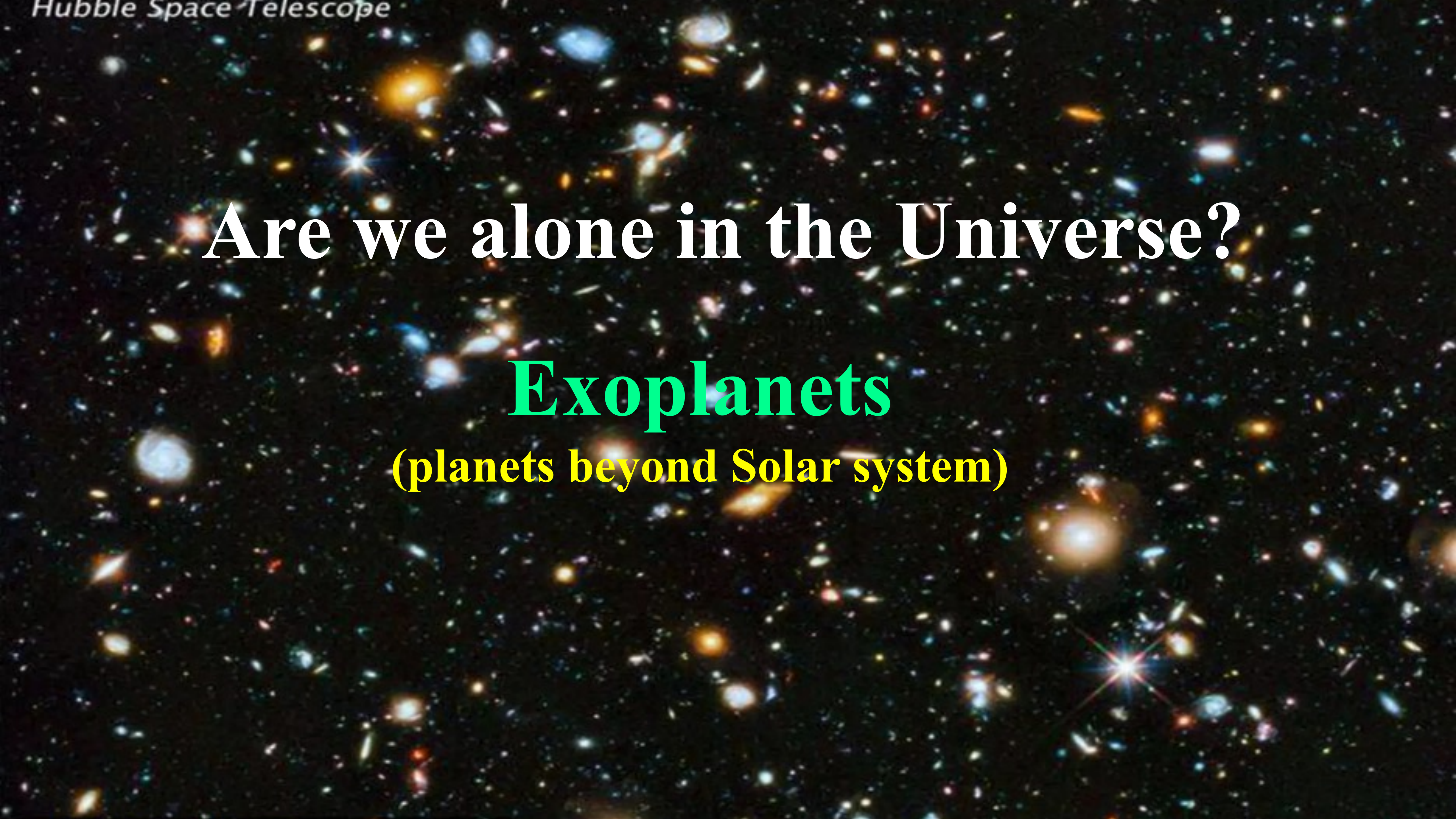


Are we alone in the Universe?

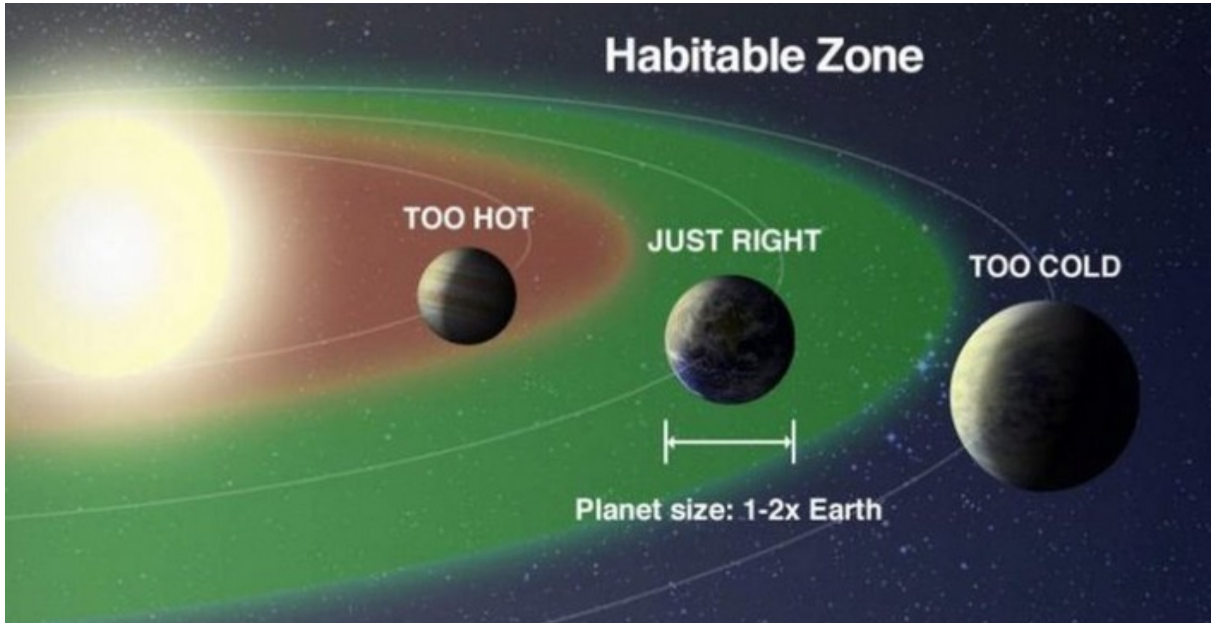
Exoplanets

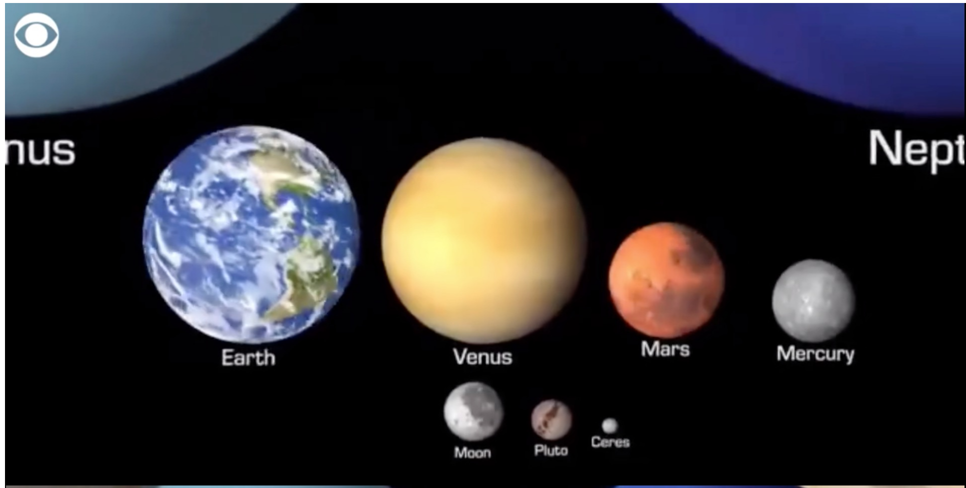
(planets beyond Solar system)

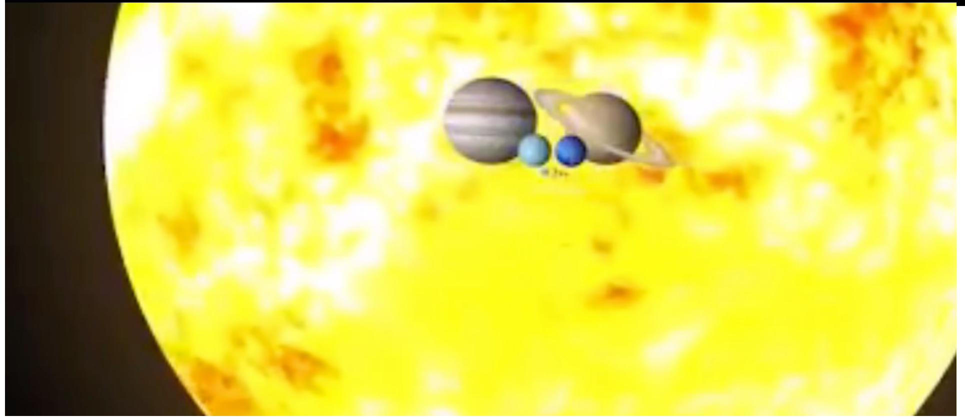
Signs of life

1. Size and structure of a planet:
- ➢ Not giant, gas/liquid , like Jupiter, but rocky, like Mars, Venus,..

2. Distance from the star:
- ➢ Not too close, but not too far for water to exist as liquid







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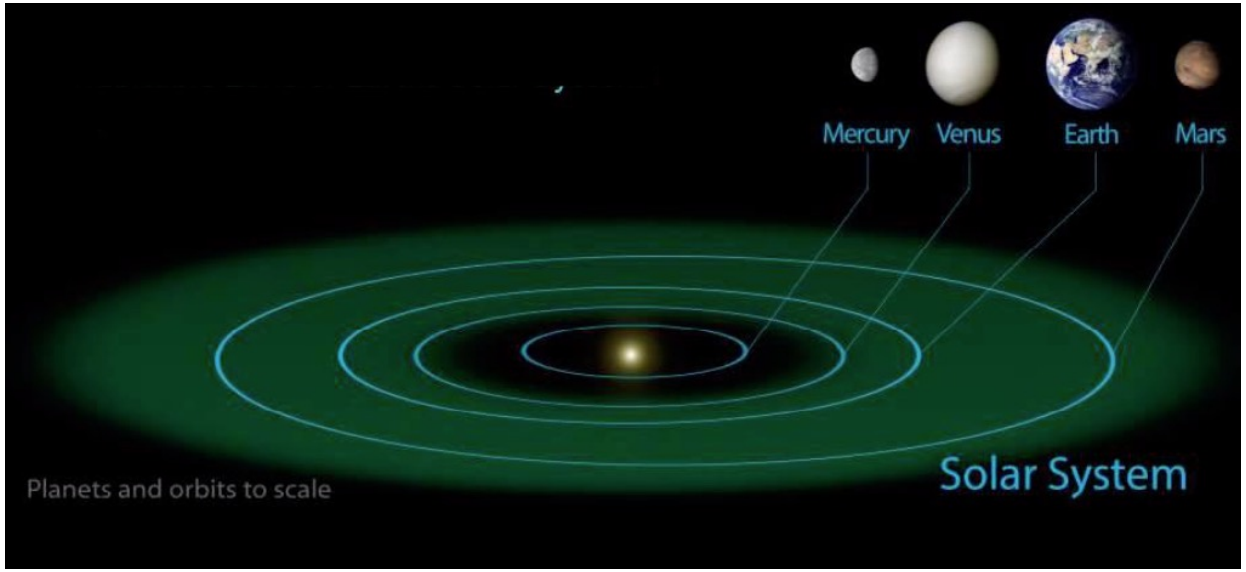
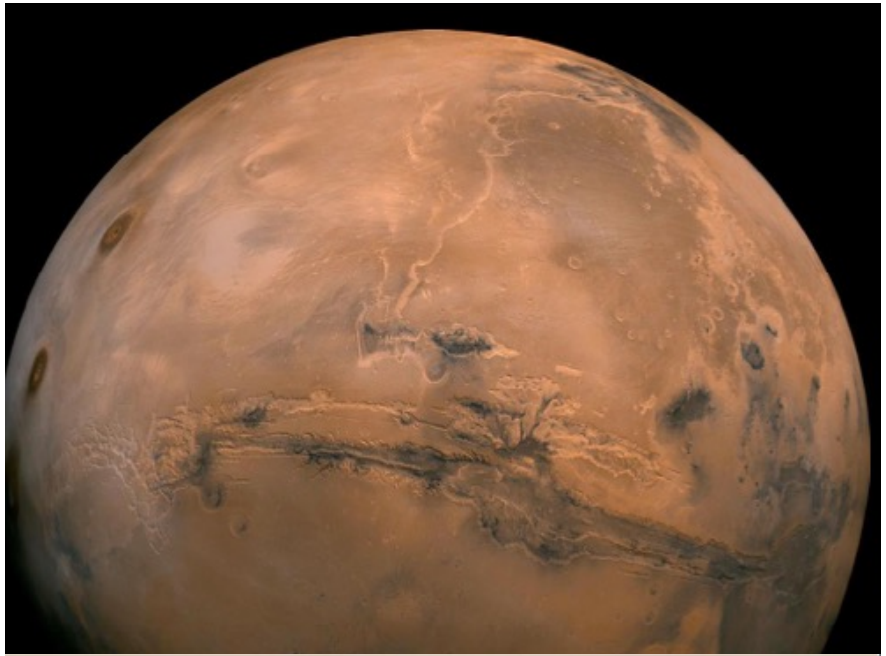


