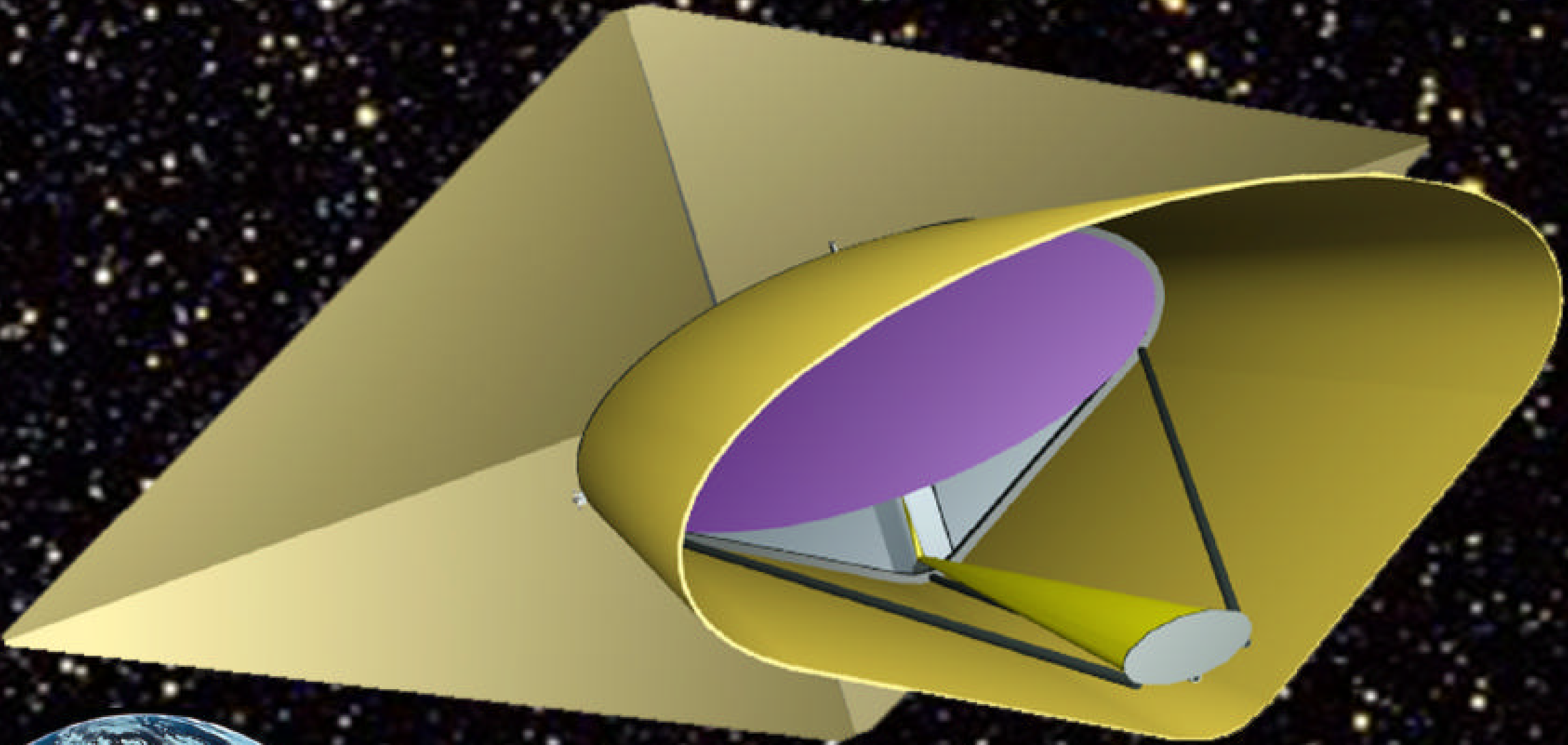
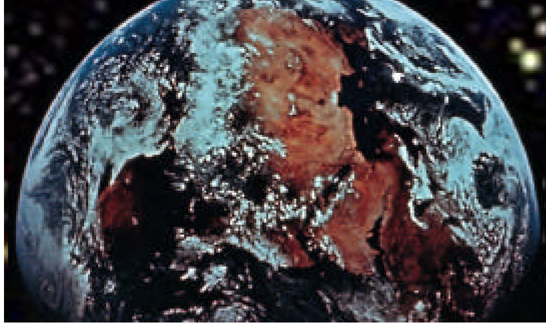
Terrestrial Planet Finder
Architecture Study





Final Architecture Review

11 December 2001 -- San Diego

Presentation Contents

Statement of Work (SOW) Compliance: Placement of SOW Items in FAR Report

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Section	**SOW Item**
2. Phenomenology & Operations Scenarios	
Planet finding & characterization	(1.4.1)
Astrophysics Opportunities	(1.4.1)
Operations Scenarios	(1.5.13)
3. Coronagraph Architecture Overview	
Spacecraft overview (incl. ACS approach)	(1.5.4)
4. Detailed Optical Design and Issues	(1.5.2)
Stray light	(1.5.3)
Contamination	(1.5.6)
Detector Requirements	(1.5.5)
5. Modeling Approach & Results	
Integrated End-to-End Model	(1.6.2)
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6. Optical System Summary	(1.4.1)
7. Integrated System Description	
Other Systems	(1.5.14)
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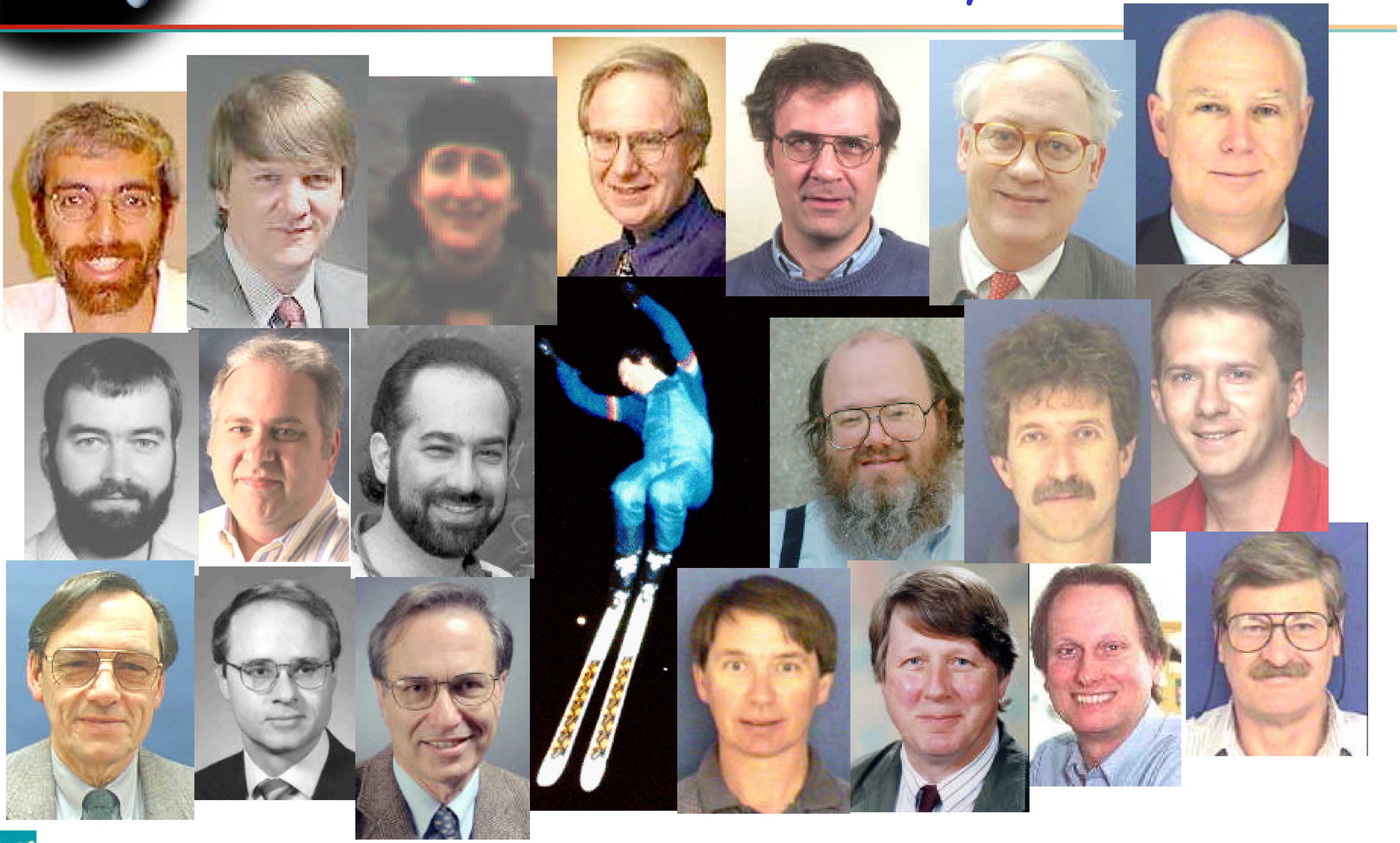
8. Integration & Test	(1.5.9)
9. Technology Roadmap	(1.8)
10. Schedule & Life-Cycle Cost	(1.7)

Section 1.
Introduction & Program Summary

Steve Kilston, Bob Brown

People
How we Meet Judging Criteria
Philosophy
History - Phase 1 Recap
Summary - Phase 2 Process and Results

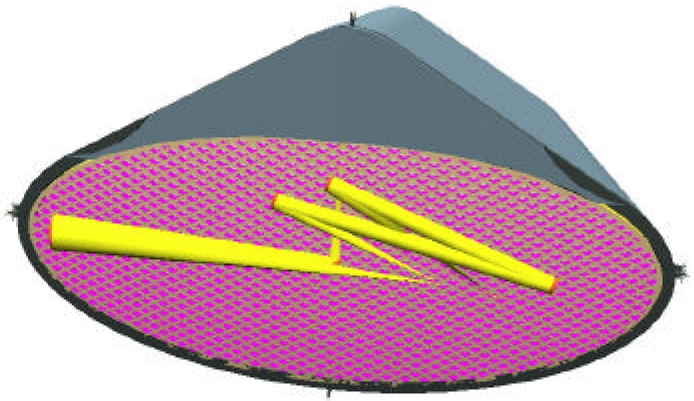
Some Leading Lights of the Ball TPF Architecture Study Team



Our People

Ball Management Team

Member	Role
Jerry Chodil	VP, Civil Space Sys.
Jim Crocker	NGST Prog. Mgr.
Hugh Davis	Deputy Prog. Mgr.
Dave Fischer	Deputy Prog. Mgr.
Steve Kilston	Program Manager
Vera Kilston	Presentations
Terry Lapotosky	ITAR Regulations
Beth McGilvray	ITAR Compliance
Janet Phillips	TAAs
Harold Reitsema	Executive Liaison
Doak Woodruff	Contracts
Lisa Yedo	Finance



Science Team

Member	Institution
Ron Allen	STScI
John Bally	U. of Colorado/CASA
Peter Bender	U. of Colorado/JILA
Torsten Böker	STScI
Alan Boss	Carnegie Inst. Wash.
Robert Brown	STScI
Tim Brown	UCAR/HAO
Chris Burrows	Consultant
Webster Cash	U. of Colorado/CASA
Dennis Ebbets	Ball
Christ Ftaclas	U. of Hawaii
Norm Jarosik	Princeton
Jeremy Kasdin	Princeton
Jim Kasting	Penn State
Marc Kuchner	Ctr. for Astrophysics
Steve Lubow	STScI
D. Mozurkewich	Naval Research Labs
Jerry Nelson	UCSC
Charley Noecker	Ball
Alan Penny	Rutherford-Appleton
A. Quirrenbach	UCSD
Sara Seager	Carnegie Inst. Wash.
David Spergel	Princeton
Robin Stebbins	NASA Goddard
Charlie Telesco	U. of Florida
Wes Traub	Ctr. for Astrophysics
Ed Turner	Princeton
Bob Woodruff	ex-Ball

Engineering Team

Member	Institution
Jim Austin	Ball
Jeff Bladt	Ball
Ira Becker	Ball
Wayne Davis	Ball
Billy Derbes	L'Garde
Edgar Choueiri	Princeton
Porter Davis	Honeywell
William Deininger	Ball
Gene Dryden	Aerojet
Kenny Epstein	Ball
Joe Girard	Ball
Carl Gelderloos	Ball
Pini Gurfil	Princeton
Paul Hannan	Ball
Tim Hawarden	Edinburgh
Tupper Hyde	Honeywell
John Lesveaux	Kodak
Mike Lieber	Ball
Mike Littman	Princeton
Jim Lundahl	Ball
Richard Miles	Princeton
Dan Peters	Ball
Dan Quenon	Honeywell
Pete Thomas	Consultant
Francis Thompson	Aerojet
Rebecca Walter	Ball
Doug Wiemer	Ball
Jeff Wynn	Kodak

Our Philosophy for the TPF Program

- Our main goal is to find the most cost-effective way to search for and begin to characterize Earth-like planets in nearby solar systems
  - As soon as possible (because it is exciting to us!)
- We have been committed to evaluate TPF options fairly, impartially exposing virtues and blemishes ("warts & all")
  - We realize that no TPF option is easy to implement
- We focused intensely on design factors critical to optical performance
  - We attacked the heart of the beast

Preview: How Visible-Light Coronagraph Architecture meets the Judging Criteria

Questions to assess suitability of an architecture in meeting TPF science goals:

1) How well does the proposed architecture meet the primary goals of TPF? Fully.

a) Can it detect Earth-like planets around a statistically interesting number of stars during the nominal mission duration, in less than half of 5-year mission?

