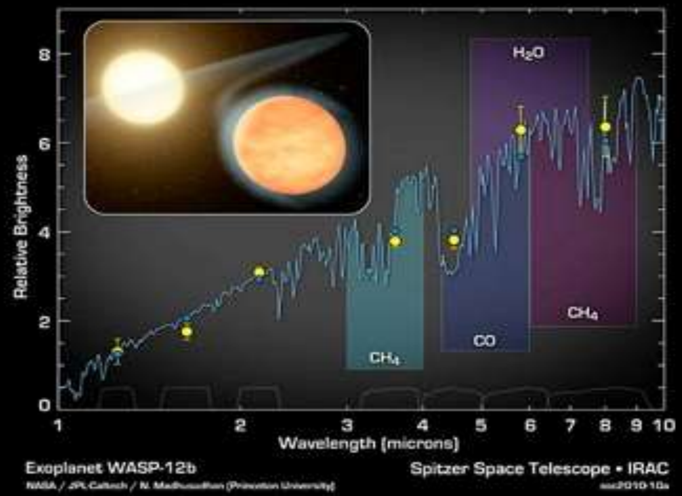
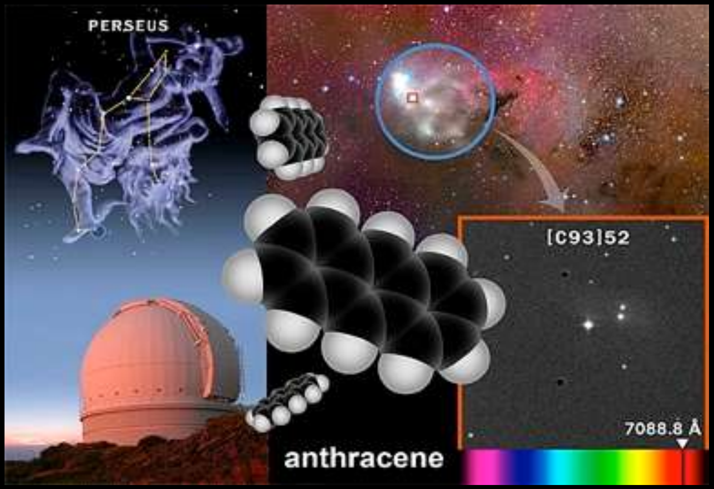
Molecular Astrophysics:
From Theory to Lab to Observations
WS 2023/24





Lecturers

Dmitry Semenov

Max Planck Institute for Astronomy (MPIA)

Theoretical and observational astrochemistry & astrophysics
http://www.mpia-hd.mpg.de/homes/semenov/
semenov@mpia.de

Giulia Perotti

Max Planck Institute for Astronomy (MPIA)

Astrochemistry of young stars and their inner disks
https://www.mpia.de/person/115165
perotti@mpia.de

Holger Kreckel

Max Planck Institute for Nuclear Physics (MPIK)

Laboratory astrophysics & molecular physics

https://www.mpi-hd.mpg.de/mpi/astrolab
holger.kreckel@mpi-hd.mpg.de

Organization

- Lectures:
  - Friday, 11:15-12:50 (5 min break)
  - Oct 20st 2023 – Feb 9th 2024

- Lecture slides and supporting literature will be made accessible as PDFs online

- Lecture credit points:

  Brief oral exam: Dima, Giulia, Holger

Literature

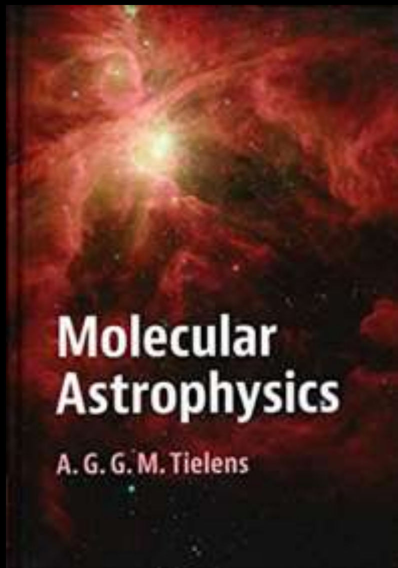
- Hartquist / Willams, “The chemically controlled cosmos” (1995)
- L. Spitzer, “Physical Processes in the Interstellar Medium”, (1998)
- A.G.G.M. Tielens, "The Physics and Chemistry of the ISM" (2007)
- B. Draine, “Physics of the interstellar and intergalactic Medium” (2010)
- A.G.G.M. Tielens, “Molecular Astrophysics" (2021)

More specialized:

- B. Ryden, “Introduction to Cosmology”
- J. Tennyson: “Astronomical Spectroscopy”
- C. Scharf: “Extrasolar Planets and Astrobiology”

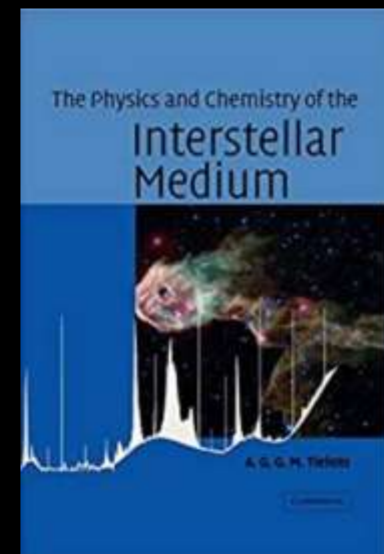
- **Relevant reviews for various topics**

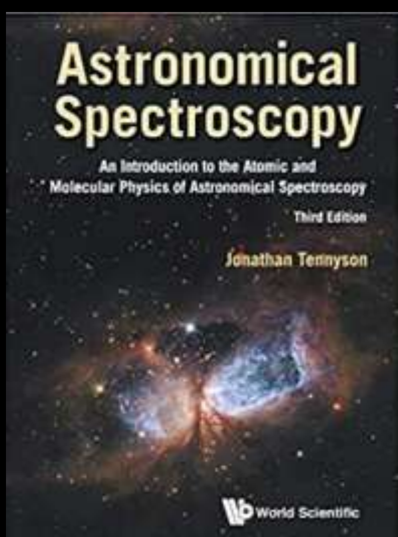
Today:
Brett McGuire,
“2021 Census of Interstellar, Circumstellar, Extragalactic,
Protoplanetary Disk, and Exoplanetary Molecules”,
The Astrophysical Journal Supplement Series 259, 30 (51pp), 2022



A.G.G.M. Tielens,
“Molecular Astrophysics"
Cambridge University Press(2021)

A.G.G.M. Tielens,
"The Physics and Chemistry of the ISM“
Cambridge University Press (2007)





J. Tennyson,
“Astronomical Spectroscopy”,
World Scientific, 3rd edition (2019)

What is “molecular astrophysics"? What is “astrochemistry?”

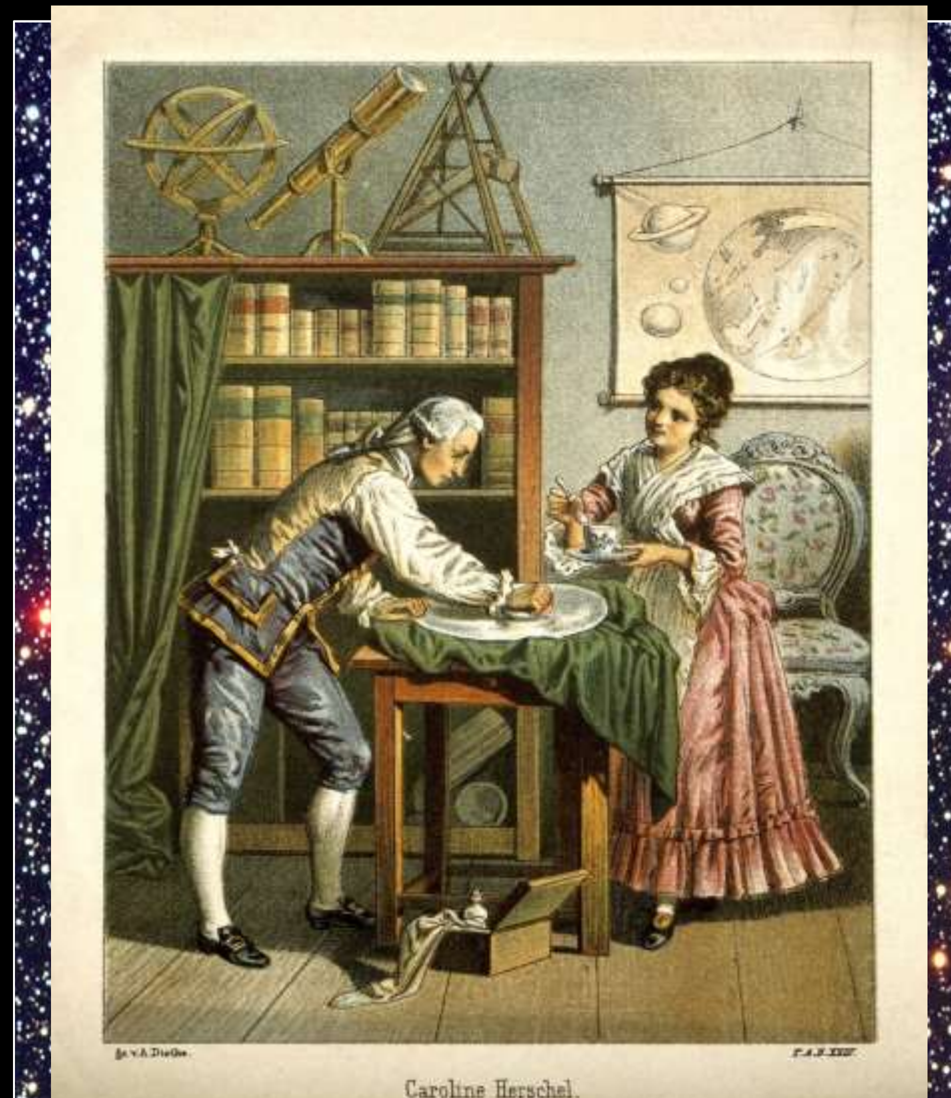
A. Eddington: "**Atoms are physics but molecules are chemistry**"

- Molecular astrophysics (or astrochemistry) is the study of formation and destruction of **Molecules in the Universe**, their interaction with radiation and their feedback on physics of the environments.
- Interdisciplinary field: **physics + chemistry+ astronomy** (+biology?)
- **Observations** are an important tool, but only in combination with **model calculations** and reliable **laboratory data** can we gain true understanding of our surroundings.

“Hier ist wahrhaftig ein Loch im Himmel!”

Wilhelm Herschel, 1774

Wilhelm Herschel
(1738-1822)



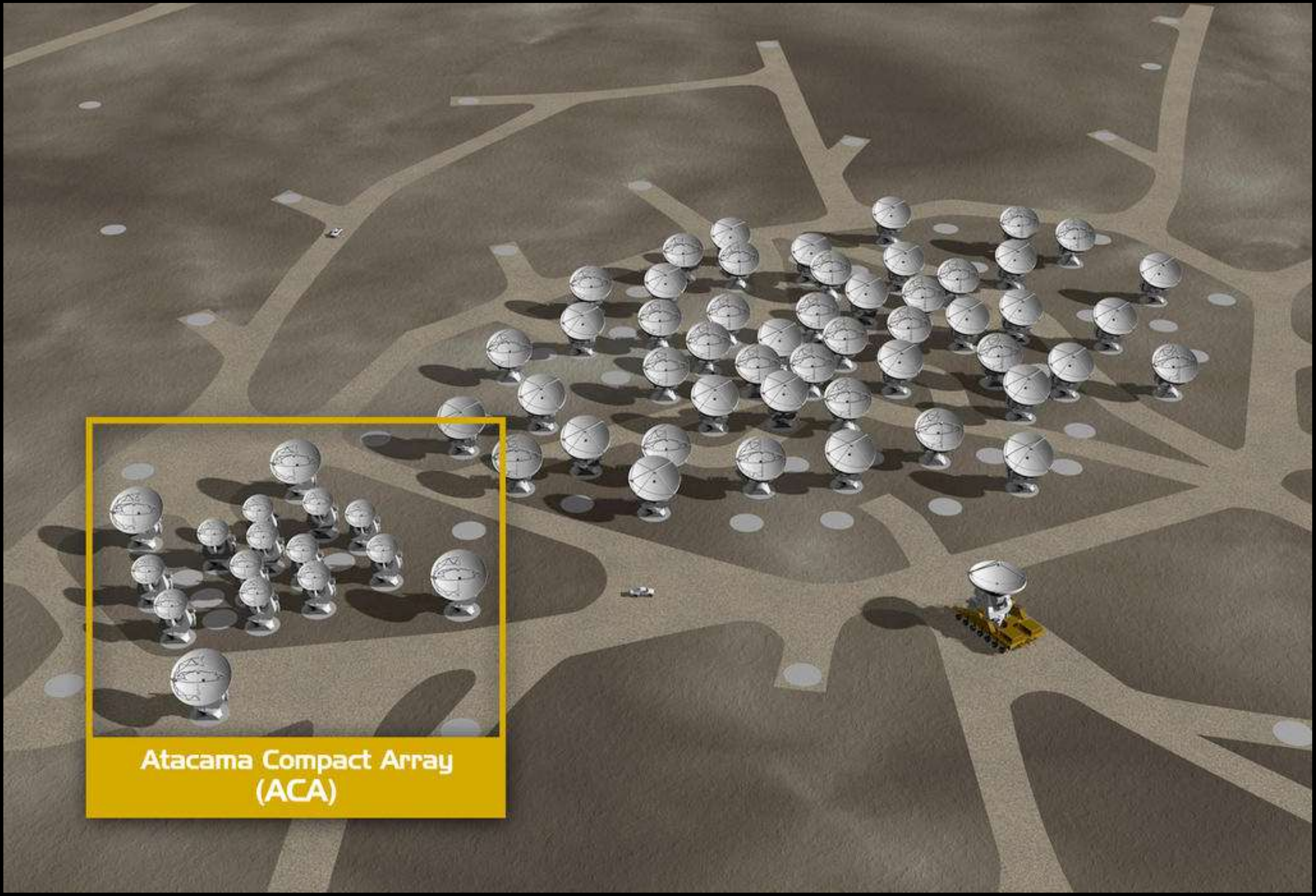
HERSCHEL Space Observatory (2009-2013)
Initiated by the European Space Agency ESA

Named after Wilhelm
and Caroline Herschel

Weight :	3,3 t
Wave length:	60-670 μm
mirror:	3,5 m

ALMA: Atacama Large Millimeter/Submillimeter Array

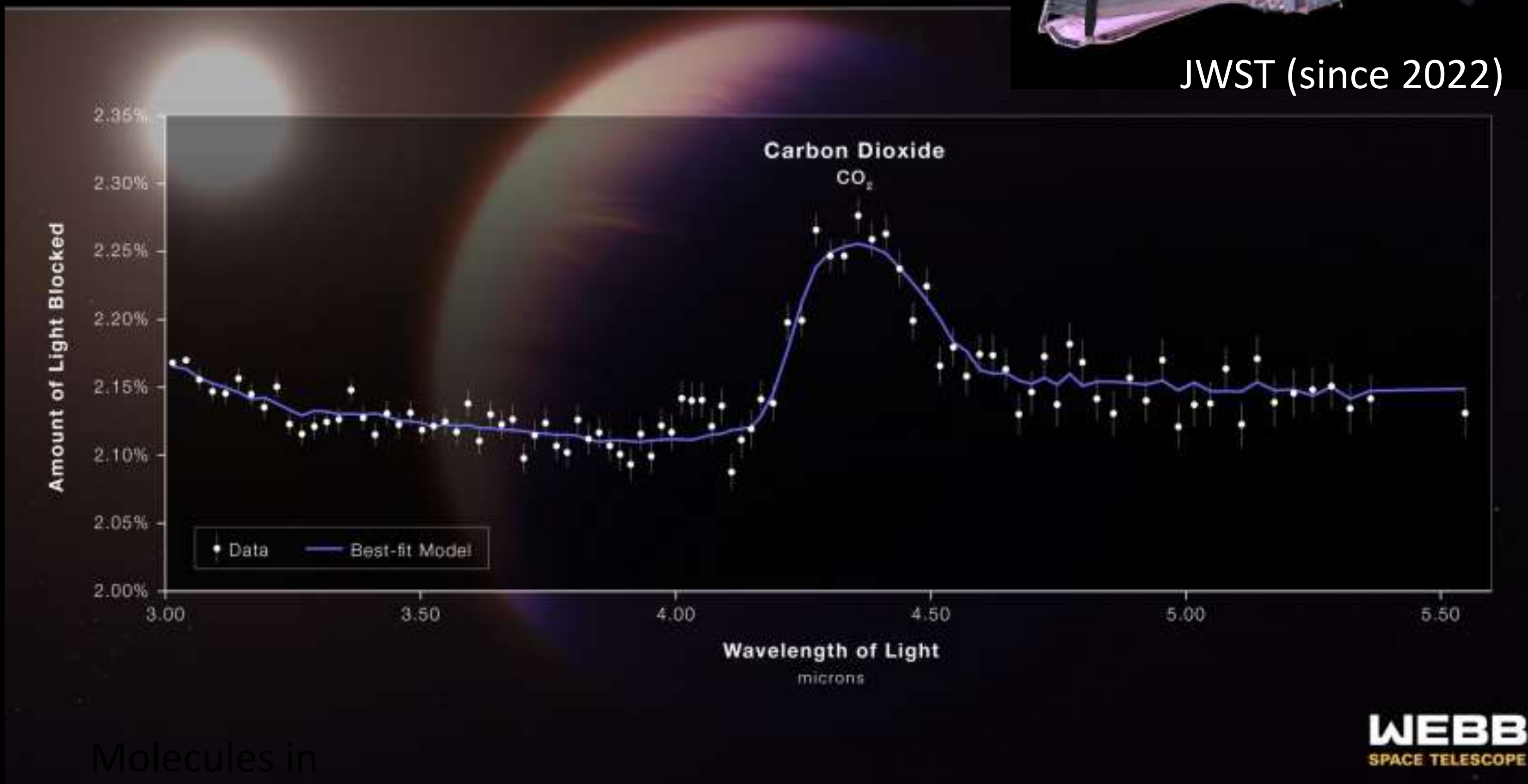
0.3mm – 9.6mm

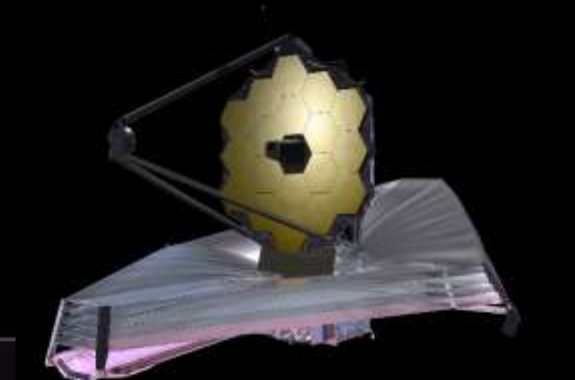


http://www.almaobservatory.org/

James Webb Space Telescope

Molecules in Exoplanet atmospheres





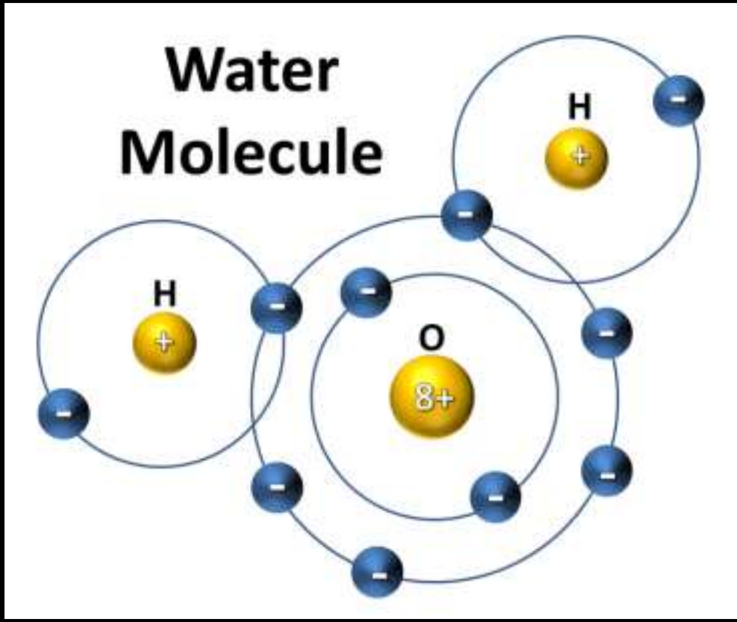
JWST (since 2022)

The space between the stars is not empty

What is Interstellar Matter made of?

Atoms vs Molecules

An atom is the smallest constituent unit of ordinary matter that has the properties of a chemical element.



A molecule is the smallest particle in a chemical element or compound that has the chemical properties of that element or compound. Molecules are made up of atoms that are held together by **chemical bonds**. These bonds form as a result of the sharing or **exchange of electrons** among atoms.

What is Interstellar Matter made of?

Molecules in Space?

BAKERIAN LECTURE.—*Diffuse Matter in Interstellar Space.*

By A. S. EDDINGTON, F.R.S.

(Received May 21, 1926.)

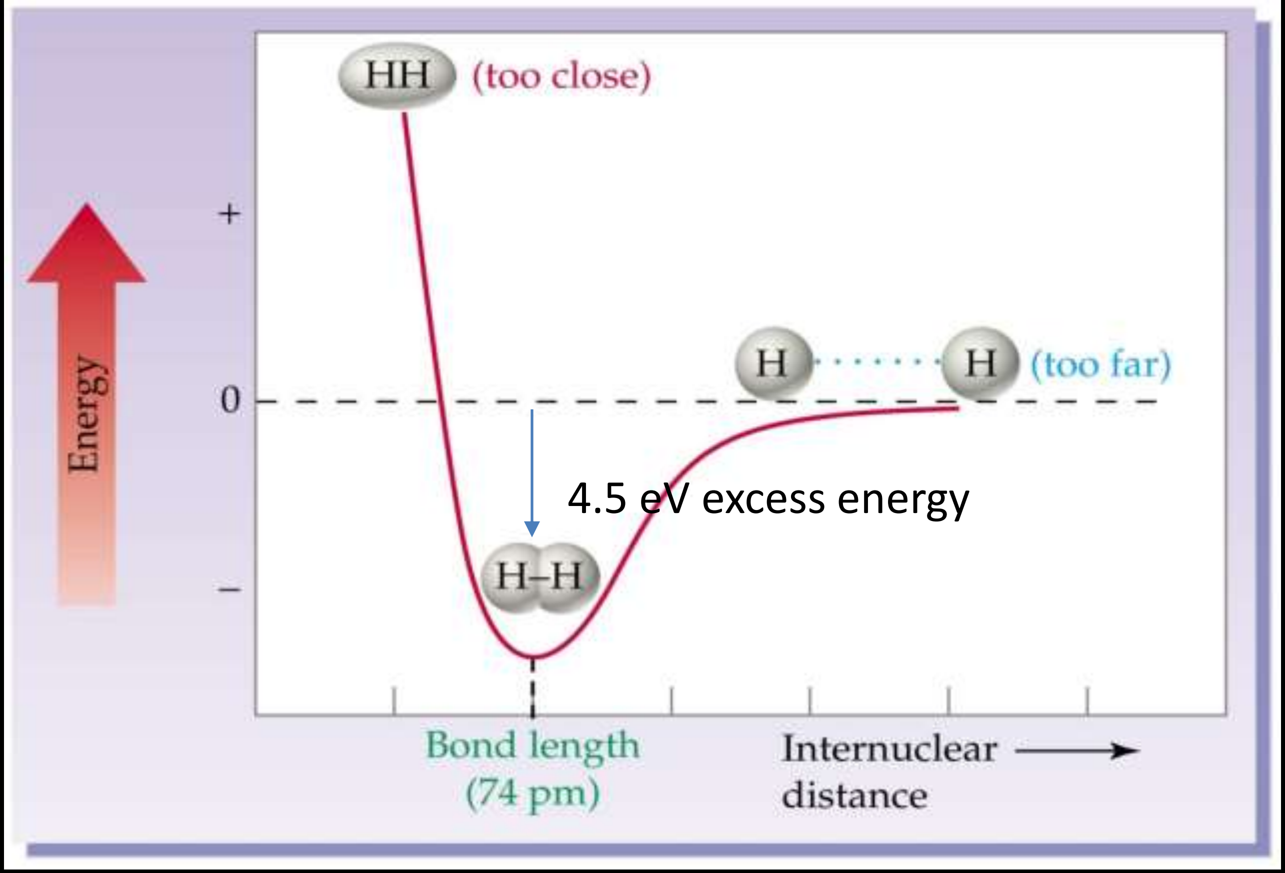
1. The title of this lecture naturally provokes the question, Is there any appreciable quantity of matter in ordinary regions of space between the stars ?

