# ASTROCHEMISTRY

## FROM THE BIG BANG TO LIFE

*Global Astrochemistry Lecture Series (GALS) 2024*

# BASICS OF ASTROPHYSICS

**Dima Semenov.** *Max Planck Institute for Astronomy, Germany*

**30.01.2024 | 15:00 - 17:00 CET**

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
NanoSpace
Funded by the European Union

# Overview

- **Basic concepts, nomenclature, limitations, ...**
- Big Bang & early Universe
- Cosmic cycle of matter
- Observational techniques, models, experiments







## About myself:

- From Saint-Petersburg, Russia
- PhD in Astrophysics (2005), Friedrich-Schiller University, Jena
- Post-doc/Staff at MPIA (Heidelberg)

semenov@mpia.de

## (Scientific) interests:

- (Sub-)millimeter observations, theoretical astrochemistry
- Star and planet formation
- Origin of life
- *Hiking, walking, photography, cooking, ...*

# What is “Astronomy/Astrophysics"?
# What is “Astrochemistry?”

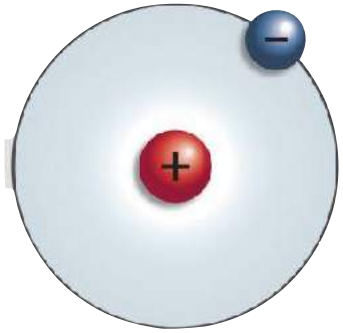
A. Eddington:
**"Atoms are physics but molecules are chemistry"**

- Molecular astrophysics (astrochemistry): formation and destruction of molecules in the Universe, their interaction with radiation and their feedback on physics of the environments

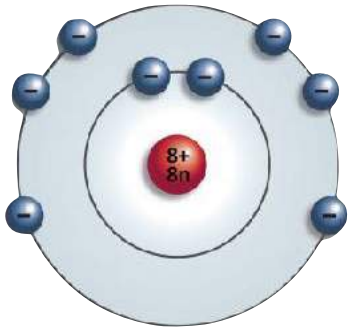
- Interdisciplinary field: physics + chemistry + astronomy (+ biology)

- Observations + Theoretical models + Laboratory data

# What is Interstellar Matter made of?
# Atoms vs Molecules



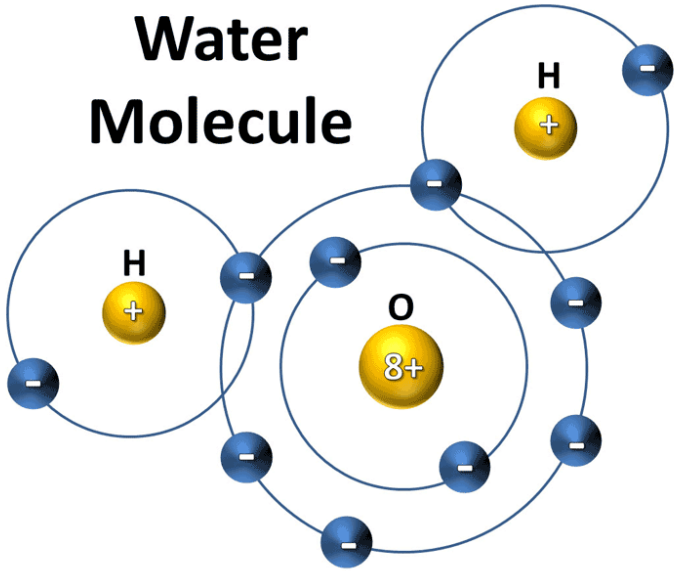
**Hydrogen atom**




**Oxygen atom**

- Atom is the smallest unit of matter
- Basic neutral particle of a chemical element
- Nucleosynthesis (Big Bang, stars)

**Water Molecule**

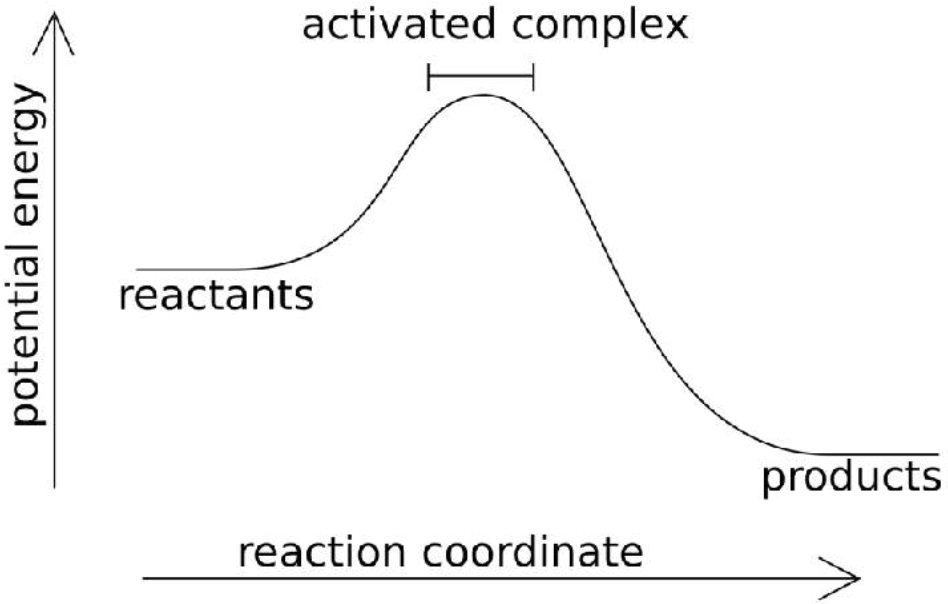



- Molecule is the smallest particle of a chemical compound
- Atoms bound by sharing electrons in the outermost $e^-$ shells (chemical bonds)

- Ion: charged atom or molecule
- Radical: have unpaired $e^-$

# Chemical reactions

- Transformation of substances by creating, changing or destruction of chemical bonds
- Rearrangement of outer (valence) electrons
- A + B ⇒ Activated complex $AB^*$ ⇒ Stabilization ⇒ C + D



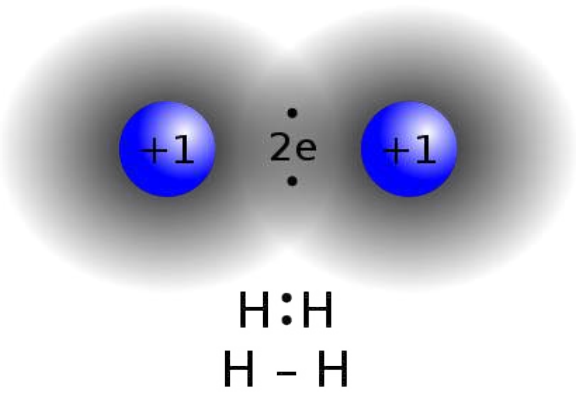
# Covalent bonds

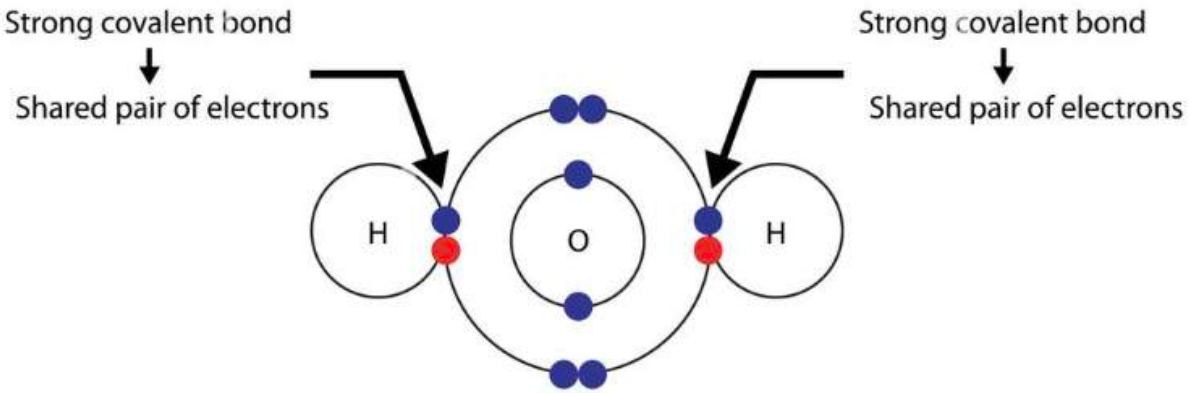
- Irving Langmuir (1919)
- Covalent bond: electron pairs shared between atoms
- Stable balance of attractive and repulsive forces
- Valence electron is an electron in the outermost shell
- Via covalent bonds, atoms may attain full valence shells ⇒

stable electronic configurations



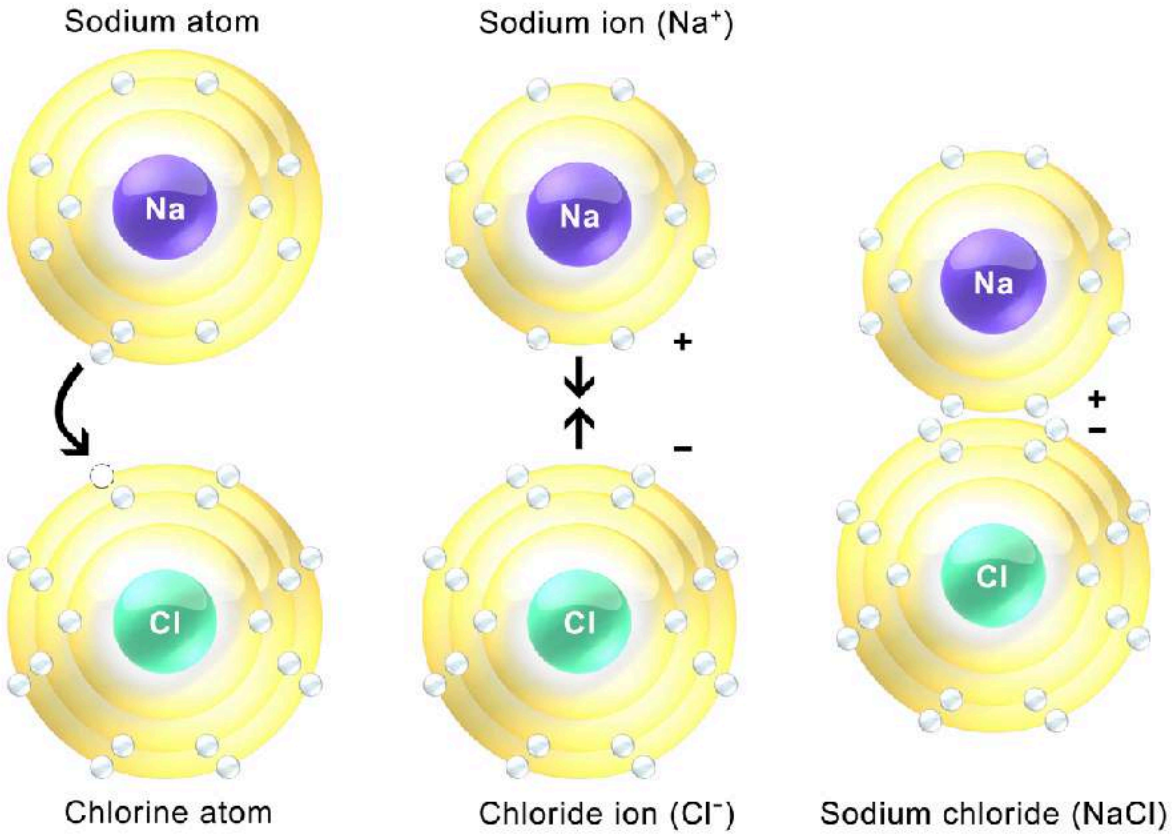
(1881 – 1957)



# Ionic bonds

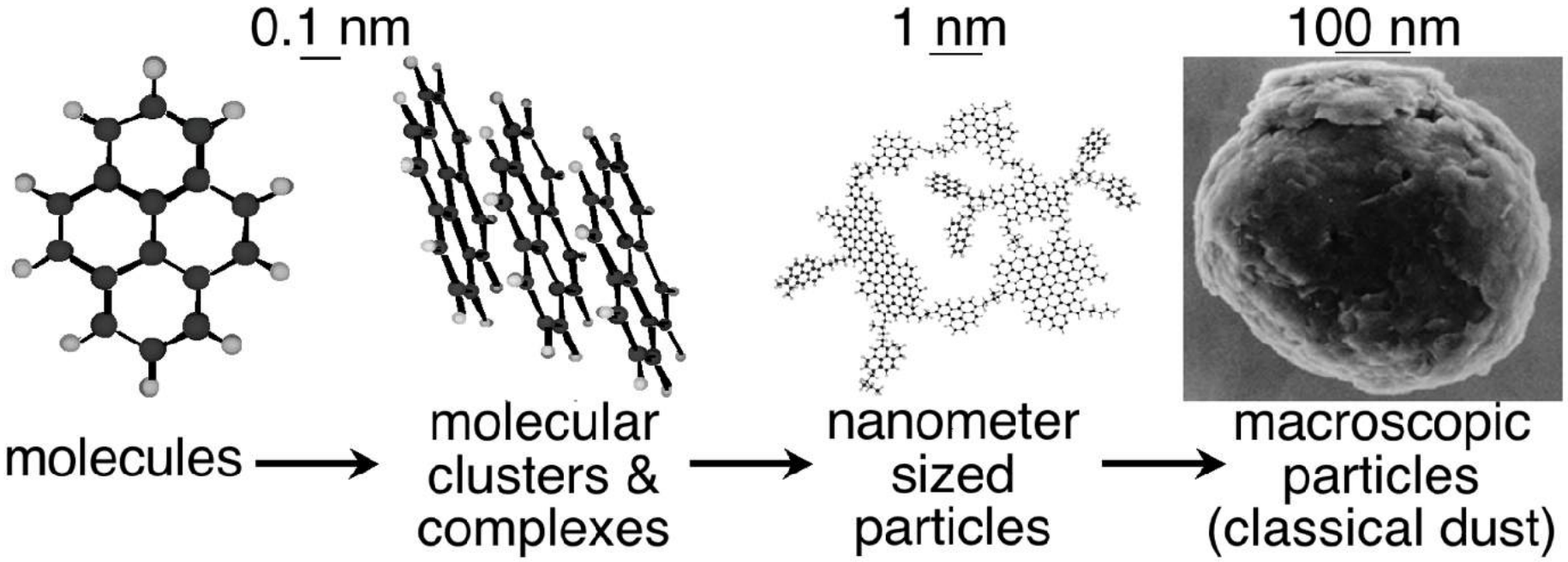
- Electrostatic attraction between oppositely charged atomic ions
- Transfer of e- to obtain full valence shells (electrovalence)
- Exists along with covalence bonding (ionic is stronger)



# Typical bond energies

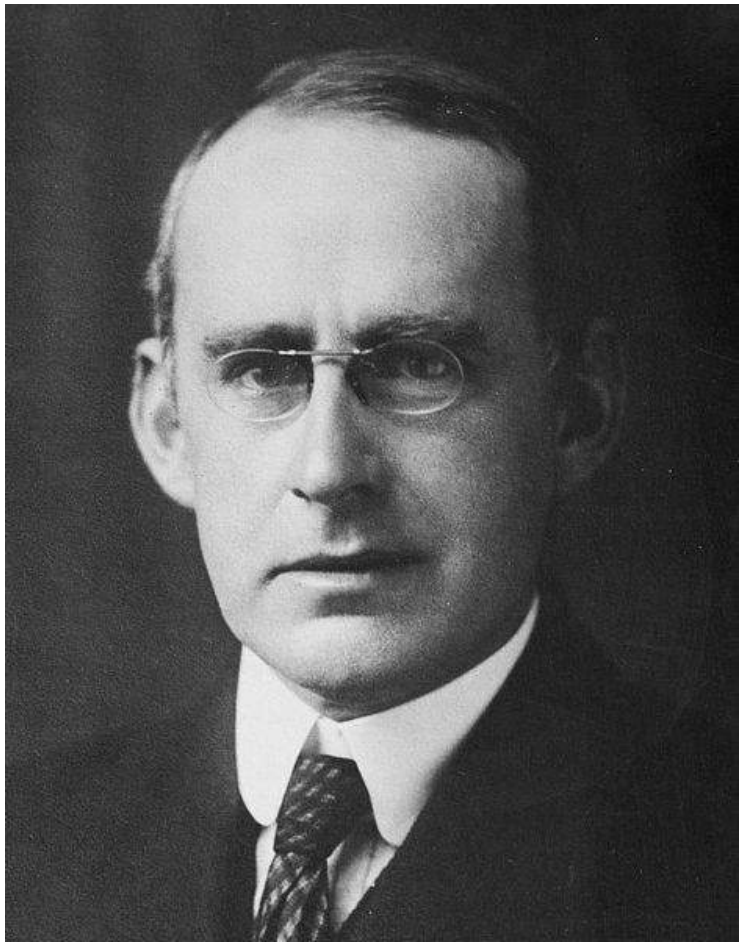
| | | |
|---|---|---|
| C≡O | **Carbon monoxide** | 11.16 eV |
| H–C≡C–H | Acetylene | 10.07 eV |
| N≡N | Nitrogen | 9.71 eV |
| NaCl | *Sodium chloride* | 7.94 eV |
| C≡N | Cyanogen | 7.77 eV |
| O=C=O | Carbon dioxide | 5.50 eV |
| O=O | Oxygen | 5.11 eV |
| H–O–H | **Water** | 5.11 eV |
| $NH_3$ | Ammonia | 4.58 eV |
| $CH_4$ | Methane | 4.49 eV |
| H–H | **Hydrogen** | 4.478 eV |
| O–H | Hydroxyl | 4.41 eV |

# What is Interstellar Matter made of? Molecules vs Dust




- Microscopic and macroscopic solids
- Sizes: ~ 0.5 nm – 1 mm ($5 \times 10^{-8}$ – 0.1 cm)
- Covalent bonds or van der Waals force or $e^-$ clouds
- Efficient absorbers of light

# What is Interstellar Matter made of? Molecules in Space? How?



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

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

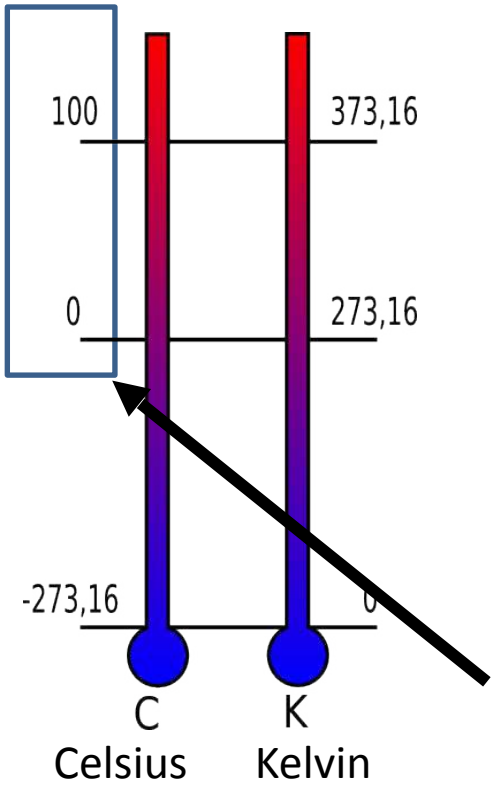
(Received May 21, 1926.)

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?

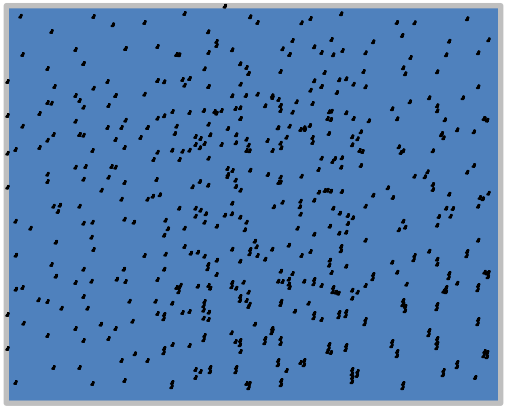
Sir Arthur Stanley Eddington (1926)

"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."

# Chemistry in space must be different …




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



Sea level on Earth:
$10^{19}$ particles pro $cm^3$



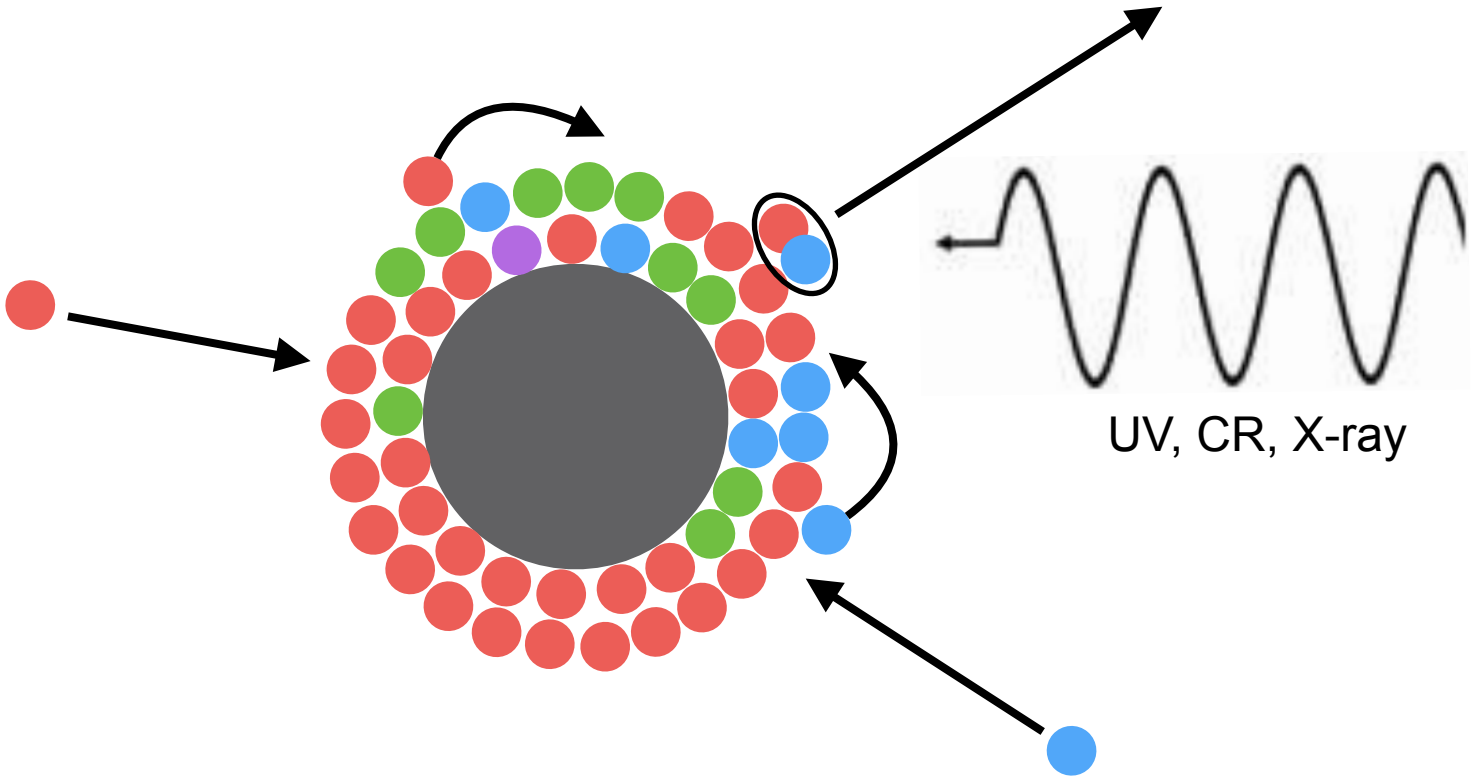
Interstellar space:
1–1000 particles pro $cm^3$

- Cryogenic temperatures (below -150 C)
- No reactions with activations barriers
- Ultra high vacuum (> $10^{-22}$ bar pressure)
- No 3-body collisions

# Gas-phase molecular processes

| Name | Representation | Example | Rate* |
|---|---|---|---|
| Radiative association | $A + B \rightarrow AB + v$ | $C^+ + H_2 \rightarrow CH_2^+$ | $\sim 10^{-10}$-$10^{-17}$ $cm^3\ s^{-1}$ |
| 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 | $A^+ + e^- \rightarrow A + v$ | $Mg^+ + e^- \rightarrow Mg + v$ | $\sim 10^{-12}$ $cm^3\ s^{-1}$ |
| Dissociative recombination | $AB^+ + e^- \rightarrow A + B$ | $HCO^+ + e^- \rightarrow CO + H$ | $\sim 10^{-7}$ $cm^3\ s^{-1}$ |
| Ionization | $A + hv \rightarrow A^+ + e^-$ | $C + hv \rightarrow C^+ + e^-$ | $\sim 10^{-10}$ x RF** $cm^3\ s^{-1}$ |
| Dissociation | $AB + hv \rightarrow A + B$ | $CO + hv \rightarrow C + O$ | $\sim 10^{-10}$ x RF $cm^3\ s^{-1}$ |

# Dust surface chemistry




1. Accretion
2. Diffusion via hopping or tunneling
3. Surface recombination: $H_2$, $H_2O$, $NH_3$, organics,…
4. Desorption or destruction (UV, X-rays, cosmic rays, ...)

# Chemical reaction databases

- Reaction products, rate constants, energy barriers,...

