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California Institute of Technology  
Pasadena, California

# Technology Development for Exoplanet Direct Imaging Missions

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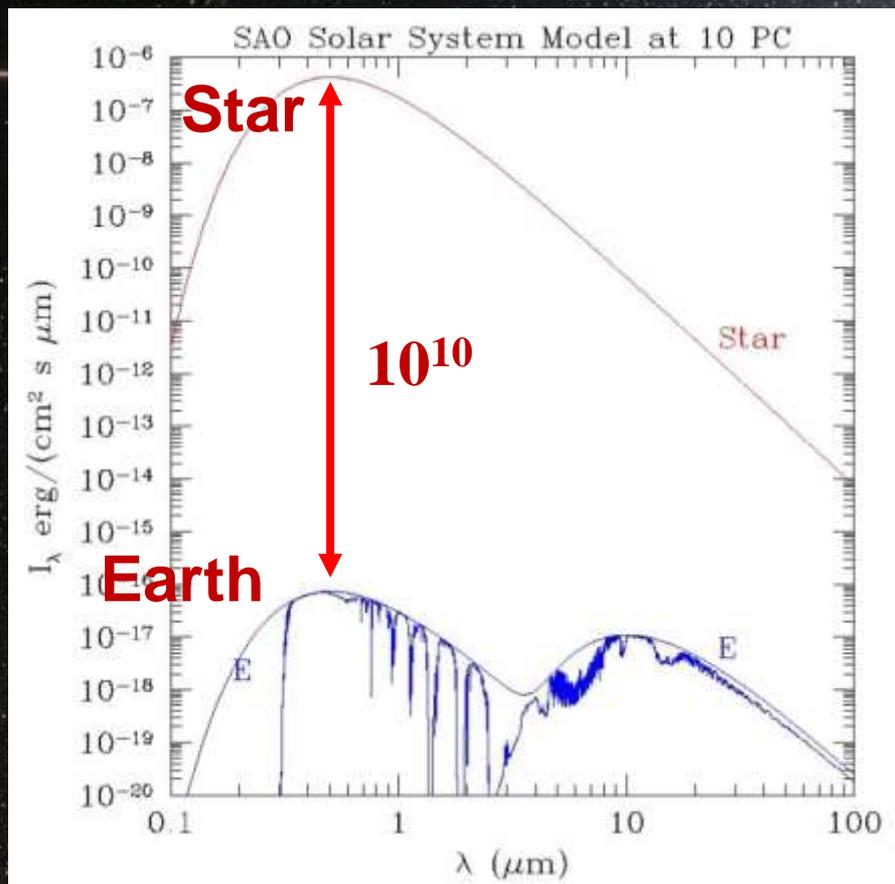
ExoPlanet Exploration Program

# Looking Back Nearly 30 years...to 1990



**Are we Alone?  
The Search for Other Earths,  
The Search for Life in the Universe**

# The Challenge



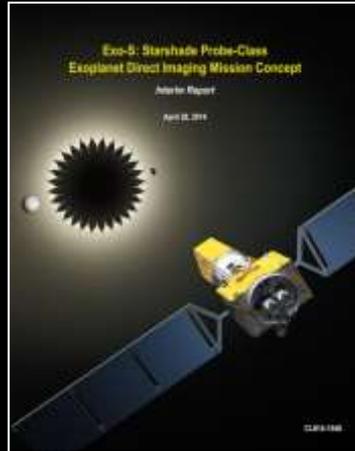
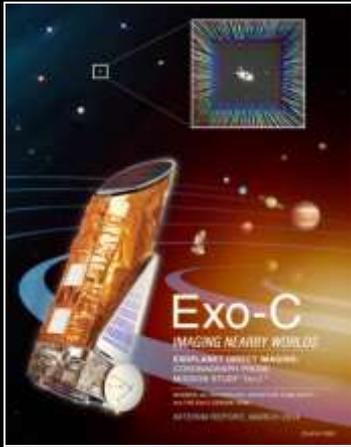


