Mid-Infrared Exoplanet Discovery and Characterization: the FKSI Mission Studies

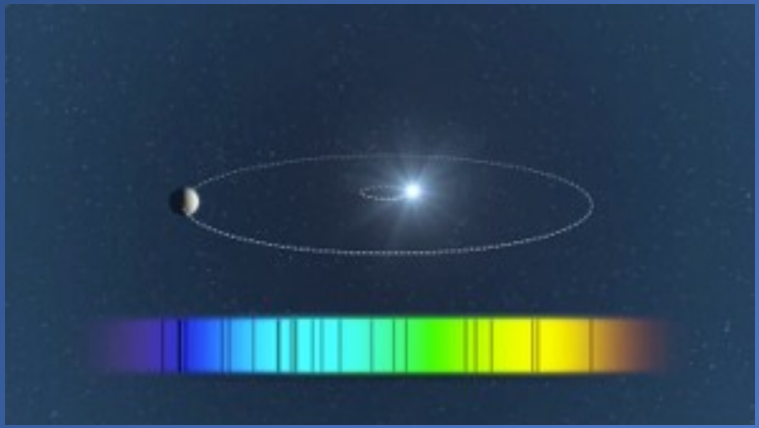
W. C. Danchi

October 2, 2017

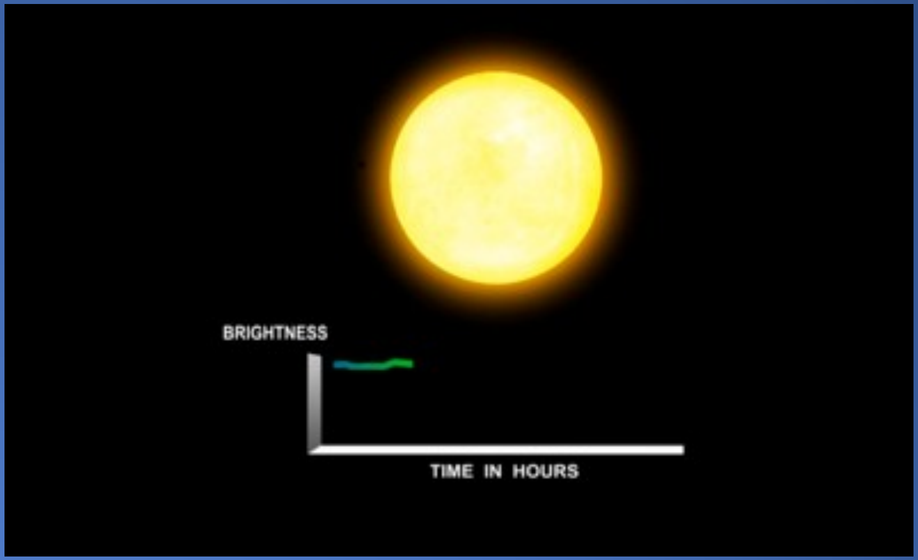
Hi-5 kickoff meeting – Liege, Belgium

How Do We Study Nearby Exoplanets?

