Space-Based Detection of Extrasolar Planets

Stephen Unwin

Jet Propulsion Laboratory

California Institute of Technology

NASA's Navigator Program:

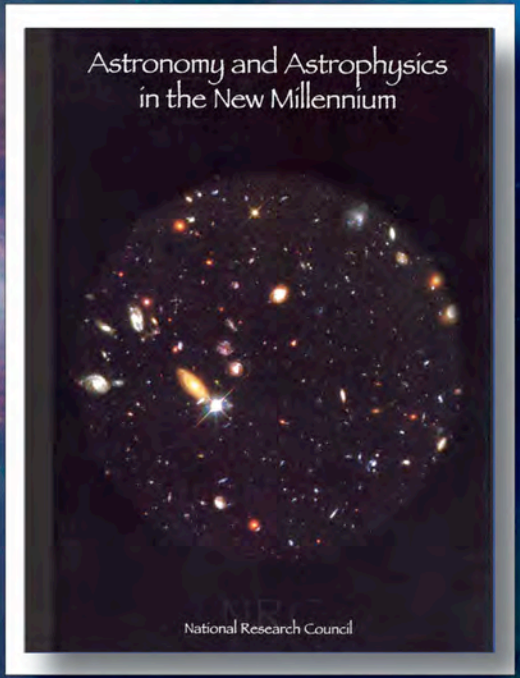
Exploring New Worlds

AIAA Space 2005 Long Beach, CA Aug 30 - Sep 1, 2005

National Aeronautics and Space Administration

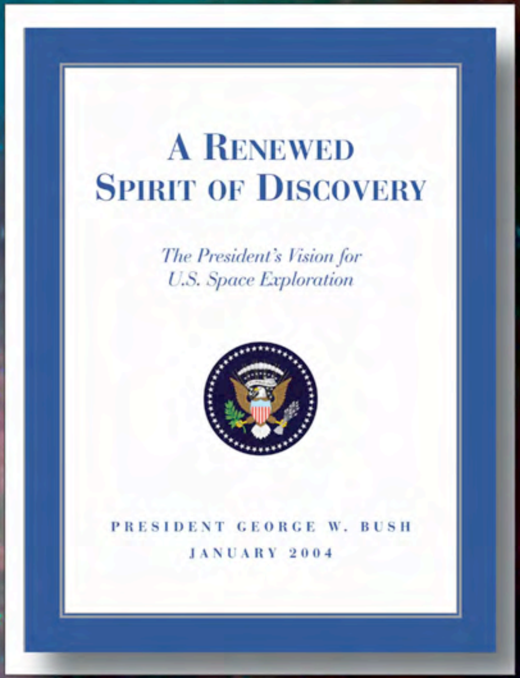
EXPLORE. DISCOVER. UNDERSTAND

Scientific and Programmatic Basis for NASA's Planet Finding Program



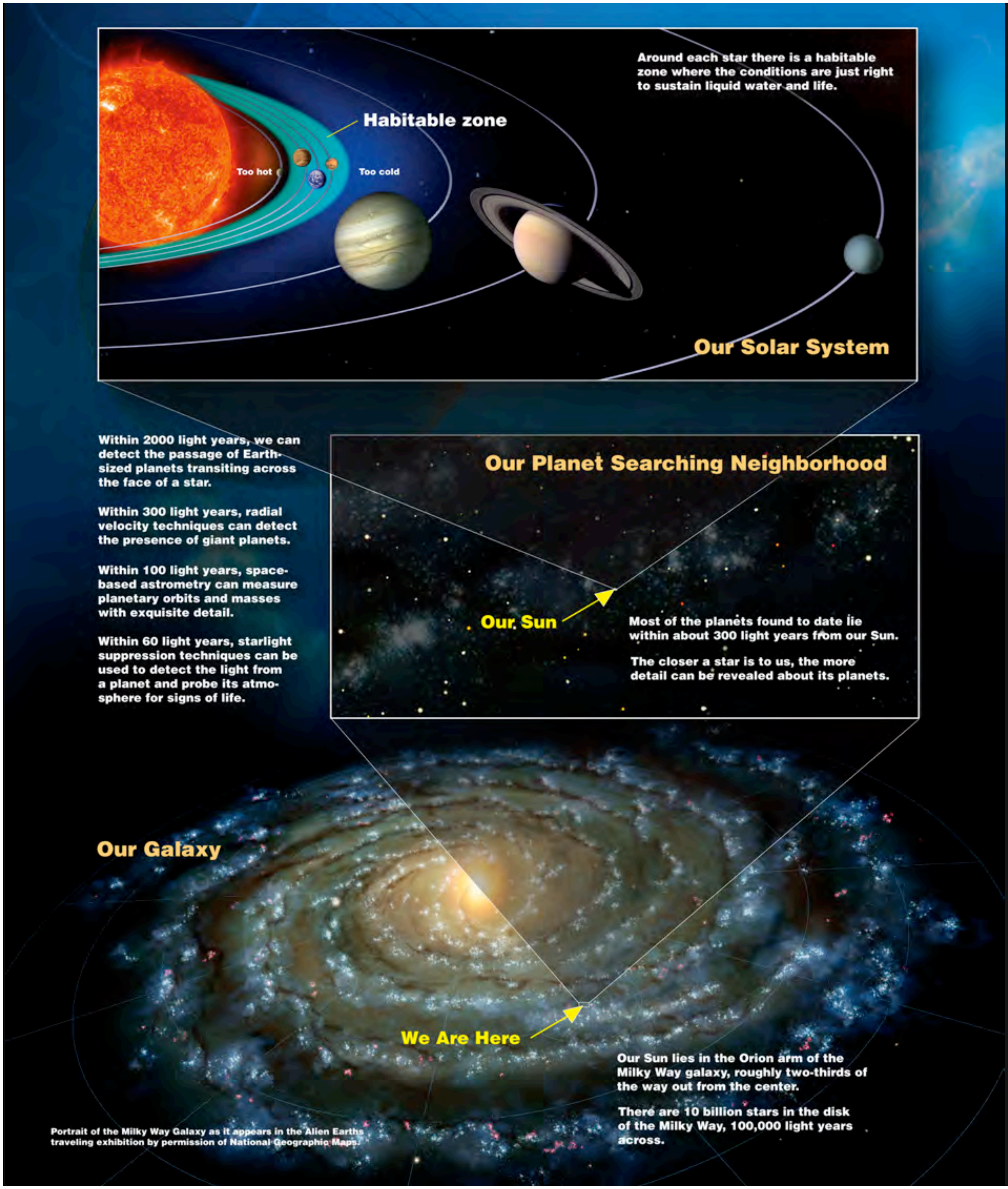
THE 2000 NRC DECADAL REVIEW

"Search for life beyond Earth, and if it is found, determine its nature and its distribution [in the Galaxy]"



VISION FOR SPACE EXPLORATION

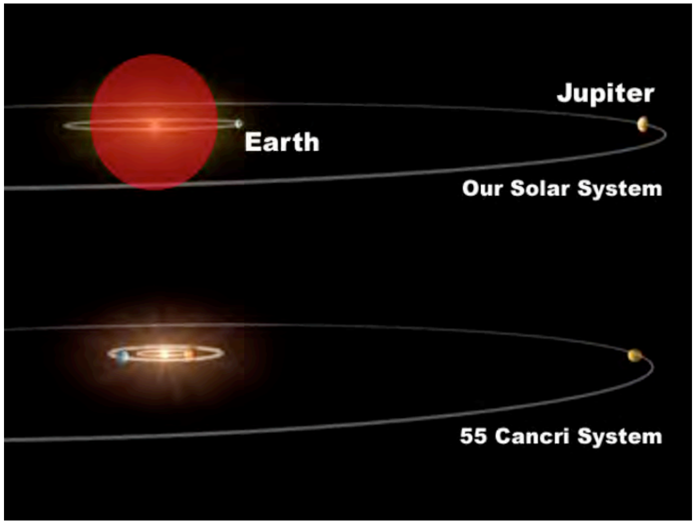
"Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars"



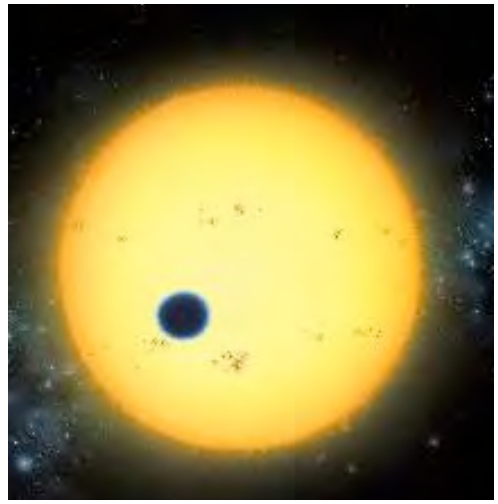
Where We Explore

- At 2000 light yr, detect Earth-size planets in transit
- At 300 light yr, radial velocity measures giant planets
- At 60 light yr, measure the masses and the light from planets and detect signs of life

