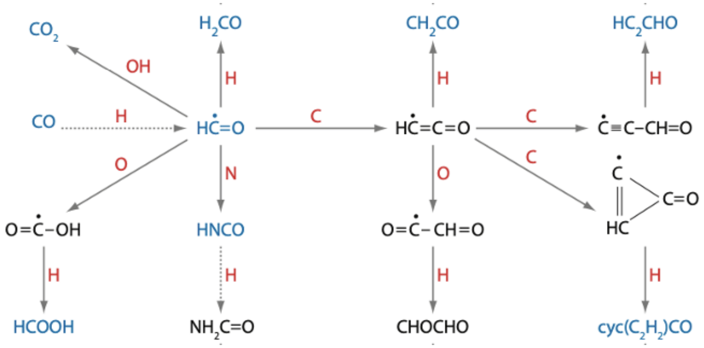


Introduction to Astrochemistry **Part 2:**

Molecular Clouds and the Formation of Stars and Planets

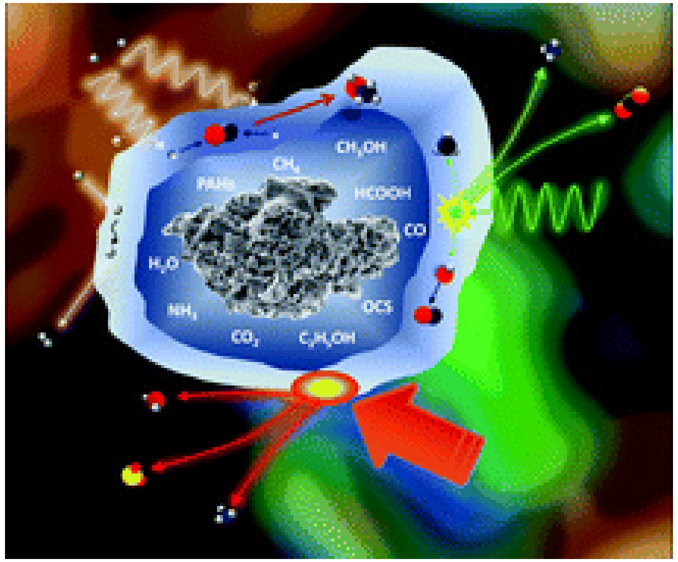
Dr. Samantha Scibelli

Jansky Fellow at the National Radio Astronomy Observatory (NRAO)

AAA.org Lecture, May 28th, 2024

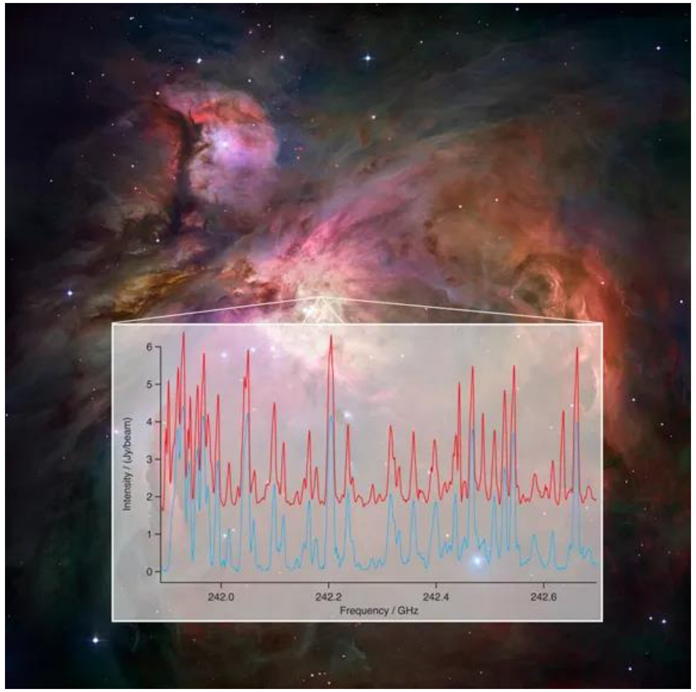
Astrochemistry is an interdisciplinary field! Including, chemistry, physics, astronomy, biology, etc.,

Modeling



Things an astro**chemist** does

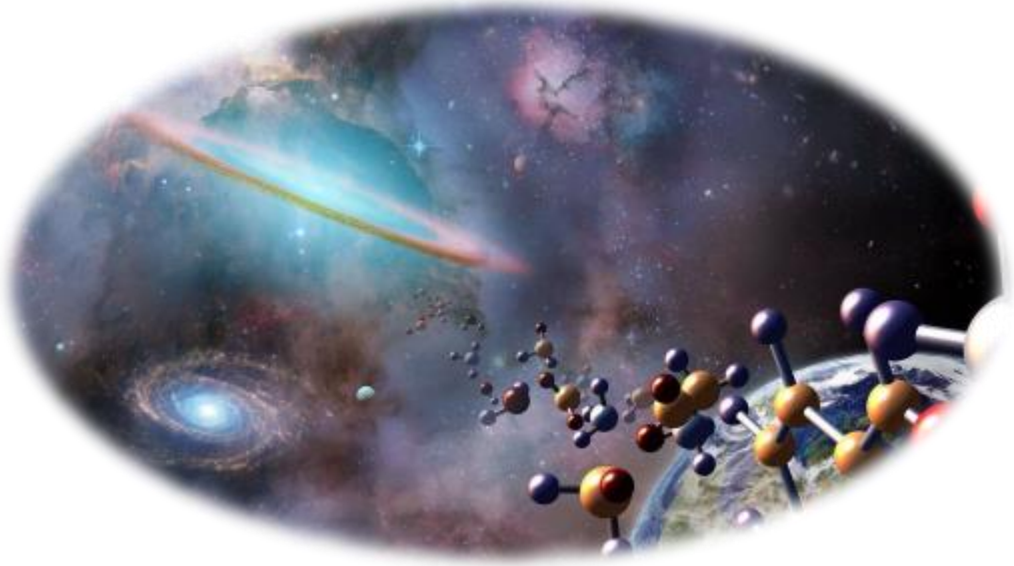
Observations



Laboratory

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

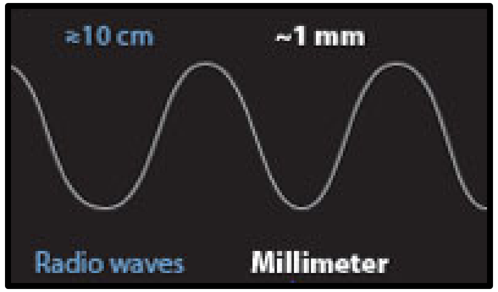


*I write about molecules with great diffidence, having not yet rid myself of the tradition that **atoms are physics, but molecules are chemistry**, but the new conclusions that hydrogen is abundant seems to make it likely that the above mentioned elements H, O, and N will frequency form molecules*

- *Sir A. Eddington, 1937*

Submillimeter and Millimeter Radio Telescopes Probe Cool Molecular Gas!

Radio telescopes let us see objects we can't see in visible light – such as the dust and gas inside dense molecular clouds that will form stars like our Sun!



This is the type of object I study! →

Starless Core B68

Visible light image

Starless Core: Birthplace of low-mass stars ($M \leq$ a few $M_\odot$)
Dense (10^4 - 10^5 cm^{-3}) & cold ($\leq$ 10K)

10K = - 441.67° F!
Low temp. at poles of Mars −243 °F

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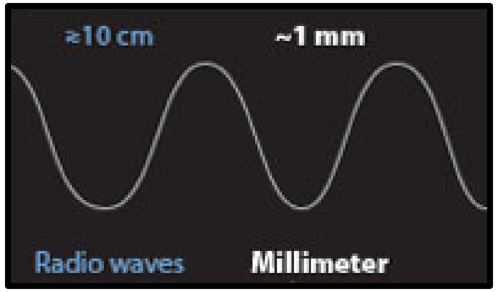

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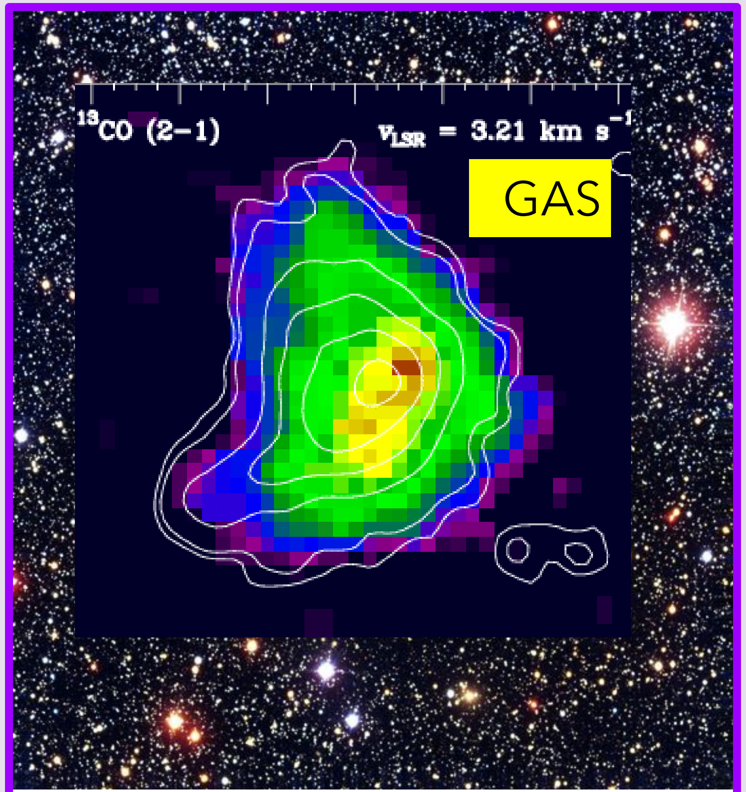
Starless Core B68

Radio light image



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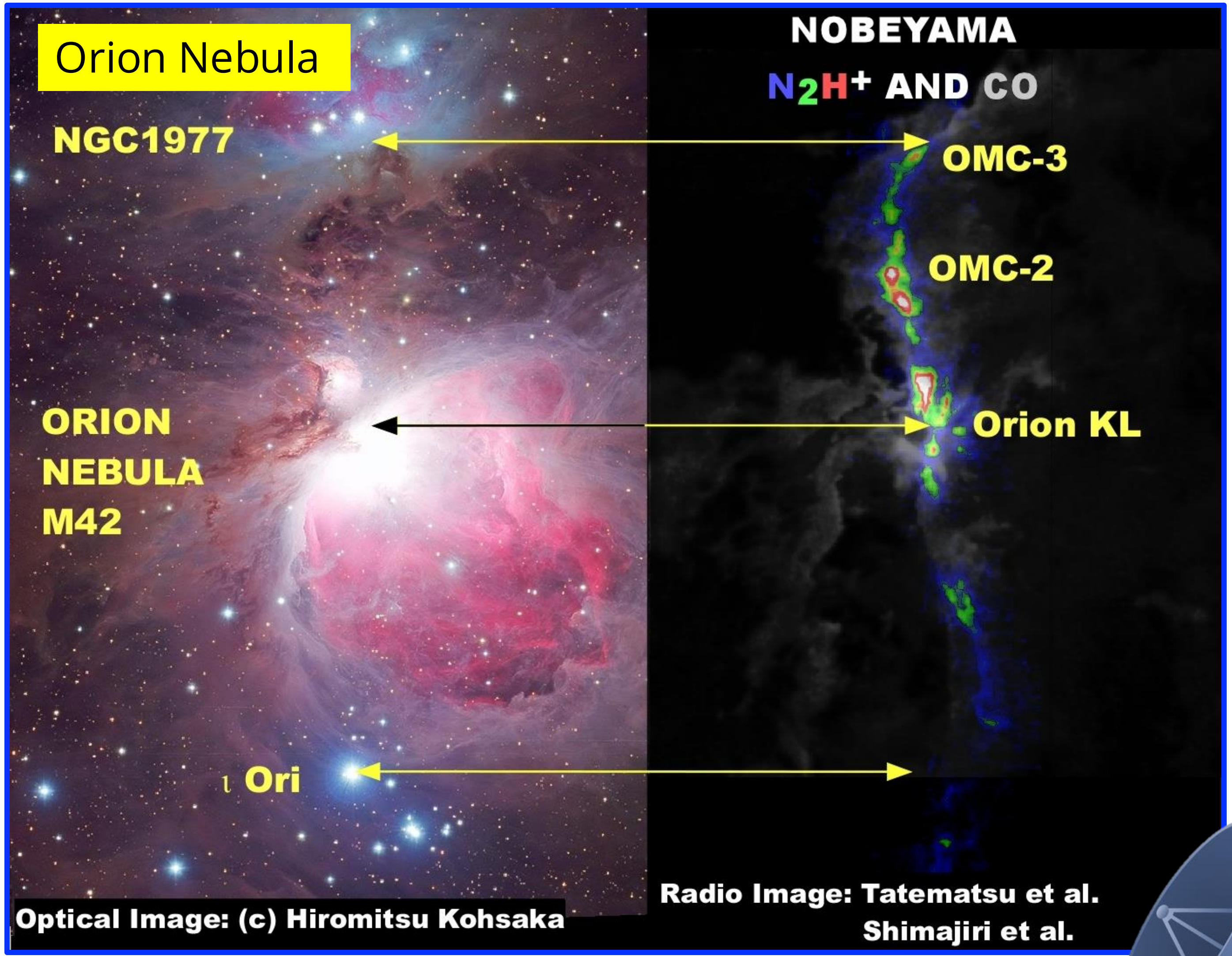
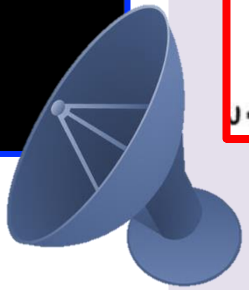
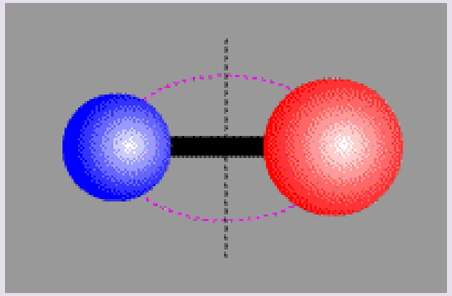


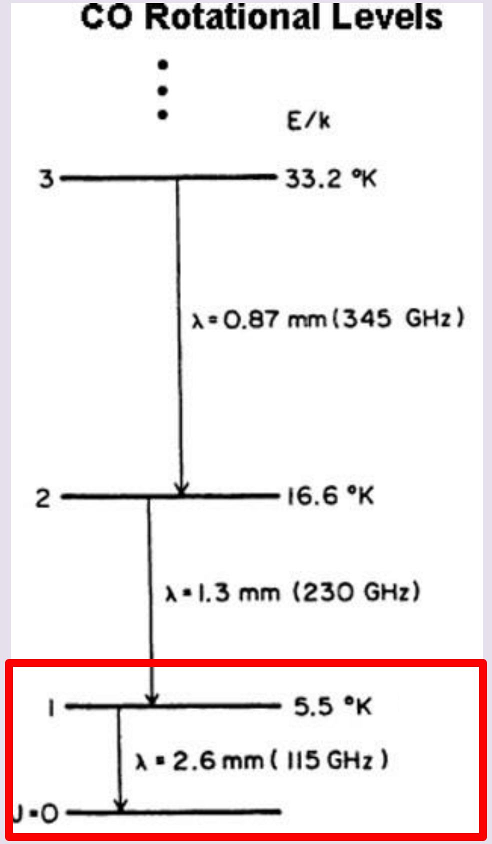
https://www.nro.nao.ac.jp/~kt/html/kt-e.html

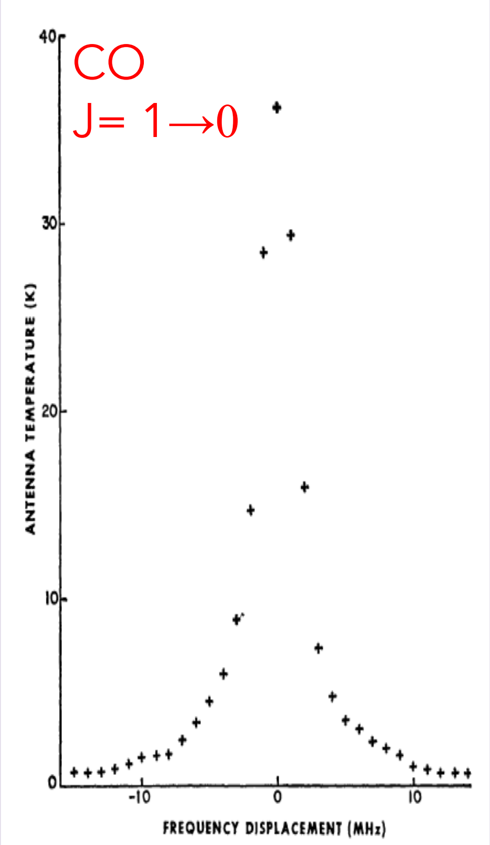


Discovery of CO

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

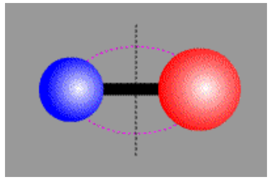




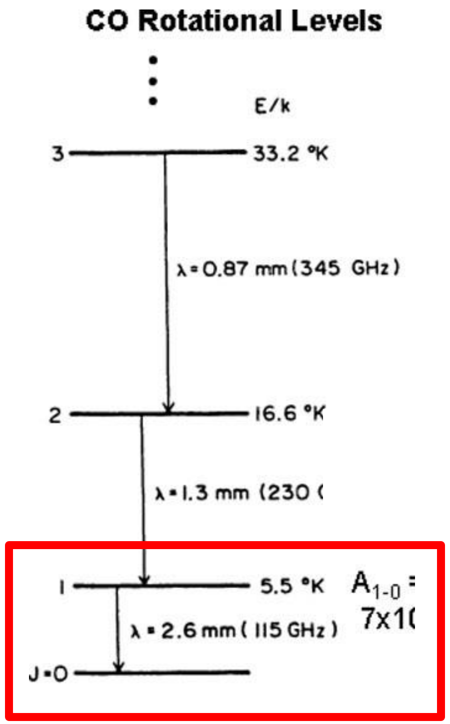


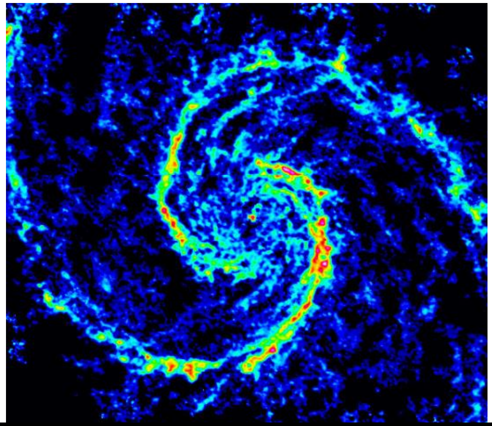
Wilson et al., 1970

Measuring the Molecular **Gas Motions**!



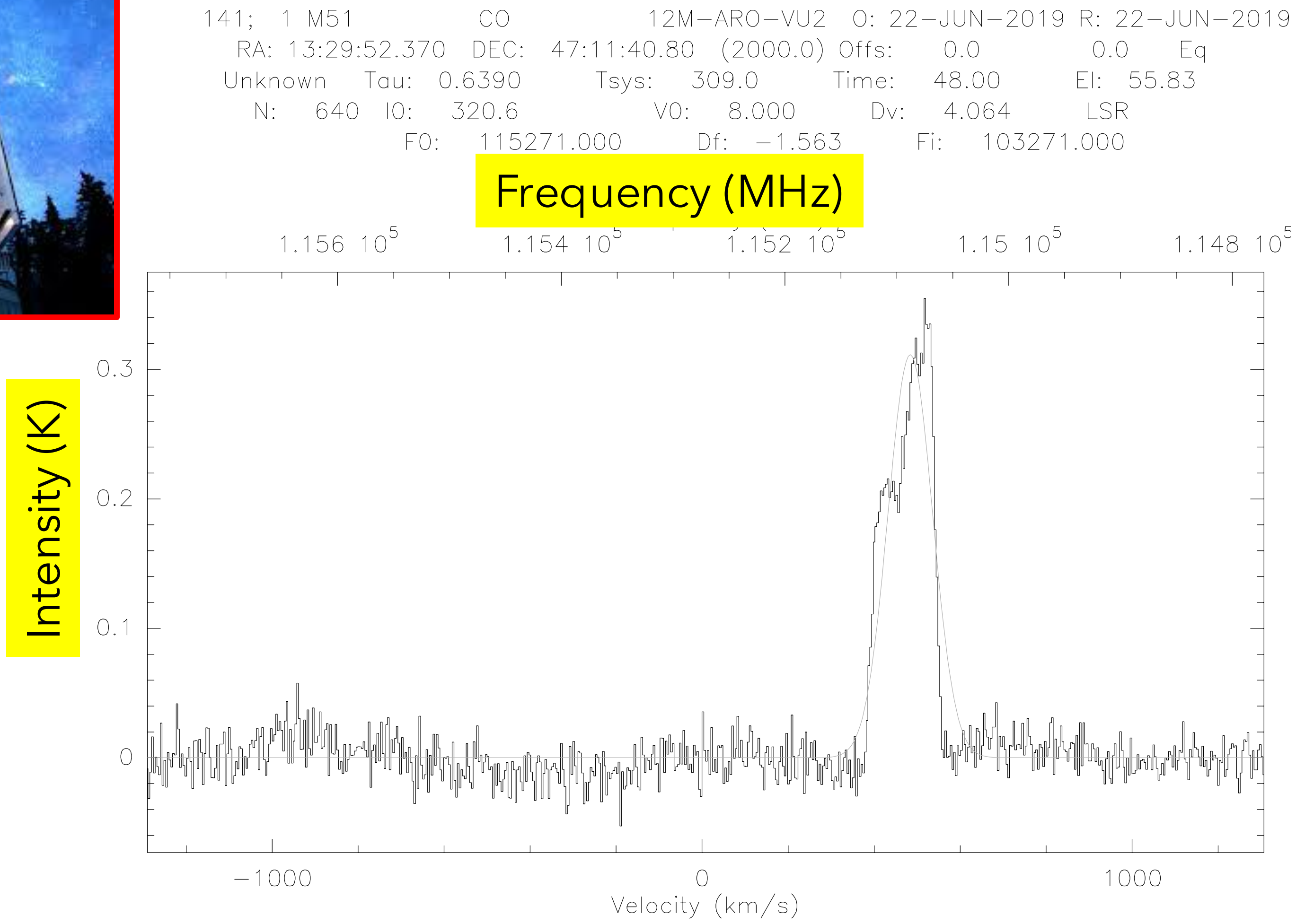
ARO 10m (SMT)



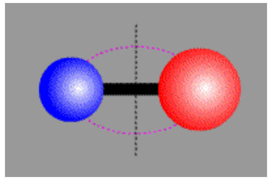


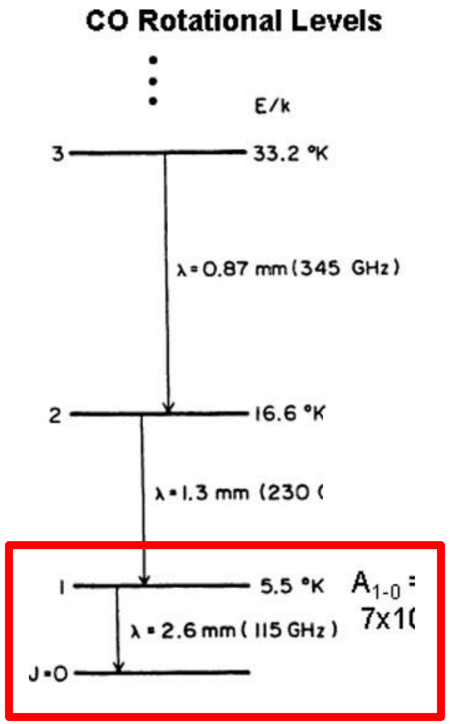
M51 – Whirlpool Galaxy

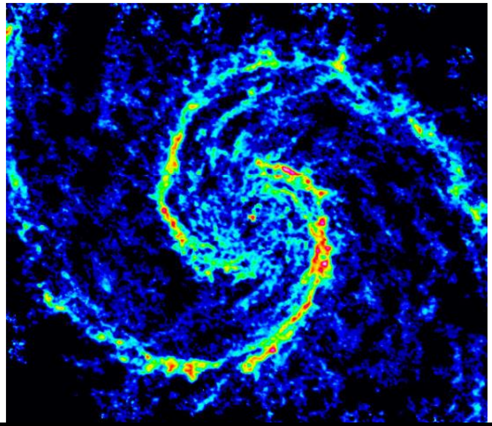
CO at 115 GHz ($J = 1 \rightarrow 0$)



Measuring the Molecular **Gas Motions**!







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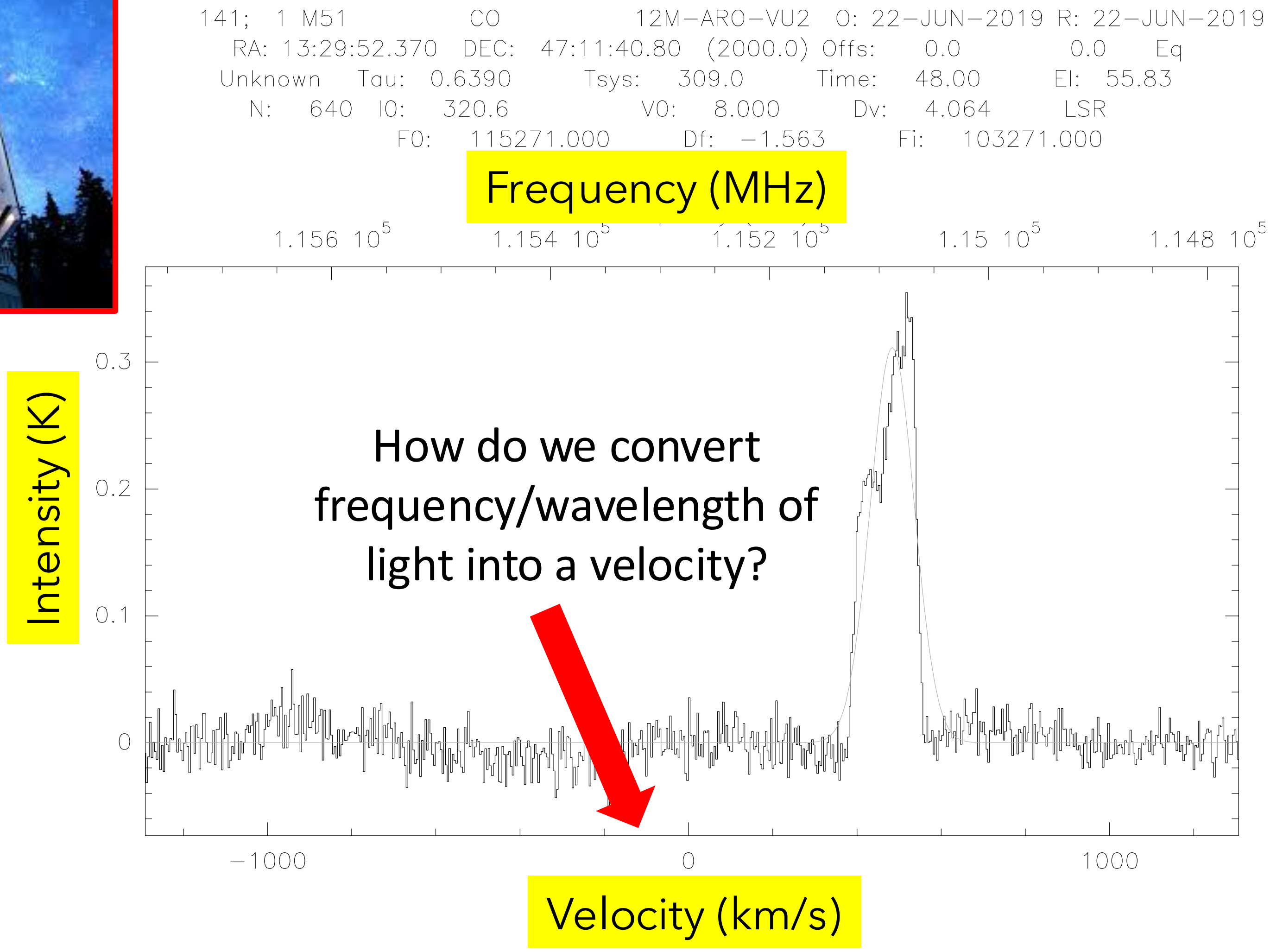
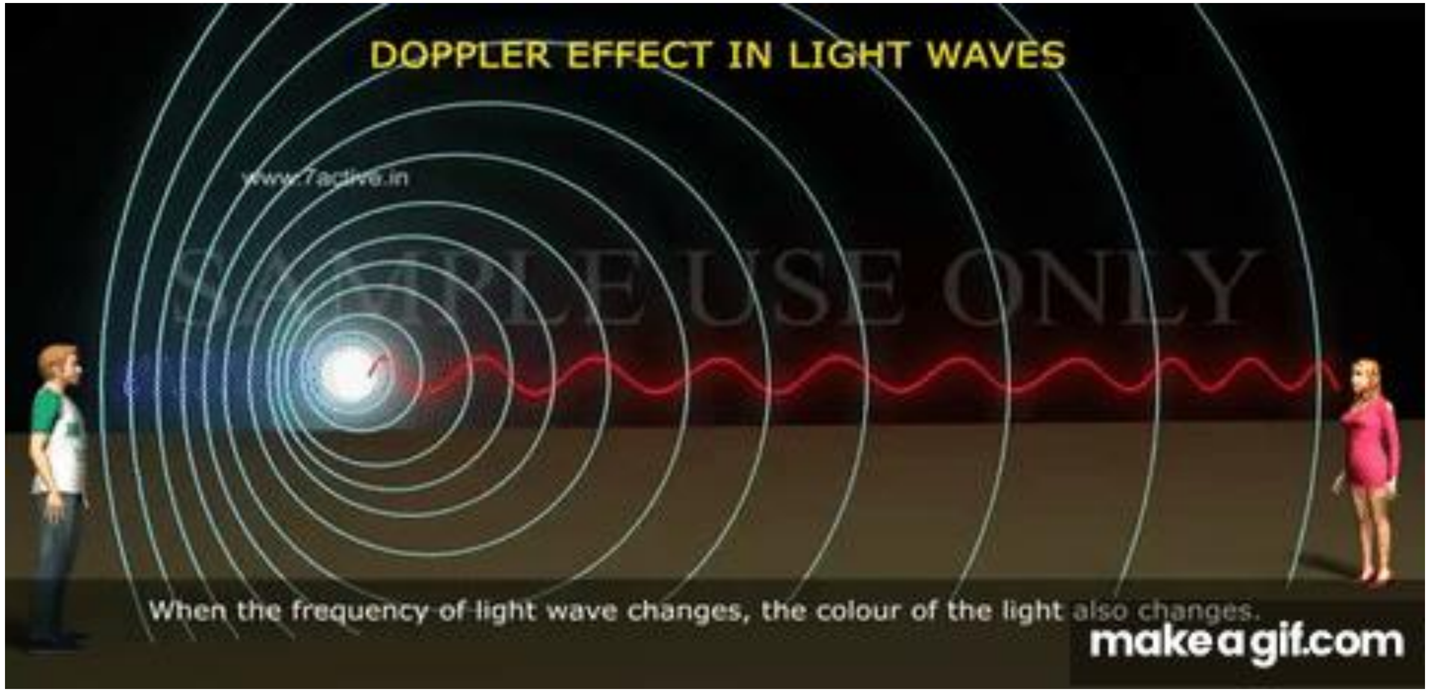




The Doppler Effect!

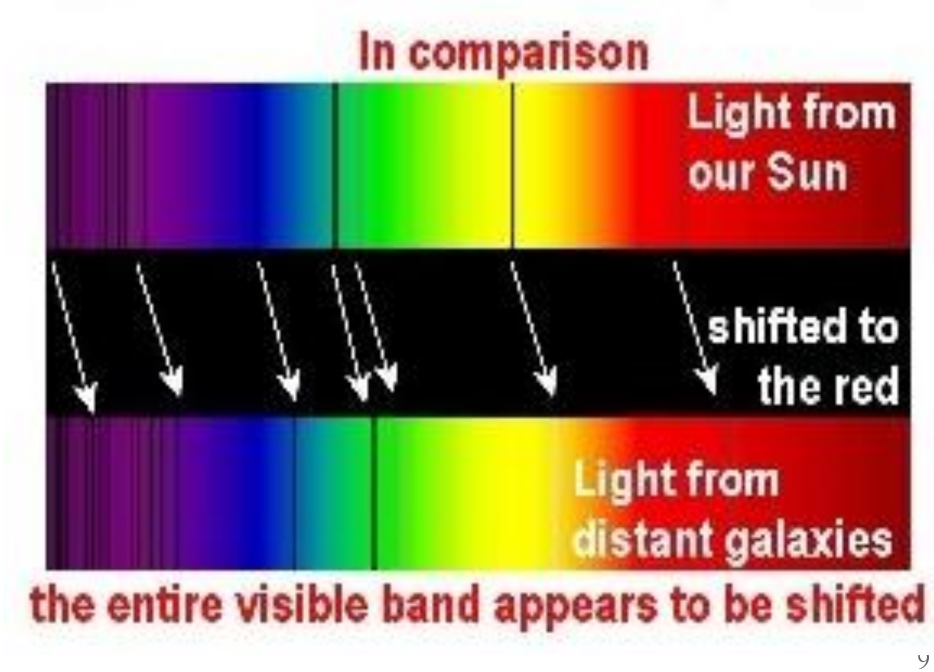
$$v = c\frac{\Delta\lambda}{\lambda}$$

Velocity

Change in Wavelength

Rest Wavelength

Speed of light



$$v = c\frac{\Delta\lambda}{\lambda}$$

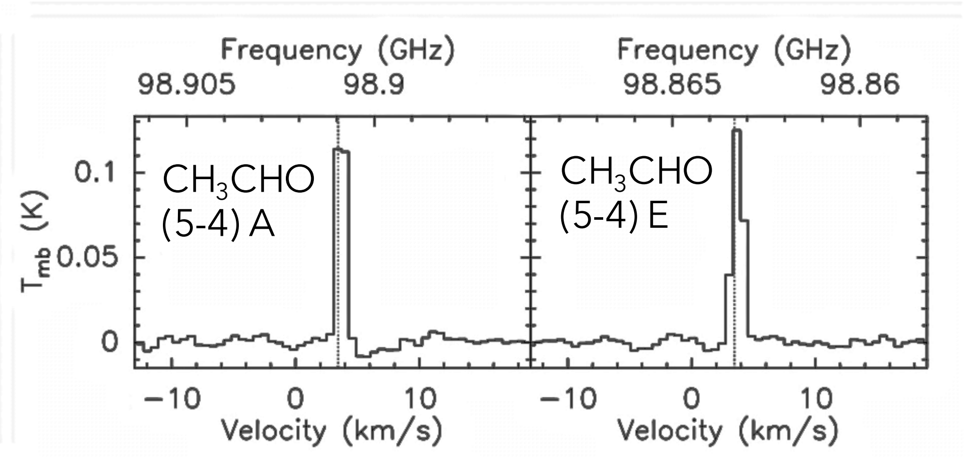
Velocity

Change in Wavelength

Rest Wavelength

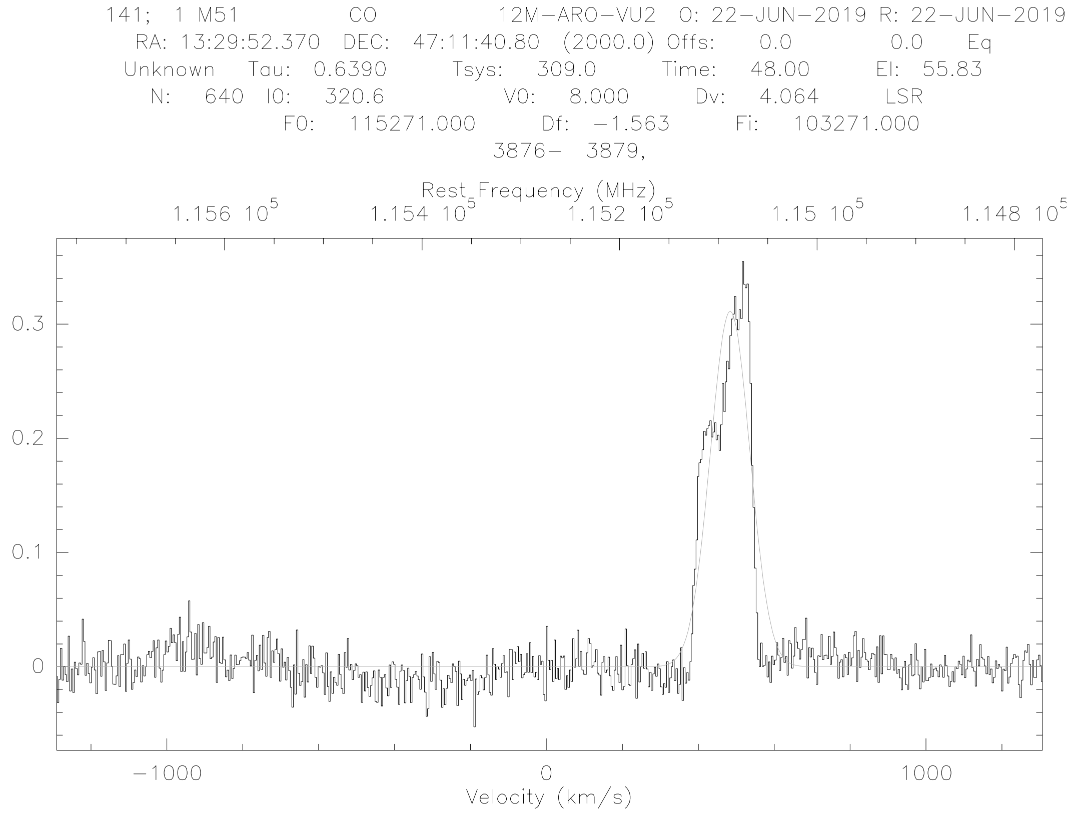
Speed of light

Galactic source, line-of-sight velocity a few km/s

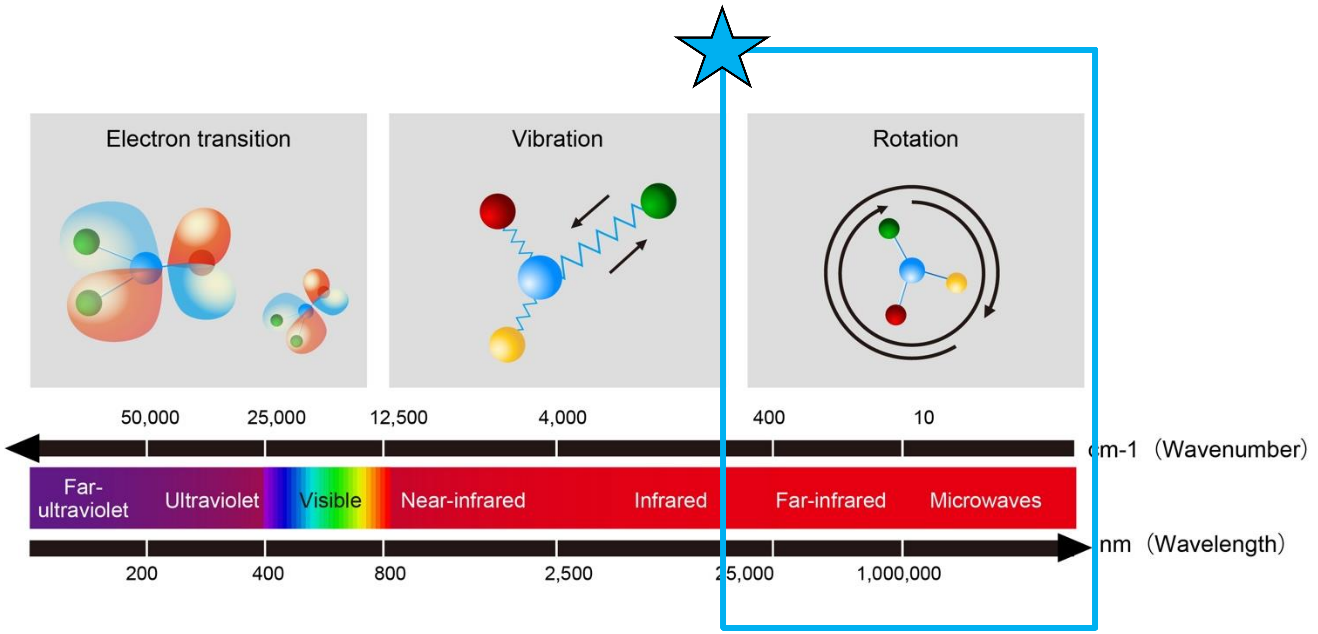


Bacmann et al. 2012

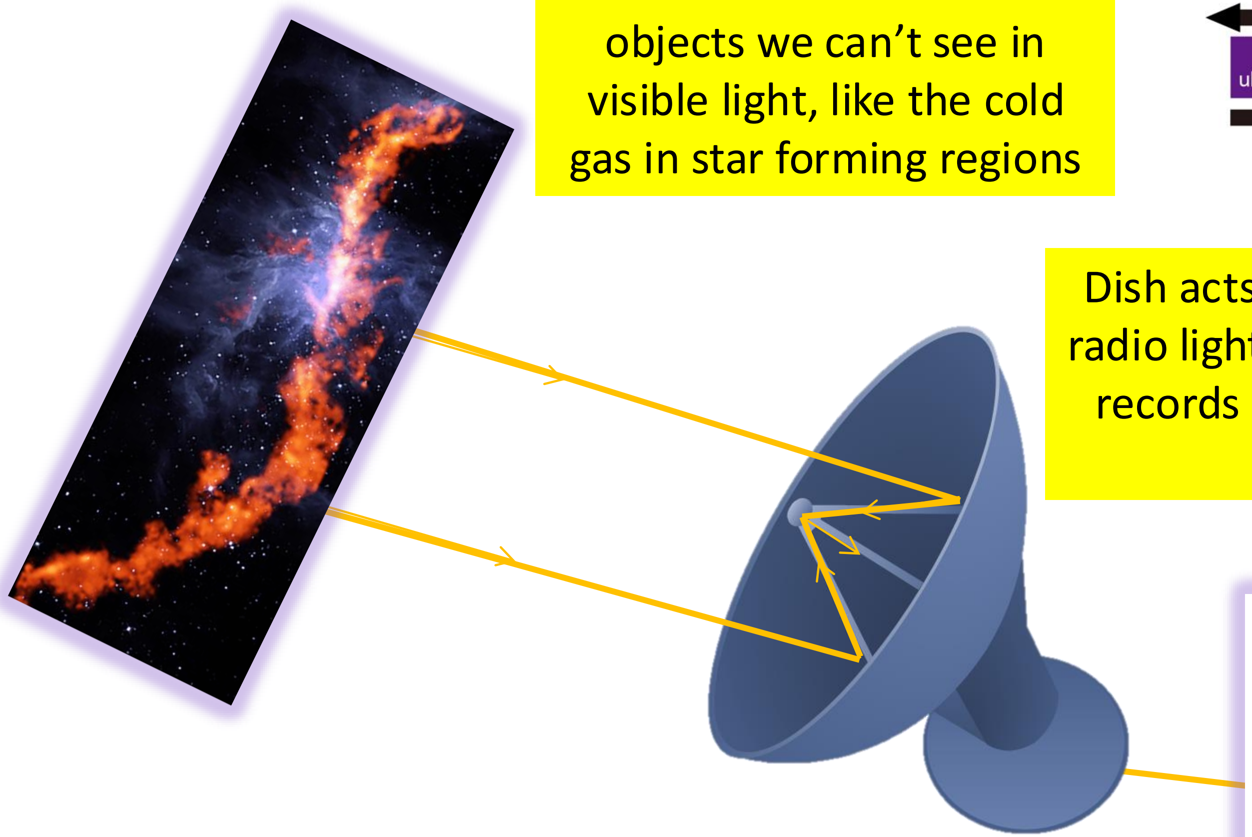
Extragalactic source, line-of-sight velocities a few hundred km/s



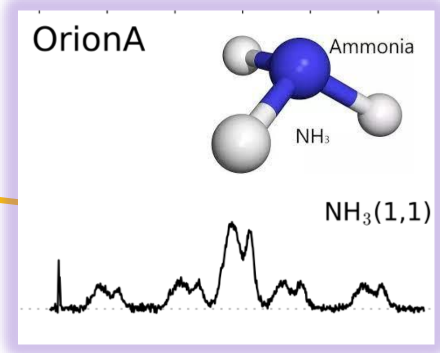
Submillimeter and Millimeter Radio Telescopes Identify Molecules via Rotational Spectroscopy!



