Are There Other Earths and Life In the Universe? A 2500 Year Quest

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From Ancient Greek Philosophers…

"There are infinite worlds both like and unlike this world of ours...We must believe that in all worlds there are living creatures and plants and other things we see in this world."--- Epicurus (c. 300 B.C)

…To Medieval Scholars…

"There are countless suns and countless earths all rotating around their suns in exactly the same way as the seven planets of our system… The countless worlds in the universe are no worse and no less inhabited than our Earth"

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

Klaatu Borada Nikto

"Your choice is simple. Join us and live in peace or pursue your present course and face obliteration. We shall be waiting for your answer. The decision rests with you."

…And Finally to Modern Science & Speculation

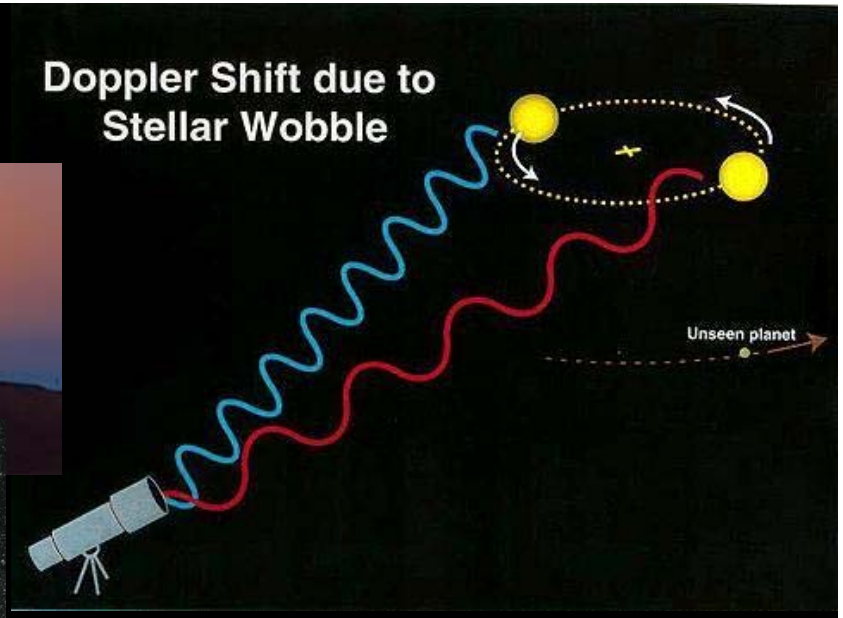
The Drake Equation

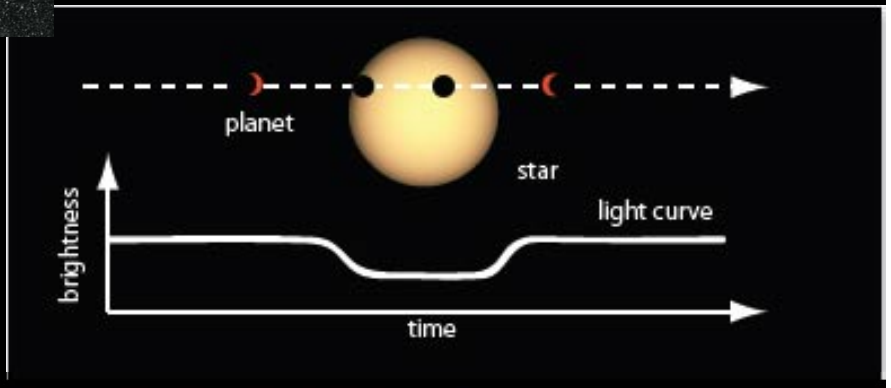
- ***N*** = The number of communicative civilizations
- ***R_**** = The rate of formation of suitable stars
- ***f_p*** = The fraction of those stars with planets.
- ***n_e*** = The number of Earth-like worlds per planetary system
- ***f_l*** = The fraction of those Earth-like planets where life develops
- ***f_i*** = The fraction of life sites where intelligence develops
- ***f_c*** = The fraction of communicative planets
- ***L*** = The "lifetime" of communicating civilizations

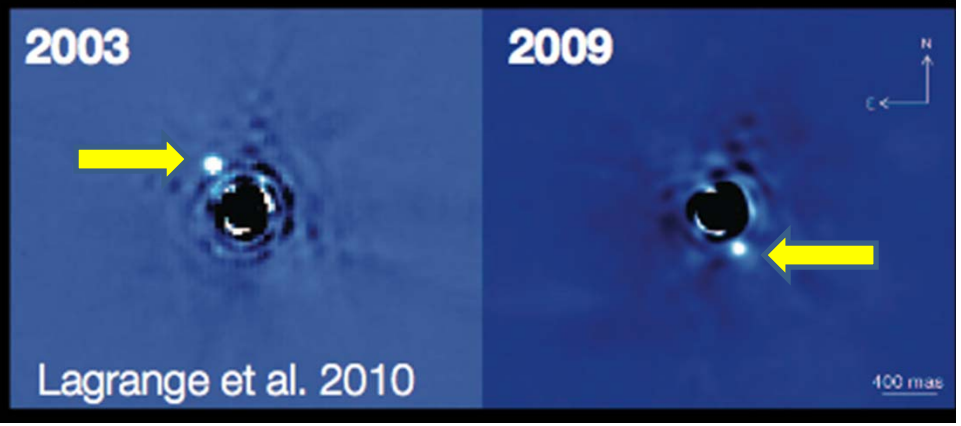
Today's Planet Census
Total planets: 1854
Multiple systems: 484

- Radial Velocity (1995)
  - 543 planets
- Transit (1999)
  - 1227 planets
  - 4661 candidates
  - 306 Habitable Zone
  - **14 R<1.25$R_\oplus$ in HZ**
- Imaging (2004)
  - 38 planets
- Microlensing
  - 32 planets
- Others (pulsar timing, astrometry)
  - 7 planets

http://exoplanetarchive.ipac.caltech.edu/







What Makes a Planet Habitable?

Environment

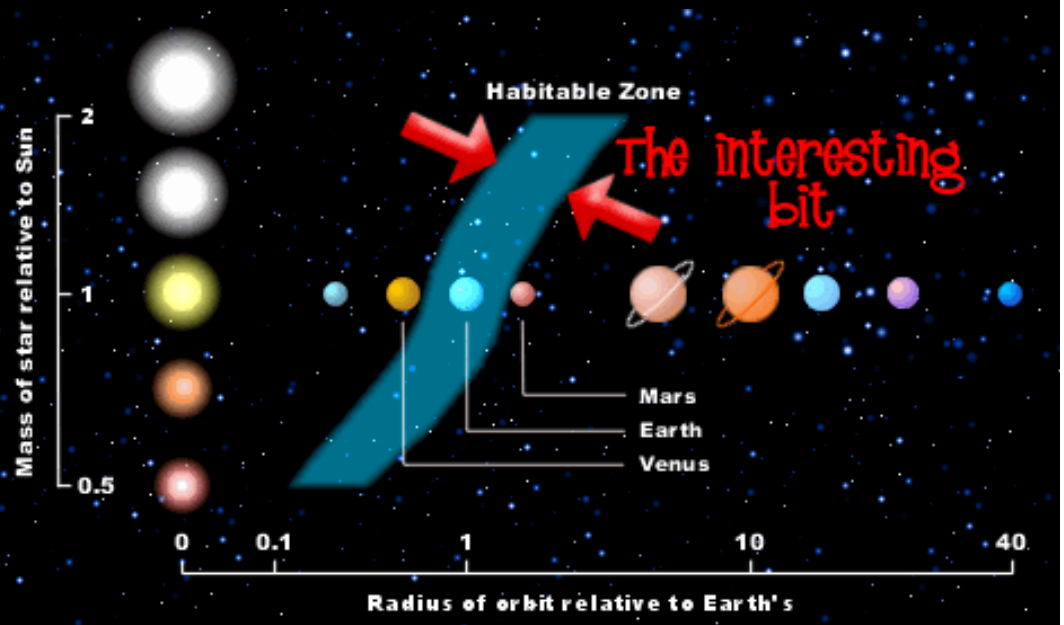
- Distance from Star
- Low eccentricity orbit for stable temperatures
- Long term orbital stability
- Low bombardment rate

