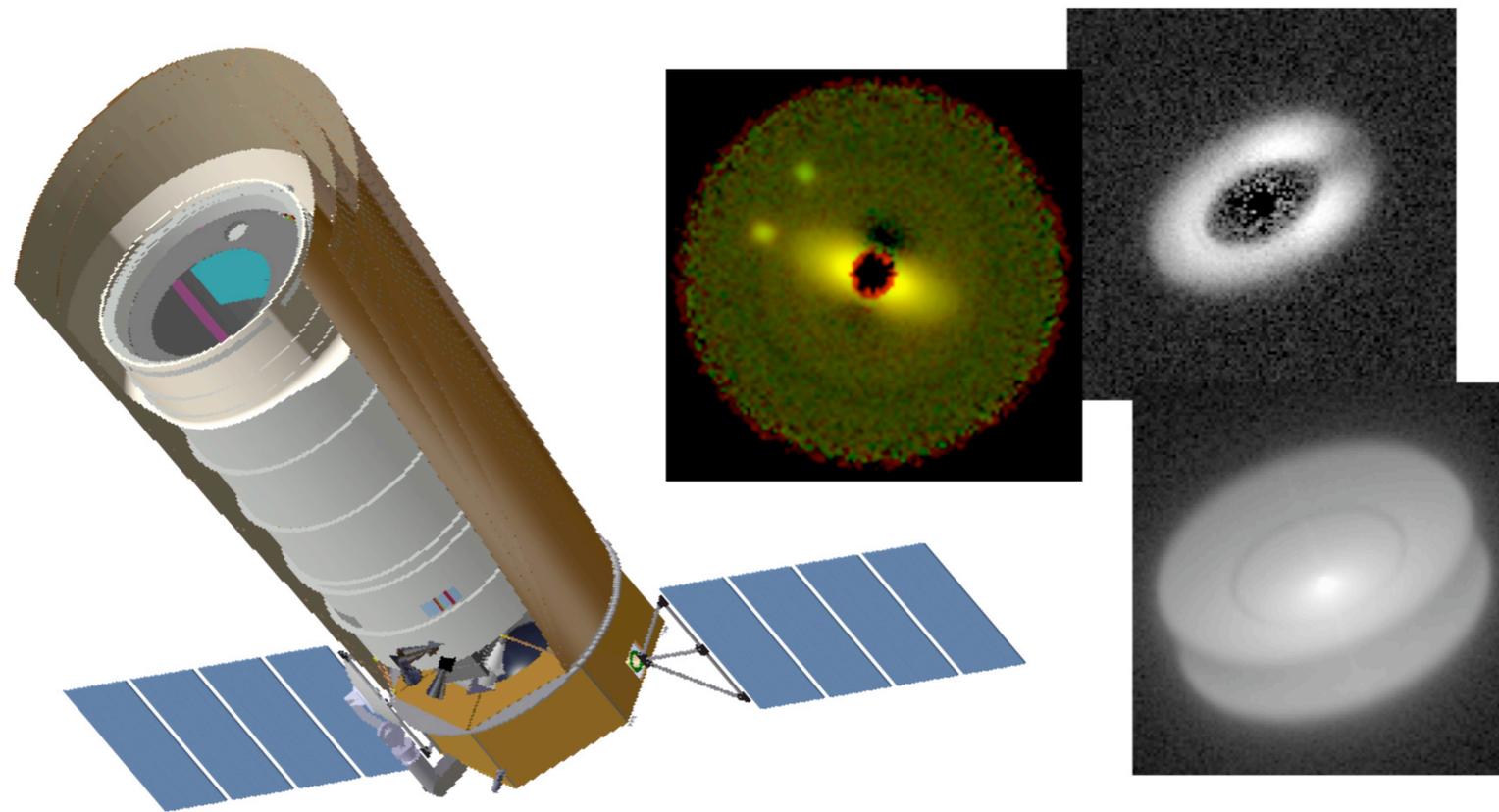


*Status and Challenges:  
A Space Coronagraph Mission for Exoplanet Imaging  
and Spectroscopy*



*John Trauger, JPL / Caltech  
Meeting of the ExoPAG – Seattle – 8 January 2011*

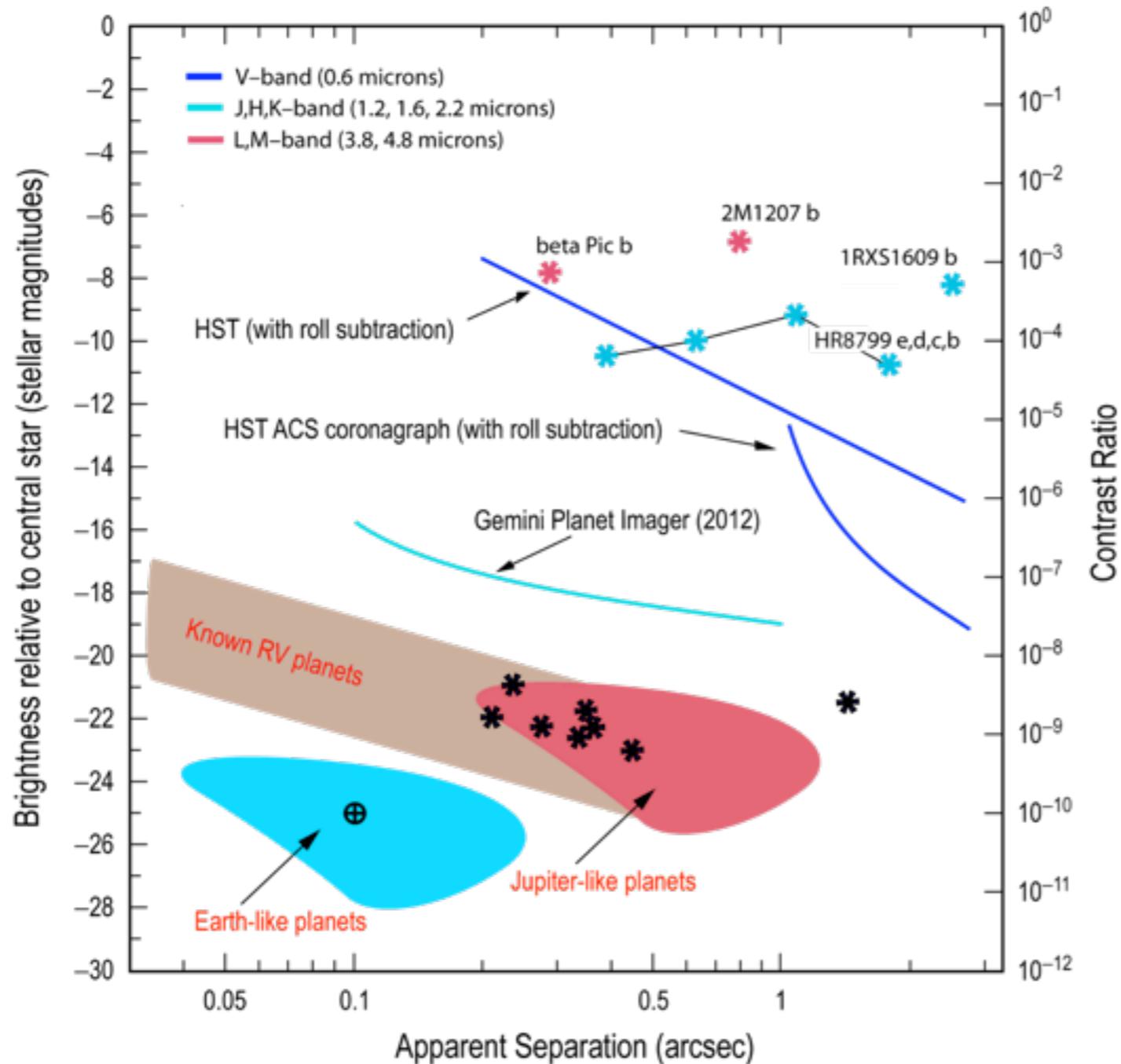
*(c) 2009 California Institute of Technology. Government sponsorship acknowledged*

## *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 is the compelling science of the coming decade, i.e., direct imaging and spectroscopy.*
- *A successful concept also supports general astrophysics (UV-visible imaging and spectroscopy) in the post-Hubble area.*
- *A coronagraph mission serves a broad range of astrophysics, since coronagraph is in essence one selectable observing mode in a very stable general astrophysics space telescope.*

