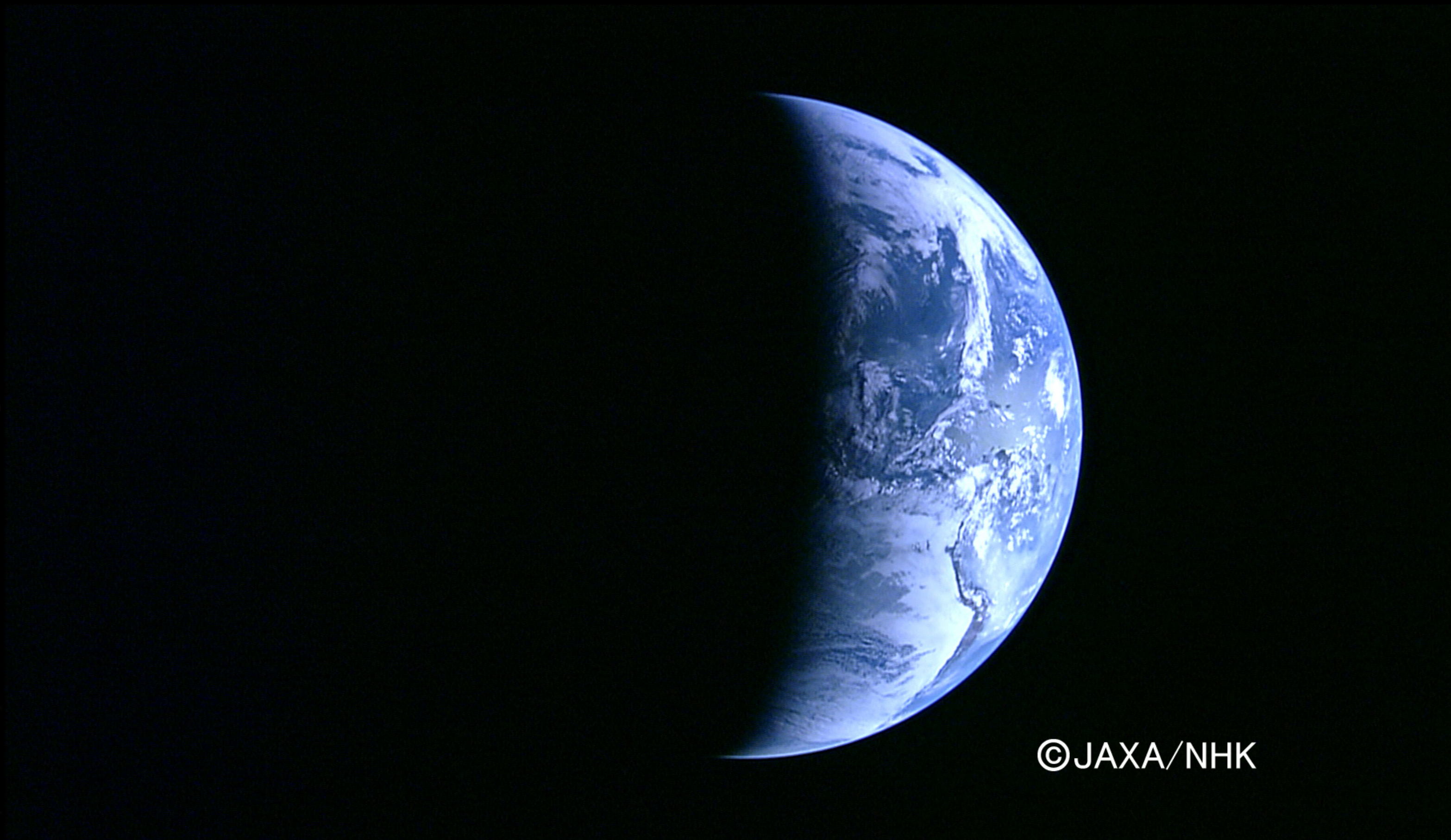
Beyond Kepler:
Direct Imaging of Earth-like Planets

- Exoplanets: past and present
- How we can image another Earth (work at NASA Ames)
- Future

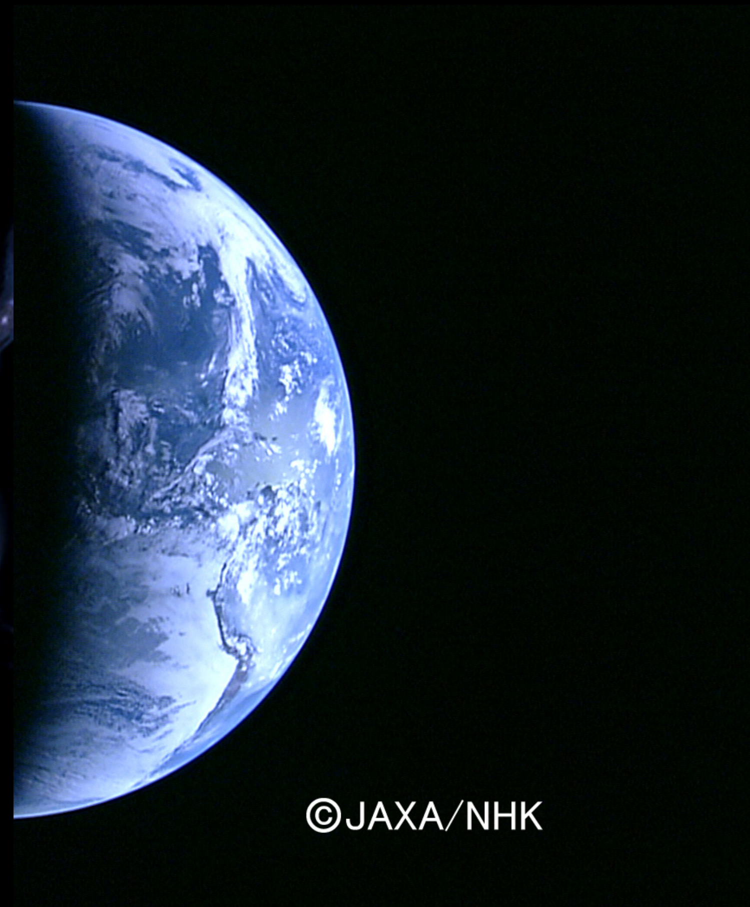
Rus Belikov

NASA Ames Research Center

MIT EAPS Department Lecture Series, April 25, 2012



Is there another Earth out there?



Is there life on it?

Thousands of years ago, Greek philosophers speculated.

"There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and planets and other things we see in this world."

Epicurius
c. 300 B.C

Some gave their lives…

” There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system. We see only the suns because they are the largest bodies and are luminous, but their planets remain invisible to us because they are smaller and non-luminous. The countless worlds in the universe are no worse and no less inhabited than our Earth”

Giordano Bruno
in De L'infinito
Universo E Mondi, 1584

In 1995, a breakthrough: the first planet around another star.

Didier Queloz and Michel Mayor

A Swiss team discovers a planet – 51 Pegasi – 48 light years from Earth.

And then the discoveries started rolling in:

"New Planet Seen Outside Solar System"
New York Times
April 19, 1996

"10 More Planets Discovered"
Washington Post
August 6, 2000

"First new solar system discovered"
USA TODAY
April 16, 1999

CNN.com / SPACE

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Exoplanet toll hits 100 as another Jupiter found

June 20, 2002 Posted: 10:07 AM EDT (1407 GMT)

(COURTESY LYNETTE COOK)

Artist's concept of an exoplanet

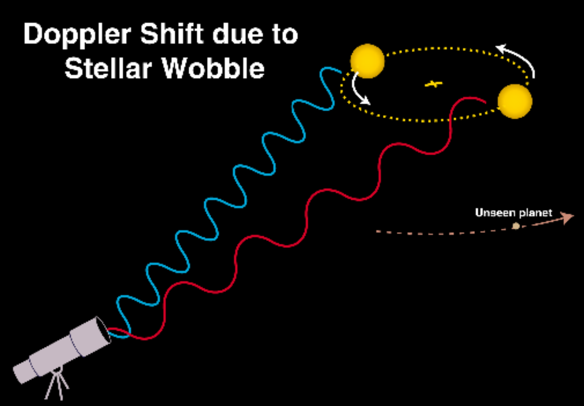
By Richard Stenger
CNN

(CNN) -- Astronomers said this week they had identified at least eight more planets outside our solar system, bringing the number of known or suspected exoplanets to about 100.

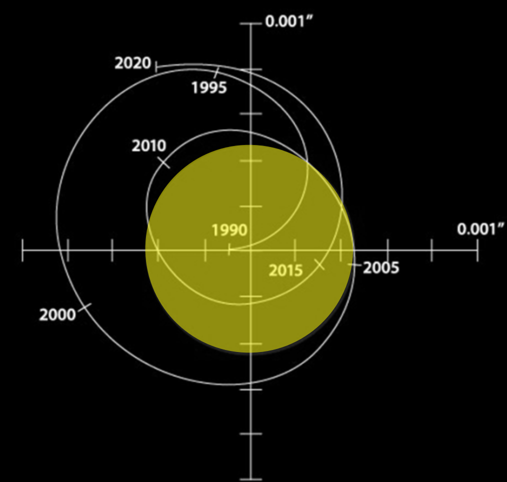
The group, unveiled during an unprecedented string of planet discoveries, includes one much like Jupiter, the second such rare find announced within days.

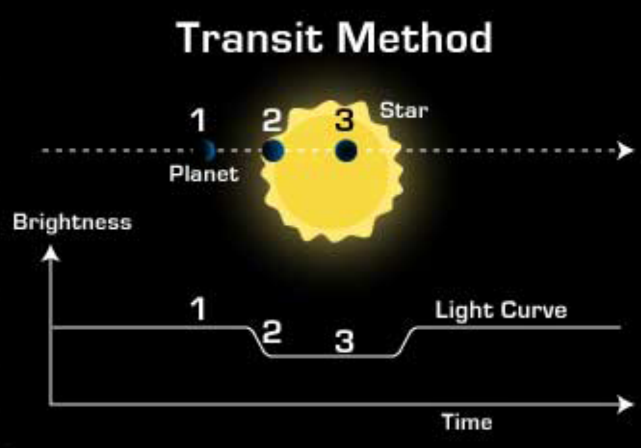
531 planets found so far, around 445 stars
Kepler: 1235 planet candidates, around 997 stars

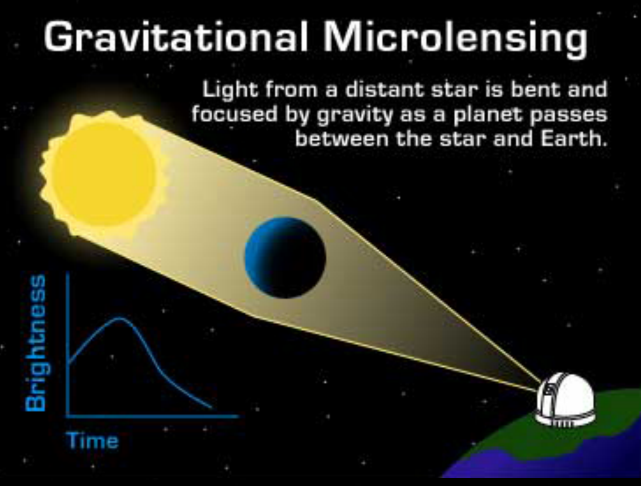
Wobble method #1: Radial Velocity



(Wobble method #2: Astrometry)

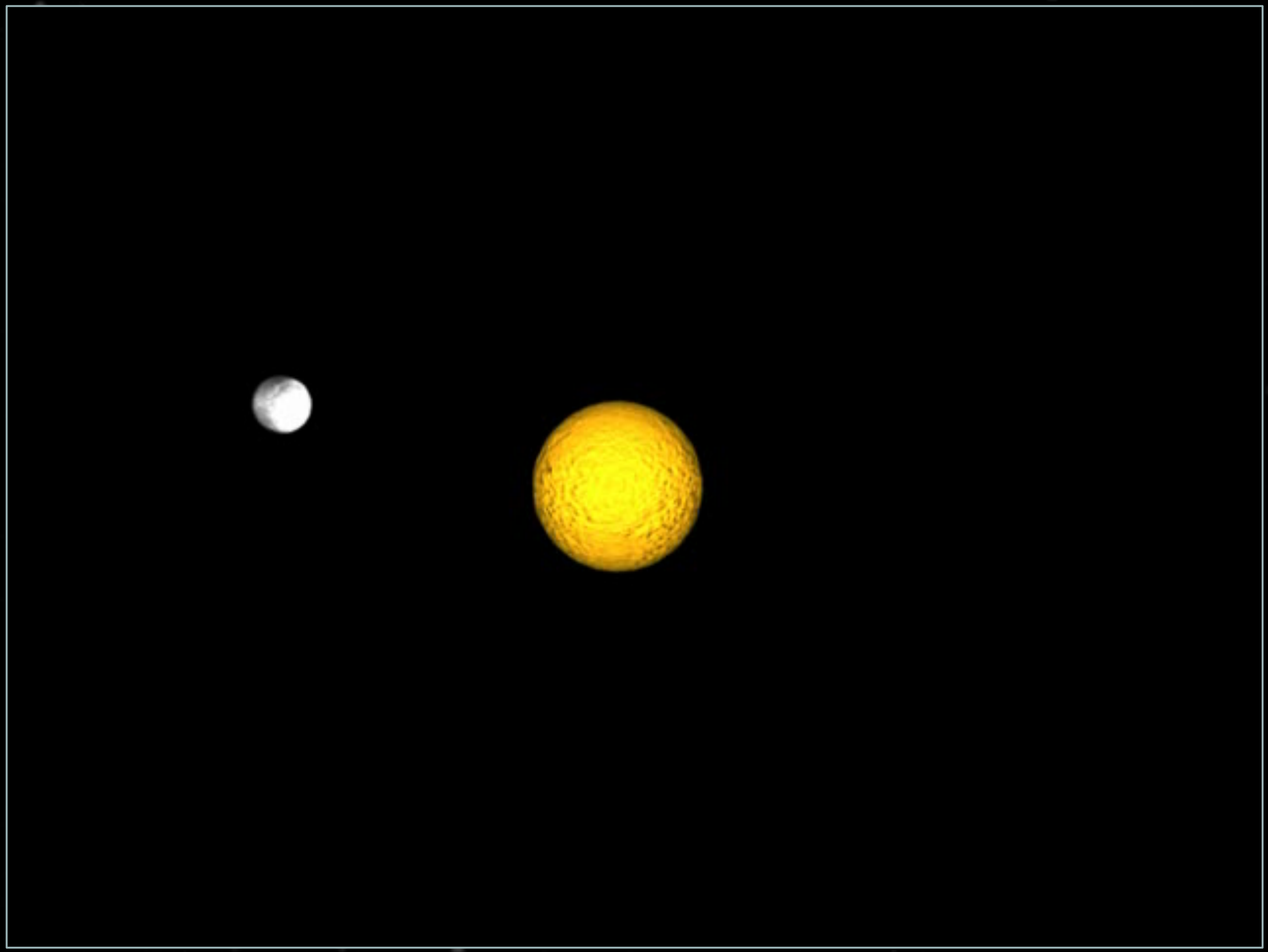






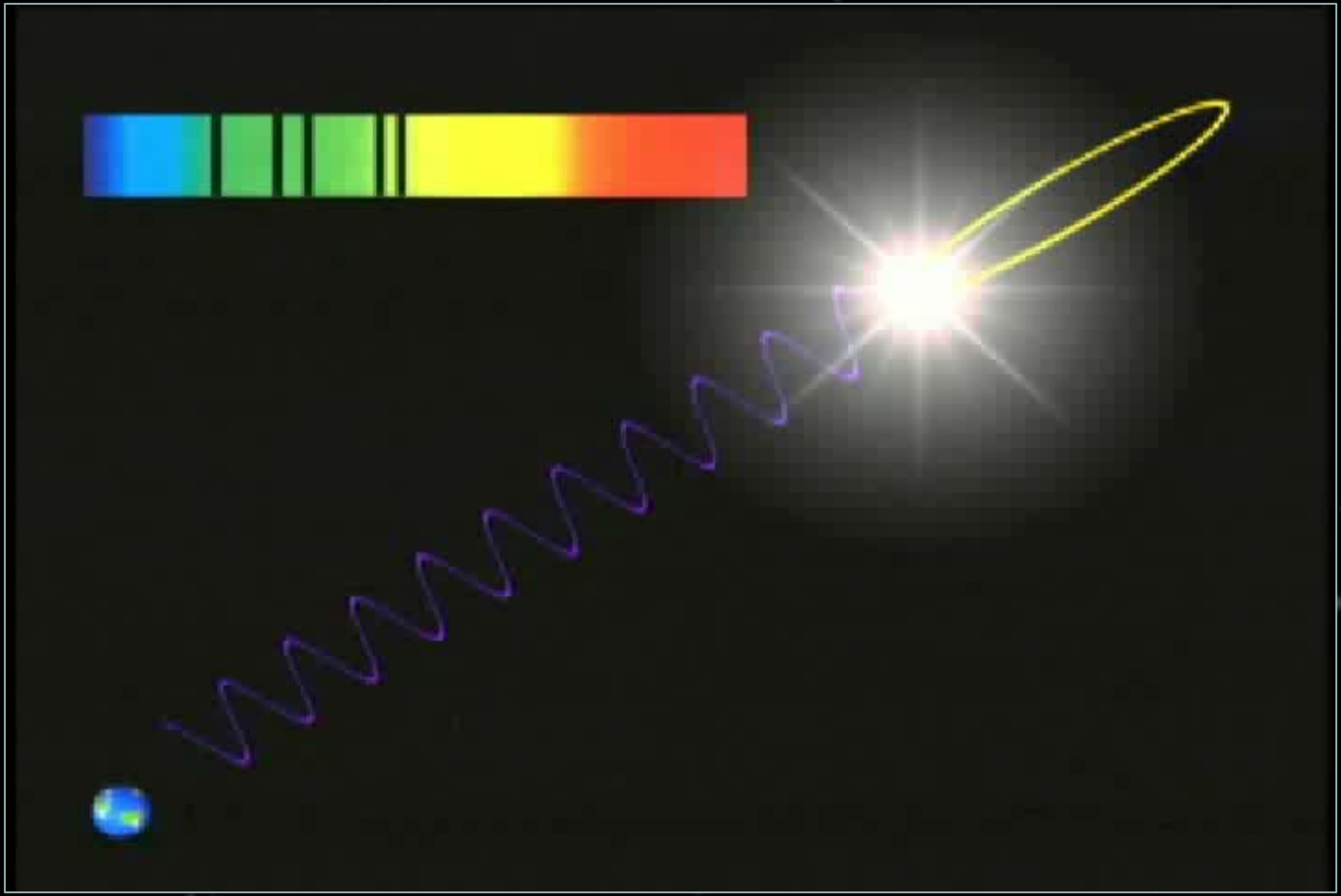
The Wobble Method

(Radial velocity / astrometry)



