

# The Future of Space-Based Interferometry

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and

The Space Interferometry Working Group - R. Allen, J. Benson,  
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and thanks to D. Leisawitz  
for significant contributions to the presentation

Presented at the NOAO "Future Directions for Interferometry" Workshop,  
held in Tucson, AZ, November 13 - 15, 2006

## Outline of Talk

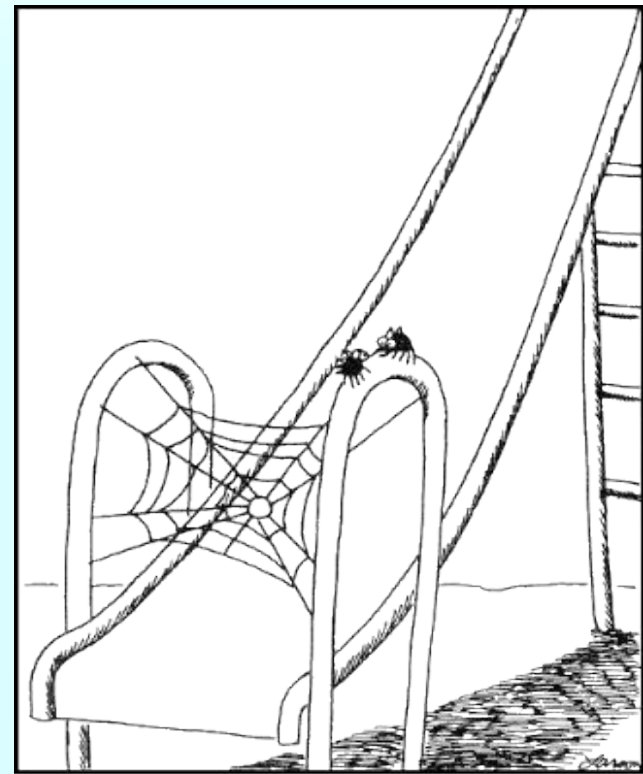
- Why Space Interferometry?
- The Current State of Space Interferometry
- Notional Path for Development of Space Interferometry
- Ground-based Testbeds for Technology Development
- Missions in Technology Study Phase  
(Precision Astrometry/Planet Detection)
- On the Path Toward the Vision Missions:  
Smaller, “Probe”-Level Missions
- The Ultimate Goals for Space Interferometry:  
The Large, Strategic (“Vision”) Missions  
(True Ultra-High Resolution Imagers)
- Enabling Technologies
- Summary/Recommendations

# Why go to Space? Tradeoffs between ground-based and space-based interferometers

- Advantages to basing interferometers in space
  - Can tilt array to point at target and avoid long delay lines required for off-axis observations
  - Can observe at wavelengths not accessible from the ground
  - Can observe continuously over long time periods (days to weeks)
  - The potential for **very** long baselines
  - Reconfigurations of array are relatively easy
  - More stable environment enables easier alignment and calibration
  - No atmosphere, no turbulence, longer integrations
  - Passive cooling of IR instruments possible
  - More control & understanding of facility, e.g.,
    - vibration control easier & more easily understood
    - No windshake
- Disadvantages to basing interferometers in space
  - More expensive
  - Harder to access

# The Current State of Space Interferometry

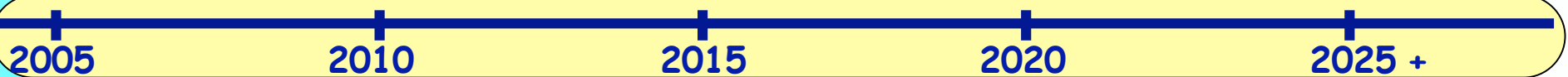
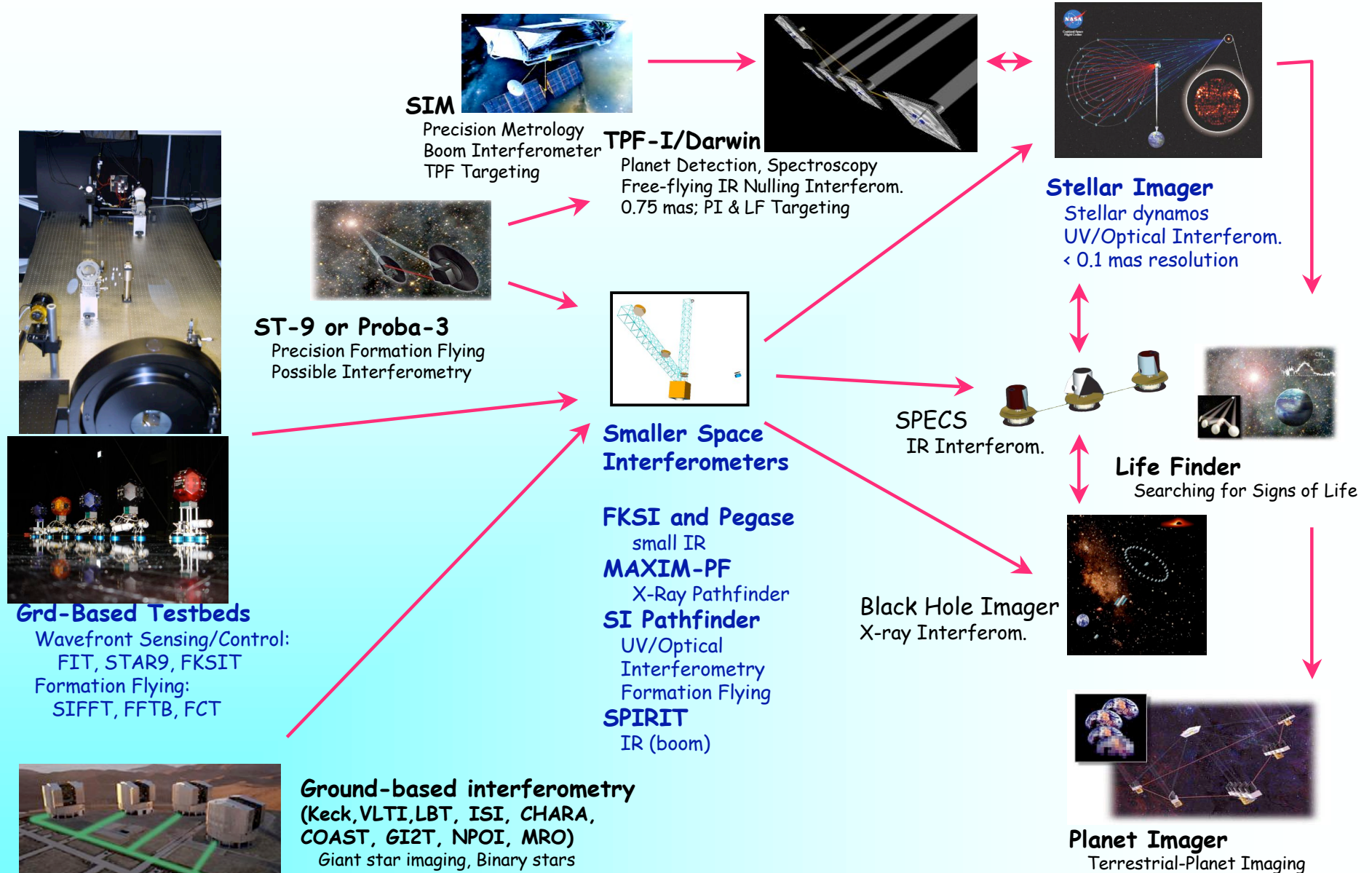
- “Yeah, that can’t be good.”
  - Sheriff Jack Carter/Eureka
- “It was the best of times, it was the worst of times, ... the spring of hope, ... the winter of despair... we had everything before us, we had nothing before us...”
  - from a “Tale of Two Cities”/Dickens
- The Working group is split between hope and despair, between giving up on significant missions and determination to make them happen and to fight the long fight (as Spitzer for HST, Werner for SST, Mather for COBE)
- Against this background, we lay out some possible paths in this talk and encourage your ideas and suggestions, because...



“If we pull this off, we’ll eat like kings.”

