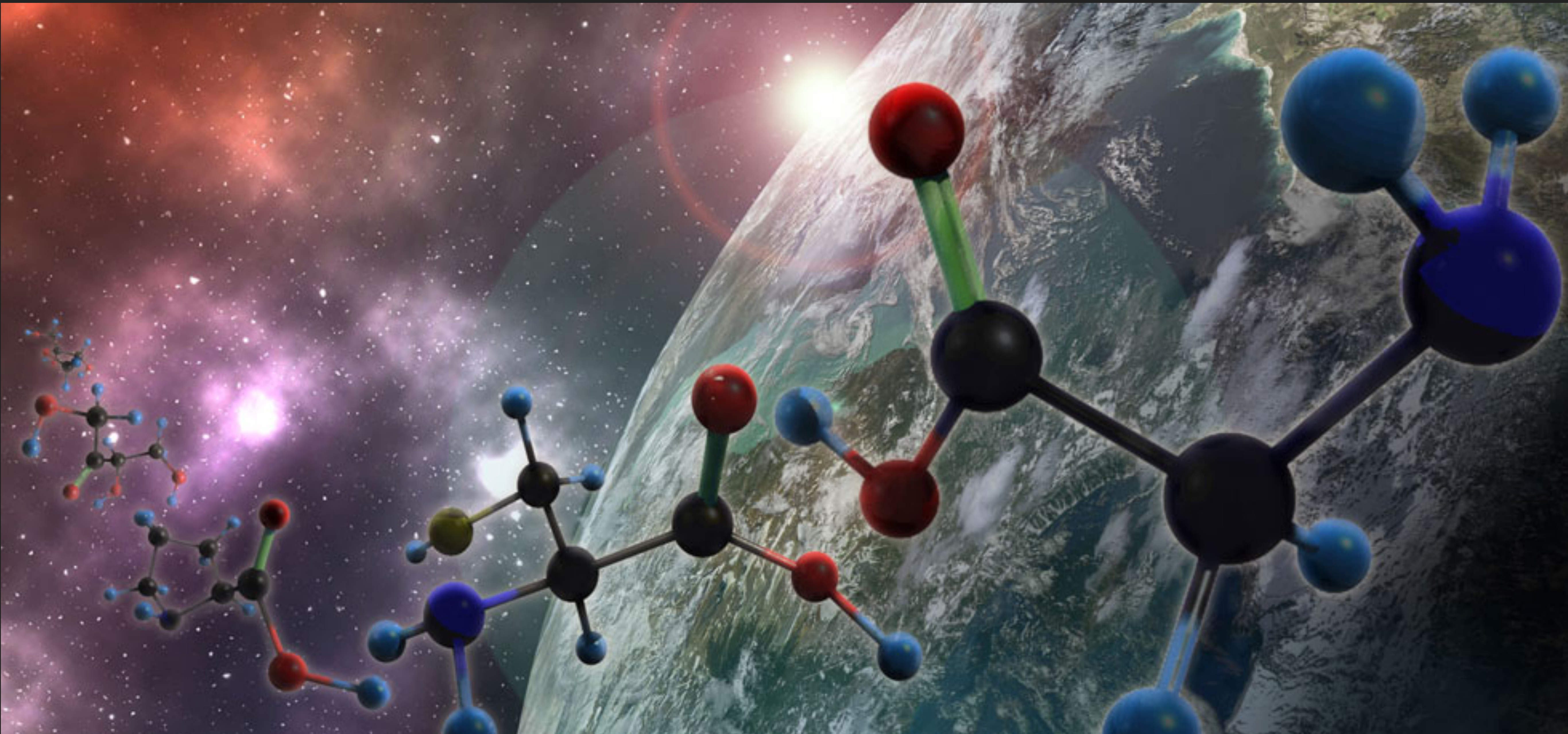
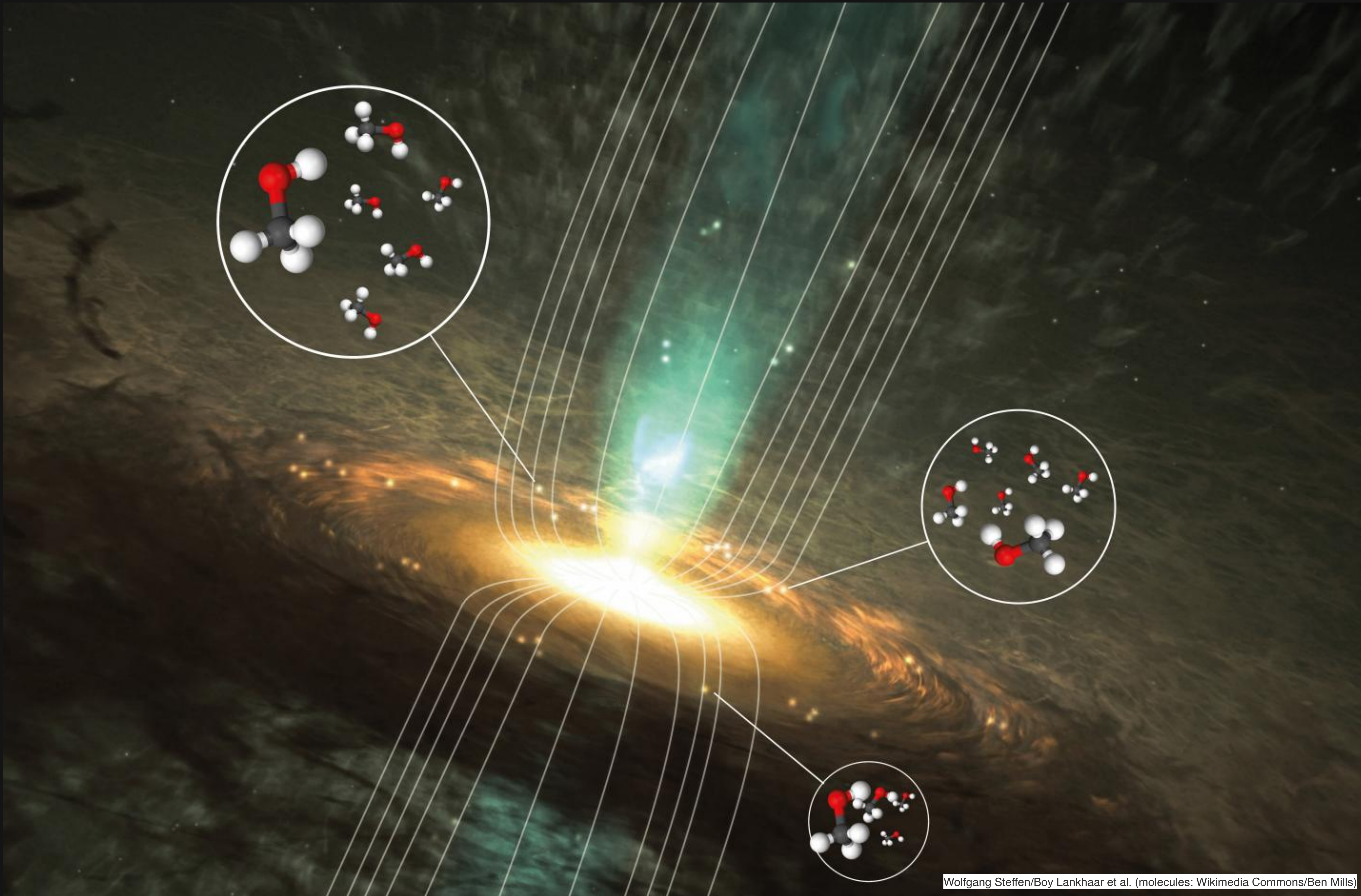
LECTURE 1

STEFANO BOVINO,
UNIVERSIDAD DE CONCEPCIÓN



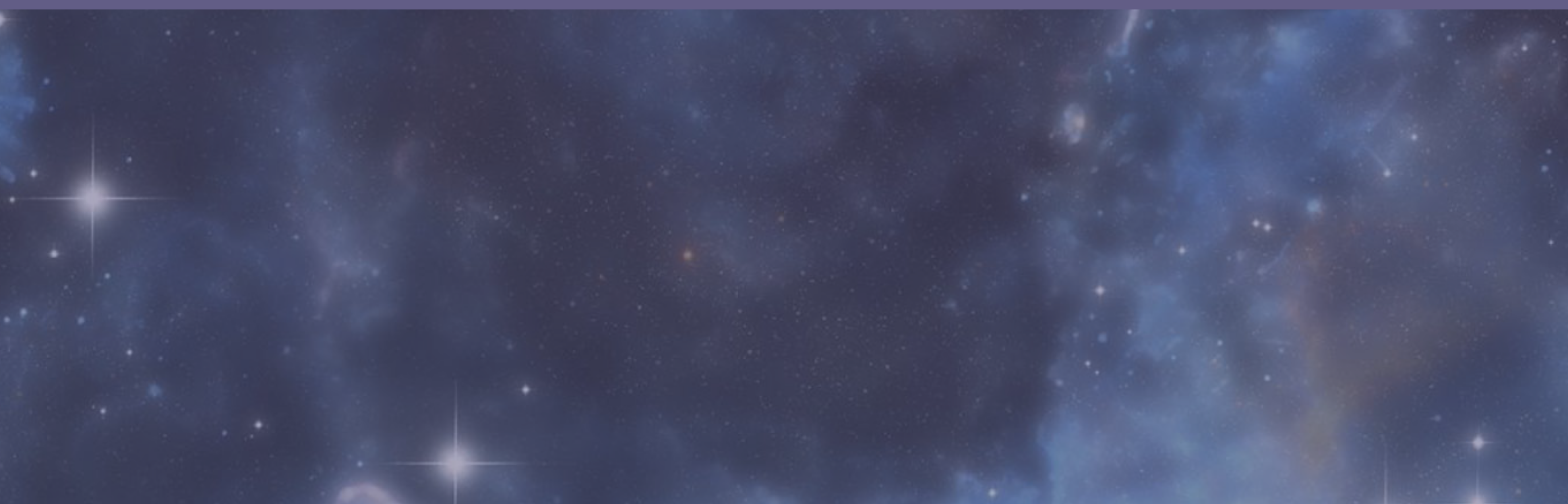
FILL IT PLEASE

WHAT IS ASTROCHEMISTRY?



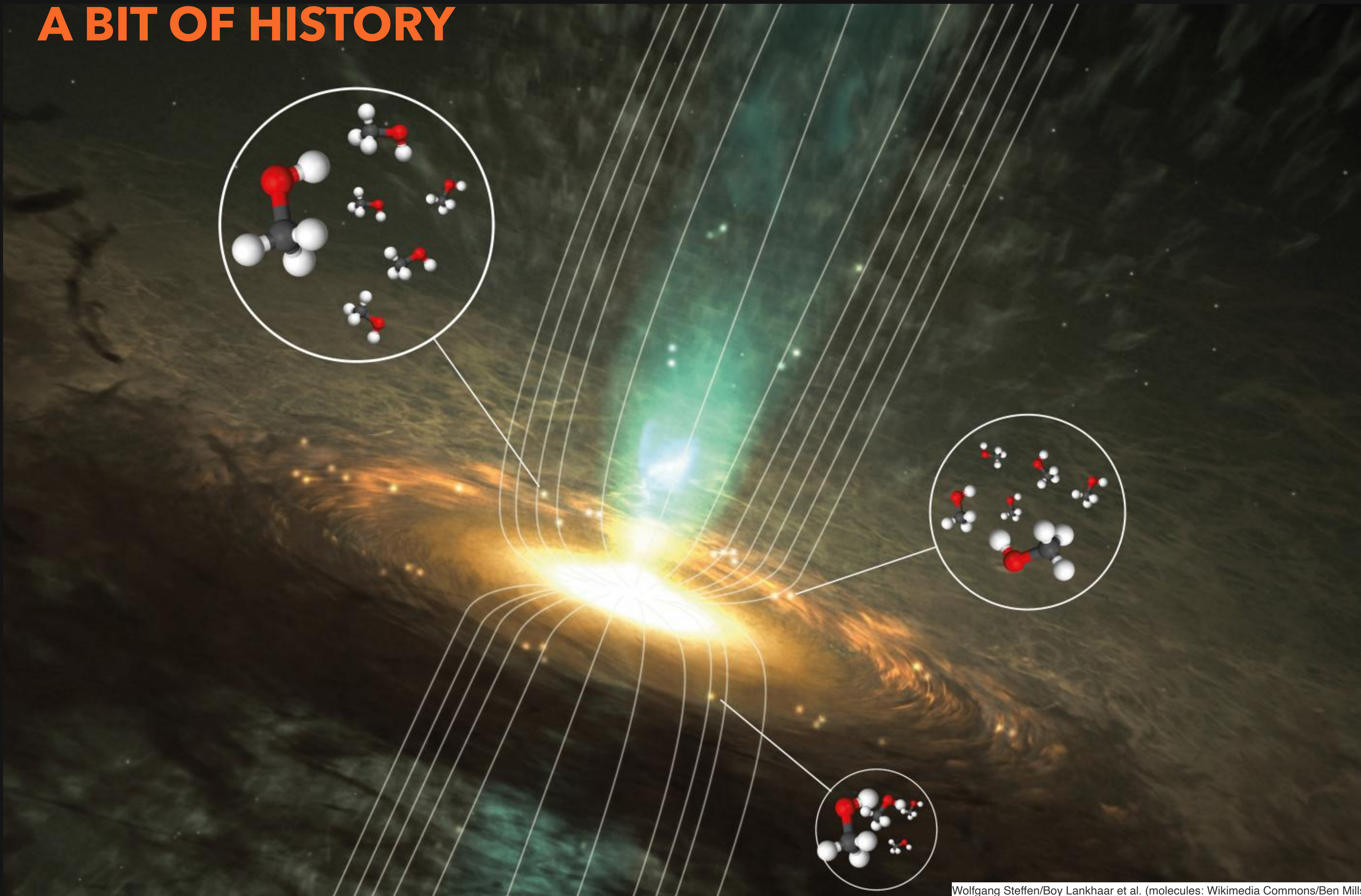
Wolfgang Steffen/Boy Lankhaar et al. (molecules: Wikimedia Commons/Ben Mills)

THE STUDY OF HOW MOLECULES AND CHEMICAL PROCESSES AFFECT THE DYNAMICS OF GALAXIES, STARS AND PLANETS FORMATION!



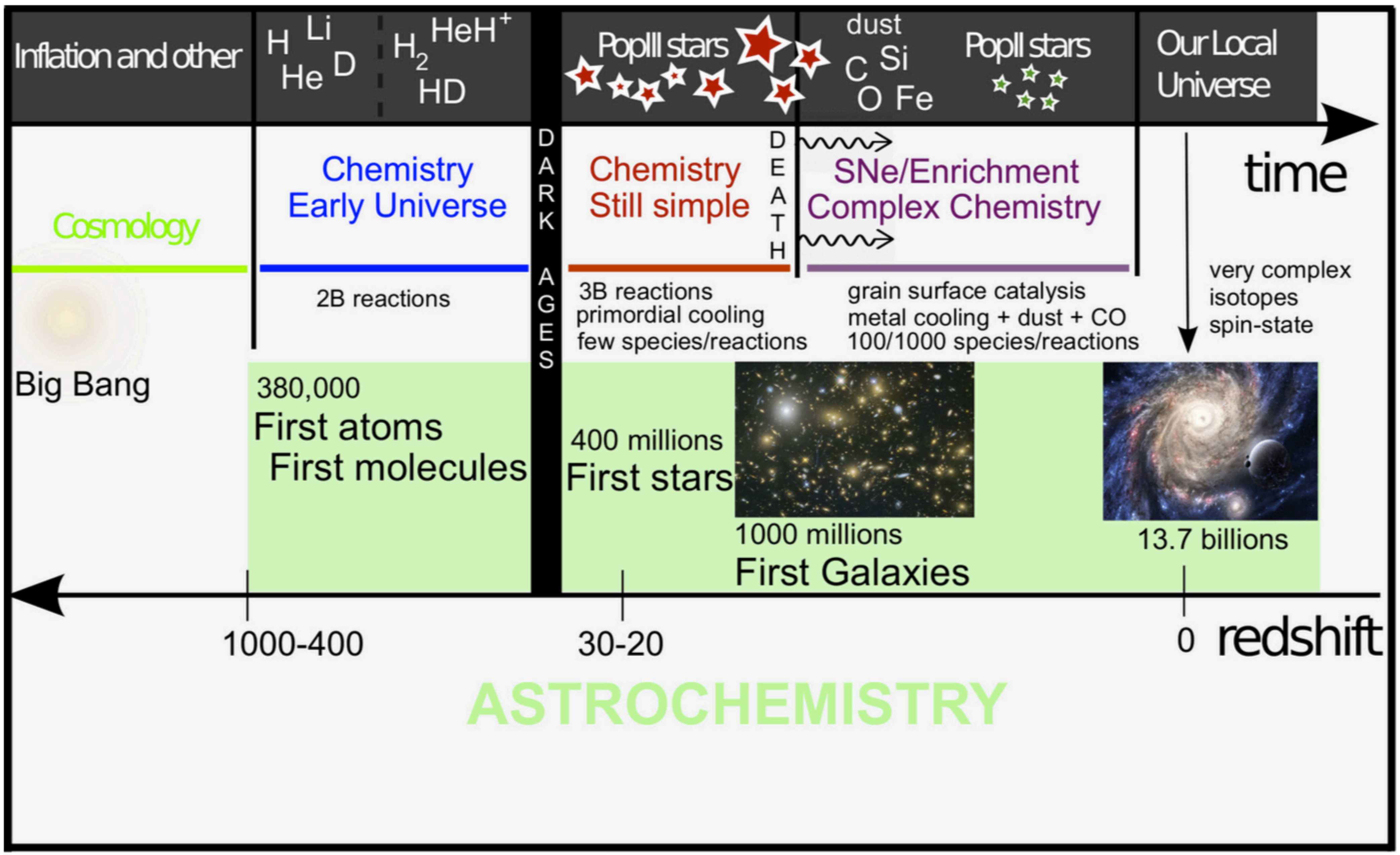
WHEN DID ASTROCHEMISTRY START?

A BIT OF HISTORY



Wolfgang Steffen/Boy Lankhaar et al. (molecules: Wikimedia Commons/Ben Mills)

IT DOES EXIST SINCE EVER (~13.7 BILLIONS YEARS - SOMETHING)



THE MOLECULAR UNIVERSE TIMELINE

Optical absorption lines of interstellar clouds towards bright stars!

1937 CH: Swings & Rosenfeld

1940 CH, CN: McKellar

1941 CH+: Douglas & Herzberg

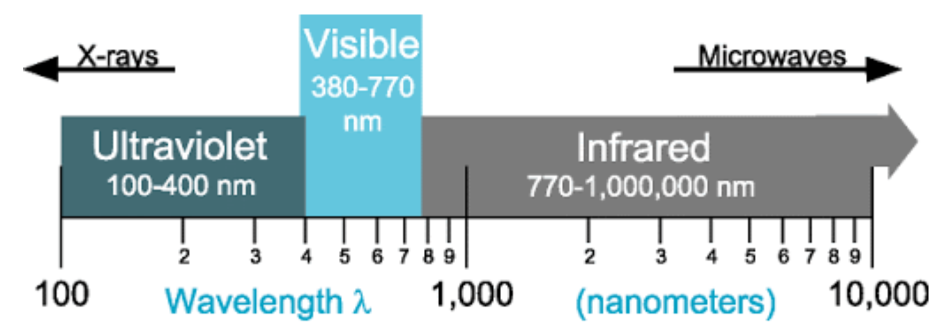


Fig. 1.1 The optical portion of the electromagnetic spectrum

Spectral lines in optical band (300 GHz and 3000 THz)

THE MOLECULAR UNIVERSE TIMELINE

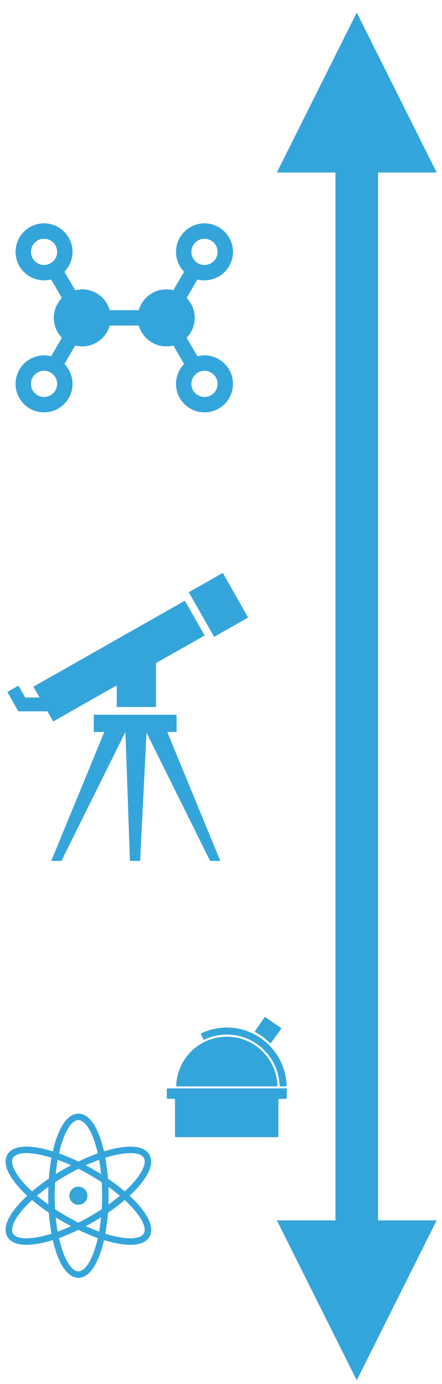
1937-1939 Eddington and Stromgren suggested the existence of H_2

I write about molecules with great diffidence, having not yet rid myself of the tradition that atoms are physics, but molecules are chemistry, but the new conclusion that hydrogen is abundant seems to make it likely that the above mentioned elements H, O, and N will frequently form molecules.

Sir A.S. Eddington 1937

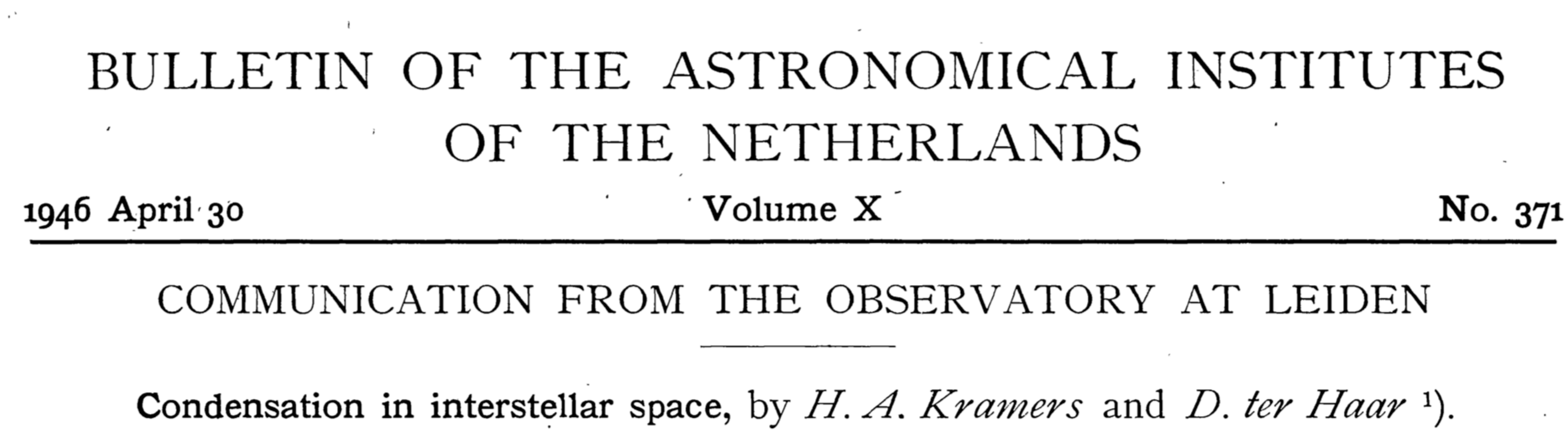
Thirty years later, Gould & Salpeter (1963) and Hollenbach et al. (1971) predicted that it could be a large fraction of all hydrogen (studying formation of H_2 on the surface of grains.

THE MOLECULAR UNIVERSE TIMELINE



1946-1951

First astrochemical models (Kramers, Bates & Spitzer)



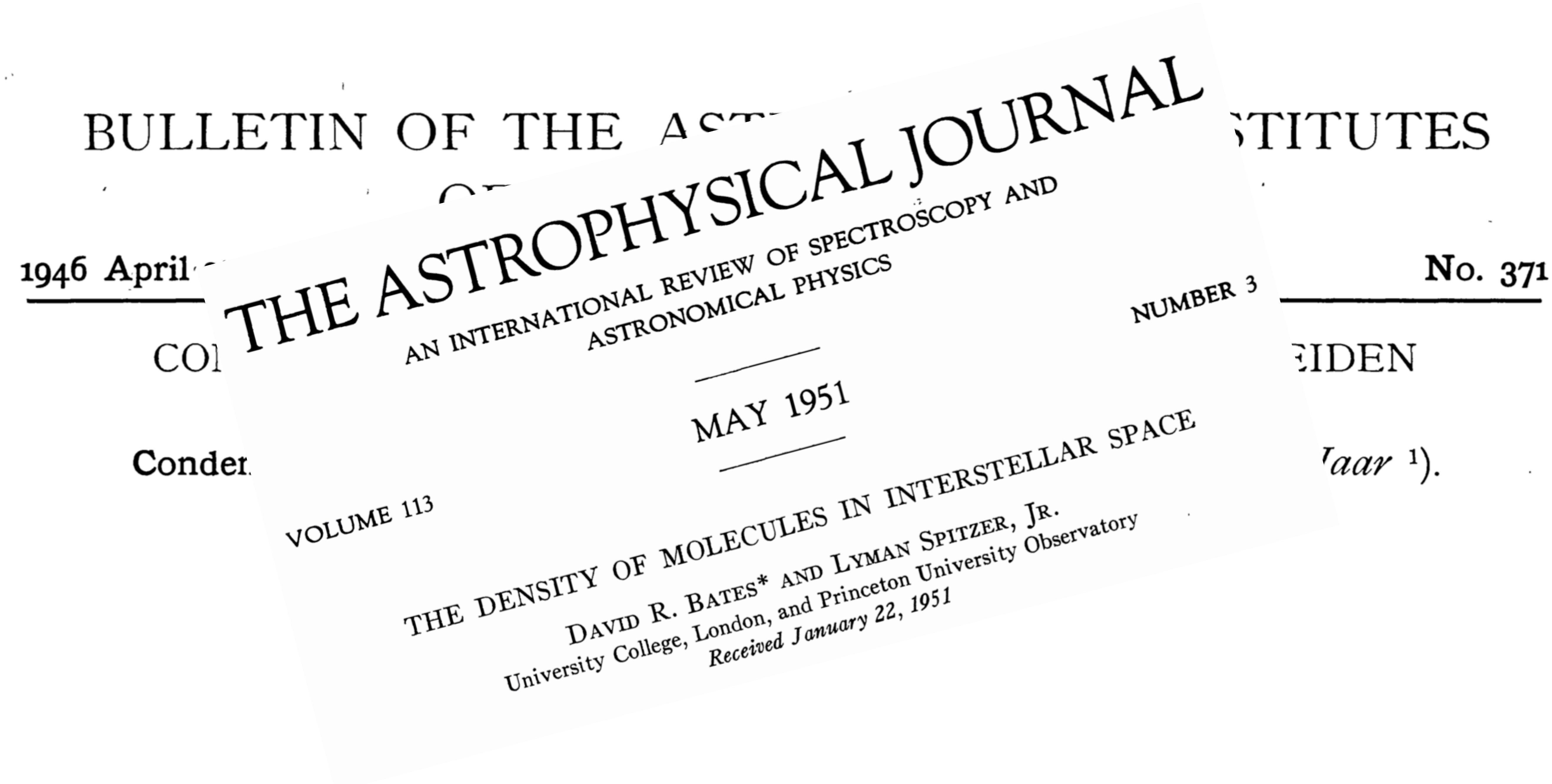
BULLETIN OF THE ASTRONOMICAL INSTITUTES OF THE NETHERLANDS

1946 April 30 | Volume X | No. 371

COMMUNICATION FROM THE OBSERVATORY AT LEIDEN

Condensation in interstellar space, by *H. A. Kramers* and *D. ter Haar* [1]).