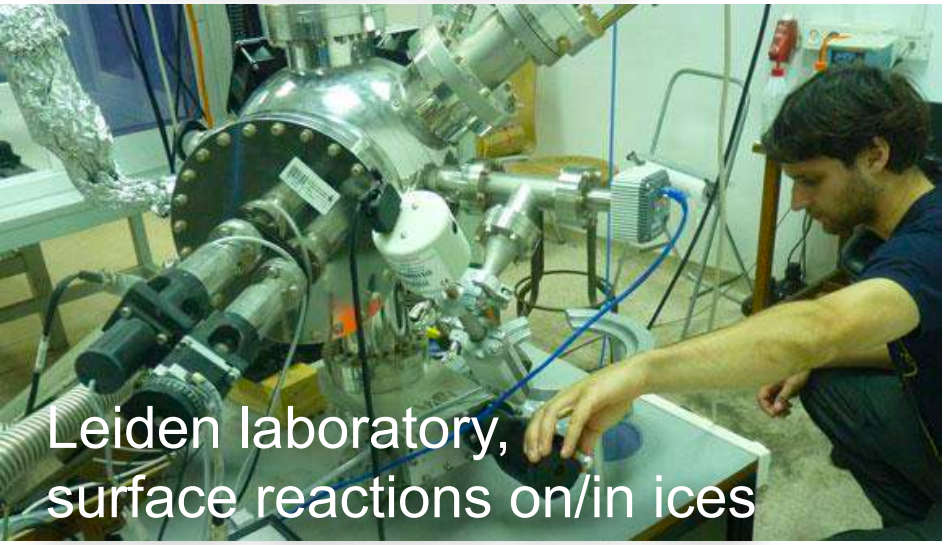
- **UMIST Database for Astrochemistry (UDfA), UK:**
  8767 reactions, 737 species, 17 elements
  https://umistdatabase.uk/database

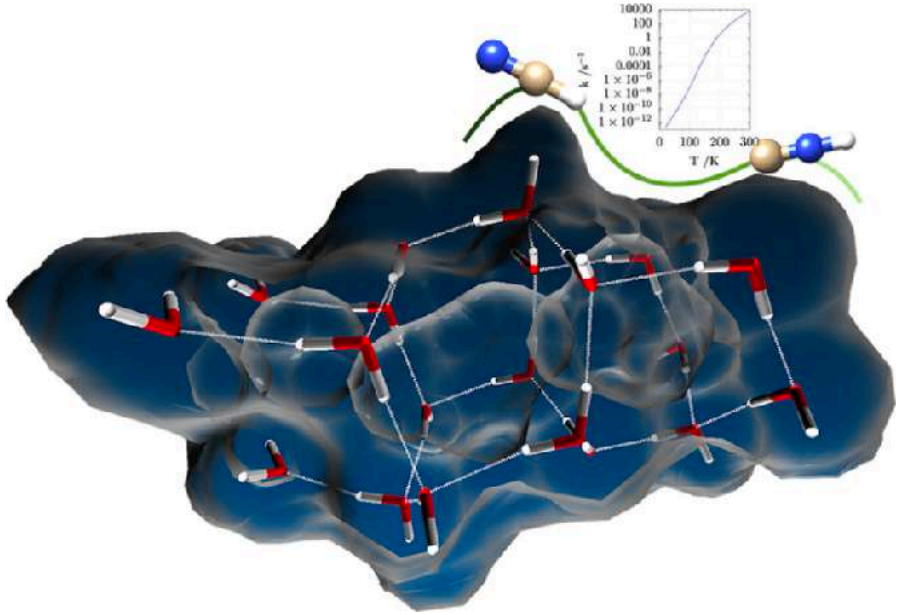
- **KInetic Database for Astrochemistry (KIDA), France**:
  7509 reactions, 489 species, 13 elements
  https://kida.astrochem-tools.org/

Only ~30 – 40 % of accurate reaction rates

# Reaction data: experiments, quantum calculations


Cryogenic Storage Ring (MPIK), ion-molecule reactions


Leiden laboratory, surface reactions on/in ices



HCN molecules on water ice cluster: density functional density (DFT)

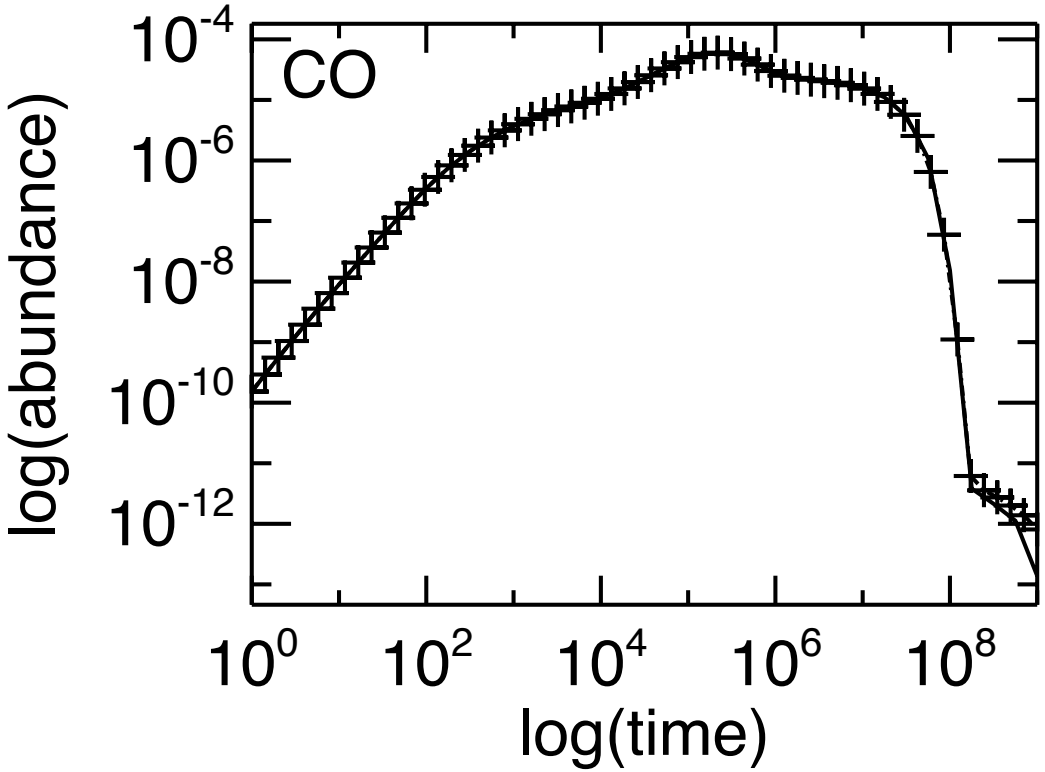
(Baiano et al. J. Chem. Theory Comput. 2022, 18, 5, 3111)

- Ultra high vacuum, cryogenic devices: expensive, time-limited
- Multi-atomic quantum systems: accurate models are slow

# Computational astrochemistry

$$\frac{\partial n_i}{\partial t} = \sum_{j,k \neq i} k_{jk} n_j n_k - n_i \sum_l k_l n_l$$

- Physical conditions
- Initial abundances
- Chemical network
- Numerical solver
- Good computer

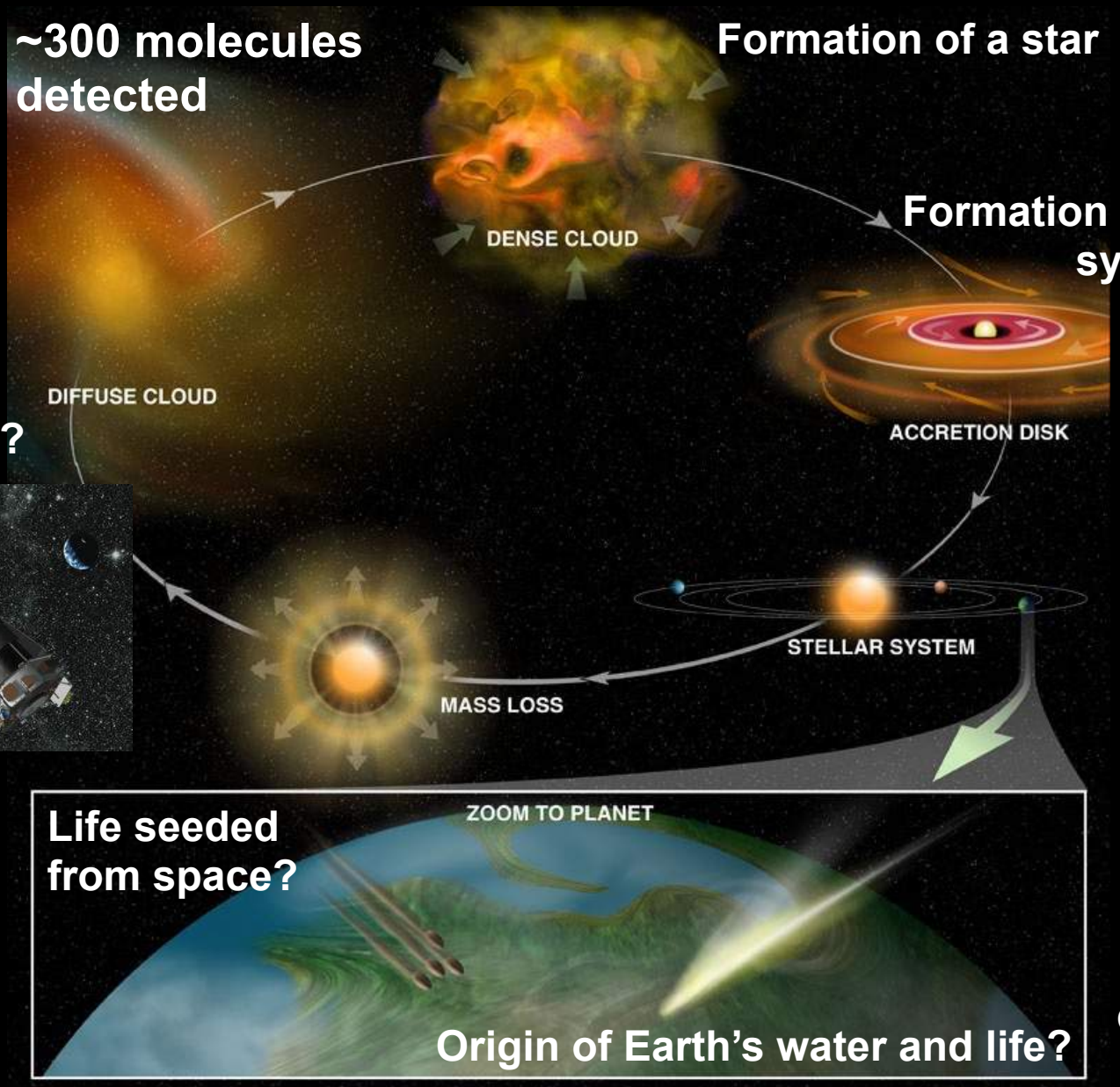


# Cosmic matter in our Galaxy (Milky Way)

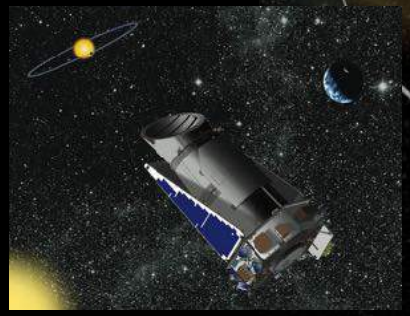



- Atomic H gas: $5 \times 10^9$ $M_{Sun}$ ($1\ M_{Sun} \sim 2 \times 10^{30}$ kg)
- Molecular $H_2$ gas: 1 – $5 \times 10^9$ $M_{Sun}$
- Dust: $5 \times 10^7$ $M_{Sun}$
- Stars: 4 – $6 \times 10^{10}$ $M_{Sun}$ (100 – 400 billion stars)

# Cosmic Life Cycle of Matter



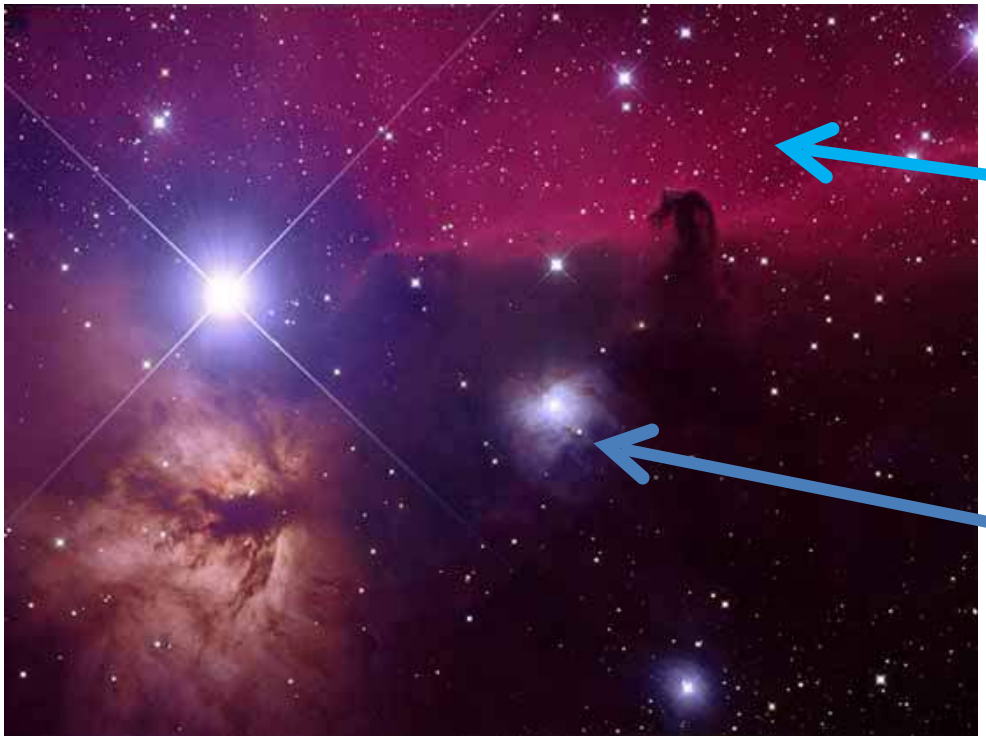

Life on exoplanets?



Credit: Bill Saxton
NRAO/AUI/NSF

# Astronomy relies on observations of radiation

Almost all information about the Universe comes from the study of electromagnetic radiation (light)



Red glow:
recombination
of ionized H atoms

Blue glow:
Light scattered by dust
particles

Telescopes take images of space objects (**Imaging**)

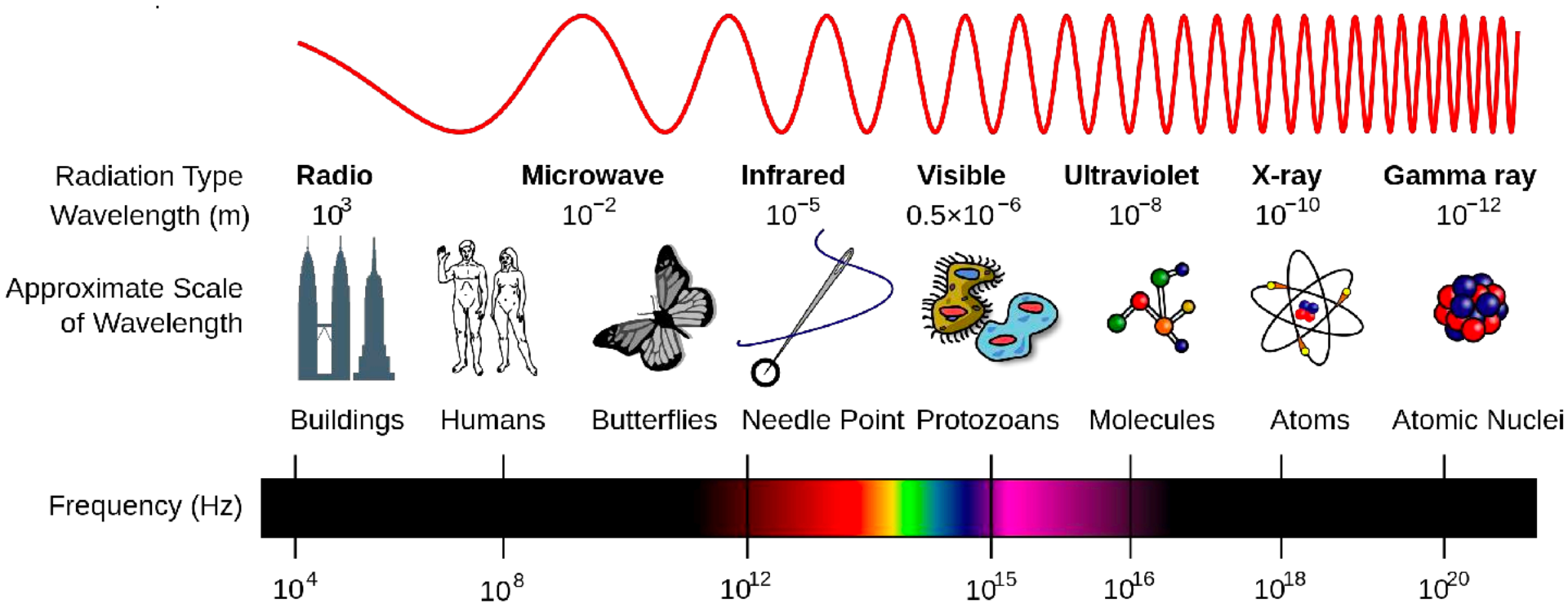
**Imaging** gives only certain hints about the composition and lacks quantitative information → **Spectroscopy**

# Photon energy, frequency, wavelength

Photon energy [eV or J]: $E = h\nu = \frac{hc}{\lambda}$

$h$ - Planck constant, $c$ - speed of light [m/s],

$\nu$ - frequency [Hz], $\lambda$ - wavelength [m]




https://en.wikipedia.org/wiki/Spectrum

# Molecular properties and spectroscopy

The Beginning: Newton (1675)



Isaac Newton
04.01.1643 – 31.03.1727

Newton used the term **“Spectrum”** in context with his experiments on the color of light:

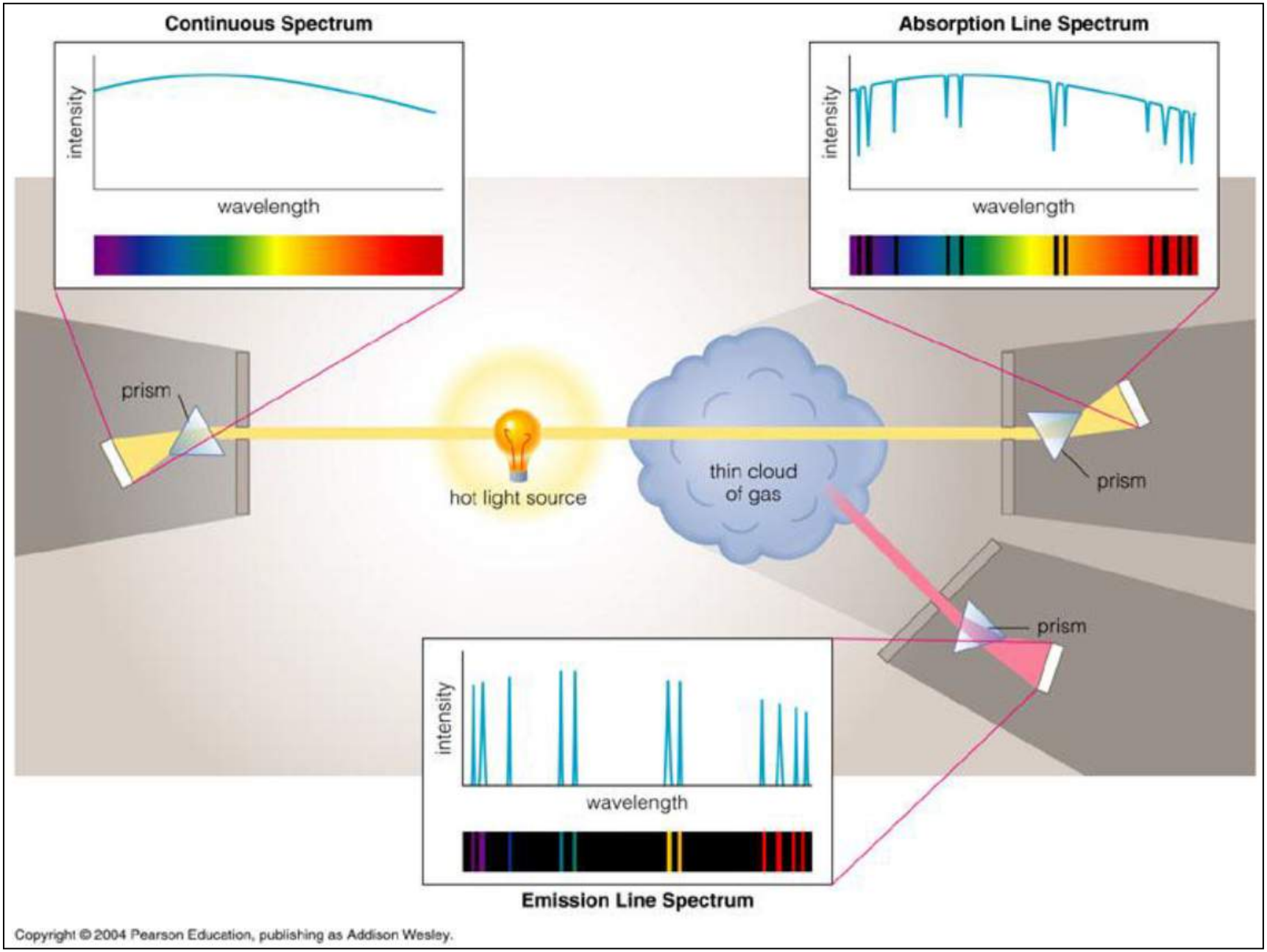
PHILOSOPHICAL
TRANSACTIONS.

*February* 19. 16[illegible].

*cular.*

Comparing the length of this coloured *Spectrum* with its breadth, I found it about five times greater; a diſproportion ſo extravagant, that it excited me to a more then ordinary curioſity of ex-

# How does Spectroscopy work?

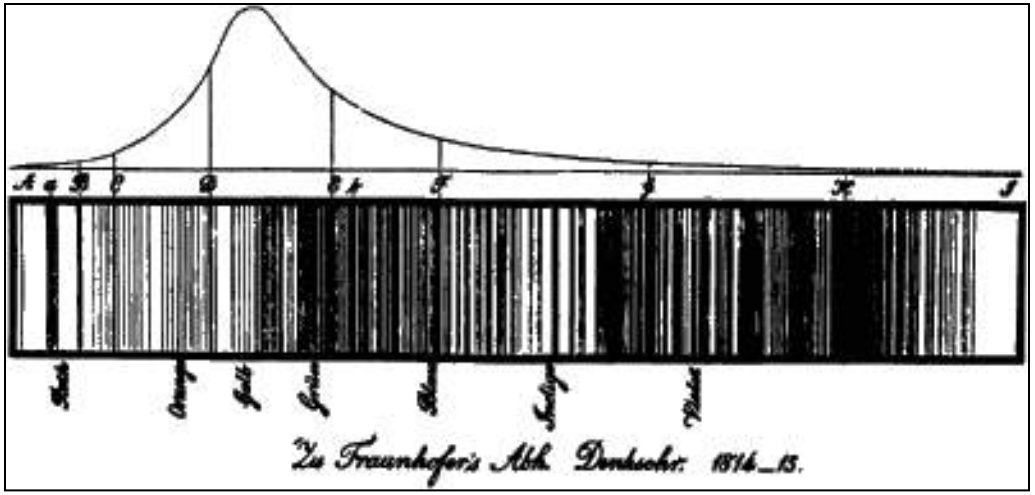


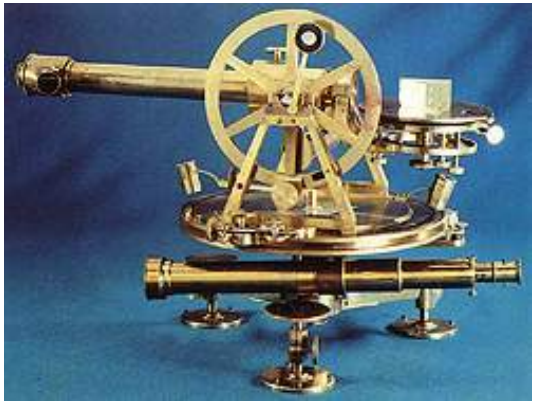

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# Fraunhofer lines in solar spectrum (1814)



Joseph von Fraunhofer
06.03.1787 – 07.06.1826



I have convinced myself by many experiments and by varying the methods that these lines and bands are due to the nature of sunlight, and do not arise from diffraction, illusion, etc. If light from a lamp is allowed to pass through the same narrow opening in the window-shutter, none of these lines are observed, only the bright line R [*referred to before*], which, however, comes exactly in the same place as the line D (Fig. 5), so that the indices of refraction of the rays D and R are the same.

# Molecular properties and spectroscopy

Kirchhoff and Bunsen: Spectroscopy pioneers in Heidelberg




Gustav Robert Kirchhoff
18.03.1824-17.10.1887

Robert Wilhelm Bunsen
31.03.1811-16.08.1899

# The Birth of Spectral Analysis: Kirchhoff (1860)

Sodium Na



THE

LONDON, EDINBURGH, AND DUBLIN

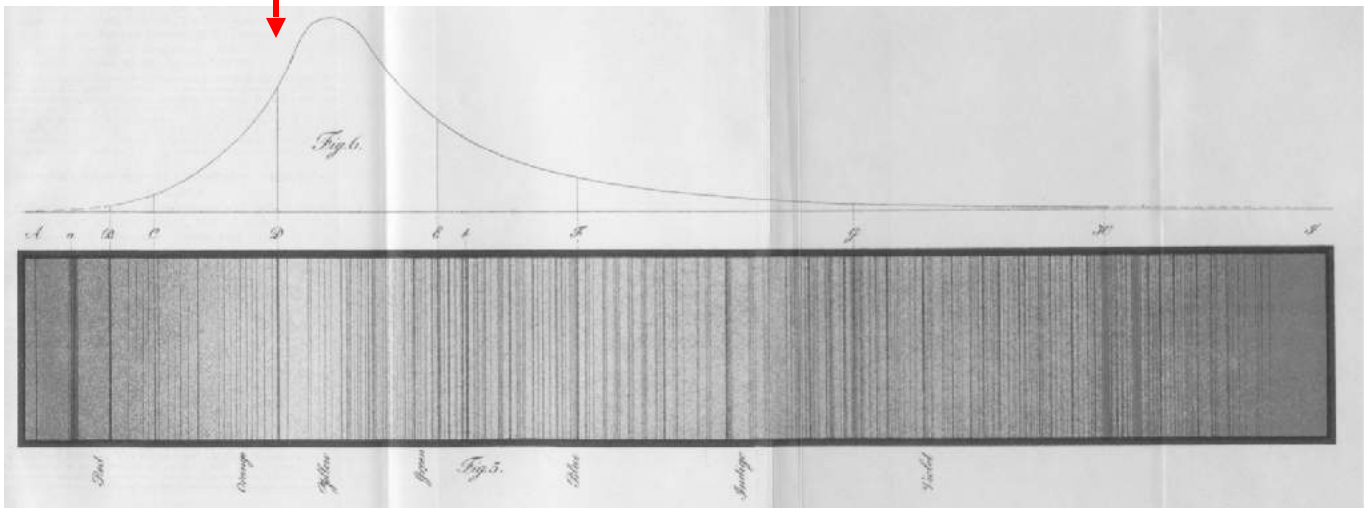
PHILOSOPHICAL MAGAZINE

AND

JOURNAL OF SCIENCE.