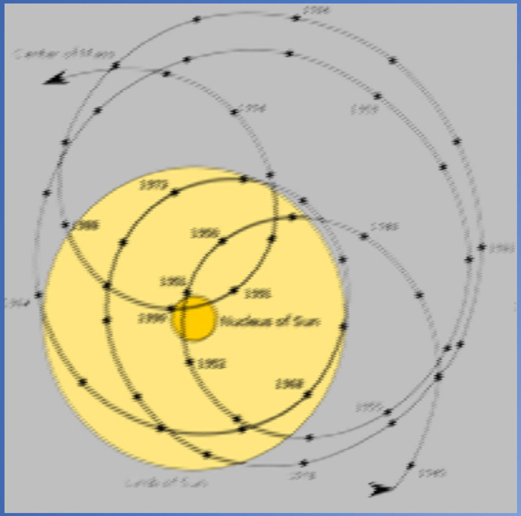
Precision Radial Velocity



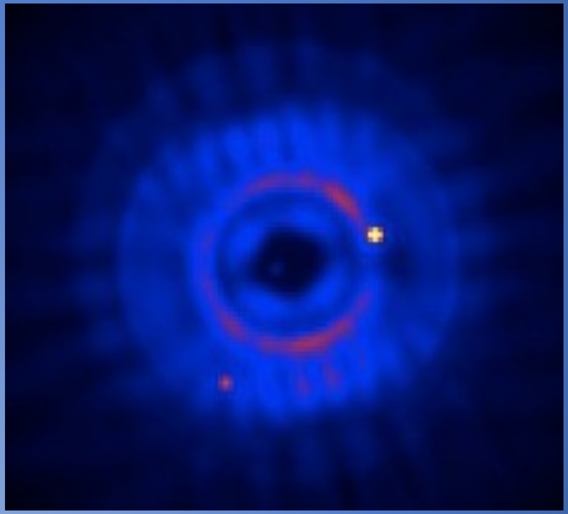
Transit & Occultation



Astrometry



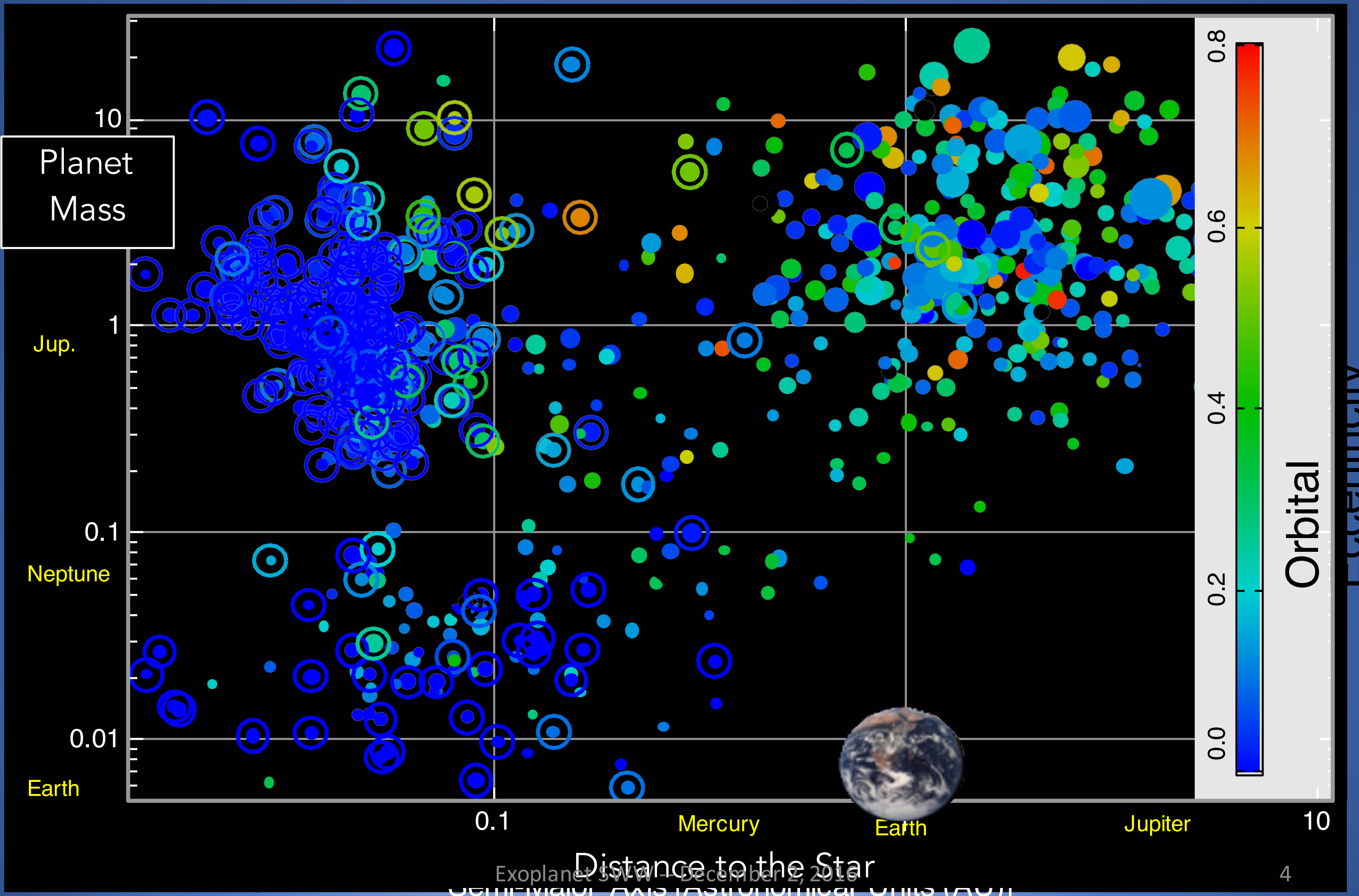
Direct Imaging



Basic Observational Problems of Exoplanets

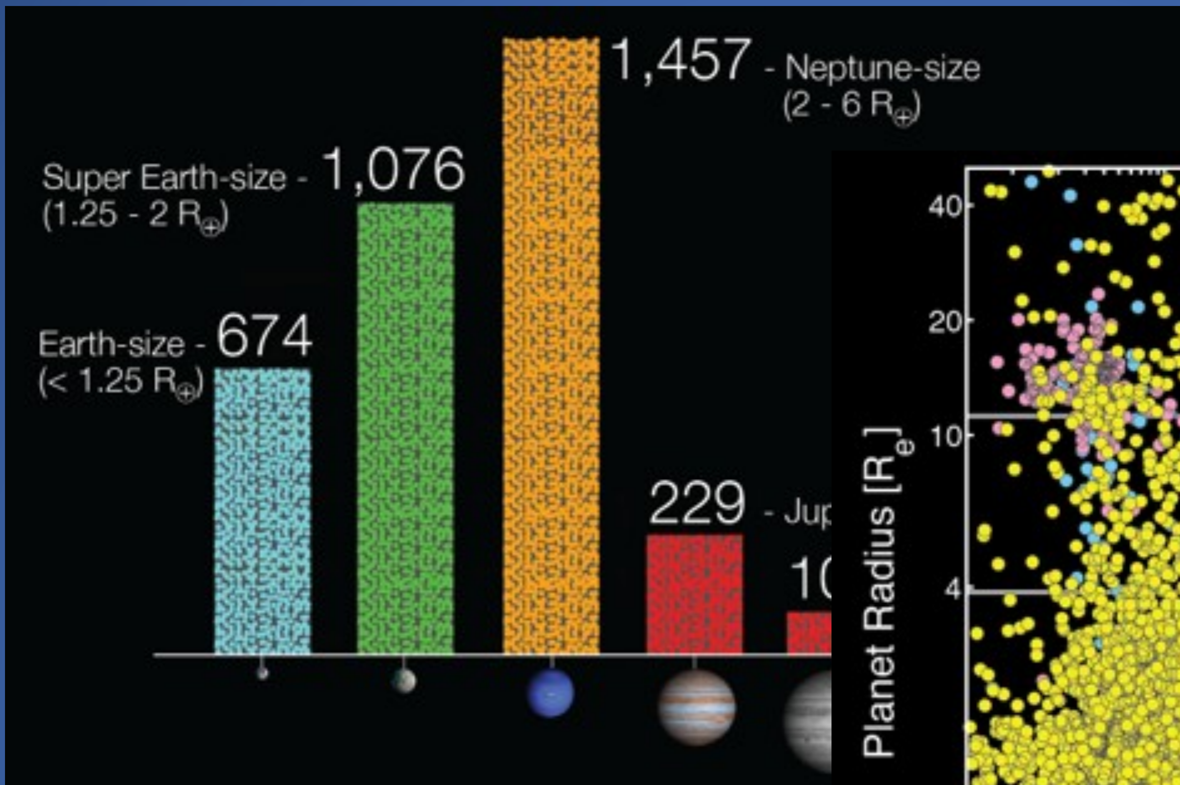
- Planet mass << Stellar mass
- Planet emission or scattering << Stellar emission
- Stars are active -- not constant in emitted power
- Stars are far away from the Sun so angular resolution is another problem (even for close ones)
- Remnant dust (exozodiacal dust) interferes with direct imaging of exoplanets
- All techniques have biases because of these sorts of issues
- No technique is perfect
- We progress because we use a variety of techniques

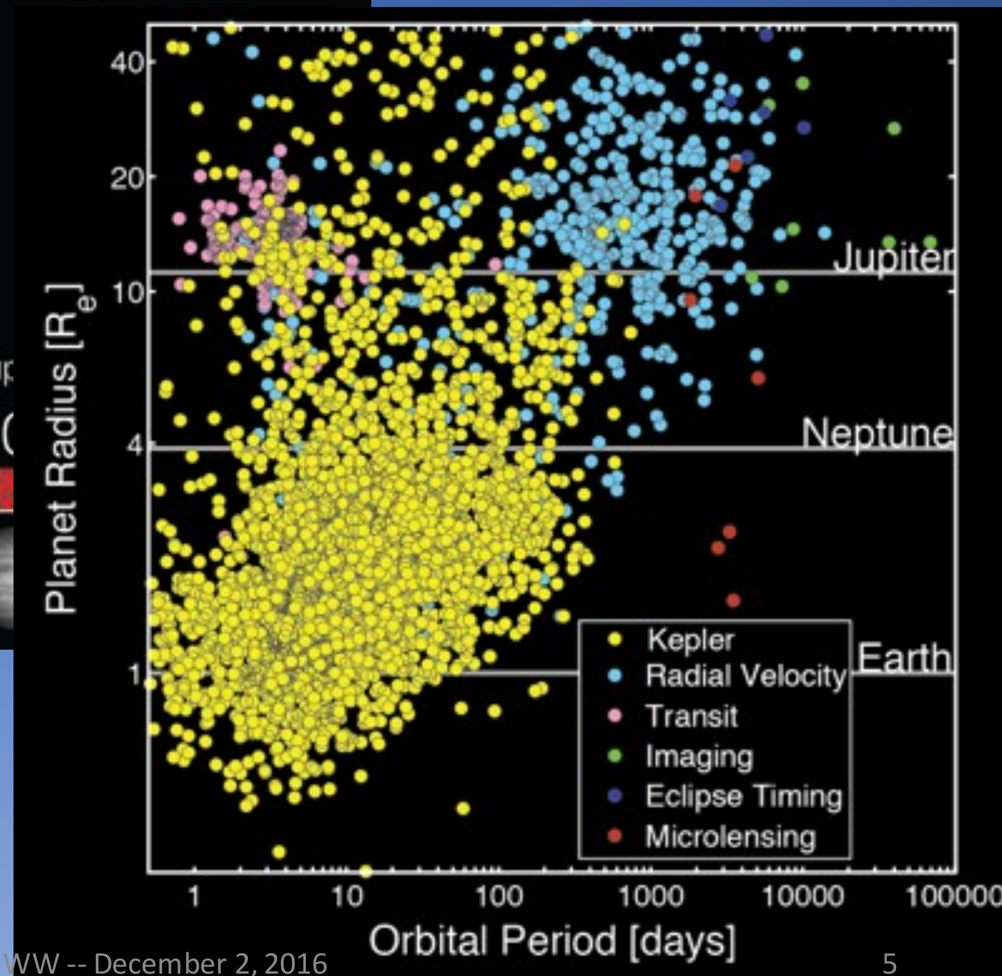
Current Confirmed Exoplanets Within 10 AU



Revolutionizing Exoplanet Statistics: The Kepler Space Telescope

Candidate Planets -- Nov 2013

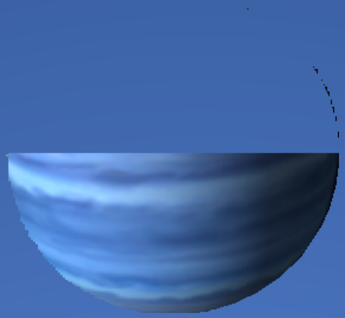




Exoplanets as Planets: Burning Questions

Jupiters

- How do they move from the birthplace, and why do they stop?
- Do their atmospheric compositions and dynamics reflect their birth history?



