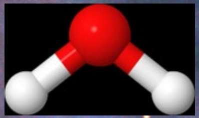
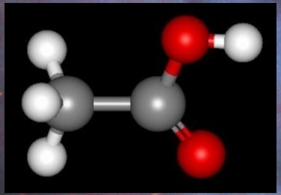
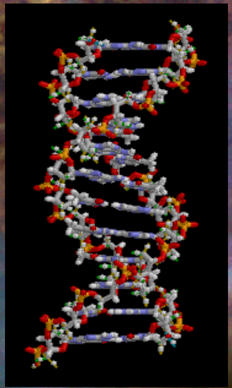
Building stars, planets and the ingredients of life in space



The critical role of dust





Ewine F. van Dishoeck

Leiden Observatory

NASA/HST
Carina nevel

Thanks to many students, postdocs, colleagues

Nanoworld symposium, Marseille, July17 2019

European Research Council

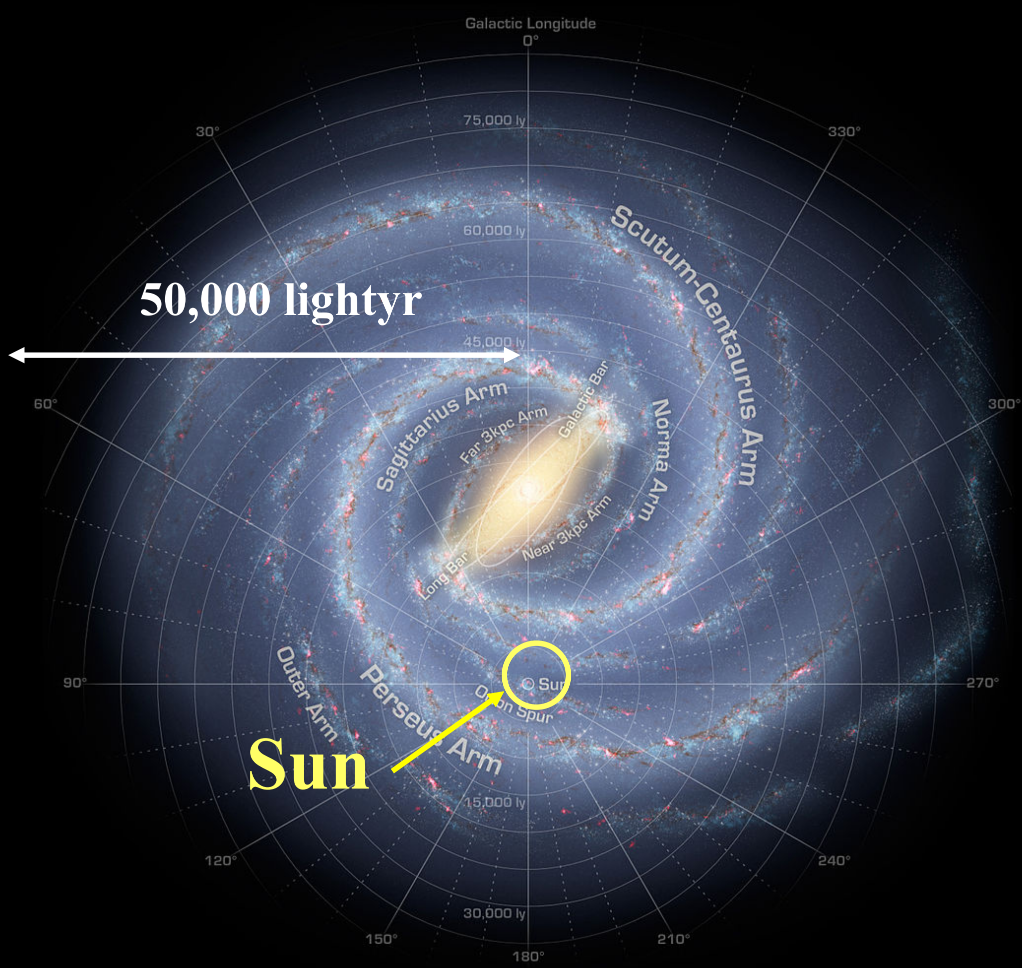
Nederlandse Organisatie voor Wetenschappelijk Onderzoek

Outline

- **The big questions**
- **The setting: interstellar space**
- **The tools: telescopes, laboratory experiments, computers**
- **The main ingredients: gas, dust and ice**
- **The play: chemical processes**
- **The plot: from clouds to disks and planets**

Tielens 2013, Rev. Mod. Phys.; Chem. Reviews 2013 special issue; Caselli & Ceccarelli 2012. Herbst & vD 2009, ARA&A, van Dishoeck+ 2014a,b, 2018

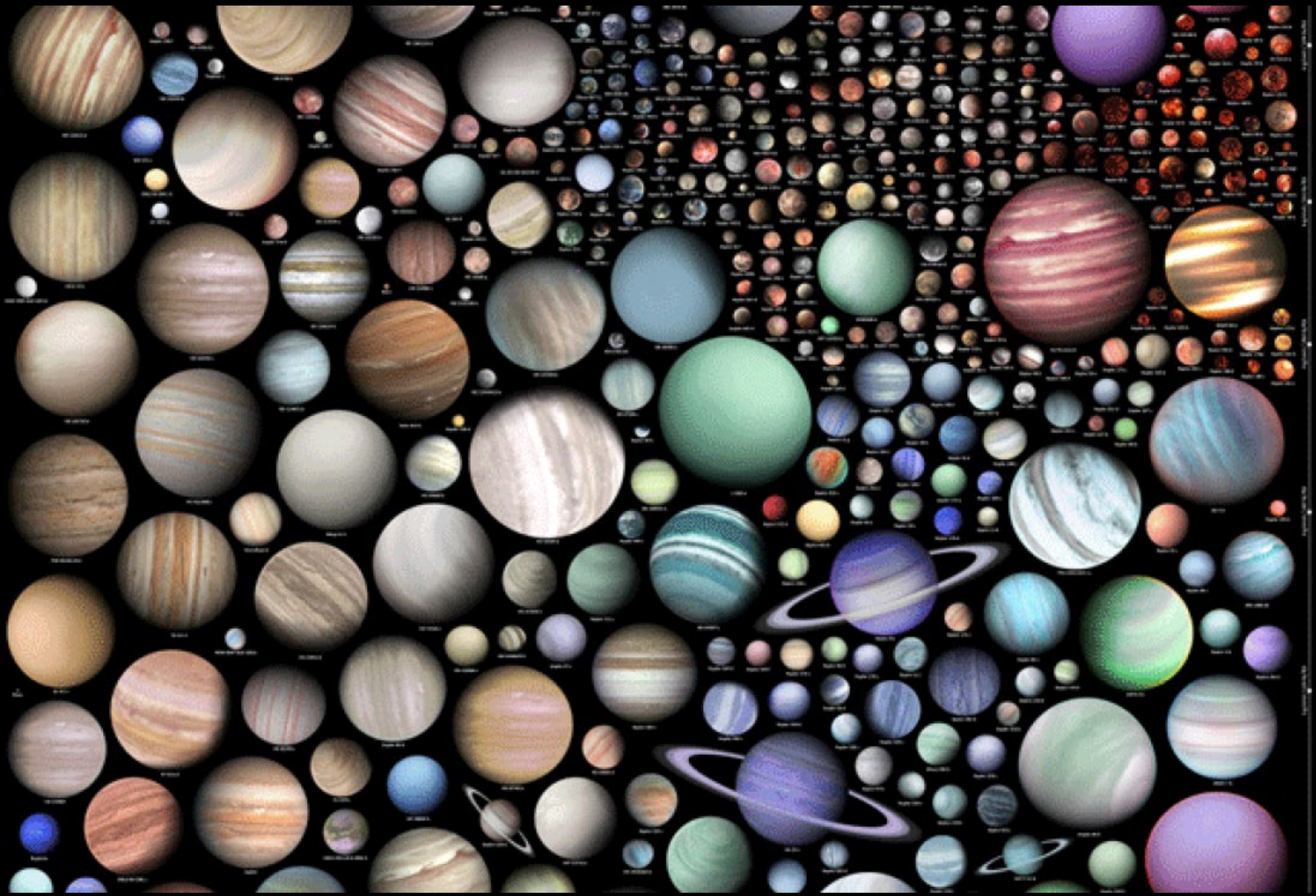
Our Milky Way



~250 billion stars

- We live on a small rocky planet around an ordinary star in a garden-variety galaxy: unique or not?

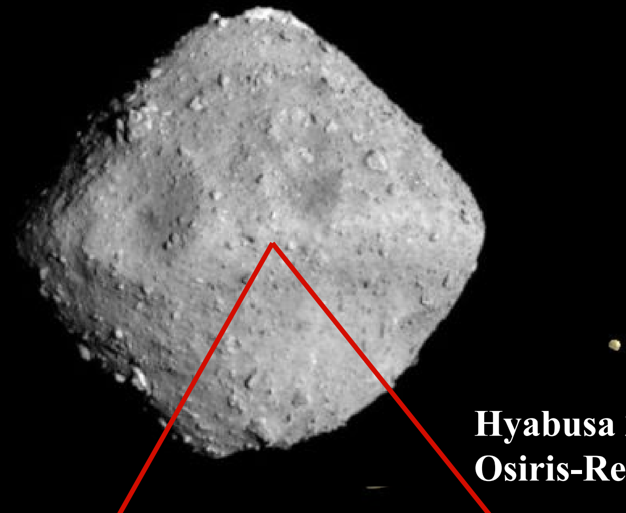
Exoplanets: what are their building blocks?



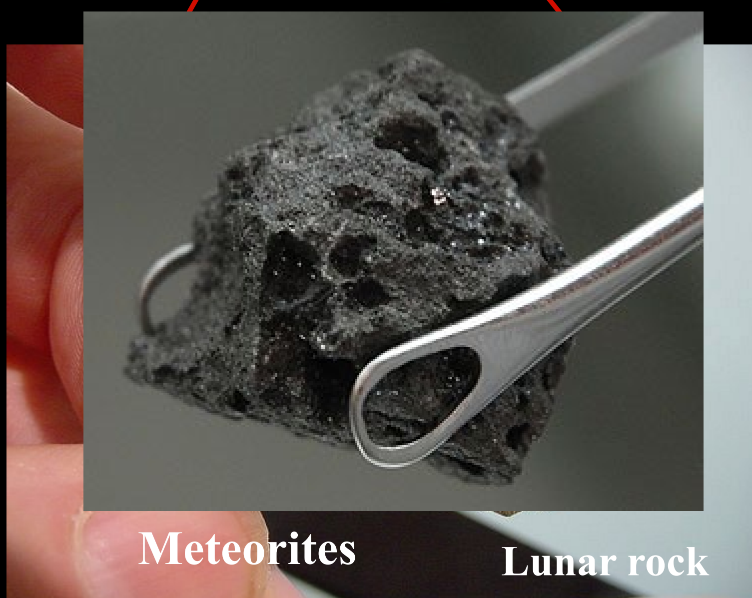
Kepler: Borucki et al. 2011, Batalha et al. 2013

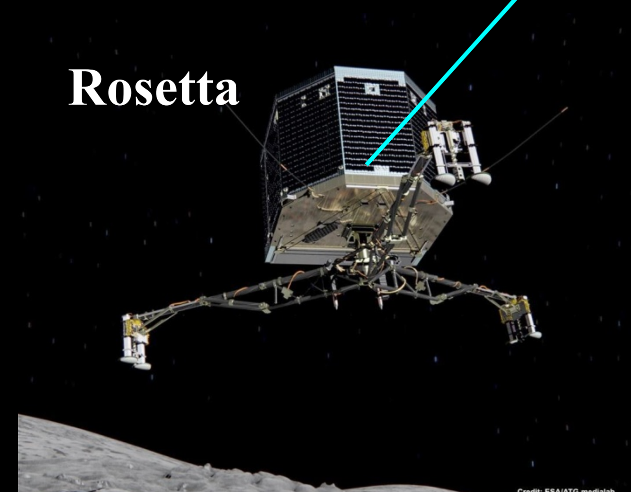
On average every star has at least one planet
Many super-Earths, mini Neptunes. Why?

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



Hyabusa 2
Osiris-Rex





Messengers from the early solar system

Where do we build molecules?

Orion nebula
Hubble Space
Telescope (HST)

Red = ionized gas
(no molecules)

Black=molecular gas

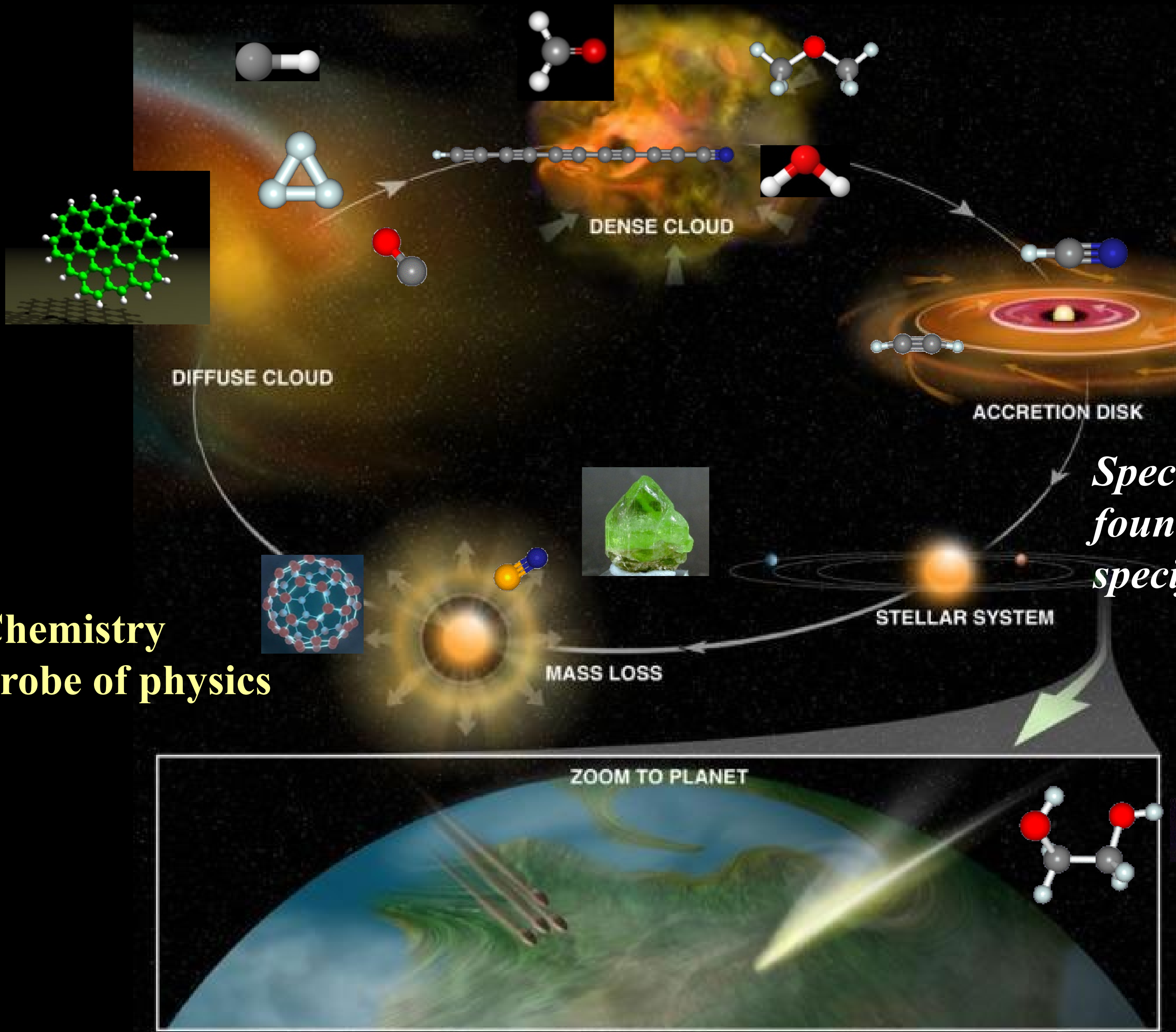
Stars and planets are formed in dark clouds

HST Carina nebula

Typical conditions: 10^4-10^5 cm^{-3}, T=10-20 K
Typical sizes: up to few lightyr (10^{18} cm)
Typical masses: up to 10^5 M_{Sun}

Dust particle 0.1 μm

From clouds to disks and planets



Specific molecules found under specific conditions

- Chemistry
- Probe of physics

Molecule images: The Astrochymist

B. Saxton
NRAO

Interdisciplinary approach

Observations

IR, submm,
VIS, UV, X-rays, …

Models

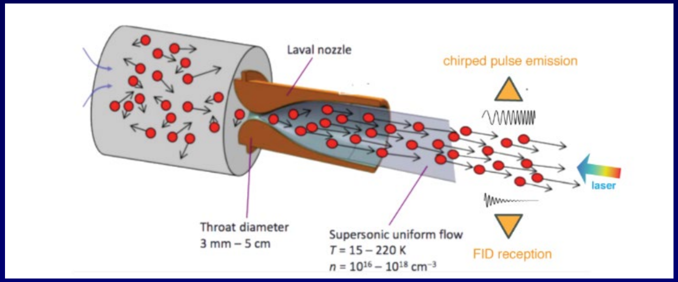
Dark clouds, shocks
Protostars
Disks
Exoplanets, ...

'Laboratory'

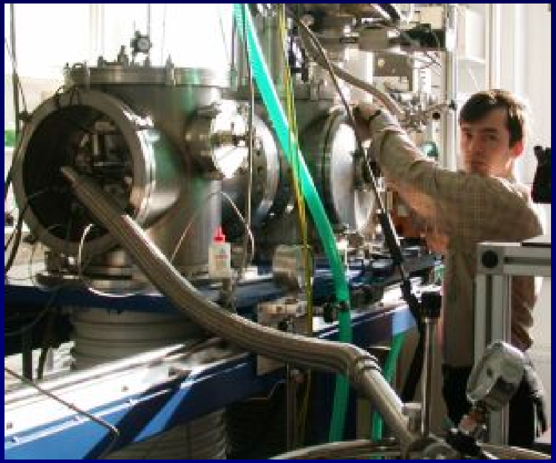
Spectroscopy,…
Collision rates, photorates, …
Chemical reaction rates
Grain surface processes, …..

Fantastic new experiments and new groups!

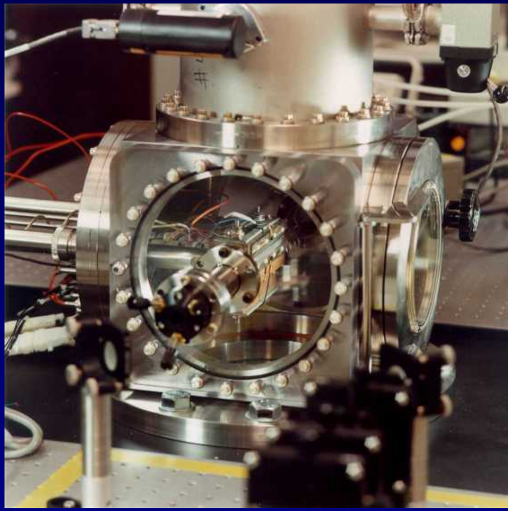
CRESU-CHIRP



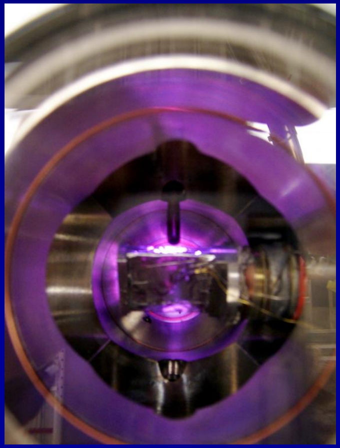
He droplets



Cavity Ringdown Spectroscopy

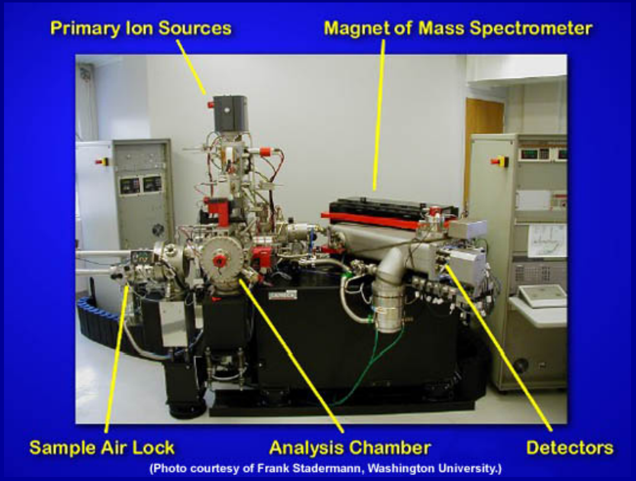


UV plasma



UHV surface science

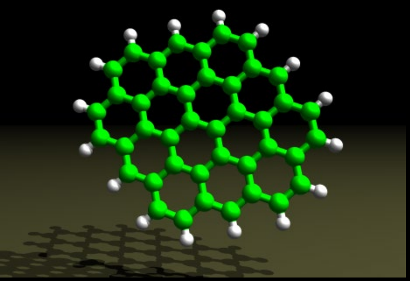
Nano SIMS



How do we observe gas, dust and ice?