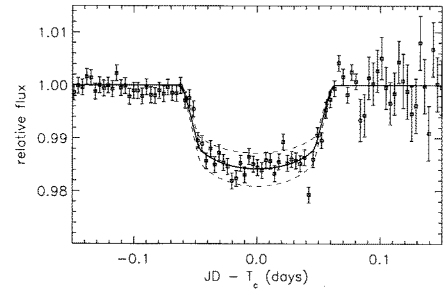
Today’s Accomplishments

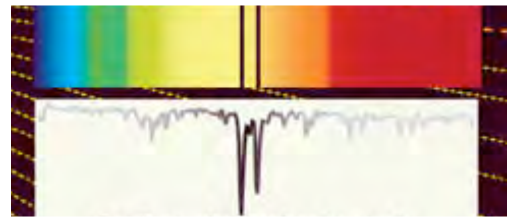


150 RV Planets

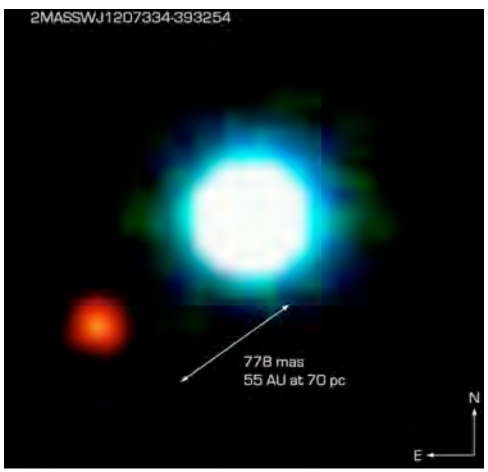


5 Transit Planets

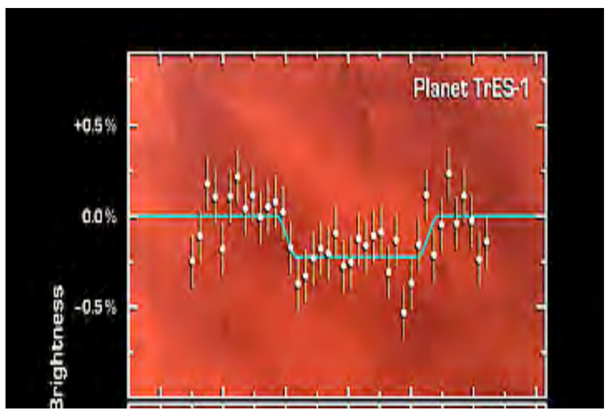




Transit Spectra



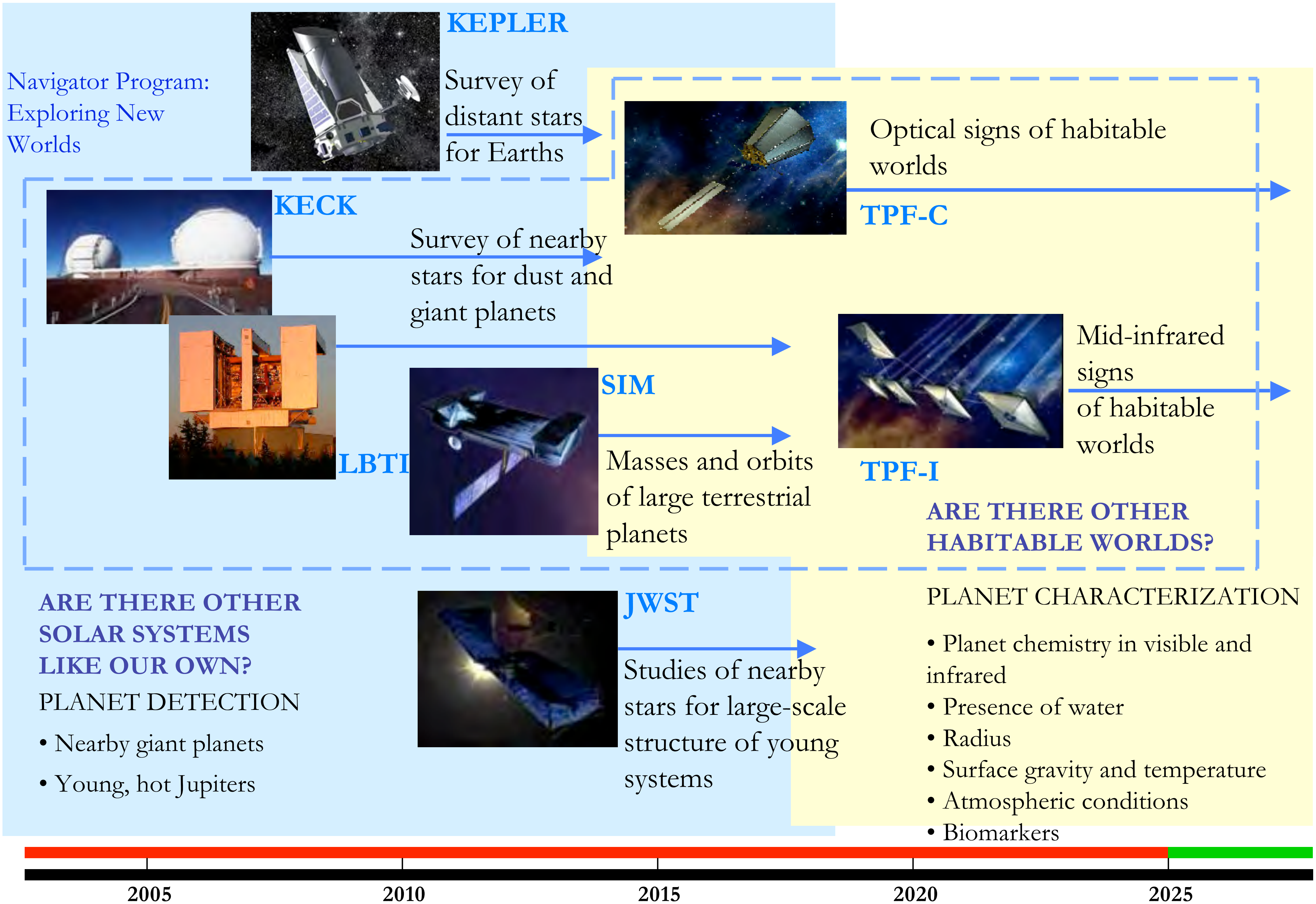
Hot Young Jupiters



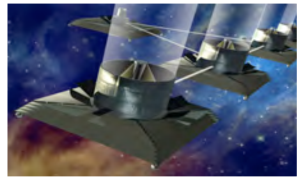
Heat from Transiting Jupiters

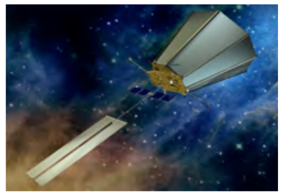
Comet and Asteroid Belts

Roadmap of Planet Finding Science



Summary of NASA's Planet Finding Missions

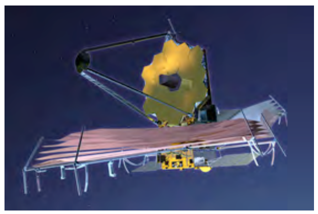




TPF-C and TPF-I (2015-2020)

- Characterize temperature, size, composition of other Earths
- Look for signatures of Life

Distant Planets



JWST (2012)

- Image Jupiter's within 5 pc
- Image disks and distant hot young Jupiters
- Follow–up Kepler "Jupiters" with spectroscopy

SIM (2011)

- Search 250 *neighboring* stars for Earths (<50 l. yr.)
- Architecture of systems
- Masses and orbits

Find Nearby Earths & Life

Kepler (2008)

- Transits to identify Jupiters → Earths around 100,000 *distant* Suns (<1,000 l. yr.) to determine incidence of Earths

Keck (2006)

- Dust disks at 10 zodi to 0.01" for nearby stars

LBTI (2008)

- Dust disks at 3 zodi to 0.5" – 25" for nearby stars

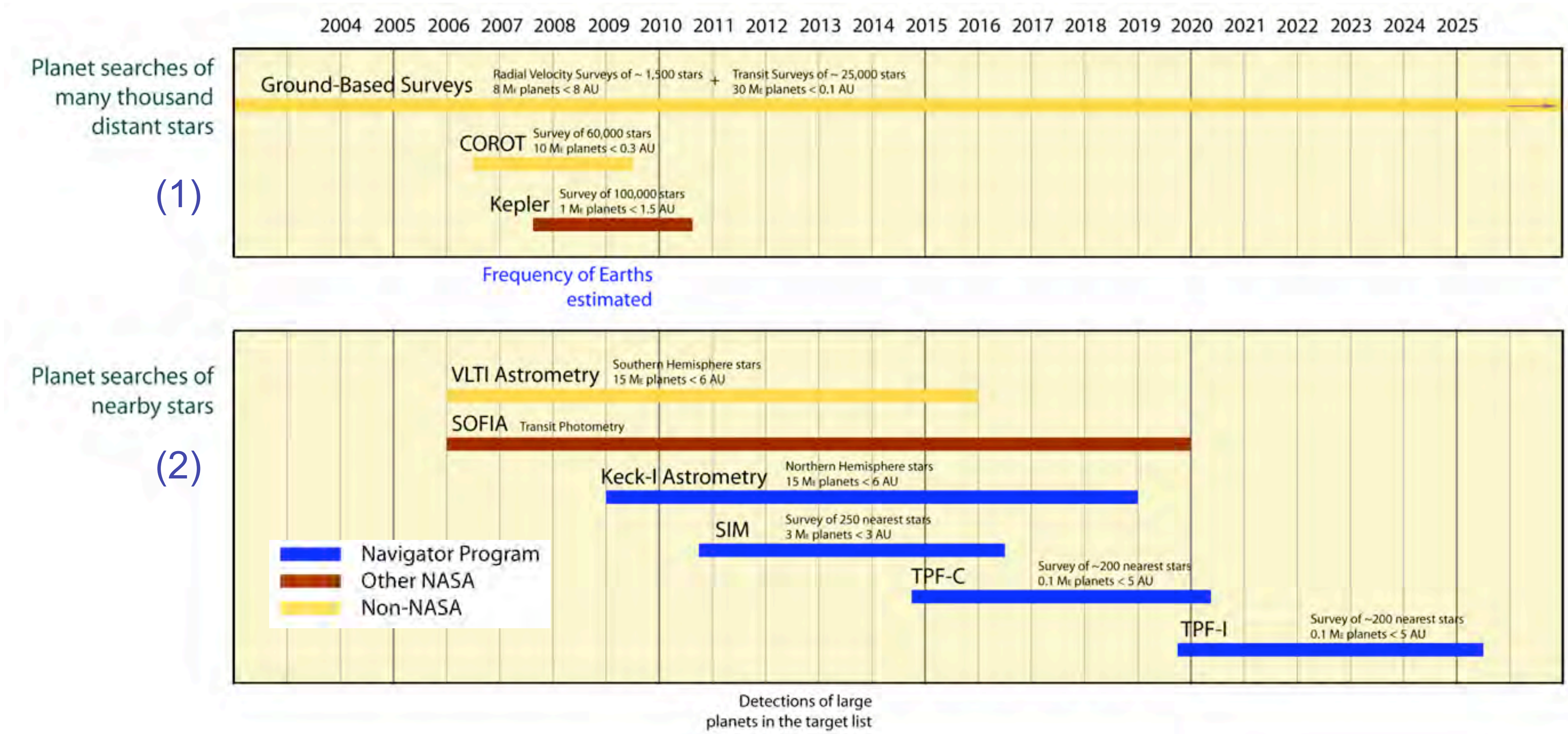
Comparative Planetology: Putting Extrasolar Planets into a Broader Context (1)