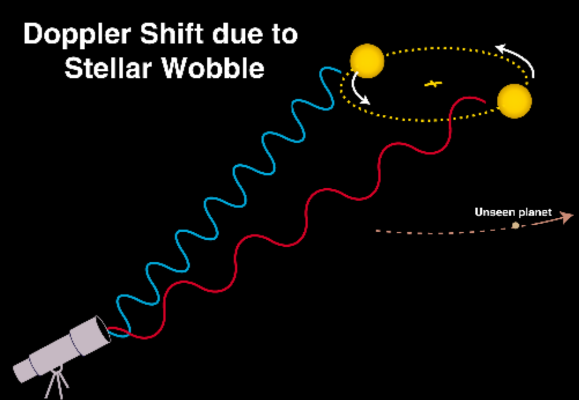
Credit: Amir Give'on and Daphna Wegner

The Wobble Method
(Radial velocity)

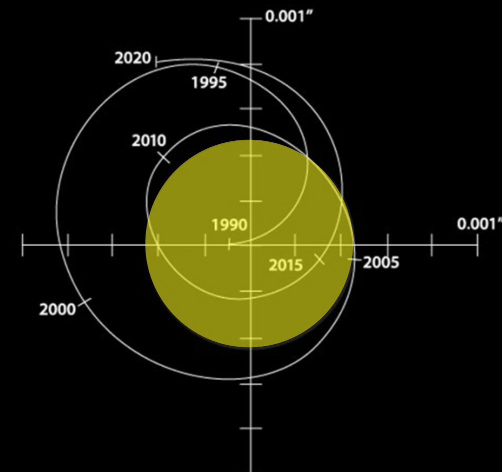


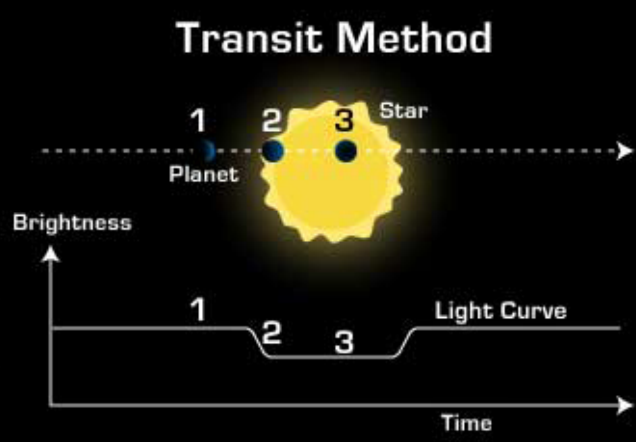
453 planets found so far, around 385 stars by indirect detection methods

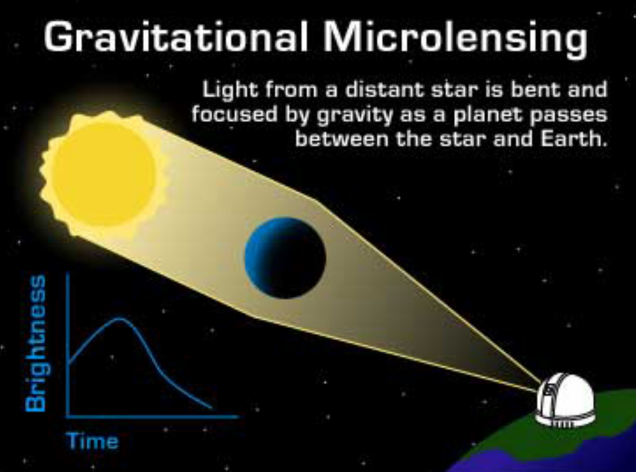
Wobble method #1: Radial Velocity



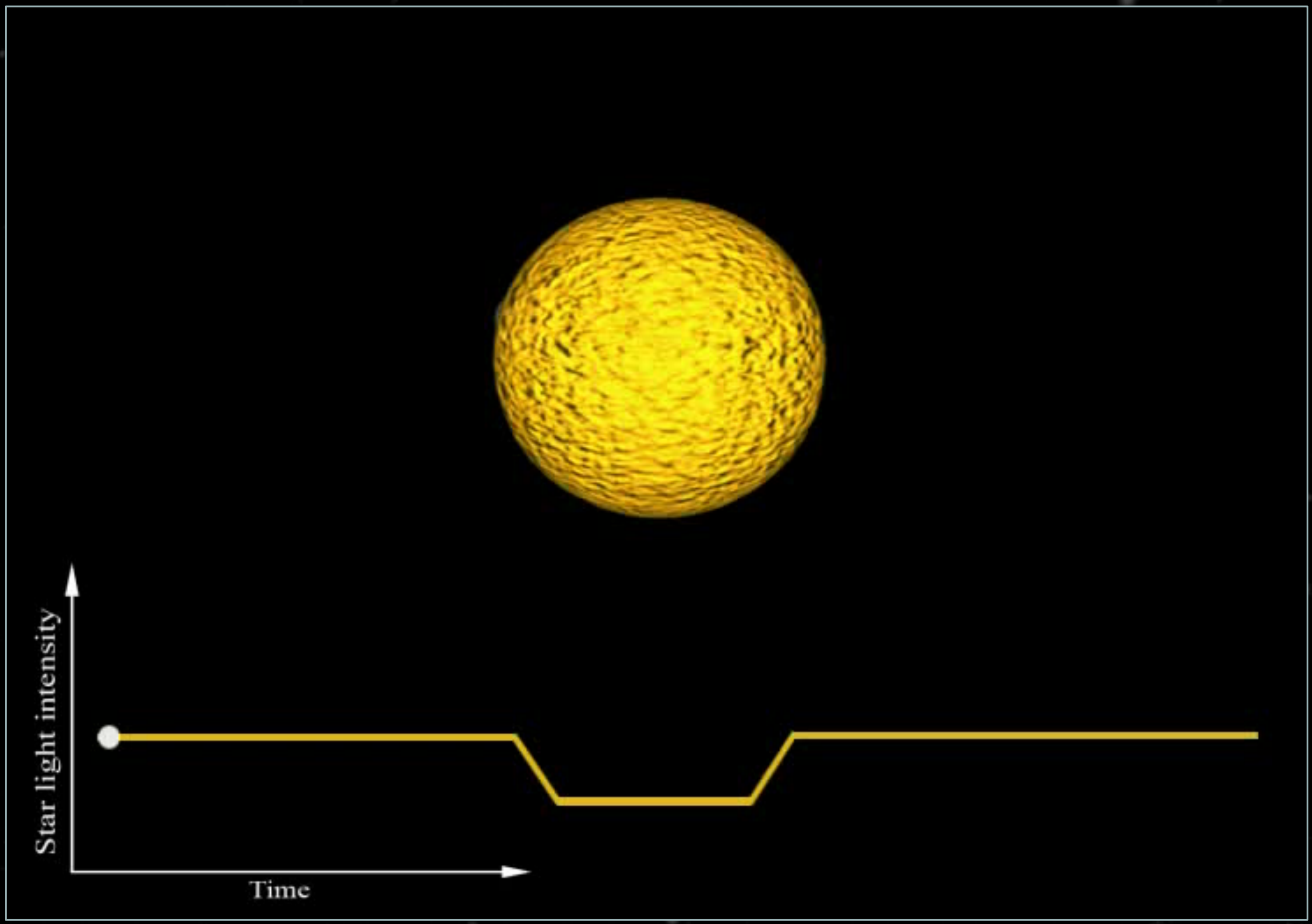
(Wobble method #2: Astrometry)







The Transit Method



Credit: Amir Give'on and Daphna Wegner

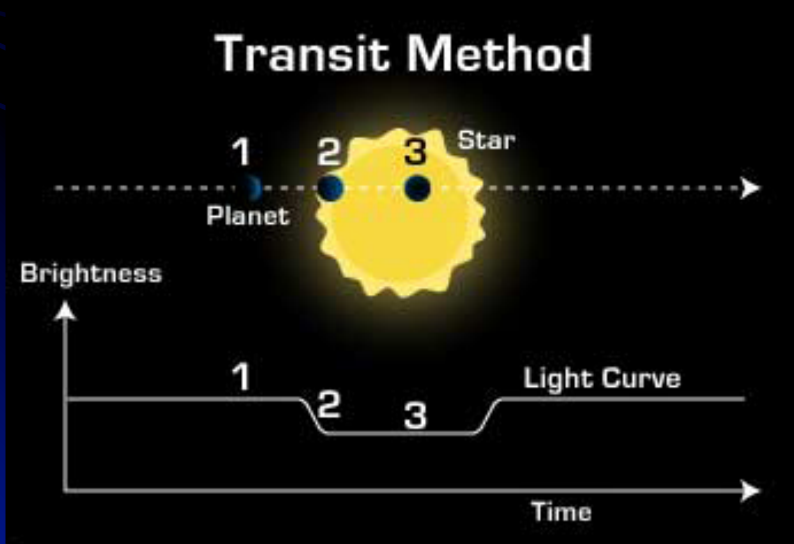
You can see transits within our Solar System!

Courtesy Bob Vanderbei

Next Venus transit: 2012 June 5-6
Next one after that: 2117 December 10–11

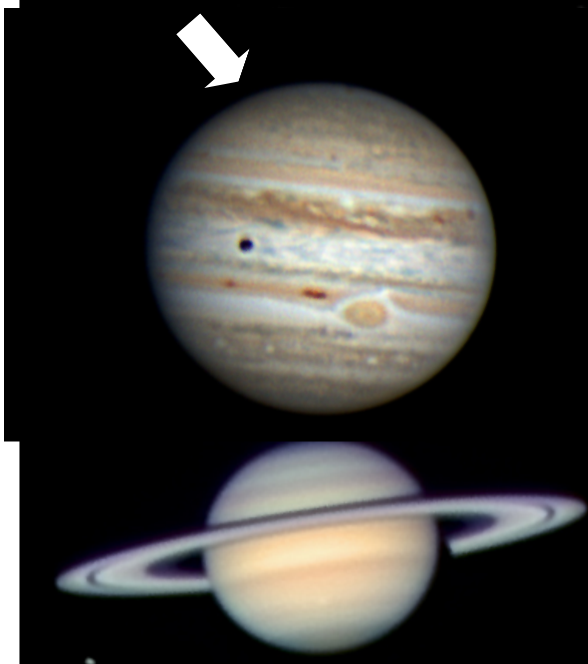
First true exo-Earth detection might come from a NASA mission called Kepler

http://kepler.nasa.gov/

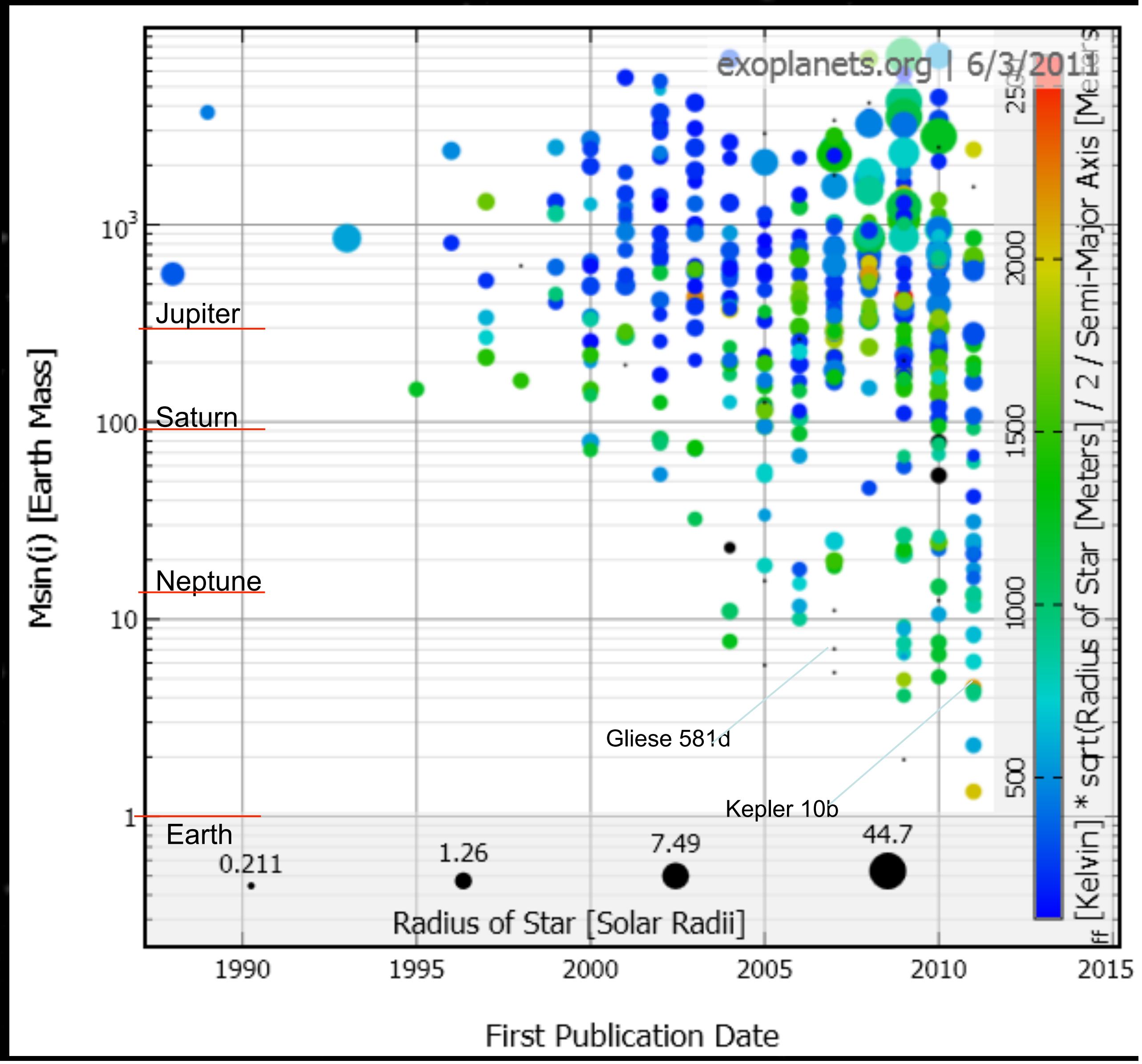


Most planets discovered so far are closer in mass to Jupiter.

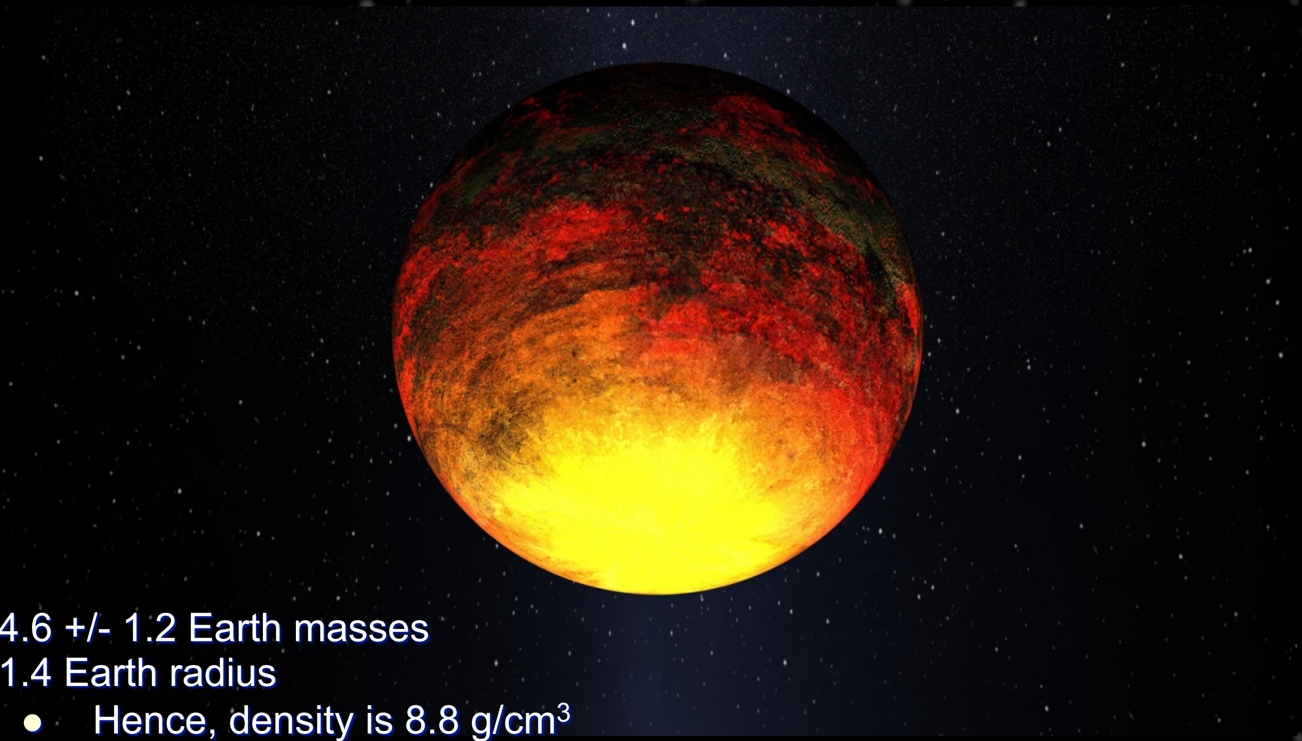
This is (mostly) what we've found



This is what we are looking for



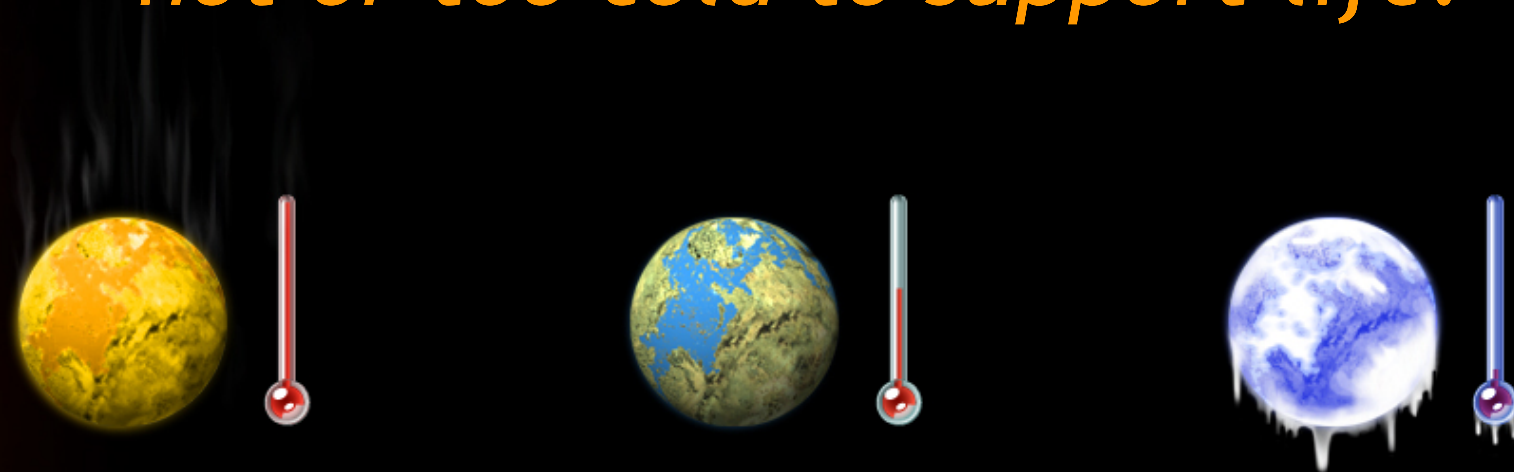
First undeniably rocky planet: Kepler 10b



- 4.6 +/- 1.2 Earth masses
- 1.4 Earth radius
  - Hence, density is 8.8 g/cm^3
- G-type star
- Distance from the star: 0.01684au
- Period: 0.8
- Temperature: 1833K

- Announcement: Batalha et. al, January 10, 2011

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



Most of them have highly elliptical orbits, or are too close to their parent stars.

