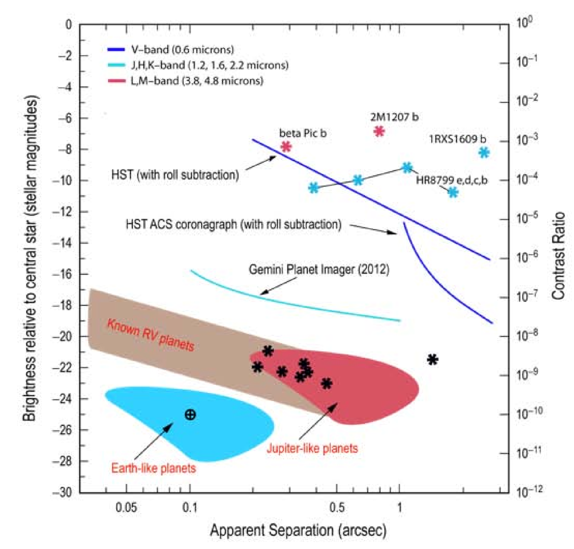
A Space Coronagraph Mission for Exoplanet Imaging and Spectroscopy

Status and Challenges in the Astro2010 Era – J. Trauger, JPL/Caltech

Rally around the science

- The Astro2010 calls for consensus on exoplanet mission readiness.
- Rally around a compelling science mission with high readiness, else cede the future of exoplanet missions to the next decadal survey.
- The astrophysics of exoplanet systems (i.e., direct imaging and spectroscopy) is the compelling science of the coming decade.
- A successful concept also advances the field of general astrophysics (UV-visible imaging and spectroscopy) in the post-Hubble area.
- **We seek a space astronomy mission in which exoplanet science, and specifically a high-performance coronagraph, appears among the Level 1 mission requirements.**

Exoplanet Discovery Space



Asterisks: known exoplanets

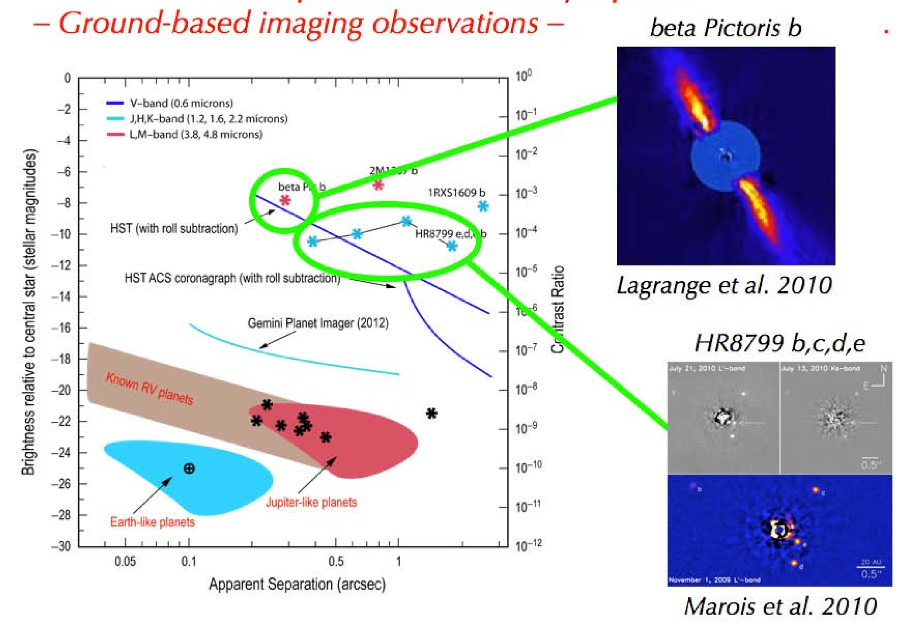
Curves: instrument capabilities

Colors: photometry bands

Blobs: regions of high likelihood for detection of Jupiter-twins and Earth-twins orbiting the nearest 100 AFGK stars