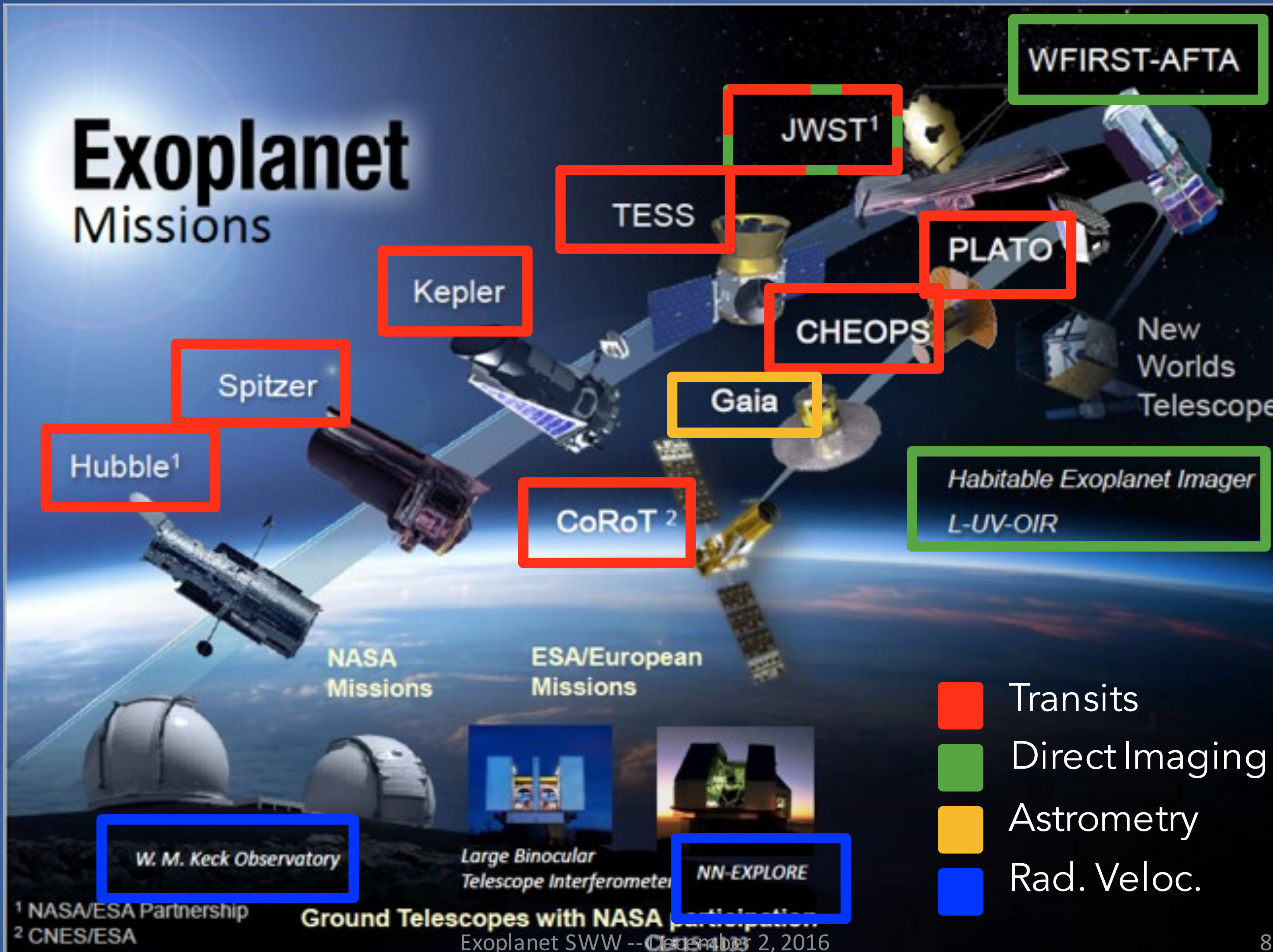
Neptunes/ Super-Earths

- Which is it — Neptune-like or Earth-like — and why?
- How do they form, and do they keep their original atmospheric composition and structure?

Super-Earths/ Earths

- What is the diversity of terrestrial planet size and composition?
- How do they form, and how do their atmospheres evolve over time?
- Which planets are habitable, or even inhabited?

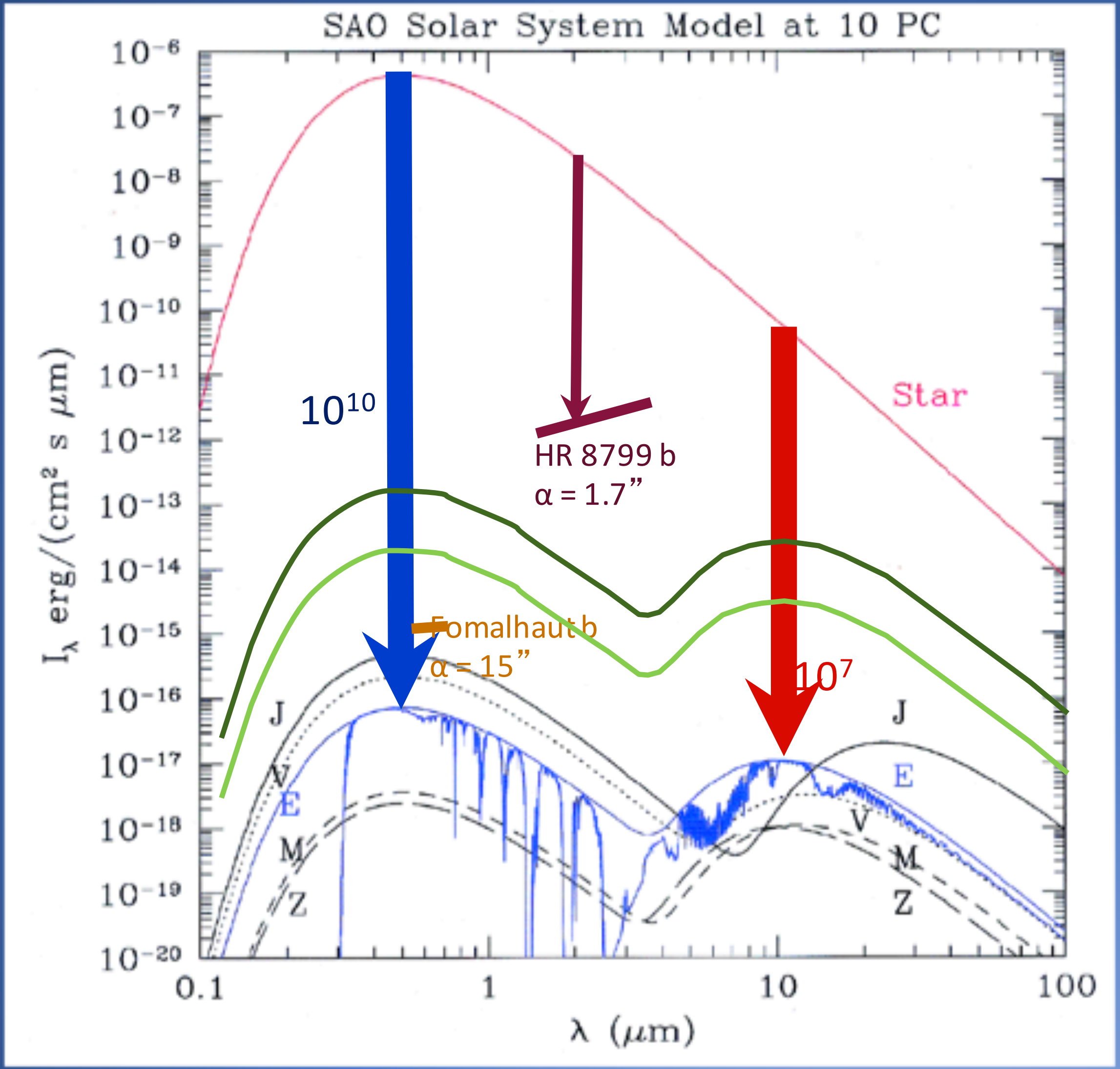

Exoplanet
Missions
WFIRST-AFTA
JWST1
TESS
PLATO
Kepler
CHEOPS
New
Worlds
Telescope
Spitzer
Gaia
Hubble1
Habitable Exoplanet Imager
L-UV-OIR
CoRoT 2
NASA
Missions
ESA/European
Missions
W. M. Keck Observatory
Large Binocular
Telescope Interferometer
NN-EXPLORE
1 NASA/ESA Partnership
2 CNES/ESA
Ground Telescopes with NASA participation


Exoplanet
Missions
WFIRST-AFTA
JWST[1]
TESS
Kepler
PLATO
CHEOPS
Spitzer
Gaia
New Worlds Telescope
Hubble[1]
CoRoT [2]
Habitable Exoplanet Imager
L-UV-OIR
NASA Missions
ESA/European Missions
Transits
Direct Imaging
Astrometry
Rad. Veloc.
W. M. Keck Observatory
Large Binocular Telescope Interferometer
NN-EXPLORE
[1] NASA/ESA Partnership
[2] CNES/ESA
Ground Telescopes with NASA participation

What about an Infrared Direct Imaging Mission?

- It isn't currently in the reasonably near-term plan
- Is the infrared a good place for exoplanet research?
- Is anything happening that is relevant to future IR exoplanet detection and characterization missions?

For Direct Imaging --The Contrast Problem



Planet Finding missions aim to:
detect Earths 10^{-10} fainter in visible.
detect Earth 10^{-7} in the IR.

Current state of the art:
Fomalhaut b: 10^{-9}, but 150x separation.
HR 8799b: 10^{-4} but 17x separation.

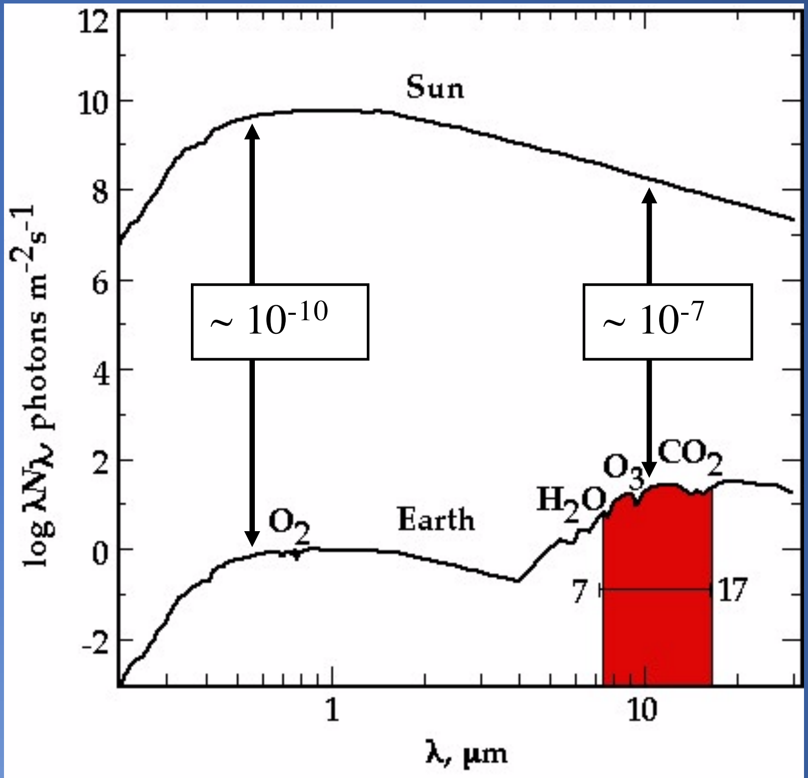
Our own Zodiacal dust:
5x 10^{-5} at 10 μm =1 zodi.

