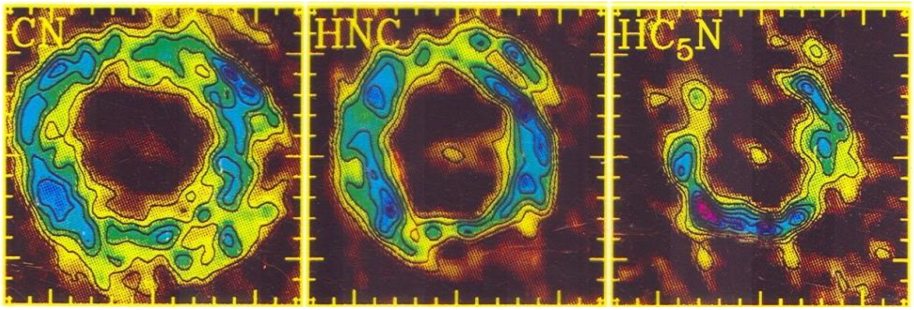
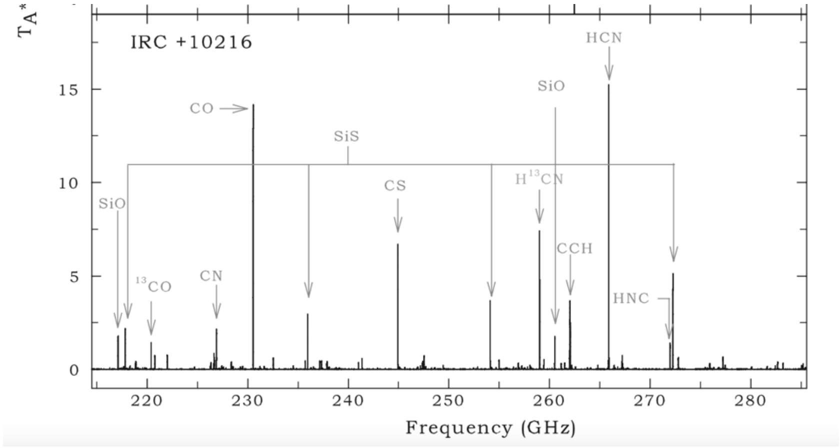




Introduction to Astrochemistry **Part 3:**

Interstellar Dust and Evolved Stars

Dr. Samantha Scibelli

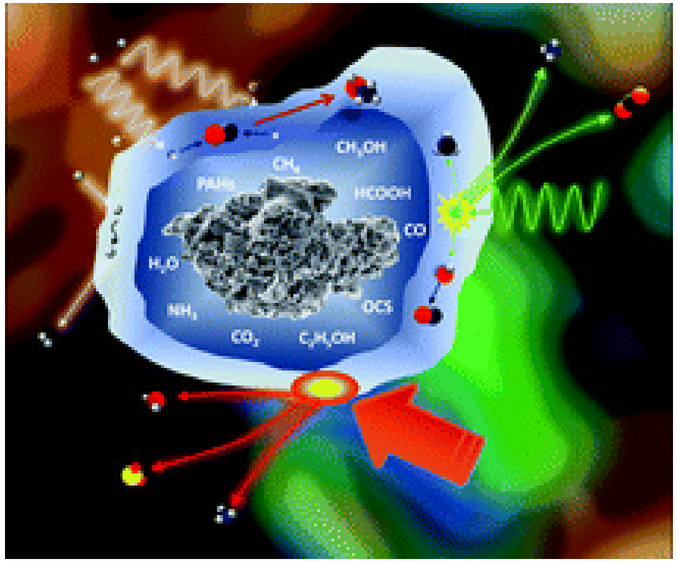
Jansky Fellow at the National Radio Astronomy Observatory (NRAO)

AAA.org Lecture, June 4th, 2024

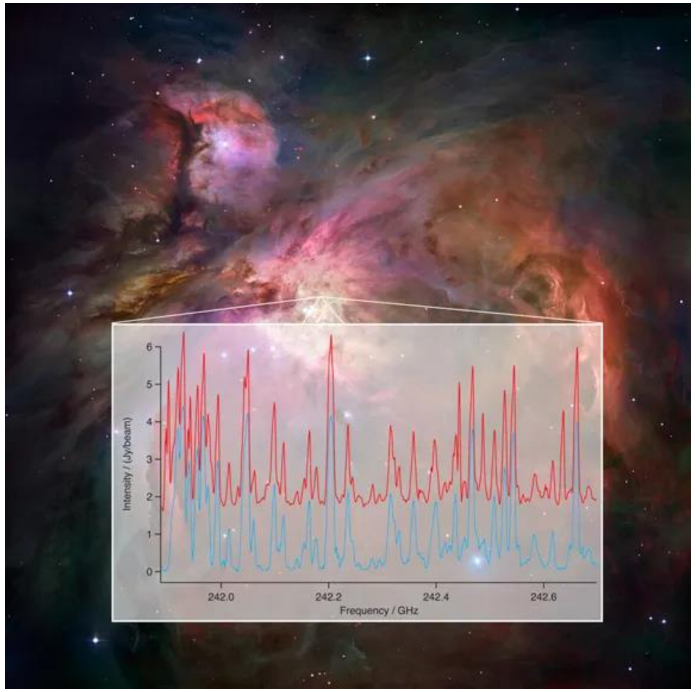
Astrochemistry is an interdisciplinary field! Including, chemistry, physics, astronomy, biology, etc.,

Things an astro**chemist** does

Modeling

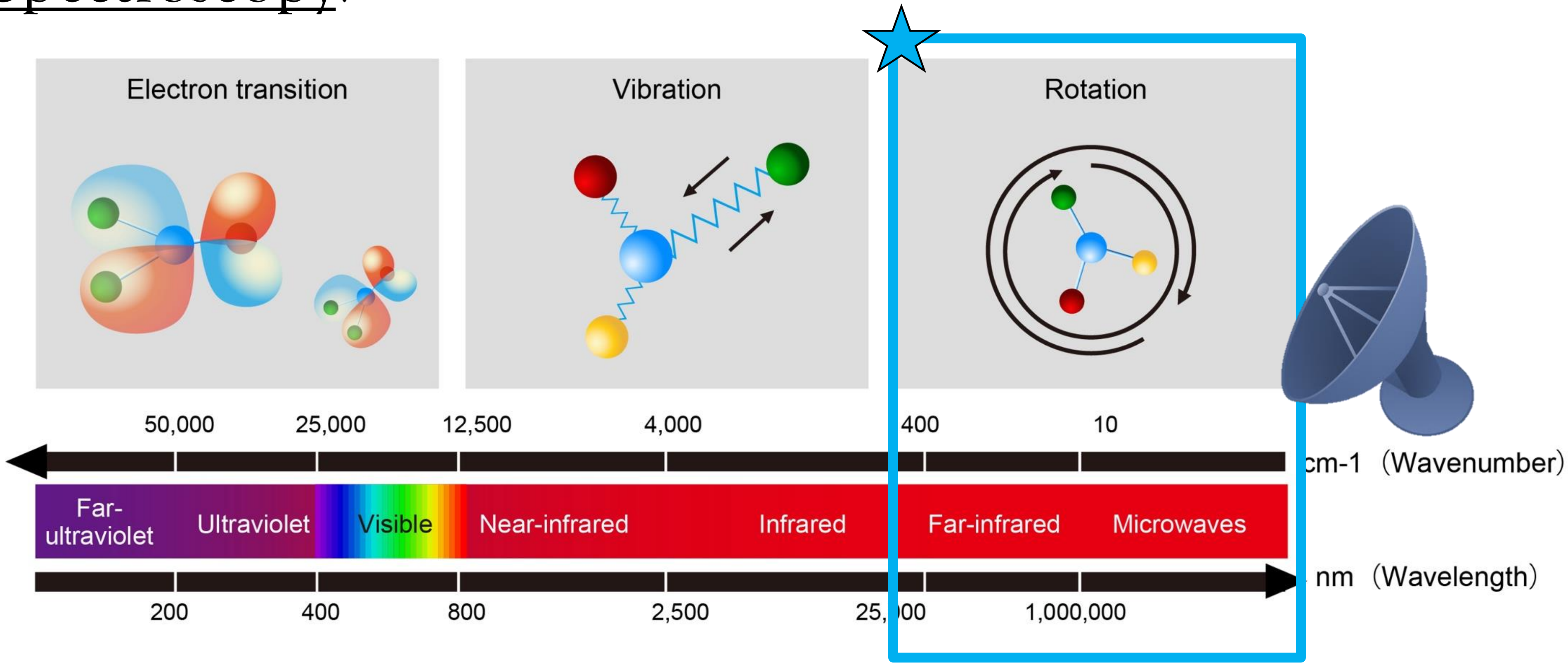


Observations



Laboratory

Submillimeter and Millimeter Radio Telescopes Identify Molecules via Rotational Spectroscopy!

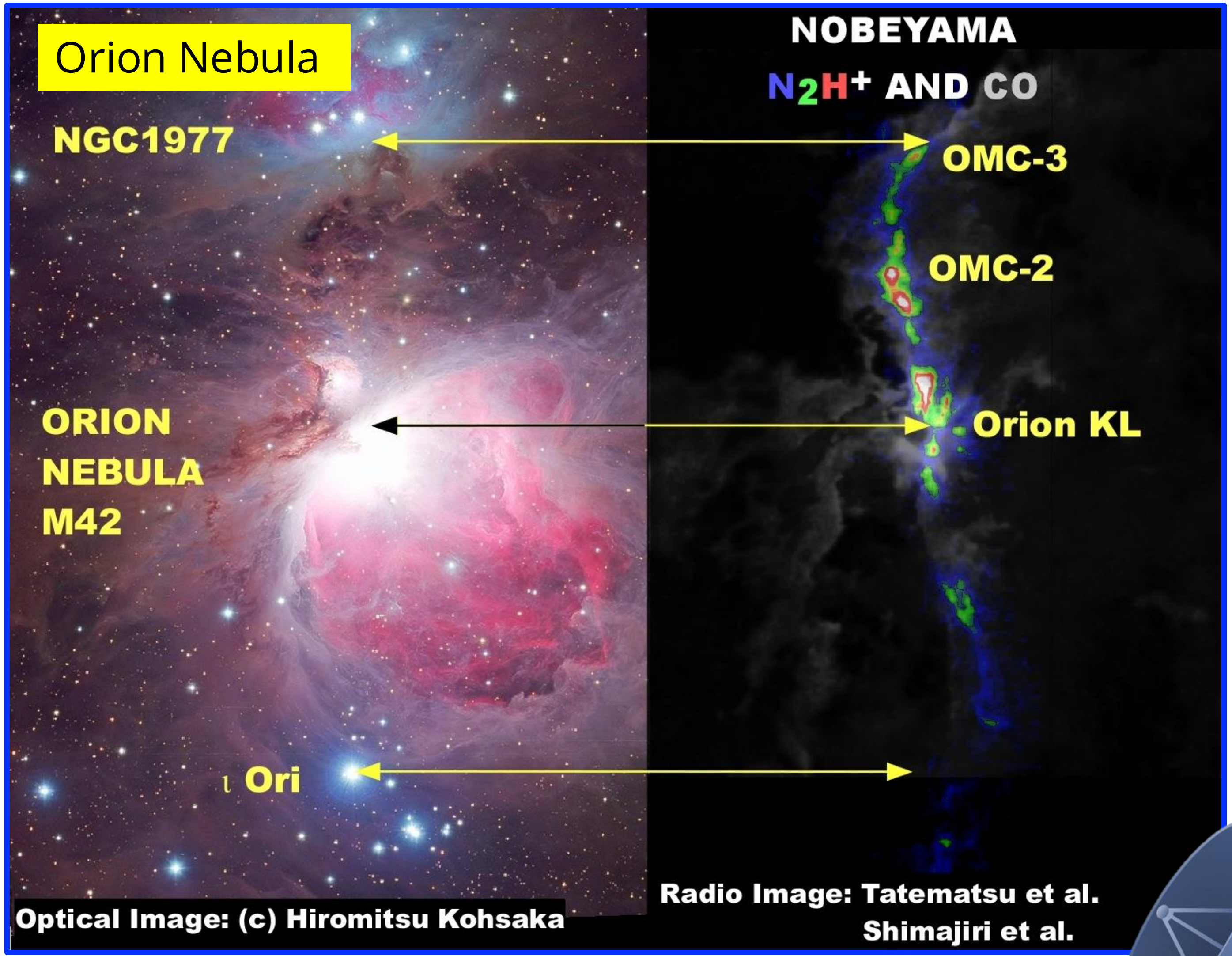


1) ELECTRONIC STATES
- electrons change levels
- energies in visible, UV

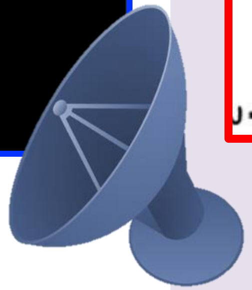
2) VIBRATIONAL STATES
- normal modes of nuclear motions
- occur in infrared region

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

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

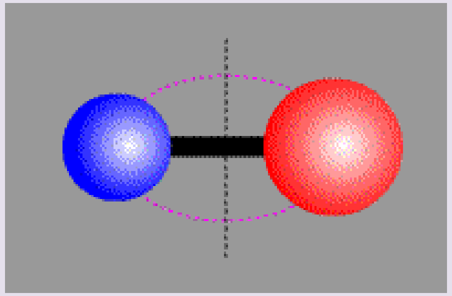


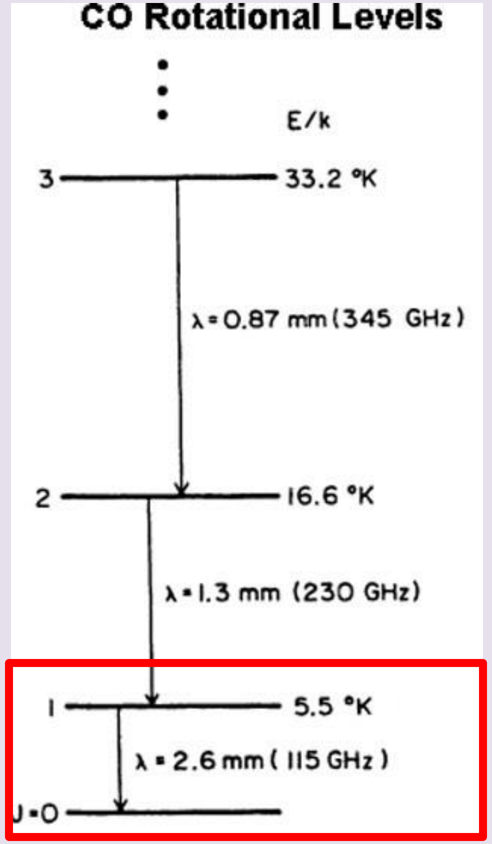
https://www.nro.nao.ac.jp/~kt/html/kt-e.html

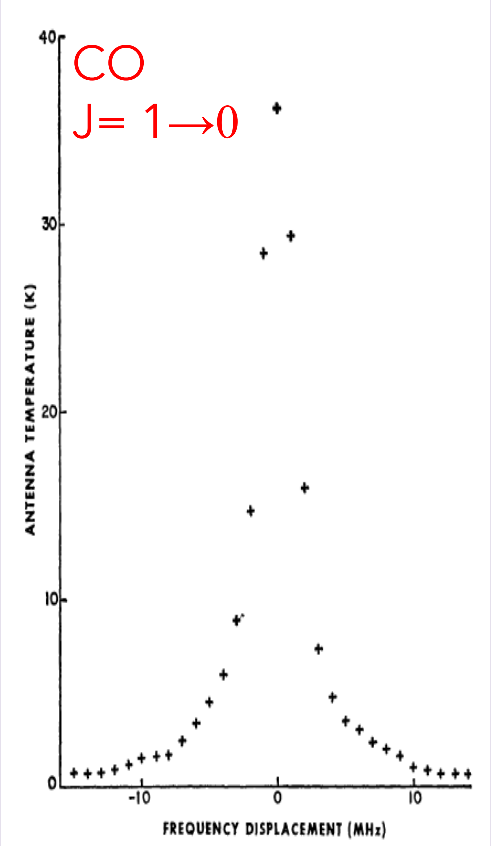


Discovery of CO

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

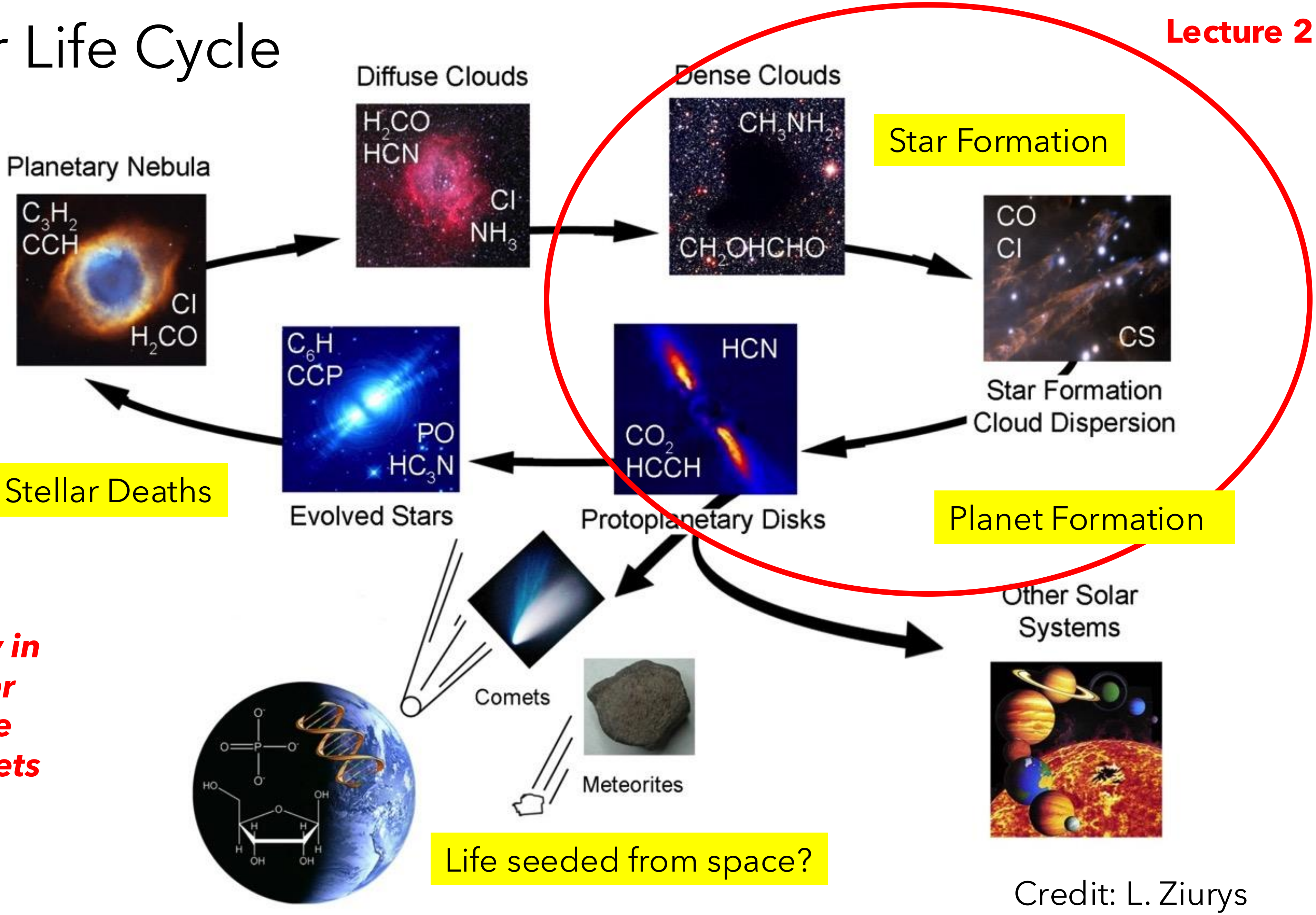






Wilson et al., 1970

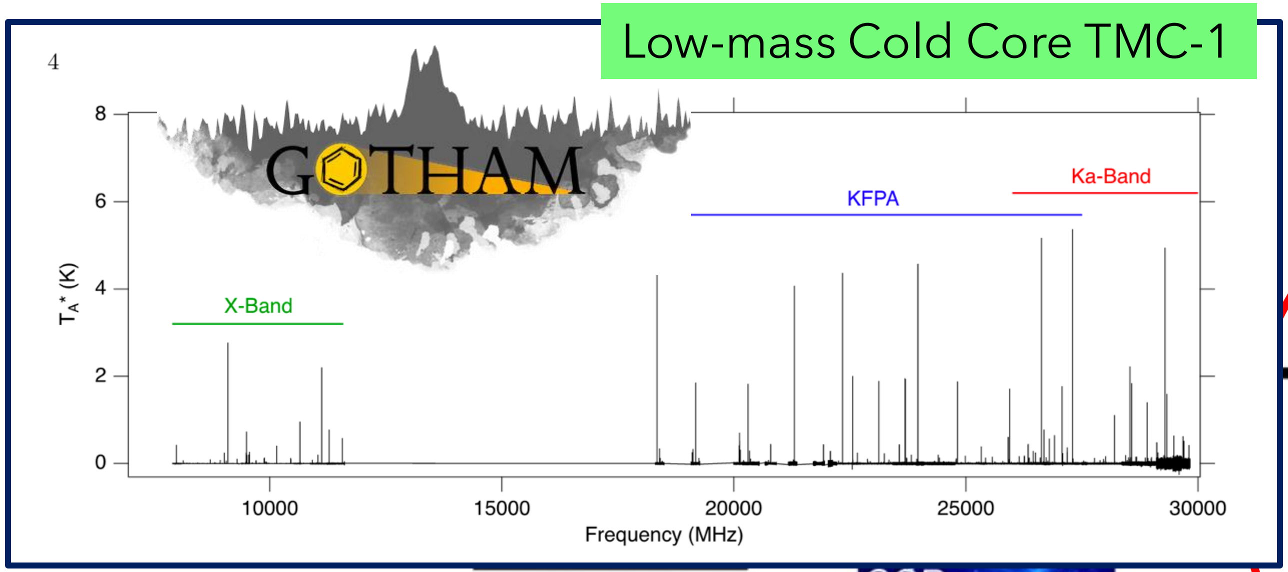
Molecular Life Cycle



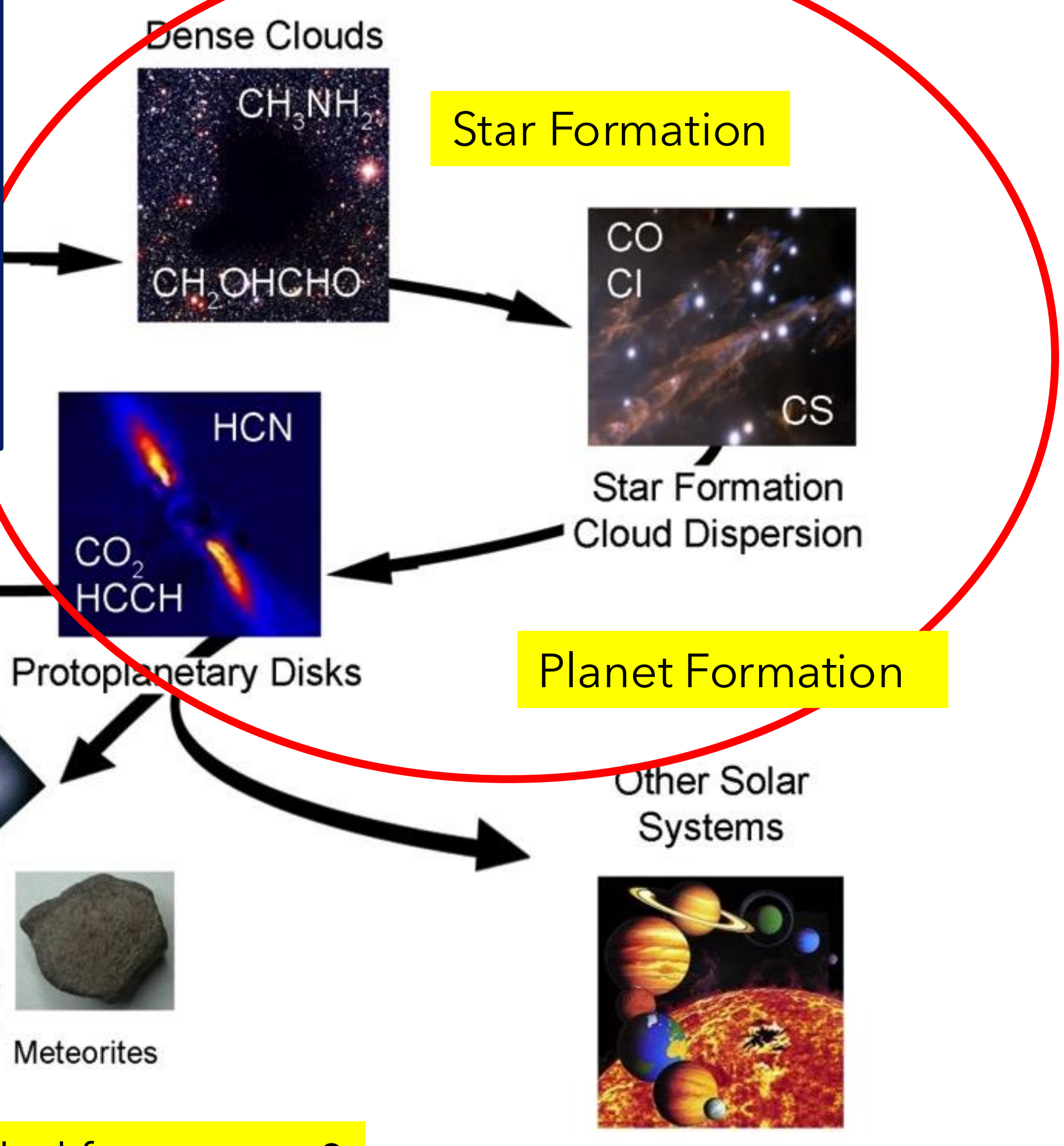
Rich chemistry in the molecular clouds where stars and planets form!

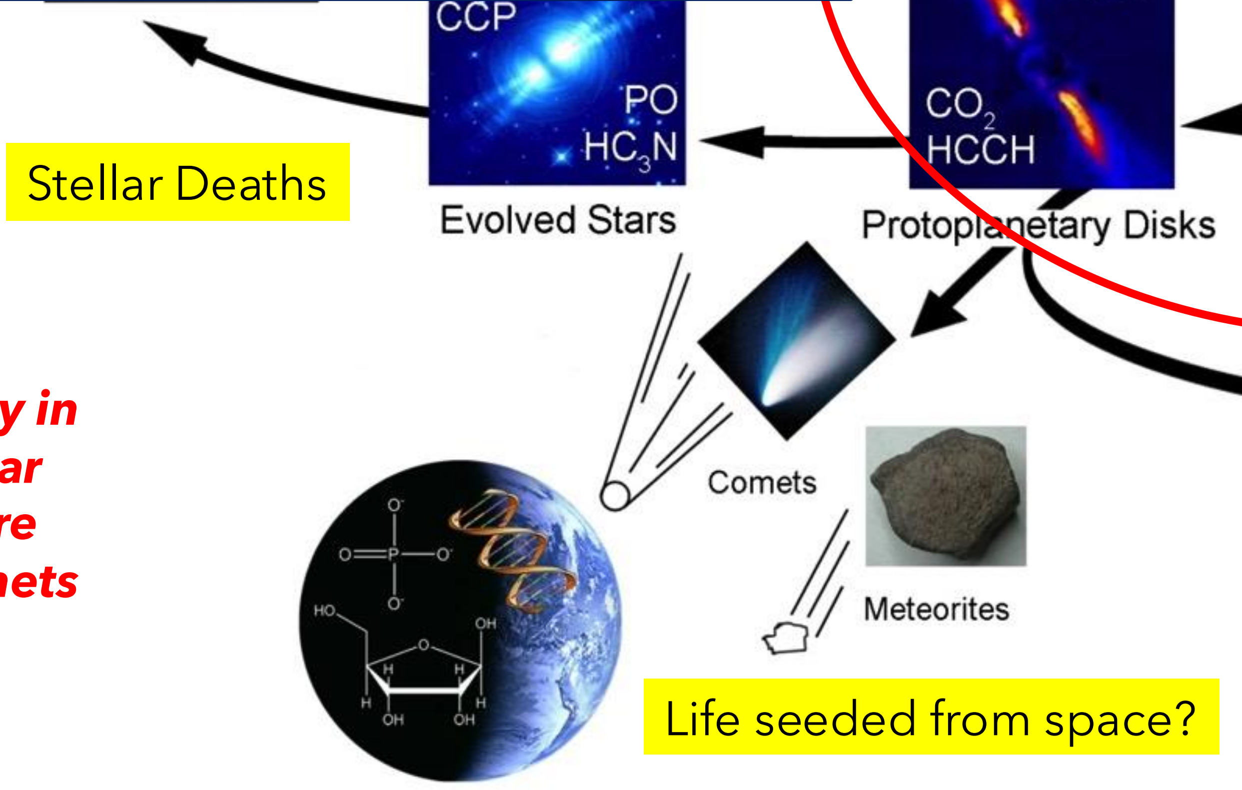
Credit: L. Ziurys

Lecture 2



McGuire et al. 2018, 2020





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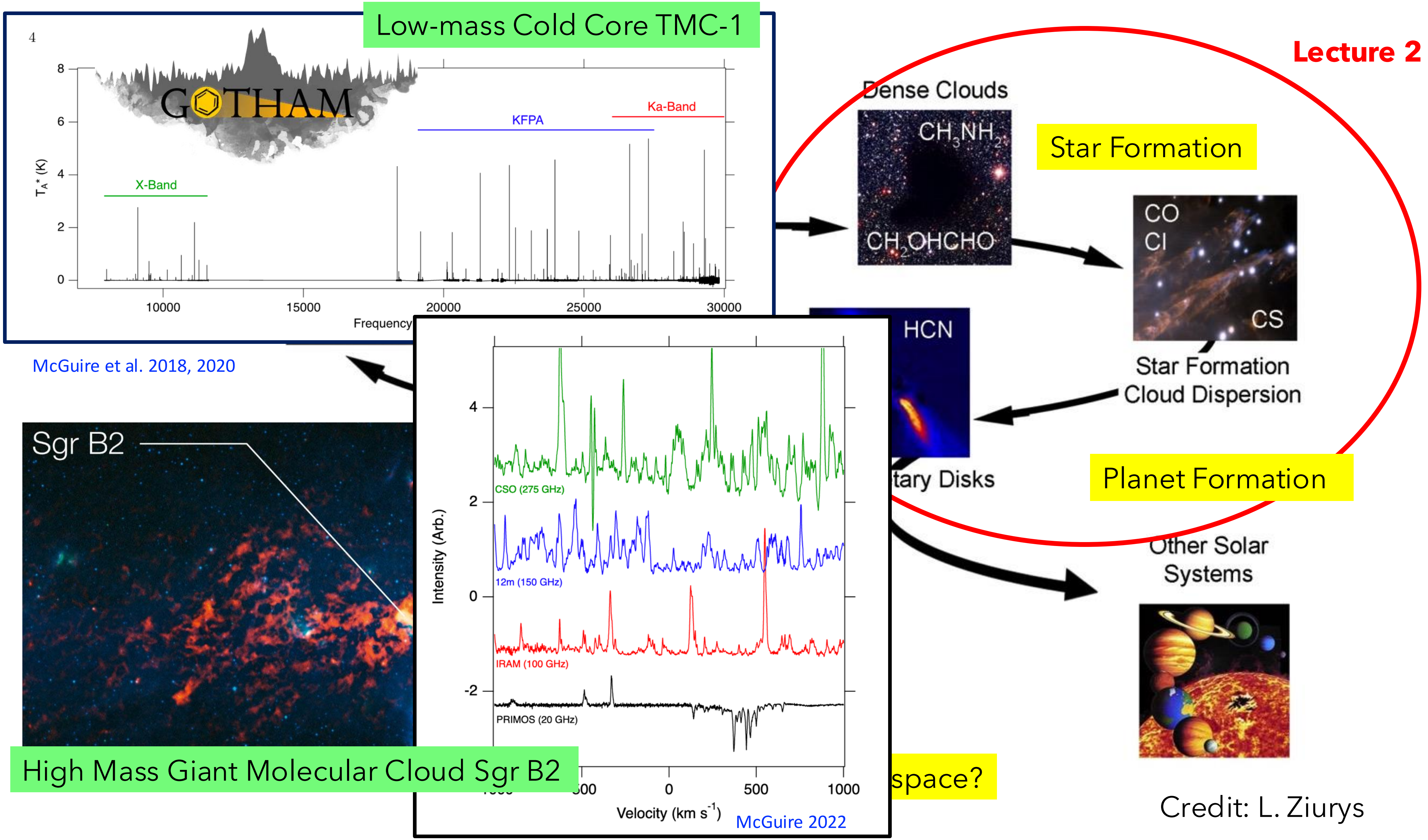
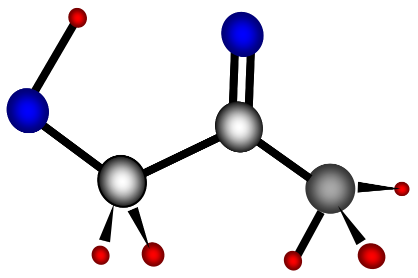

Low-mass Cold Core TMC-1
GOTHAM
X-Band
KFPA
Ka-Band
T_A* (K)
Frequency
10000
15000
20000
25000
30000
McGuire et al. 2018, 2020
Sgr B2
High Mass Giant Molecular Cloud Sgr B2
CSO (275 GHz)
12m (150 GHz)
IRAM (100 GHz)
PRIMOS (20 GHz)
Intensity (Arb.)
Velocity (km s^-1)
McGuire 2022
Lecture 2
Dense Clouds
CH3NH2
CH2OHCHO
Star Formation
CO
CI
CS
Star Formation
Cloud Dispersion
HCN
tary Disks
Planet Formation
Other Solar
Systems
space?
Credit: L. Ziurys

Molecule Formation (*in Molecular Clouds*)



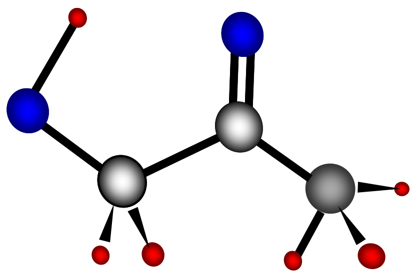
- Typical Conditions in molecular gas:
  - low Densities (10 -10^7 cm^{-3}; < 10^{-12} torr)
    - compared to Earth atmosphere (~10^{19} cm^{-3})
  - low Temperatures: T ~ 10 – 100 K → **Severely restricts allowed chemical processes!**

  - *only two body collisions*

  - reactions must be **exothermic!**

Credit: L. Ziurys

Molecule Formation (*in Molecular Clouds*)



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  - *only two body collisions*
  - reactions must be **exothermic!**

Basic Chemical Scheme:

1) H_2 formed on grain surfaces: H + H + grain → H_2 + grain

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

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

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

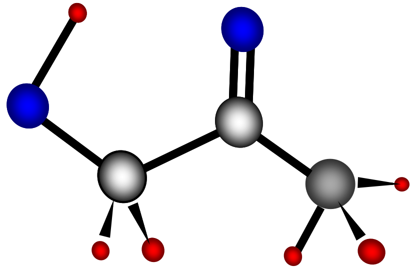
$H_3^+ + CO \rightarrow \mathbf{HCO^+} + H$

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

etc.