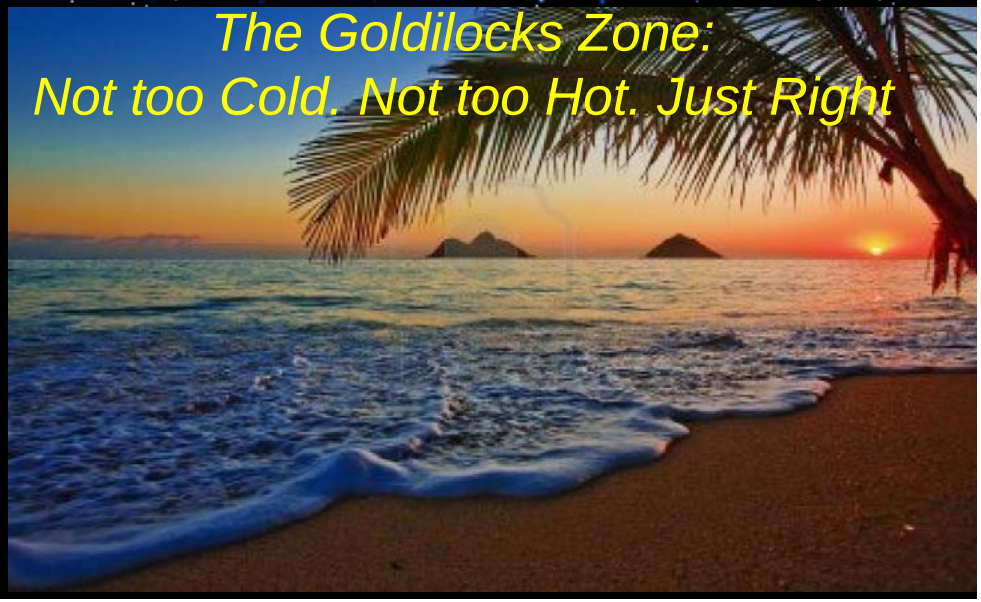
Planet size & mass

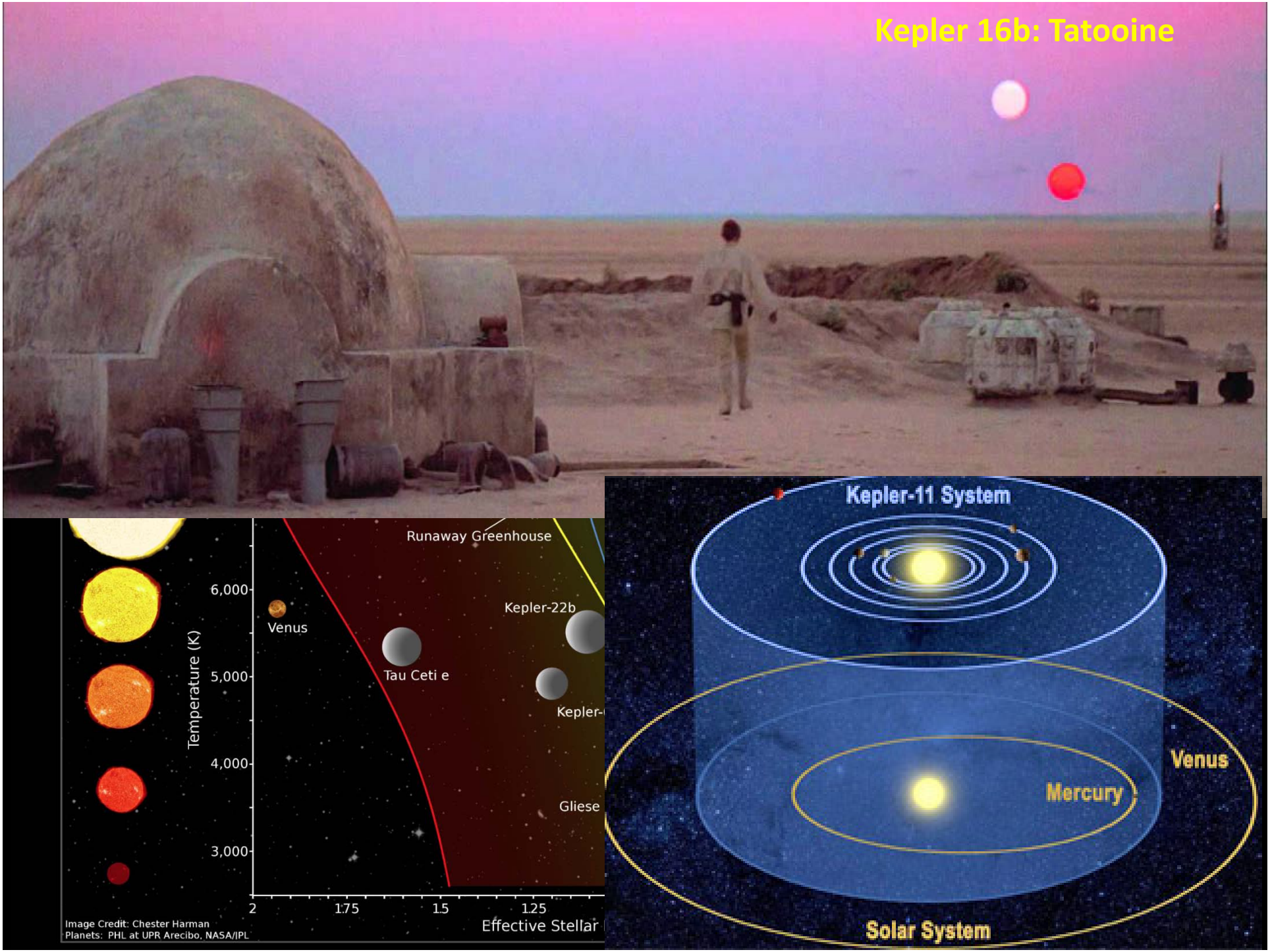
- Retain atmosphere
- Plate tectonics for active carbon cycle
- Magnetic field for solar wind protection

