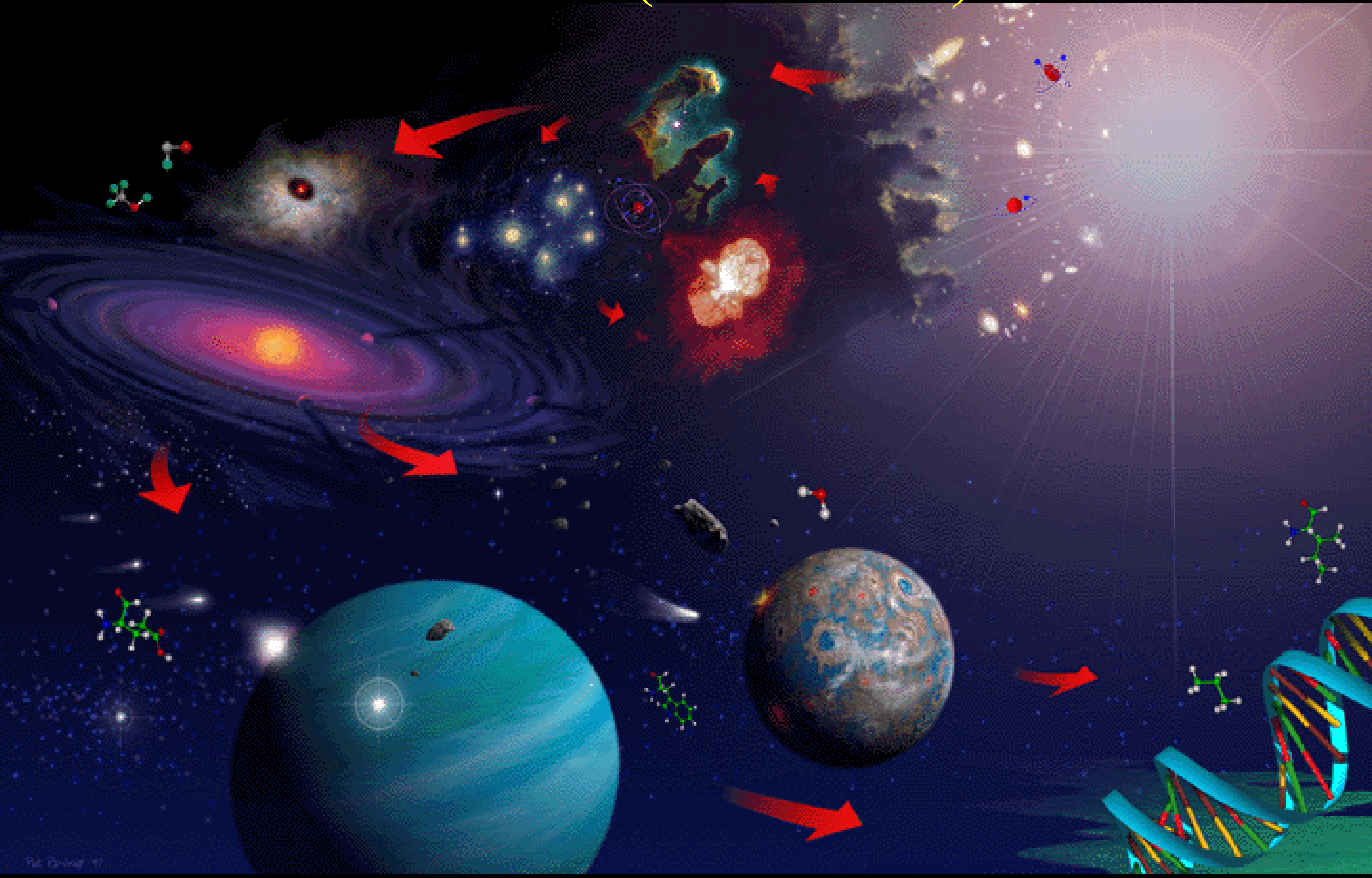
The Search for (Habitable) Planets

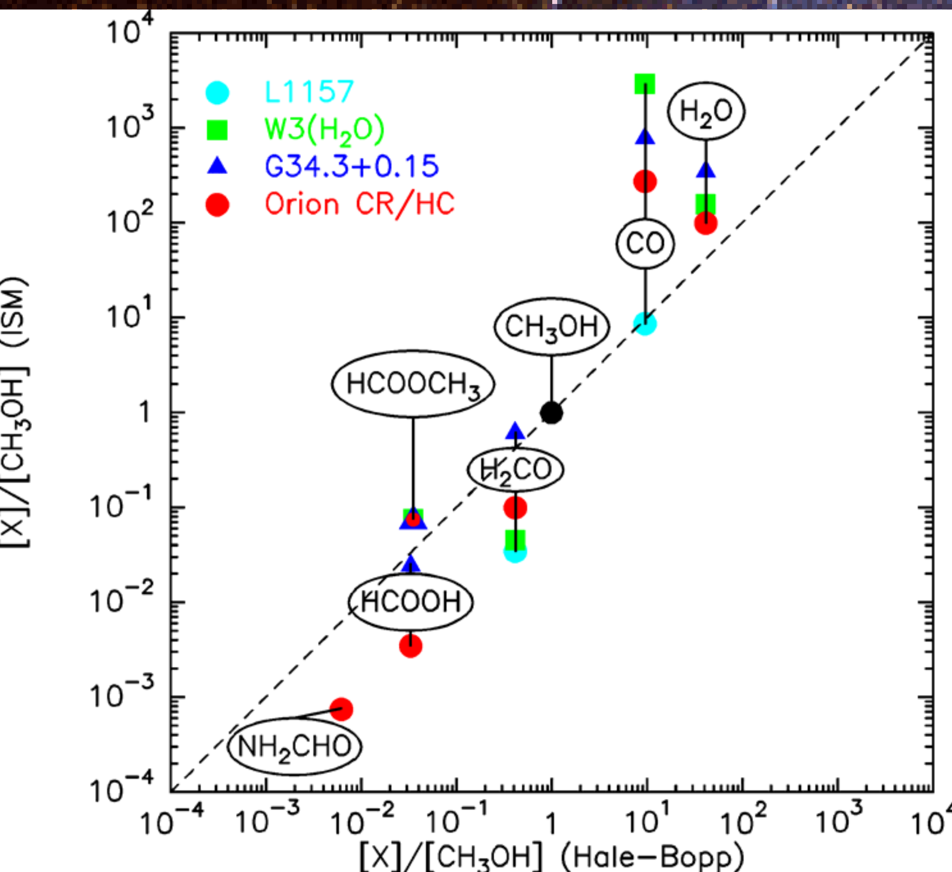


C. Beichman, JPL

Fundamental Facts To Remember About the Search for Planets and Life

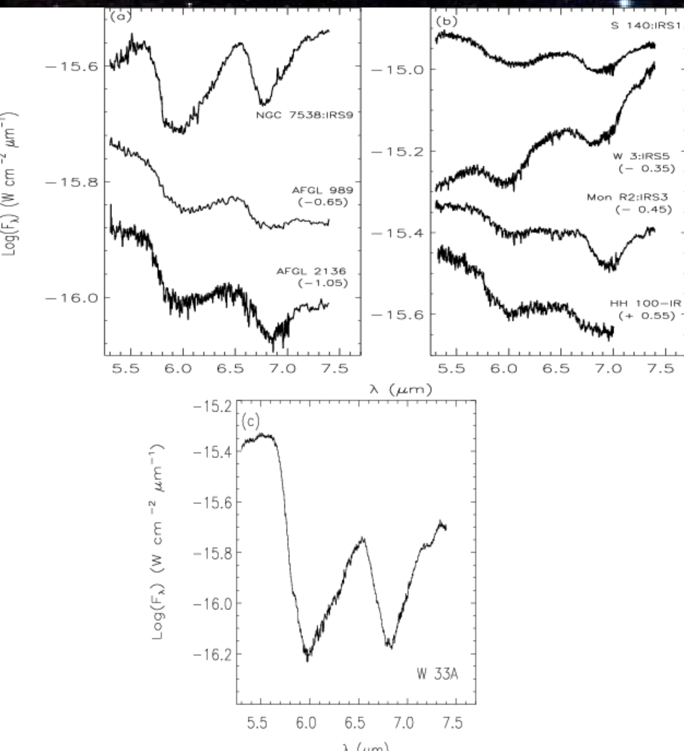
- The necessary ingredients of life are widespread
  - Observation reveals uniformity of physical and chemical laws
  - Origin of the elements and their dispersal is well understood
  - Carbon bond is unique and ubiquitous! Forget Silicon life.
- Life on Earth can inhabit harsh environments
  - Micro- and environmental biology reveal life in extremes of temperature, chemistry, humidity
- Life affects a planetary environment in a detectable way
  - Our own atmosphere reflects the presence of primitive through advanced life
- Planets are a common outcome of star formation
  - Modern theory of *star* formation makes *planet* formation likely

Organic Chemistry Ubiquitous: Comets



H2O	100	IR	
CO	23	radio, IR, UV	
CO2	6	IR	a)
*CH4	0.6	IR	
*C2H2	0.1	IR	
*C2H6	0.3	IR	
CH3OH	2.4	radio, IR	
H2CO	1.1	radio	
*HCOOH	0.09	radio	
*CH3CHO	0.02	radio	
*HCOOCH3	0.08	radio	
*NH3	0.7	radio	
HCN	0.25	radio, IR	
*HNC	0.04	radio	
*CH3CN	0.02	radio	
*HC3N	0.02	radio	
*HNCO	0.1	radio	
*NH2CHO	0.015	radio	
H2S	1.5	radio	
*SO	0.3	radio	
*SO2	0.2	radio	
*OCS	0.4	radio, IR	
CS2	0.2	UV, radio	b)
*H2CS	0.02	radio	
S2	0.005	UV	c)