# Exoplanet Discovery Space



*Asterisks: known exoplanets*

*Curves: instrument capabilities*

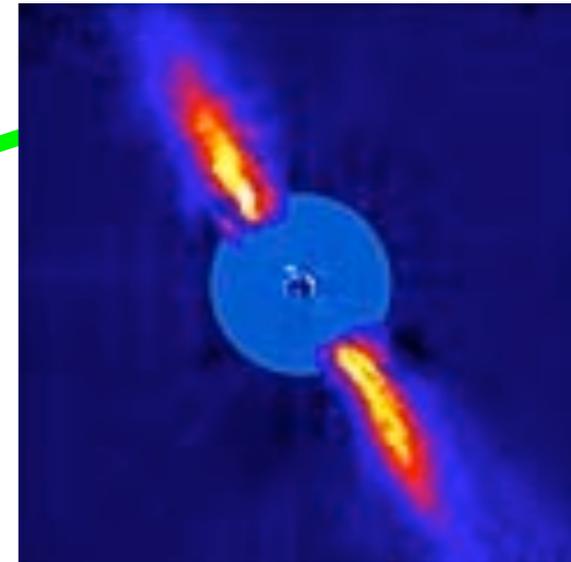
*Colors: photometry bands*

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

# Exoplanet Discovery Space

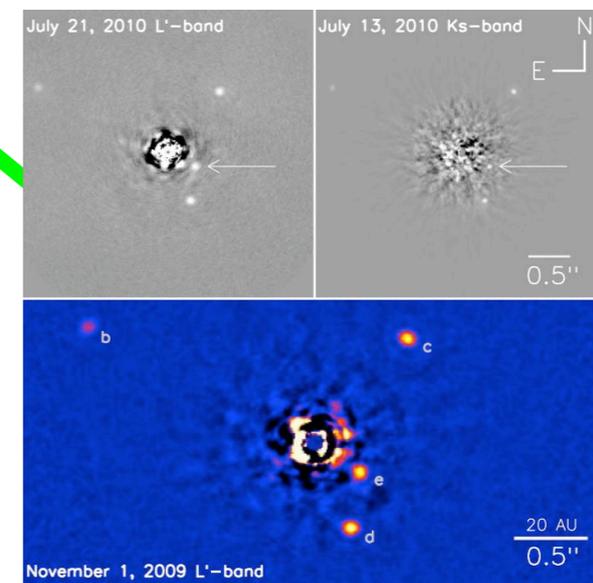
– Ground-based imaging observations –

*beta Pictoris b*

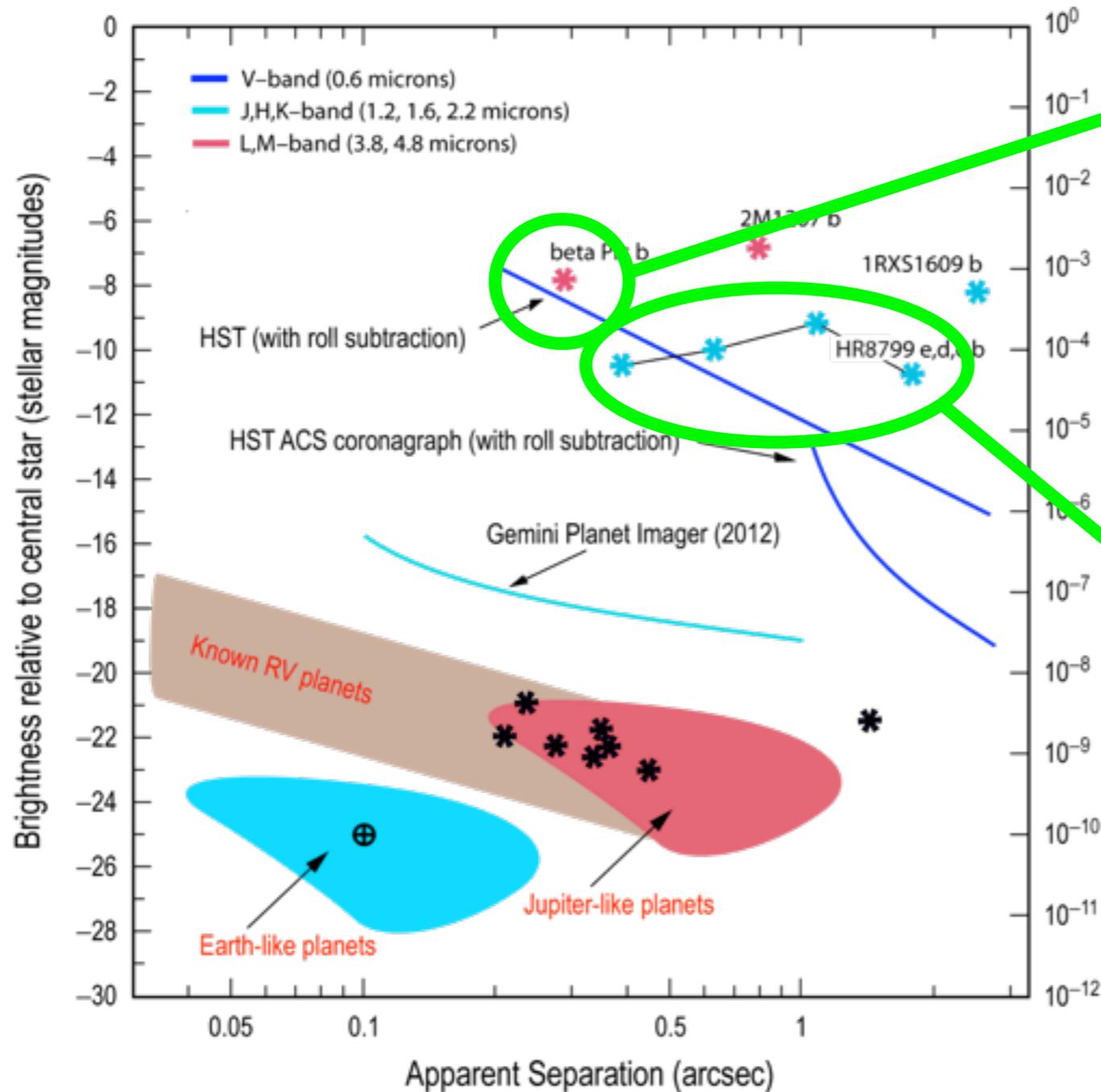


*Lagrange et al. 2010*

*HR8799 b,c,d,e*



*Marois et al. 2010*

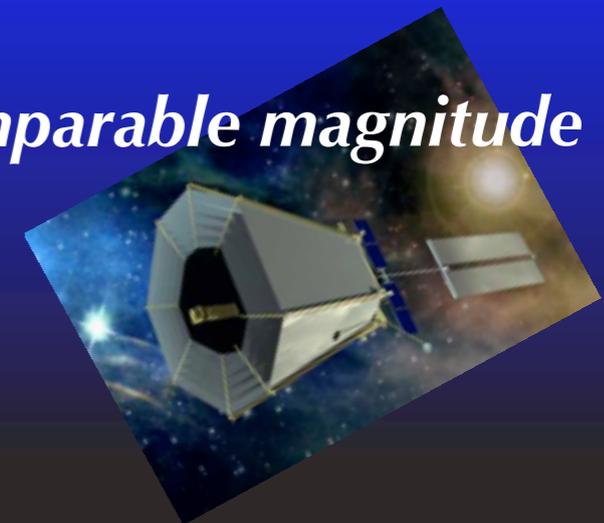


# *Space and ground-based coronagraphy: worlds apart*

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

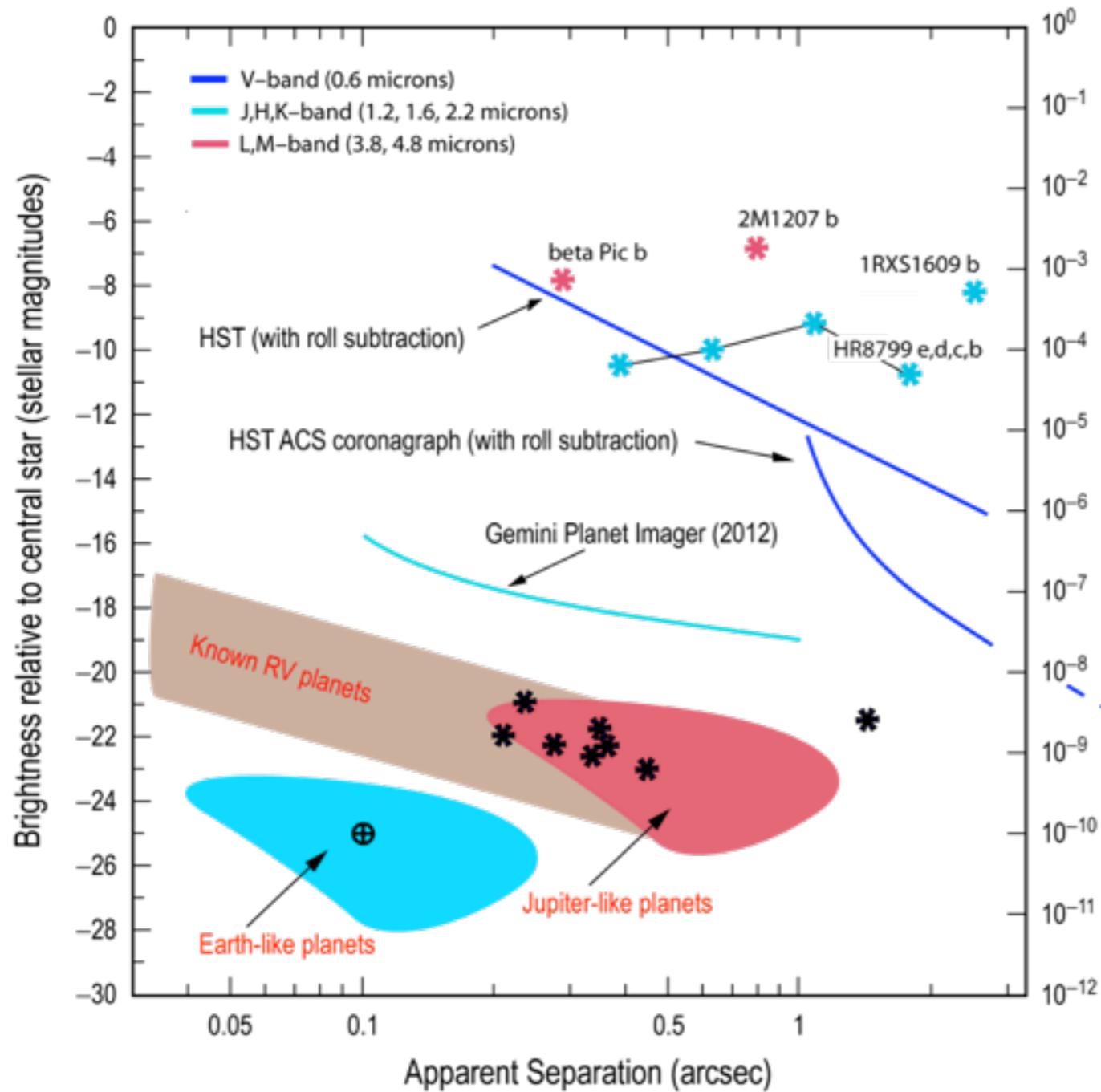


*Space based:  $C \sim 1e-7$  to  $1e-10$   
Wavefront phase and amplitude errors are of comparable magnitude  
Iterative active wavefront sensing and control  
Spectral difference imaging does not work  
Sensitivity extends to mature cool exoplanets*

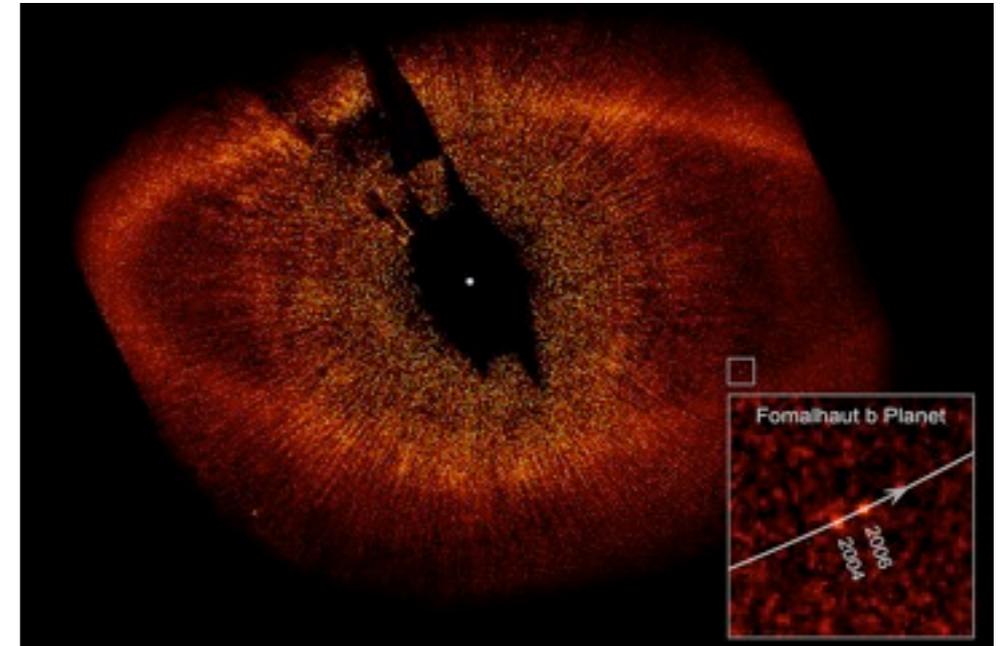


# Exoplanet Discovery Space

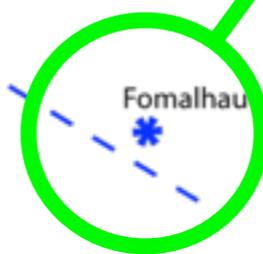
– Hubble ACS coronagraph observations –



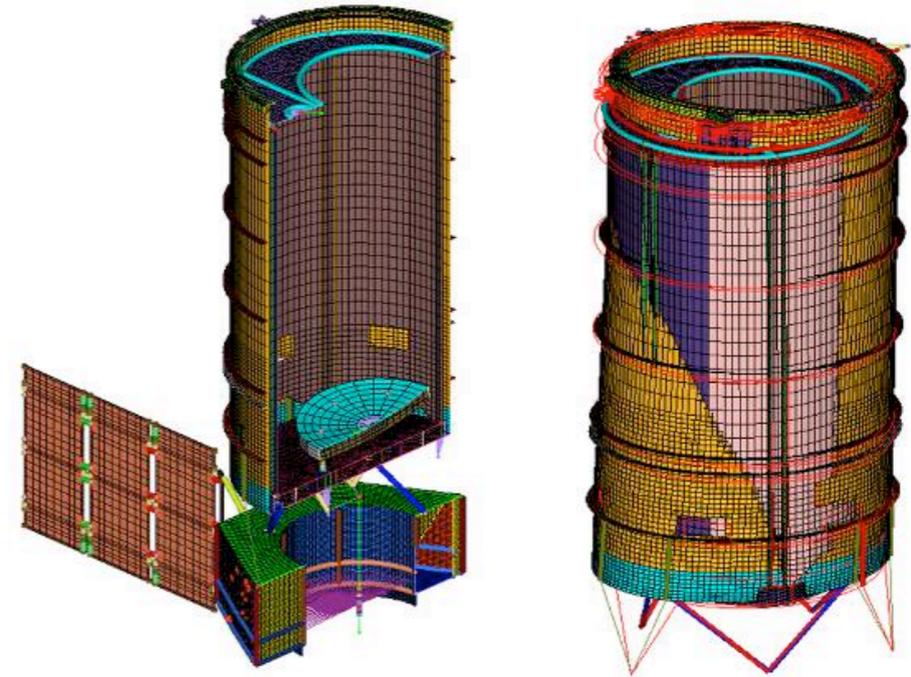
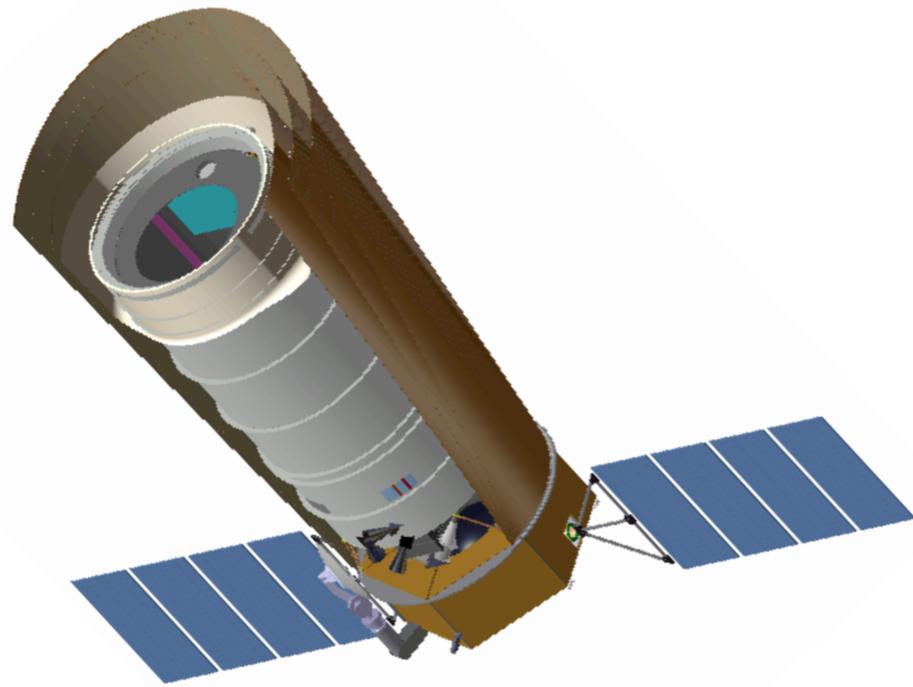
Fomalhaut b



