Exploring the Central ArcSecond: Future Prospects for Interferometry

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With lots of help from Oliver Lay, Peter Lawson, TPF-I SWG

Probing The Central Arcsecond

- Angular resolution remains the final new frontier in astronomical measurement at visible and IR wavelengths
- Interferometry and its sibling Adaptive Optics are opening the way to sub-arcsecond & eventually milli-arcsecond imaging, and micro-arcsecond astrometry
- Long term capabilities utilizing interferometry will find other Earths and have the potential to revolutionize our conception of humanity’s place in the Universe

Exciting Near- and Mid-Term Prospects In Ground-Based Interferometry

- Keck-I (near IR V^2 and 10 um nuller only)
  - Near-term plans to improve V^2 performance and add wavelengths
  - Funded program to add Laser Guide Star AO and Dual Star feed
- VLTI
  - Well-planned, continental wide approach to interferometry
  - → We should all move to Europe
- CHARA & PTI
  - Active but underfunded programs in interferometry
- NPOI
- Keck-I (Outriggers).
  - Looking for a home. Donations accepted.
- OHANA
  - Demonstrate multi-telescope, long baseline interferometry in anticipation of Optical VLA
- Magdelena Ridge Observatory

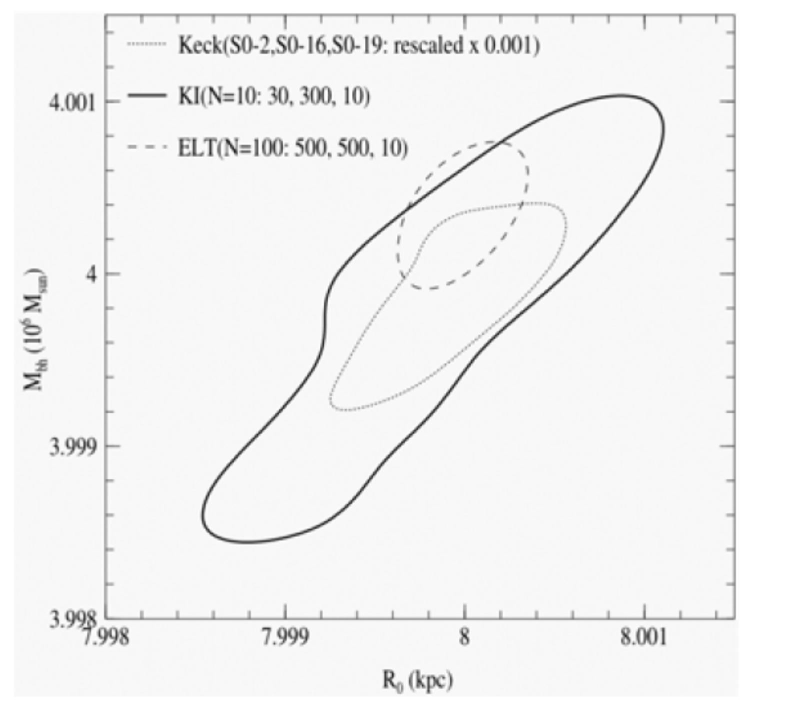
These interferometers are moving beyond targets from Ptolemy's Almagest stellar catalog (150 AD) into HD (1924 AD) and NGC (1888 AD) catalogs → Very exciting science

Near- and Mid-Term Science Goals

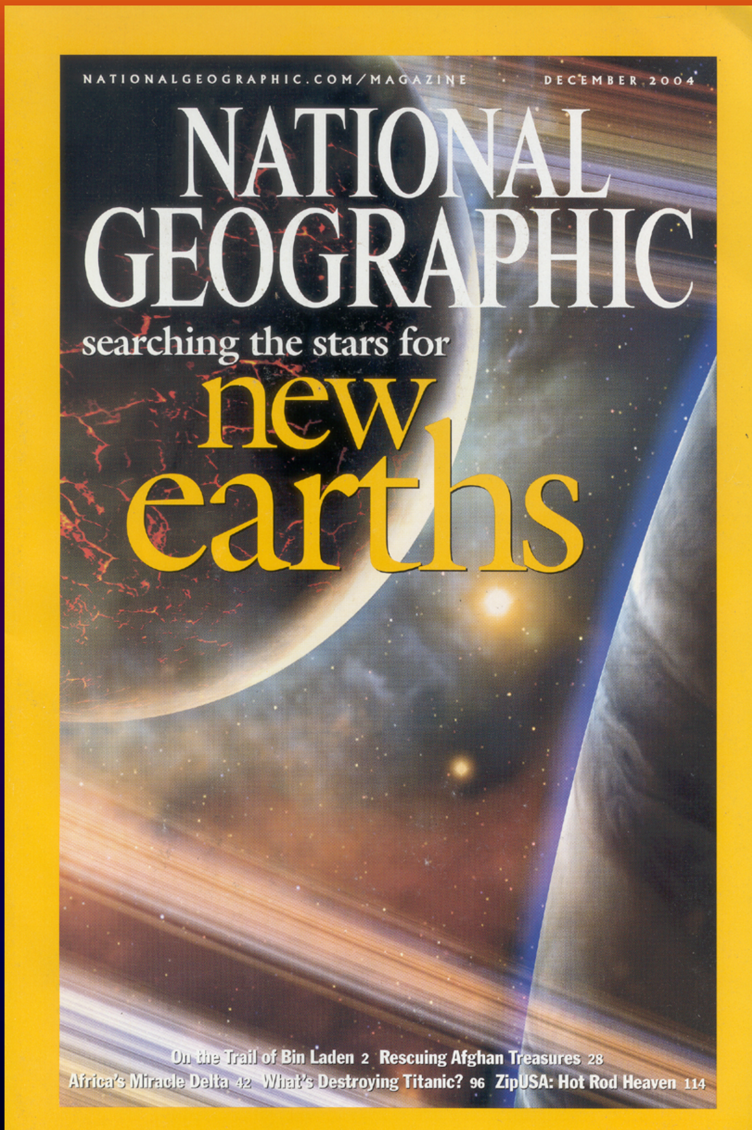
- Basic Stellar Properties
  - Diameters from V^2
  - Orbits and masses from astrometry
- Gas Giant Planets
  - Differential Phase
  - Astrometry (PHASES @ PTI)
- Young Stars
  - Structure of disks
- Evolved Stars
  - Structure of extended atmospheres and dust clouds
- Galactic Center
  - Mass of central black hole
- AGN
  - Structure of Broad/Narrow Line Regions

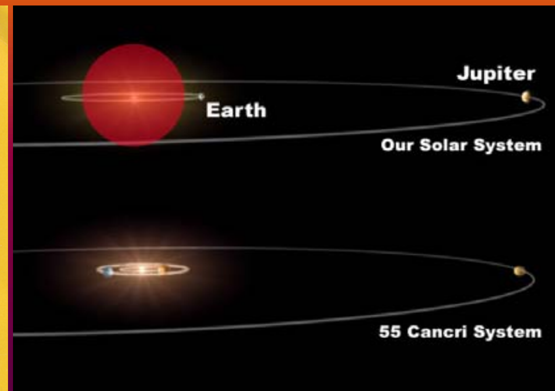
Upgraded Keck-I Performance

Performance	*K* limit (mag.)	Astrometric accuracy (μas)
Current	9	1000
Upgraded		
Protoplanetary disks	14	n/a
AGNs	14	n/a
Exoplanets	9.5	100
Galactic Center	15	30

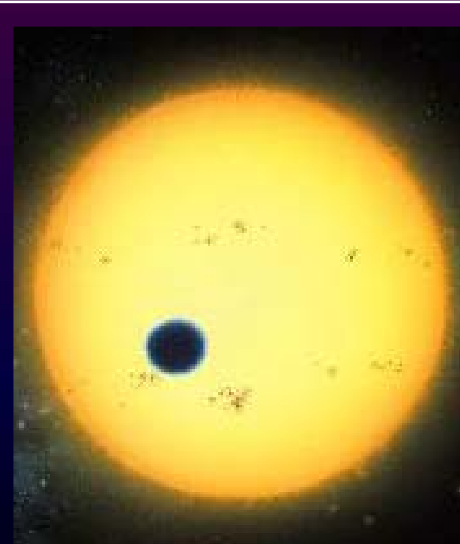


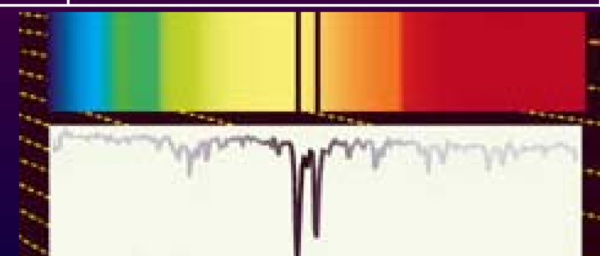
Planet Finding: A Rapidly Growing Field With Enormous Public Appeal