- Meets SWG requirement: Search 90% (on average) of HZ of 150 FGK stars

b) Does it cover wavelengths that are indicative of 1) the presence of an atmosphere, 2) habitability, and 3) extant life?

- Yes, visible-band biomarkers have been shown to be fully adequate

2) Do the signal to noise calculations include reasonable assumptions about the targets (stars and planets), important instrumental efficiency terms, and important noise sources with reasonable values (including astrophysical sources)?

- Thorough allowance for phenomenology, noise, and instrumental factors; negligible confusion and noise from astrophysical sources at visible wavelengths

3) Can the architecture provide information on full range of objects and structures in the planetary systems being studied (e.g. Giant planets, Exo-zodiacal dust clouds, etc) ?

- Sensitive to planets far from stars (wide FOV); exozodi detectable at 5 x solar

How Visible-Light Coronagraph Architecture meets Judging Criteria -- 2

4) Does the proposed architecture have natural scientific precursor of more limited scope? List scientific goals, legacy to TPF, mission size (by cost or analogy).

- Yes: Jupiters, maybe Earths; prove technologies; 2.4-m HST w/CODEX (~$50M), 1.8-m Eclipse (~$300M), > 3m Planetary System Imager (~$500M NRA Prop.)

5) What is the potential of this architecture for general astrophysical observing?

- Extremely high: UV/Visible 10 mas imaging over 2 x 2 arcmin FOV, spectroscopy

6) How would requirement for a general astrophysical capability affect the facility (e.g. complexity, additional instruments, target limitations, mission lifetime)?

- Very little: coronagraph naturally suited for astrophysics without modification; UV/Vis. WFOV imager & spectrograph low cost; coatings; adequate observ. time

Questions to assess the technology requirements of an architecture for TPF:

7) Are all of the critical technology development needs identified? If no, list any additional technology needs.

- We believe Section 9 accounts for all technology areas needing development

a) Are the most challenging technology needs ("tall tent poles") for this architecture correctly identified? If no, indicate what you believe them to be. Also Section 9.

- We've found tallest poles: large optics, wavefront stability, amplitude uniformity

How Visible-Light Coronagraph Architecture meets Judging Criteria -- 3

b) What is your overall assessment of the difficulty of the proposed technological approach relative to the current state of the art?

- Significant concerns exist: large mirror, WFC limits on spectral bandwidth, etc.

8) Are there alternative approaches to substitute for any of the critical technologies?

- Yes: active microthermal control, variable pupil control, dichroic filters, etc.

9) Is there an appropriate plan for developing all critical technologies to the necessary level of performance? List additional recommendations.

- Yes: ground tests & demos, extensive integrated modeling, space precursors

10) Are the metrics for evaluating technologies appropriate and sufficient? If not, suggest alternatives.

- Yes: sub-Angstrom surface & DM stability, 10^{-4} amplitude uniformity & stability

11) Are there other programs (NASA or otherwise) that would require similar technology? Are they currently funding its development?

- NGST, Airborne Laser, Space-Based Laser: yes, they're funding relevant tech.

12) Are technologies that can be validated only in space identified appropriately? Explain why or why not.

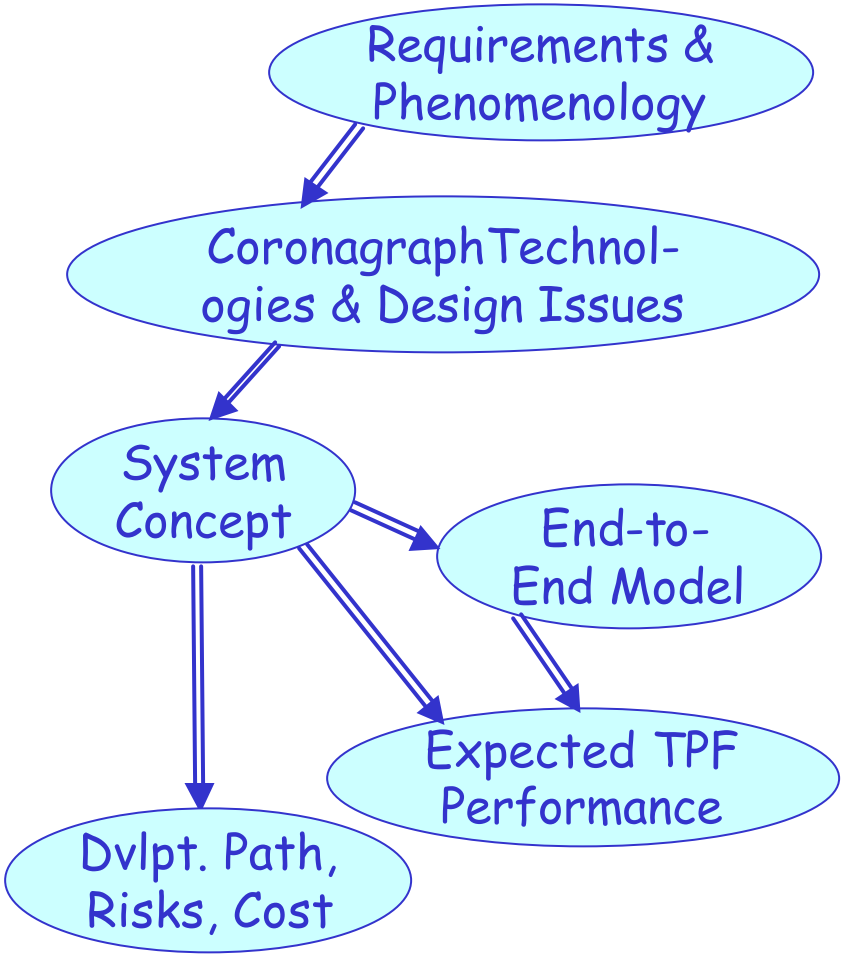
- Yes: Section 9 discusses vibration control and large, precision optical systems

History of Ball TPF Team Phase 1 Work

- Phase I work in 2000 was guided by Bob Brown, our Principal Scientist, and our Science Team
- We explored relative capabilities and problems of 29 relevant architecture concepts, and ranked the 21 which might have a chance of performing the TPF mission
- We performed many scientific analyses and explored unique approaches
- The candidates recommended by our team for further study were visible-light coronagraph options and infrared interferometer options
- Our best-value TPF architecture concept, subject to feasibility:
  - Single spacecraft with visible-light, monolithic-mirror coronagraph options
    - Costs less, planet SNR better (needn't compete with entire zodi disk)

Phase 2 Process Provided the Information Needed to Assess Architecture Suitability

- Phase 2, during 2001, deepened our understanding of the TPF visible-light coronagraph options
  - In many meetings and analyses, our astronomers and optics experts refined the design preferences
  - We focused on the critical optical issues: stray-light management, stability of optical surfaces, and signal-to-noise ratio (SNR) vs. inner working distance (IWD, closest observable star-planet angles)
  - Our primary results were obtained via creation and use of an integrated end-to-end model

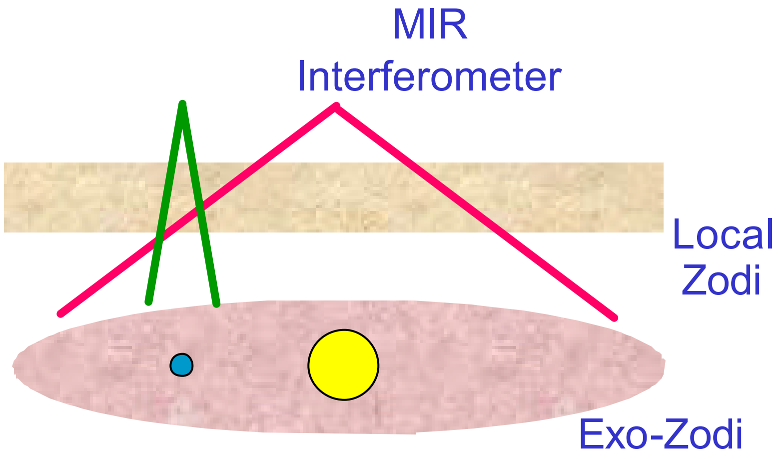


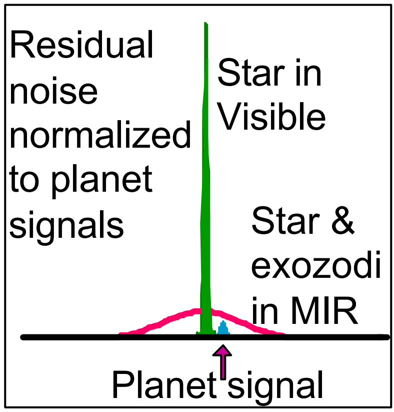
Our Study Begins by Clearly Understanding Top-Level Requirements & Phenomenology

- Main TPF requirements from Science Working Group (SWG)
  - Survey 150 FGK stars' habitable zones for light from terrestrial planets
  - Search for spectral signatures of biomarkers on planets found
  - Observe astrophysical phenomena during half the mission
  - Do all this between 2015 and 2020, and for a reasonable cost (< $ 2B)
- Phenomenological factors for extrasolar planet observations
  - Actual set of stars close to sun: their luminosities, colors, and distances
  - Derivable habitable-zone angular extents as viewed from TPF
  - Predicted planet signal strengths and comparison to stellar noise signal

Virtues of a Visible-Light Coronagraph for the TPF Mission

1. A visible-? coronagraph sees less noise than an interferometer in the pixel where the planet is detected, thus higher SNR





Noise where planet signal is detected, from star and exozodi, can be lower for the visible, dependent also on exozodi level and instrument performance

In the planet pixel, the star's visible light only needs to be reduced by a factor a bit over 10^6, not the 10^{10} commonly quoted

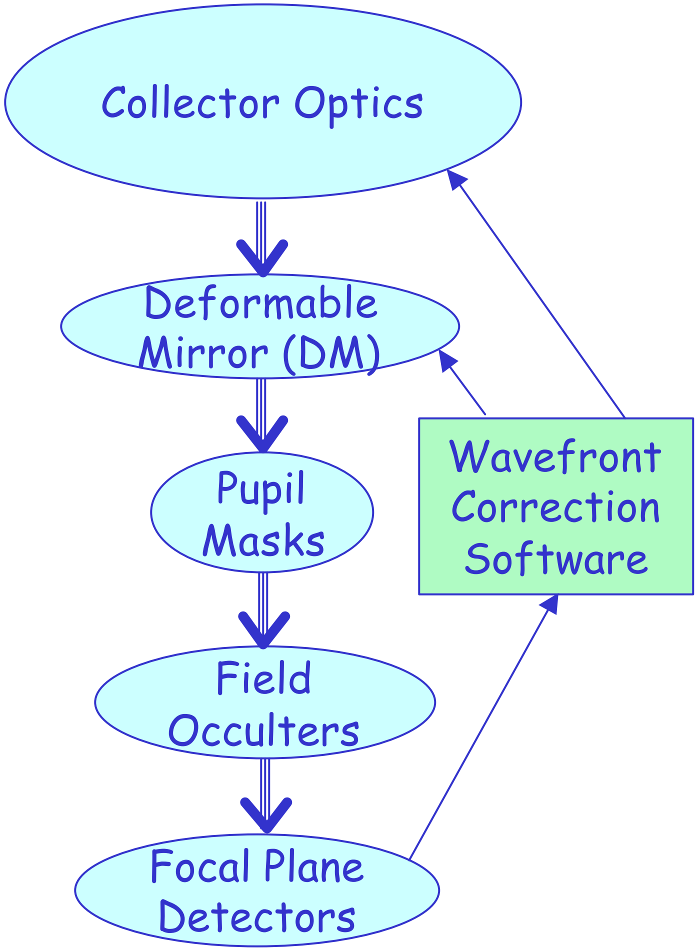
2. Good spectral biomarkers are found in both the visible and IR ? regions

Phenomenology Implications

- Implications of phenomenology for required performance
  - Key factors: Inner Working Distance (IWD), Integration Time needed
  - IWD ? 40 mas needed to see habitable zone (HZ) inner edge for 150 stars
    - But with IWD = 60 mas can see 92% of best 150 stars' "total" HZ
  - Most TPF concepts need lengthy system rotations to fully search HZs
    - Must minimize integration times at each angle, & calibration times too
  - Large apertures are needed, for small IWDs and integration times