THE MOLECULAR UNIVERSE TIMELINE


BULLETIN OF THE AST... ...STITUTES

1946 April ... No. 371

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Conder... ...Vaar [1]).

THE ASTROPHYSICAL JOURNAL

AN INTERNATIONAL REVIEW OF SPECTROSCOPY AND ASTRONOMICAL PHYSICS

VOLUME 113 MAY 1951 NUMBER 3

THE DENSITY OF MOLECULES IN INTERSTELLAR SPACE

DAVID R. BATES* AND LYMAN SPITZER, JR.

University College, London, and Princeton University Observatory

Received January 22, 1951

THE MOLECULAR UNIVERSE TIMELINE

Primate Astrochemistry

1946-1951

First astrochemical models (Kramers, Bates & Spitzer)

FIGURE I

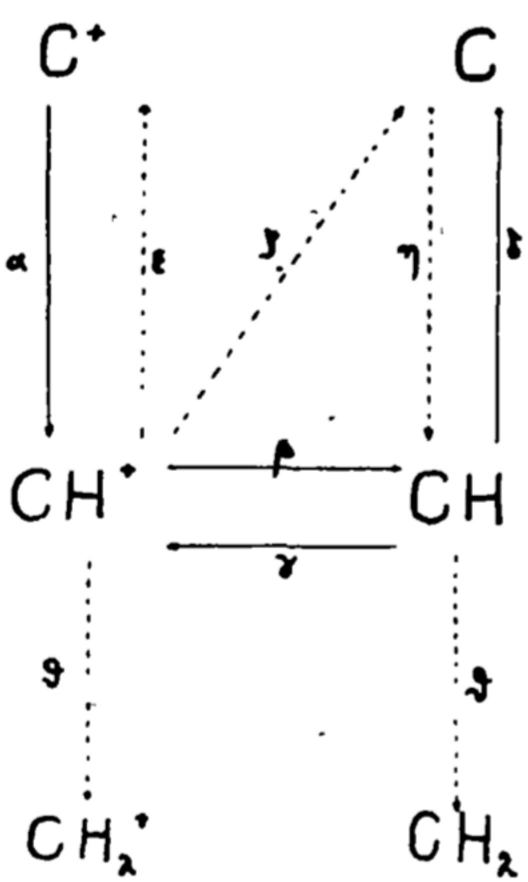


TABLE I

Process	Description	Frequency
α : $C^+ + H \rightarrow CH^+ + h\nu$	(radiation capture)	$N_\alpha = 10^{-17} \cdot \rho_{C^+} \cdot \rho_H \cdot$
β : $CH^+ + el \rightarrow CH + h\nu$	(electron capture)	$N_\beta = 3 \cdot 10^{-13} \cdot \rho_{el} \cdot \rho_{CH^+} \cdot$
γ : $CH + h\nu \rightarrow CH^+ + el$	(photoionization)	$N_\gamma = 2 \cdot 10^{-11} \cdot \rho_{CH} \cdot$
δ : $CH + h\nu \rightarrow C + H$	(photodissociation)	$N_\delta = 10^{-11} \cdot \rho_{CH} \cdot$
ε : $CH^+ + h\nu \rightarrow C^+ + H$	(photodissociation)	$N_\varepsilon \sim 10^{-15} \cdot \rho_{CH^+} \cdot$
ζ : $CH^+ + el \rightarrow C + H$	(electron capture leading to dissociation)	$N_\zeta \sim 3 \cdot 10^{-14} \cdot \rho_{el} \cdot \rho_{CH^+} \cdot$
η : $C + H \rightarrow CH + h\nu$	(radiation capture)	$N_\eta = 7 \cdot 10^{-18} \cdot \rho_C \cdot \rho_H \cdot$
$\vartheta^{(\prime)}$: $CH^{(+)} + H \rightarrow CH_2^{(+)}$	("mechanical" capture)	$N_{\vartheta^{(\prime)}} \leqslant 7 \cdot 10^{-17} \cdot \rho_{CH^{(+)}} \cdot \rho_H \cdot$

WHEN THE FIRST ASTROCHEMICAL MODELS?

1946-1951

First astrochemical models (Kramers, Bates & Spitzer)

Primate Astrochemistry

TABLE 2

Process	Rate Coefficient: Designation	Rate Coefficient: Value
a) $C+H \rightarrow CH+h\nu$	γ_1	2×10^{-18} cm³/sec $[\frac{1}{9}C(^3P_0+3\,^3P_1+5\,^3P_2)]$ 6×10^{-18} cm³/sec $[C(^3P_0)]$
b) $C^+ +H \rightarrow CH^+ +h\nu$	γ_2	2×10^{-18} cm³/sec $[\frac{1}{3}C^+(^2P_{1/2}+2\,^2P_{3/2})]$ 0 $[C^+(^2P_{1/2})]$
c) $CH+h\nu \rightarrow CH^+ +e$	β_1	8×10^{-12} sec⁻¹
d) $CH^+ +e \rightarrow CH+h\nu$ e) $CH^+ +e \rightarrow CH'+h\nu$ $CH' \rightarrow$ (i) $CH+h\nu$	α_1	7×10^{-12} cm³/sec
$CH' \rightarrow$ (ii) $C+H$ f) $CH^+ +e \rightarrow C+H$	α_2	Unknown (probably small but conceivably large)
g) $CH+h\nu \rightarrow C+H$	β_2	
h) $CH+h\nu \rightarrow C^+ +H$	β_3	

$$n(CH) = n(H)\left[\frac{\gamma_1\{(\alpha_1+\alpha_2)n(e)+\beta_3\}n(C)+\gamma_2\alpha_1 n(e)\,n(C^+)}{\beta_3(\beta_1+\beta_2)+\{\beta_1\alpha_2+\beta_2(\alpha_1+\alpha_2)\}n(e)}\right]$$

$$n(CH^+) = n(H)\left[\frac{\gamma_1\beta_1 n(C)+\gamma_2(\beta_1+\beta_2)\,n(C^+)}{\beta_3(\beta_1+\beta_2)+\{\beta_1\alpha_2+\beta_2(\alpha_1+\alpha_2)\}n(e)}\right],$$

WHEN THE FIRST ASTROCHEMICAL MODELS?

1946-1951

First astrochemical models (Kramers, Bates & Spitzer)

Primate Astrochemistry

1. From these models it was already clear that detection contained important astrophysical information

2. These studies provided useful probes of interstellar regions

3. For instance: CH and CN were easily explained by equilibrium models while CH^+ required more dynamics (e.g. post-shock chemistry)

4. Two types of interstellar regions:

   $t_{chem} < t_{dyn}$ (equilibrium) and $t_{chem} > t_{dyn}$ (non-eq) [<u>VERY IMPORTANT</u>]

THE MOLECULAR UNIVERSE TIMELINE (RADIO AND UV ASTRONOMY)

For various reasons (distraction towards space flight) no real development during 1941-1969

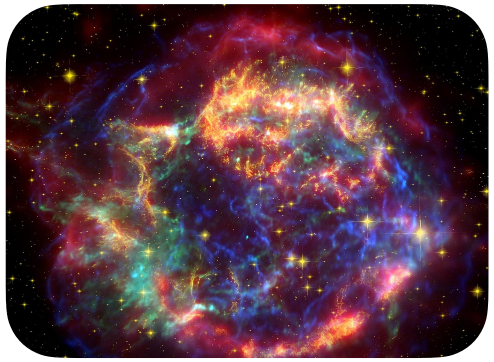
Late '60

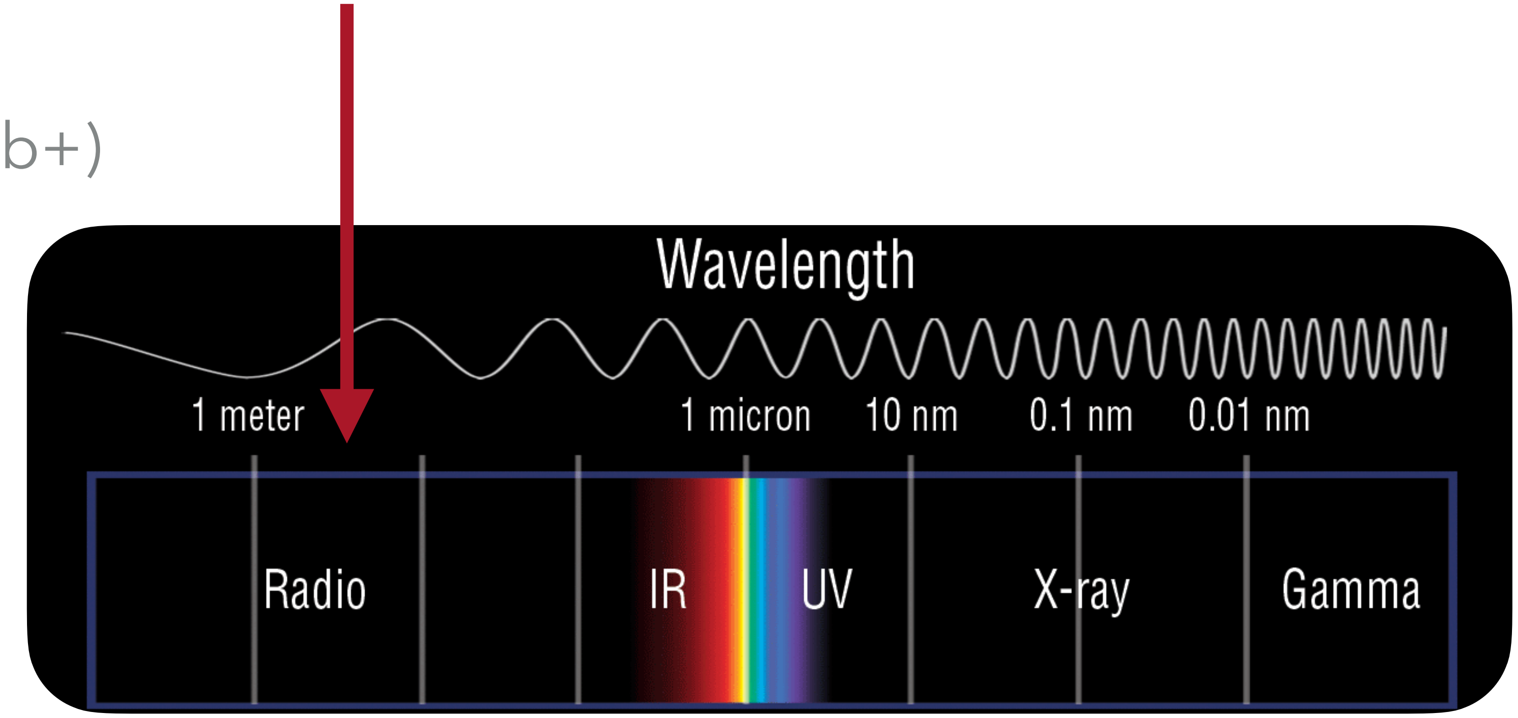
Development of radioastronomy which started during WWII
Rotational spectroscopy

1963

OH (in radio at 18 cm by Weinreb+)

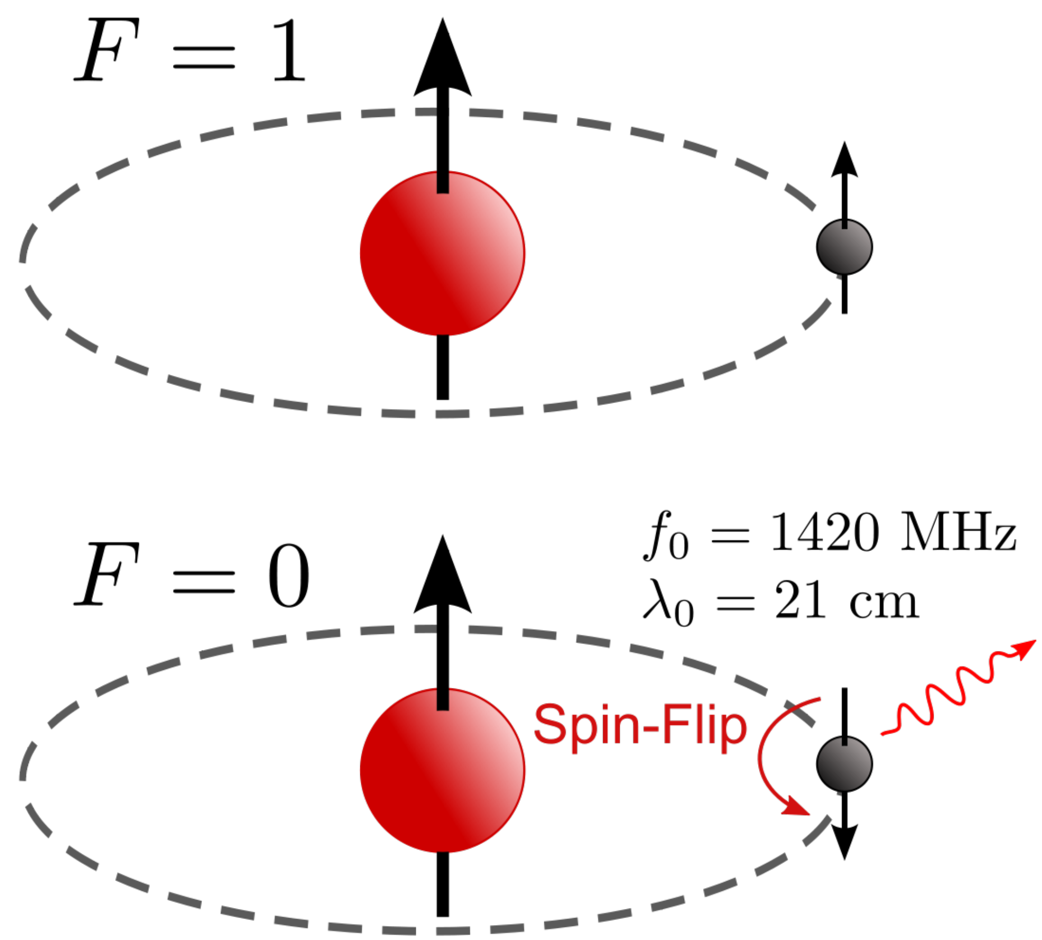
towards SNR Cassiopeia A



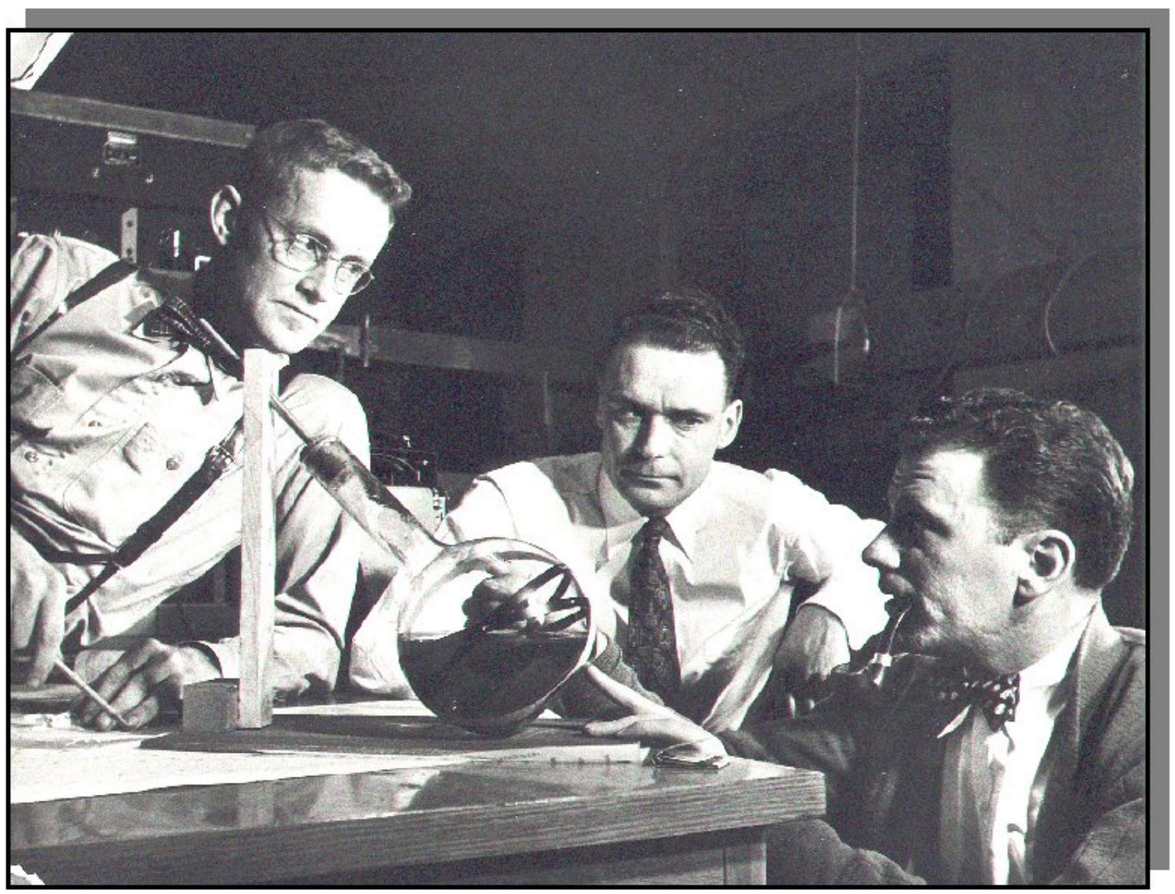


Radioastronomy & HI 21 cm line

1944 - Hendrik van de Hulst predicts the existence of the HI 21-cm



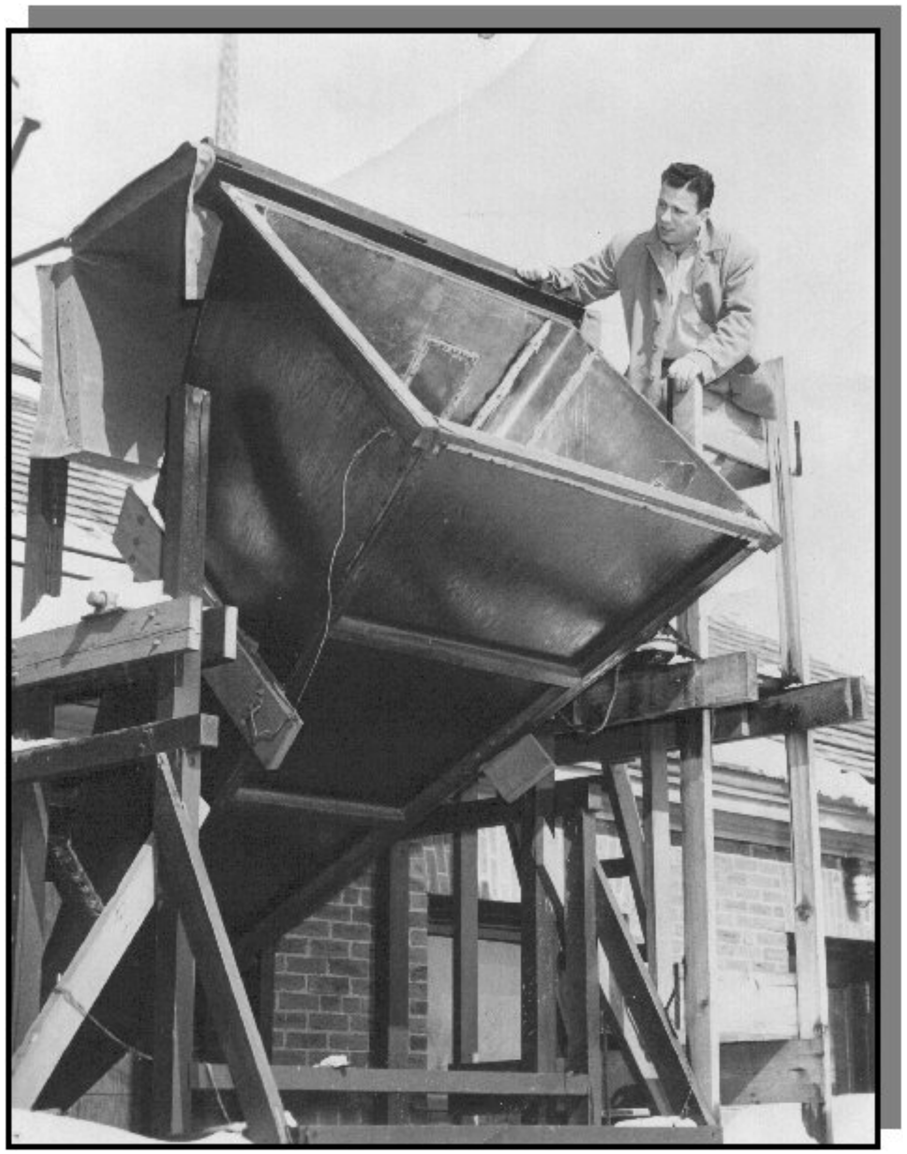
1950 - Doc Ewen worked 40 hours a week to design and build the apparatus for the new cyclotron at Harvard



+ he has to complete his PhD (working at nights and week-ends)

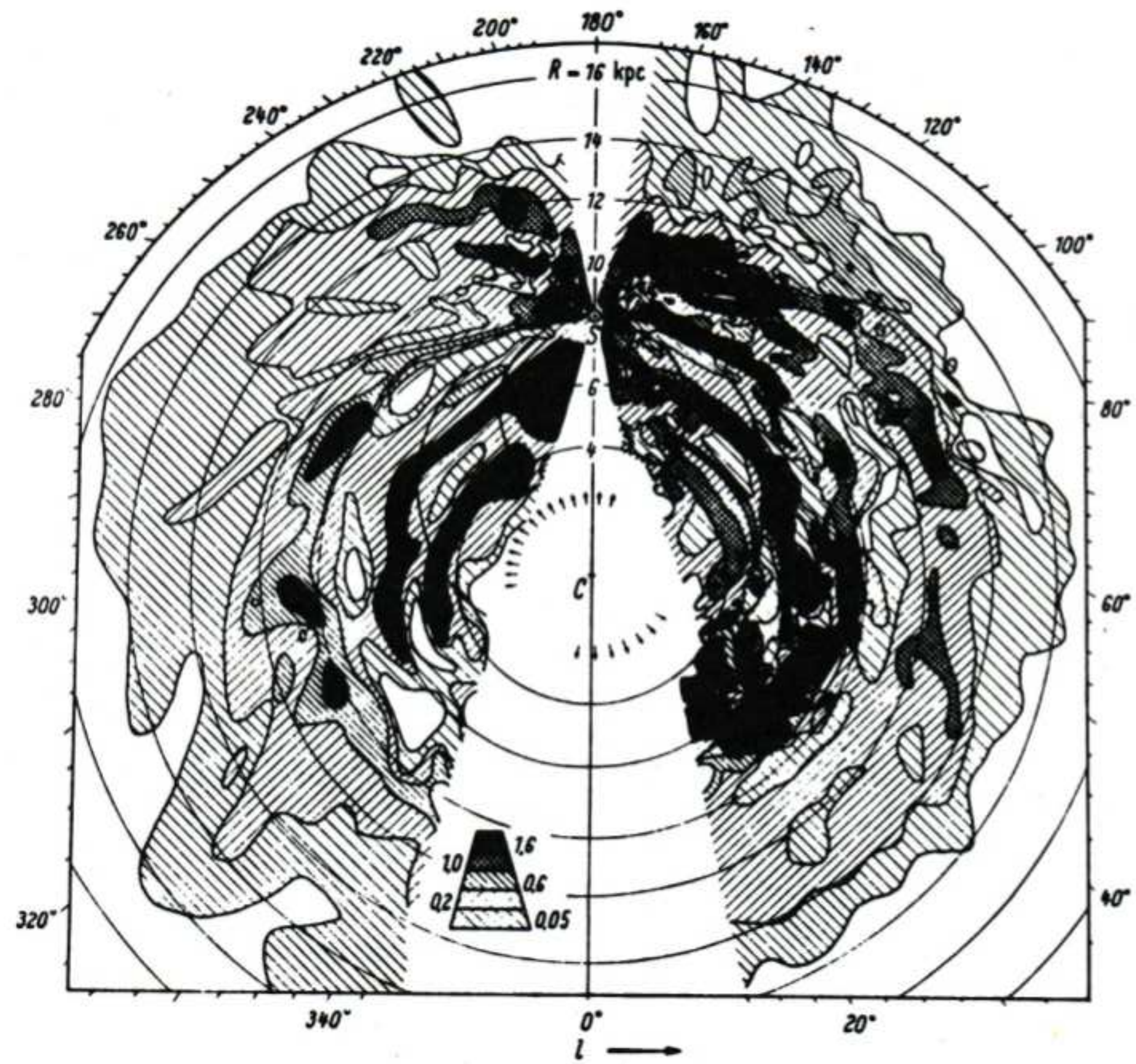
+ Building a receiver to detect 21 cm HI line (supervised by Purcell)

