CSH Distinguished Lecture 2017

Prof. Dr. Ewine van Dishoeck

Leiden University, NL

Building stars, planets and the ingredients for life in space

Host:

Dr. Maria Drozdovskaya [CSH & IAU Gruber Foundation Fellow]

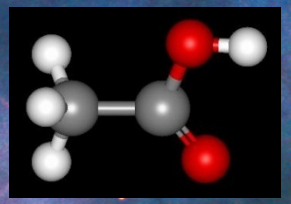
Bern, CH

October 20th, 2017

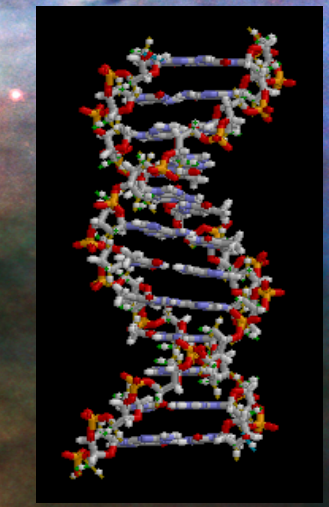
UNIVERSITÄT BERN

CSH
CENTER FOR SPACE AND HABITABILITY

Building stars, planets and the ingredients for life between the stars



Ewine F. van Dishoeck
Leiden Observatory



CSH Public lecture, Bern, October 20 2017

NASA/HST
Carina nevel

Origin of stars, planets and our solar system has long fascinated mankind

Stars
Kandinsky

Starry night
Van Gogh

Milky Way dreaming
Australia aboriginal art

Raven stealing Sun
Pacific Northwest art

Inspiration from Paul Klee

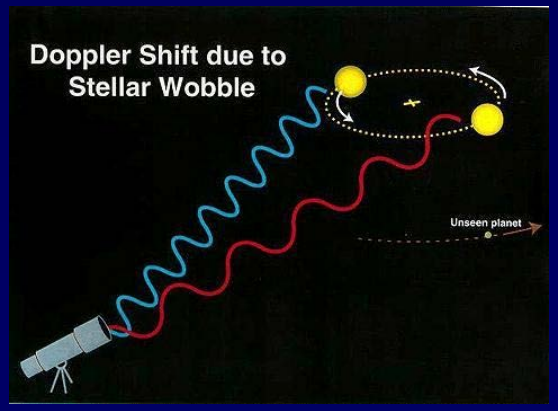
Blue night

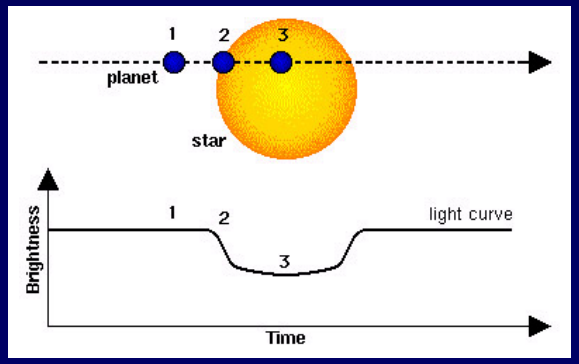
Cosmic composition

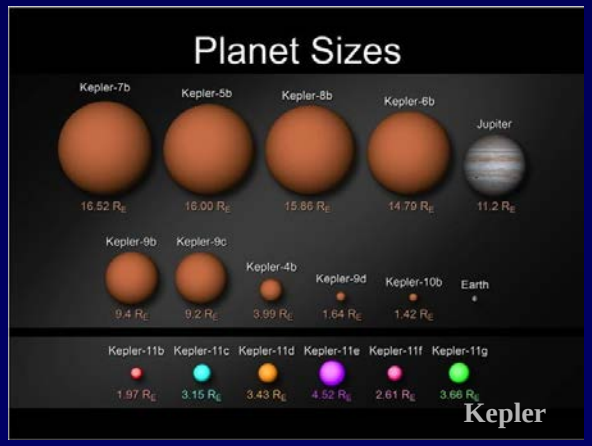
‘Color is the place where our brain and the universe meet’

Discovery of exoplanets leads to fundamental questions

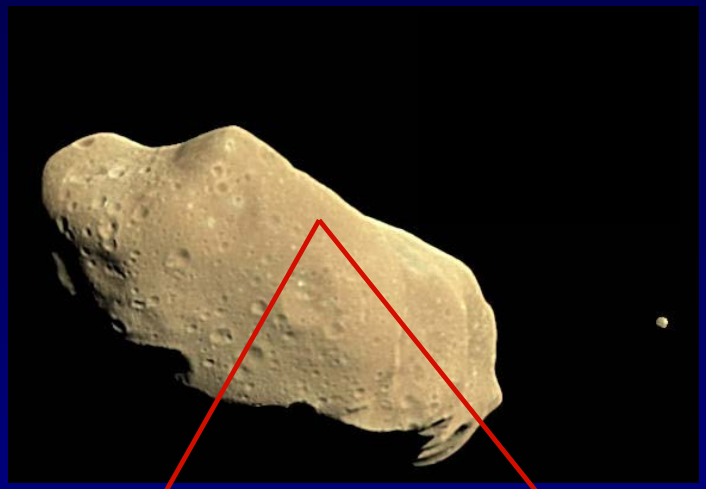
- Where and how are stars and planets born?
- How unique is our solar system?
- Which planets could be habitable?

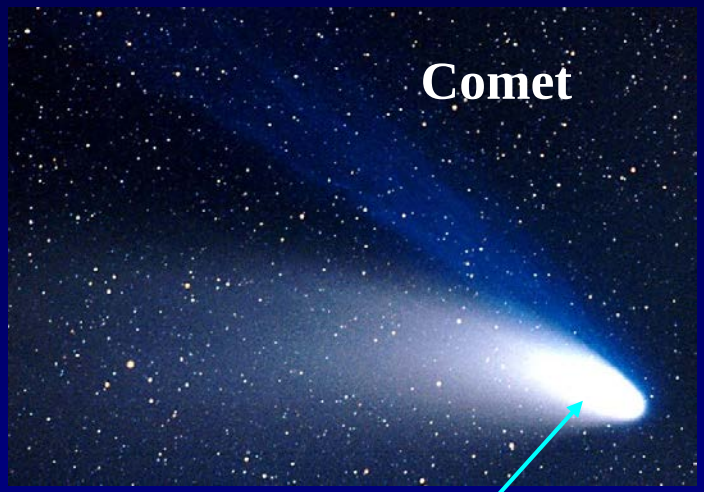


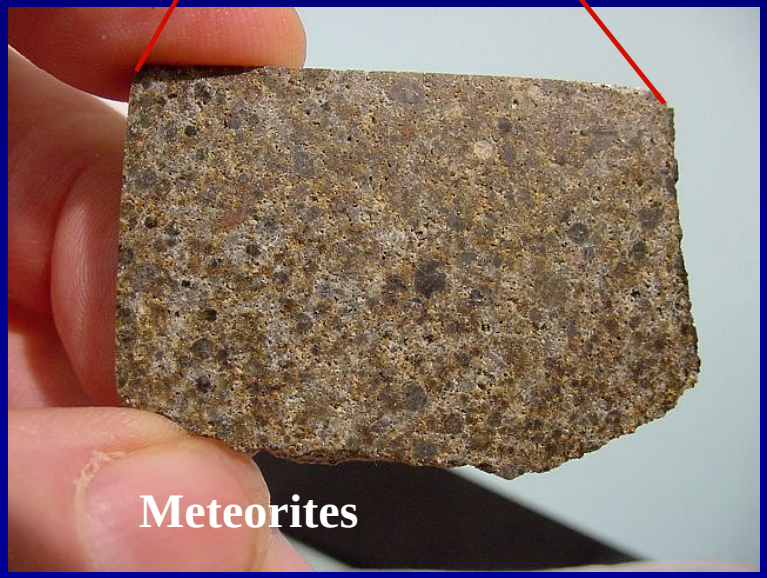


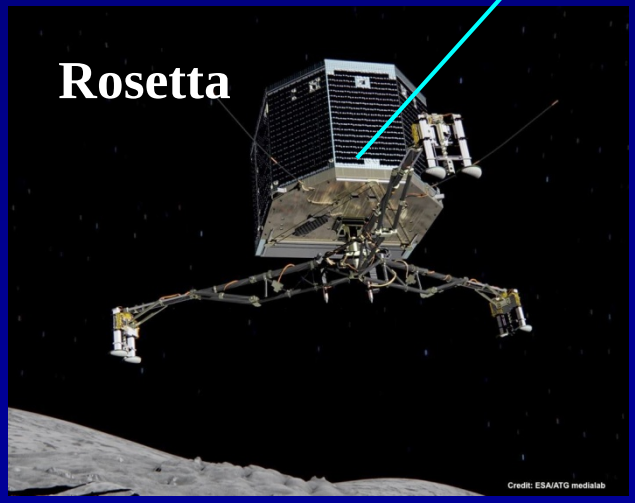


Billion dollar question: how were ‘we’ formed 4.5 billion years ago?



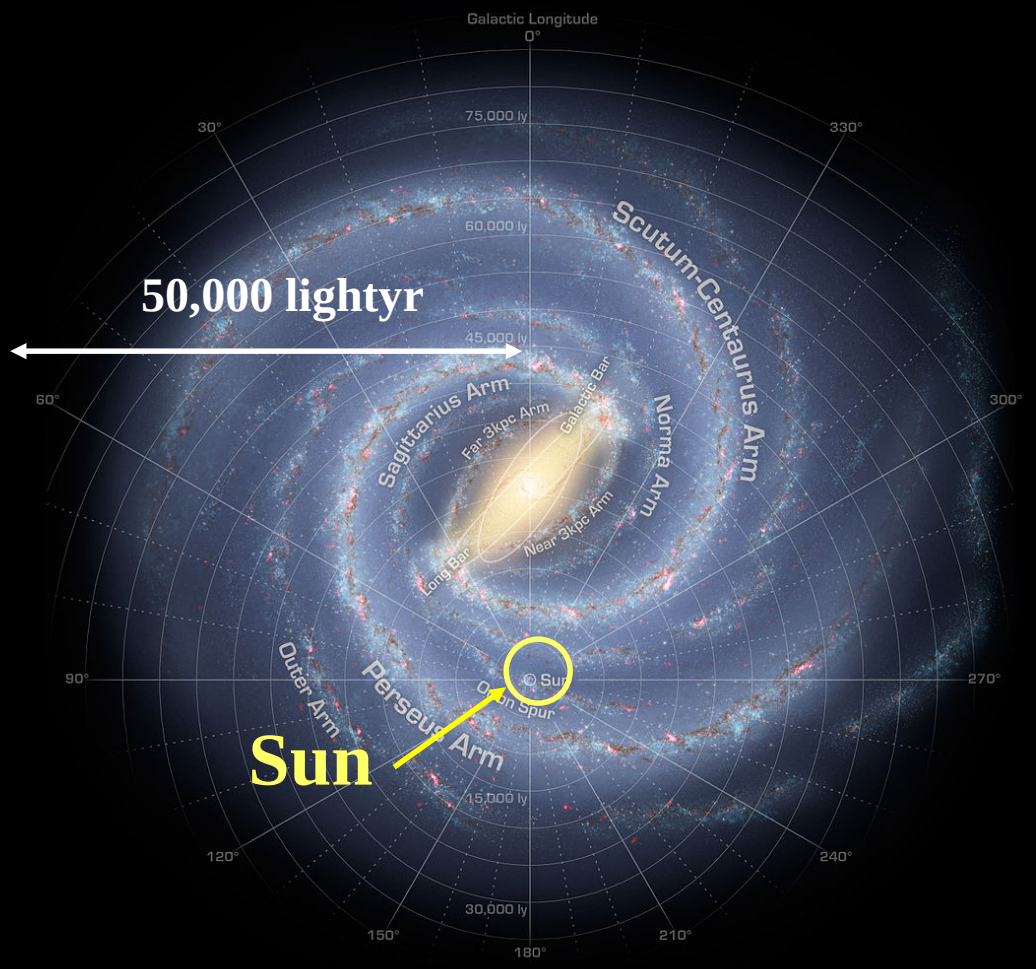






Meteorites and comets are messengers from the early solar system

Our Milky Way



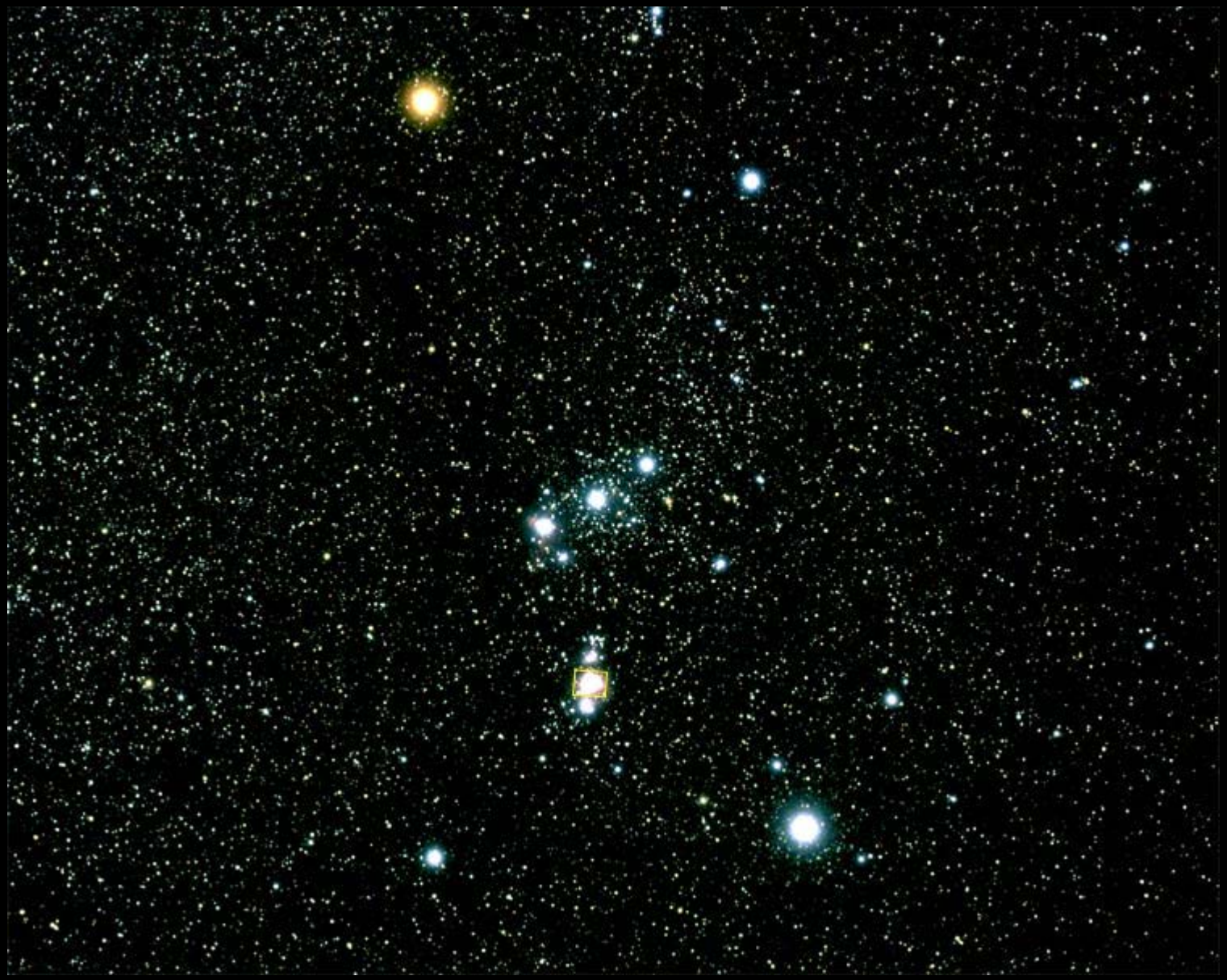
Galaxy = Collection of ~200 billions stars

We live on a small planet circling an ordinary star located in the outskirts of galaxy, of which there are several hundred billion in the Universe

Birthplaces of stars:

Interstellar Clouds

- Space between stars not empty, but filled with a very dilute gas
- Stars are born inside clouds



Orion nebula:

Nursery of thousands of new stars

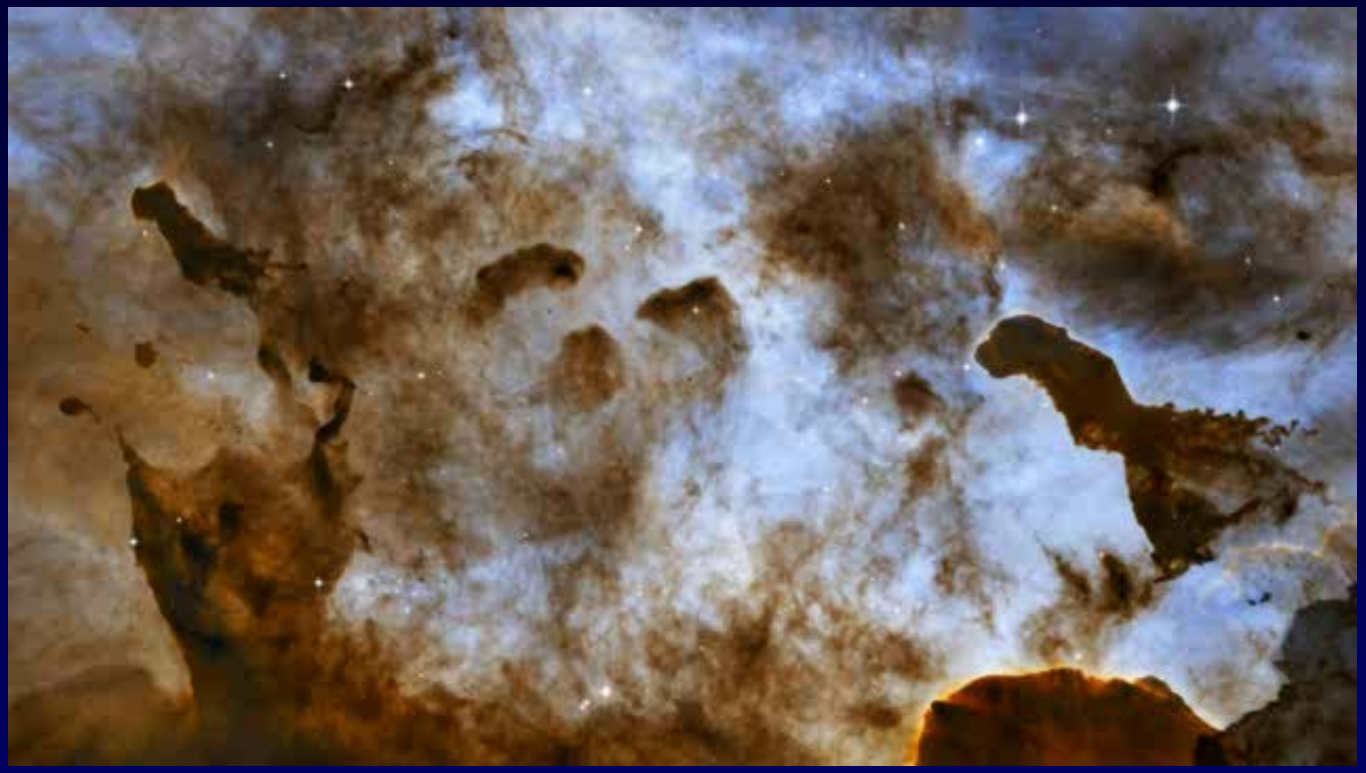
ESO-VLT
ISAAC image
McCaughrean et al. 2001

'The chaotic material of future Suns'

W.Herschel (1789)