Composition

- Water and volatiles
- Solid surface for life

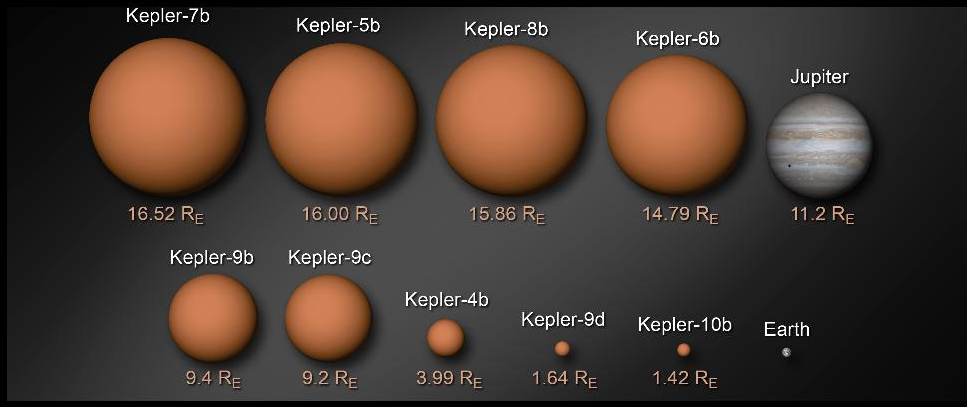





Kepler 16b: Tatooine
Runaway Greenhouse
Venus
Kepler-22b
Tau Ceti e
Kepler-
Gliese
Temperature (K)
6,000
5,000
4,000
3,000
2
1.75
1.5
1.25
Effective Stellar
Image Credit: Chester Harman
Planets: PHL at UPR Arecibo, NASA/IPL
Kepler-11 System
Venus
Mercury
Solar System

Planet Characteristics

- Broad range of properties
  - Gas Giants (Jupiters/Saturn)
  - Ice Giants (Neptune/Uranus)
  - Rocky Planets (Super Earths)
- Incidence of planets rises with smaller size
  - Transits: >15 % of stars, rocky planets (2-4R_{Earth}, P<50 d)
  - 2-4R_{Earth} ~100% for M stars
  - Radial Velocity: 25 % of stars, have rocky planets (~2M_{Earth}, P<50 d)
- Earth analogs in Hab. Zone
  - 2-10% overall, but perhaps 25% for M stars



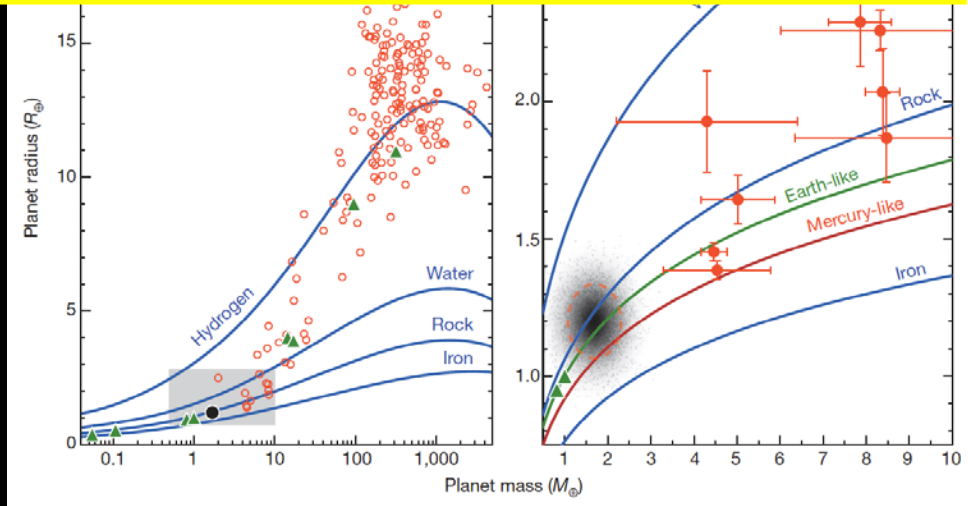
Parameter	Smallest	Largest
Mass	2 M_{Earth}	>13 $M_{Jupiter}$
Radius	1.3 R_{Earth}	2.2 $R_{Jupiter}$
Density (water=1)	0.08 (<Styrofoam)	>10 (iron,7; lead,11)
Orbital Dist.	0.014 AU	Few 100s AU
Orbital Period	2 days	Few 100 years
Eccentricity	0	0.97
Temperature	>3000 C	<-150 C

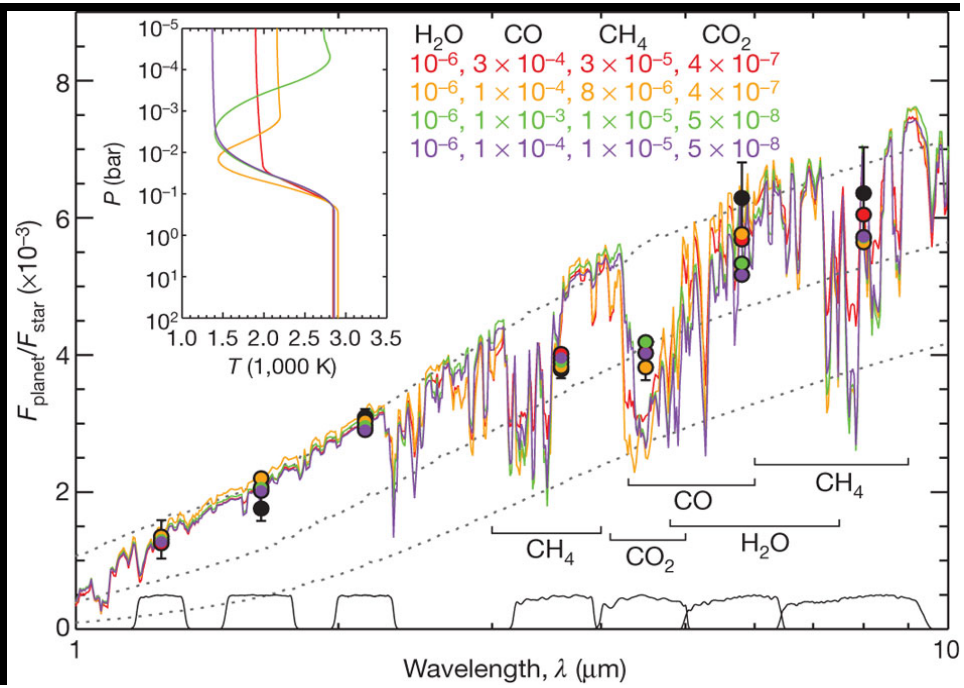
What We Learn From Transits

On the subject of stars … We shall never be able by any means to study their chemical composition. *--- August Comte, 1835*