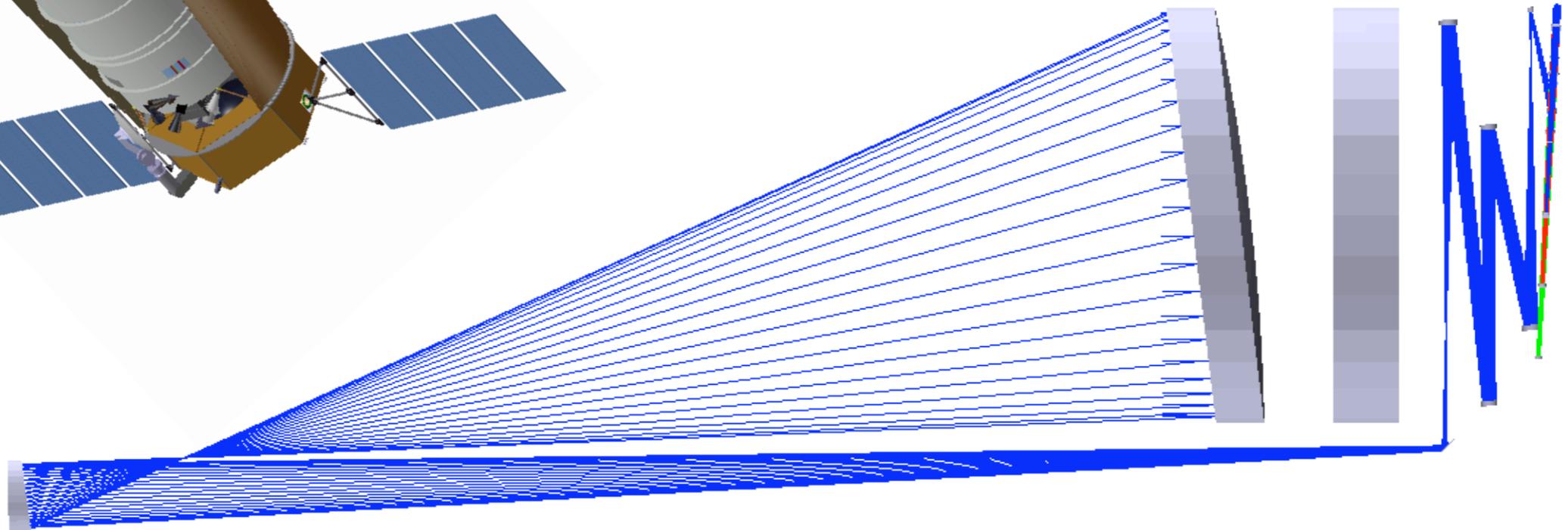
Kalas et al. 2008



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

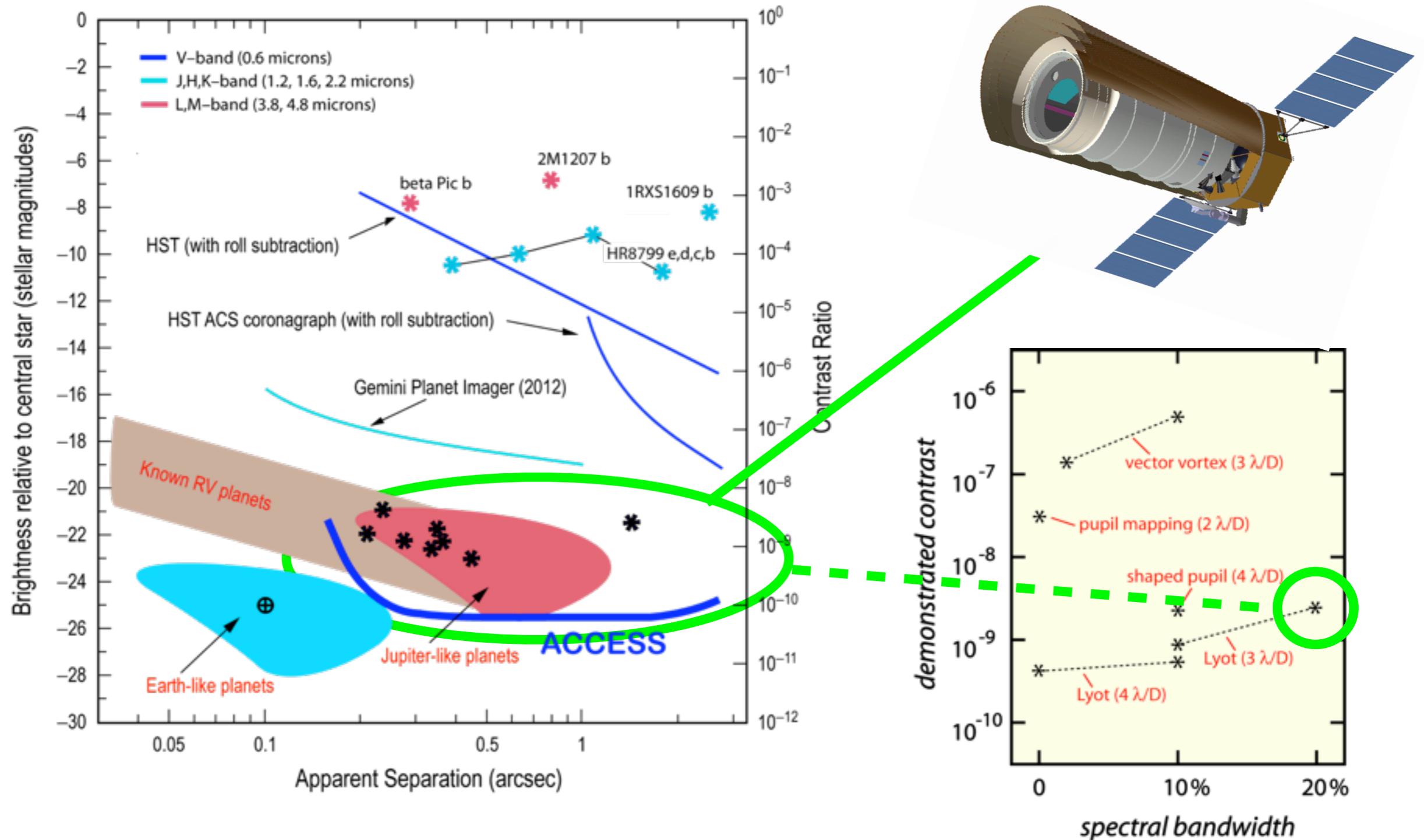


RED Feature Lines outline undeformed shape



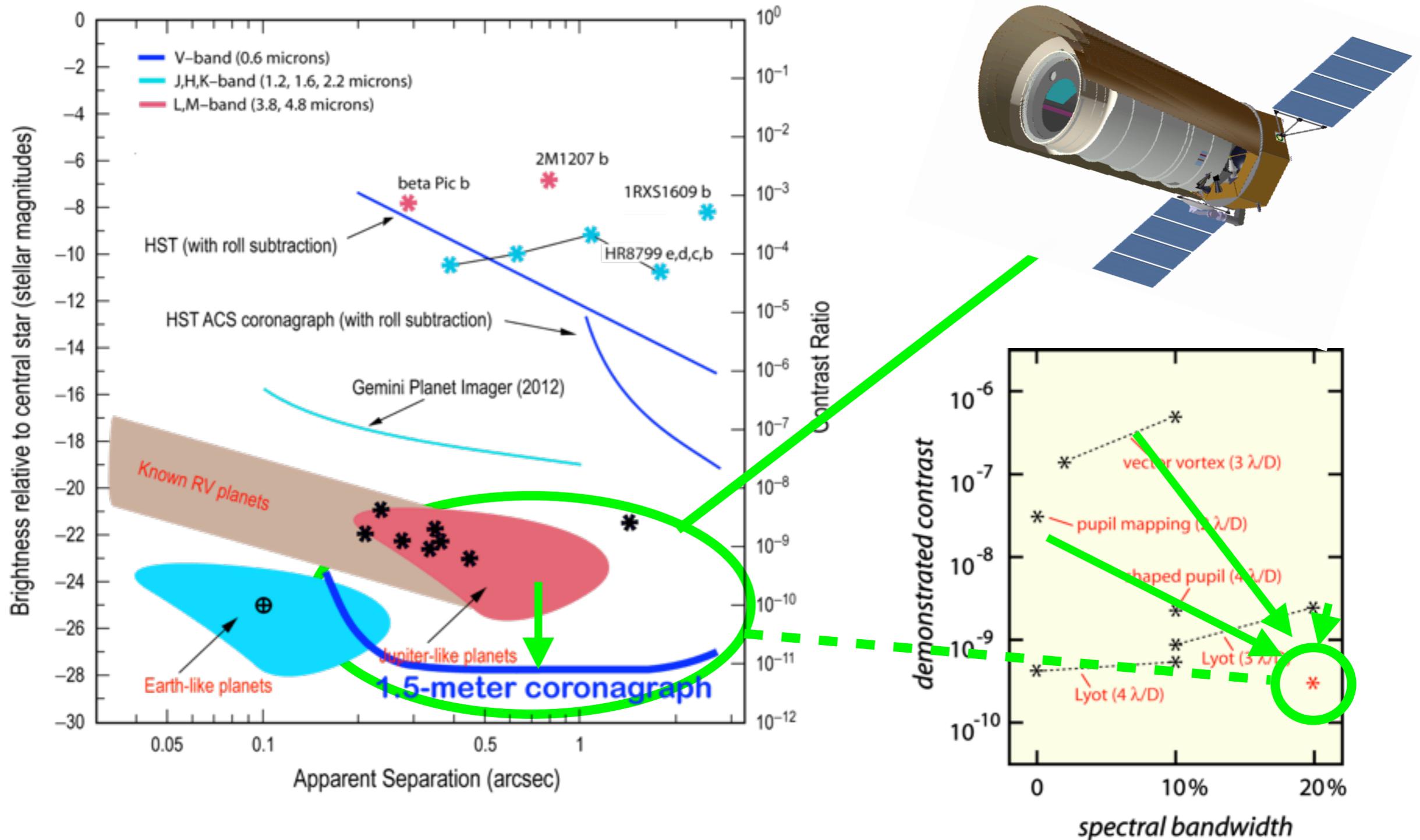
# Exoplanet Discovery Space

– Linking mission concepts to demonstrated coronagraph performance –



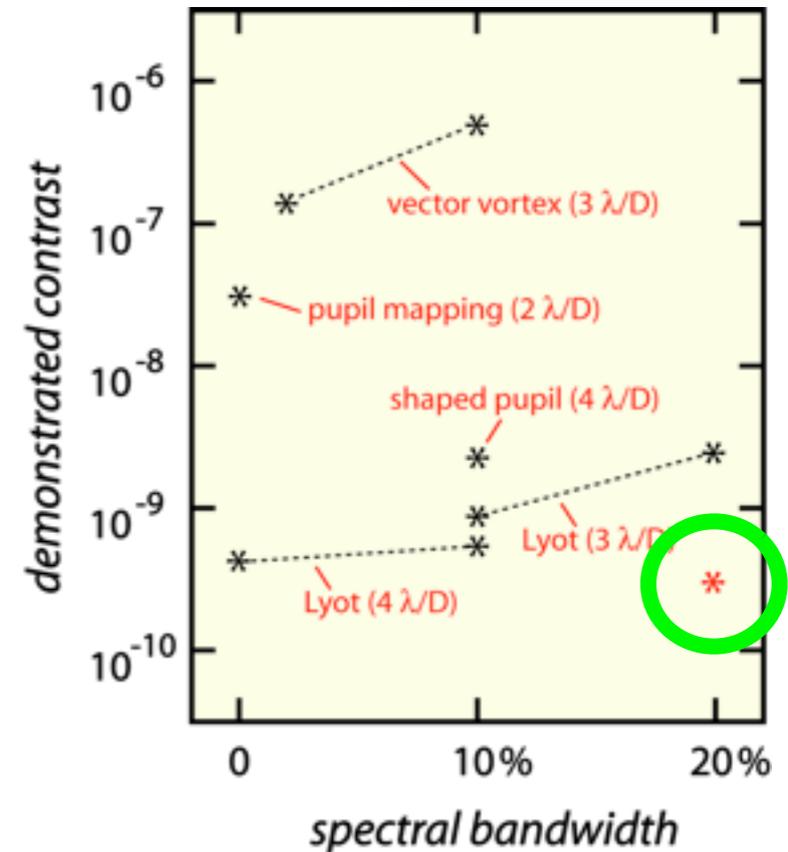
