ASTROCHEMISTRY

FROM THE BIG BANG TO LIFE

Global Astrochemistry Lecture Series (GALS) 2024

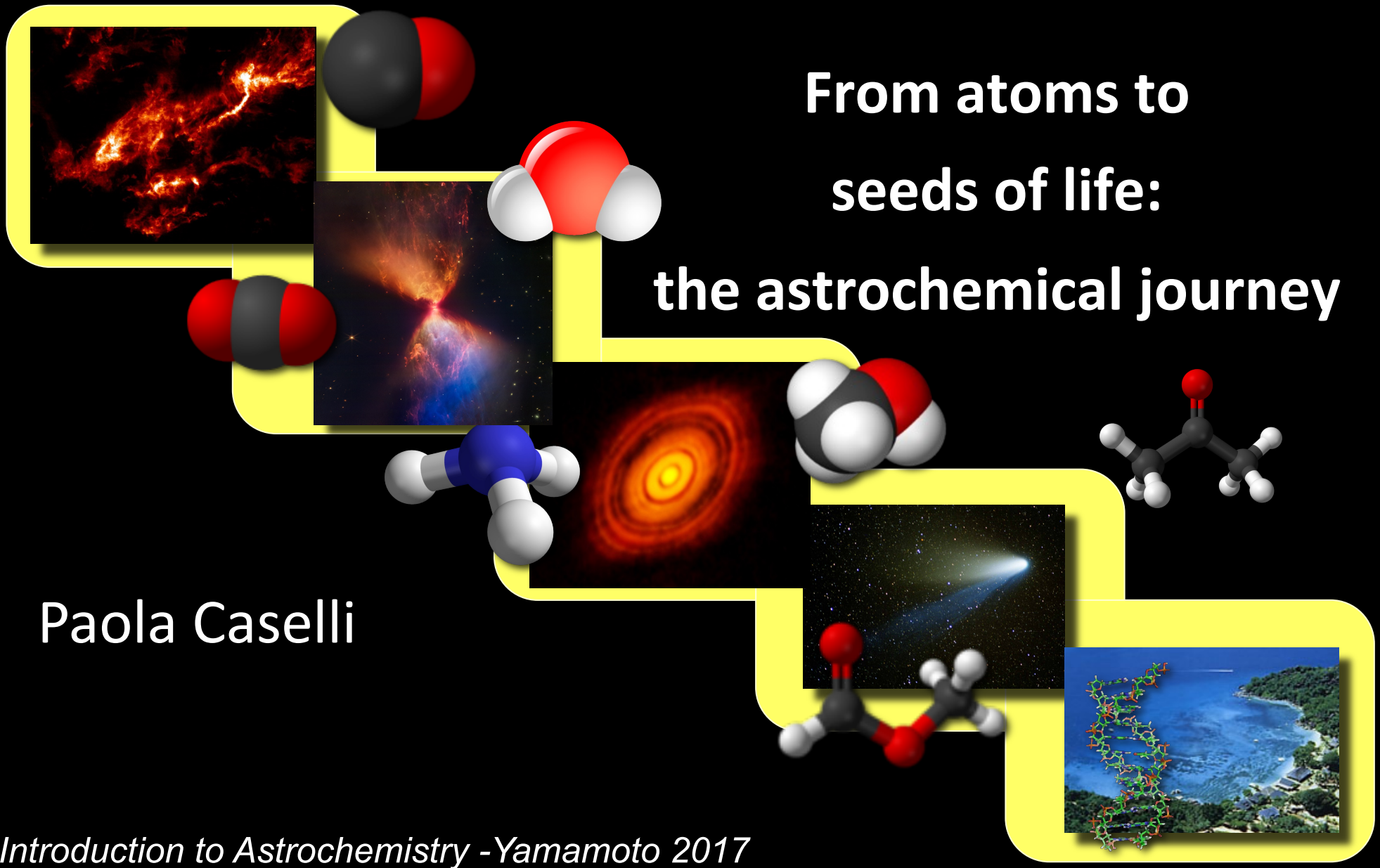
FROM ATOMS TO THE SEEDS OF LIFE: THE ASTROCHEMICAL JOURNEY

Paola Caselli. *Max Planck Institute for Extraterrestrial Physics, Germany*

23.02.2024 | 15:00 - 17:00 CET

cost EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY
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Center for Astrochemical Studies
Max Planck Institute for Extraterrestrial Physics



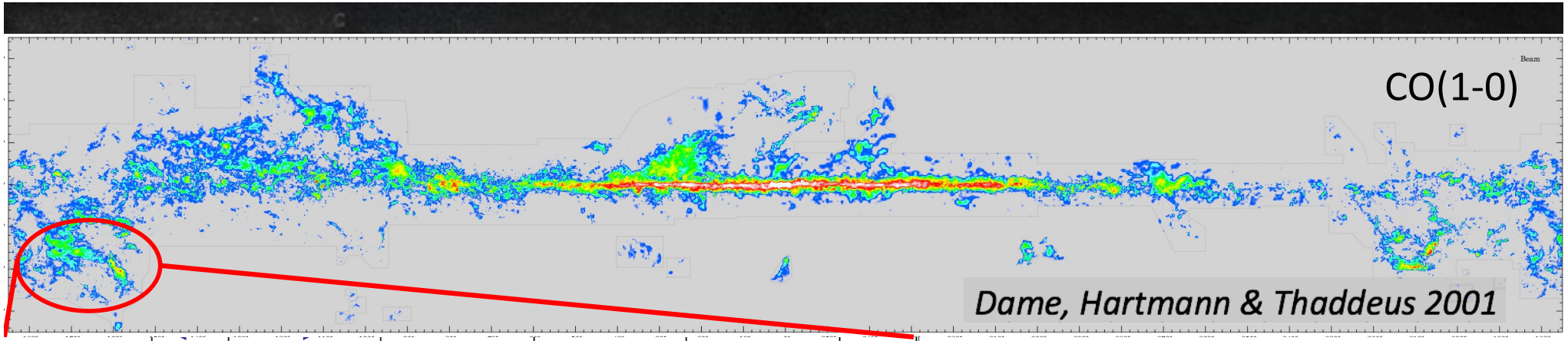
From atoms to seeds of life: the astrochemical journey

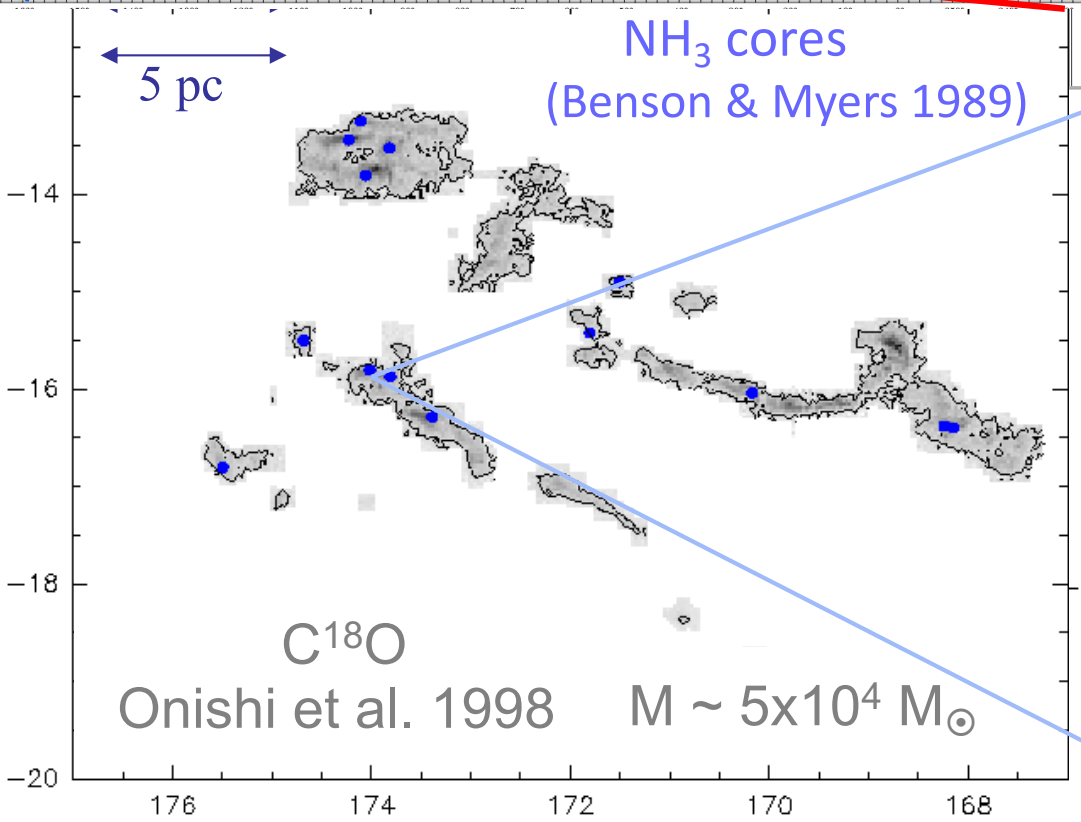
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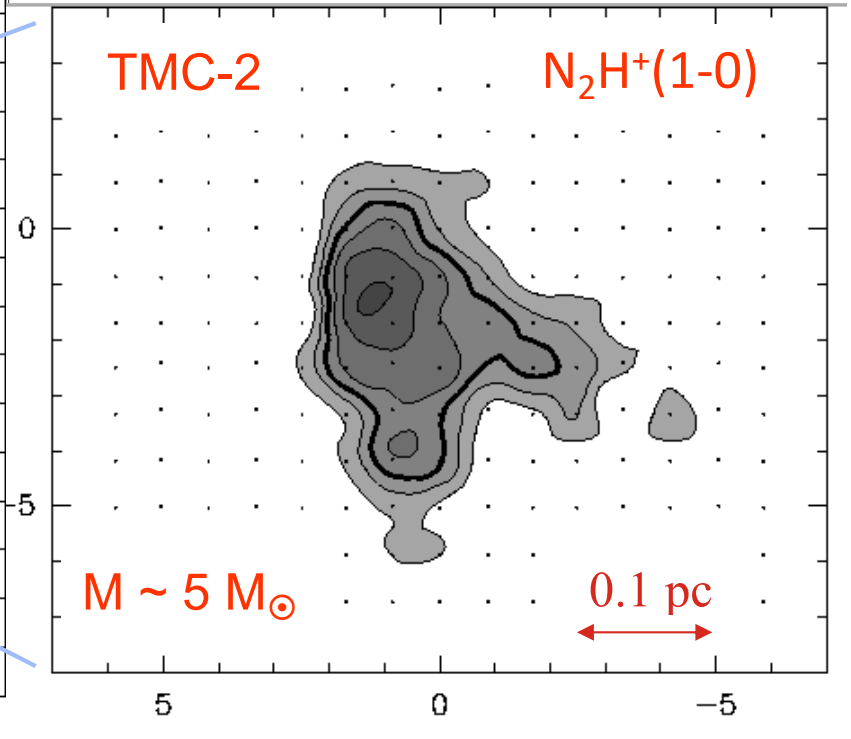
Introduction to Astrochemistry -Yamamoto 2017

Molecular clouds and star formation

~ 100,000 light years







Interstellar molecules: seeds of life in space

(total known: >270)

2 atoms		3 atoms		4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H_2	SiO	C_3*	CO_2*	c-C_3H	C_5*	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-C_6H_6*	C_{60}*
AlF	SiS	C_2H	NH_2	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7	C_{70}*
AlCl	CS	C_2O	H_3^+(*)	C_3N	C_4Si	C_2H_4*	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN	C_{60}^+*
C_2**	HF	C_2S	SiCN	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$	$C_2H_5OCH_3$	c-C_6H_5CN
CH	HD	CH_2	AlNC	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	C_6H_2	HC_7N	CH_3CHCH_2O			
CH^+	FeO?	HCN	SiNC	C_2H_2*	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H	CH_3OCH_2OH			
CN	O_2	HCO	HCP	NH_3	CH_4*	CH_3SH	c-C_2H_4O	l-HC_6H*	$CH_3C(O)NH_2$				
CO	CF^+	HCO^+	CCP	HCCN	HC_3N	HC_3NH^+	H_2CCHOH (?)	CH_2CHCHO(?)	C_8H^-				
CO^+	SiH?	HCS^+	AlOH	HCNH$^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	PO	HOC^+	H_2O^+	HNCO	HCOOH	NH_2CHO	CH_3NCO	H_2NCH_2CN	CH_3CH_2SH(?)				
SiC	AlO	H_2O	H_2Cl^+	HNCS	H_2CNH	C_5N	HC_5O (2017)	CH_3CHNH	CH_3NHCHO				
HCl	OH^+	H_2S	KCN	$HOCO^+$	H_2C_2O	l-HC_4H*	$HOCH_2CN$	CH_3SiH_3	HC_7O				
KCl	CN-	HNC	FeCN	H_2CO	H_2NCN	l-HC_4N		$H_2NC(O)NH_2$					
NH	SH^+	HNO	HO_2	H_2CN	HNC_3	c-H_2C_3O							
NO	SH	MgCN	TiO_2	H_2CS	SiH_4*	H_2CCNH (?)							
NS	HCl^+	MgNC	C_2N	H_3O^+	H_2COH^+	C_5N^-							
NaCl	TiO	N_2H^+	Si_2C	c-SiC_3	C_4H^-	HNCHCN							
OH	ArH^+	N_2O	HS_2	CH_3*	HC(O)CN	SiH_3CN							
PN	N	NaCN	HCS	C_3N^-	HNCNH	C_5S (?)							
SO	NO^+?	OCS	HSC	PH_3	CH_3O	MgC_4H							
SO^+	NS^+	SO_2	NCO	HCNO	NH_4^+								
SiN	HeH^+	c-SiC_2	CaNC	HOCN	H_2NCO^+								
				HSCN	$NCCNH^+$								
				H_2O_2	CH_3Cl								
				C_3H^+	MgC_3N								
				HMgNC									
				HCCO									
				CNCN									
				HONO									
				MgC_2H									