Exozodiacal dust becomes a problem:
10 zodi or above.

LBTI can show us what exists (planets or dust disks) at faint levels around nearby stars.

Detecting Earth-area Planets is Difficult and the Thermal Infrared is a Good Spectral Region

- Detecting light from planets beyond solar system is hard:
  - Earth sized planet emits few photons/sec/m^2 at 10 µm
  - Parent star emits 10^6 more
  - Planet within 1 AU of star
  - Exozodi dust emission in target solar system x 300 brighter than earth-area planet for equivalent of *ONE* Solar System Zodi



In 2009 we had the Exoplanet Community Report:

The exoplanet community's top priority is that a line of probe-class missions for exoplanets be established, leading to a flagship mission at the earliest opportunity.

The Infrared Chapter:

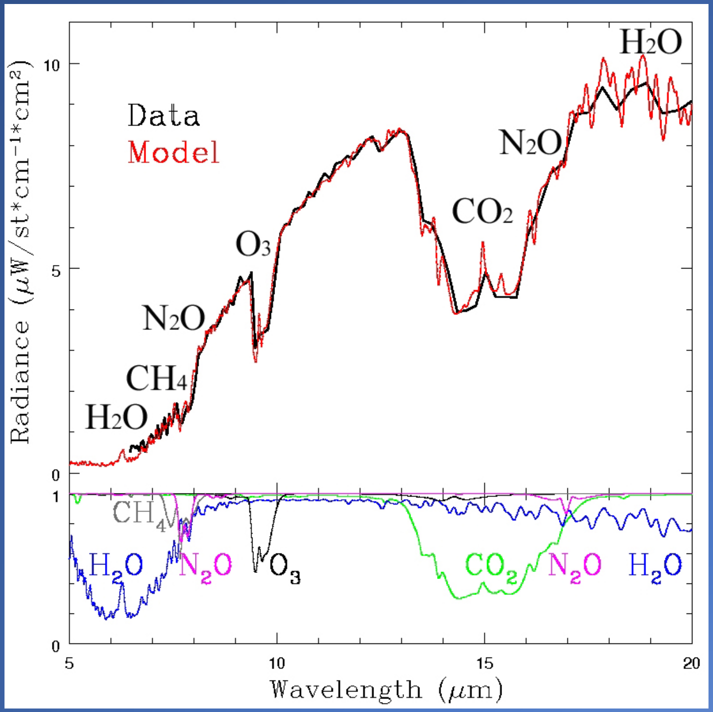
4 Infrared Imaging

William Danchi, NASA Goddard Space Flight Center, Chair

Peter Lawson, Jet Propulsion Laboratory, Co-Chair

Olivier Absil, Rachel Akeson, John Bally, Richard K. Barry, Charles Beichman, Adrian Belu, Mathew Boyce, James Breckinridge, Adam Burrows, Christine Chen, David Cole, David Crisp, Rolf Danner, Peter Deroo, Vincent Coudé du Foresto, Denis Defrère, Dennis Ebbets, Paul Falkowski, Robert Gappinger, Ismail D. Haugabook, Sr., Charles Hanot, Thomas Henning, Phil Hinz, Jan Hollis, Sarah Hunyadi, David Hyland, Kenneth J. Johnston, Lisa Kaltenegger, James Kasting, Matt Kenworthy, Alexander Ksendzov, Benjamin Lane, Gregory Laughlin, Oliver Lay, Réne Liseau, Bruno Lopez, Rafael Millan-Gabet, Stefan Martin, Dimitri Mawet, Bertrand Mennesson, John Monnier, Naoshi Murakami, M. Charles Noecker, Jun Nishikawa, Meyer Pesesen, Robert Peters, Alice Quillen, Sam Ragland, Stephen Rinehart, Huub Rottgering, Daniel Scharf, Eugene Serabyn, Motohide Tamura, Mohammed Tehrani, Wesley A. Traub, Stephen Unwin, David Wilner, Julien Woillez, Neville Woolf, and Ming Zhao

Earth Spectrum Peaks in the mid-IR

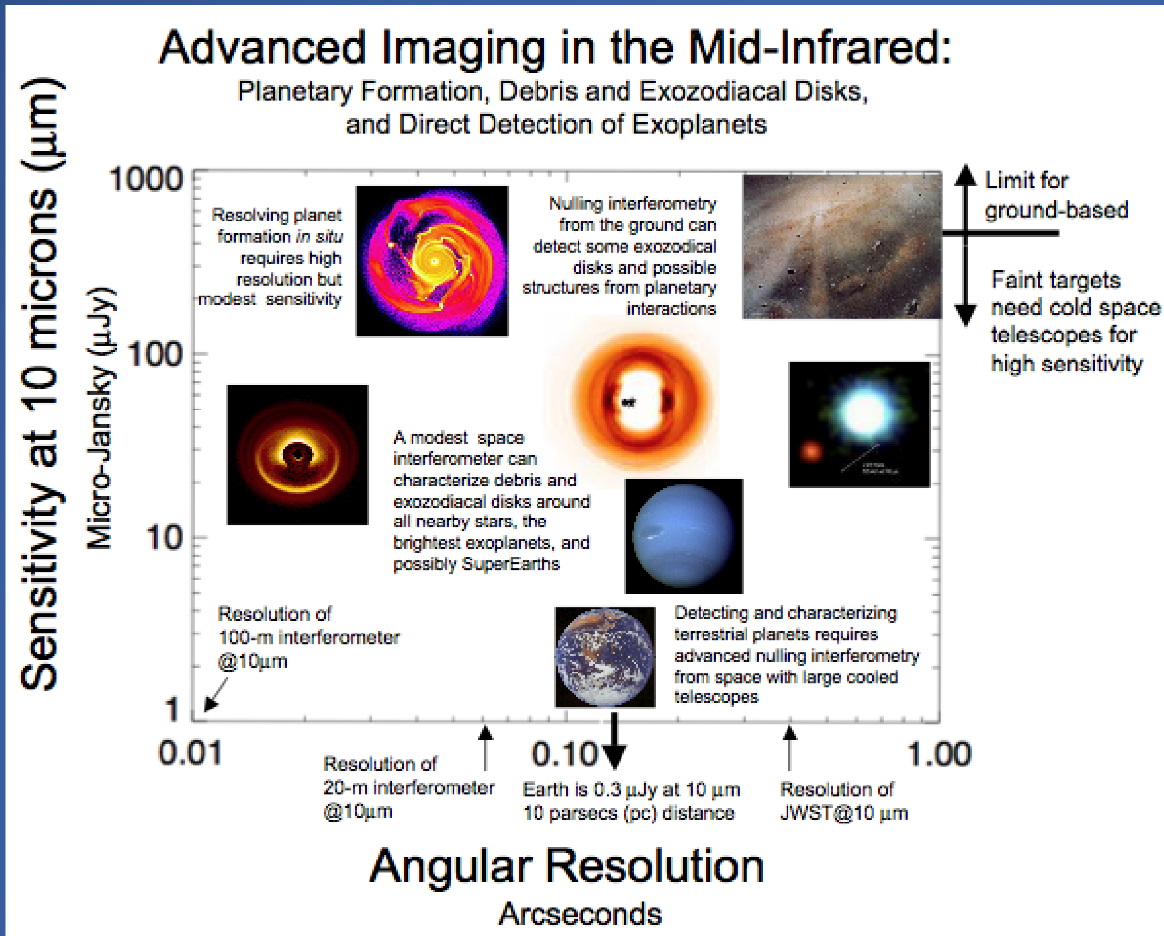


Earth's spectrum shows absorption features from many species, including ozone, nitrous oxide, water vapor, carbon dioxide, and methane

Biosignatures are molecules out of equilibrium such as oxygen, ozone, and methane or nitrous oxide.

Spectroscopy with R ~ 50 is adequate to resolve these features.

