# A Roadmap for NASA's Search for Other Earths

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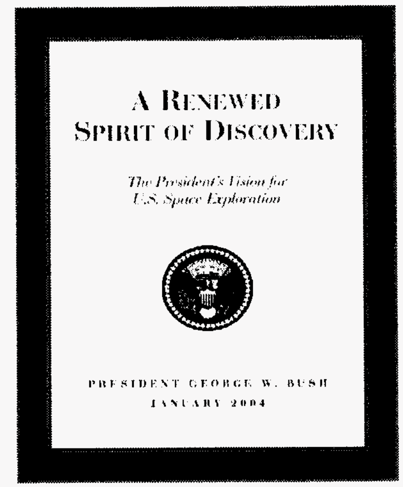
# Agency strategic objective

## ***Conduct advanced telescope searches for Earth-like planets and habitable environments around neighboring stars***

*The President's Vision for US Space Exploration* (2004)
requests NASA to pursue
*"advanced telescope searches for Earth-like planets and habitable environments around other stars"*




*"Do there exist many worlds, or is there but a single world? This is one of the most noble and exalted questions in the study of Nature."*

Albertus Magnus (1193-1280)

# Key Science Questions

- Where are the nearest giant planets?
- Where are the nearest terrestrial planets?
- How many planets are there around nearby stars?
- How does star formation lead to planet formation?

**Detect planets & planetary systems**

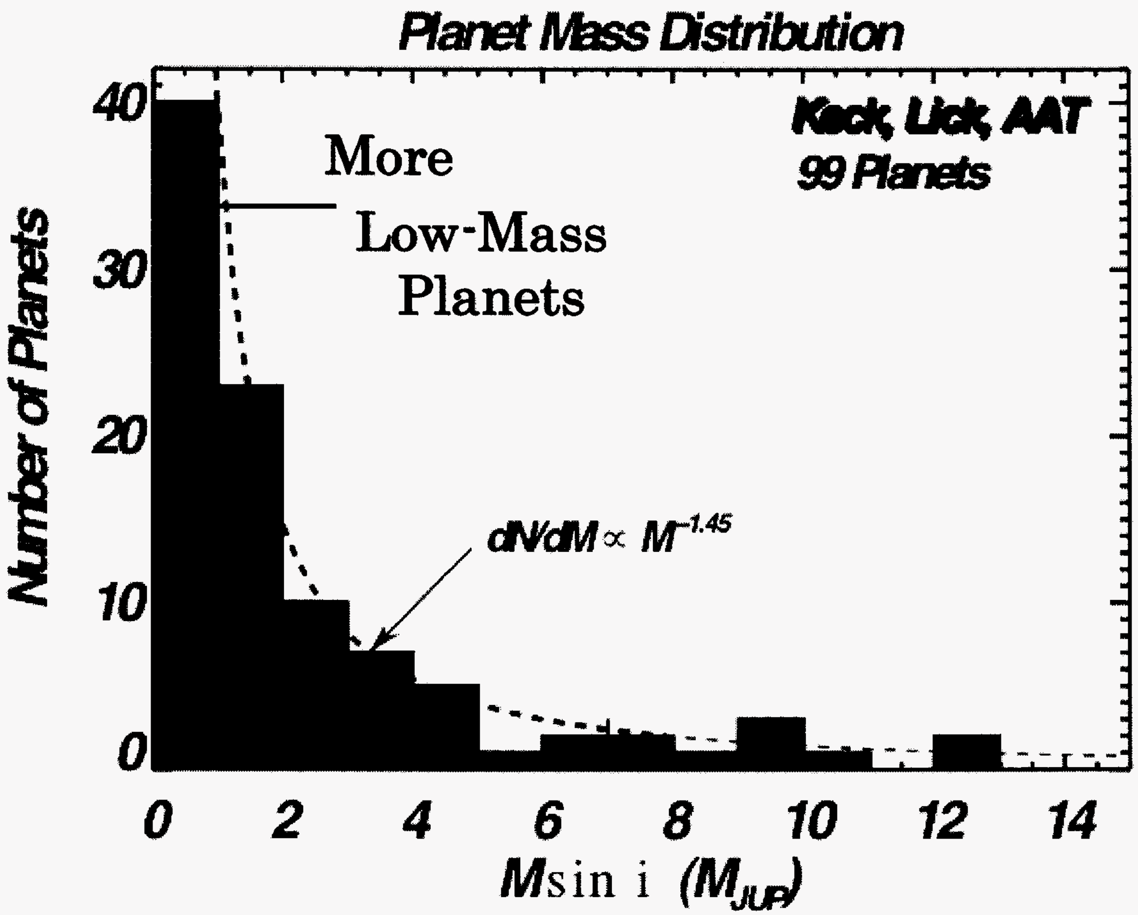
- What are the properties of these planets?
- Can we understand these properties?