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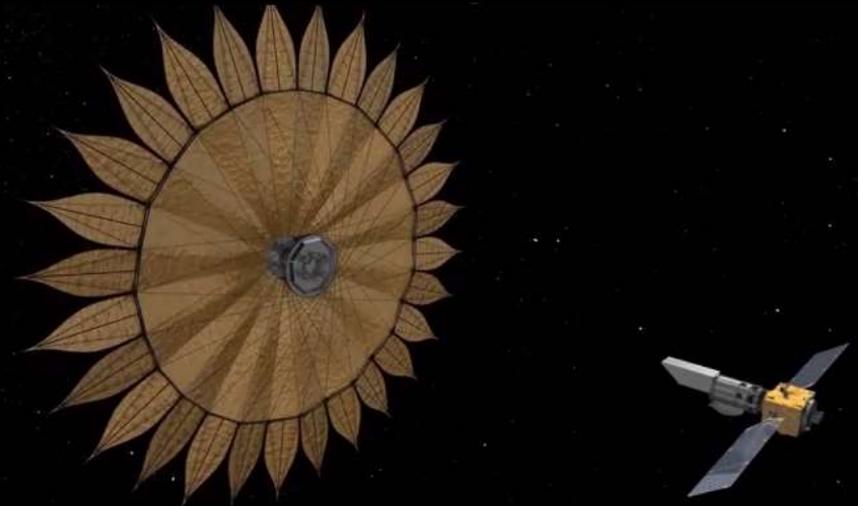
# Starlight Suppression for High-Contrast Imaging



ExoPlanet Exploration Program



## External Occulter - Starshade



## Internal Occulter – Coronagraph



<http://exep.jpl.nasa.gov>



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# WFIRST-AFTA

*Wide-Field Infrared Survey Telescope (WFIRST)  
Astrophysics Focused Telescope Assets (AFTA)*



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**Wide-Field  
Instrument**

## Coronagraph Instrument

- Imaging and spectra channels
- 0.4 – 1  $\mu\text{m}$  bandpass
- $\leq 10^{-9}$  detection contrast
- 100 mas inner working angle at 0.4  $\mu\text{m}$
- $R \sim 70$

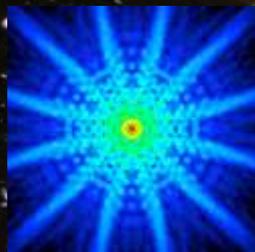
## Coronagraph Science

- Imaging and spectroscopy of exoplanet atmospheres down to a few Earth masses
- Study populations of debris disks

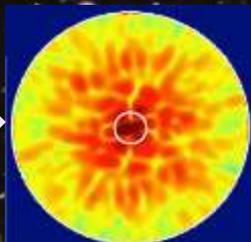
2.4m HST-like  
telescope

**Coronagraph  
Instrument**

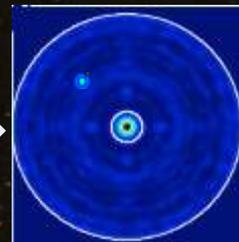
**No Mask**



**With Mask**



**With Mask and  
Deformable Mirrors**



**AFTA's coronagraph will develop the technologies for a future exo-Earth mission**



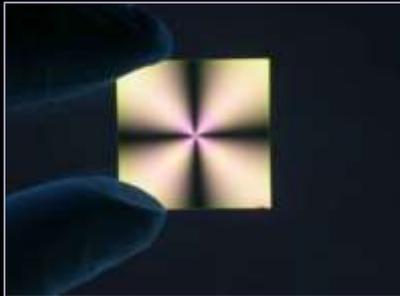
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# Technology Development for Coronagraphs (Internal Occulters)

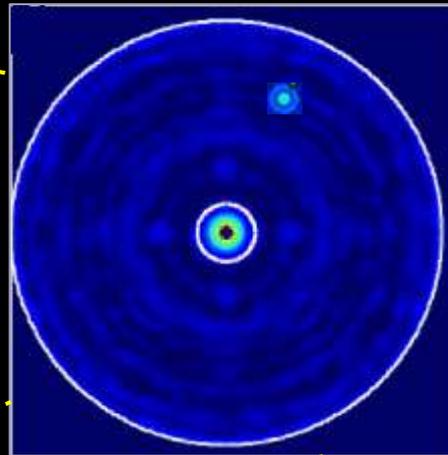


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## Occulting Masks/ Apodizers