- There are four broad areas of research:

(1) <u>Surveys of large number of stars</u>

- – Provide fundamental knowledge of the statistics of planetary systems
- – Inform the design and scope of *Navigator Program* missions such as TPF-C and TPF-I

(2) Space missions in the *Navigator Program* such as SIM PlanetQuest are central to the <u>search for nearby planetary systems</u>

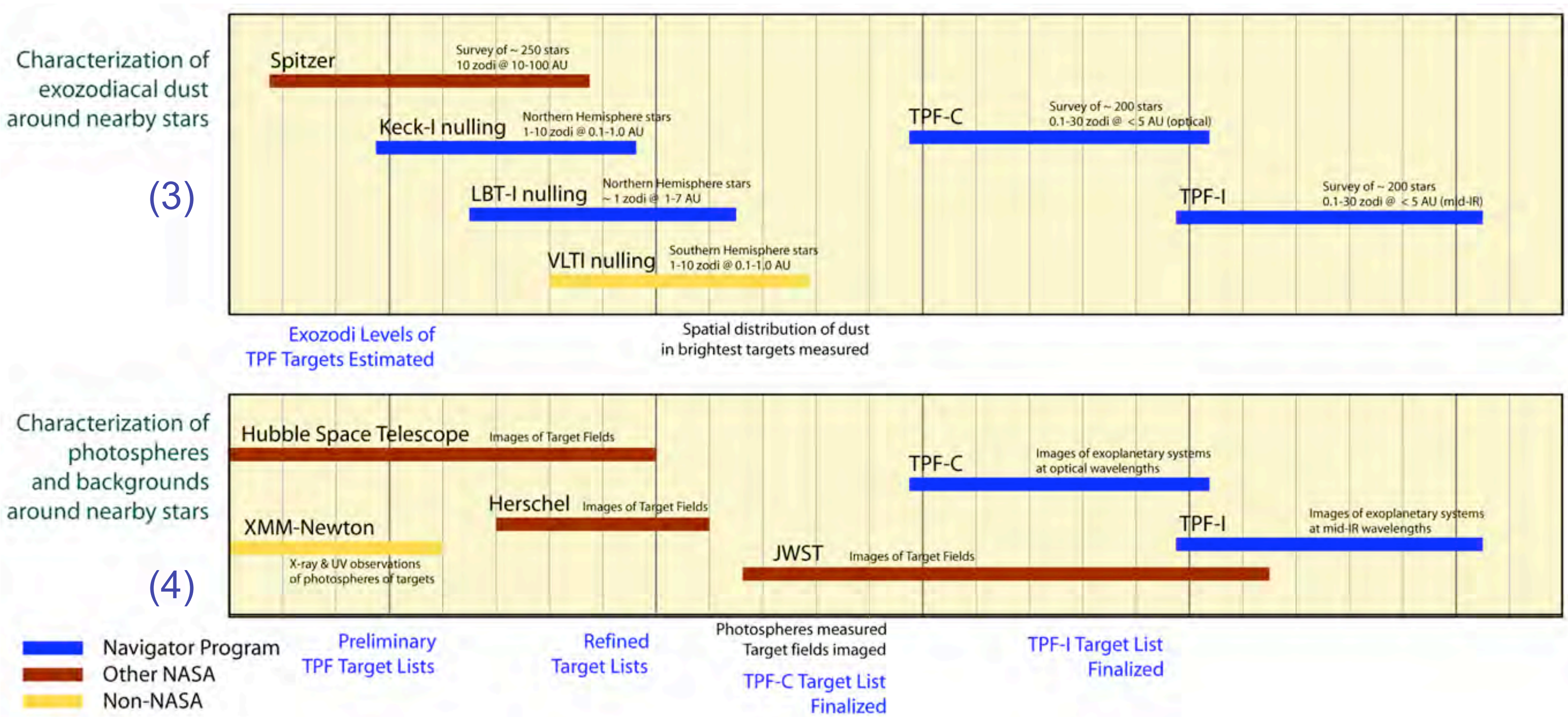


Comparative Planetology: Putting Extrasolar Planets into a Broader Context (2)

(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

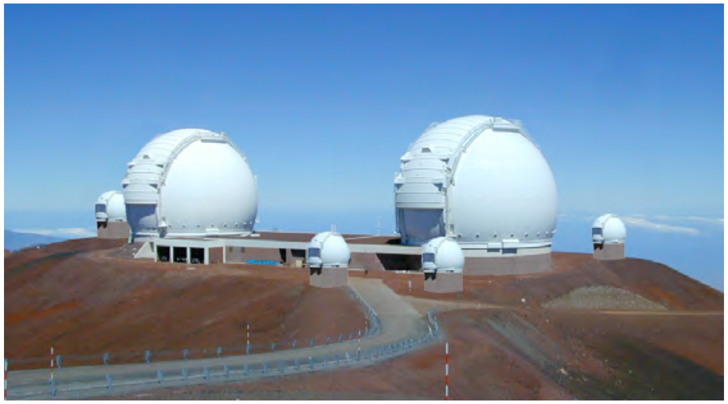


A Stepwise Approach to Long-Term Science Objectives

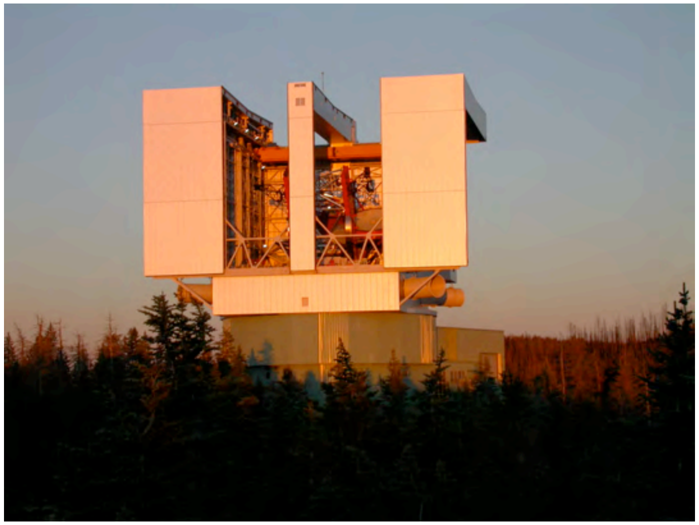
Conduct advanced telescope searches for Earth-like planets and habitable environments			
	Phase 1: 2005-2015	**Phase 2: 2015-2025**	**Phase 3: 2025 +**
Planet Detection	a)Measure the frequency of Earth-like planets in a statistically representative sample [COROT ,Kepler] b)Radial velocity surveys detect additional Jupiter analogs and nearby planets with less than 10 M_{earth} [Ground] c)First SIM planet detections	a) Astrometric detection of M > 3 M_{earth} planets in habitable zone within 10 parsecs [SIM] b) Phometric detection of M > 0.5 M_{earth} planets in stellar habitable zone within 10 parsecs [TPF-C] c) Photometric detection of M > 0.5 M_{earth} planets in stellar habitable zone within 100 parsecs [TPF-I]	a) Detection of planetary moons in nearby extrasolar system [Planet Imager] b) Detection of planets outside the solar neighborhood [Planet Imager]
Planet Characterization	a) Characterization of atmosphere of hot Jupiters seen in transiting events [Ground, HST, Spitzer] b) Detect and characterize brown dwarves and Jupiter through their emission [JWST]	a)Measure Mass [SIM] b)Measure radius and surface temperature [TPF-C+TPF-I] c)Detect basic atmospheric composition and presence of clouds [TPF-C+TPF-I] d)Characterize gross surface Properties [TPF-C] e)Detect new classes of planets [SIM, TPF-C, TPF-I] f)Detect Tracers of life [TPF]	a) Detect biogenic atmospheric tracers [LFI] b) Detect presence of life [LFI] c) Characterization of new planetary families [LFI] d) Direct imaging of extrasolar planets [Planet Imager]
Planet Formation and Habitability	Observe the formation and evolution of stars, galaxies, and planetary systems, from the first luminous objects to our own neighborhood [Spitzer, SOFIA, Herschel, JWST]	Observe the development of conditions for life, from the first release of the chemical elements in the first stars, through the formation of protoplanetary disks, to the chemistry and physics of the Solar System [SOFIA, JWST,SAFIR]	a) Observe proto-planetary disks with the resolution needed to detect Earths in formation [FIRSI] b) Trace the chemical evolution of the early universe [Large UV/Optical Imager]

Ground Observatories Lay Groundwork for the Space Missions

Keck Interferometer (KI) and
Large Binocular Telescope Interferometer (LBTI)



Goal: to understand target stars themselves, and the dusty environments in which planetary systems reside