We have to search beyond our solar system

Mars photos



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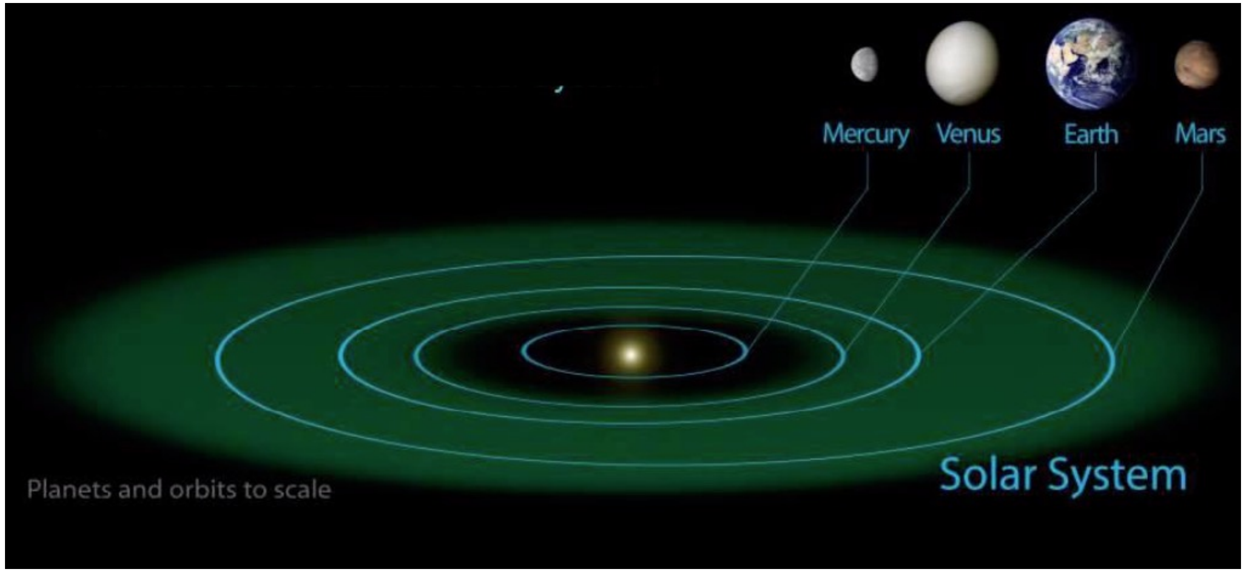
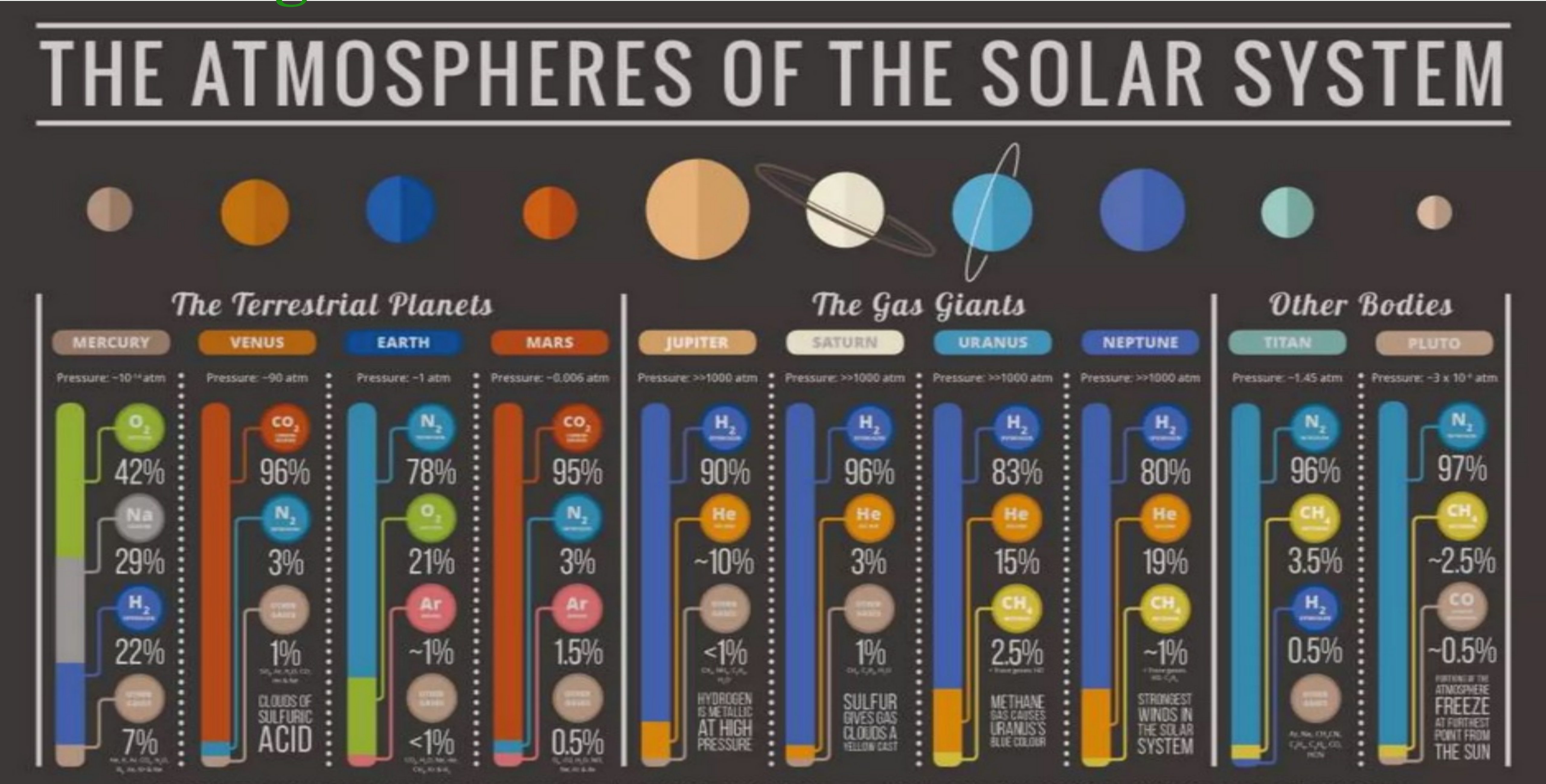


3. Long lived, stable stars:

➢ **G**-type (yellow, our Sun), K-type (orange, long living)

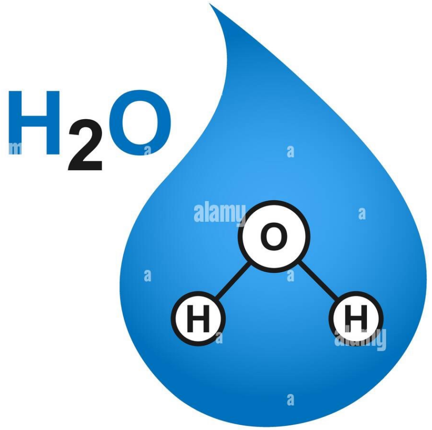
Signs of life



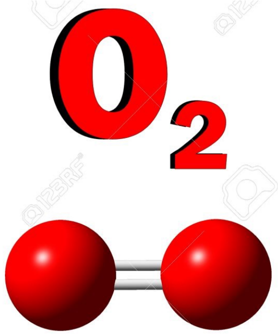
Signs of life

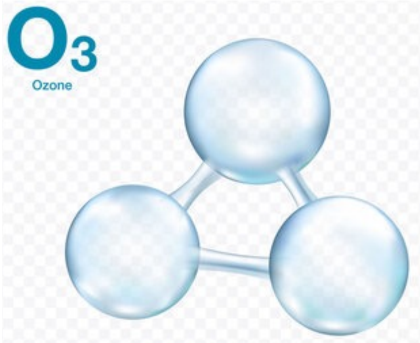
4. Chemistry:

- Liquid (gas phase) water

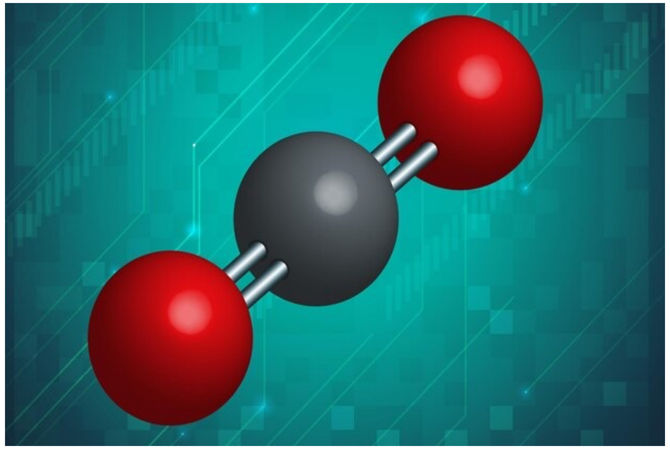


- Oxygen, O_2 (Ozone, O_3)

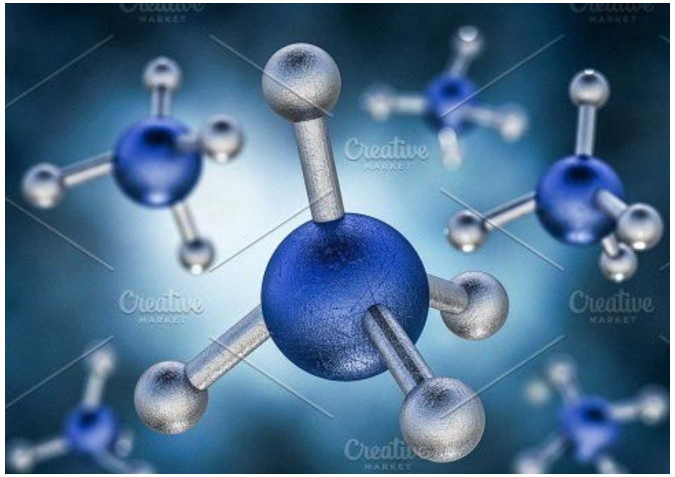




- Carbon dioxide, CO_2



- Methane, CH_4



Other chemical forms may exist too, but the Earth-like is the 1st to look for

Hunting for habitable exoplanets around the nearest very-low-mass stars

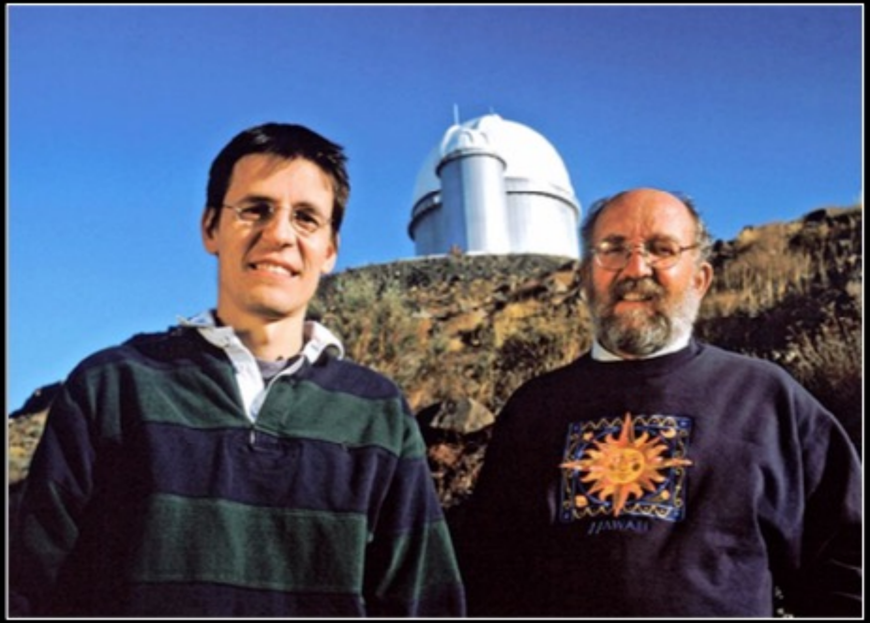
1995: beginning of the exoplanet era

A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.