Gliese 581 d: confirmed potentially habitable planet

- 7-14 Earth masses: Super Earth
- Distance from the star: 0.22au
- Orbital period: 66.8 days
- Receives 30% the intensity of sunlight on Earth (75% of Mars)

- Announced: 21 April 2009
  - Radial velocity
  - Michel Mayor et. al.,
  - Observatory of Geneva
  - HARPS instrument on ESO 3.6m telescope, La Silla, Chille

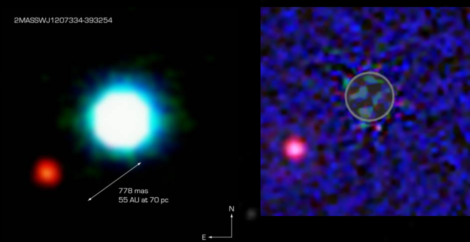
Kepler exoplanet candidates

http://vimeo.com/19642643

(Courtesy of Jer Thorpe, New York Times'
Data Artist in Residence and a visiting
professor at New York University)

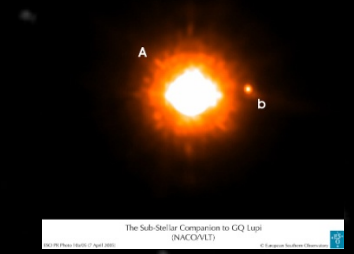
Holy grail of detection methods: direct imaging

2M 1207 (2005)



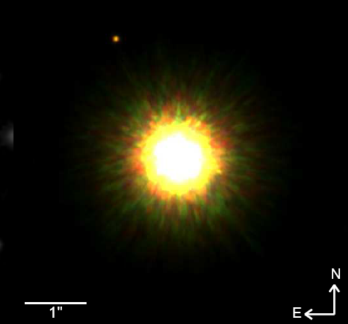
- Left: VLT, IR light with adaptive optics, April 2004. *Gael Chauvin et. al., ESO.*
- Right: Hubble, IR light, January 2005. *NASA / ESA / Glenn H. Schneider, et al*
- Brown dwarf host, 8 million years, 1000C, 5 Jupiter masses, 54a.u., 2,500 year period

GQ Lupi (2005)



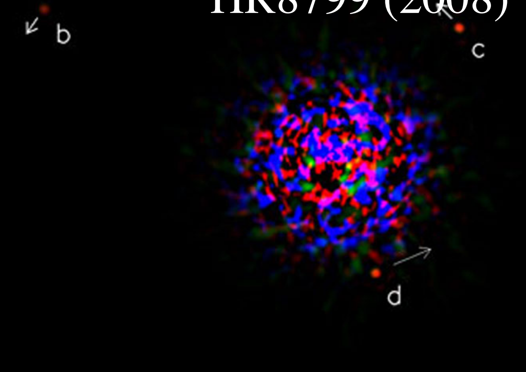
- VLT, NACO adaptive optics infrared camera, March 2005. *Ralph Neuhäuser et. al., ESO.*
- few million years, 50a.u., 1200 year period, 2000K, 1-42 Jupiter masses.

1RXS J160929.1-210524 (2008)



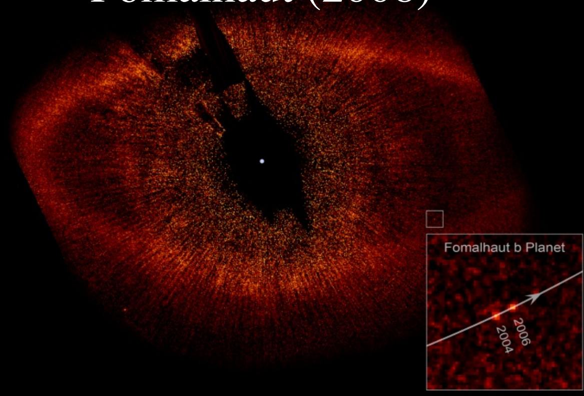
- Gemini North, NIRI + ALTAIR, August 2008. *Lafreniere et. al., U of Toronto.*
- Solar-type host, 8 million years, 330 a.u., 1800K, 7-11 Jupiter masses

HR8799 (2008)



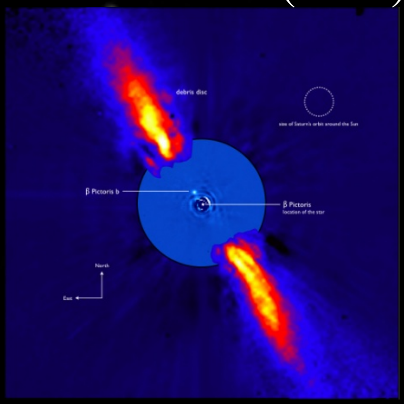
- Keck / Gemini , AO and ADI in infrared, Nov. 2008, *Christian Marois et. al.*
- 60 million years, 24, 38, 68 a.u.; 10, 10, 7 Jupiter masses

Fomalhaut (2008)



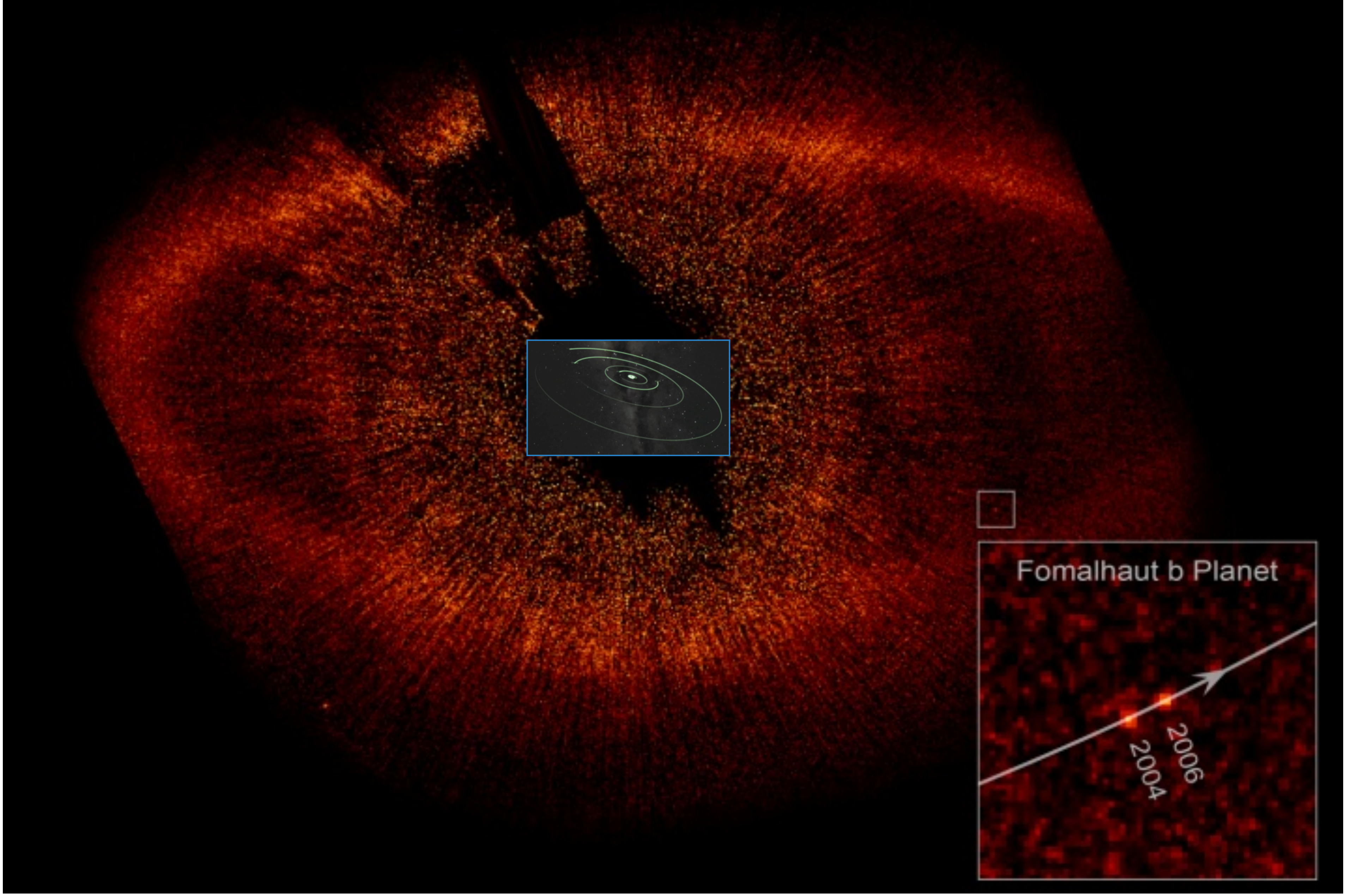
- Hubble, visible light, *Paul Kalas et. al.*, Nov 2008.
- 200 million years, 0.054-3 Jupiter masses, 115 a.u. 1500K

Beta Pictoris (2008)

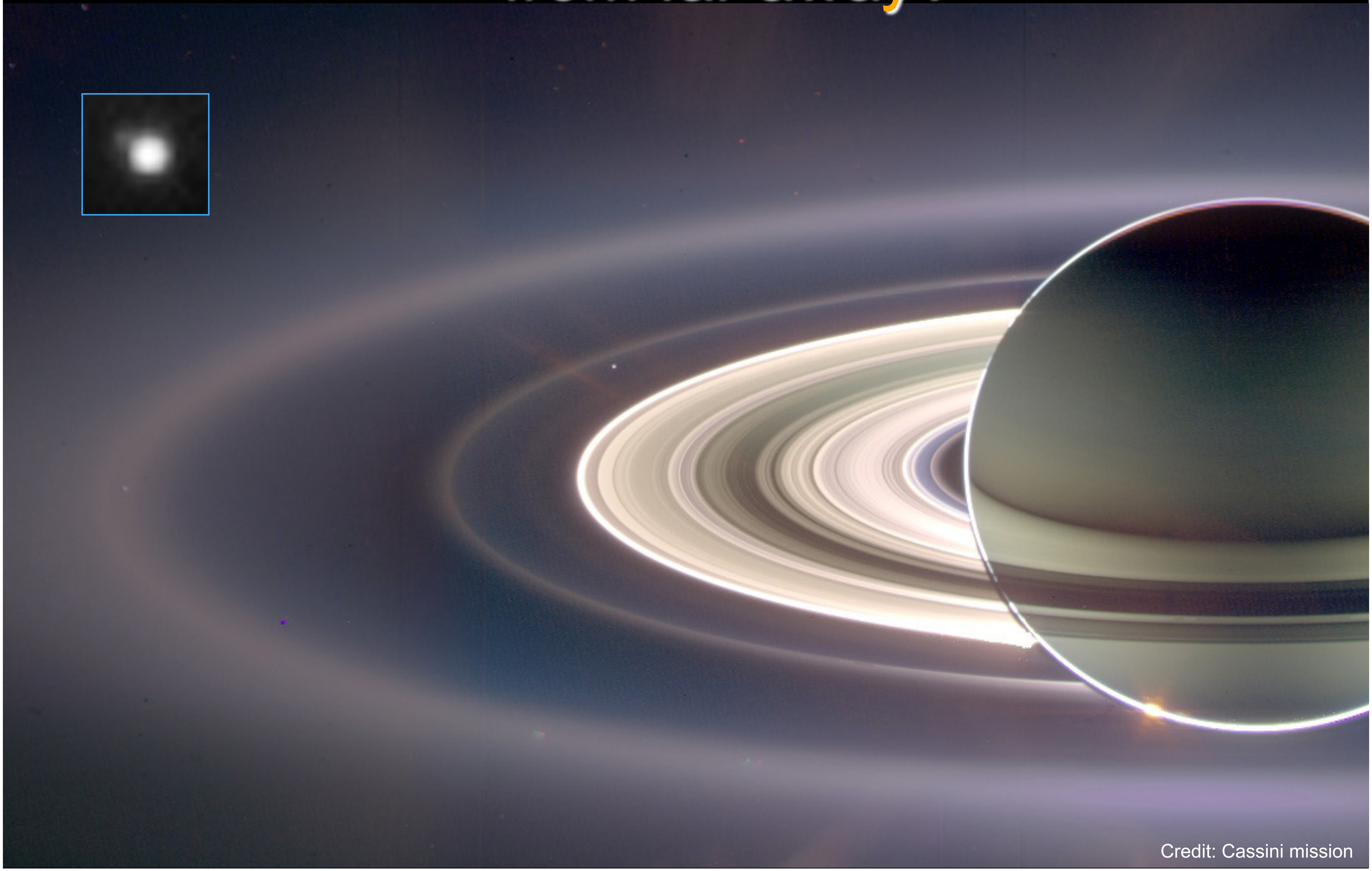


- VLT, *Anne-Marie Lagrange et. al.*, Nov 2008.
- 12 million years, 8 Jupiter masses, 8 a.u. 1500K

Solar system vs. Fomalhaut

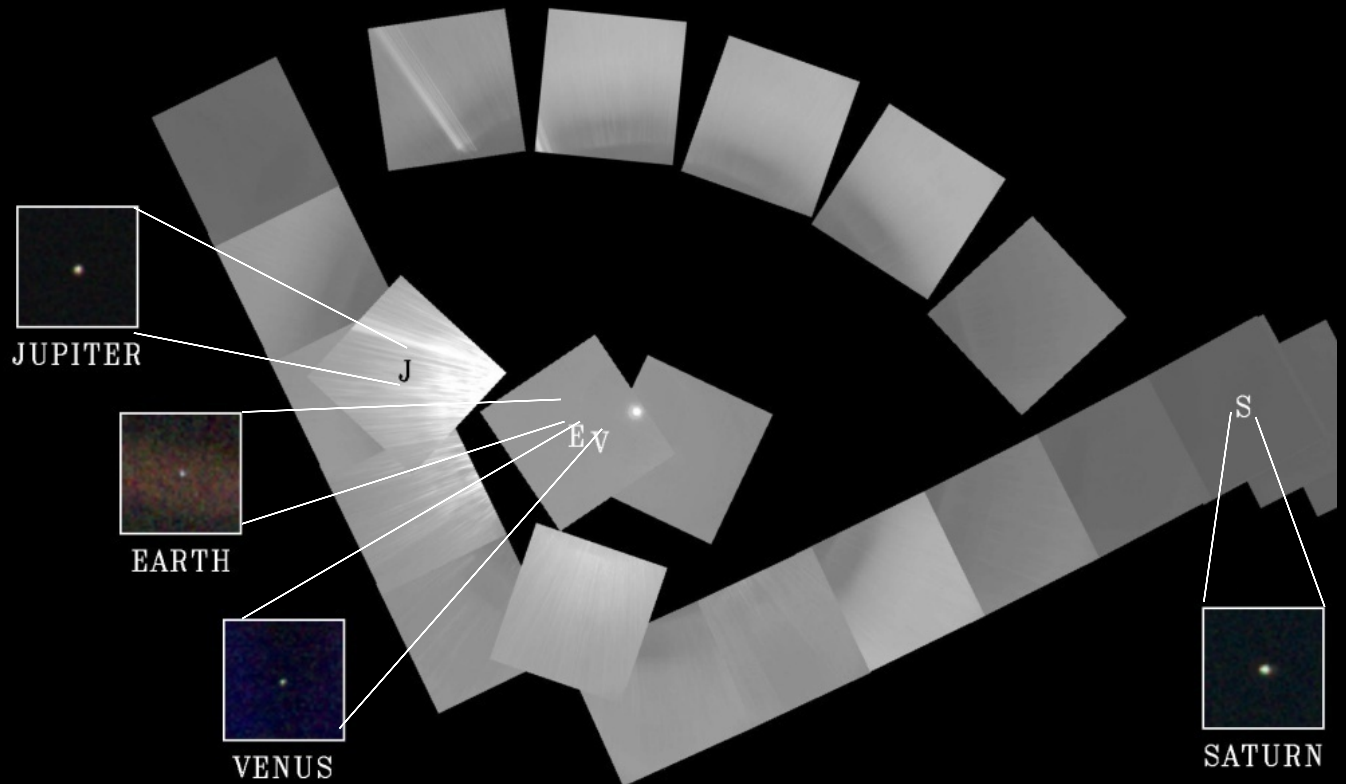


What does the Solar System look like from far away?



Credit: Cassini mission

What does the Solar System look like from far away?



- Feb 14, 1990
- 6 light-hours (4 billion miles away)
- Nearest star (Alpha Cen) is 4.2 light YEARS away (2.5 trillion miles away)
- Earth is ~10^{10} times (25 magnitudes) dimmer than the Sun, and would appear ~ 0.8” away for Alpha Cen

Credit: Voyager mission


Stars are a billion times brighter…


…than the planet
…hidden
in the glare.


Like this firefly.