Radio waves let us see objects we can't see in visible light, like the cold gas in star forming regions

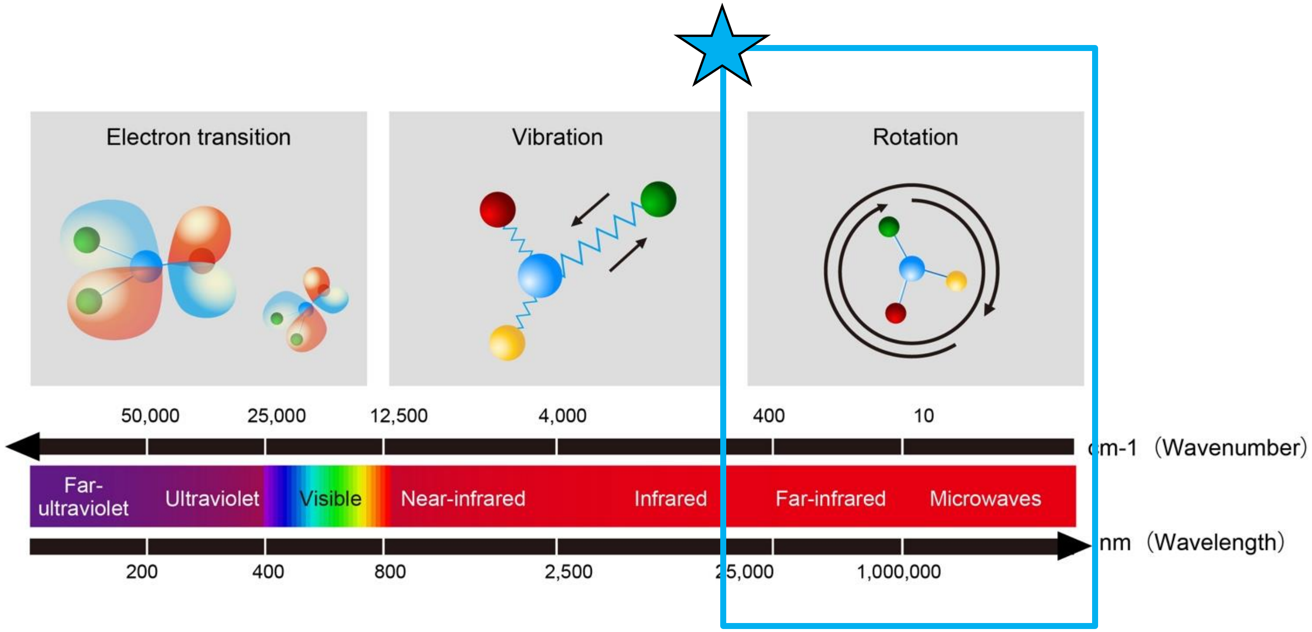


Dish acts like a mirror and focuses long wavelength radio light onto electronic device that receives it and records an objects' ***spectrum***, i.e., it's intensity vs. frequency (or wavelength)



We know if a bright line occurs where a certain molecule is predicted to emit at, **we have identified that molecule**!

Submillimeter and Millimeter Radio Telescopes Identify Molecules via Rotational Spectroscopy!



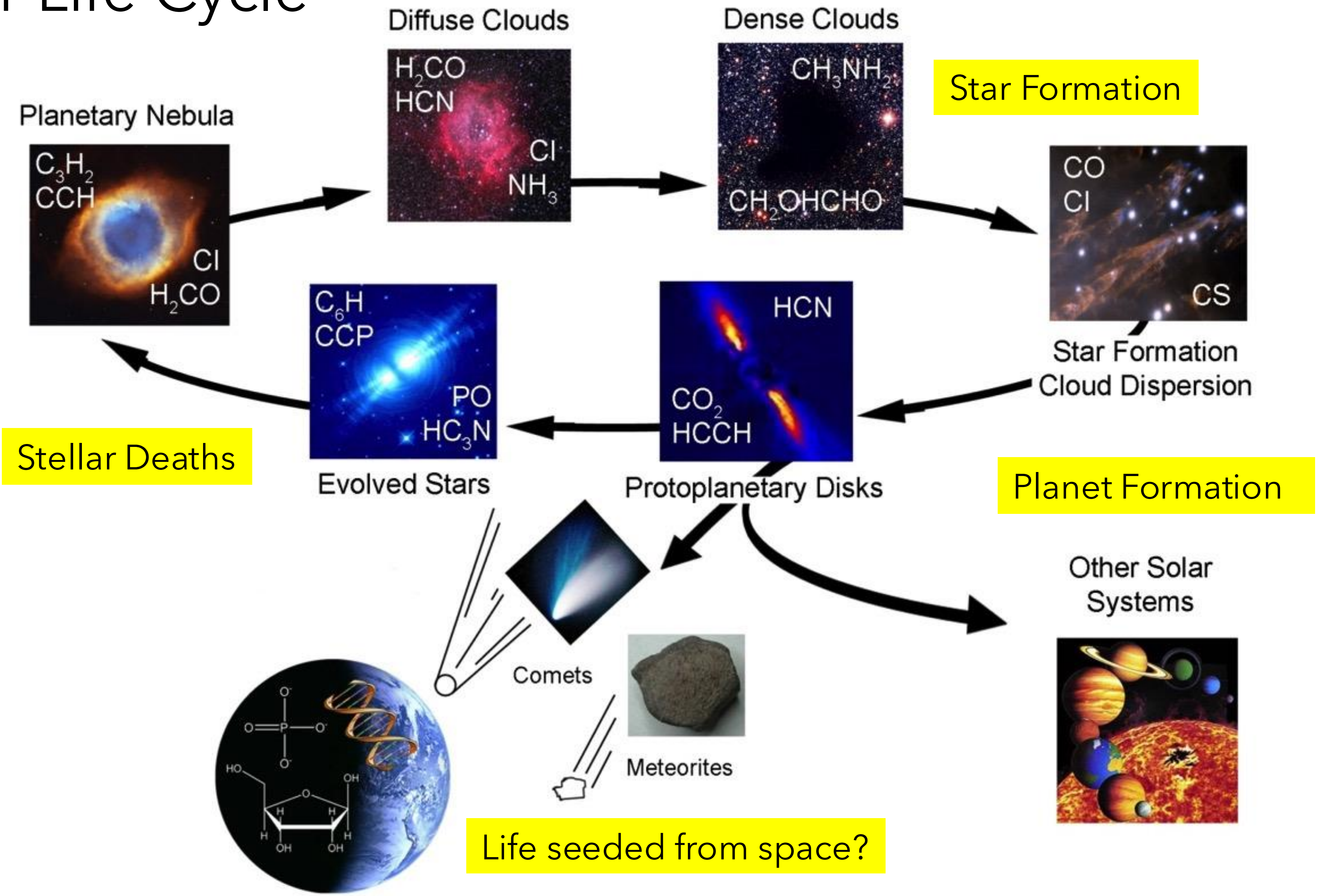
How do we know what frequency?
Online databases of laboratory measurements!

Home Basic Advanced FAQ OSU

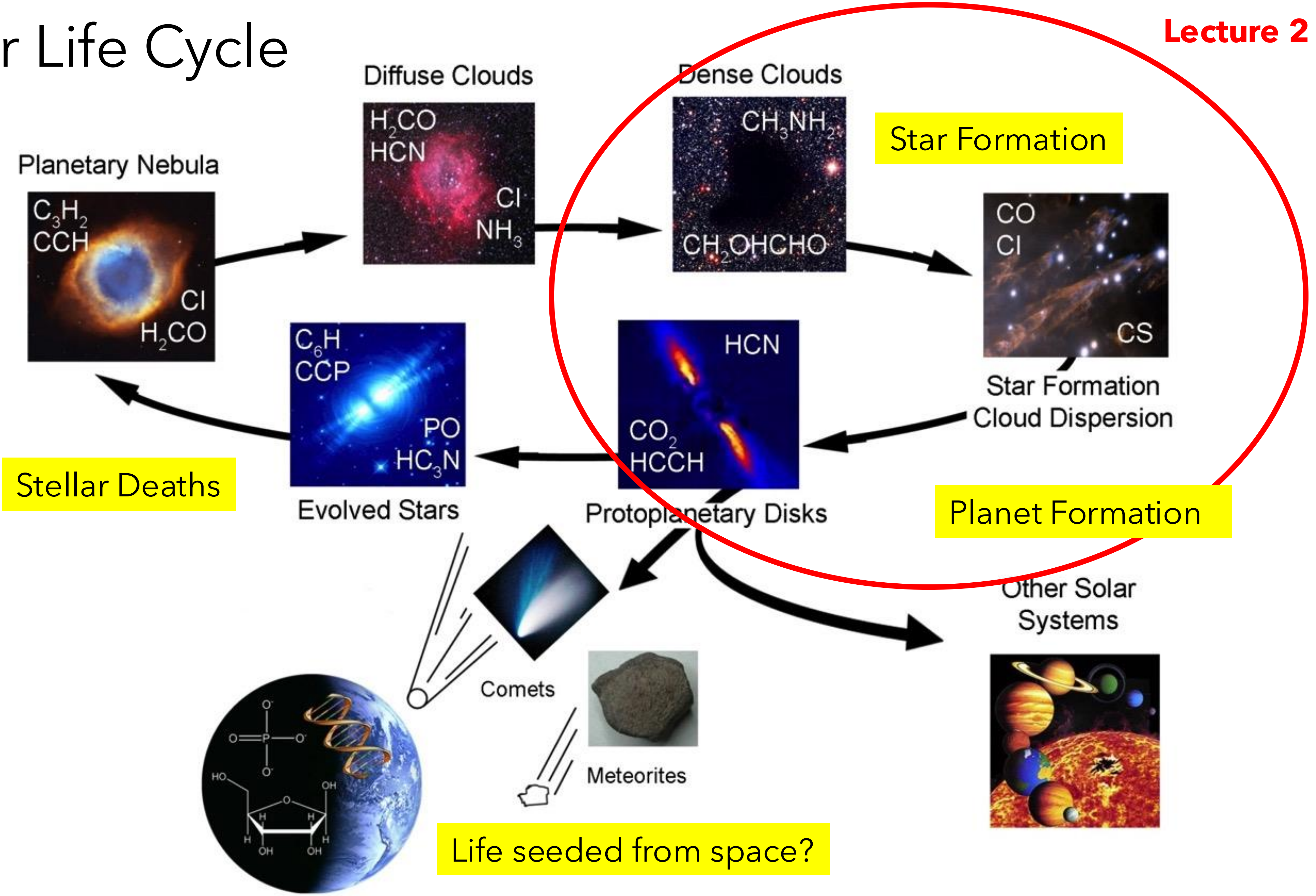
#	Species	Chemical Name	Ordered Frequency (GHz) (rest frame, redshifted)	Resolved QNs	CDMS/JPL Intensity	Lovas/AST Intensity	E_L(K)	E_U(K)	Linelist
1	CO v = 0	Carbon Monoxide	115.2712018, 115.2712018	1-0	-5.0105	60.00	0.000	5.53211	CDMS

https://splatalogue.online

Molecular Life Cycle

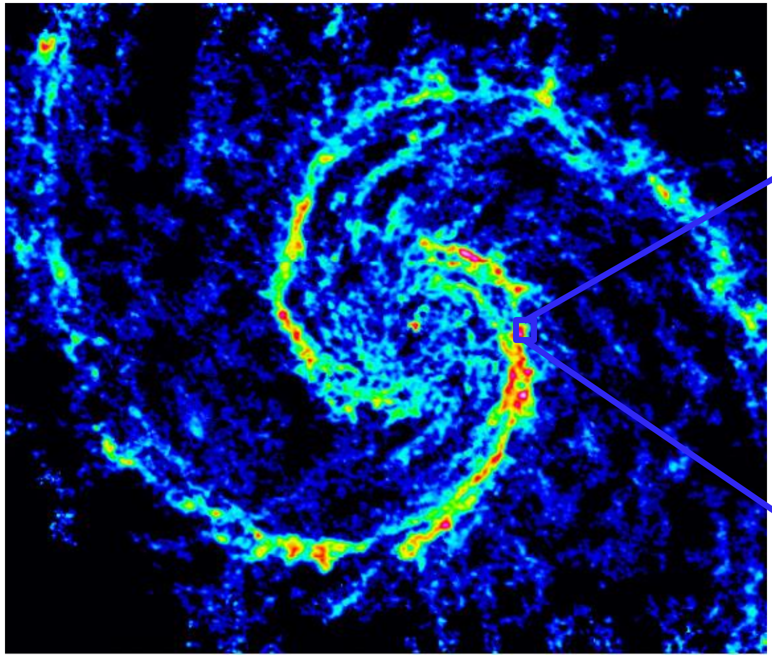


Molecular Life Cycle



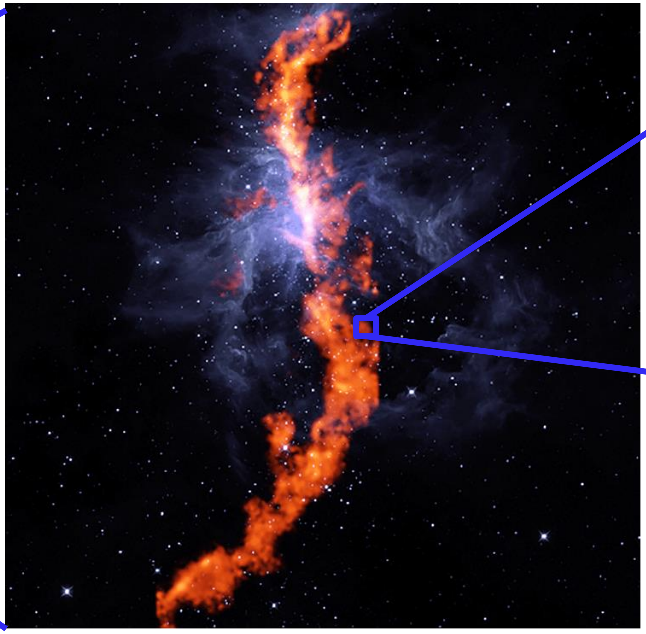
Cool clouds of gas: A birthplace for stars

Galaxy



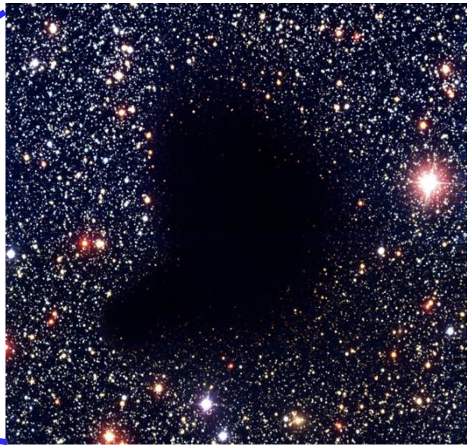
Sizes: ~100,000 light yrs / 30,660 Parsecs

Filamentary Molecular Cloud



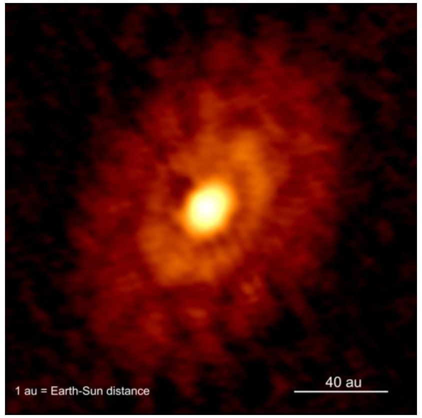
30-40 light yrs / 10's of Parsecs

Dense Starless Core



~ a few x 0.1 parsec

Young Stellar Object



Stars!

~ a few x 0.0001 parsec

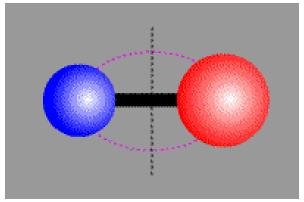
Cool clouds of gas: A birthplace for stars

- Astronomers for centuries: Interstellar Space, realm of atomic material

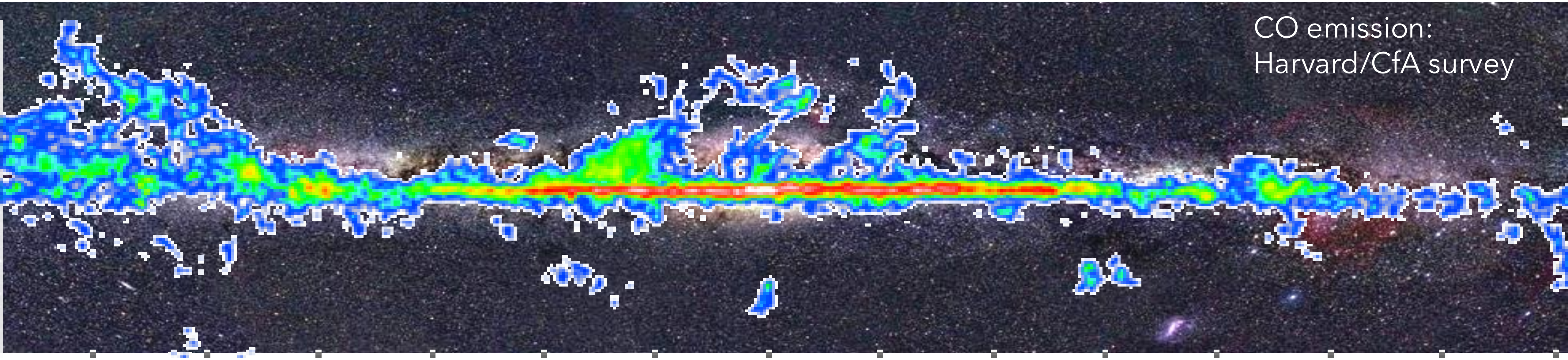
~100,000 light yrs.

Cool clouds of gas: A birthplace for stars and molecules!

- Astronomers for centuries: Interstellar Space, realm of atomic material
- Radio and MILLIMETER astronomy changed the paradigm!



~100,000 light yrs.



- Molecular Gas widespread in the Galaxy (CO: J = 1-0 transition)
- Inner 10 kpc of Galaxy: 50% MOLECULAR ⇒ 10^{10} solar masses

- Molecules in massive, dense clouds: M ~ 1 – 10^6 $M_\odot$
- Typical Conditions: T ~ 10 – 50 K; n ~ 10^3 – 10^6 cm^{-3}: COLD and DIFFUSE

Cool clouds of gas: A birthplace for stars and molecules!

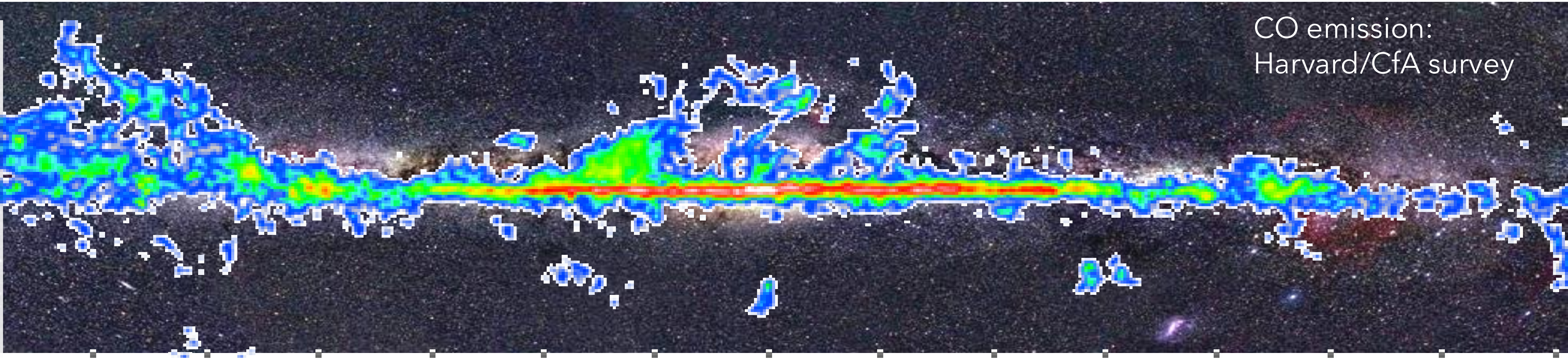
Astronomical scales different from our normal experience!

Molecular clouds live 1,000,000 – 10,000,000 yrs.

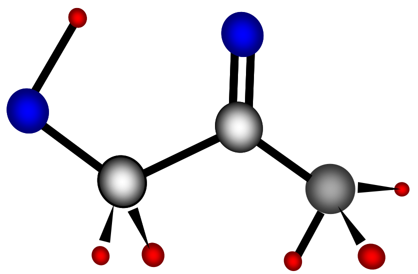
Motions/Speeds: 1 km/s ~ 3600 km/hour is about 5 x faster than a jet plane (at this speed, 4 days to Moon or 5 days to the Sun or 1 million years to the nearest star!

1 km/sec = 1 parsec (3.26 light yrs.) in 1 million years

~100,000 light yrs.



Molecule Formation

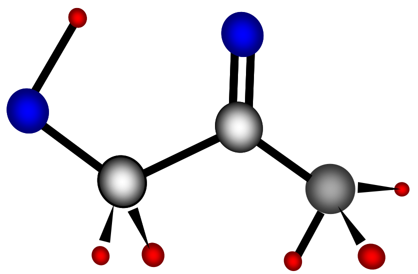


Despite different physical conditions and timescales, molecules do form!

- 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!**

Molecule Formation



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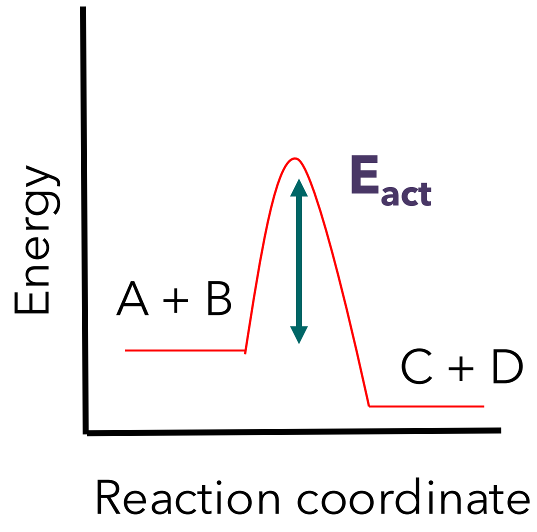


*A reaction that results in products of greater stability (lower energy) than the reactants gives off energy and is said to be **exothermic***

- **Severely restricts allowed chemical processes!**
  - *only two body collisions*
    - *i.e, three-body reactions such as*

      $A + B + C \rightarrow ABC* \rightarrow AB + C$

      in majority of cases NOT POSSIBLE
  - cannot overcome activation energy barriers E_{act}
  - reactions must be **exothermic!**

Credit: L. Ziurys

Molecule Formation

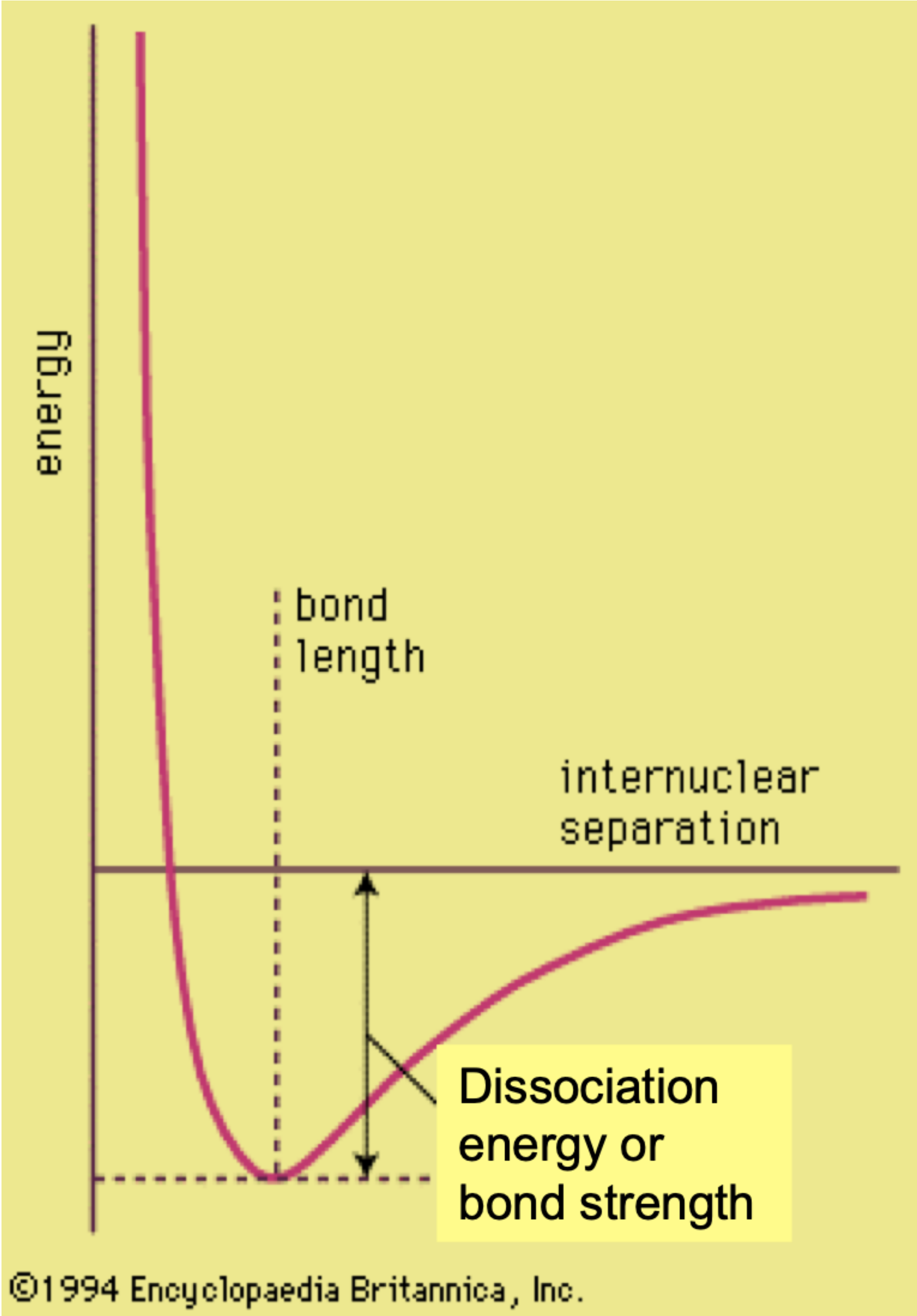
Exothermic?

Molecule	Dissociation energy (eV)
H_2	4.48
CH	3.47
OH	4.39
CH^+	4.09
OH^+	5.10

Which reactions can form?

$C + H_2$ □ $CH + H$?? **$C^+ + H_2$ □ $CH^+ + H$??**

$O + H_2$ □ $OH + H$?? **$O^+ + H_2$ □ $OH^+ + H$??**



Credit: P. Caselli

Molecule Formation

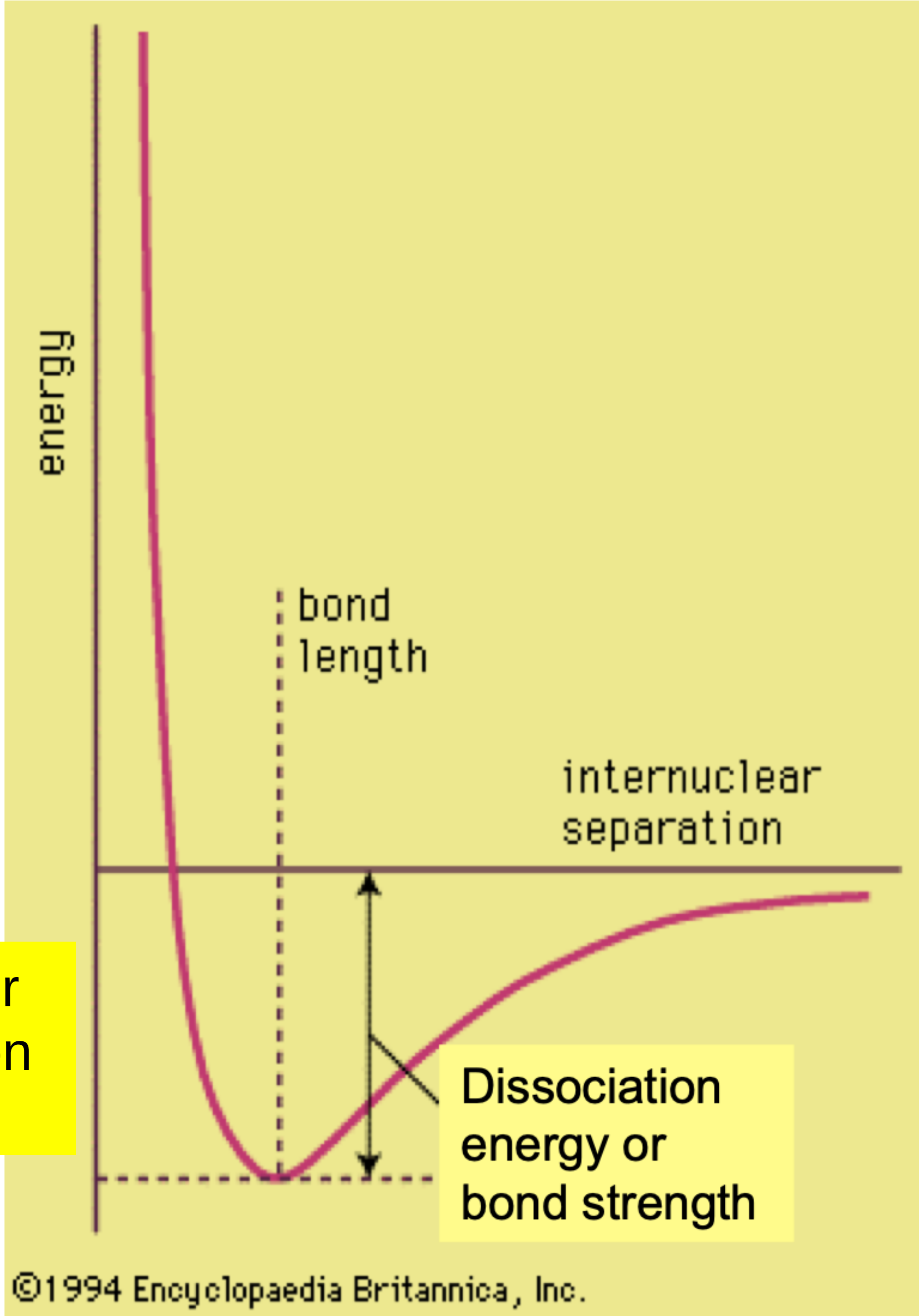
Exothermic?

Molecule	Dissociation energy (eV)
H_2	4.48
CH	3.47
OH	4.39
CH^+	4.09
OH^+	5.10

C + H_2 □ CH + H ??

4.48eV vs. 3.47 eV

The bond strength of H_2 is larger than that of CH thus, the reaction is **not energetically favorable**!



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Molecule Formation

Exothermic?