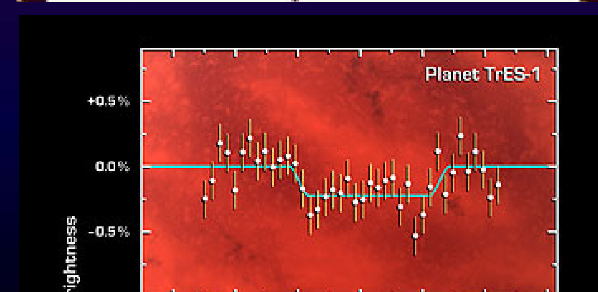




180 Radial Velocity Planets	Hundreds of Comet and Asteroid Belts
5 Transiting Systems	Spectra & Heat Output

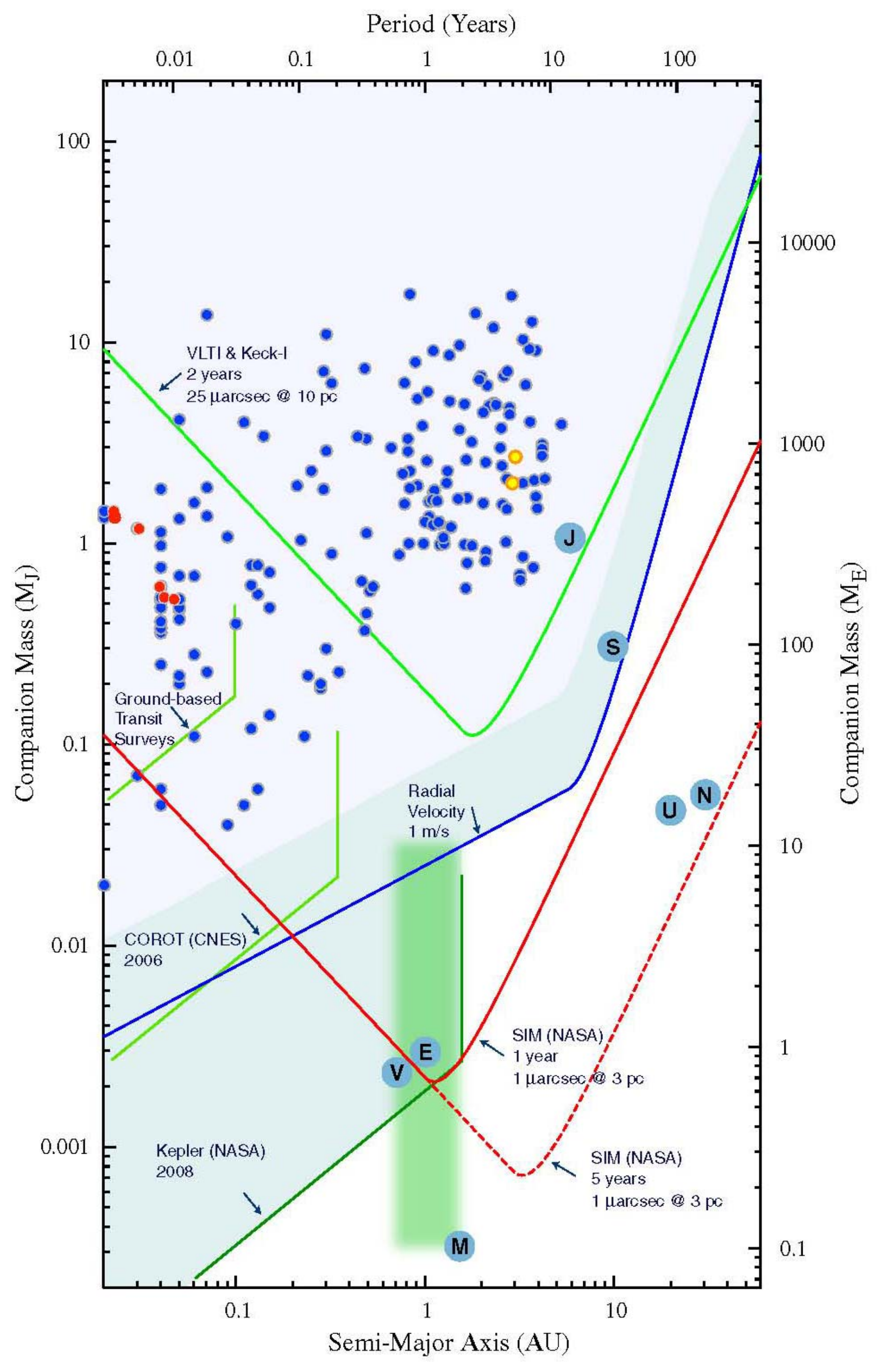






Indirect Techniques Finding Wide Range of Planets

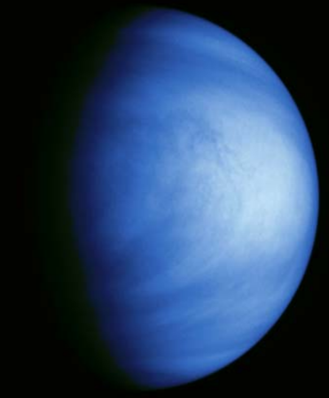
- Radial velocity prolific
  - Uranus → Jupiter mass
  - <0.1 AU to >5 AU
  - Incidence ∝ [Fe/H]^2
- Transits up and coming
  - R & M (from RV) → density
  - Photometry and spectra →albedo and T
  - Space missions will expand
- Microlensing
  - Lowest mass planet (5.5 M_{Earth})
  - Jupiter's are rare (?)



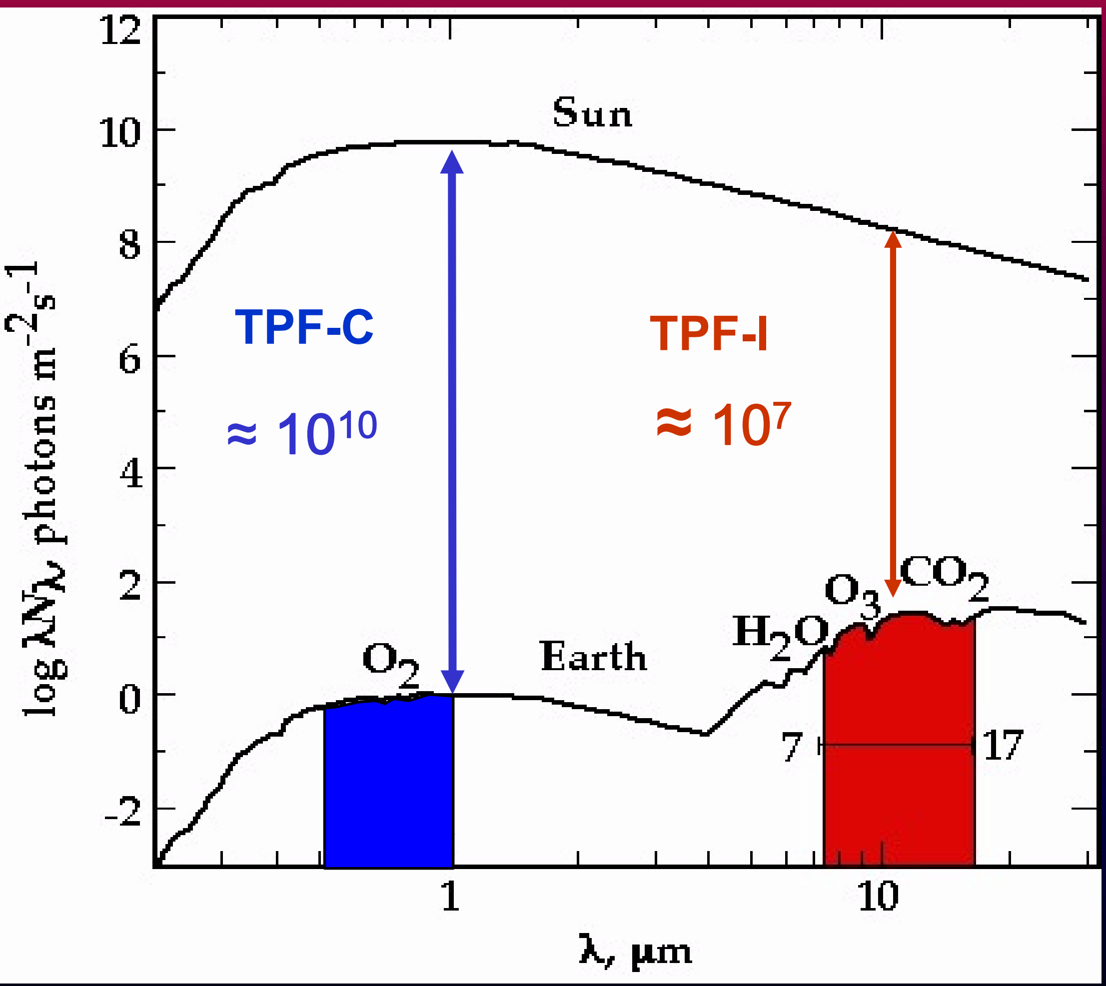
• No Solar System Analogs yet discovered or even detectable

Characterizing Other Earths and Searching for Life

- Multiple datasets needed to characterize terrestrial planets and to search for life
  - Masses & Orbits, Visible Photons & IR Photons
  - → Synergy of SIM, TPF-C, TPF-I
- 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)



Terrestrial Planet Finders (TPFs)



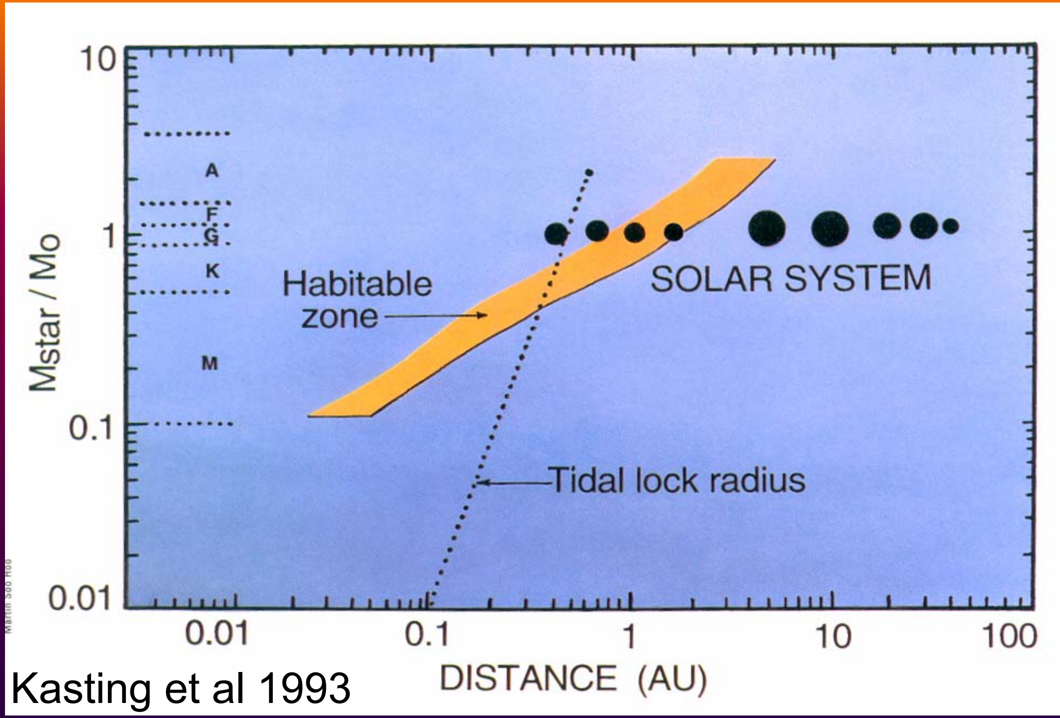
Visible or thermal-IR?