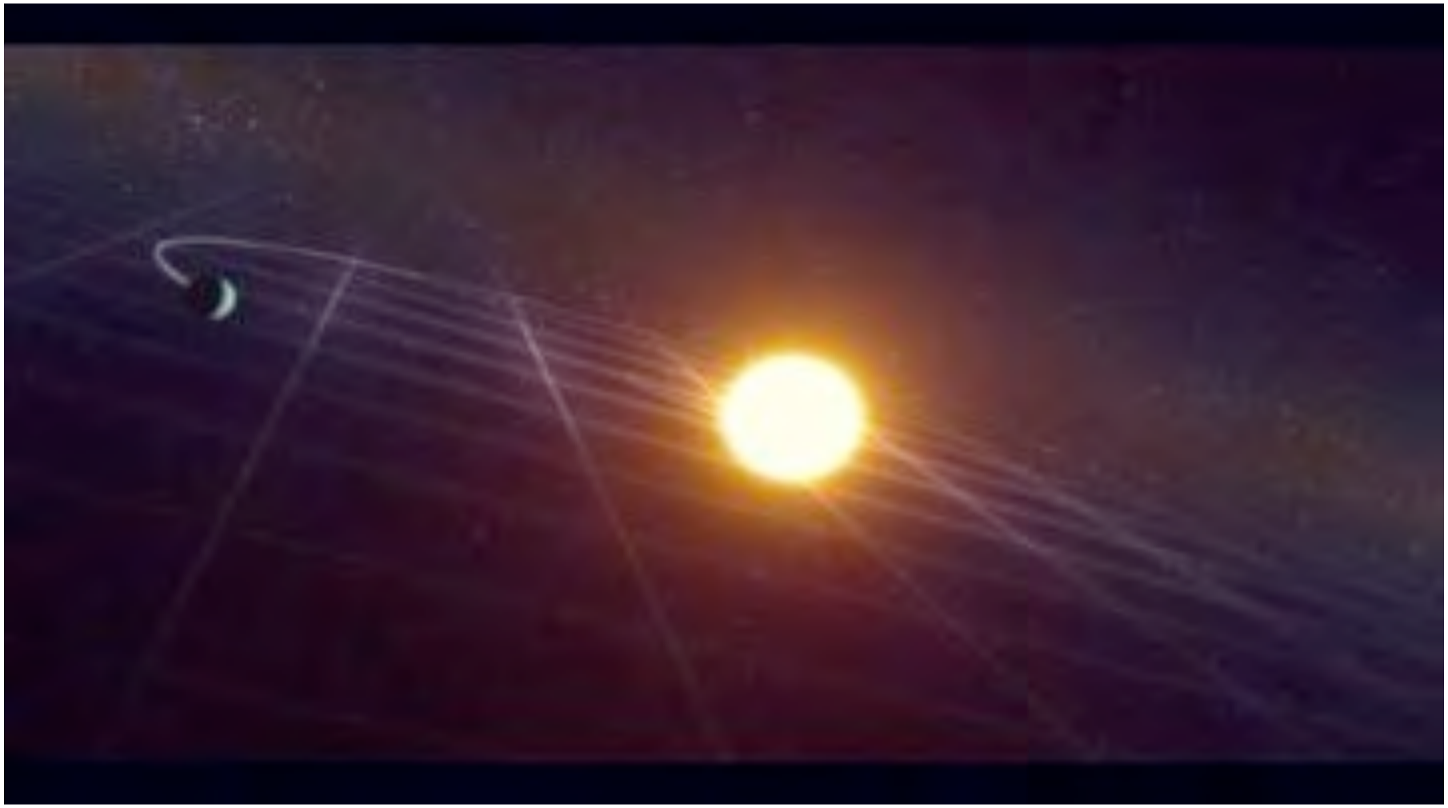
- Determine the mass of exo-zodiacal clouds as small as 10 zodi around nearby stars by nulling out the star. Most sensitive to angular scale about 0.01" (Keck-Keck)
- Imaging zodiacal dust disks as small as 3 zodis on angular scales from 0.5"-25" for up to 50 nearby stars (LBTI)
- High-resolution (milliarcsecond scale) imaging of disks in which planets may be forming (KI outriggers)
- Wide-field imaging (Fizeau) interferometry to study sub-structure in dust disks (LBTI)
- Direct detection of brown dwarfs and 'warm Jupiters' (Keck-Keck)
- Indirect detection of Uranus-size planets via astrometry (KI outriggers)
- Study surface structure of giant stars - shells, outflows (LBTI)

Together SIM, TPF-C, and TPF-I Obtain Complete Understanding of Planetary Systems

- Each mission provides key measurements that extend our knowledge of other worlds
- SIM measures *mass,* the most important single property and a key determinant of habitability
- SIM measures orbit size: does the planet lie in the 'Habitable Zone'? Is the orbit circular or elliptical? Are there multiple planets?
- TPF-C will directly detect Earth-like planets, estimate their size, and search for 'biomarker' molecules O_2, O_3, and H_2O
- TPF-I will directly detect Earth-like planets, measure their temperatures, and perform very sensitive searches for H_2O, O_3, and CO_2
- The *combination* of the three missions allows a complete characterization of: mass, size, density, albedo, temperature, atmospheric composition, and perhaps variability (seasons?)

How SIM PlanetQuest Detects Planets

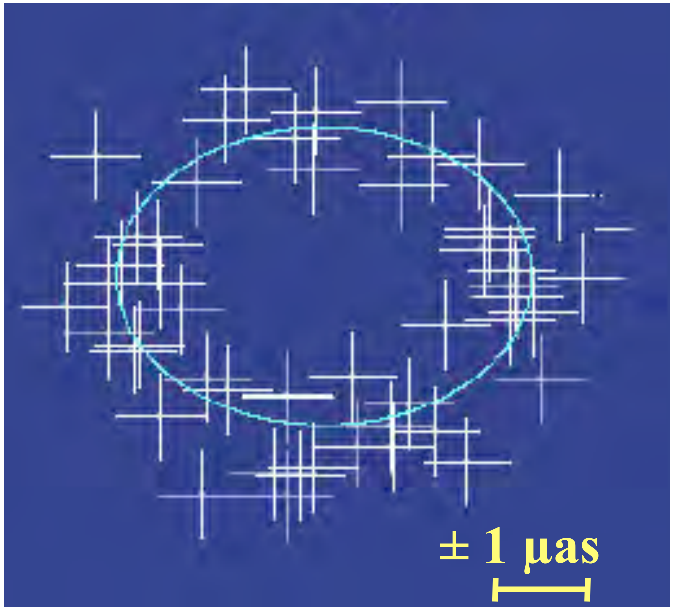
- Star and planet orbit their common center of mass
- Star appears to “wobble”
- Back-and-forth (radial velocity) detectable by Doppler shift by ground telescopes
- Transverse (astrometric) motion detectable by SIM

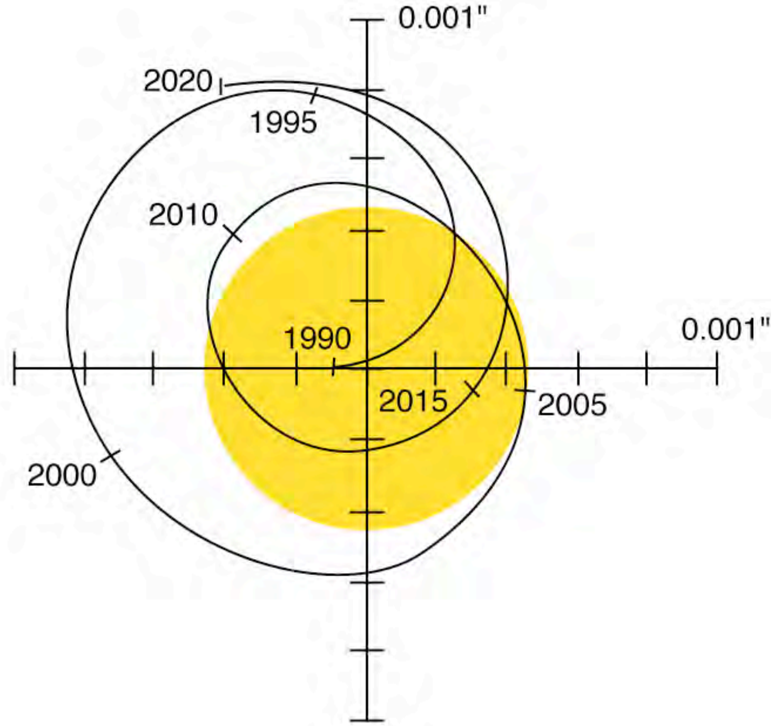


Astrometric Planet Detection

A microarcsecond (1 μas) is SIM's goal accuracy in a single measurement

– Equals the thickness of a nickel when viewed at the distance of the Moon !





"The wobble effect": our Solar System as seen at 30 light-years distance

- Sun-Jupiter wobble = 0.5 milliarcsec
- Sun-Earth wobble = 0.3 μarcsec

Searching for Terrestrial Planets with SIM PlanetQuest

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 $M_\oplus$ at 10 pc
- Sensitivity limit of ~1 $M_\oplus$ at 3 pc

