VENUE:

Department of Physics and Astronomy

Galileo Galilei Institute for Theoretical Physics

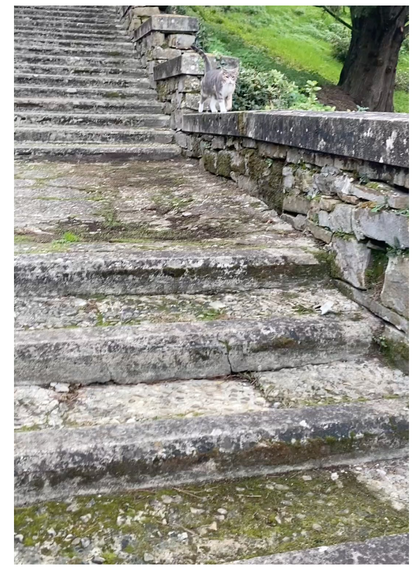
ASTR 5340 - Introduction to Radio Astronomy
Contact: sscibell@nrao.edu

GREEN BANK OBSERVATORY
National Radio Astronomy Observatory

Views!

Foods!

Cats! 



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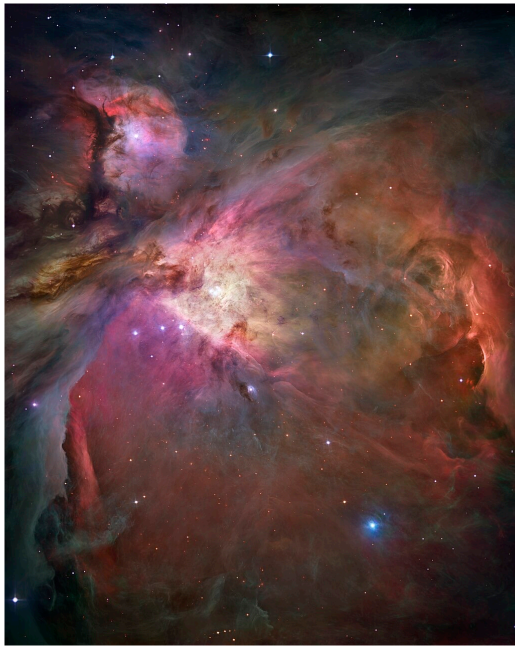
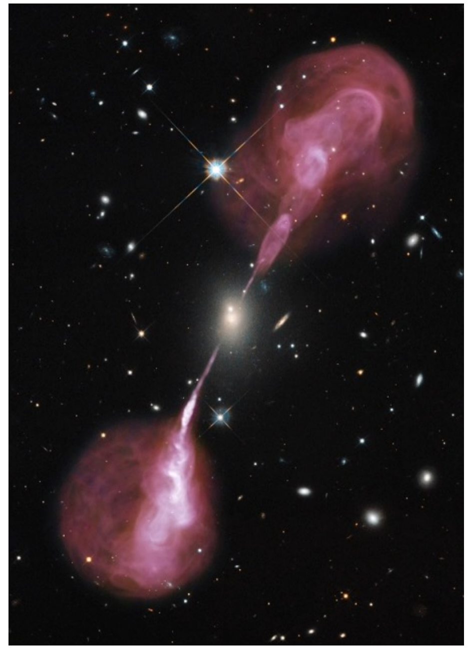
Emission Mechanisms

Spectral Lines (ERA Chap. 7)

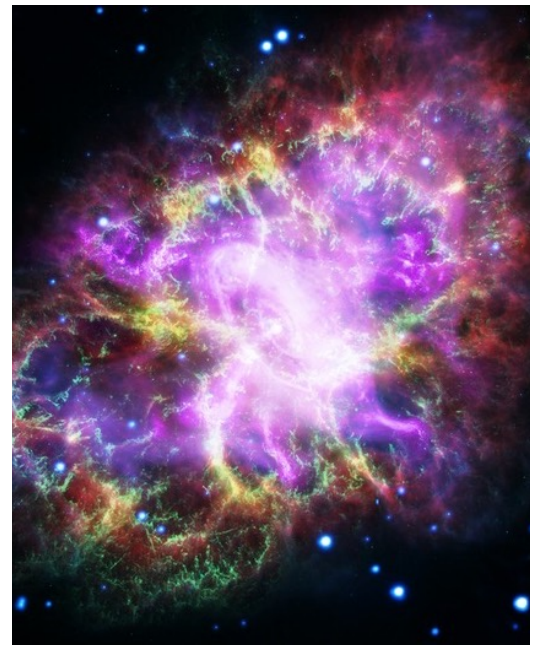
Free-Free (ERA Chap. 4)



Synchrotron (ERA Chap. 5)



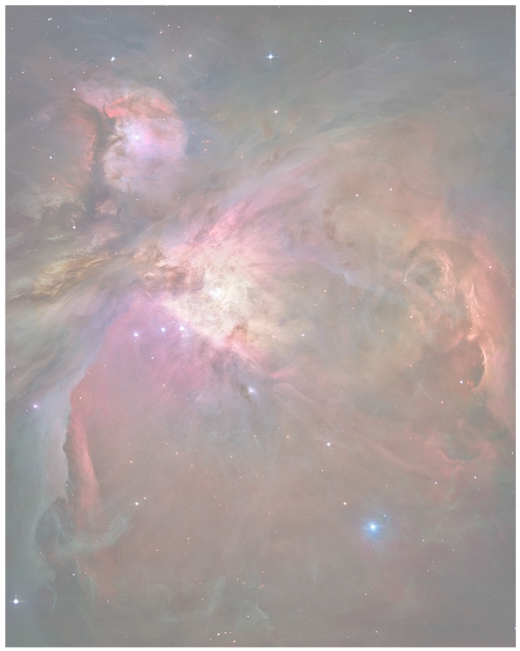
Pulsars (ERA Chap. 6)



Emission Mechanisms

Spectral Lines (ERA Chap. 7)

Free-Free (ERA Chap. 4)



Synchrotron (ERA Chap. 5)

Pulsars (ERA Chap. 6)

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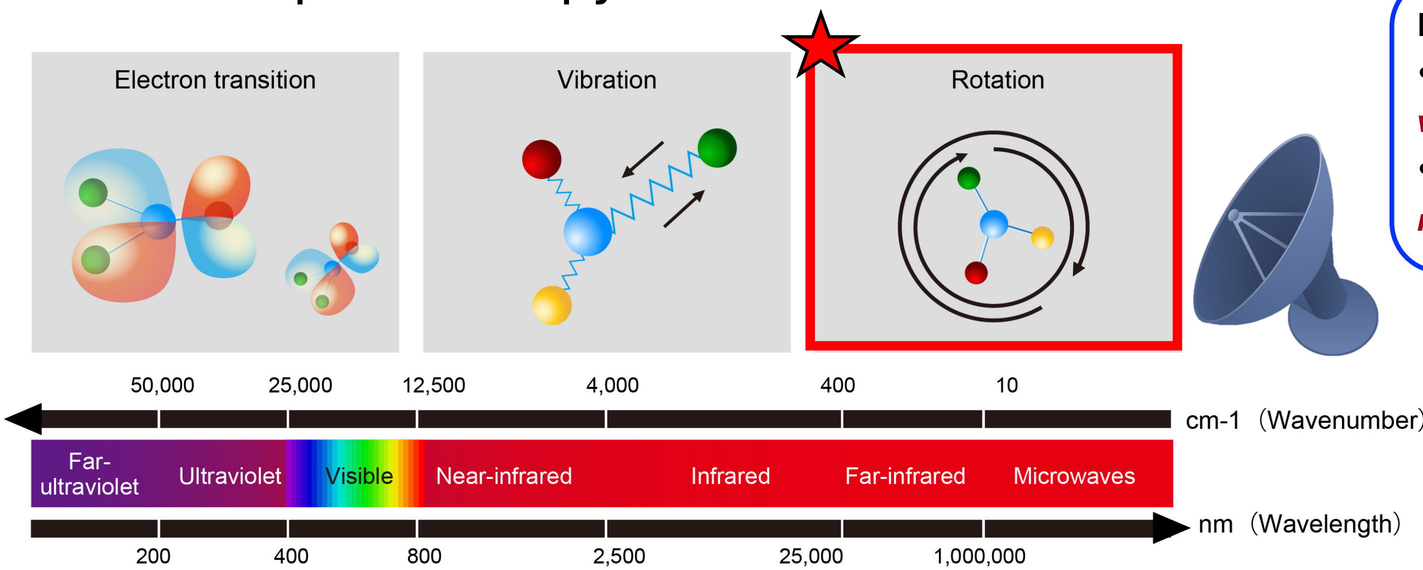
Submillimeter and Millimeter Radio Telescopes Identify Molecules via Rotational Spectroscopy!



Important to know all because...

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

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

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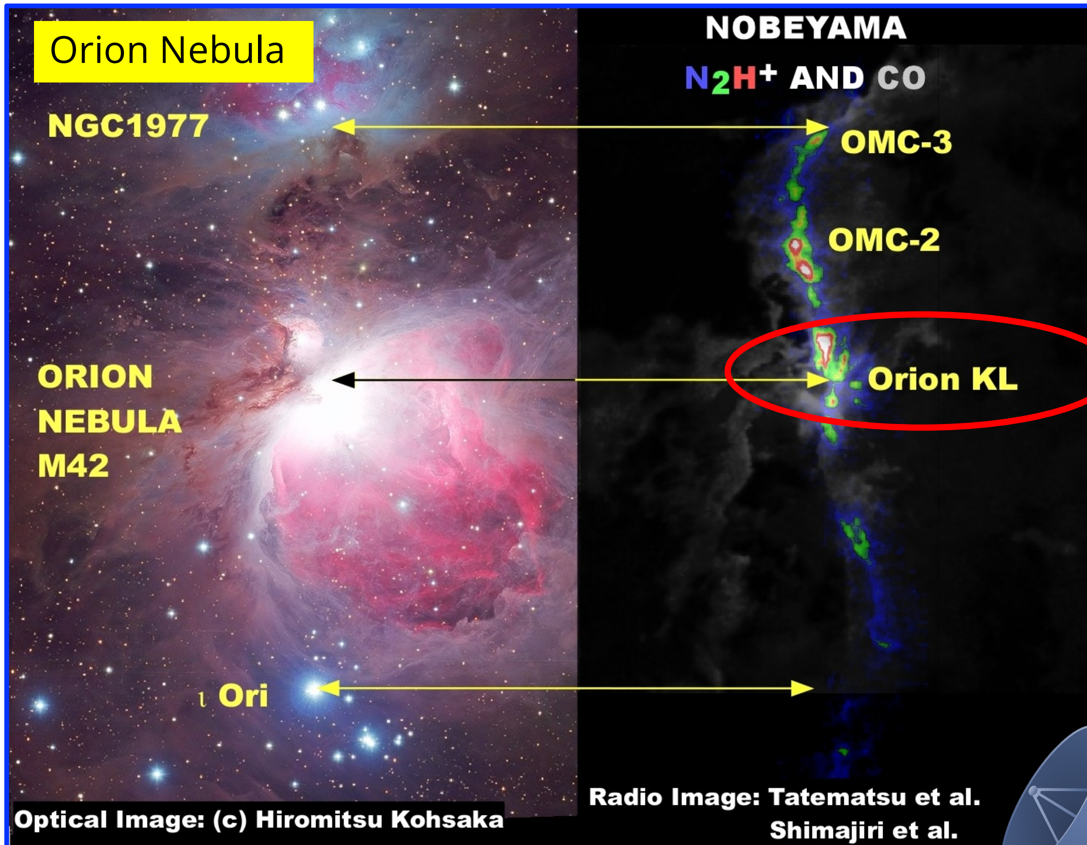
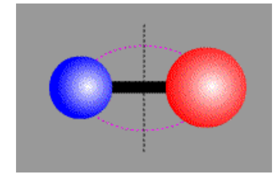
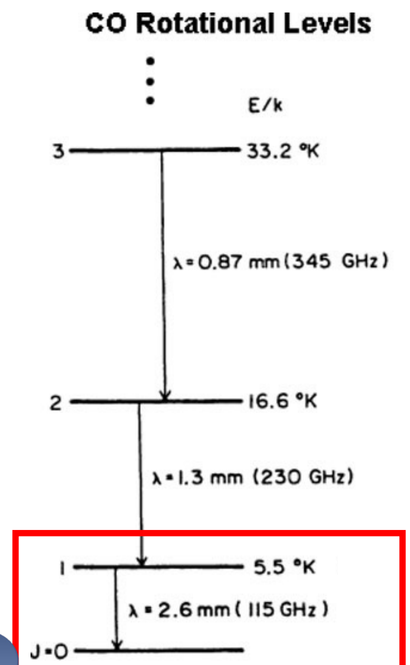


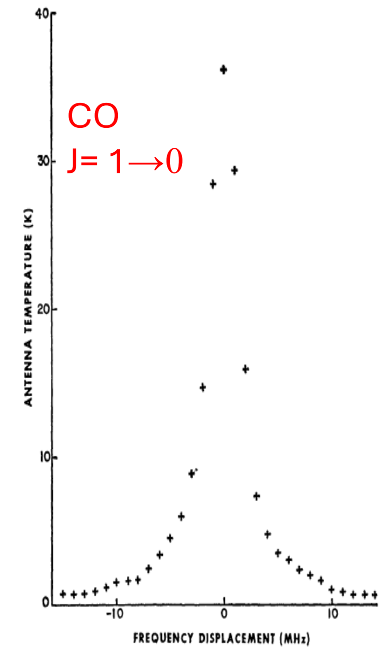
https://www.nro.nao.ac.jp/~kt/html/kt-e.html

Discovery of CO

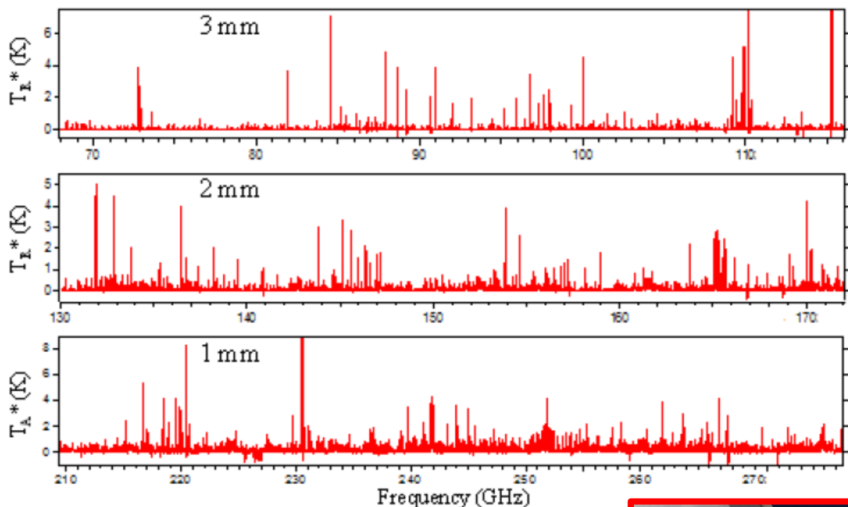
in the Star Forming Region,
Orion KL at 115 GHz
(J = 1 → 0 transition)
in 1970 at **Kitt Peak, Arizona!**



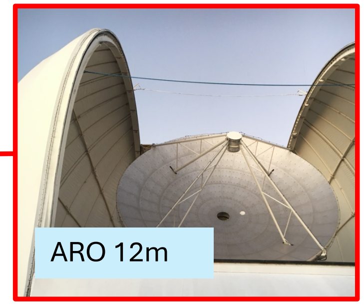


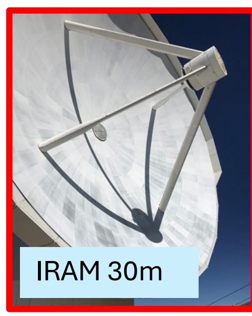


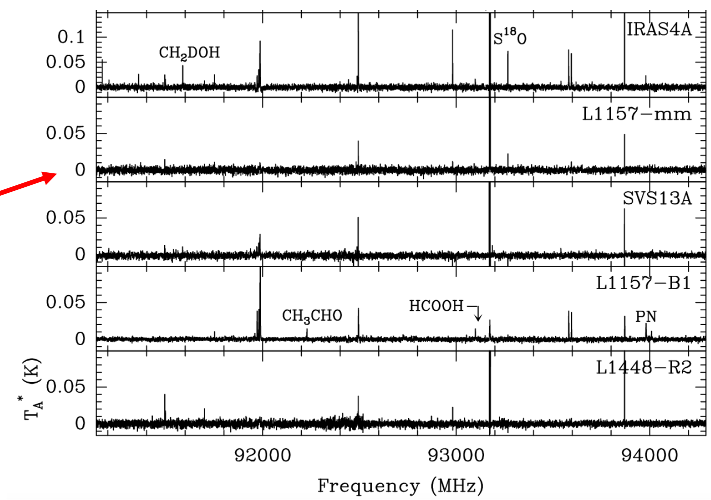
Rotational Lines of Molecules at Radio Wavelengths



Credit: L. Ziurys







Lefloch 2018

- We look at the **excitation conditions** of a molecule to know what to look for
- We use **radiative transfer** to calculate physical parameters, such as column densities and masses

Line Radiative Transfer (ERA 7.3, 7.4, +7.7, THz Astronomy Chap. 2)

*Key Things to Remember!

Excitation Temperature is defined by the **Boltzmann equation** and gives the ratio of the populations in each level (T_{ex} or T_X):

$$T_{ex} = \frac{h\nu/k}{\ln \frac{n_l g_u}{n_u g_l}},$$

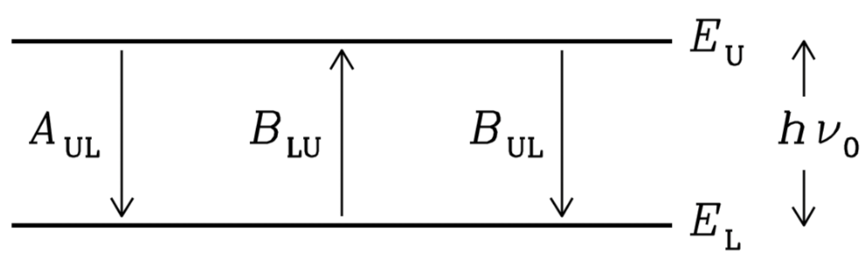
*** When $T_{ex} \sim T_k$ then LTE a good approximation!**

Optically thick lines (e.g., ^{12}CO) or dust emission can be used to determine the **temperature** of a cloud!

Optically thin lines (e.g., ^{13}CO or $C^{18}O$) or dust emission is directly proportional to the **cloud's optical depth** (and thus column density and cloud mass)!

To get column density, N_L, you need to know the <u>physical states</u> of your molecule and <u>calculate the spontaneous emission coefficient</u>

Fig. 7.5 (ERA)



In practice... we look up these terms in Splatalogue!
https://splatalogue.online

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Line Radiative Transfer (ERA 7.3, 7.4, +7.7, THz Astronomy Chap. 2)

***Key Things to Remember!**

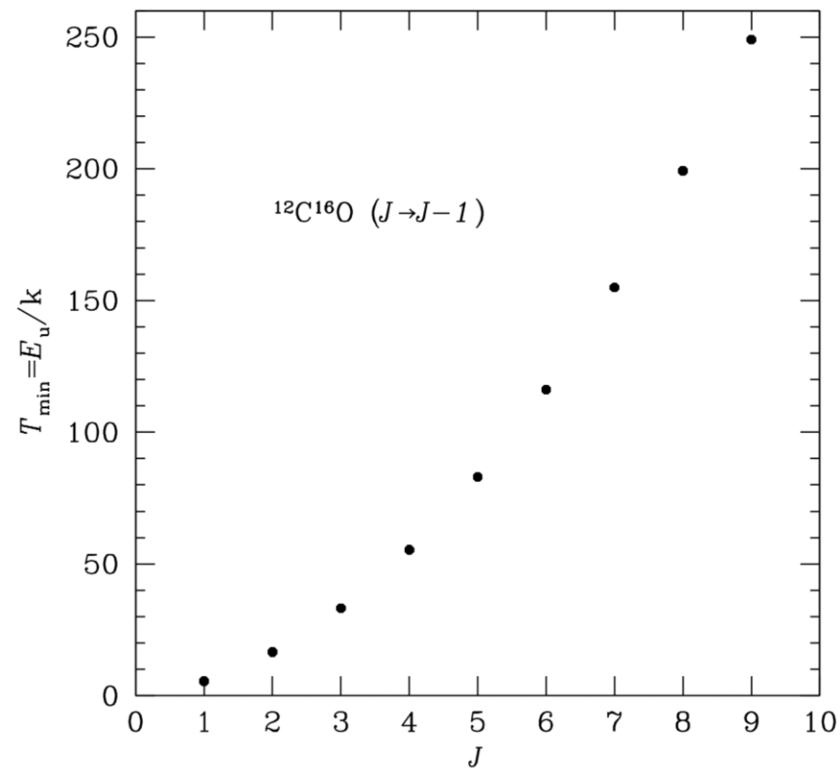
Related to A_{UL}, the **upper energies** give clues into what type of environments are molecular lines are likely to emit at and are directly connected to the minimum gas temperature needed for significant collisional excitation,

$$T_{\min} \sim \frac{E_{\rm rot}}{k}$$

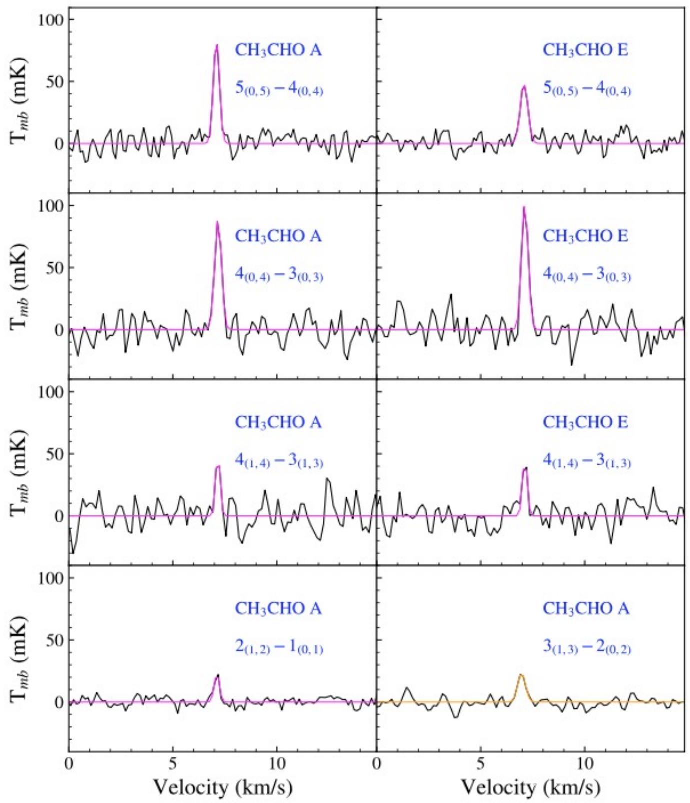
$$\sim \frac{J\,(J+1)\,h^2}{2 \cdot 4\pi^2 I k} = \frac{hJ}{4\pi^2 I}\,\frac{h\,(J+1)}{2k} = \frac{E_{\rm U}}{k}$$