"It is difficult to admit the existence of molecules in interstellar space because when once a molecule becomes dissociated there seems no chance of the atoms joining up again."

Sir Arthur Stanley Eddington (1926)

Why it‘s not so straightforward to make molecules in space

Example: Binding energy of hydrogen molecules 4.5 eV



No attractive force, no efficient transitions

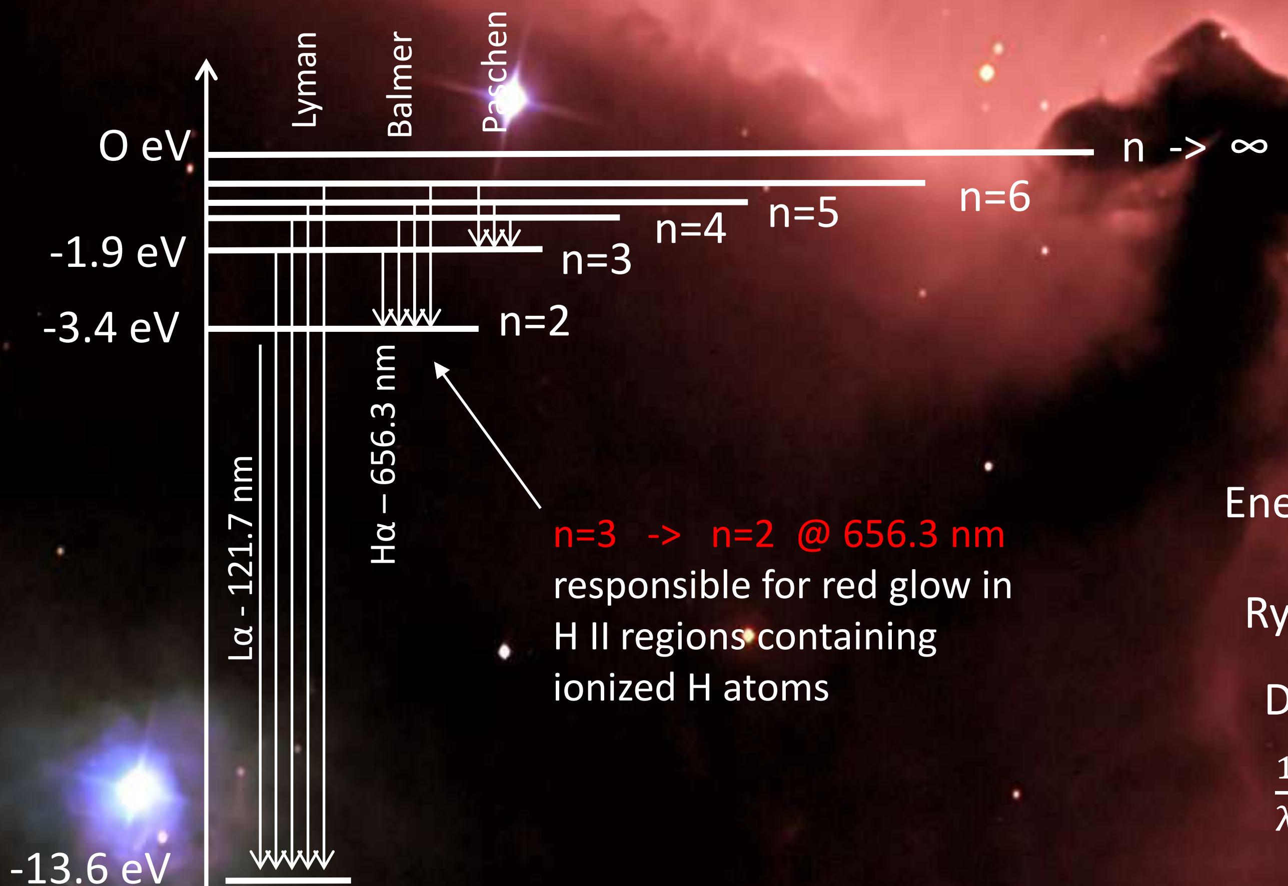
no pathway to emit radiation und get rid of excess energy

H + H $\longrightarrow$ H_2 + photon extremely inefficient

The information we gather from space is encoded in the light emitted from distant objects

(and in the visible we see the hot stuff -> atomic lines)

Hydrogen Atom



Energy levels: $E_n = - R_H \frac{Z^2}{n^2}$

Rydberg $R_H = 13.6$ eV

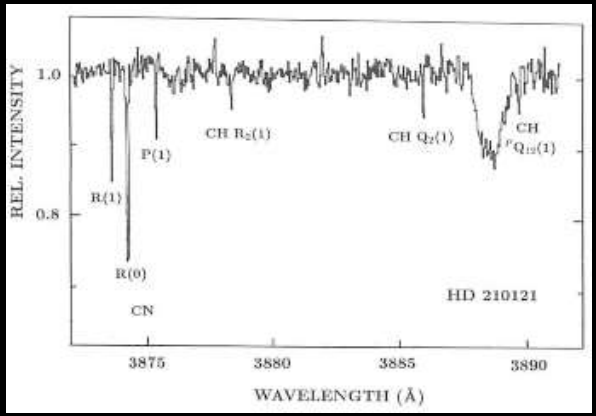
Discrete transitions:

$$\frac{1}{\lambda} = \frac{1}{hc}(E_{n1} - E_{n2})$$

History of molecular observations in space I

Sharp absorption bands (optical):

- CH: Swings & Rosenfeld (1937)
- CN: McKellar (1940)
- CH^+: Douglas & Herzberg (1941)

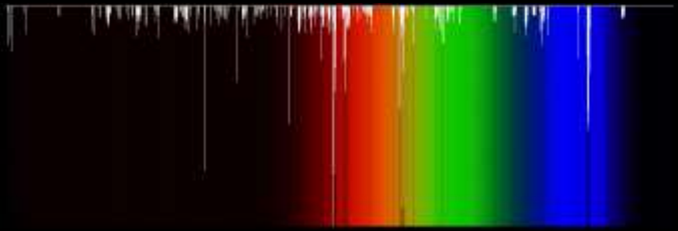


G. Herzberg, J. Roy. Soc. Can. 82, 115, (1988)

"Historical Remarks on the discovery of interstellar molecules"

Diffuse Interstellar Bands (DIBs), optical:

- Discovered by Mary L. Heger (1922)
- Probably molecular carriers
- Remain (largely) unidentified to date

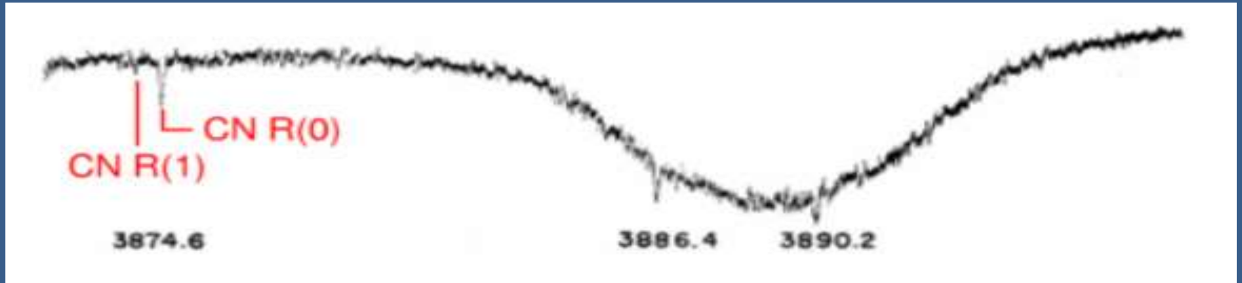


B.J. McCall, R.E. Griffin, Proc. R. Soc. A 469, 0604 (2012)

"On the discovery of the diffuse interstellar bands"

First Molecules identified in Space!

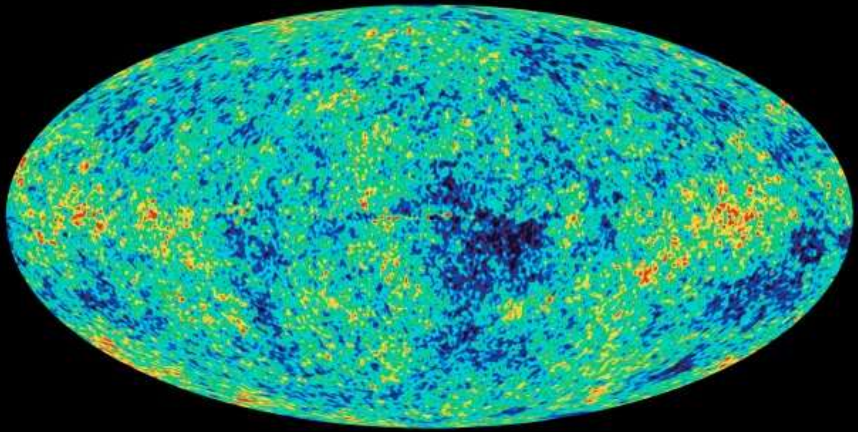
- Detection of CH in 1937, CN in 1940
- Detection of the first molecular ion CH^+ in 1941



CN Temperatur ≈ 2.3K ± 0.5K (-271° C)

Andrew McKellar
Pub. Astr. Soc. Pacific
1940

Cosmic
Microwave
Background



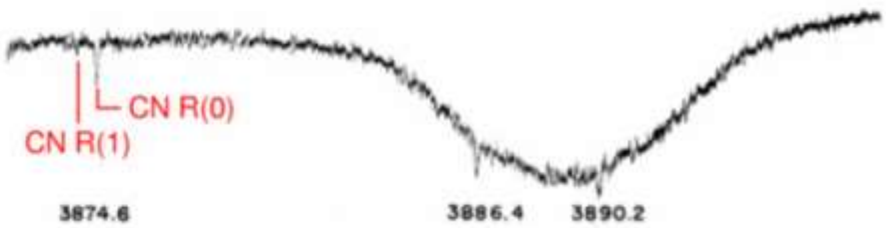
T= 2.72548K

Nobel award
Penzias,Wilson
1978

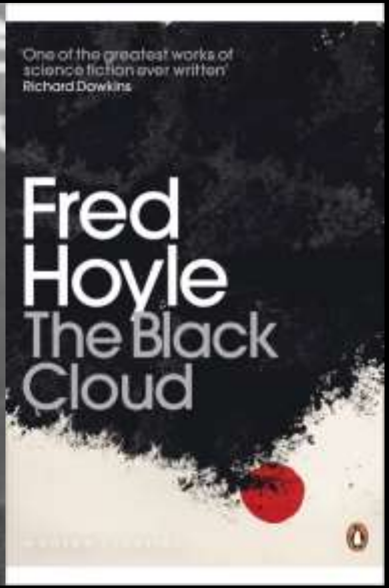
Molecules in Space: A missed opportunity early on?

History

The first observations of the CMB were made by McKellar using interstellar molecules in 1940. The image at right shows a spectrum of the star zeta Oph taken in 1940 which shows the weak R(1) line from rotationally excited CN. The significance of these data was not realized at the time, and there is even a line in the 1950 book *Spectra of Diatomic Molecules* by the Nobel-prize winning physicist Gerhard Herzberg, noting the 2.3 K rotational temperature of the cyanogen molecule (*CN*) in interstellar space but stating that it had "only a very restricted meaning." We now know that this molecule is primarily excited by the CMB implying a brightness temperature of $T_o = 2.729 \pm 0.027$ K at a wavelength of 2.64 mm (Roth, Meyer & Hawkins 1993).



A further irony is that one person did make the connection between McK
1950 review (1950, Observatory, 70, 194-195) of a book by Gamow and
Energy-Sources"). Hoyle was one of the three inventors of the Steady St
Bang model. Hoyle wrote: "[the Big Bang model] would lead to a tempe
whole of space much greater than McKellar's determination for some reg
cosmological model gives values from which $T_o = 11$ K can be compute
Hoyle did not consider Alpher and Herman's paper (1949, Phys. Rev., 75
with $T_o = 1$ K and one with $T_o = 5$ K. Thus the uncertainties in the cosm
to be a confirmation of the Big Bang instead of a refutation of it. But non
the interstellar CN data, and thus the CMB remained undiscovered until
discrepancy, and gives $T_o = 50$ K in his book "Creation of the Universe"



http://www.astro.ucla.edu/~wright/CMB.html

History of molecular observations in space II

- Radio telescopes:

- H I 21 cm: Ewen & Purcell (1951)

- OH 18 cm: Weinreb et al. (1963)

- NH_3 1 cm: Cheung, Townes et al. (1968)

“How easy, how exciting!” C.H.Townes

- H_2O 1 cm: Cheung, Townes et al. (1969)

C.H. Townes. ASP Conf. Ser. 356, 2006
“The discovery of Insterstellar Water Wapor and Ammonia at the Hat Creek Radio Observatory”

- UV telescopes: Copernicus (1970):

  H_2 at ≈ 125nm (1970), later N_2

- (Sub-)millimeter telescopes:

  CO at 115 GHz (1970), H_2CO (1970), ...

Today we know: Molecules Everywhere!

Known Interstellar and Circumstellar Molecules (July 2000)

Number of Atoms

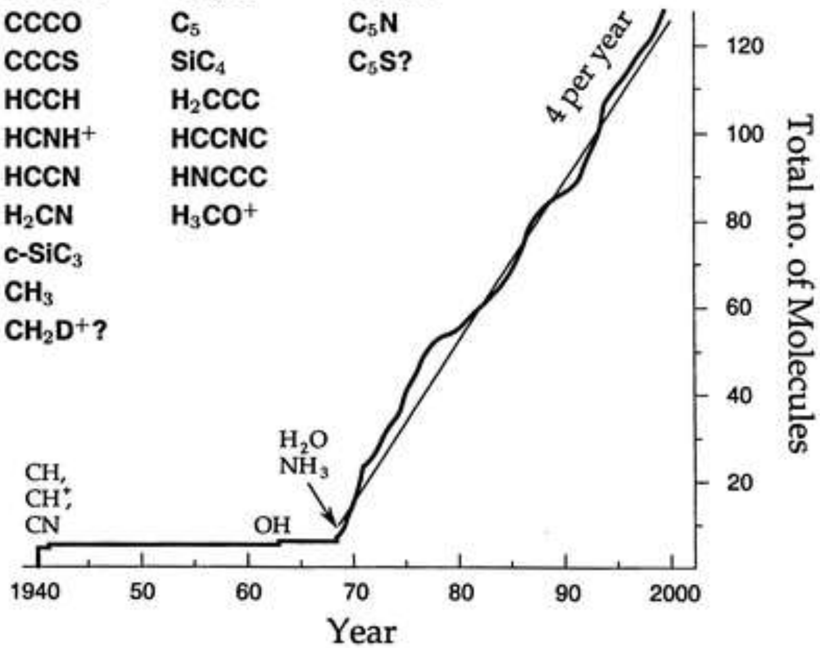
2	3	4	5	6	7	8	9
H_2	H_2O	NH_3	SiH_4	CH_3OH	CH_3CHO	CH_3CO_2H	CH_3CH_2OH
OH	H_2S	H_3O^+	CH_4	NH_2CHO	CH_3NH_2	HCO_2CH_3	$(CH_3)_2O$
SO	SO_2	H_2CO	CHOOH	CH_3CN	CH_3CCH	CH_3C_2CN	CH_3CH_2CN
SO^+	HN_2^+	H_2CS	$HC\equiv CCN$	CH_3NC	CH_2CHCN	C_7H	$H(C\equiv C)_3CN$
SiO	HNO	HNCO	CH_2NH	CH_3SH	HC_4CN	H_2C_6	$H(C\equiv C)_2CH_3$
SiS	SiH_2?	HNCS	NH_2CN	C_5H	C_6H		C_8H
NO	NH_2	CCCN	H_2CCO	HC_2CHO	c-CH_2OCH_2		
NS	H_3^+	HCO_2^+	C_4H	$CH_2=CH_2$	C_7^-?		
HCl	NNO	CCCH	c-C_3H_2	H_2CCCC			
NaCl	HCO	c-CCCH	CH_2CN	HC_3NH^+			
KCl	HCO^+	CCCO	C_5	C_5N			
AlCl	OCS	CCCS	SiC_4	C_5S?			
AlF	CCH	HCCH	H_2CCC				
PN	HCS^+	$HCNH^+$	HCCNC				
SiN	c-SiCC	HCCN	HNCCC				
NH	CCO	H_2CN	H_3CO^+				
CH	CCS	c-SiC_3					
CH^+	C_3	CH_3					
CN	MgNC	CH_2D^+?					
CO	NaCN						
CS	CH_2						
C_2	MgCN						
SiC	HOC^+						
CP	HCN						
CO^+	HNC						
HF	SiCN						
	KCN?						

10
CH_3COCH_3
$CH_3(C\equiv C)_2CN$?

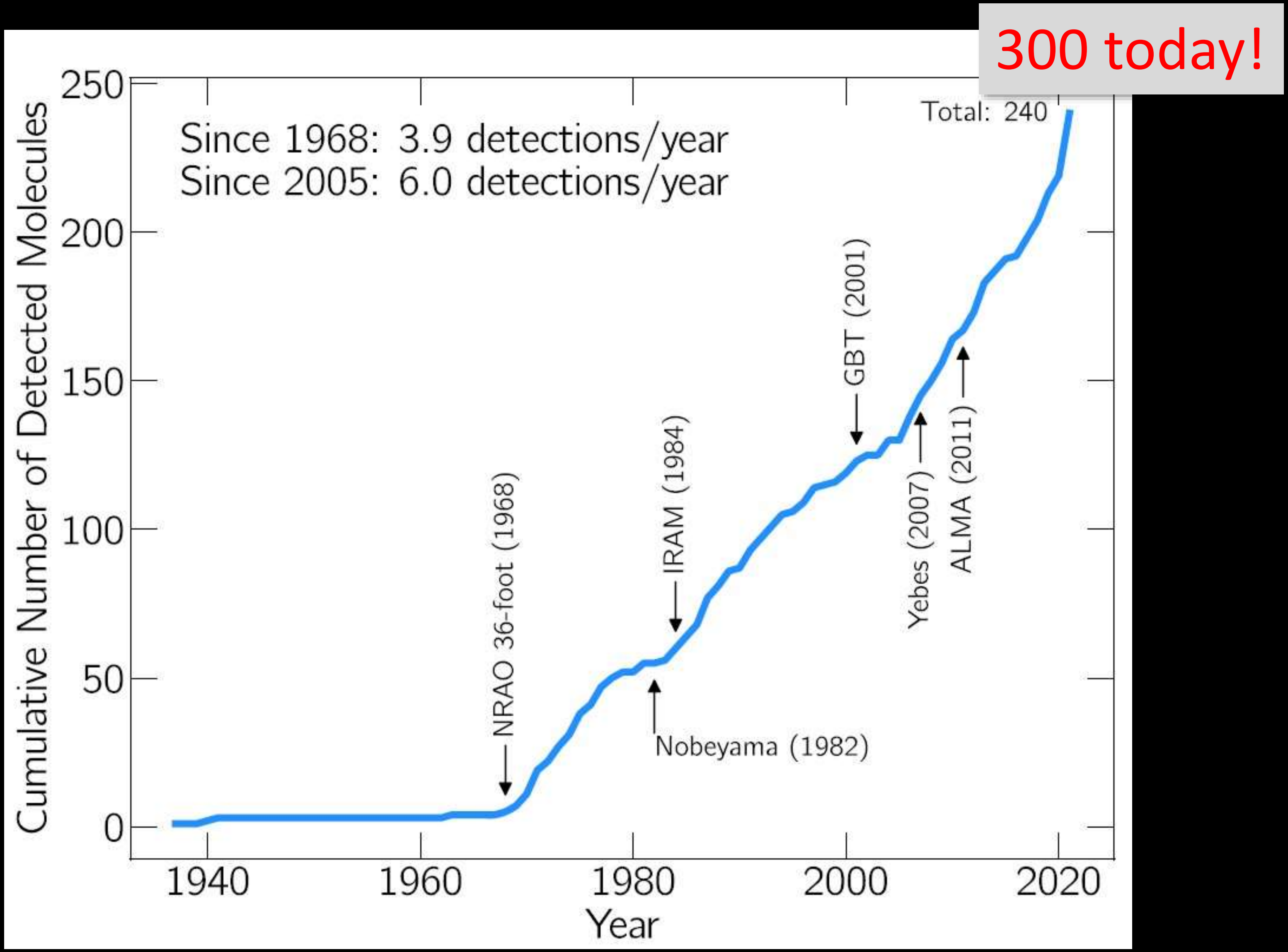
11
$H(C\equiv C)_4CN$

13
$H(C\equiv C)_5CN$

Total: 123



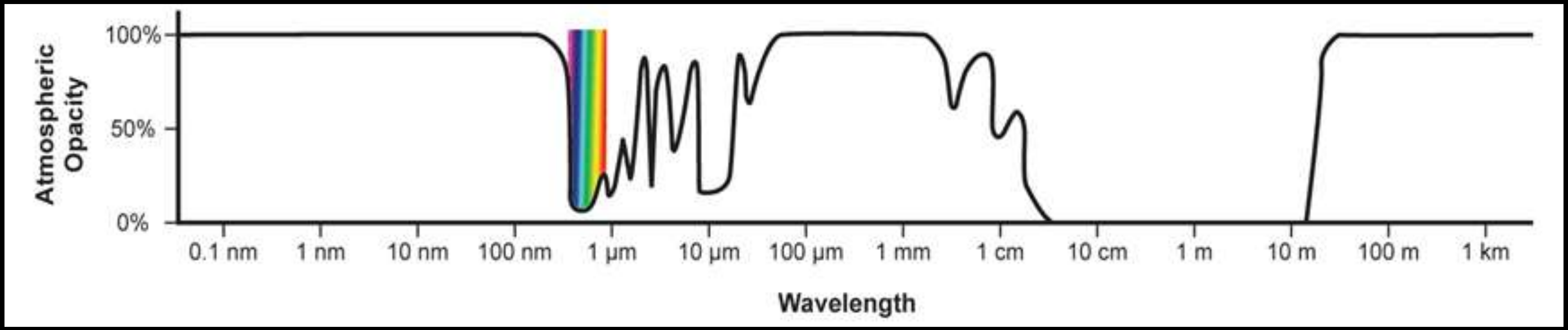
Today we know: Molecules Everywhere!



