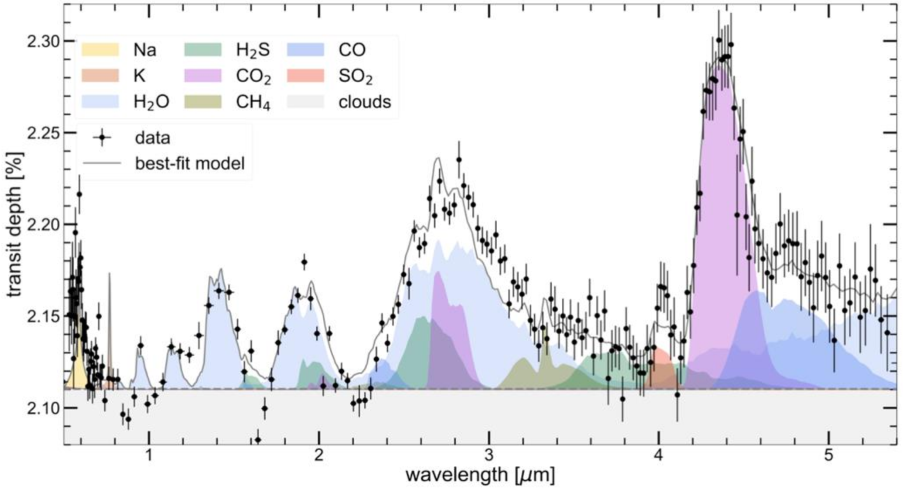


Introduction to Astrochemistry **Part 4**:

Life Seeded from Space? Comets and Exoplanets

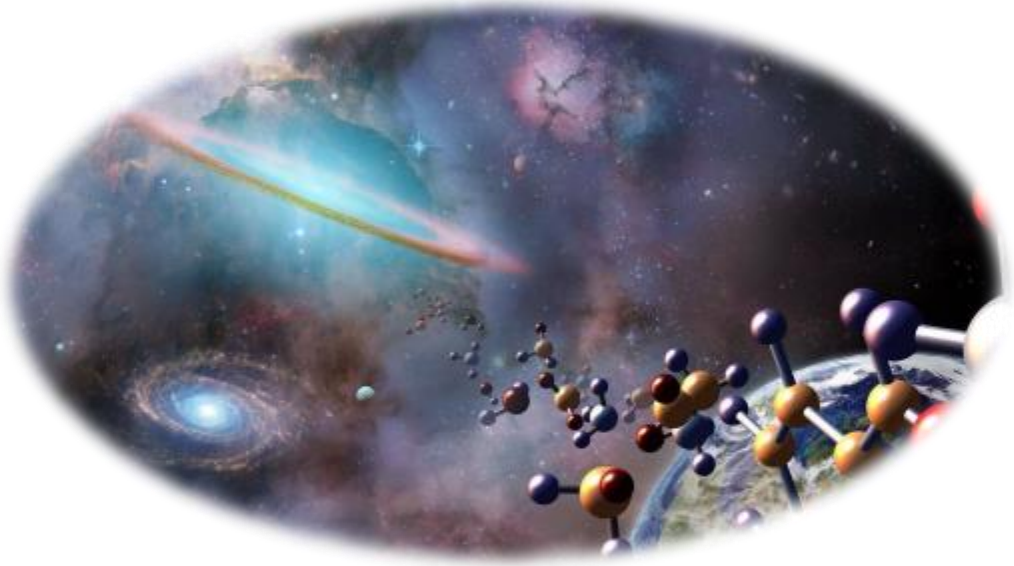
Dr. Samantha Scibelli

Jansky Fellow at the National Radio Astronomy Observatory (NRAO)

AAA.org Lecture, June 11^{th}, 2024

Astrochemistry, or "Molecular Astrophysics"

Definition: The study of the formation and destruction of molecules in the Universe, their interaction with radiation, and their feedback on physics of the environments

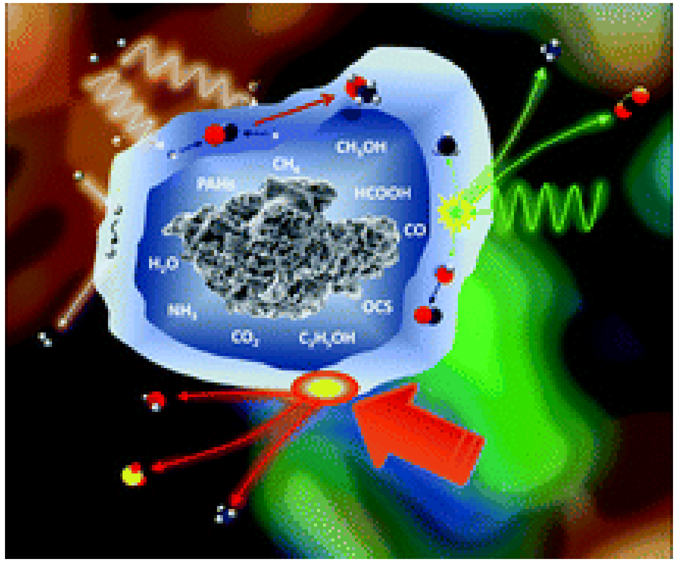


*I write about molecules with great diffidence, having not yet rid myself of the tradition that **atoms are physics, but molecules are chemistry**, but the new conclusions that hydrogen is abundant seems to make it likely that the above mentioned elements H, O, and N will frequency form molecules*

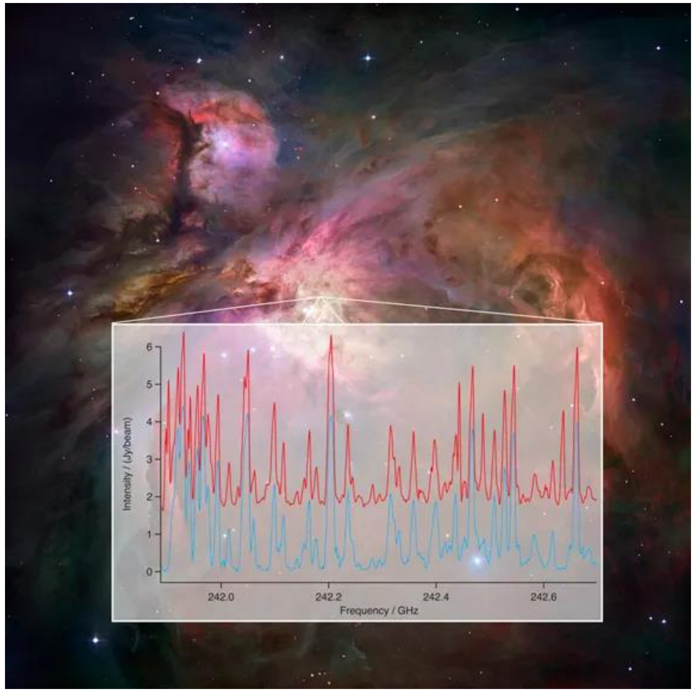
- *Sir A. Eddington, 1937*

Astrochemistry is an interdisciplinary field! Including, chemistry, physics, astronomy, biology, etc.,

Modeling



Observations



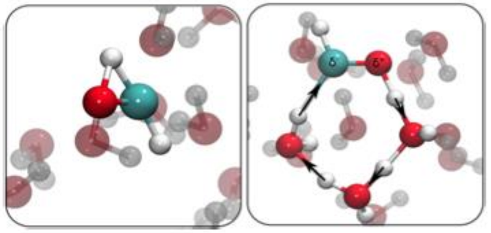
Things an astro**chemist** does

Laboratory

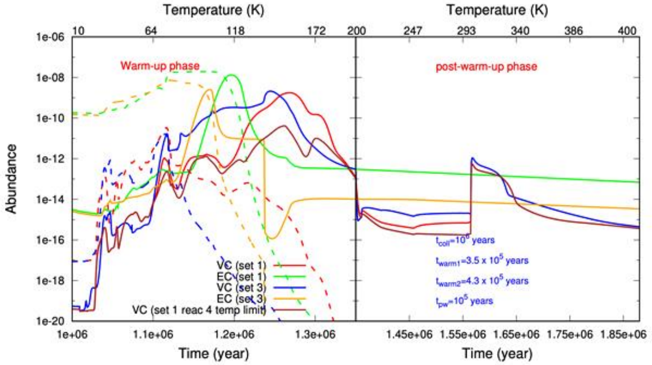
Astrochemistry is an interdisciplinary field! Including, chemistry, physics, astronomy, biology, etc.,

Modeling

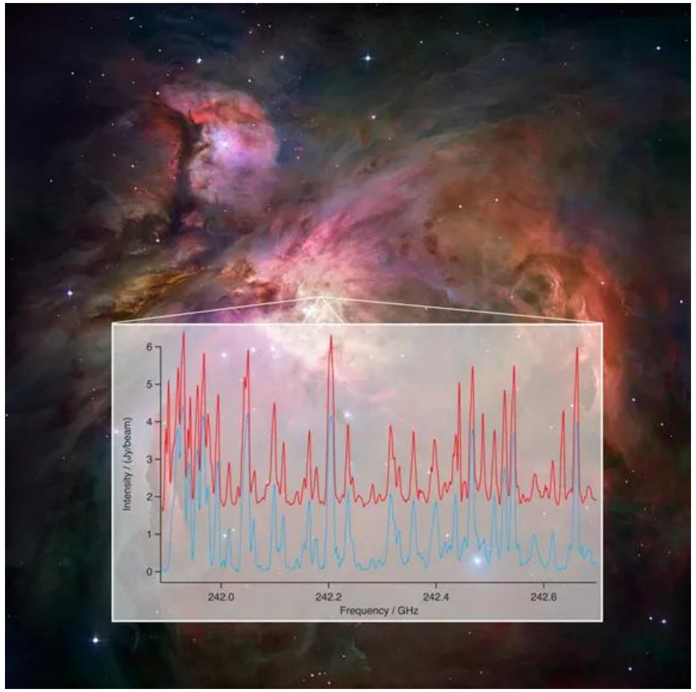
Computational chemistry



Simulations of chemical networks



Observations



Things an astro**chemist** does

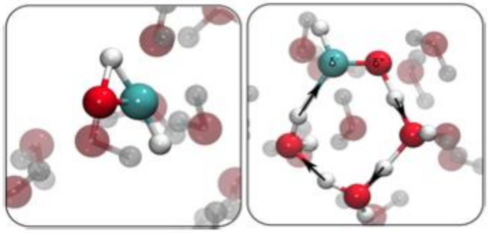
Laboratory

Astrochemistry is an interdisciplinary field! Including, chemistry, physics, astronomy, biology, etc.,

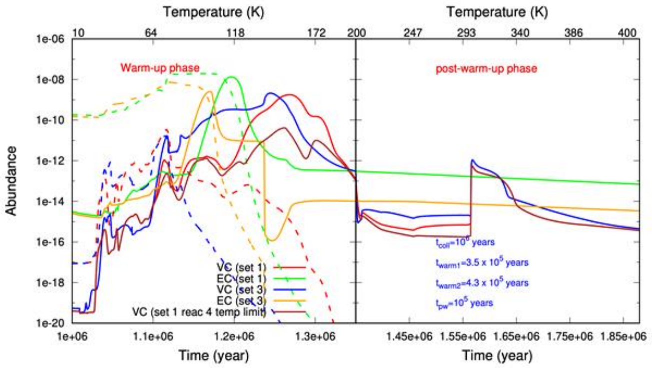
Things an astro**chemist** does

Modeling

Computational chemistry



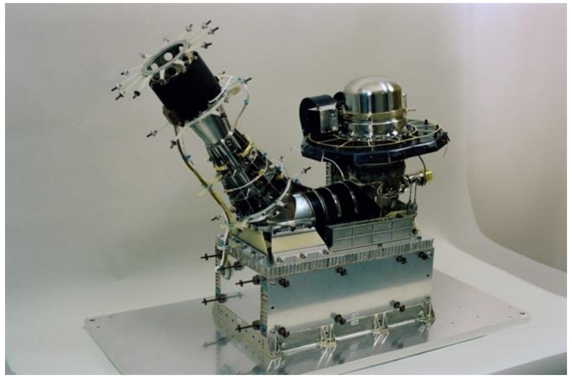
Simulations of chemical networks



Observations

Millimeter Telescopes

Mass Spectrometers



Laboratory

A Molecular Universe!

2 Atoms		3 Atoms		4 Atoms		5 Atoms		6 Atoms	7 Atoms
CH	NH	H_2O	MgCN	NH_3	SiC_3	HC_3N	C_4H^-	CH_3OH	CH_3CHO
CN	SiN	HCO^+	H_3^+	H_2CO	CH_3	HCOOH	CNCHO	CH_3CN	CH_3CCH
CH^+	SO^+	HCN	SiCN	HNCO	C_3N^-	CH_2NH	HNCNH	NH_2CHO	CH_3NH_2
OH	CO^+	OCS	AlNC	H_2CS	PH_3	NH_2CN	CH_3O	CH_3SH	CH_2CHCN
CO	HF	HNC	SiNC	C_2H_2	HCNO	H_2CCO	NH_3D^+	C_2H_4	HC_5N
H_2	N_2	H_2S	HCP	C_3N	HOCN	C_4H	H_2NCO^+	C_5H	C_6H
SiO	CF^+	N_2H^+	CCP	HNCS	HSCN	SiH_4	$NCCNH^+$	CH_3NC	c-C_2H_4O
CS	PO	C_2H	AlOH	$HOCO^+$	HOOH	c-C_3H_2	CH_3Cl	HC_2CHO	CH_2CHOH
SO	O_2	SO_2	H_2O^+	C_3O	l-C_3H^+	CH_2CN	MgC_3N	H_2C_4	C_6H^-
SiS	AlO	HCO	H_2Cl^+	l-C_3H	HMgNC	C_5	HC_3O^+	C_5S	CH_3NCO
NS	CN^-	HNO	KCN	$HCNH^+$	HCCO	SiC_4	NH_2OH	HC_3NH^+	HC_5O
C_2	OH^+	HCS^+	FeCN	H_3O^+	CNCN	H_2CCC	HC_3S^+	C_5N	$HOCH_2CN$
NO	SH^+	HOC^+	HO_2	C_3S	HONO	CH_4	H_2CCS	HC_4H	HC_4NC
HCl	HCl^+	SiC_2	TiO_2	c-C_3H	MgCCH	HCCNC	C_4S	HC_4N	HC_3HNH
NaCl	SH	C_2S	CCN	HC_2N	HCCS	HNCCC	CHOSH	c-H_2C_3O	c-C_3HCCH
AlCl	TiO	C_3	SiCSi	H_2CN		H_2COH^+		CH_2CNH	
KCl	ArH^+	CO_2	S_2H					C_5N^-	
AlF	NS^+	CH_2	HCS					HNCHCN	
PN	HeH^+	C_2O	HSC					SiH_3CN	
SiC	VO	MgNC	NCO					MgC_4H	
CP		NH_2	CaNC					CH_3CO^+	
		NaCN	NCS					H_2CCCS	
		N_2O						CH_2CCH	

8 Atoms	9 Atoms	10 Atoms	11 Atoms	12 Atoms	13 Atoms	PAHs	Fullerenes
$HCOOCH_3$	CH_3OCH_3	CH_3COCH_3	HC_9N	C_6H_6	C_6H_5CN	1-$C_{10}H_7CN$	C_{60}
CH_3C_3N	CH_3CH_2OH	$HOCH_2CH_2OH$	CH_3C_6H	n-C_3H_7CN	$HC_{11}N$	2-$C_{10}H_7CN$	C_{60}^+
C_7H	CH_3CH_2CN	CH_3CH_2CHO	C_2H_5OCHO	i-C_3H_7CN		C_9H_8	C_{70}
CH_3COOH	HC_7N	CH_3C_5N	CH_3COOCH_3	1-C_5H_5CN			
H_2C_6	CH_3C_4H	CH_3CHCH_2O	CH_3COCH_2OH	2-C_5H_5CN			
CH_2OHCHO	C_8H	CH_3OCH_2OH	C_5H_6				
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	CH_3NHCHO						
NH_2CONH_2	$H_2CCCHCCH$						
$HCCCH_2CN$	$HCCCHCHCN$						
CH_2CHCCH	H_2CCHC_3N						

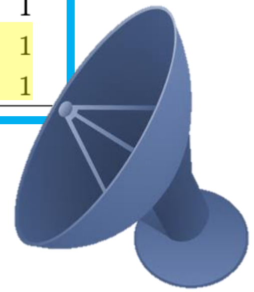
>300 Molecules

McGuire 2022; https://arxiv.org/pdf/2109.13848

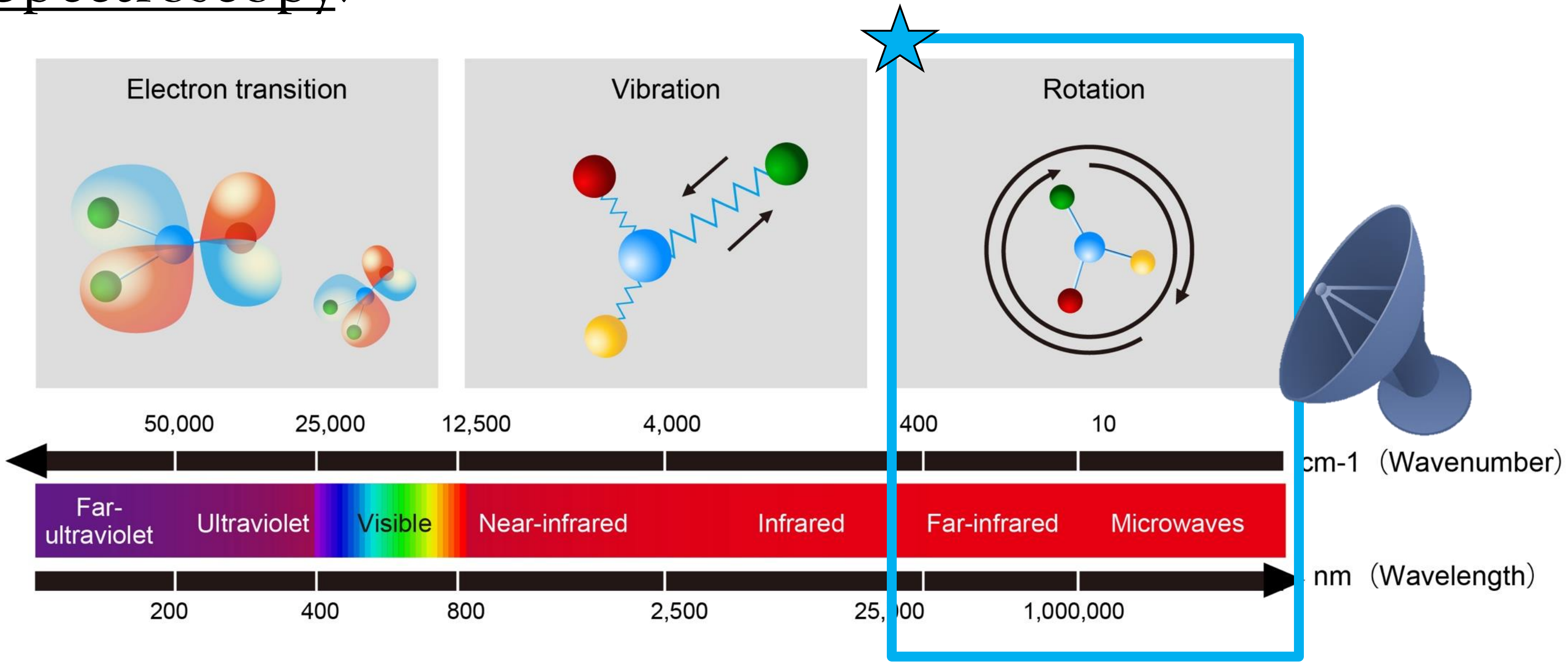
of molecule discoveries per observatory

Facility	#	Facility	#
IRAM 30-m	64	SMA	2
NRAO 36-ft	33	SEST	2
GBT 100-m	28	SOFIA	2
NRAO/ARO 12-m	27	Hat Creek 20-ft	2
Yebes 40-m	19	IRTF	2
Nobeyama 45-m	15	PdBI	2
NRAO 140-ft	13	OVRO	2
Bell 7-m	8	MWO 4.9-m	2
ALMA	8	Hubble	1
SMT	7	IRAS	1
Herschel	7	BIMA	1
Parkes	5	NRL 85-ft	1
FCRAO 14-m	5	ATCA	1
ISO	5	Mitaka 6-m	1
APEX	4	McMath Solar Telescope	1
Onsala 20-m	4	UKIRT	1
KPNO 4-m	4	Odin	1
Effelsberg 100-m	4	FUSE	1
Algonquin 46-m	3	KAO	1
Mt. Wilson	3	Mt. Hopkins 60-in	1
Spitzer	3	Aerobee-150 Rocket	1
Haystack	3	Millstone Hill 84-ft	1
CSO	2	Goldstone	1

> 90% Identified by Radio Astronomy!



Submillimeter and Millimeter Radio Telescopes Identify Molecules via Rotational Spectroscopy!



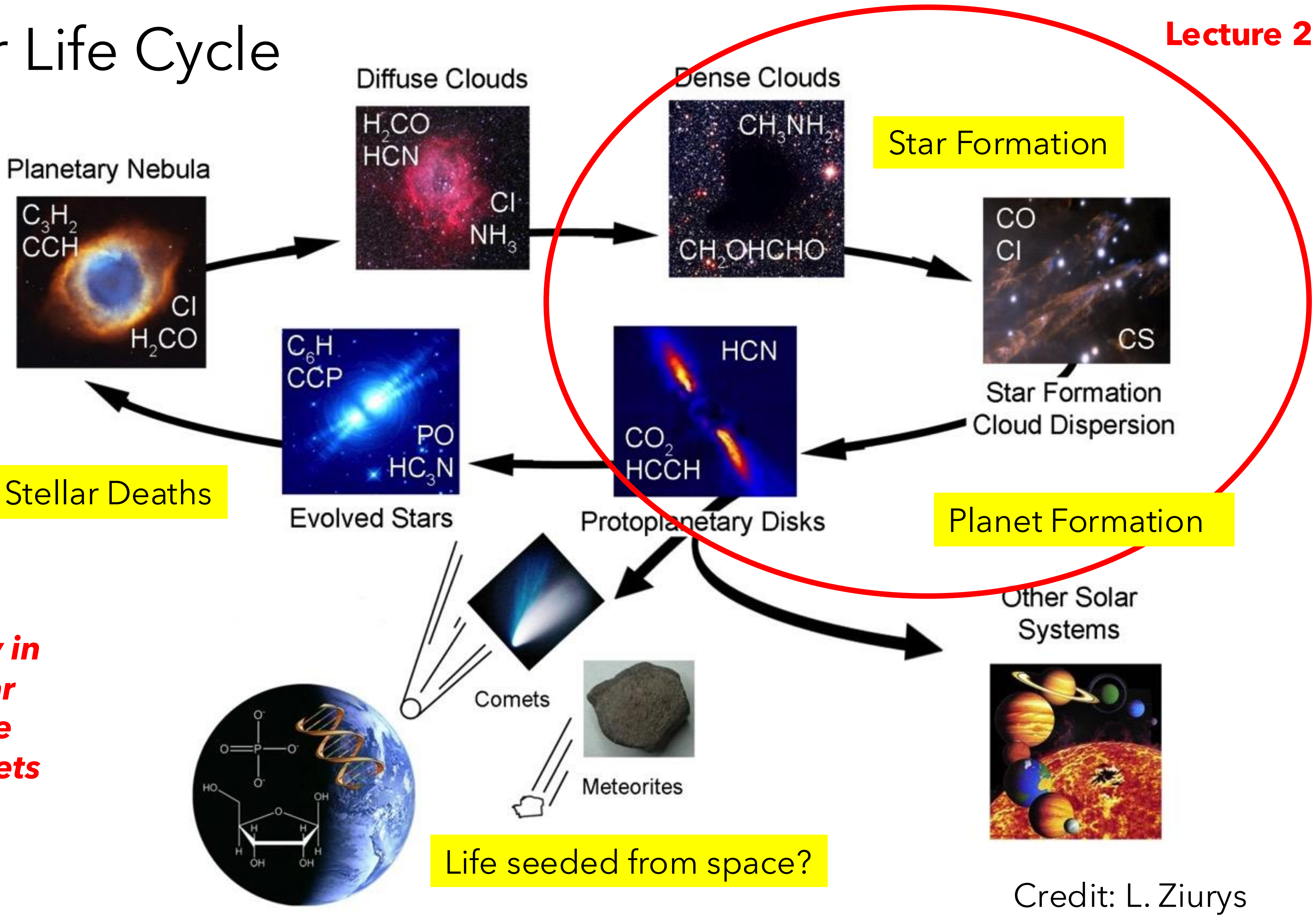
1) ELECTRONIC STATES
- electrons change levels
- energies in visible, UV

2) VIBRATIONAL STATES
- normal modes of nuclear motions
- occur in infrared region

3) ROTATIONAL STATES
- end-on-end motion of nuclei
- energies in microwave/millimeter-wave regions

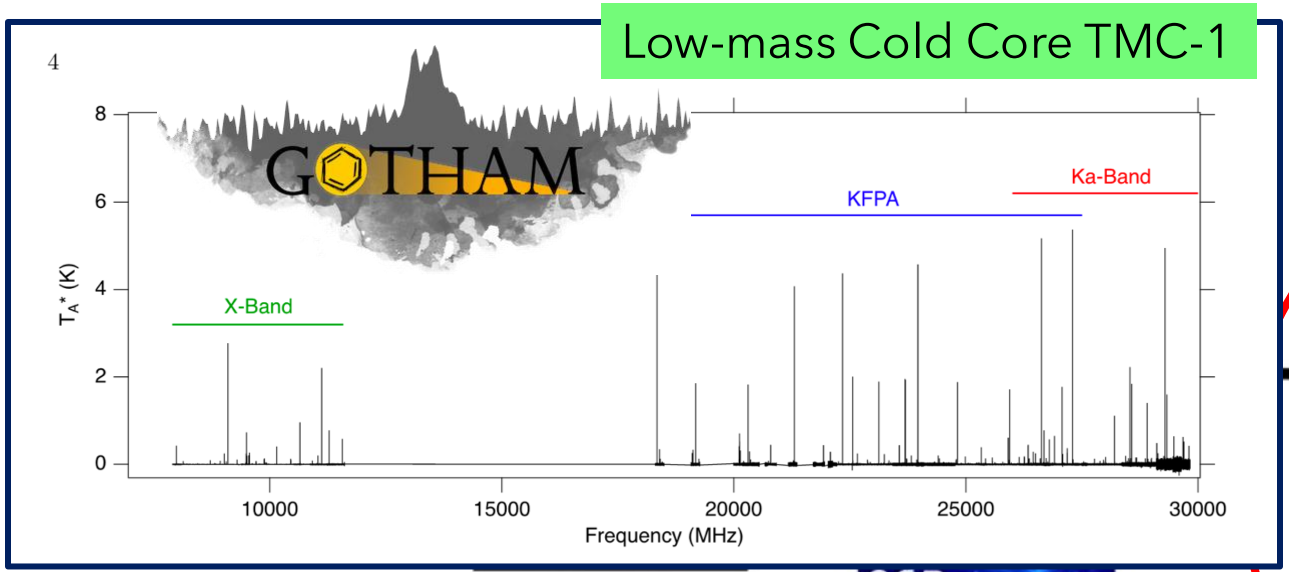
- *Electronic states have* ***vibrational/rotational structure***
- *Vibrational states have* ***rotational structure***

Molecular Life Cycle

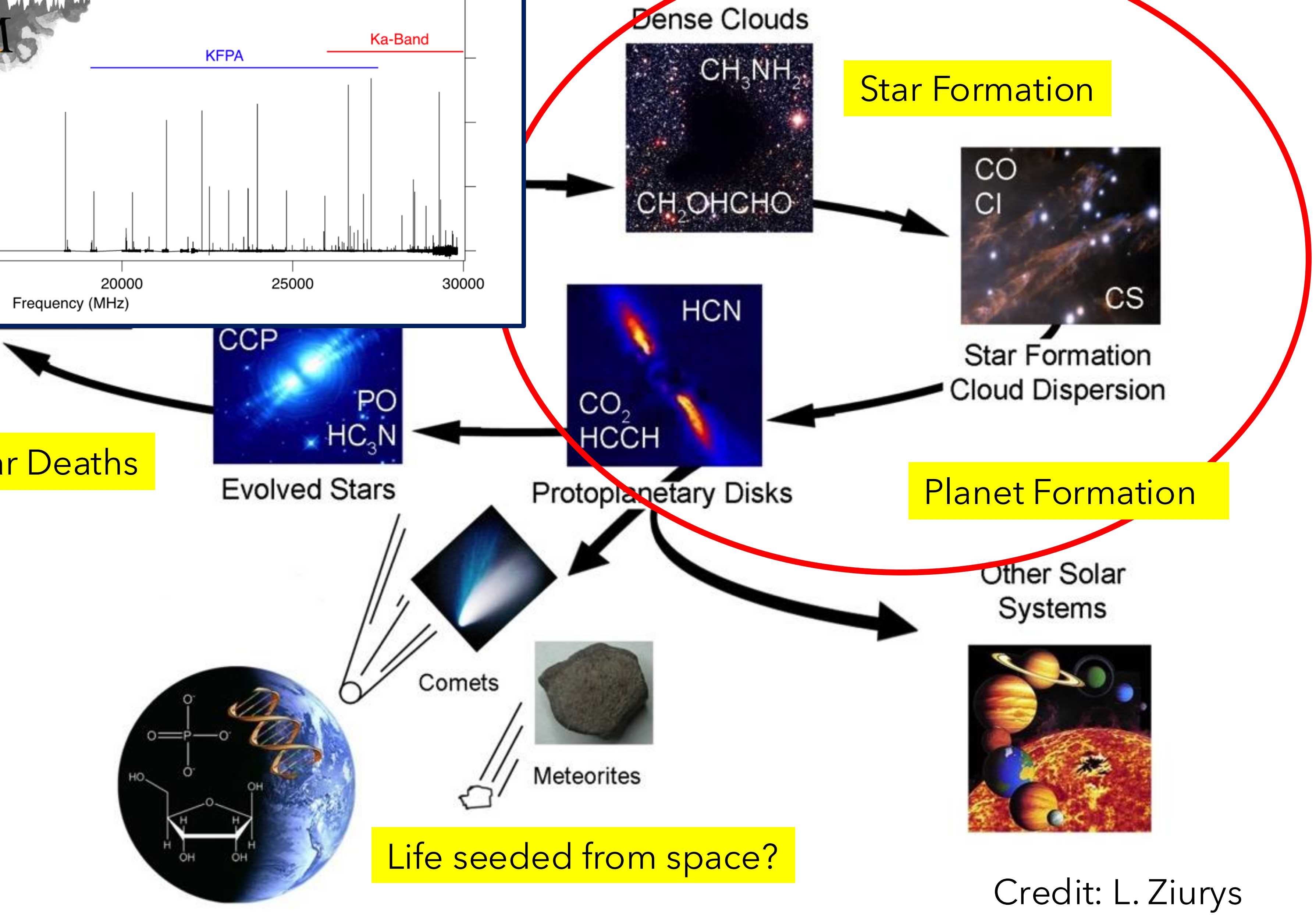


Rich chemistry in the molecular clouds where stars and planets form!