From visible to infrared light

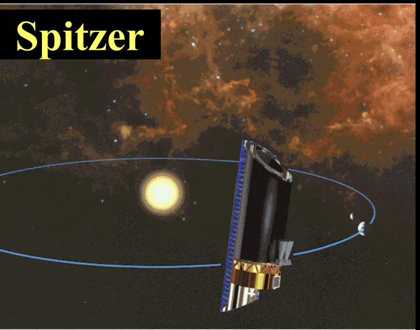
HH 46 star-forming region



Spitzer image:

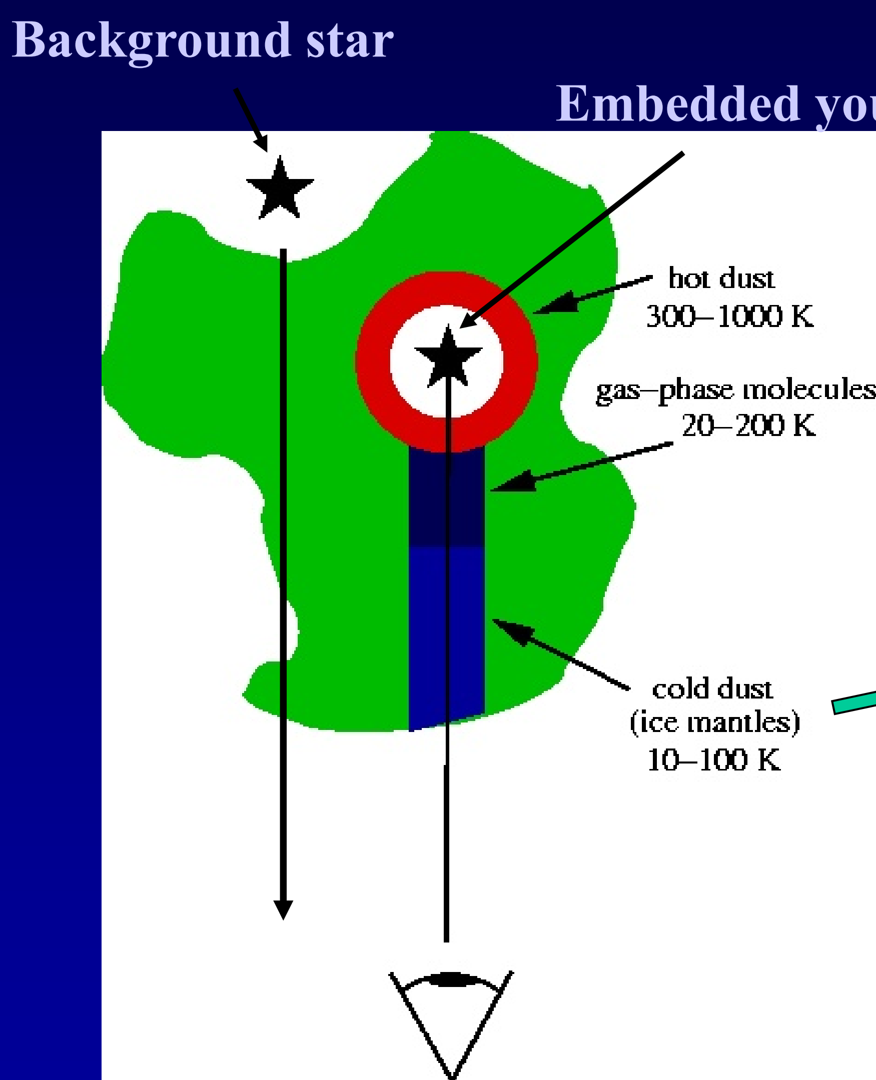
Red= 8 μm: PAH
Green= 4.5 μm: H_2
Blue= 3 μm: stars

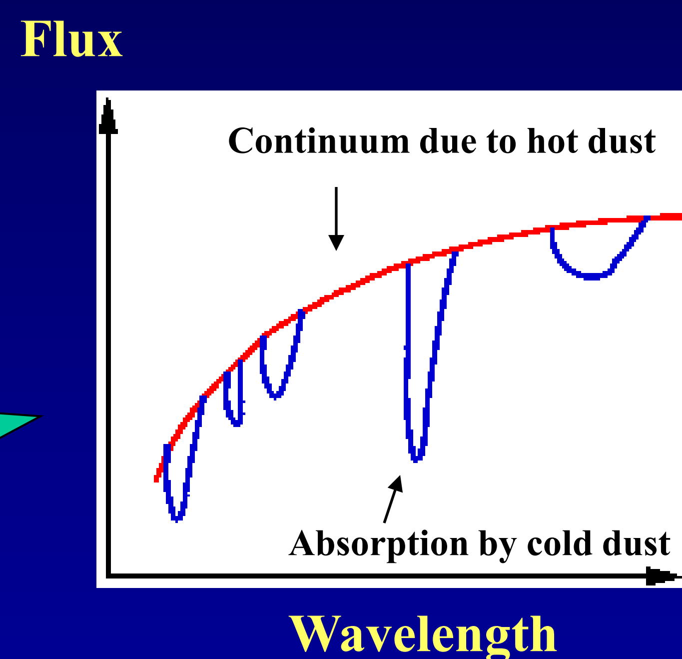
Noriega-Crespo et al. 2004
Spitzer animation



Need long wavelengths to penetrate dusty regions

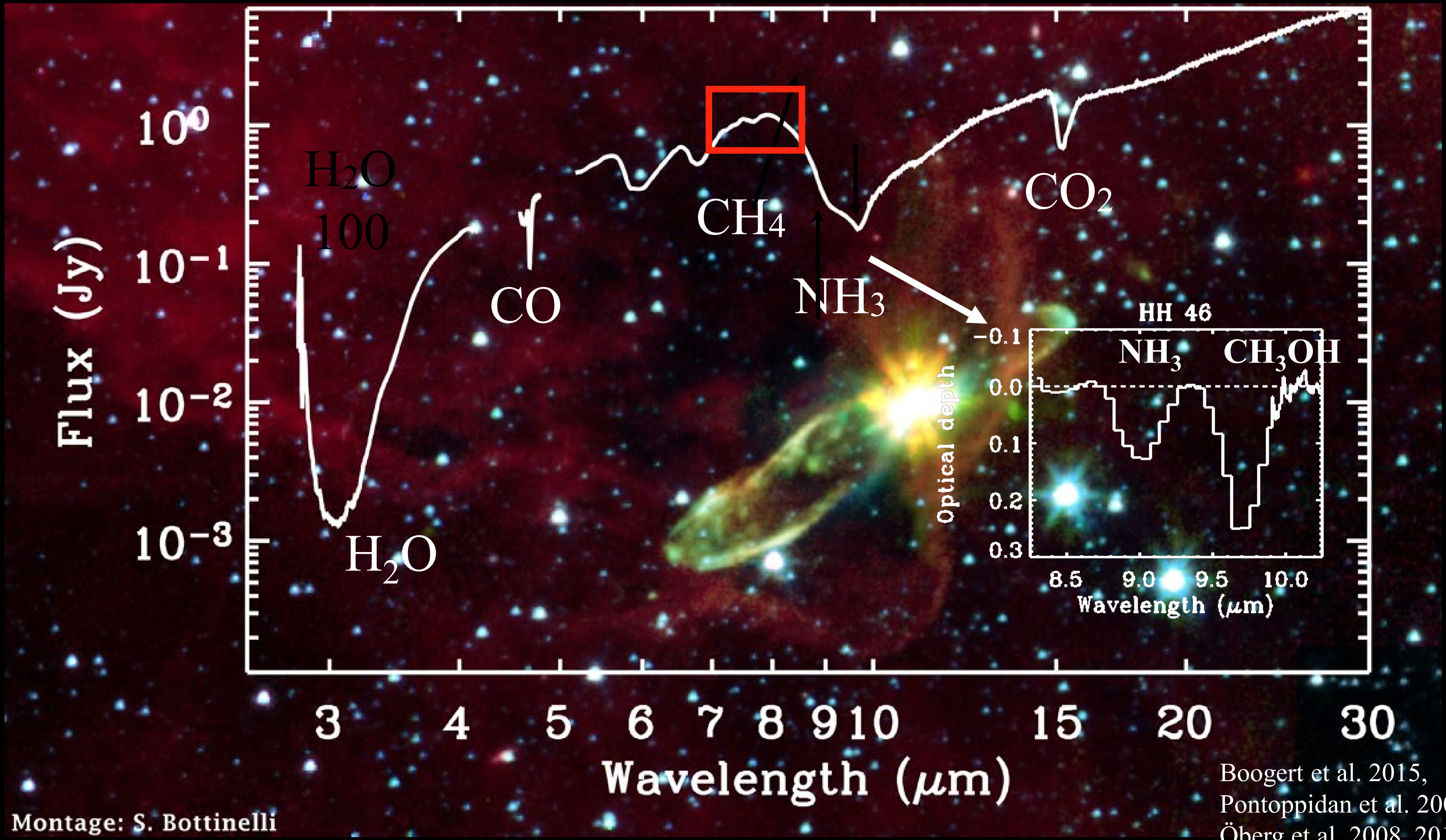
Infrared: absorption and emission





Infrared: vibrational transitions of gases *and* solids (silicates, ices)
Also emission from hot gases (~1000 K)

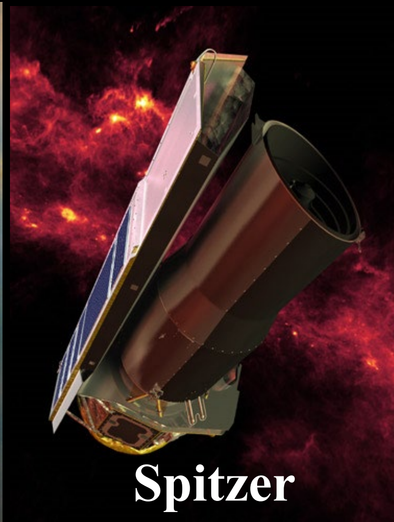
Interstellar ices



Boogert et al. 2015,
Pontoppidan et al. 2008,
Öberg et al. 2008, 2011
Gibb et al. 2004

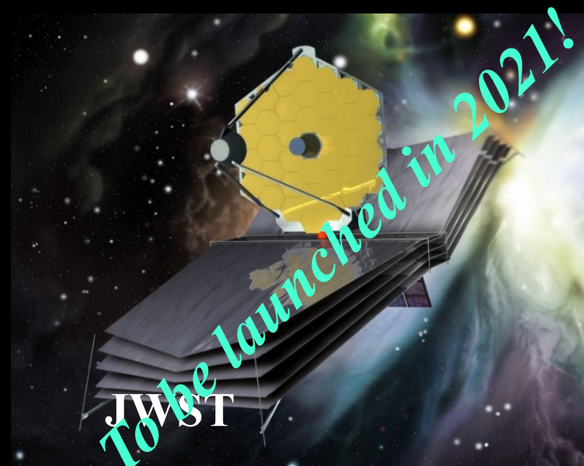
- Ices can contain significant fraction (>50%) of heavy element abundances
-

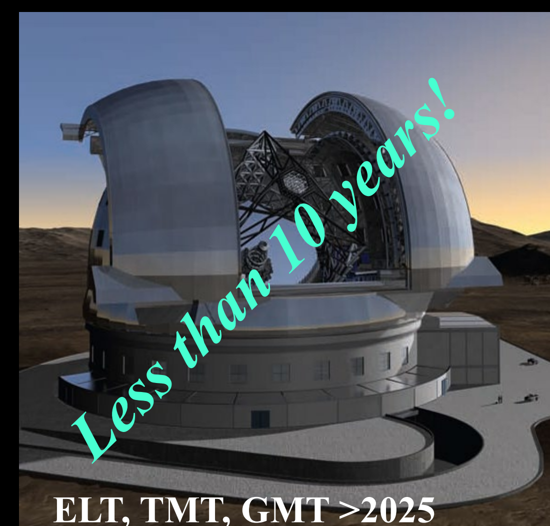
Fantastic facilities for astrochemistry



SOFIA

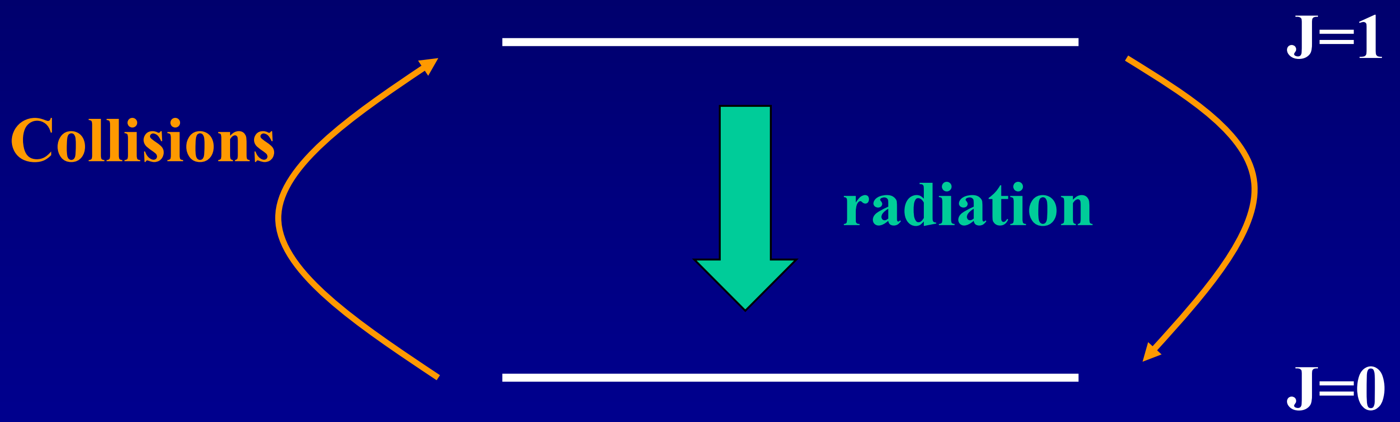
VLT





(Sub)millimeter: emission

Only gases, but down to very low abundances (10^{-12})



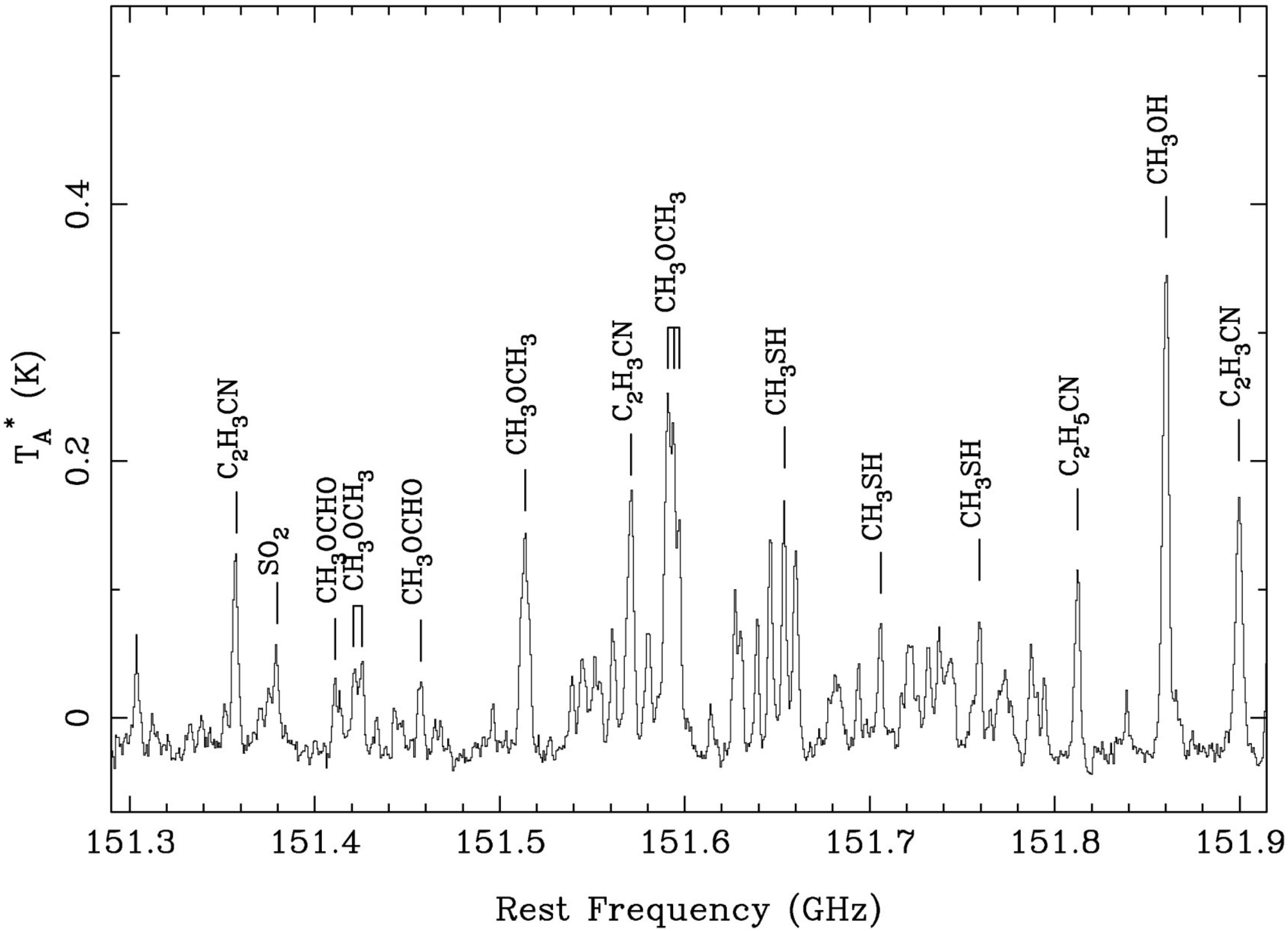
Pure rotational transitions

Higher transitions probe higher temperatures and densities: $n_{cr} \propto \mu_D^2 \nu^3$

- Line profile $\Rightarrow$ kinematics

- Line strength $\Rightarrow$ abundances (through radiative transfer)

Molecules found everywhere!

