National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

Navigator Program

…Exploring New Worlds

Space Interferometry Mission (SIM) PlanetQuest *and* Terrestrial Planet Finder (TPF)

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February 15, 2005

NASA Strategic Vision Goal #4

- How Did the Elements of Life Originate? (*JWST*)
  - We now know that the elements of life are widespread and have their origin in the Big Bang and supernovae, but ***when, after the Big Bang, did the first habitable environments and life itself come into being?***
- Where do Planets Come From? (*SIM & TPF*)
  - We now know that stars and planets formed together from clouds of gas and dust, but ***what processes led to planets like our own, warmed for billions of years by our sun to just the right temperature and blessed with abundant water and the elements of life?***
- Are There Other Habitable Worlds? (*TPF & SIM*)
  - We now know that life occupies an astounding range of ecological niches on Earth, but ***are habitable environments common in other solar systems and can we use remote sensing to find other habitable or inhabited planets?***

"Conduct advanced telescope searches for Earth-like planets and habitable environments around neighboring stars."

Outline

- Searching and characterizing extrasolar planetary systems:
  - An integrated approach with SIM PlanetQuest and TPF
- Keck Interferometer Summary (technology and science precursor)
- Science objectives of SIM
- SIM technology progress and programmatic update
- Comparative Planetology and TPF Foundation Science
- TPF-C science and technology update
- TPF-I and ESA/Darwin collaboration
- Conclusions

Keck Interferometer

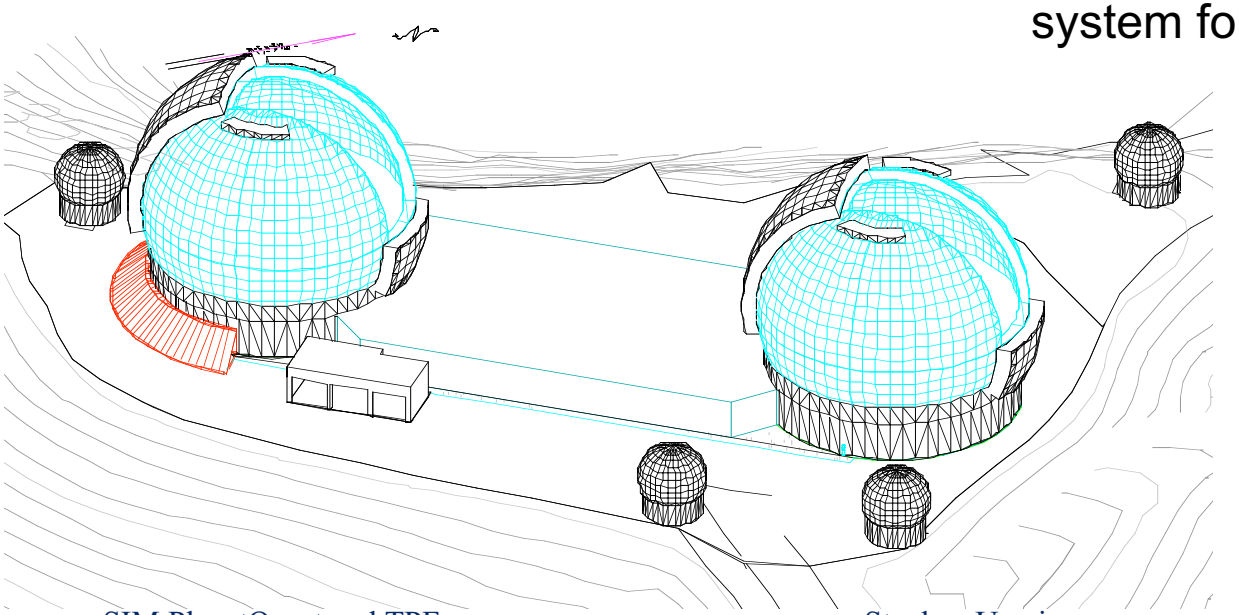
Keck – Keck Interferometry
- V2
- Nulling
- Diff Phase

Outrigger Interferometry
- Astrometry
- Imaging (6 telescope array)

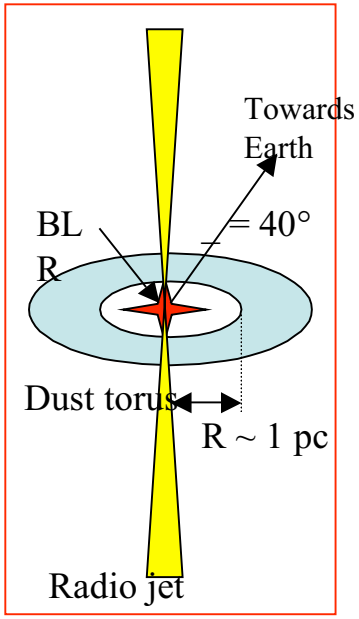
Outriggers delayed due to political and legal issues related to getting building permits for the outrigger telescopes. Recent progress is encouraging.

Astrometry ~30uas aimed at long term Monitoring to detect long period planets

The goal of 6 telescope array is to image dust disks during star/planetary system formation.



Keck – Keck Interferometry

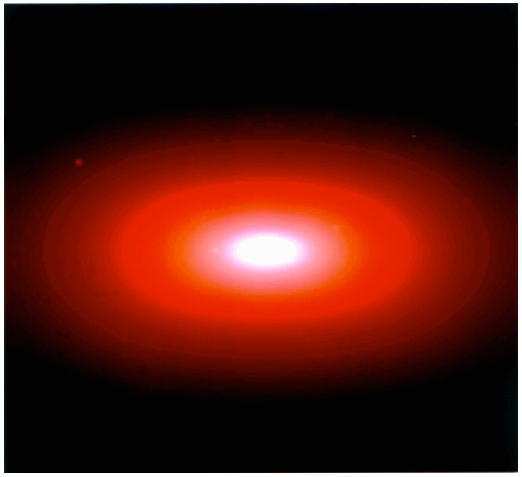


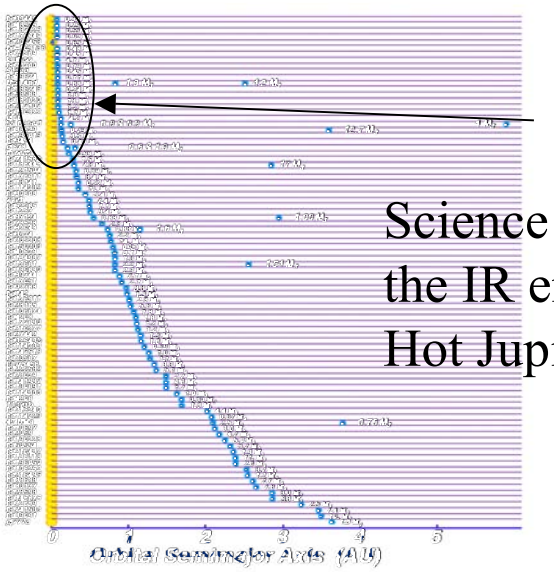
V^2 Interferometry measured the size of the near IR emission from the accretion disk

Status: Operational
Available to the NASA/CARA community

10um Nuller, to measure the exo-zodi dust level at the 10~30 zodi level

Status: At Mauna Kea, Debugging phase.
ORR scheduled for Jan 06





Science goal is to detect the IR emission from Hot Jupiters.

NRC endorses SIM PlanetQuest

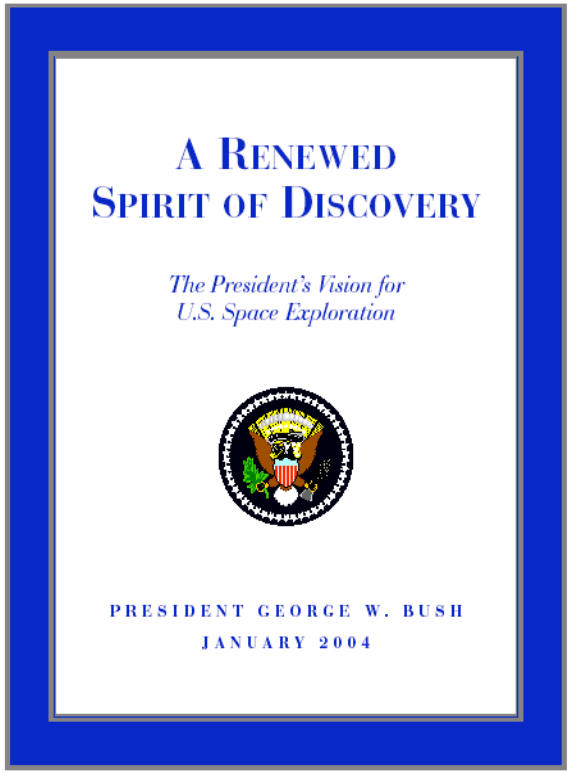
- CAA reaffirms scientific importance of SIM (2002)
  - *"The CAA reaffirms the scientific excitement of the 2001 AASC for the important new planet-finding narrow-angle science capability of SIM."*
- Decadal (McKee & Taylor) Review (2001)
  - *"...reaffirms the 1991 NRC Committee by endorsing the completion of AIM"*
  - *"... enable the discovery of planets much more similar to Earth in mass and orbit than those detectable now"*
  - *"...survey the Milky Way 1000 times more accurately than is possible now"*
- Decadal (Bahcall) Review endorses AIM [now SIM PlanetQuest] (1991)
  - *"... would permit definitive searches for planets around nearby stars"*
  - *"... trigonometric distances throughout the galaxy"*
  - *"... would demonstrate the technology required for future missions"*

2001 NRC Decadal Review

NRC Recommendations for TPF

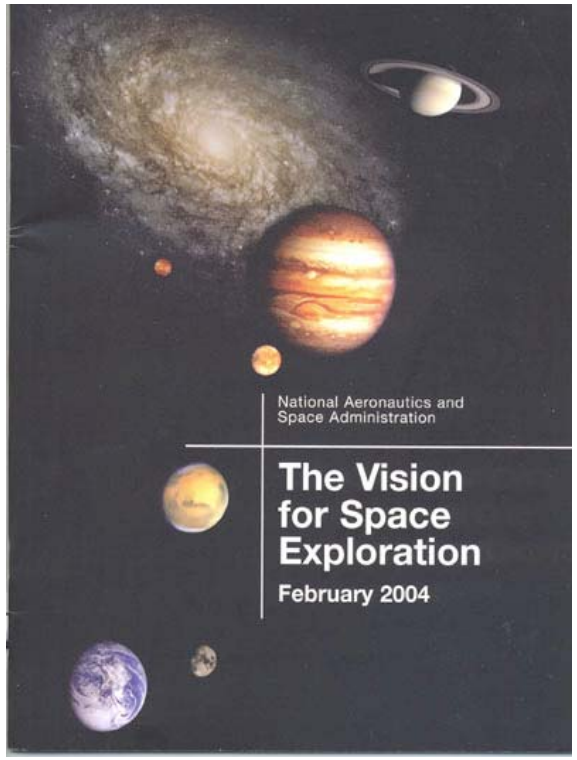
- Decadal Review endorses TPF (2000)
  - "…Search for life beyond the Earth, and if it is found, determine its nature and distribution in the Galaxy. This goal is so challenging and of such importance that it could occupy astronomers for the foreseeable future."
- CAA endorses TPF's multi-wavelength approach (2004)
  - "Furthermore, the identification of biomarkers (i.e., spectroscopic features indicative of chemical balances attributable to biogenic activity) requires observations in spectra that span not only the optical but also the mid-infrared (IR) bands"
  - "What can be learned from the combination of TPF-C and TPF-I data is... far greater than what either mission alone would yield".