Credit: L. Ziurys

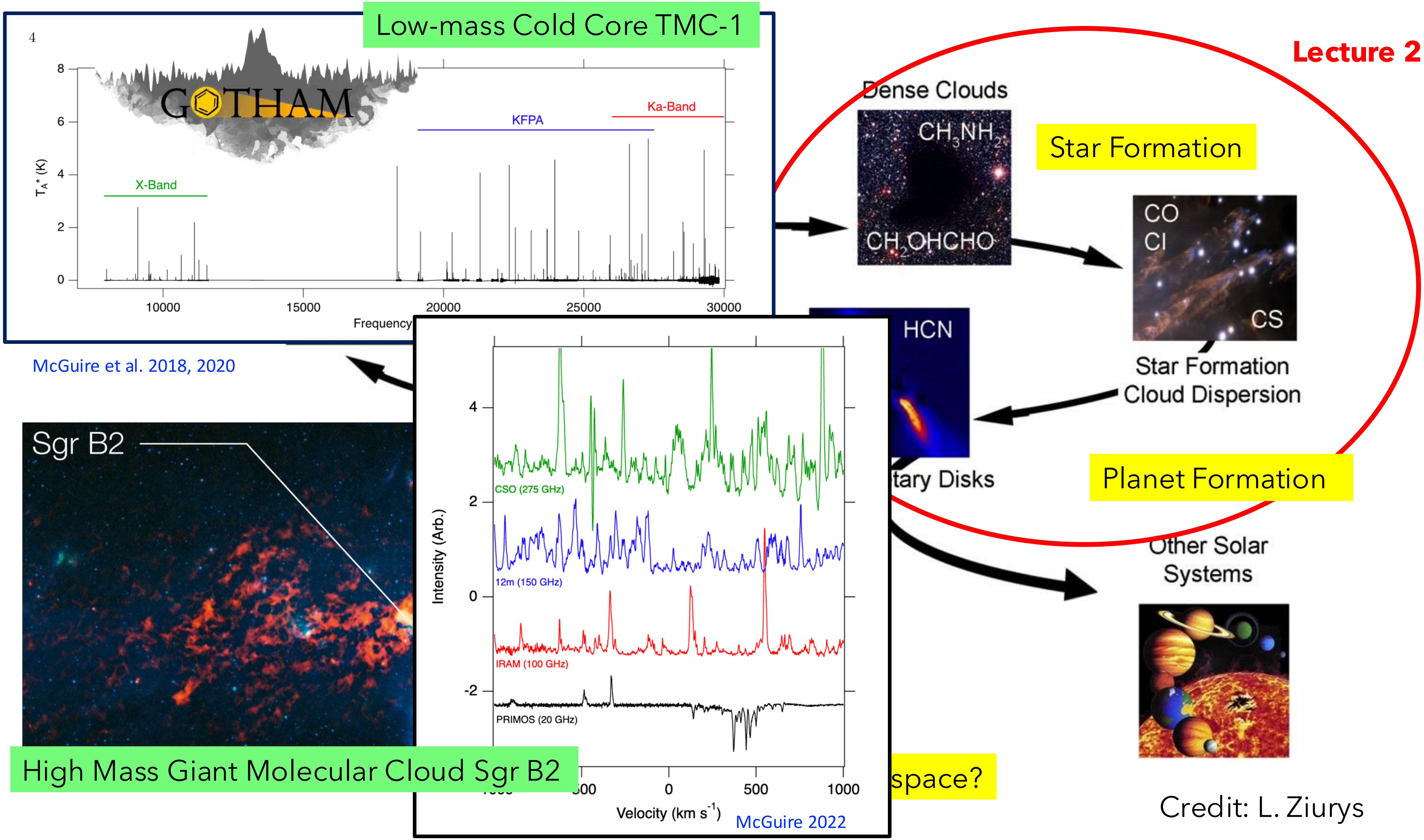


McGuire et al. 2018, 2020



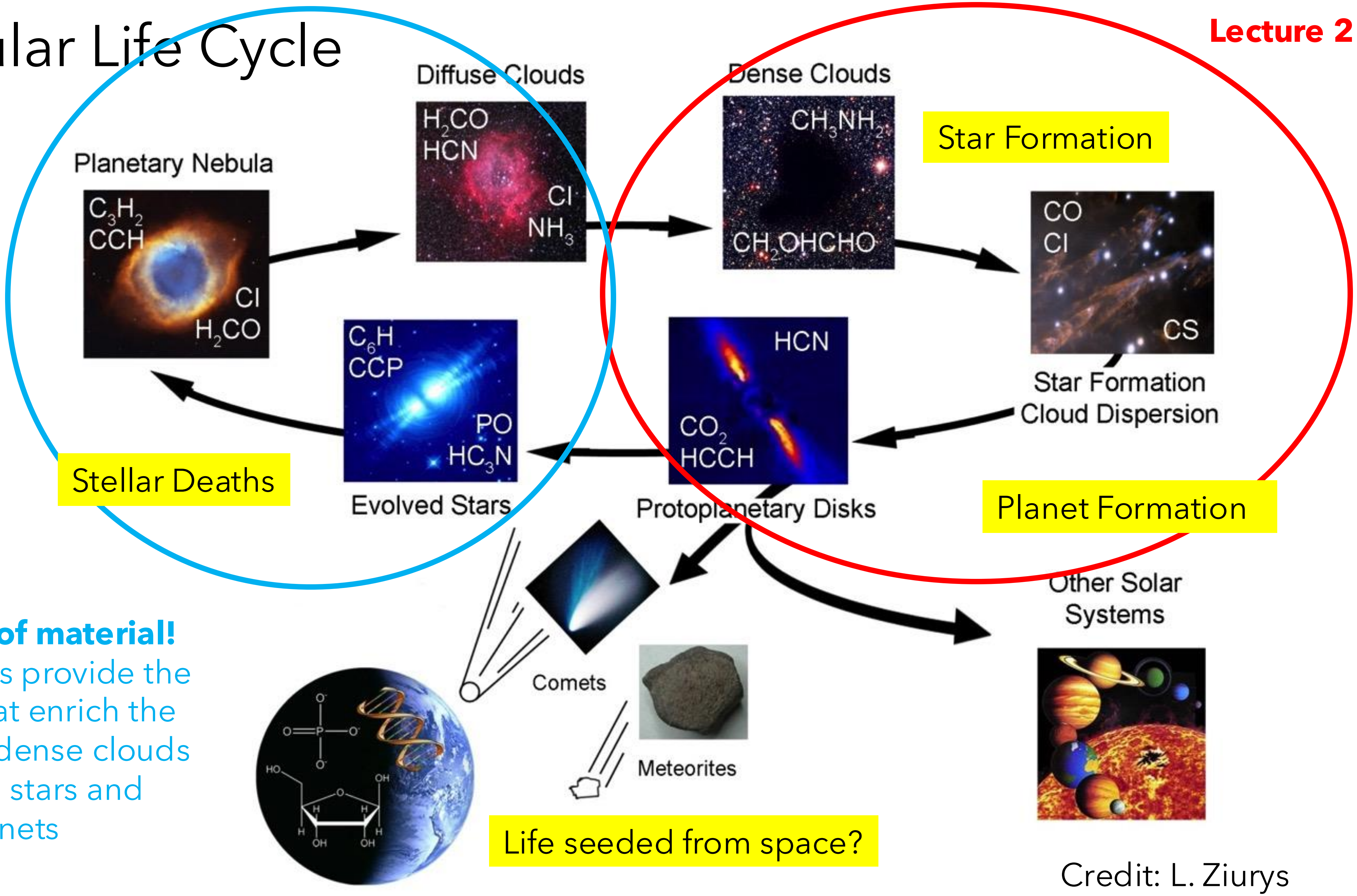
Rich chemistry in the molecular clouds where stars and planets form!

Credit: L. Ziurys


Low-mass Cold Core TMC-1
GOTHAM
X-Band
KFPA
Ka-Band
Frequency
McGuire et al. 2018, 2020
Lecture 2
Dense Clouds
CH3NH2
CH2OHCHO
Star Formation
CO
CI
CS
Star Formation
Cloud Dispersion
HCN
tary Disks
Planet Formation
Other Solar
Systems
Sgr B2
High Mass Giant Molecular Cloud Sgr B2
CSO (275 GHz)
12m (150 GHz)
IRAM (100 GHz)
PRIMOS (20 GHz)
Intensity (Arb.)
Velocity (km s-1)
McGuire 2022
space?
Credit: L. Ziurys

Molecular Life Cycle

Lecture 3

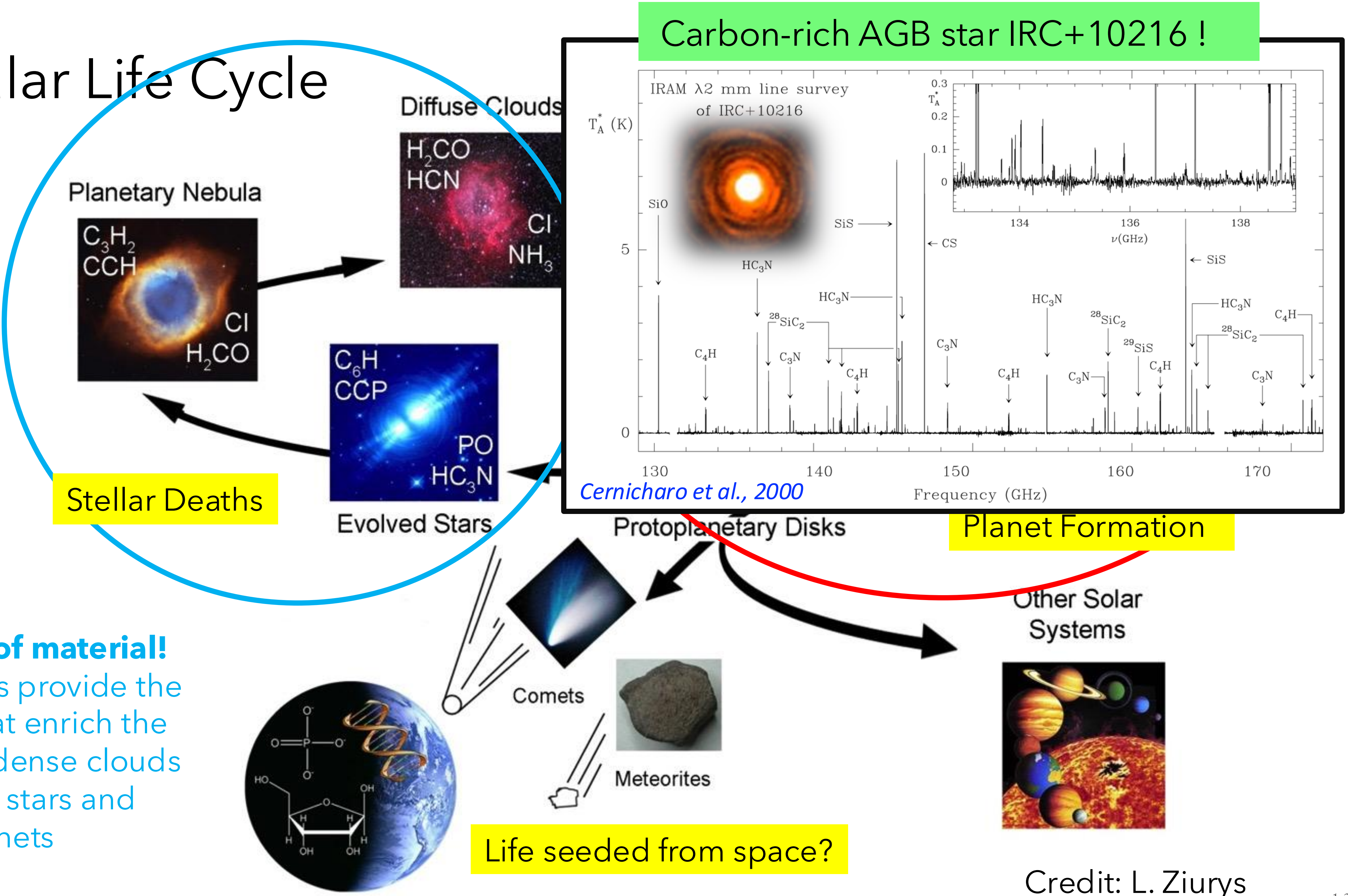


Recycling of material!
Evolved stars provide the material that enrich the diffuse and dense clouds that form stars and planets

Credit: L. Ziurys

Molecular Life Cycle

Lecture 3



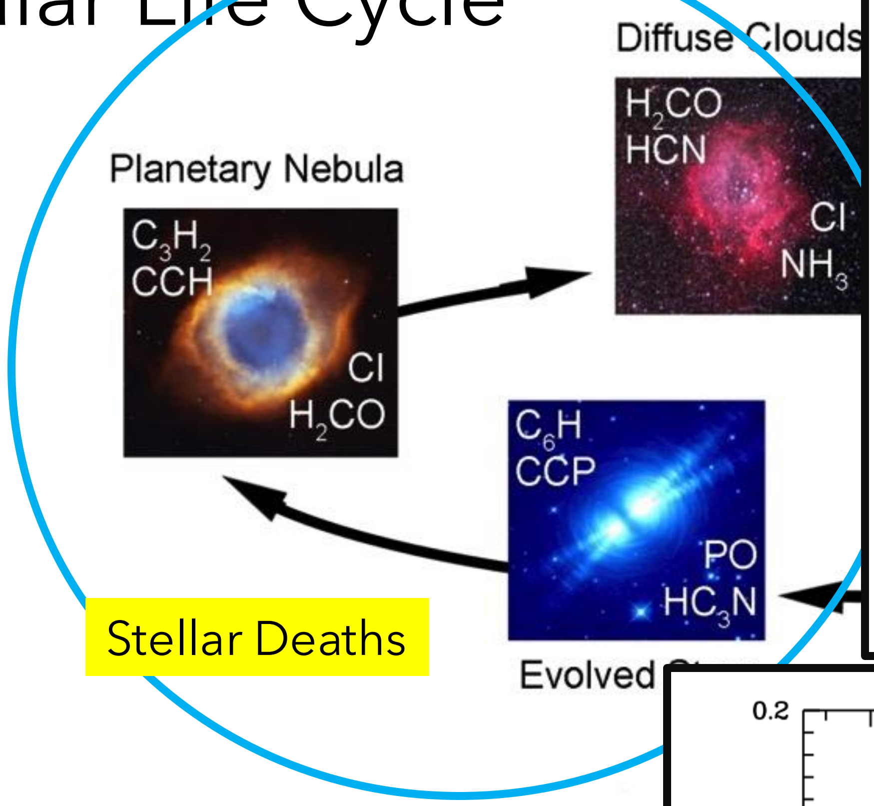
Recycling of material!

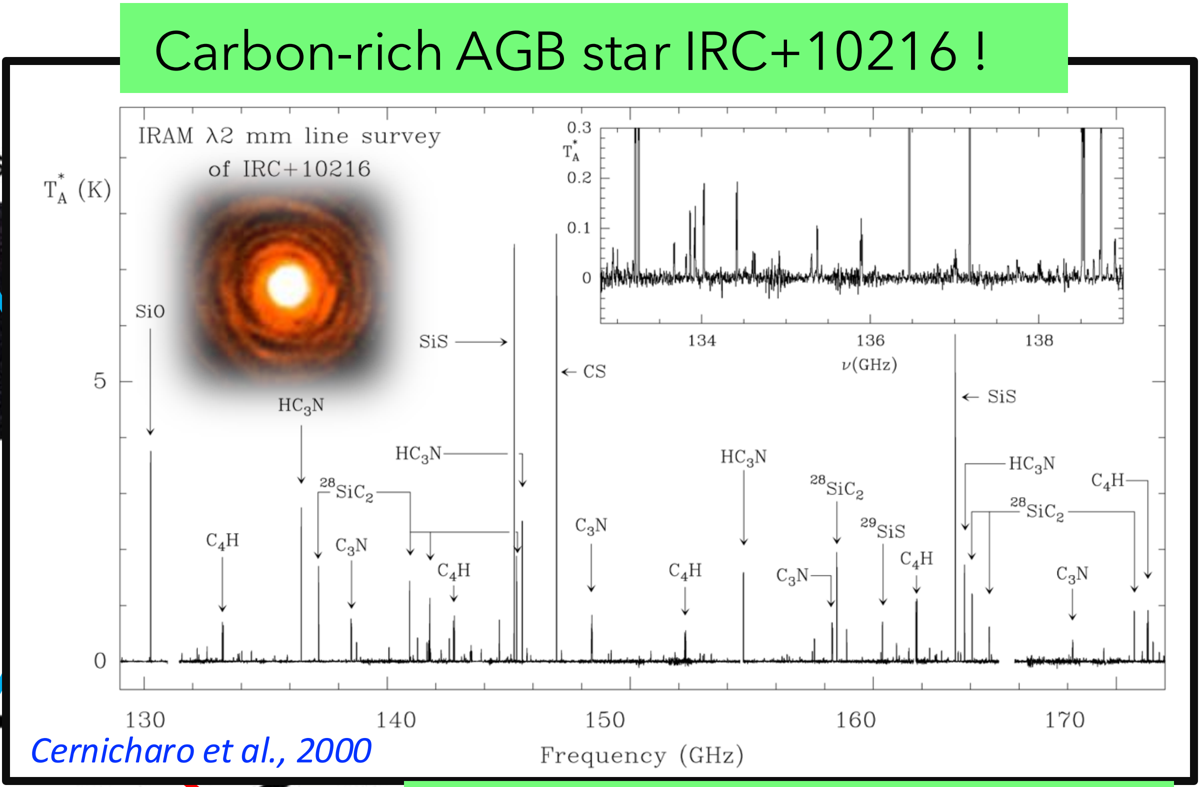
Evolved stars provide the material that enrich the diffuse and dense clouds that form stars and planets

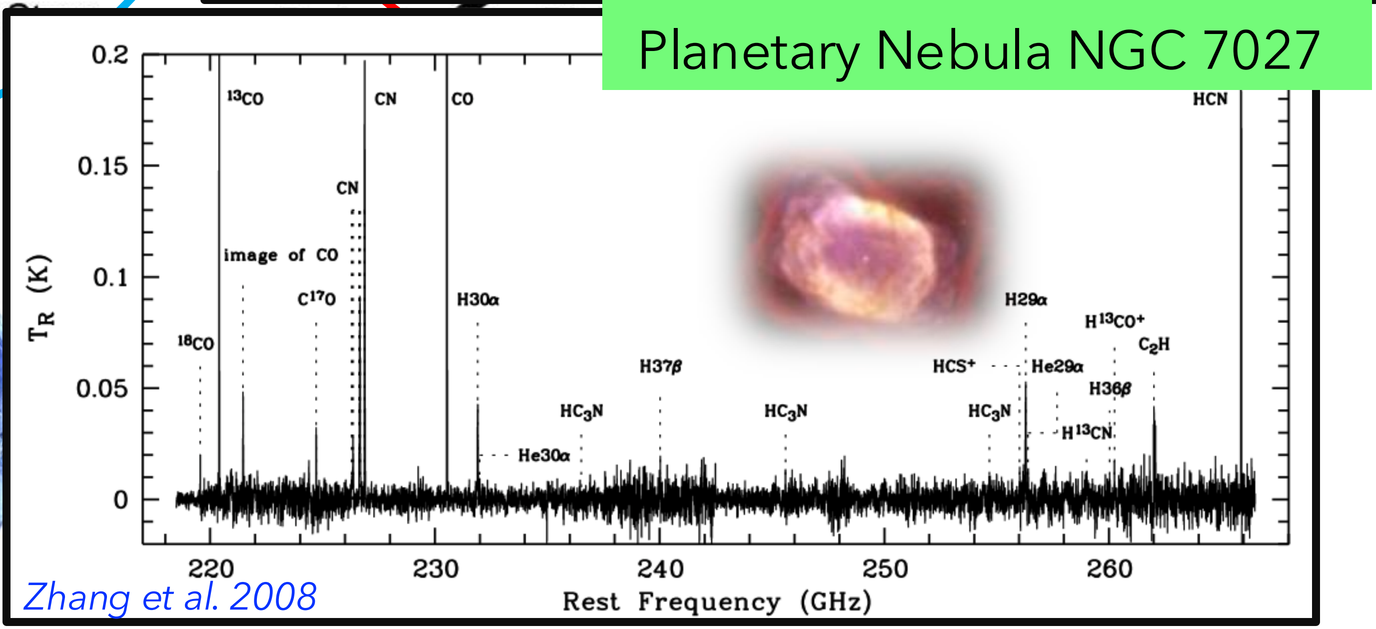
Credit: L. Ziurys

Molecular Life Cycle

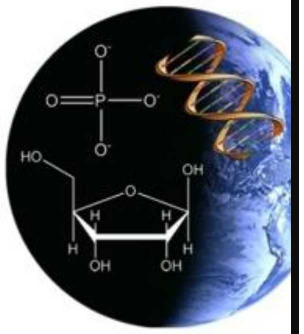
Lecture 3



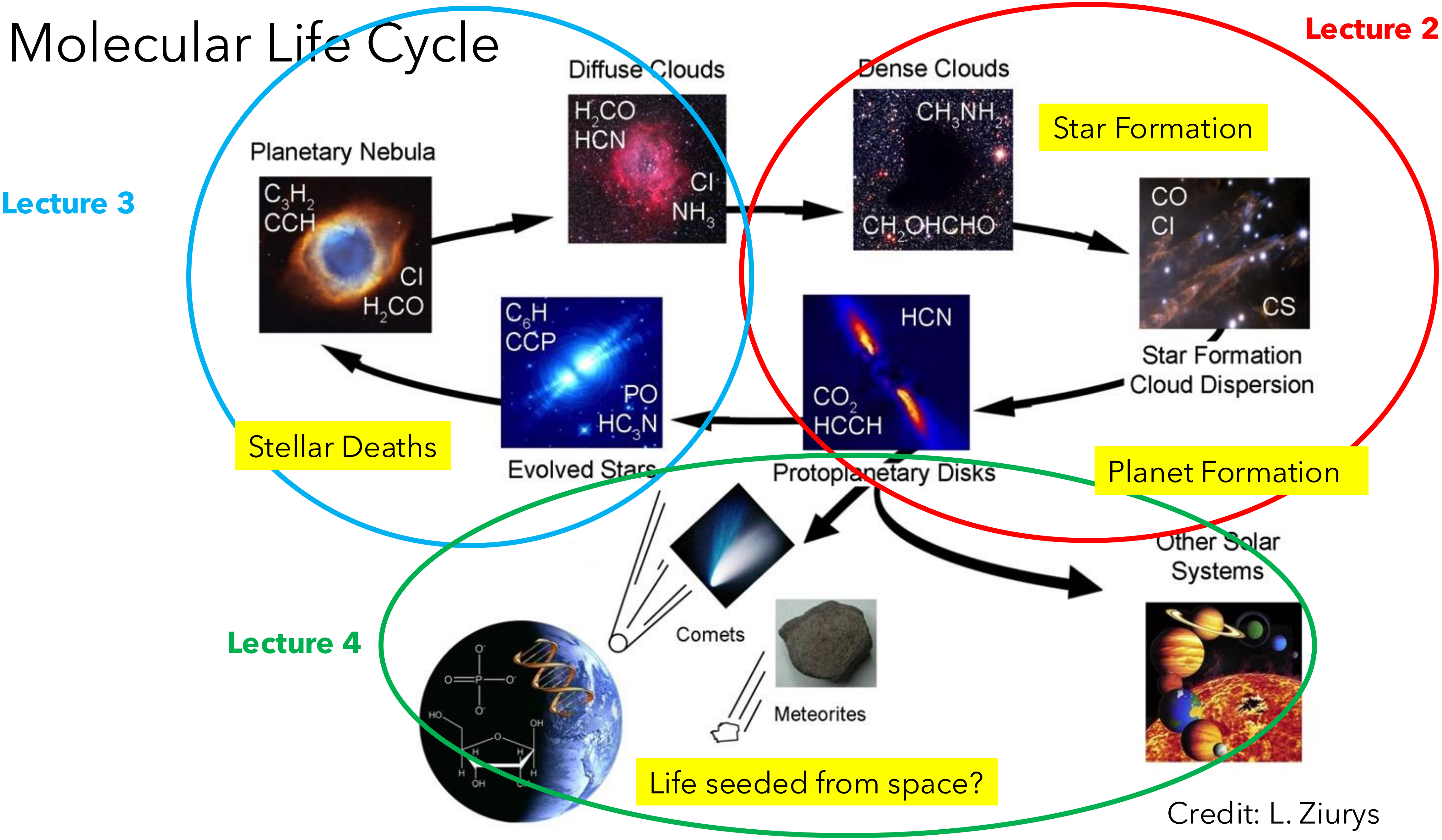




Recycling of material!
Evolved stars provide the material that enrich the diffuse and dense clouds that form stars and planets



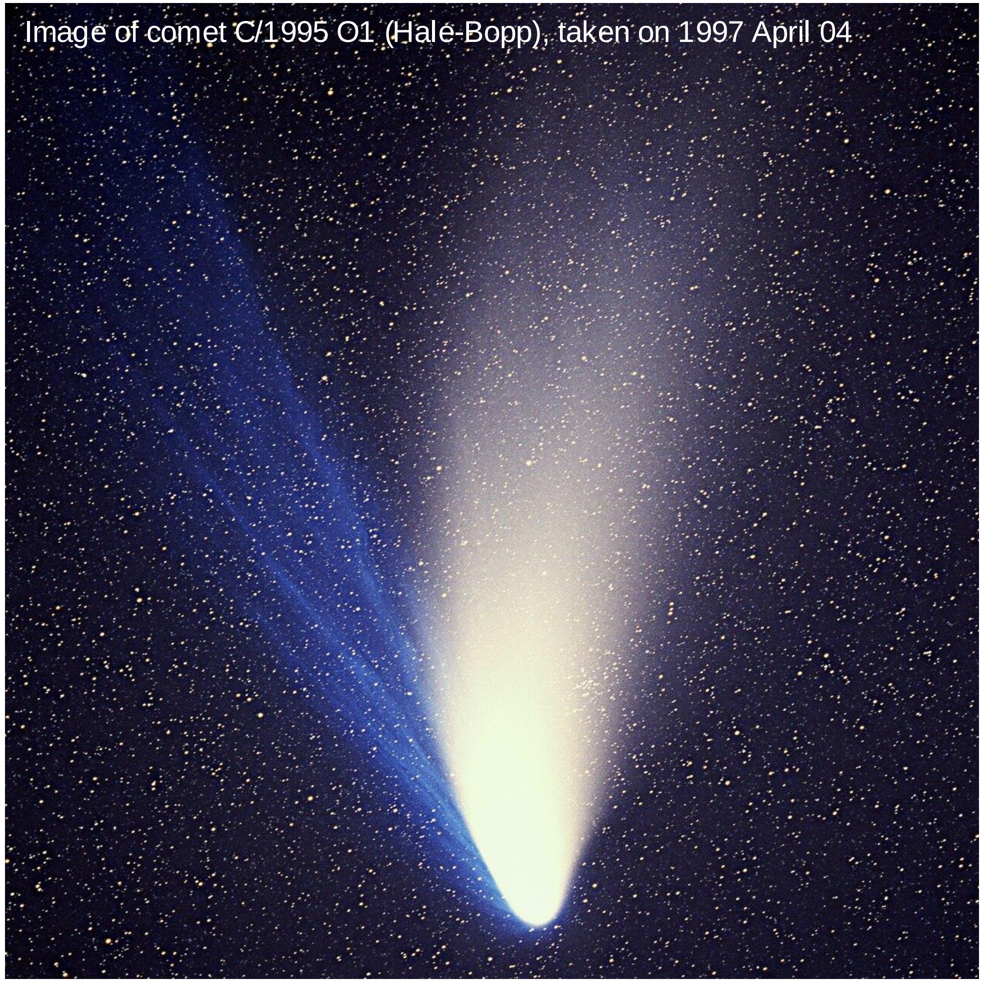
Molecular Life Cycle



Credit: L. Ziurys

Comets – Structure and Composition

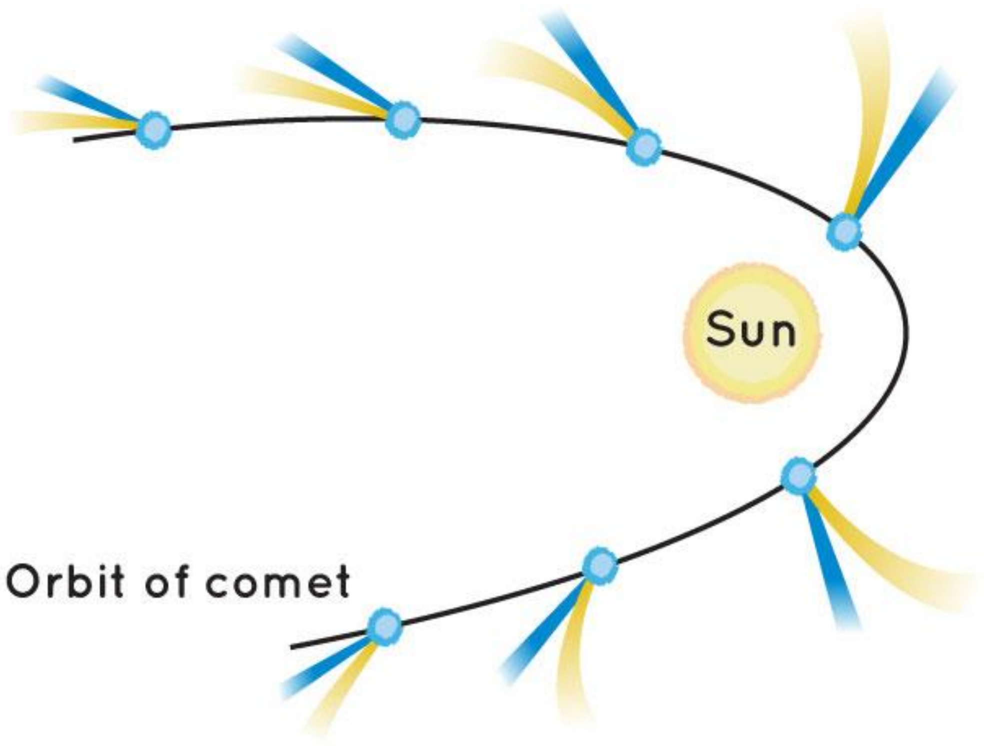
- Small, fragile, irregularly shaped bodies
- Composed of mixture of non-volatile grains and frozen gases
- Structures diverse and dynamic
- Over half the material is **ICE**
- A "dirty iceberg" or "dirty snowball”