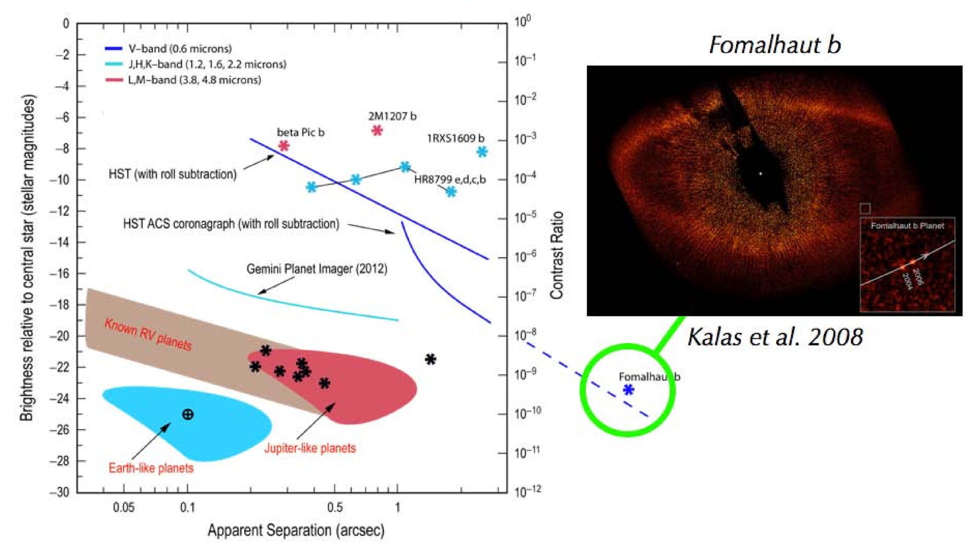
Exoplanet Discovery Space

– Ground-based imaging observations –

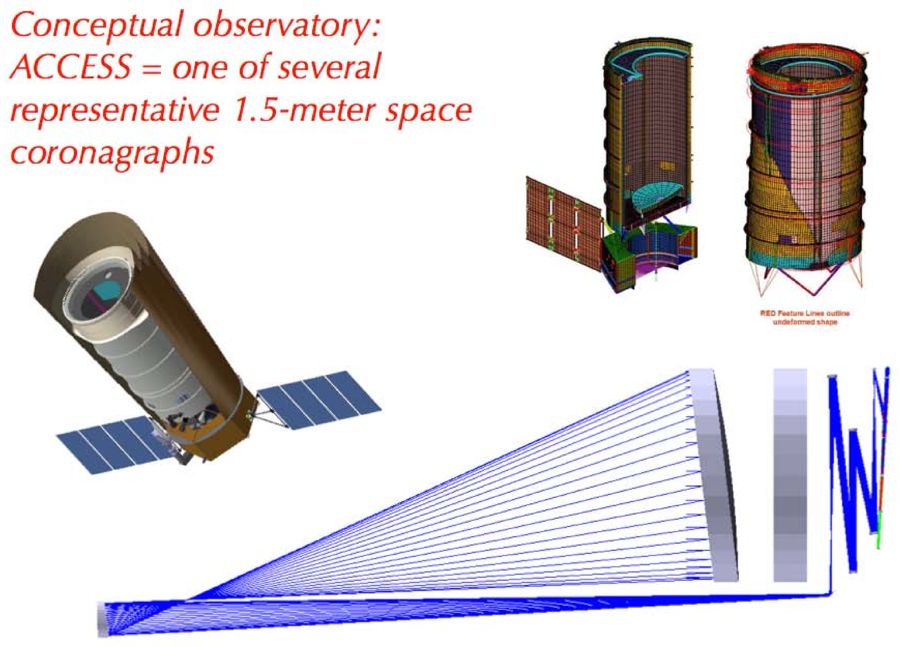


Exoplanet Discovery Space

– Hubble ACS coronagraph observations –

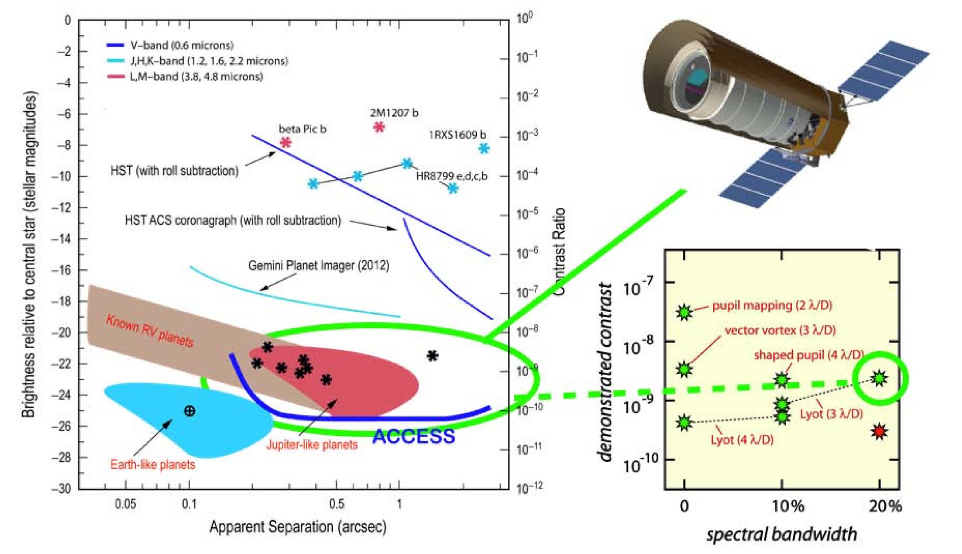


Conceptual observatory: ACCESS = one of several representative 1.5-meter space coronagraphs