Orion nebula as seen by Hubble

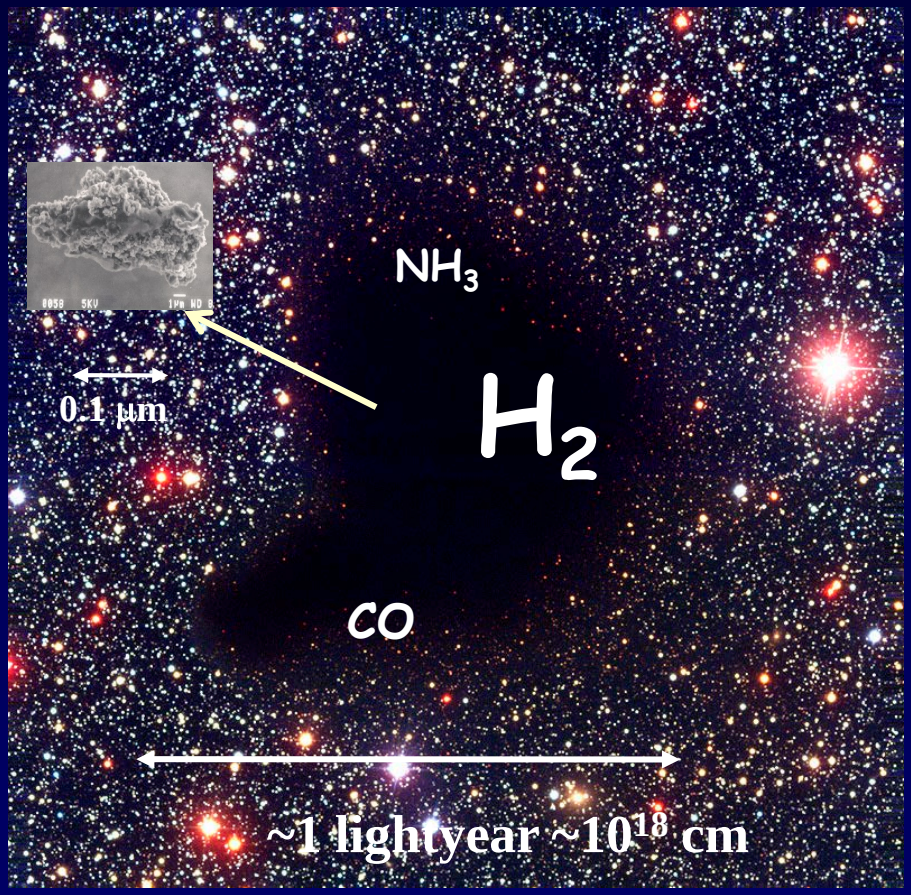
Stars are formed in dark clouds



NASA/ HST Carina nebula

Typical sizes: up to several lightyr (fewx10^{18} cm)
Typical masses: up to 10^5 M_{Sun} (but efficiency only a few%)

Dark clouds: ‘coal sacks’

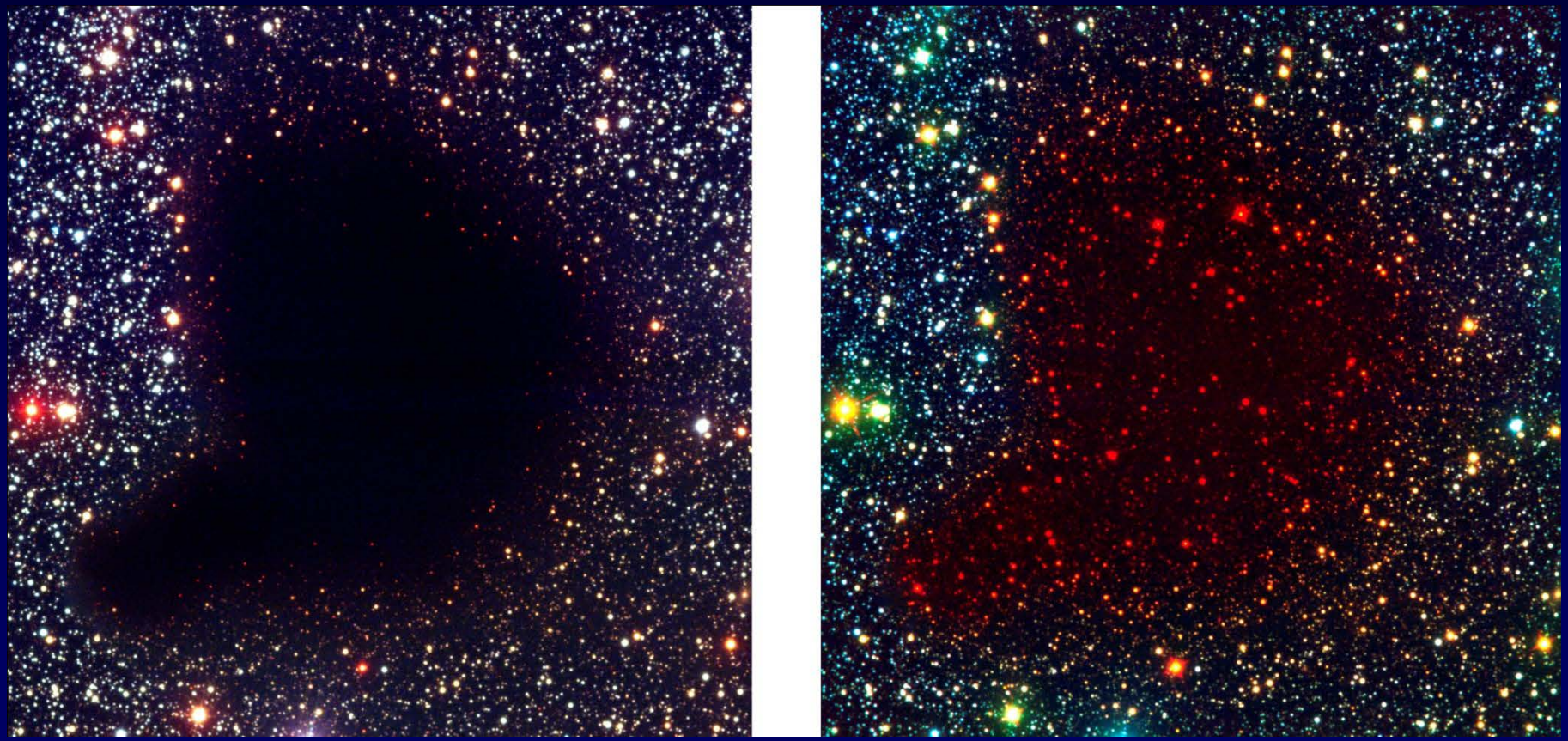


- 99% gas (H_2)
  1% dust (0.1 μm silicates + carbonaceous material)
- Temperature: ~10 K
- Density: ~10000 particles per cubic cm (million times less than in lab)
- Cosmic rays, UV

→ *Unique physical-chemical laboratory!*

How do we study what is happening inside clouds?

Optical **Infrared**

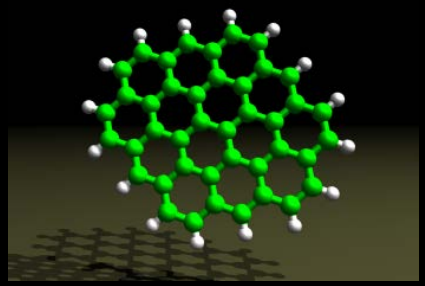


Long wavelengths!

Alves et al. 2001

From visible to infrared light

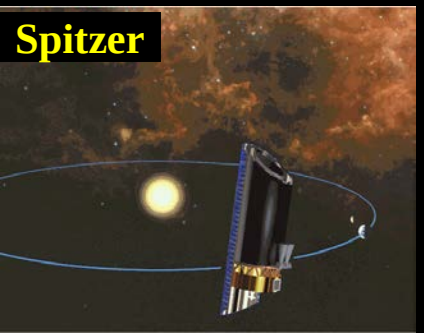
HH 46 star-forming region



Spitzer image:

Red= 8 μm: PAH
Green= 4.5 μm: H_2
Blue= 3 μm: stars

Noriega-Crespo et al. 2004

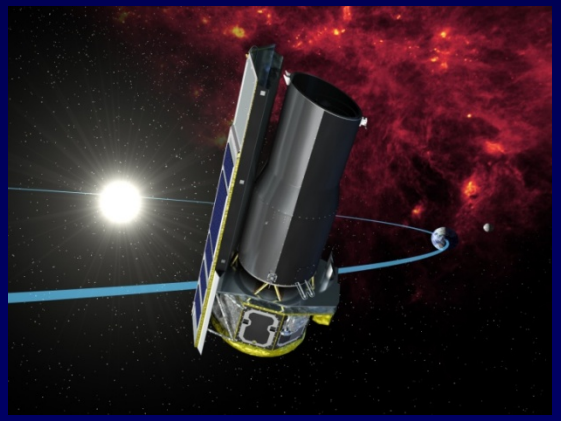


Need long wavelengths to penetrate dusty regions

Space telescopes

ISO
1995-1998

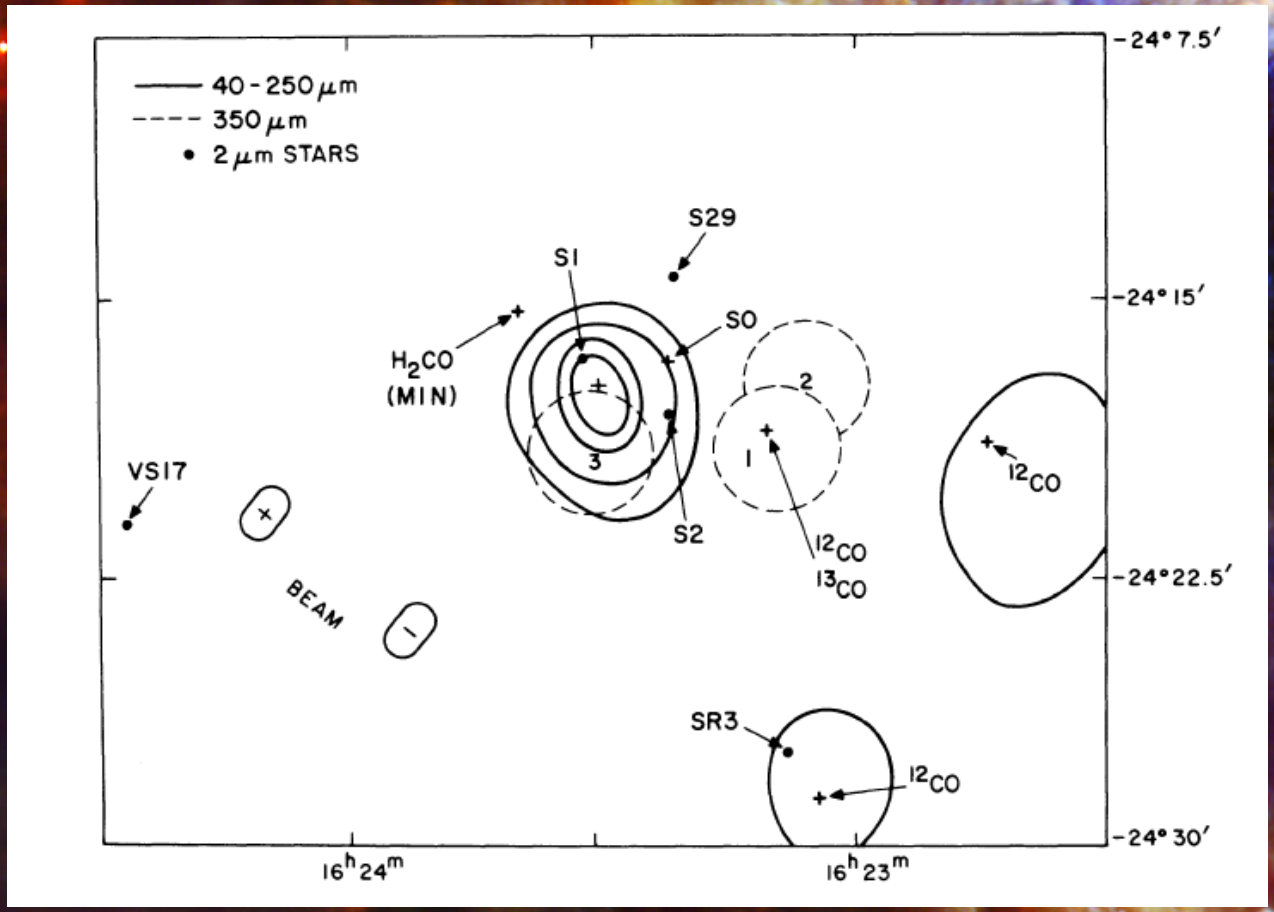
Herschel 3.5 m
2009-2013
HIFI-instrument



Spitzer
2003-2009

Large fraction of infrared radiation from space is blocked by our atmosphere (in particular H_2O, O_2 and CO_2)

Herschel:
Lifting the veil of star-forming clouds



100μm map of the ρ-Oph star forming cloud: Fazio et al. 1976

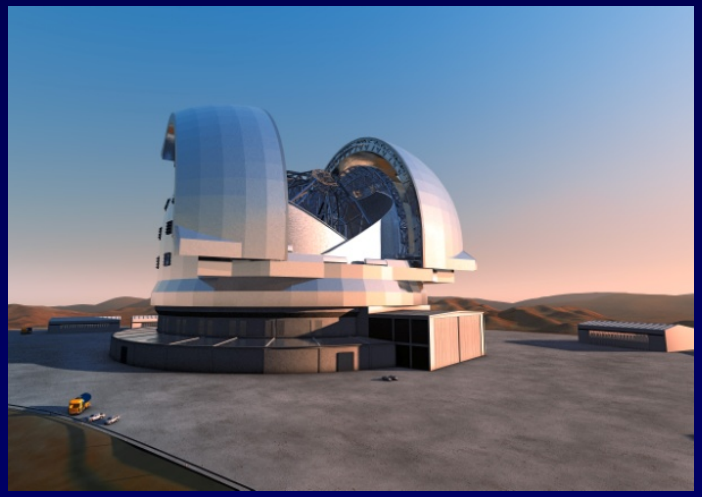
Rosette molecular cloud
PACS & SPIRE 70-350 μm Motte et al. 2010

Ground-based infrared telescopes

From 8-10m to 30-40m diameter

ESO Very Large Telescope

Keck



Future: ELT, TMT, GMT

Atacama Large Millimeter Array (ALMA)

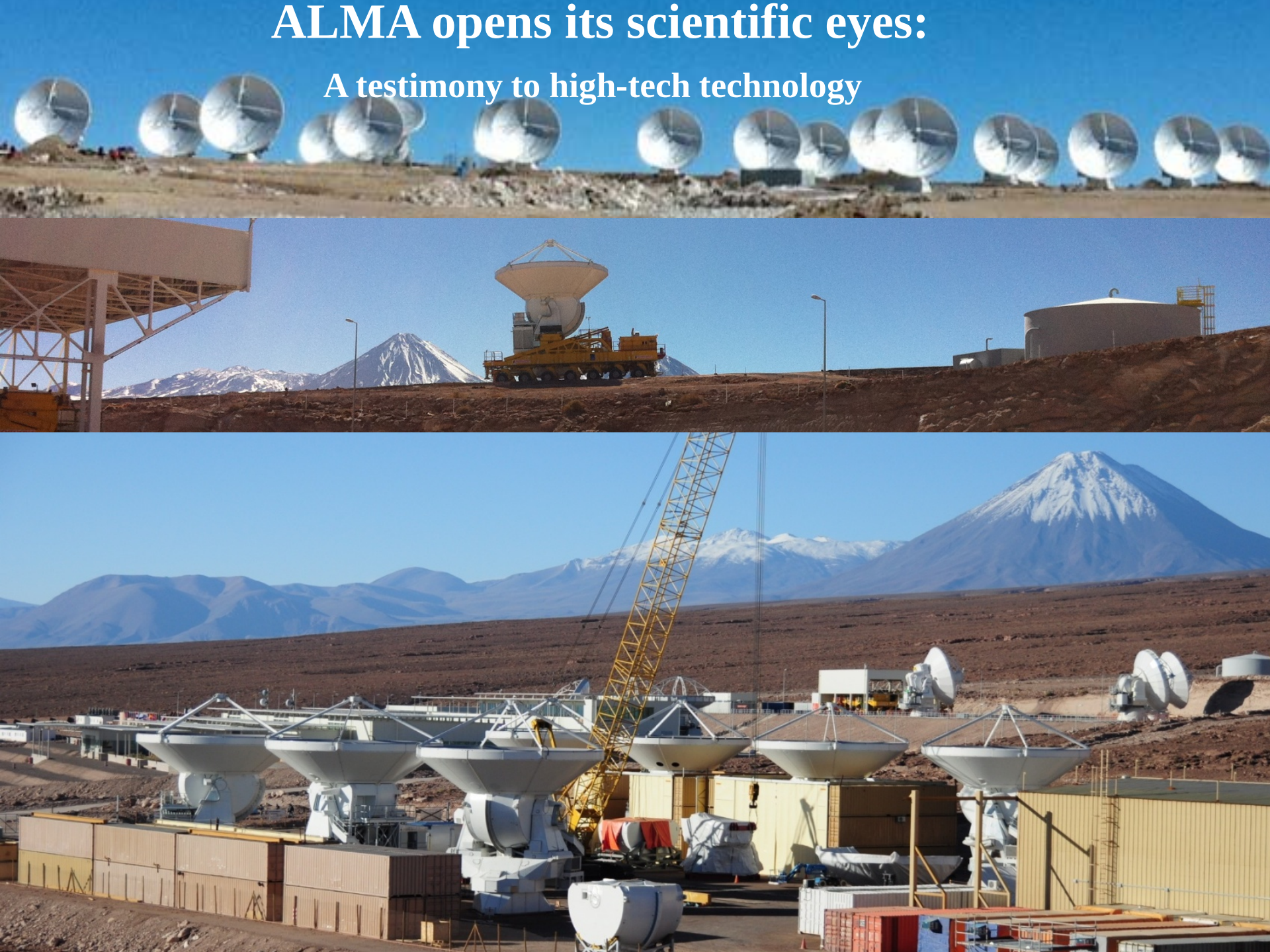
54x12m + 12x7 m antennas

0.3-3 millimeter
84-950 GHz

ALMA observes cold dust (continuum)
and myriad of molecules (lines)

ALMA opens its scientific eyes:

A testimony to high-tech technology

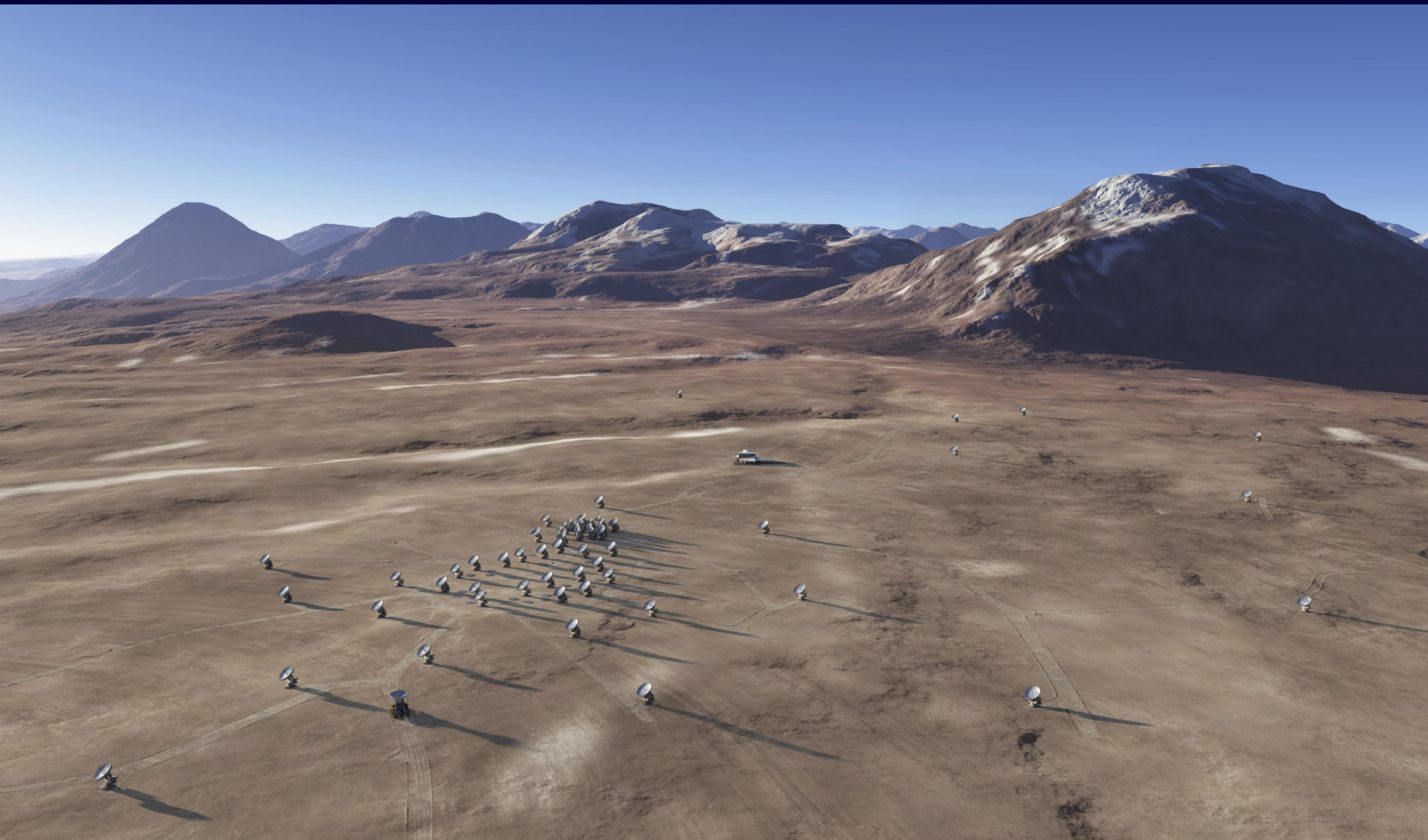


Atacama Large Millimeter Array (ALMA)

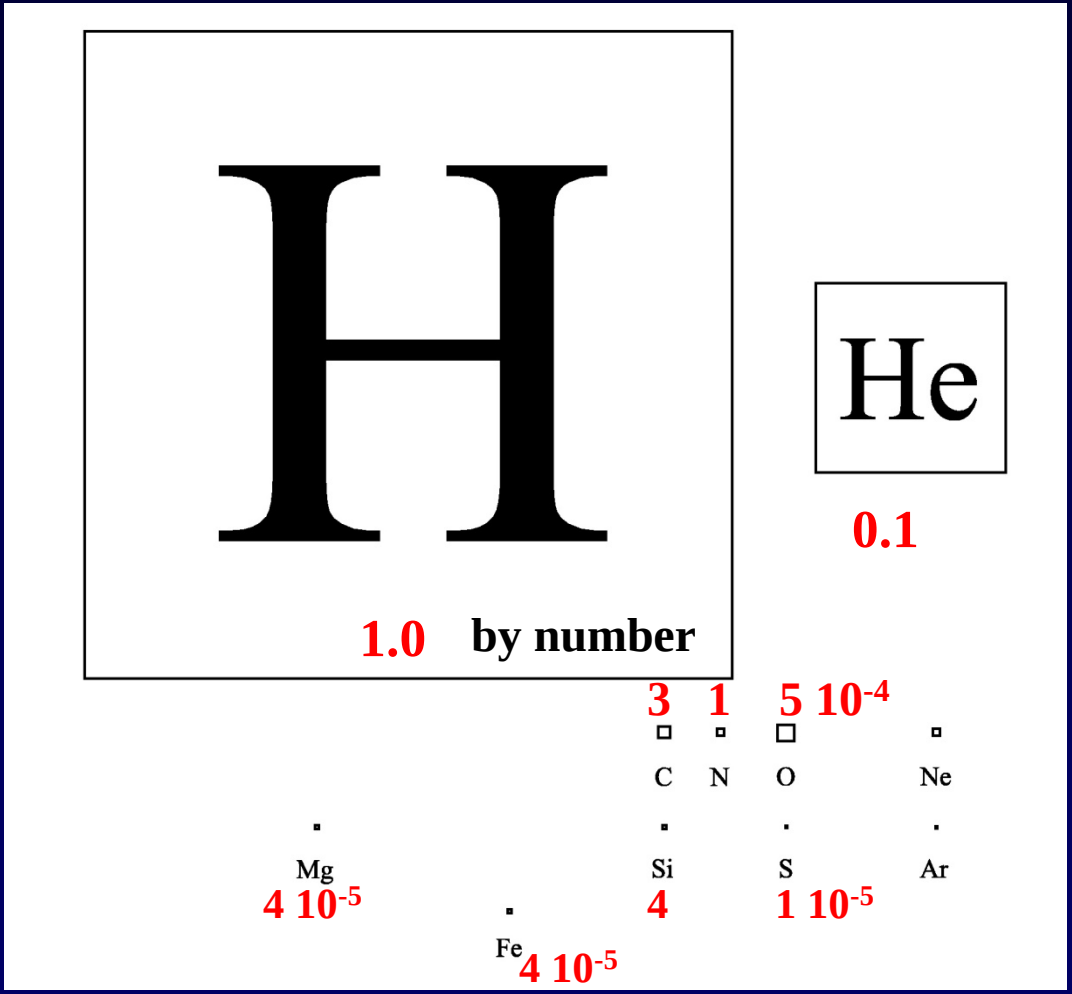
Inauguration March 13, 2013

A breathtaking experience!

Llano de Chajnantor
5000 m



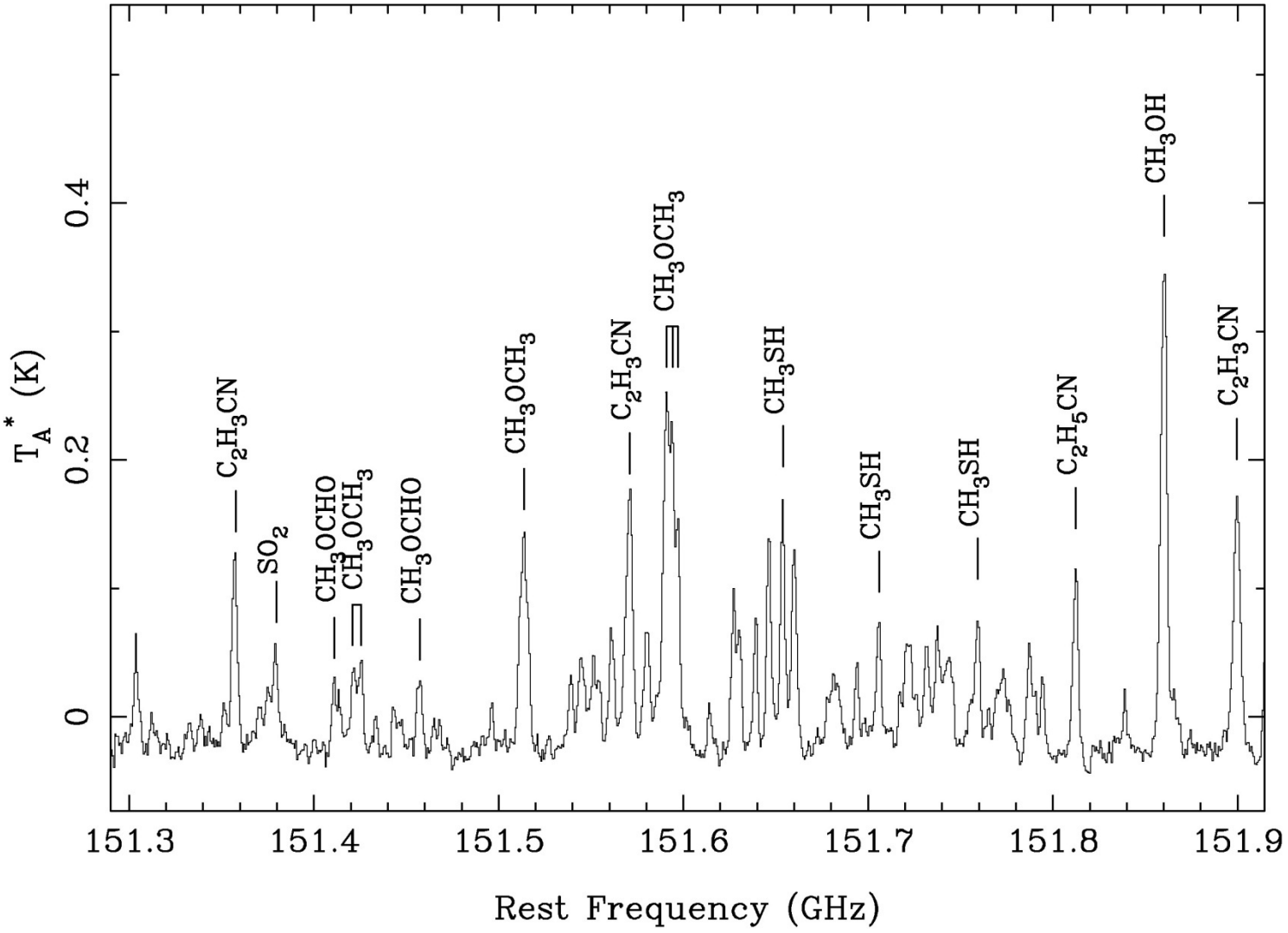
The Astronomers' Periodic Table



Dust grains: 10^{-12} by number

B. McCall 2001

Chemical factory in space!



Massive young star G327

Gibb et al. 2000

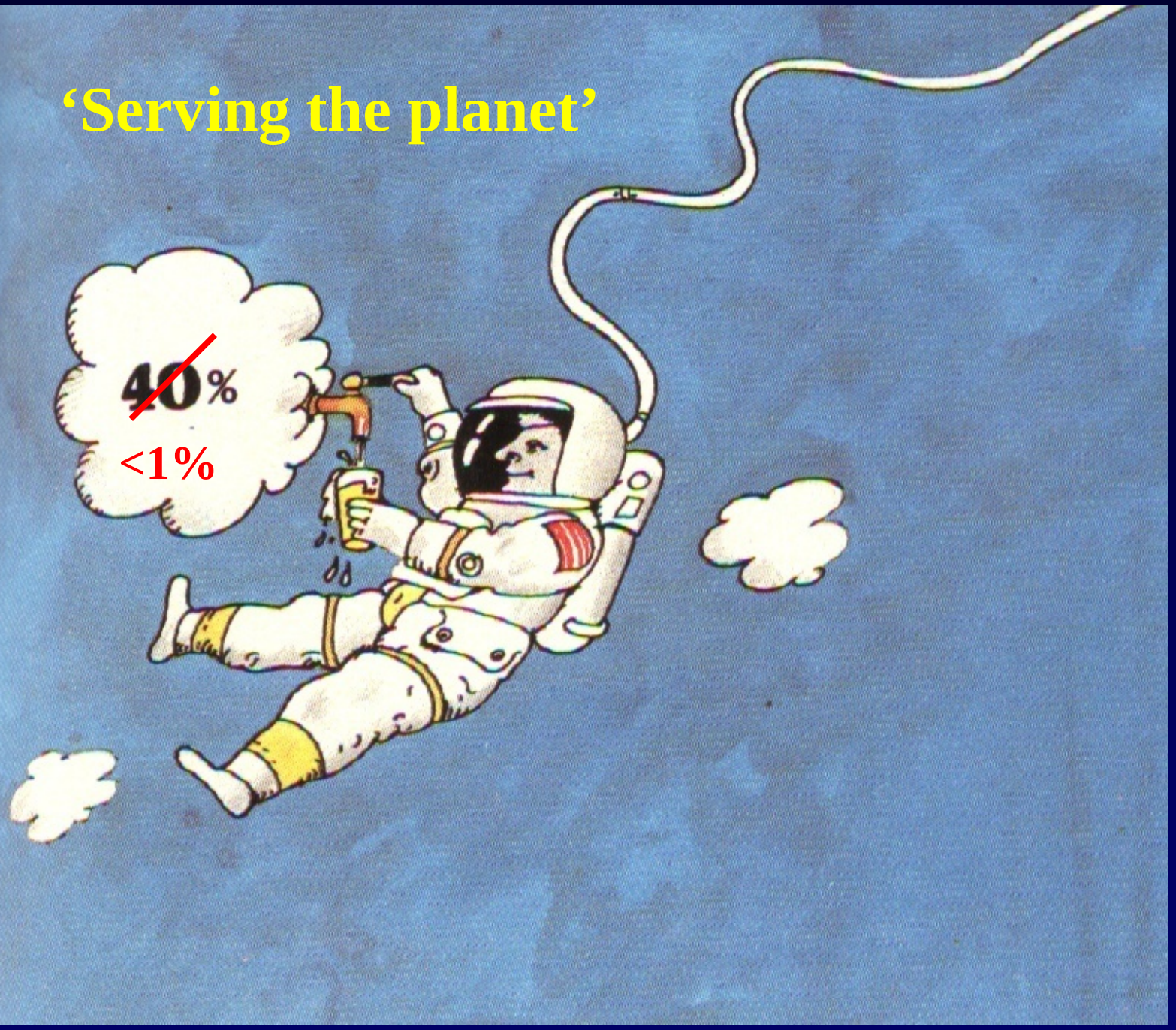
Each molecule has a uniqe fingerprint

Molecules between the stars

- More than 180 different molecules found
- Ordinary molecules

NH_3, H_2O, H_2CO, CH_3CH_2OH, ….

‘Serving the planet’



Molecules between the stars

- **More than 180 different molecules found**
- **Ordinary molecules**

  NH_3, H_2O, H_2CO, CH_3CH_2OH, ….
- **Exotic molecules**

  HCO^+, N_2H^+, HCCCCCCCN, ….

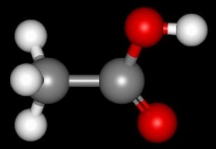
$\Rightarrow$***Unusual molecules***

(rare on Earth but not in space)

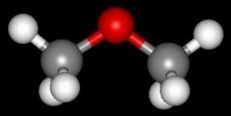
Some complex organic molecules

'Molecular bricks for life'

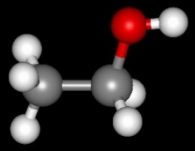
Detected



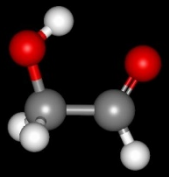
Acetic acid



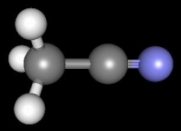
Di-methyl ether



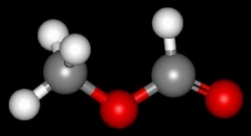
Ethanol



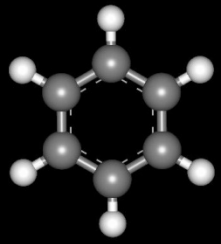
Sugar



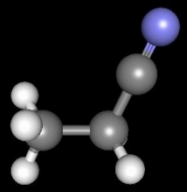
Methyl cyanide



Methyl formate

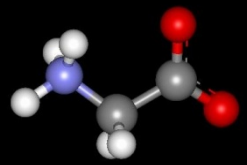


Benzene

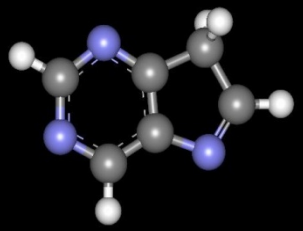


Ethyl cyanide

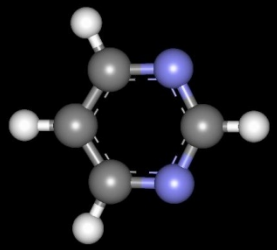
Not (yet) detected



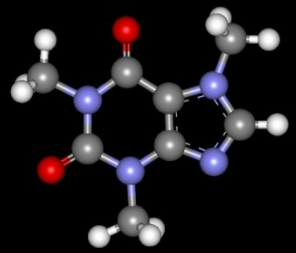
Glycine



Purine



Pyrimidine

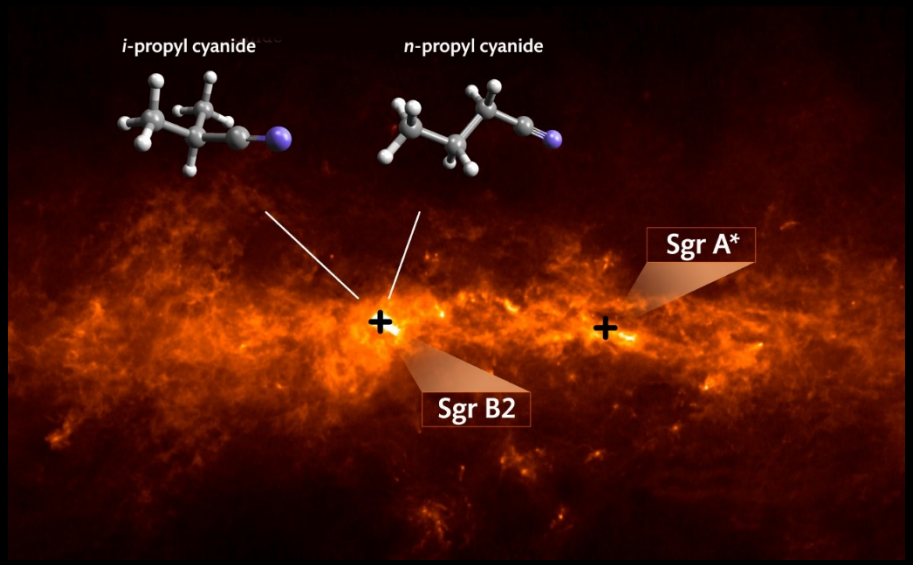


Caffeine

ALMA: How far does chemical complexity go?