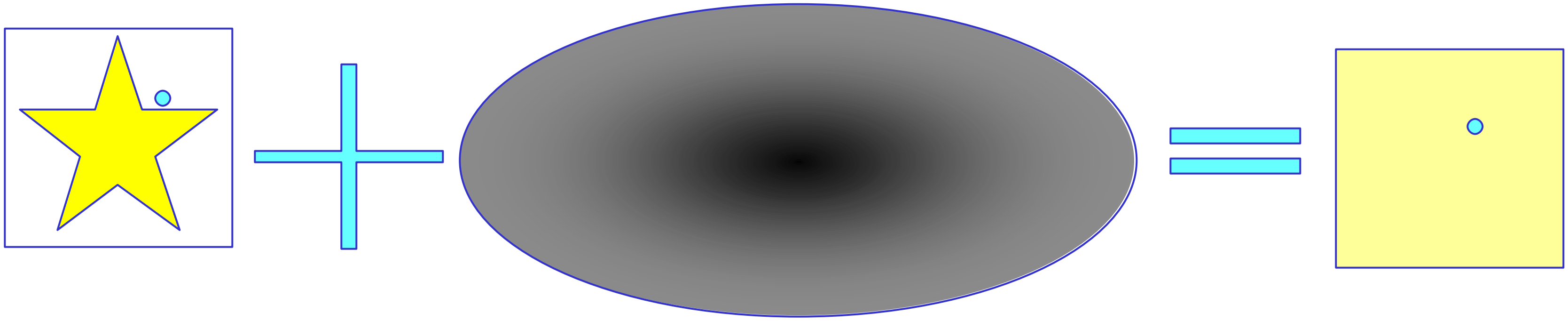
Design Issues & Enhanced Coronagraph Technologies Identified & Explored

- Essential to coronagraph quality are wavefront & straylight control
- New technology developments make possible extremely high-performance coronagraph options
  - Deformable mirrors
  - Large, lightweight primary mirrors with actuator control
  - Superpolished optics
  - Advanced pupil and mask designs
  - Tightly controlled thermal and structural disturbances affecting the wavefront

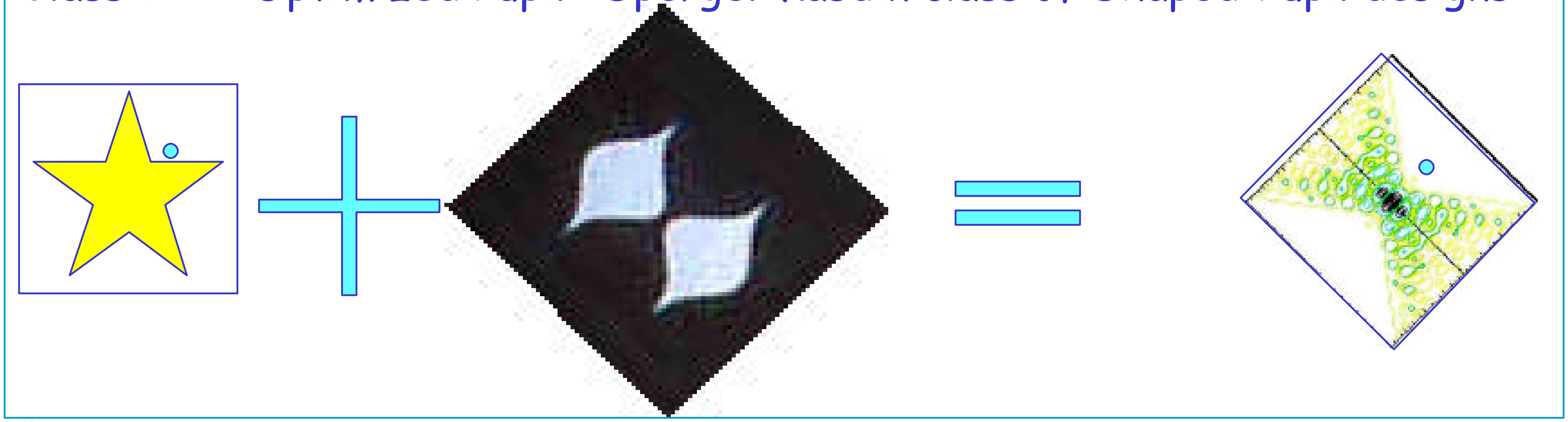


We Focused on Two Optical Approaches for a Coronagraph to Detect a Planet

Class 1 -- Classical Coronagraph: Gaussian-type Image-Plane Occulter



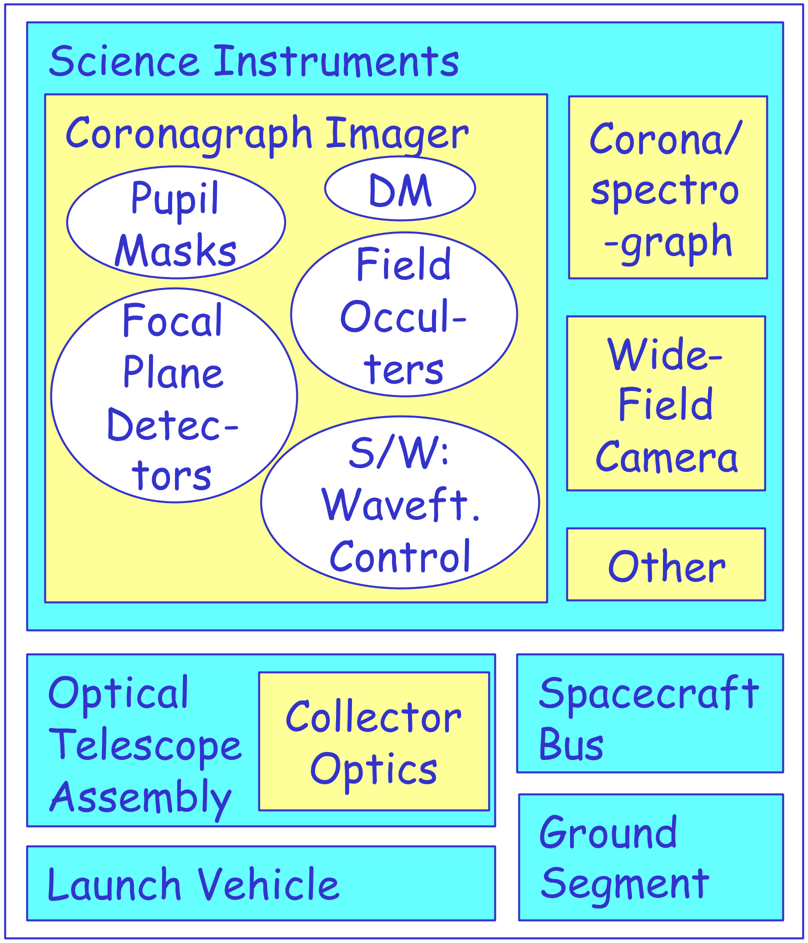
Class 2 -- Optimized Pupil: Spergel-Kasdin class of Shaped-Pupil designs



System Concept & Design Options

A major virtue of the coronagraph concept -- direct heritage from HST and NGST, same major system elements, not a huge stretch

Prime focus of our design effort was optimization of coronagraph imager design & performance



Science Instruments

Coronagraph Imager

Pupil Masks

DM

Field Occulters

Focal Plane Detectors

S/W: Waveft. Control

Corona/spectro-graph

Wide-Field Camera

Other

Optical Telescope Assembly

Collector Optics

Spacecraft Bus

Launch Vehicle

Ground Segment

Overview of the TPF Coronagraph Observatory

Major Features

Optics

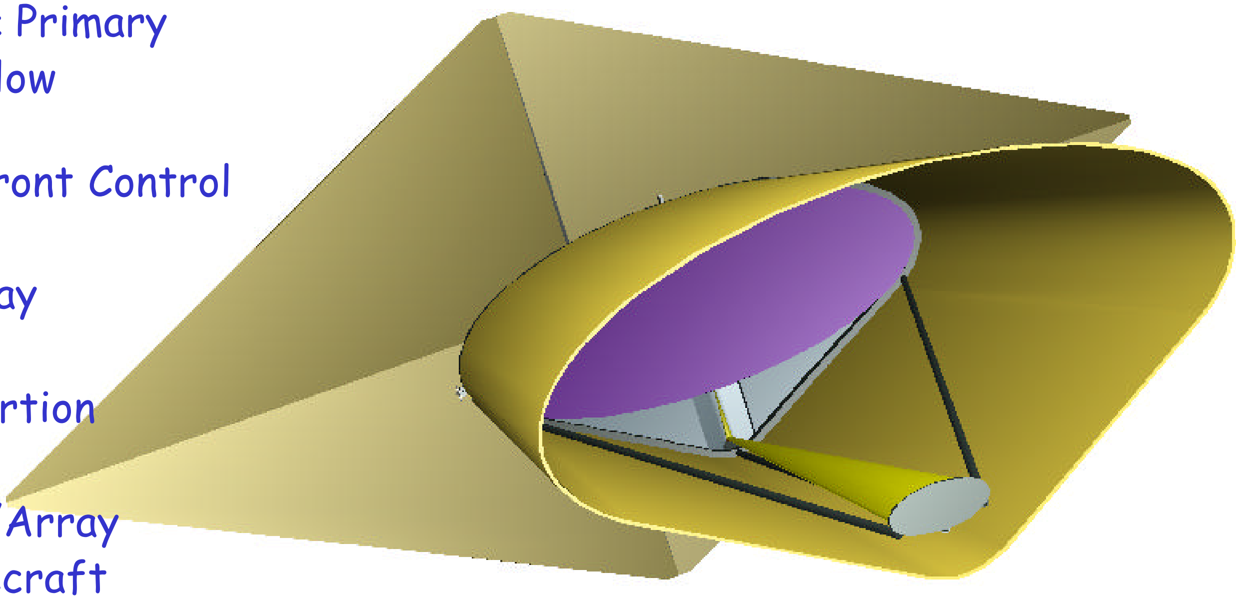
- 10 x 4 Meter Monolithic Primary
- Off Axis Design – very low diffraction
- Adaptive Optics Wavefront Control

Orbit

- Earth Trailing Drift Away
- Stop Drift @ 0.2 AU
- Delta IV H – direct insertion

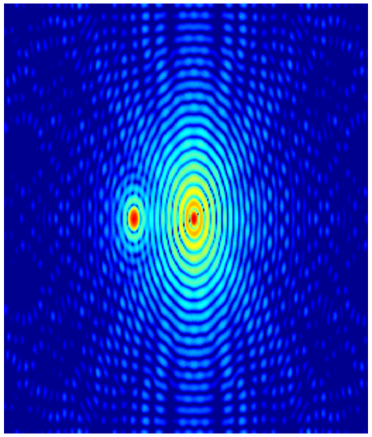
Other

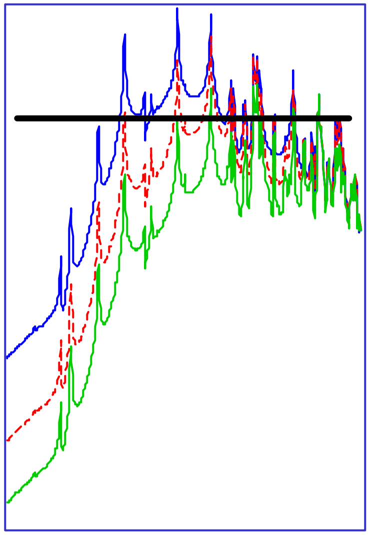
- Articulated Sun Shield/Array
- 3 Axis Stabilized Spacecraft
- Launch Mass ~6,000 kg
- Power 2.1 KW EOL
- 5 Yr Design Life (10 yrs of Expendables)



End-to-End Model

- Main goals for TPF coronagraph model
  - Characterize entire optical system for SNR
  - Examine performance effects due to pupil and mask choices
    - Help recommend preferred design options
  - Calculate realistic integration times for detections & spectra
- Primary issue -- stray light at exoplanet image positions
  - Driven by wavefront quality at critical spatial frequencies
  - Must determine sensitivities to jitter, thermal changes, structural deformations, creaking
- Modeling approach-- based on realistic engineering inputs
  - Analyses and models capture design's structural responses to attitude control system and thermal influences
  - Matlab modules capture component and subsystem relations
  - Simulink module integration yields end-to-end performance





Expected TPF Science Performance -- Summary of Main Modeling Results

- Classical or shaped pupil coronagaph with 4 m x 10 m monolithic primary mirror will achieve 40 - 60 mas IWD
- SNR of 5 (broad band) generally achieved in < 5 hour integration time
- Data collection rate suffices to search near 150 stars, gather spectra of 50 planets, and acquire astrophysics observations in a 5-yr. Mission (serendipity mode + targeted observations)
- Very stable thermal distribution is the most challenging implementation goal; vibration levels are within reach of performance requirements

Risk & Cost Summary

- Simplicity of the visible-light coronagraph gives its development and operation very low relative and absolute risk to achieve TPF goals
  - Following a conservative technology plan keeps risk to minimum
  - Small number of new technologies minimizes overall program time & money
  - System performance can be largely validated in ground testing
  - Clear and feasible precursor path of smaller space coronagraphs

- Experience and advances in designs, devices, materials, processes, and astronomy are making possible better and better cost-benefit ratios
  - Cost well under that of Hubble Space Telescope, with 7 x larger mirror area
  - Maximizes benefits: achieves full TPF mission, including lots of astrophysics

