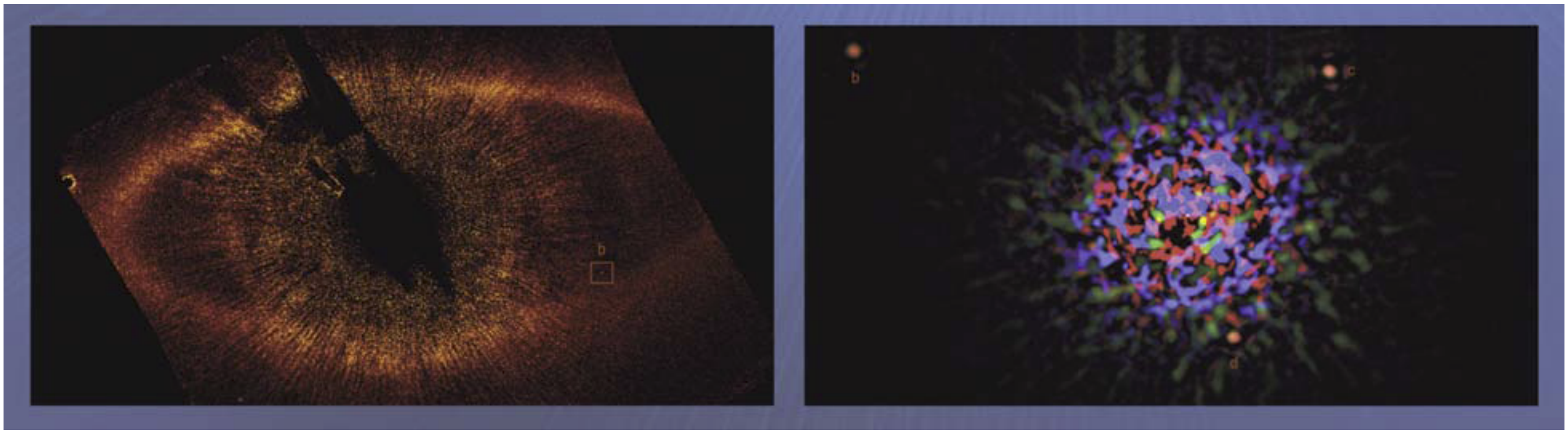
How Giovanni's Balloon-Borne Telescope Contributed to Today's Search for Life on Exoplanets



Wesley A. Traub

Jet Propulsion Laboratory, California Institute of Technology

Symposium for Giovanni Fazio

Harvard-Smithsonian Center for Astrophysics

27-28 May 2009

Balloon-Borne Telescope

- 1970s: Bob Noyes suggests building an FTS for Giovanni Fazio's 1-m telescope.
- Calculate Earth's spectrum with Mark Stier.
- Get NASA grant to build FTS, with Nat Carleton.
- First flights from Palestine, Texas.

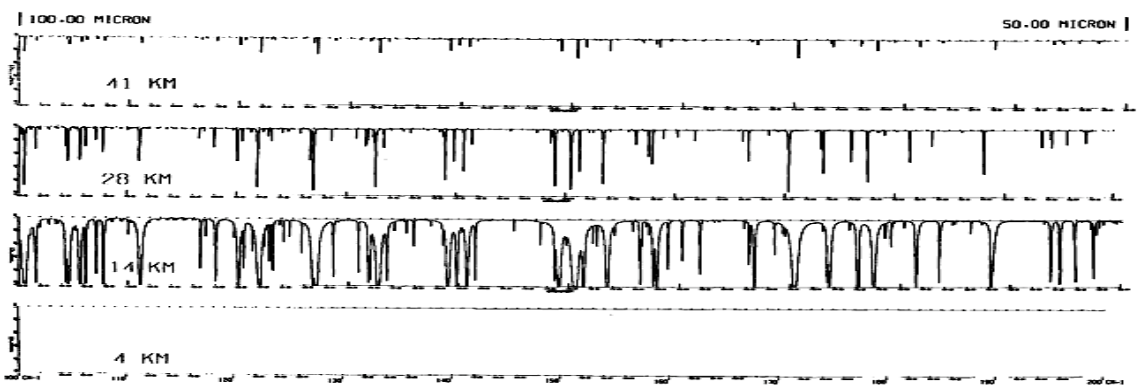


Fig. 2. Atmospheric transmission at four altitudes with an air mass of 2.0 and a rectangular bandpass of 0.05-cm^{-1} width.

February 1976 / Vol. 15, No. 2 / APPLIED OPTICS

Earth spectrum calculation, Traub & Stier (1976)

Photos: John Brasunas, GSFC

Observing with 1-m Telescope

348 STIER, TRAUB, FAZIO, WRIGHT, AND LOW Vol. 226

TABLE 1

OBSERVATIONS WITH THE 40–250 MICRON FILTER

Object (1)	UT 1977 Apr 26 (2)	$\alpha('')$ (3)	η (4)	h (km) (5)	n_{obs} (6)	$(S/N)_{obs}$ (7)	P/P_{Mars} (8)	$P/P_{thermal}$ (9)	T (K) (10)
Venus........	10^h32^m	49.23	7.1	28.7	43	80000	$>111 \pm 10$	0.1	$T_B > 232 \pm 13$
Mars........	10 15	4.58	10.1	28.7	18	720	1.0	0.1	(Calibration $T_B = 242.2$)
Ceres........	09 07	0.81	2.9	28.7	21	16	0.0222 ± 0.0023	0.1	$T_B = 195 \pm 12$
Saturn.......	04 05	17.46	1.4	28.7	22	2000	2.83 ± 0.27	0.5	$T_e = 85.6 \pm 3$ if $T_{Tring} = T_e$
Uranus......	04 47	4.07	1.6	28.9	40	20	0.0271 ± 0.0033	0.6	$T_e = 58.5 \pm 2$
Neptune.....	05 28	2.31	3.3	28.7	2	7	0.0092 ± 0.0017	0.6	$T_e = 59.7 \pm 4$

Measuring internal heat of outer planets with far-infrared photometer, with Stier, Fazio, Wright, Low (1978)

GEOPHYSICAL RESEARCH LETTERS, VOL. 8, NO. 10, PAGES 1075-1077, OCTOBER 1981

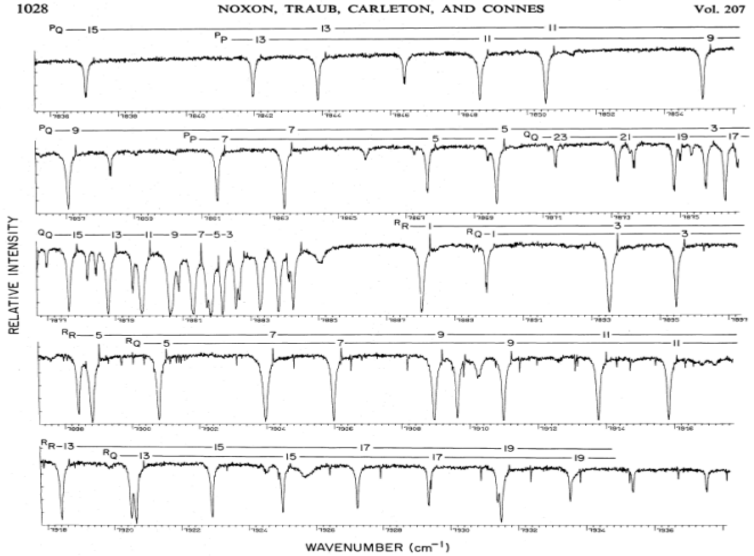
STRATOSPHERIC HF AND HCl OBSERVATIONS
(15 June 1981)

W. A. Traub and K. V. Chance

Center for Astrophysics
Harvard College Observatory and Smithsonian Astrophysical Observatory
60 Garden St., Cambridge, MA 02138

Switching to spectroscopy of ozone layer in stratosphere (much easier!), with Chance, Johnson, Jucks (1981)

1028 NOXON, TRAUB, CARLETON, AND CONNES Vol. 207



Measuring oxygen etc. on Venus & Mars etc. from the ground, with Noxon, Carleton, Connes (1976)

44 W.A. TRAUB & N.P. CARLETON

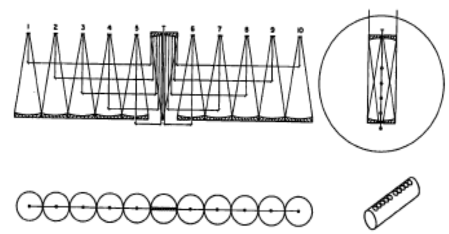


Figure 1. Schematic diagram showing light path within a single module of the COSMIC telescope array. Individual light-collecting telescopes numbered 1 to 10 each feed a central combining telescope via light paths which are of equal length. Side, end and top views are shown along with a reduced scale external view. To combine two or more modules end-to-end, the light paths would be arranged in a different fashion, so that no delicate manual adjustments would be needed during orbital assembly.

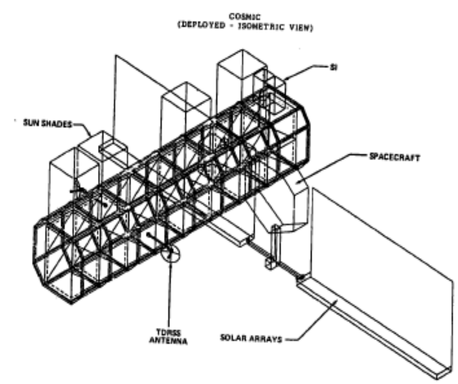
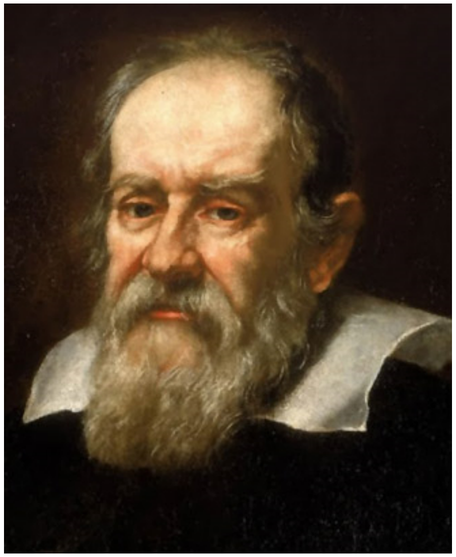
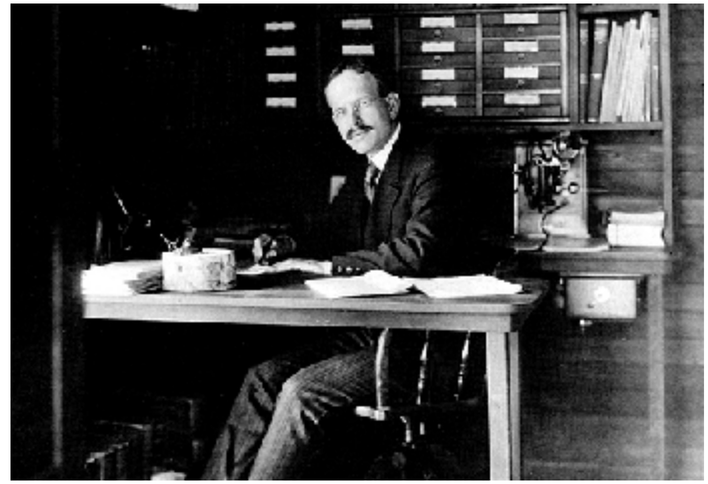


Figure 2. Fiber-composite optical support structure for a linear COSMIC, as developed at NASA-MSFC. The material and design are direct outgrowths of the Space Telescope program.