Serabyn – Vector Vortex Mask

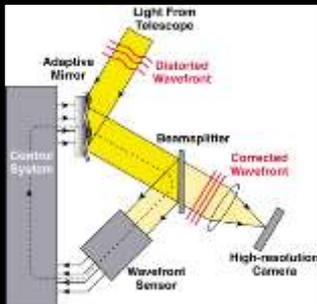


## System Demonstration



Jet Propulsion Laboratory

## Low Order Wavefront Sensing and Control

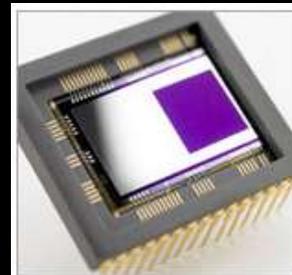


## Deformable Mirrors



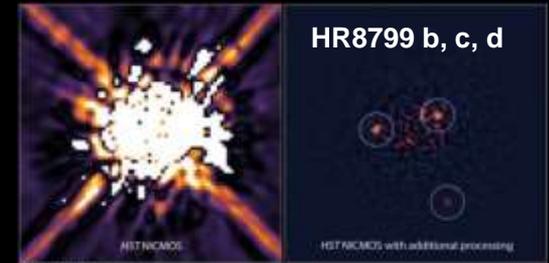
Xinetics

## Ultra-Low-Noise Visible Detectors



e2v Electron Multiplying CCD

## Image Post Processing



Soumer et al. 2011



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# The External Occulter – the Starshade



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The starshade could launch together with a telescope.  
Once in space, it would split off and move into position  
to block the starlight.



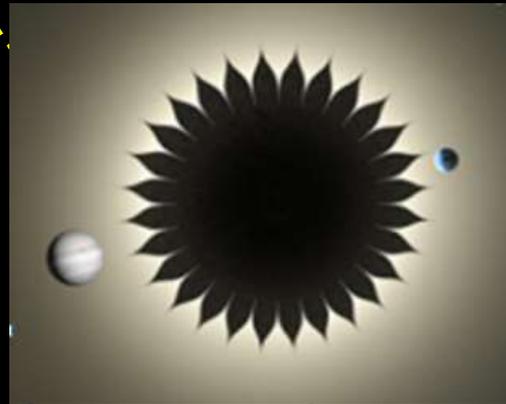
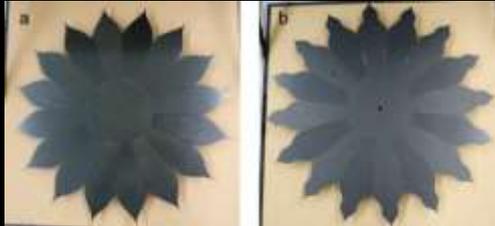
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# Technology Development for Starshades (External Occulters)

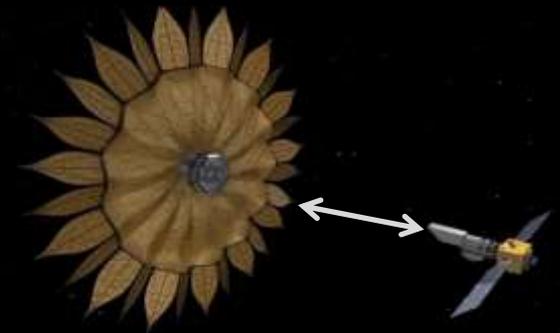


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## Control of Scattered Light



## Formation Flying



## Validation of Optical Models



NGAS

## Starshade Deployment



NGAS, Princeton, JPL

## Petal Prototype



Princeton, JPL



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# Deployment Testing at Northrop Grumman (Astro-Aerospace)



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Demonstration of starshade development model

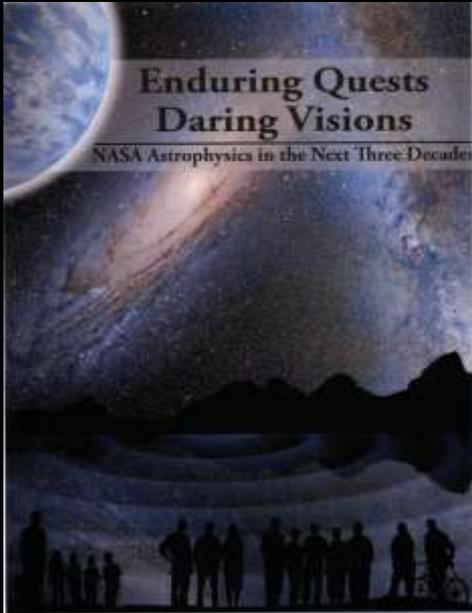


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# Formative Era: Large UV-Optical-IR Telescope



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	LUVOIR Surveyor
Formation flying	
Interferometry: precision metrology	
X-ray interferometry	
High-contrast imaging techniques	
Optics deployment and assembly	
Broadband coatings	
X-ray optics	
Large-format detector arrays	
New detector capabilities	
Cryogenics	