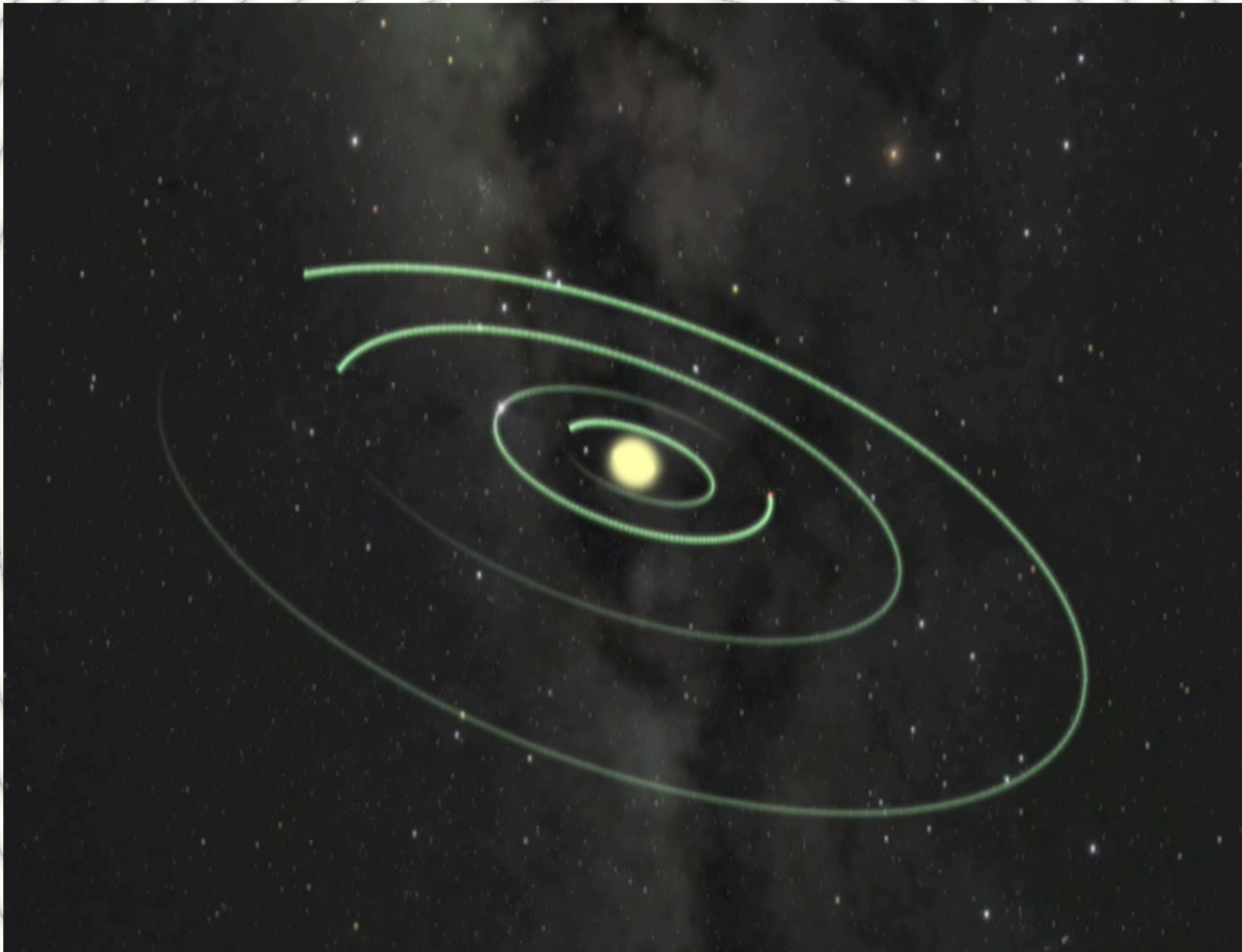

How we may image
another Earth

Main Engineering Challenge

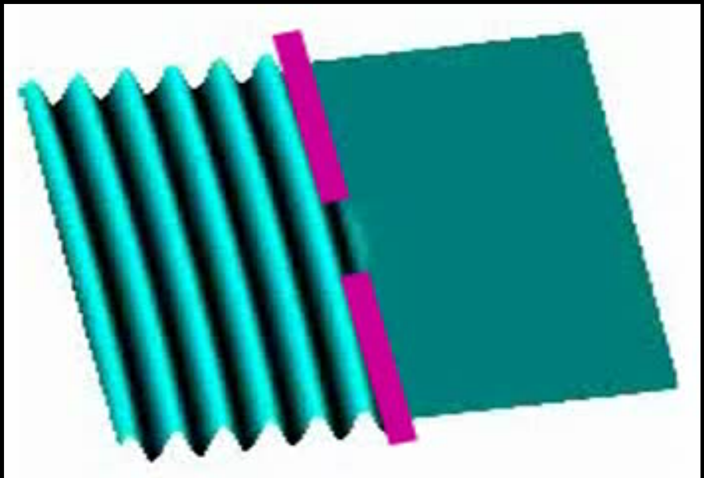
- Contrast : 10^{10}
- Inner working angle: ~100mas
  - (2 λ/D, or diffraction ring widths)

What are the main obstacles?

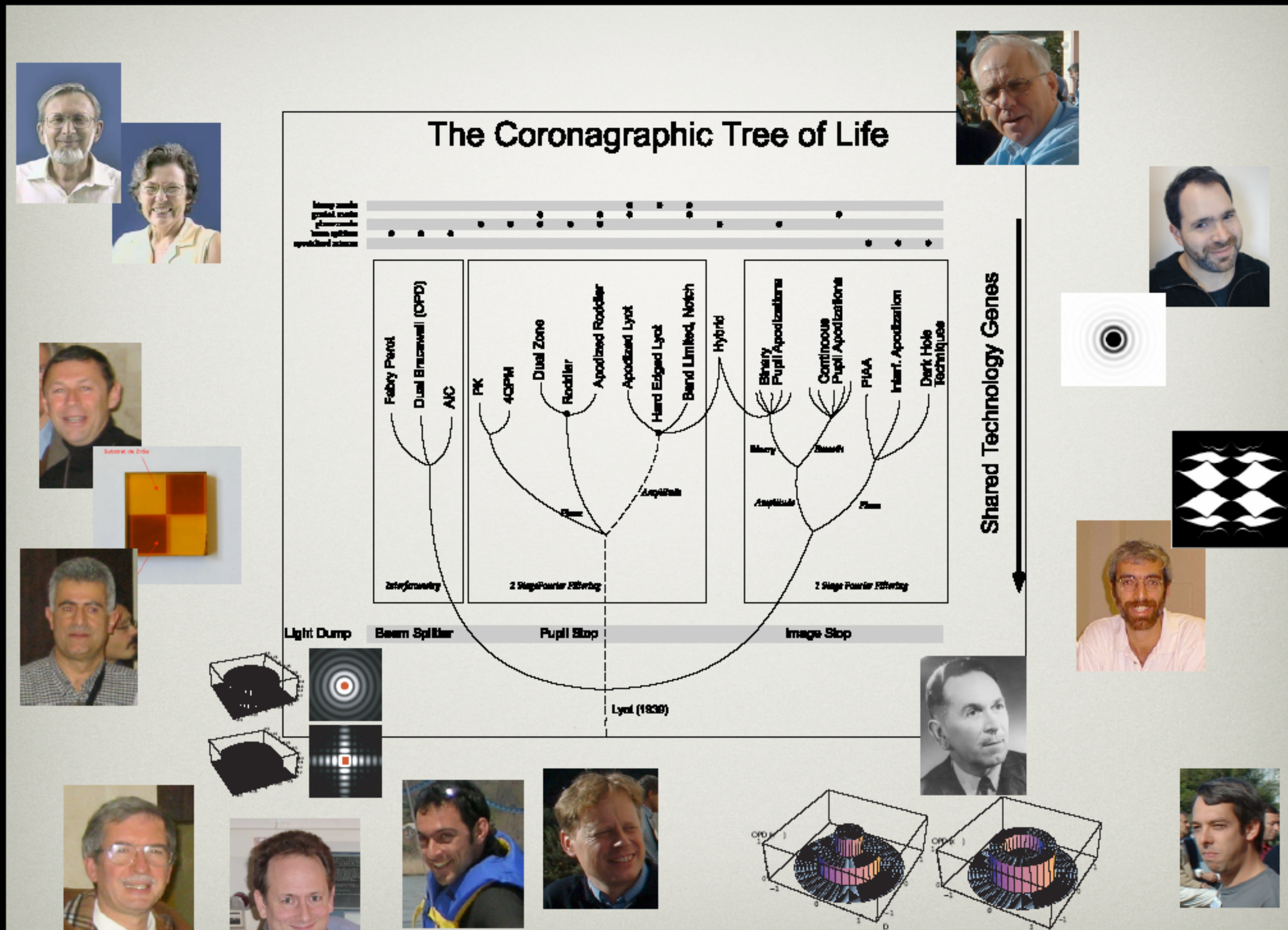
Can the Hubble do it?



All waves generate ripples when disturbed by a hard edge: diffraction

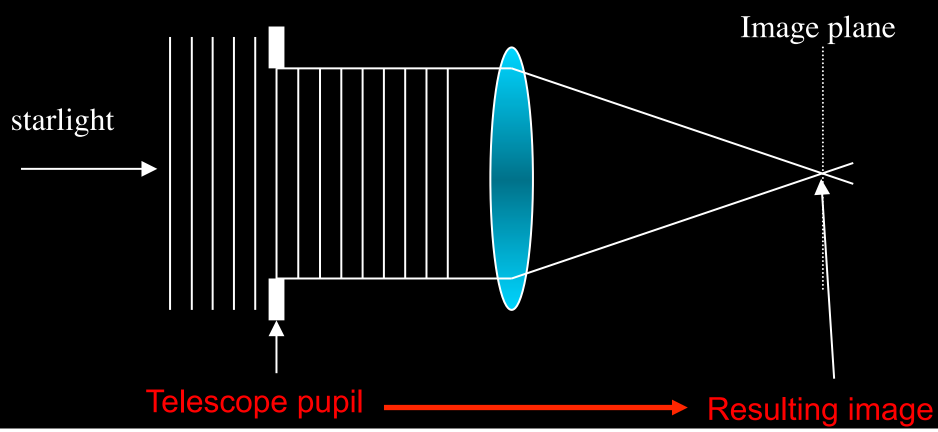


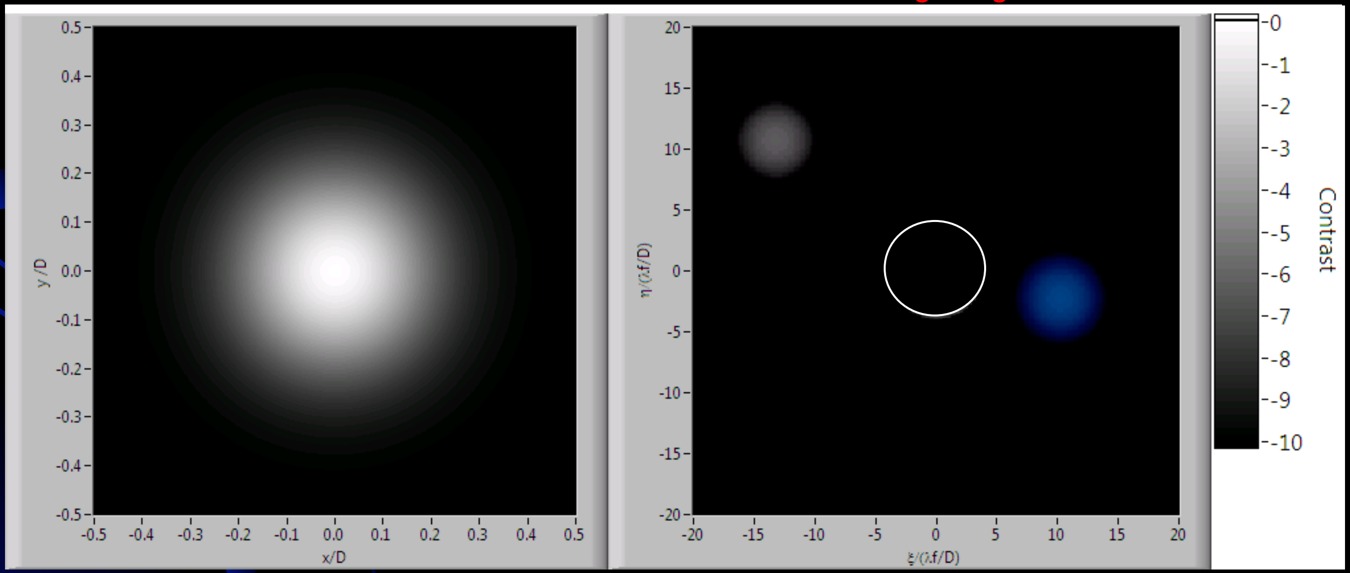
Many different solutions (coronagraphs)



Courtesy of James Lloyd

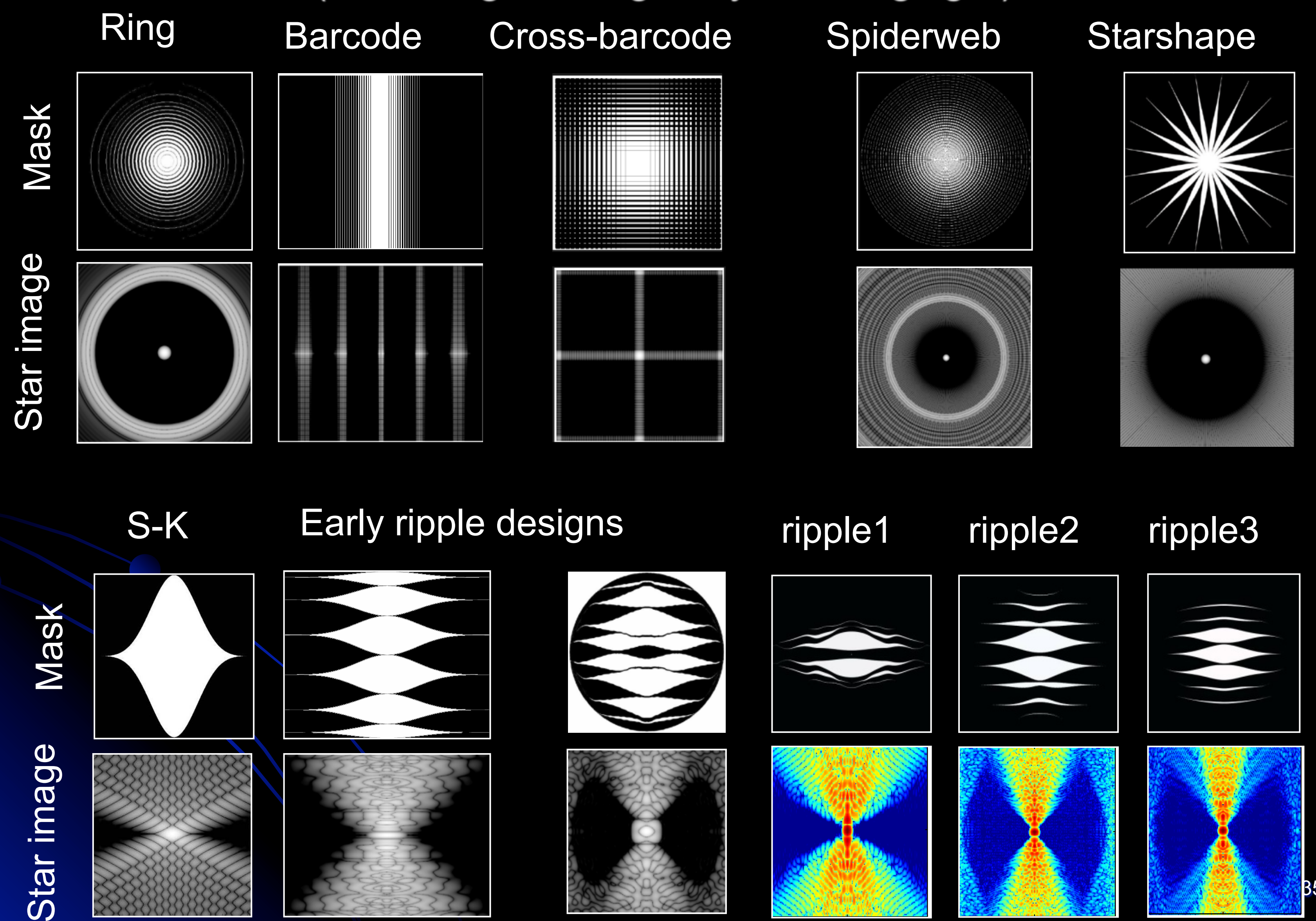
My favorite solution to diffraction: Soften the edges!





Shaped Pupil Zoo

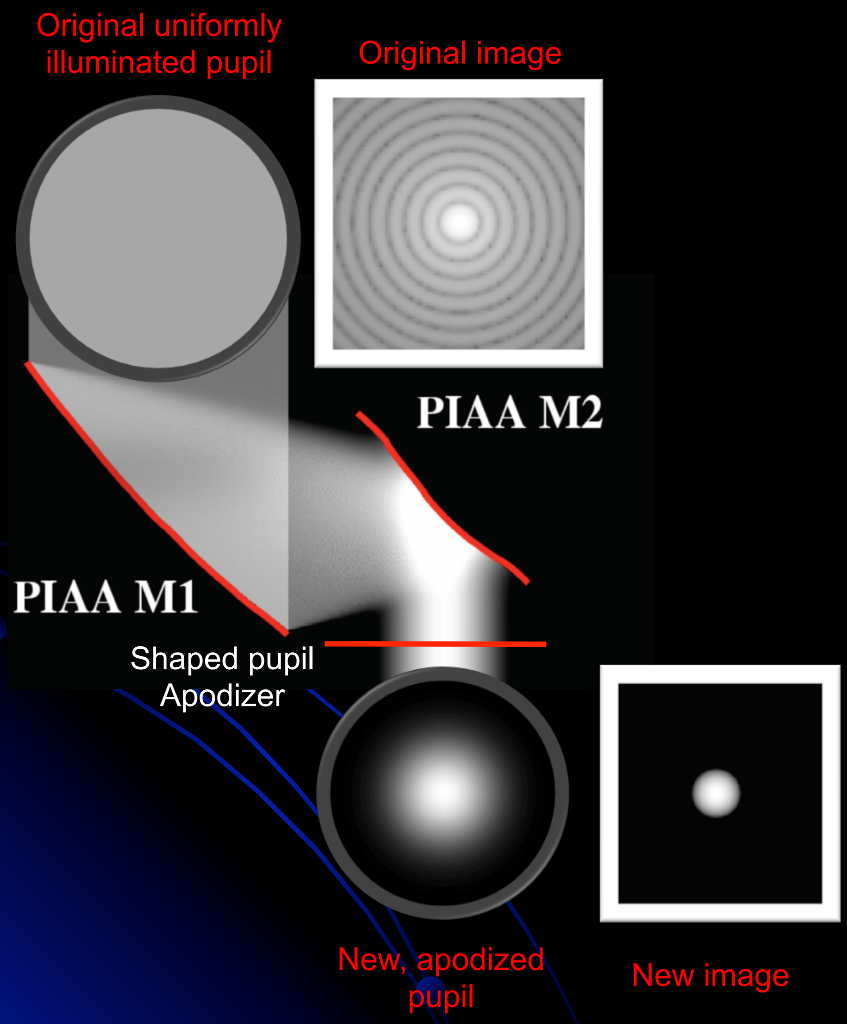
(Softening the edges by blocking light)



Spergel, Kasdin, Vanderbei, Belikov 2003-2007

PIAA: phase-induced amplitude apodization

(Softening the edges by reshaping light)