Getting interested in "beyond Hubble" telescopes with Carleton, Gursky, Lacasse, Shao (1985)

For many years, telescopes looked like this. We lived with diffraction & "seeing".

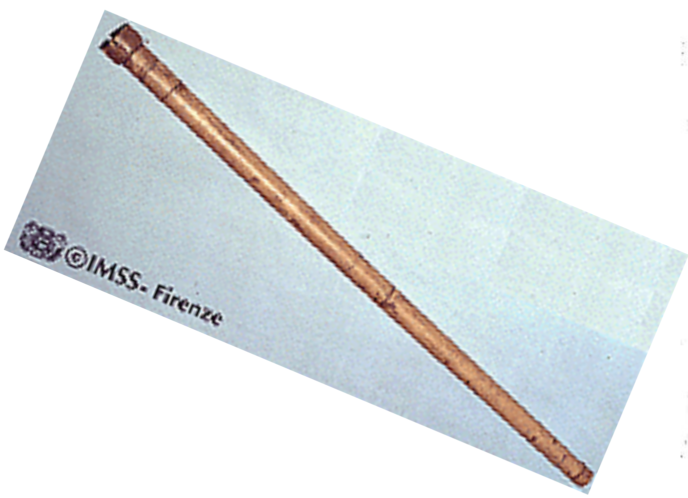


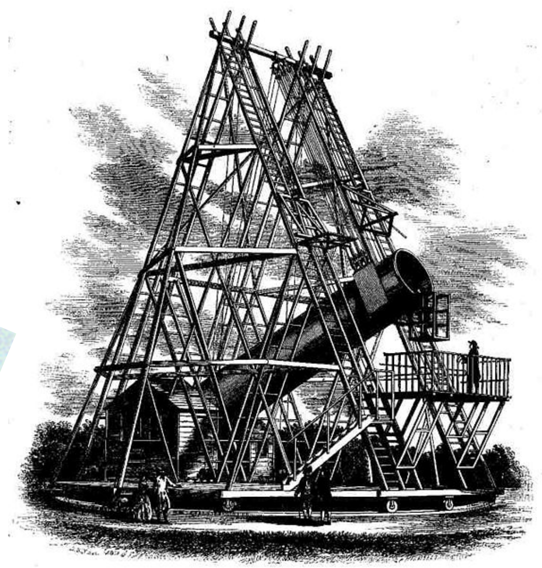


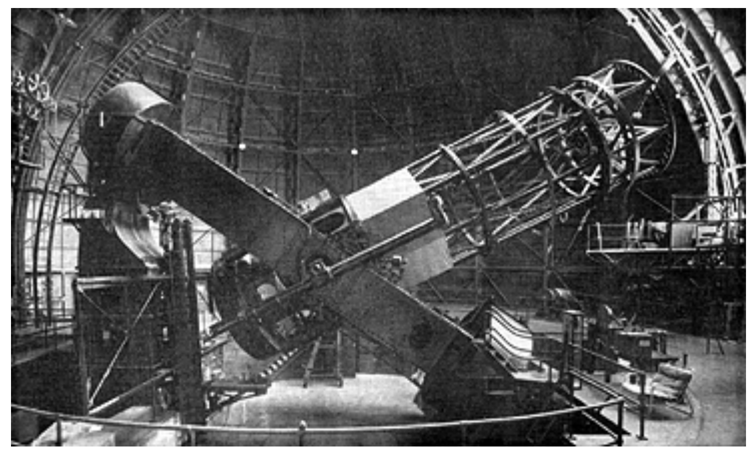
Herschel's Reflecting Telescope, 1789

George Ellery Hale & Hooker Telescope, Mt. Wilson, ~1920

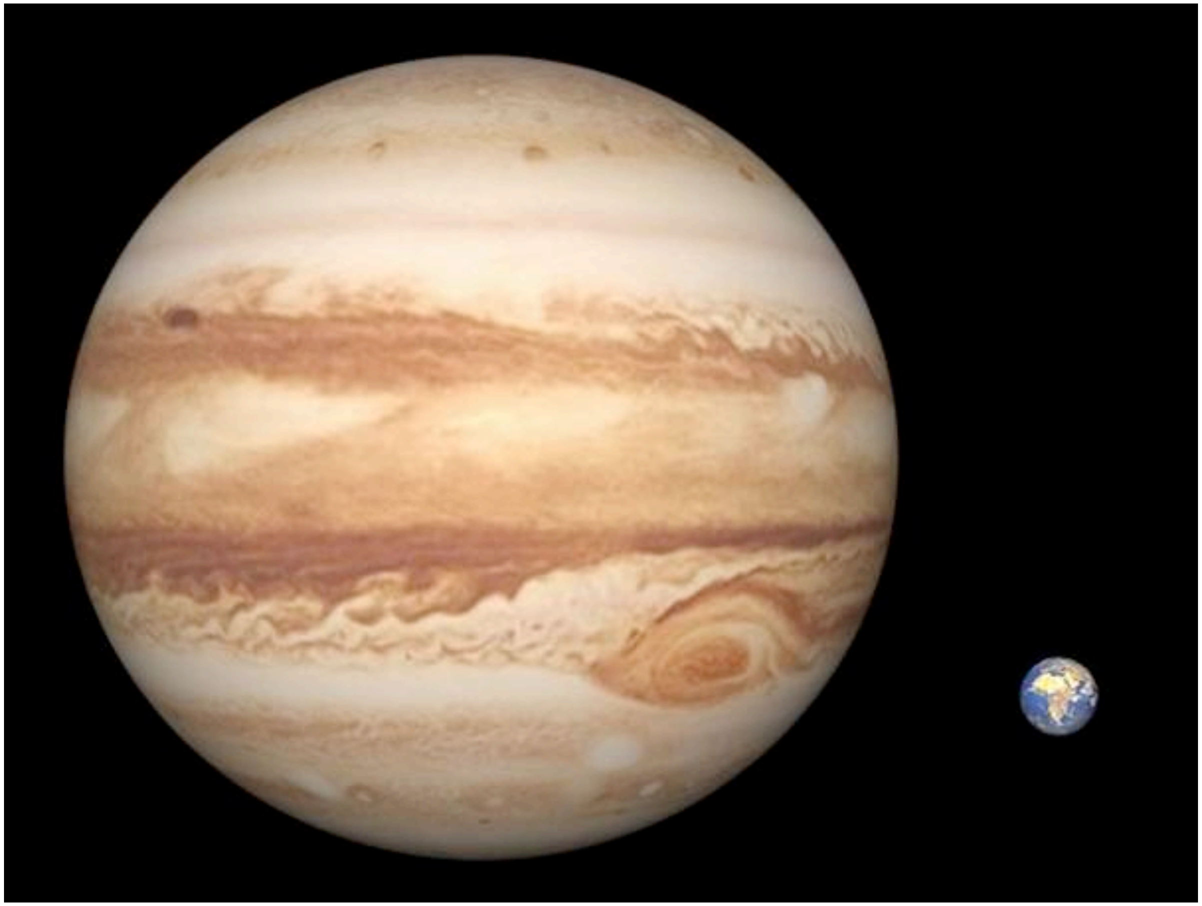
Galileo, 1609







We learned the true sizes and compositions of the planets

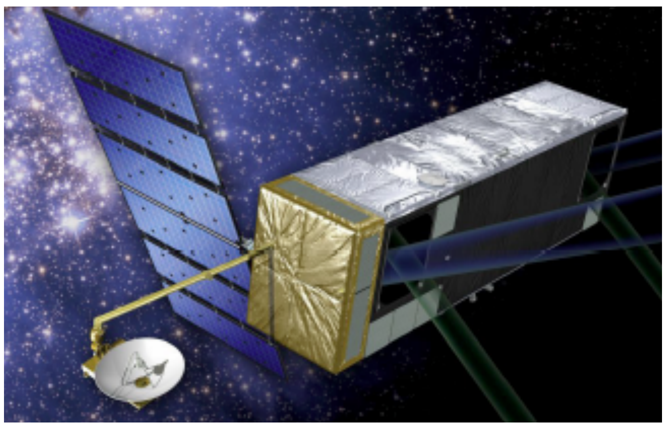


Jupiter's diameter is eleven times greater than the Earth's,
and it has over 300 times the mass.

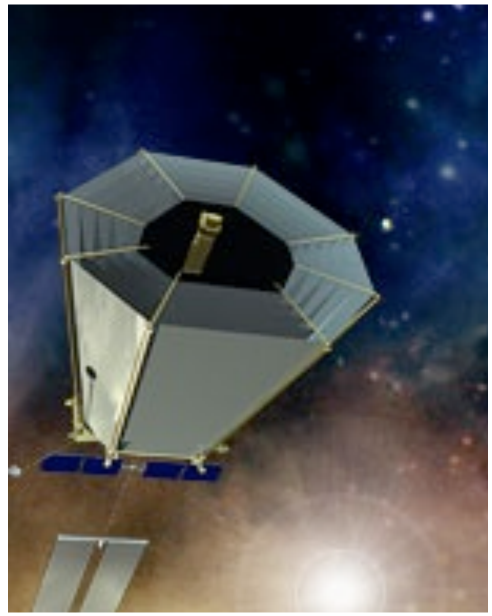
Fast-forward 20 years….

