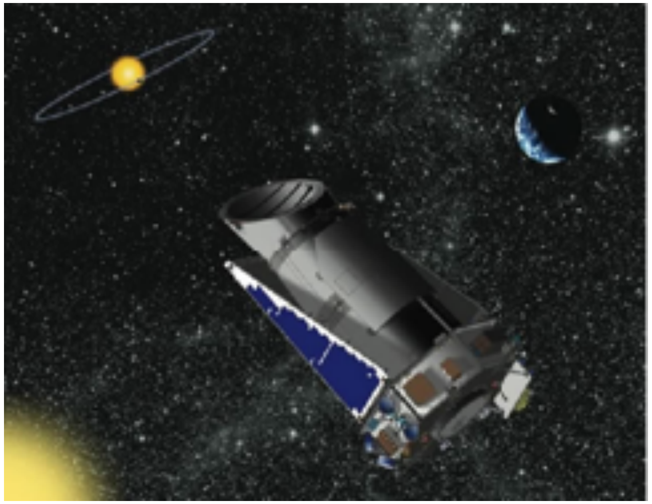
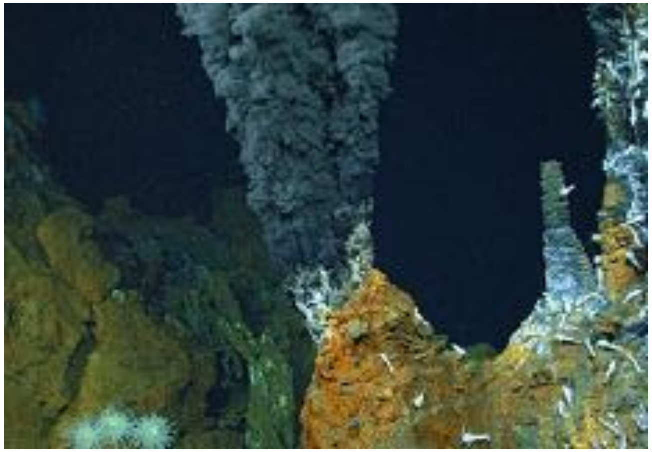
Lecture 13: Planetary Atmospheres, Exoplanets, Water, Life and all that …

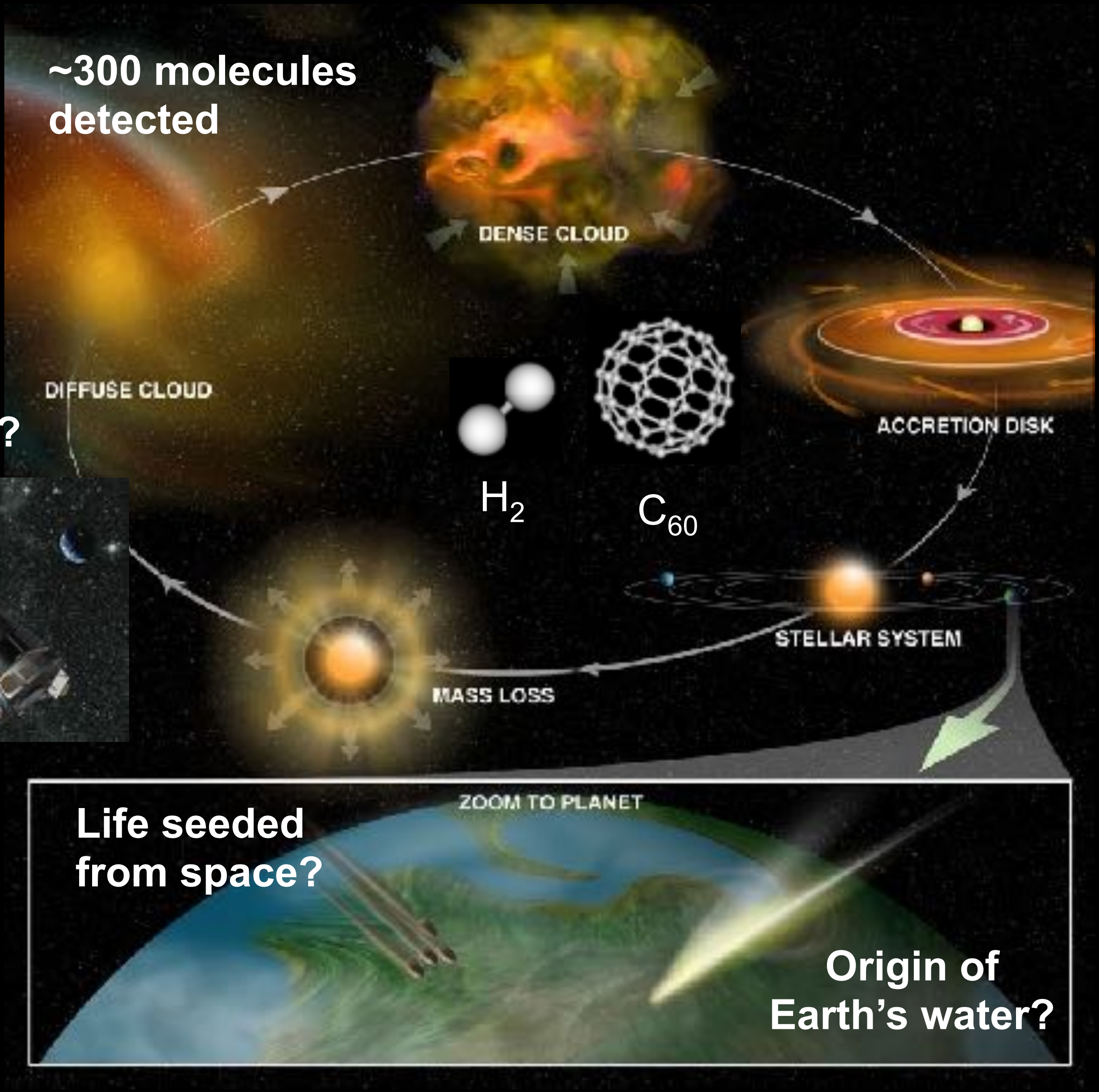


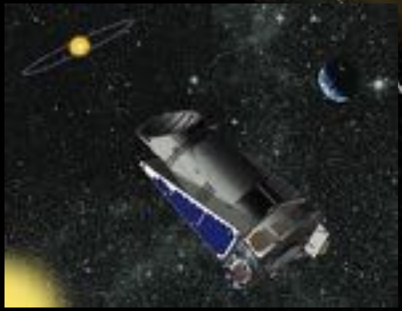


Outline

- Exoplanets: Detection techniques, Statistics, Surprises, ...
- Origin of Life: Theories, Key prebiotic syntheses, Habitability, ...

From Molecules in Space to the Origin of Life



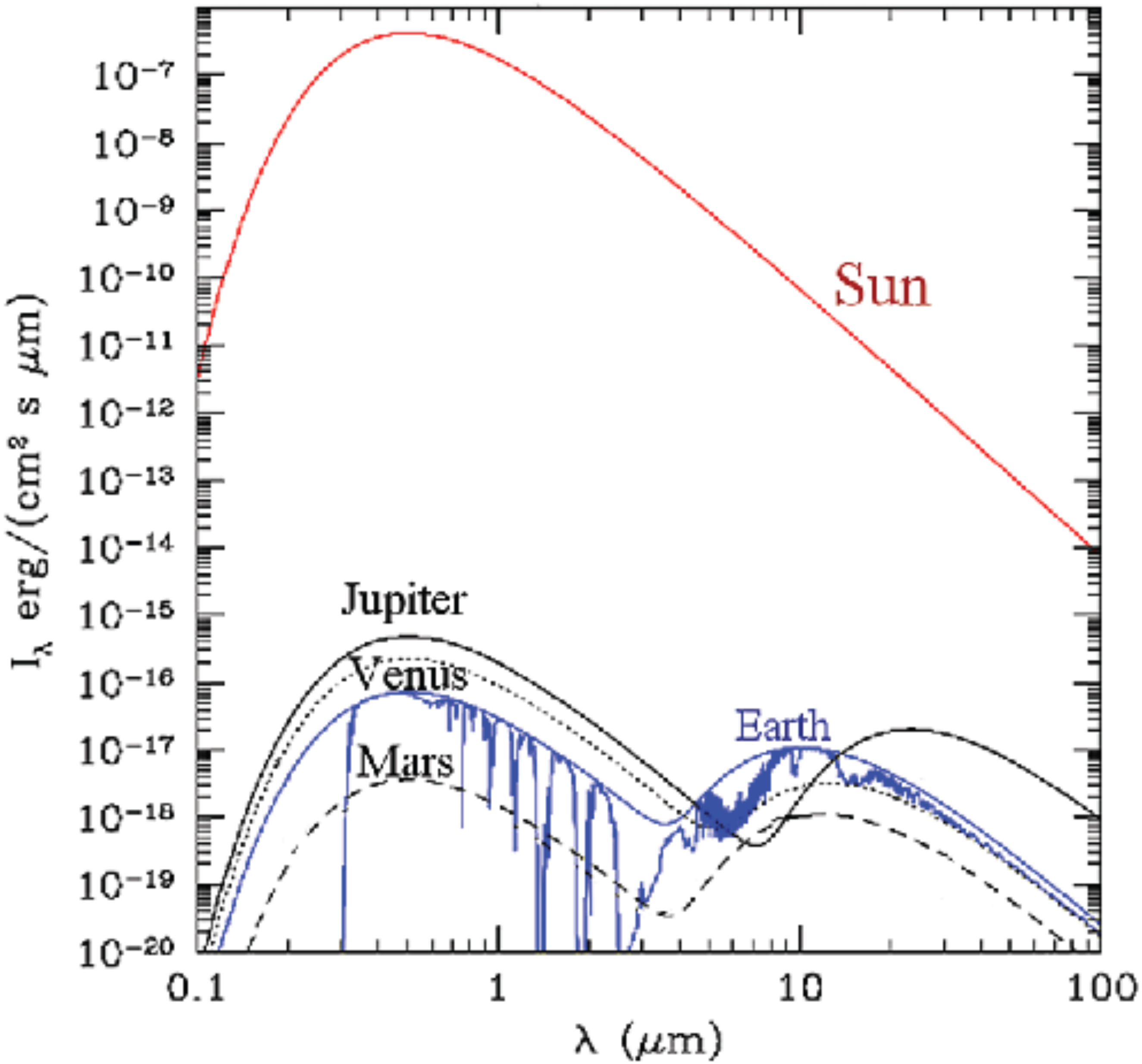


Life on exoplanets?

Credit: Bill Saxton
NRAO/AUI/NSF

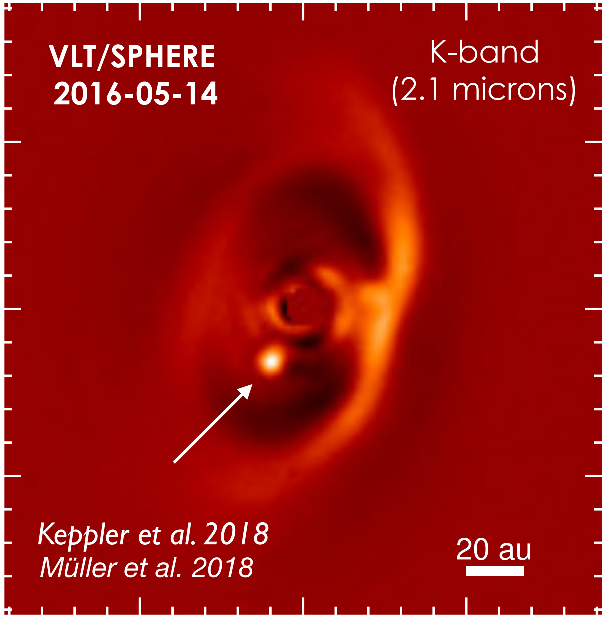
Extrasolar Planets: Why are they hard to detect?

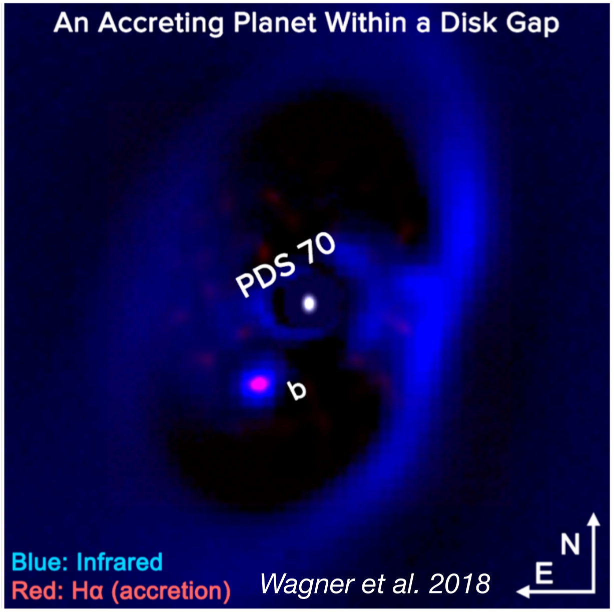
The light flux of a planet is lower by ~10 orders of magnitude wrt the central star

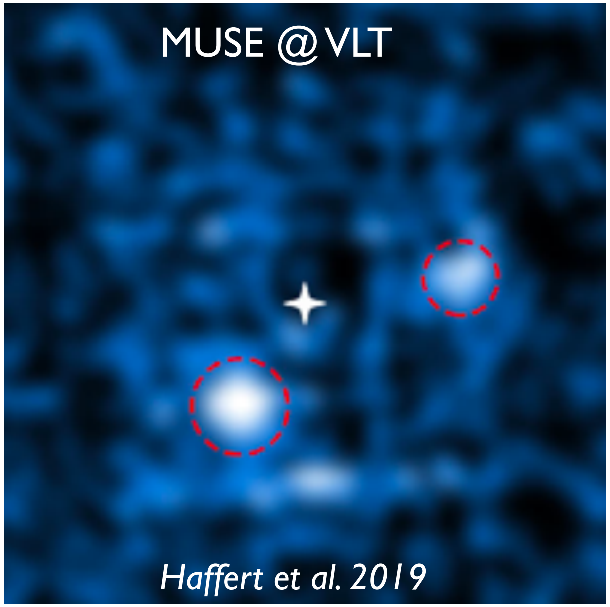


Kaltenegger et al, Astrobiology 10, 1 (2010)

Young gas planets in PDS70 disk

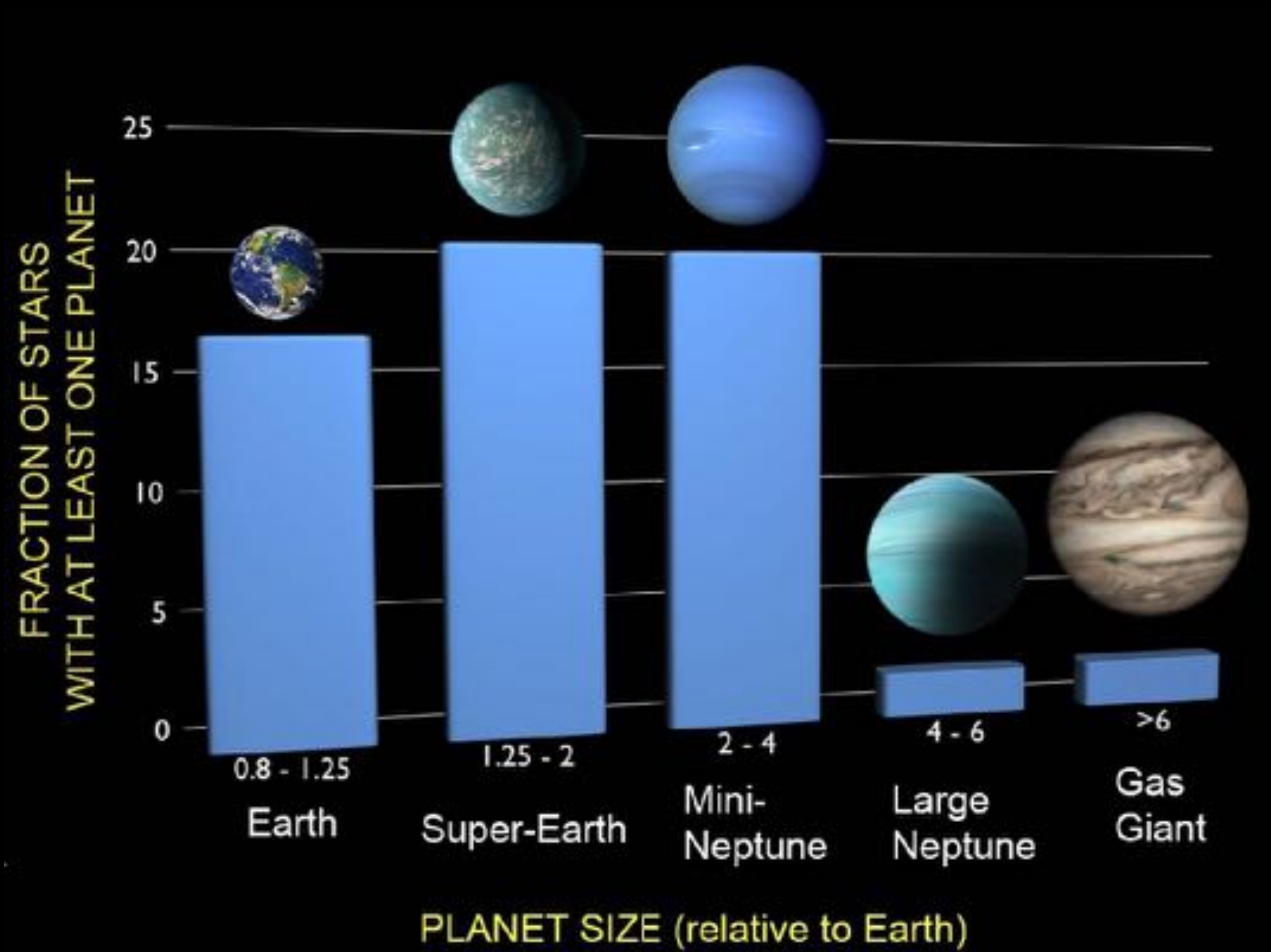






- Sun-like star with disk, ~ 5 Myr old
- Two gas giant planets at 21.5 and 35.5 au (2:1 resonance)
- Planets are accreting gas
- Hubble and JWST spectroscopy

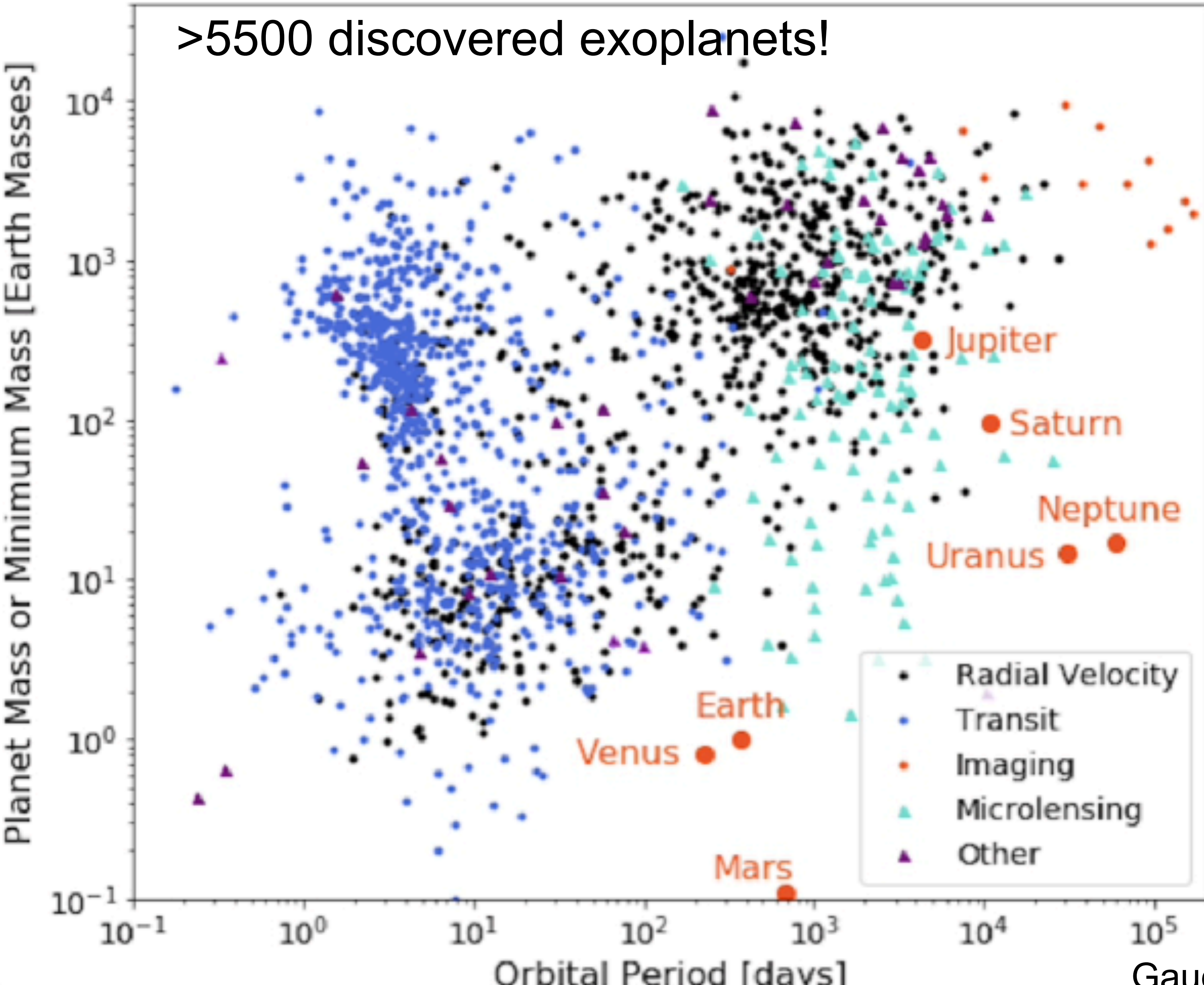
Almost every sun-like star has a planet



Based on Kepler statistics corrected for incompleteness and false positives

Credit: F. Fressin (CfA)

Exoplanetary statistics: https://exoplanet.eu/



Gaudi et al. (2020)

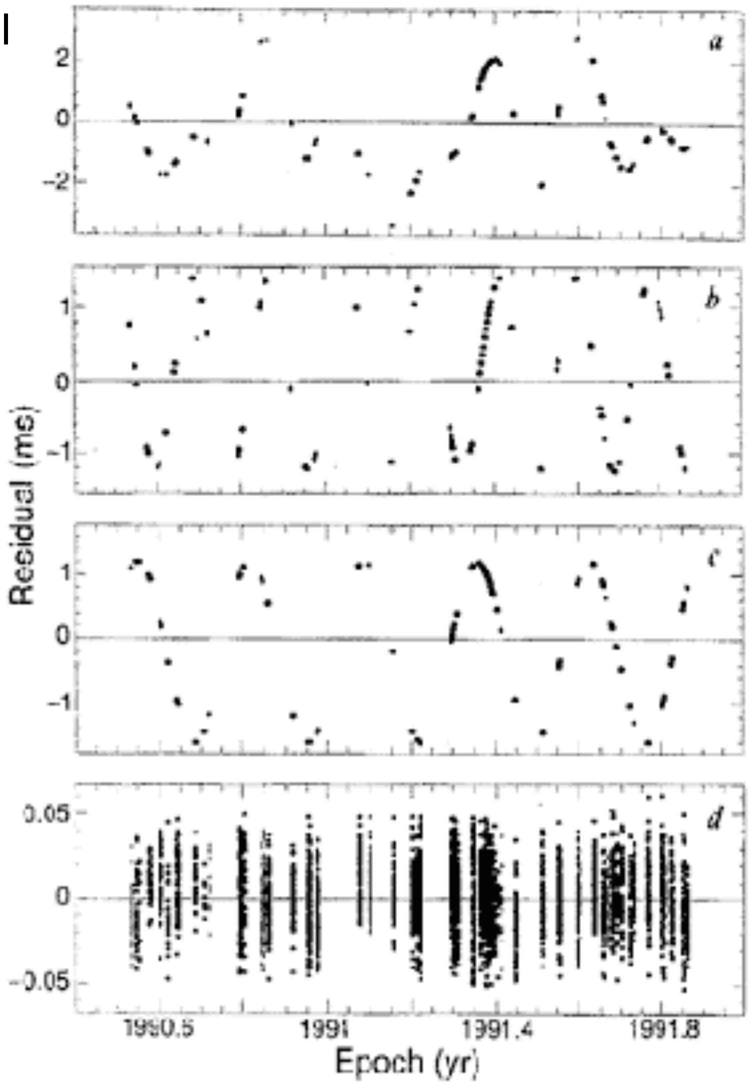
The First Exoplanet Detection – Pulsar Timing
(Pulsar: fast rotating neutron star)

Pulse arrival time residuals

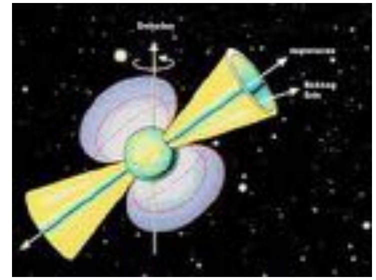
Fitting for a 98 day periodicity

Fitting for a 66 day periodicity

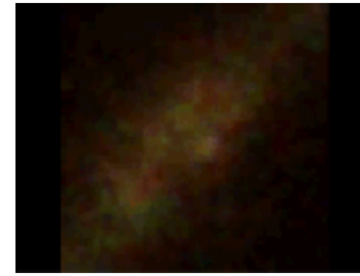
Fitting for both 98 and 66 day periodicities



Wolszczan & Frail, Nature 355,145 (1992)