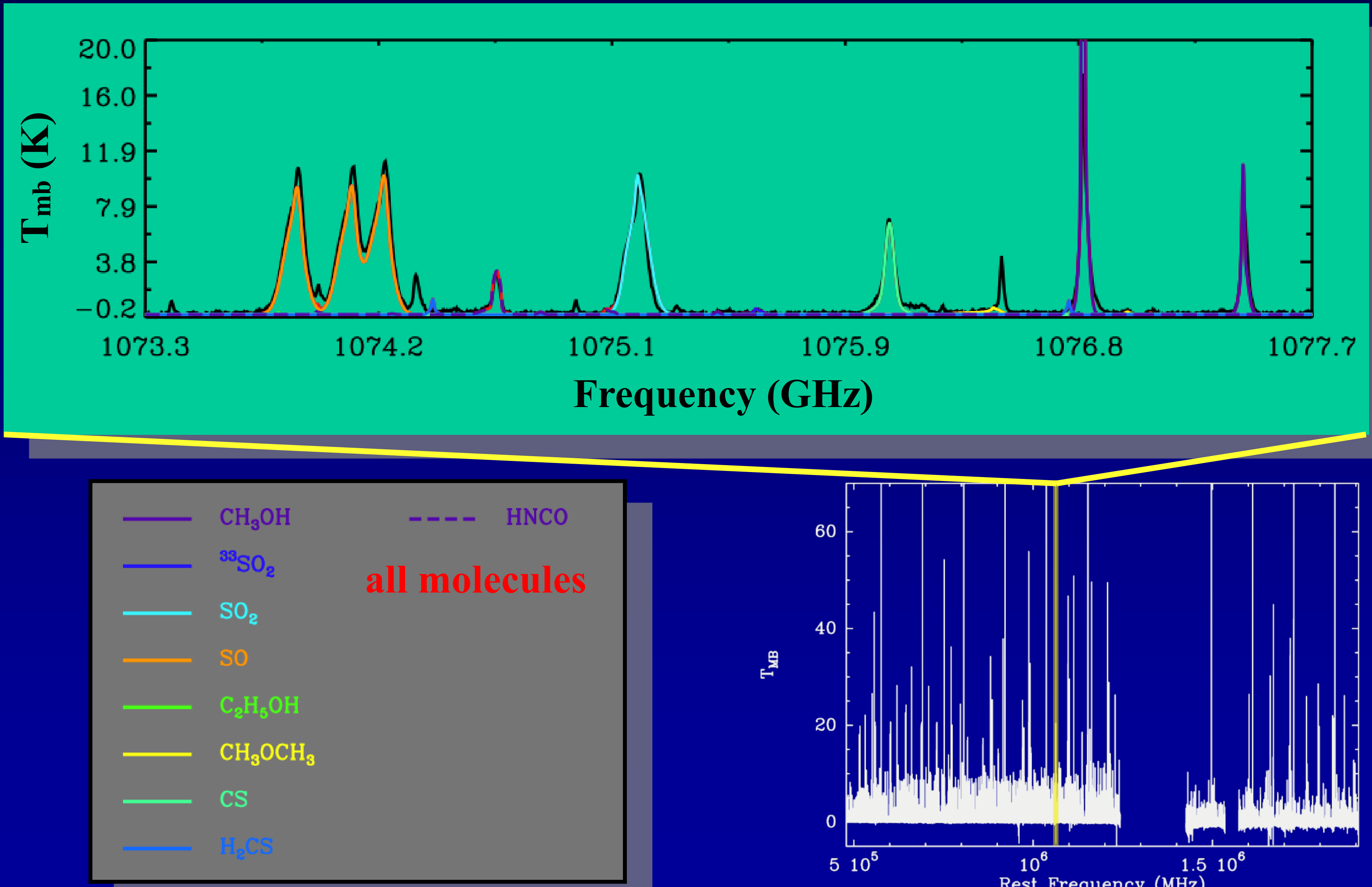


Massive young star G327

Gibb et al. 2000

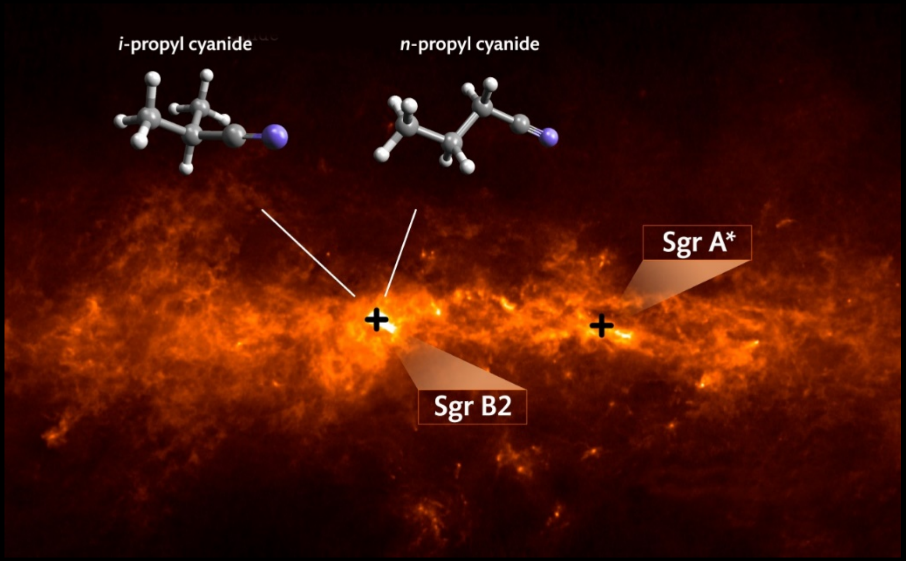
Each molecule has a unique spectrum ('fingerprint')

Identifying and modeling emission



Crockett, Neill, Bergin et al. 2014, 2015

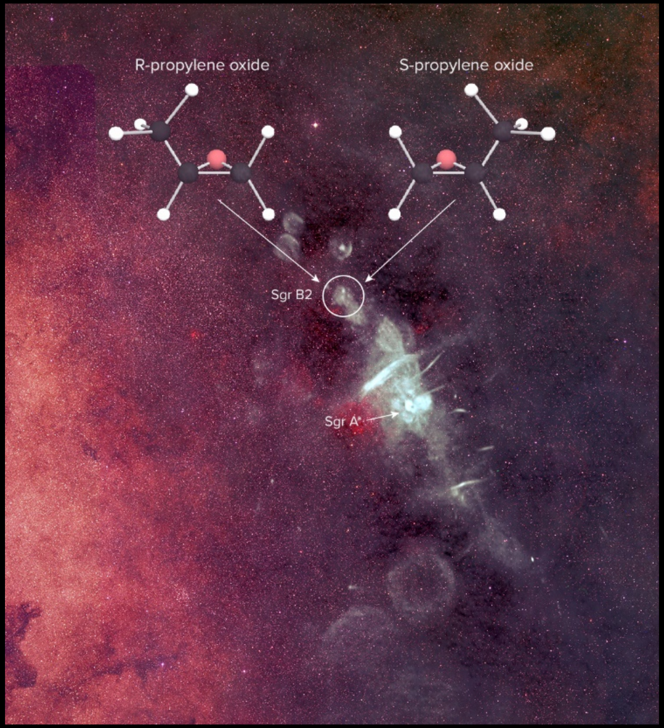
Recent new detections



Such side chains are characteristics of amino acids

ALMA
Belloche et al. 2014

First chiral molecule



McGuire et al. 2016
GBT, ATCA

Atacama Large Millimeter Array (ALMA)

The Astrochemistry machine

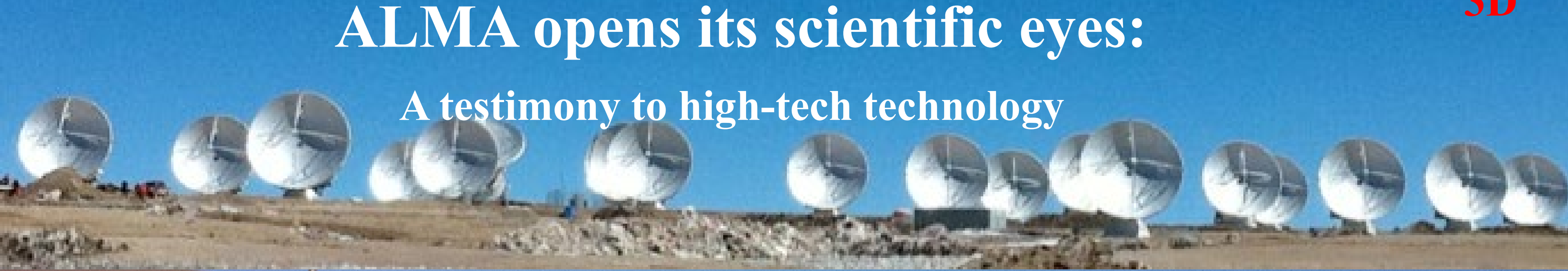
54x12m + 12x7 m antennas

0.3-3 millimeter
84-950 GHz

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

ALMA opens its scientific eyes:

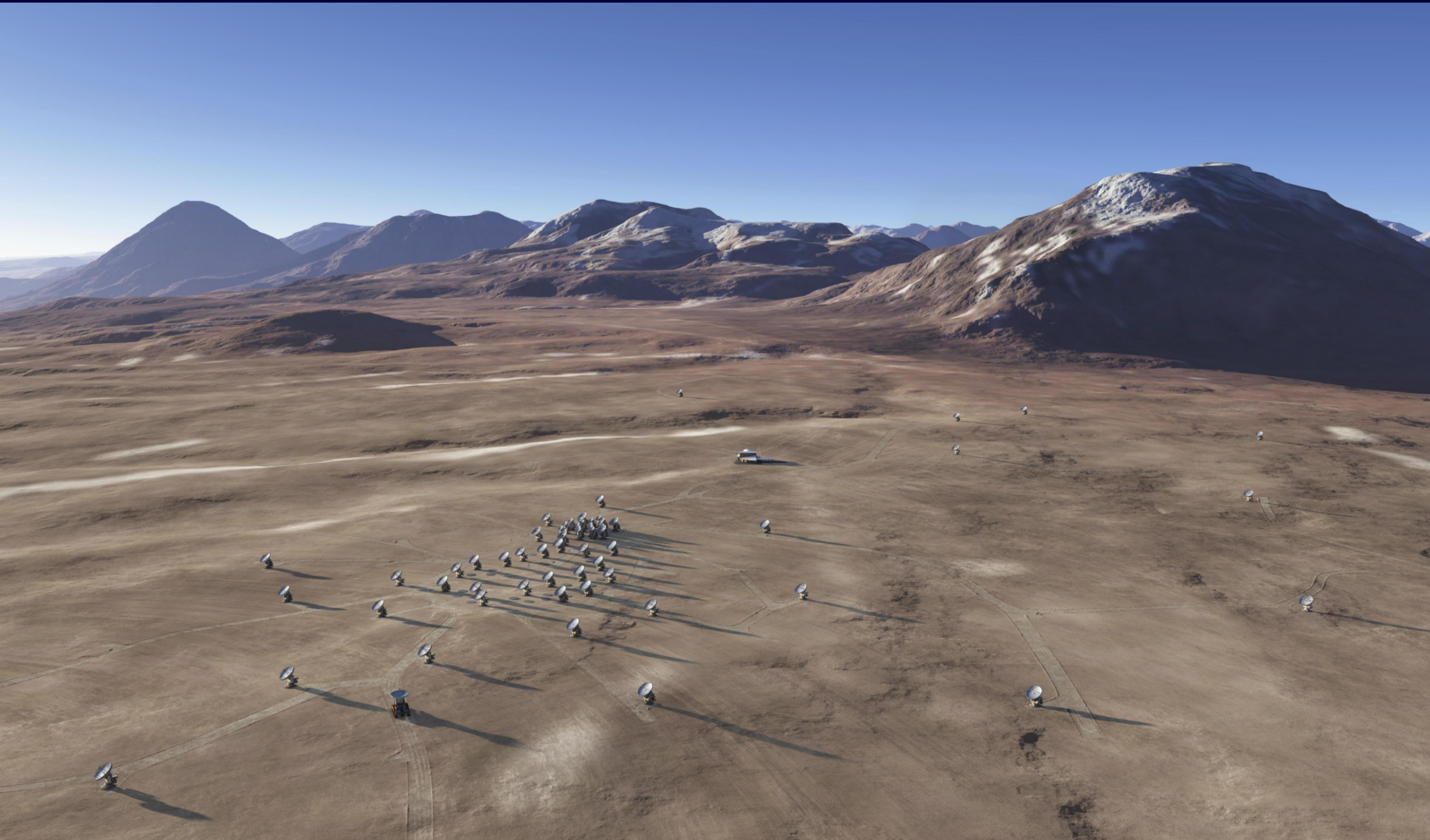
A testimony to high-tech technology



Atacama Large Millimeter Array (ALMA)

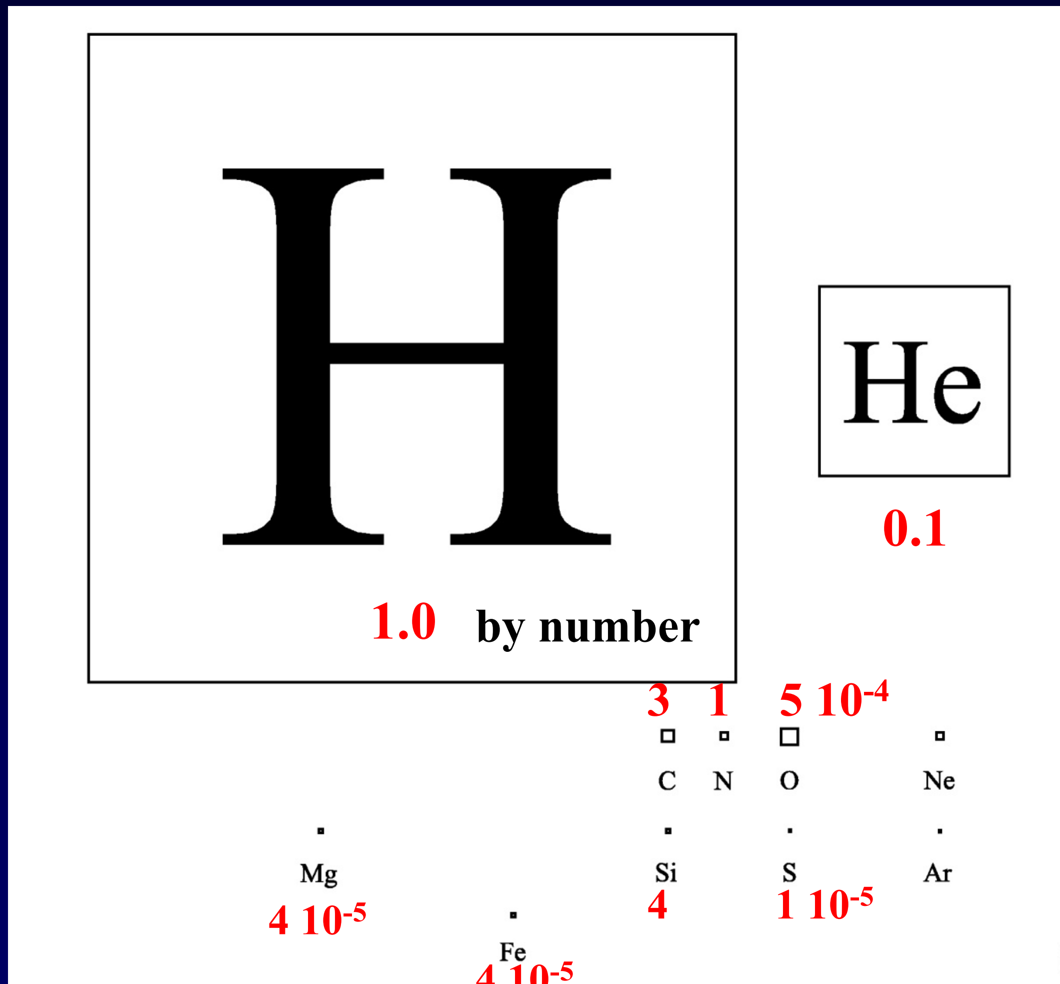
A breathtaking experience!

Llano de Chajnantor
5000 m



The main players

The Astronomers' Periodic Table



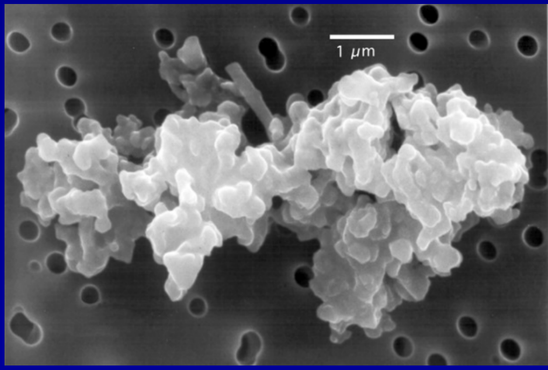
B. McCall 2001

United Nations Educational, Scientific and Cultural Organization

International Year of the Periodic Table of Chemical Elements

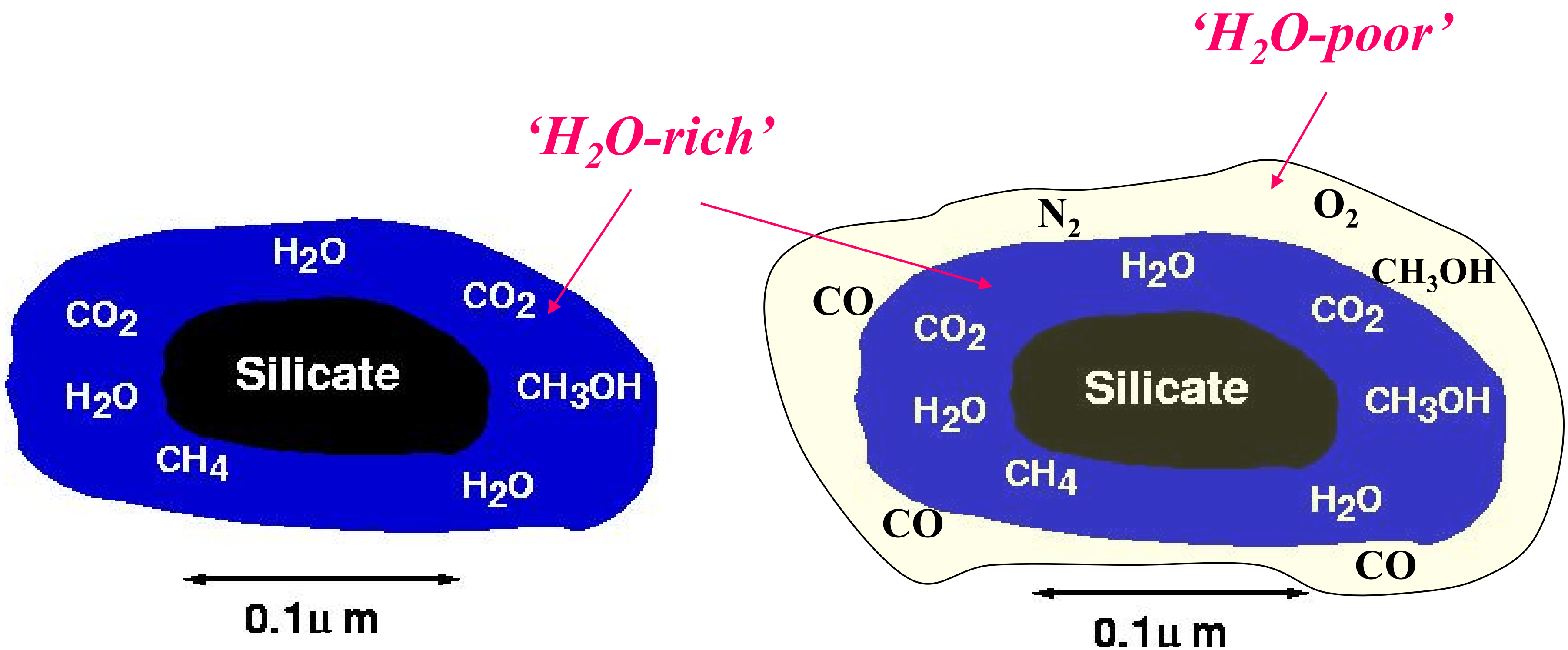
Interstellar dust

- Detected and studied through extinction, reflection, thermal emission, polarimetry, spectroscopy, ...
- Amorphous silicates and carbonaceous material
- Typical size ~0.1 μm, size distribution $a^{-3.5}$
    - Most of surface area in smaller grains ~20 nm
    - Grain growth in dense cores and disks few μm – few cm
- Irregular shape
    - Both physisorption and chemisorption sites



Porous interplanetary dust particle
Wikipedia/D. Brownlee

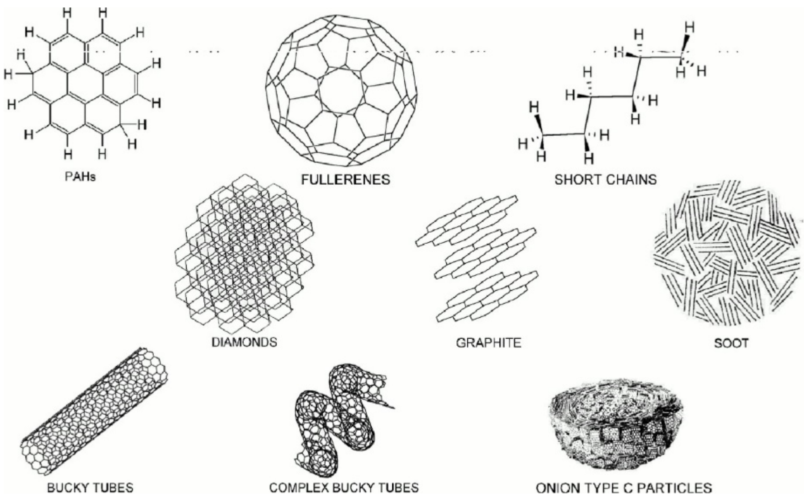
Interstellar ices



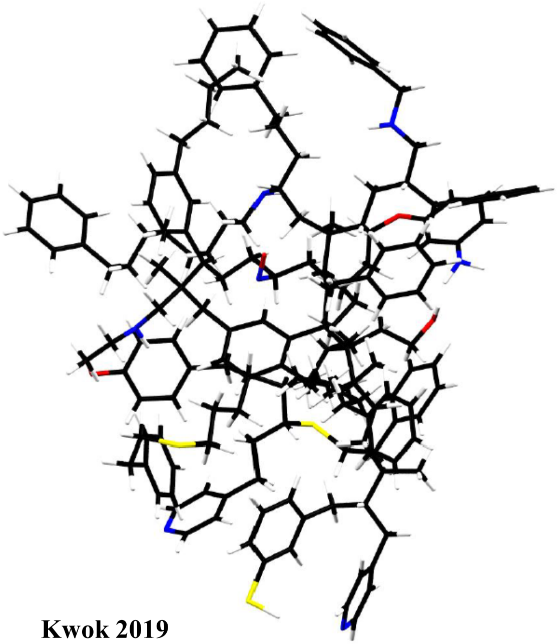
- Atoms and molecules freeze out at low temperatures
- Hydrogenation of O,C,N and CO → H_2O, CH_4, NH_3, CH_3OH
- Different ice phases seen in IR spectra