Sensitivity and Resolution in the Mid-IR



Ground-based interferometry in the IR:

- Limited sensitivity
- Long baselines available
- Good for studying protoplanetary disks

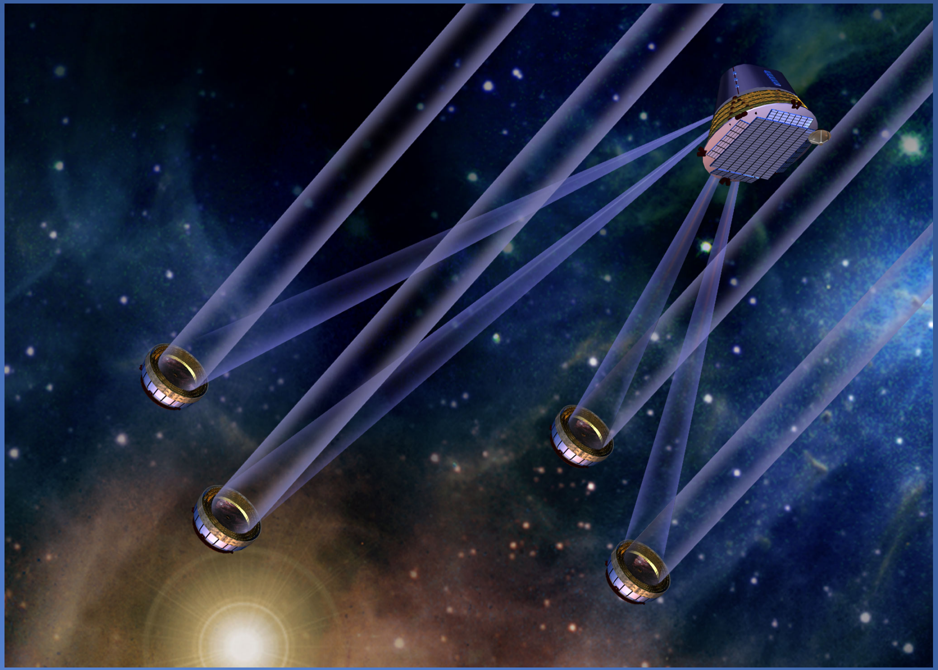
Space-based interferometry:

1. Structurally Connected interferometer (limited baseline length)
   - Exozodi levels for ALL TPF/Darwin stars
   - Debris Disks
   - Characterize Warm & Hot Planets & Super Earths
2. Formation-flying or tethers (long baselines)
   - Detect and characterize many Earth-sized planets
   - Transformational astrophysics

Terrestrial Planet Finder Interferometer

Salient Features

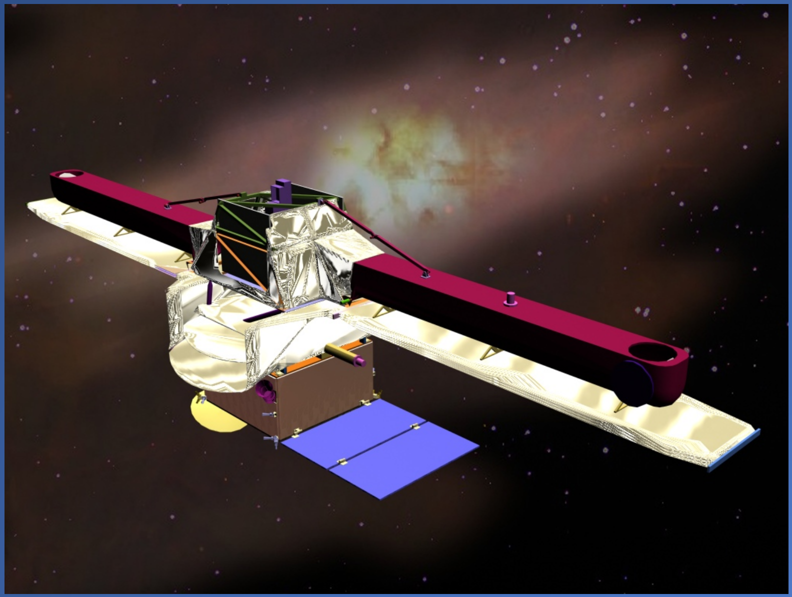
- Formation flying mid-IR nulling Interferometer
- Starlight suppression to 10^{-5}
- Heavy launch vehicle
- L2 baseline orbit
- 5 year mission life (10 year goal)
- Potential collaboration with European Space Agency



Science Goals

- Detect as many as possible Earth-like planets in the habitable zone of nearby stars via their thermal emission
- Characterize physical properties of detected Earth-like planets (size, orbital parameters, presence of atmosphere) and make low resolution spectral observations looking for evidence of a *habitable* planet and bio-markers such as O_2, CO_2, CH_4 and H_2O
- Detect and characterize the components of nearby planetary systems including disks, terrestrial planets, giant planets and multiple planet systems
- Perform general astrophysics investigations as capability and time permit

A Small Structurally Connected Interferometer; The Fourier-Kelvin Stellar Interferometer (FKSI) Mission



PI: Dr. William C. Danchi
Exoplanets & Stellar Astrophysics, Code 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:

- **Observe Circumstellar Material**
  - Exozodi measurements of nearby stars and search for companions
  - Debris disks, looking for clumpiness due to planets
- **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
- **Star formation**
  - Evolution of circumstellar disks, morphology, gaps, rings, etc.
- **Extragalactic astronomy**
  - AGN nuclei

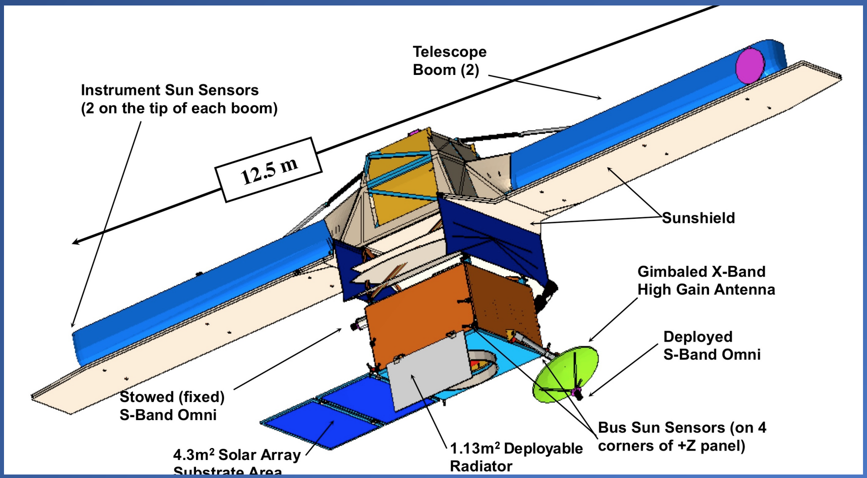
Key Features of Design:

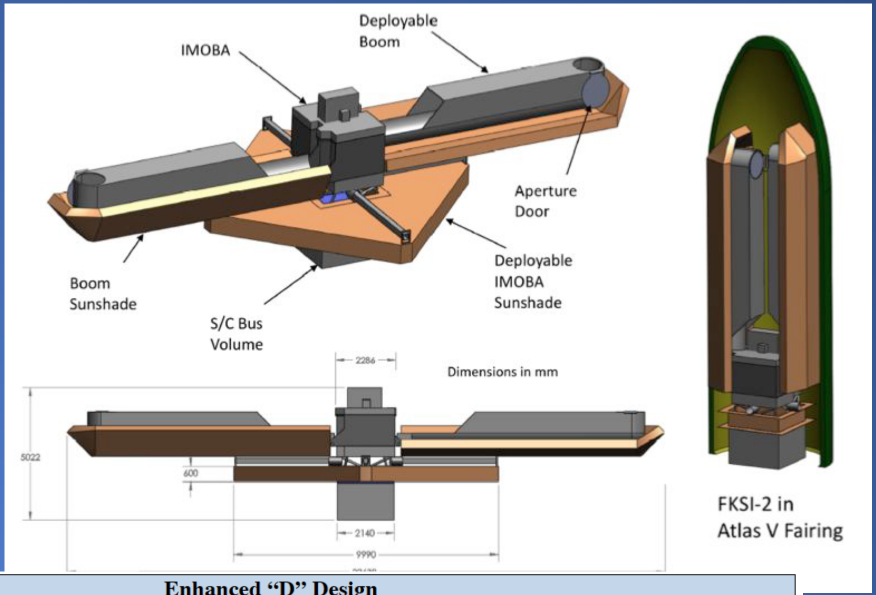
- ~0.5 m diameter aperture telescopes
- Passively cooled (<70K)
- 12.5 m baseline
- 3 – 8 um (or 10 TBR) micron science band
- 0.6-2 micron band for precision fringe and angle tracking
- Null depth better than 10^-4 (floor), 10^-5 (goal)
- R=20 spectroscopy on nulled and bright outputs of science beam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

FKSI

- Most recent work in 2009-2010 time frame – mission design studies:
  - Center wavelength from 5 to 10 µm
  - Baseline from 12.5 m to 20 m
  - Mirror diameter from 0.5 m to 1.0 m
  - Passive cooling to 40 K
  - JWST cryocooler for detectors operating at longer wavelengths
  - Did performance calculations to see how many super-Earths and Earth-sized planets could be detected
  - Work was published in SPIE in 2010, and other conference proceedings
- Also worked with Nice to to use the **PERSEE** for FKSI related issues:
  - Test imaging capabilities with realistic scene consisting of star, planet, and exozodi
  - Test of pathlength control for realistic boom and reaction wheel noise sources