Based on Ehrenfreund 2003

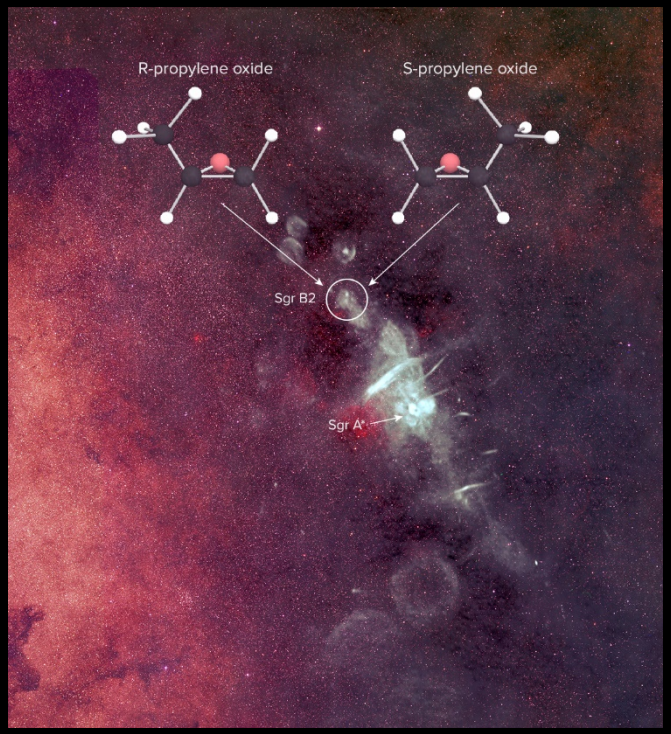
Molecules are branching out



Such side chains are characteristics of amino acids

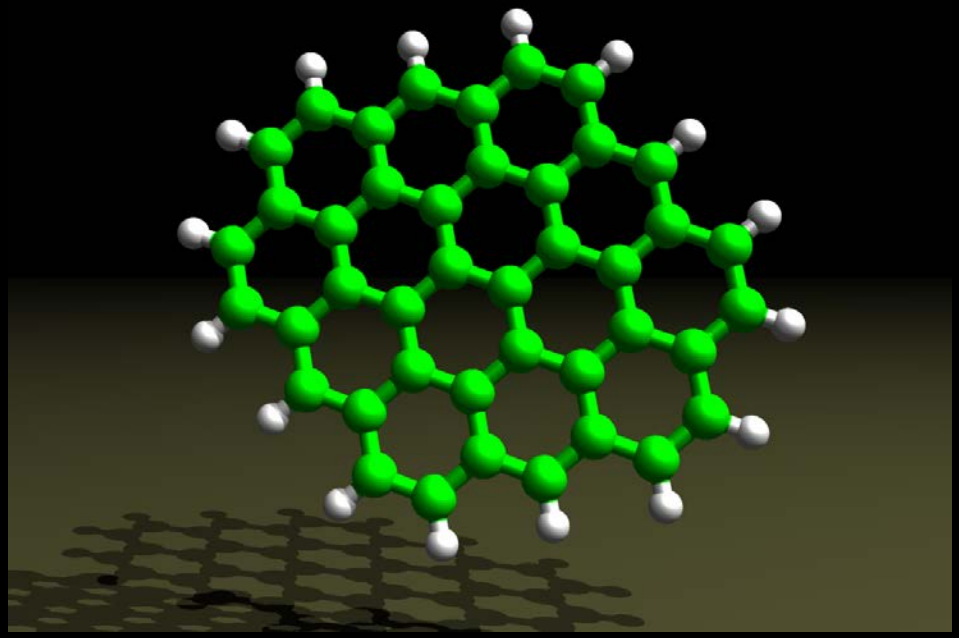
ALMA
Belloche et al. 2014

First chiral molecule



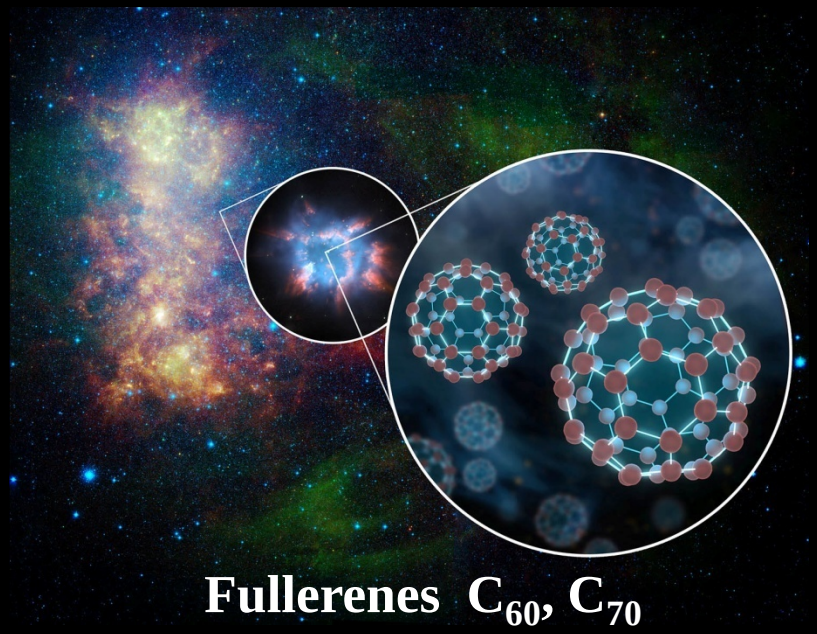
McGuire et al. 2016
GBT, ATCA

Very large carbonaceous molecules



Polycyclic Aromatic Hydrocarbons

H. Kroto Nobel prize

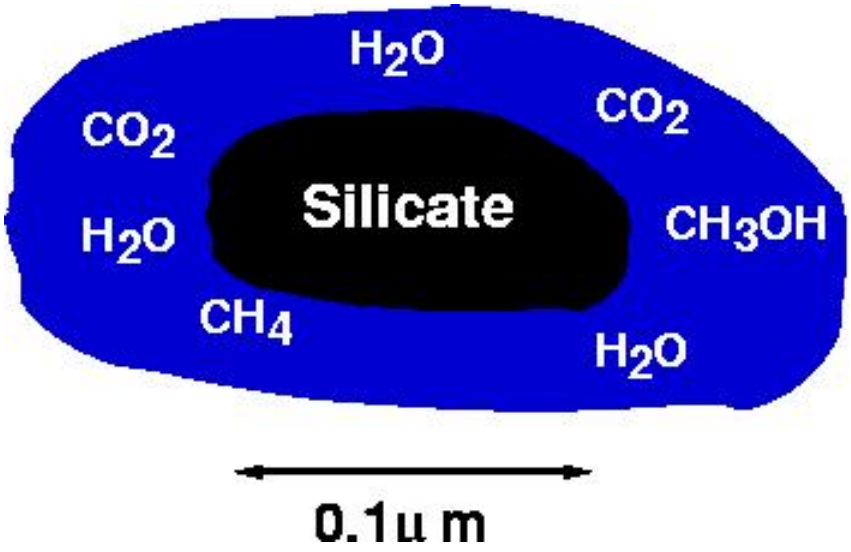


Fullerenes C_{60}, C_{70}

Cami et al. 2010

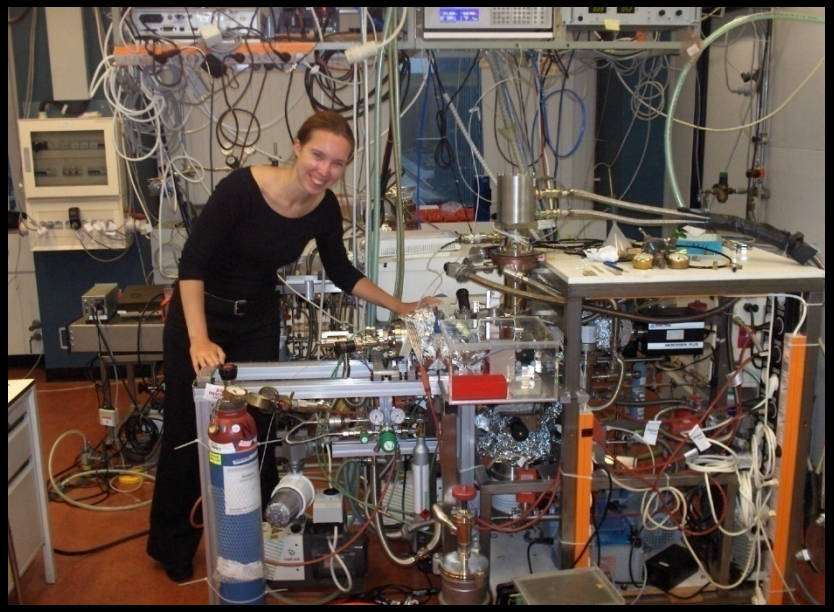
The interstellar ice cocktail

Atoms and molecules freeze-out onto cold dust grains
$\Rightarrow$ hydrogenation, e.g. O $\rightarrow$ H_2O



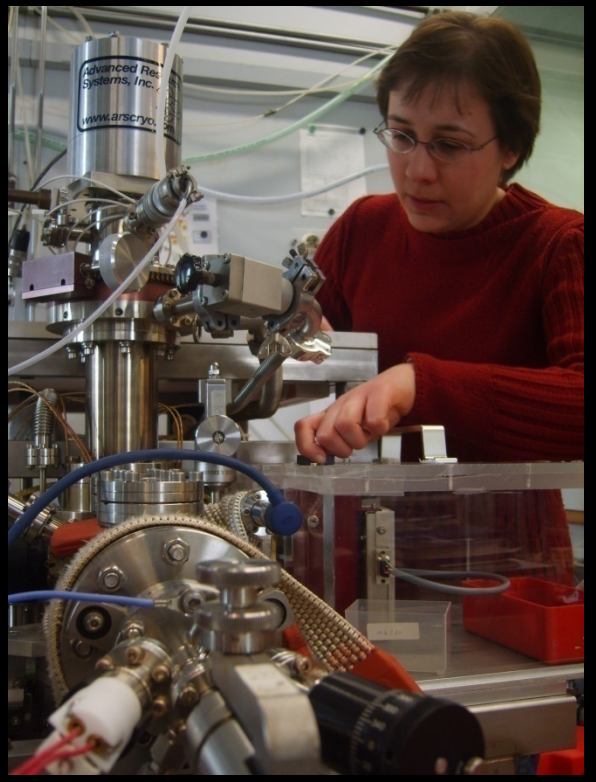
Surface chemistry dominates during star formation

Sackler laboratory for astrophysics at Leiden Observatory



‘Simulating 1 cm^3 of interstellar space’

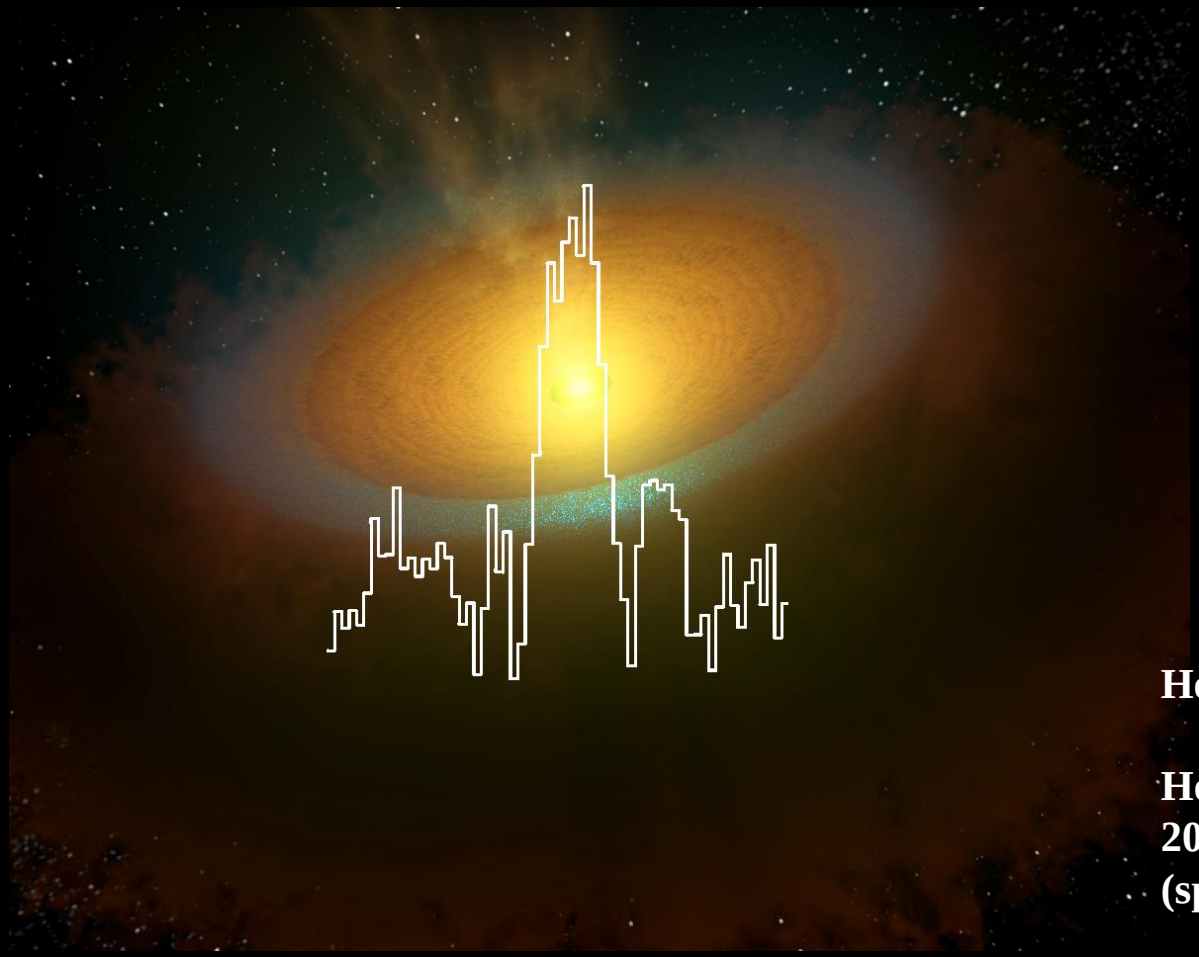
Harold Linnartz



Formation of water on dust grains

Based on laboratory experiments in Leiden, Paris, Japan
Cuppen et al. 2010

Detection of cold water reservoir in a planet-forming disk

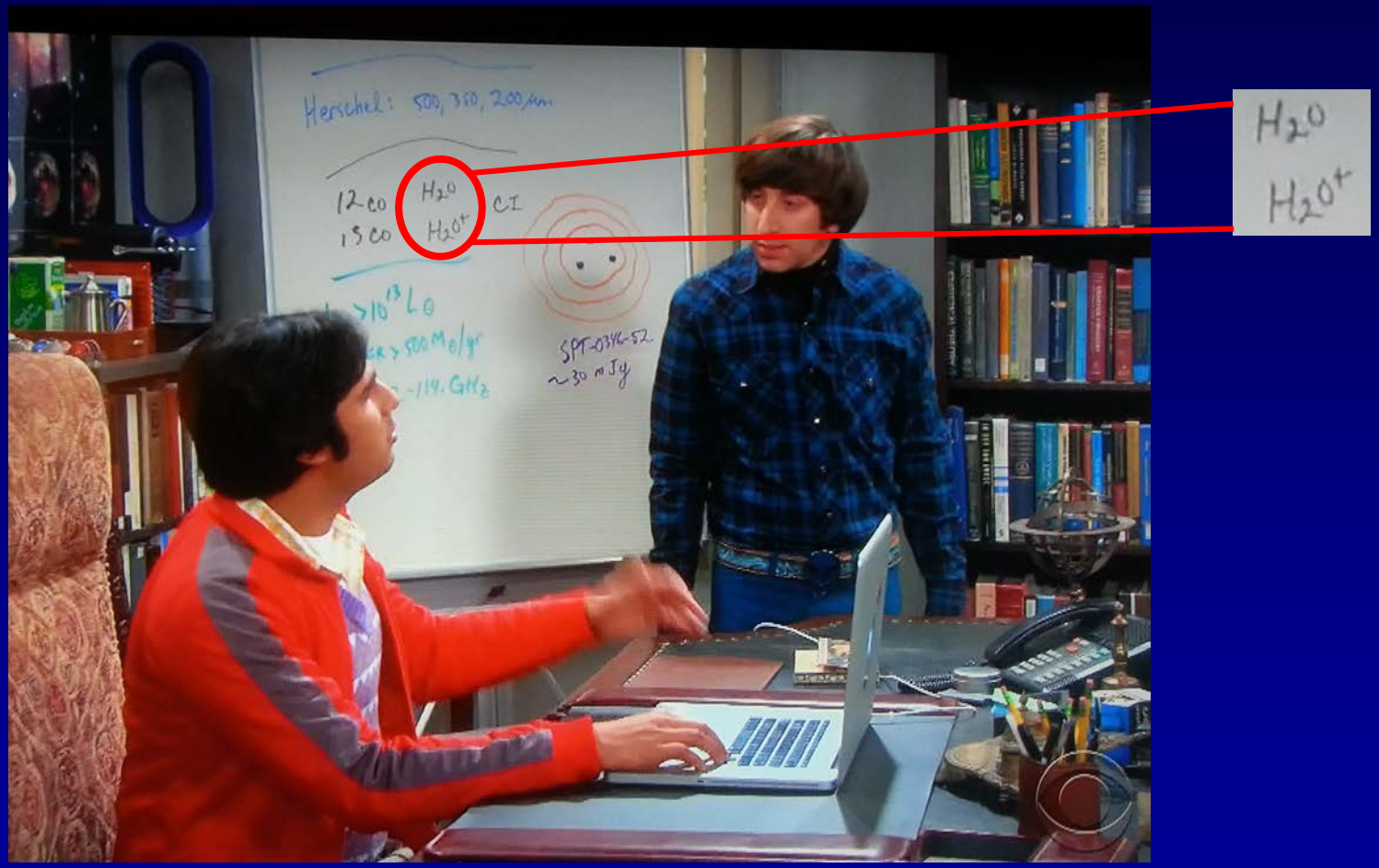


Herschel-HIFI

Hogerheijde et al. 2011, Science
(spatially unresolved)

Signal indicates presence of ~6000 oceans of ice

Herschel, water and the Big Bang theory



Summary so far

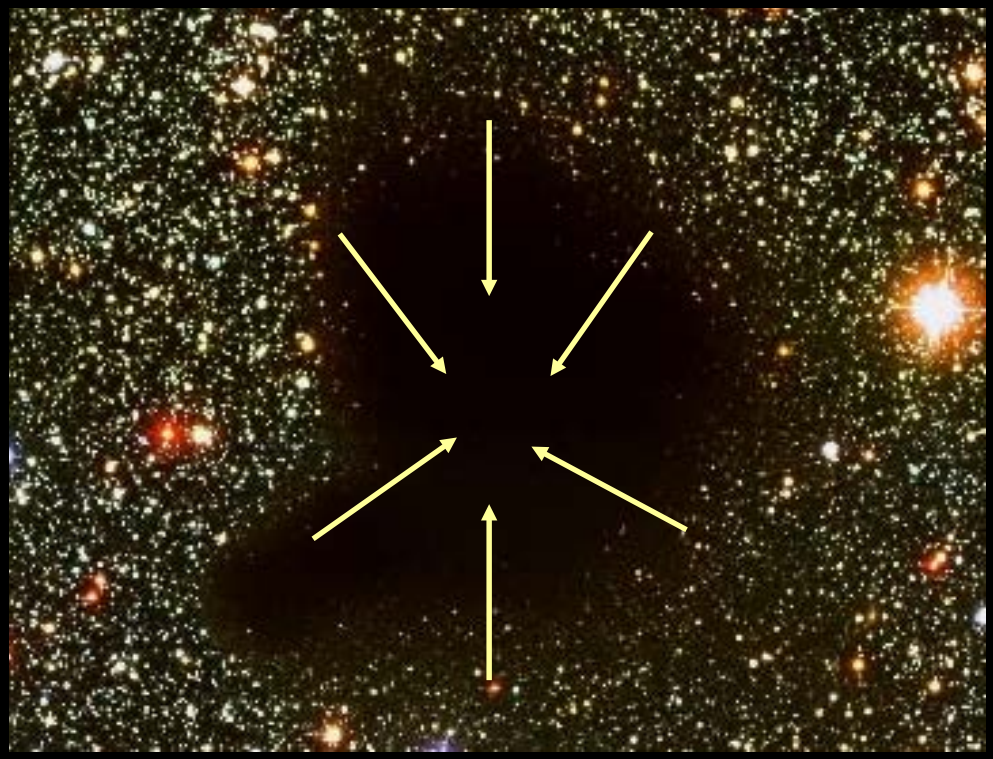
- **Interstellar clouds have a rich chemical composition in spite of cold and tenuous conditions**

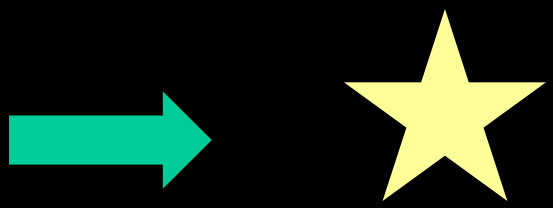
- **Complex organic molecules and water are found around nearly all forming stars, throughout the entire Milky Way**

⇒ Building blocks for prebiotic material are widespread

How is a new planetary system formed?