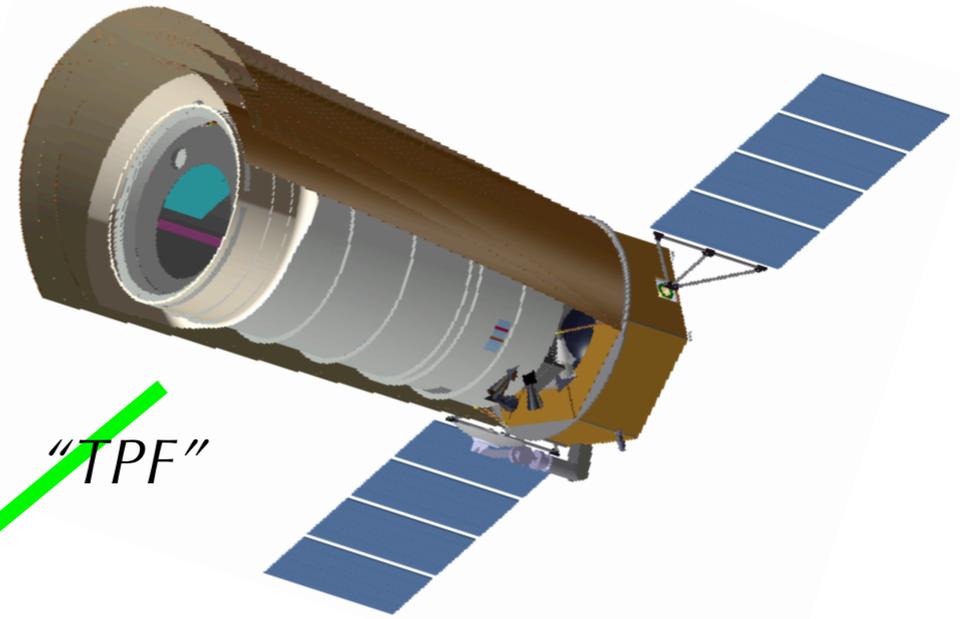
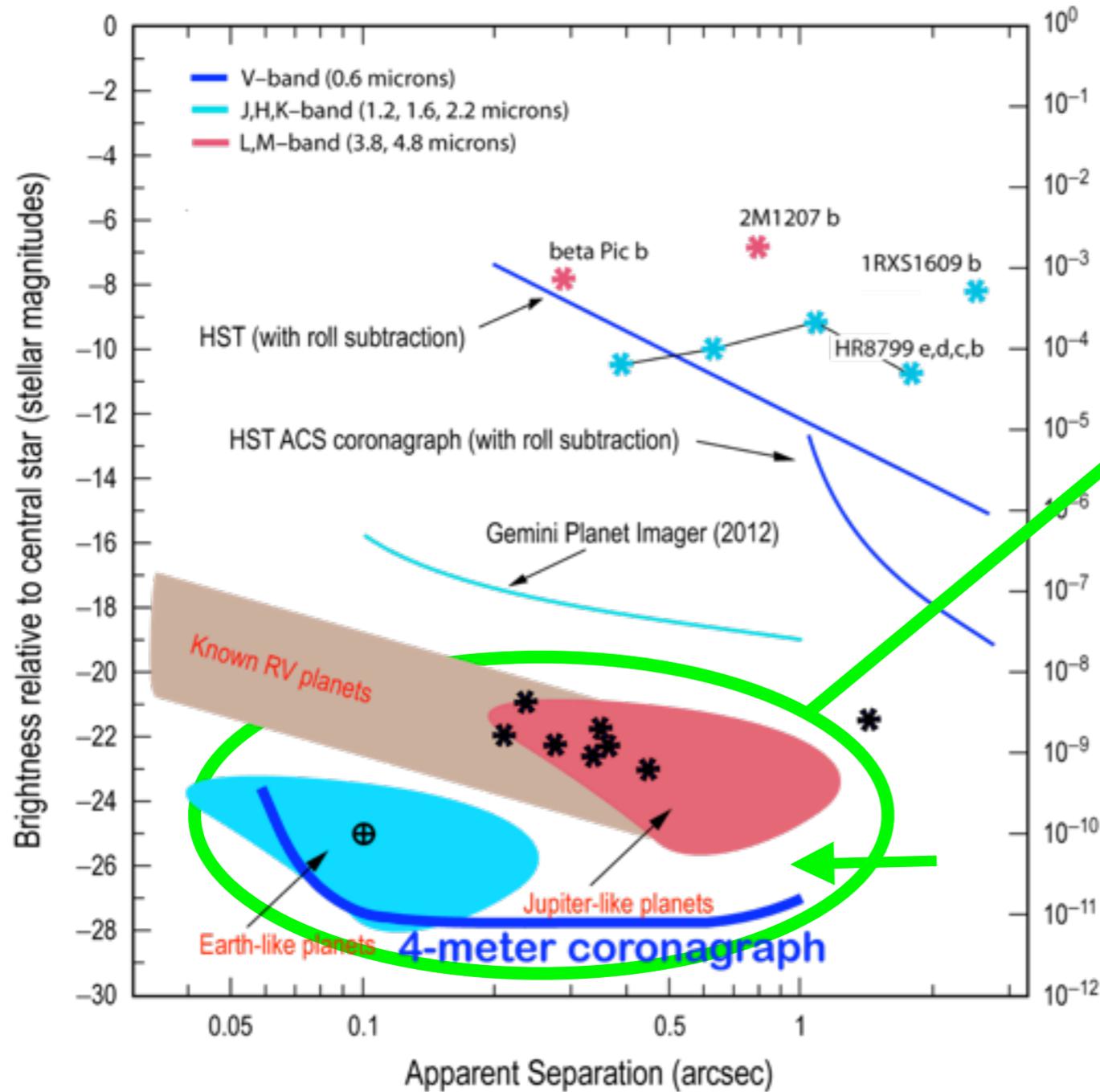
# Exoplanet Discovery Space

– Performance goal for the coming three years –

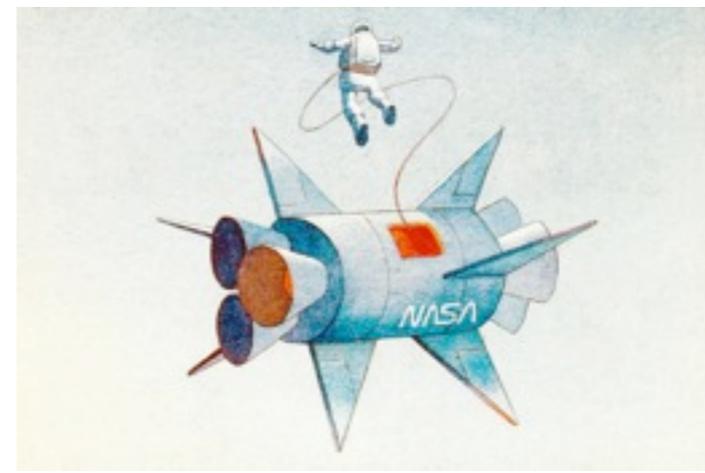


# Exoplanet Discovery Space

– Extrapolation from 1.5 to 4 meter telescope aperture –



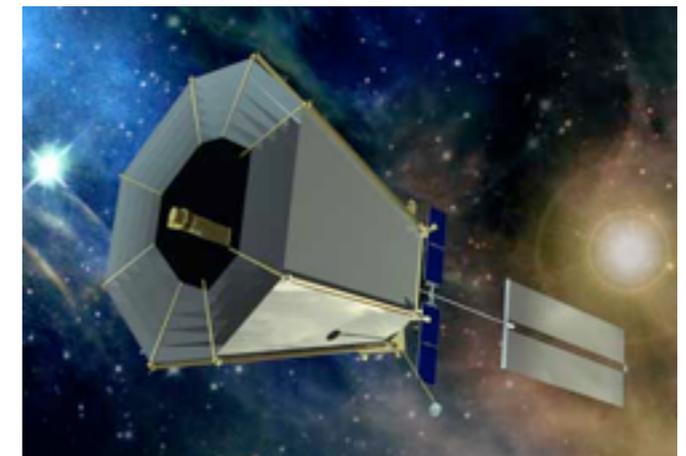
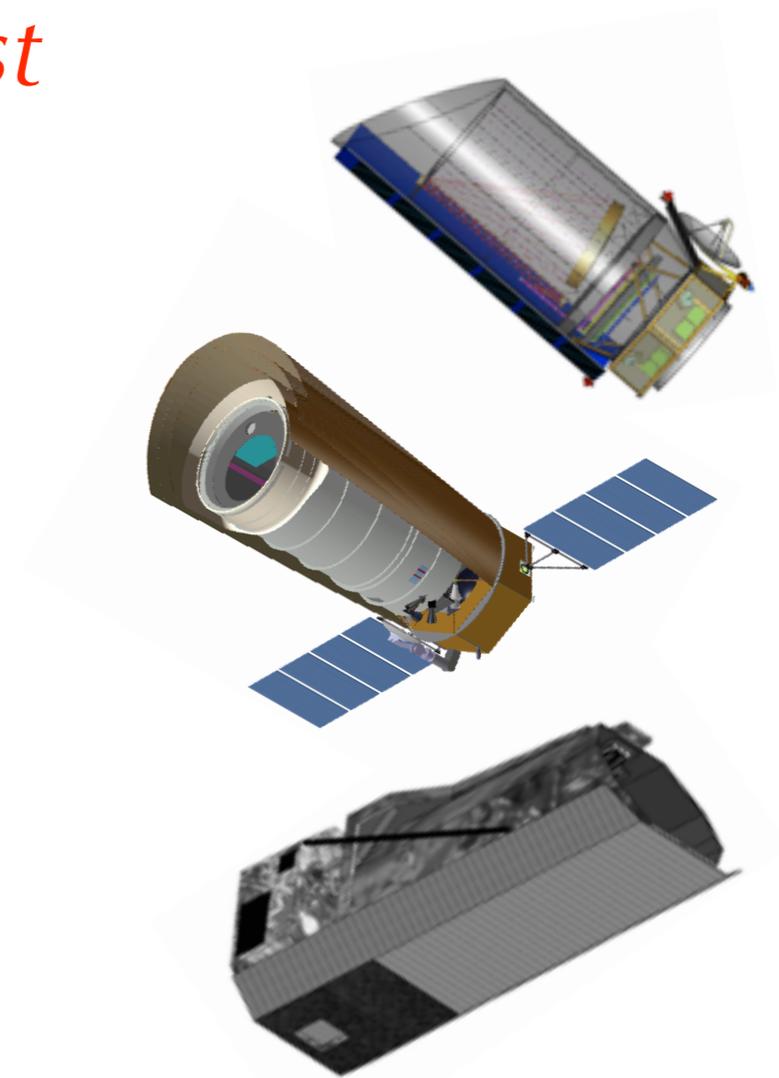
## *High readiness by 2014*