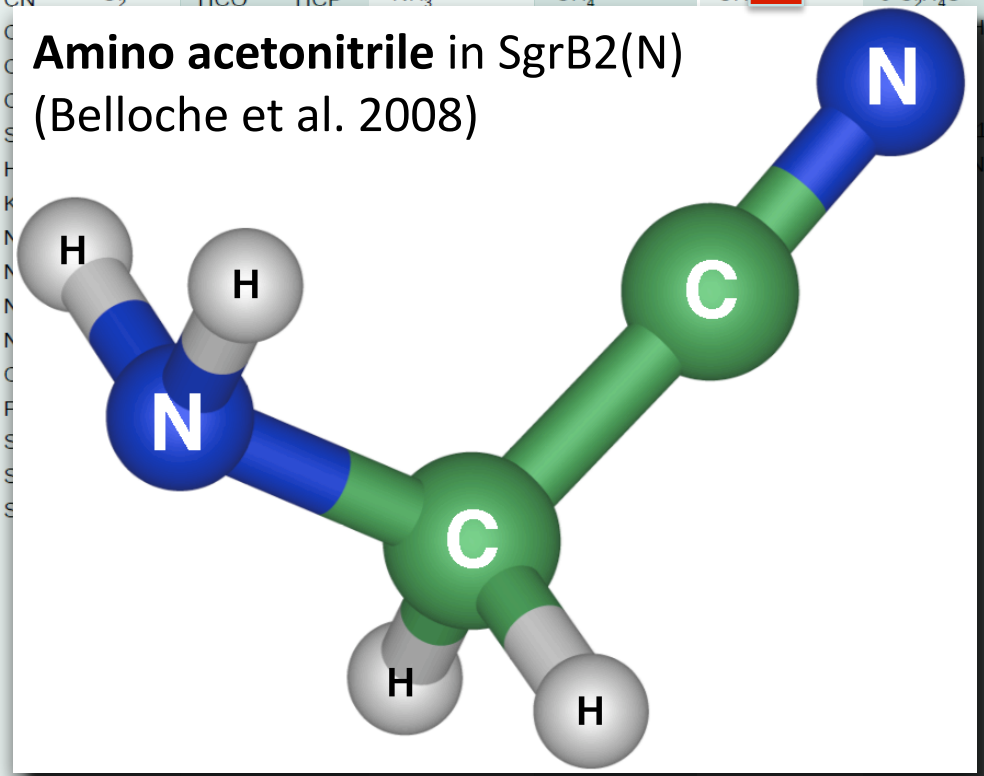
https://cdms.astro.uni-koeln.de/classic/molecules (courtesy C. Endres) *McGuire 2021*

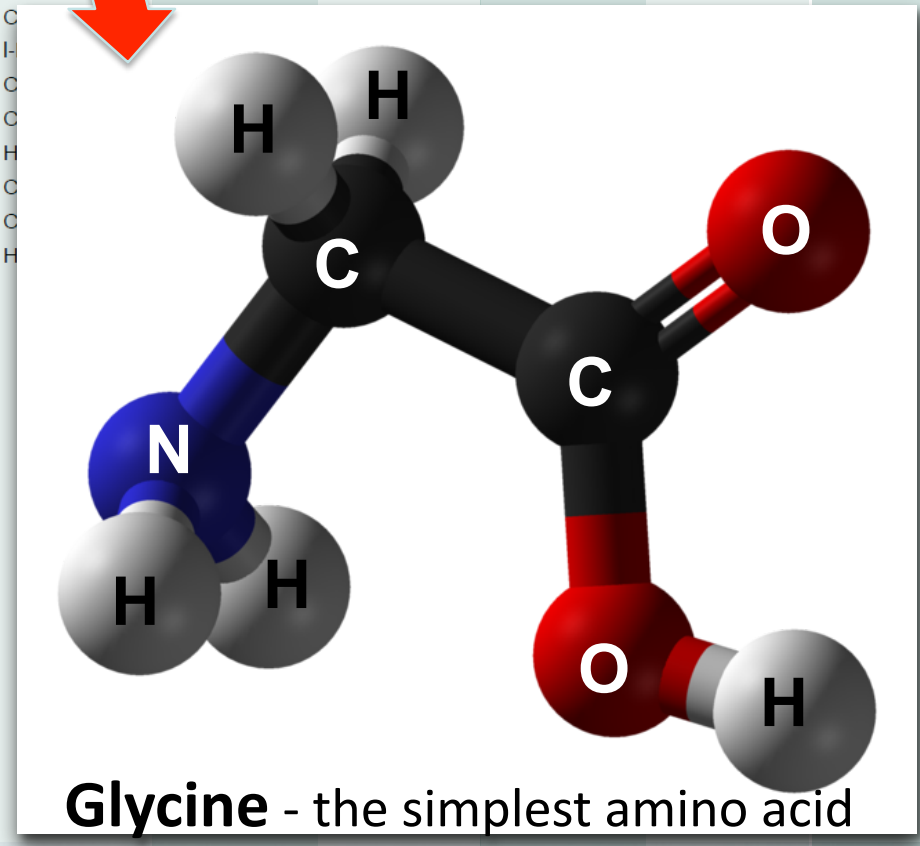
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CH^+	FeO?	HCN	SiNC	C_2H_2*	H_2CCN	CH_3OH	CH_3NH_2						
CN	O_2	HCO	HCP	NH_3	CH_4*	CH$_2$NH	c-C_2H_4O						

Amino acetonitrile in SgrB2(N)
(Belloche et al. 2008)





Glycine - the simplest amino acid

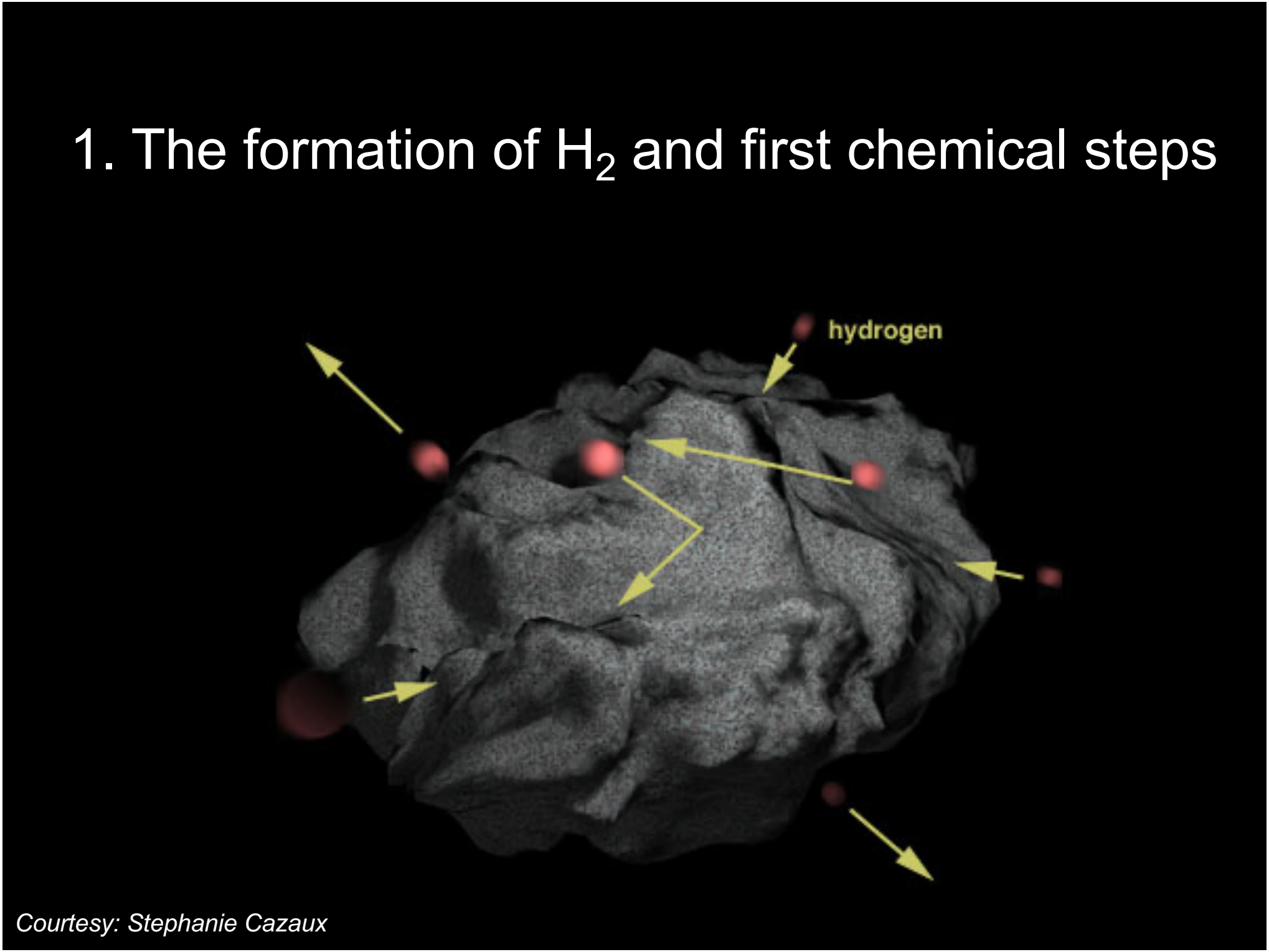
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McGuire 2021

Outline

1. The formation of H_2 and first chemical steps
2. The formation of H_3^+
3. The chemistry initiated by H_3^+
4. Formation and destruction of CO
5. Nitrogen chemistry
6. Ice formation and freeze-out
7. The importance of cosmic rays
8. Complex Organic Molecules (COMs)

1. The formation of H_2 and first chemical steps



Courtesy: Stephanie Cazaux

How do molecules form in the interstellar medium ?

The most elementary chemical reaction is the association of A and B to form a molecule AB with internal energy:

$$A + B \rightarrow AB^*$$

The molecule AB^* must lose the internal energy. In the Earth atmosphere, where the number of particles per cubic centimeter (cc) is very large (~10^{19}), the molecule loses its energy via three-body reactions:

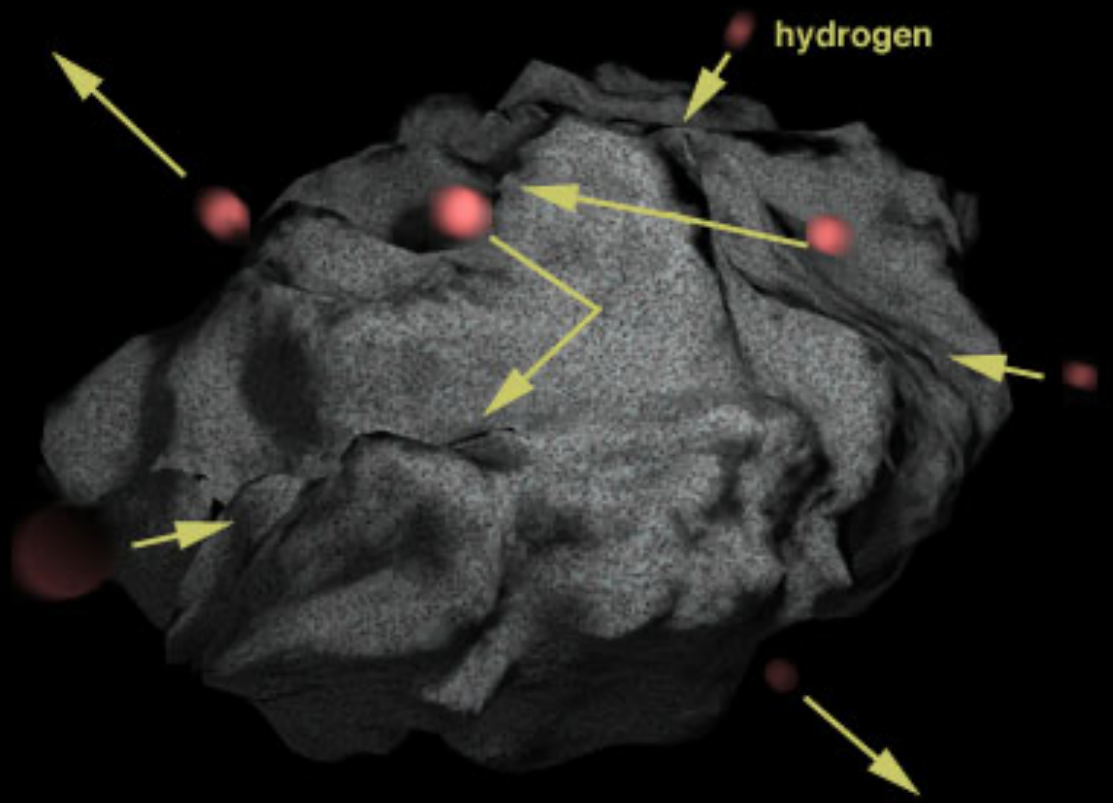
$$AB^* + M \rightarrow AB$$

But this is not an efficient process in interstellar clouds, where the number of particles per cc ranges between a few hundred and 10^7.

The reaction that starts the chemistry in the interstellar medium is the one between two hydrogen atoms to form molecular hydrogen:

$$H + H \rightarrow H_2$$

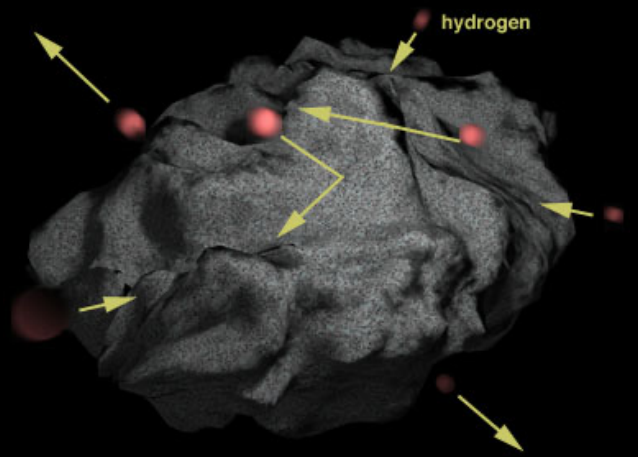
This reaction happens on the surface of dust grains.