Source: wikipedia

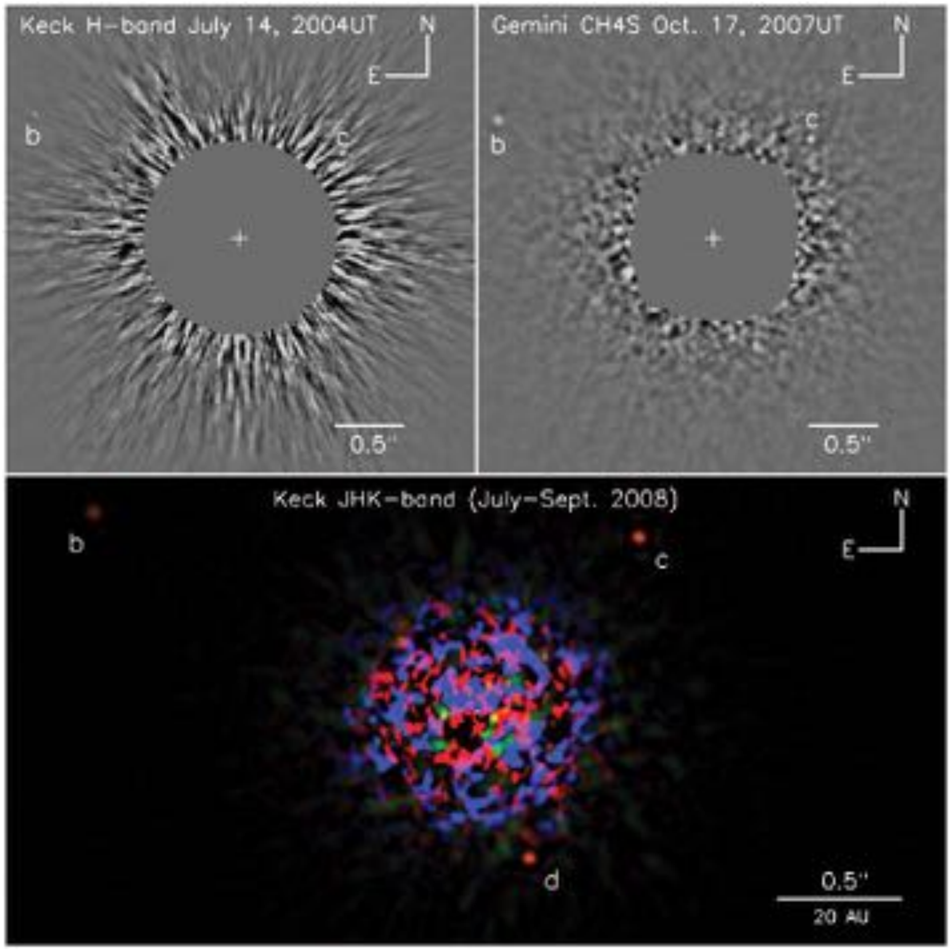


Slow motion

- Millisecond radio pulsars allow for precise timing measurements
- 1st confirmed exoplanet detection by Wolszczan & Frail (1992) found 2 roughly earth-mass planets
- Even very small planets can be detected (~1/10 M_{earth})
- Not suitable for large searches due to scarcity of pulsars
- Orbiting planets unlikely to be habitable

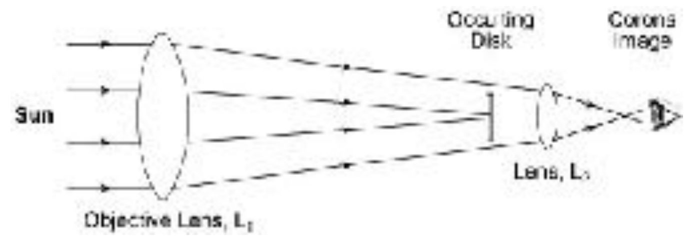
Observations: Arecibo telescope

Exoplanet detection – Direct Imaging



Marois et al. 2008

- With a coronagraph to block the stellar light, direct imaging is possible

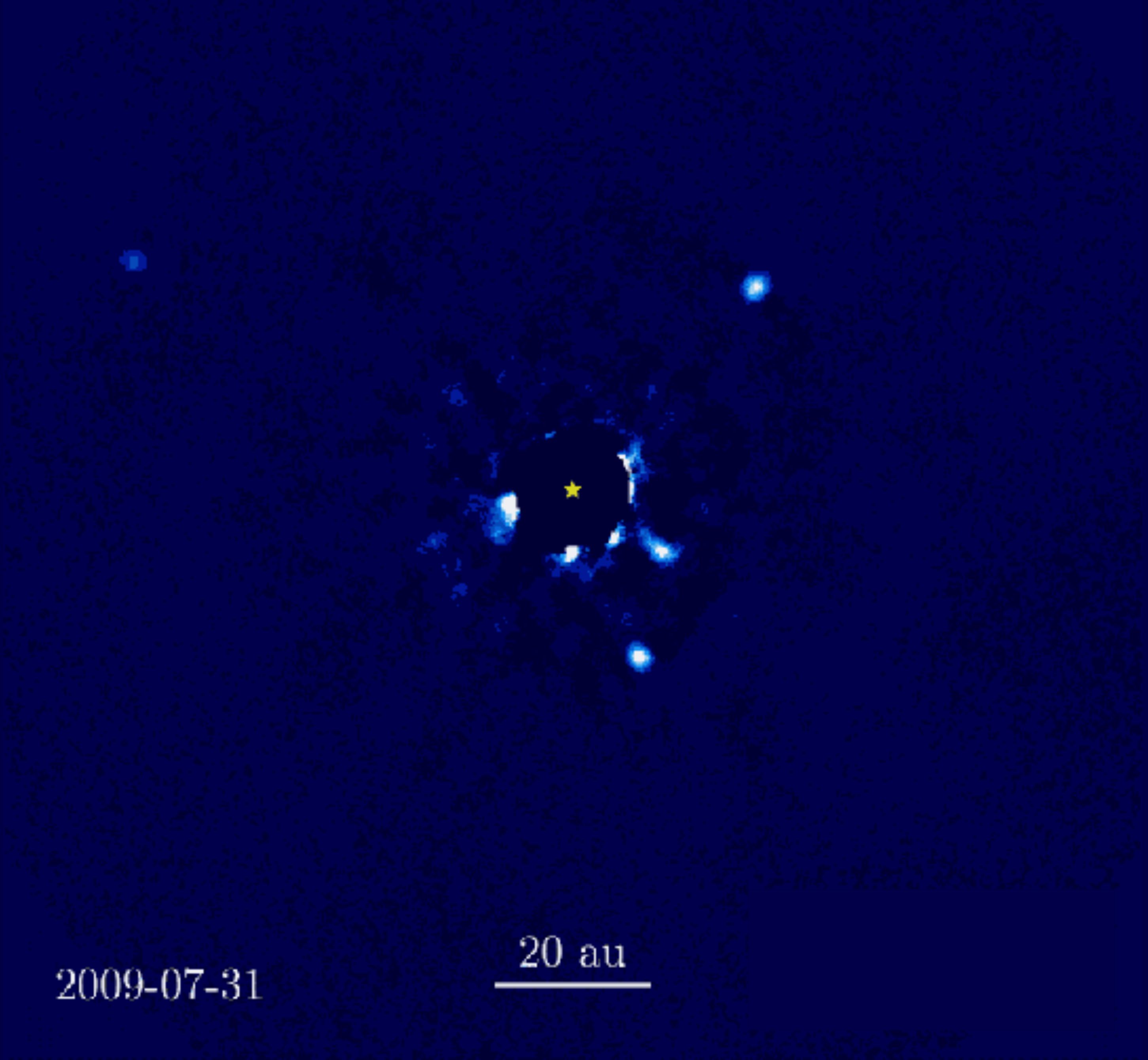


- High contrast imaging leaves residual speckle artifacts

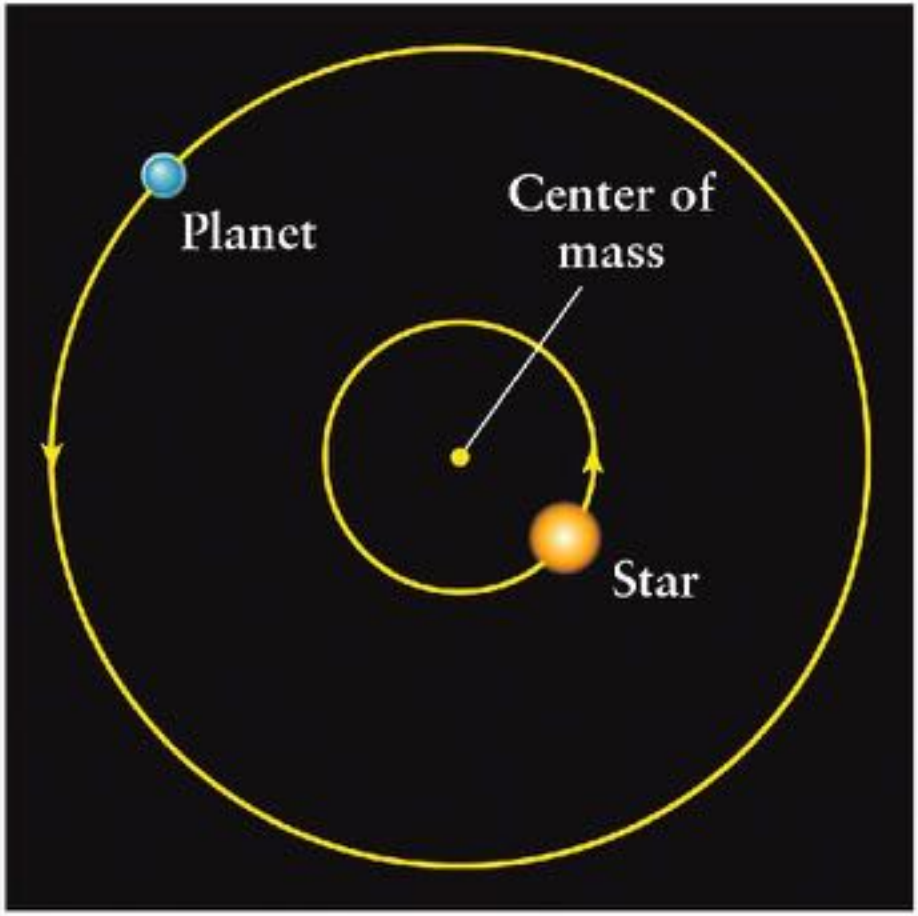
- Requires large orbits and large planets: > a few M_{jup}, with orbital separation > 100 - 1000 AU

Keck and Gemini telescopes

Exoplanets around HR 8799 (optics), Keck 10m



Exoplanet Detection – Radial Velocity / Astrometry



//www.astro.wisc.edu/~townsend/

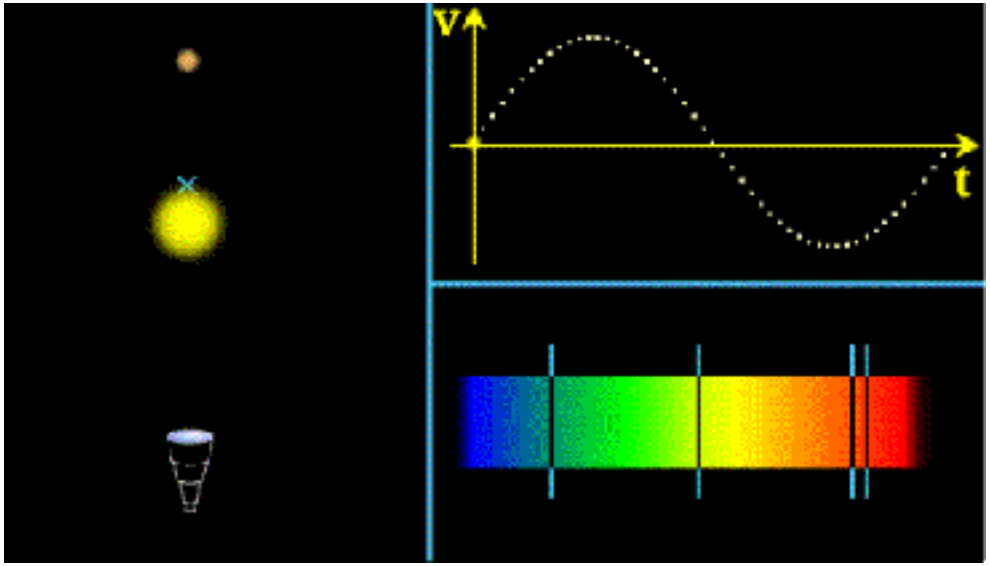
Radial velocity

• Wobble in stellar position due to gravitational influence of orbiting planet
• Detect Doppler shift due to wobble spectroscopically

Astrometry

- (2D position on the sky) also possible for detecting wobble,
- requires ~1 milli-arcsecond accuracy**: GAIA!**

Exoplanet Detection – Radial Velocity



Credit: Observatorio de París / ASM Emmanuel Pécontal

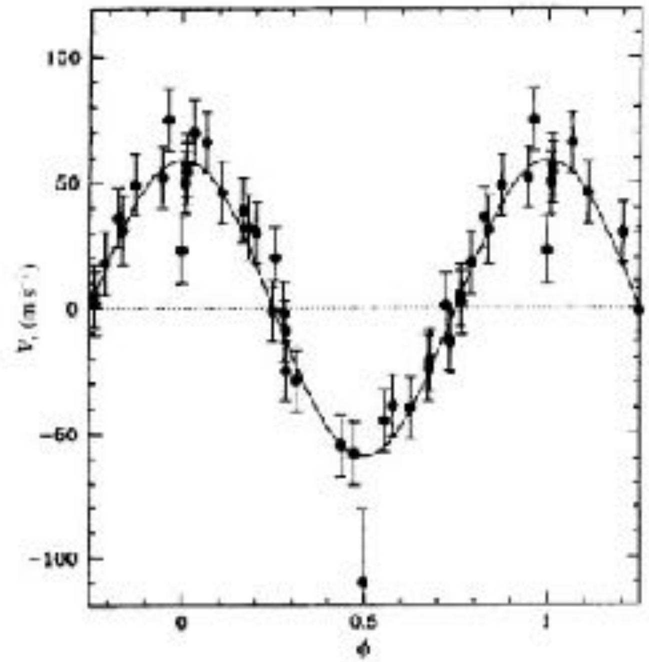
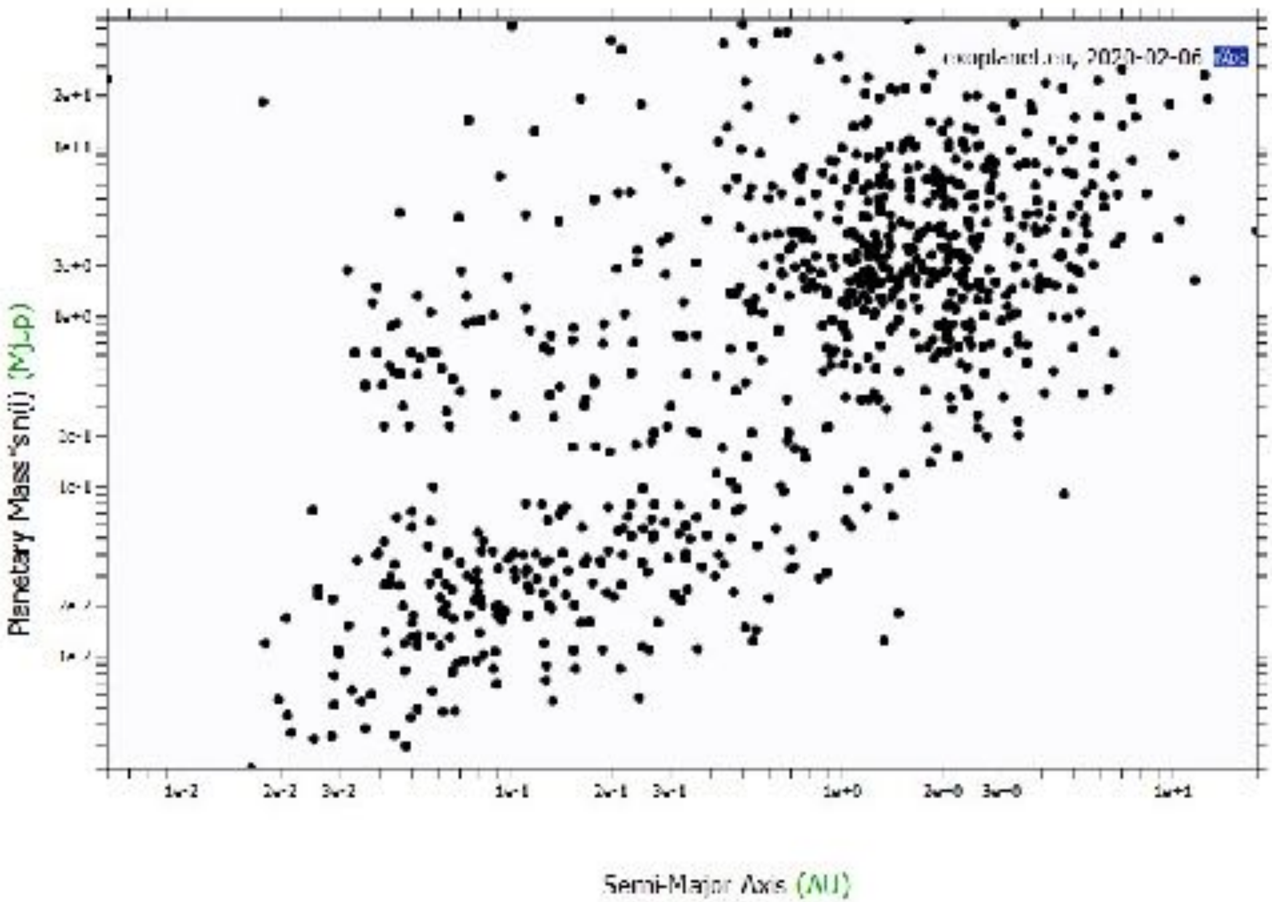


Fig. 5 Original radial velocity curve of the star 51 Peg, phased to a period of 4.23 days, obtained with the ELODIE spectrograph (Mayor & Queloz 1995). The signal is caused by an orbiting companion with a minimum mass of 0.47 M_{Jup}, revealing for the first time an exoplanet around another solar-type star.

- Wobble in stellar position due to gravitational influence of orbiting planet
- Detect Doppler shift due to wobble
- Can be done with earthbound telescopes and accurate spectrometers

Nobel prize of 2019
Michel Mayor,
Didier Queloz

Exoplanet detection – Radial Velocity



- Uncertainty in inclination leads to sin(i) uncertainty in planet mass
- Stellar spectrum variations limit current accuracy to ~1 m/s
- Particularly sensitive to detecting close-in and massive planets
- Requires long monitoring time to detect long orbits

Planets detected by radial velocity:
shown are 822 of 882 (exoplanet.eu / 06 Feb 2020)

Limits of radial velocity method: accuracy 1 m/s
Observation time: 7.5 years
(to observe complete orbit)

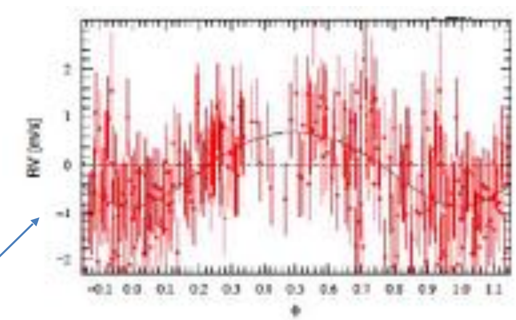
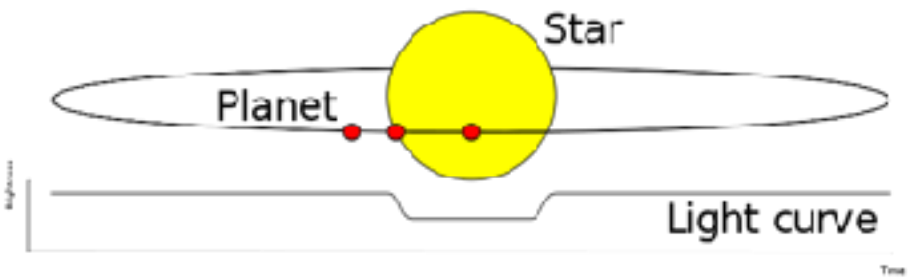


Fig. 2.— The phase-folded data for the detection of a planet orbiting HD 85512 (Figure 1) from Pepe et al. 2011).

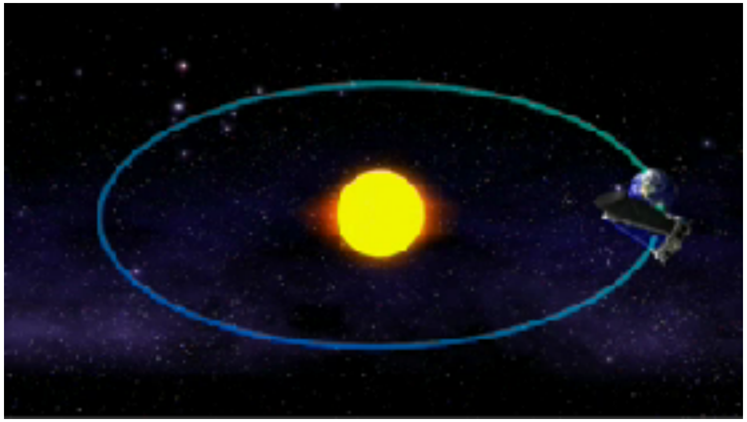
Exoplanet detection – Transit



Wikipedia, "Methods of detecting extrasolar planets"

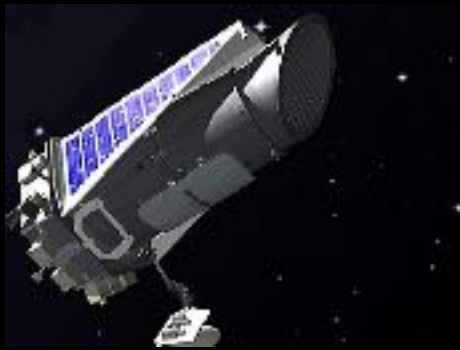
Drop in brightness: $\text{Depth} = \left(\frac{R_p}{R_\star}\right)^2$

Kepler's sole scientific instrument is a photometer that continually monitors the brightness of over 145,000 main sequence stars in a fixed field of view. (Wikipedia)

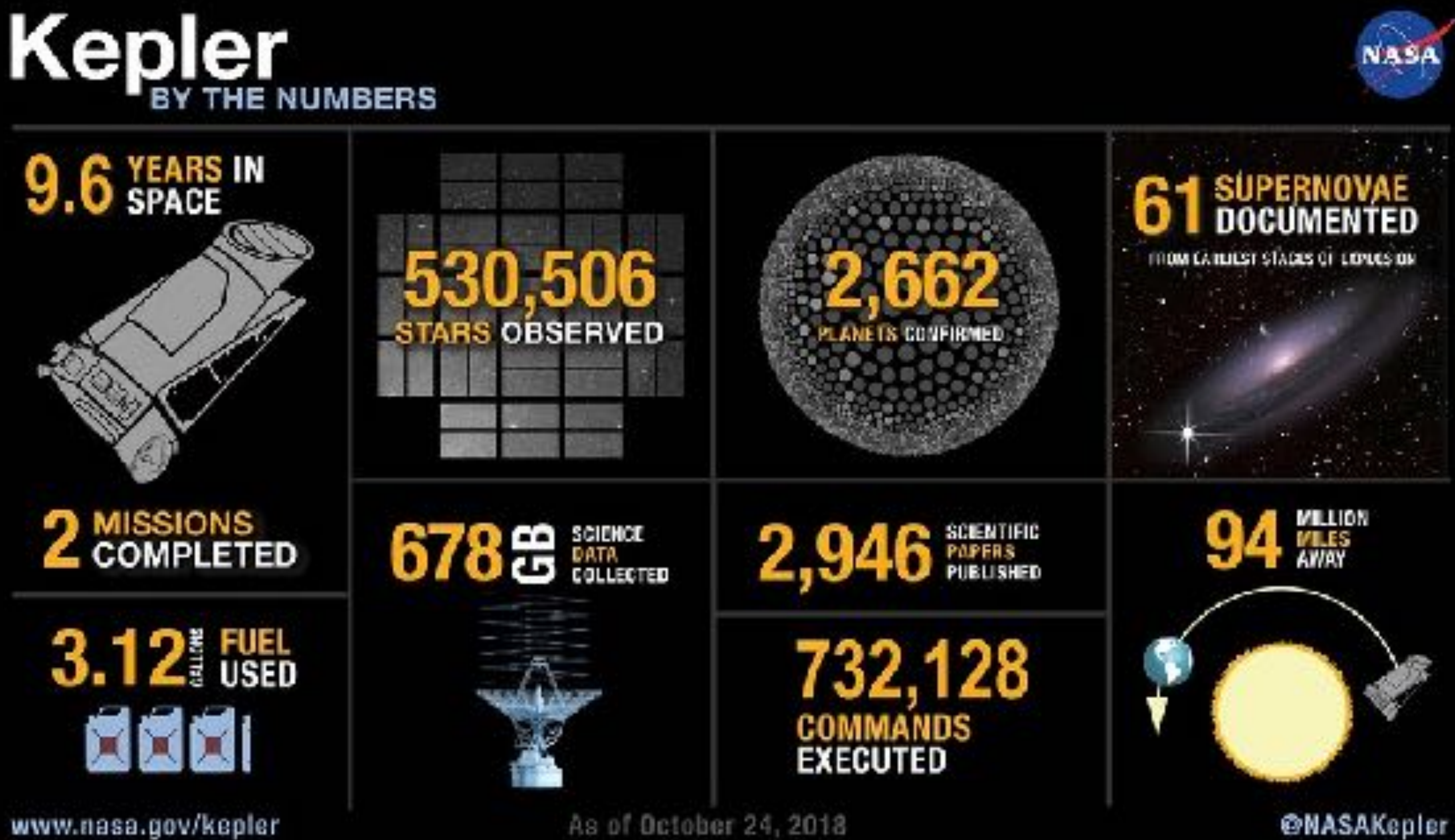


- Dip in intensity of light when orbiting planet blocks the star
- Secondary transit, when star goes behind the star, can also be detected
- Direct measure of the size of the planet from eclipse depth.
- Extensive monitoring campaigns (Kepler, Corot, TESS, ...)