*The Farside/Gary Larson*

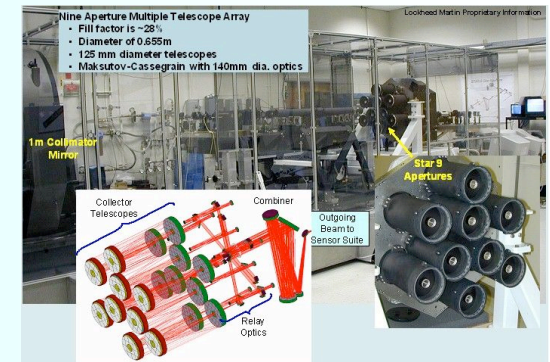
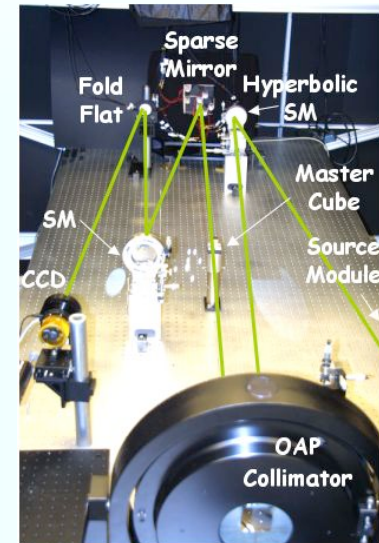
# Notional Path for Development of Space Interferometry





# Ground-Based Testbeds Developing Technologies for Space-Based Interferometers. I.

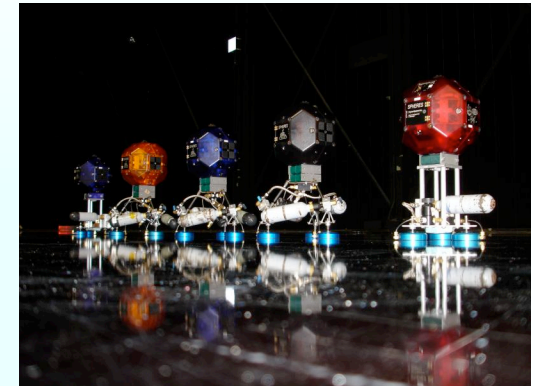
- **The GSFC Fizeau Interferometer Testbed (FIT; Carpenter, Lyon, Liu, Mozurkewich, Dogoda et al.)**
  - developing nm-level closed-loop optical control for large arrays (7-18 separate articulated apertures) based on analysis of science data stream, to enable UV/optical/x-ray Fizeau imaging interferometry (e.g., SI, BHI/MAXIM, LF, PI)
- **The LMATC STAR-9 Testbed**
  - Tests wavefront sensing and control for a “somewhat sparse” array (fill-factor ~ 28%): Diameter of 0.655 m, Individual telescopes 125 mm in diameter
- **GSFC Wide-field Imaging Interferometry Testbed (WIIT; Leisawitz, Rinehart et al.)**
  - demonstrate use of detector array for spatial multiplexing in a Michelson optical/IR interferometer, to enable far-IR imaging of arcmin scale fields of view at high resolution & simultaneously provides spectral information. Enables far-IR interferometers SPIRIT & SPECS; also applicable to TPF-I



# Ground-Based Testbeds Developing Technologies for Space-Based Interferometers. II.

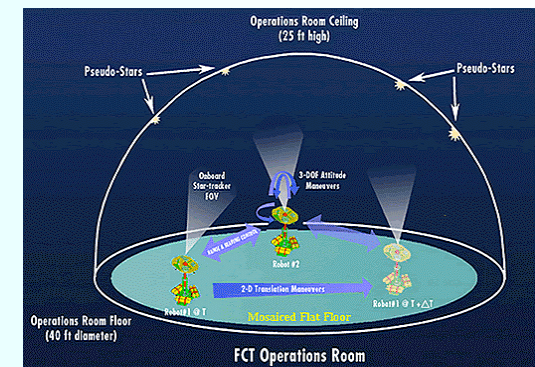
- **The GSFC/MSFC/MIT Synthetic Imaging Formation Flying Testbed (SIFFT; Carpenter, Lyon, Stahl, Miller et al.)**

- Develops and demonstrates algorithms for autonomous precision formation flying: Formation Capture (deployment), Maintenance, and Reconfiguration, Synthetic Imaging maneuvers.
- Uses MIT-developed SPHERES (Synchronized Position Hold Engage and Reorient Experimental Satellites) experiment on the MSFC Flat Floor Facility



- **The JPL Formation Control Testbed (FCT; A. Ahmed, J. Keim, J. Shields)**

- Uses multiple 6DOF robots on air-bearings with on-board guidance and control (G&C) capability for development and validation of Formation Flying control architectures and algorithms.
- Demonstrates Formation Acquisition, Observation-on-the-fly maneuver, Collision Avoidance



- **The GSFC Formation Flying Testbed (FFTB; J. Leitner, J. W. Mitchell, R. J. Luquette)**

- a hardware-in-the-loop test environment for formation navigation and control.
- Modular, hybrid, dynamic simulation facility for end-to-end GN&C design and analysis of formation flying spacecraft.
- Two recent significant upgrades to the FFTB are a message-oriented middleware (MOM) architecture, and a software crosslink for inter-spacecraft ranging.

# Ground-Based Testbeds Developing Technologies for Space-Based Interferometers. III.

- **FKSI Optics Testbed (Danchi et al.)**
  - Nulling Interferometer that will obtain a null depth  $\sim 10^{-4}$ ,
  - Perform verification of fiber “wavefront clean up” with a variety of fiber characteristics/specifications,
  - Perform sensitivity studies and develop alignment plan and procedures for nuller
- **TPF Planet Detection Testbed (Stefan Martin)**
  - demonstrate deep, stable nulling and planet detection.
  - Simulates a dual chopped Bracewell interferometer.
  - Comprised of a four beam star and planet source and nulling beam combiner. Has many control systems designed to achieve stability of alignments and optical path differences over long periods of time.
  - Interactions between designs for phaseplate systems that achromatically invert the electric field of one of each pair of the incoming beams to achieve the null and the choice of fringe tracking schemes is being investigated.

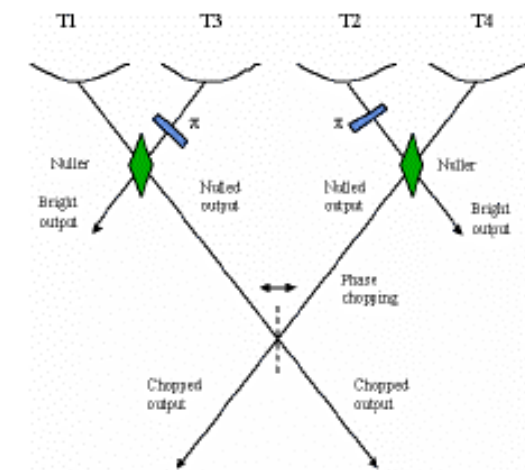
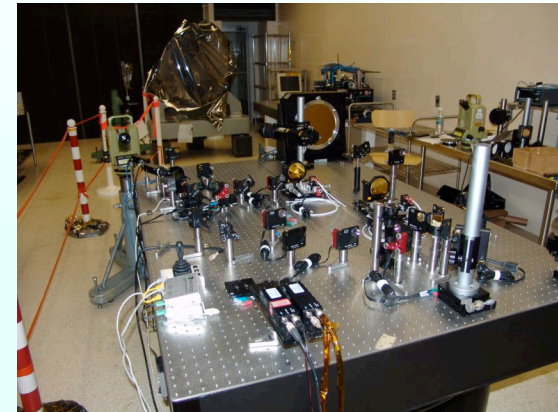


Figure 2: General layout of the beamcombiner showing the four telescopes, the two nullers and the cross-combiner.



# Missions in the Twilight Zone or “Technology Study” Phase (Precision Astrometry/Planet Detection)

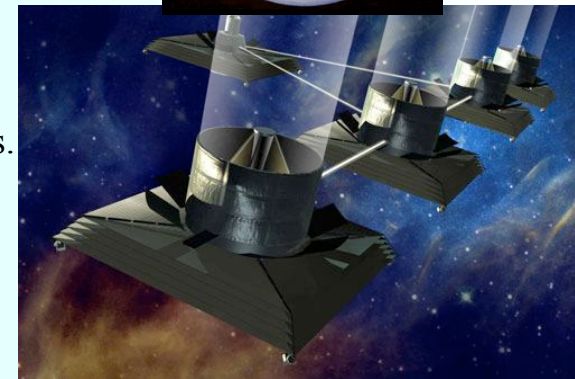
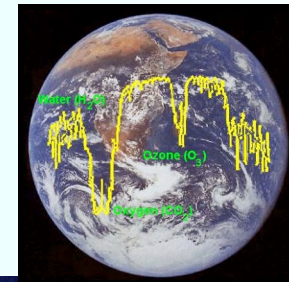
- **Space Interferometry Mission (SIM)**

- Was key mission in NASA’s *Origins Program*
- Precision astrometry on stars to  $V=20$
- Optical interferometer on a 9-m structure
  - One science interferometer, Two guide interferometers
- Global astrometric accuracy: 4 microarcseconds ( $\mu\text{as}$ )
  - At end of 5-year mission lifetime
- Narrow-field astrometric accuracy: **1  $\mu\text{as}$** , in a single measurement
- Typical observations take about 1 minute
- ~ 5 million observations in 5 years;
- No imaging or nulling