Credit: L. Ziurys

Comets – Structure and Composition

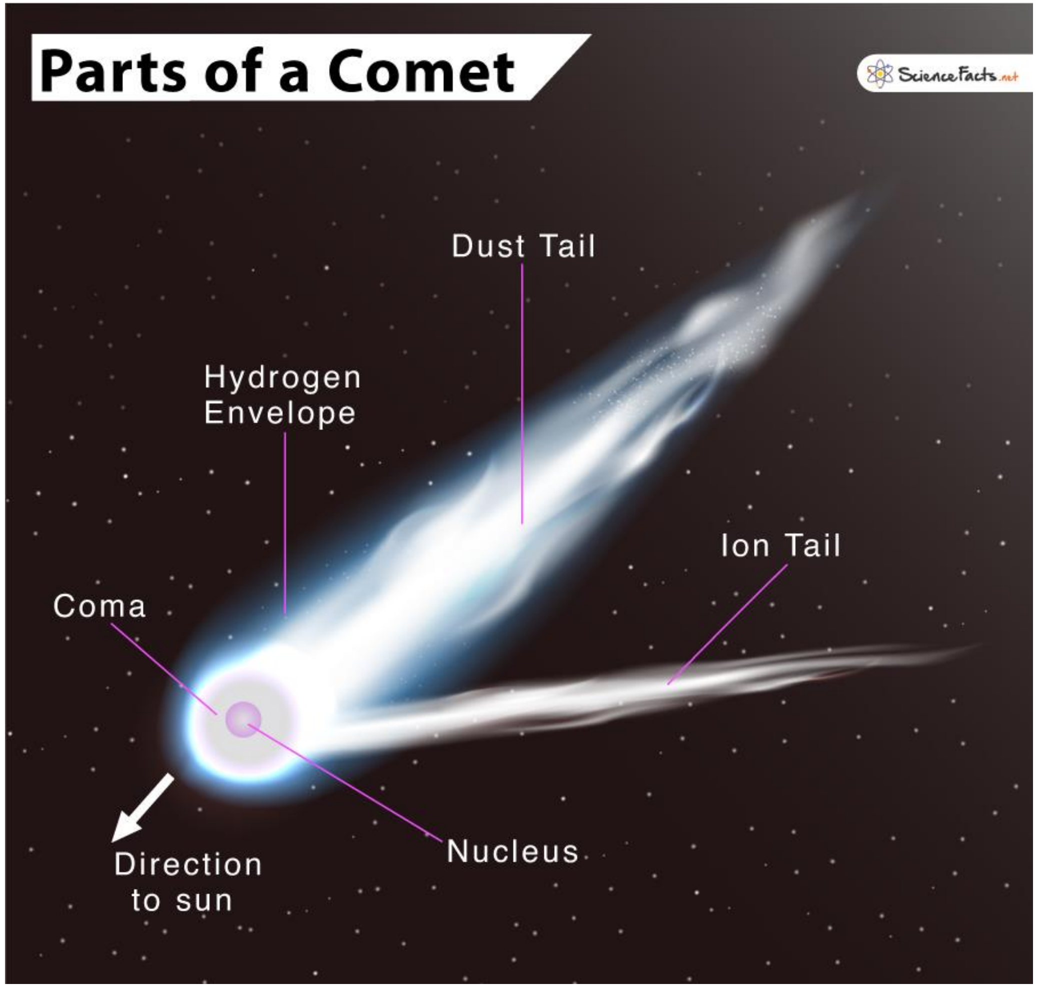
- Highly elliptical orbits: bring them very close to **Sun**
- As approach Sun, comets develop enormous tails of luminous material → Called a ***coma***
- Extend for ***millions of kilometers*** from head
- Usually grows in size and brightness near sun
- Seen by reflected sunlight
- As coma develops, **dust reflects more sunlight**
- Direction: away from the Sun
- When far from Sun: nucleus is cold/ frozen solid



Credit: L. Ziurys

Comets – Structure and Composition

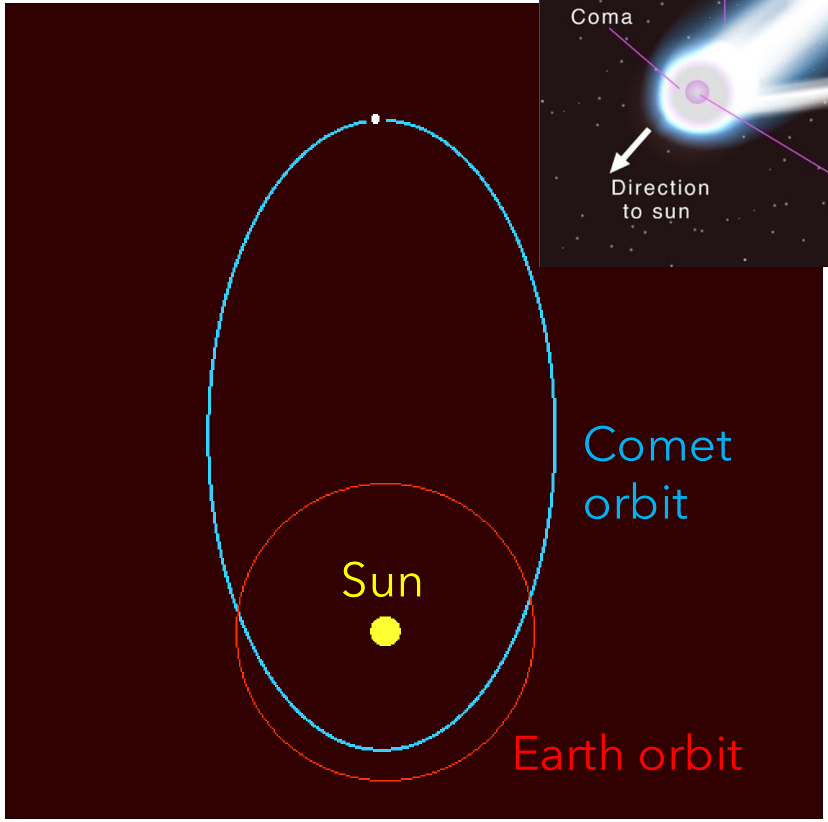
- Gas in coma absorbs ultraviolet radiation and begins to fluoresce
  - At ~ 5 AU from the Sun, fluorescence usually more intense than reflected light.
  - As comet absorbs **UV**, chemical processes release ***hydrogen***
- Forms *hydrogen envelope* (not seen from Earth as the emission absorbed by atmosphere, instead detected by spacecraft)
- Small, bright nucleus (less than 10 km in diameter) visible in middle of coma
- Coma and the nucleus together constitute head of comet

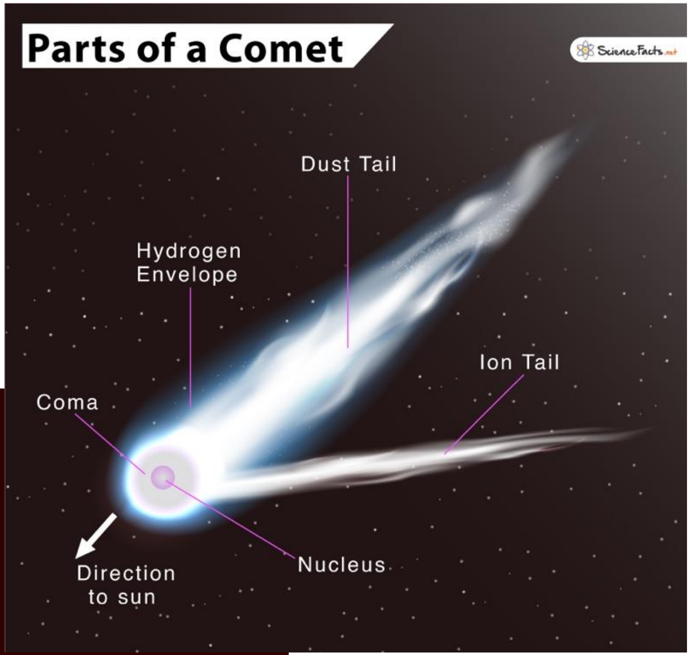


Credit: L. Ziurys

Comets – Structure and Composition

- Sun's radiation pressure and solar wind accelerate materials
- Pushed **away from comet head**
- Acceleration depends on **the size/mass** of materials
- Massive dust tails accelerated slowly; thus **curved**
- Ion tail is much less massive: accelerated greatly
- **Nearly straight line** extending away from Sun
- Can be swung deeply into space, often beyond orbit of Pluto



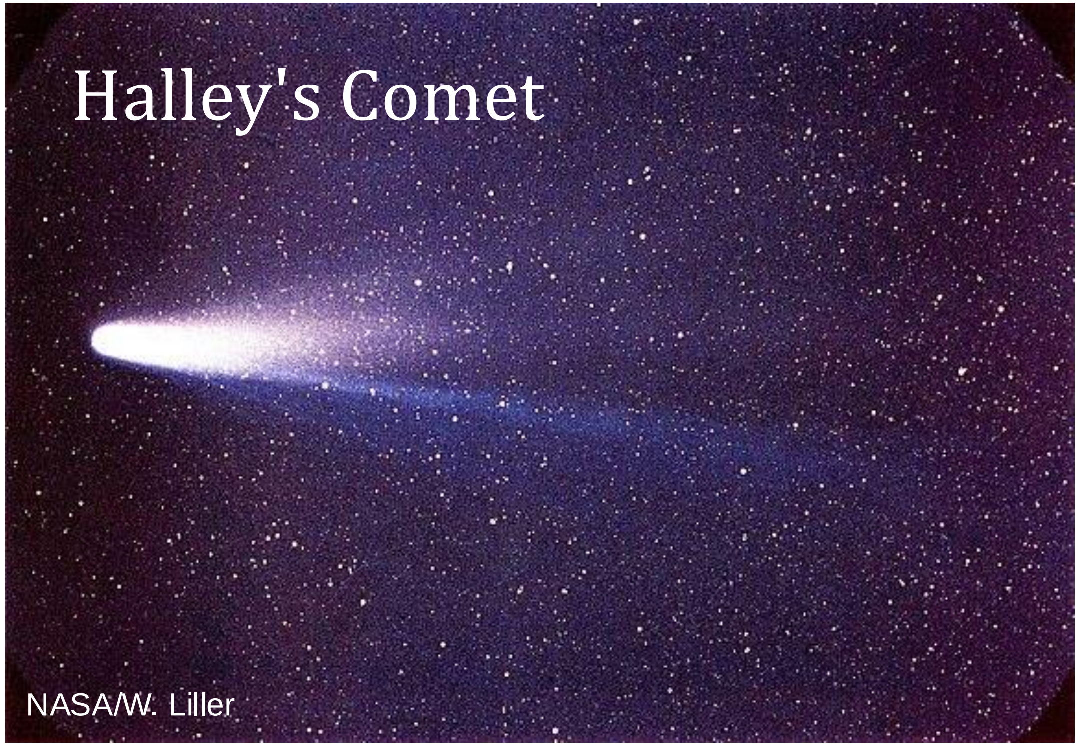


Credit: L. Ziurys

Comet Origins: **Short Period**

- Two types of comets
  - ***Short Period*** and ***Long Period***

- **Short Period Comets**
  - Arise in the **Kuiper Belt** (Kuiper-Belt objects)
  - Region with icy bodies around Neptune's orbit
    - ⇒ 50 AU from sun
    - ⇒ over 1,000 KBO's
  - Full orbit around sun and back: 200 yrs.
  - Travel in **plane of solar system**
  - Routinely reappear
  - Typical example: Halley's Comet
  - ***Processed*** material



Credit: L. Ziurys

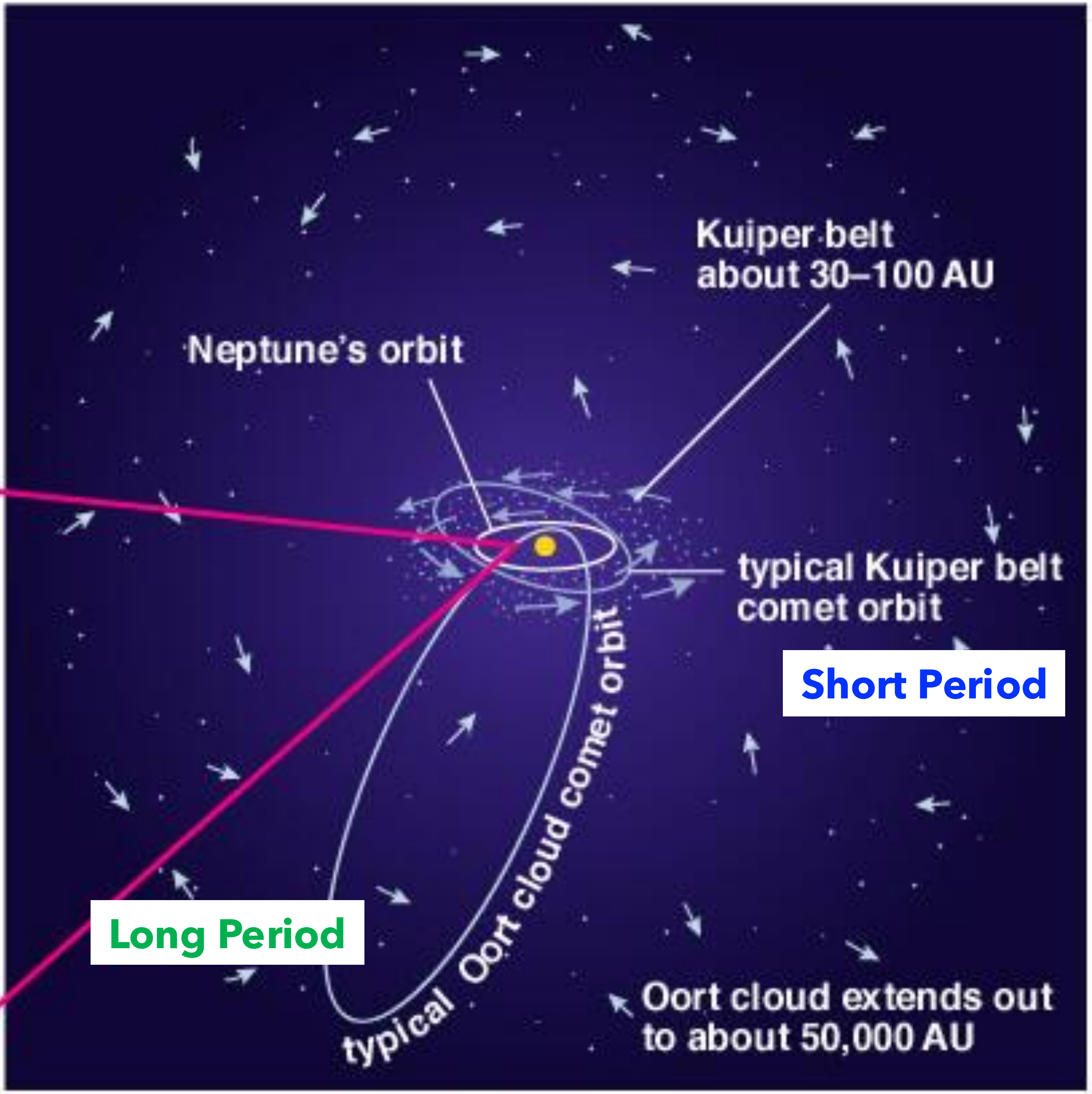
Comet Origins: **Long Period**

- **Long Period Comets**
  - Originate in **Oort Cloud**
  - Immense spherical cloud surrounding Solar System
  - Remnant **molecular cloud**
  - Extends 18 trillion miles from Sun (100,000 AU)
  - Edge of Solar System: sun's gravitational influence ends
  - Contains **billions of icy bodies** in solar orbit
- Passing stars disturb orbit of a given body in Oort cloud
  - creates a long period comet
  - such comets weakly bound to sun
  - often only appear once
    - 4,000 yrs. to 30 million yrs.
  - Orbits **perpendicular** to Plane of ecliptic
  - Hale-Bopp a good example
  - Represent ***Pristine*** Material

Credit: L. Ziurys

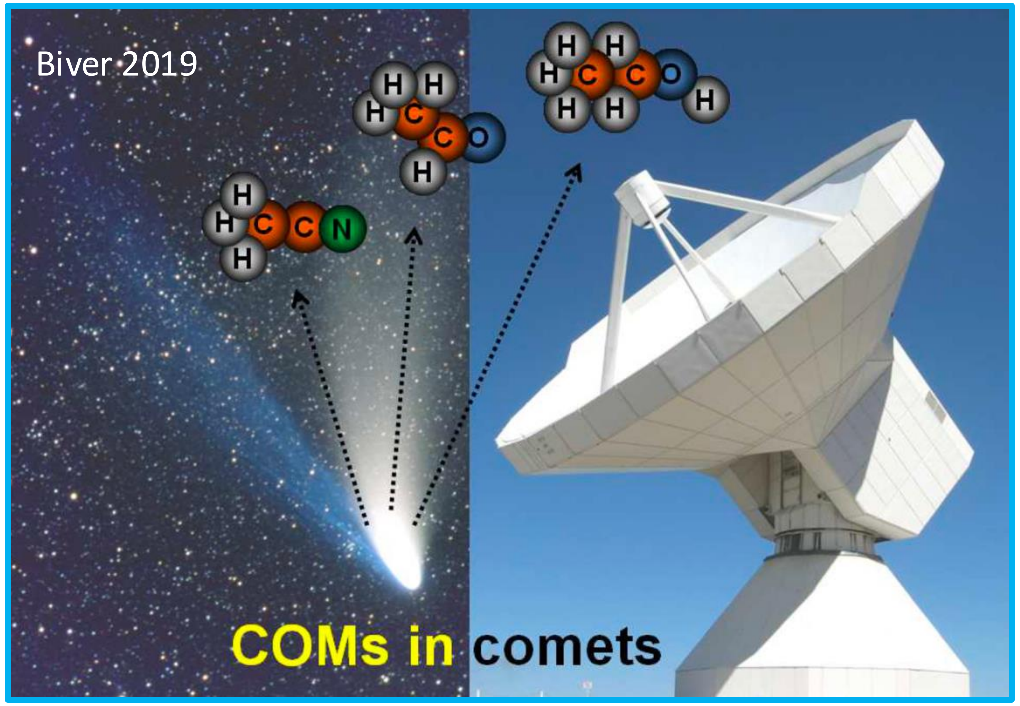
Comet Origins

Oort Cloud:
Contains **pristine** material of original Molecular Cloud!



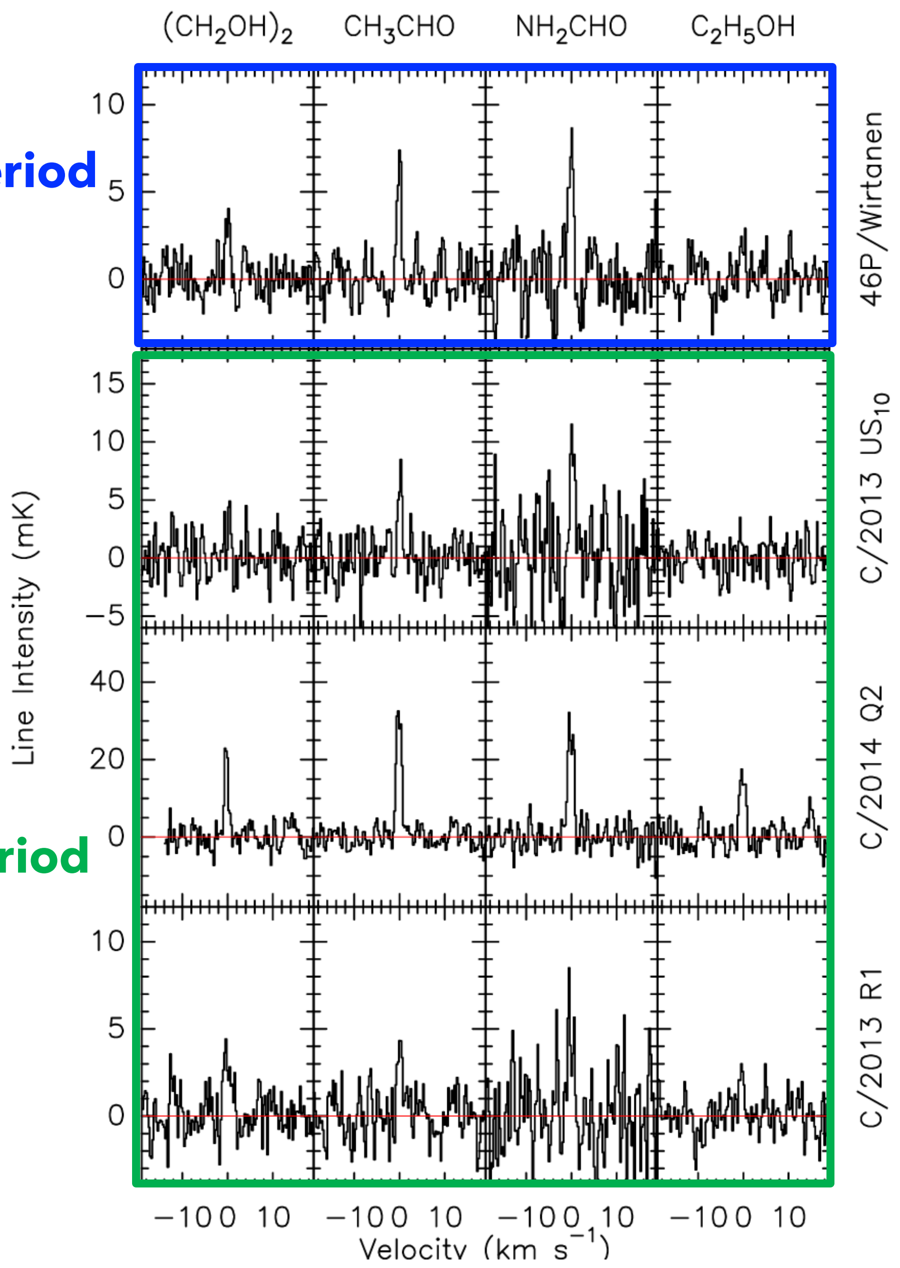
Complex Comet Chemistry!

Rotational spectra of the complex organic molecules (COMs) ethylene glycol, $(CH_2OH)_2$, acetaldehyde, CH_3CHO, formamide, NH_2CHO, and ethanol, C_2H_5OH, obtained from IRAM 30m radio telescope observations of various comets →



Short-period

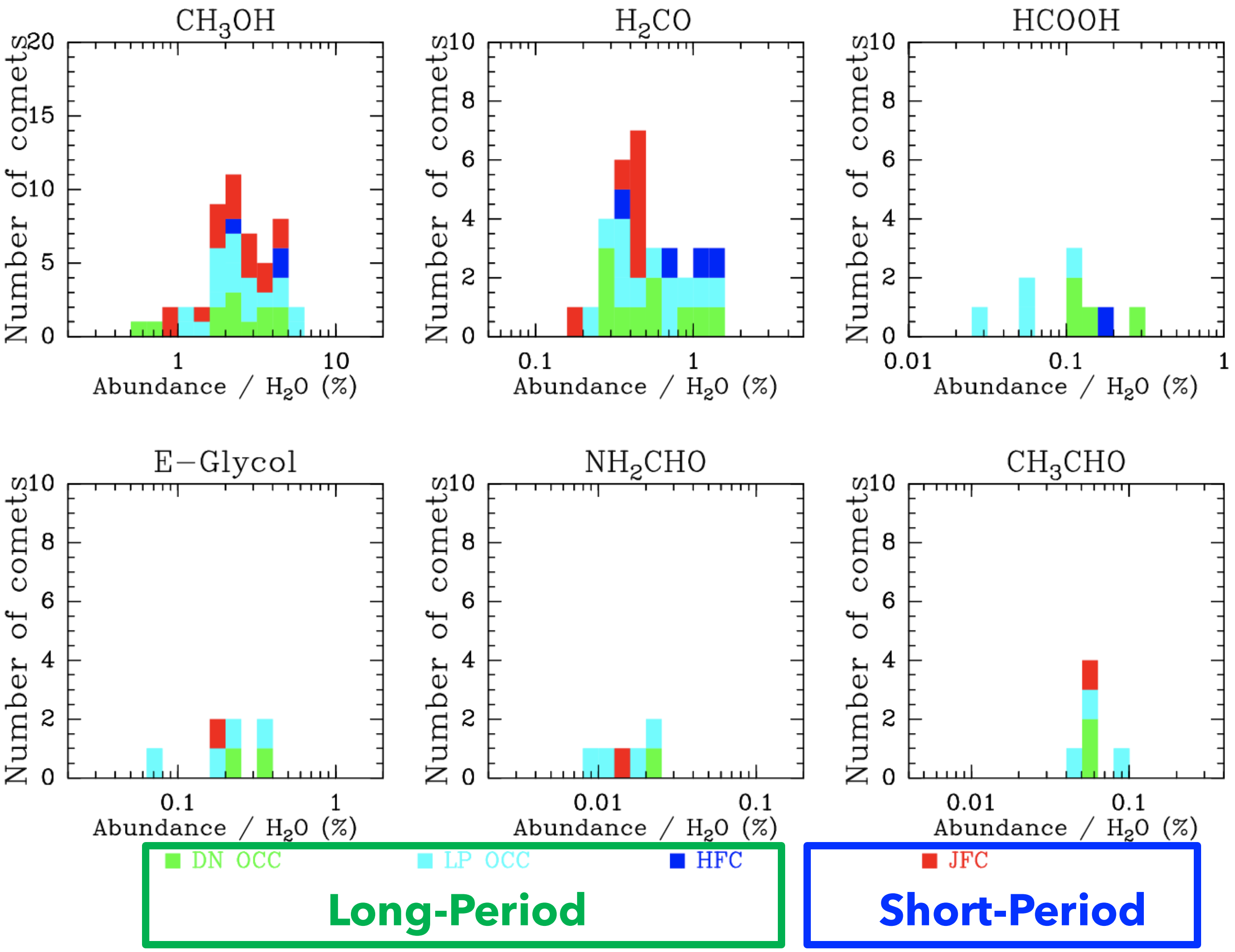
Long-period



Complex Comet Chemistry!