Enhanced FKSI Design





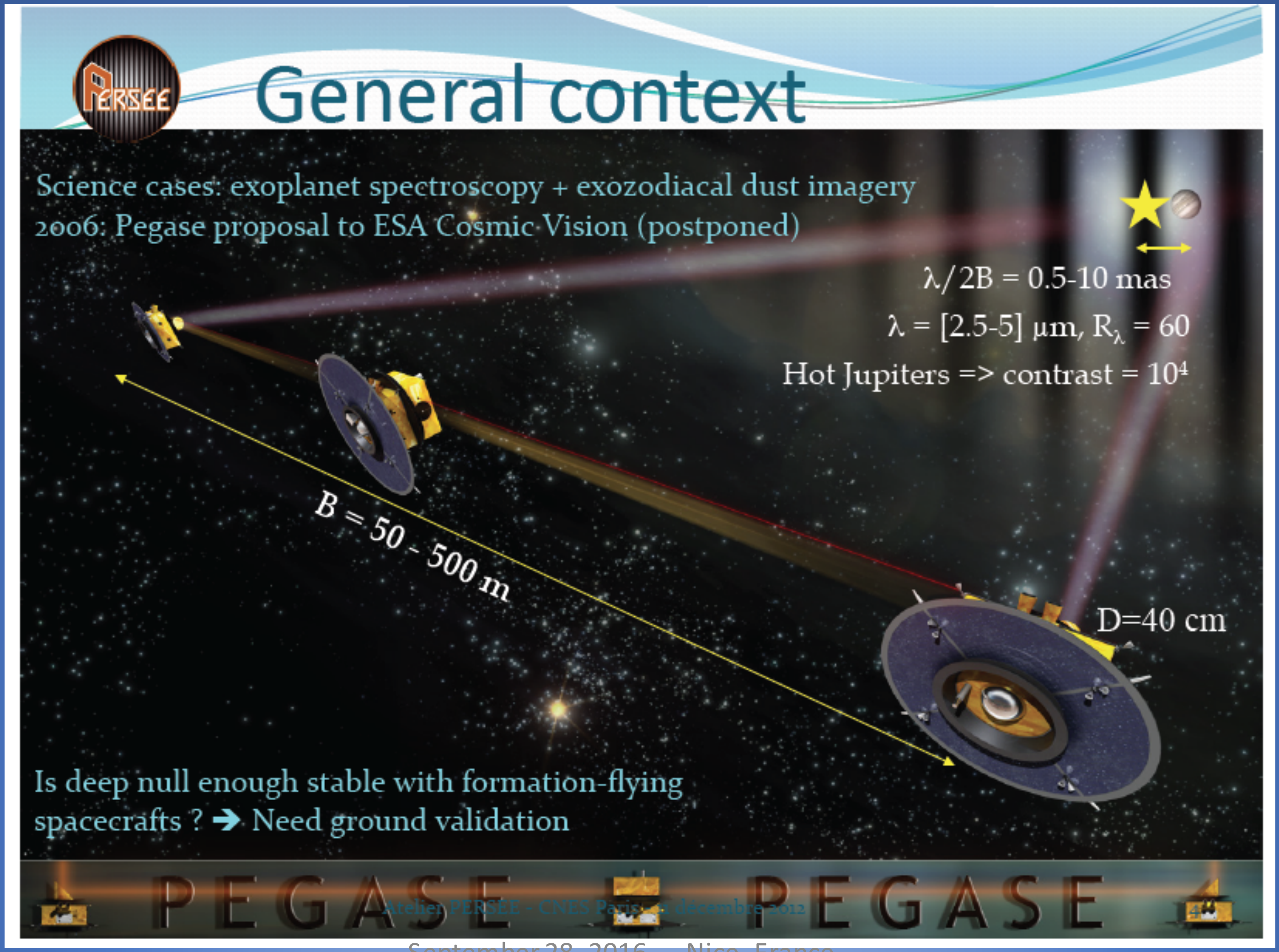
Basic Assumptions:
SNR = 5 for detection
SNR = 10 for spectroscopy (R = 20 at 10 μm)
3 sets of observations per star (visits)
< 2 years total
< 7 days total per star
T_{earth} = 288 K
Earth albedo = 0.3
Inclination angle of planet orbit = 45°
Sunshade FOR = ± 45°
1 SSZ emission from observed system's dust disk

Enhanced "D" Design Tel = 1 m					
R_{Planet}	Total	N_F	N_G	N_K	N_{Spec}
1 R_{Earth}	4	0	1	3	4
2 R_{Earth}	34	6	16	12	16
Tel = 1.5 m					
1 R_{Earth}	15	0	7	8	4
2 R_{Earth}	95	35	48	12	27
Tel = 2.0 m					
1 R_{Earth}	29	3	14	12	12
2 R_{Earth}	138	65	61	12	43

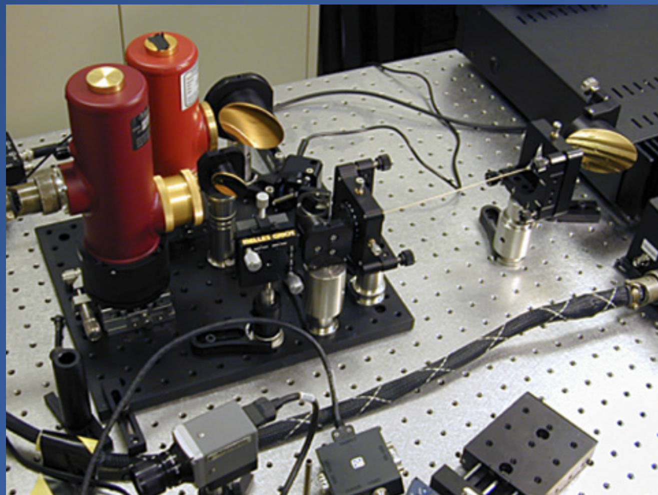
Results of simulations using the TPF performance simulator of Dubovitsky & Lay for an enhanced FKSI but with 1-, 1.5-, and 2-m diameter telescopes. N_X is the number of 1 or 2 R_{Earth} exoplanets detected in the population of F, G and K dwarf stars within 30 pc. N_{spec} are the number of these target planets for spectroscopic characterization of the atmosphere.

Danchi, Barry 2010 SPIE

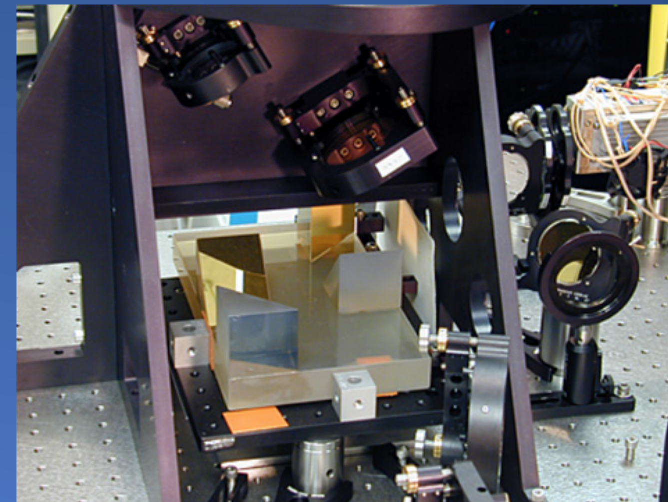
French (CNES) PEGASE mission concept



Laboratory Testbed Milestones



View of a chalcogenide glass fiber, in use within the Adaptive Nuller testbed. The fiber can be seen being fed by an off-axis parabola, to the right, prior to the spectrometer and single-pixel detector.



Side view of the periscope assembly of the Achromatic Nulling Testbed.

- MILESTONE #1 – Compensation of intensity and phase demonstrated by Adaptive Nuller testbed. Intensity compensated to 0.2% and phase to 5 nm rms across a 3 µm band centered at 10 µm
- MILESTONE #2 – Demonstration of precision formation flying maneuvers in a ground-based robotic testbed, with traceability to flight
- MILESTONE #3 – Demonstration of broadband nulling at the flight requirements of 1.0×10^{-5}, using 34% bandwidth centered at 10 µm. Monochromatic nulls demonstrated to 5×10^{-7}.
- MILESTONE #4 – Laboratory demonstration of detection of planet signal 10^6 times fainter than a star while using array rotation, chopping, and averaging.