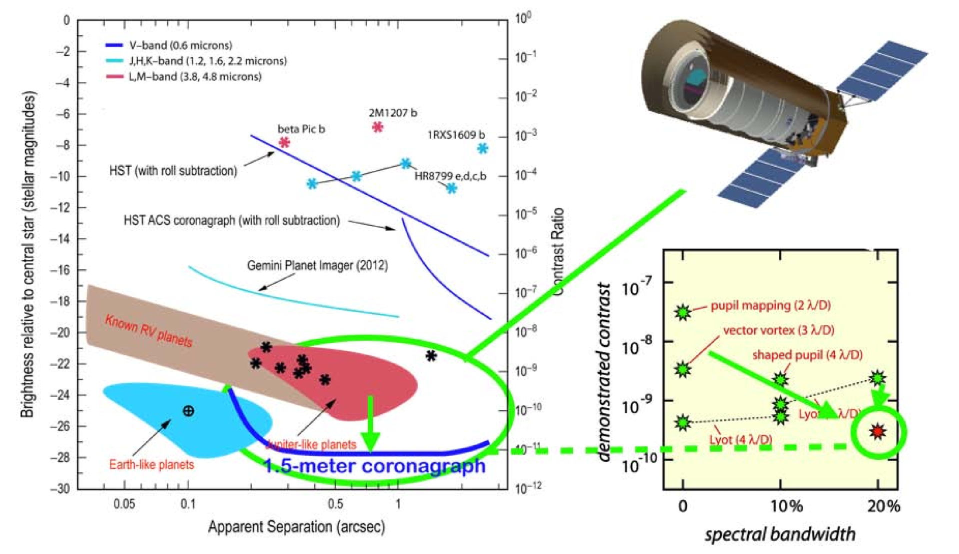
Exoplanet Discovery Space

– Linking mission concepts to demonstrated coronagraph performance –



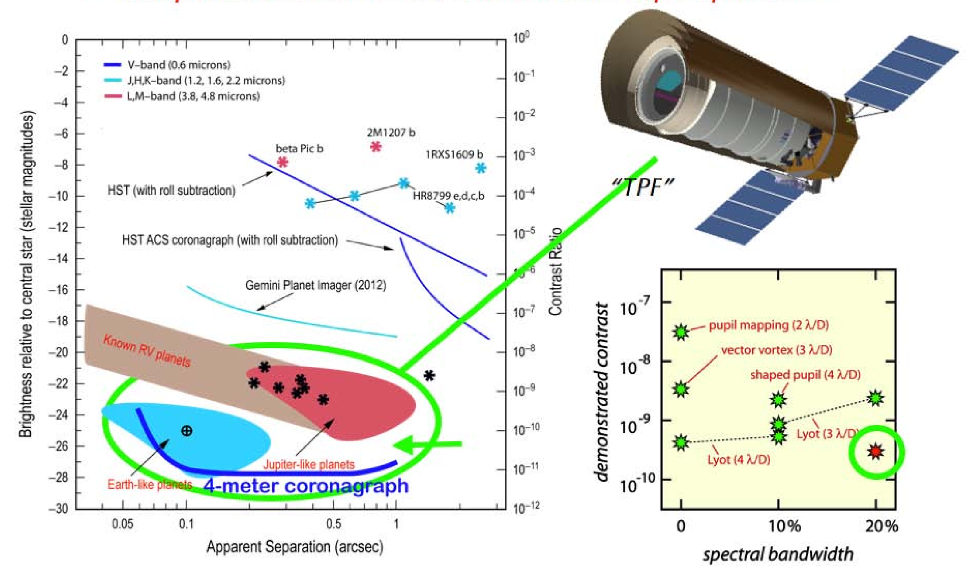
Exoplanet Discovery Space

– Performance goal for the coming three years –

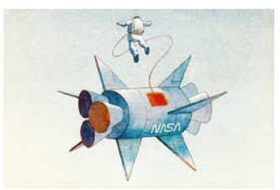


Exoplanet Discovery Space

– Extrapolation from 1.5 to 4 meter telescope aperture –



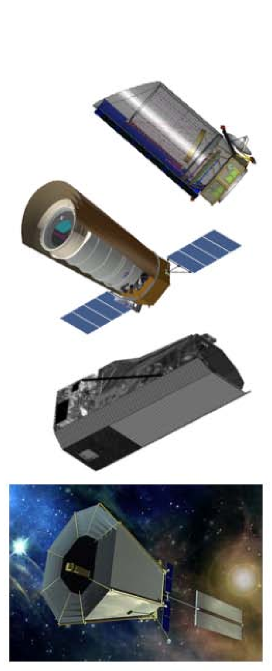
High readiness by 2014



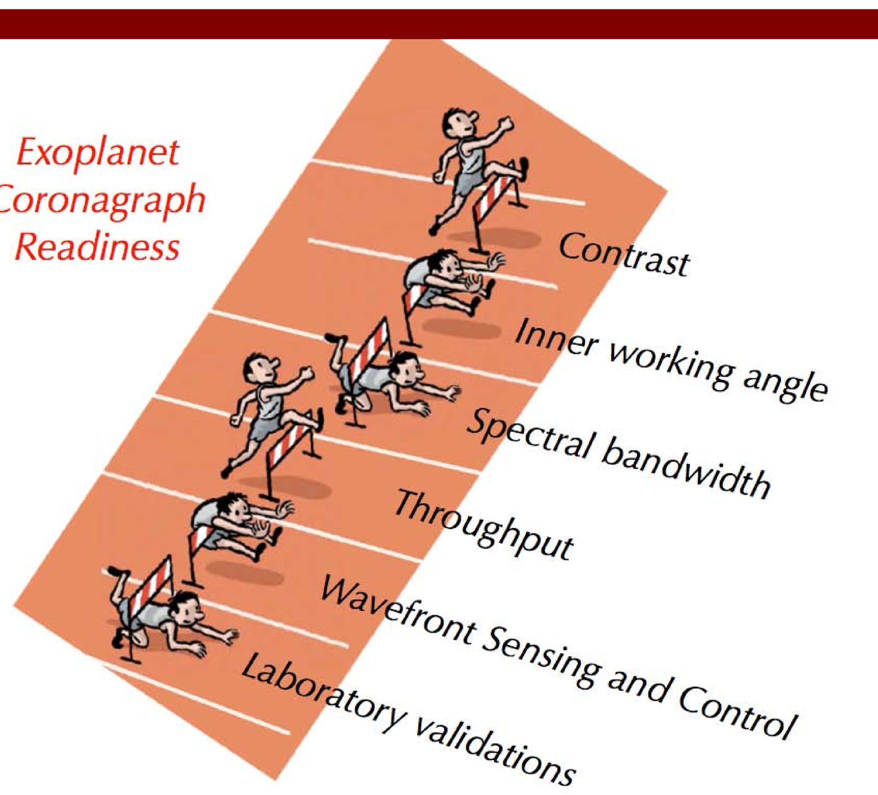
- Let's not miss our last best chance for exoplanets at the mid-decade.
- Compelling science, not the specific coronagraph design, is the justification for an exoplanet mission.
- Only high TRL coronagraph systems will be relevant in the mid-decade decision.
- Fish or cut bait: there will **always** be a "better idea" in the coming year – holding out for "better" may defeat our opportunity for a mission in the coming decade.
- The general astrophysics community does not understand – and is reluctant to endorse – high-contrast coronagraphs, hence we have an obligation to provide coherent and constructive discourse with our colleagues.