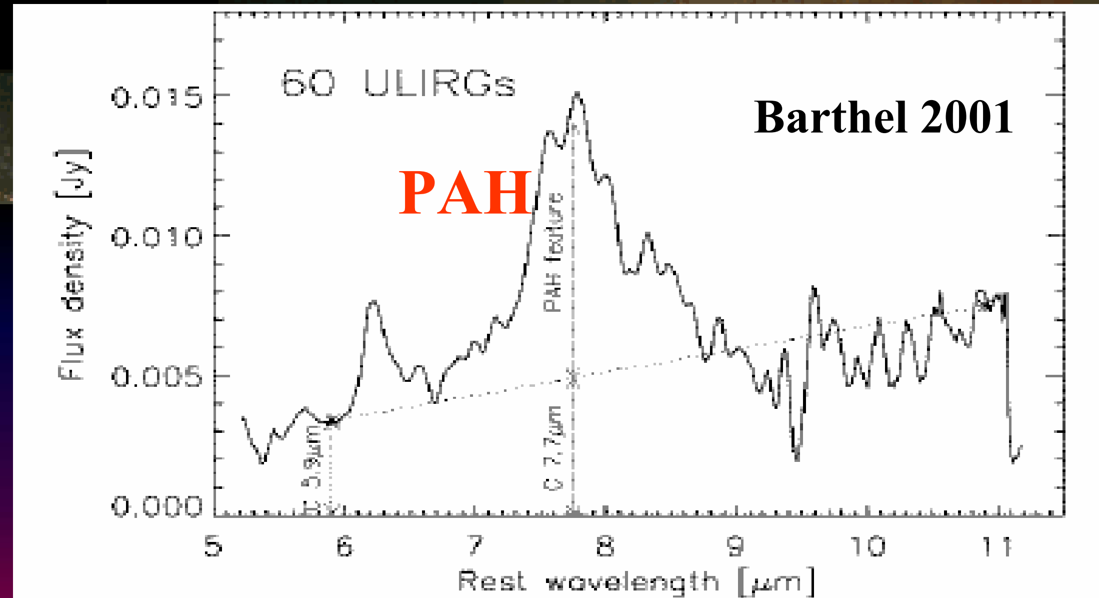
…Star & Planet Forming Regions…

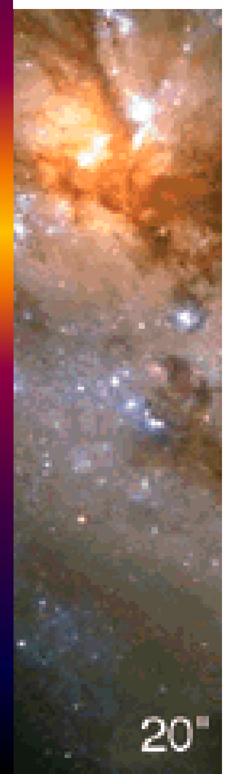


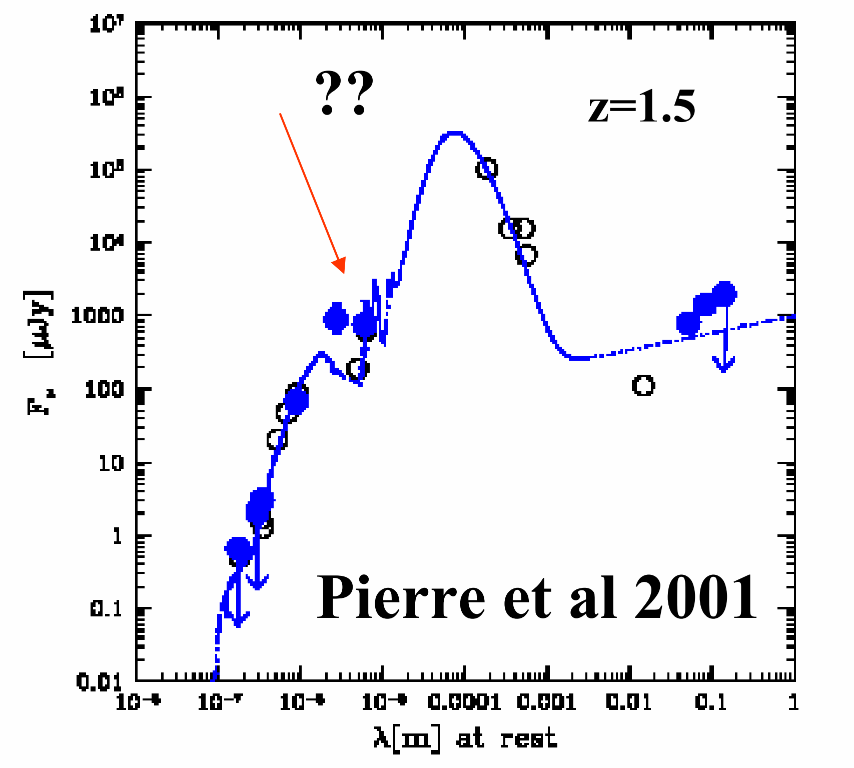
IR, submm, mm spectra reveal gas phase, ices, mineralogical signatures of many species, incl: H_2O, CO_2, CH_3OH, CO, CH_4, formic acid (HCOOH) and formaldehyde (H_2CO), etc.

…and distant galaxies

- Polycyclic Aromatic Hydrocarbons (PAHs)
  - Complex 2-D carbon molecules (>25 carbon atoms)
  - Found in many active galaxies
- Perhaps in distant quasar at z~1.5 (wait for SIRTF)
- CO detected in a very distant quasar (z=4.1!)
  - Found with more complex species in more nearby objects

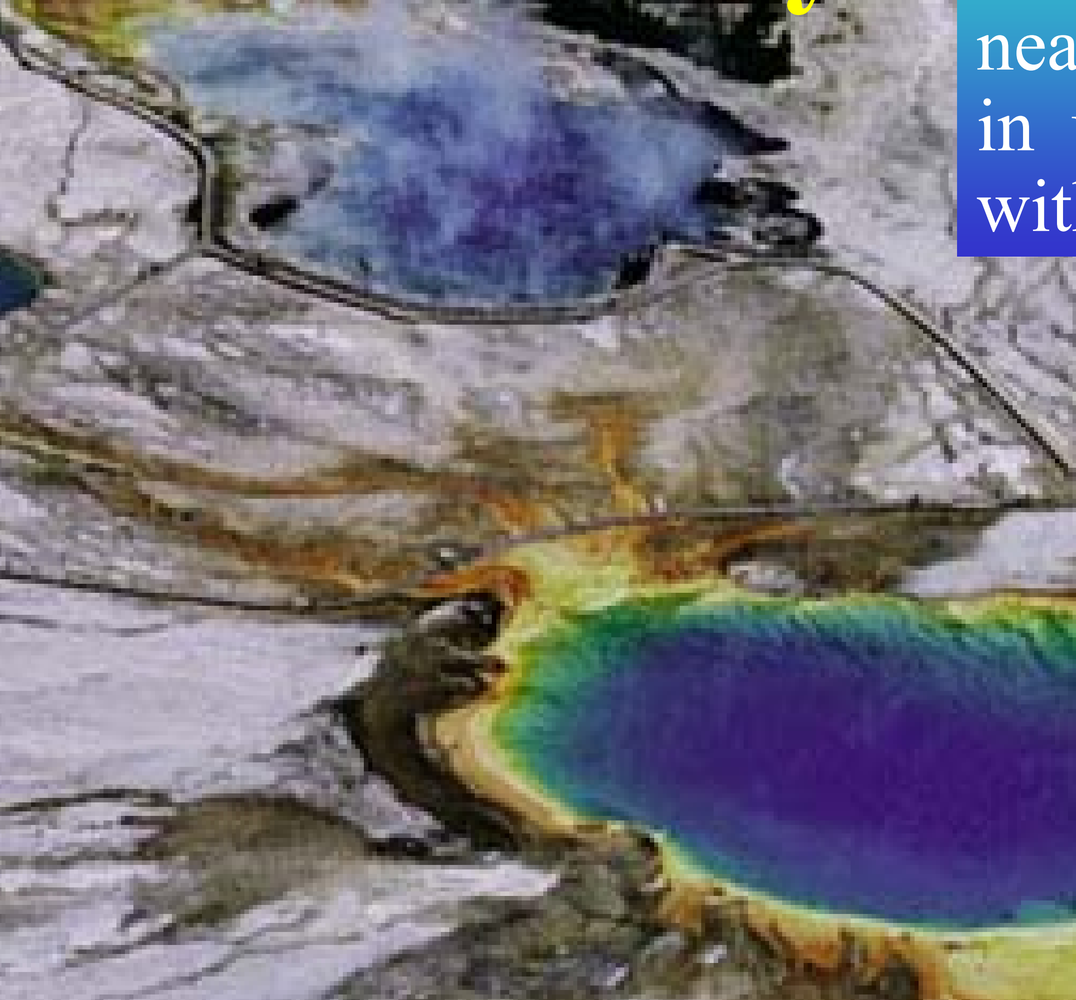


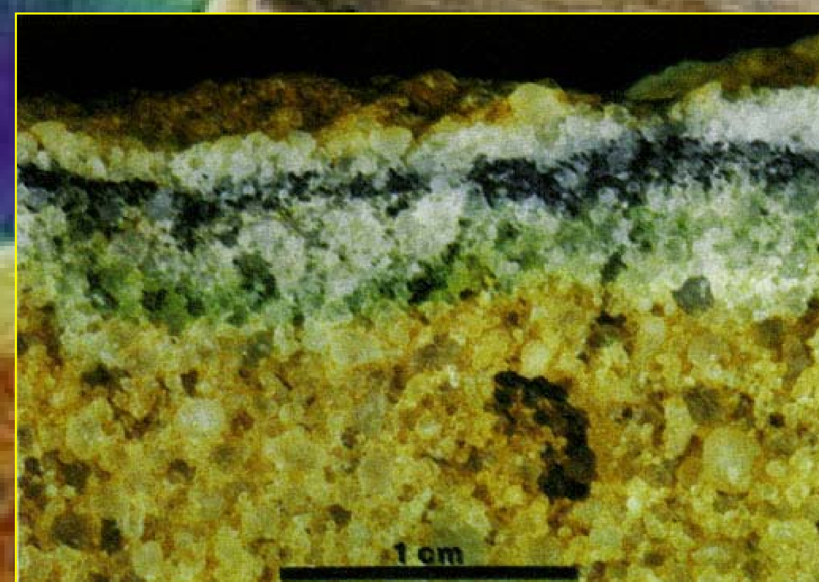




Life is Hardy

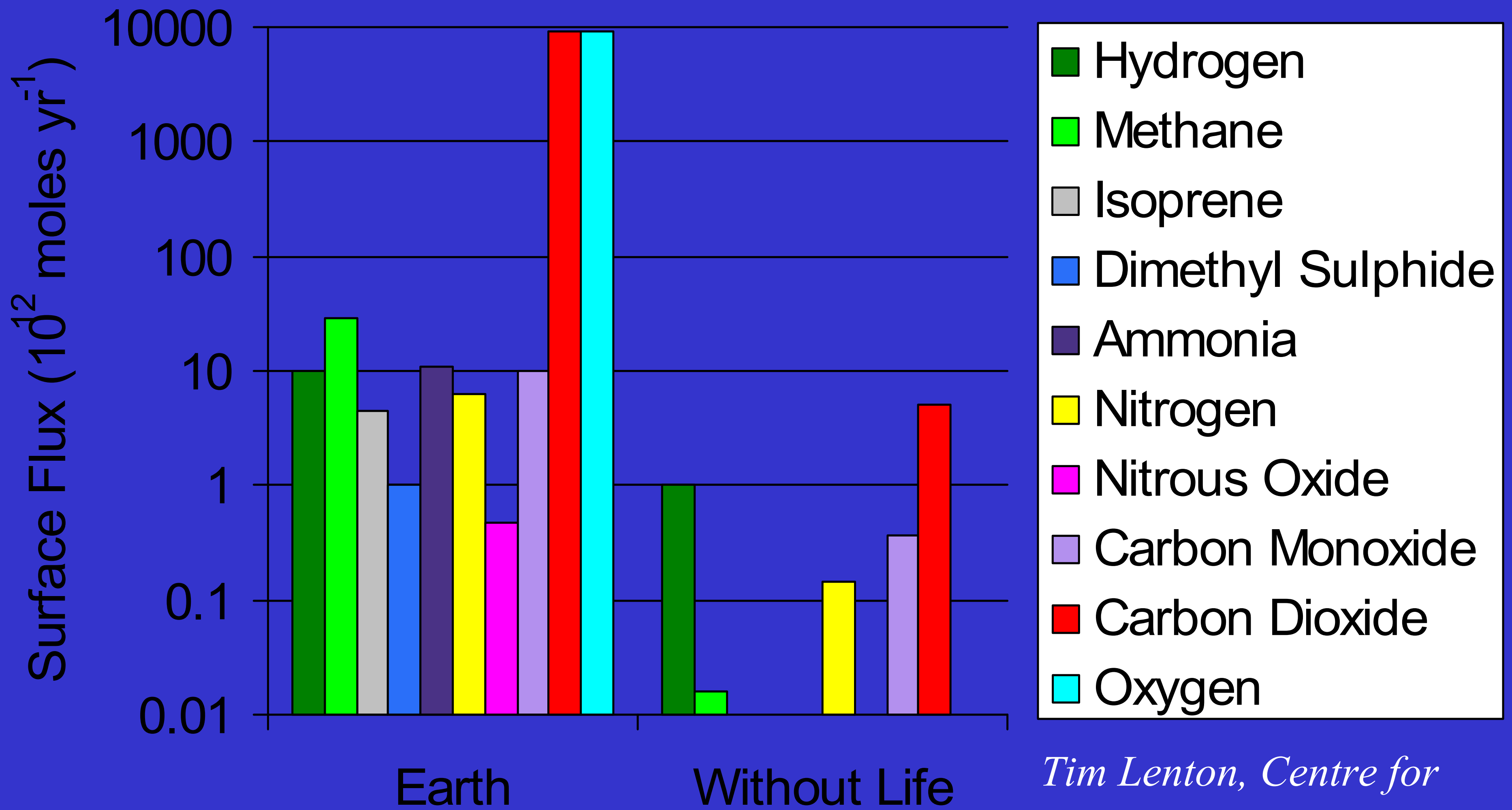
- Extremophiles can live in hot (~120 C!) acid lakes, near undersea volcanic vents, in underground aquifers, and within rocks in Antarctica