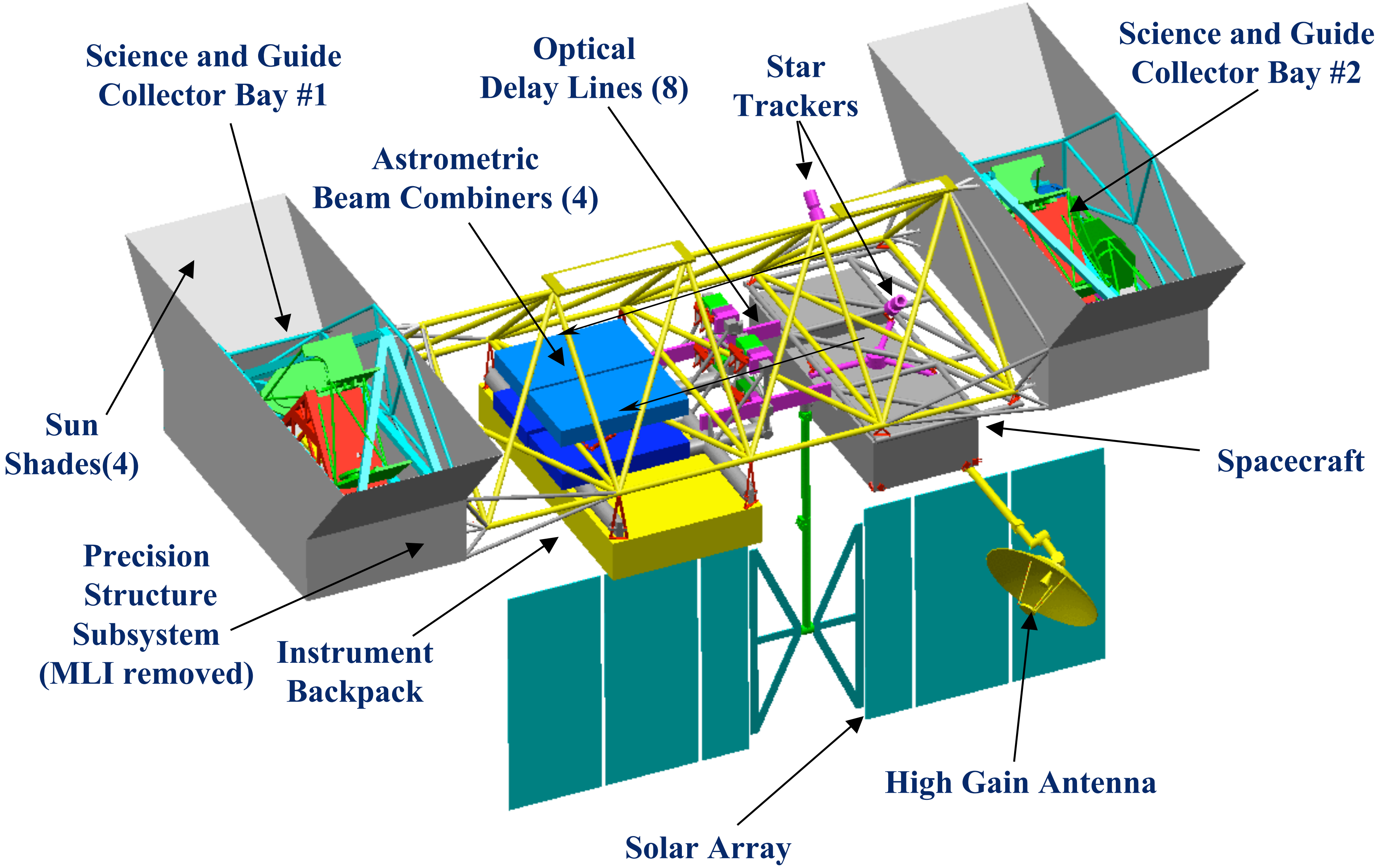
A Broad Survey for Planets

- 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?

SIM PlanetQuest
Flight System Architecture



SIM Technology Milestones are 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
- ***All of these technology milestones are now complete!***

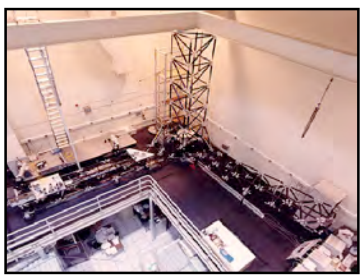
Component Technology 1-4
Complete

Subsystem/System Testbeds 5-7
Complete

Modeling/Testbed Integration 8
Completed July 2005

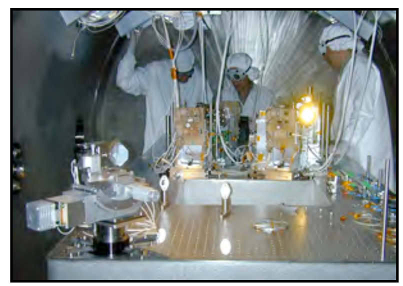
Completed July 2005

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



STB-1

MAM



KITE

STB-3

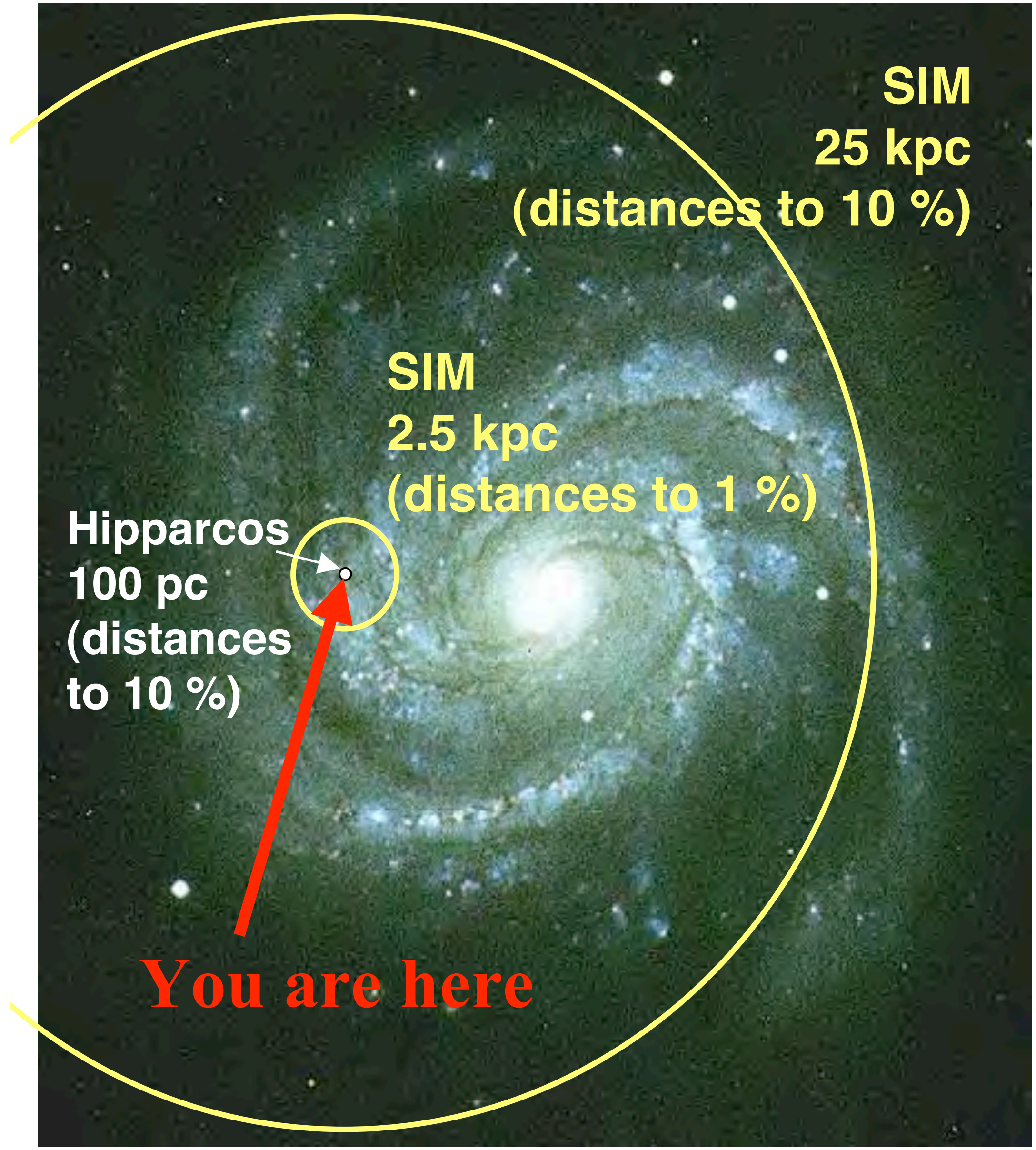
Subsystem-level Testbeds

System-level Testbed

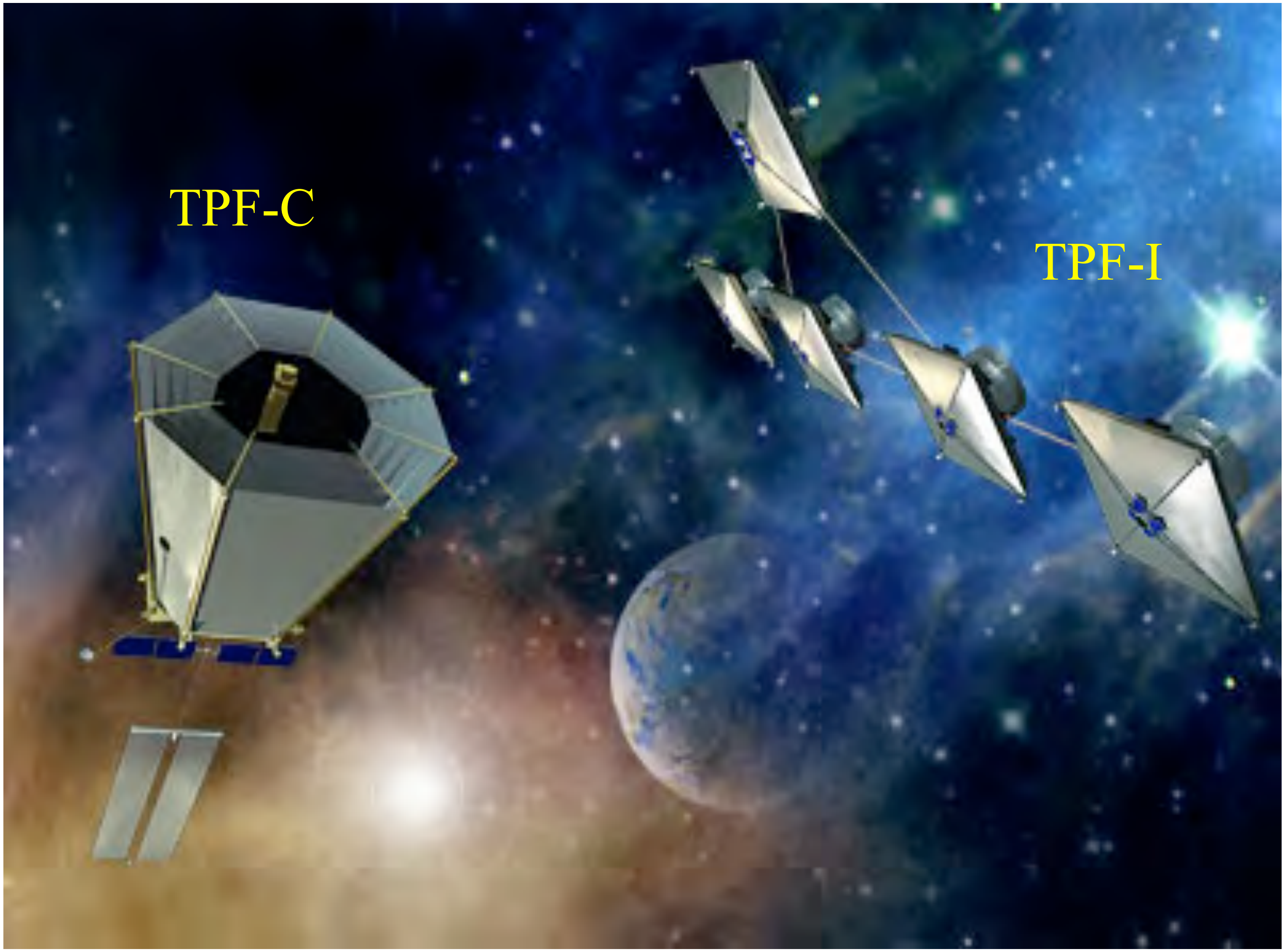
SIM's Reach Extends Across our Entire Galaxy to do "Precision Astrophysics"