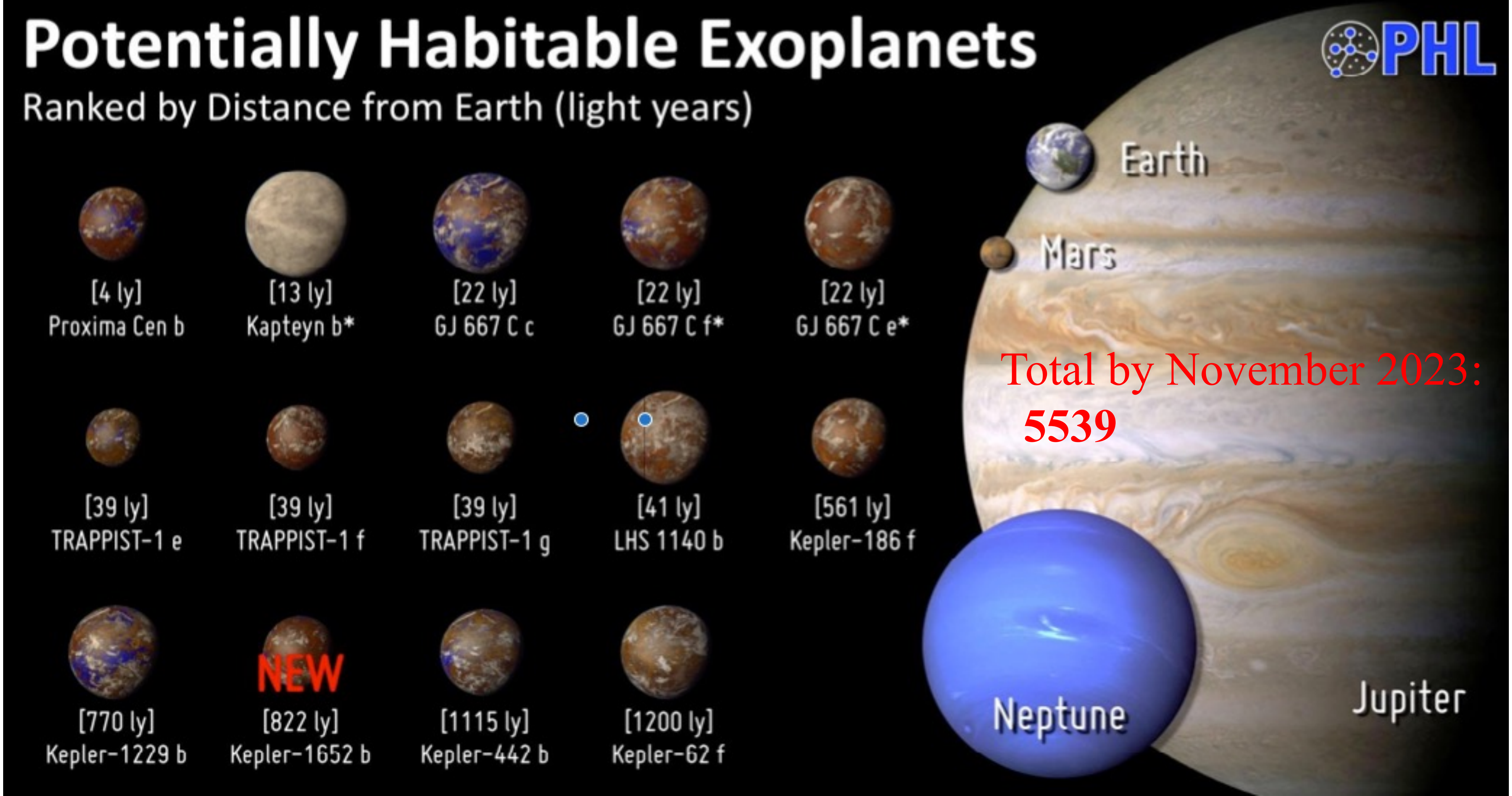


Didier Queloz Michel Mayor

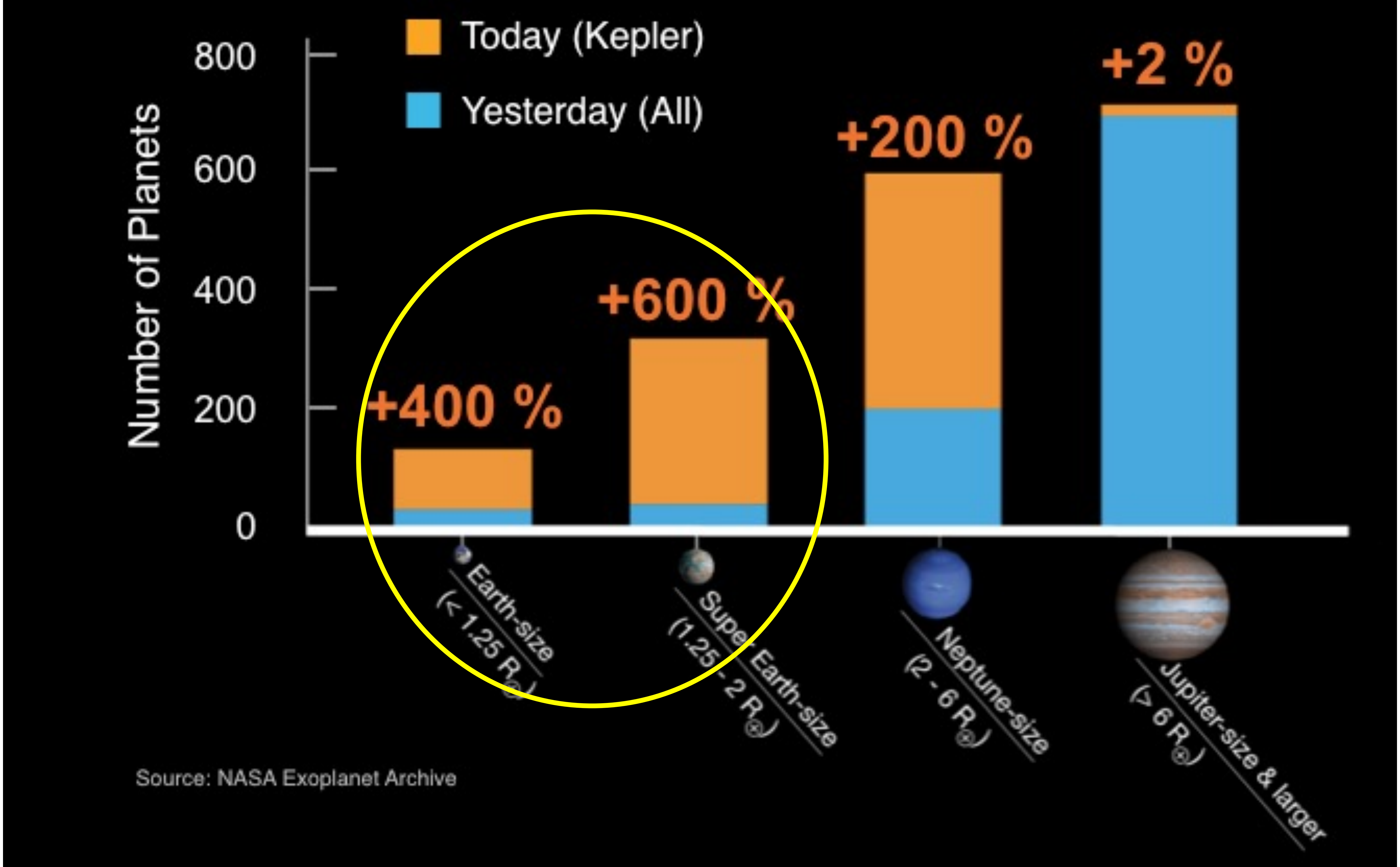
A giant planet in very short orbit around a *Sun-like star*

Found by Swiss

A few dozen possible biospheres



Total by November 2023:
5539

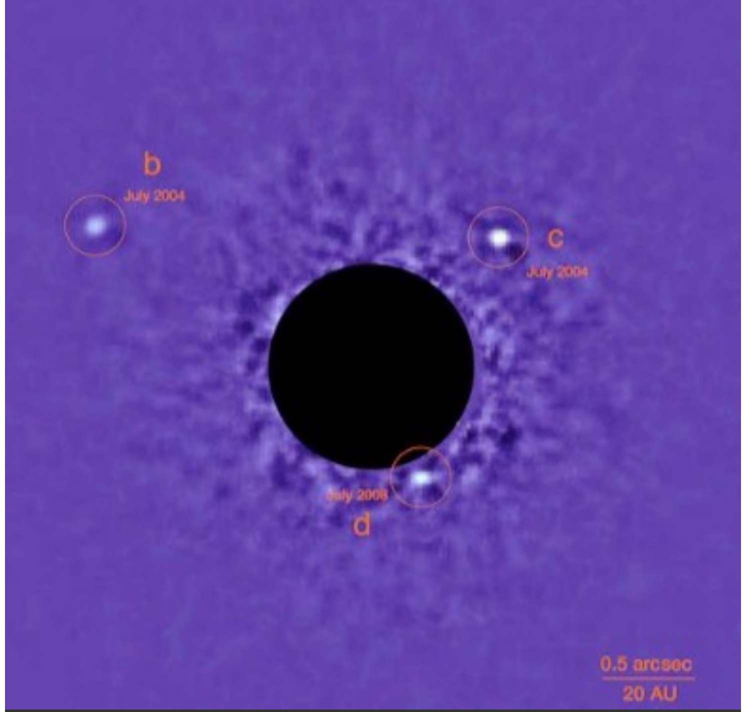


Today (Kepler)
Yesterday (All)
Number of Planets
800
600
400
200
0
+400 %
+600 %
+200 %
+2 %
Earth-size
(< 1.25 R⊕)
Super Earth-size
(1.25 - 2 R⊕)
Neptune-size
(2 - 6 R⊕)
Jupiter-size & larger
(> 6 R⊕)
Source: NASA Exoplanet Archive

How to find exoplanets?