- Life needs water, a source of energy, and cosmically abundant elements

Earth's Gases With And Without Life



Tim Lenton, Centre for Ecology and Hydrology

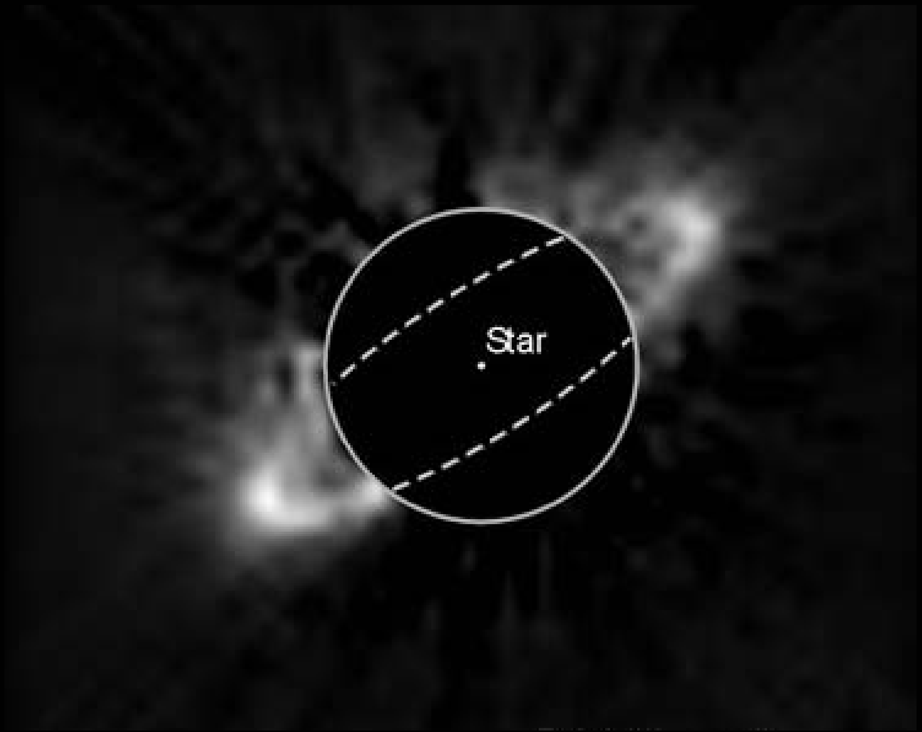
Signatures of Life

- *Oxygen* or its proxy *ozone* is most reliable biomarker
  - *Ozone* easier to detect at low *Oxygen* concentrations but is a poor indicator of quantity of *Oxygen*
- *Water* is considered essential to life.
- *Carbon dioxide* indicates an atmosphere and oxidation state typical of terrestrial planet.
  - Long wavelength lines in both near (1 μm) and mid-IR (16 μm) drives angular resolution and system temperature (mid-IR)
- Abundant *Methane* can have a biological source
  - Non-biological sources might be confusing
  - High spectral resolution and short wavelength rejection
- Find an atmosphere out of equilibrium
- Expect the unexpected → provide broad spectral coverage

Visible and mid-IR provide significant atmospheric signatures and potential biomarkers

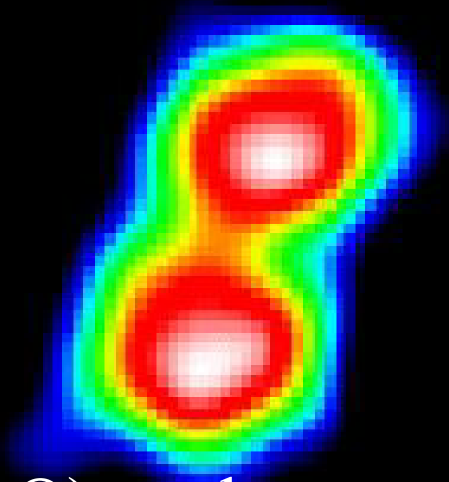
Star Formation & Protoplanetary Disks

- The formation of planets is an integral part of our theory of how stars form
  - Hundreds of planetary masses of gaseous and solid material in the protostellar disk
- Solar System-scale dust disks found around nearby stars

