1962 to 2006: NASA's Search for Extra-Solar Planets and Life Around Nearby Stars

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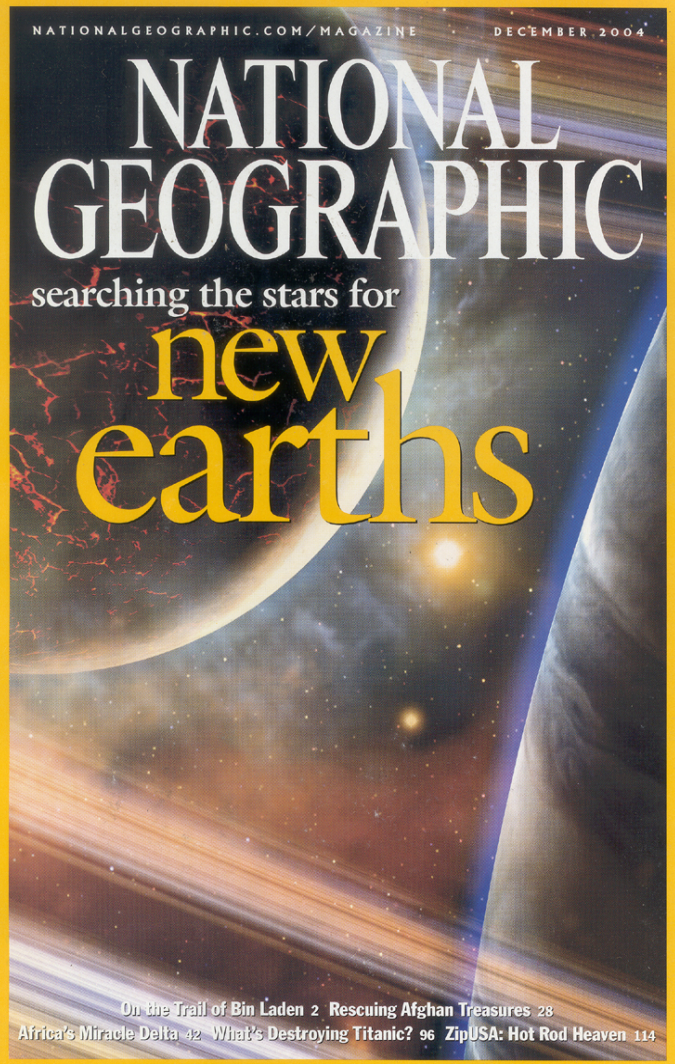
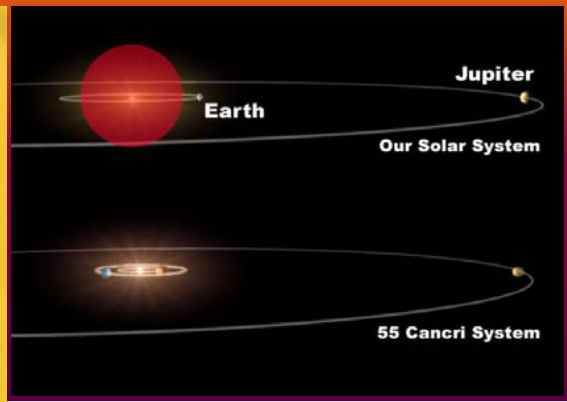
7 July 2006

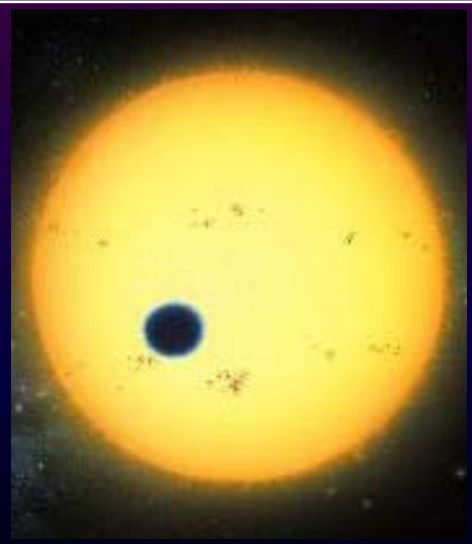
*"Sentence **first**--*
***verdict** afterwards."*
Queen of Hearts

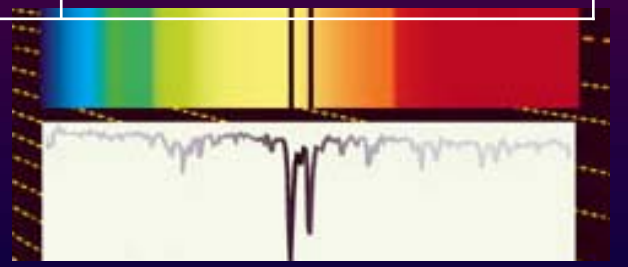
Planet Finding: A Rapidly Growing Field With Enormous Public Appeal