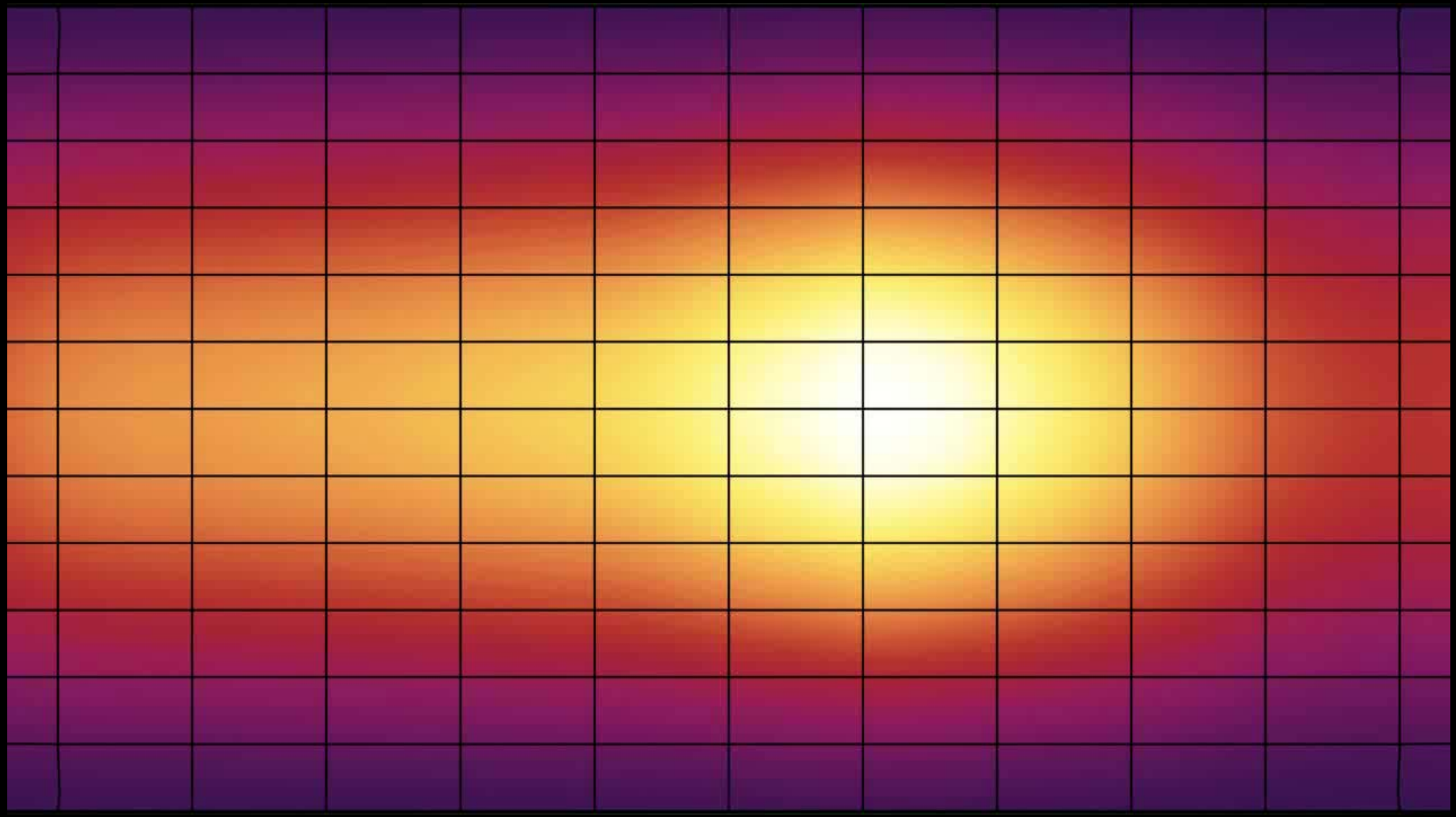
- Orbit distance & inclination
- Planet radius and mass → density & bulk composition
- Star/Planet orbit alignment
- Hints of additional planets
- Presence of rings/moons?
- Reflected light (albedo)
- Atmospheric structure
- Global Circulation (Weather)

- Atmospheric structure and composition (Visible & IR spectra)