Programmatic basis for SIM and TPF



A Renewed Spirit of Discovery

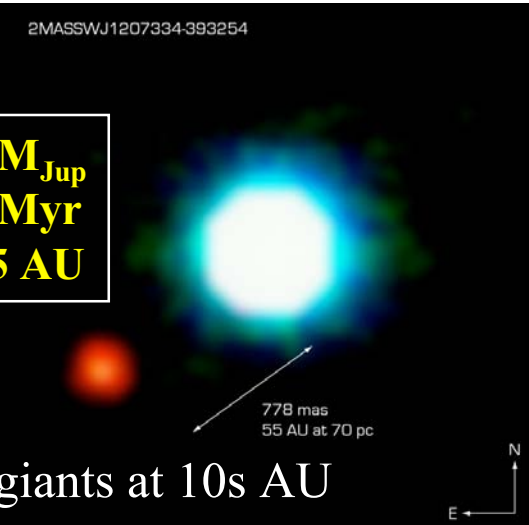
"Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars"



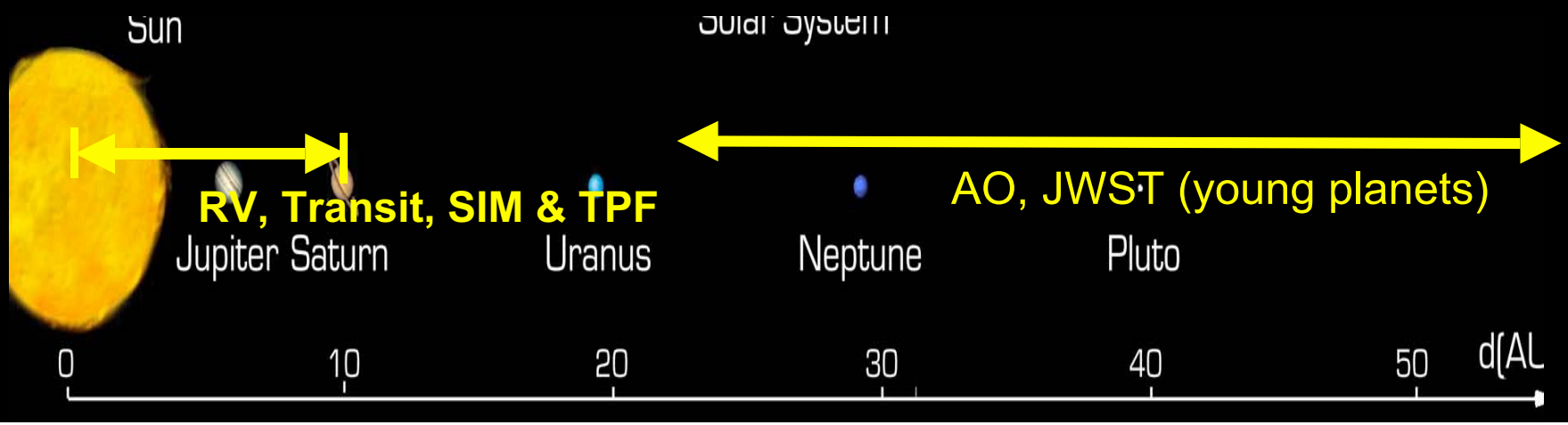
Vision for Space Exploration

"The Terrestrial Planet Finder will be capable of finding Earth-like planets and detecting the chemicals in their atmospheres"

Detecting Planets: Big and Small, Near and Far

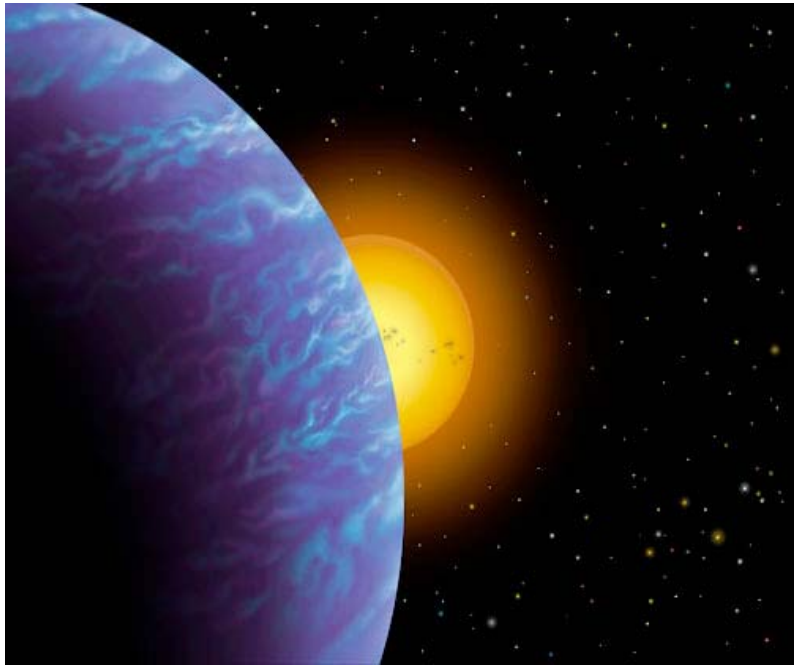


- Distant planets around YOUNG stars
  - ESO/VLT and other AO systems beginning to detect gas giants at 10s AU
    - NICMOS confirmation of common proper motion (Schneider et al)
  - At 5 μm NIRCAM on JWST will be powerful tool for finding distant young planets (3λ/D=0.6"@4.6 μm =30~100 AU at 50-150 pc)
- Large and small planets in inner solar system
  - Indirect detection by RV, astrometry (SIM) around nearby stars
  - Transit (ground, COROT/Kepler) and micro-lensing detection for distant stars
  - Direct detection by Keck-I/LBT-I, TPF-C/I



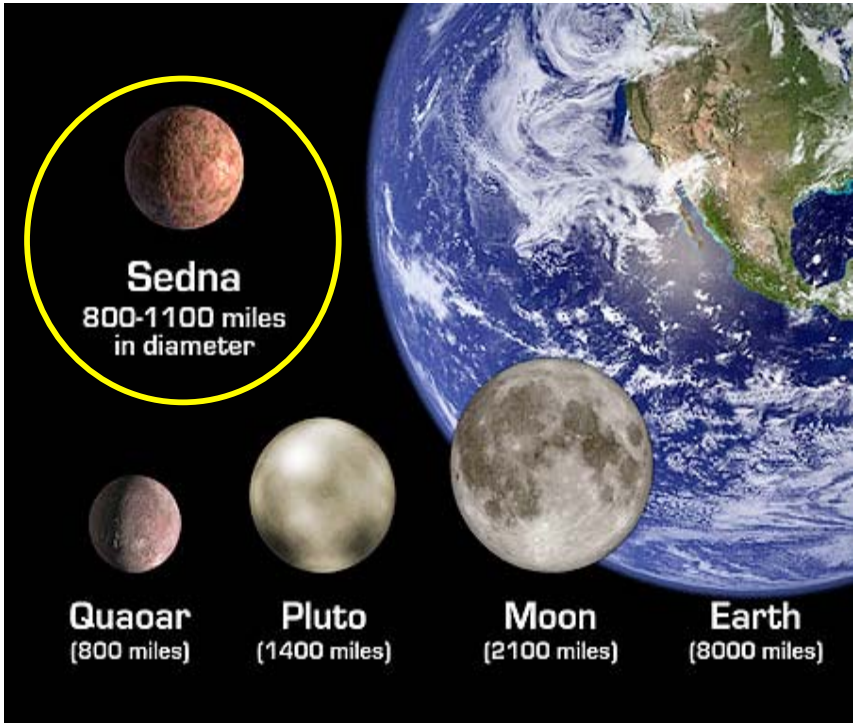
Planet Finding with SIM & TPF

- Determine the architecture of planetary systems, e.g. number of planets, masses and orbits
- Detect terrestrial planets in the habitable zones around nearby stars
- Characterize planetary atmospheres to search for signatures of life
- Detect and characterize all the constituents of other planetary systems to understand context of habitable planets



What Will We Learn About Other Earths?

- Orbital Parameters (SIM)
  - Stable orbit in habitable zone
- Characteristics for habitability
  - Mass (SIM)
  - Temperature (TPF)
  - Temperature Variability (SIM)
  - Radius (TPF)
  - Albedo (TPF)
  - Surface gravity (SIM+TPF)
  - Composition (TPF)
  - Atmospheric conditions (TPF)
  - Presence of water (TPF)
  - Temporal variability (TPF)
- Solar System Characteristics
  - Influence of other planets (SIM)
  - Presence of comets or asteroids (TPF)



- Indicators of Life (TPF)
  - Multiple spectral lines in different wavebands confirm initial detections and extend physical interpretation
  - For planets with atmospheres (and modest cloud cover), IR characterizes atmosphere while visible sees planetary surface

Searching for Terrestrial Planets with SIM

What We Don't Know

- Are planetary systems like our own common?
- What is the distribution of planetary masses?
  - Only astrometry measures planet masses unambiguously
- Are there low-mass planets in 'habitable zone' ?