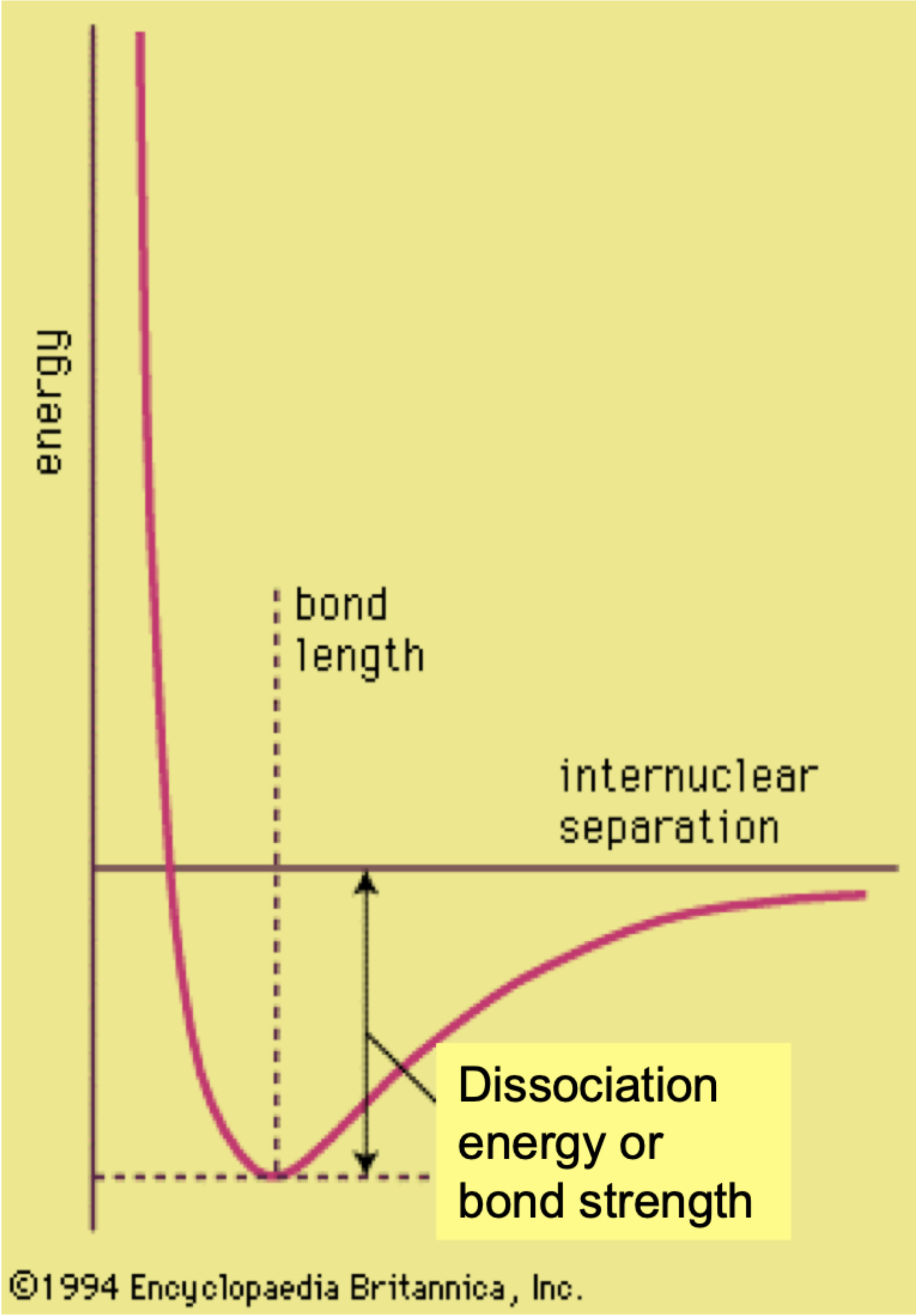
Molecule	Dissociation energy (eV)
H_2	4.48
CH	3.47
OH	4.39
CH^+	4.09
OH^+	5.10

$C + H_2 \rightarrow CH + H$?? (endothermic by 1.11 eV)

$C^+ + H_2 \rightarrow CH^+ + H$?? (endothermic by 0.39 eV)

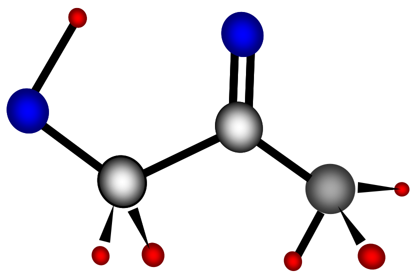
$O + H_2 \rightarrow OH + H$?? (endothermic by 0.09 eV)

$O^+ + H_2 \rightarrow OH^+ + H$?? (exothermic by 0.62 eV!)



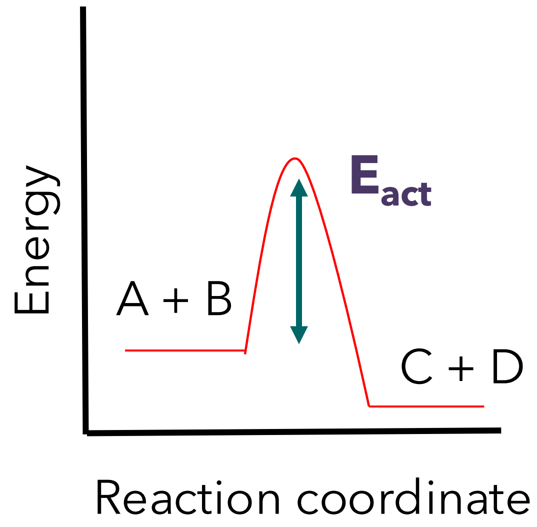
Credit: P. Caselli

Molecule Formation



Despite different physical conditions and timescales, molecules do form!

Reactions (gas-phase) that ARE possible:



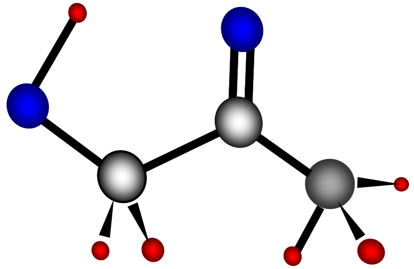
* ION-MOLECULE

$$\mathbf{A + B^+ \rightarrow C + D^+}$$

- Two-body and typically exothermic with no E_{act}
- roughly 50% have no reaction barriers
- proceed quickly (fast collisional rates)
- **networks of Ion-Molecule reactions create interstellar molecules**
- only reactions fast enough to form chemical species given cloud lifetimes (t ~ 10^6 yrs.)

Credit: L. Ziurys

Molecule Formation



Despite different physical conditions and timescales, molecules do form!

Types of ION-MOLECULE reactions

1) Hydrogen Abstraction: $A^+ + H_2 \rightarrow AH^+ + H$

$O^+ + H_2 \rightarrow OH^+ + H$
$OH^+ + H_2 \rightarrow H_2O^+ + H$
$H_2O^+ + H_2 \rightarrow H_3O+ + H$

2) Heavy-Atom Synthesis: $AH^+ + CO \rightarrow ACO^+ + H$

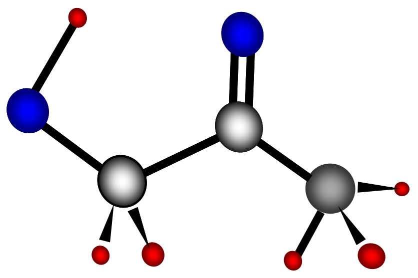
$CH_4^+ + CO \rightarrow CH_3CO^+ + H$

3) Carbon Addition: $C^+ + AH \rightarrow AC^+ + H$

$C^+ + NH_3 \rightarrow H_2CN^+ + H$
$C^+ + H_2CO \rightarrow HCCO^+ + H$

Credit: L. Ziurys

Molecule Formation



Despite different physical conditions and timescales, molecules do form!

Reactions (gas-phase) that ARE possible:

* Neutral-Neutral Reactions

$$A + B \rightarrow C + D$$

- usually need **radical** atom or molecule

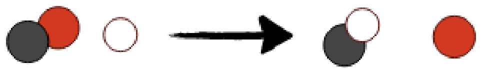
Example: $NO + N \rightarrow N_2 + O$

Example: the formation of water in hot (T > 400 K) gas is powered via

$O + H_2 \rightarrow OH + H$, followed by, $OH + H_2 \rightarrow H_2O + H$

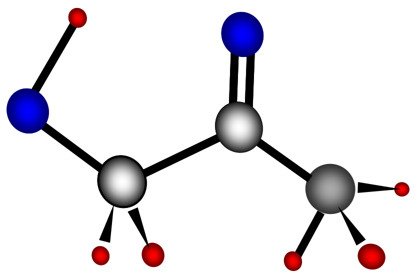
★ Bond rearrangement

Ion-molecule, neutral-neutral or charge transfer



Credit: L. Ziurys

Molecule Formation



Despite different physical conditions and timescales, molecules do form!

Reactions (gas-phase) that ARE possible:

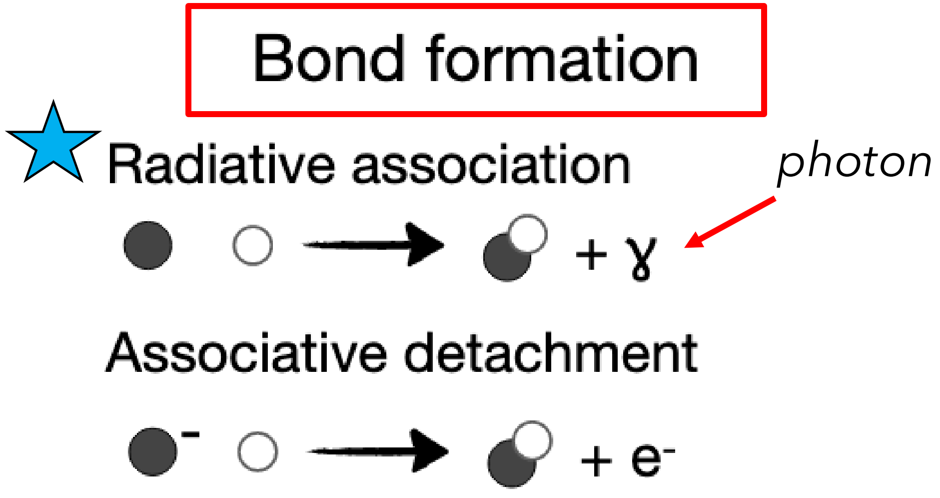
* Radiative Association

photon

$$A^+ + B \rightarrow AB^+ + h\nu$$

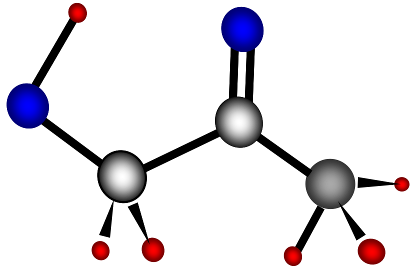
Example: $C^+ + H_2 \rightarrow CH_2^+ + h\nu$

- Tends to only be important for reactions where the **reactants are very abundant** and thus collisions are plentiful, which in practice implies that one of the reactants is the most common element in the Universe, i.e., hydrogen!



Credit: L. Ziurys

Molecule Formation



Despite different physical conditions and timescales, molecules do form!

Reactions (gas-phase) that ARE possible:

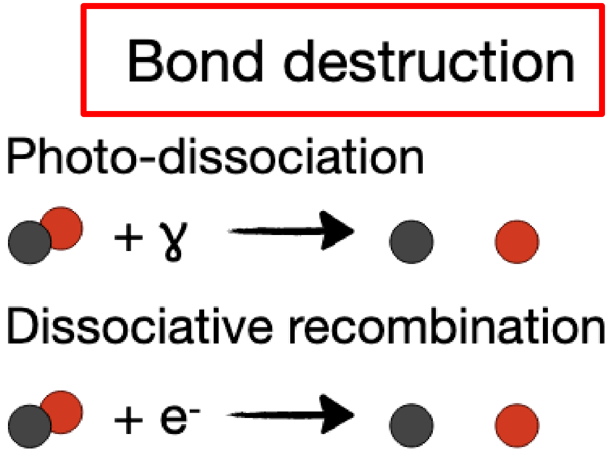
* Photo-dissociation

$AB + h\nu \rightarrow A + B$

* Dissociative Electron Recombination

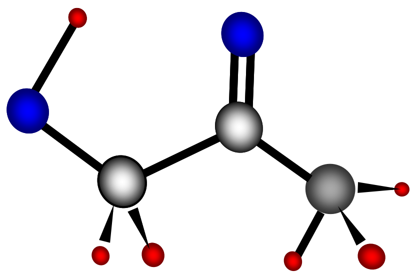
$A^+ + e^- \rightarrow B + C$ (neutral products)

Example: $HCNH^+ + e^- \rightarrow HCN, HNC + H$



Credit: L. Ziurys

Molecule Formation

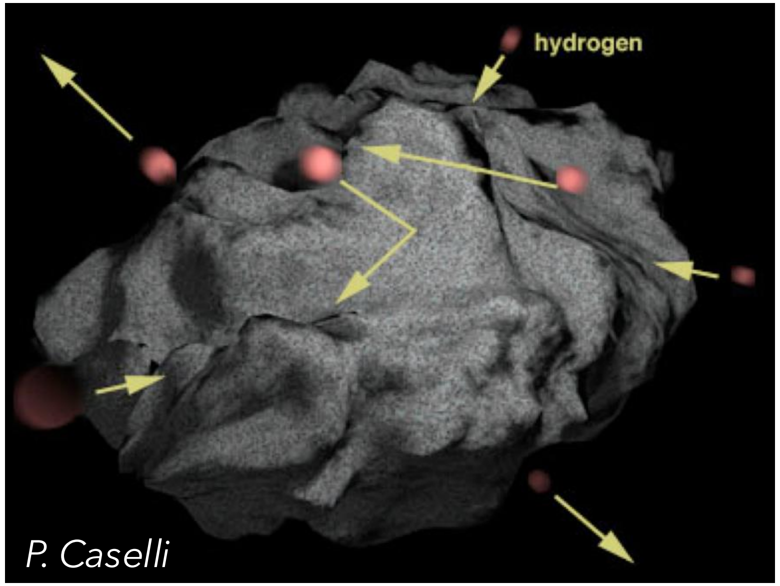


Despite different physical conditions and timescales, molecules do form!

Reactions on **Grain Surfaces** **very important**!

$H + H \rightarrow H_2$

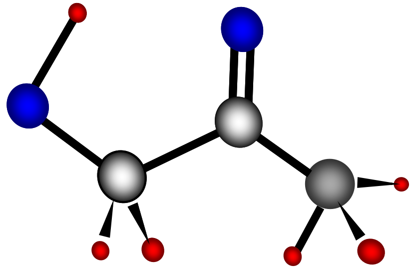
- **This reaction that starts the chemistry in the interstellar medium!**
- Releases energy so H_2 can leave grain
- H_2 MUST form on grains!



- In general, less known (hard to discern processes on grains)
- Gas is cold: everything freezes on grains
- May create larger species on grains (> 6 atoms)

Credit: L. Ziurys

Molecule Formation



Basic Chemical Scheme:

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

2) Gas-phase reactions in initiated by cosmic rays (photons)

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

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

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

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

etc.

Interstellar Chemistry Is KINETICALLY CONTROLLED, NOT THERMODYNAMICALLY

$He^+ + H_2 \rightarrow$ does not occur at low T

INSTEAD:

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

$He^+ + CO \rightarrow C^+ + O + He$

$C^+ \rightarrow$ organic compounds

Credit: L. Ziurys

Molecule Formation

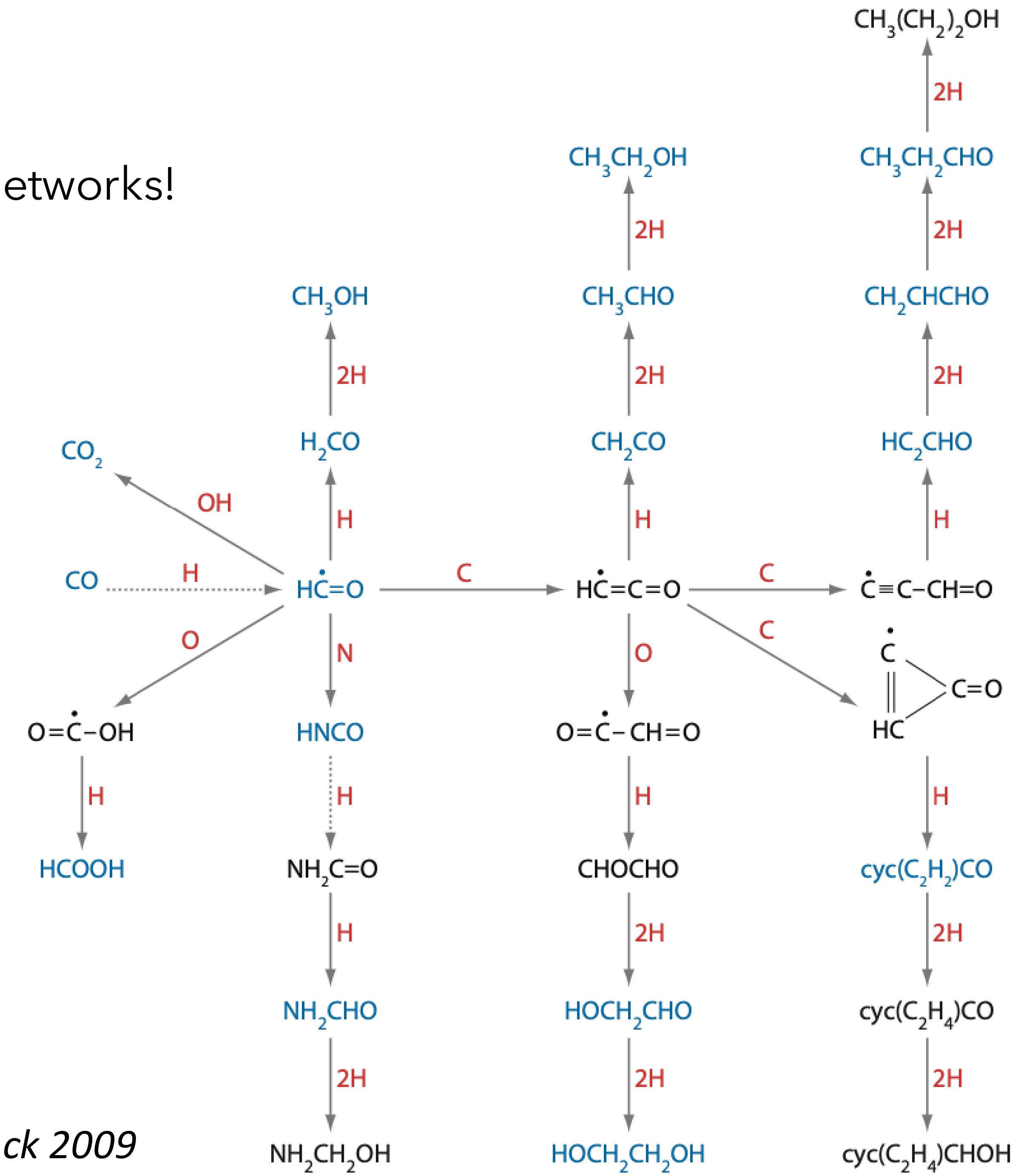
Large chemical reaction networks!

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

- Broken arrows indicate reactions with activation energy barriers

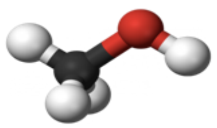
- Where 2H is shown, a barrier penetration reaction followed by exothermic addition

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



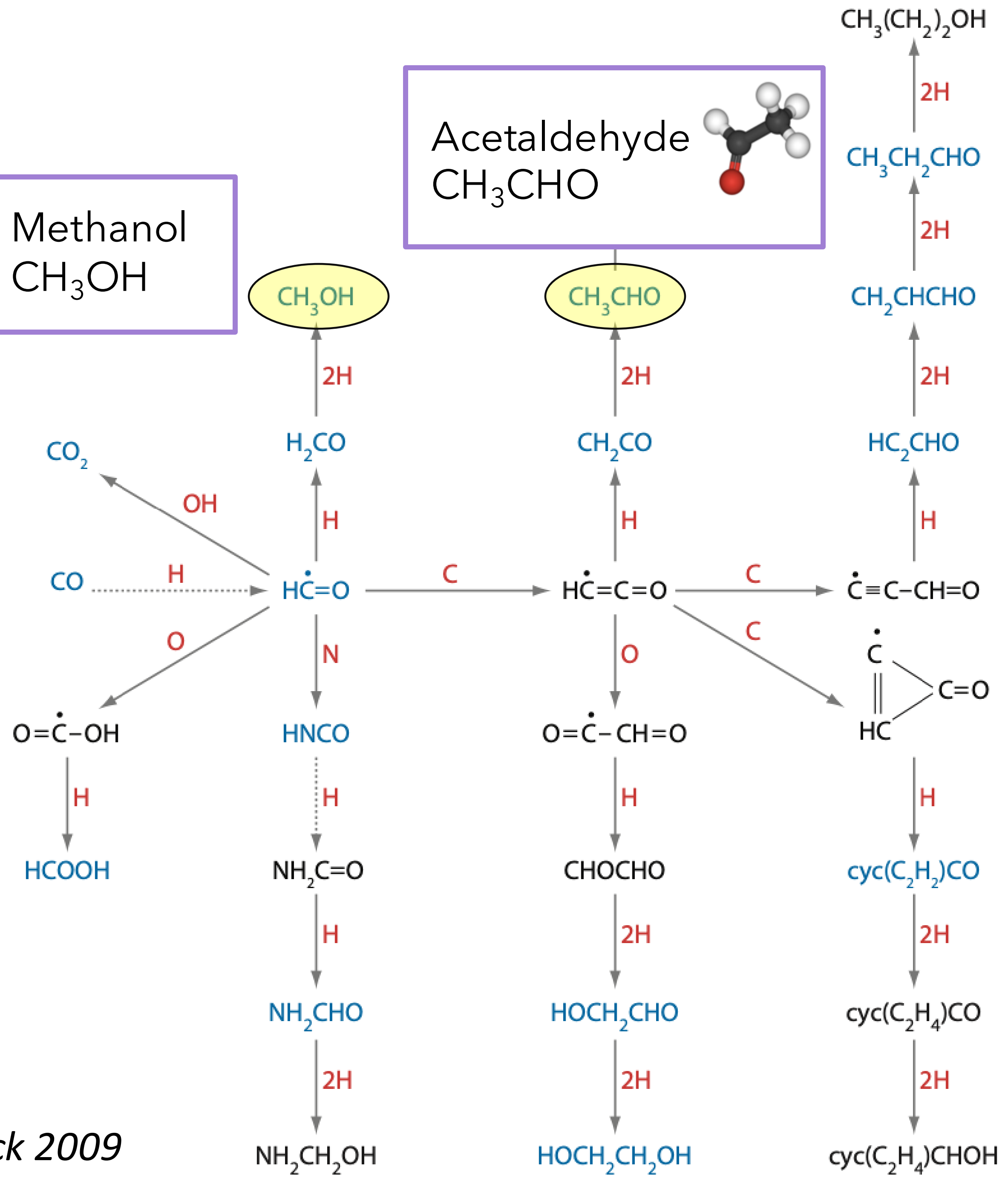
Herbst & van Dishoeck 2009

Molecule Formation



Methanol
CH_3OH

Acetaldehyde
CH_3CHO



<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

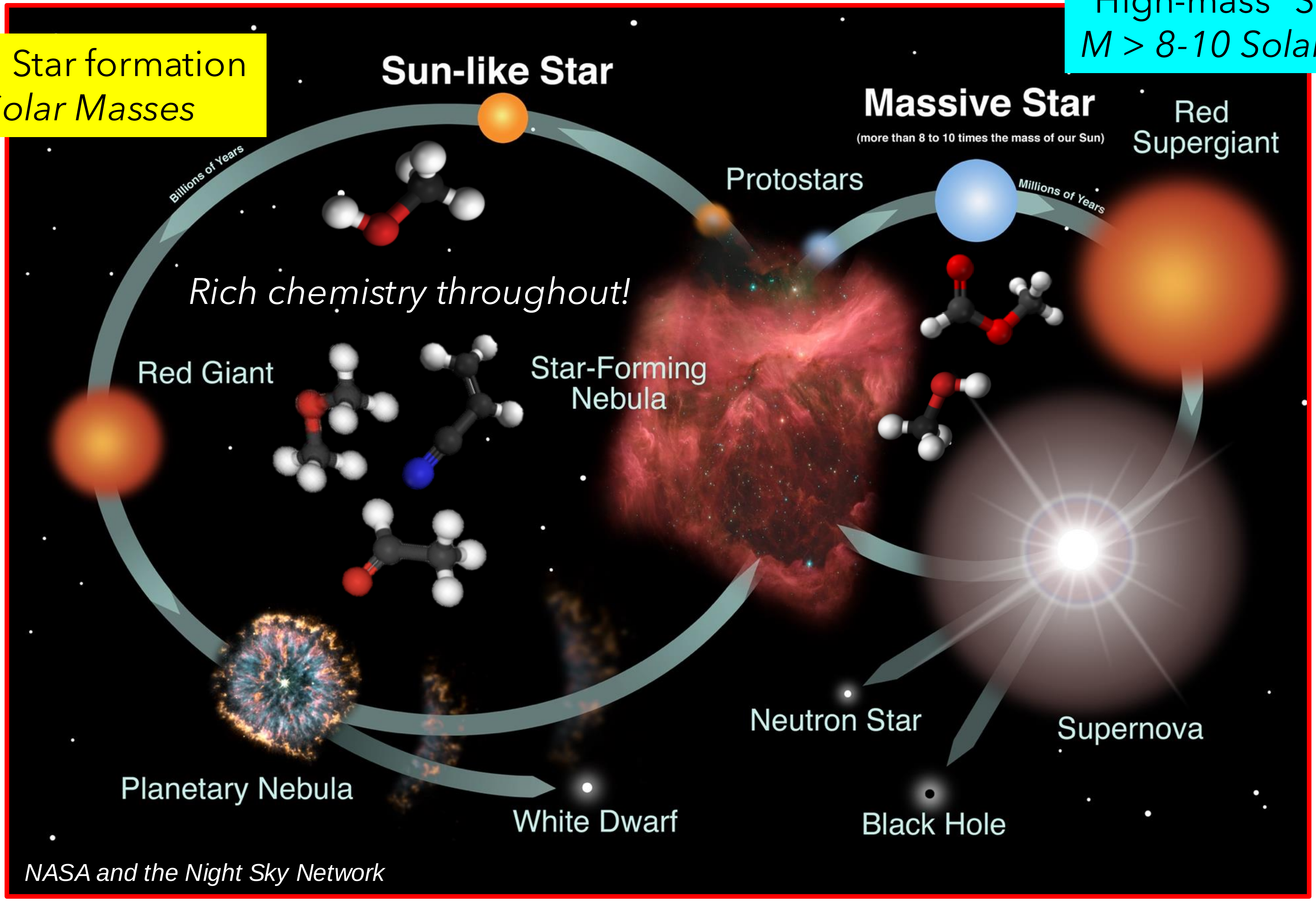
- Molecules in blue detected in <u>star-forming molecular clouds</u>!

Herbst & van Dishoeck 2009

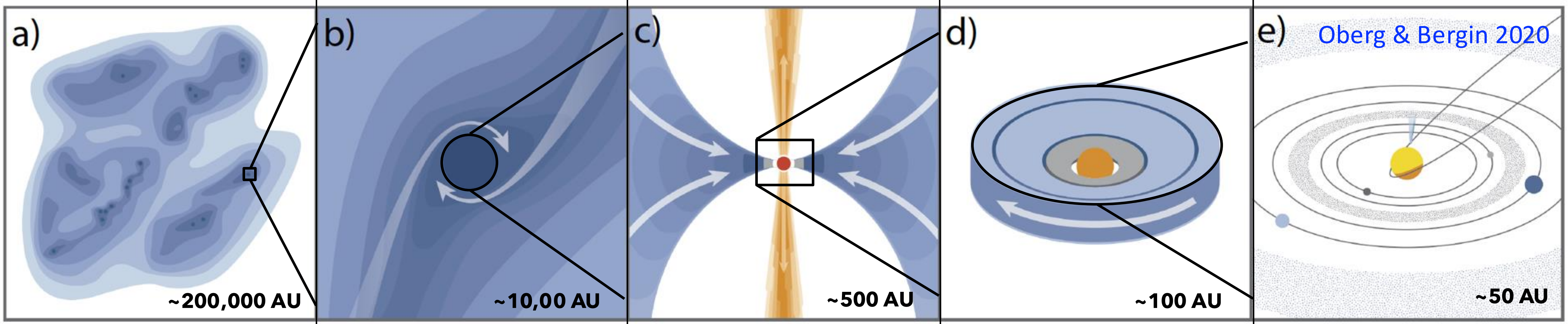
Cool clouds of gas: A birthplace for stars and molecules!

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

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

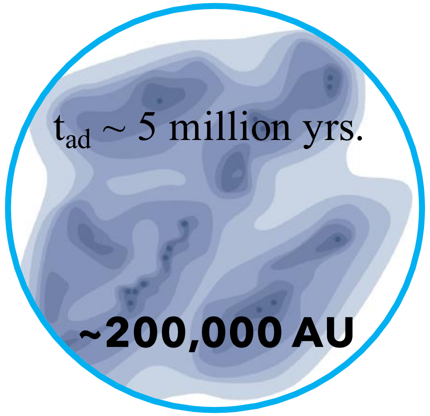


Astrochemistry in Low-mass ($M \leq$ a few $M_\odot$) Star Formation

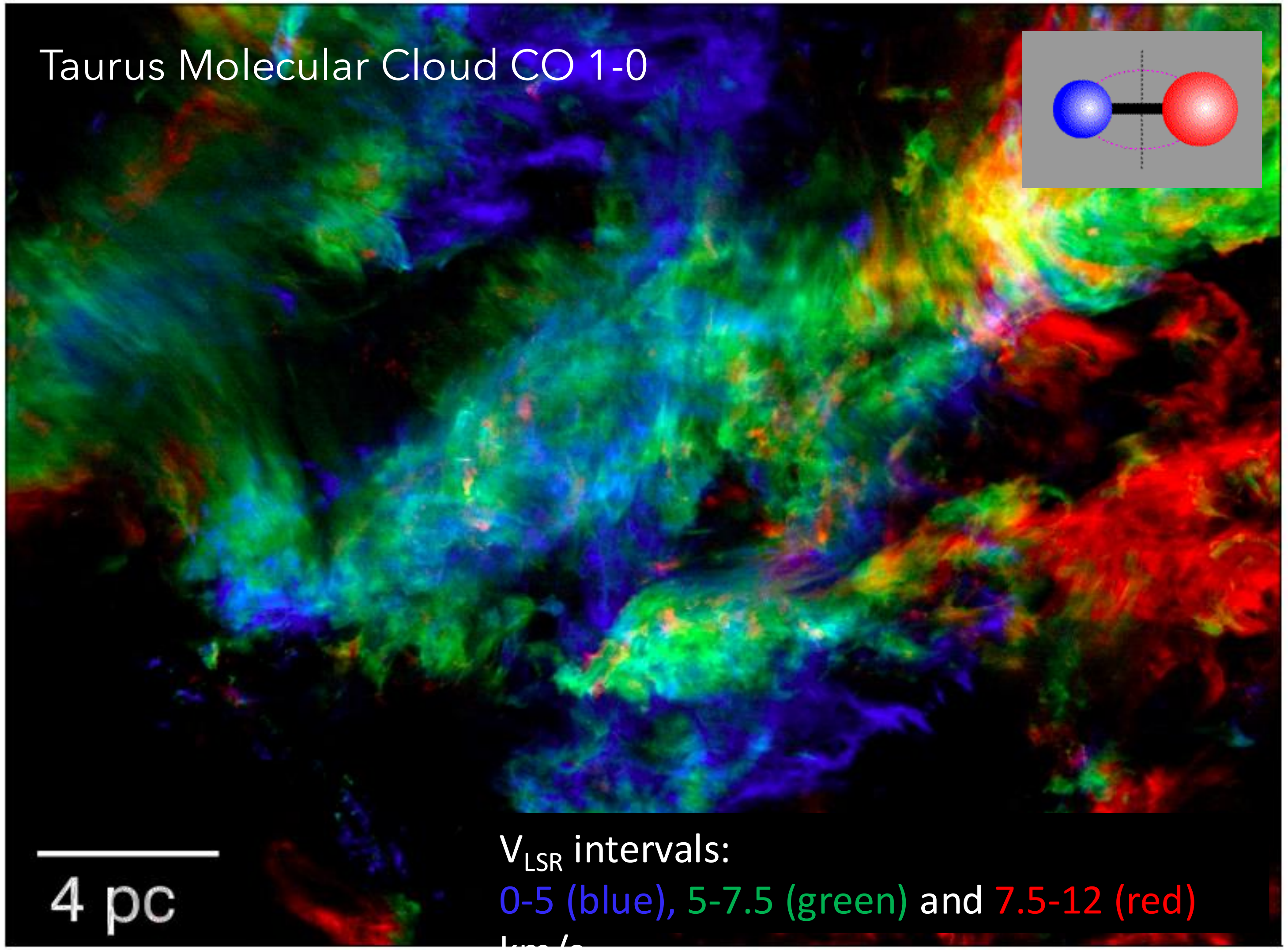


Dense starless cores embedded in larger filaments	**Dense (10^5 cm^{-3}) & cold (10K) prestellar cores that will dynamically collapse**	**Protostar forms. Accretion of remnant cloud material. Outflows present.**	**Pre-main sequence star left with a circumstellar disk**	**Rocky and icy planets continue to grow into mature planetary system**
t_{ad} ~ 5 million yrs.	t_{iso} ~ .2 million yrs.	~1 million yrs.	1-10 million yrs.	10-50 million yrs.

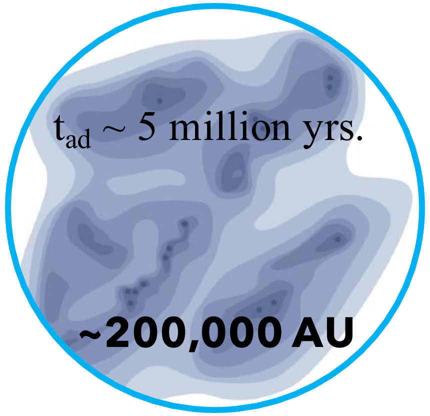
Astrochemistry in Low-mass ($M \lesssim$ a few $M_\odot$) Star Formation



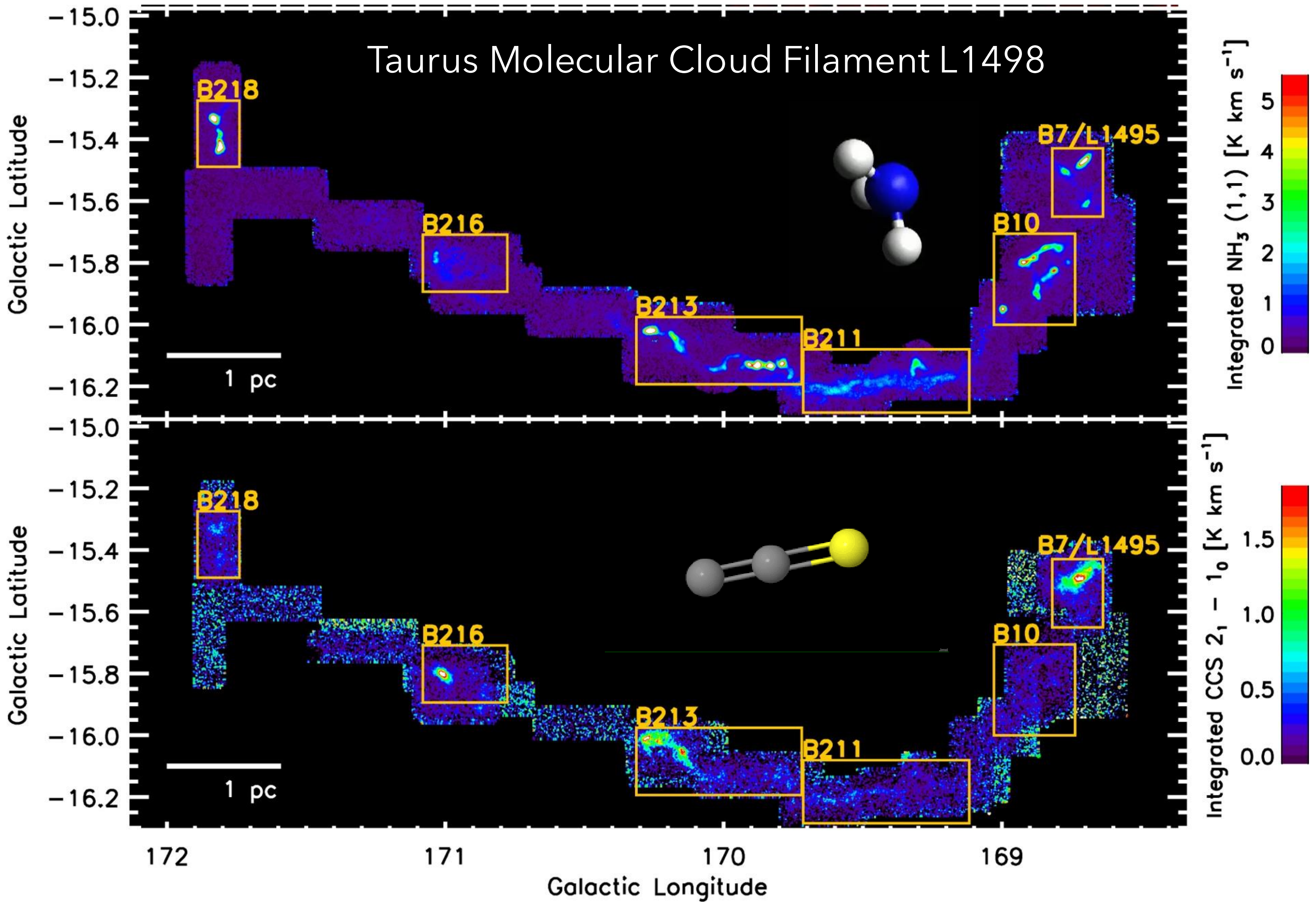
***Molecular* clouds** **are comprised of molecular gas (mostly H_2 and CO) and dust which form filamentary structures**



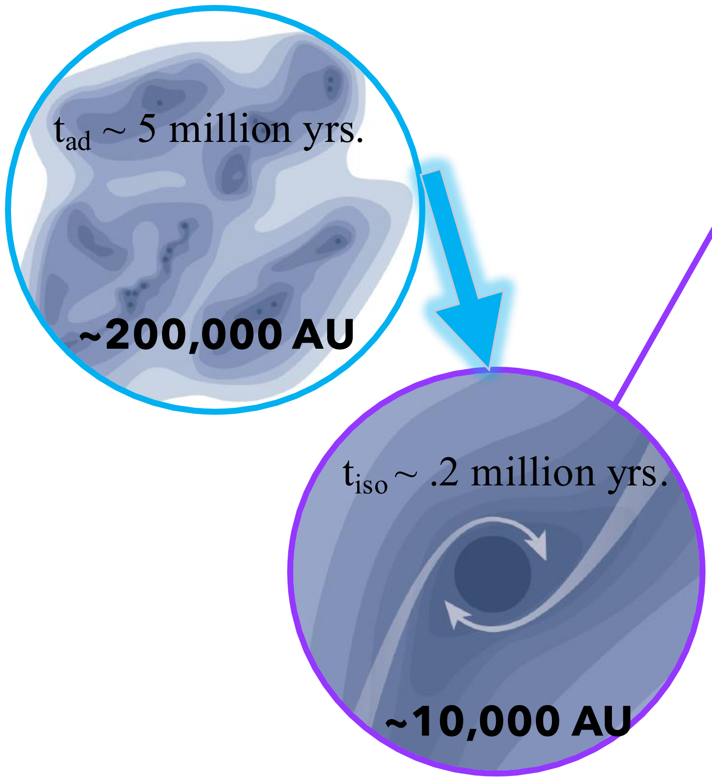
Astrochemistry in Low-mass ($M \leq$ a few $M_{\odot}$) Star Formation