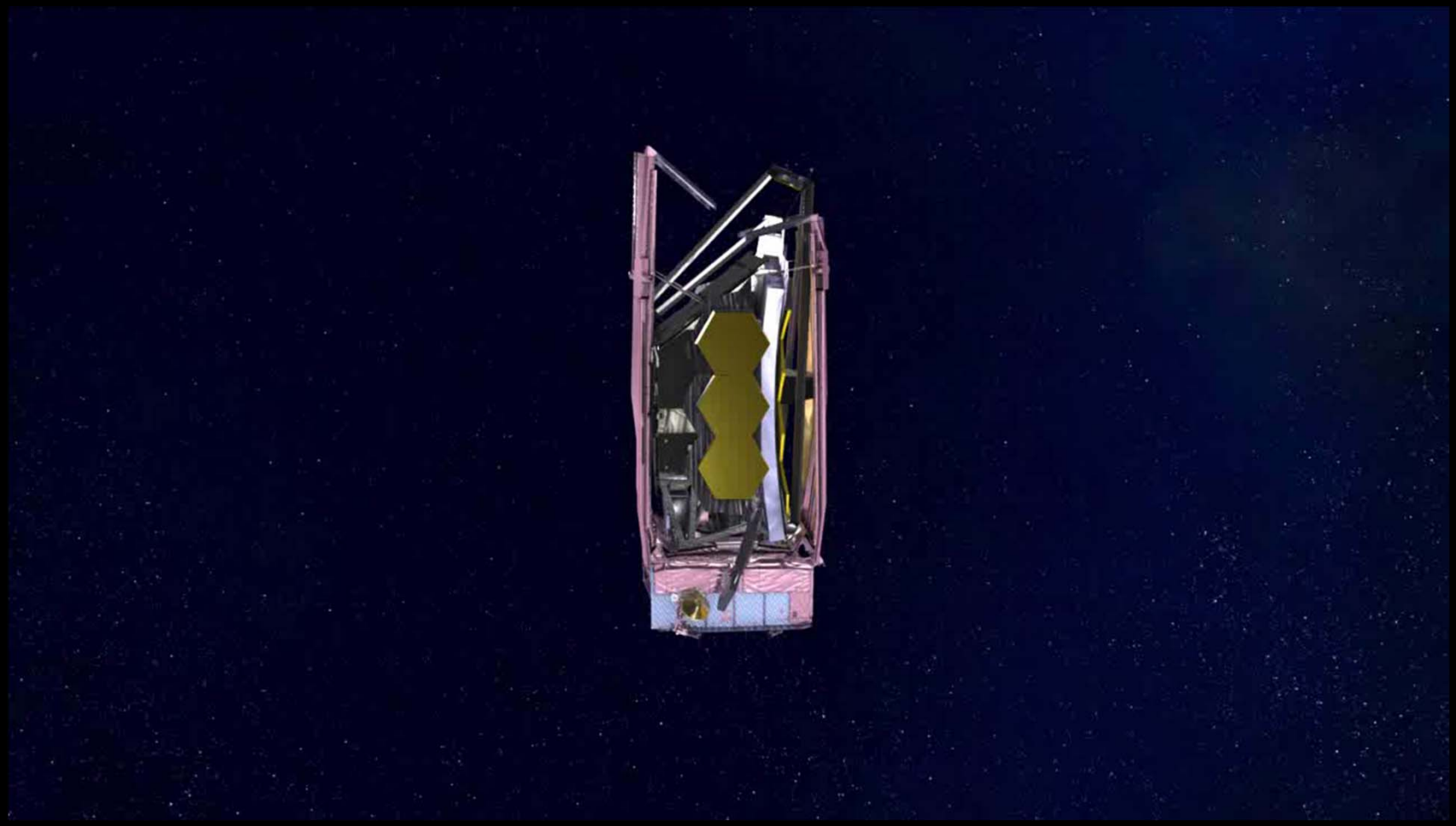


Mapping Weather on HD 189733b

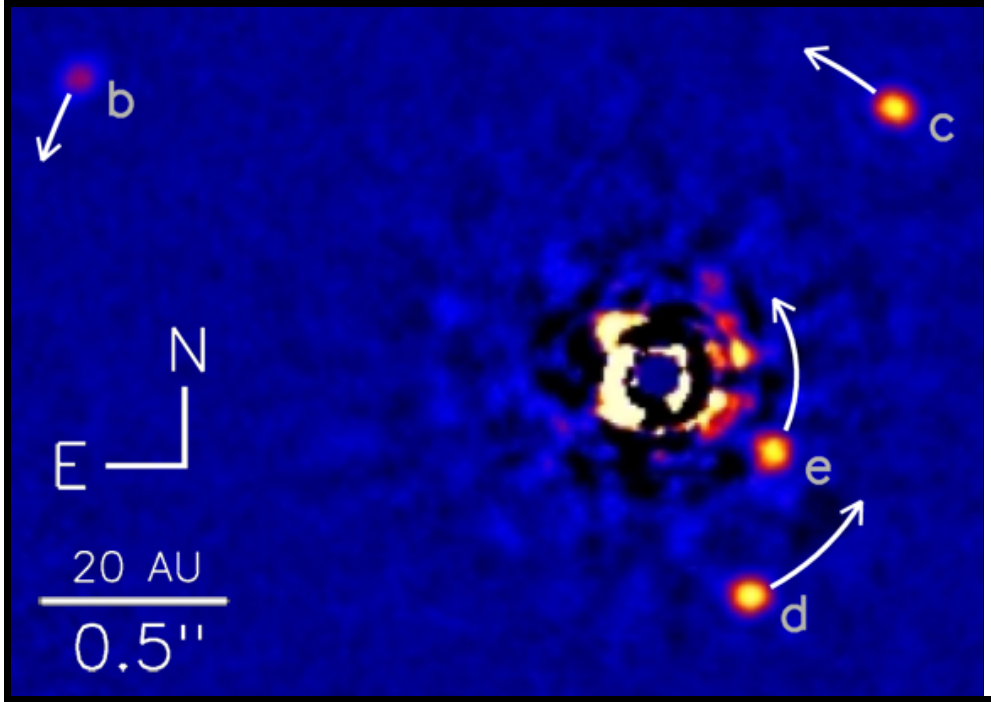


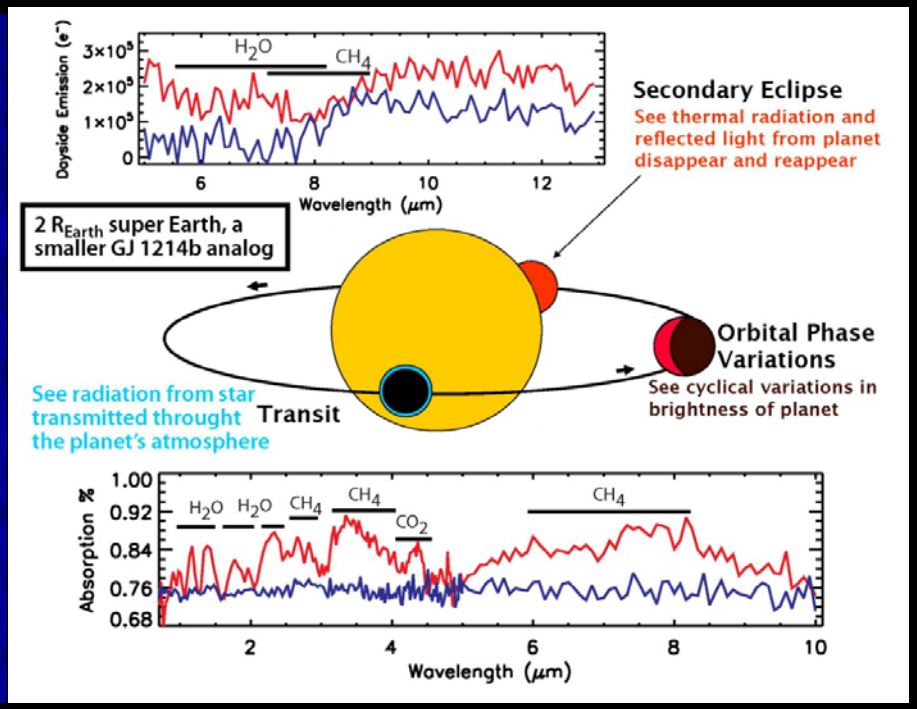
An infrared heat map taken by Spitzer during a whole orbit reveals a hot spot (930C vs 650C) displaced from the subsolar point by supersonic winds (10,000 km/h)

JWST: The Next (Very) Big Thing



JWST Exoplanet Science

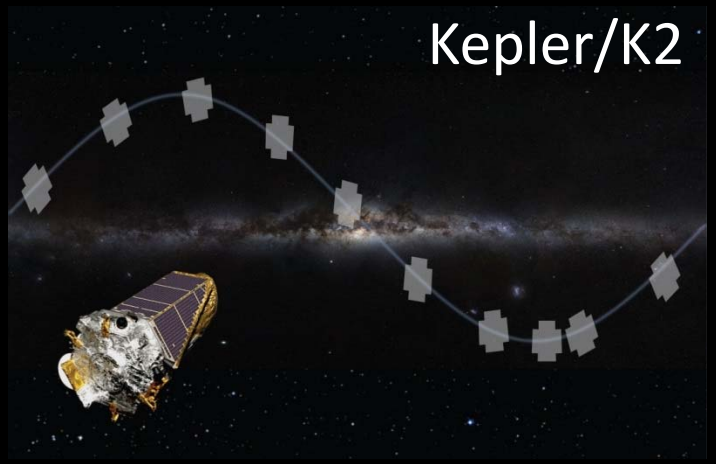


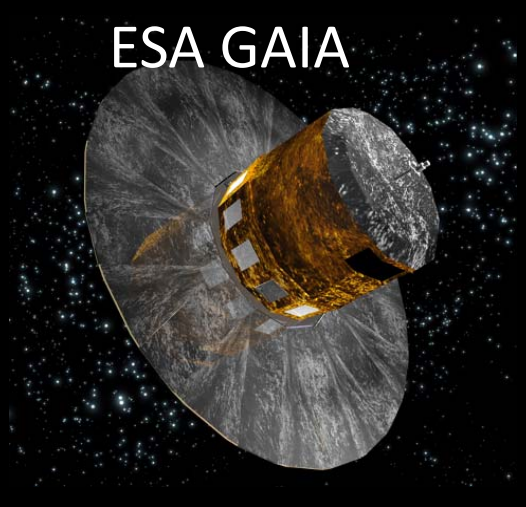


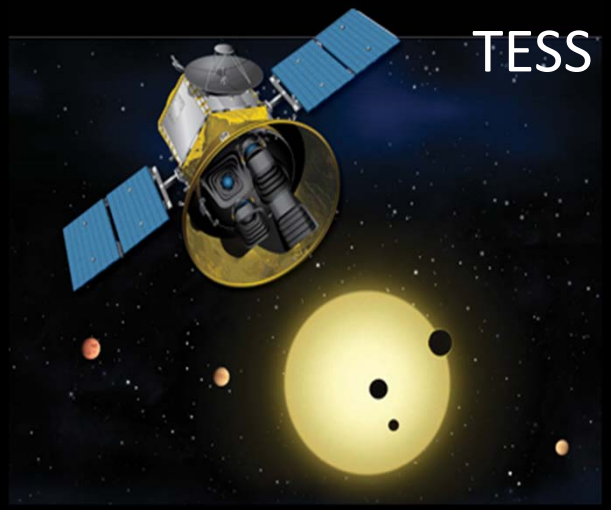
- Imaging to find and characterize young, hot planets (Jupiters to Saturns)