- Contrast ratio:
  10^{10} in the visible
  10^{7} in the thermal-IR

Courtesy: Chas Beichman, JPL

Search the Habitable Zone

- The goal of TPF is to find and characterize rocky planets within the *habitable zones* of their parent stars
- HZ is reasonably wide as a consequence of feedback between CO_2 and climate:

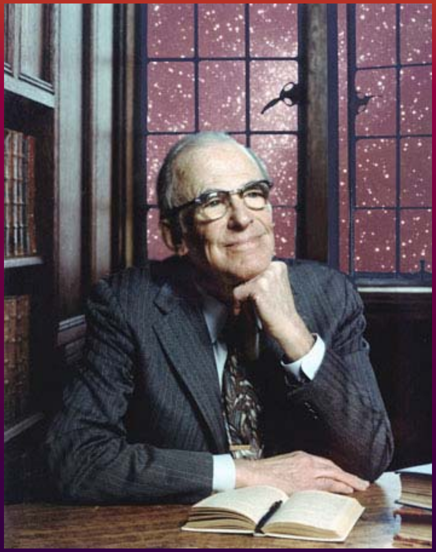


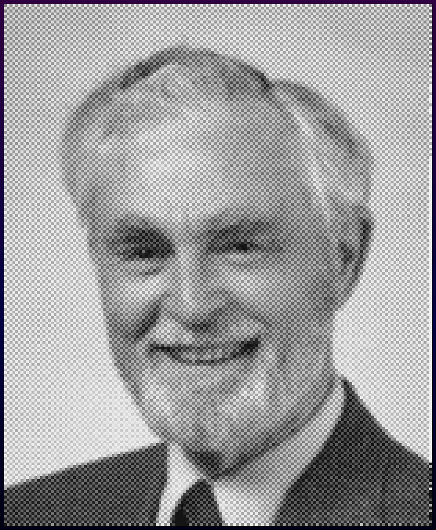
Kasting et al 1993

  - As a planet's climate cools, volcanic CO_2 should build up in its atmosphere warming planet
- HZ sets angular resolution requirement (1 AU HZ around G star at 10 pc subtends 0.1")
  - Need roughly 0.050 mas →8 m in visible, 80 m in mid-IR

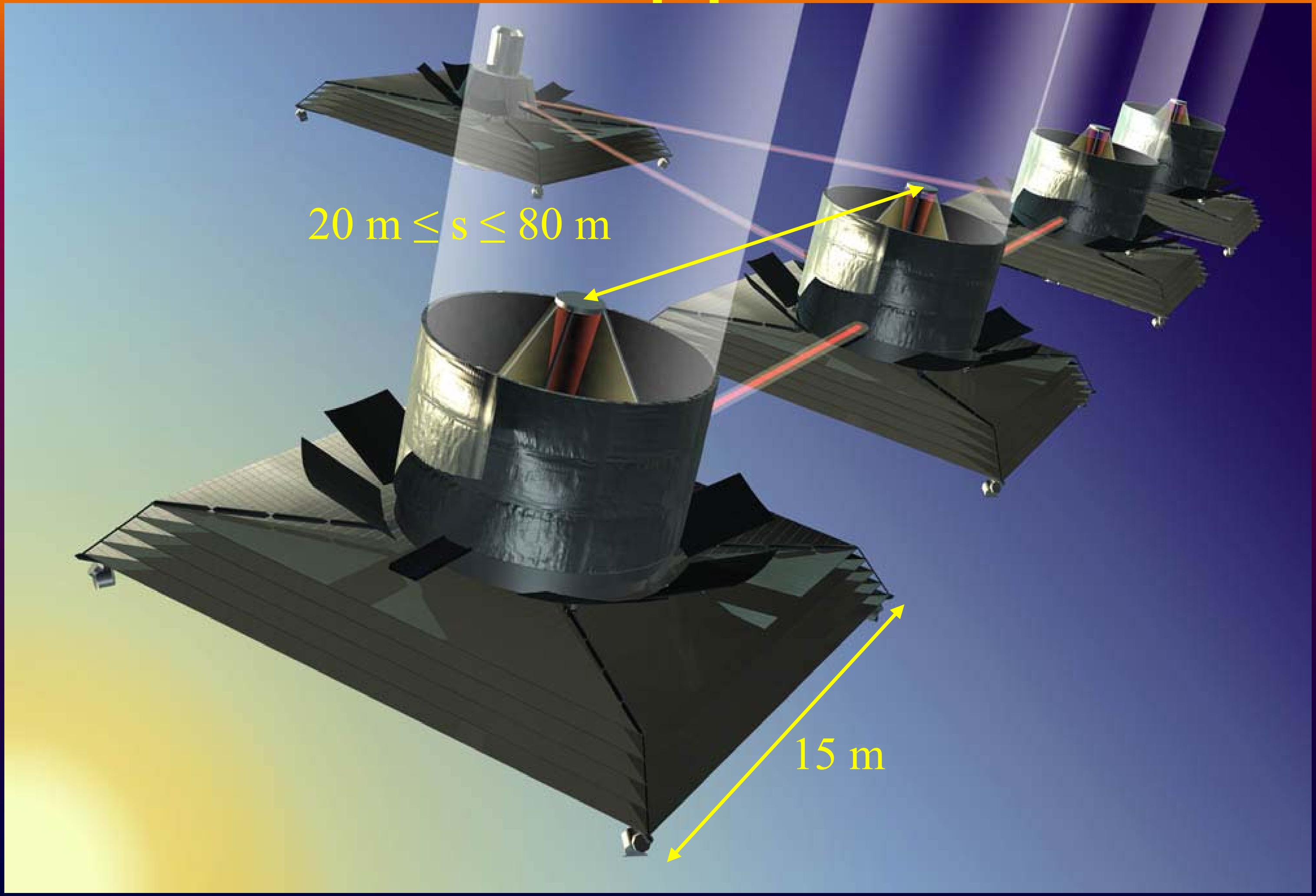
Beginnings of TPF Concepts

- "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



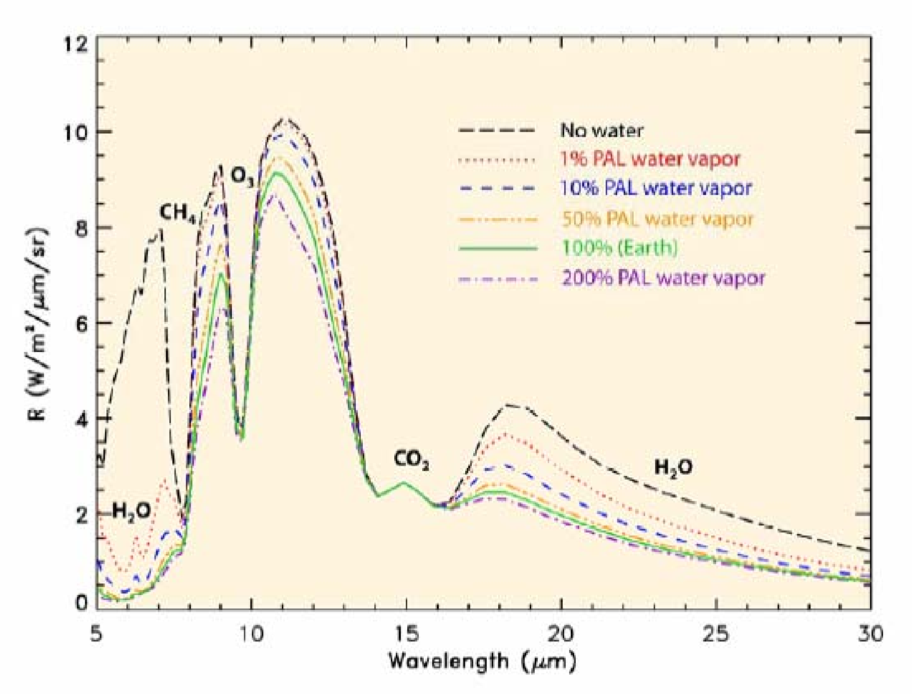


TPF Dual Chopped Bracewell



TPF-I Science Requirements

- TPF-I is optimized to find and characterize planets around ~250 stars and to search for signs of habitability and life



Key Parameter	*TPF-I*
Star types	F G K & others
Habitable Zone	0.7--1.5 AU scaled as $L^{1/2}$
# stars to search	150-250 stars
Completeness for each star	90%
Minimum # visits per target	3-5
Minimum planet size	0.5-1 Earth Area
Geometric albedo	Earth's
Color	At least 3 bands
Spectral range and resolution	6.5-18 μm R=25 [50]
Characterization completeness	Spectra of 50% of detected planets
Giant planets	Jupiter flux, 5 AU, 50% of stars
Maximum tolerable exozodi	10 times solar system zodiacal cloud

Illustrative Target Star Requirements

Stellar Age	>1 Gyr for reduced zodiacal emission; development of life	**Evolutionary Phase***	Dwarf or sub-giant
Spectral Type*	F-K, some M stars	**Metallicity**	Optimize [Fe/H]> for planet fraction
Variability*	$\Delta V<0.1$ mag	**Giant Planet Companions***	None close to habitable zone
Distance*	< 30 pc for planet brightness, angular separation	**Background Confusion**	Avoid confusion from stars (low galactic latitude) or background galaxies
Multiplicity*	Nothing within 10" for stable planetary orbits and instrumental confusion effects	**Position in Ecliptic***	<45 deg for telescope cooling
Exo-zodiacal Emission	<10-20 times solar system level for noise, confusion		

**Parameters included in initial culling of Hipparcos catalog*

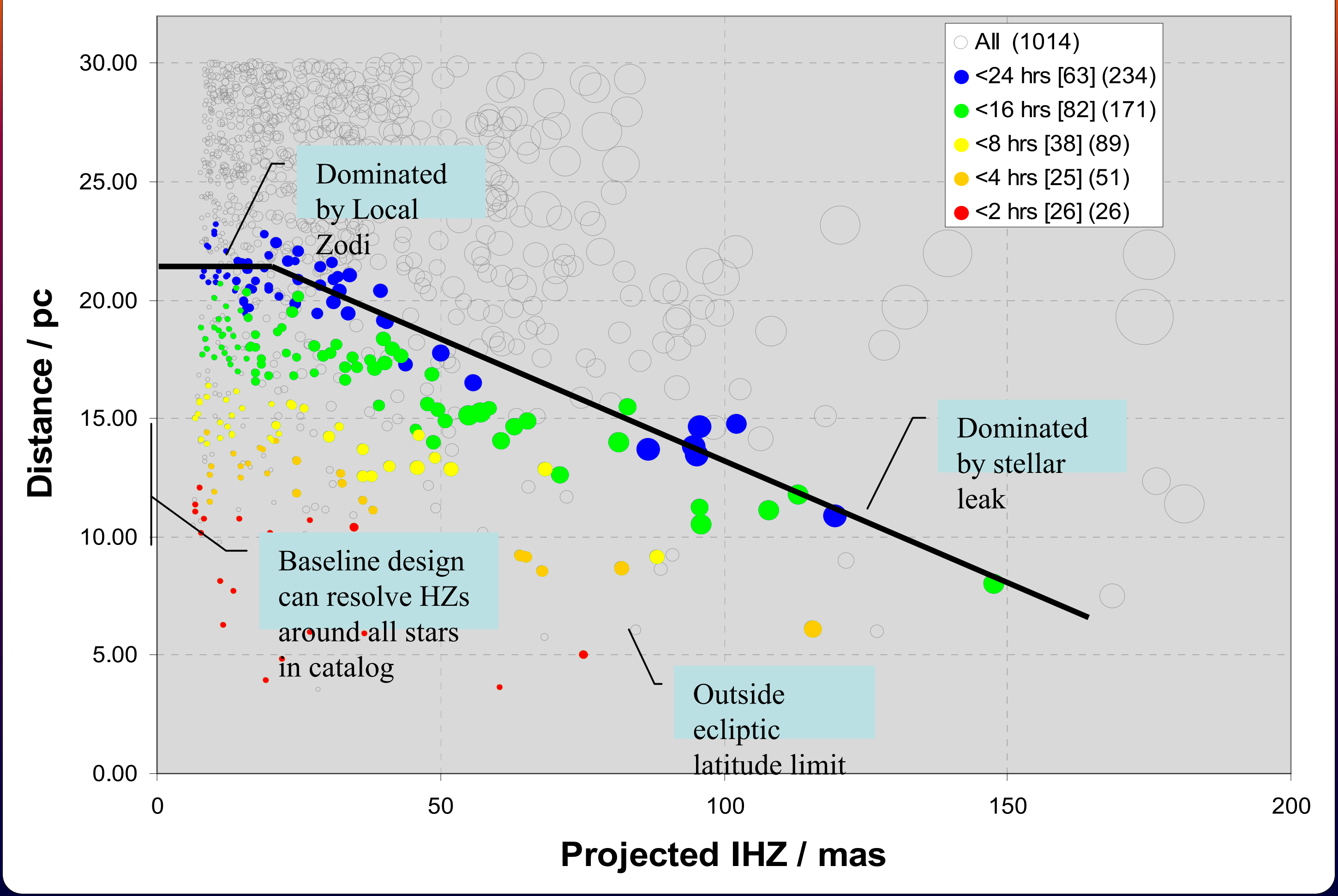
TPF-I Target Star List

Start with nearby Hipparcos stars (< 30 pc): 2350 stars

Science/Engineering culls		Stars left
Apparent magnitude	< 9	1299
Bolometric luminosity	< 8	1284
Luminosity class	IV,V	1247
B-V index	> 0.3	1184
Variability	< 0.1	1143
No Companions	50 AU	1014
Ecliptic Position	($\|\beta\|<45^o$)	650
Multiplicity	<10"	**620**