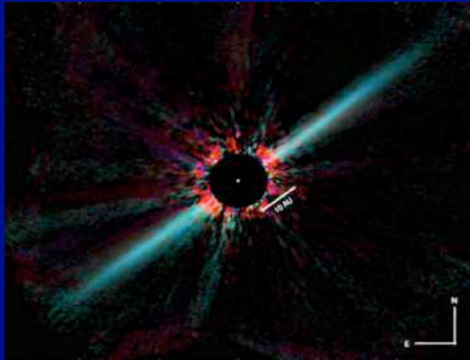
Technology Investments

Technology	Cost
SIM Technology up to Phase B	$600 M
Keck Interferometer	$120 M
LBTI	$20 M +
JPL Testbeds (AcNT, AdNT, PDT, etc.)	$60 M
TOTAL	$800 M +

A number of smaller mission concepts and testbeds, such as FKSI, PICTURE, SPIRIT and WIIT testbed, BETTII, and Nulling Coronagraph Testbed(s), also have contributed, at the cost of $10 M+

Astro2010
Research & Analysis Recommendations

- ***Space-based Interferometry***
  - ***Space-based interferometry serves critical roles in exoplanet studies. It provides access to a spectral range that can not be achieved from the ground and can characterize the detected planets in terms of atmospheric composition and effective temperature. Sensitive technology has already been proven for missions like JWST, SIM, and Spitzer, and within NASA's preliminary studies of TPF***



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

Status of FKSI since 2009

- A white paper on FKSI was submitted to the US Decadal Survey Committee in 2009, with about 50 signatories
- The committee had several questions about the FKSI concept, and the team responded to the questions with an addendum to the original submission
- In 2010 the Decadal Survey did not recommend SIM continue (in the famous footnote) even though SIM had passed through BOTH Phase A and B. It was ready to go to KDP-C, which would allow it to be built.
- In the aftermath of the Decadal NASA HQ shut down all work on SIM, and about a year later shut down the Keck Interferometer, effectively curtailing its large investments regarding exoplanet detection and characerization in the infrared.
- What has happened since?

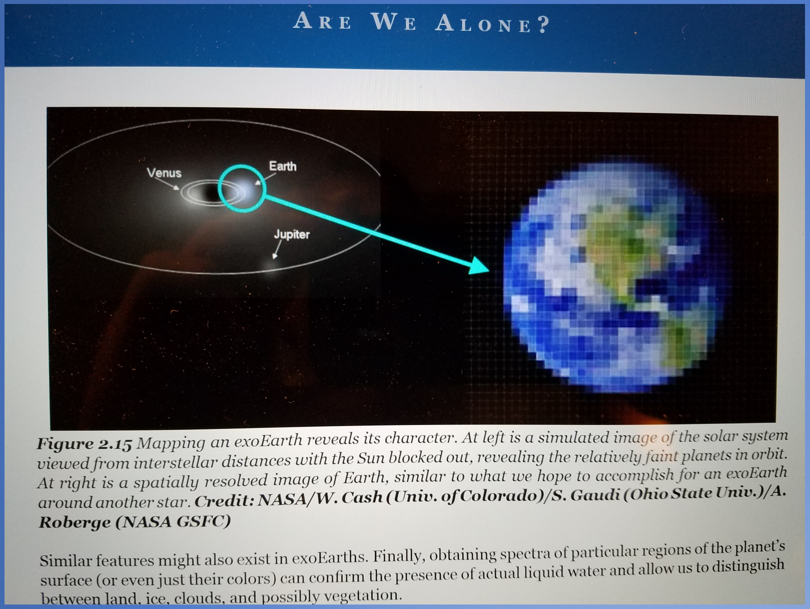
Technical Readiness for a Small Structurally Connected Interferometer

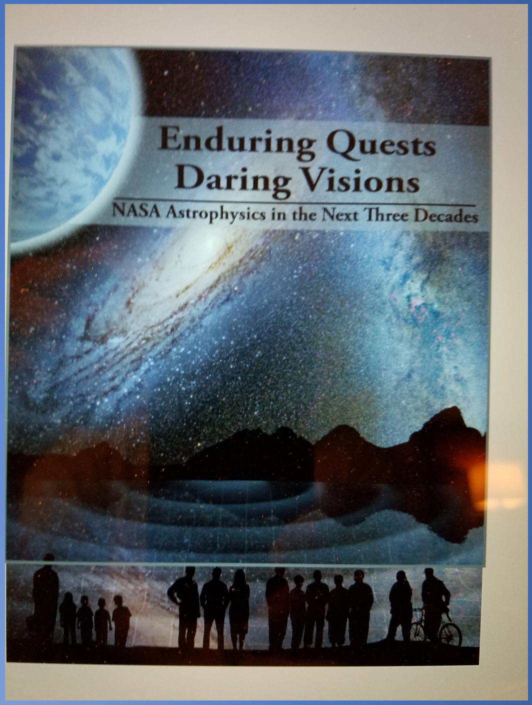
Item	Description	TRL 2010	TRL 2017	Notes
1	Cryocoolers	6	8	Source: JWST
2	Precision cryogenic structure	6	8	Source: JWST
3	Detectors (near-infrared)	6	8	Source: HST, JWST Nircam
4	Detectors (mid-infrared)	6	8	Source: Spitzer IRAC, JWST MIRI
5	Cryogenic mirrors	6	8	Source: JWST
6	Optical fiber for mid-infrared	4	4	Source: TPF-I
7	Sunshade	6	8	Source: JWST
8	Nuller Instrument	5-6	5-6	Source: Keck Interferometer Nuller, TPF-I project, LBTI HOSTS (in operation – cryogenic nuller)
9	Precision cryogenic delay line	6	6	Source: ESA Darwin

*Note: The requirement for the FKSI project is a null depth of 10^{-4} in a 10% bandwidth. Laboratory results with the TPF-I testbeds have exceeded this requirement by an order of magnitude (Lawson et al. 2008).

NASA’s Vision

- NASA’s long term roadmap: “Enduring Quests, Daring Visions,” had an “Exo-Earth Mapper” as a long-term goal, which is a large formation flying space interferometer, but it provided no technical pathway to get there.
- In the planning it had a great leap from LUVOIR to the Exo-Earth mapper.





Notional Timeline

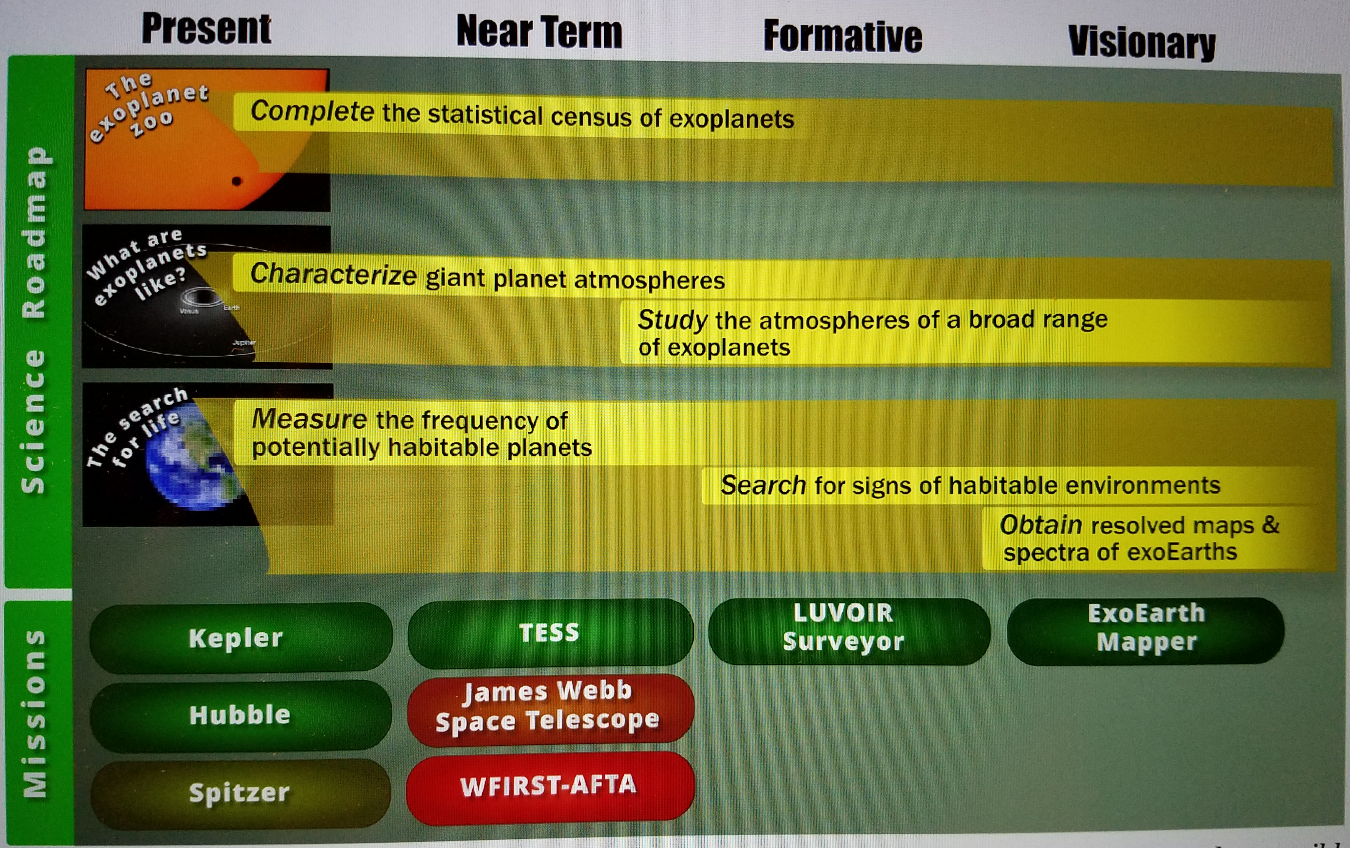
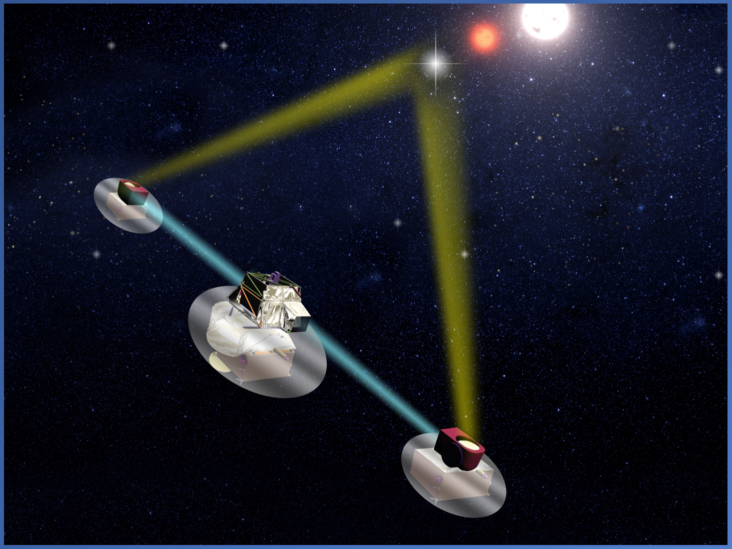