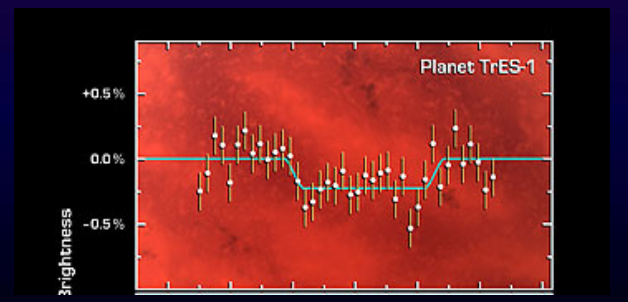




180 Radial Velocity Planets	Hundreds of Comet and Asteroid Belts
5 Transiting Systems	Spectra & Heat Output





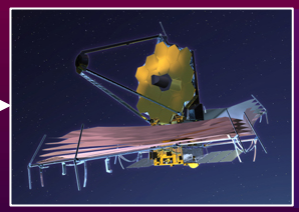


Summary of NASA's Planet Finding Missions

TPF-C/I

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

Distant Planets



JWST

- Image 1-2 Jupiter's within 5 pc
- Image disks and distant hot young Jupiter's
- Follow–up Kepler "Jupiter's" with spectroscopy

SIM

- Search 200 *neighboring* stars for Earths (<30 pc)
- Determine architecture of systems
- Measure masses and orbits

Find Nearby Earths & Life

Kepler (2008)

- Transits to identify Jupiter's → Earths around 100,000 *distant stars* (<1 kpc) to determine incidence of Earths

Keck-I (2006)

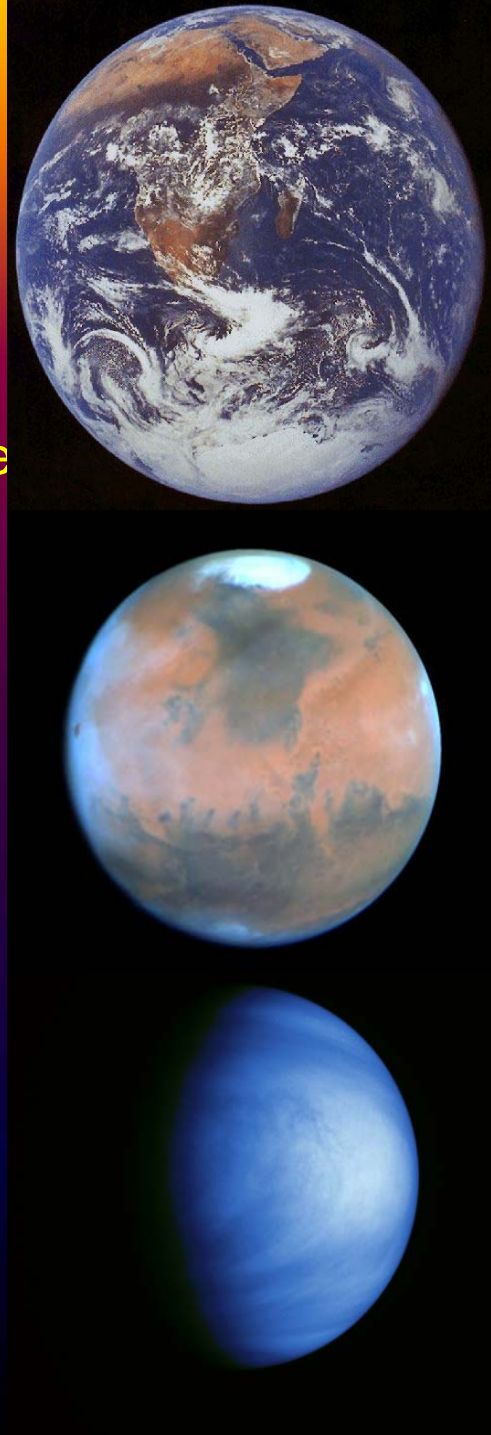
- Dust disks at 10-100 zodi for nearby stars

LBTI (2008)