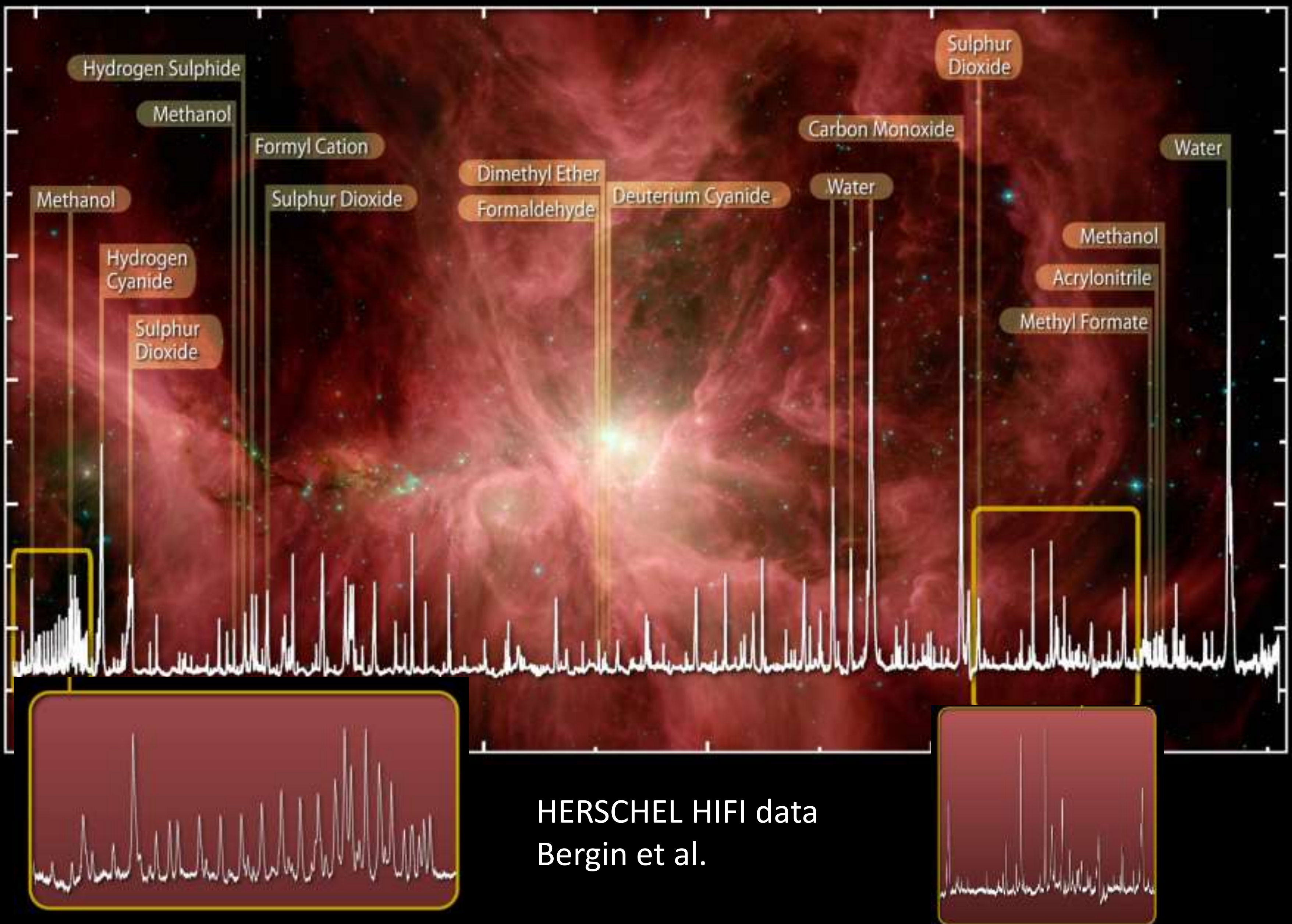
McGuire, ApJS 259, 30 (51pp), 2022

History of molecular observations in space III

- IR telescopes: IRAS (1983): 0.6 m, **12–100 μm**,
  first sky survey, dust (β Pictoris disk)
- Infrared Space Observatory (1995–1998): 0.6 m, **2.5–240 μm**,
  dust & molecules (H_2O, HF, OH, OI, C_6H_6, CH_3, CO_2, ...), infrared clouds
- Spitzer Space Telescope (2003–2009): 0.8 m, **3–180 μm**, high-sensitivity imaging and mapping, dust & molecules (OH, H_2O, C_2H_2, ...)
- Herschel Space Observatory (2009–2012): 2.4 m, **60–670 μm**,
  high-sensitivity imaging and mapping,
  dust & molecules (CH_3OH, H_2S, HCN, SO_2, H_2CO, H_2O, ...)



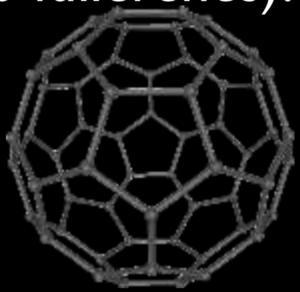
Molecular clouds decoded

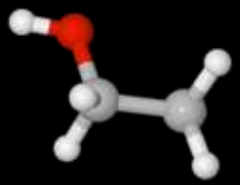


HERSCHEL HIFI data
Bergin et al.

Detected Molecules

- 241 interstellar & circumstellar molecules
- 74 extragalactic molecules
- 9 in exoplanet atmospheres
- Up to 13 atoms (since 2010 => 60 and 70 fullerenes)!



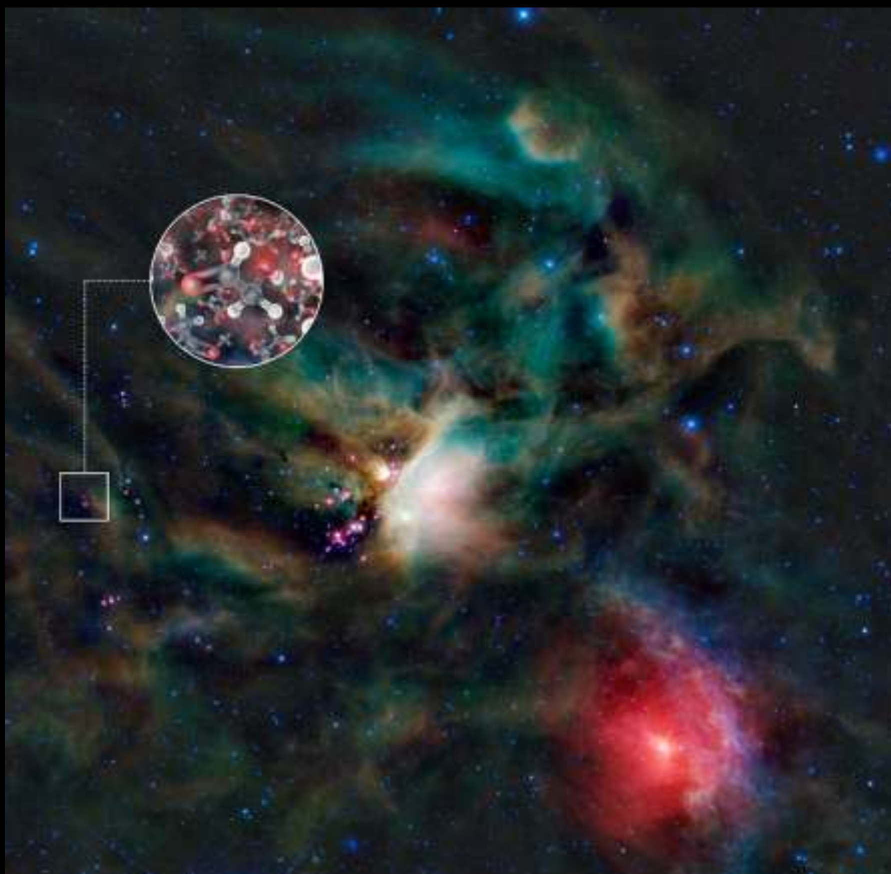


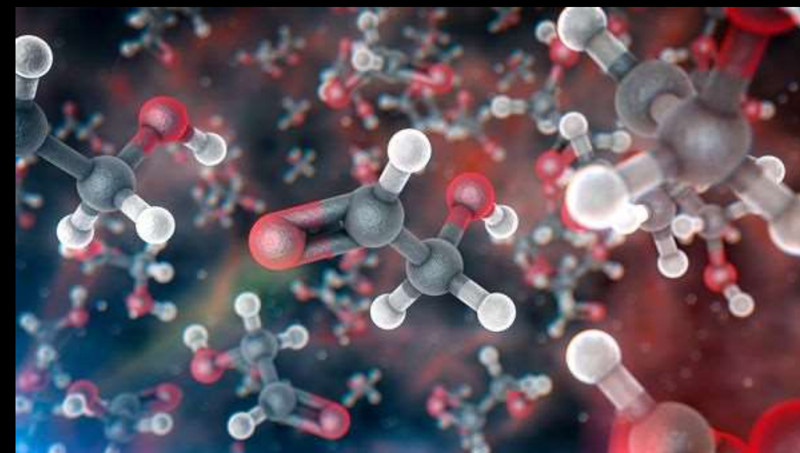
- 30 positive ions (cations)
- 6 negative ions (anions)
- ~various free radicals
- ~various strcutural isomers and isotopologues
- 6 linear and 6 cyclic species (including simplest PAH, C_6H_6)

- >10 Si-, 6 P-, and 5 Cl-bearing species
- >10 metal-bearing species
- > 10 species with deuterium

Some of the more interesting cases:

Sugar and alcohol in space





IRAS 16293-2422

Observations:ALMA

Glycolaldehyde ($HOCH_2$-CH=O)

Jørgensen *et al.* 2012 *ApJ* **757** L4

Some of the more interesting cases:

Sugar and alcohol in space

“Astronomers find alcohol cloud spanning 288 billion miles”

www.phys.org

SPIEGEL ONLINE DER SPIEGEL SPIEGEL TV

Anmelden

WISSENSCHAFT

Schlagzeilen | Wetter | DAX 10.703,51 | TV-Programm | Abo

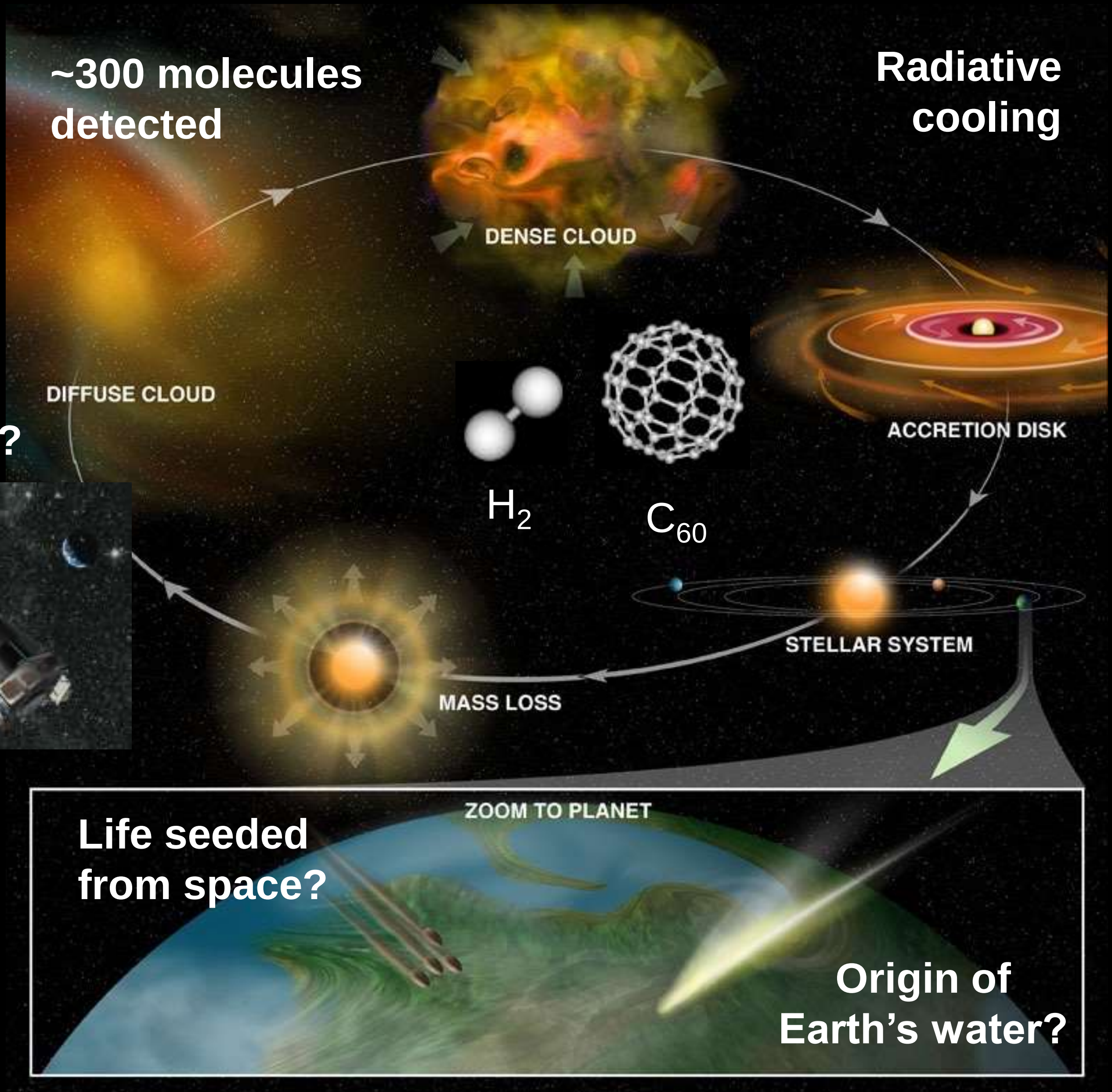
Nachrichten > Wissenschaft > Weltall > Alkohol-Wolke: Riesen-Fahne im All

Alkohol-Wolke

Riesen-Fahne im All

Britischen Astronomen ist ein berauschender Fund gelungen. Mitten in der Milchstraße schwebt eine 463 Milliarden Kilometer lange Alkoholwolke. Die schlechte Nachricht: Menschen können sie nicht trinken.

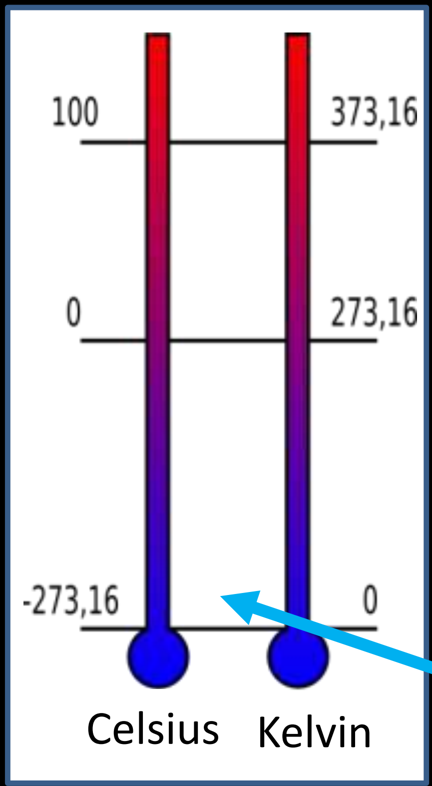
Cosmic Chemistry Cycle



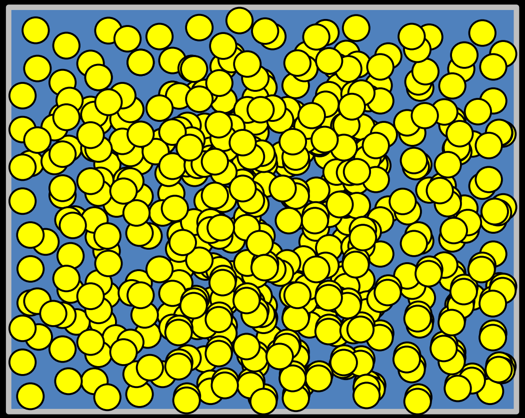
Life on exoplanets?

Credit: Bill Saxton
NRAO/AUI/NSF

Chemistry in space must be different …

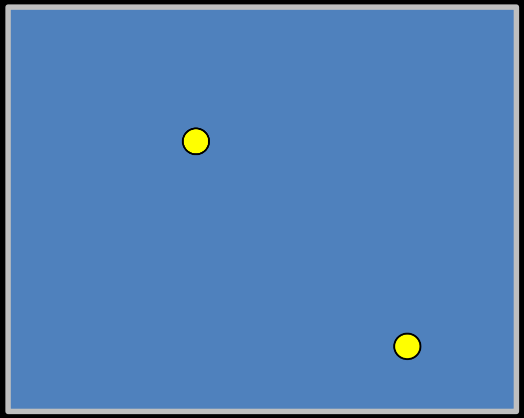


In interstellar space temperatures and densities are low.



1 atmosphere:
10^{19} particles pro cm^3

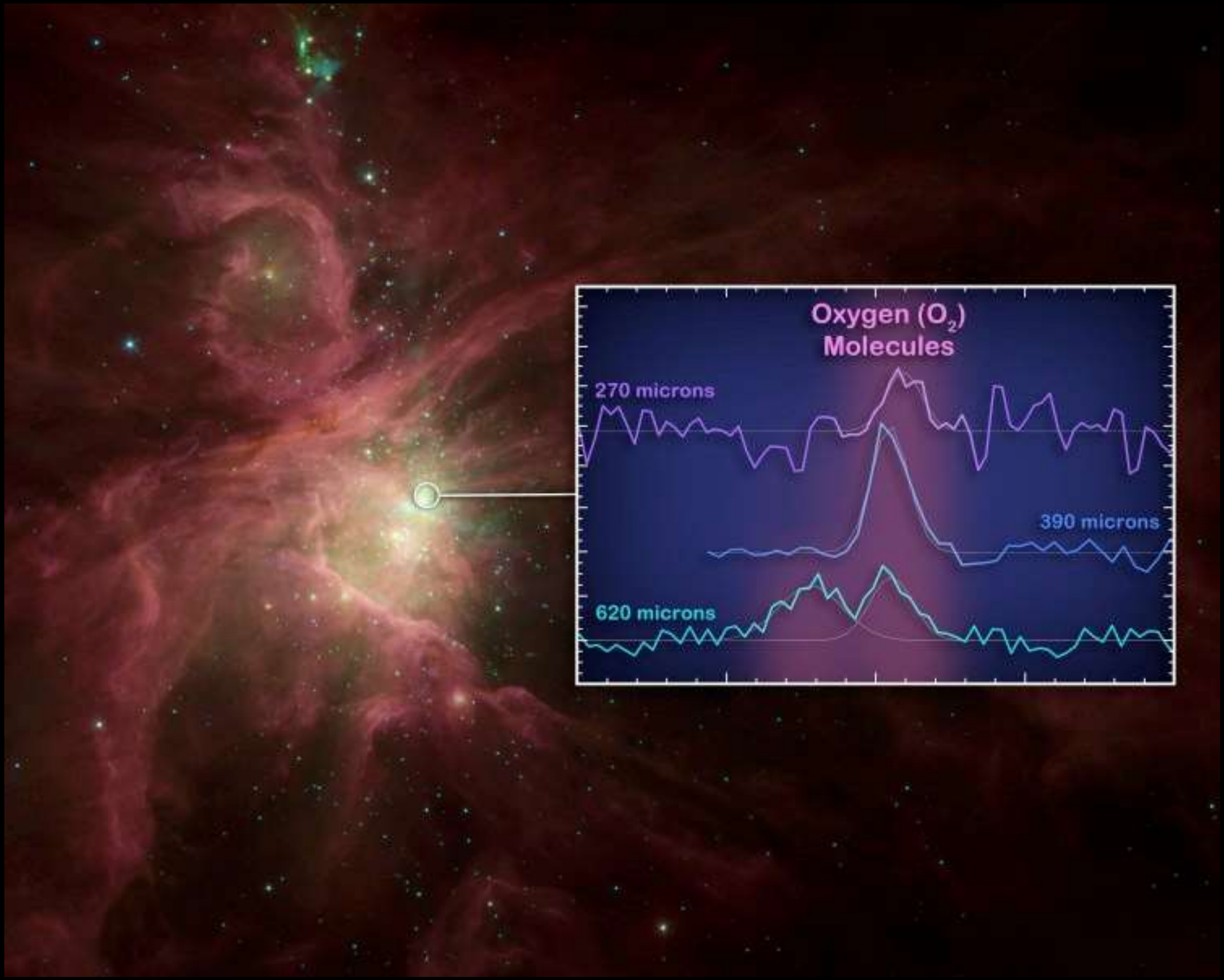
T=10-100 K
(-263C to -173C)



Space:
0,0000000000000001 atmospheres

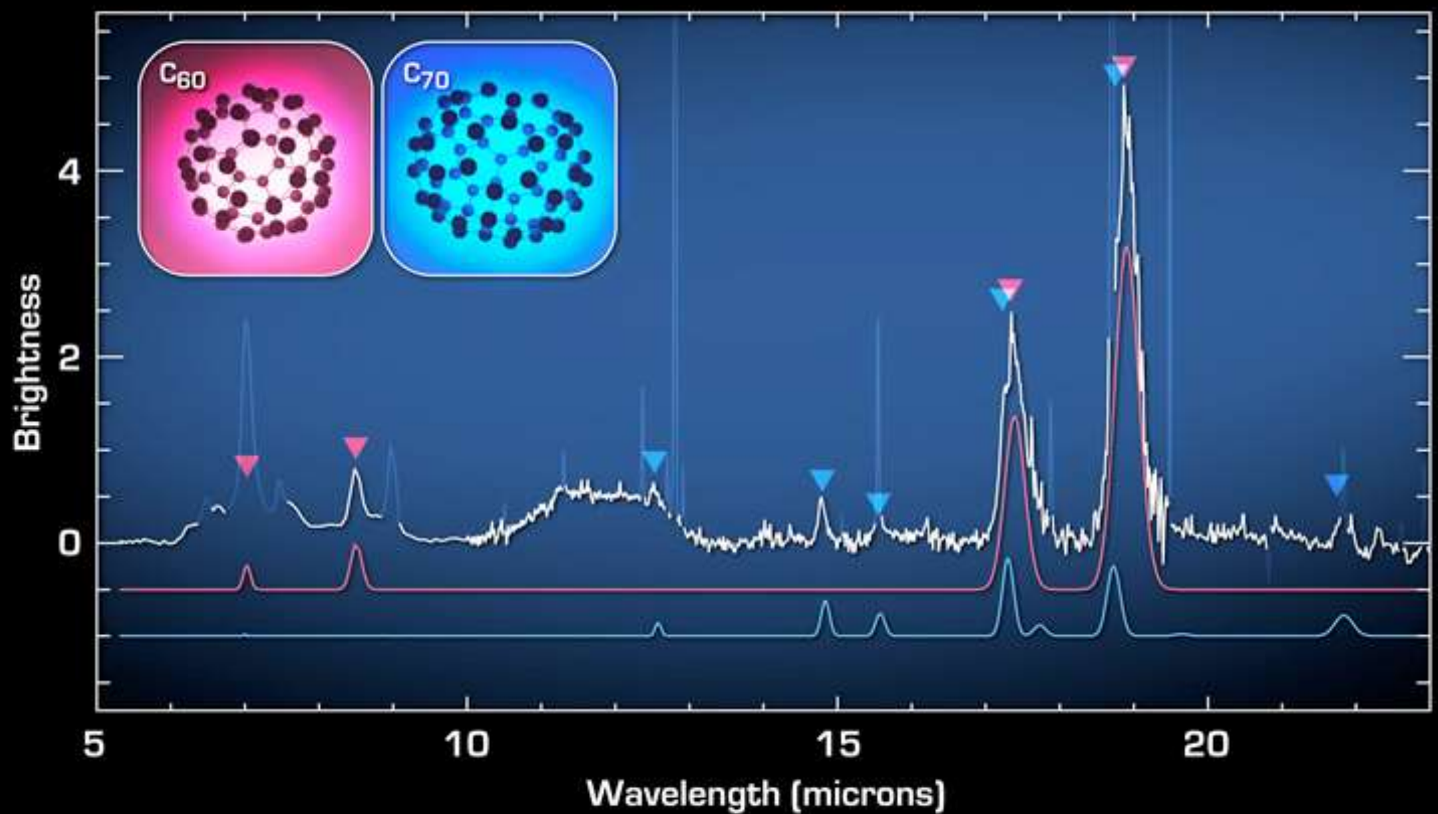
No endothermic reactions!
No reactions with activations barriers!
No 3-body reactions!