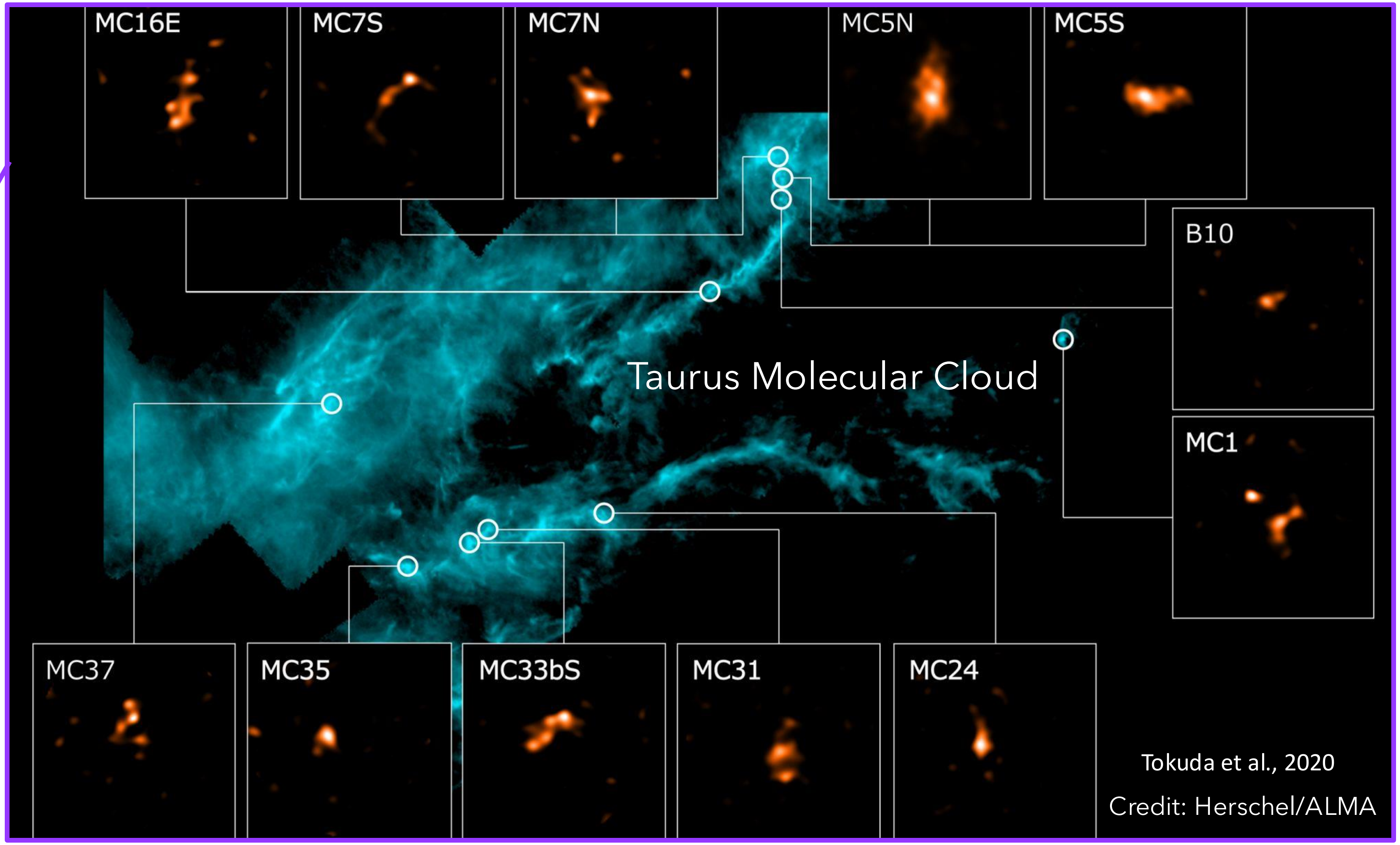
The filamentary structures are also traced by more 'exotic' molecular species, such as NH_3 and CCS



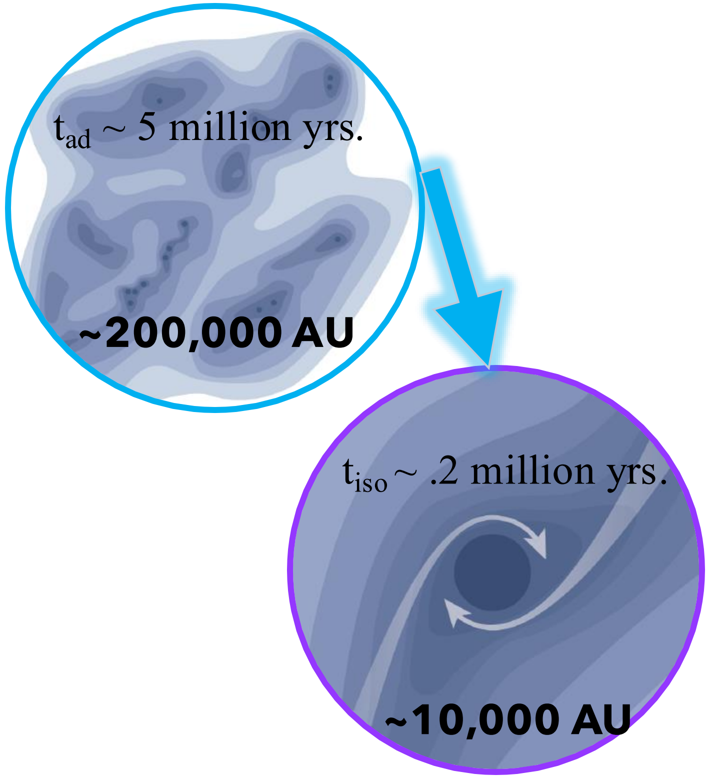
Astrochemistry in Low-mass ($M \leq$ a few $M_{\odot}$) Star Formation



Dense (10^5 cm^{-3}) & cold (10K) *starless* and dynamically evolved *prestellar* cores collapse due to gravity and external cloud pressure

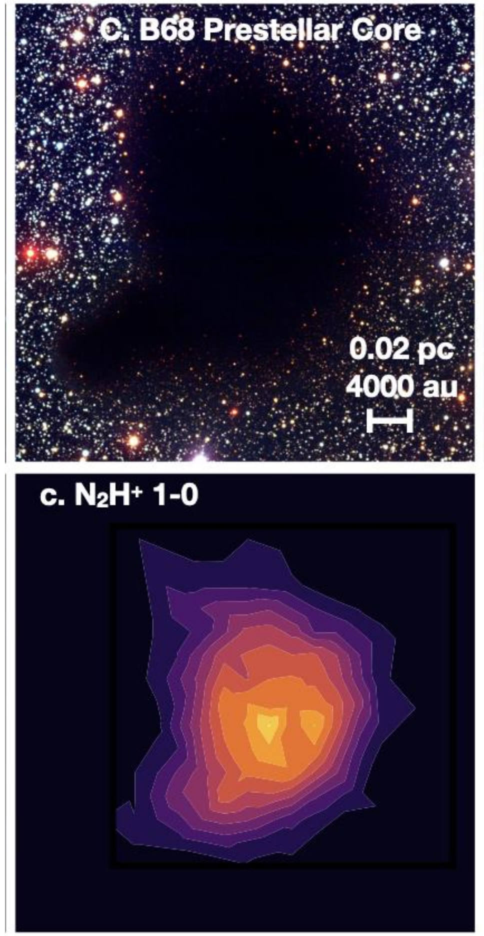


Astrochemistry in Low-mass (M ≤ a few $M_\odot$) Star Formation



Dense (10^5 cm^{-3}) & cold (10K) *starless* and dynamically evolved *prestellar* cores collapse due to gravity and external cloud pressure

- **DARK CLOUDS / Cold Cores**
  - indicated by absence of visible light
  - Molecular lines characterized by **narrow, "sharp" line profiles**
  - Very **COLD**: T ~ 10 - 20 K
  - **Dense**: n ~ 10^3-10^5 cm^{-3}
  - Typical masses: 1 $M_\odot$ – 10^3 $M_\odot$
  - Hydrogen in form of **H_2**
- Traced by dust extinction, far-IR dust emission, radio lines of molecules
  - Most compact form known as "Bok Globules" →
  - Certain dark clouds known to be CARBON-RICH (C >O): Taurus
    - in general ISM, O/C ~ 1.5
- **Quiescent:** no violent outflows or energetic motions

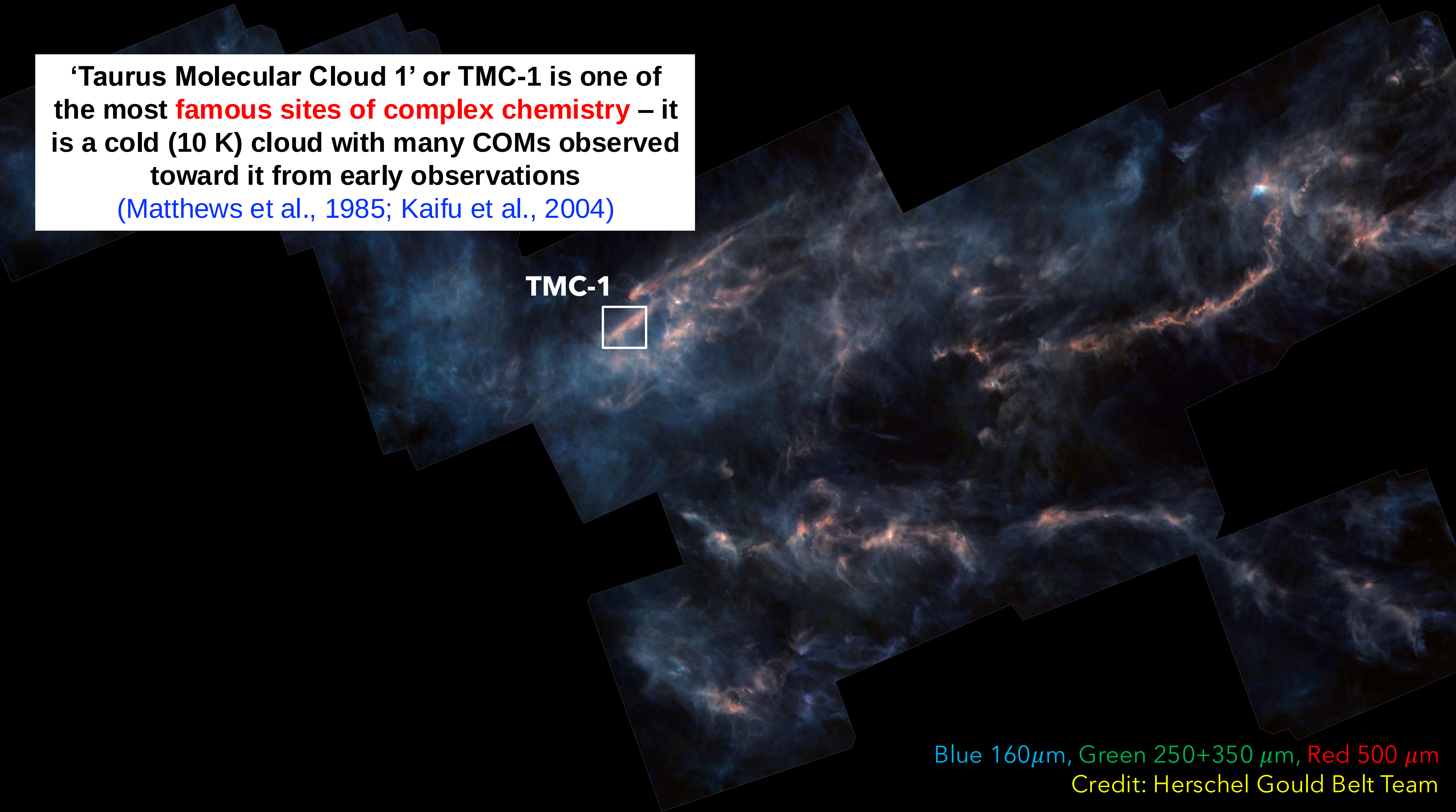


Oberg & Bergin 2020

Credit: L. Ziurys

‘Taurus Molecular Cloud 1’ or TMC-1 is one of the most famous sites of complex chemistry – it is a cold (10 K) cloud with many COMs observed toward it from early observations

(Matthews et al., 1985; Kaifu et al., 2004)



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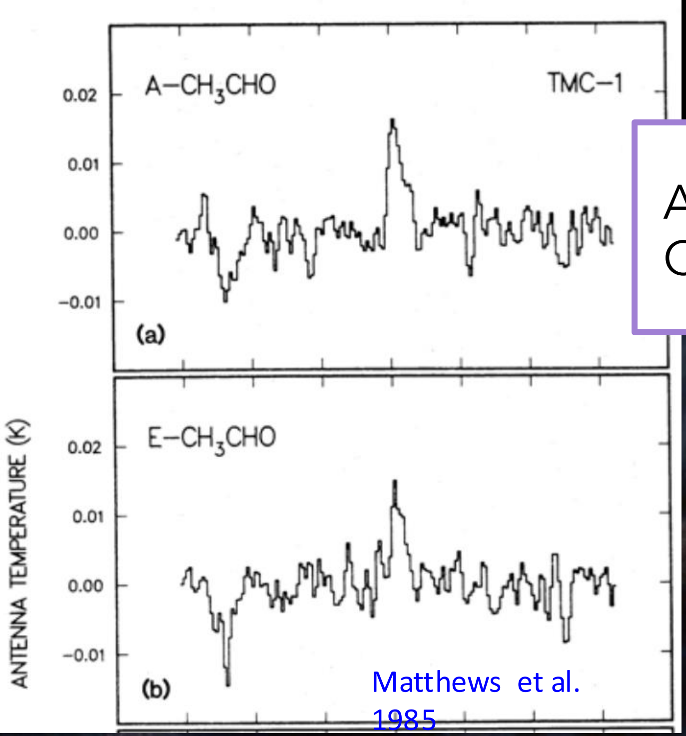
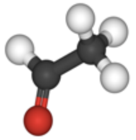


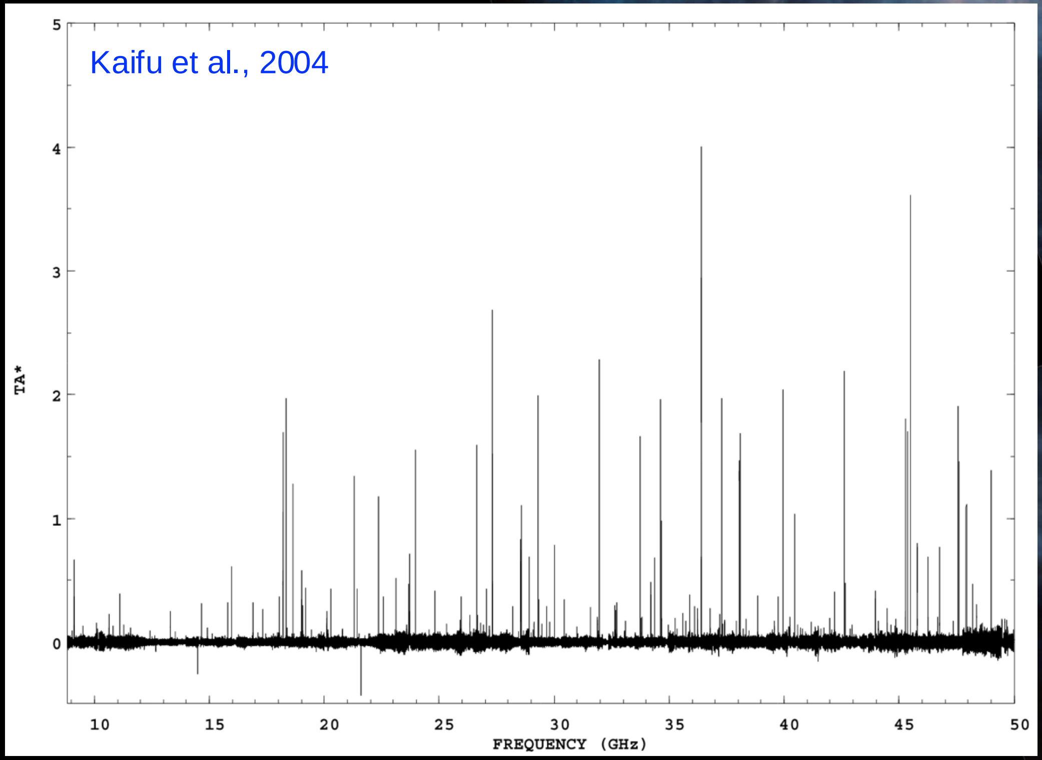
Matthews et al. 1985

Acetaldehyde

CH_3CHO



TMC-1



Blue 160μm, Green 250+350 μm, Red 500 μm

Credit: Herschel Gould Belt Team

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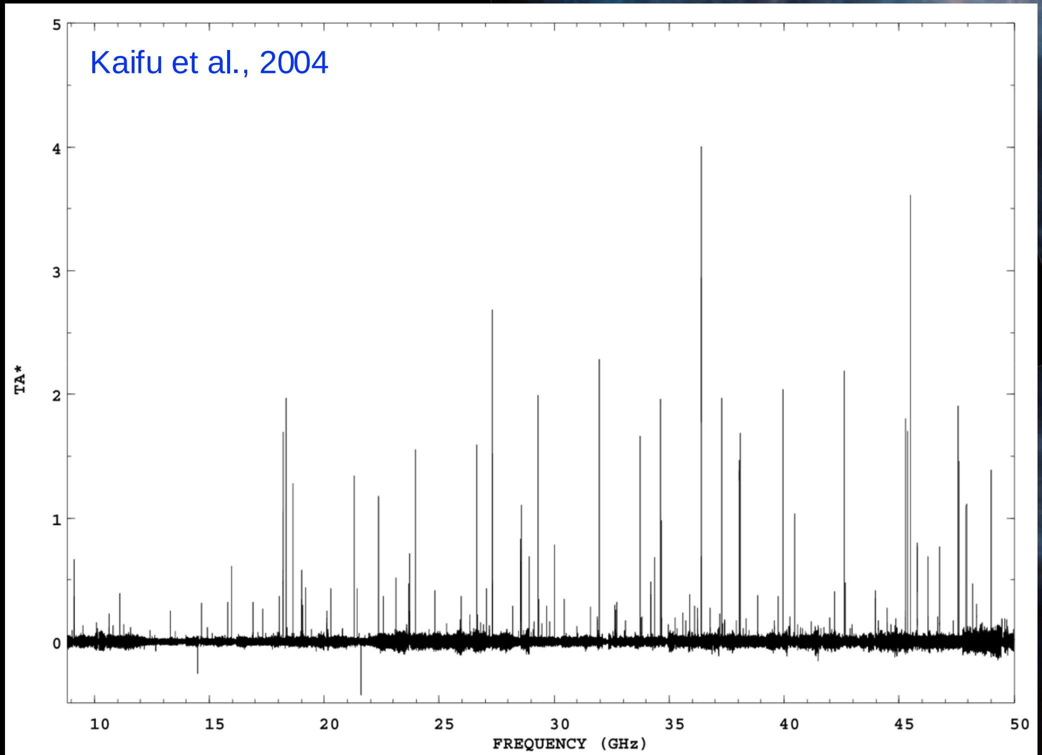
TMC-1



# of molecule discoveries per source

Source	#	Source	#
Sgr B2	69	L1527	2
TMC-1	57	L1544	2
IRC+10216	55	NGC 2024	2
LOS Cloud	42	NGC 7023	2
Orion	24	NGC 7027	2
L483	9	TC 1	2
W51	8	W49	2
VY Ca Maj	6	CRL 2688	1
B1-b	4	Crab Nebula	1
DR 21	4	DR 21(OH)	1
IRAS 16293	4	Galactic Center	1
NGC 6334	4	IC 443G	1
Sgr A	4	K3-50	1
CRL 618	3	L134	1
G+0.693-0.027	3	L183	1
NGC 2264	3	Lupus-1A	1
W3(OH)	3	M17SW	1
rho Oph A	3	NGC 7538	1
Horsehead PDR	2	Orion Bar	1

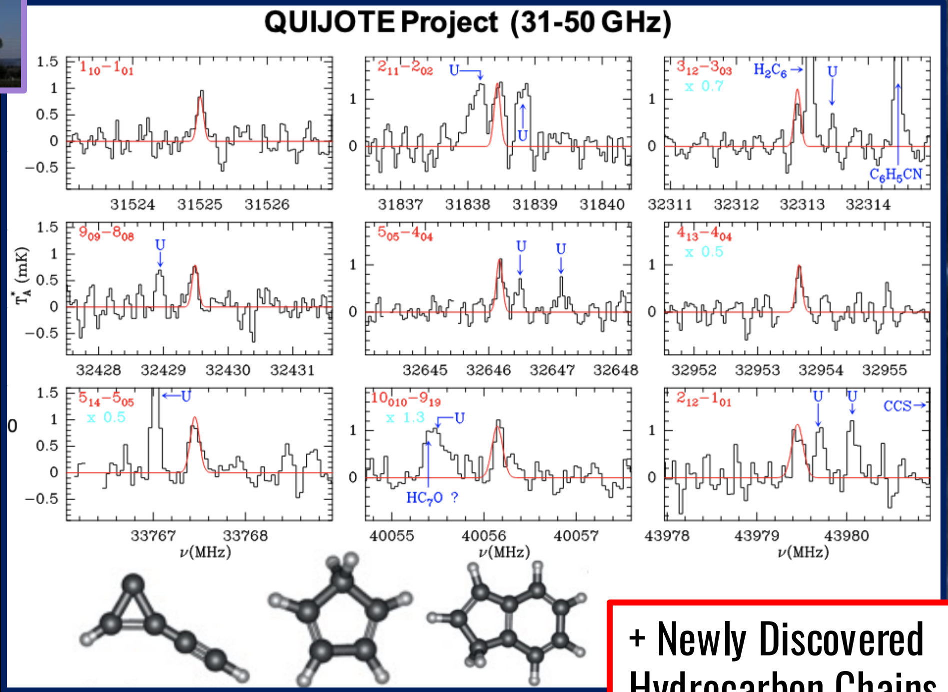
McGuire 2022

Blue 160μm, Green 250+350 μm, Red 500 μm
Credit: Herschel Gould Belt Team

Sensitive, unbiased line surveys are ongoing and continually finding new molecules in TMC-1!

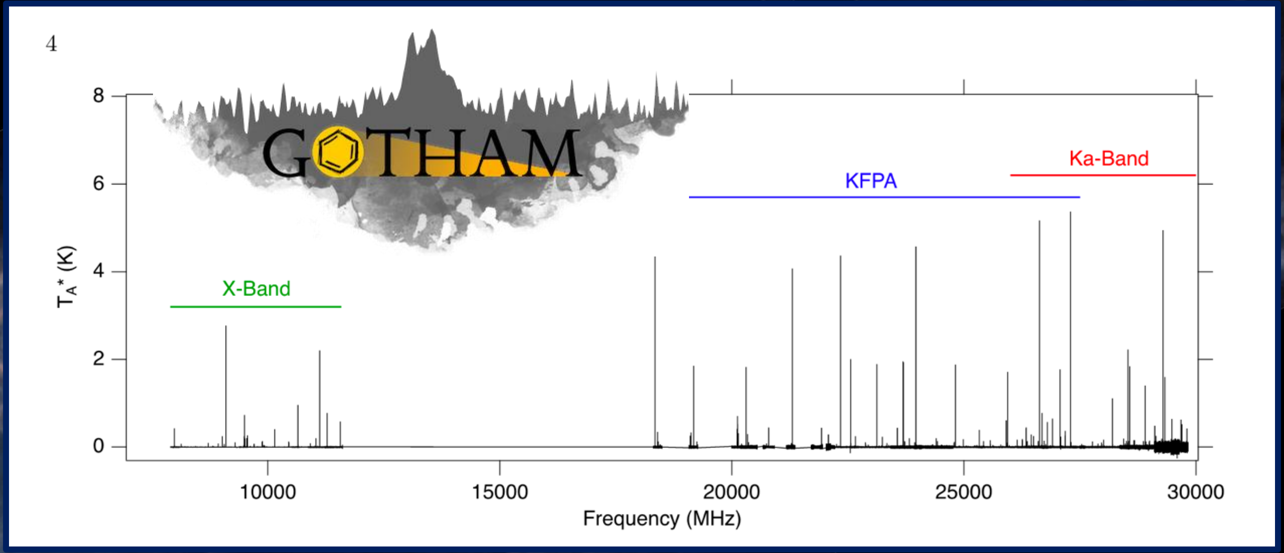
TMC-1

Yebes 40m Dish



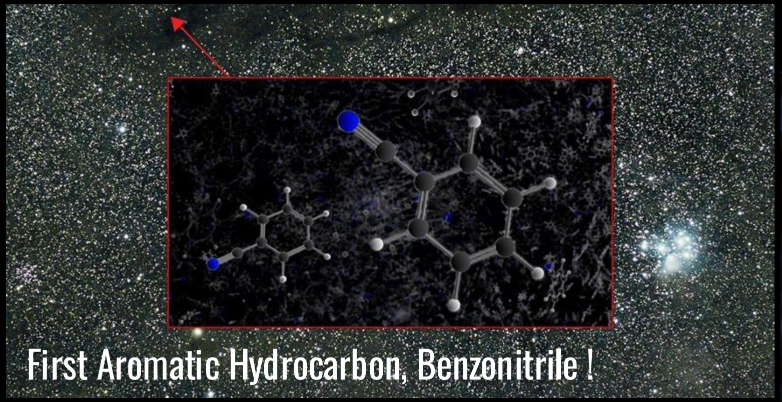
Cernicharo et al., 2021 & QUIJOTE team

+ Newly Discovered Hydrocarbon Chains and Cycles



McGuire et al. 2018, 2020

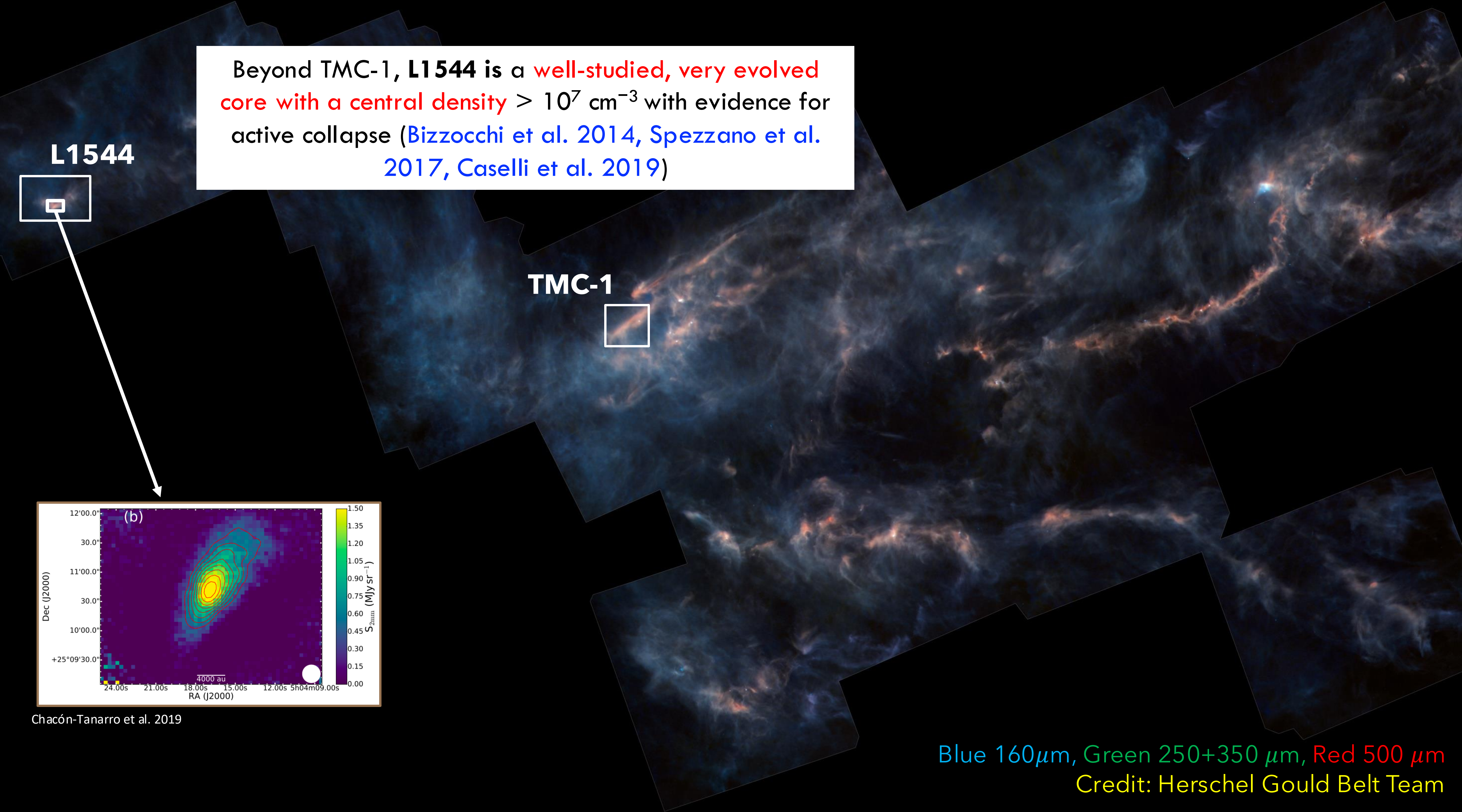
GBT 100m Dish



Blue 160μm, Green 250+350 μm, Red 500 μm

Credit: Herschel Gould Belt Team

Beyond TMC-1, **L1544 is** a well-studied, very evolved core with a central density > 10^7 cm^{-3} with evidence for active collapse (Bizzocchi et al. 2014, Spezzano et al. 2017, Caselli et al. 2019)



Chacón-Tanarro et al. 2019

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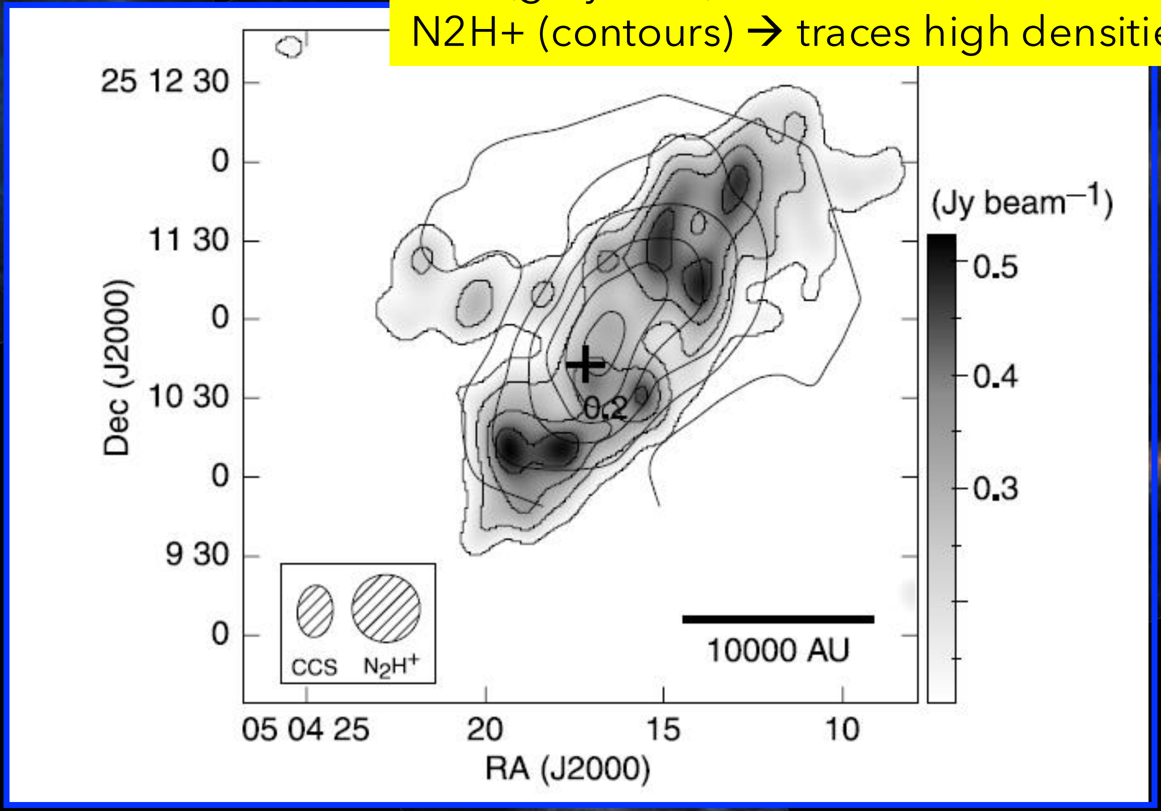
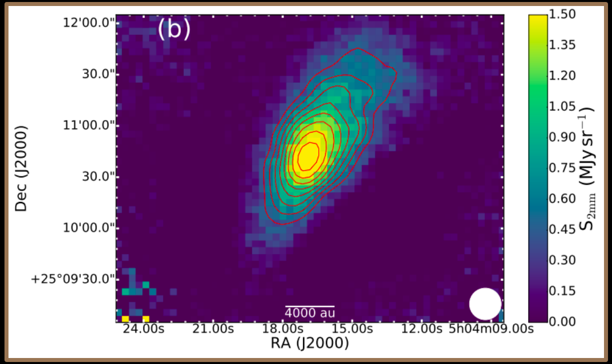
L1544

CCS (greyscale) → freeze out towards denser and colder center
N2H+ (contours) → traces high densities in and around core





Chacón-Tanarro et al. 2019

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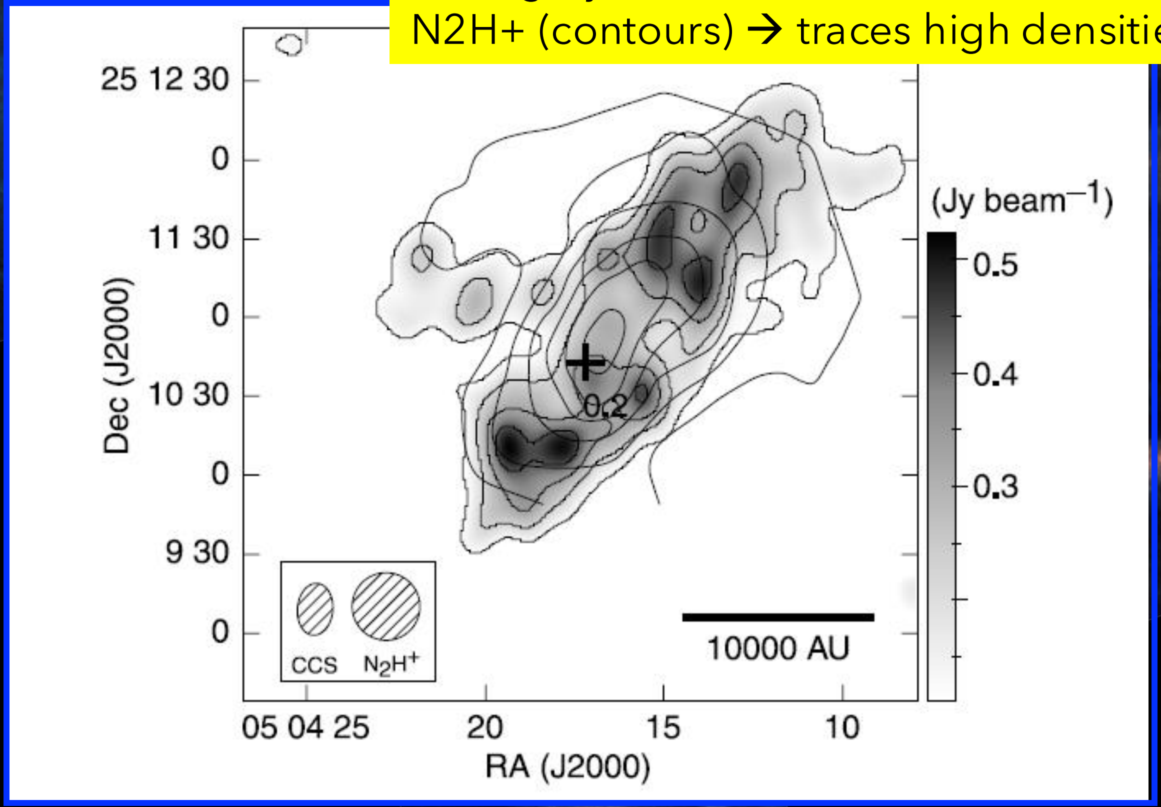

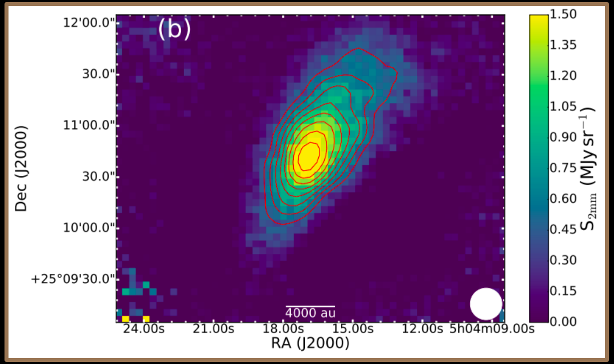

Chacón-Tanarro et al. 2019

**Molecules are powerful probes of the physical conditions!*

Blue 160μm, Green 250+350 μm, Red 500 μm
Credit: Herschel Gould Belt Team

L1544

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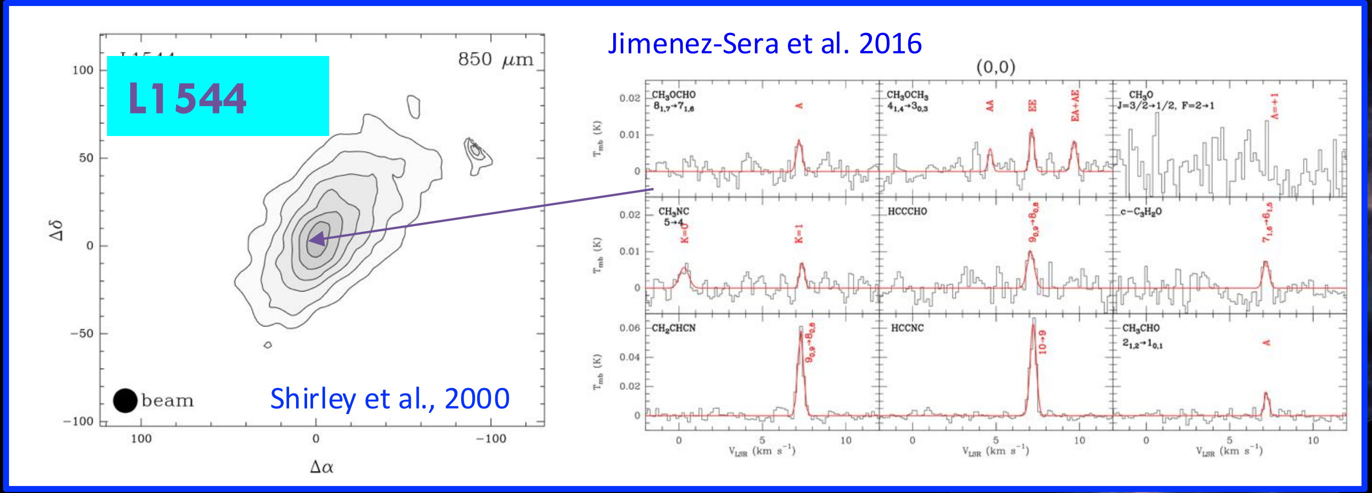
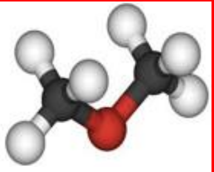
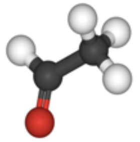
One of the first sites of COMs detections in **isolated prestellar core**!