JULY—DECEMBER, 1860.






therefore, from the occurrence of the lines D in the solar spectrum, the presence of sodium in the sun's atmosphere may be concluded.

# Molecules wrt Atoms: a multitude of energy levels ($e^-$, vibration, rotation )

Electronic Transitions:

E = 1-15 eV

Visible-UV

Vibrational Transitions:

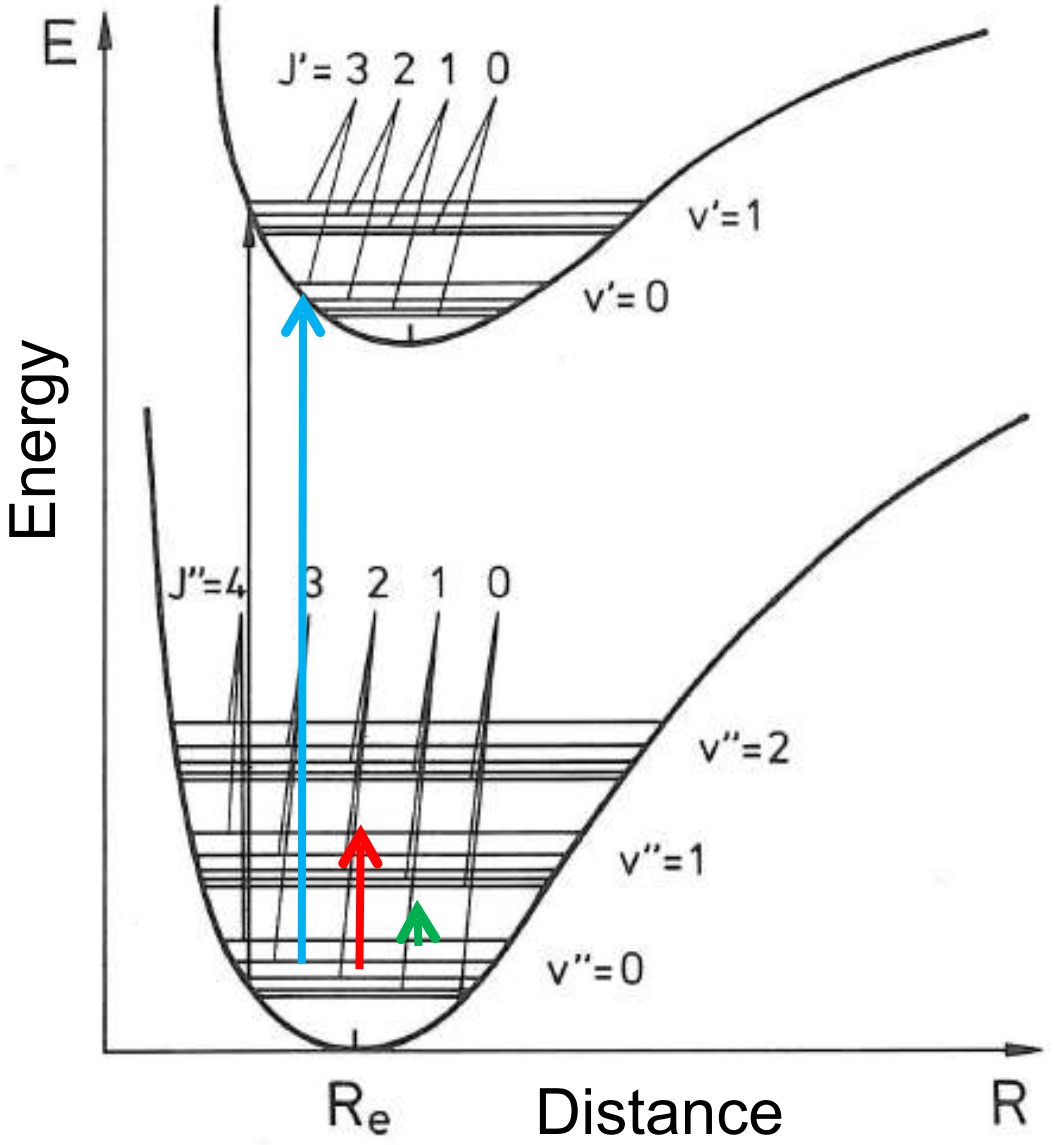
E = 0.1-1 eV

Infrared

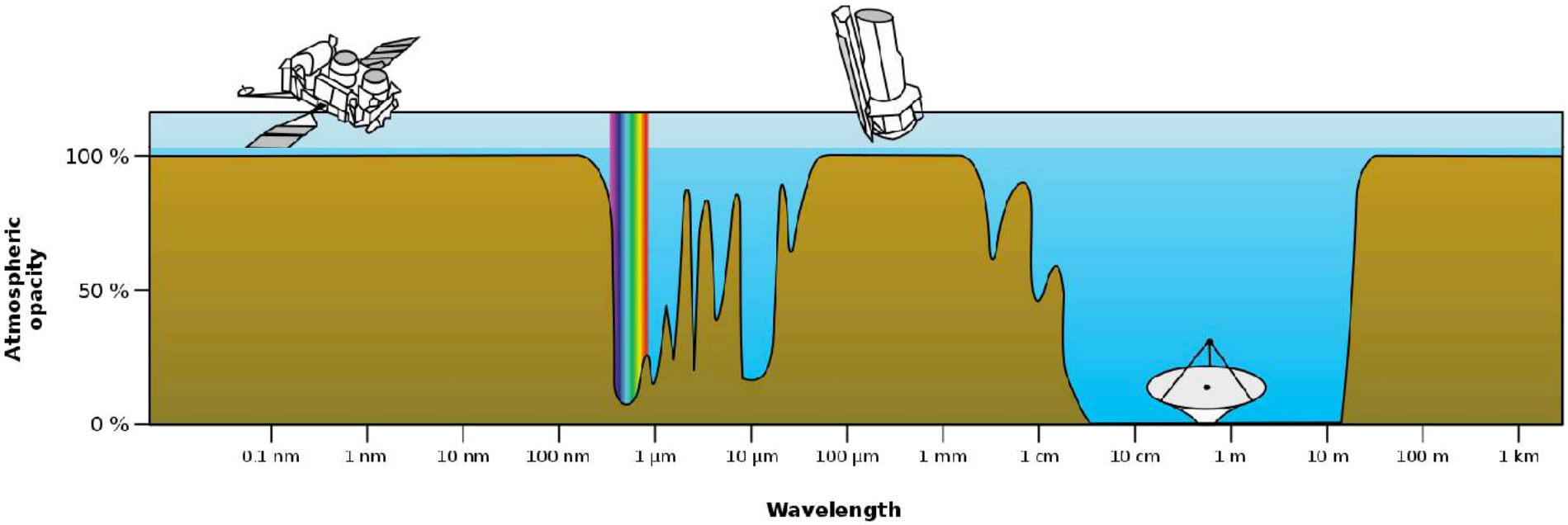
Rotational Transitions:

E = 0.01-0.1 eV

(sub)-Millimeter



# Earth atmosphere is on the way

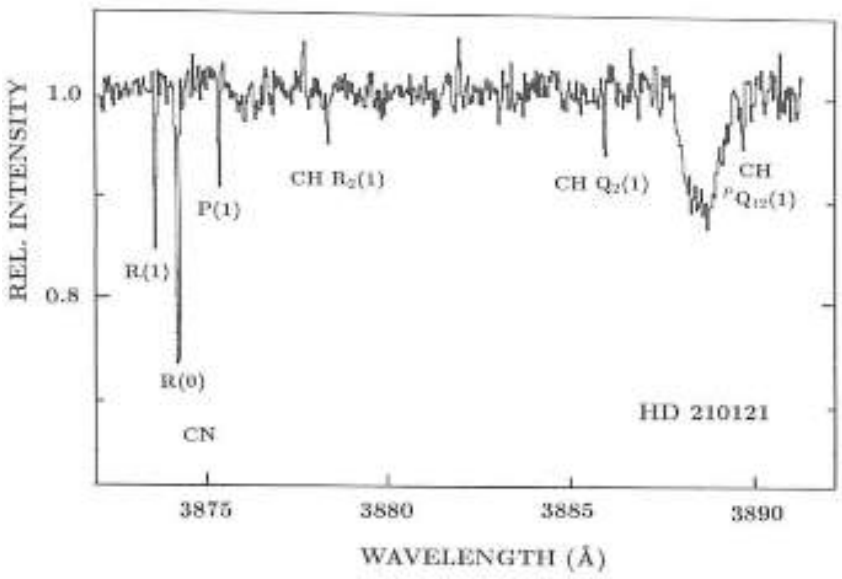



- Space only:
  - X-ray & UV (< 300nm)
  - Mid-IR/sub-mm (20 µm – 0.3 mm)
  - Long radio wavelengths (>10 m)

# History of molecular observations in space

## Absorption bands (optics):

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

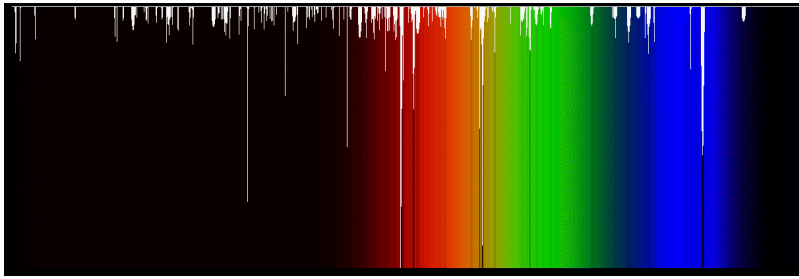



G. Herzberg, J. Roy. Soc. Can. 82, 115, (1988)

"Historical Remarks on the discovery of interstellar molecules"

## Diffuse Interstellar Bands (DIBs), optics:

- Discovered by Mary L. Heger (1922)
- Large 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"

# History of molecular detections in space

- **Radio telescopes:**

- HI @ 21 cm: Ewen & Purcell (1951)
- OH @ 18 cm: Weinreb et al. (1963)
- $NH_3$ @ 1 cm: Cheung, Townes et al. (1968)
- $H_2O$ @1 cm: Cheung, Townes et al. (1969)



- **UV telescopes:**

- Copernicus (1970): $H_2$ at ≈ 125nm (1970), later $N_2$

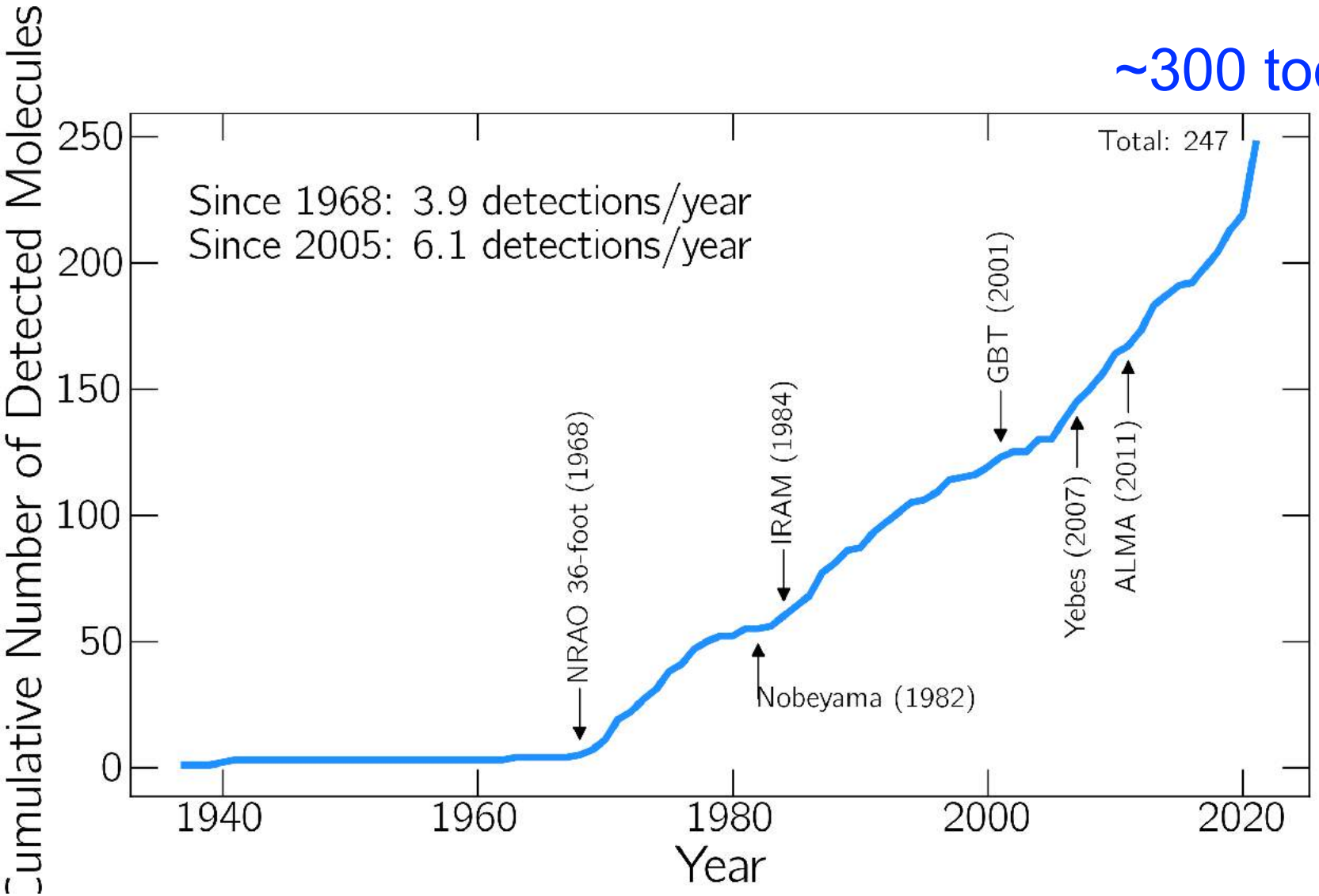


- **(Sub-)millimeter telescopes:**

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

# History of molecular detections in space

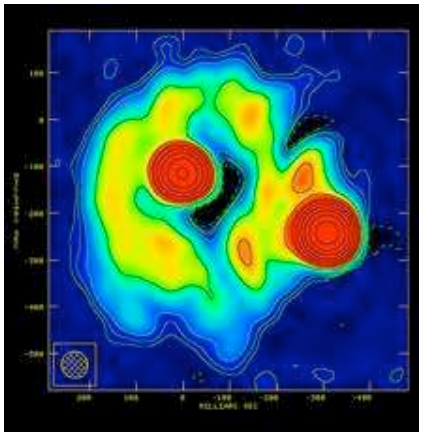
~300 today!



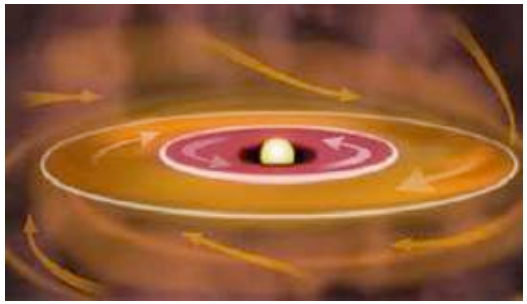

McGuire, ApJS 259, 30 (51pp), 2022

# Molecules are everywhere!

- Appeared in early Universe
- High-redshift quasars and galaxies
- Interstellar and circumstellar medium
- Solar system: solar photosphere, atmospheres, comets, meteorites, moons, ...
- Exoplanets









# Today we know: Molecules Everywhere!

**2 Atoms**

CH, CN, $CH^+$, OH, CO, $H_2$, SiO, CS, SO, SiS, NS, $C_2$, NO, HCl, NaCl, AlCl, KCl, AlF, PN, SiC, CP, NH, SiN, $SO^+$, $CO^+$, HF, $N_2$, $CF^+$, PO, $O_2$, AlO, $CN^-$, $OH^+$, $SH^+$, $HCl^+$, SH, TiO, $ArH^+$, $NS^+$, $HeH^+$, VO, $PO^+$, SiP

**3 Atoms**

$H_2O$, $HCO^+$, HCN, OCS, HNC, $H_2S$, $N_2H^+$, $C_2H$, $SO_2$, HCO, HNO, $HCS^+$, $HOC^+$, $SiC_2$, $C_2S$, $C_3$, $CO_2$, $CH_2$, $C_2O$, MgNC, $NH_2$, NaCN, $N_2O$, MgCN, $H_3^+$, SiCN, AlNC, SiNC, HCP, CCP, AlOH, $H_2O^+$, $H_2Cl^+$, KCN, FeCN, $HO_2$, $TiO_2$, CCN, SiCSi, $S_2H$, HCS, HSC, NCO, CaNC, NCS, $MgC_2$, HSO

**4 Atoms**

$NH_3$, $H_2CO$, HNCO, $H_2CS$, $C_2H_2$, $C_3N$, HNCS, $HOCO^+$, $C_3O$, *l*-$C_3H$, $HCNH^+$, $H_3O^+$, $C_3S$, *c*-$C_3H$, $HC_2N$, $H_2CN$, $SiC_3$, $CH_3$, $C_3N^-$, $PH_3$, HCNO, HOCN, HSCN, HOOH, *l*-$C_3H^+$, HMgNC, HCCO, CNCN, HONO, MgCCH, HCCS, HNCN, $H_2NC$, $HCCS^+$

**5 Atoms**

$HC_3N$, HCOOH, $CH_2NH$, $NH_2CN$, $H_2CCO$, $C_4H$, $SiH_4$, *c*-$C_3H_2$, $CH_2CN$, $C_5$, $SiC_4$, $H_2CCC$, $CH_4$, HCCNC, HNCCC, $H_2COH^+$, $C_4H^-$, CNCHO, HNCNH, $CH_3O$, $NH_3D^+$, $H_2NCO^+$, $NCCNH^+$, $CH_3Cl$, $MgC_3N$, $HC_3O^+$, $NH_2OH$, $HC_3S^+$, $H_2CCS$, $C_4S$, CHOSH, HCSCN, $HC_3O$, NaCCCN, $MgC_3N^+$

**290 Molecules**

**Last Updated: 2 Jul 2023**

**6 Atoms**

$CH_3OH$, $CH_3CN$, $NH_2CHO$, $CH_3SH$, $C_2H_4$, $C_5H$, $CH_3NC$, $HC_2CHO$, $H_2C_4$, $C_5S$, $HC_3NH^+$, $C_5N$, $HC_4H$, $HC_4N$, *c*-$H_2C_3O$, $CH_2CNH$, $C_5N^-$, HNCHCN, $SiH_3CN$, $MgC_4H$, $CH_3CO^+$, $H_2CCCS$, $CH_2CCH$, HCSCCH, $C_5O$, $HCCNCH^+$, $C_5H^+$, *c*-$C_5H$, $HC_4S$, HMgCCCN, $MgC_4H^+$

**7 Atoms**

$CH_3CHO$, $CH_3CCH$, $CH_3NH_2$, $CH_2CHCN$, $HC_5N$, $C_6H$, *c*-$C_2H_4O$, $CH_2CHOH$, $C_6H^-$, $CH_3NCO$, $HC_5O$, $HOCH_2CN$, $HC_4NC$, $HC_3HNH$, *c*-$C_3HCCH$, $MgC_5N$, $CH_2C_3N$, *l*-$H_2C_5$, $NC_4NH^+$, $MgC_5N^+$

**12 Atoms**

$C_6H_6$, *n*-$C_3H_7CN$, *i*-$C_3H_7CN$, $C_2H_5OCH_3$, 1-$C_5H_5CN$, 2-$C_5H_5CN$, *n*-$CH_3CH_2CH_2OH$, *i*-$CH_3CH_2CH_2OH$, 1-$C_5H_4CCH$

**8 Atoms**

$HCOOCH_3$, $CH_3C_3N$, $C_7H$, $CH_3COOH$, $H_2C_6$, $CH_2OHCHO$, $HC_6H$, $CH_2CHCHO$, $CH_2CCHCN$, $NH_2CH_2CN$, $CH_3CHNH$, $CH_3SiH_3$, $NH_2CONH_2$, $HCCCH_2CN$, $CH_2CHCCH$, $MgC_6H$, $C_2H_3NH_2$, HOCHCHOH, HCCCHCCC, $C_7N^-$, $CH_3CHCO$, $MgC_6H^+$

**9 Atoms**

$CH_3OCH_3$, $CH_3CH_2OH$, $CH_3CH_2CN$, $HC_7N$, $CH_3C_4H$, $C_8H$, $CH_3CONH_2$, $C_8H^-$

**10 Atoms**

$CH_3COCH_3$, $HOCH_2CH_2OH$, $CH_3CH_2CHO$, $CH_3C_5N$, $CH_3CHCH_2O$, $CH_3OCH_2OH$, $H_2CCCHC_3N$, $C_6H_4$, $C_2H_5NCO$, $HC_7NH^+$, $CH_3CHCHCN$, $CH_2CCH_3CN$, $CH_2CHCH_2CN$

**13+ Atoms**

$C_6H_5CN$, $HC_{11}N$, *c*-$C_5H_4CCH_2$, 1-$C_{10}H_7CN$, 2-$C_{10}H_7CN$, $CH_2CHCH_3$, $CH_3CH_2SH$, $HC_7O$, $CH_3NHCHO$, $H_2CCCHCCH$, HCCCHCHCN, $H_2CCHC_3N$

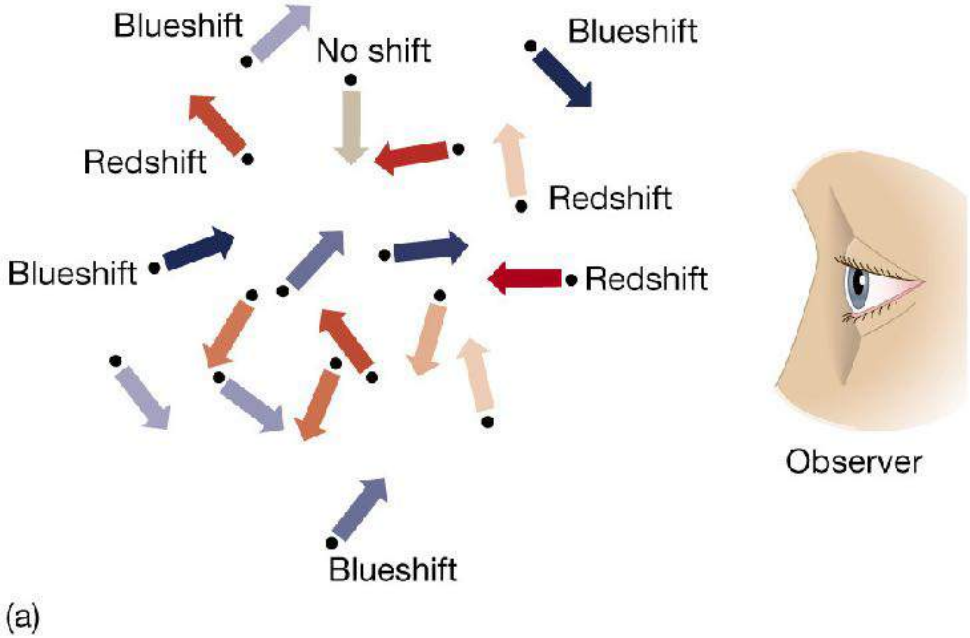
**11 Atoms**

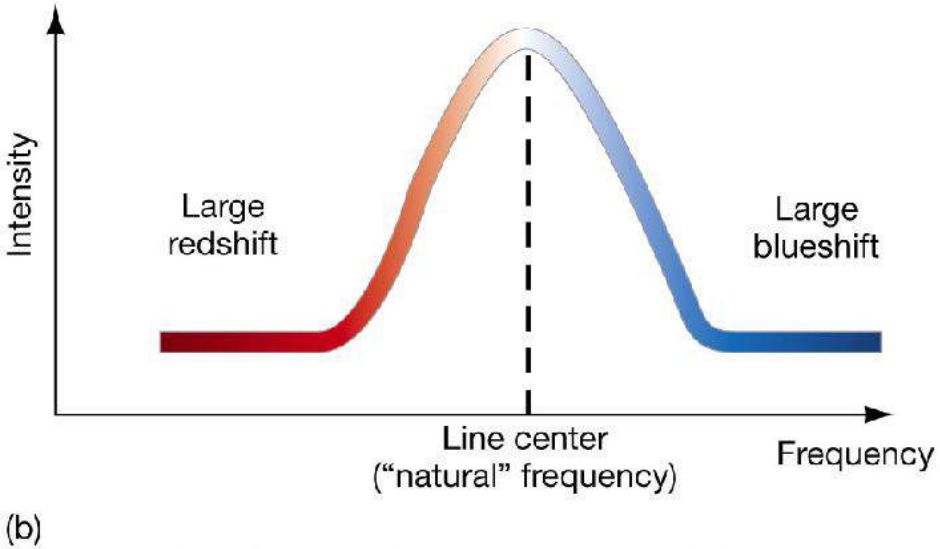
$HC_9N$, $CH_3C_6H$, $C_2H_5OCHO$, $CH_3COOCH_3$, $CH_3COCH_2OH$, $C_5H_6$, $NH_2CH_2CH_2OH$, $CH_2CCHC_4H$, $C_{10}H^-$, $C_4H_5CN$

$C_9H_8$, 2-$C_9H_7CN$, $C_{60}$, $C_{60}^+$, $C_{70}$

McGuire (2022): https://arxiv.org/abs/2109.13848

# Molecular lines




- Line shape and width:
  - Temperature
  - Gas motions (Kinematics)
  - Pressure, etc...