Credit: L. Ziurys

Molecule Formation (*in Molecular Clouds*)



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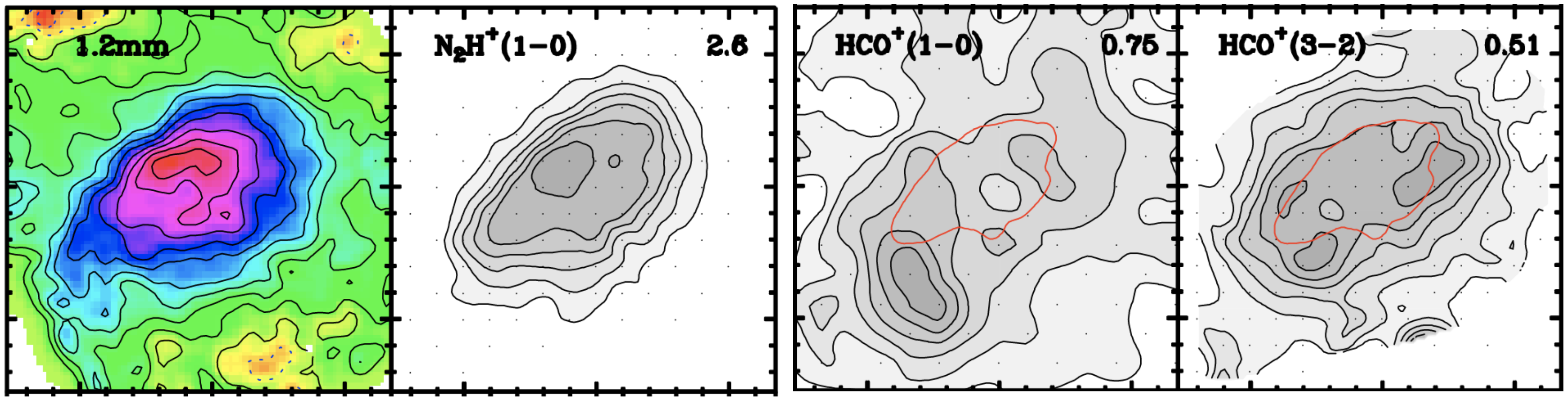
$H_3^+ + N_2 \rightarrow \mathbf{N_2H^+} + H$

etc.

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



Tafalla 2006

Molecule Formation (*in Molecular Clouds*)

Large chemical reaction networks!

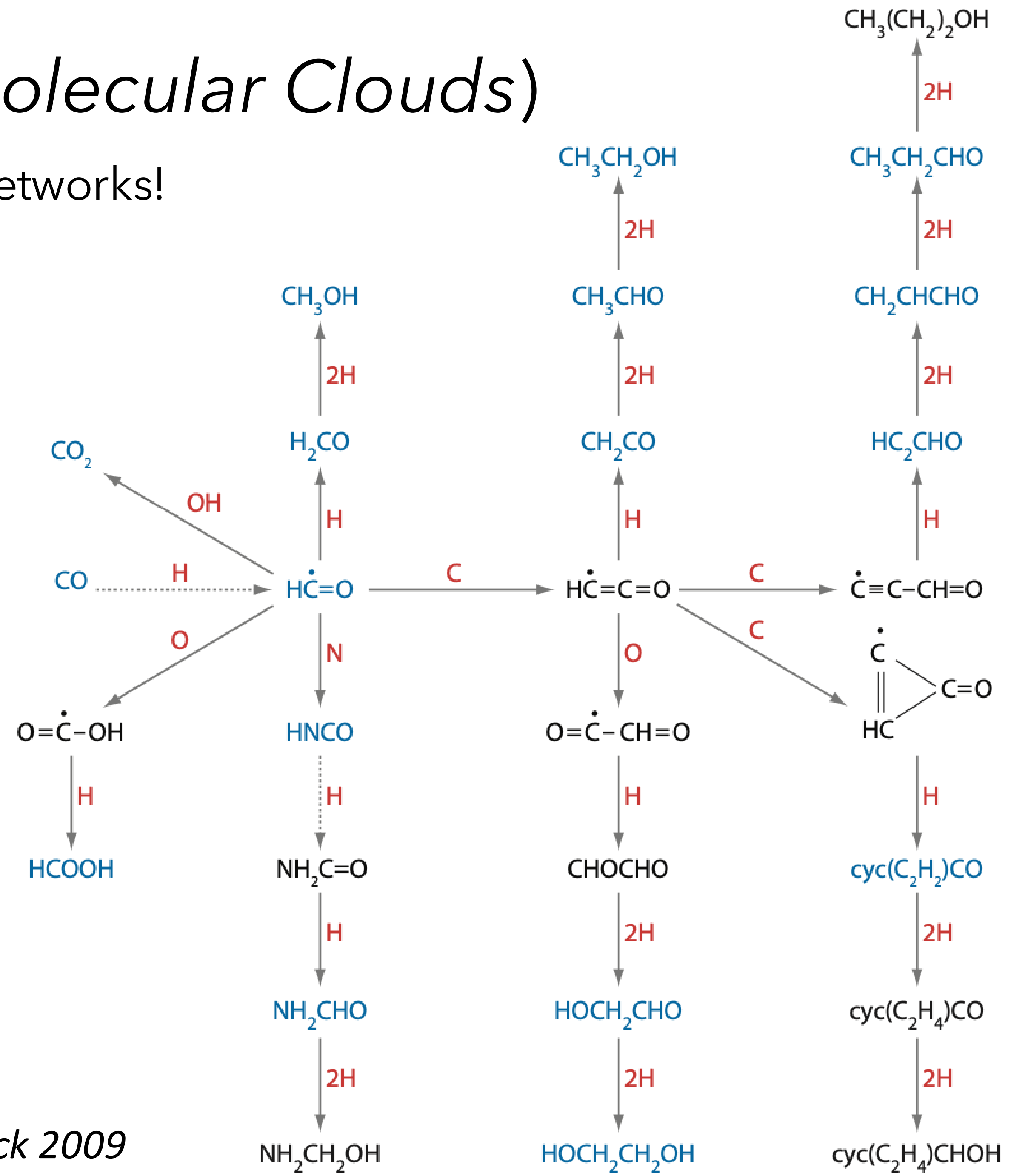
- Organic chemistry on interstellar grains resulting from cold H addition reactions to CO

- Broken arrows indicate reactions with activation energy barriers

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

- Molecules in blue detected in star-forming molecular clouds!

Herbst & van Dishoeck 2009



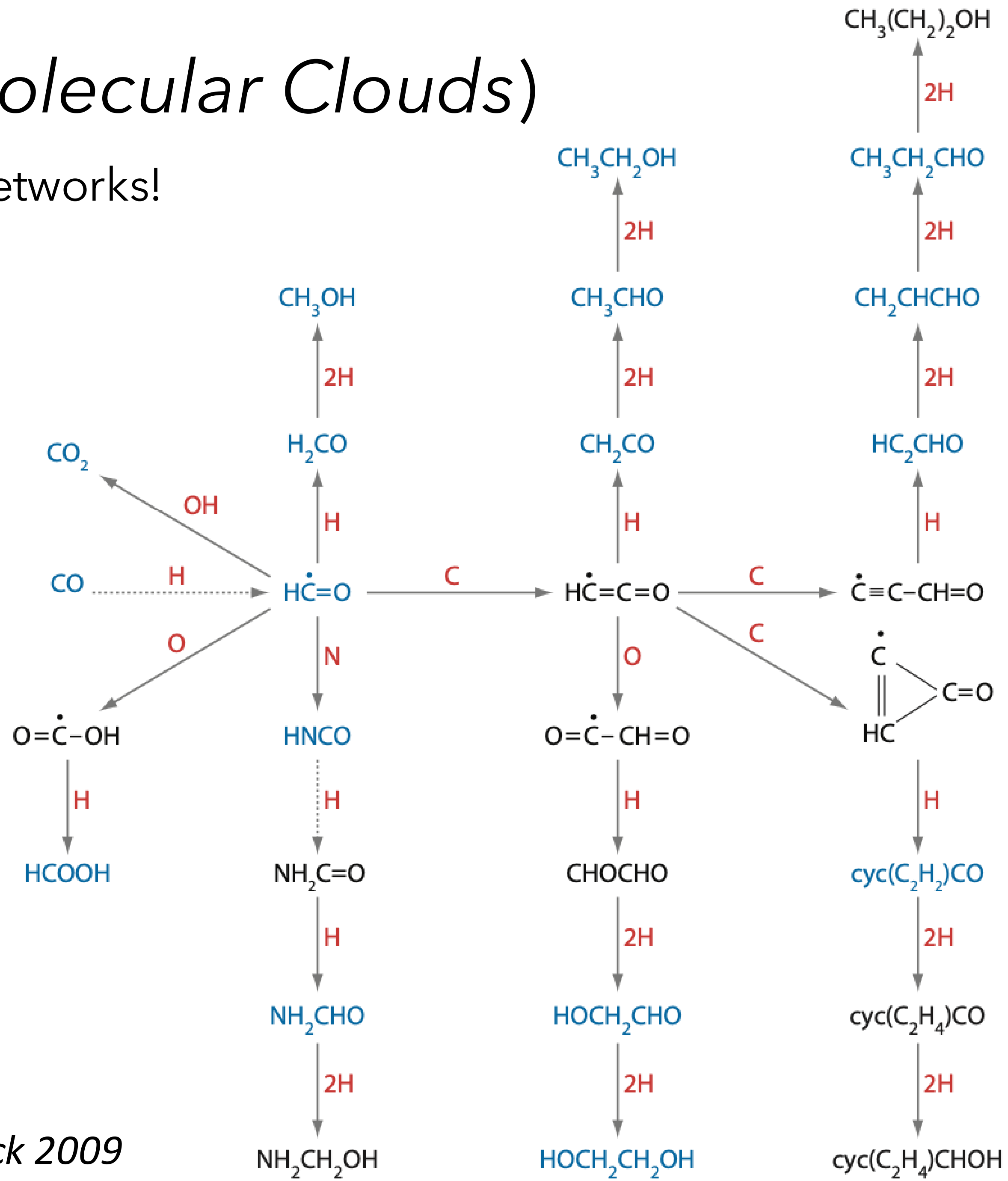
Molecule Formation (*in Molecular Clouds*)

Large chemical reaction networks!

Complex Organic Molecules

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

- Molecules in blue detected in
star-forming molecular clouds!

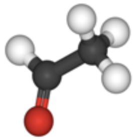


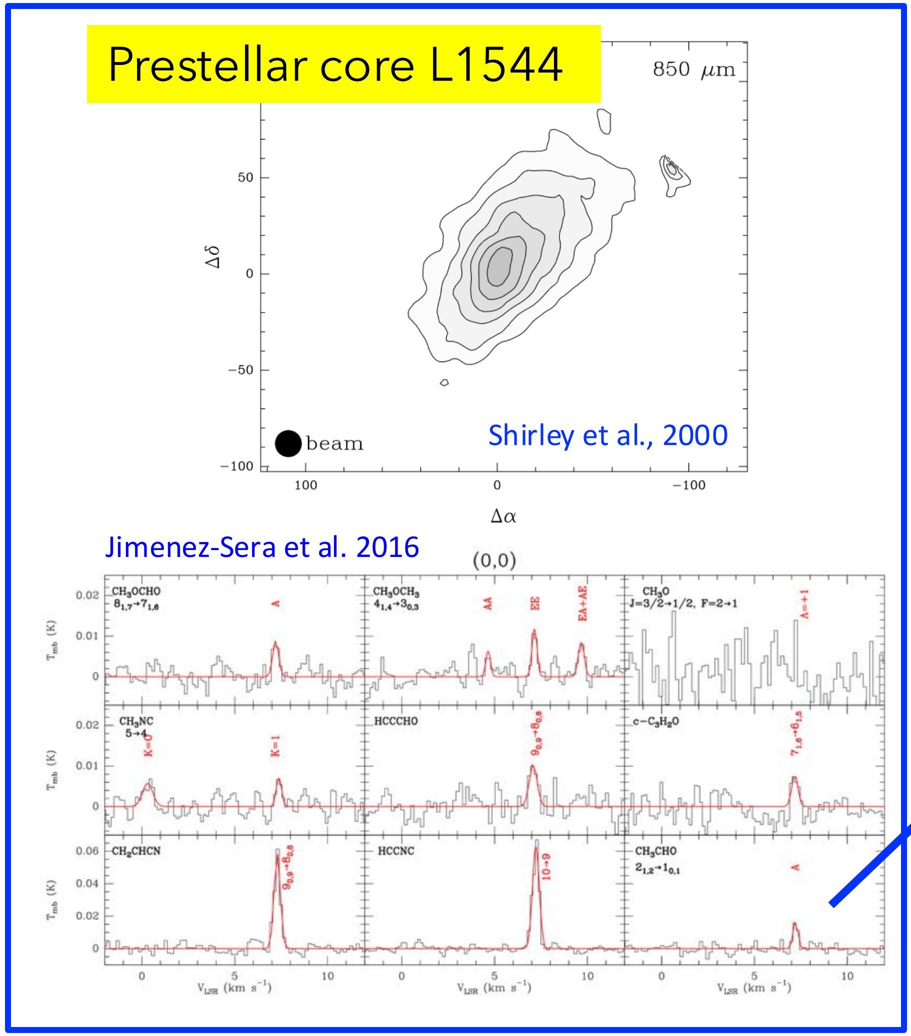
Herbst & van Dishoeck 2009

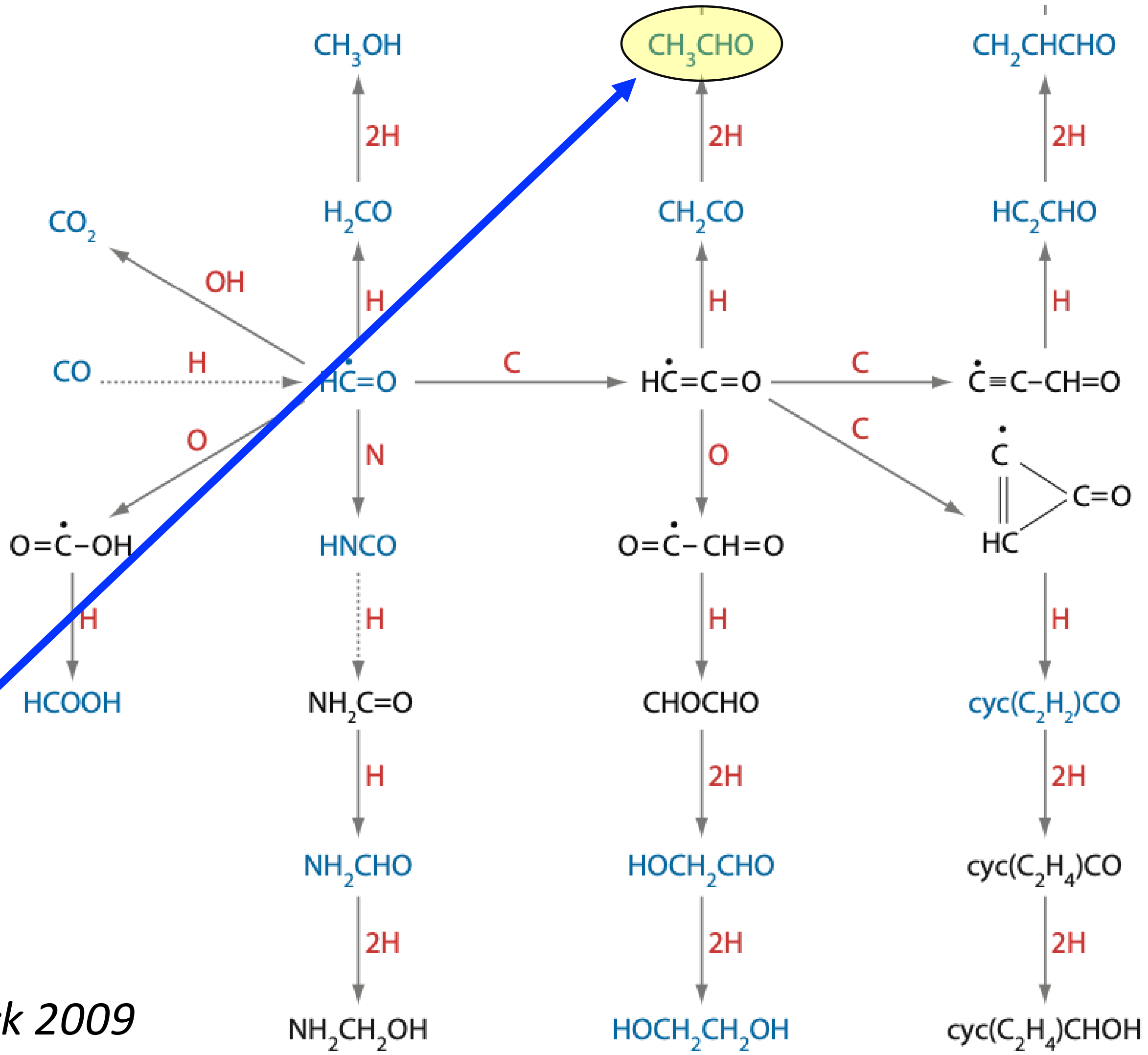
Molecule Formation (*in Molecular Clouds*)

Large chemical reaction networks!

Acetaldehyde
CH_3CHO



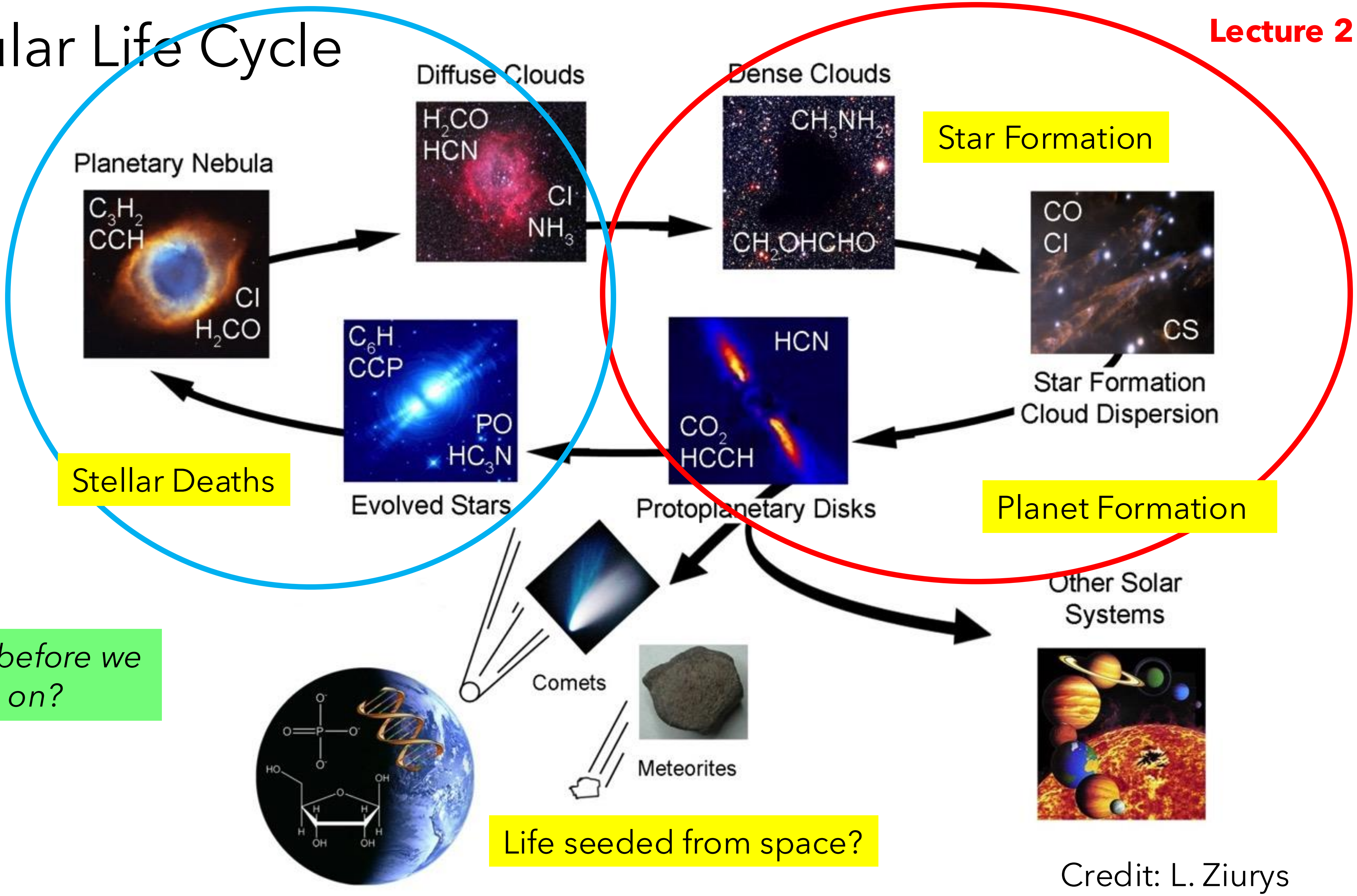




Herbst & van Dishoeck 2009

Molecular Life Cycle

Lecture 3



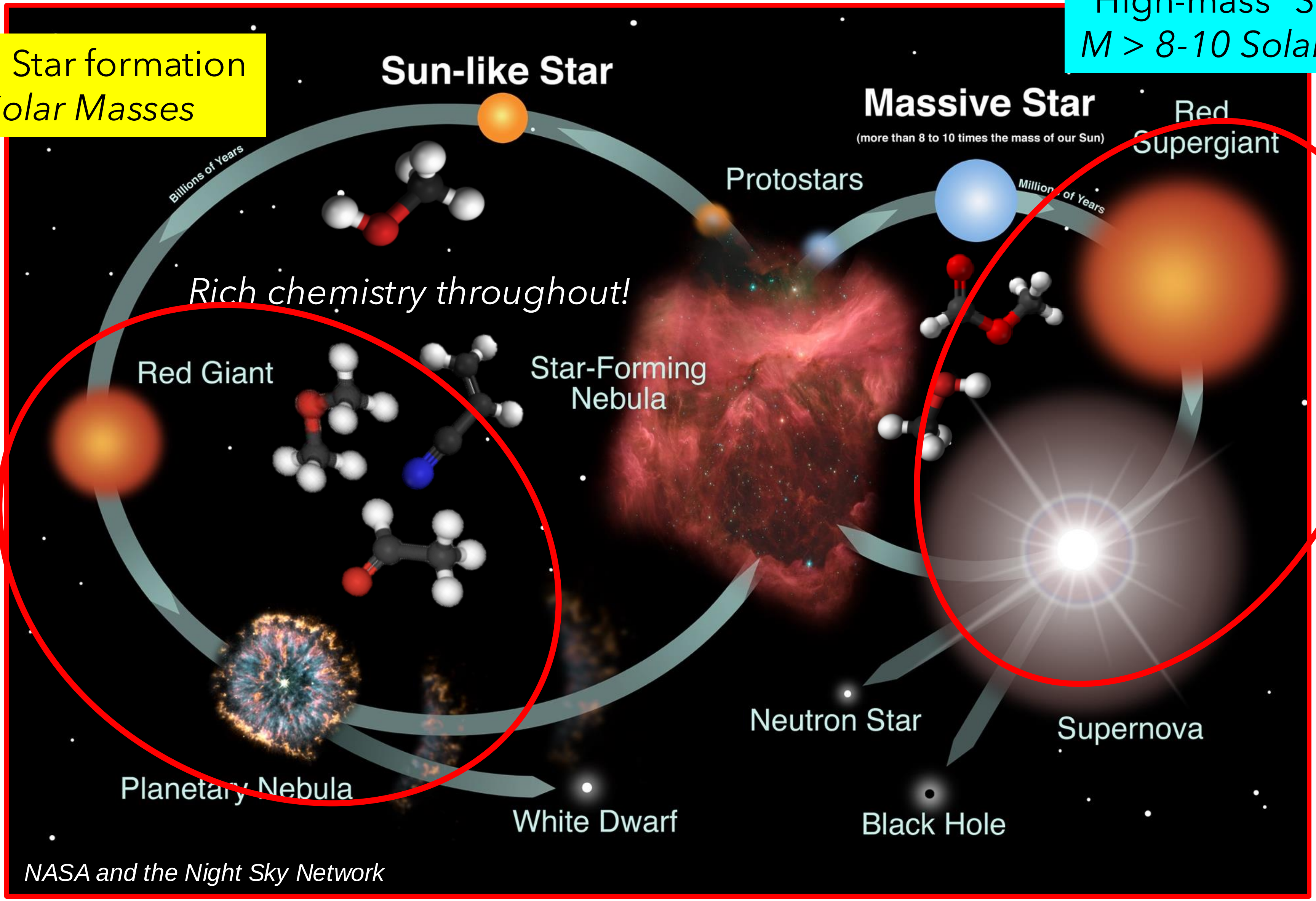
Questions before we move on?

Credit: L. Ziurys

Evolved Stars – the end stage of star formation

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

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



Evolved Stars – the end stage of star formation

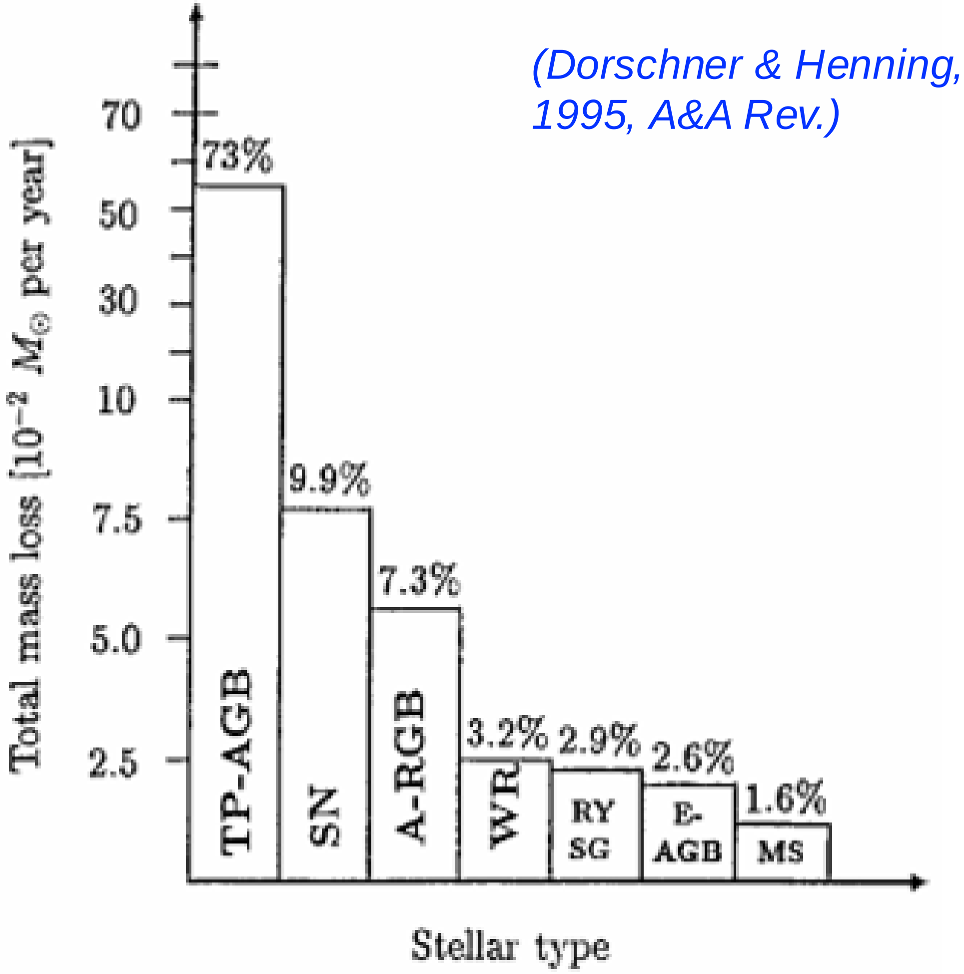
- **IMPORTANT** in astrochemistry because material is cycled back to the ISM!
- Mass loss from evolved stars

  ⇒ ***Supplies 85% of material in ISM***
- Material cycled in

  circumstellar shells 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

Evolved Stars – the end stage of star formation!