Exoplanet Mission Readiness Checklist

- ✓ Coronagraph performance
- ✓ Telescope thermal and dynamic stability
- ✓ Telescope pointing control
- ✓ Optical wavefront control and stability
- ✓ Method for speckle / planet discrimination
- ✓ Photon-counting imaging sensors
- ✓ End-to-end performance models
- ✓ End-to-end laboratory validations

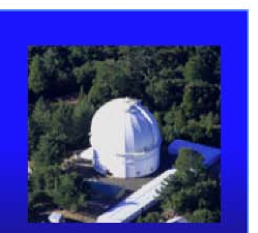


Exoplanet Coronagraph Readiness

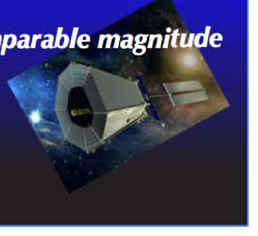


Space and ground-based coronography: worlds apart

Ground based: C ~ 1e-3 to 1e-7
Phase dominated wavefront errors
Real-time adaptive optics to maximize Strehl
Spectral difference imaging works
Sensitive to young warm exoplanets



Space based: C ~ 1e-7 to 1e-10
Wavefront phase and amplitude errors are of comparable magnitude
Iterative active wavefront sensing and control
Spectral difference imaging does not work
Sensitivity extends to mature cool exoplanets



The demonstrated state of exoplanet coronagraphy

Lyot coronagraph demonstrations and goals

Contrast demonstrations with metallic and metal+dielectric Lyot masks:

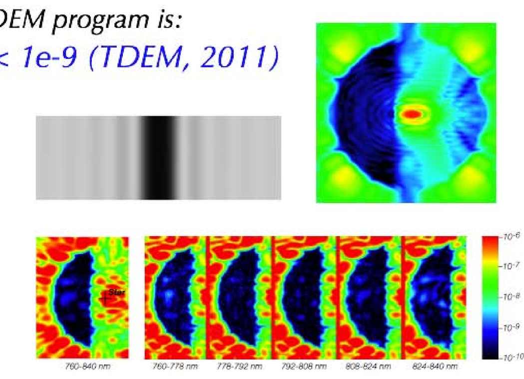
IWA = 3 λ/D, 20% BW, C = 2.7 e-9 (ACCESS, 2009)

IWA = 4 λ/D, 10% BW, C = 6 e-10 (TPF-C M2, 2008)

Milestone #1 for the hybrid Lyot TDEM program is:

IWA = 3 λ/ D, 20% BW, C < 1e-9 (TDEM, 2011)

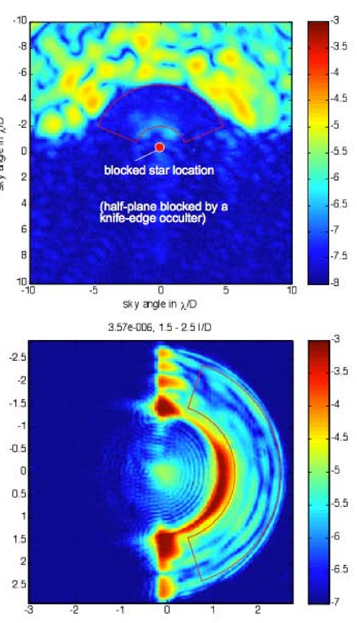
- Profiled metal+dielectric layers control complex (amplitude and phase) wavefront
- Optimized design for improved contrast (3e-10) at 3 λ/D over 20% bandwidth, and throughput (60%) is the goal of a 2010-11 TDEM program.