Today's telescope ideas are not as limited by diffraction and seeing, so we can ask the ***Big Questions:***

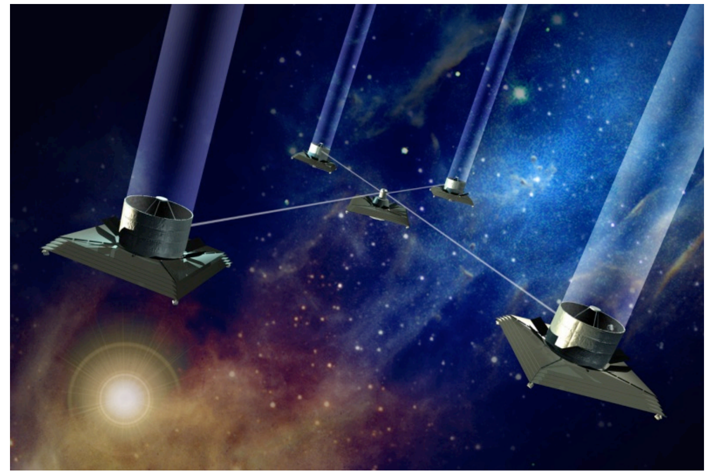
- Are there Earth-like planets around nearby stars?
- Are there signs of life on these planets?



Space Interferometer Mission (SIM Lite)
Proposed for coming decade

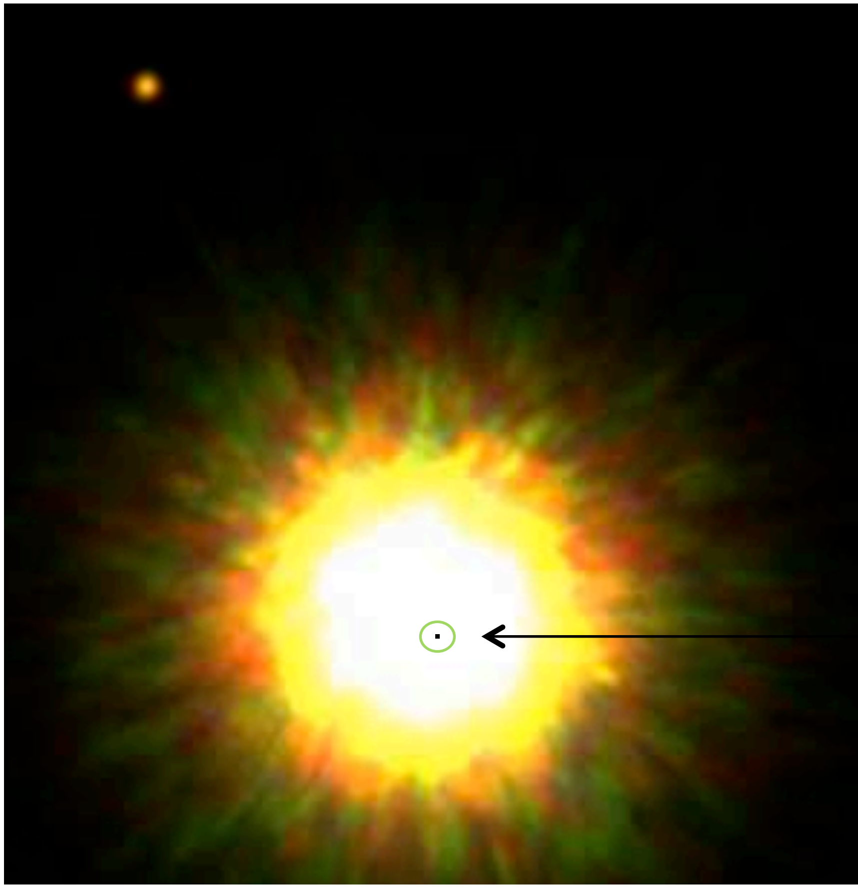


Terrestrial Planet Finder Coronagraph/Occulter (TPF-C/O)
Proposed for late in coming decade



Terrestrial Planet Finder Interferometer (TPF-I)
Proposed for next decade

First claimed exoplanet image: 1RXS J160929.1-210524

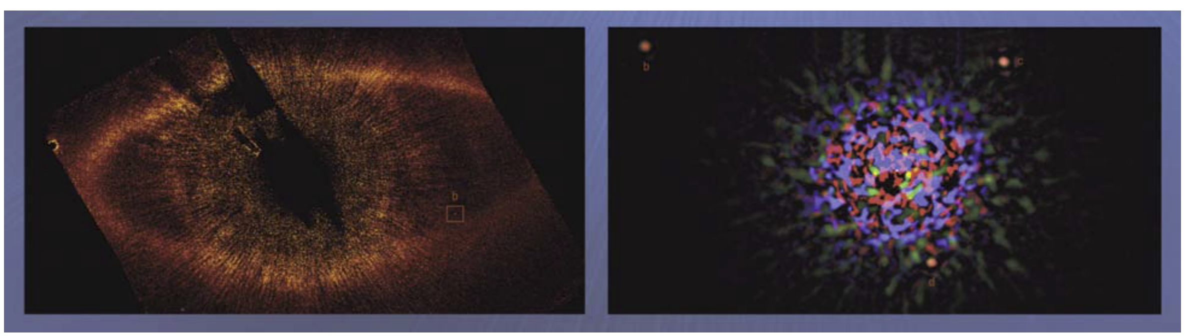


Location: (16 h, -23 deg)
Upper Scorpius Association
Distance ~ 145 pc

Separation:
2.22 arcsec = 330 AU

Visible brightness ratio:
~ 1,000,000x or 15 mag

If this were a nearby star, the Earth's orbit would be hidden in the glare.



Fomalhaut b
HR 8799 b, c, d

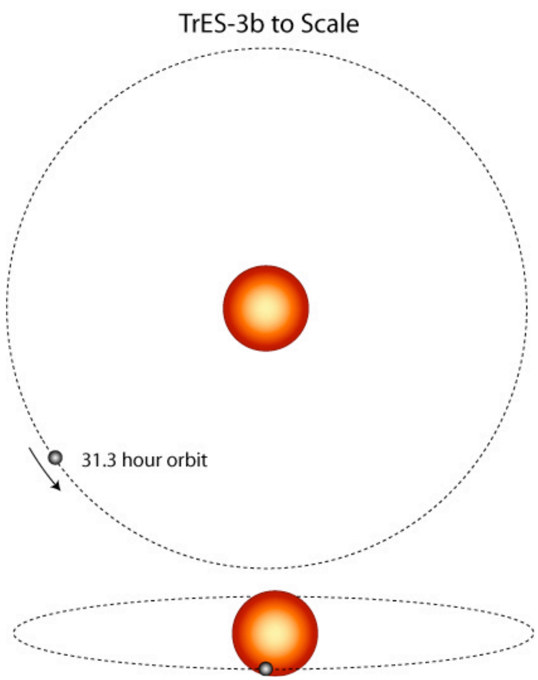
How do we find exoplanets?

- Radial velocity (the Doppler effect)
- Transits (a mini eclipse of the star)
- Gravitational lensing (Einstein said light bends near a star)
- Astrometry (elliptical motion on the sky)
- Infrared interferometer (several small telescopes working together)
- Visible coronagraph telescope (block the star inside the telescope)
- Visible occulter (block the star from far away)

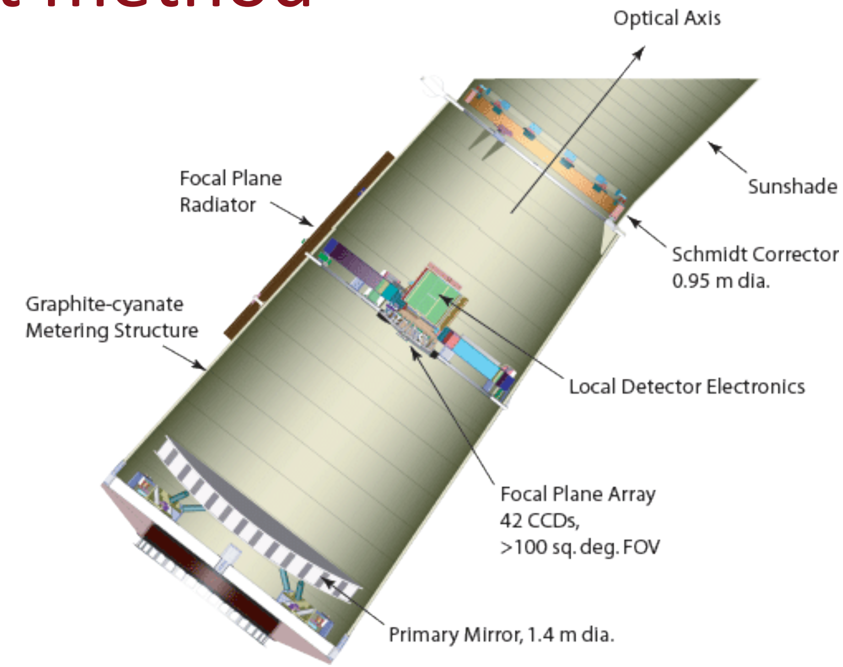
Radial velocity method

If a star moves toward us and later away from us (owing to a planet), then its spectrum will be blue-shifted and later red-shifted.