A Deep Search for Earths

- Are there Earth-like (rocky) planets orbiting the nearest stars?
- Focus on ~250 stars like the Sun (F, G, K) within 10 pc
- Detection limit of ~3 M_e at 10 pc
- Sensitivity limit of ~1.5 M_e at 5 pc

A Broad Survey for Planets

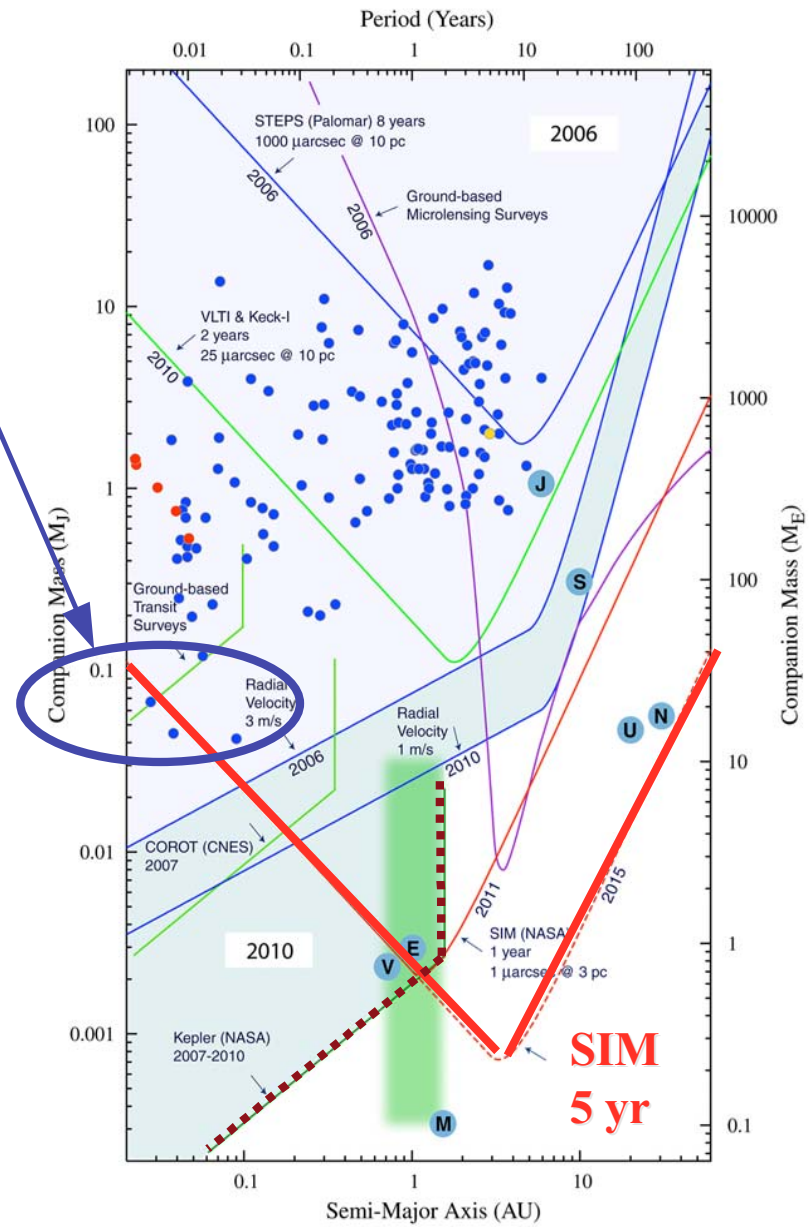
- Is our solar system unusual?
- What is the range of planetary system architectures?
- Sample 2,000 stars within ~25 pc with sensitivity <<Jupiter mass

Evolution of Planets

- How do systems evolve?
- Is the evolution conducive to the formation of Earth-like planets in stable orbits?
- Do multiple Jupiters form and only a few (or none) survive?

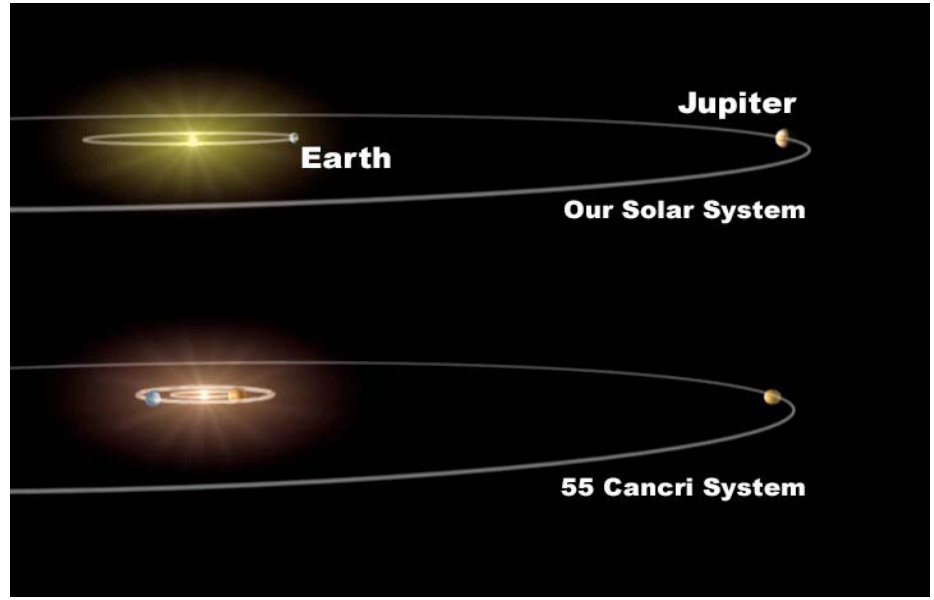
Are Terrestrial Planets Common?

- Radial velocities have found over 130 planets around nearby stars (<100 pc)
  - Three new Neptune-mass planets (15 Earth-Mass!) reported in orbits inside Mercury's
- Kepler will use transits to determine incidence of Earth like planets (around distant stars)
- SIM will determine architecture of planetary systems and identify ~3 M_{Earth} planets around nearby stars out to 10 pc
- SIM will extend the search to Earth-mass planets, with a survey of 250 nearby stars
- Complete 5-year survey will include planets in 10-20 year orbits
- First detections of terrestrial planets could occur within the first year or so

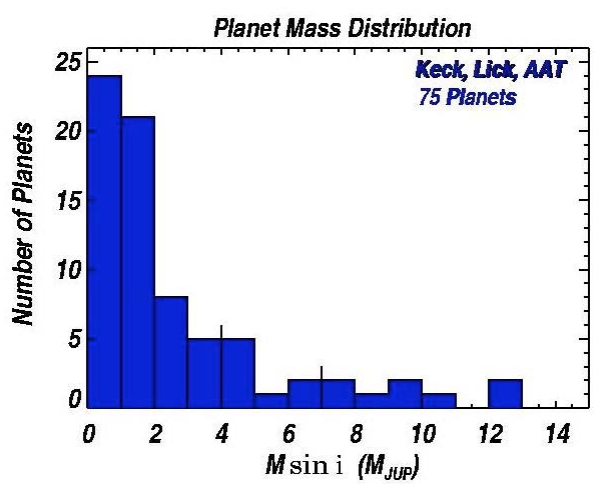


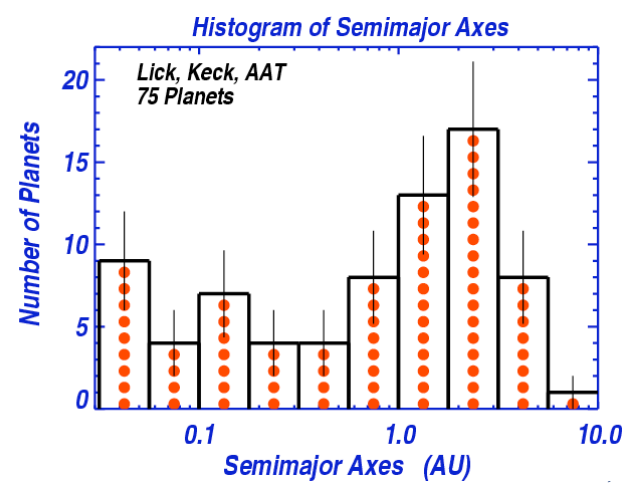
Broad Survey of Planetary Systems

- Out of ~130 planetary systems discovered to-date, only one resembles our Solar System, so:
  - Is our solar system typical or unusual?
  - Are planets more common around sun-like stars?
  - What are the 'architectures' of other planetary systems? → coplanar?
- **SIM will survey ~2,000 stars within ~~100 pc with sensitivity ~Neptune mass**



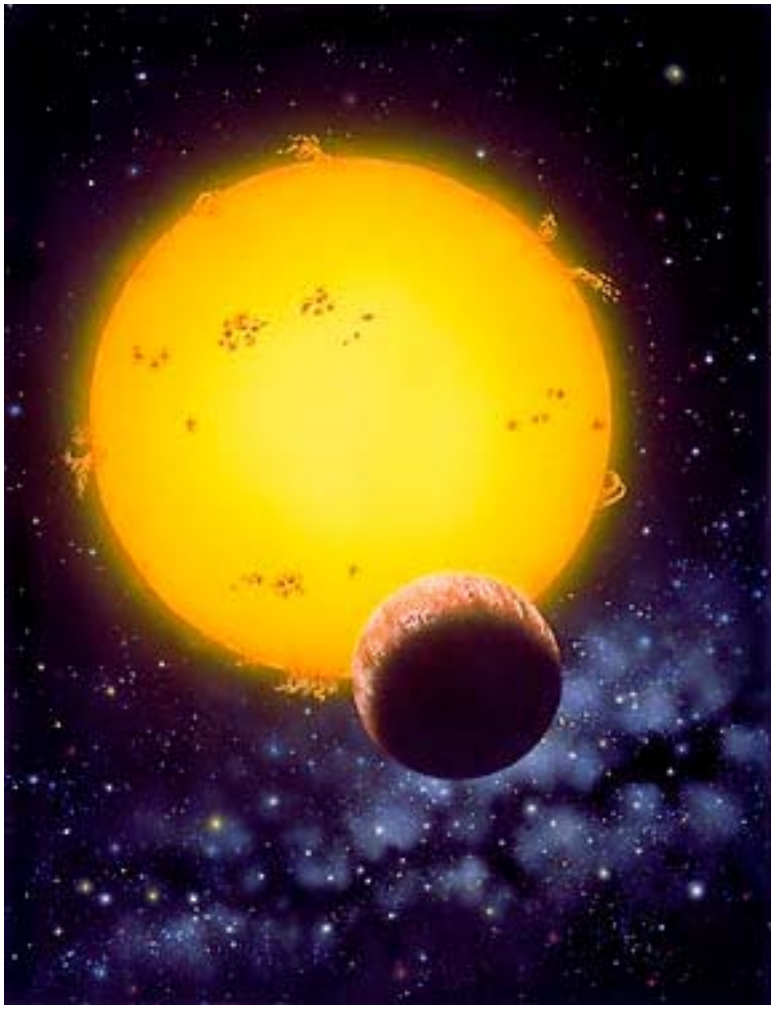
55 Cancri: a planetary system like our own?





Planets around Young Stars

- What fraction of young stars have gas-giant planets?
- Do gas-giant planets form at the "water-condensation" line?
  - Survey ~200 stars to a level adequate to find Jovian or smaller planets on orbits <1 AU to >5 AU around stars from 25-150 pc
  - *Only SIM can do this*: active stellar atmospheres and rapid rotation preclude RV or transit searches
- Does the incidence, distribution, and orbital parameters of planets change with age and protostellar disk mass?
  - Study of clusters with ages spanning 1-100 Myr
  - Combine with Spitzer data
- Understand the formation and orbital migration mechanisms of the giant planets
  - Do multiple Jupiters form and only a few (or none) survive?