Figure 2.16 *Schematic of the Exoplanets Roadmap, with science themes along the top and a possible mission sequence across the bottom.* ***Credit: F. Reddy (NASA GSFC)***

divide its image into a number of smaller pieces, like having more pixels in a digital photo. This demands

Astrophysics Formation Flying Concept Fourier-Kelvin Stellar Interferometer (FKSI)



Key Science Goals
- Observe Circumstellar Material
- Detect >20 Extra-solar Giant Planets
- Star Formation
- Extragalactic Astronomy

PI: Dr. William C. Danchi, Exoplanets & Stellar Astrophysics, Code 667

- 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 Features of Design
  - ~0.5 m diameter aperture telescopes
  - Passively cooled (<70K)
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  - Null depth better than 10^-4 (floor), 10^-5 (goal)
  - R=20 spectroscopy on nulled and bright outputs of science beam combiner

A Small Structurally Connected Interferometer; The Fourier-Kelvin Stellar Interferometer (FKSI) mission could be made into a distributed spacecraft mission (ref. ESA Pegase proposal)

Submitted to HQ for consideration as a Distributed Spacecraft Mission Concept

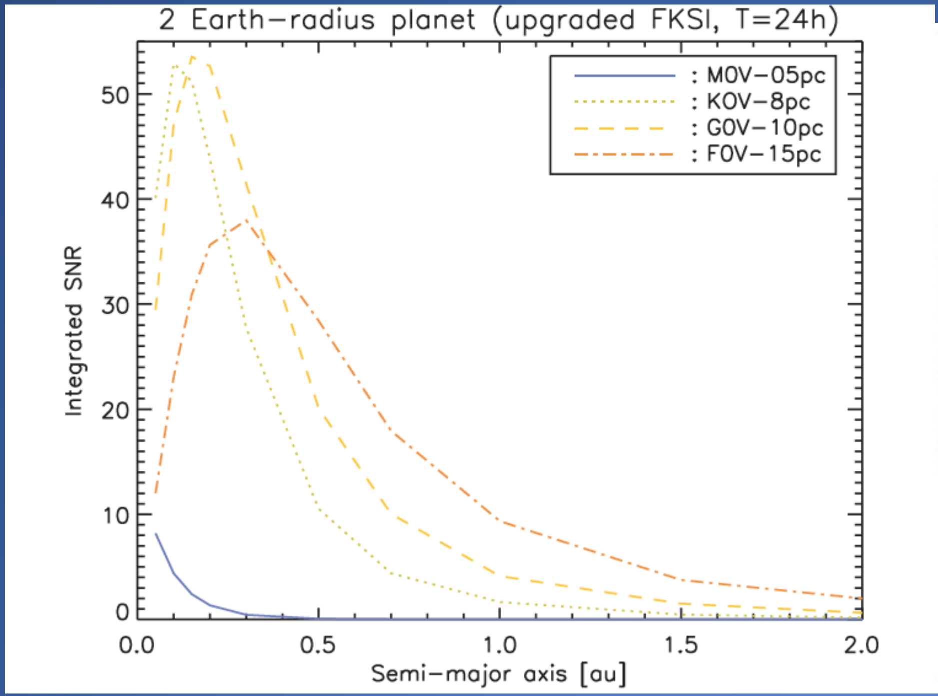
New Opportunity & Question to you

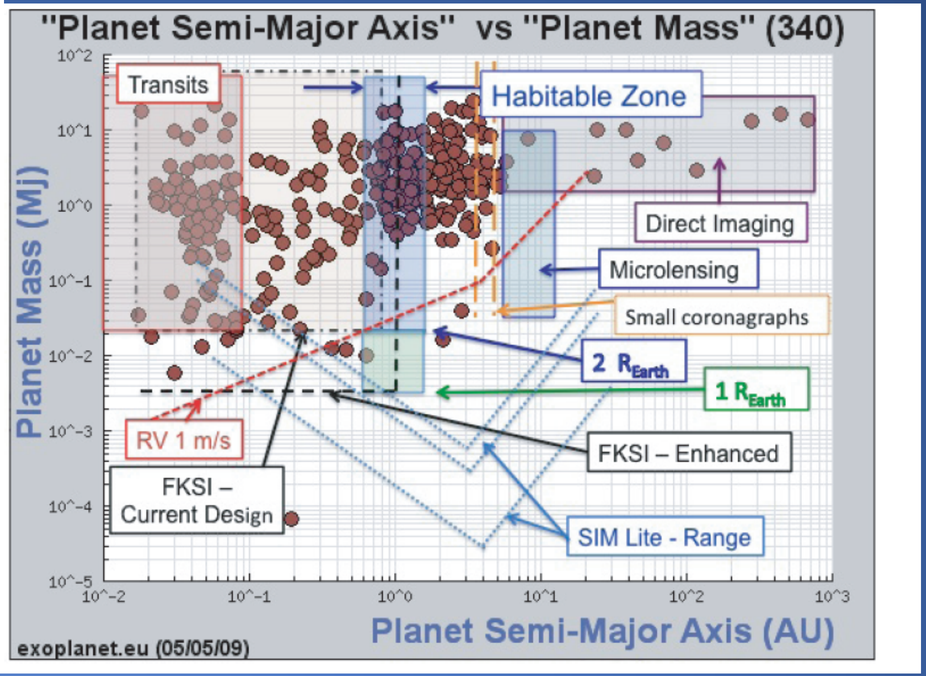
- There is an RFI that just came out looking for mission concepts with smallsats costing under $80 M that can do good science (science based).
- Also, the RFI was looking for technology demonstrations that could do some new science, but not with a clearly defined budget.

- Can we make a small interferometer that could fit into one of these categories?

Backup material

Enhanced FKSI Exoplanet Discovery Space





Simulations of FKSI performance with 1-2 m class telescopes at 40K and a 20-m baseline demonstrate that many 2 Rearth super-Earths and a few Earth-twins can be discovered and characterized within 30 pc of the Sun.

Discovery space for exoplanets for FKSI and other mission concepts and techniques

NB: This is old and needs updating

Astro2010
Research & Analysis Recommendations

- ***Ground-based interferometry***
  - ***Ground-based interferometry serves critical roles in exoplanet studies. It provides a venue for development and demonstration of precision techniques including high contrast imaging and nulling, it trains the next generation of instrumentalists, and develops a community of scientists expert in their use.***
  - ***We endorse the recommendations of the "Future Directions for Interferometry" Workshop and the ReSTAR committee report to continuing vigorous refinement and exploitation of existing interferometric facilities (Keck, NPOI, CHARA and MRO), widening of their accessibility for exoplanet programs, and continued development of interferometry technology and planning for a future advanced facility***
  - ***The nature of Antarctic plateau sites, intermediate between ground and space in potential, offers significant opportunities for exoplanet and exozodi studies by interferometry and coronagraphy.***
- ***Space-based Interferometry***
  - ***Space-based interferometry serves critical roles in exoplanet studies. It provides access to a spectral range that can not be achieved from the ground and can characterize the detected planets in terms of atmospheric composition and effective temperature. Sensitive technology has already been proven for missions like JWST, SIM, and Spitzer, and within NASA's preliminary studies of TPF***

Backup – TRL Definitions

TRL 9
- Actual system "flight proven" through successful mission operations

TRL 8
- Actual system completed and "flight qualified" through test and demonstration (ground or space)

TRL 7
- System prototype demonstration in a space environment

TRL 6
- System/subsystem model or prototype demonstration in a relevant environment (ground or space)

TRL 5
- Component and/or breadboard validation in relevant environment

TRL 4
- Component and/or breadboard validation in laboratory environment

TRL 3
- Analytical and experimental critical function and/or characteristic proof-of-concept

TRL 2
- Technology concept and/or application formulated

TRL 1
- Basic principles observed and reported