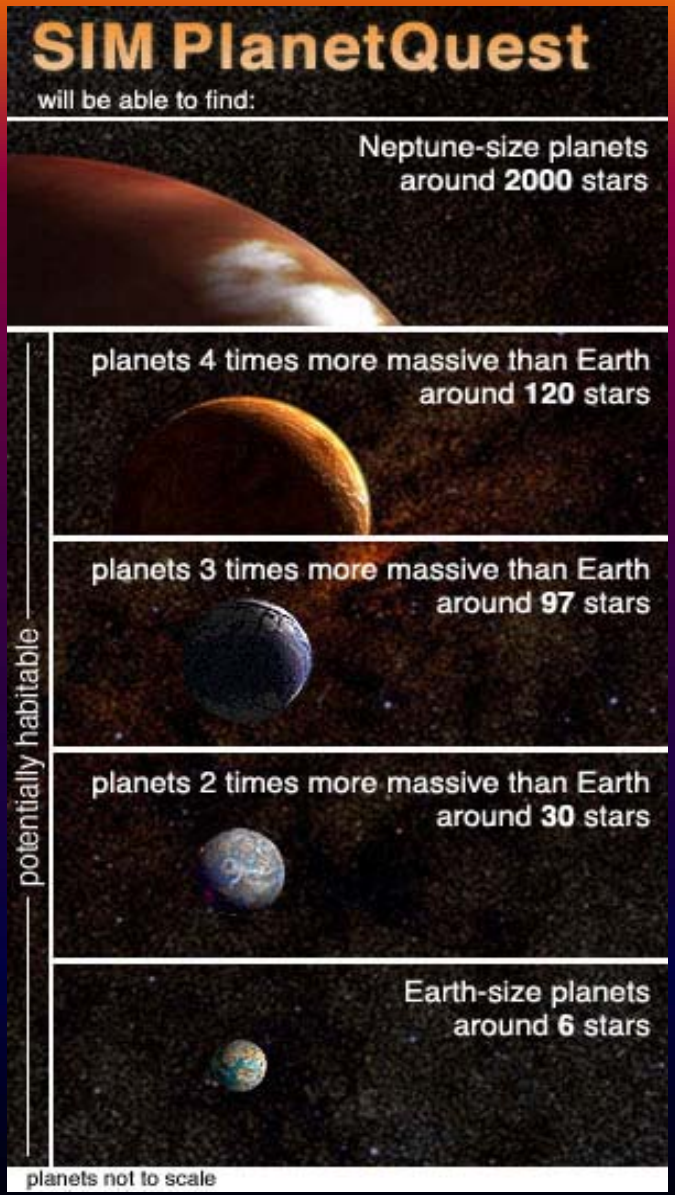
- Dust disks at 3-10 zodi for nearby stars

Overall Planet Finding Program Finds Other Earths and Searches for Life

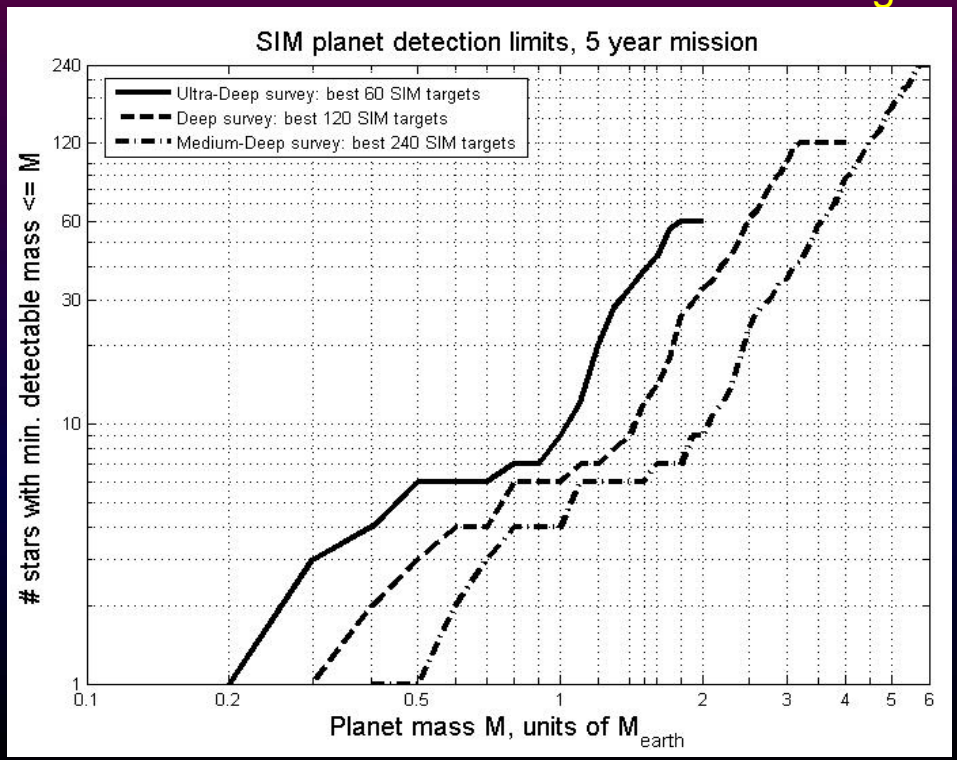
- 3 Science Teams and 2 Roadmap Teams identified synergy of SIM, TPF-C, TPF-I
  - Need Masses, Orbits, Visible Photons, IR Photons to Characterize Planets, Search For Life
- Orbital Parameters
  - Identify stable orbits in habitable zone (SIM)
- Characteristics for habitability
  - Mass --- Fundamental parameter (SIM)
  - Orbital Temperature Variability (SIM)
  - Radius (SIM and TPF-I)
  - Albedo (SIM and TPF-C)
  - Surface gravity (SIM and TPF-I/C)
  - Temperature (TPF)
  - Atmospheric Composition (TPF)
- Solar System Characteristics
  - Influence of other planets (SIM)
  - Presence of comets or asteroid belts (TPF)
- Indicators of Life (TPF)