(7.116 & 7.118)

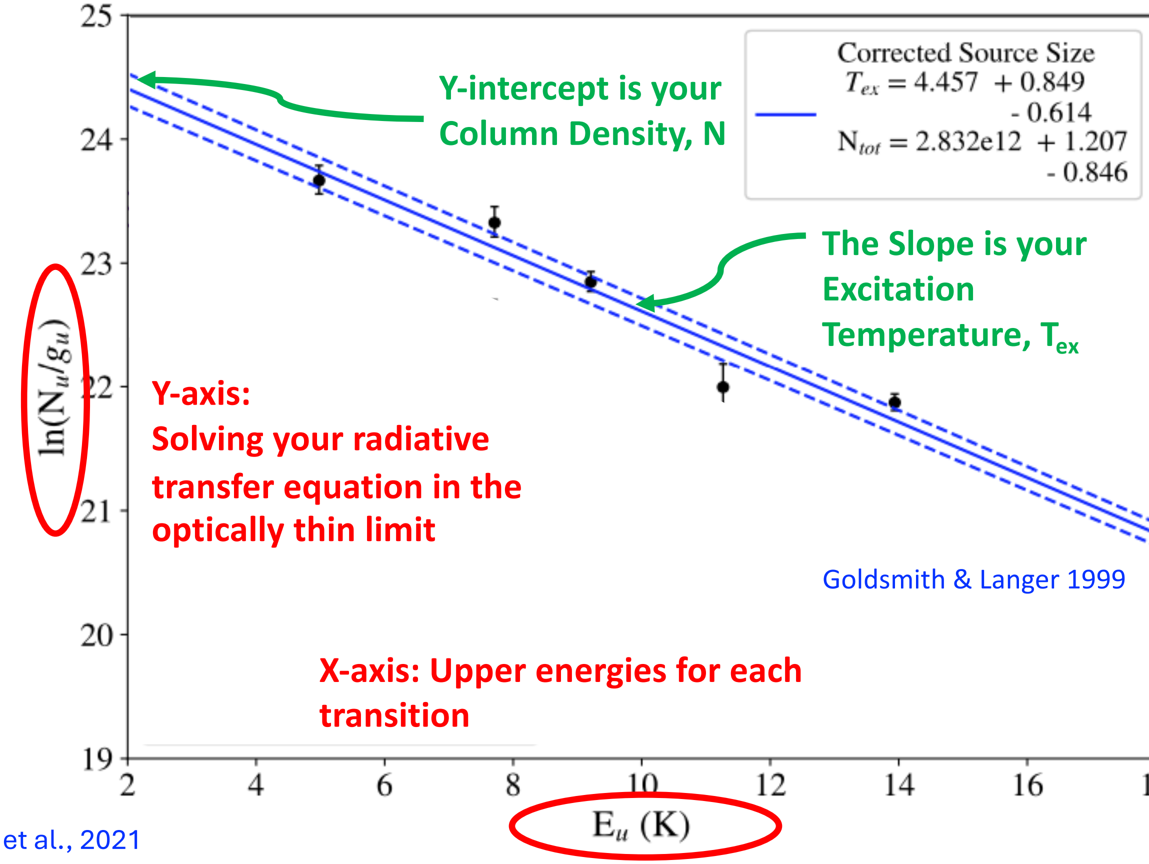
Fig. 7.15 (ERA)



Practical use → Rotation Diagrams

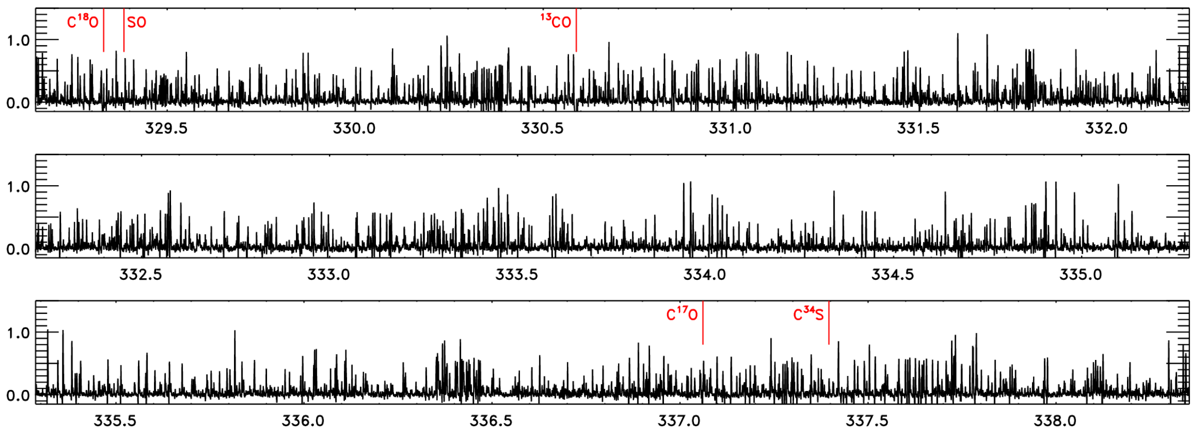


Scibelli et al., 2021



Isotopologues (ERA 7.7)

"Molecules that differ only in isotopic composition; that is, only in the numbers of neutrons in their component atoms"



Jørgensen et al. 2016

"The process called <u>isotopic fractionation</u> comes into play when it becomes energetically favorable to substitute an abundant isotope with a less abundant one"

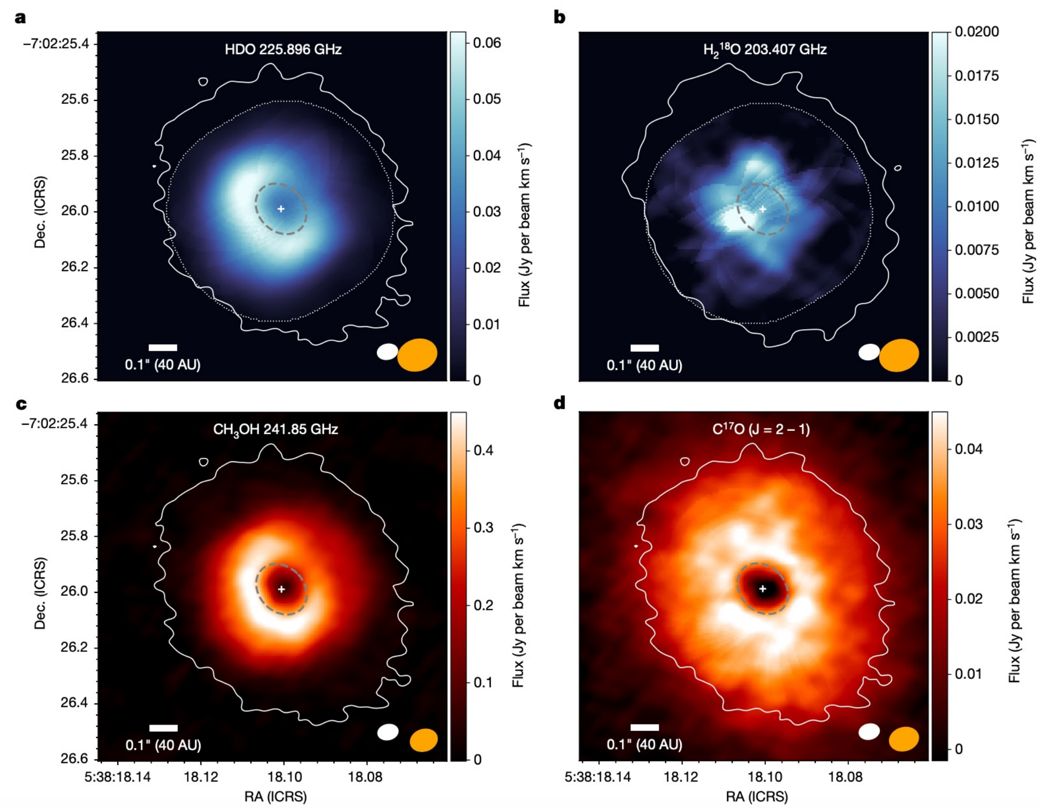
E.g.,
$C^{18}O$, ^{13}CO, $C^{17}O$, $C^{34}S$, $H^{13}CO+$, $HC^{18}O+$, $H^{13}CN$, $H^{15}CN$, ^{29}SiO, $^{13}CH_3OH$, DCN, DCO^+

Isotopologues (ERA 7.7)

Benefits of observing Isotopes:

- **Usually optically thin lines**
  - Therefore can be used to measure the column densities needed to estimate the total mass of molecular gas in a source
  - Intensity ratios of optically thin lines from different J levels can be used to measure excitation temperature, which is close to the kinetic temperature in LTE

- ***Chemical 'clocks' that can age molecular clouds and trace the chemical evolution***



disk of V883 Ori

Tobin 2023, Nature

Isotopologues (ERA 7.7)

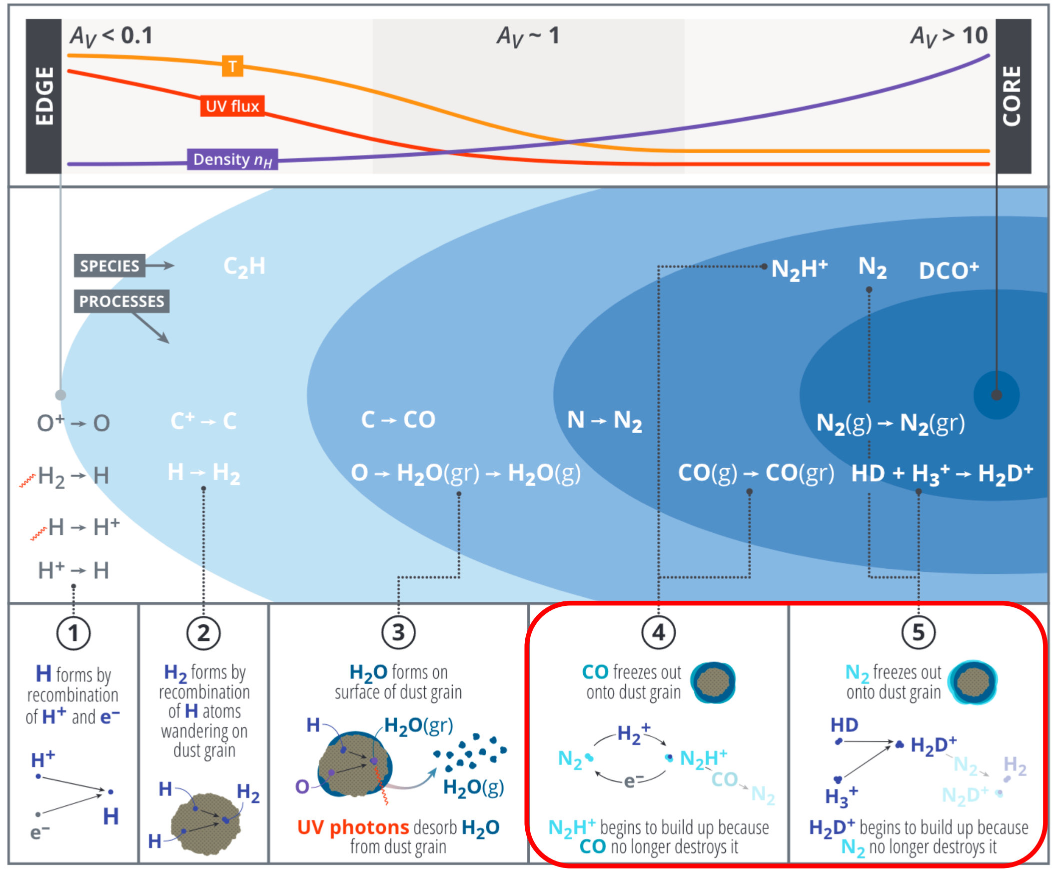
Benefits of observing Isotopes:

- ***Chemical 'clocks' that can age molecular clouds and trace the chemical evolution***

Big Question in Astrochemistry:

How much of the material formed early on in the molecular cloud gets inherited to the next stages of star and planet formation?

Isotopes help us answer this question!



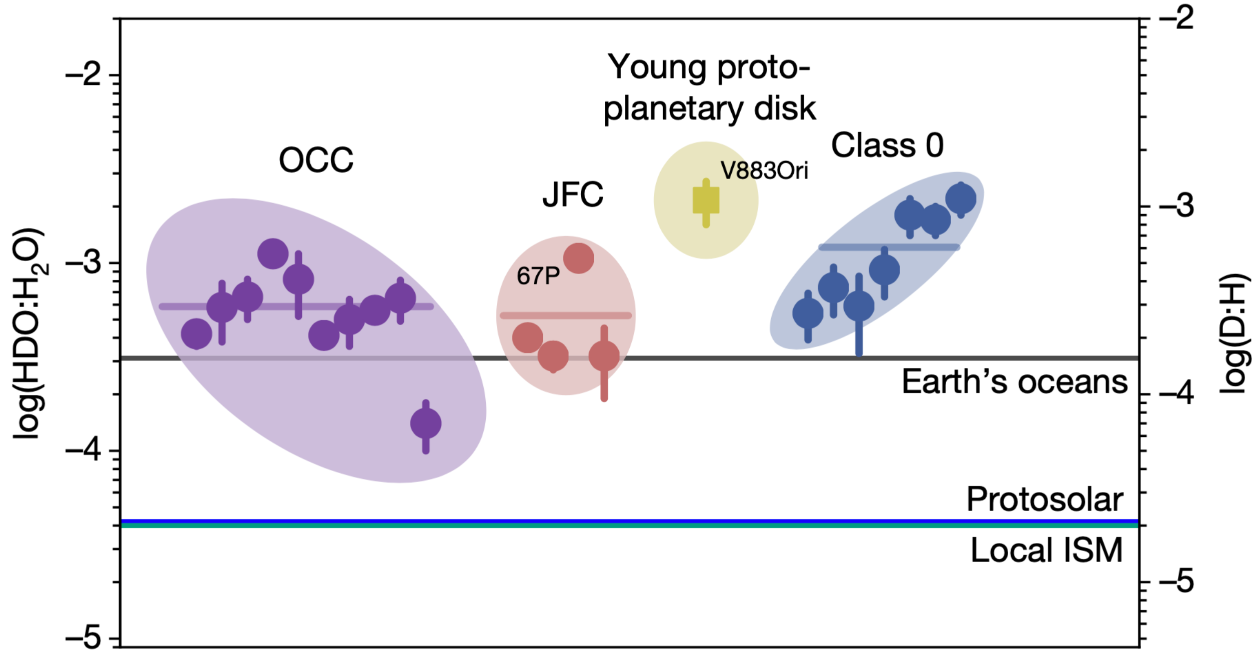
Oberg & Bergin 2021

Isotopologues (ERA 7.7)

HDO:H2O ratio does not strongly evolve from the protostar phase to the disk!

Limited reprocessing of material from early star formation to solar system bodies

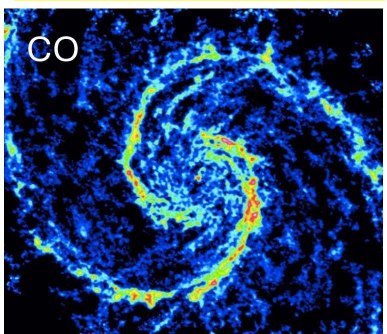
Comets → Disk → Protostars



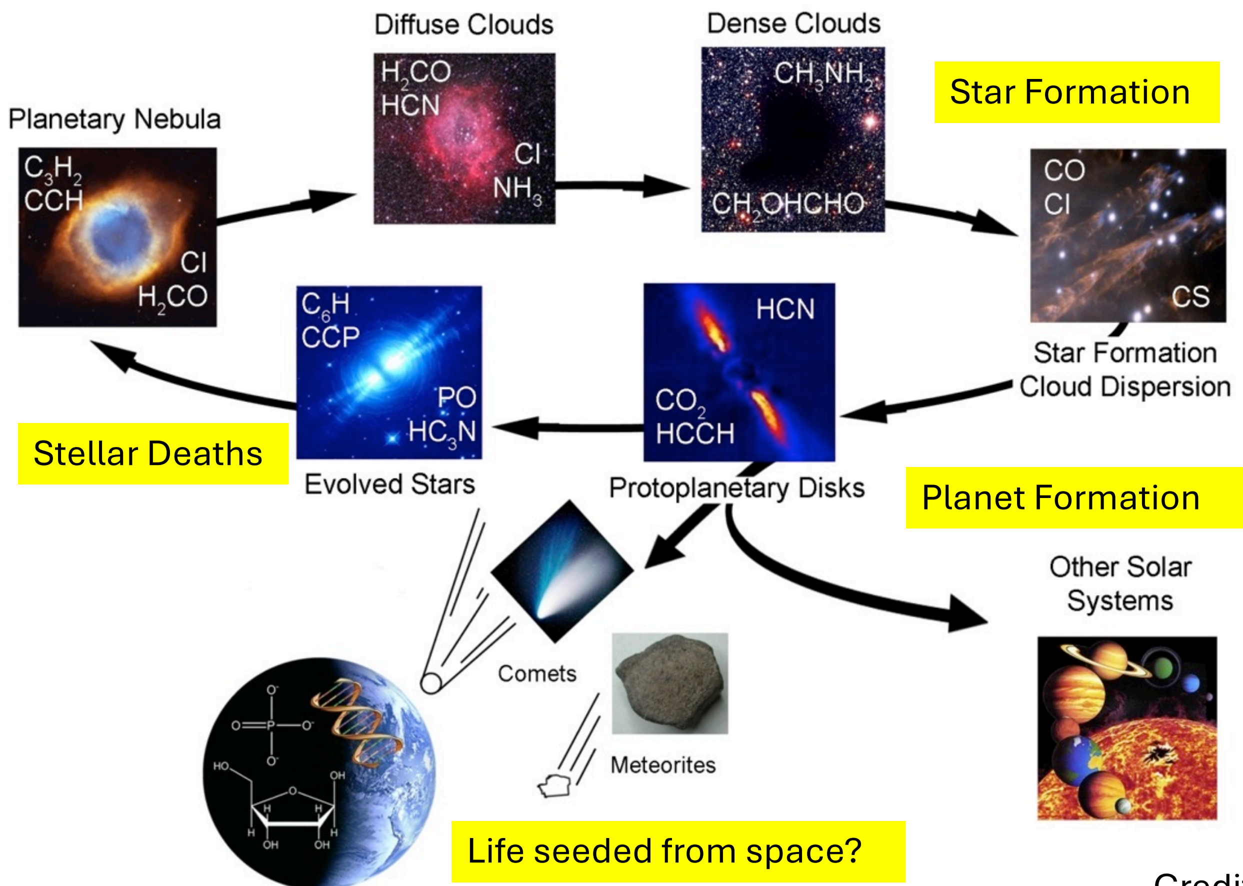
Tobin 2023, Nature

Molecular Life Cycle

Within Galaxies… →



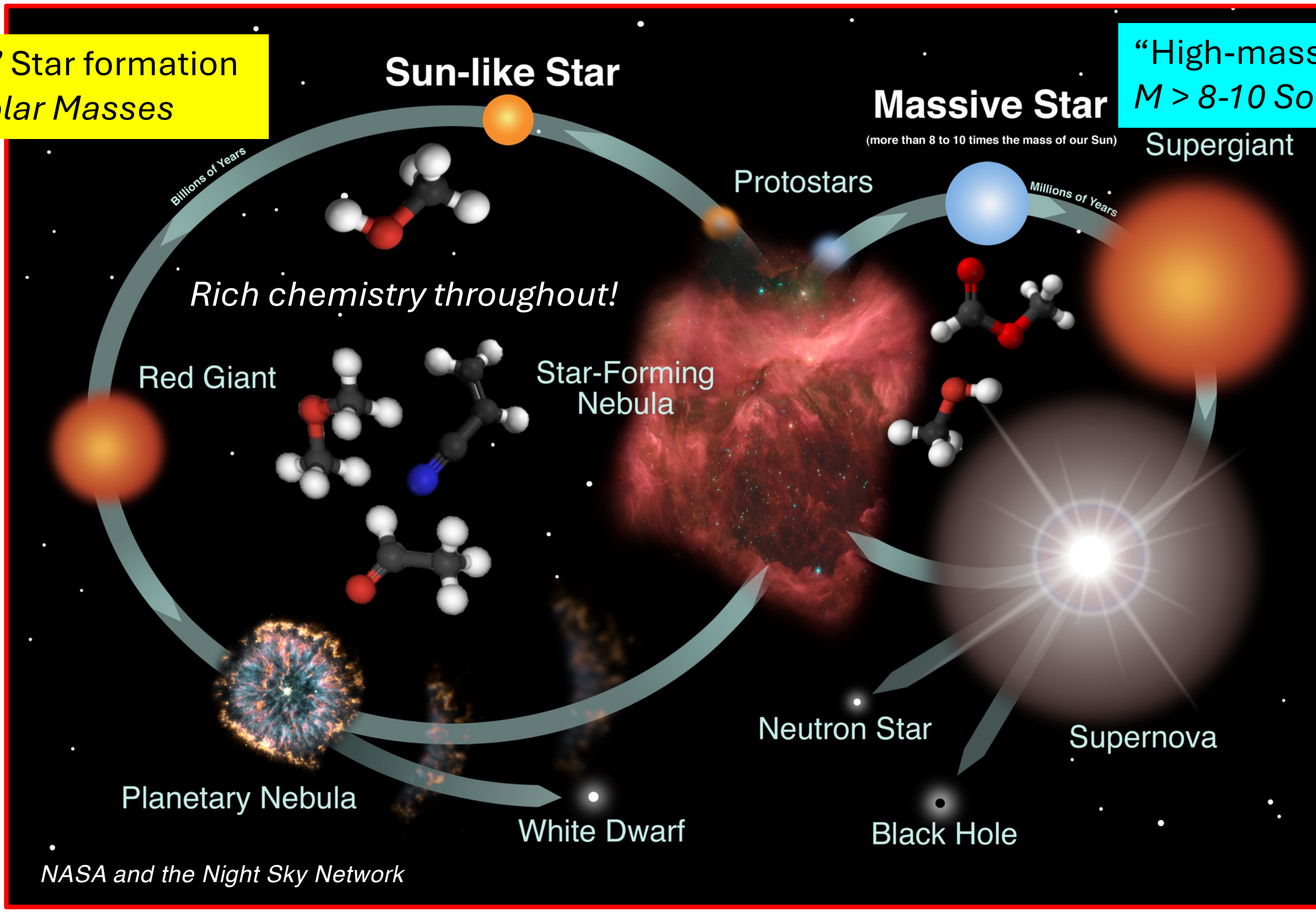
M51 – Whirlpool Galaxy



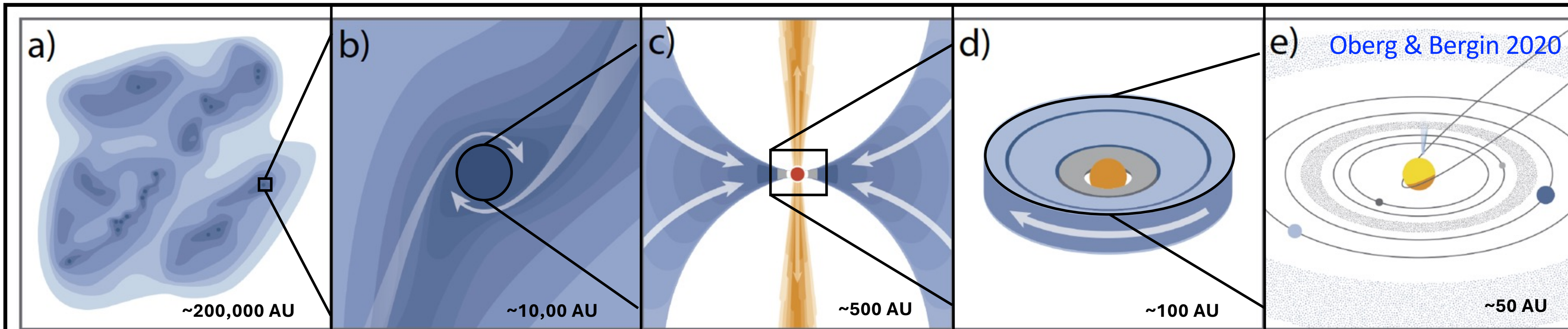
Credit: L. Ziurys

“Low-mass” Star formation
M < a few Solar Masses

“High-mass” Star formation
M > 8-10 Solar Masses



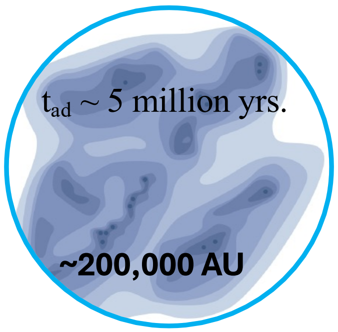
Low-mass ($M \leq$ a few $M_{\odot}$) Star Formation



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
$t_{ad} \sim 5$ million yrs.	$t_{iso} \sim .2$ million yrs.	~1 million yrs.	1-10 million yrs.	10-50 million yrs.