- **Terrestrial Planet Finder – I (TPF-I)/IRSI-Darwin**

- Detect Earth-like planets; perform spectroscopic analysis on planetary atmospheres; perform synthetic imaging & astrophysics
- IR Nulling interferometer or visible coronagraph (TPF options)
- Survey stars within ~30 parsecs over five year mission duration
- Four collector spacecraft; one combiner spacecraft, orbit at L2
- 45-135 m baseline for planet-finding; <1 km baseline for astrophysics.
- Current Status: TPF-I now only Technology study,  
TPF-I and Darwin TE-SAT committees to dissolve end 2006  
NASA/ESA letter of agreement terminates end 2006  
Darwin to be proposed for ESA Cosmic Vision for 2020  
Order of TPF-I and TPF-C TBD



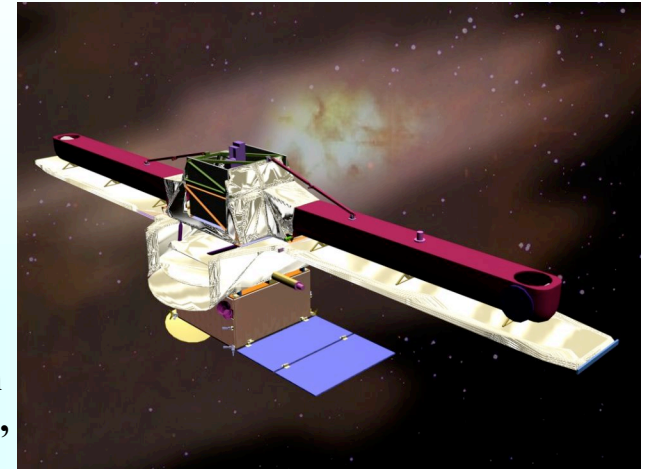
# On the Path Toward the Vision Missions: Smaller, “Probe”-Level Missions

- Goals
  - Good science
  - More moderate costs
  - Technology development and demonstration
- Examples
  - FKSI, PEGASE
  - SPIRIT, SI-PF, MAXIM-PF

# Moderate-sized Missions. I.

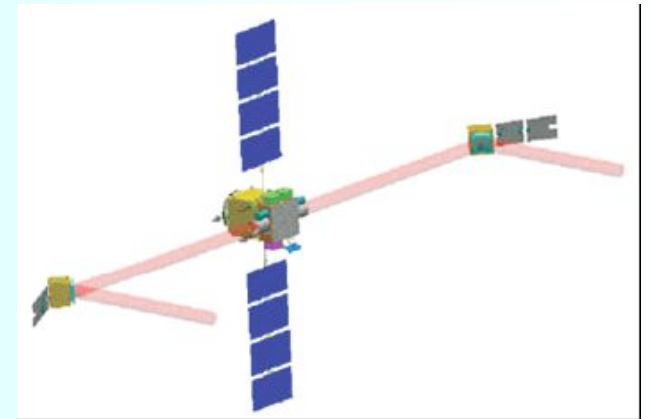
- **Fourier Kelvin Stellar Interferometer (FKSI)**

- ~0.5 m telescopes, Passively cooled ( $<70\text{K}$ ) , 12.5 m baseline
- 3 – 8 (or 10 TBR) micron science band
- 0.6-2 micron band for fringe and angle tracking
- Null depth better than  $10^{-4}$  (floor),  $10^{-5}$  (goal)
- R=20 spectroscopy on nulled/bright outputs of science beam combiner
- **Science: Detect >20 Extra-solar Giant Planets, Observe Circumstellar Material (exo-Zodi, debris disks), Star formation (Evolution of circumstellar disks, morphology, gaps, rings, etc.), Extragalactic astronomy (AGN nuclei)**
- **Contact: Bill Danchi/NASA**



- **PEGASE**

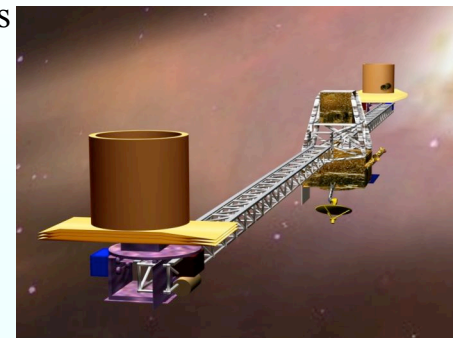
- 3 formation flying satellites in orbit about L2
- Two 40-cm telescopes, Passively cooled (55 K)
- baselines: 2x25m, 2x250m, or 2x500m
- fringe sensor (0.5-1.5 micron range) for optical path control and visibility measurements
- 2 siderostats bring beams to central beam combiner
- 2-3 year mission lifetime
- **Science: Spectroscopy of hot, giant exoplanets (Pegasides), Spectroscopy of Brown Dwarfs, Circumstellar Disks, Dust tori in AGN nuclei; Gas envelopes, stellar wind dynamics, debris disks, exo-zodi; Coronal line emission from active stars**
- **Contact: ESA/CNES**



## Moderate-sized Missions. II.

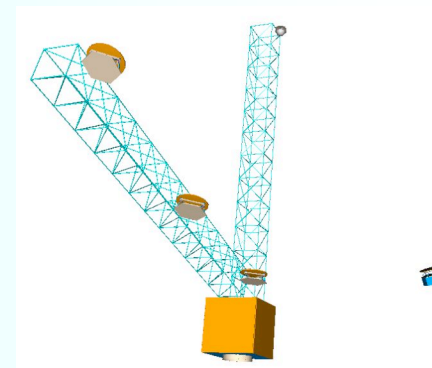
- **SPIRIT (Precursor to SPECS)**

- 0.3" imaging,  $\lambda/\Delta\lambda = 3000$  spectroscopy w/ 1' FOV over range 25 – 400 microns
- Two 1 m telescopes move along rotating boom for dense  $u$ - $v$  plane sampling, scanning optical delay line for spectroscopy (“double Fourier”)
- Sensitivity limited by astrophysical backgrounds, with optics cryocooled to 4 K
- Launch to Sun-Earth L2 as early as 2015 - 2020
- **Science: Learn how planetary systems form & acquire their chemical organization, Image the structure in debris disks to understand how and where planets form, Learn how high-redshift galaxies formed/ merged**
- **Contact: Dave Leisawitz/NASA**



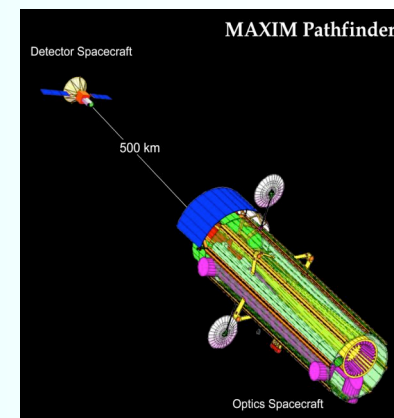
- **Stellar Imager Pathfinder (SI-PF)**

- A small UV/Optical Space Interferometer with 3-5 free-flying or boom-mounted s/c with baselines  $\sim 50$  m and performing beam combination with UV light and demonstrating true imaging interferometry
- to be launched within a decade
- Such a mission with a small # of spacecraft requires frequent reconfigurations and limits observations to targets whose variability does not preclude long integrations *but tests most of the technologies needed for the full-size SI*
- **Science: enable significant new science by exceeding HST's resolution by  $\sim 20\times$ , including surface imaging of the apparently largest stars, interacting binary systems, central regions of AGN's, etc.**
- **Contact: Ken Carpenter/NASA**



- **MAXIM-Pathfinder (MAXIM-PF)**

- Two formation-flying s/c separated by 500 km
- 100 micro-arcsec resolution ( $1000\times >$  Chandra)
- 1 to 2 m baseline, optics on single s/c
- **Science: imaging nearby stars at x-ray wavelengths**
- **Contact: Keith Gendreau/NASA**



# The Ultimate Goals for Space Interferometry

## – The Large, Strategic (“Vision”) Missions

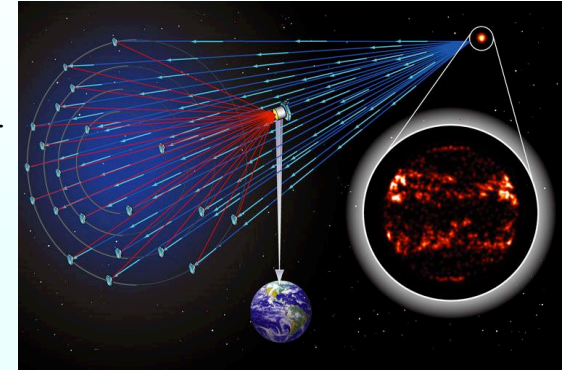
- True ultra-high angular resolution imagers
- Great science
- Realistically, Great Observatory<sup>+</sup> mission level costs
- Examples
  - **SI , SPECS, BHI/MAXIM , LF, PI**