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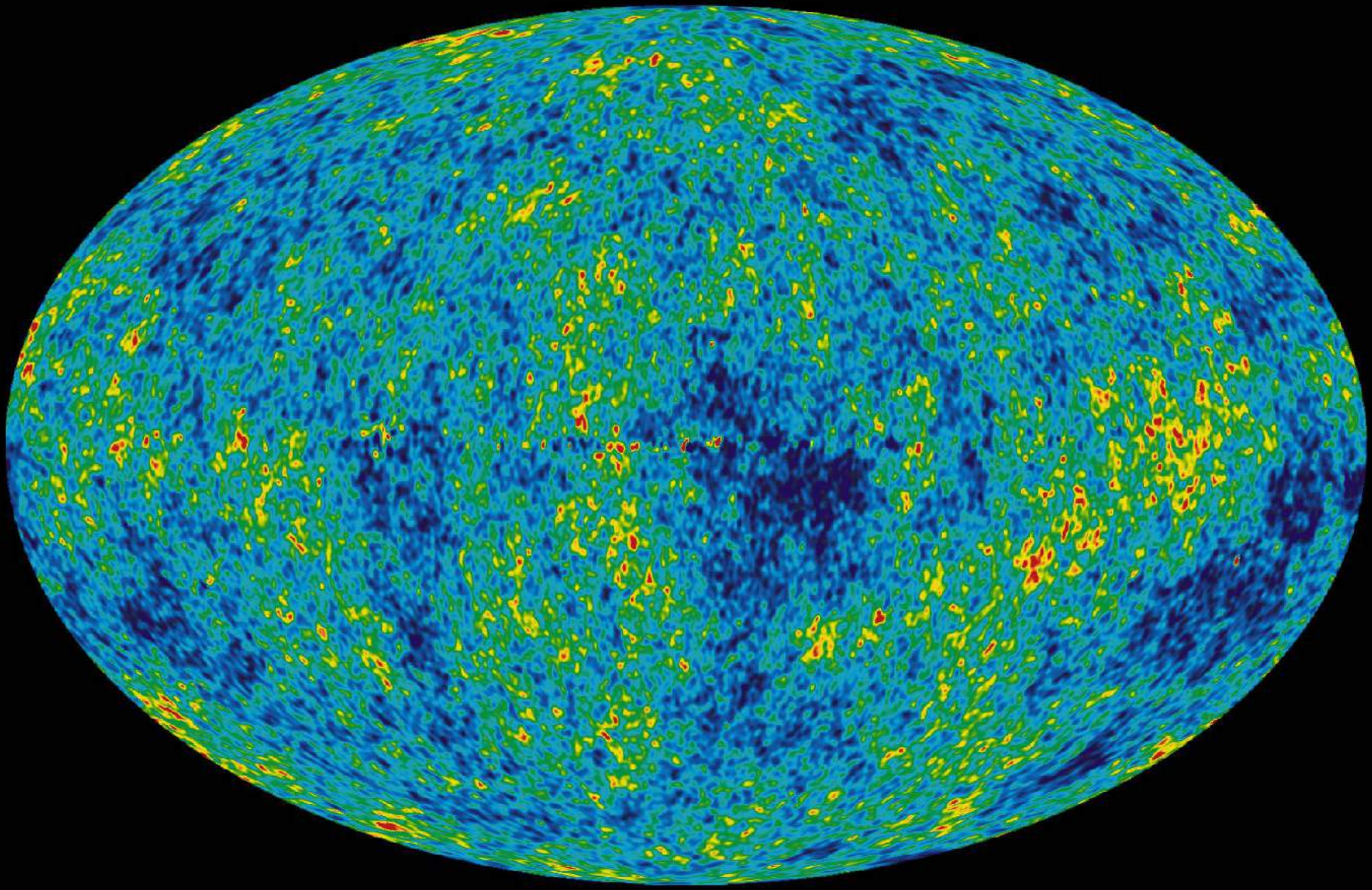
# Importance of molecules in space

- **Probes of physical conditions:**
  - Temperature
  - Density
  - Ionization
  - Gas kinematics

- **Feedback on environment:**
  - Heating and cooling gas

- **Chemical composition:**
  - Chemical processes (radicals, ions,...)
  - "Age" indicators
  - Prebiotic chemistry (origin of life?)

# Big Bang and Early Universe



# Big Bang Nucleosynthesis: t ~ 10 s – 20 min

$p + p \longrightarrow D + e^+ + \nu_e$

$n + n \longrightarrow D + e^- + \nu_e$

$p + n \longrightarrow D + \gamma$

$D + p \longrightarrow {}^3He + \gamma$

$D + n \longrightarrow {}^3H + \gamma$

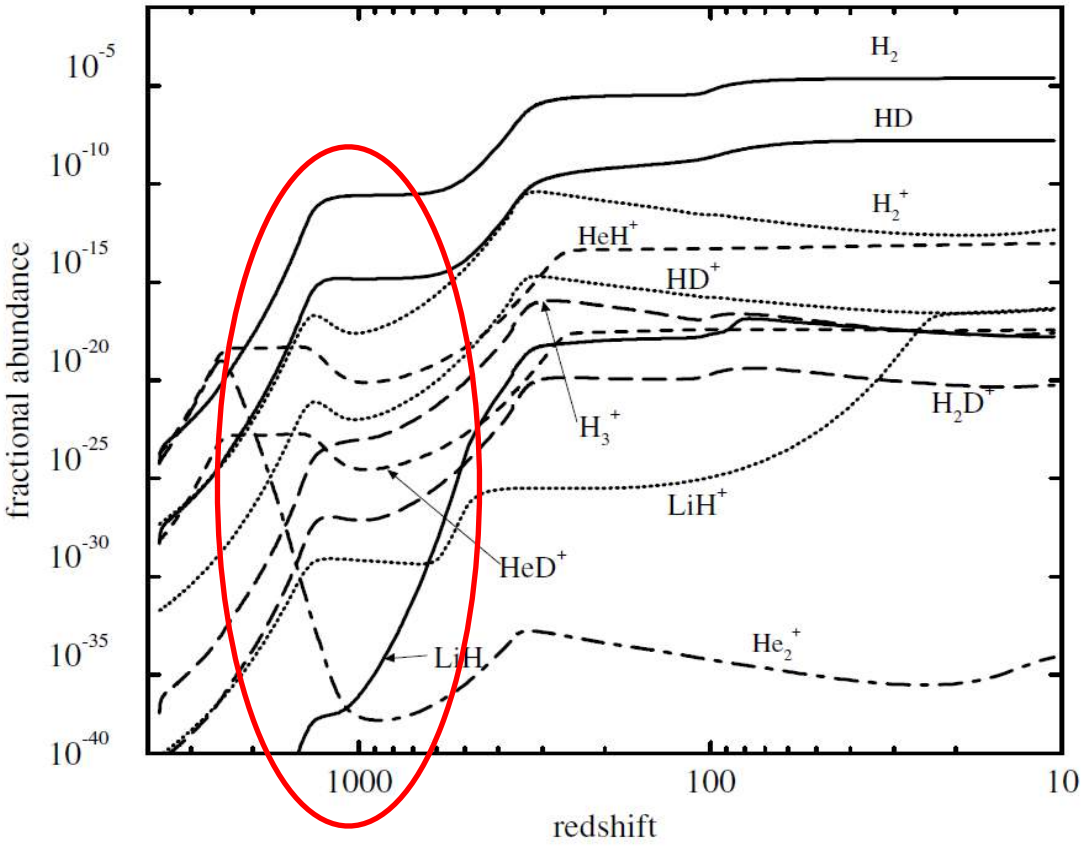
$D + D \longrightarrow {}^4He$ or ${}^3H$ or ${}^3He$ + ....

${}^3He + p, n, D \longrightarrow {}^4He$ + ....

- BBN: H, D, He, Li with well-predicted abundances
- No primordial nucleosynthesis after Li-7
- Heavier elements produced in stars (3 x ${}^4He \longrightarrow {}^{12}C$)

# First molecules (redshift z < 1000)

$$z = \frac{\lambda_{observed} - \lambda_{emitted}}{\lambda_{emitted}}$$ ("age" and distance indicator)




Ion-molecule reactions

Strong radiation: ionization

**The First Molecule: $HeH^+$**

$$\begin{aligned} \mathrm{He} + \mathrm{H}^+ &\rightarrow \mathrm{HeH}^+ + \gamma\,, \\ \mathrm{He} + \mathrm{He}^+ &\rightarrow \mathrm{He}_2^+ + \gamma\,. \end{aligned}$$

**The first neutral molecule: $H_2$**

$$\begin{aligned} \mathrm{HeH}^+ + \mathrm{H} &\rightarrow \mathrm{H}_2^+ + \mathrm{He}, \\ \mathrm{H}_2^+ + \mathrm{H} &\rightarrow \mathrm{H}_2 + \mathrm{H}^+, \end{aligned}$$

Lepp, Stancil, Dalgarno, J. Phys. B., At. Mol. Opt. Phys 35 (2002) R57-R80

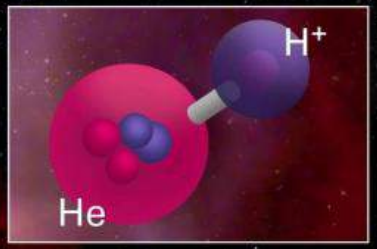
# Recent astronomical detection of $HeH^+$

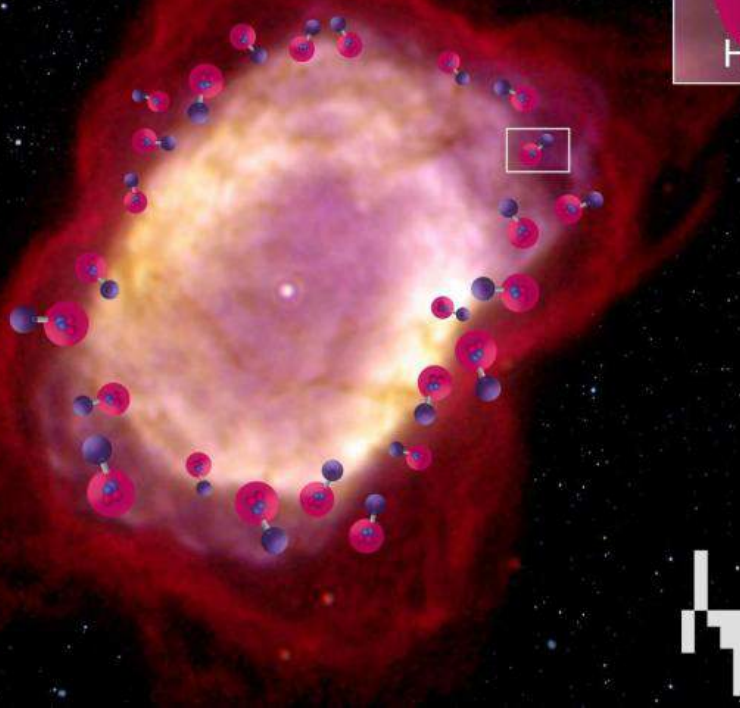



Güsten et al, Nature 568, 357 (2019)

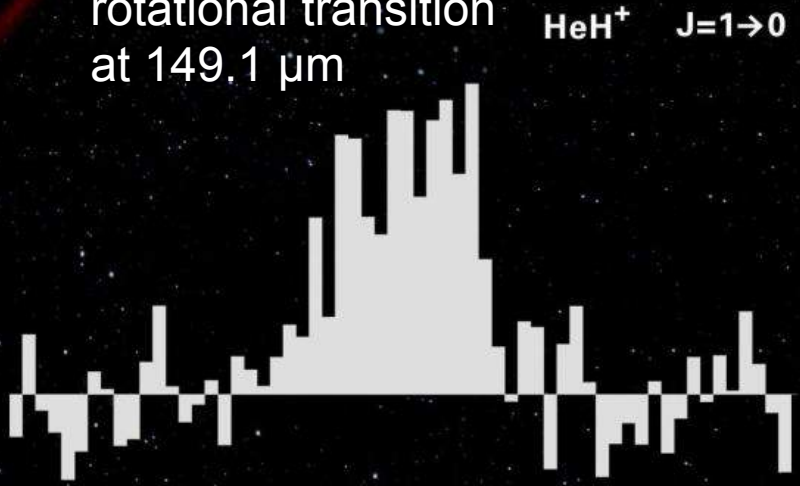
First Molecule detected!

**(But: in a planetary nebula)**

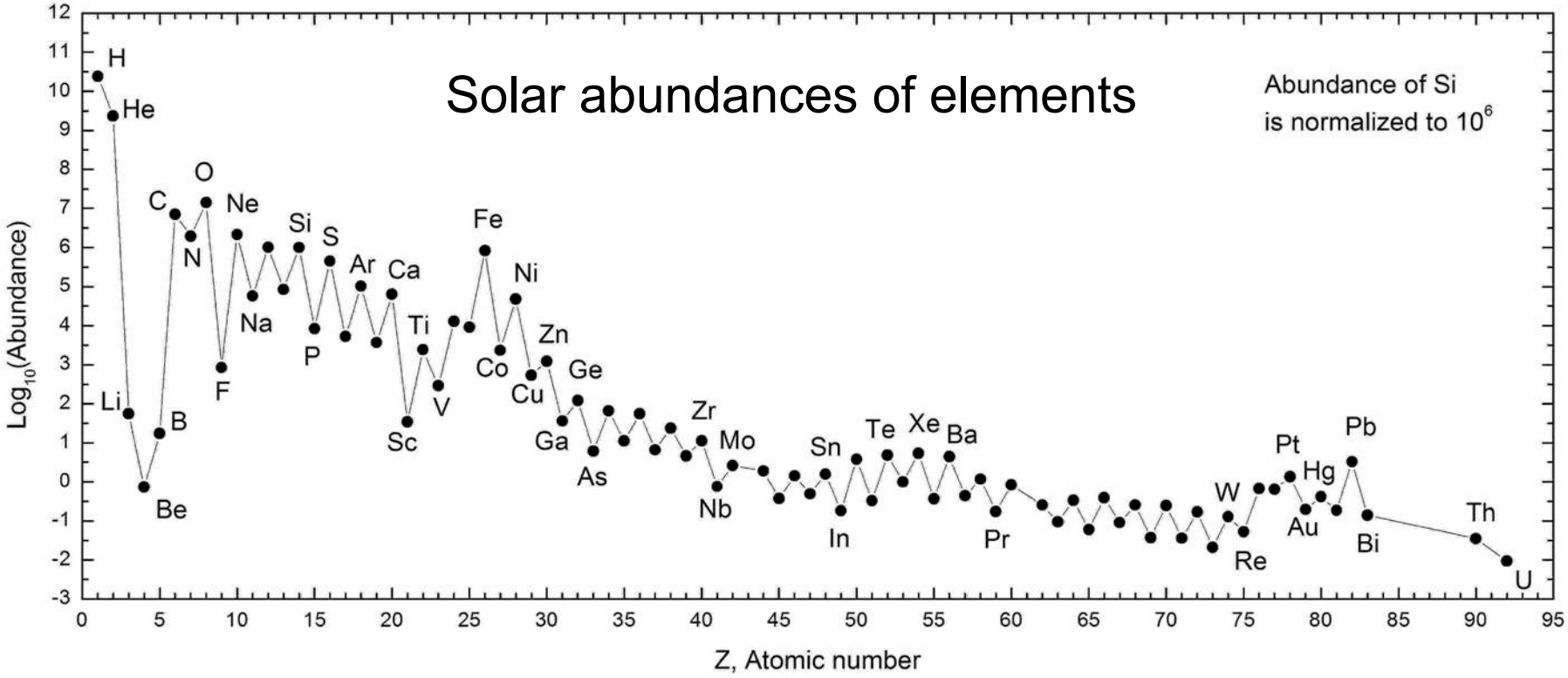


Ground state
rotational transition
at 149.1 μm

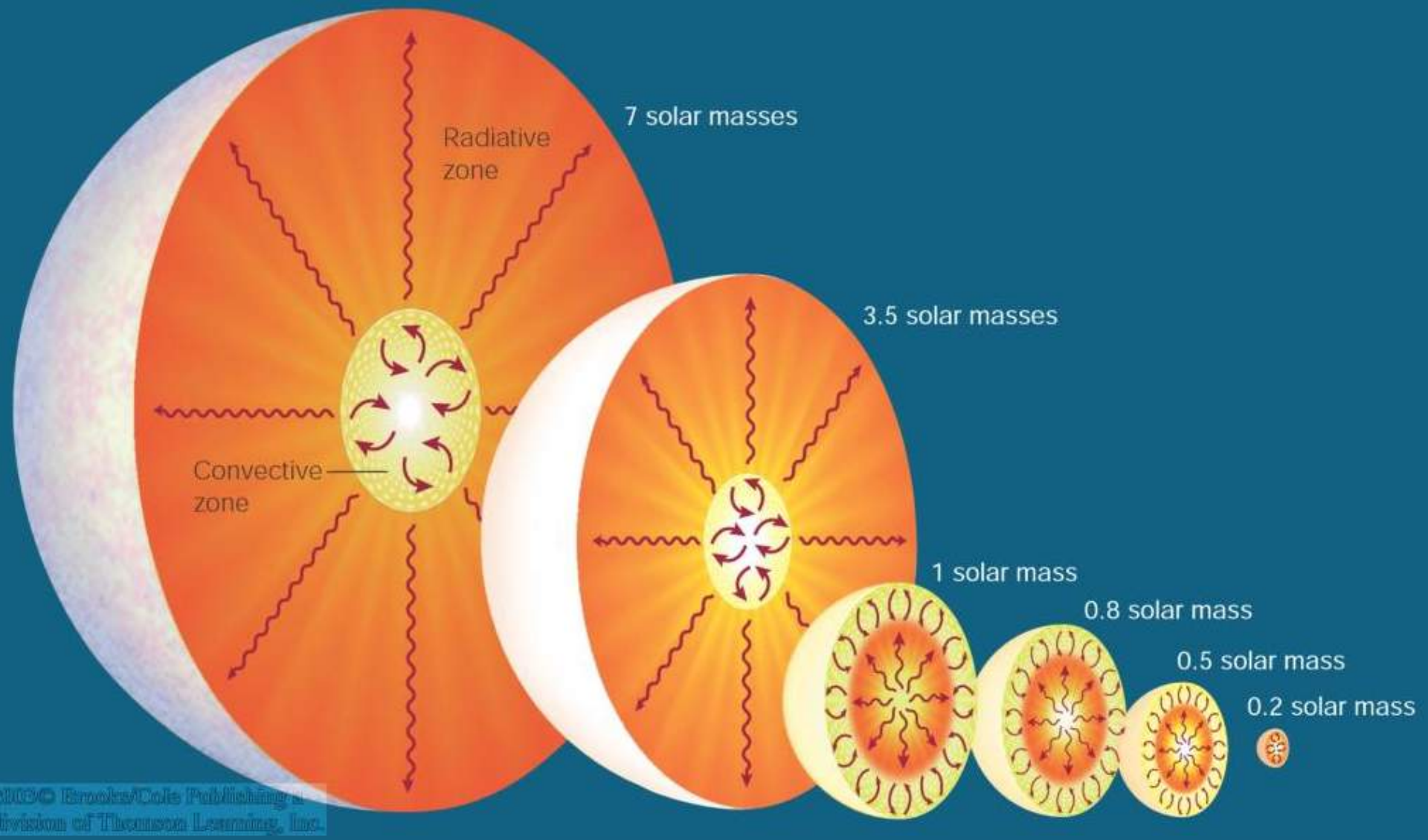


# Stellar nucleosynthesis




- Decrease of abundances with atomic number:
  - Drop at Li, Be, B
  - Sawtooth pattern (even > odd)
  - Local peak at Fe and Ni

# Structure of stars




- Interiors: T >$10^6$ K, density >150 g/$cm^3$
- Photospheres: T ~ few 1000 K, density < $10^{-6}$ g/$cm^3$

# Stellar nucleosynthesis: H-burning

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

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

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

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

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

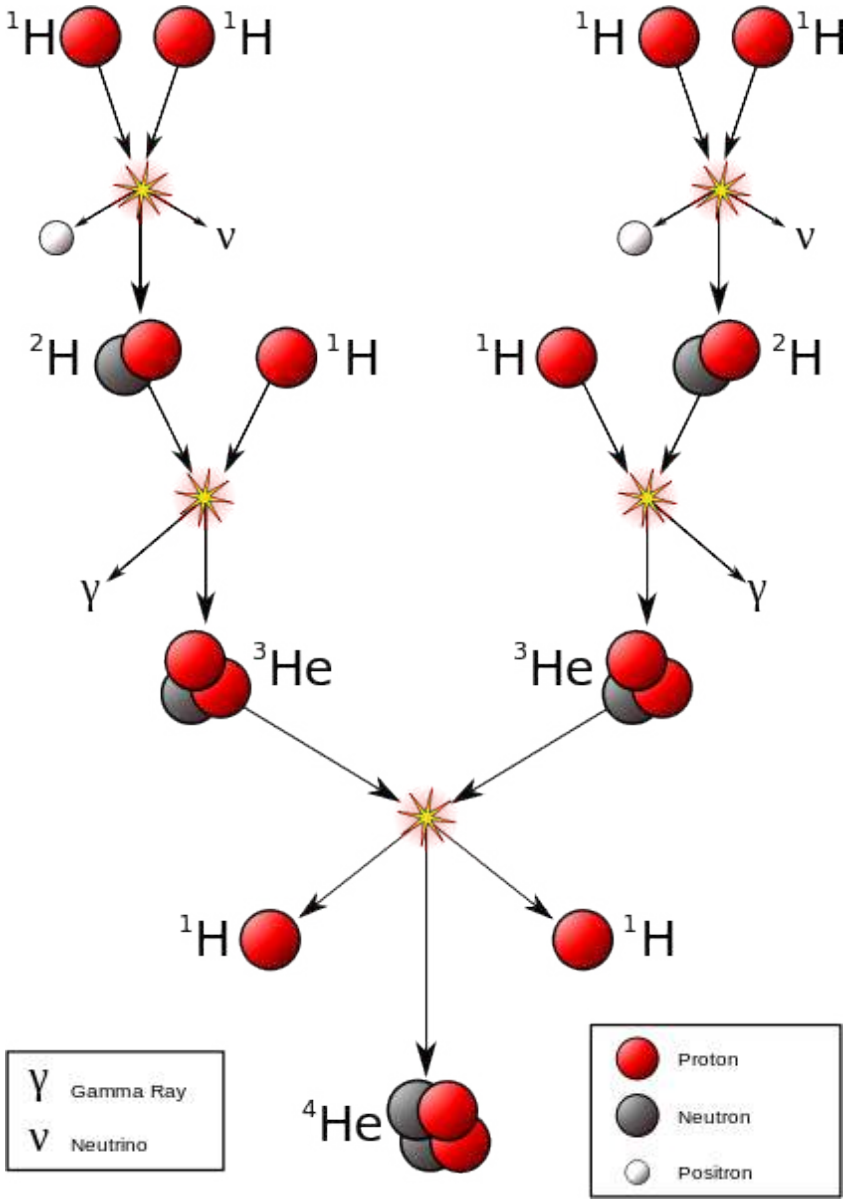
- PP-II cycle, $T > 14 \times 10^6$ K:

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

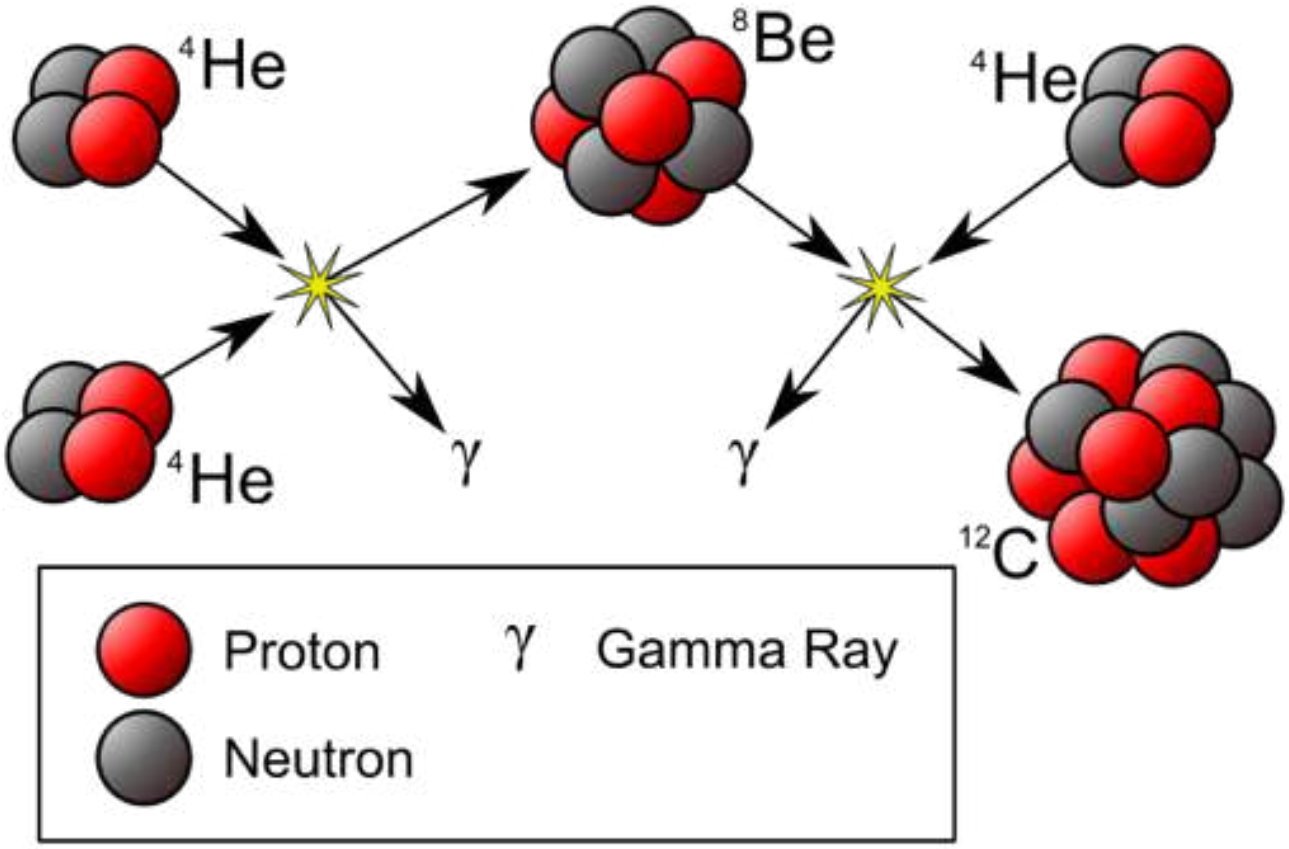
  $^7Be + \beta^- = {}^7Li + \nu_e$

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

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



# Stellar nucleosynthesis: He-burning (triple–alpha process)



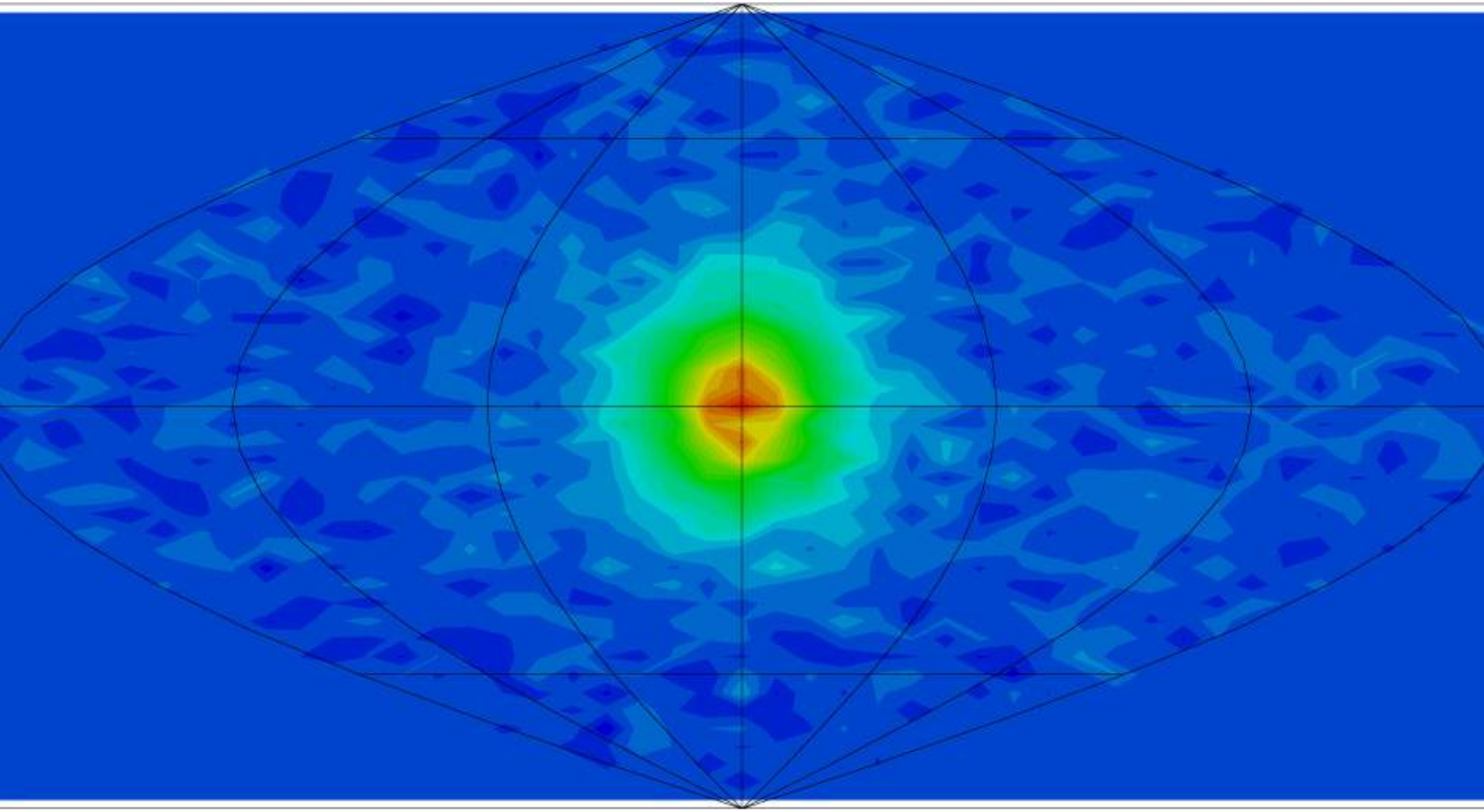

Fred Hoyle



(1915 – 2001)

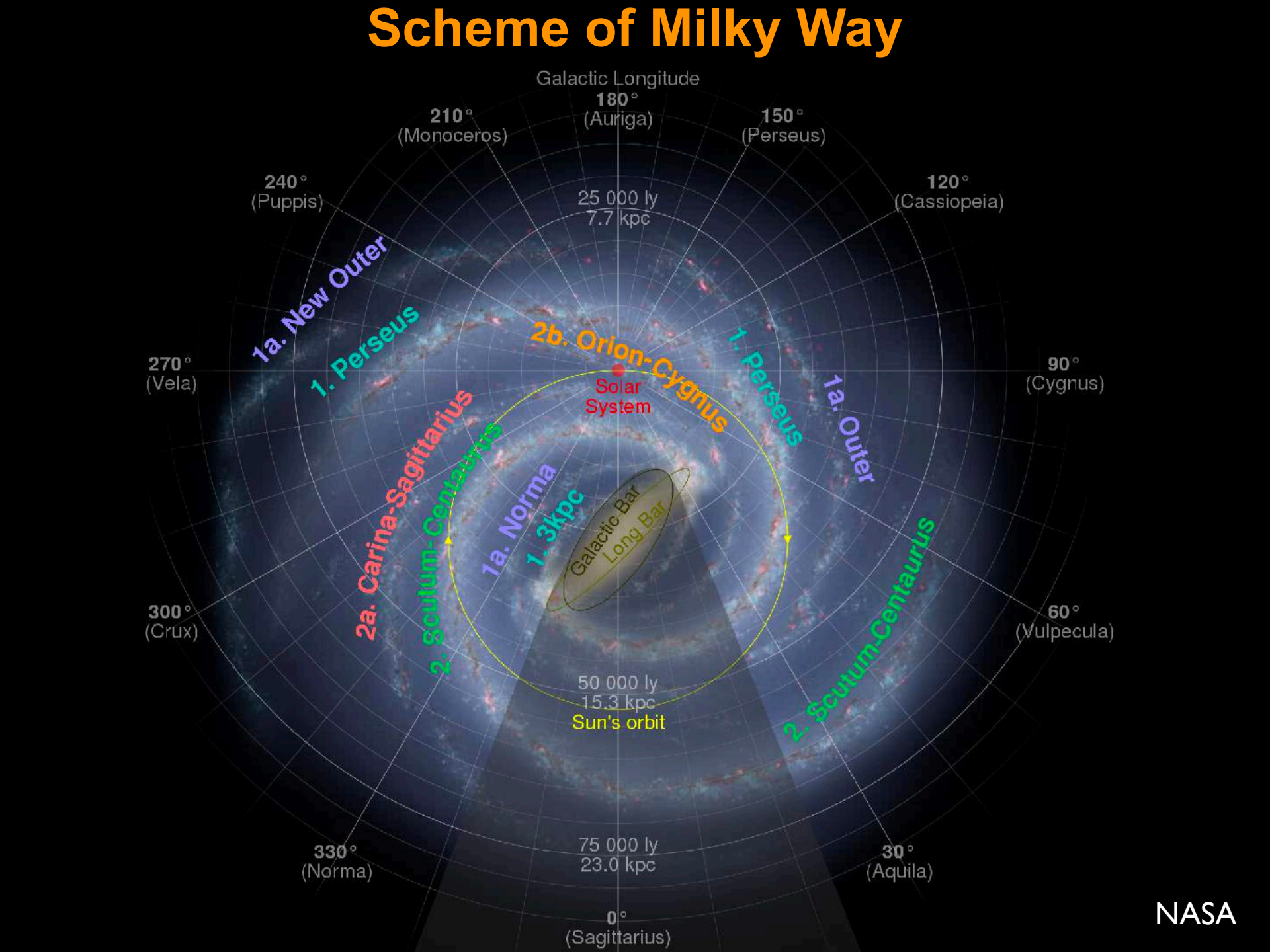
- Stars more massive than Sun
- Requires T ~ 100 x $10^6$ K
- Fast 3-body process → extreme densities

# Neutrino "image" of the Sun's core



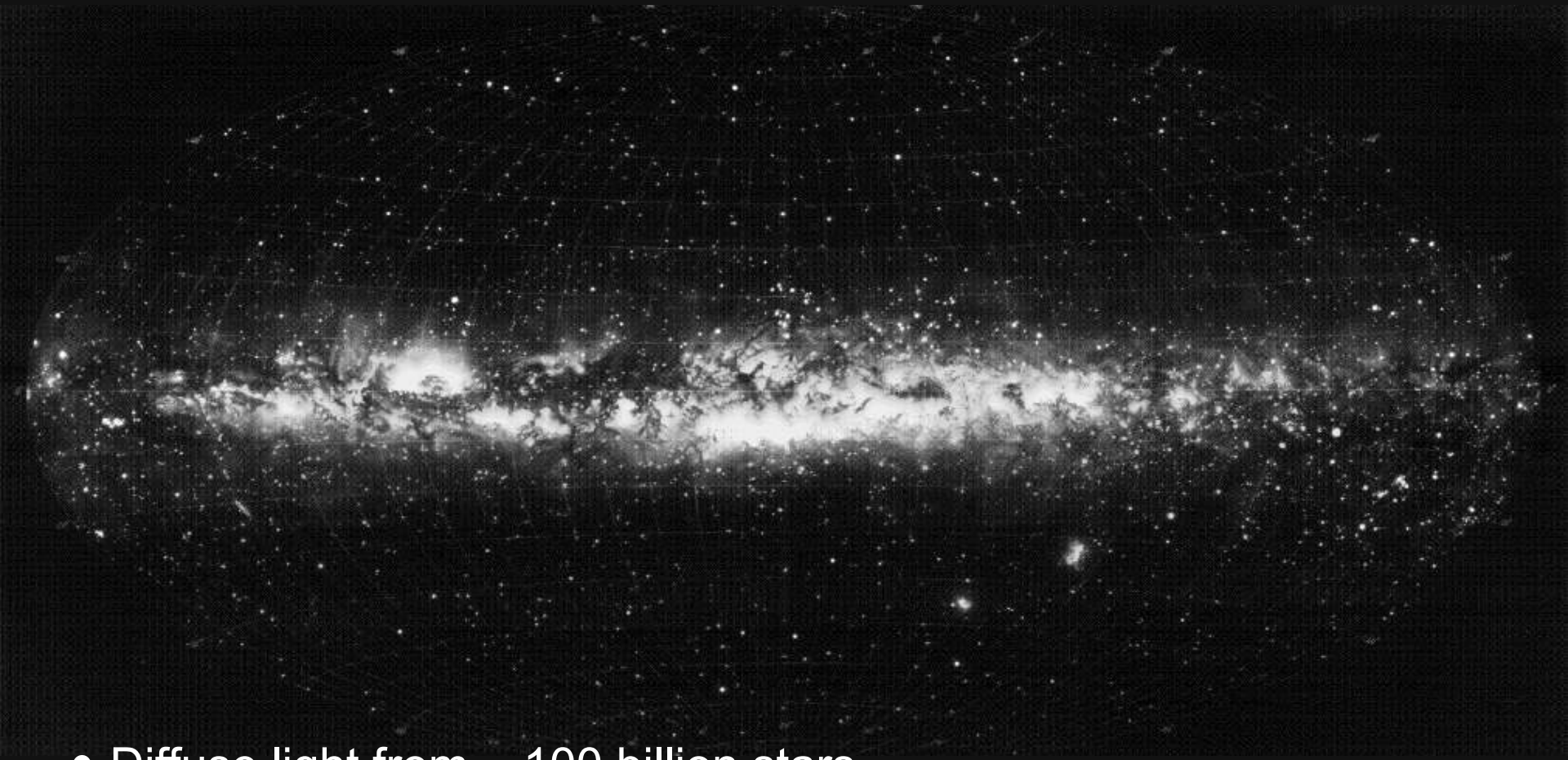
- Super-Kamiokande experiment: detection of solar neutrinos (flavour, intensity, direction,...)

# Scheme of Milky Way




NASA

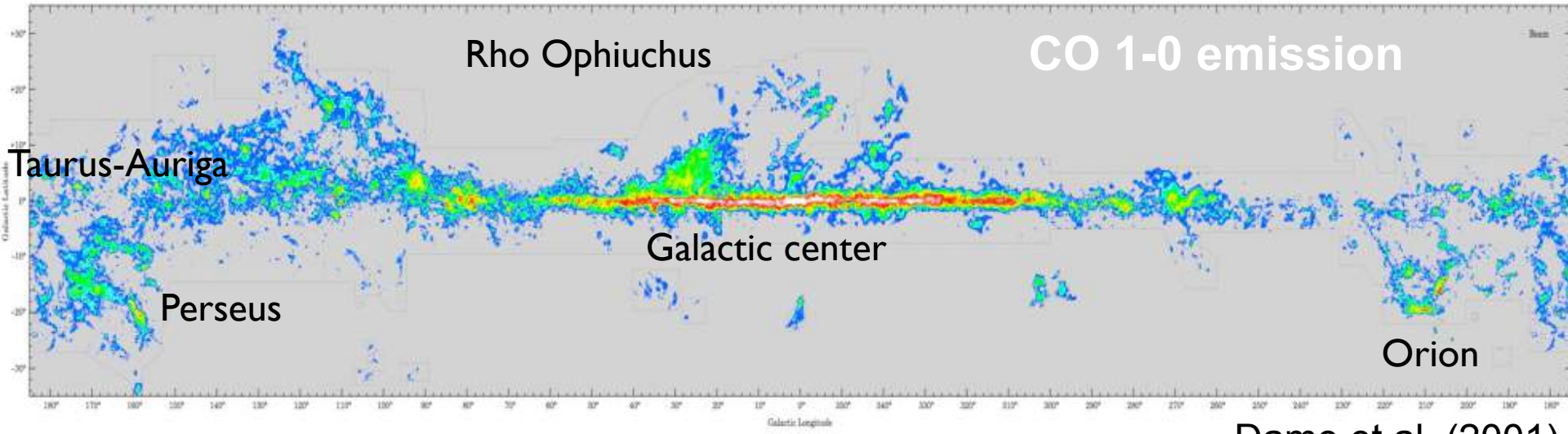
# Our Galaxy (optics)



- Diffuse light from ~ 100 billion stars
- Dark "patches": absorption by dust clouds (silicates, C)

Credit: Lund observatory

# Diffuse and dense interstellar medium



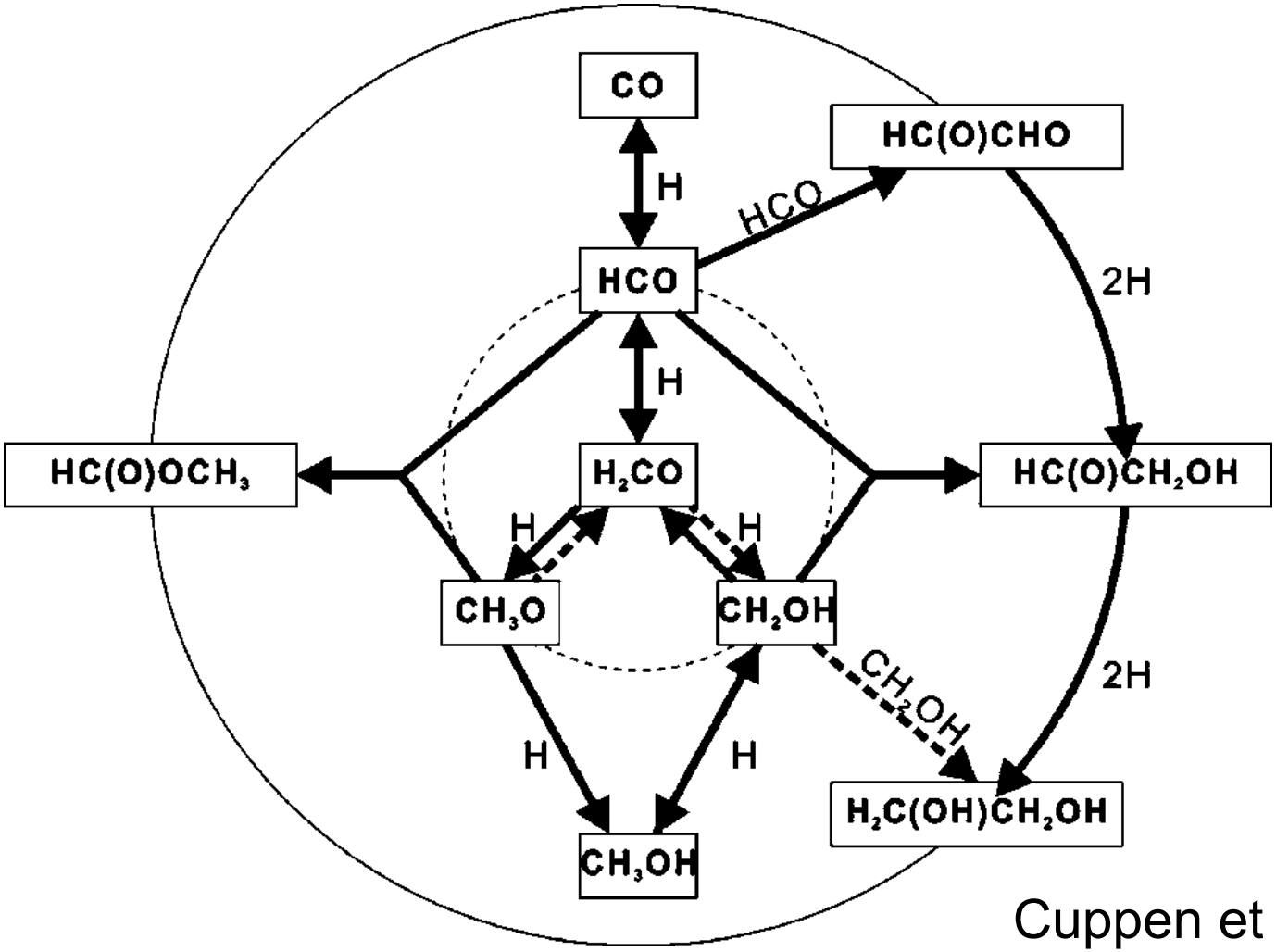

Dame et al. (2001)

- Giant Molecular Clouds:
  - Mass: ~$10^4$ – $10^7$ $M_{Sun}$ (2 x $10^{34}$ – 2 x $10^{37}$ kg)
  - Size: ~10 – 200 pc (3.1 x $10^{14}$ – 6.2 x $10^{15}$ km)
- Large-scale diffuse gas: T ~ 100 K, density ~ $10^2$ $cm^{-3}$
- Small 0.1 pc dense clouds: T ~ 10 – 20 K, density ~ $10^4$ $cm^{-3}$

# Gas-phase reactions in interstellar medium



# Surface chemistry in interstellar medium




Cuppen et al. (2016)

- Simple ices (CO) are converted to complex organic molecules

# HERSCHEL Space Observatory (2009-2013)
# (European Space Agency ESA)

Far-Infrared:  60 – 670 μm

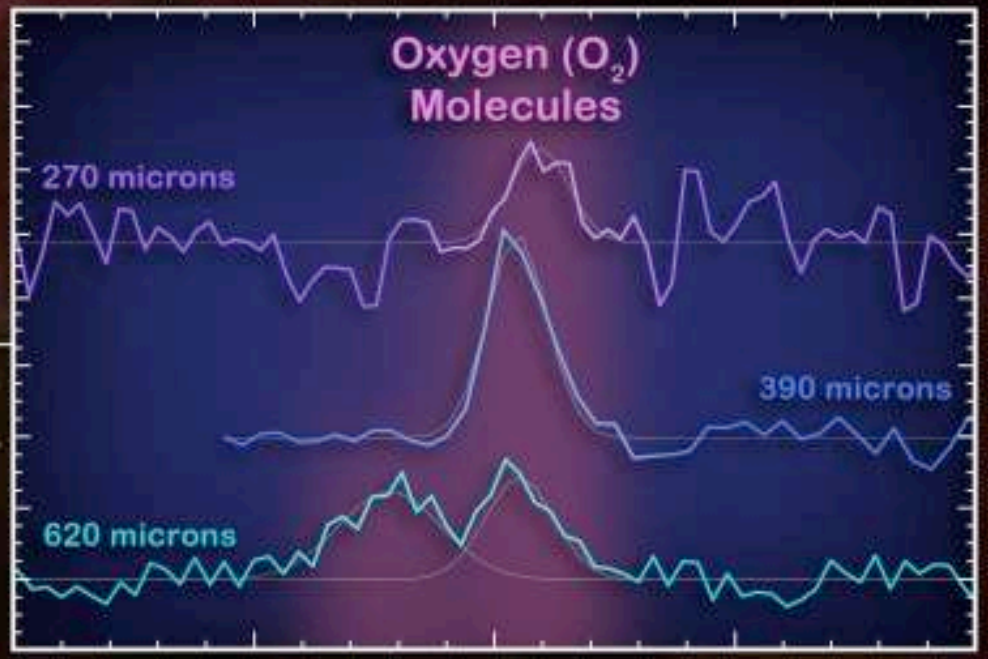
Named after Wilhelm and Caroline Herschel





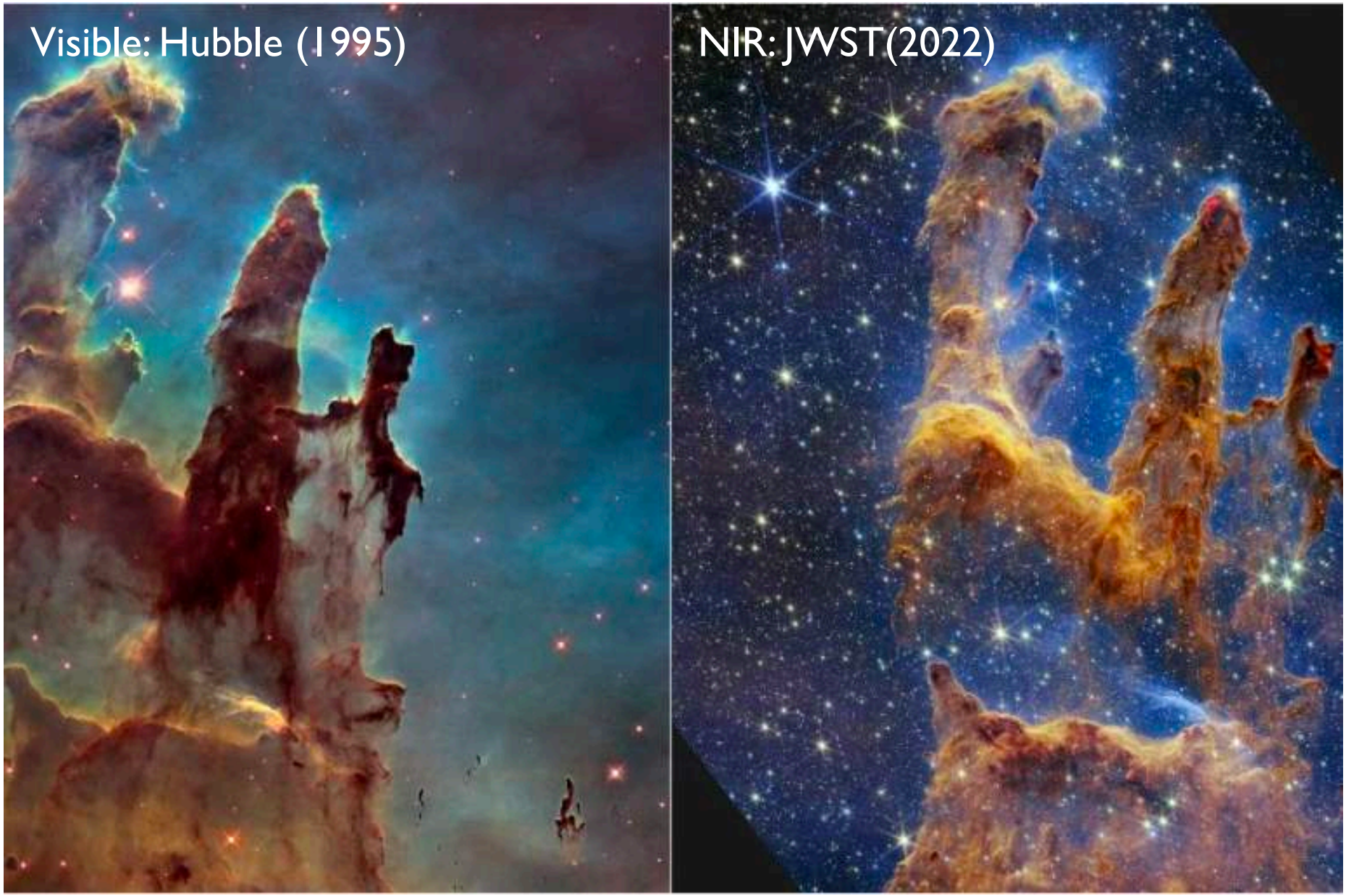
Star-formation complex Cygnus-X

# $O_2$ in Orion, Herschel




Goldsmith et al. (2011)