The demonstrated state of exoplanet coronagraphy

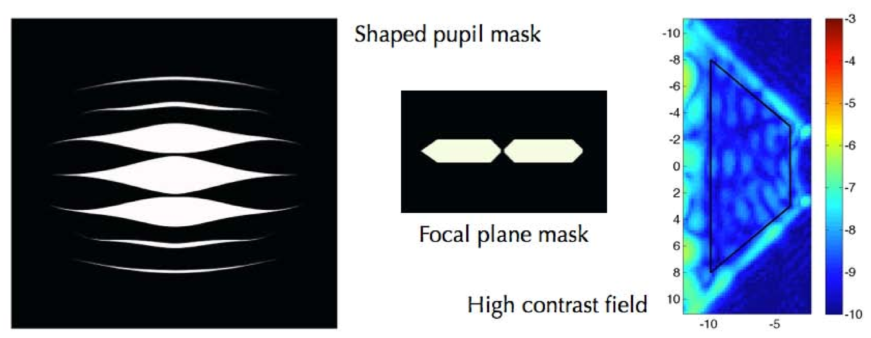
Pupil mapping demonstrations

The pupil mapping (PIAA) coronagraph has achieved IWA = 2 λ/D, monochromatic, C = 3e-8 with the Generation 1 PIAA mirrors now on the HCIT testbed (Kern et al. 2010). Generation 2 mirrors, designed for 20% bandwidths (Guyon 2008) have been manufactured by Tinsley and are now active on on the Ames testbed (Belikov 2010)



The demonstrated state of exoplanet coronagraphy

Shaped pupil coronagraph experiments with HCIT

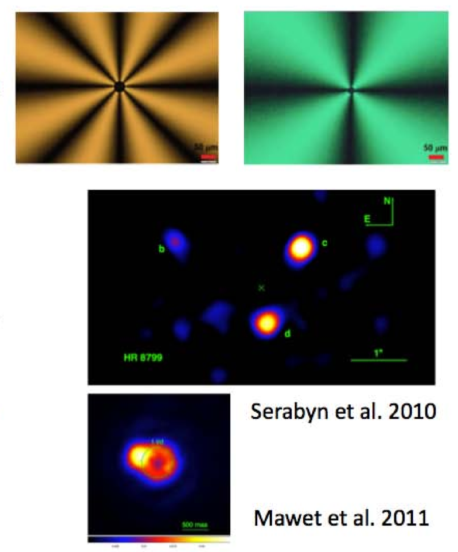


At left, the transmittance profile of a representative shaped pupil apodization (black indicates opaque, white indicates clear). At center, the corresponding "bowtie" image plane mask. This "Ripple 3" design achieved 2.4e-9 contrast in 10% bandwidth averaged over the 4-10 λ/D dark field (outlined) on the HCIT. (Belikov et al. 2007)

The demonstrated state of exoplanet coronagraphy

Vector Vortex Coronagraph

- Phase-based coronagraph
- Small inner working angle, high throughput, simplicity of integration (Lyot-type layout)
- Status:
  - Generation 1 of devices:
    - Second-order masks installed at Palomar, used to image exoplanets and companions down to 1-2 λ/d in the near-infrared using adaptive optics.
    - Fourth-order mask tested in the visible on the HCIT in 2008 (~10^{-7} over 10% BW)
  - Generation 2:
    - Technological development financed through APRA and SBIR programs
    - Improved definition of the center (40 µm => 5 µm)
    - Achromatic (goal 10^{-9} over 20% BW)