+ Dust Formation!

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

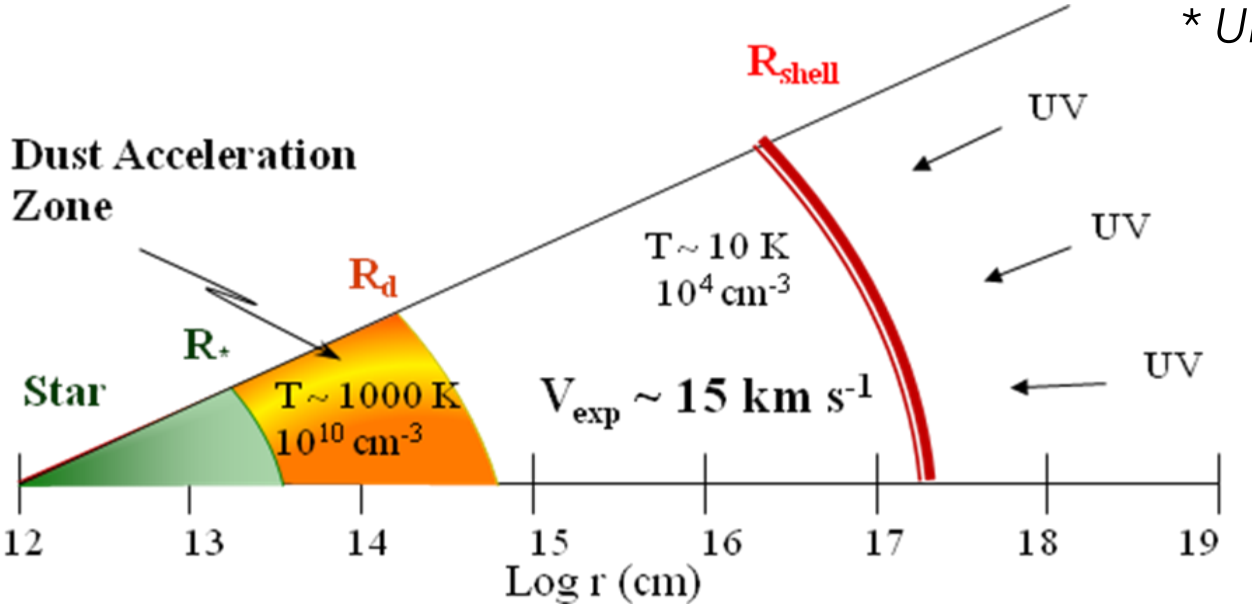
  ⇒ ***Supplies 85% of material in ISM***

- Material cycled in

  circumstellar shells ⇒

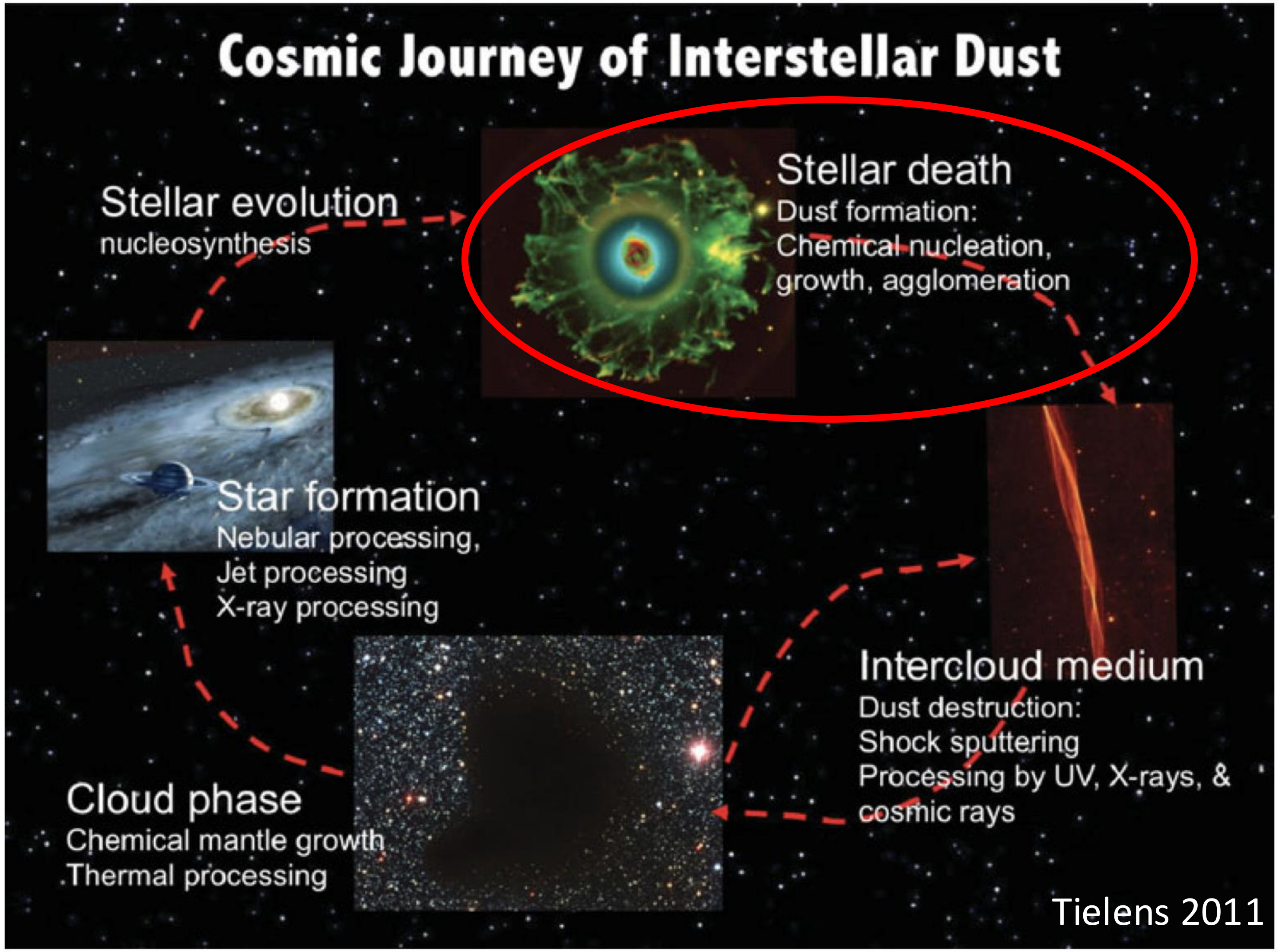
- Shell is COOL; ***Dust grains form***
- Molecules also form there then transported outward

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

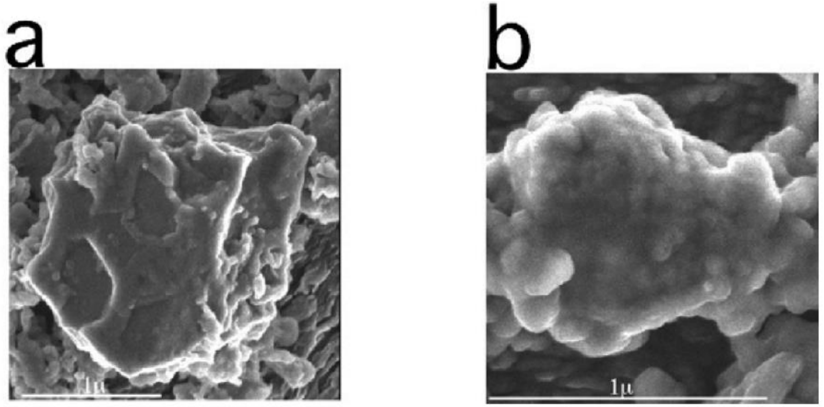


Credit: L. Ziurys

Evolved Stars – the end stage of star formation!



+ Dust Formation!



Pristine presolar SiC grains from the Murchison meteorite (Bernatowicz et al. 2003)

Evolved Stars – the end stage of star formation!

+ Dust Formation!

Table 1. Inventory of dust in space

Oxide dust	Carbonaceous dust	Other
amorphous silicates (I,C,S)	PAHs (I,C,S)	silicon nitride Si_3N_4 (S)
crystalline forsterite, Mg_2SiO_4 (C,S)	Fullerene, C_{60} (C,I)	magnesium sulfide, MgS (C)
crystalline enstatite ($MgSiO_3$) (C,S)	Amorphous Carbon (C,I,S)	Carbonate (C,I)
Silica, SiO_2 (C)	Graphite (C,I,S)	Ice (C,I)
aluminum oxide, Al_2O_3 (C,S)	Diamond (C,S)	
spinel, $MgAl_2O_4$ (C,S)	silicon carbide, SiC (C,I ?,S)	
titanium oxide, TiO_2 (S)	other carbides (C ?, S)	
hibonite, $CaAl_{12}O_{19}$ (S)		
Magnesium iron oxide, $Mg_{0.1}Fe_{0.9}O$ (C)		

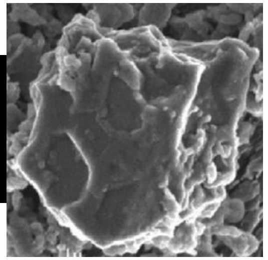
Legend: I: Spectroscopic evidence for presence in interstellar dust. C: Spectroscopic evidence for presence in circumstellar dust. S: Present as stardust in meteoritic or cometary material (For a discussion, see Tielens 2001, Zinner 2003).

Tielens 2011

I

C

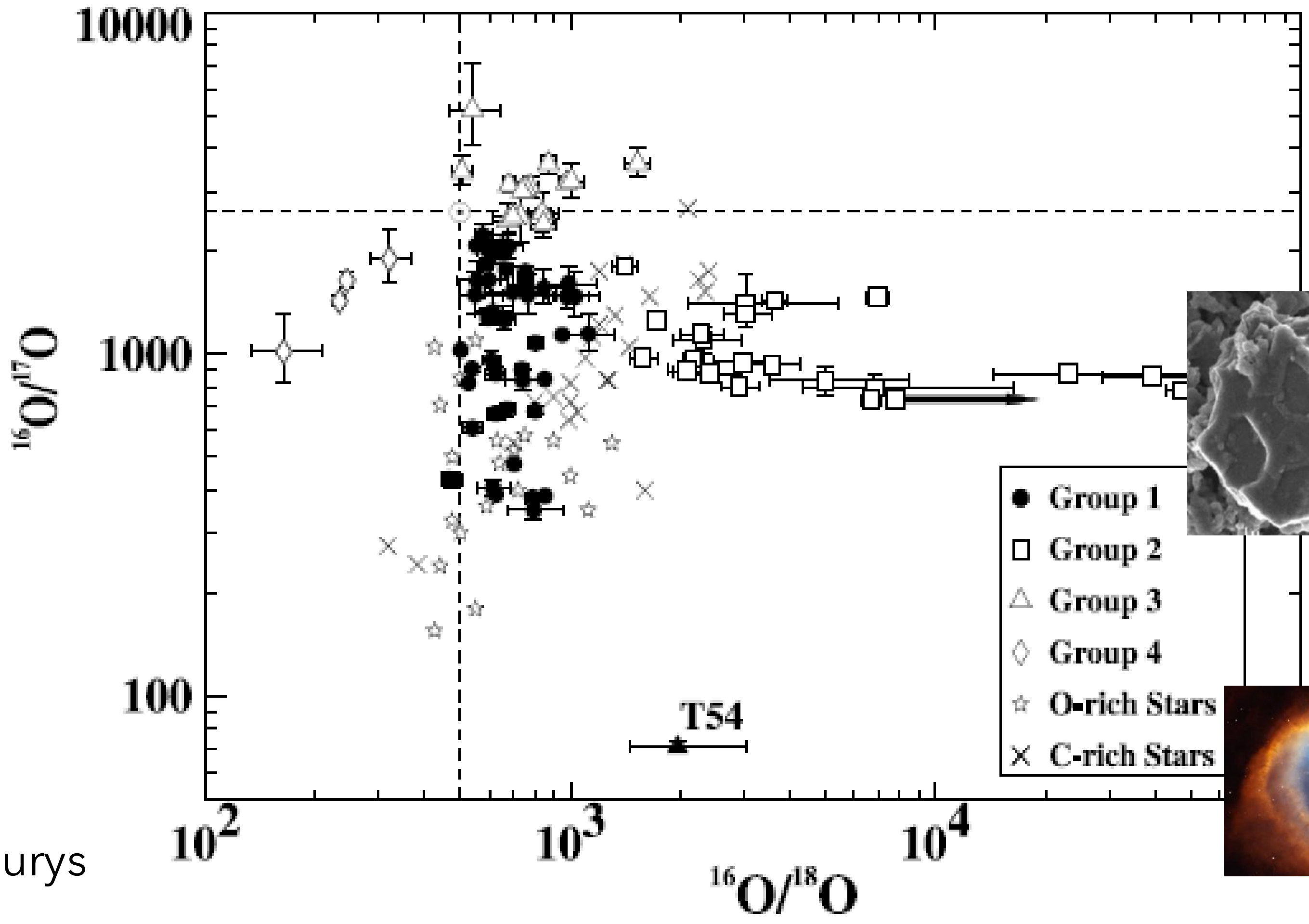
S

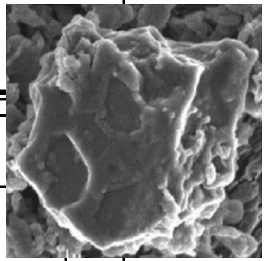


Dust grains in meteorites directly linked to the dust grains created during stellar deaths!

Evolved Stars – the end stage of star formation!

+ Dust Formation!

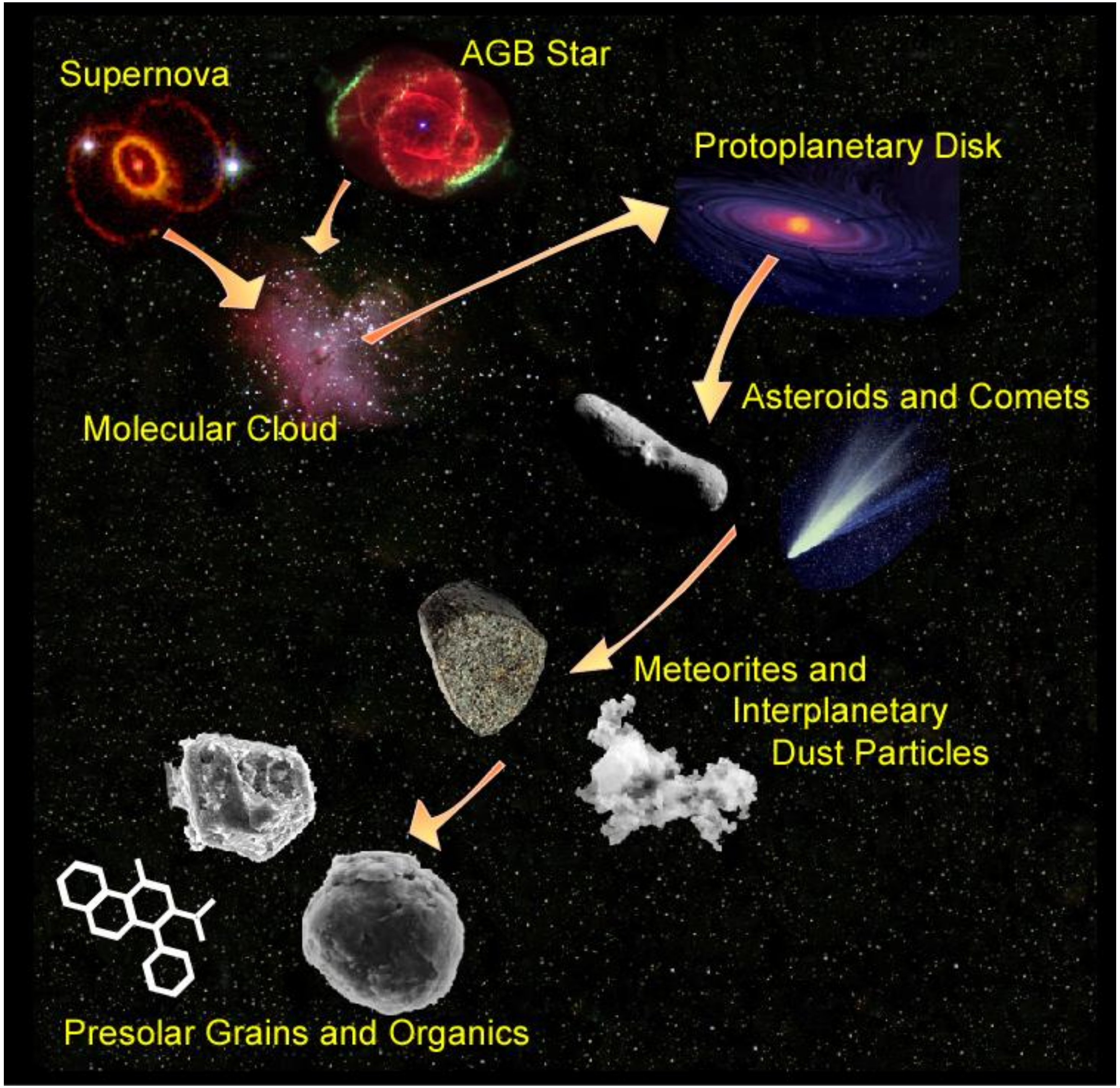




Credit: L. Ziurys

Dust grains in meteorites directly linked to the dust grains created during stellar deaths!

Evolved Stars provide the material that enrich the later stages of star and planet formation!

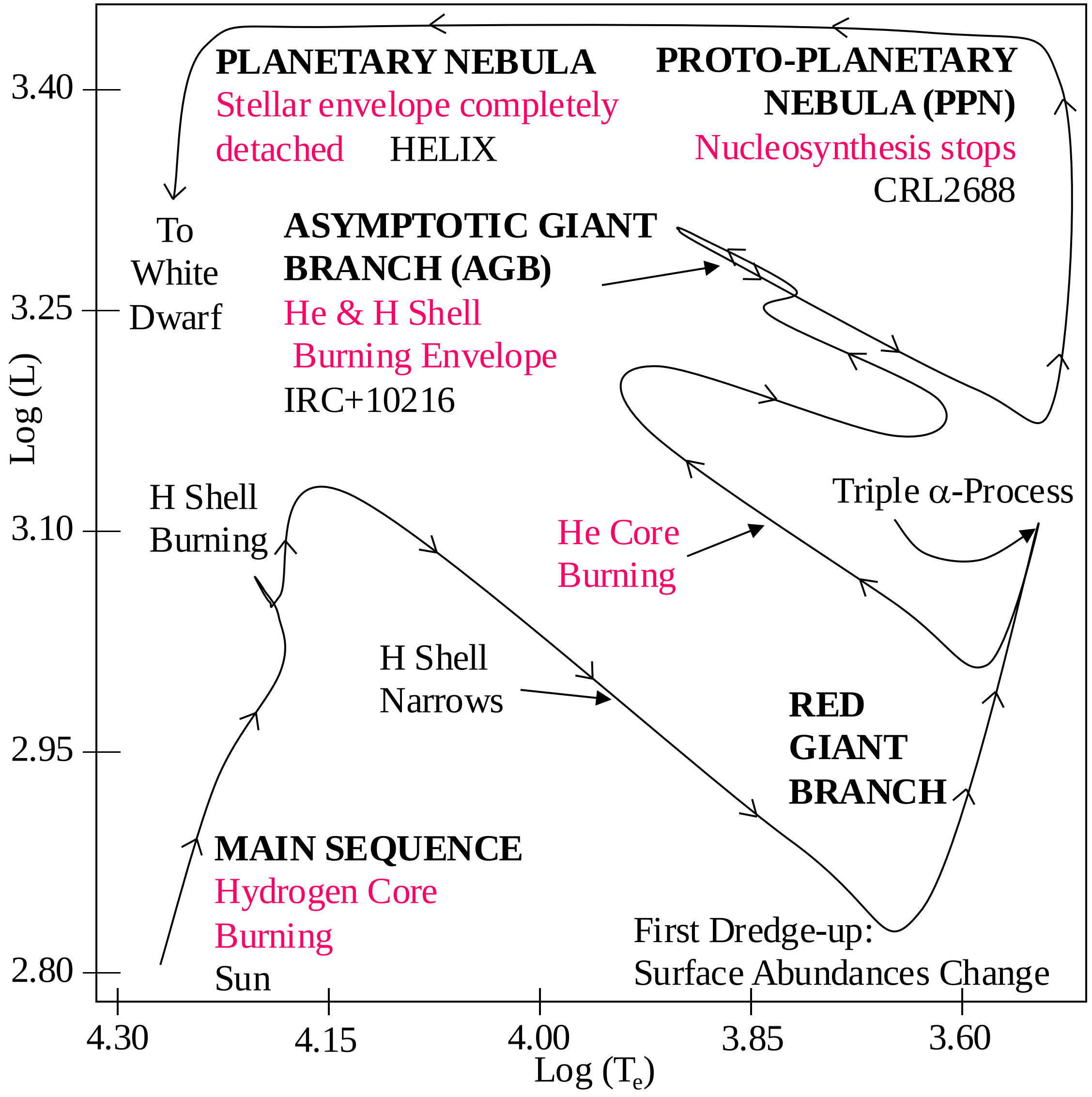


Chemistry in Evolved Stars – lifecycle and mass loss is key!

- **Mass loss** starts due to convection, shock waves
- Radiation pressure on grains
- Usually associated with **helium-burning phases** in evolved (old) stars
- Stars with *highest mass loss* (M ~ 10^{-6} - 10^{-4} $M_{\odot}$/yr)

  ⇒ *Asymptotic Giant Branch (AGB) Stars (low mass)*

  ⇒ *Red Supergiants (RSG) and Yellow Hypergiants (high mass; rare!)*



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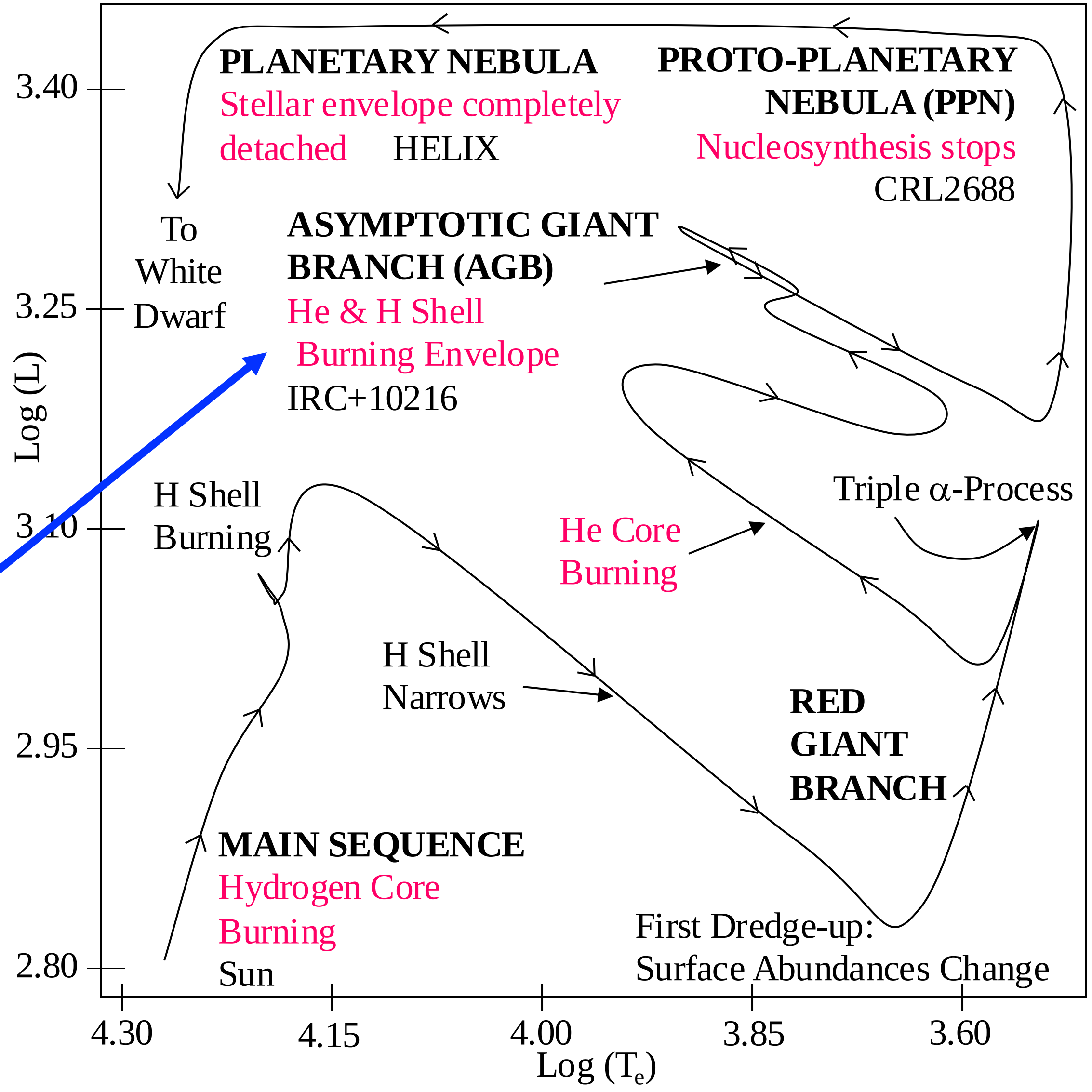


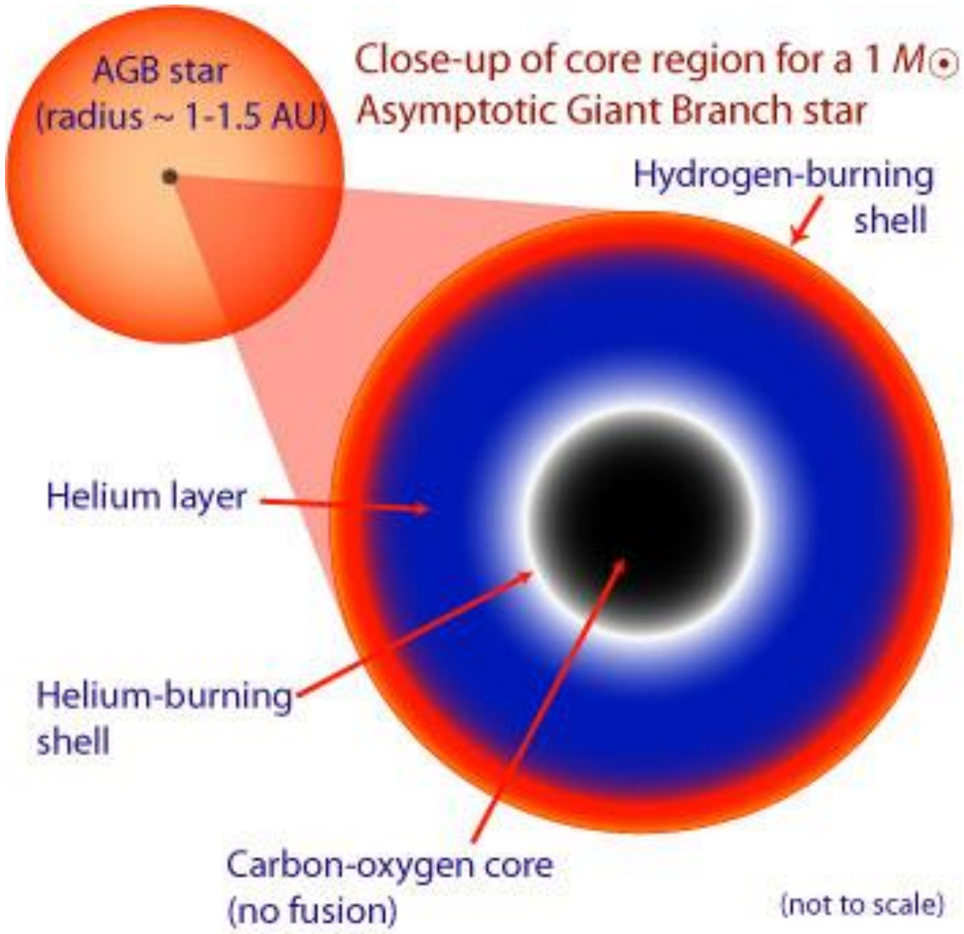
Credit: L. Ziurys

Asymptotic Giant Branch (AGB) Stars

AGB (1 - 8 $M_{\odot}$)

- H, He-burning shells around a carbon core
- He-shell creates instabilities
- Convective mixing or dredge-up
- can undergo "third dredge-up"

$\Rightarrow$ mixes carbon form CNO cycle to surface such that C > O



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$\Rightarrow$ mixes carbon form CNO cycle