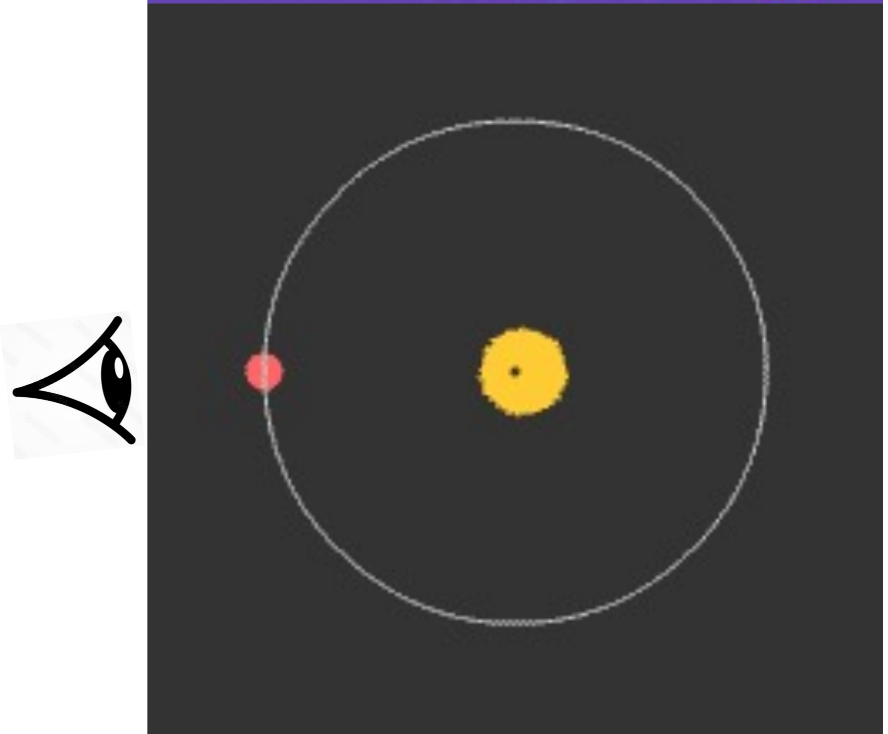
1. Exoplanets can only exceptionally be **directly imaged** (as bright spots):

- Planet reflects light of the star
- Planet is remote but large
- Planet rotates in the plane of the sky



2. **Radial Velocity Method:**

- Star and the planet rotates around the common center of mass
- Star moves slightly back and forth relative to an observer
- Light from the star experiences <u>periodic Doppler shift</u>
- Detection of the shift and the period enables an estimate of the planet that disturbs the star motion (planet remains invisible); Iodine gas spectral lines; accuracy of radial motion ± 3 m/s.



How to find exoplanets?

2. **Transit Method:**

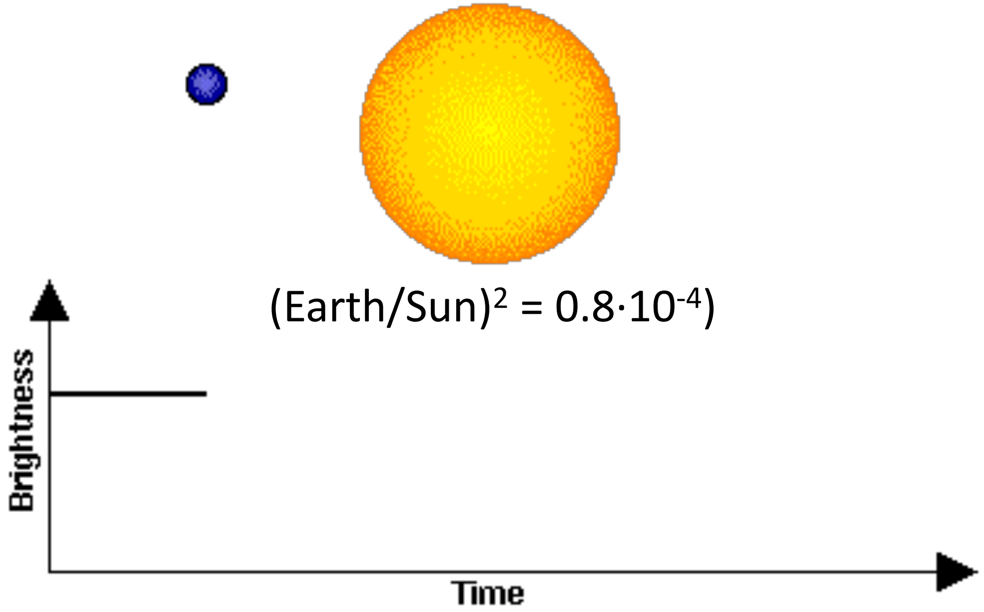
- Detects tiny reduction of the star's brightness upon the planet passing in front of the star. The reduction (*Transient Depth*): $TD = (\frac{d^P}{D*})^2$

is periodic; detectable only, if the planet orbit intersects the star disc on the side of observer.

$$S / N \propto \sqrt{t_{tr} \cdot N_{tr}}$$

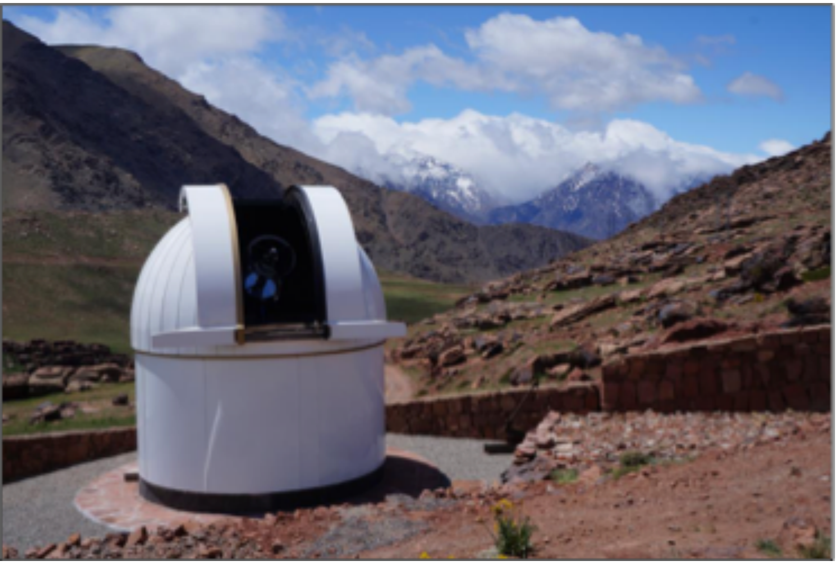
- Statistically, orbits of only a small fraction of planets allow for observation of transits:

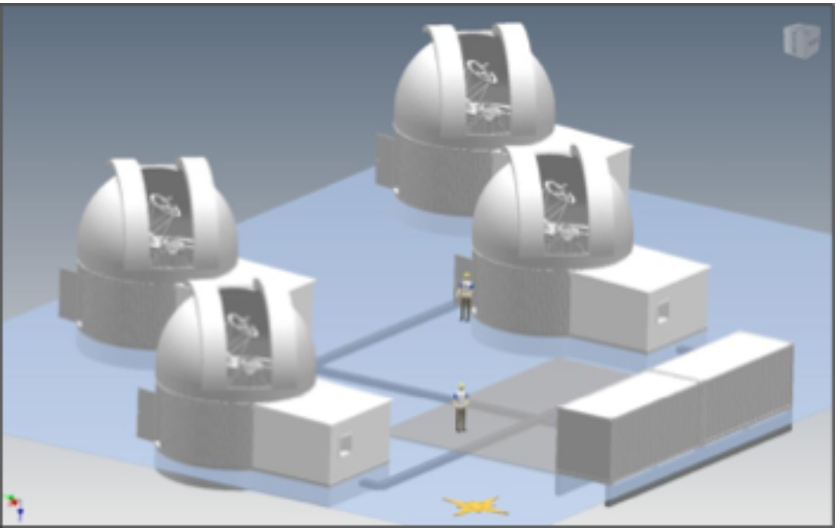
$P = \frac{D*}{D}$, where ***D*** is the star's orbit major axis.

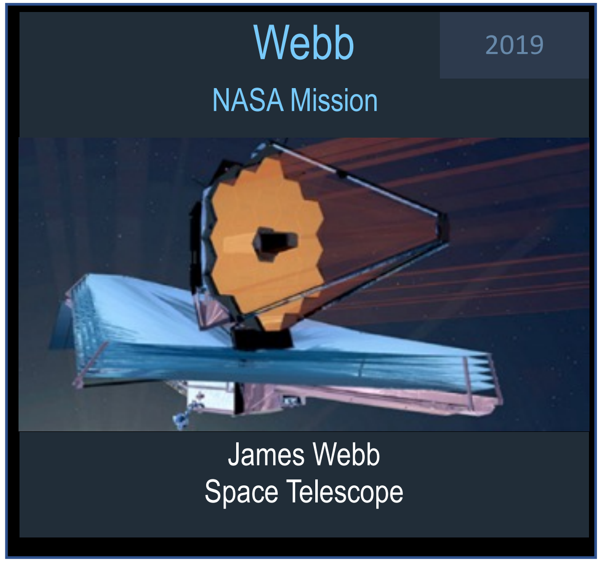


Transit Properties of Solar System Objects					
Planet	Orbital Period P (years)	Semi-Major Axis a (A.U.)	Transit Duration (hours)	Transit Depth (%)	Geometric Probability (%)
Mercury	0.241	0.39	8.1	0.0012	1.19
Venus	0.615	0.72	11.0	0.0076	0.65
Earth	1.000	1.00	13.0	0.0084	0.47
Mars	1.880	1.52	16.0	0.0024	0.31
Jupiter	11.86	5.20	29.6	1.0100	0.089
Saturn	29.5	9.5	40.1	0.75	0.049
Uranus	84.0	19.2	57.0	0.135	0.024
Neptune	164.8	30.1	71.3	0.127	0.015
	$P^2M^* = a^3$		13sqrt(a)	$\% = (d_p/d^*)^2$	d*/D