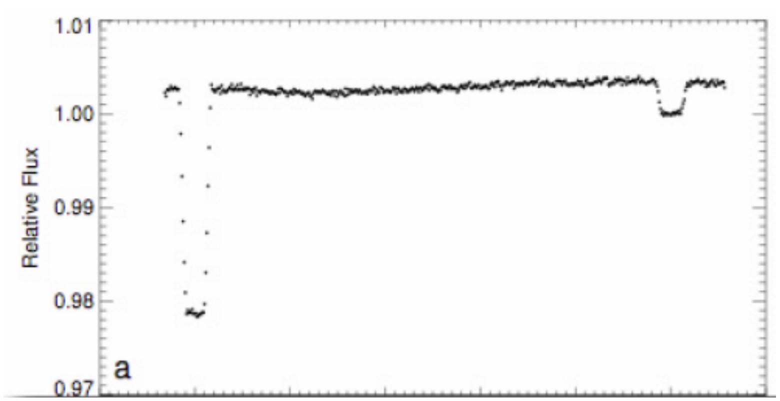
Transit method



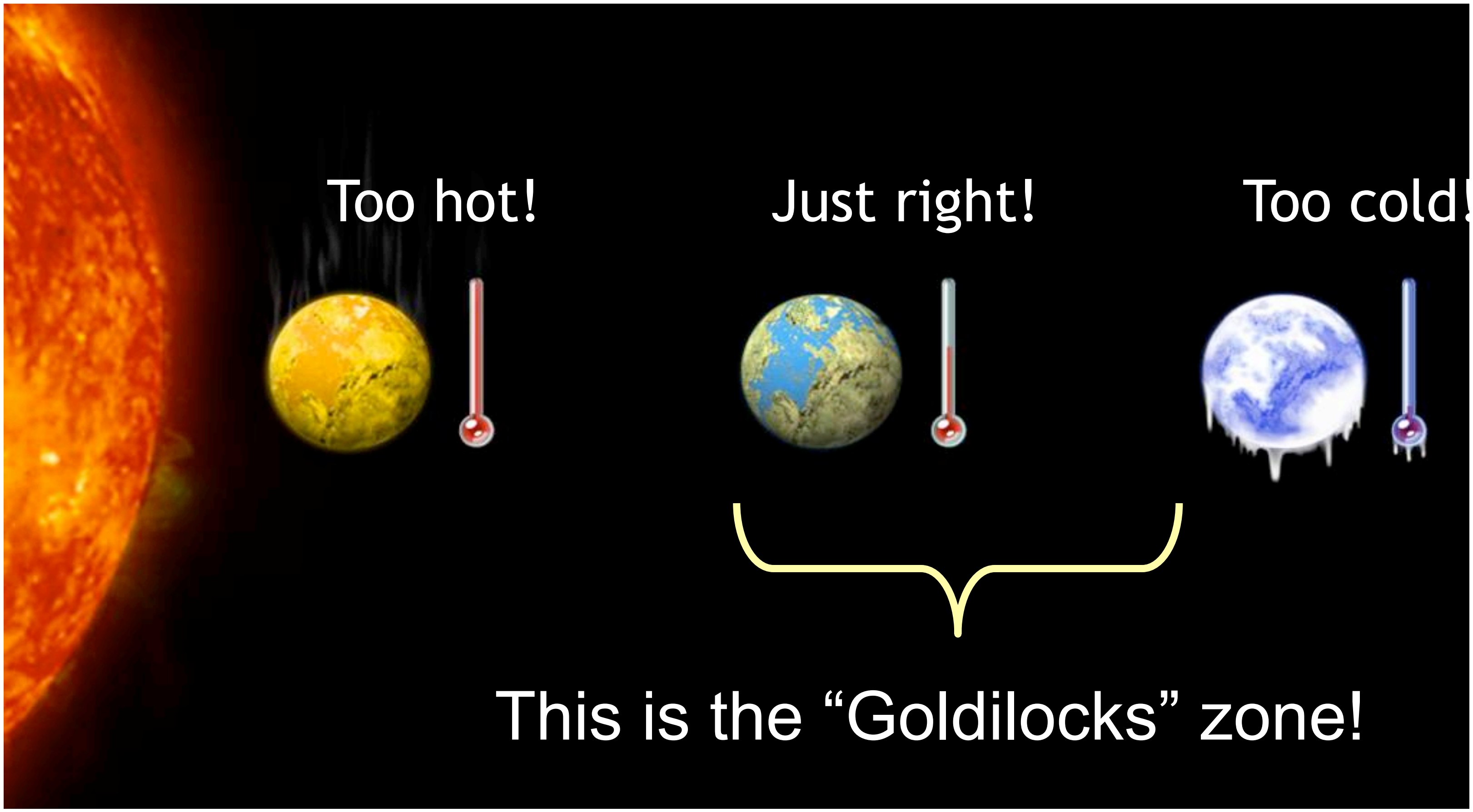
Spitzer: infrared



Corot & Kepler: visible

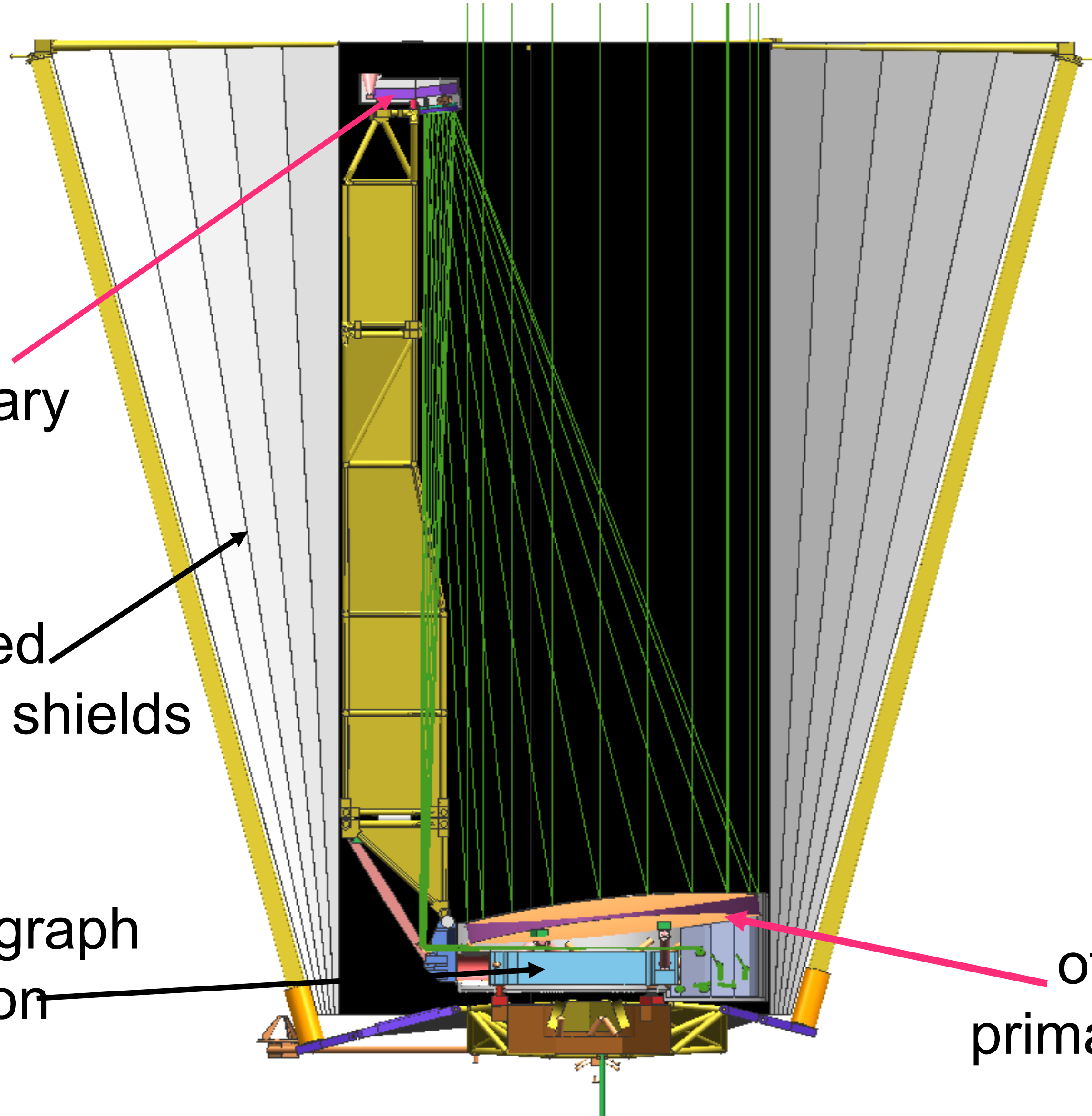


Many of the new planets are too hot or too cold to support life

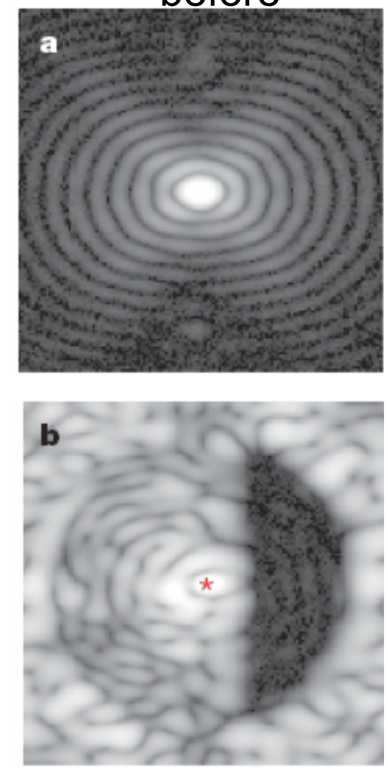


Terrestrial Planet Finder Coronagraph (TPF-C)

TPF-Coronagraph

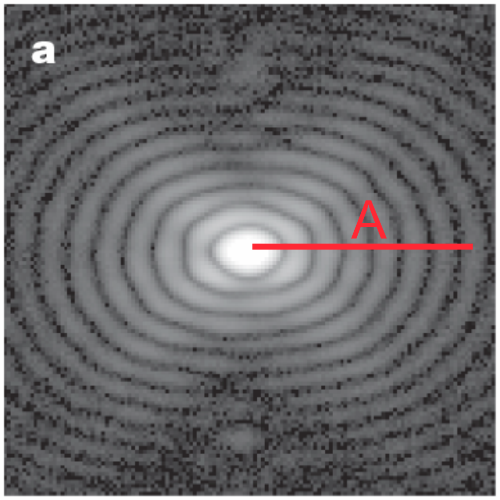


before

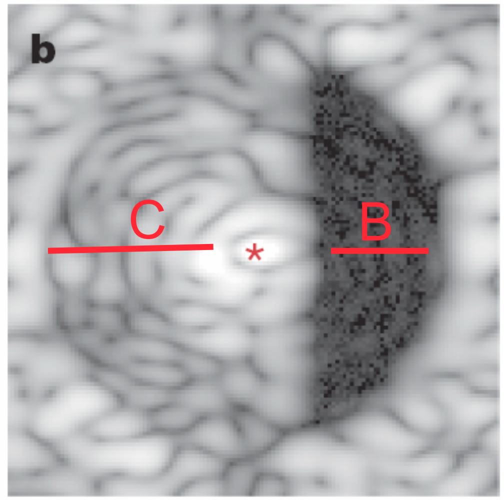


after

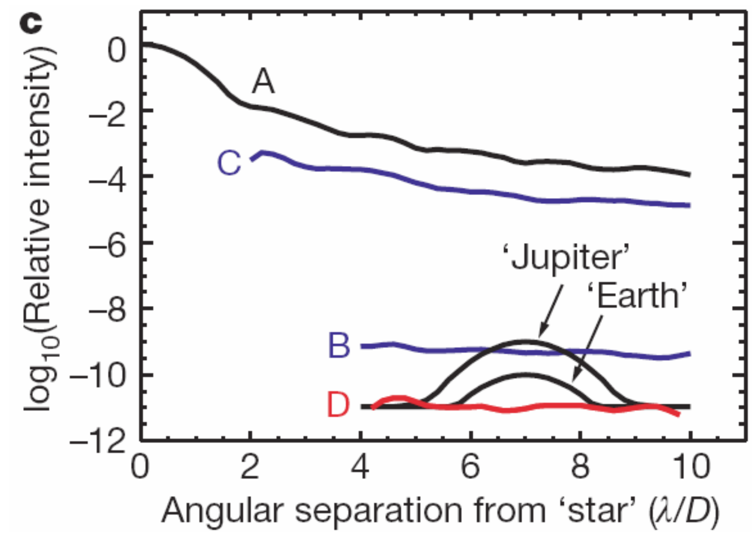
Lab demo of $(1 - \mathrm{sinc}^2)^2$ mask