The Kepler Mission

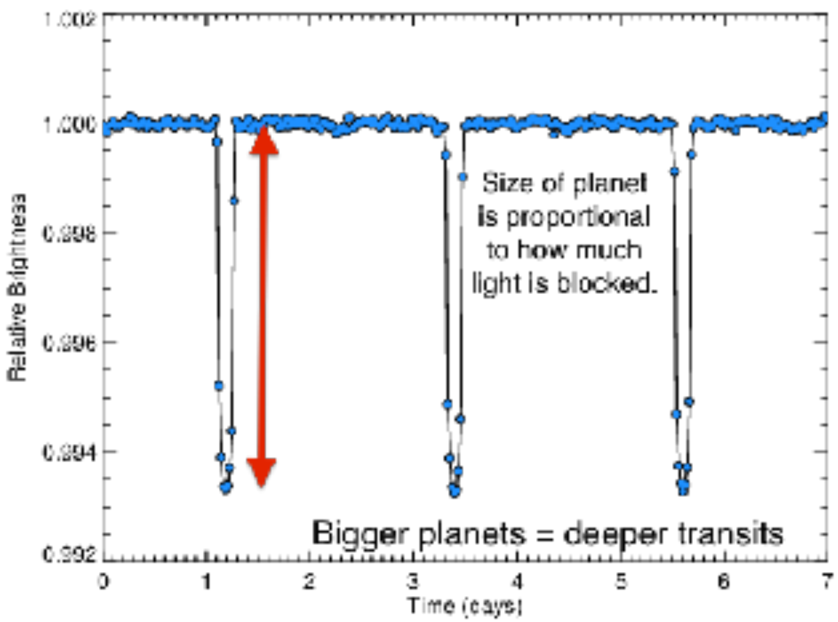


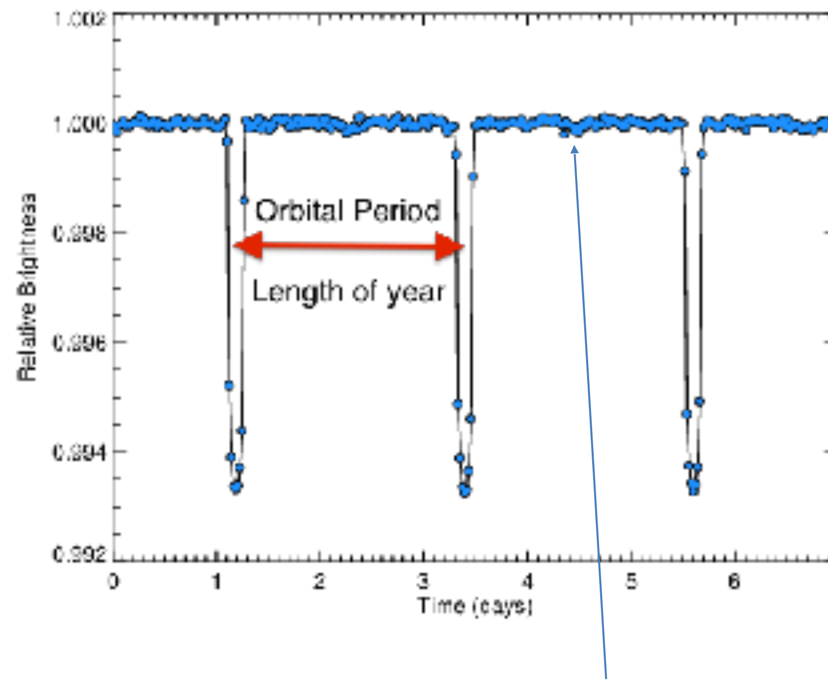
Kepler observed 150000 stars continuouosily, using a photometer consisting of 42 CCDs with 2200x1042 pixels each.



Exoplanet detection – Transit

Example: Kepler data on HAT-P-7 b (Hot Jupiter type planet discovered 2008)





Intensity decrease by 0.6%:

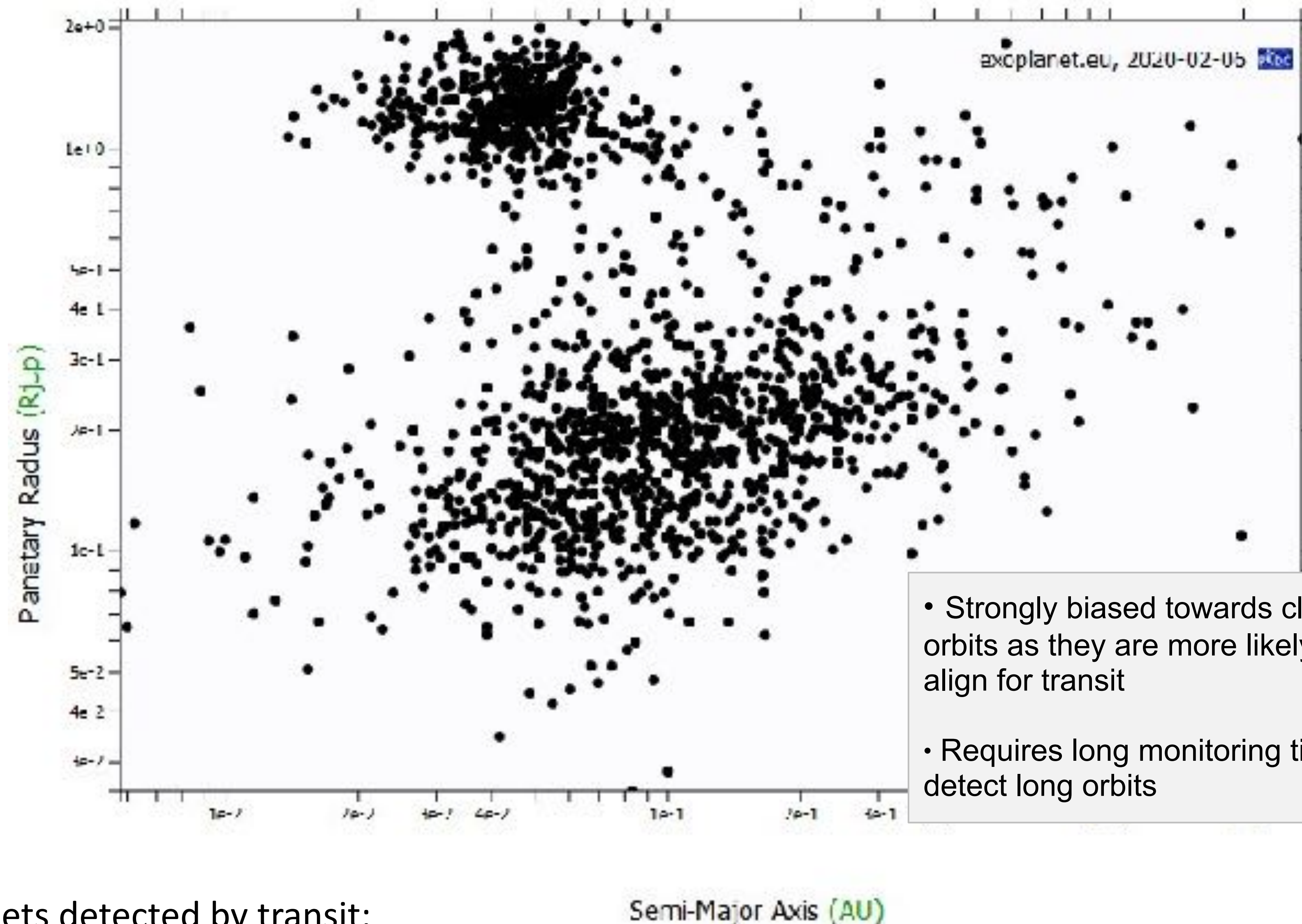
$$R_p = R_\star \sqrt{\mathrm{Depth}}$$

$$R_* = 2R_{sun} \longrightarrow R_p = 0.15\ R_{sun} \approx 1.5\ R_{jup}$$

When the planet goes behind the star, any light from the planet, either starlight reflected off the planet's surface, or light being emitted by the planet because it is glowing hot, is blocked. This decrease in brightness is called the "secondary eclipse", and for planets is usually quite small.

Source: https://www.cfa.harvard.edu/~avanderb/tutorial

Exoplanet detection – Transit

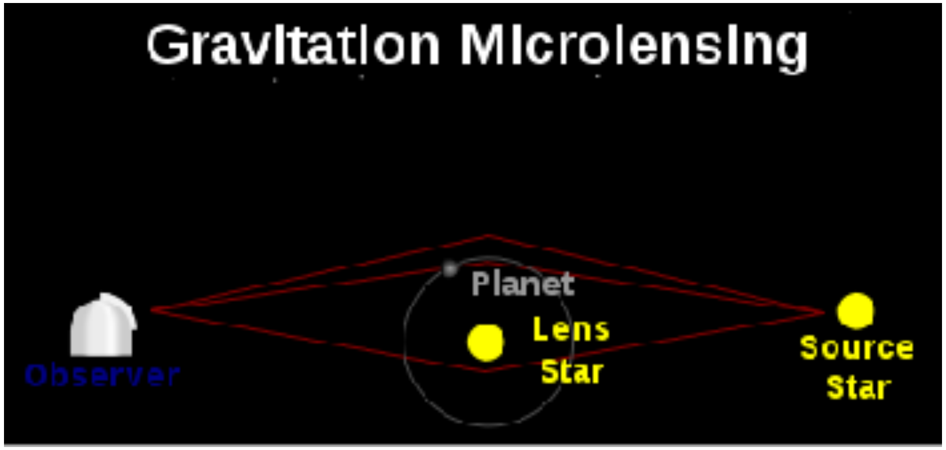


• Strongly biased towards close-in orbits as they are more likely to align for transit

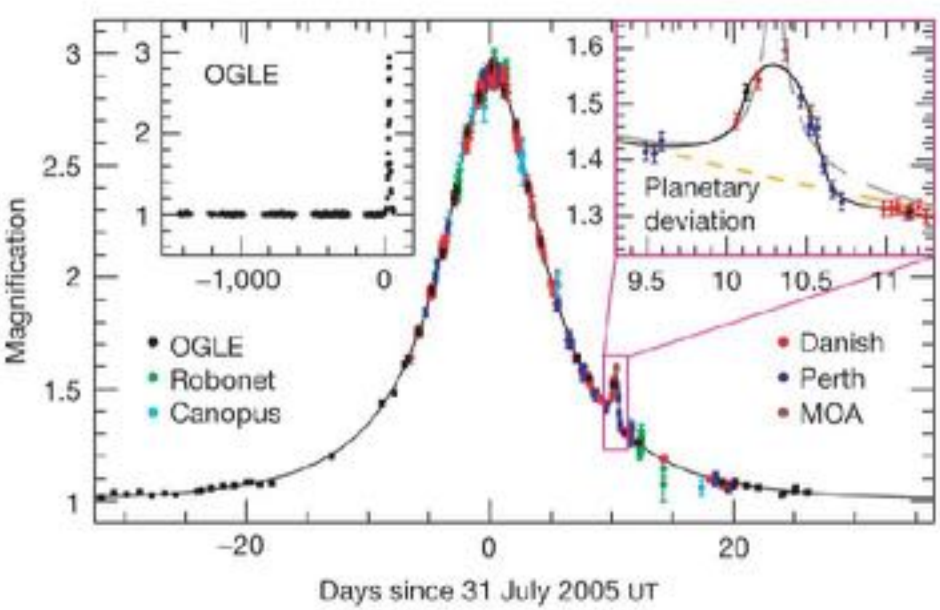
• Requires long monitoring time to detect long orbits

Planets detected by transit:
shown are 2971 of 2990 (exoplanet.eu / 06 Feb 2020)

Exoplanet detection – Microlensing



Wikipedia, "Gravitational microlensing"

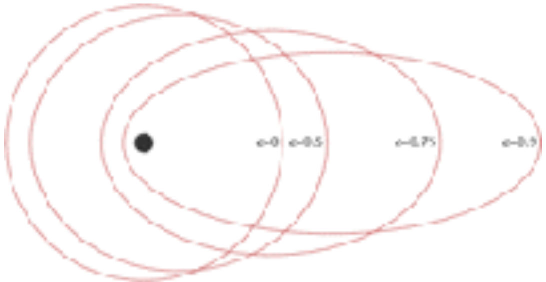


Beaulieu et al. Nature 439, 437 (2006)

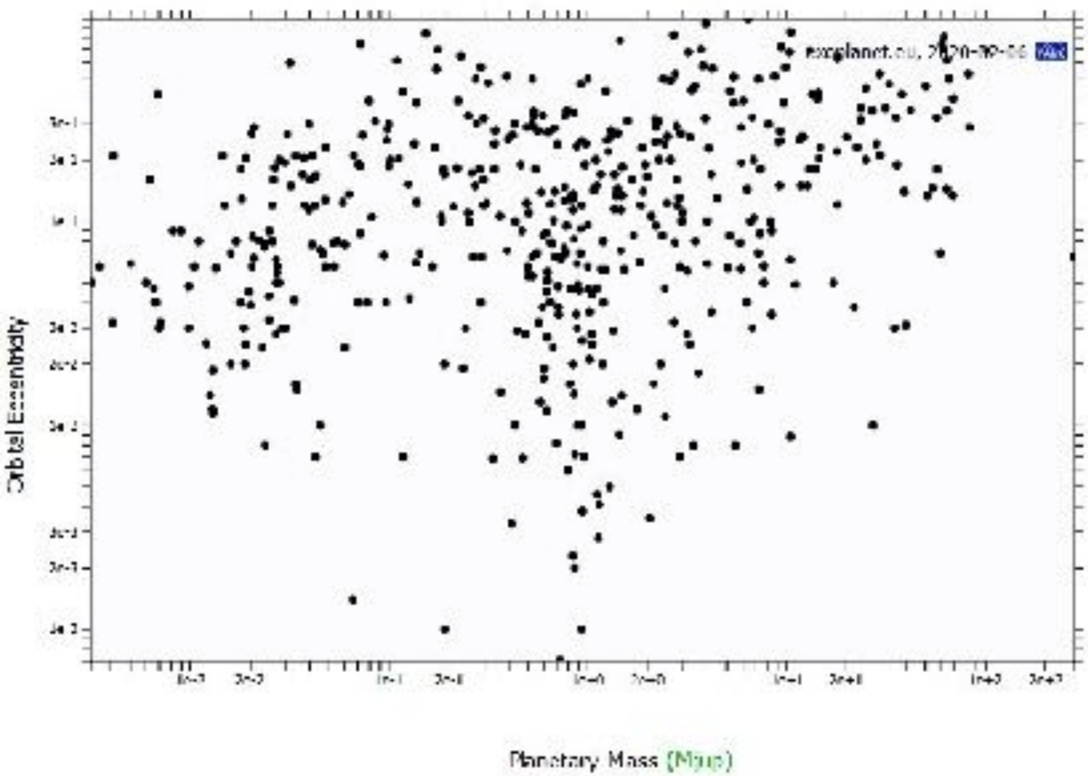
- Increase in intensity of background star light when intervening lens star passes. Planet is detectable as secondary increase in intensity
- 51 detected this way to date (exoplanet.eu 09.02.2017)
- Not reproducible, and in fact often the lens star is never even observed
- With large monitoring campaigns, can be used in a statistical manner to understand prevalence of earth-like planets

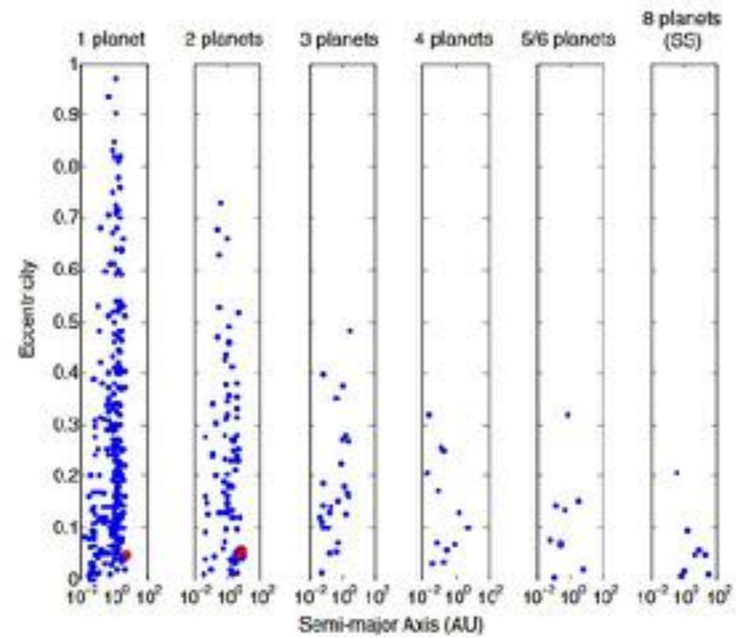
Exoplanet detection – Surprises

Earth eccentricity: 0.017



- Lots of non-circular orbits
- Formation is assumed to be on circular orbits – perturbations from interplanet dynamics?
- Solar system planets have e = 0 **Is our solar system unusual?**
- **Correlation with multiplicity (number of planets in a system)**

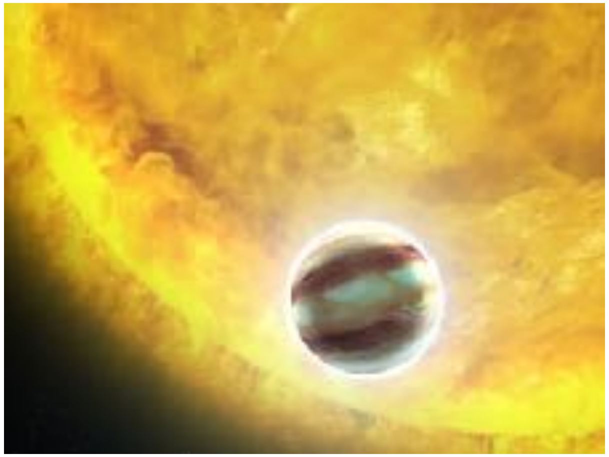




There appears to be an anti-correlation between eccentricity and multiplicity

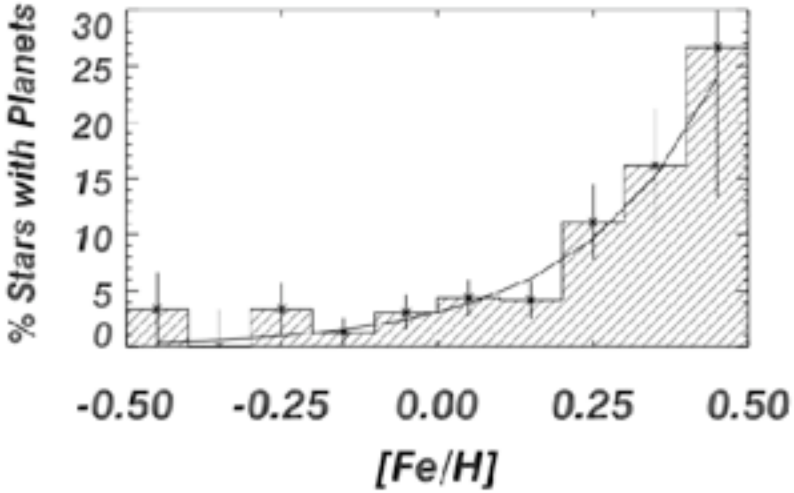
Limbach & Turner, PNAS 112, 20 (2015)

Exoplanet Detection – Surprises



Artist's conception, nasa.gov

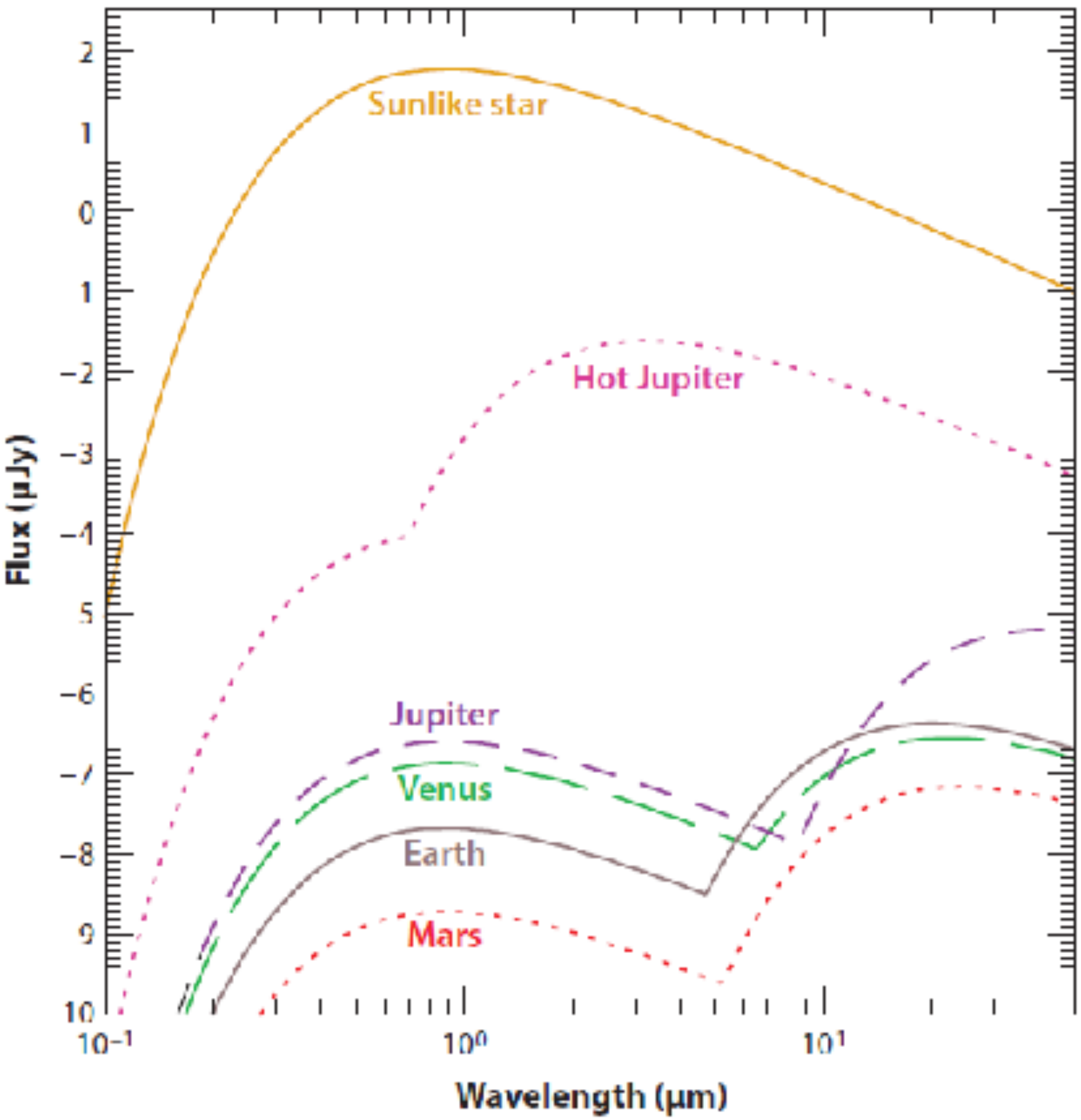
- 'Hot Jupiters'
- We used to believe they should be formed at large radii. Radial migration?



Marcy et al. 2005

- Stellar metallicity dependence
- Implications for planet formation?