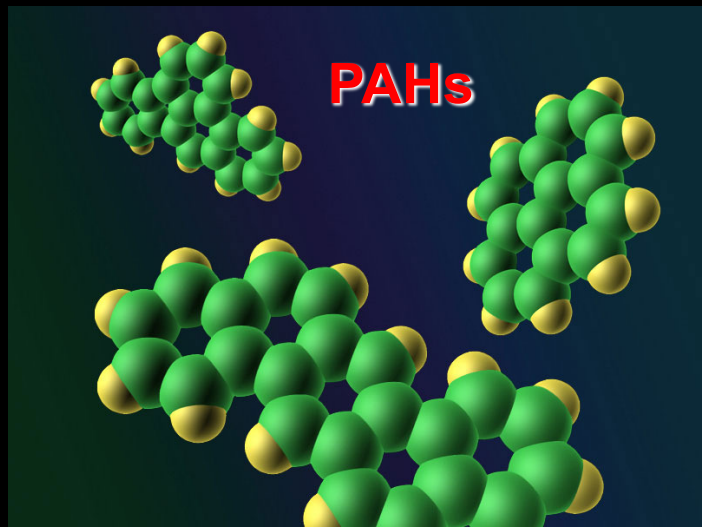
The H_2 formation rate ($cm^{-3}\ s^{-1}$) is given by (Gould & Salpeter 1963; Hollenbach & Salpeter 1970; Jura 1974; Pirronello et al. 1999; Cazaux & Tielens 2002; Bergin et al. 2004; Cuppen & Herbst 2005; Cazaux et al. 2008):

$$R_{H_2} = \frac{1}{2} n_H v_H A n_g S_H \gamma$$

$$\sim 10^{-17} - 10^{-16} cm^{-3} s^{-1}$$



$n_H \equiv$ gas number density
$v_H \equiv$ H atoms speed in gas-phase
$A \equiv$ grain cross sectional area
$n_g \equiv$ dust grain number density
$S_H \equiv$ sticking probability
$\gamma \equiv$ surface reaction probability



(for H_2 formation on PAHs see: Habart+2004; Boschman+2015)

Once H2 is formed, the fun starts…

H_2 is the key to the whole of interstellar chemistry. Some important species that might react with H_2 are C, C+, O, N… To decide whether a certain reaction is chemically favored, we need to examine internal energy changes.

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

Question: Can the following reactions proceed in the cold interstellar medium?

$C + H_2 \rightarrow CH + H$??

$C^+ + H_2 \rightarrow CH^+ + H$??

$O + H_2 \rightarrow OH + H$??

$O^+ + H_2 \rightarrow OH^+ + H$??

Once H2 is formed, the fun starts…

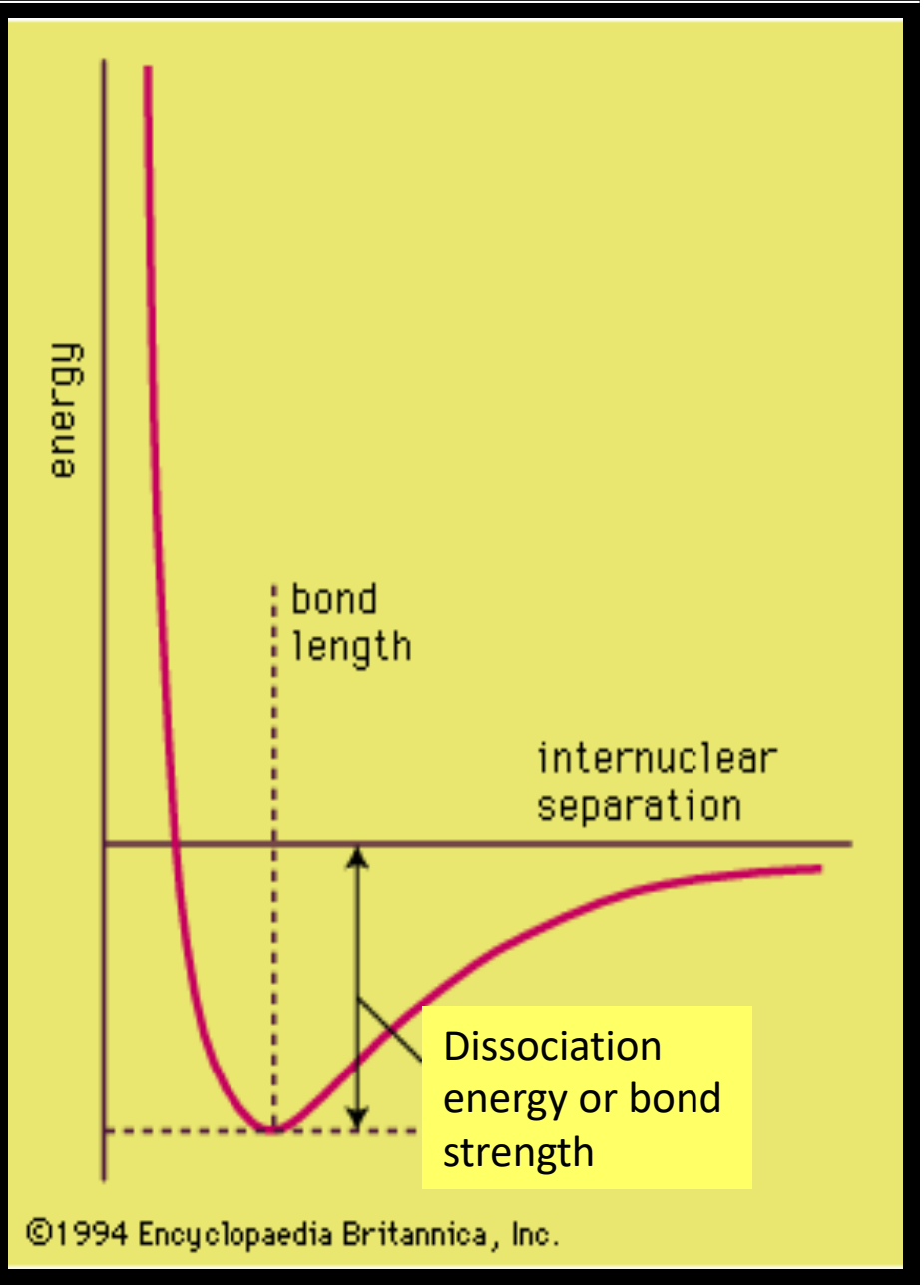
$C + H_2 \rightarrow CH + H$??

4.48 eV

3.47 eV

The bond strength of H_2 is larger than that of CH ➔ the reaction is not energetically favorable.

The reaction is endothermic (by 4.48-3.47 = 1.01 eV) and cannot proceed in cold clouds, where $k_b T < 0.01$ eV !



Once H2 is formed, the fun starts…

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

$C + H_2 \not\rightarrow CH + H$ (endothermic by 1.01 eV)

$C^+ + H_2 \not\rightarrow CH^+ + H$ (endothermic by 0.39 eV)

$O + H_2 \not\rightarrow OH + H$ (endothermic by 0.09 eV)

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

Rate coefficients and activation energies

The rate coefficient k ($cm^3\ s^{-1}$) of a generic reaction A + B -> C + D is given by:

$$k = \langle \sigma v \rangle$$

$\sigma \equiv$ total cross section of the reactants
$v \equiv$ relative velocity
<The average is performed over the thermal distribution>

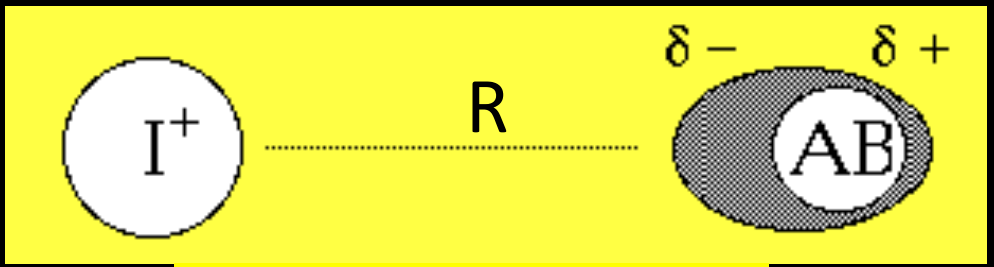
Most reactions possess activation energies E_a (~0.1-1 eV) even if exothermic and k is given by the Arrhenius formula (Herbst 1990):

$$k = a(T) exp(-E_a / k_B T)$$

Ion-Neutral reactions

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

Exothermic ion-molecule reactions do not possess activation energy because of the strong long-range attractive force (Herbst & Klemperer 1973; Anicich & Huntress 1986):



$$V(R) = - \alpha \, e^2/2R^4$$

$$k_{LANGEVIN} = 2 \pi e(\alpha/\mu)^{1/2}$$
$$\sim 10^{-9} \text{ cm}^3 \text{ s}^{-1}$$

independent of T

Neutral-Neutral reactions

$$A + BC \rightarrow AB + C$$

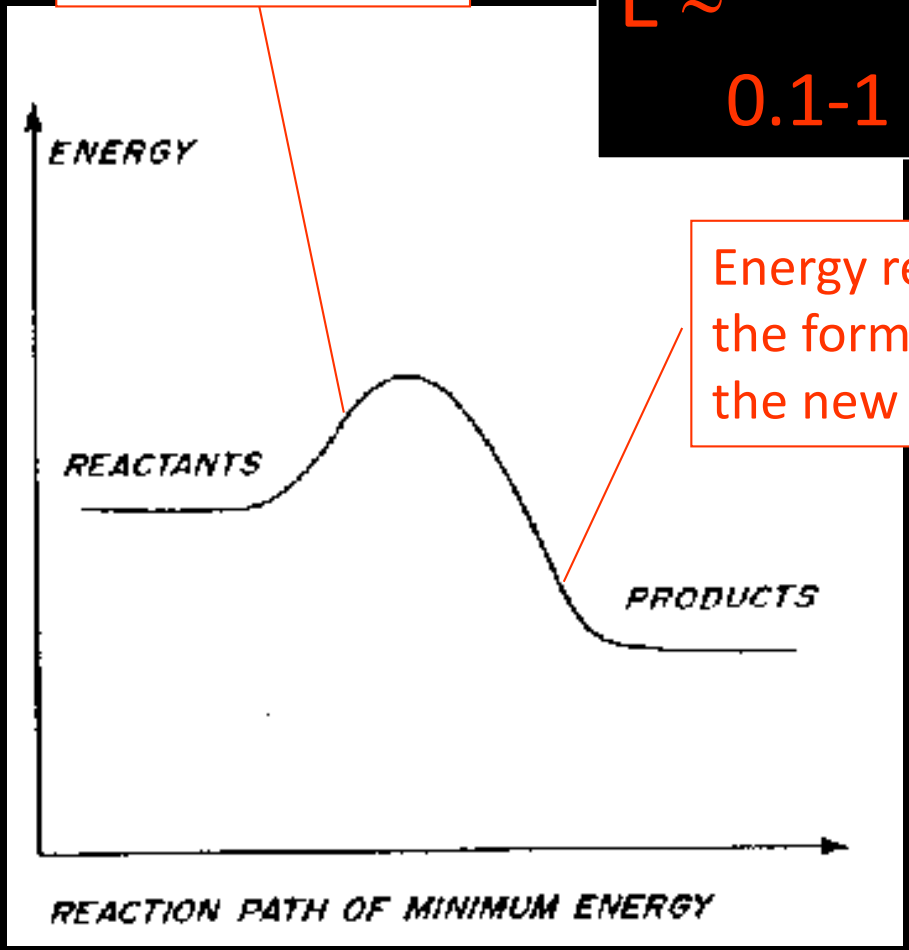
Energy to break the bond of the reactant BC.

$E \sim$ 1 eV for endothermic reactions

0.1-1 eV for exothermic reactions

Energy released by the formation of the new bond AB.

$k_b T < 0.01$ eV in molecular clouds



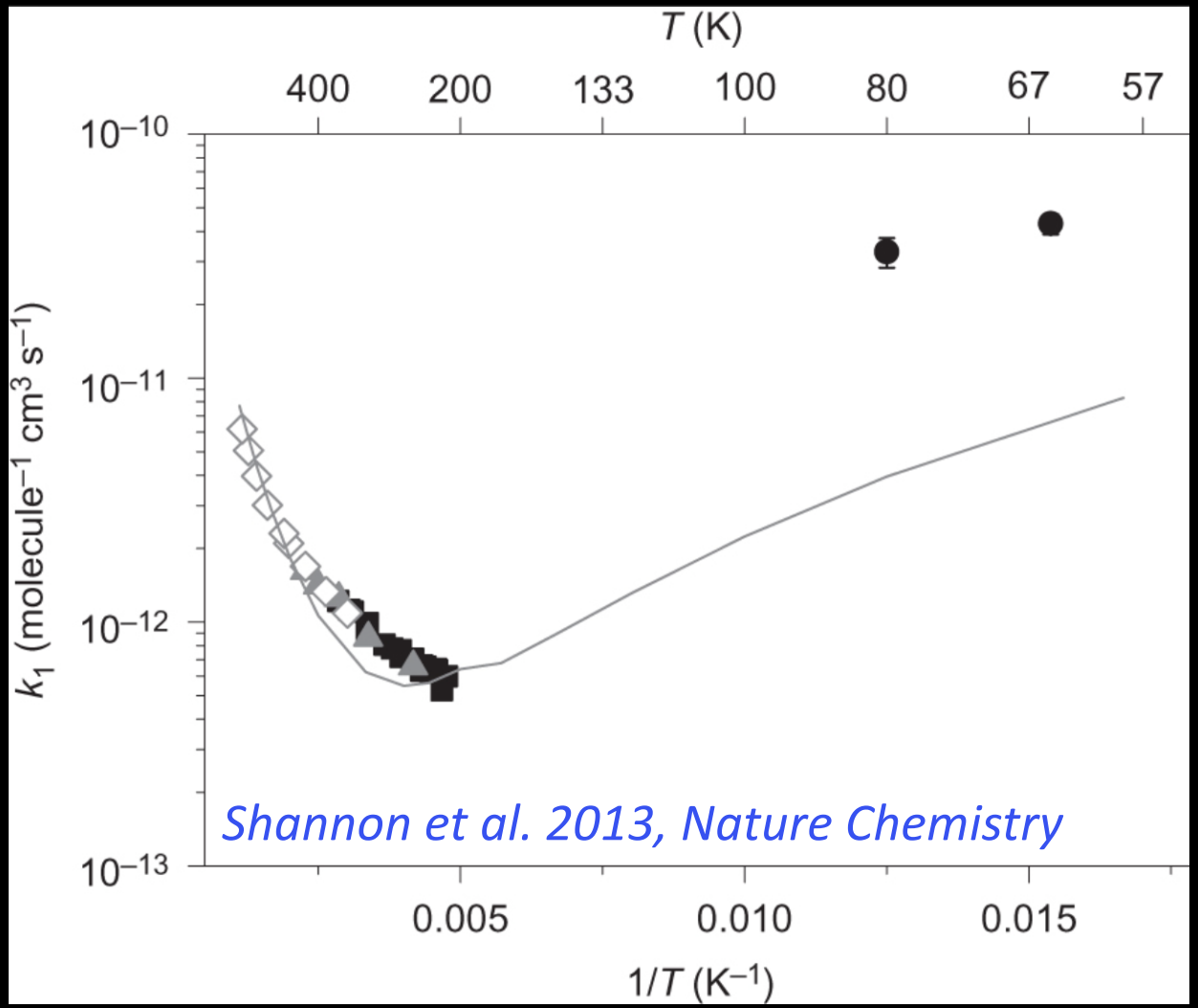
Example: $O + H_2 \not\rightarrow OH + H$
(does not proceed in cold clouds)

Duley & Williams 1984, Interstellar Chemistry;
Bettens et al. 1995, ApJ

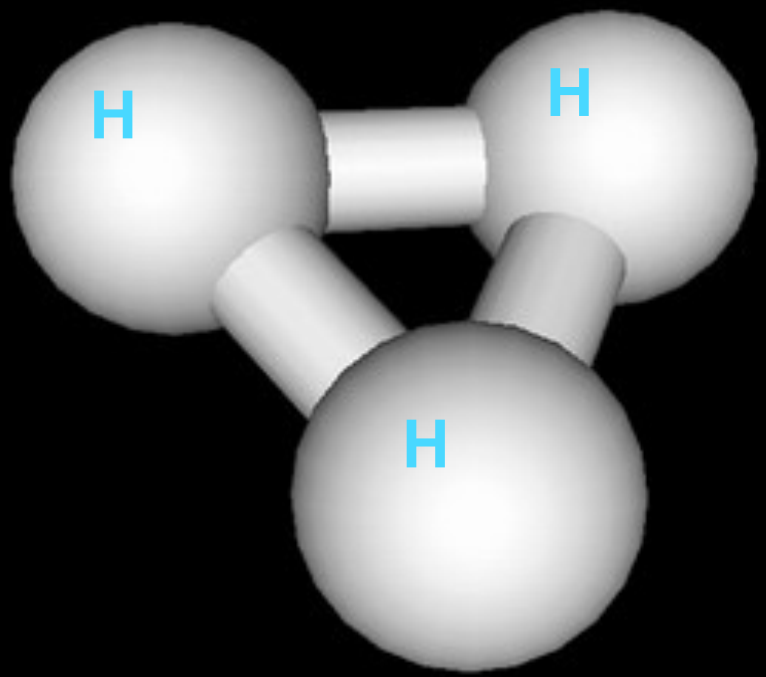
Neutral-Neutral reactions

$OH + CH_3OH \rightarrow CH_3O + H_2O$

Accelerated chemistry at low interstellar temperatures, facilitated by tunneling.