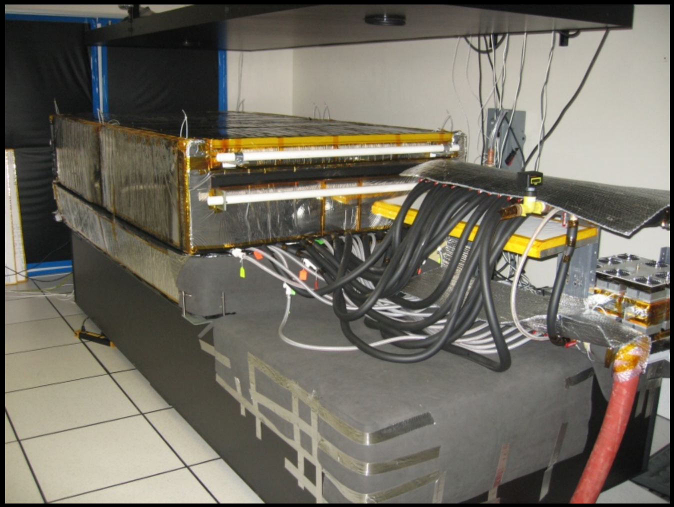
No photons are wasted!
(well, almost)

- PIAA was invented by Olivier Guyon (orignally from France)
- while working at Subaru telescope (Japanese)
- And is being developed by NASA (US agency)

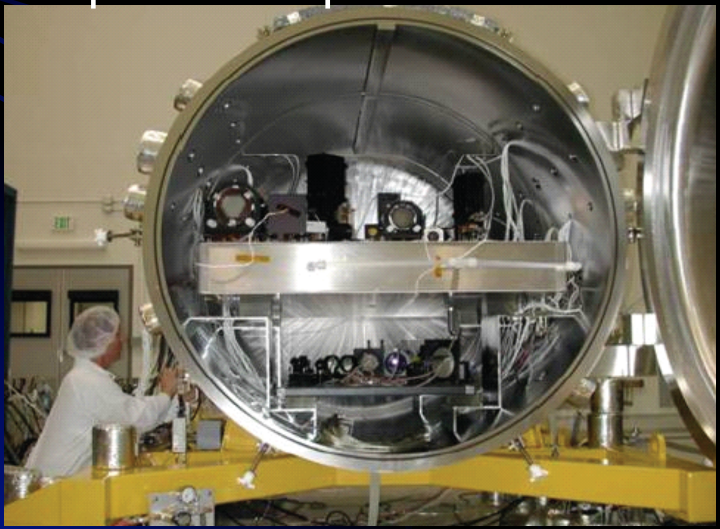
Ruslan Belikov, NASA Ames Coronagraph Laboratory

PIAA Technology Development

Ames Coronagraph Experiment (ACE)

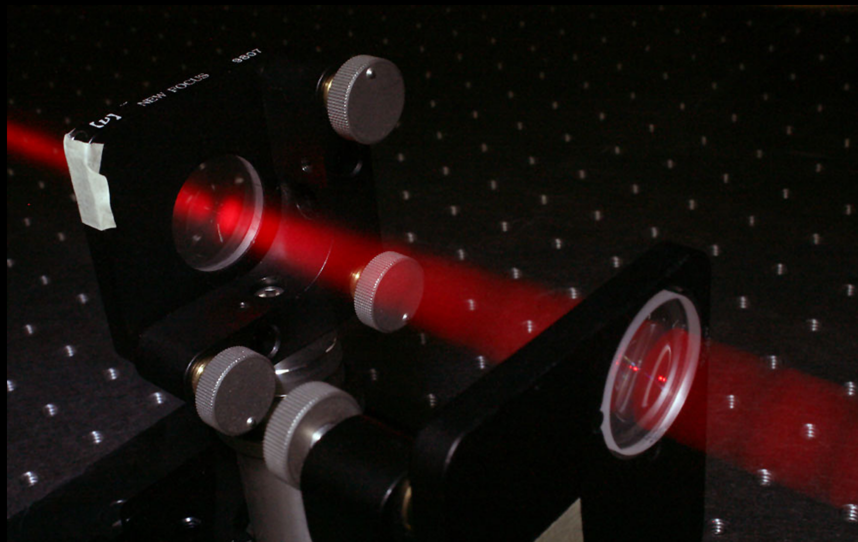


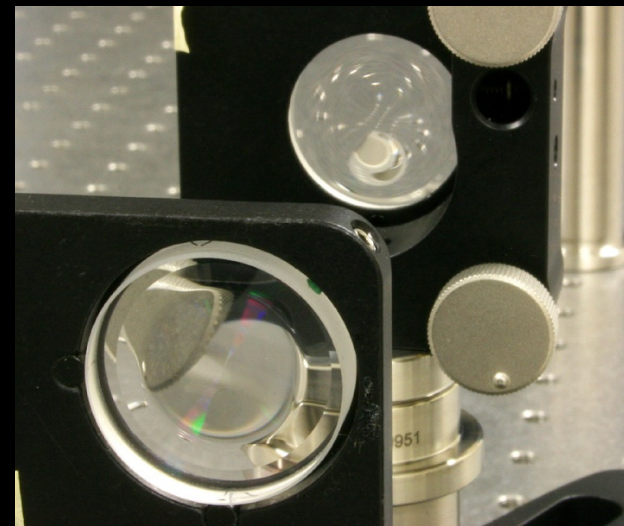
In a partnership with JPL's HCIT



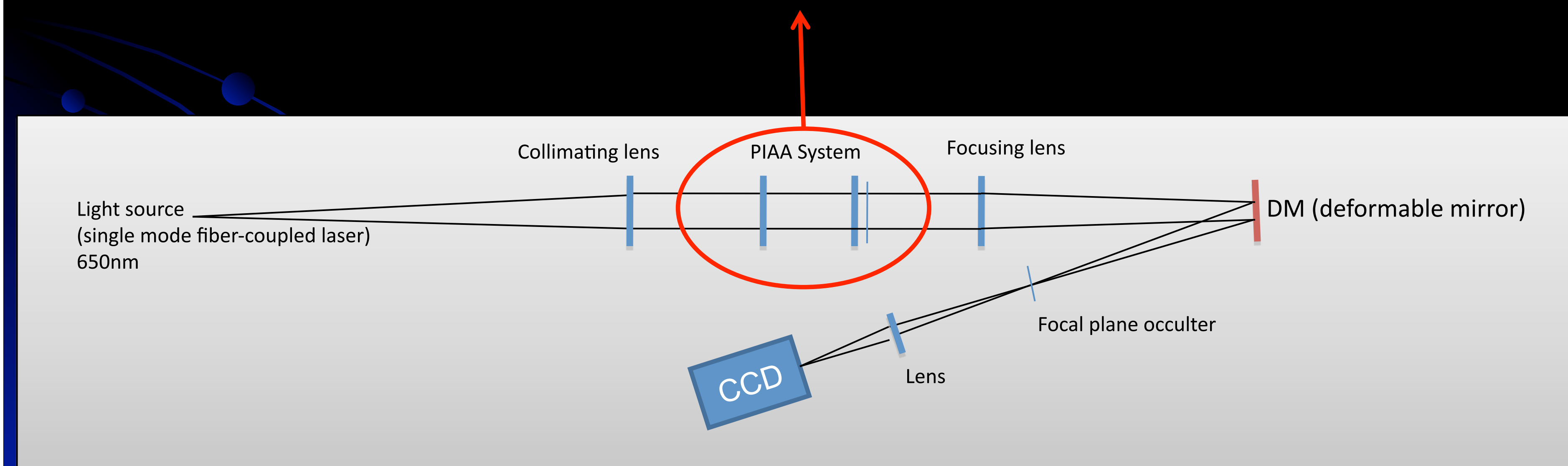
- Ames Coronagraph Testbed
  - Dedicated to testing PIAA and related technologies
  - In temperature-stabilized air
  - Flexible, rapidly reconfigurable
  - Initial validation (TRL 1-4) of PIAA and related technologies
    - MEMS DMs
    - WFC architecture trades
    - Alternative masks/occulters
  - PIAAgen2 mirror manufacture
- JPL/HCIT
  - TRL 4+ validation (including vacuum)
  - testing a variety of coronagraphs

NASA Ames Coronagraph Experiment (ACE)

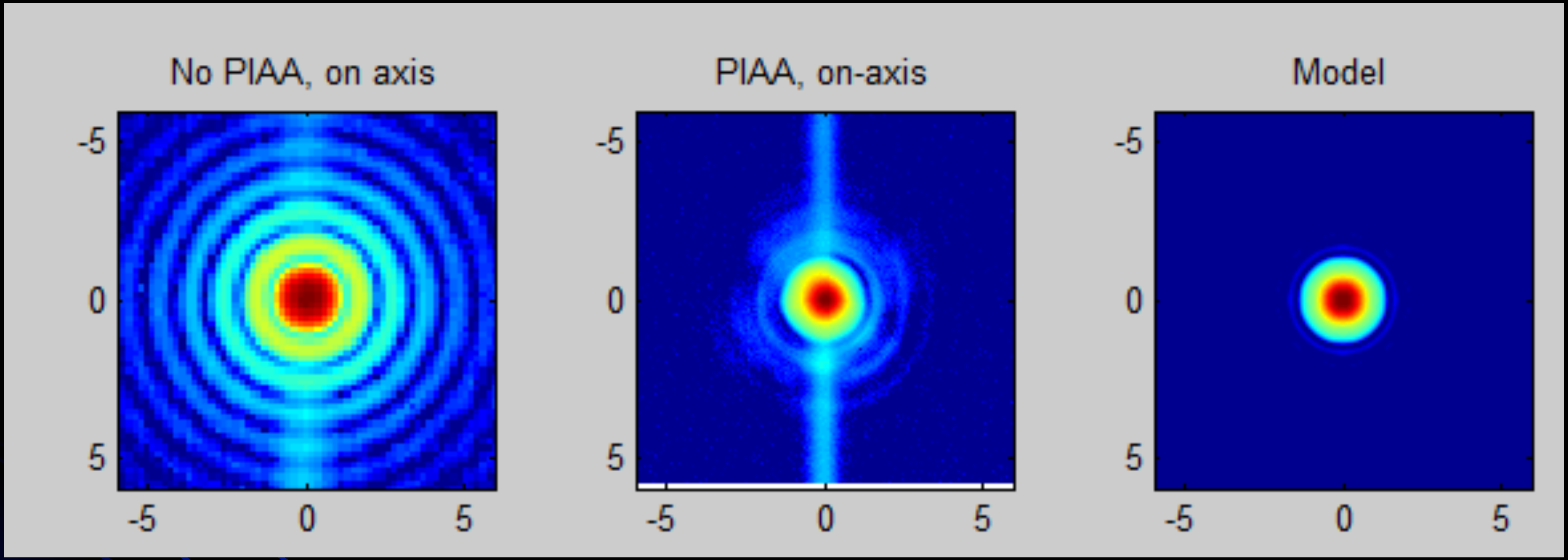




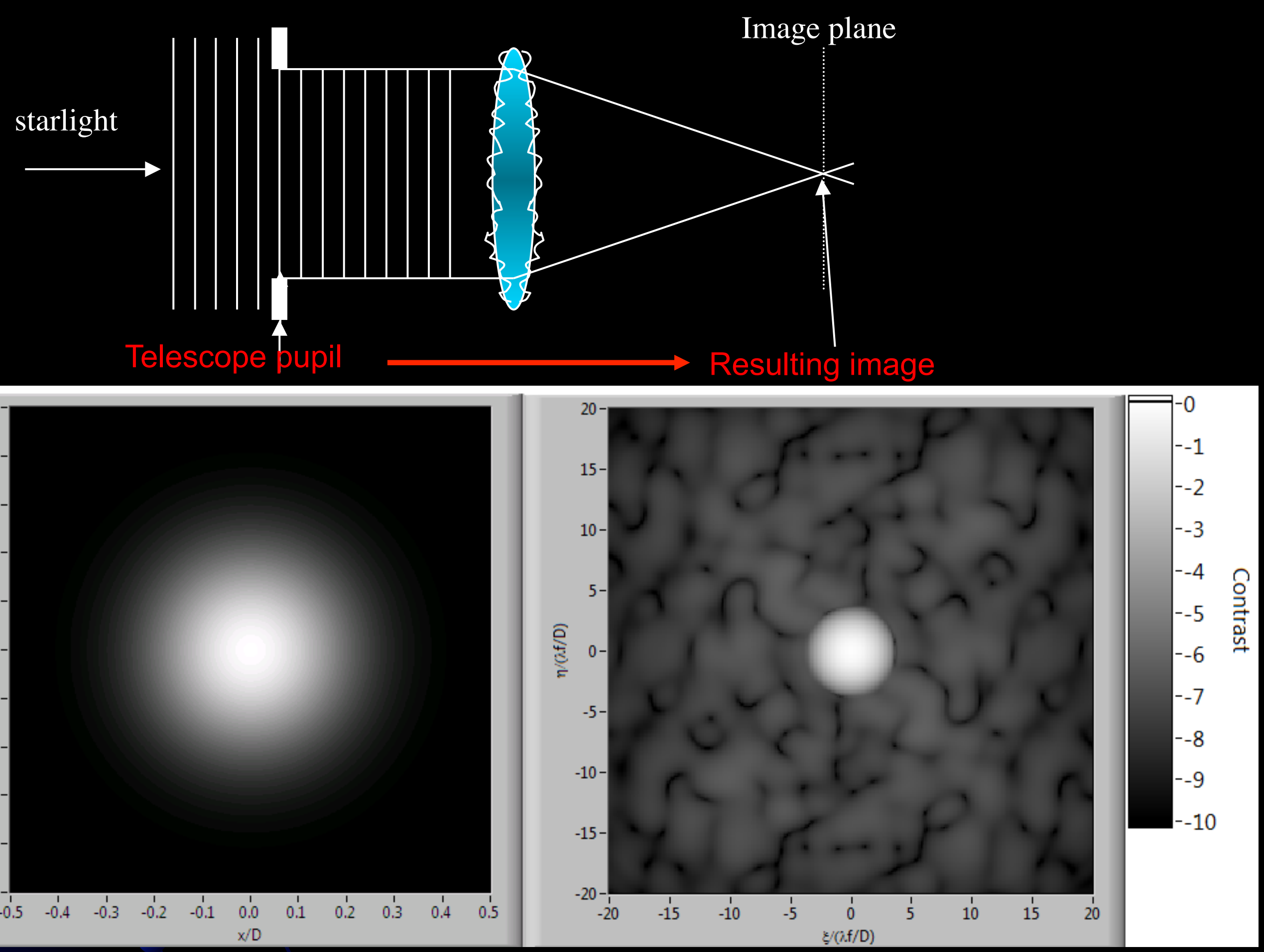
- PIAA optics made by Axsys, diamond-turned CF2, 16mm active diameter