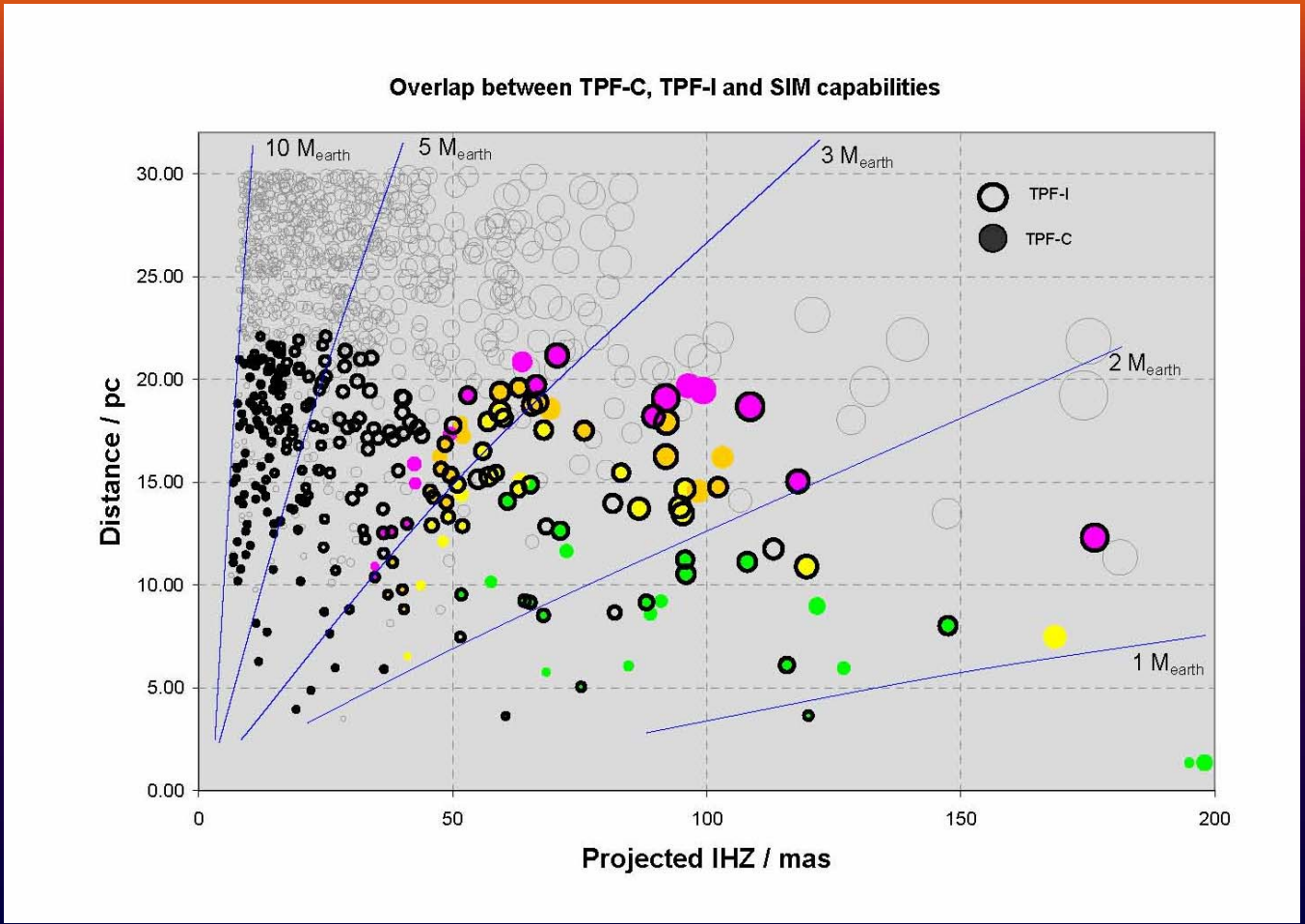
SIM Planet Finding Capabilities



- Potentially Habitable Planets are defined as:
  - Terrestrial planets in the habitable zone, where HZ = (0.7 to 1.5)$(L_{star}/L_{sun})^{0.5}$ AU
  - Mass: 0.33 $M_\oplus$ to 10 $M_\oplus$ and Radius: 0.5 $R_\oplus$ to 2.2 $R_\oplus$
  - Orbit: $e \leq 0.35$
- Deep search of 120 nearby stars within 30 parsecs.
- Based on a 5 year science mission, with
  - 1 uas single measurement accuracy with a 1.4 μas differential measurement in ~ 20 minutes, and
  - An allocation of 17% of SIM mission observing time.