O_2 in Orion, 487–1121 GHz, Herschel



Goldsmith et al. (2011)

Detection of fullerenes (C_{60} & C_{70})



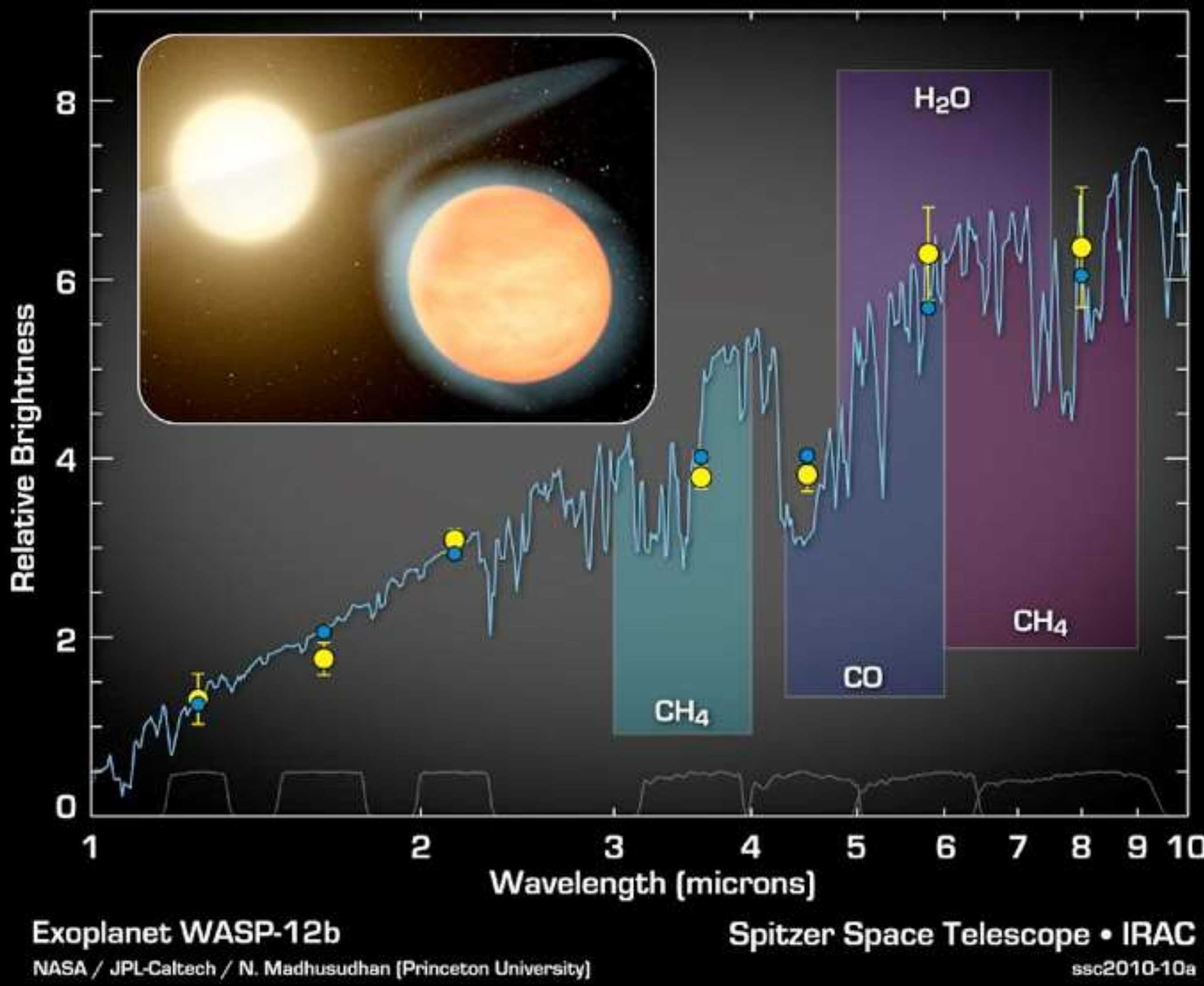
Buckyballs In A Young Planetary Nebula

NASA / JPL-Caltech / J. Cami (Univ. of Western Ontario/SETI Institute)

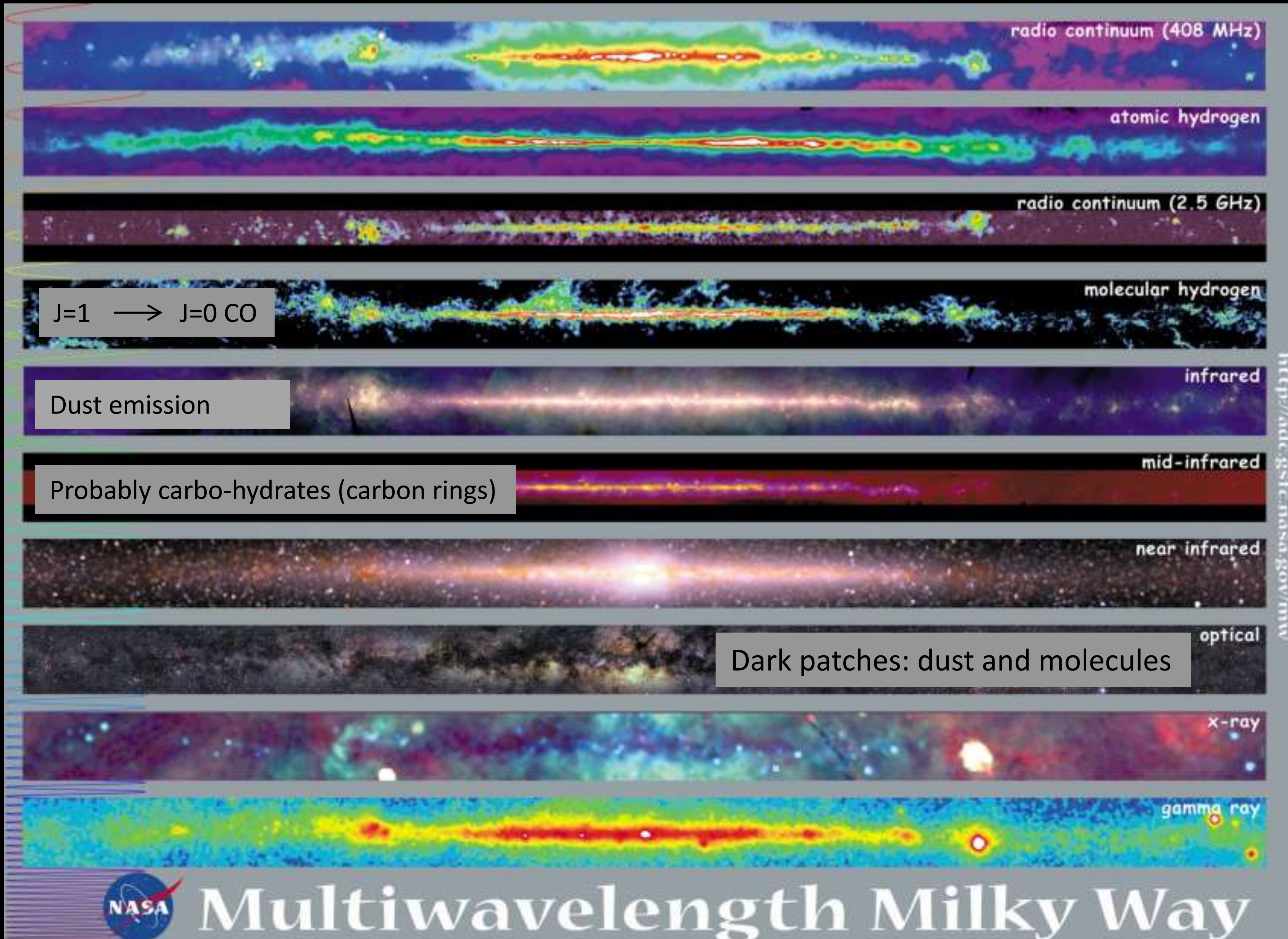
Spitzer Space Telescope • IRS

ssc2010-06a

Molecules, exoplanet WASP-12b, Spitzer

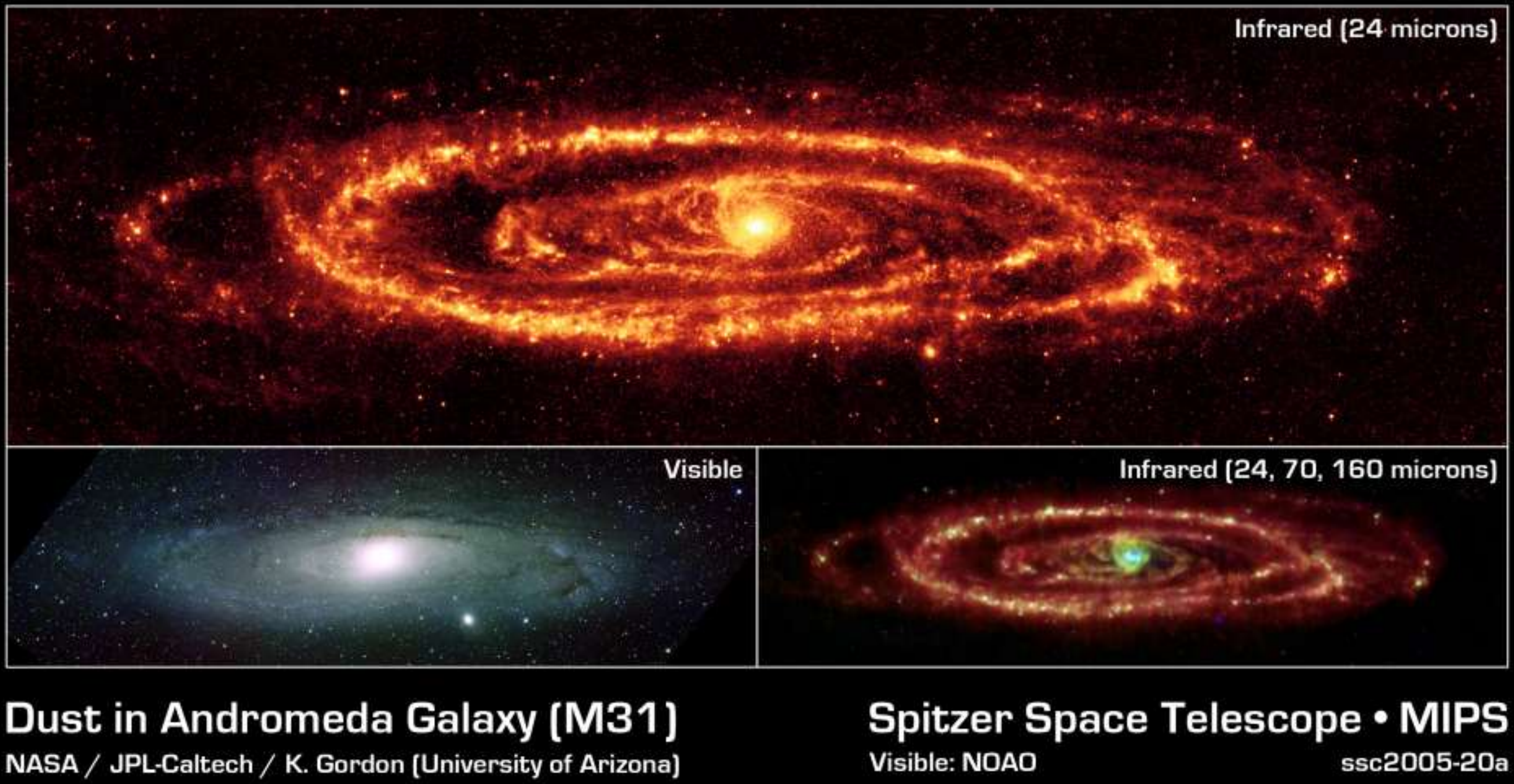


Where the molecules are



https://mwmw.gsfc.nasa.gov/ “The multiwavelength milky way”

Andromeda Galaxy (M31)



Sagittarius B2: "Large Molecule Heimat"

ATLASGAL, submillimeter (red) + Midcourse Space Experiment (MSX), IR (green and blue)

- Giant molecular cloud near the center of the milky way
- more than 3700 spectral lines associated with complex organic molecules

nature astronomy

LETTERS

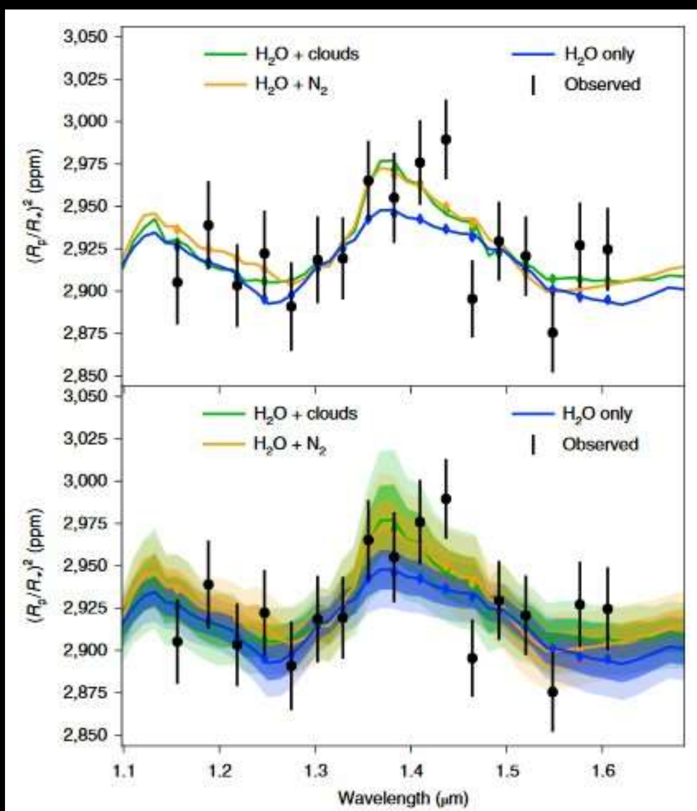
https://doi.org/10.1038/s41550-019-0878-9

Corrected: Author Correction

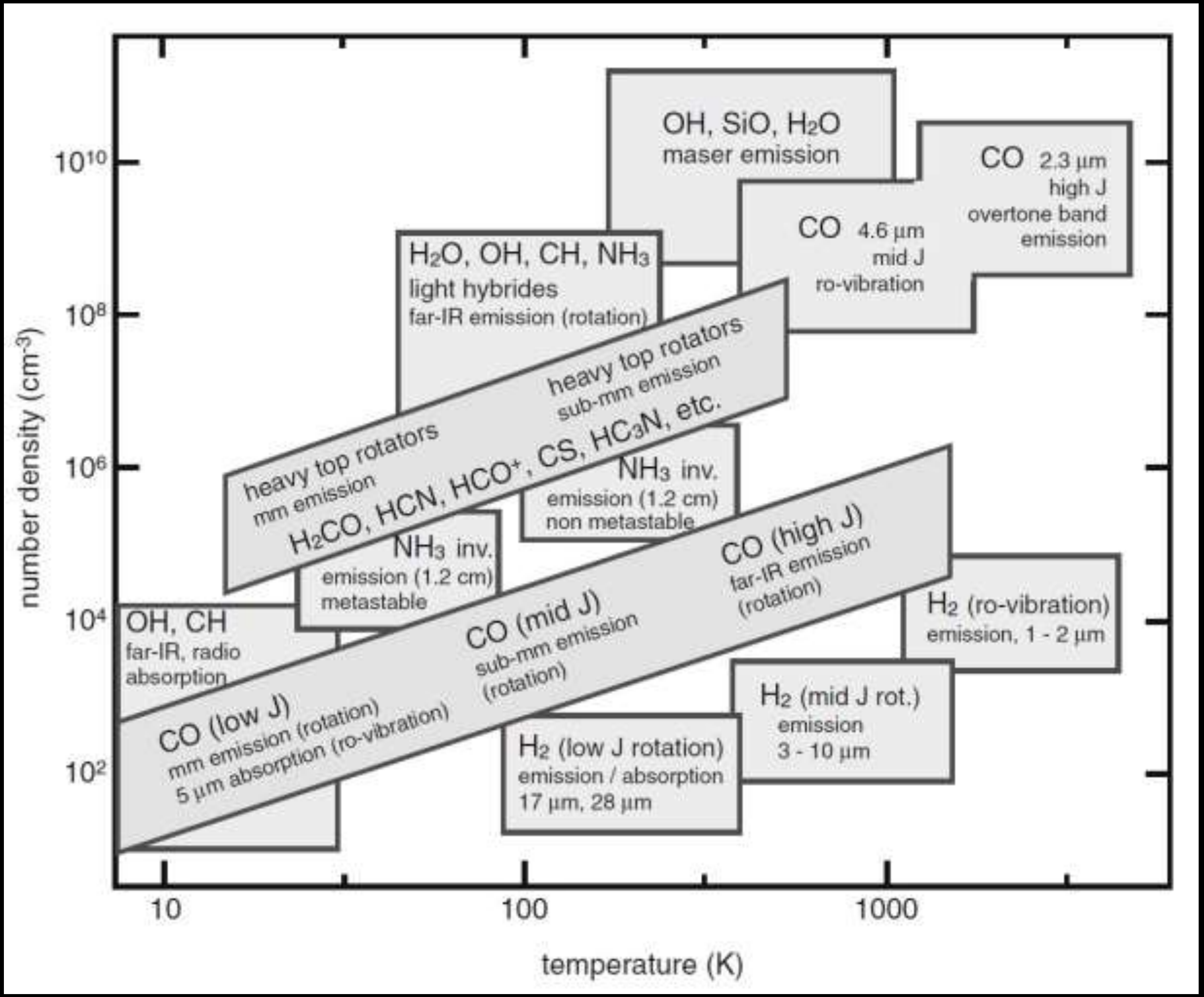
Water vapour in the atmosphere of the habitable-zone eight-Earth-mass planet K2-18 b

Angelos Tsiaras*, Ingo P. Waldmann*, Giovanna Tinetti, Jonathan Tennyson and Sergey N. Yurchenko

Nature Astronomy (2019)



Where the molecules are



R.S. Klessen, S.C.O. Glover, "Physical Processes in the Interstellar Medium", Saas-Fee Advanced Course 43, (Adapted from R. Genzel 1991)

Importance of molecules

- Unique probes of physical conditions
  - Temperature
  - Density
  - Ionization balance

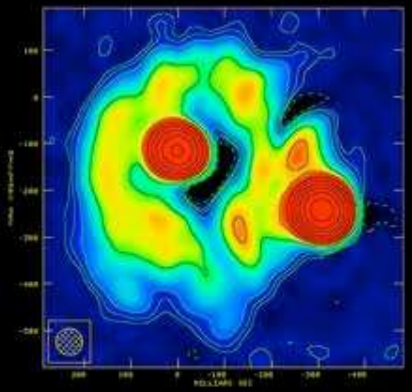
- Molecules may change the physical conditions
  - Coolants of gas
  - Electron recombination

- Chemical composition and evolution
  - Organic chemistry
  - Biology

Molecules are everywhere!

Molecules are found everywhere in the Universe:

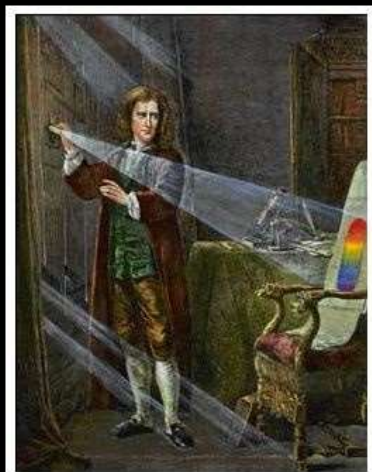
- Appeared in the Early Universe, a few min after Big Bang
- High-z quasars and galaxies
- Milky Way: interstellar and circumstellar medium
- Solar system: solar photosphere, planet. atmospheres, comets, meteorites



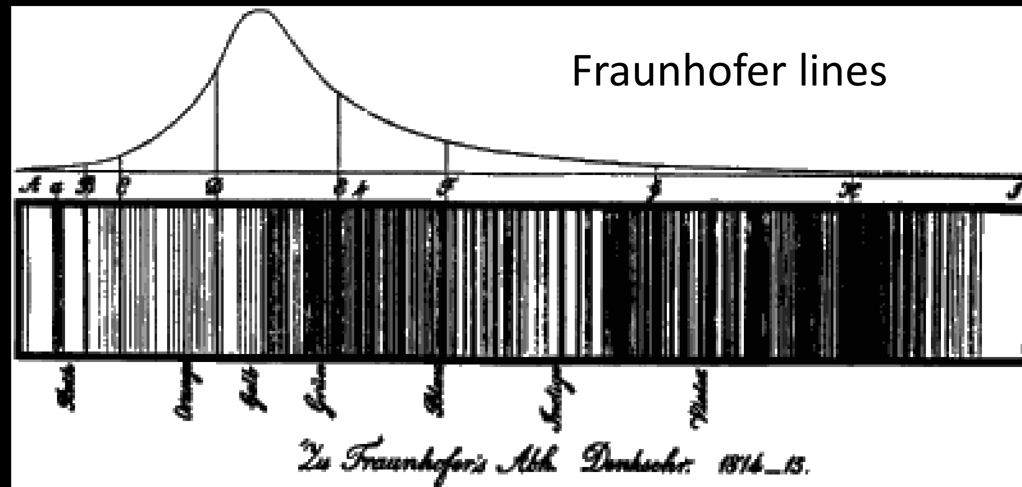
Outline

1) Introduction: Molecules in Space	(20.10.23)
2) Molecular Properties and Spectroscopy	(27.10.23)
3) Different ways to detect Molecules	(03.11.23)
4) Early Universe	(10.11.23)
5) Gas-phase chemical processes and the first molecules	(17.11.23)
6) Stellar nucleosynthesis and origin of elements	(24.11.23)
7) Laboratory Astrophysics: Gas phase experiments	(01.12.23)
8) Diffuse and dense interstellar medium	(08.12.23)
9) Dust evolution and surface chemistry	(15.12.23)
10) Laboratory astrophysics: dust and surface experiments	(12.01.24)
11) Protostars	(19.01.24)
12) Protoplanetary disks	(26.01.24)
13) Planetary atmospheres, exoplanets, life	(02.02.24)
14) Excursion MPIK / MPIA	(09.02.24)

2. Molecular properties and spectroscopy

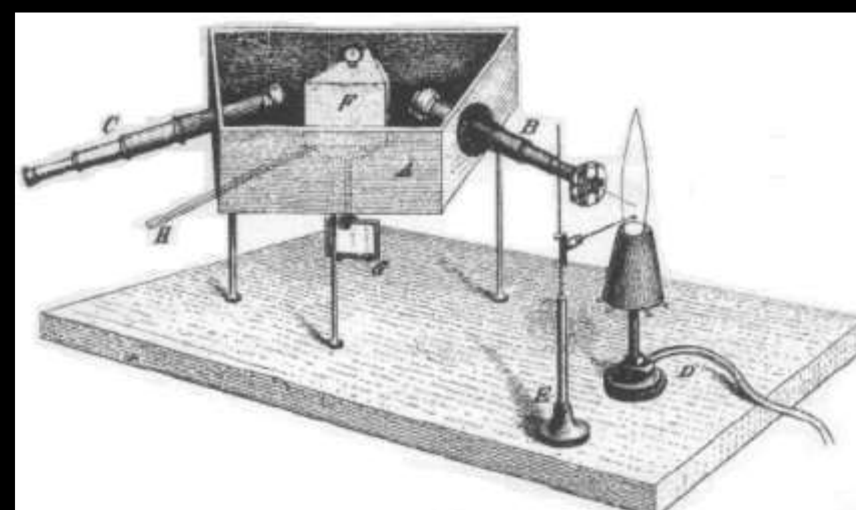


Newton

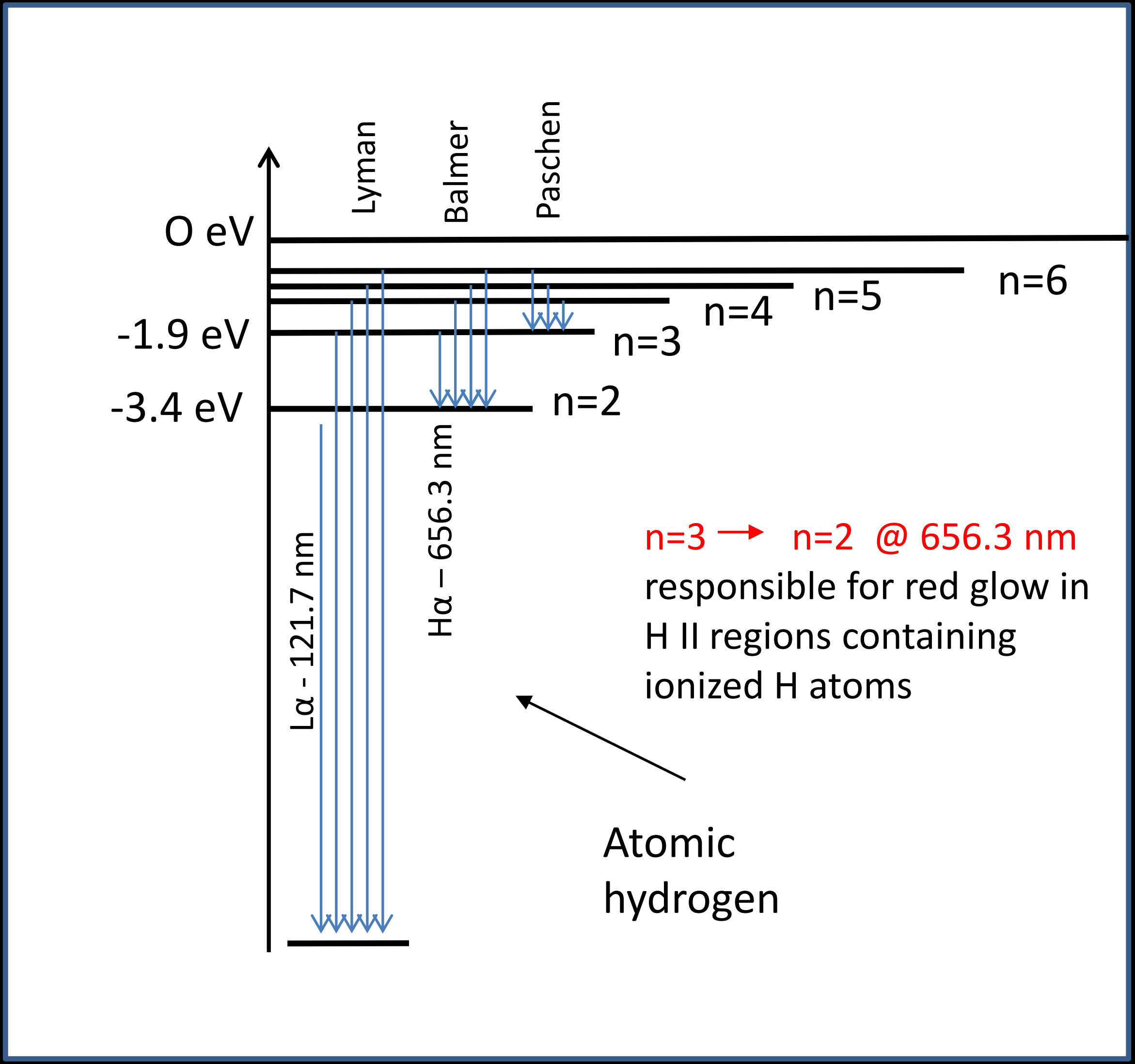


Kirchhoff

Bunsen



2. Molecular properties and spectroscopy



2. Molecular properties and spectroscopy

Electronic Transitions:

ΔE = 1-15 eV

Visible-UV

Vibrational Transitions:

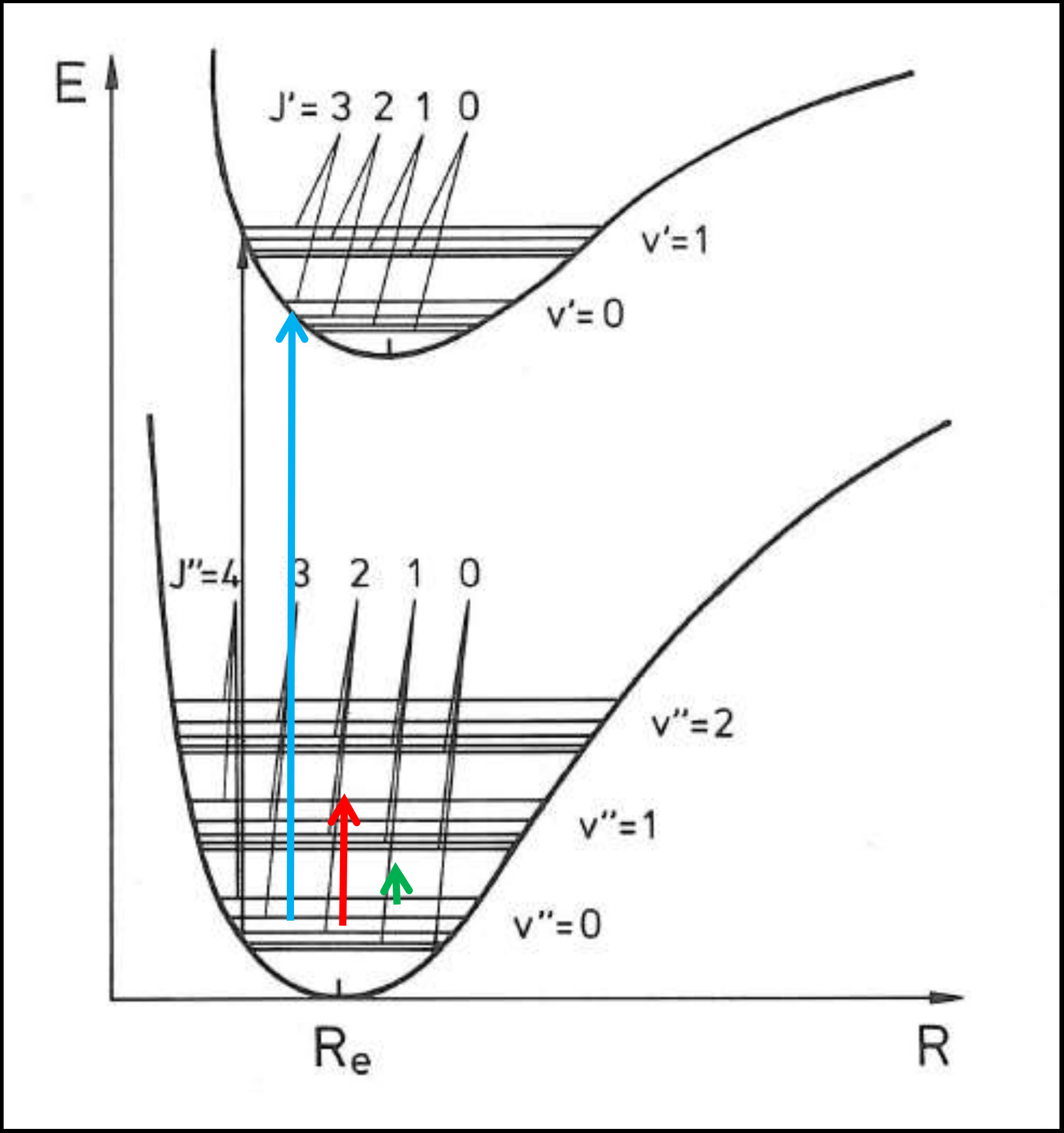
ΔE = 0.1-1 eV

Infrared

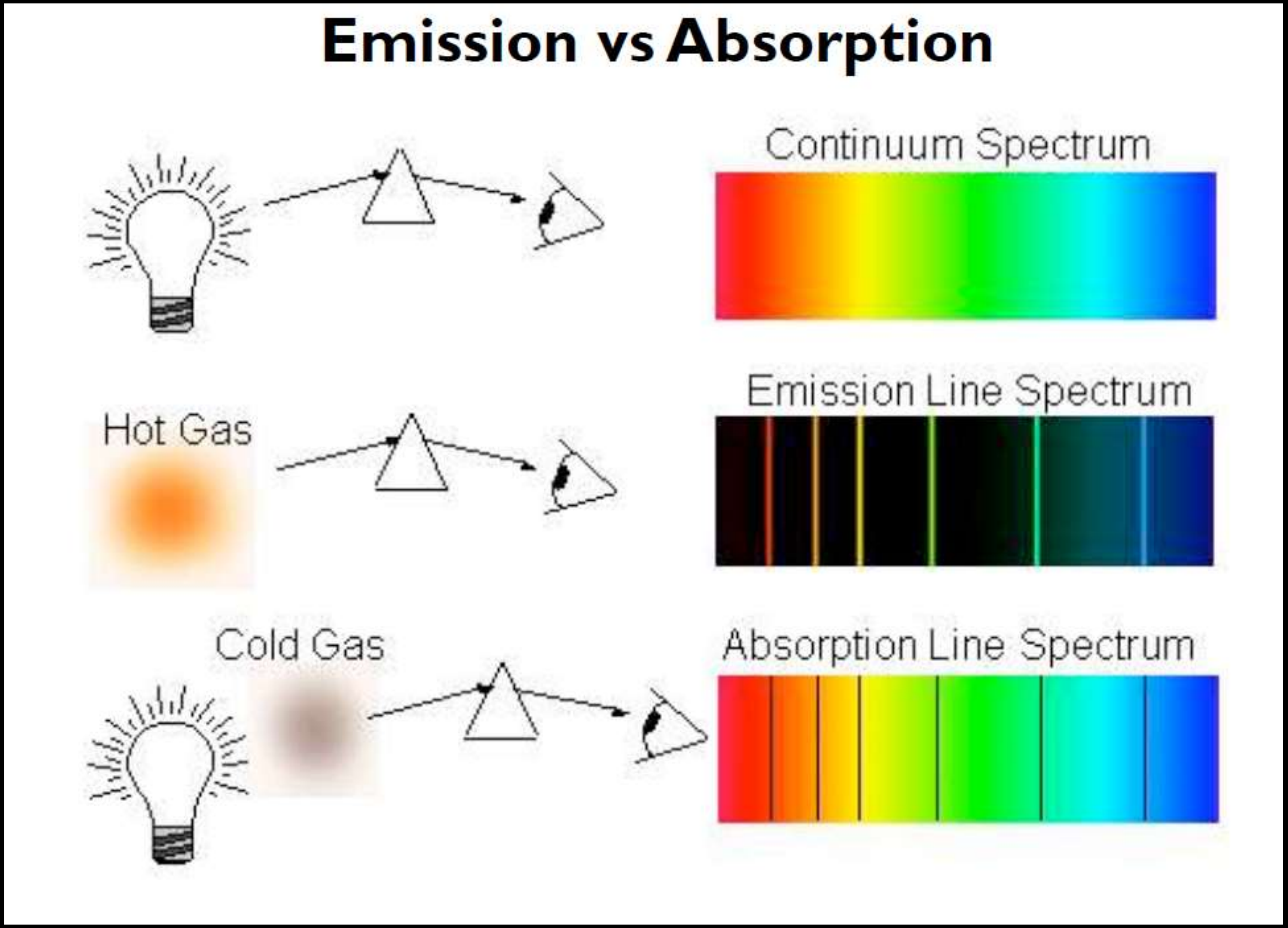
Rotational Transitions:

ΔE = 0.01-0.1 eV

(sub)-Millimeter



3. Different ways to detect molecules



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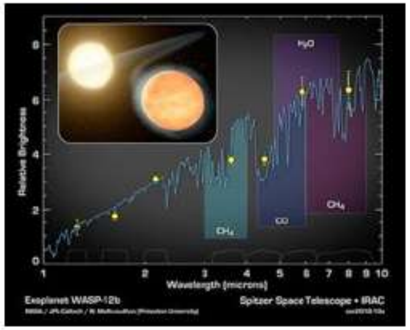
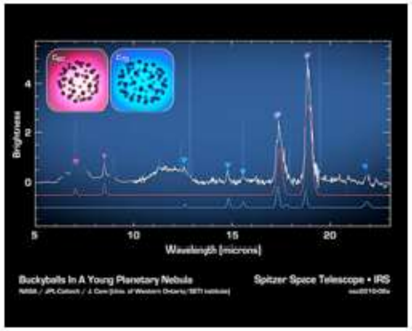
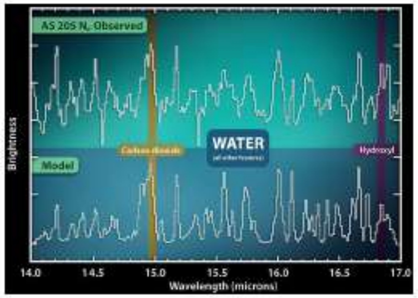
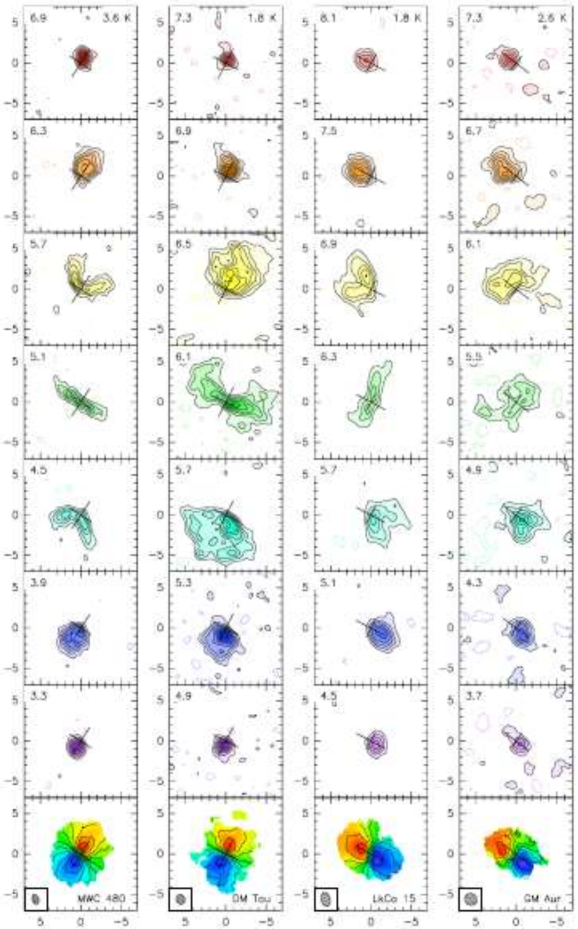
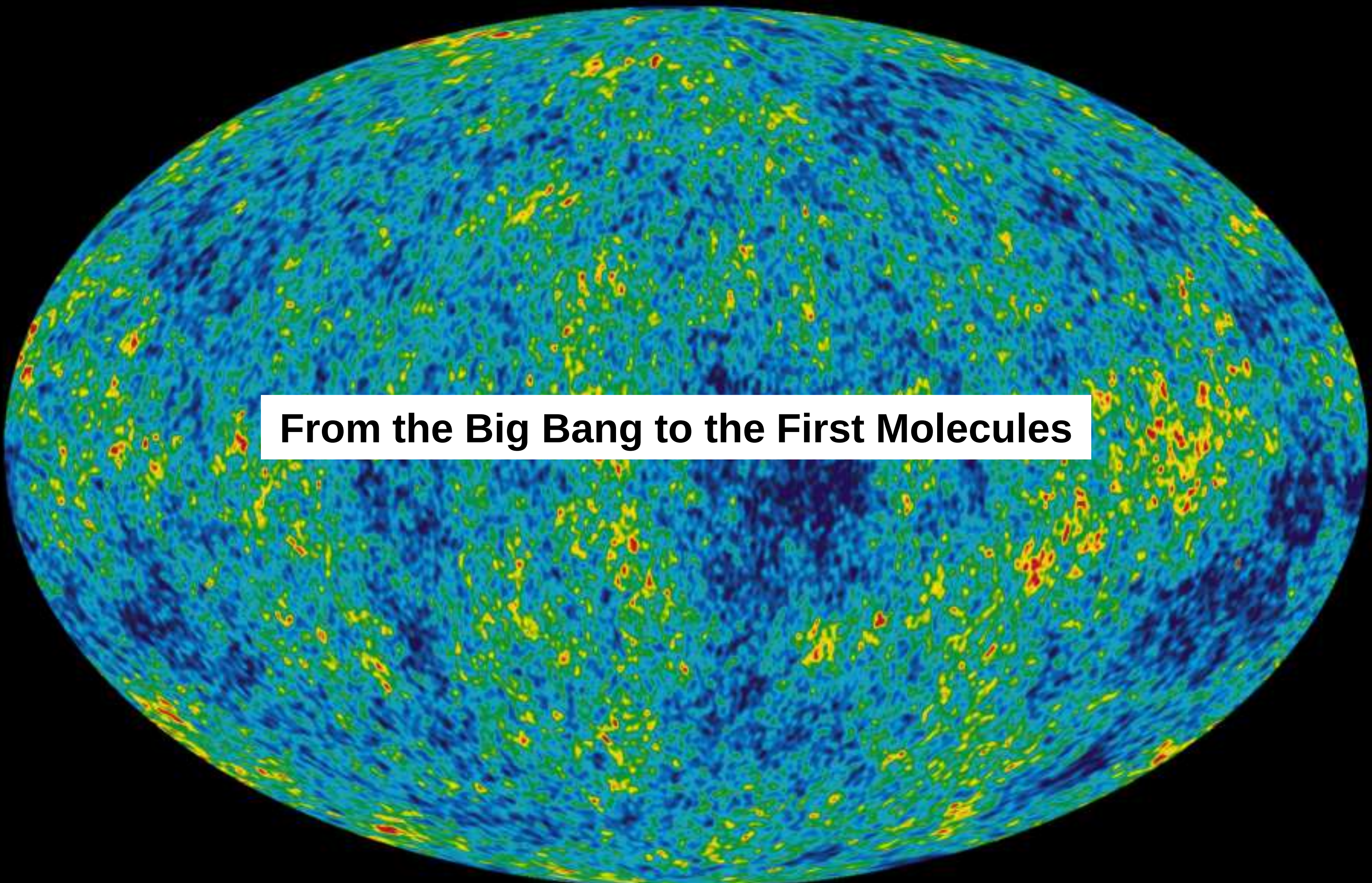




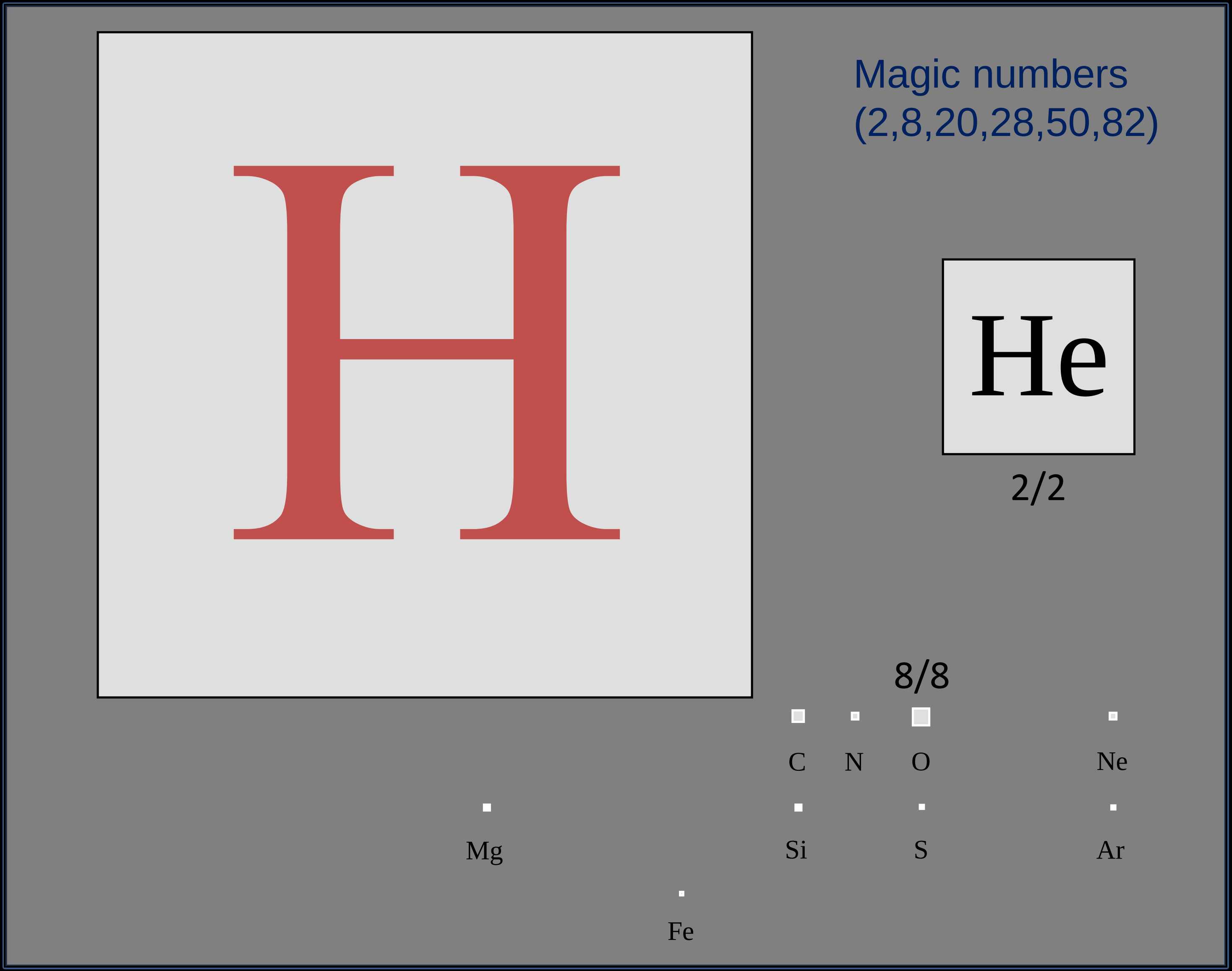




4. Early Universe

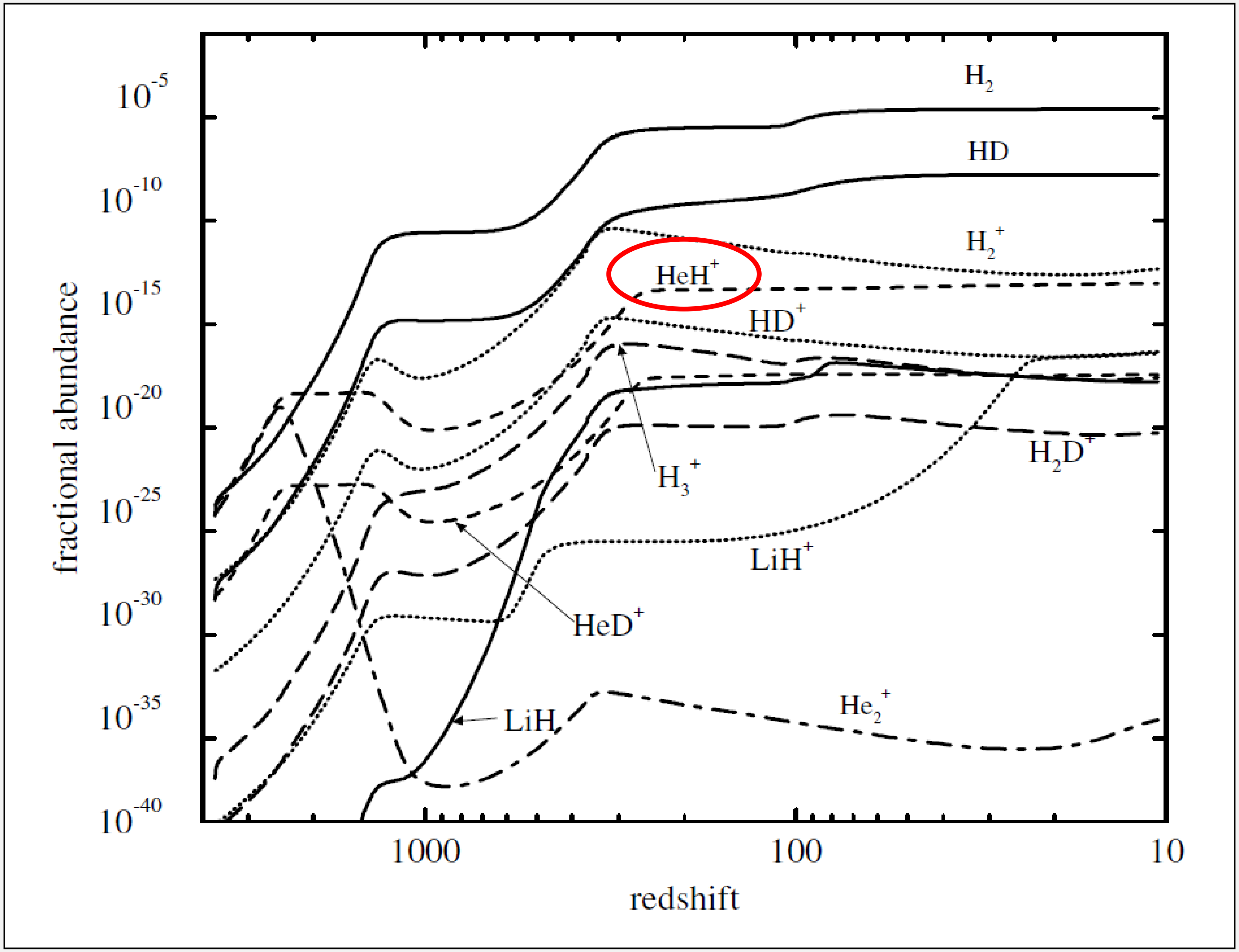


4. Early Universe

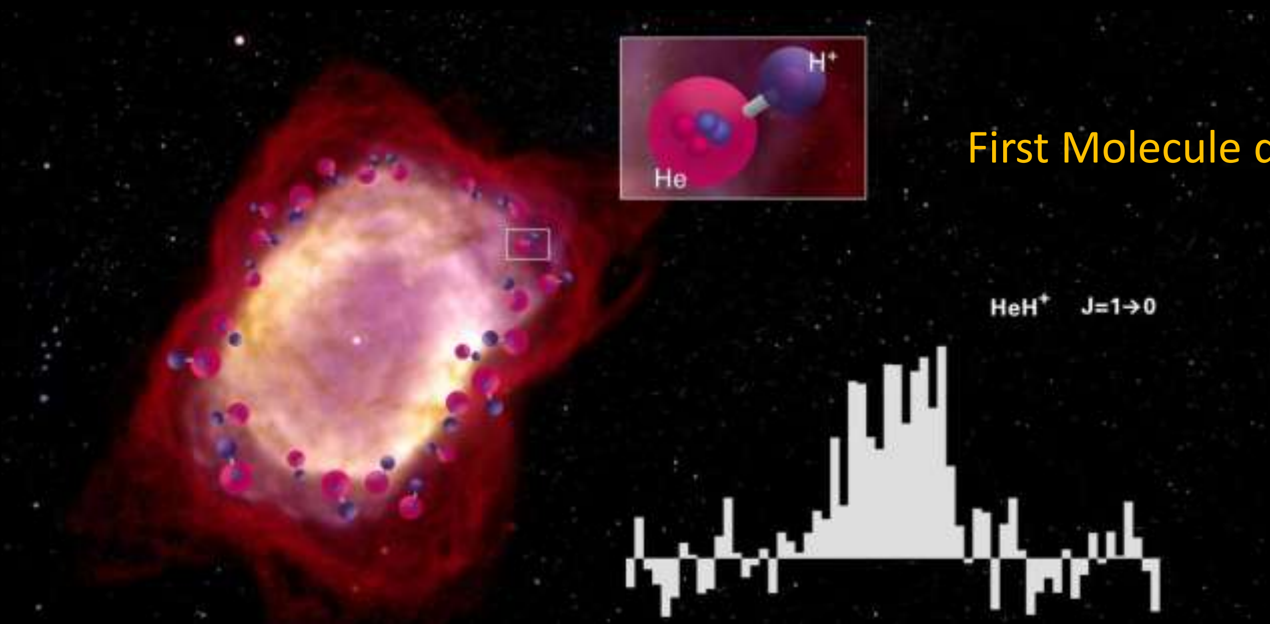


4. Early Universe

The First Molecules



4. Early Universe

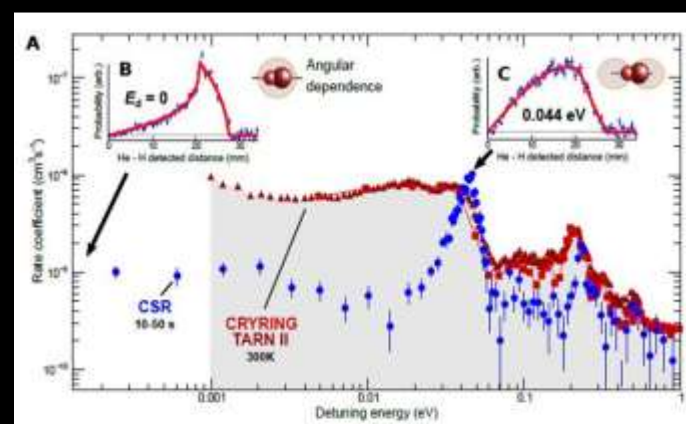


First Molecule detected!