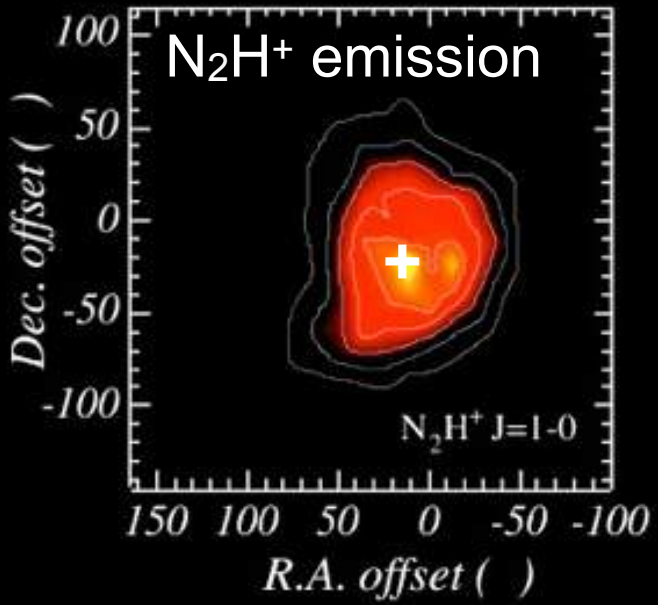
# "Eagle" nebula:  Pillars of Creation

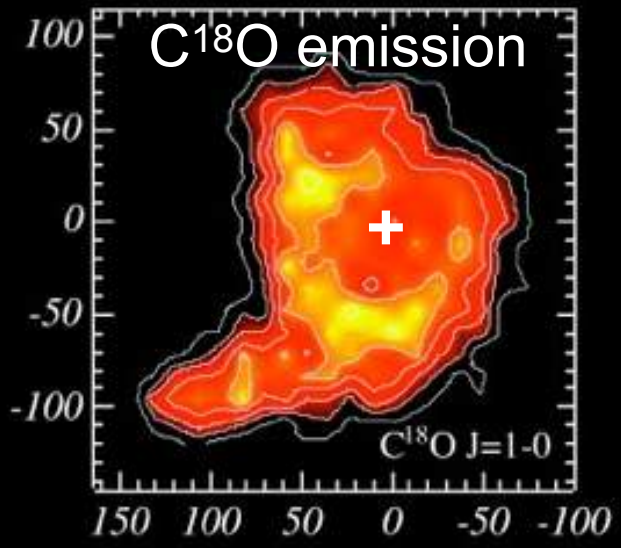


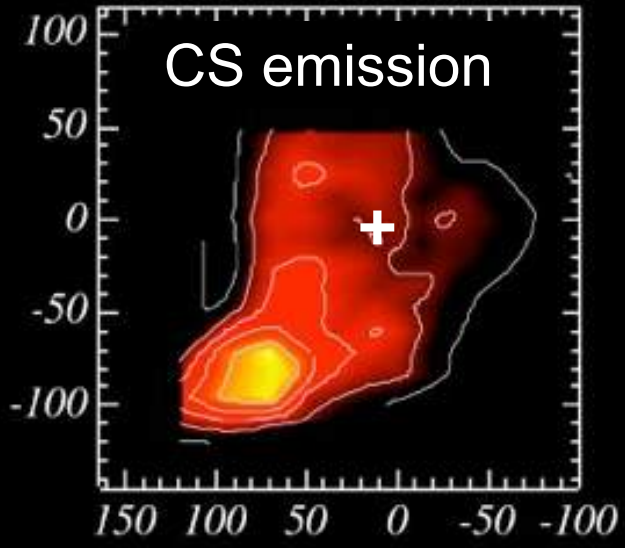

Gas, dust and young forming stars in Eagle nebula (Serpens)

# Dense cloud Barnard 68, dust and gas

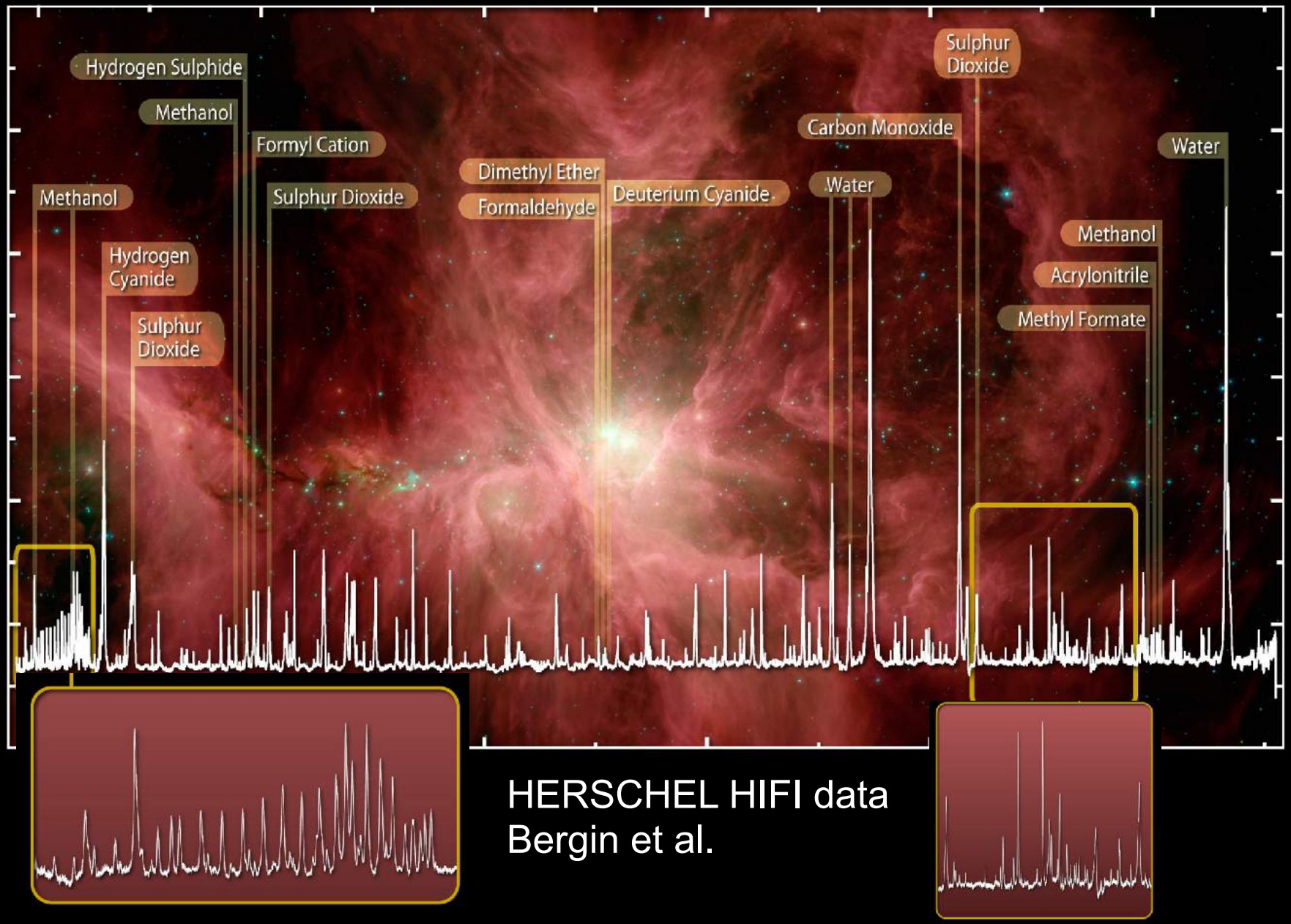


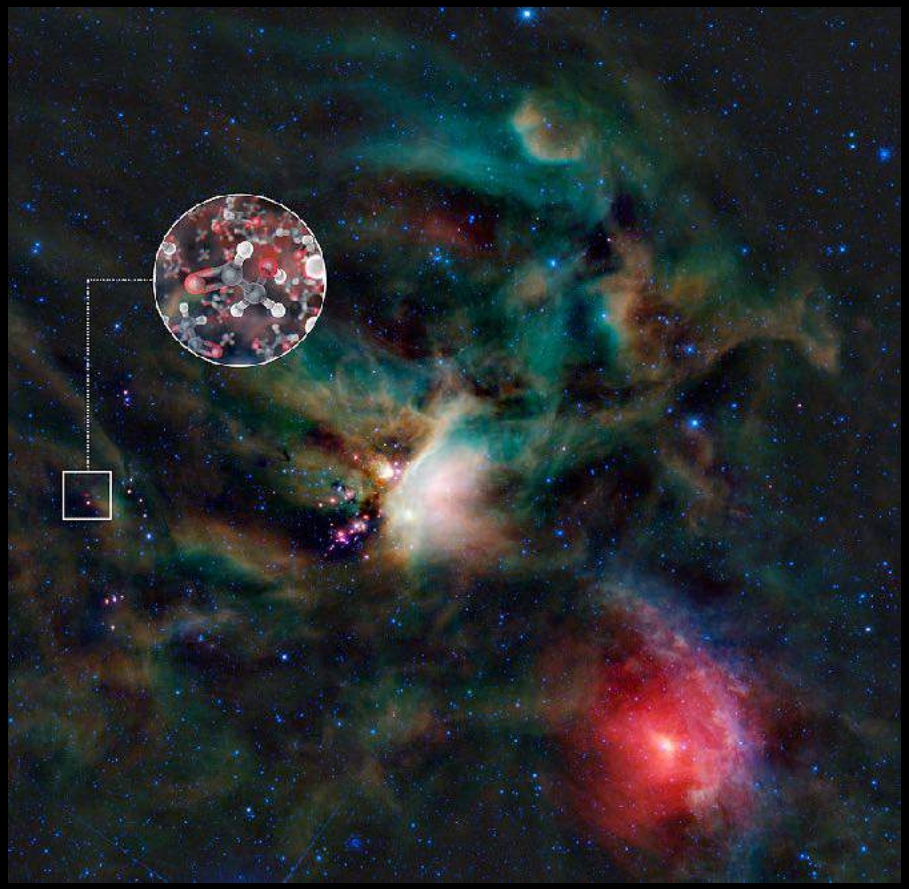



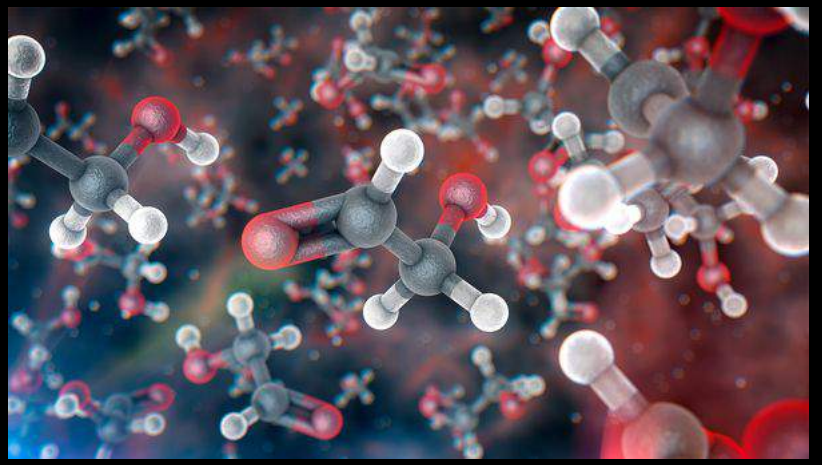
# Chemistry in molecular clouds decoded




HERSCHEL HIFI data
Bergin et al.

# Sugar and alcohol in space





IRAS 16293-2422

Observations: ALMA

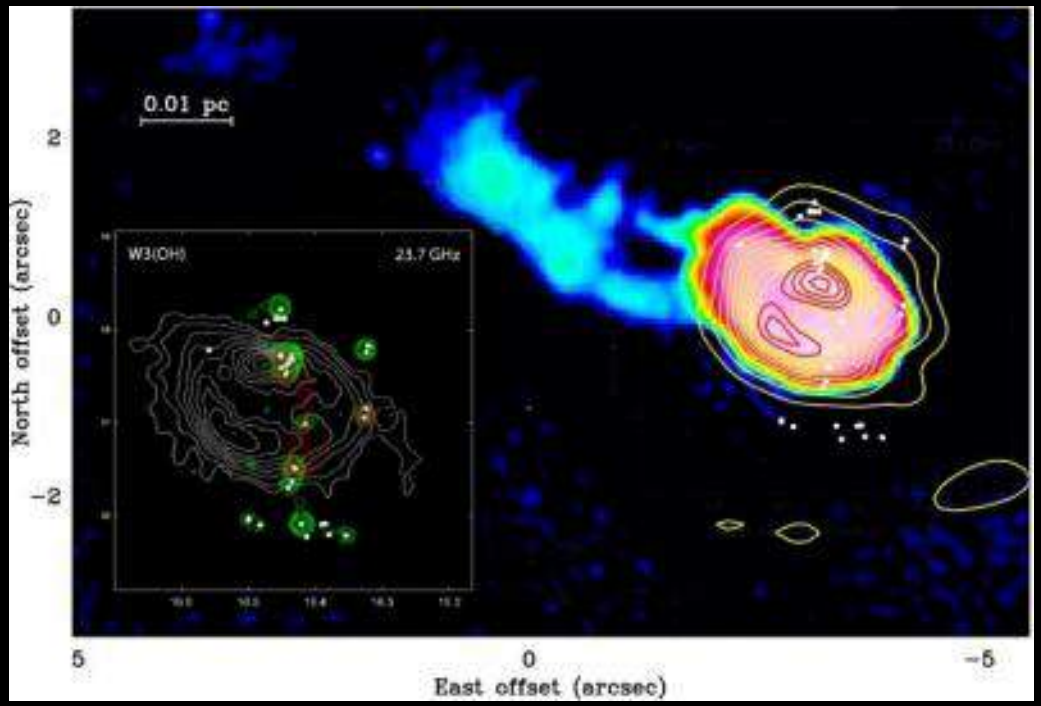
**Glycolaldehyde** ($HOCH_2$-CH=O)

Jørgensen *et al.* 2012 *ApJ* **757**, 4

# Sugar and alcohol in space

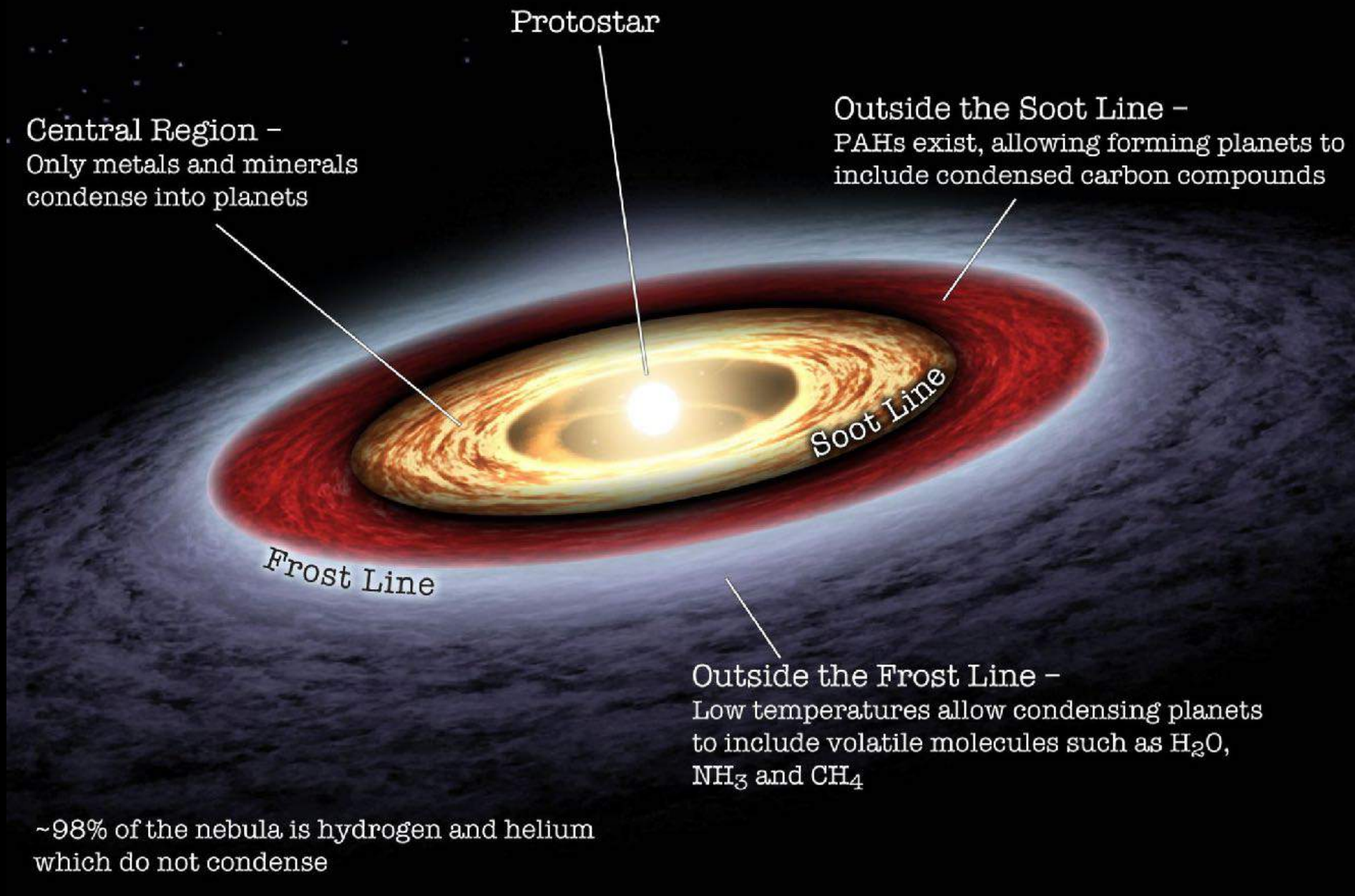
**“Astronomers find alcohol cloud spanning 288 billion miles”**