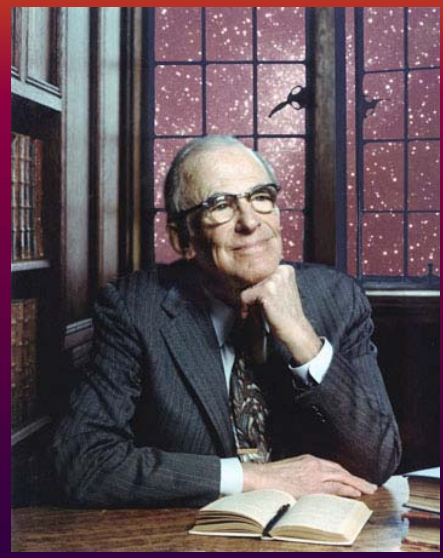
Synergy between SIM/TPF-C/TPF-I

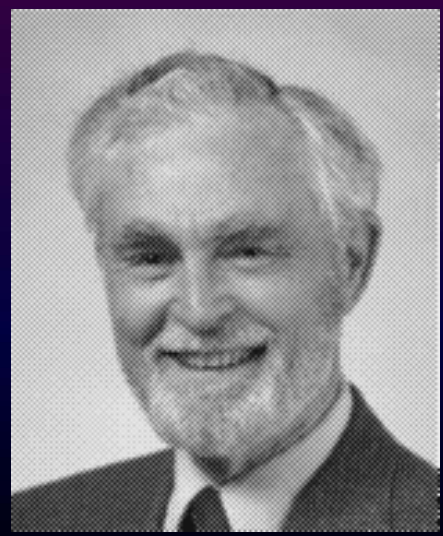


At least 35 stars observable in common between SIM, TPF-C and TPF-I/Darwin will enable synergistic characterization and search for biomarkers

Beginnings of Modern Planet Searches

- "This [*the search for planets beyond the solar system*] is a matter of very great philosophical and cultural as well as of scientific interest. Our view of man and his place in the universe naturally depend very much on whether planetary systems like our own are exceptional or whether they occur very frequently throughout the Galaxy." --- Lyman Spitzer in "*The Beginnings and Future of Space Astronomy*," American Scientist, 1962, 50, pp 473-484
  - This article outlined optical coronagraphic approaches to the problem of direct detection of planets in visible light
- R.N. Bracewell, "Detecting Nonsolar Planets By Spinning Infrared Interferometer," Nature **274**, 780-781 (1978) developed the concept of the nulling interferometer for direct detection in the mid-infrared





Brief History of Studies And Recommendations

- *NAS/NRC Studies*
  - *Origin and Evolution of Life Implications for the Planets: A Scientific Strategy for the 1980s*, Committee on Planetary Biology and Chemical Evolution (1981)
  - Committee on Planetary and Lunar Exploration, Space Studies Board, *Strategy for the Detection and Study of Other Planetary Systems and Extrasolar Planetary Materials: 1990-2000*, National Academy Press, Washington, D.C., 1990.
  - Astronomy and Astrophysics Survey Committee, National Research Council, Astronomy and Astrophysics for the 1990s, 1991. (*SIM/AIM*)
  - Astronomy and Astrophysics in the New Millennium, National Research Council, 2000 (SIM mission and TPF technology)
- *NASA Studies*
  - *Project Orion: A Design Study of a System for Detecting Extrasolar Planets, NASA SP-436.* D.C. Black and W.E. Brunk, Eds., 1980,
  - *Planetary Astronomy Committee of the Solar System Exploration Division, Other Worlds From Earth: The Future of Planetary Astronomy,* NASA, 1989.
  - Toward Other Planetary Systems (TOPS), NASA, 1992
  - Exploring Neighboring Planetary Systems (ExNPS), NASA, 1996
  - Terrestrial Planet Finder (TPF), NASA/JPL, 1999
  - Summary Report on Architecture Studies for the Terrestrial Planet Finder, NASA/JPL 2002
  - Report of the Science and Technology Definition Team for the Terrestrial Planet Finder, NASA/JPL, 2006