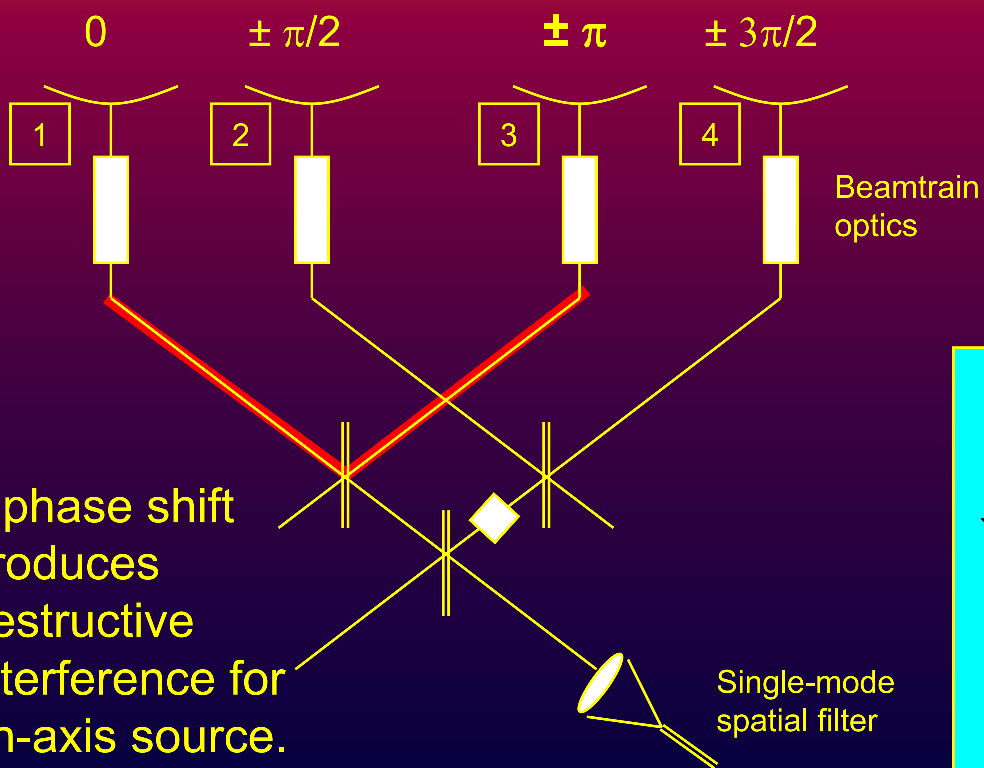
Mostly F,G,K stars with no close companions and no variables

Integration time to detect 1 Earth mass @ 5σ

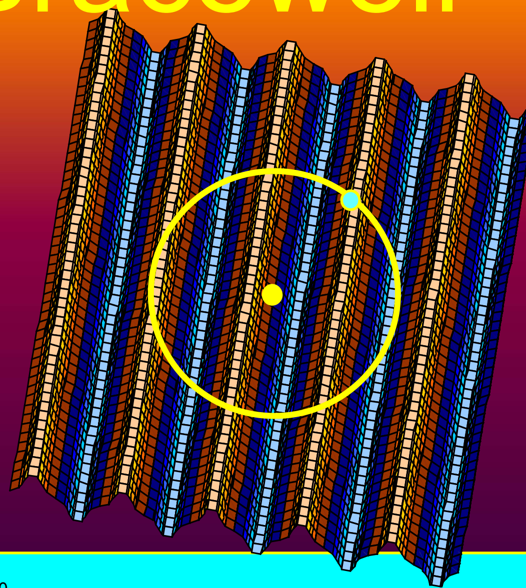


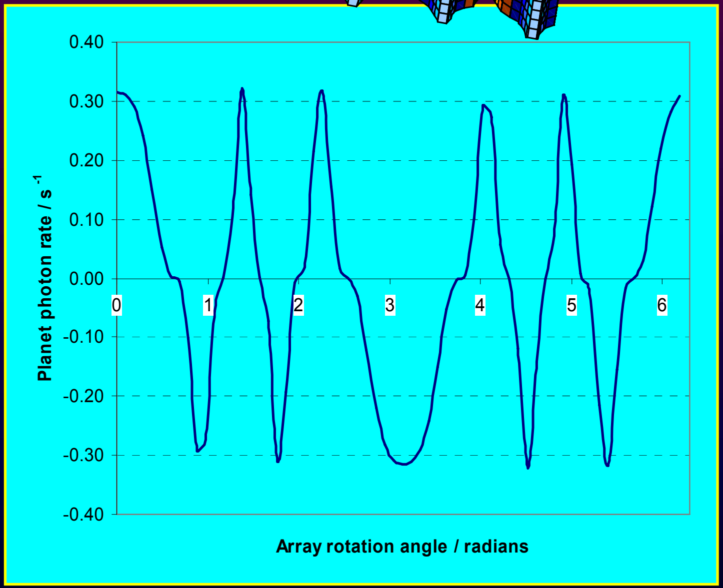
TPF-I can study 250 stars in a 2 year survey mode leaving time for follow-up and general astrophysics

Chopped Dual Bracewell



π phase shift produces destructive interference for on-axis source. Planet light passes through

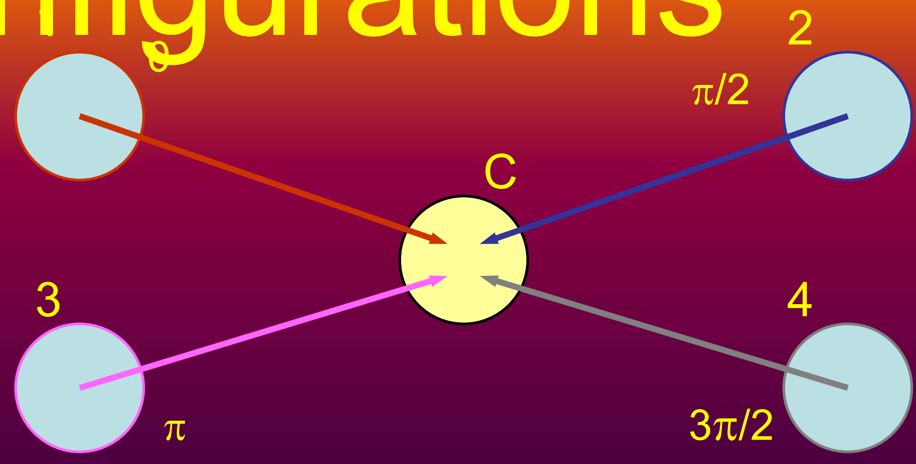




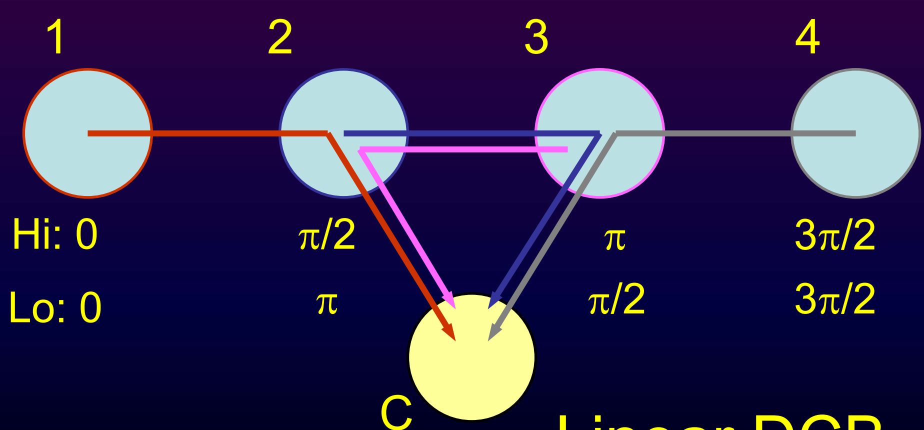
- Purely asymmetric response => only sensitive to planet
- Phase chop reduces systematic errors

TPF-I Configurations

- TPF-I project has examined numerous nulling configurations for performance, ease of I&T, robustness, etc.