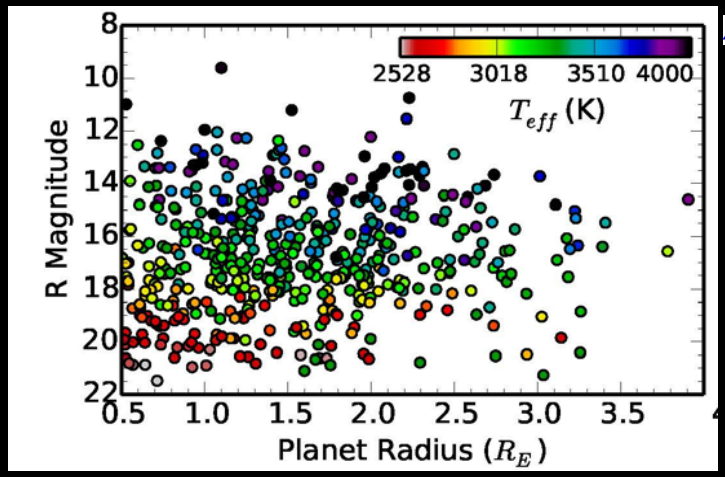
- Transit spectroscopy to characterize Jupiters →Super Earths
- JWST won't find or study Earth Analogs ☹