Section 2:
Phenomenology and Operations Scenarios
Dennis Ebbets

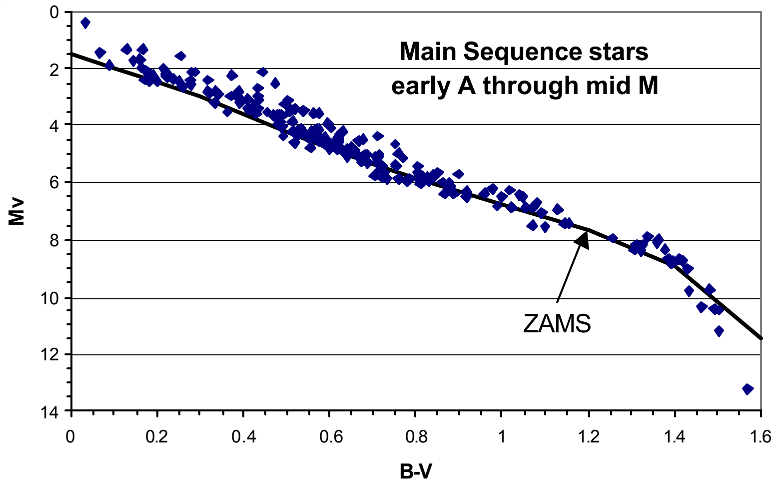
Planet Finding and Characterization
Astrophysical Opportunities

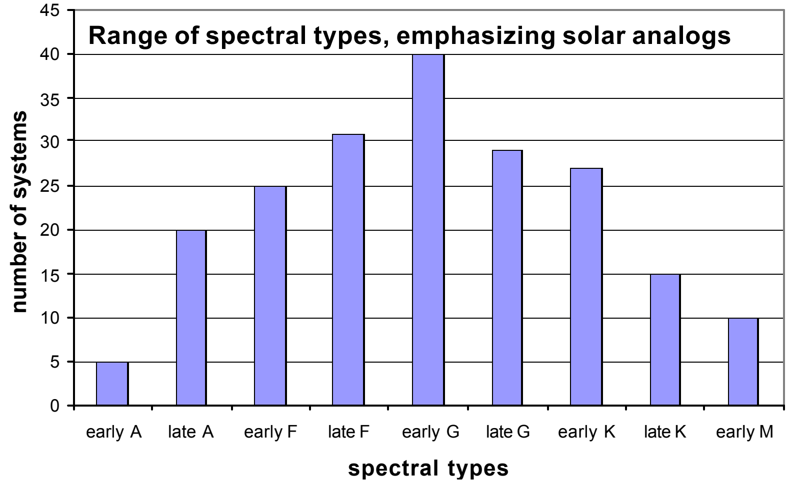
Real Stars Help us Describe Observables Relevant to the TPF Scientific Objectives

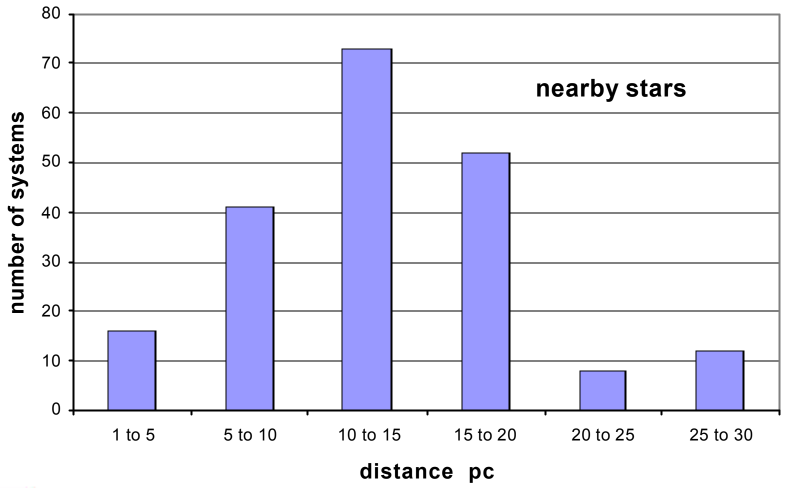
- Define population of stars, select a favorable sample
  - single, Main Sequence, A0 - M4
  - spectral type bins, nearest stars in each bin
- Define properties of interesting planets
  - within HZ, 1/2 - 2x Earth diameter, 1/2 to 2x Earth albedo
- Infer observable properties of planets for each star
  - geometric, photometric, temporal, spectroscopic
- Range and distribution of observable properties defines the "search space" in which TPF must perform
- Develop plausible strategies for observing and operating that achieve the scientific objectives, and are compatible with observatory architecture and mission constraints.
- Reveal implications on system size, lifetime, efficiency etc.

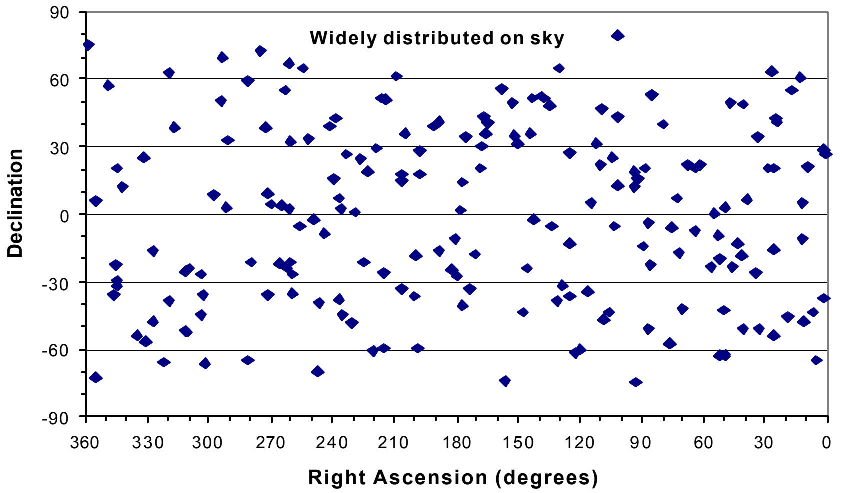
We've Identified Suitable Sample of Stars

(1150 in initial set, 202 selected for this study)



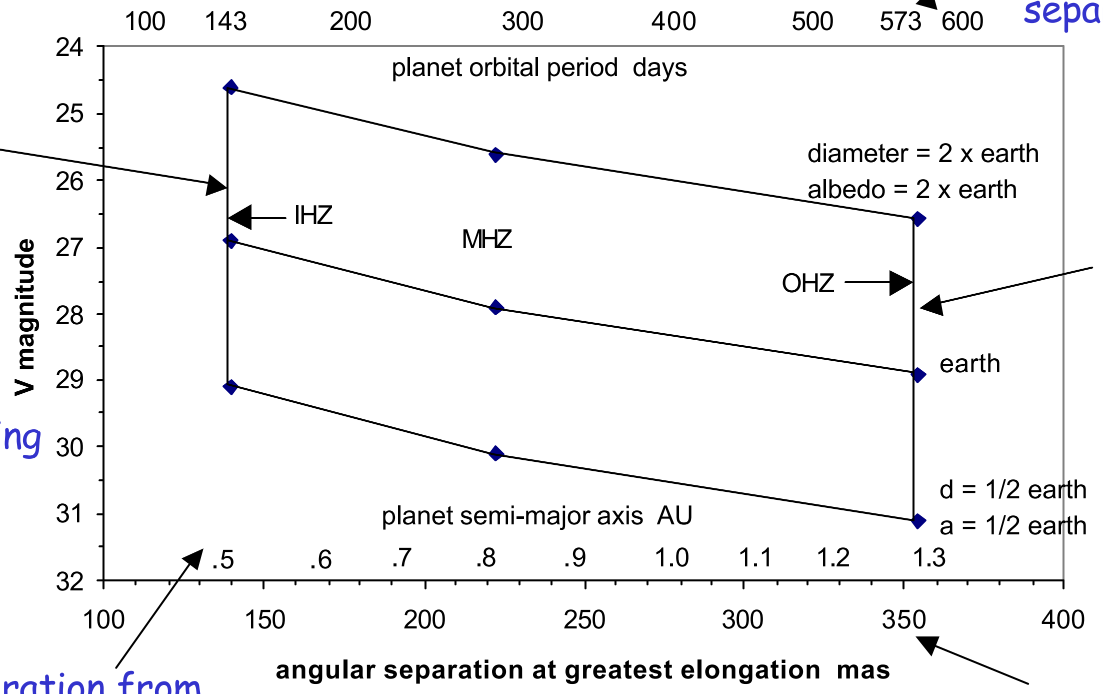






How the Range of Planet Observables can be Calculated for any Star

? Ceti: G8V, d=3.65 pc, V=3.5, B-V=0.72, m=0.8m$_{sun}$



Orbital period from separation & Kepler's law

IHZ = becomes too hot for surface liquid water

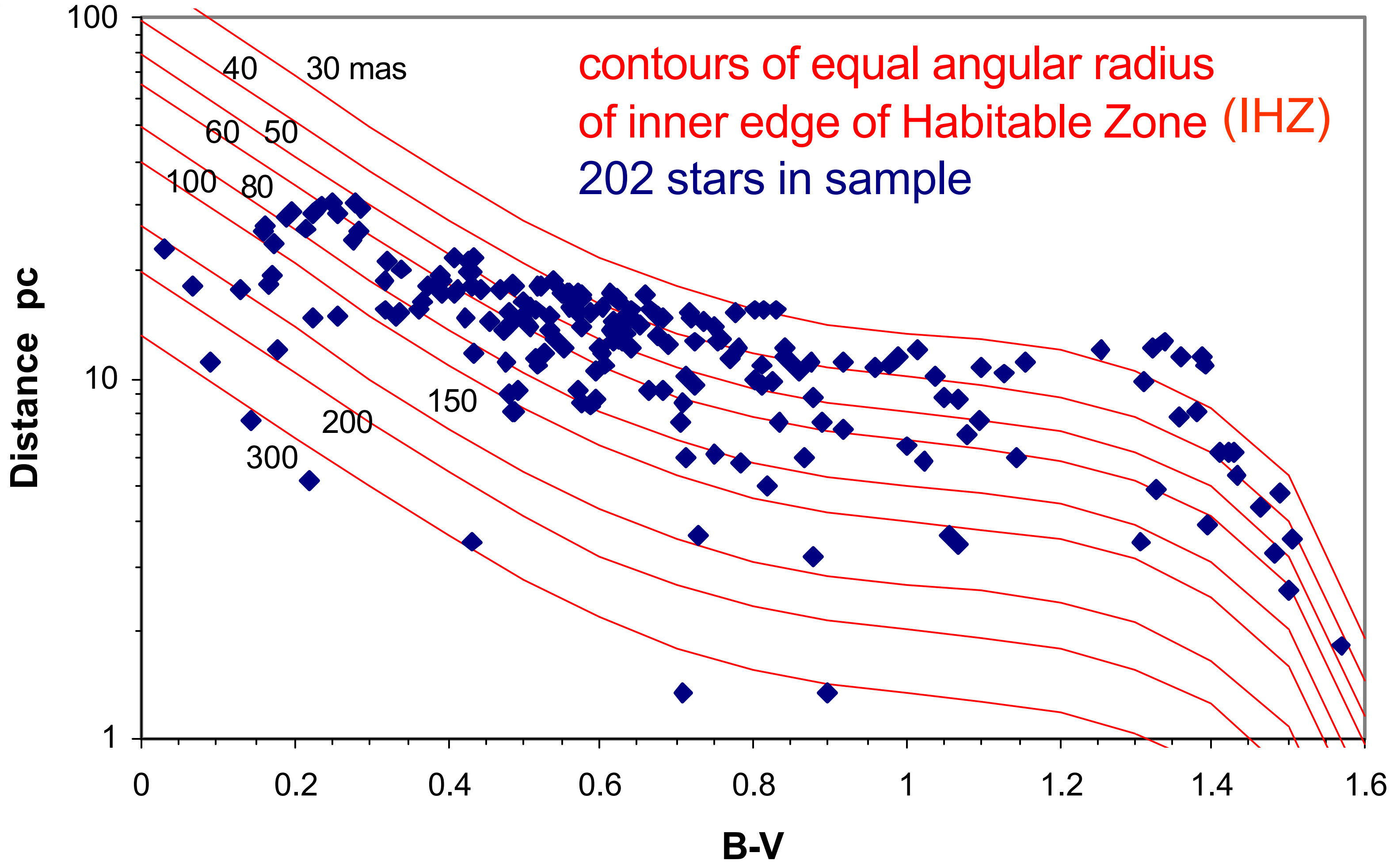
OHZ = becomes too cold for surface liquid water

V magnitude from Lambertian scattering of starlight

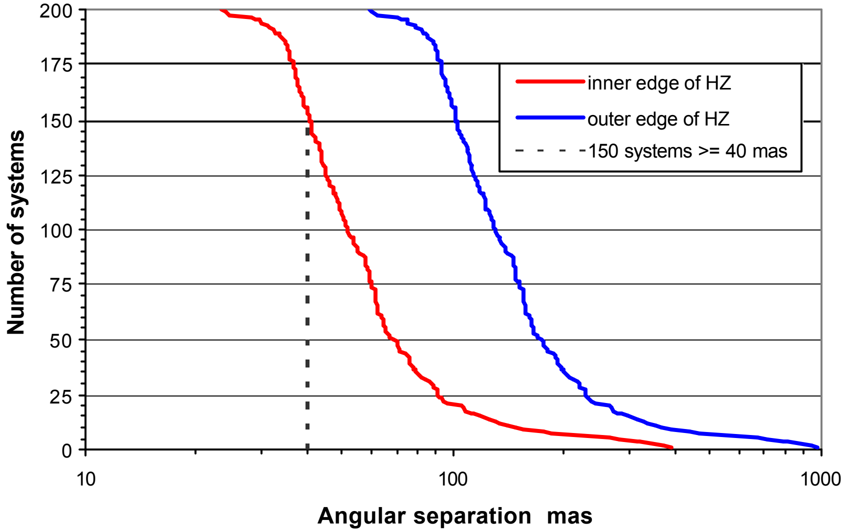
Physical separation from stellar properties & definition of HZ