Collapse of cloud





Star formation in Orion

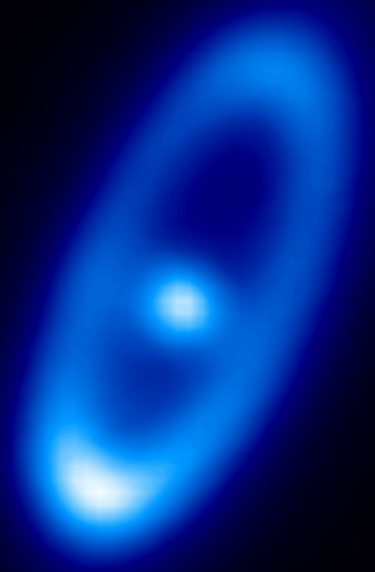
C.R. O’Dell

AMNH/SDSC

Technology has come a long way

Dusty rings probing planet formation in action

IRAS
1984

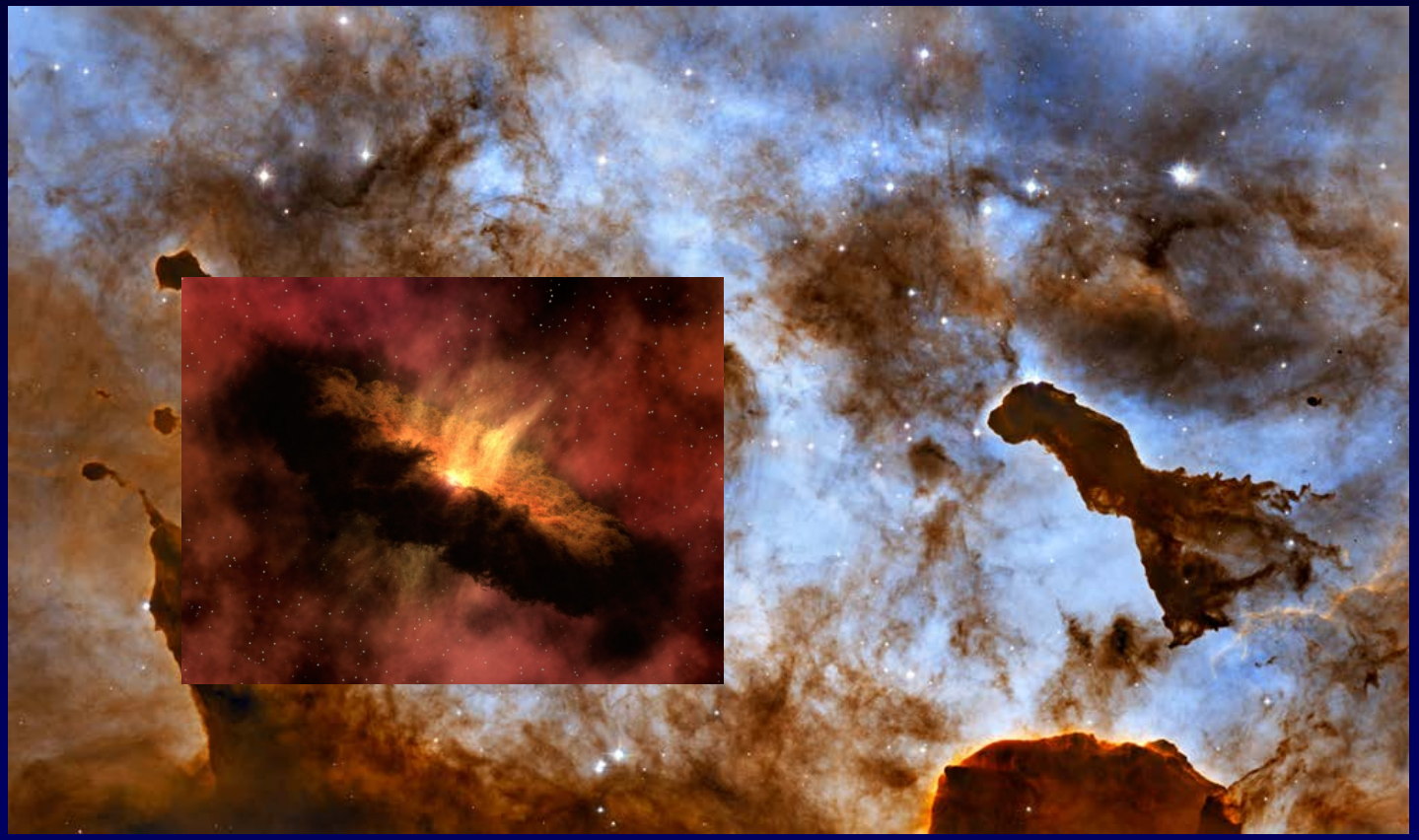


Fomalhaut
Herschel PACS
70 μm

Acke et al. 2012

- Small dust grains produced by collisions of planetesimals
- Two planets sheperding the dust ring

Disks are small

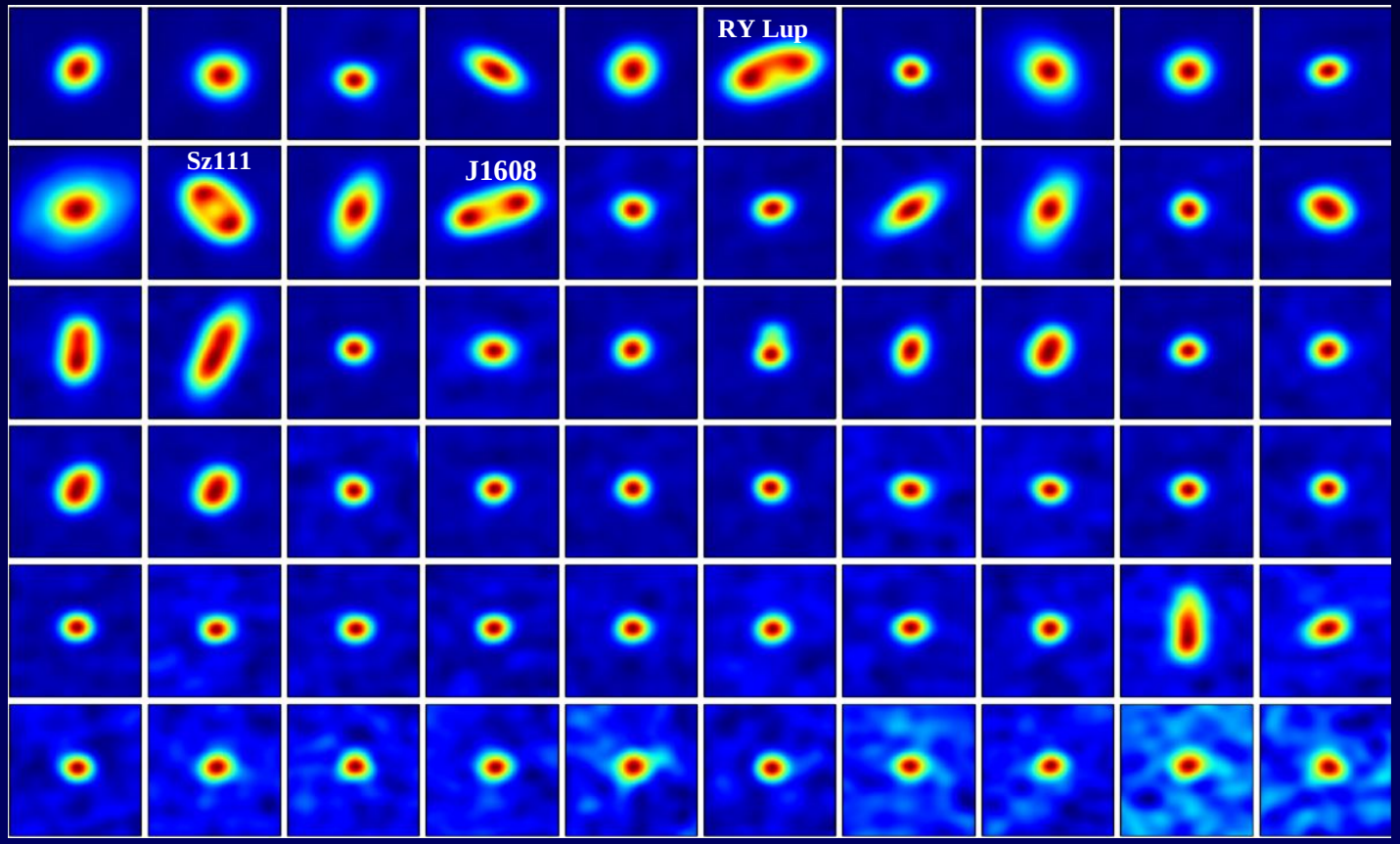


Carina nebula
HST

Cloud: 10^{18} **cm**
Collapsing Core: 10^{17} **cm**
Disk: 10^{15} **cm (100 AU; 1 AU = distance Sun-Earth)**

Sharpness of ALMA is needed to zoom in on forming stars and disks

ALMA detects disks in 1 minute!



2”x2”

0.35”
(20 AU radius)

1-2 min
per source

330 GHz
cont

Ansdell, Willians
et al. 2016

Survey *all* T Tauri stars in Lupus in dust, 70% detected

→ *Test disk evolution models*

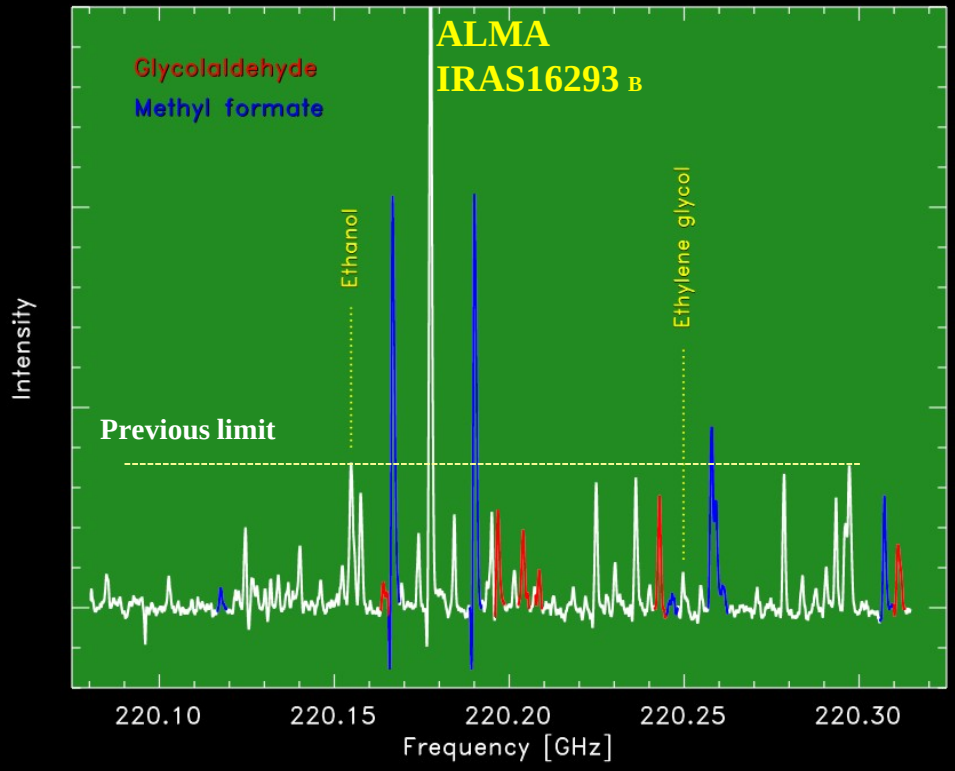
Protoplanetary Disks

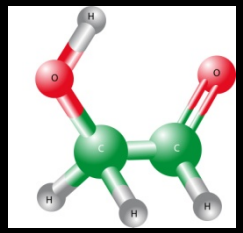
- **Nearly all young stars surrounded by disks**
- **Sizes of disks comparable to that of our own solar system**
- **Masses of some disks enough to form a solar system (1% of mass Sun, 10x mass of Jupiter)**
  - **others enough to form Earth-like planets**

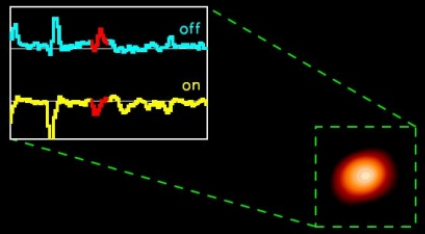
=> *Ingredients for planet formation are common*

Detection of sugar +water in solar-system precursor

Sweet result from ALMA





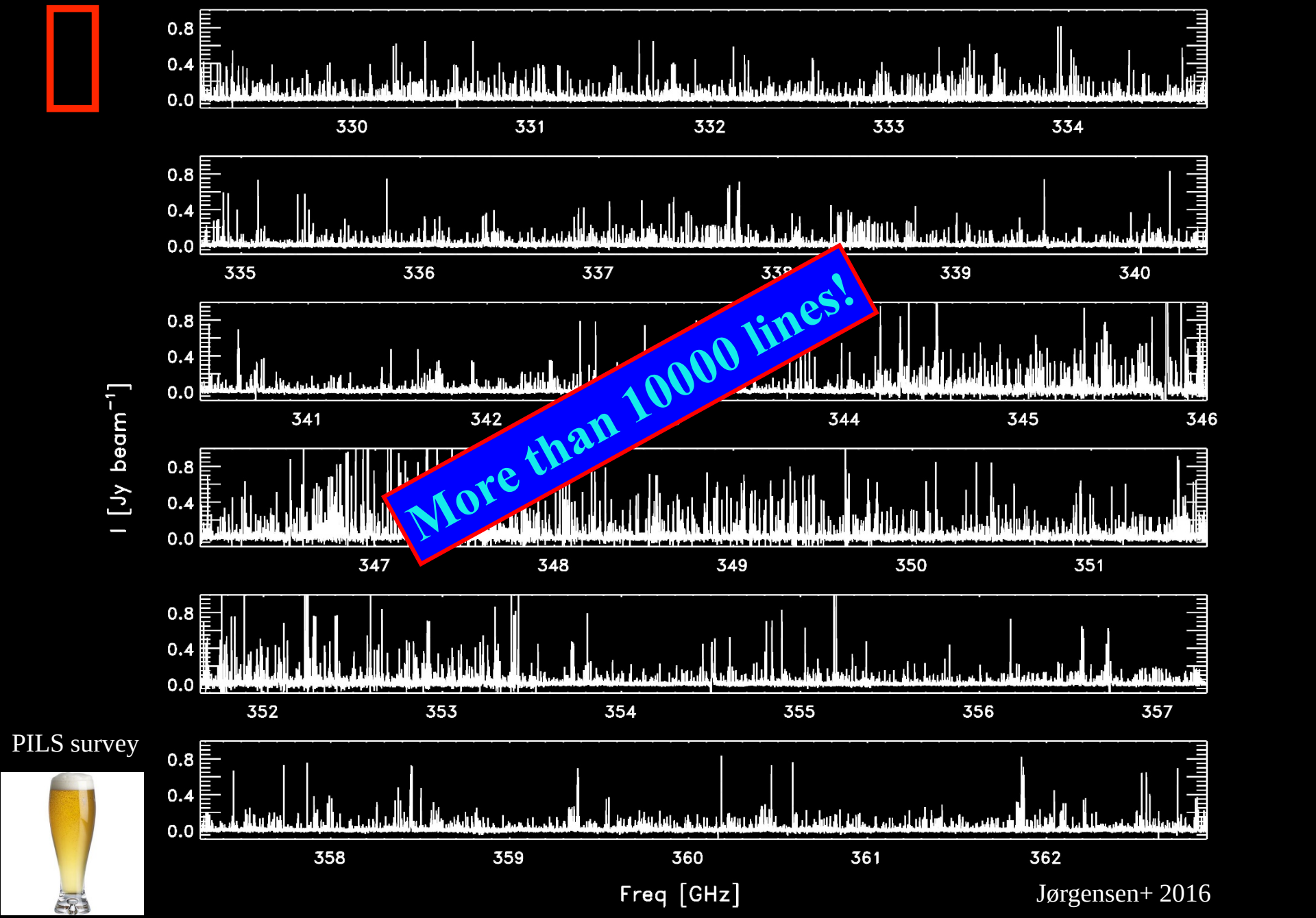


150AU

Jørgensen et al. 12

Complex molecules found on solar system scales!
(orbit of Uranus, 25 AU)

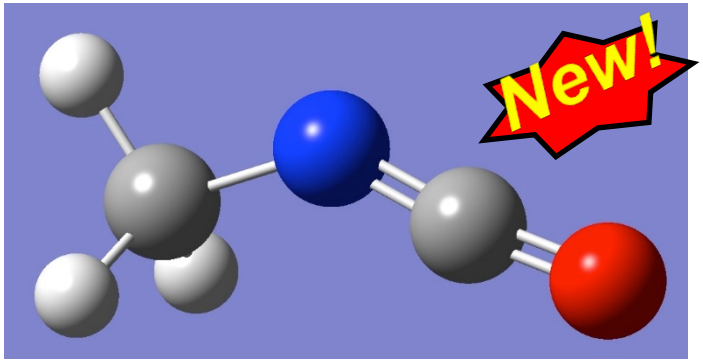
Full spectral survey of IRAS 16293–2422B



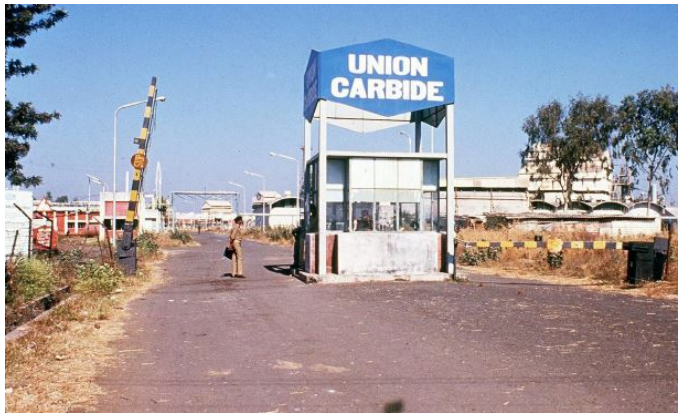
PILS survey

Jørgensen+ 2016

Some complex molecules around solar mass protostars



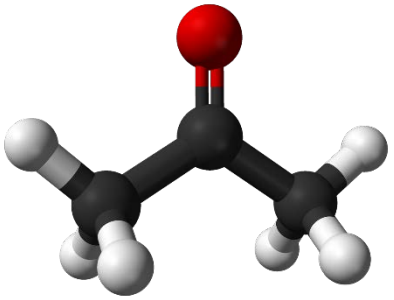
Methyl isocyanate
'Prebiotic' molecule



Ligterink et al. 2017, Maríin-Domenéch et al. 2017

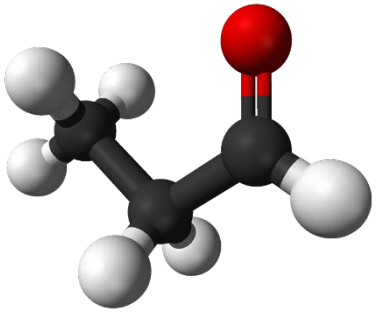
Acetone

New!

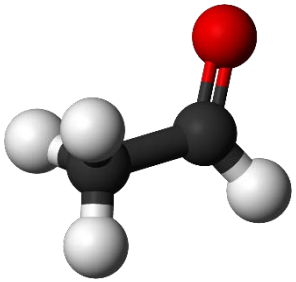


Propanal

New!