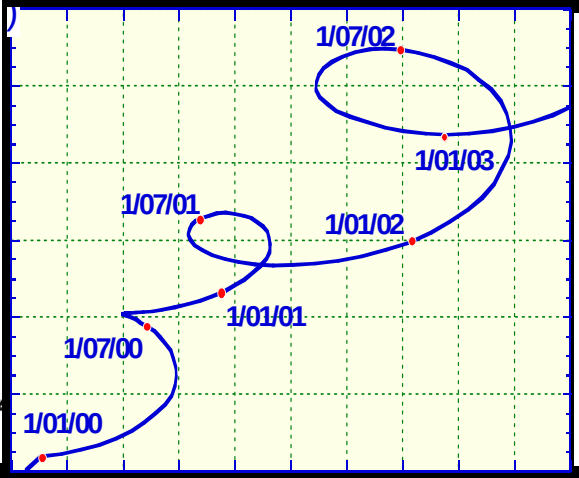
Next Steps In The Exoplanet Census

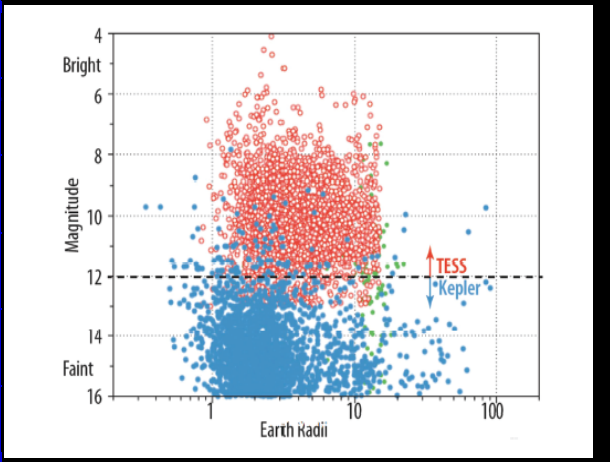






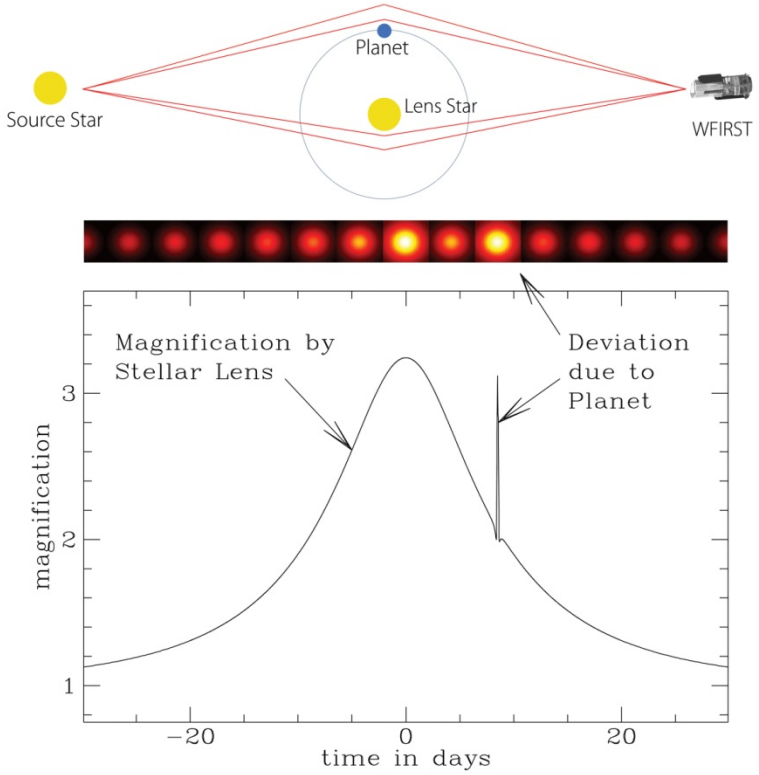


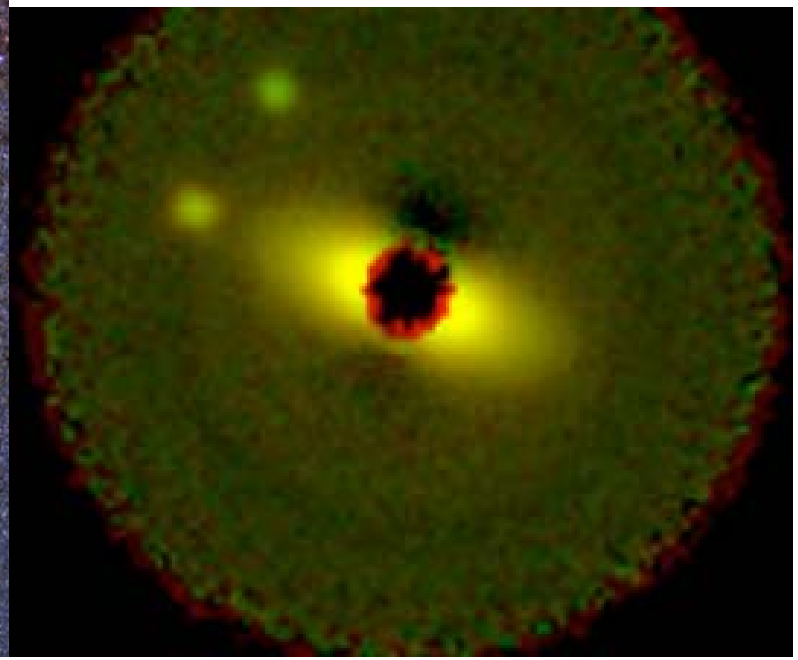


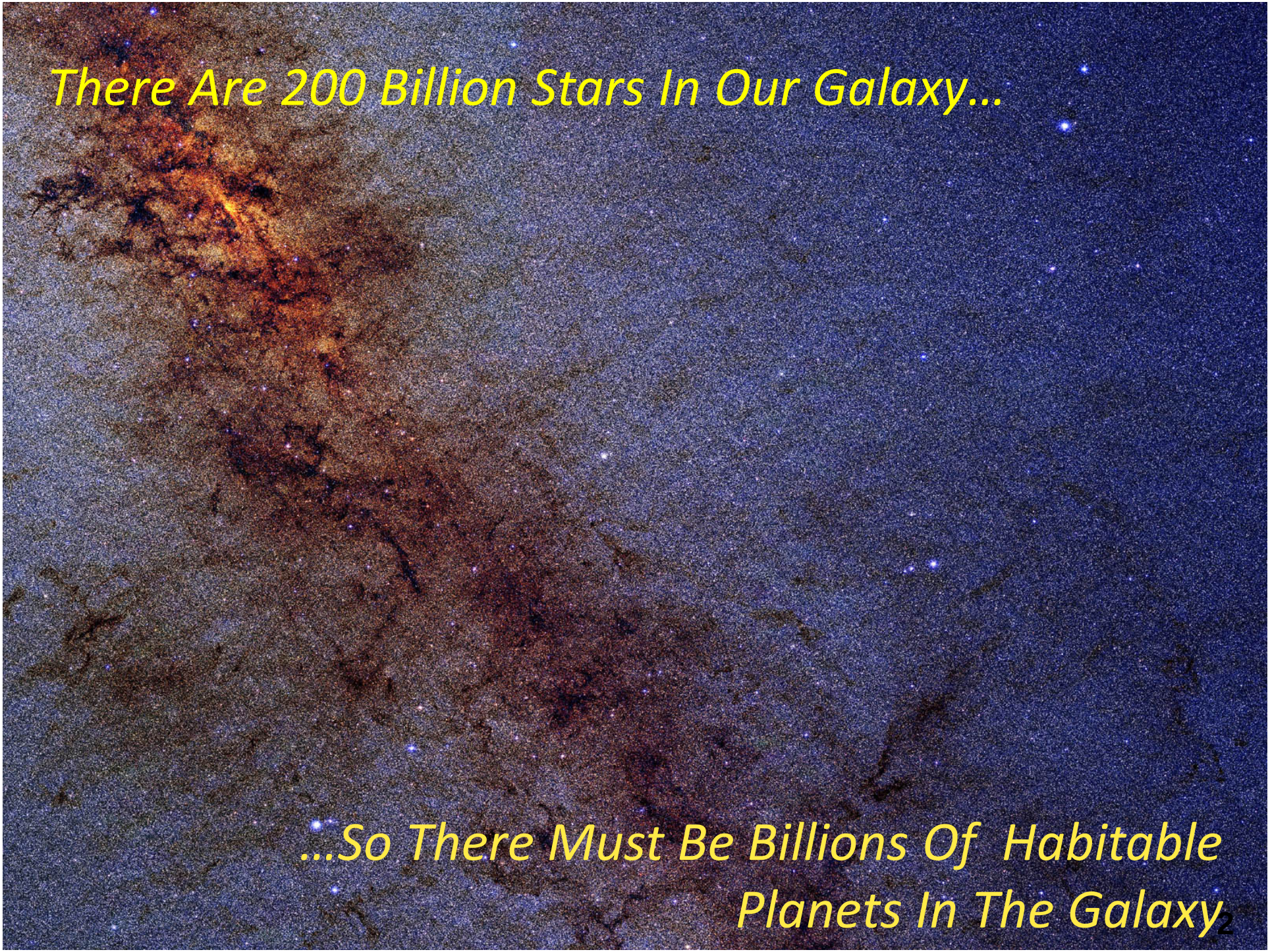


Planetary System Cartography Complete

- WFIRST camera probes architecture around the "ice-line" where planets form with microlensing
- WFIRST Coronagraph makes first direct images of **mature** gas and ice giants in reflected light

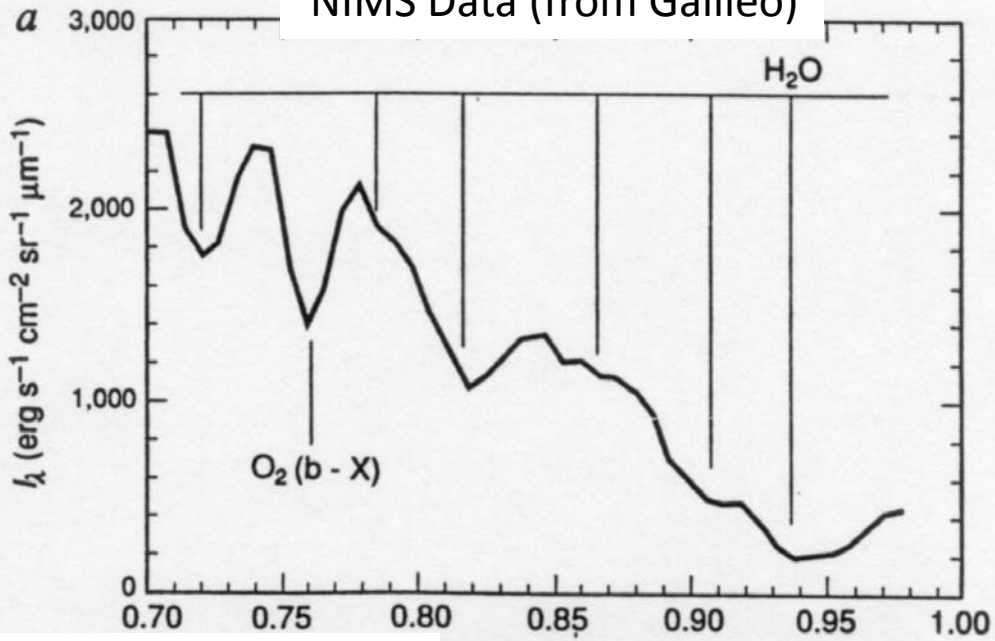




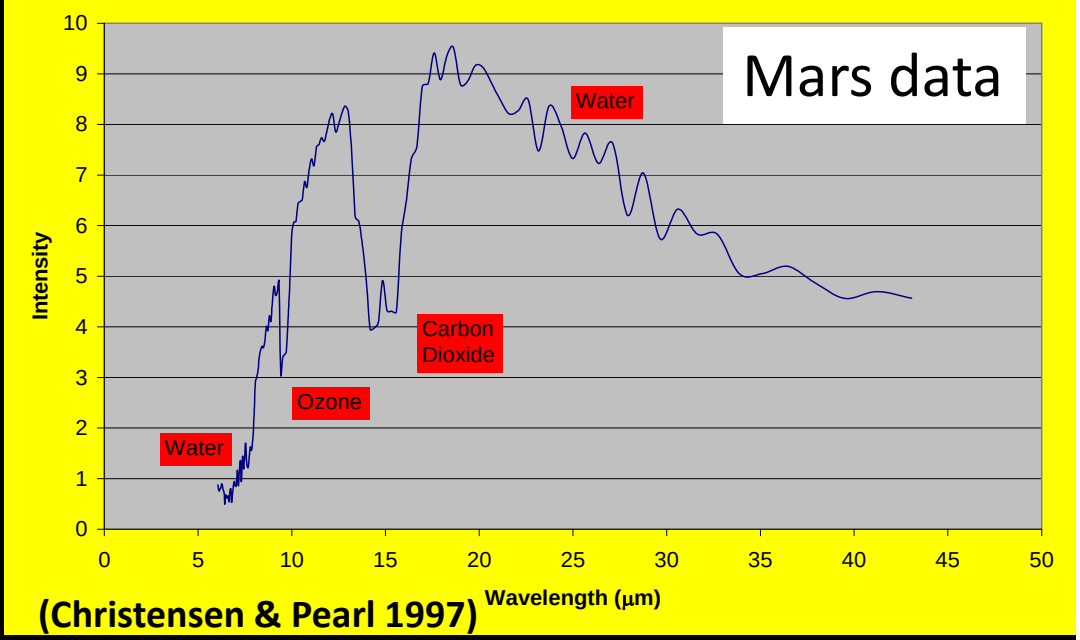

There Are 200 Billion Stars In Our Galaxy…
…So There Must Be Billions Of Habitable Planets In The Galaxy