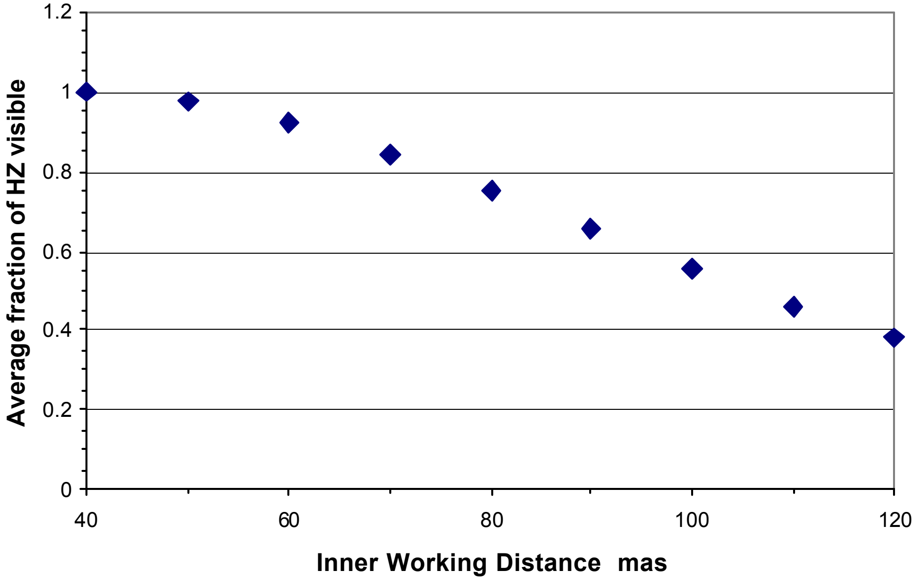
Angular separation from physical separation & distance

Goal of Detecting Planets in the HZ sets the Geometrical Requirements



Inner and Outer Edges of the HZ Define the Basic Geometrical Requirements





Purely geometrical properties are independent of wavelength or architecture

Any system planned to view the entire HZ of 150 stars must have:

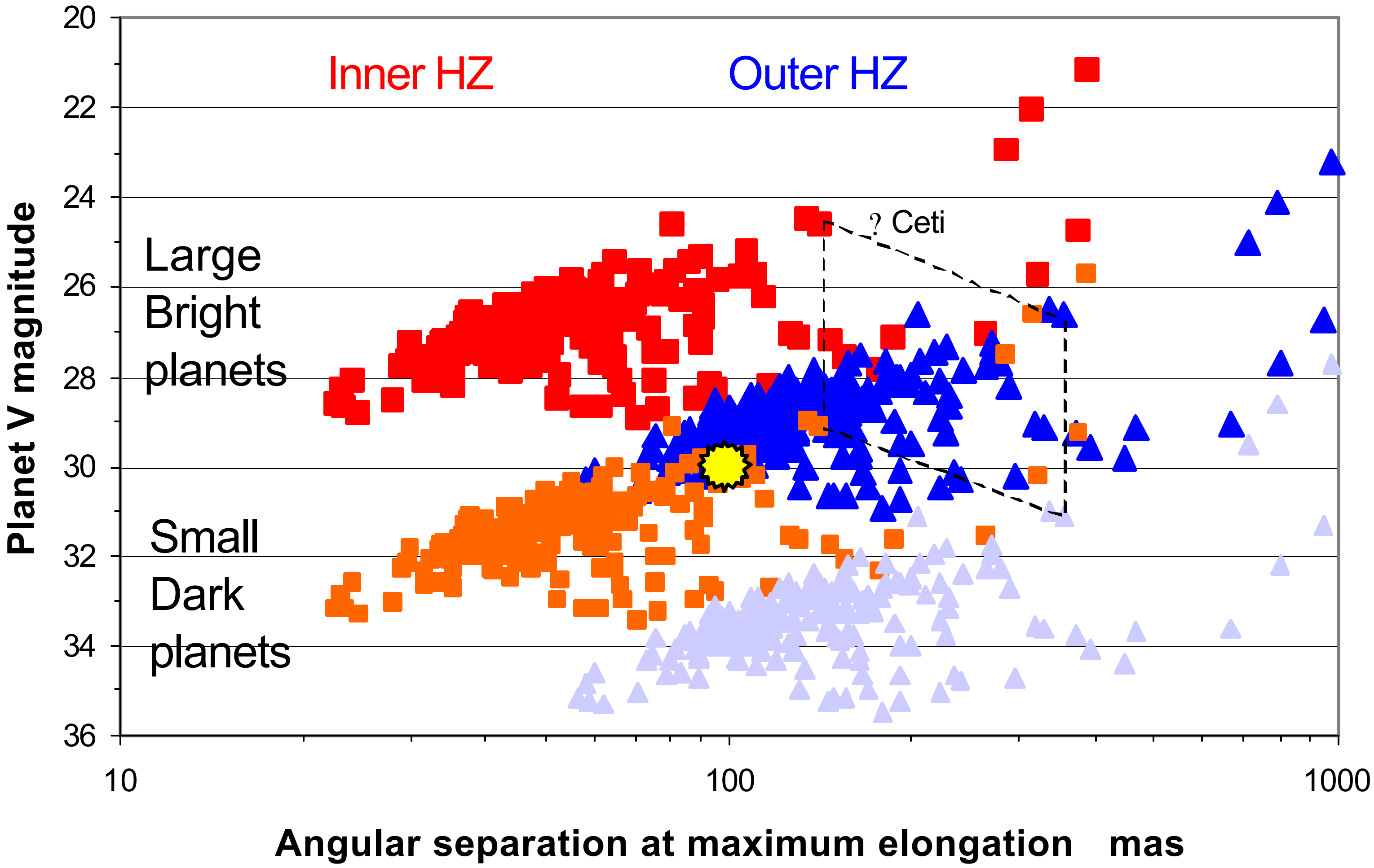
Inner Working Distance
- 40 milliarcseconds or less

Outer Working Distance
- 1 arc second or larger

Scientific utility of a system with less than full performance can be evaluated:

If IWD = 80 mas
190 stars: we can see at least part of HZ
36 stars: can see 100% of HZ
Average radial fraction visible = 0.75
155 stars: > 50% radius visible

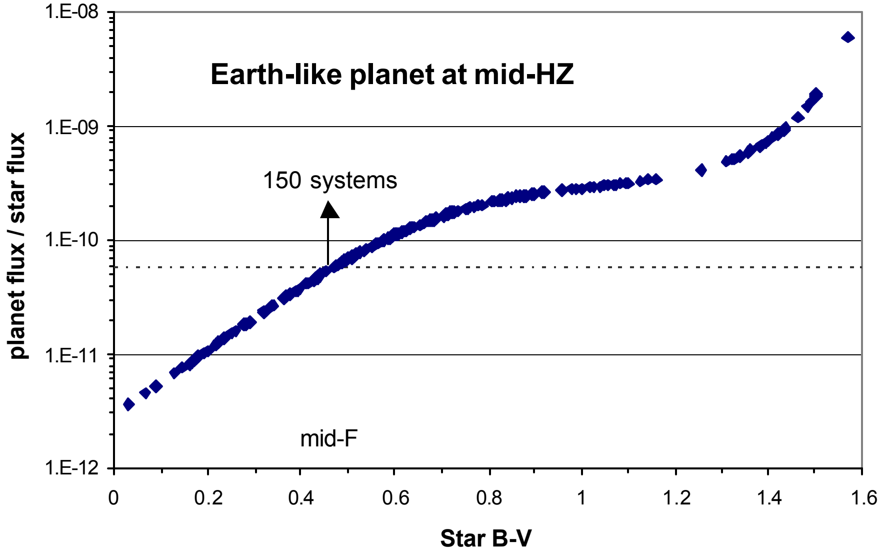
Expected Planet Brightnesses Range adds Photometric Requirements for TPF Design

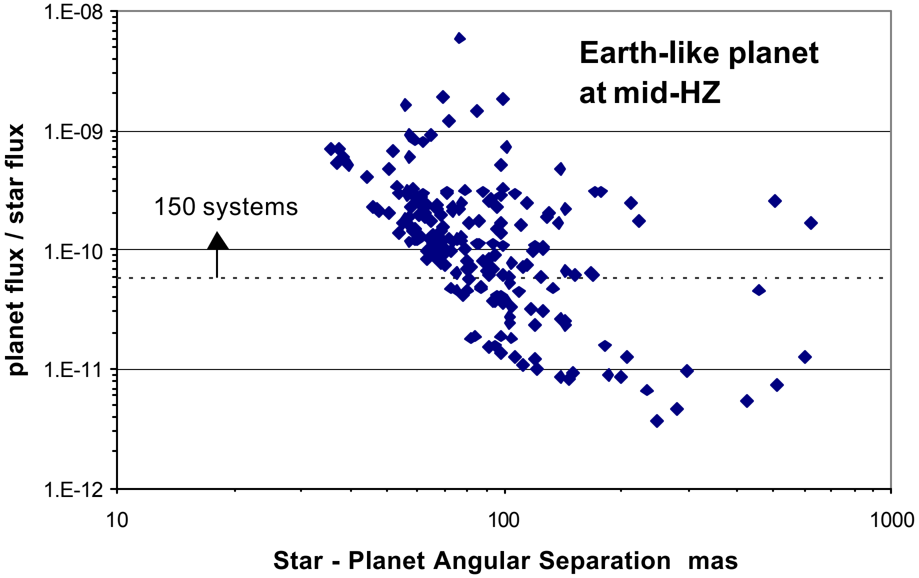


Planet's Reflected Light is Very Faint Compared to the Star's Total Light

Planet-star contrast correlates with stellar spectral type and follows inverse main-sequence brightness relation:

- Main-sequence stars get much fainter with redder spectral type





Detecting enough planets for a good statistical sample requires detecting some over 10^{10} fainter than their stars

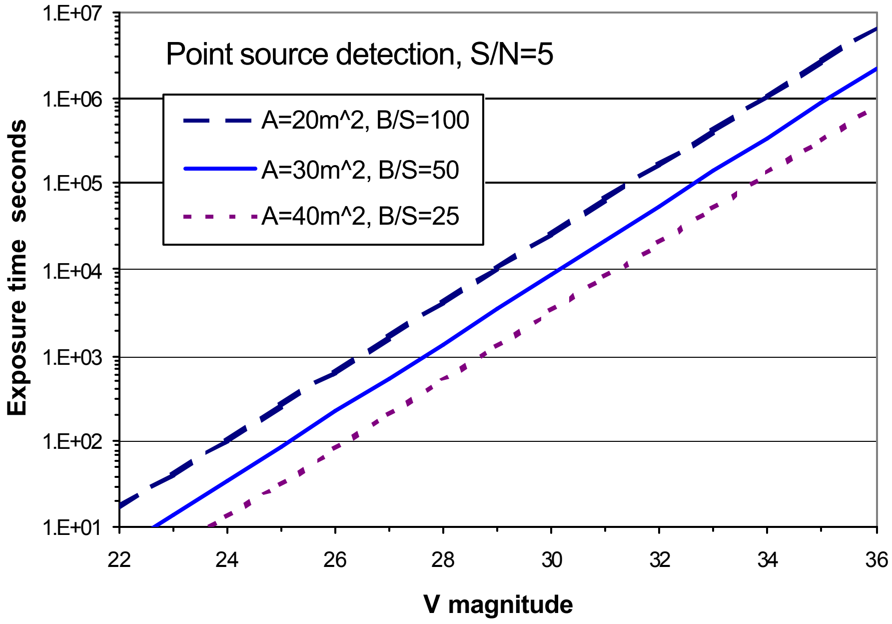
Since planets are so faint, must suppress or calibrate out these backgrounds:

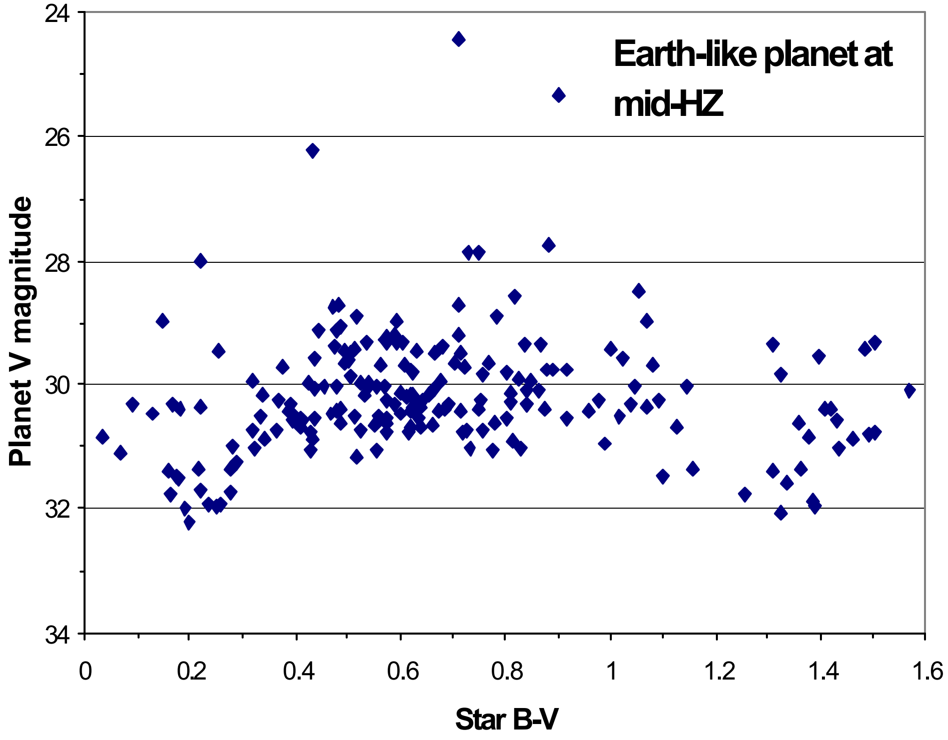
- Detector dark & read noise
- Local & exo-zodi, faint galaxies
- Diffraction, speckles, scattered light

Required Sensitivity and Exposure Times Based on Expected Planet Brightnesses

Sensitivity is related to:

- Aperture area
- Throughput
- Backgrounds
- Target brightness
- S/N desired
- Exposure time available

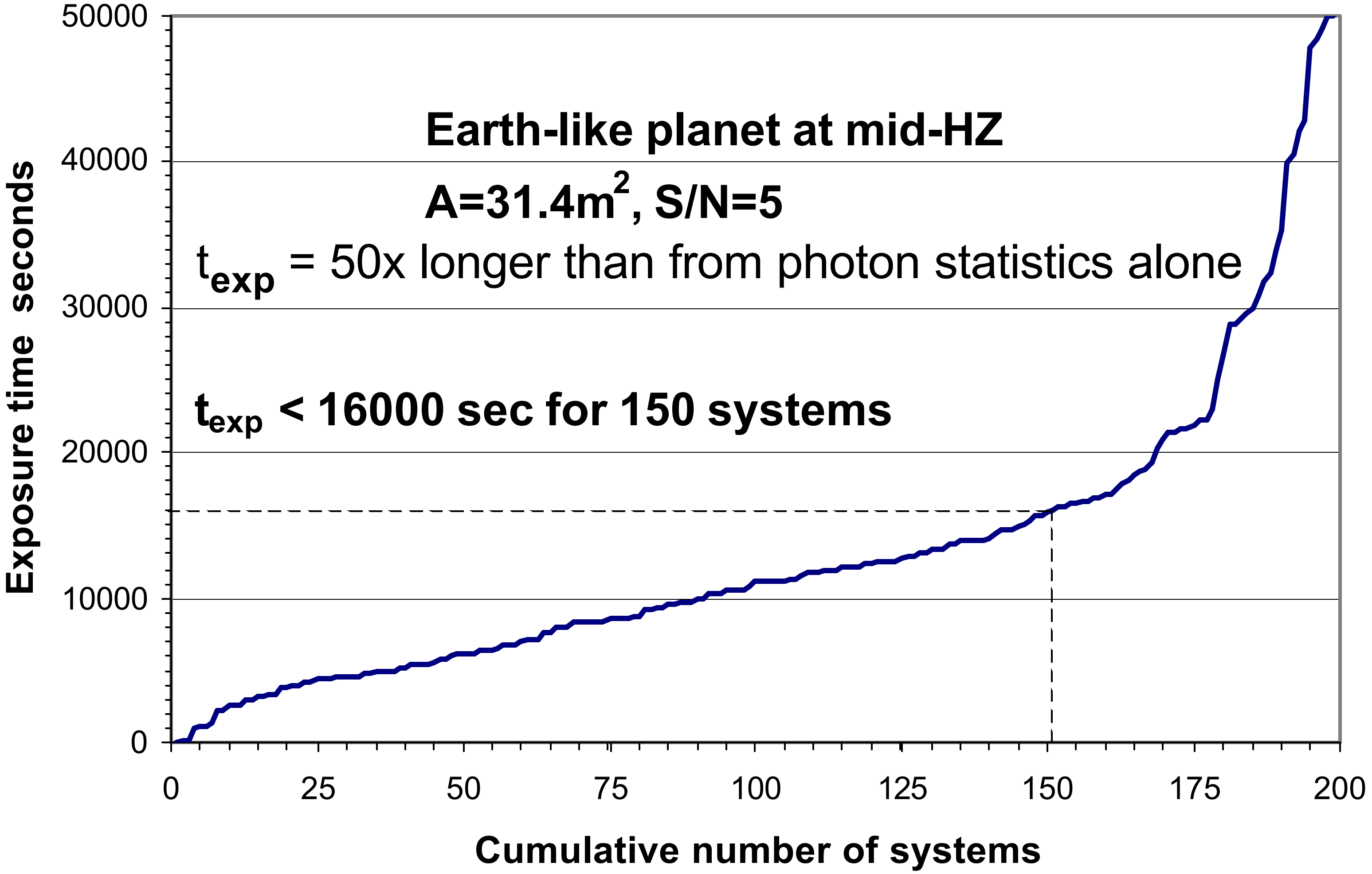




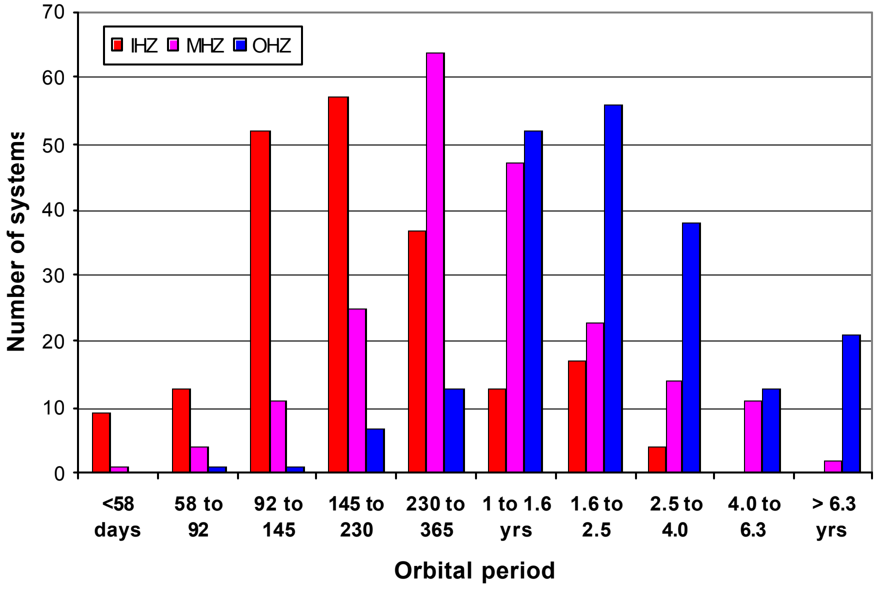
A & M stars' planets in the HZ are fainter because those stars put out less visible light in proportion to their total flux, and also because A stars are more distant.

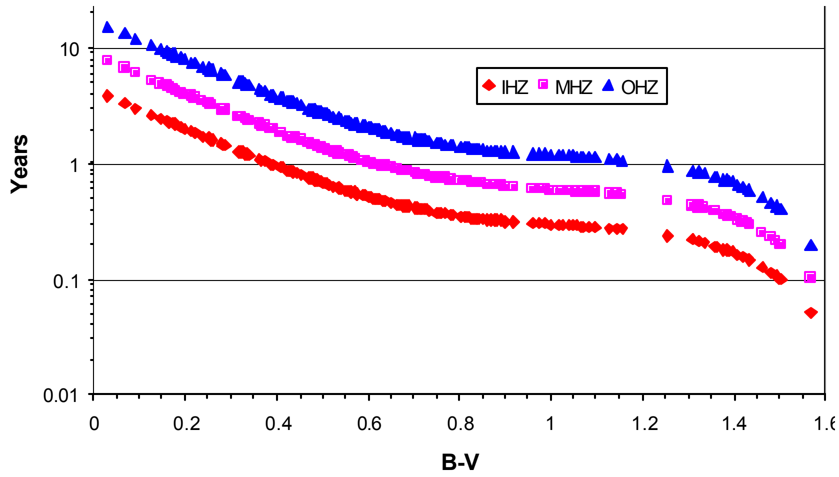
OHZ about 1 magnitude fainter than MHZ

10 x 4 m Coronagraph views 150 HZs in Suitable Int.Time -- avg. 2.5 hr., 4.5 hr. max



Planet Orbital Periods Dictate Number & Frequency of Revisits, & Mission Lifetime

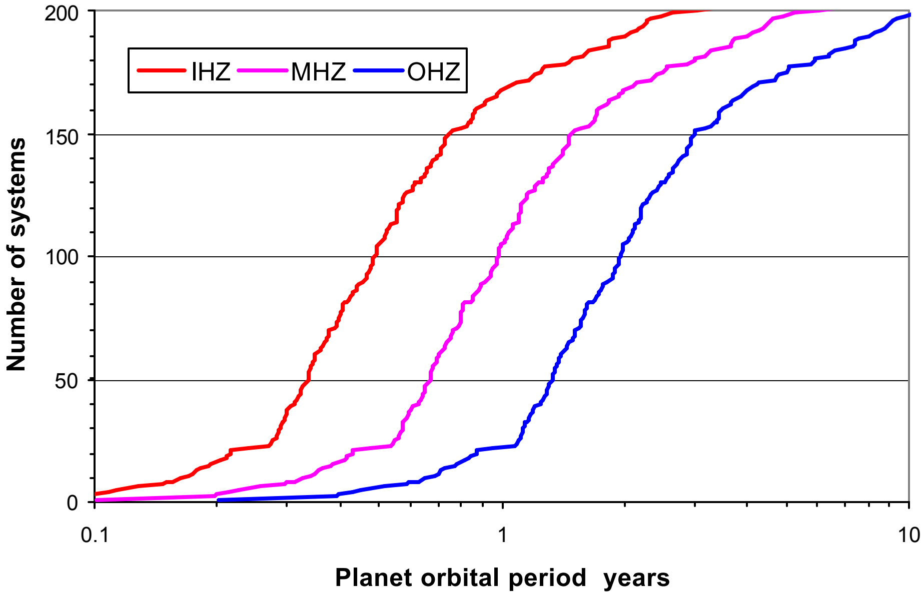




Shortest periods are 18 days for inner HZ of M4 stars

Longest periods are 15 years for outer HZ of A0 stars

These periods influence the observing sequence planned for the 5-yr mission time constraint