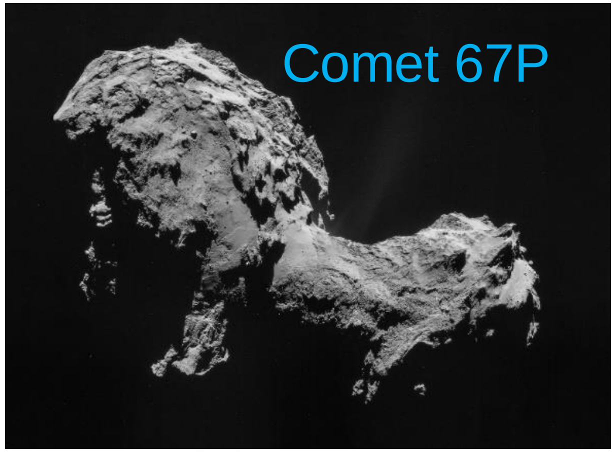
Biver 2019

- Abundances in comets measured as production rates with respect to water, H_2O
- Histogram shows the distribution of the abundance relative to water of several COMS detected in more than 6 comets.
- The scatter in abundances (relative to water or methanol) of the COMs is less than one order of magnitude and the abundances do not seem to depend on the dynamical family (long-period Oort cloud comets, OCC, or short-period Jupiter family comets, JFC) of the comet



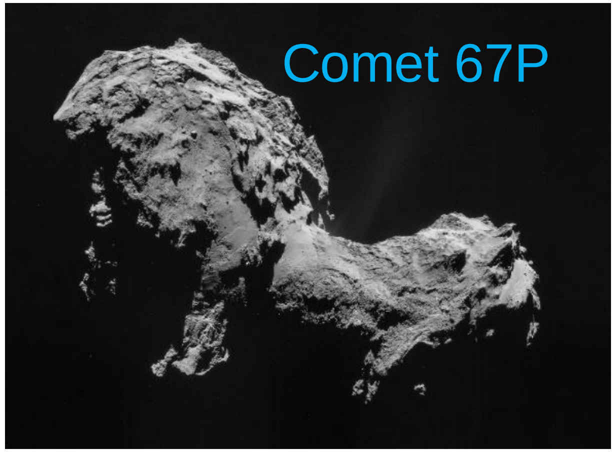
Complex Comet Chemistry!
Special Case: the Rosetta Mission to JFC 67P

- **Rosetta Mission:** Mission to the Jupiter Family Comet (JFC) **67P/Churyumov-Gerasimenko, or 67P**
- Launched in March 2004 and made a 10-year journey across the solar system to arrive at its target in 2014



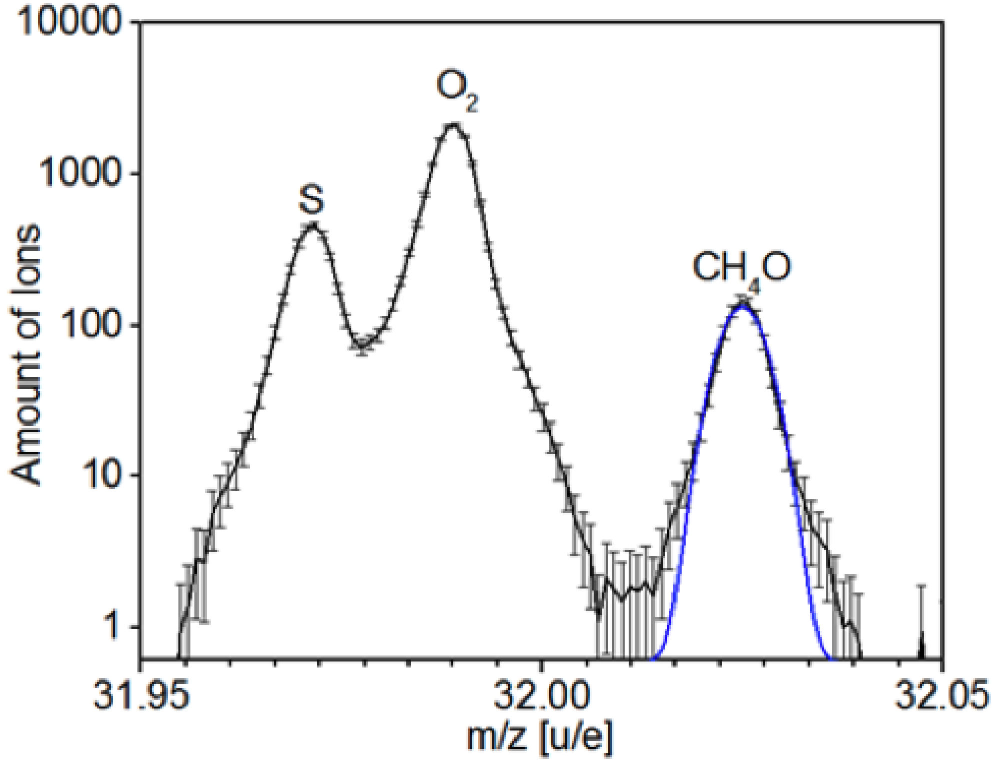
Complex Comet Chemistry!
Special Case: the Rosetta Mission to JFC 67P

- **Rosetta Mission:** Mission to the Jupiter Family Comet (JFC) **67P/Churyumov-Gerasimenko, or 67P**
- Launched in March 2004 and made a 10-year journey across the solar system to arrive at its target in 2014
- **Philae lander:** Spacecraft landed on **Comet Nucleus**
- Philae lander carried mass spectrometer called ROSINA
    - Measured spectrum of comet 'dust'
    - First detailed, *in situ* **measurements of the chemical composition of a comet's atmosphere, or coma**
    - Analyses the various isotopes of atoms such as xenon and rare organic molecules, including sulfur-containing compounds



Complex Comet Chemistry!
Special Case: the Rosetta Mission to JFC 67P

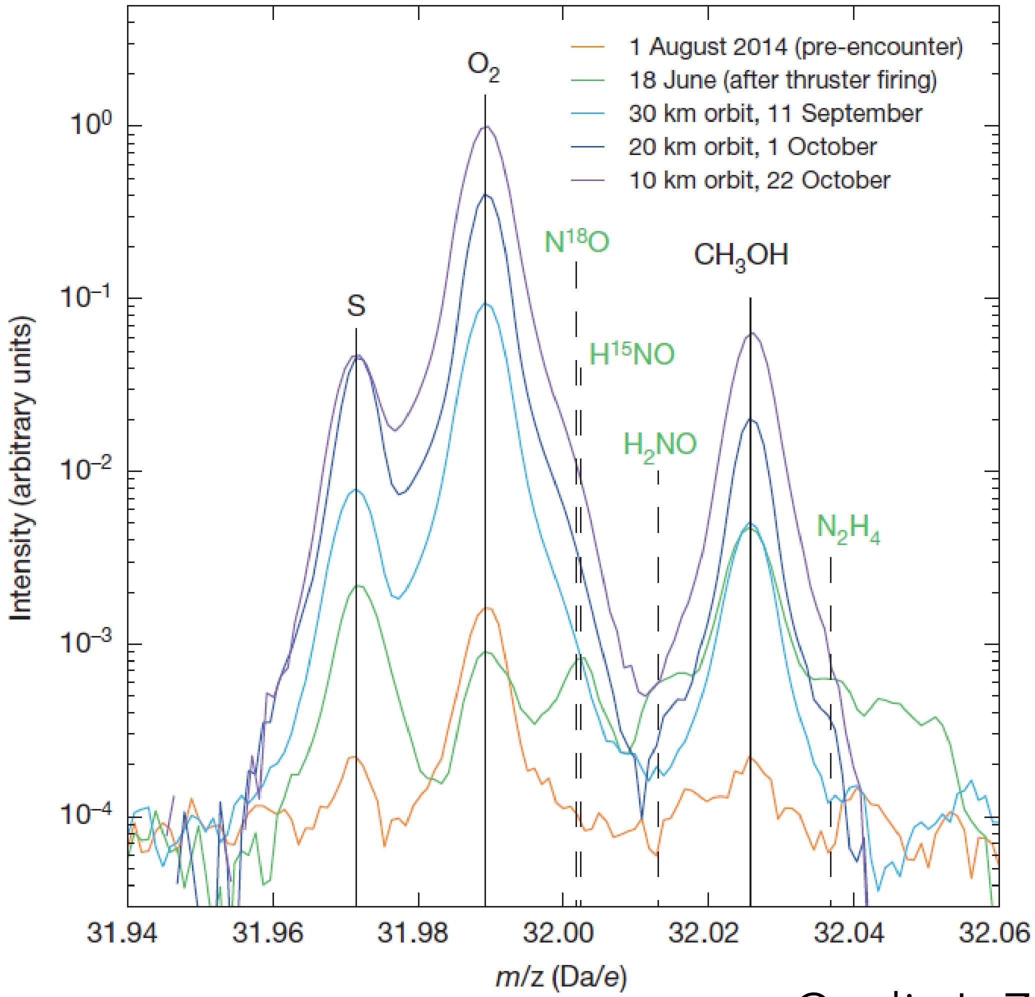
- Mass spectrometer called ROSINA – Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
- Double Focusing Mass Spectrometer (DFMS) designed to detect the cometary volatiles originating from both the cometary bulk material and the ejected particle
  - Uses electron impact ionization to ionize very low energy cometary molecules
  - **Molecules separated according to their mass-to-charge ratios (m/z)**
- Lots of O_2 – never detected before in comets!



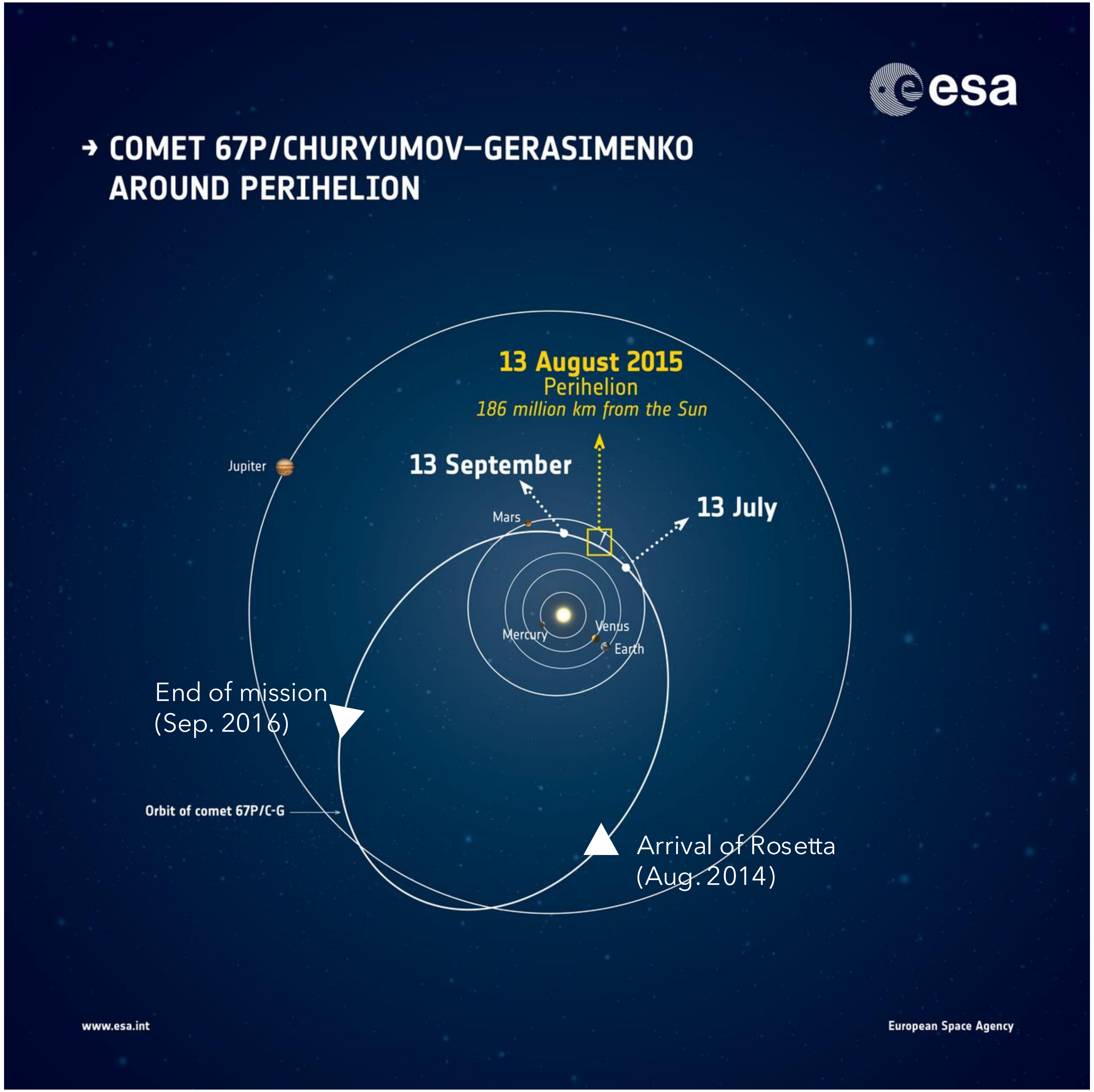
Schuhmann et al., 2019

Complex Comet Chemistry!
Special Case: the Rosetta Mission to JFC 67P

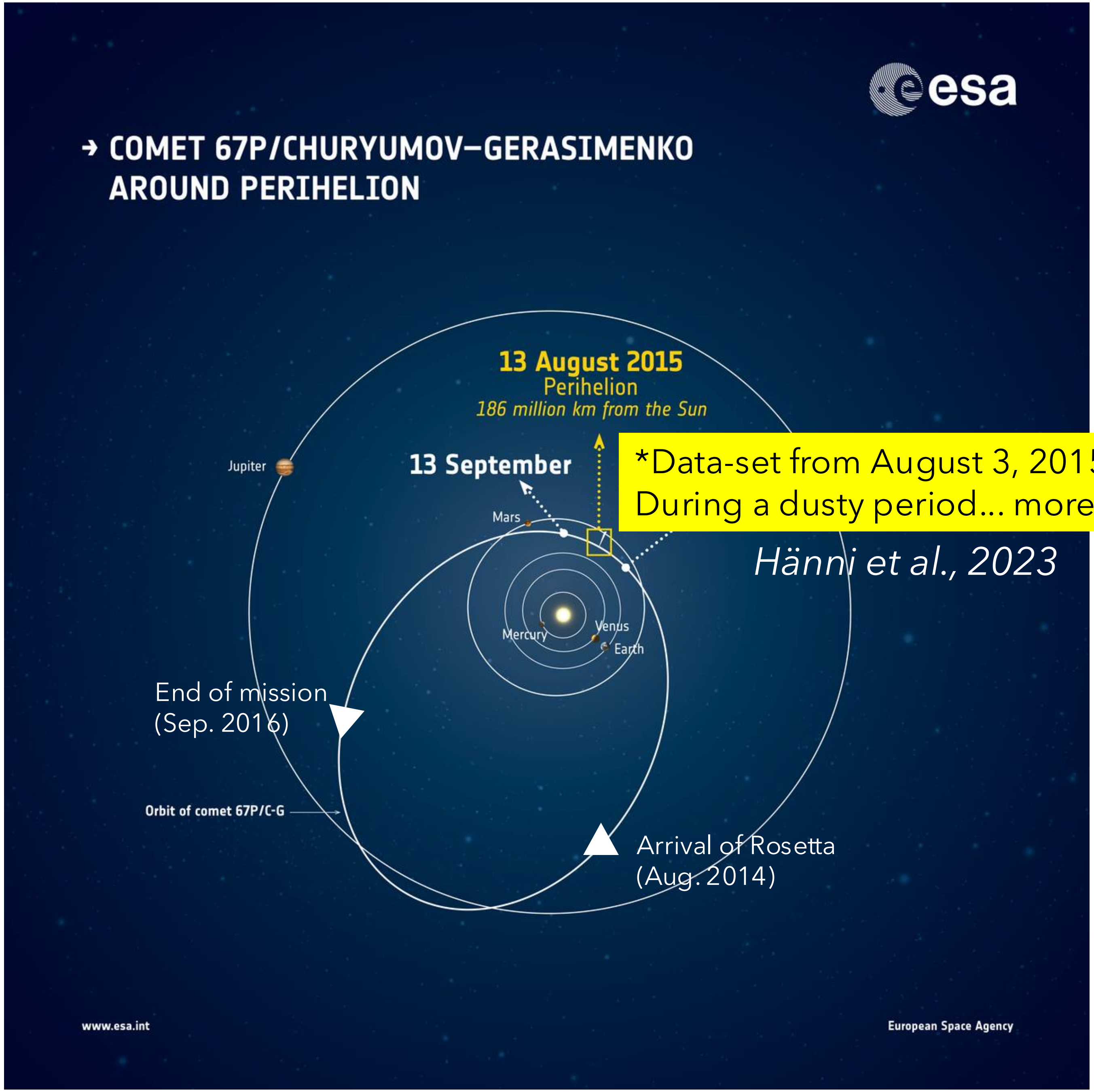
- Mass spectrometer called ROSINA – Rosetta Orbiter Spectrometer for Ion and Neutral Analysis
- Double Focusing Mass Spectrometer (DFMS) designed to detect the cometary volatiles originating from both the cometary bulk material and the ejected particle
    - Uses electron impact ionization to ionize very low energy cometary molecules
    - **Molecules separated according to their mass-to-charge ratios (m/z)**
- Lots of O_2 – never detected before in comets!
    - Dynamical → Closer to the sun enhanced desorption of species



Credit: L. Ziurys



landru79 on Twitter/European Space Agency



*Data-set from August 3, 2015
During a dusty period… more complex molecules!

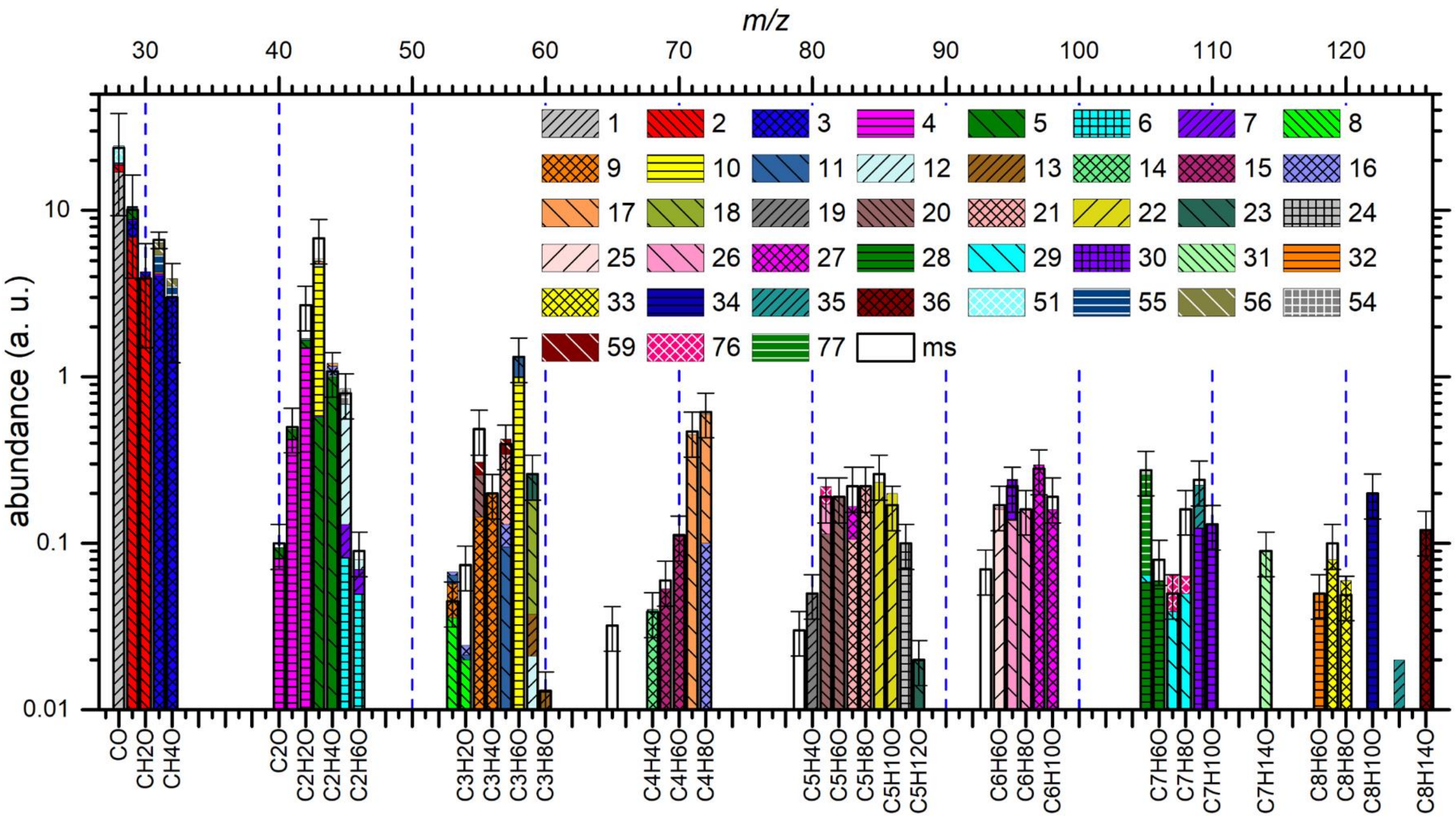
Hänni et al., 2023

landru79 on Twitter/European Space Agency

Complex Comet Chemistry!

Special Case: the Rosetta Mission to JFC 67P

- Double Focusing Mass Spectrometer (DFMS) technique again used, sorting molecules by their **mass-to-charge ratios (m/z)**
- This new study derive a minimum of 63 $C_nH_mO_x$ candidate molecules!
- Though large oxygen bearing species my have similar configurations/masses (i.e., isomers CH_3OCH_3 and CH_3CH_2OH), the authors use probability (Occam's razor) to predict what molecules are likely present



Hänni et al., 2023

Complex Comet Chemistry!

Special Case: the Rosetta Mission to JFC 67P

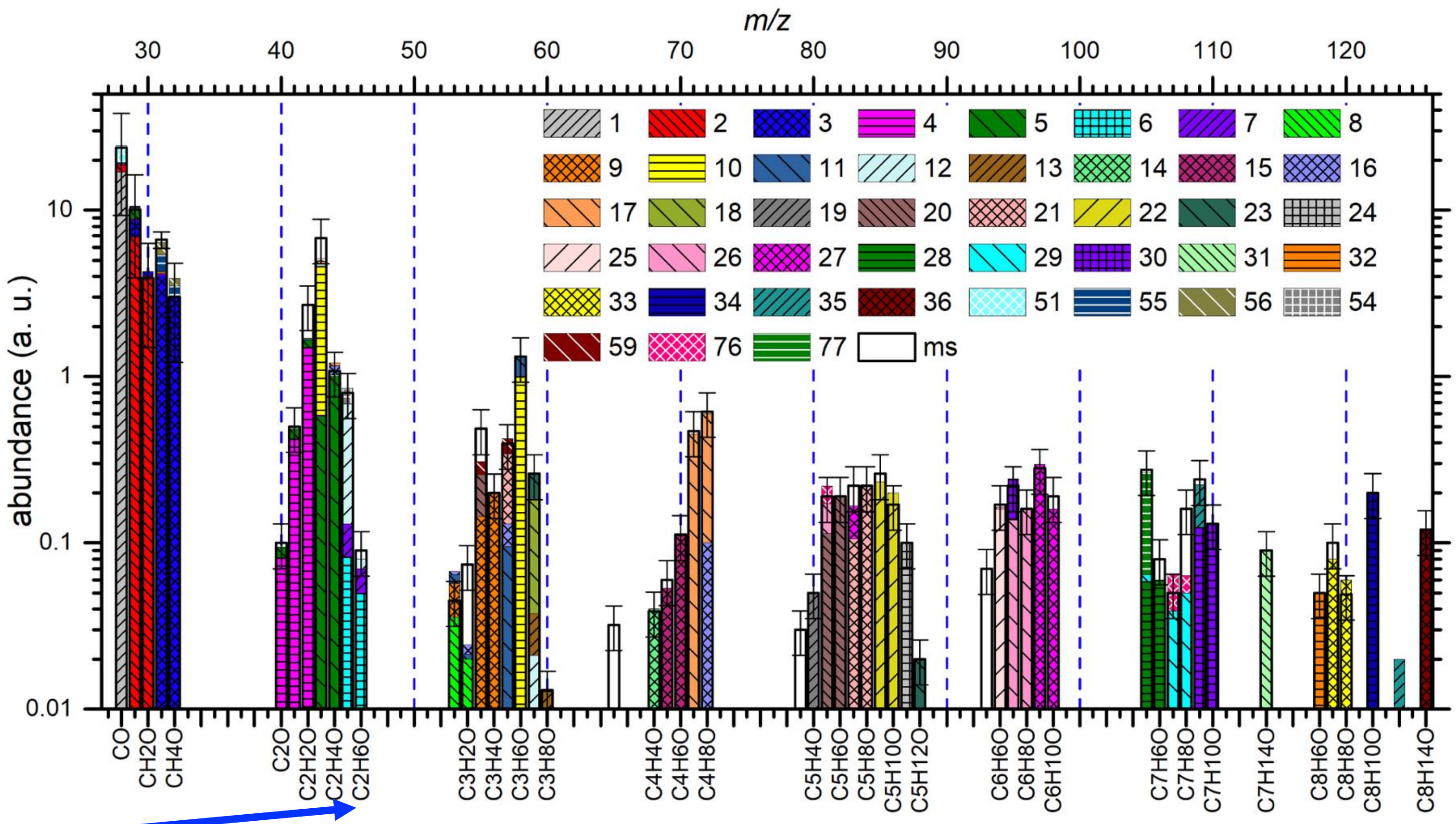
It gets complicated!

isomers

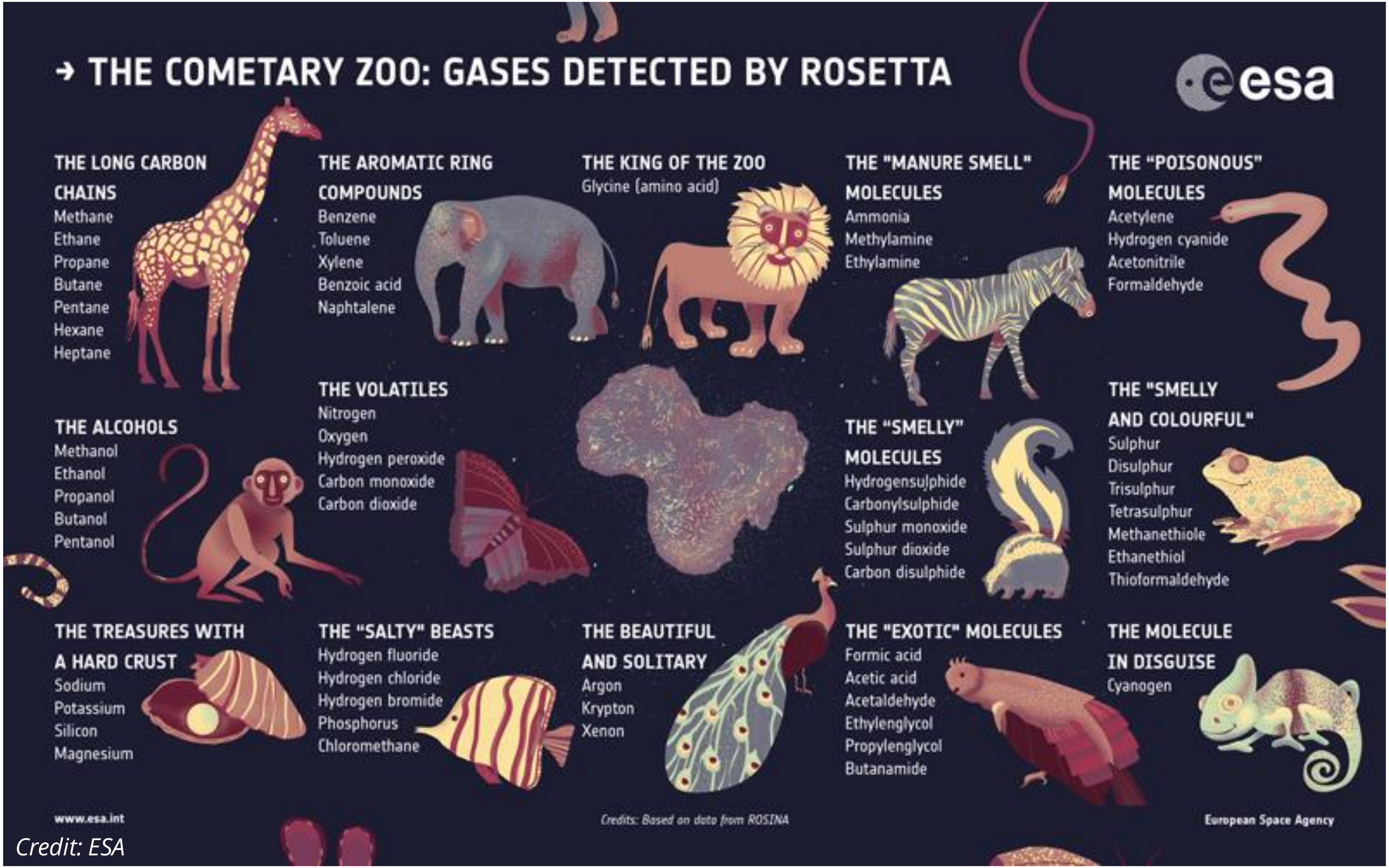
CH_3OCH_3 and CH_3CH_2OH

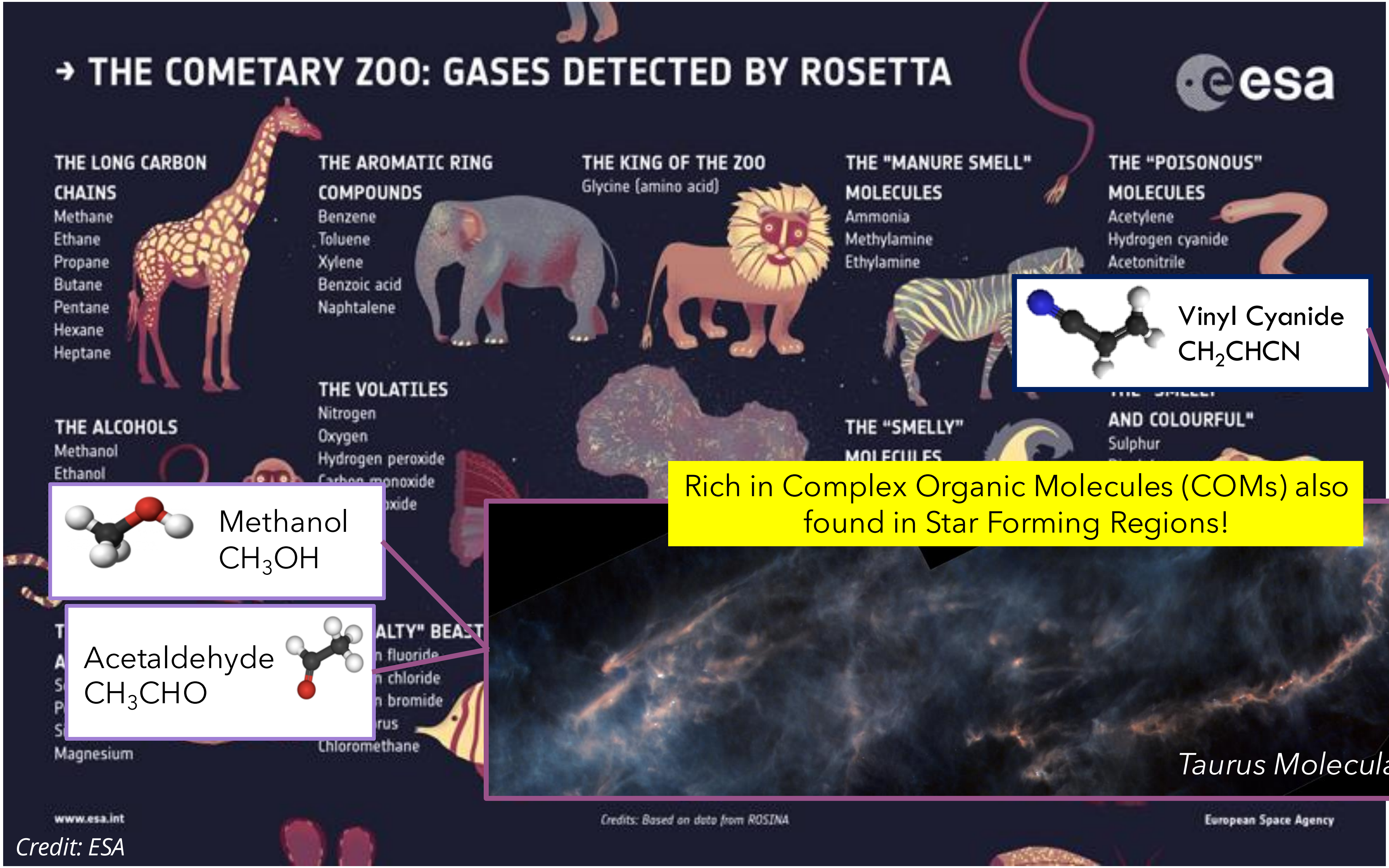
Dimethyl ether and **Ethanol**

C_2H_6O



Hänni 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 VOLATILES
Nitrogen
Oxygen
Hydrogen peroxide
Carbon monoxide
Carbon dioxide
THE ALCOHOLS
Methanol
Ethanol
Propanol
Butanol
Pentanol
THE "SMELLY" MOLECULES
Hydrogensulphide
Carbonylsulphide
Sulphur monoxide
Sulphur dioxide
Carbon disulphide
THE "SMELLY AND COLOURFUL"
Sulphur
Disulphur
Trisulphur
Tetrasulphur
Methanethiole
Ethanethiol
Thioformaldehyde
THE TREASURES WITH A HARD CRUST
Sodium
Potassium
Silicon
Magnesium
THE "SALTY" BEASTS
Hydrogen fluoride
Hydrogen chloride
Hydrogen bromide
Phosphorus
Chloromethane
THE BEAUTIFUL AND SOLITARY
Argon
Krypton
Xenon
THE "EXOTIC" MOLECULES
Formic acid
Acetic acid
Acetaldehyde
Ethylenglycol
Propylenglycol
Butanamide
THE MOLECULE IN DISGUISE
Cyanogen
www.esa.int
Credits: Based on data from ROSINA
European Space Agency
Credit: ESA