Tielens & Hagen 1982

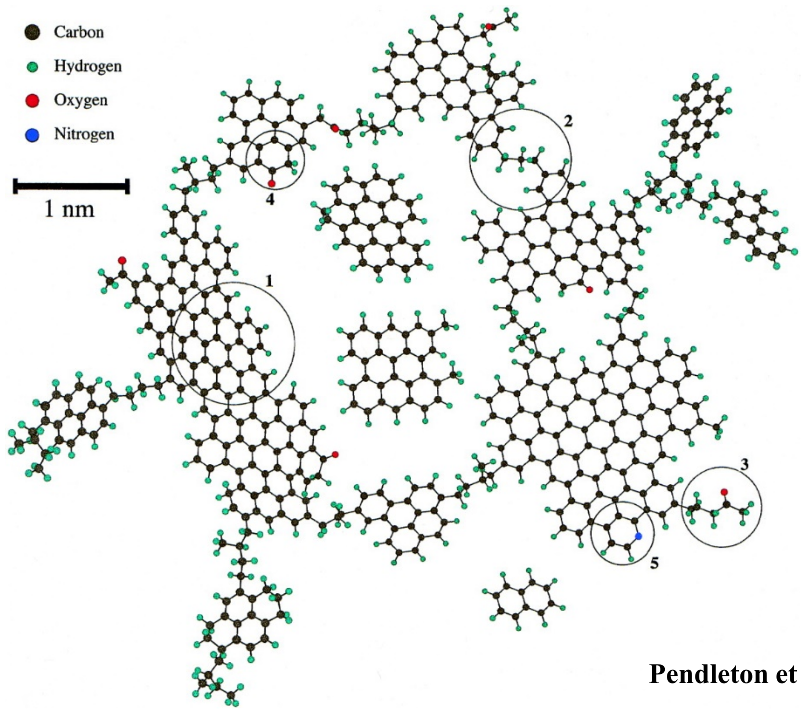
Solid carbonaceous material



Tielens



Kwok 2019



Pendleton et al. 1999

Chemical processes

Chemical networks contain thousands of reactions
but only a few different types of reactions

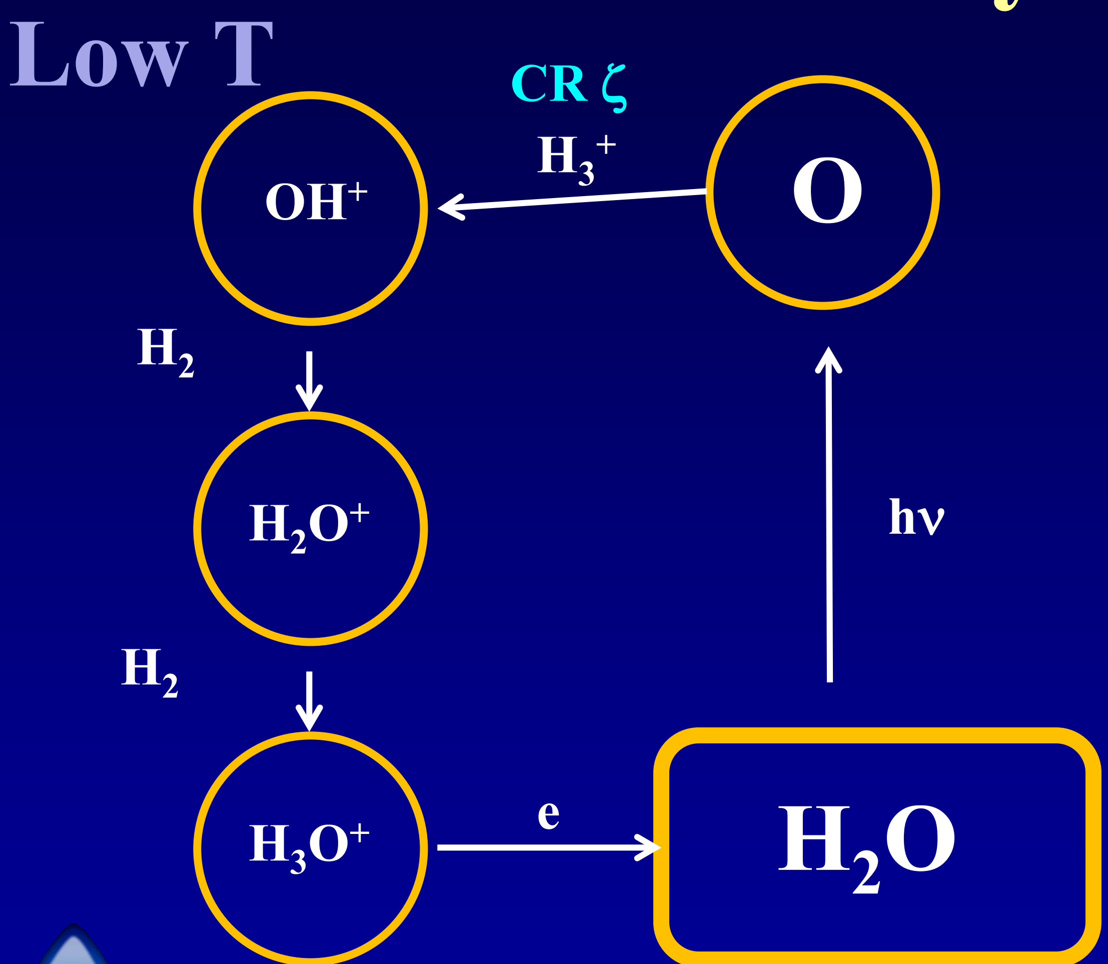
Densities low → two-body processes, no LTE chemistry

Types of processes: two body

- **Formation of bonds**
  - Radiative association: $X^+ + Y \rightarrow XY^+ + h\nu$
  - Grain surface: $X + Y{:}g \rightarrow XY + g$ H_2!
- **Destruction of bonds**
  - Photo-dissociation: $XY + h\nu \rightarrow X + Y$
  - Dissociative recombination: $XY^+ + e \rightarrow X + Y$
- **Rearrangement of bonds**
  - Ion-molecule reactions: $X^+ + YZ \rightarrow XY^+ + Z$
  - Neutral-neutral reactions: $X + YZ \rightarrow XY + Z$

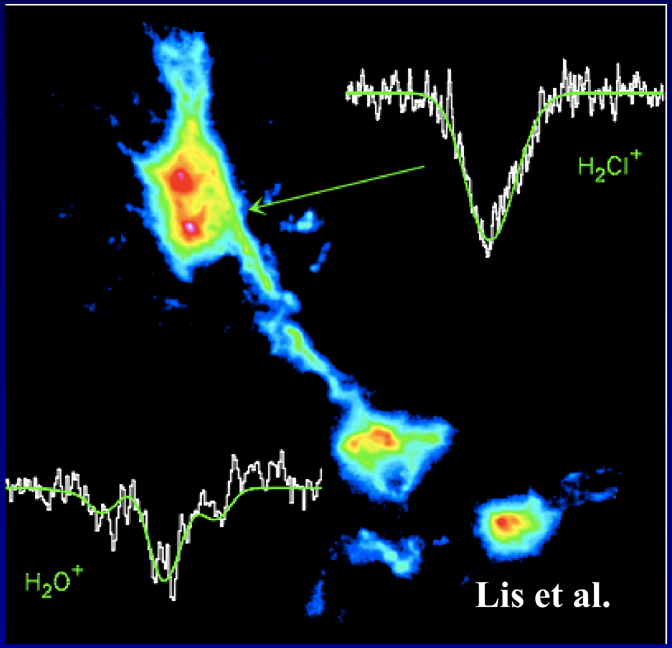
- Ions produced by UV and cosmic rays (high energy protons)

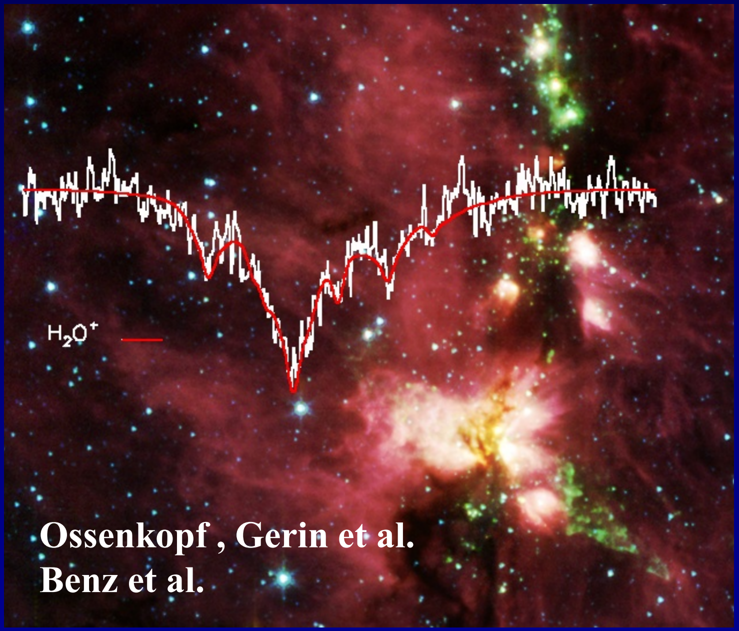
Water chemistry as example



Van Dishoeck et al. 2013,
Chemical Reviews

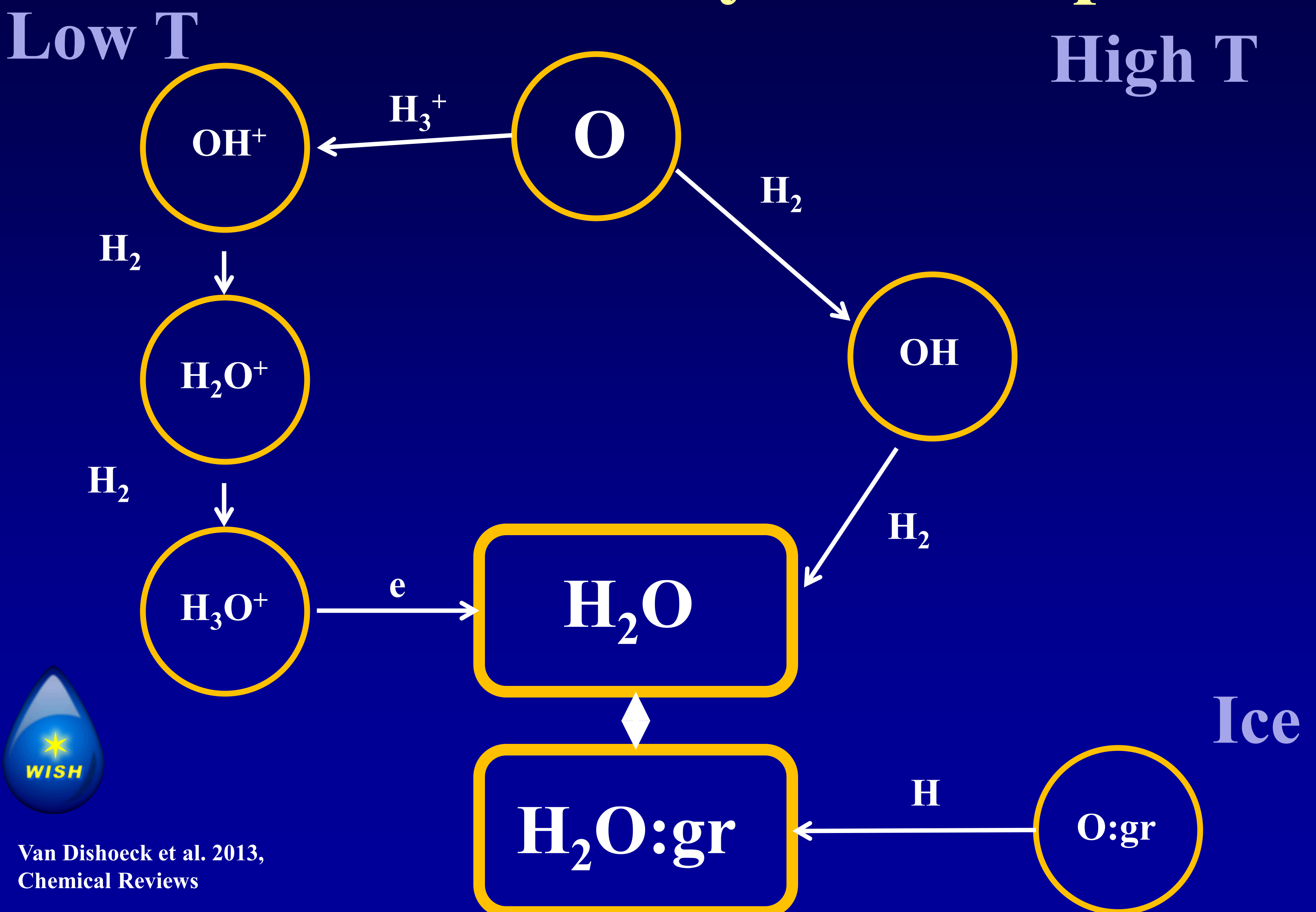
Testing basic ion-molecule chemistry: Hydrides with Herschel





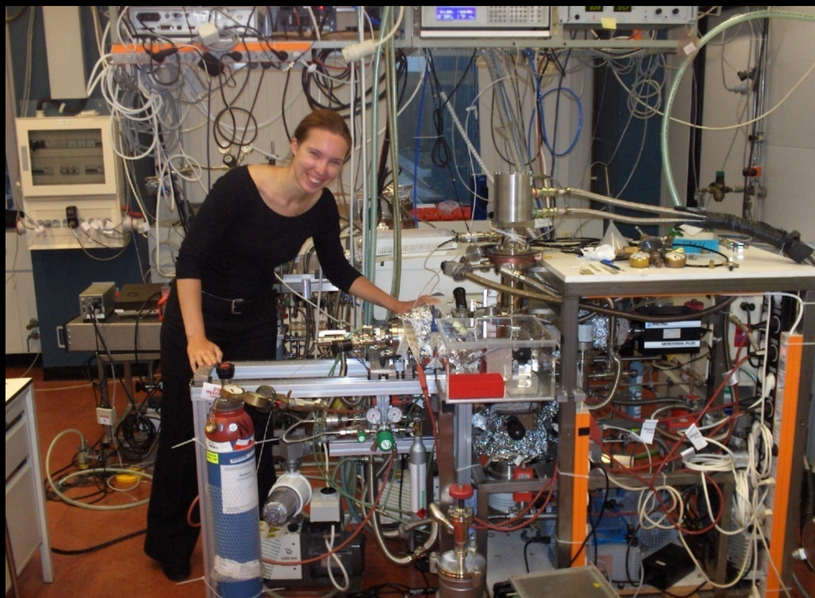
Intermediates OH^+ and H_2O^+ now detected!
Probe of cosmic ray ionization rate

Water chemistry as example



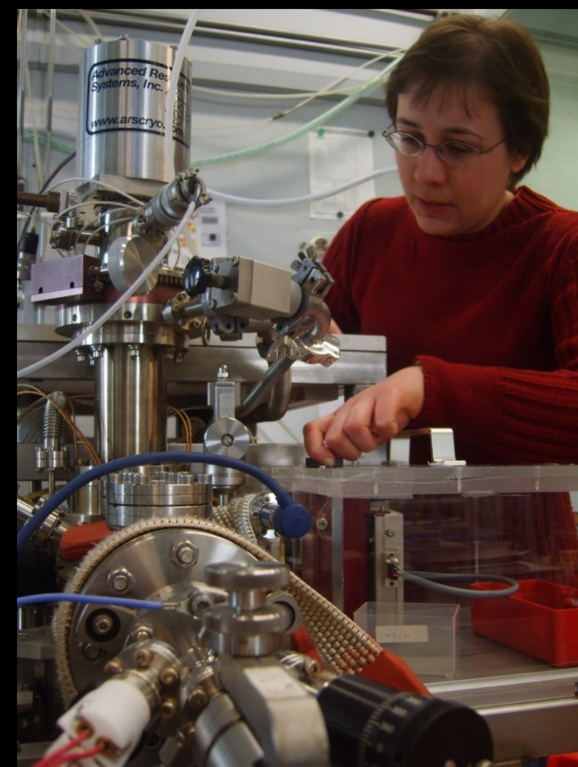
Van Dishoeck et al. 2013,
Chemical Reviews

Leiden laboratory for astrophysics



Karin Öberg

‘Simulating 1 cm^{-3}
of interstellar space’



Harold Linnartz

Formation of water on grains

'Water on Earth is older than the Sun itself'

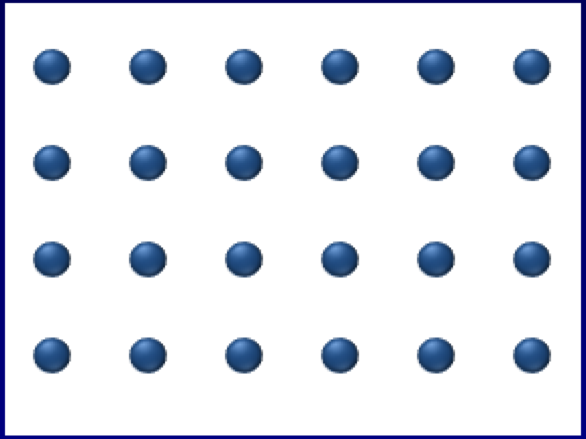
Based on lab data
Leiden, Japan, Paris
Cuppen et al. 2010
Tielens & Hagen

Surface diffusion

- **Site to site hop**

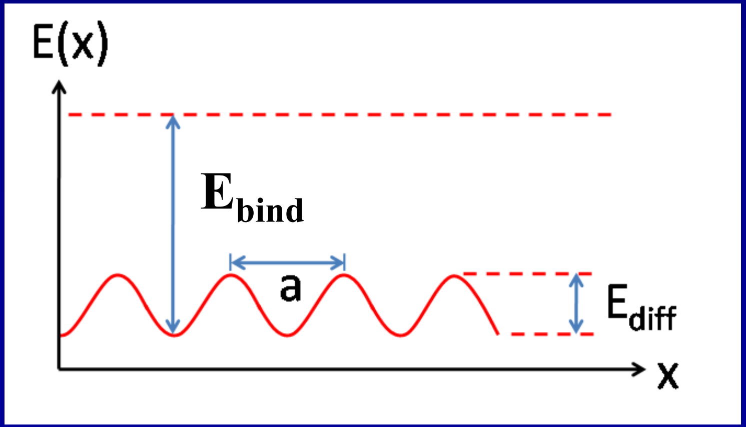
  $K_{hop} = \nu \exp(-E_{hop}/kT_s)$

- **Usually $E_{hop} = c^{st}\, E_{bind}$**
  - **c^{st} varies from 0.3-0.7**



Wikipedia.org

- **Diffusion barriers change from site to site**
- **Importance of tunneling**
- **Competion with reaction**

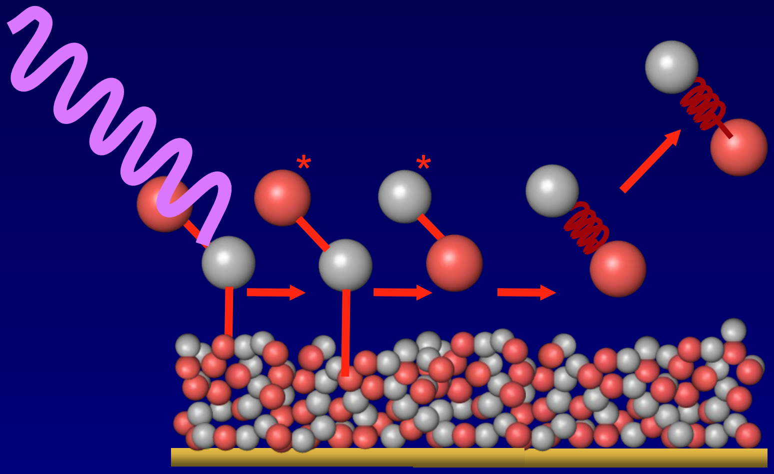


Note critical role of surface temperature!

Cuppen et al. 2017

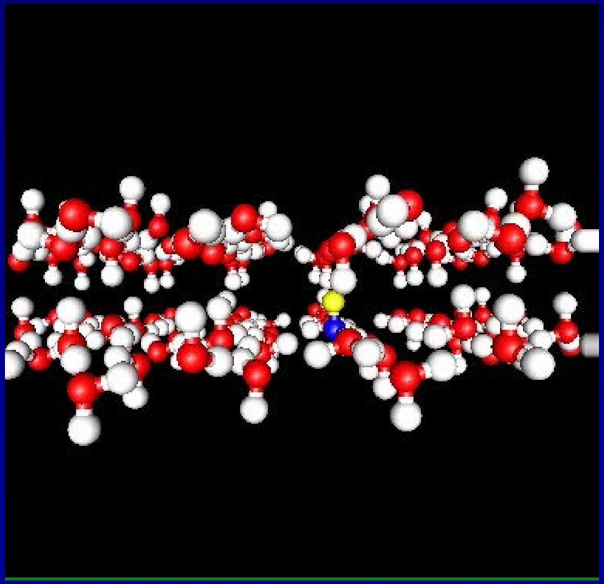
Getting molecules off the grains at low T: photodesorption

- Typical efficiencies of 10^{-3} per incident photon



Öberg et al. 2007, 2009.