**Characterize planets**

- Which planets are habitable?
- Are there signs of life on these planets?

**Determine habitability & search for signs of life**

# Planet Mass Distribution




**Three Neptunes:**

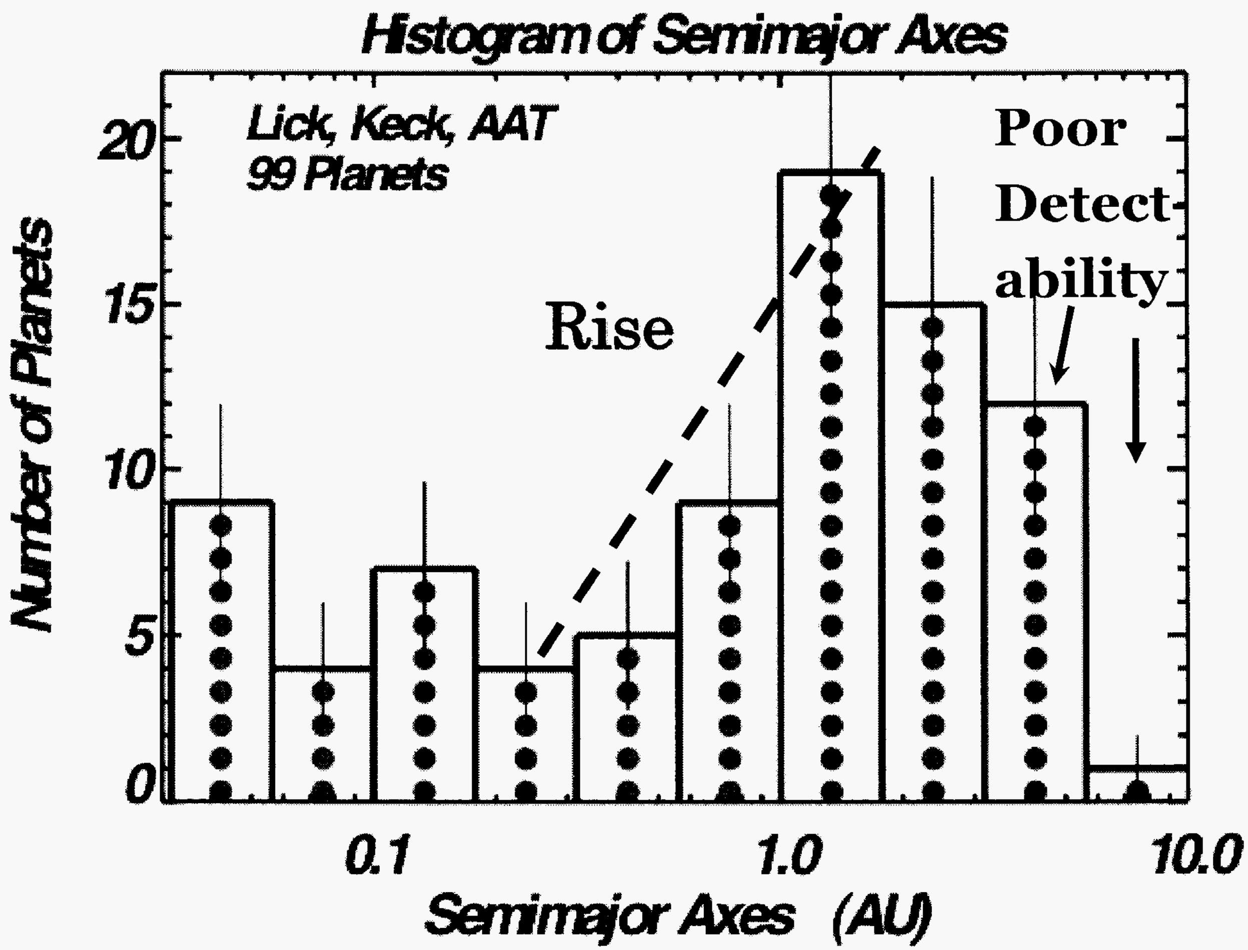
- **Gl 436**
- **55 Cnc d**
- **m Ara**

**( Butler et al.**
**McArthur et al.**
**Santos et al. )**

From Geoff Marcy

**(Exclude 1st bin.)**

# Doppler Survey of 1330 Nearby Sun-like Stars




From Geoff Marcy

**Extrapolation:**
**6% of stars have giant planets beyond 3 AU**

**Model:**
**Inward migration:**
**planets in place**
**as disk vanishes**

Armitage, Livio, Lubow, Pringle et al. 2002

Trilling, Benz, Lunine 2002

# Planet Formation and Habitability

***How does star formation lead to planet formation?***

- How do stars and disks interact?
  - Driving accretion, and outflow, chemical processing, setting rotation rate
- When do planets form?
  - Initial mass and composition of disks
  - How mass of disk evolves with time
- Where do planets form and how do they migrate?
  - Planet-disk interaction sets final system architecture
  - Giant planets are the bigger siblings (protectors and bullies) of the system

***How do the components of life come to reside on terrestrial planets?***

- When did the Universe form the raw materials necessary for planets and life?
  - Comparisons in galactic environs and across time
  - Creation of elements
- What was the origin of the interstellar dust that seeded the formation of planets ?
  - Dust production in main and evolved stars,
  - Formation of hydrocarbons
- How did chemical/physical processes transform the composition of disks into molecules necessary for life?
- How were volatiles and organic molecules delivered to terrestrial planets?

# Planet Characterization

- **Measure global properties of the planet**
  - Orbit
  - Mass
  - Radius (→ density, surface gravity)
  - Surface Temperature
  - Rotation Rate
- **Characterize planetary atmosphere**