**www.phys.org**



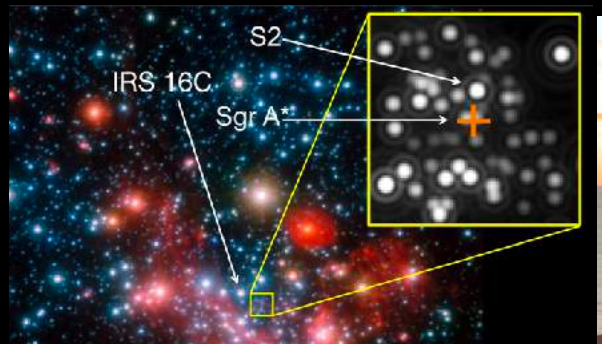



# Protoplanetary disks



# Very Large Telescope (since 1998)
# (European Southern Observatory ESO)

UV-visual: 300 nm – 20 µm




Supermassive black hole
Sgr A* in Milky Way

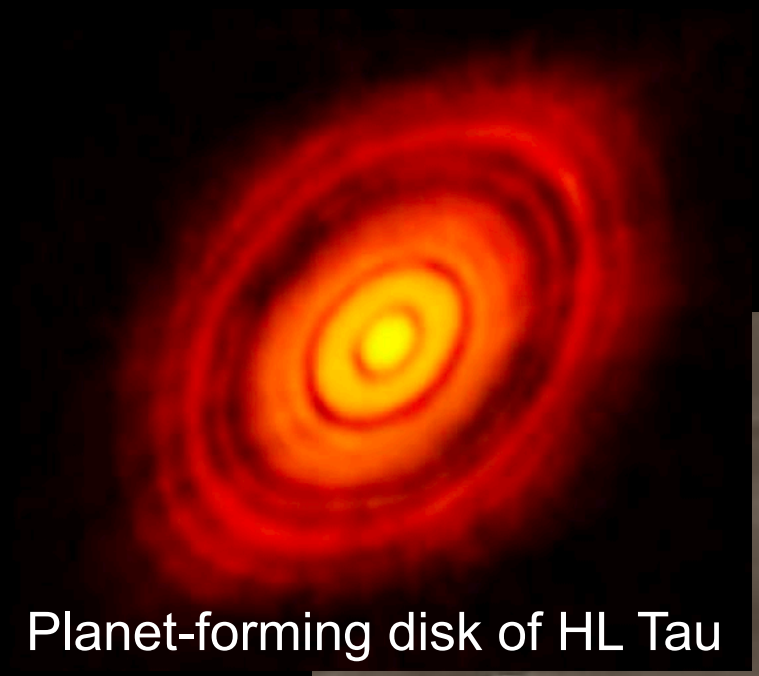


Young planets in PDS70

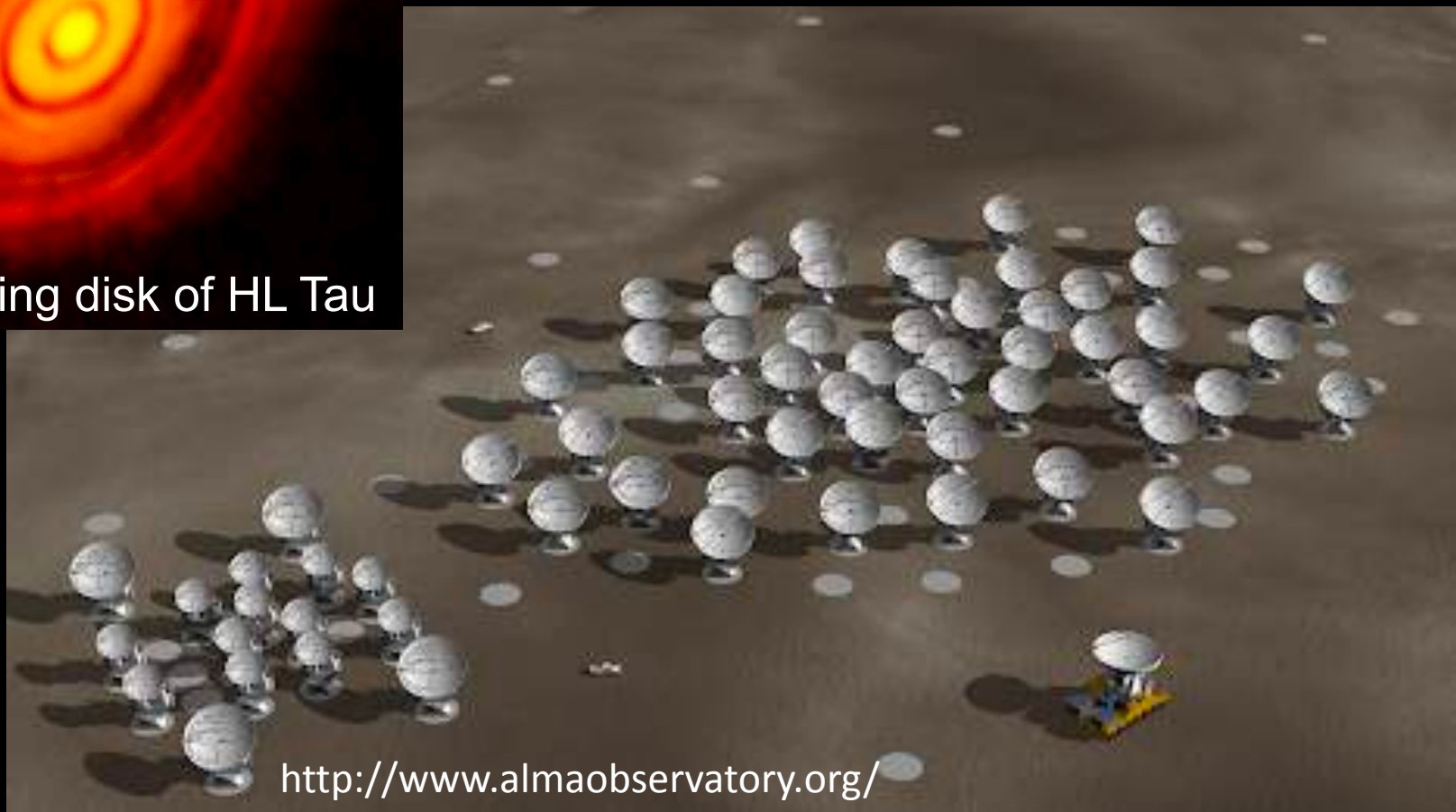


# Atacama Large Millimeter/Submillimeter Array

Radio: 0.3 mm – 9.6 mm

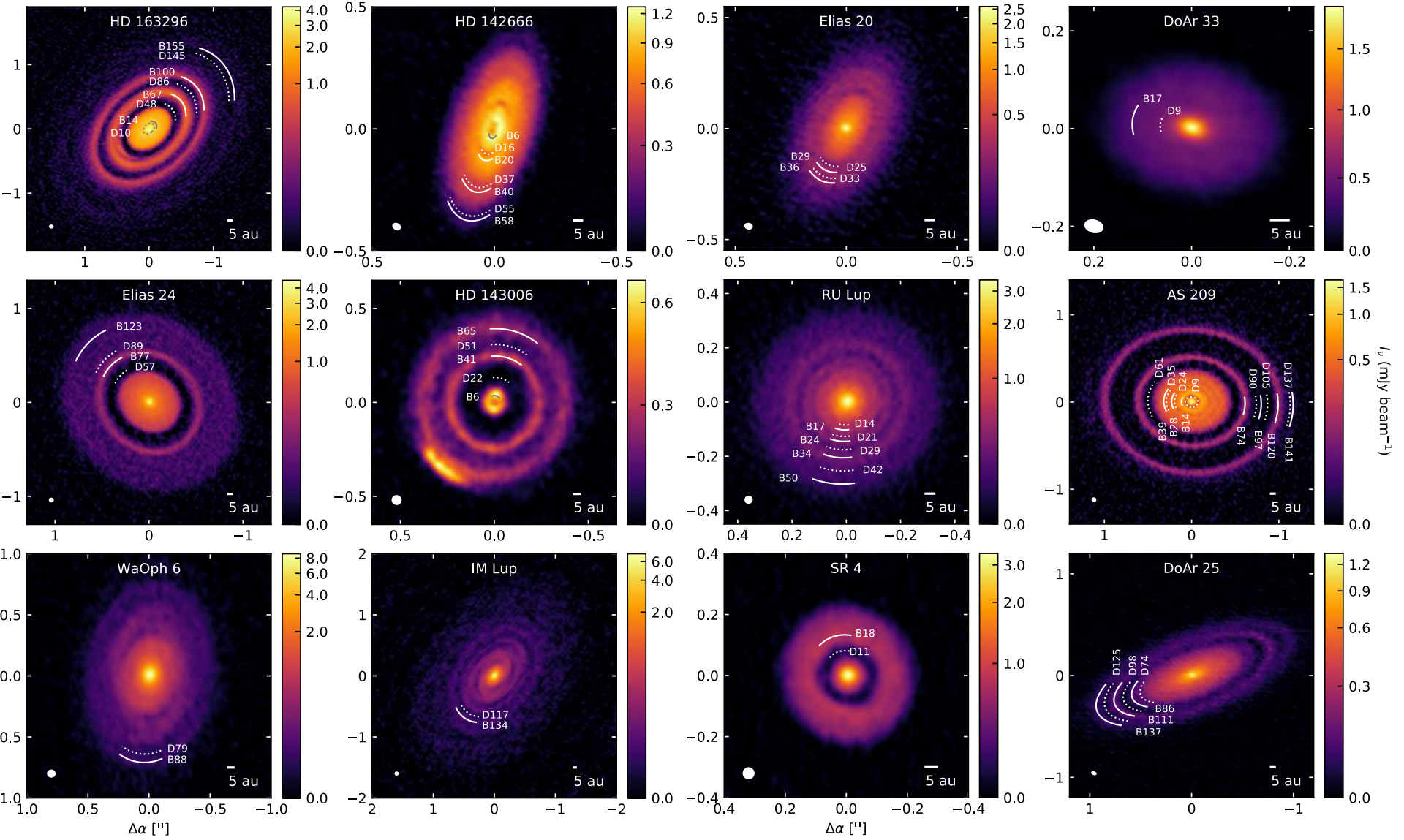


Planet-forming disk of HL Tau



http://www.almaobservatory.org/

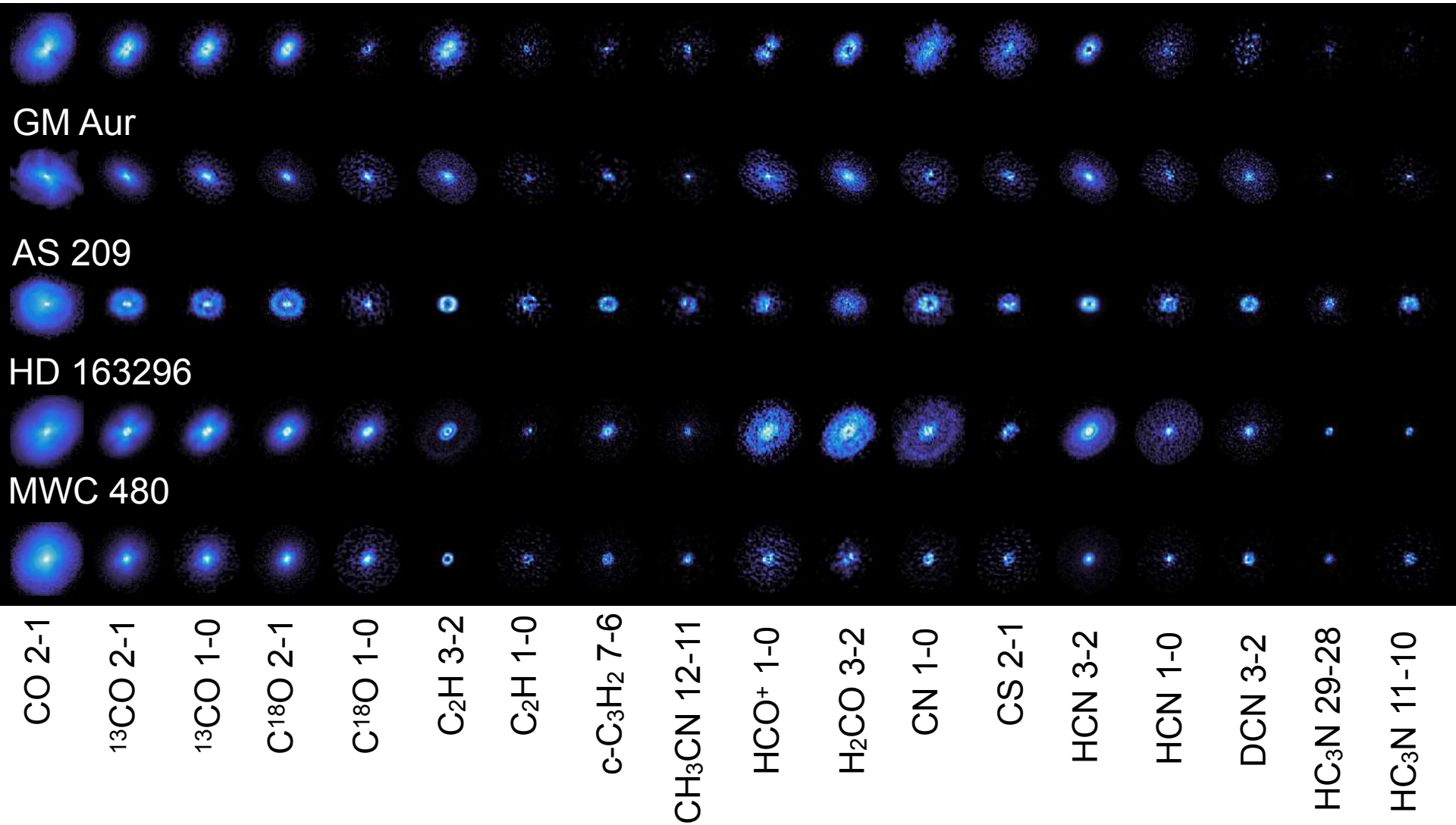
# Protoplanetary Disks with ALMA: thermal dust emission at 1.25 mm




- Multiple rings, gaps, spirals → planets?

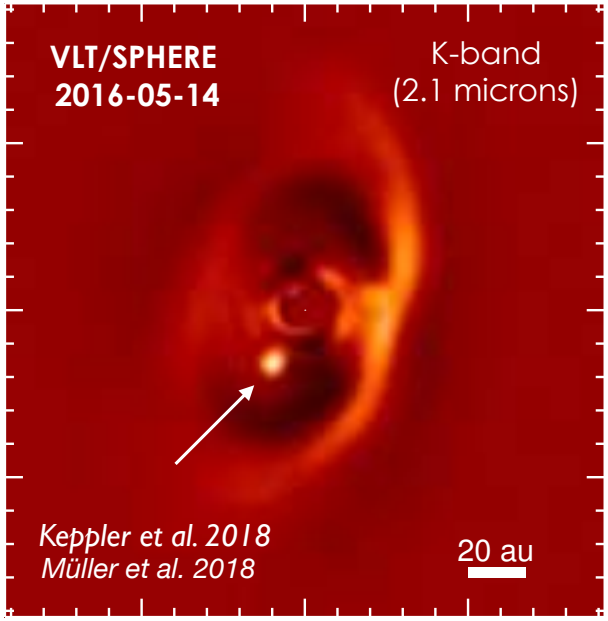
Andrews ea (2018)

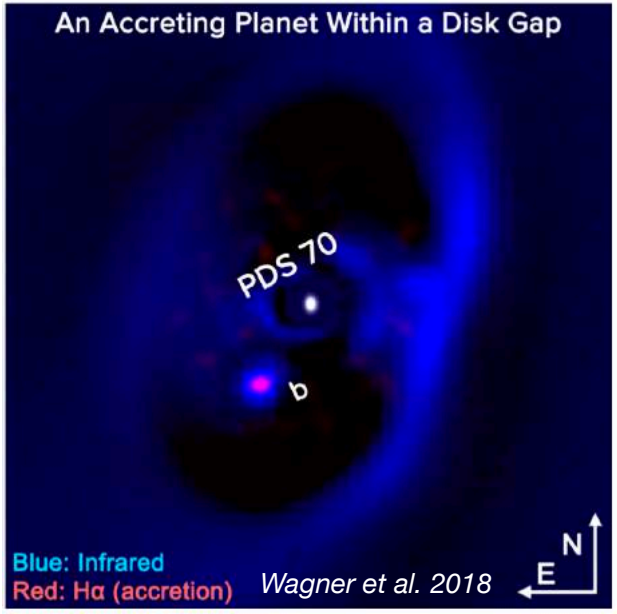
# Protoplanetary Disks with ALMA: many molecules!

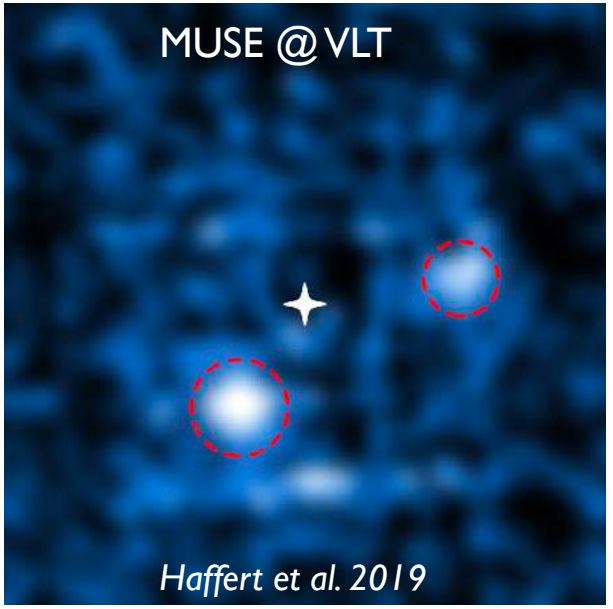



- CO, CN, HCN, $C_nH_m$, organics
- Gas sub-structures: planets? chemical effects? excitation?

# Young gas planets in PDS70 disk



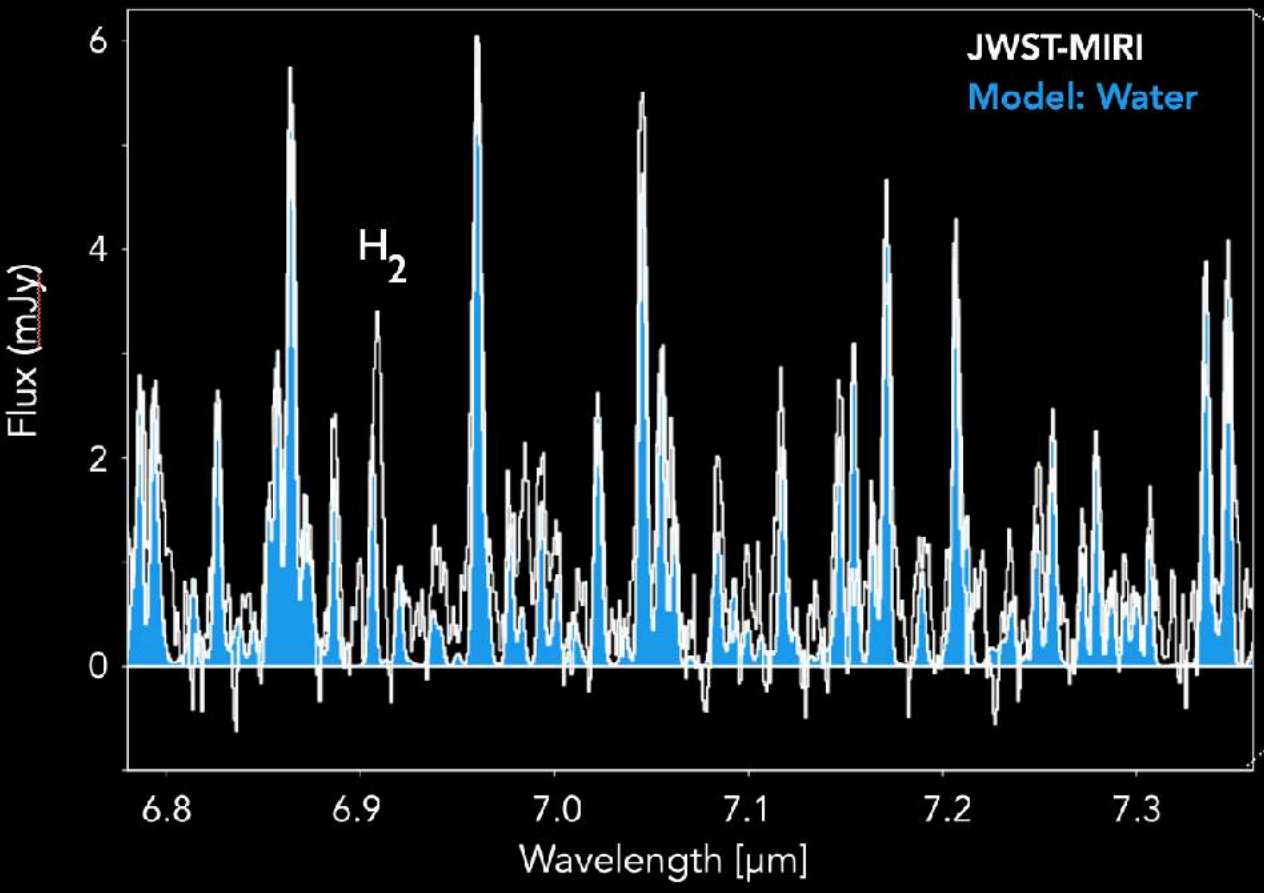



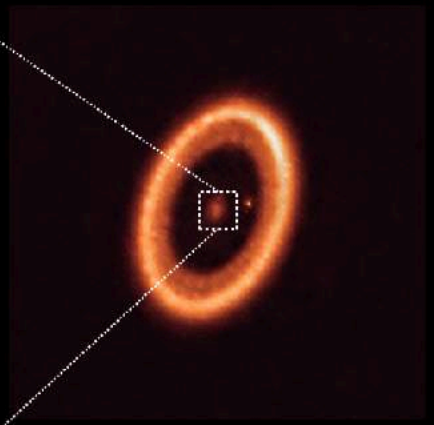

- Sun-like star with disk, ~ 5 Myr old
- Two gas giant planets at 21.5 and 35.5 au (2:1 resonance)
- Planets are accreting gas
- Hubble and JWST spectroscopy

# James Webb Space Telescope (>2021)

## Water detection in a planet-hosting disk PDS70

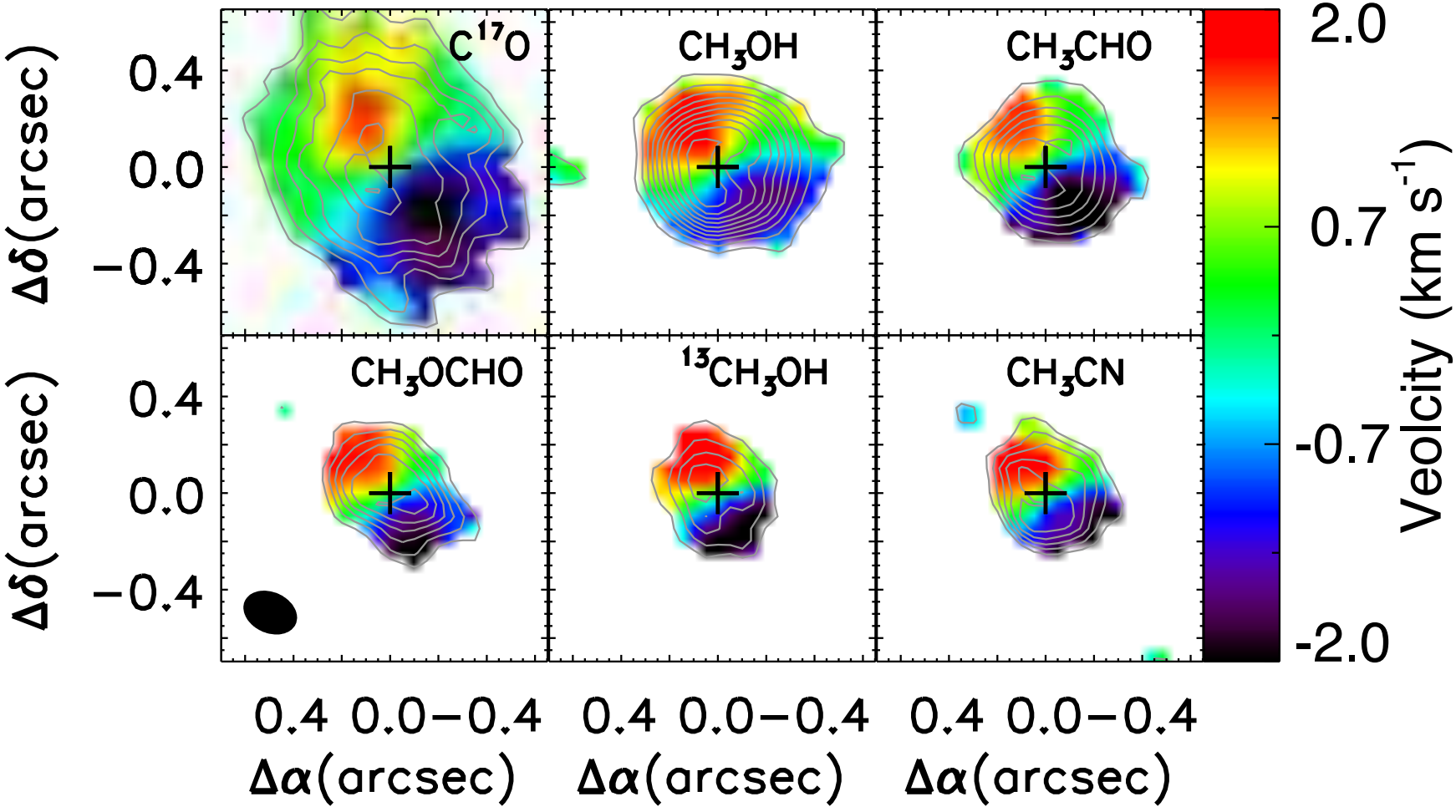



Temperature: 600 K
Column Density: 1.4 x $10^{18}$ $cm^{-2}$
Emitting radius: < 1 AU



Nascent Solar System
5.5 Myr old

# Organics in disks (V883 Ori; ALMA)



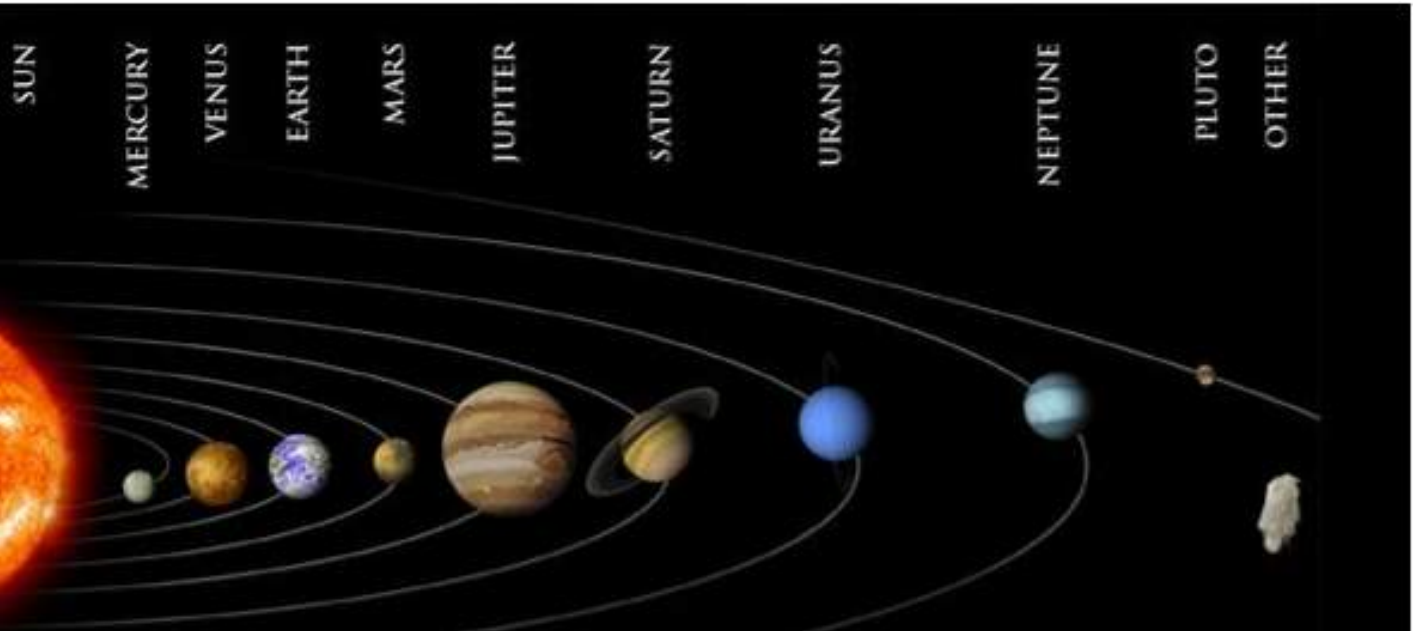

van t'Hoff et al. (2018), Lee et al. (2019)

- Methanol, acetone, acetonitrile, acetaldehyde, and methyl formate
- Formed via icy chemistry & sublimated

# Solar system (planets, moons, comets...)

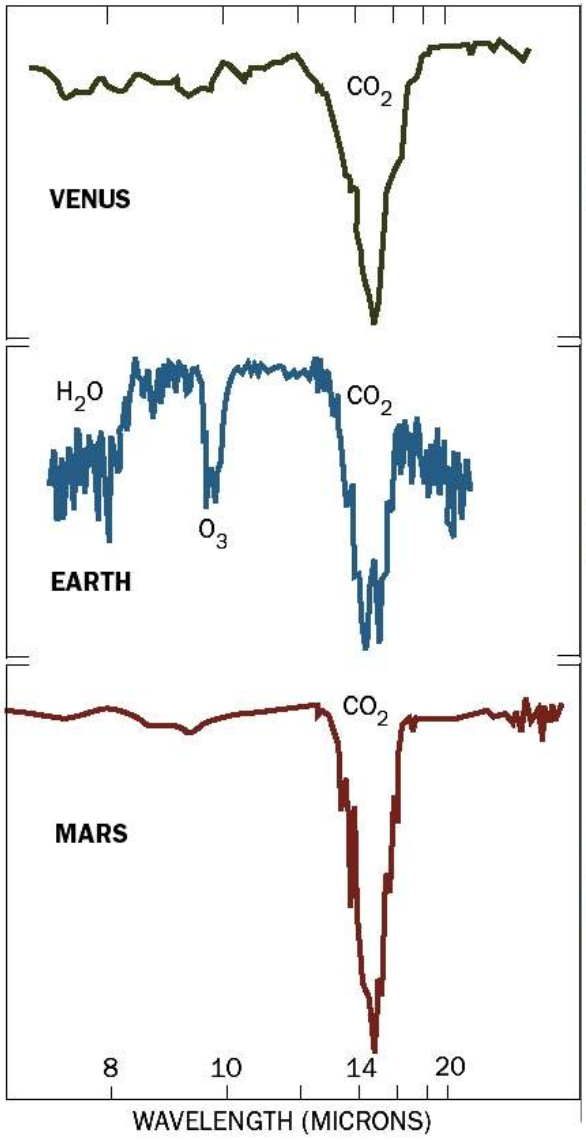
- **A gravitationally bound body that is not massive enough for nuclear fusion, but large enough to become round under the influence of its own gravitation**

- Upper Mass limit ≈ 13 $M_{jup}$, where 1 $M_{jup}$ = 317 $M_{Earth}$ (2 x $10^{27}$ kg)
- **Rocky Planets** in our solar system: Mercury, Venus, Earth, Mars (0.06 – 1 $M_{Earth}$)
- **Gas giants**: Jupiter, Saturn, Uranus, Neptune (14 – 317 $M_{Earth}$)
- Planet has to dominate its neighbourhood (that's what "killed" Pluto)