1950-1951- Purcell received 500 USD to build the antenna



6 weeks later - Muller & Oort confirmed the detection

Discovery of spiral arms (neutral HI)



Oort, 1958

Cold HI emitting @ 21-cm makes up most of the mass of the ISM gas in the Milky Way

Its observation represented a revolution

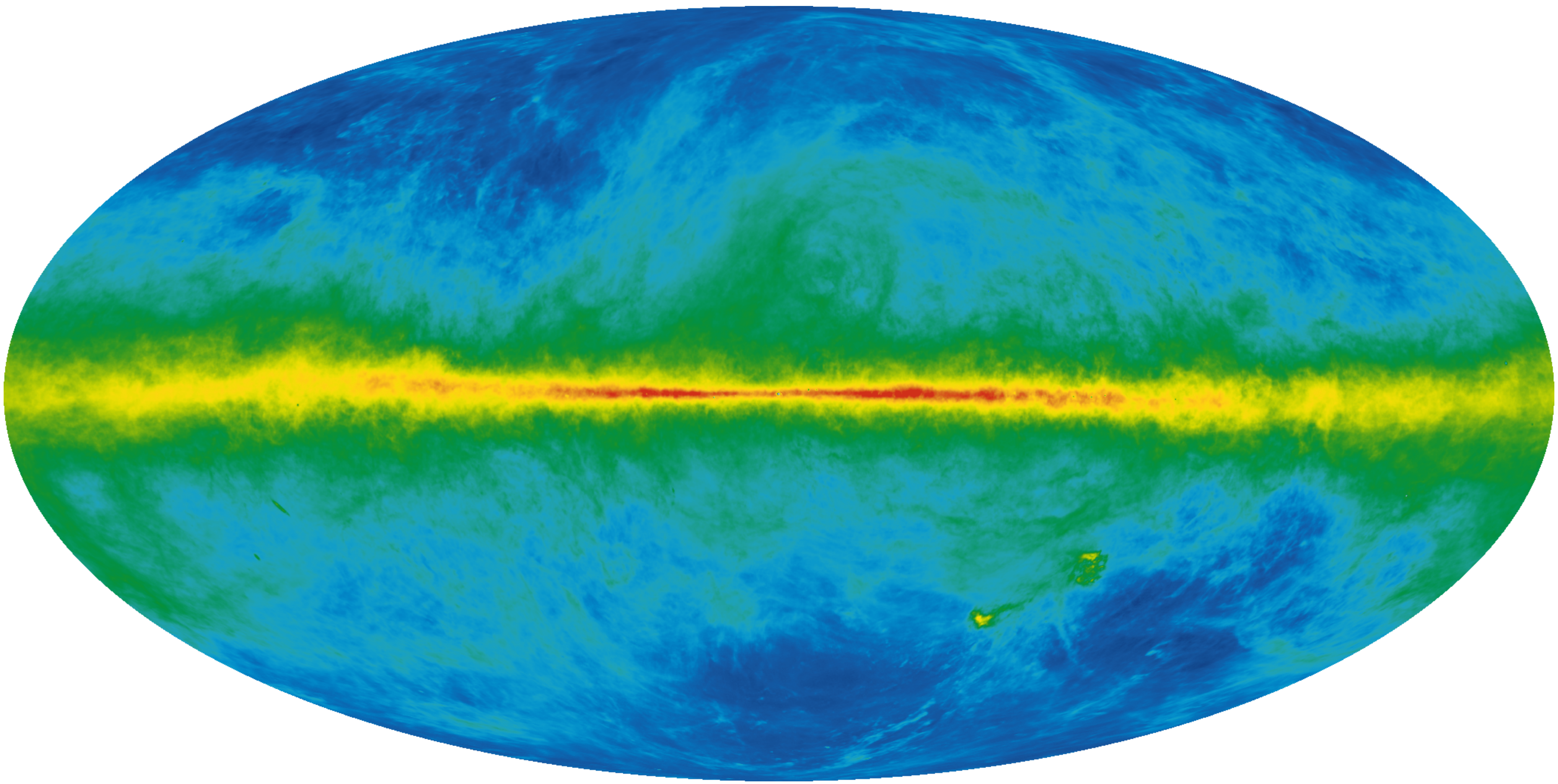
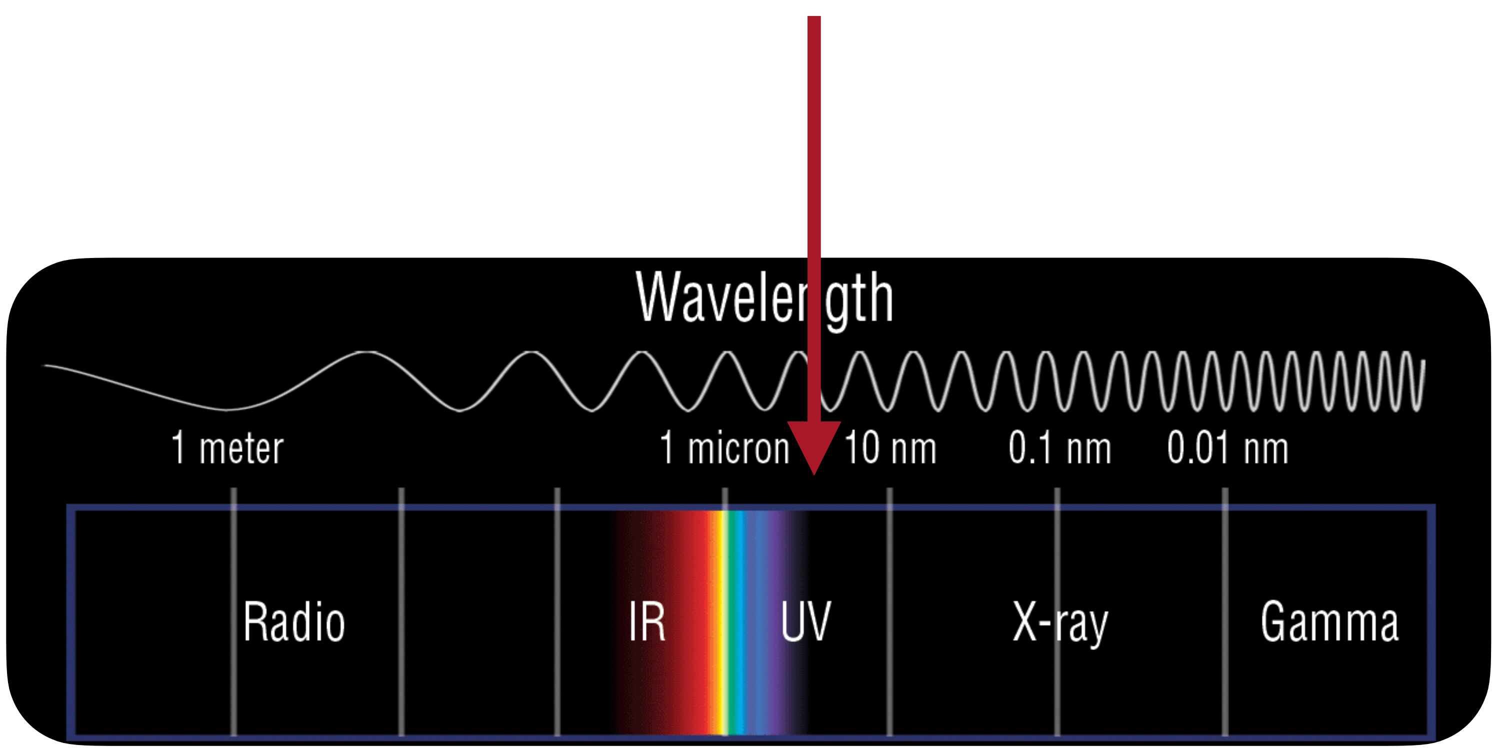


Image Credits: N(HI) HI4PI Col

THE MOLECULAR UNIVERSE TIMELINE (RADIO AND UV ASTRONOMY)

1968	NH_3 (First polyatomic molecule in radio @ 1 cm by Cheung, Townes+)
1969	H_2O (Cheung+ at 1 cm, i.e. 22 GHz)
>1970	Development of UV astronomy + mm (first detection of H_2 and CO)



THE MOLECULAR UNIVERSE TIMELINE (RADIO AND UV ASTRONOMY)

1970	H_2 (Carruthers, First detection in absorption towards the star zeta-Persei, N[H_2] ~1.3 x 10^{20} cm^{-2})
1973	H_2 (Smith in absorption towards delta-Scorpii N[H_2] ~3 x 10^{19} cm^{-2})

ROCKET OBSERVATION OF INTERSTELLAR MOLECULAR HYDROGEN

George R. Carruthers
E. O. Hulburt Center for Space Research, Naval Research Laboratory, Washington, D.C. 20390
Received 1970 June 22

ABSTRACT

The Lyman resonance-absorption bands of interstellar molecular hydrogen have been observed in the far-ultraviolet spectrum of the star ξ Persei. The column density of H_2 is estimated to be about 1.3×10^{20} cm^{-2}. The column density of interstellar atomic hydrogen, determined from the Lα absorption line in the same spectrum, is about 4.2×10^{20} cm^{-2}. Hence, in this line of sight, where visual total extinction by dust is about 1 mag, nearly half of the total hydrogen may be in molecular form. This is in agreement with theoretical predictions.

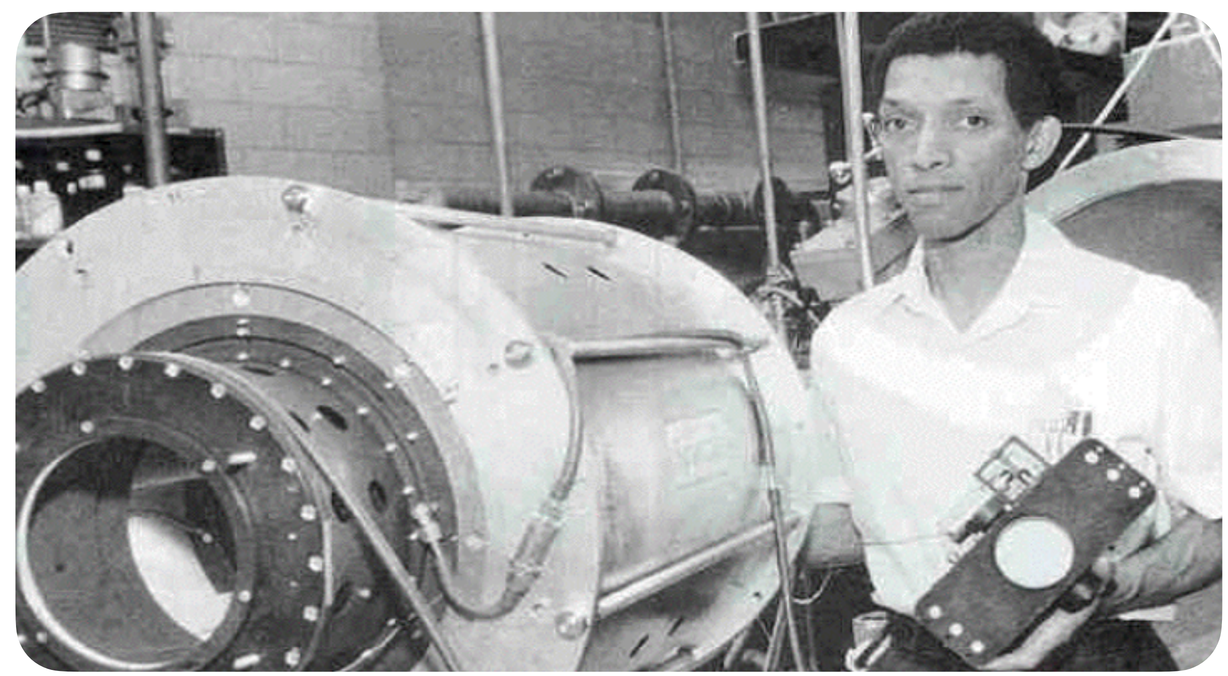
INTERSTELLAR MOLECULAR HYDROGEN OBSERVED IN THE ULTRAVIOLET SPECTRUM OF DELTA SCORPII

Andrew M. Smith
NASA, Goddard Space Flight Center,
Greenbelt, Maryland
Received 1972 October 26

ABSTRACT

Molecular-hydrogen bands of the Lyman and Werner systems have been observed in the ultraviolet, interstellar spectrum of δ Sco. The average molecular column density is 3.5 (+2.2, −0.9) $\times 10^{19}$ cm^{-2}, and the average temperature of the gas of which the molecules are part is 47° K. Minimum and maximum gas temperatures are 25° and 98° K, respectively. The observed column density of hydrogen atoms is $(1.5 \pm 0.5) \times 10^{21}$ cm^{-2}, and hence the ratio of the number of hydrogen atoms in molecular form to the total number of hydrogen atoms in either atomic or molecular form is 0.044 (+0.070, −0.018).

Subject headings: interstellar medium — molecules, interstellar — ultraviolet — stars, individual



George Carruthers
Pioneer of UV astronomy

> 1980 First mm surveys: discovery of many new molecules

ORION MOLECULAR CLOUD (MM ASTRONOMY)

D = 400 pc **Nearby high-mass star-forming cloud with strong lines emission (HST image)**

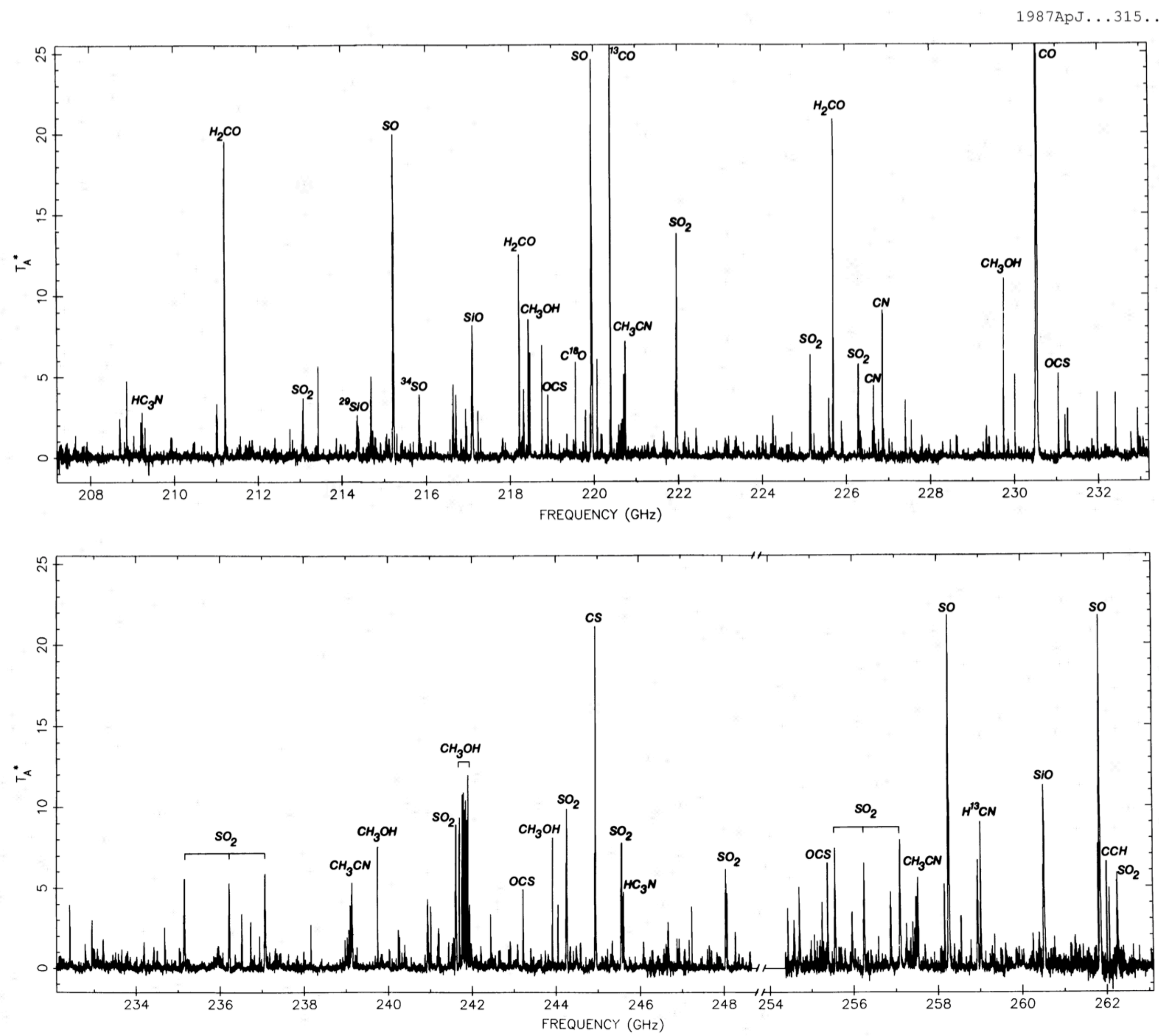
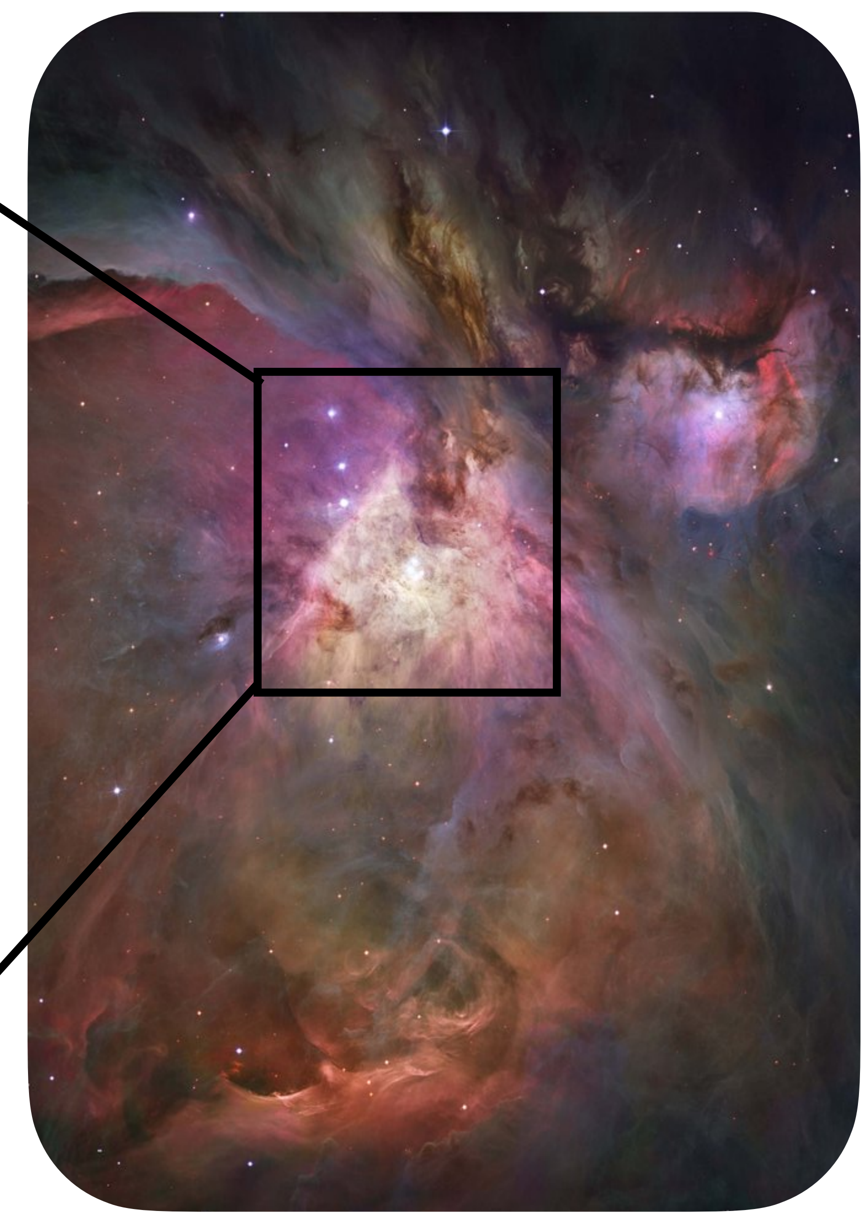
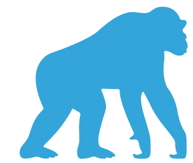


Fig. 1.—Compressed view of the OVRO spectral line survey of OMC-1



Sutton+1985, Blake+1986, Blake+1987

THE MOLECULAR UNIVERSE TIMELINE (IR ASTRONOMY)

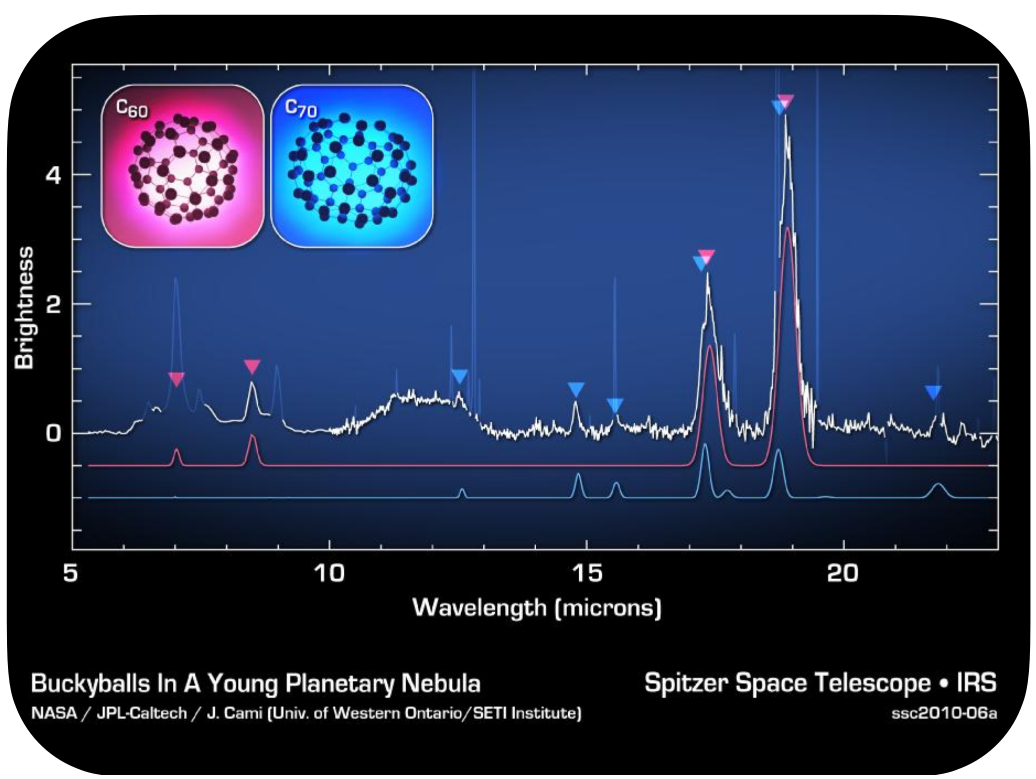


Evolved Astrochemistry

>1980 Development of IR astronomy
First full-sky survey @ 12, 25, 60, and 100 micron
IRAS: obs. of dust particles and PAH

1995-1998 Infrared Space Obs.
First survey at 2-200 micron (symm. mol. C_6H_6, CH_3, C_2H_4, CO_2)
Nature and composition of grains, H_2 in shocks