2. The formation of H_3^+

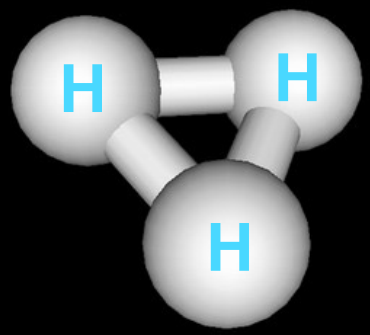


After the formation of molecular hydrogen, cosmic rays ionize H_2 initiating fast routes towards the formation of complex molecules in dark clouds:

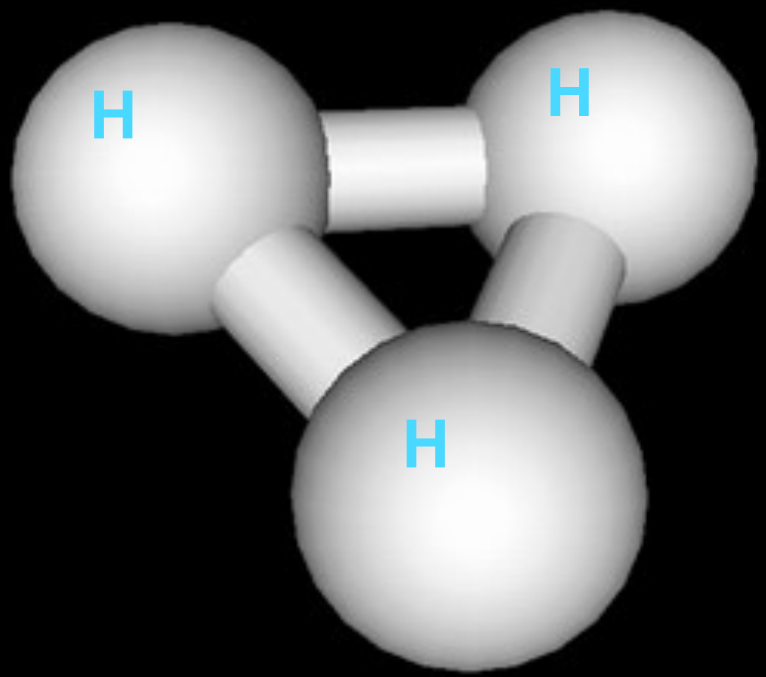
$$H_2 + \text{c.r.} \rightarrow H_2^+ + e^- + \text{c.r.}$$

Once H_2^+ is formed (97% of the times a c.r. hits H_2), it very quickly reacts with the abundant H_2 molecules to form H_3^+, the most important molecular ion in interstellar chemistry.

$$H_2^+ + H_2 \rightarrow H_3^+ + H$$

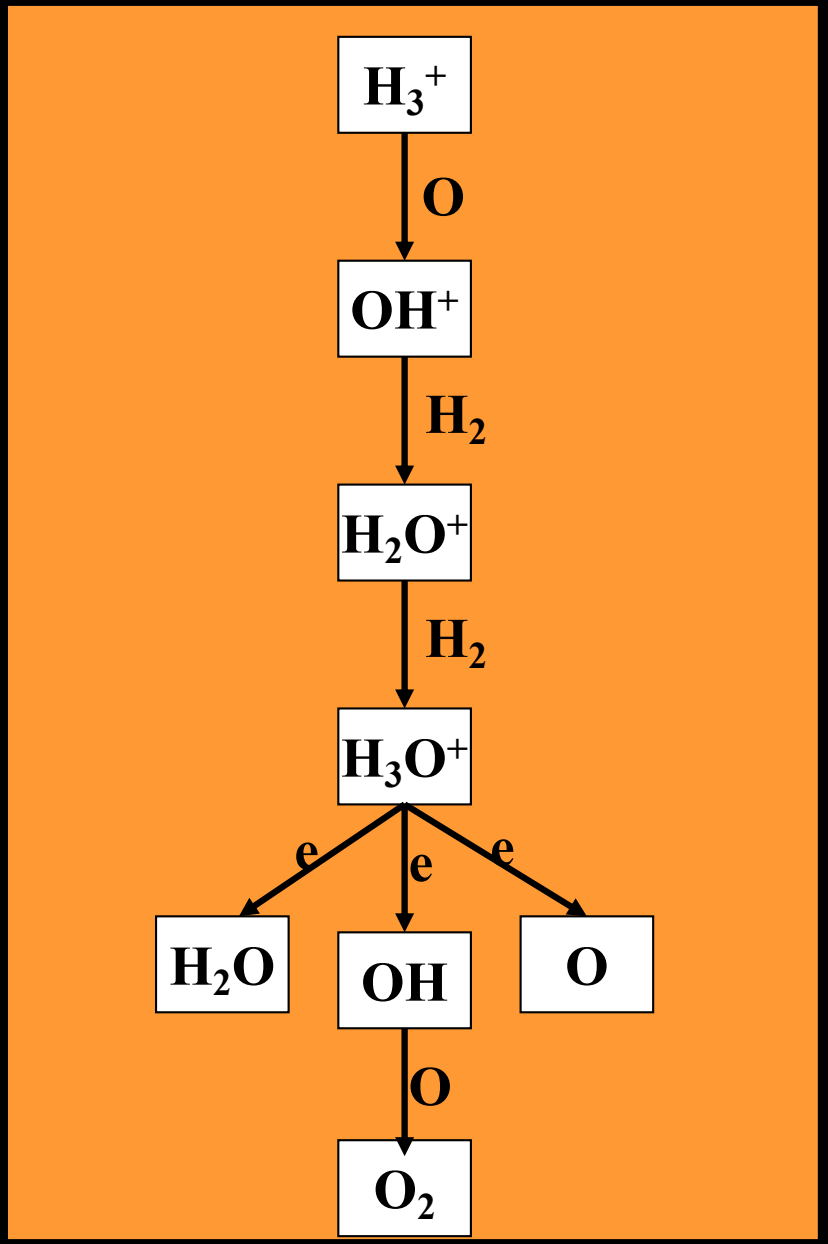


3. The chemistry initiated by H_3^+



Once H_3^+ is formed, a cascade of reactions greatly enhances the chemical complexity of the ISM.

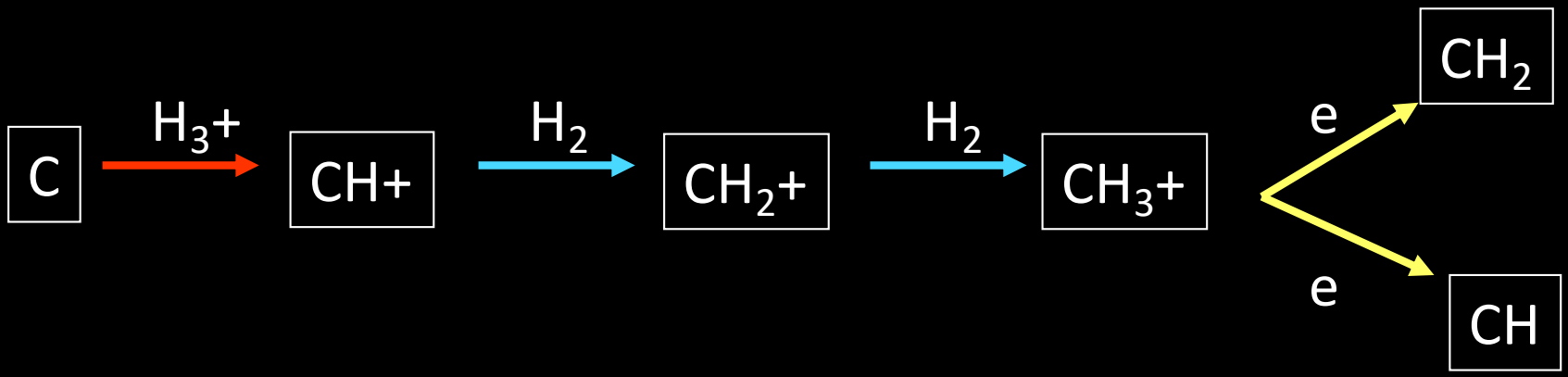
In fact, H_3^+ can easily donate a proton and allow larger molecules to form.



Example ➔
OXYGEN CHEMISTRY (the gas-phase formation of water and O_2 in dark clouds)

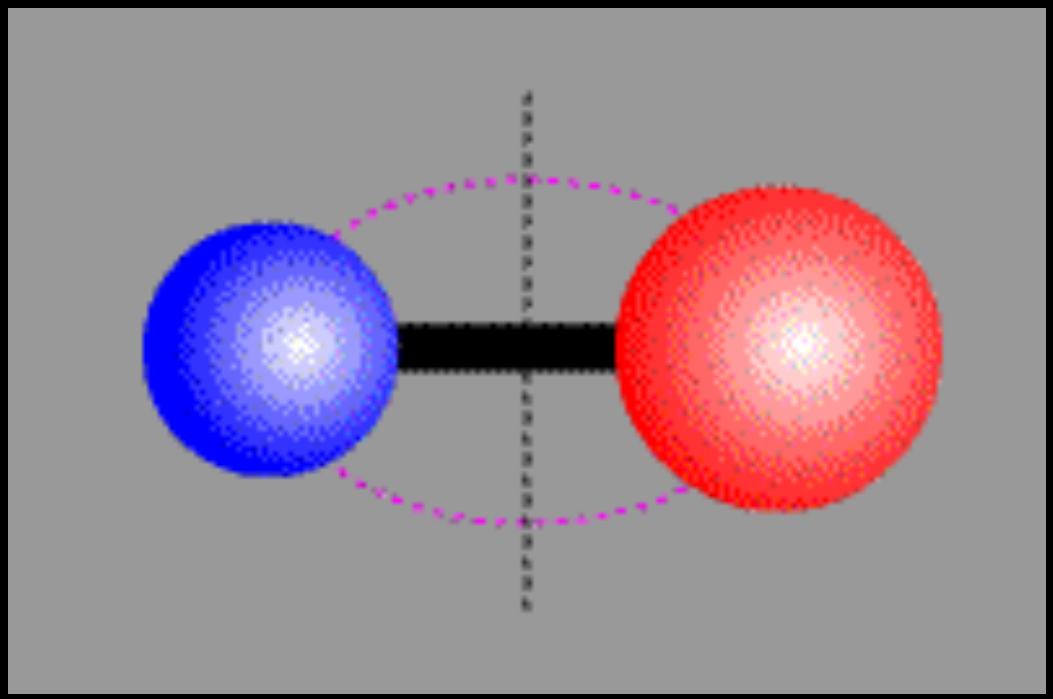
CARBON CHEMISTRY (the formation of hydrocarbons)

The formation of more complicated species from neutral atomic carbon begins with a sequence very similar to that which starts the oxygen chemistry:



A. Proton transfer from H_3^+ to a neutral atom;
B. Hydrogen abstraction reactions terminating in a molecular ion that does not react with H_2;
C. Dissociative recombination with electrons.

4. Formation and destruction of CO



[a] $C + H_3O^+ \rightarrow HCO^+ + H_2$

[b] $O + CH_3^+ \rightarrow HCO^+ + H_2$

[c] $HCO^+ + e \rightarrow CO + H$ is the most important source of CO.

CO is very stable and difficult to remove. It reacts with H_3^+:

[d] $H_3^+ + CO \rightarrow HCO^+ + H_2$

but reaction [c] immediately reform CO.