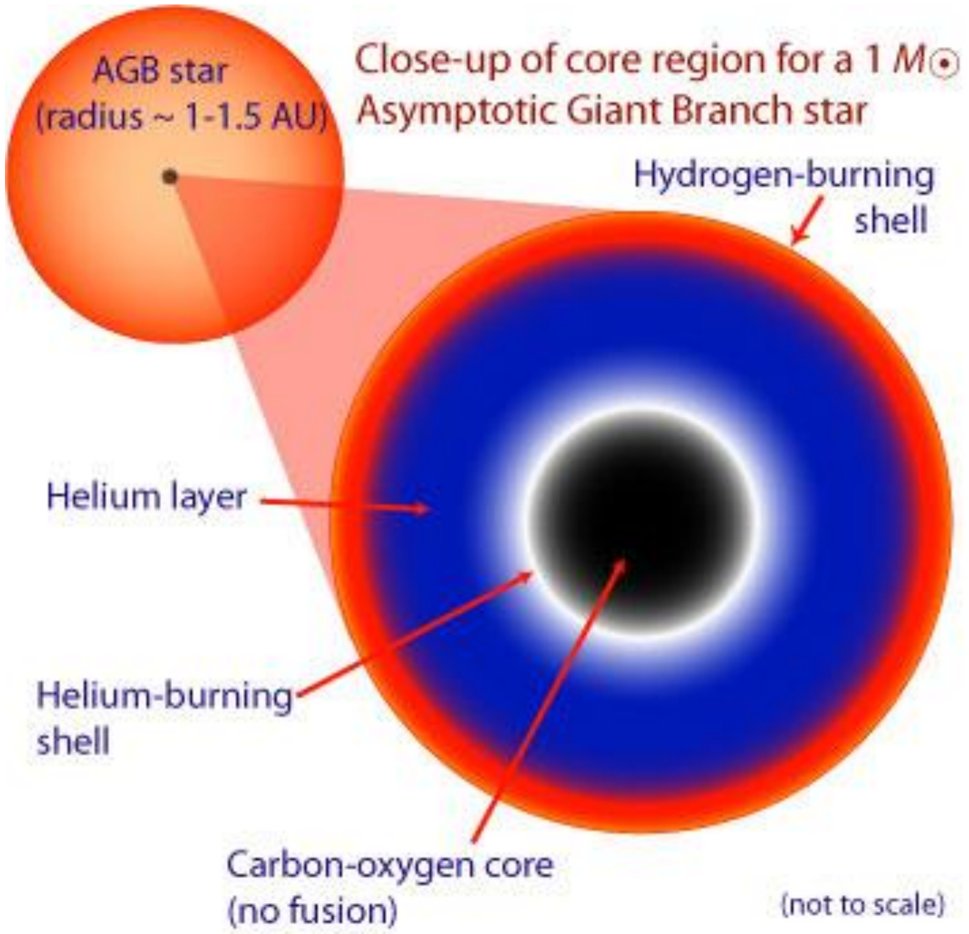
to surface such that C > O

- **Nucleosynthesis:** makes star and envelope:

O > C or C >O

Carbon-rich **or** ***oxygen-rich***

- Stars start with **O ~ 0.5 C** (ISM ratio)
- **Third-dredge** up on the AGB: $^4He \rightarrow {}^{12}C$
- Creates a carbon star with **C ~ 0.5 O**



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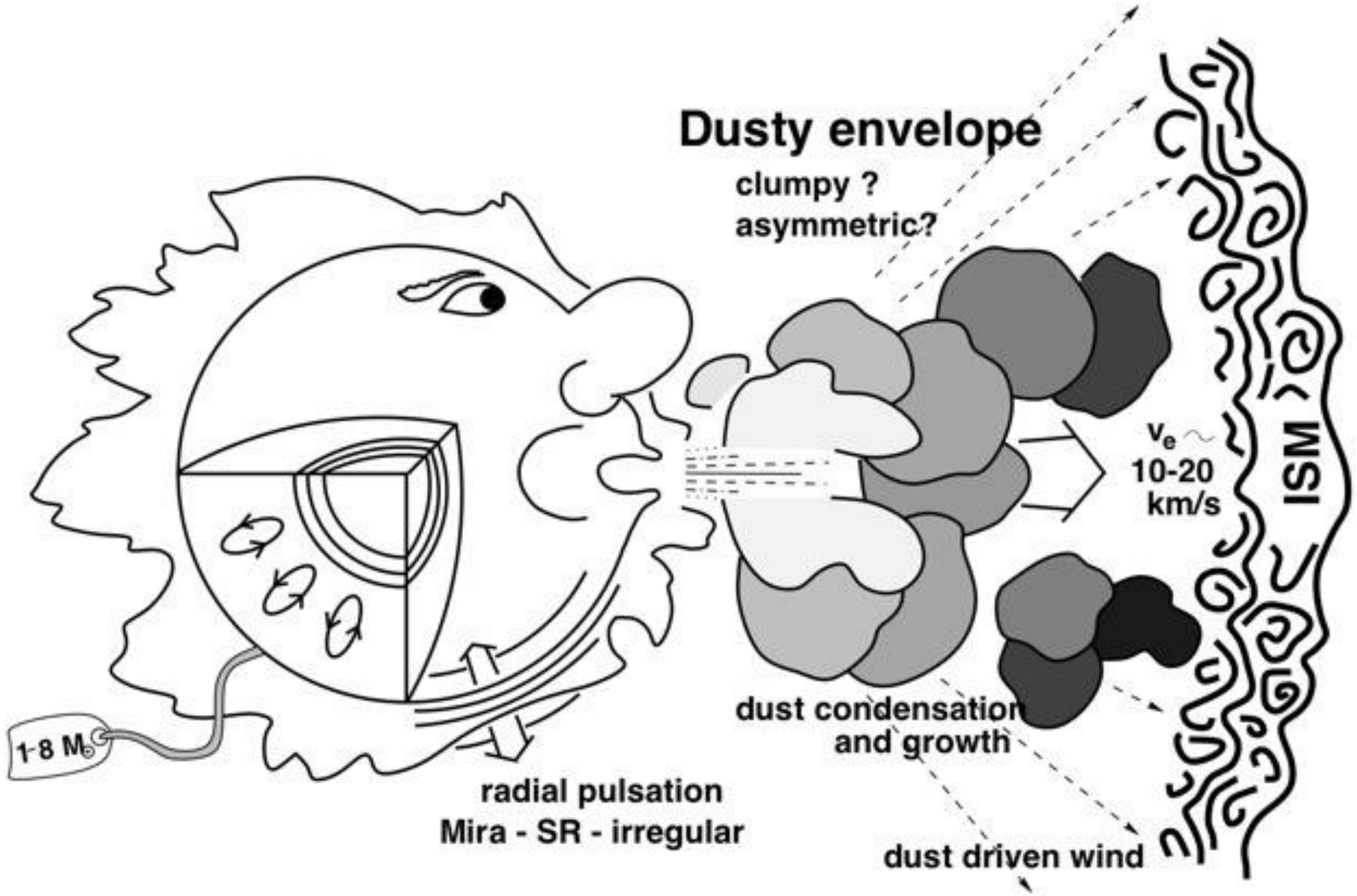
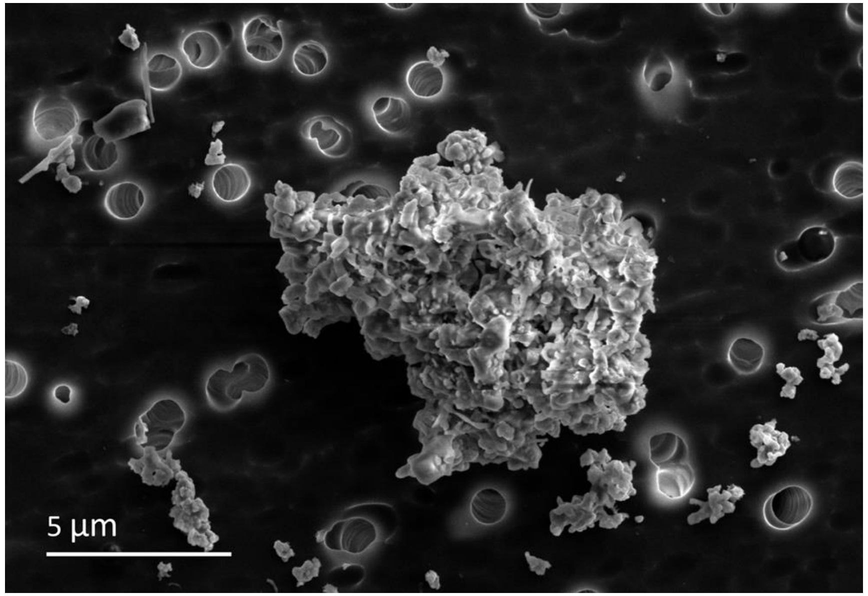
Asymptotic Giant Branch (AGB) Stars



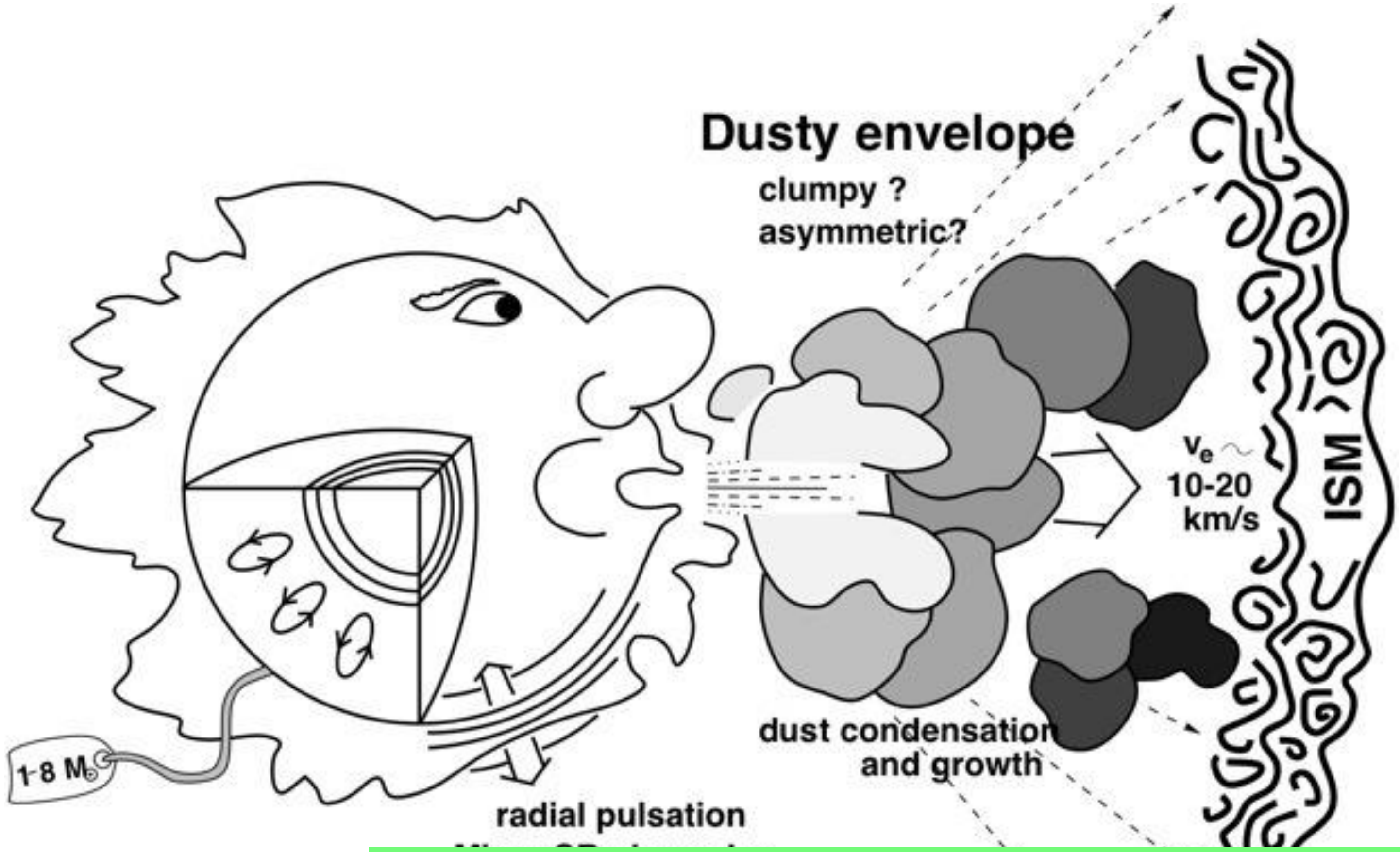
Olofsson 2011

Dust Grains born from material ejected in stars!



Credit: Hope Ishii, University of Hawai'i.

Asymptotic Giant Branch (AGB) Stars



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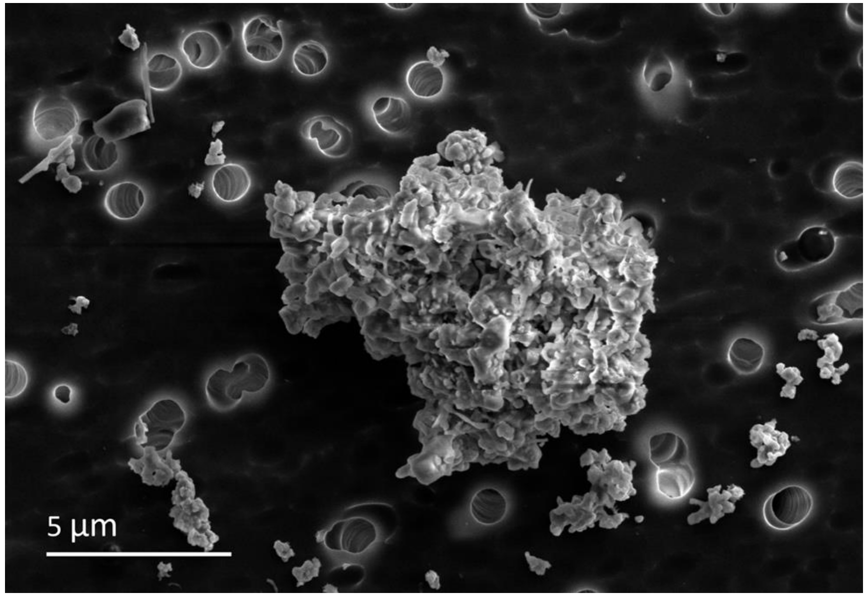


Credit: Hope Ishii, University of Hawai'i.

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

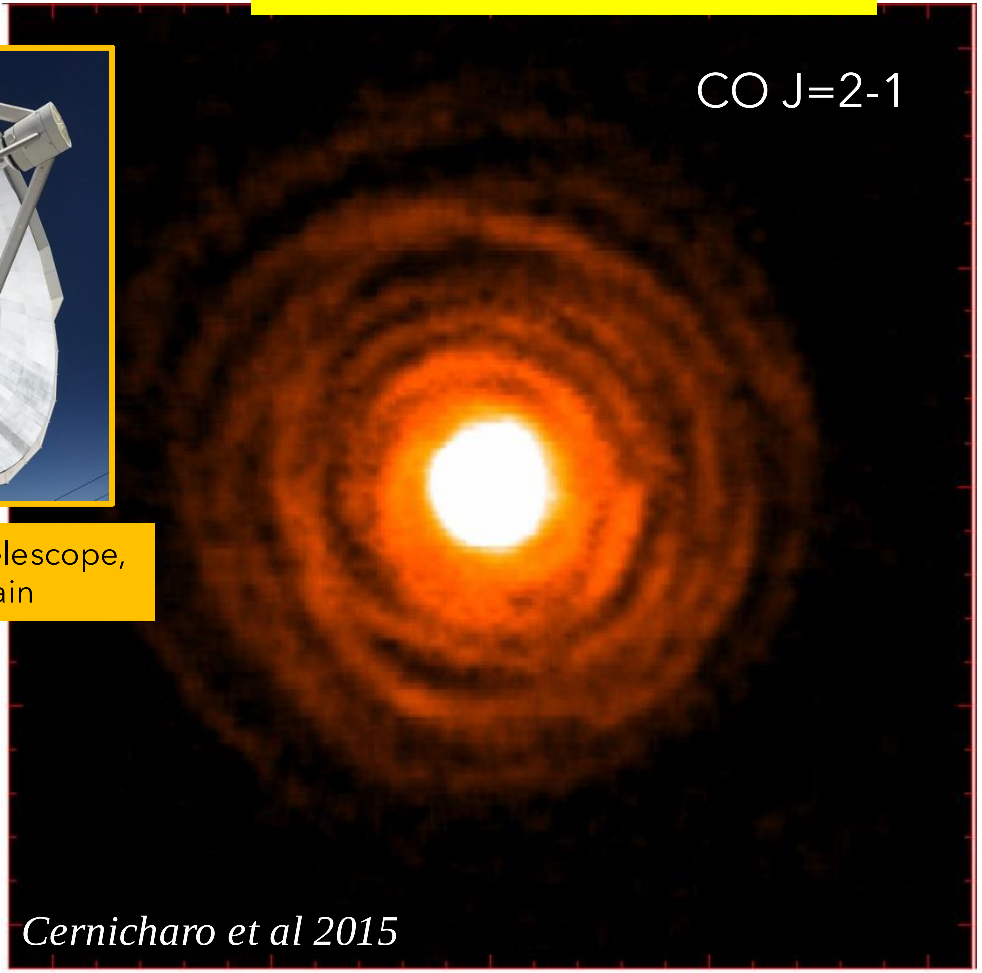
Olofsson 2011

Asymptotic Giant Branch (AGB) Stars

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

(Also known as CW Leonis)

IRAM 30m Radio Telescope, Granada, Spain



Cernicharo et al 2015

\# of molecule discoveries per source

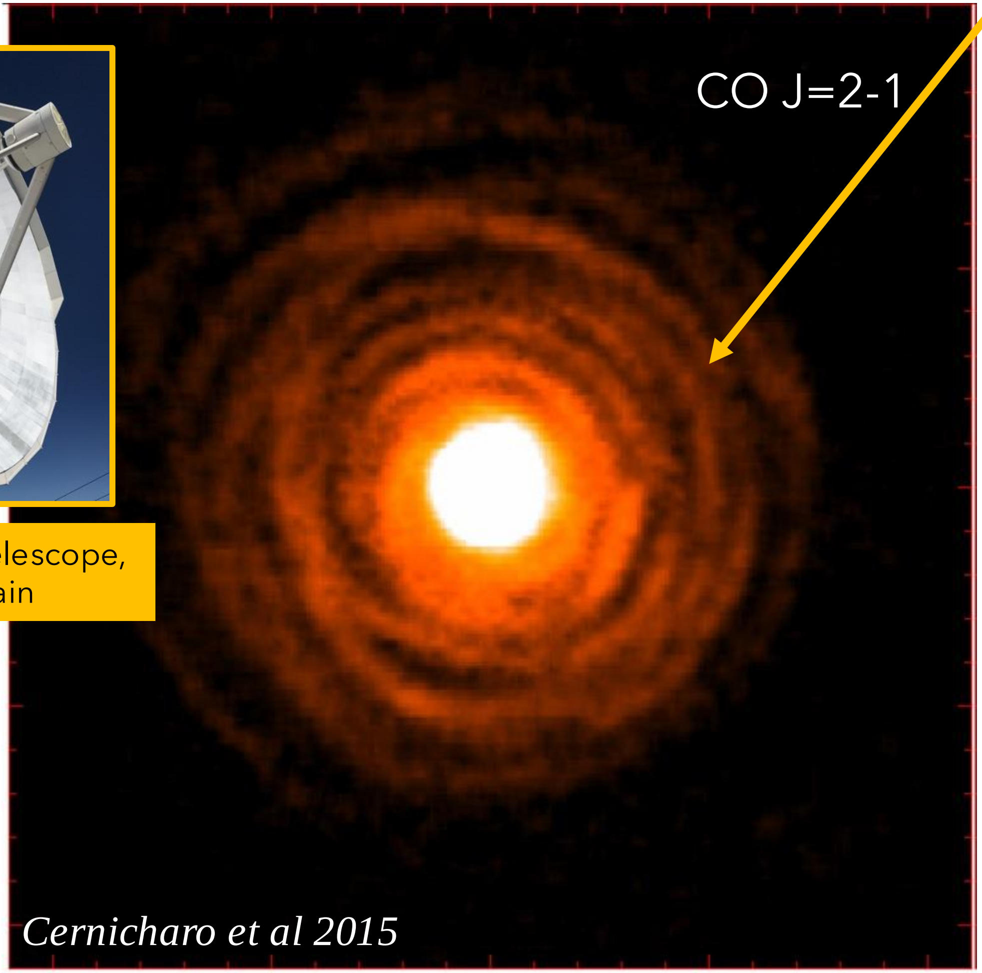
Source	#	Source	#
Sgr B2	69	L1527	2
TMC-1	57	L1544	2
IRC+10216	55	NGC 2024	2
LOS Cloud	42	NGC 7023	2
Orion	24	NGC 7027	2
L483	9	TC 1	2
W51	8	W49	2
VY Ca Maj	6	CRL 2688	1
B1-b	4	Crab Nebula	1
DR 21	4	DR 21(OH)	1
IRAS 16293	4	Galactic Center	1
NGC 6334	4	IC 443G	1
Sgr A	4	K3-50	1
CRL 618	3	L134	1
G+0.693-0.027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

Asymptotic Giant Branch (AGB) Stars

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

IRAM 30m Radio Telescope, Granada, Spain



Outer Shell Circumstellar Chemistry!

- Neutral-neutral reactions with free radicals
- n ~10^5 cm^{-3} and lower with T ~ 25 K
- Penetration of UV photons from ambient star light
- Formation of radicals and some ions
- Photodissociation "long carbon-chain formation"

$HCN + h\nu \rightarrow CN + H$

$HCCH + h\nu \rightarrow CCH + H$

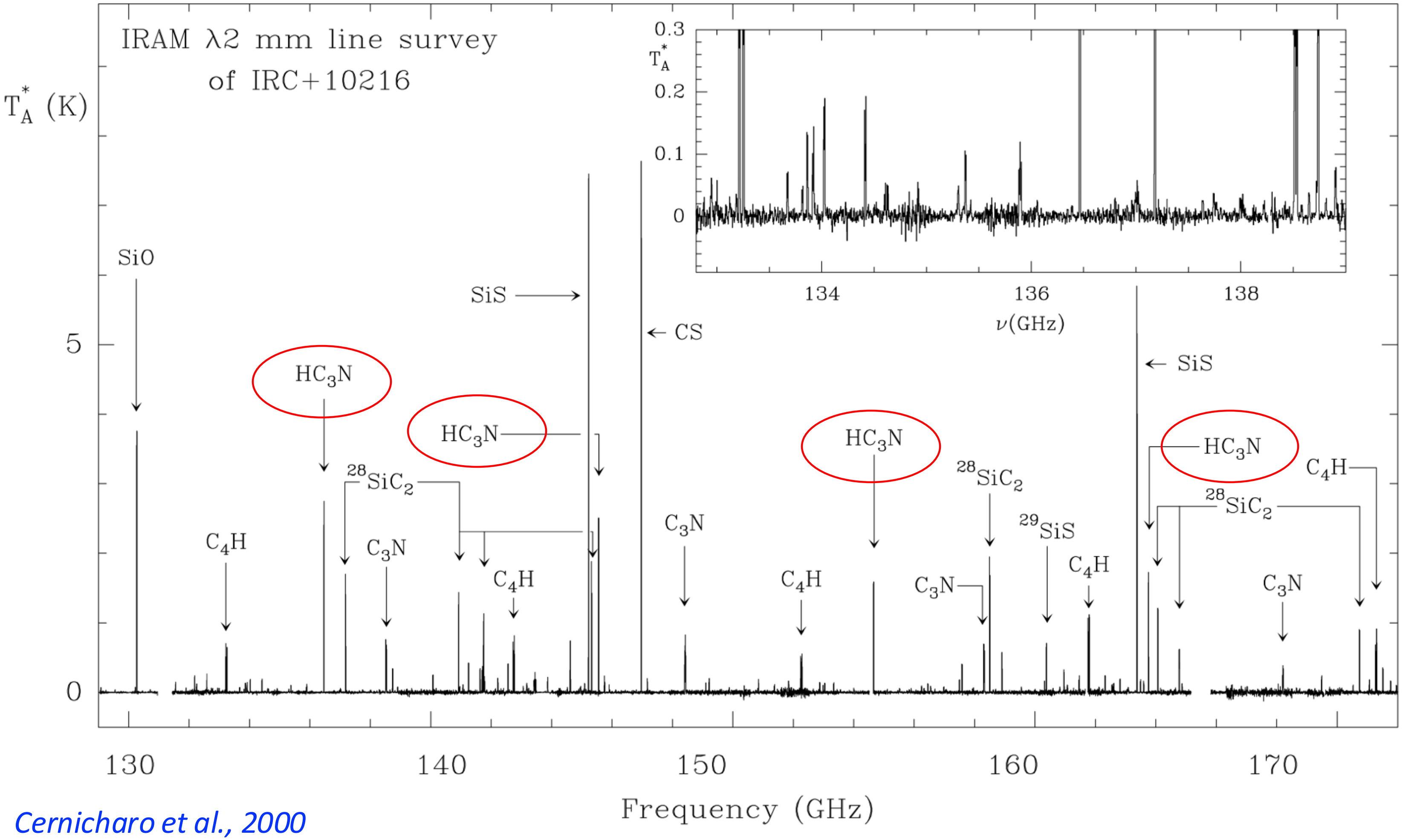
CN and CCH then react with other neutral species building multi-carbon chains!

$CN + HCCH \rightarrow \mathbf{HC_3N} + H$

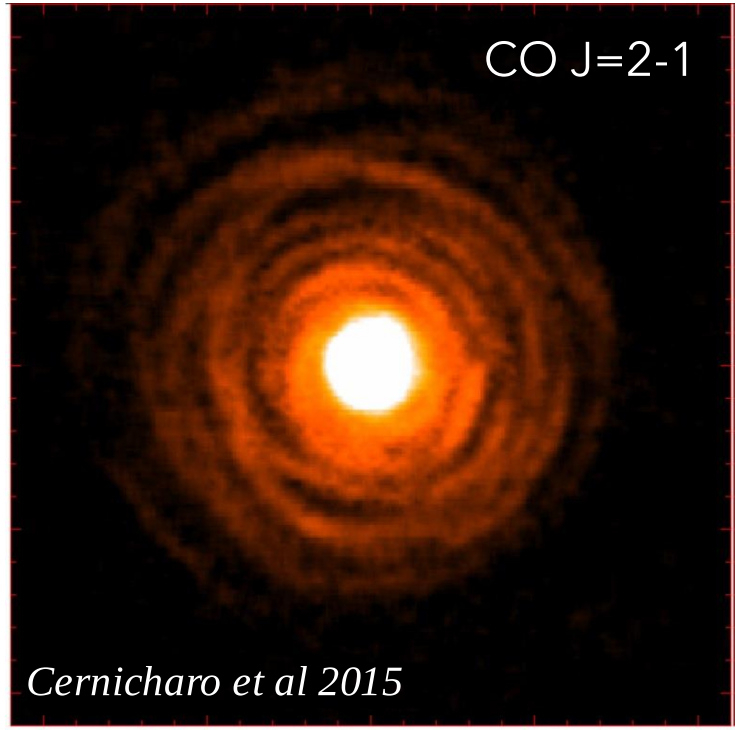
Credit: L. Ziurys

Asymptotic Giant Branch (AGB) Stars

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



Cernicharo et al., 2000



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

Asymptotic Giant Branch (AGB) Stars

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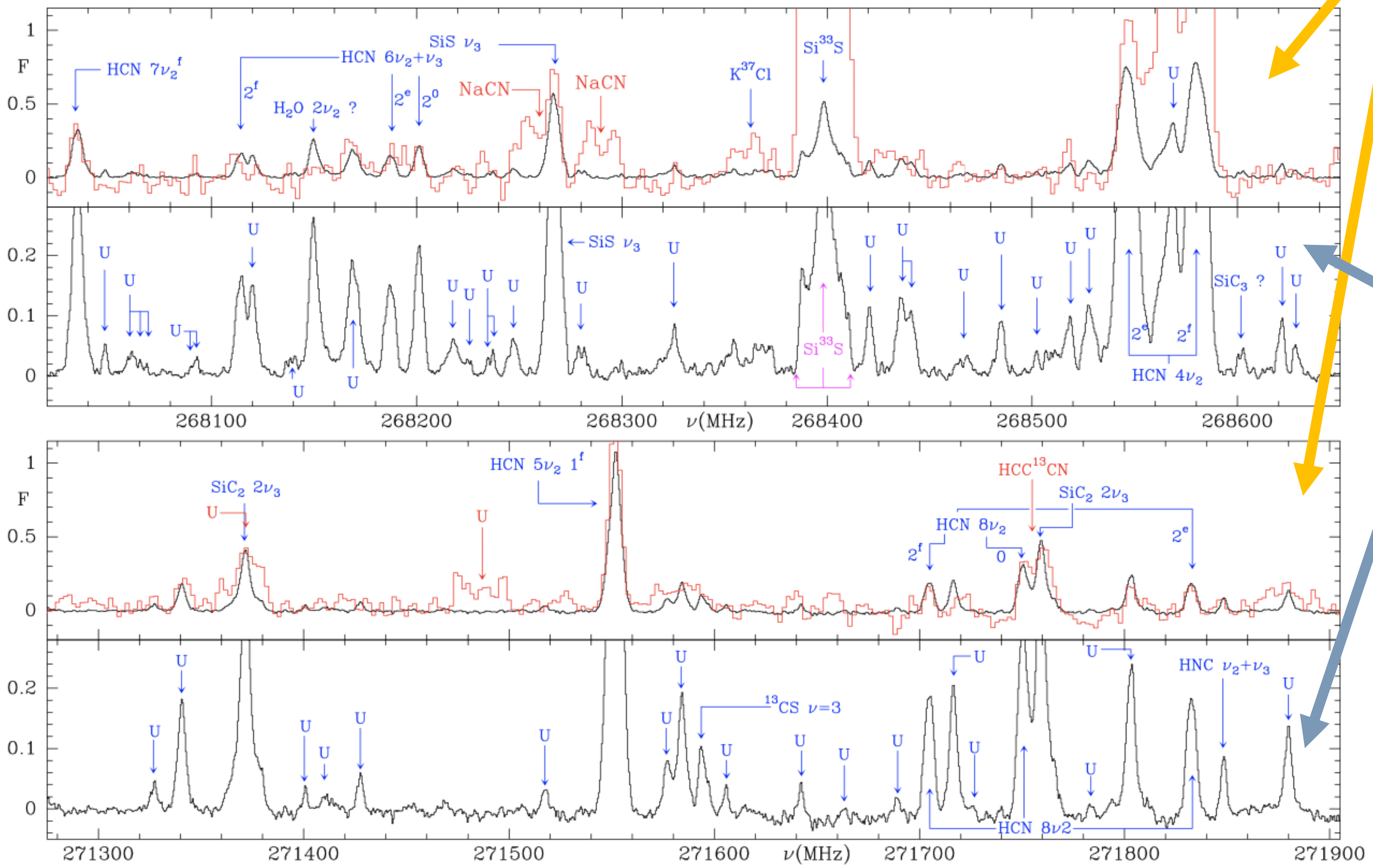


IRAM 30m Radio Telescope, Granada, Spain

ALMA interferometer

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

Cernicharo et al., 2013

Asymptotic Giant Branch (AGB) Stars

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

Molecular Maps:

Freeze-out and Photochemistry in action

• Maps of "parent" and "daughter" molecules in envelope of IRC+10216 →

• **HCN** the parent

• Photodissociation produces **CN**

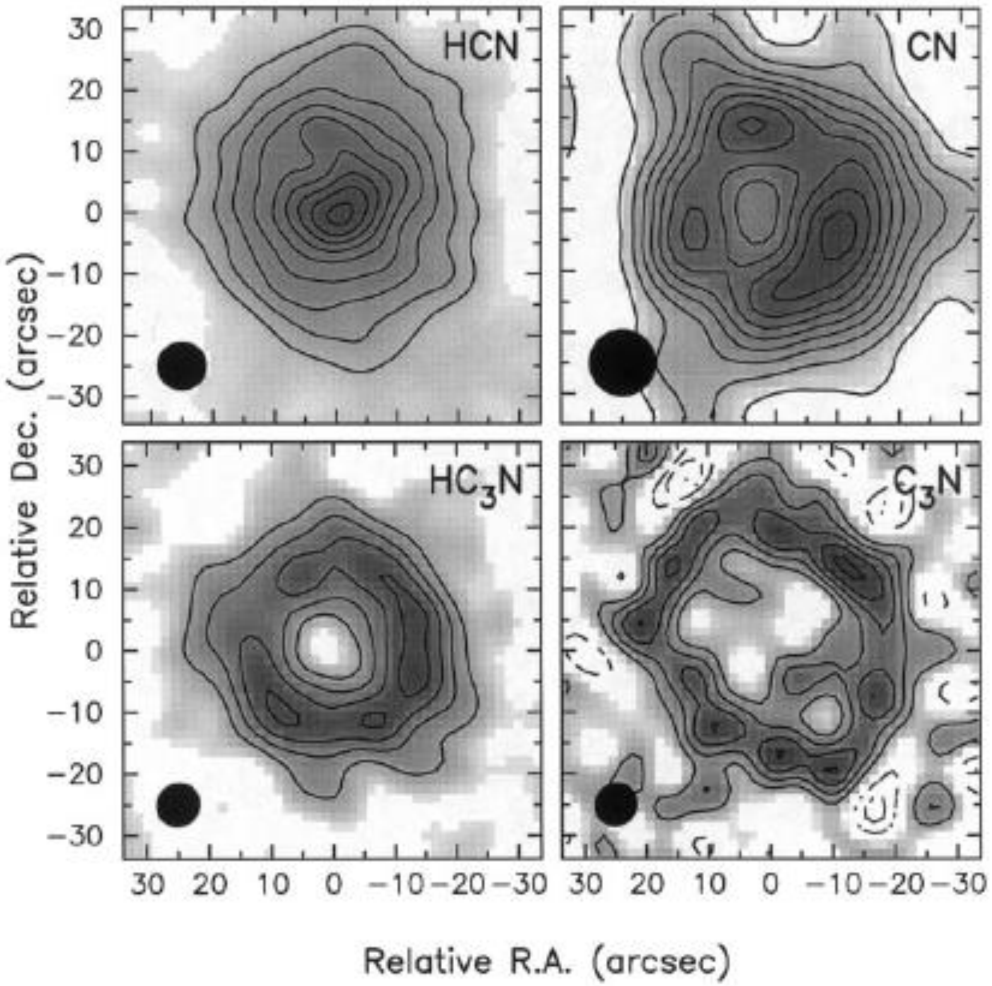
• CN reacts to form C_3N, HC_3N, etc.

e.g.,

$HCN + h\nu \rightarrow CN + H$

$HCCH + h\nu \rightarrow CCH + H$

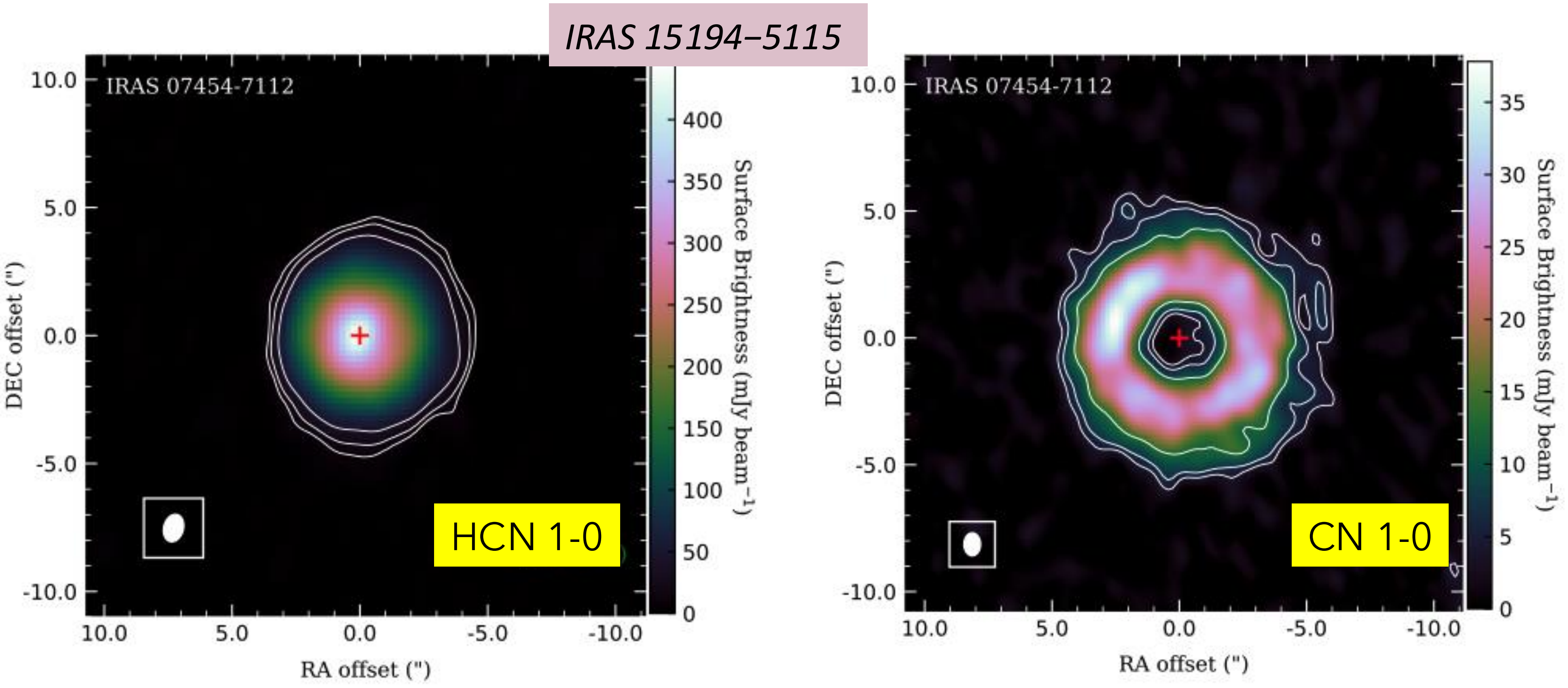
$CN + HCCH \rightarrow \mathbf{HC_3N} + H$



Credit: L. Ziurys

Asymptotic Giant Branch (AGB) Stars

More recent observations show other carbon-rich stars show similar structure!



Unnikrishnan 2023

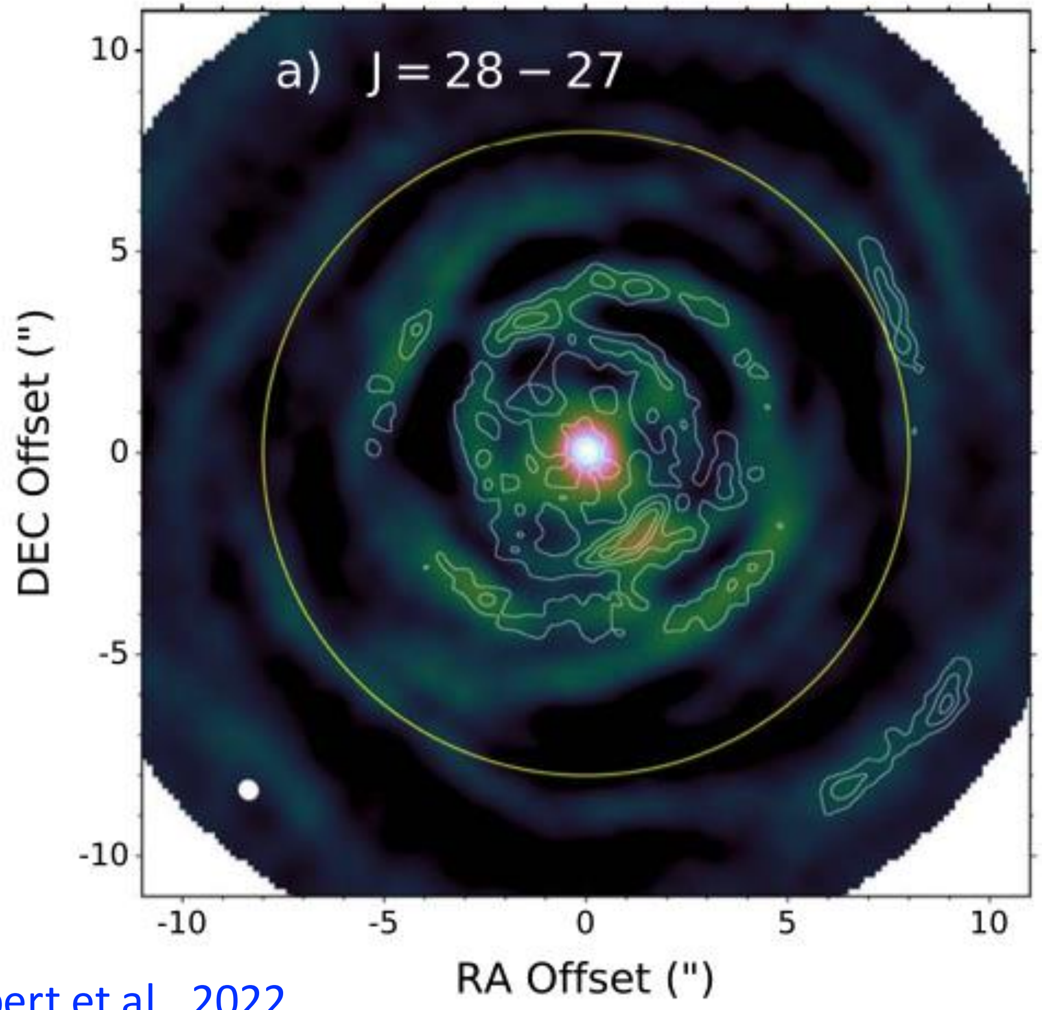
Asymptotic Giant Branch (AGB) Stars

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

But! Warm HC_3N shows a more compact distribution!

- Implication: photochemistry is occurring more rapidly in warmer layers
- A solar-like companion (binary) emitting UV photons in the inner wind is likely driving the photochemistry

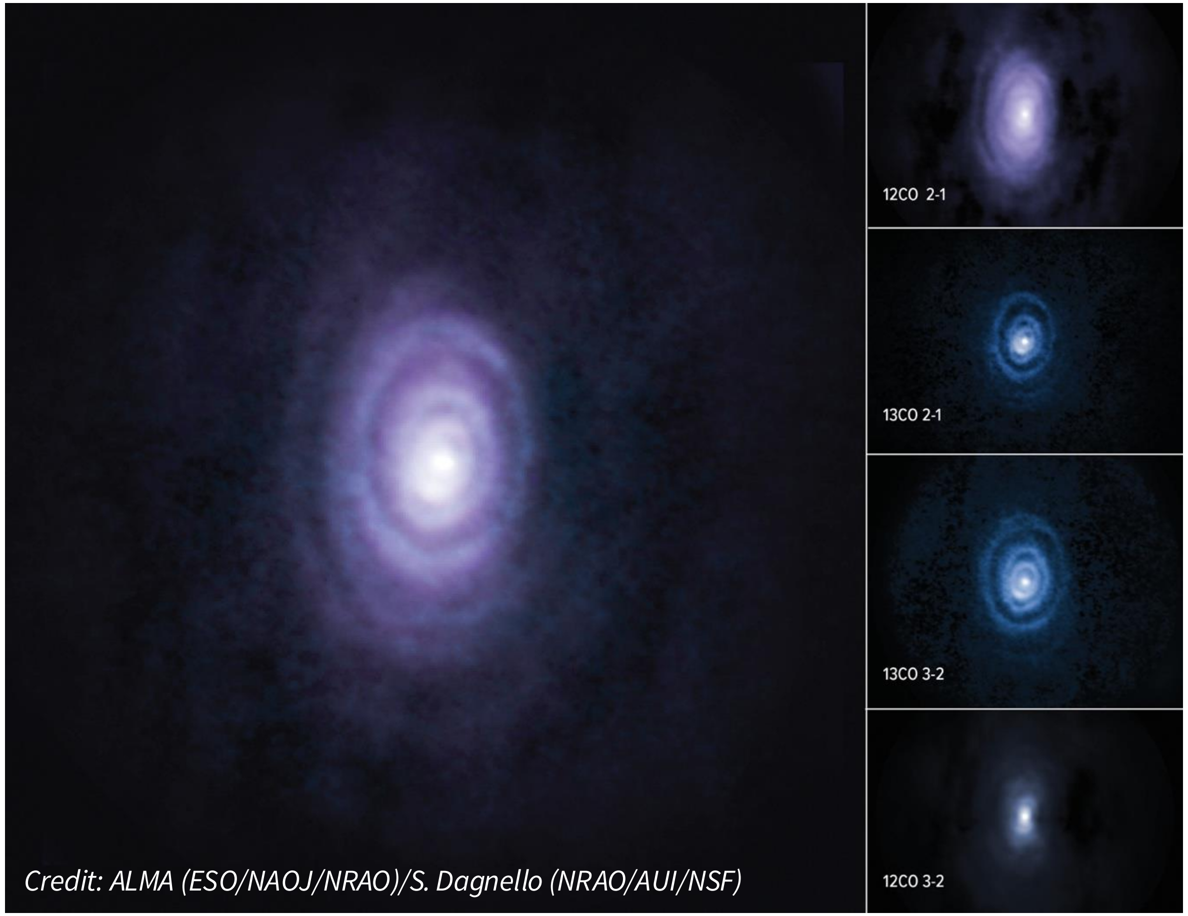
Contours: HC_3N J = 28-27
Colormap: ^{13}CO J=3-2



Siebert et al., 2022

Asymptotic Giant Branch (AGB) Stars

Known Binary: Carbon-rich star V Hydrae

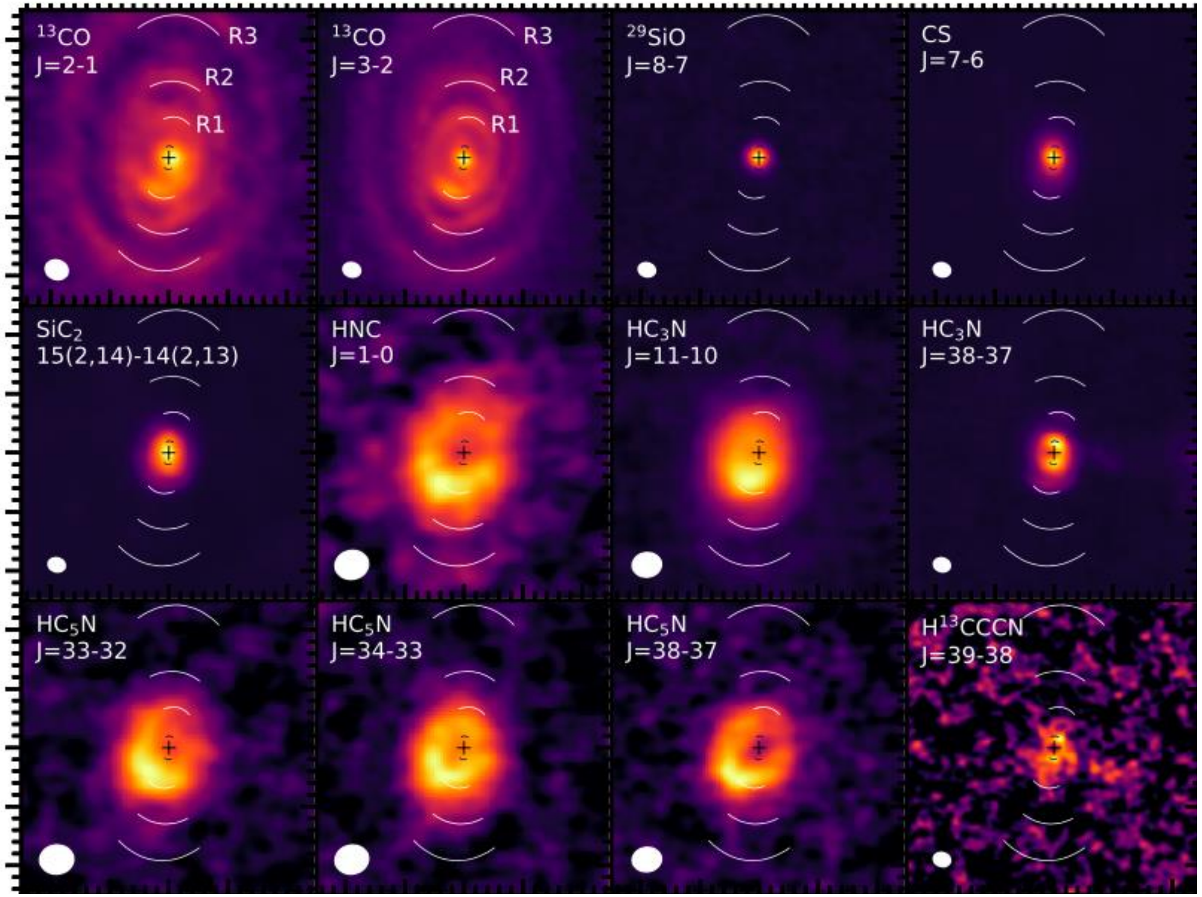


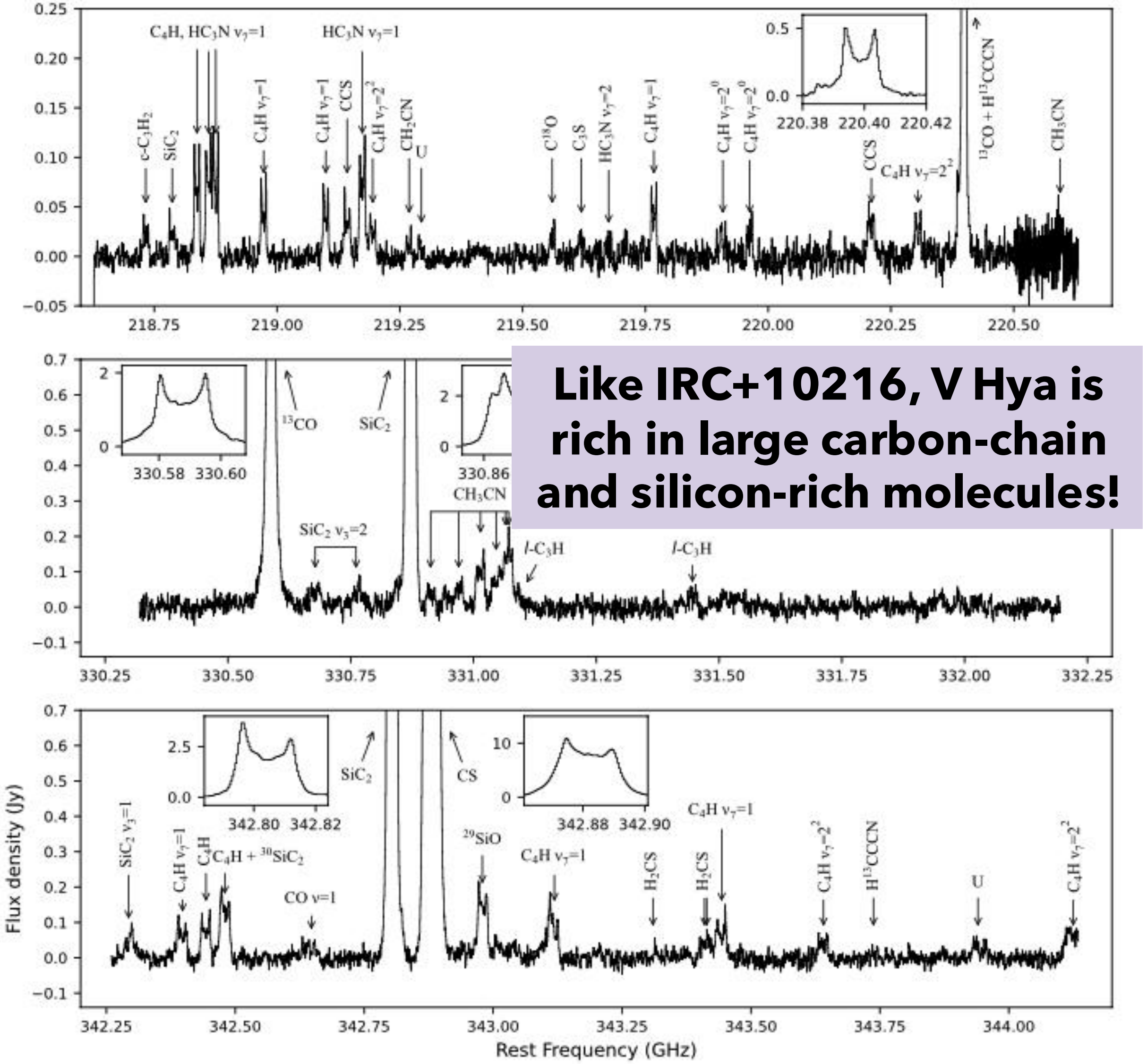
Sahai et al. (2022)

- V Hydrae has been caught in the process of shedding its atmosphere in a series of expanding and outflowing rings
- First time these outflowing rings are seen during this end stage of stellar evolution!
- V Hydrae also is known to produce high-speed, intermittent jets of material!
- These extreme-scale plasma eruptions happen roughly every 8.5 years and the presence of a nearly invisible companion star

Asymptotic Giant Branch (AGB) Stars

Known Binary: Carbon-rich star V Hydrae

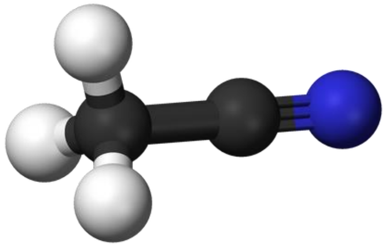




Like IRC+10216, V Hya is rich in large carbon-chain and silicon-rich molecules!

Siebert et al., 2024 (in review)

Asymptotic Giant Branch (AGB) Stars



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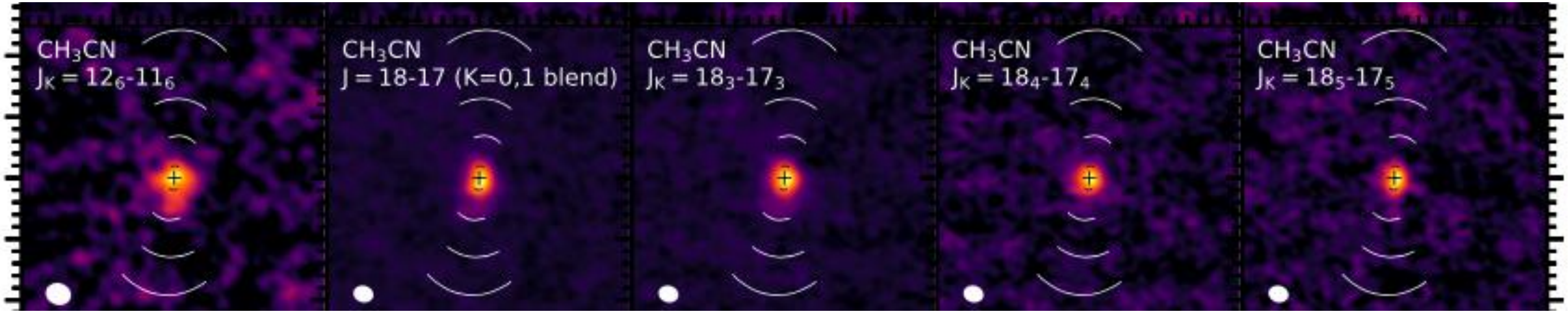
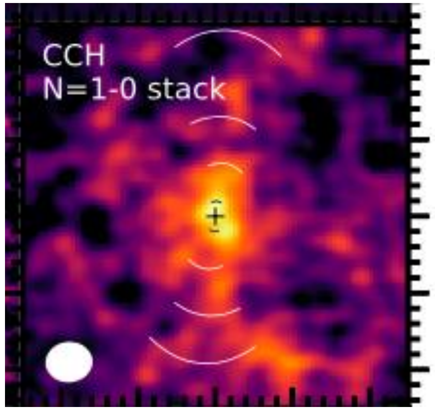


Compact emission of CCH and the complex organic molecule (COM) CH_3CN – increased photochemistry from the binary?

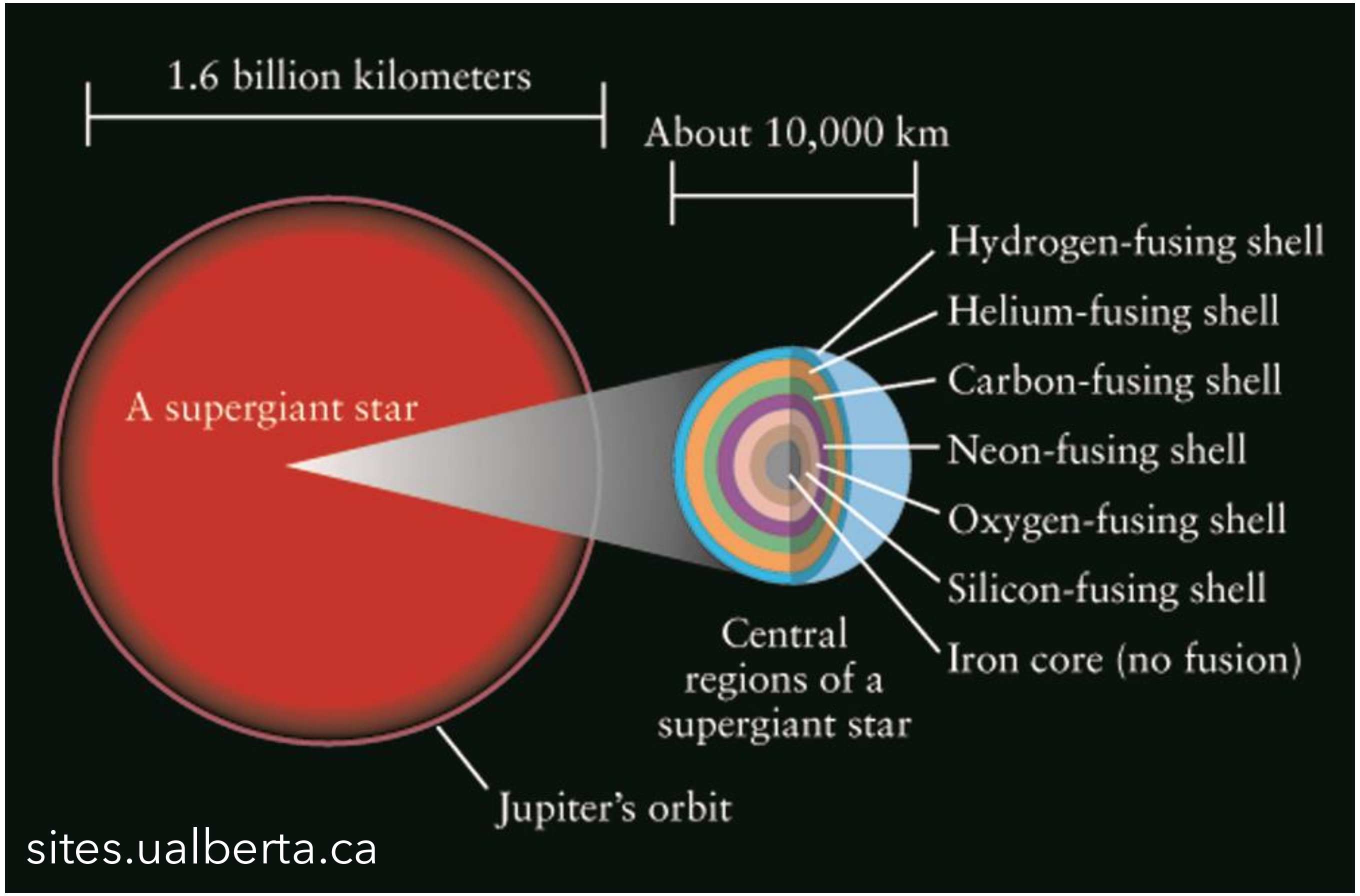


Siebert et al., 2024 (in review)

Supergiant Stars

Red Supergiant Phase (M ~ 10 - 30 $M_\odot$)

- Similar to Red Giants, but larger
- Ignite helium in core-burning
- So massive, can ignite other elements
- Multiple burning shells in C, O, etc
- evolve to **supernova**



Credit: L. Ziurys

Supergiant Stars

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- Ignite helium in core-burning
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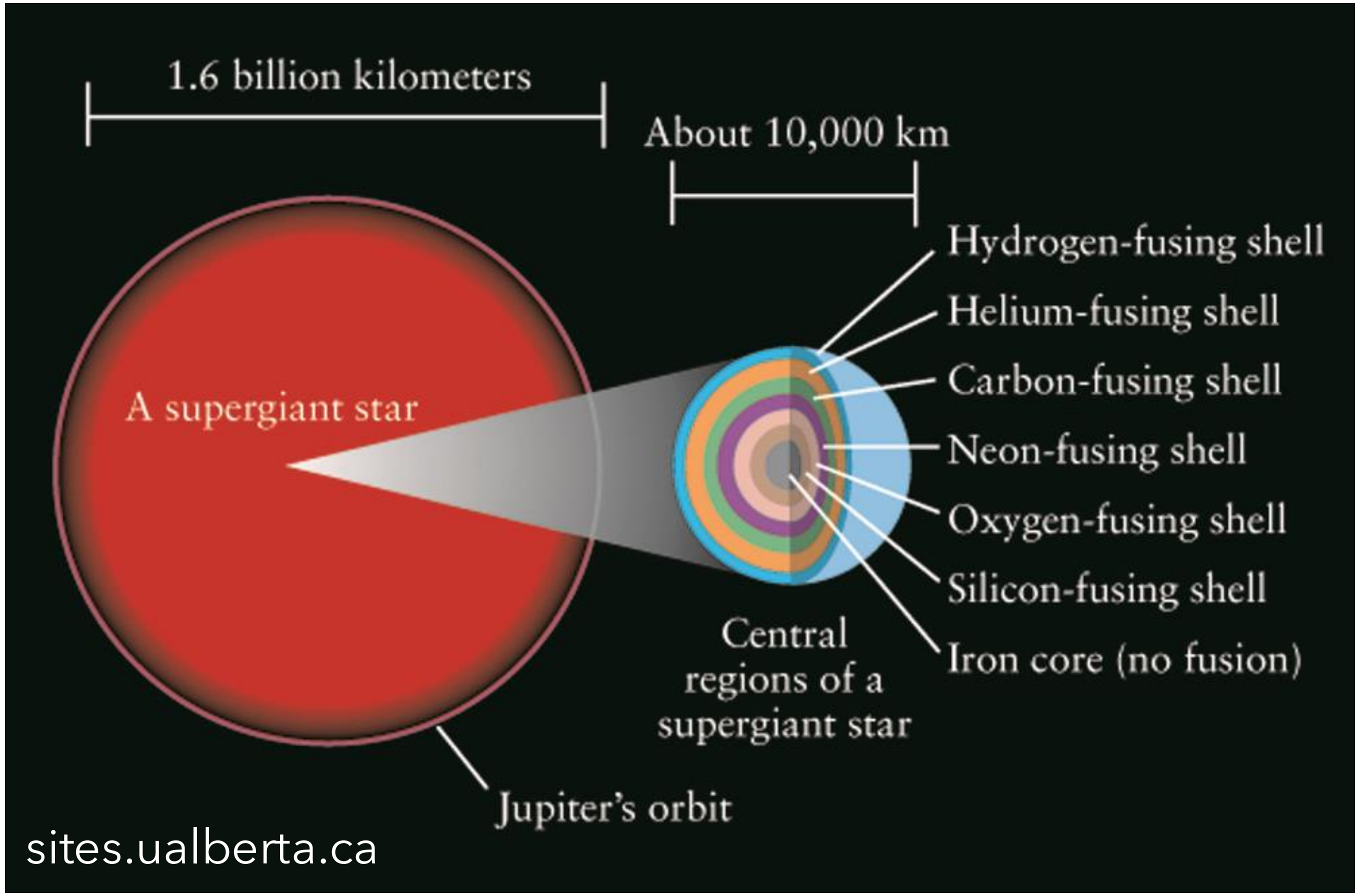
Massive *Supergiant stars* (~ 40 $M_{\odot}$)