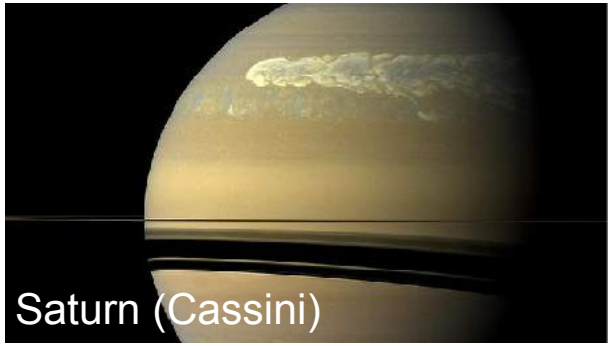



G. Basri & M.E. Brown, Annu. Rev. Earth Planet. Sci. 2006. 34: 193-216

# Solar system (planets, moons, comets...)





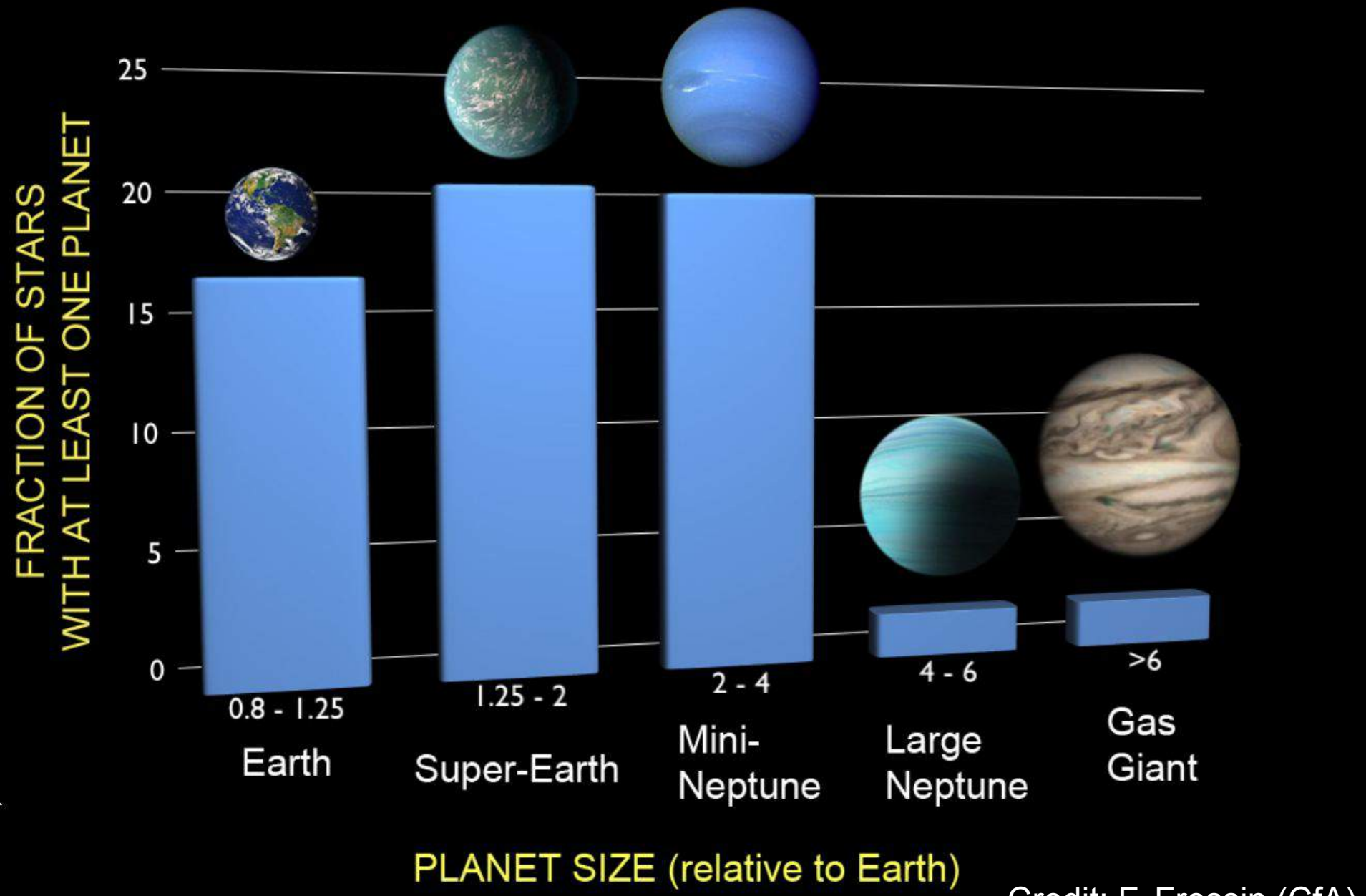







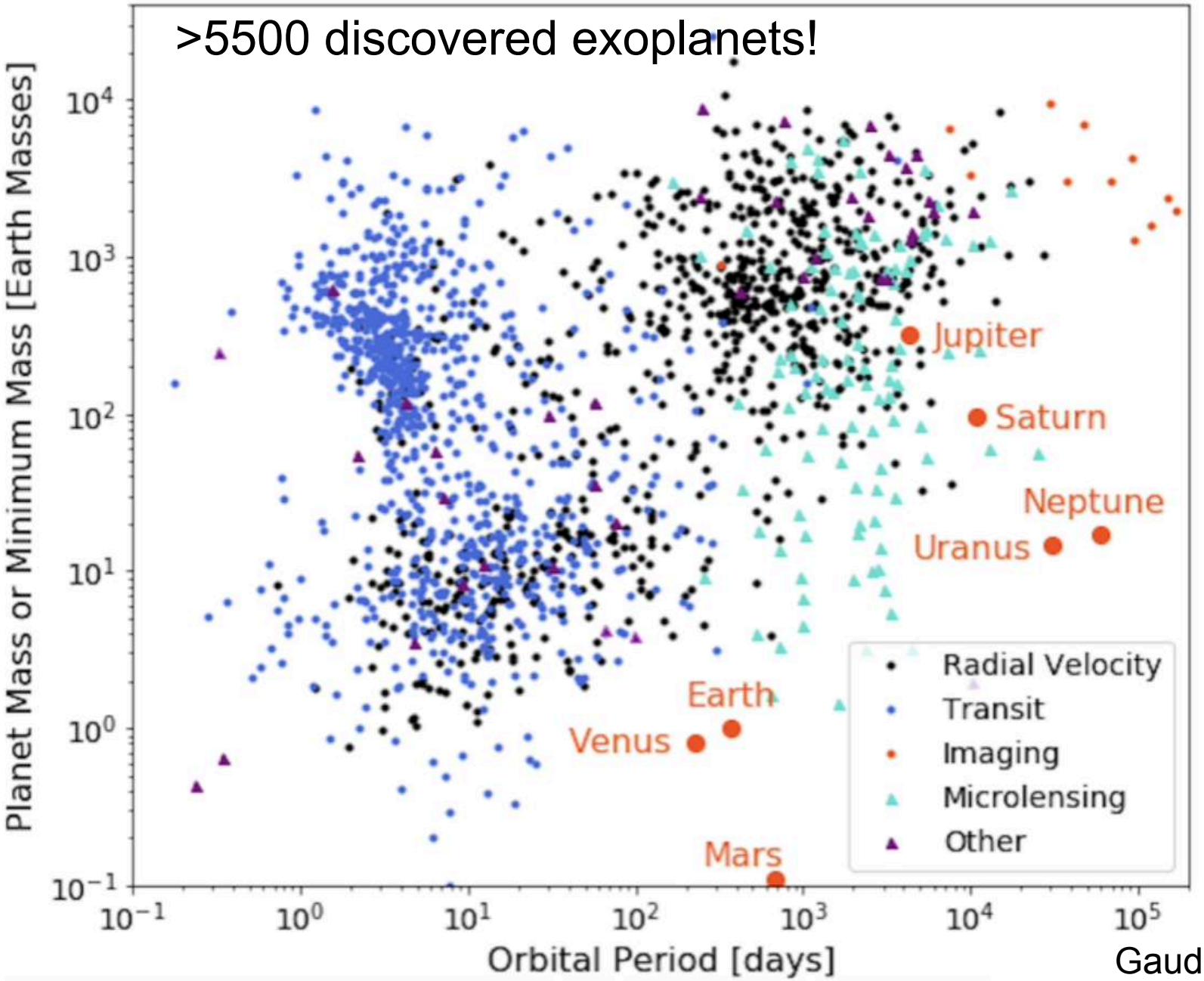


# Exoplanets: Almost every star has them



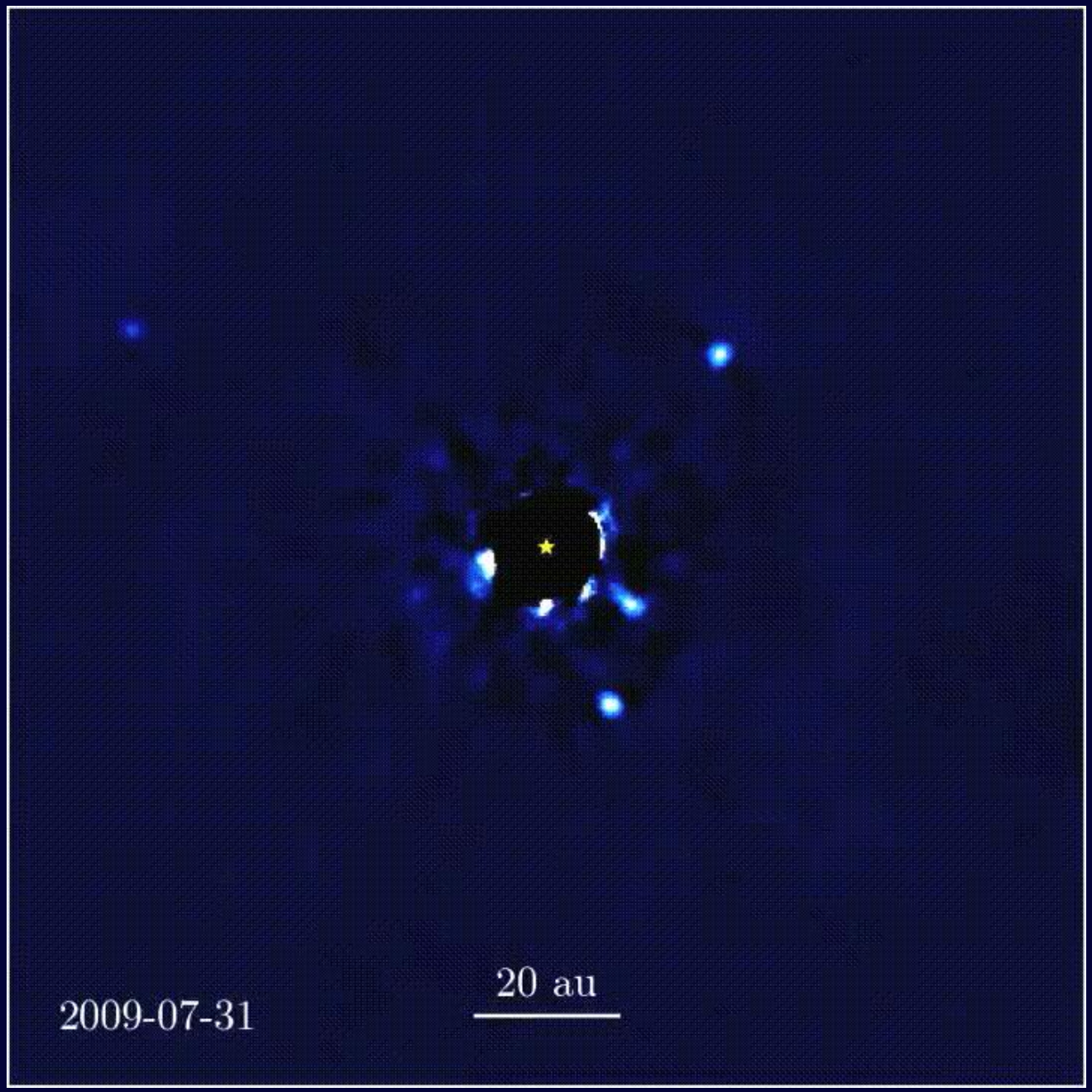

Credit: F. Fressin (CfA)

# Exoplanetary statistics: https://exoplanet.eu/

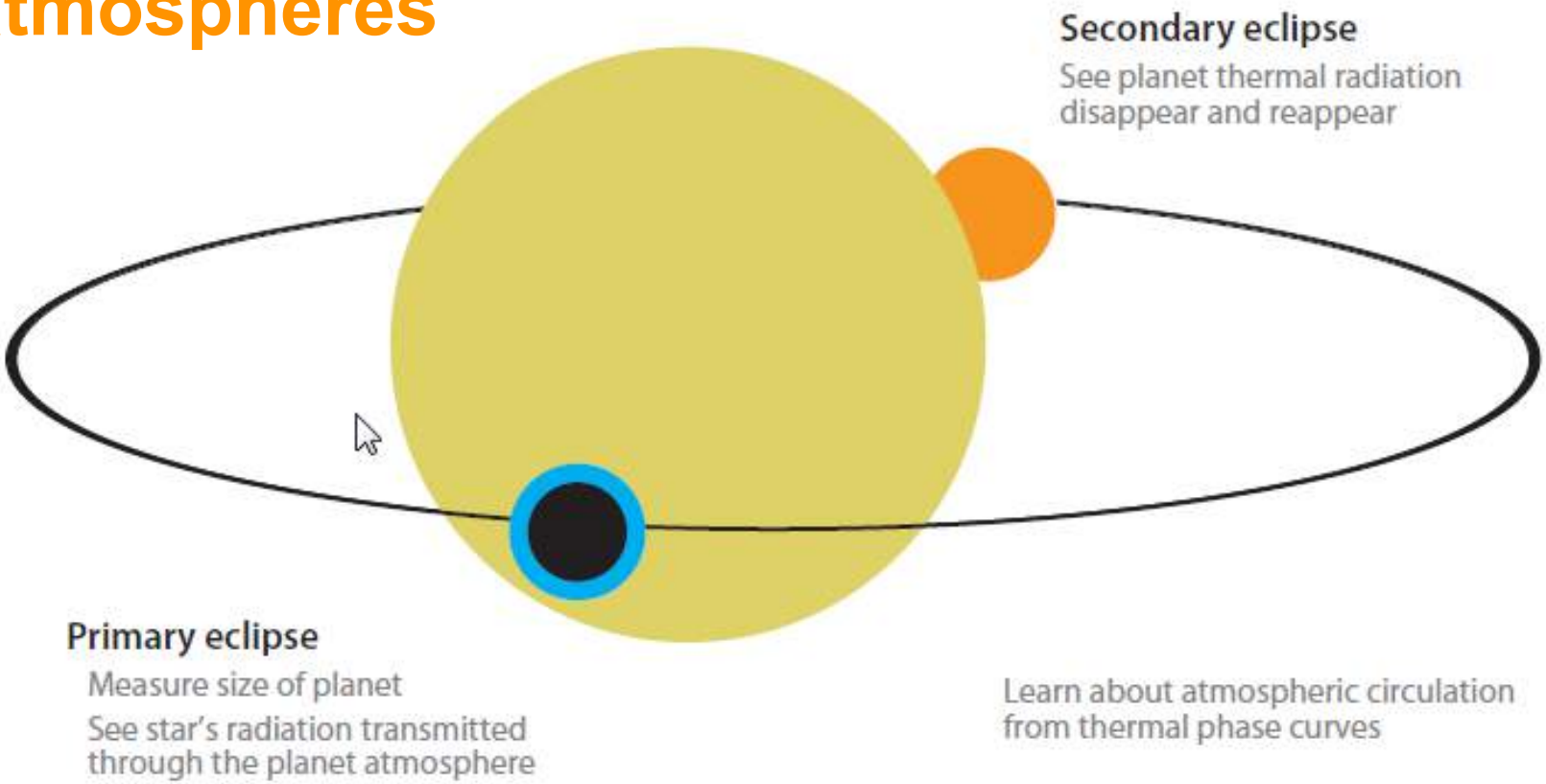



Gaudi et al. (2020)

# Exoplanets around HR 8799 (optics), Keck 10m



# How to infer information on planetary atmospheres

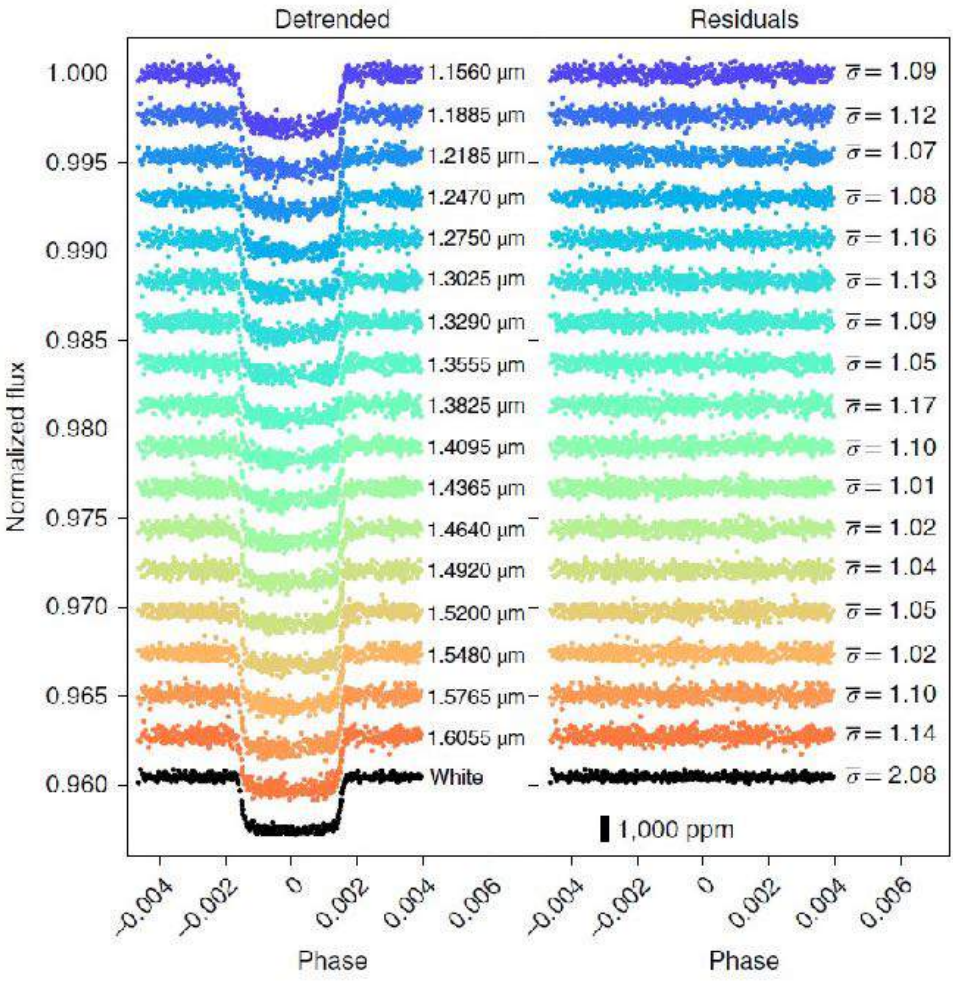


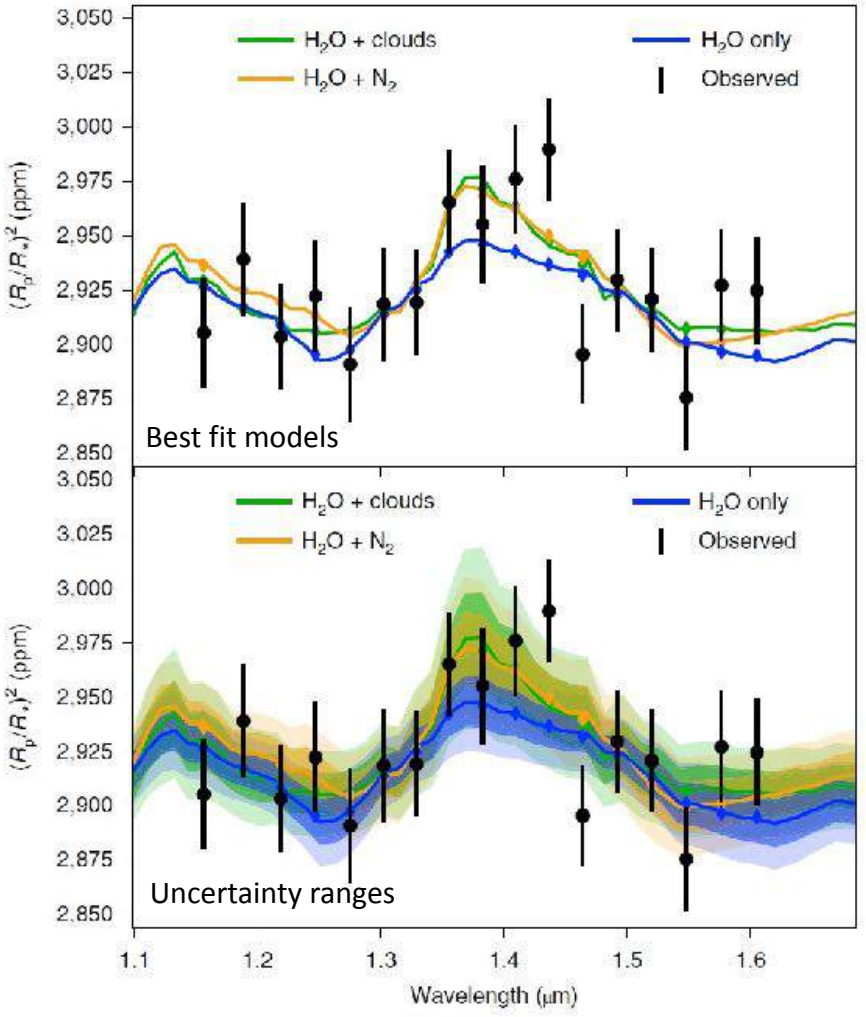

- Spectroscopy of planetary transits at different wavelengths
- Atmospheric properties, composition (upper layers)
- Atmospheric models (physics, dynamics, chemistry, clouds,...)

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

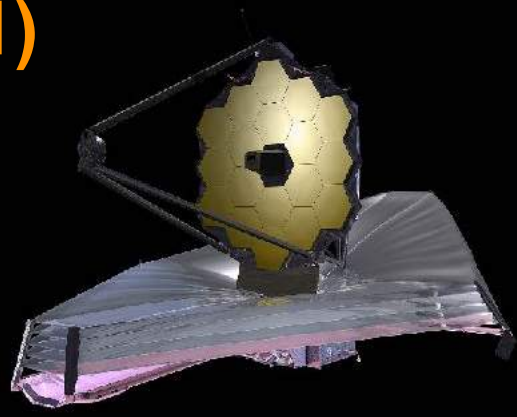
# Water in super-Earth K2-18b, Hubble

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



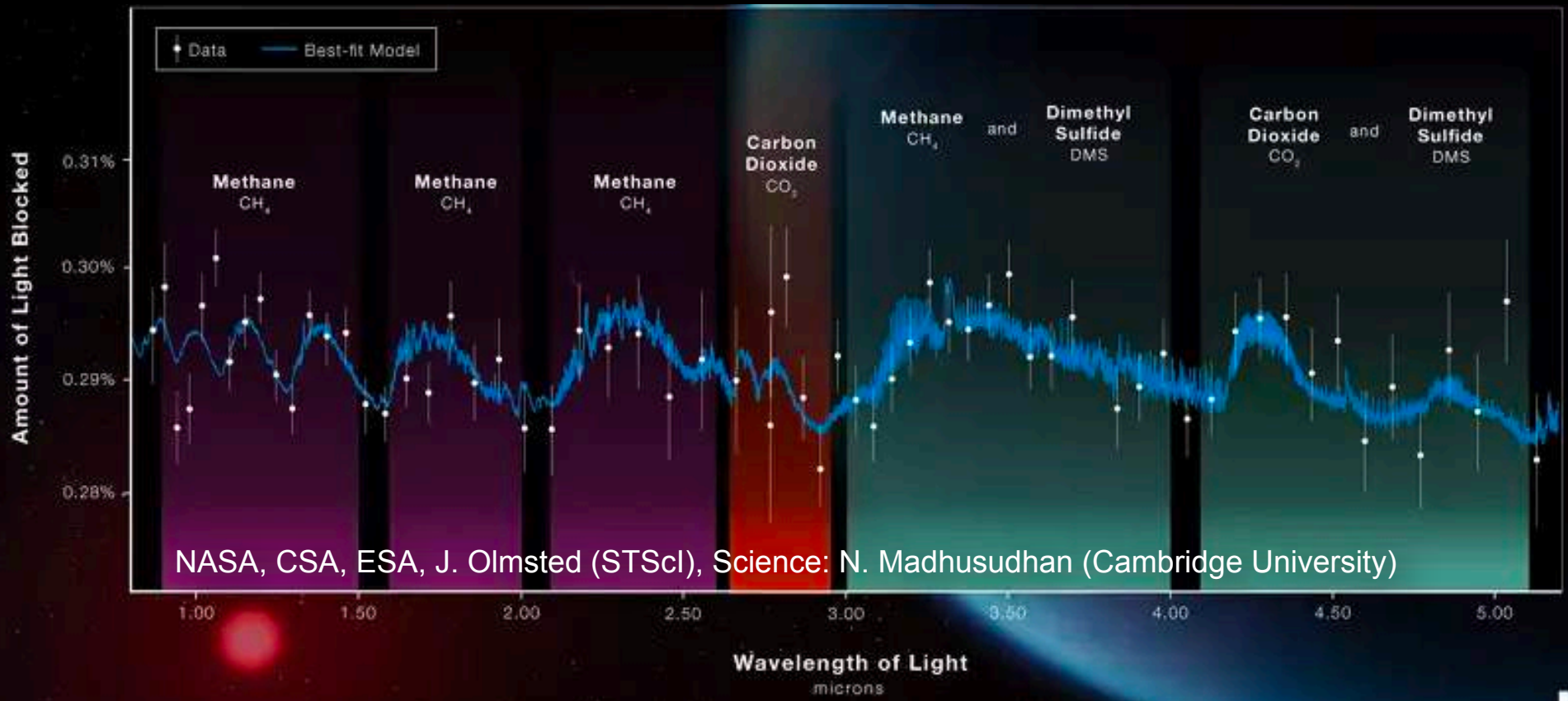



# James Webb Space Telescope (>2021) (National Aeronautics and Space Administration NASA)



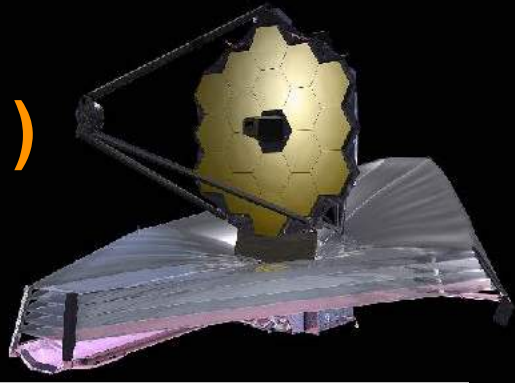
Near/Mid-Infrared: 0.6 – 28 μm

Atmospheric spectrum of super-Earth K2-18b




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

# James Webb Space Telescope (>2021)



Atmospheric spectrum of super-Neptune WASP–107b