# “Vision” Missions. I.

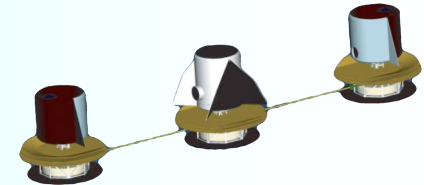
- **Stellar Imager (SI)**

- UV-Optical Interferometer to provide 0.1 mas imaging (+ spectroscopy) of stellar surfaces and interiors, interacting binaries, SN, AGN, QSO's, etc.
- Mission Concept: 20-30 “mirrorsats” formation-flying with beam combining hub, baselines ~ 100 - 1000 m, Mission duration: ~10 years
- A “Flagship” (Vision) mission in the 2005 SSSC Roadmap and a candidate “Pathways to Life Observatory” in the 2005 EUD Roadmap
- Launch ~ 2024, to Sun-Earth L<sub>2</sub>
- **Science: study the magnetic field structures that govern: formation of stars & planetary systems, habitability of planets, space weather, and transport processes on many scales in Universe**
- **Contact: Kenneth Carpenter/NASA**



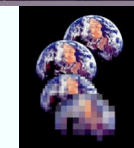
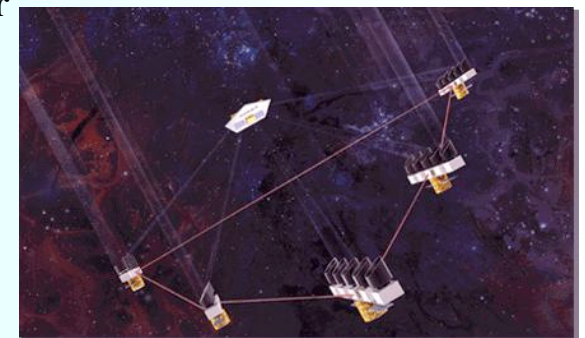
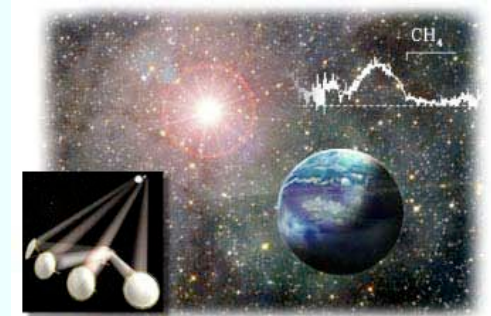
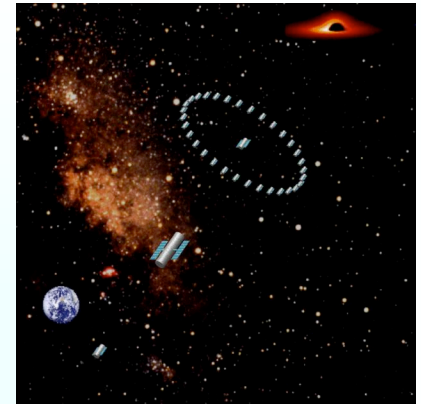
- **Sub-mm Probe Evolution of Cosmic Structure (SPECS)**

- 0.01'' imaging,  $\lambda/\Delta\lambda = 3000$  spectroscopy in a 1' FOV over 40 – 640 microns, baselines up to 1 km, launch to Sun-Earth L2 in ~2025 – 2030
- Two 4 m afocal telescopes in tethered formation for dense  $u$ - $v$  plane sampling, scanning optical delay line for spectroscopy (“double Fourier”)
- Sensitivity limited by astrophysical backgrounds, with optics cooled to 4 K
- recommended in the Decadal Report for investment in technology and as a successor to SAFIR and by the IR astronomical community in the “Community Plan for Far-IR/Submillimeter Space Astronomy”
- **Science: definitive ID of structures in protostellar disks, probe the atmospheres of giant planets, image the dust in debris disks, probe the epoch of the formation of the first stars, heavy elements, and dust, study processes that influenced the history of galaxy formation**
- **Contact: Dave Leisawitz/NASA**



## “Vision” Missions. II.

- **Micro-arcsec X-ray Imaging Mission (MAXIM/BHI)**
  - 0.1 microarcsec x-ray imaging, baselines up to 10 km, beam combiner 50,000? km distant, launch to Sun-Earth L2
  - 1,000,000x the resolution of HST
  - See: <http://maxim.gsfc.nasa.gov>
  - **Science: Direct x-ray imaging of a black hole event horizon**
  - **Contact: Keith Gendreau/NASA**
- **Life Finder (LF)**
  - Successor to TPF, to search for spectroscopic signs of life on extra-solar planets
  - Large array of telescopes flying in formation, will combine infrared light to produce high-resolution spectra of the atmospheres of extra-solar planets.
  - **Science: enable a search for markers of biological activity, such as seasonal variations in the levels of methane and other gases, changes in atmospheric chemistry and spectral variations in the dominant biomass.**
- **Planet Imager (PI)**
  - Concept: An interferometer composed of interferometers: 5 formation flying interferometers, each composed of five 8-m mirrors (to yield 25x25 pixel images)
  - **Ultimate Goal of NASA Origins Program: Obtain resolved images of terrestrial-type planets around other stars**



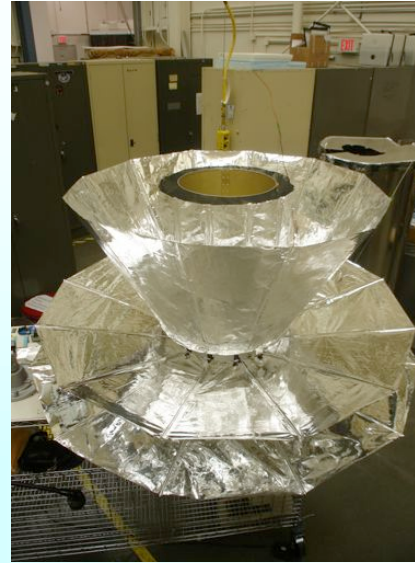
# **Major Technology Development Needs**

**(Examples from SPECS and SI)**

# *SPECS Enabling Technology*

- Kilopixel arrays of detectors with  $NEP < 10^{-19} \text{ W/Hz}^{1/2}$
- High-capacity, efficient cryocoolers
- Cryogenic mechanisms
  - Long-stroke cryogenic delay line
  - Fast-steering mirrors
- \* • Tethered formation flying (requires technology demonstration in space)
- Algorithm development for wide-field imaging interferometry

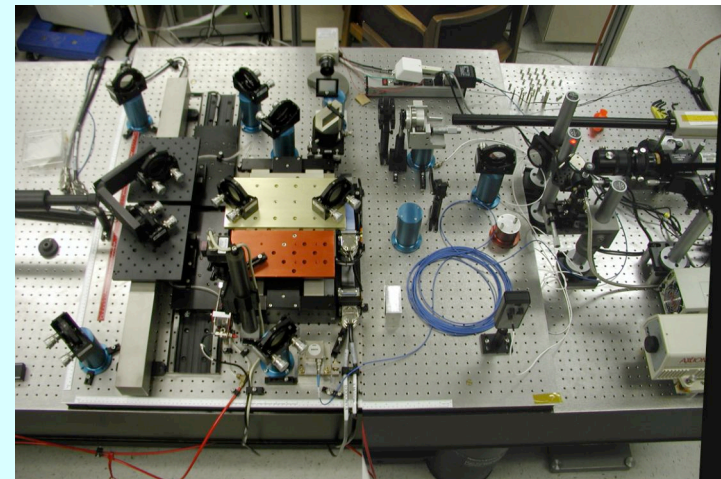
\* All technologies except tethered formation flying are needed for other future missions, such as SPIRIT, SAFIR and TPF-I.



SCOTT is a sub-scale engineering test unit at Goddard designed to validate a thermal model for large 4 K space telescopes. Cryocoolers, rather than expendable cryogenics, will cool future far-IR telescopes and instruments.



SPHERES-Tether (MIT and Payload Systems, Inc.) was developed to experiment with tethered formation flight control. Shown here at the MSFC flat floor facility.



The Wide-field Imaging Interferometry Testbed at Goddard is a scale model of SPECS. WIIT is used to develop and evaluate techniques for interferometric spatial-spectral "image" synthesis.