What makes SIM unique:

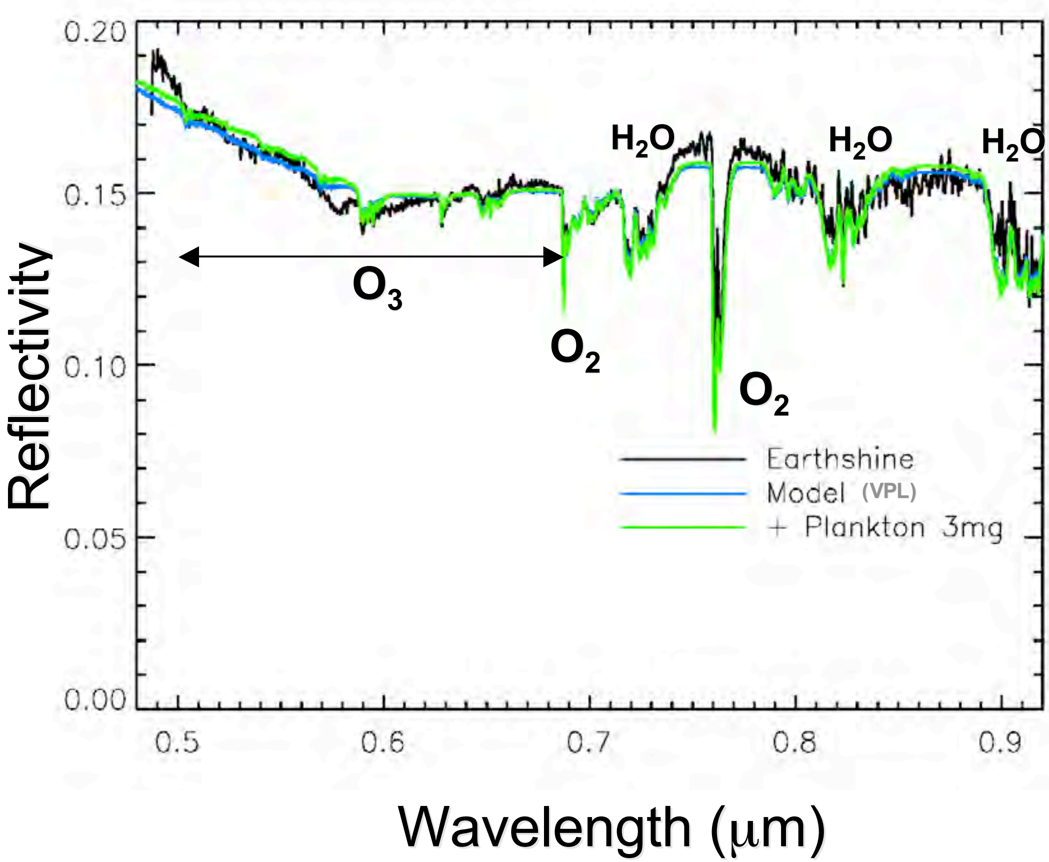
- Extreme astrometric precision
  - 4 μas (microarcsec) positions
  - 4 μas/yr proper motions
  - 1 μas differential positions
- Ability to observe faint targets
  - V <~ 20
- Flexible scheduling
  - optimize for specific science objectives

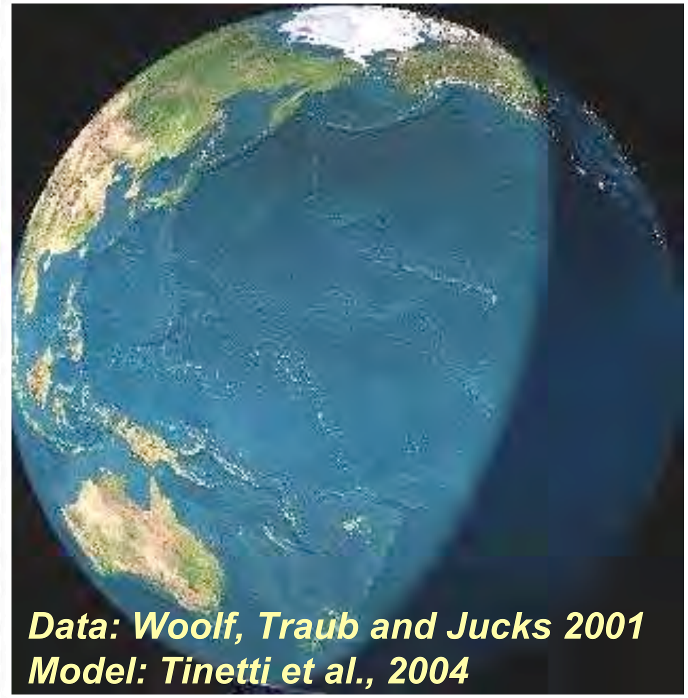


Terrestrial Planet Finder Missions



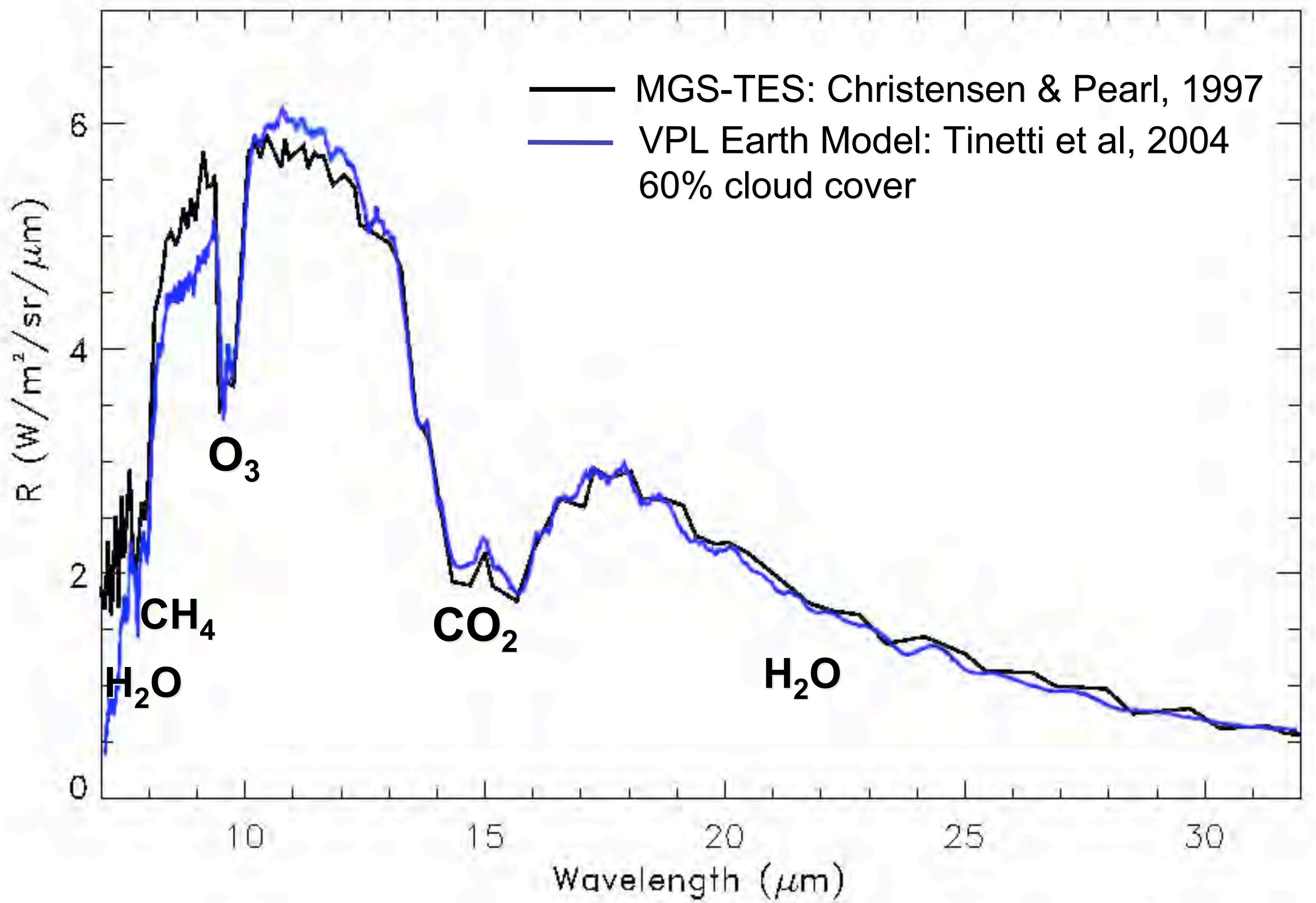
Biosignatures in the Earth's Visible Spectrum





- O_2 (for life) & water (for habitability) are relatively easy to detect
- Surface biosignatures such as chlorophyll may also be detectable
- Would like to observe CO_2 at 1.06 and 1.2 μm

Biosignatures in the Earth's Mid-IR Spectra



The Mid-IR is sensitive to atmospheric trace gases which could indicate habitability or life

TPF-I Collaboration with ESA

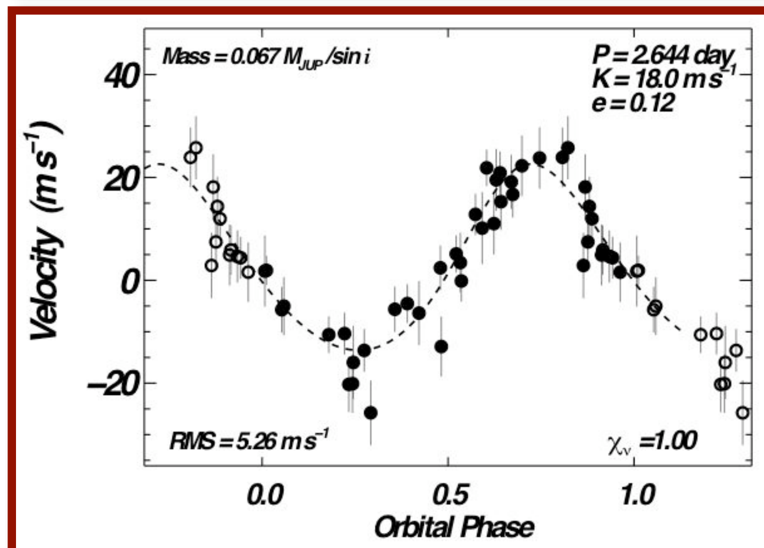
- Strong support for exo-planetary research in ESA's Cosmic Vision Program
  - ESA currently studying the *Darwin* mission, a formation flying, nulling infrared interferometer
- Current NASA-ESA Interactions
  - Letter of Agreement in place
  - Joint annual TPF/Darwin science meetings
  - Representation on Science Teams