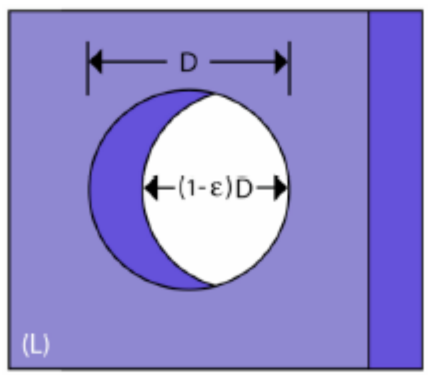
Star image (no mask)



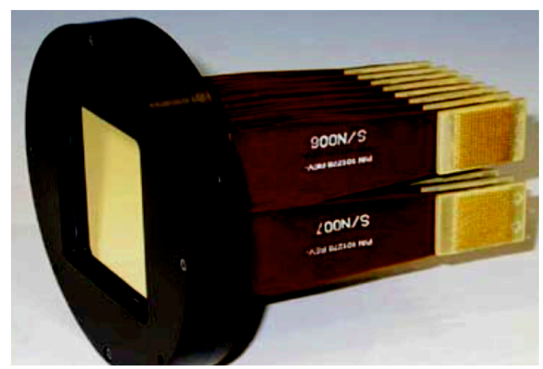
Star image (with mask)



Focal-plane mask



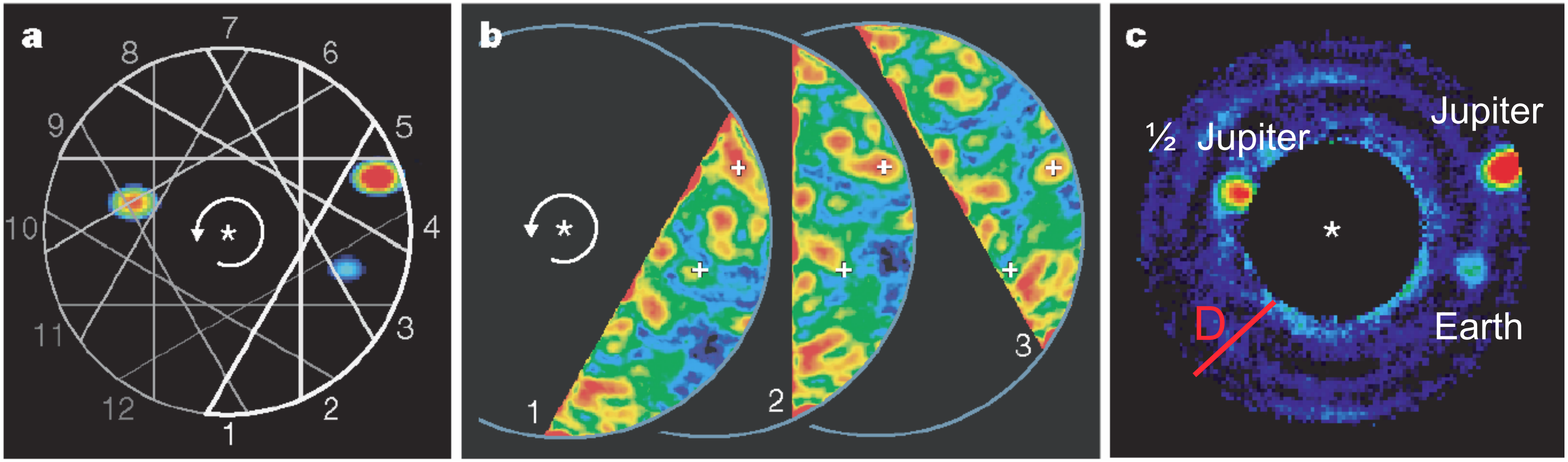
Pupil-plane stop



Deformable mirror

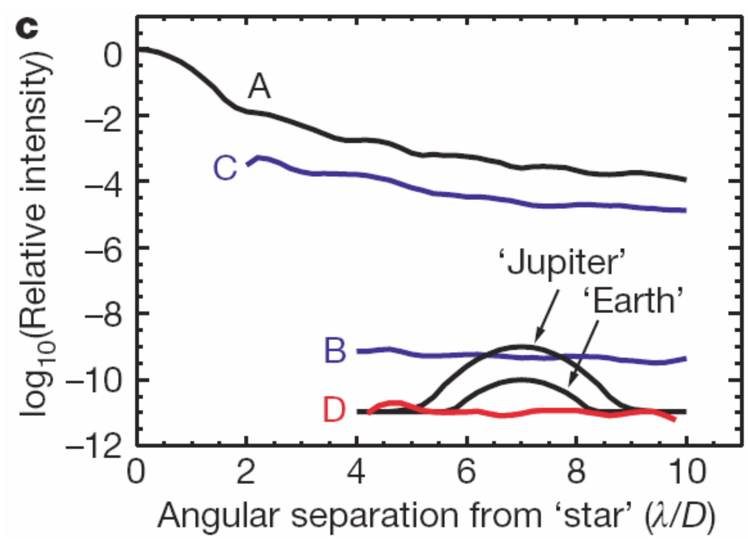
Trauger & Traub, Nature, April 2007

Lab demo, with planets added



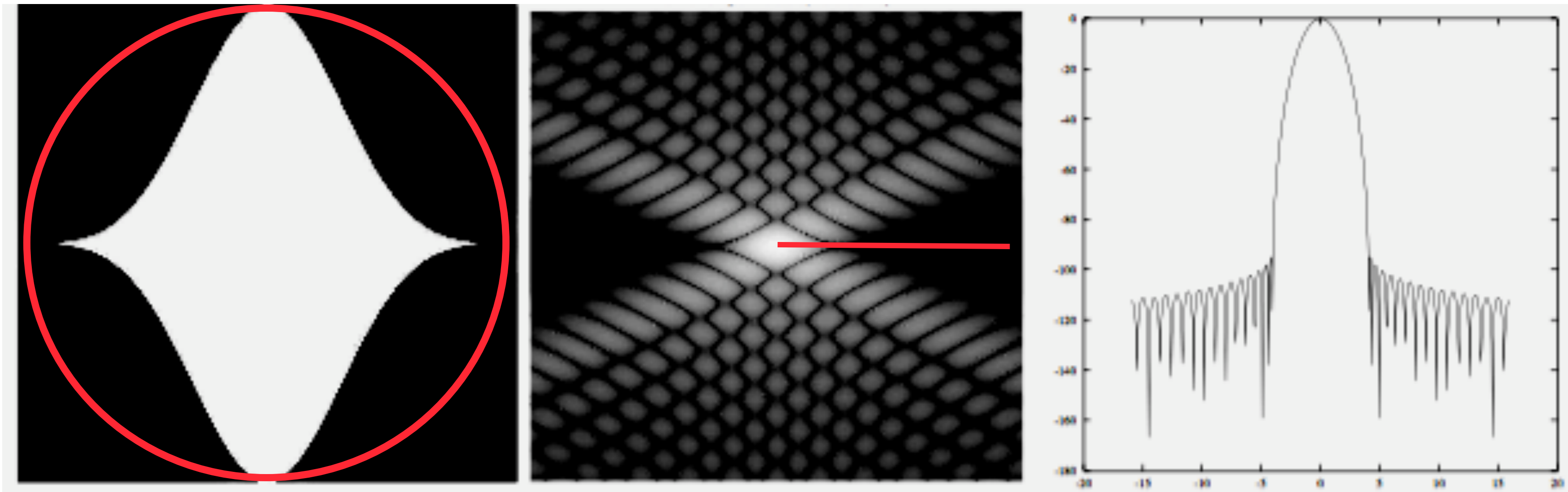
500 D-shaped images of dark hole,
Rotated to sample annulus on sky,
Planets added,
Common speckles removed,
Planets pop out of noise.

Shows that Earth could have been detected.