A Tightly Integrated Program: Kepler→ SIM→TPF-C→TPF-I

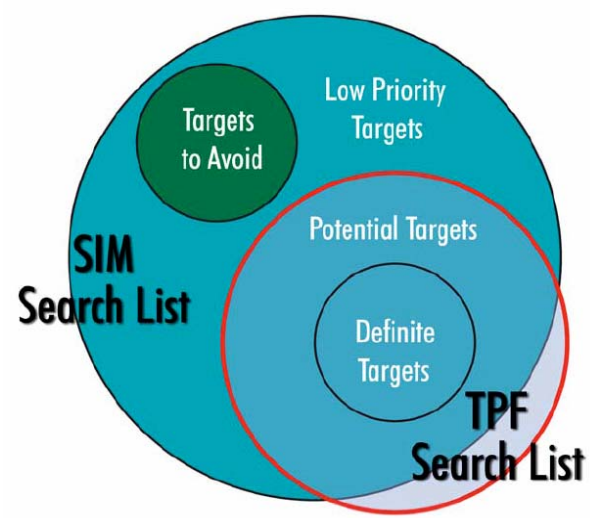
- Kepler will detect ~1 Earth radius planets in 1 AU orbits around *distant* stars to determine $\eta_{\oplus}$
- SIM will detect first Earth-mass objects around nearby stars
  - Determine planetary orbits and masses, critical parameters for determining habitability
  - Optimize target selection for TPF
- TPF-Coronagraph will make first direct detections of light from terrestrial planets and begin remote sensing characterization and search for signposts of life
- TPF-Interferometer will extend survey to more distant stars, complete physical characterization of planets, including habitability, and ensure robust detection capability for life

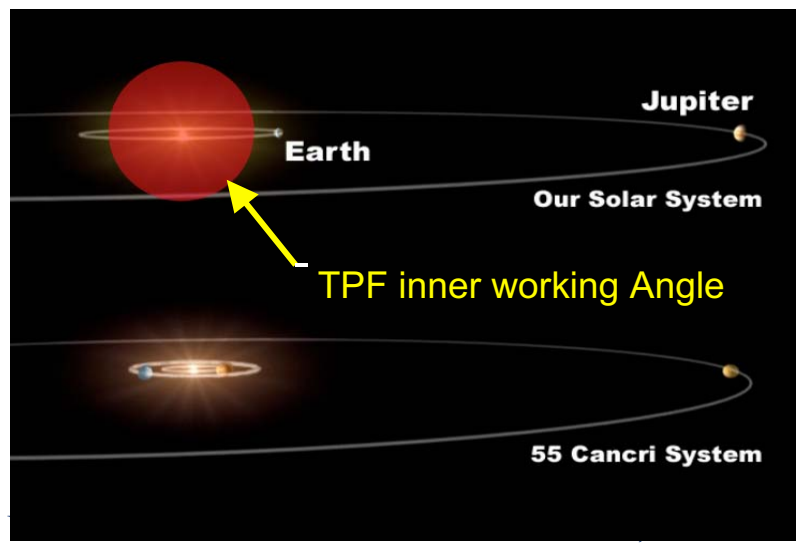
SIM, TPF-C, and TPF-I Science: Complementary & Synergistic

- SIM
  - Measures mass - *the primary property of a planet* - determining surface gravity and potential for long-lived atmosphere
  - Determines orbit radius, eccentricity, inclination affecting planet's temperature and variability → long term stability
- TPF-C
  - Measures brightness, crude orbital information, day/night phase variations
  - Measures habitability- and bio- signatures such as H_2O, O_2, O_3
- TPF-C + SIM
  - SIM's mass estimate of the planet can be used to determine surface gravity and key atmospheric properties (scale height and lifetime) and ties TPF observations (chemistry) to a physical atmospheric model
  - Orbital elements from SIM helps assess orbital stability and long-term habitability
- TPF-C + TPF-I + SIM
  - Complete physical characterization of planet (incl. temperature, radius, albedo, mass, density)
  - Robust determination of atmospheric properties (habitability), and signatures of life

SIM and TPF Combination Enables Efficient Planet Search

- SIM searches ~250 closest stars for terrestrial planets
  - $3M_{Earth}$ at 10 pc, 5 yrs (5σ), prior to TPF-C
  - $1.5M_{Earth}$ at 10 pc, 10 yr (5σ), prior to TPF-I
- Combine TPF detections to find new planets (and masses) in SIM data
- SIM identifies best targets for TPF to maximize science return
  - *Definite targets*: stars with terrestrial-mass planets in Habitable Zone (HZ)
  - *Potential targets*: stars with low SNR sign of a planet in HZ
  - *Low priority targets*: stars with no hint of terrestrial-mass planets
  - *Avoid targets*: stars with a giant planet in HZ
  - **Enrich the TPF 'yield' by as much as a factor ~3, if $\eta_{\oplus} \sim 0.1$**
- Schedule TPF observations using SIM orbital information → efficient





SIM Science Team

Key Science Projects

Dr. Geoffrey Marcy	U. California, Berkeley	Planetary Systems
Dr. Michael Shao	NASA/JPL	Extrasolar Planets
Dr. Charles Beichman	NASA/JPL	Young Planetary Systems and Stars
Dr. Andrew Gould	Ohio State University	Astrometric Micro-Lensing
Dr. Edward Shaya	Raytheon ITSS Corp.	Dynamic Observations of Galaxies
Dr. Kenneth Johnston	U.S. Naval Observatory	Reference Frame-Tie Objects
Dr. Brian Chaboyer	Dartmouth College	Population II Distances & Globular Clusters Ages
Dr. Todd Henry	Georgia State University	Stellar Mass-Luminosity Relation
Dr. Steven Majewski	University of Virginia	Measuring the Milky Way
Dr. Ann Wehrle	MSC/Caltech	Active Galactic Nuclei

Mission Scientists

Dr. Guy Worthey	Washington State University	Education & Public Outreach Scientist
Dr. Andreas Quirrenbach	U. California, San Diego	Data Scientist
Dr. Stuart Shaklan	NASA/JPL	Instrument Scientist
Dr. Shrinivas Kulkarni	Caltech	Interdisciplinary Scientist
Dr. Ronald Allen	Space Telescope Science Inst.	Synthesis Imaging Scientist

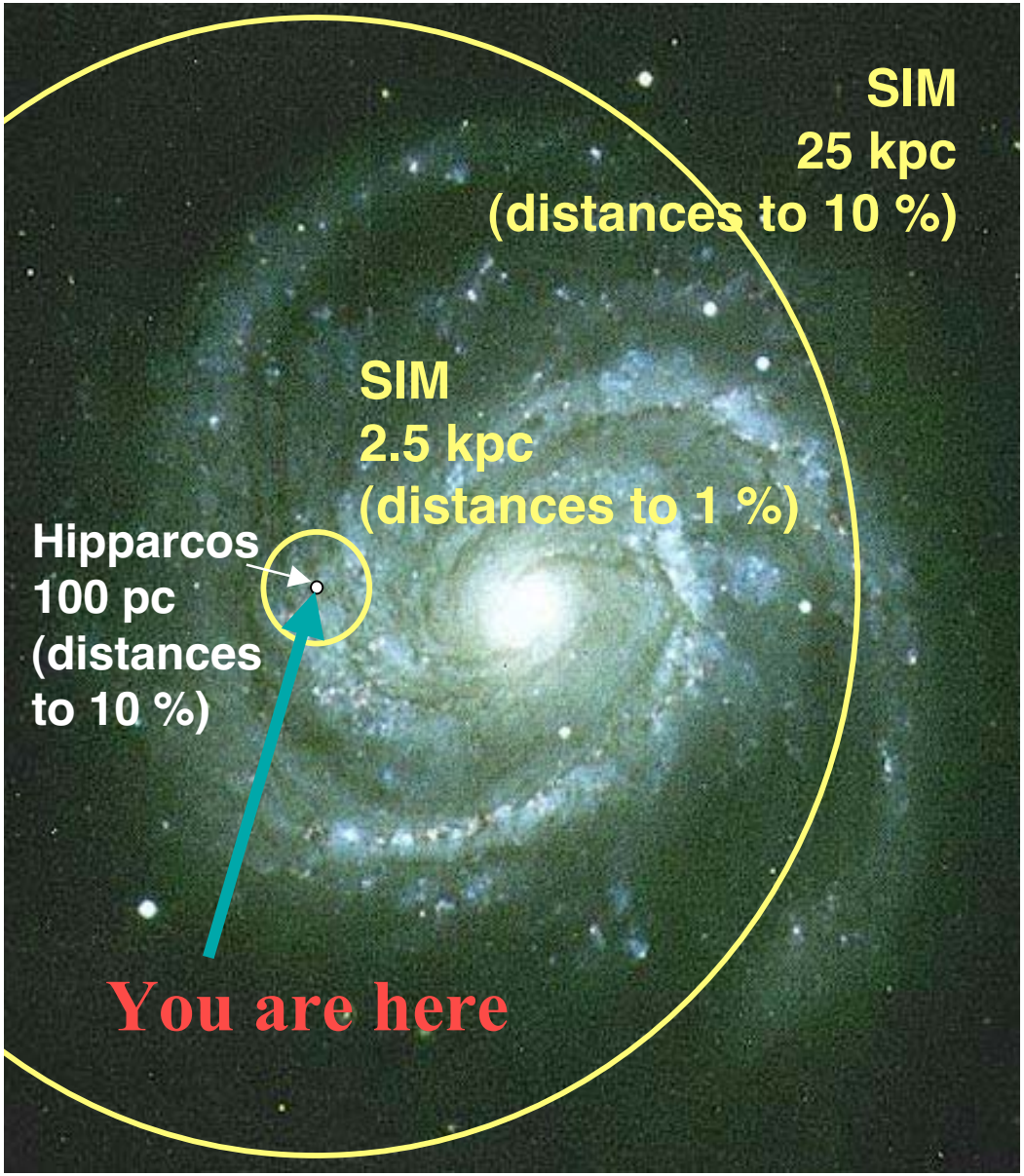
Only Principal Investigators listed. Including co-investigators the SIM Science Team has 86 members.