Telescopes on Earth, in air and space



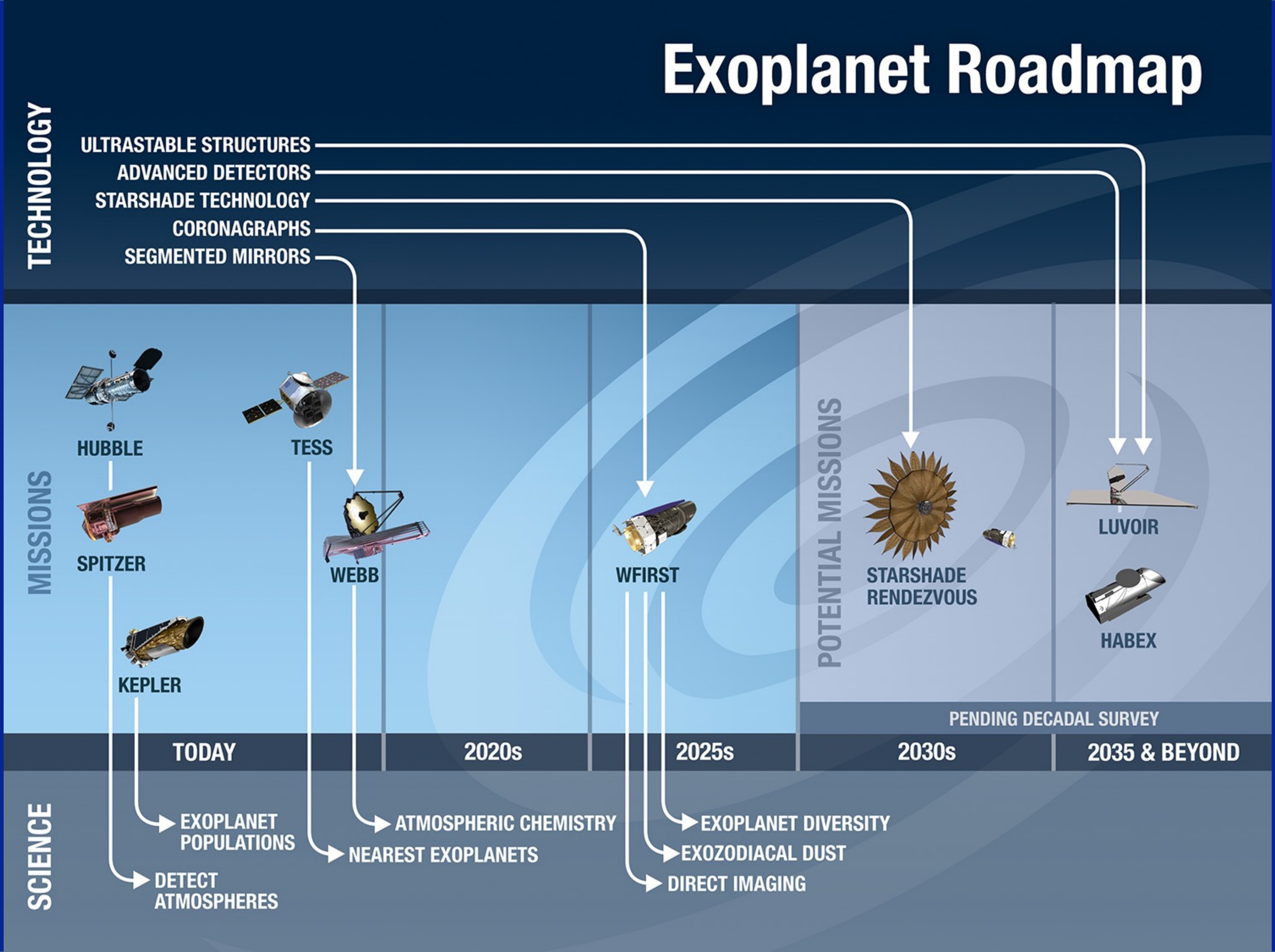




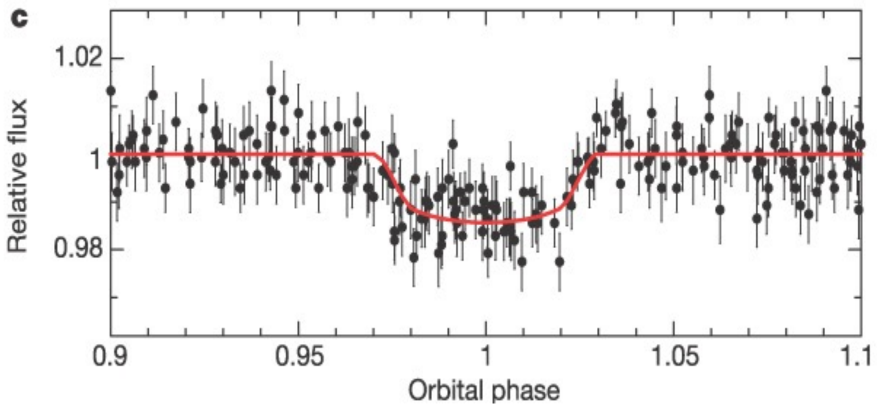
Spectral range and signal stability are limited by atmosphere

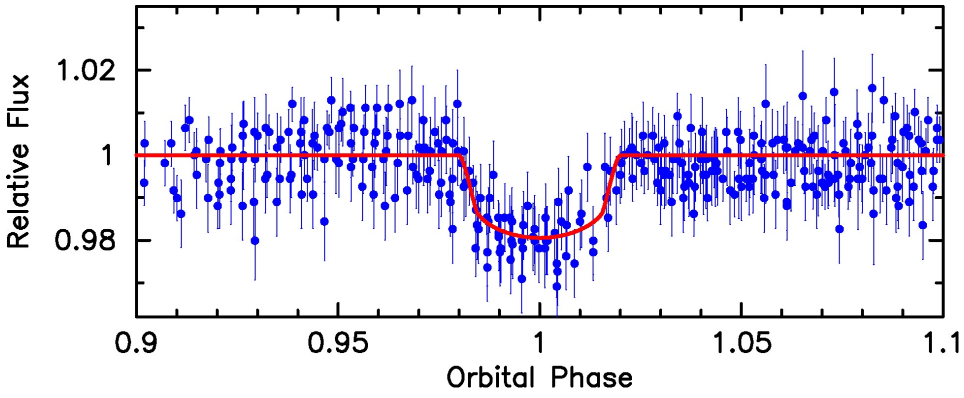
Any wavelength, but expensive and limited lifetime


+ MIDEX/MO (2023), SMEX/MO (2025), etc.
Spitzer
8/25/2003
Kepler
3/7/2009
Formulation
Implementation
Primary Ops
Extended Ops
Webb
2019
WFIRST
Mid 2020s
Euclid (ESA)
2020
Chandra
7/23/1999
XMM-Newton (ESA)
12/10/1999
NuSTAR
6/13/2012
Swift
11/20/2004
Fermi
6/11/2008
IXPE
2021
Hubble
4/24/1990
XARM (JAXA)
2021
ISS-NICER
6/3/2017
ISS-CREAM
8/14/2017
GUSTO
2021
SOFIA
Full Ops 5/2014
+ Athena (late 2020s), LISA (mid 2030s)
Revised
December 1, 2017

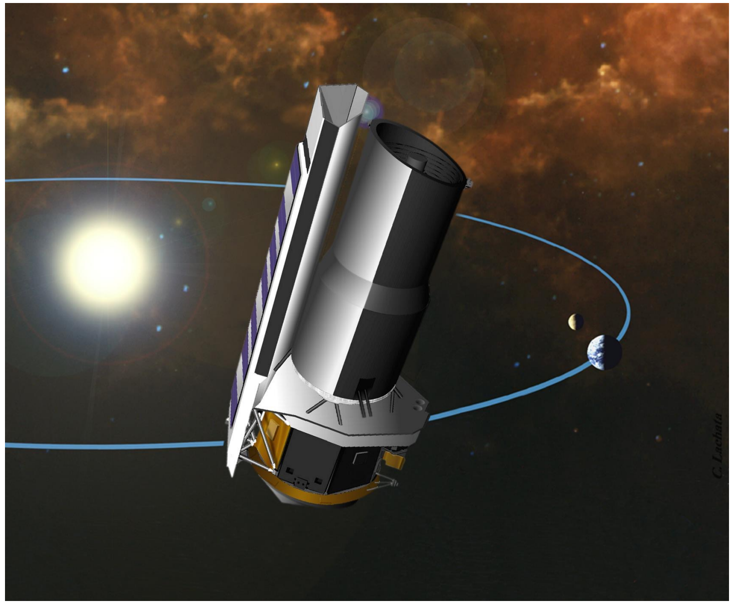

Exoplanet Roadmap
TECHNOLOGY
ULTRASTABLE STRUCTURES
ADVANCED DETECTORS
STARSHADE TECHNOLOGY
CORONAGRAPHS
SEGMENTED MIRRORS
MISSIONS
HUBBLE
TESS
SPITZER
WEBB
WFIRST
KEPLER
POTENTIAL MISSIONS
STARSHADE RENDEZVOUS
LUVOIR
HABEX
PENDING DECADAL SURVEY
TODAY
2020s
2025s
2030s
2035 & BEYOND
SCIENCE
EXOPLANET POPULATIONS
ATMOSPHERIC CHEMISTRY
EXOPLANET DIVERSITY
NEAREST EXOPLANETS
EXOZODIACAL DUST
DETECT ATMOSPHERES
DIRECT IMAGING

Detecting transients

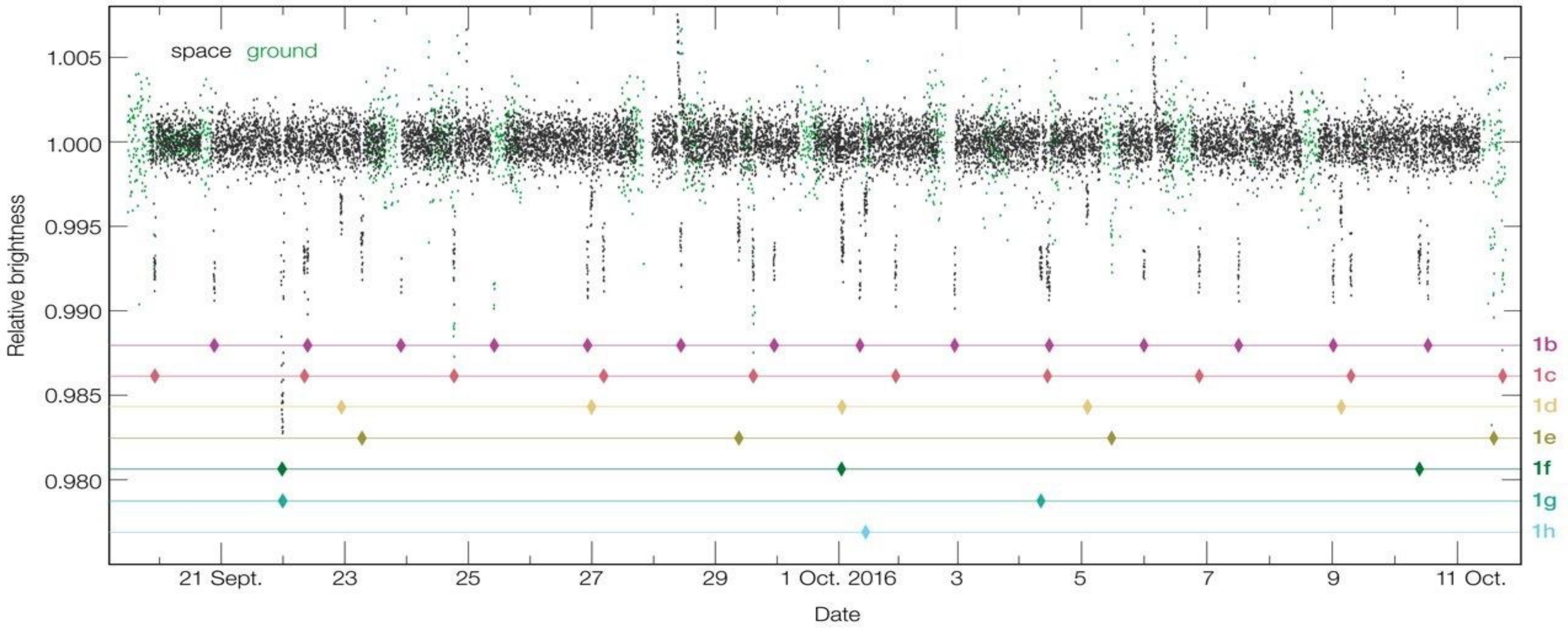




Transits of 2planets recorded by Earth-based telescopes over three months.

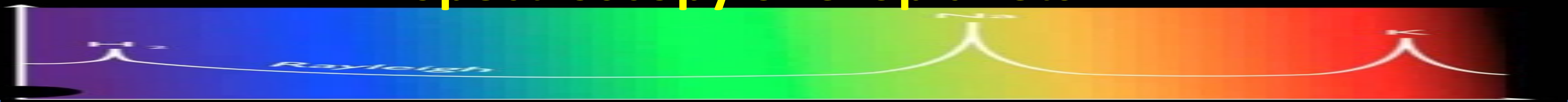


SPITZER orbital telescope (NASA, 2016)



34 transits during 20 days of observation

Spectroscopy of exoplanets

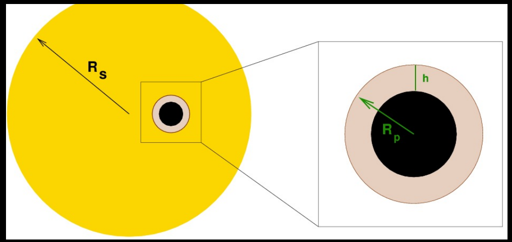


1. Transmission

Detects spectrum of the star light that is attenuated by the planet atmosphere

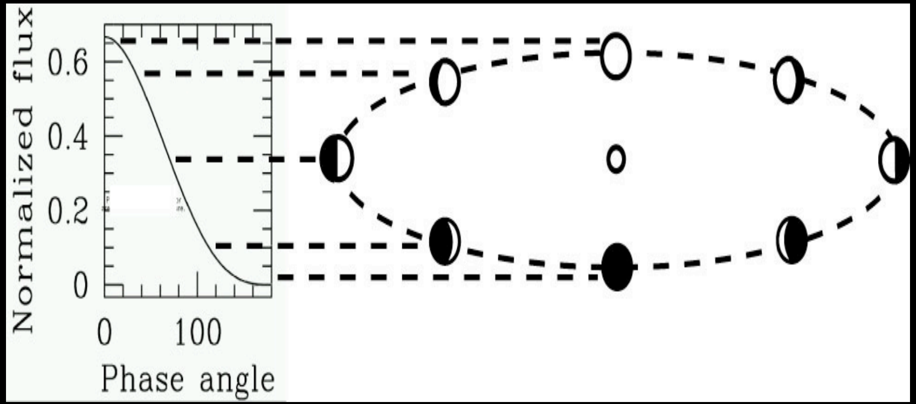
a) Measure spectrum of the star without planet (out of transient)
b) Measure spectrum of the star with the planet (during transient)
c) The spectrum of the planet is the difference of the two.