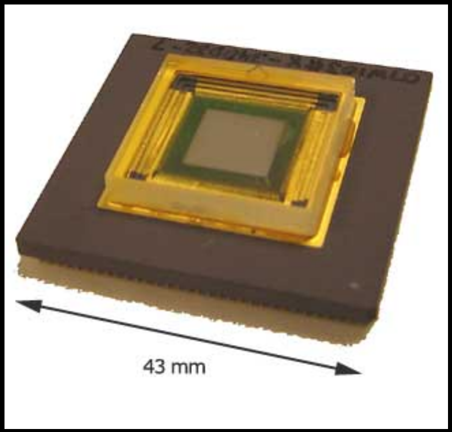
Initial Images from the Lab

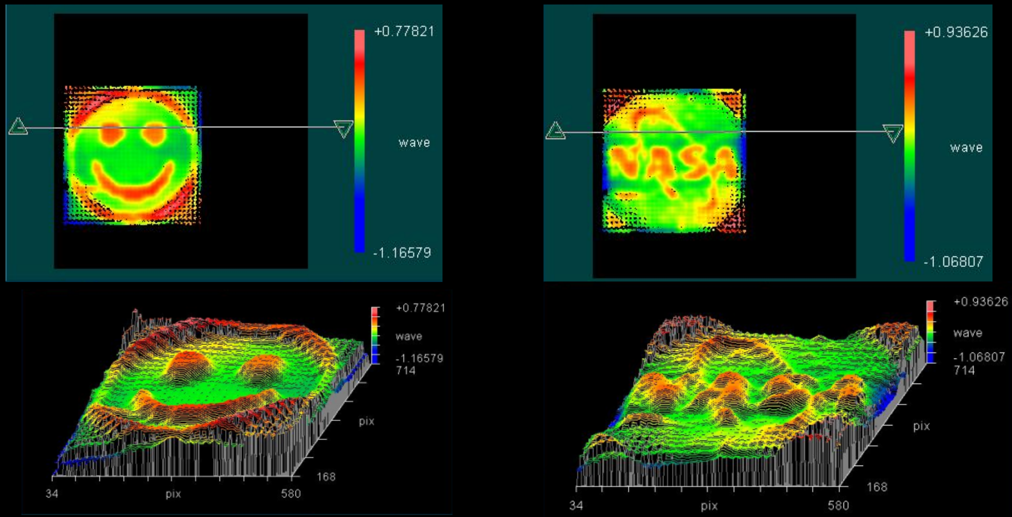


Main practical problem: optical aberrations

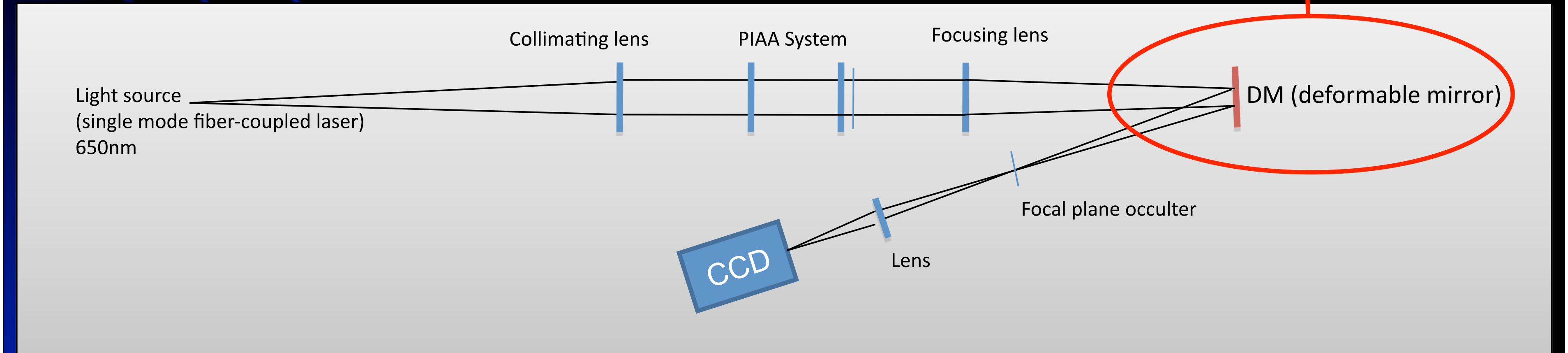


Solution: use a deformable mirror

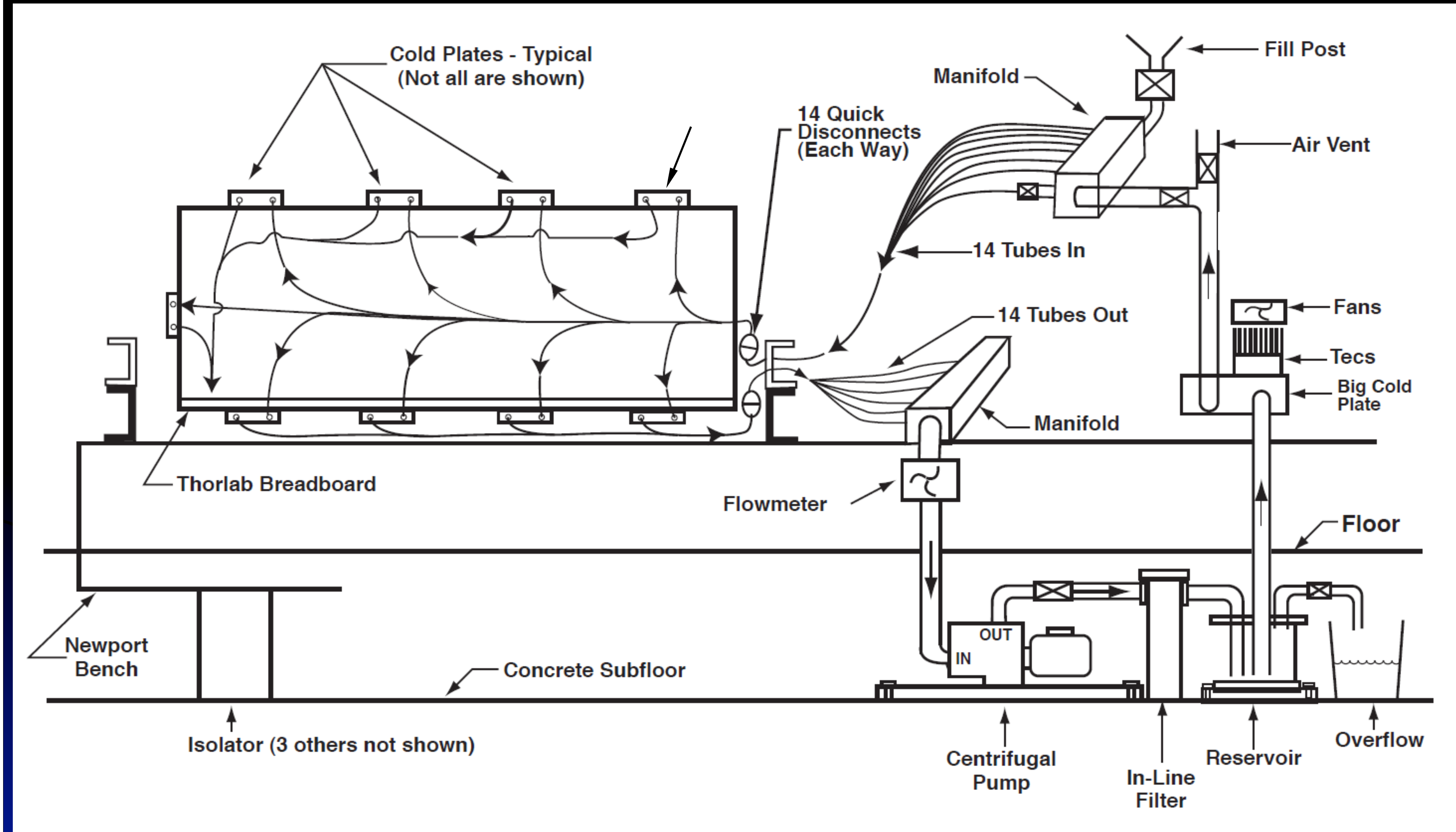




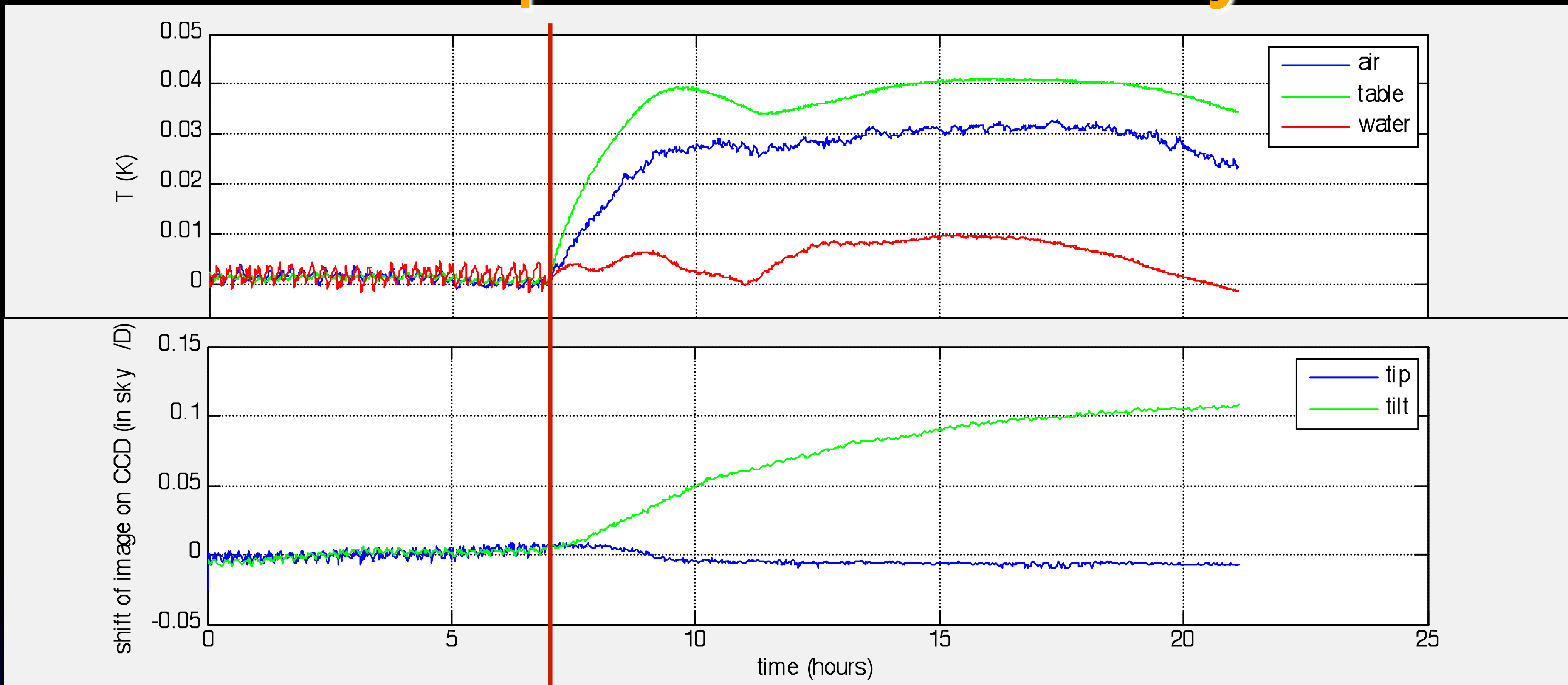
- Made by Boston Micromachines, 32x32 actuators, 10mm active area



Active thermal control system



Temperature Stability



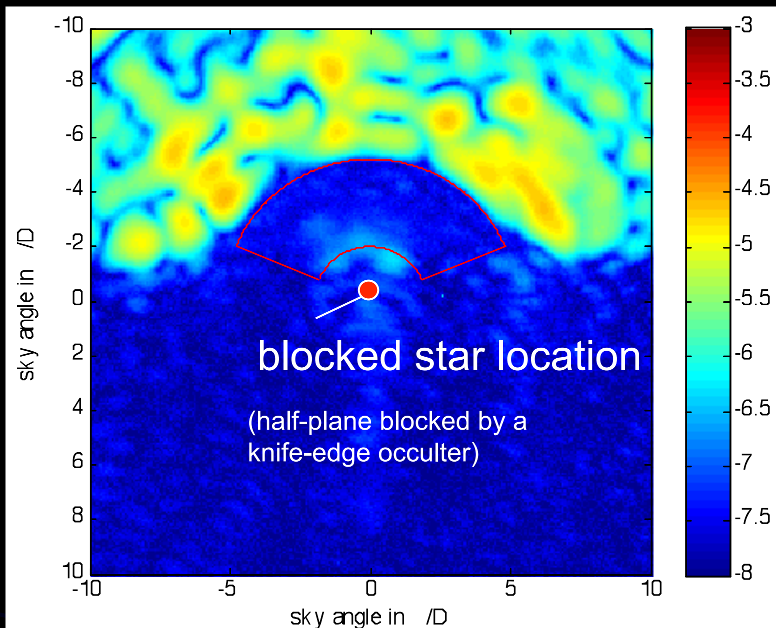
Active thermal control ON ⟵ ⟶ Active thermal control OFF

- Outside the enclosure, temperature varies by ~ 0.5K.
- Inside the enclosure (active thermal control OFF), temperatures vary by ~ 50mK, causing tip/tilt errors of about 0.1 λ/D
- With ATC ON, can sustain the following root mean square values:
  - Air T: 0.9mK
  - Table: 0.4mK
  - Water: 1.3mK
  - Tip/tilt: 4.8e-3 λ/D (limited by insufficient tuning of the ATC algorithm)
  - According to simulations, such tip/tilt will limit contrast to ~1e-9 at 2 λ/D

Ruslan Belikov,
NASA Ames Coronagraph Laboratory

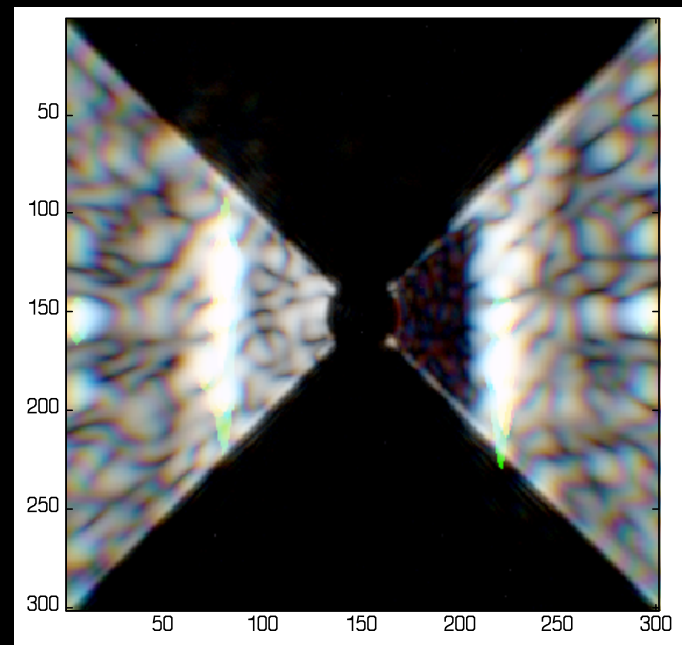
Lab results

Ames (PIAA Coronagraph, 2010)



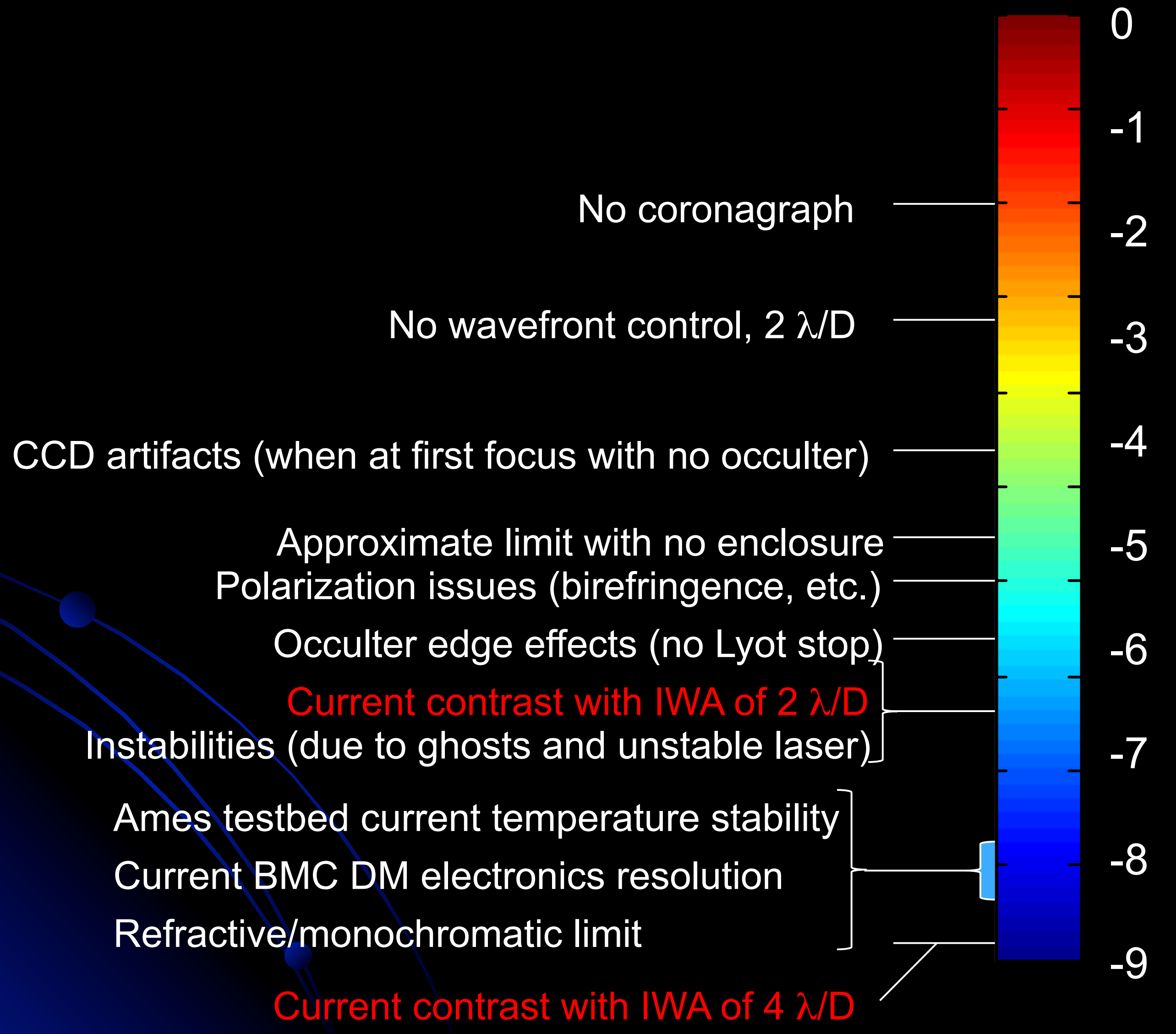
Contrast: 5.4 x 10^{-8}
IWA: 2 λ/D
Bandwidth: 650nm monochromatic

JPL's HCIT (shaped pupils, 2007)



Contrast: 2.4 x 10^{-9}
IWA: 4 λ/D
Bandwidth: 10% @ 800nm

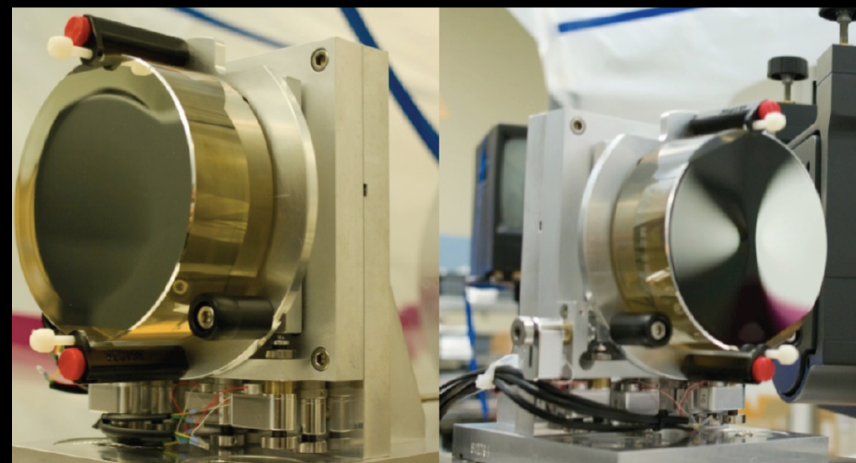
Contrast map



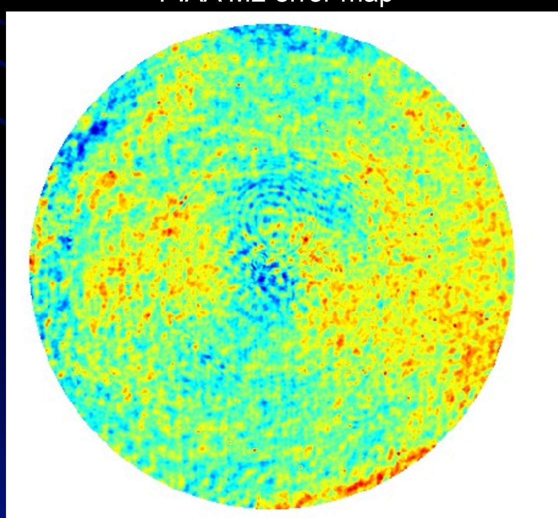
New NIBF system developed at Tinsley for PIAA mirror manufacturing

The L3-Tinsley NIBF (Narror Ion Beam Figuring) system

PIAA Mirrors



PIAA M2 error map



- Mirrors are critical for broadband operation
- Will be tested at JPL and Ames
- PIAA M2 has been completed, with rms surface figure of 3.8nm (out to 90 cycles per aperture)
- PIAA M1 currently being processed
- Simulations show that with a 2DM wavefront control system, this surface figure will enable (in absence of other limiting factors) ~ 4e-10 contrast at 2 λ/D in a 760-840nm band.

ACE team members and collaborators

NASA Ames Research Center

Tom Greene	ARC testbed director
Peter Zell	ARC testbed manager
Rus Belikov	technical lead
Eugene Pluzhnik	experiments
Fred Witteborn	thermal enclosure
Dana Lynch	optical design

UofA/Subaru

(PIAA design and consulting)

Olivier Guyon

UCSC

(DM characterization)

Donald Gavel

Daren Dillon

NASA Jet Propulsion Lab

John Trauger

Andy Kuhnert

Brian Kern

Marie Levine

Wesley Traub

Stuart Shaklan

Amir Give'on

Laurent Pueyo

Tinsley Laboratories

(PIAA mirror manufacture)

Daniel Jay

Asfaw Bekele

Lee Dettmann

Bridget Peters

Titus Roff

Clay Sylvester

Lockheed Martin

(Optical design)

Rick Kendrick

Rob Sigler

Alice Palmer

Future

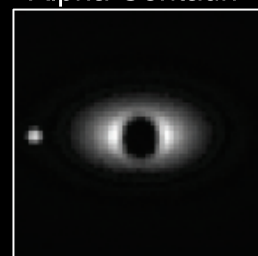
A Sampling of Possible Missions

(using PIAA)

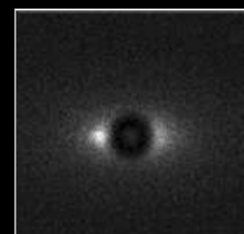
PECO mission concept
(Guyon et. al..)