Direct vs kick-out mechanism



Andersson et al. 2006, 2008
Arasa et al. 2010, 2011, 2015

Alternative:
Chemical desorption?
Dulieu et al. 2013
Minissale et al. 2015

Thermal sublimation temperatures

Volatile → Refractory (silicates)

	Species	T_{subl} (lab) (K)
Less volatile	H_2O	150
	CH_3OH	99
	HCN	95
	SO_2	83
	NH_3	78
	CO_2	72
	H_2CO	64
	H_2S	57
	CH_4	31
	CO	25
Most volatile	N_2	22

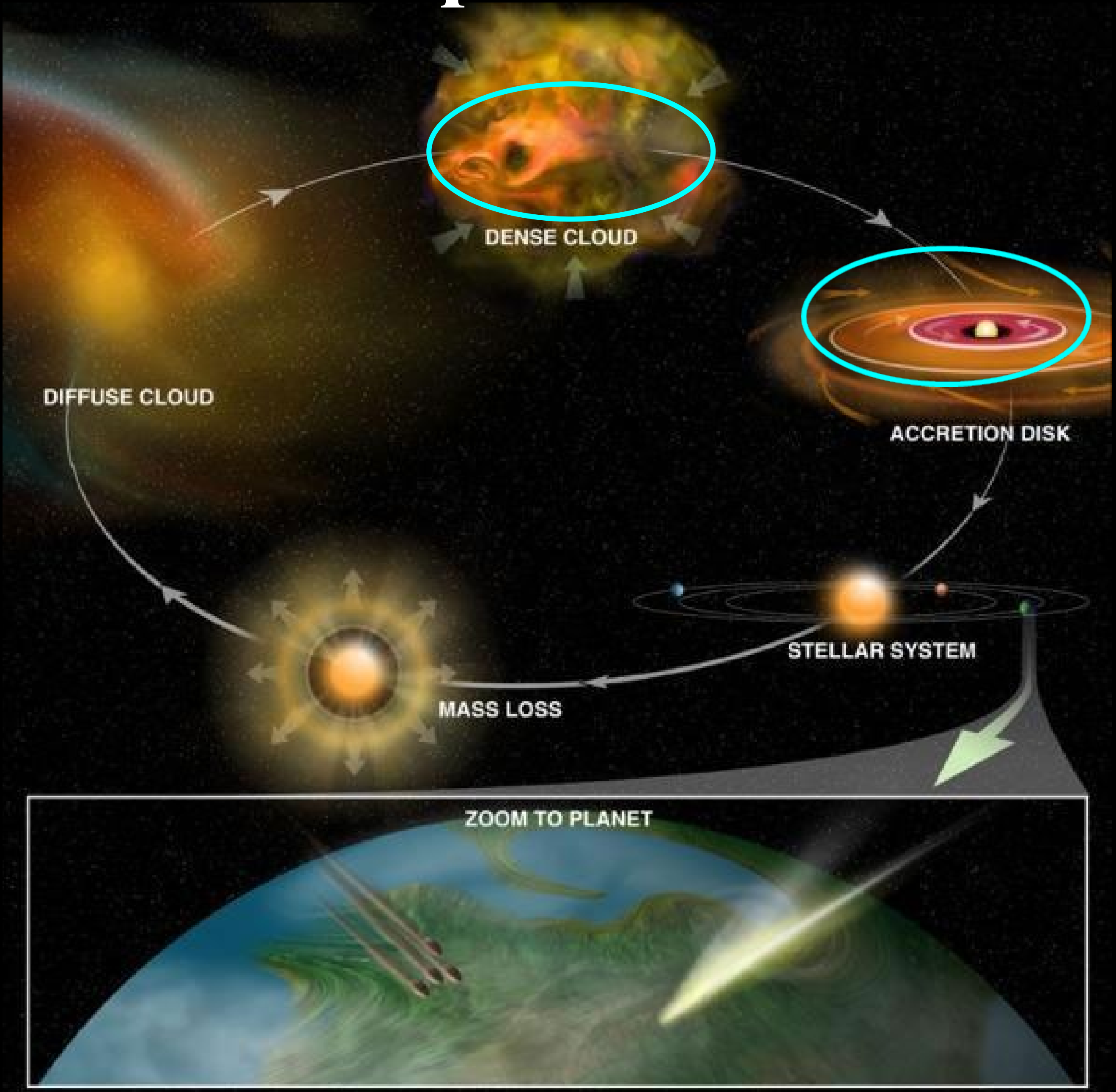
$k_{evap} = \nu \exp(-E_{bind}/kT_s)$

Collings et al. 2004
Mumma et al. 1993

Sublimation temperatures for pure ices as measured in lab; values in space are lower because of lower pressure and slower heating rates

From clouds to disks

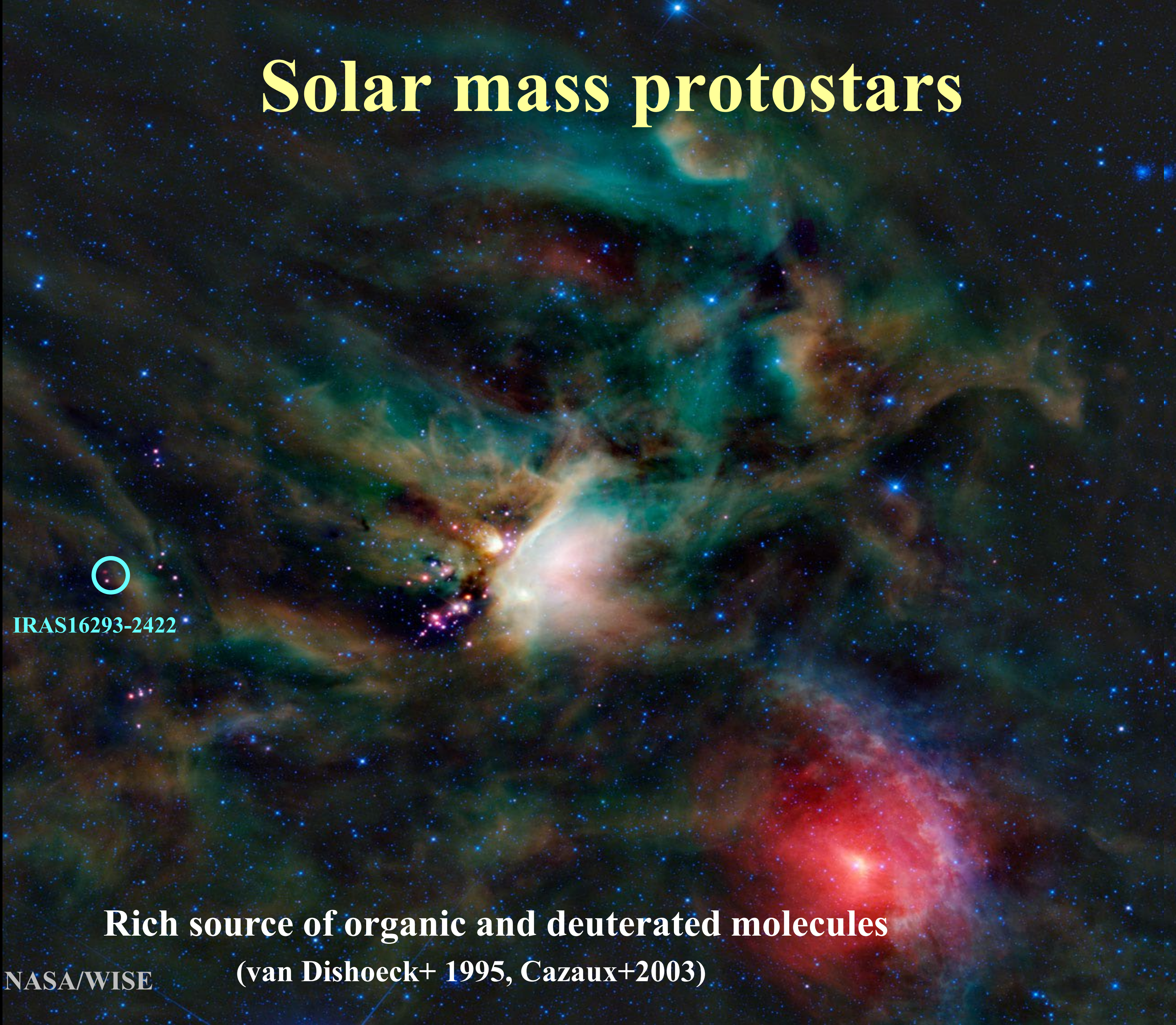
Star- and planet formation



B. Saxton
NRAO

Solar mass protostars

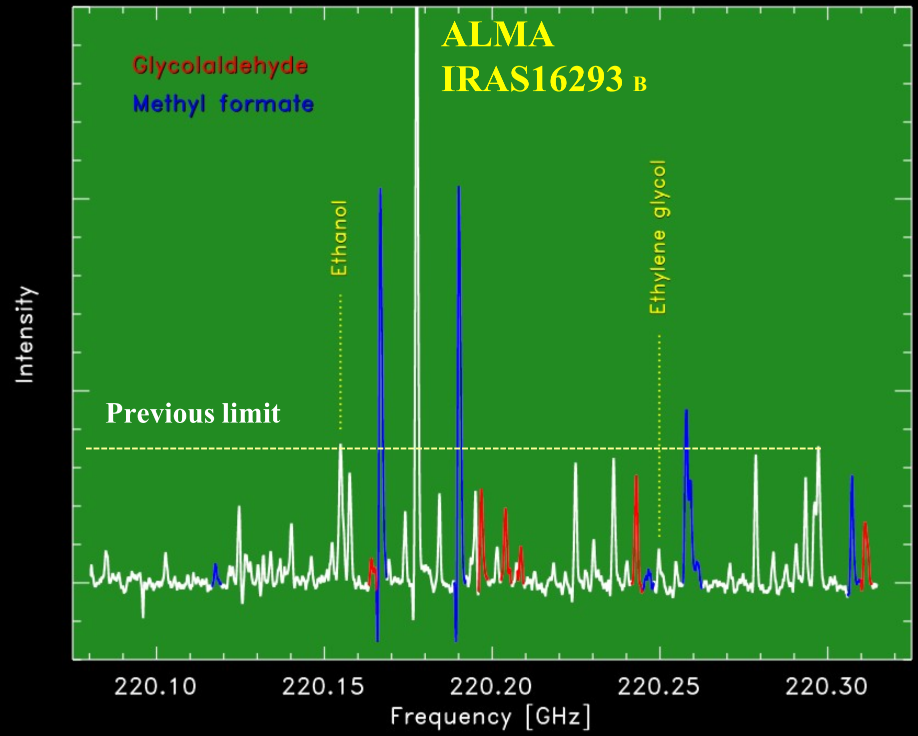
Ophiuchus d=125 pc low-mass star-forming region



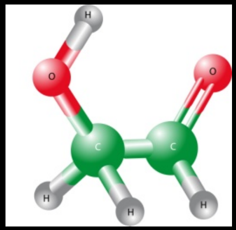
Rich source of organic and deuterated molecules

(van Dishoeck+ 1995, Cazaux+2003)

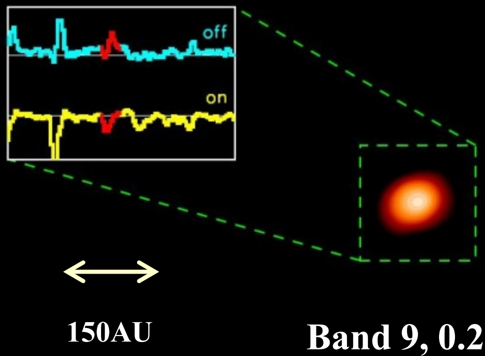
Detection of 'sugar' near solar-mass protostar



6 glycolaldehyde lines in Band 6 and
7 lines in Band 9 identified; T_{ex}=300 K



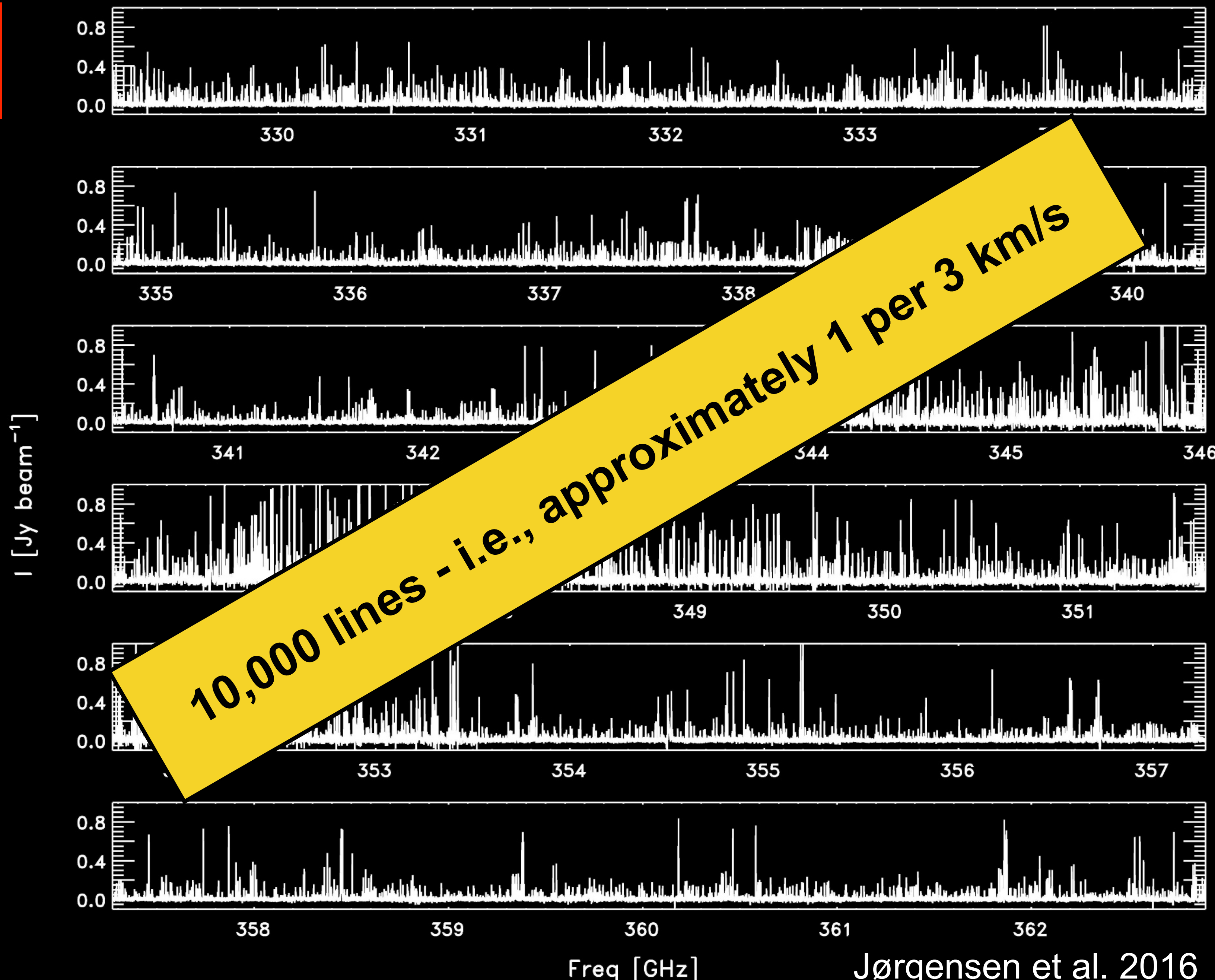
IRAS16293
d=125 pc



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

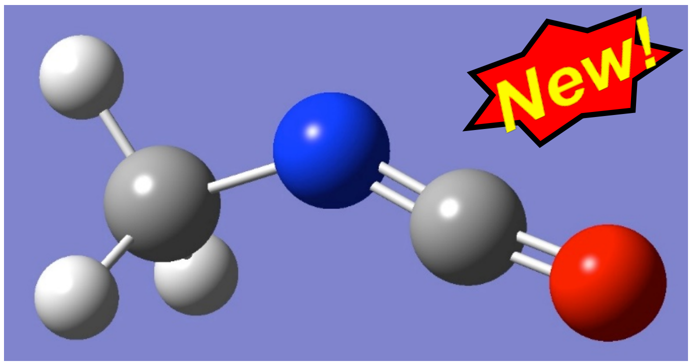
Jørgensen et al. 12

PILS survey: Full spectral survey of IRAS 16293–2422



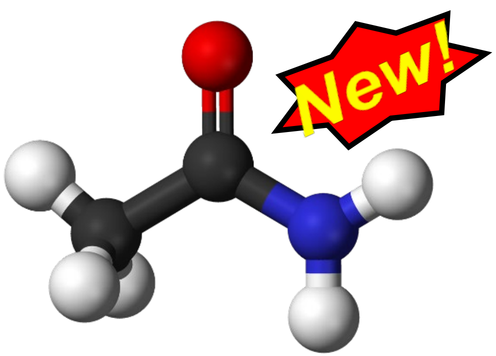
Jørgensen et al. 2016

Some complex molecules around solar mass protostars



Methyl isocyanate
'Prebiotic' molecule

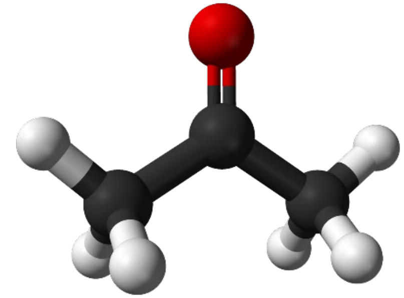
Ligterink et al. 2017, Martín-Domenéch et al. 2017



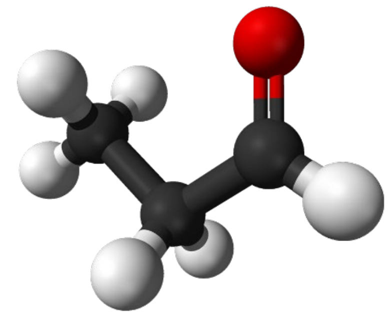
Acetamide (but no glycine yet)