Observations & Quotations

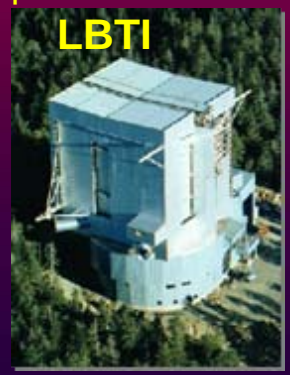
- Bahcall report (NRC 1991) endorses AIM/SIM:
  - "… would permit definitive searches for planets around nearby stars";
  - "… trigonometric distances throughout the galaxy";
  - "… would demonstrate the technology required for future missions"
- McKee/Taylor report (NRC 2000) sets 4 strategic goals including: "*Search for life beyond Earth, and if it is found, determine its nature and distribution. This goal is so challenging and of such importance that it could occupy astronomers for the foreseeable future.*"
  - "…reaffirms the recommendations of the 1991 Astronomy and Astrophysics Survey Committee by endorsing the completion of …the Astrometric Interferometry Mission (now called the Space Interferometry Mission.)"
  - "NASA should pursue a vigorous program of technology development to enable the construction of TPF to begin this decade."
- President weighs in: *"Conduct advanced telescope searches for Earth-like planets and habitable environments around other stars"*
- Congress weighs in: *"…the conferees expect that NASA will continue funding for the Terrestrial Planet Finder."* (FY06 Appropriations Conference Agreement)
- The NASA Administrator comments on TPF: "*I do think that it is important to note that we are delaying missions (TPF), not simply abandoning them."* February 9, 2006
- The House weighs in (again):
  - "The recommendation provides funding for the continuation of the Terrestrial Planet Finder (TPF). TPF will study all aspects of planets outside our solar system to find earthlike planets and study those planets' ability to maintain life."
  - "The recommendation includes the requested level of $98,500,000 [*in the President's budget!*] for the Space Interferometry Mission (SIM). This mission will permit a dramatic leap in our understanding of many processes in astrophysics and is a key mission in NASA's search for Earth-like planets and life. Technologies being developed for SIM are also critical to the next generation of space-based telescopes." (House Appropriations Committee, June 28, 2006)

The Navigator Program

"Conduct advanced telescope searches for extra-solar planets and habitable environments." --- NASA Vision

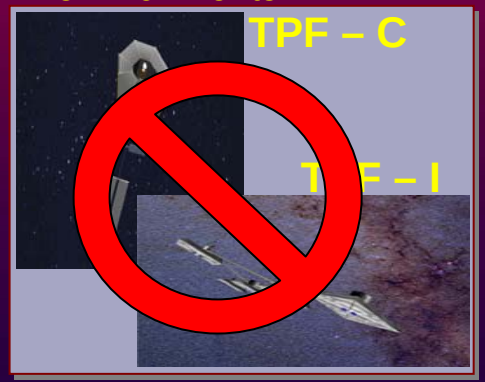
- Characterize inner exo-zodiacal dust environments
- Identify long-period planets ("Earth-Jupiters")

- Characterize outer dust environments
- Observe giant planets



- Search for terrestrial planets
- Characterize planetary systems
- Determine planet mass

- Find and characterize exo-solar planets and habitable environments



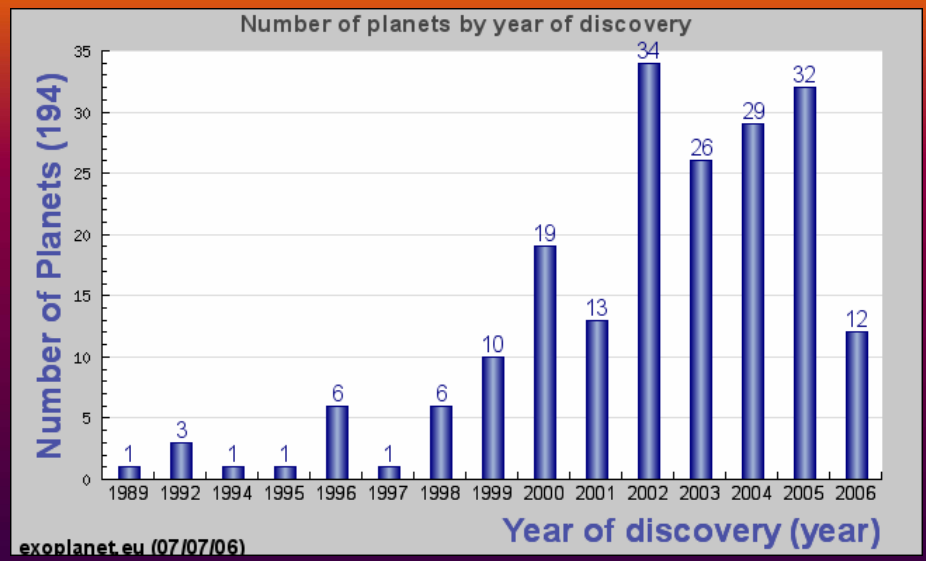
- Science community development through Michelson Science Center
- Research support through Michelson Fellowships, TPF – Foundation Science and TPF – Technology contracts