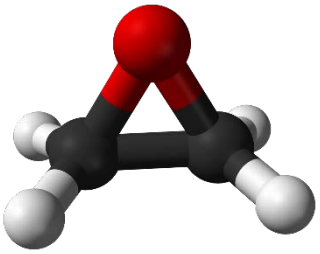


Acetaldehyde



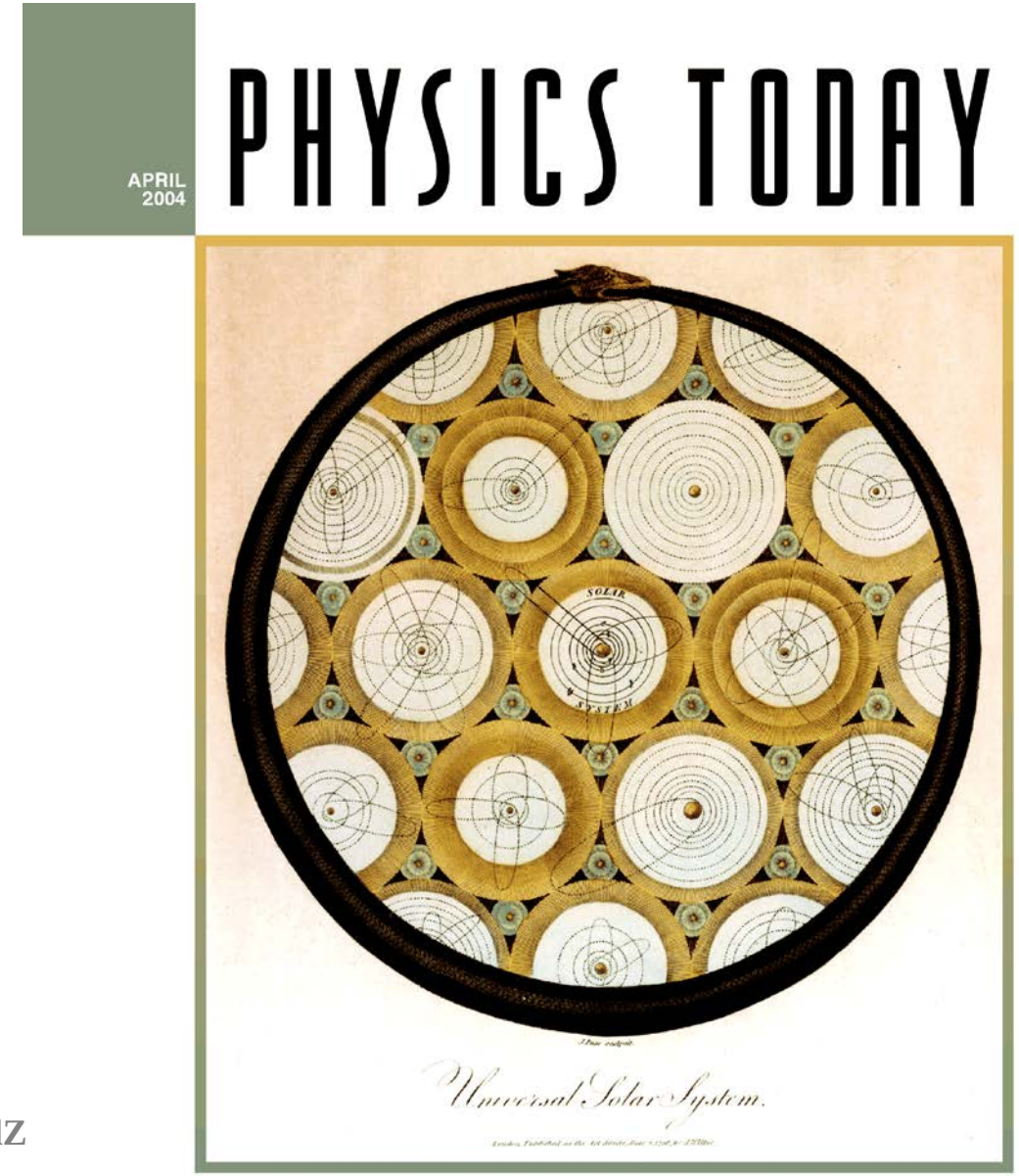
Ethylene oxide

New!



Lykke et al. 2017

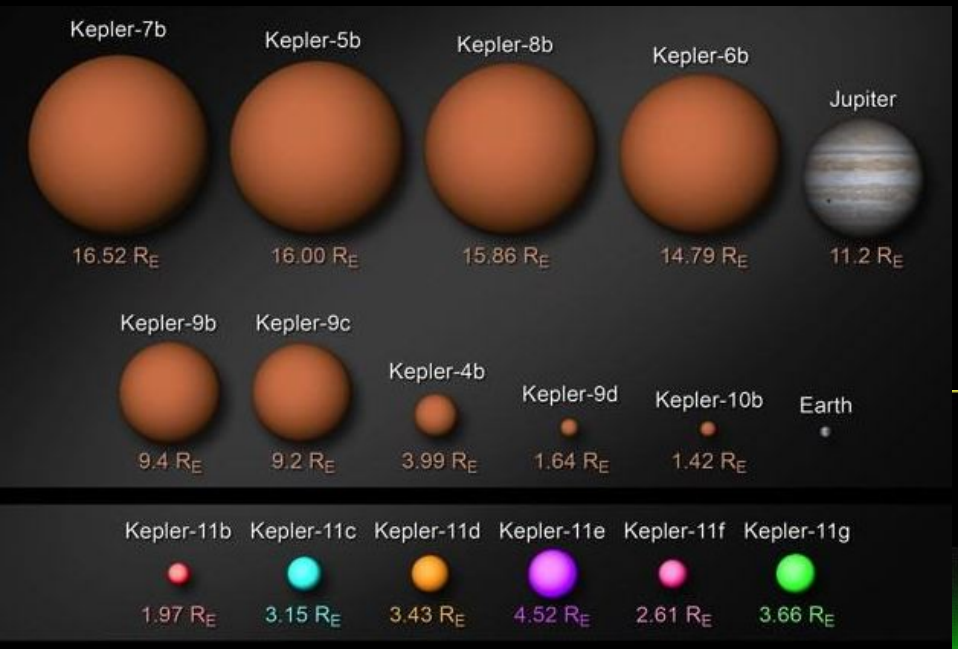
Diversity of Planetary Systems



English engraving
1798

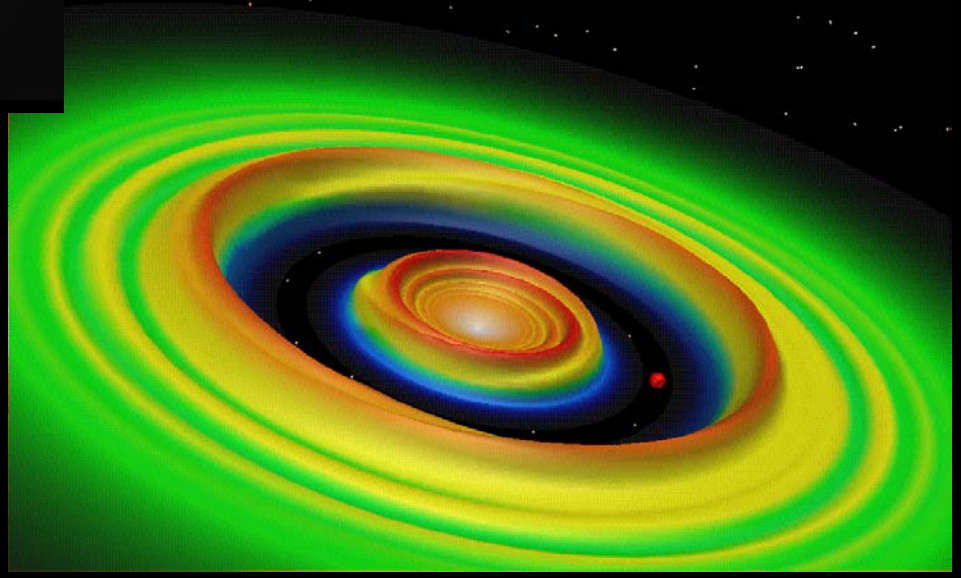
Collection EvD+TdZ

Origin of exoplanetary diversity?



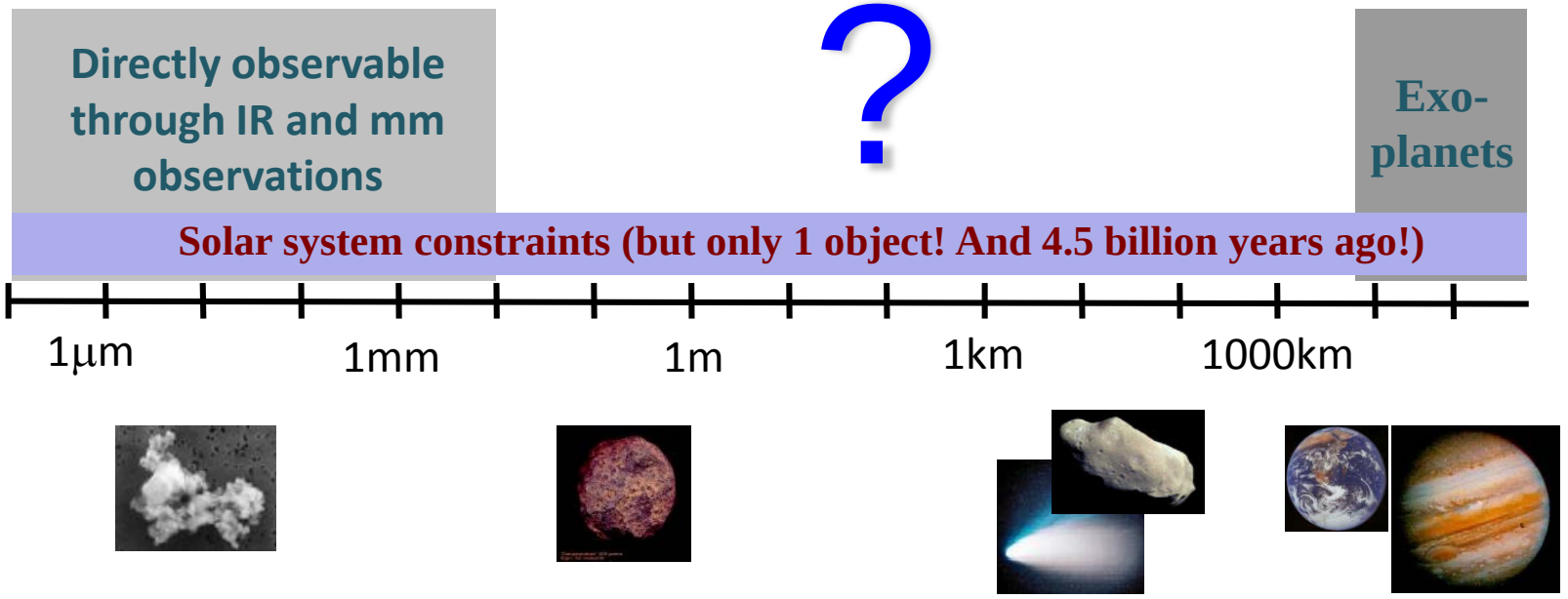
Kepler: Borucki et al. 2011
>3000 exoplanets

Answer lies in past, when planets were formed from circumstellar disks



Hydro simulation Bryden et al. 1999

Planets form. But how?