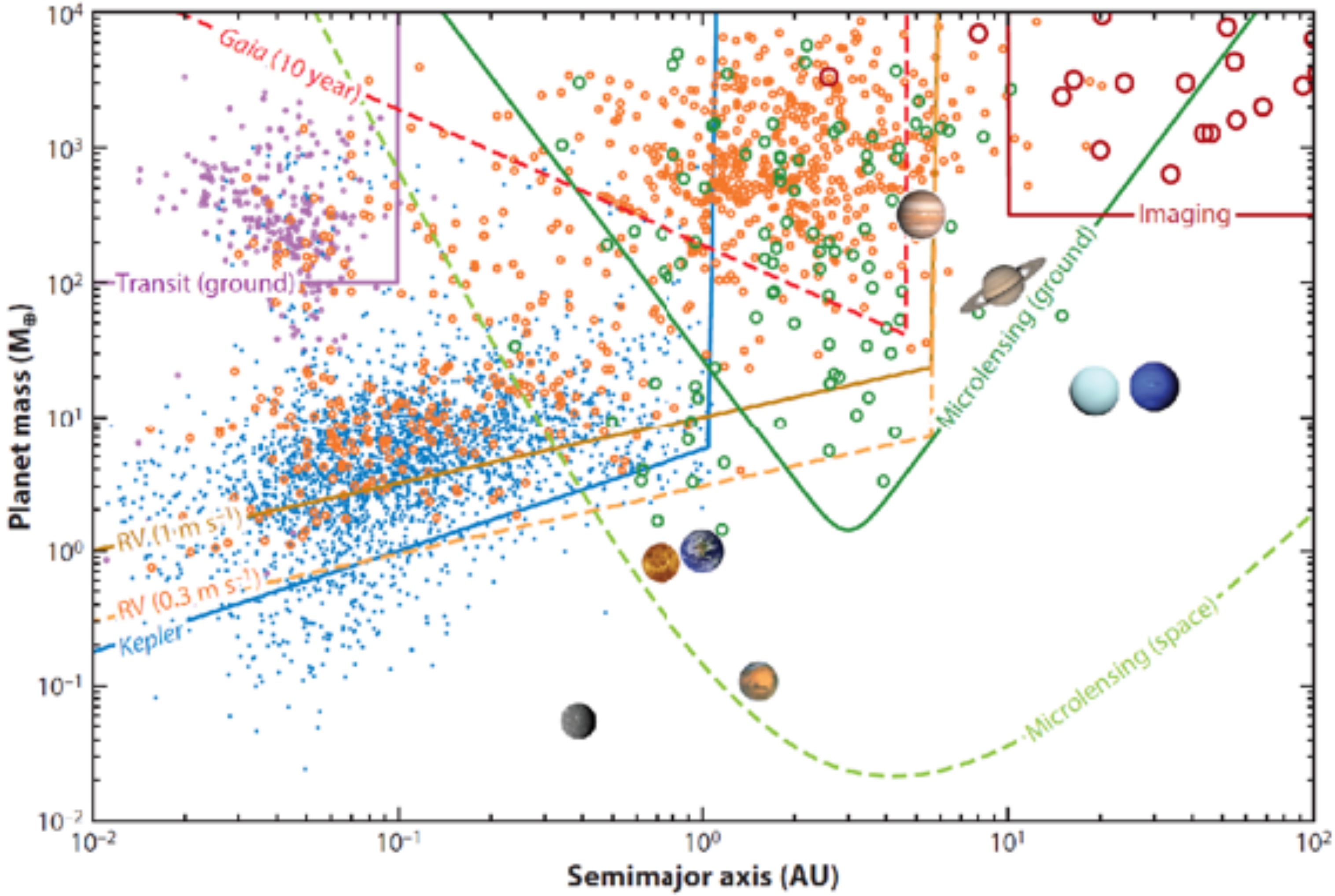
Hot Jupiters: massive planets very close to their host star



Surface temperatures
> 1000 K

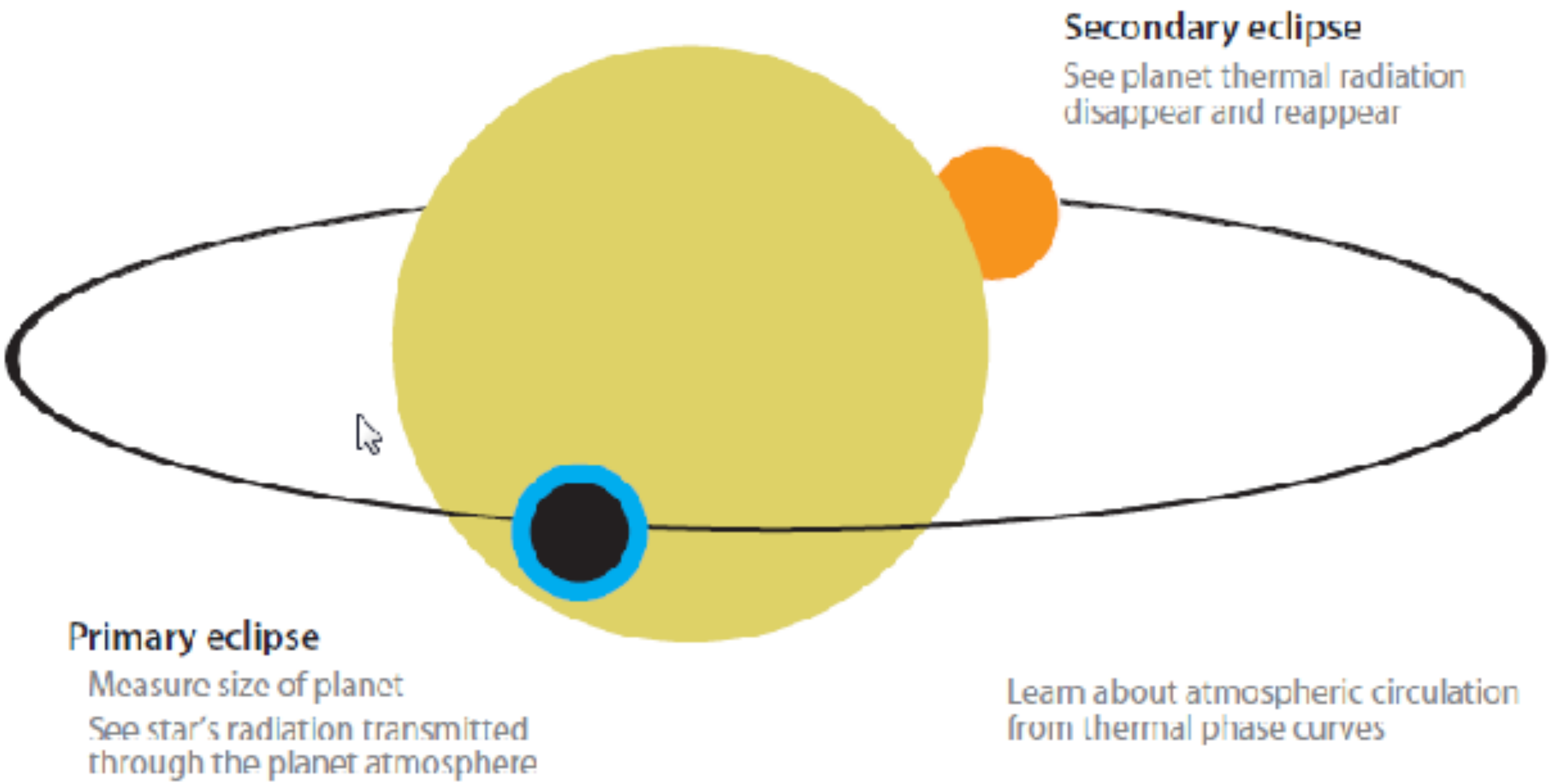
Flux ratio
between planet and star favorable in the IR:
10^{-4} compared to 10^{-9} for ordinary, colder planets

Different Methods – Different Biases



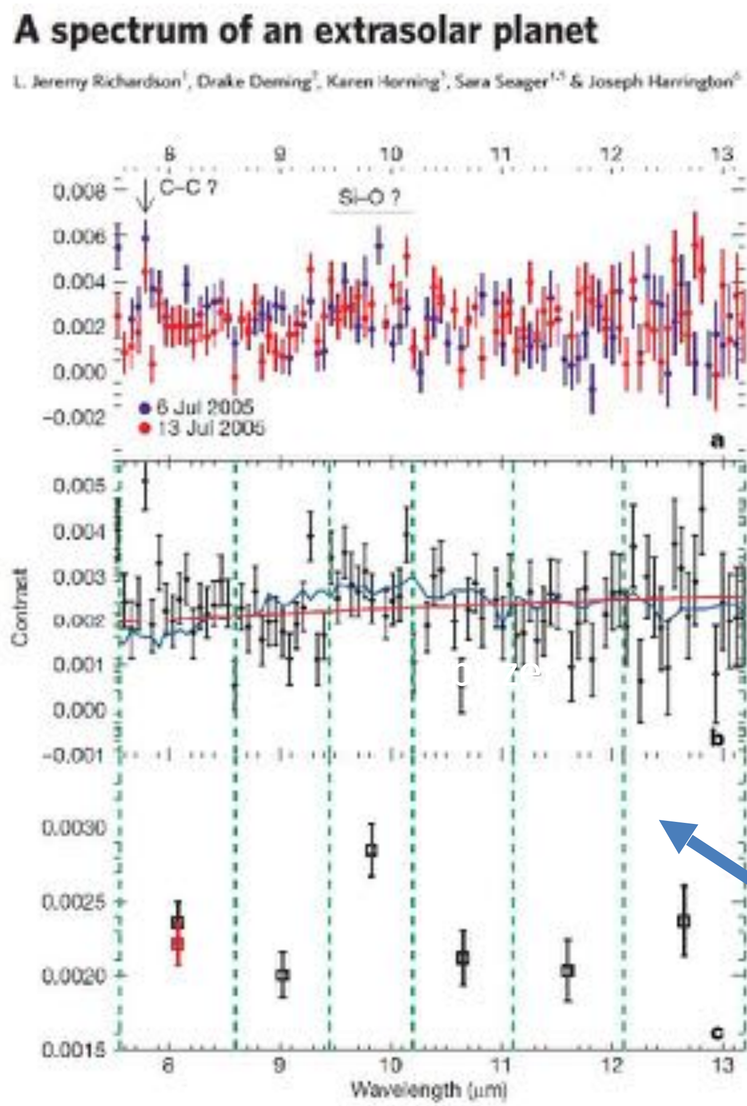
Zhu & Dong, "Exoplanet Statistics and Theoretical Implications",
Annu. Rev. Astron. Astrophys. 59, p. 291-336 (2021)

How to infer information on planetary atmospheres

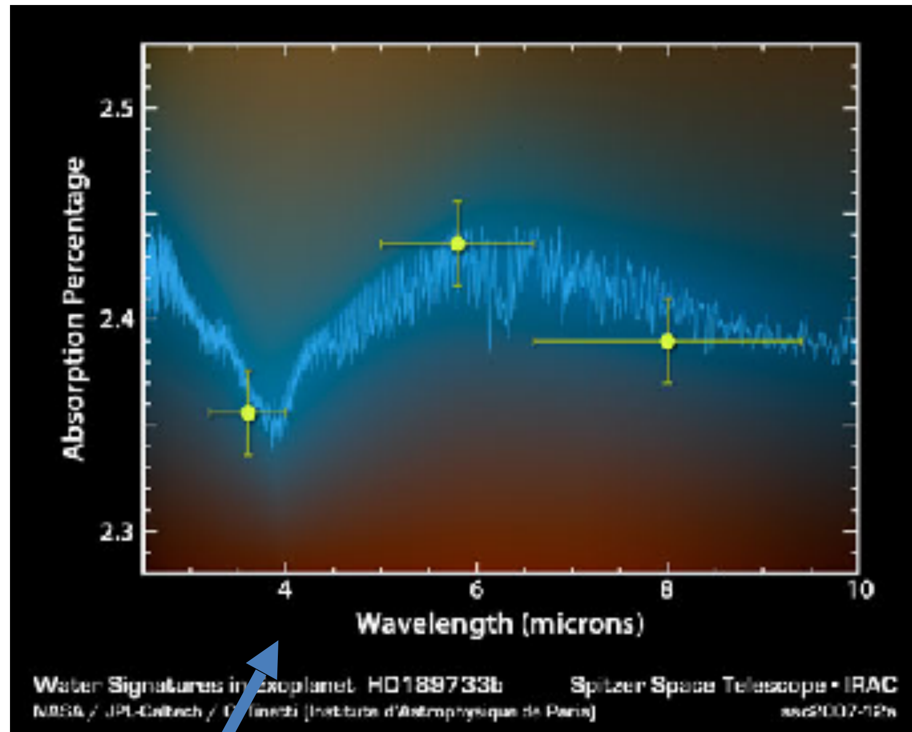


Seager and Deming, Annu. Rev. Astron. Astrophys. 2010. 48:631–72

First Spectra



Water Signature in an Exoplanet

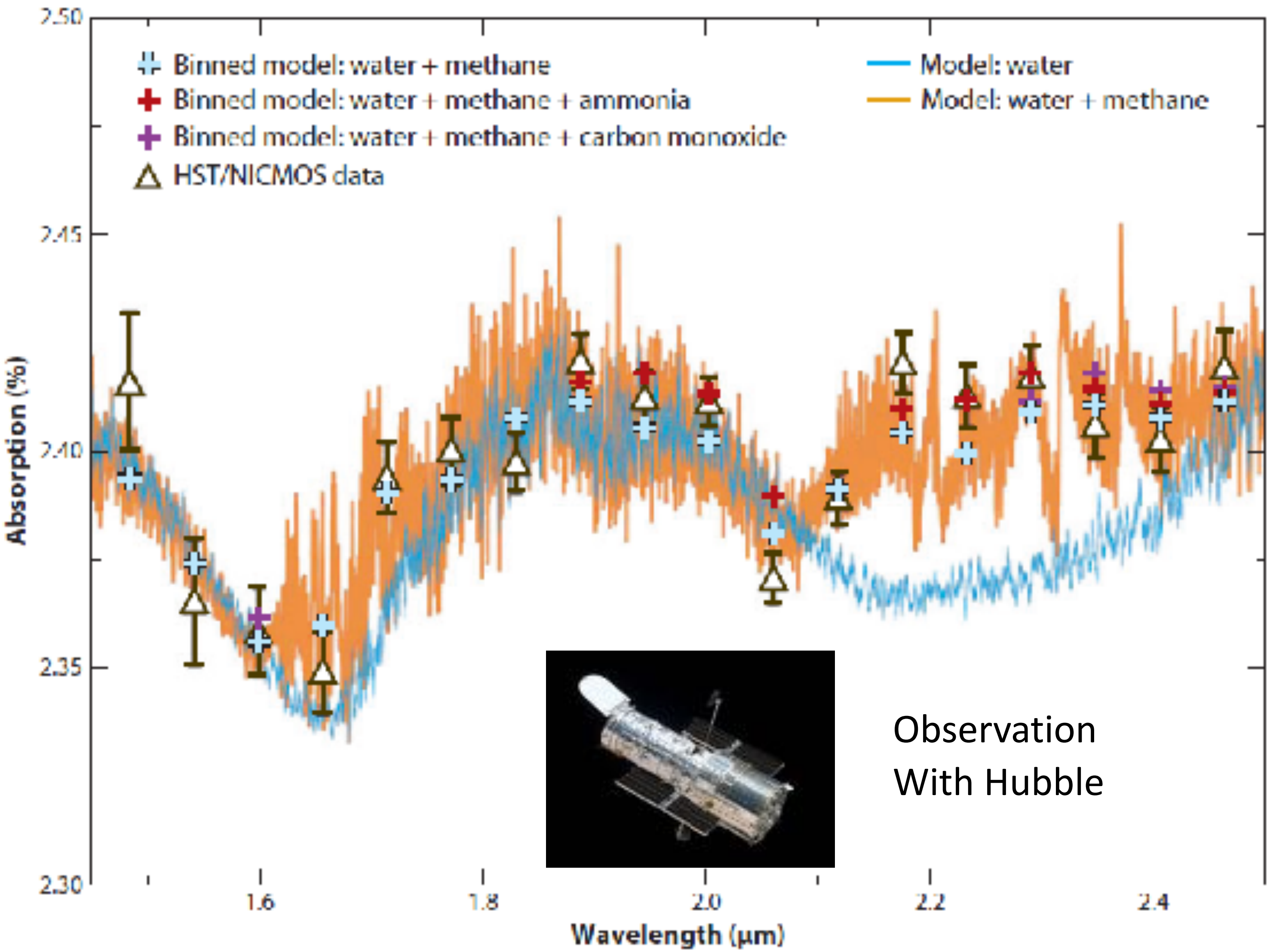


Spitzer observations

Richardson et al., Nature 445, 892 (2007)

Tinetti et al., Nature 448, 169 (2007)

Methane Signatures

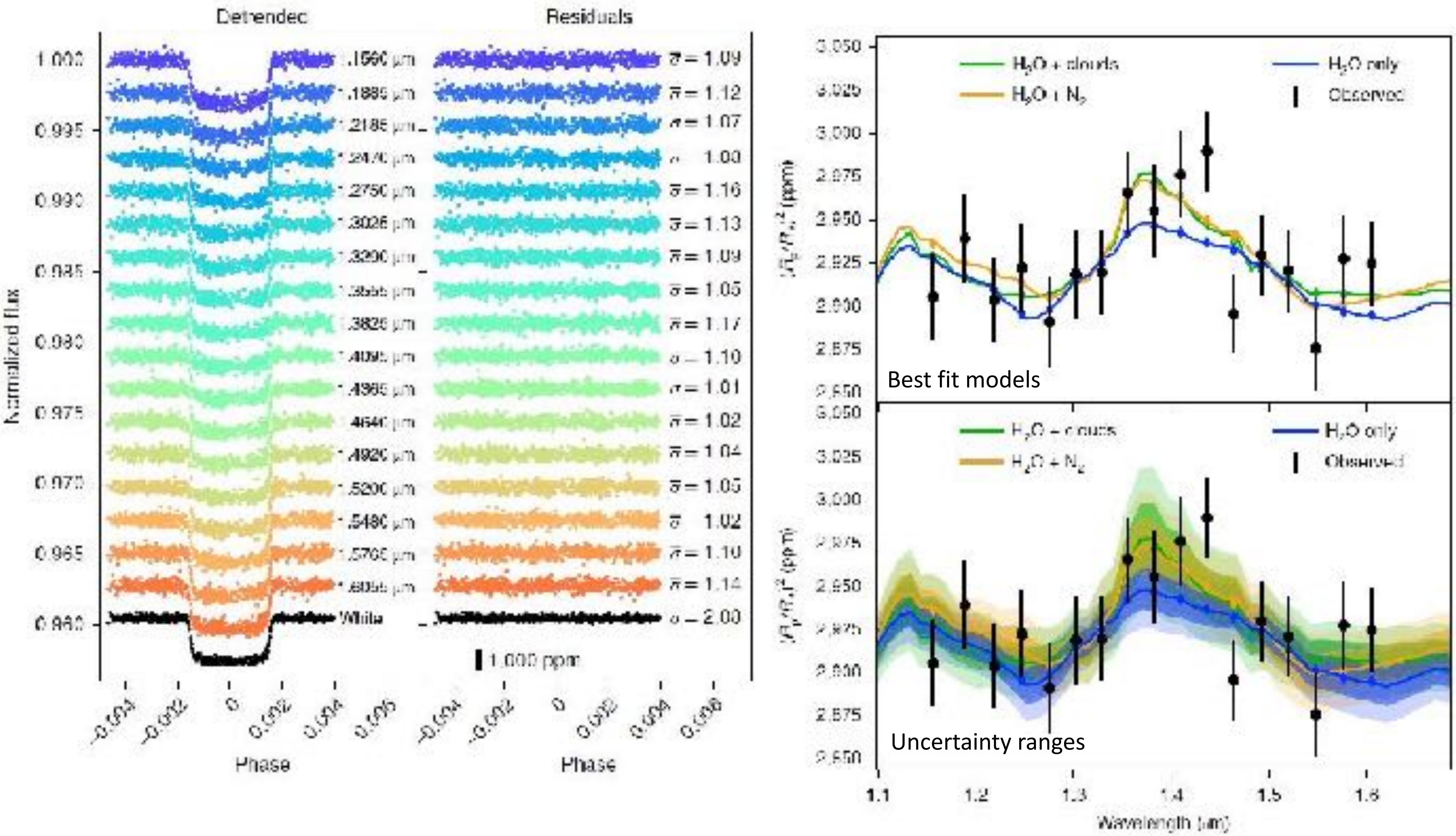


Observation
With Hubble

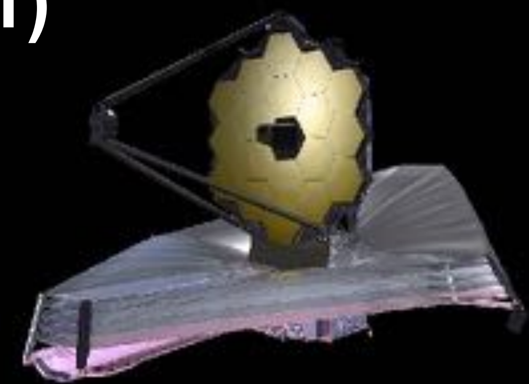
HD 189733 / from Swain, Vasisht & Tinetti (2008).

Water in super-Earth K2-18b, Hubble

Water in the atmosphere of ~ 8 x M_{Earth} exoplanet

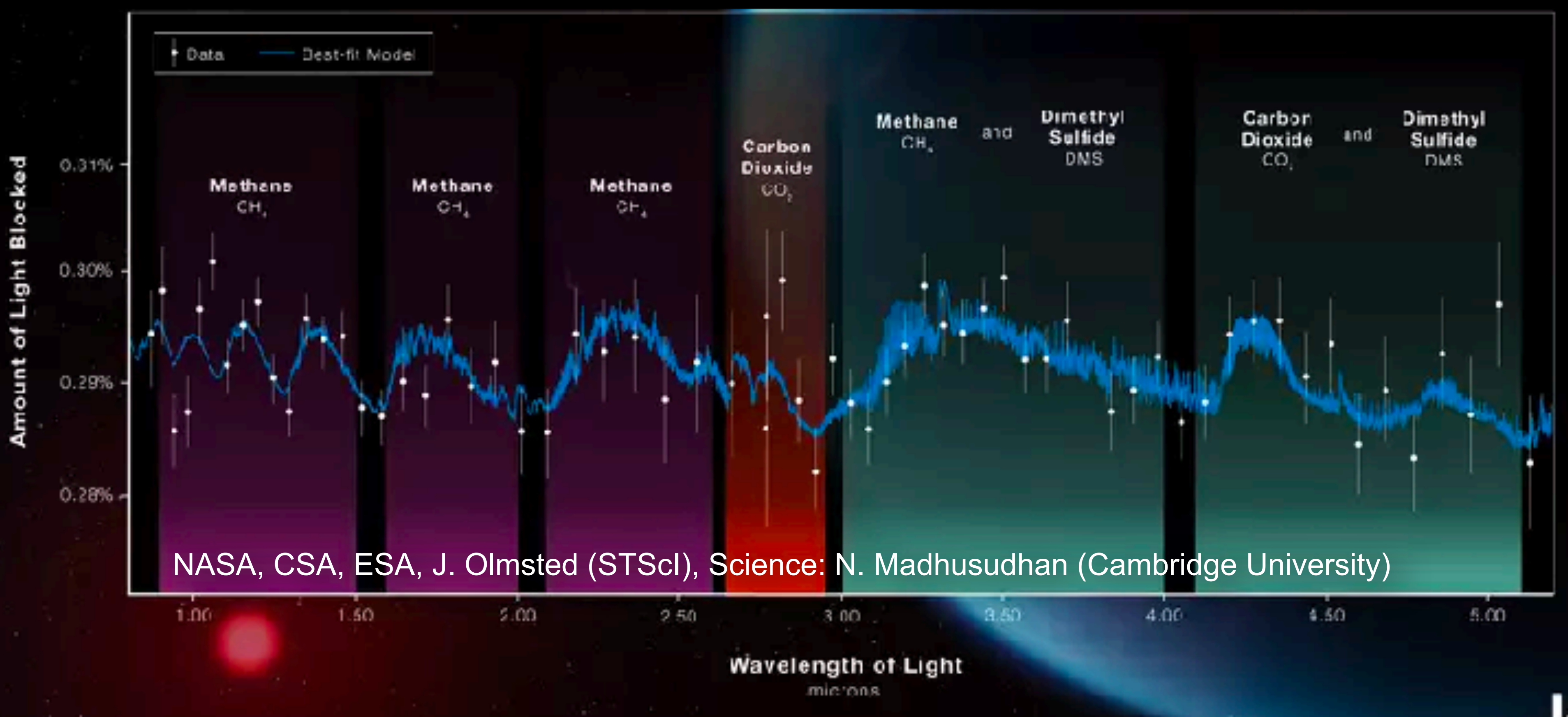


James Webb Space Telescope (>2021) (National Aeronautics and Space Administration NASA)



Near/Mid-Infrared: 0.6 – 28 µm

Atmospheric spectrum of super-Earth K2-18b



NASA, CSA, ESA, J. Olmsted (STScI), Science: N. Madhusudhan (Cambridge University)

Origin of Life: HIFOL collaboration

https://www.mpia.de/3500788/HIFOL

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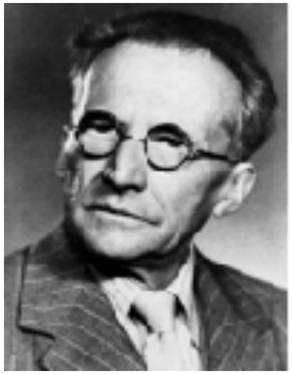
News from the Initiative

From Space to Earth: Uncovering the Potential Role of Meteorites in Kick-Starting Life

A collaboration of HIFOL scientists from the Max Planck Institute for Astronomy, McMaster University, the Institute for Theoretical Astrophysics at Heidelberg University, and Ludwig Maximilian University of Munich has extended our understanding of how the building blocks of life might have reached our planet and helped to give birth to the first living organisms.

Many of these necessary life-building blocks, so-called prebiotic molecules, were discovered in carbonaceous chondrites—a class of meteorites. These molecules could have played a crucial role in the formation of the first RNA molecules on early Earth. RNA molecules are believed to be a critical intermediate step toward the emergence of living systems. RNA can store genetic information, catalyze its own polymerization, and self-replicate, crucial functions associated with all life. This solves an old "chicken-or-the-egg" dilemma in the origins of life, as modern life needs many mutually dependent and complex molecules to achieve these functions. But RNA alone can impersonate all these roles and might therefore be the stepping stone between dead and alive matter. Later in evolution, DNA might have taken over from RNA and now stores the genetic blueprints of all modern life, including us.

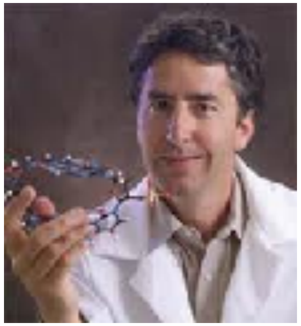
What is Life?



Attempts at a definition:

Erwin Schrödinger(physicist): ... life as that which resists decaying to disorder and equilibrium. This definition relates to the second law of thermodynamics, which states that closed systems will naturally gain entropy, or disorder, over time. Living things can work against this trend.