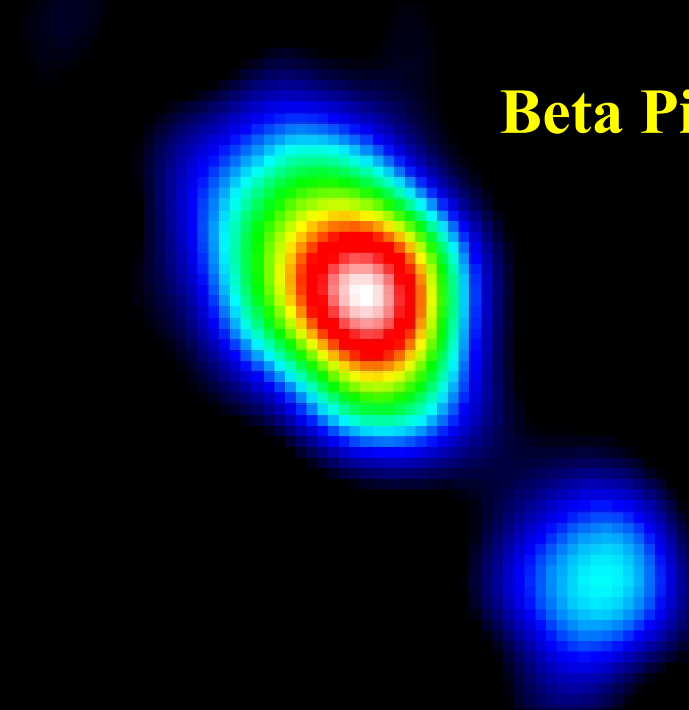


Debris Disks From the Ground

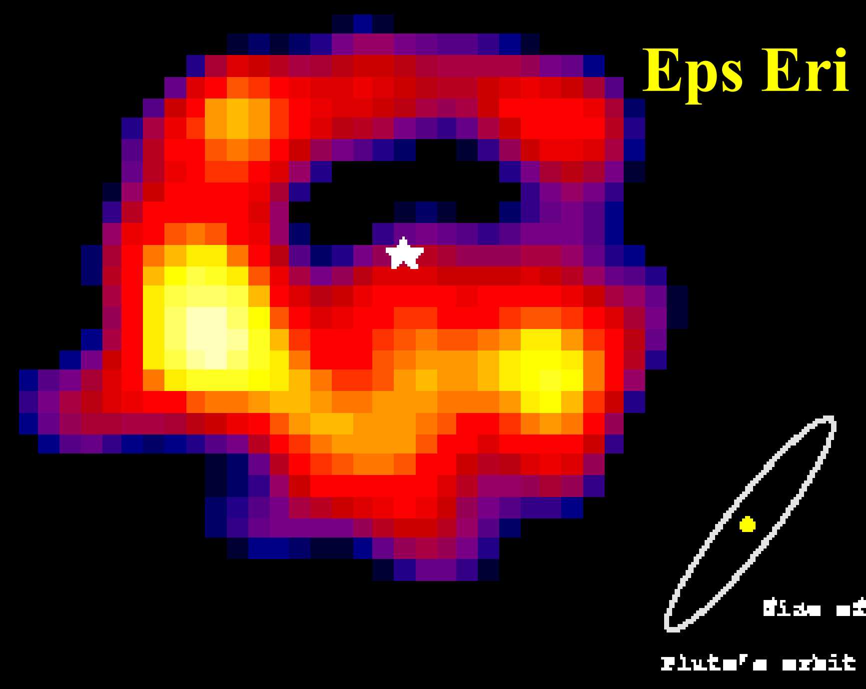
Fomalhaut



Beta Pic

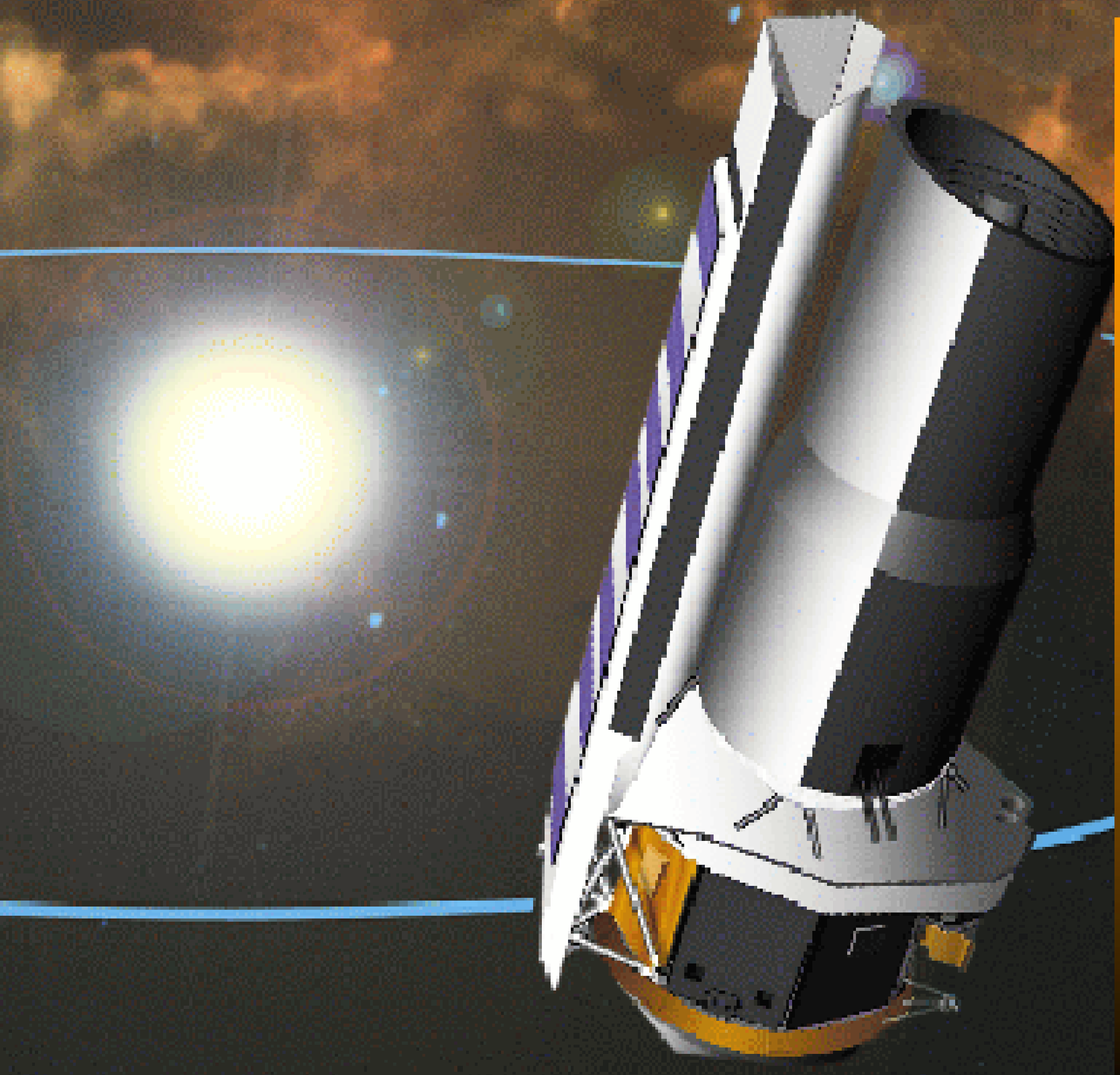


Eps Eri



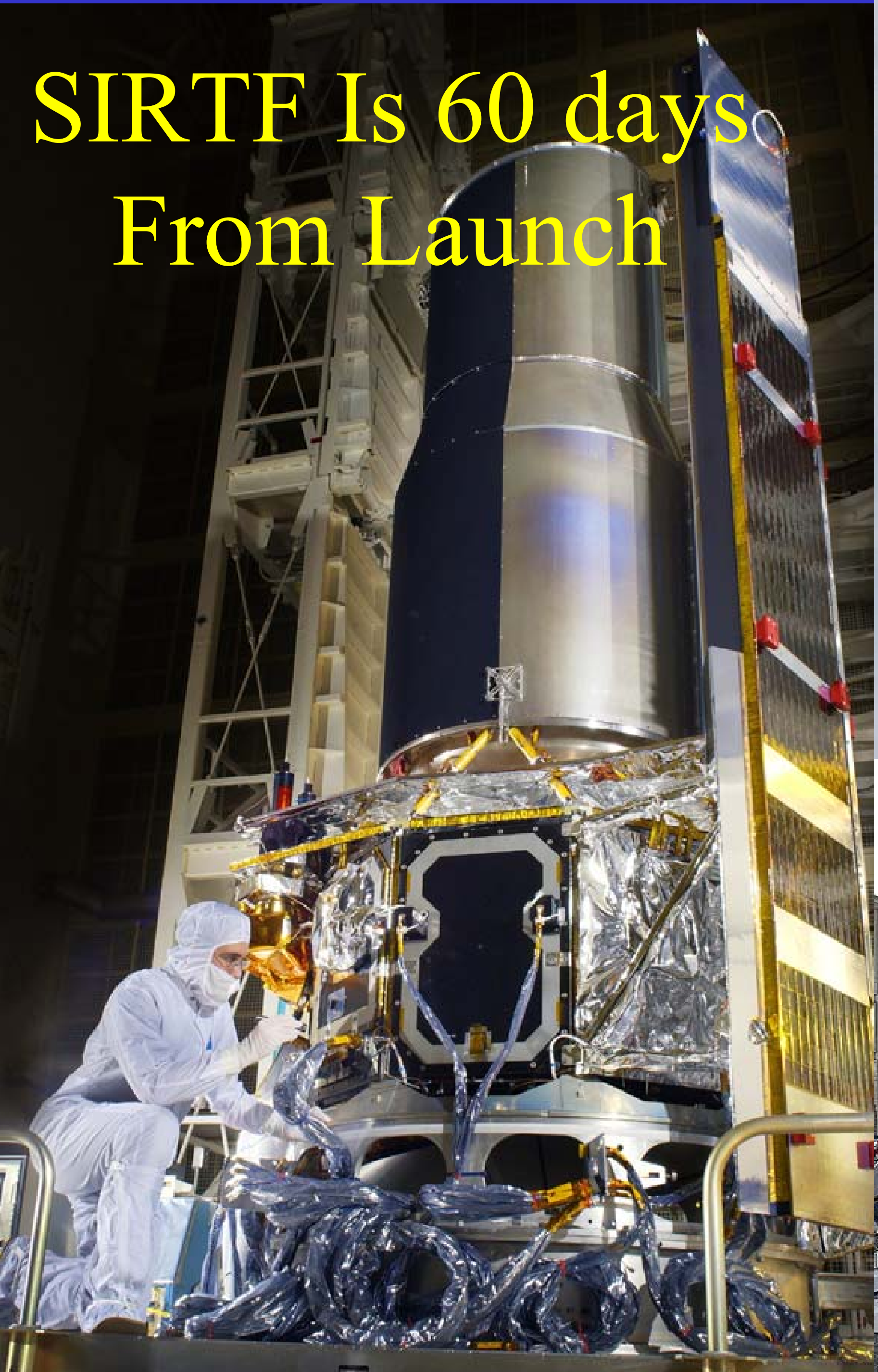
- Millimeter (OVRO), and submillimeter (JCMT) observations show structure in disks around bright disks
  - Clumping on 100 AU scale
  - Evacuated cavities
- Many groups searching for planets using AO

SIRTF Observations of Disks



- NASA's *next* Great Observatory will map, survey, take spectra of 100s stars
  - single, binary
  - with, without planets
  - Lo/high metals
  - 1 Myr to 5 Gyr
  - Grain composition
  - Reach 1-10x Kuiper belt at 70 μm
- SIRTF launches April 28 (oops), August TBD after 25 years!

SIRTF Is 60 days From Launch



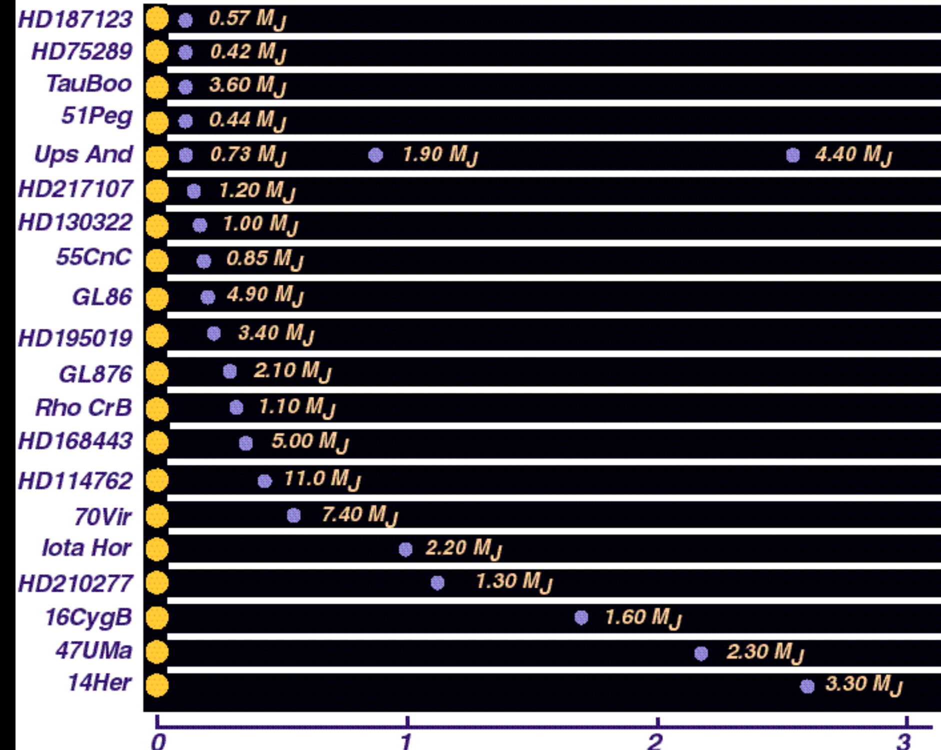
SIRTF/MIPS Volume Limited Sample

- Observations at 24, 70, 160 μm will detect disks at levels of a few times our own Kuiper Belt via IR excess at long wavelengths (80 K→ 10-50 AU)
  - Investigate incidence of disks as f(spectral type, age, metallicity, planets)
- SIRTF will detect only higher levels of emission from dust in "habitable zone" (x100 local zodiacal cloud) due to poor contrast with star
  - Interferometers (Keck-I, LBT-I) will provide better measure of inner zodiacal clouds

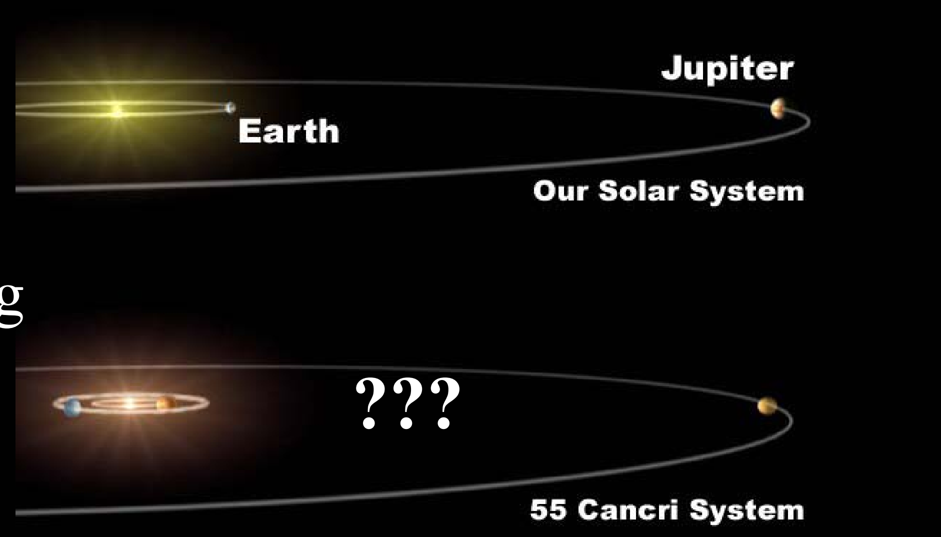
	Any Age	Known Age
FGK	139	48
F5-F9	36	16
G0-G4	40	15
G5-G9	27	6
K0-K5	36	11
with Plane	38	

Gas Giant Planets

- Over 100 planets found using radial velocity wobble
  - ~10% of stars have planets
  - Most orbits < 2-3 AU
  - Half may be multiple systems

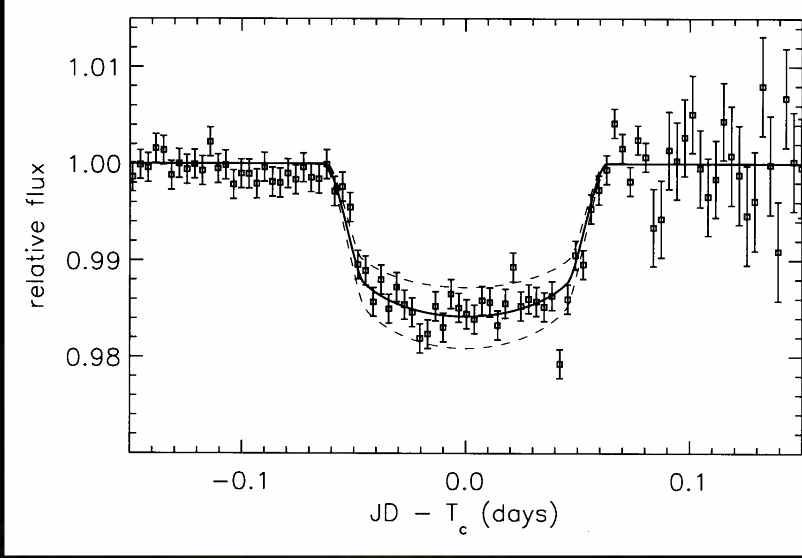


- Planets on longer periods starting to be identified
  - 55 Cancri is solar system analog
- Astrometry (SIM) and radial velocity will determine solar system architecture to few $M_\oplus$

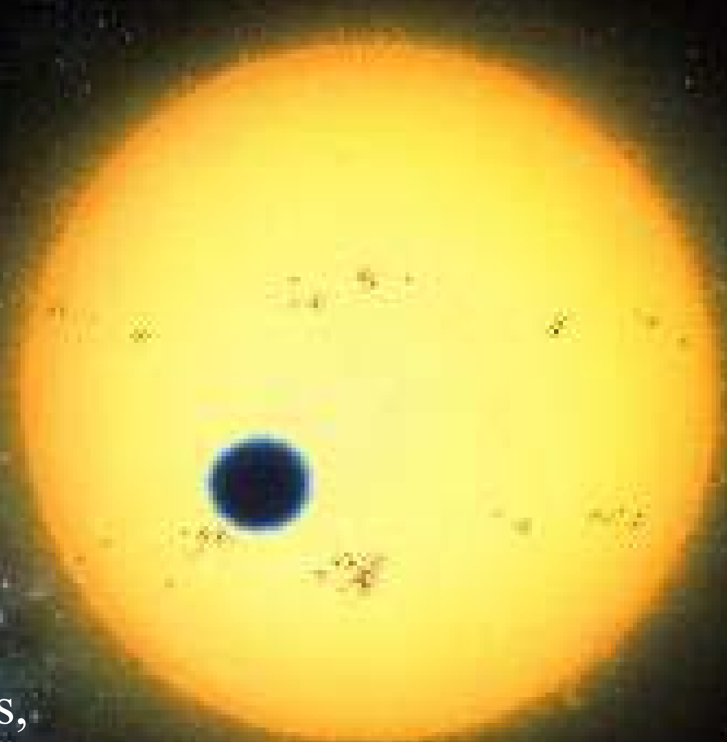


Marcy et al.