Trauger & Traub, Nature, April 2007

Shaped-pupil mask



Spergel-Kasdin prolate-spheroidal mask

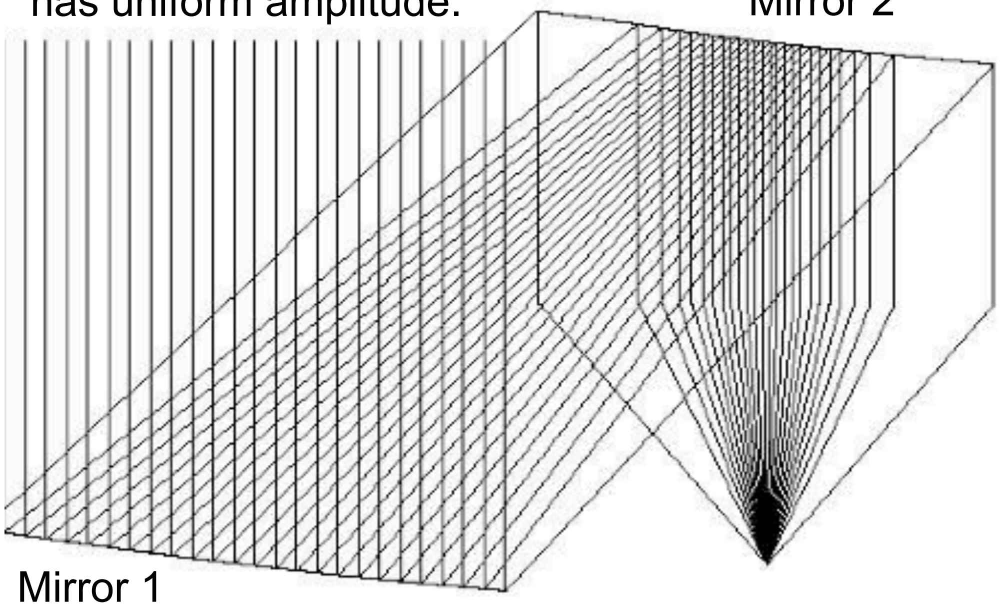
dark areas < 10^{-10} transmission

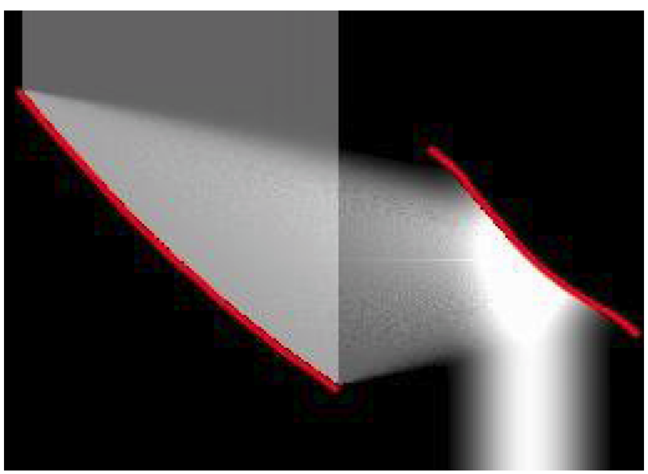
PSF cut along horizontal axis

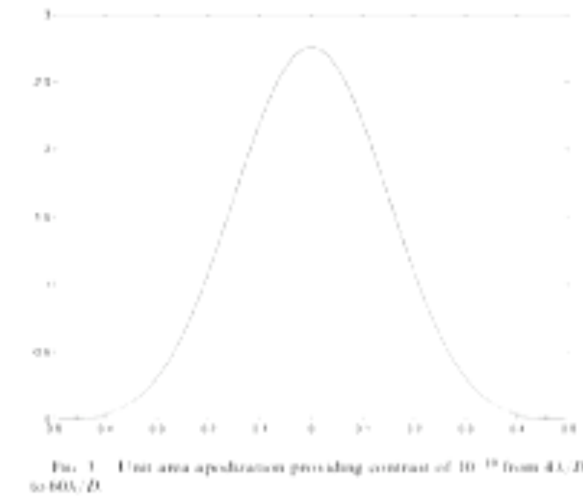
Kasdin, Vanderbei, Littman, & Spergel, 2004

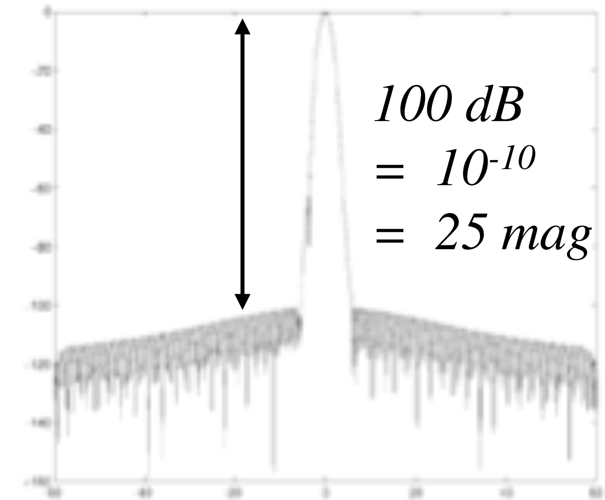
$$E_{\text{out}}(\tilde{x},\tilde{y}) = A_{\text{out}}(\tilde{r}) \int\int \frac{1}{\lambda Q(\tilde{x},\tilde{y},x,y)} e^{2\pi i Q(\tilde{x},\tilde{y},x,y)/\lambda} A_{\text{in}}(r)\,dy\,dx$$

Input wavefront from star has uniform amplitude.









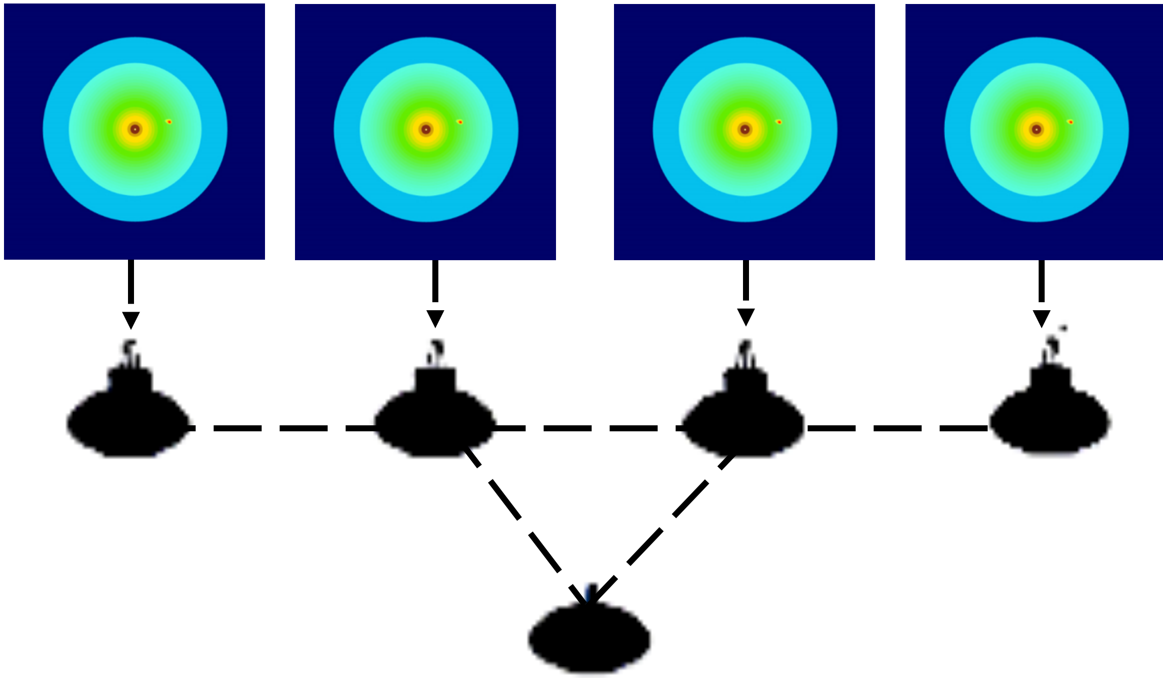
Pupil Mapping:

Image of star is ~gaussian with *very weak* "Airy rings".

Guyon, A&A 2003;   Traub & Vanderbei, ApJ 2003

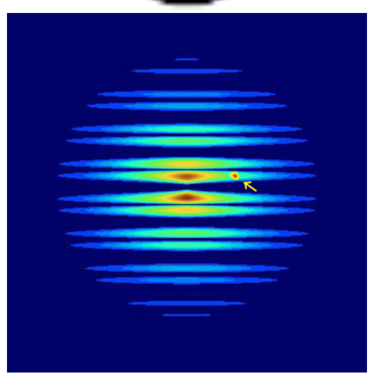
Terrestrial Planet Finder Interferometer (TPF-I)

TPF-Interferometer

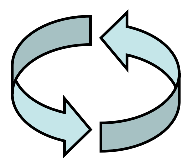


1. star, planet, & zodi,
seen as a single (not resolved) blob
by each telescope

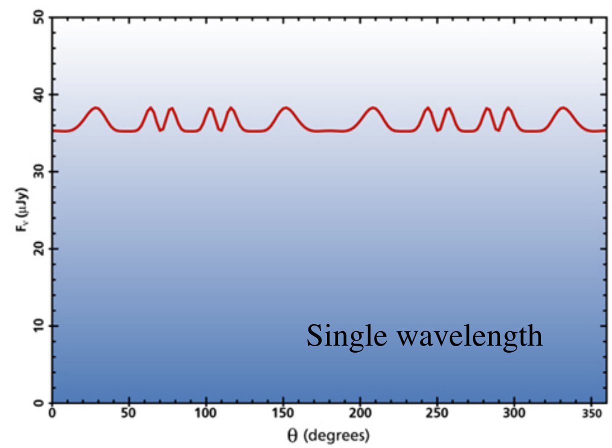
2. four collector telescopes
& one combiner, plus delay lines,
all free-flying



3. transmission pattern, times sky image,
seen as a single blob;
total amount of light received is noted