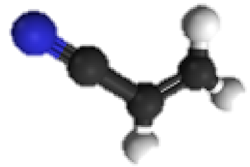




Dimethyl Ether CH_3OCH_3

Acetaldehyde CH_3CHO





Vinyl Cyanide CH_2CHCN

Blue 160μm, Green 250+350 μm, Red 500 μm
Credit: Herschel Gould Belt Team

L1544

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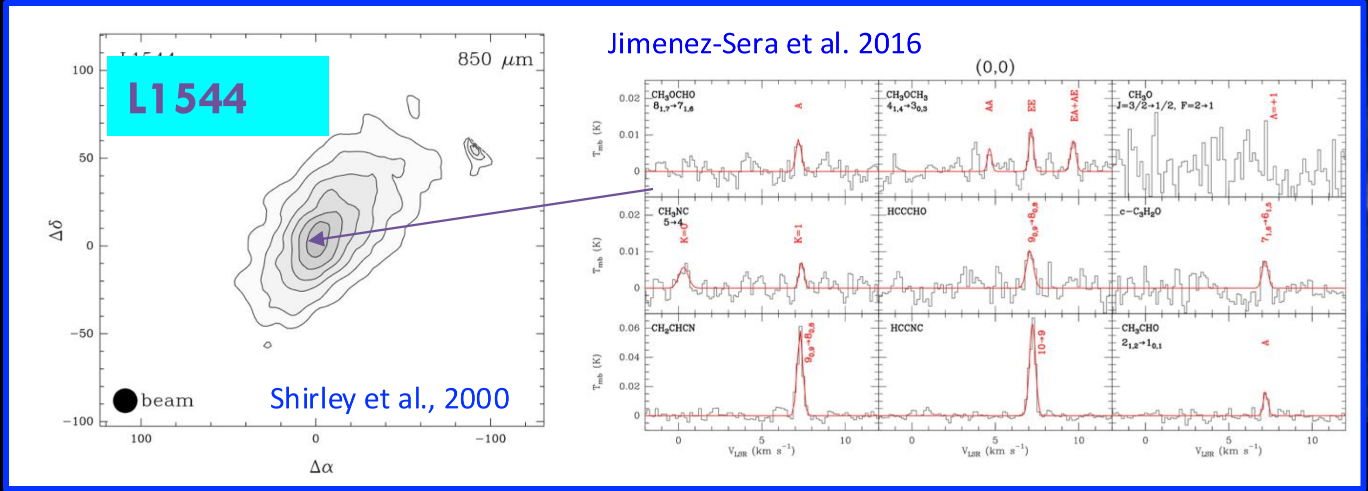
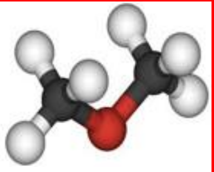
Are complex organic molecules (COMs) common at the earliest stages of low-mass star formation, i.e., in more ‘typical’ starless and prestellar cores?

One of the first sites of COMs detections in **isolated prestellar core**!





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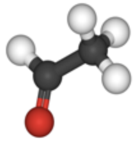

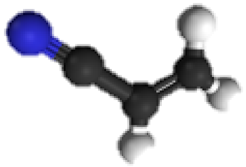

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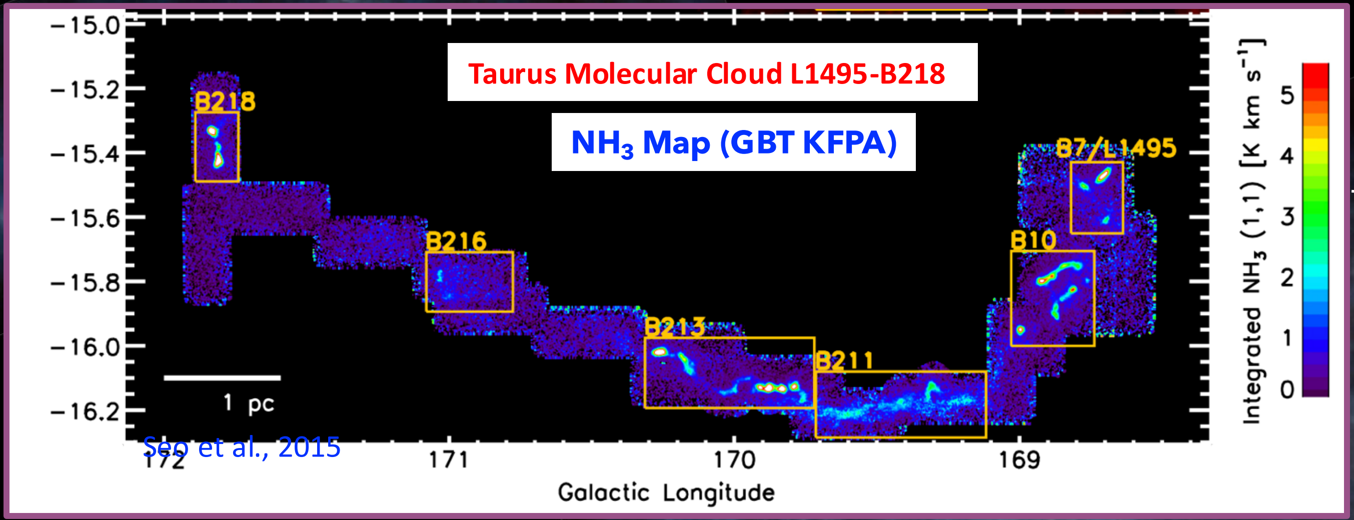
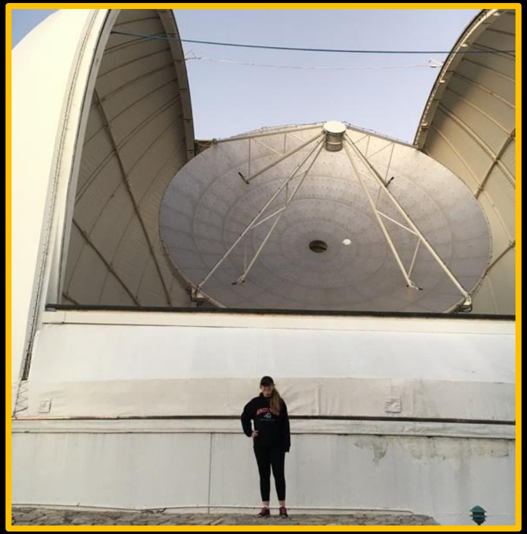
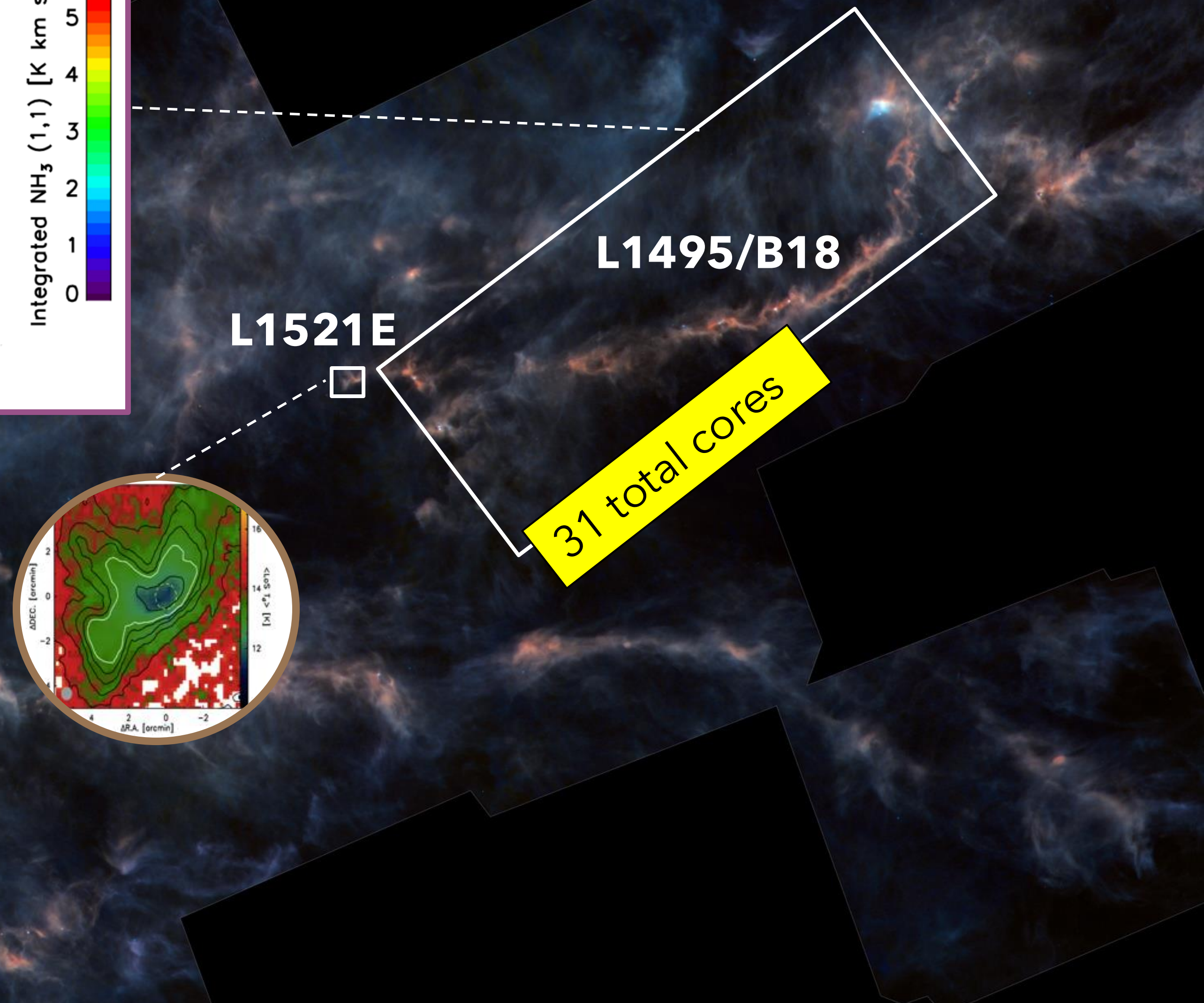


First night of PhD observing in 2017



12m Radio Telescope, Kitt Peak, AZ

In my PhD research, I studied 'typical' starless and prestellar cores in the Taurus Molecular Cloud!



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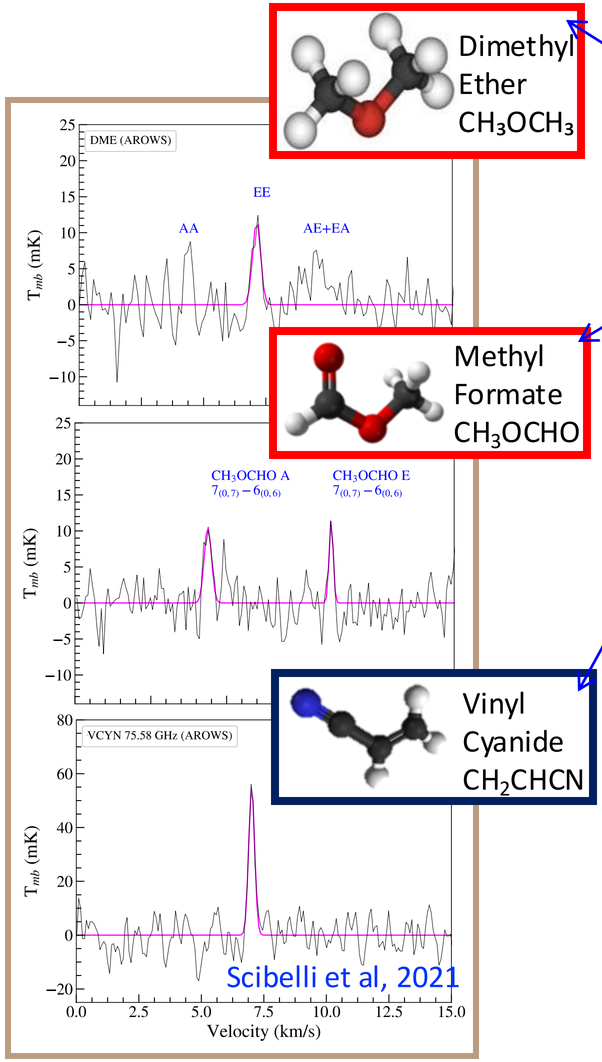
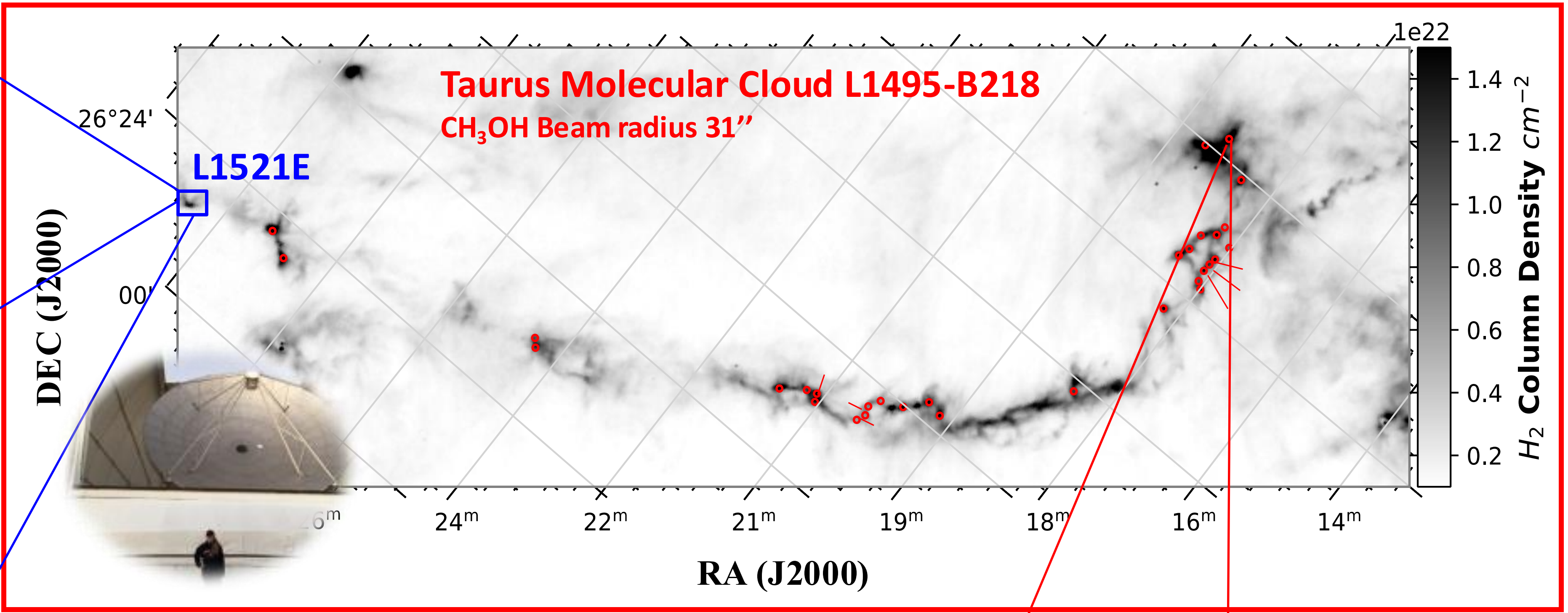
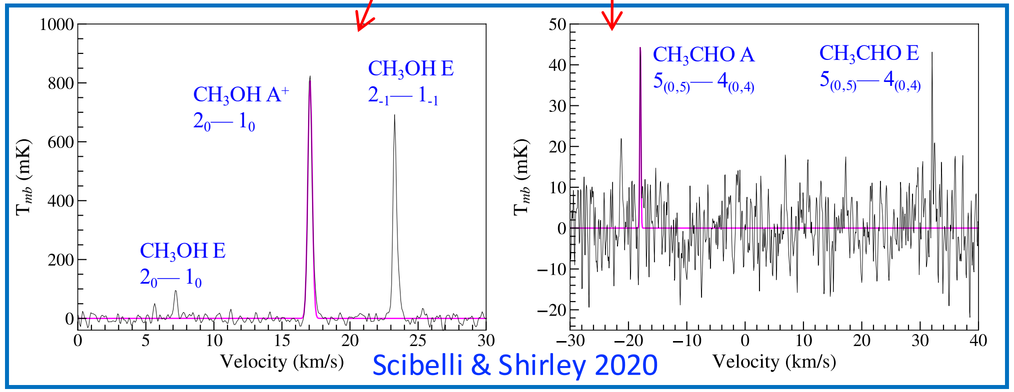
Astrochemistry in Low-mass (M ≤ a few M$_\odot$) Star Formation



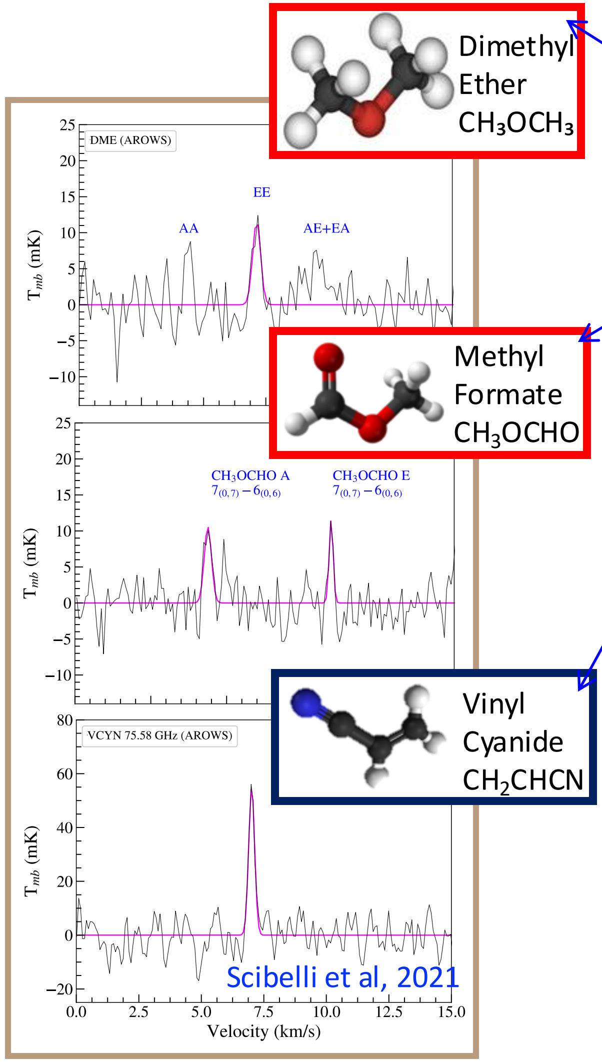


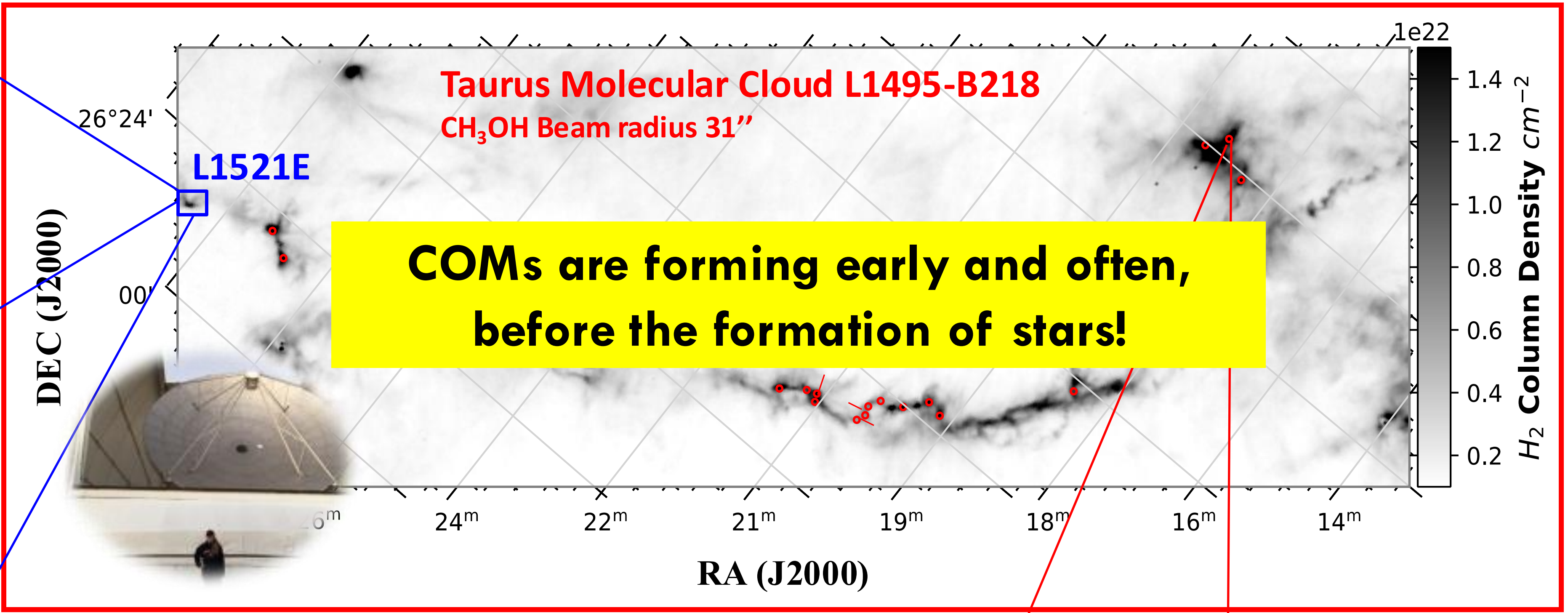
Observations with the Arizona Radio Observatory (ARO) 12m show COMs are prevalent in 31 more 'typical' starless and prestellar cores – **methanol (CH_3OH) found in 100% & acetaldehyde (CH_3CHO) found in 70%!** →

← PLUS even higher complexity found in young, starless core L1521E!



Astrochemistry in **Low-mass (M ≤ a few M$_\odot$)** Star Formation





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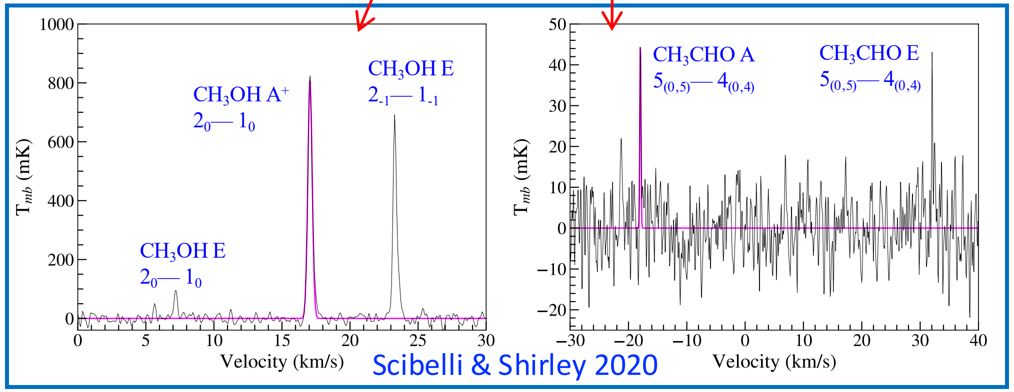
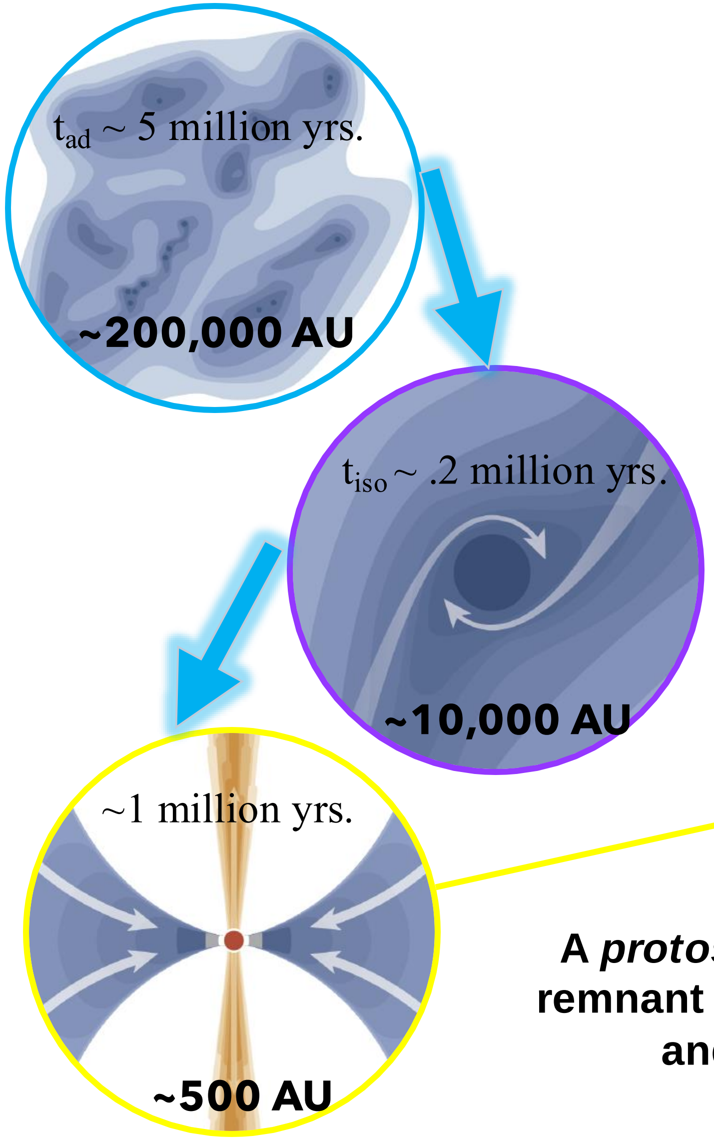
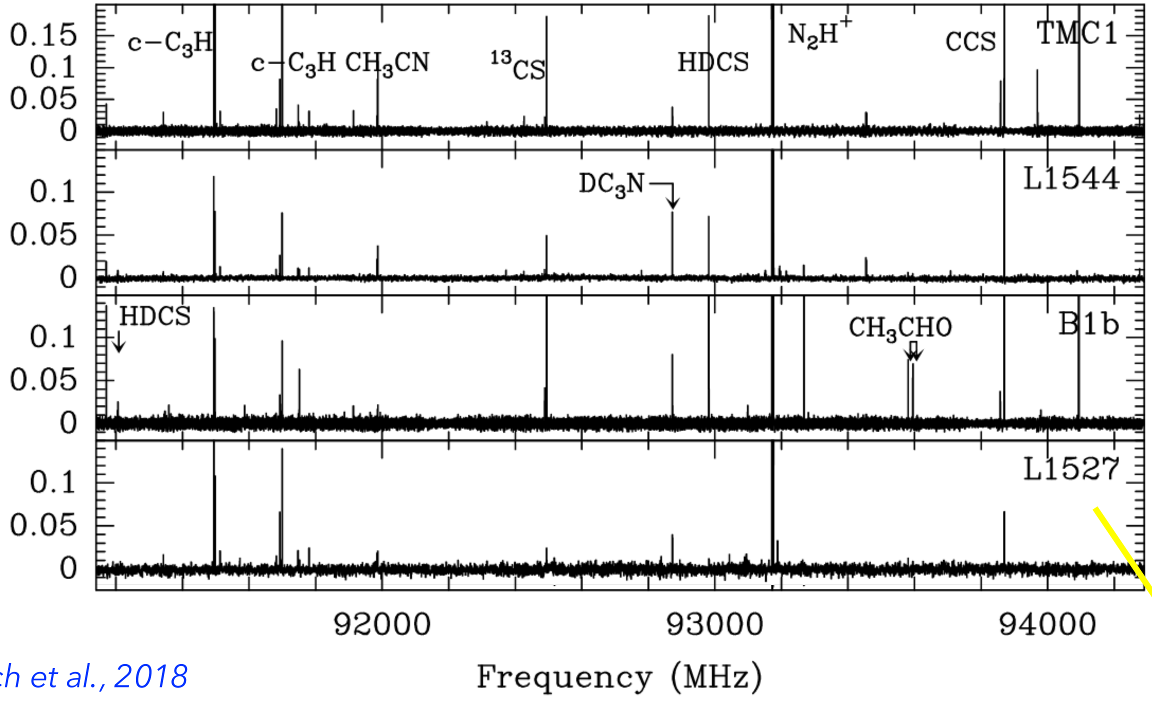


Astrochemistry in Low-mass ($M \leq$ a few $M_{\odot}$) Star Formation

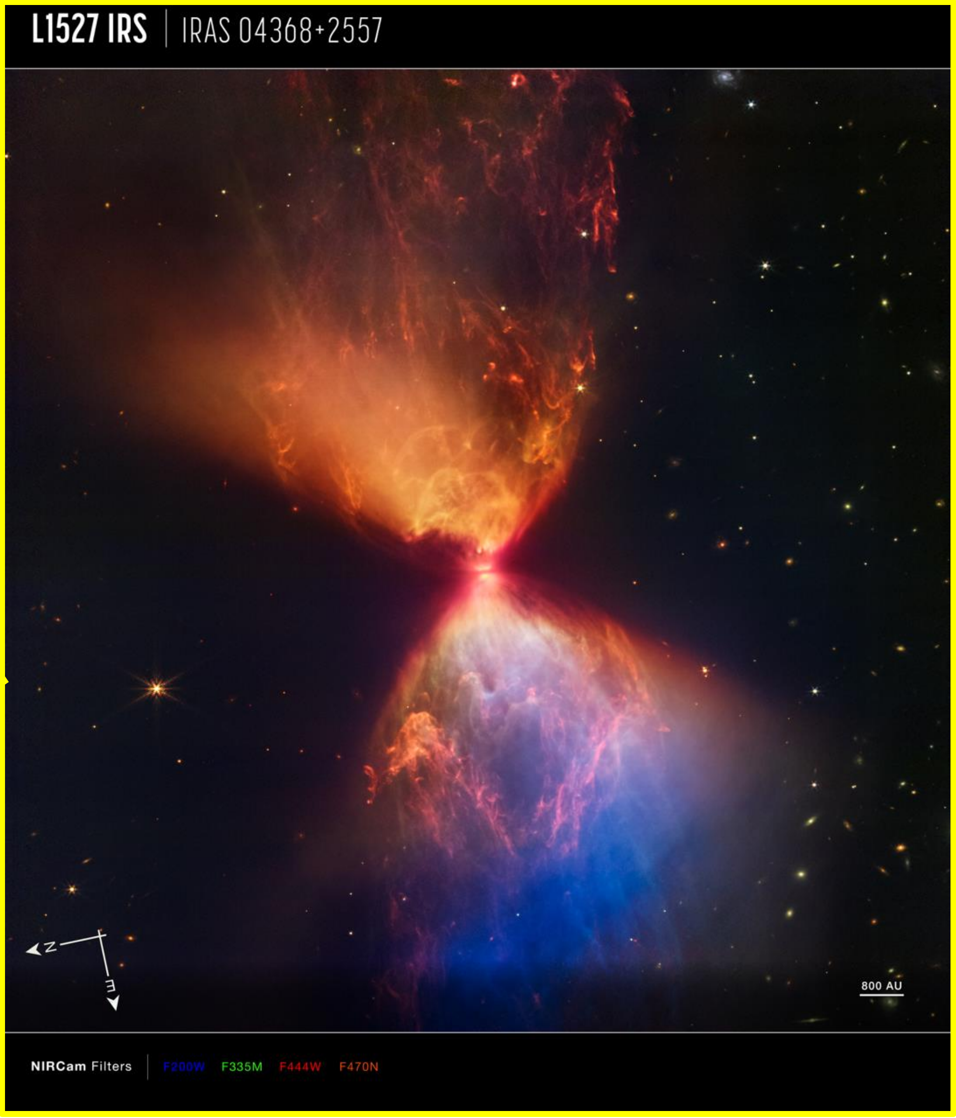


A *protostar* forms. Accretion of remnant cloud material. Outflows and jets are present.

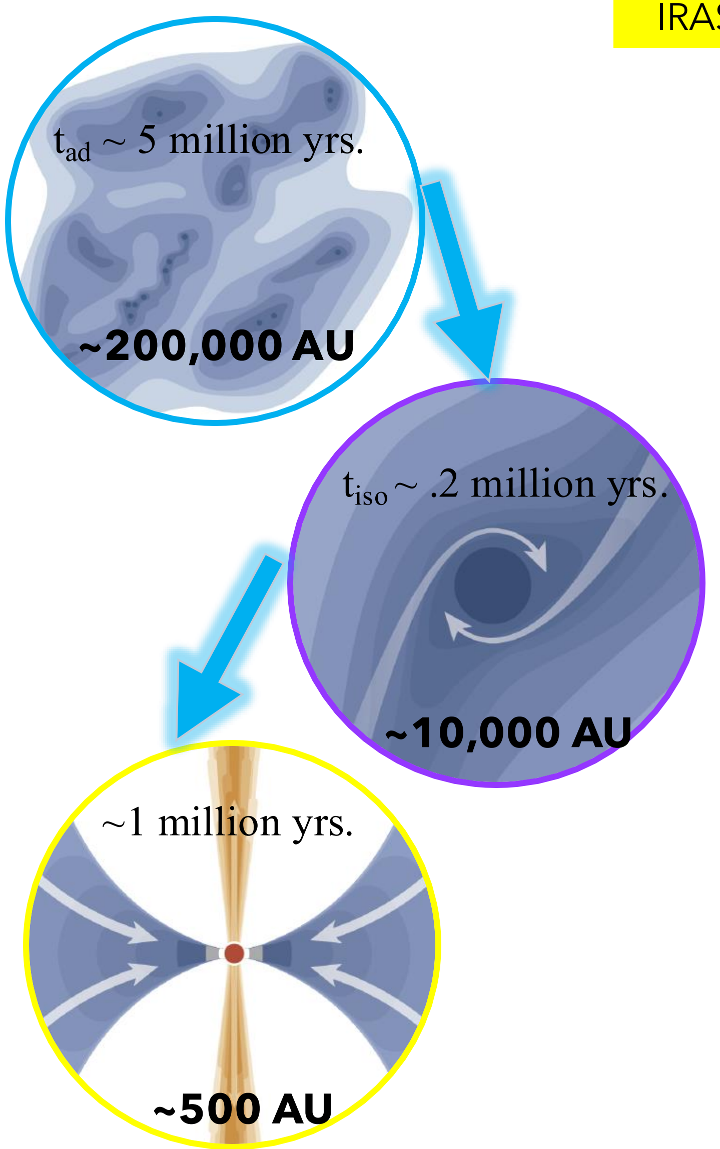
Astrochemistry in Low-mass ($M \leq$ a few $M_\odot$) Star Formation



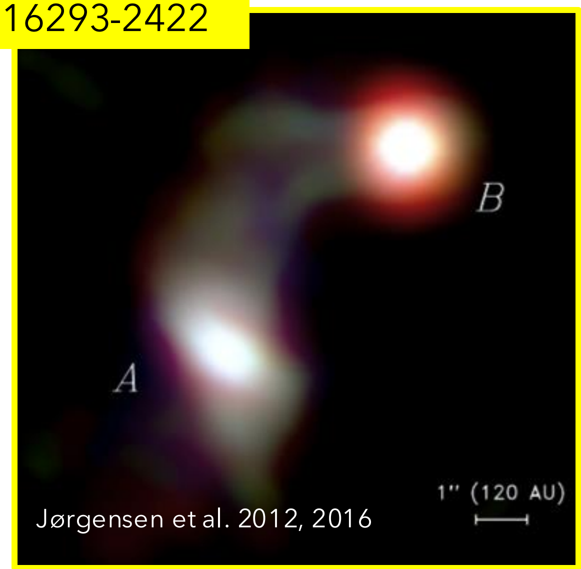
Lefloch et al., 2018



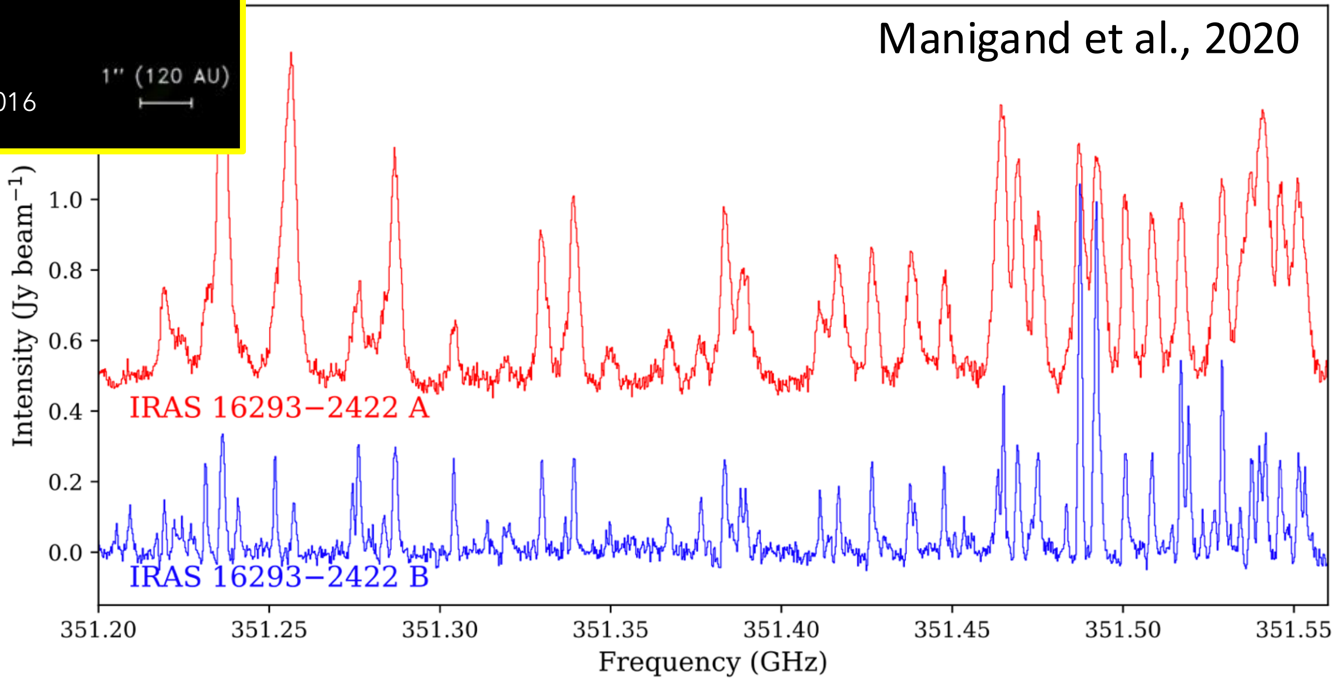
Astrochemistry in Low-mass ($M \leq$ a few $M_\odot$) Star Formation