- Undergo ***more violent mass loss***
- *Create* ***huge circumstellar*** envelopes
- Shocks, convective cells bursting through atmosphere
- Supergiant stars: **oxygen-rich!**

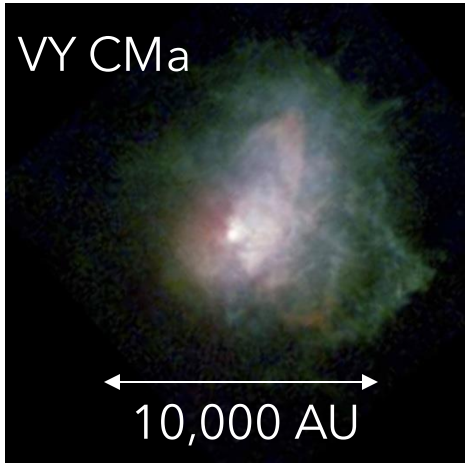


sites.ualberta.ca

Credit: L. Ziurys

Supergiant Stars

Oxygen-rich Supergiant star VY Canis Majoris



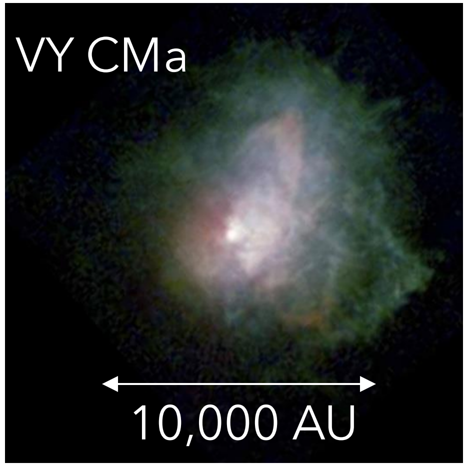
# of molecule discoveries per source

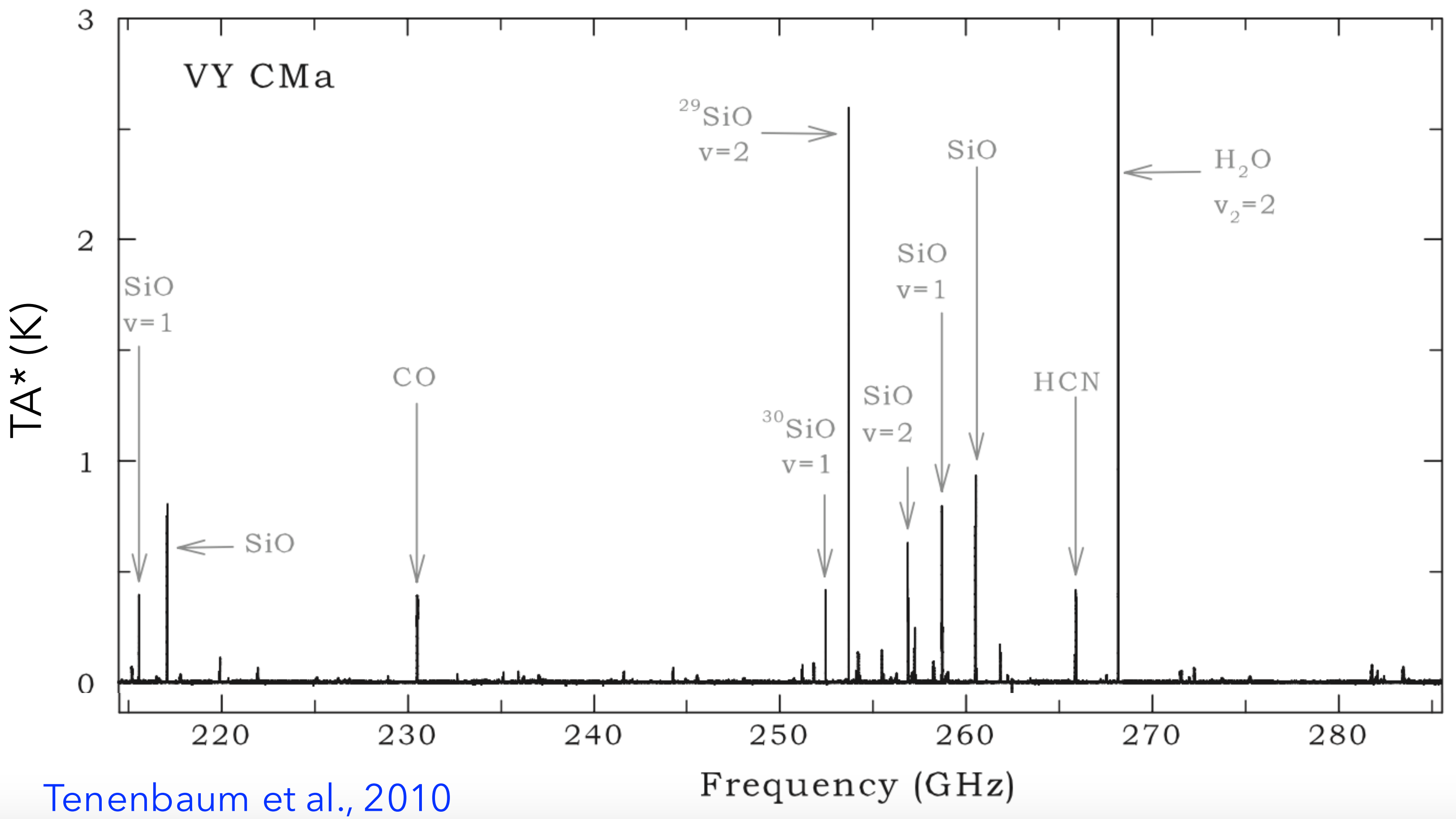
Source	#	Source	#
Sgr B2	69	L1527	2
TMC-1	57	L1544	2
IRC+10216	55	NGC 2024	2
LOS Cloud	42	NGC 7023	2
Orion	24	NGC 7027	2
L483	9	TC 1	2
W51	8	W49	2
VY Ca Maj	6	CRL 2688	1
B1-b	4	Crab Nebula	1
DR 21	4	DR 21(OH)	1
IRAS 16293	4	Galactic Center	1
NGC 6334	4	IC 443G	1
Sgr A	4	K3-50	1
CRL 618	3	L134	1
G+0.693-0.027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

Supergiant Stars

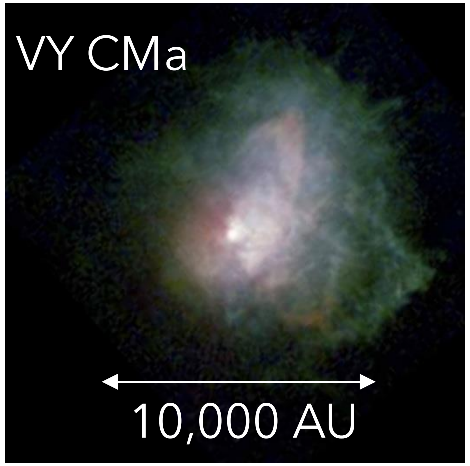
Oxygen-rich Supergiant star VY Canis Majoris

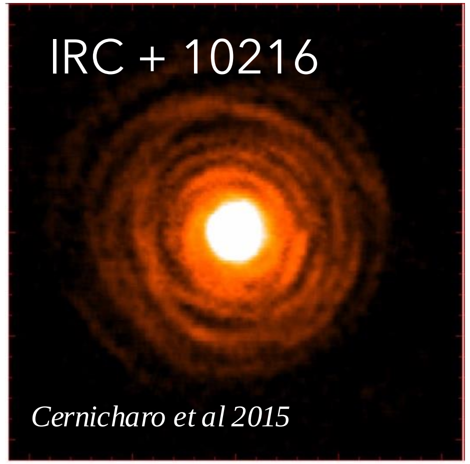


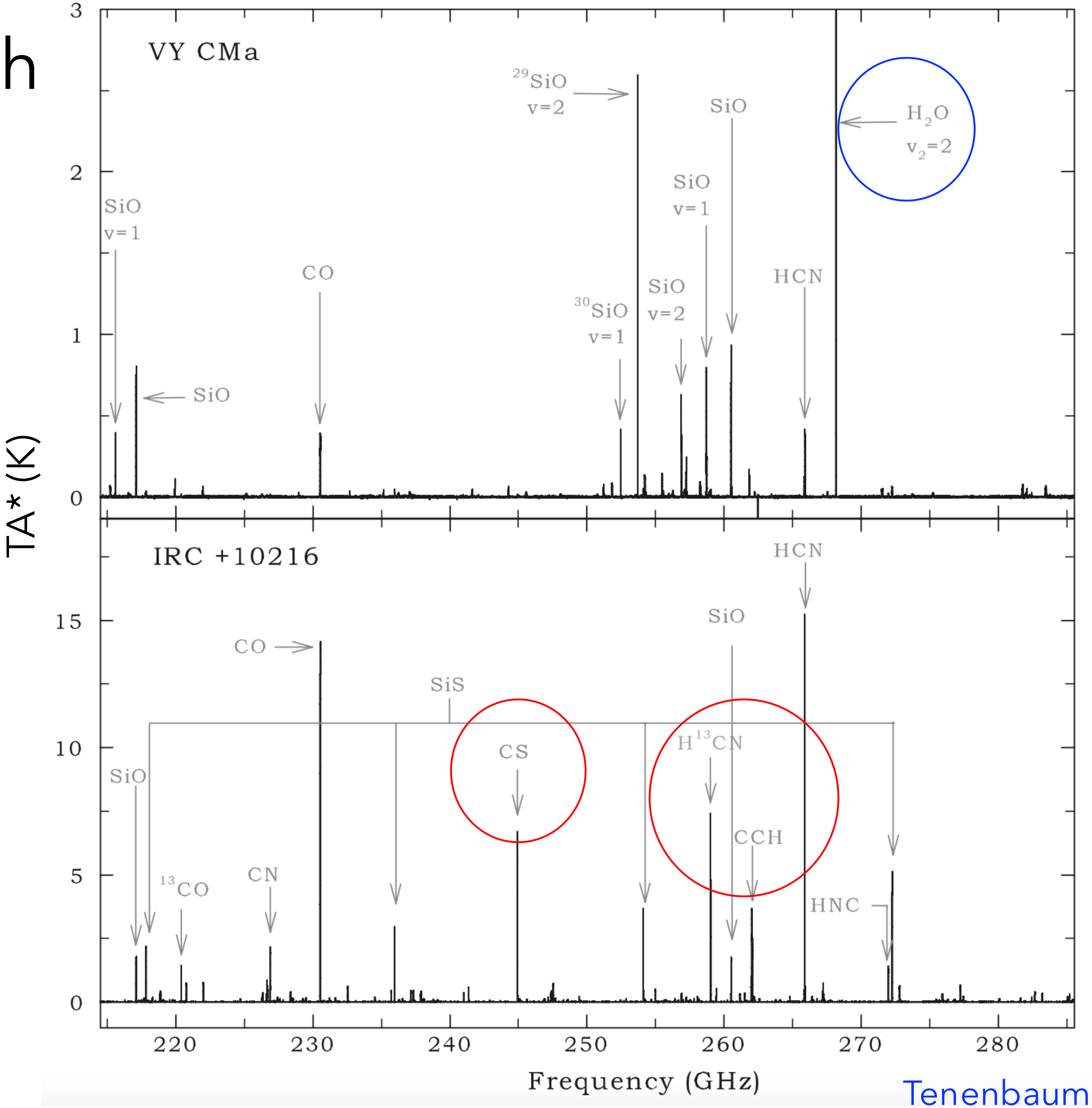


Tenenbaum et al., 2010

C-rich vs. O-rich





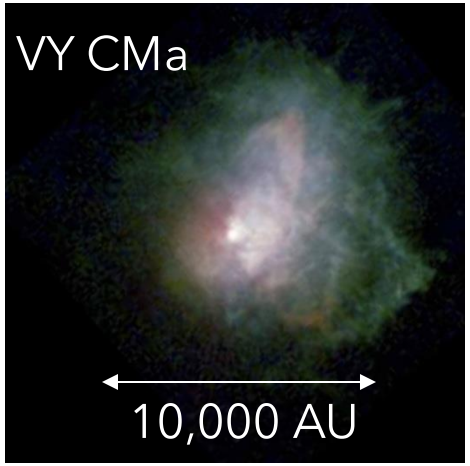


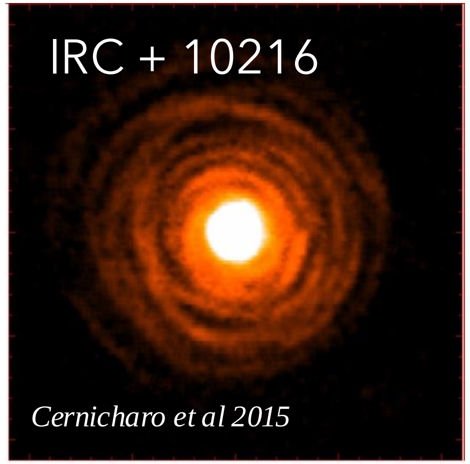
O-rich: **H_2O, SiO, CO**

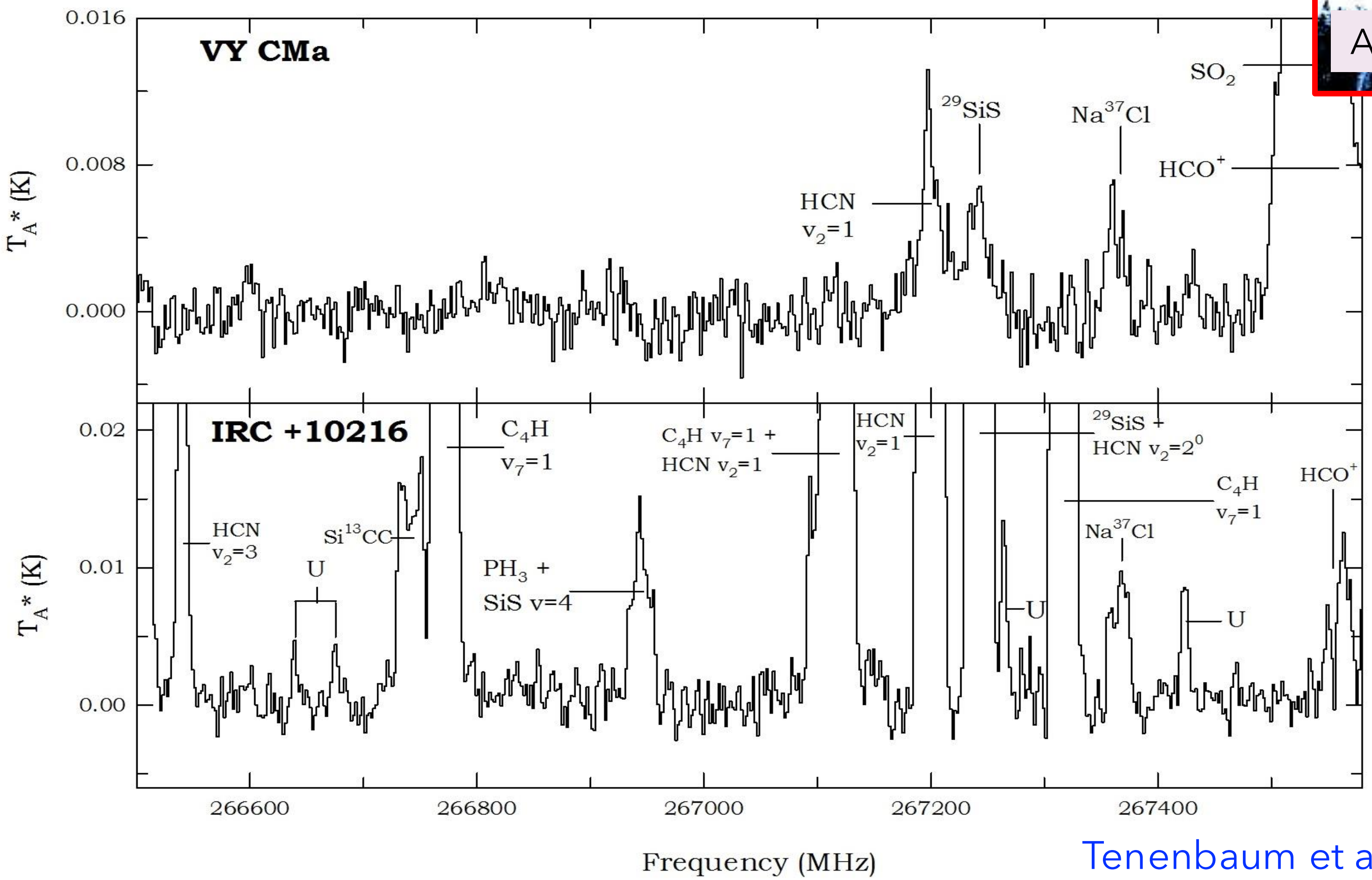
C-rich: **CO, HCN, H_2C_2, SiS, CS, CH_4**

Tenenbaum et al., 2010

C-rich vs. O-rich





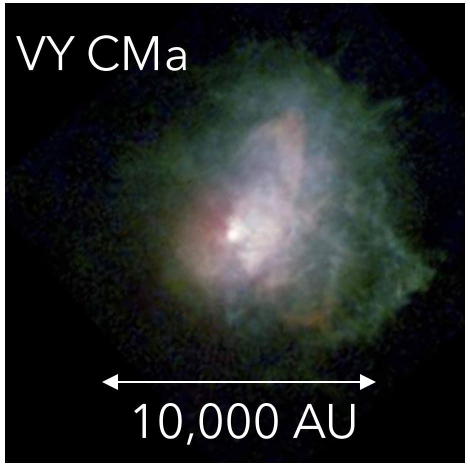


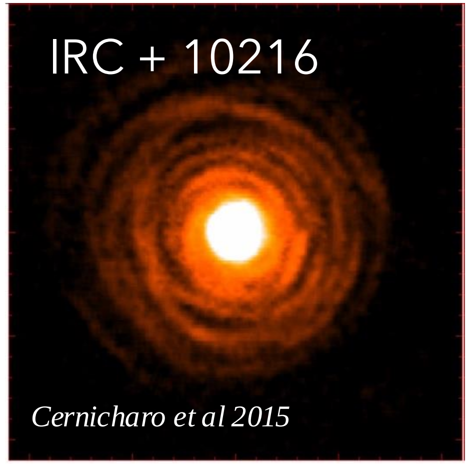
Tenenbaum et al., 2010

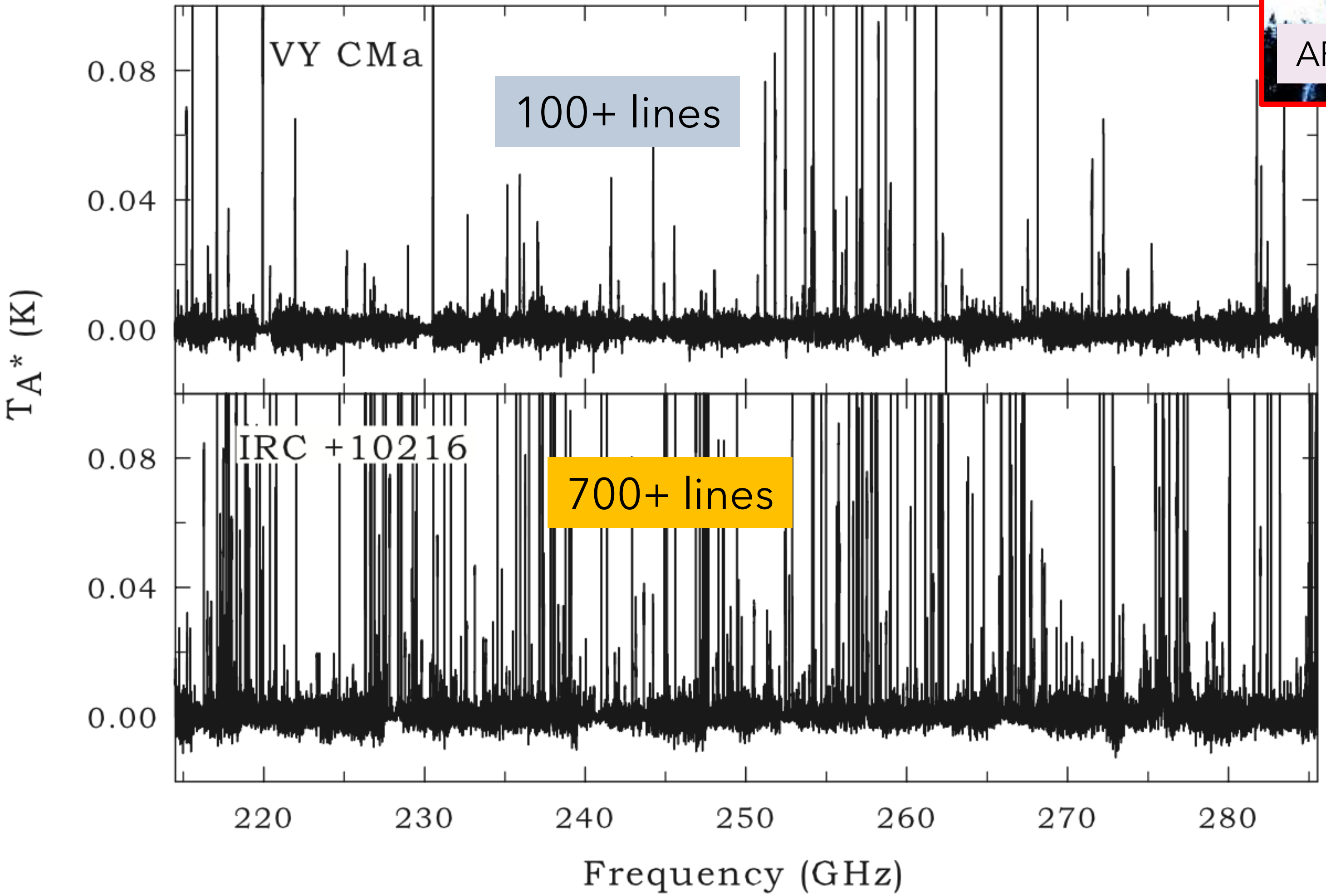
- VY CMa Spectrum dominated by **SO_2, SiO, SiS**
- IRC+10216 Spectrum dominated by **C_4H, HCN**

C-rich vs. O-rich

Both objects overall **very** line rich!





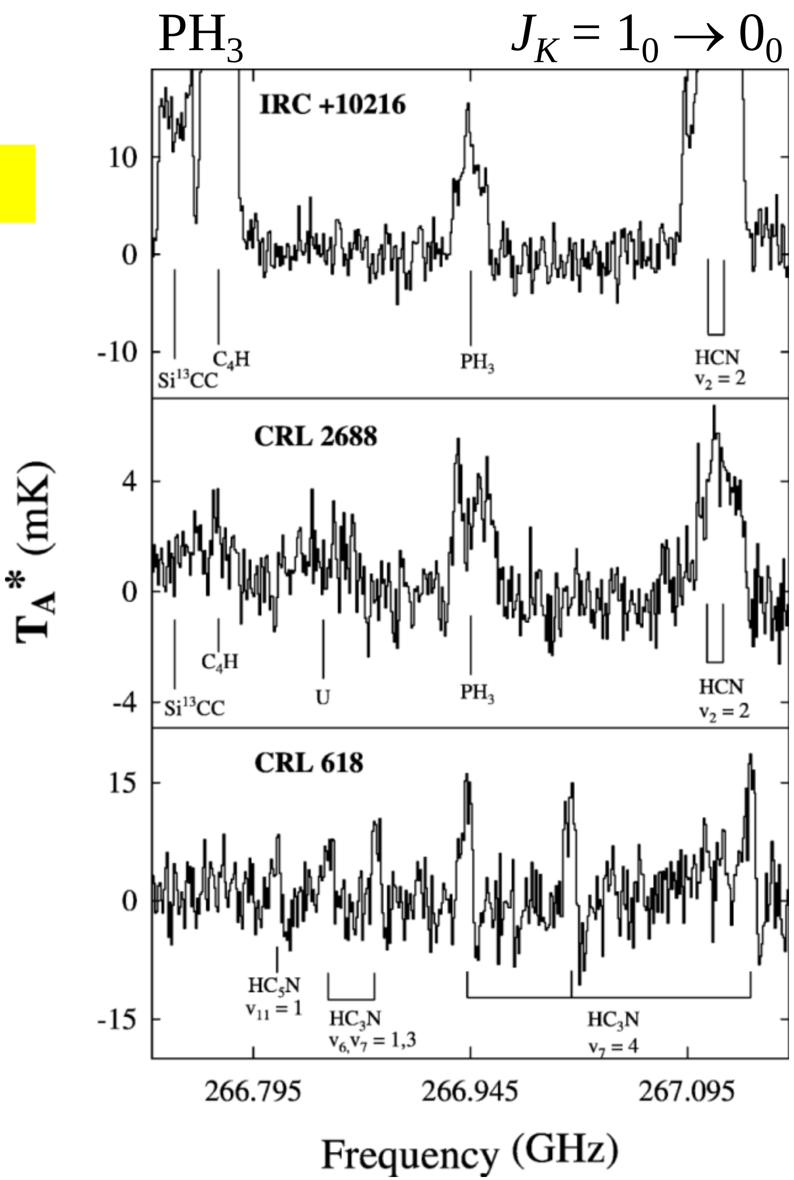


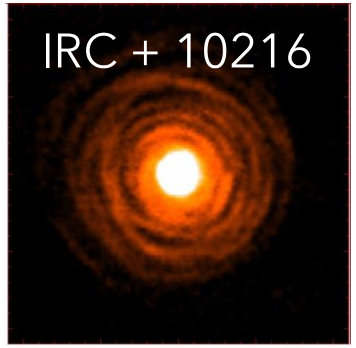
**NOTE: VY Cma is ~10x farther away!*

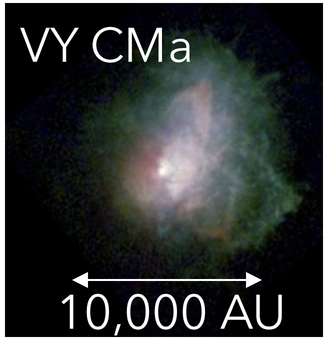
Tenenbaum et al., 2010

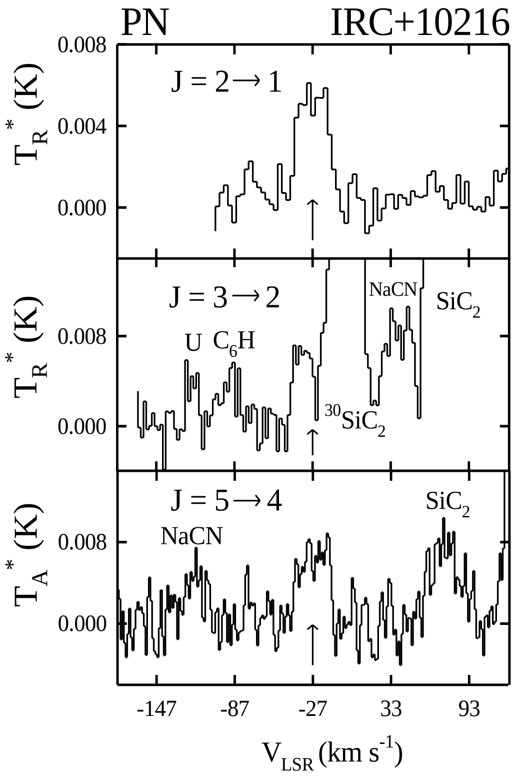
Phosphorous in Evolved Stars

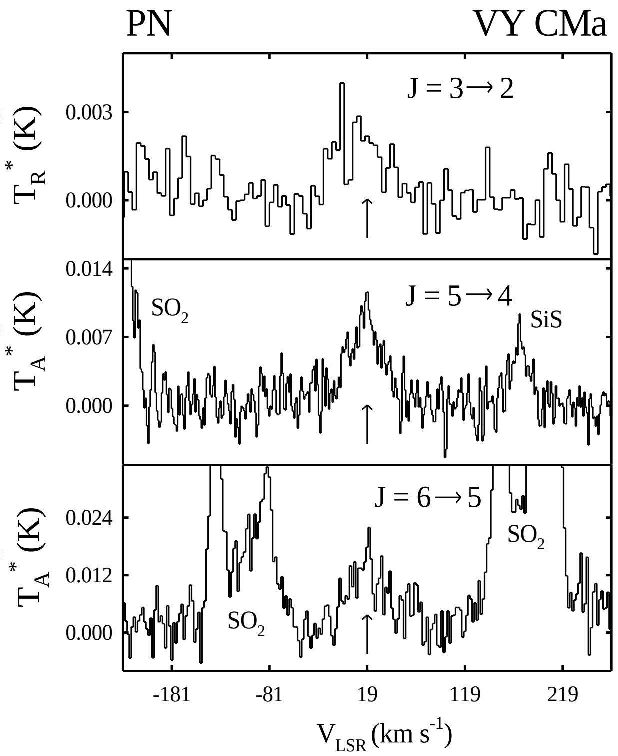
Phosphine! →











Credit: L. Ziurys

Milam et al. 2008
Tenenbaum & Ziurys 2008

Metals in Evolved Stars

- Metals typically found in molecular form:

Al, Mg, Na, K, Fe

- In C-rich envelopes

  ⇒ ***Cyanides, Halides***

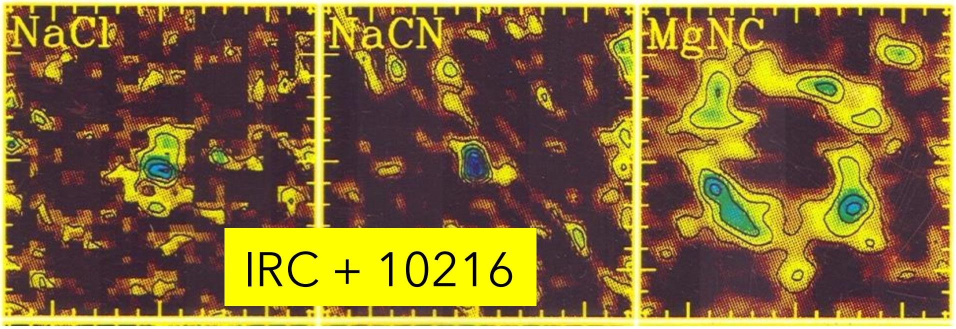
- Now in O-rich Envelopes

  ⇒***Oxides, Hydroxides***

- First definitive detections

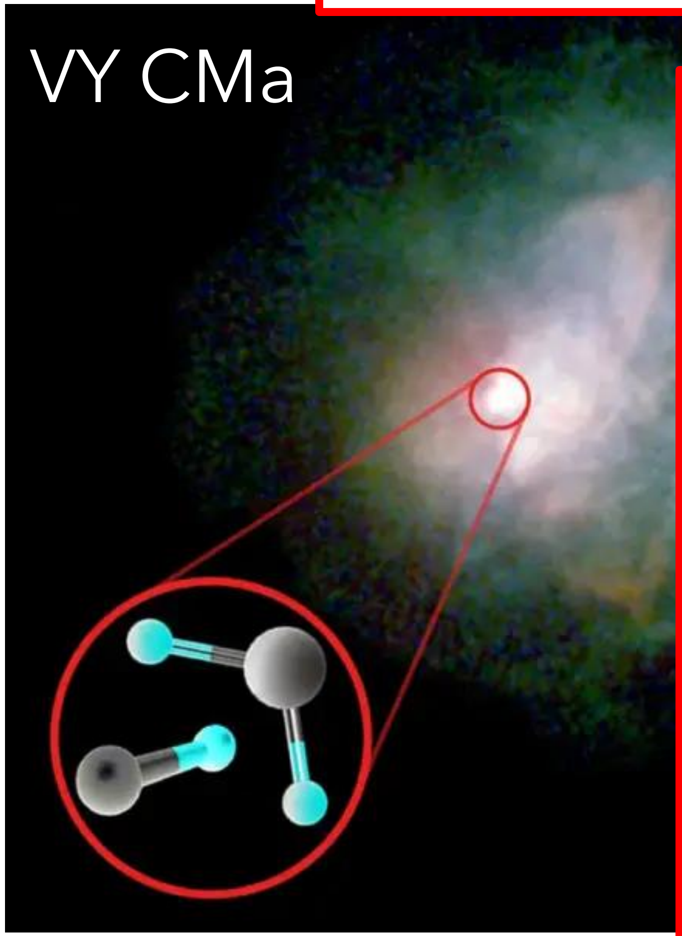
of ***Fe and Ti –bearing*** species

  ⇒ **MgCN** species most common

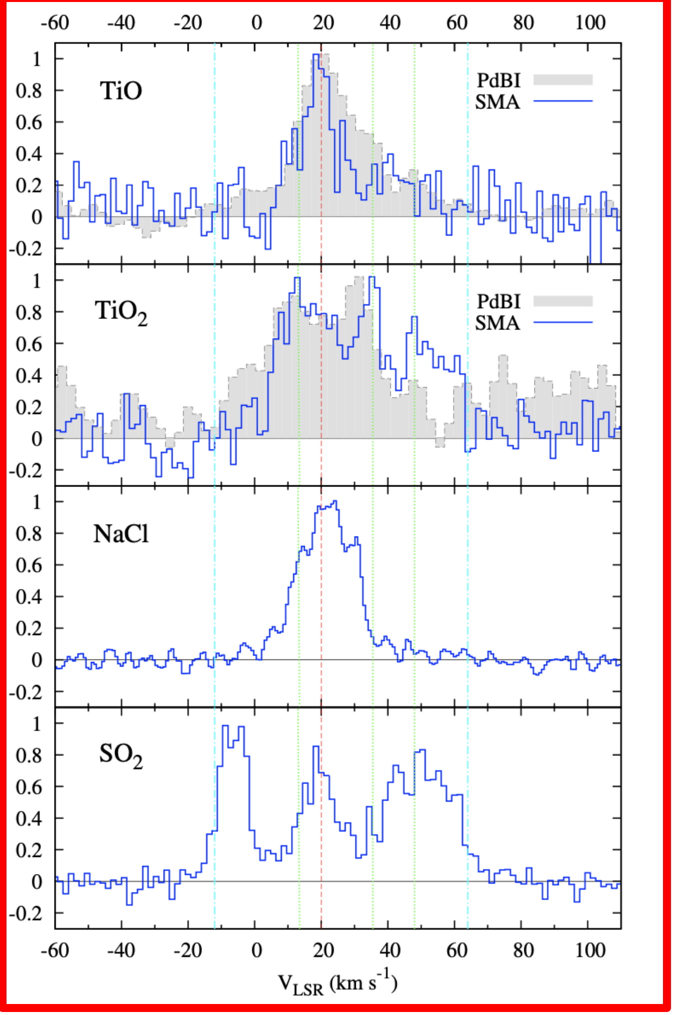


Credit: L. Ziurys

Detection of TiO and TiO_2!