Simulated exoEarth images in
the 500-600nm band
(with 1 zodi and exozodi)

Alpha Centauri

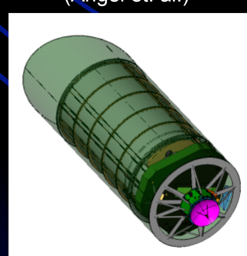


Tau Ceti

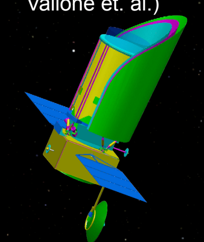


Courtesy of K. Cahoy

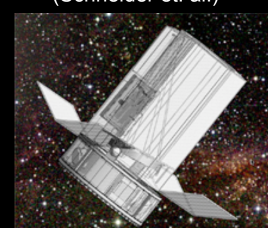
WFCT (4m)
(Angel et. al.)



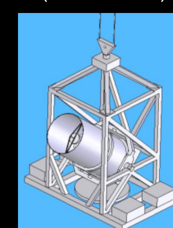
ACCESS (1.5m)
(Trauger et. al.,
Vallone et. al.)



EXCEDE (0.7m)
(Schneider et. al.)



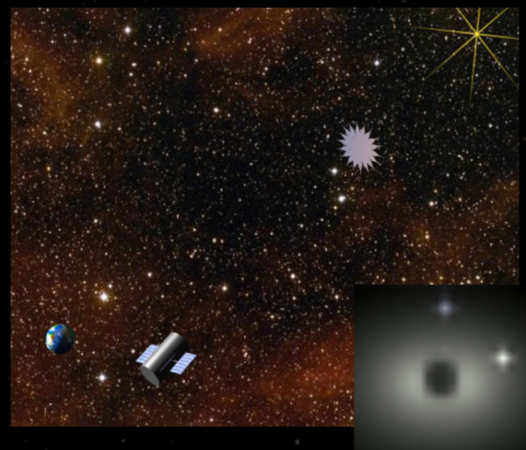
Planetscope (0.5m)
(Traub et. al.)



A Sampling of Possible Missions

(other techniques)

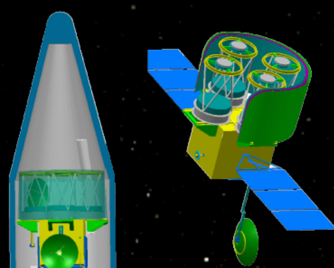
NWO



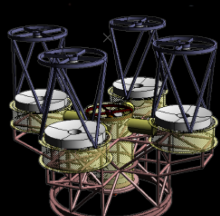
The New Worlds Observer features a distant external occulter between a telescope and a nearby star. The occulter removes the direct light from the star, revealing the planetary system free from stellar glare.

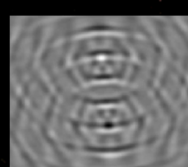
DAVINCI

DAVINCI has the potential to detect many exoplanets, including exo-Earths, using four 1.1-meter telescopes arrayed on a 4-meter baseline.



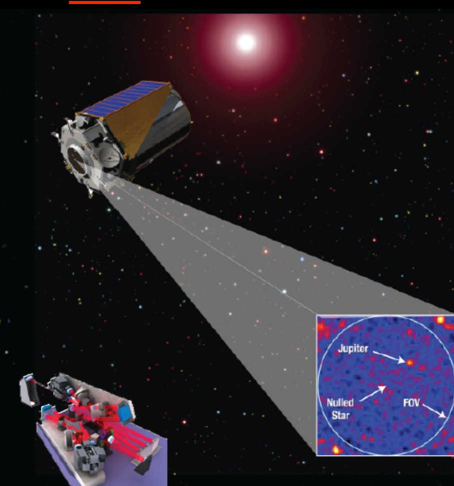
DAVINCI stowed in its 5-meter launch fairing (left) and deployed in space (right).





EPIC

The Extrasolar Planetary Imaging Coronagraph (EPIC) is a medium-class mission to study exoplanets. The mission science goals are to detect and characterize gas giant planets, and to study exoplanetary system architectures. A system-level demonstration of 10^9 contrast white light nulling is currently underway at Goddard Space Flight Center.



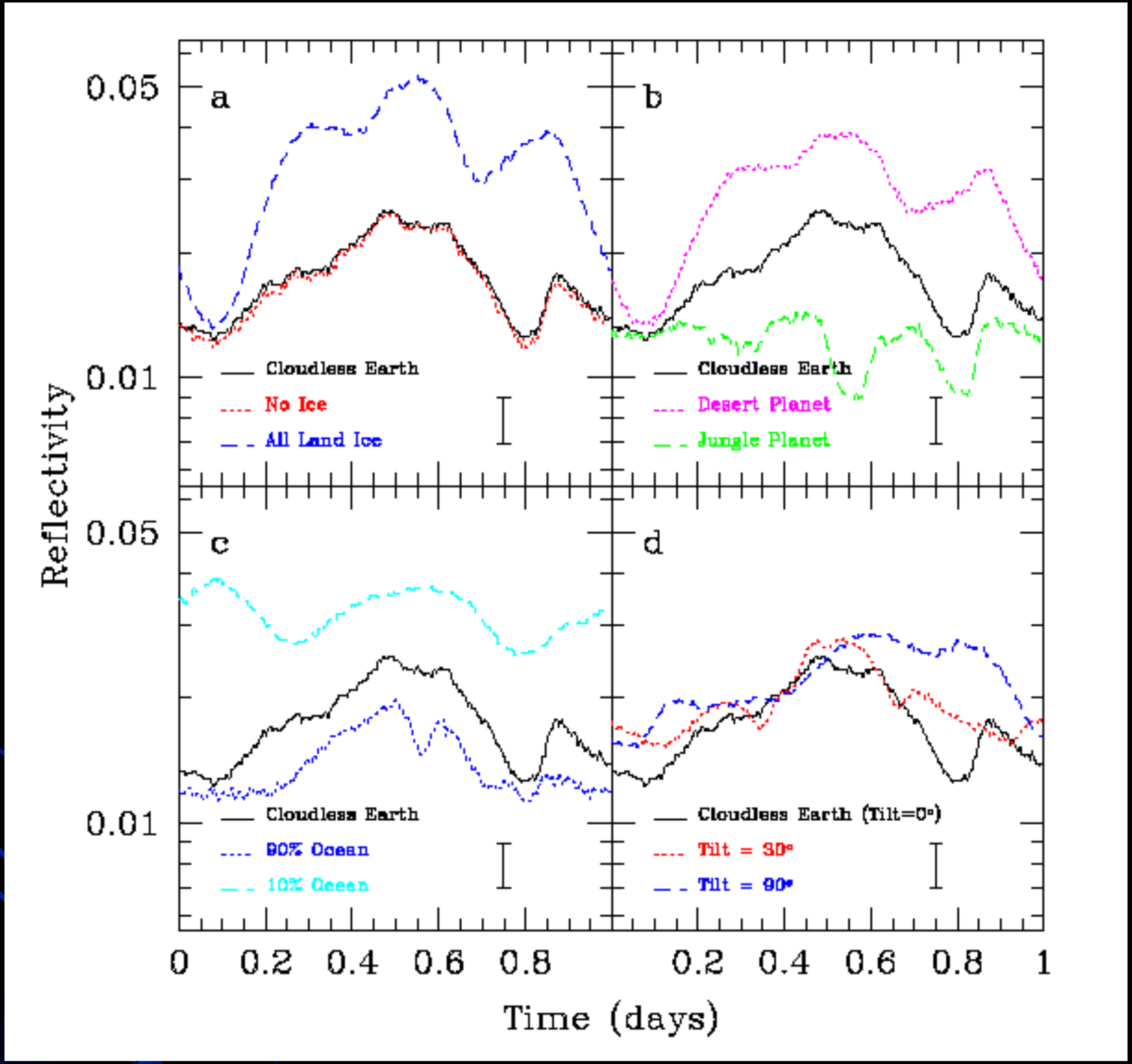
EPIC's Visible Nulling Coronagraph (VNC) optical bench

Once we have an image of an exo-Earth what can we do with it?

Simulation of a PECO image of an exo-Earth around Alpha Centauri

Photometry

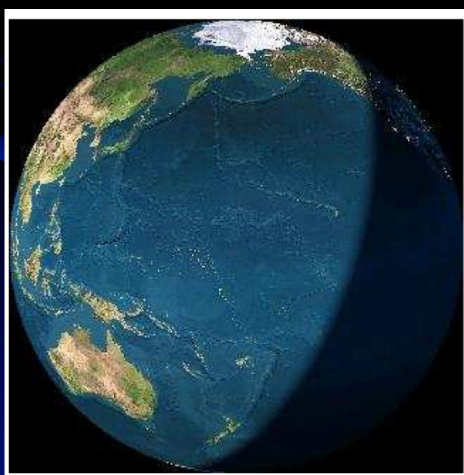
(can determine length of day, surface type, weather)

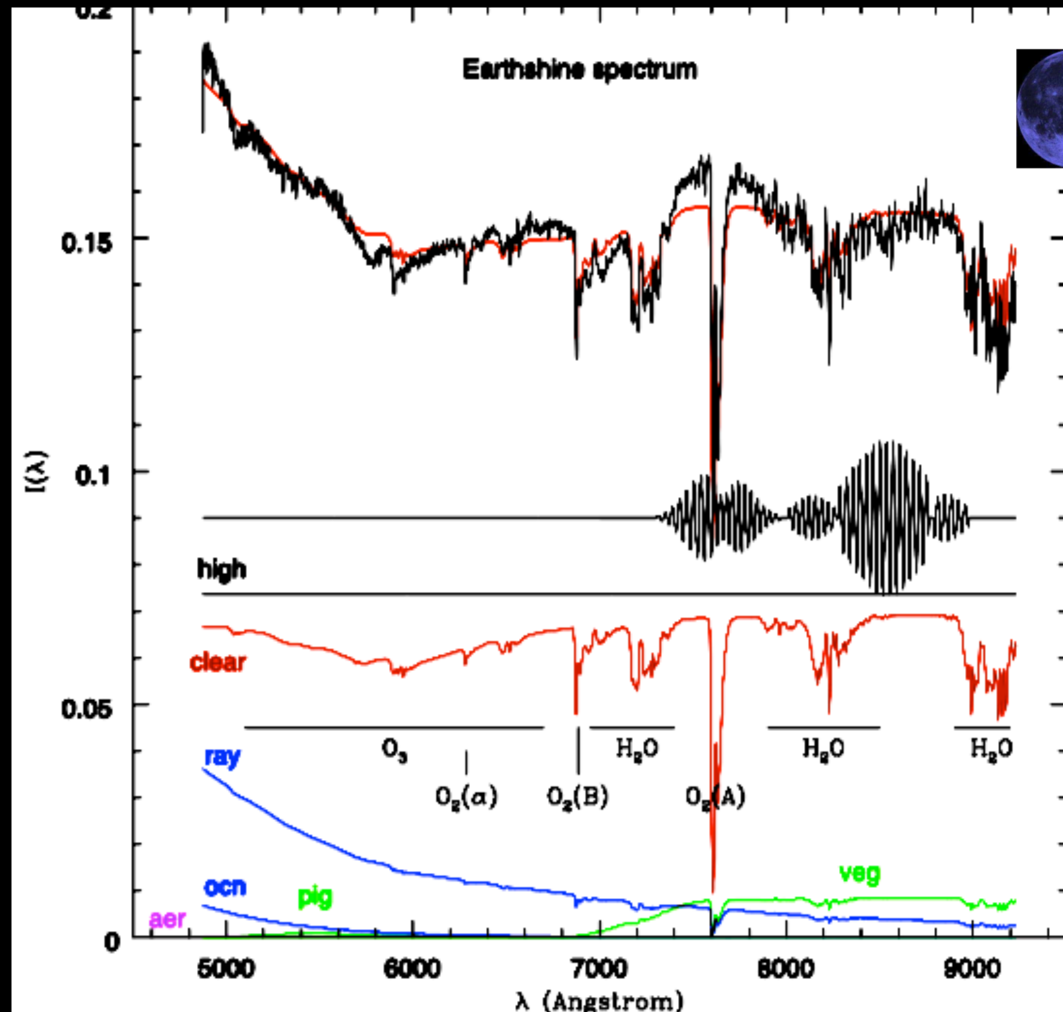


E. B. Ford, S. Seager & E. L. Turner, Nature, 2001

Spectroscopy (composition)

Water
Oxygen
Atmospheric Pressure
(Rayleigh Scattering)
Plant Life: Red Edge!

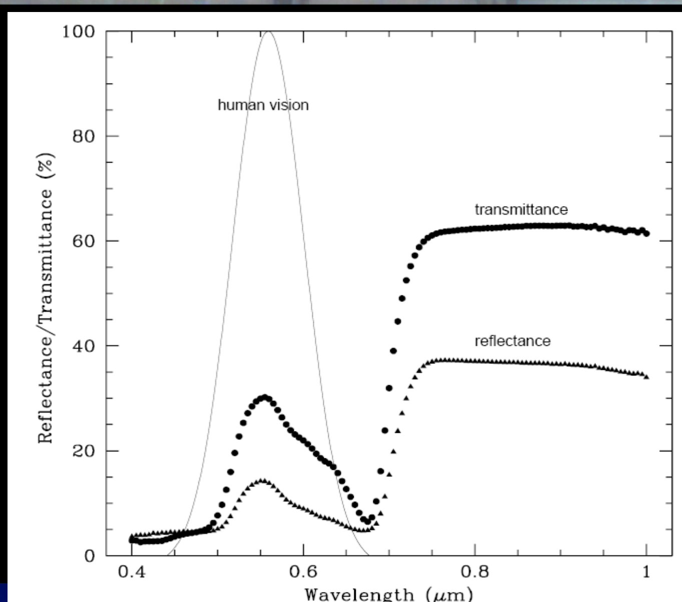




visible light infrared light

Ref.: Woolf, Smith, Traub, & Jucks, ApJ 2002

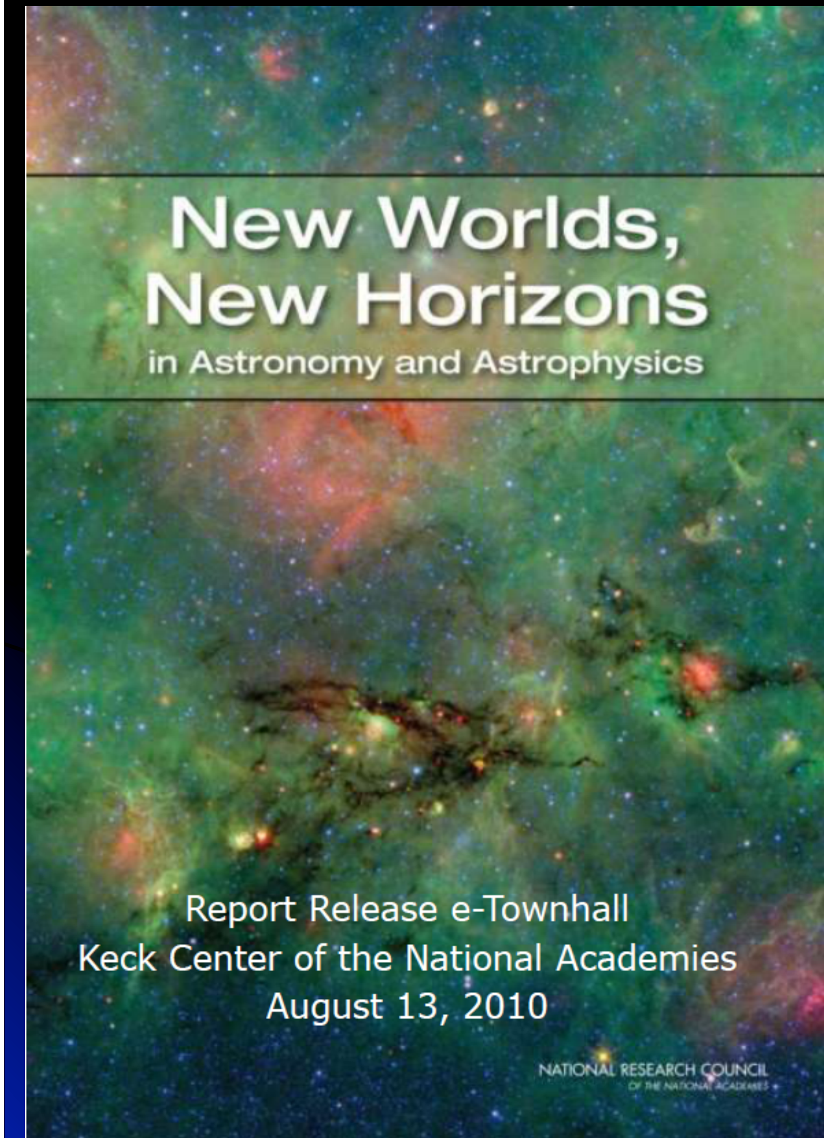
Red Edge



Seager et al. 2005; Data from Middleton & Sullivan 2000

By Sydney Harris

The 2010 Astrophysics Decadal survey (Astro2010)



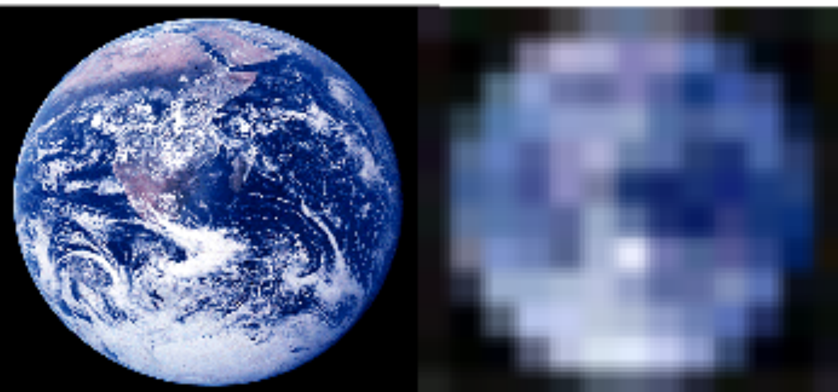
- Negotiated by NRC with Agencies (NASA, NSF, DOE)
- – The Committee on Astro2010 will survey the field of space- and ground- based astronomy and astrophysics, recommending priorities for the most important scientific and technical activities of the decade 2010-2020. The principal goals of the study will be to carry out an assessment of activities in astronomy and astrophysics, including both new and previously identified concepts, and to prepare a concise report that will be addressed to the agencies supporting the field, the Congressional committees with jurisdiction over those agencies, the scientific community, and the public.