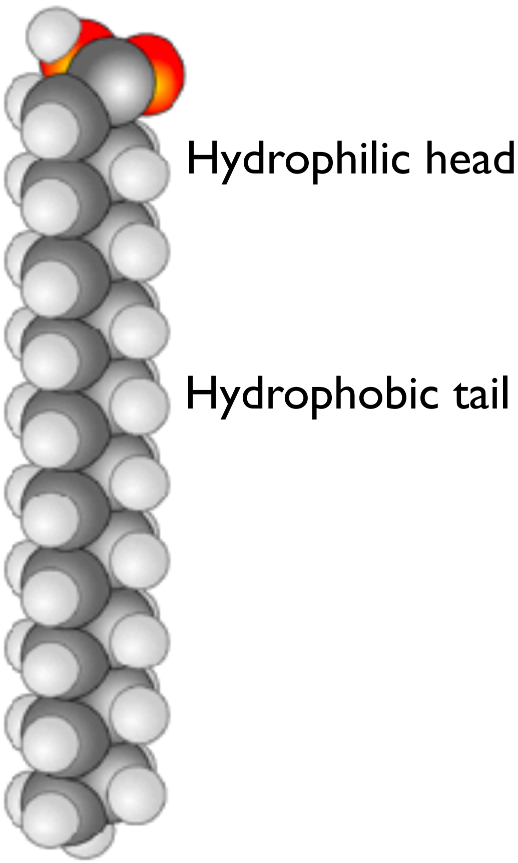
"Any population of entities which has the properties of multiplication, heredity, and variation."
John Maynard Smith (evolutionary biologist and geneticist)



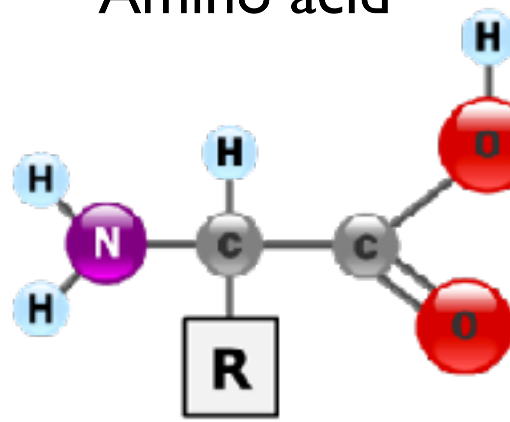
"Life is a self-sustaining system capable of Darwinian evolution."
Gerald Joyce (biochemist)

Life Building blocks: lipids, amino acids, nucleotides...

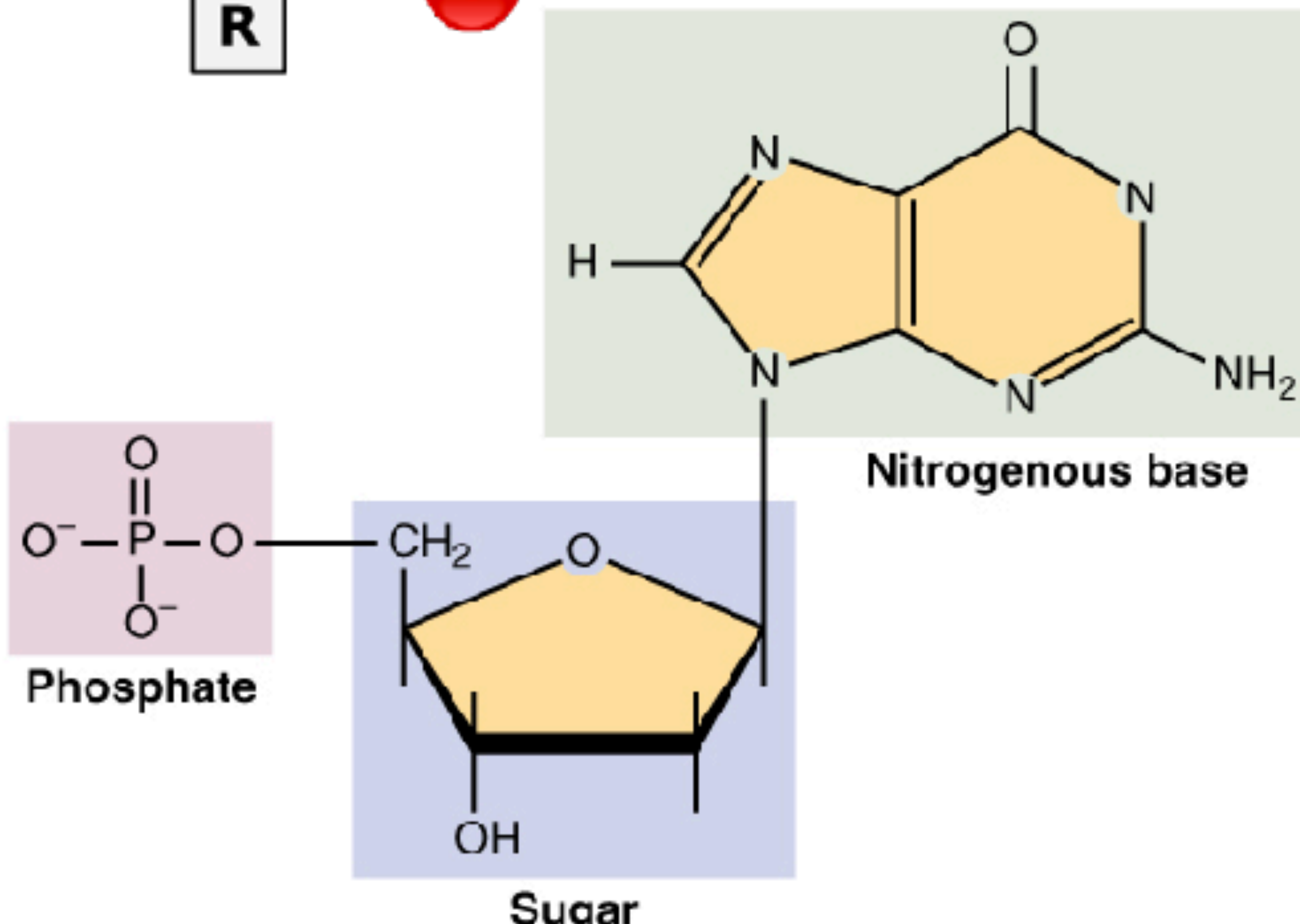
Phospholipids



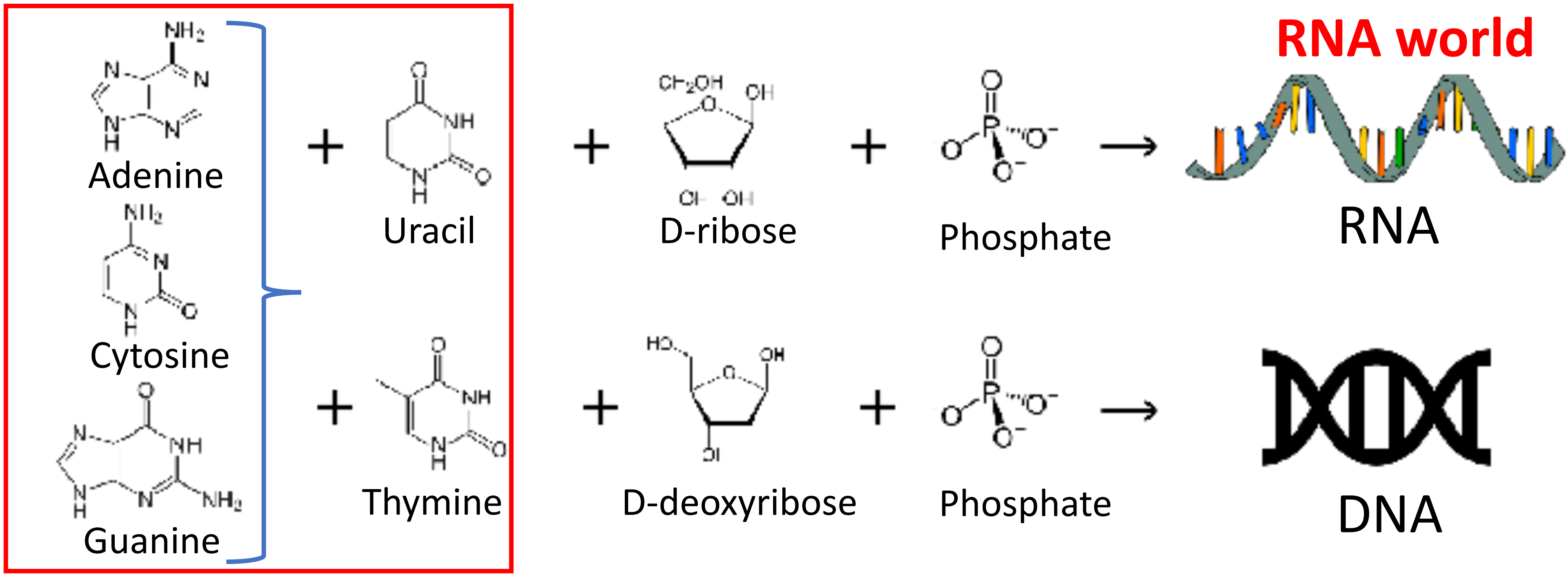
Amino acid



Nucleotide



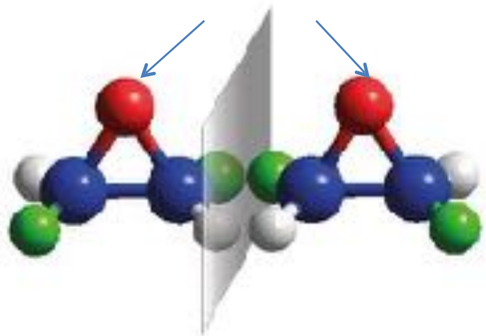
Life Building blocks: RNA, DNA



Chirality: a Fundamental Property of Nature

Chiral molecules can be either
Left-handed or Right- handed
The enantiomers are mirror images

Enantiomers

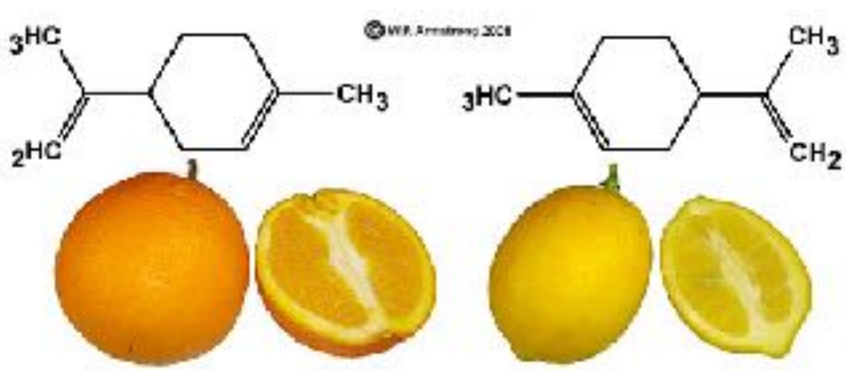


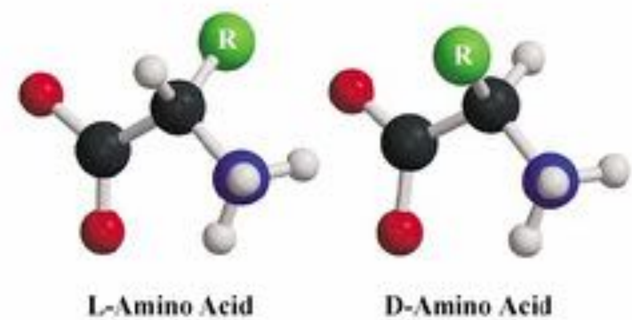
Life on Earth is (homo)chiral

100 000 : 1

Enantiomers

R-(+)-Limonen L-(-)-Limonen

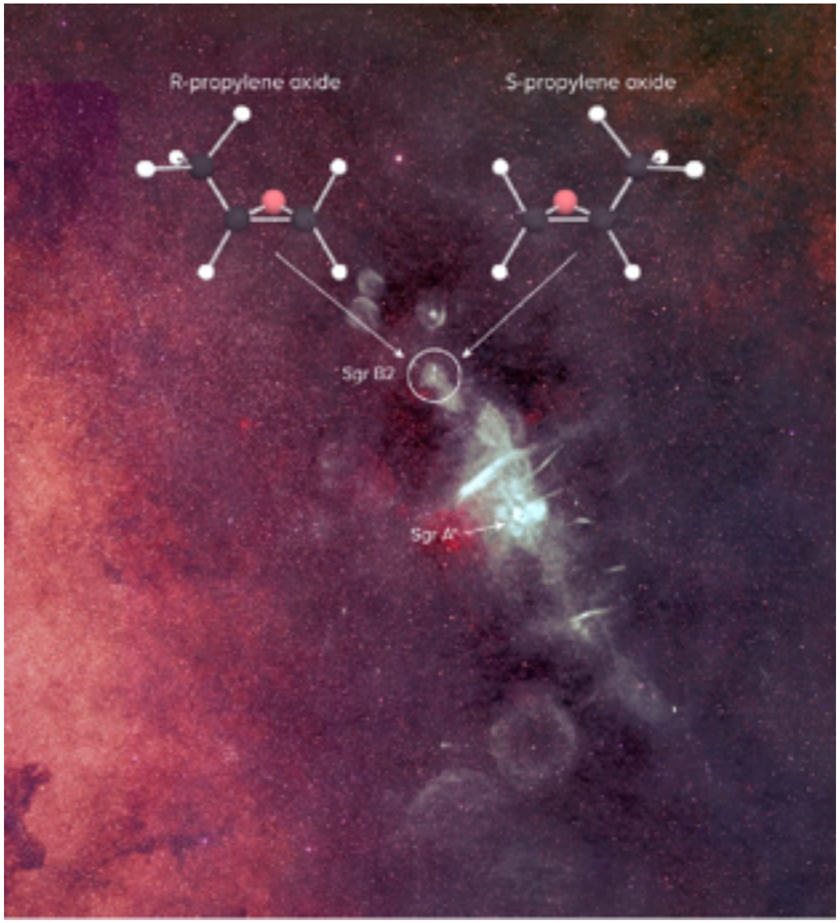




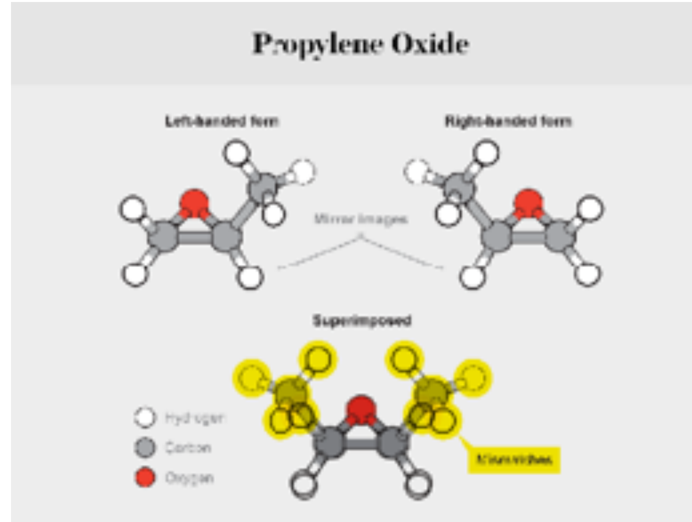
All amino acids found in proteins occur in the L-configuration

Why? Nobody knows

Chiral molecule detected in space



But: No information on enantiomeric excess



ASTROCHEMISTRY

Discovery of the interstellar chiral molecule propylene oxide (CH_3CHCH_2O)

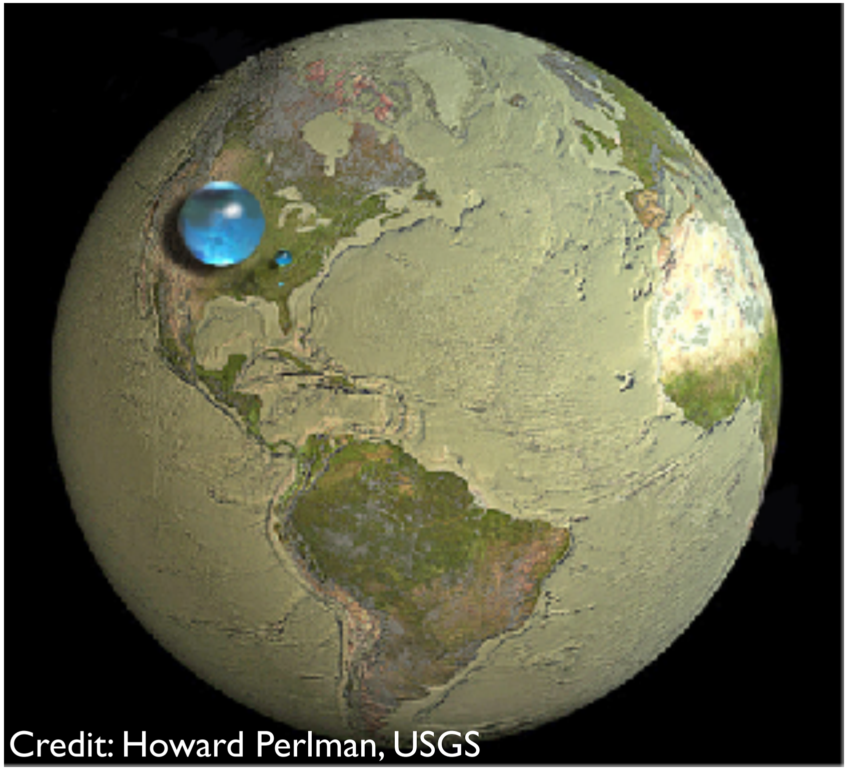
Brett A. McGuire,[1,2*†] P. Brandon Carroll,[3*†] Ryan A. Loomis,[4] Ian A. Finneran,[3] Philip R. Jewell,[1] Anthony J. Remijan,[1] Geoffrey A. Blake[3,4]

Detection in molecular clouds indicates that chiral molecules were present in space long before solar systems.

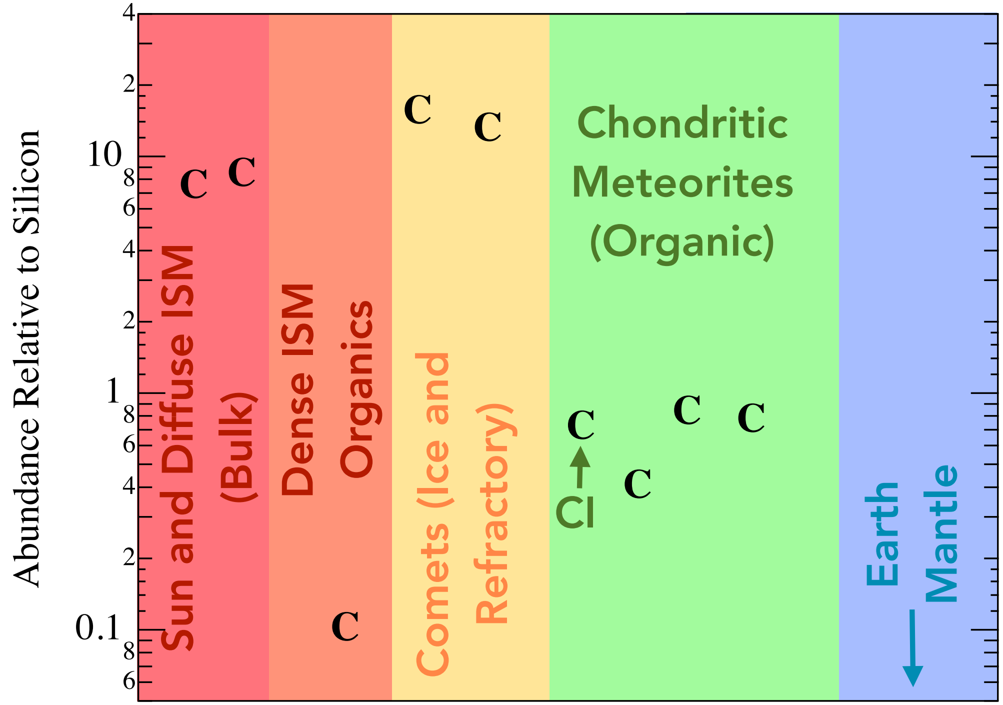
Did they seed handedness on Earth?

Earth: Water and Carbon Budgets

Earth surface water: 0.7%



Earth surface carbon: ~0.002%

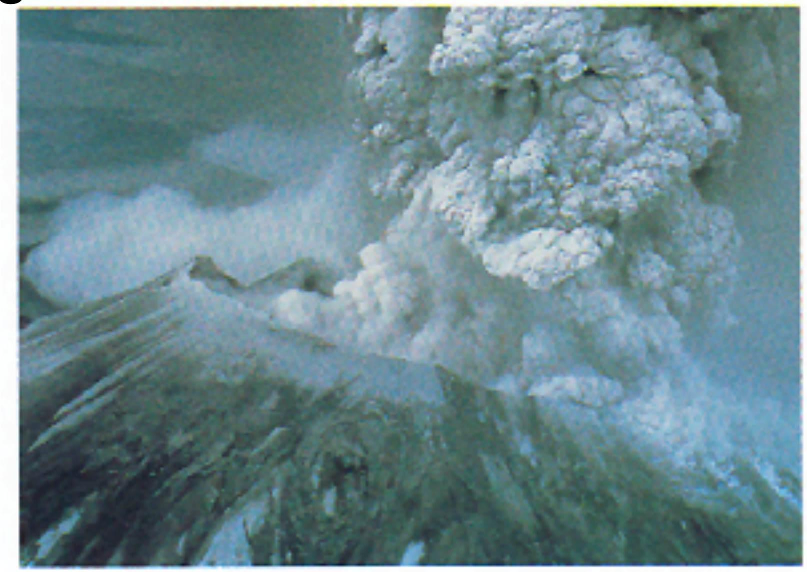


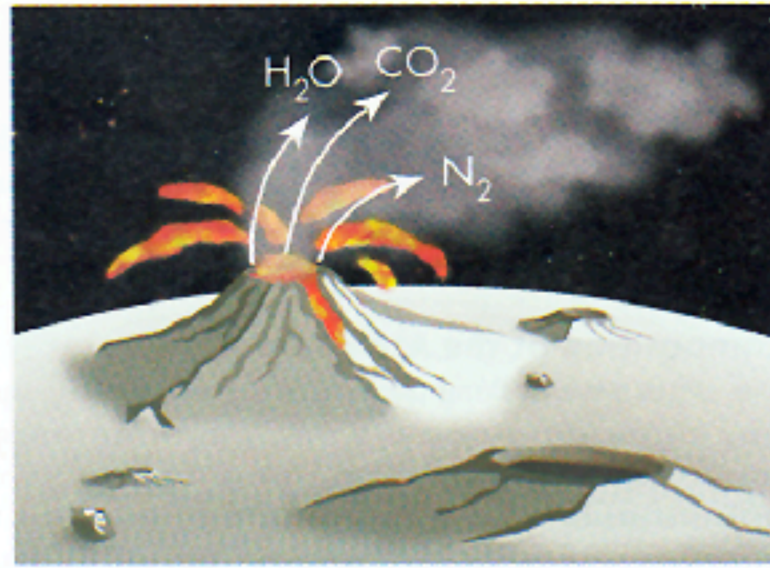
Bergin et al. (2014), Faraday Diss.