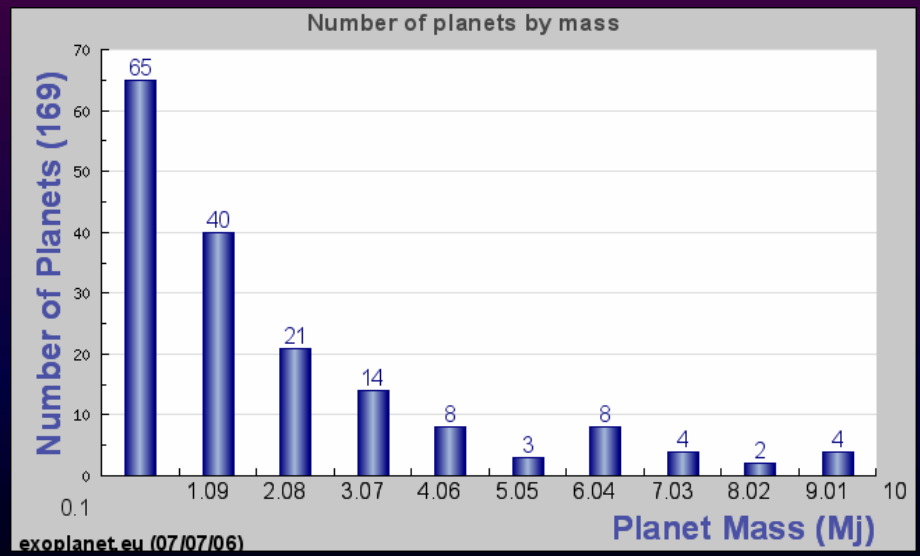
What is Left?

- With cancellation/deferral of Keck Outriggers, SIM, and TPF there remains little in the way of searches for NEARBY planets
  - Ground-based radial velocity studies are 5-10x worse than level needed to detect 1 $M_{\oplus}$ planets in 1 AU (10 cm/sec amplitude)
- Kepler will identify planets around distant stars
  - JWST will follow-up more massive planets
- JWST will image hot Jupiters around young stars, but not Jupiters in reflected light and not Earths.

What Is Lost?

- First space mission (SIM) to look for earth-like planets around nearest stars
- Leadership in wide range of fields based on global astrometry
- Present/future (young) scientists who want to develop comparative planetology and search for life on other planets with Keck-I, SIM, TPF, etc
  - Loss of near term funding and long term support through dedicated missions
- 15+ year program of technology development in interferometry, precision wavefront sensing and control, coronagraphy, formation flying
  - Existing and future generations of technologists and engineers in NASA Centers, Universities, and Industry who would build SIM and TPF and lay the groundwork for future missions using these technologies





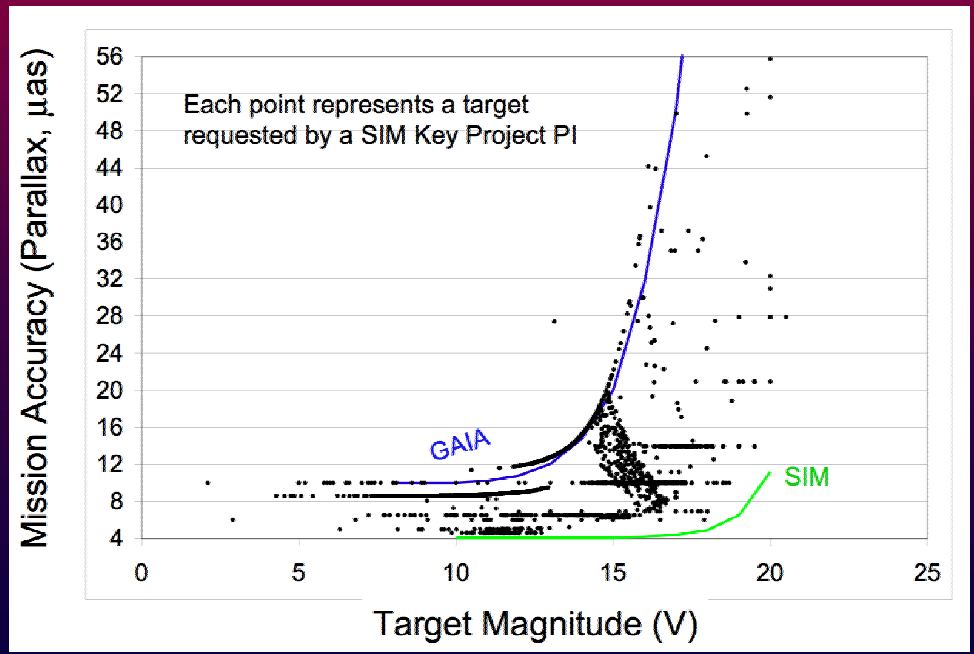
SIM Specific Discussion

SIM Astrophysics

- SIM does much more than just planet finding with 60% of SIM science time for non-planetary astrophysics
- High precision astrometry applied to definitive studies of
  - Distance scale problem
  - Age scale (star clusters)
  - Mass-luminosity relation
  - Galactic structure / stellar populations / dynamics
  - Dark matter (from galaxy scale to MACHO candidates)
  - Local group dynamics / cosmology
  - AGN structure
  - Black holes, other stellar remnants, x-ray binaries
  - Establish the inertial frame 50x more precisely than ICRF
  - *Target of opportunity capability*
- PLUS: 1/3 of total science time still available for *new* cutting edge science goals through GO program