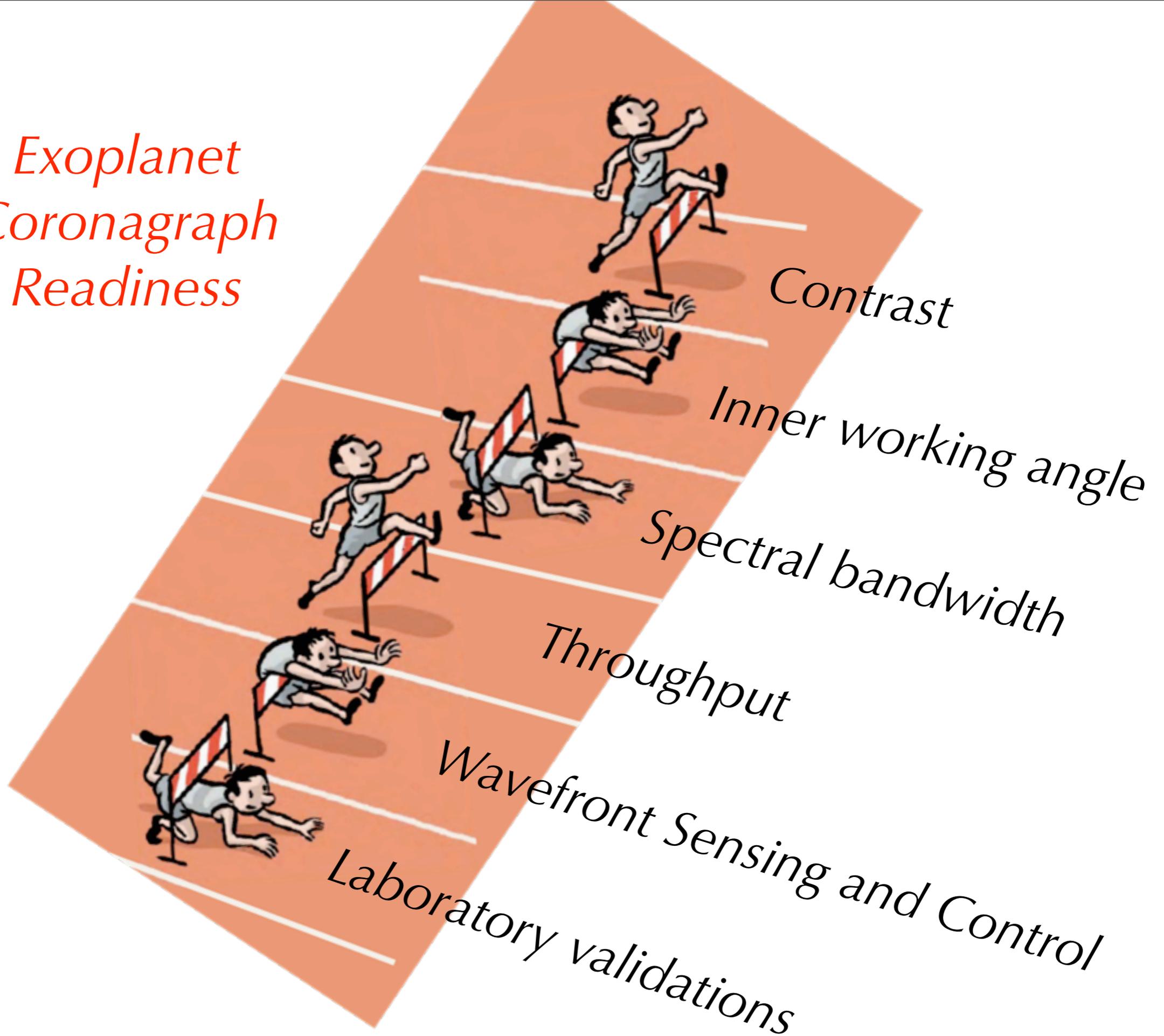
- *Let's not miss our last best chance for exoplanets at the mid-decade.*
- *Compelling science, not the specific coronagraph design, is the justification for an exoplanet mission.*
- *Only high TRL coronagraph systems will be relevant in the mid-decade decision.*
- *Fish or cut bait: there will **always** 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*



# The demonstrated state of exoplanet coronagraphy

## Lyot coronagraph demonstrations and goals

Contrast demonstrations with metallic and metal+dielectric Lyot masks:

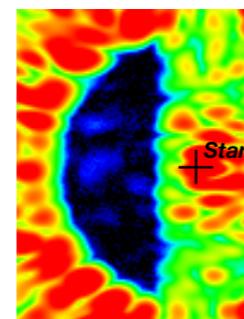
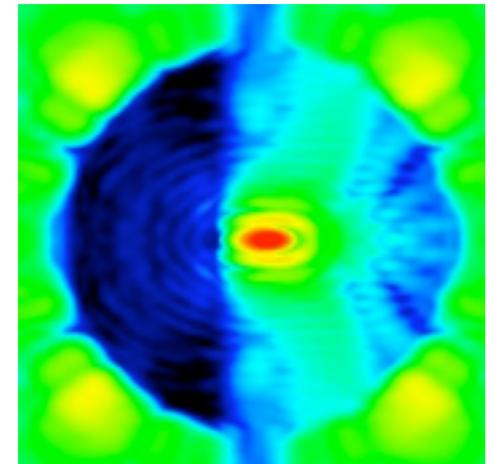
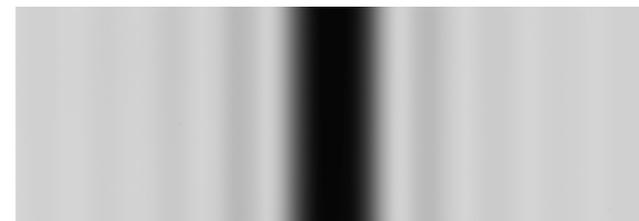
$IWA = 3 \lambda/D$ , 20% BW,  $C = 2.7 e-9$  (ACCESS, 2009)

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

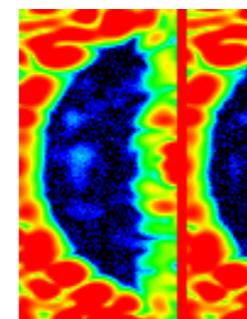
Milestone #1 for the hybrid Lyot TDEM program is:

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

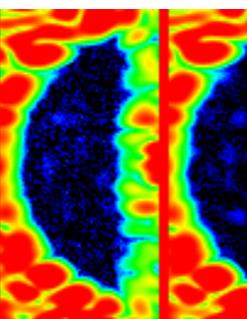
- Profiled metal+dielectric layers control complex (amplitude and phase) wavefront
- Optimized design for improved contrast ( $3e-10$ ) at  $3 \lambda/D$  over 20% bandwidth, and throughput (60%) is the goal of a 2010-11 TDEM program.



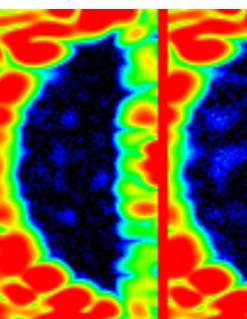
760-840 nm



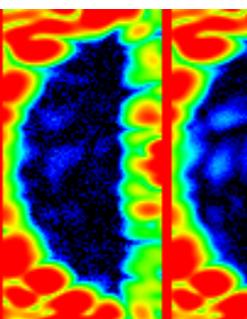
760-778 nm



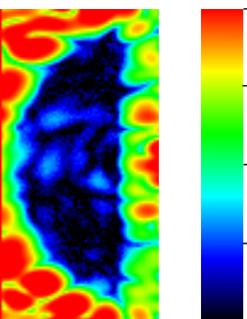
778-792 nm



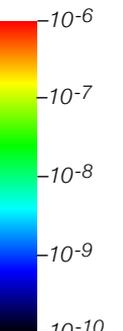
792-808 nm



808-824 nm



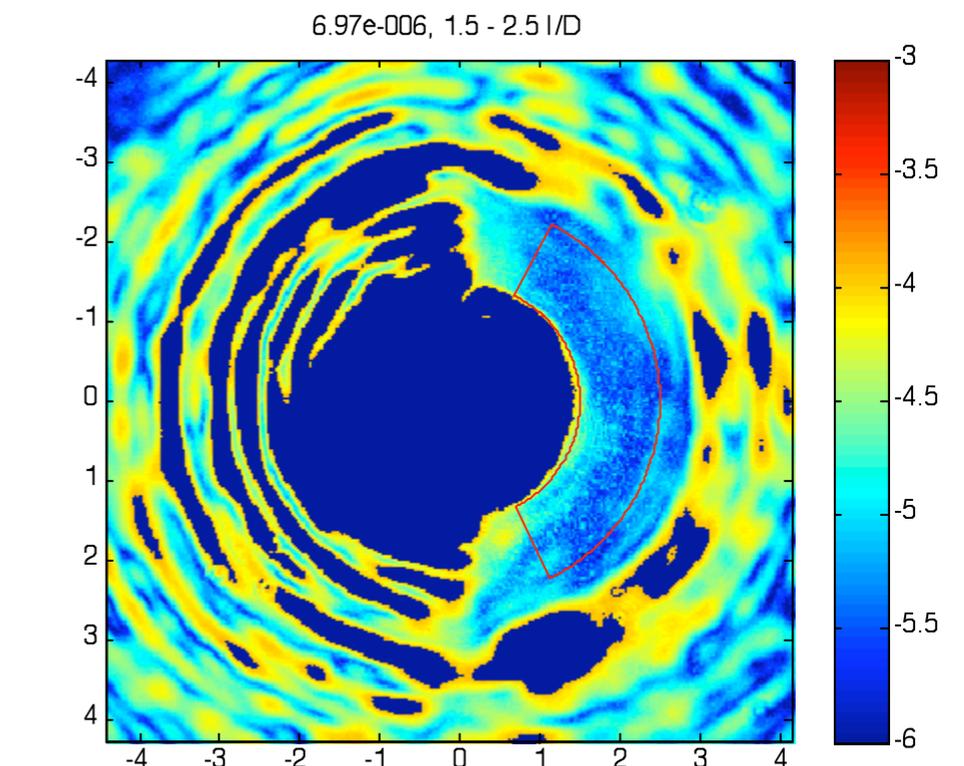
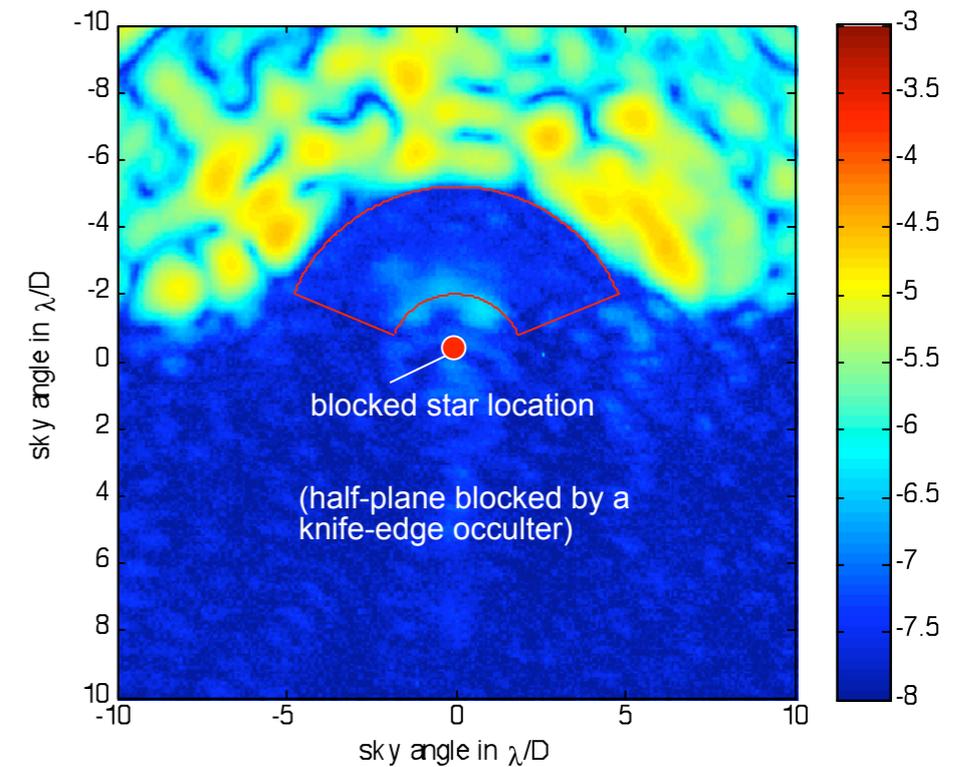
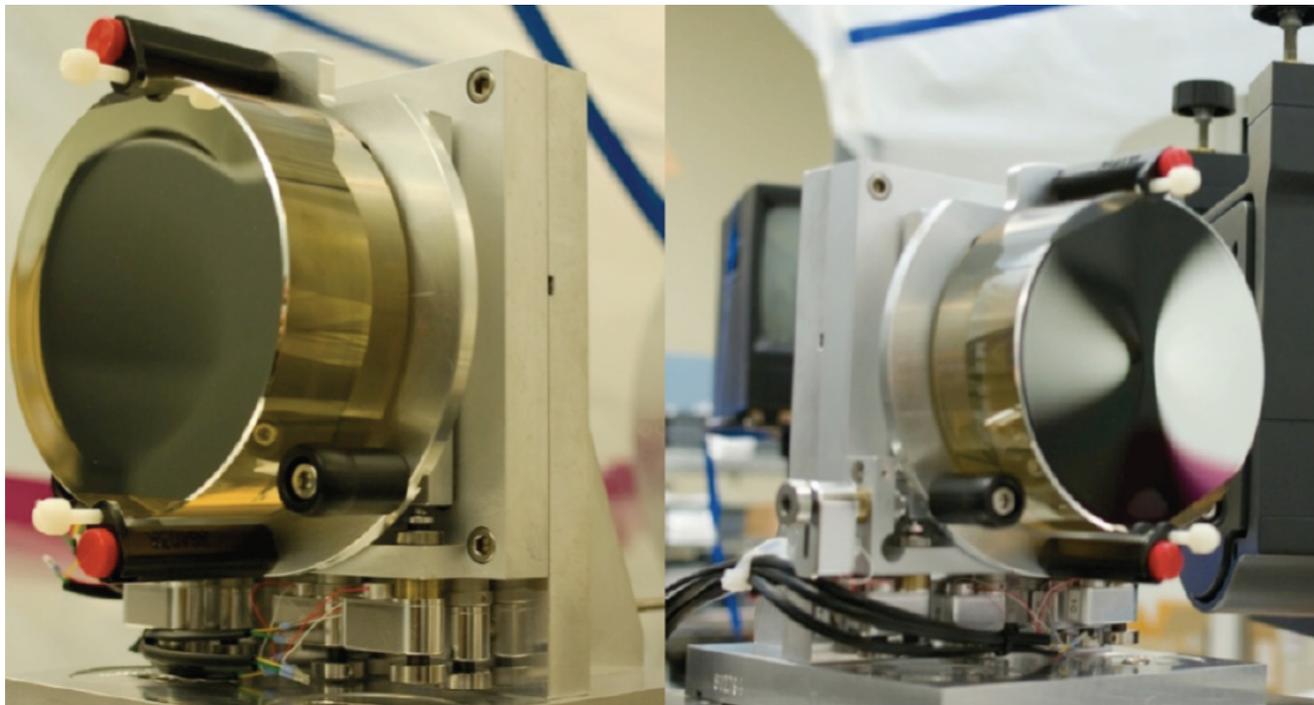
824-840 nm