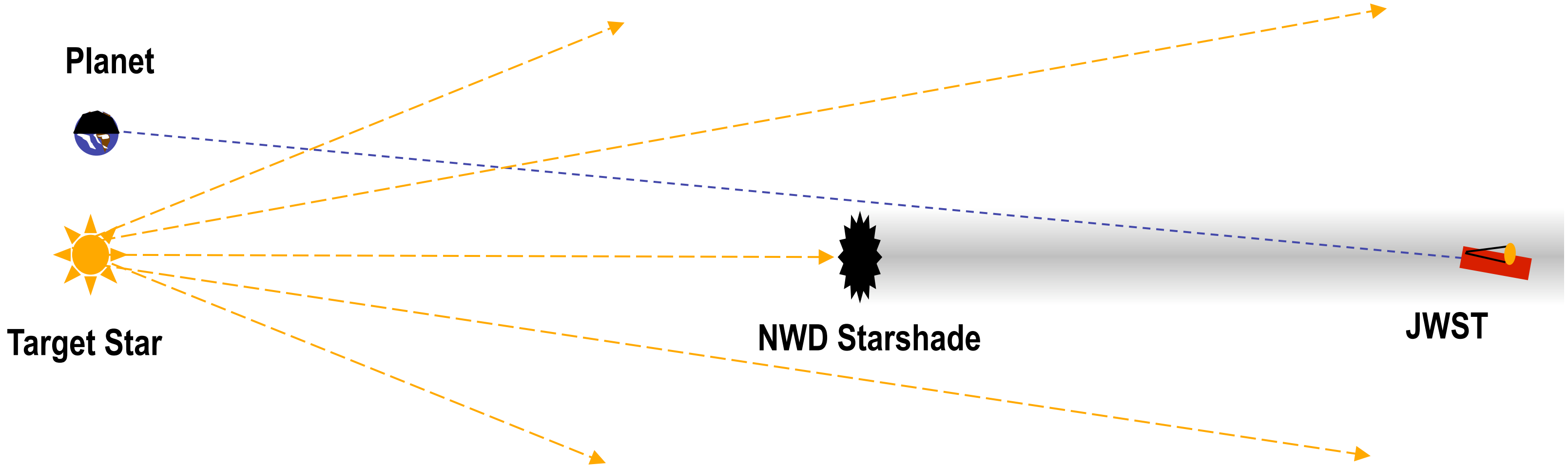
4. array
rotates



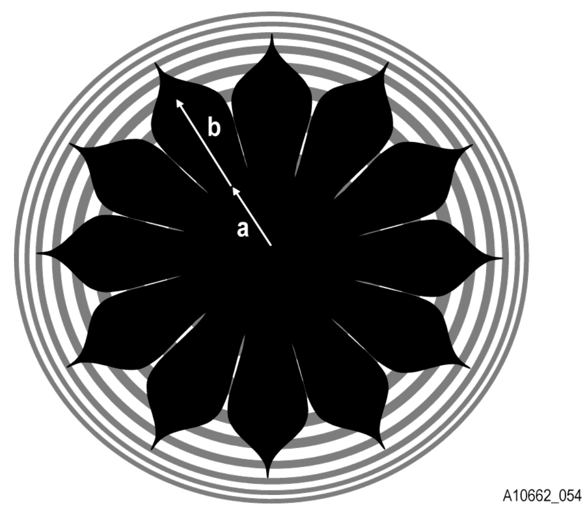
5. measured total light level,
as array rotates a full turn
(bumps are the planet)

Terrestrial Planet Finder Occulter (TPF-O)

Occulter

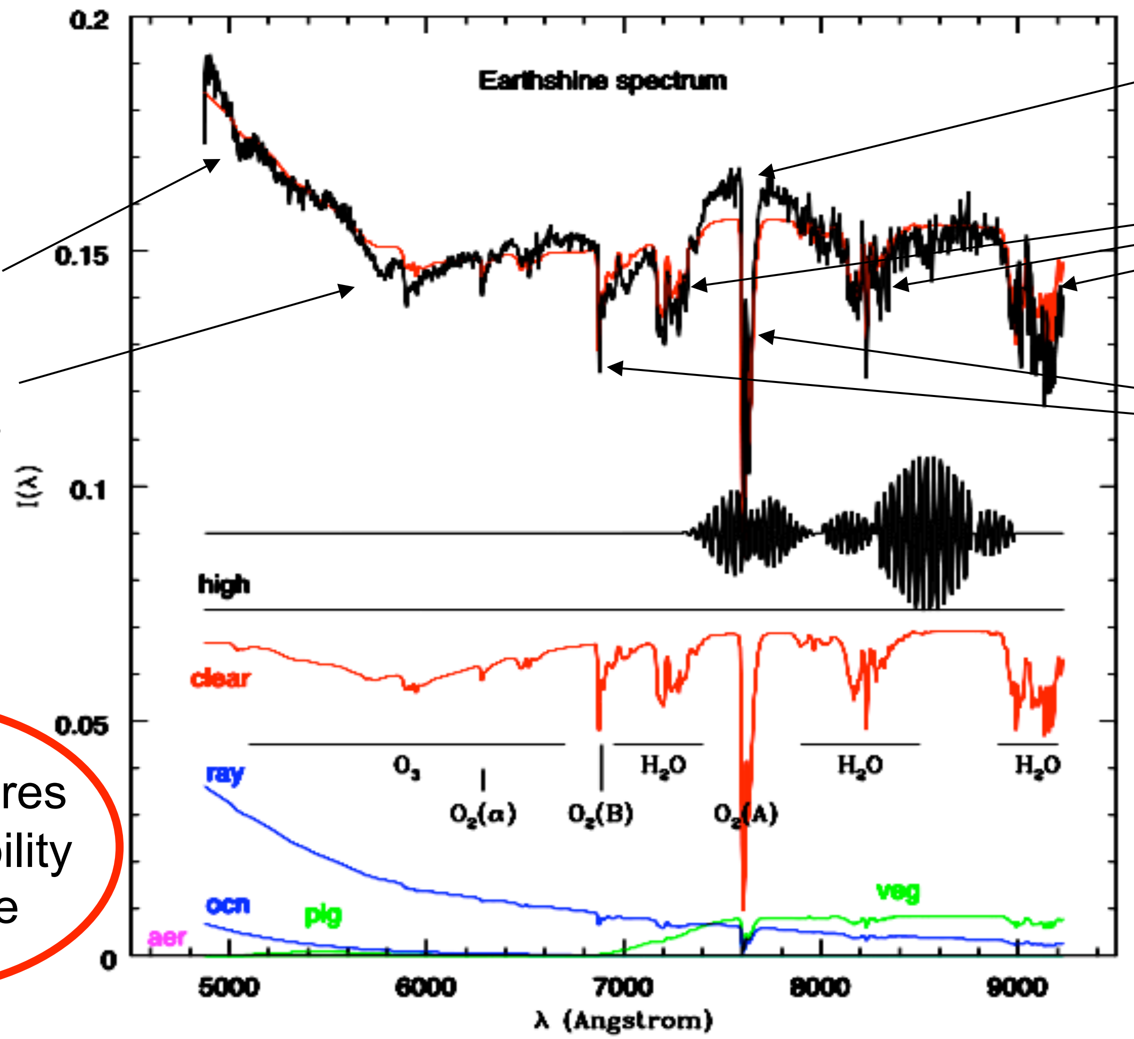


- Big telescope (planet is faint!)
- Big occultor (few times size of telescope)
- Big separation (to see close to star)

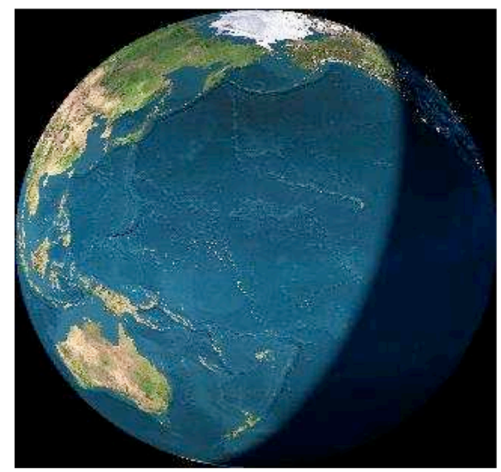


Spectra

Visible Earthshine Spectrum



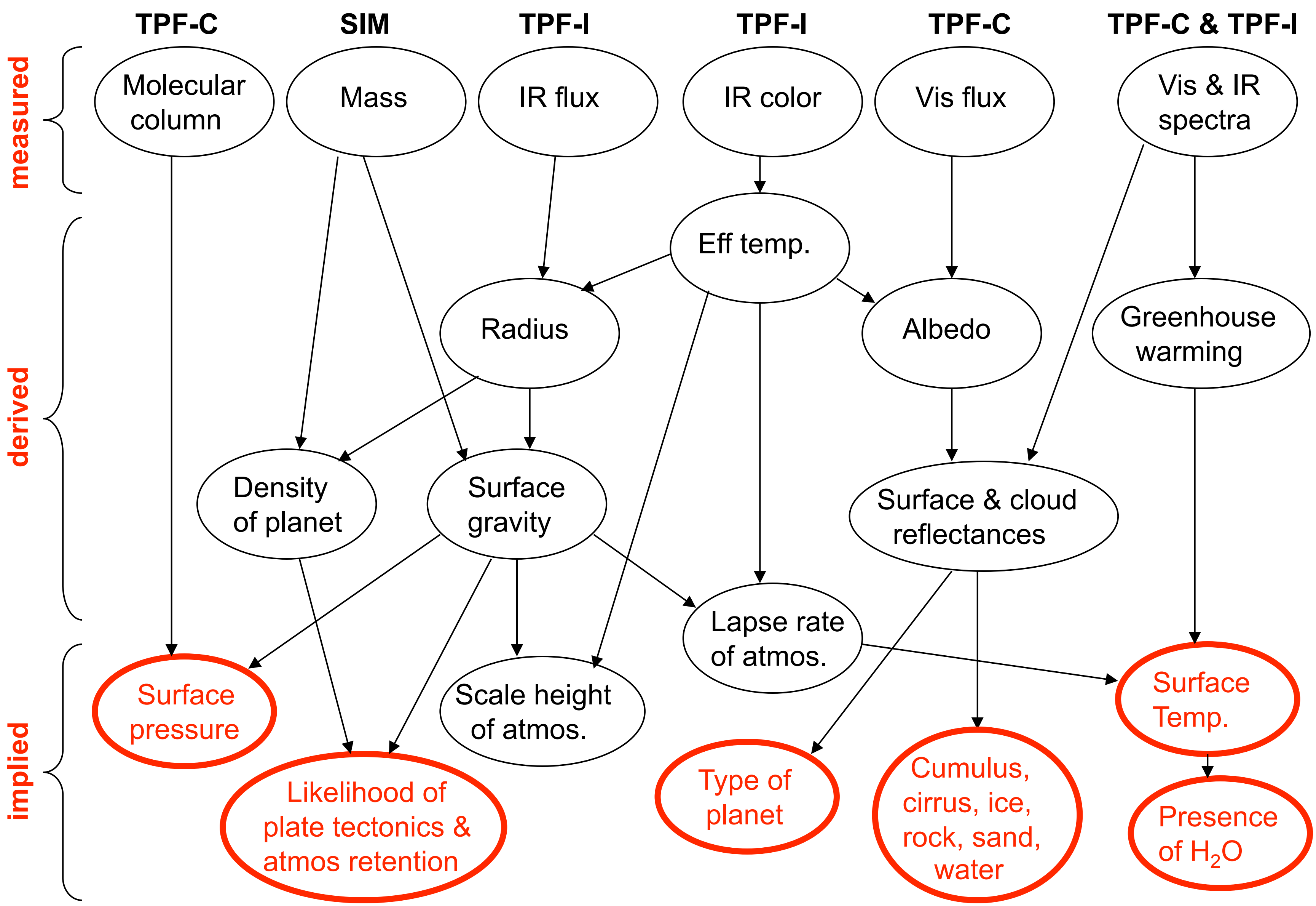
Marked features show habitability & signs of life