Sofia Teleskop

Güsten et al, Nature 568, 357 (2019)

Storage Ring study of HeH^+ destruction



Novotny et al., Science **365**, 676–679 (2019)

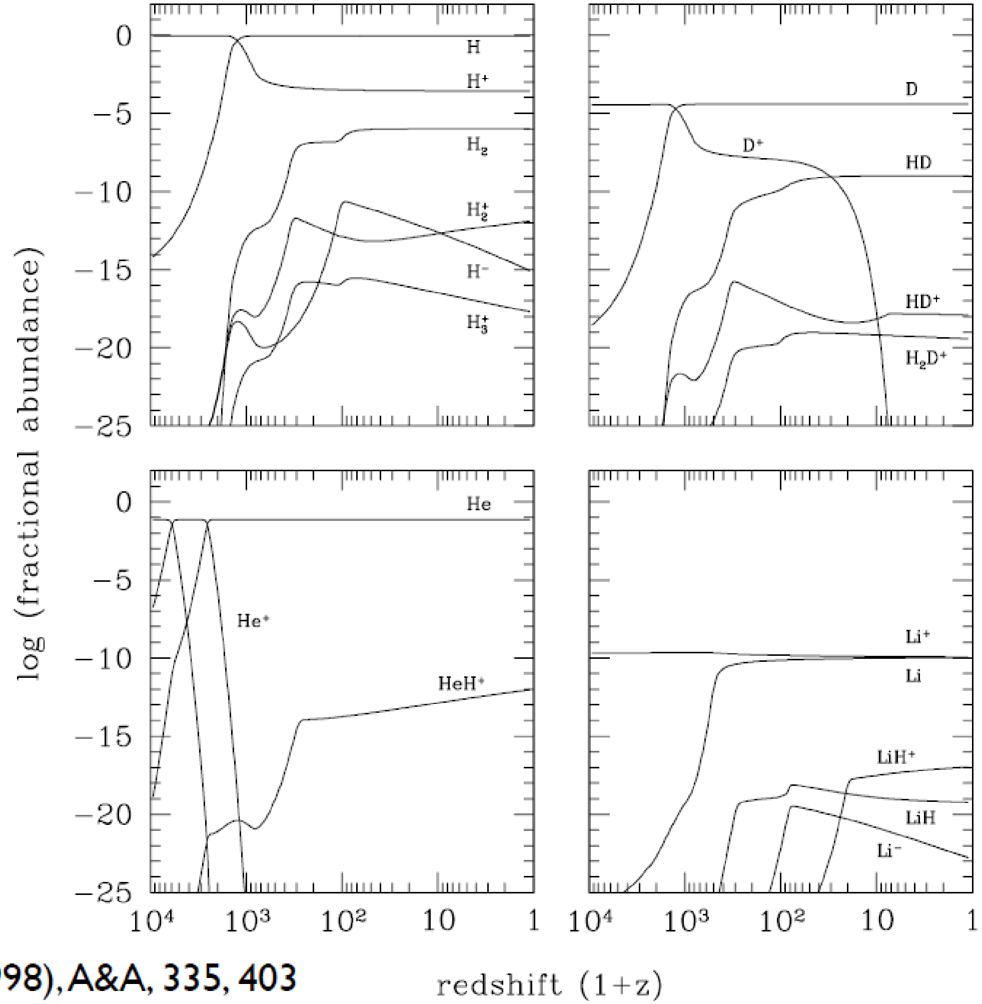
5. Gas-phase molecular processes

Name	Representation	Example	Rate*
Radiative association	$A + B \rightarrow AB + \nu$	$C^+ + H_2 \rightarrow CH_2^+$	$\sim 10^{-10}$-10^{-17} cm^3 s^{-1}
Ion-molecule	$A^+ + B \rightarrow C^+ + D$	$CO + H_3^+ \rightarrow HCO^+ + H_2$	$\sim 10^{-7}$-10^{-10} cm^3 s^{-1}
Neutral-neutral	$A + B \rightarrow C + D$	$O + CH_3 \rightarrow H_2CO + H$	$\sim 10^{-10}$-10^{-16} cm^3 s^{-1}
Charge transfer	$A^+ + B \rightarrow B^+ + C$	$C^+ + Mg \rightarrow C + Mg^+$	$\sim 10^{-9}$ cm^3 s^{-1}
Radiative recombination	$A^+ + e^- \rightarrow A + \nu$	$Mg^+ + e^- \rightarrow Mg + \nu$	$\sim 10^{-12}$ cm^3 s^{-1}
Dissociative recombination	$AB^+ + e^- \rightarrow A + B$	$HCO^+ + e^- \rightarrow CO + H$	$\sim 10^{-7}$ cm^3 s^{-1}
Ionization	$A + h\nu \rightarrow A^+ + e^-$	$C + h\nu \rightarrow C^+ + e^-$	$\sim 10^{-10}$ x RF** cm^3 s^{-1}
Dissociation	$AB + h\nu \rightarrow A + B$	$CO + h\nu \rightarrow C + O$	$\sim 10^{-10}$ x RF cm^3 s^{-1}

Arrhenius rate: $k = \alpha \left(\frac{T}{300}\right)^{\beta} \exp\left(-\gamma/T\right)$

5. Gas-phase molecular processes

Summary: abundances of early molecules



Galli, Palla (1998), A&A, 335, 403

6. Stellar Nucleosynthesis and origin of elements

Hydrogen Burning

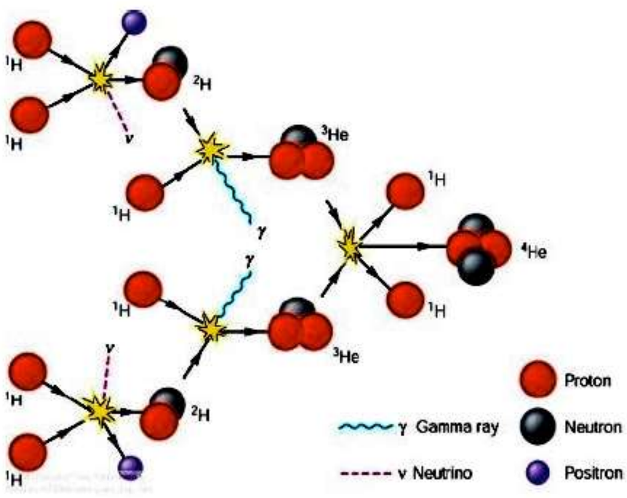
- PP-I cycle, $T > 4 \times 10^6$ K: $4\ {}^1H \Rightarrow {}^4He$:

  $2\ ({}^1H + {}^1H = {}^2D + \beta^+ + \nu_e + 0.42\ MeV)$

  $(\beta^+ + \beta^- = \gamma + 1.02\ MeV)$

  $2\ ({}^1H + {}^2D = {}^3He + \gamma + 5.49\ MeV)$

  ${}^3He + {}^3He = {}^4He + 2\ {}^1H + 12.86\ MeV$



- PP-II cycle, $T > 14 \times 10^6$ K:

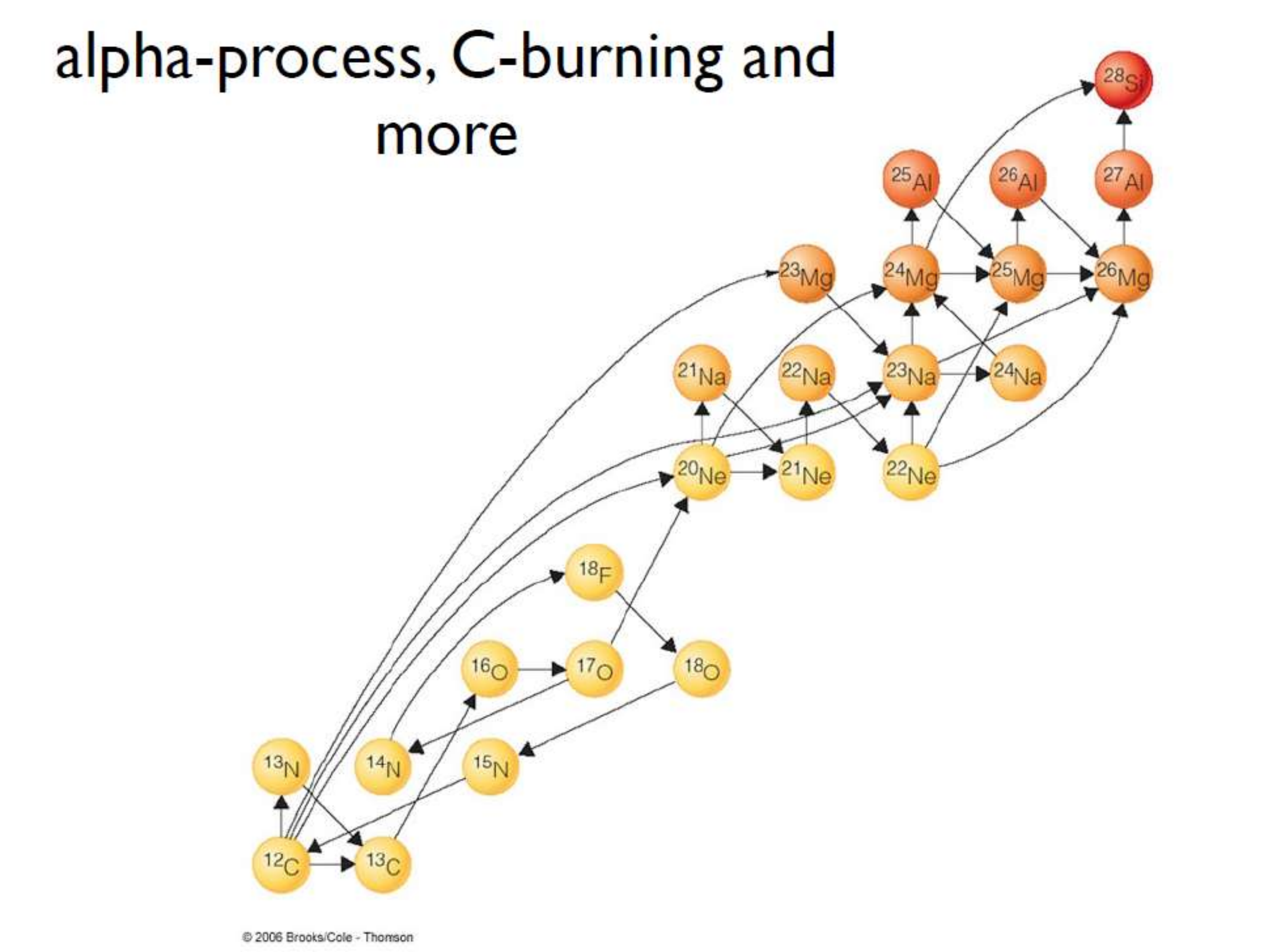
  ${}^3He + {}^4He = {}^7Be + \gamma$

  ${}^7Be + \beta^- = {}^7Li + \nu_e$

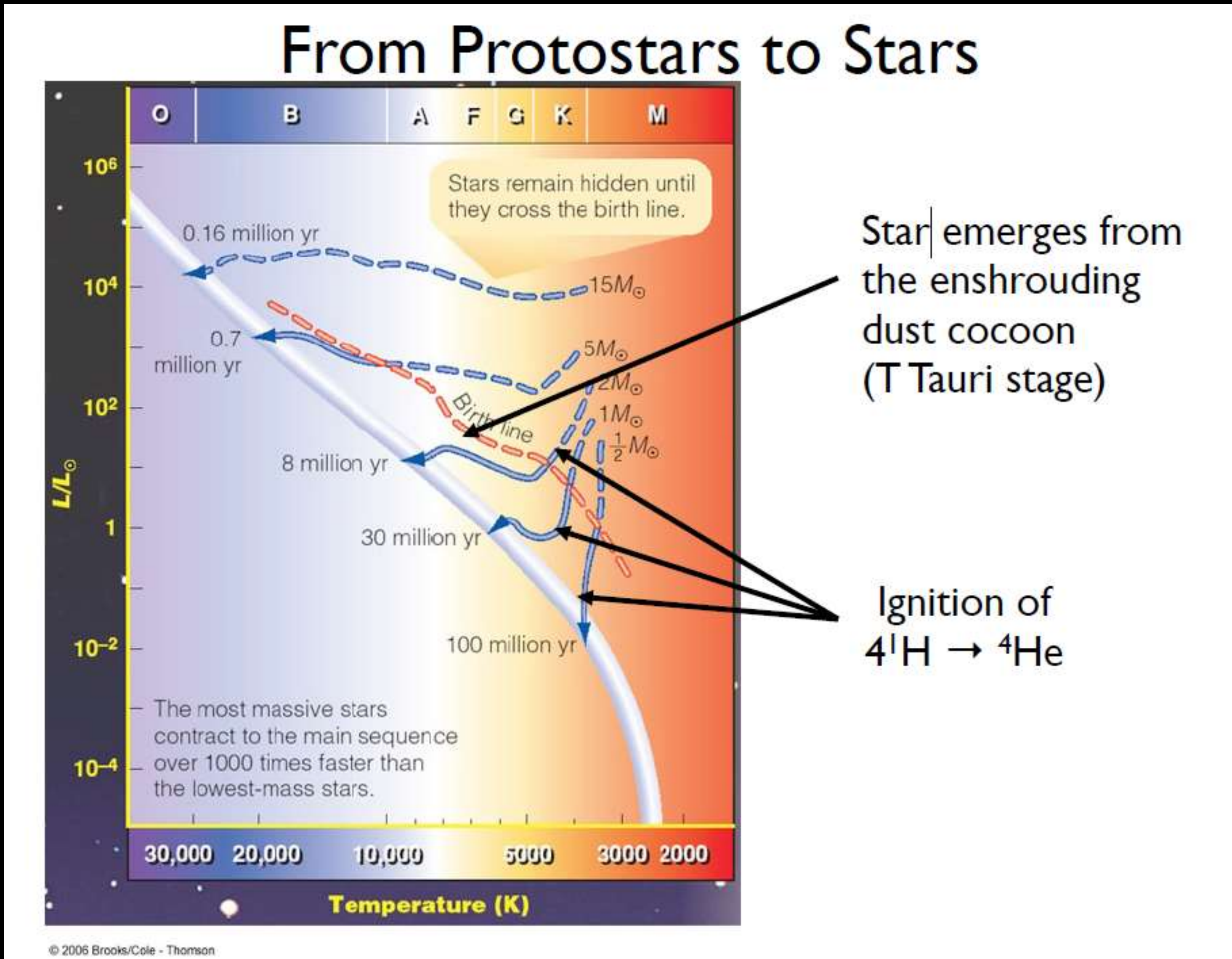
  ${}^7Li + {}^1H = 2\ {}^4He$

- In the Sun, PP-I = 86 %, PP-II = 14 %

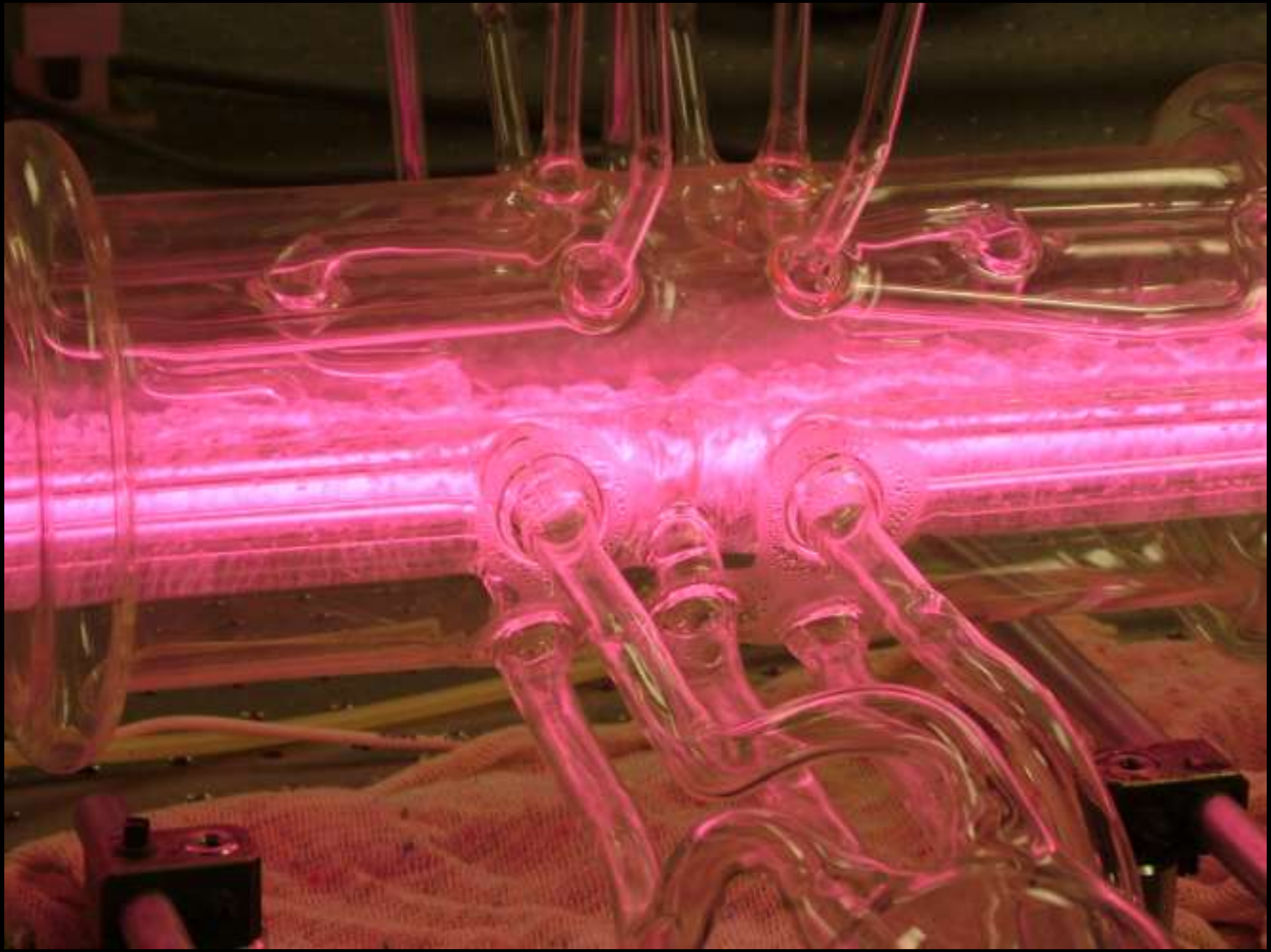
6. Stellar Nucleosynthesis and origin of elements



6. Stellar Nucleosynthesis and origin of elements



7. Laboratory astrophysics: gas-phase experiments

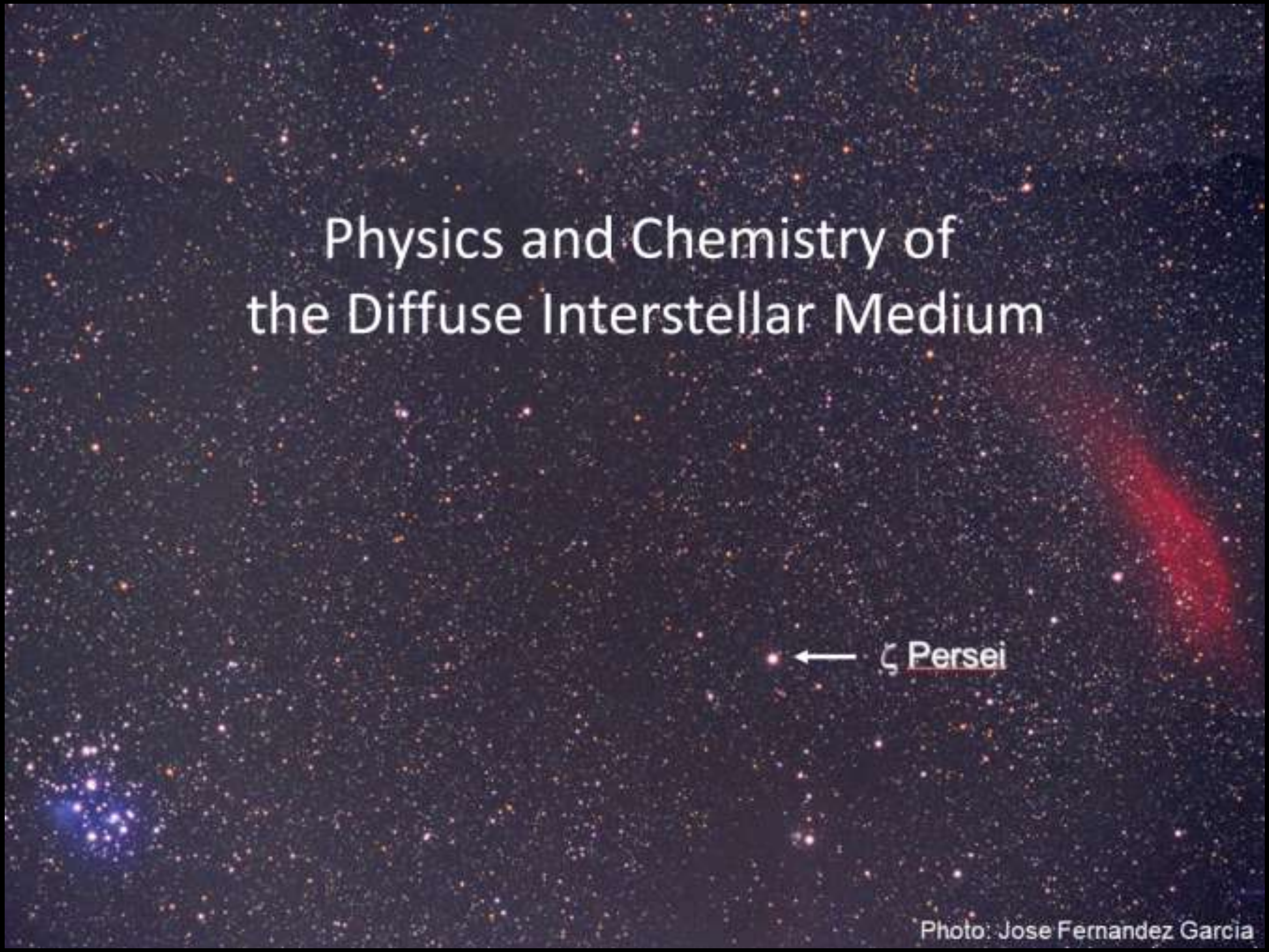


7. Laboratory astrophysics: gas-phase experiments

The Cryogenic Storage Ring CSR at MPIK (Heidelberg)