# The demonstrated state of exoplanet coronagraphy

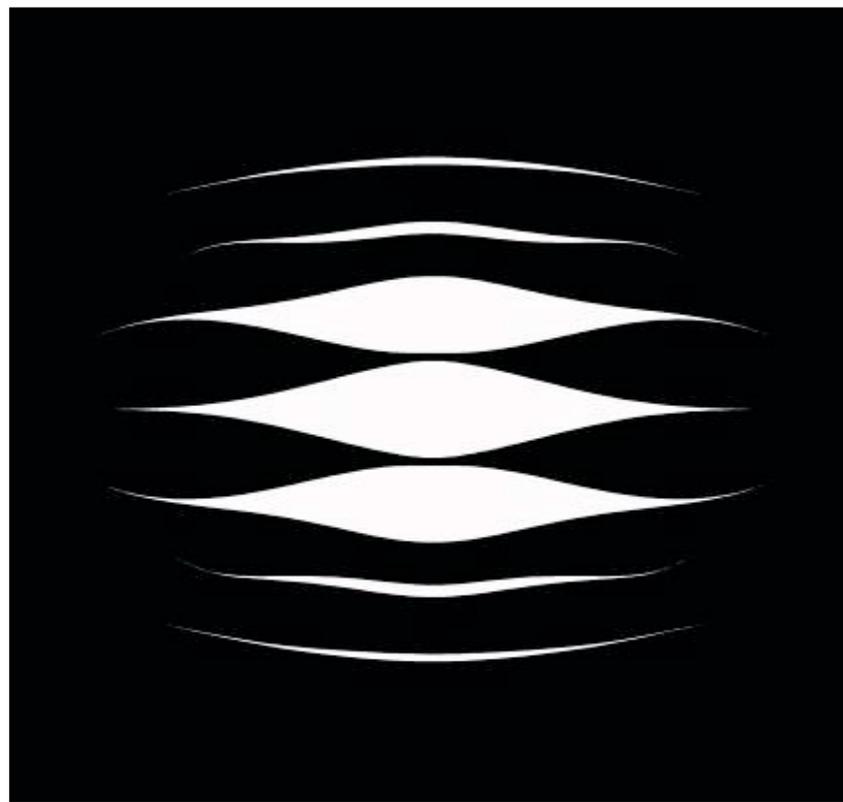
## Pupil mapping demonstrations

The pupil mapping (PIAA) coronagraph has achieved  $IWA = 2 \lambda/D$ , 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)

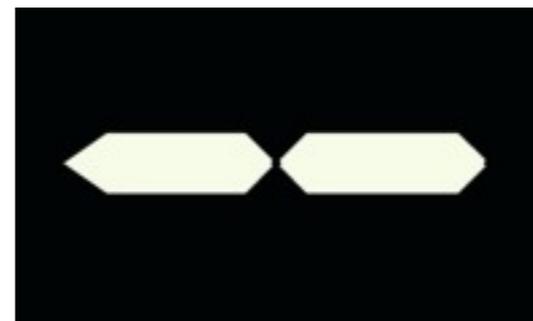


# The demonstrated state of exoplanet coronagraphy

## Shaped pupil coronagraph experiments with HCIT

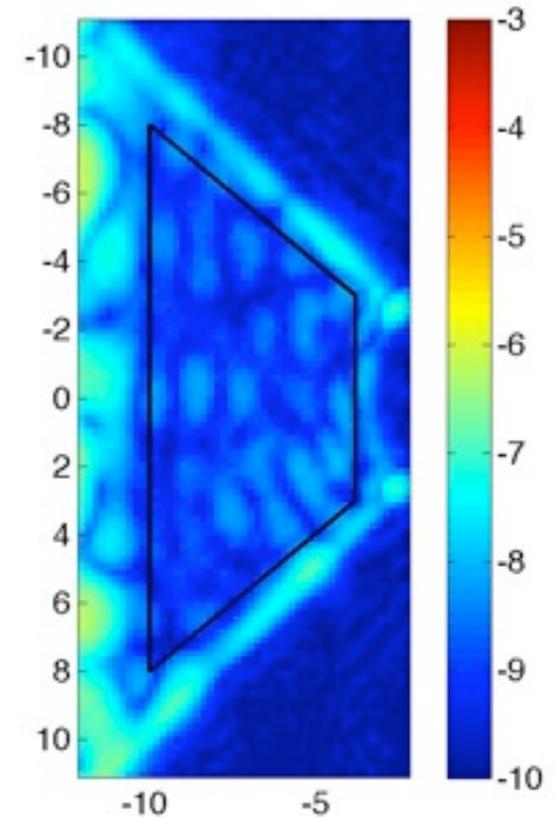


Shaped pupil mask



Focal plane mask

High contrast field



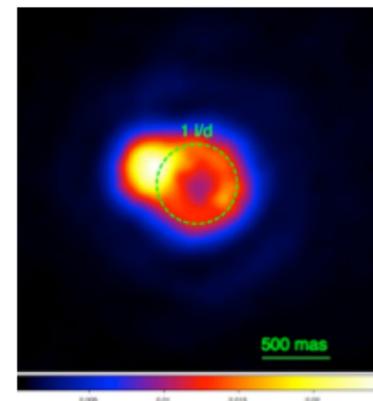
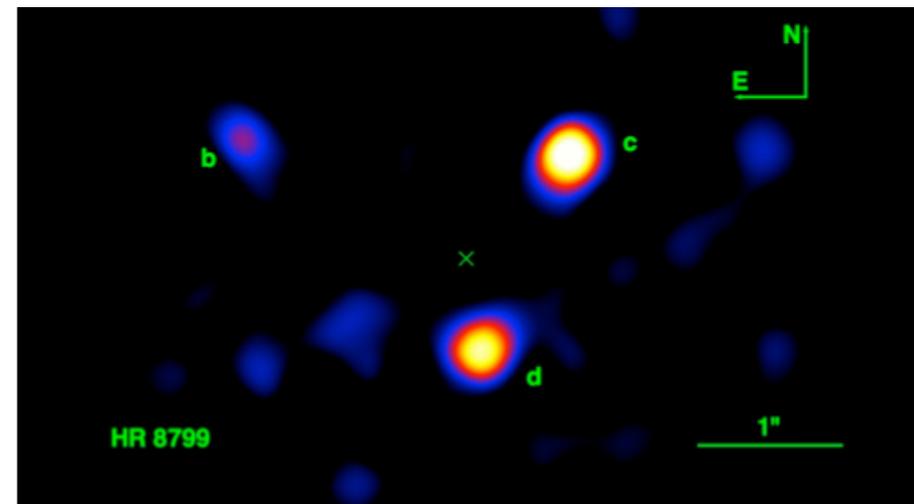
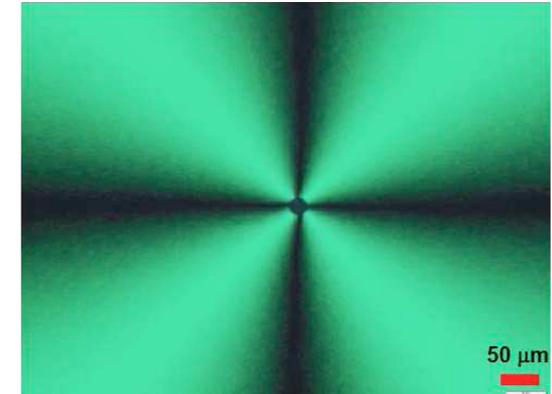
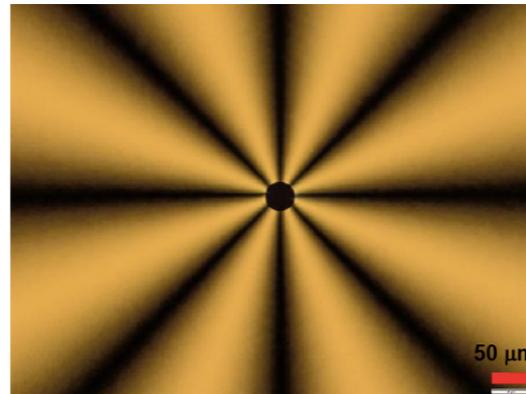
At left, the transmittance profile of a representative shaped pupil apodization (black indicates opaque, white indicates clear). At center, the corresponding “bowtie” image plane mask. This “Ripple 3” design achieved  $2.4e-9$  contrast in 10% bandwidth averaged over the  $4-10 \lambda/D$  dark field (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  $1-2 \lambda/d$  in the near-infrared using adaptive optics.
    - Fourth-order mask tested in the visible on the HCIT in 2008 ( $\sim 10^{-7}$  over 10% BW)
  - Generation 2:
    - Technological development financed through APRA and SBIR programs
    - Improved definition of the center ( $40 \mu\text{m} \Rightarrow 5 \mu\text{m}$ )
    - Achromatic (goal  $10^{-9}$  over 20% BW)