Ligterink et al. 2018

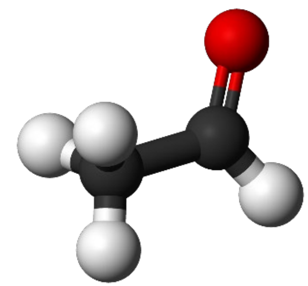
Acetone



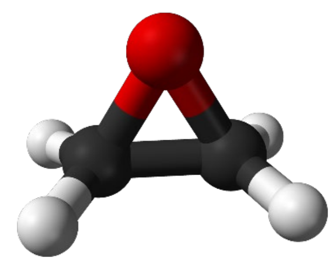
Propanal



Acetaldehyde

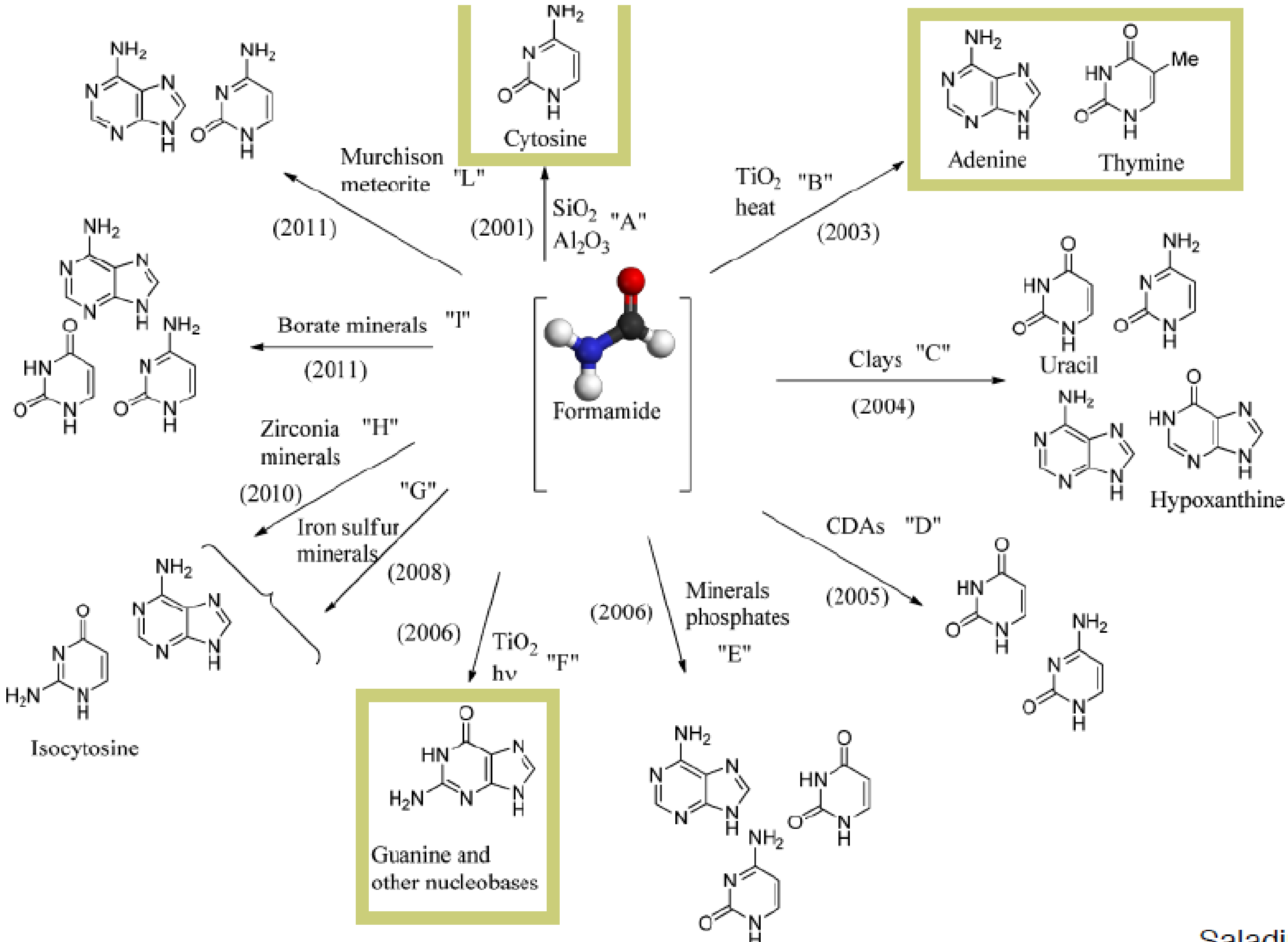


Ethylene oxide



Lykke et al. 2017

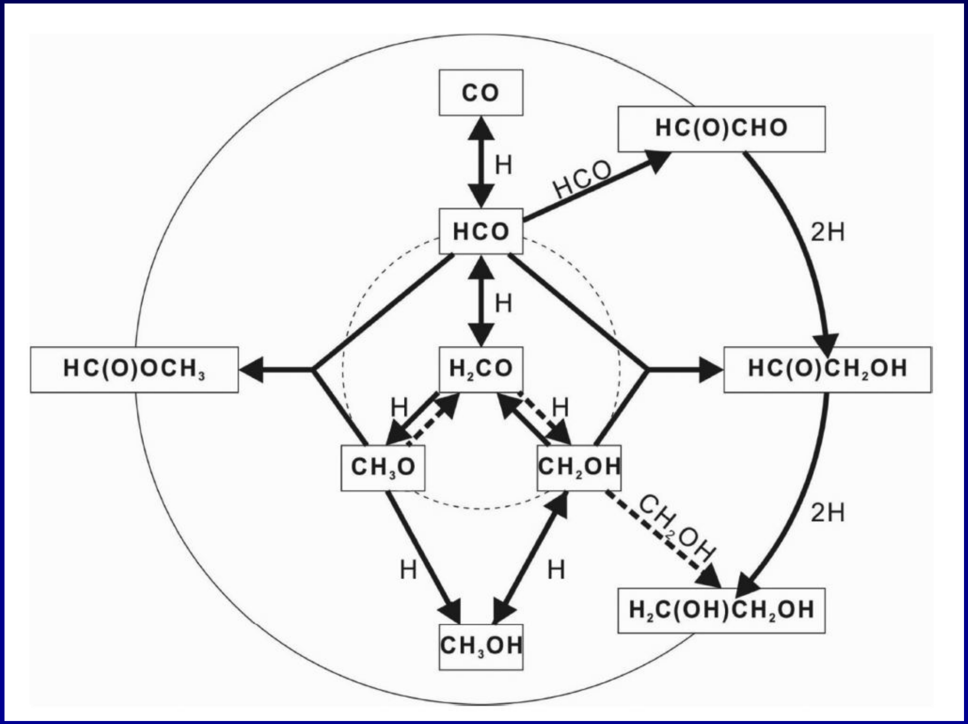
From formamide to amino acids and bases



Saladino+ 2012

Making complex molecules at low *T*

CO hydrogenation

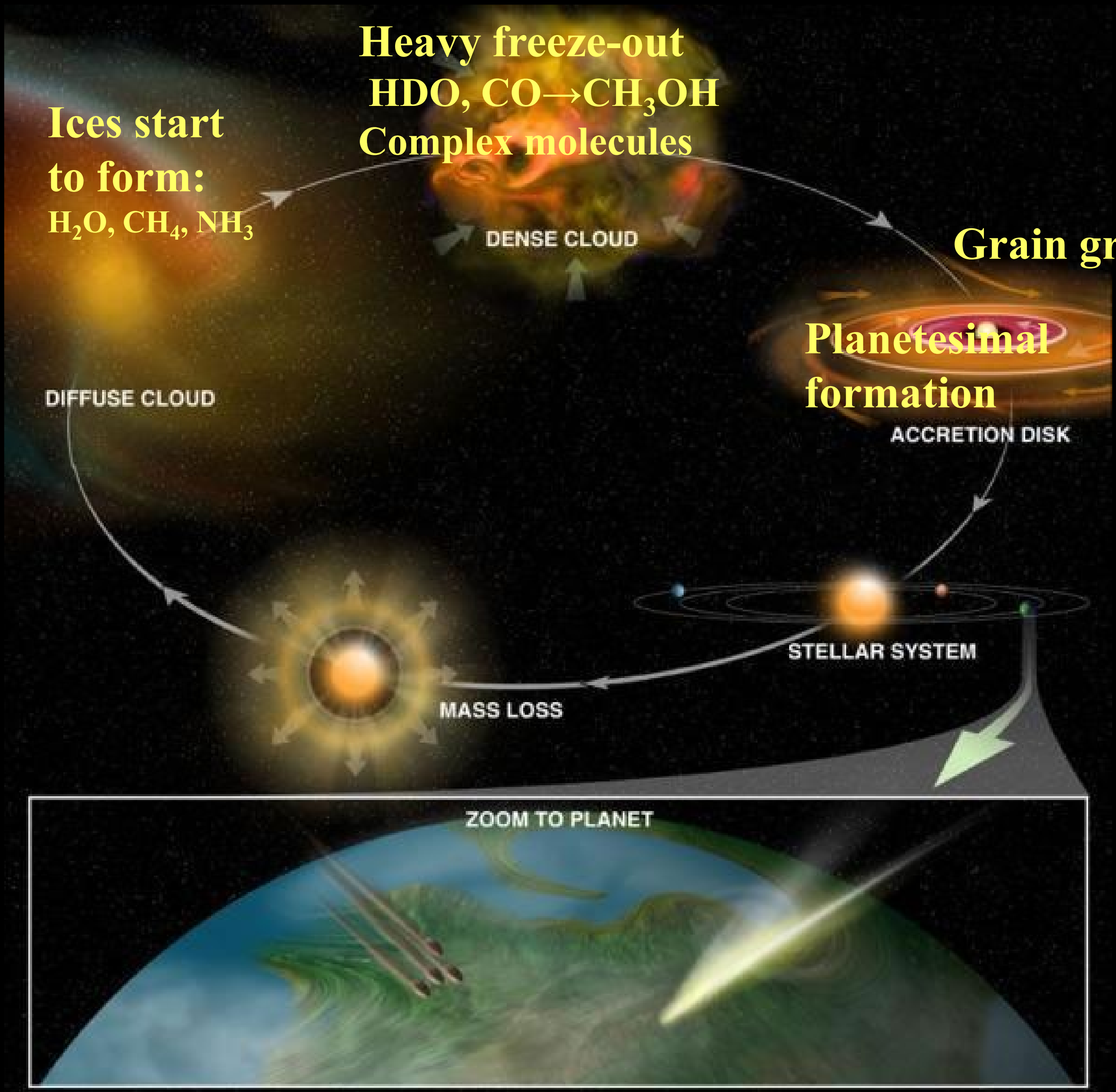


Fedoseev et al. 2015, 2017
Chuang et al. 2016, 2016

Reactions proceed already at 15 K, without need for heating or UV!

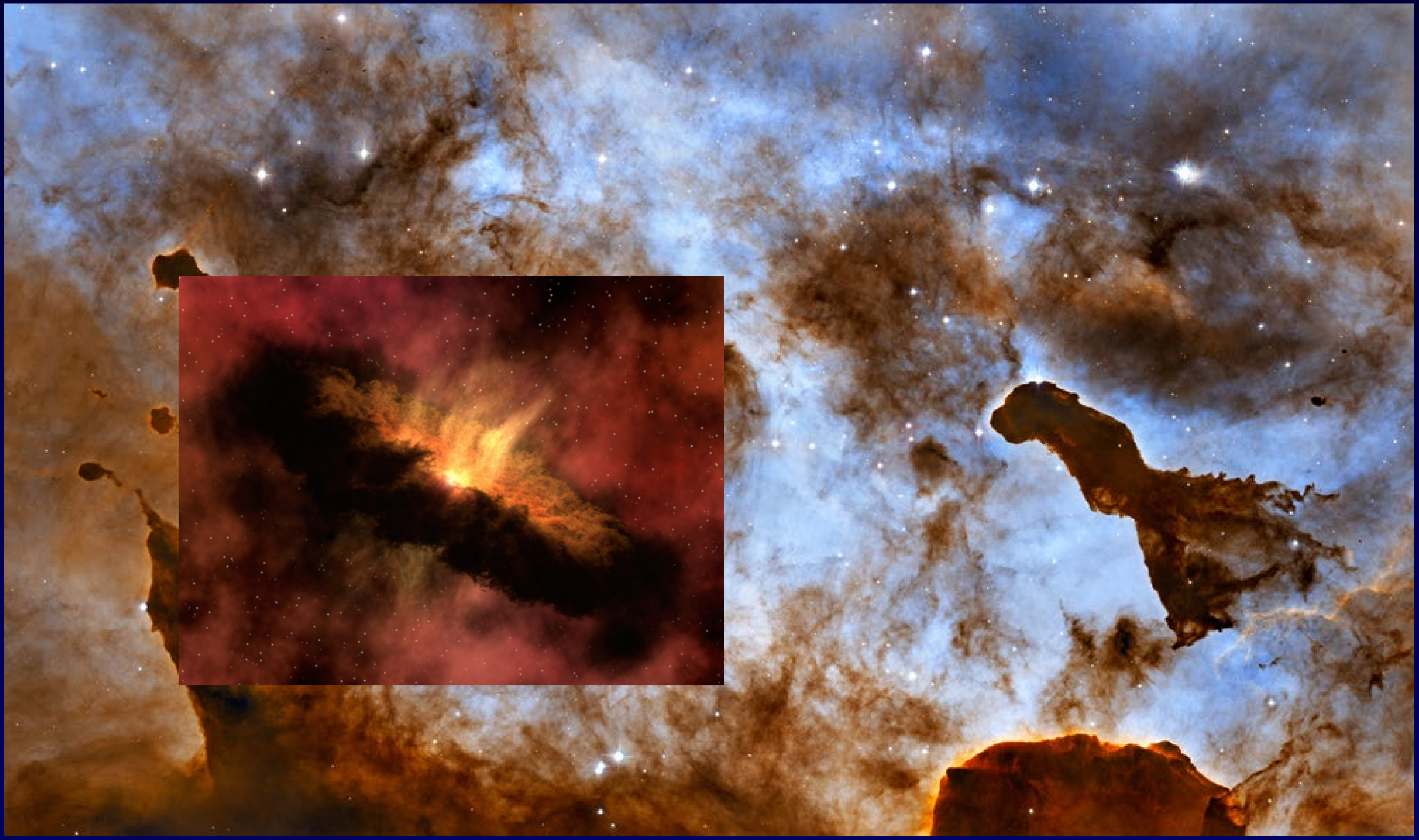
Can even make glycerol! *(Fedoseev et al. 2017)*

From clouds to disks and planets



B. Saxton
NRAO

Planets are formed in disks but disks are small



Carina nebula
HST

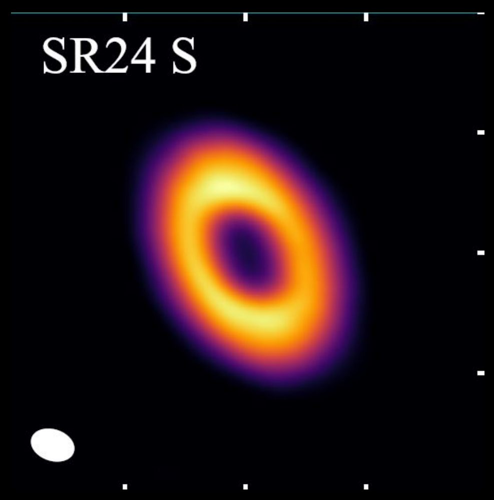
Cloud: 10^{18} cm
Disk: 10^{15} cm (100 AU; 1 AU = distance Sun-Earth
100AU ~1” at distance Taurus, Oph)

Need ALMA to zoom in to planet-forming zones of disks

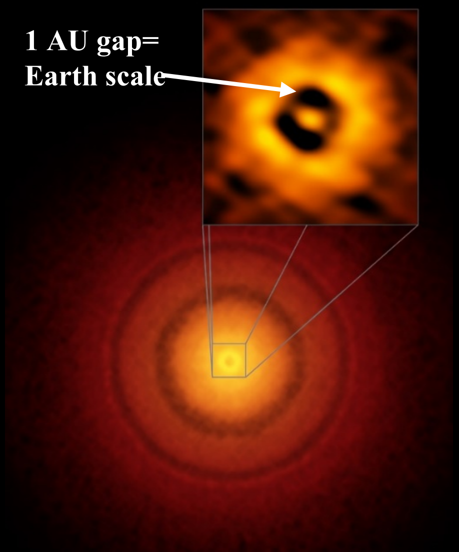
New era of observational planet formation

Not yet clear what is causing these rings, cavities, dust traps...

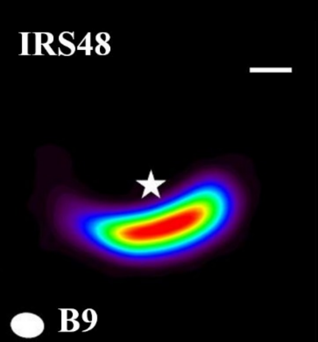
HL Tau young disk
ALMA partnership
et al. 2015



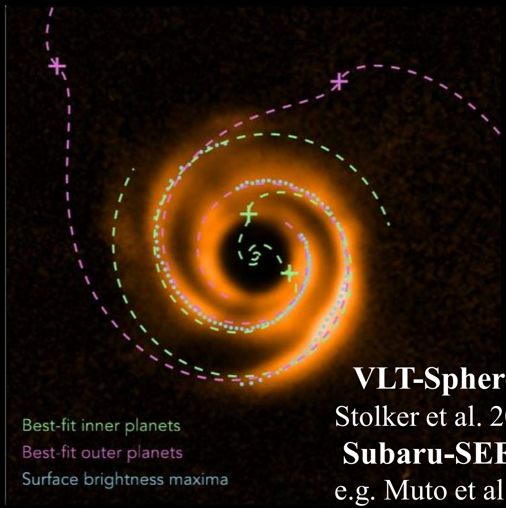
ALMA: Pinilla et al. 2017



ALMA TW Hya
Andrews et al. 2016



ALMA: van der Marel et al. 2013, 2016

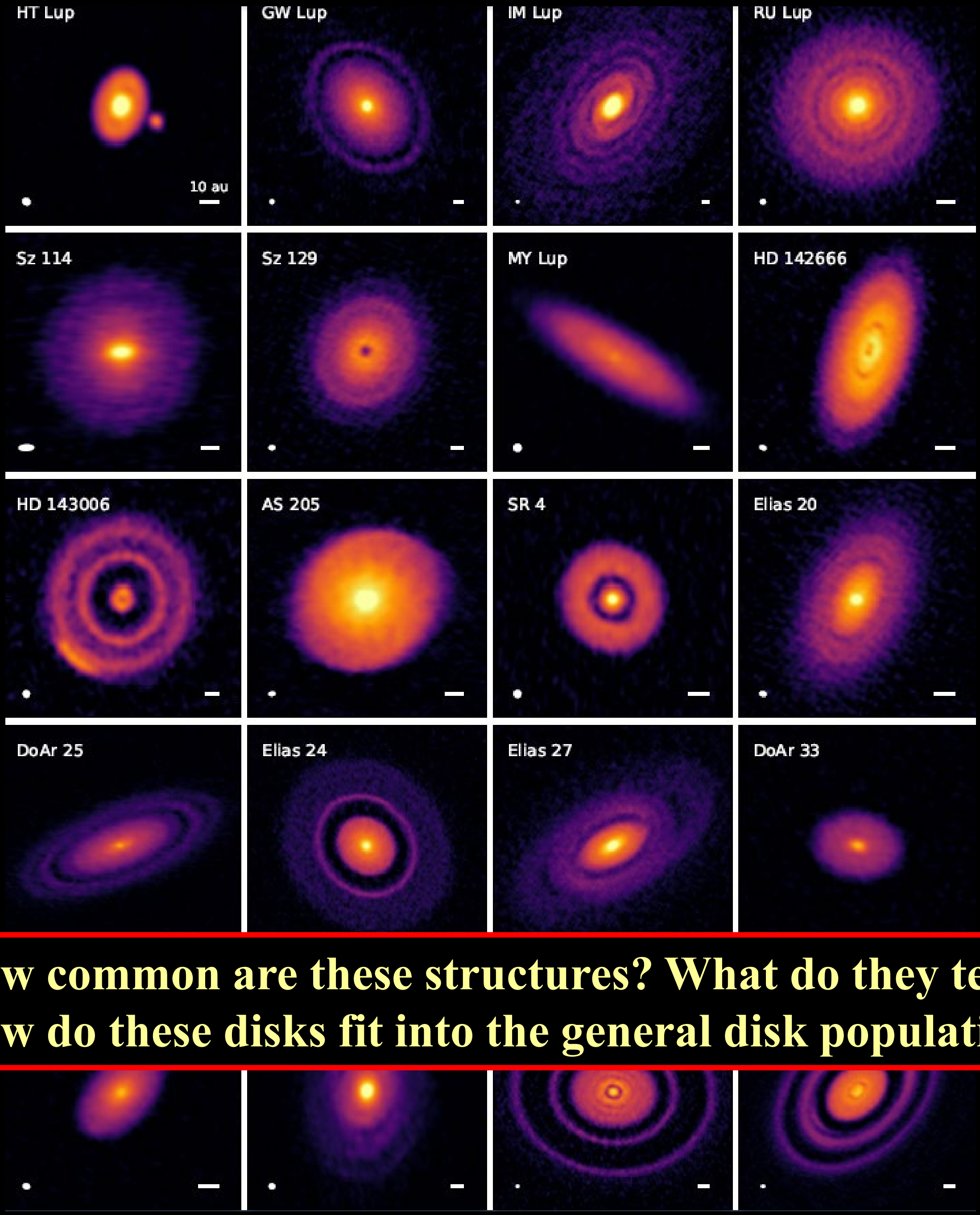


VLT-Sphere, Gemini-GPI
Stolker et al. 2016
Subaru-SEEDS
e.g. Muto et al. 2012

ALMA:
Fedele et al. 2017

DSHARP Sample

Andrews, Huang et al. 2018

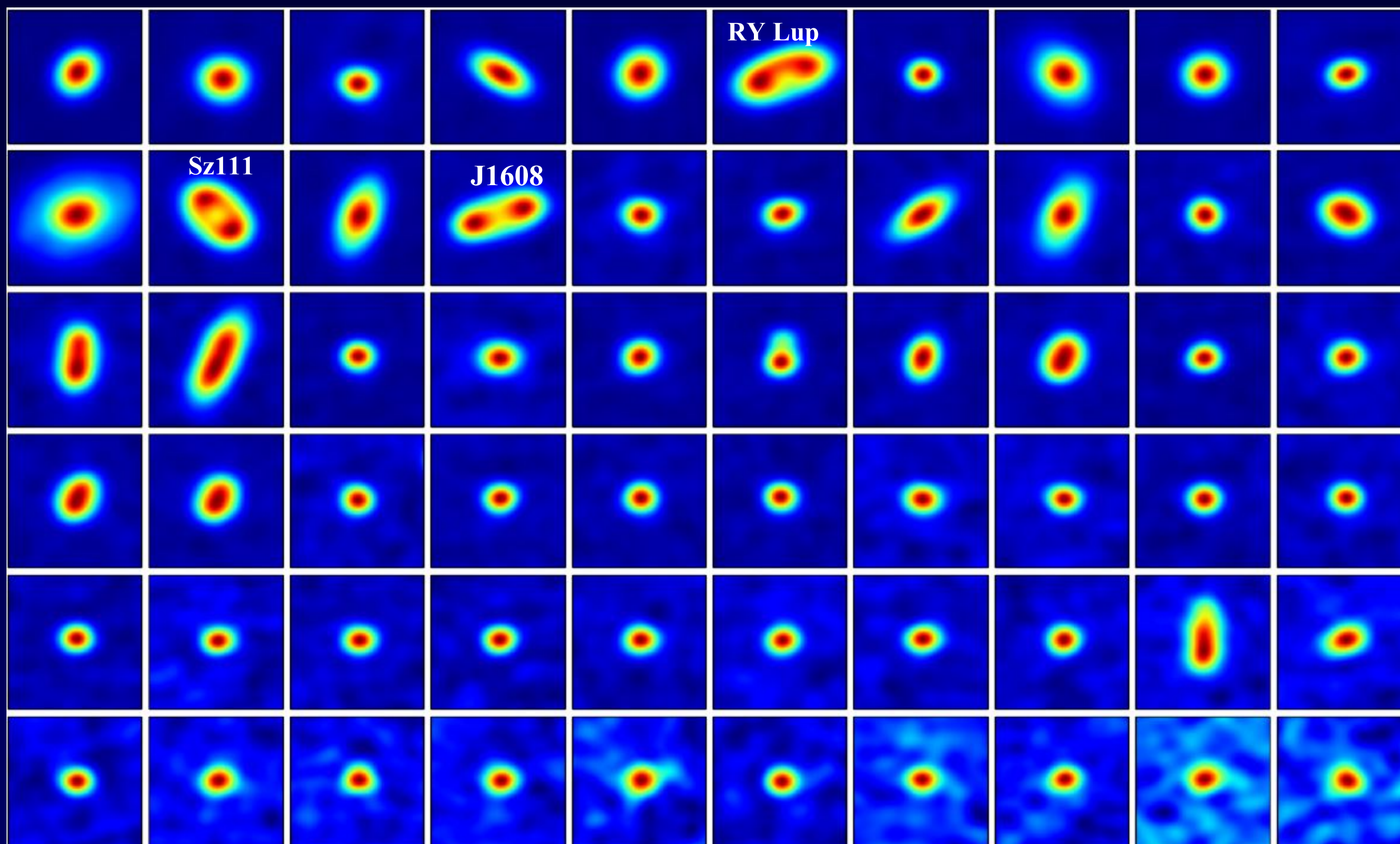


- How common are these structures? What do they tell us?
- How do these disks fit into the general disk population?