Transit Determines Planet's Properties

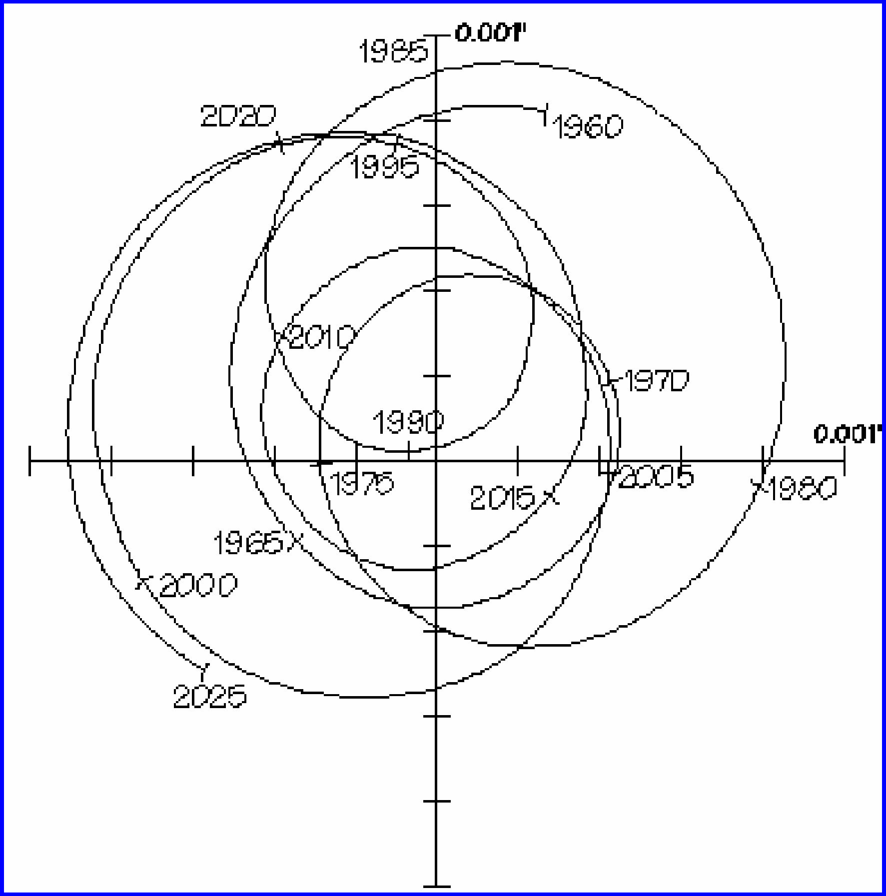


- Transits of HD 209458 determine properties of another Solar System
  - Confirmation of planet interpretation
  - Inclination= 85.9°
  - Mass= 0.69 ± 0.07 M_{jup}
  - Radius =1.35 ± 0.06 R_{jup}
  - Density= 0.35 g/cc <Saturn
- Active ground based efforts using 10 cm to 10 m telescopes
- COROT, Kepler and Eddington will find few→hundreds of Earths, thousands of Jupiters
- Spectroscopy probes atmosphere
  - Cloud heights, heavy-element abundances, temperature and vertical temperature stratification, and wind velocities

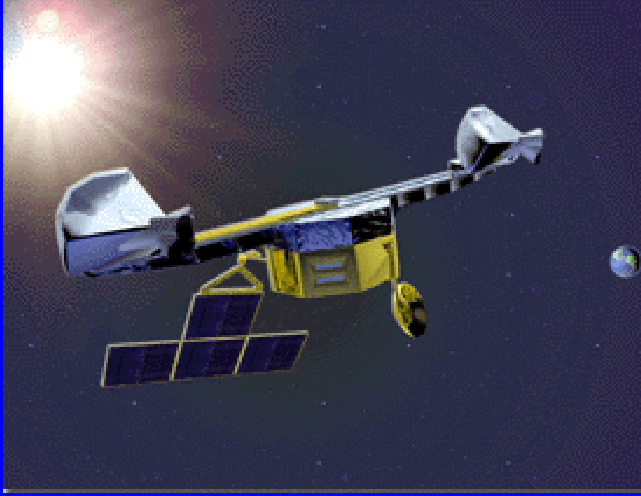


Astrometric Search for Planets

- Astrometry measures positional wobble due to planets
- Interferometry enables measurements at the micro-arcsecond level
- Result of new observing systems will be a census of planets down to a few M_{earth} over the next 10-20 years



Interferometery Is One Key to Planet Detection



- Break link between diameter, baseline
- Enables precision astrometry, high resolution imaging, starlight nulling

- Make astrometric census of planets
- Detect "Hot Jupiter's"
- Detect exo-zodiacal dust clouds
- Image protostellar disks

Space Interferometer Mission (SIM) Will Make Definitive Planet Census

What We *Don't* Know

- Are planetary systems like our own common?
- What is the distribution of planetary masses?
  - Only astrometry measures planet masses unambiguously
- Are there low-mass planets in 'habitable zone' ?

A Deep Search for Earths

- Are there Earth-like (rocky) planets orbiting the nearest stars?
- Focus on ~250 stars like the Sun (F, G, K) within 10 pc
- Sensitivity limit of ~3 M_e at 10 pc requires 1 μas accuracy

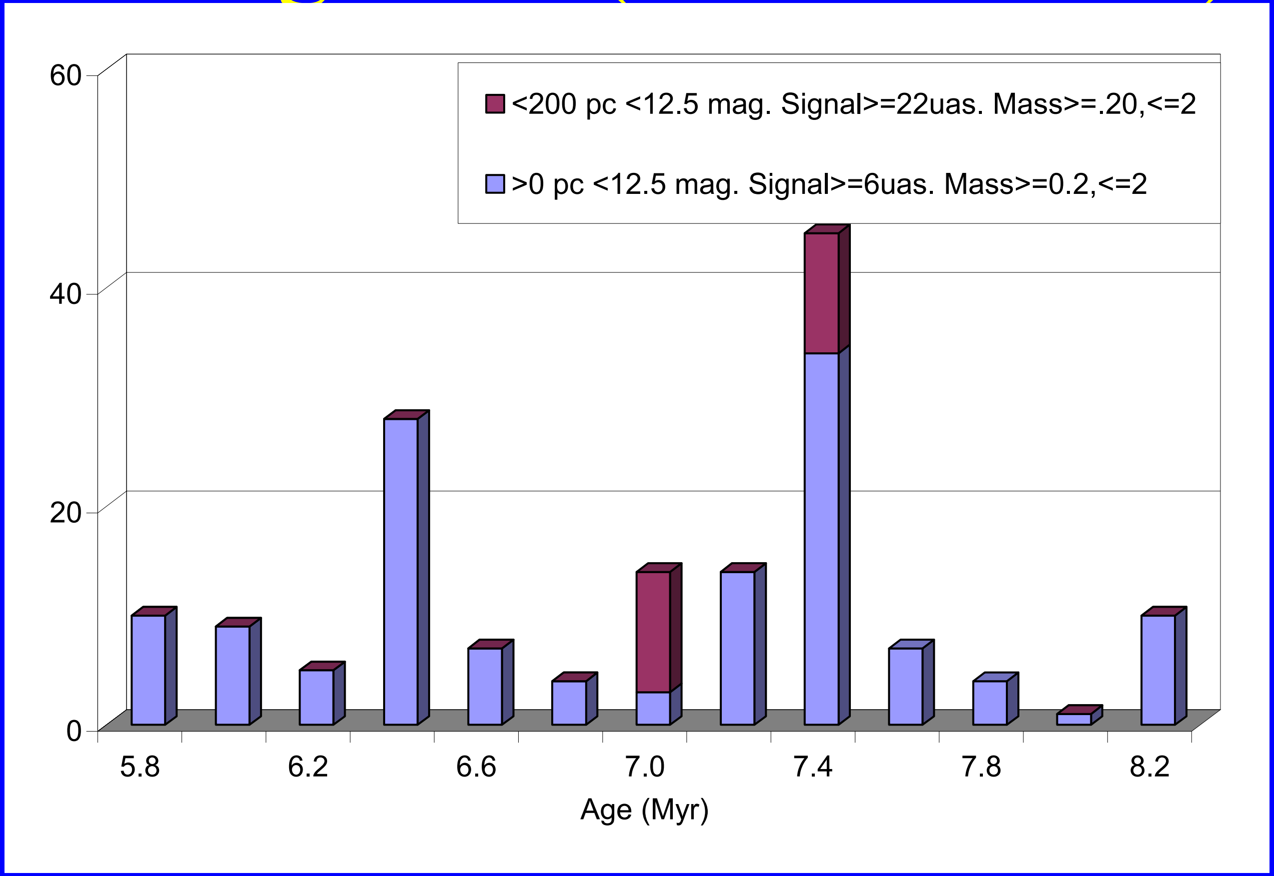
A Broad Survey for Planets

- Is our solar system unusual?
- What is the range of planetary system architectures?
- Sample 2000 stars within ~25 pc at 4 μas accuracy

Evolution of Planets

- How do systems evolve?
- Is the evolution conducive to the formation of Earth-like planets in stable orbits?
- Do multiple Jupiters form and only a few (or none) survive?

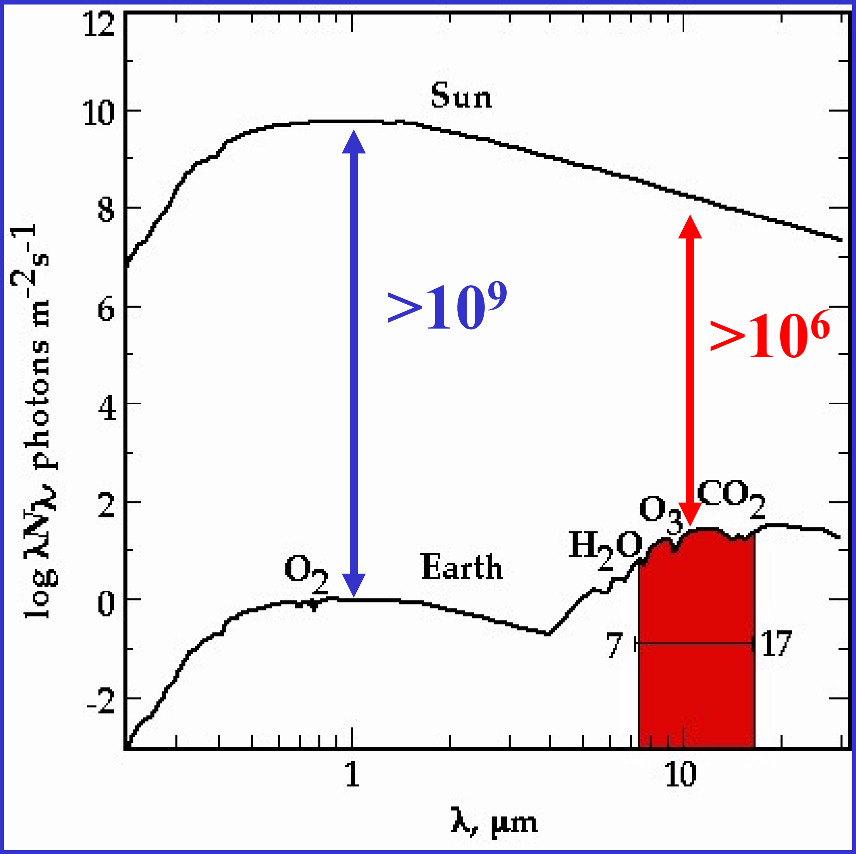
Search for Planets Around Young Stars (SIM-PLAYS)



- Survey young stars with variety of ages, masses (0.2-2 M_o) to look for gas-giant planets (>1 M_J at 1-10 AU)
  - Clusters include Taurus, Oph, Sco-Cen, TW Hya, Chamaeleon, etc