# *SI Enabling Technologies/Technical Challenges*

## ■ formation-flying of ~ 10-30 spacecraft

- deployment and initial positioning of elements in large formations
- real-time correction and control of formation elements
- staged-control system (km  $\rightarrow$  cm  $\rightarrow$  nm)
- aspect control to 10's of micro-arcsec
- positioning mirror surfaces to 2 nm
- variable, non-condensing, continuous micro-Newton thrusters

## ■ precision metrology

- multiple modes to cover dynamic range of 2 nm over multi-km baselines

## ■ wavefront sensing & real-time, autonomous analysis

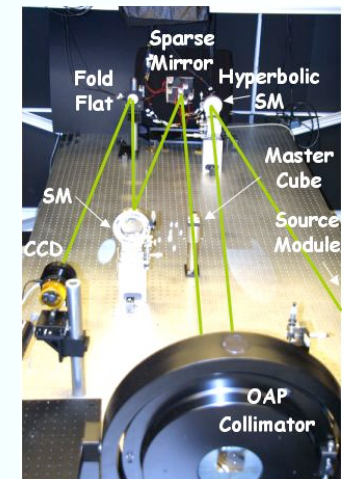
## ■ methodologies for ground-based validation of distributed systems

## ■ additional challenges

- mass-production of “mirrorsat” spacecraft:  
cost-effective, high-volume fabrication, integration, & test
- long mission lifetime requirement
- light-weight UV quality mirrors with km-long radii of curvature  
(perhaps deformable UV-quality flats)
- larger format (6k x 6k) energy resolving detectors with finer energy resolution (R=100)



SPHERES option (SIFFT) to investigate free-flying formation control and synthetic imaging maneuvers (GSFC/MSFC/MIT).



The GSFC Fizeau Interferometer Testbed (FIT) is developing nm-level wavefront sensing and closed-loop control of many-element sparse aperture systems. (GSFC/SigmaSp/Seab.)



# Summary

- Notional Development Path Presented
  - Ground-Based Testbeds
    - FIT, STAR9, WIIT, SIFFT, FCT, FFTB, FKSIT, TPF-PD
  - In-Flight Technology Development
    - ST9, Proba-3
  - Precision Astrometry/Planet Detection
    - SIM, TPF-I/Darwin
  - Smaller, Probe-Level, Space-based interferometers
    - FKSI, PEGASE, SPIRIT, SI-Pathfinder, MAXIM-PF
  - Strategic “Vision” Missions –  
Ultra-High Angular Resolution Imaging Interferometers
    - SI, SPECS, MAXIM/BHI, LF, PI

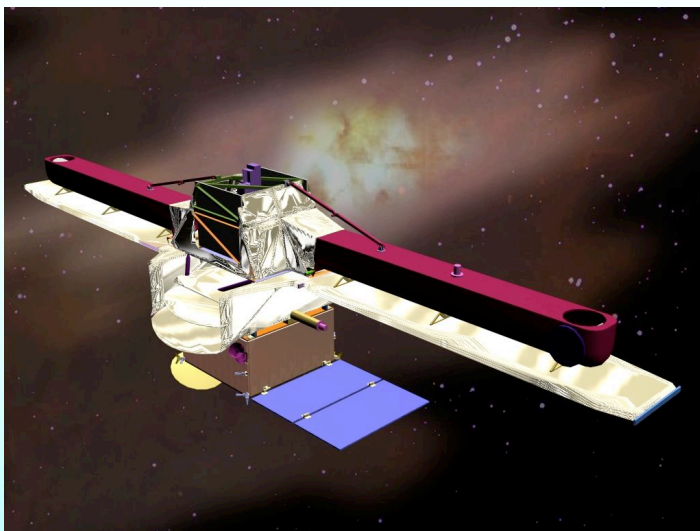
# Recommendations

- The need for ultra-high angular resolution space observations is inevitable: despite the current negative environment for new missions, the community should continue to push for a reasoned and measured development path to reach that goal across multiple wavelengths – it will be a long, but worthwhile pursuit
- A major strategic recommendation of this working group is that “Precursor” formation-flying interferometer space mission(s), which do both technology development and simple, but significant science be pursued
  - Proposed pure technology development missions (e.g. NEXUS for JWST and STARLIGHT for TPF) have a poor track record for being approved for flight
  - But technology steps to large formation flying interferometers are very large and intermediate/precursor missions are critical to ensure success and to make full-up missions credible
  - Therefore we must have science goal(s) along with technology development goal(s) to create an attractive package to ensure success

# **Appendix**

## **Additional Information on the Mission Concepts and their Science Goals**

# FKSI MISSION CONCEPT



**PI: Dr. William C. Danchi**

Exoplanets & Stellar Astrophysics/667

NASA Goddard Space Flight Center

## Technologies:

- Infrared space interferometry
- Large cryogenic infrared optics
- Passive cooling of large optics
- Mid-infrared detectors
- Precision cryo-mechanisms and metrology
- Precision pointing and control
- Active and passive vibration isolation and mitigation

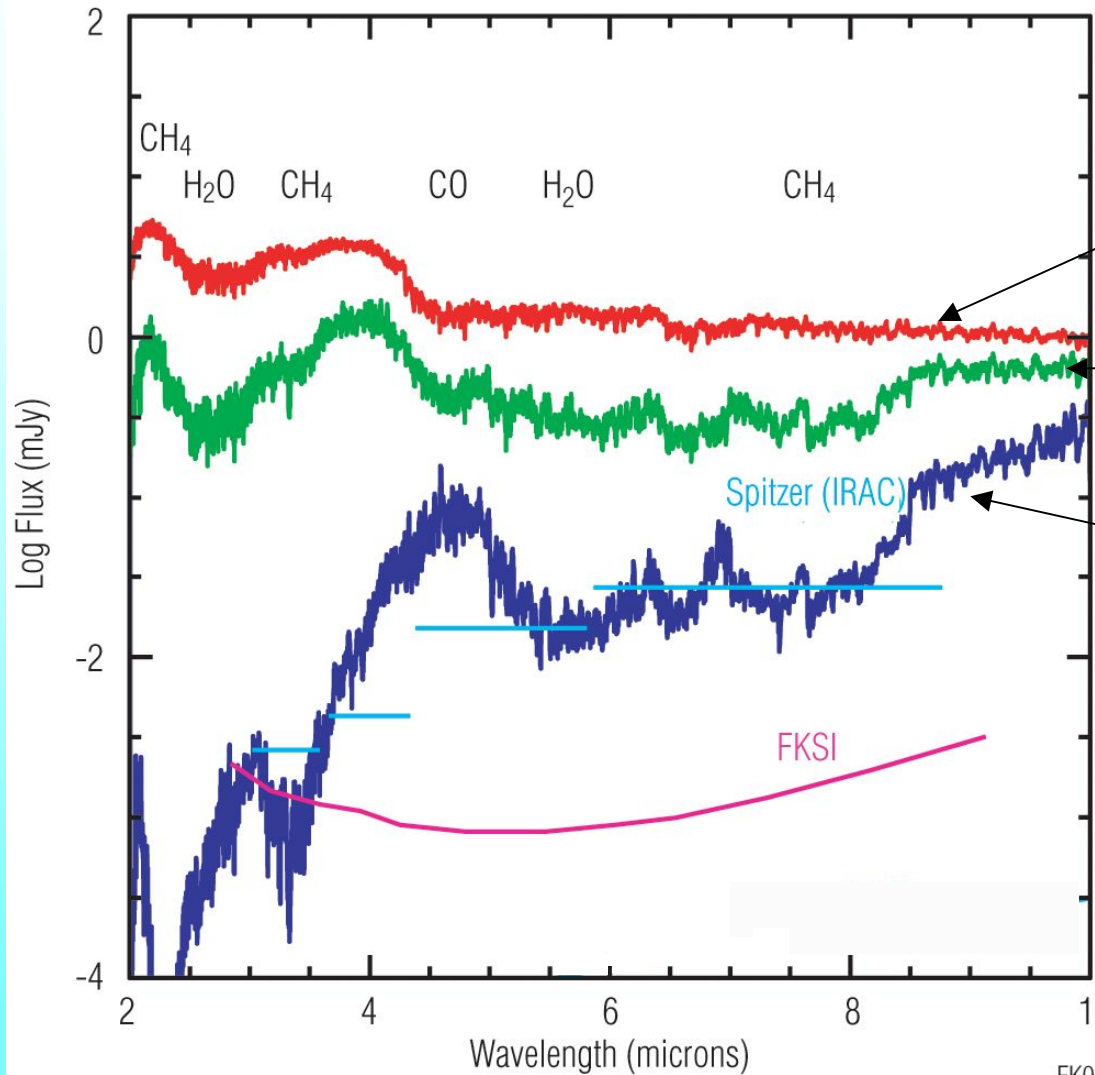
## Key Science Goals:

- **Detect >20 Extra-solar Giant Planets**
  - Characterize atmospheres with R=20 spectroscopy
  - Observe secular changes in spectrum
  - Observe orbit of the planet
  - Estimate density of planet, determine if rocky or gaseous
  - Determine main constituents of atmospheres
- **Observe Circumstellar Material**
  - Exozodi measurements of nearby stars and search for companions
  - Debris disks, looking for clumpiness due to planets
- **Star formation**
  - Evolution of circumstellar disks, morphology, gaps, rings, etc.
- **Extragalactic astronomy**
  - AGN nuclei