  - Determine composition (e.g., detect CO2)
  - Detect key biomarkers (e.g., H2O, O2, O3, CH4, N20)
  - Measure atmospheric pressure (Rayleigh scattering)
  - Detect presence of clouds
- **Characterize surface properties**
  - Detect red edge of vegetation
  - Detect continents
- **Search for Signs of Life**

National Aeronautics and Space Administration

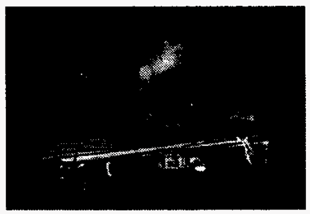
# Summary of NASA's Planet Finding Missions

**TPF-C (2015) and TPF-I (2019)**

- Detect terrestrial and giant planets
- Characterize orbit, mass, temperature, size
- Characterize atmosphere and surface
- Determine habitability
- Search for signs of life

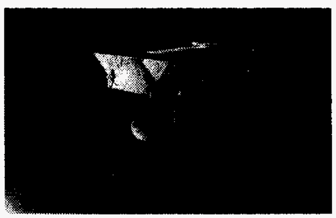
Find Nearby Earths & Life

Distant Planets



**JWST (2012)**

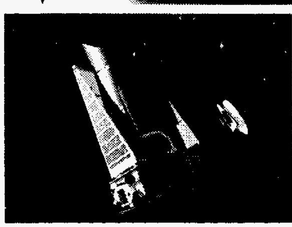
- Image Jupiter's within 5 pc
- Image disks and distant hot young giants
- Follow–up Kepler giants with spectroscopy



**SIM (2011)**

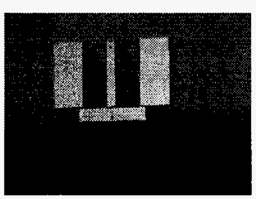
- Search 250 *neighboring* stars for Earths (<50 l. yr.)
- Architecture of systems
- Masses and orbits

Find Nearby Earths



**Kepler (2008)**

- Transits to identify Jupiter's →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

National Aeronautics and Space Administration

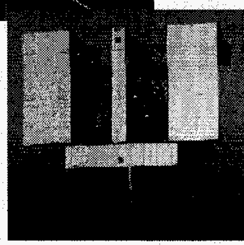
# Roadmap of Planet-Finding Science

Navigator Program: Exploring New Worlds

**KEPLER**

Survey of distant stars for Earths

**KECK**

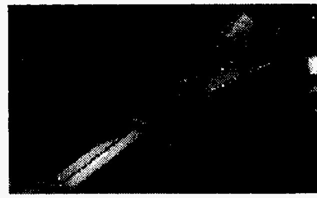


**LBTI**

Survey of nearby stars for dust and giant planets

**SIM**

Masses and orbits of large terrestrial planets



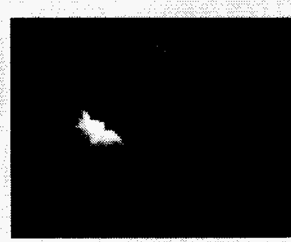
**TPF-C**

Optical signs of habitable worlds

**TPF-I**

Mid-infrared signs of habitable worlds

**ARE THERE OTHER HABITABLE WORLDS?**



**JWST**

Studies of nearby stars for large-scale structure of young systems

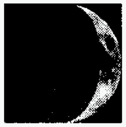
**ARE THERE OTHER SOLAR SYSTEMS LIKE OUR OWN?**