Molecular Line Data

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



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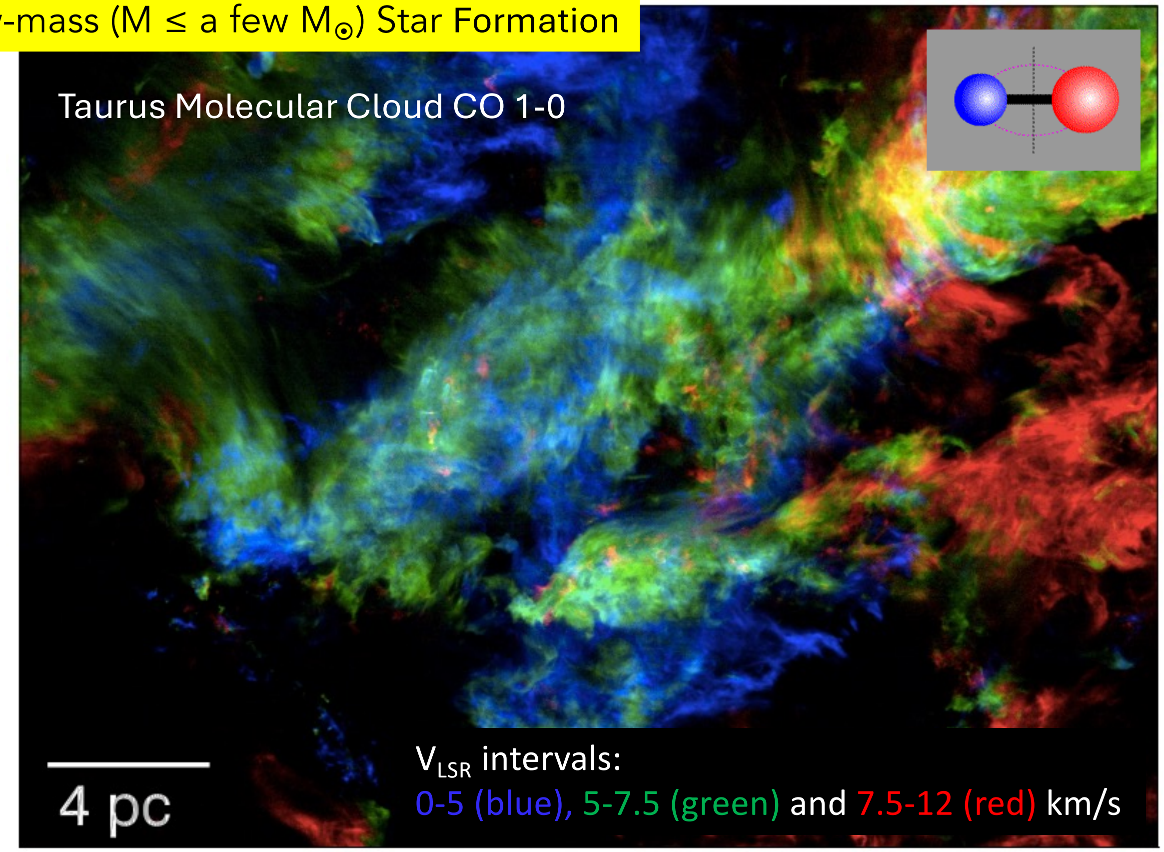
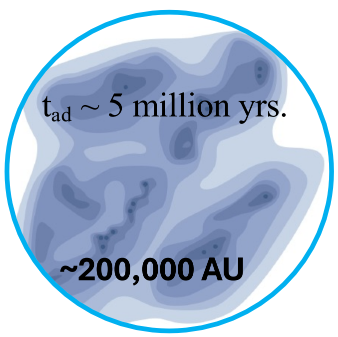
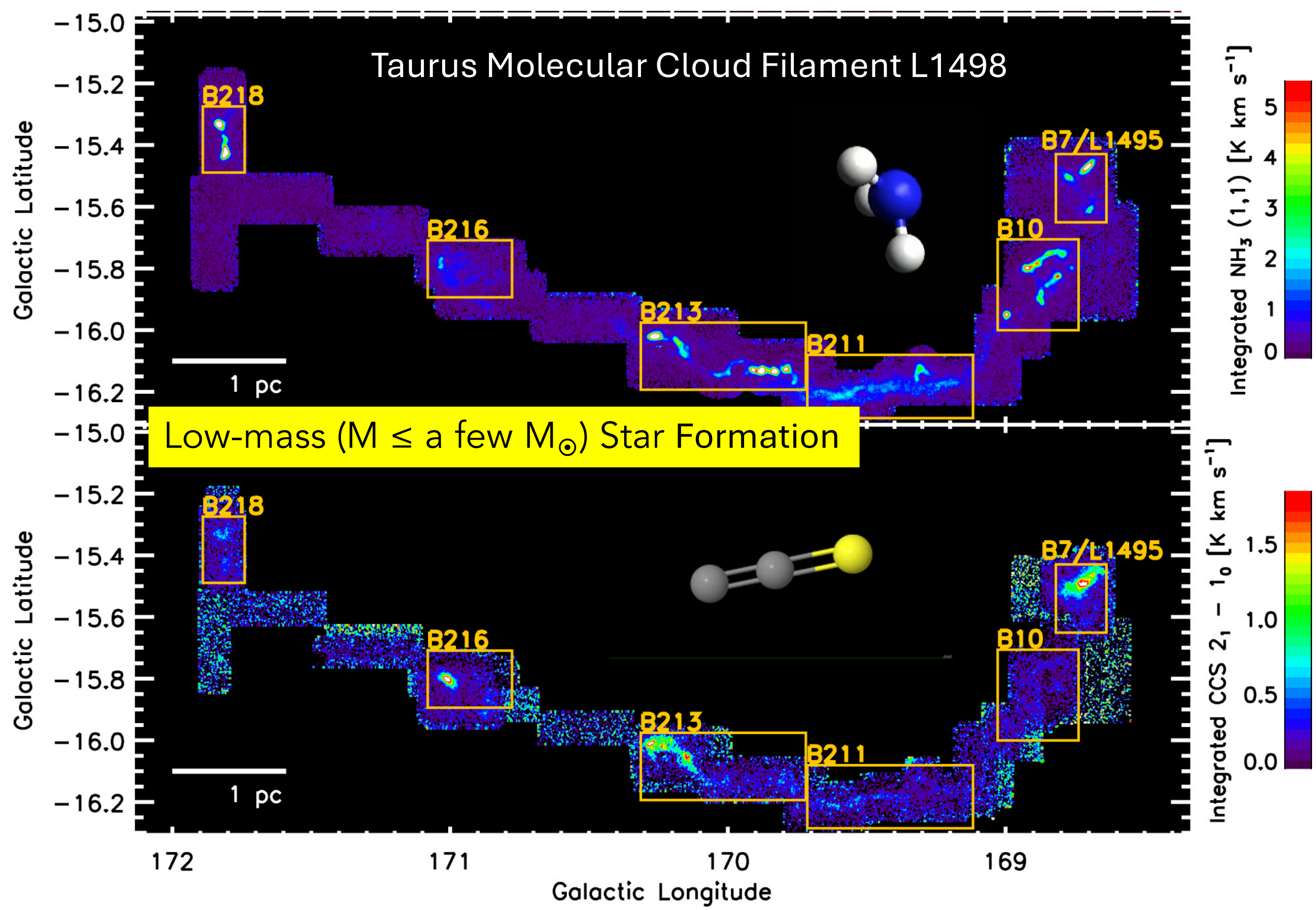


Molecular Line Data

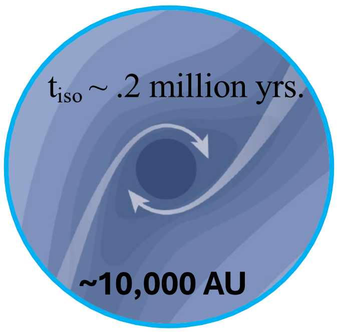
The filamentary structures are also traced by more 'exotic' molecular species, such as NH_3 and CCS

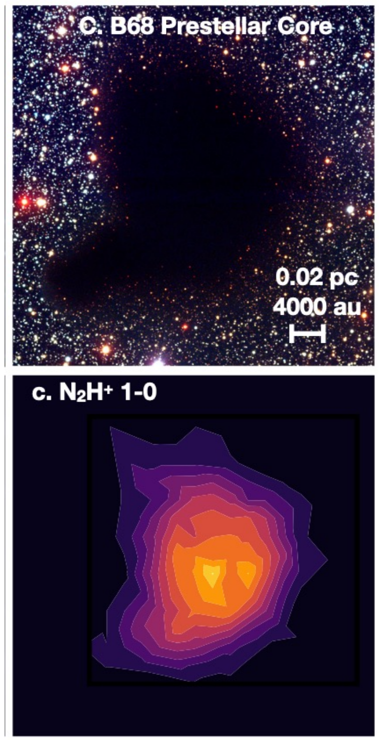




Molecular Line Data

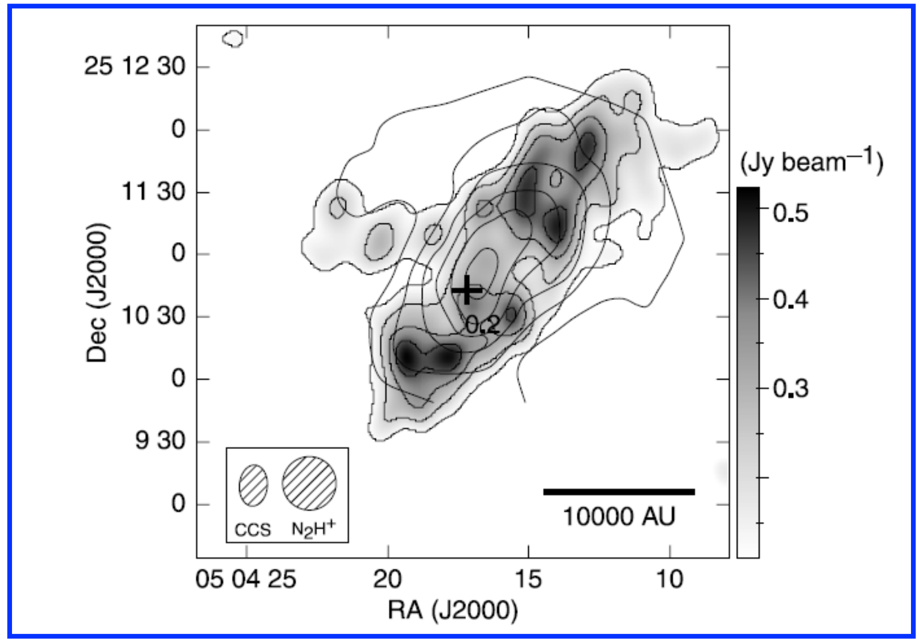
Dense (10^5 cm^{-3}) & cold (10K) *starless* and dynamically evolved *prestellar* cores collapse due to gravity and external cloud pressure



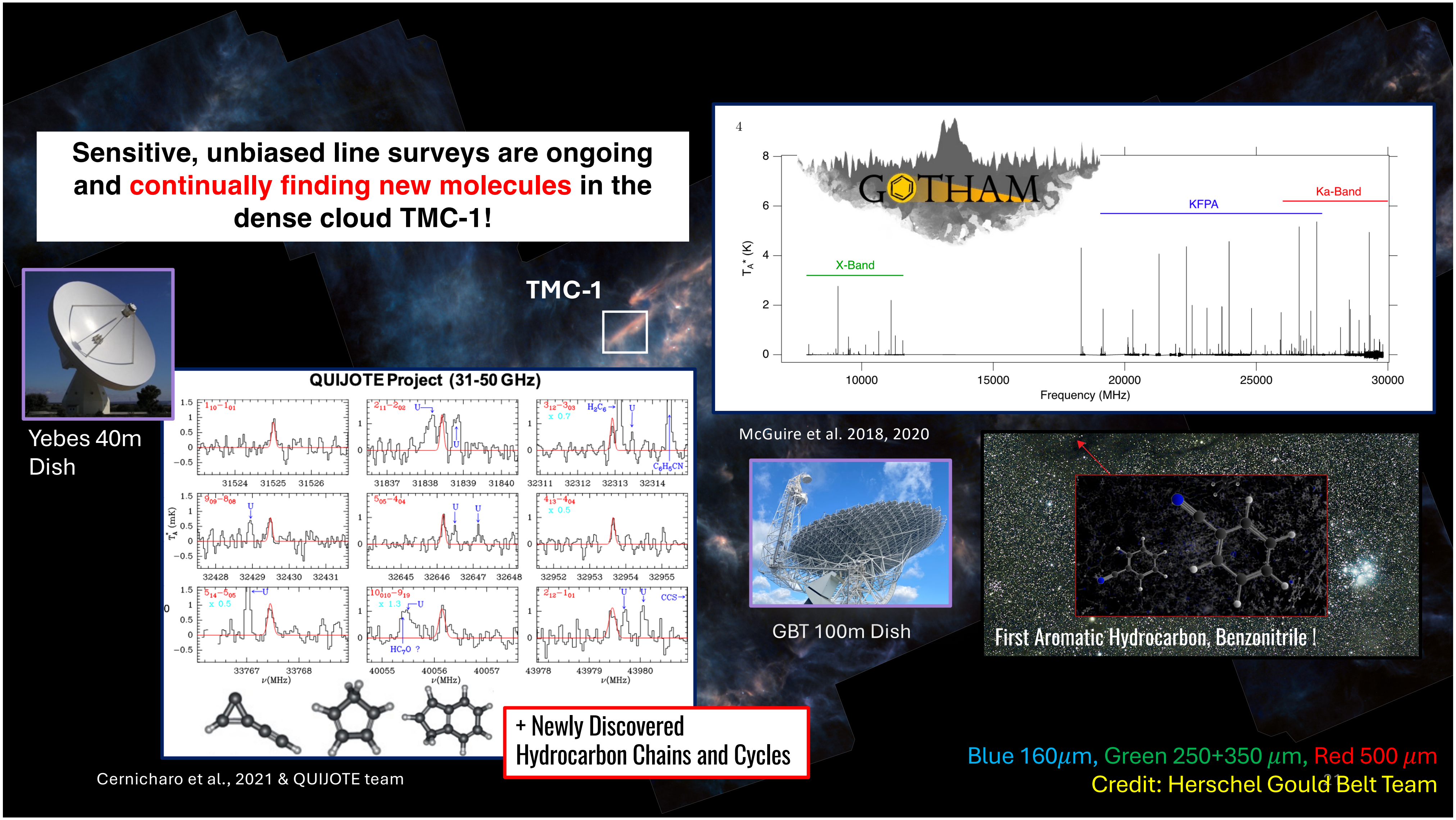


Oberg & Bergin 2020

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

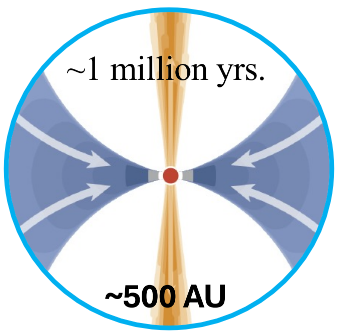


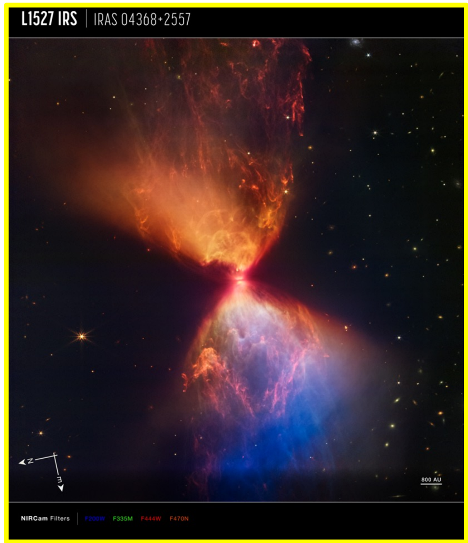
**Molecules are powerful probes of the physical conditions!*


Sensitive, unbiased line surveys are ongoing and continually finding new molecules in the dense cloud TMC-1!
TMC-1
Yebes 40m Dish
QUIJOTE Project (31-50 GHz)
ν(MHz)
+ Newly Discovered Hydrocarbon Chains and Cycles
Cernicharo et al., 2021 & QUIJOTE team
GOTHAM
X-Band
KFPA
Ka-Band
Frequency (MHz)
McGuire et al. 2018, 2020
GBT 100m Dish
First Aromatic Hydrocarbon, Benzonitrile !
Blue 160μm, Green 250+350 μm, Red 500 μm
Credit: Herschel Gould Belt Team

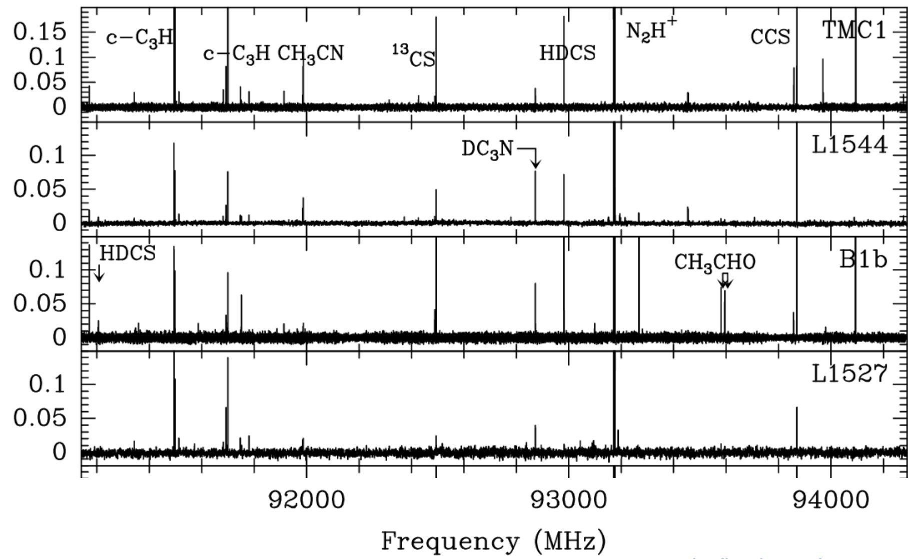
Molecular Line Data

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





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



Lefloch et al., 2018

Molecular Line Data

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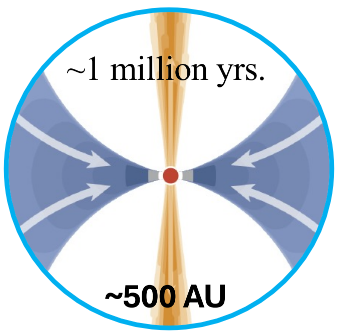
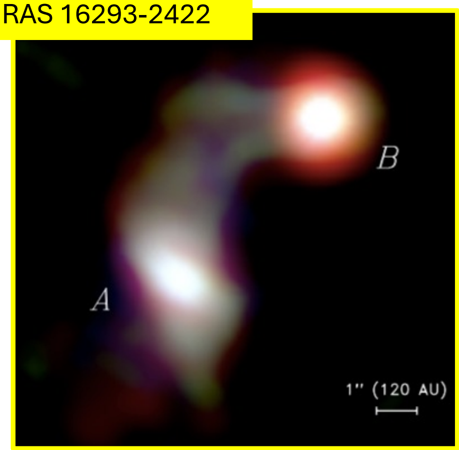
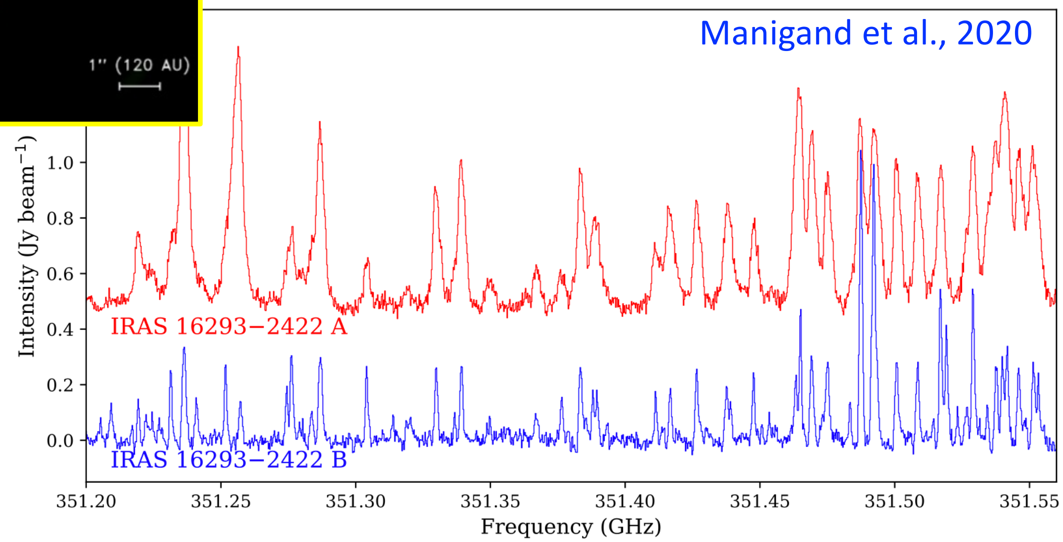