Darwin Science Goals:

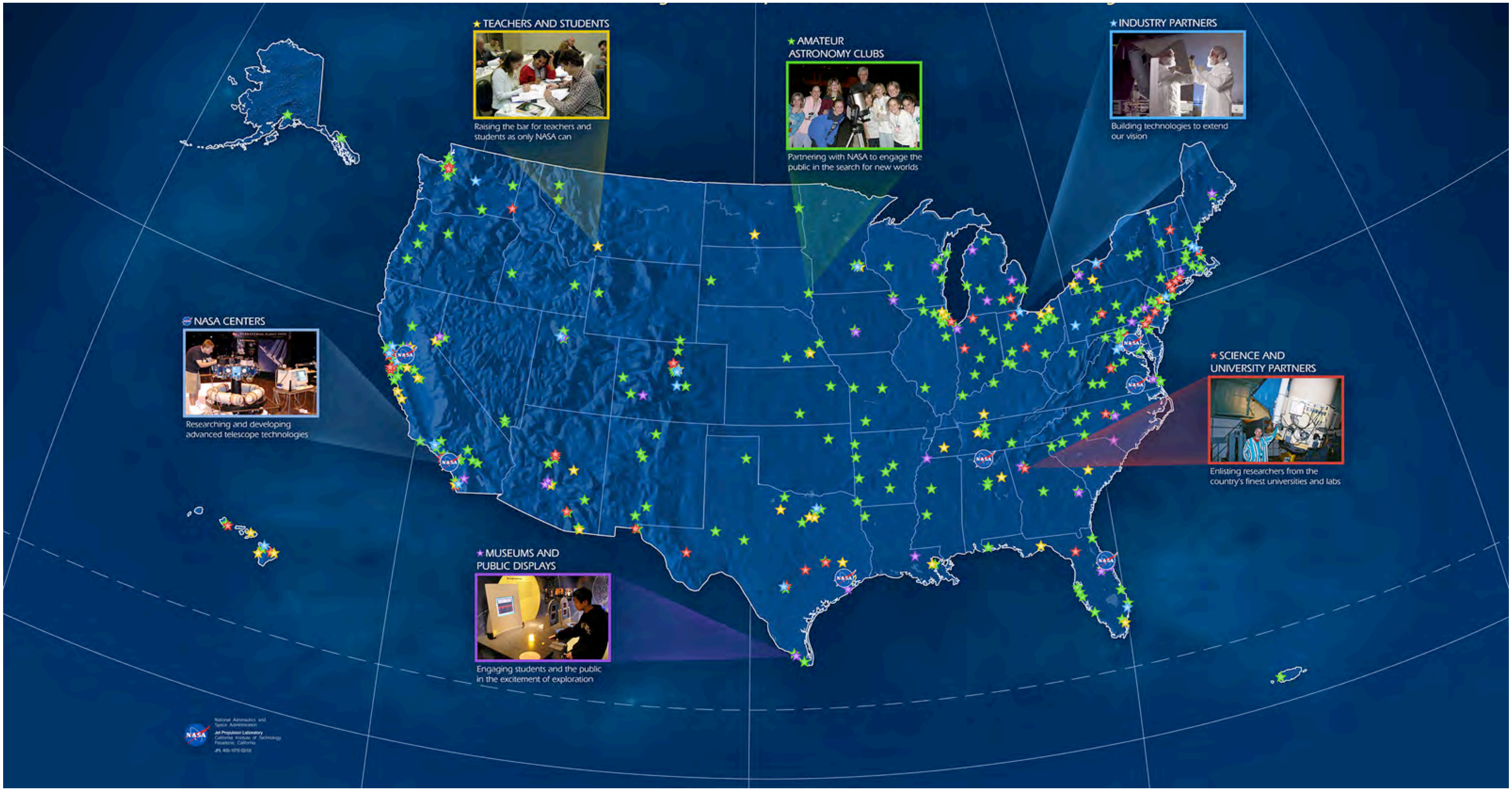
Find Earth-like planets around nearby Solar type stars and characterize them, with regard to their ability to host "life as we know it"

Michelson Science Center: Developing the Community

- Michelson Program
  - Fellowships (~28 in program)
    - 5 PhDs generated
    - 122 refereed publications
  - Summer Workshops
    - 1998: Interferometry – Flagstaff
    - 1999: Interferometry – Caltech
    - 2000: Interferometry – Berkeley
    - 2001: Interferometry – Flagstaff
    - 2002: Interferometry – Boston
    - 2003: Interferometry – Caltech
    - 2004: Coronagraphy – Caltech
    - 2005: Astrometry – Caltech
  - Visitor Program
- Keck Operations Support
  - Keck PI Data Awards
  - MOWG and TAC coordination
- Hosting Conferences and Workshops
  - TPF/Darwin ‘04
  - Young Stellar Objects ‘05
  - Cool Stars 14 in ‘06



A National Journey of Exploration and Discovery



Navigator Program: Public Engagement through...

… bold, innovative approaches ...

Public Outreach

Informal Education

Formal Education

Science Outreach

Research & Development

… pursuing a common goal

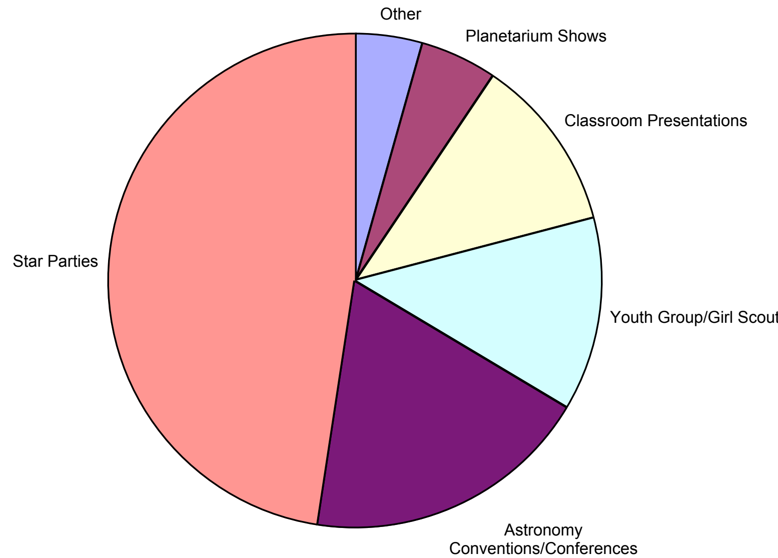
To inspire the next generation . . .

… of explorers.

Supporting public engagement programs and partnerships in all 50 states reaching hundreds of thousands of students, teachers, and large segments of the general public.

Night Sky Network: Making an Impact

One Example of Public Outreach



Becoming a NASA Collaboration:

- Origins Education Forum
- Structure & Evolution of the Universe Education Forum
- Solar System Education Forum
- Several mission EPO programs are looking to join

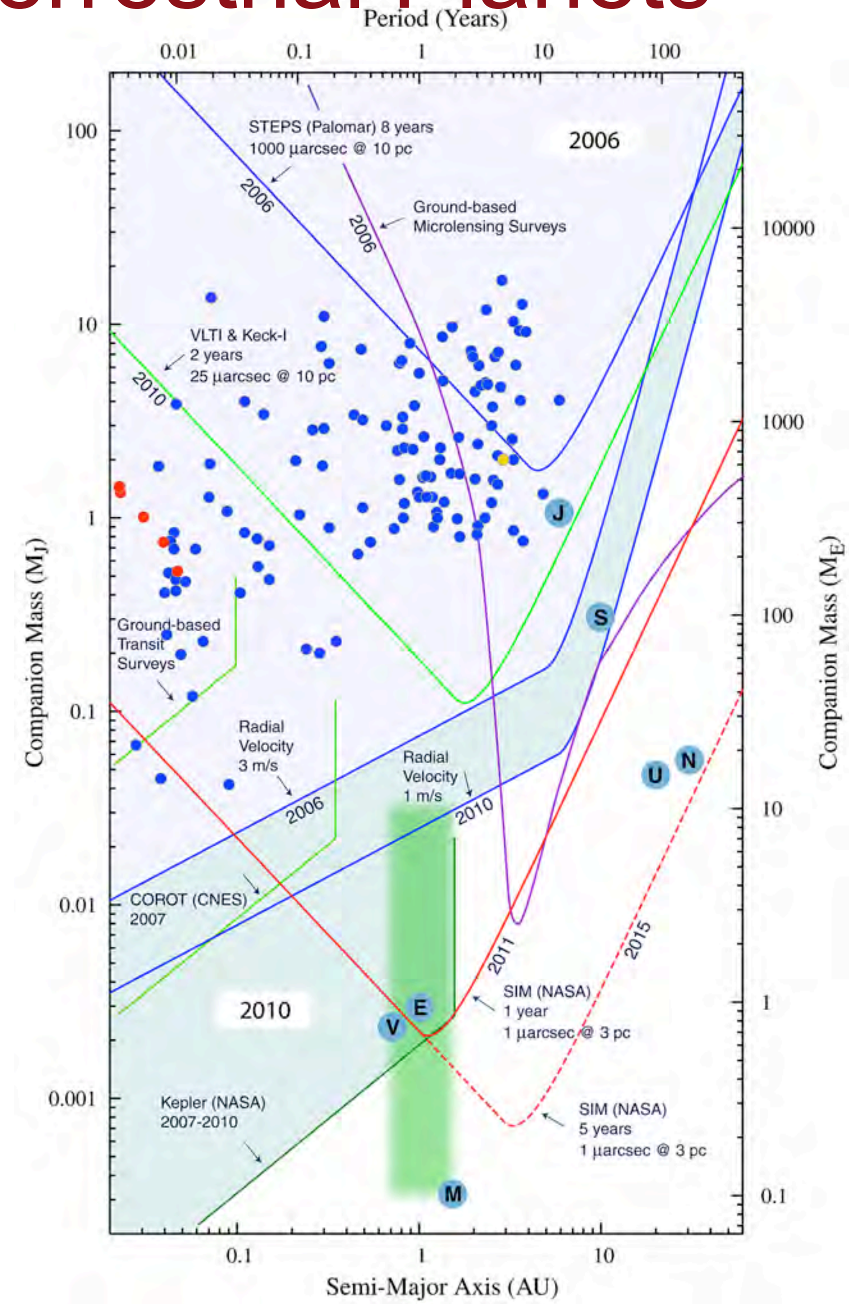
Planet Finding Has Strong Public and Scientific Support