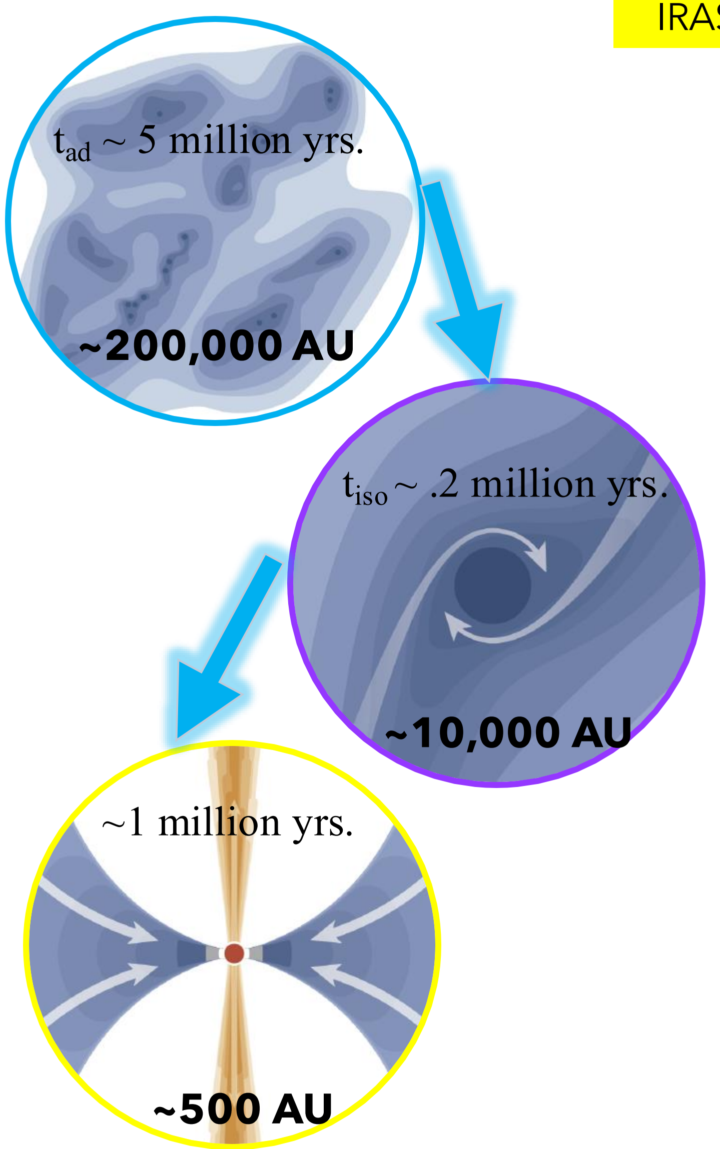
IRAS 16293-2422



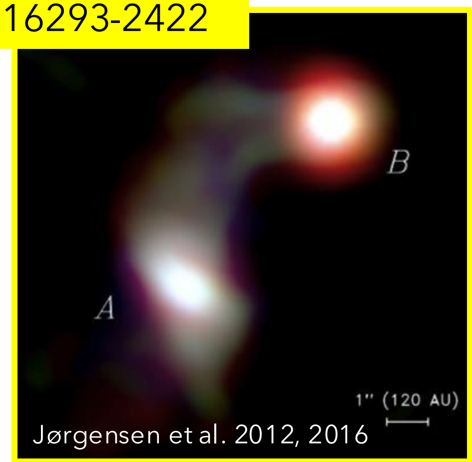
Large program targeting many lines: ALMA PILS

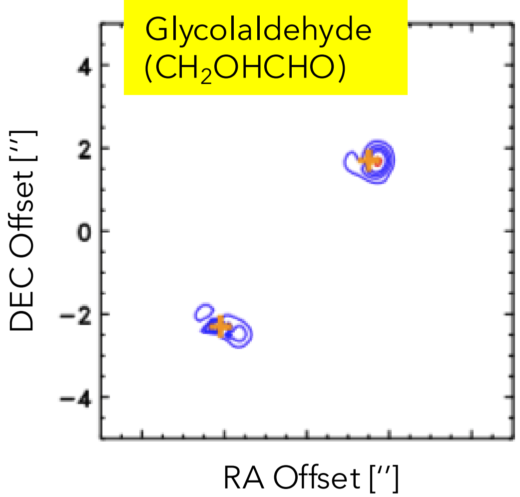


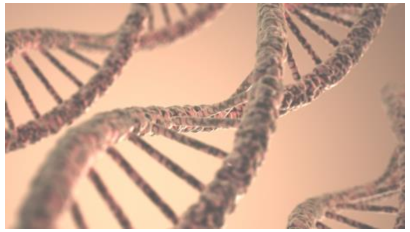
Astrochemistry in Low-mass (M ≤ a few $M_\odot$) Star Formation



IRAS 16293-2422

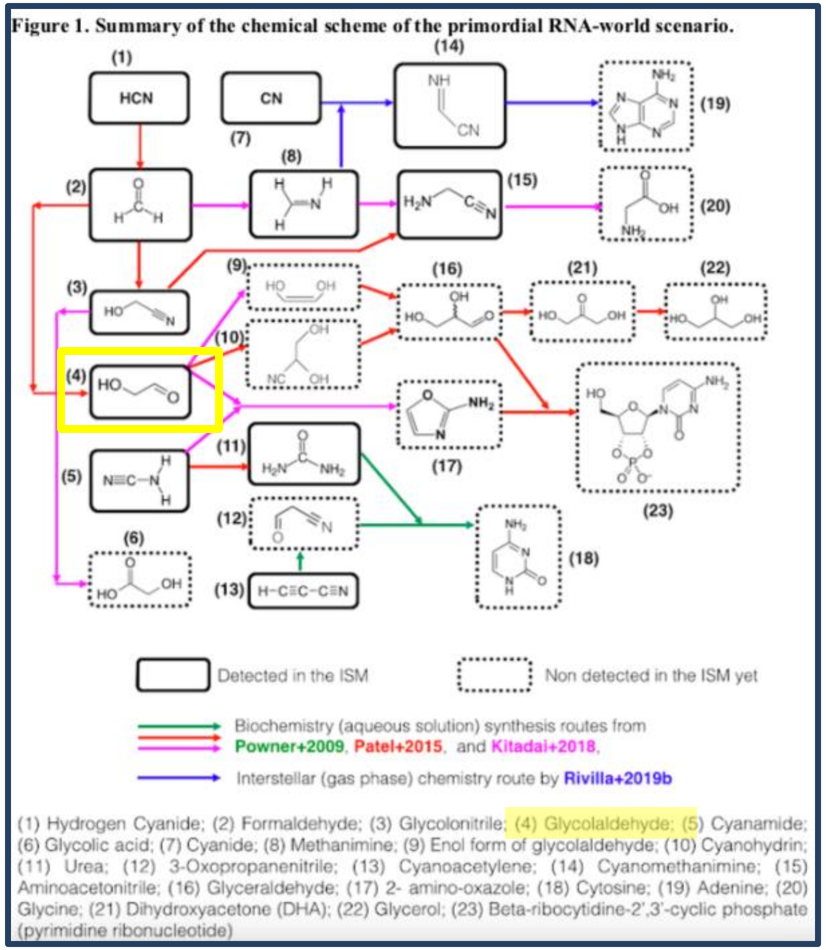






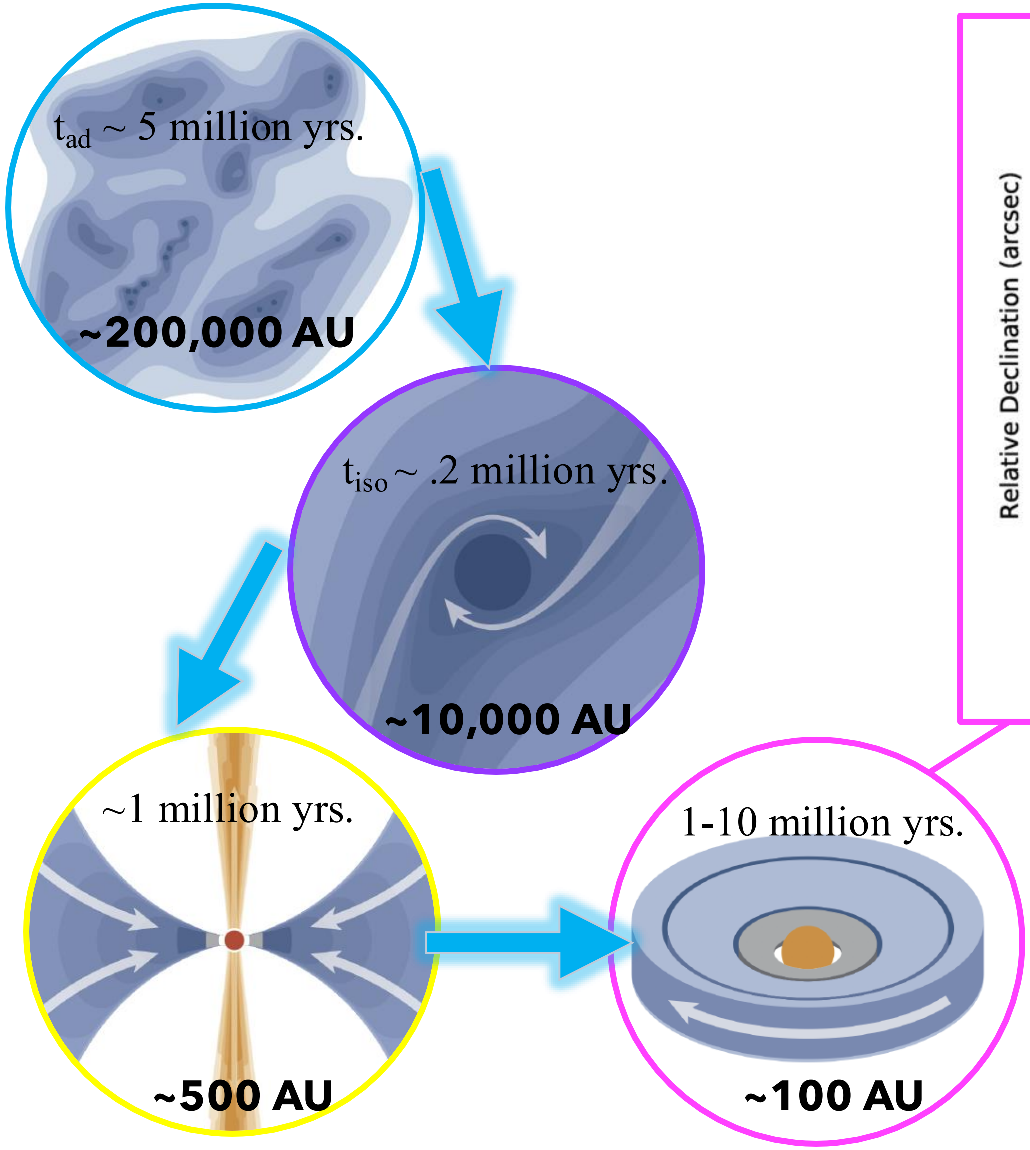
Life appeared on Earth about 4 billion years ago, but we do not know the processes that made it possible.

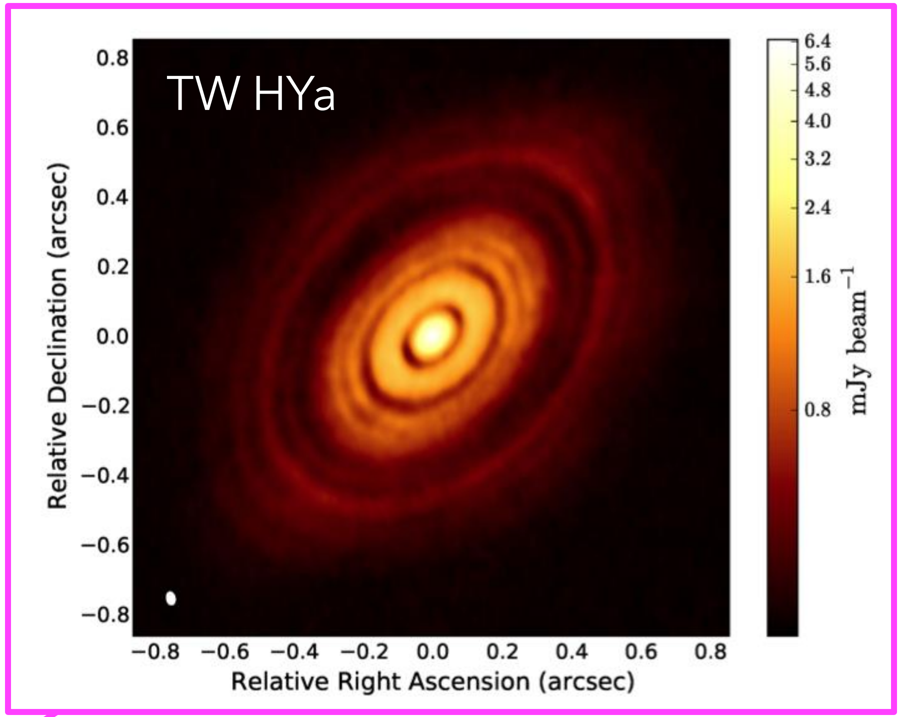
One of the proposed scenarios is the so-called ribonucleic acid RNA-world, which suggests that early forms of life relied solely on (RNA) to store genetic information and to catalyze chemical reactions.



Jimenez-Serra et al. 2020

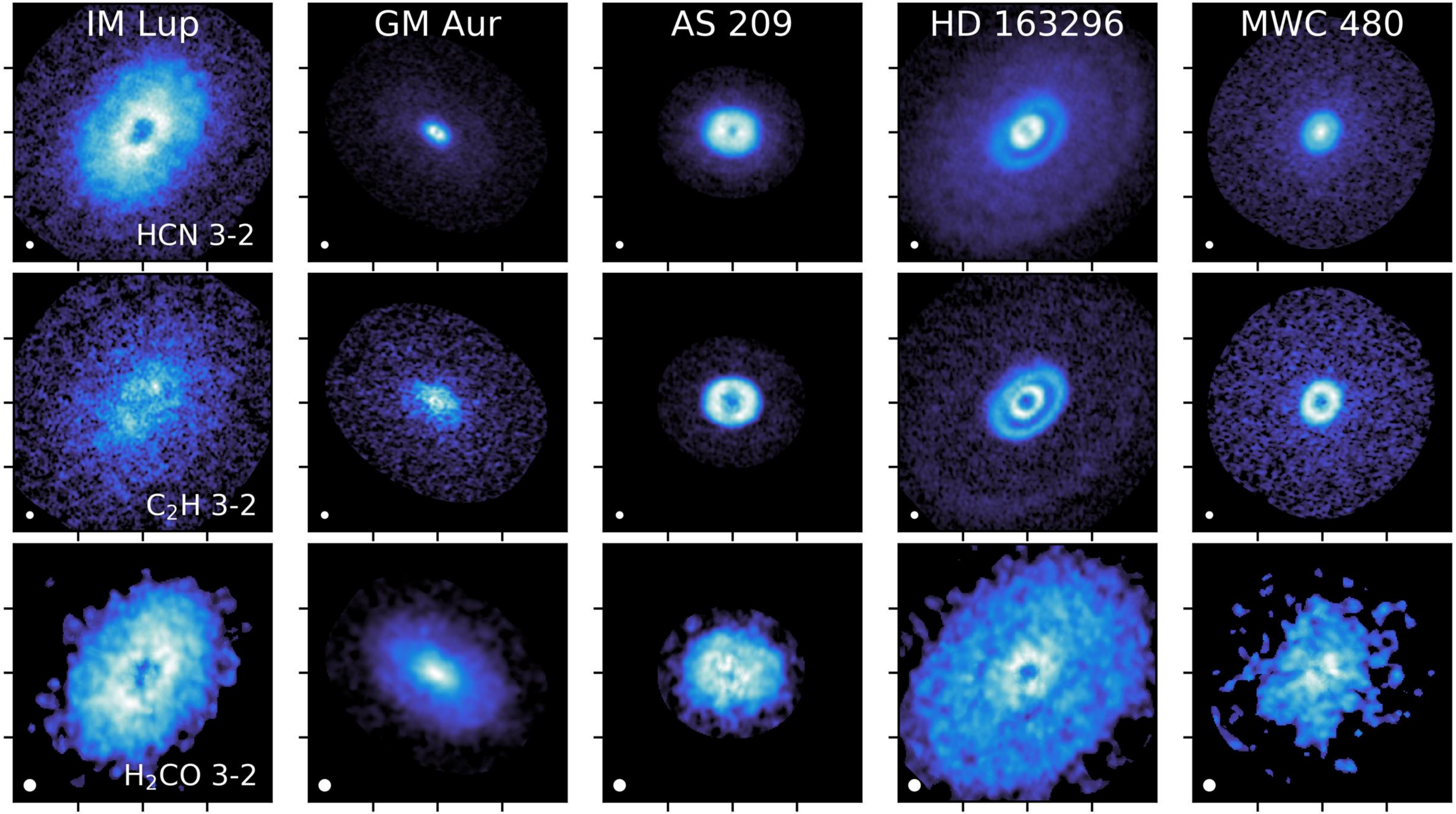
Astrochemistry in Low-mass ($M \lesssim$ a few $M_\odot$) Star Formation





A *protoplanetary disk* disks show gaps in rings that signify some planet formation!

Astrochemistry in Low-mass ($M \leq$ a few $M_{\odot}$) Star Formation

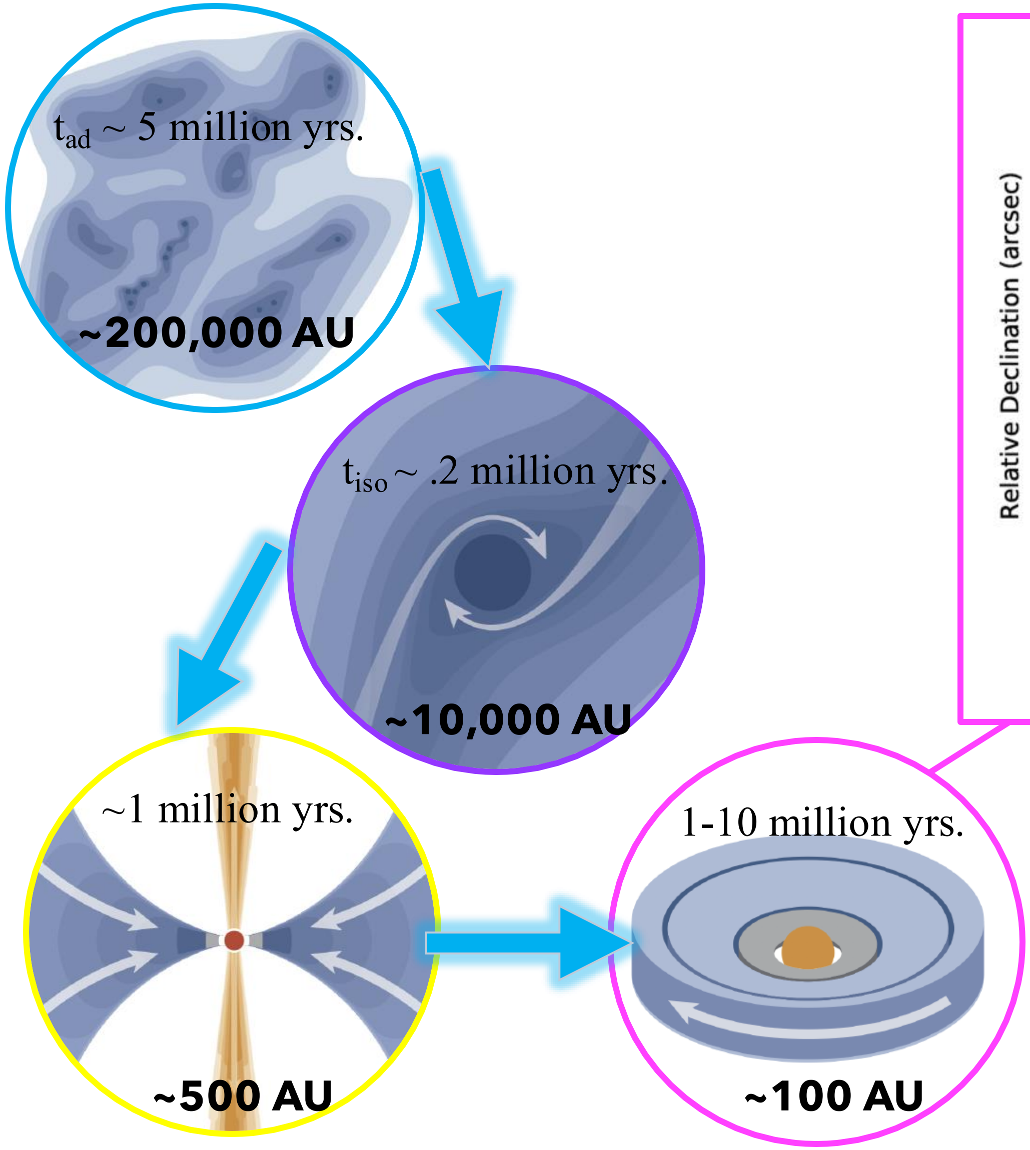


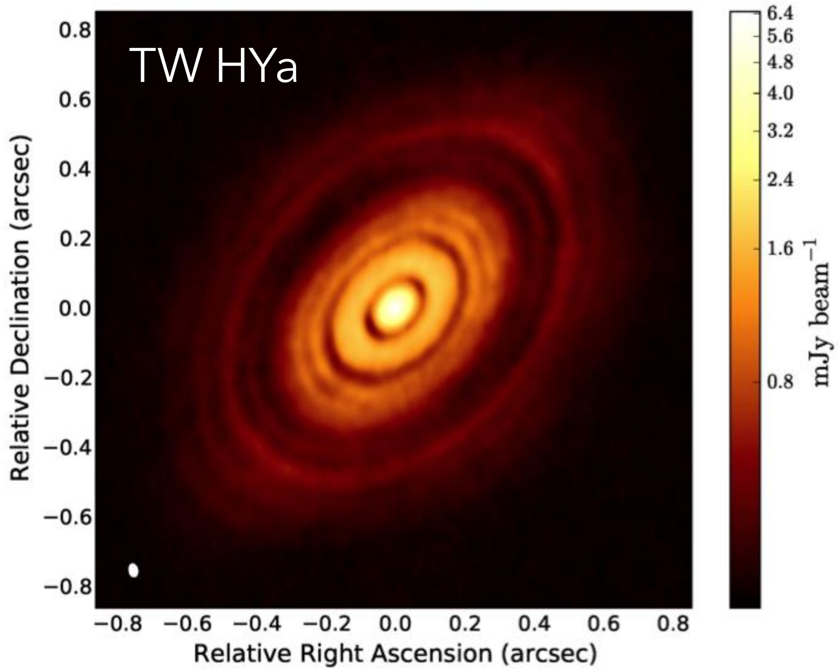
MAPS Large Program

Disk structure is even seen in molecular emission!

Oberg et al., 2021

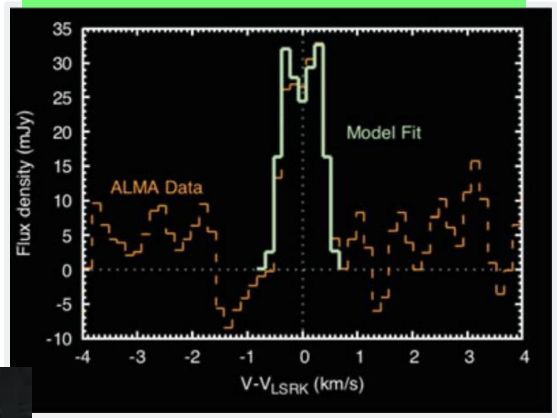
Astrochemistry in **Low-mass ($M \leq$ a few $M_\odot$)** Star Formation





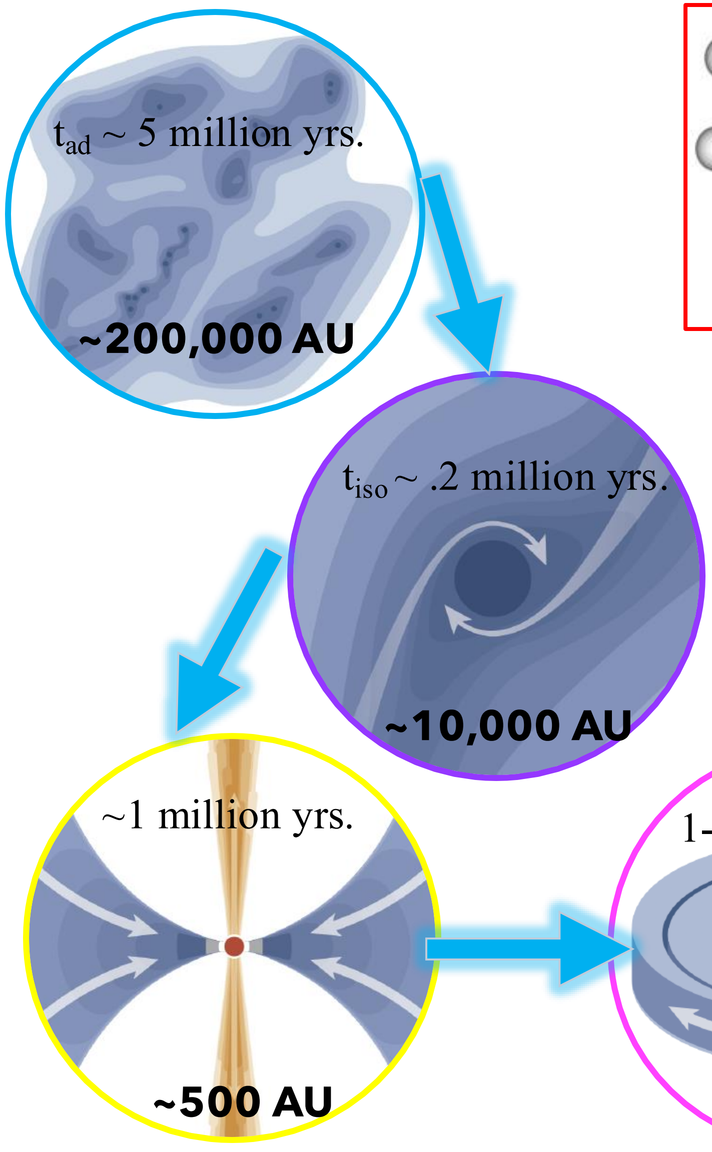
Challenging to observe COMs in such small objects, need sensitive telescopes!

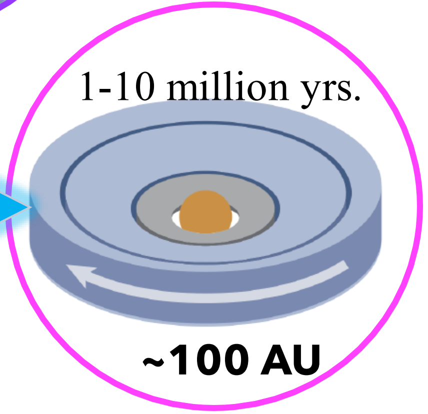
Methanol, CH_3OH, line profile

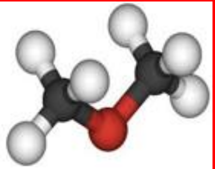


Walsh et al. 2016, 2017

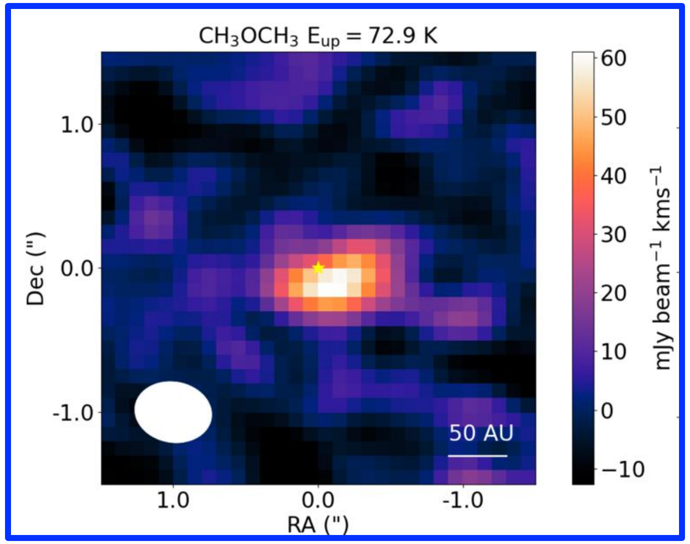
Astrochemistry in Low-mass ($M \leq$ a few $M_{\odot}$) Star Formation





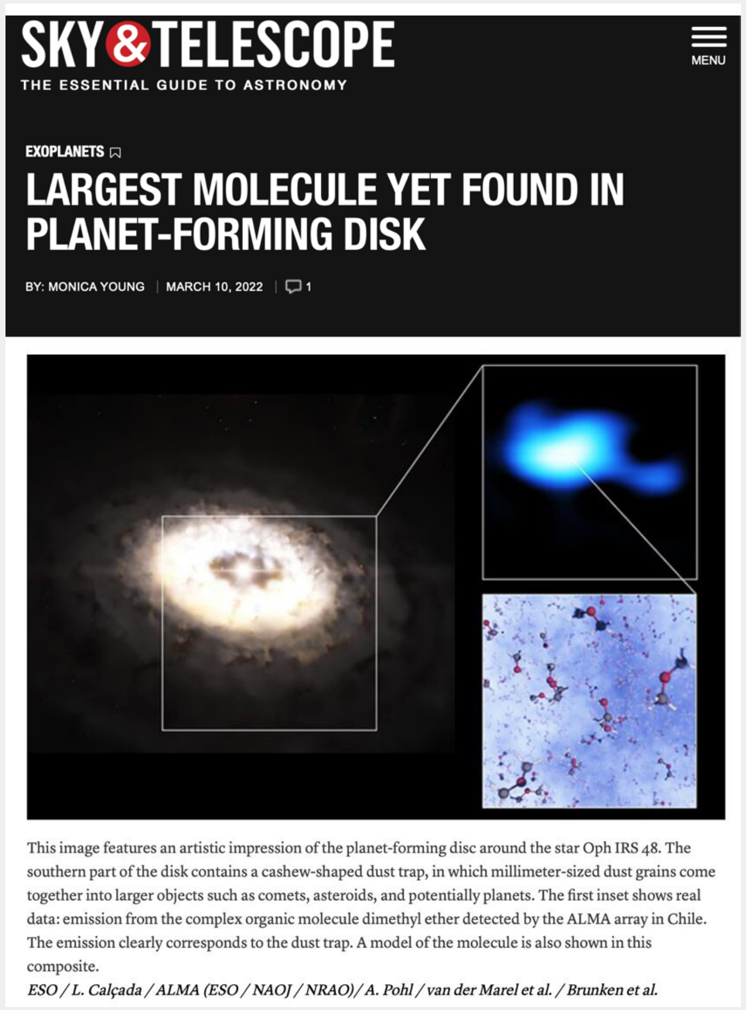


Dimethyl Ether CH_3OCH_3



Brunken et al. 2022

Around disks of higher-mass stars, more complex COMs are being detected!



SKY&TELESCOPE

THE ESSENTIAL GUIDE TO ASTRONOMY

MENU

EXOPLANETS

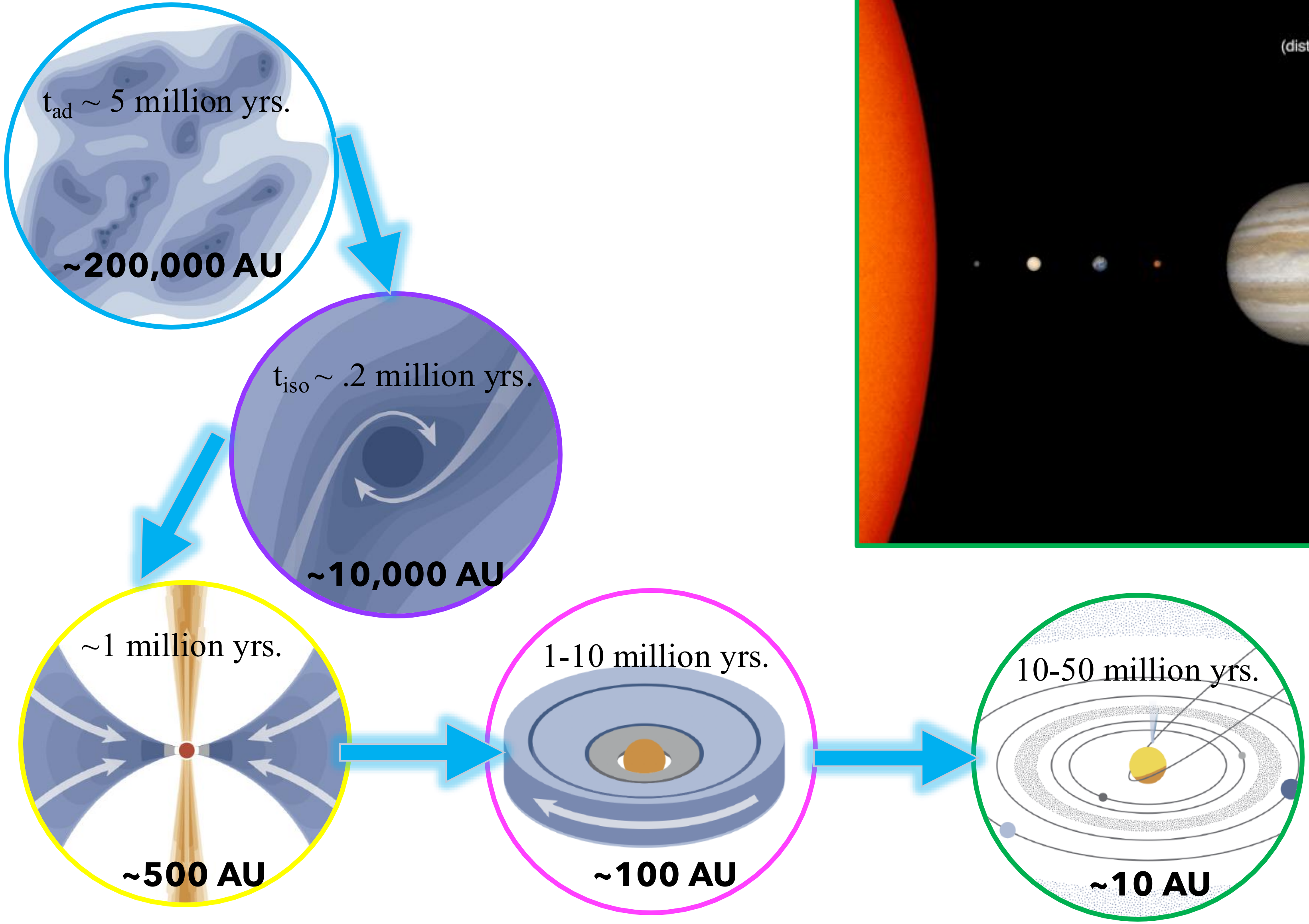
LARGEST MOLECULE YET FOUND IN PLANET-FORMING DISK

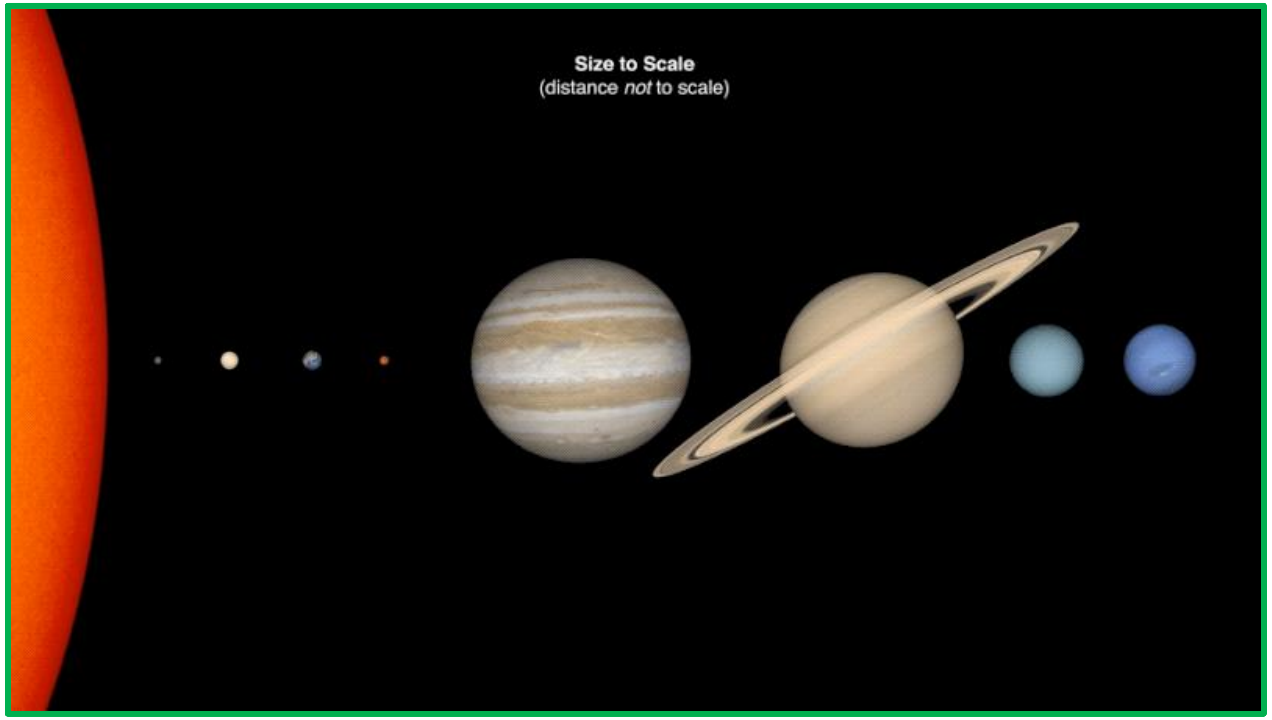
BY: MONICA YOUNG | MARCH 10, 2022 | 1

This image features an artistic impression of the planet-forming disc around the star Oph IRS 48. The southern part of the disk contains a cashew-shaped dust trap, in which millimeter-sized dust grains come together into larger objects such as comets, asteroids, and potentially planets. The first inset shows real data: emission from the complex organic molecule dimethyl ether detected by the ALMA array in Chile. The emission clearly corresponds to the dust trap. A model of the molecule is also shown in this composite.

ESO / L. Calçada / ALMA (ESO / NAOJ / NRAO)/ A. Pohl / van der Marel et al. / Brunken et al.