Temperatures down to 6 K and pressure < 10^{-17} atmospheres

8. The diffuse and dense interstellar medium



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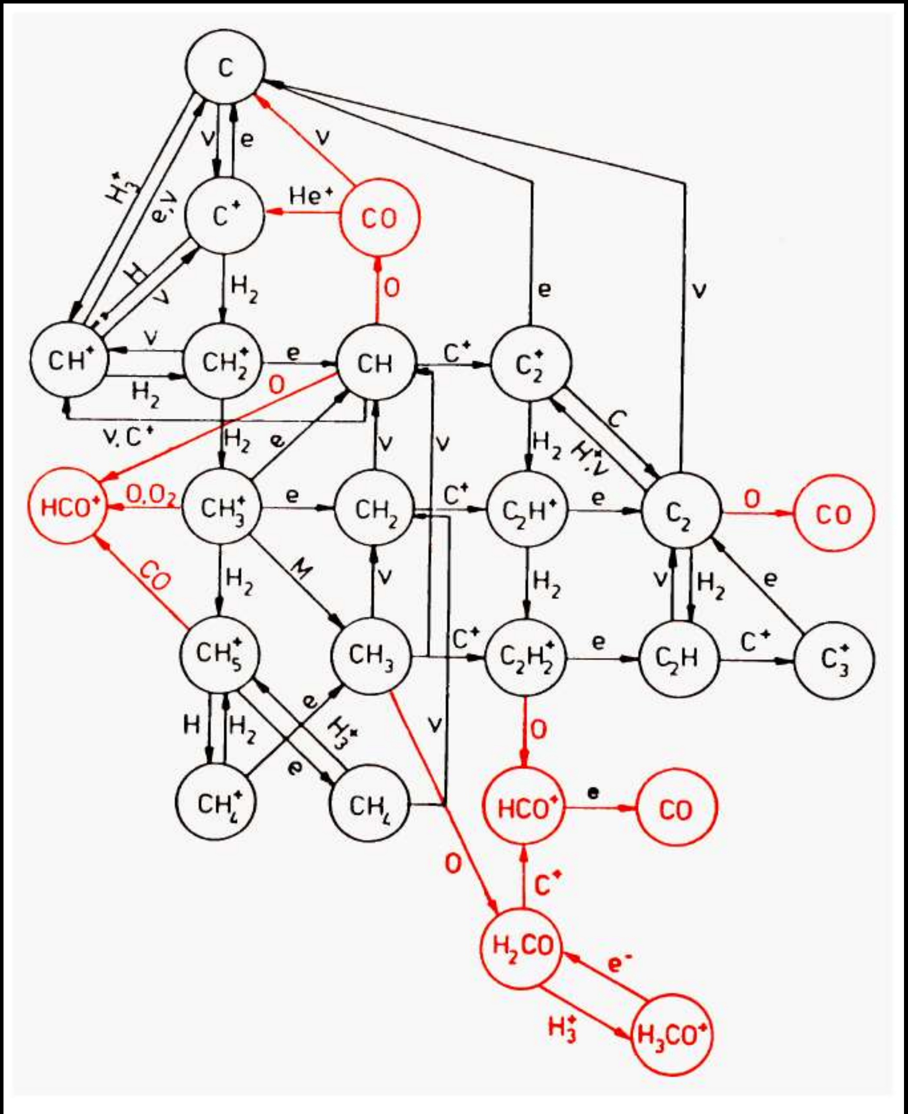
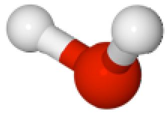


8. The diffuse and dense interstellar medium

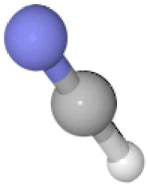
Gas-phase formation of hydrocarbons

$C^+ + H_2 \Rightarrow CH_2^+$



$CH_2^+ + H_2 \Rightarrow CH_3^+ + H$

$CH_3^+ + H_2/O \Rightarrow CH_5^+/HCO^+ + H_2$



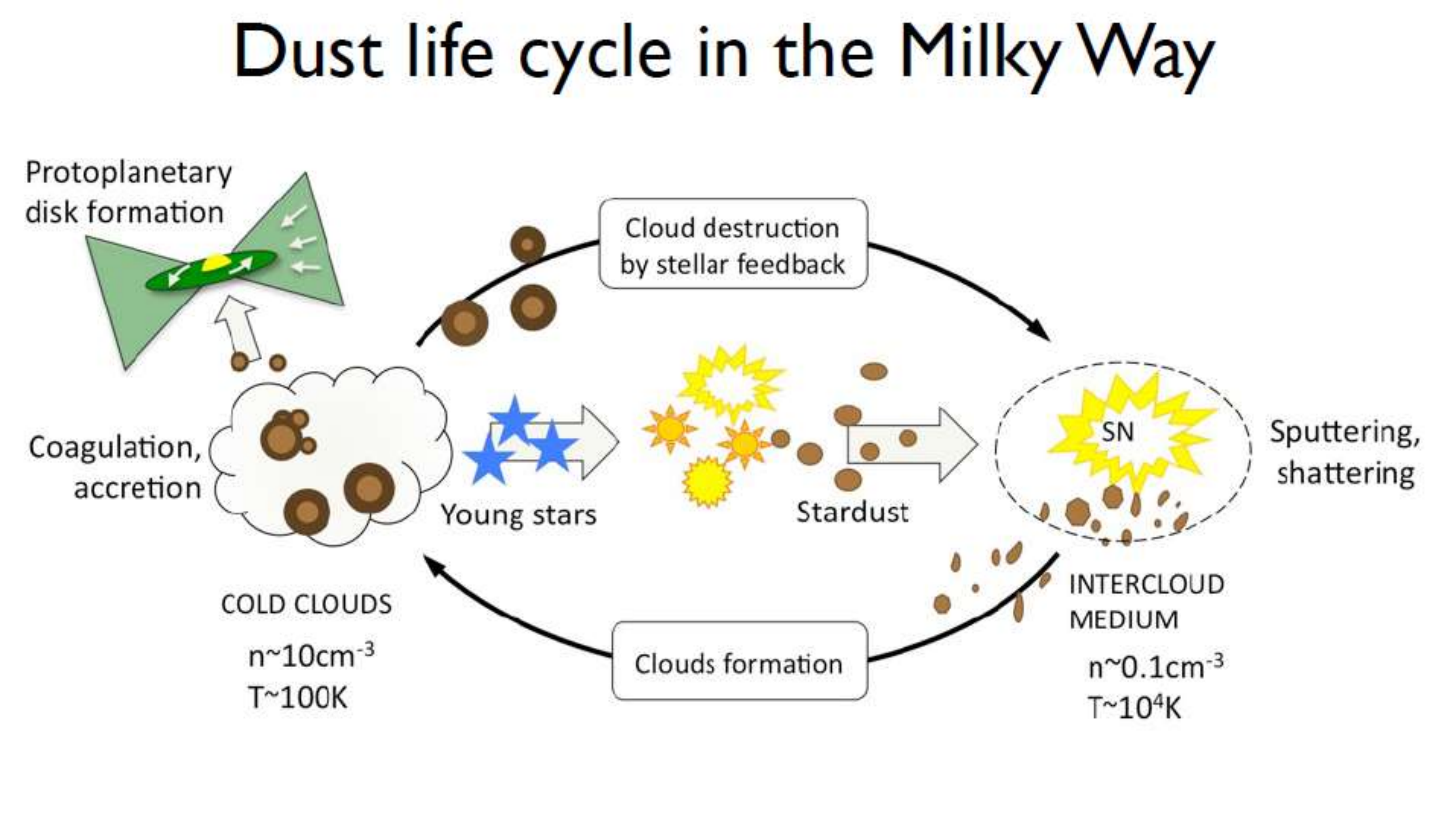
$CH_5^+ + e- \Rightarrow CH_3 + H_2$

$CH_3 + O \Rightarrow H_2CO$

$CH_3^+ + H_2O \nRightarrow CH_3OH_2^+$ (too low rate, Luca et al. 2002)

$CH_3OH_2^+ + e- \Rightarrow CH_3OH + H$ (3 ± 2%, Geppert et al. 2006)

9. Dust evolution and surface processes



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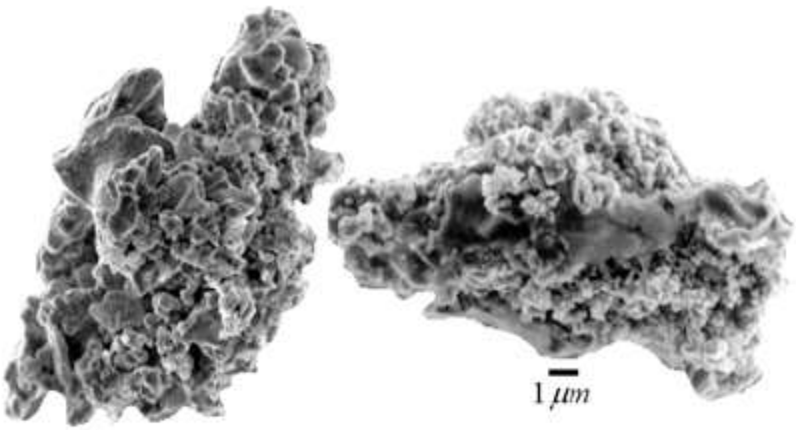
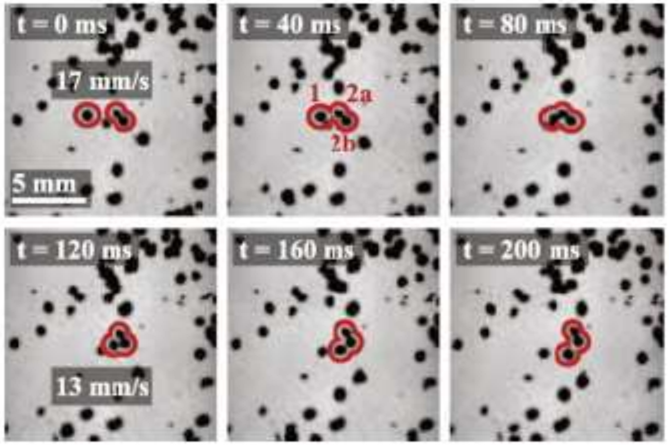
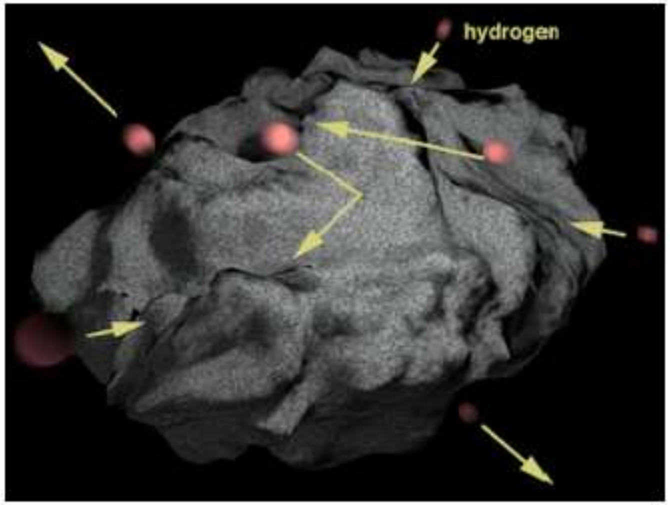


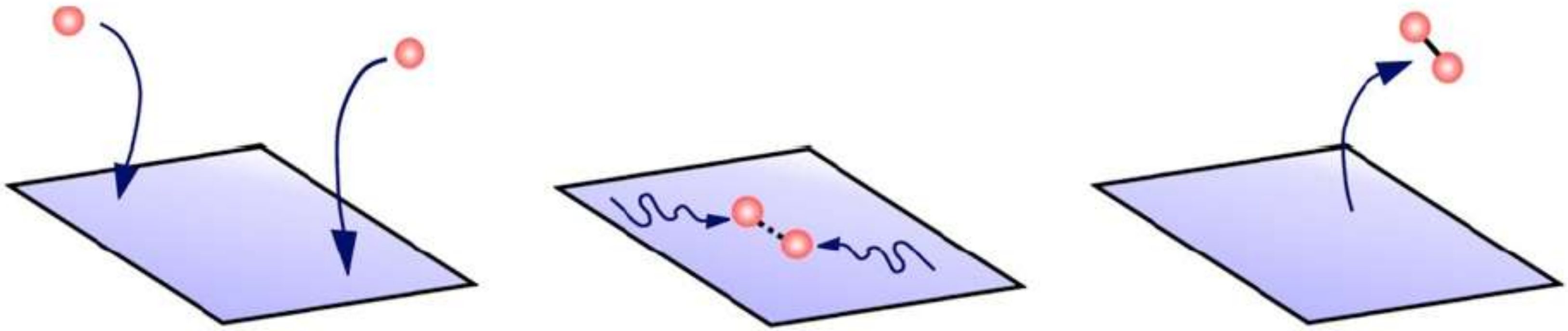




9. Dust evolution and surface processes

Formation of molecules on surfaces

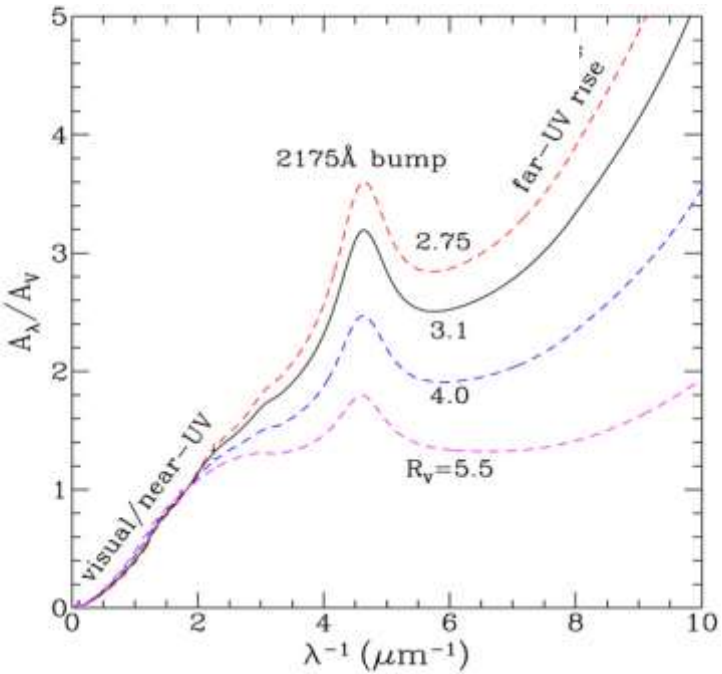
- Heterogenous reaction at the dust particle's surface
  - H_2 formed by such a reaction (Gould & Salpeter 1963)



- 2 mechanisms:
  - 2 H meet on surface (Langmuir-Hinshelwood)
  - 1 gaseous H meets an H on surface (Eley-Rideal)

10. Laboratory astrophysics: surface and dust experiments

Interstellar Extinction Curve

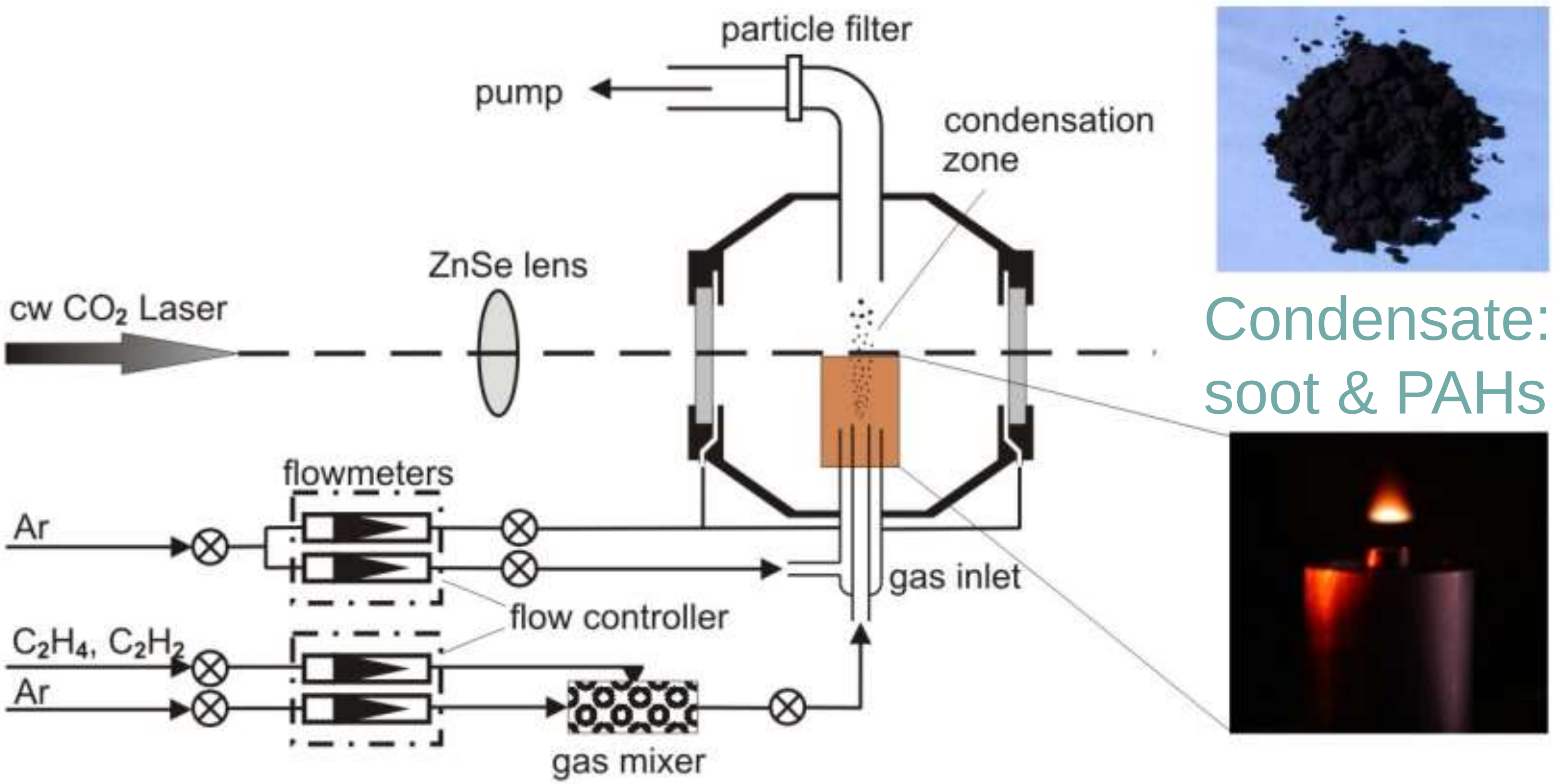


- Grain absorption and scattering processes at a certain wavelength λ are correlated with the size of the particle
- Rise towards the UV means that there are **a lot more small particles**

10. Laboratory astrophysics: surface and dust experiments

Gas-phase condensation by Laser Pyrolysis

Cornelia Jäger MPIA / Friedrich Schiller Universität Jena

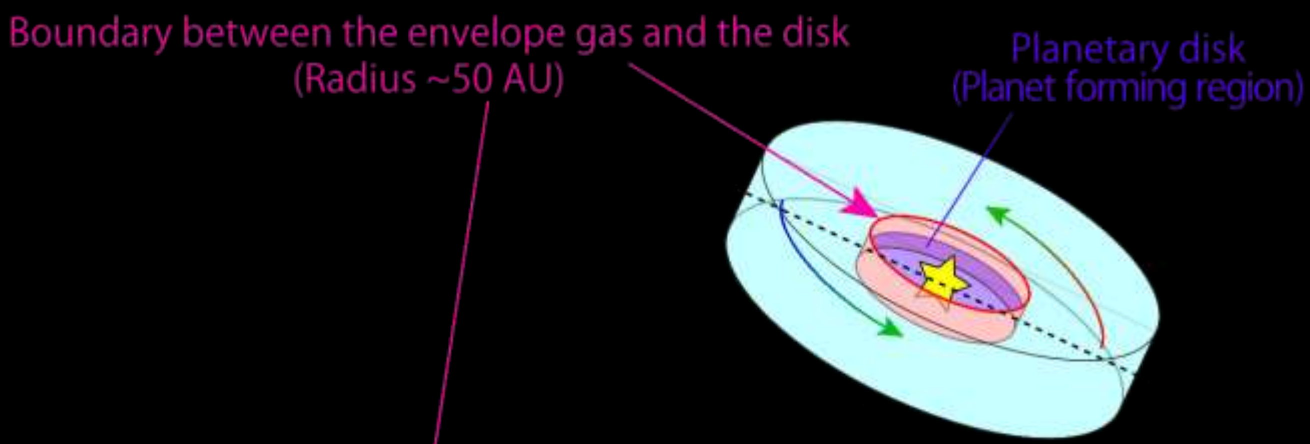


10. Laboratory astrophysics: surface and dust experiments

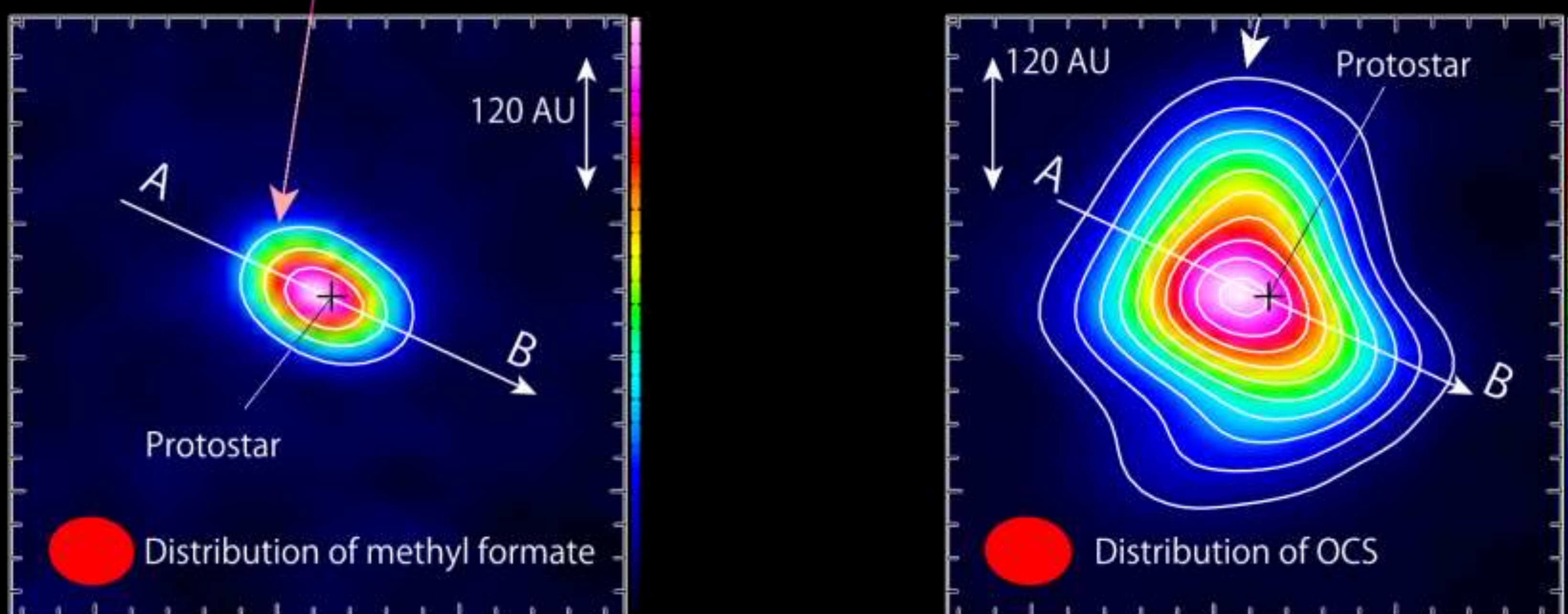
Cosmic Dust Analyzser

Dust accelerator

11. Protostars



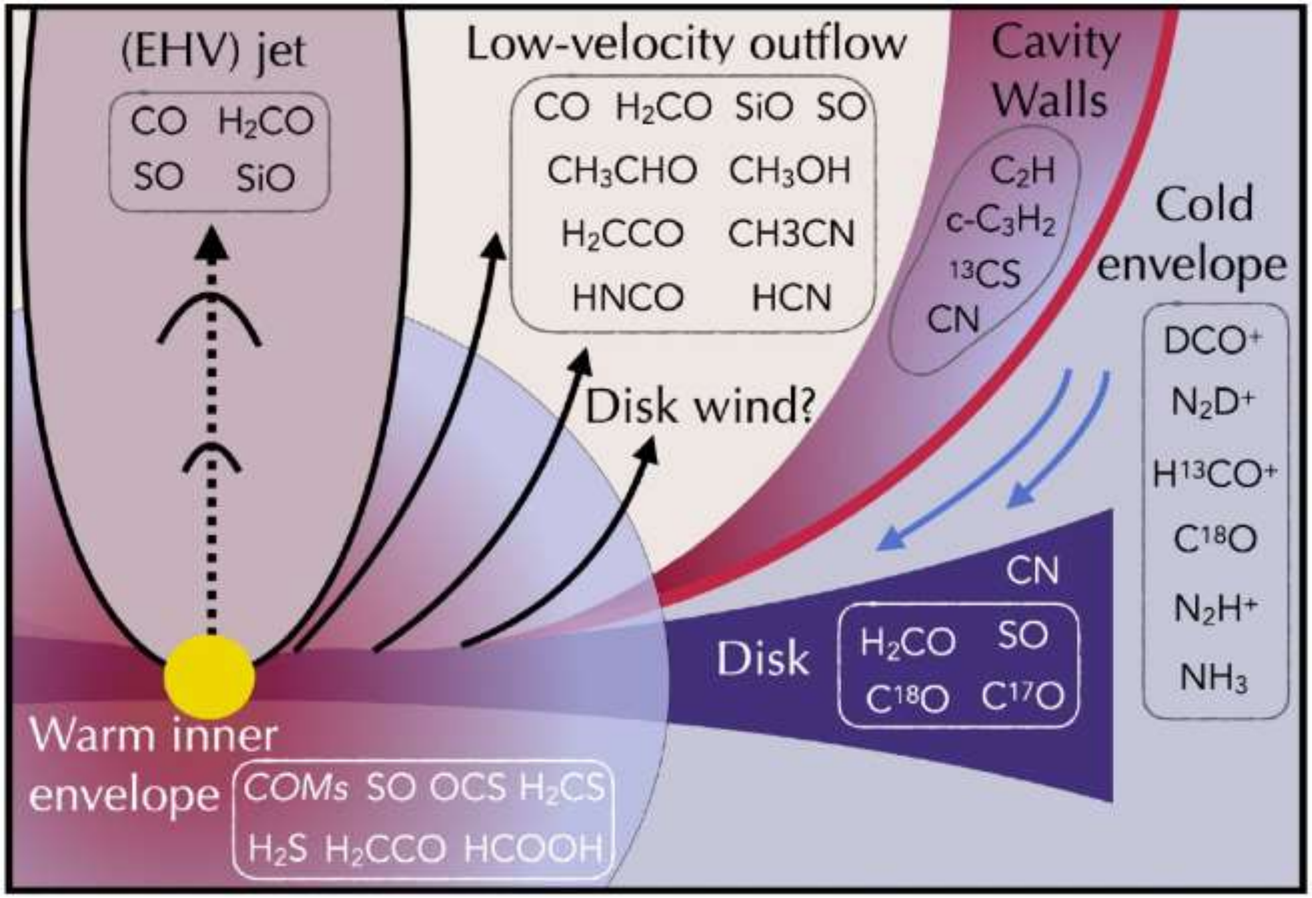
ALMA detects
organic molecules
around newborn star