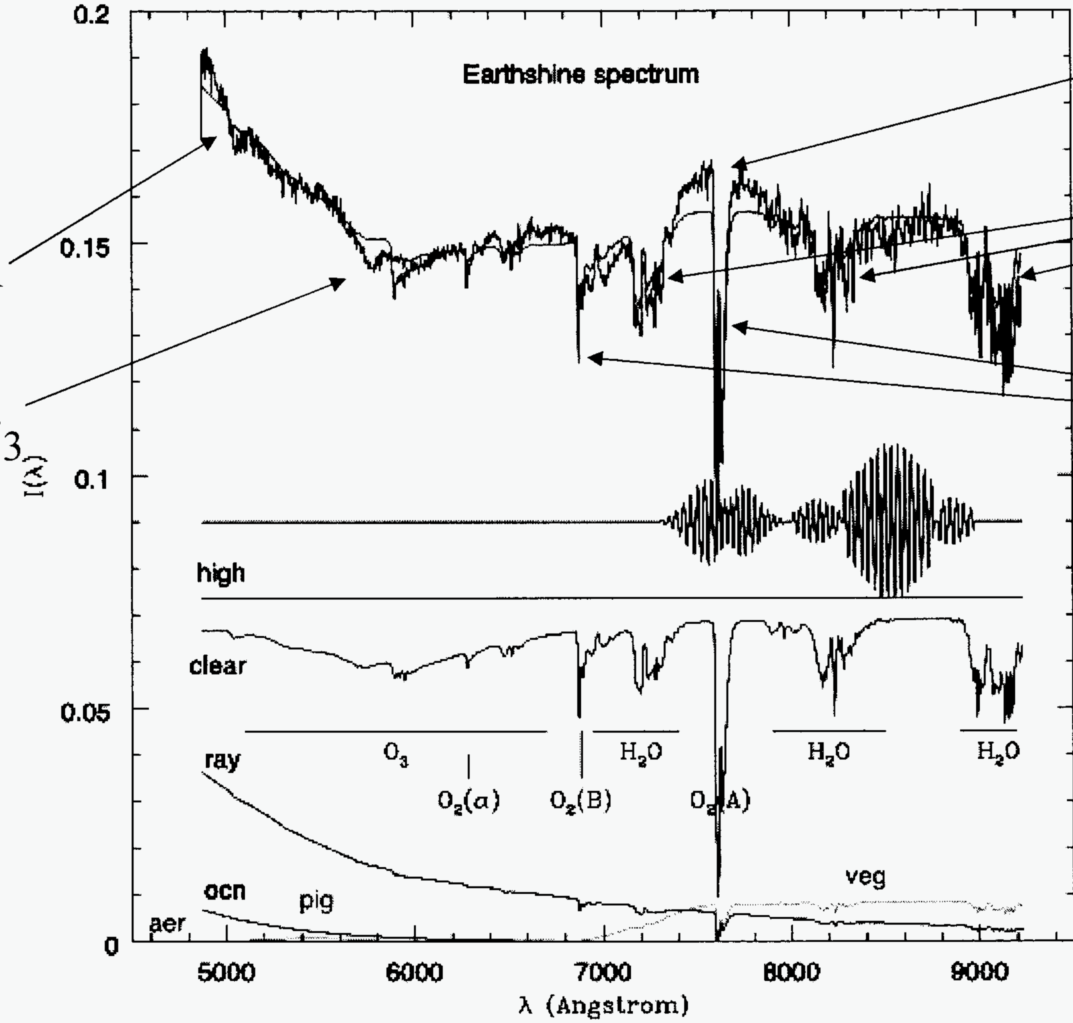
PLANET DETECTION
- Nearby giant planets
- Young, hot Jupiter's