The sensitivity is governed by the relative thickness of atmosphere. The most sensitive method.



2. Reflection

a) Measure spectrum of the star.
b) Measure spectrum of the light reflected from the planet, when it is further than the star from the observer, but outside of the star disc.
c) The difference gives absorption by the atmosphere and by the surface together.



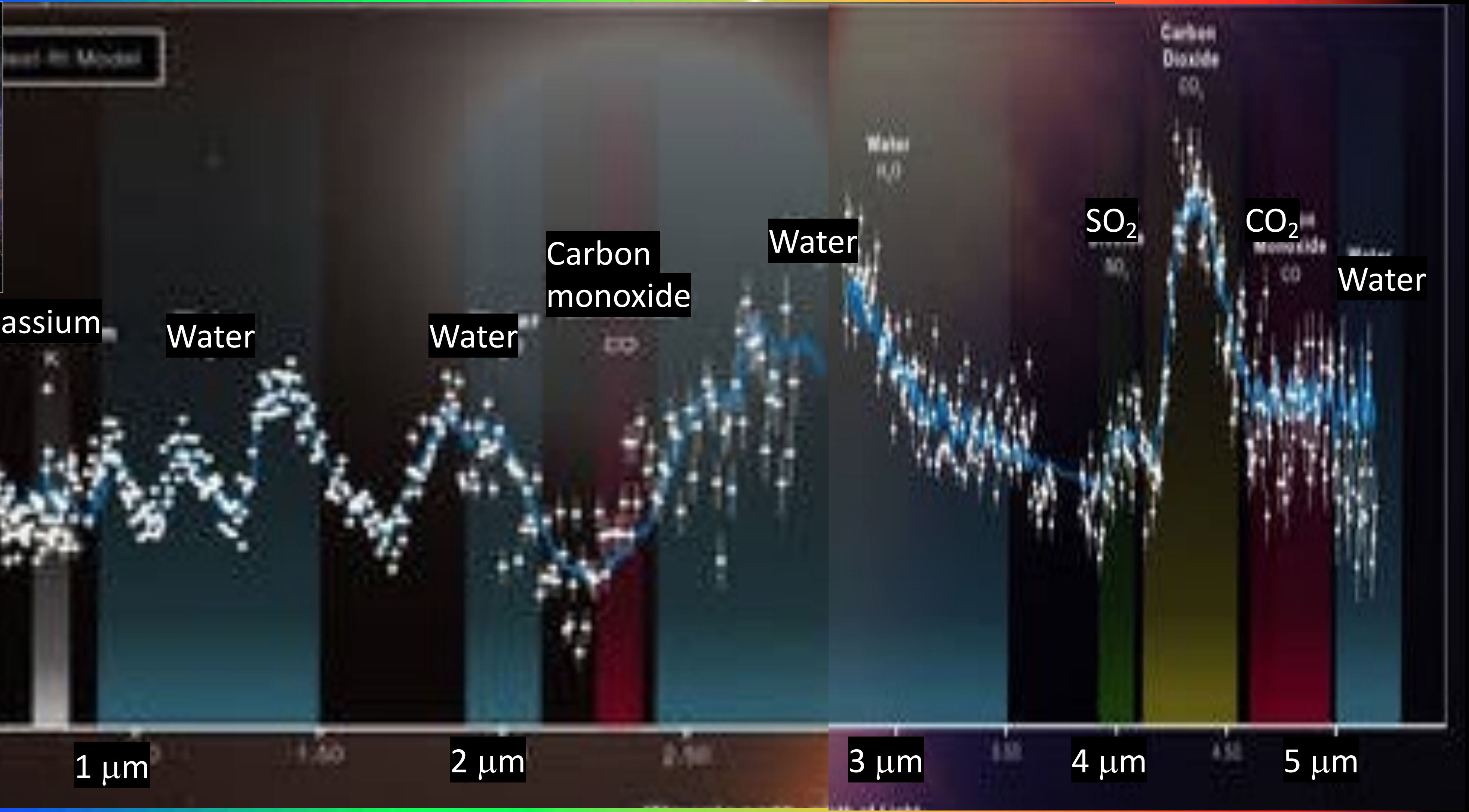
3. Emission

Detects spectrum of the planet, when it is closer than the star to the observer, but outside of the star disc.

Gives information on chemistry of the planet atmosphere, but also of its surface.

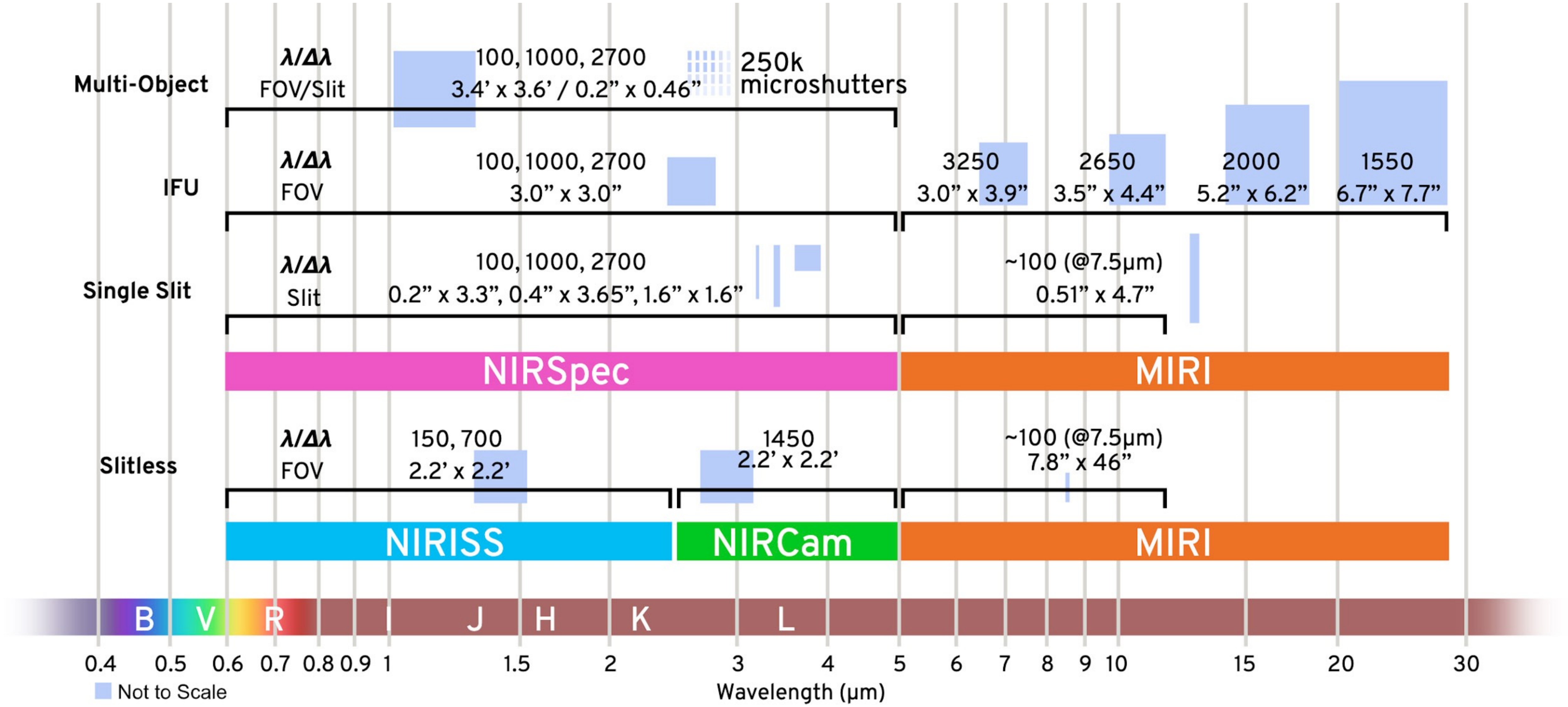
What we are looking for?

Biomarker gases: **O_2, O_3, CH_4, CO_2**



James Webb space telescope, March 2023

Webb instrumentation



NIRSpec

Mechanisms:

• Filter Wheel Assembly (FWA) – 8 positions, carrying 4 long pass filters for science, 2 broadband filters for target acquisition, one closed and one open position
• Micro Shutter Assembly (MSA) – for multi-object spectroscopy but also carrying the fixed slits and IFU aperture
• Grating Wheel Assembly (GWA) – 8 positions, carrying 6 gratings and one prism for science and one mirror for target acquisition

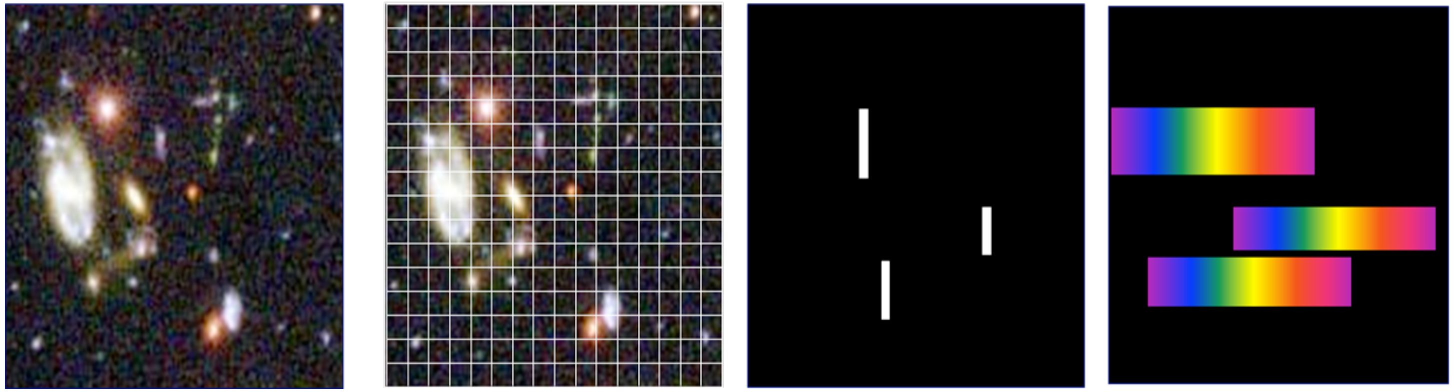
Operational temperature 38 K

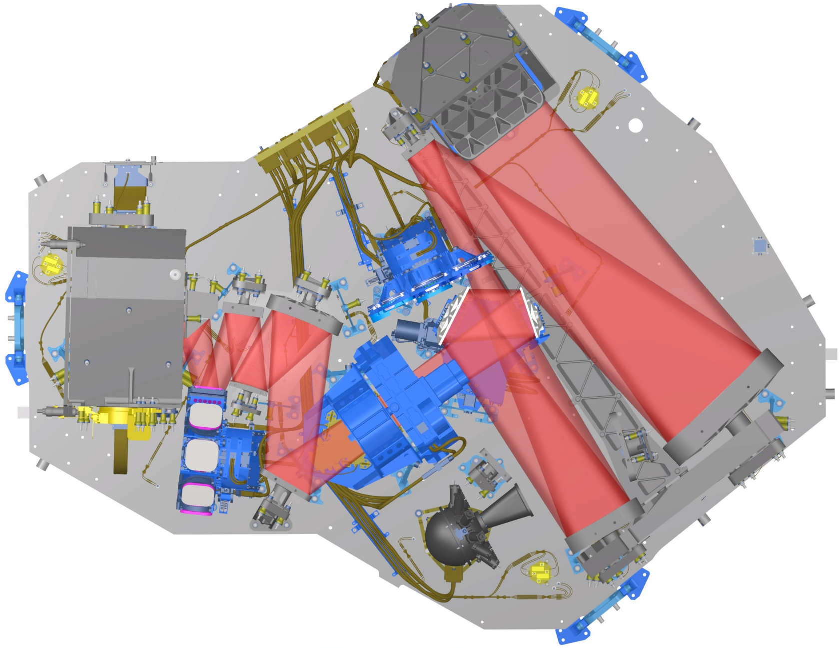
Operational modes:

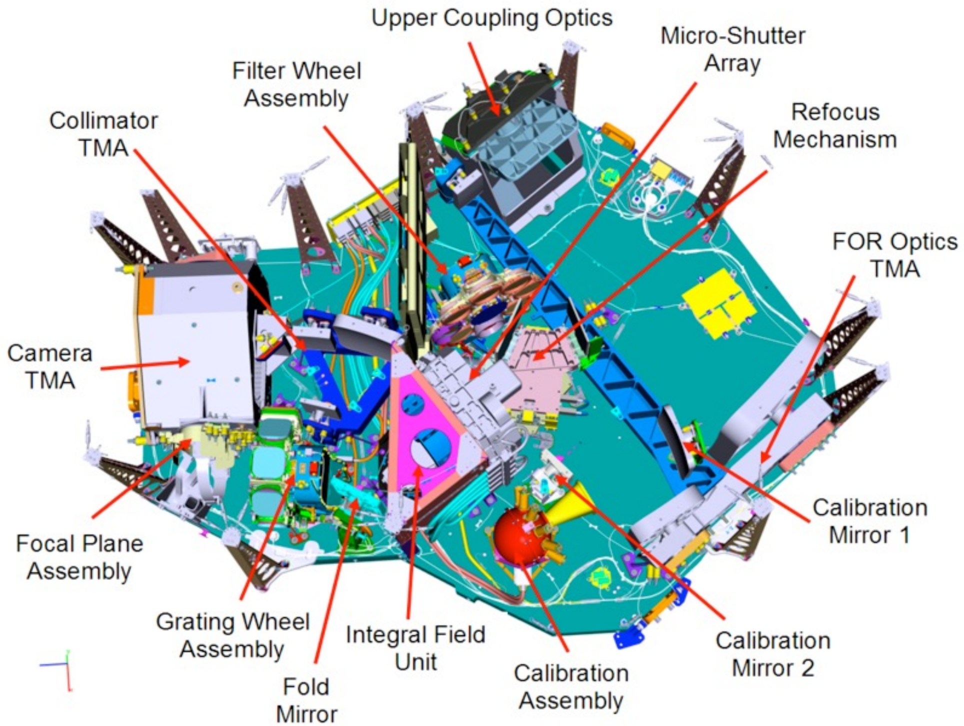
- Multi-Object Spectroscopy (up to 100 objects at time)
- Integral Field Unit (spatially resolved objects like galaxies; up to 30 slices)
- SLIT (narrows field of view; e.g., for transits)
- Image (photos)

Multi-object spectroscopy (4 arrays of 250 000 micro shutters)

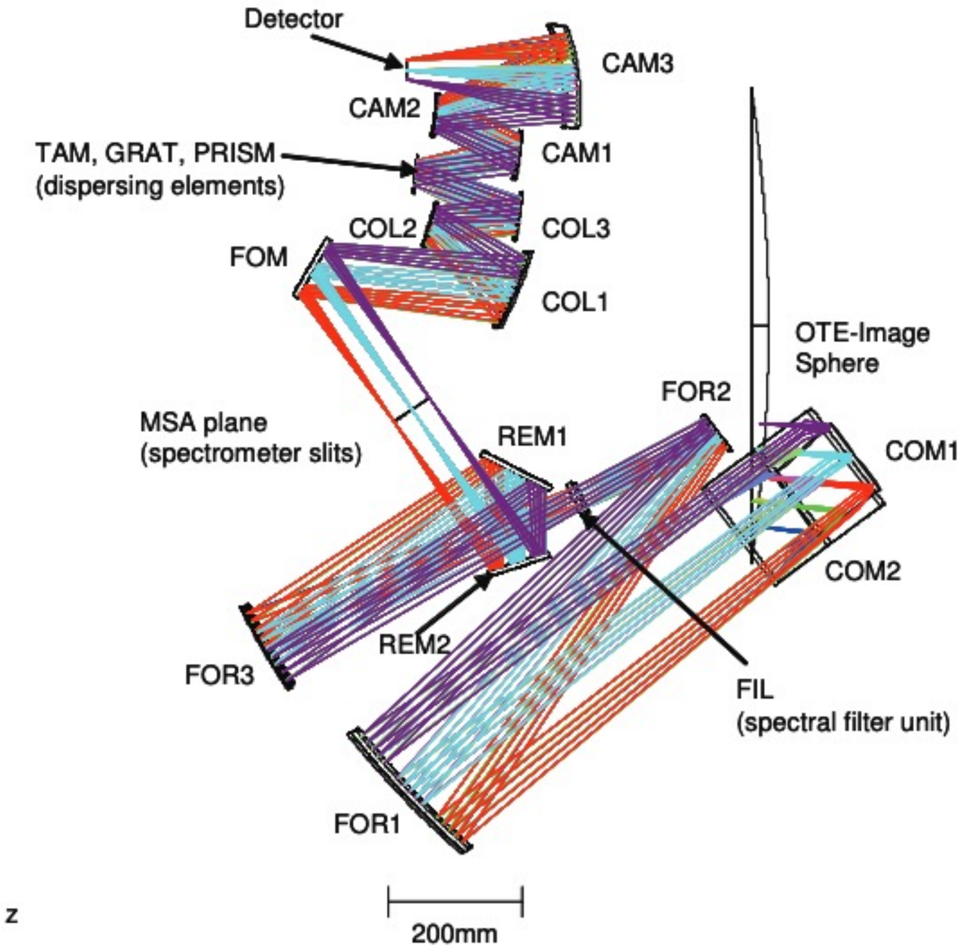
Scene on the sky | **Scene on the shutter mask** | **Selection of Objects** | **Spectra on the detector**