X-Array



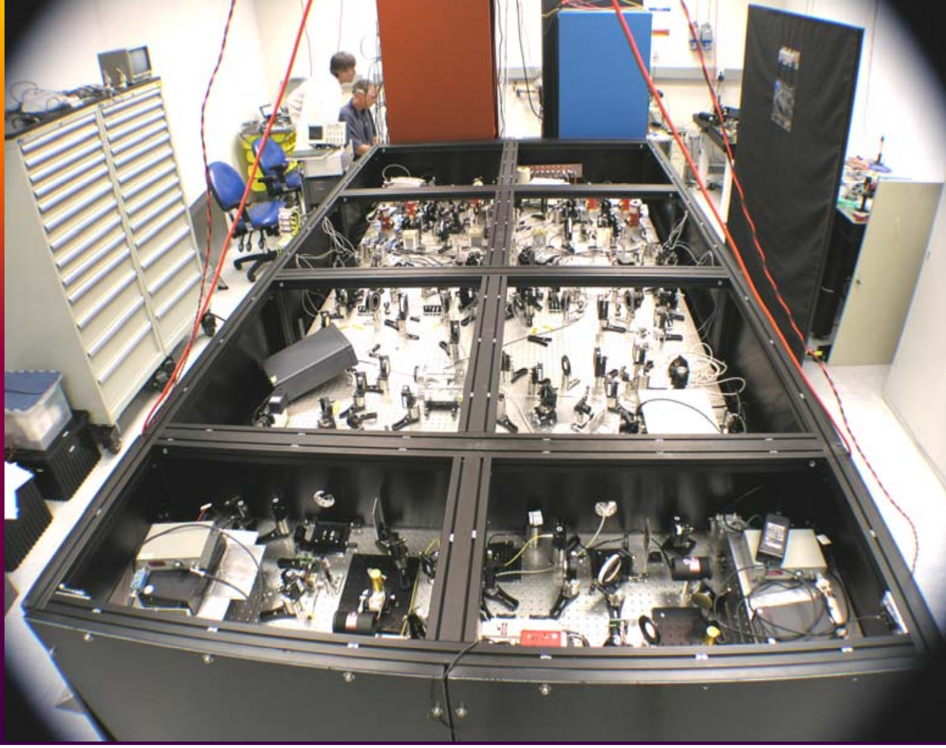
Linear DCB

- Continuing development of nulling schemes and ideas for control of systematic errors in leakage in US (Lay, Danchi, Lane…) and in Europe

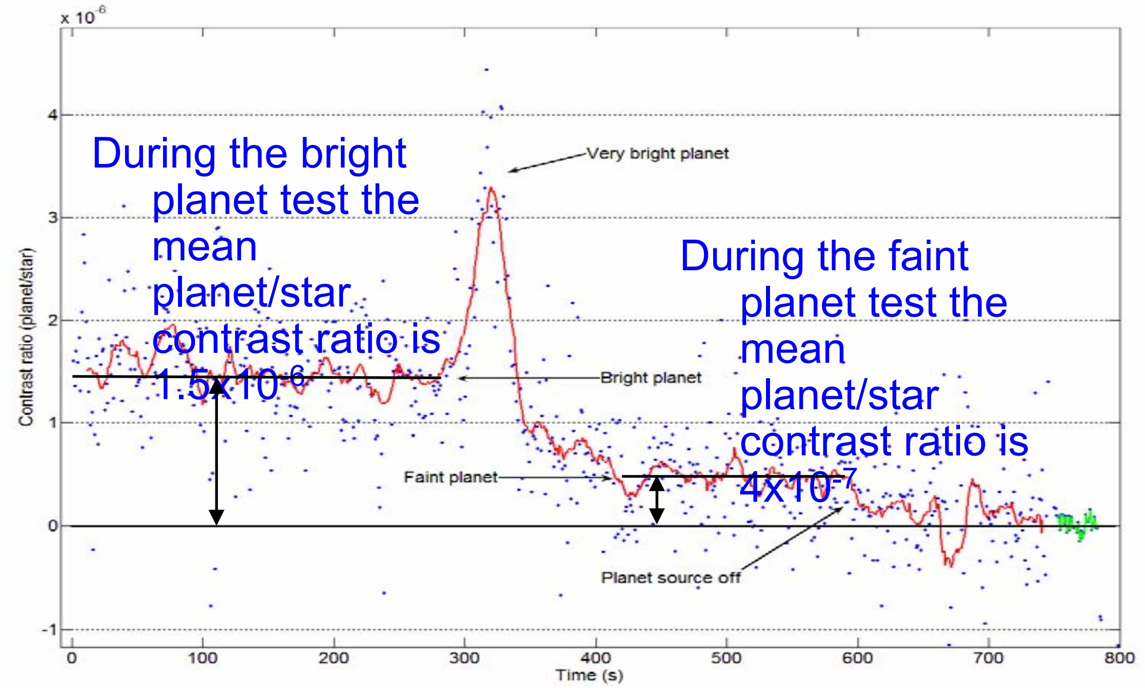
TPF-I Technology Metrics

Technology	Specs	Performance to date	Performance target prior to Phase A	Flight Performance (preliminary)
Nulling	Average null depth	9.1×10^{-5}	Less than 1.0×10^{-6}	Less than 7.5×10^{-7}
	Amplitude control	2.0%*	0.12%	0.13%
	Phase control	2.0 nm*	2.0 nm	1.5 nm
	Stability timescale	Not tested	5,000 s	> 50,000 s
	Bandwidth	8.5 to 10.4 μm (20%)	8.3 to 10.7 μm (25%)	7 to 17 μm
Formation Flying	Number of S/C	2 Robot	2 or 3 Robots	5 S/C
	Relative control	Not tested	5 cm range 60 arcsec bearing	2 cm range 20 arcsec bearing
		*800-900 nm wavelength		

Planet Detection Testbed



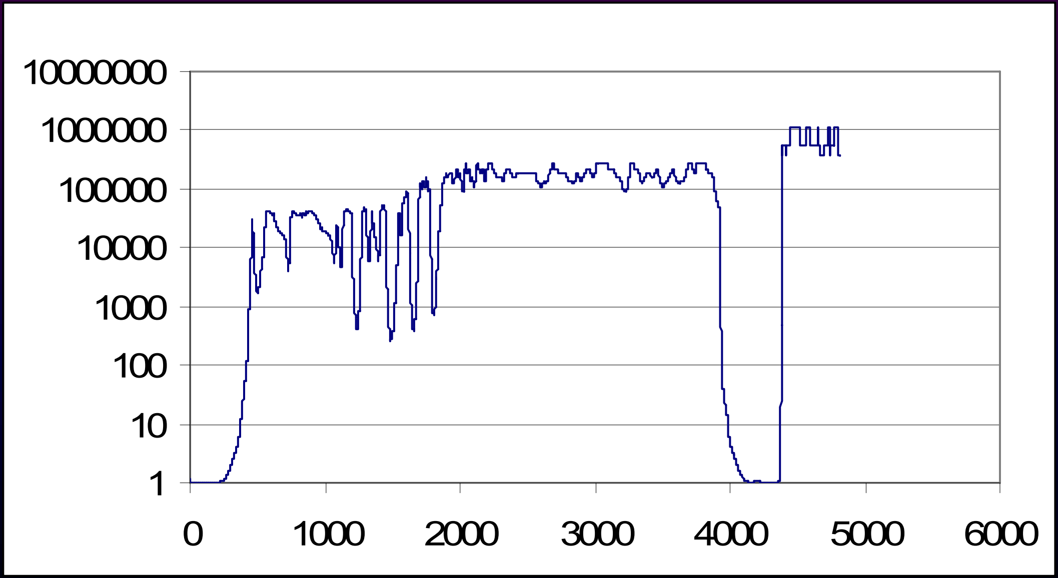
- Planet detection at 10μm with phase modulation
  - < 1×10^{-5} mean null depth
  - Stable for >10 minutes
  - Phase chopping of the planet signals at the thermal source
- Star/planet contrast
  - Faint planet = 4×10^{-7}
  - Bright planet = 1.5×10^{-6}



Achromatic Nulling Testbed

Best performance to date

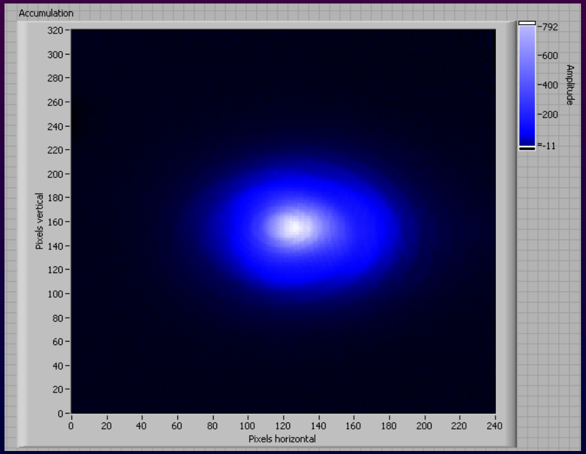
- 200,000:1 null achieved in 10 μm **laser** light
- 15,000:1 nulls at 25% bandwidth



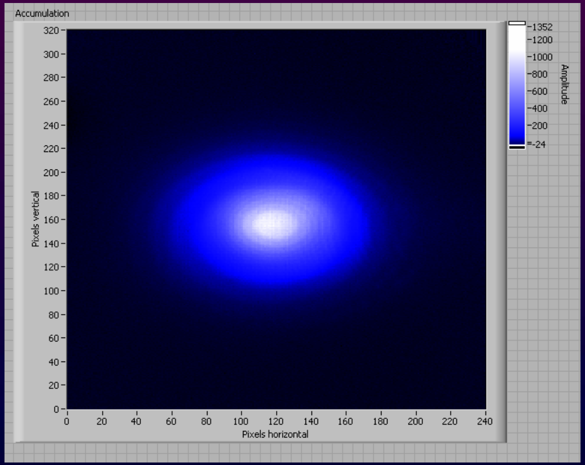
TPF-I: Spatial filters

- Naval Research Lab (NRL) and University of Tel Aviv (TAU) have developed first of a kind single-mode infrared fibers for use as spatial filters in the TPF-I nulling testbeds.
  - NRL chalcogenide fibers are designed for 7-11 μm, and have shown 16 dB rejection of unwanted modes
  - TAU silver halide fibers are designed for 10-17 μm, and have shown 20 dB rejection (4 new fibers)

- All fibers displayed required single mode behavior

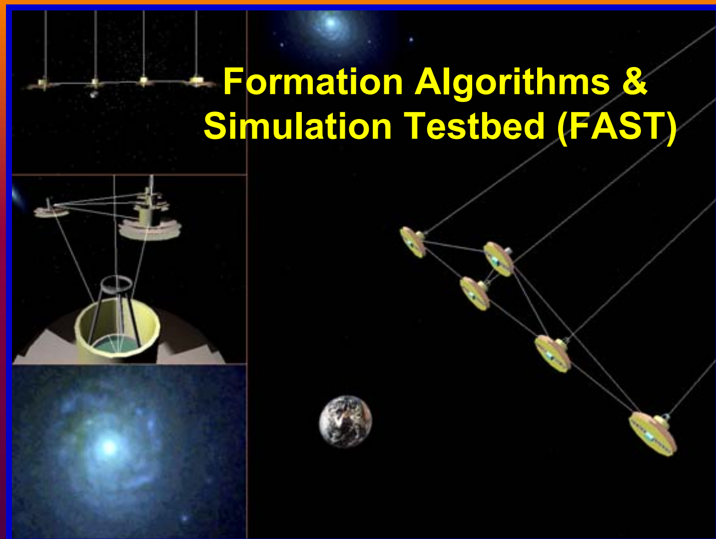


NRL chalcogenide fiber:
16db rejection of higher order modes

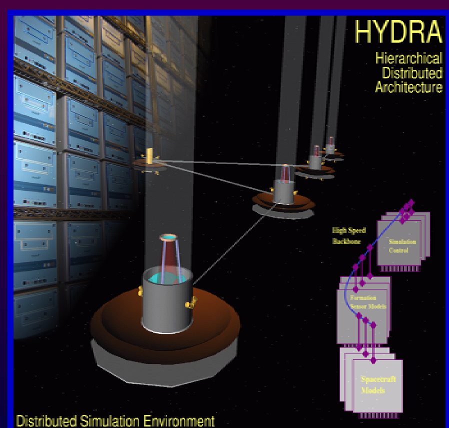


Tel Aviv University silver halide fiber:
20db rejection of higher order modes

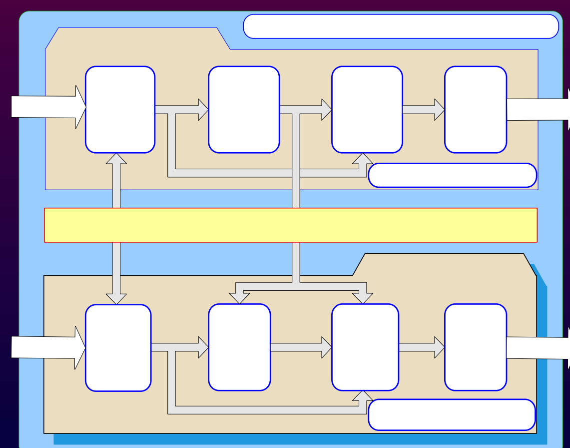
Formation Flying Technology

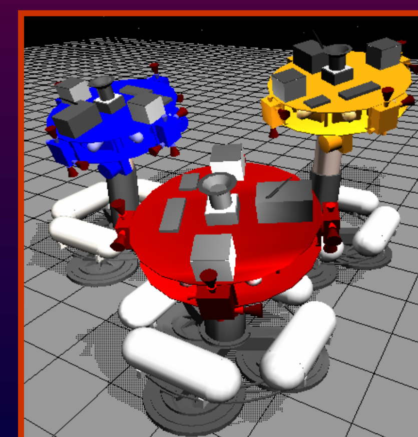

Formation Algorithms & Simulation Testbed (FAST)