- Earth is water and carbon dry
- Also N and S are depleted
- Formed in inner solar nebula, T > 150 K (loss of volatiles)

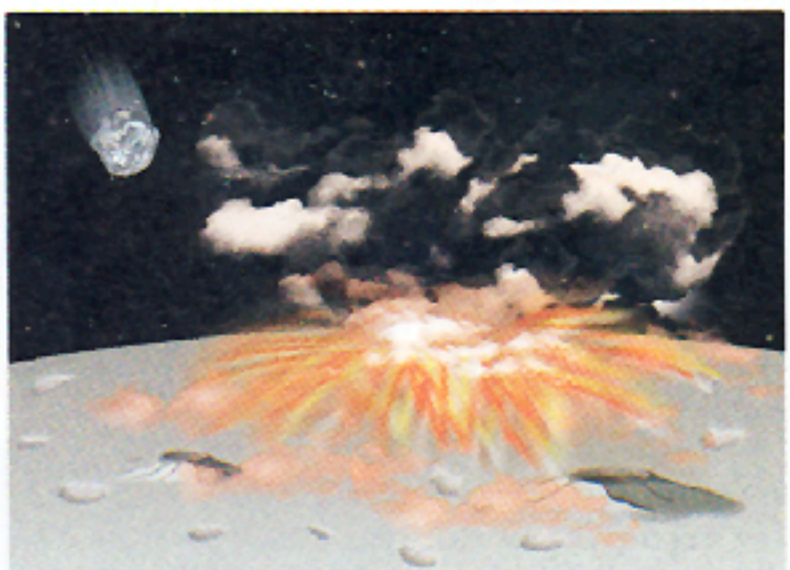
Early Earth Atmosphere & Hydrosphere

Endogenous



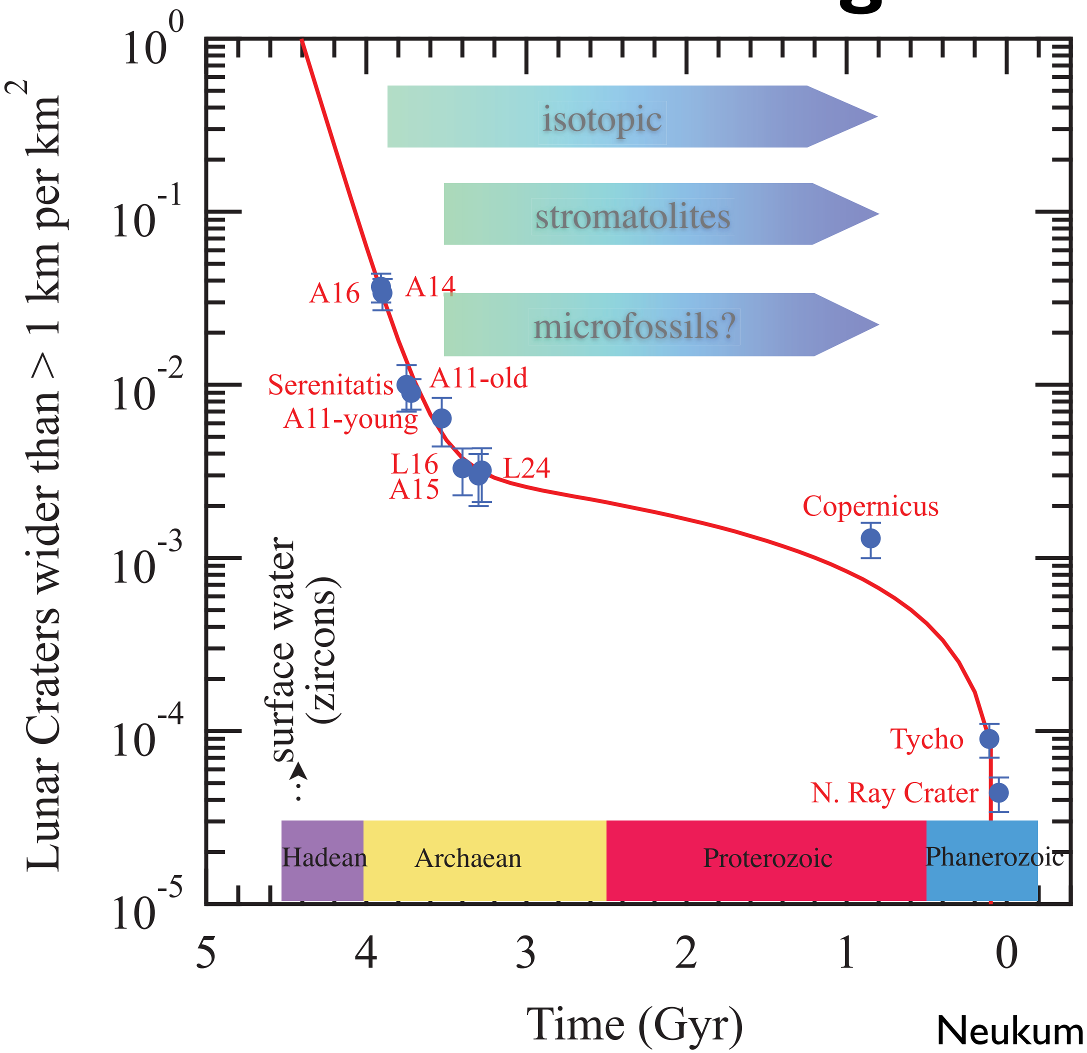


Exogenous



c

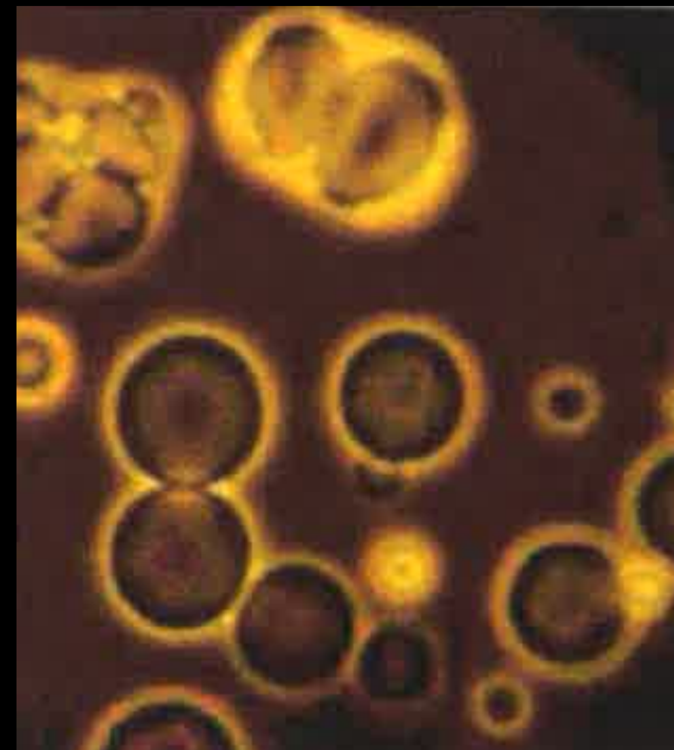
Evidence for Intense Bombardment: Lunar Cratering Records



Neukum et al. (2001); Bergin et al. (2014)

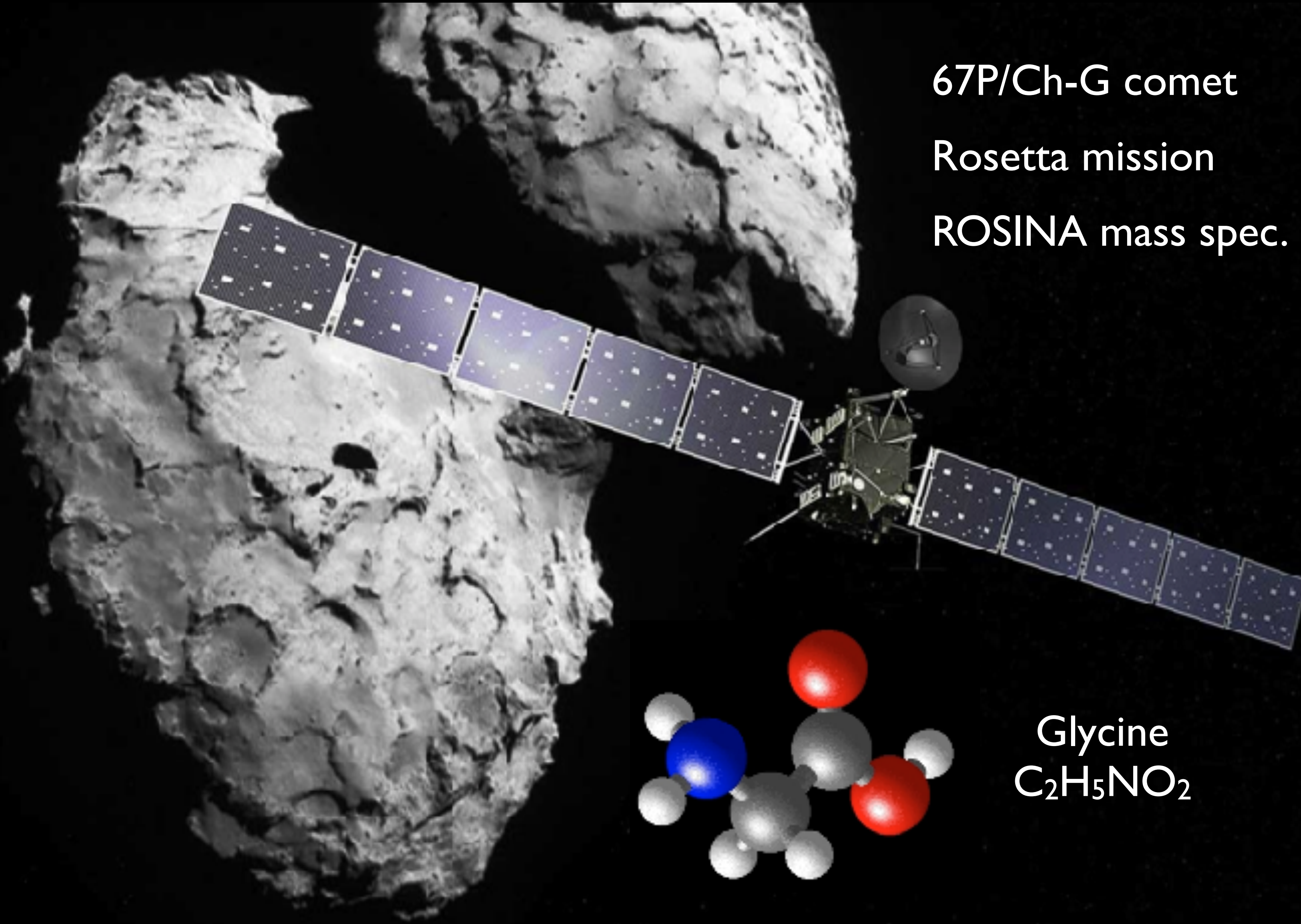
- High rate during first ~0.8–1 Gyr
- Final orbital rearrangement of giant planets

H_2O and Organics in Carbonaceous Meteorites



- <10-25% water: Earth water-like D/H
- <4% of carbon: insoluble/soluble = 70%/30%
- ~70 amino acids (8 are found in proteins): high D/H ~ 10^{-3}
- Carboxylic acids, hydrocarbons, alcohols, S–, P–molecules

Glycine in 67P/Ch-G Comet



67P/Ch-G comet

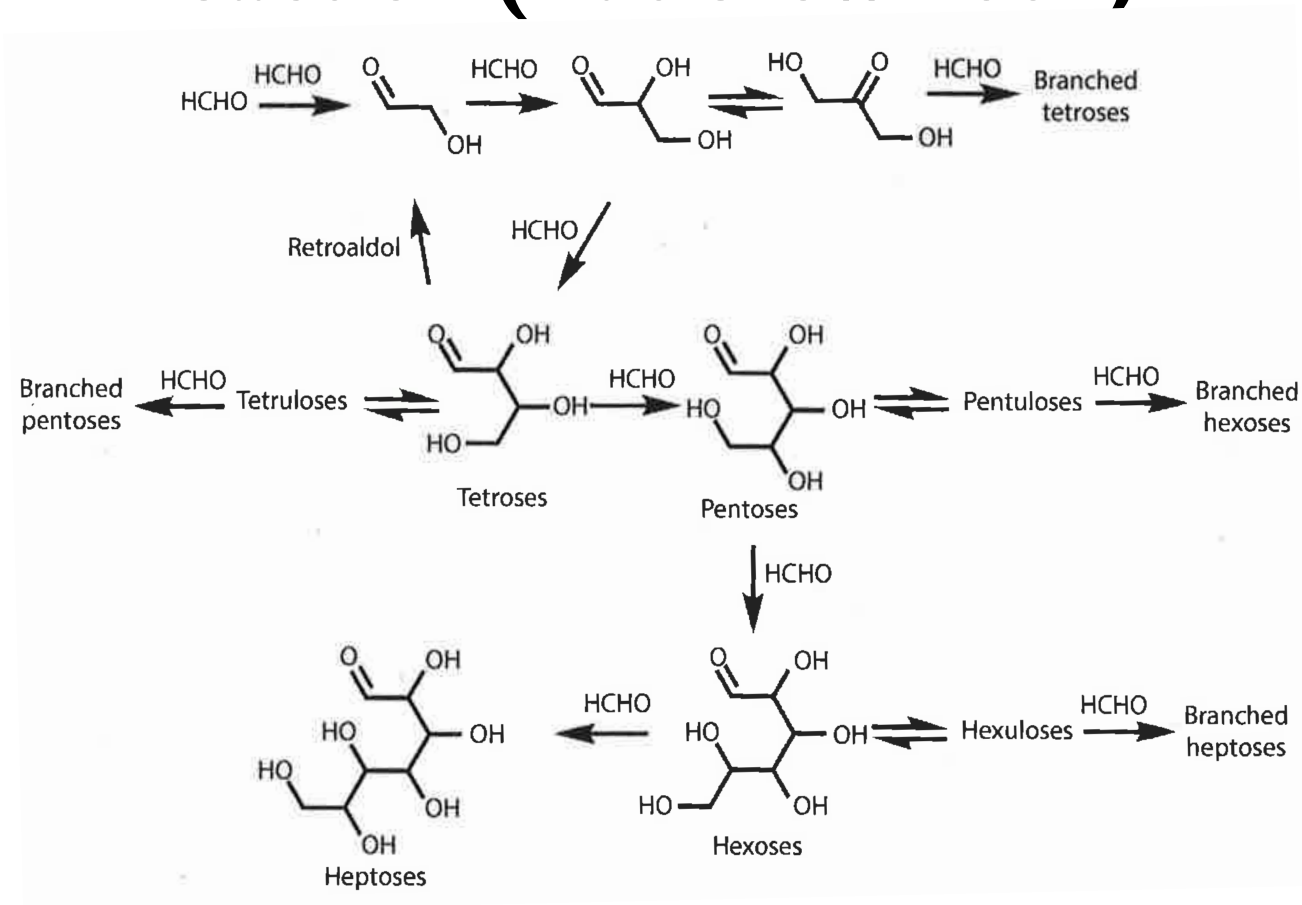
Rosetta mission

ROSINA mass spec.

Glycine

$C_2H_5NO_2$

Formation of Sugars from H_2CO: Formose Reaction (Butlerow 1861)



- Autocatalytic + Ca: n x H_2CO ⇒ n-C sugar (n=5: ribose, deoxyribose)
- Works with borate minerals (Ricardo et al. 2004)

Fischer-Tropsch Synthesis

$$(2n + 1)\,H_2 + n\,CO \rightarrow C_nH_{2n+2} + n\,H_2O$$

- Catalyst (Fe, Ni, rare metals, silicate, clay,…)
- T > 500 K, high pressures (>10 bars)
- Hydrocarbons, alcohols, oxidated hydrocarbons
- Could work on very early Earth or inside carbon and water-rich asteroids


DEUTSCHES REICH

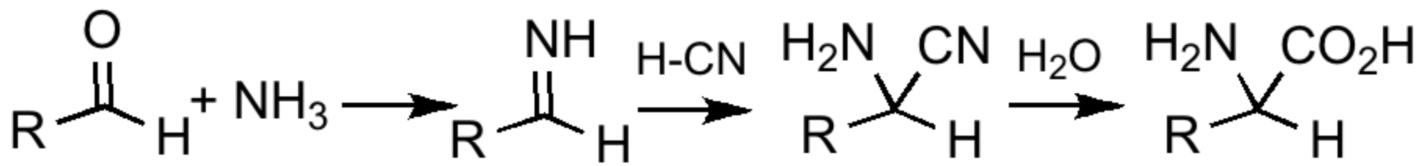
REICHSPATENTAMT

PATENTSCHRIFT

KLASSE 12o GRUPPE 1

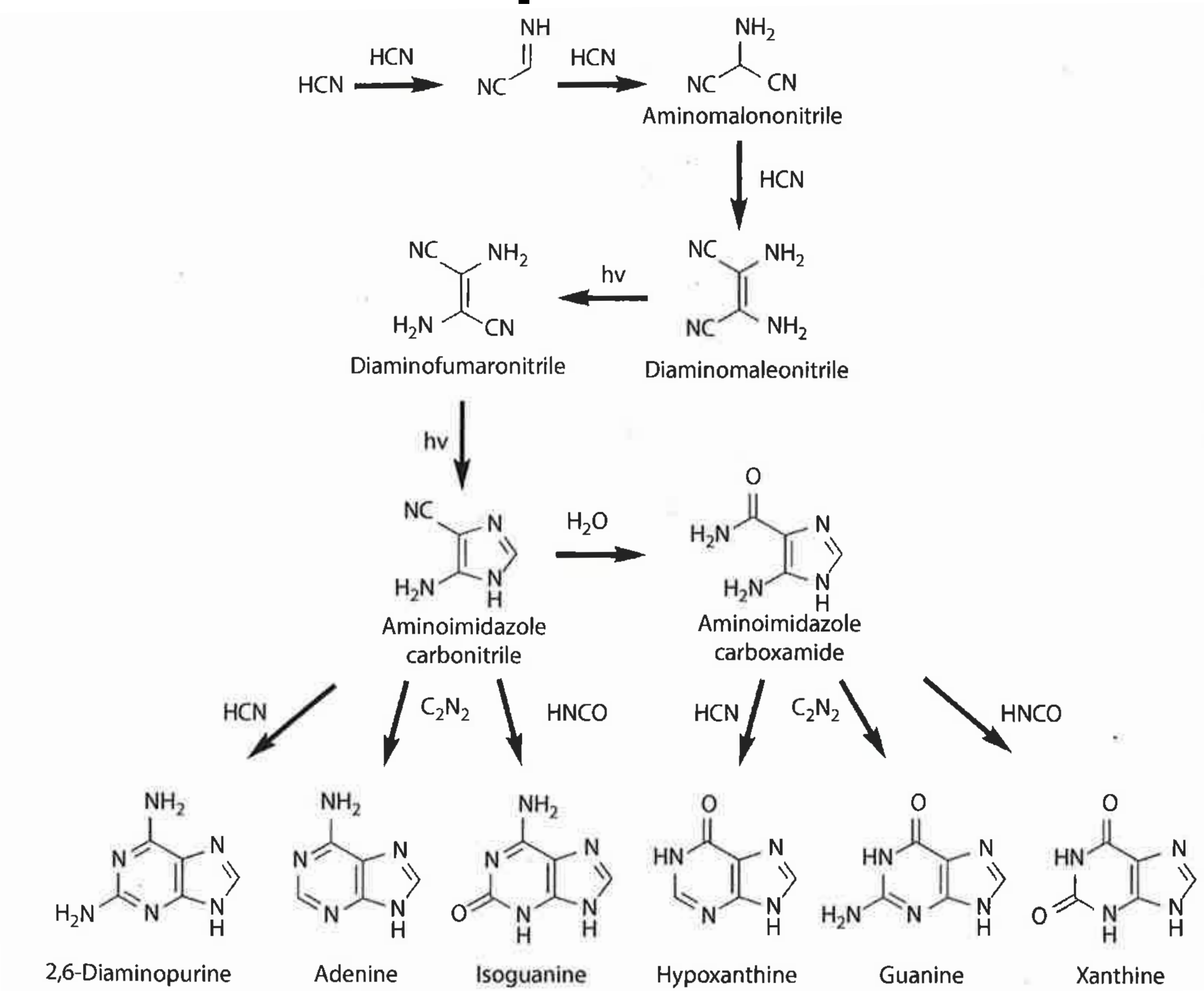
Dr. Franz Fischer und Dr.-Ing. Hans Tropsch in Mülheim, Ruhr

Strecker Synthesis (Strecker 1850)



- Synthesis of amino acids from aldehydes/ketones
- Requires NH_3 and CN/HCN and the presence of liquid water
- Racemic mixtures of amino acids, amines, etc.

Polymerization of Aqueous HCN: Amino Acids



- Oró & Kimbal (1961): 5 HCN ⇒ $C_5H_5N_5$ (adenine)
- Requires HCN, water and light

The Origin of Life: Some keywords and concepts

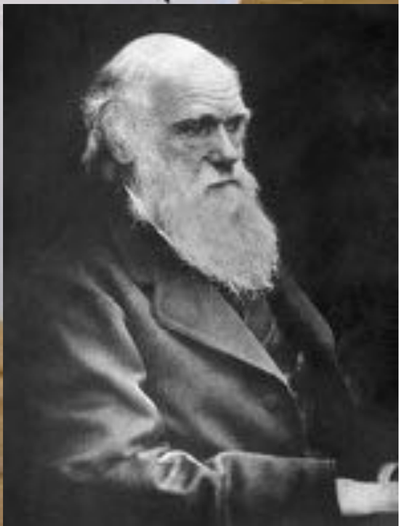
Darwin's warm little pond:

"But If (and oh what a big if) we could conceive in **some warm little pond** with all sorts of ammonia and phosphoric salts, **light, heat, electricity etc. present**, that a protein compound was chemically formed, ready to undergo still more complex changes at the present such matter would be instantly devoured, which would not have been the case before living creatures were formed."

Charles Darwin (1809-1882) in a letter to Botanist J.D. Hooker in 1871 Cambridge University archives

Crucial ingredients:

- **Liquid solution, rich in chemicals (primordial soup)**
- **Energy source**



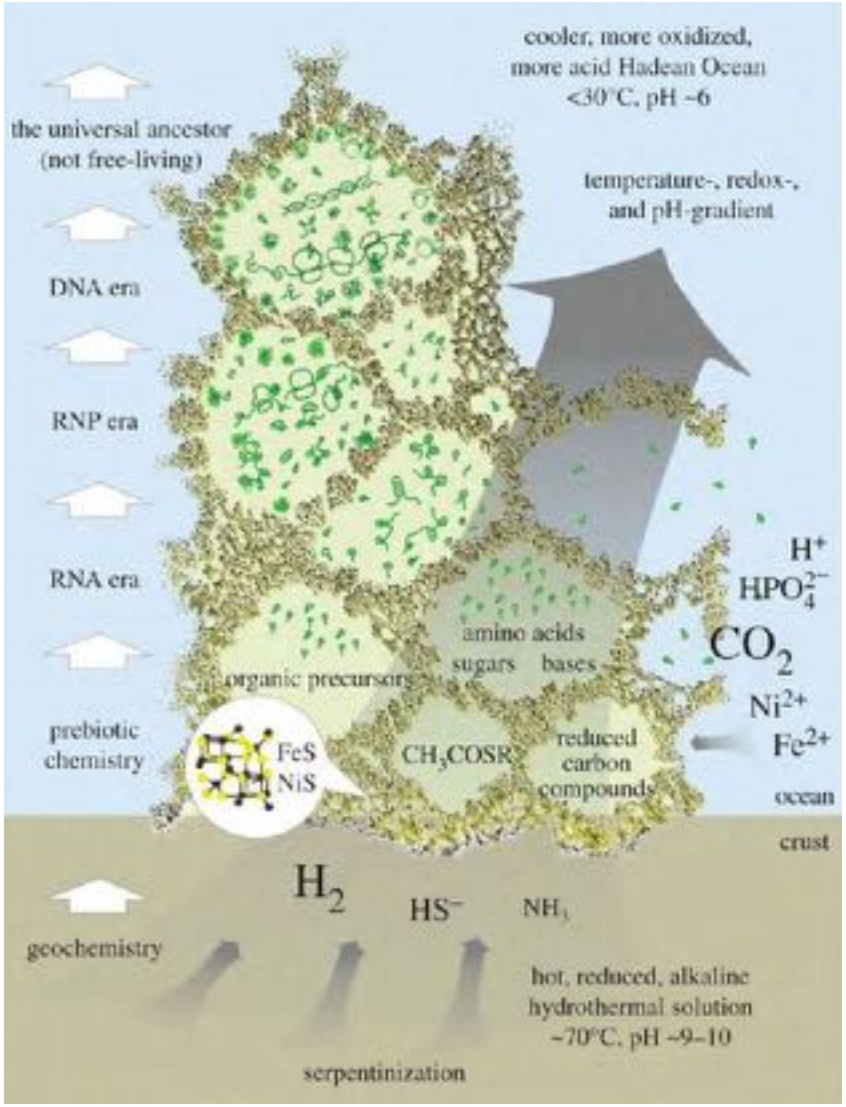
Origin of Life:

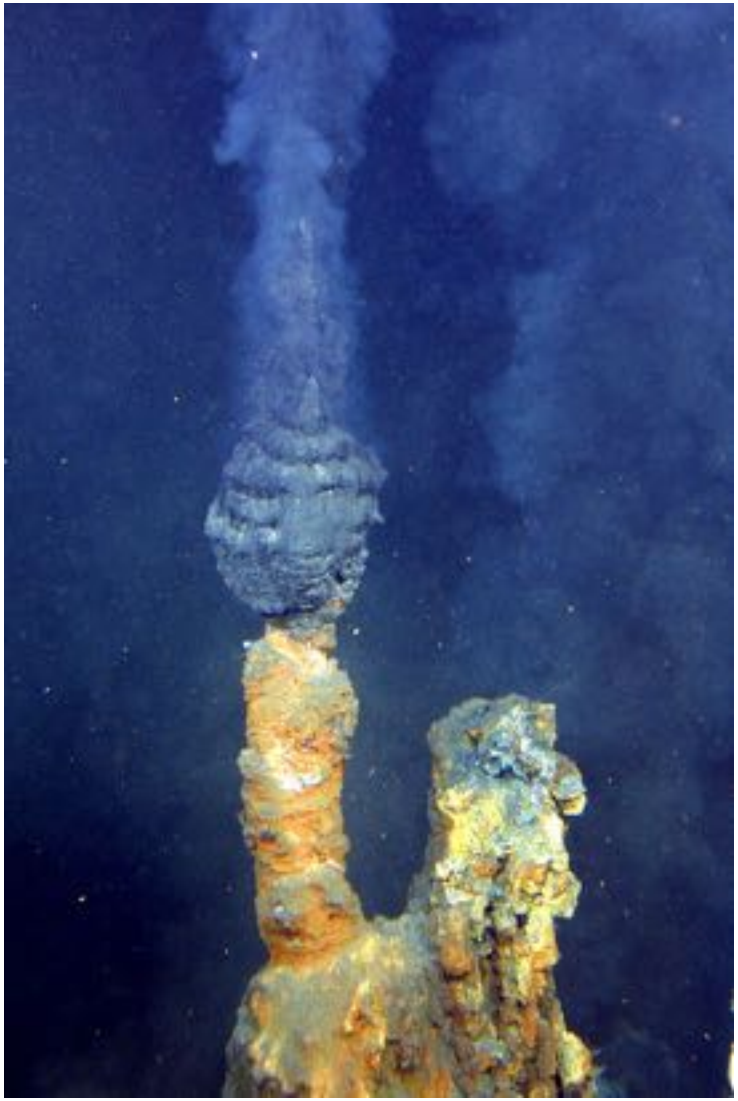
The Oparin-Haldane theory (1924-1929)