SIM and GAIA Carry Out Very Different Science Programs

- Both SIM and GAIA use astrometry to address a wide range of astrophysical questions
- GAIA observes a large number of stars at *low accuracy*
  - Most science relies on averaging data from many stars
- SIM selects samples of targets tailored to science questions
  - Observes each star at *very high accuracy*
  - *Most are too faint to observe with GAIA*
- SIM's ability to detect planets is 70 times better than GAIA
- *Virtually all SIM Science Team targets are beyond the reach of GAIA's capability*

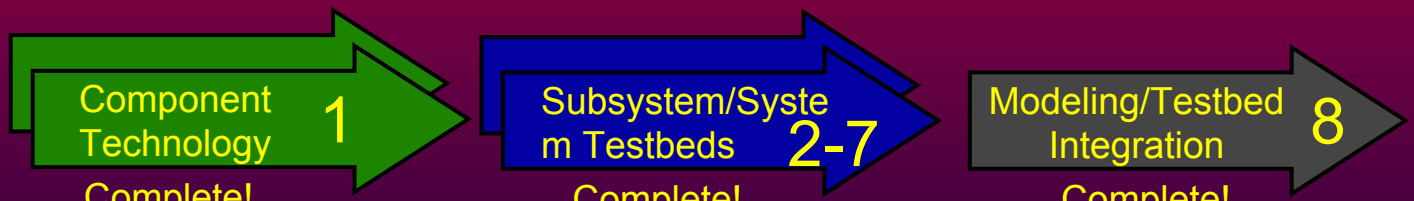


SIM Science (and fraction accomplished by GAIA)

Key SIM Science Project Objectives	GAIA %
Find Earth-sized planets in Habitable Zone	0%
Reconnaissance of young planetary systems	~0%
Unbiased galactic mass function (from microlensing)	0%
Star masses to 1% (SIM program emphasizes difficult types)	~0%
Motion in/of QSO's, AGN's	0%
Exo-Planetary system contents census	>Jupiter
Local Galaxy group mass distribution (from motions)	8%
Age of galaxy (from globular clusters and stellar models)	20%
Structure of Galaxy (size, spiral arms, tidal streams, bulge, halo)	~50%
Coordinate frame tie to cosmological standard of rest (QSO's)	~50%

SIM Technology Development - Complete!

- Technology plan laid out in mid-1990s
- NASA HQ and SIM project laid out 8 Key Technology Gates in 2001
  - 4 Gates prior to Phase B start; 4 more Gates prior to Phase C/D start
- All 8 Technology Gates were completed on schedule with external peer review
- External reviewers & NASA sponsor have concurred: ***Technology is complete***.
- NASA & Project have established 9 Engineering milestones for Phase B/C/D



Goal-Level Performance & TRL-6 Maturity Has Been Demonstrated


MAM


KITE


STB-3

Technology Gate 8


TOM-3 + Int'd Modeling

Subsystem-level Testbeds

System-level Testbed

Modeling/Testbed Integration

The Facts About SIM Cost

- SIM Implementation cost (phase C/D) is $1,200M in FY05$
  - Includes launch vehicle and reserves
- Phase C/D cost & schedule are extraordinarily robust
  - 54% budget reserve on the Instrument
  - 43% budget reserve on project cost excluding launch vehicle
  - 19% budget reserve on the launch vehicle
  - I&T/ATLO planned schedule longer than Spitzer & Chandra actuals
- Delay to 2015 costs more due to extended Phase B & inflation
- In RY dollars, the costs for a 2011 and 2015 launches are:

LRD	2011	2015	Delta	
Sunk Cost	$ 510M	$510M	zero	
Phase B 'to-go' (>FY06)	$ 340M	$800M	$460M	
Phase C/D cost	$ 800M	$890M	$ 90M	
Phase C/D Reserve (43%) & LV	$ 610M	$680M	$ 70M	= **$1.2B FY05$**
5-year operations	$ 460M	$540M	$ 80M	
Total:	$2,720M	$3,420M	$700M	

- The Project is technically ready to launch in late 2011 and would save more than $700M

What Should Come Next?

- NASA has deviated drastically from 2 decades of recommendations and planning concerning searches for planets, and research into planet formation, evolution, and the possible presence of life on other worlds
- An NAS/NRC group, either CAA, NRC Review Team, or "NASA Astrophysics Performance Assessment Committee," should look over the 20 year history of Academy recommendations in these areas to assess whether the broad wishes of the scientific (astrophysics, planetary, astrobiology) community are being carried out.