Methanol
CH_3OH

Acetaldehyde
CH_3CHO

Vinyl Cyanide
CH_2CHCN

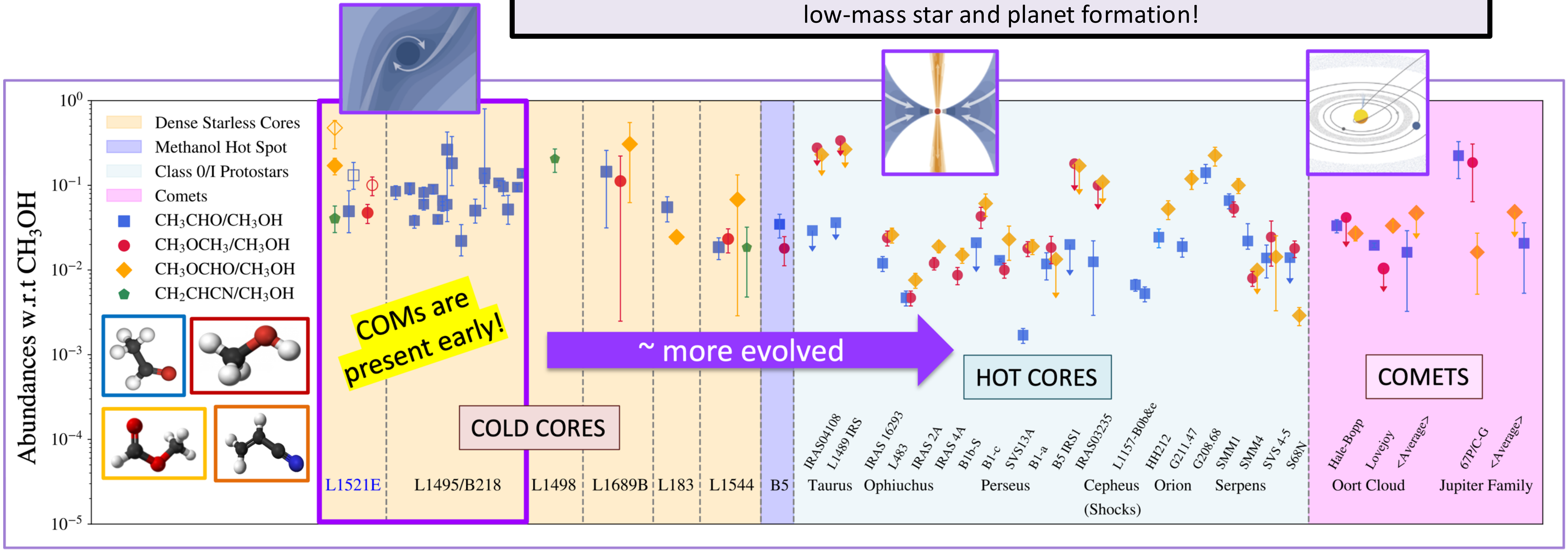
Rich in Complex Organic Molecules (COMs) also found in Star Forming Regions!

Taurus Molecular Cloud

Credit: ESA

Complex Comet Chemistry – Link to Star and Planet Formation!

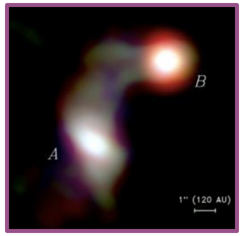
The general agreement in COM abundances across all stages suggests at least some of the COMs formed in starless and prestellar cores are being *inherited* to later stages of low-mass star and planet formation!

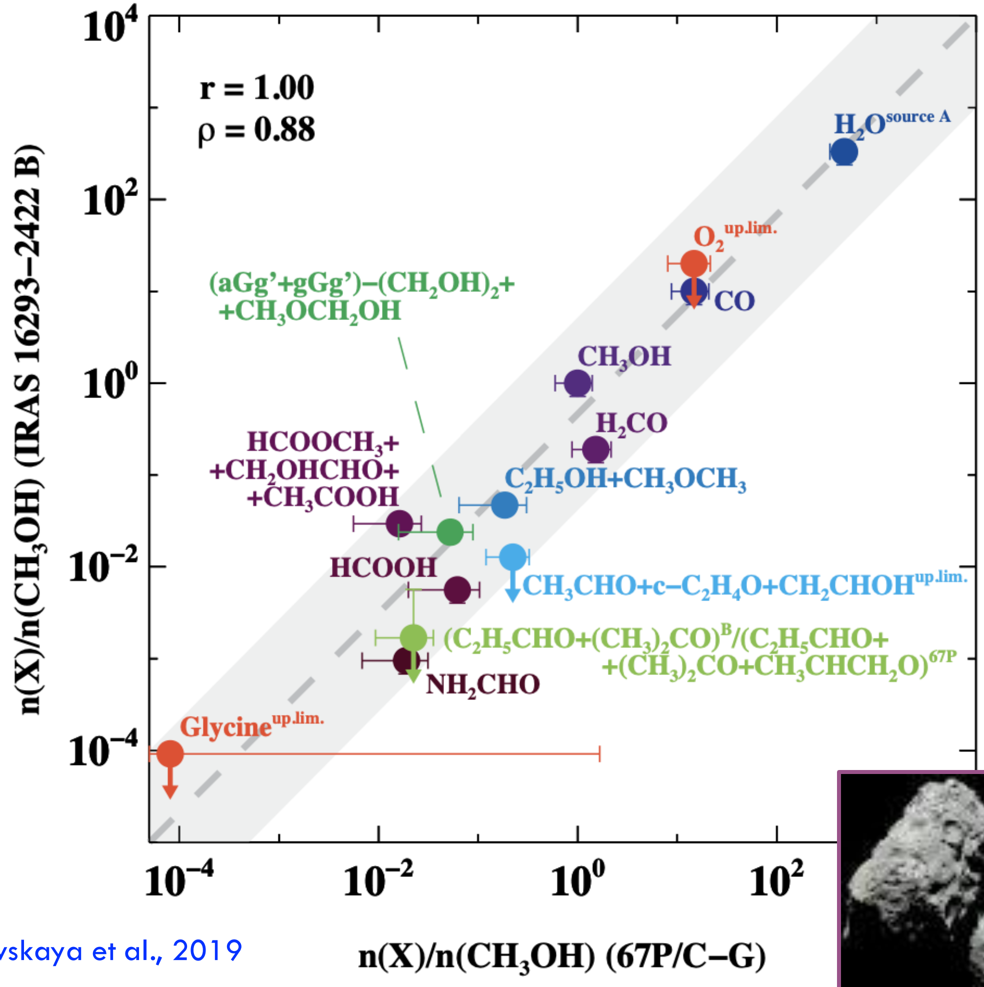


[L1495] **Scibelli & Shirley 2020,** [L1498] Jiménez-Serra et al. 2021, [L183] Lattanzi etal. 2020, [L1544] Jimenez-Serra et al. 2016, [L1689B] Bacmann et al. 2012, [B5] Taquet et al. 2017, [B1-c, B1-bs and S68N] van Gelder et al. 2020, [IRAS2A, IRAS4A] Taquet et al. 2015, López-Sepulcre et al. 2017; [IRAS 16293-2422] Jaber et al. 2014, Jørgensen et al. 2018, [SVS313A] Bianchi et al. 2019, [IRAS03245, B1-a, B5, IRS 1, SVS 4-5, IRAS 04108, L1489 IRAS], Graninger et al. 2016, Bergner et al. 2017, [SMM1, SMM4], Lee et al. 2019, Hsu et al. 2020 [HH212, G211.47, G208.68], Öberg et al. 2011, Taquet et al. 2015, [L483] Jacobsen et al. 2019, [L1157-Boe L1157-Bob] Codella et al. 2020, [B335] Imai et al. 2016. , [Hale-Bop and Lovejoy] Biver & Bockelée-Morvan 2019, [67P/ChuryumovGerasimenko(67/C-G)] Schuhmann et al. 2019 & Rubin et al. 2019

Adapted from Scibelli et al., 2021

Complex Comet Chemistry – Link to Star and Planet Formation!

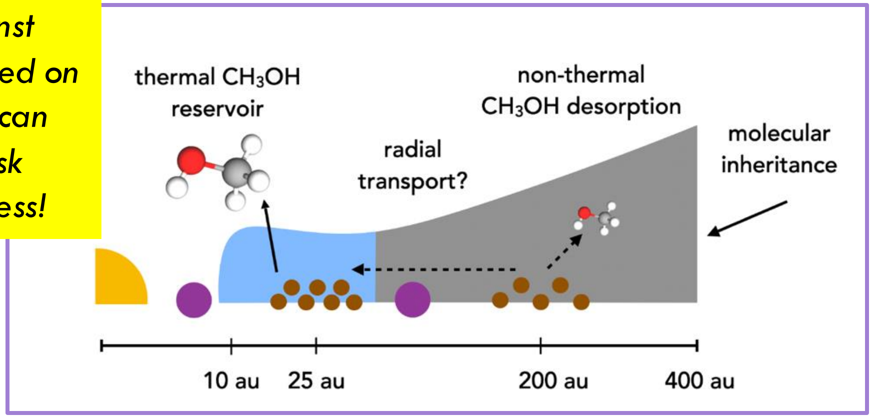




Drozdovskaya et al., 2019

← Additional evidence that molecules observed in protostars and comets could be inherited from the cold ***prestellar core*** phase!

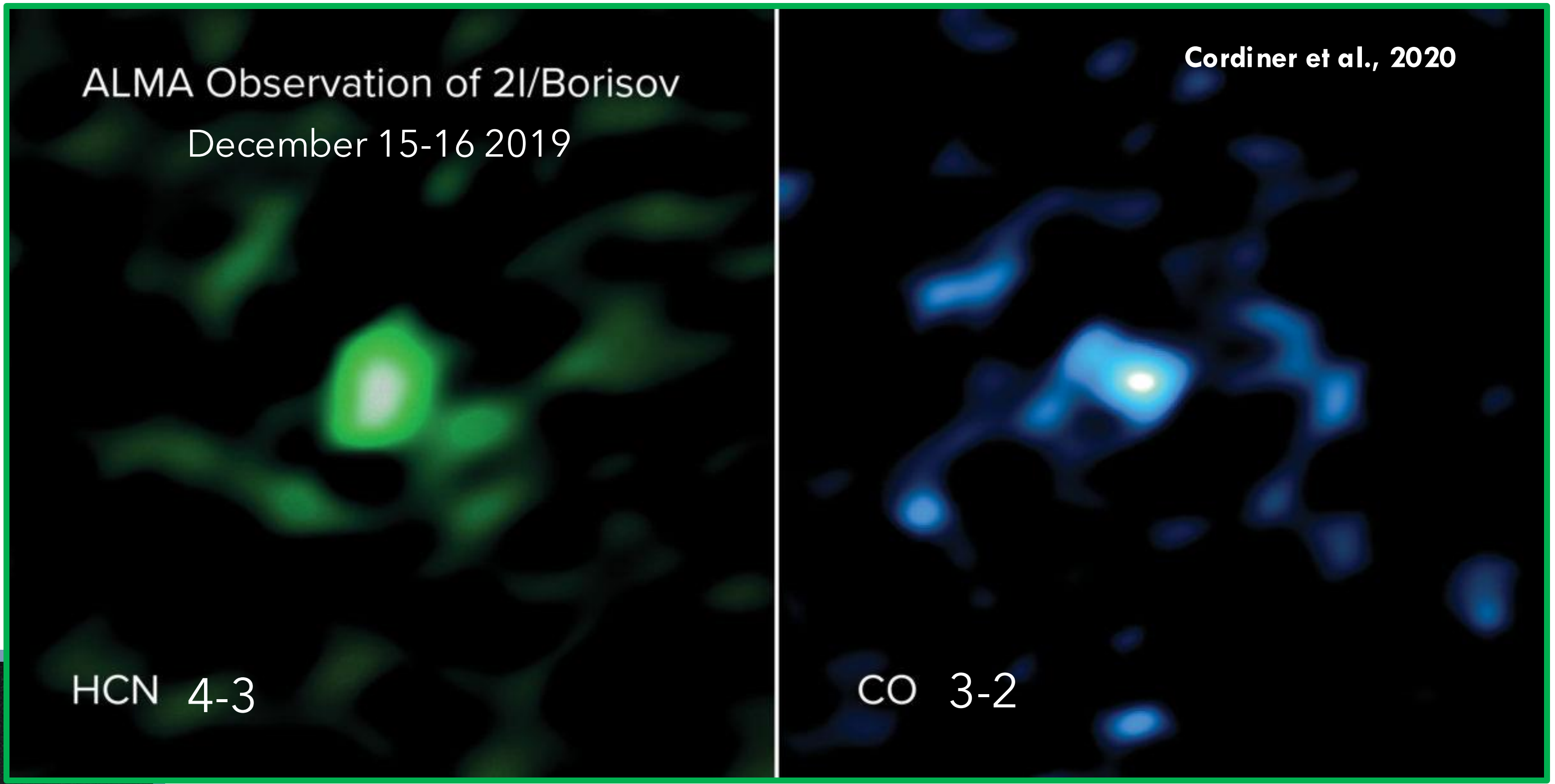
**CH_3OH is a good tracer molecule to compare against because it is formed on the grains and can survive the disk formation process!*



Booth et al., 2021

Interstellar Comet Chemistry!

- The first confirmed **interstellar** comet!
- The **HCN** abundance similar to that of comets in our Solar System
- The **CO** abundance is among the highest observed in any comet within 2 au of the Sun!
- 2I/Borisov must have formed in a relatively CO-rich environment in the very cold, outer regions of a distant protoplanetary accretion disk (similar to our our proto-Kuiper belt)



Maps from rotational line spectra

Emergence of Life on Earth, or *Elsewhere*?

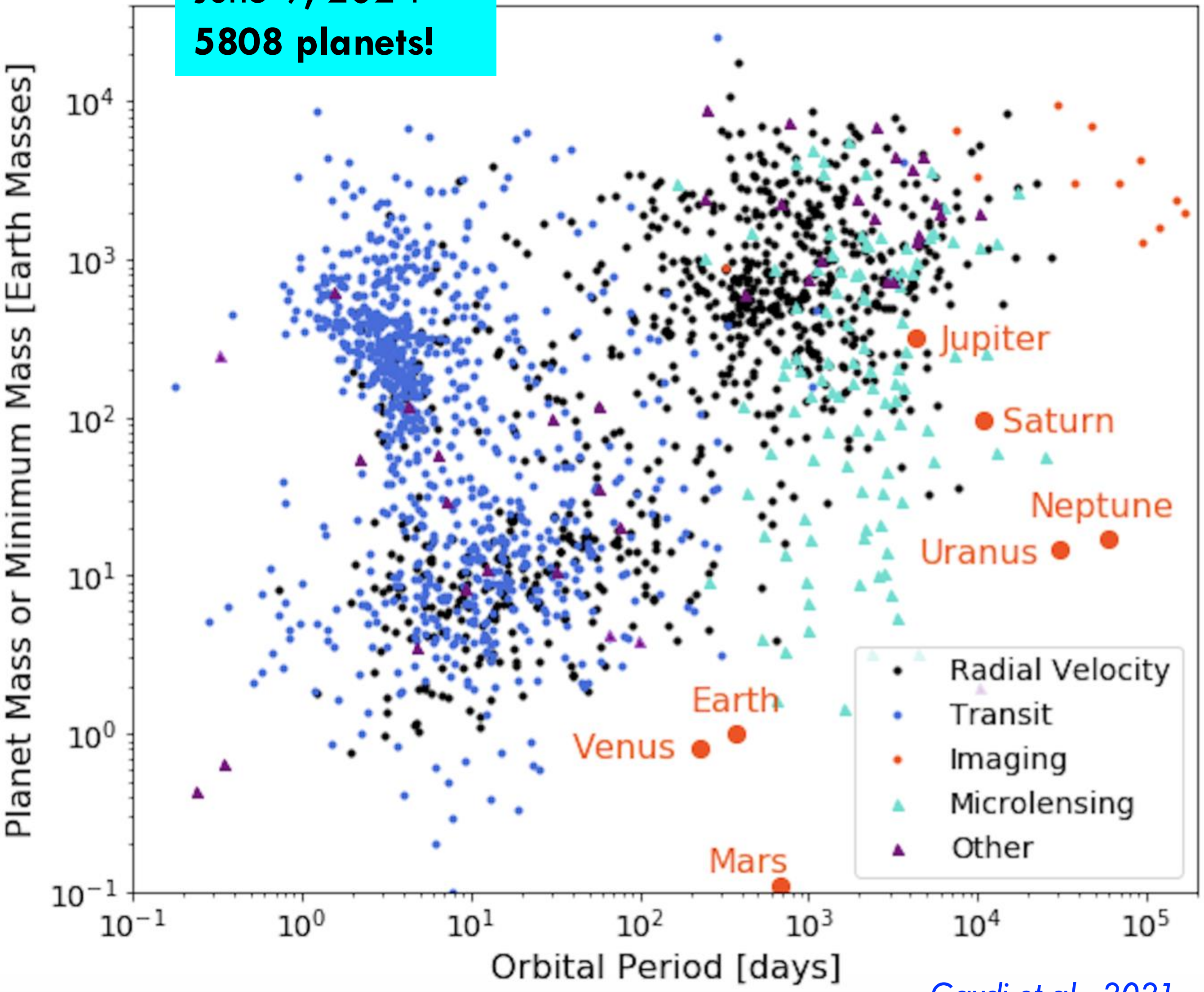
- Some of the complex chemistry formed in molecular clouds are inherited to the later stages of star and planet formation, including comets formed in the debris disks of solar systems, that can then **seed the chemistry needed for life on Earth or other planets**

Exoplanets

Exoplanet → a **planet**, which is defined as 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, **around another star**

Last update:
June 9, 2024
5808 planets!

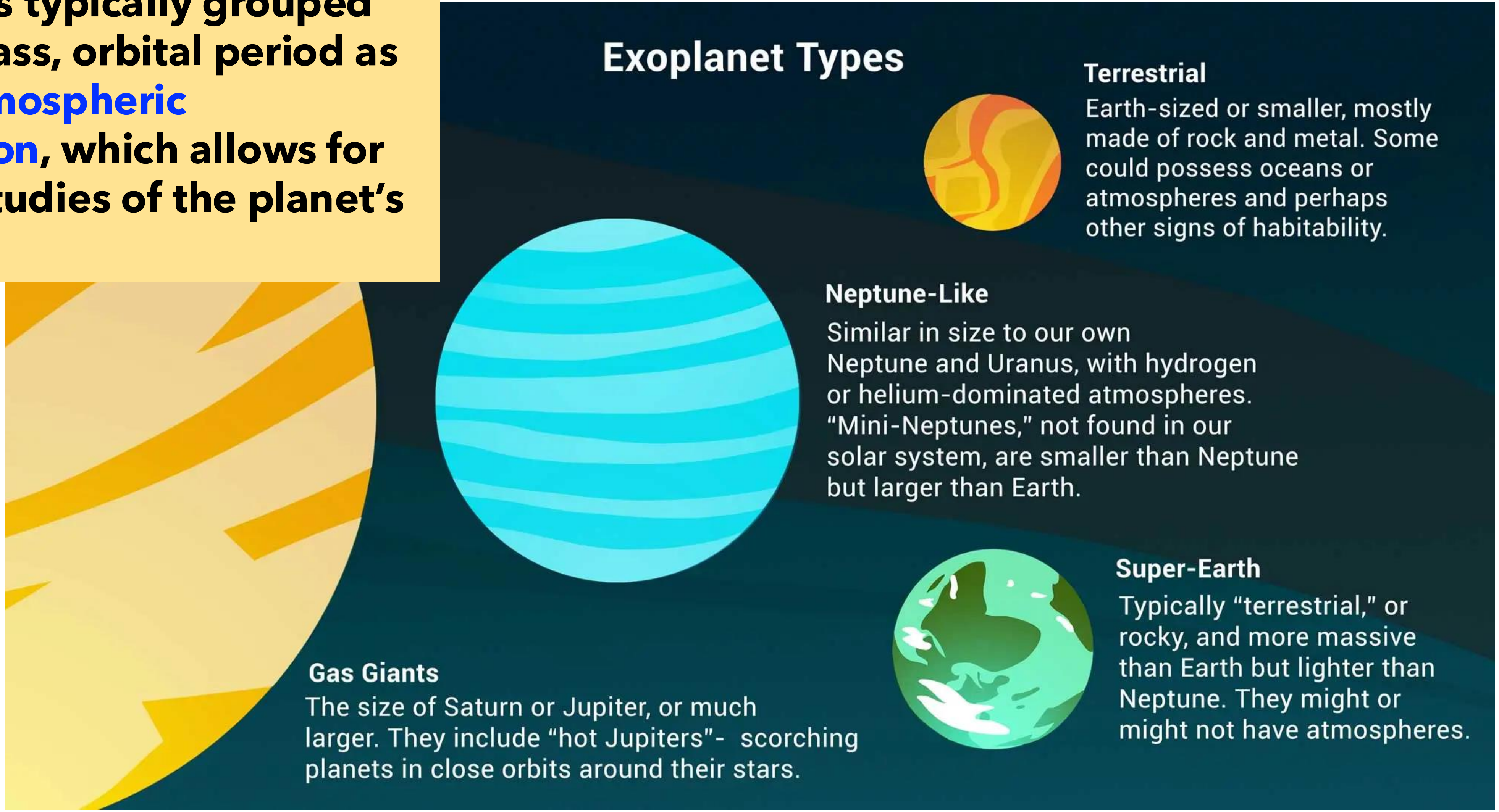
Exoplanet Statistics:
http://exoplanet.eu



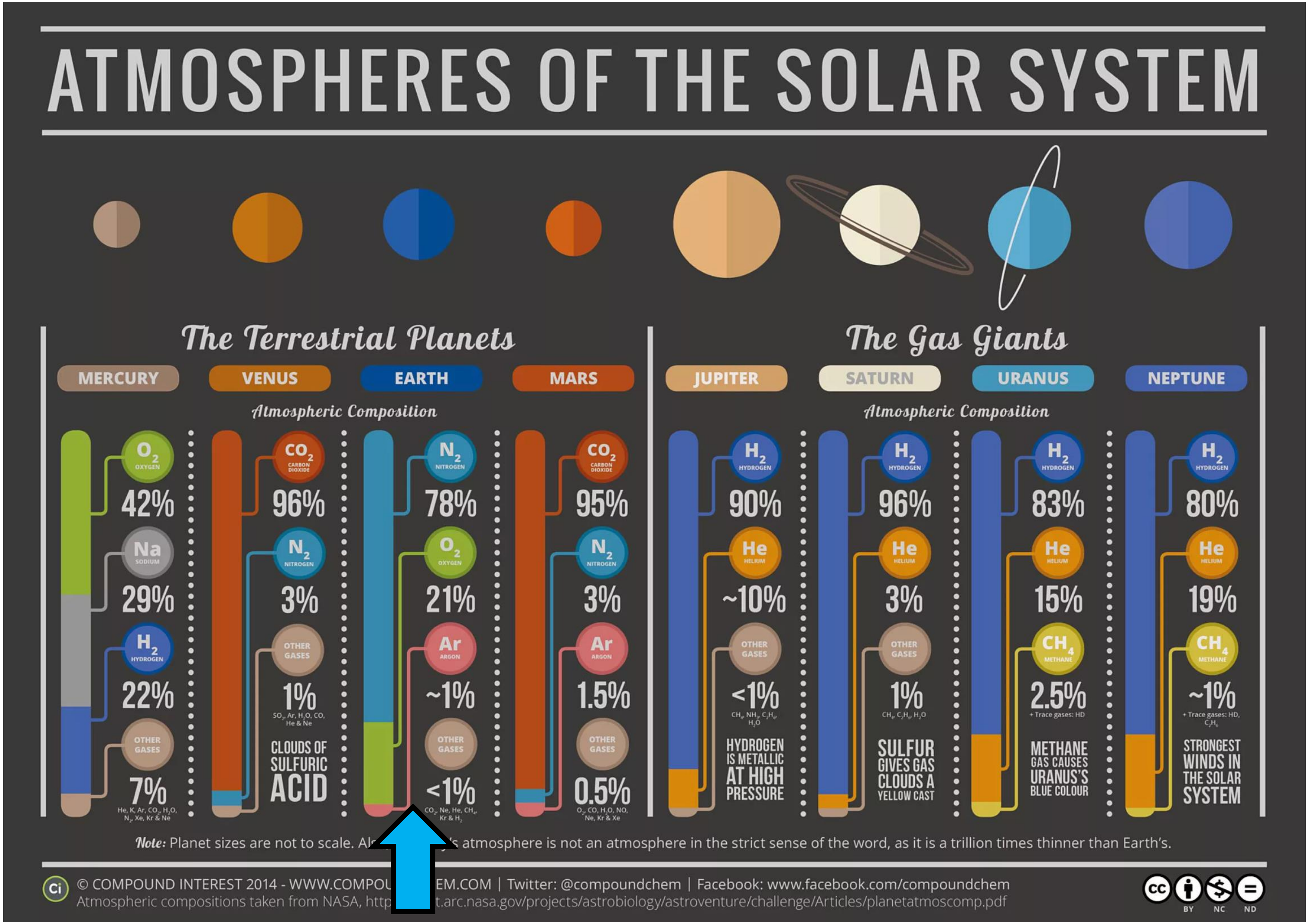
Gaudi et al., 2021

Exoplanets

- **Exoplanets typically grouped by size, mass, orbital period as well as atmospheric composition, which allows for detailed studies of the planet's *chemistry***



NASA/JPL-Caltech/Lizbeth B. De La Torre

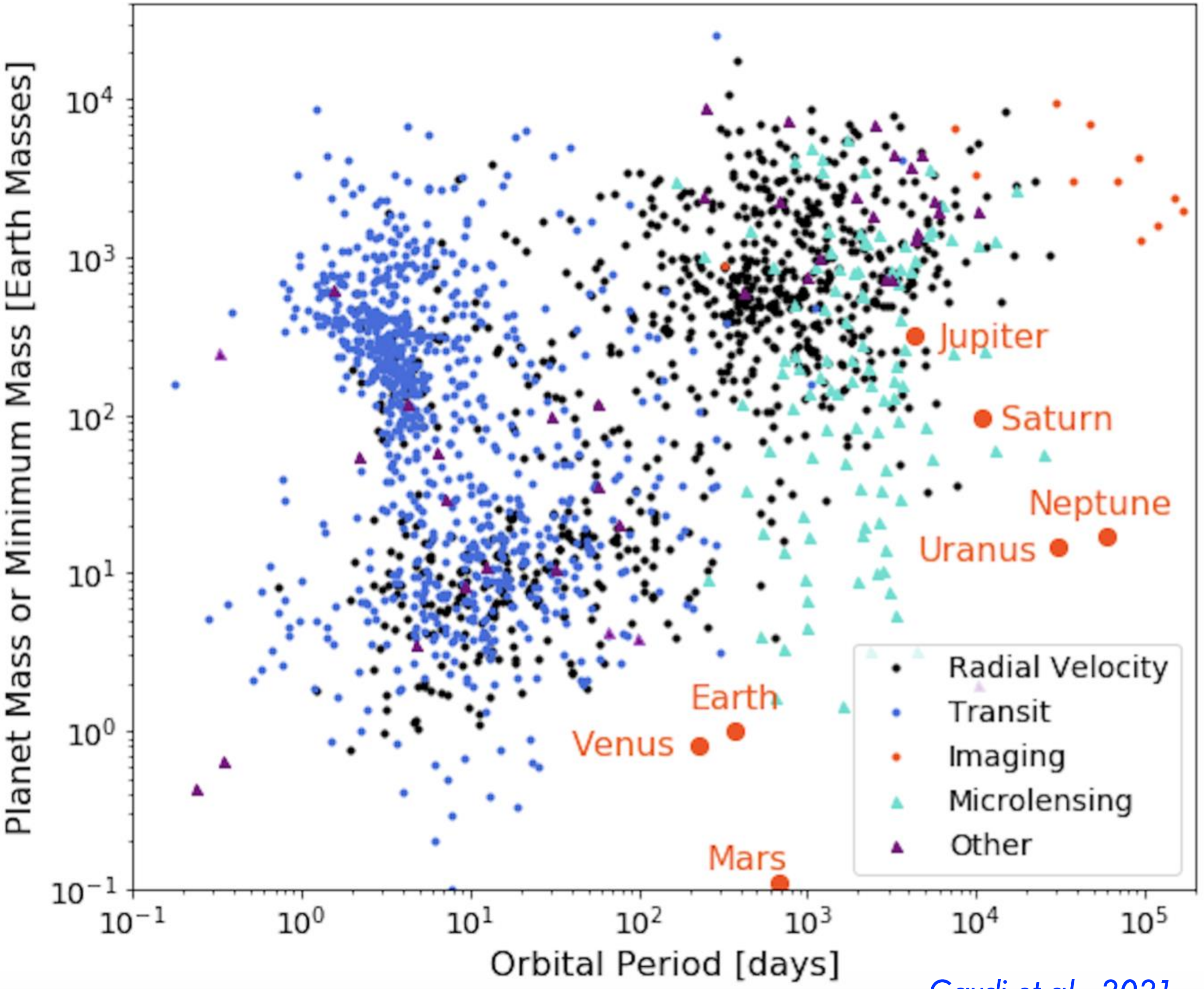


How does the composition of atmospheres of solar system objects (**Earth** in particular!) compare to those of exoplanets?