IRAS 16293-2422



Large program targeting many lines: ALMA PILS



Molecular Line Data

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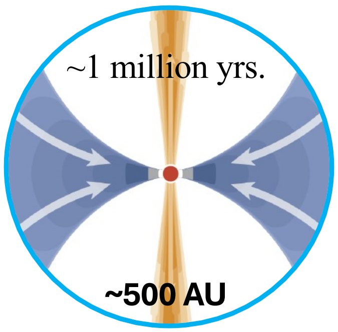
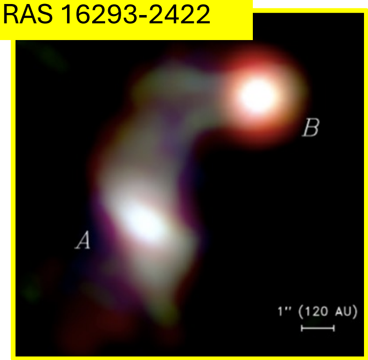
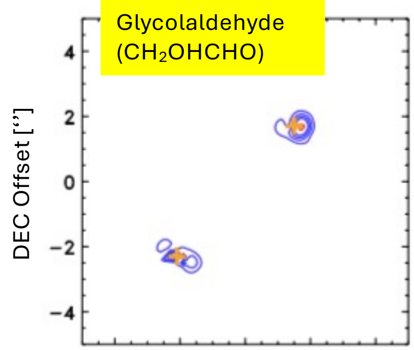


IRAS 16293-2422

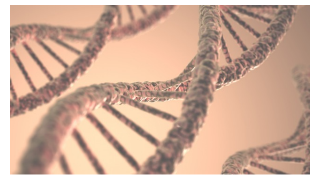


Jørgensen et al. 2012, 2016

Glycolaldehyde (CH_2OHCHO)

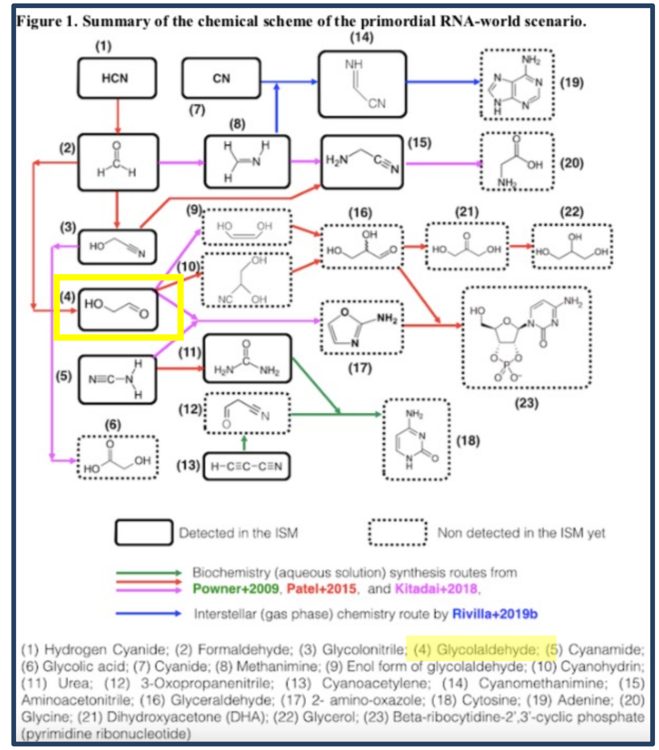


Low-mass (M ≤ a few $M_{\odot}$) Star Formation



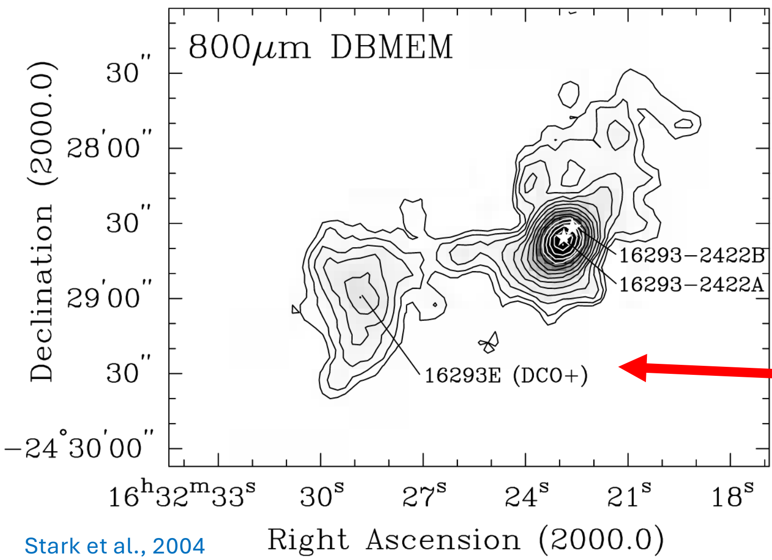
Life appeared on Earth about 4 billion years ago, but we do not know the processes that made it possible.

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.

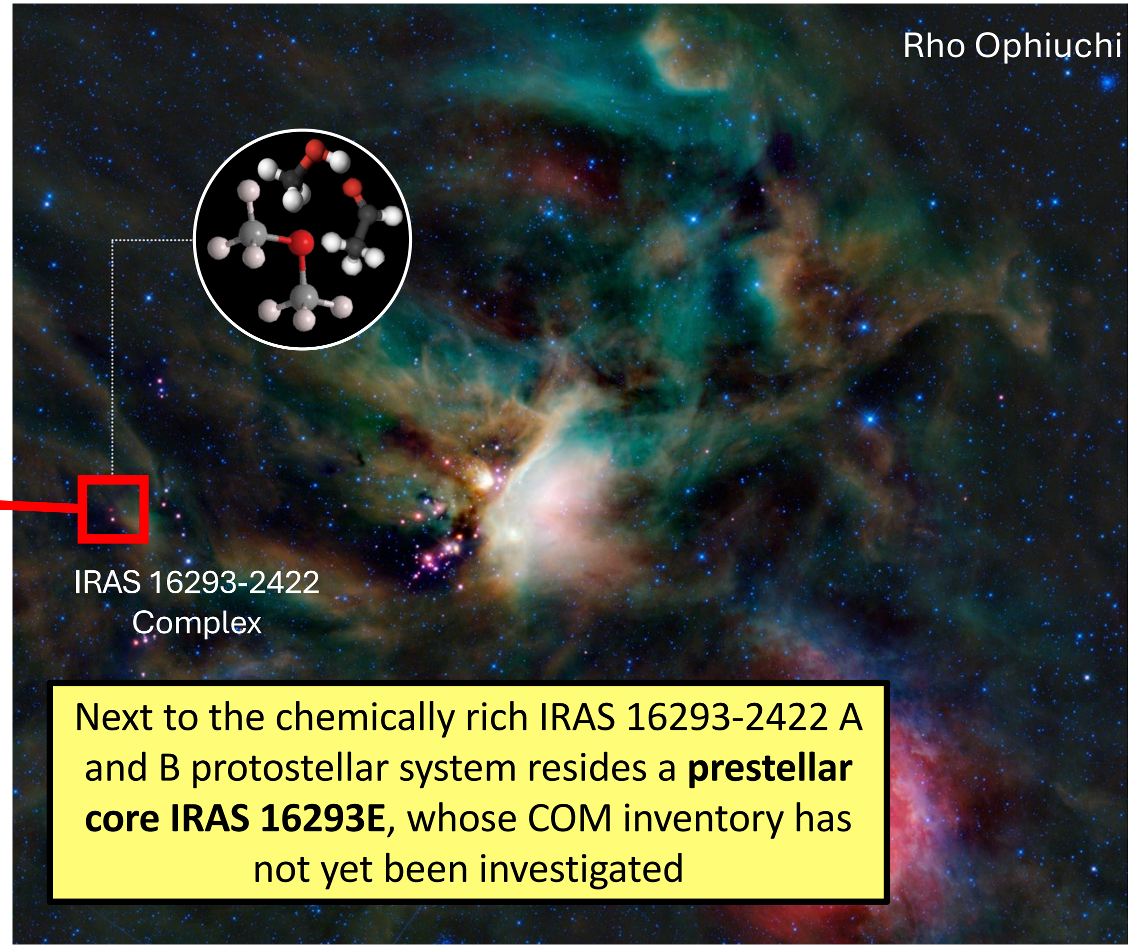


Jimenez-Serra et al. 2020

IRAS 16293E



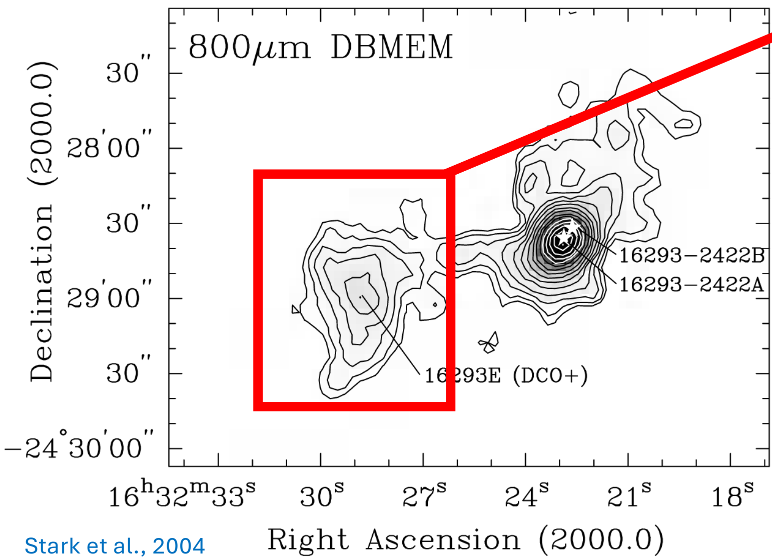
Stark et al., 2004



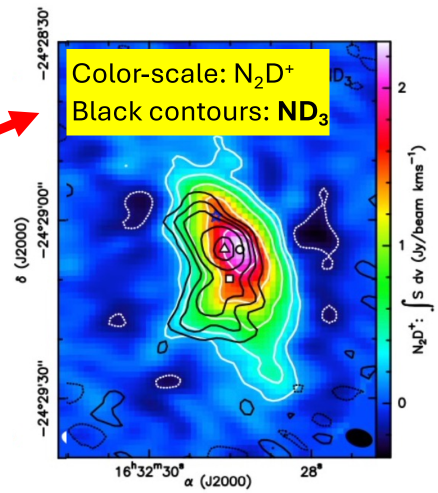
Fractionation II, Florence, Italy, Nov 4th- 7th, 2024
Contact: sscibell@nrao.edu

Arizona Radio Observatory
YEBES
National Radio Astronomy Observatory
NRAO
NSF

IRAS 16293E



Stark et al., 2004



Lis et al., 2016

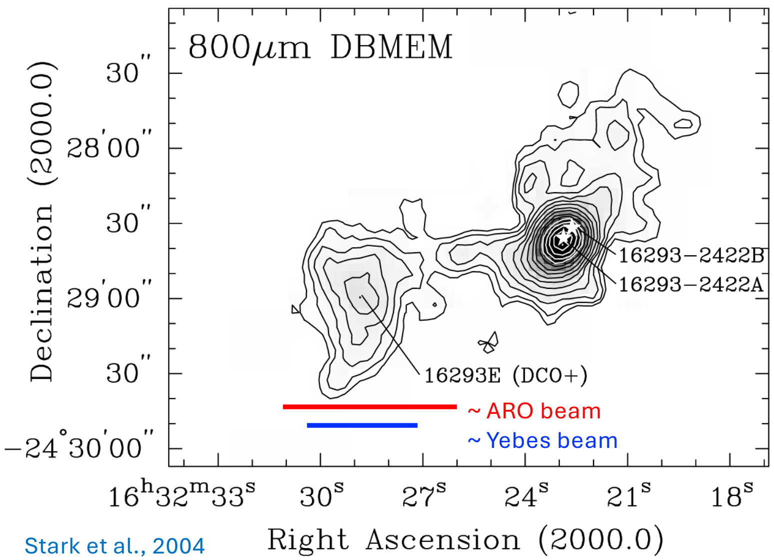
Additionally, IRAS 16293 A, B and E all show some of the **highest levels of deuteration** in the ISM!

- **Deuterated COMs (dCOMs)** in particular provide an **exciting probe into chemical histories**, as high deuteration levels in protostellar systems (e.g., IRAS16293 A and B with 2-8% and D_2/D ~ 20%) compared to typical values in the ISM (D/H ~ 10^{-5}) suggest **COMs are forming during the time deuteration is enhanced – in cold (10 K) prestellar cores!**

- To date, only a handful (< 3) of prestellar cores have had detections of both singly- and doubly-deuterated versions of the simplest COM – methanol (Lin et al., 2023)

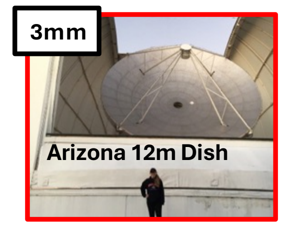
IRAS16292E is a prime target to search for COMs and dCOMs!

IRAS 16293E



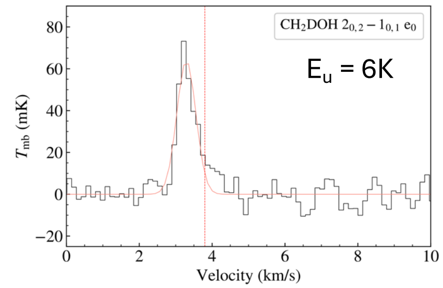
Stark et al., 2004

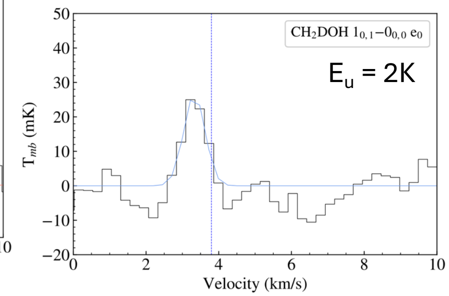
Single-pointed observations w/



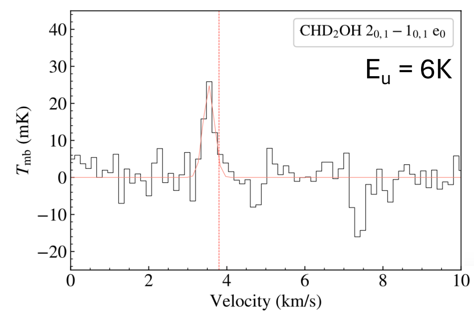
+

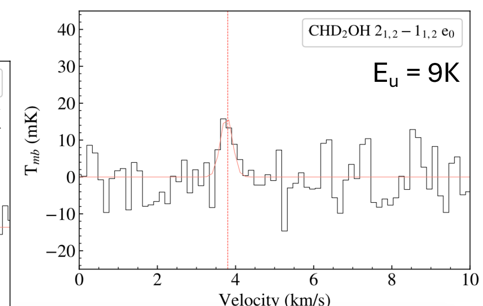
Singly Deuterated Methanol!





Doubly Deuterated Methanol!





Scibelli et al., in prep

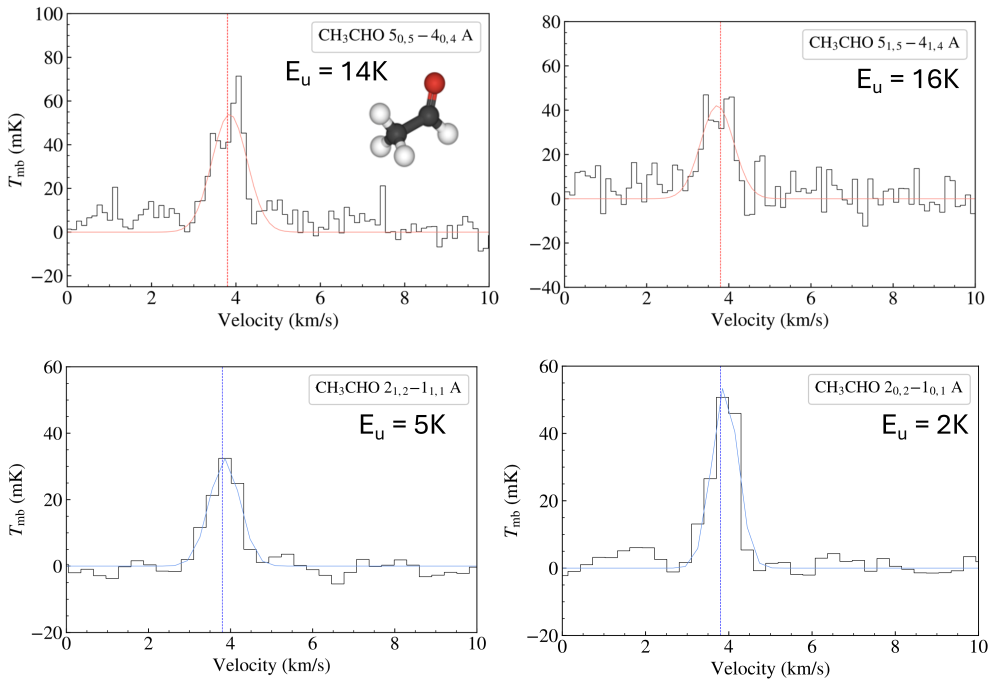
Fractionation II, Florence, Italy, Nov 4th- 7th, 2024
Contact: sscibell@nrao.edu

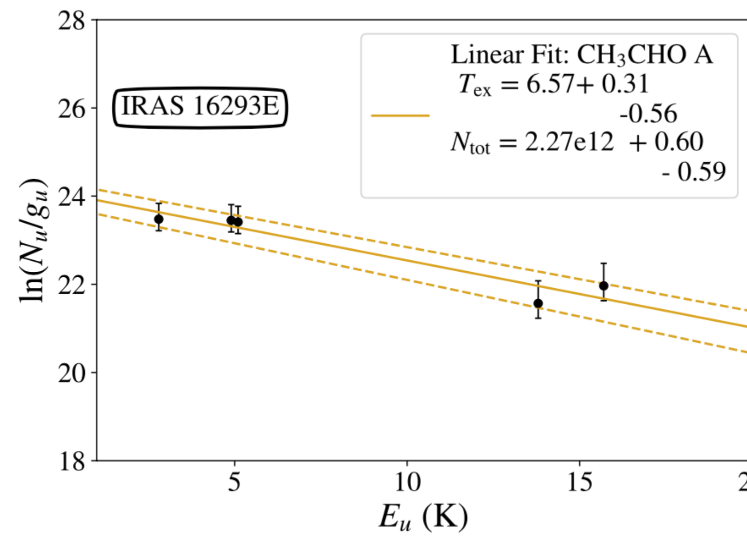
Arizona Radio Observatory · YEBES · AUI · National Radio Astronomy Observatory · NSF

IRAS 16293E

COM and dCOM column densities and excitation temperatures

Acetaldehyde





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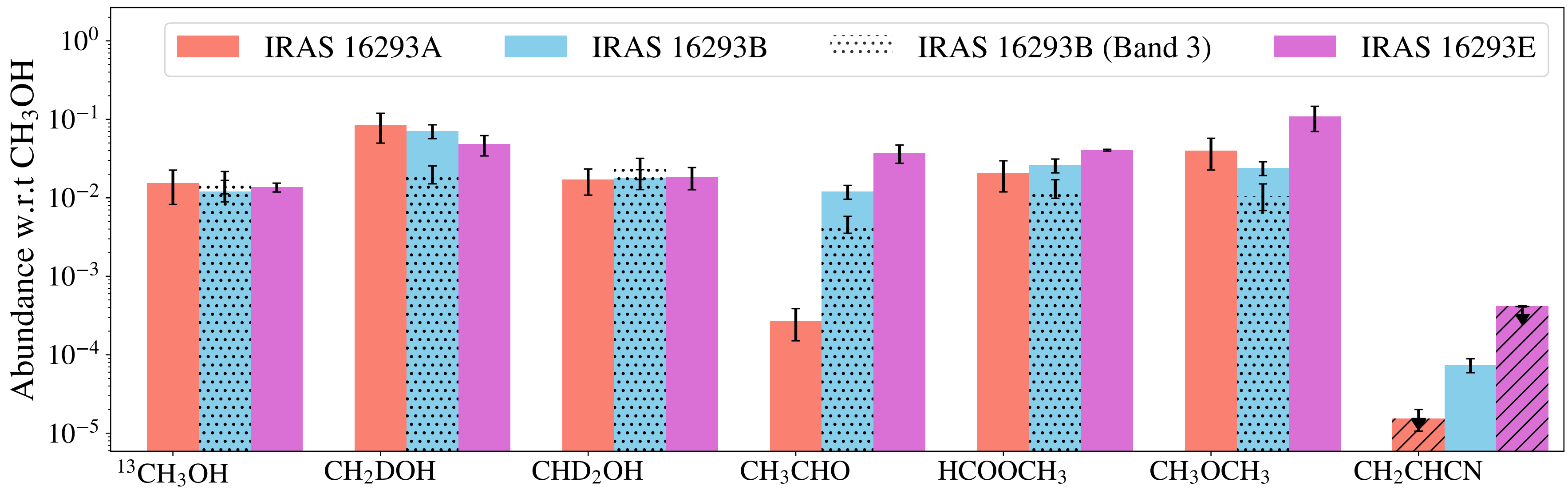
Arizona Radio Observatory
YEBES
National Radio Astronomy Observatory
NRAO
NSF

IRAS 16293E

Striking similarity in abundances in IRAS 1293 A, B and E!
In particular, CHD_2OH shows the best agreement

The enhanced deuterated methanol in protostars IRAS 16293 A and B was set during the prestellar phase!

