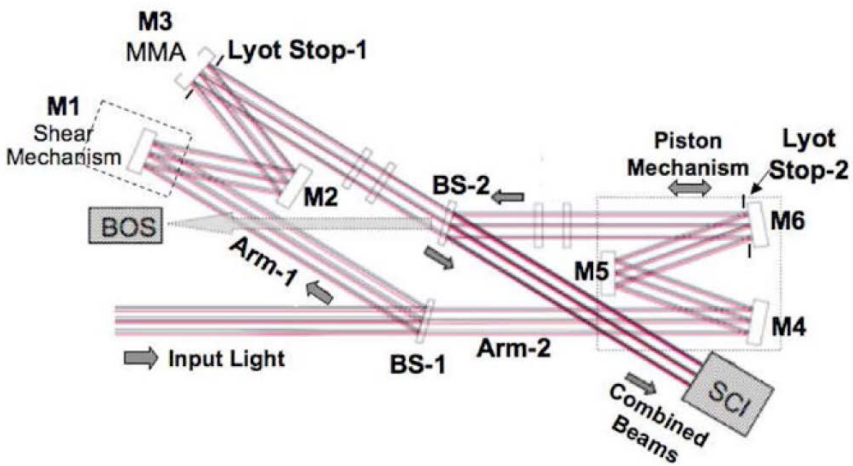


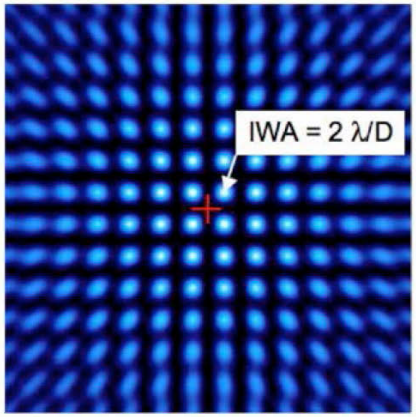
ATLAST ***Advanced Technology Large-Aperture Space Telescope***

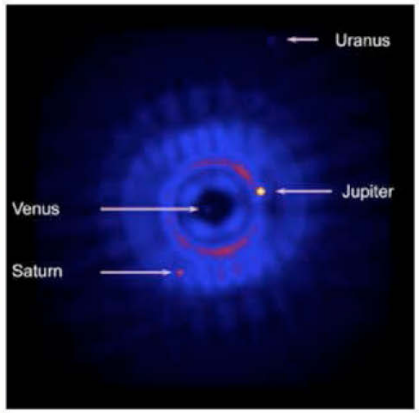
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Visible Nulling Coronagraph
M. Clampin (NASA GSFC)









6 of 7 awards in 2009-2011: Technology Demonstrations for Exoplanet Missions 2009

Avalanche Photodiode Arrays
D. Figer (Rochester Institute of Technology)

Table 2. Proposed Detector Performance

Parameter	Now	Project Goal	Long-term Goal
Format	64x64[a]	256x256	1024x1024
Pixel Size	50 μm[b]	25 μm	15 μm
Read Noise	zero	zero	zero
Dark Current (@170 K)	2 e^-/s/pixel @215 K	<0.002 e^-/s/pixel	<0.001 e^-/s/pixel
Power[c] (mW)	not measured	<100	<250
QE[d] (350nm, 650nm, 1000nm)	35%,50%,15%	50%,80%,30%	50%,80%,30%
Latent Image in 1000 seconds (after full well)	zero	zero	zero
Fill Factor	75%[e]	100%	100%
Technology Readiness Level	3	5	6

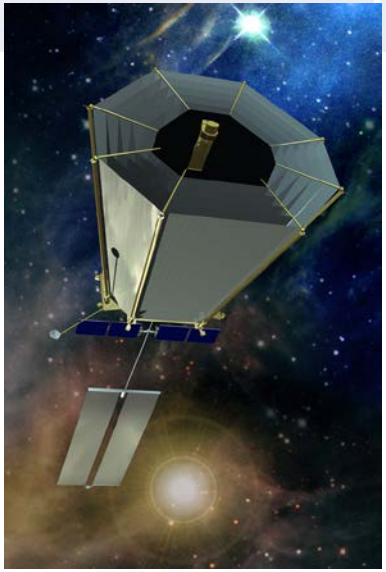
[a] A 256x256 ROIC is in fabrication, but the hybridized device has 64x64 pixels.
[b] The 256x256 ROIC in fabrication has 25 μm pixels, but the hybridized device has 50 μm pixels.
[c] This quantity should be compared to detector+digitization electronics in other detectors.
[d] These values include the probability that photogenerated charges induce an avalanche.
[e] Requires lenslet array.