SIM's Reach Extends Across our Entire Galaxy

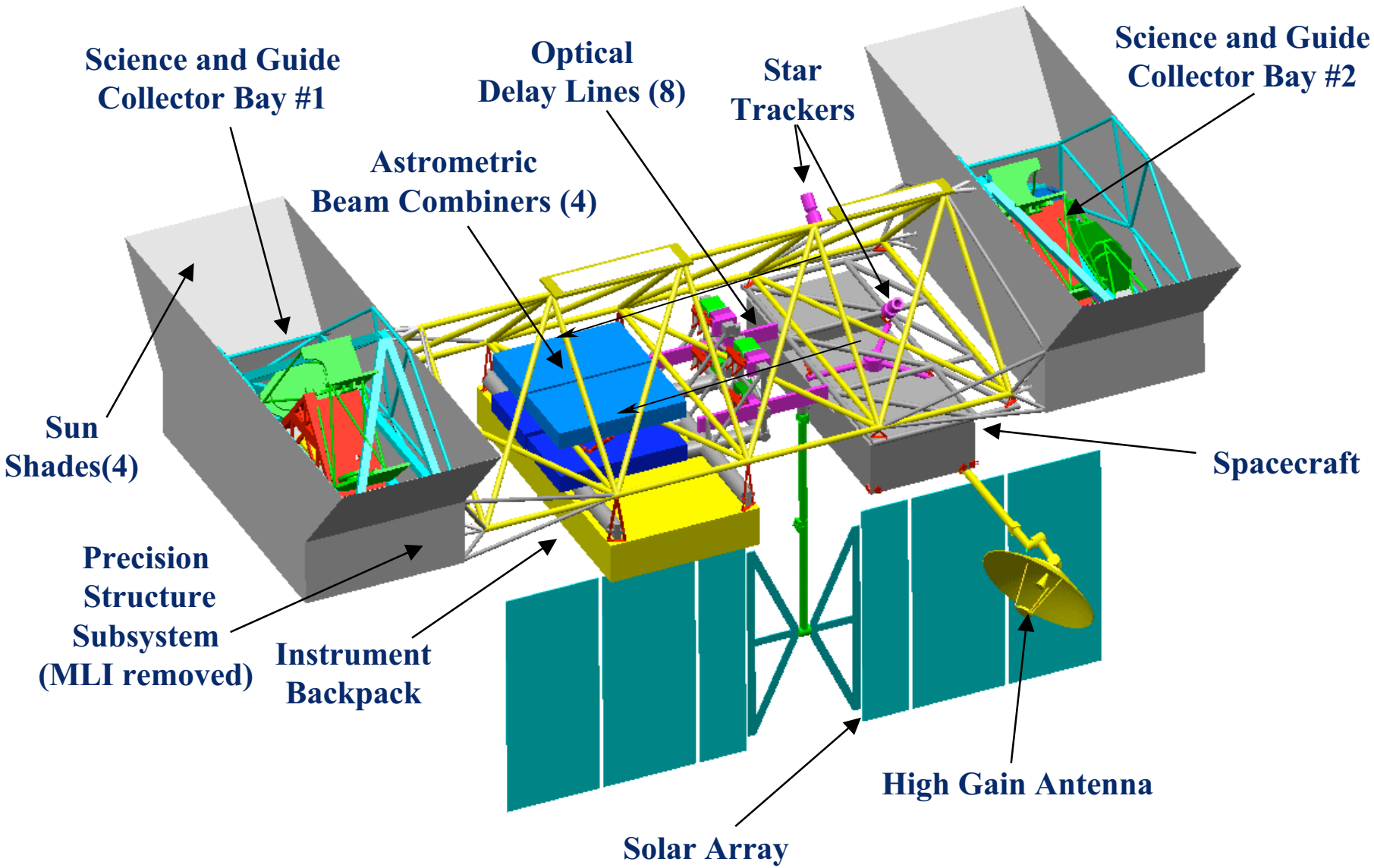
What makes SIM unique:

- Extreme astrometric precision
  - 4 μas (microarcsec) positions
- Ability to observe faint targets
  - V <~ 20
- Flexible scheduling
  - optimize for specific science objectives

- This combination of capabilities lets SIM do *"precision astrophysics"* across our entire Galaxy - and beyond

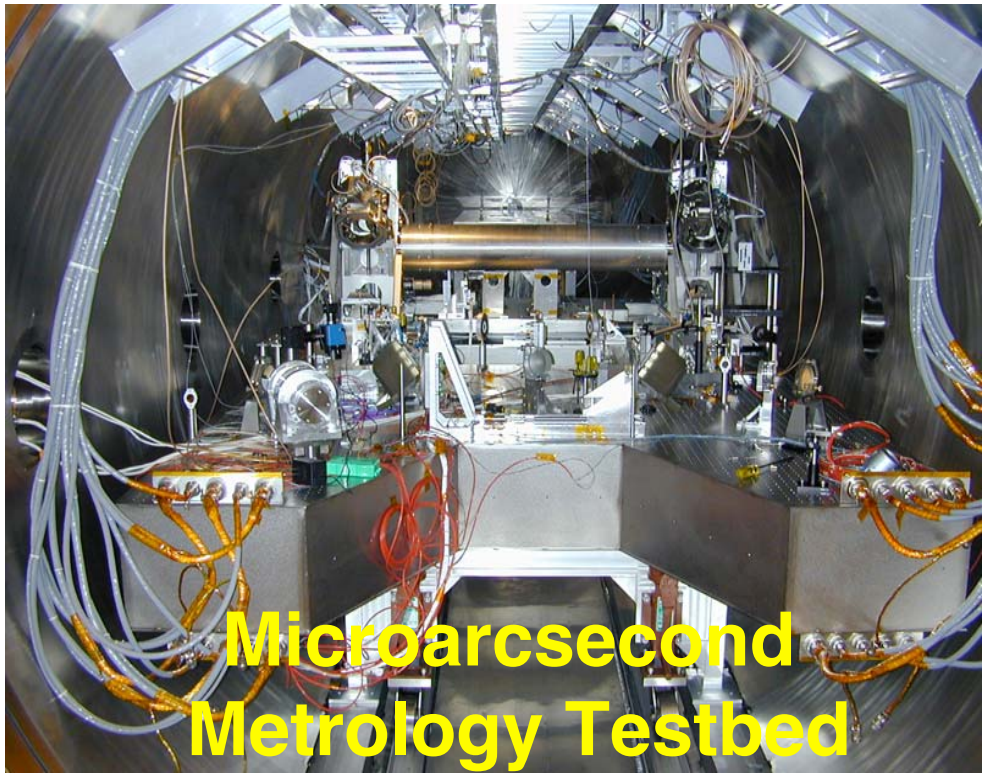


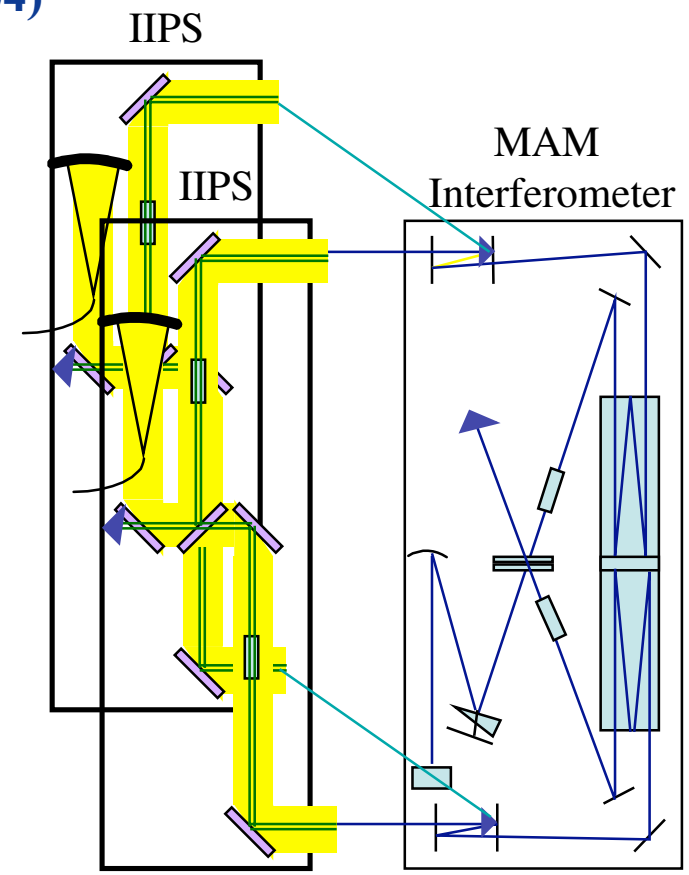
Flight System Architecture



Technology Lab Demos

- The SIM project has met several major milestones to demonstrate *microarcsec astrometric accuracy* in the lab:
  - 3 µas narrow angle demonstration (before starting Phase B, 2003)
  - 10 µas wide angle demonstration
  - **~1 µas narrow angle demonstration (Sep 2003)**
  - **~4 µas wide angle demonstration (May 2004)**

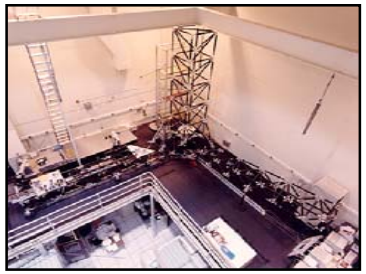




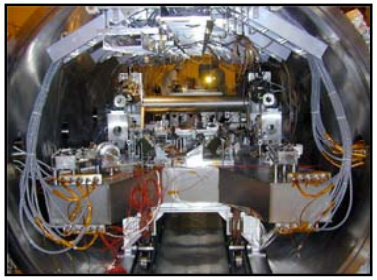
SIM Technology Nearly Complete

- NASA HQ and SIM project laid out 8 Milestones in 2001
  - 4 milestones prior to Phase B start
  - 4 more milestones prior to Phase C/D start
- Technology is on schedule! One milestone remains…

Goal-level performance has already been demonstrated in the SIM Testbeds!



STB-1



MAM

KITE

STB-3

Subsystem-level Testbeds

System-level Testbed

SIM Mission Re-Design Effort

- Project received letter from HQ on Jan 24 requesting re-design of the mission
- Constraints on the re-design:
  - $1.0 – 1.2B (FY05 $) Phase C/D cost, 30% reserve, LV included
  - Level 1 Requirements are open to re-negotiation
  - *Must* support President's vision for space exploration via planet finding, plus benefit to TPF
- Project received FY05 cut of $15.1M
  - Impact on current team (JPL and NGST) is in work
- Project is in the process of prioritizing work to determine what tasks continue and what activities ramp down based on the following criteria:
  - Technology Gate #8 completion
  - Mission re-design activities
- Project requested to return to HQ in July 2005 with re-designed mission for presentation and evaluation
  - Following successful HQ review, CAA evaluation will be requested