2003-2009 Spitzer Space Telescope (High-sensitivity) Ices, silicates, PAHs

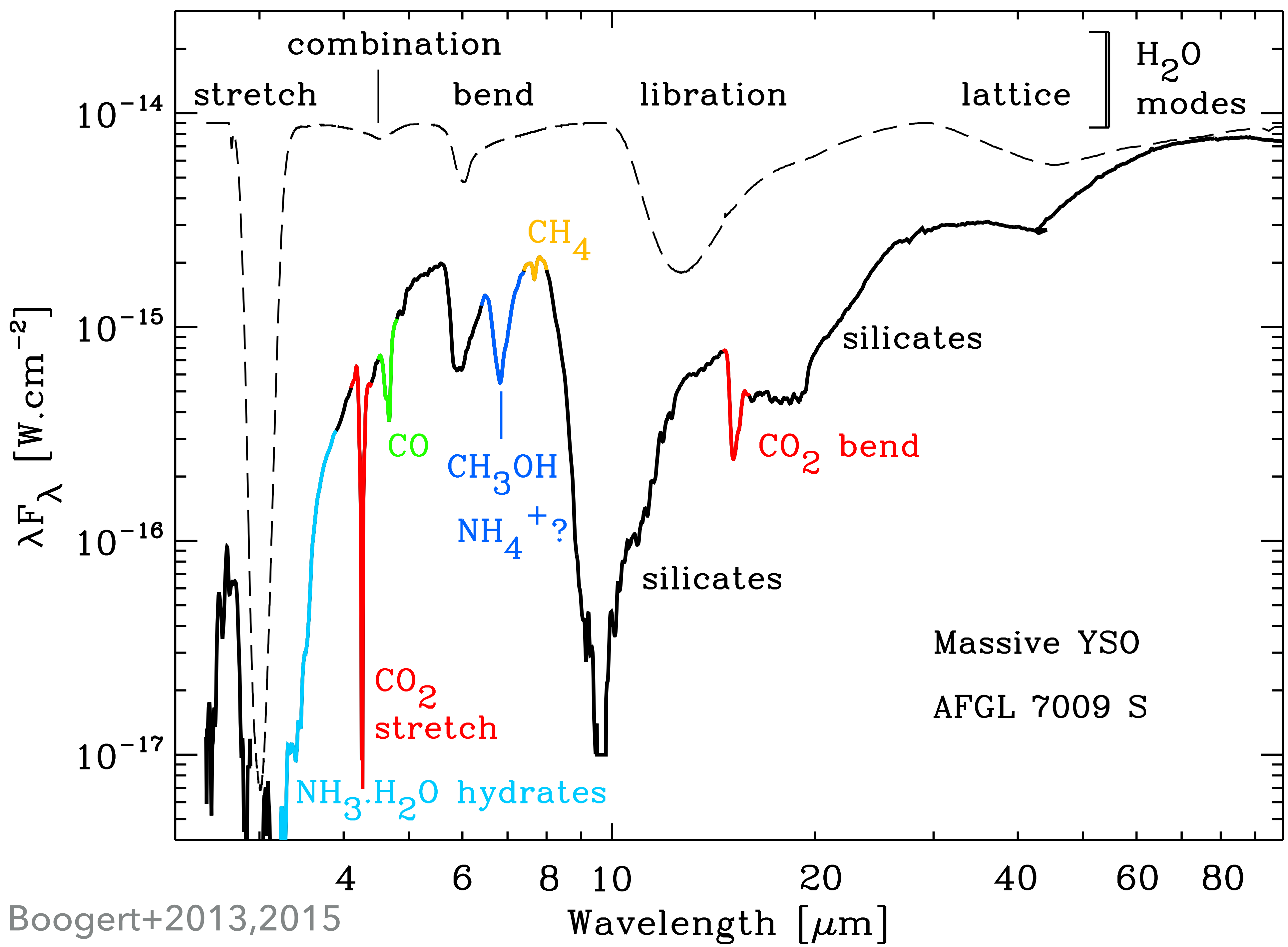


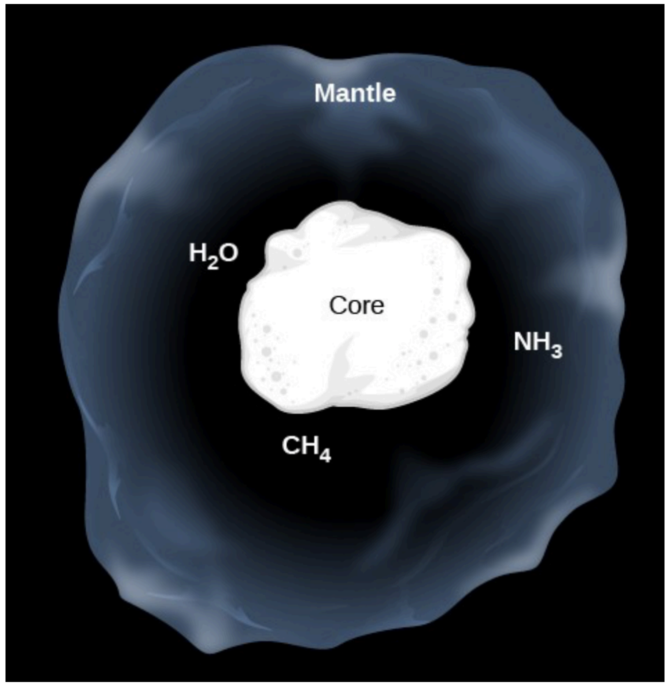
1980

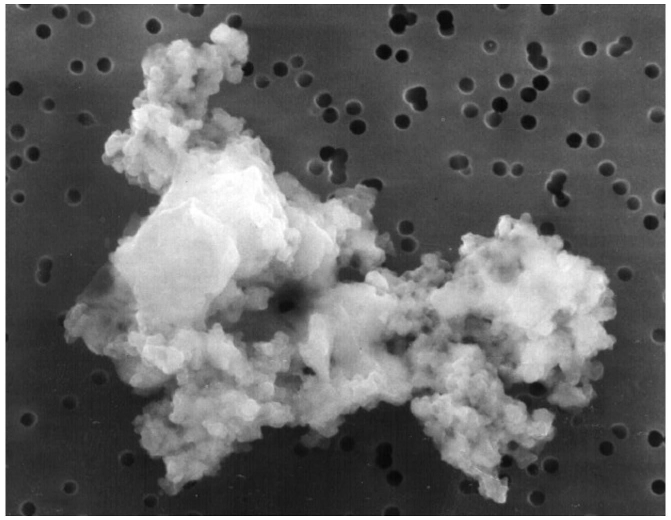
2009

THE MOLECULAR UNIVERSE TIMELINE

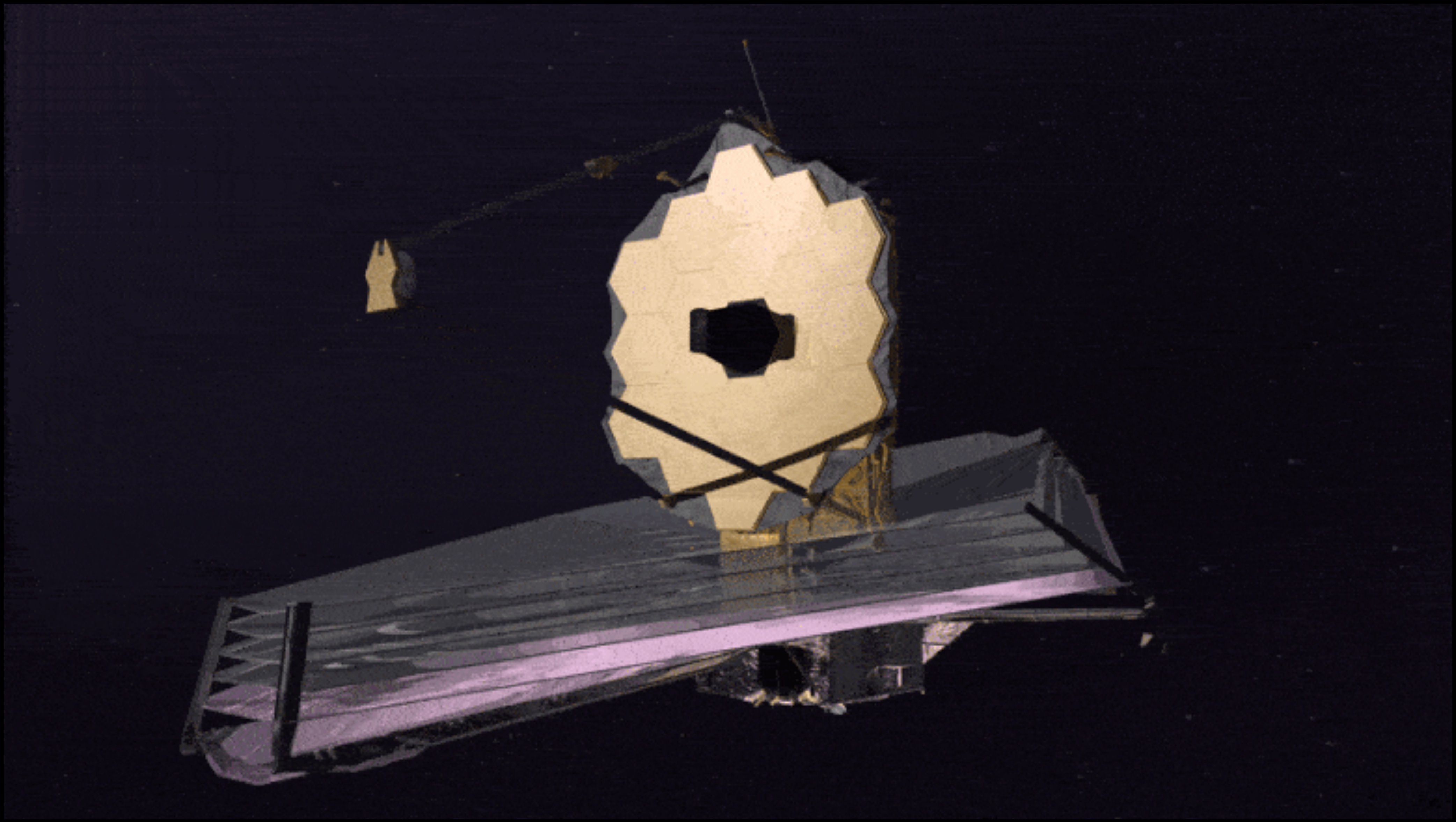
INVENTORY OF ICES

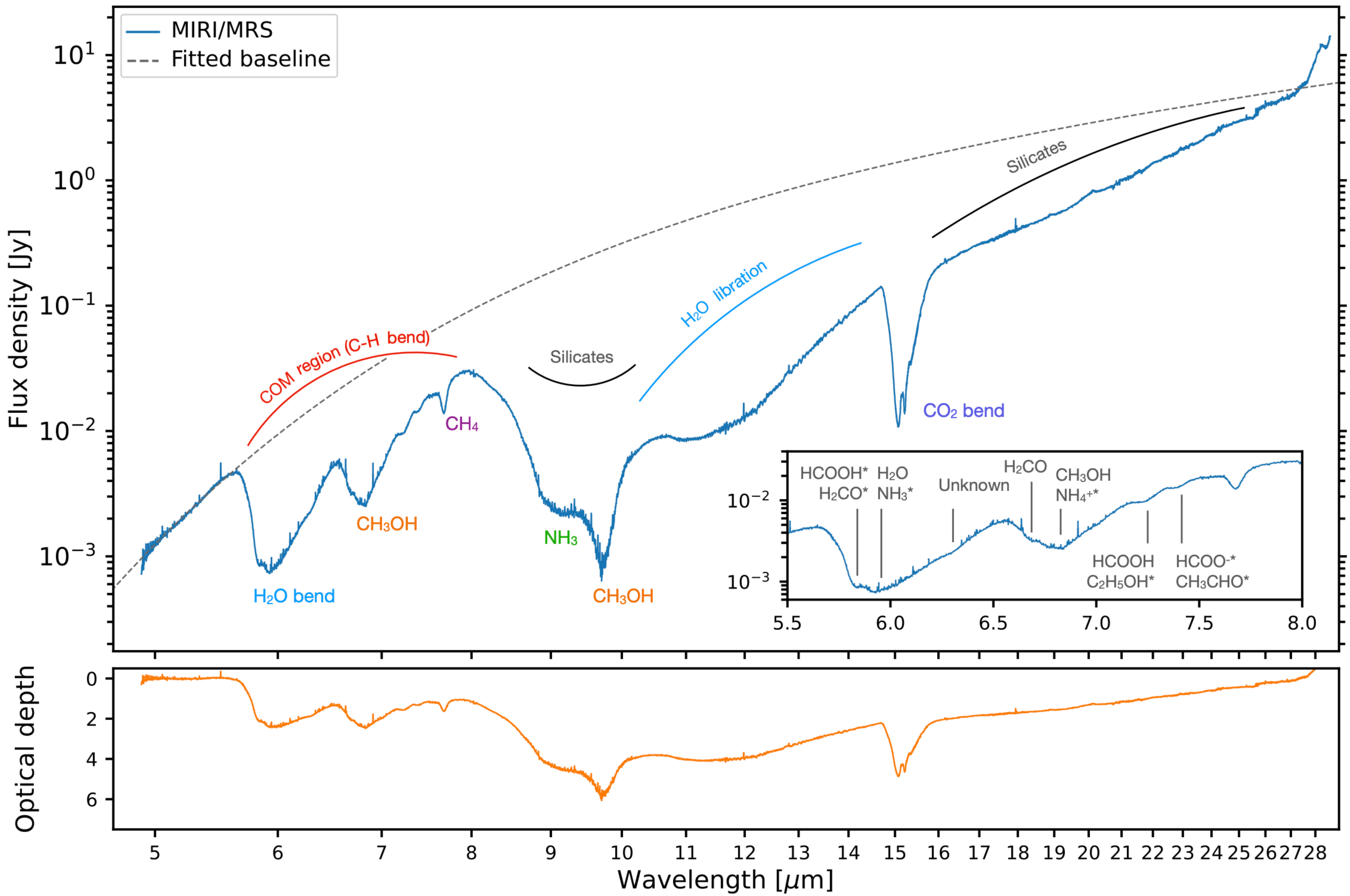




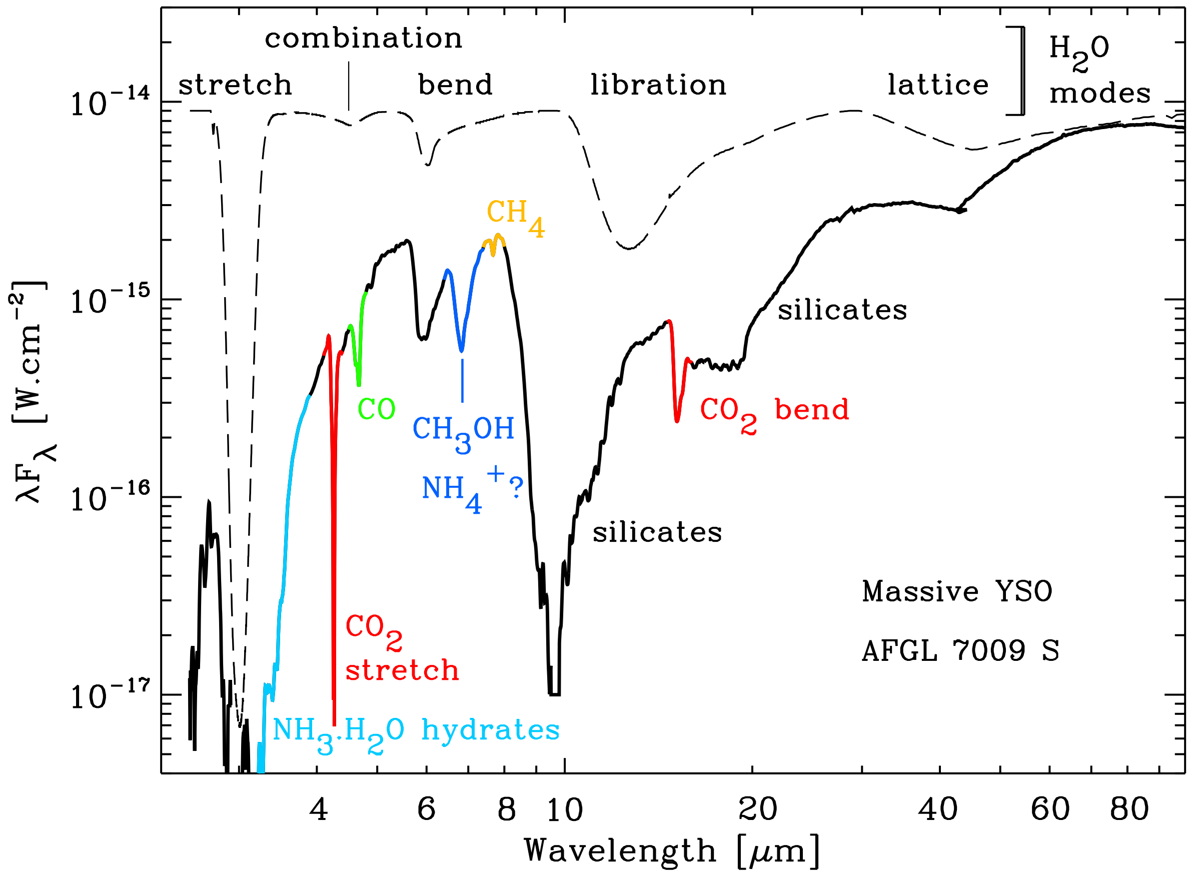


Boogert+2013,2015





Yao-Lun Yang+, 2022, August



They confirmed some of the laboratory and observational work

They also found some new interesting features @6.31 and 7.24 micron

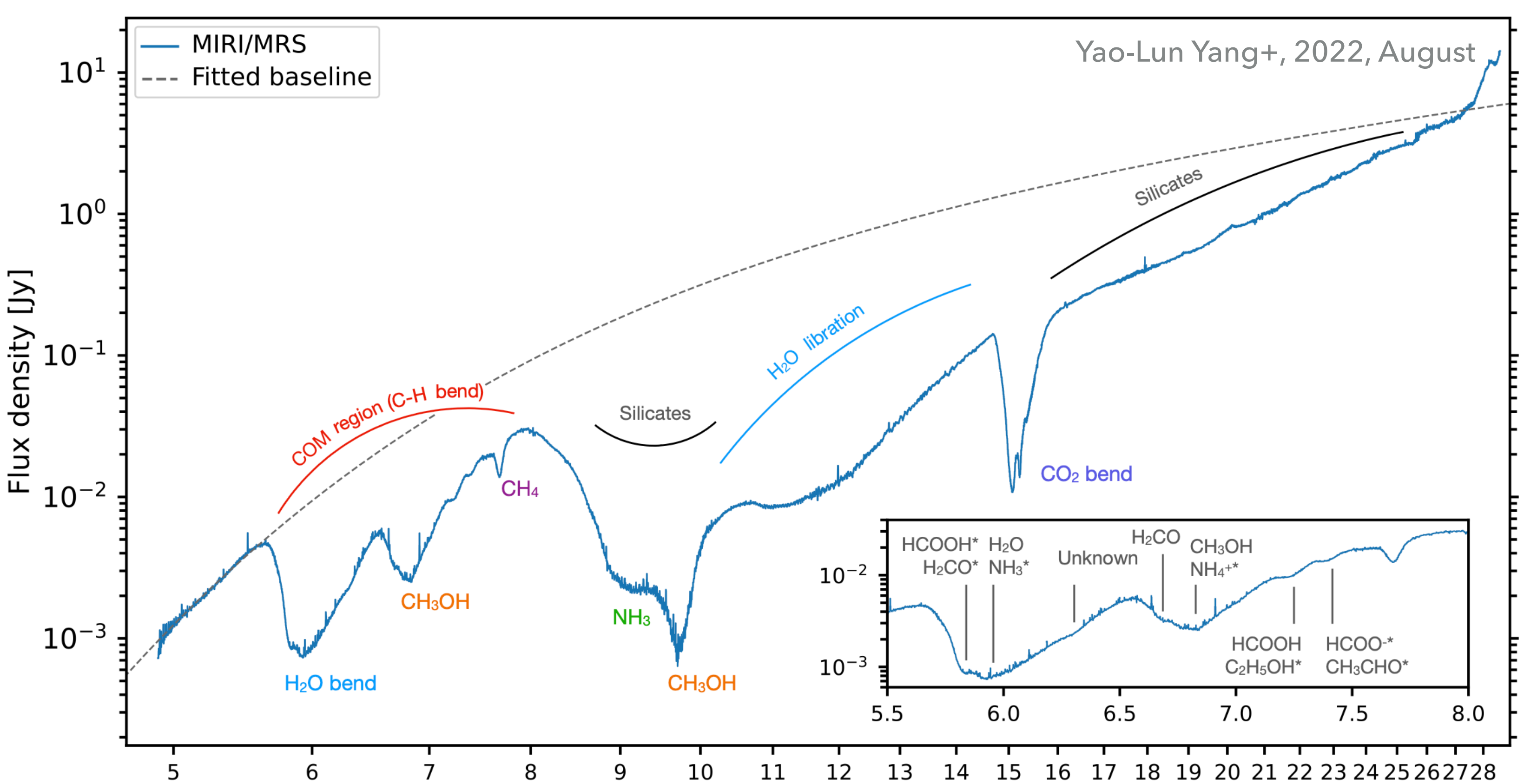
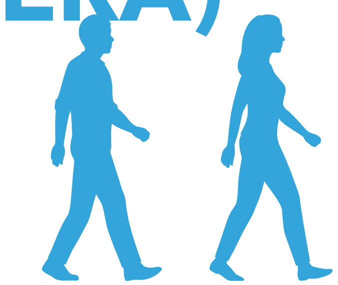


Table 1. Notable ice features

Wavelength (μm)	Type	Identification
5.83	single	HCOOH*, H_2CO*
6	multiple	H_2O, NH_3*
6.31	single	unknown
6.7	single	H_2CO
6.8	multiple	CH_3OH, NH_4^+*
7.24	single	HCOOH, C_2H_5OH*
7.41	single	$HCOO^-$*, CH_3CHO*
7.7	single	CH_4, SO_2*, C_2H_5OH*
9	single	NH_3, CH_3OH*, C_2H_5OH*
9.7	single	CH_3OH
11	single/broad	H_2O, C_2H_5OH*, CH_3CHO*, $HCOOCH_3$*
15.2	multiple	CO_2

*Potential/ambiguous identification

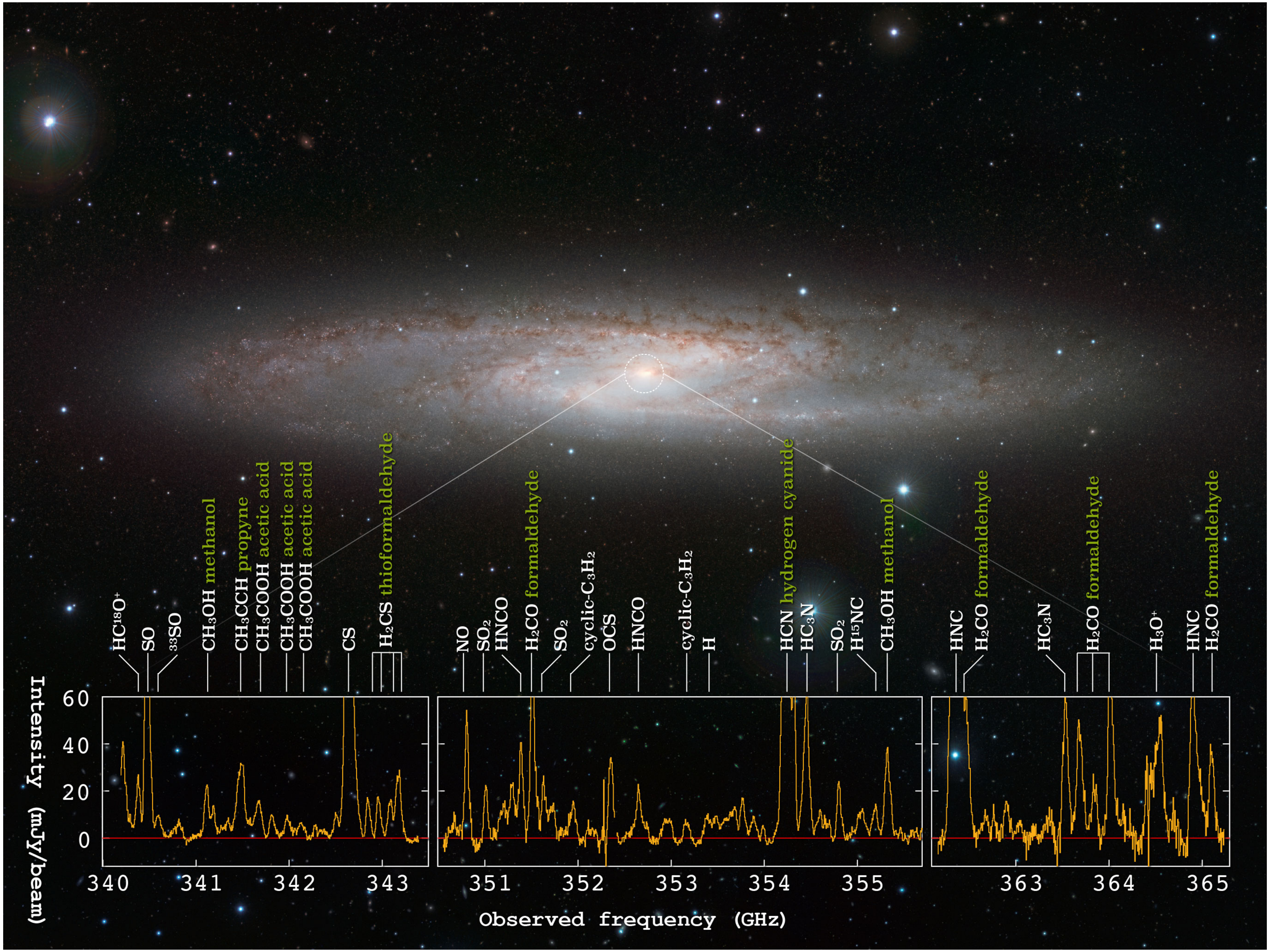
THE MOLECULAR UNIVERSE TIMELINE (ALMA ERA)



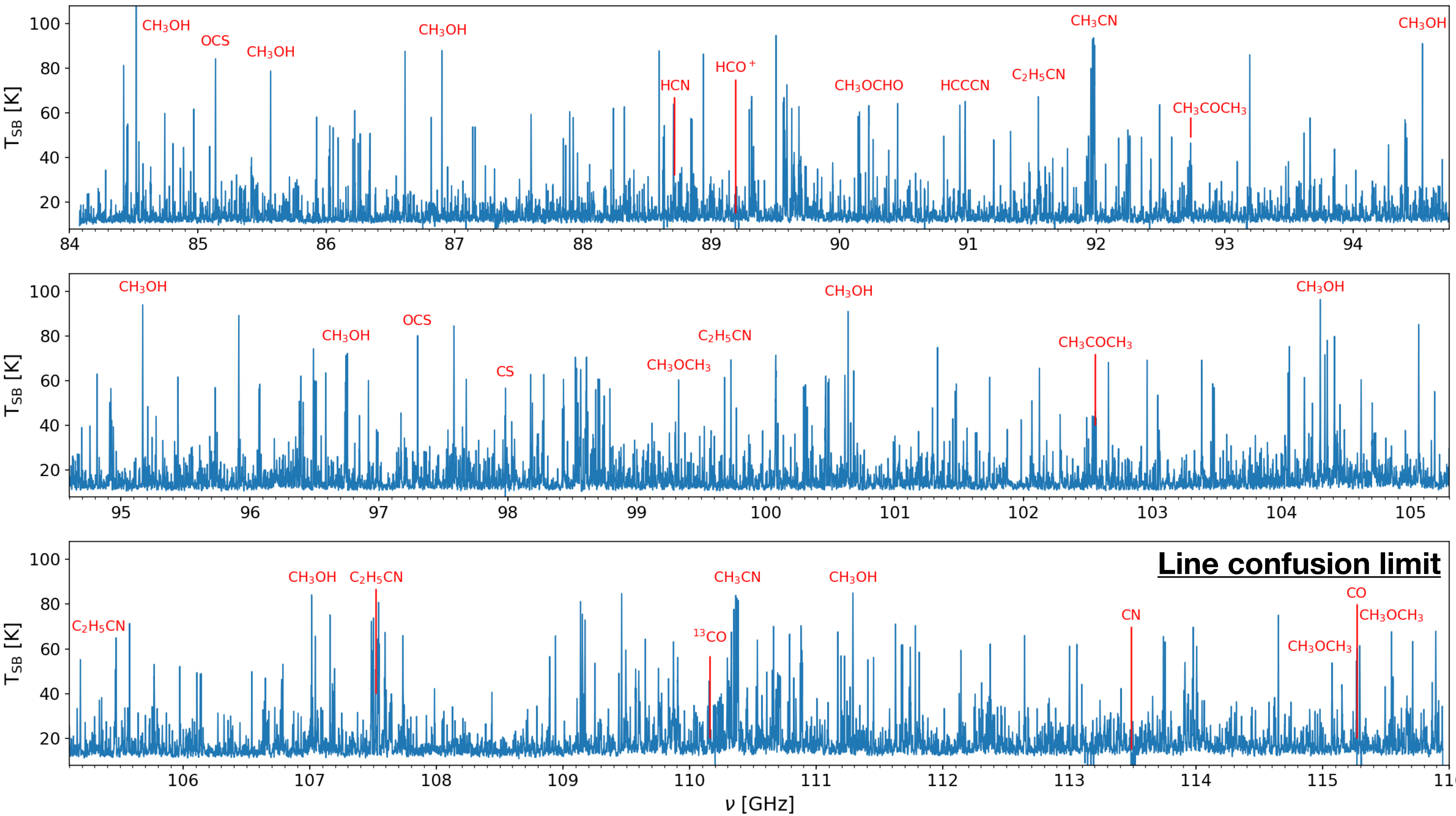
Established Astrochemistry

2004 ALMA CONSTRUCTION STARTED

2018 ~ 200 molecules have been detected (not counting isotopes) (https://www.astro.uni-koeln.de/cdms/molecules)