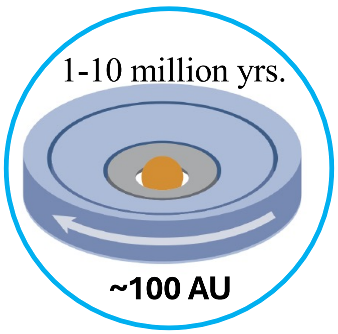


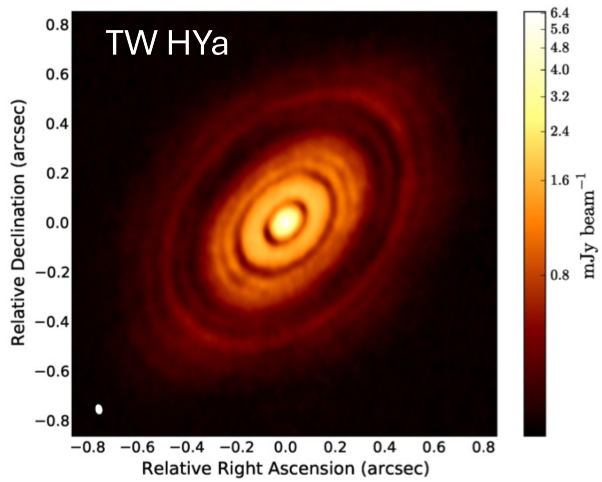
Including data from: Jørgensen et al. 2018; Calcutt et al. 2018; Manigand et al. 2020; Drozdovskaya et al. 2022, Nazari et al. (2024)

Scibelli et al., in prep

Molecular Line Data

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

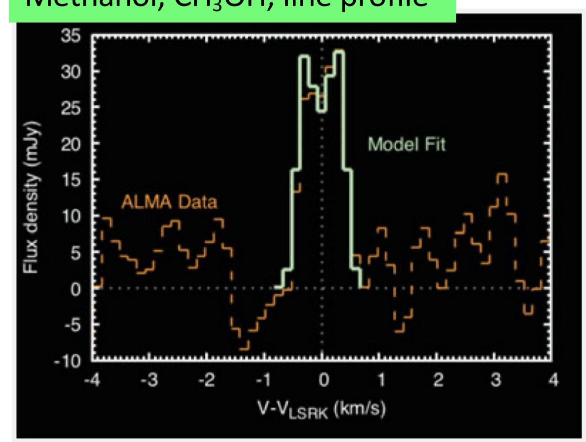




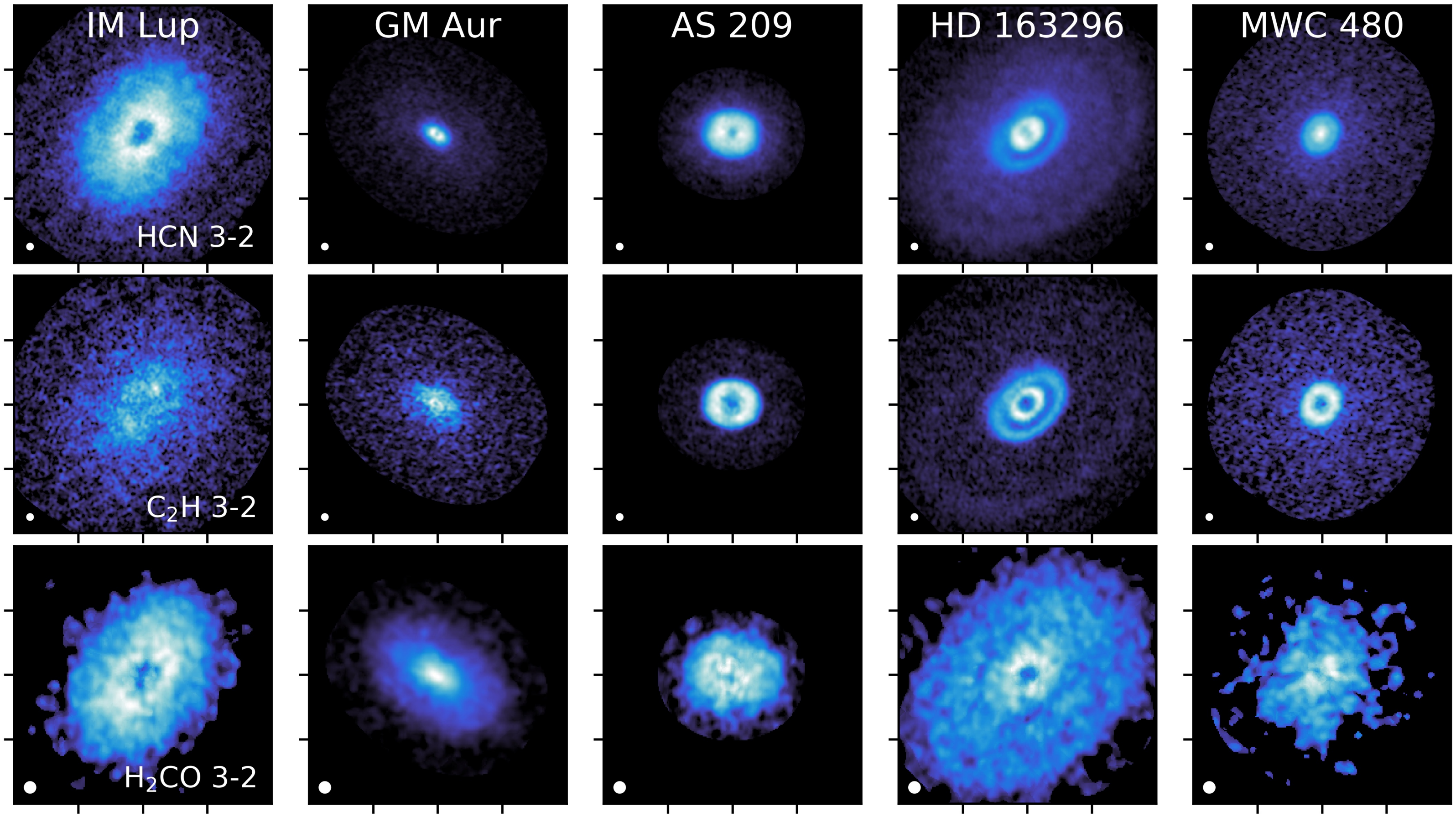
Low-mass (M ≤ a few $M_\odot$) Star Formation

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

Methanol, CH_3OH, line profile



Walsh et al. 2016, 2017



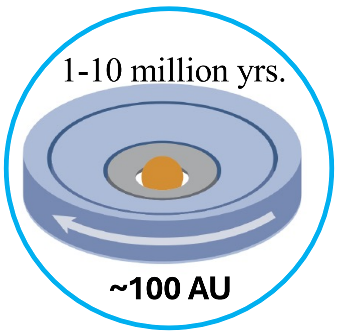
MAPS
Large Program

Disk structure is even seen in molecular emission!

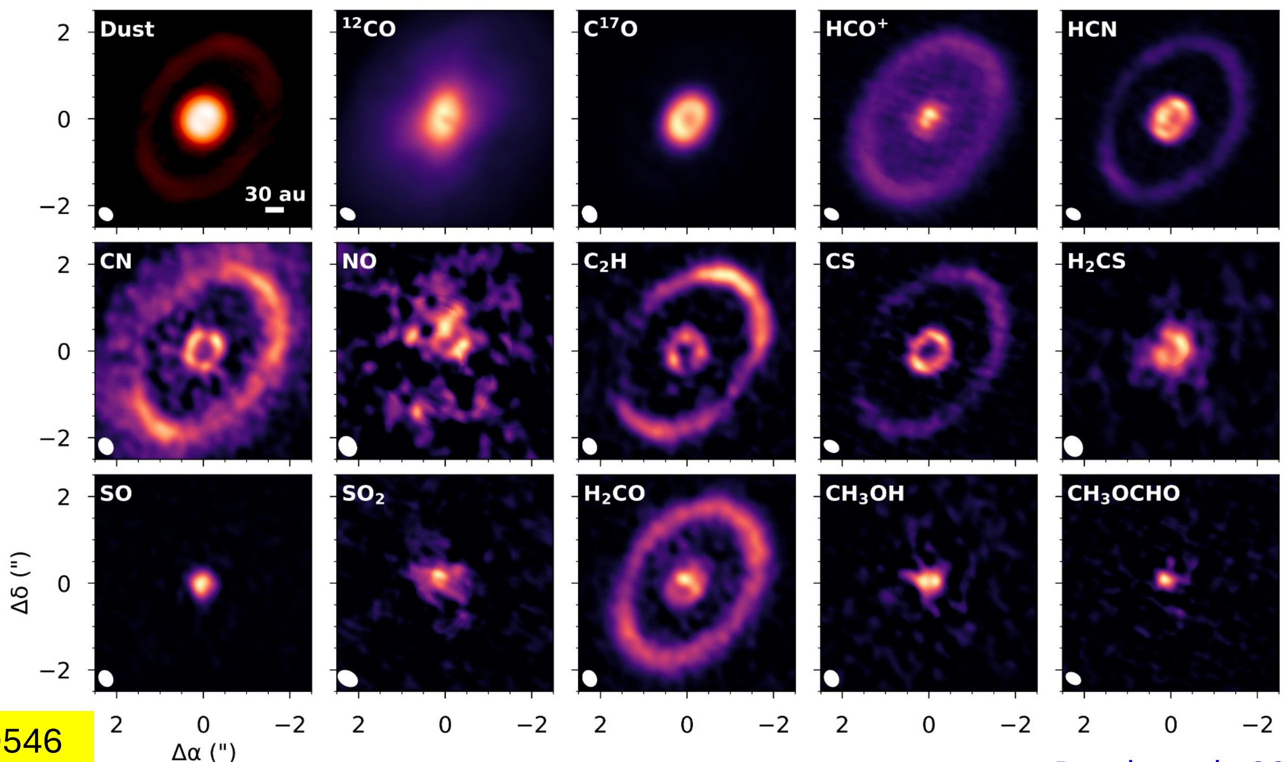
Oberg et al., 2021

Molecular Line Data

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



Larger COMs now seen in disks around more massive A and B stars!

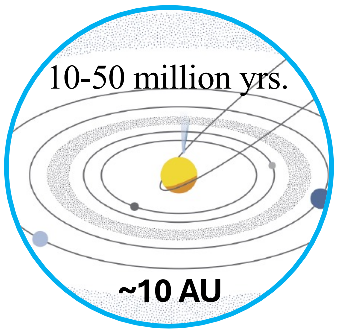


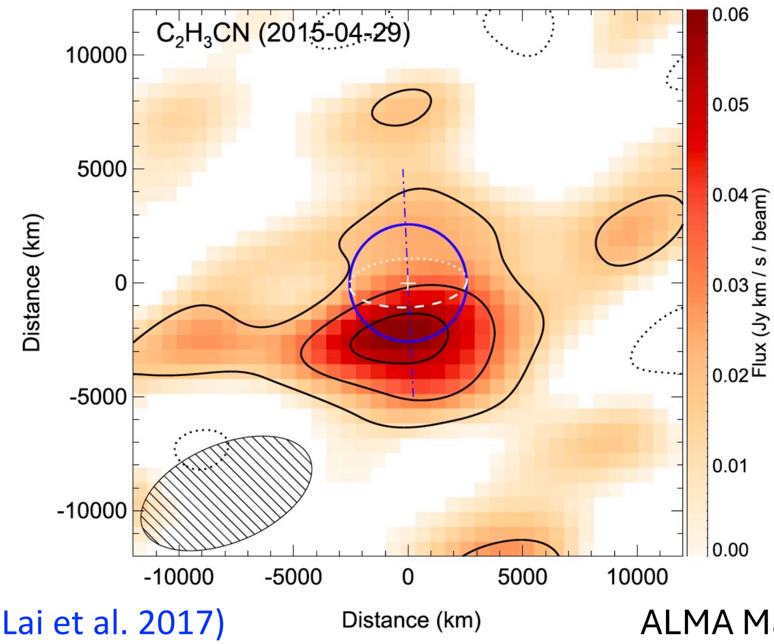
HD 100546

Booth et al., 2024a

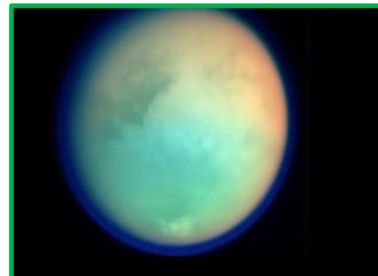
Molecular Line Data

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





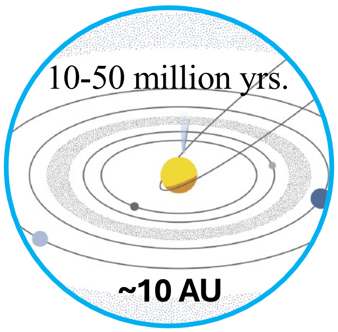
(Lai et al. 2017) ALMA Map

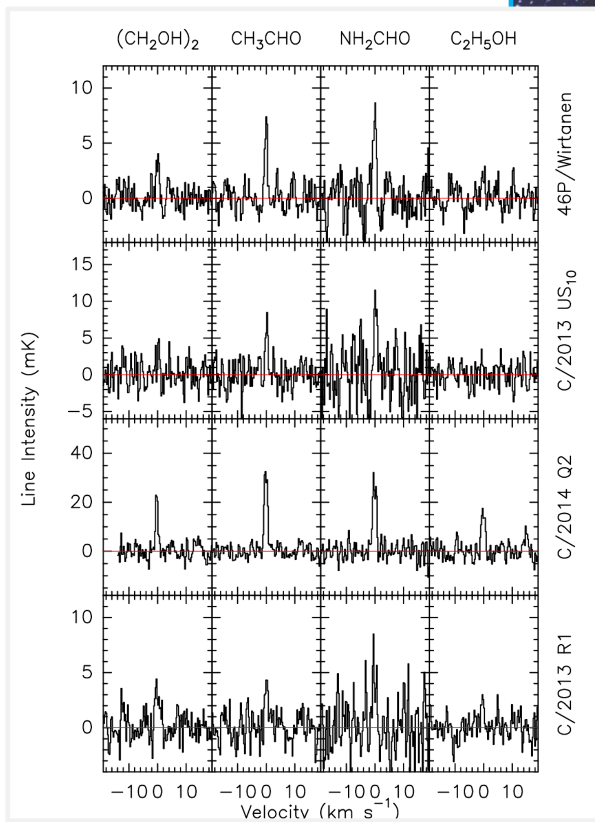


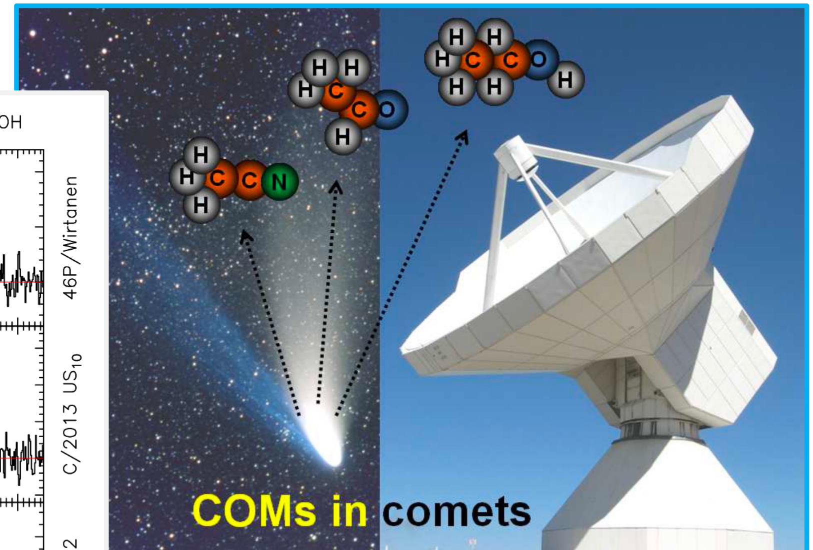
In Titan's atmosphere vinyl cyanide, CH_2CHCN, detected. Thought to be important for forming cell-like membranes in liquid methane oceans

Molecular Line Data

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





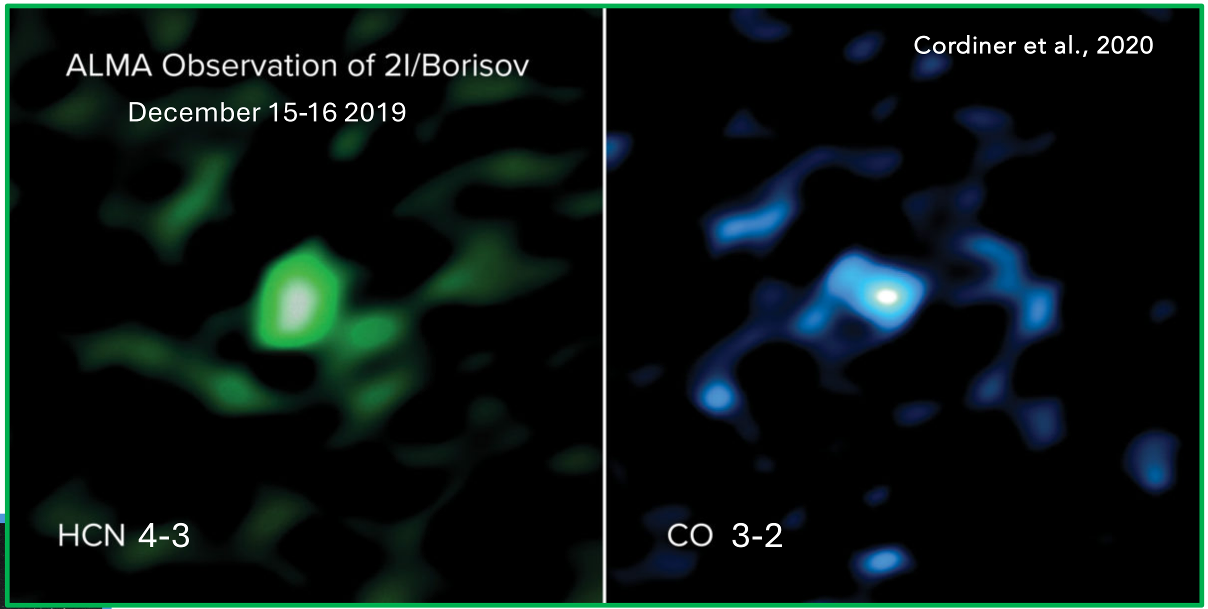


Biver 2019

GREEN BANK OBSERVATORY
National Radio Astronomy Observatory

Molecular Line Data

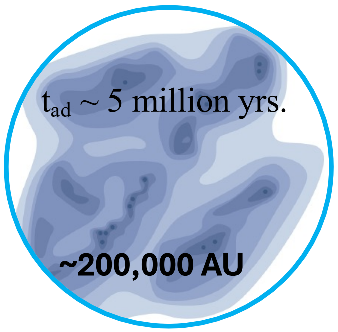
- The first confirmed interstellar comet!
- The HCN abundance similar to that of comets in our Solar System
- The CO abundance is among the highest observed in any comet within 2 au of the Sun!
- 2I/Borisov must have formed in a relatively CO-rich environment in the very cold, outer regions of a distant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