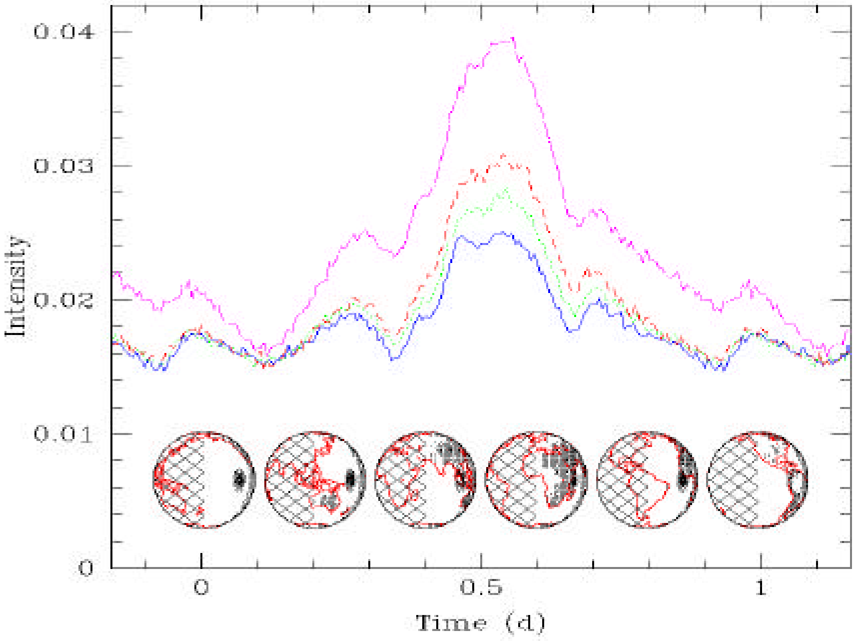
Biomarkers at Visible Wavelengths

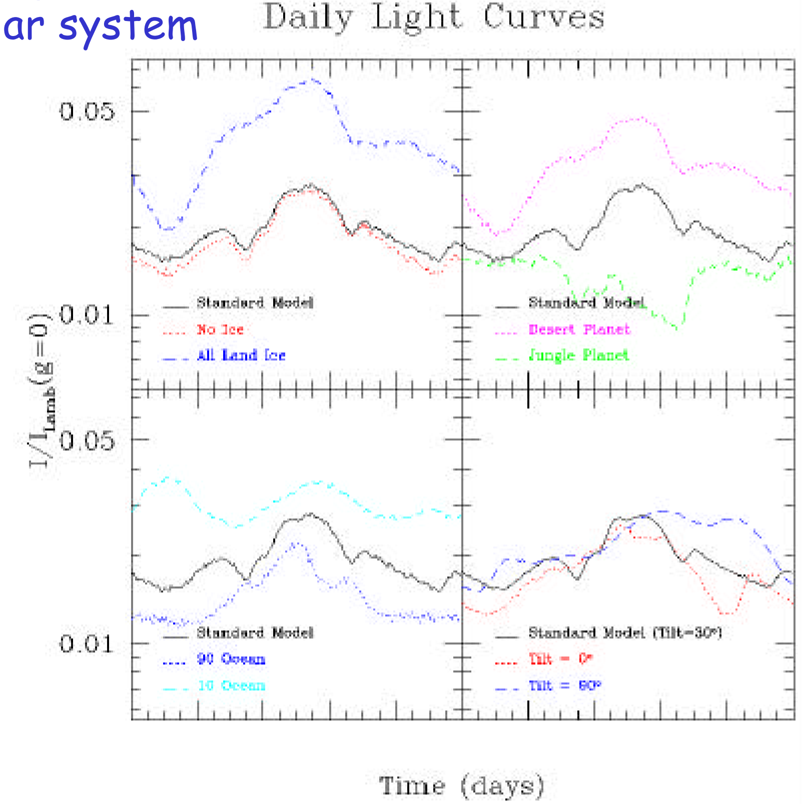
- Main indicators of life in the visible at low spectral resol. are O_2 and O_3
  - Auxiliary indicators (temperature, albedo, clouds vs. rock, chlorophyll, etc.)
  - Secular (temporal) variations
- Fairly strong evidence for life would be simultaneous presence of O_2 plus a reduced gas such as CH_4 or N_2O
  - CH_4 & N_2O lines are very weak in today's atmosphere
  - CH_4 should be easily detectable in visible in an anoxic atmosphere, thus a potential indicator for life prior to rise of O_2 in planet's atmosphere, but N_2O shouldn't be there because photolyzes rapidly in absence of O_2 and O_3
- This does not rule out other gases, or tell in what ways an oxygenated, alien biosphere would be different from our own

A Few Remarks on Other Planet Observables of Interest for TPF

(Much more information can be found in Ball's Prelim. Arch. Review volume)

- HD 209648b's detected atmospheric signature was predicted (first by our team member Sara Seager and collaborator D. Sasselov) and thus we can predict what an extrasolar planet atmosphere might look like even under different conditions than in our own solar system
- Diurnal & annual variations might be seen




Daily Light Curves

A Few Remarks on Planetary System Observables of Interest for TPF

(Much more information can be found in Ball's Prelim. Arch. Review volume)

- How common are planets; what is the diversity of planetary systems?
  - Planetary systems like ours may be rare, since most stars form in OB assns.
  - A visual TPF can access disks stripped clean of their host clouds
  - An imaging coronagraph can often view entire outer planetary systems
- Chemical and physical makeup of disks
  - Imaging and spectroscopy can help diagnose grain size distribution and composition, & evolution of these properties with stellar age & environment
- Macroscopic proto-planetary bodies
  - Search for disk gaps produced by planetary sweeping, induced spiral density waves, and debris clouds produced by proto-planetary collisions
  - At visible wavelengths, TPF can probe the properties of disks in silhouette

A Few Remarks on Astrophysics Observables of Interest for TPF

(Much more information can be found in Ball's Prelim. Arch. Review volume)

- Multiple scientific instruments on a telescope assembly hosting the TPF visible-light coronagraph can acquire the following astrophysics data:
  - Coronagraphy
    - black hole dynamical environments (coronagraph with spectroscopy)
  - Wide-field visible/UV imagery
    - space Optical-UV telescopes overcome the opacity of our atmosphere, and provide stable, high resolution wide-field imaging (ground AO is, in contrast, very difficult for large fields)
    - high-resolution wide-field imaging & detailed dynamics of distant galaxies
    - stellar environments in YSOs over range of stellar ages, metallicities, etc.; disks and jets
  - UV/visible spectroscopy
    - stellar oscillation studies of faint stars
    - elements formation & distribution -- stellar end-phases, chemical evolution
    - history of galaxy building from stellar population studies in nearby galaxies
  - Polarimetry
    - Interstellar Medium structure and constitution -- starting point for star formation

Expected Phenomenology Guides our TPF Design & Operations Approach

- TPF mission objectives are clearly articulated in terms of types of stars, nature of planets, and number of systems
- Search space of observable phenomena is summarized as follows:

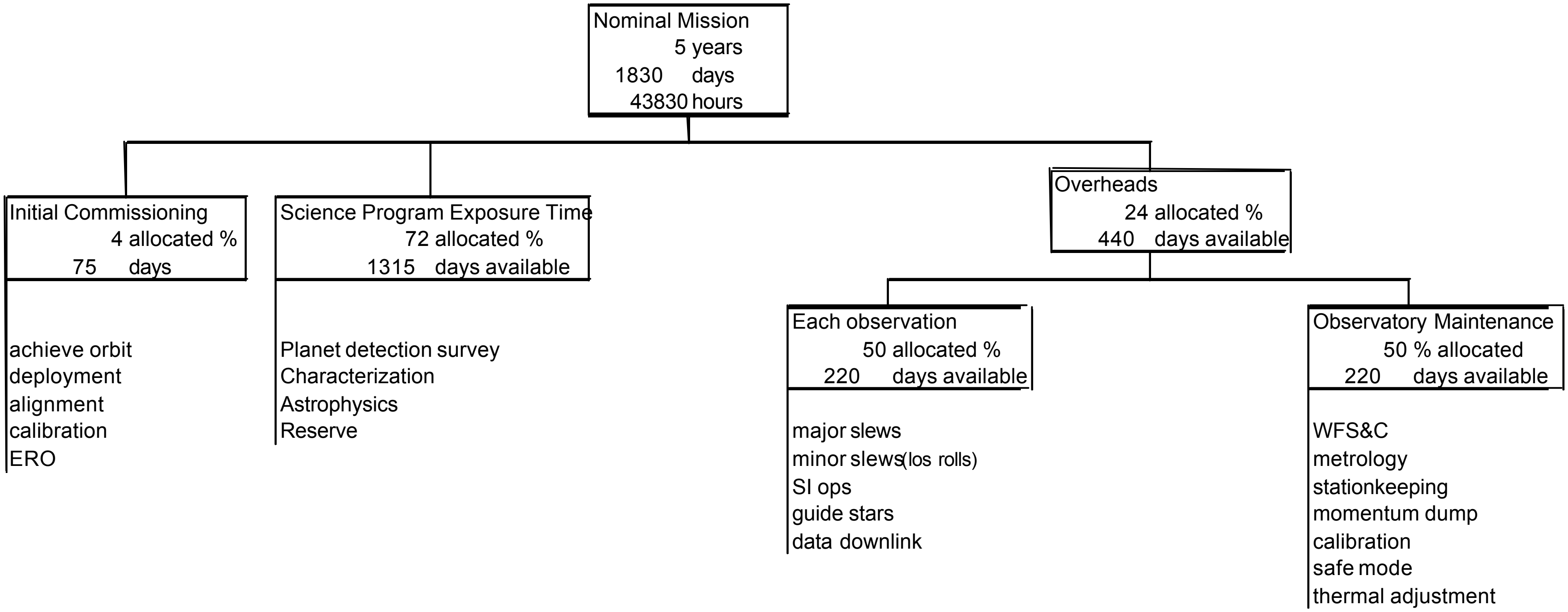
Targets	>1000 potentially available
Locations	Uniformly distributed on sky
IWD	40 mas to observe 100% of HZ for 150 stars
	60 mas allows 92% of HZ (avg) for 150 stars
OWD	> 1 arc sec
Orbital periods	18 days for IHZ of M stars
	15 years for OHZ of A stars
Planet V magnitudes	$26 < V < 34$
Planet/star contrast	10^{-8} to 10^{-12}
Exposure times	< 4.5 hours for S/N = 5 detection in many cases

Our Operational Scenarios Address the SWG's Scientific Priorities

- Search 150 solar-type stars for terrestrial planets
  - Discovery survey
  - System characterization
  - Terrestrial planet characterization
- Study other planetary phenomena
  - Systems with "hot Jupiters" (using the combined light)
  - Exozodi disks
- Conduct non-planetary astrophysical research

Does a visible-light coronagraph offer a viable approach to meeting these objectives?

A “Top-Down” Allocation Distributes Time Between Exposures and Overheads



Nominal Mission
5 years
1830 days
43830 hours

Initial Commissioning
4 allocated %
75 days

- achieve orbit
- deployment
- alignment
- calibration
- ERO

Science Program Exposure Time
72 allocated %
1315 days available

- Planet detection survey
- Characterization
- Astrophysics
- Reserve

Overheads
24 allocated %
440 days available

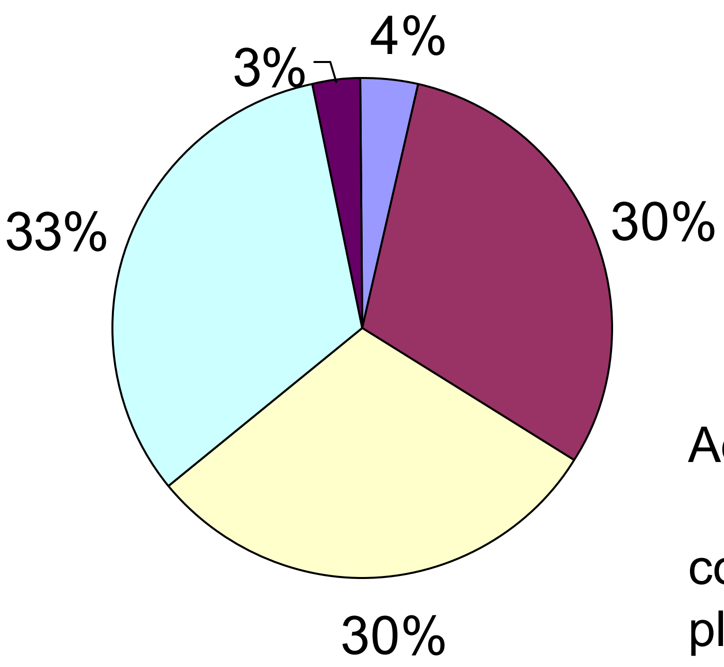
Each observation
50 allocated %
220 days available

- major slews
- minor slews(los rolls)
- SI ops
- guide stars
- data downlink

Observatory Maintenance
50 % allocated
220 days available

- WFS&C
- metrology
- stationkeeping
- momentum dump
- calibration
- safe mode
- thermal adjustment

Mission Priorities Determine Time Allocations



5 years = 1826 days

Activity	% of mission	days
commissioning	4	73
planet detection survey	30	548
planet characterization	30	548
astrophysics	33	603
reserve	3	55
total	100	1826

We Suggest an Incremental Approach to Planet Detection and Characterization

Phase	Objective	Observations
Planet discovery	Detect presence of point-source or zodi disk with geometry & brightness consistent with planetary system.	Small number of broad-band images.
Confirmation	Objects are associated with the star and seen in reflected light. Not other stars or background galaxy.	Deeper images to confirm with higher S/N. Several filters to confirm colors consistent with reflected light. Time series to detect motion.
System characterization	Determine number of planets in HZ, orbits, brightness, Strongest atmospheric tracers. Characterize zodi cloud.	Deep images to detect faintest planets. Time series to measure orbits. Photometric, polarimetric or low res spectra to detect atmosphere.
Planet characterization	Measure temporal variations, sensitive atmospheric tracers, biomarkers.	Time sequence photometry. Medium resolution spectra for atmospheric tracers and biomarkers.