Formation Control Testbed (FCT)



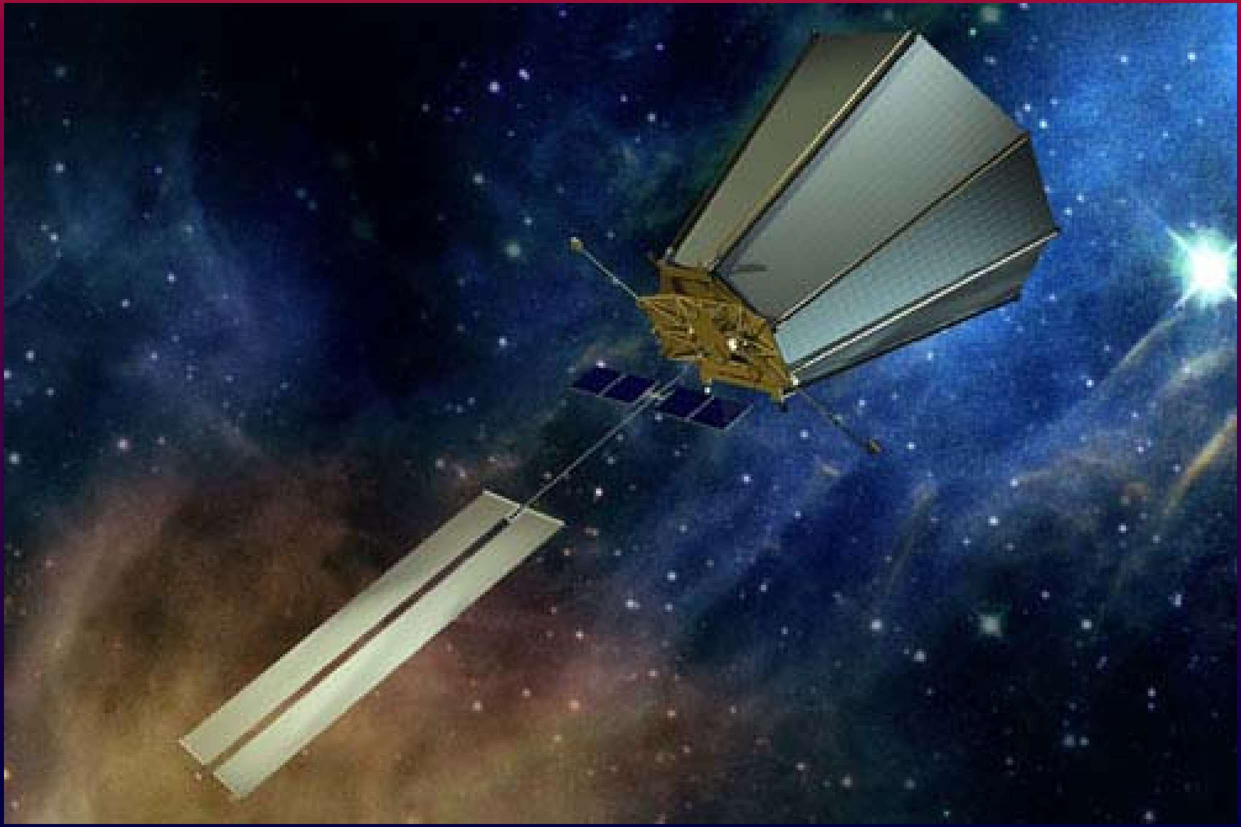
Distributed Realtime Simulation Architecture


Formation Flying Control Architecture


Ground Testbed Performance Simulation

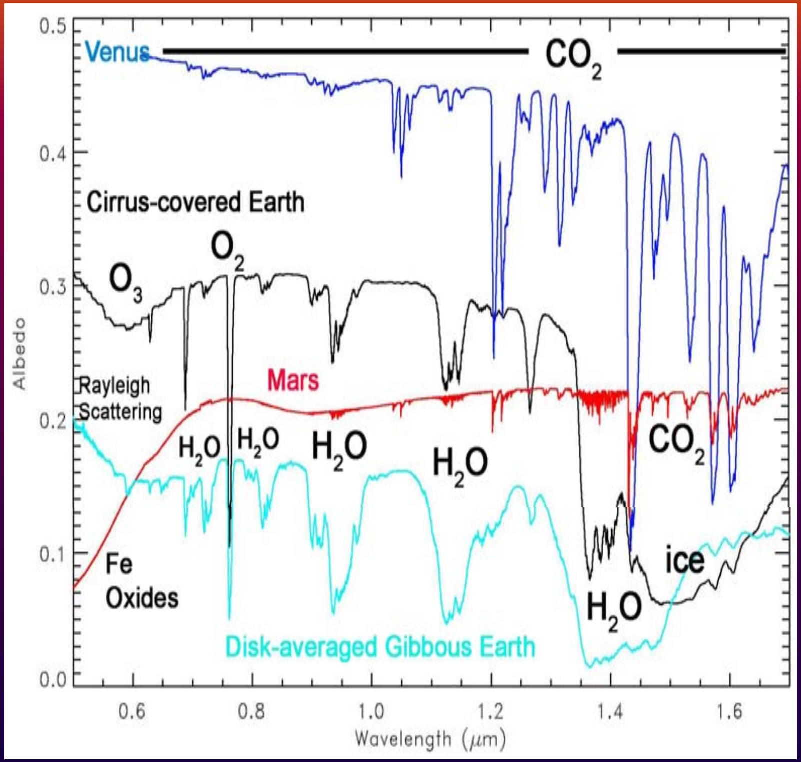
- **Demonstrated Two Robot based Formation Flying in Formation Control Testbed**
- **Completed Formation Control Software to Robots**
  - **Integrated FF Inter-Spacecraft Communication (ISC) software**
  - **Integrated Inter-S/C Clock Timing and Synchronization software**

TPF-C: Visible/near-IR Coronagraph

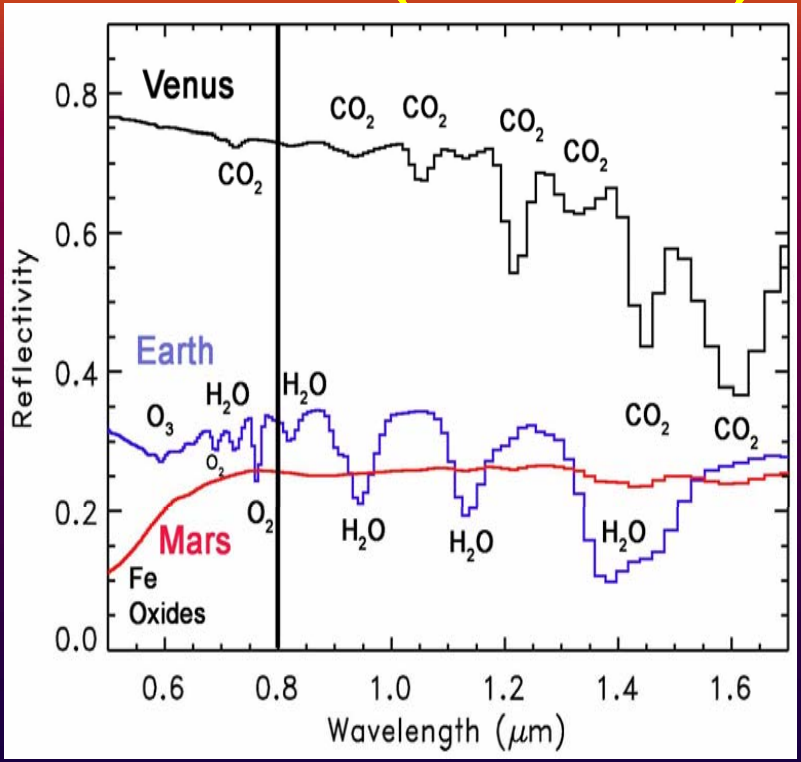


- TPF science also demands visible light data using a single telescope
- Advantages: single spacecraft and telescope
- Disadvantages: high contrast ratio between planet and star

Simulated visible/near-IR spectra of Venus, Earth, & Mars (TPF-C)