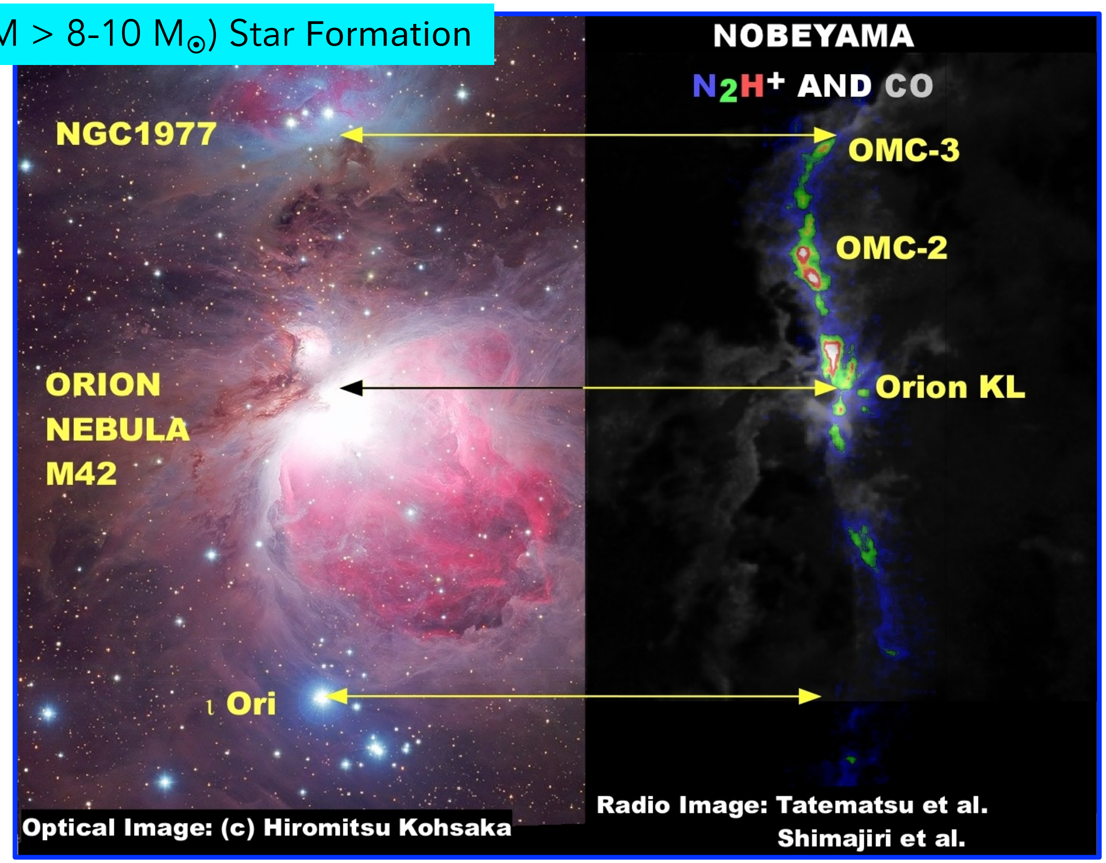
Maps from rotational line spectra

Molecular Line Data

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

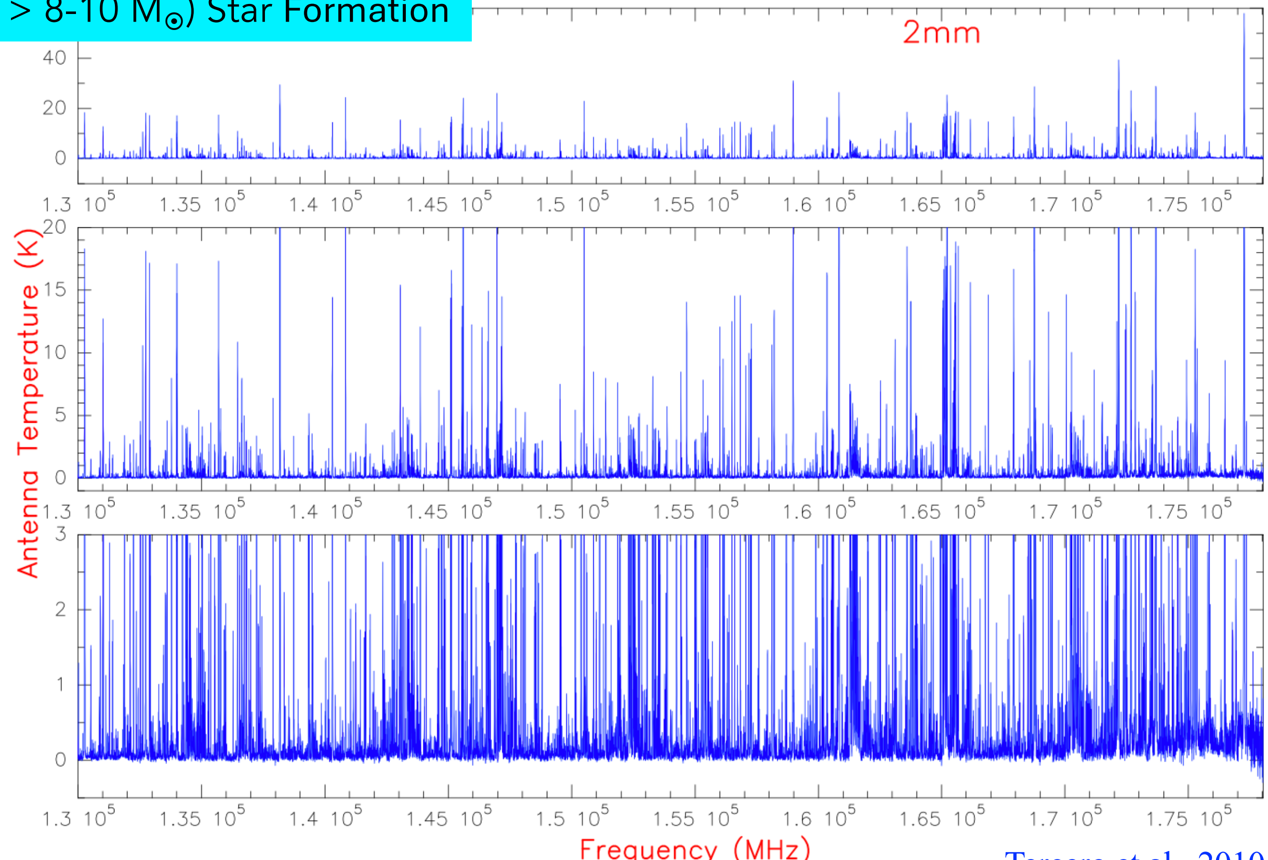


High-mass ($M > 8\text{-}10\ M_\odot$) Star Formation

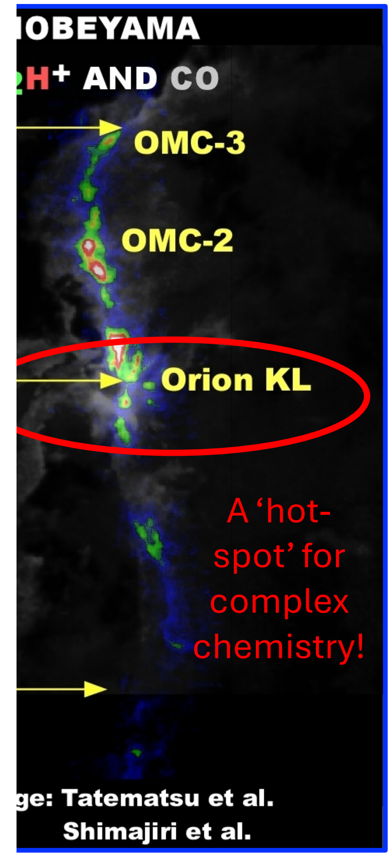


https://www.nro.nao.ac.jp/~kt/html/kt-e.html

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



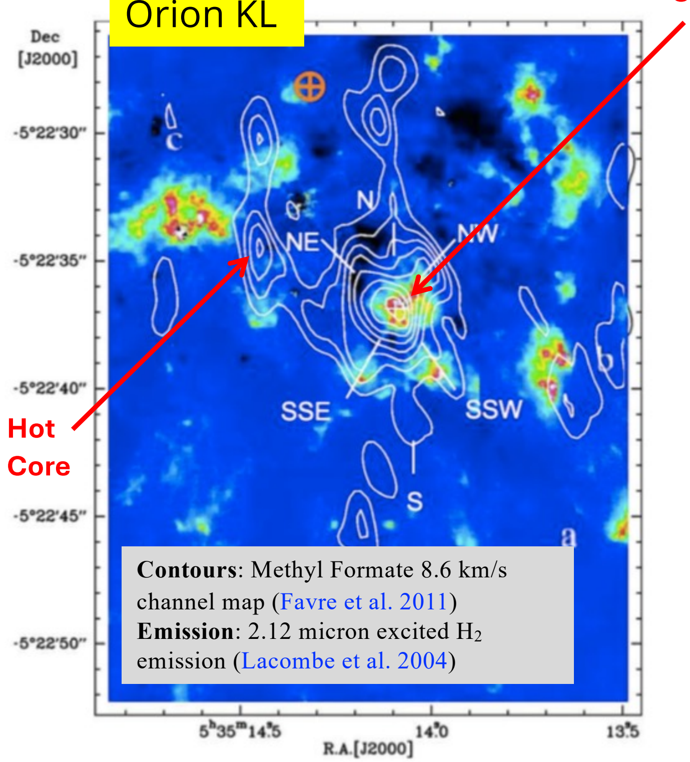
Tercero et al., 2010



Molecular Line Data

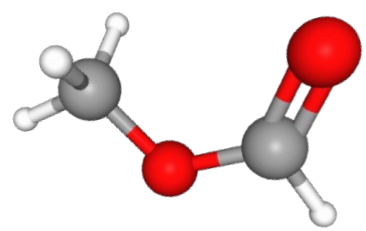
High-mass (M > 8-10 $M_\odot$) Star Formation

Orion KL



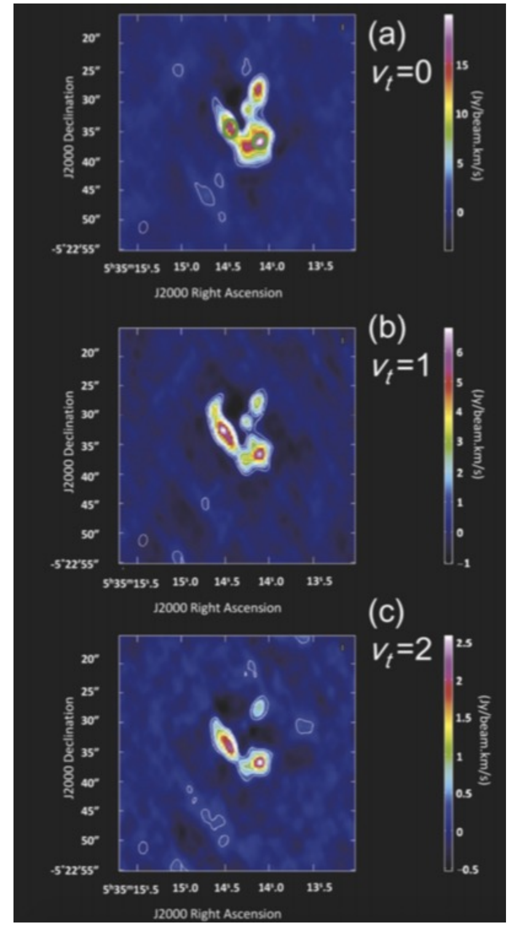
Contours: Methyl Formate 8.6 km/s channel map (Favre et al. 2011)
Emission: 2.12 micron excited H_2 emission (Lacombe et al. 2004)

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

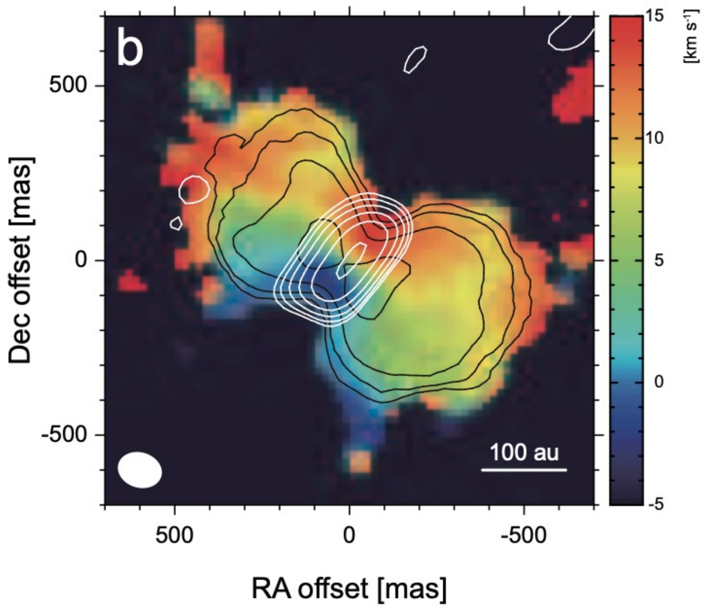


Molecular Line Data

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

Orion Source I

SiO emssion



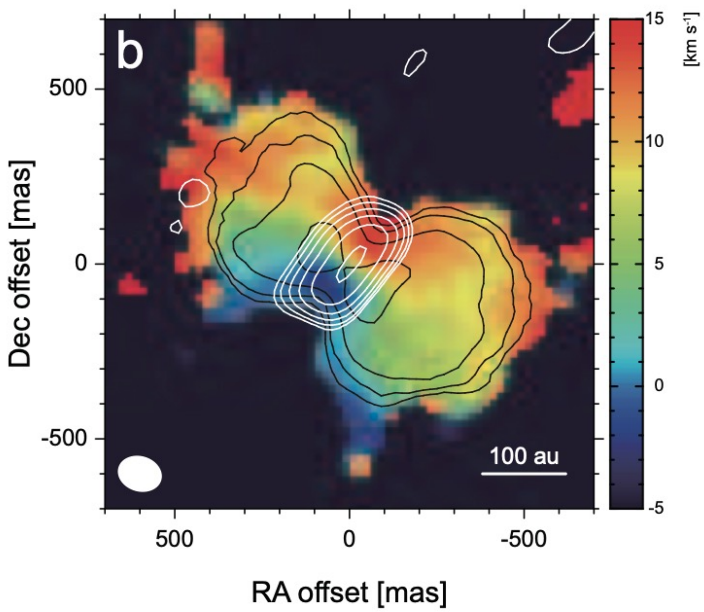
The presence of a **disk-outflow** system (Hirota et al. 2017) indicates that "Orion source I" is accreting, confirming its nature as a young, forming star.

Molecular Line Data

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

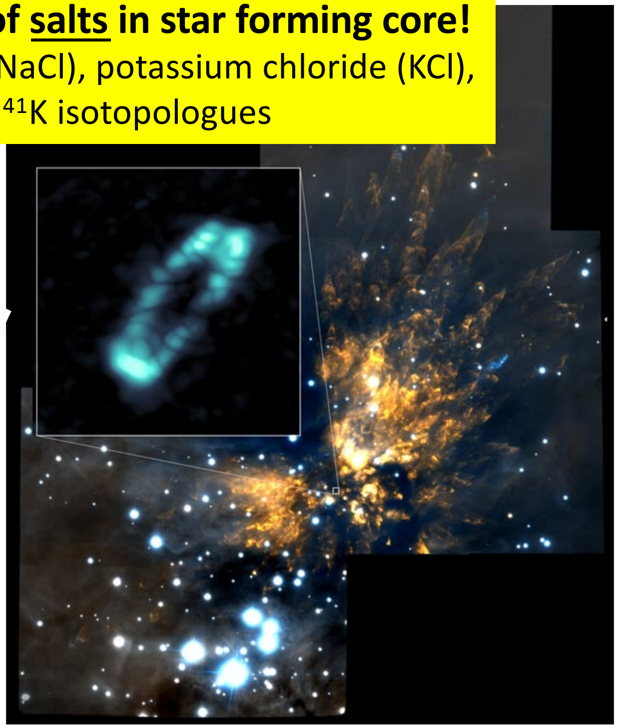
Orion Source I

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 salts in star forming core!
Sodium chloride (NaCl), potassium chloride (KCl), and their ^{37}Cl and ^{41}K isotopologues

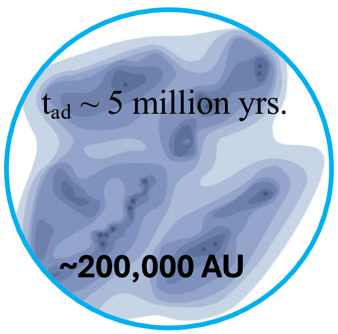


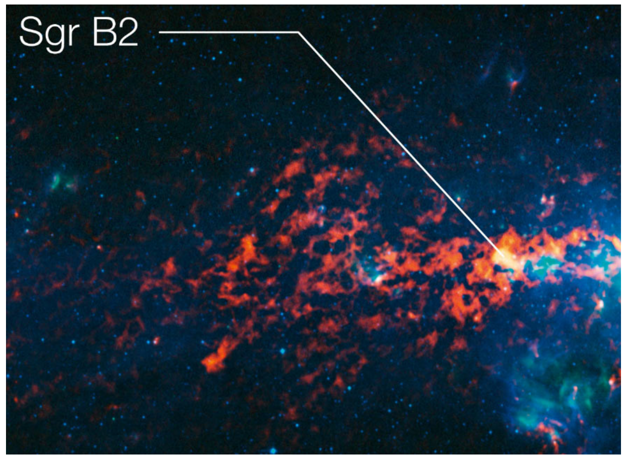
Ginsburg et al. 2019.

Molecular Line Data

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

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





"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

Molecular Line Data

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

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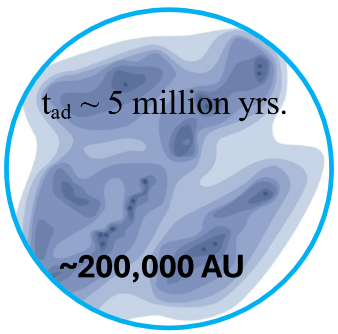

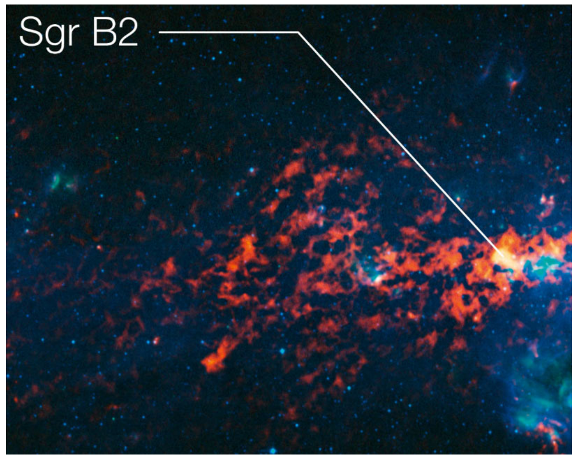

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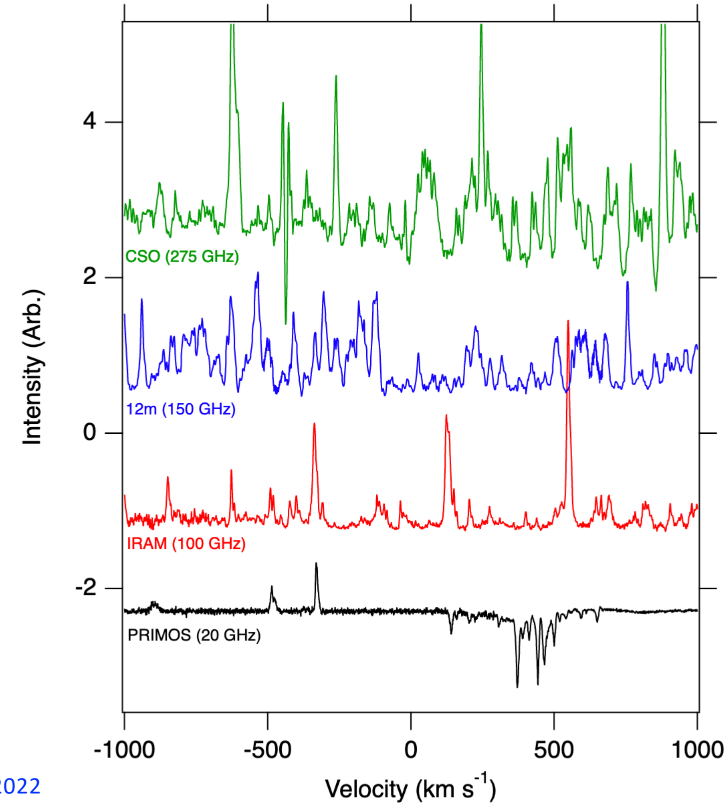
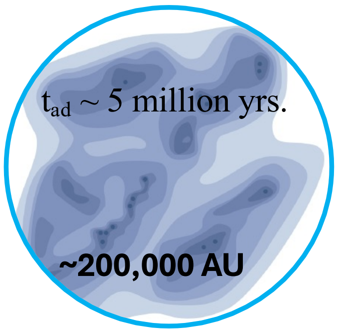


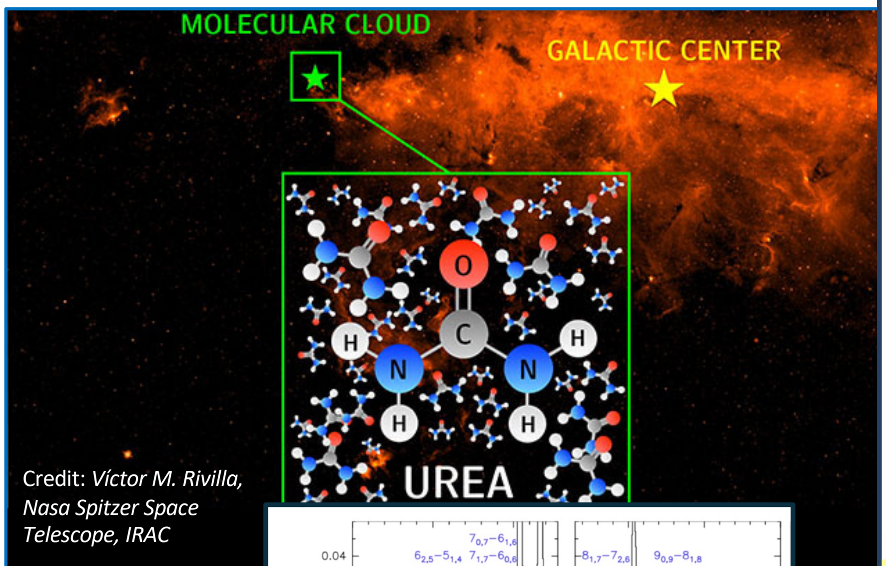
McGuire 2022

Molecular Line Data

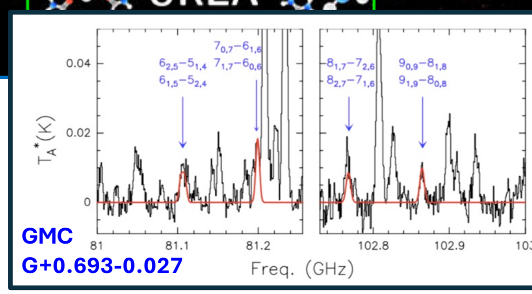
High-mass (M > 8-10 $M_\odot$) Star Formation

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



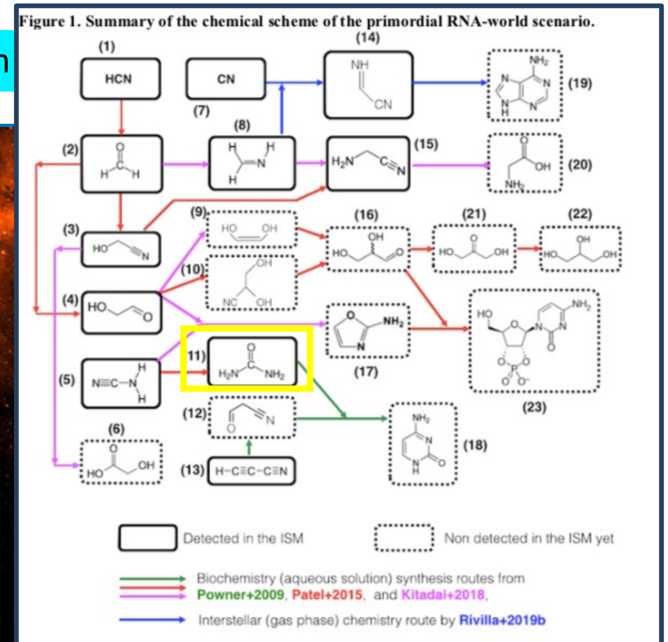


Credit: *Víctor M. Rivilla, Nasa Spitzer Space Telescope, IRAC*



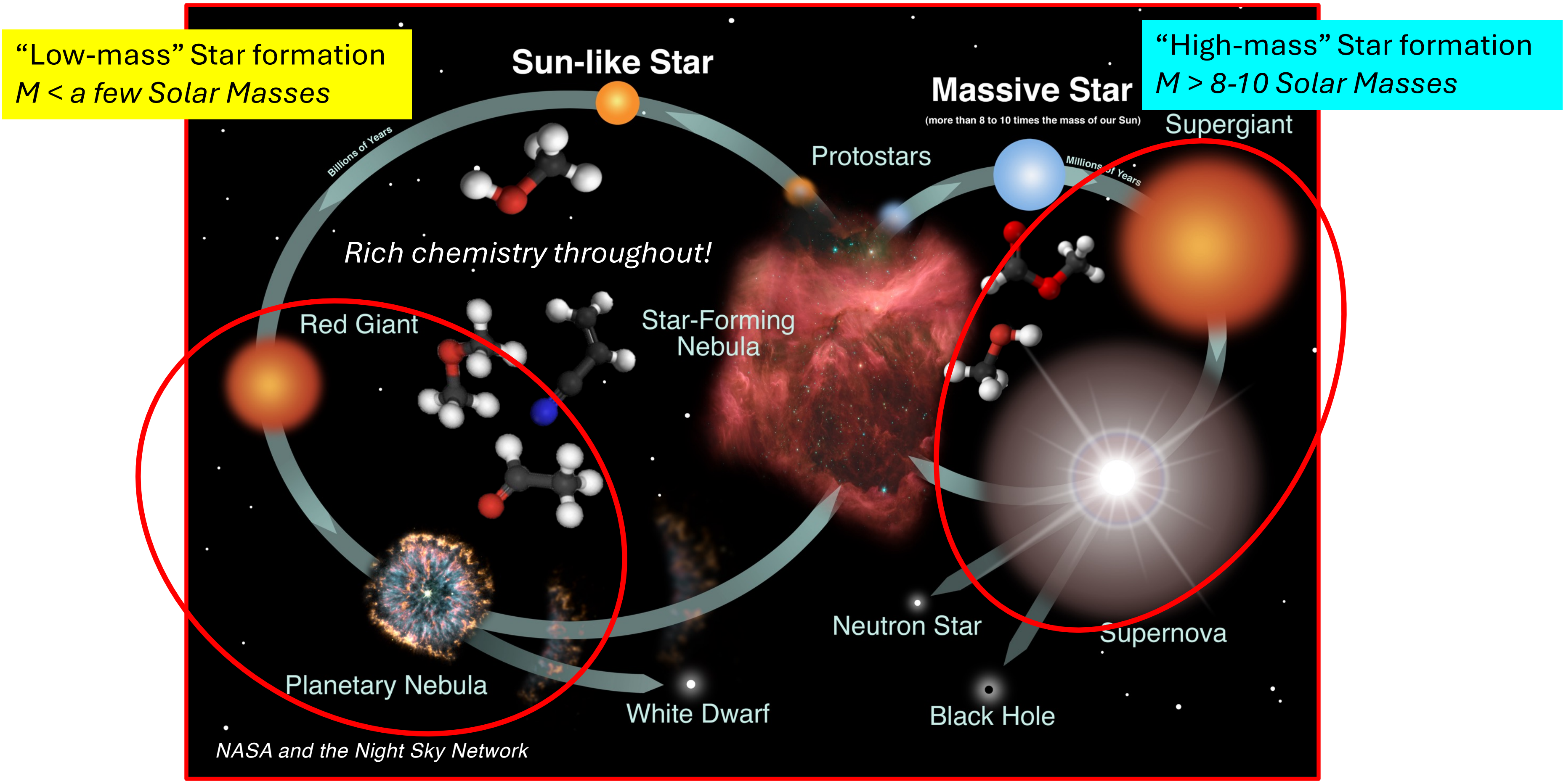
Recent Detections of biologically relevant molecule UREA (NH_2CONH_2)

!