## Key Features of Design:

- ~0.5 m diameter aperture telescopes
- Passively cooled (<70K)
- 12.5 m baseline
- 3 – 8 (or 10 TBR) micron science band
- 0.6-2 micron band for precision fringe and angle tracking
- Null depth better than  $10^{-4}$  (floor),  $10^{-5}$  (goal)
- R=20 spectroscopy on nulled and bright outputs of science beam combiner

# FKSI Sensitivity Estimate and Comparison



EGPs at  
distances  
from star:

0.05 AU

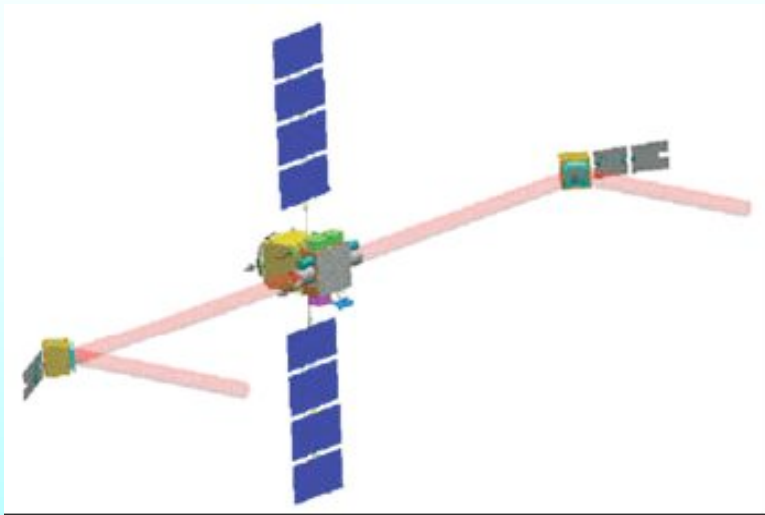
0.1 AU

0.5 AU

FKSI sensitivity is  
sufficient to detect  
and characterize  
EGP atmospheres



# PEGASE – CNES Science Payload for Formation Flying Technology Mission



## Key Features of Design:

- 3 formation flying satellites in orbit about L2
- Two 40-cm telescopes
- Passively cooled (55 K)
- baselines: 2x25m, 2x250m, or 2x500m
- fringe sensor (0.5-1.5 micron range) for optical path control and visibility measurements
- 2 siderostats bring beams to central beam combiner
- 2-3 year mission lifetime
- Observe 50 targets with 50% duty cycle

## Technologies:

- Formation flying technology mission
- Infrared space interferometry
- Passive cooling (55 K) of HgCdTe focal plane array
- Simple Bracewell, two-telescope interferometer

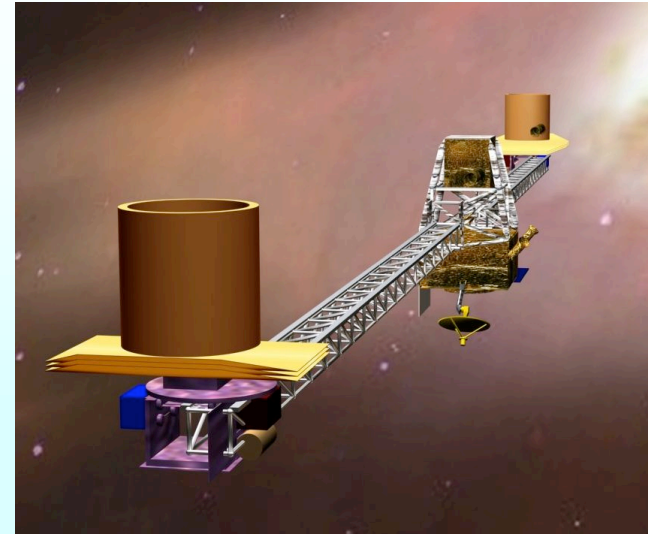
## Key Science Goals:

- **Spectroscopy of hot, giant exoplanets (Pegasides)**
  - Infer physical nature and test atmospheric models
- **Spectroscopy of Brown Dwarfs**
  - Constrain effective temperature, radius, composition, and structure of their atmosphere
  - Estimation of mass by observation of binary systems
- **Circumstellar Disks**
  - To illuminate planetary formation processes
  - Detect inner rim of the disk, the sublimation radius of the dust grains
  - Interaction of the stellar magnetosphere with inner dust
- **Additional Goals**
  - Dust tori in AGN nuclei
  - Gas envelopes, stellar wind dynamics, debris disks, exo-zodi
  - Coronal line emission from active stars

# Space Infrared Interferometric Telescope (SPIRIT):

## SPIRIT was

- recommended by the IR astronomical community in the “Community Plan for Far-IR/Submillimeter Space Astronomy” in addition to the more ambitious roadmap missions SAFIR and SPECS
- selected for study by NASA as a candidate Origins Probe (guidelines for planning: US\$670M, launch opportunities at 4-year intervals starting in the next decade)



## SPIRIT Primary Science Objectives

- Learn how planetary systems form from protostellar disks, and how they acquire their chemical organization
- Characterize the family of extrasolar planetary systems by imaging the structure in debris disks to understand how and where planets of different types form
- Learn how high-redshift galaxies formed and merged to form the present-day population of galaxies

## Mission Description

- A single instrument provides
  - 0.3 ( $\lambda/100 \mu\text{m}$ ) arcsecond imaging and
  - $\lambda/\Delta\lambda = 3000$  spectroscopy in a
  - 1 arcmin field of view over the
  - spectral range 25 – 400  $\mu\text{m}$
- Two 1 m telescopes movable along rotating boom for dense  $u$ - $v$  plane sampling, scanning optical delay line for spectroscopy (“double Fourier”)
- Sensitivity limited by astrophysical backgrounds
  - optics cryocooled to 4 K
  - “zeptobolometer” detector arrays
- Launch to Sun-Earth L2 as early as 2015 - 2020

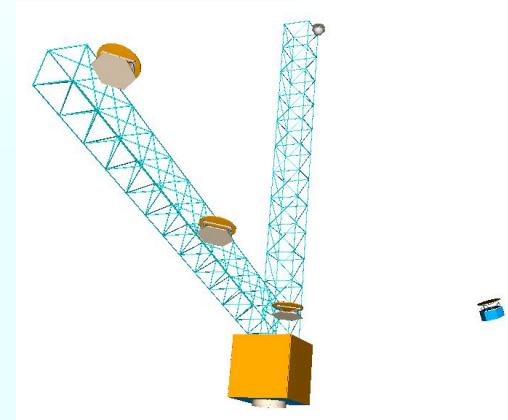
NASA Contact:

David Leisawitz (David.T.Leisawitz@nasa.gov)

# “Stellar Imager (SI) Pathfinder” Mission

## A small UV/Optical Space Interferometer

- to be launched within a decade
- with a modest # (3-5) of free-flying or boom-mounted spacecraft
- with modest baselines ( $\sim 50$  m)
- performing beam combination with UV light and demonstrating true imaging interferometry
- will enable significant new science by exceeding HST’s resolution by  $\sim 20\times$

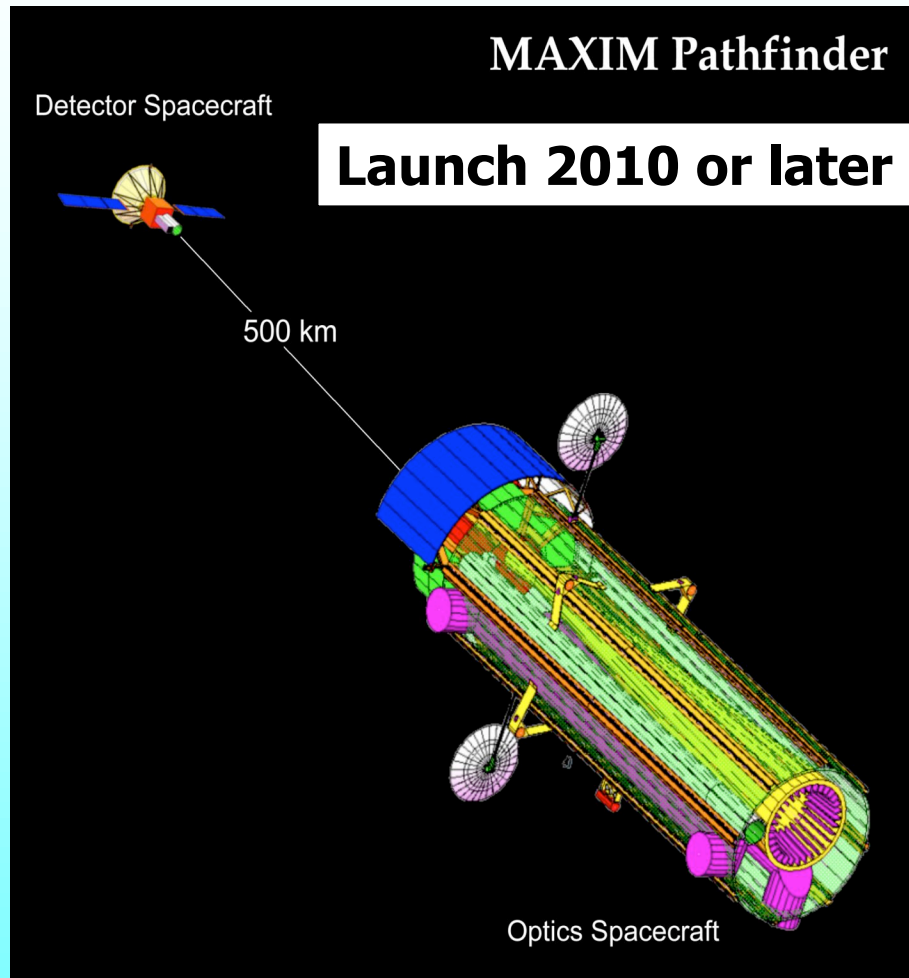


- Such a mission with a small # of spacecraft
  - requires frequent reconfigurations and limits observations to targets whose variability does not preclude long integrations
  - *but tests most of the technologies needed for the full-size SI array*