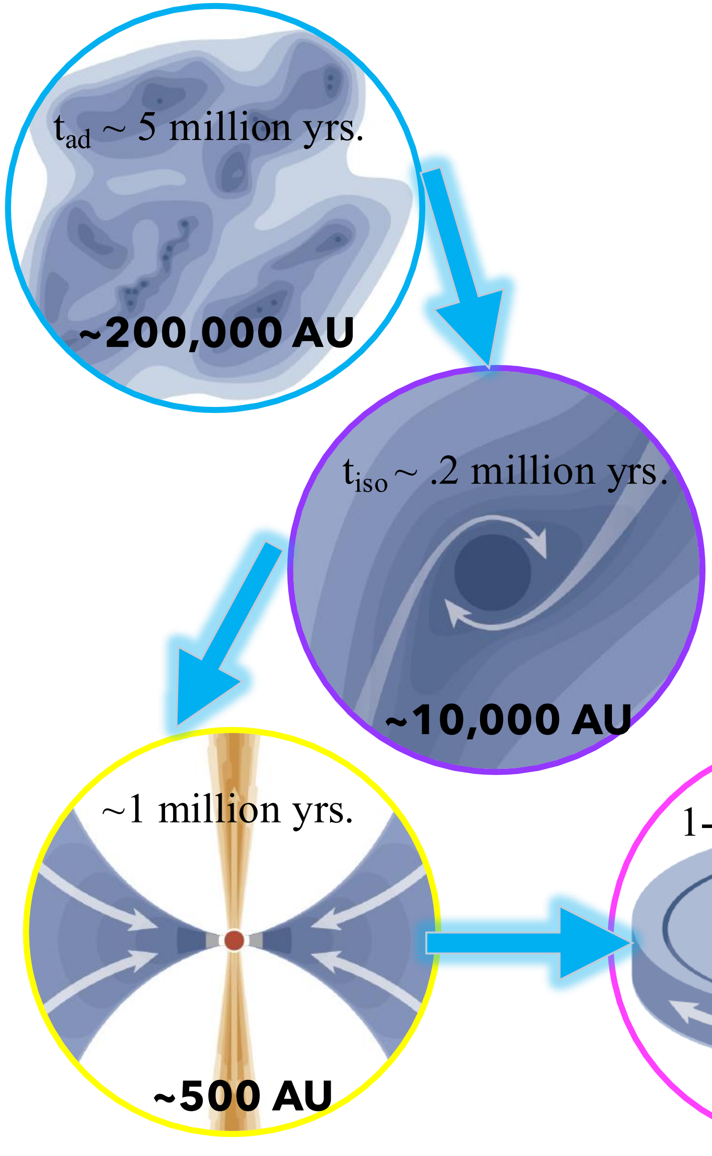
Astrochemistry in **Low-mass ($M \leq$ a few $M_{\odot}$)** Star Formation

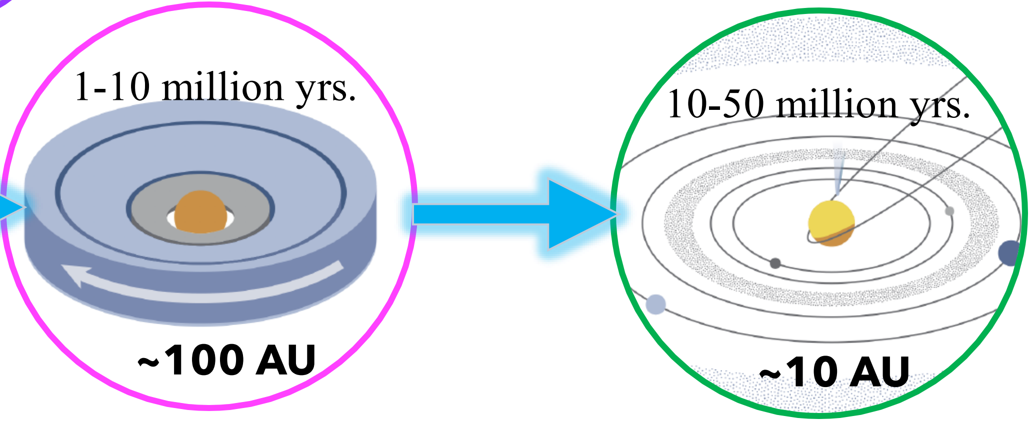




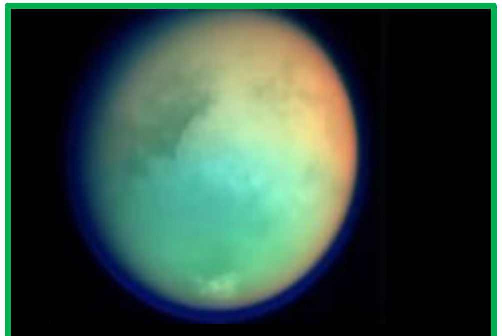
Rocky and icy planets and moons, as well as planetesimals (e.g., asteroids, comets), continue to grow into a mature *planetary system*

Astrochemistry in Low-mass ($M \leq$ a few $M_\odot$) Star Formation

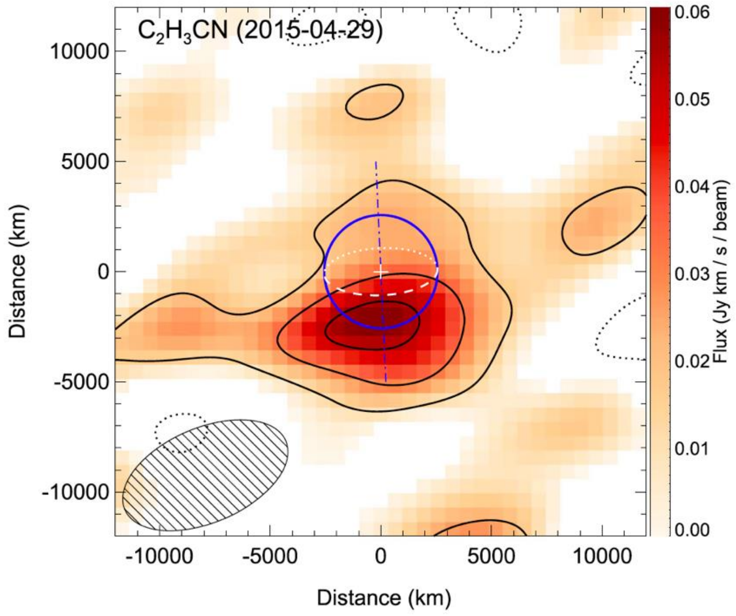




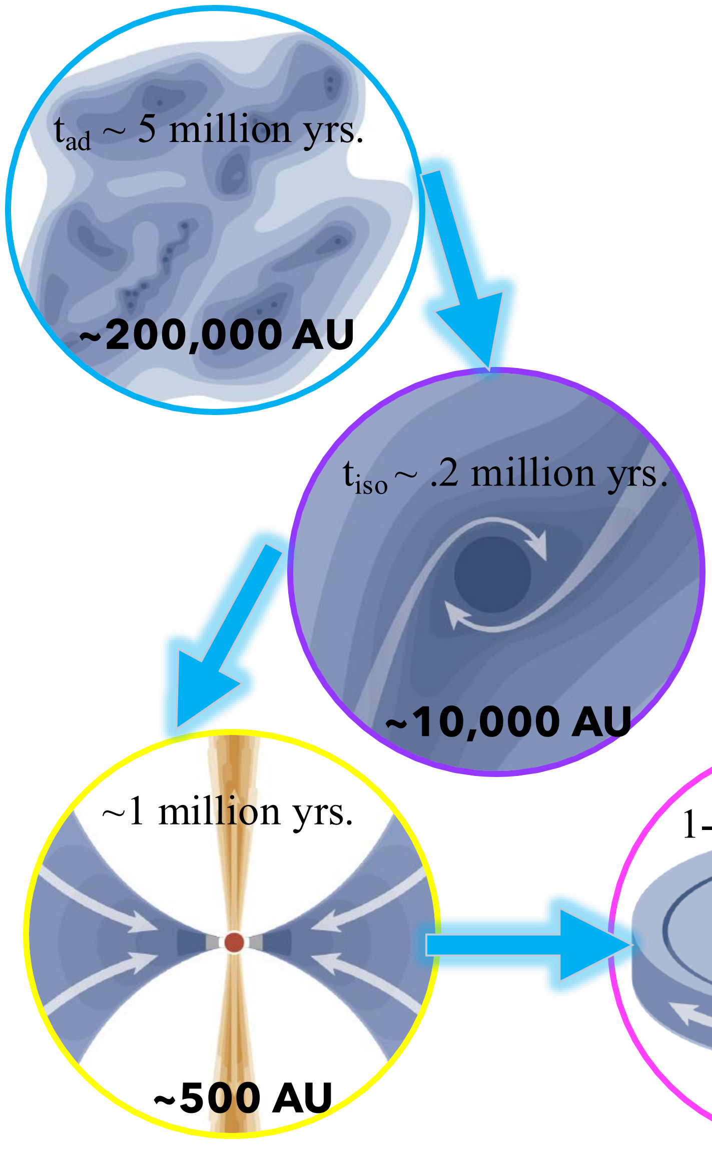
Rocky and icy planets and moons, as well as planetesimals (e.g., asteroids, comets), continue to grow into a mature *planetary system*

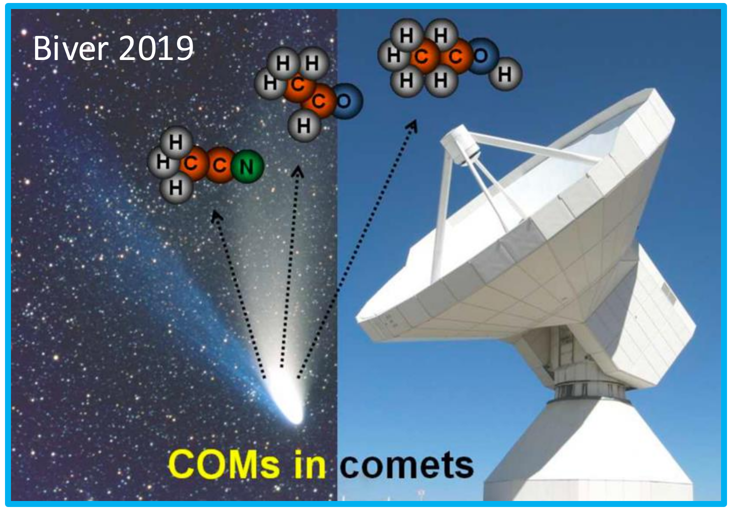


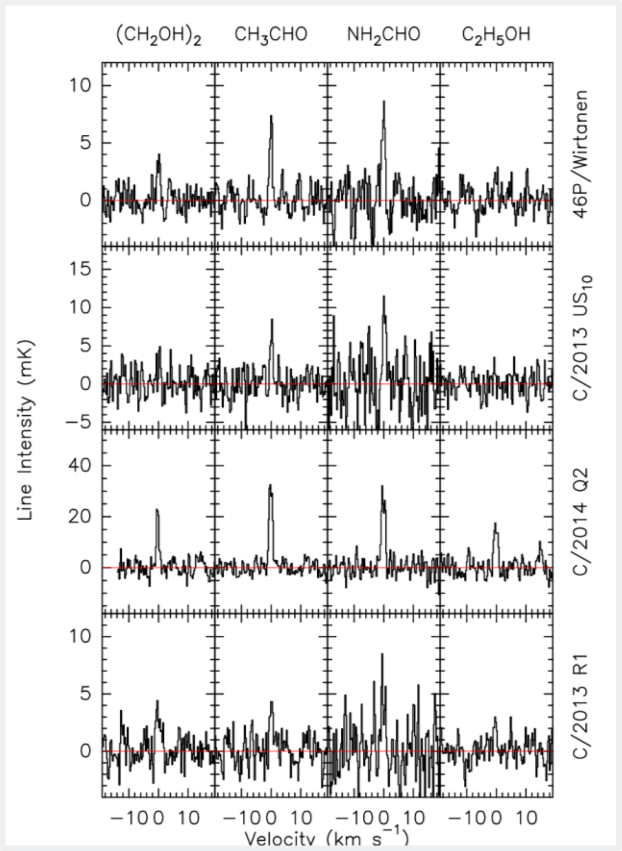
In Titan's atmosphere vinyl cyanide, CH_2CHCN, detected. Thought to be important for forming cell-like membranes in liquid methane oceans (Lai et al. 2017)

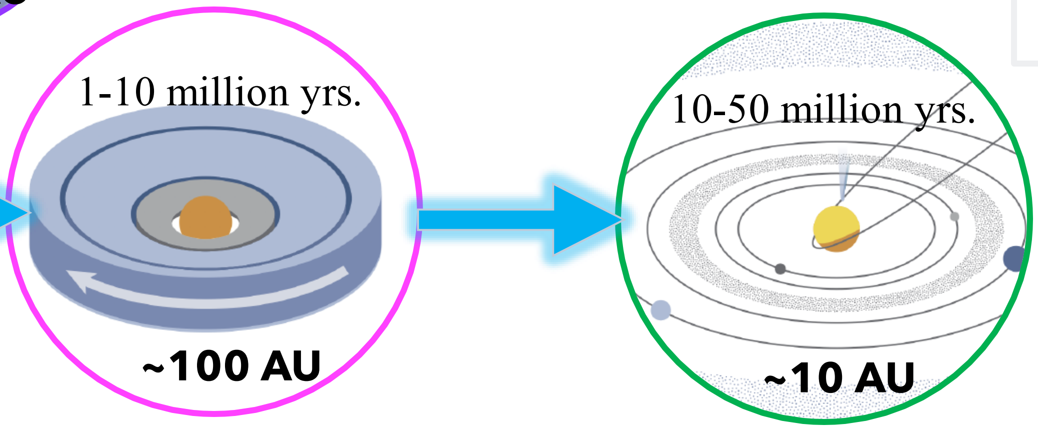


Astrochemistry in Low-mass (M ≤ a few $M_\odot$) Star Formation



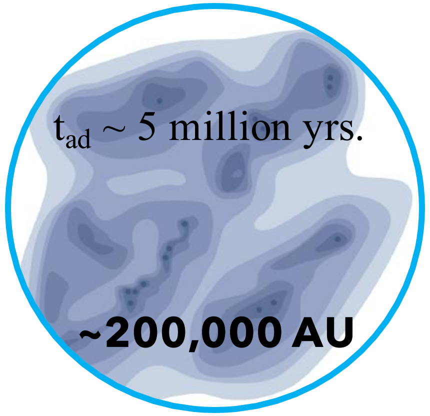




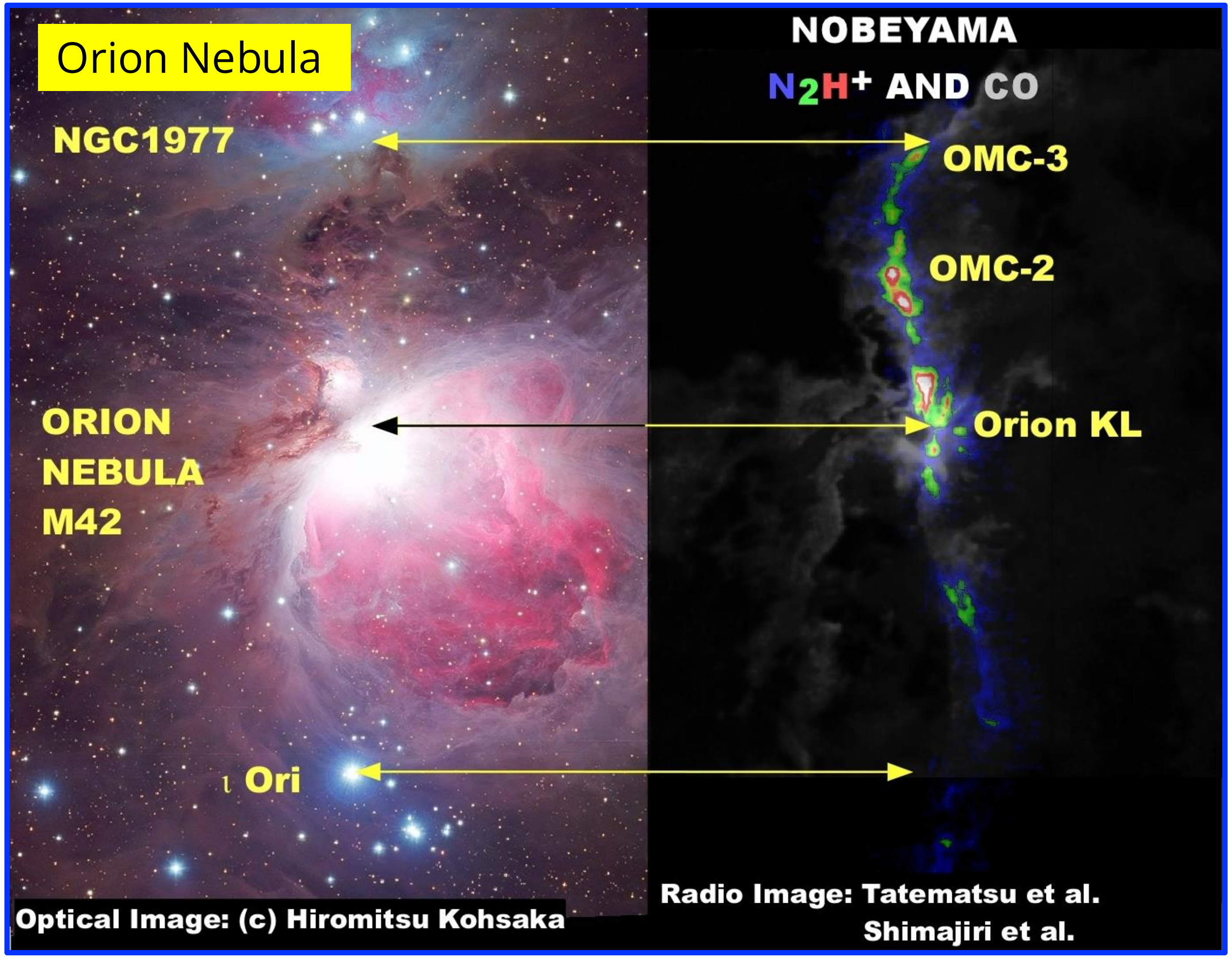


Rocky and icy planets and moons, as well as planetesimals (e.g., asteroids, comets), continue to grow into a mature *planetary system*

Astrochemistry in High-mass (M > 8-10 $M_{\odot}$) Star Formation



Molecular clouds (CO) and ***filaments (N_2H+)*** **also present in high-mass regions**

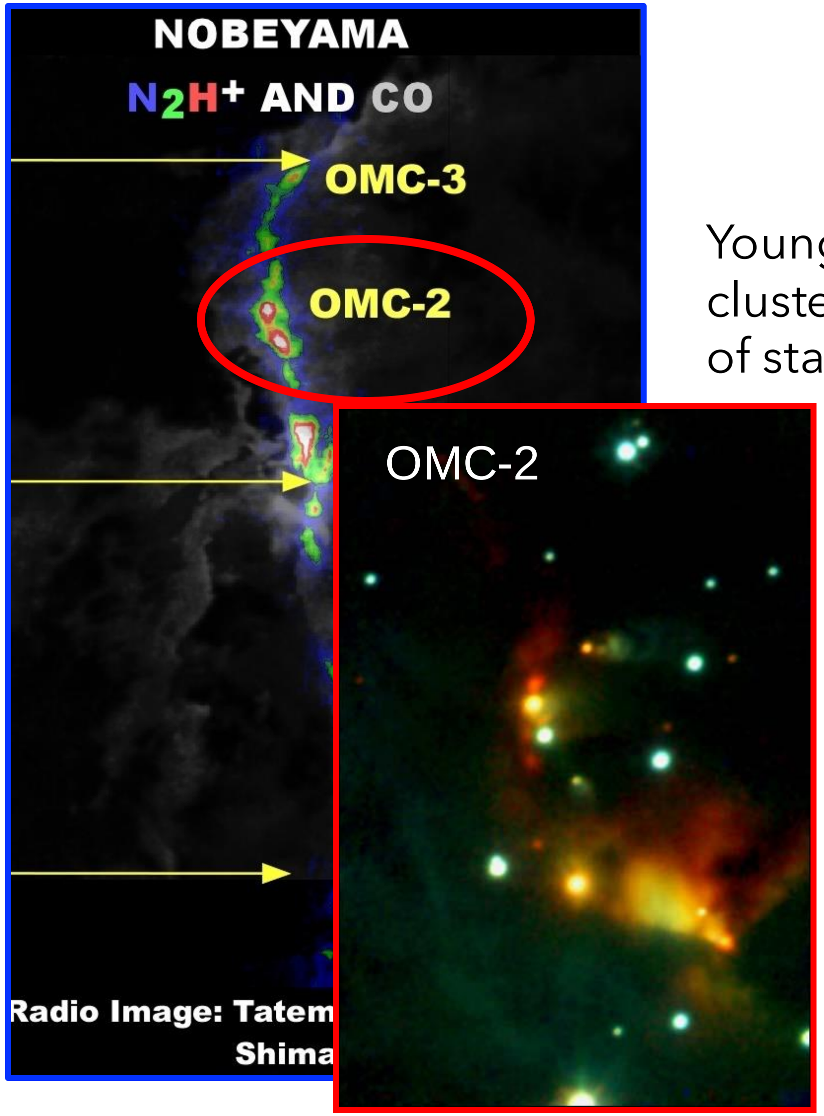


https://www.nro.nao.ac.jp/~kt/html/kt-e.html

Astrochemistry in High-mass (M > 8-10 M$_\odot$) Star Formation

GIANT MOLECULAR CLOUDS

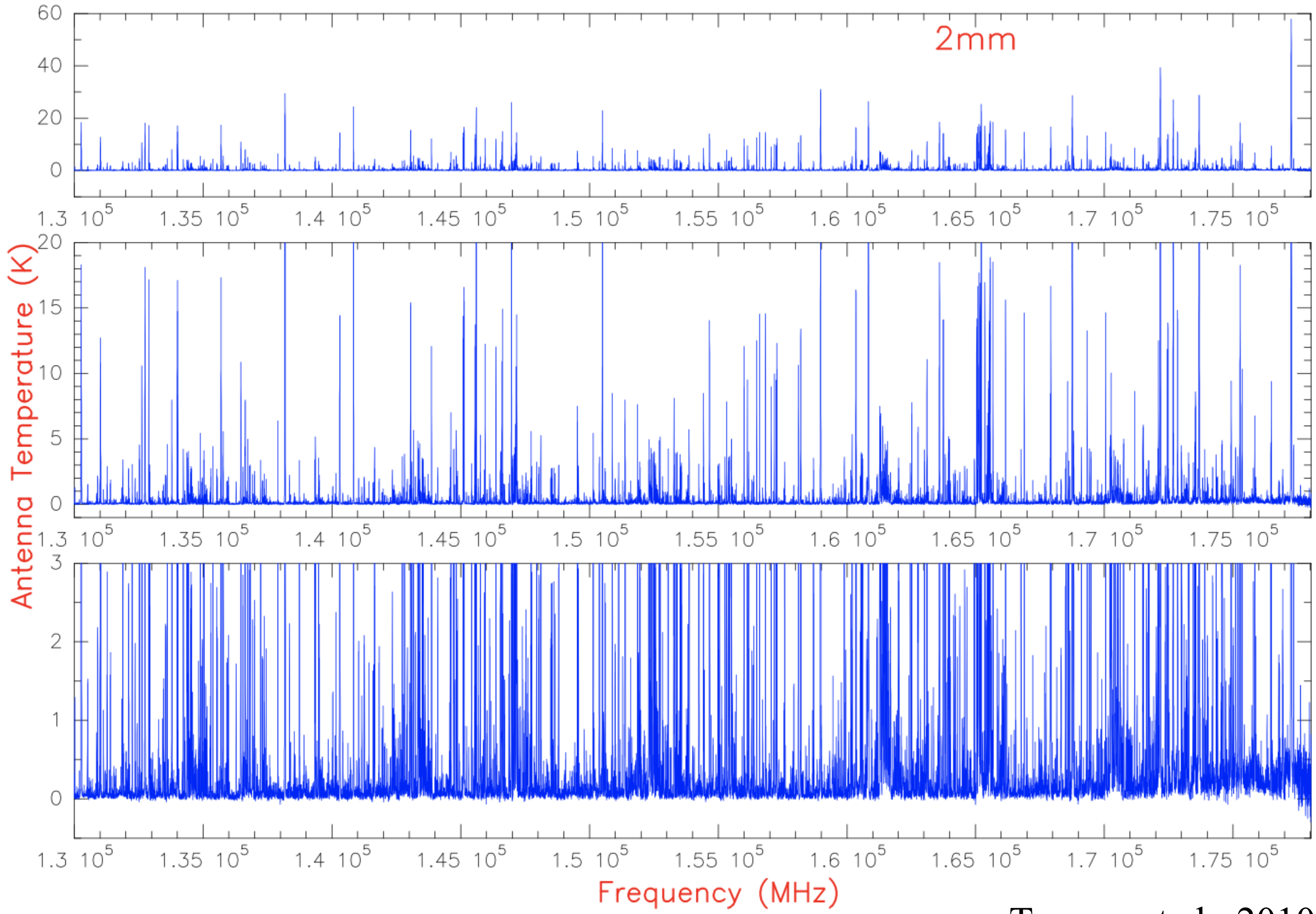
- Denser and warmer than low-mass dark clouds
- T ~ 50 – 100 K
- n ~ 10^4 – 10^6 cm^{-3}
- Masses of 10^4 -10^6 M$_\odot$
- Not gravitationally stable
  - ⇒ ***Collapse to form stars and solar systems***
  - ⇒ ***Lifetimes of ~ 10^6-10^7 years***
- Often contain **protostellar cores**
  - T ~ 100 – 200 K
  - n ~ 10^7 – 10^8 cm^{-3}
  - emit intensely in infrared and heat up surrounding gas
- Can be traced in IR, radio and infrared lines of molecules
  - both rotational and ro-vibrational transitions
- Sites of most massive star formation (Hot OB stars)



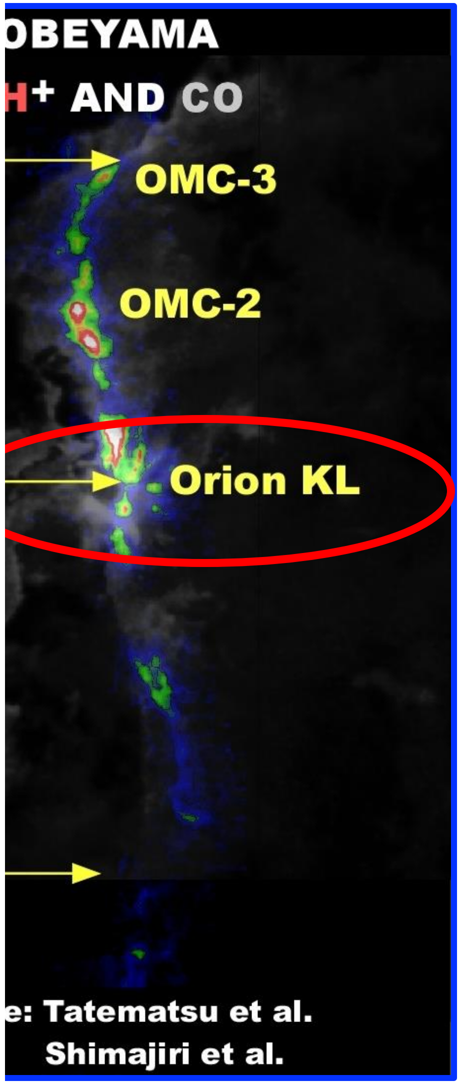
Young cluster of stars

Credit: L. Ziurys

Astrochemistry in High-mass (M > 8-10 $M_{\odot}$) Star Formation

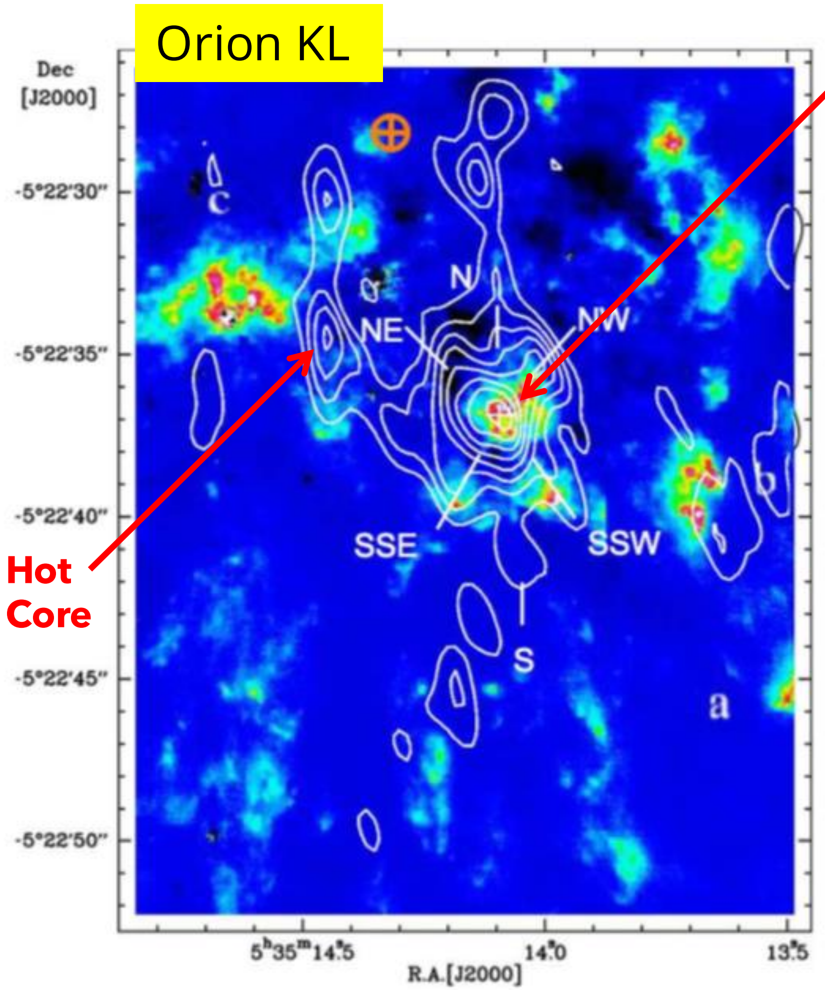


Tercero et al., 2010



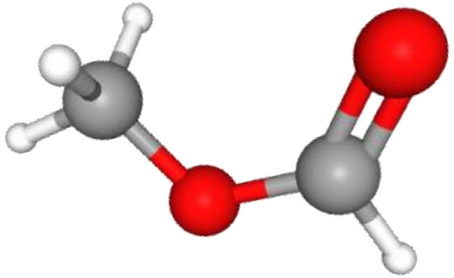
A 'hot-spot' for complex chemistry!

Astrochemistry in High-mass (M > 8-10 $M_\odot$) Star Formation



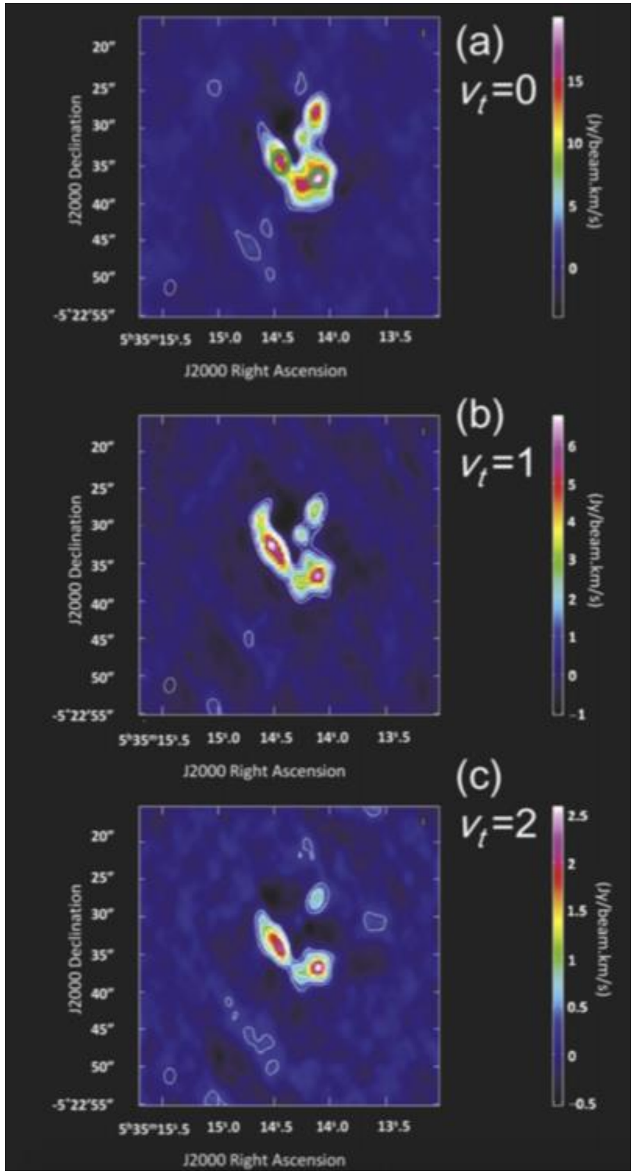
Contours: Methyl Formate 8.6 km/s channel map (Favre et al. 2011)
Emission: 2.12 micron excited H_2 emission (Lacombe et al. 2004)

8-atom molecule, Methyl Formate, $HCOOCH_3$, tracing the star-forming 'hot core'



First identification of rotational transitions in the second vibrationally excited state!

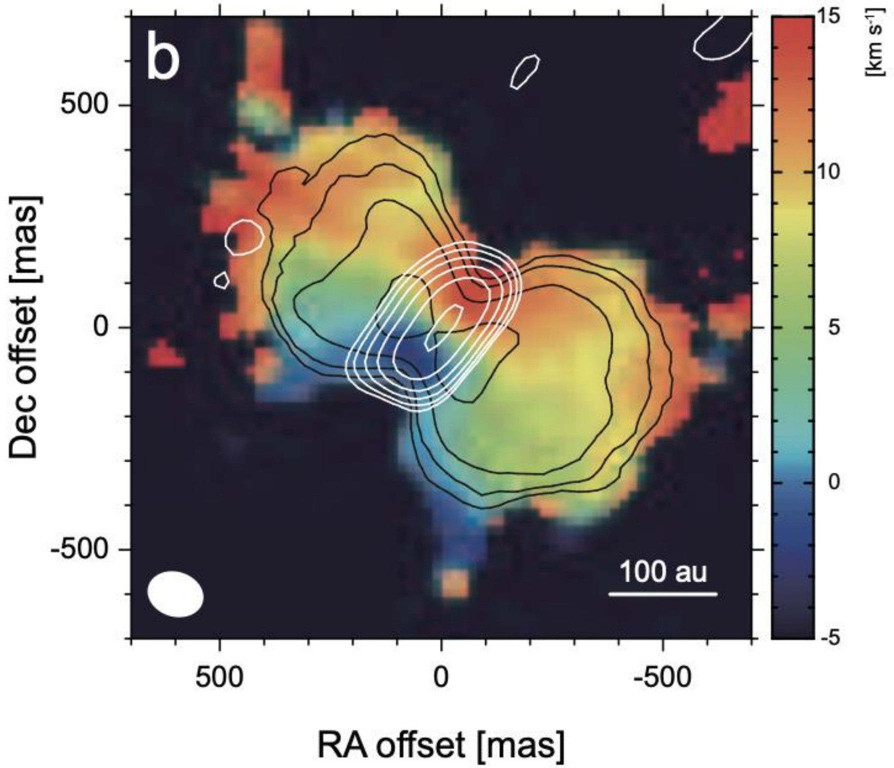
Sakai et al. 2015



Astrochemistry in High-mass (M > 8-10 $M_{\odot}$) Star Formation

Orion Source I

SiO emssion

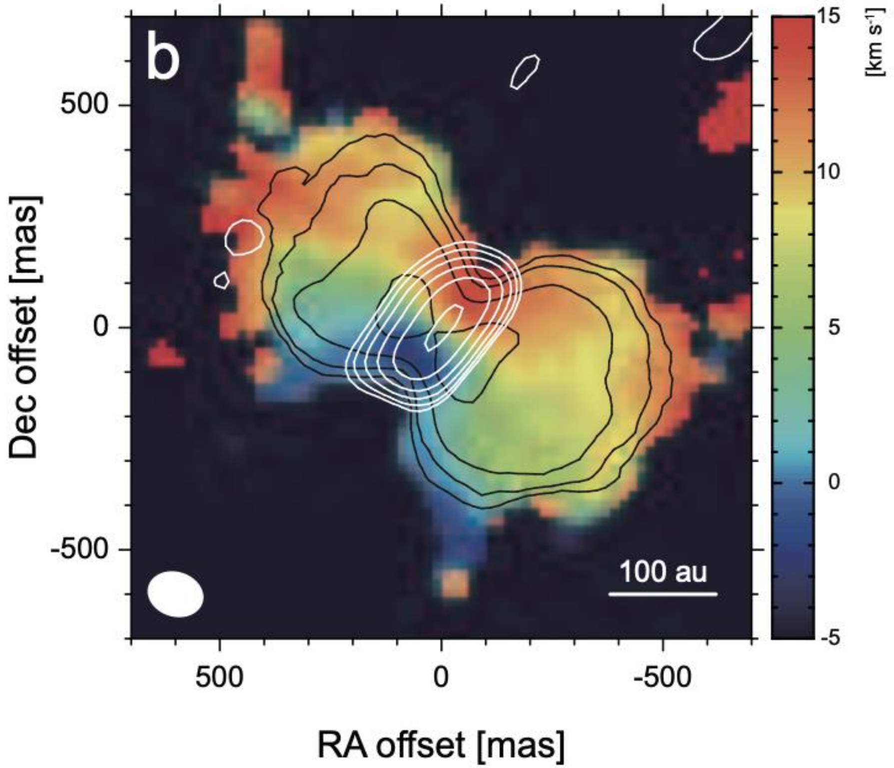


The presence of a **disk-outflow** system (Hirota et al. 2017) indicates that "Orion source I" is accreting, confirming its nature as a young, forming star.

Astrochemistry in High-mass (M > 8-10 $M_{\odot}$) Star Formation

Orion Source I

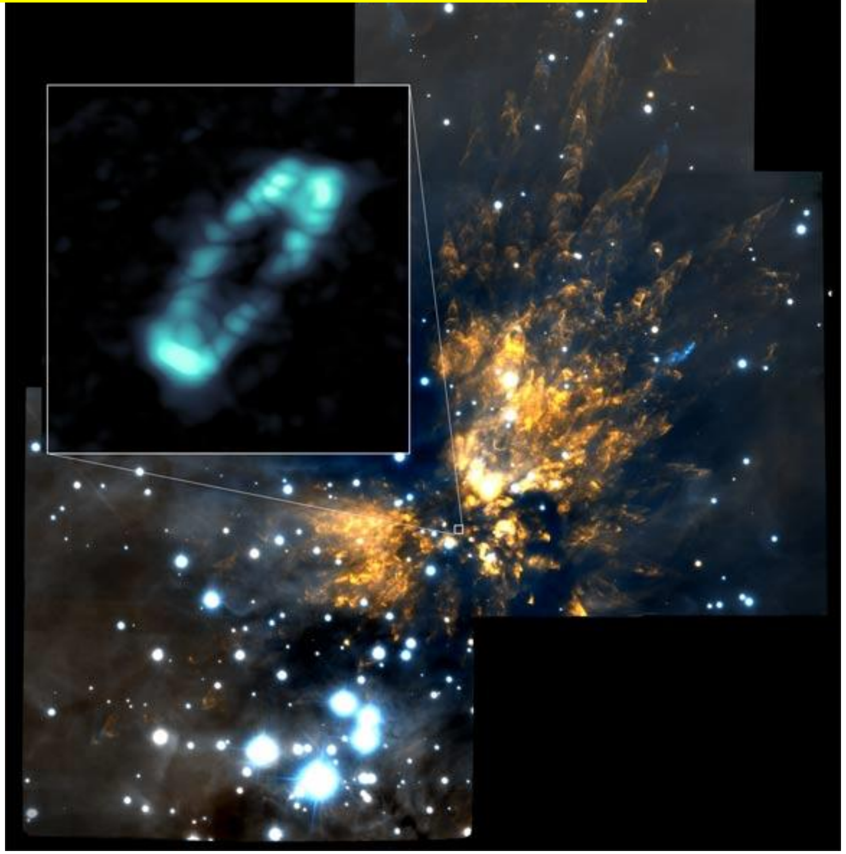
SiO emssion



The presence of a **disk-outflow** system (Hirota et al. 2017) indicates that "Orion source I" is accreting, confirming its nature as a young, forming star.