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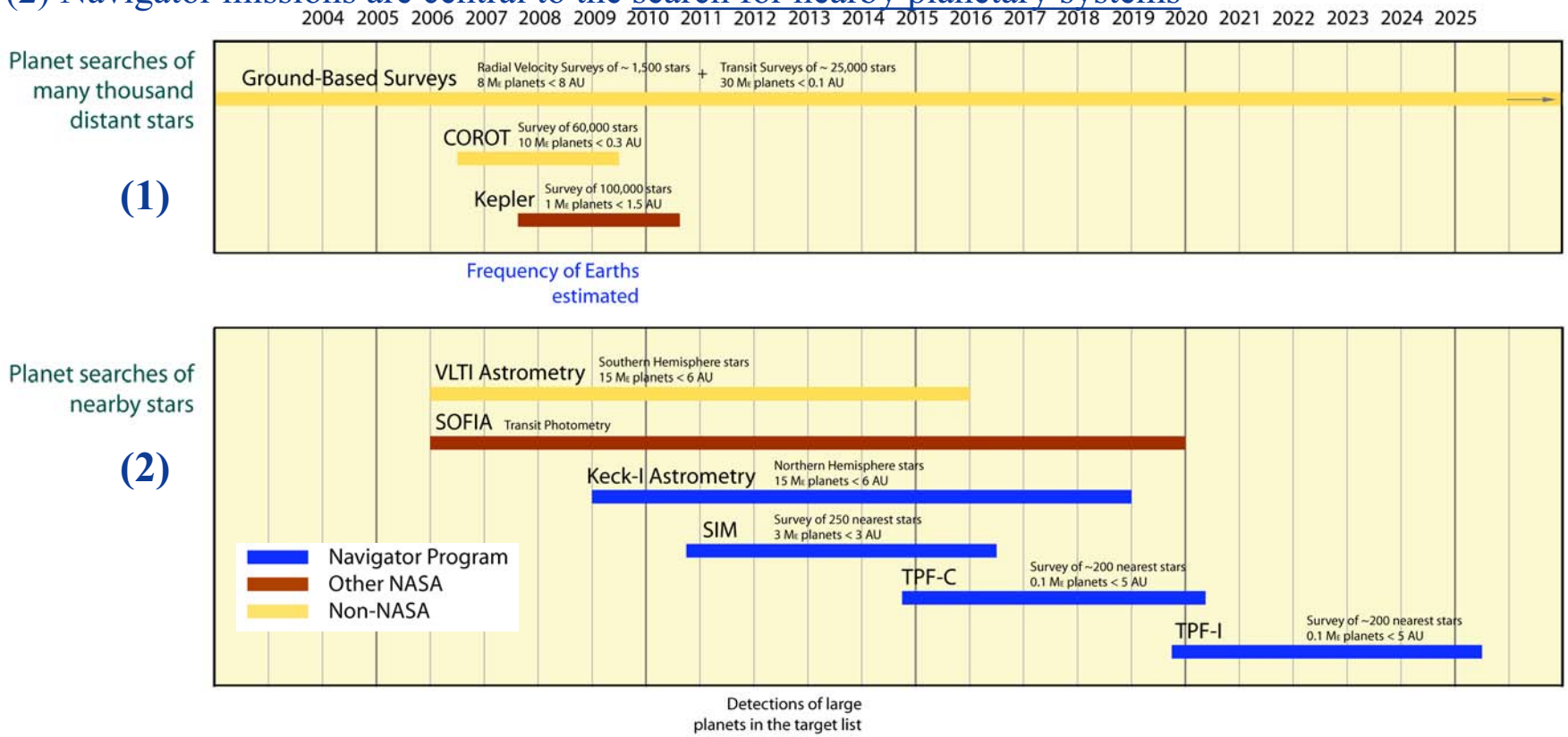
Comparative Planetology: Putting Extrasolar Planets into a broader context (1)

- NASA through the Navigator program and through R&A activities like the TPF Foundation Science and the Michelson Fellowships are building a scientific community and preparing the scientific foundation for SIM and TPF
- Navigator missions make major contributions in 3 out of 4 major areas
  - (1) Surveys of large number of stars are important to Navigator goals:
    - Provide fundamental knowledge of the statistics of planetary systems
    - Inform the design and scope of Navigator missions
  - (2) Navigator missions are central to the search for nearby planetary systems

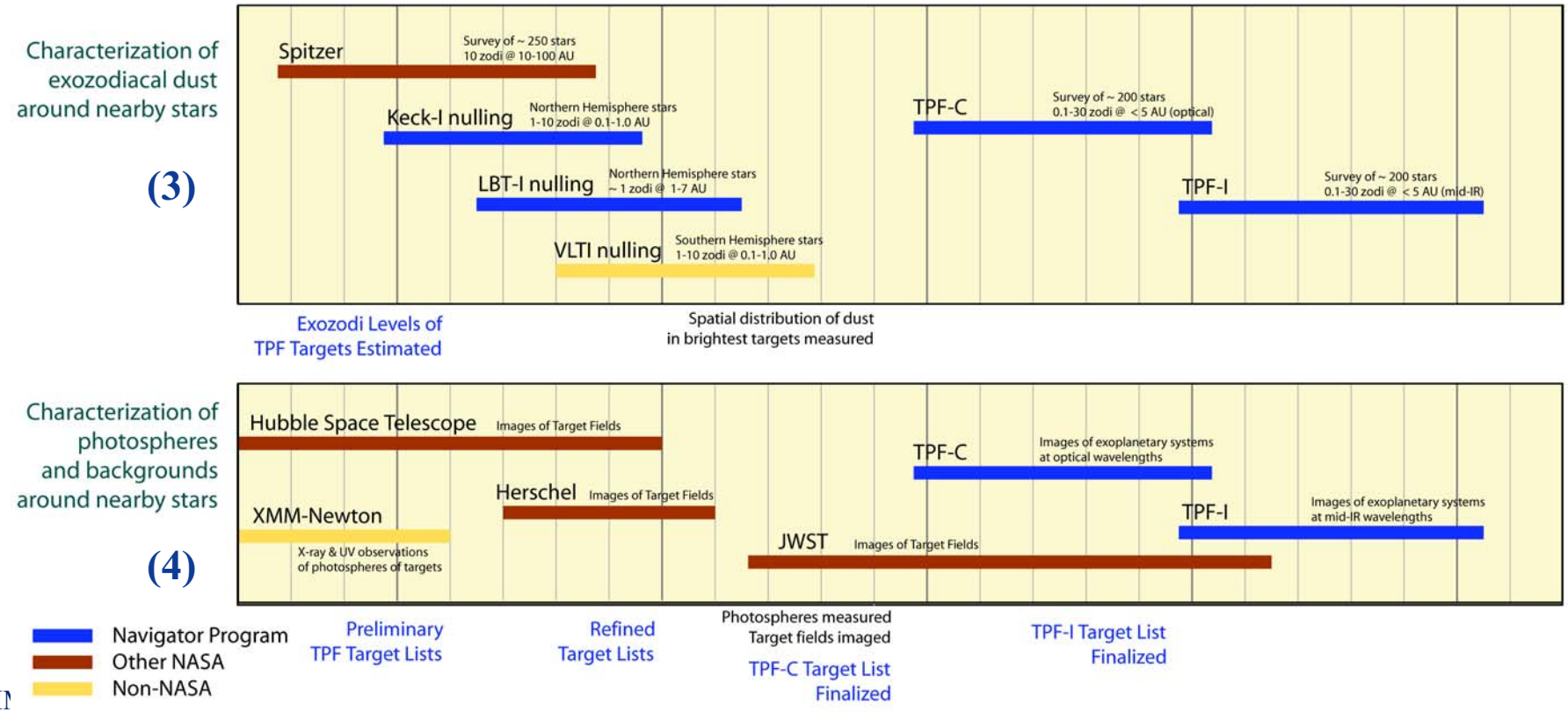


Comparative Planetology: Putting Extrasolar Planets into a broader context (2)

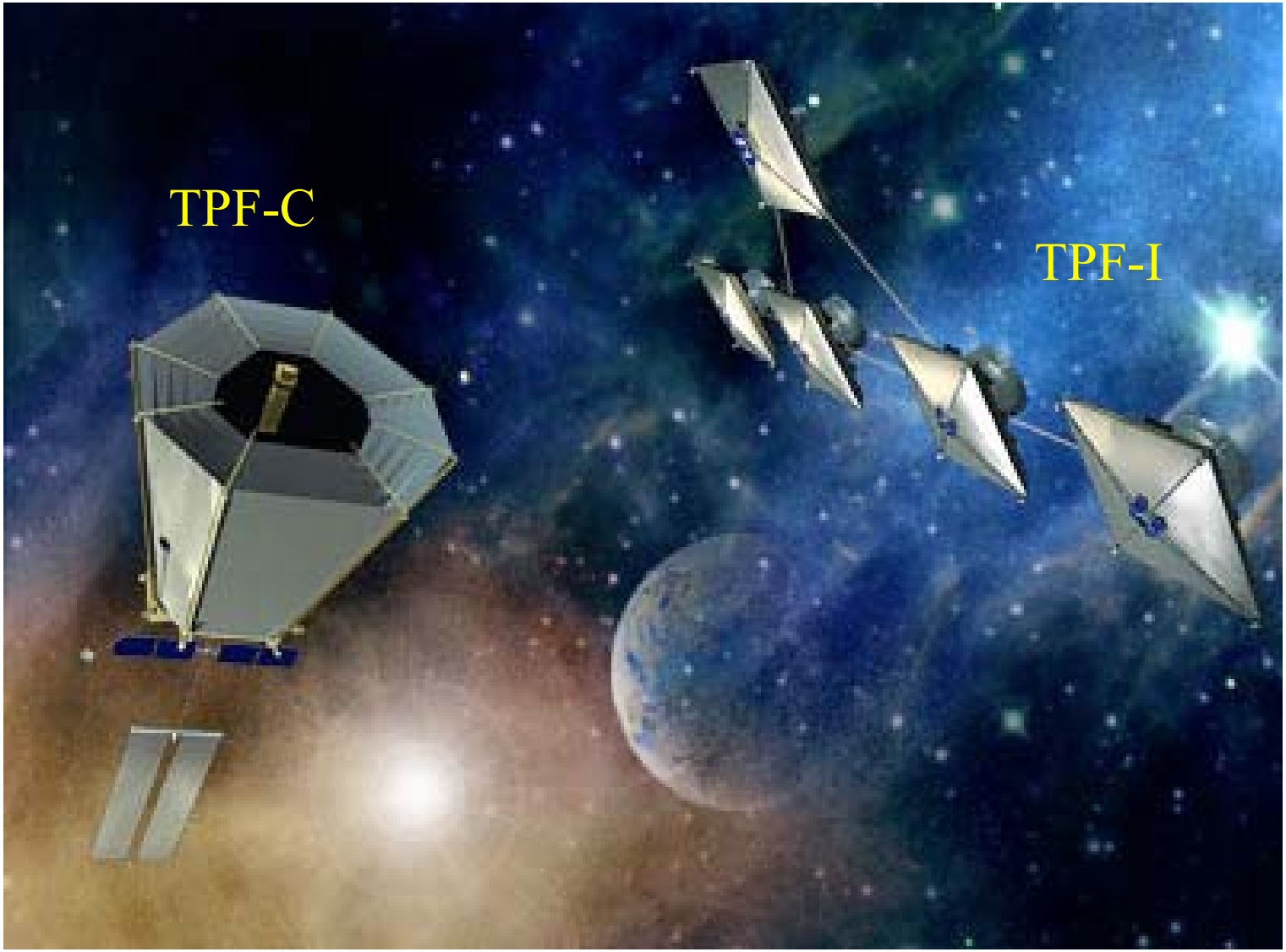
(3) Characterizing Exozodiacal dust is important to understanding the formation of planetary systems

- Exozodiacal dust hinders the detection of planets, so estimating its prevalence is important to the search missions

(4) Understanding the planet host stars provides fuller understanding of the formation and evolution of planetary systems