~ 200 molecules have been detected (not counting isotopes)
(https://www.astro.uni-koeln.de/cdms/molecules)



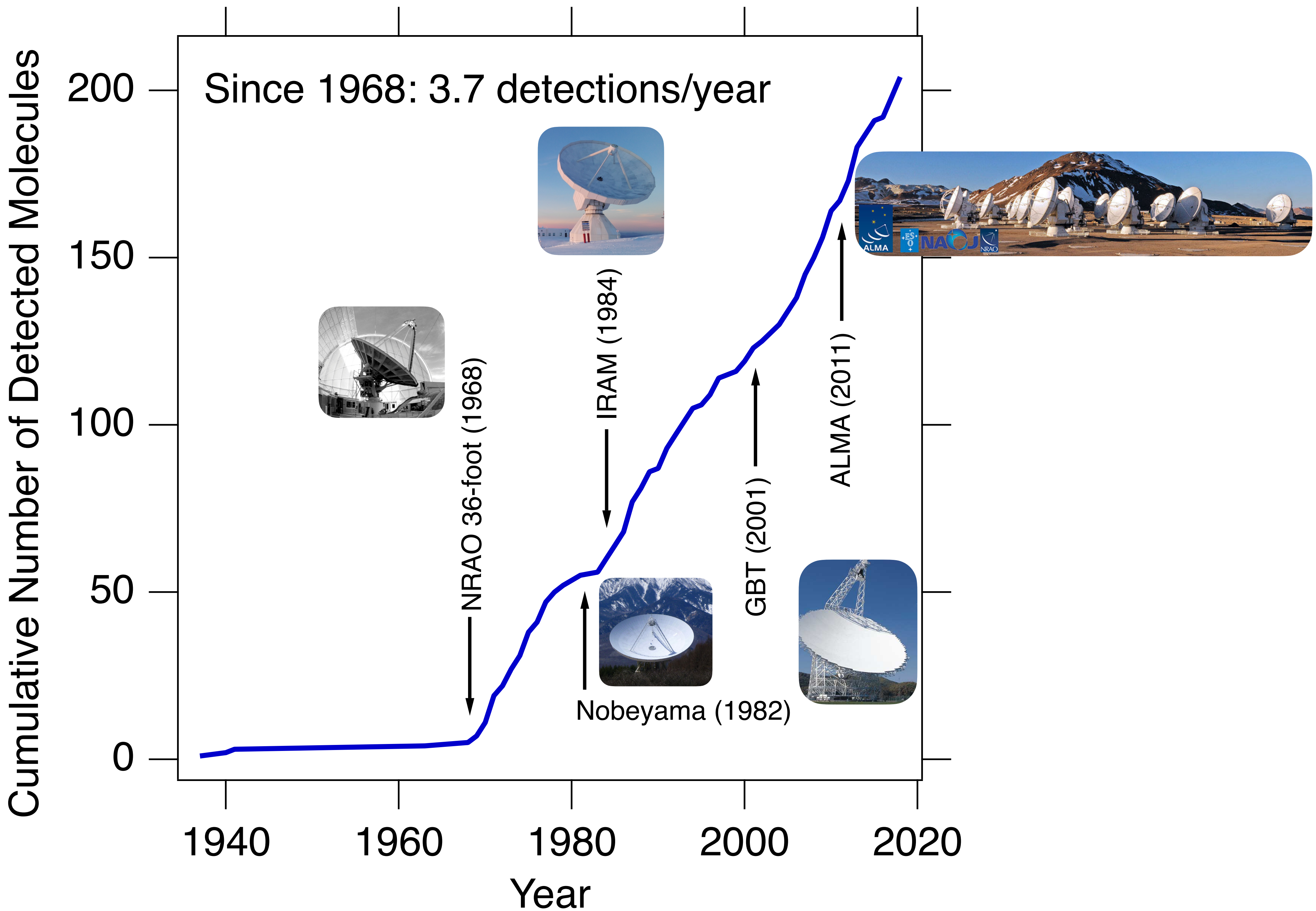
GUAPOS Survey, Mininni, 2020

HTTPS://CDMS.ASTRO.UNI-KOELN.DE/CLASSIC/MOLECULES

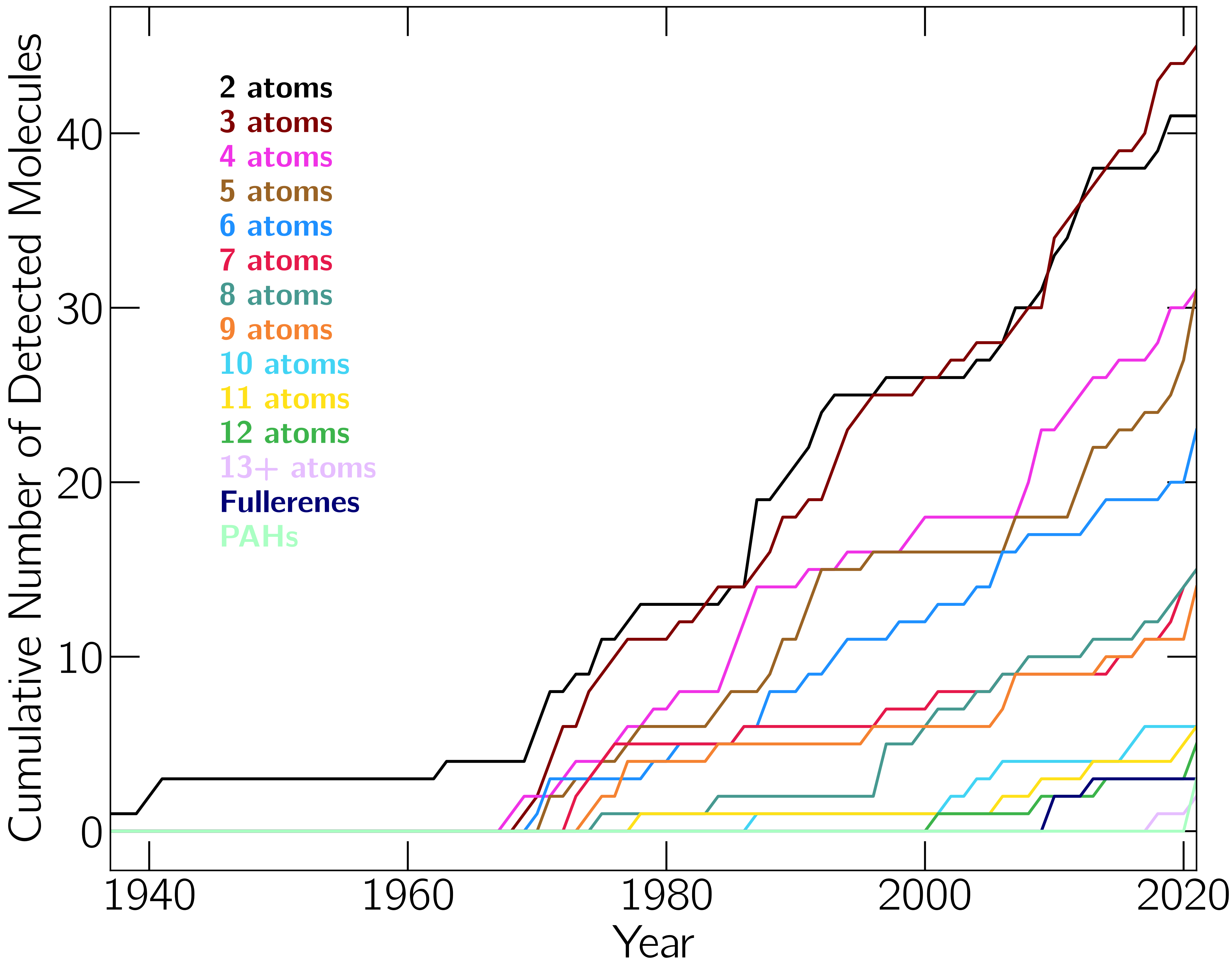
Molecules in the Interstellar Medium or Circumstellar Shells (as of 03/2018)

2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H_2	C_3 *	c-C_3H	C_5 *	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6 *	C_{60} *
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN	C_{70} *
AlCl	C_2O	C_3N	C_4Si	C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN	C_{60}^+ *
C_2**	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$	$C_2H_5OCH_3$?	c-C_6H_5CN 2018
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	C_6H_2	HC_7N	CH_3CHCH_2O 2016			
CH^+	HCN	C_2H_2*	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H	CH_3OCH_2OH 2017			
CN	HCO	NH_3	CH_4 *	CH_3SH	c-C_2H_4O	l-HC_6H *	$CH_3C(O)NH_2$				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO (?)	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	HNCO	HCOOH	NH_2CHO	CH_3NCO	H_2NCH_2CN	CH_3CH_2SH (?)				
SiC	H_2O	HNCS	H_2CNH	C_5N	HC_5O 2017	CH_3CHNH	CH_3NHCHO ? 2017				
HCl	H_2S	$HOCO^+$	H_2C_2O	l-HC_4H *		CH_3SiH_3 2017	HC_7O 2017				
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	SiH_4 *	H_2CCNH (?)							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-							
NaCl	N_2H^+	c-SiC_3	C_4H^-	HNCHCN							
OH	N_2O	CH_3 *	HC(O)CN	SiH_3CN 2017							
PN	NaCN	C_3N^-	HNCNH								
SO	OCS	PH_3	CH_3O								
SO^+	SO_2	HCNO	NH_4^+								

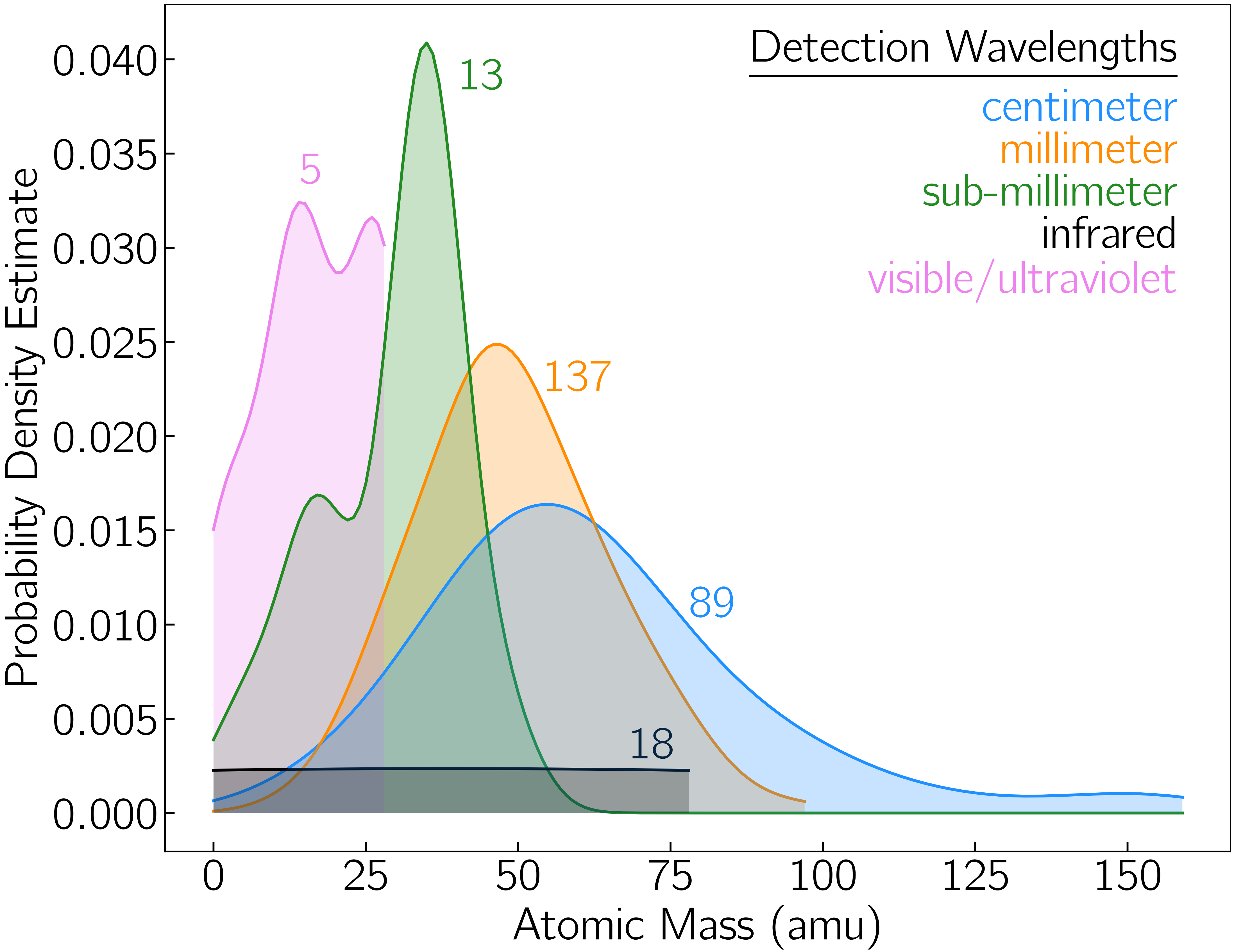
INCOMPLETE



McGuire, 2020



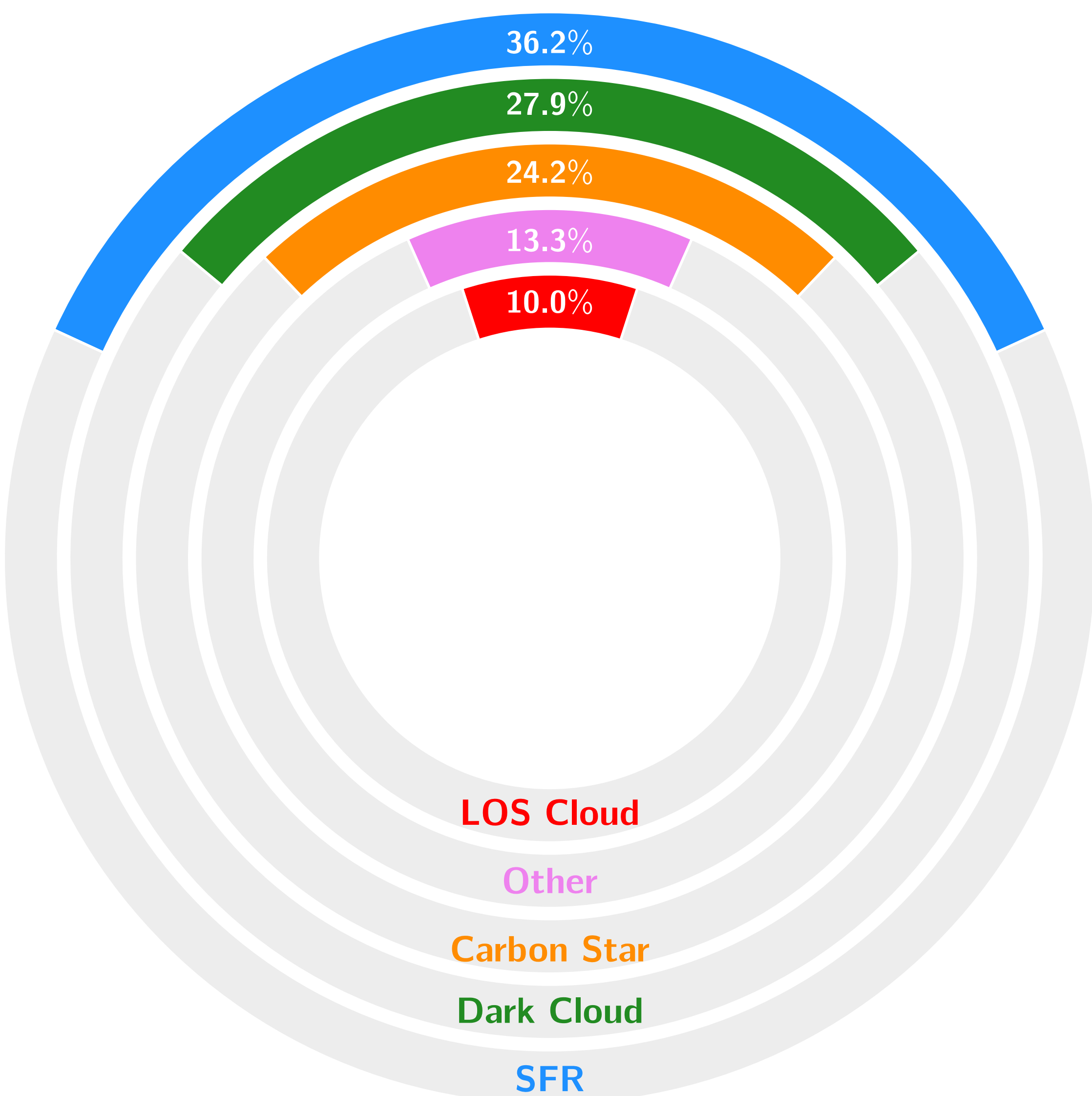
McGuire, 2020

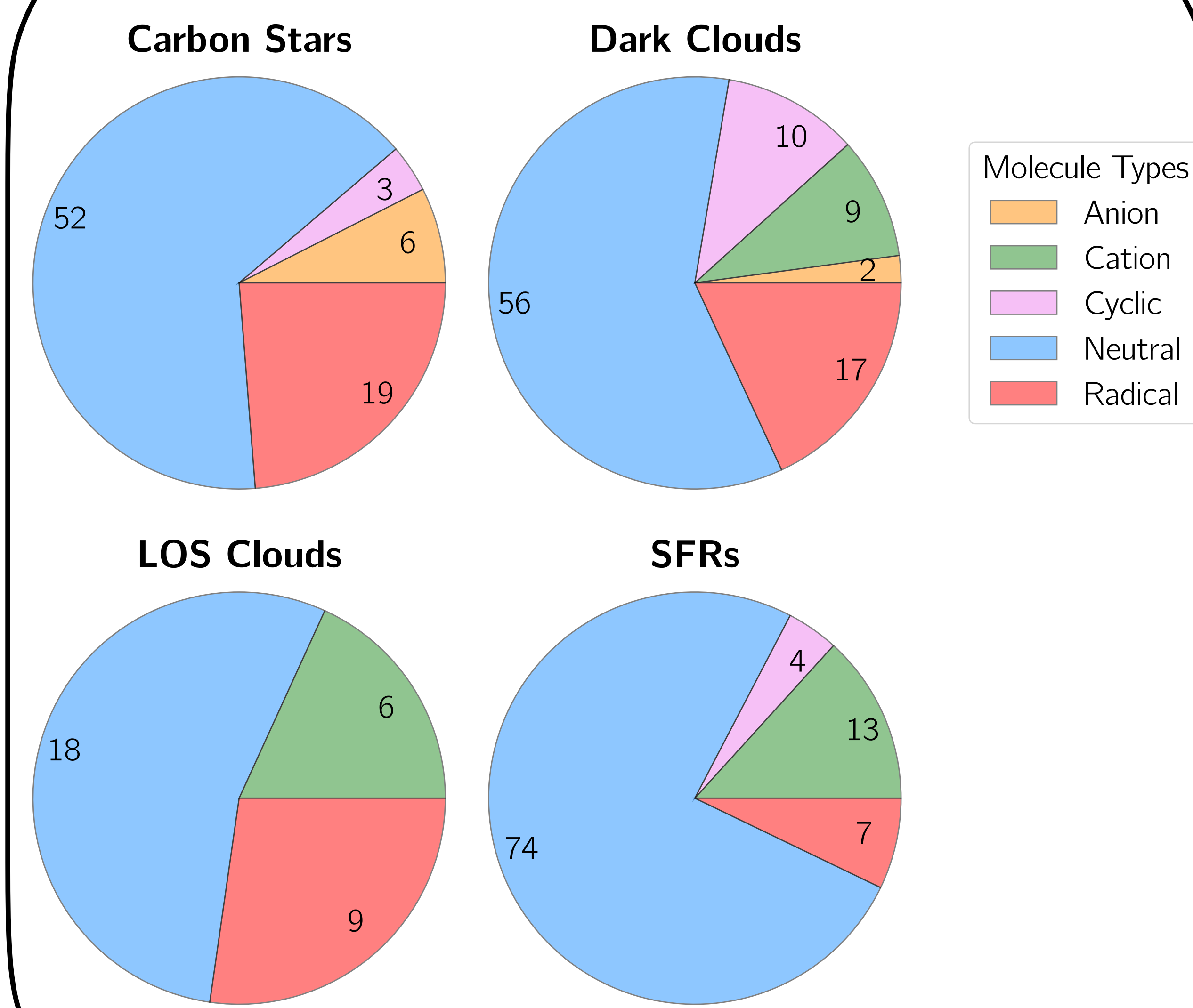


McGuire, 2020

Where most of the molecules are

More than 50% of molecules observed in dark clouds and SFR



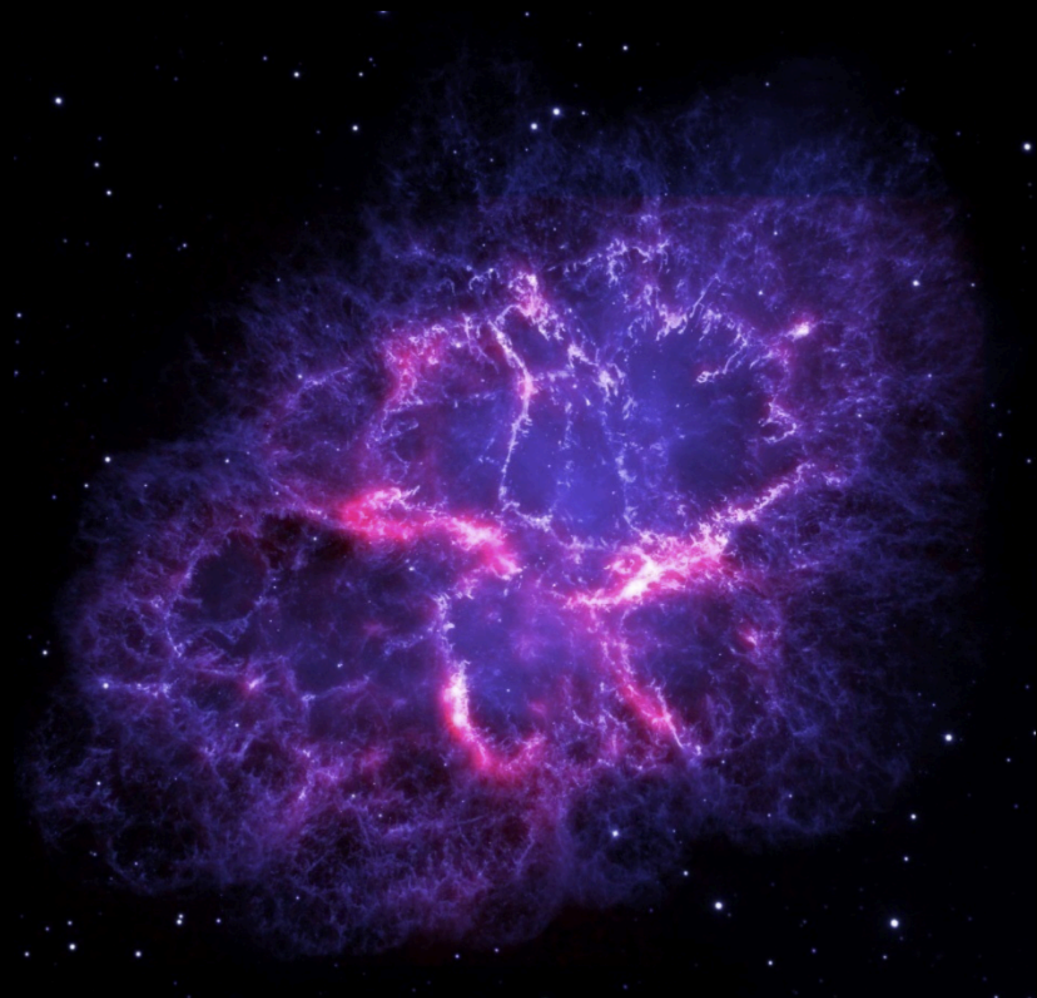


85% are neutral

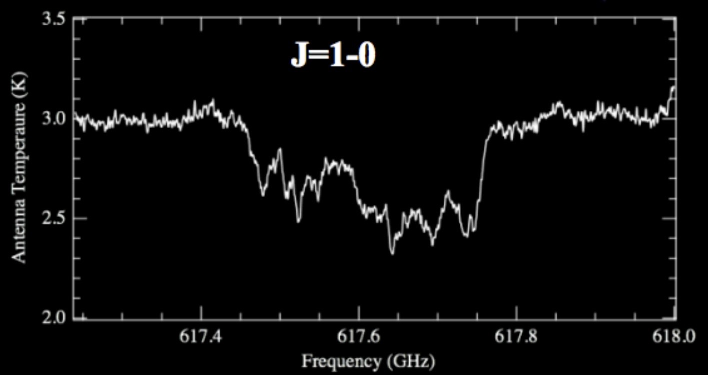
McGuire, 2020

First interstellar noble gas molecule!