Unbiased survey of disks

1 minute each!

2”x2”



0.35”
(20 AU radius)

1-2 min
per source

330 GHz
cont

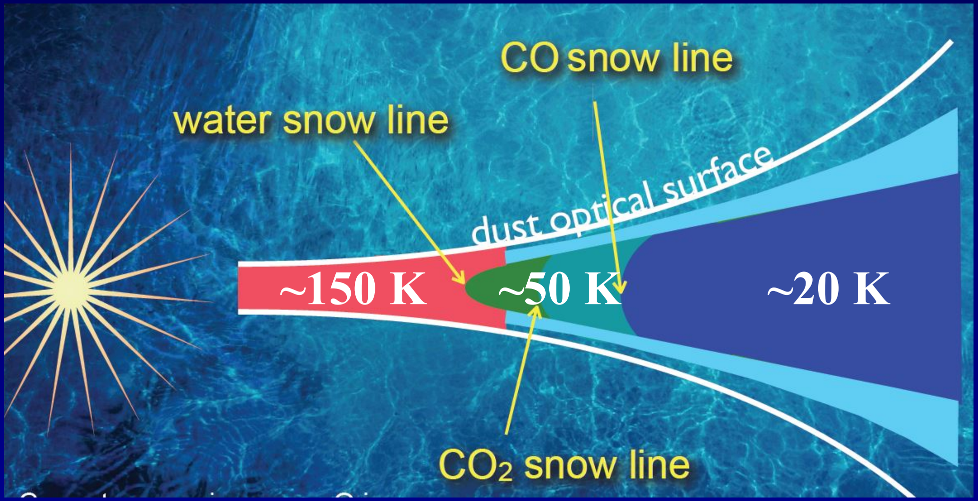
Ansdell, Williams,
EvD et al. 2016, 2018

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

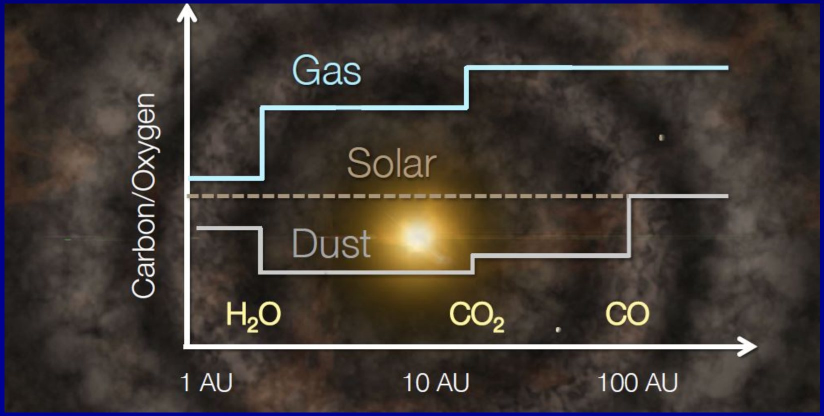
→ Material for planet formation is common

Lupus ALMA
Disks Survey

Disk structure and snowlines



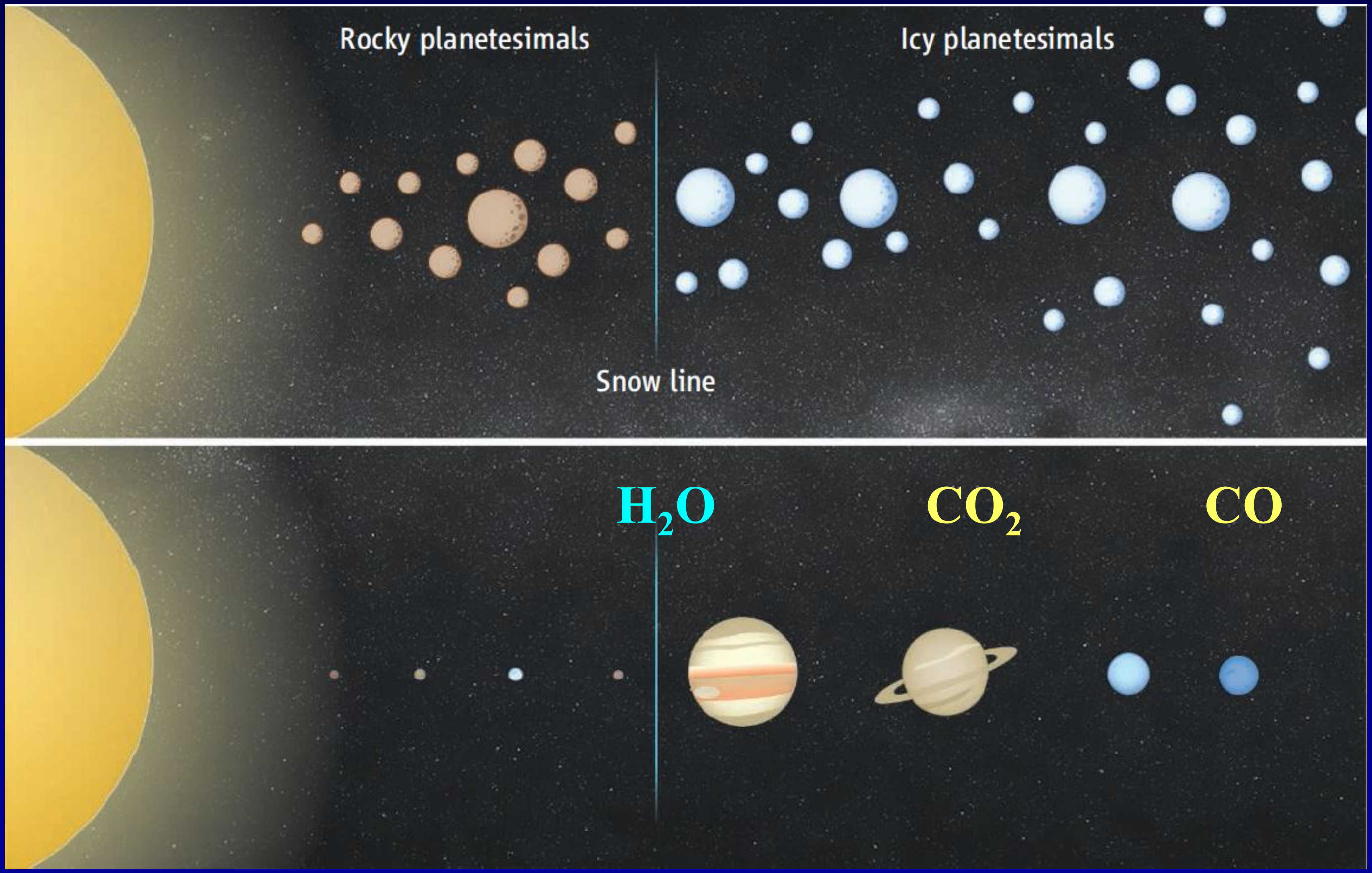
Öberg, Bergin et al. 2011



- Snowline enhances mass of solids → *planet formation, dust traps*
- Freeze-out changes C/O ratio gas and ice → *planet atmosphere*