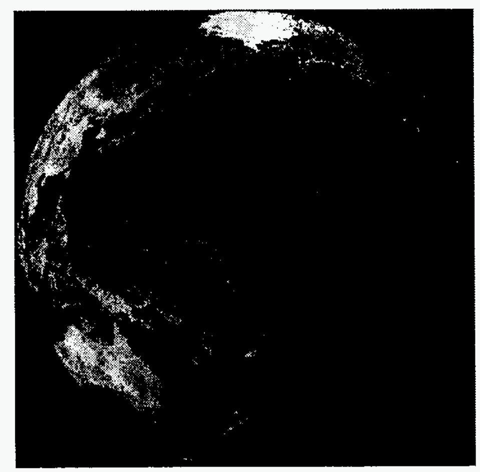
PLANET CHARACTERIZATION
- Planet chemistry in visible and infrared
- Presence of water
- Radius
- Surface gravity and temperature
- Atmospheric conditions
- Biomarkers

2005 | 2010 | 2015 | 2020 | 2025

# Visible spectrum of Earth: validation



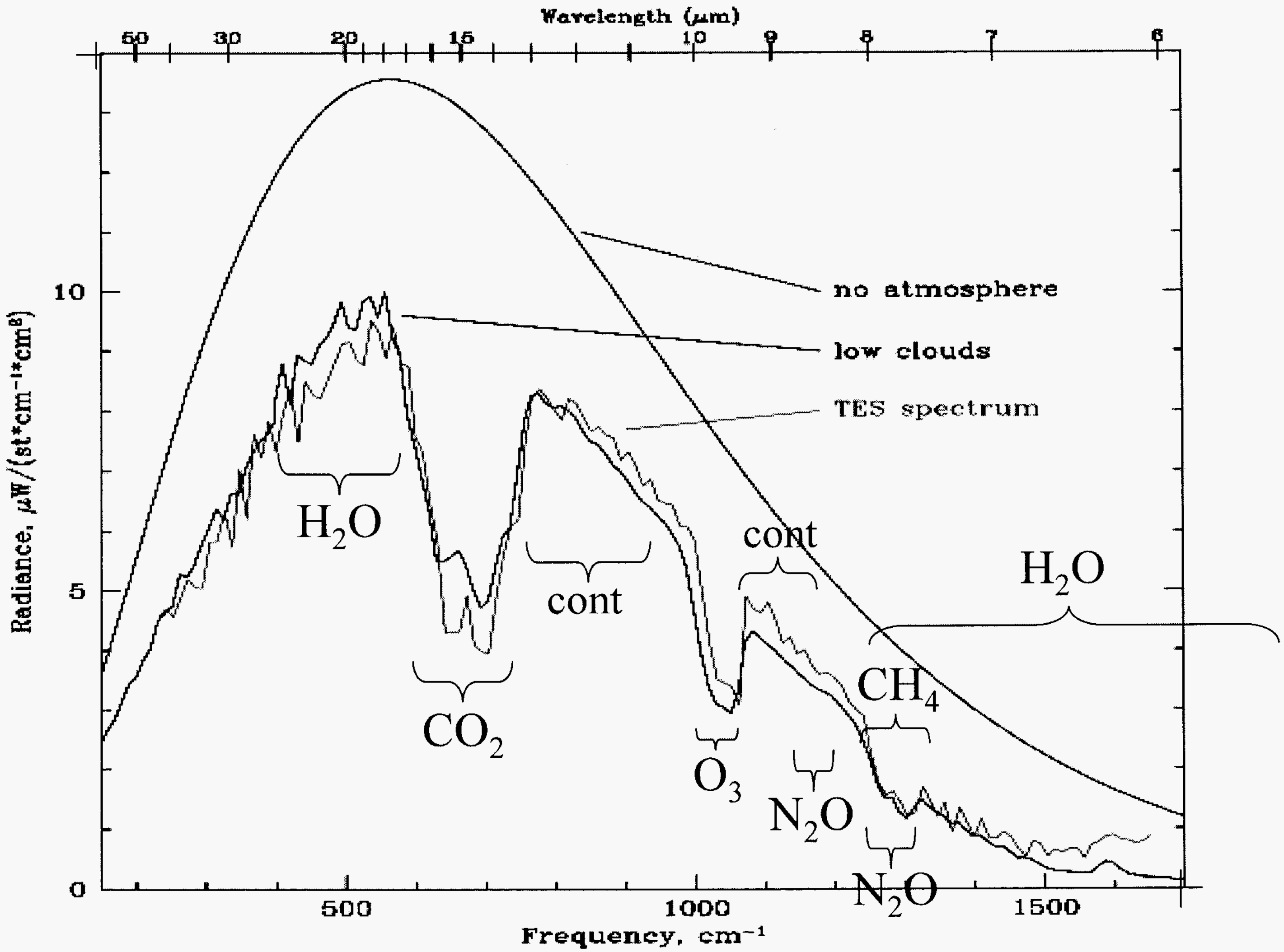


- **Observed Earthshine, reflected from dark side of moon.**

***Ref.: Woolf, Smith, Traub, & Jucks, ApJ 574, p.430, 2002***

# Infrared spectrum of Earth: validation




- Integrated light of Earth, seen by TES enroute to Mars; $CO_2$, $O_3$, $H_2O$ dominate.