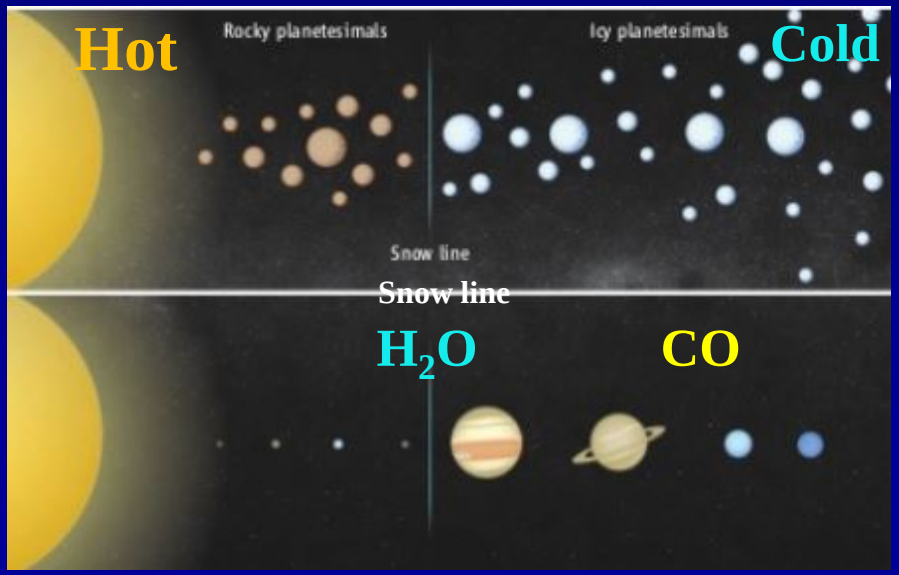


Particles must grow ≈13 orders of magnitude in size in ≈few x 10^7 yr

C. Dullemond

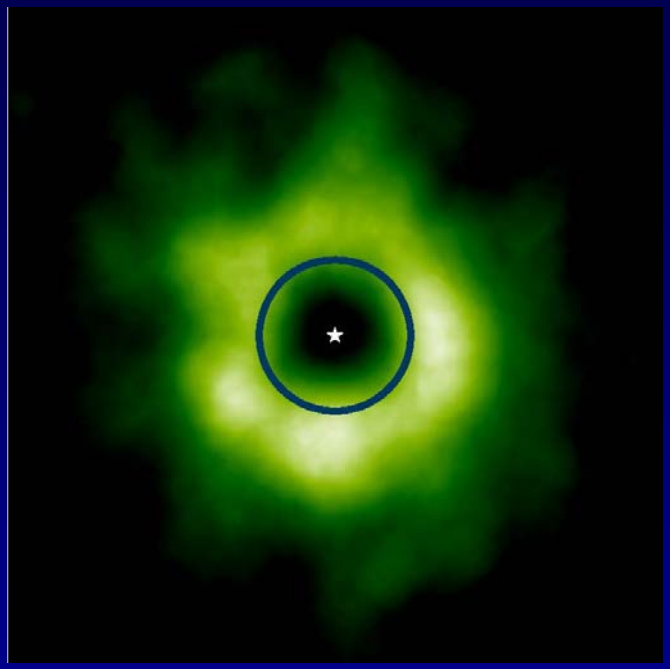
Snowlines

Ice-covered grains promote planet formation



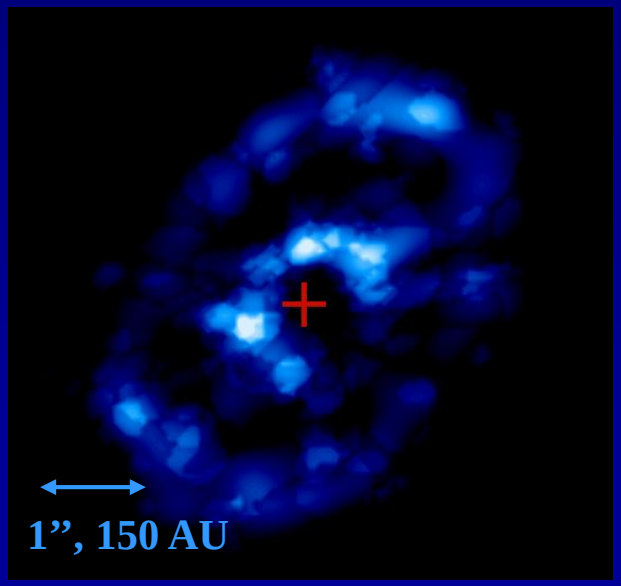
Akeson 2011

CO snowlines with ALMA



TW Hya N_2H^+ image ALMA
Qi et al. 2013

N_2H^+ and DCO^+ are enhanced when CO is frozen out



IM Lup
ALMA

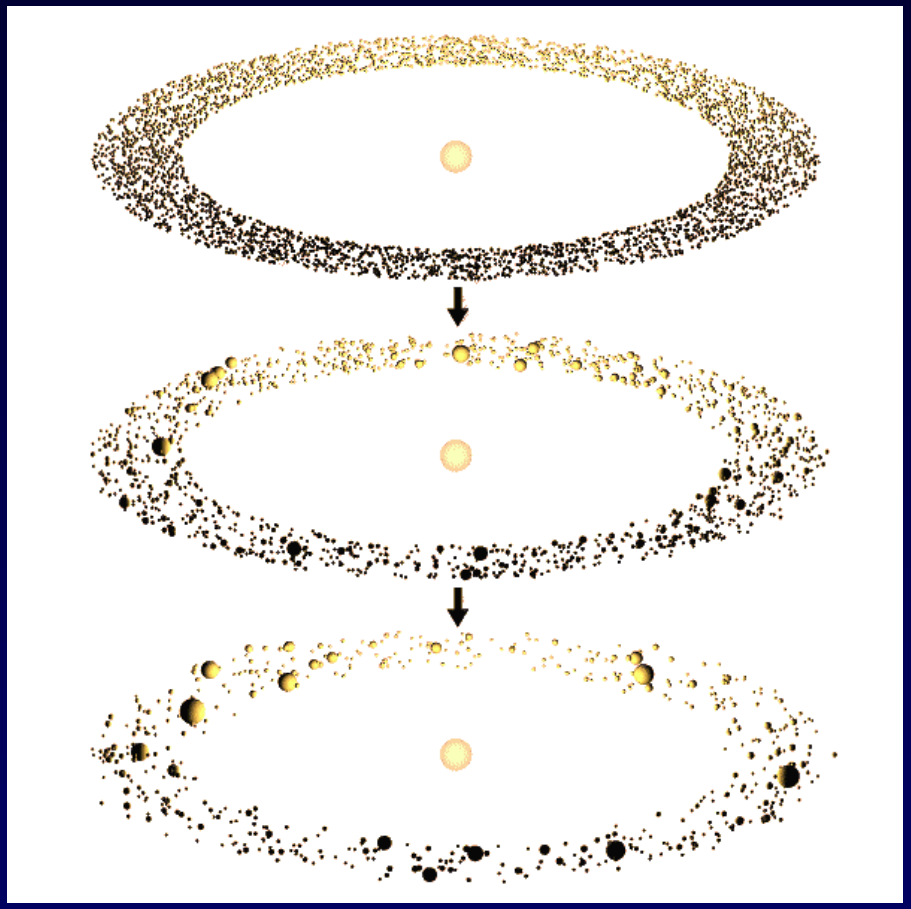
Double rings!
DCO^+ 3-2

Mathews et al. 2013
Öberg et al. 2015

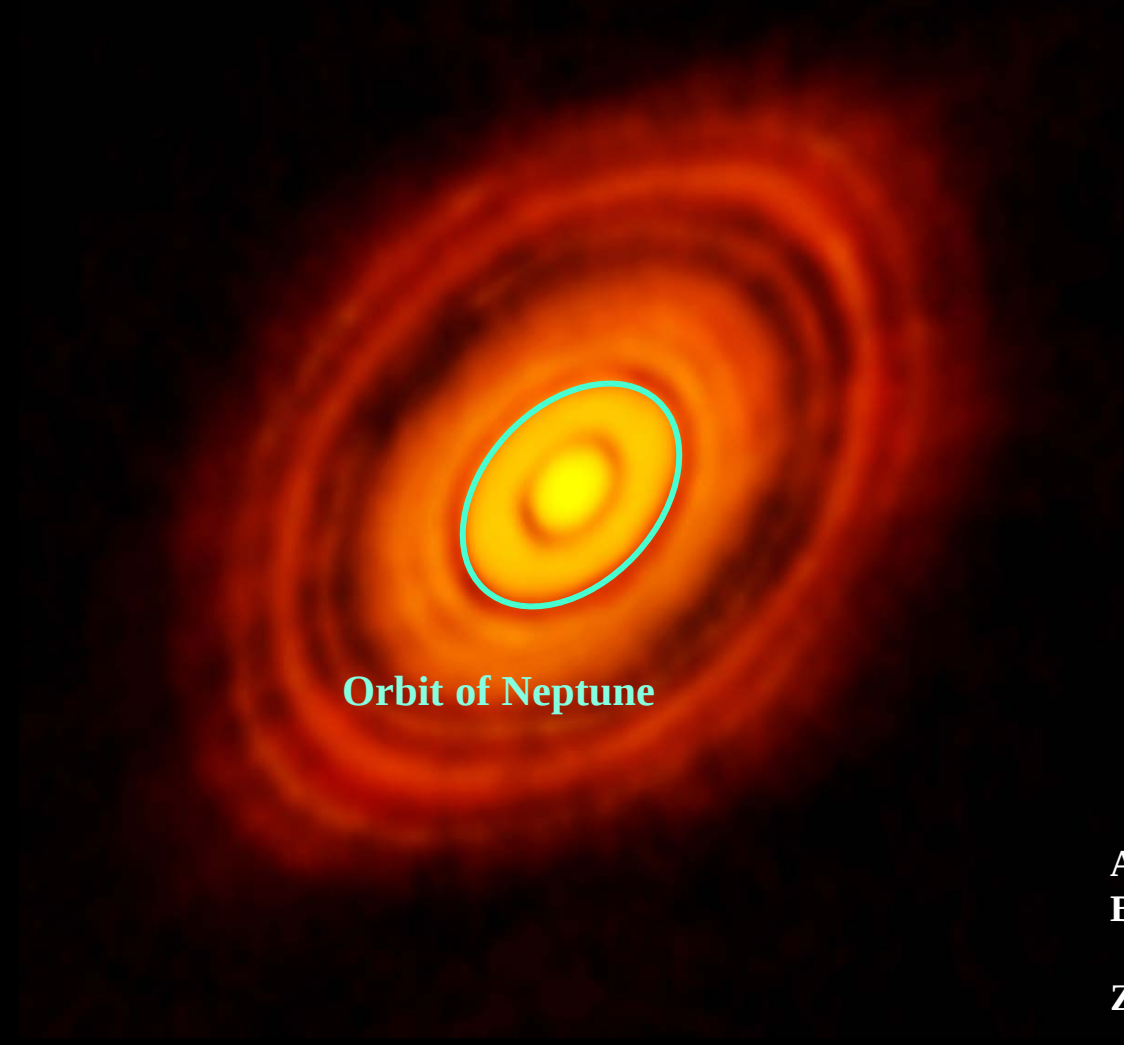
From grains to planetesimals

www.eso.org

From dust grains to planetesimals



Young disks: Ice lines and planetesimals



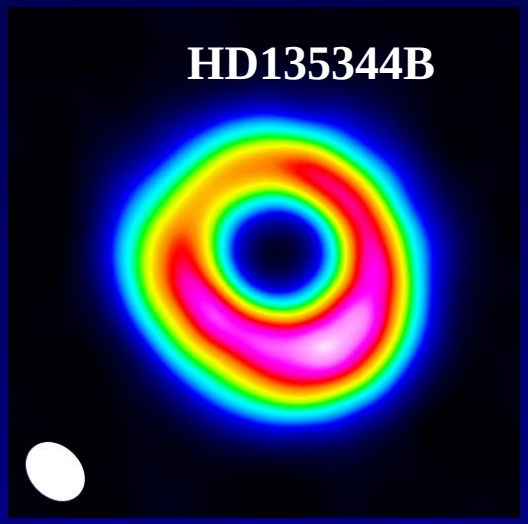
ALMA ~20 mas
(few AU resolution)
HL Tau

ALMA partnership,
Brogan et al. 2015

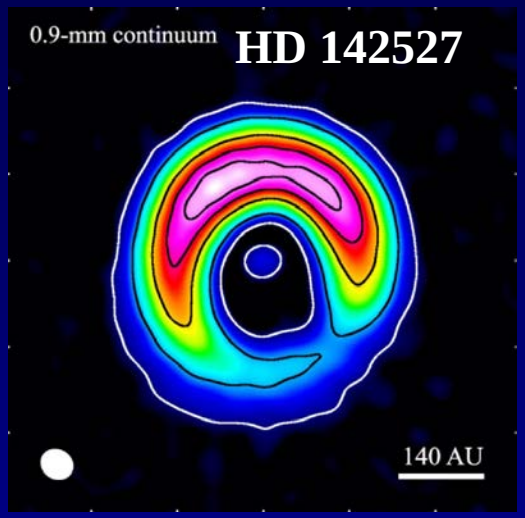
Zhang et al. 2015

Several rings seen but origin still debated

Planet-forming disks and dust traps seen with ALMA



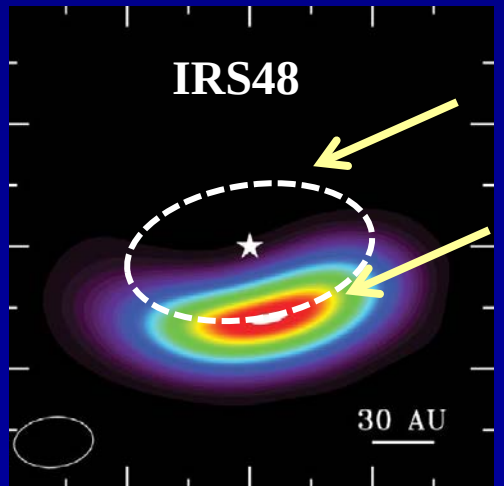
Perez et al. 2013,
Pinilla et al. 2015



Contrast factor 28

Casassus et al. 2013, Fukagawa et al. 2013

animation

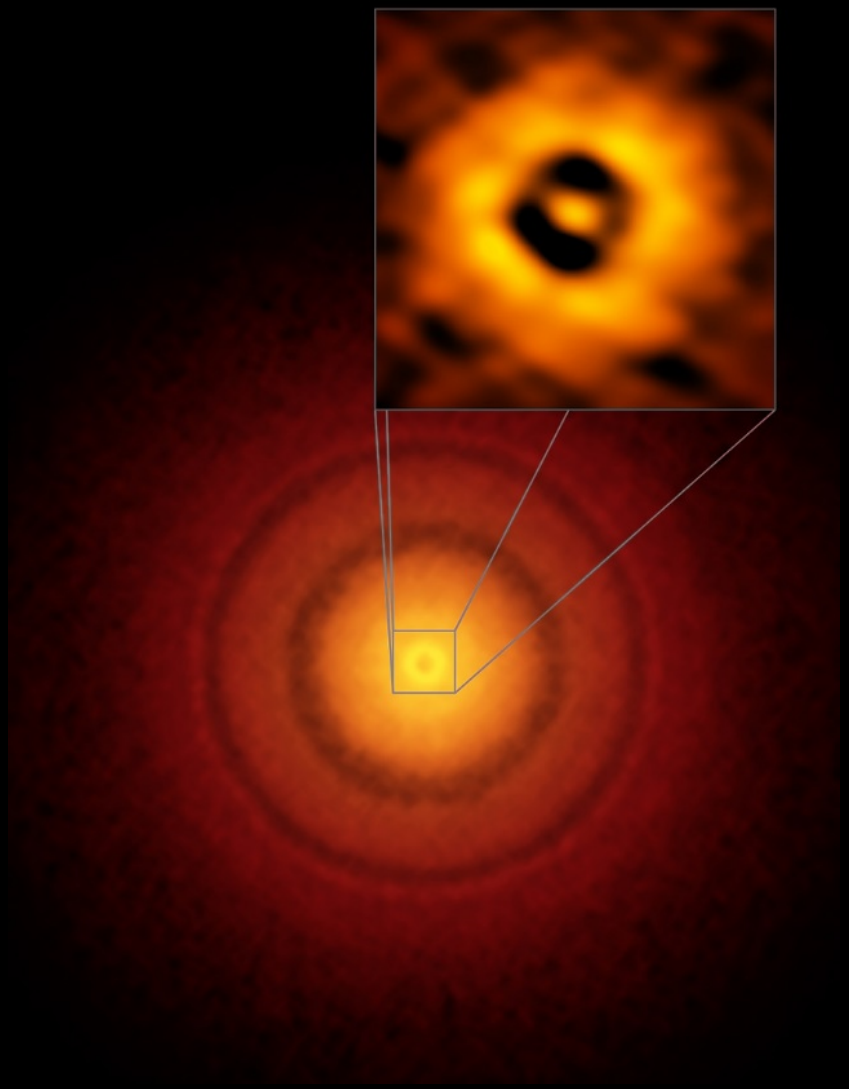


No mm dust

390 σ

Van der Marel et al. 2013 Science

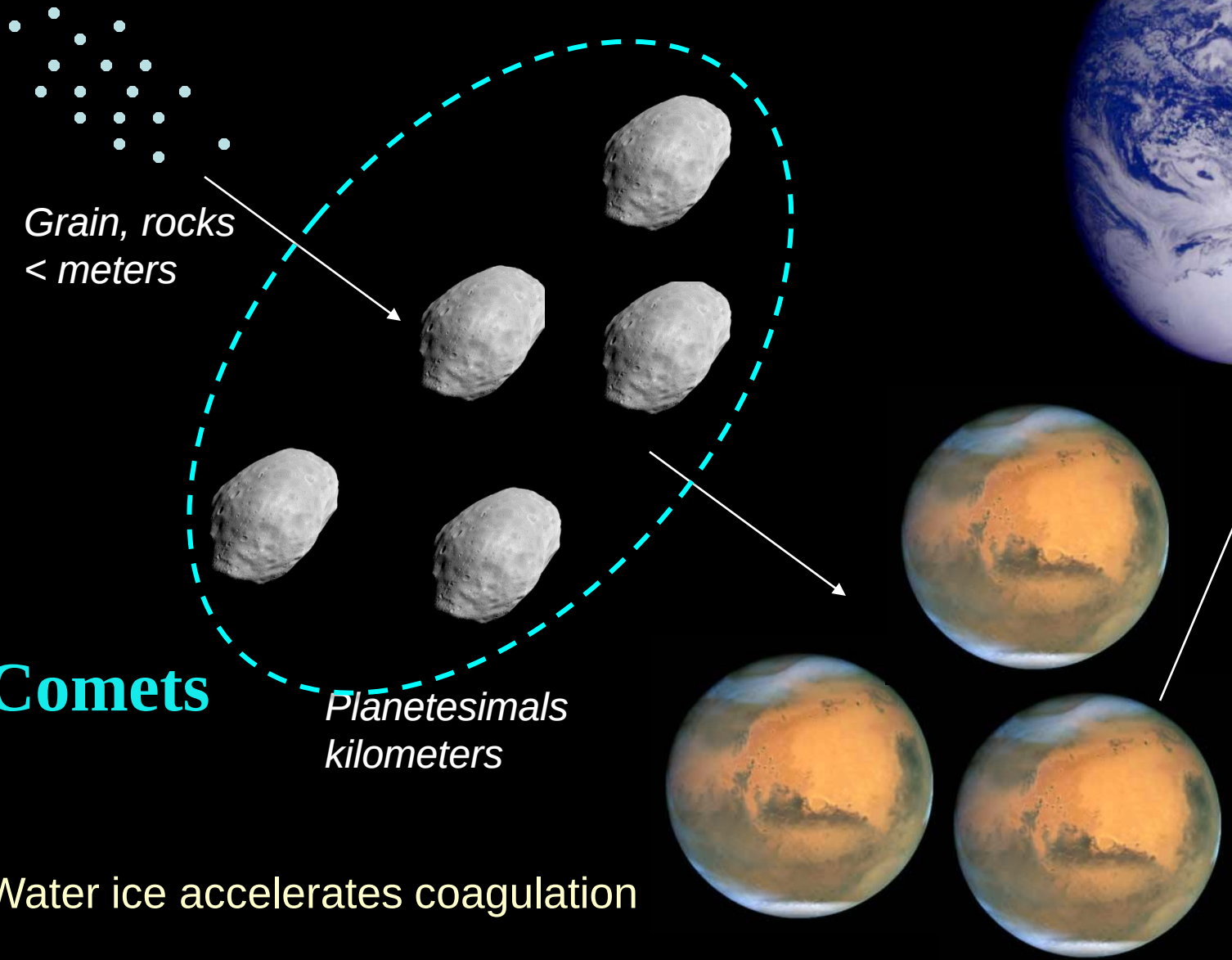
Planet on Earth-like orbit?



TW Hya
ALMA

Andrews et al. 2016

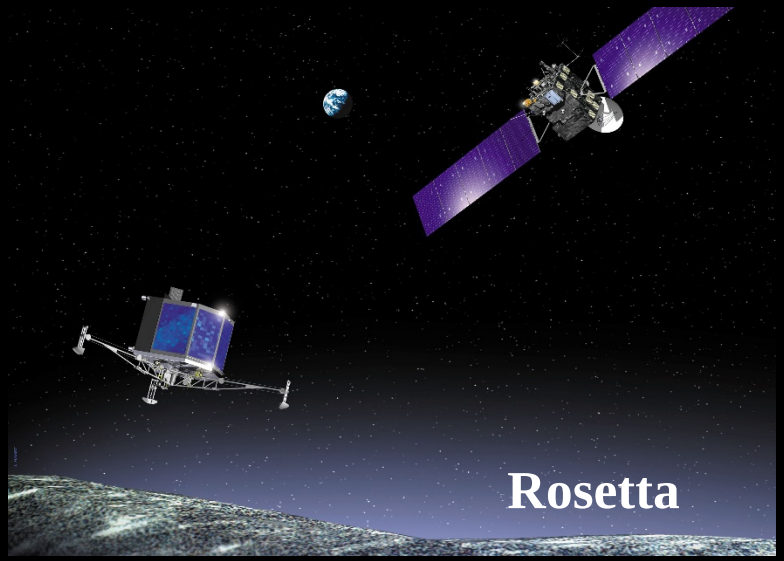
From icy grains to planetesimals to embryos to planets



J. Lunine

How about our own early solar system?
Look at comets

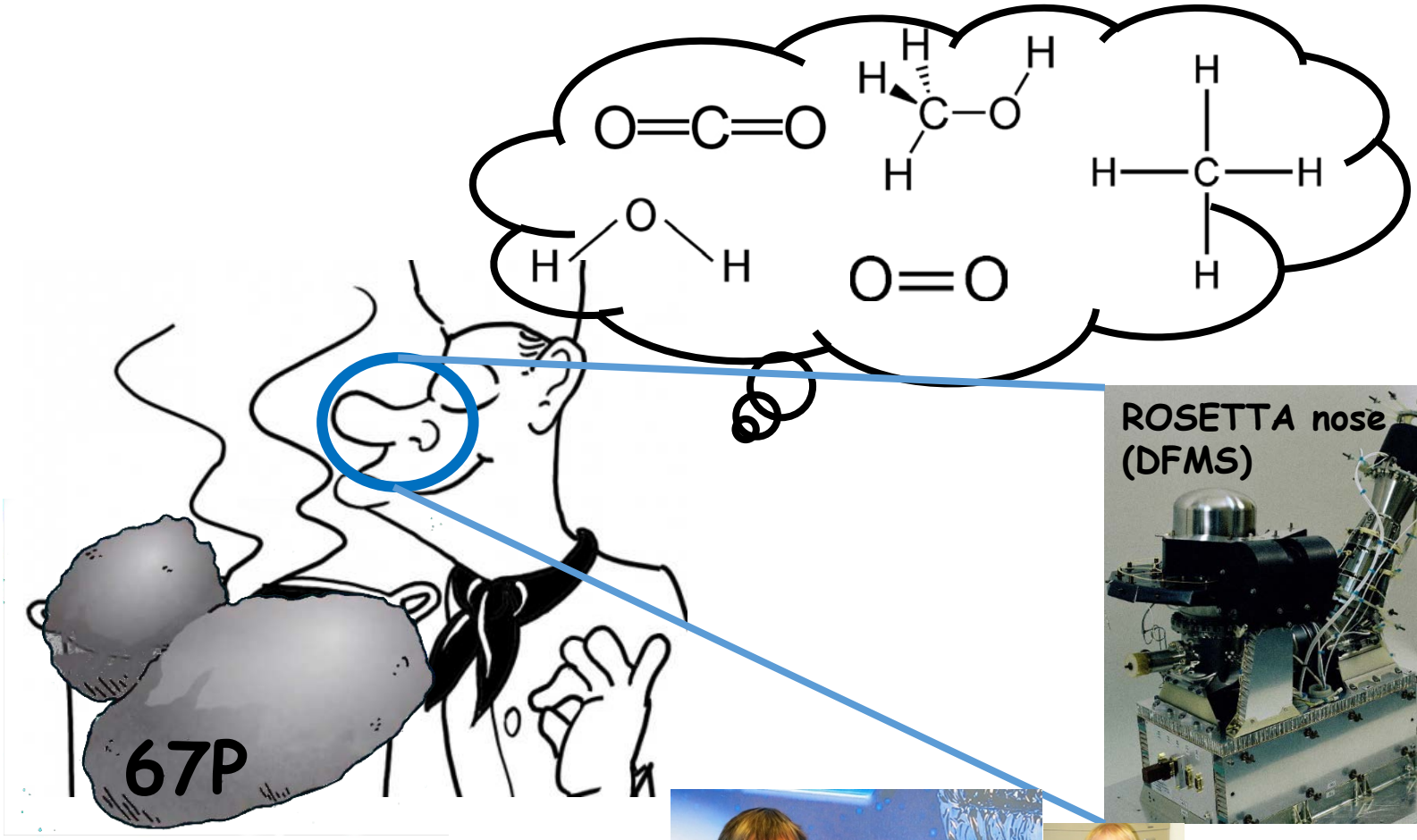
Comet
Hale-Bopp



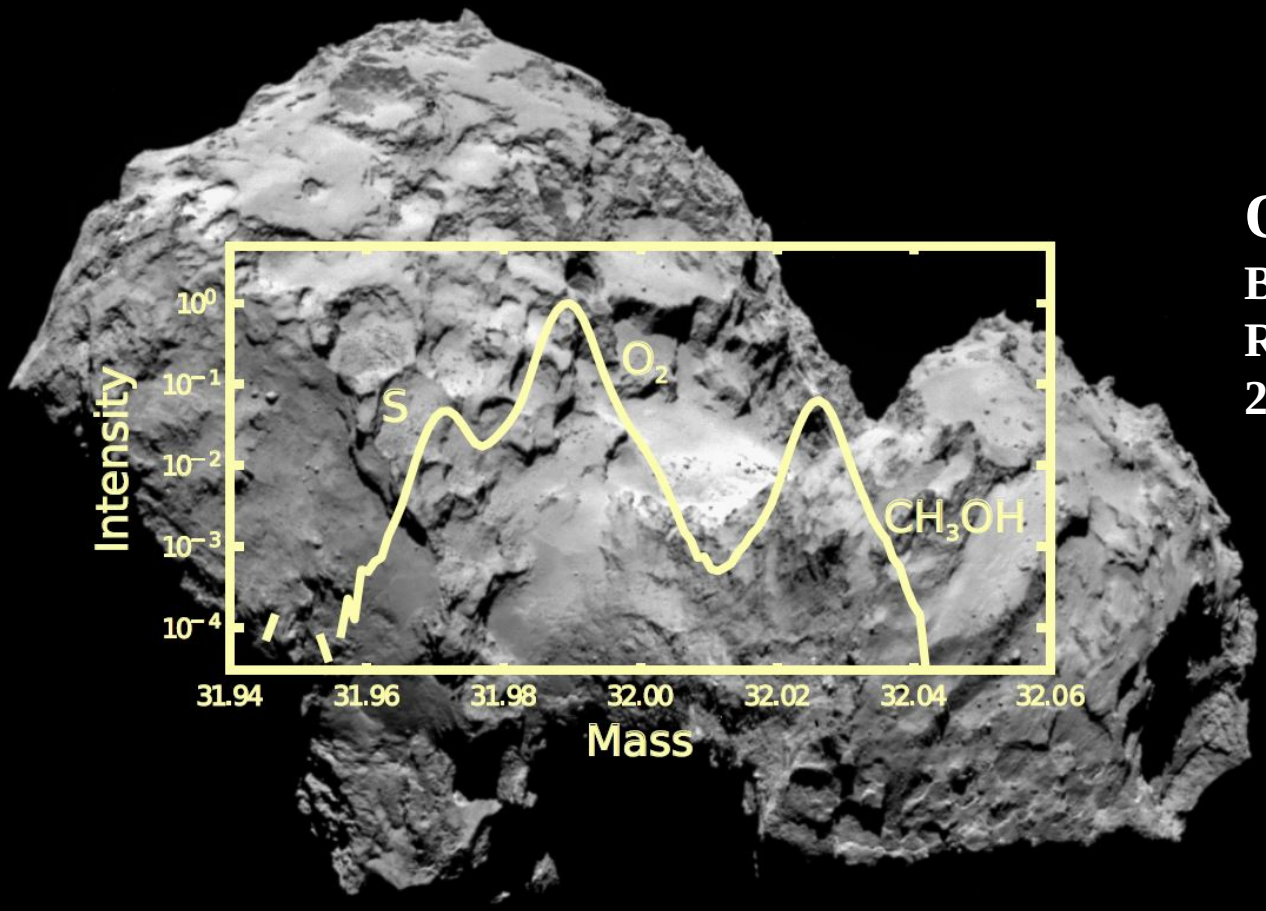
Comet 67P/C-G

Chemical composition comets comparable with interstellar ices

ROSETTA has a very good nose (DFMS)



Abundant O_2 in comets!