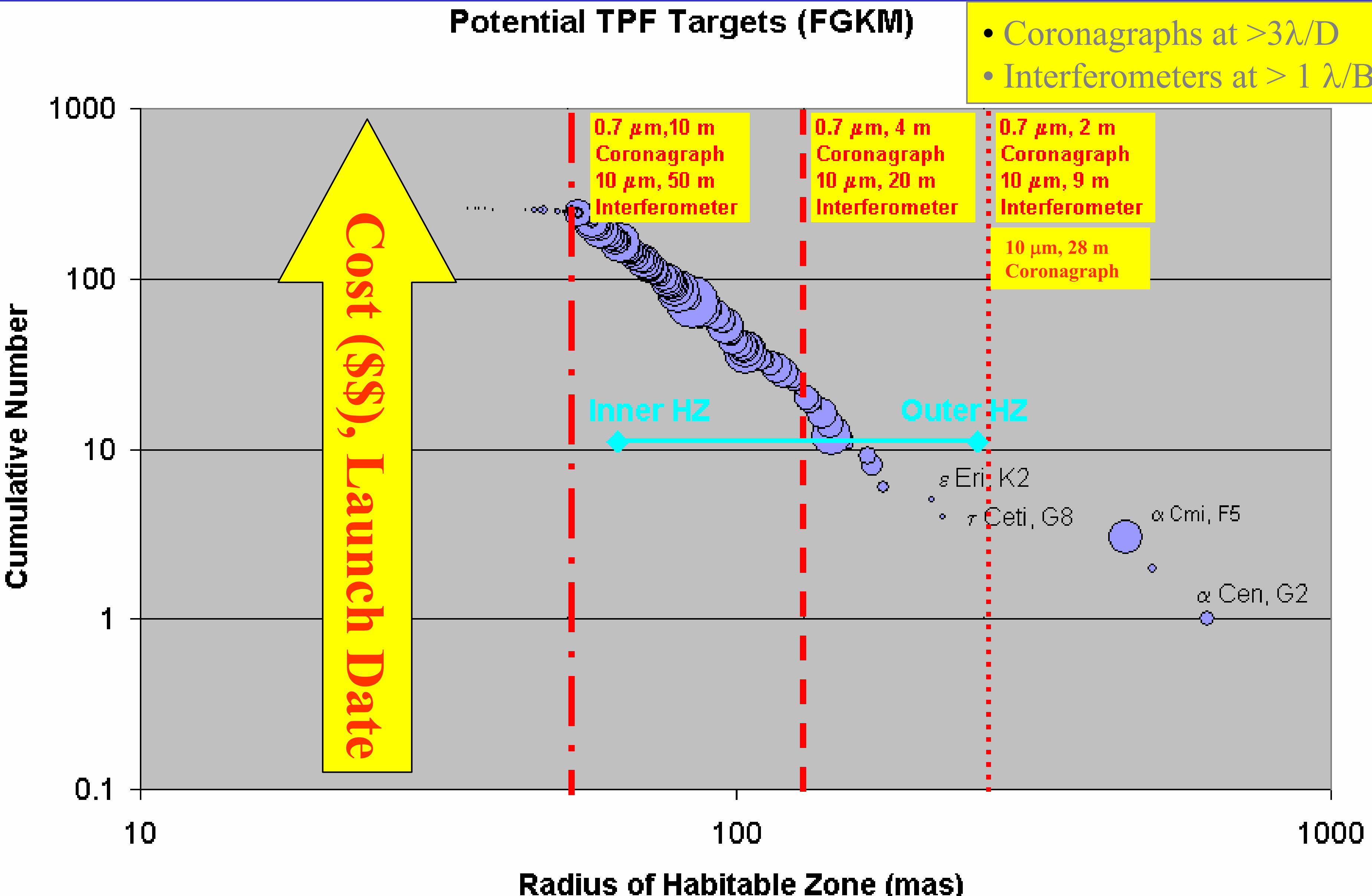
Four Hard Things About TPF

- Solar neighborhood is sparsely populated
  - Fraction of stars with Earths (in habitable zone) unknown
  - Unknown how far we need to look to ensure success
  - Surveying substantial number of stars means looking to ~15 pc Sensitivity (relatively easy)
- Detection in hours → spectroscopy in days.
  - Integration time ∝ (distance/diameter)^4
  - Need 12 m^2 of collecting area (≥4 m) for star at ~10 pc
- Angular resolution (hard)
  - 100 mas is enough to see ~25 stars, but requires ≥4 m coronagraph or ≥20 m interferometer
  - Baseline/aperture ∝ distance
- Starlight suppression (hard to very hard)
  - 10^{-6} in the mid-IR
  - 10^{-9} in the visible/near-IR

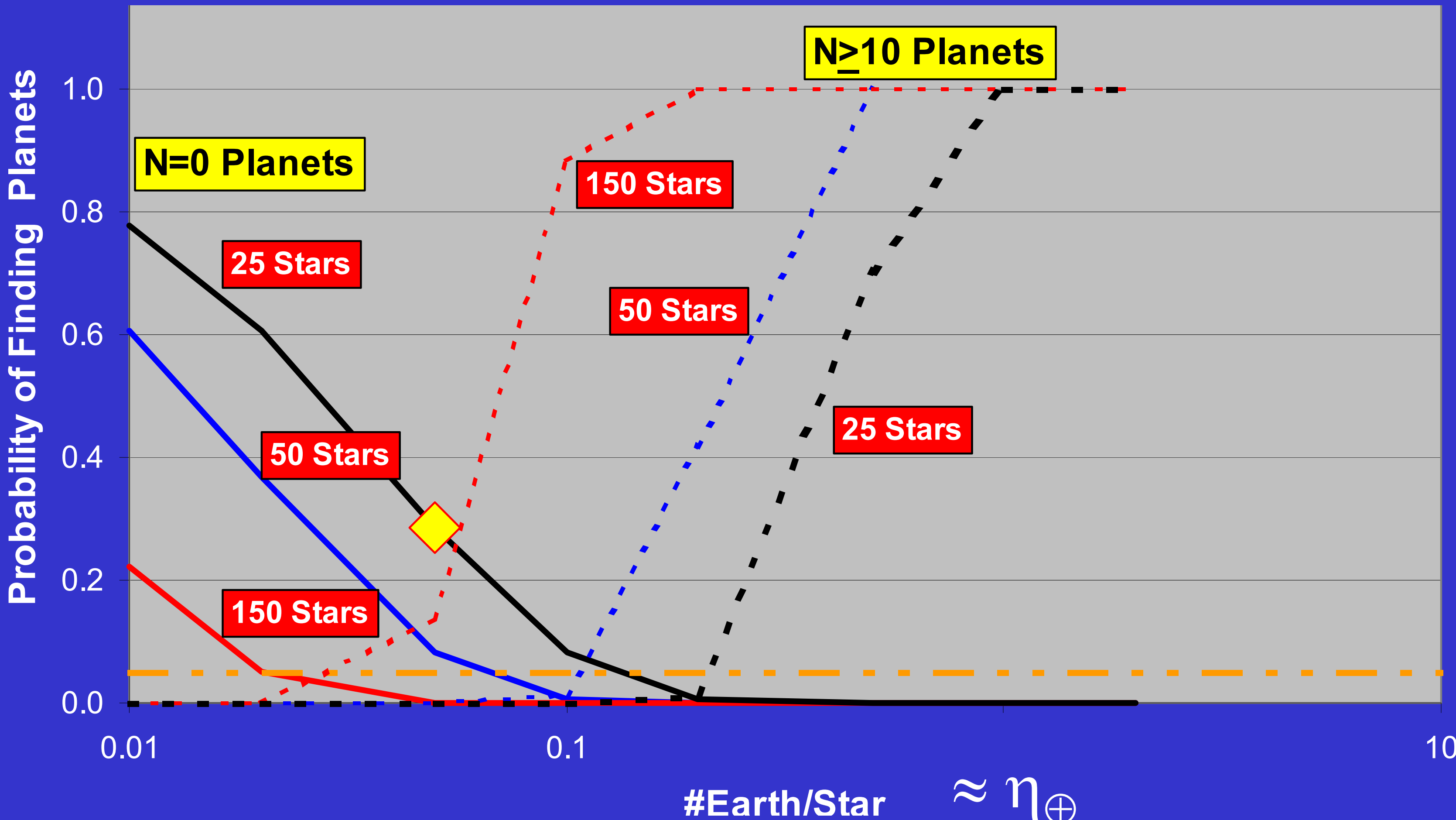


The Challenge of Angular Resolution

- Coronagraphs at >3λ/D
- Interferometers at > 1 λ/B



How Many Planets Are Enough ?



- How many planets to avoid mission *failure* ($N_p = 0$)
- How many planets for comparative planetology ($N_p > 10$)

$\eta_\oplus$ → # Stars → Dist → (Aperture, Baseline) → Cost → Schedule

TPF Science Requirements-I

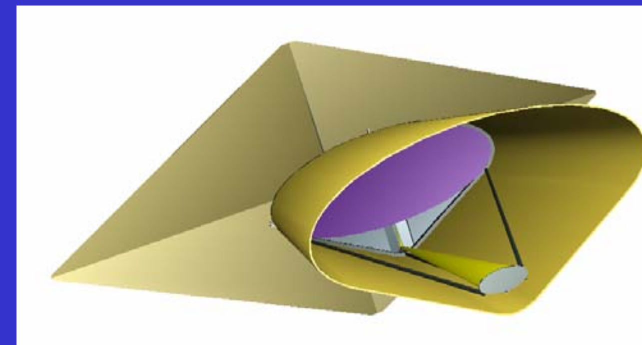
- Detect and characterize terrestrial-sized planets around nearby stars.
- Satisfy requirements for “core sample” of 30 (late-F, G and K dwarf) stars
- Partially satisfy requirements for “extended” sample of 120 stars (late-F, G, and K dwarf) as well as M-dwarf, early-F, and A- star targets of opportunity.
  - Survey of core and extended stars, including at least 3 visits, should be completed in ~2 years.
  - Additional visits of detected planets to determine orbits beyond the 2 year detection phase.
- A “TPF stretch mission” should meet the above requirements for the full sample of ~150 stars.
- Within the CHZ (0.9-1.1 AU for a G-type star $\propto L^{1/2}$), TPF shall be able to detect with 95% completeness, terrestrial planets at least half the surface area of the Earth with Earth’s albedo.
  - Within a more generously defined HZ (0.7-1.5 AU for a G-dwarf), TPF shall be able to detect an Earth-sized planet with Earth albedo with 95% completeness.

TPF Science Requirements-II

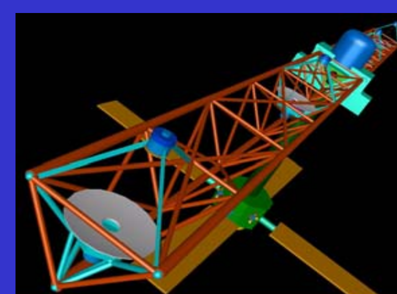
- TPF must be able to obtain spectra in an effort determine the existence of an atmosphere, detect water, detect carbon dioxide (in the infrared), and detect oxygen/ozone or methane if these are present in astrobiologically interesting quantities.
  - The wavelength range 0.5-0.8 μm (1.05 μm desirable) in the optical and 6.5-13 μm (17 μm desirable) in the infrared, with spectral resolutions of 75 and 25, respectively.
  - Spectrometer capable of R>100 for the brightest sources.
  - Detection of Rayleigh scattering and the absorption edges desirable
- Strong desire for large field of view, 0.5″ -1″ , to search the nearest stars for terrestrial planets and to characterize giant planets in Jupiter-like orbits

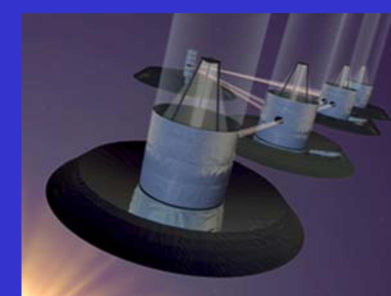
TPF Candidate Architectures

- Visible Coronagraph
  - System concept is relatively simple, 4-10 m mirror on a single spacecraft
  - Components are complex
    - Build adequately large mirror of appropriate quality ($\lambda/100$)
    - Hold ($\lambda/3{,}000$) with ($\lambda/10{,}000$) stability during observation with deformable mirror
- IR Interferometer
  - Components are simple: 3-4 m mirrors of average quality
  - System is complex: 30 m boom or separated spacecraft with ~ nm stability



Visible Coronagraphs



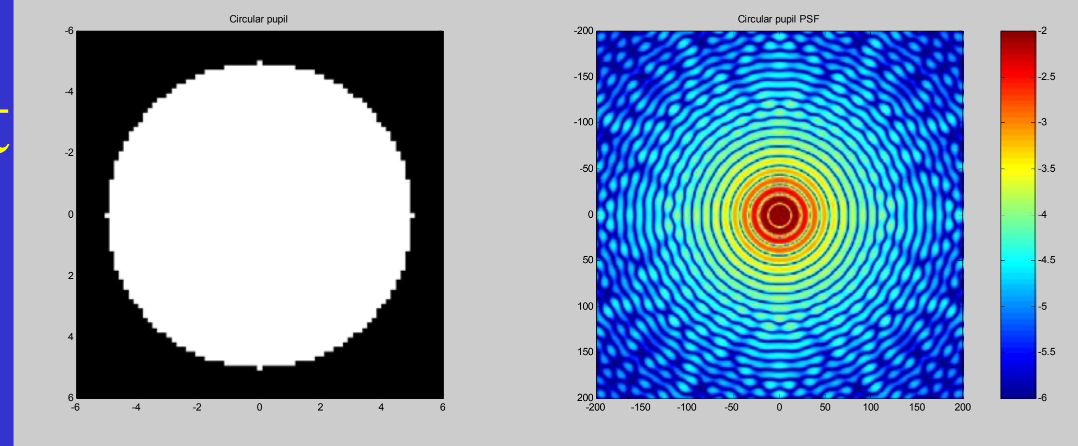


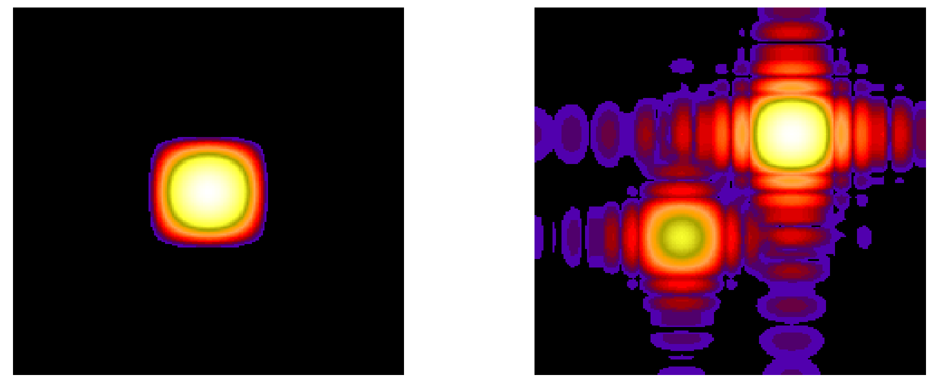
IR Interferometers

Control of Star Light

- Control *diffracted* light with apodizing pupil and/or image plane masks
  - Square masks
  - Graded aperture
  - Multiple Gaussian masks
  - Band limited masks
  - Nulling interferometer
  - Etc., etc.