The main mechanisms for removing CO are:

[e] $He^+ + CO \rightarrow He + C^+ + O$

[f] $h\nu + CO \rightarrow C + O$

Some of C^+ can react with OH and H_2O (and very slowly with H_2):

[g] $C^+ + OH \rightarrow CO^+ + H$

[h] $CO^+ + H_2 \rightarrow HCO^+ + H$

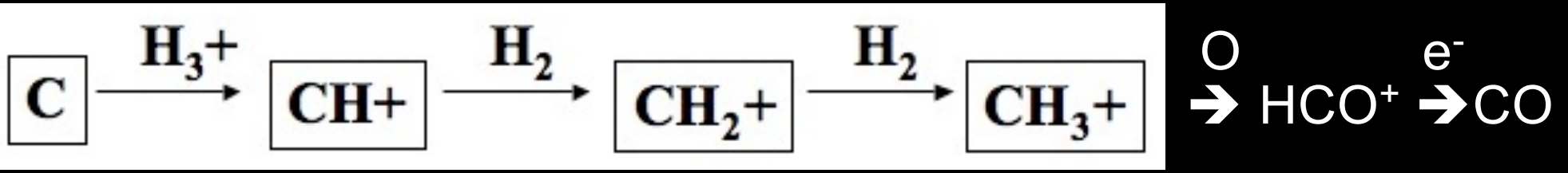
[i] $C^+ + H_2O \rightarrow HCO^+ + H$

The timescale to form CO

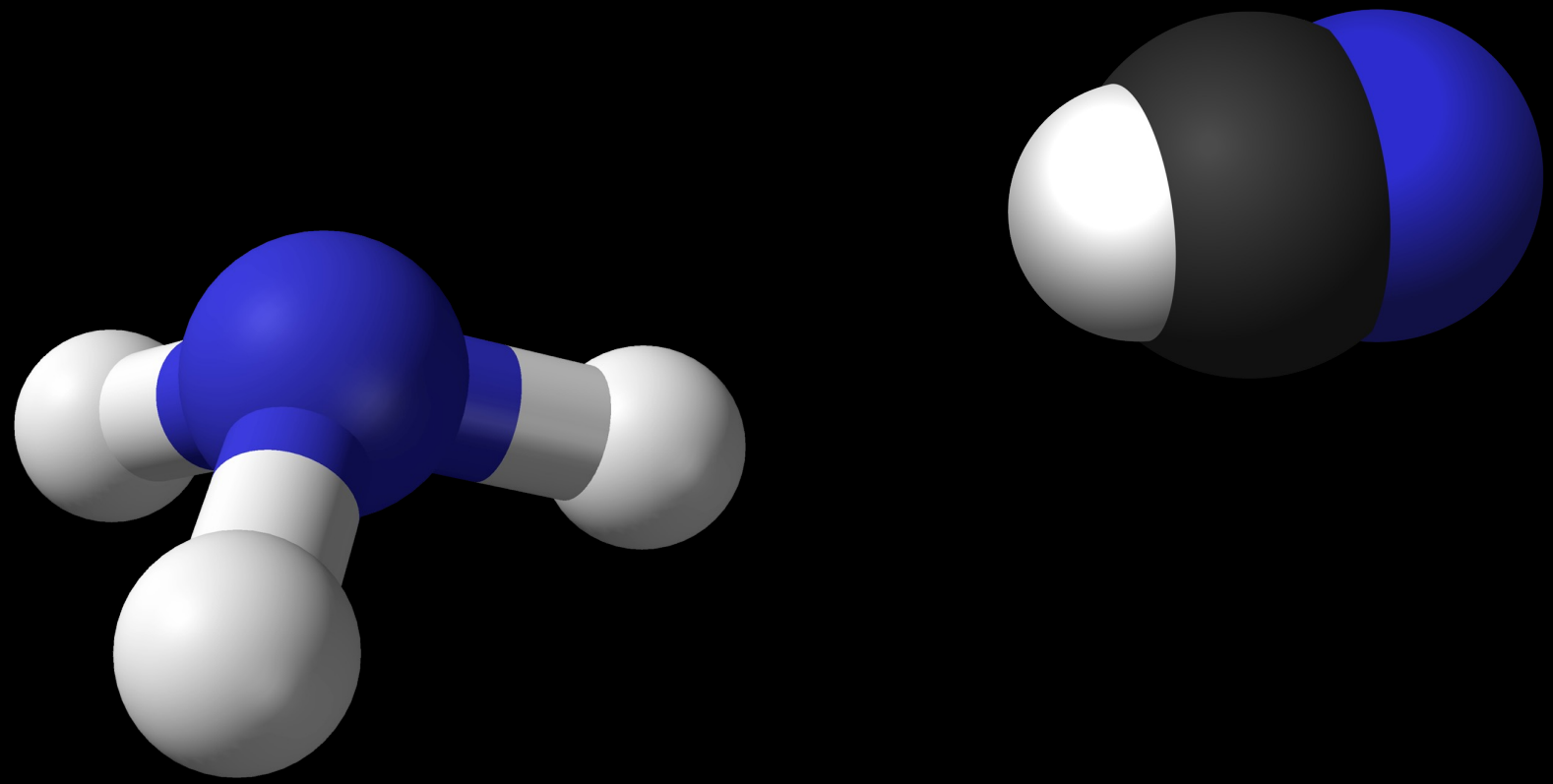
Assume: dark region where all H is in H_2 and all atoms more massive than He are in neutral atomic form.

The timescale on which almost all carbon becomes contained in CO ($n_O > n_C$) is at least equal to the timescale for one H_2 to be ionized for every C: $n_C/[\zeta\, n(H_2)] = 2\, n_C/[\zeta\, n_H]$.

For $\zeta = 3\times10^{-17}\ s^{-1}$ and $n_C/n_H = 10^{-4}$, the above expression gives a value of about $2\text{x}10^5$ yr.



5. Nitrogen chemistry



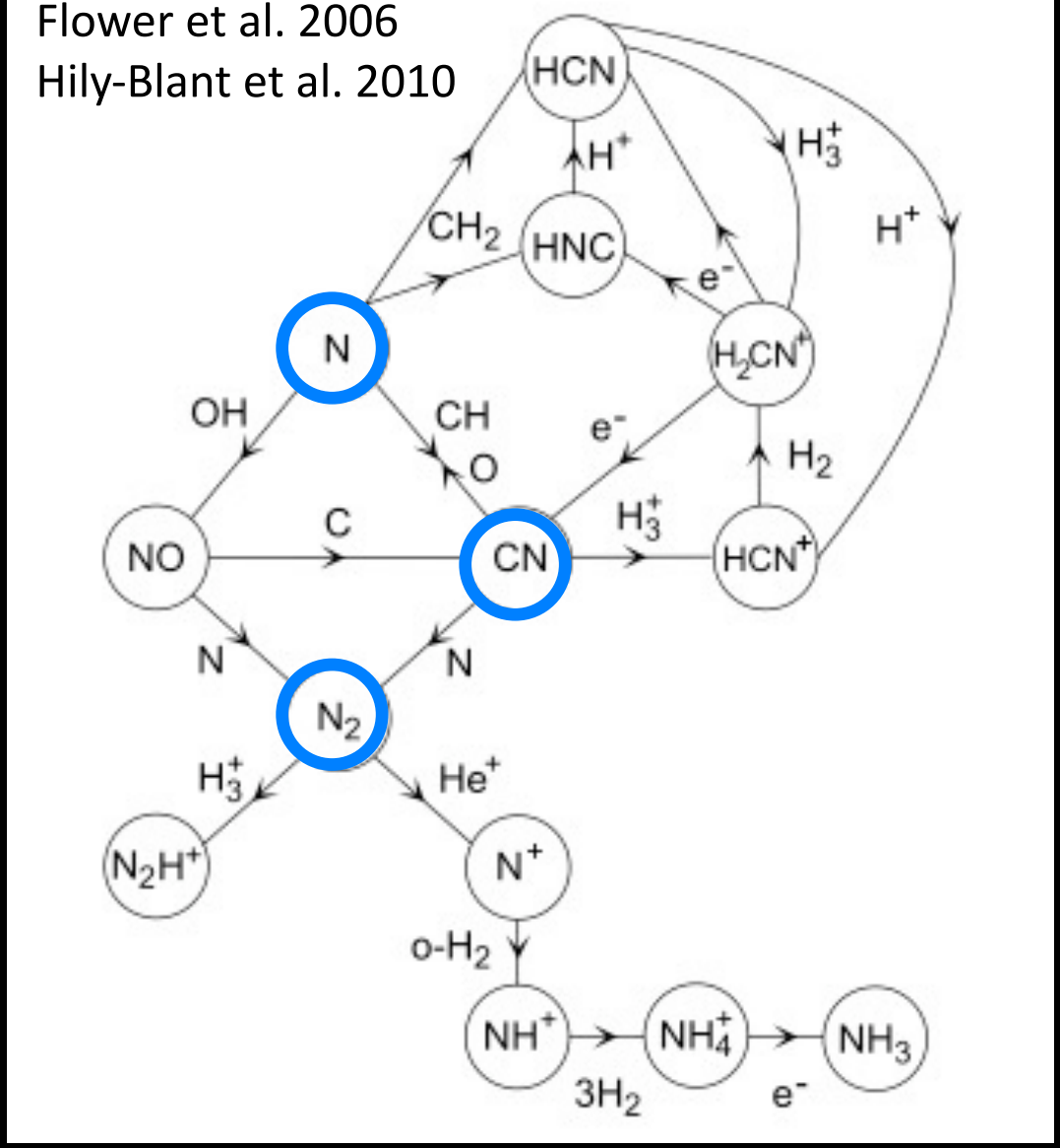
$$N + H_3^+ \not\rightarrow NH^+ + H_2$$

$$N + OH \rightarrow NO + H$$

$$N + CH \rightarrow CN + H$$

$t_{N2} \sim 10^6$ yr in UV-shielded clouds (about 5 times longer than t_{CO})

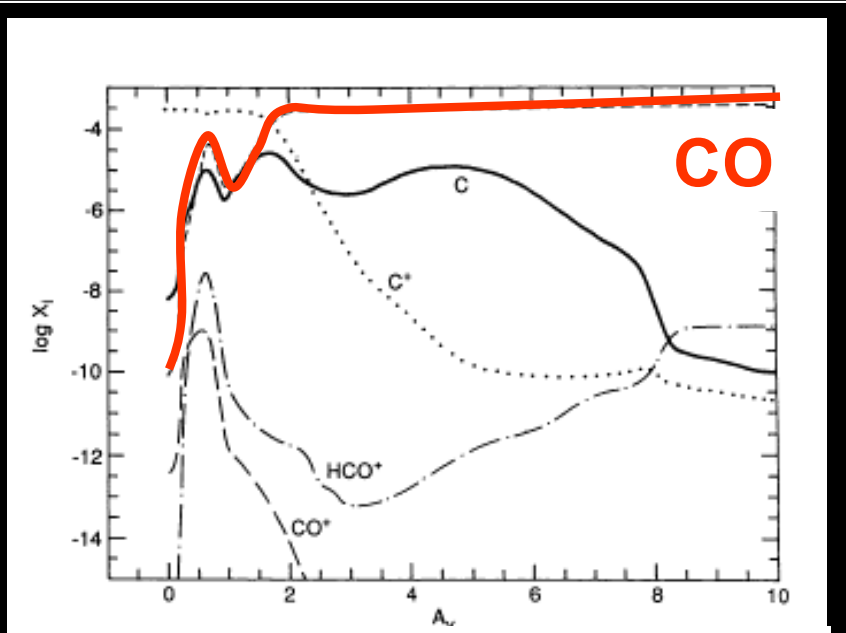
Flower et al. 2006
Hily-Blant et al. 2010

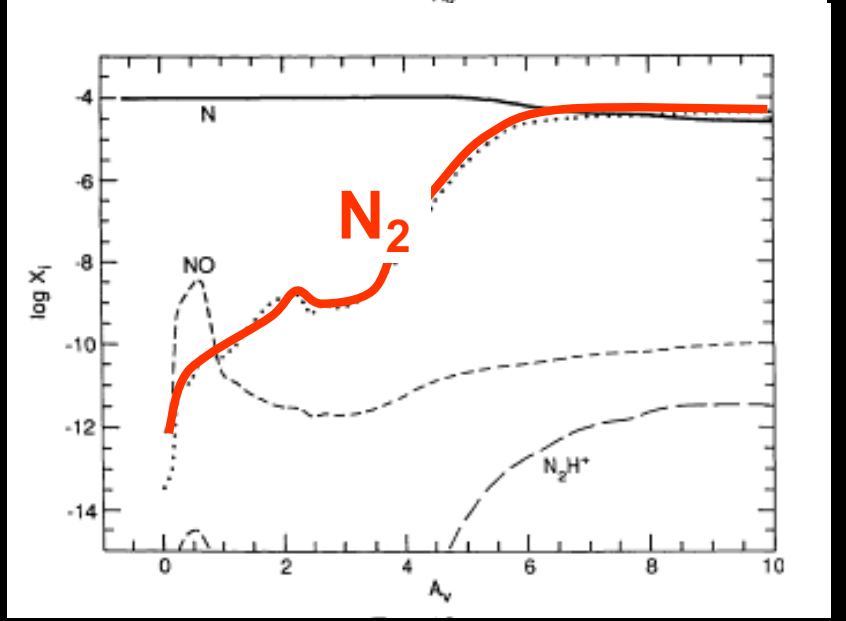


$\mathcal{N}_2$ *vs. CO*

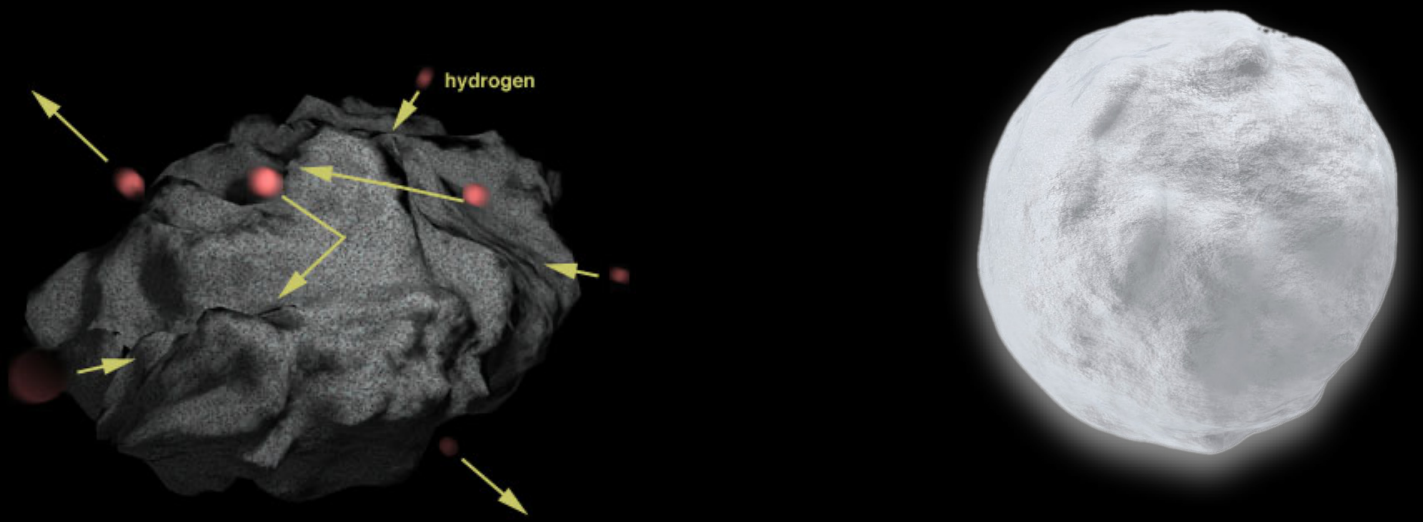
Chemistry in Photodissociation Regions (PDRs)
Sternberg & Dalgarno 1995