NASA Contact: Ken Carpenter (Kenneth.G.Carpenter@nasa.gov)

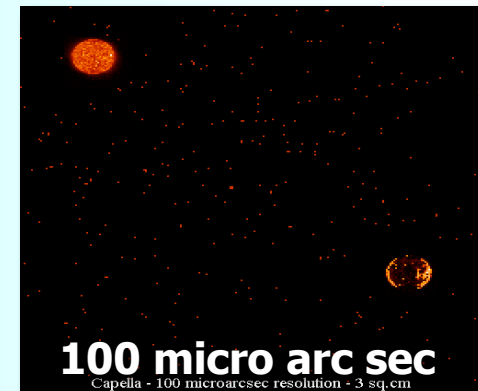
# MAXIM Pathfinder:

## Demonstrate an X-ray interferometer in space



*Two formation-flying spacecraft  
separated by 500 km*

- 100 micro-arc sec resolution
  - ***1000 times better than Chandra!***
- 1 to 2 m baseline
  - **optics on single spacecraft**
- Science:
  - **Imaging nearby stars**

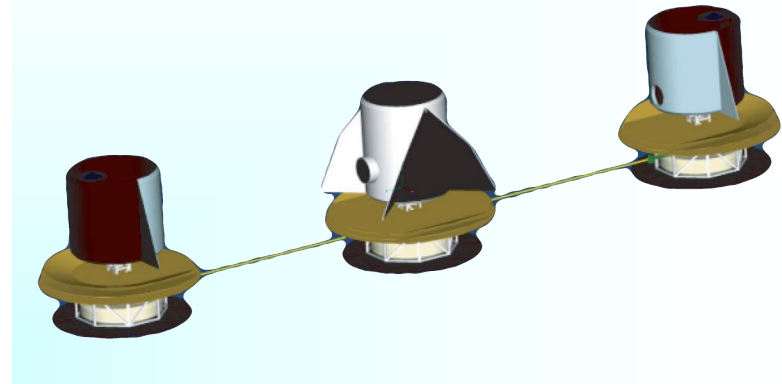


NASA Contact: Keith Gendreau (Keith.C.Gendreau@nasa.gov)

# *Submillimeter Probe of the Evolution of Cosmic Structure (SPECS)*

## **SPECS was**

- recommended in the Decadal Report for investment in technology and as a successor to SAFIR
- recommended by the IR astronomical community in the “Community Plan for Far-IR/Submillimeter Space Astronomy” as the culmination in a series of missions leading toward progressively higher angular resolution
- selected for study by NASA as a “vision mission”



## **Mission Description**

### **SPECS Primary Science Objectives**

- SPECS will enable the definitive identification of structures in protostellar disks during the early stages of star and planet formation,
- probe the atmospheres of giant planets,
- image the dust in debris disks, revealing the structures created by planets,
- probe the epoch of the formation of the first stars, heavy elements, and dust, and
- elucidate the processes that influenced the history of galaxy formation

- A single instrument provides
  - 0.01 ( $\lambda/100 \mu\text{m}$ ) arcsecond imaging and
  - $\lambda/\Delta\lambda = 3000$  spectroscopy in a
  - 1 arcmin field of view over the
  - spectral range 40 – 640  $\mu\text{m}$
  - possible high spectral resolution mode
- Two 4 m afocal telescopes in tethered formation for dense  $u$ - $v$  plane sampling, scanning optical delay line for spectroscopy (“double Fourier”)
- Sensitivity limited by astrophysical backgrounds
  - optics cryocooled to 4 K
  - “zeptobolometer” detector arrays
- Launch to Sun-Earth L2 in ~2025 - 2030

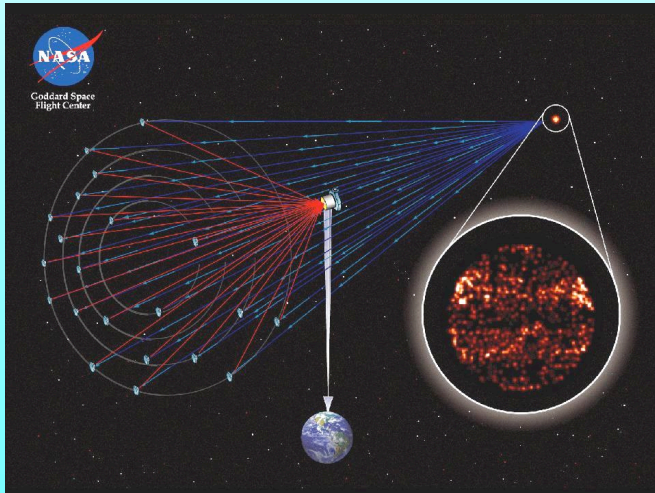
Study Lead: Martin Harwit (Cornell)

NASA Contact: David Leisawitz (David.T.Leisawitz@nasa.gov)



# Stellar Imager (SI): UV/Optical Space Interferometry

- UV-Optical Interferometer to provide 0.1 mas imaging (+ spectroscopy) of
  - magnetic field structures that govern: formation of stars & planetary systems, habitability of planets, space weather, transport processes on many scales in Universe
- A “Flagship” (Vision) mission in the 2005 SSSC Roadmap and a candidate “Pathways to Life Observatory” in the 2005 EUD Roadmap
- Mission Concept
  - 20-30 “mirrorsats” formation-flying with beam combining hub
  - Launch ~ 2024, to Sun-earth L<sub>2</sub>
  - baselines ~ 100 - 1000 m
  - Mission duration: ~10 years



## Prime Science Goals

**image surface/sub-surface features of distant stars;  
measure their spatial/temporal variations to  
understand the underlying dynamo process(es)**

**improve long-term forecasting of solar and stellar  
magnetic activity**

**understand the impact of stellar magnetic activity on  
planetary climates and life**

**understand transport processes controlled by  
magnetic fields throughout the Universe**

**perform high angular resolution studies (imaging +  
spectroscopy) of Active Galactic Nuclei, Quasars,  
Supernovae, Interacting Binary Stars, Forming  
Stars/Disks**

<http://hires.gsfc.nasa.gov/si/>

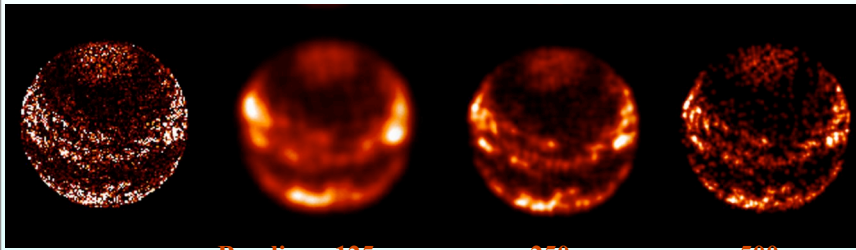
NASA Contact: Ken Carpenter (Kenneth.G.Carpenter@nasa.gov)

# What Will Stellar Imager See?

Solar-type star at 4 pc in CIV line

Model

*SIsim* images



Baseline: 125m

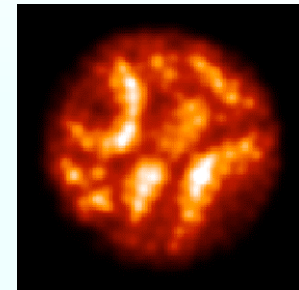
250m

500 m

Evolved giant star at 2 Kpc in Mg H&K line

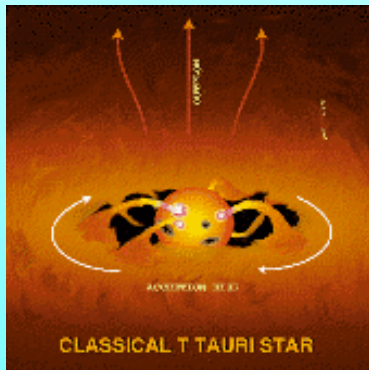
Model

*SIsim* image (2mas dia)