$^{36}ArH^+$

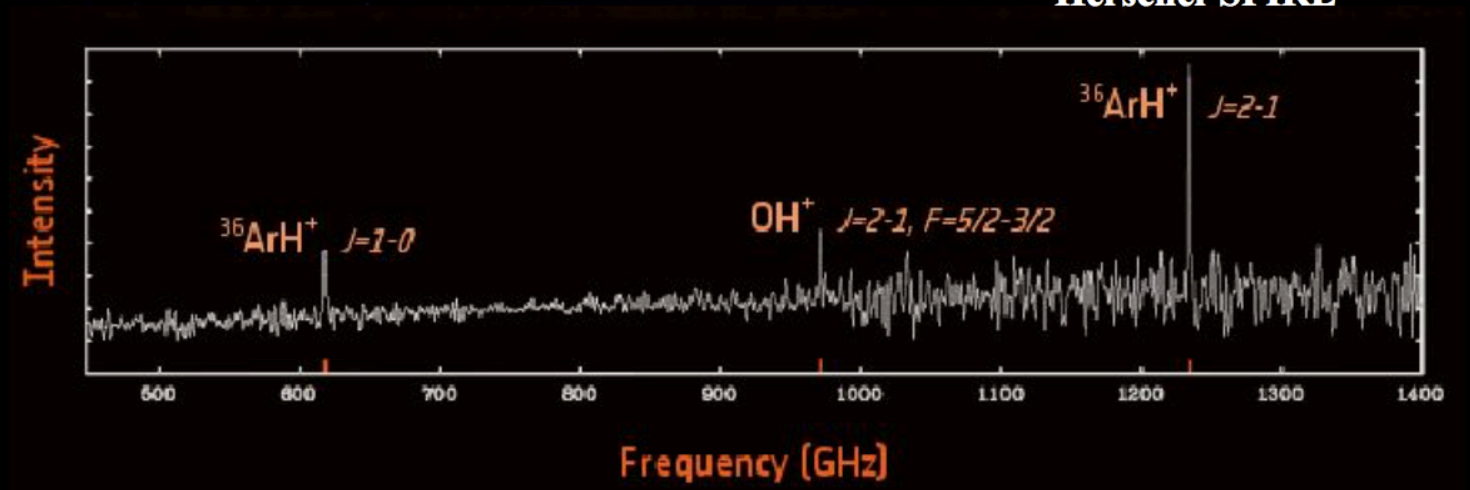


Crab nebula
Hubble+ Herschel



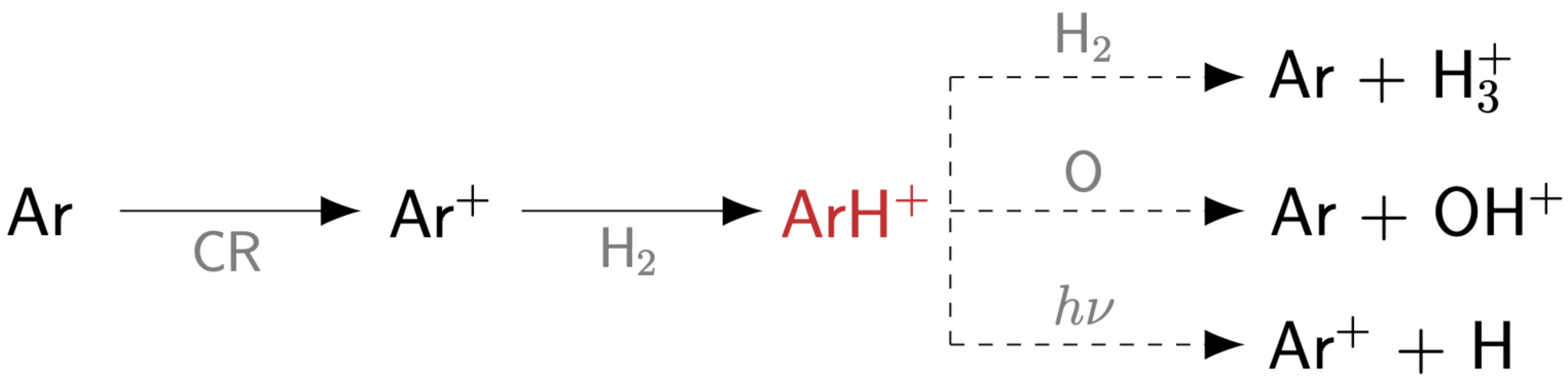
Schilke et al. 2014
Herschel-HIFI Sgr B2

Barlow et al. 2013
Herschel-SPIRE



FIRST INTERSTELLAR NOBLE GAS MOLECULE

Jacob+2022



- 617 GHz absorption line identified by Barlow+2013
- A molecule which traces purely atomic gas (diffuse, $f(H_2) \sim 10^{-4}$-10^{-2})
- It is a tracer of cosmic-rays (very reliable)

Astromolecule of the Month

January 2016

HeH$^+$

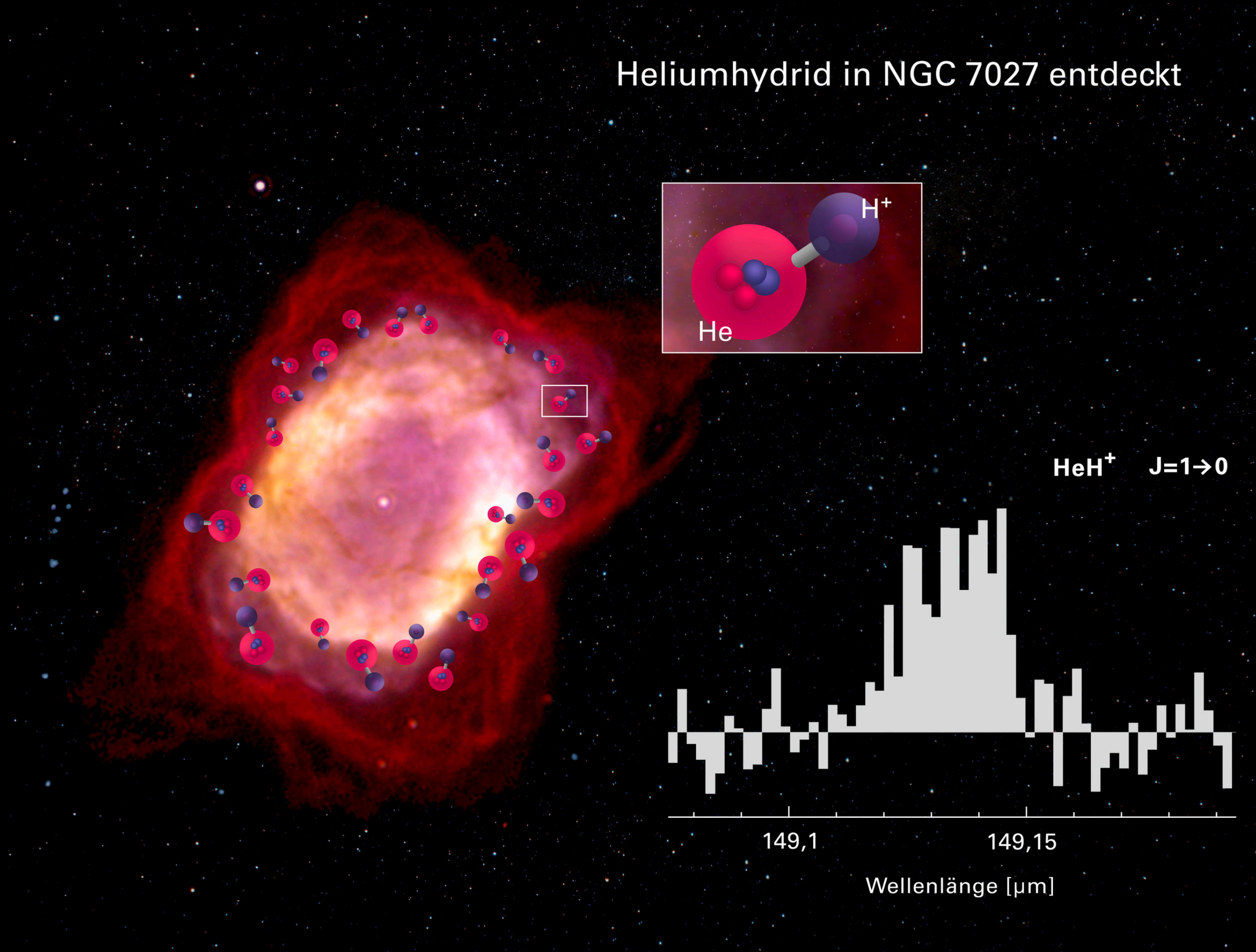
The helium hydride ion, HeH$^+$, is thought to be involved in some of the earliest chemistry to occur in the universe, formed through the radiative association reaction

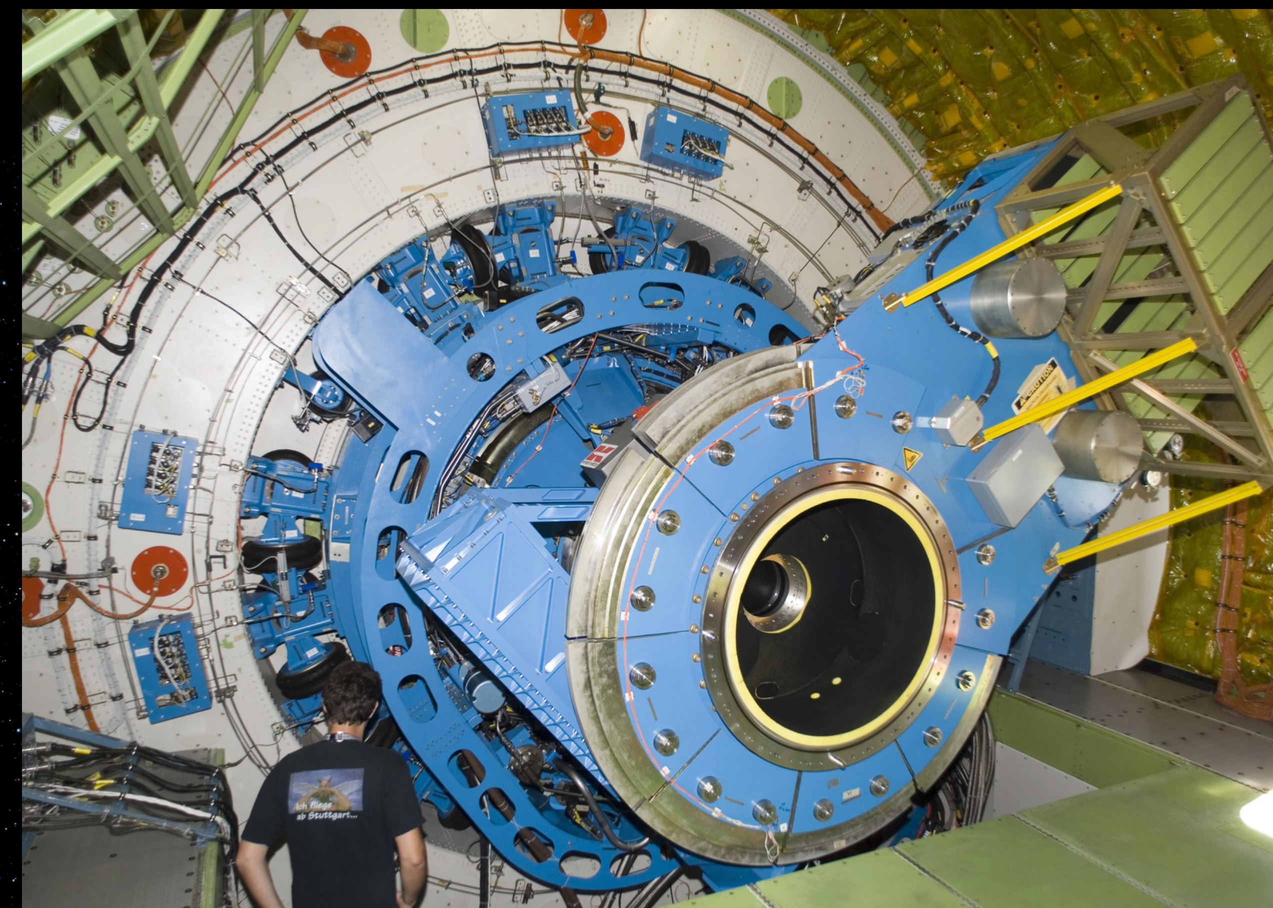
$$He + H^+ \rightarrow HeH^+ + h\nu$$

In fact, recent calculations by Bovino et al. indicate that its abundance in the early universe may have been 10 times greater than previously thought.

Since HeH$^+$ is readily destroyed by reactions with most neutral species, it has proven difficult to detect it in the modern era. The most recent effort was a search for the J=1–0 transition toward a high redshift quasar by Zinchenko et al. in 2011. While they observed something very weak shifted slightly from the expected frequency, the weakness, narrow linewidth, and anomalous velocity cast of the feature doubt that it is due to HeH$^+$. Previously, Liu et al. had unsuccessfully sought for HeH$^+$ toward the planetary nebula NGC 7027.

Güsten+2019



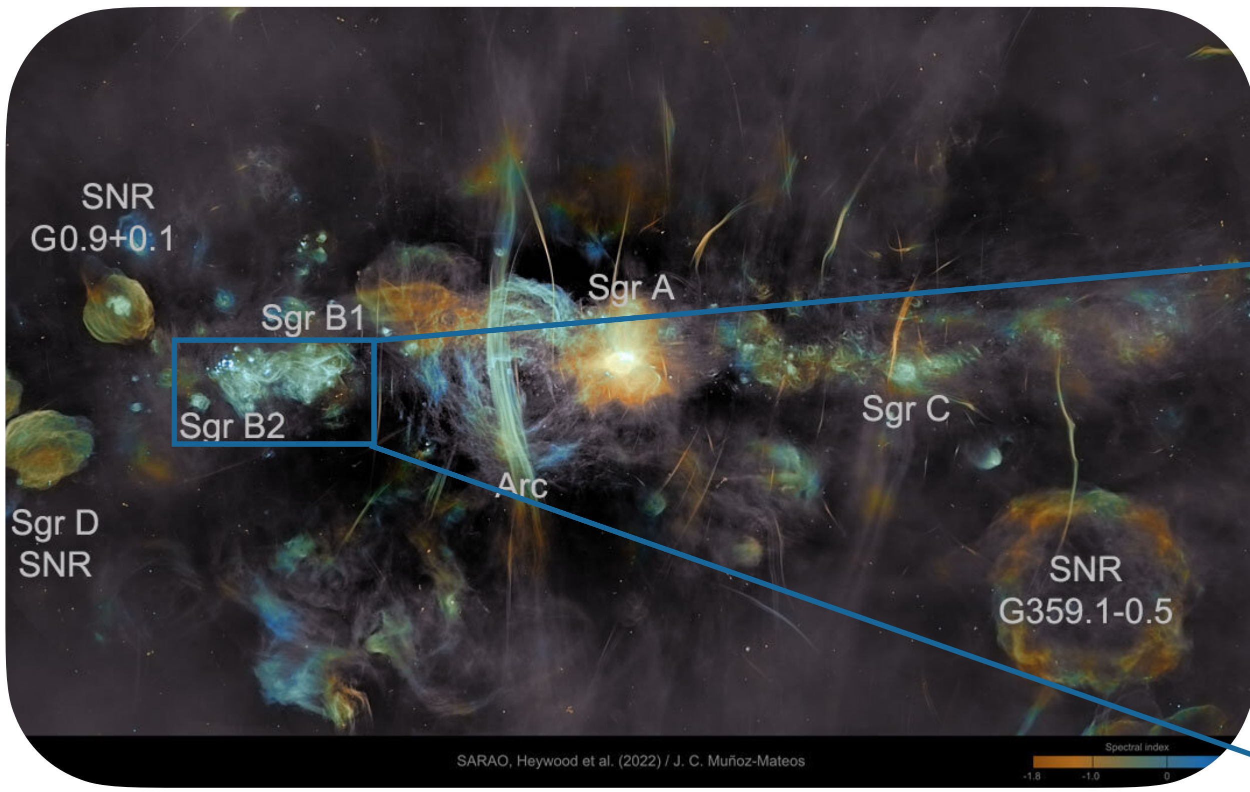


Observed with SOFIA in a planetary nebula

SECOND INTERSTELLAR NOBLE GAS MOLECULE

SAGITTARIUS B2: COMPLEX ORGANIC MOLECULES

GMC @ 120 pc from the center of the MW



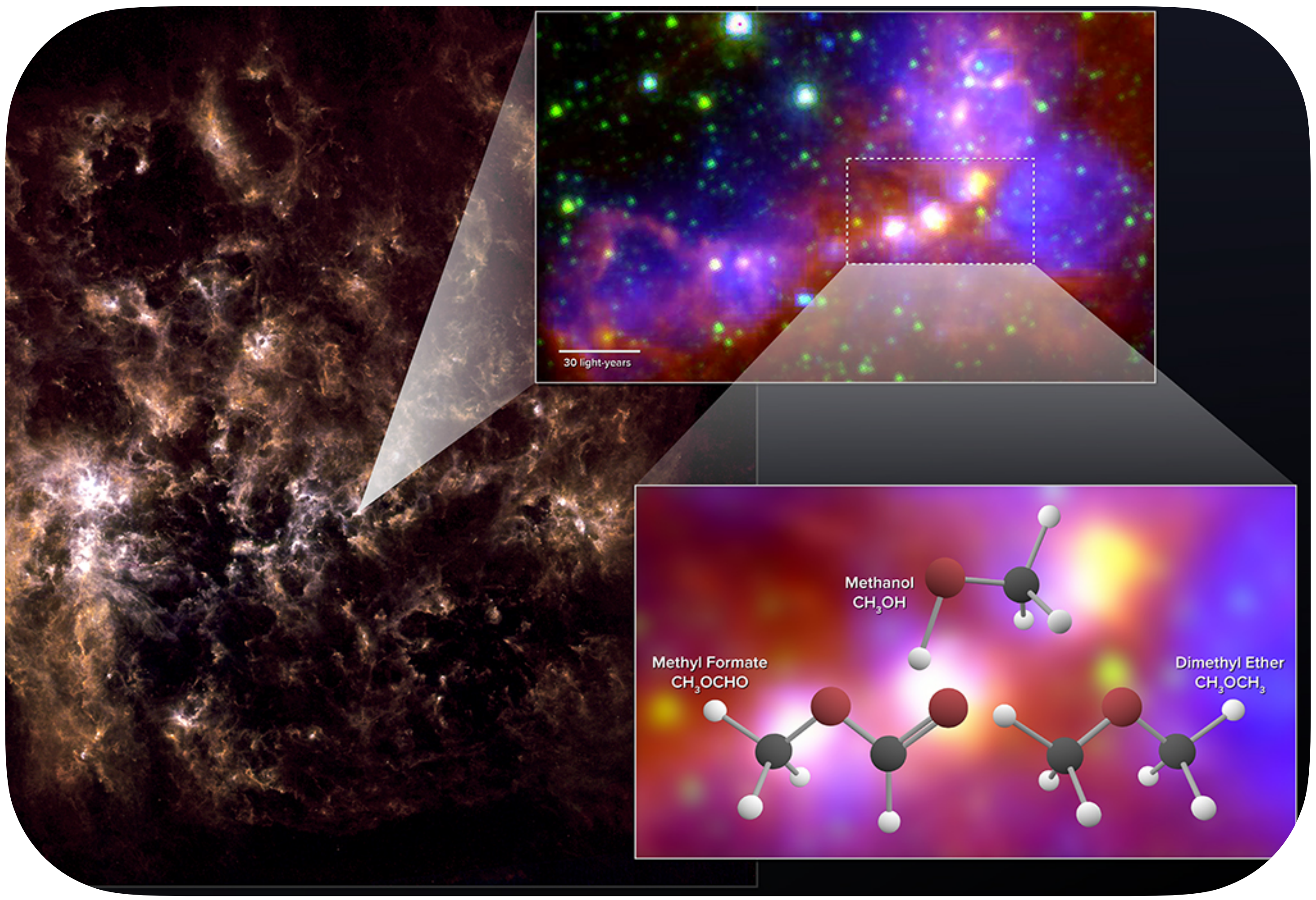
One of the largest GMC in our galaxy (M ~ 3 x 10^6 M_sun)

It is well known for tasting like raspberries and smelling like rum!

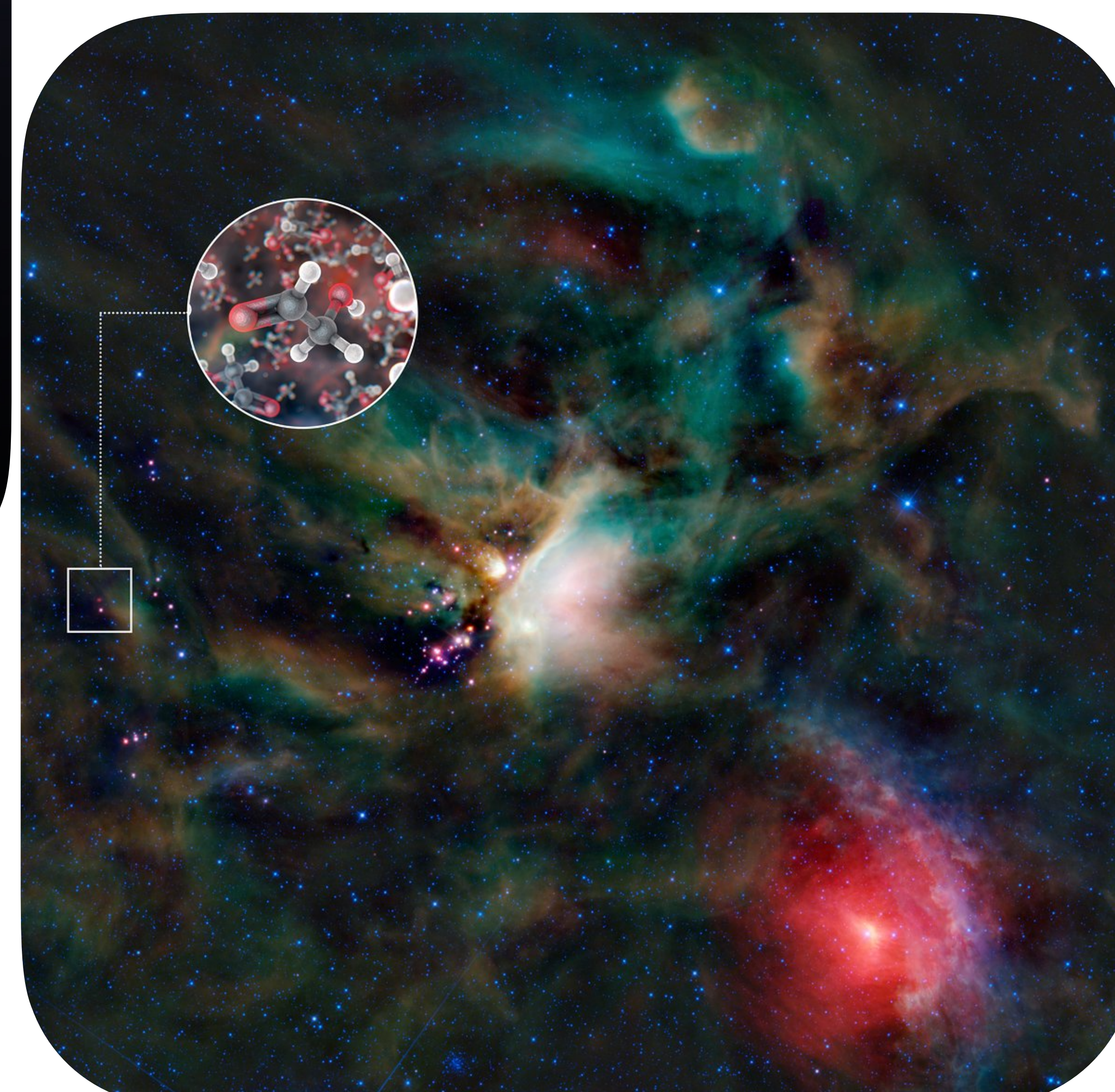
It contains ethyl formate which is an ester known for tasting like raspberries.

It also contains enough ethanol for each person on earth to drink 300,000 pintes a day for a billion years.

COMPLEX ORGANIC MOLECULES



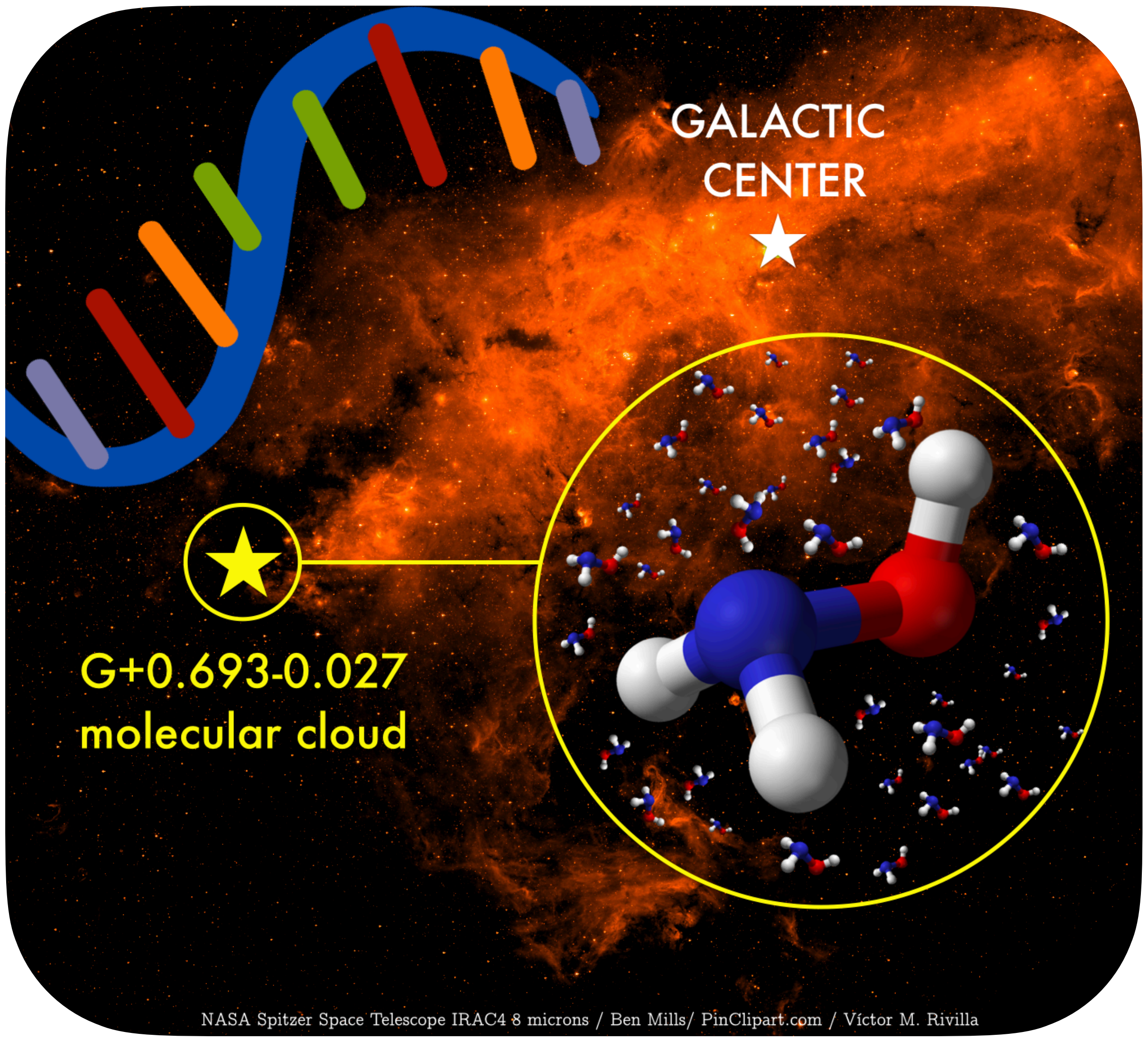
Glycolaldehyde: observed close to a star similar to our Sun (the simplest molecules related to sugars).