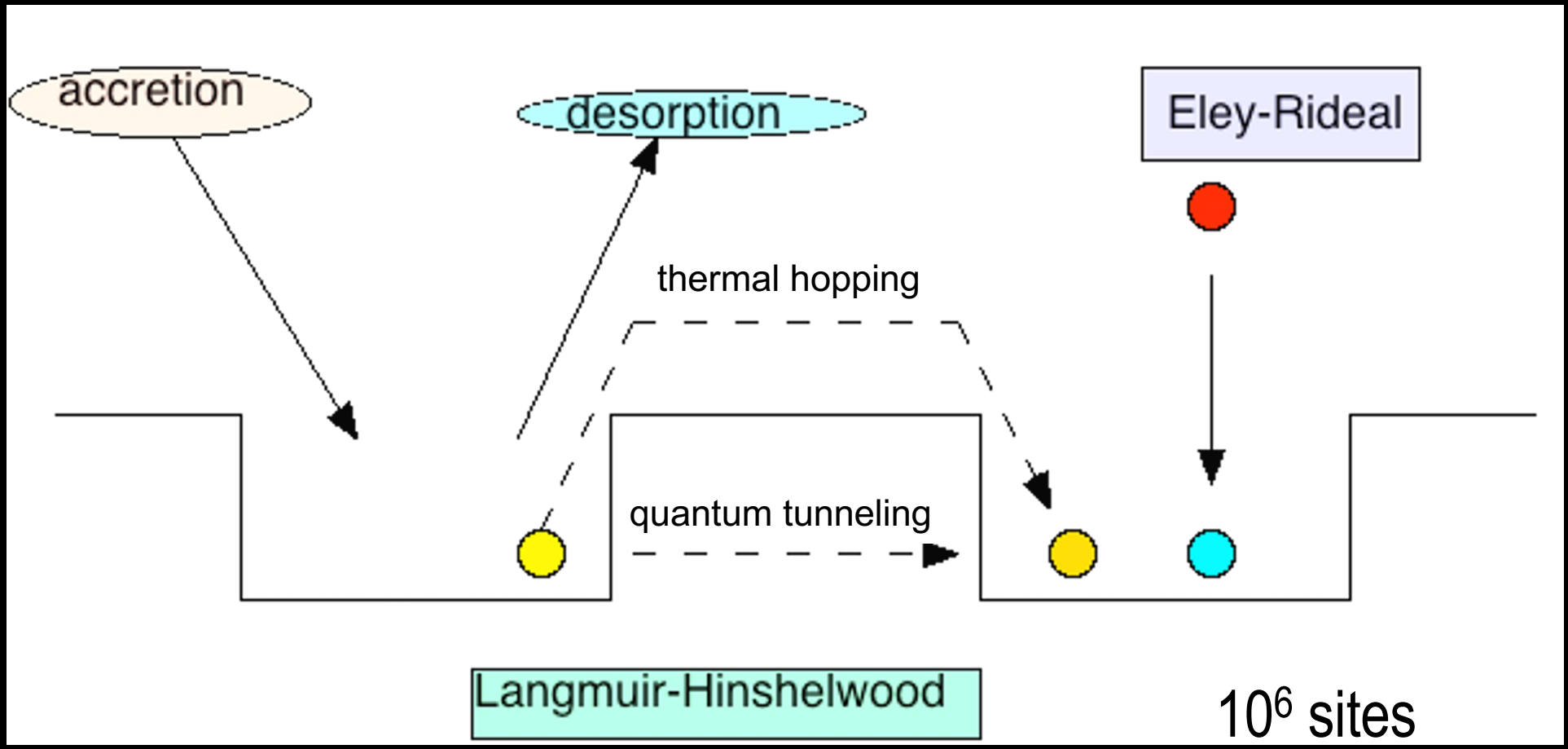




6. Ice formation and freeze-out



Surface Chemistry



Tielens & Hagen (1982); Tielens & Allamandola (1987); Hasegawa et al. (1992); Tielens 1993; Cazaux & Tielens (2002); Cuppen & Herbst (2005); Cazaux et al. (2008); Garrod (2008); Garrod+(2022)

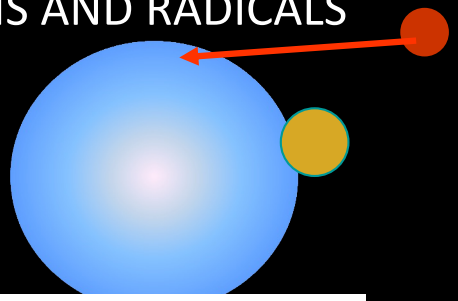
Fast H diffusion and association reactions

REACTANTS: MAINLY MOBILE H, H_2 AND (at T > 20-30K) HEAVIER ATOMS AND RADICALS

A + B → AB association

$H + H \rightarrow H_2$

$H + X \rightarrow XH$ (X = O, C, N, CO, etc.)



Accretion

$\propto 10/[T_k^{1/2}\ n(H_2)/(10^4\ cm^{-3})]$ days

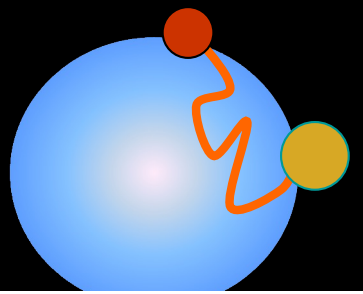
WHICH CONVERTS

$O \rightarrow OH \rightarrow H_2O$

$C \rightarrow CH \rightarrow CH_2 \rightarrow CH_3 \rightarrow CH_4$

$N \rightarrow NH \rightarrow NH_2 \rightarrow NH_3$

$CO \rightarrow HCO \rightarrow H_2CO \rightarrow H_3CO \rightarrow CH_3OH$

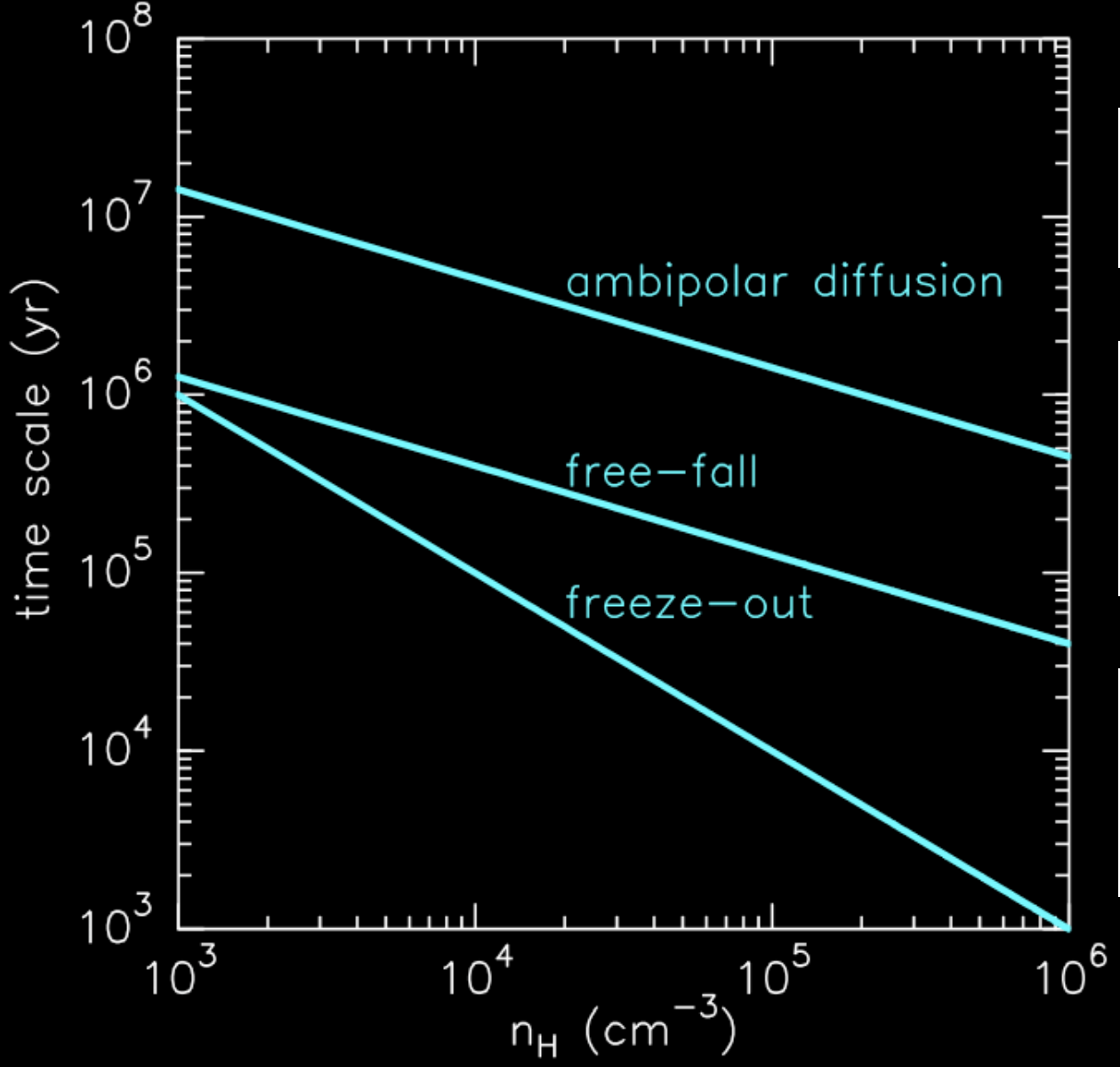


Diffusion+Reaction

$t_{qt}(H) \sim 10^{-5}$–10^{-3} s

e.g. Watson & Salpeter 1972; Tielens & Hagen 1982; Hasegawa et al. 1992; Caselli et al. 1993; Cuppen & Herbst 2005; Garrod et al. 2008; Cazaux et al. 2010

Dynamical and freeze-out timescales



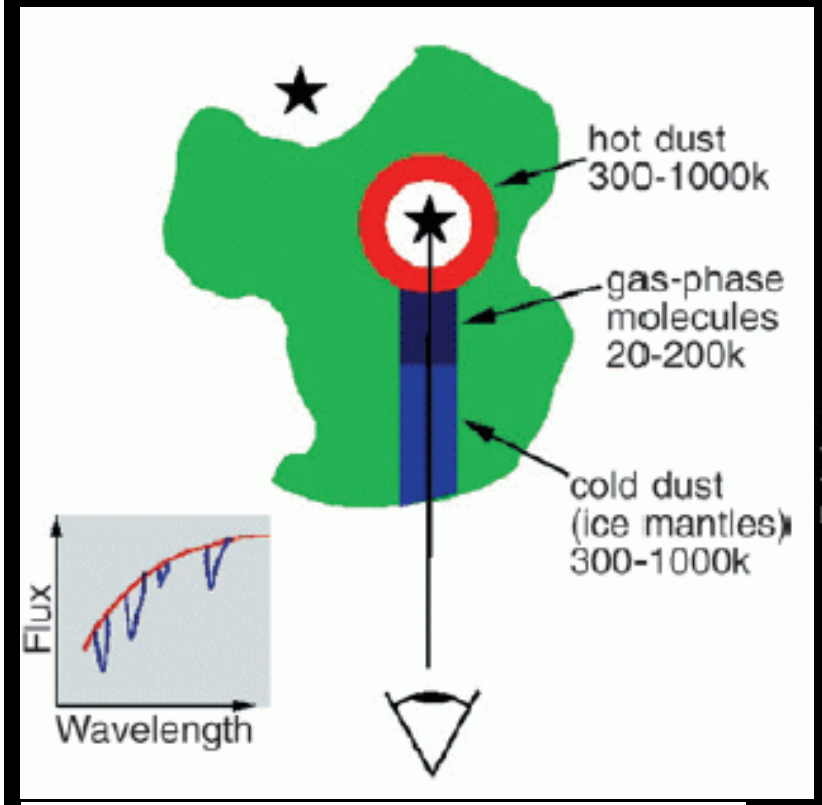
$$t_{ambipolar} \approx 2.5 \times 10^{13}\, x(e) \text{ yr}$$
$$\approx 4.5 \times 10^{8} / \sqrt{n_H} \text{ yr}$$

$$t_{free-fall} = \sqrt{\frac{3\pi}{32 G \rho}}$$
$$\approx 4 \times 10^{7} / \sqrt{n_H} \text{ yr}$$

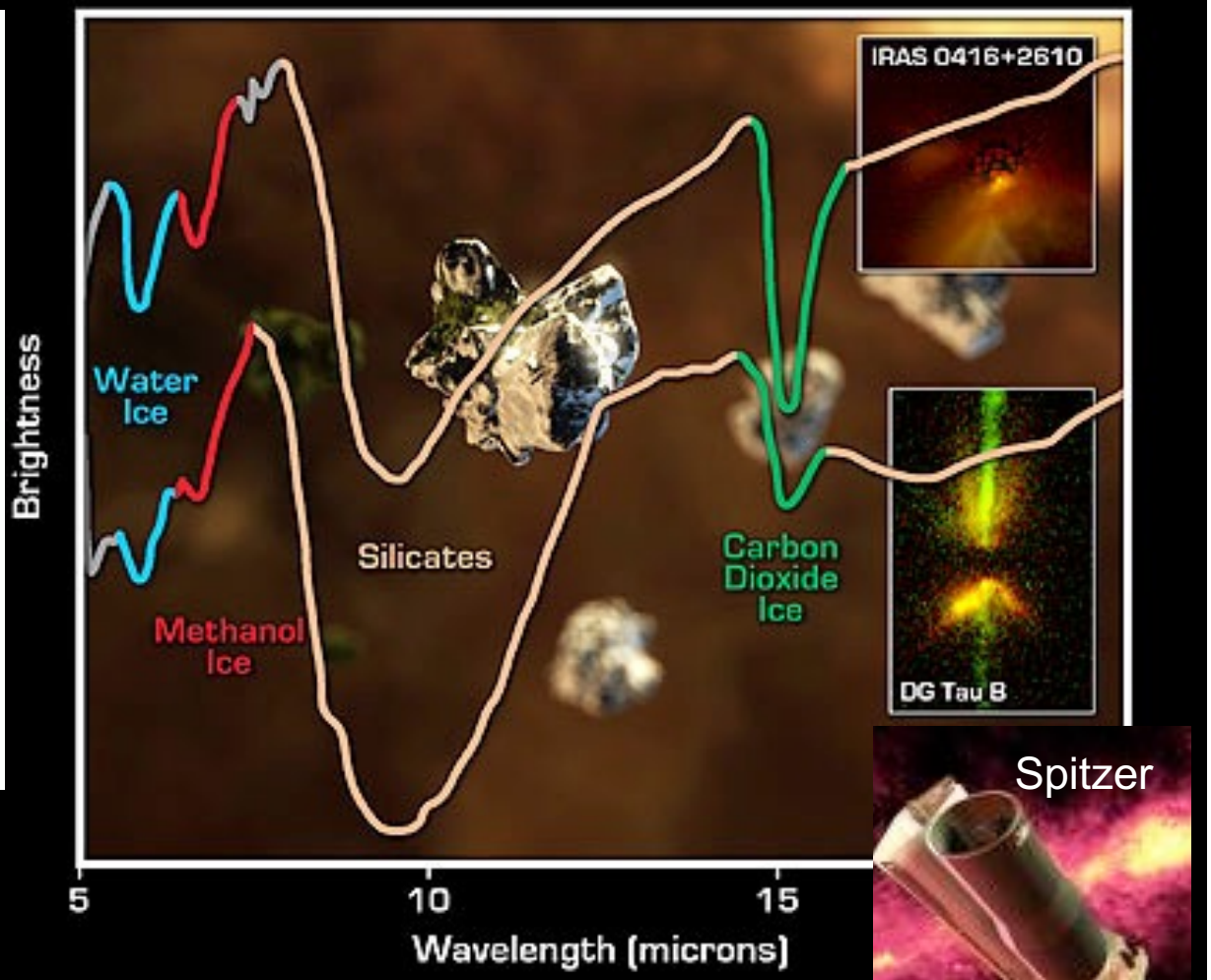
$$t_{freeze-out} = \frac{1}{\alpha n_d \pi a_d^2 \mathrm{v}_t}$$
$$\approx 10^{9} / n_H \text{ yr}$$