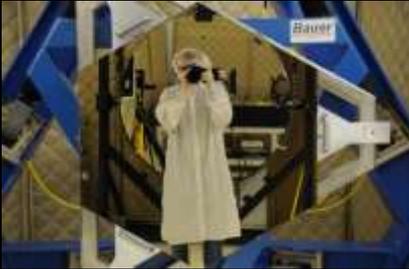
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# Formative Era: Large UV-Optical-IR Telescope (LUVOIR)



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## Optics Deployment and Assy



SiC Active Hybrid Mirror, Xinetics



MOIRE, BATC



Lightweight ULE, ITT



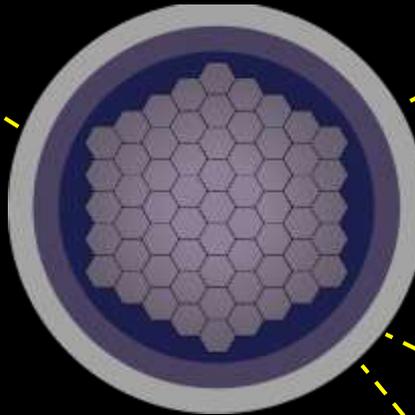
Visible Nuller, GSFC



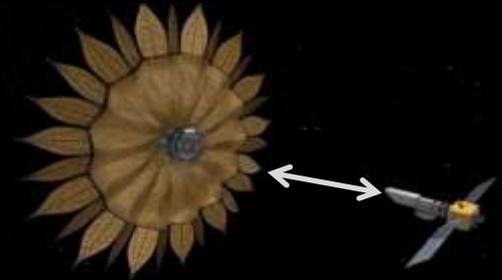
Pupil Mapping, Univ. Arizona



Starshade  
 NGAS, Princeton, JPL



## Formation Flying



## Broadband Mirror Coatings

## Telescope Mechanical Isolation Systems

## Starlight Suppression Systems



# Technology Needs and Priorities

- You are invited to read more about
  - Quantified technology gaps (needs, capabilities)
  - Past and current work conducted through SAT / ROSES / TDEM

<http://exep.jpl.nasa.gov>

- Next call: November 2014

Science Goal	Capability	Needed Technologies	Technology Gaps
Detection of life	Spectroscopy of light from direct exoplanet imaging	starlight suppression (internal and external occulters)	Coronagraph Technology Gap List  Starshade Technology Gap List

Table A.4 Starshade Technology Gaps Listed in Priority Order

ID	Title	Description	Current	Required
S-1	Control of Starshade	Starshade control system	None	Required
S-2	Starshade Alignment	Starshade alignment system	None	Required
S-3	Starshade Deployment	Starshade deployment system	None	Required
S-4	Starshade Maintenance	Starshade maintenance system	None	Required
S-5	Starshade Protection	Starshade protection system	None	Required

Table A.3 Coronagraph Technology Gaps Listed in Priority Order

ID	Title	Description	Current	Required
C-1	Coronagraph Technology	Coronagraph technology	None	Required
C-2	Coronagraph Alignment	Coronagraph alignment system	None	Required
C-3	Coronagraph Deployment	Coronagraph deployment system	None	Required
C-4	Coronagraph Maintenance	Coronagraph maintenance system	None	Required
C-5	Coronagraph Protection	Coronagraph protection system	None	Required



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# Visionary Era: Exo Earth Mapper



## Exo-Earth Mapper

	LUVOIR Surveyor	ExoEarth Mapper
Formation flying		
Interferometry: precision metrology		
X-ray interferometry		
High-contrast imaging techniques		
Optics deployment and assembly		
Broadband coatings		
X-ray optics		
Large-format detector arrays		
New detector capabilities		
Cryogenics		

- **Formation-Flying Telescope Arrays**
  - 500 m<sup>2</sup> collecting area
  - >370km baseline
- **Interferometer Technologies**
  - Precision Laser Metrology
  - Beam combination,
  - Aperture synthesis
  - Formation Flying



SPACECRAFT IMAGE BY T. HERBST /

# Exoplanet Missions

Hubble

Spitzer

Kepler

CoRoT

TESS

Gaia

CHEOPS

JWST

PLATO

WFIRST

New Worlds Telescope

Ground-based Observatories

Science

Technology

Opportunity



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# Acknowledgements



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