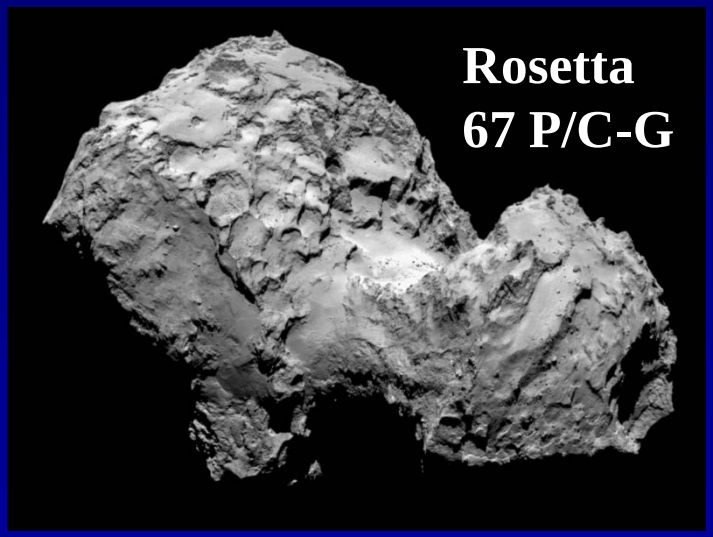
O_2/H_2O~4%
Bieler et al.
Rubin et al.
2015

Needs low H/O
Taquet et al.
2016

High abundance of O_2 suggests our solar system was formed in a dense warmish cloud (20-30 K vs 10 K)

Young disk – comet comparison

- **Young disk: observe just sublimated ices**
- **Comet: measure coma molecules *in situ***



→ THE COMETARY ZOO: GASES DETECTED BY ROSETTA

esa

THE LONG CARBON CHAINS
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane

THE AROMATIC RING COMPOUNDS
Benzene
Toluene
Xylene
Benzoic acid
Naphtalene

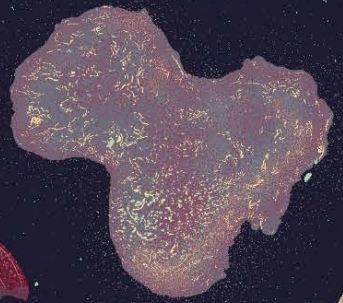
THE KING OF THE ZOO
Glycine (amino acid)

THE "MANURE SMELL" MOLECULES
Ammonia
Methylamine
Ethylamine

THE "POISONOUS" MOLECULES
Acetylene
Hydrogen cyanide
Acetonitrile
Formaldehyde

THE ALCOHOLS
Methanol
Ethanol
Propanol
Butanol
Pentanol

THE VOLATILES
Nitrogen
Oxygen
Hydrogen peroxide
Carbon monoxide
Carbon dioxide



THE "SMELLY" MOLECULES
Hydrogensulphide
Carbonylsulphide
Sulphur monoxide
Sulphur dioxide
Carbon disulphide

THE "SMELLY AND COLOURFUL"
Sulphur
Disulphur
Trisulphur
Tetrasulphur
Methanethiole
Ethanethiol
Thioformaldehyde

THE TREASURES WITH A HARD CRUST
Sodium
Potassium
Silicon
Magnesium

THE "SALTY" BEASTS
Hydrogen fluoride
Hydrogen chloride
Hydrogen bromide
Phosphorus
Chloromethane

THE BEAUTIFUL AND SOLITARY
Argon
Krypton
Xenon

THE "EXOTIC" MOLECULES
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide

THE MOLECULE IN DISGUISE
Cyanogen

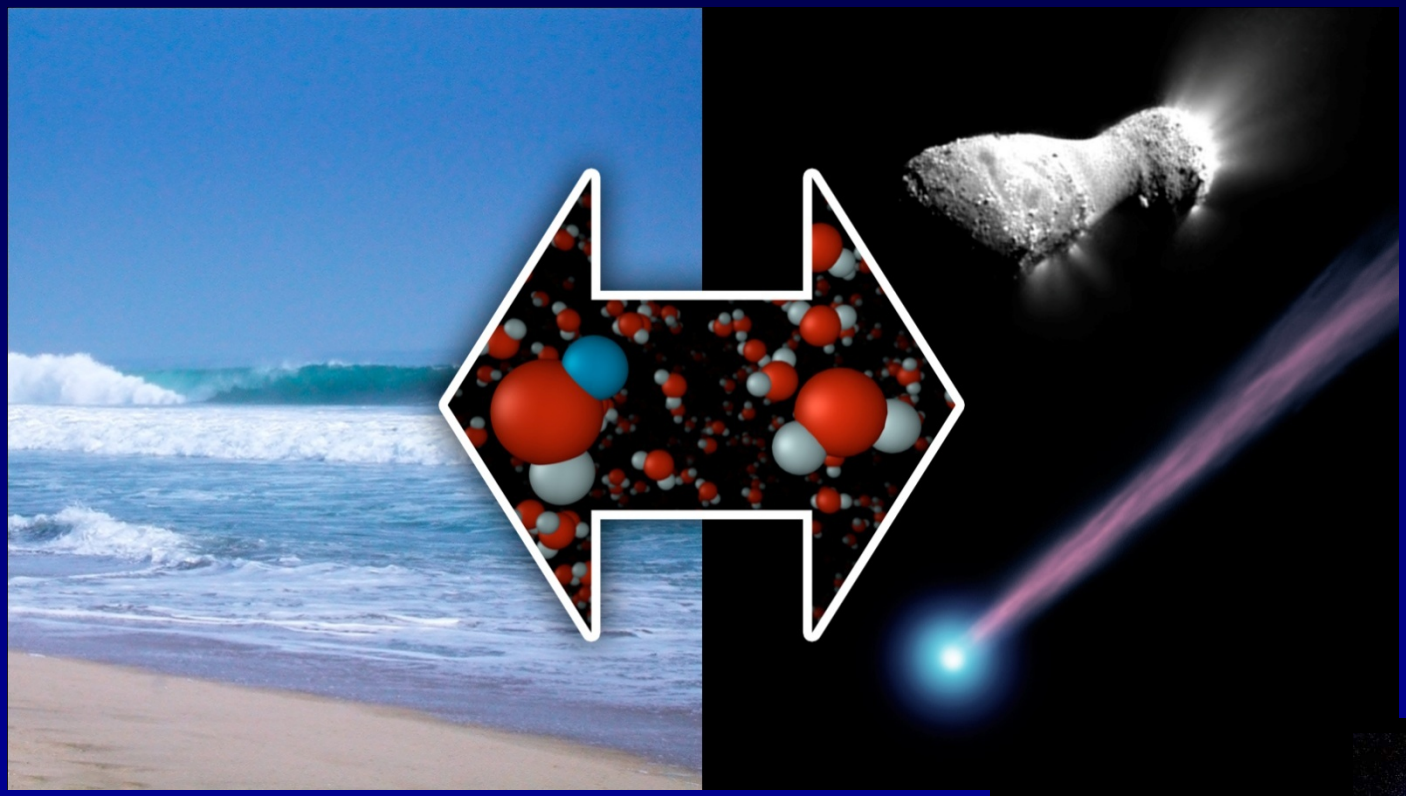
www.esa.int

Credits: Based on data from ROSINA

European Space Agency

ESA/K. Altwegg

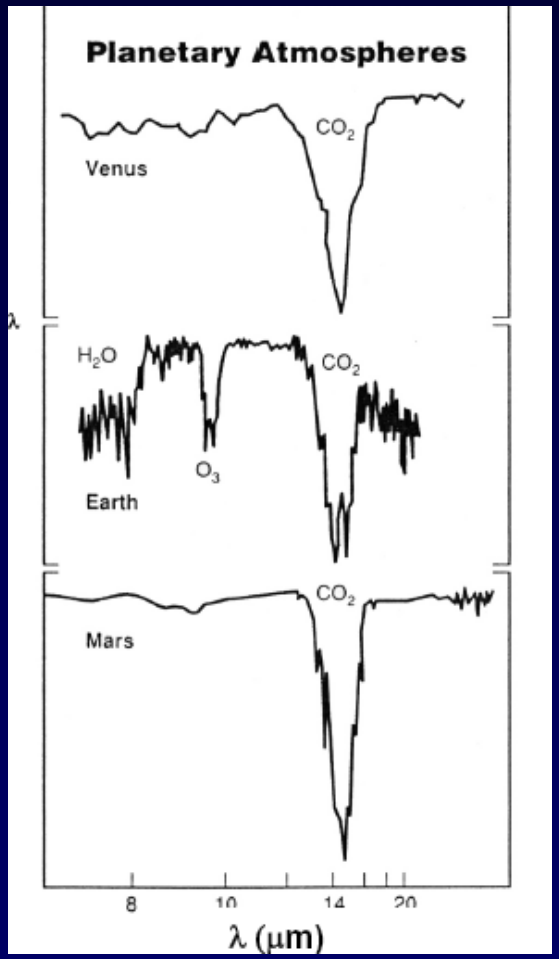
Origin water and organics on Earth?

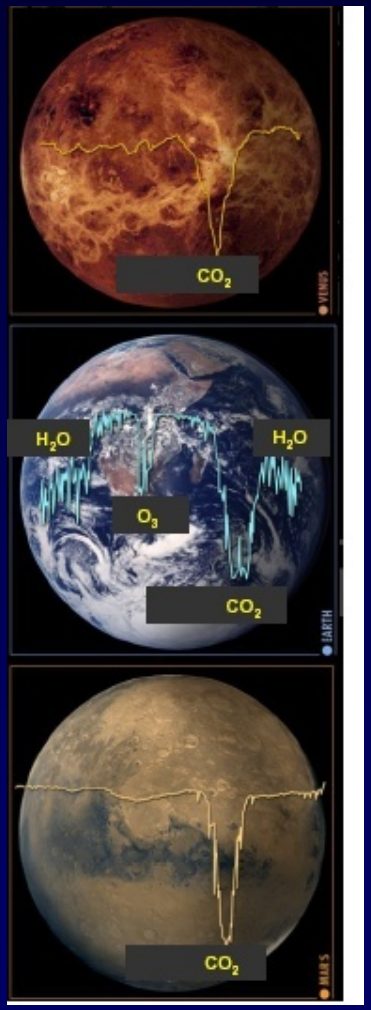


ESA/NASA
Herschel-HIFI
Hartogh et al.

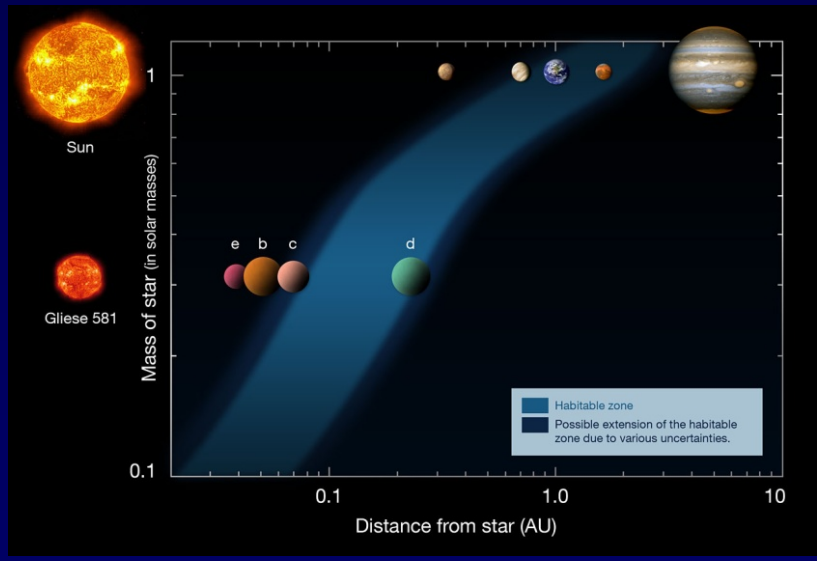
Similar ratio: $HDO/H_2O=1.5\ 10^{-4}$

Search for water in planetary atmospheres





Earth lies in the ‘habitable zone’ where water is liquid

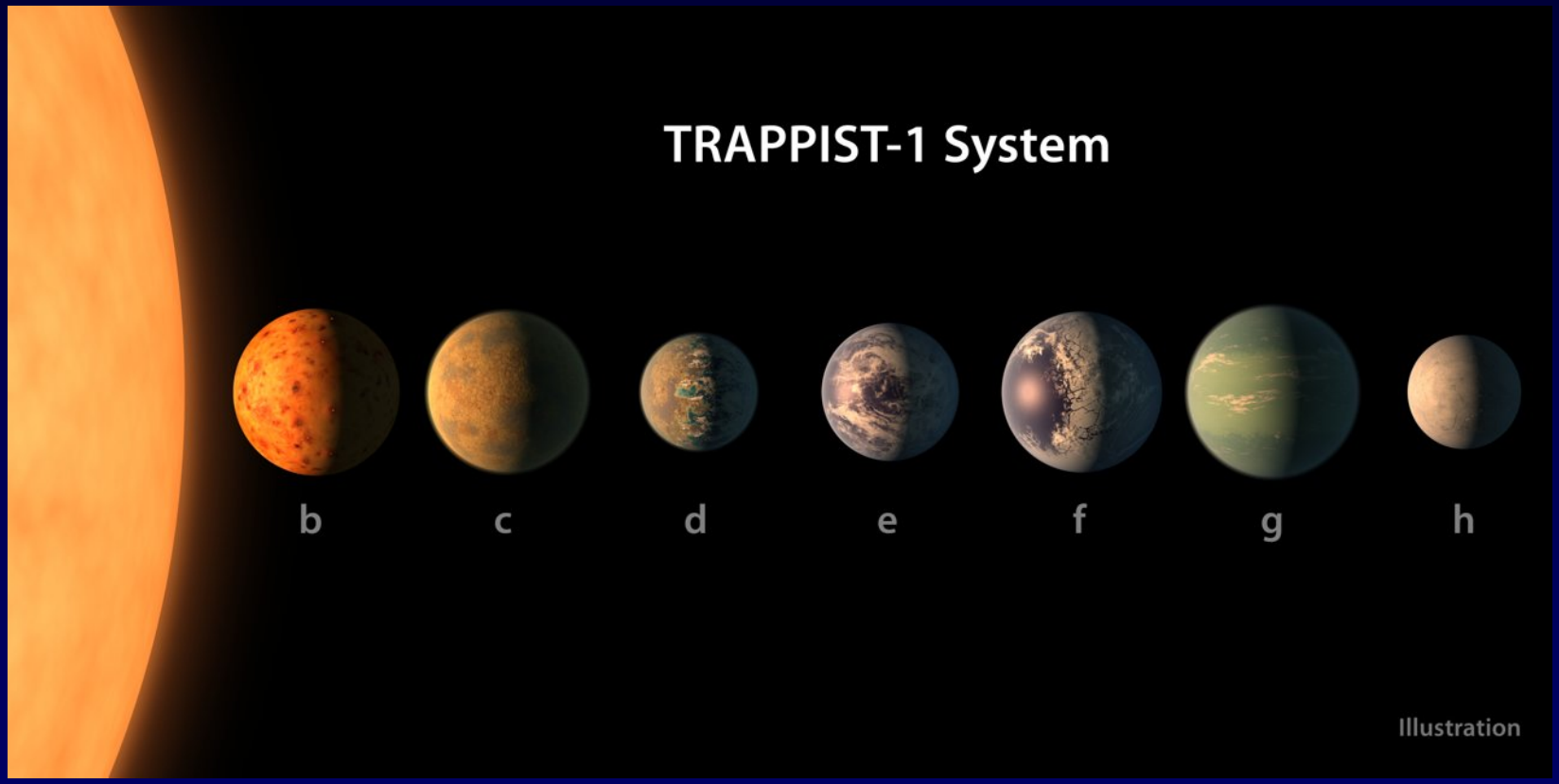


Life on the nearest planet?

Anglada-Escudé et al. 2016

With ELTs we can answer the question: ‘Are we alone?’

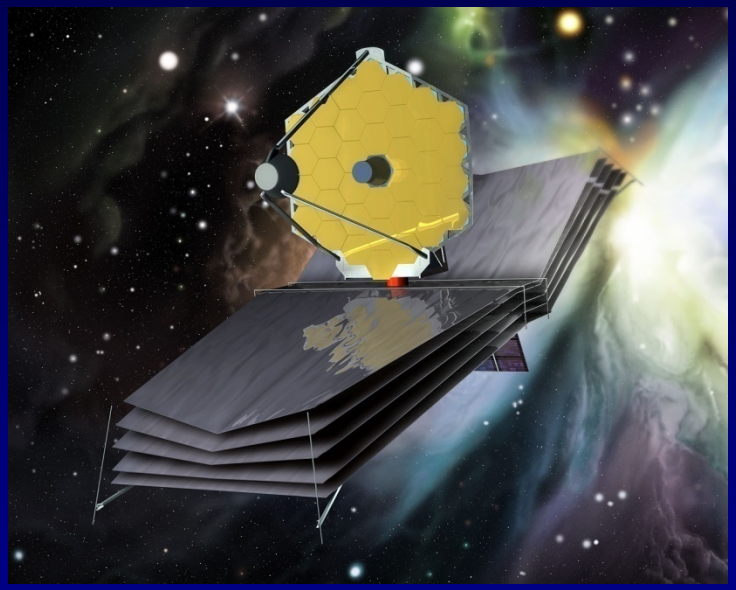
Life on Trappist 1 planets?



Gillon et al. 2017

7 Earth-like planets
3 in habitable zone

Future Telescopes



James Webb
Space Telescope
~6 m diameter
2019: MIRI instrument!

Extremely
Large Telescopes

E-ELT
~39m diameter
~ 2025

Summary

- **Chemical ingredients are present throughout space and are associated with forming stars**
- **Planetary systems are possible around the majority of stars**
  - **But what kind of planets are formed?**
- **Chemistry on solar system scales is now being unravelled with new instrumentation**

How were ‘we’ formed 4.5 billion yr ago

Vielen Dank!

Acknowledgments

- **Figures and movies from:**
  - **European Southern Observatory**
    www.eso.org
  - **NASA/Hubble Space Telescope**
    hubblesite.org
  - **NASA/Spitzer Space Telescope**
    www.spitzer.caltech.edu
  - **ESA/Herschel Space Observatory**
    herschel.esac.esa.int
  - **Atacama Large Millimeter array**
  - **www.almaobservatory.org**
  - **ESA Rosetta mission to comet**
    sci.esa.int/rosetta/