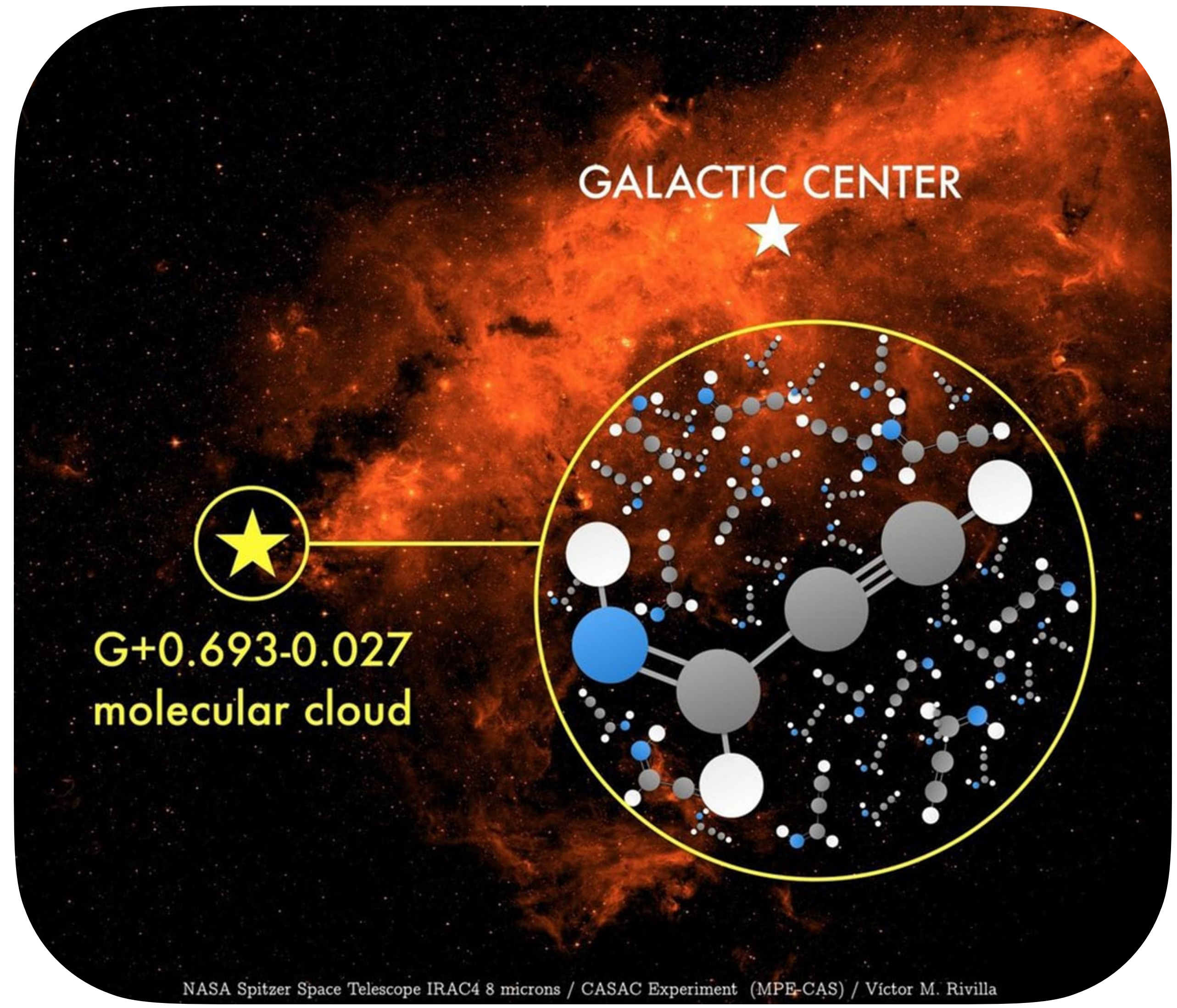


- Hydrogen (H)
- Carbon (C)
- Oxygen (O)

Credit: ALMA (ESO/NAOJ/NRAO)/L. Calçada (ESO) & NASA/JPL-Caltech/WISE Team

COMPLEX ORGANIC MOLECULES





Hydroxylamine

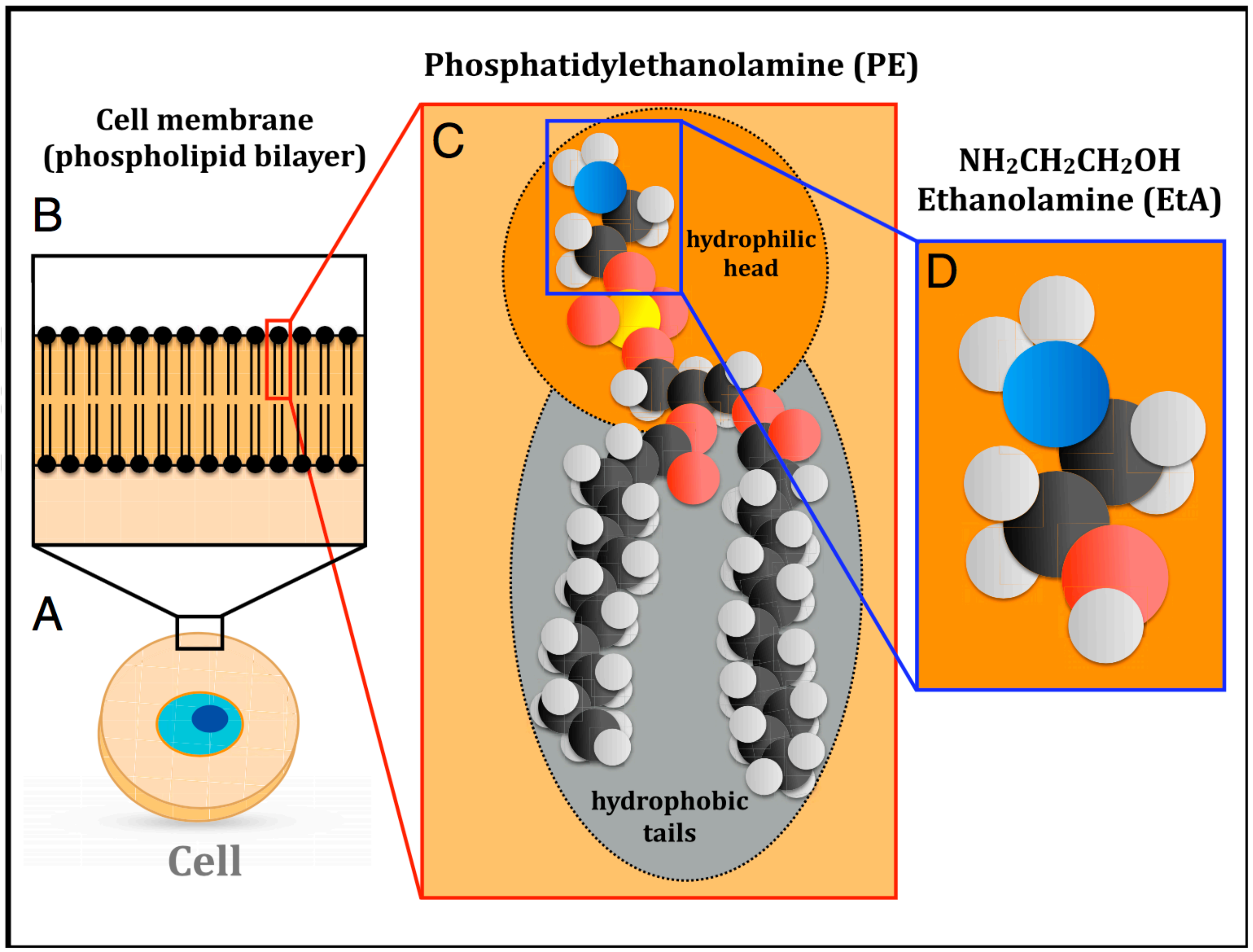
Precursor of RNA

- Nitrogen (N)
- Hydrogen (H)
- Carbon (C)
- Oxygen (O)

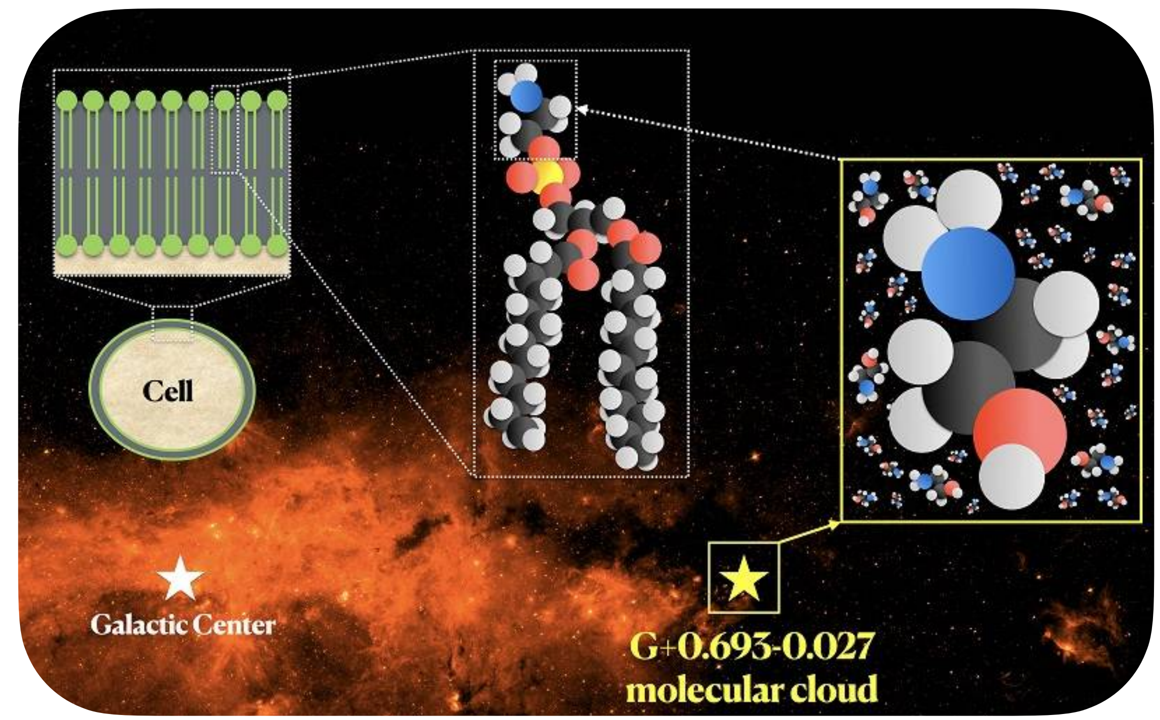
Propargylimine

Building block of amino-acid

COMPLEX ORGANIC MOLECULES



Ethanolamine

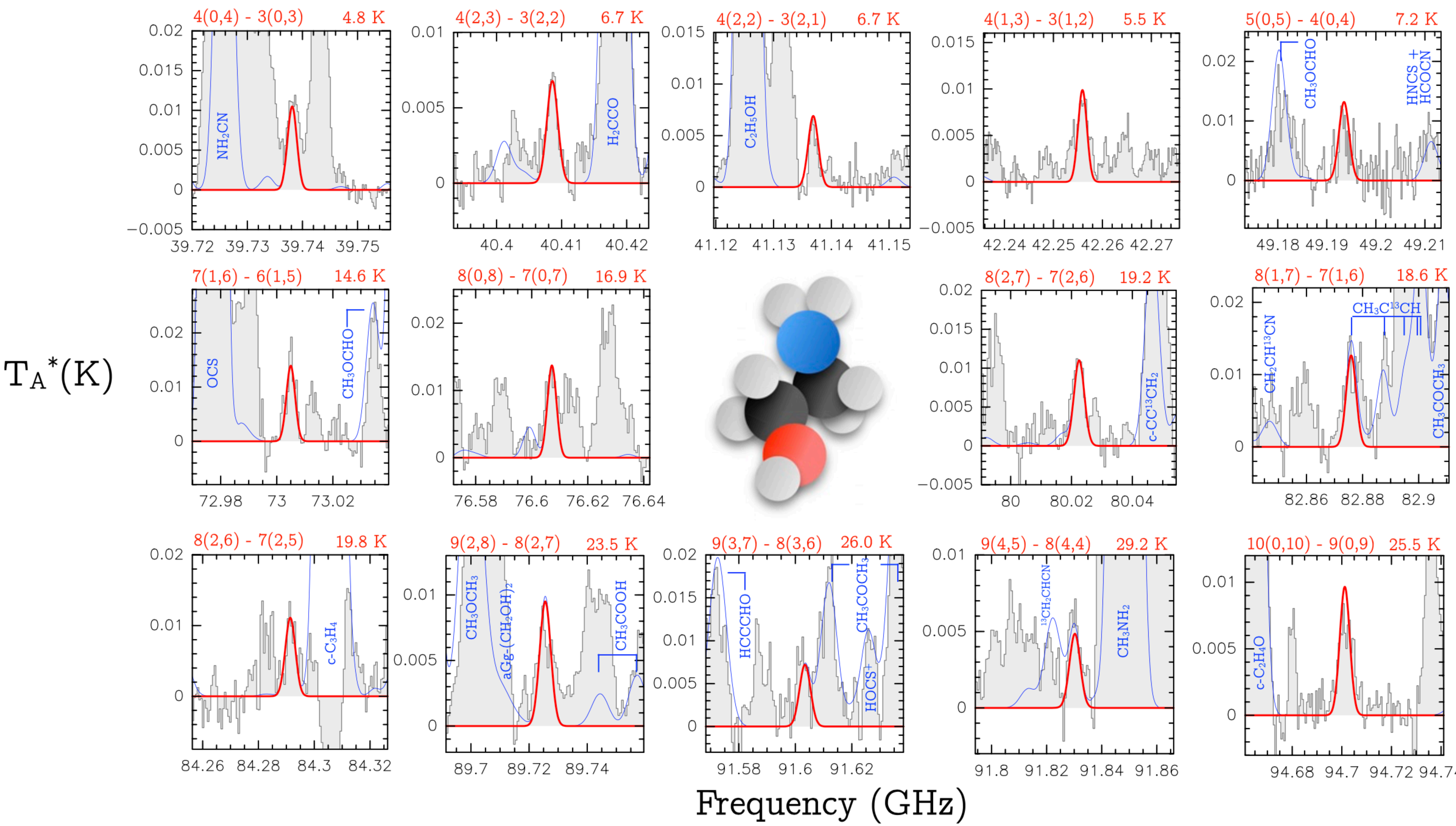


- Nitrogen (N)
- Hydrogen (H)
- Carbon (C)
- Oxygen (O)

Relevant role in the evolution of the first cellular membranes needed for the emergence of life (from a proto-solar nebula to early Earth).

Credits: Rivilla+2022

COMPLEX ORGANIC MOLECULES (IRAM)



Credits: Rivilla+2022

LARGE MOLECULE STATISTICS

Table 3
List of Detected Interstellar Molecules with Eight or More Atoms, Categorized by Number of Atoms, and Vertically Ordered by Detection Year

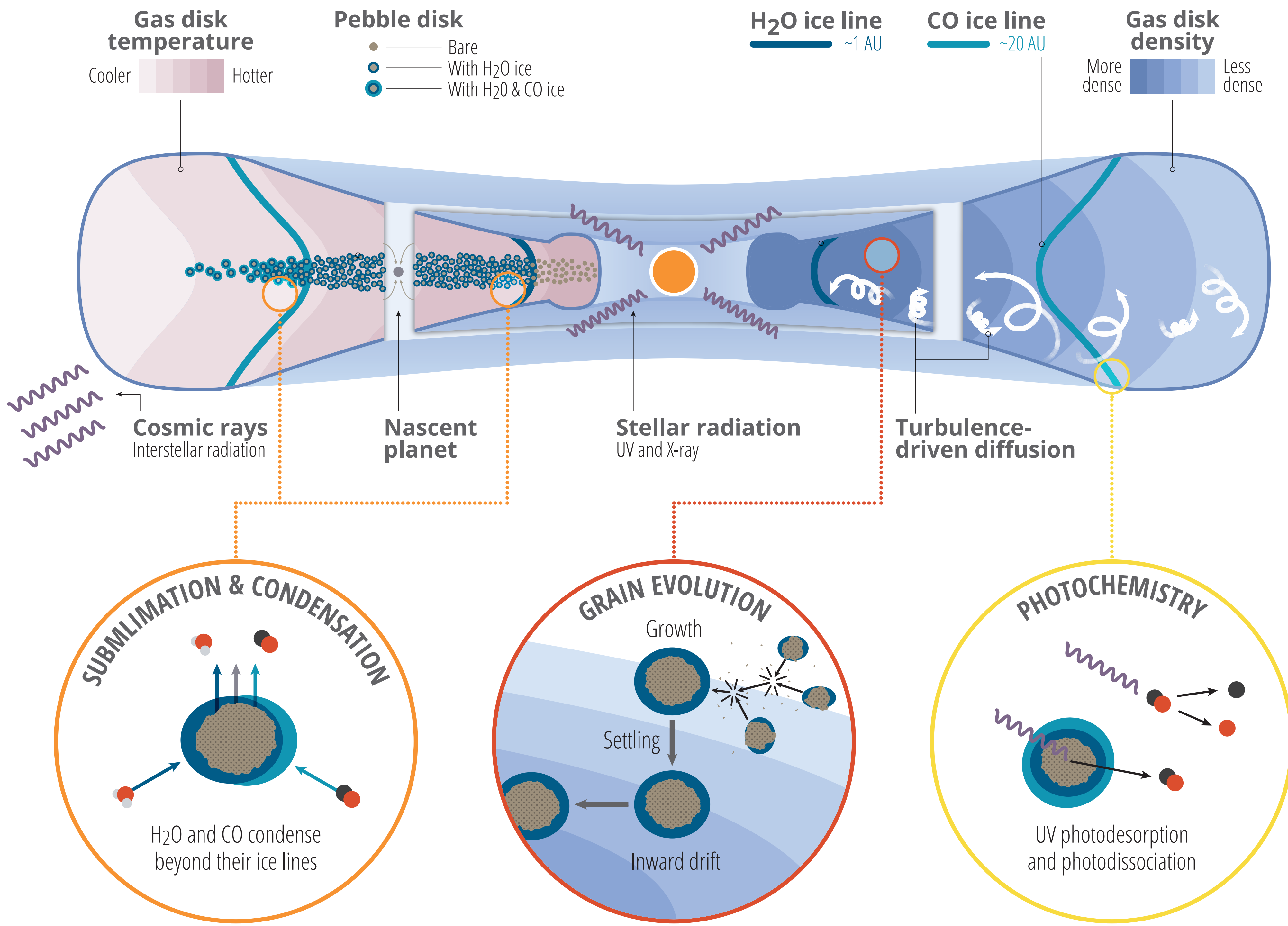
8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	Fullerenes
$HCOOCH_3$	CH_3OCH_3	$(CH_3)_2CO$	HC_9N	C_6H_6	c-C_6H_5CN	C_{60}
CH_3C_3N	CH_3CH_2OH	$HO(CH_2)_2OH$	CH_3C_6H	n-C_3H_7CN		C_{60}^+
C_7H	CH_3CH_2CN	CH_2CH_2CHO	CH_3CH_2OCHO	i-C_3H_7CN		C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3			
H_2C_6	CH_3C_4H	CH_3CHCH_2O				
CH_2OHCHO	C_8H	CH_3OCH_2OH				
HC_6H	CH_3CONH_2					
CH_2CHCHO	C_8H^-					
CH_2CCHCN	CH_2CHCH_3					
NH_2CH_2CN	CH_3CH_2SH					
CH_3CHNH	HC_7O					
CH_3SiH_3						

Table 9
Total Number of Detections that Each Source Contributed to for the Molecules Listed in Section 3

Source	#	Source	#
Sgr B2	67	NGC 7023	2
IRC+10216	51	TC 1	2
TMC-1	34	W49	2
Orion	24	CRL 2688	1
LOS Clouds	22	Crab Nebula	1
L483	8	DR 21(OH)	1
W51	8	Galactic Center	1
VY Ca Maj	5	IC 443G	1
B1-b	4	IRAS 16293	1
DR 21	4	K3-50	1
NGC 6334	4	L134	1
Sgr A	4	L1527	1
CRL 618	3	L1544	1
NGC 2264	3	L183	1
W3(OH)	3	Lupus-1A	1
rho Oph A	3	M17SW	1
Horsehead PDR	2	NGC 7027	1
NGC 2024	2	NGC 7538	1

Credits: McGuire2019

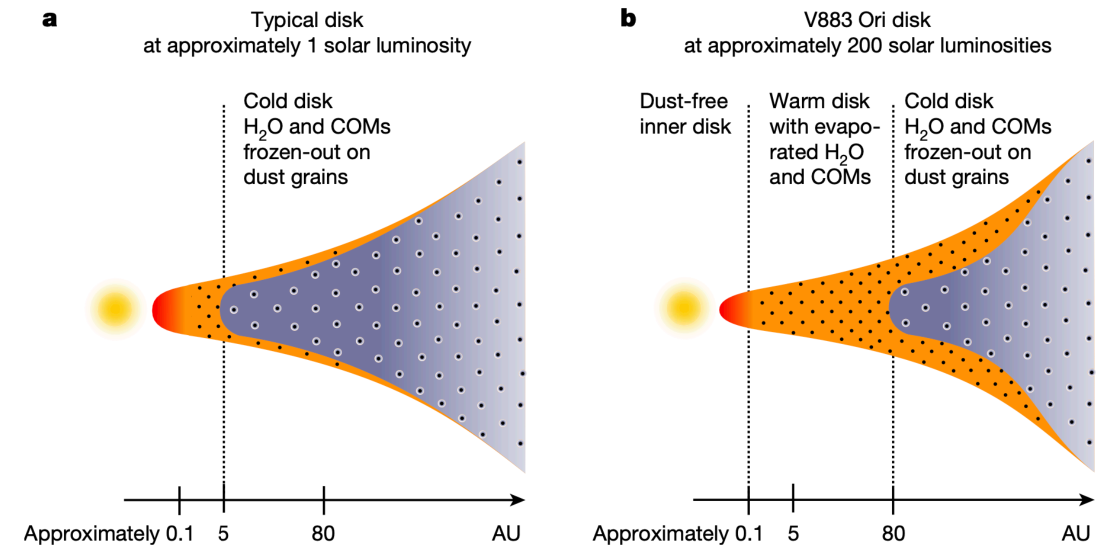
NEW DISCOVERIES

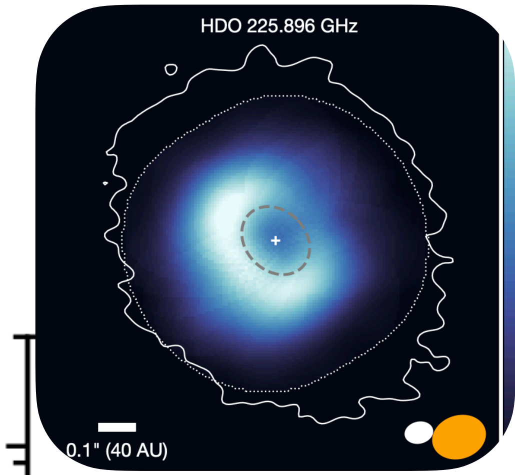


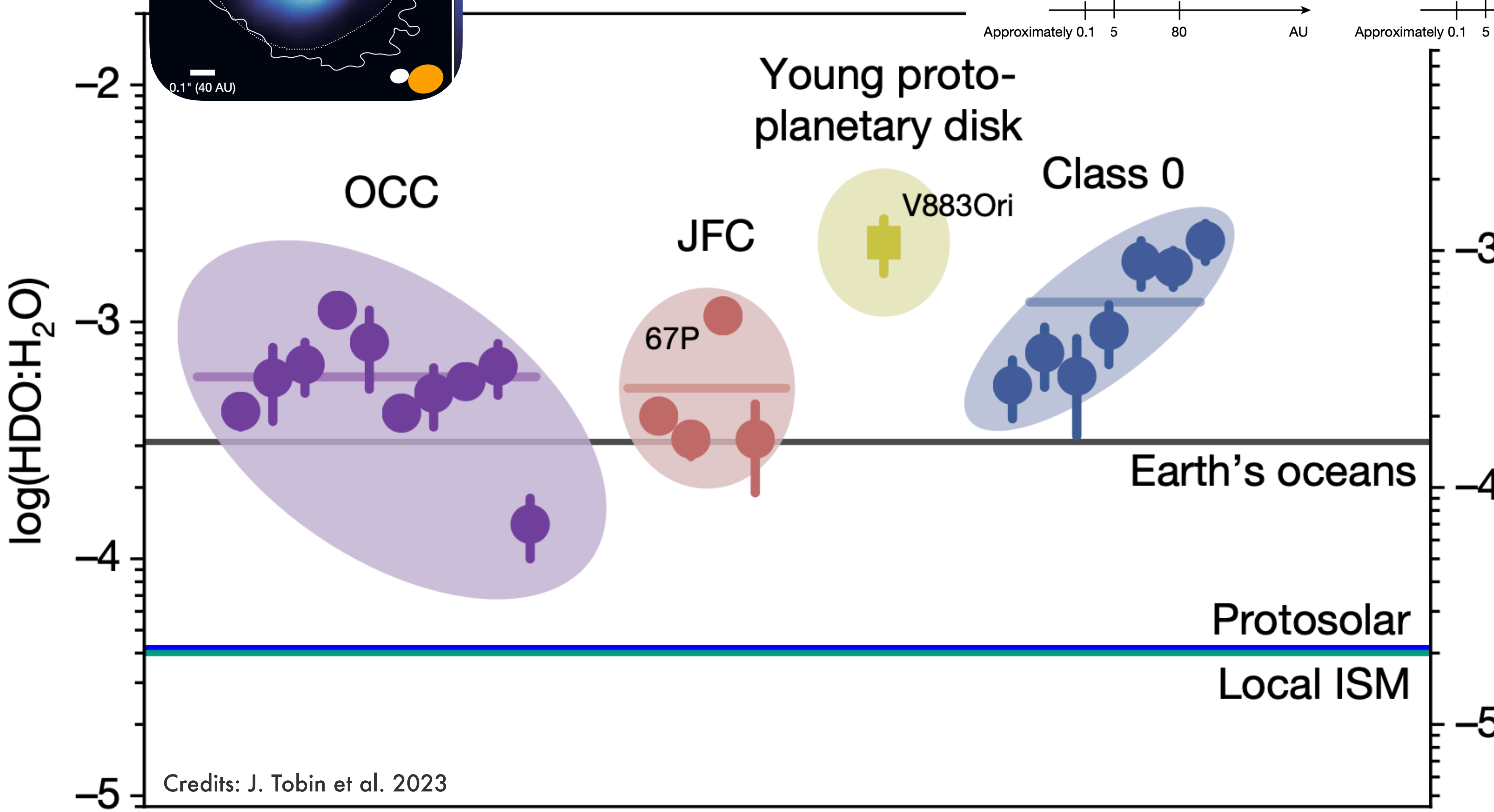
Credits: Öberg2019

NEW DISCOVERIES

in V883 Orionis the snow line is located further from the star, there is sufficient gaseous water to be detectable