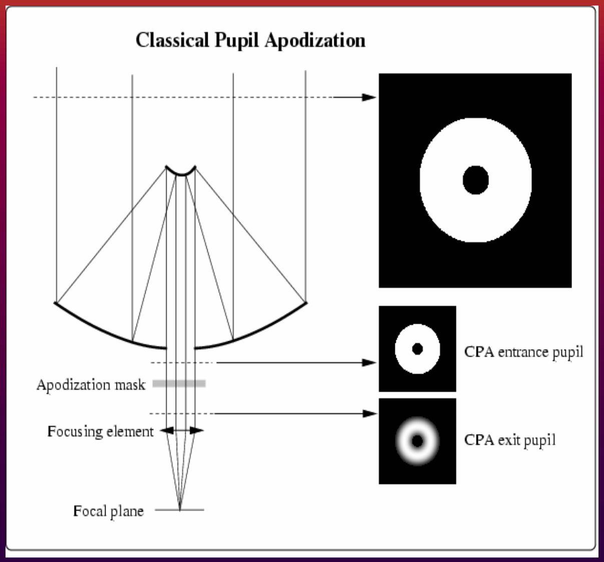
High resolution



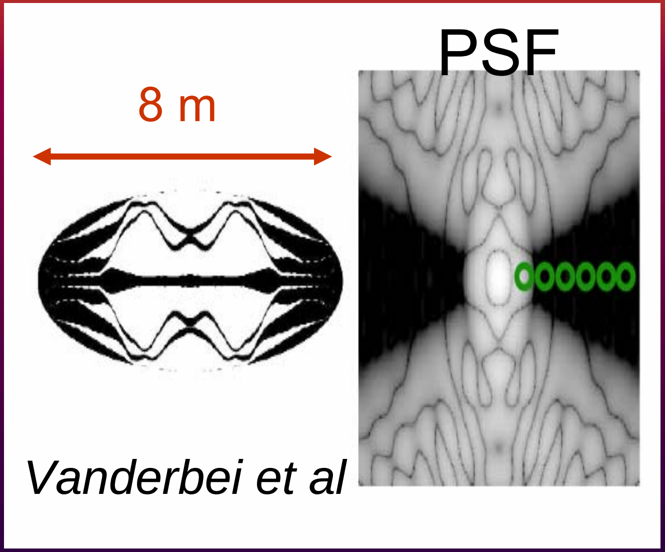
R (=λ/Δλ) = 70

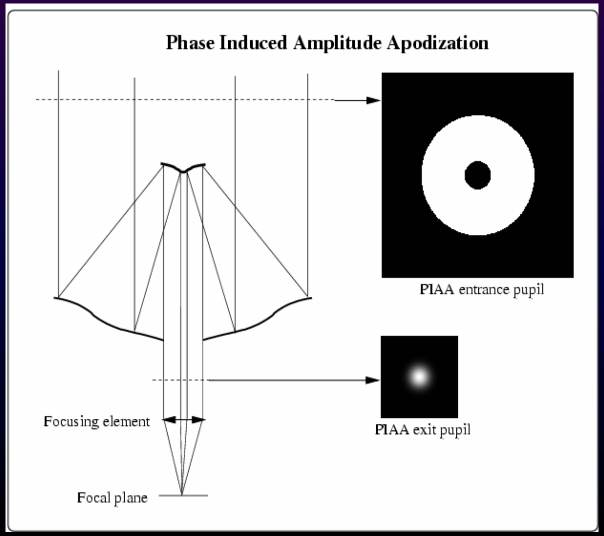
Courtesy of Vikki Meadows, Caltech

Extremely Exciting Investigation of Coronagraphic Technologies

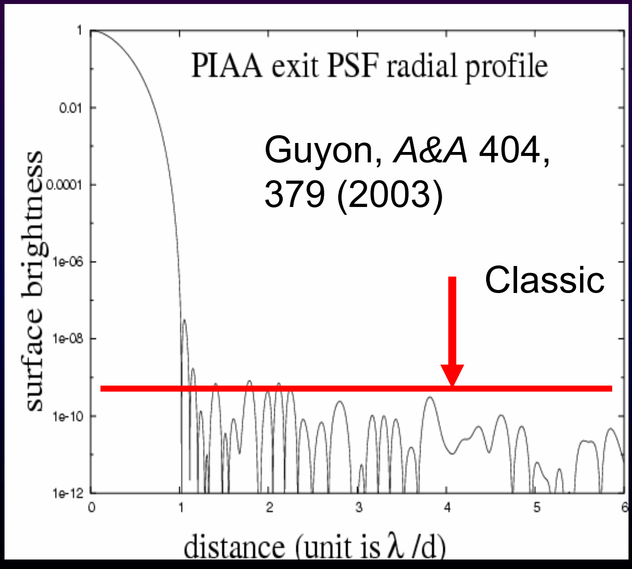


"Classical TPF-C" Coronagraph combines complex Lyot mask for diffracted light control plus DM for scattered light control. Works at 4λ/D.





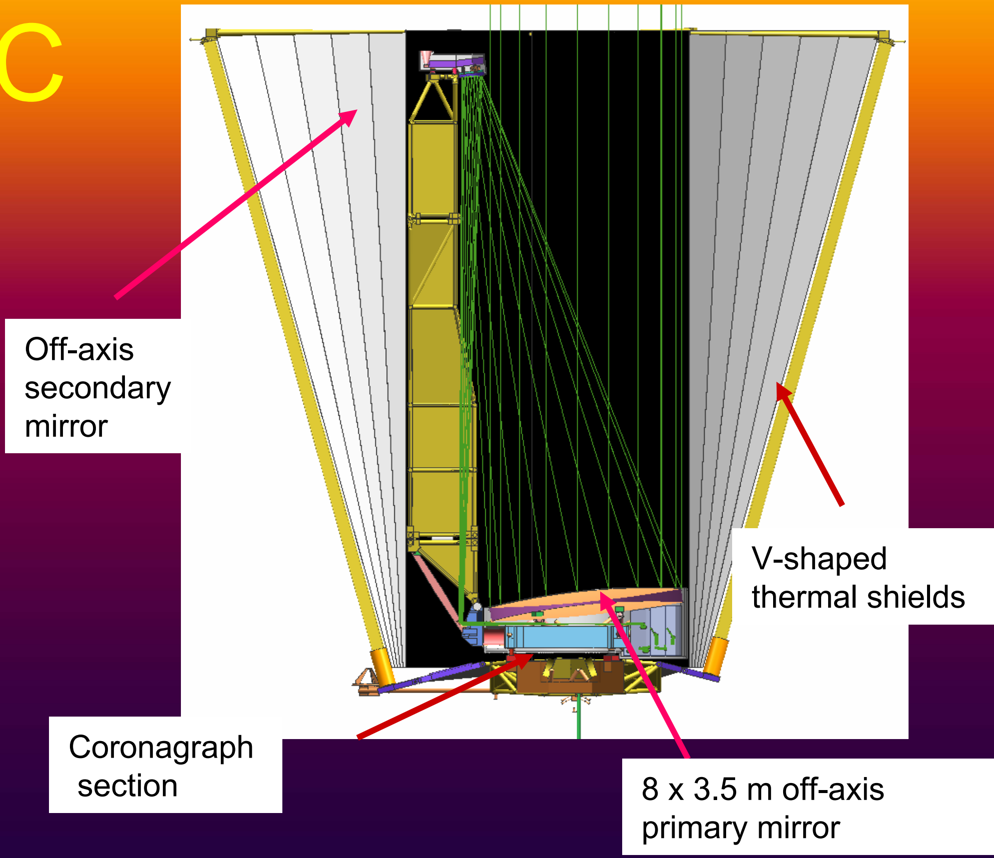
Pupil remapping coronagraph tapers input pupil for diffracted light control plus DM for scattered light control. Works at λ/D. → Smaller telescope?

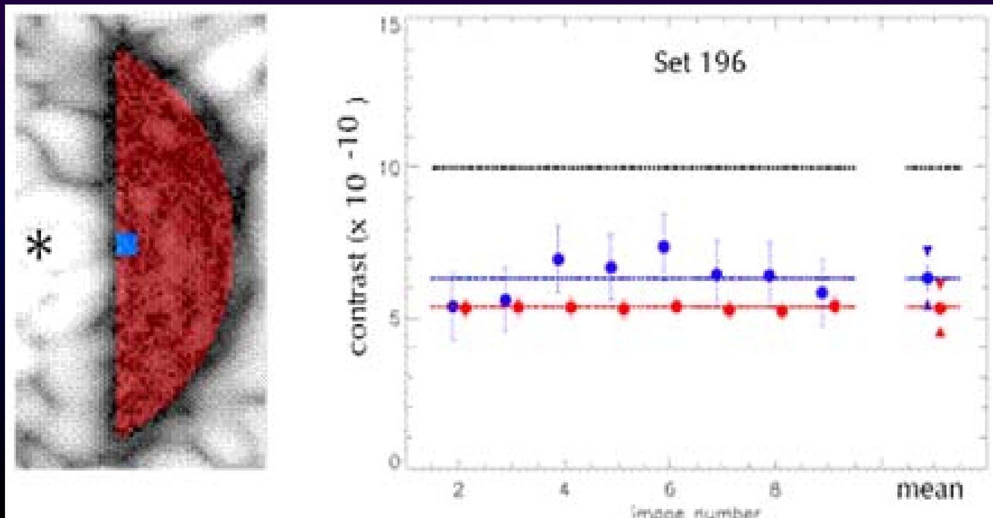


Status of TPF-C

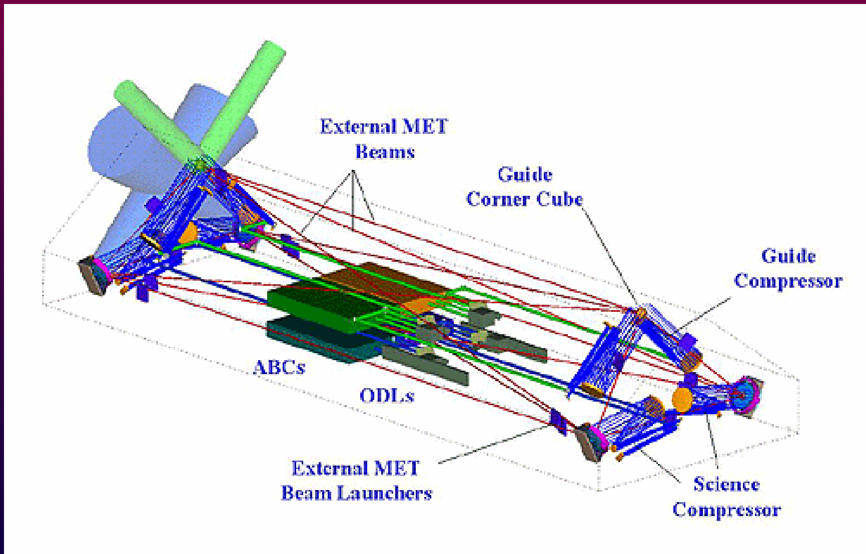
- TPF-C flight baseline design based on study by Science and Technology Definition Team (STDT)

- TPF-C technology plan:
  - First milestones has demonstrated 10^{-9} contrast in monochromatic light.
  - Second milestone for 10^{-9} contrast in broadband light are under way.