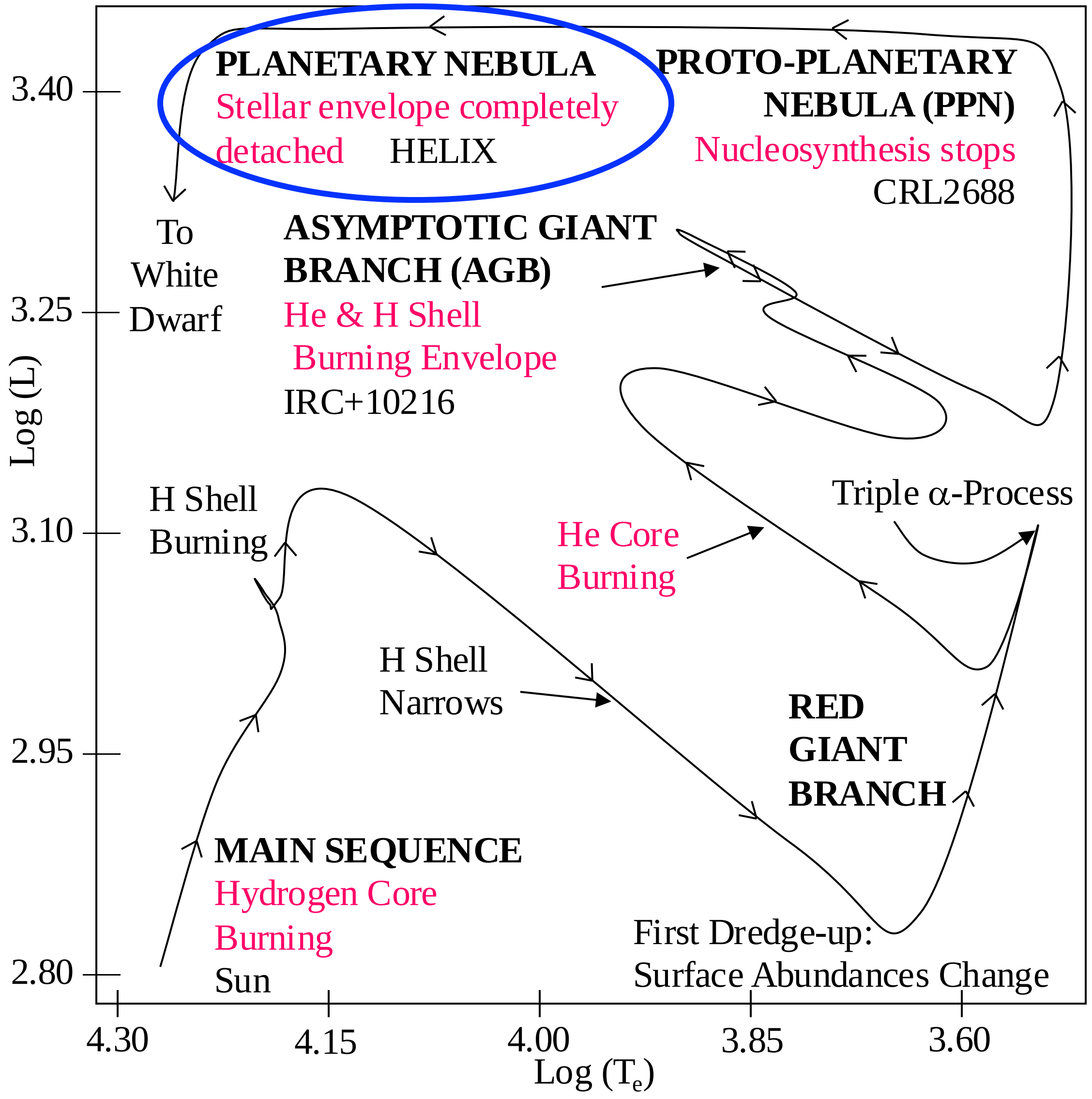


Kaminski et al., 2013



Chemistry in **Planetary Nebula**

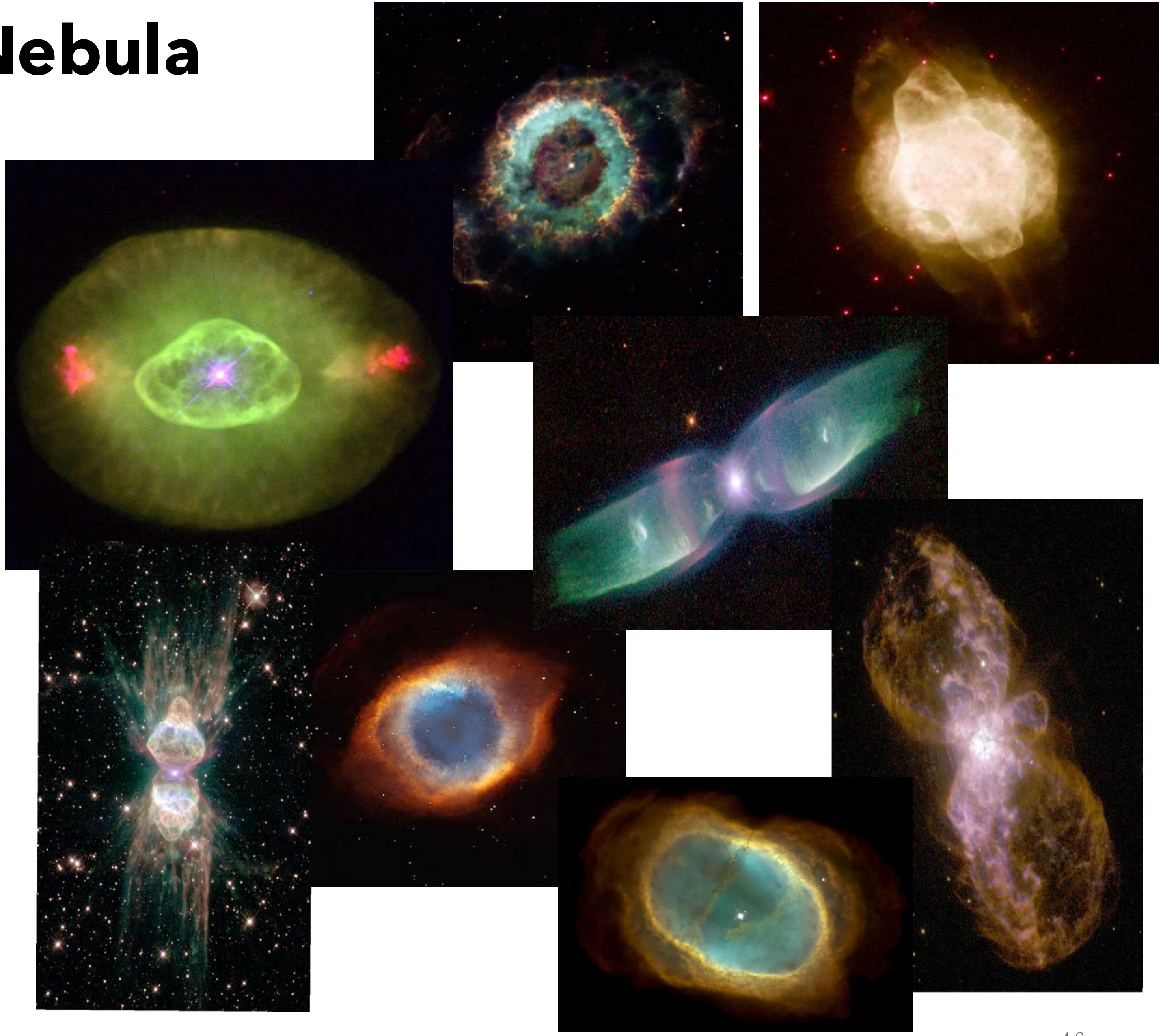
- Final stage in life cycle of most stars (~1-8 $M_{\odot}$)
- Follows (AGB) phase ***w/ molecule-rich circumstellar shells***
- Mass Loss continues into PNe phase!
- Nucleosynthesis ceases
- Central Star exposed: Hot UV-emitting white dwarf with mass ~ 0.5 $M_{\odot}$
- Remnant AGB shell flows far from star ⇒ becomes *highly ionized*
- T_{star} ~ 100,000 K.
- Timescales: 10,000 – 12,000 yrs



Credit: L. Ziurys

Chemistry in **Planetary Nebula**

- Material cycled ***through PNe phase***
  - ⇒ ***83%*** of interstellar material
- Material ends up in diffuse clouds
- Collapse to form dense clouds
- Evaluating PNe ejecta crucial
  - ⇒ Composition of ISM
  - ⇒ Galactic Chemical Evolution
- PNe traced by highly excited atomic lines
  - [O III], [OII], CII, Ne II, He II, and [N II]
- *Can molecules exist here?*



Credit: L. Ziurys

Chemistry in **Planetary Nebula**

Yes, there should be MOLECULES!

- **UV radiation** from central star intense
- Some photochemistry occurs
- **Theory/Models predicts overall molecular content**

  $\Rightarrow$ steadily decreases with time

  $\Rightarrow$ early increase due to photochemistry
- By 10,000 years, molecular abundance drops

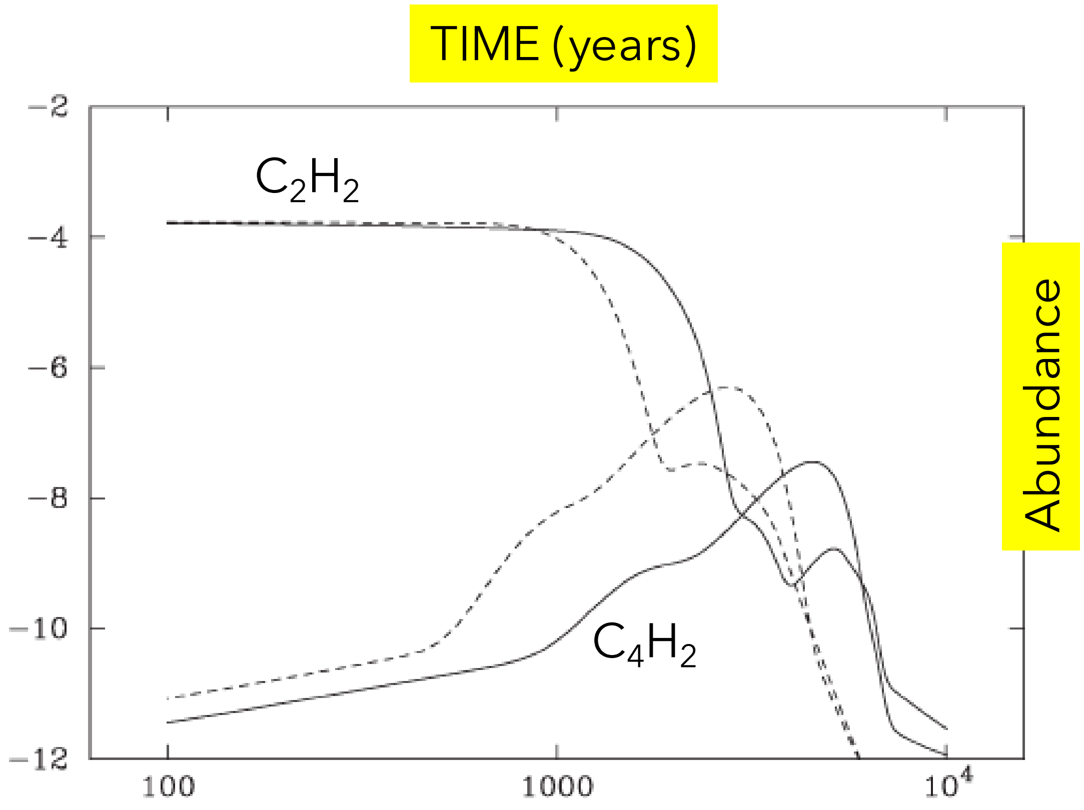
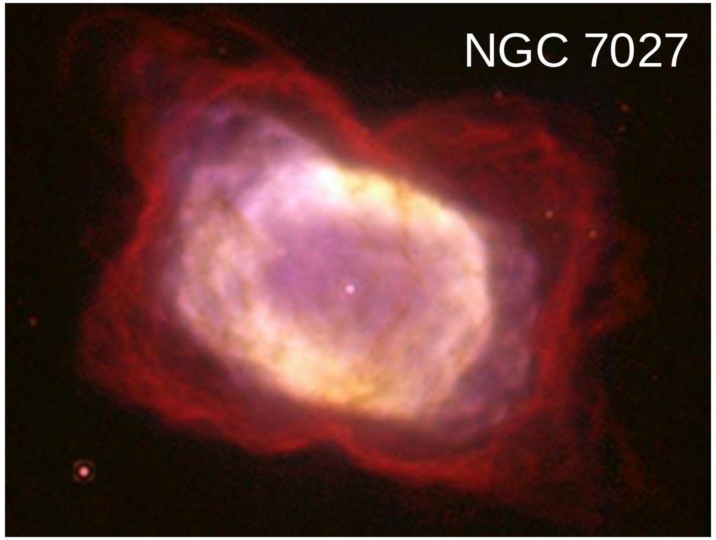


Figure 3. Clump (solid lines) and interclump (dashed lines) abundances for C_2H_2 (uppermost solid line) and C_4H_2. The time is measured in years and the fractional abundance is with respect to the total number of hydrogen atoms.

Credit: L. Ziurys

Chemistry in **Planetary Nebula**

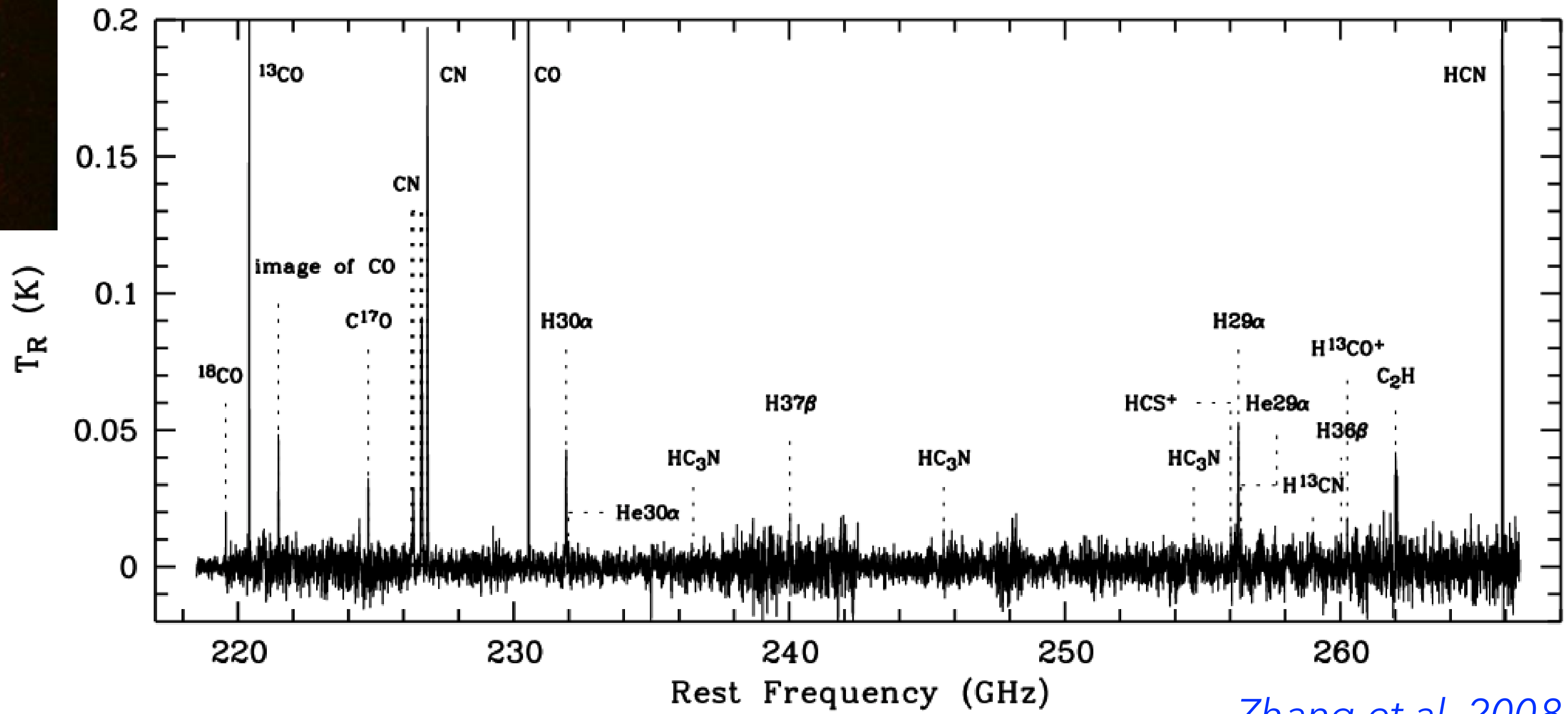


Young PN: ***~ 700 years old***

T_{star} ~ 200,000 K

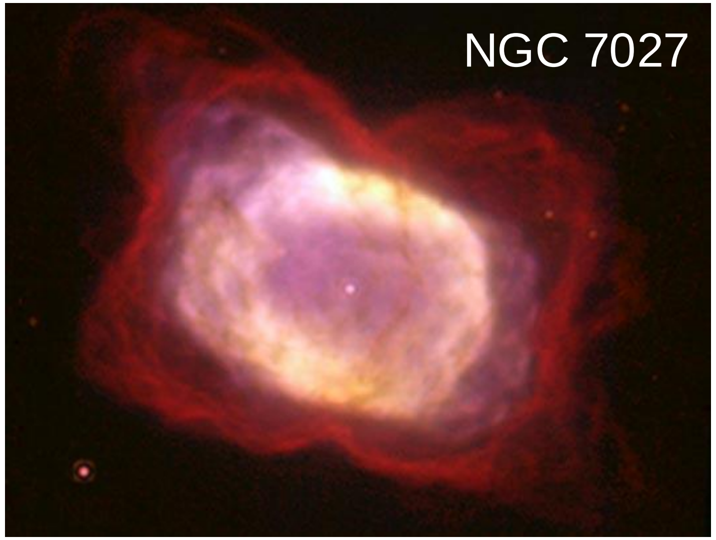
Molecular Content:

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



Zhang et al. 2008

Chemistry in **Planetary Nebula**



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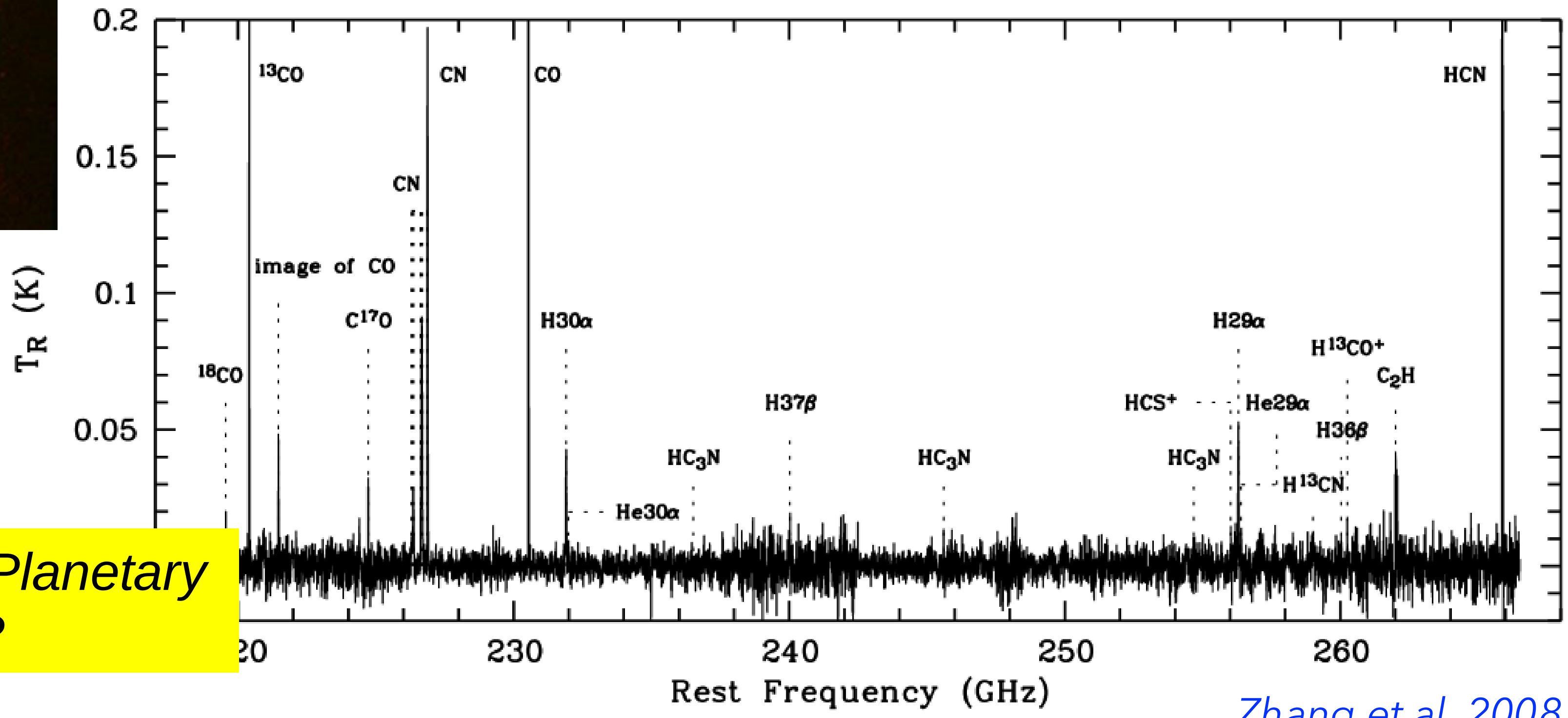


But what about OLDER Planetary Nebulae (> 1000 yrs) ??

Zhang et al. 2008

Chemistry in **Planetary Nebula**

- Age: **12,000 yrs**
- Extended spatial distribution > 1,000″
- Highly ionized atomic gas (e.g. O'Dell et al. 2004, Meaburn et al. 2005)
- Lines of H I, [S II], [N II], C I, and [O I]
- **H_2 and CO** also detected
- **Coincident** with ionized gas
- One position: rich molecular content:
- Bachiller et al. (1997): **HCN, HNC, HCO^+, CN**
- Tenenbaum et al. (2009): **C_2H, c-C_3H_2, H_2CO**
- Look at the molecular content globally….