- RECOMMENDED PROGRAM:

- Large-scale (prioritized)
  1. Wide Field InfraRed Survey Telescope (WFIRST)
  2. Explorer Program augmentation
  3. Laser Interferometer Space Antenna (LISA)
  4. International X-ray Observatory (IXO)
- Mid-scale (prioritized)
  1. New Worlds Technology Development Program
  2. Inflation Technology Development Program
- Small-scale

Mission to resolve features on planets: 2050?

Simulated *Planet Imager* View of the Earth



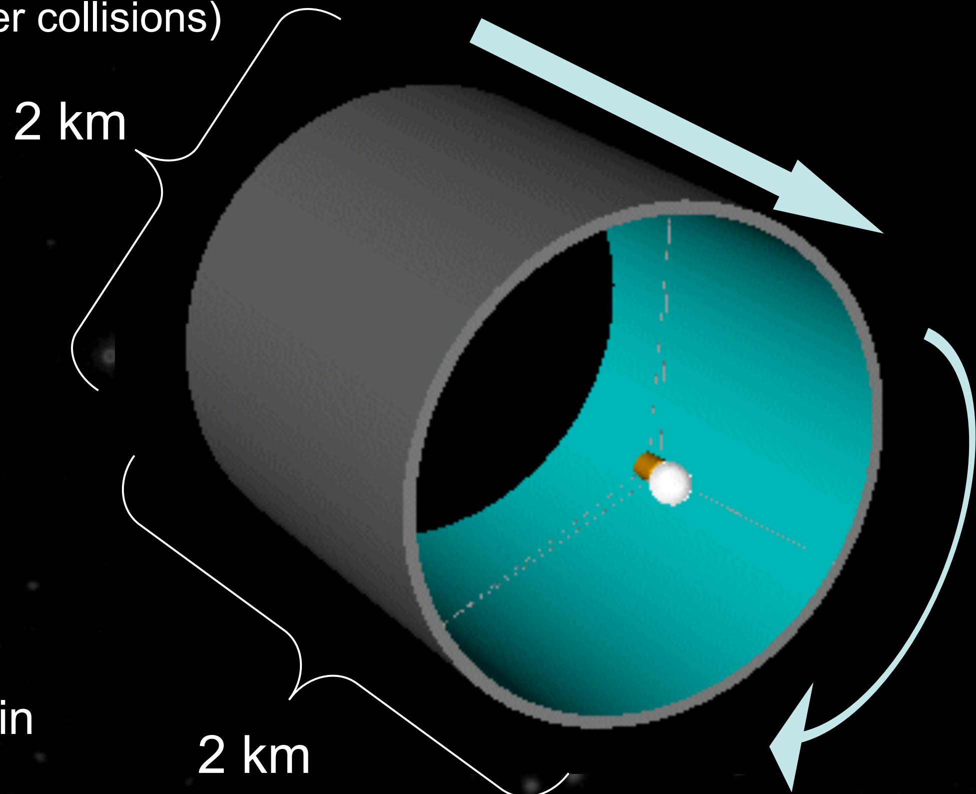
Probe to Alpha Centauri:
"before this century is out" – Geoff Marcy

How will we go to an exo-Earth?

1 Million travelers, 100 Million ton mass, ~ $ 20 Trillion, Launch 2500 A.D.

600 km/s cruising speed
(lower power, softer collisions)

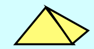
On-board observatories



One-way voyage: 10,000 years to ε Eridani

1 rpm yields 1 g of inward acceleration

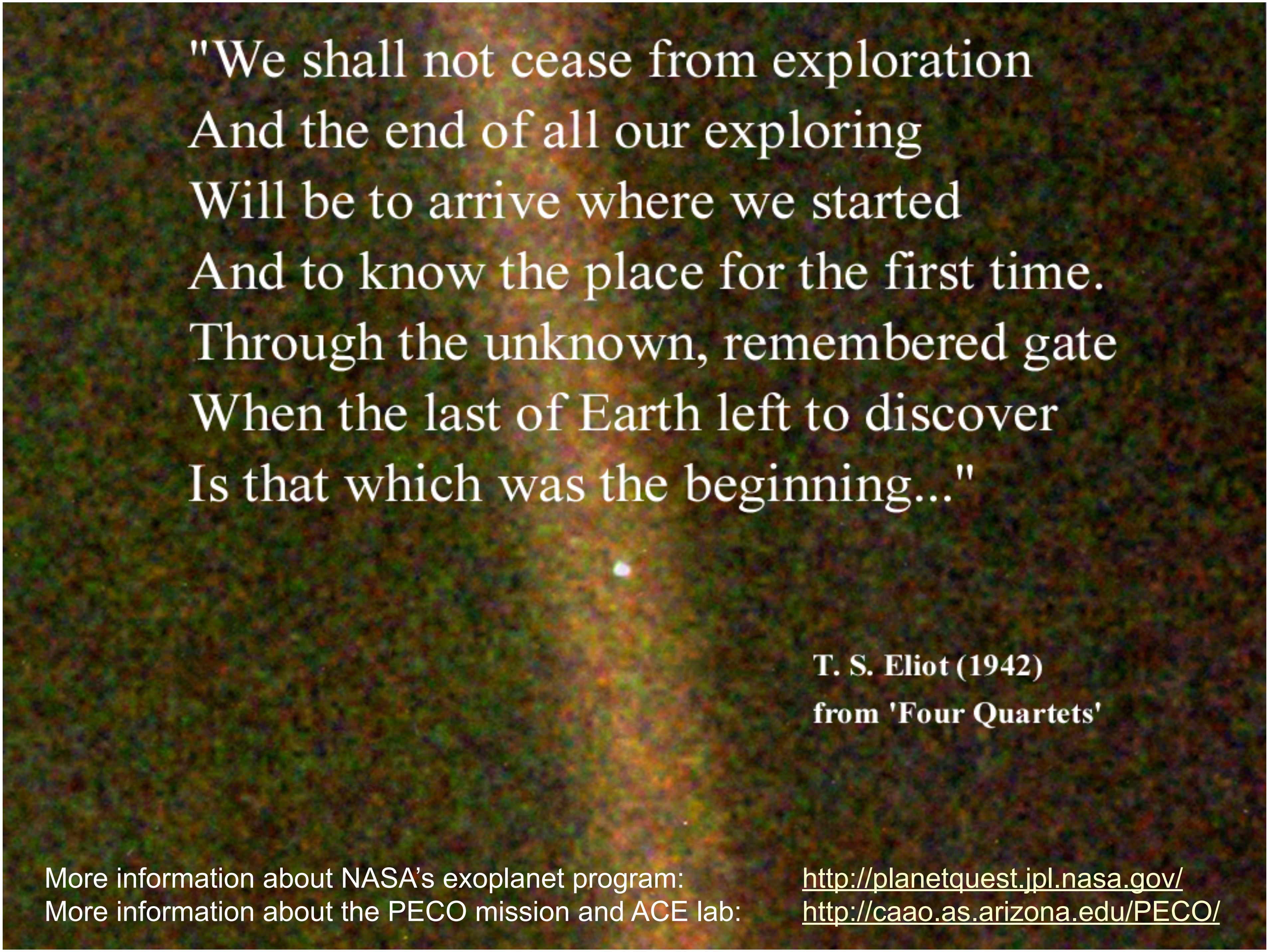
10 decks
water shielding in outermost deck
living/working floor area:
125 m²/person



Great Pyramid of Cheops, to scale, for comparison; has 1/16 mass of ship

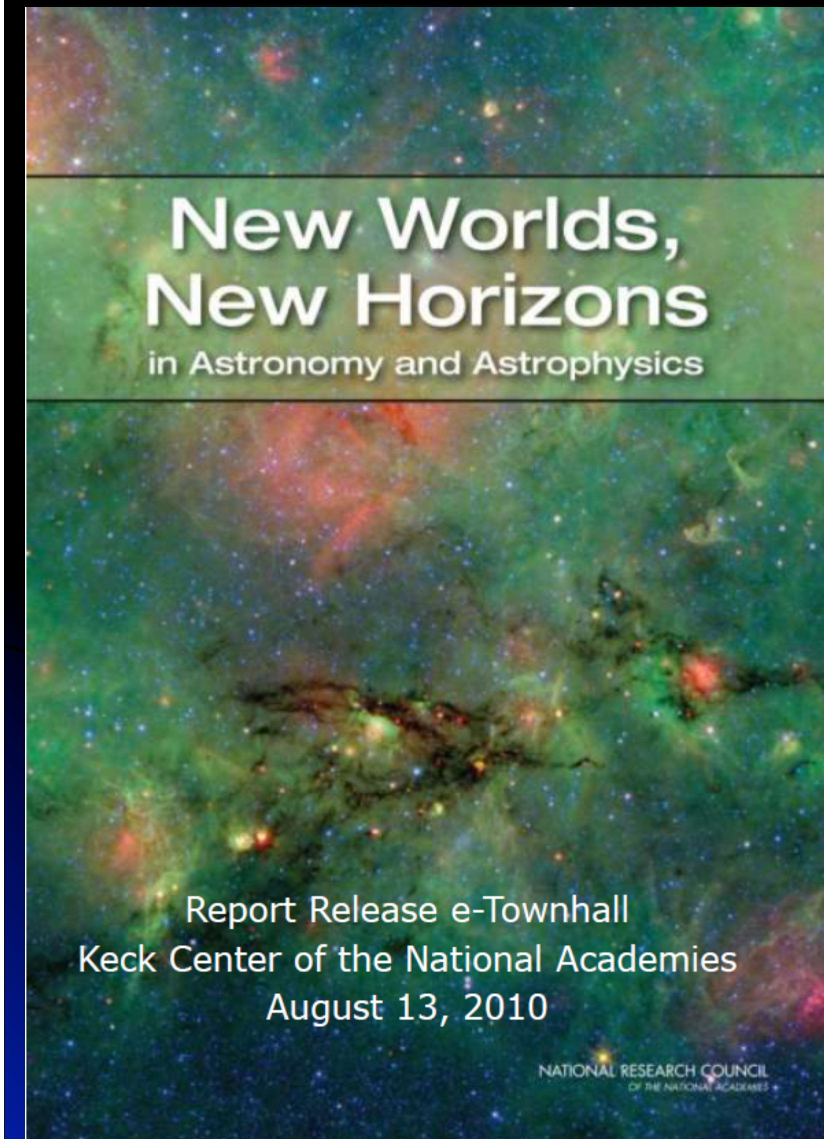
Possible implications of finding another “pale blue dot”?

- Realizing we may not be alone
- Save the human race
- Legacy of our generation
- Inspiration, and learning about ourselves


"We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And to know the place for the first time.
Through the unknown, remembered gate
When the last of Earth left to discover
Is that which was the beginning..."
T. S. Eliot (1942)
from 'Four Quartets'
More information about NASA's exoplanet program: http://planetquest.jpl.nasa.gov/
More information about the PECO mission and ACE lab: http://caao.as.arizona.edu/PECO/

backup

The 2010 Astrophysics Decadal survey (Astro2010)



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Science Objectives

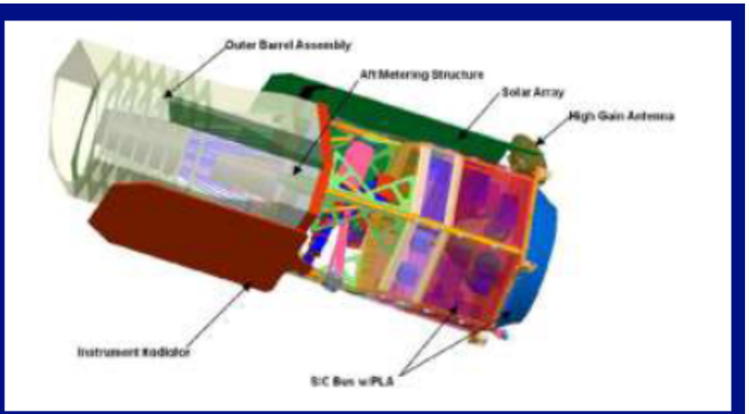
- Building on the science priorities identified by the survey, the recommended program is organized by three science objectives that represent its scope:
    - Cosmic Dawn
    - New Worlds
    - Physics of the Universe

- Success in attaining these science goals will enable progress on a much broader front
- Also foster unanticipated discoveries

Recommended Program

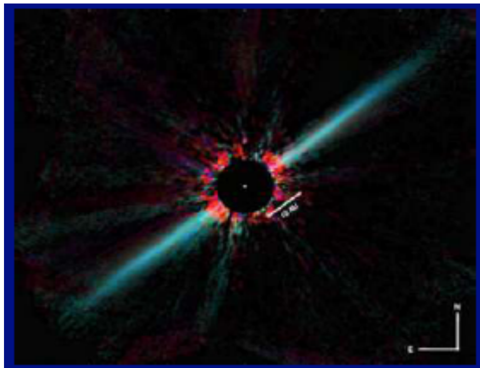
- Large-scale (prioritized)
  1. Wide Field InfraRed Survey Telescope (WFIRST)
  2. Explorer Program augmentation
  3. Laser Interferometer Space Antenna (LISA)
  4. International X-ray Observatory (IXO)
- Mid-scale (prioritized)
  1. New Worlds Technology Development Program
  2. Inflation Technology Development Program
- Small-scale

WFIRST - Science



Near infrared wide-field telescope with a *set* of key science objectives:

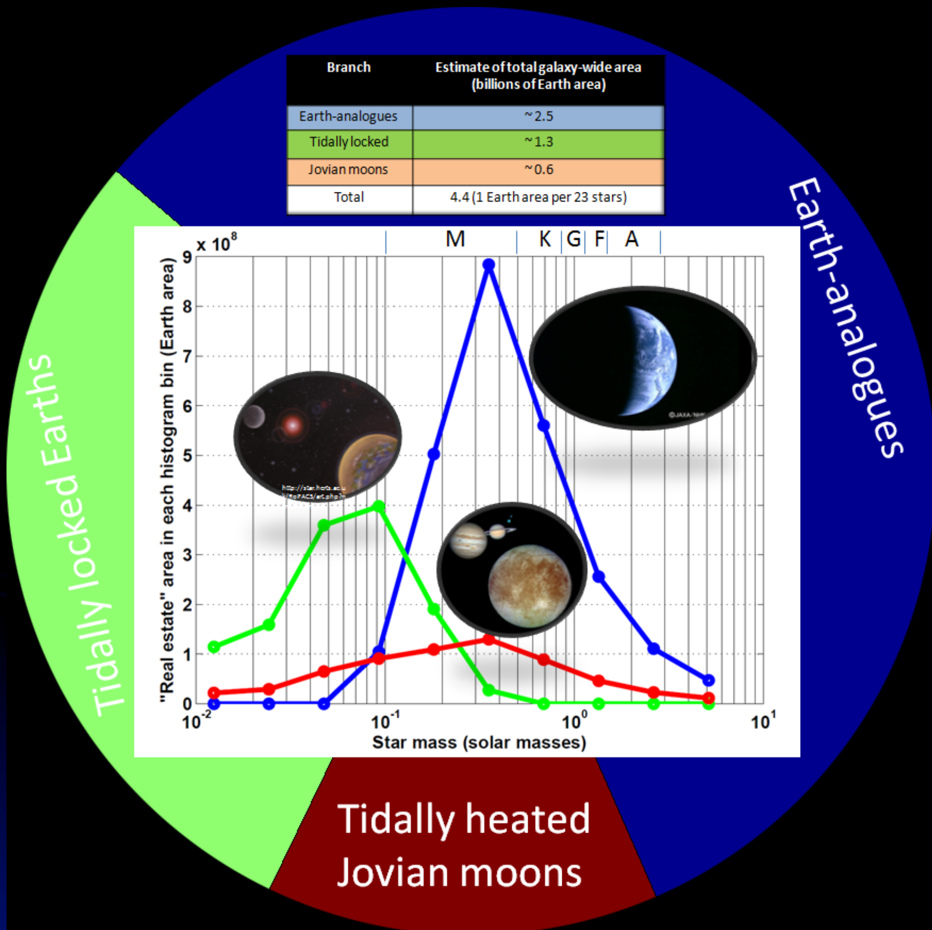
– Dark energy (part of a coherent ground-space strategy):
  - Baryon acoustic oscillations
  - Distant supernovae
  - Weak lensing
– Exoplanet statistics
  - Gravitational microlensing
– Guest investigator mode enabling survey investigations



New Worlds Technology Development Program

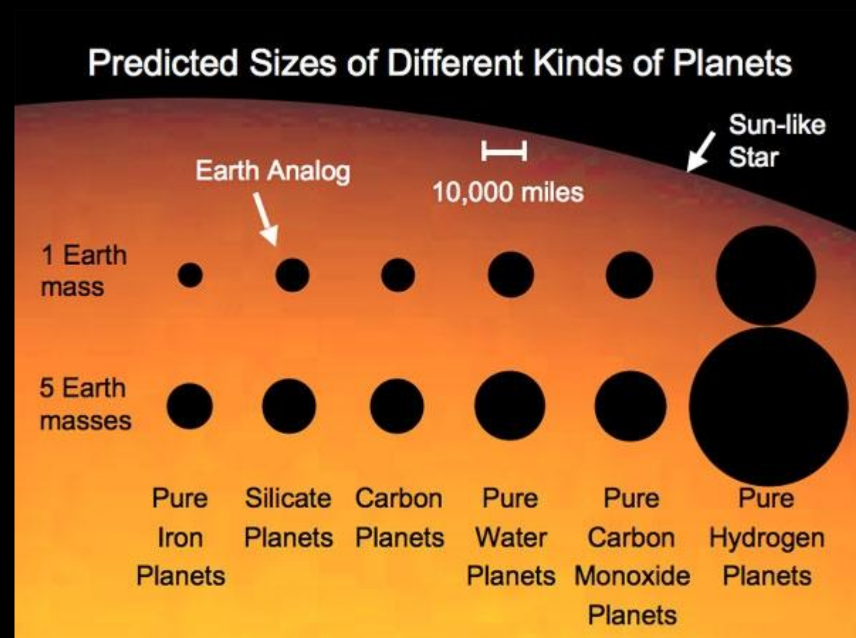
- To achieve New Worlds objective – studying nearby, habitable exoplanets - need preliminary observations before choosing a flagship mission:
  - Planetary demography over wide range of conditions:
    - Kepler, WFIRST, integrated ground-based program
  - Measurement of zodiacal light:
    - Ground-based telescopes.
    - Sub-orbital and explorer mission opportunities.
- In parallel, need technology development for competing approaches to make informed choice in second half of decade
- **RECOMMEND $100-200M over decade**
- Planned integrated ground-space exoplanet program

Potentially a rich diversity of habitable planets



Branch	Estimate of total galaxy-wide area (billions of Earth area)
Earth-analogues	~2.5
Tidally locked	~1.3
Jovian moons	~0.6
Total	4.4 (1 Earth area per 23 stars)

Belikov and Kuchner, in prep.



Seager, Kuchner, et. Al., 2007