Credits: J. Tobin et al. 2023

→ THE COMETARY ZOO: GASES DETECTED BY ROSETTA

esa

THE LONG CARBON CHAINS
Methane
Ethane
Propane
Butane
Pentane
Hexane
Heptane

THE AROMATIC RING COMPOUNDS
Benzene
Toluene
Xylene
Benzoic acid
Naphtalene

THE KING OF THE ZOO
Glycine (amino acid)

THE "MANURE SMELL" MOLECULES
Ammonia
Methylamine
Ethylamine

THE "POISONOUS" MOLECULES
Acetylene
Hydrogen cyanide
Acetonitrile
Formaldehyde

THE ALCOHOLS
Methanol
Ethanol
Propanol
Butanol
Pentanol

THE VOLATILES
Nitrogen
Oxygen
Hydrogen peroxide
Carbon monoxide
Carbon dioxide

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

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

THE TREASURES WITH A HARD CRUST
Sodium
Potassium
Silicon
Magnesium

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

THE BEAUTIFUL AND SOLITARY
Argon
Krypton
Xenon

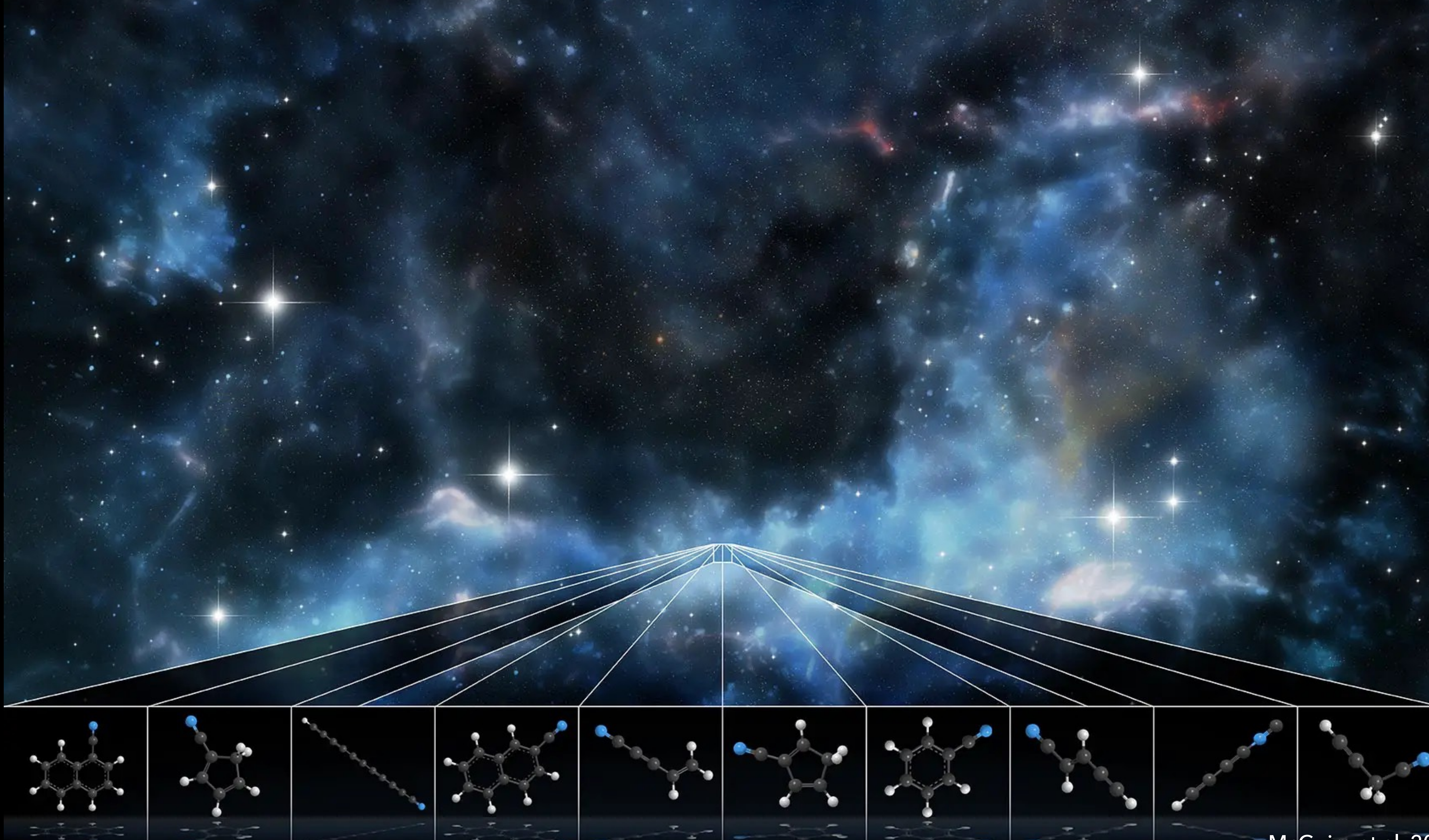
THE "EXOTIC" MOLECULES
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide

THE MOLECULE IN DISGUISE
Cyanogen

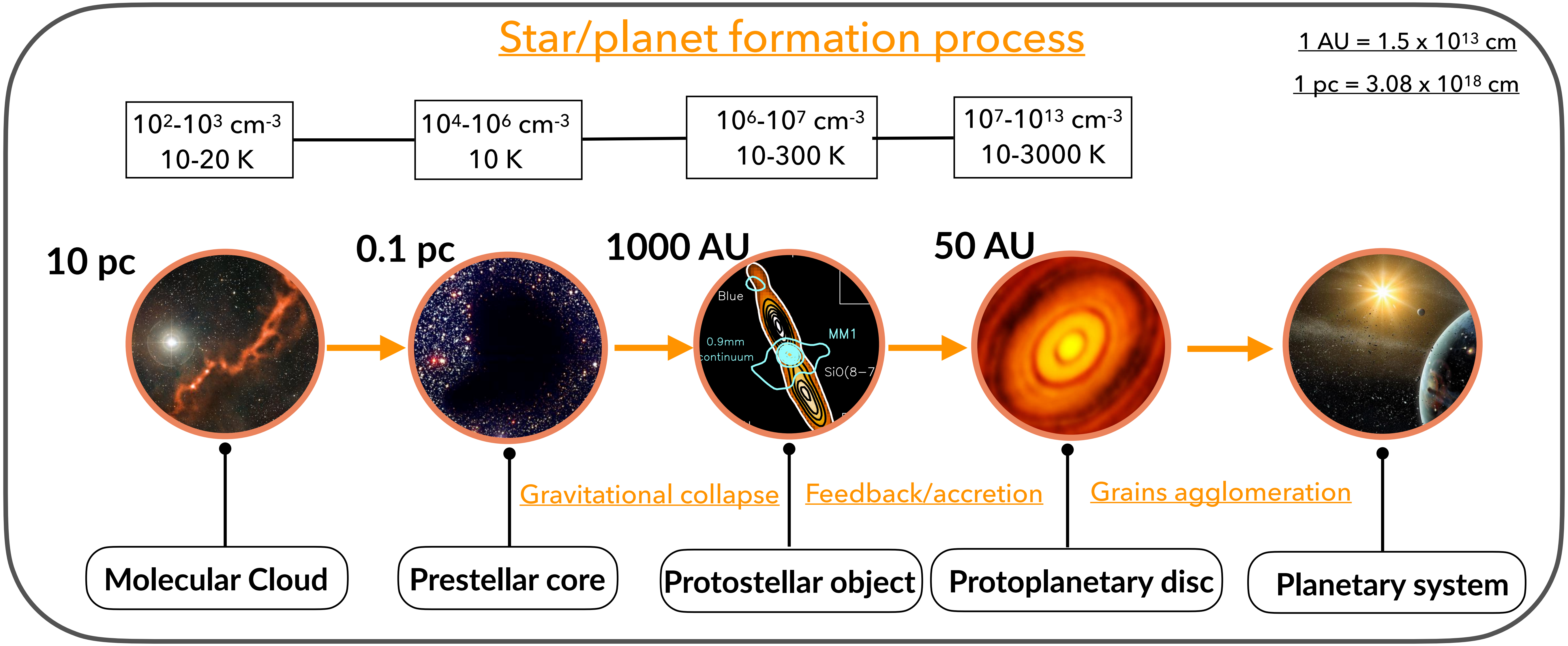
Credits: Based on data from ROSINA

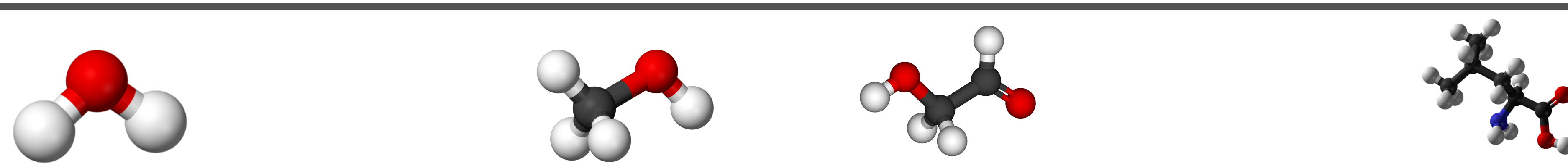
Observation of a dozen of PAHs in a dark molecular cloud

It suggests that PAHs are not just the byproducts of dying stars, but may be assembled from smaller molecules.



McGuire et al. 2022





Formation of simple molecules
Surface chemistry

Formation of complex molecules*
Desorption due to T-increase

Conservation / delivery of
old molecules+life

Molecular Complexity

*COMs: molecules with at least 6 atoms (must include C, Herbst & Van Dishoeck 2009)

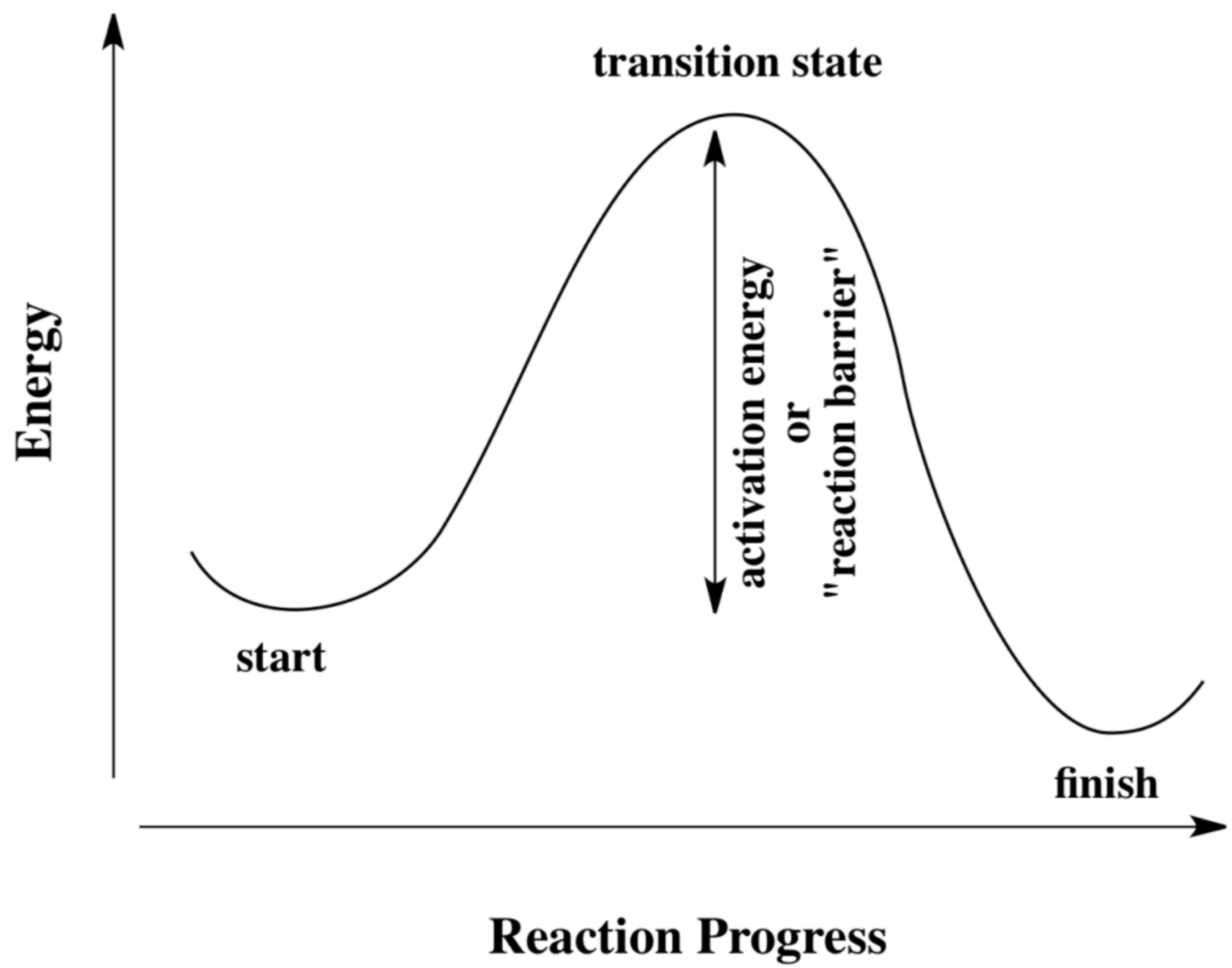
SEARCHING FOR MOLECULES IS NOT EASY

Where's Wally? In Space

Credits: AstroBites, Abygail Waggoner

SEARCHING FOR MOLECULES IS NOT EASY

COMs and prebiotic molecules difficult to observe: need theoretical support



Kinetics / models

Provide a way to compare with observations. If the results do not match it means we miss some chemical / physical process

Credits: AstroBites, Abygail Waggoner

SEARCHING FOR MOLECULES IS NOT EASY

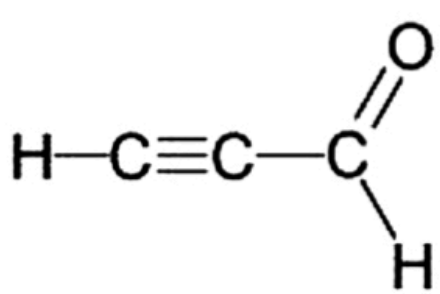
How many ways I have to arrange atoms in a molecule?

- Hydrogen (H)
- Carbon (C)
- Oxygen (O)

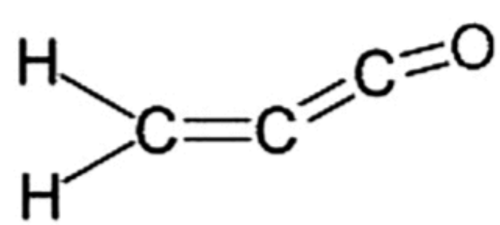
Waldo Isomer

Waldo

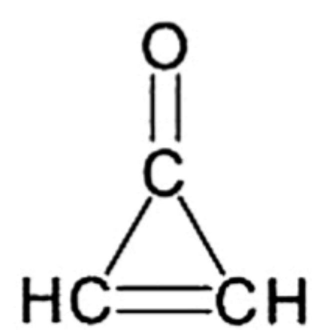
Waldo Isomer



propynal
HCCCHO



propadienone
CH_2CCO



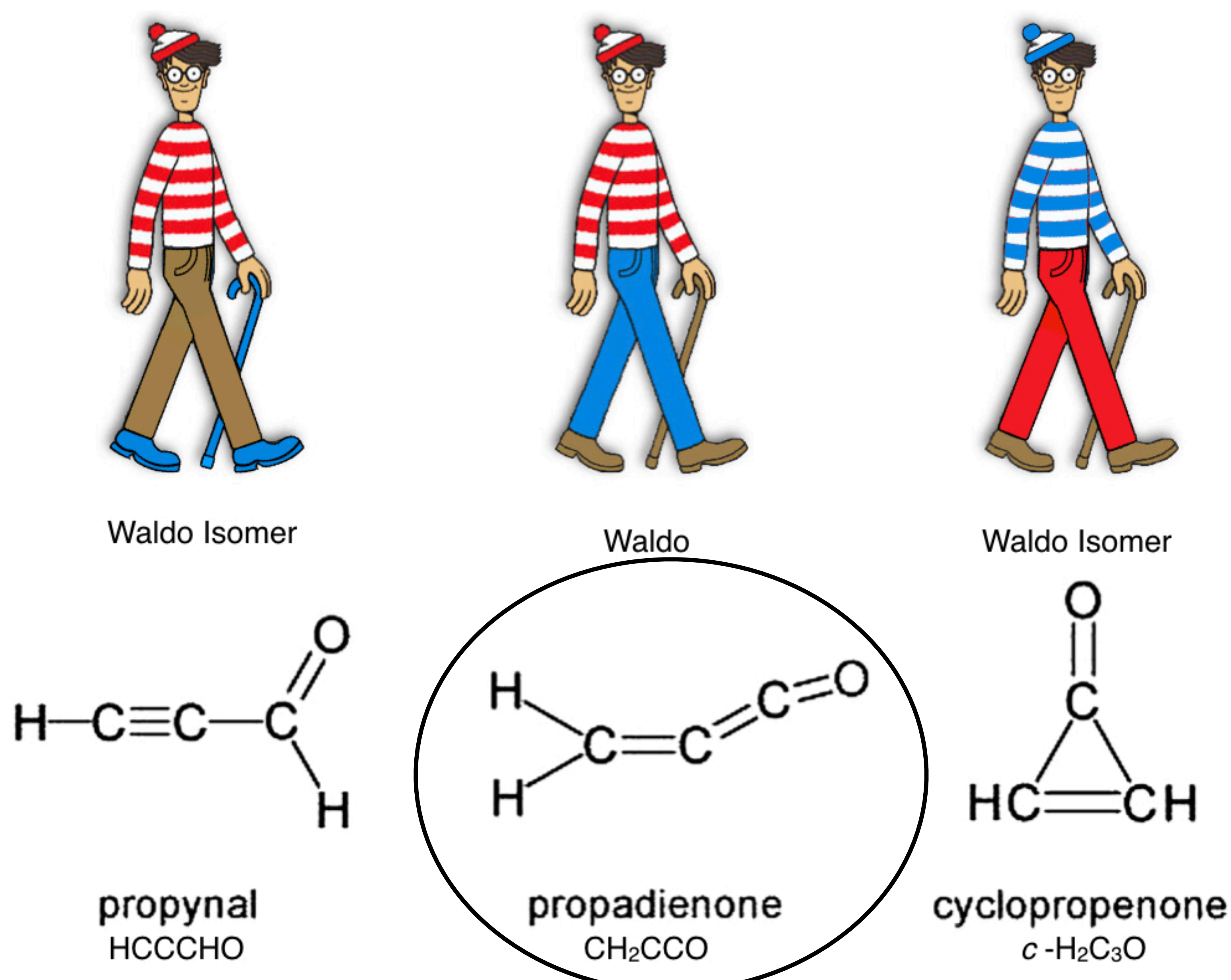
cyclopropenone
c-H_2C_3O

ISOMERS

Credits: AstroBites, Abygail Waggoner

SEARCHING FOR MOLECULES IS NOT EASY

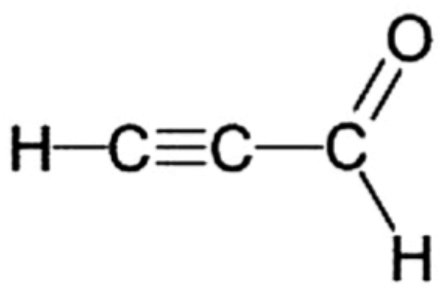
Propadienone is the most stable isomer: is it the most abundant?



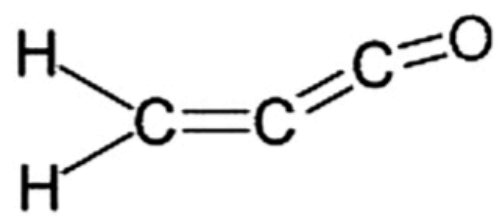
Credits: AstroBites, Abygail Waggoner

SEARCHING FOR MOLECULES IS NOT EASY

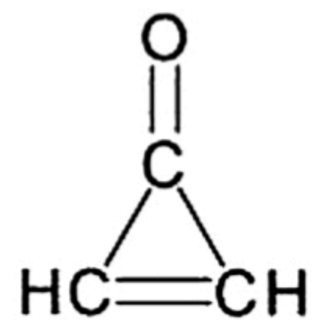
OBSERVATIONS question the minimum energy principle and the idea on relying on kinetics for chemical models



propynal
HCCCHO



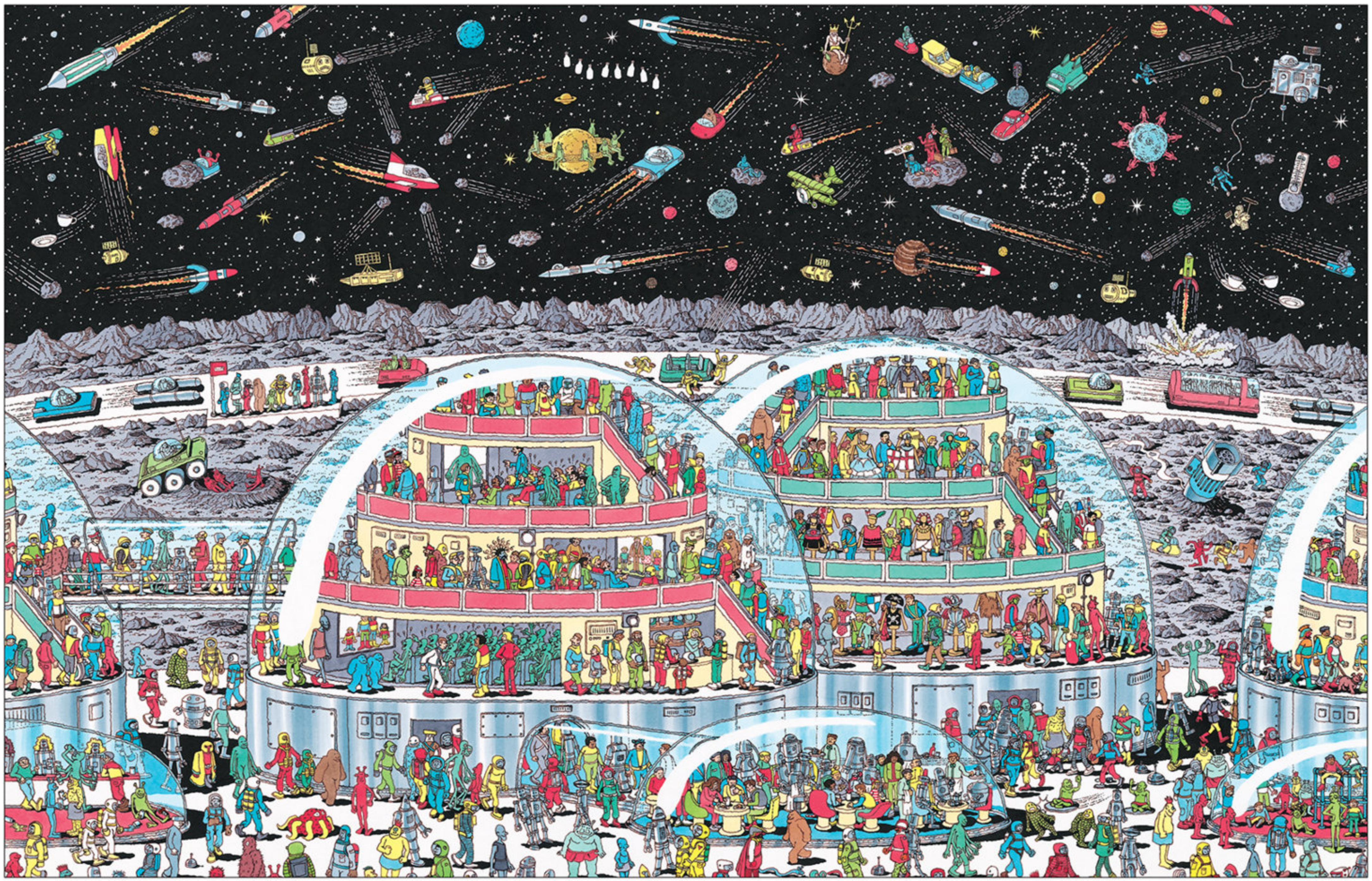
propadienone
CH_2CCO



cyclopropenone
c-H_2C_3O

Credits: AstroBites, Abygail Waggoner

WE WILL FIND WALLY IN A FEW LECTURES



Where's Wally? In Space

Credits: AstroBites, Abygail Waggoner