Alexander Oparin
1894 –1980

John B.S.Haldane
1892 - 1964

Alternative energy source: Hydrothermal Vents



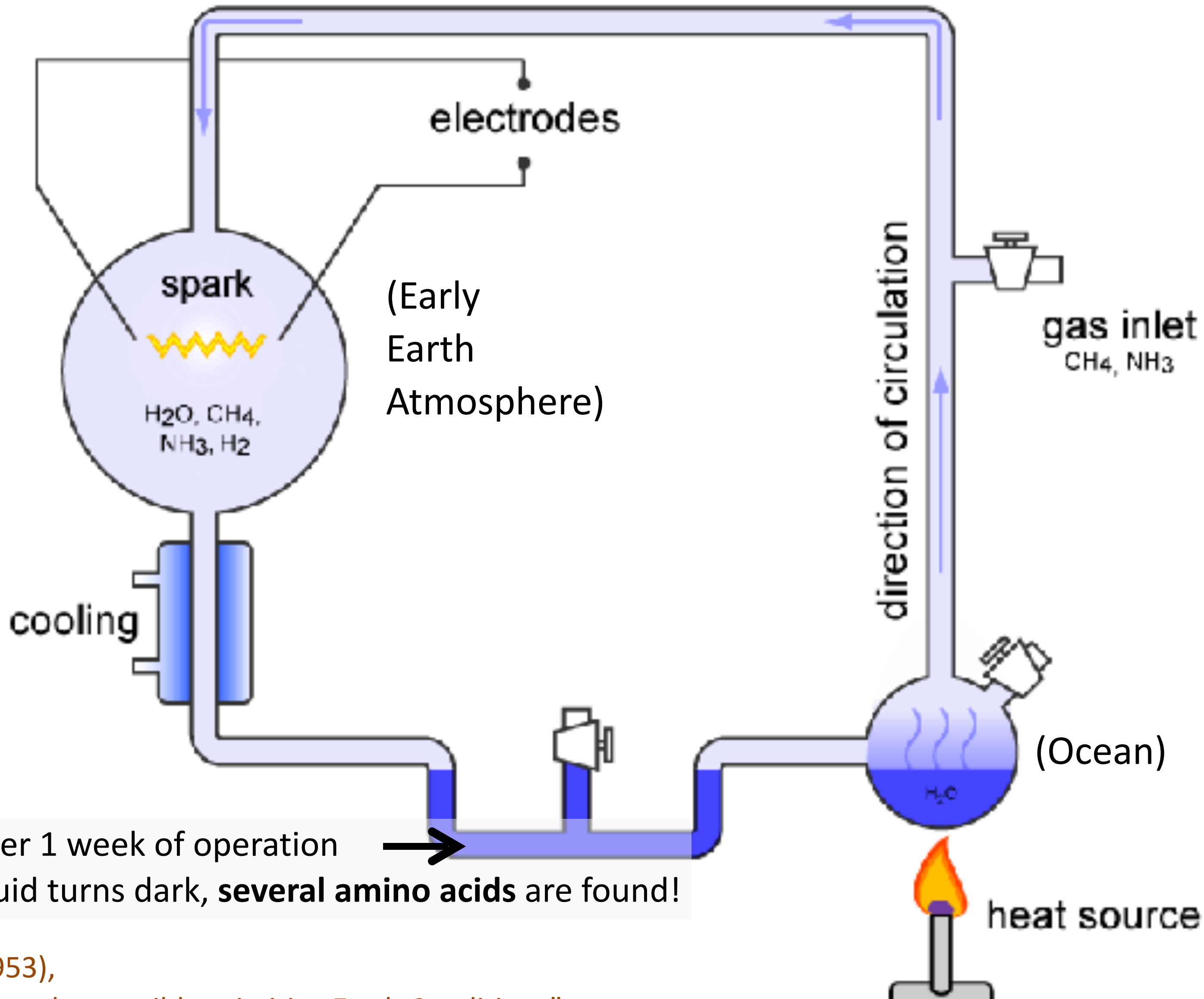


Sousa et al., Phil. Trans. Royal Soc. B 368: 20130088

Testing the Primordial Soup Theory: the Miller-Urey Experiment


Stanley Miller

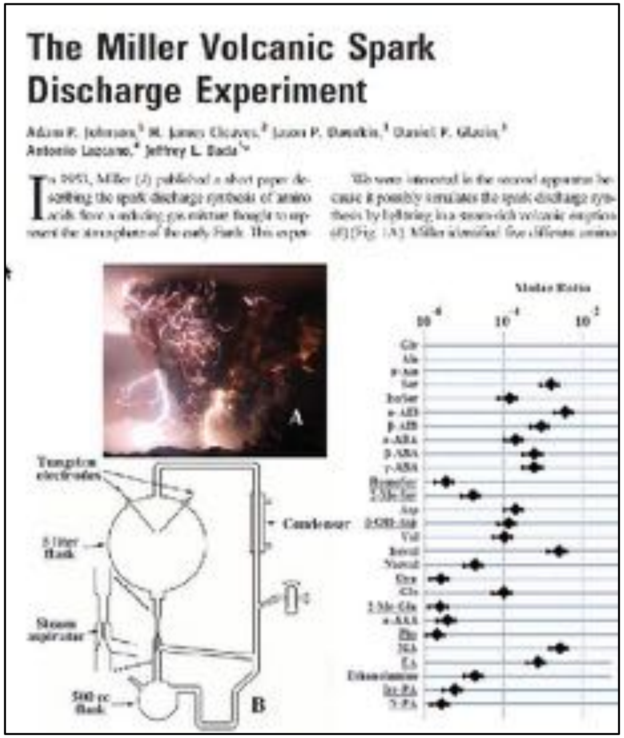

Harold Urey



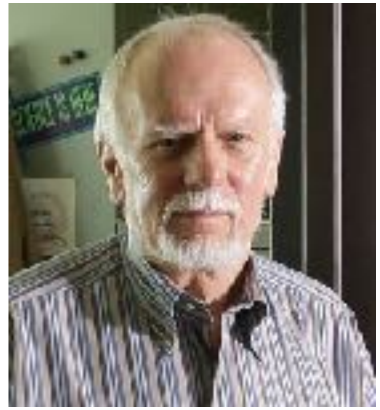
After 1 week of operation liquid turns dark, **several amino acids** are found!

S. Miller, Science **117**, 528 (1953), "A Production of Amino Acids under possible primitive Earth Conditions"

Miller-Urey Revisited

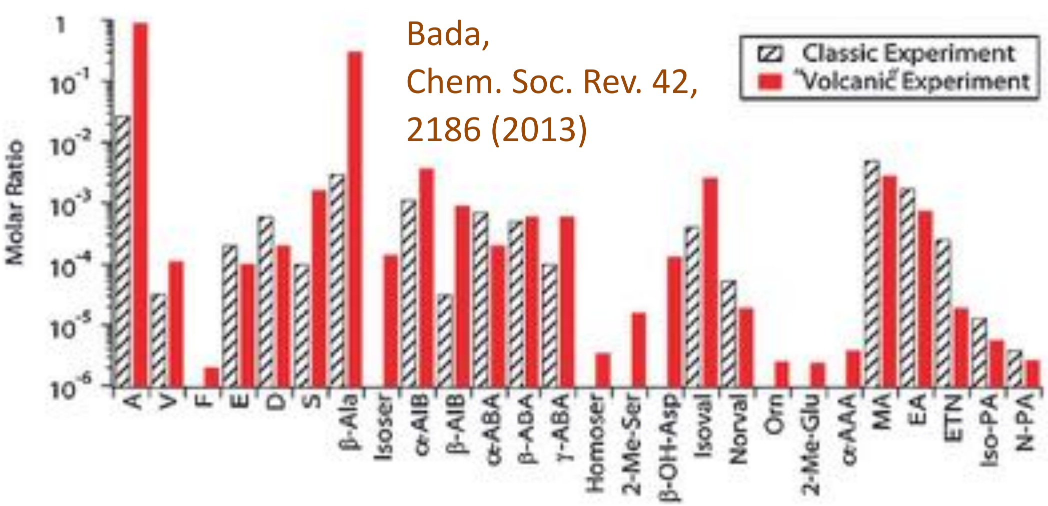


The Miller Volcanic Spark Discharge Experiment



Jeffrey L. Bada

Johnson et al.,
Science 322 404 (2008)



Bada,
Chem. Soc. Rev. 42,
2186 (2013)

	Apparatus One	Apparatus Two	Apparatus Three
Glycine (Gly)	1	1	1
Alanine (Ala)	2.7×10^{-2}	0.9	1.4
β-Alanine (β-Ala)	0.003	0.3	0.9
Serine (Ser)	1.0×10^{-4}	1.6×10^{-3}	2.7×10^{-3}
Isoserine (IsoSer)	Not detected	1.4×10^{-4}	Not detected
α-Amino-Isobutyric Acid (α-AIB)	1.1×10^{-3}	3.7×10^{-3}	7.1×10^{-2}
β-Amino-Isobutyric Acid (β-AIB)	3.2×10^{-5}	9.0×10^{-4}	4.8×10^{-2}
α-Amino-Butyric Acid (α-ABA)	7.0×10^{-4}	2.0×10^{-4}	Not detected
β-Amino-Butyric Acid (β-ABA)	5.0×10^{-4}	6.0×10^{-4}	4.7×10^{-2}
γ-Amino-Butyric Acid (γ-ABA)	1.0×10^{-4}	6.0×10^{-4}	1.4×10^{-2}
Homo Serine (HomoSer)	Not detected	3.4×10^{-6}	Not detected
2-Methyl Serine (2-Me-Ser)	Not detected	1.6×10^{-5}	Not detected
Aspartic Acid (Asp)	6.0×10^{-4}	2.0×10^{-4}	2.5×10^{-3}
β-hydroxy-Aspartic Acid (β-OH-Asp)	Not detected	1.3×10^{-4}	Not detected
Valine	3.3×10^{-5}	1.1×10^{-4}	Not detected
(EA)	1.7×10^{-3}	7.4×10^{-4}	Not detected
Ethanolamine	2.5×10^{-4}	1.9×10^{-5}	7.2×10^{-2}
Isopropylamine (Iso-PA)	1.3×10^{-5}	5.7×10^{-6}	Not detected
n-Propylamine (N-PA)	3.8×10^{-6}	2.6×10^{-6}	Not detected

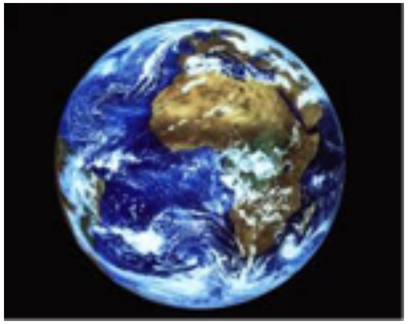
Recent (2007-2008) re-analysis of Miller's preserved residues (with modern analytic methods) finds many more Amino acids!

But no enantiomaric excess!

(that means no preference for left- or right-handed molecules)

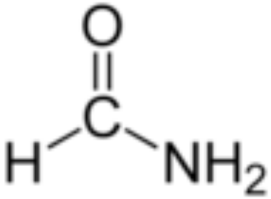
Why is Water So Essential for Life on Earth

- The liquid phase facilitates chemical reactions,
- In a liquid reactants move freely, they can encounter each other much more frquently than in a solid,
- Frozen water floats, insulates lower layers from freezing,
- Water is an excellent solvent for salts,



Which of these points are “geocentric”?

- Chemical reactions also happen in the gas phase and in solids,
- Water ice has higher albedo than liquid water. That means that although it will protect lower layers from freezing, it will also lead to colder surfaces and thus more freezing,
- Ammonia is liquid at lower temperatures than water, the range over which ammonia is liquid for relevant planetary surface pressures is greater than for water,
- E.g., formamide (CH_3NO) has a larger liquid temp range (225-480 K) and is an excellent solvant for polar materials.



formamide

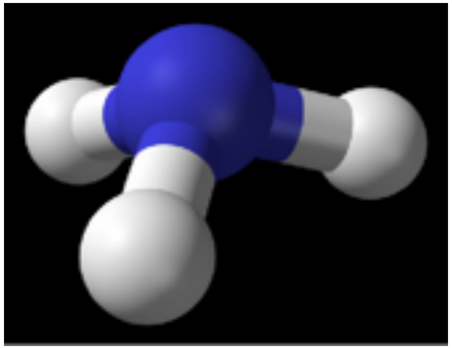
Alternatives to Water

TABLE 6.1 Freezing and Boiling Points (at 1 atm) of Some Solvents

Solvent	Freezing Point (K)	Boiling Point (K)
Ammonia	195	240
Dihydrogen	14	20
Dinitrogen	63	77
Ethane	101	184
Formamide	273	493
Helium		4
Hydrazine	275	387
Hydrogen cyanide	260	299
Hydrogen fluoride	190	293
Hydrogen sulfide	192	213
Methane	91	112
Neon	25	27
Sulfuric acid	283	563
Water	273	373

Committee on the Limits of
Organic Life in Planetary Systems, 2007

Example: Liquid Ammonia NH_3



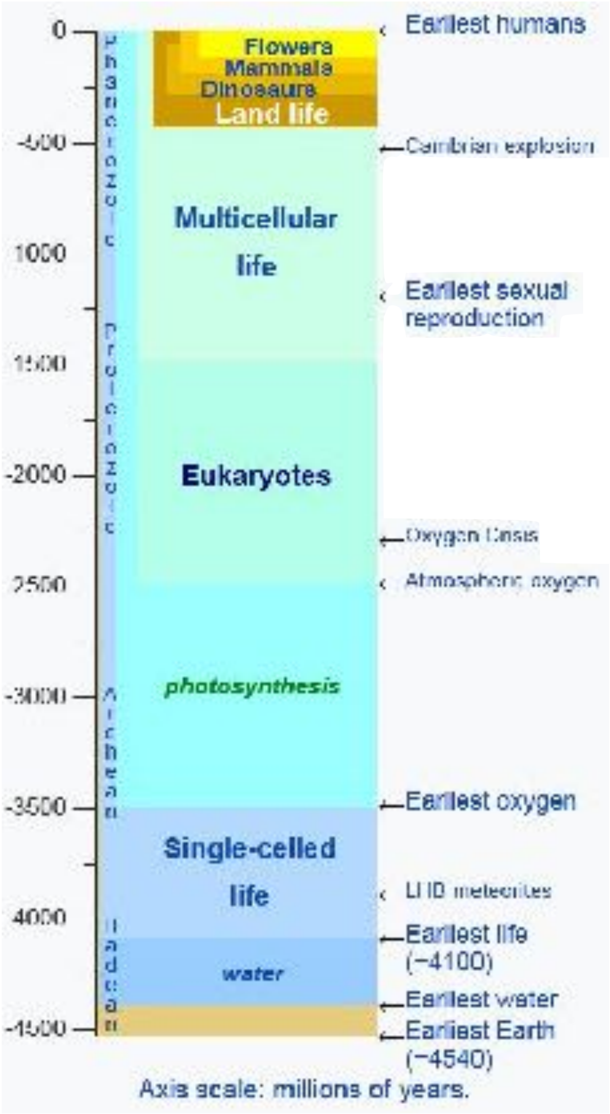
- Very similar properties to water,
- Liquid between 195-240 K at 1atm,
- Even wider liquid range at high P,
- Probably abundant in the solar system,
- Good solvent for organic molecules

How to find signatures of life? First: let's have a look at our own planet:

Earth's Atmosphere over Time

Epoch	Age (Gyr ago)	Mixing Ratios CO_2	CH_4	O_2	O_3	N_2O
0..........	3.9	1.00E−01	1.65E−06	0	0	0
1..........	3.5	1.00E−02	1.65E−03	0	0	0
2..........	2.4	1.00E−02	7.07E−03	2.10E−04	8.47E−11	5.71E−10
3..........	2.0	1.00E−02	1.65E−03	2.10E−03	4.24E−09	8.37E−09
4..........	0.8	1.00E−02	4.15E−04	2.10E−02	1.36E−08	9.15E−08
5..........	0.3	3.65E−04	1.65E−06	2.10E−01	3.00E−08	3.00E−07

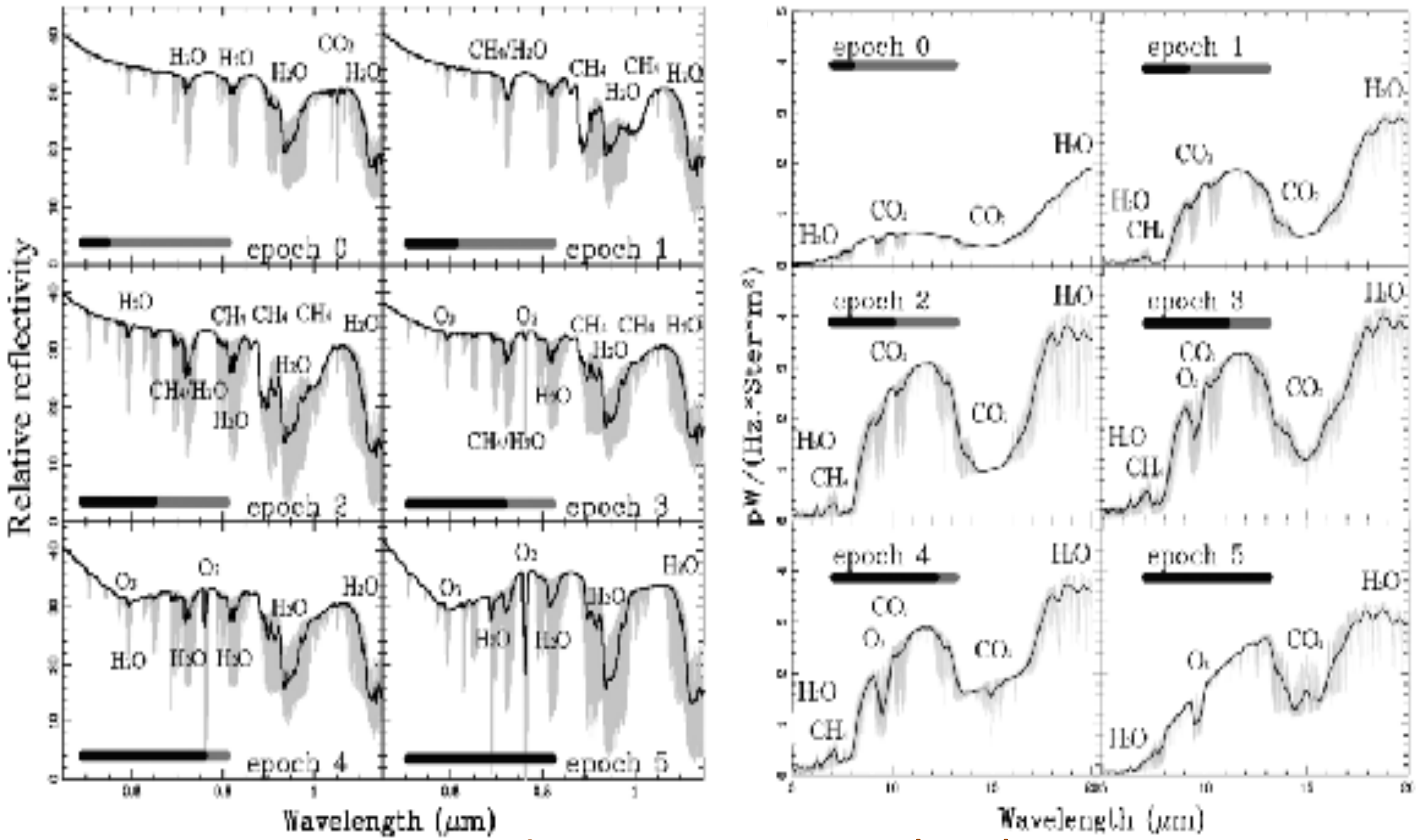
Epoch 0: mainly carbon dioxide originating from volcanoes,
Epoch 1: loss of carbon dioxide (into rocks), life creates CH_4, no OH,
Epoch 2: Maximum CH_4 level reached, organic Haze shows up, lower temperatures,
Epoch 3: Rise of oxygen, decrease of methane, ice ages,
Epoch 4: Further rise of O_2, although still lower than today
Epoch 5: present day atmosphere and vegetation



The appearance of eukaryotes coincides with the creation of oxygen.
(A eukaryote is any organism whose cells contain a nucleus and other organelles enclosed within membranes.)

Kaltenegger, ApJ 659, 598 (2007)

Simulated Evolution of Earth's Atmosphere over time



Kaltenegger ApJ 659, 598 (2007)

Without plants or bacteria our atmosphere would contain virtually no oxygen!

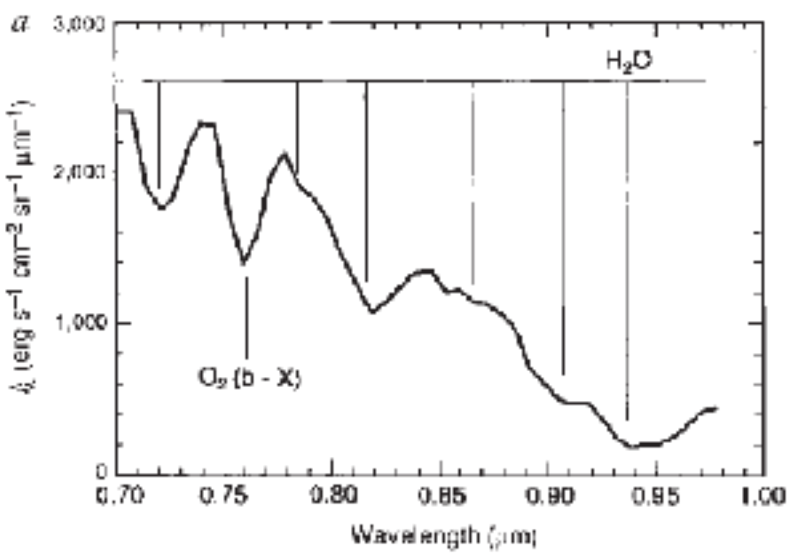
Other gases like Methane (CH_4) or nitrous oxide (NO) are also considered as **bio-signature gases,** but they also have strong abiotic production mechanisms.

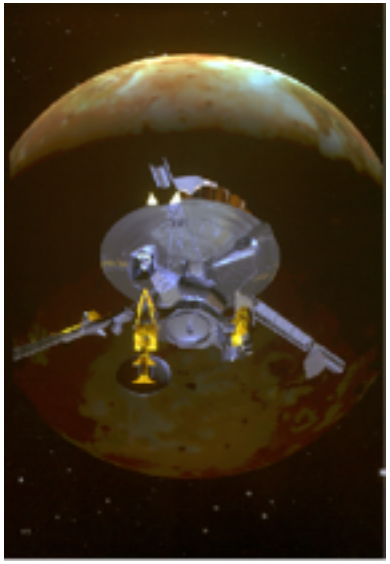
A search for life on Earth from the Galileo spacecraft

Carl Sagan*, W. Reid Thompson*, Robert Carlson†, Donald Gurnett‡ & Charles Hord§

* Laboratory for Planetary Studies, Cornell University, Ithaca, New York 14853, USA
† Atmospheric and Cometary Sciences Section, Jet Propulsion Laboratory, Pasadena, California 91109, USA
‡ Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242-1479, USA
§ Laboratory for Atmospheric and Space Physics, University of Colorado, Boulder, Colorado 80309, USA

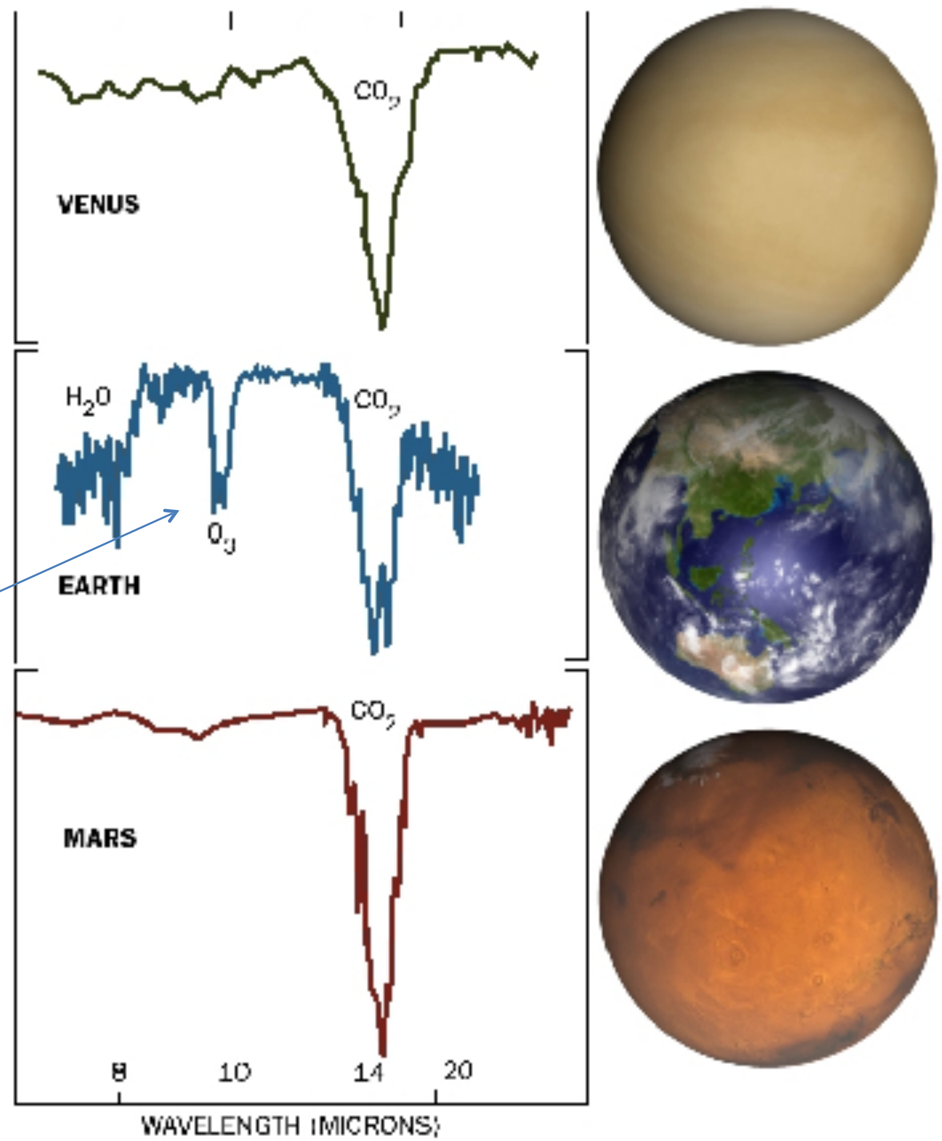
In its December 1990 fly-by of Earth, the Galileo spacecraft found evidence of abundant gaseous oxygen, a widely distributed surface pigment with a sharp absorption edge in the red part of the visible spectrum, and atmospheric methane in extreme thermodynamic disequilibrium; together, these are strongly suggestive of life on Earth. Moreover, the presence of narrow-band, pulsed, amplitude-modulated radio transmission seems uniquely attributable to intelligence. These observations constitute a control experiment for the search for extraterrestrial life by modern interplanetary spacecraft.