(1) Hydrogen Cyanide; (2) Formaldehyde; (3) Glycolonitrile; (4) Glycolaldehyde; (5) Cyanamide; (6) Glycolic acid; (7) Cyanide; (8) Methanimine; (9) Enol form of glycolaldehyde; (10) Cyanohydrin; (11) Urea; (12) 3-Oxopropanenitrile; (13) Cyanoacetylene; (14) Cyanomethanimine; (15) Aminoacetonitrile; (16) Glyceraldehyde; (17) 2- amino-oxazole; (18) Cytosine; (19) Adenine; (20) Glycine; (21) Dihydroxyacetone (DHA); (22) Glycerol; (23) Beta-ribocytidine-2',3'-cyclic phosphate (pyrimidine ribonucleotide)

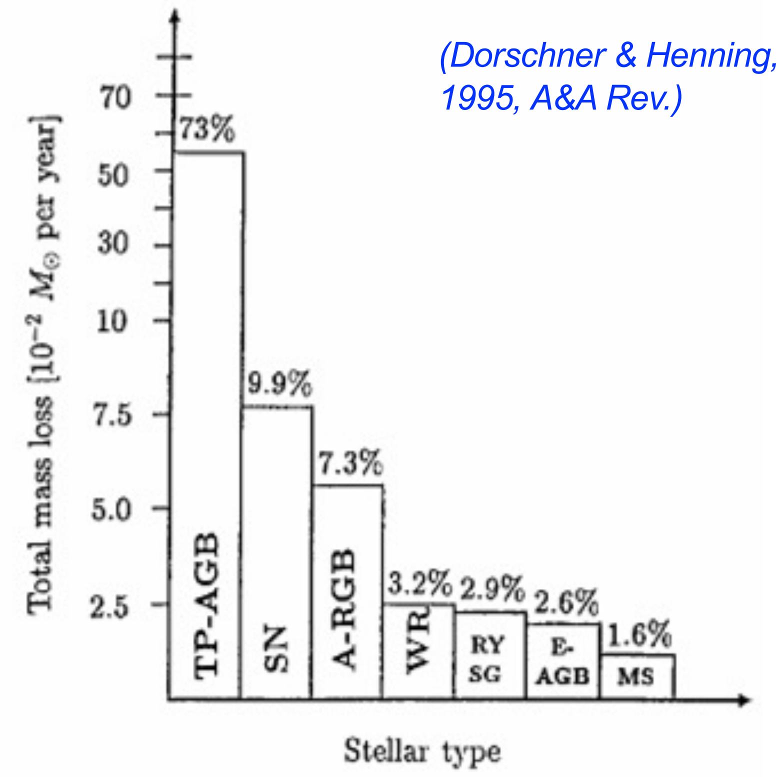
Jiménez-Serra et al. 2020



ASTR 5340 - Introduction to Radio Astronomy
Contact: sscibell@nrao.edu

EVOLVED STARS

- **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 of low-mass giants***
- Remainder from Supernoave and Wolf-Rayet Stars
- Material ends up in diffuse clouds
- Collapse to form dense clouds
- Important in evaluating
  - ⇒ Composition of ISM
  - ⇒ Galactic Chemical Evolution

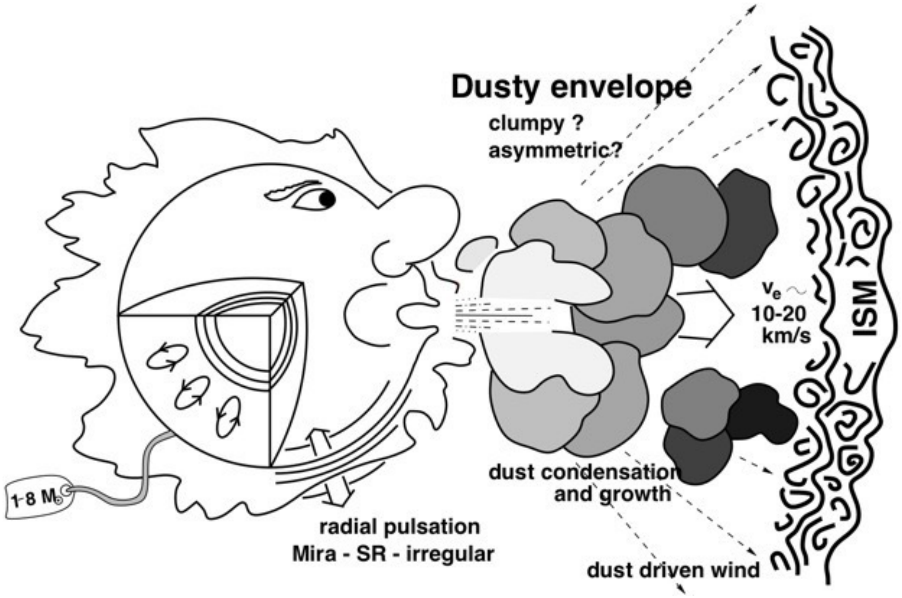


(Dorschner & Henning, 1995, A&A Rev.)

Credit: L. Ziurys

Molecular Line Data

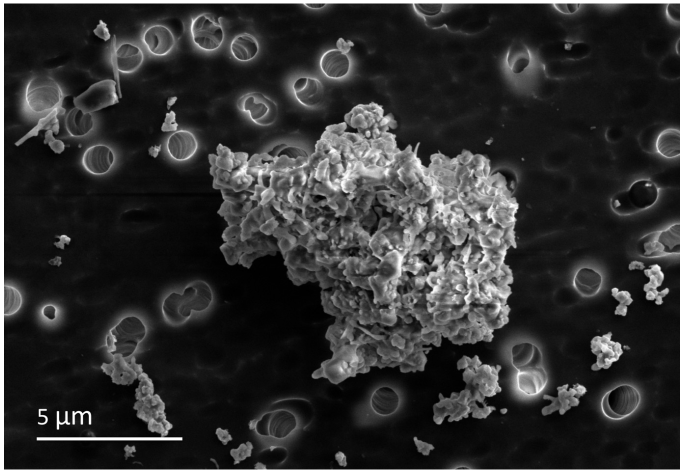
Asymptotic Giant Branch (AGB) Stars



Olofsson 2011

What does this mean for molecule formation? We know that where there is dust, molecules are likely form!!

Dust Grains born from material ejected from stars!



Credit: Hope Ishii, University of Hawai'i.

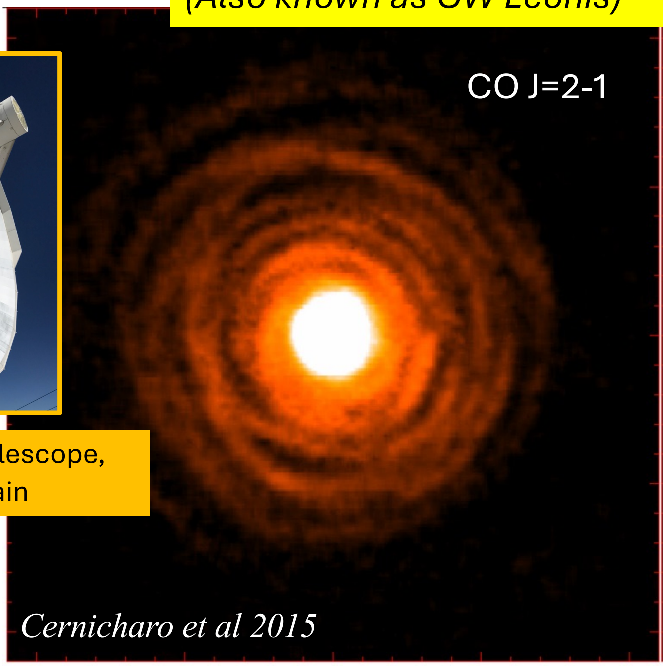
Molecular Line Data

Asymptotic Giant Branch (AGB) Stars

"Famous" case: Carbon-rich star IRC+10216 !

(Also known as CW Leonis)

IRAM 30m Radio Telescope, Granada, Spain



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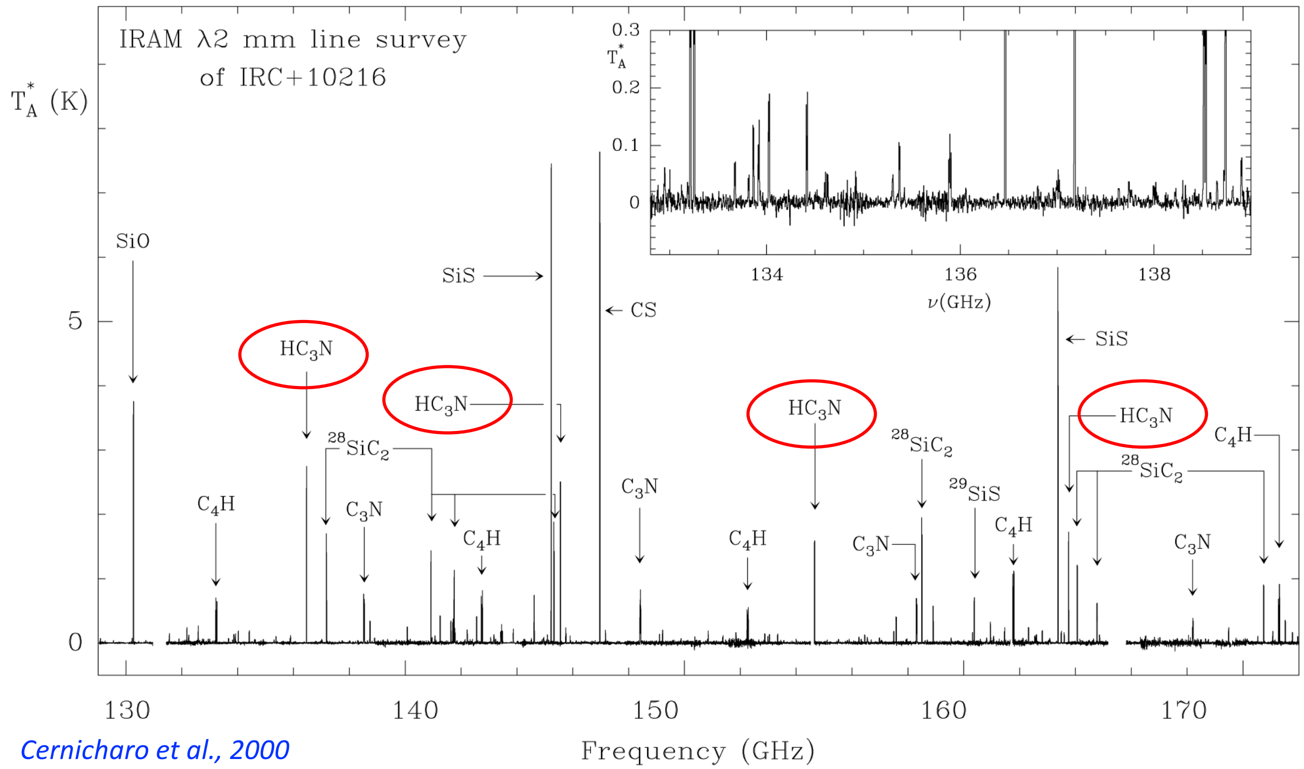
Horsehead PDR	2	Orion Bar	1

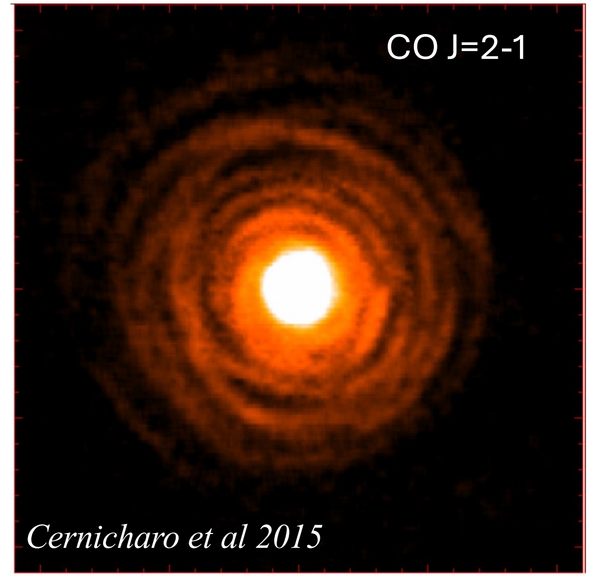
McGuire 2022

Molecular Line Data

“Famous” case: Carbon-rich star IRC+10216 !



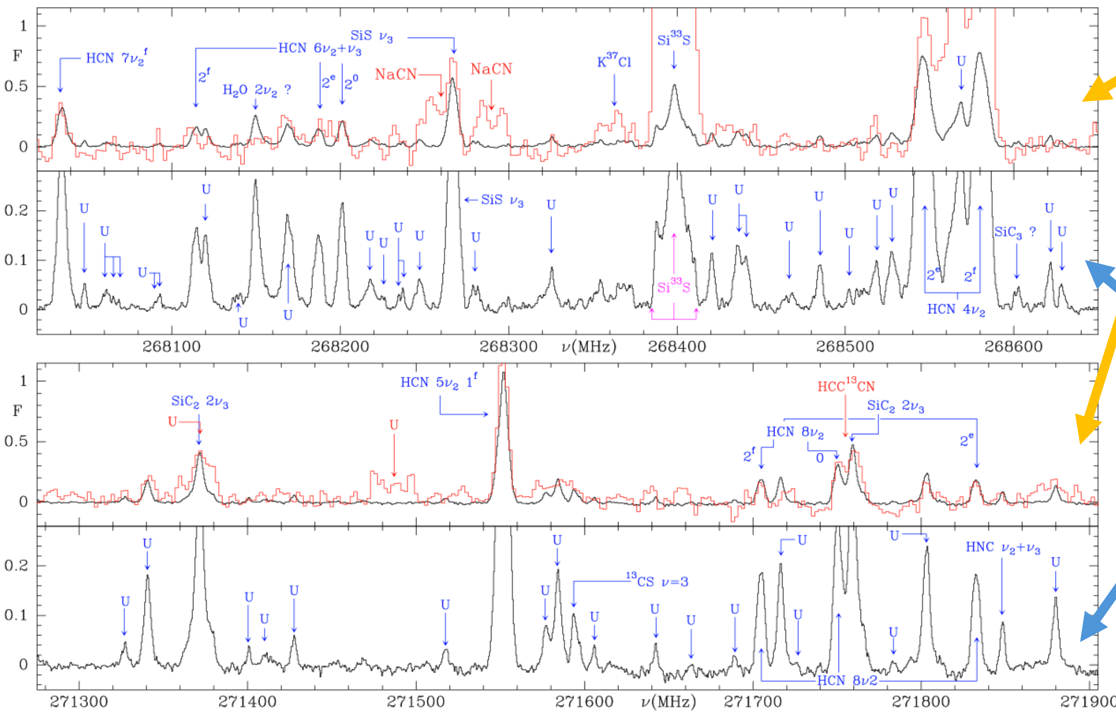
Cernicharo et al., 2000



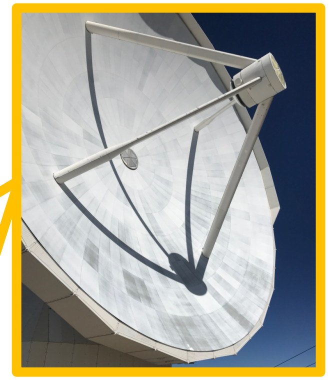
Rich in large carbon-chain and silicon-rich molecules!

Molecular Line Data

“Famous” case: Carbon-rich star IRC+10216 !



Cernicharo et al., 2013



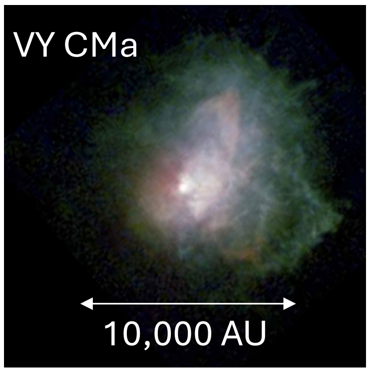
IRAM 30m Radio Telescope, Granada, Spain

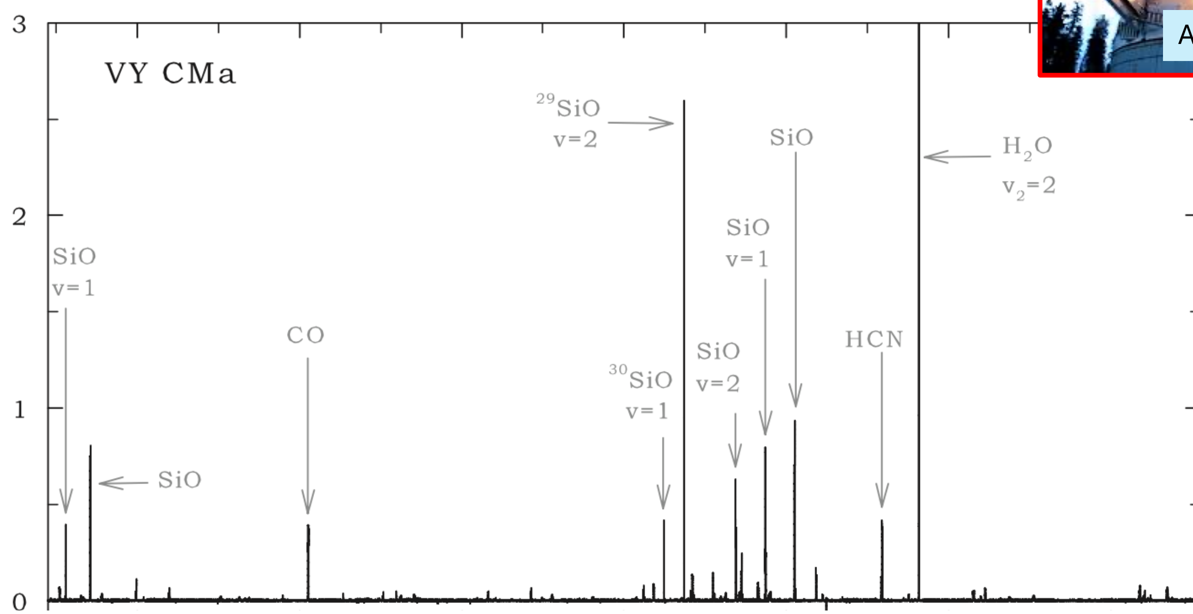
'Zooming in' with higher resolution and more sensitive telescope → Many ‘U’ lines, which are ‘unidentified’ !