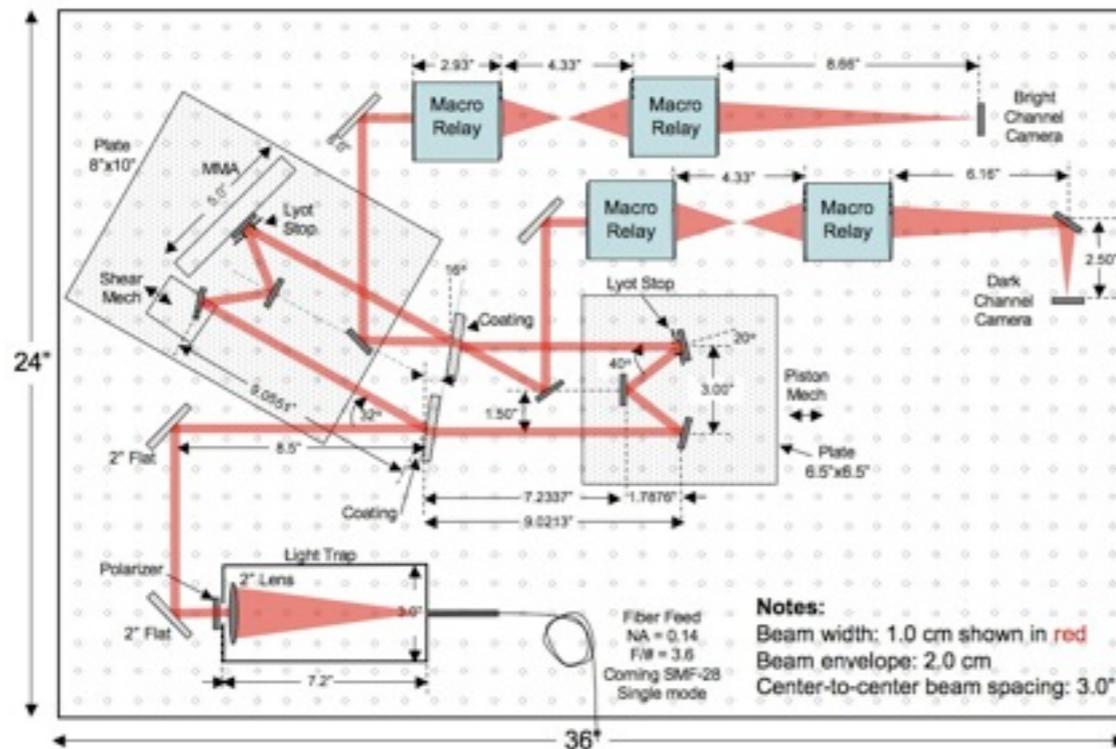


Serabyn et al. 2010

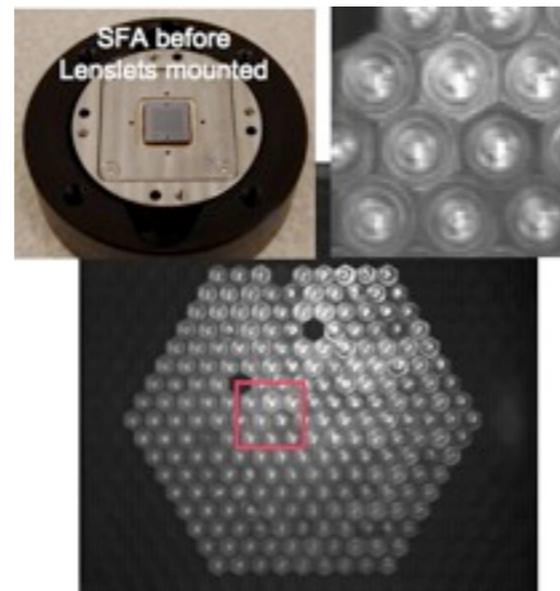
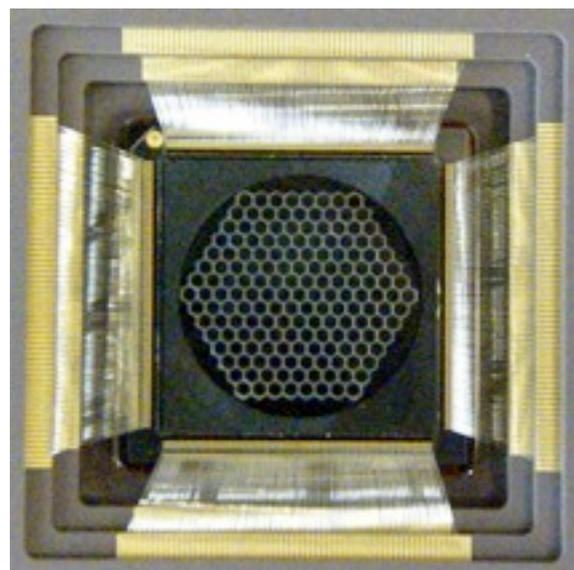
Mawet et al. 2011

# The demonstrated state of exoplanet coronagraphy

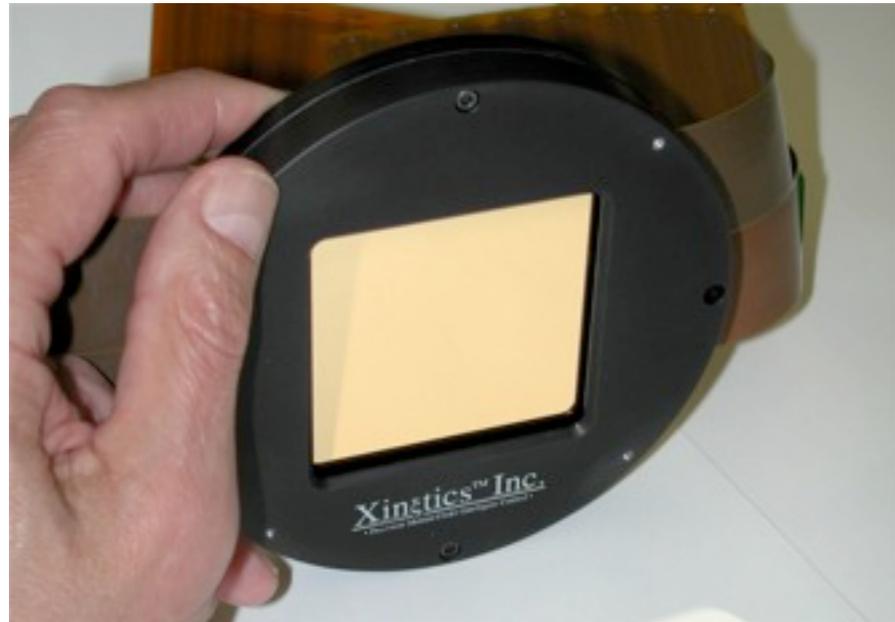
## Visible nuller coronagraph



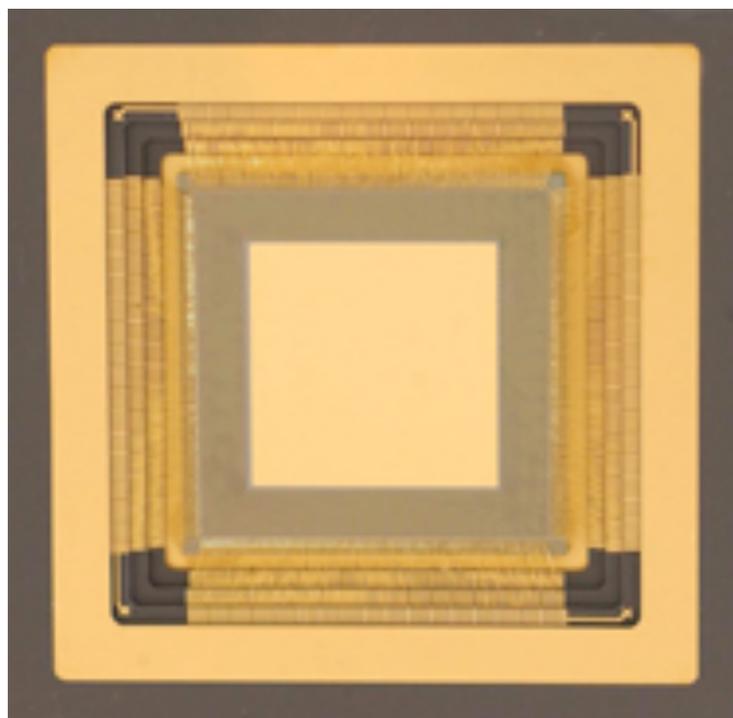
- VNC development is active at GSFC (Lyot et al.) and at JPL (Sandhu et al.)
- Segmented MEMS DMs from both Boston Micromachines and IRIS-AO are under consideration.
- Spatial filters, consisting of a bundle of 1000 single mode fibers coupled with lenslet arrays, are now being perfected and tested.
- Starlight suppression of  $1e-8$  has been demonstrated in laser light (Lyot et al. 2010).



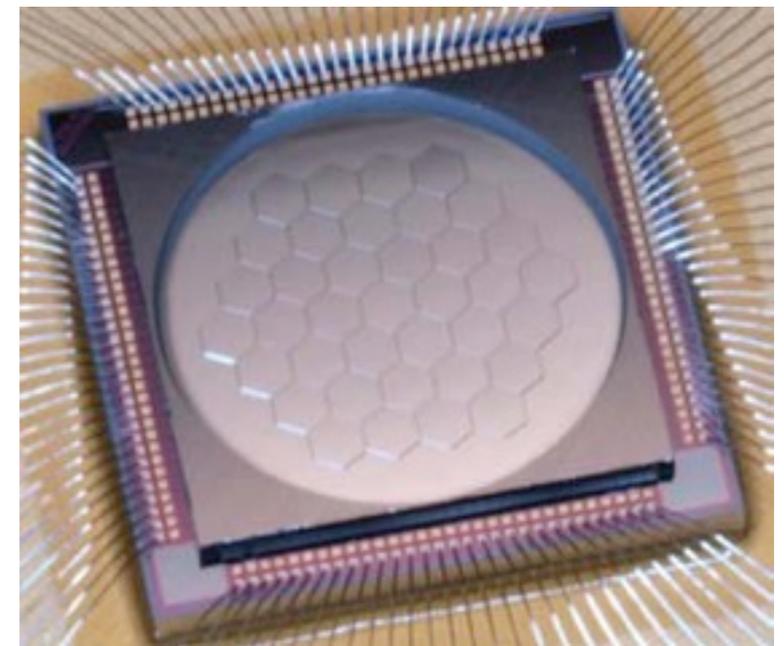
## *All coronagraphs require deformable mirrors for precise wavefront control*



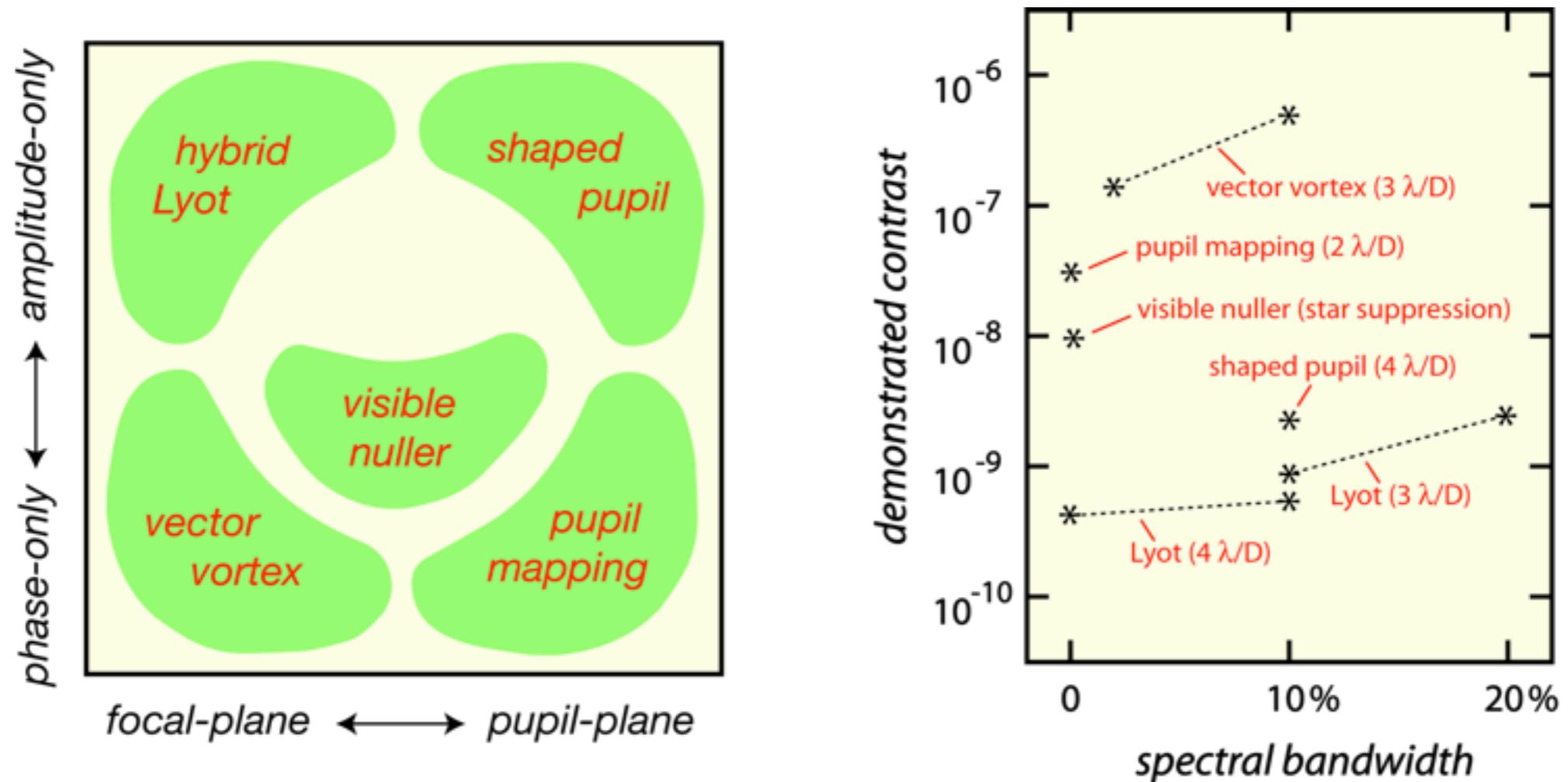
*HCIT experiments have been carried out with Xinetics DMs. Fused silica facesheet is polished nominally to  $\lambda/100$  rms. Surface figure (open loop) has been shown to be settable to 0.05 nm rms and stable to 0.01 nm rms over periods of 6 hours or more in a vacuum testbed environment. Protoflight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