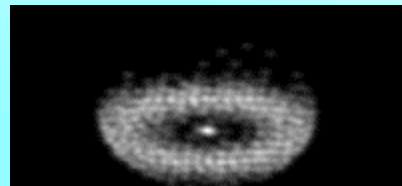


Baseline: 500 m

*SI* imaging of planet forming environments:  
magnetosphere-disk interaction region

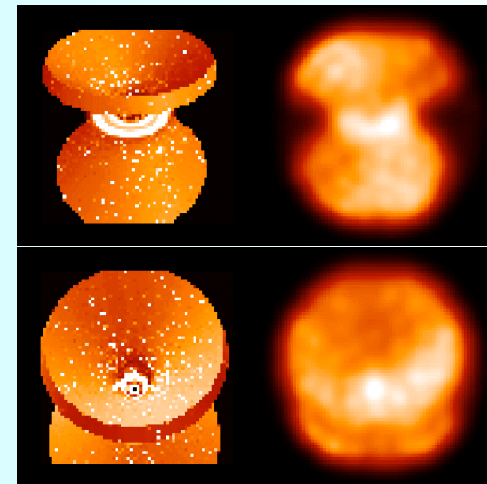


0.1 mas



*SI* simulation in  
Ly  $\alpha$ -fluoresced H2 lines  
Baseline: 500 m

*SI* imaging of nearby AGN will differentiate  
between possible BELR geometries & inclinations

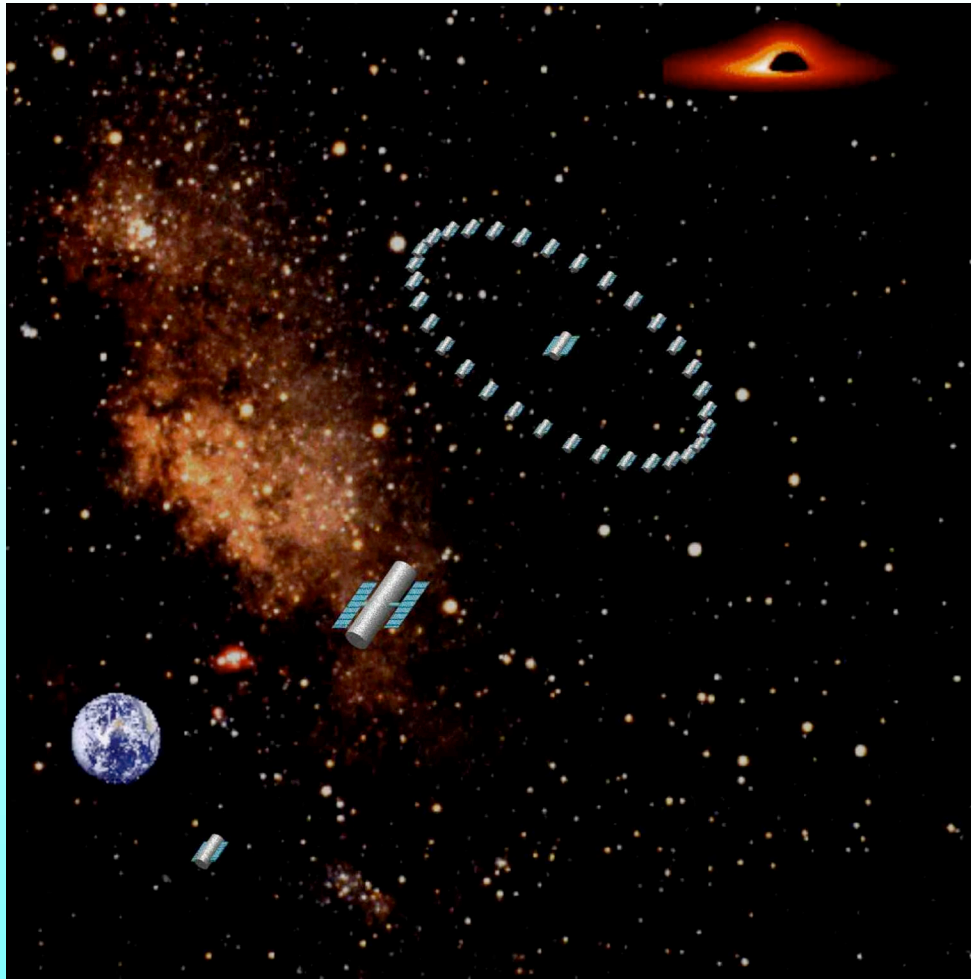


0.1 mas

model

*SI* simulations in CIV line  
(500 m baseline)

# Micro-Arcsecond X-ray Interferometry Mission (MAXIM): *Image a Black Hole!*



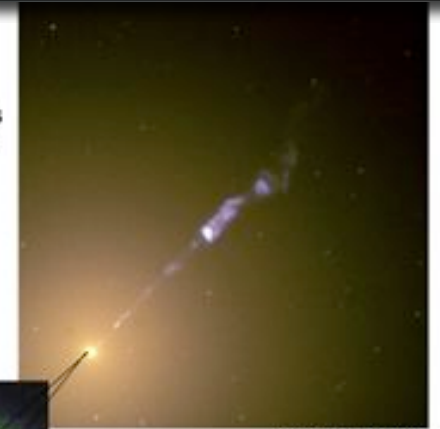
**Direct image of a black hole event horizon**

➡ **Fundamental importance to physics**

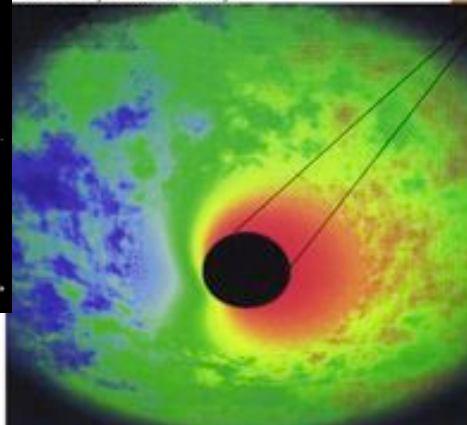
## **Galaxy M87 -- What Hubble Sees**

Jets of particles shoot out at near light speed from a suspected black hole in the galaxy core.  
Resolution = 0.1 arcsec.

Credit: Benjamin C. Bromley



Credit: NASA/HST



## **Galaxy M87 -- What MAXIM Sees**

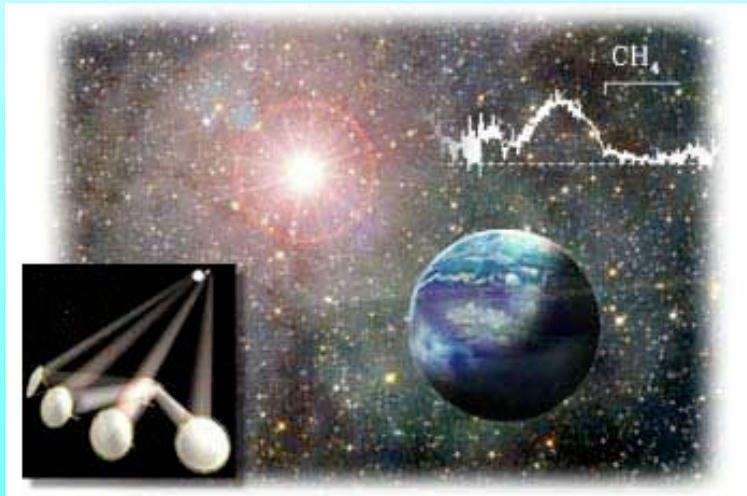
With 1,000,000x the resolution of Hubble, MAXIM would zoom in to image the suspected black hole.  
Resolution = 0.1 micro arcsec.

<http://maxim.gsfc.nasa.gov/>

NASA Contact: Keith Gendreau (Keith.C.Gendreau@nasa.gov)

# Life Finder (LF)

- Successor to TPF, to search for spectroscopic signs of life on extra-solar planets
  - Large array of telescopes flying in formation.
  - The telescopes would combine infrared light to produce high-resolution spectra of the atmospheres of extra-solar planets.
  - It would enable a search for markers of biological activity, such as seasonal variations in the levels of methane and other gases, changes in atmospheric chemistry and spectral variations in the dominant biomass.



*This montage shows an artist's concepts of Life Finder (foreground), an extrasolar terrestrial planet, and a spectrum.*



# Planet Imager (PI)

- Ultimate Goal of NASA Origins Program: Obtain resolved images of terrestrial-type planets around other stars
- Strawman Concept: An interferometer composed of interferometers: 5 formation flying interferometers, each composed of five 8-m mirrors (to yield 25x25 pixel images)