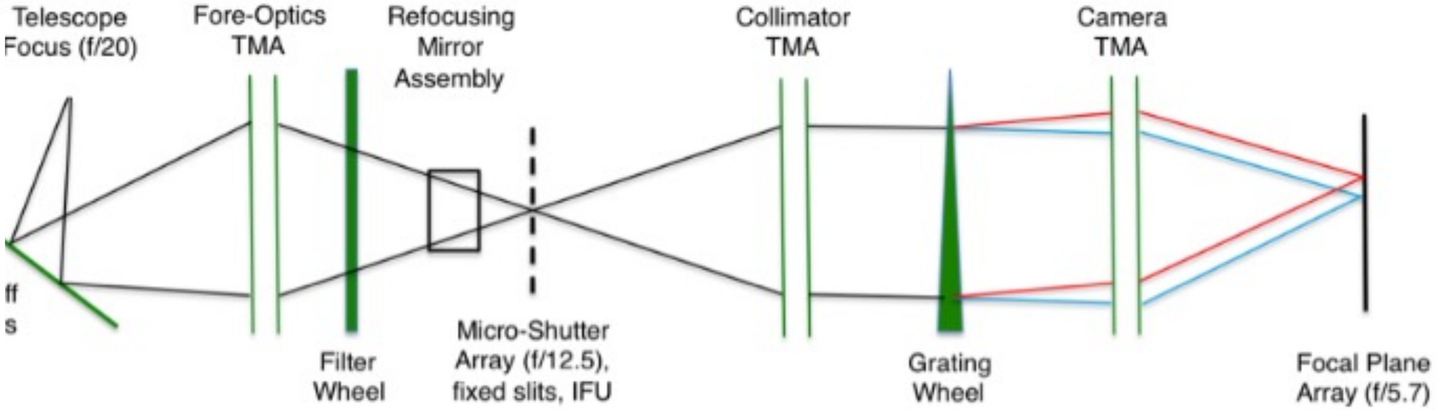




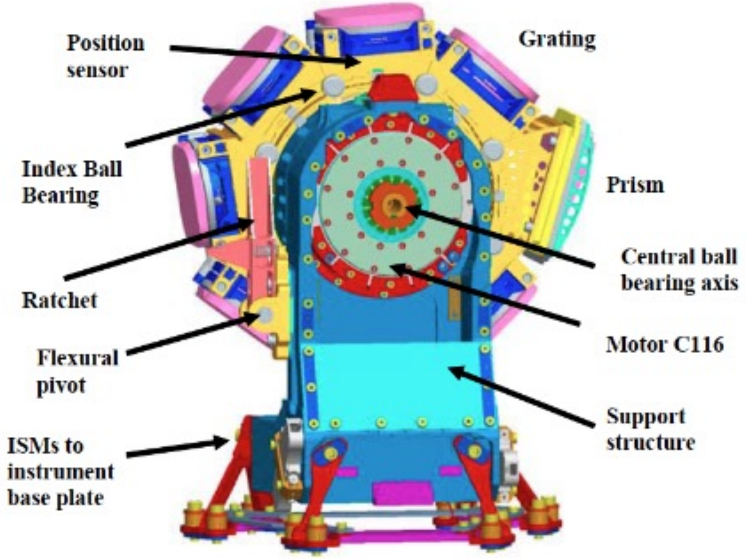


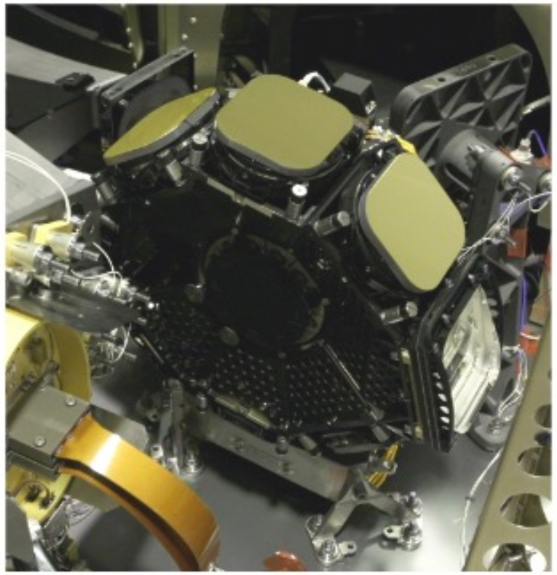
NIRSpec





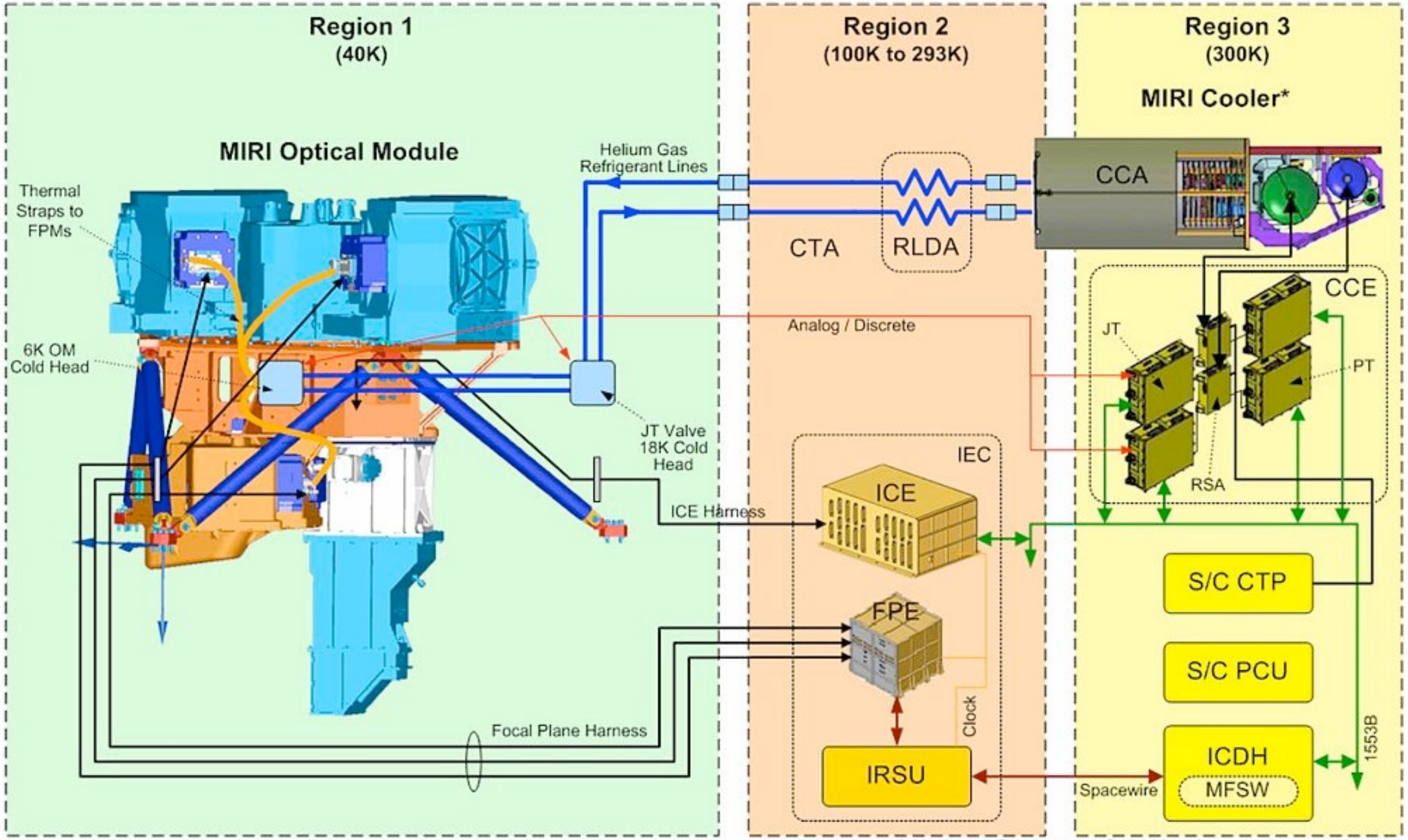
Simplified optical scheme



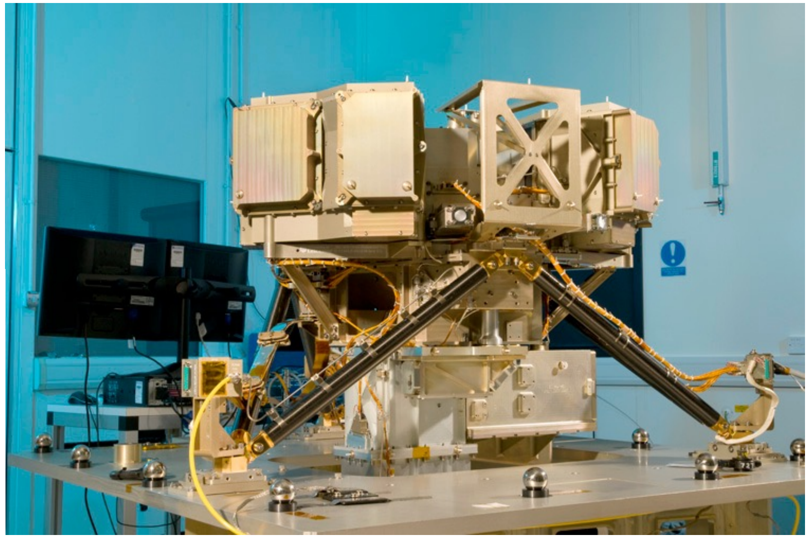


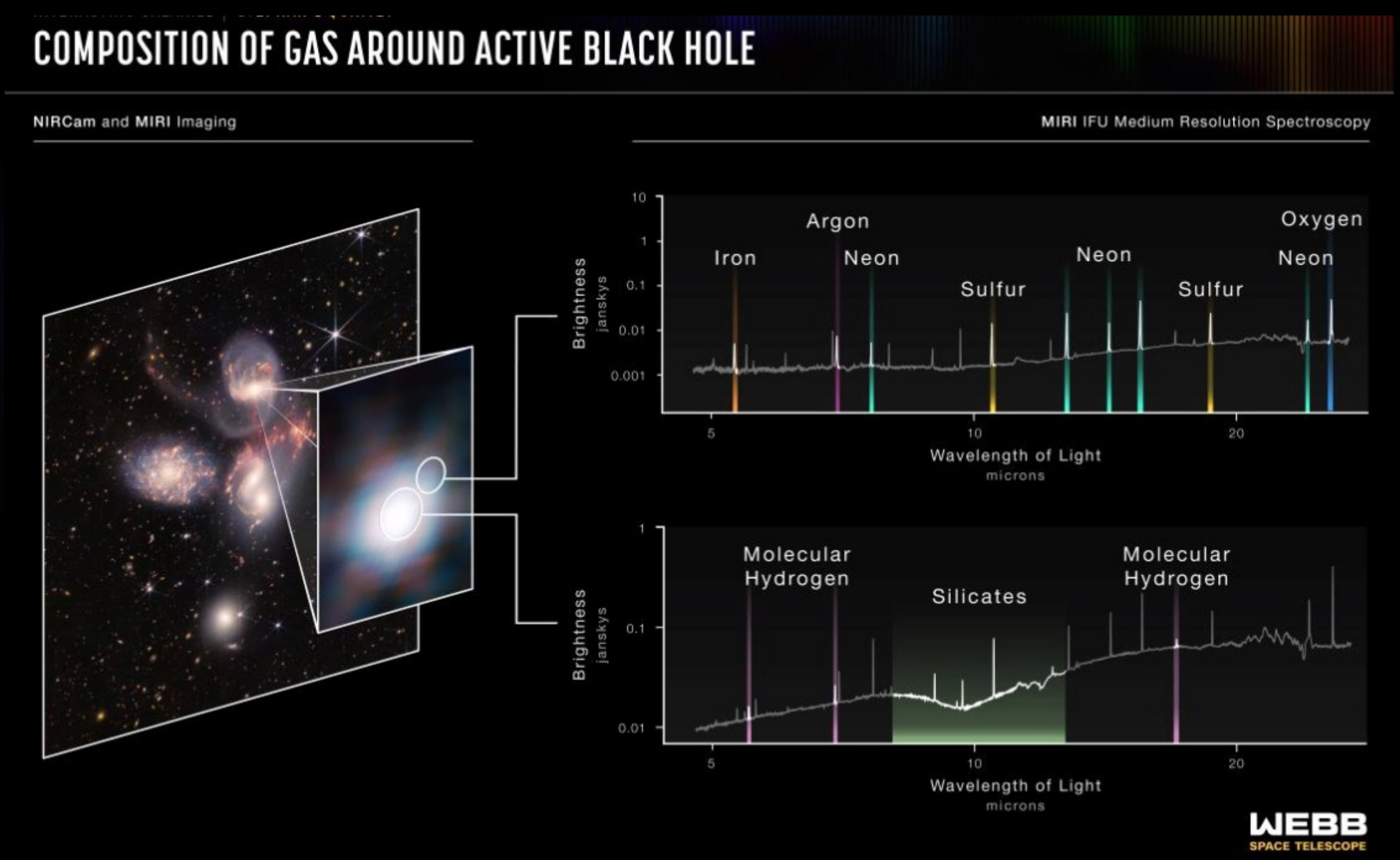
MIRI (4.6-28.6 μm)

Operational temperature 7 K



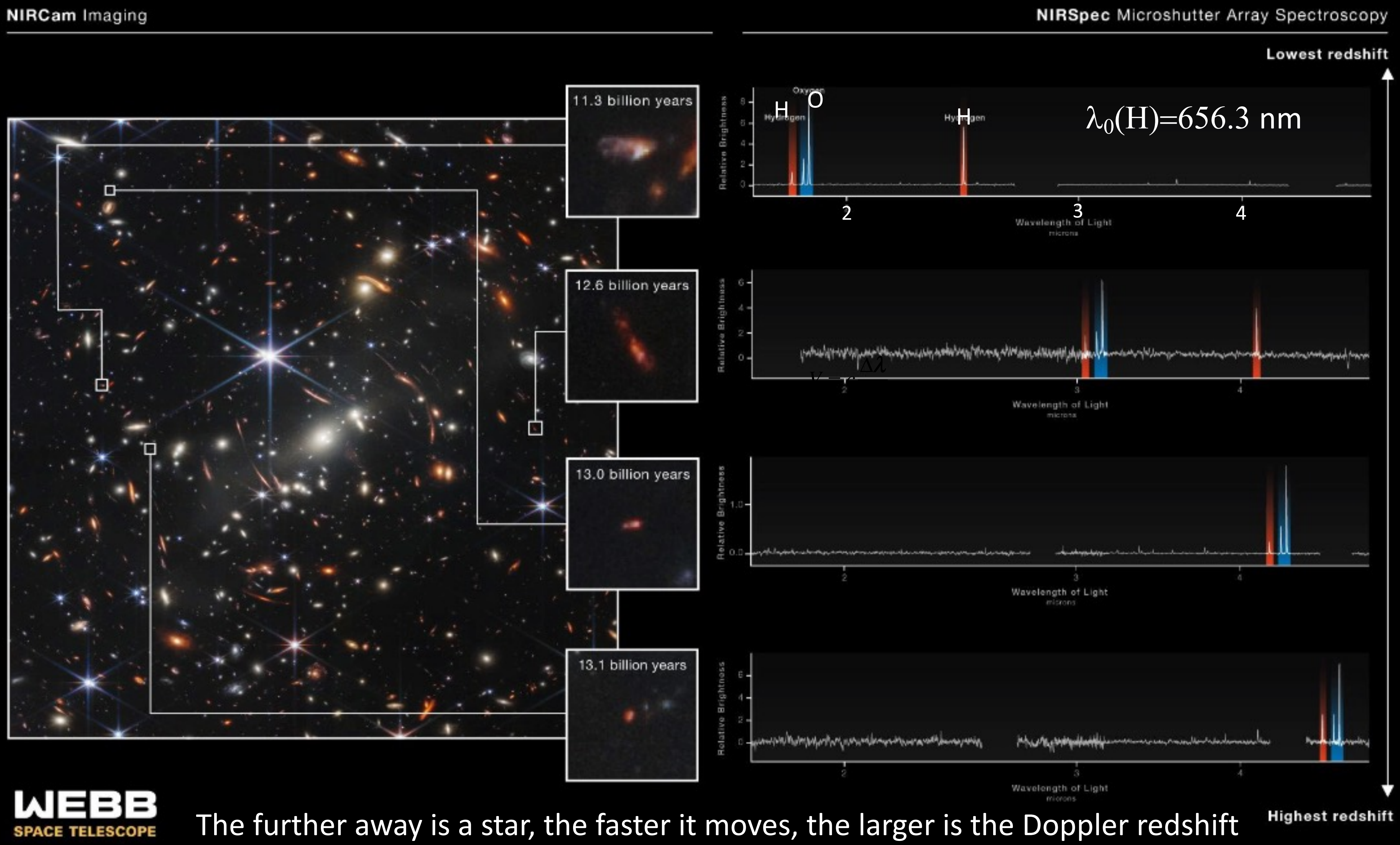
* Notional Cooler and Cold Head arrangement shown





The bright white "spots" and "streaks" are high-altitude clouds of condensed convective storms. Dark ribbons north of the equatorial region have little cloud cover. The large pink spot is narrow jet stream traveling 515 kilometres per hour.

WEBB determines age of galaxies by measuring doppler shift



$$V = c\frac{\Delta\lambda}{\lambda}$$

The further away is a star, the faster it moves, the larger is the Doppler redshift

Webb images: “Cosmic Cliffs” in the Carina Nebula (NIRCam and MIRI Composite Image)