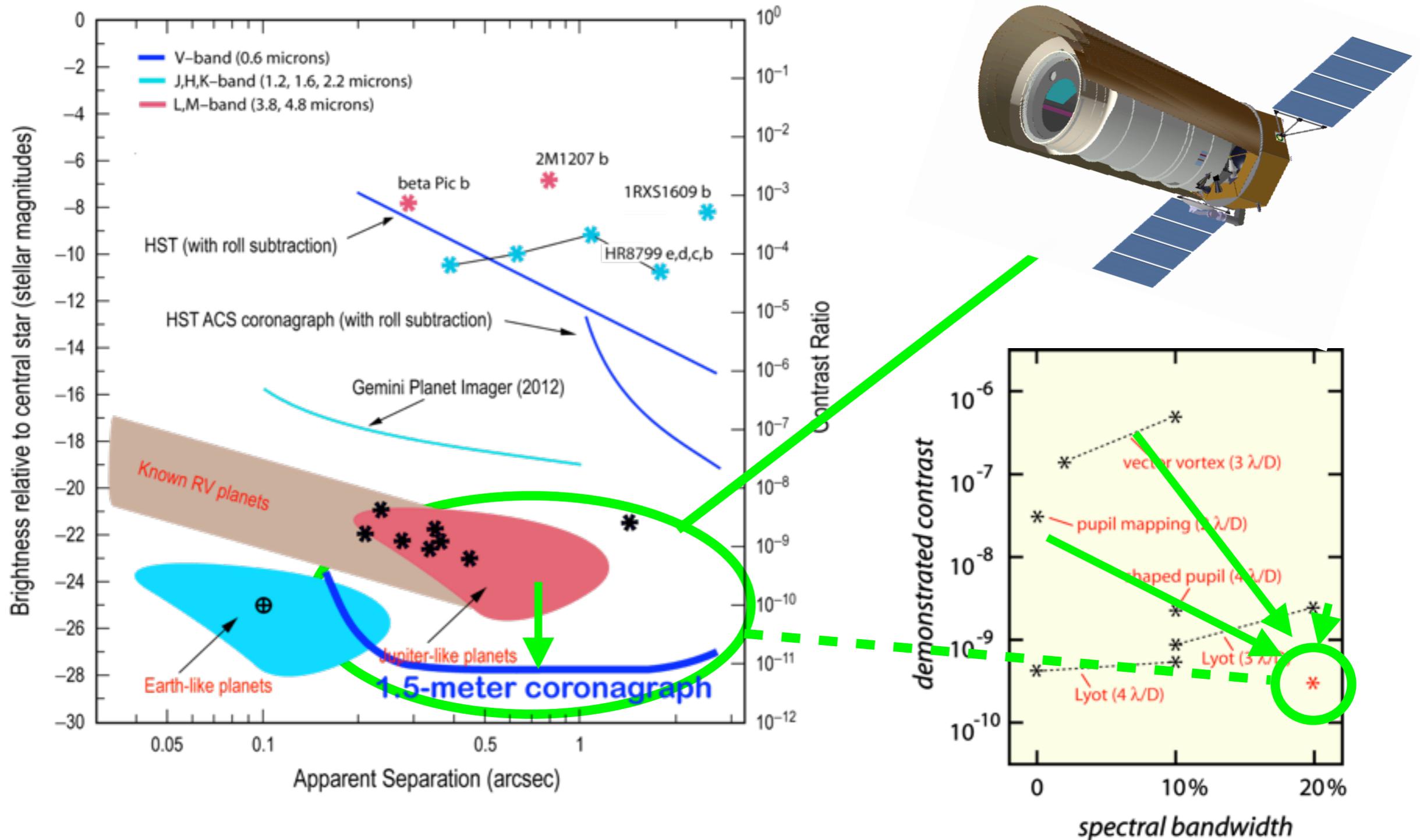
# The demonstrated state of exoplanet coronagraphy



- *Laboratory verified performance provides objective criteria for comparisons among the representative coronagraph types.*
- *Demonstrated raw contrast, spectral bandwidth, inner working angle, throughput, cost/complexity, can be used to inform a high fidelity exoplanet mission simulation.*

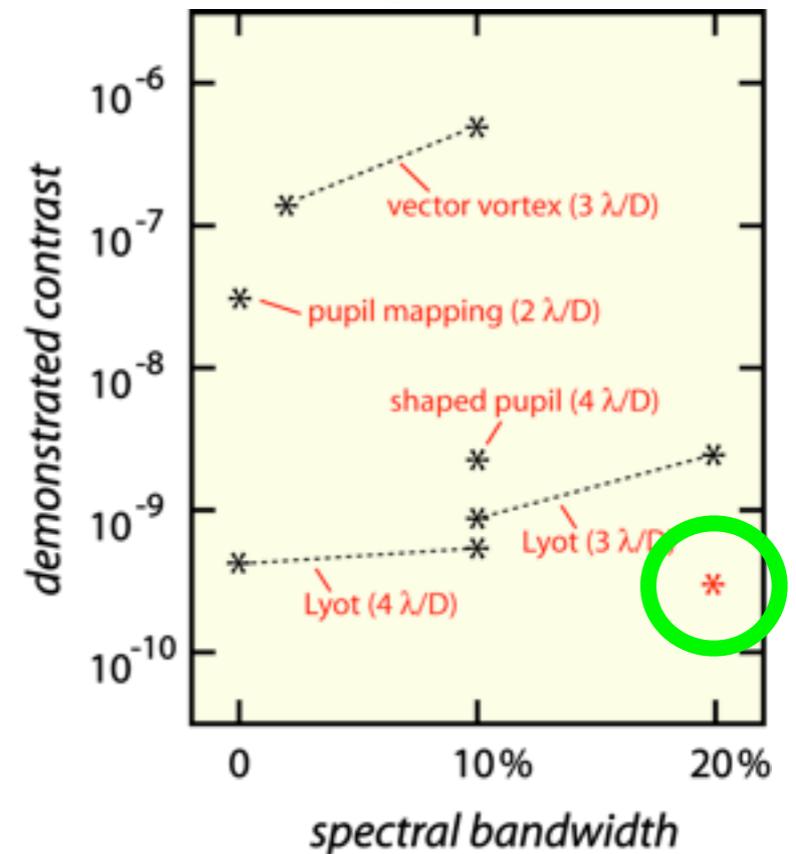
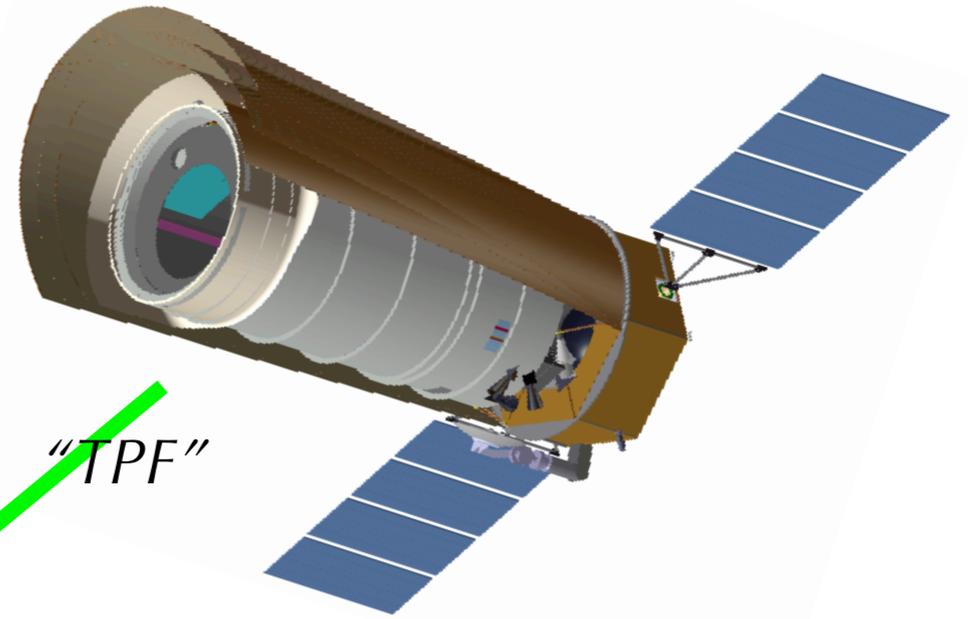
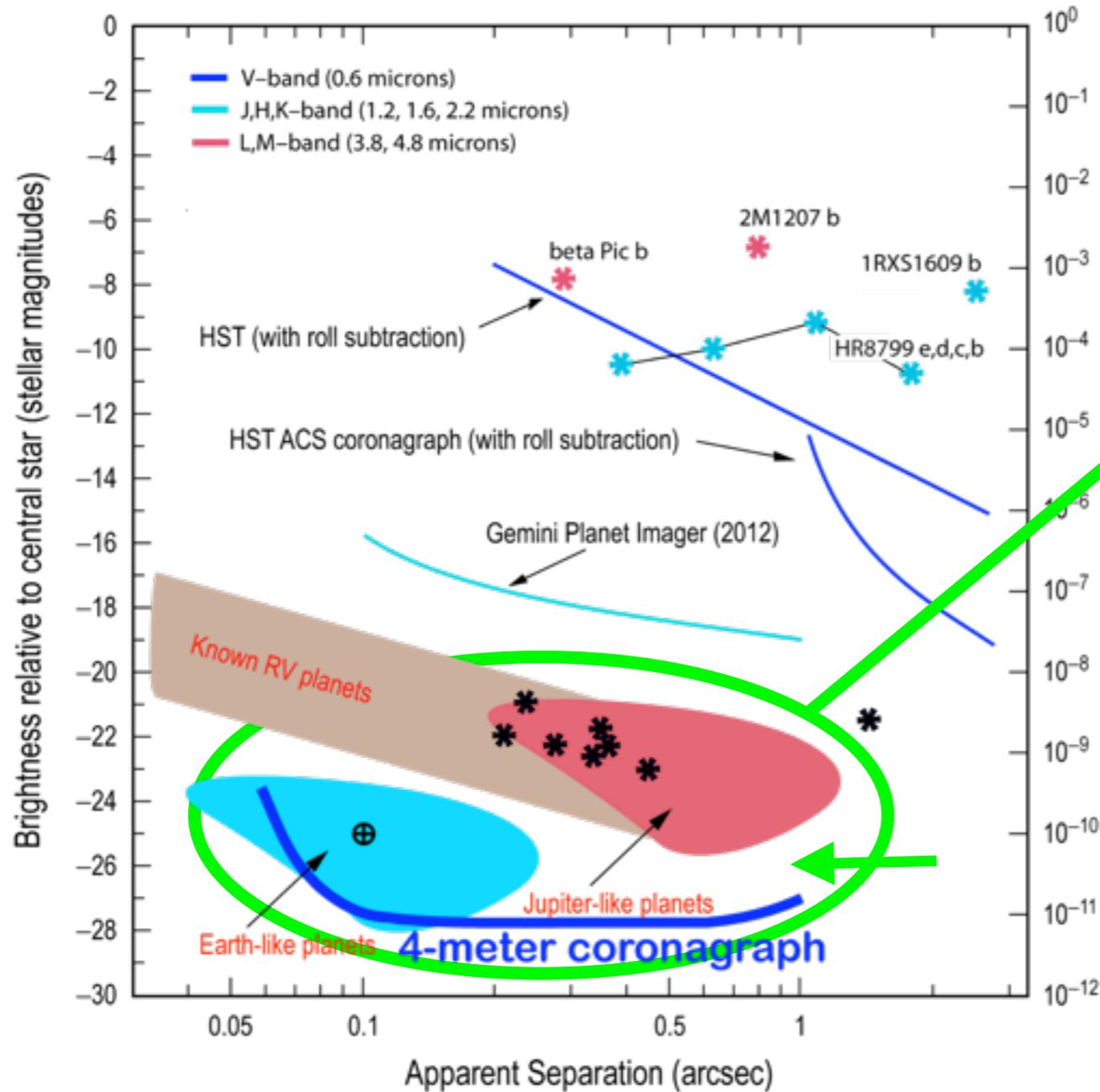
# Exoplanet Discovery Space

– Performances goal for the coming three years –



# Exoplanet Discovery Space

– Extrapolation from 1.5 to 4 meter telescope aperture –



*Next three years are critical for  
**concept validation***

- *Advances in demonstrated contrast, spectral bandwidth, inner working angle, and nulling algorithms by 2014.*
- *Laboratory validation of performance models, including pointing control methods and strategies for planet/speckle discrimination.*
- *Validation of high contrast imaging, wavefront control, and speckle discrimination with a flight-configured coronagraph instrument in a flight simulating environment.*
- *Develop a compelling exoplanet reference science mission grounded on validated coronagraph performance models.*

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

- *The past few years have seen good progress, spurred on by institutional investments as well as NASA programs.*
- *Thanks to NASA for the ASMCS and TDEM programs, which enabled the community to set relevant and timely goals (milestones) that are fresh and current in the thinking of the exoplanet community.*
- *But! Are the research and development enabled by NASA programs (SAT, APRA) adequate to bring exoplanet technologies to a readiness level that justifies the endorsement of the astronomy community?*
- *We need to rally our community around a compelling exoplanet reference science mission grounded on validated coronagraph performance models.*

End