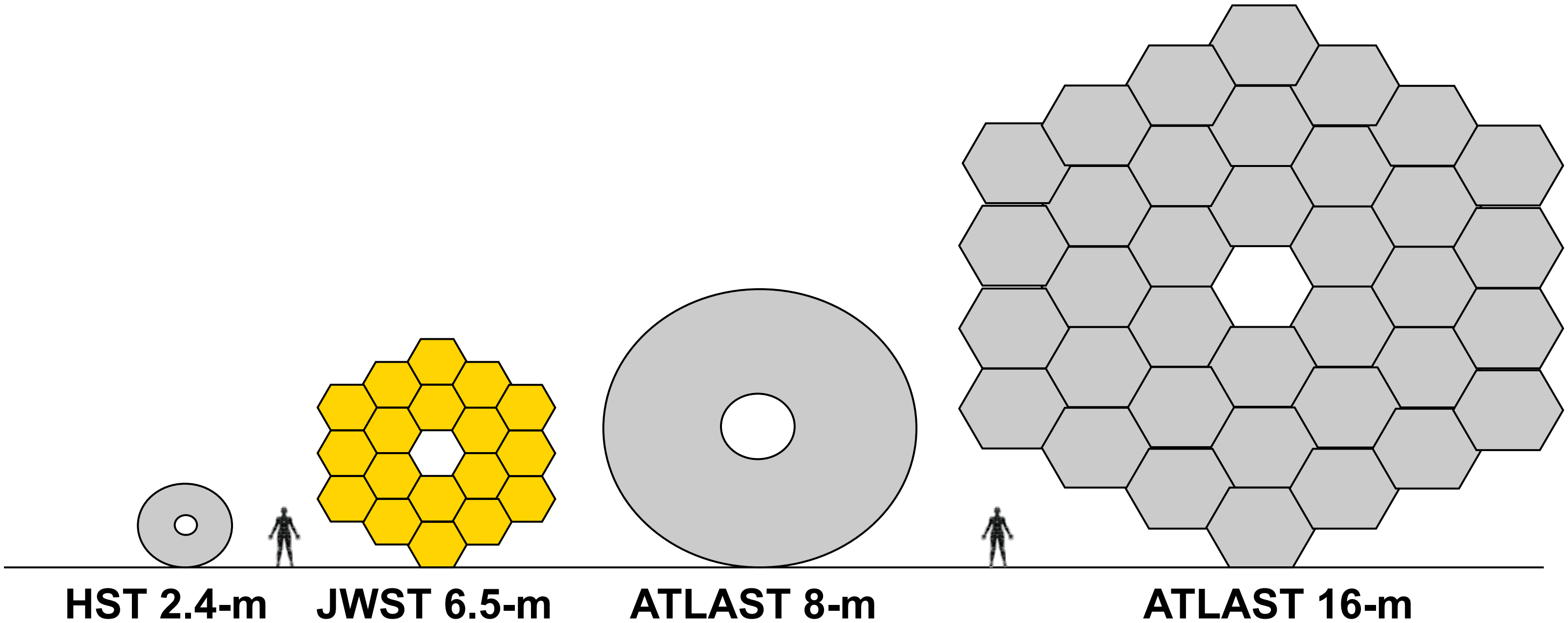
- Observed Earthshine, reflected from dark side of moon.

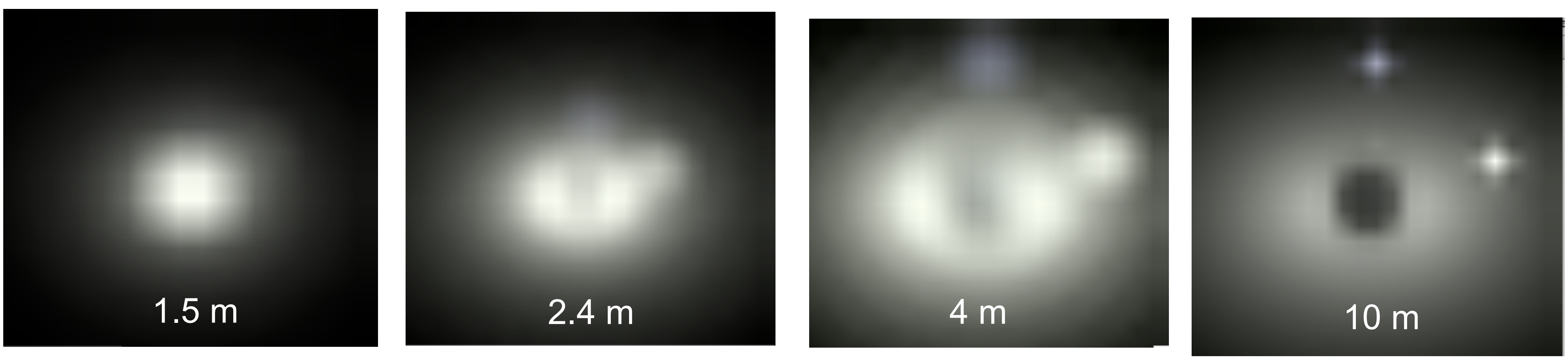
Woolf, Smith, Traub, & Jucks, ApJ 574, p.430, 2002

Habitability of an Earth-like Planet



Planets *vs* zodi: telescope size matters





Ref.: (upper) M. Postman et al., ATLAST study; (lower) W. Cash et al., NWO study.

Species SNRs & abundance uncertainties

Table 1: **Habitability and Bio-Signature Characteristics**

Feature	λ (nm)	Δλ (nm)	SNR	Significance
Reference continuum	~750	11	10	
Air column	500	100	4	Protective atmosphere
Ozone (O_3)	580	100	5	Source is oxygen; UV shield
Oxygen (O_2)	760	11	5	Plants produce, animals breathe
Cloud/surface reflection	750	100	30	Rotation signature
Land plant reflection	770	100	2	Vegetated land area
Water vapor (H_2O)	940	60	16	Needed for life

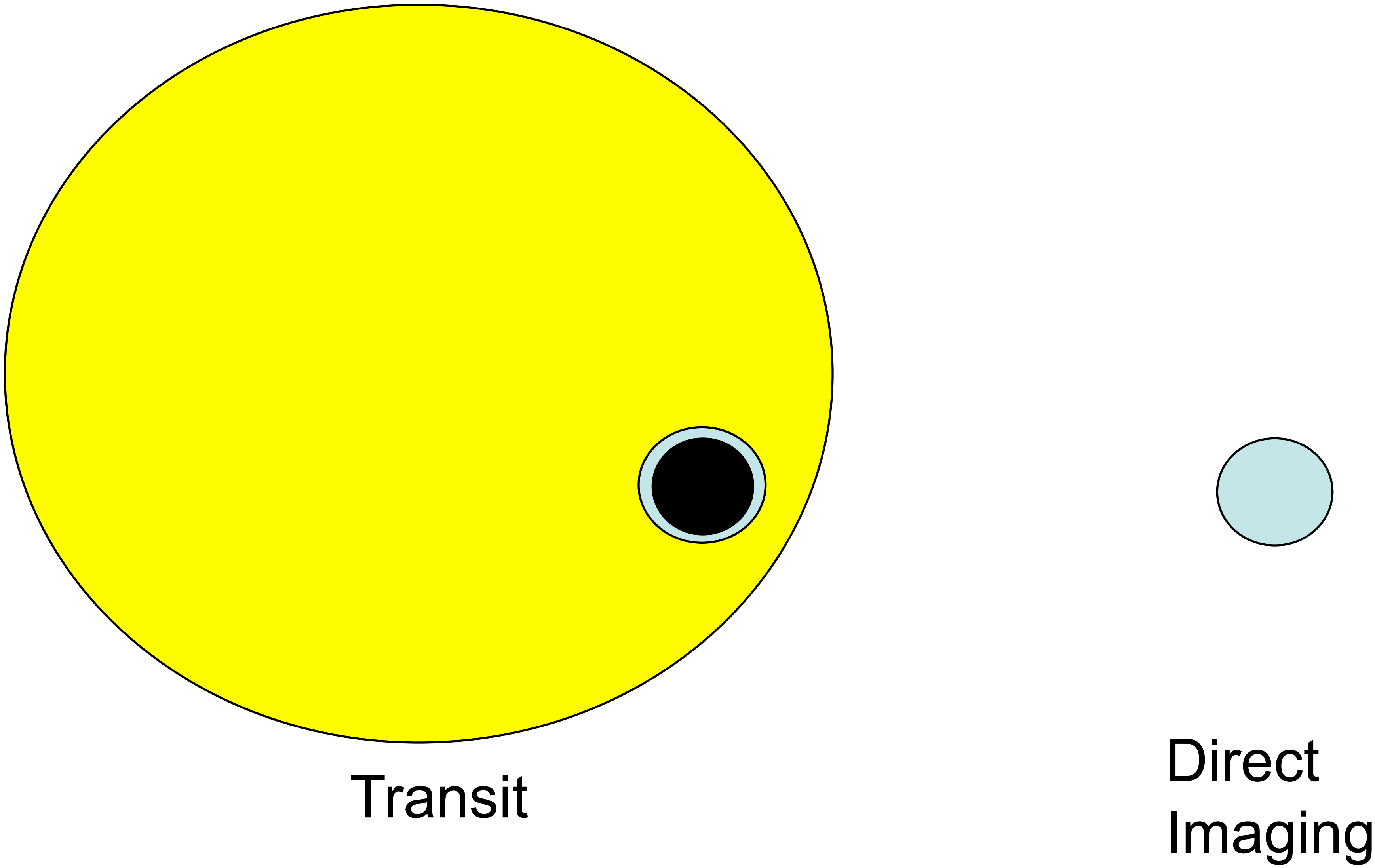
Bottom line:
An 8-m telescope can characterize nearby Earths,
and search for signs of life.

Ref.: M. Postman et al. 2009, ATLAST study.

Thank you !

And thanks, Giovanni !!

A Tale of Two Geometries



Visible Radius