The Final Frontier: Finding Habitable Planets and Life

NIMS Data (from Galileo)



Sagan et al. (1993)



(Christensen & Pearl 1997)

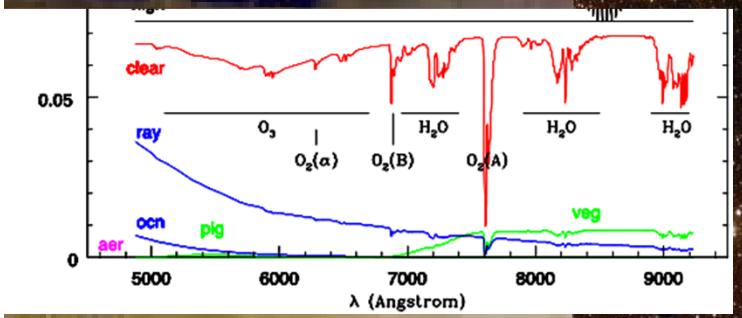
2045: Life Finder Launches

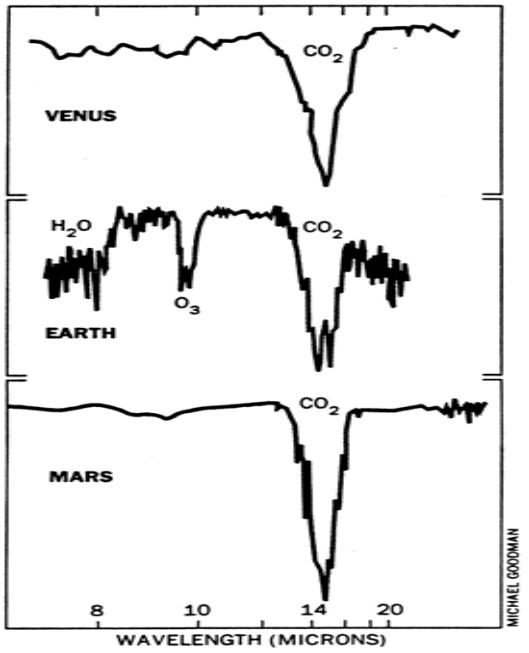
3 of 10 Habitable planets show evidence of photosynthetic life

Visible Coronagraph

Darwin IR Interferometer

External Occulter

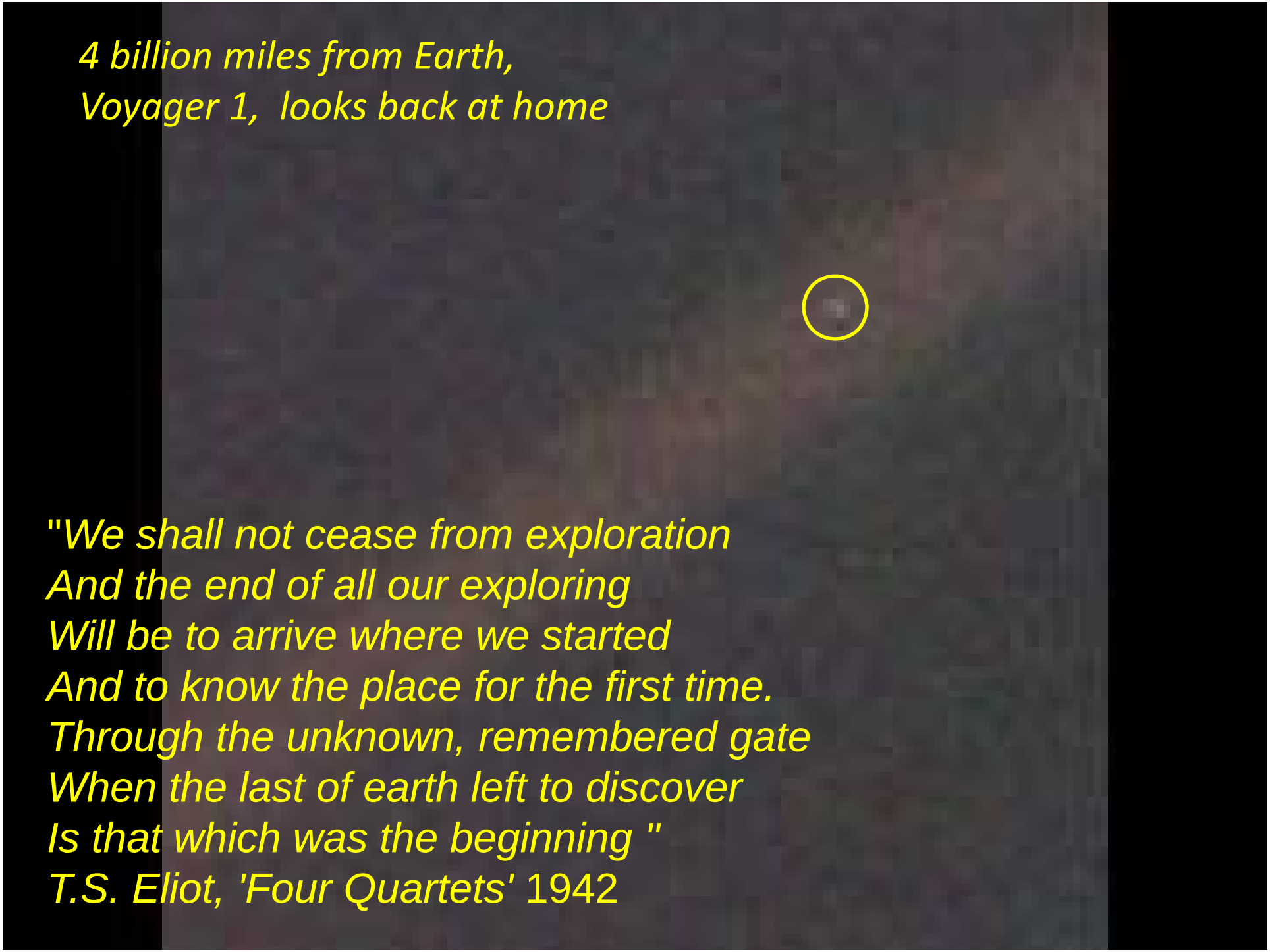




2055: We Leave The Cocoon

Mars colonists find non-DNA life forms in deep aquifer

One of Jill Tarter's scientific grandchildren receives first SETI signal


4 billion miles from Earth,
Voyager 1, looks back at home
"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, 'Four Quartets' 1942