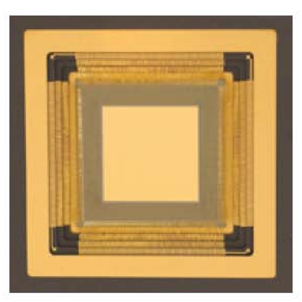


Serabyn et al. 2010

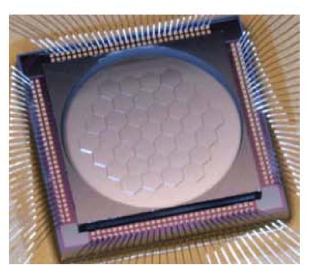
Mawet et al. 2011

All coronagaphs require deformable mirrors for precise wavefront control

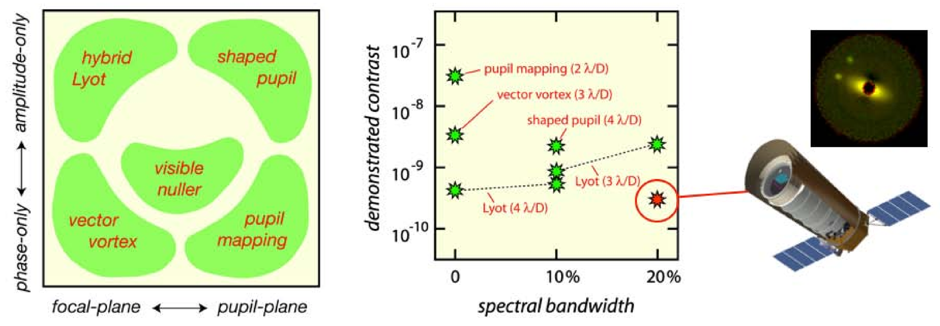
HCIT experiments have been carried out with Xinetics DMs. Fused silica facesheet is polished nominally to λ/100 rms. Surface figure (open loop) has been shown to be settable to 0.05 nm rms and stable to 0.01 nm rms over periods of 6 hours or more in a vacuum testbed environment. Protoflight qualification is in progress at JPL.



MEMS DMs manufactured by Boston Micromachines (left) and IRIS-AO (right) can be configured with either continuous or segmented mirror facesheets. MEMS DMs are actively in use in all testbeds other than HCIT.



The demonstrated state of exoplanet coronagraphy



- The best laboratory performance (as of April 2011) for four major space coronagraph methods has been achieved in JPL's High Contrast Imaging Testbed.
- Raw instrument contrast, spectral bandwidth, and proximity of the high contrast field of view to the central star are indicated in the performance plot.
- Visible nuller coronagraph has achieved 10-8 suppression of the central star, but has yet to demonstrate a high contrast field of view, hence is not plotted here.
- Required instrument contrast and bandwidth for an Earth-finding coronagraph mission – the goal of current SAT/TDEM and APRA efforts – is shown as the red star.

Next three years are critical for **the validation of leading technologies**

- Continuing advances in demonstrated contrast, spectral bandwidth, inner working angle, and nulling algorithms by 2015.
- Laboratory validation of performance models, including pointing control methods and strategies for planet/speckle discrimination in a flight simulating environment.
- Mission design based on demonstrated laboratory performance and various existing (TPF, ASMCS) engineering concept models.
- We seek **objective criteria** for readiness, based on a compelling exoplanet science reference mission grounded on validated coronagraph performance models.
- **Known coronagraph technologies lead to a class of viable mission concepts that could be ready for downselect by mid-decade.**

Next three years are critical for **building consensus in the exoplanet community**

- The past few years have seen good progress, largely thanks to strategic institutional initiatives and NASA investments.
- Competitive NASA programs (ASMCS, SAT, APRA) have allowed the **exoplanet community** to develop technologies and concepts that are fresh and current in the exoplanet community.
- We need to rally our community around compelling exoplanet science and a mission grounded on validated coronagraph performance models.
- Reach a community consensus by mid-decade, else cede the future exoplanet mission to the next decadal survey.