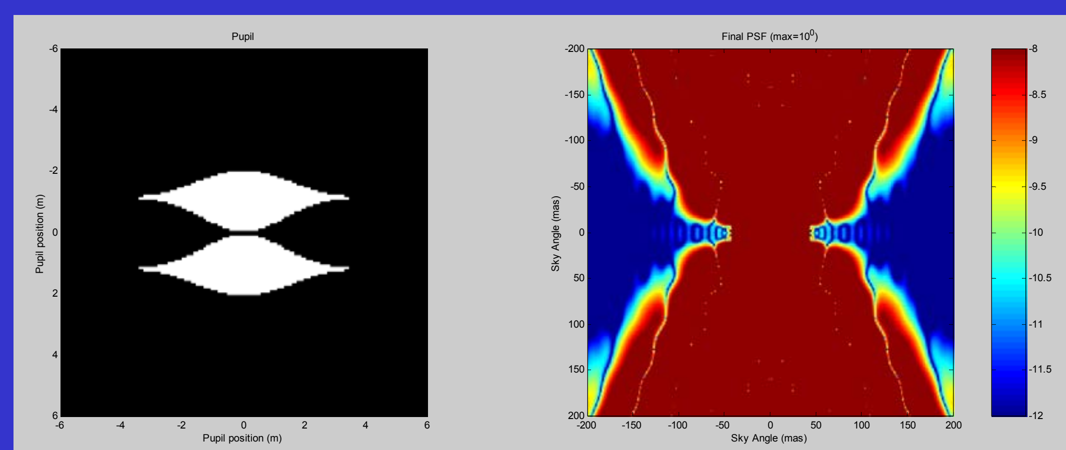
- Control *scattered* light
  - Deformable mirror with 10,000 actuators for final 1/3000 wavefront (<1 Å)
  - Single mode fiber array





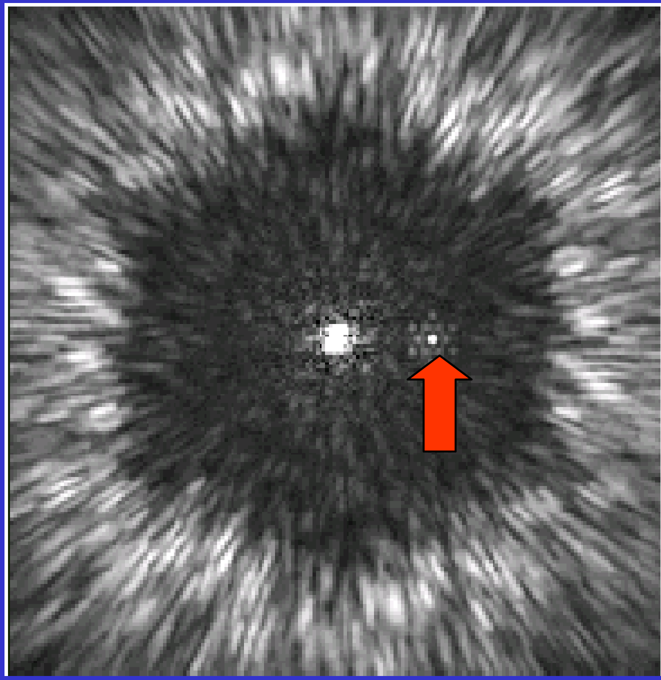
Apodized Square Aperture

100:1 Star to Planet Ratio Apodization

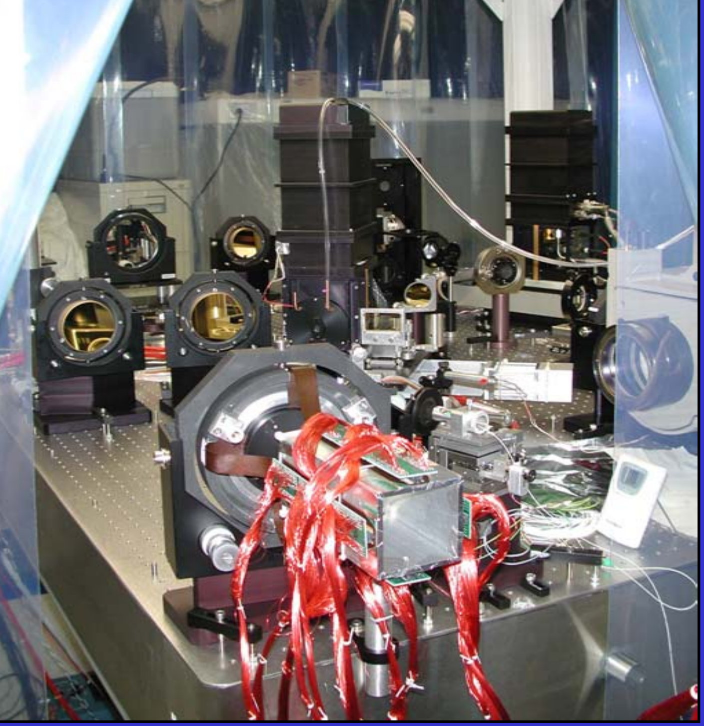


Visible Light Planet Detection

- A simple coronagraph on NGST could detect Jupiters around the closest stars as well as newly formed Jupiters around young stars
- Advanced coronagraph/apodized aperture telescope
  - 2 telescope (Jupiters)
  - 4 m telescope (Jupiters and nearest 30 Earths)
  - 8~10 m telescope (full TPF goals)
- Presence and Properties of Planets
  - Planet(s) location and size×reflectivity
  - Atmospheric or surface composition
  - Rotation →surface variability
  - Radial and azimuthal structure of disks

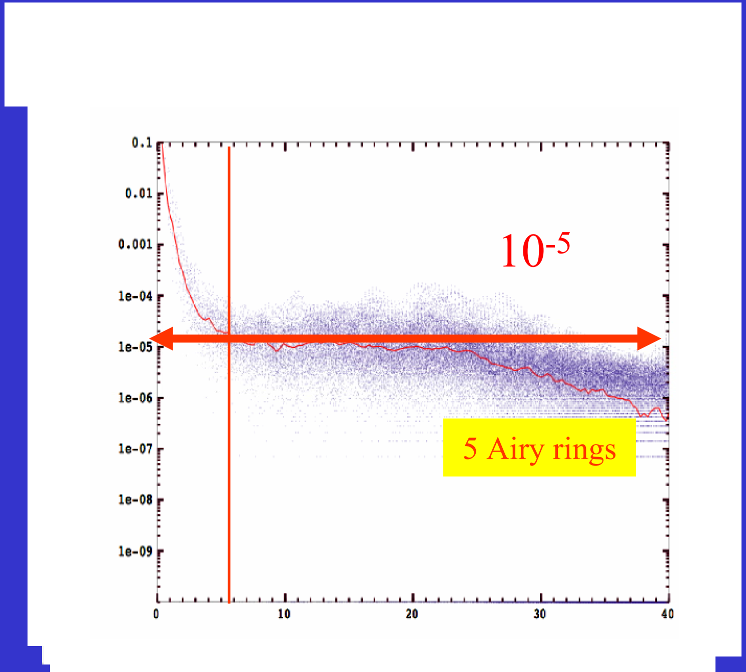


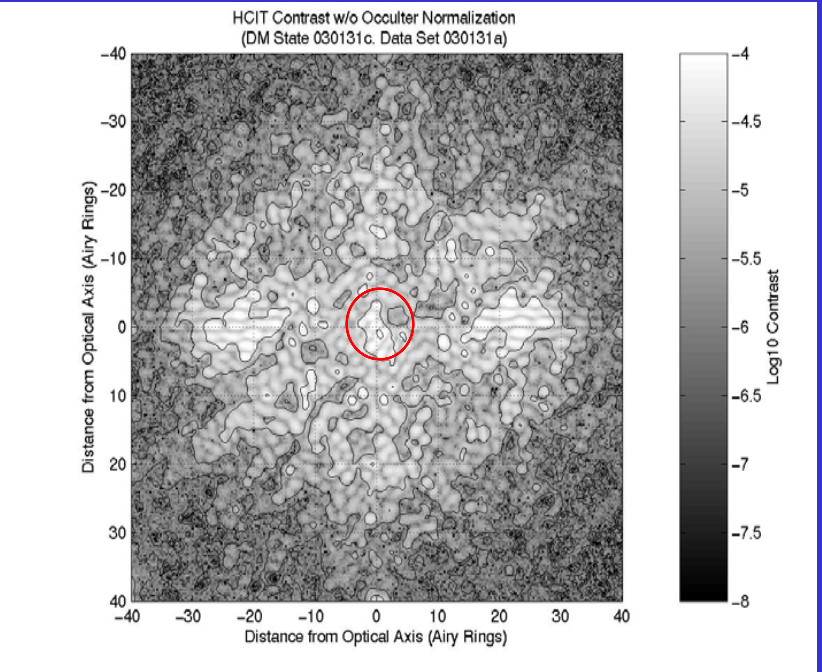
Simulated NGST coronagraphic image of a planet around Lalande 21185 (M2Vat 2.5pc) at 4.6 μm



Coronagraph Status

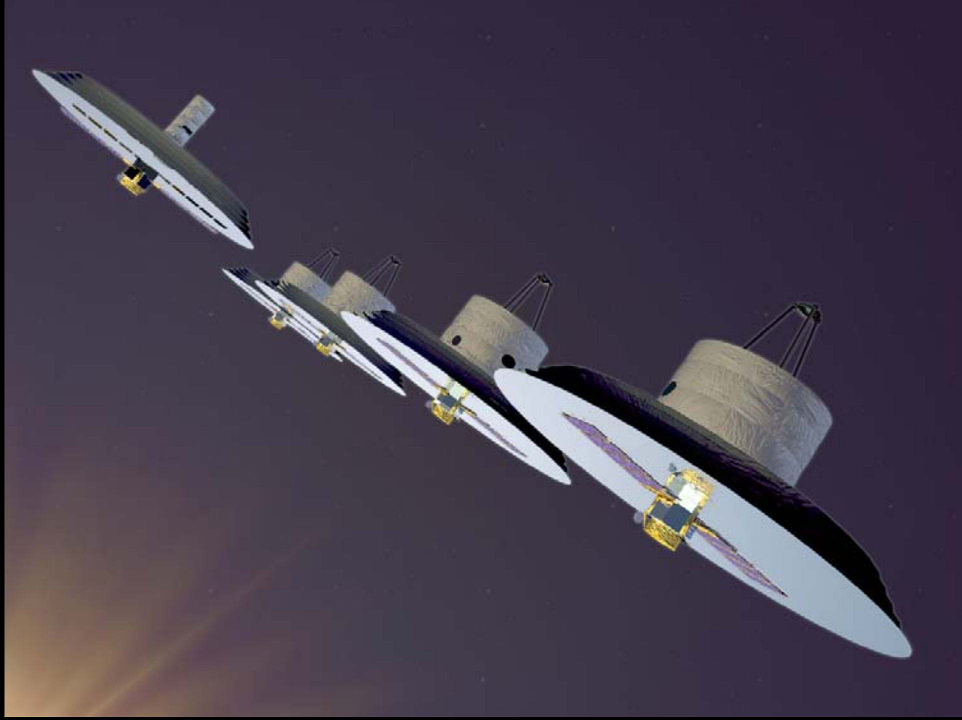
- Current contrast limited to 10^{-5} due to DM imperfections and lab seeing
  - New DM due from Xinetics
- Kodak selected to provide large (1.8m), high precision (<5 nm) mirror
- Innovative ideas to improve angular resolution by combining interferometer and coronagraph ideas
  - Vis nuller has achieved $<10^{-7}$-10^{-8} effective null