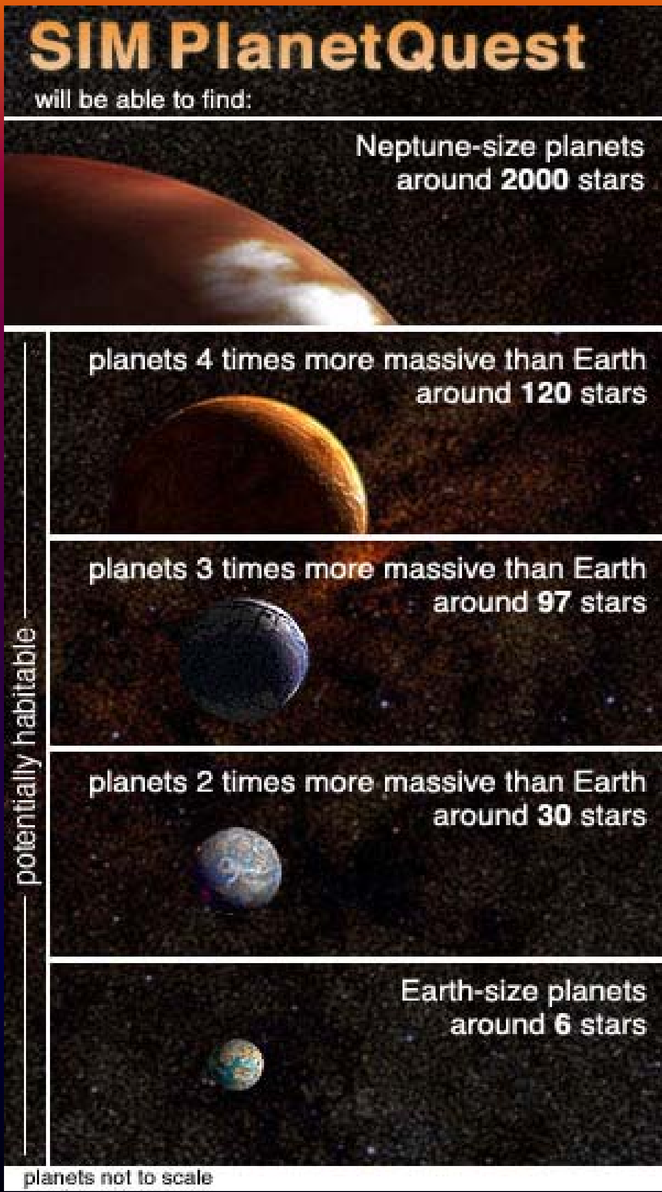




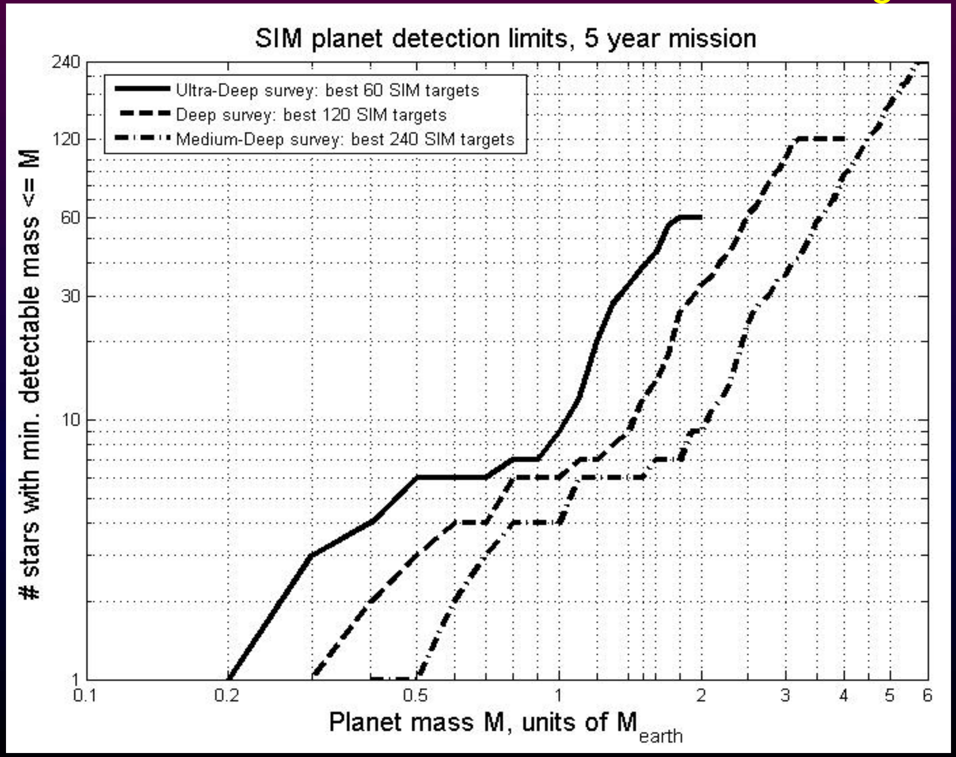
Space Interferometer Mission (SIM PlanetQuest)



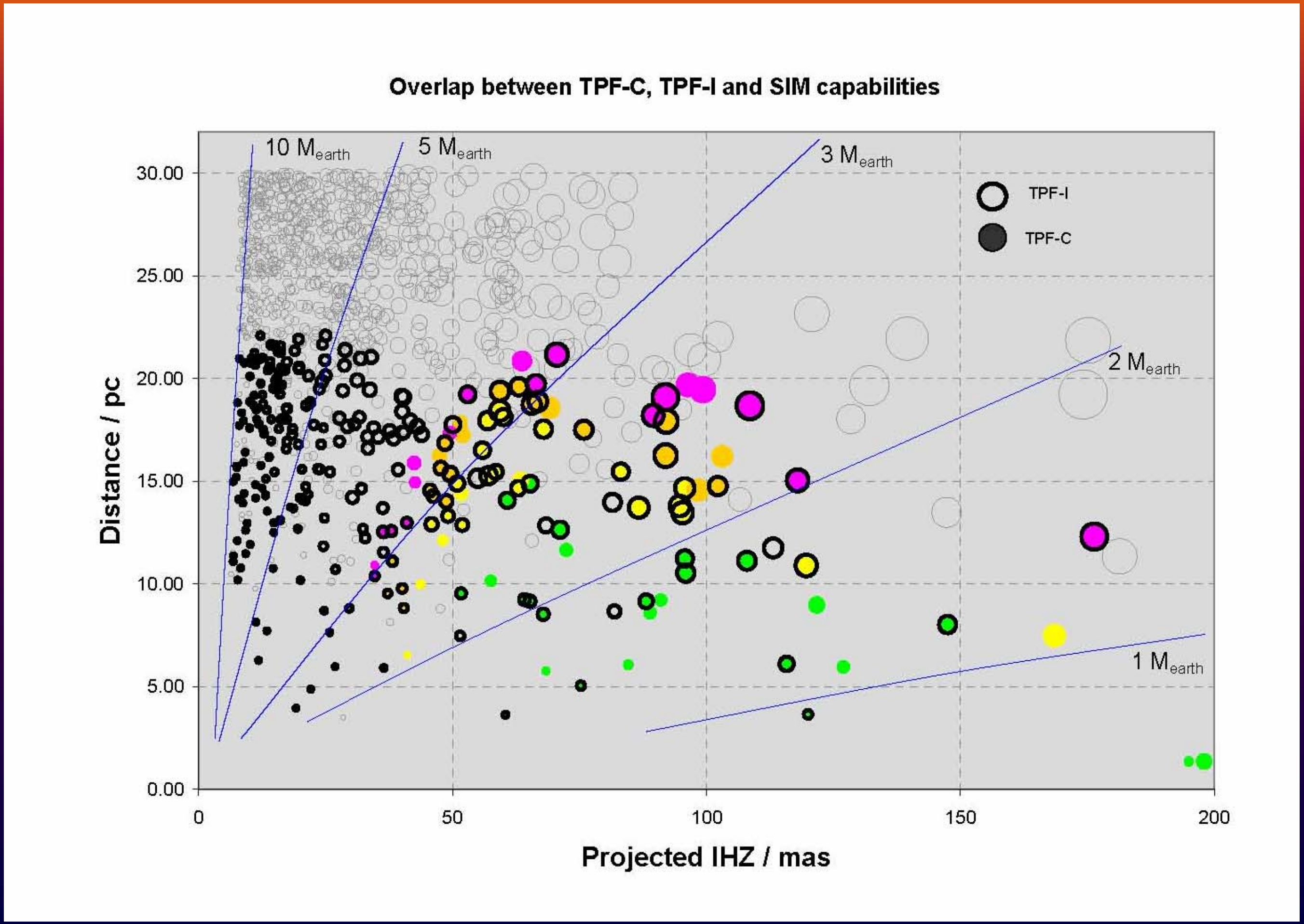
SIM Planet Finding Capabilities



- Potentially Habitable Planets are defined as:
  - Terrestrial planets in the habitable zone, where HZ = $(0.7 \text{ to } 1.5)(L_{star}/L_{sun})^{0.5}$ 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 with TPF-C/TPF-I/SIM



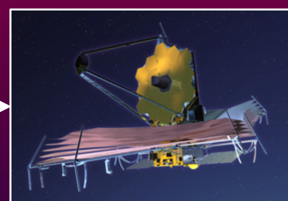
Over 35 stars observable in common between SIM, TPF-C and TPF-I/Darwin will enable synergistic characterization and search for biomarkers

Summary of NASA's Planet Finding Missions

TPF-C/I

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

Distant Planets



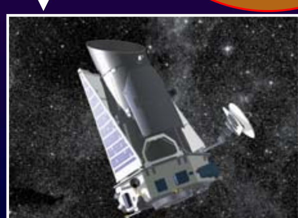
JWST

- 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

Long Delays due to funding problems at all levels of NASA

Keck-I (2006)

- Dust disks at 10-100 zodi for nearby stars

LBTI (2008)

- Dust disks at 3-10 zodi for nearby stars

"Space Science In Love" --- A Parable For Our Times

NASA Executive (Exec) --- The space science program has been closed by the plague!

Project Scientist ---Oh, that.

Executive --- by order of the NASA Administrator

Project Scientist --- Let me explain about the space business… The natural condition is one of unsurmountable obstacles on the road to imminent disaster. Believe me, to be closed by the plague is a bagatelle in the ups and downs of running a space mission.

Exec --- So what do we do ?

Project Scientist --- Nothing. Strangely enough, it all turns out well.

Exec --- How ?

Project Scientist --- I don't know. It's a mystery.

NASA Enforcer --- Should I kill him?

Suddenly, an Email alert comes in…

NASA Watch --- The space program is reopened. By order of the NASA Administrator, the missions are restarted

TPF Project Scientist

TPF Science Team

It's a mystery, but it all turns out well

Conclusions

- Scientific case for TPF-I/C is becoming progressively stronger as we find smaller and smaller planets located at or near the habitable zone
  - Strong progress on challenging technologies of nulling and formation flying and in identifying robust mission designs
  - Strong collaboration with ESA on TPF-I/Darwin concepts
  - ***TPF-I/Darwin and TPF-C will detect habitable planets in the lifetime of somebody in this room!***
- Present-day NASA funding environment is poor, but strong public and science community pressure to provide a minimum level of support for technology development and mission design
- Progress in ground-based interferometry and Adaptive optics (especially LGS) continues on a slow but steady pace and offers exciting possibilities for young instrumentalists & scientists

What should YOU do?

- Do not lose hope as adults mess up NASA program
  - New measurement capabilities such as interferometry have always propelled progress in astronomy
- Consider your personal skill set broadly
  - Coronagraphs and AO systems (NGS and LGS) on large ground-based telescopes are just single dish interferometers
  - Need people skilled in wavefront sensing and control
- Take near-term opportunities for state-of-the-art science: work on exciting (ground-based) instruments, spend modest amount time on future space systems
- When NASA regains its senses, you'll be ready
  - Interferometry will only reach its full potential in space
- Apply for a Michelson Fellowship