Studying the Atmosphere of Exoplanets: Transit Spectroscopy

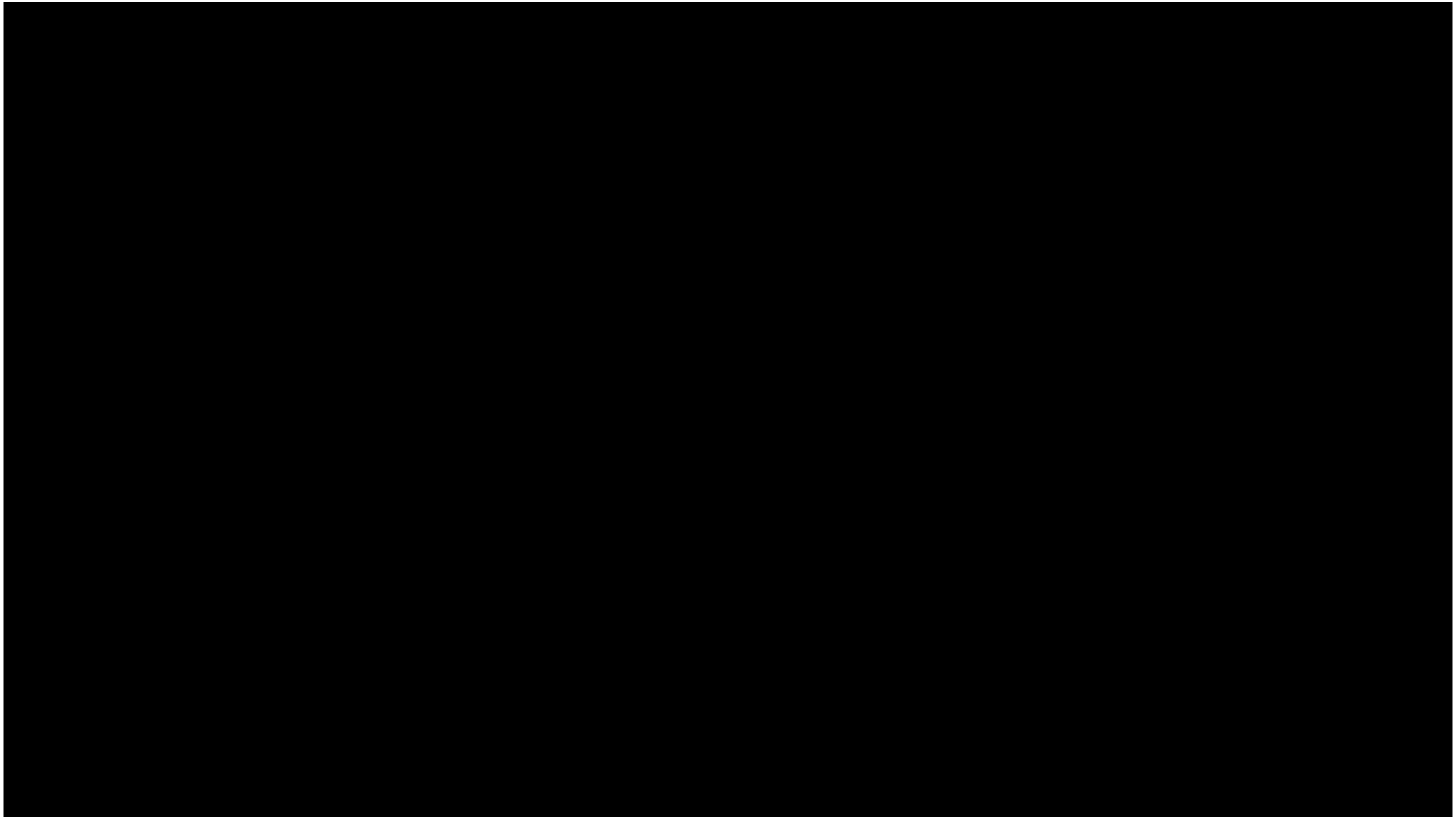
- Most planets with relativity short orbital periods discovered by the **transit method** (in **blue** →)

- When a planet crosses directly between us and its star, we see the star dim slightly because the planet is blocking out a portion of the light



Gaudi et al., 2021

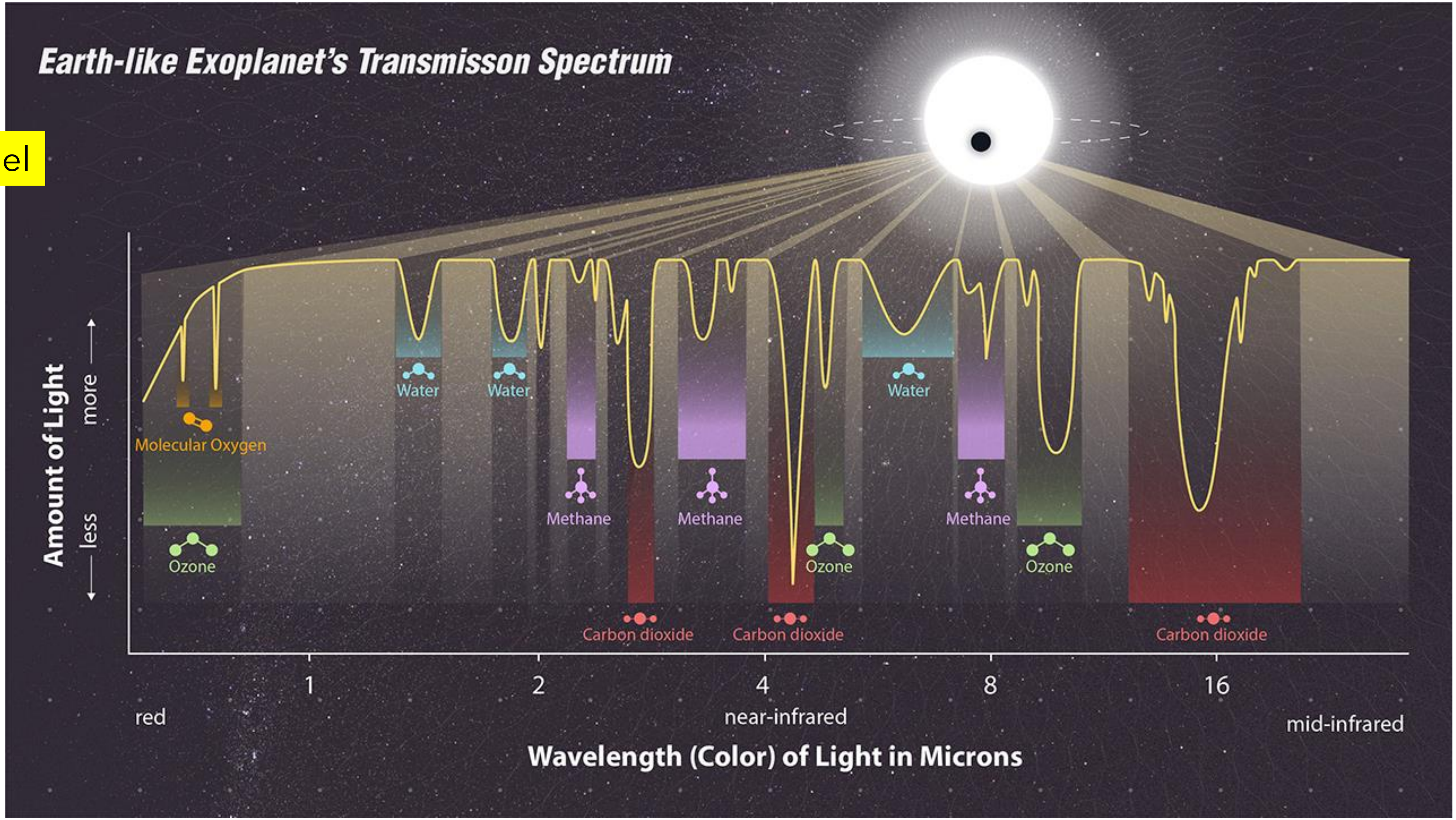
Studying the Atmosphere of Exoplanets: Transit Spectroscopy



NASA; Visualizations by Dan Gallagher

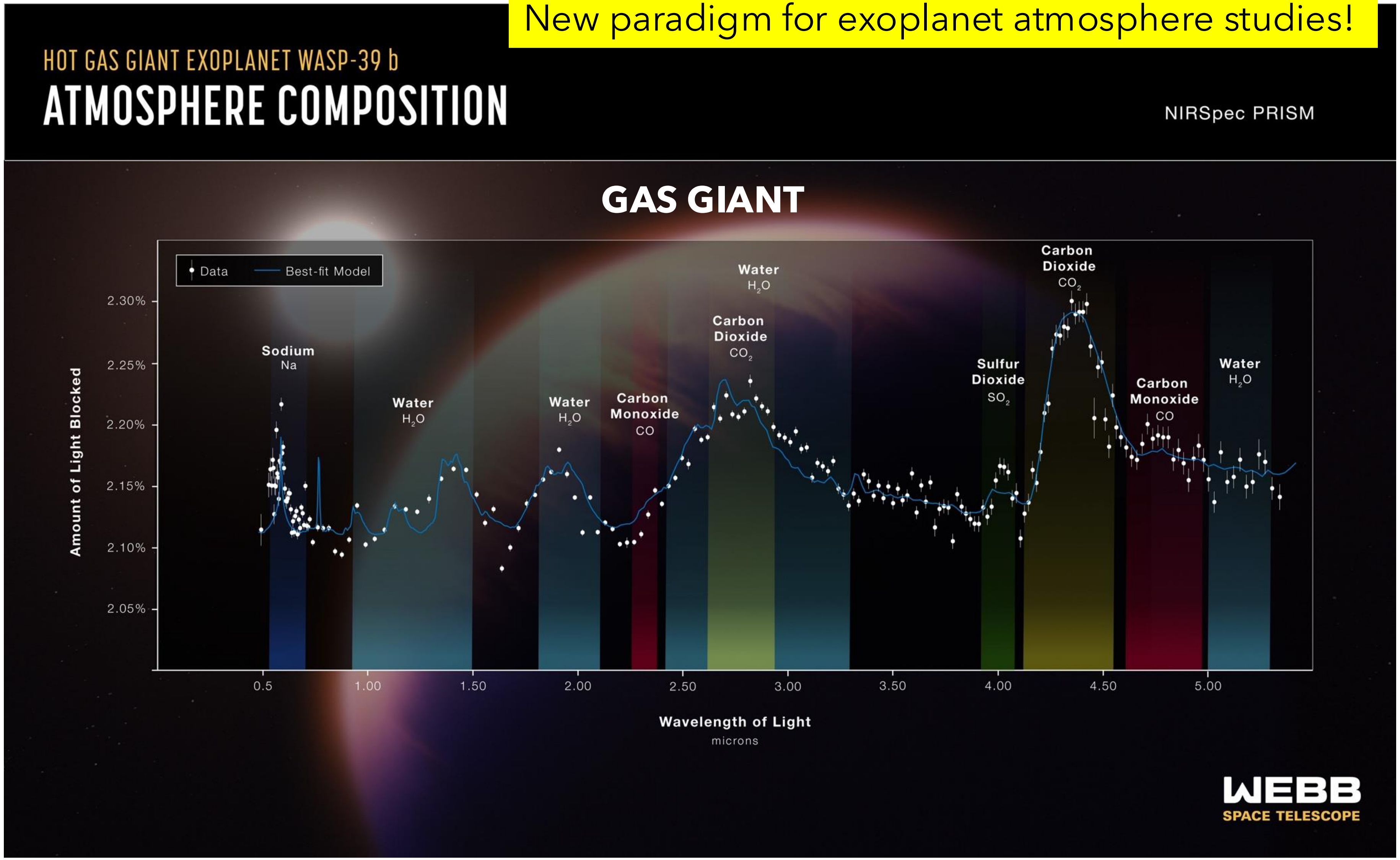
Studying the Atmosphere of Exoplanets: Transit Spectroscopy

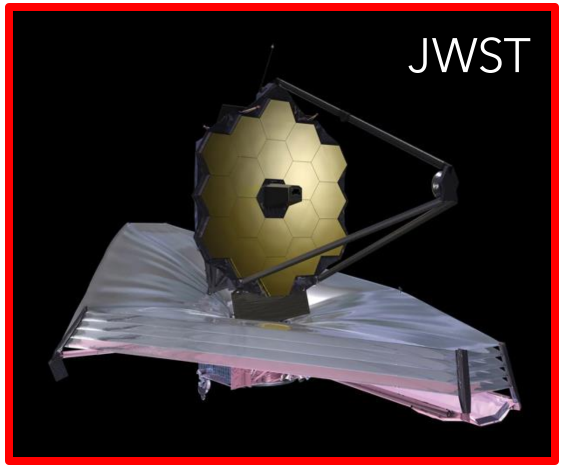
Model



Studying the Atmosphere of Exoplanets: Transit Spectroscopy

New paradigm for exoplanet atmosphere studies!

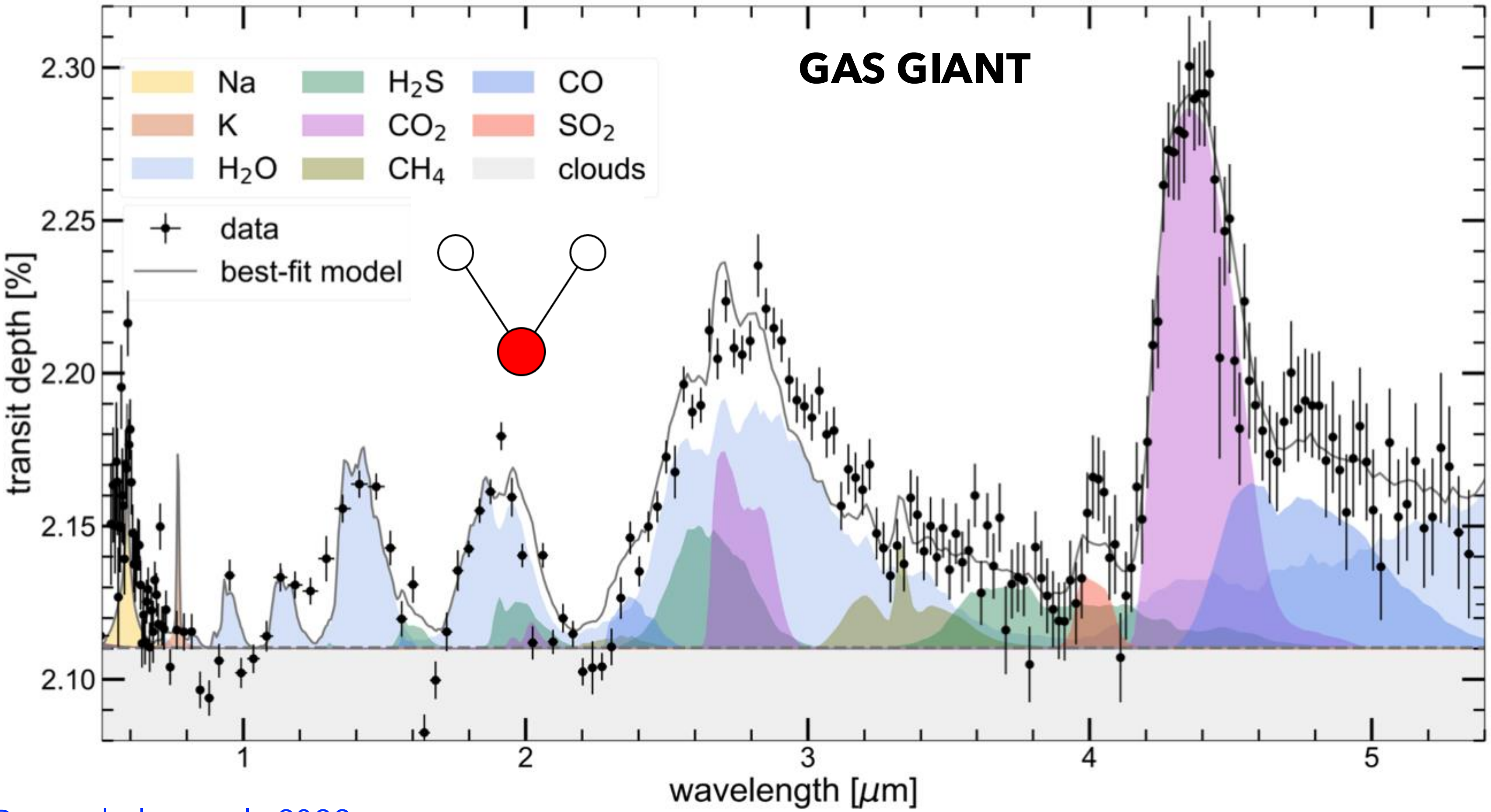




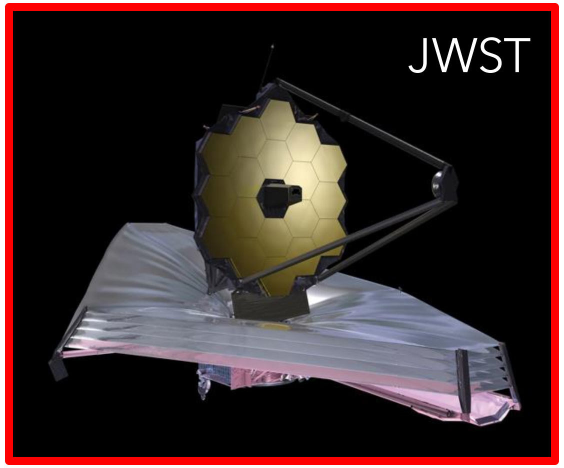
← Press release image

Studying the Atmosphere of Exoplanets: Transit Spectroscopy

New paradigm for exoplanet atmosphere studies!



Rustamkulov et al., 2022

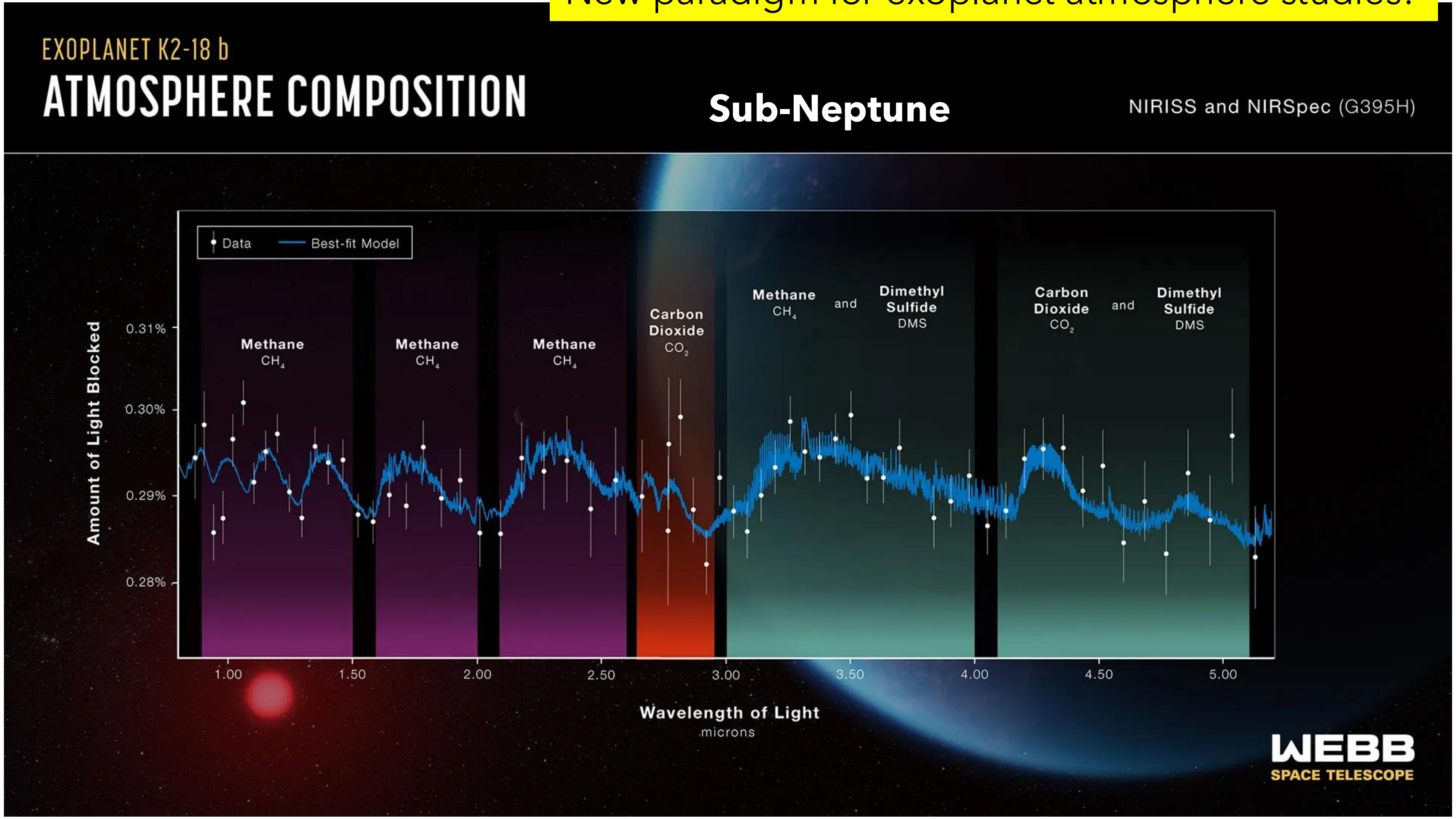


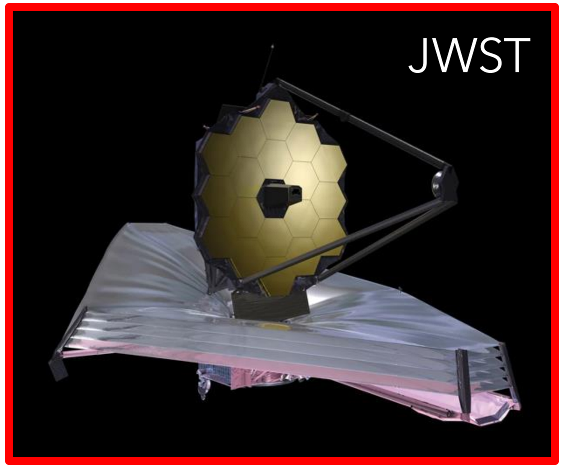
← Published Data

Overlapping IR Vibrational modes used to detect molecules!

Studying the Atmosphere of Exoplanets: Transit Spectroscopy

New paradigm for exoplanet atmosphere studies!

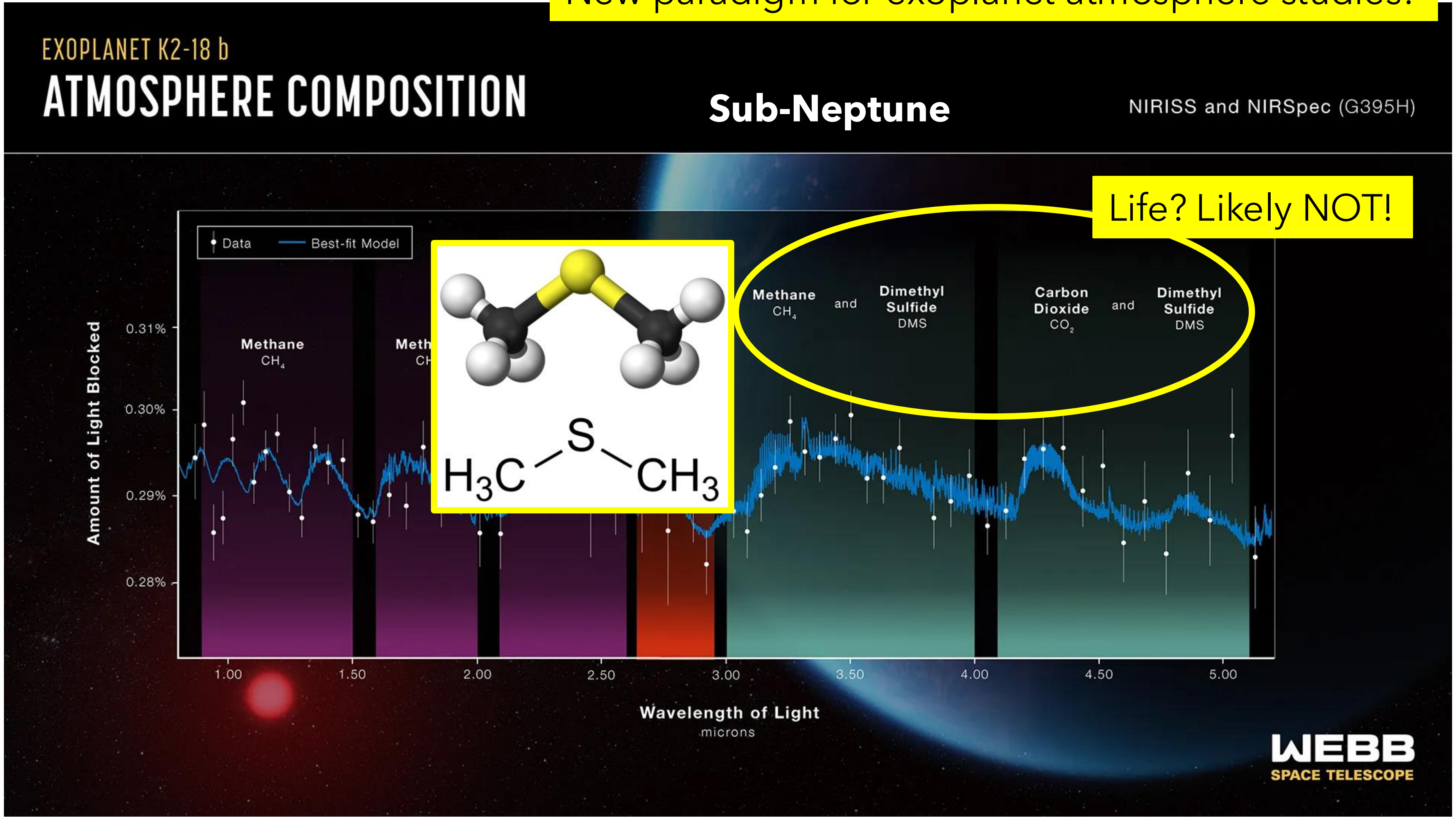


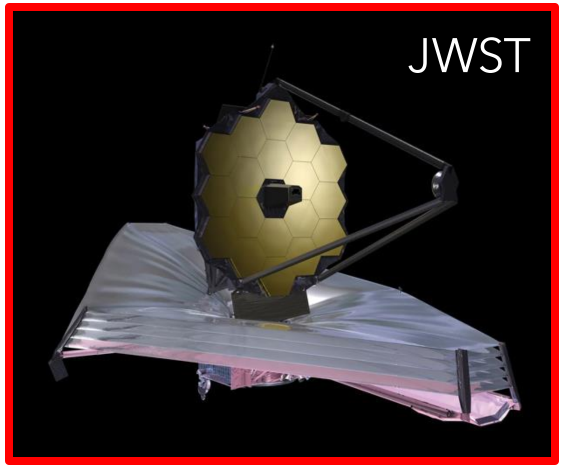


← Press release image

Studying the Atmosphere of Exoplanets: Transit Spectroscopy

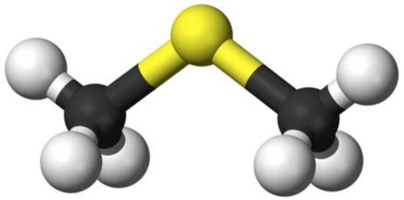
New paradigm for exoplanet atmosphere studies!