## SIM + TPF-C + TPF-I Give 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: is the orbit 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 O2, O3, and H2O, plus Rayleigh scattering and the 'red edge' of vegetation.
- TPF-I will directly detect Earth-like planets, measure their temperatures, and search for H20, O3, N2O and CO2.
- The *combination* of the three missions allows a complete characterization of mass, size, density, albedo, temperature, atmospheric composition, and perhaps variability (seasons?).

# Synergy between SIM, TPF-C, and TPF-I

| | SIM | TPF-C | TPF-I |
|---|---|---|---|
| **Orbital Parameters** | | | |
| Stable orbit in habitable zone | **Meas** | **Meas** | **Meas** |
| **Characteristics for Habitability** | | | |
| Planet temperature | Est | Est | **Meas** |
| Temperature variability due to distance changes | **Meas** | **Meas** | **Meas** |
| Planet radius | *Coop* | *Coop* | **Meas** |
| Planet albedo | *Coop* | *Coop* | *Coop* |
| Planet mass | **Meas** | Est | Est |
| Surface gravity | *Coop* | *Coop* | *Coop* |
| Atmospheric and surface composition | *Coop* | **Meas** | **Meas** |
| Time-variability of composition | | **Meas** | **Meas** |
| Presence of water | | **Meas** | **Meas** |
| **Solar System Characteristics** | | | |
| Influence of other planets, orbit coplanarity | **Meas** | Est | Est |
| Comets, asteroids, and zodiacal dust | | **Meas** | **Meas** |
| **Indicators of Life** | | | |
| Atmospheric biomarkers | | **Meas** | **Meas** |
| Surface biosignatures (red edge of vegetation) | | **Meas** | |

# Key cooperative opportunities

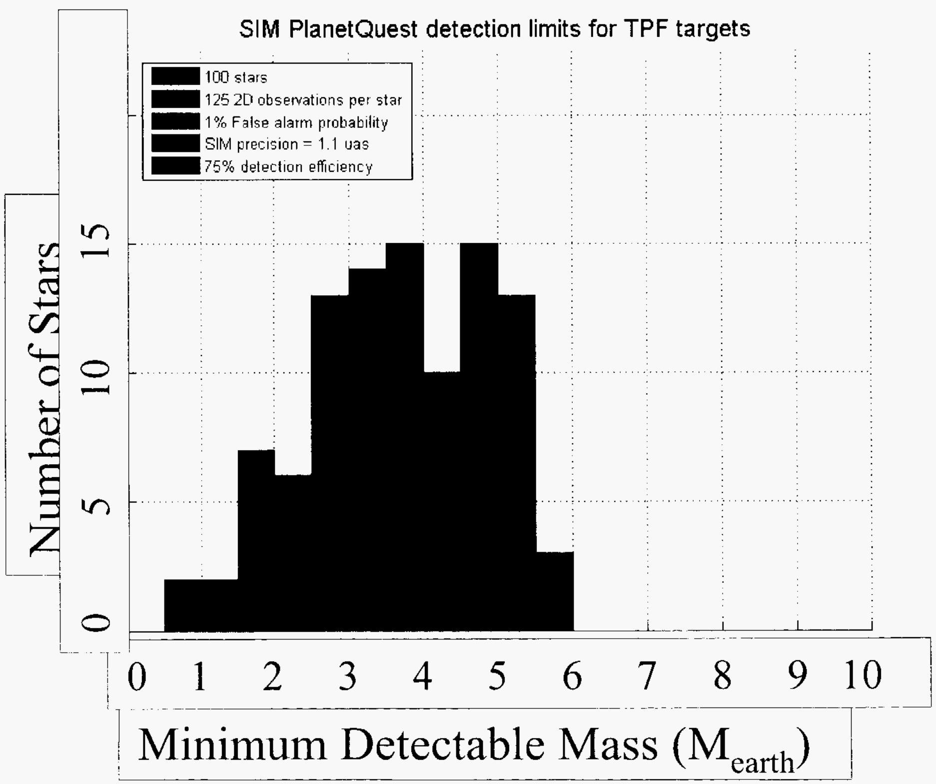
- **International Collaborations**
  - ESA has an active planet finding program.
  - Collaboration on ESA with Herschel, and ESA/CSA on JWST
  - TPF-I/Darwin may be a joint mission.
- **Synergistic Ground-Based Observations**
  - New 20-30 meter class ground-based telescopes enable spectroscopic follow-up of planets detected by SIM, TPF-C and TPF-I. Requires significant investment in ground-based AO technologies
  - New 20-30 meter class ground-based telescopes enable optical spectroscopic follow-up of JWST observations
  - Atacama Large Millimeter Array (ALMA) provides high resolution millimeter and sub-millimeter imaging and spectroscopy of star-forming regions.
- **Inter-agency collaboration on light-weight optics**