7 of 7 awards in 2009-2011: Technology Demonstrations for Exoplanet Missions 2009

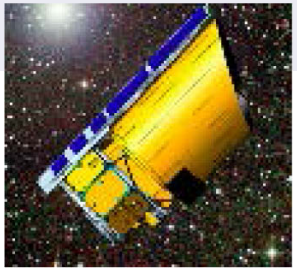
National Aeronautics and Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

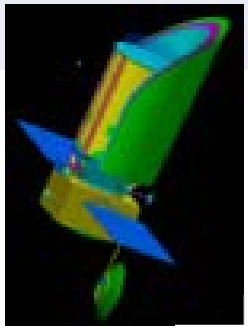
Gallery of Exoplanet Mission Concepts



TPF-C *Terrestrial Planet Finder Coronagraph*

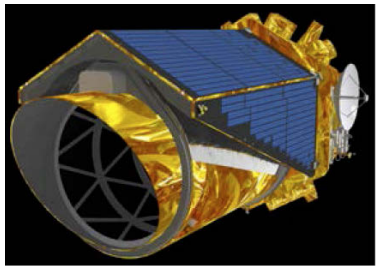


PECO *Pupil-Mapping Exoplanet Coronagraphic Observe*

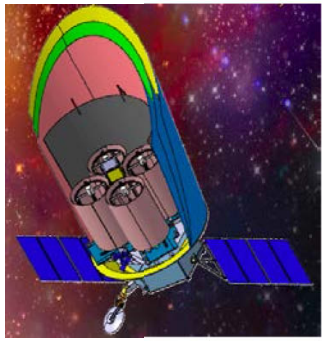


ACCESS *Actively-Corrected Coronagraph for Exoplanet System Studies*

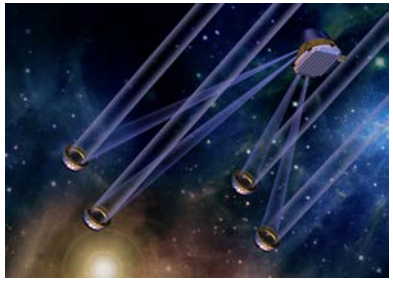
NWO
New Worlds Observer



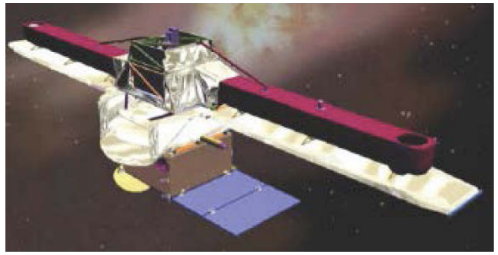
EPIC *Extrasolar Planetary Imaging Coronagraph*