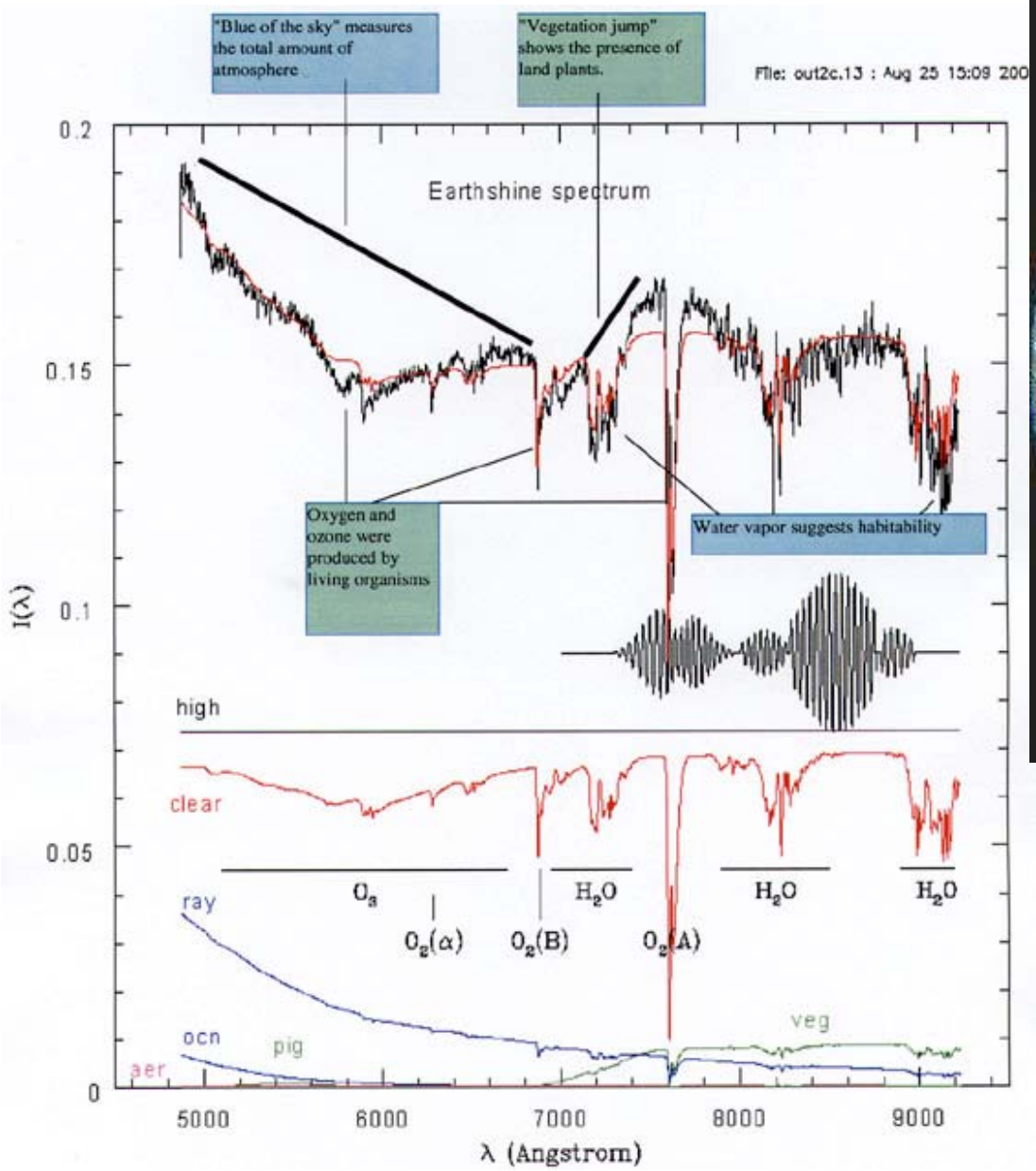
Terrestrial Planet Finder Missions

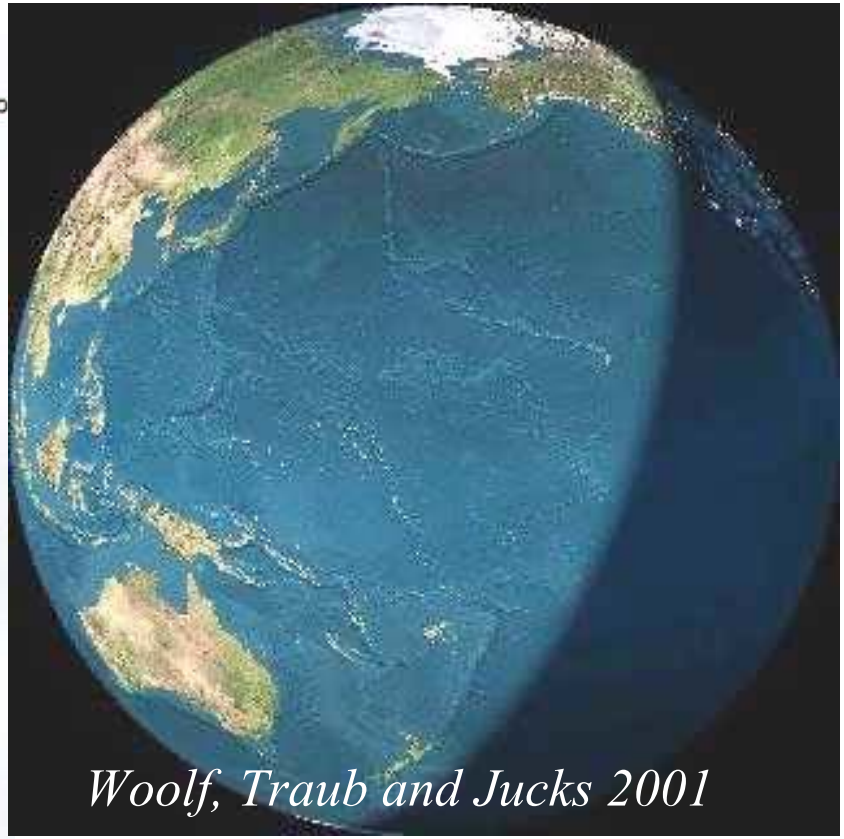


TPF-C science objectives

- Directly detecting Earth-like planets in the *habitable zones* (r = 0.7-1.5 AU) of nearby (distance ~< 20 pc) FGK stars
  - ~35 stars to 90% completeness
  - Another ~120 stars to lower completeness
- Measuring Earth-like planet frequency, physical & orbital characteristics
  - Combine TPF and SIM data to fully utilize lower-confidence SIM detections → more planet masses
- Spectrally characterizing their atmospheres for biomarkers
  - (O_2, H_2O, CO_2, …)

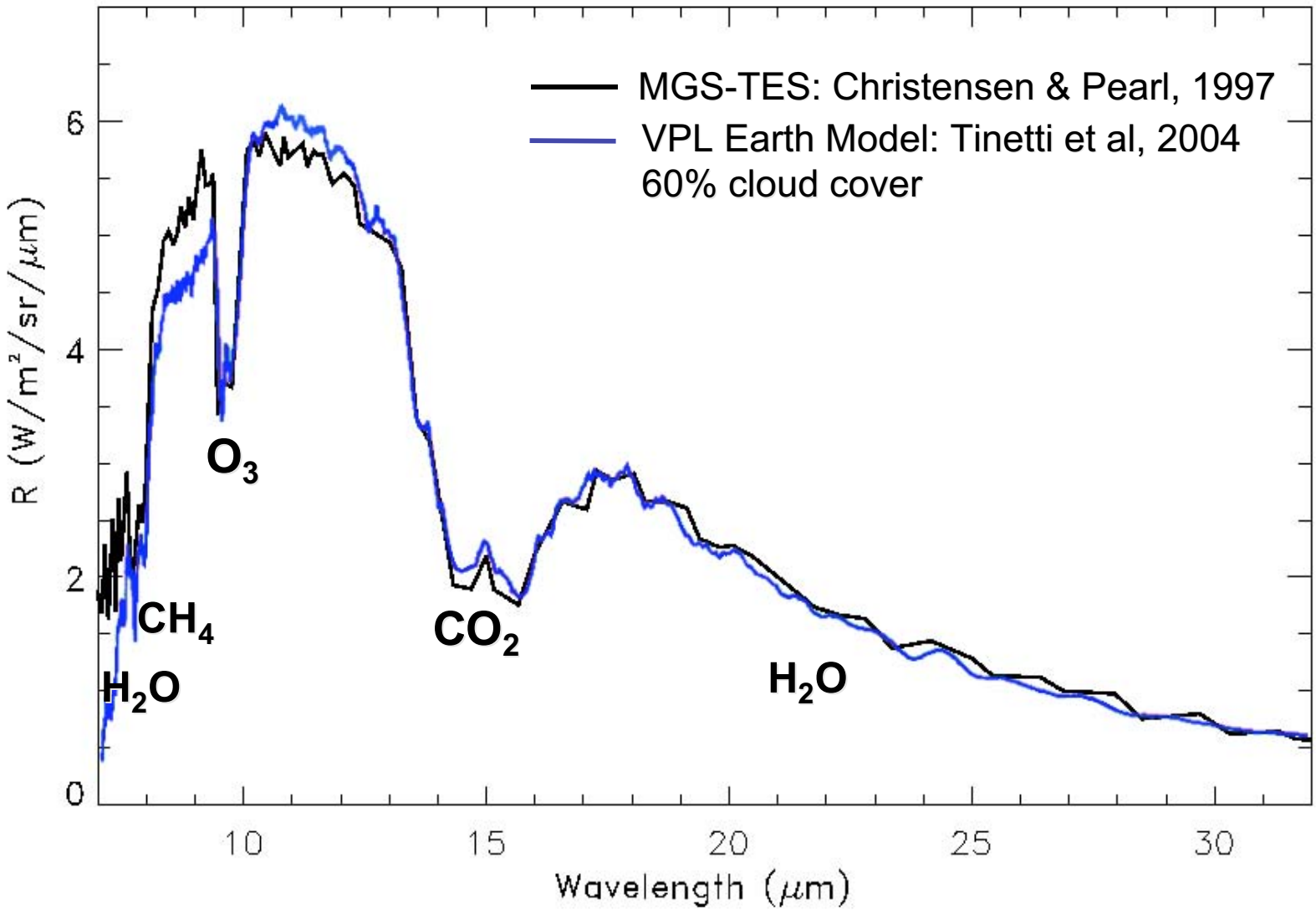
Earthshine: Example of the Visible Spectrum TPF-C aims to observe





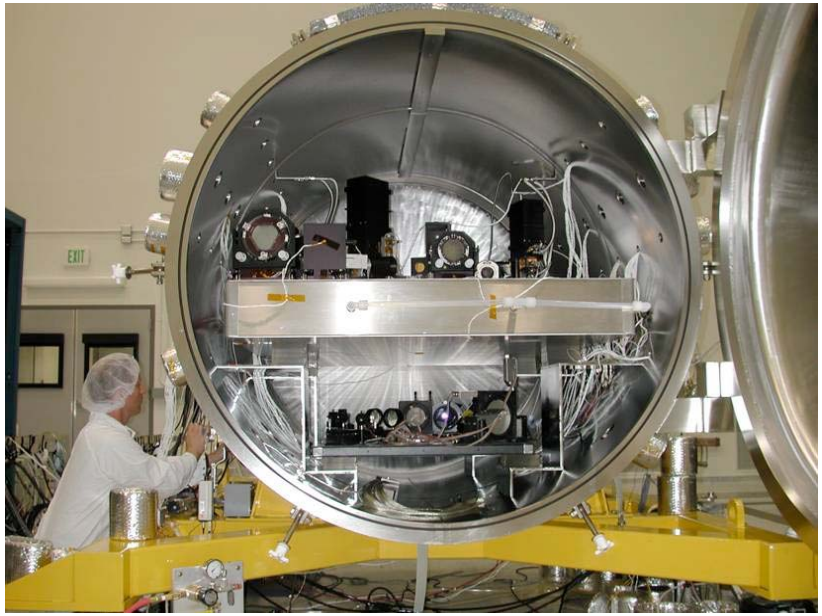
- Oxygen A-band and water are excellent bio-markers
- CO_2 at 1 μm drives long wavelength performance
- Resolution of 75 is adequate
- Surface features, e.g. chlorophyll