Target stars for Planet Detection Survey will be Carefully Selected

- Theoretical analyses such as discussed above
- Precursor observations with positive results
  - FAME - Jupiters outside HZ
  - Kepler - frequency of TPs vs spectral type
  - Ground-based V_{radial} - no hot Jupiters within HZ
- Proxy phenomena
  - exozodi disks
  - stellar metallicity, activity, multiplicity
  - stellar age and evolutionary state
  - confusion from point and diffuse sources
- Instrumental considerations
  - sensitivity estimates
  - stray light from nearby stars

Strategy Options for Terrestrial Planet Discovery Phase

- Cream-skimming - most favorable brightness & geometry
  - Survey 150 stars deeply enough to detect earth-like or brighter planets
  - Pros - large number of stars
  - Cons - could overlook smaller, fainter, but interesting TPs
- Drain the lake - entire range of brightness & geometry
  - Concentrate on stars for which a TP will be among the brightest and easiest to see
  - Observe deep enough to guarantee detection of all planets bigger and brighter than some lower limit of interesting TP
  - Pros - exhaustive characterization of some stars
  - Cons - smaller number of systems
- Combination - use appropriate strategy for each star

Example: ? Ceti Discovery Phase

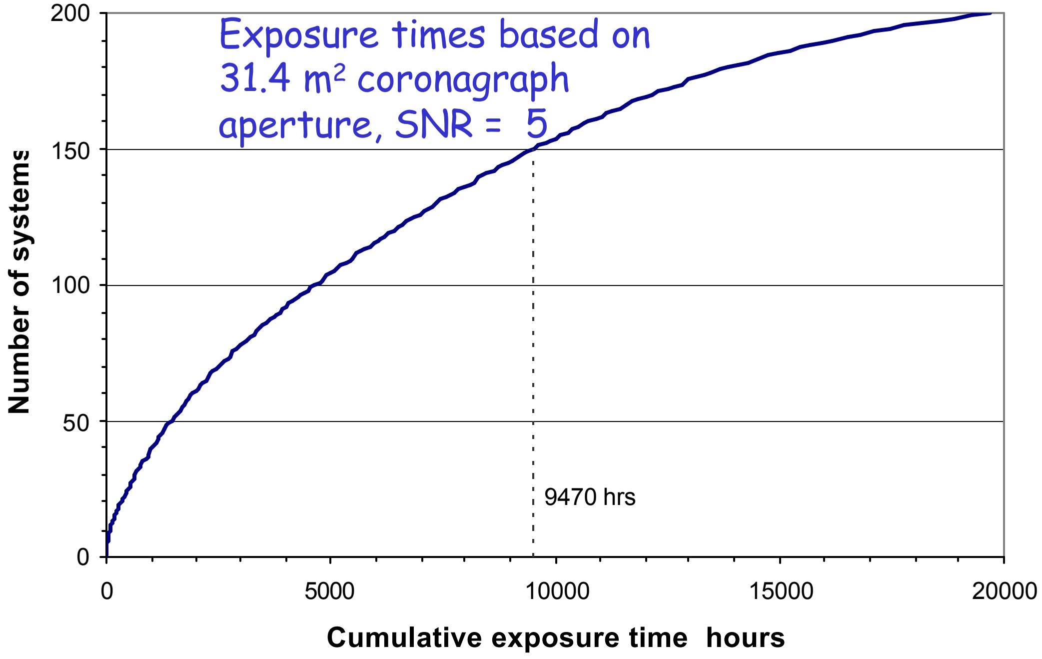
(bright enough for “drain the lake” approach)

1st observation near start of observing season
    1 hr. deep enough to detect earth at mid HZ
2nd obs. 18 days later, 1/8 of shortest orbital period
    1 hr. detect earth at mid HZ
3rd obs. 36 days after first, 1/8 of mid HZ period
    5 hrs. detect 1/2 earth at mid HZ
4th obs. 72 days after first, 1/8 of outer HZ period
    5 hrs. detect 1/2 earth at mid HZ
5th obs. 72 days after fourth, 1/8 of outer HZ period
    15 hrs. detect 1/2 earth at outer HZ

total elapsed time interval = 198 days = 6.6 months

If planets detected at any time, transition to confirmation phase.
If no planets detected after 5th epoch, infer with 90% confidence that no planet brighter than 1/8x Earth exists in HZ

A Planet Detection Survey can be designed to observe 150 stars



Exposure times based on 31.4 m^2 coronagraph aperture, SNR = 5

30% of 5yr mission = 13150 hrs
72% efficiency allows 9470 hrs of exposure time

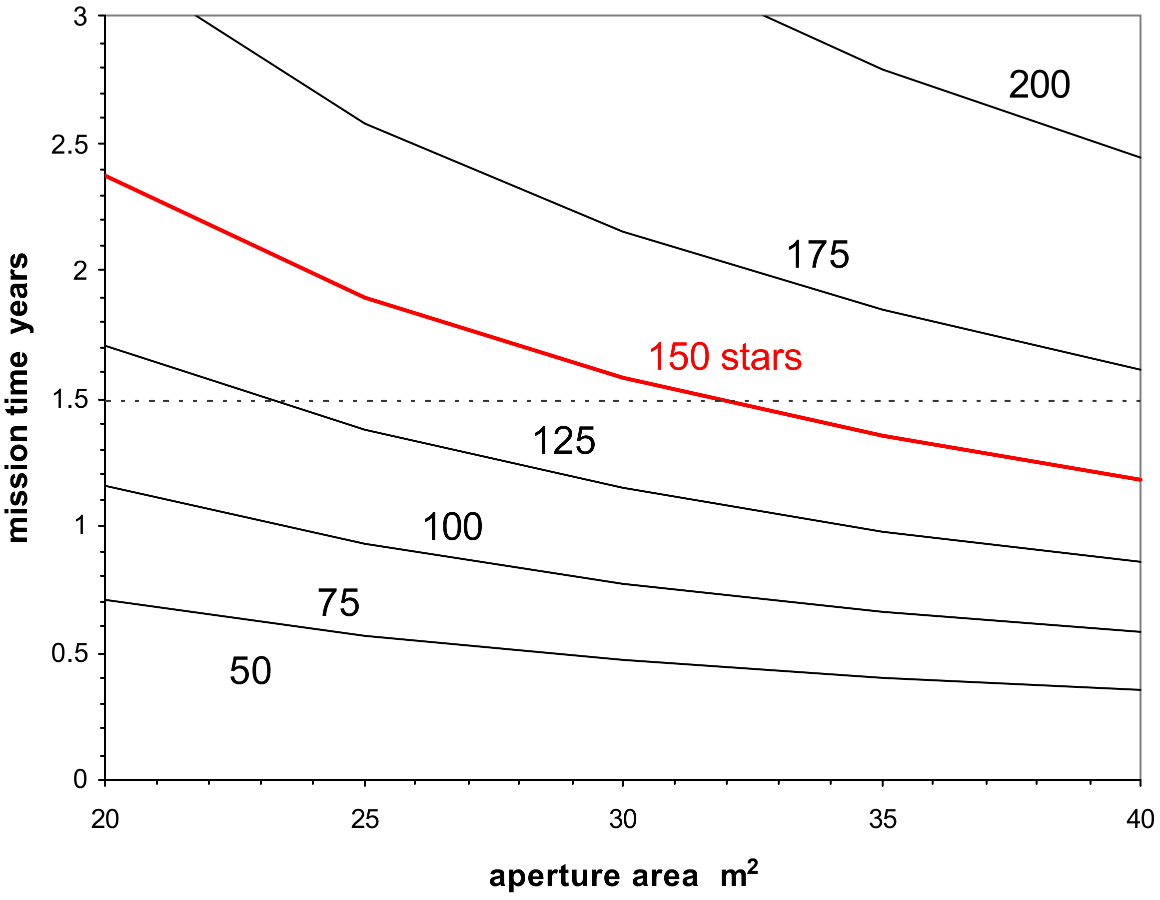
Approach for this calculation = cream-skimming

Initial exposure time was calculated to detect an <u>Earth at mid-HZ</u> (exp. time 50x photon stats. time only)

2 epochs with initial exposure time
2 epochs with 5x initial exposure
1 epoch with 15x initial exposure

(not quite deep enough to reach smallest and faintest planets)

Number of Stars Searched Depends on Aperture and Mission Lifetime



Life-cycle costs can help referee these trades

Instrument characteristics:
- aperture area
- system throughput
- background light suppression
- field of regard
- overhead times

Mission lifetime
- fraction dedicated to survey

Survey strategy
- number & type of stars
- depth of planet search
- repeat visits

Typical Sequence During Discovery Phase

- Slew to target
- Settle
- Acquisition of target star for fine track
- Wave-front adjustment
- Exposures
- Roll
- Settle
- Wavefront adjustment
- Exposures
- …

30% of 5-year Mission is Allocated for Characterization of Terrestrial Planets

Planet Characterization	
50	number of systems with planets found
3	additional visits for orbit determination
2	filters each visit
2	roll or dither positions
2	hours per exposure
1200	hours for orbit follow-up
50	number of planets for low resolution spectroscopy
2	spectroscopic configurations
40	hours exposure time each
4000	hours for low resolution spectroscopy
10	planets for medium resolution spectroscopy
2	spectroscopic configurations
200	hours exposure time each
4000	hours for medium resolution spectroscopy
9200	hours required
13149	hours allocated for characterization
70%	required nominal efficiency

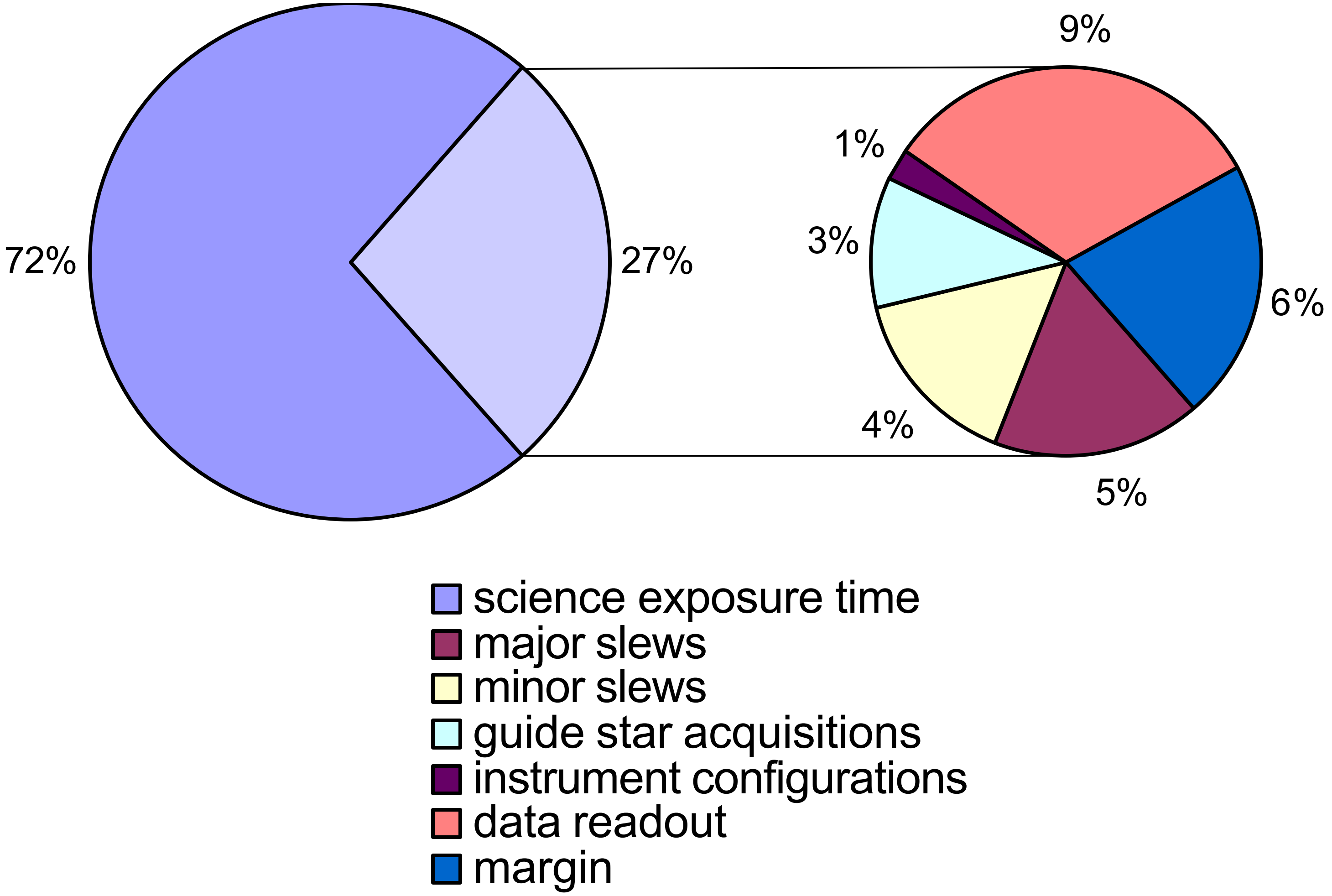
Investigations of Other Systems with Interesting Circumstellar Phenomena

- Protoplanetary accretion disks
- Zodi debris disks
- Close-in giant planets
- Giant planets in eccentric orbits
- Binary stars
- Evolved systems (WD companions)

33% of 5-year mission is Allocated for Specific Astrophysics Targets

General astrophysics	
Extragalactic targets	
	AGN, QSOs, jets
Circumstellar ejecta	
	YSO jets, LBV, novae, SN, evolved binaries, Wolf-Rayet stars, giants & supergiants
Circumstellar environments	
	protoplanetary disks, debris disks, exo-zodis
200	targets
2	vists per target
4	filters per visit
4	roll or dithers
1.5	hours per exposure
9600	hours of exposure time
14463.9	hours allocated to astrophysics
	(more astrophysics hrs. if few planets found)
66%	required nominal efficiency

Time for Overhead Functions can be Estimated and Budgeted



Summary of Conclusions Based on Operations Scenarios

- TPF mission objectives can be clearly articulated in terms of types of stars, nature of planets and number of systems
  - Should be refined by SWG and published as one or more DRM
- Exposure times range from few minutes to 4.5 hours for Earth at mid-HZ (S/N = 5)
- 30m^2 is about the smallest aperture that can complete both the planet and astrophysics missions in the allotted time
- Need to suppress stray light so planet can be detected in 50x ideal photon limit exposure time
- Can survey & characterize 150 systems in 5 years
- Needs ~70% mission efficiency - consider operability in design
- A reflected light coronagraph appears to be a viable approach to meet the currently understood scientific objectives of TPF