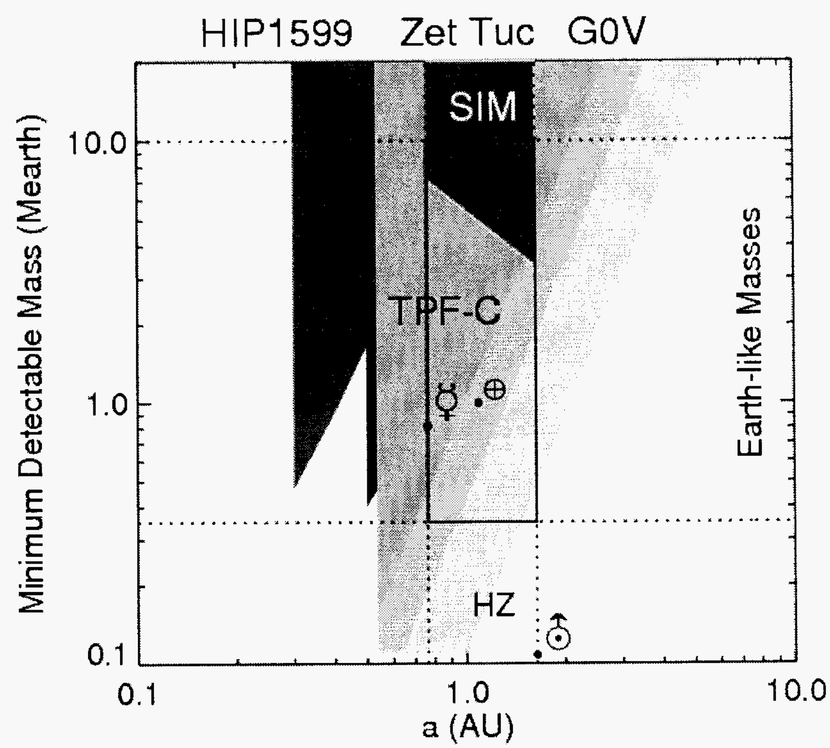
# End

Backup slides follow

# Planet Detection Techniques

- Radial velocity searches
- Astrometry
- Transit Searches
- Gravitational Microlensing
- Direct Detection



# Recent Achievements (1995-2005)

## Planet Detection

- Radial velocity surveys detect 150 extrasolar planets and reveal new types of planets (Hot Jupiters) and unexpected properties of planetary systems.
- Microlensing surveys and transit searches find additional planets

## Planet Characterization

- Spitzer directly detects thermal emission from hot Jupiters
- Transit surveys measure mass and radii of extrasolar planets.
- HST observations characterize atmosphere of transiting hot Jupiter: detect gas evaporation from hot Jupiter

## Planet Formation and Habitability

- HST and Spitzer reveal galaxies in formation
- Spitzer observes proto-planetary disks in environments around stars ranging in mass from less than 1/10th mass of the Sun (brown dwarfs) to massive stars.
- Spitzer detects icy organic compounds, raw ingredients for life, in young star-forming region