11. Protostars

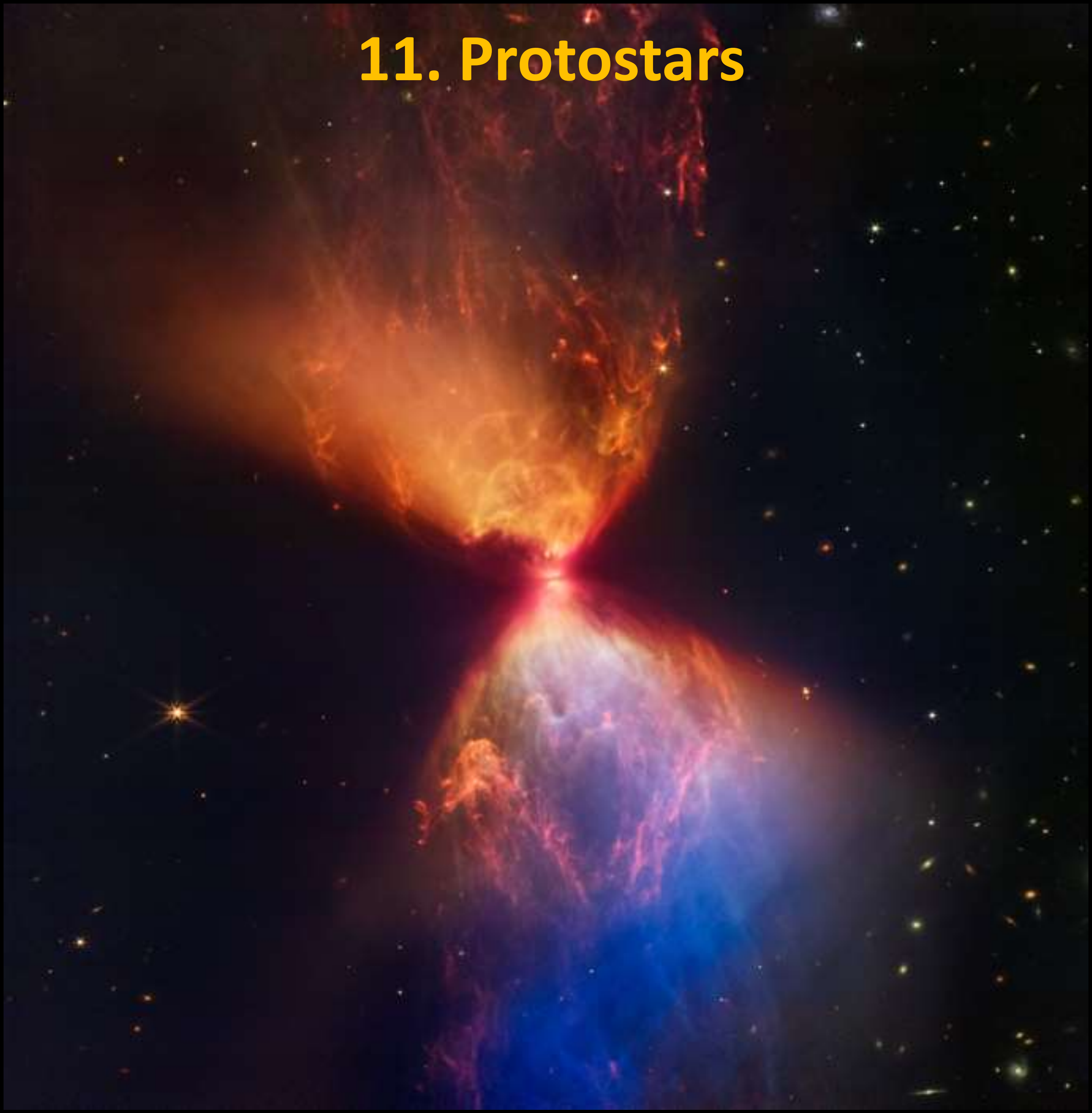
Which molecule traces what ?

Chemical diagnostics of protostellar sources

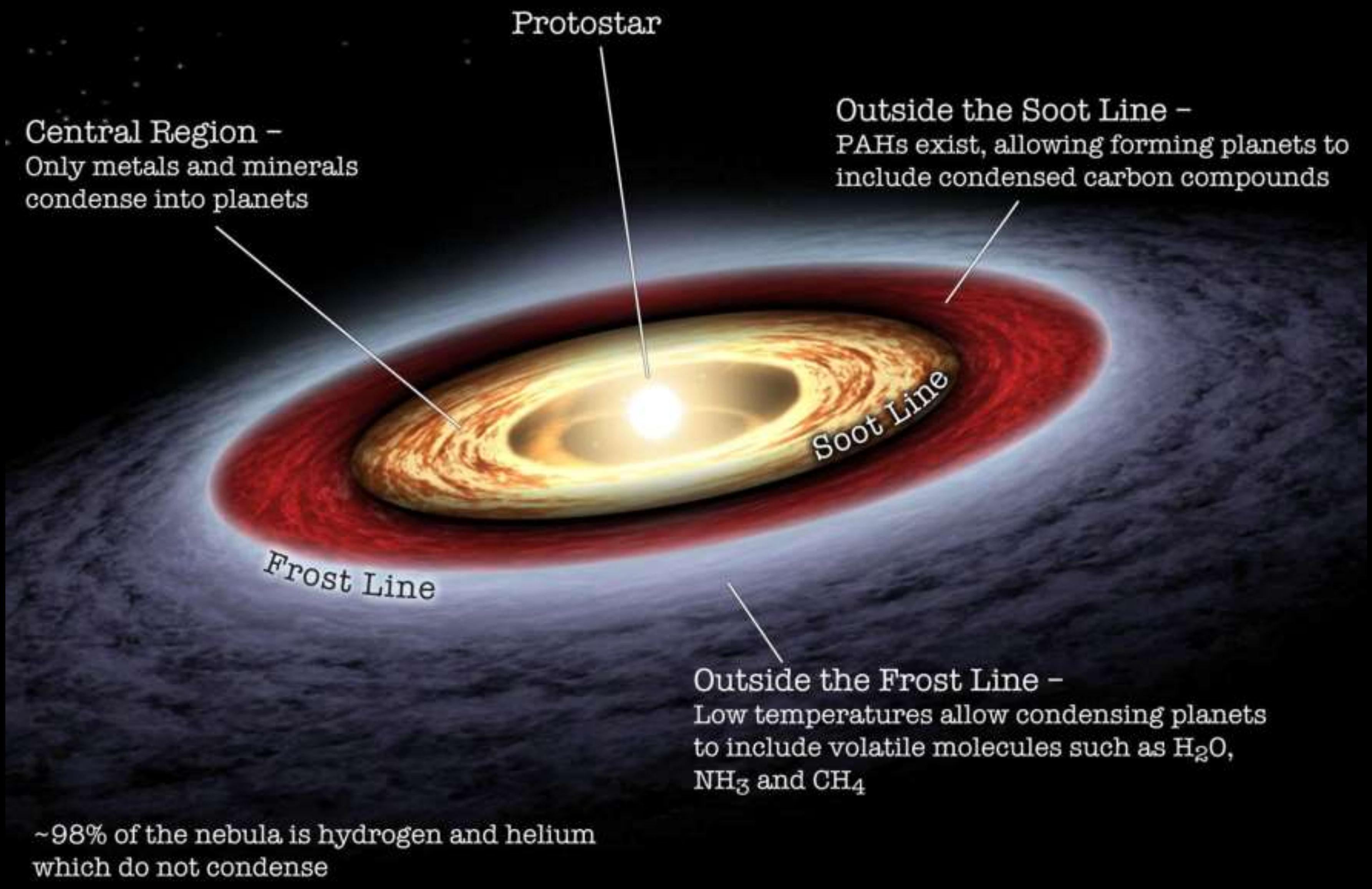


Tychoniec et al. 2021

11. Protostars



12. Protoplanetary disks



12. Protoplanetary disks

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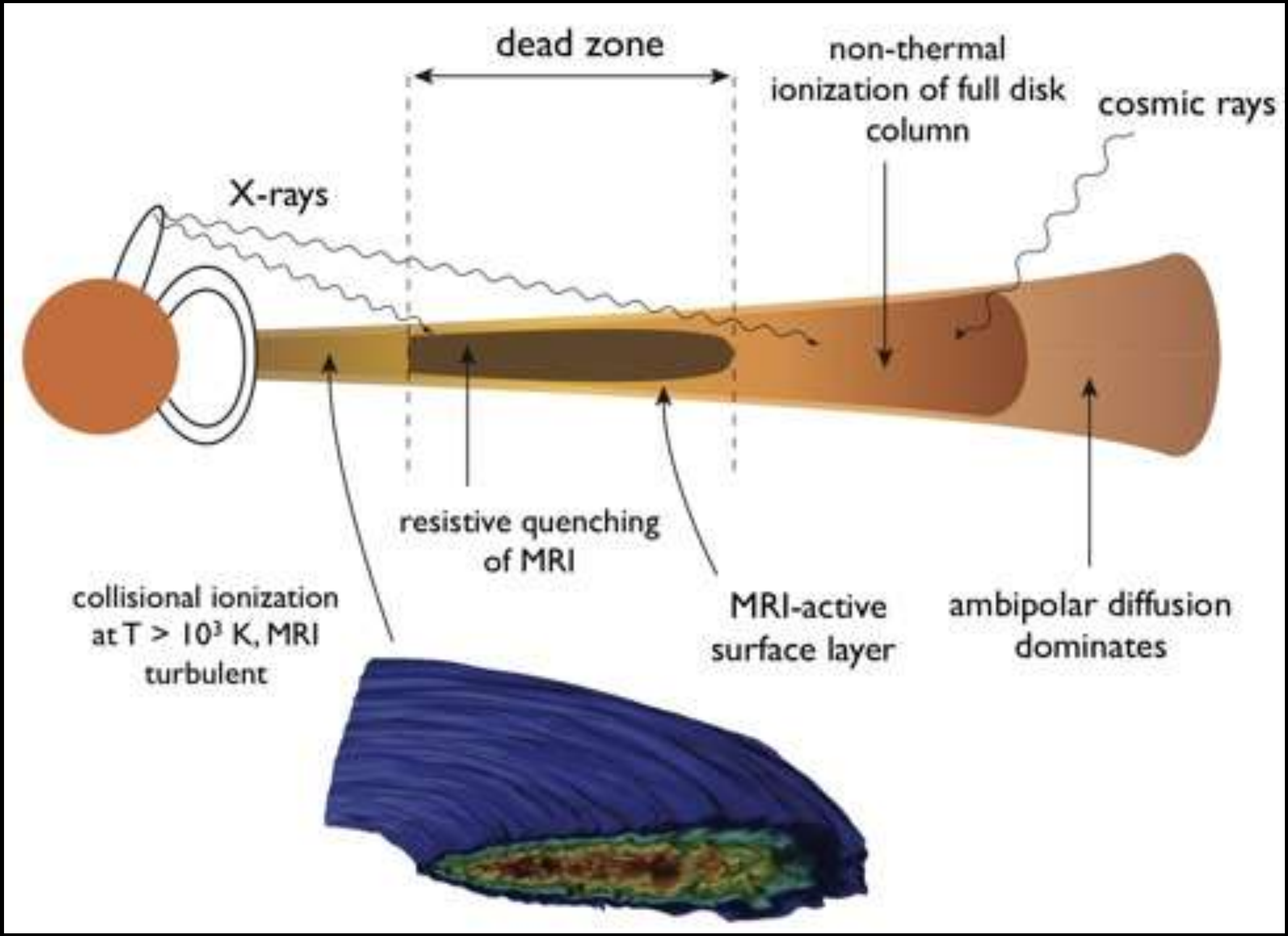
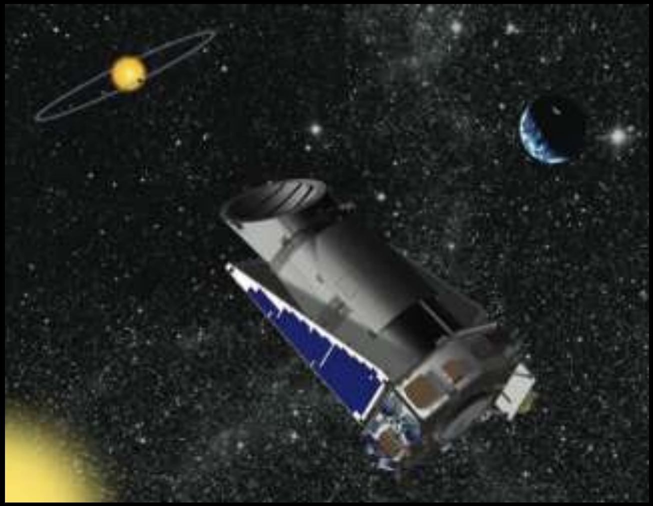


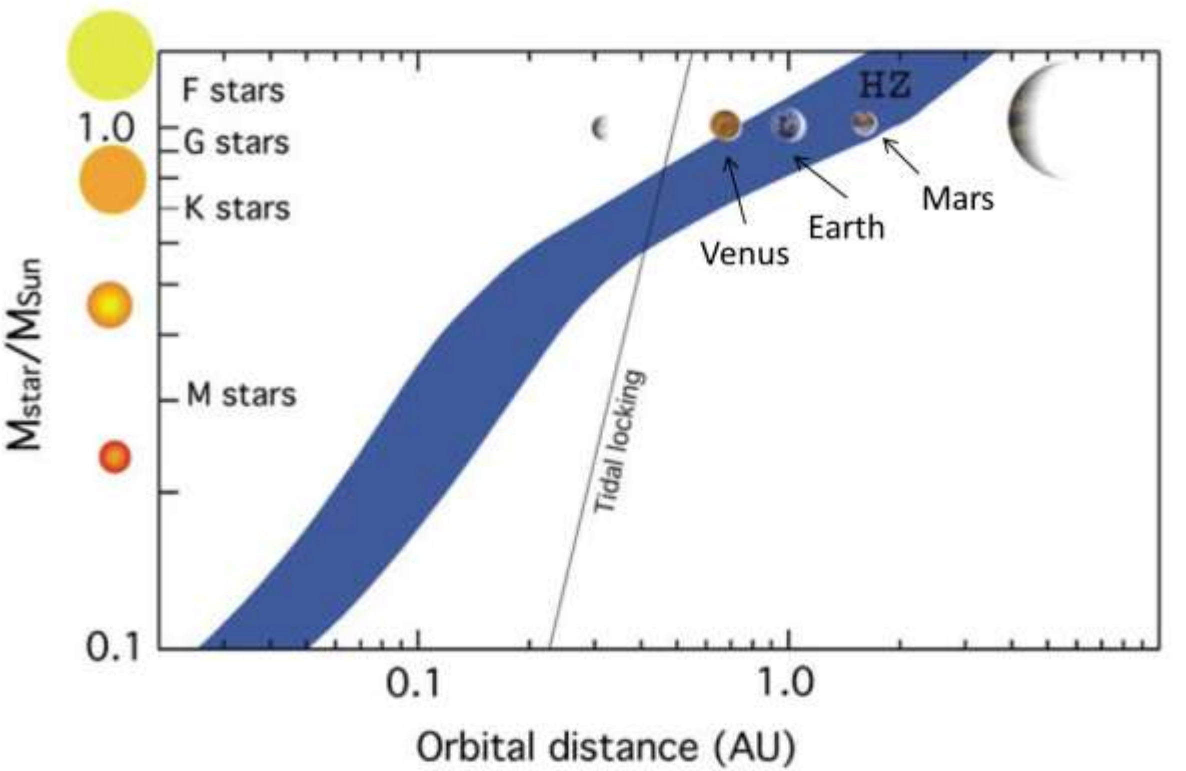
13. Planetary atmospheres, exoplanets, water, and life



13. Planetary atmospheres, exoplanets, water, and life

The habitable zone

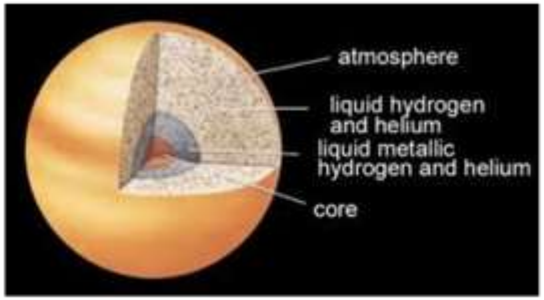
Based on the existence of liquid water on a rocky Earth-like planet



13. Planetary atmospheres, exoplanets, water, and life

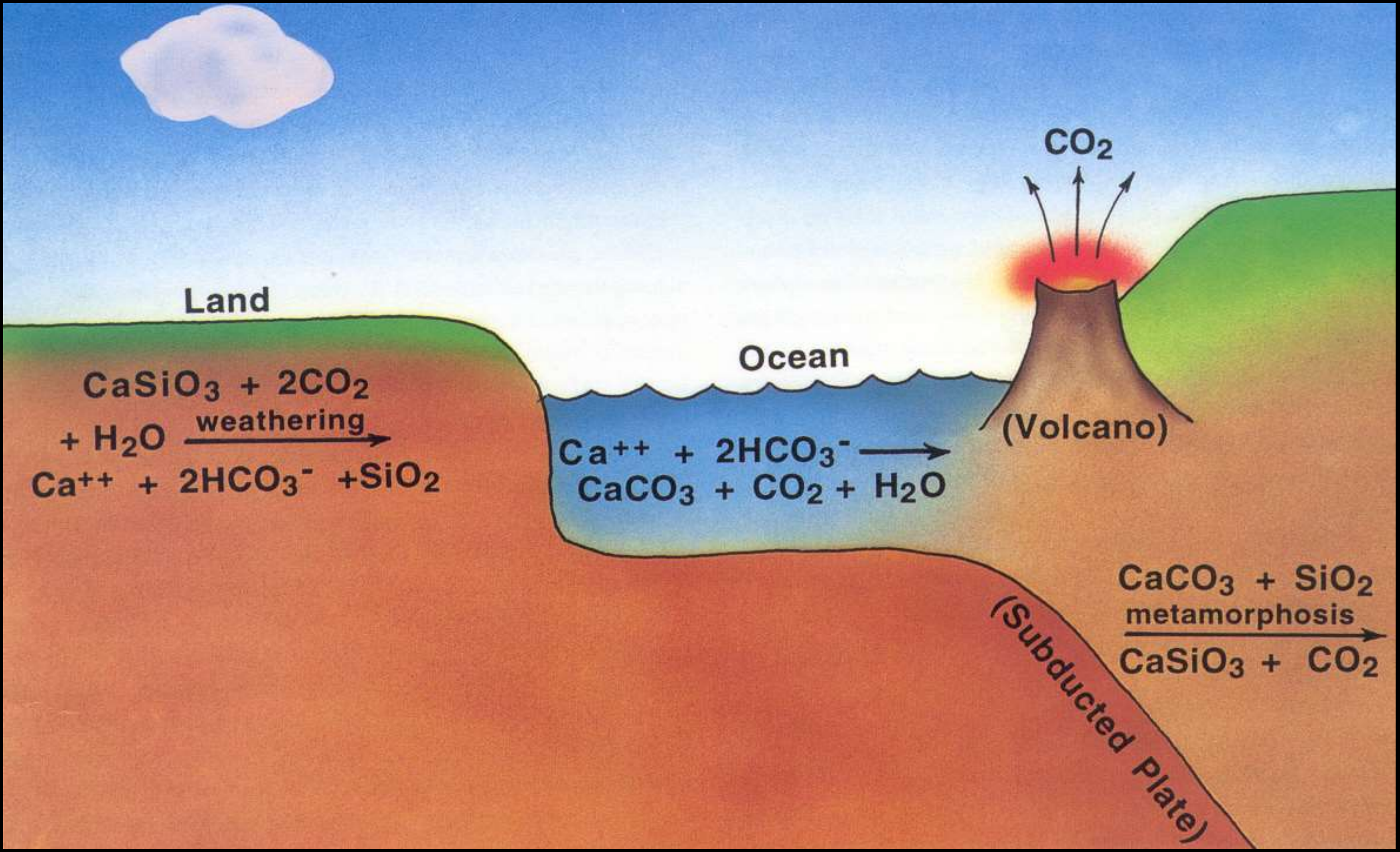
Saturn's Atmosphere

- 96.3% molecular hydrogen,
- 3.25% helium,
- Small amounts of C2H2, NH3, CH4,
- Yellow color from sulfur
- Some ammonia crystals,
- Surface temp: -139C @ 1bar
  -189C @ 0.1 bar



Great white spot
Giant storm

13. Planetary atmospheres, exoplanets, water, and life



14. Excursion

Literature

- Hartquist / Willams, “The chemically controlled cosmos” (1995)
- L. Spitzer, “Physical Processes in the Interstellar Medium”, (1998)
- A.G.G.M. Tielens, "The Physics and Chemistry of the ISM" (2007)
- B. Draine, “Physics of the interstellar and intergalactic Medium” (2010)
- A.G.G.M. Tielens, “Molecular Astrophysics" (2021)

More specialized:

- B. Ryden, “Introduction to Cosmology”
- J. Tennyson: “Astronomical Spectroscopy”

Today:

- B. McGuire, “2021 Census of Interstellar, Circumstellar, Extragalactic, Protoplanetary Disk, and Exoplanetary Molecules”, ApPS 259, 30 (51pp), 2022
- G. Herzberg, “Historical Remarks on the discovery of interstellar molecules” J. Roy. Soc. Can. 82, 115, (1988)
- C.H. Townes., “The discovery of Insterstellar Water Wapor and Ammonia at the Hat Creek Radio Observatory” , ASP Conf. Ser. 356, 2006