Sagan et al., Nature 365, 715 (1993)

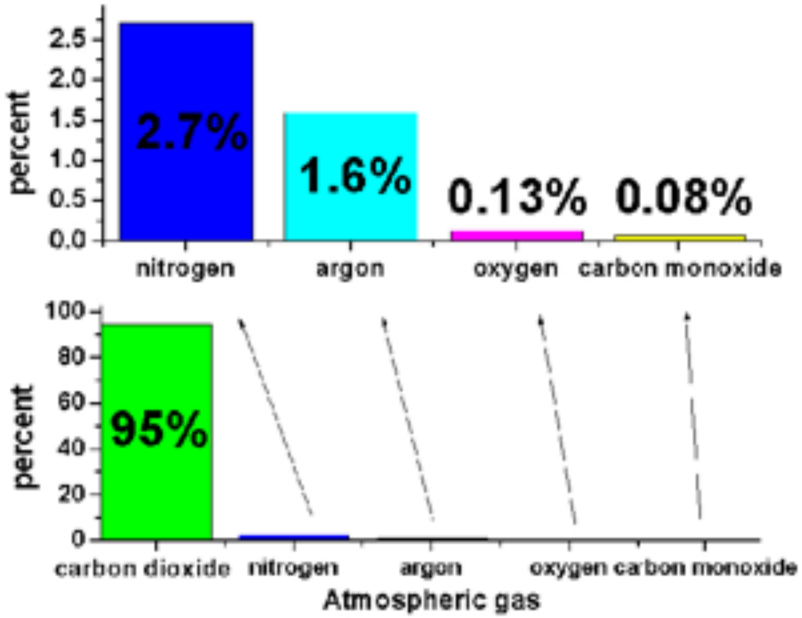
Our solar system as an example

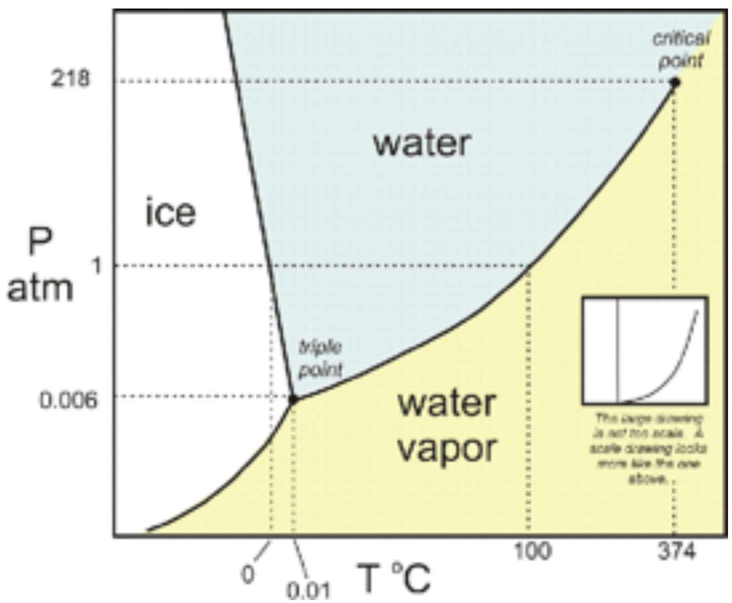


Life!

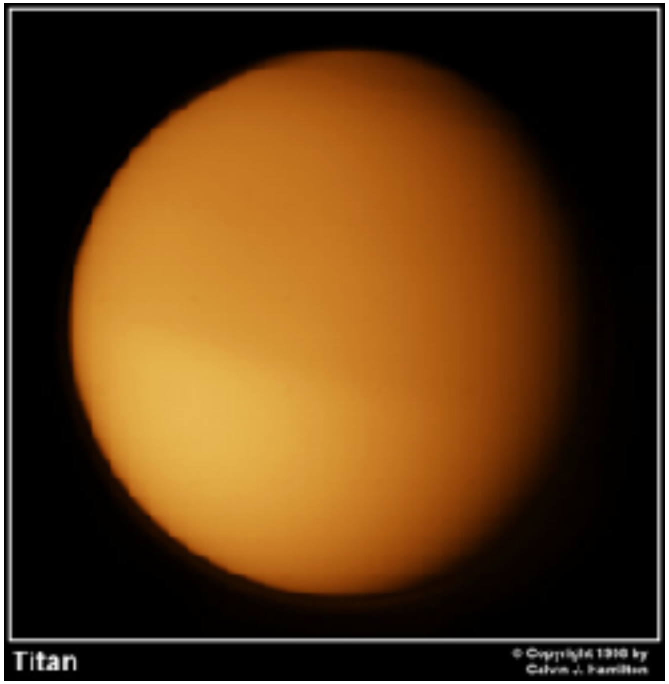
Planetary Atmospheres: Mars

- Surface temperature between 20C and -80C,
- **No magnetic field,**
- **Exposed to Solar Winds,**
- Surface pressure 0.006 bar,
- Water can only be liquid at low elevations,
- At higher elevations,
  water is either solid or gaseous,
- Weak magnetic field, low gravity
  → solar wind may have blown away gas





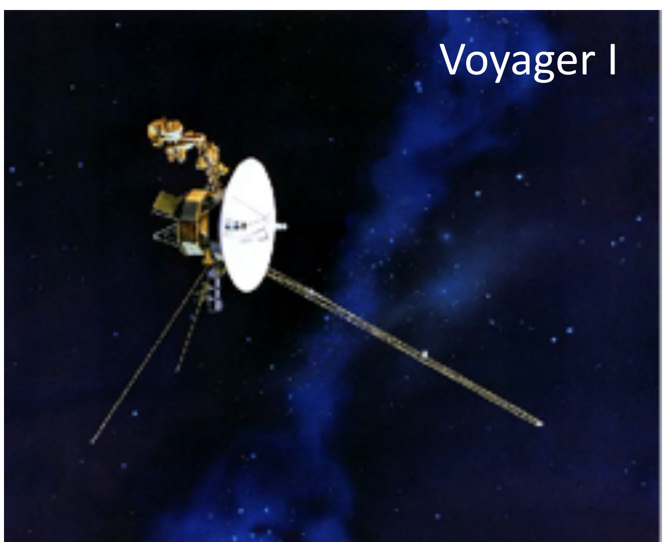
Exploring Titan



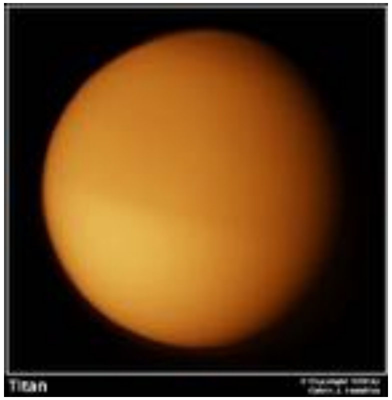
Saturn's biggest satellite, 2nd biggest in solar system (behind Ganymede).

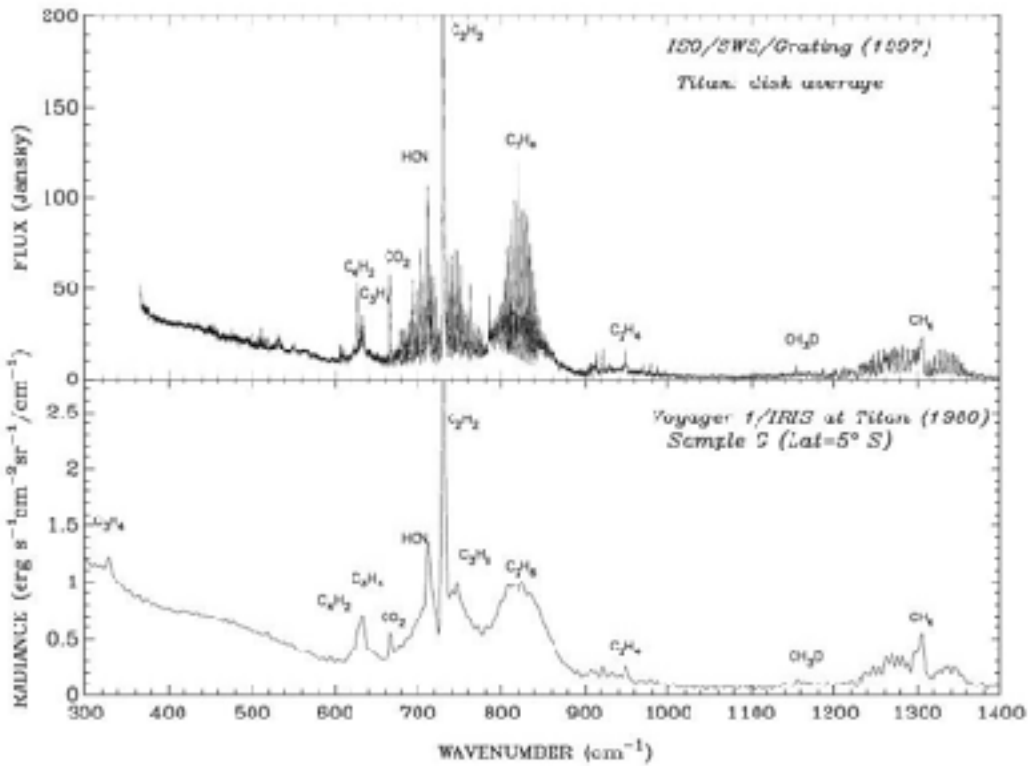
Titan has an atmosphere that hides the surface perpetually, 1.5 atmospheres

From Earth, methane was detected spectroscopically. When Voyager 1 flew by, this methane was confirmed, but it was realized that nitrogen (N_2) was the dominant gas in the atmosphere.



Titan's Atmosphere

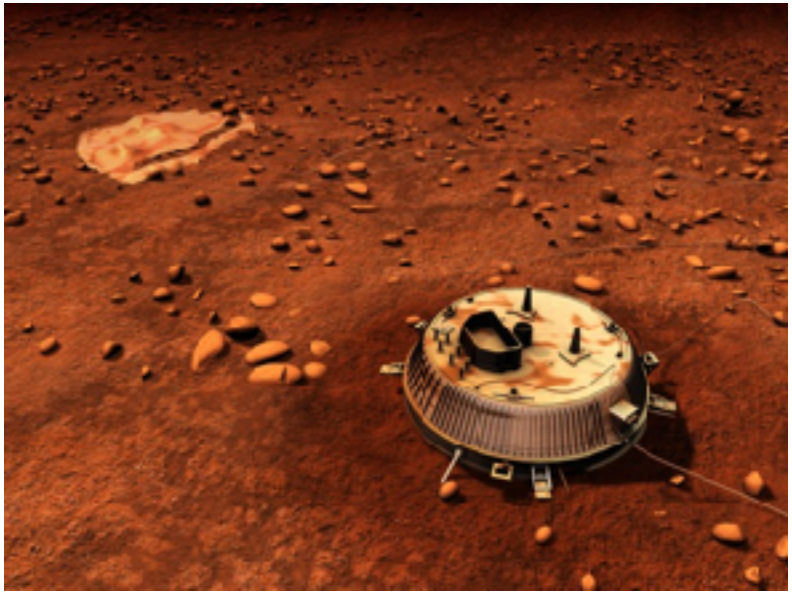


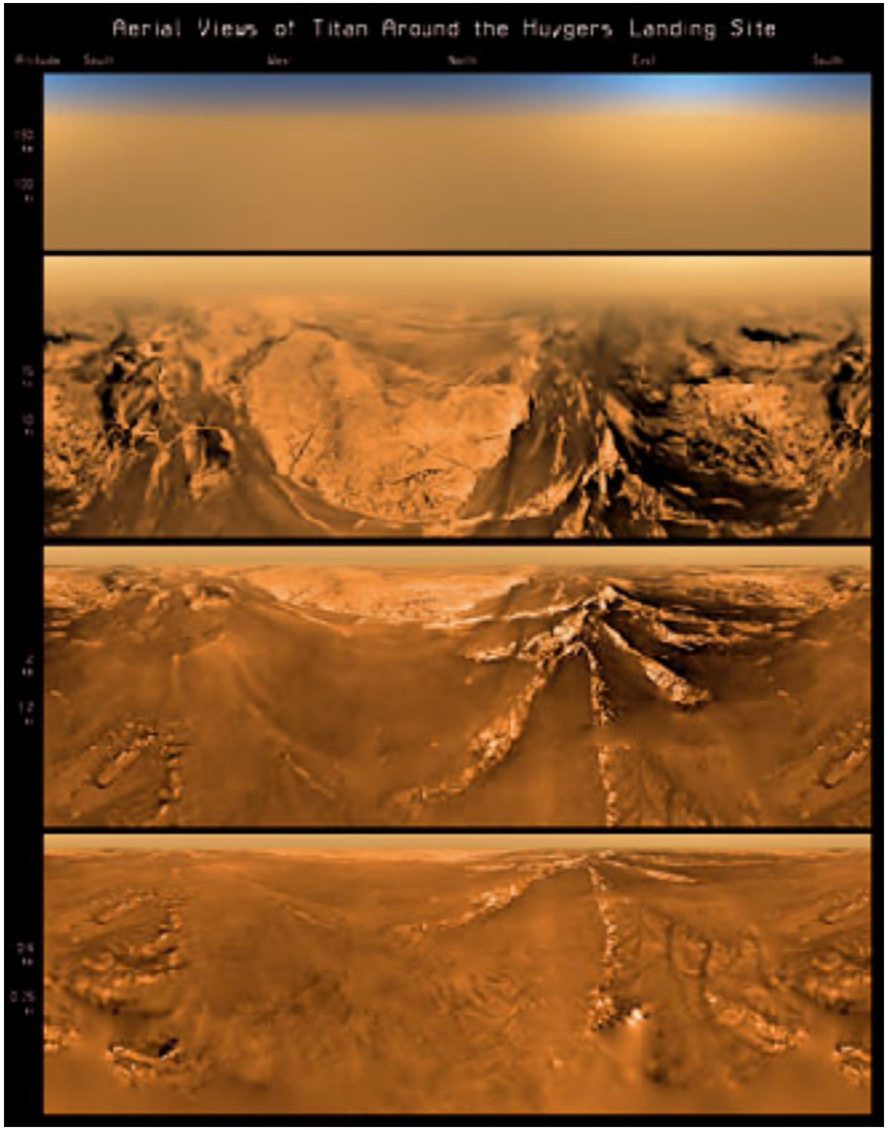


Composition of Titan's Atmosphere

Major constituent		*Percent*
Nitrogen	(N_2)	82 – 99
Methane	(CH_4)	1 – 6
(Argon?)	(Ar)	<1 – 6
Minor constituent		***Parts per million***
Hydrogen	(H_2)	2,000
Hydrocarbons		
Ethane	(C_2H_6)	20
Acetylene	(C_2H_2)	4
Ethylene	(C_2H_4)	1
Propane	(C_3H_8)	1
Methylacetylene	(C_3H_4)	0.03
Diacetylene	(C_4H_2)	0.02
Nitrogen compounds		
Hydrogen cyanide	(HCN)	1
Cyanogen	(C_2N_2)	0.02
Cyanoacetylene	(HC_3N)	0.03
Acetonitrile	(CH_3CN)	0.003
Dicyanoacetylene	(C_4N_2)	condensed
Oxygen compounds		
Carbon monoxide	(CO)	50
Carbon dioxide	(CO_2)	0.01

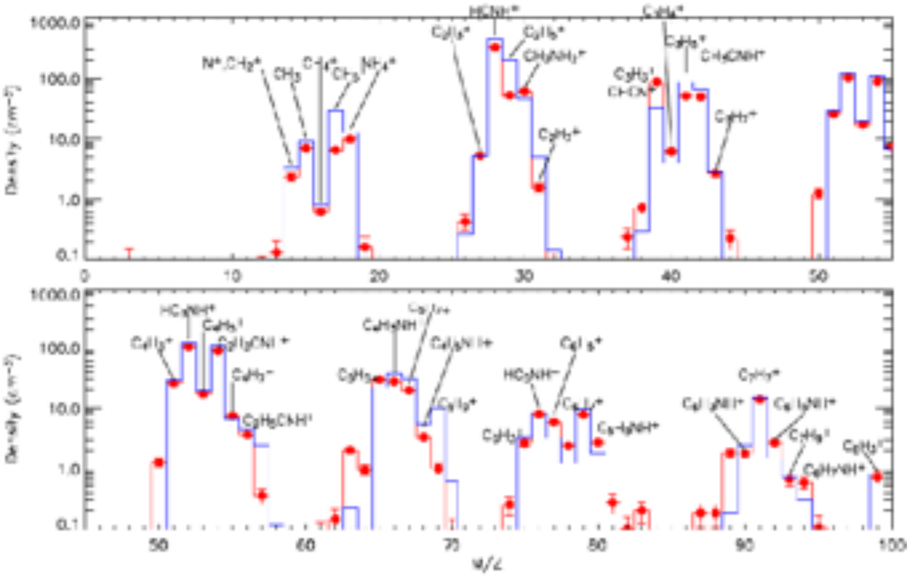
The Cassini Huygens Probe

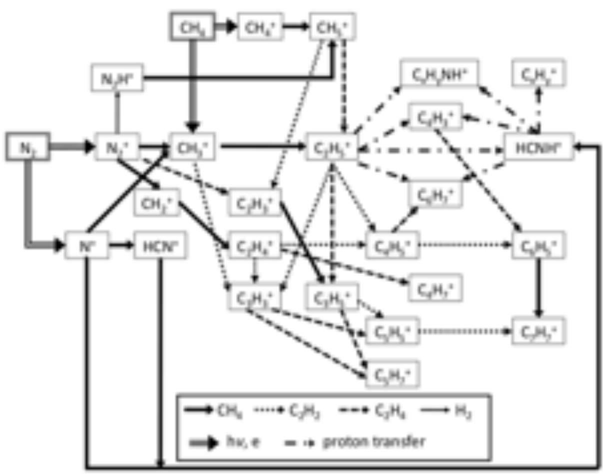


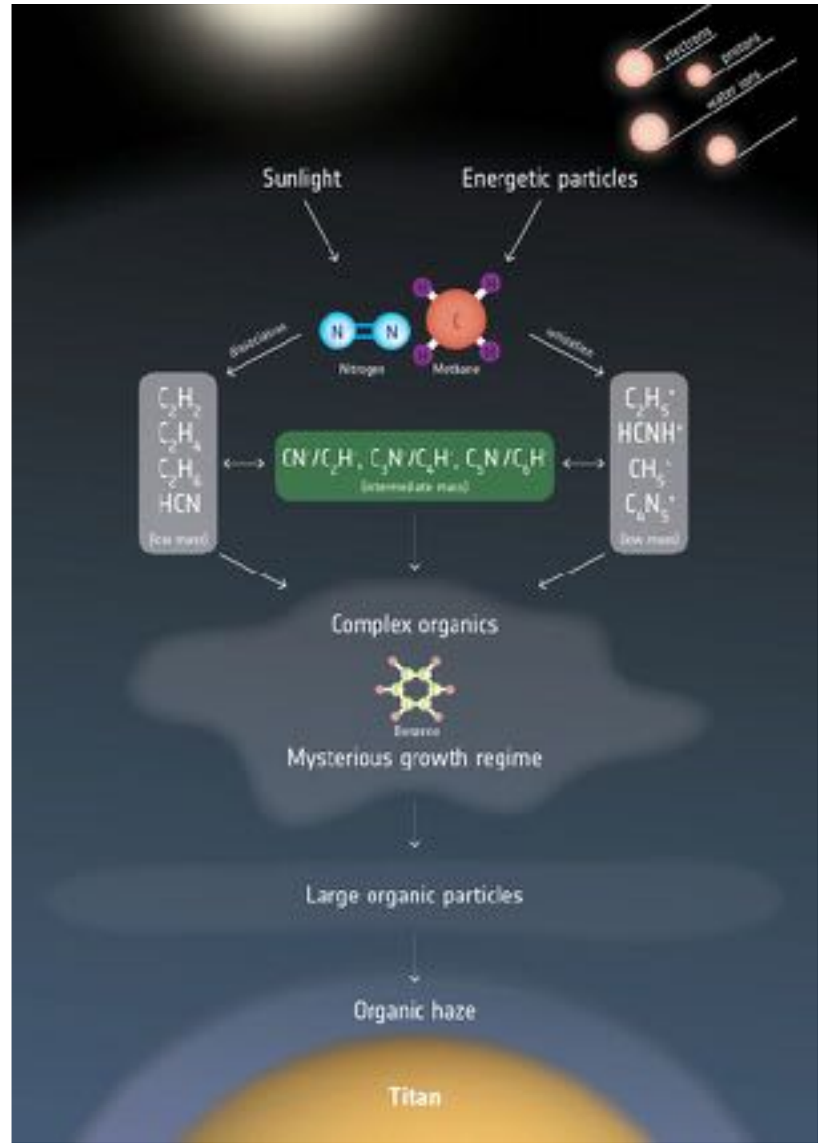


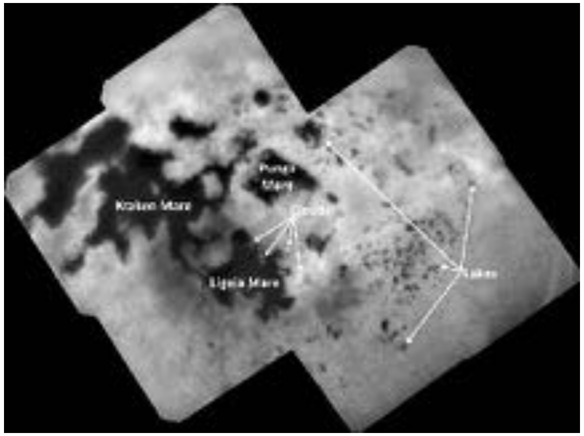
Complex ion-neutral chemistry in Titan’s atmosphere

Ion and Neutral Mass Spectrometer (INMS)



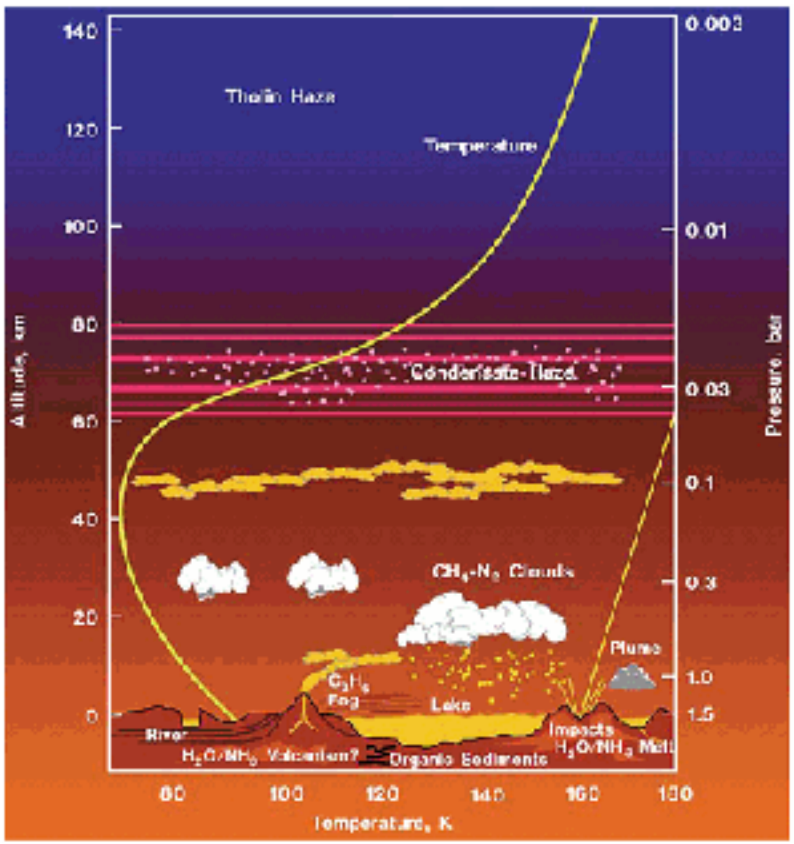






Lakes On Titan

Titan / Earth similarities



- Titan's atmosphere is made mainly of N_2 (like Earth's)
- Surface pressure of 1.5 bar (Titan) to 1 bar (Earth)
- Methane appears to exists in solid/ liquid/gas form on Titan, like water on Earth
- Complex Methane cycle on Titan (water cycle on Earth)
- Titan is the only planetary object known with liquid lakes
- Organic molecules and ions found: HCN, HC_3N, C_2N_2, etc ..

Titan's atmosphere is the most complex organic laboratory in our solar system.