- Highest scientific endorsements from NAS, NRC committees
- Great public interest --- numerous newspaper, magazine, television
- Excellent cooperation at NASA centers (JPL, GSFC, ARC)
- Strong engagement with dozens of universities
- Major industry involvement in early technology → C/D mission development

Backup slides

Deep Search for Terrestrial Planets

- Several Neptune-sized planets have been discovered recently
  - Planets with masses of 15-30 Earth-masses appear to be common
  - They all have short orbit periods (3 - 10 days) and orbit very close to the star
  - But these are not Earth-like planets: they have very short periods and are more than 15 times as massive
- SIM will extend the search to Earth-mass planets, with a survey of 250 nearby stars
- Complete survey will reach ~3 Earth-masses in 5 years
- First detections of terrestrial planets could occur within the first year

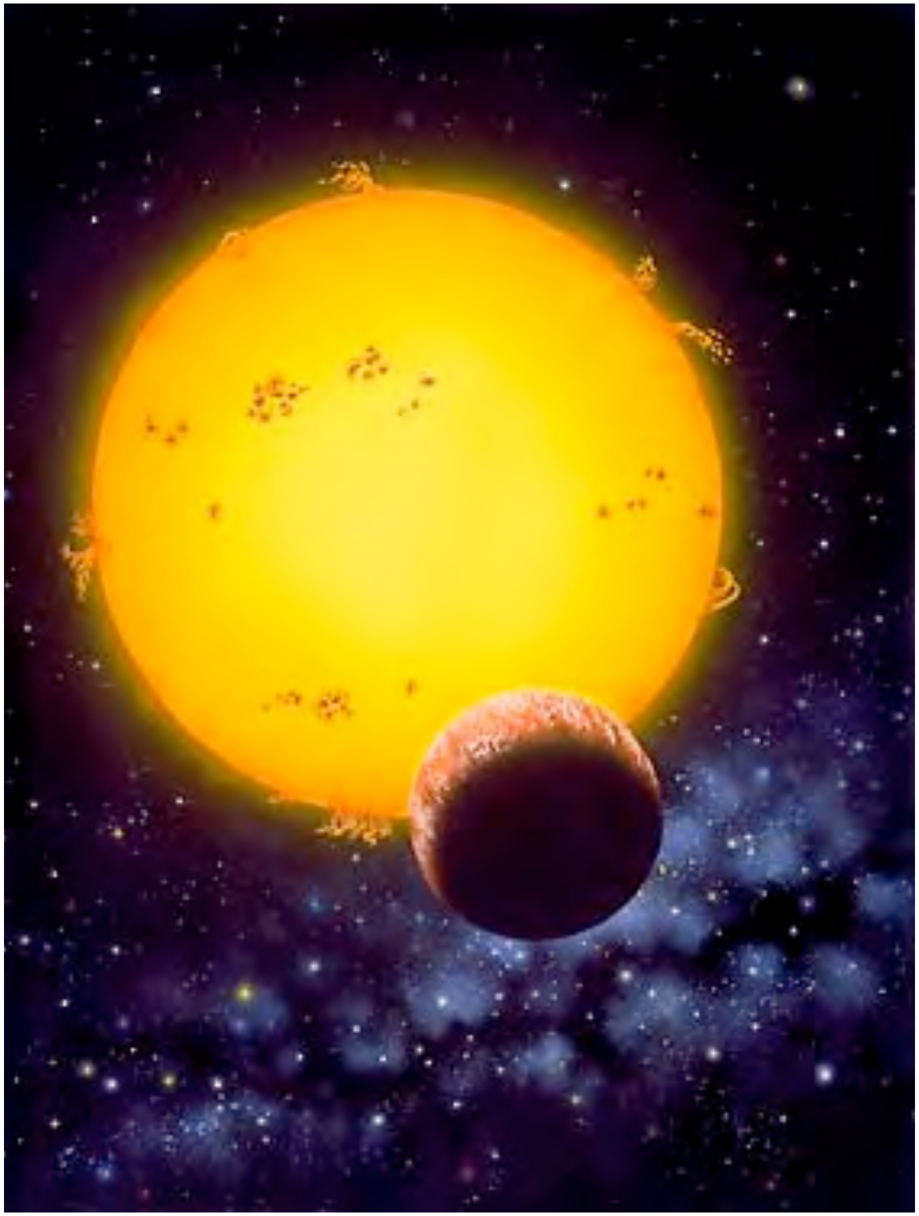


Planets around Young Stars

- How do planetary 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?

SIM will:

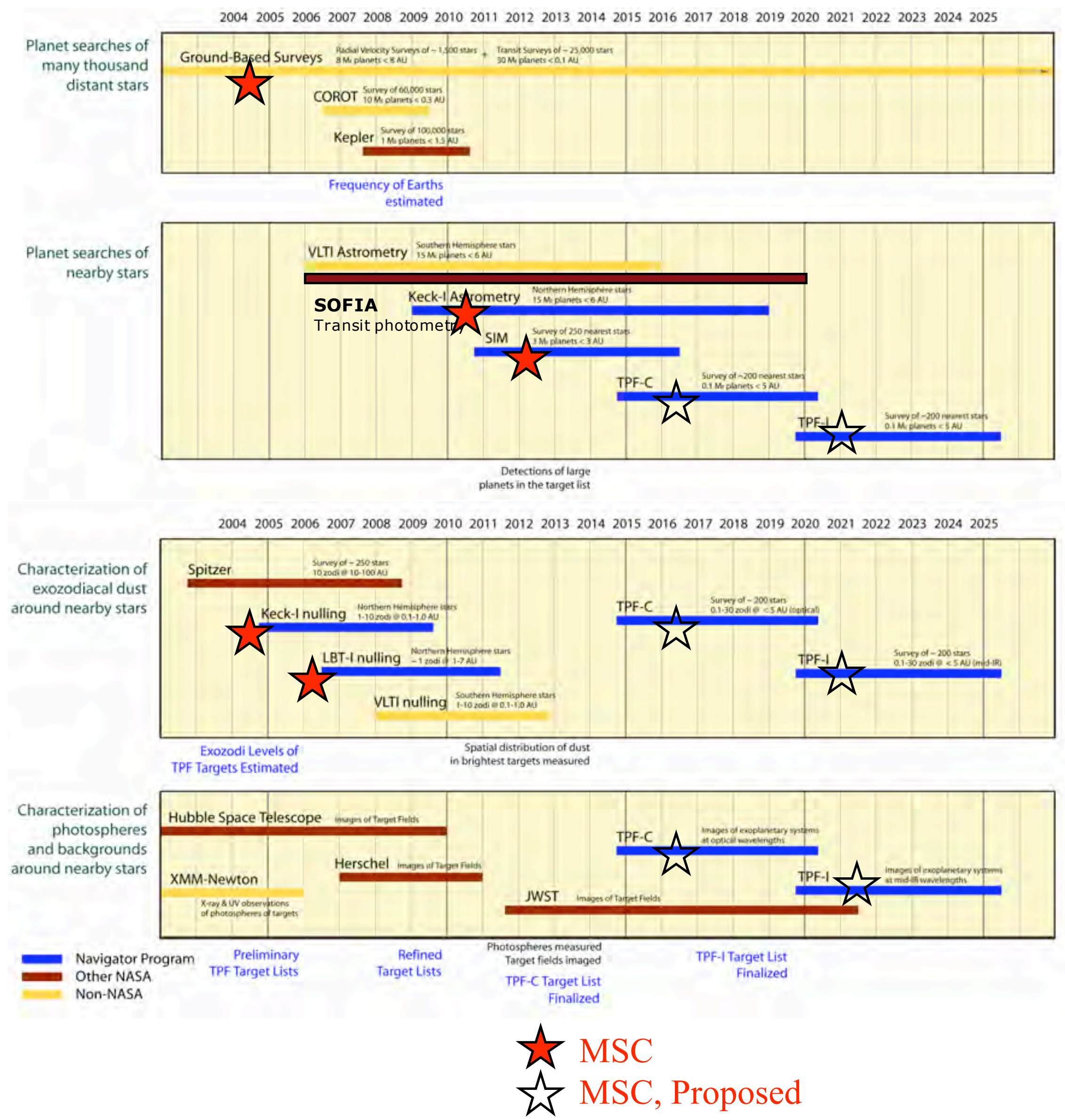
- Search for Jupiter-mass planets around ~200 young stars (cTTs, wTTs, young nearby clusters)
  - range of ages 10-100 Myr
- Measure the ages and 'evolutionary state' of ~100 young stars
  - Need precise distances and companion orbits
  - Calibrate pre-MS evolutionary tracks



Michelson Science Center: a Major Role in Searches for Earth-Like Planets

The MSC participates through:

- *Missions*
  - Keck Interferometer (KI)
  - Large Binocular Telescope Interferometer (LBTI)
  - Space Interferometry Mission (SIM)
- *Science activities*
  - Michelson Program
  - Conferences
- *Science data archives*
  - Keck Observatory Archive (KOA)
  - SIM and Terrestrial Planet Finder (TPF) preparatory science archive
  - Stellar Archive and Retrieval System (StARS)



Structured Technology Preparation for Mission Readiness Reduces Risk