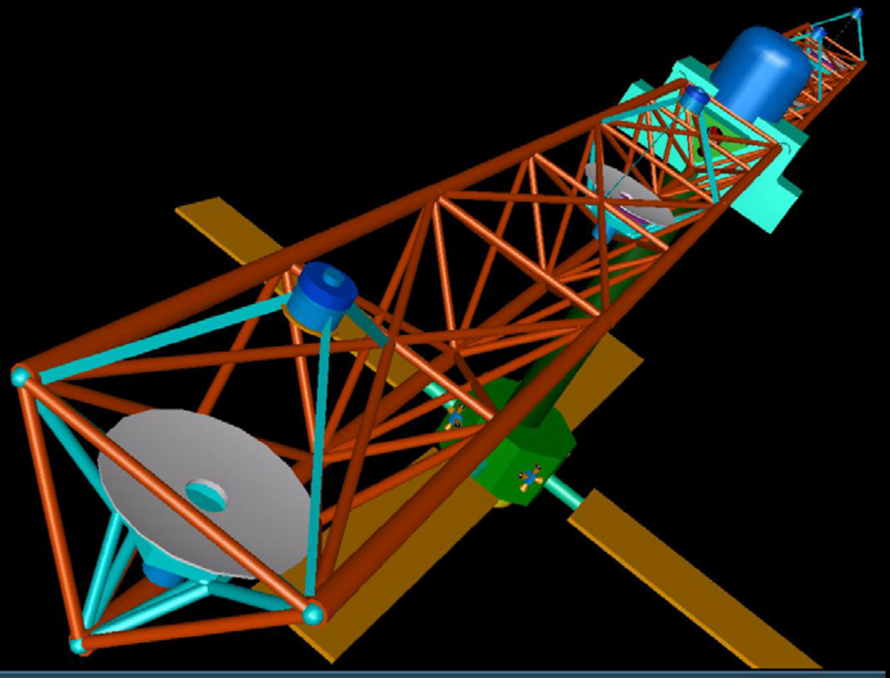




IR Interferometer

Goal	Earth at 10 pc	Time
Planet?	R=3/SNR=5	2.0 h
Atmosphere? (CO_2, H_2O)	R=20/SNR=10	2.3d
Habitable? (O_3, CH_4)	R=20/SNR=25	15d

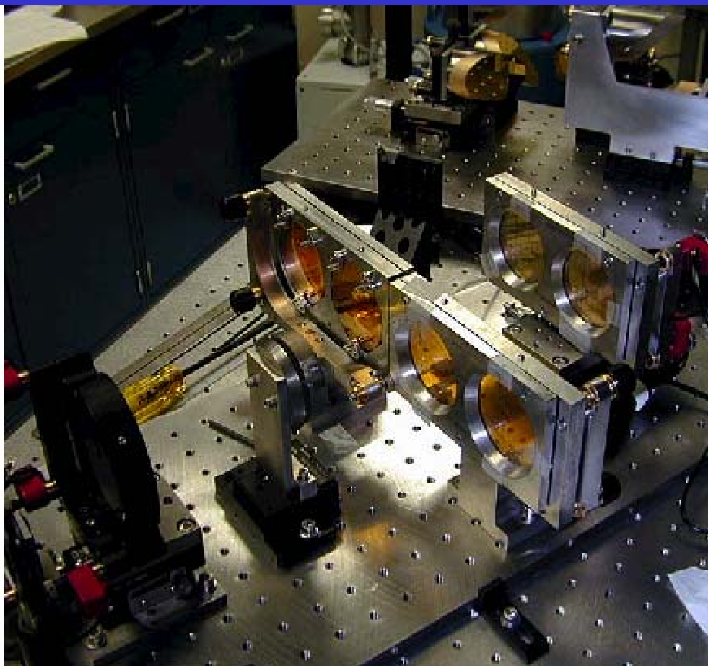


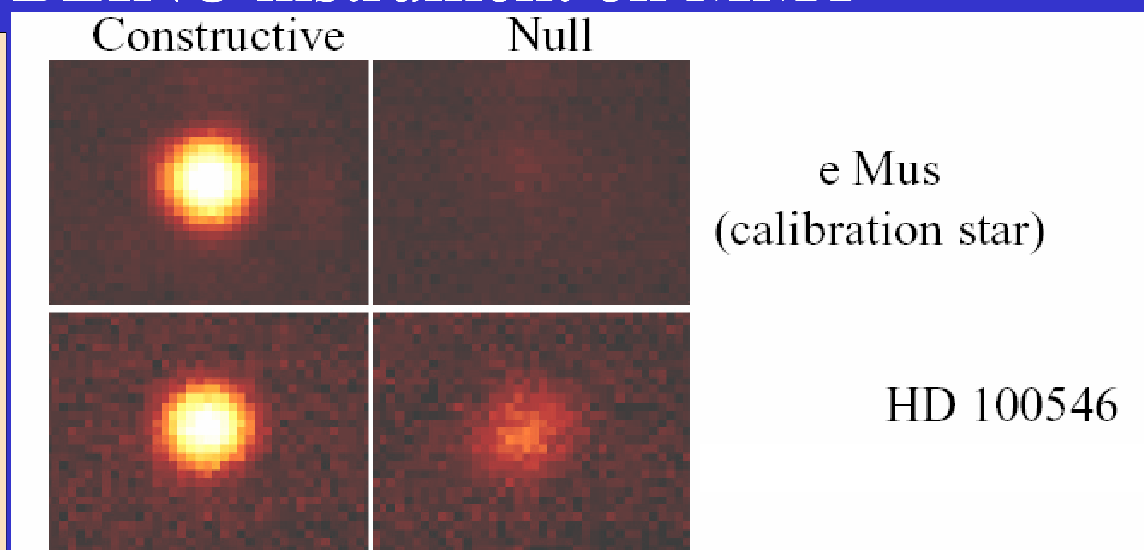


- Interferometer with cooled two to four 3~4 m mirrors
  - 30 m boom for minimum resolution
  - 75-1000 m baseline using formation flying for maximum sample size
- Key question is configuration
  - Trade between null depth, stability, physical length and resolution

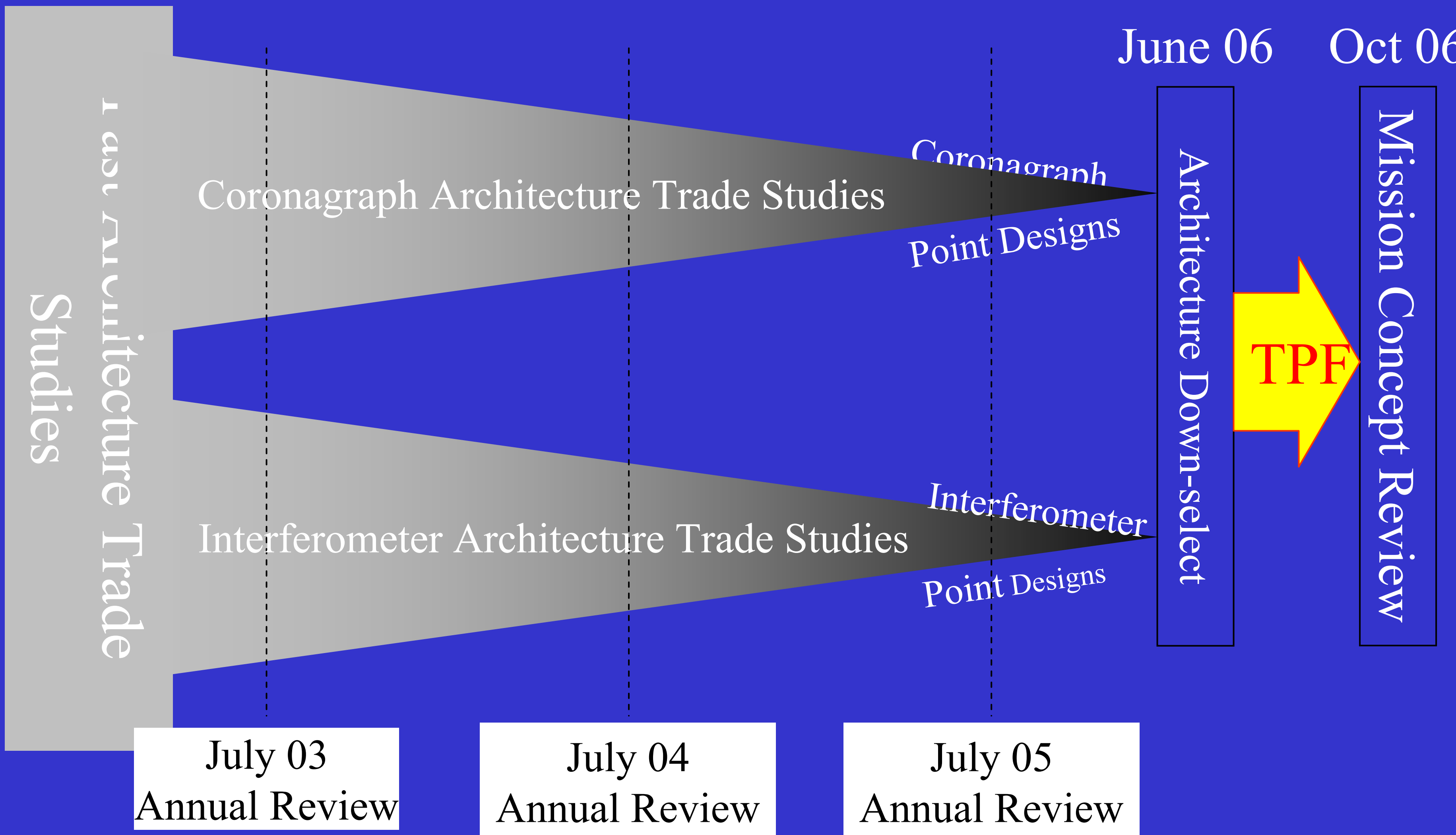
IR Nulling

- JPL Modified Mach-Zender (Serabyn et al)
  - 1.4×10^{-6} null *laser* null @ 10.6 um
  - Aim for 10^{-6} null target *broadband*
    - Add spatial filter and stabilization
    - Develop fully cryogenic system
- UofA group (Hinz et al) demonstrated nulling at $\leq 1\%$ with BLINC instrument on MMT





Selection of Final Architecture



Overriding goal: Find one design that is scientifically compelling and technologically ready for 2008 NAS Decadal Review and 2015 launch

TPF Science Roadmap

- Coordinated observing/theoretical program to address questions affecting TPF/Darwin architecture/scope
- What is $\eta_{\oplus}$?
  - Transits (MOST,COROT, Kepler/Eddington)
  - Theory extrapolating from gas giant statistics → terrestrial planets
- What is level of exo-zodiacal emission?
  - SIRTF (Kuiper belts @ 3-300 of AU)
  - Keck-I/LBT-I/VLT-I (Zodiacal clouds at ~0.3-3 AU)
  - Theory extrapolating from dust distribution → terrestrial planets
- What wavelength region should we observe?
  - Atmospheric and bio-markers from visible to mid-IR
- What are physical properties of giant planets?
  - Advance understanding and demonstrate techniques
- What controls orbital stability in region of habitable zone?
  - Are solar systems "dynamically full" with planets in all stable orbits?
- What are properties of target stars
  - Activity, presence of giant planets, zodi disks, gal/x-gal backgrounds

5-10% of TPF budget will support scientific activities

Collaboration on TPF/Darwin

- Strong ESA/NASA interest in joint planet-finding mission
  - Collaborative architecture studies
  - Discussions on technology planning and development
- Joint project leading to launch ~2015
  - Scientific and/or technological precursors as required and feasible