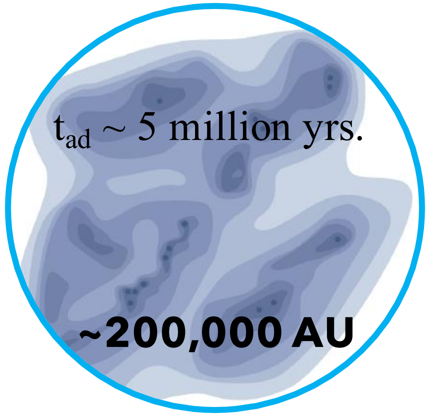
First detection of <u>salts</u> in star forming core!

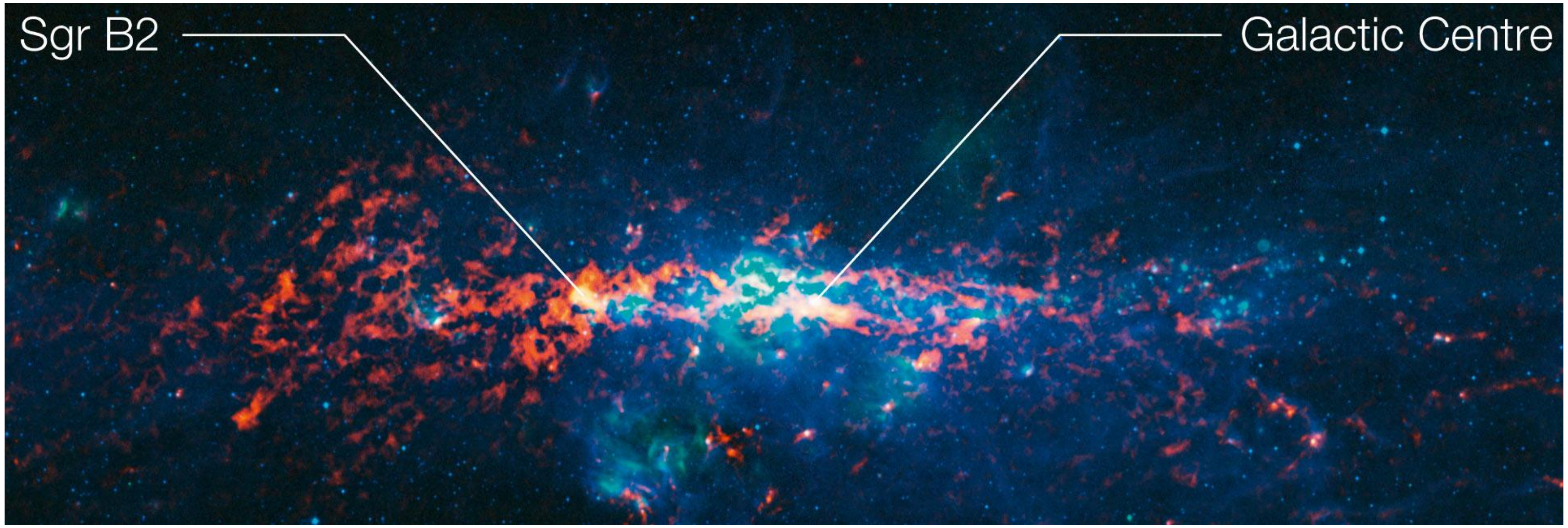
Sodium chloride (NaCl), potassium chloride (KCl), and their ^{37}Cl and ^{41}K isotopologues,



Adam Ginsburg *et al.* 2019.

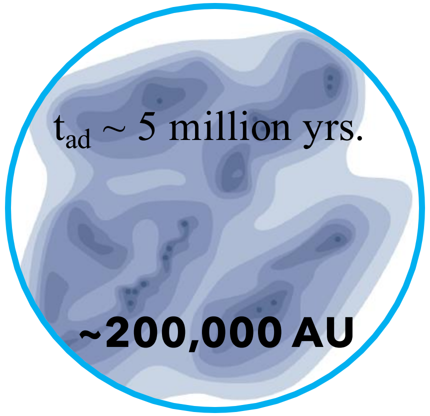
Astrochemistry in High-mass ($M > 8\text{-}10\ M_\odot$) Star Formation





At the center of our galaxy, high mass clouds are chemically rich!

Astrochemistry in High-mass (M > 8-10 $M_{\odot}$) Star Formation



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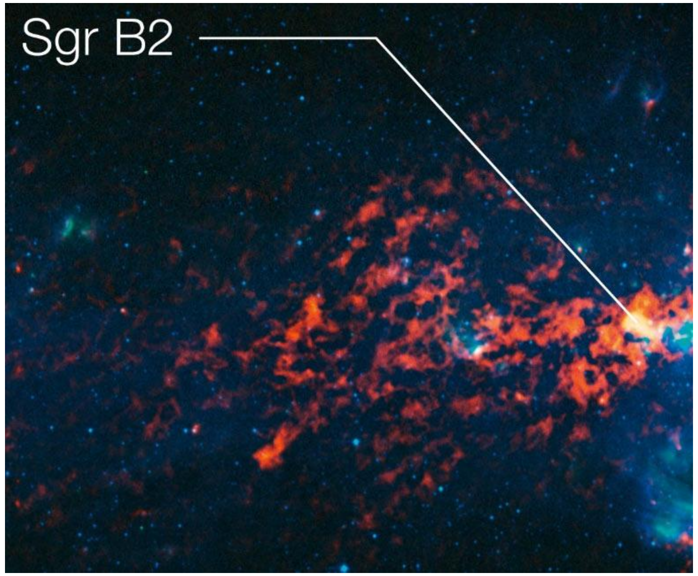


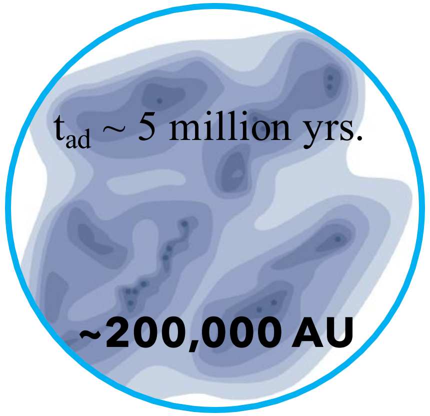
"Famous" cloud Sgr B2 is the #1 source of new molecule detections! Lots of complex chemistry!

# of molecule discoveries per source

Source	#	Source	#
Sgr B2	69	L1527	2
TMC-1	57	L1544	2
IRC+10216	55	NGC 2024	2
LOS Cloud	42	NGC 7023	2
Orion	24	NGC 7027	2
L483	9	TC 1	2
W51	8	W49	2
VY Ca Maj	6	CRL 2688	1
B1-b	4	Crab Nebula	1
DR 21	4	DR 21(OH)	1
IRAS 16293	4	Galactic Center	1
NGC 6334	4	IC 443G	1
Sgr A	4	K3-50	1
CRL 618	3	L134	1
G+0.693-0.027	3	L183	1
NGC 2264	3	Lupus-1A	1
W3(OH)	3	M17SW	1
rho Oph A	3	NGC 7538	1
Horsehead PDR	2	Orion Bar	1

McGuire 2022

Astrochemistry in High-mass ($M > 8\text{-}10\ M_\odot$) Star Formation



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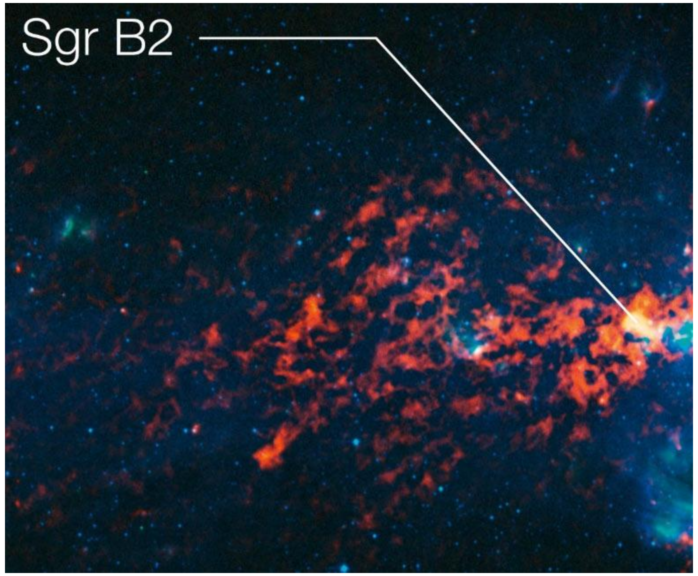
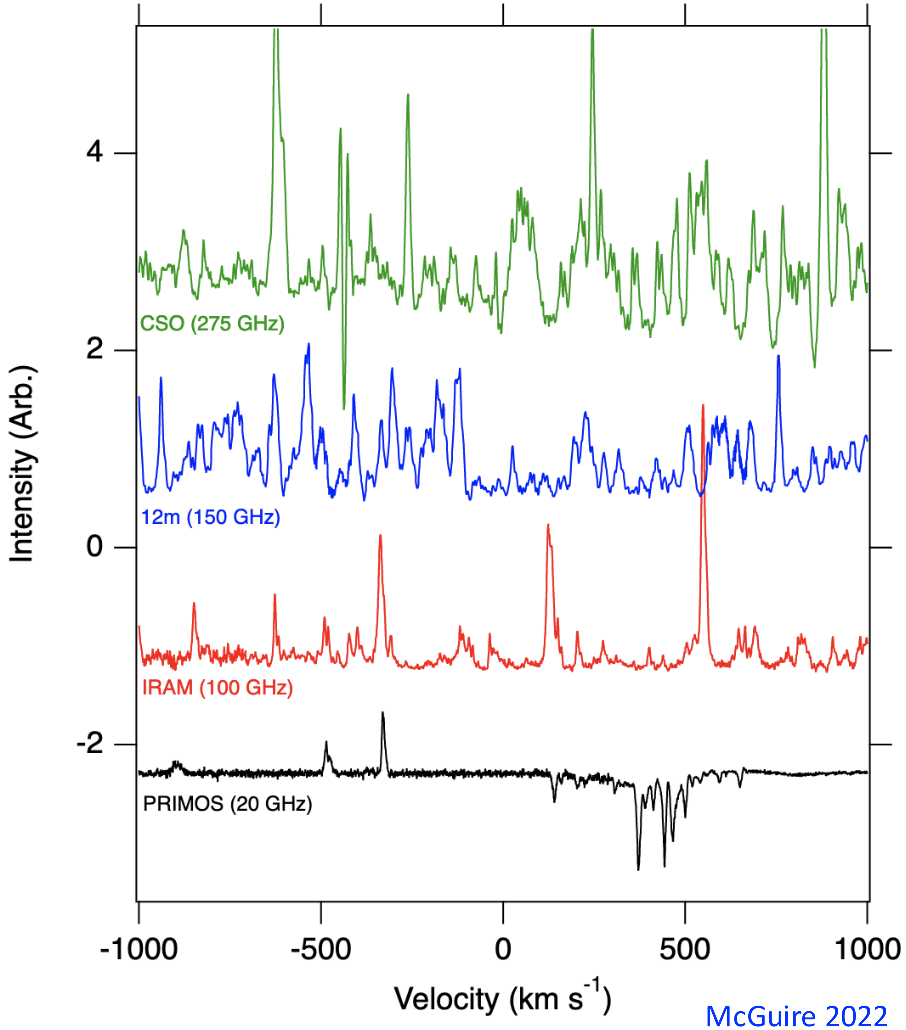
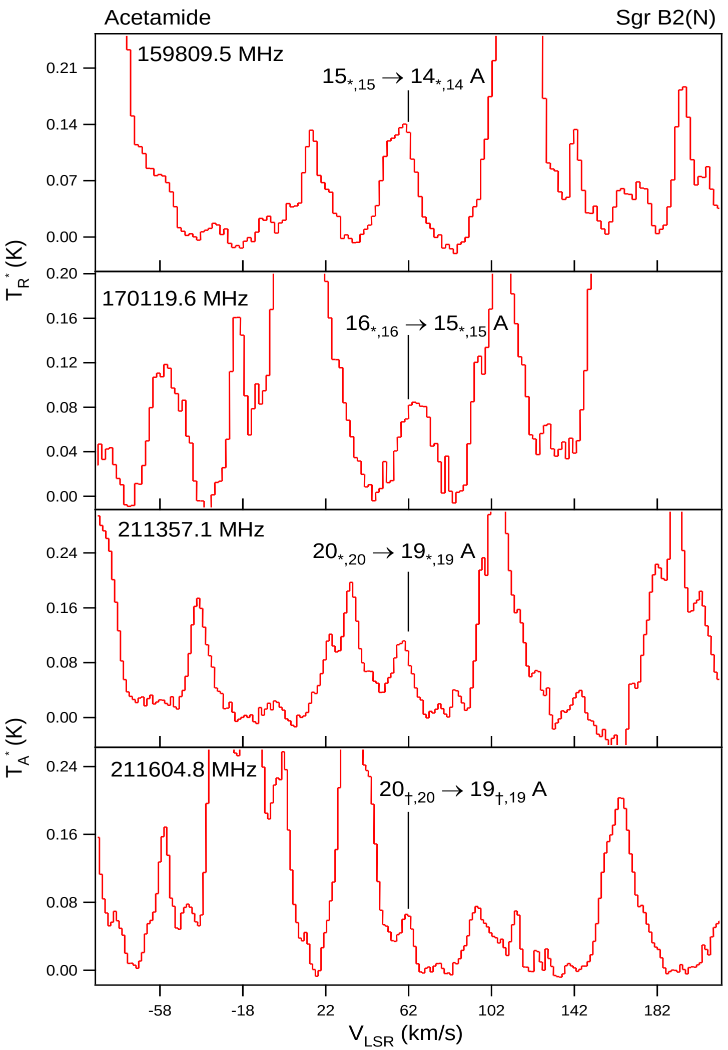


Many line surveys done at different frequencies, across the millimeter and submillimeter spectrum →

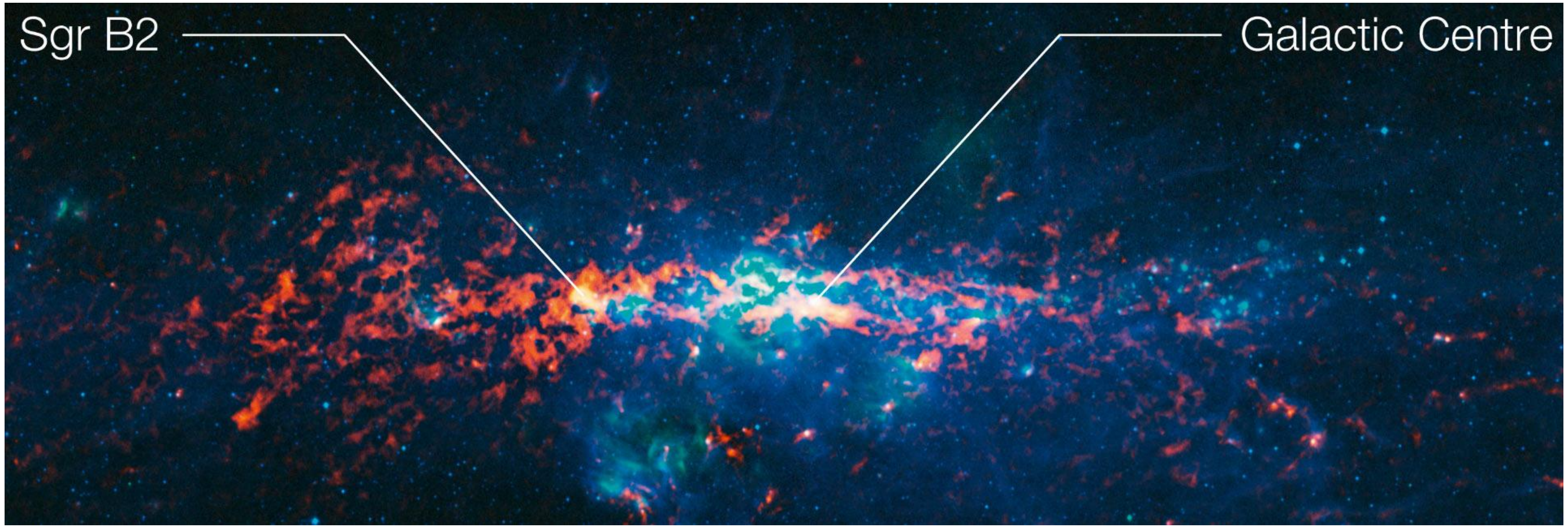


McGuire 2022

Astrochemistry in High-mass ($M > 8\text{-}10\ M_\odot$) Star Formation

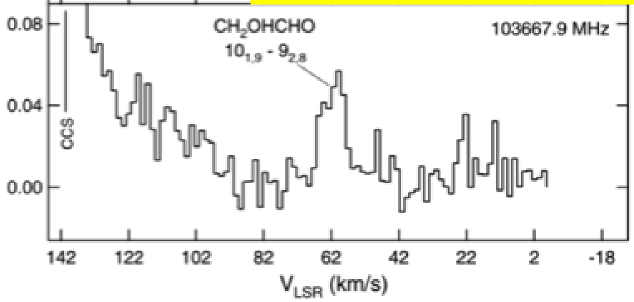


(Halfen et al. 2011; 2013)



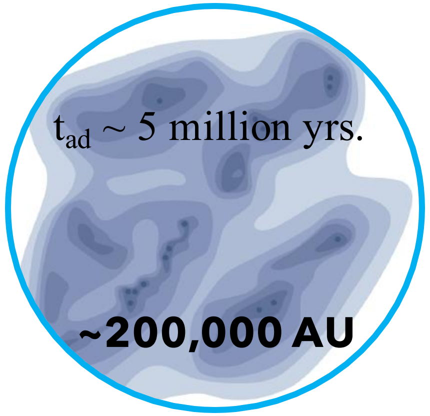
- Much broader lines
- **Asymmetric** line profiles
- Multiple velocity components
- Line confusion

Glycolaldehyde (CH_2OHCHO)



(Hollis et al. 2000, Halfen et al. 2006)

Astrochemistry in High-mass ($M > 8\text{-}10\ M_\odot$) Star Formation



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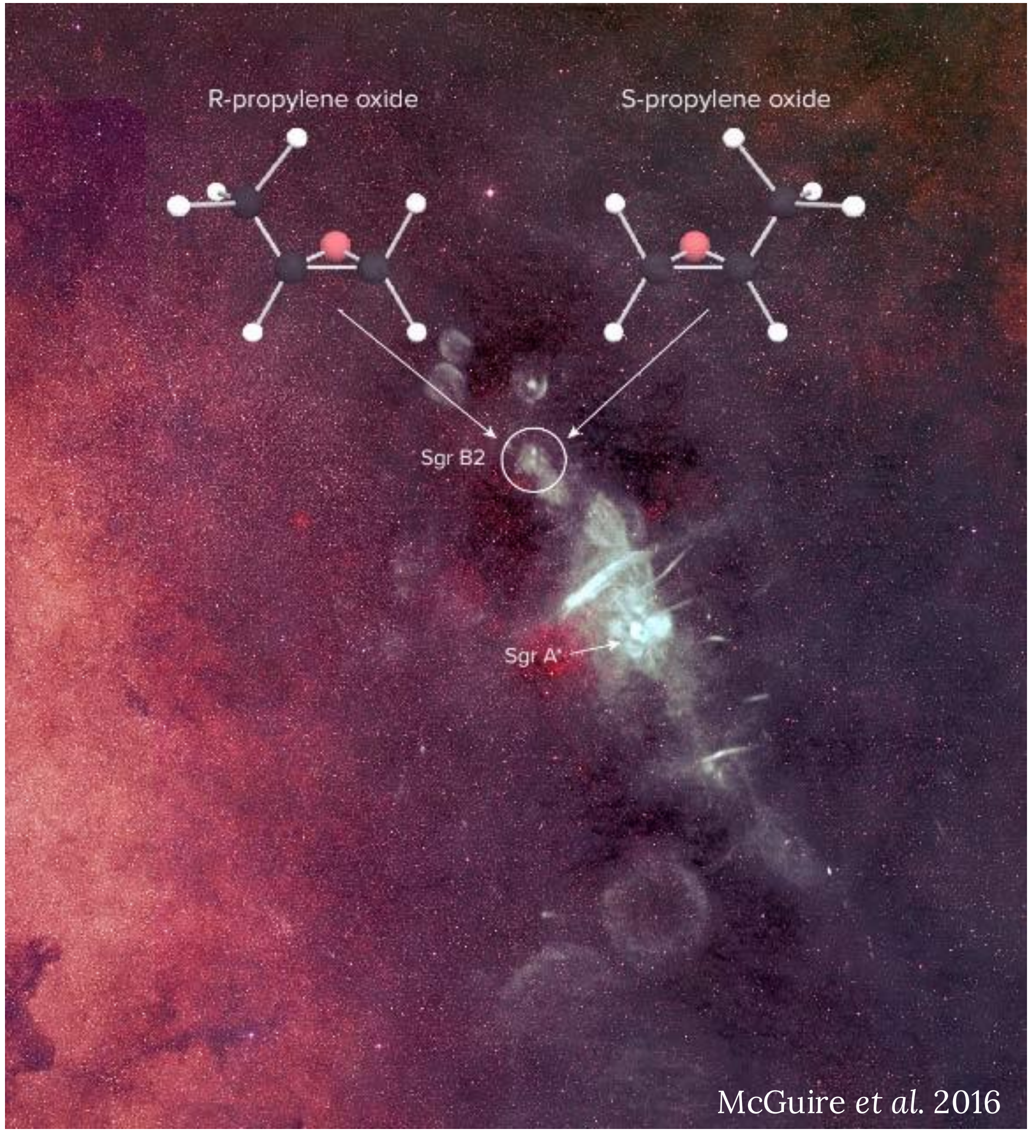
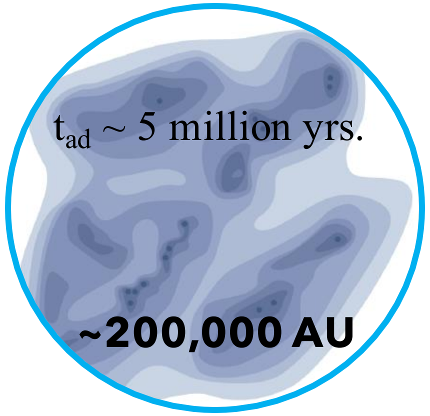


McGuire *et al.* 2016

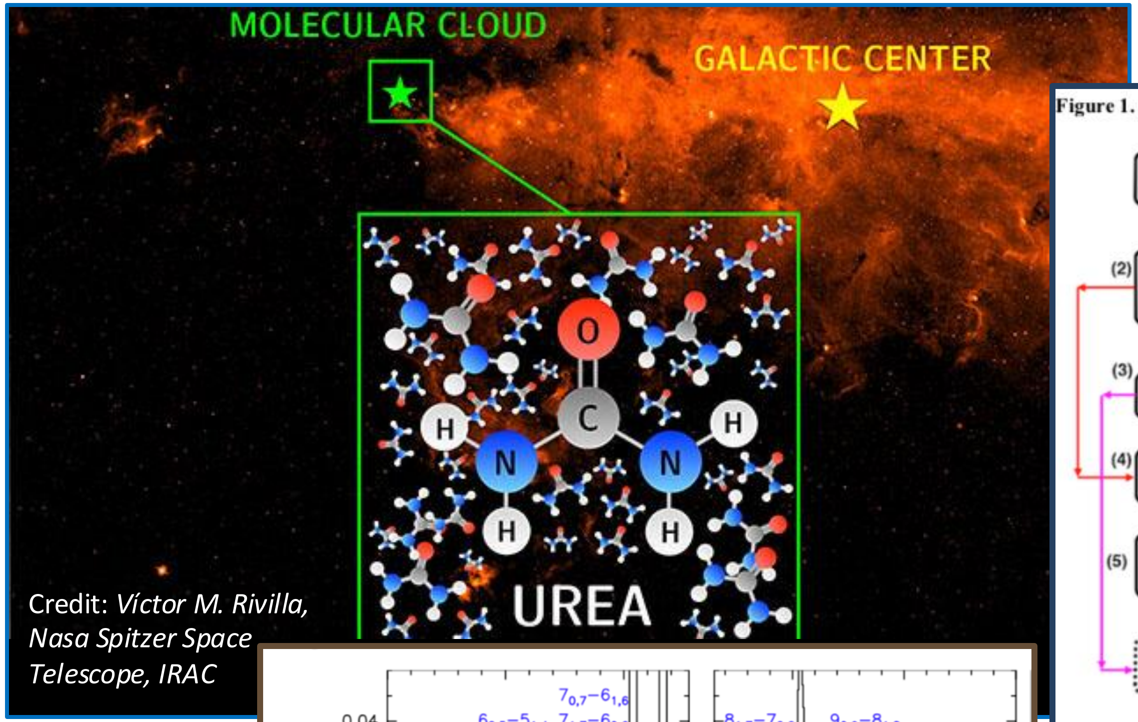
First chiral molecule detected in interstellar space toward the Sgr B2 star forming cloud!

Propylene oxide, CH_3CHCH_2O

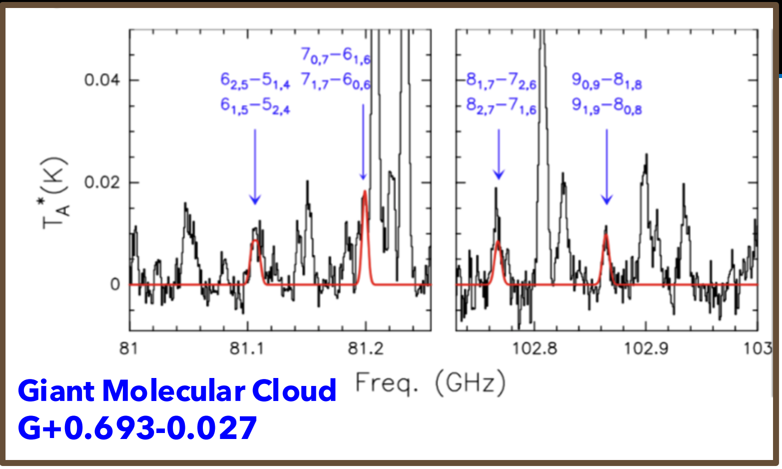
Astrochemistry in High-mass ($M > 8\text{-}10\ M_\odot$) Star Formation

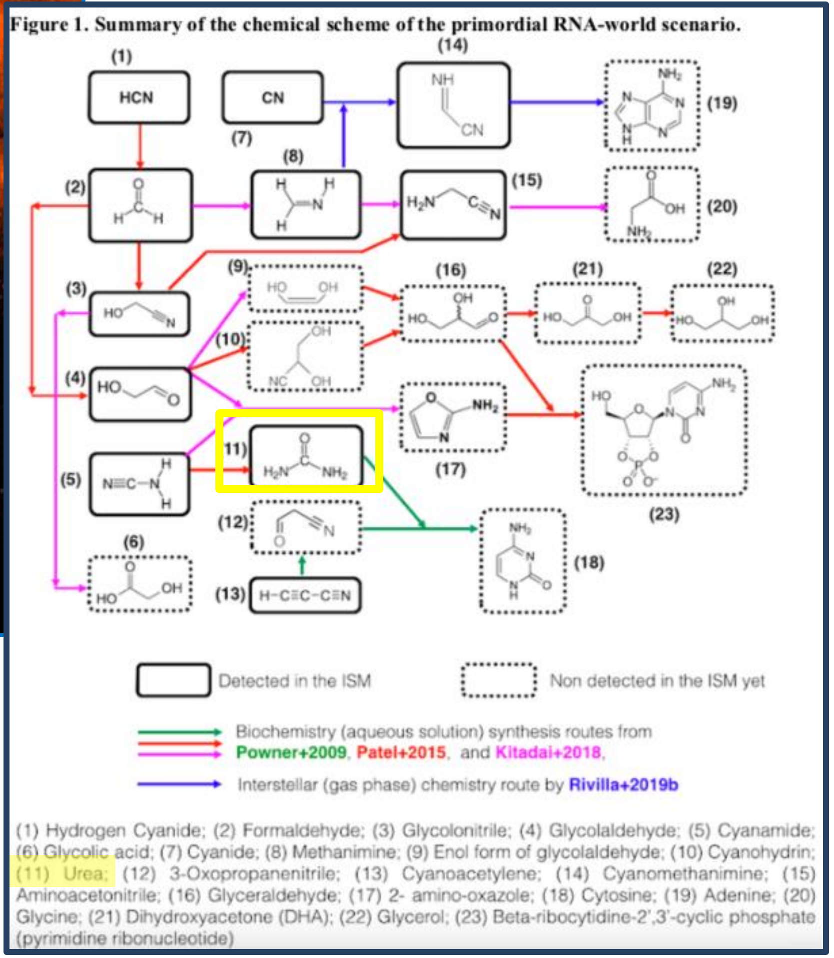


At the center of our galaxy, high mass clouds are chemically rich!



Recent Detections of biologically relevant molecule UREA (NH_2CONH_2) !

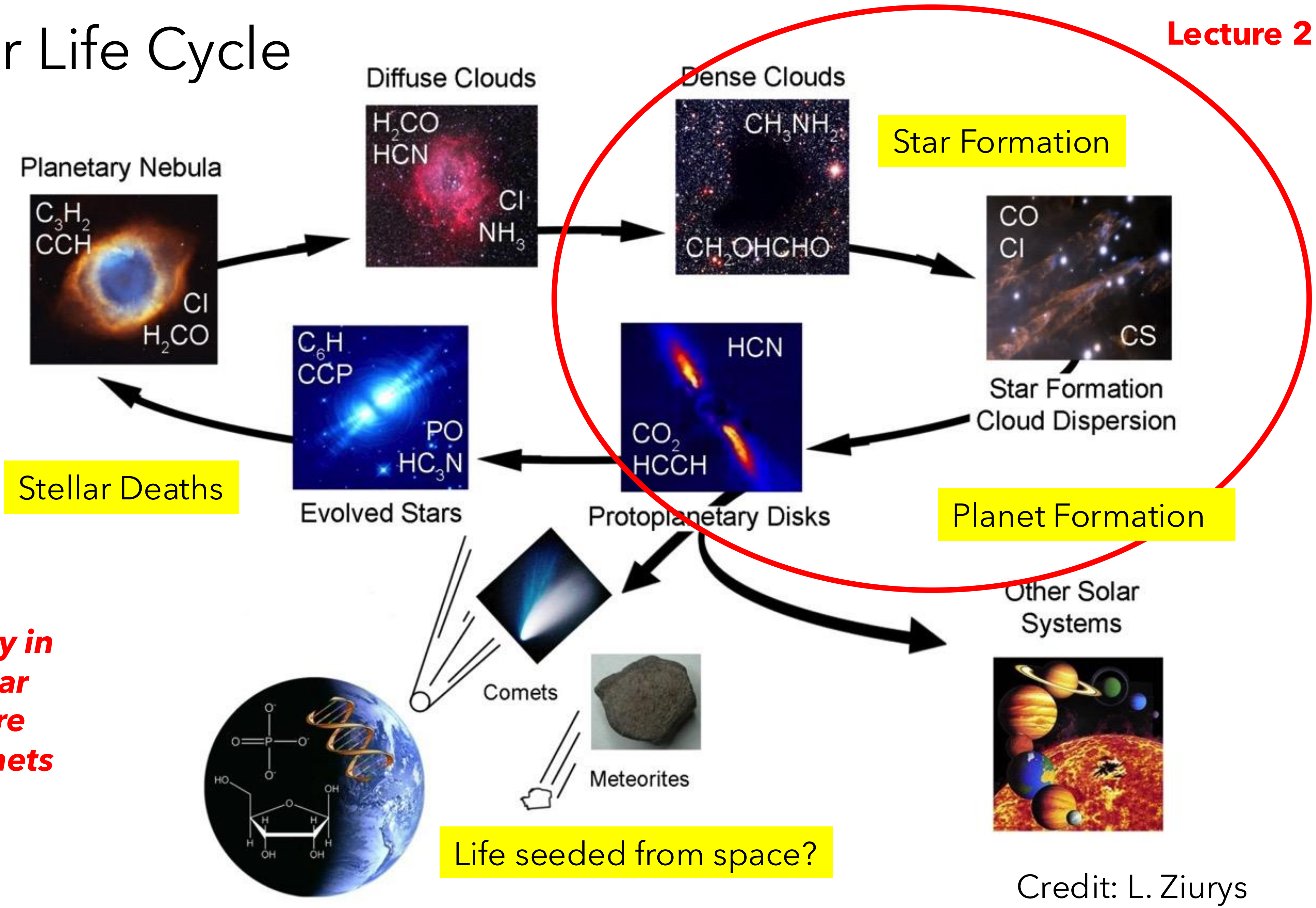




Jiménez-Serra et al. 2020

Molecular Life Cycle

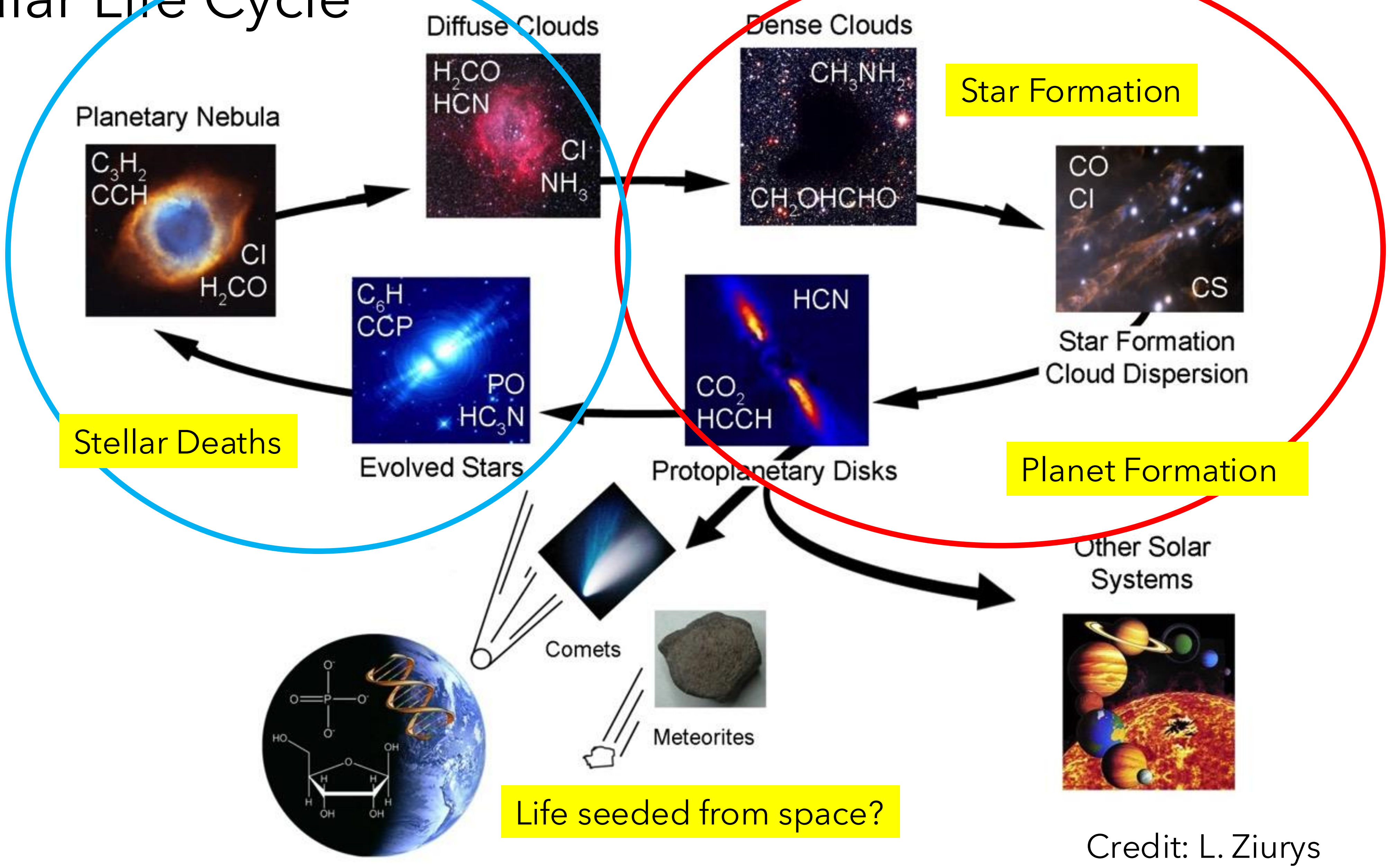
Lecture 2



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

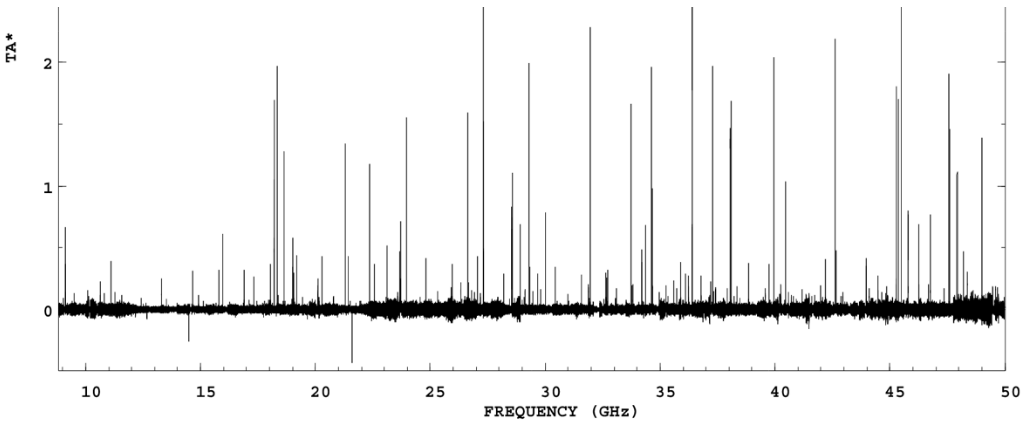
Credit: L. Ziurys

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, the rotational spectra of molecules can be used to trace the **motions of the gas,** as well as the densities and temperatures.

- 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!

- Molecule formation proceeds via **exothermic reactions** (where the products are at lower energy than the reactants) and is usually done via ion-molecule reactions initiated by cosmic rays (high energy photons).

- A rich inventory of **complex organic molecules (COMs**) have been detected in virtually **all stages of low-mass and high-mass star formation**!

Questions?


ROBERT C. BYRD
GREEN BANK TELESCOPE
Dedicated August 25, 2000 Green Bank, West Virginia