Walmsley 1991; Bergin&Tafalla (2007)

Evidence of icy mantles: absorption features

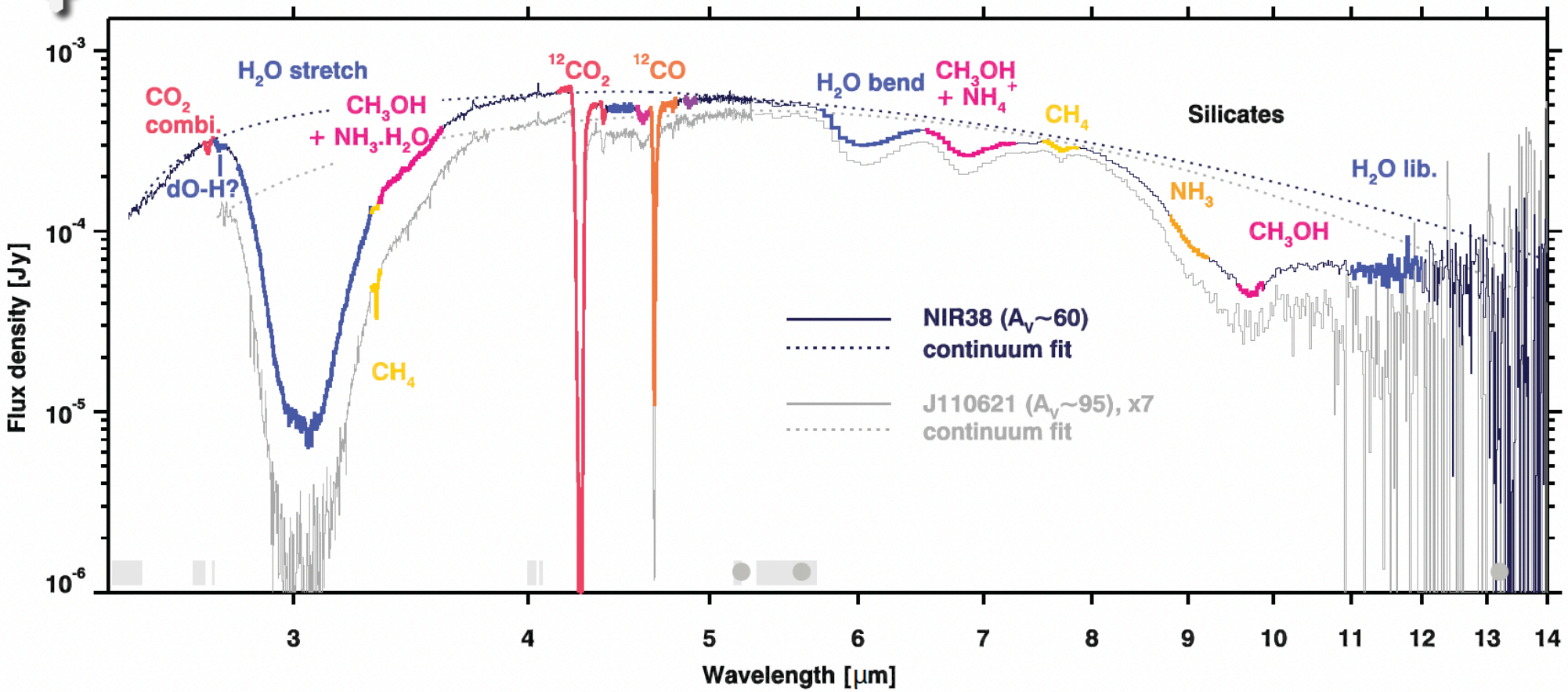


from van Dishoeck et al. 2003



Pontoppidan+2007; Chiar+2011; Boogert+2015

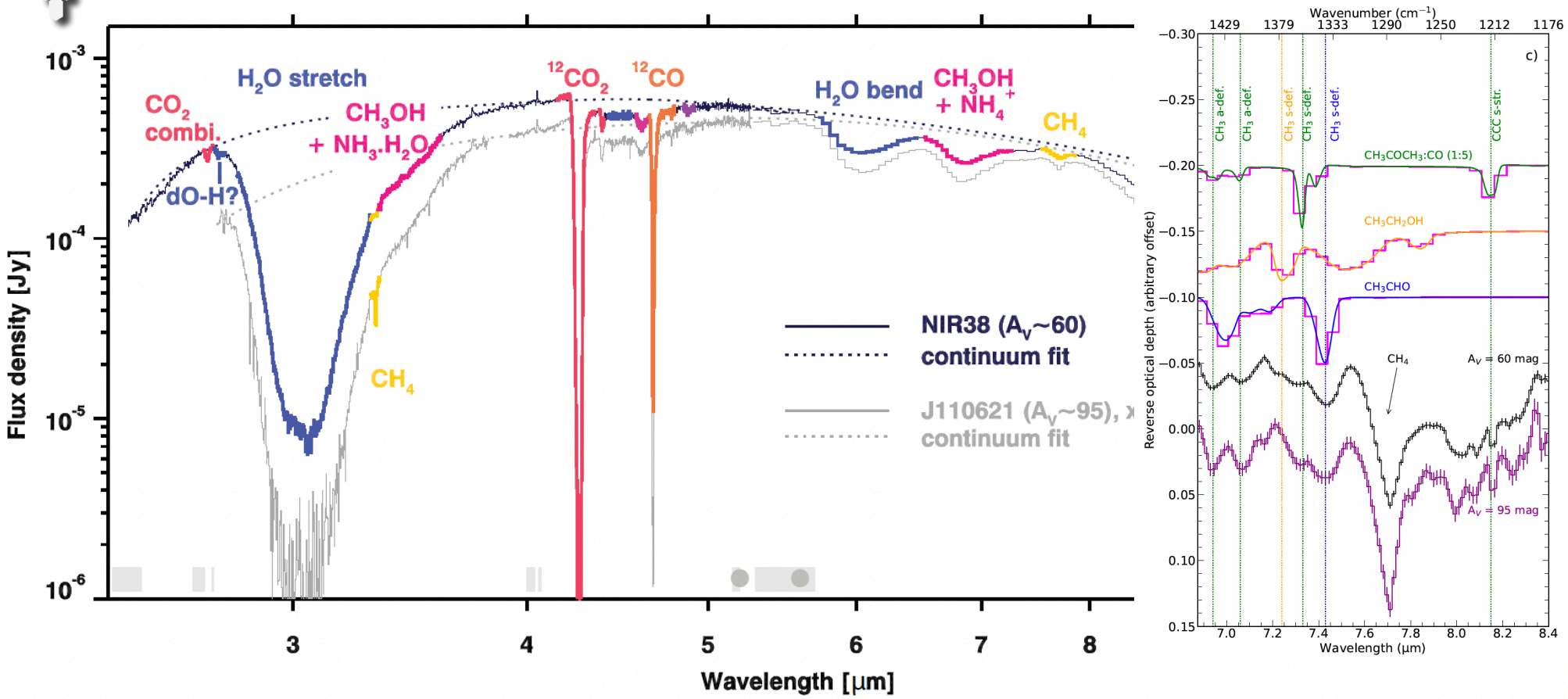
JWST inventory of dense molecular clouds ices



McClure, Rocha, Pontoppidan+ICE AGE collaboration 2023, Nature Astronomy

See also: Rocha, van Dishoeck, Ressler+2023, in press

JWST inventory of dense molecular clouds ices

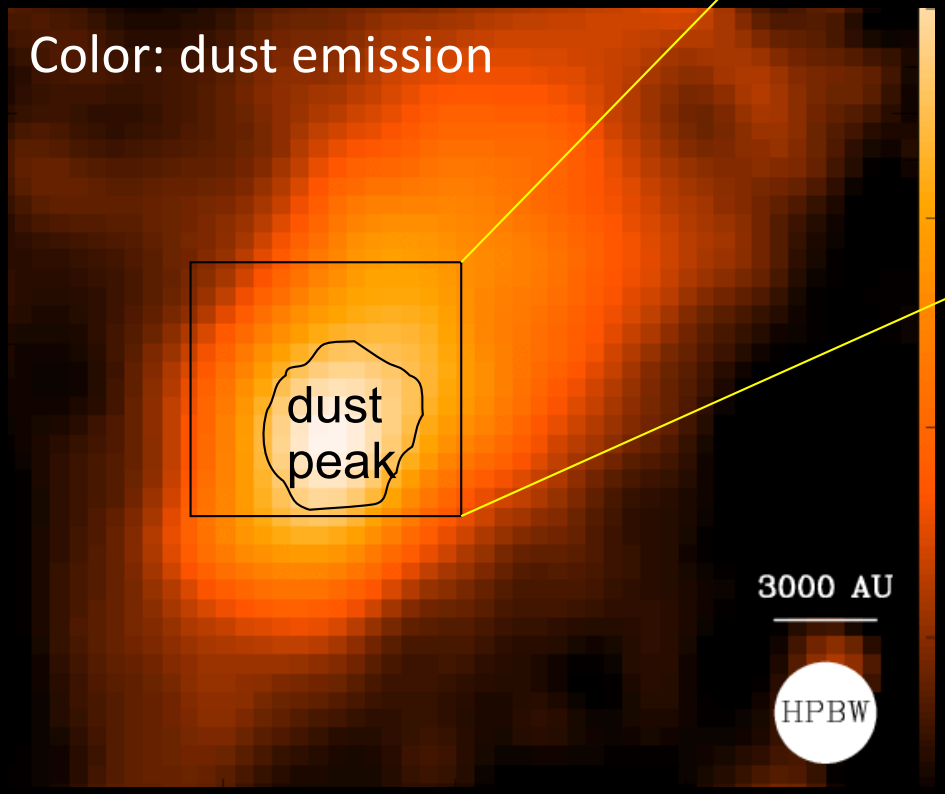


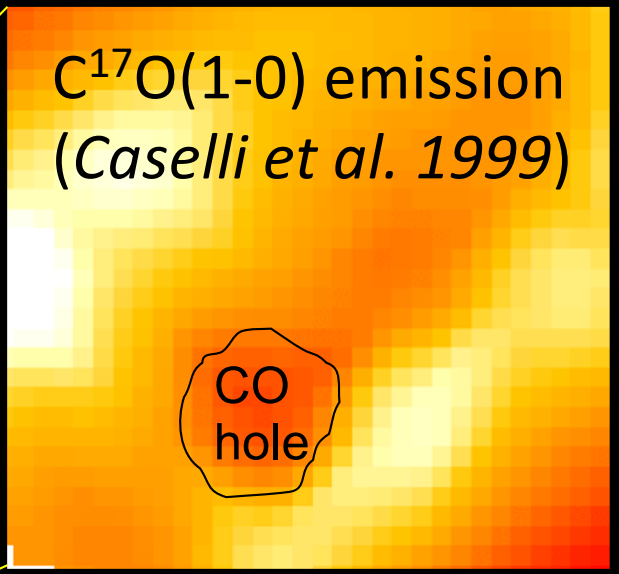
McClure, Rocha, Pontoppidan+ICE AGE collaboration 2023, Nature Astronomy

See also: Rocha, van Dishoeck, Ressler+2023, in press

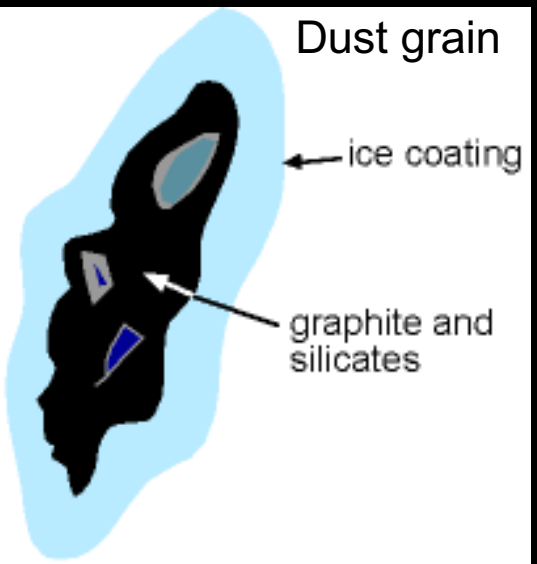
Evidence of freeze-out: CO "holes"