Importance of snowlines

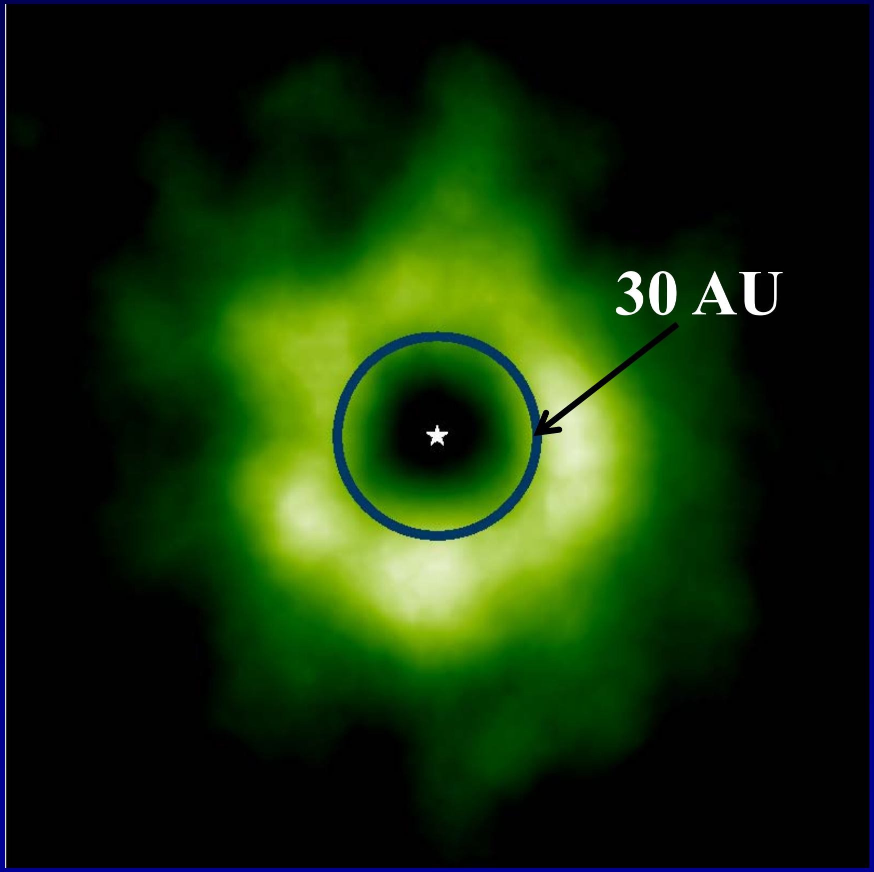
High T → Low T



Akeson 2011

Ices increase solid mass

Imaging the CO snowline with ALMA



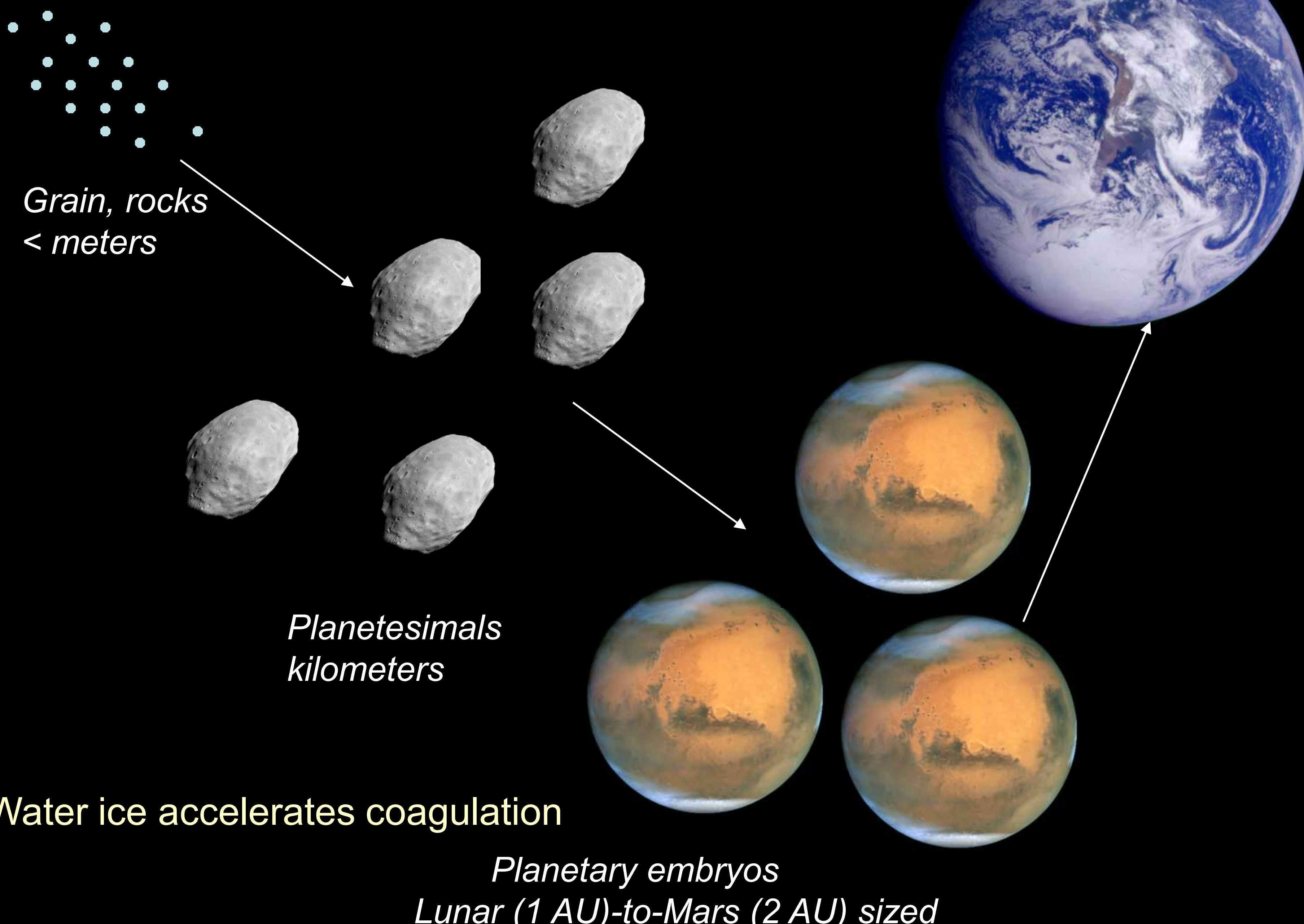
TW Hya
Face-on disk
d=68 pc

N_2H^+ 4-3

Qi, Öberg et al. 2013

N_2H^+ appears when CO freezes out
→ Tracer of snowline

From icy grains to planetesimals to embryos to planets



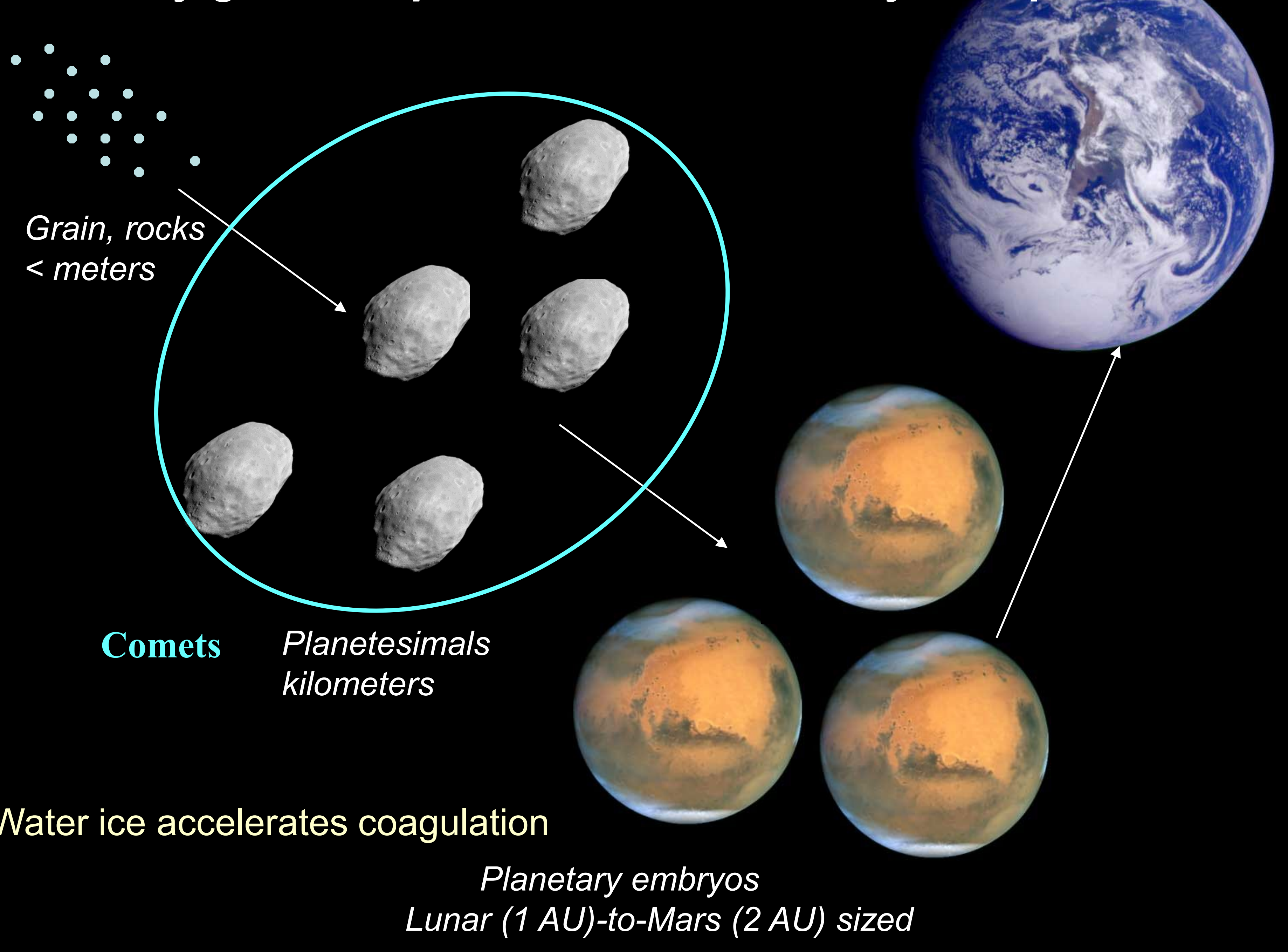
Water ice accelerates coagulation

Building planetary systems

ESO

www.eso.org

From icy grains to planetesimals to embryos to planets

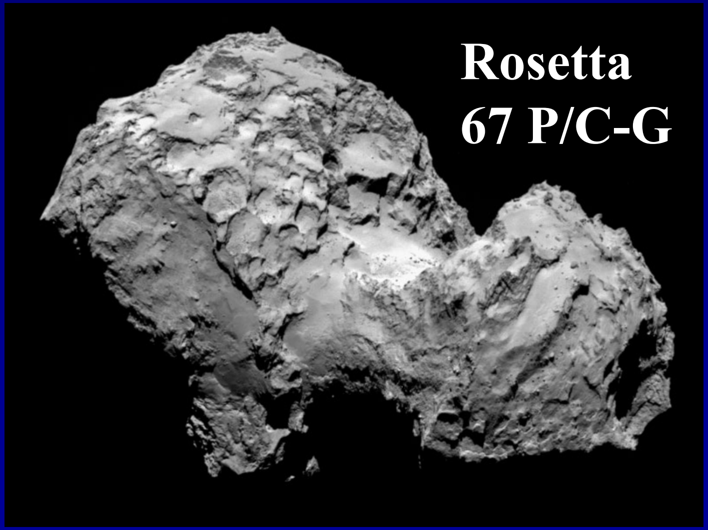


Water ice accelerates coagulation

Young disk – comet comparison

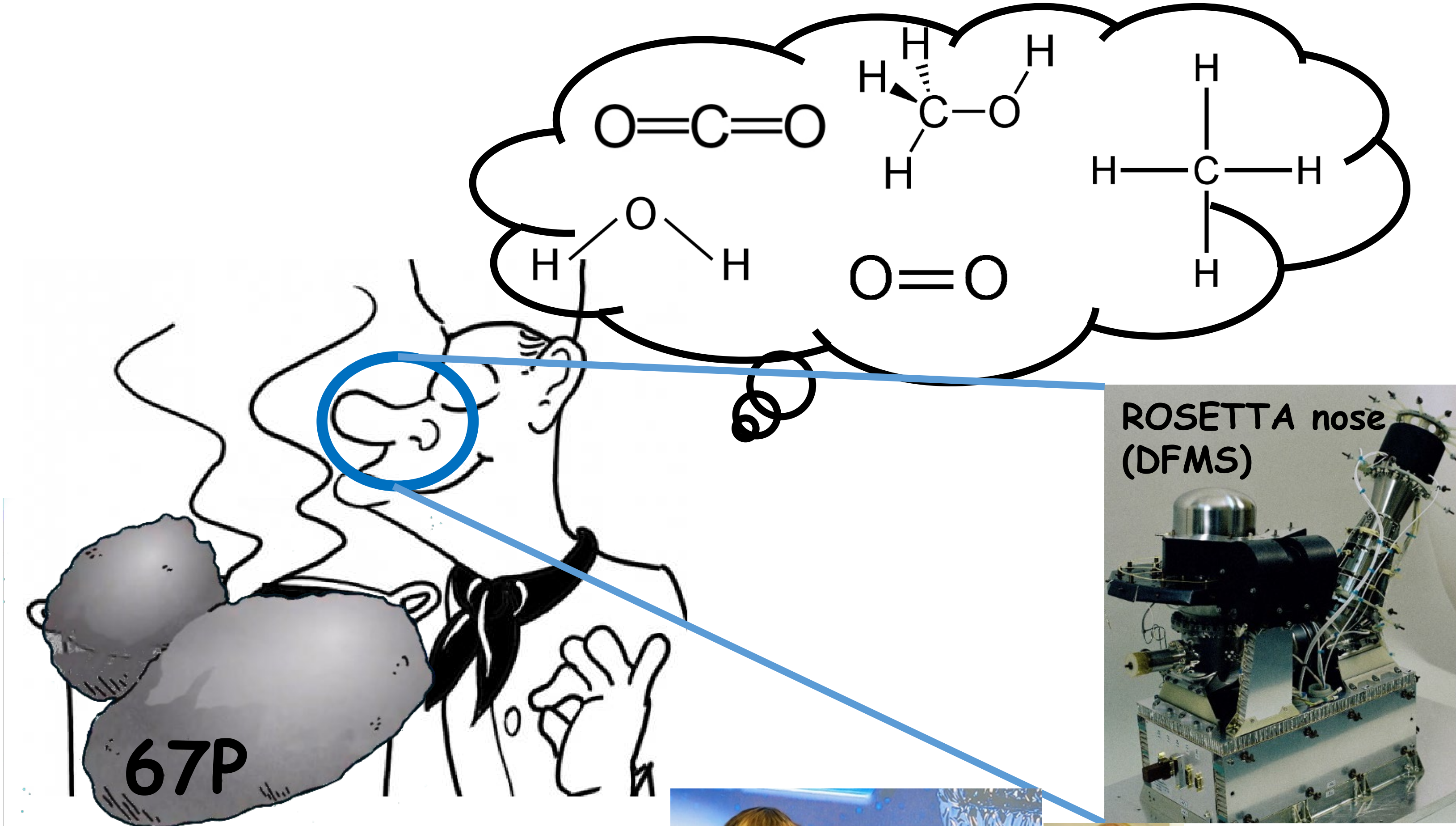
- **Young disk: observe just sublimated ices**
- **Comet: measure coma molecules *in situ***

NASA/Caltech/SSC R. Hurt animation

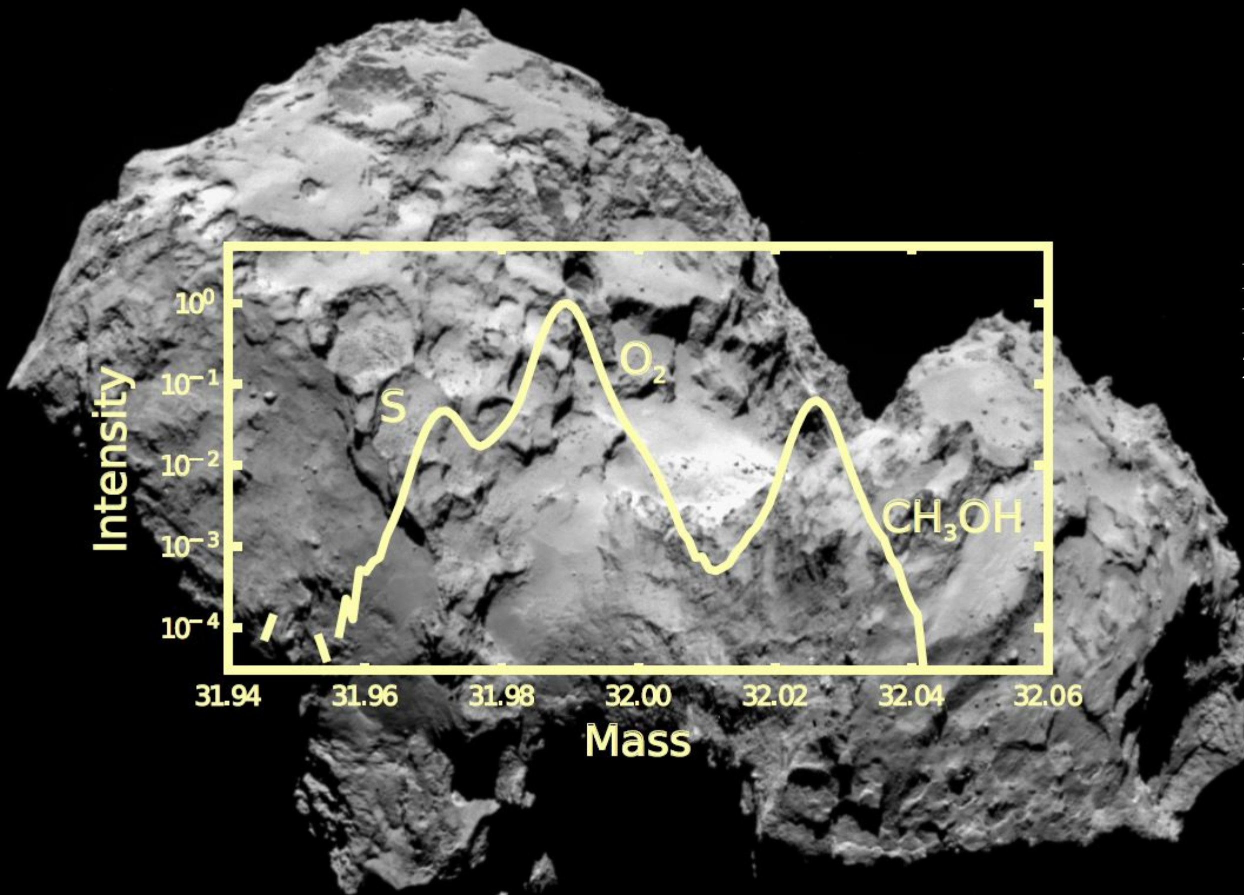


Are ices preserved from cloud to comet?

ROSETTA had a very good nose (DFMS)



Abundant O_2!



O_2/H_2O~4%

Bieler et al.
Rubin et al.
2015

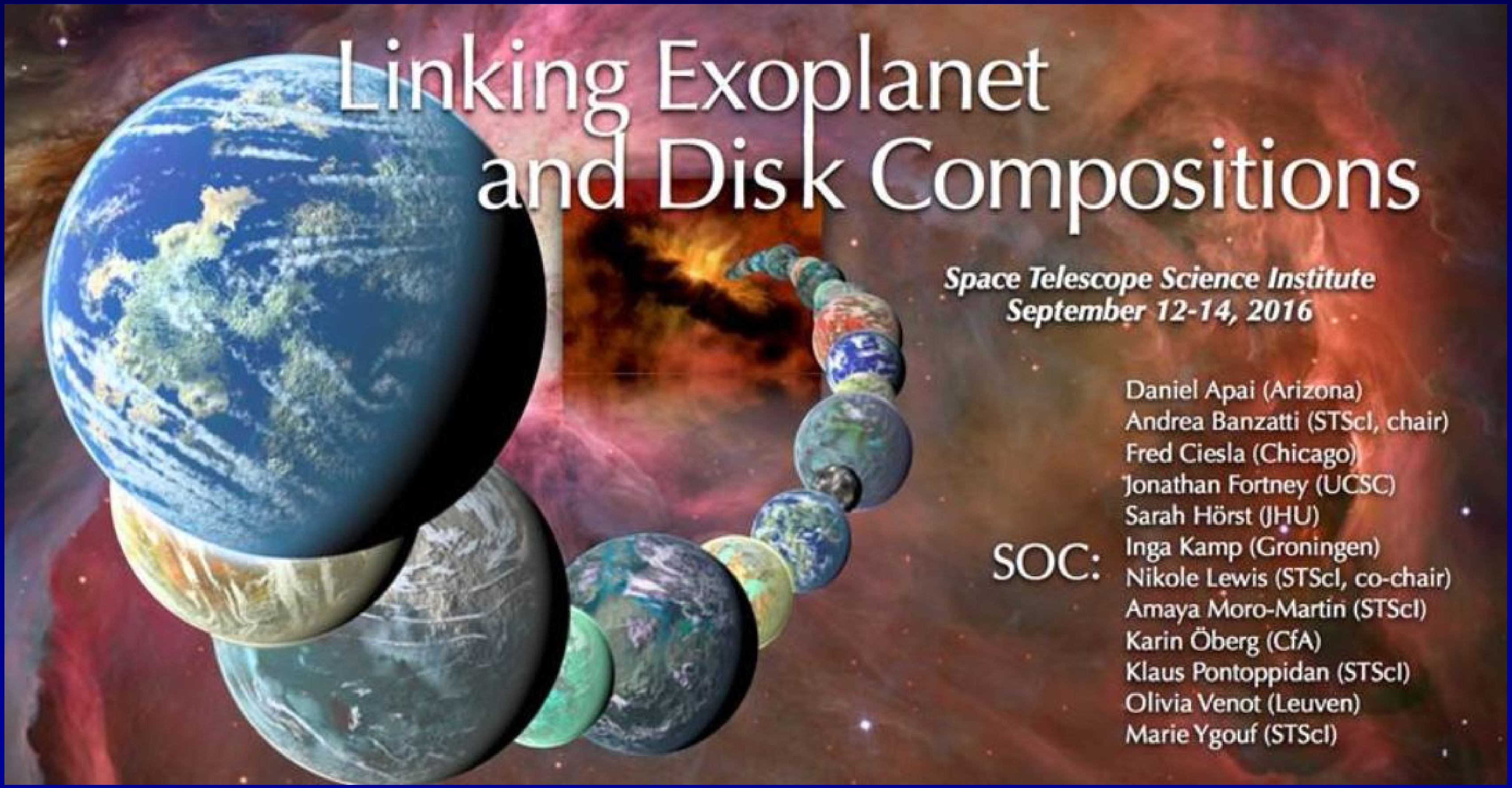
Needs low H/O

Taquet et al.
2016

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

Abiotic production of O_2 → No unique biomarker

The next step



International Astronomical Union 100 yr

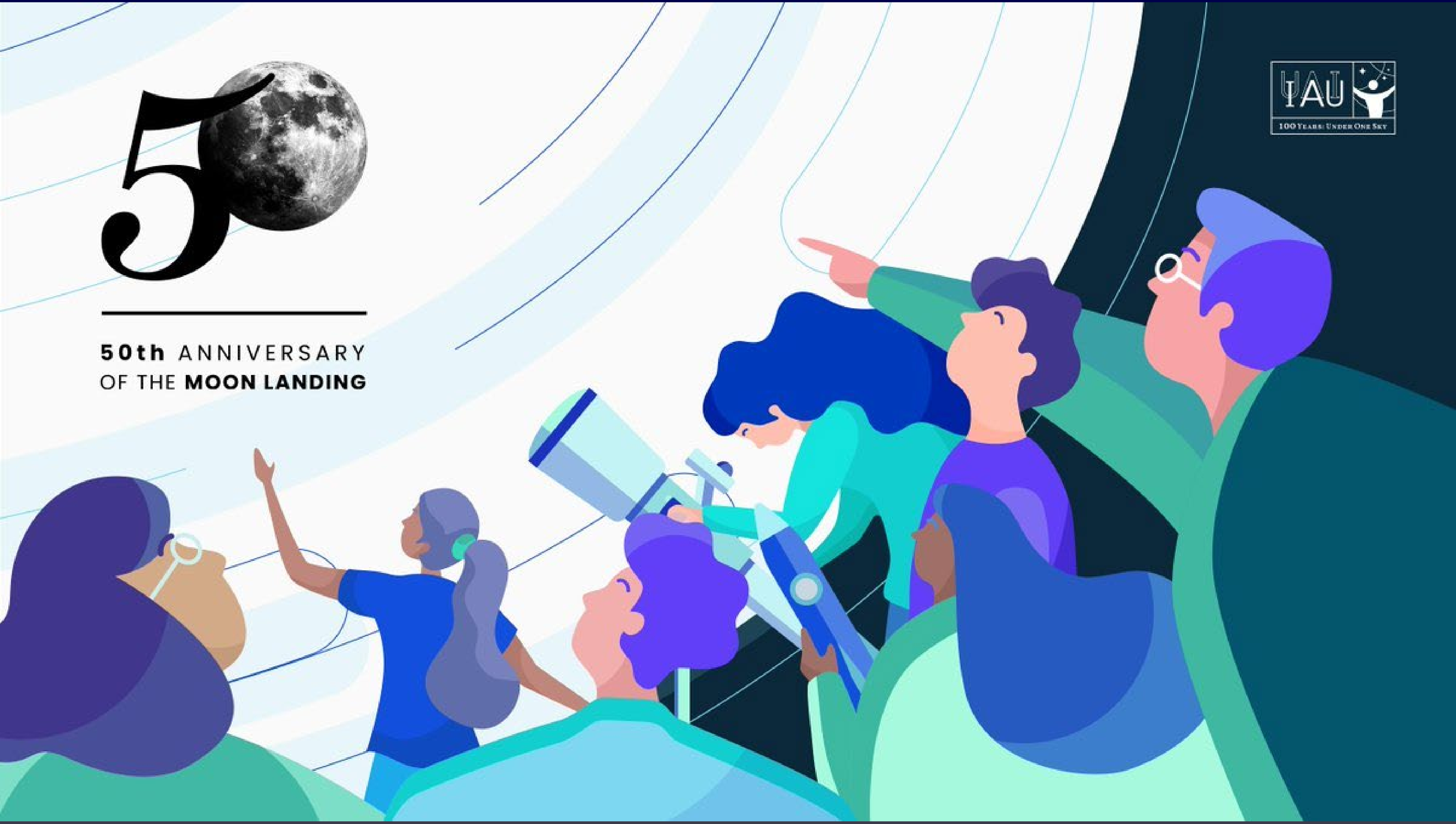
IAU

100 YEARS: UNDER ONE SKY

www.iau-100.org #IAU100

>4000 events in >100 countries

Celebrate a century of astronomical discoveries, technological progress and cultural impact



50th Anniversary Moon Landing (20-21 July)

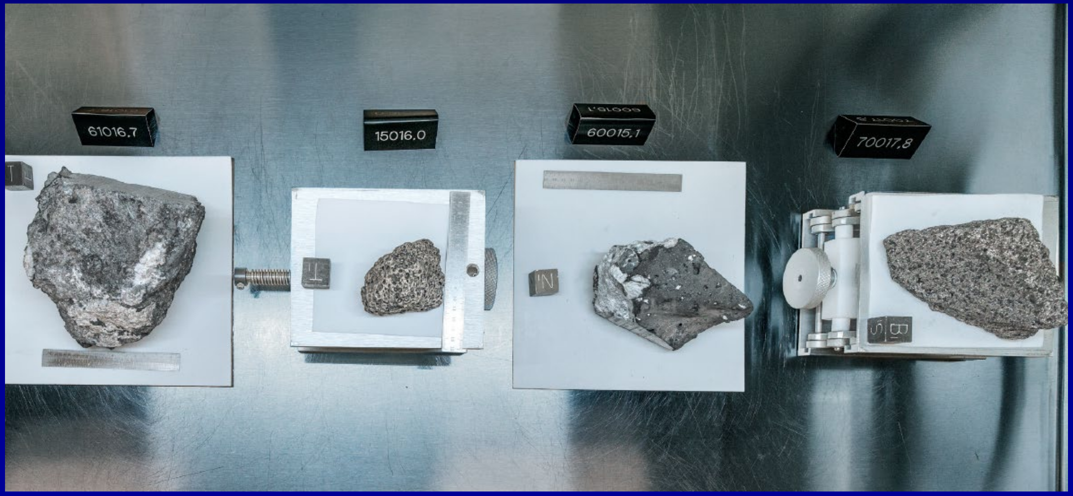
Organisation of large star-parties observing the Moon.

Goal: Actions in 100 Countries!

Partial eclipse Moon yesterday!

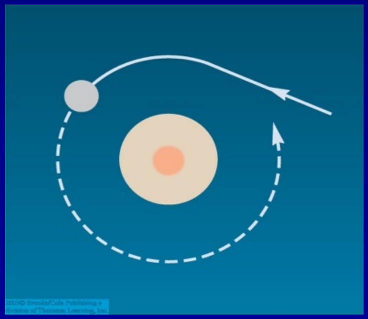
Lunar rocks: what have they told us?

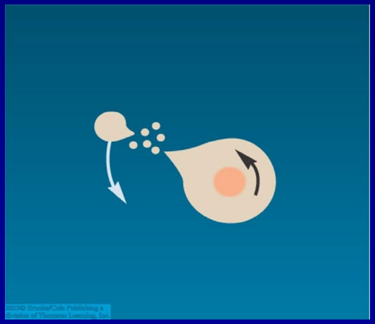
- Moon surface is ancient: 3-4.5 Gyr
- Origin of the Moon
- Origin of our Solar System

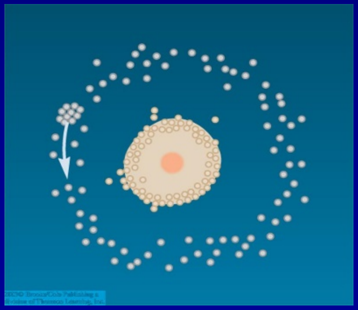


Pre-Apollo models for the Moon

- Earth captured passing body
- Young Earth spun so fast that a blob separated
- Earth and Moon formed together from solar nebula disk (with all other planets)



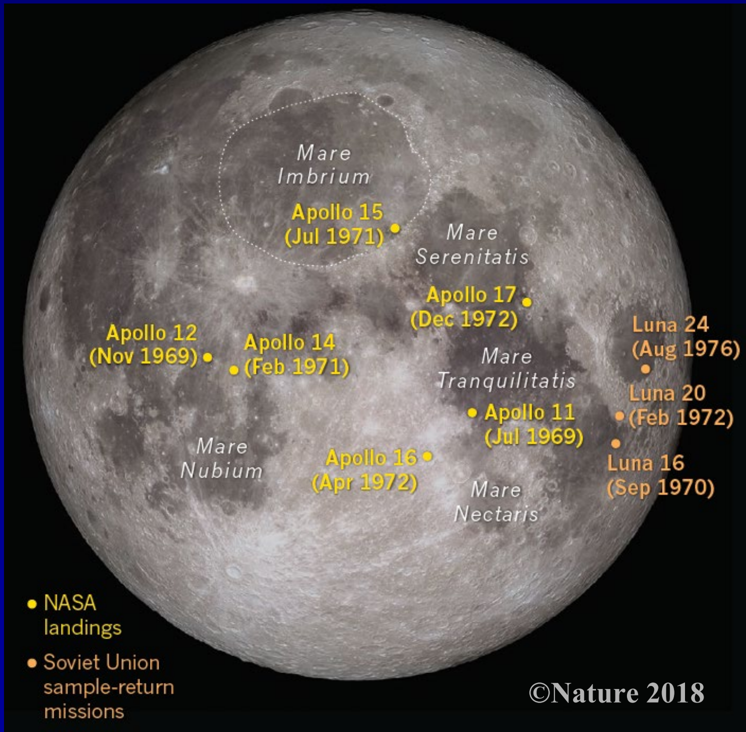




Giant impact hypothesis

- Mars-sized body hit Earth 4.5 Gyr ago, ejecting part of Earth's crust and mantle into space
- Cooling → Moon formation
- Lines of evidence
  - Similar composition
  - Moon core has little iron
  - Dryness of rocks
  - Magma ocean (lunar highlands)

Need rocks from different parts of the Moon (and study Mars, asteroids, comets material)



We are all world citizens under the same beautiful sky