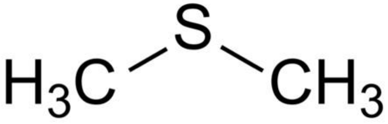




← Press release image

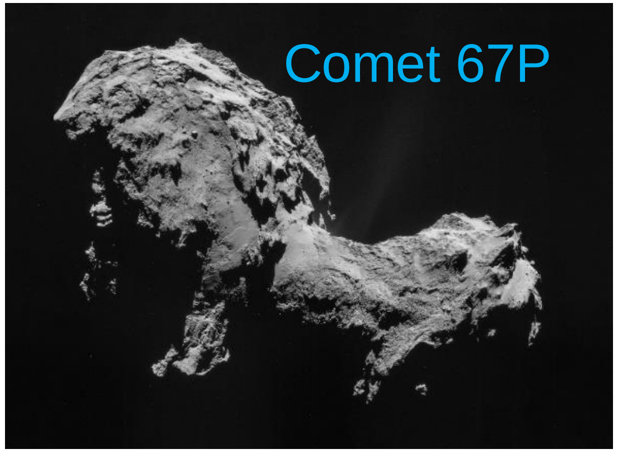
Dimethyl Sulfide

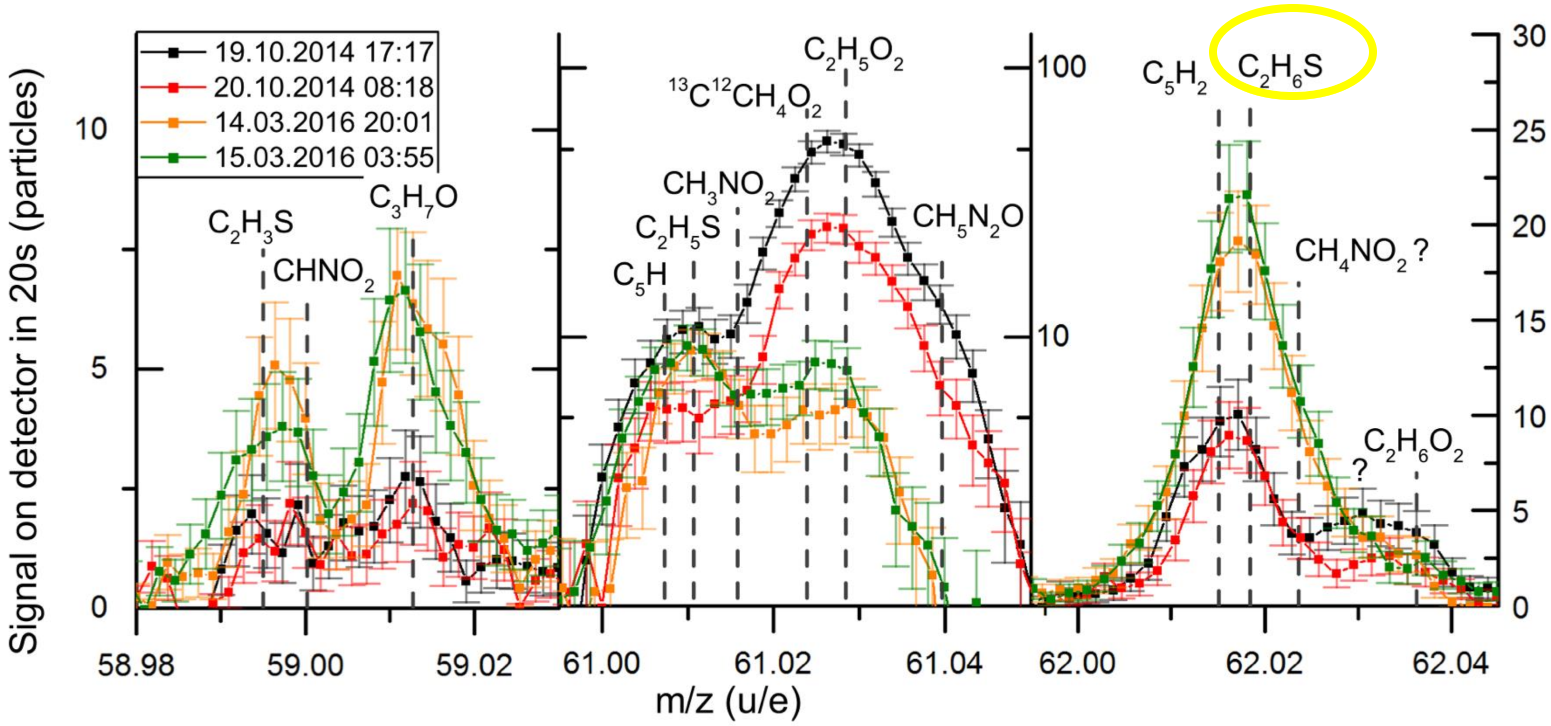




Also detected in 'lifeless' comet 67P!

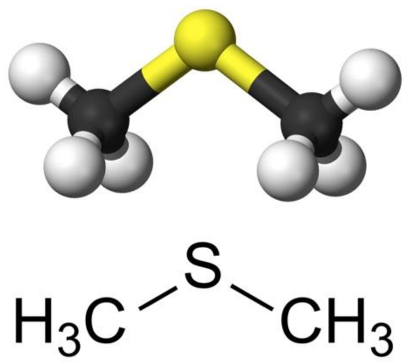
- Though, with this method still cannot distinguish between the two isomers (C_2H_6S) **ethanethiol** and **dimethyl sulfide**!
- Updated analysis in 2024 claim to confirm its presence *(Hänni et al.,)*





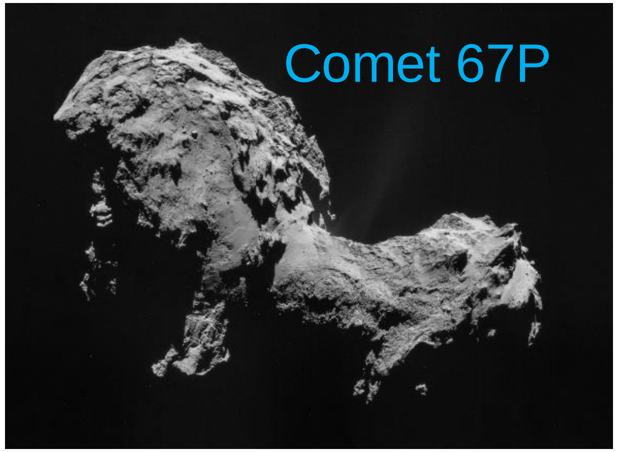
Calmonte et al., 2016

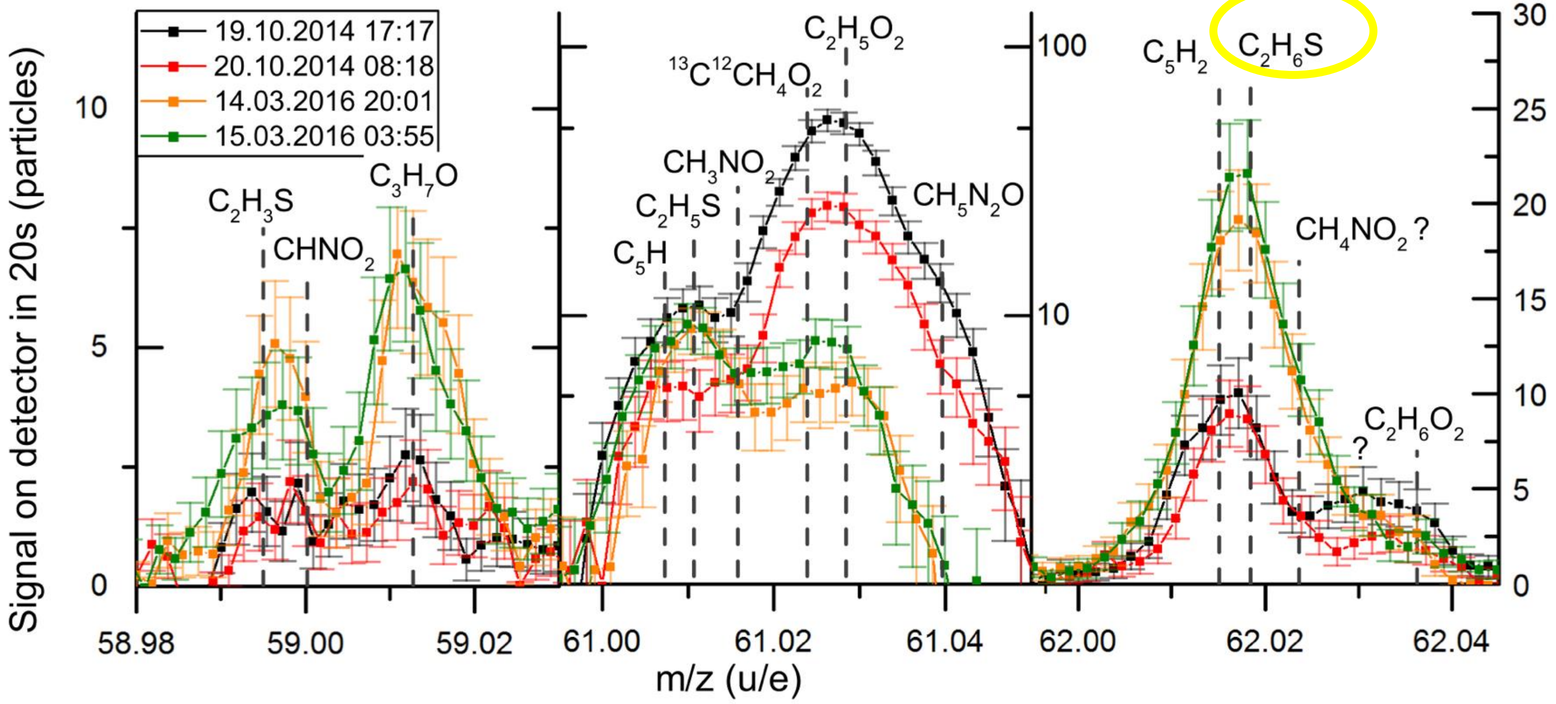
Dimethyl Sulfide



Also detected in 'lifeless' comet 67P!

- Though, with this method still cannot distinguish between the two isomers (C_2H_6S) **ethanethiol** and **dimethyl sulfide**!
- Updated analysis in 2024 claim to confirm its presence *(Hänni et al.,)*



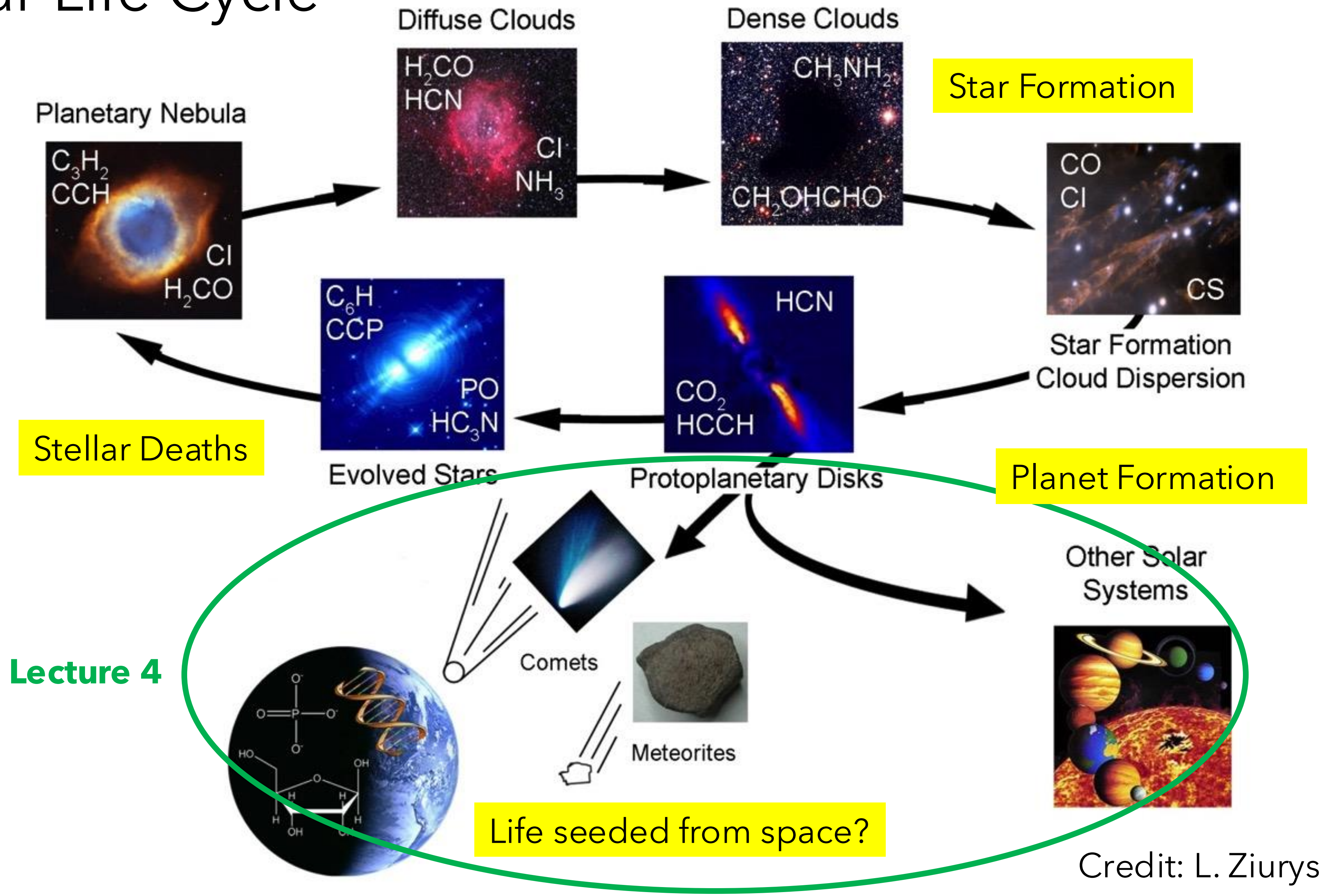


Calmonte et al., 2016

Molecular 'signs of life' have often already been detected in the cold depths of space!

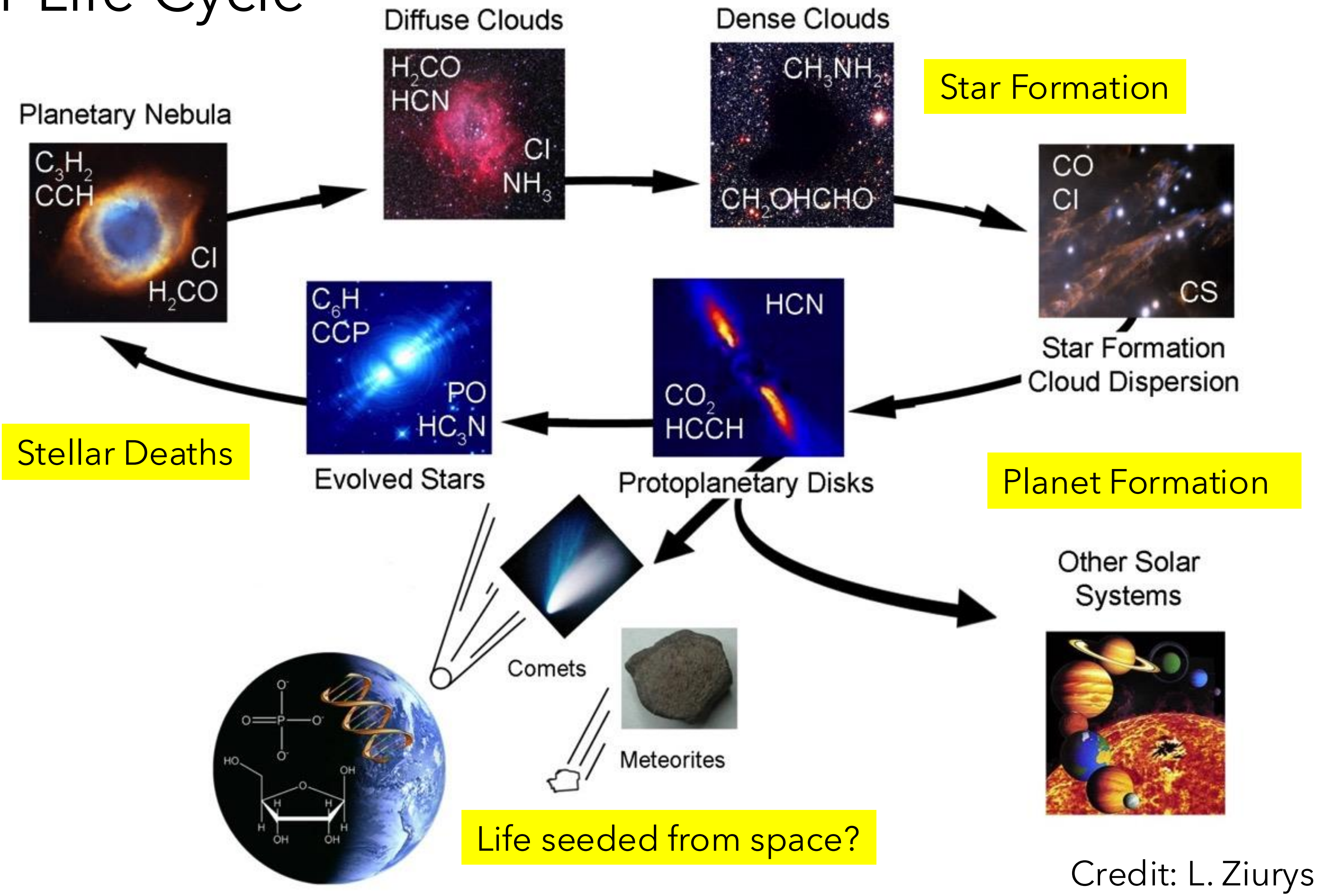
Molecular Life Cycle

The **building blocks for life** on **Earth**, and potentially **other worlds**, were likely seeded from star and planet-forming material (such as **comets**!)



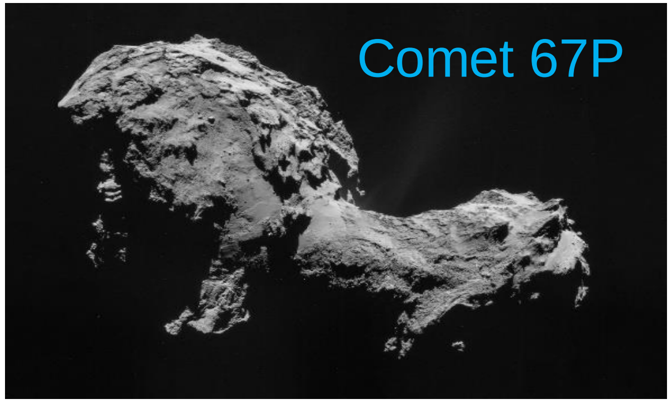
Credit: L. Ziurys

Molecular Life Cycle



Credit: L. Ziurys

SUMMARY:



- Reminder! **Submillimeter and millimeter radio telescopes are powerful instruments** that let observational astrochemists (like myself) study the **rotational spectra** of interstellar molecules in high detail!

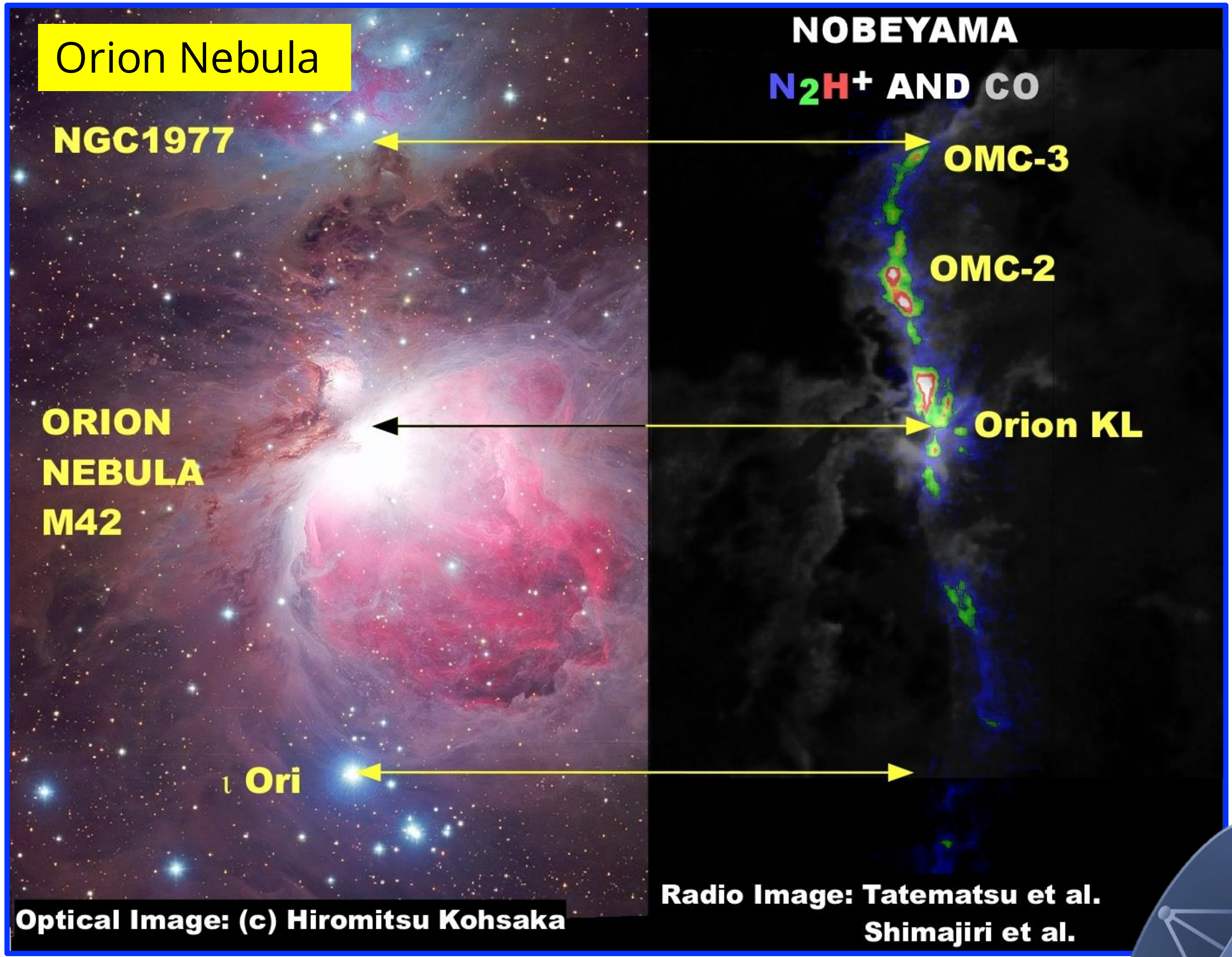
- Cold molecular clouds are the birthplaces of stars and planets. Within molecular clouds, **H_2 forms on the surfaces of interstellar dust grains** and is released into the gas – this is the start of chemistry in the interstellar medium!

- Dust grains are formed in the circumstellar shells of evolved stars, specifically AGBs! Dust and molecular gas is transported outward in winds, enriching the interstellar medium! **Mass loss from Evolved stars supplies ~85% of the material in the ISM!** The dust and molecules enrich the surrounding **diffuse** gas and eventually the dense gas that goes on to form stars and planets!

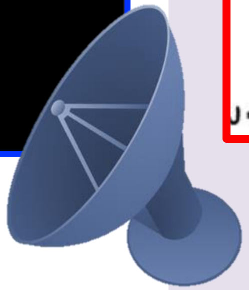
- Comets are remnants from when solar systems formed and, due to their dusty and hydrogen rich comas, their chemistry can be studied at millimeter wavelengths. Comet 67P is an interesting case, as a fly-by mission was able to measure the composition of the coma via mass spectroscopy. **The abundance of the complex molecules seen in comets is like that seen in other stages of star formation, suggesting inheritance.**

- With the advent of of JWST, exoplanet atmospheres are beginning probed in exquisite detail. **Do not, however, be fooled by 'signs of life' from molecules often detected in the cold depths of space!**

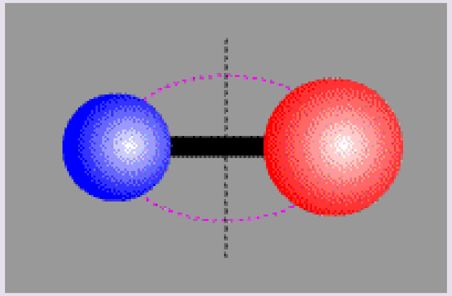
Questions?
+ Takeaways from the Class!

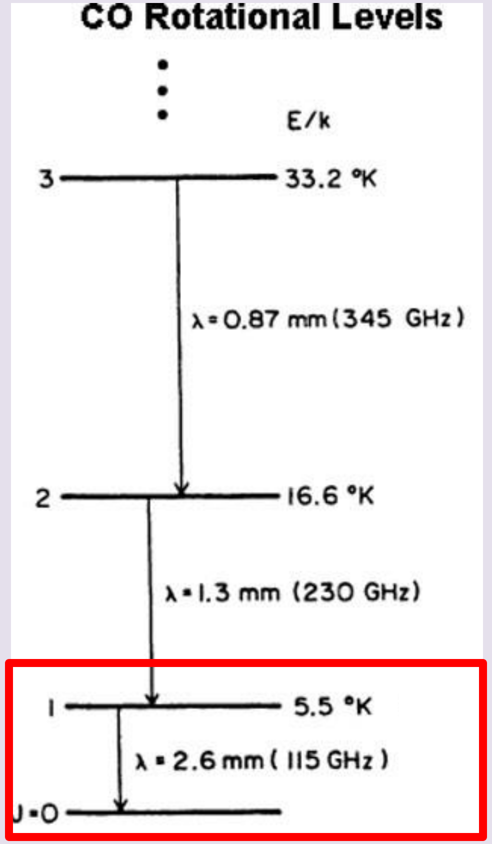


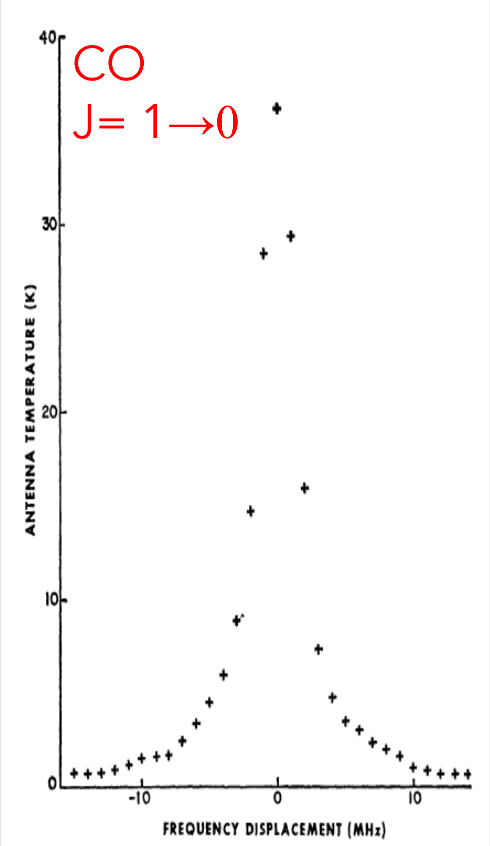
https://www.nro.nao.ac.jp/~kt/html/kt-e.html



Discovery of CO
in the Star Forming Region,
Orion KL at 115 GHz
(J = 1 → 0 transition)
in 1970 at **Kitt Peak, Arizona!**

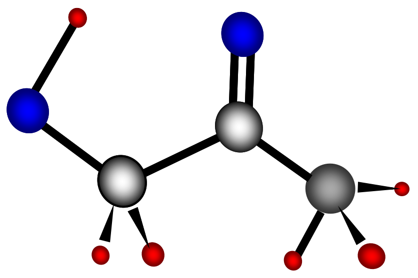






Wilson et al., 1970

Molecule Formation (*in Molecular Clouds*)



- Typical Conditions in molecular gas:
  - low Densities (10 - 10^7 cm^{-3}; < 10^{-12} torr)
    - compared to Earth atmosphere (~10^{19} cm^{-3})
  - low Temperatures: T ~ 10 – 100 K → **Severely restricts allowed chemical processes!**

    - *only two body collisions*

    - reactions must be **exothermic!**

Basic Chemical Scheme:

1) H_2 formed on grain surfaces: $H + H + \text{grain} \rightarrow H_2 + \text{grain}$

2) Gas-phase reactions initiated by cosmic rays (photons, γ) and proceed via ion-molecule reactions

$$H_2 + \gamma \rightarrow H_2^+ + e + \gamma'$$

$$H_2^+ + H_2 \rightarrow \mathbf{H_3^+} + H$$

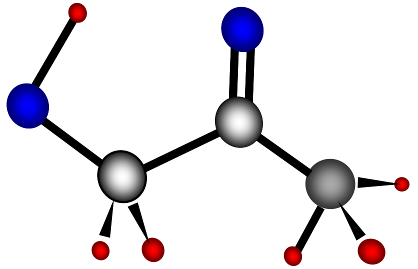
$$H_3^+ + CO \rightarrow \mathbf{HCO^+} + H$$

$$H_3^+ + N_2 \rightarrow \mathbf{N_2H^+} + H$$

etc.

Credit: L. Ziurys

Molecule Formation (*in Molecular Clouds*)



Basic Chemical Scheme:

1) H_2 formed on grain surfaces: $H + H + \text{grain} \rightarrow H_2 + \text{grain}$

2) Gas-phase reactions initiated by cosmic rays (photons, γ) and proceed via ion-molecule reactions

$H_2 + \gamma \rightarrow H_2^+ + e + \gamma'$

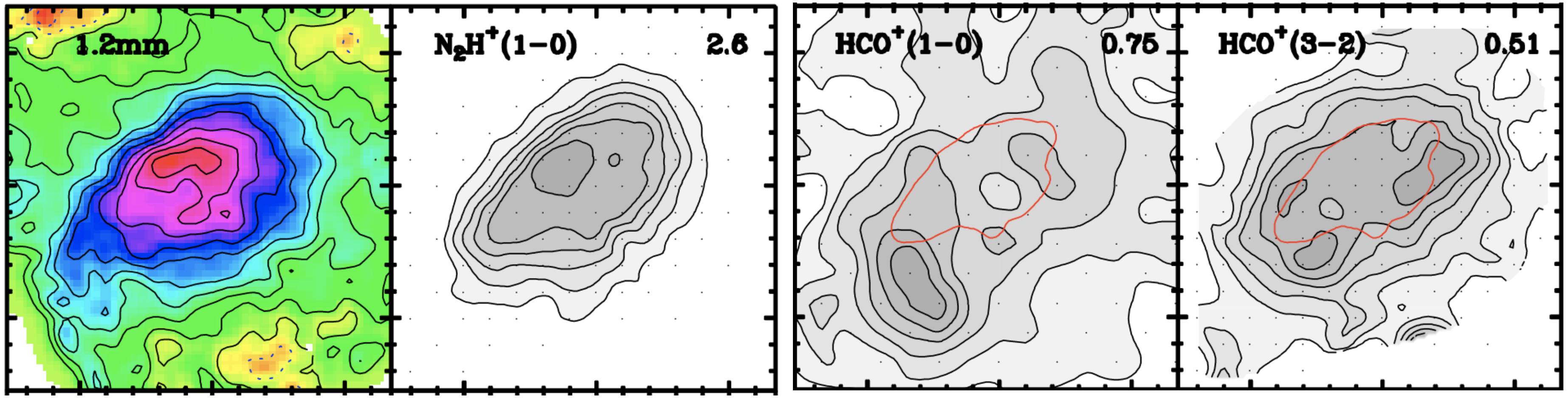
$H_2^+ + H_2 \rightarrow \mathbf{H_3^+} + H$

$H_3^+ + CO \rightarrow \mathbf{HCO^+} + H$

$H_3^+ + N_2 \rightarrow \mathbf{N_2H^+} + H$

etc.