Molecular Line Data

Supergiant Stars

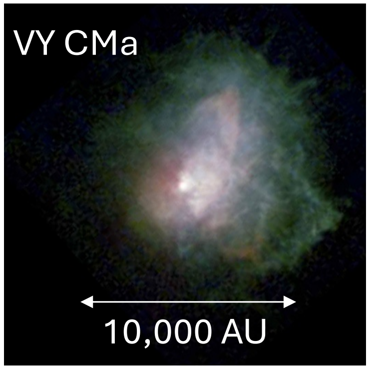
Oxygen-rich Supergiant star VY Canis Majoris

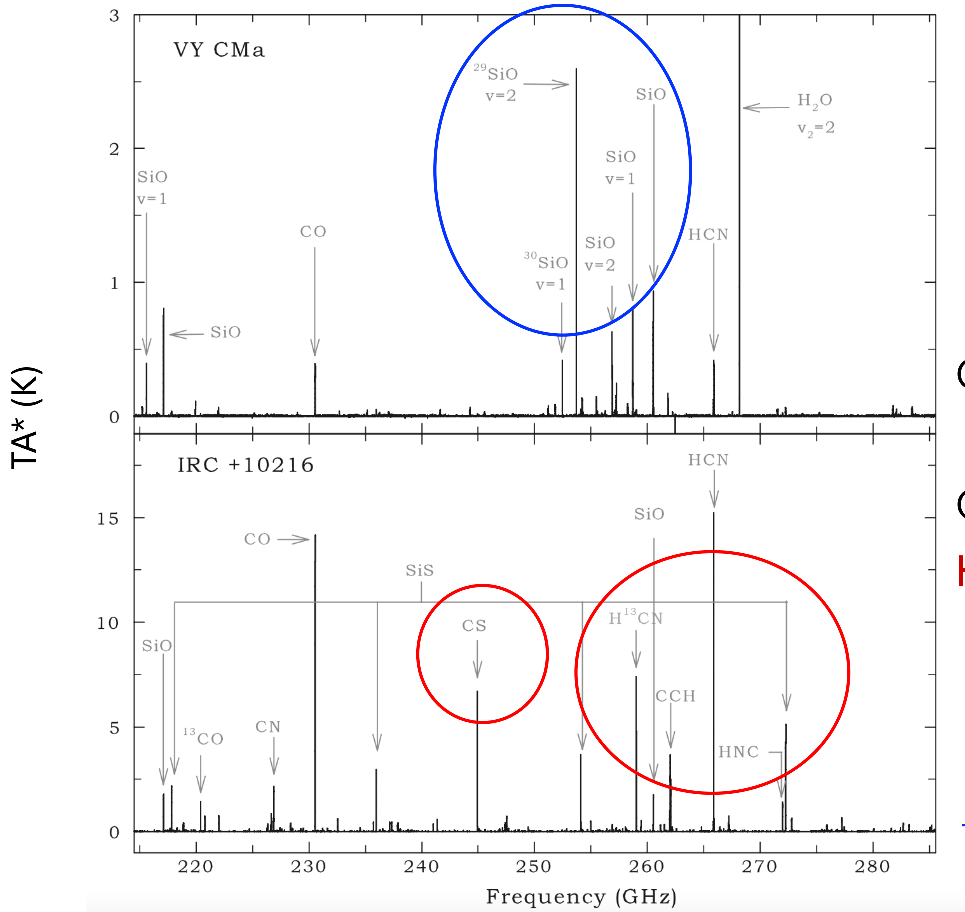




Tenenbaum et al., 2010

C-rich vs. O-rich



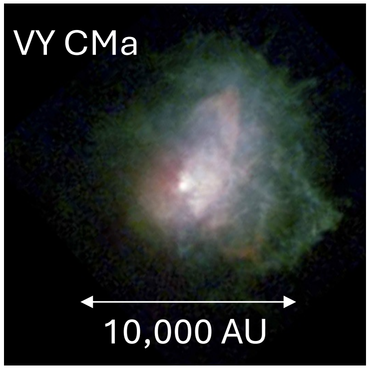


O-rich: H_2O, SiO, CO

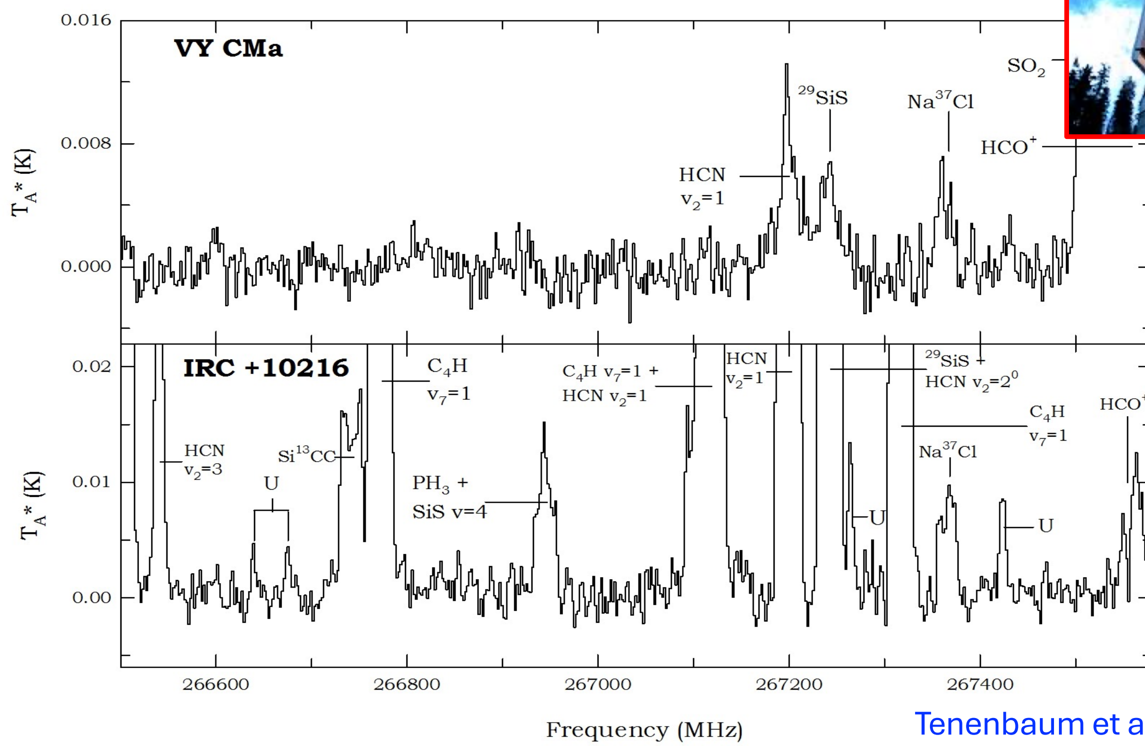
C-rich: CO, HCN, H_2C_2, SiS, CS, CH_4

Tenenbaum et al., 2010

C-rich vs. O-rich



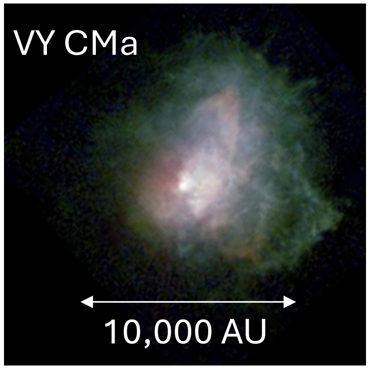
- VY CMa Spectrum dominated by **SO_2, SiO, SiS**
- IRC+10216 Spectrum dominated by **C_4H, HCN**



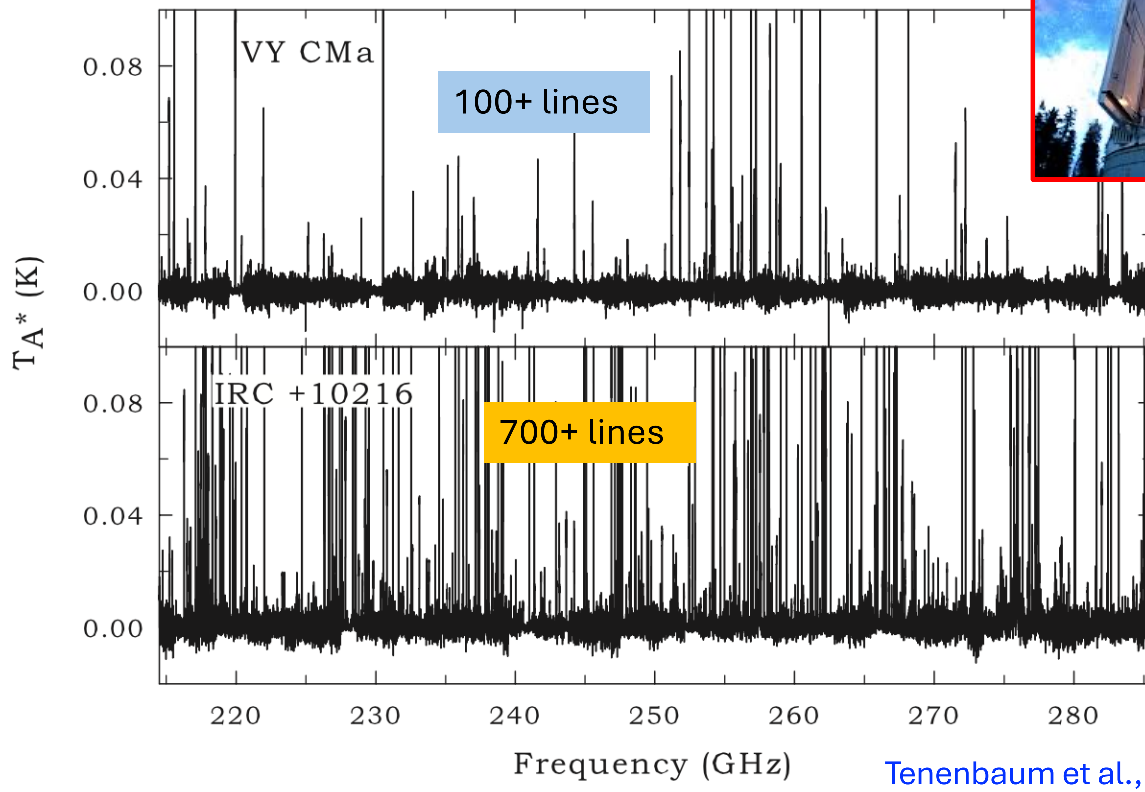
Tenenbaum et al., 2010

GREEN BANK OBSERVATORY
National Radio Astronomy Observatory

C-rich vs. O-rich



Both objects overall **very** line rich!



Tenenbaum et al., 2010

**NOTE: VY Cma is ~10x farther away!!!*

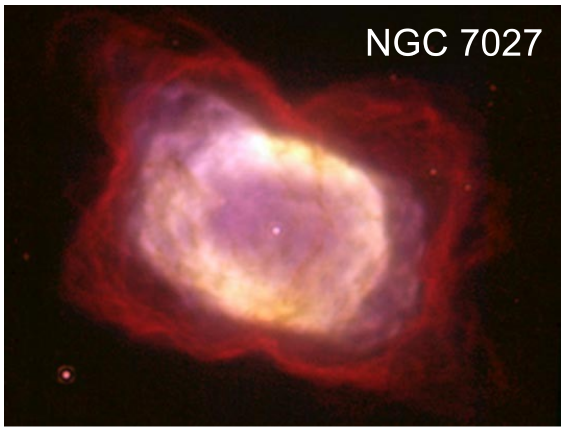
Molecular Line Data

Planetary Nebula

ASTR 5340 - Introduction to Radio Astronomy
Contact: sscibell@nrao.edu

Molecular Line Data

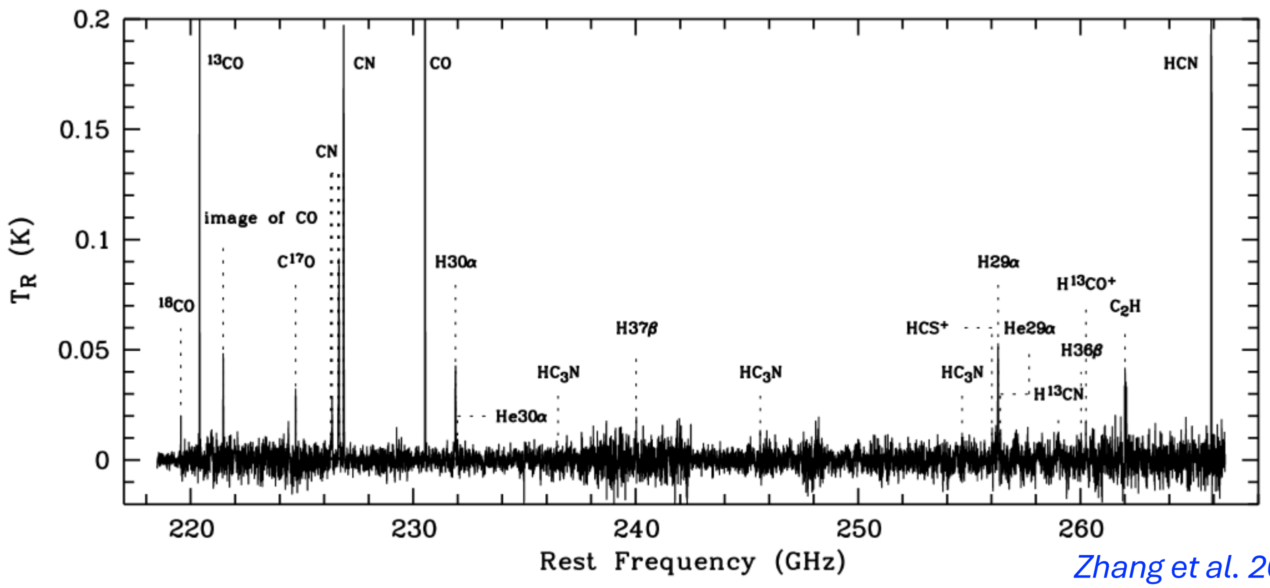
Planetary Nebula



Young PN: ***~ 700 years old*** T_{star} ~ 200,000 K

Molecular Content:

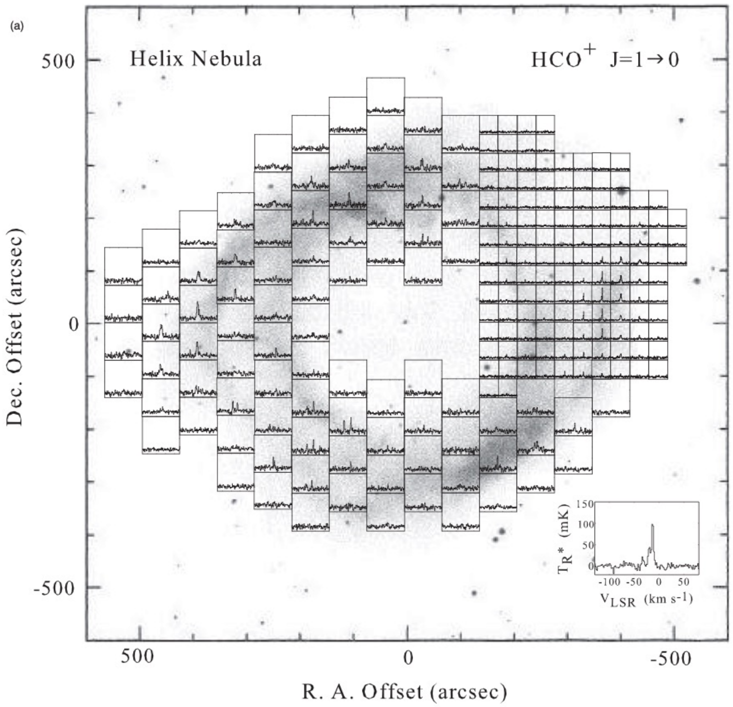
CO, CN, HCN, HCO^+, N_2H^+, CCH, C_3H_2, HC_3N, OH, CH, CH^+



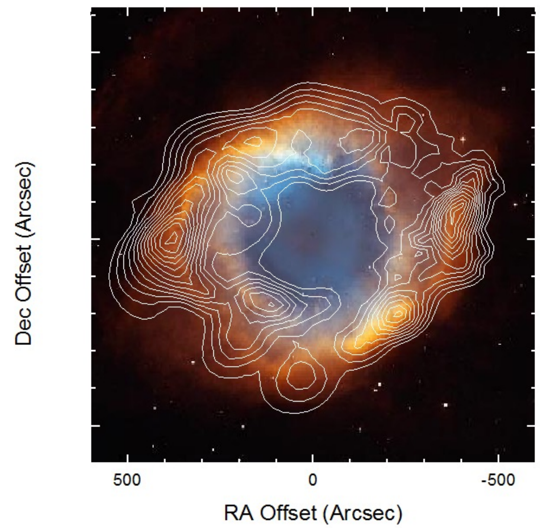
Zhang et al. 2008

Molecular Line Data

Oldest Known Planetary Nebula: **The Helix**



Planetary Nebula

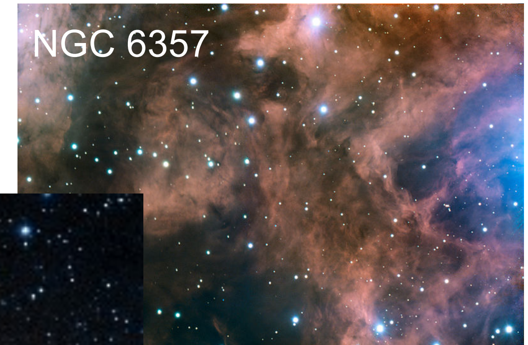


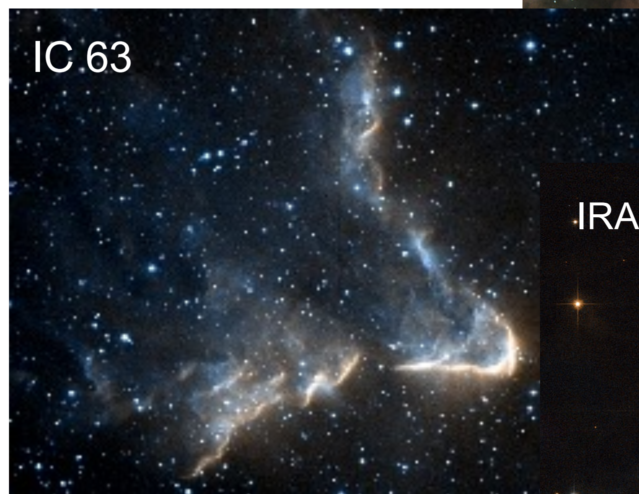
Zeigler et al., 2013

Diffuse Clouds

Lack a *Definite Morphology*

- Semi-transparent in the visible ($A_v \sim 1$)
- Total hydrogen column density: $N \sim 10^{21}$ cm^{-2}
- Readily penetrated by UV radiation





Credit: L. Ziurys

Diffuse Clouds

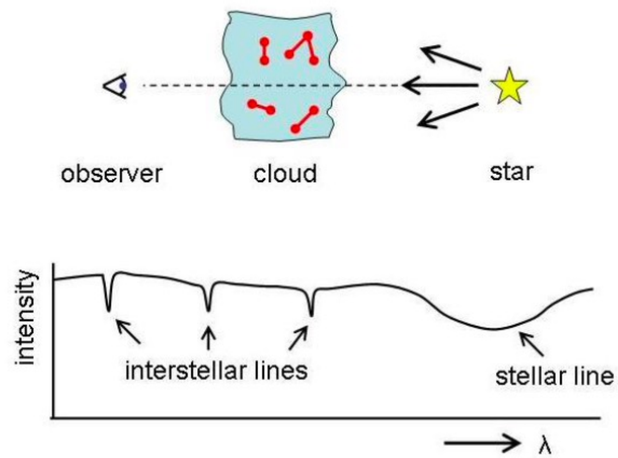
Lack a *Definite Morphology*

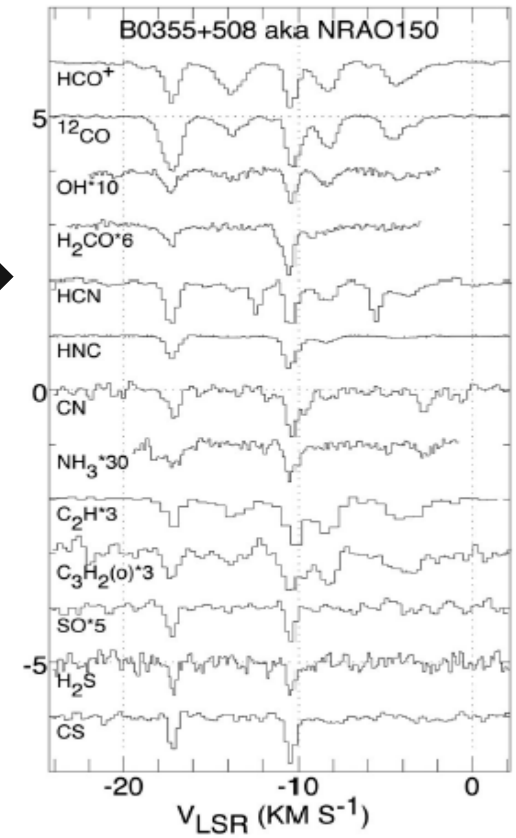
- Semi-transparent in the visible (A_v ~ 1)
- Total hydrogen column density: N ~ 10^{21} cm^{-2}
- Readily penetrated by UV radiation

- Densities low: No radio/mm emission lines
- Not sufficient density for collisional excitation
- Molecules observed in ABSORPTION
- Common molecules observed

  OH, H_2 (HD), CH, C_2, CH^+, NH, CO, H_3^+

*line of sight to the blazar/radio-continuum source ➔





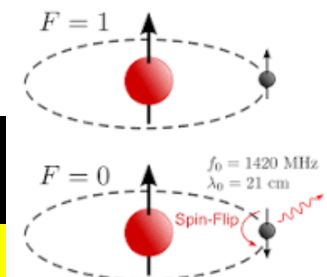
Credit: L. Ziurys

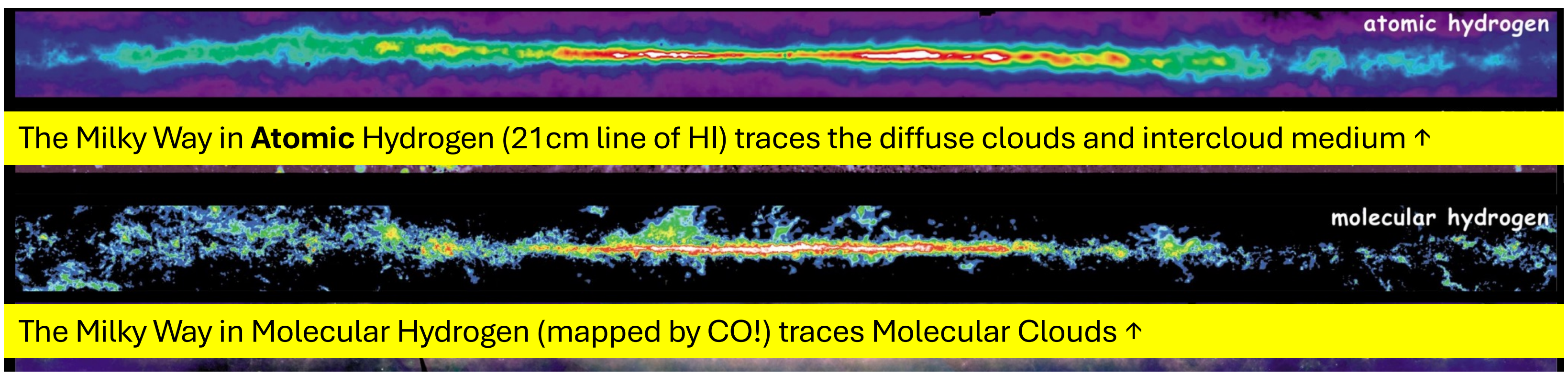
Diffuse Clouds

Lack a *Definite Morphology*

- Semi-transparent in the visible (A_v ~ 1)
- Total hydrogen column density: N ~ 10^{21} cm^{-2}
- Readily penetrated by UV radiation

- Best traced by **21 cm HI line**
  - T_k ~ 100 K
  - n ~ 1 - 100 particles/cm^3 ($H^0 + H_2$)
  - x_e ~ 10^{-3} (*Fractional ionization*)





The Milky Way in **Atomic** Hydrogen (21cm line of HI) traces the diffuse clouds and intercloud medium ↑

The Milky Way in Molecular Hydrogen (mapped by CO!) traces Molecular Clouds ↑

Reminder! Typical Conditions of Molecular Clouds: T ~ 10 – 50 K; n ~ 10^3 – 10^6 cm^{-3}

Credit: L. Ziurys