Oldest Known Planetary Nebula: **The Helix**

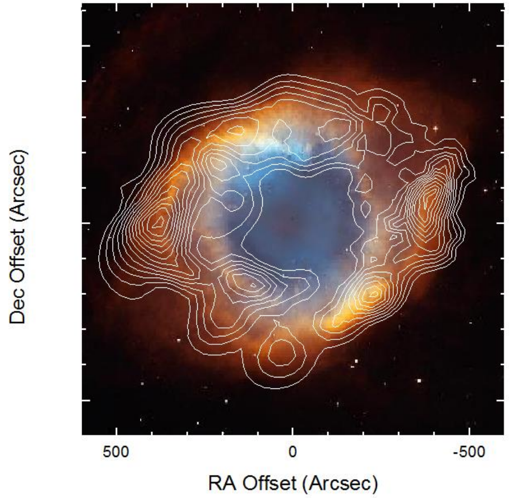
Credit: L. Ziurys

Chemistry in **Planetary Nebula**

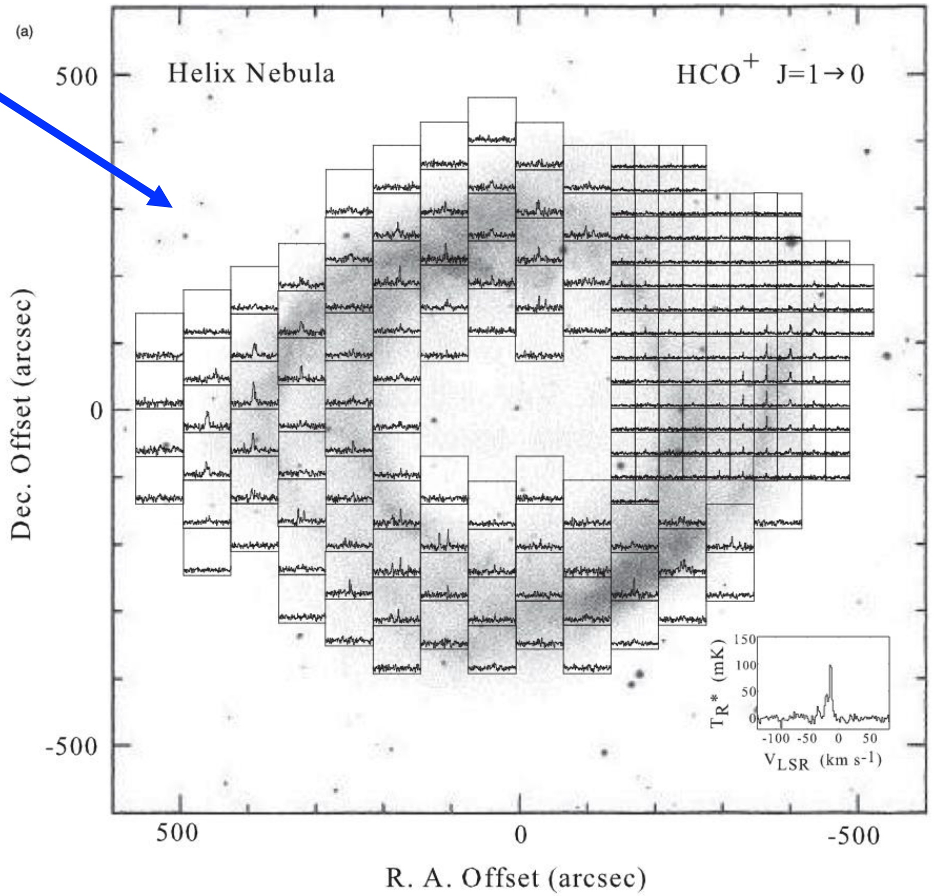
- Observe across nebula H_2CO and HCO^+
- ***Dense gas*** across Helix

  $n(H_2) \sim 0.3 - 8 \times 10^5$ cm^{-3}
- **$T_K \sim 20 – 45$ K**
- Mapped $J = 1 \rightarrow 0$ transition of HCO^+ across entire nebula
- First time for old PNe
- Found at most positions
- HCO^+ emission *follows*

  optical atomic image
- $HCO^+/H_2 \sim 10^{-8}$



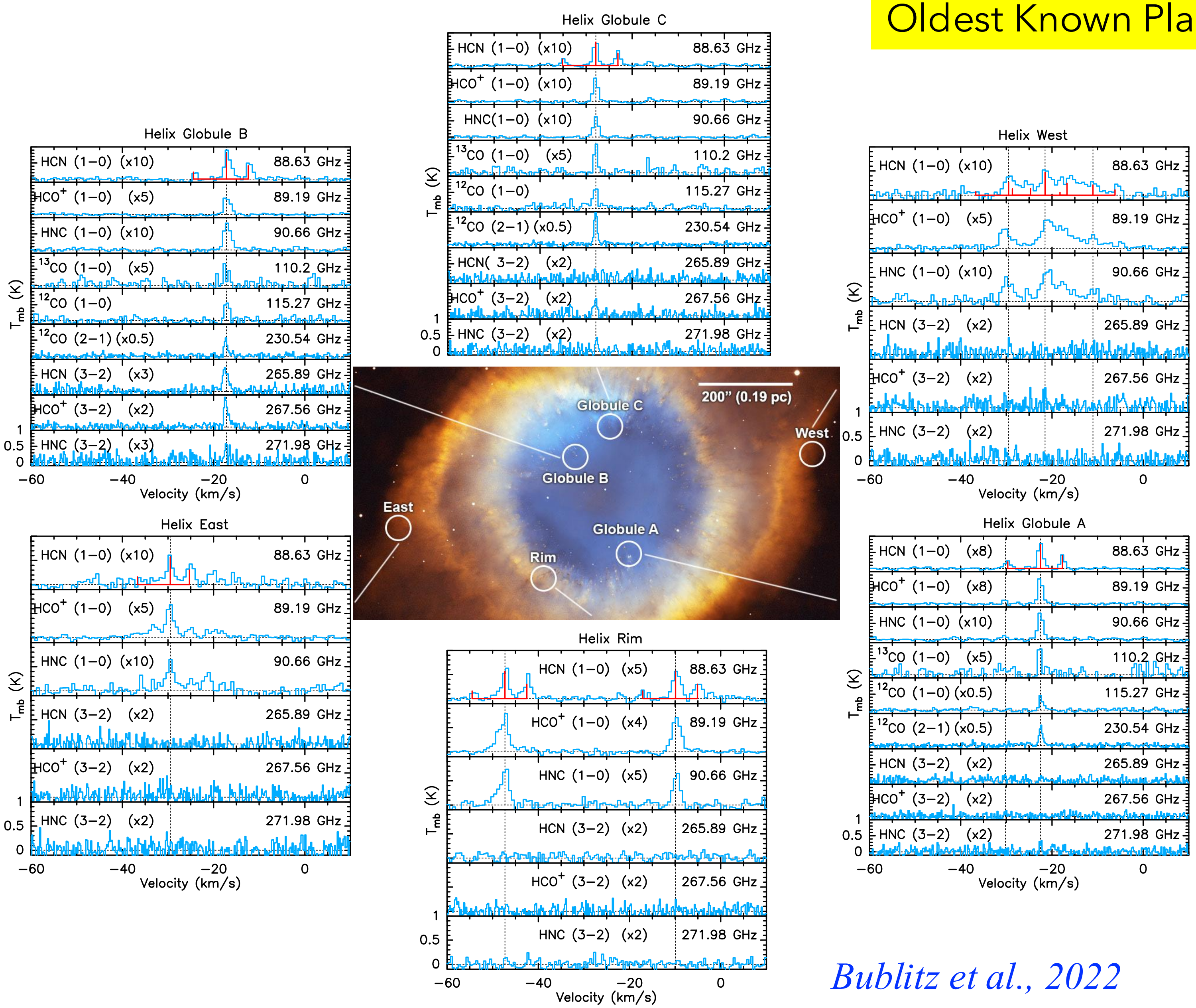
Oldest Known Planetary Nebula: **The Helix**



Zeigler et al., 2013

Credit: L. Ziurys

Oldest Known Planetary Nebula: **The Helix**



Bublitz et al., 2022

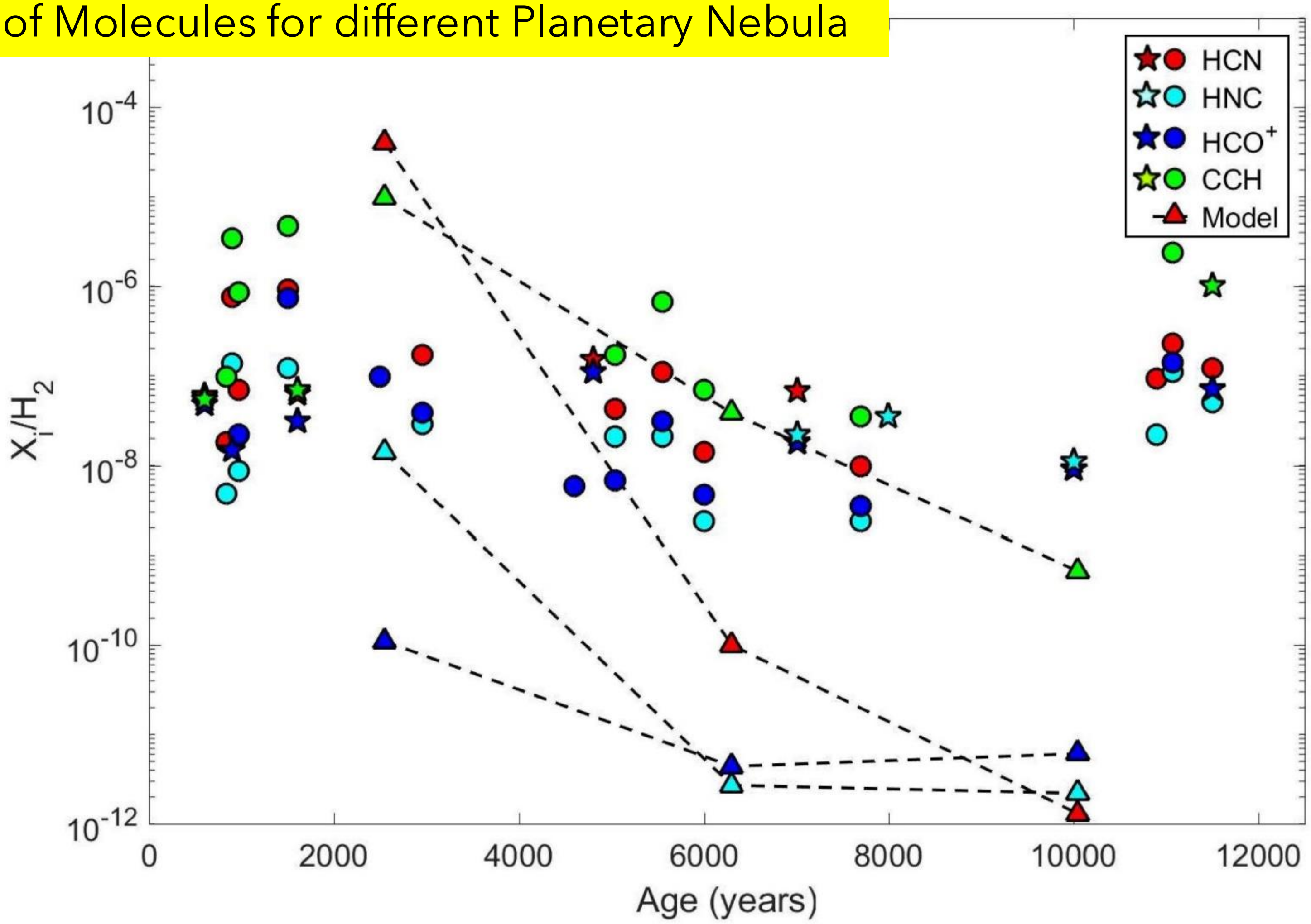
- HCO^+ across Helix → X-ray irradiation in outer regions where photodissociation is limited and cold gas and ionized molecules abundant
- increase of HNC/HCN ratio with radial distance – indicate dependence not only on UV irradiation but gas pressure and density

Chemistry depends on environment and physical properties of the gas!

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

Abundance of Molecules for different Planetary Nebula

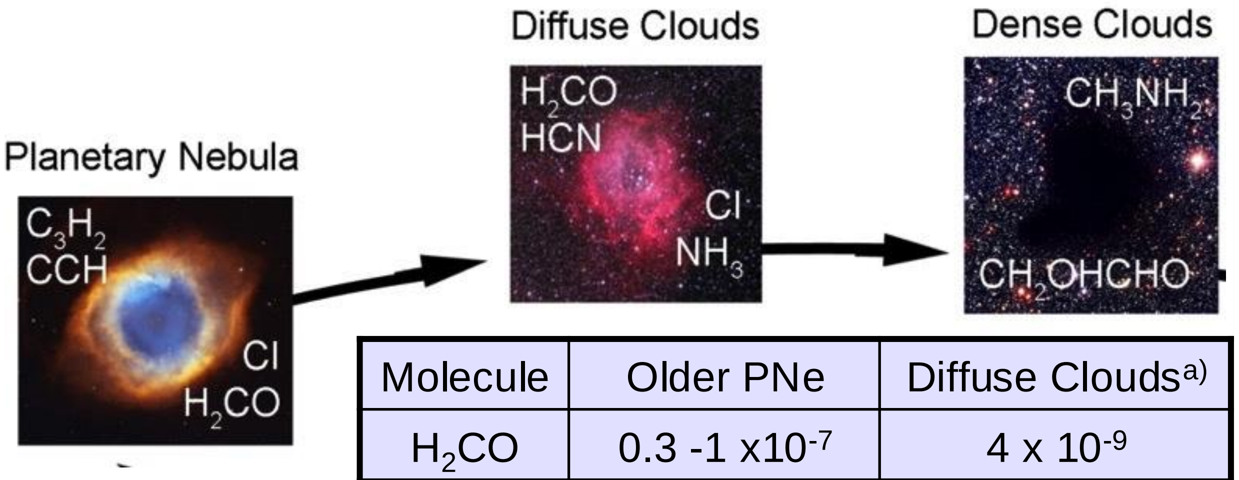
- Molecule abundances stay *constant with age*
- Not destroyed by Photodissociation
- Survive in dense clumps! with $n(H_2) \sim 10^6$ cm^{-3}
- Molecular clumps ejected into diffuse ISM
- ***Preserve C-enrichment***



Credit: L. Ziurys

Planetary Nebula connection to **Diffuse Clouds**

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



Molecular Abundances →

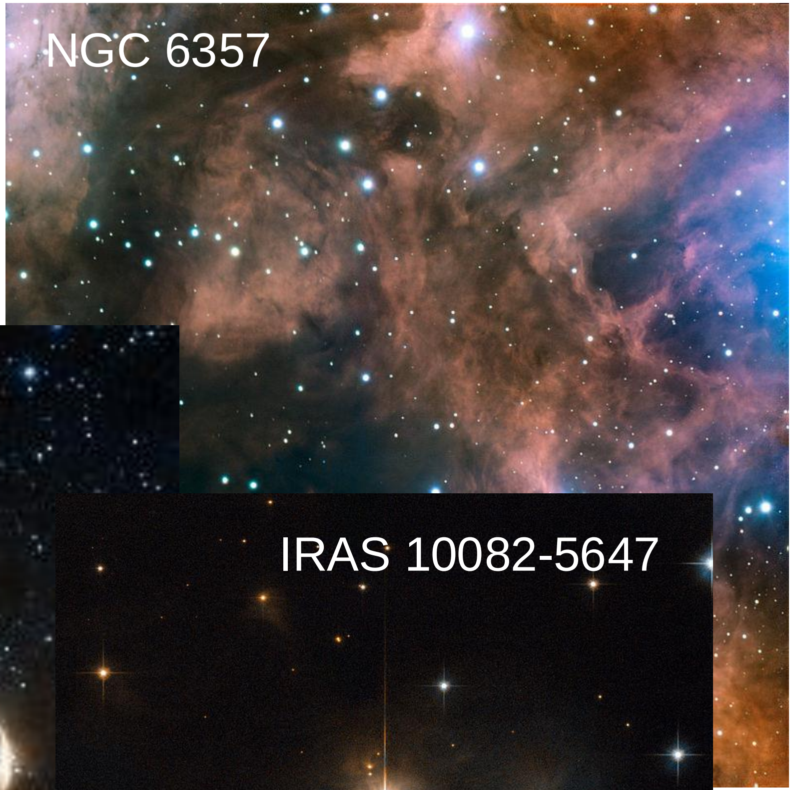
Molecule	Older PNe	Diffuse Clouds[a)]
H_2CO	$0.3 - 1 \times 10^{-7}$	4×10^{-9}
C_2H	1×10^{-6}	3×10^{-8}
$c\text{-}C_3H_2$	1×10^{-8}	1×10^{-9}
CO	$0.5 - 9 \times 10^{-4}$	3×10^{-6}
CN	3×10^{-6}	2×10^{-8}
HCN	5×10^{-7}	3×10^{-9}
HNC	3×10^{-7}	6×10^{-10}
HCO^+	$0.1 - 5 \times 10^{-8}$	2×10^{-9}
SO	$0.2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

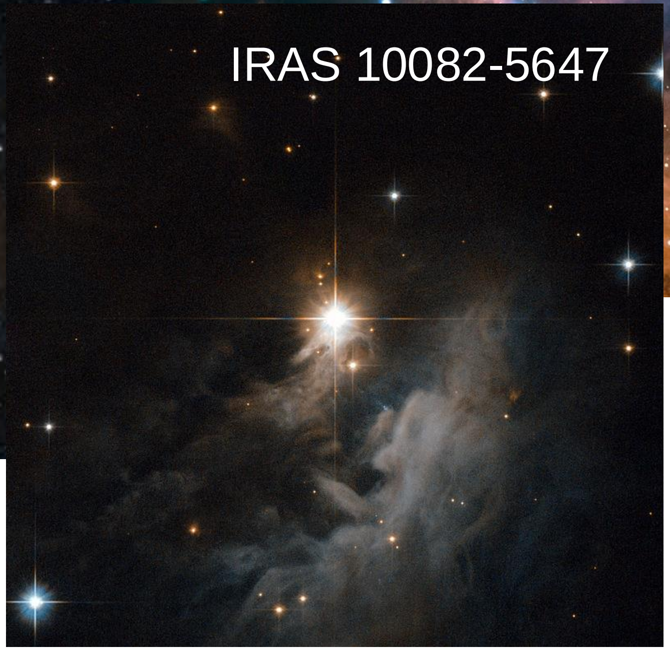
a) Liszt et al. 2006

Credit: L. Ziurys

Diffuse Clouds – Definition and Chemical Makeup

- 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

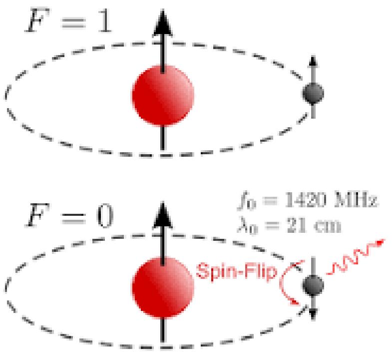


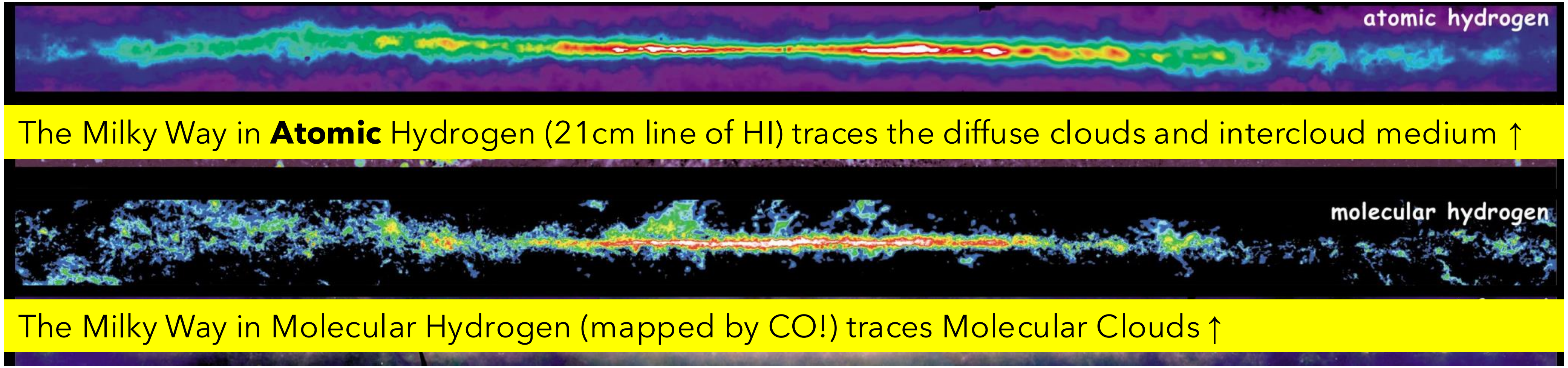


Diffuse Clouds – Definition and Chemical Makeup

- 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 H I 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 ↑

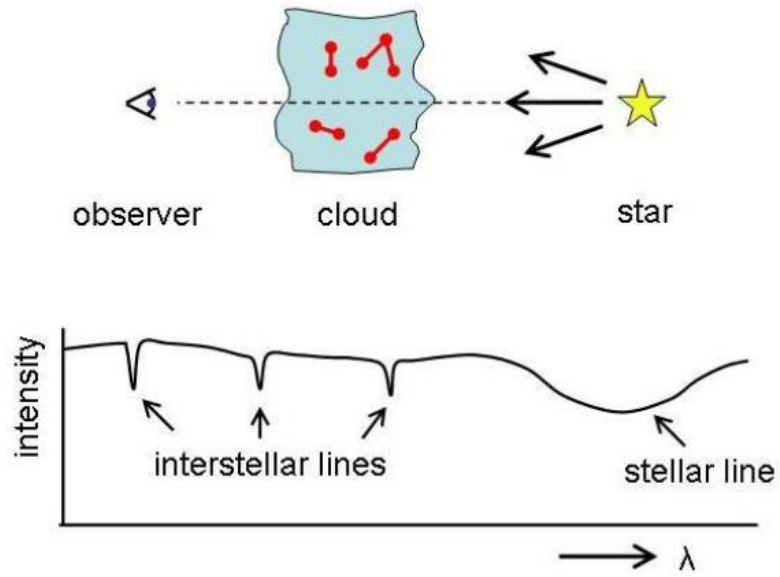
Reminder! Typical Conditions of Molecular Clouds: T ~ 10 – 50 K; n ~ 10^3 – 10^6 cm^{-3}

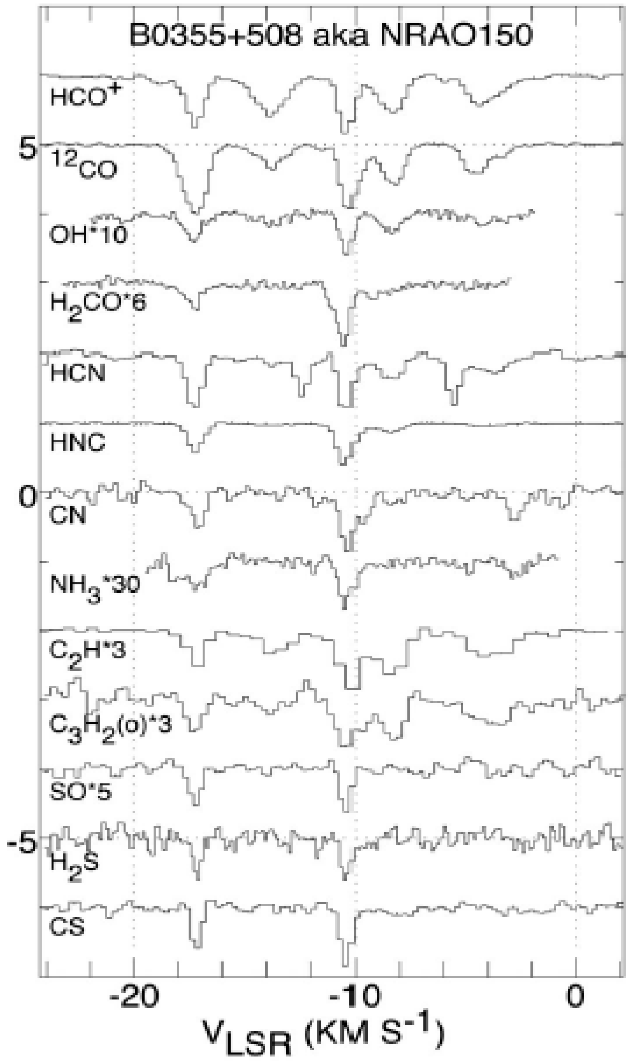
Diffuse Clouds – Definition and Chemical Makeup

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

- 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^+

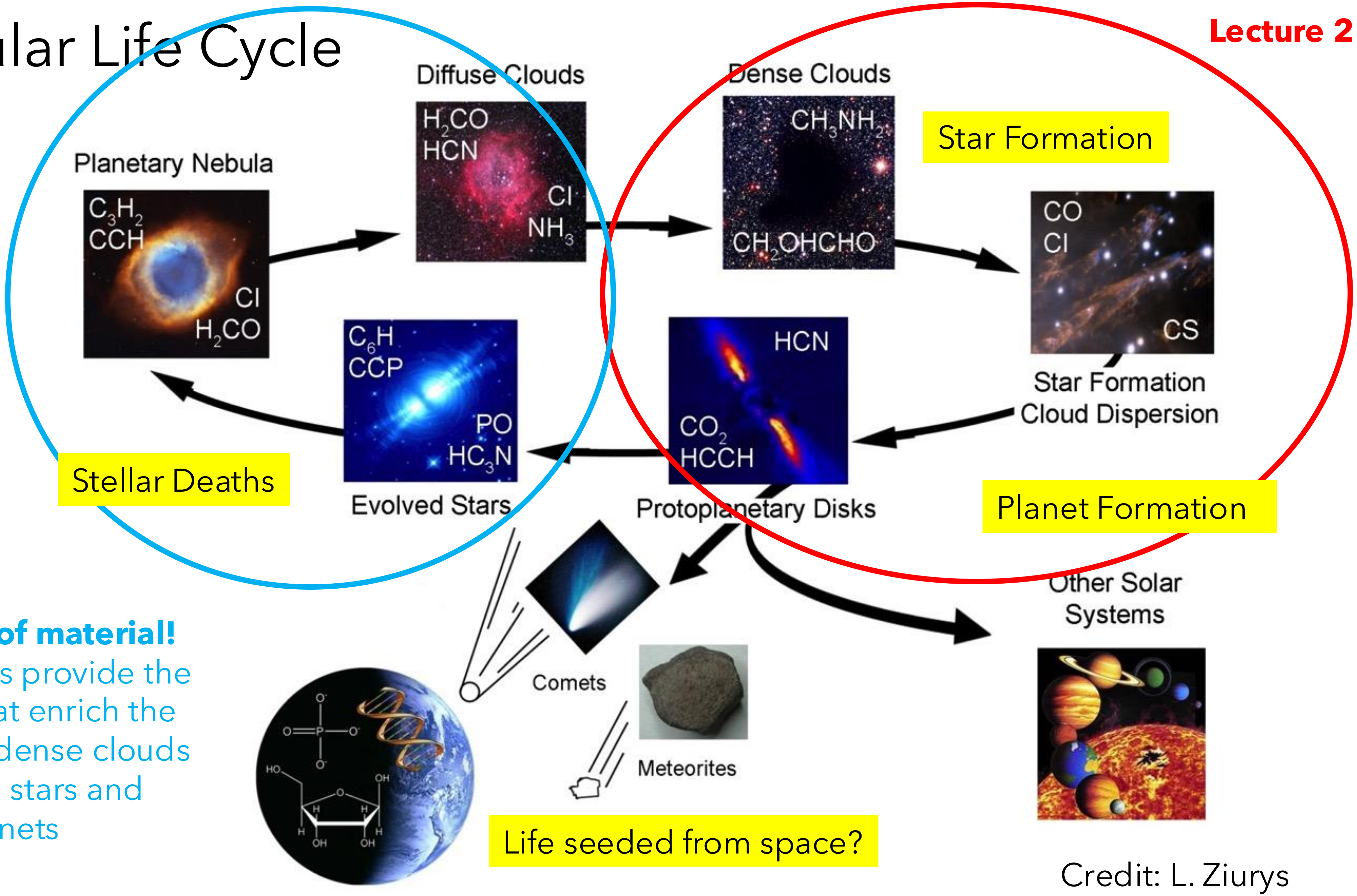




Credit: L. Ziurys

Molecular Life Cycle

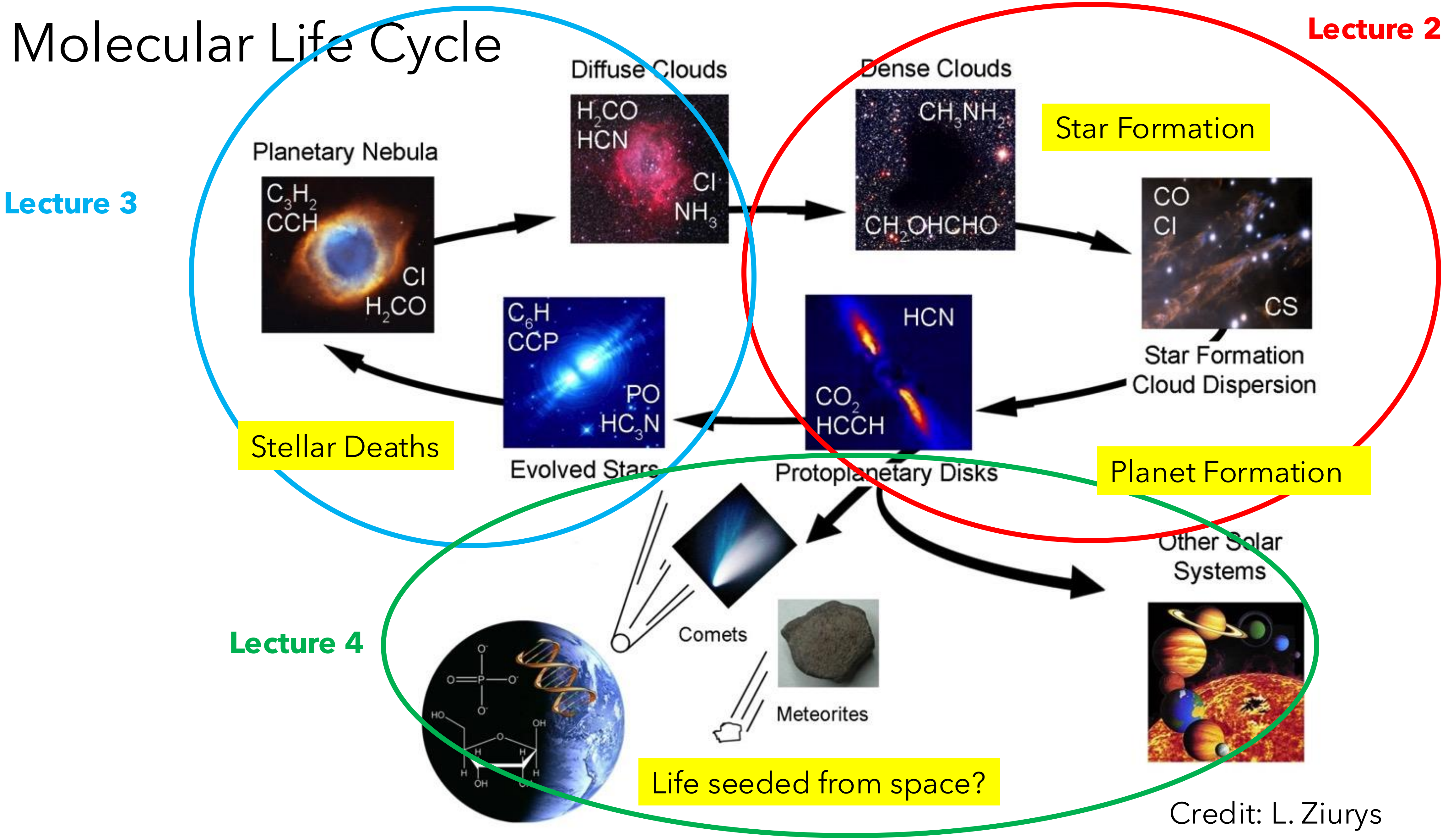
Lecture 3



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

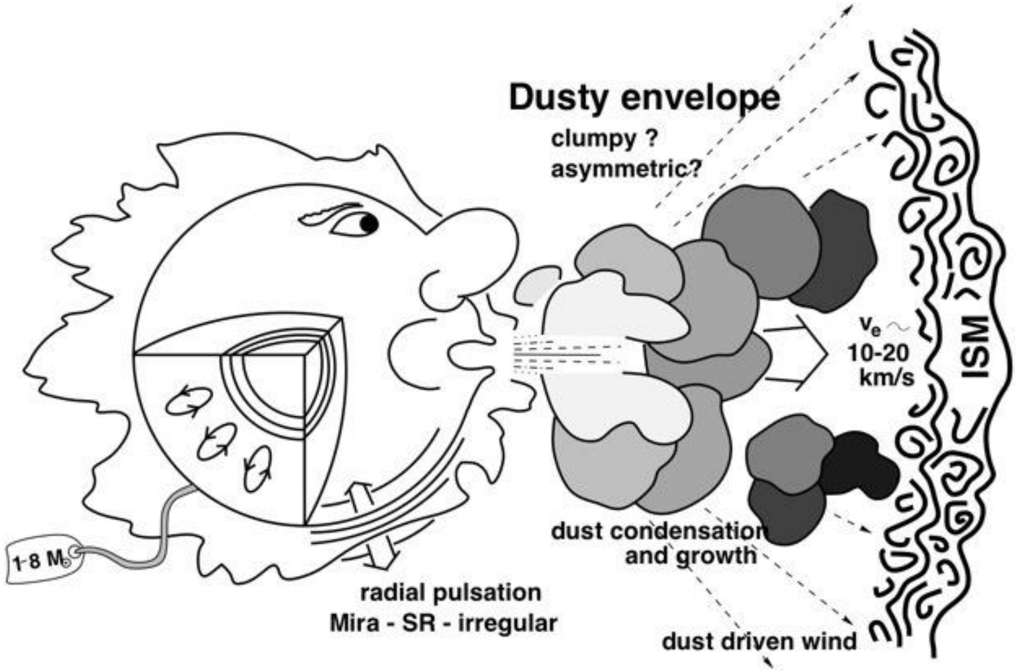
Credit: L. Ziurys

Molecular Life Cycle



Credit: L. Ziurys

SUMMARY:



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

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

- Dust grains are formed in the circumstellar shells of evolved stars, specifically AGBs! Dust and molecular gas is transported outward in winds, enriching the interstellar medium! **Mass loss from Evolved stars supplies ~85% of the material in the ISM!**

- **Evolved stars show a rich chemistry** in the submillimeter and millimeter spectrum, which is regulated by photochemistry (photon chemistry) from the central star.

- In the **planetary nebula phase molecule abundances stay consistent with age**, and thus are not destroyed by photodissociation! These molecules enrich the surrounding **diffuse** gas and eventually the dense gas that goes on to form stars and planets!


Visible light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Dedicated August 25, 2000 Green Bank, West Virginia

Questions?