O3
Occulting Ozone Observatory

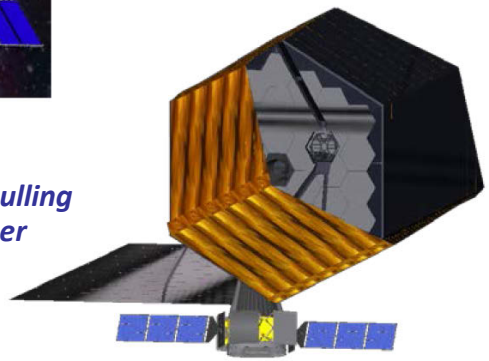


TPF-I *Terrestrial Planet Finder Interferometer*



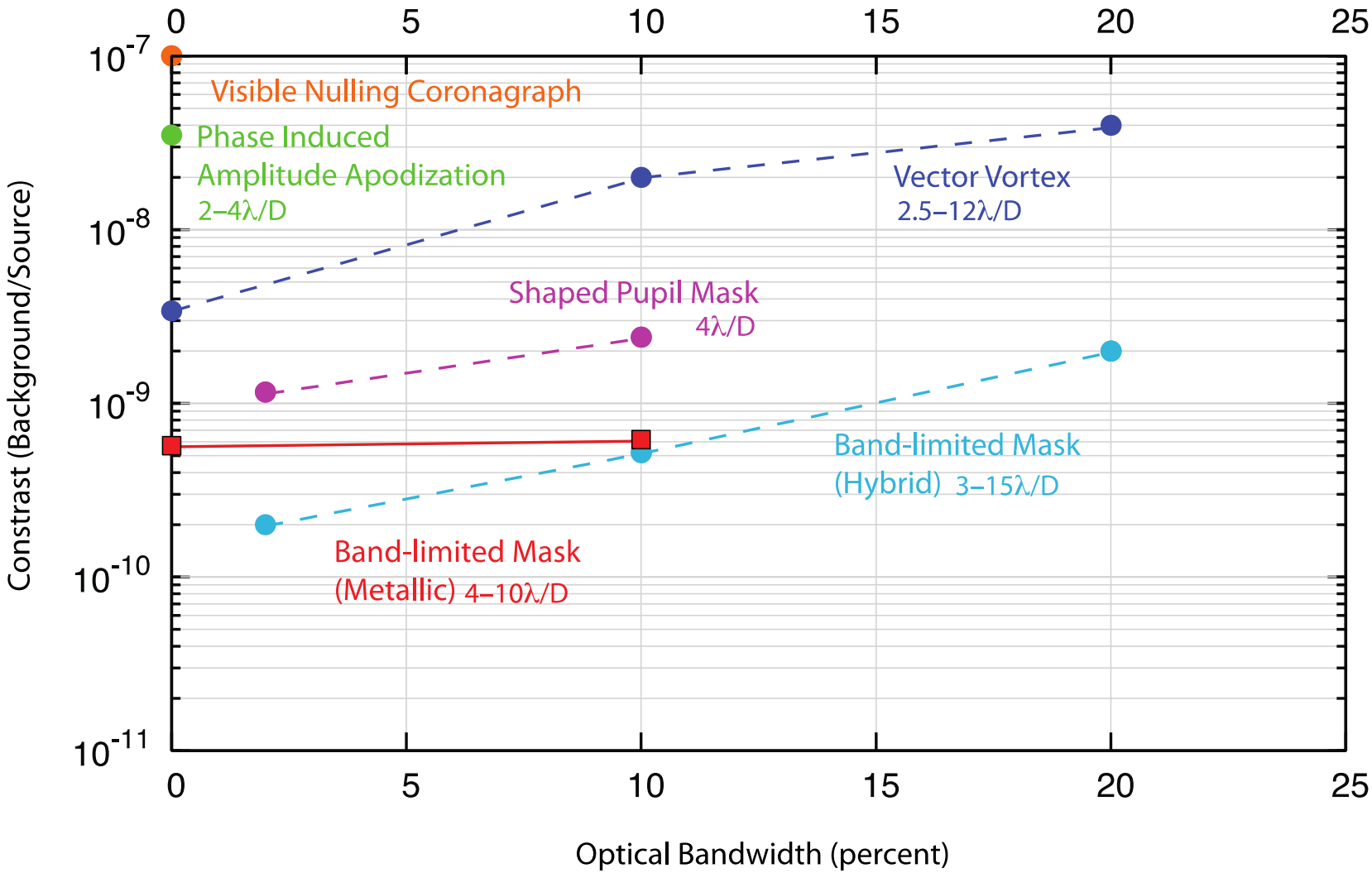
FKSI *Fourrier-Kelvin Stellar Interferometer*

DAViNCI *Dilute Aperture Visible Nulling Coronagraph Imager*



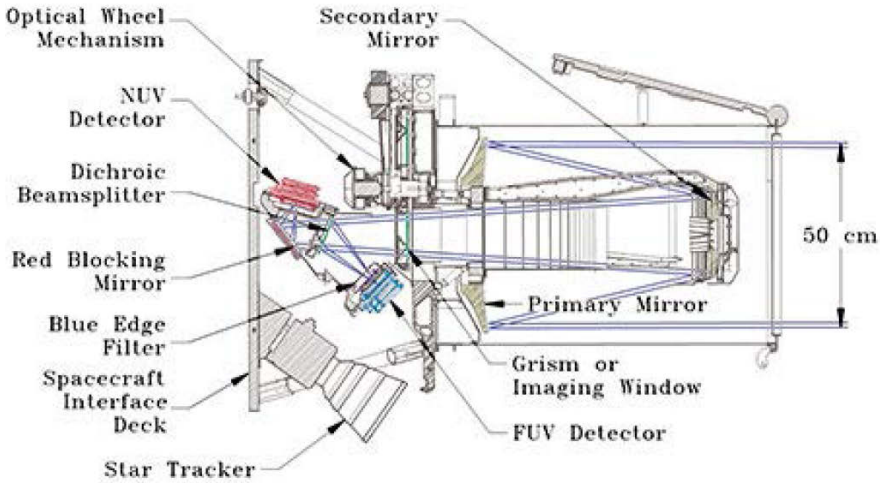
ATLAST *Advanced Technology Large-Aperture Space Telescope*

State-of-the-Art in Coronagraph Laboratory Experiments



UV/Optical and Exoplanet Mission?

Example: GALEX (2003–2011)



The most cost-effective way to improve sensitivity for a UV telescope would be to develop better UV detectors and more efficient coatings – not by going to larger mirrors

Exoplanet missions need mirrors at least 4-m in diameter

A starshade design would not impose additional constraints on a UV telescope, other than adding navigator beacons or sensors

A coronagraph design typically requires an unobscured, off-axis primary, and polarization-preserving multi-layer coatings, thus imposing numerous additional requirements on the telescope

Acknowledgements

This work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration

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Government sponsorship acknowledged