Starless core L1498 → CO frozen out on grains thus less HCO^+



Tafalla 2006

Molecule Formation (*in Molecular Clouds*)

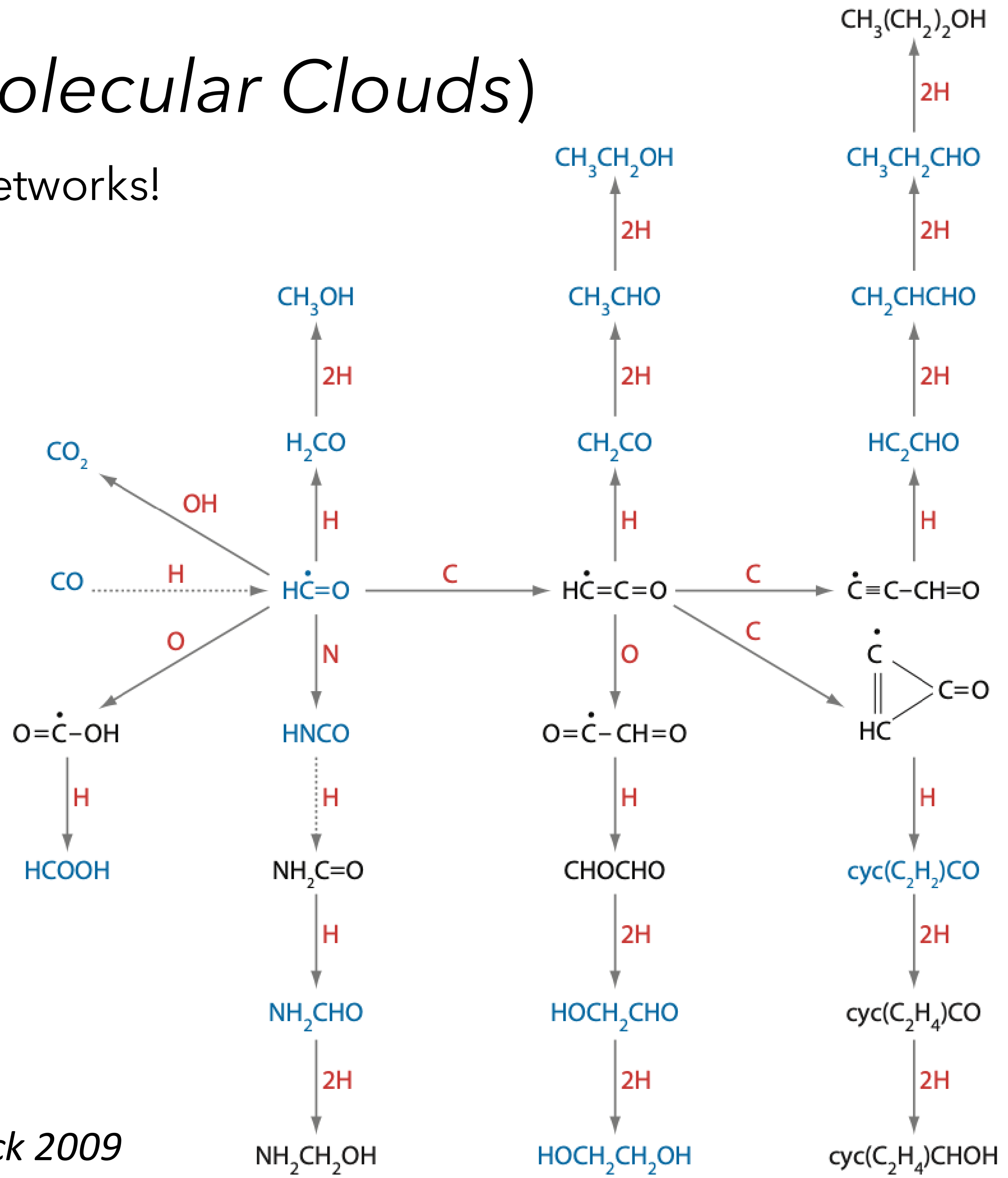
Large chemical reaction networks!

- Organic chemistry on interstellar grains resulting from cold H addition reactions to CO

- Broken arrows indicate reactions with activation energy barriers

- Where 2H is shown, a barrier penetration reaction followed by exothermic addition

- Molecules in blue detected in <u>star-forming molecular clouds</u>!



Herbst & van Dishoeck 2009

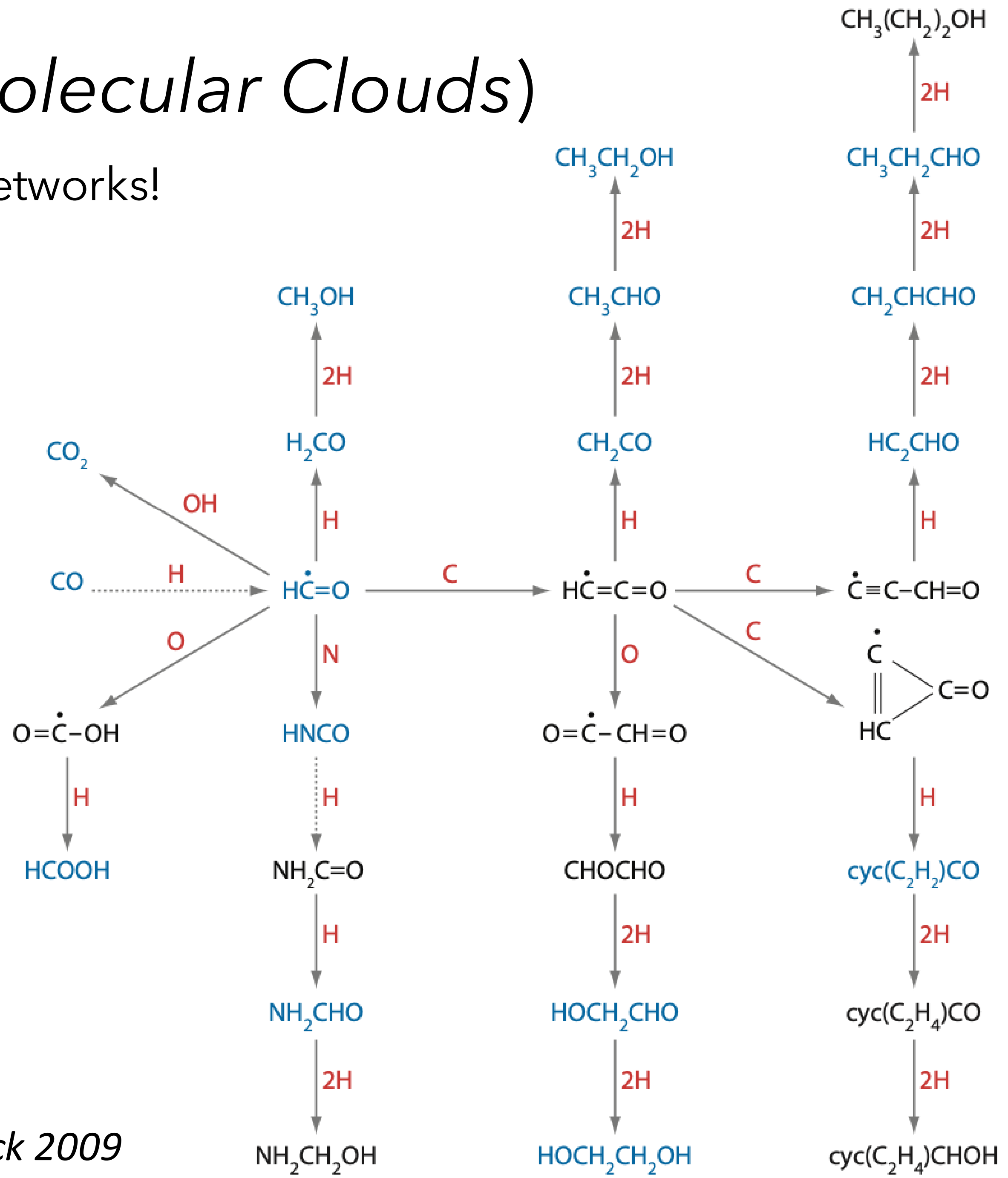
Molecule Formation (*in Molecular Clouds*)

Large chemical reaction networks!

<u>C</u>omplex <u>O</u>rganic <u>M</u>olecules

- Contains at least 6 or more atoms
- Contains at least one carbon atom

- Molecules in blue detected in <u>star-forming molecular clouds</u>!

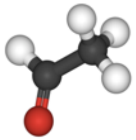


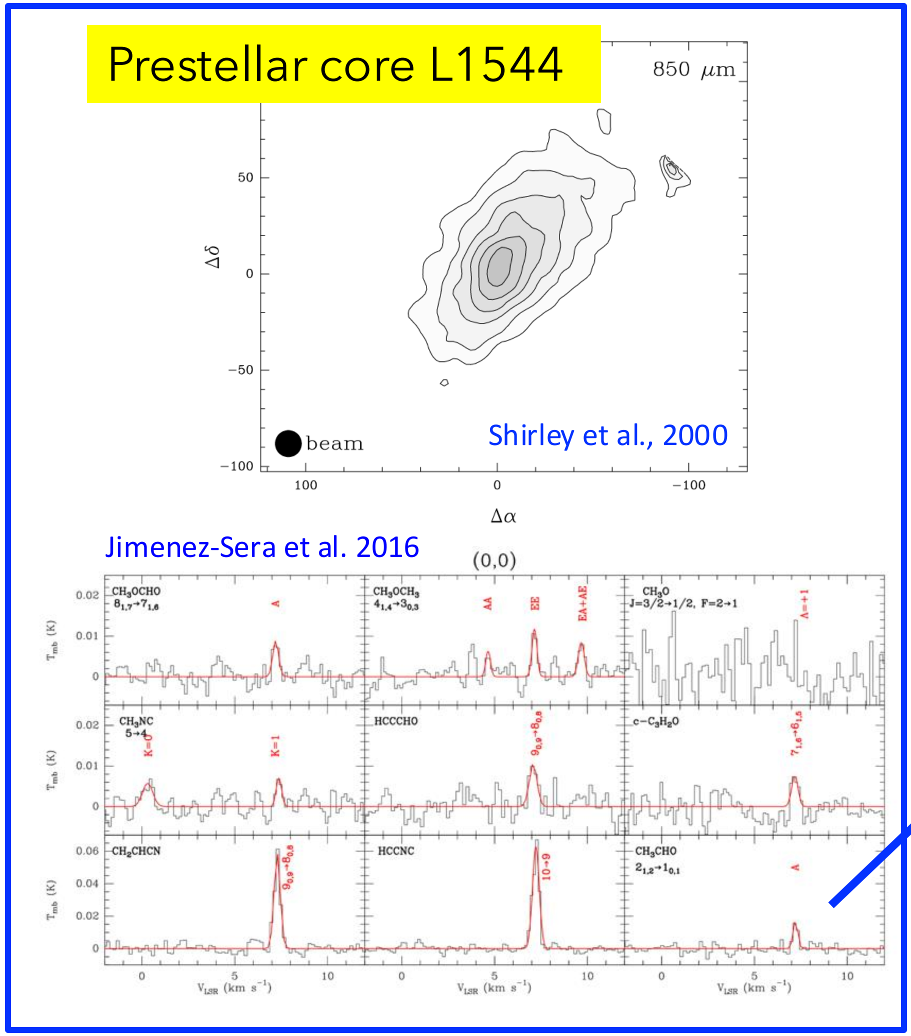
Herbst & van Dishoeck 2009

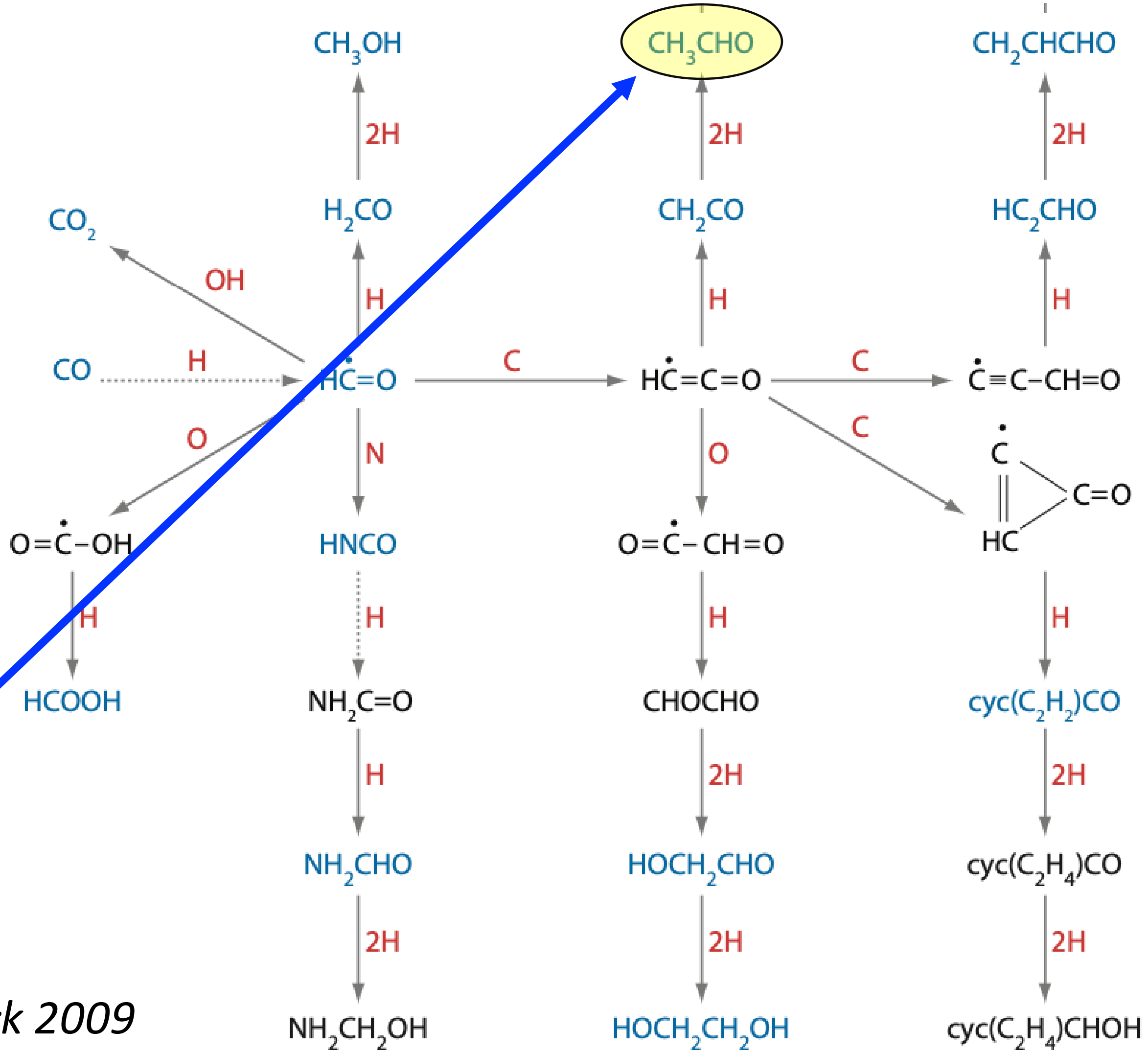
Molecule Formation (*in Molecular Clouds*)

Large chemical reaction networks!

Acetaldehyde
CH_3CHO





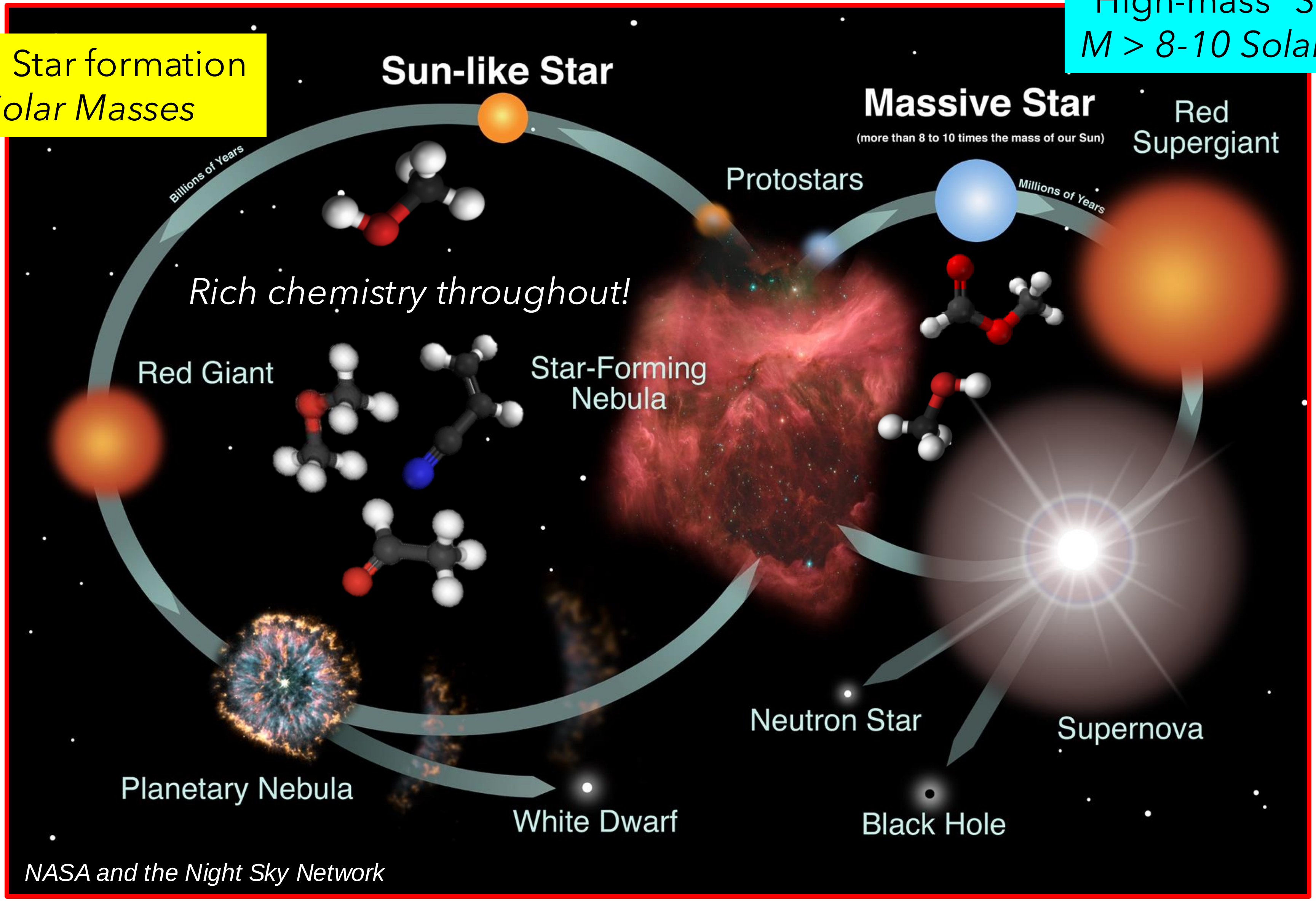


Herbst & van Dishoeck 2009

Evolved Stars – the end stage of star formation

"High-mass" Star formation
M > 8-10 Solar Masses

"Low-mass" Star formation
M < a few Solar Masses



Evolved Stars – the end stage of star formation!

+ Dust Formation!

- **IMPORTANT** in astrochemistry because material is cycled back to the ISM!
- Mass loss from evolved stars

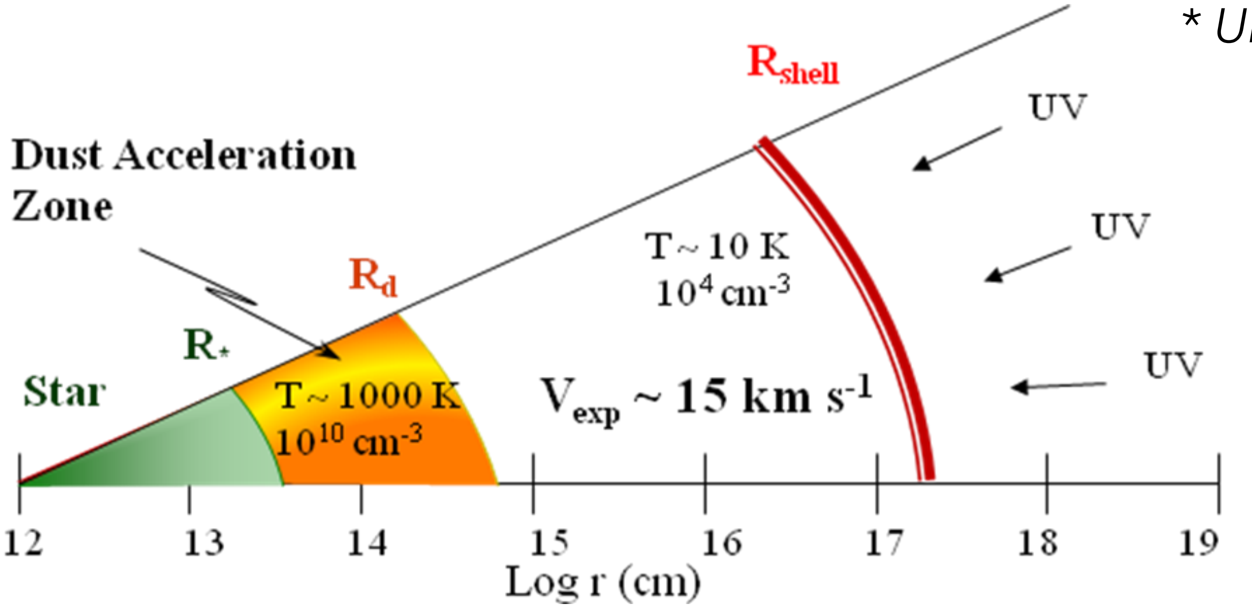
  ⇒ ***Supplies 85% of material in ISM***

- Material cycled in

  circumstellar shells ⇒

- Shell is COOL; ***Dust grains form***
- Molecules also form there then transported outward

* *Universe 99% gas (mostly hydrogen), 1% dust (by mass)*

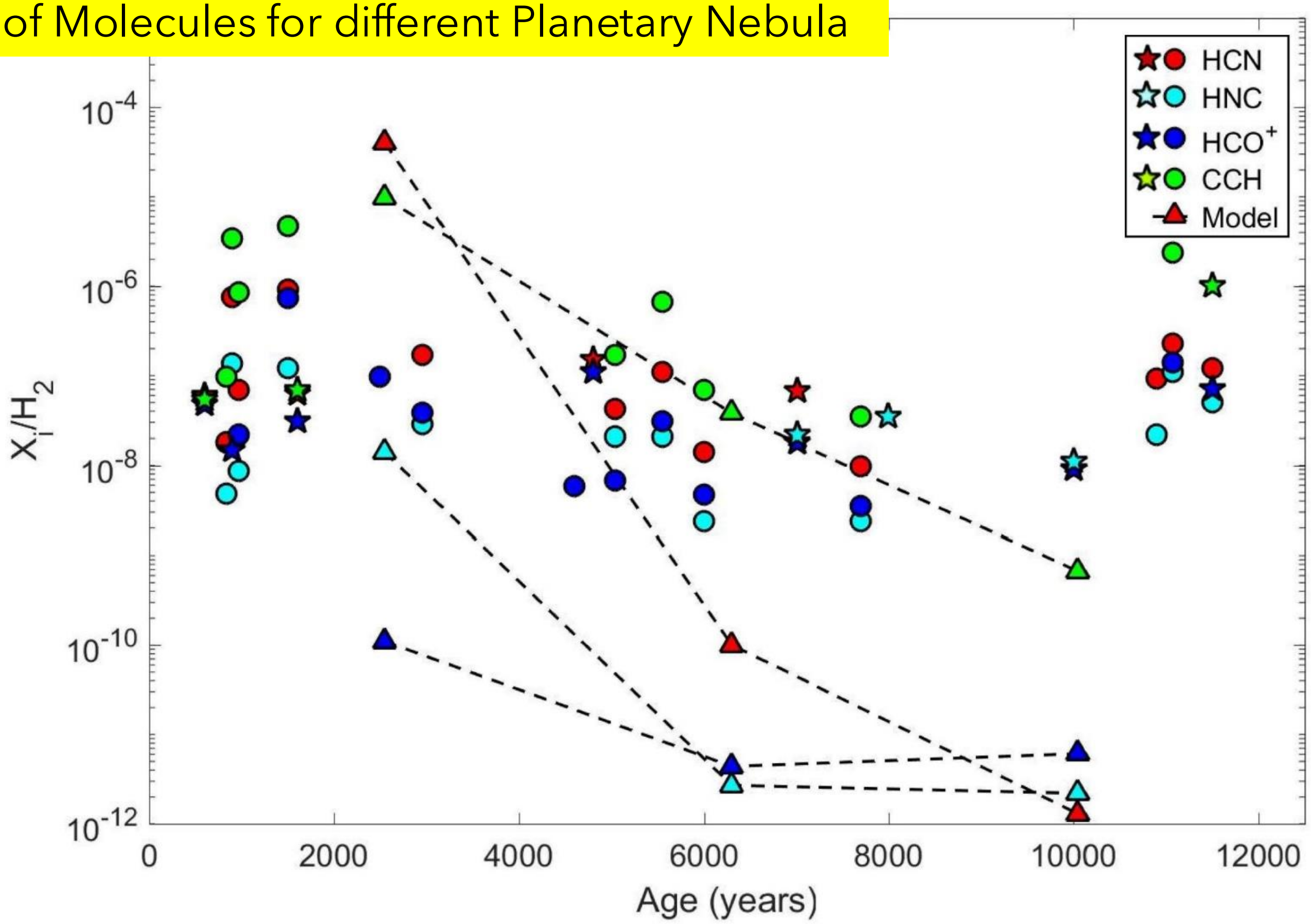


Credit: L. Ziurys

Chemistry in **Planetary Nebula** – Observations vs. Models

Abundance of Molecules for different Planetary Nebula

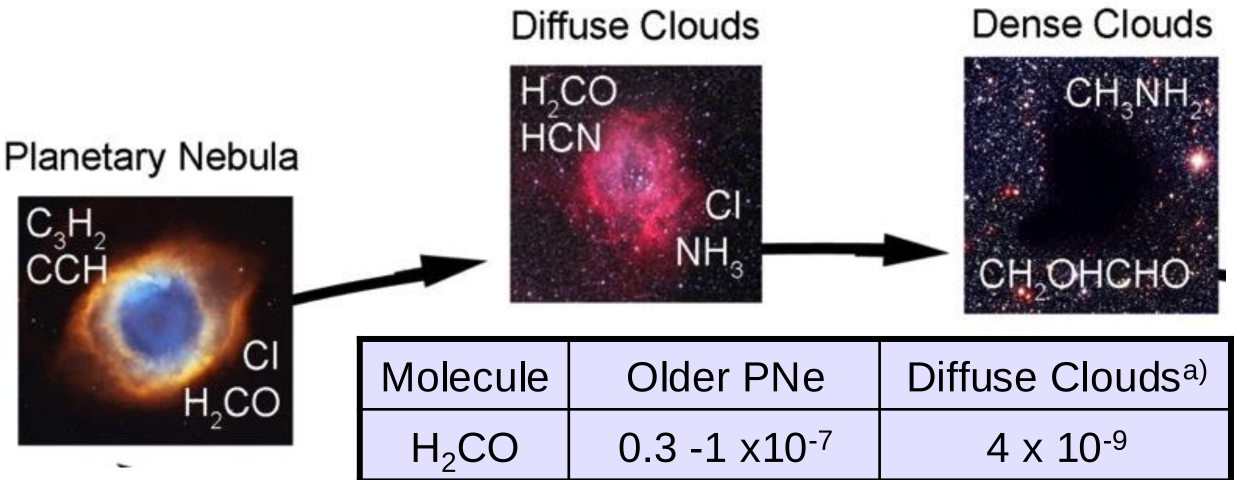
- Molecule abundances stay *constant with age*
- Not destroyed by Photodissociation
- Survive in dense clumps! with $n(H_2) \sim 10^6$ cm^{-3}
- Molecular clumps ejected into diffuse ISM
- ***Preserve C-enrichment***



Credit: L. Ziurys

Planetary Nebula connection to **Diffuse Clouds**

- Planetary Nebulae **disperse into diffuse ISM**
- Molecular gas entering diffuse ISM in clumps
- Evidence from Observations of **Diffuse Clouds**
- Diffuse Clouds and Planetary Nebulae similar set of **molecules**



Molecular Abundances →

Molecule	Older PNe	Diffuse Clouds[a)]
H_2CO	$0.3 - 1 \times 10^{-7}$	4×10^{-9}
C_2H	1×10^{-6}	3×10^{-8}
$c\text{-}C_3H_2$	1×10^{-8}	1×10^{-9}
CO	$0.5 - 9 \times 10^{-4}$	3×10^{-6}
CN	3×10^{-6}	2×10^{-8}
HCN	5×10^{-7}	3×10^{-9}
HNC	3×10^{-7}	6×10^{-10}
HCO^+	$0.1 - 5 \times 10^{-8}$	2×10^{-9}
SO	$0.2 – 2 \times 10^{-7}$	8×10^{-10}
CS	2.8×10^{-8}	1×10^{-9}

a) Liszt et al. 2006

Credit: L. Ziurys