Biosignatures in the Earth's MIR Spectra

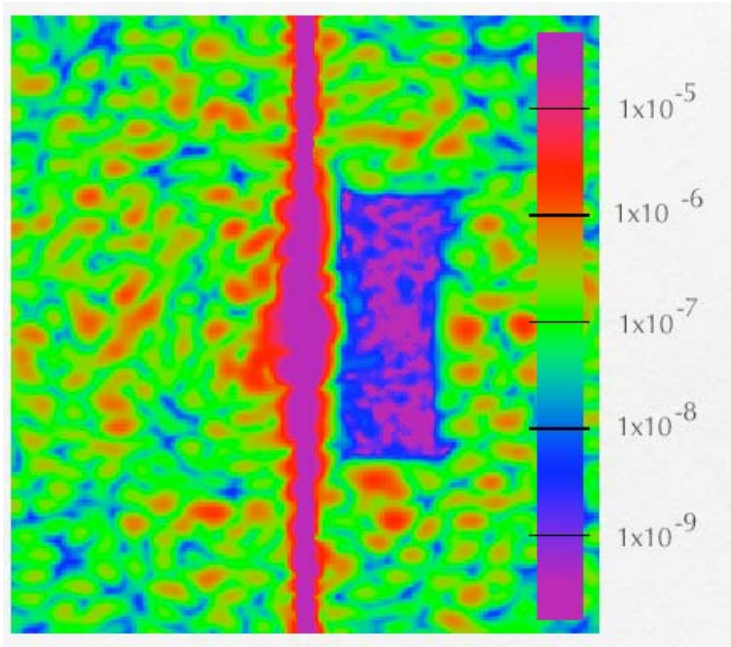


The MIR is sensitive to atmospheric trace gases which could indicate habitability or life.

Laboratory Coronagraph now blocking starlight by a billion:1



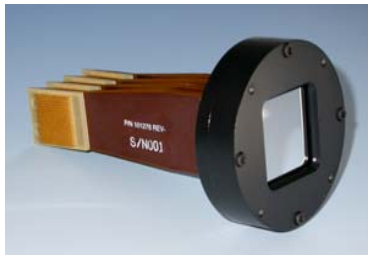
High Contrast Imaging Testbed Facility



Linear sinc^2 occultor

High Actuator Density Deformable Mirrors

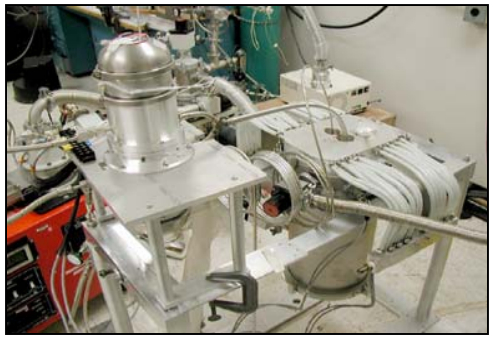
1024



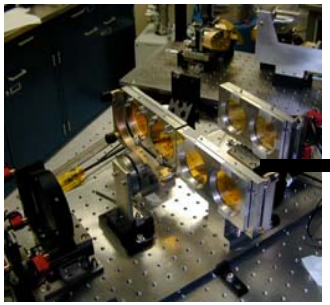
4096

- Average contrast = 1×10^{-9}
  - 4th Airy ring, 800nm
- Minimum contrast = 3×10^{-10}
- Stability 5×10^{-11}/hr
- TPF contrast requirement 10^{-10}

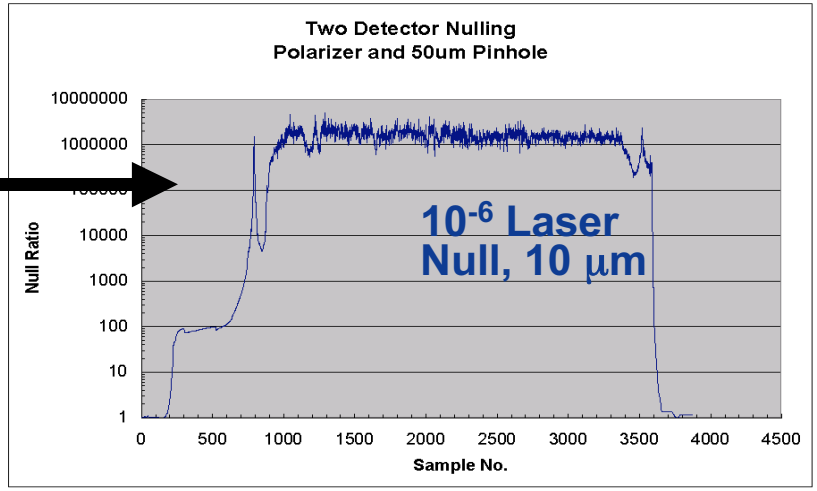
TPF Interferometer Technology Progress



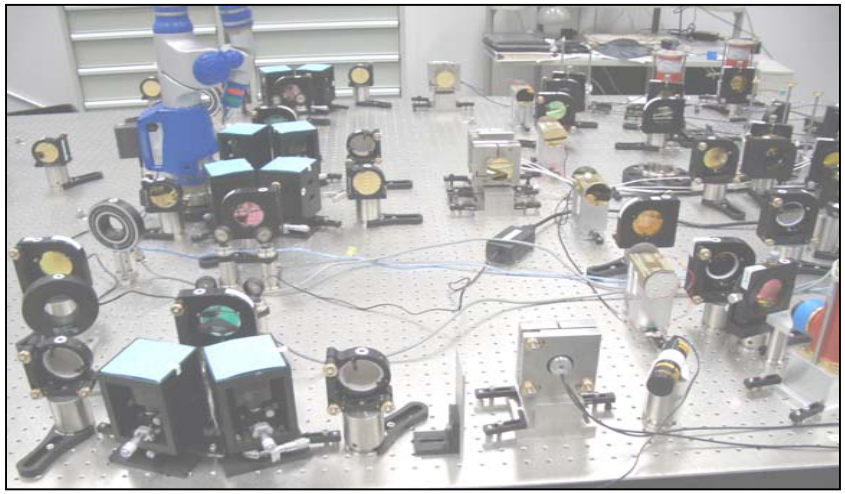
Advanced cryocooler for sub-10k nulling



2-beam nuller



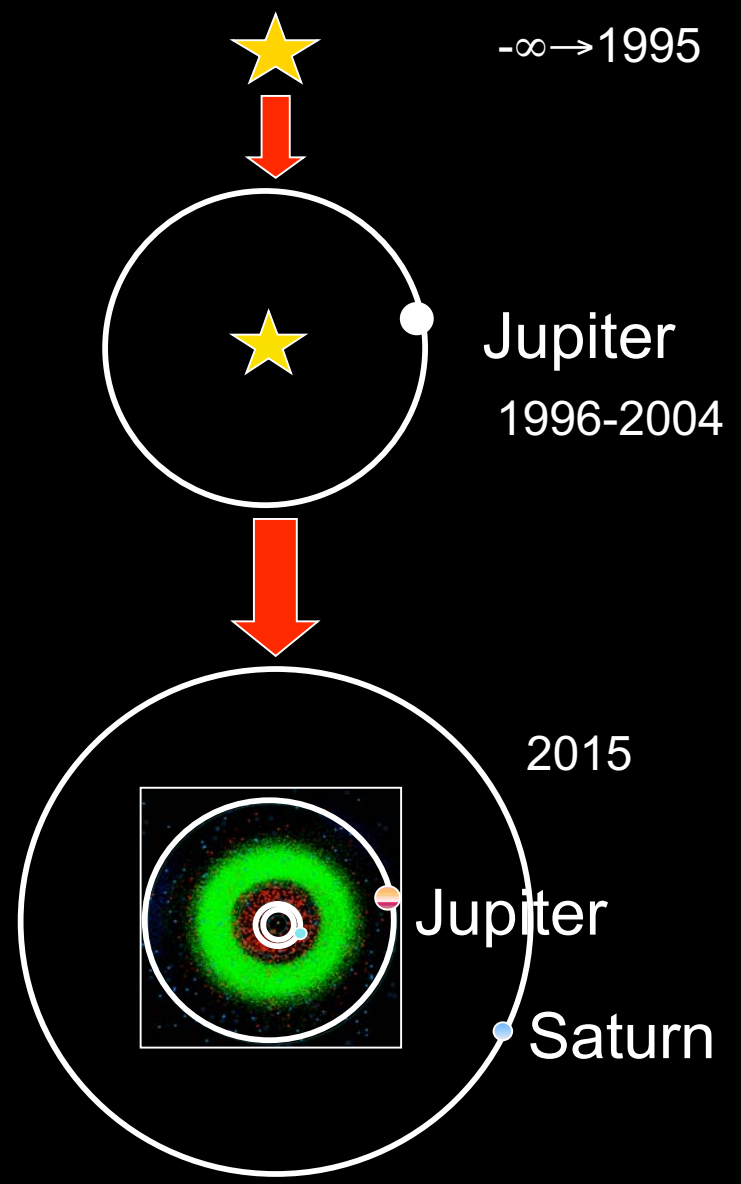
Formation control testbed



4-beam nuller

Interactions with ESA/Darwin

- Darwin Science Goals: *Find Earth-like planets around nearby Solar type stars and characterize them, with regard to their ability to host "life as we know it"*
- Strong support for exo-planetary research in ESA's Cosmic Vision Program
  - ESA currently studying the Darwin mission, a formation flying, nulling infrared interferometer
- Darwin aiming towards launch in 2015
  - ESA-only or ESA-led mission
  - Interaction with NASA under discussion
- Current NASA-ESA Interactions
  - Letter of Agreement in place
  - Joint annual TPF/Darwin science meetings
  - Representation on Science Teams (TPF-I SWG and ESA TE-SAT)

What Will We Know In 20 Years: After Kepler, SIM, JWST, TPF-C, TPF-I?

- Where are the habitable or inhabited planets in the solar neighborhood
- In which solar systems and under what conditions, if any, do habitable or inhabited planets reside
- What are the inter-relationships between all constituents of planetary systems
  - Properties of Terrestrial Planets
  - Properties of Gas Giants 1~100 AU
  - Properties of zodiacal clouds (comets, asteroids)
- We will have used a full range of precursor science activities and the suite of space missions that constitute the "Origins program"