# Expected Achievements

| ***Conduct advanced telescope searches for earth-like planets and habitable environments*** | | | |
|---|---|---|---|
| | **Phase 1: 2005-2015** | **Phase 2: 2015-2025** | **Phase 3: 2025 beyond** |
| Planet Detection | a)Measure the frequency of Earth-like planets in a statistically representative sample [Corot ,Kepler]<br>b)Radial velocity surveys detect additional Jupiter analogs and nearby planets with less than 10 $M_{earth}$ [Ground]<br>c)First SIM planet detections | a) Astrometric detection of M > 3 $M_{earth}$ planets in habitable zone within 10 parsecs [SIM]<br>b) Phometric detection of M > 0.5 $M_{earth}$ planets in stellar habitable zone within 10 parsecs [TPF-C]<br>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]<br>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]<br>b) Detect and characterize brown dwarves and Jupiter through their emission [JWST] | a) Measure Mass [SIM]<br>b) Measure radius and surface temperature [TPF-C+TPF-I]<br>c) Detect basic atmospheric composition and presence of clouds [TPF-C+TPF-I]<br>d) Characterize gross surface Properties [TPF-C]<br>e) Detect new classes of planets [SIM, TPF-C, TPF-I] | a) Detect biogenic atmospheric tracers [LFI]<br>b) Detect presence of life [LFI]<br>c) Characterization of new planetary families [LFI]<br>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 (2012+)] | 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] | ) Observe proto-planetary disks with the resolution needed to detect Earths in formation [FIRSI]<br>b) Trace the chemical evolution of the early universe [Large UV/Optical Imager] |

# Near-Term Program (2005-2014)

## The rapid pace of planet discovery will likely to continue to accelerate in the coming decade

- Kepler (2008 launch) determines the frequency of Earth-like planets by detecting planetary occultations around stars 200-600 parsecs from the Sun
- Keck-I and LBT-I detect presence of zodiacal light and measure its evolution as a function of stellar age.
- Ground-based radial velocity surveys detect sub-10 Earth mass planets
- SIM (2011 launch) begins a census of the local neighborhood. SIM measures the masses of planets and characterizes the architectures of nearby systems. SIM reports first rocky planet detections (2014)

## Infrared telescopes will enable exploration of planet-forming environments and study of the emergence of structure

- Spitzer (2003-2008) continues to explore the properties of star-forming systems
- JWST (2011 launch) explores the emergence of the first stars and the formation of the building blocks of life and images brown dwarf companions. JWST is an NASA/ESA/CSA collaboration.
- SOFIA characterizes star-forming regions, proto-planetary disks and images brown dwarf companions.

## Foundational Work

- Research and Analysis program lays the groundwork for following decade by developing new techniques for identifying biosignatures through global observations and for understanding the formation, evolution, and spectra of planets and stars.

## Exploiting Science Opportunities

- Explorer and Discovery missions enable rapid responses to science opportunities

# Mid-Term Program (2015-2025)

## This will be the decade of "New Earths"

- SIM continues its survey of nearby stars. SIM announces detection of ~3 Earth mass planets (2016) and characterizes architecture of nearby planetary systems.
- TPF-C (2015 launch) directly detects terrestrial planets around nearby star systems. Some of these planets may be Earth-like, while other planets have radically new properties ("water worlds," super-Europas)
- TPF-I (2019 launch) searches for terrestrial planets over a larger volume of the Galaxy. It significantly increases our catalog of known terrestrial planets. ESA and NASA may collaborate on TPF-I
- The combination of TPF-C and TPF-I measurements yields determination of planetary radii and surface temperature. TPF-C and TPF-I could detect the first signs of planetary habitability and even the presence of life
- Large ground-based telescopes (20-30m) follow up on SIM and TPF planet detections.
- NASA Research and Analysis program develops new techniques for identifying biosignatures through global observations, for understanding the formation and evolution of planets and stars and the physical and spectral properties of the newly discovered planets

## Significant advances in our understanding of the emergence of the first structures and the physics of planet formation

- JWST detects the earliest known stars and galaxies. It traces the formation of structure and of the components of life from the early universe to nearby star-forming regions. TPF-C and TPF-I will provide complementary high resolution measurements.
- SOFIA measures chemical properties of star-forming regions. SAFIR will measure the extent, structure and compositions of planet-forming disks at high spatial resolution.

## Origin Probes, Discovery, and Explorer program enables flexible responses to new scientific opportunities. RA program supports foundation for field.

# Long-Term Program (2025-

- Life Finder will be design to detect the unambiguous signs of life around nearby stars
- Far Infrared Space Interferometers (FIRSI) will be able to image planet forming disks
- TPF-I and FIRSI will be technology path-finders for kilometer-scale constellations capable of imaging extrasolar planets. These space interferometers will revolutionize astronomy by providing ultra-high resolution imaging.
- Large-Aperture UV/Optical Telescope, a successor to HST at UV and optical wavelengths traces the emergences of elements
- NASA Research and Analysis program focuses on interpreting the biosignatures detected through global observations and understanding the full links between star formation, environment, and habitability.