"Catastrophic" CO freeze-out within the central 7000 au



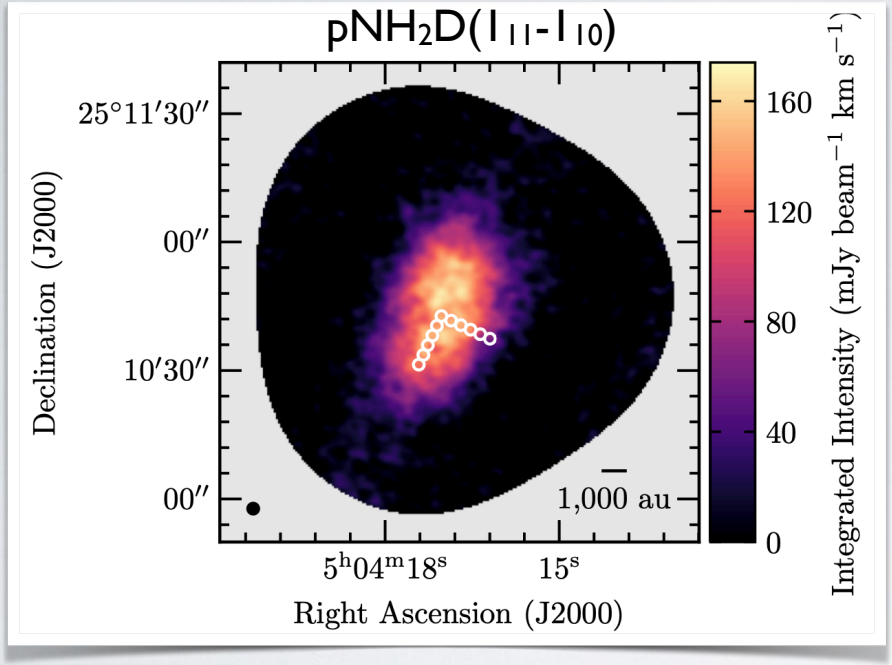


Molecules freeze out onto dust grains in the center of pre-stellar cores

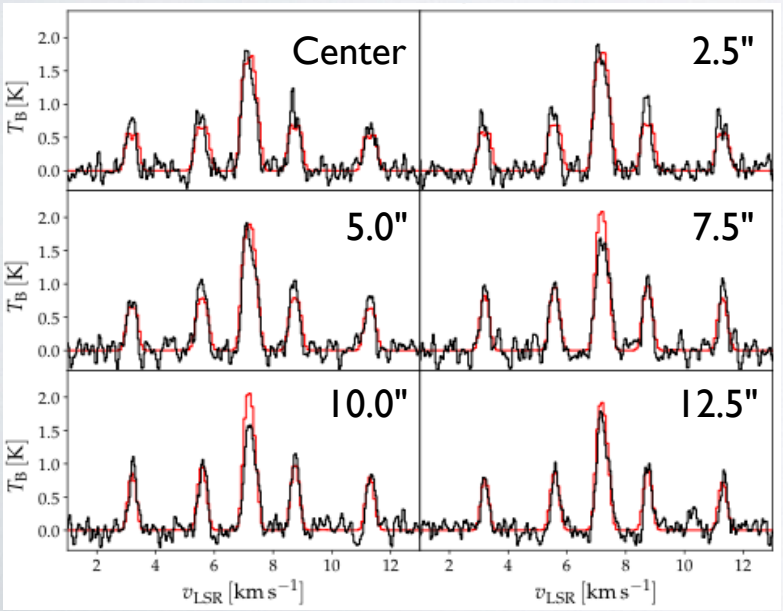


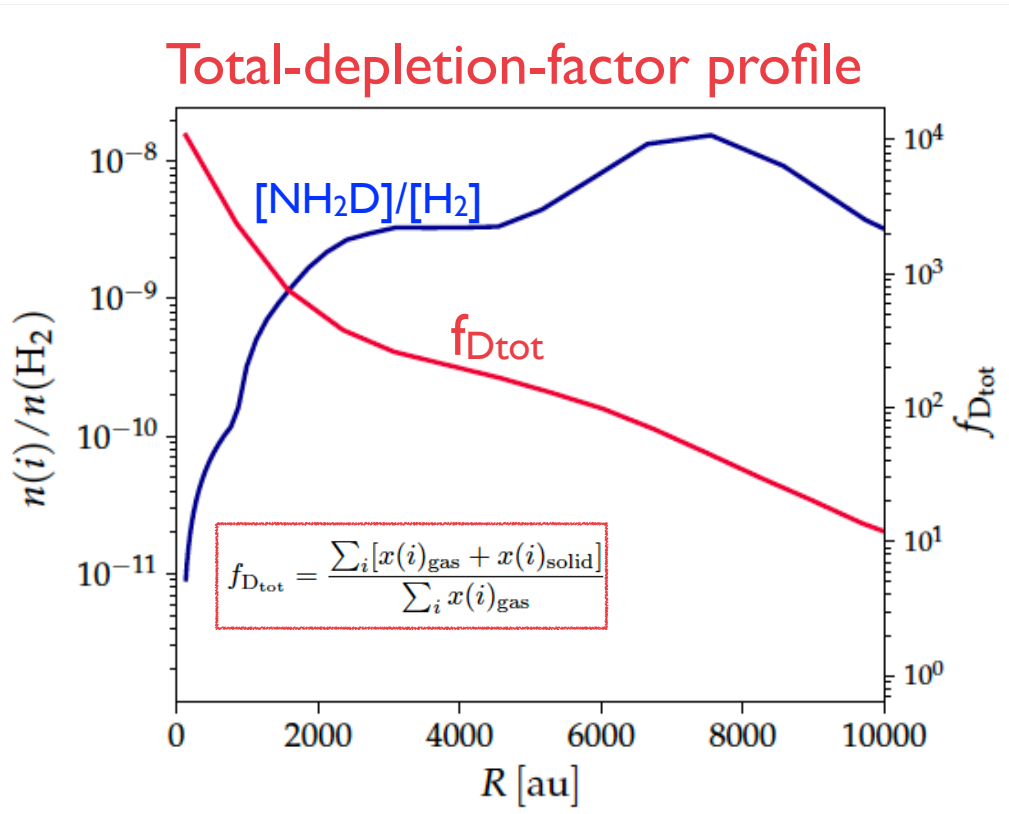
>90% of CO molecules are frozen onto dust grains

In the central 2000 au, 99.99% of all species heavier than He are frozen onto dust grains



L1544 **ALMA**-Band 3 observations + comparison with gas-grain chemical/RT model: *NH_2D abundance sharply drops in the central 2000 au.*





Caselli, Pineda, Sipilä+2022 (+Pineda+2022)

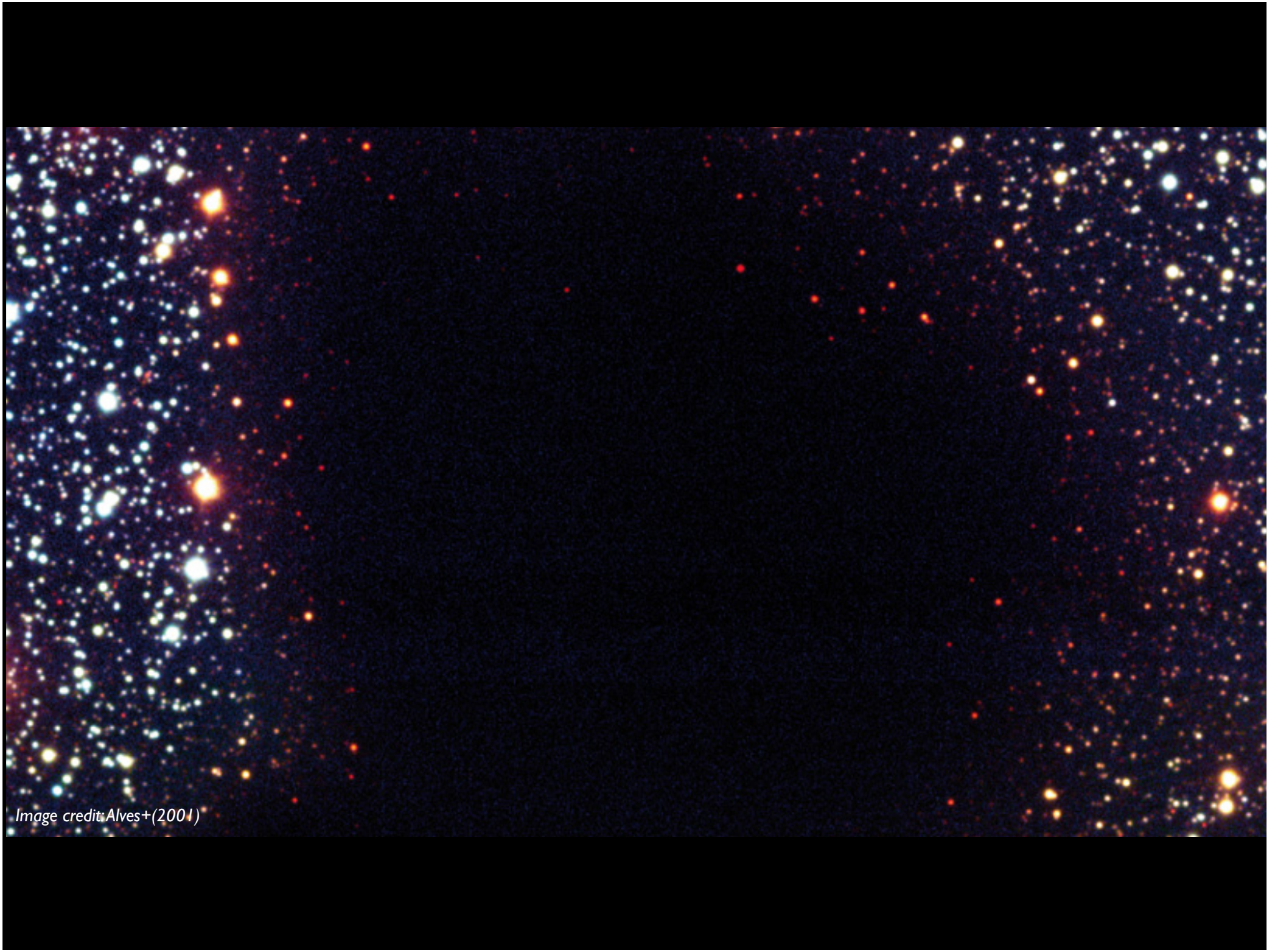
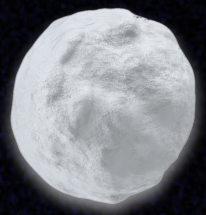

Image credit: Alves+(2001)


Image credit: Alves+(2001)

Just before stellar birth, almost all (99.99%) species heavier than He are expected to reside on dust grain surfaces in the central 2000 au of pre-stellar cores.



Dust grains are covered with thick icy mantles, storing molecules for the next stages of planet formation.

Image credit: Alves+(2001)

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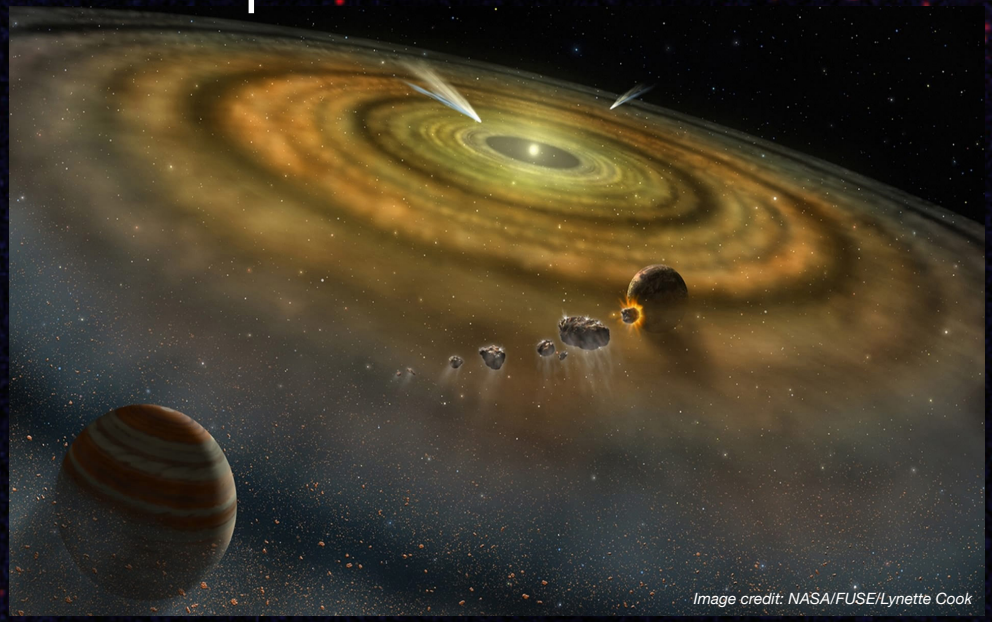


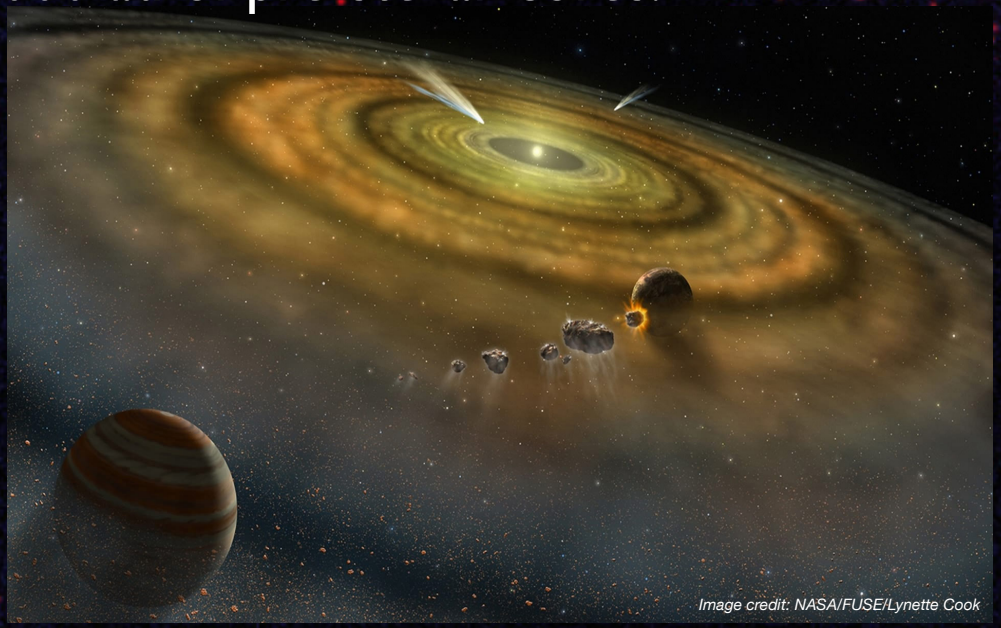
Image credit: NASA/FUSE/Lynette Cook

Dust grains are covered with thick icy mantles, storing molecules for the next stages of planet formation.

Image credit: Alves+(2001)



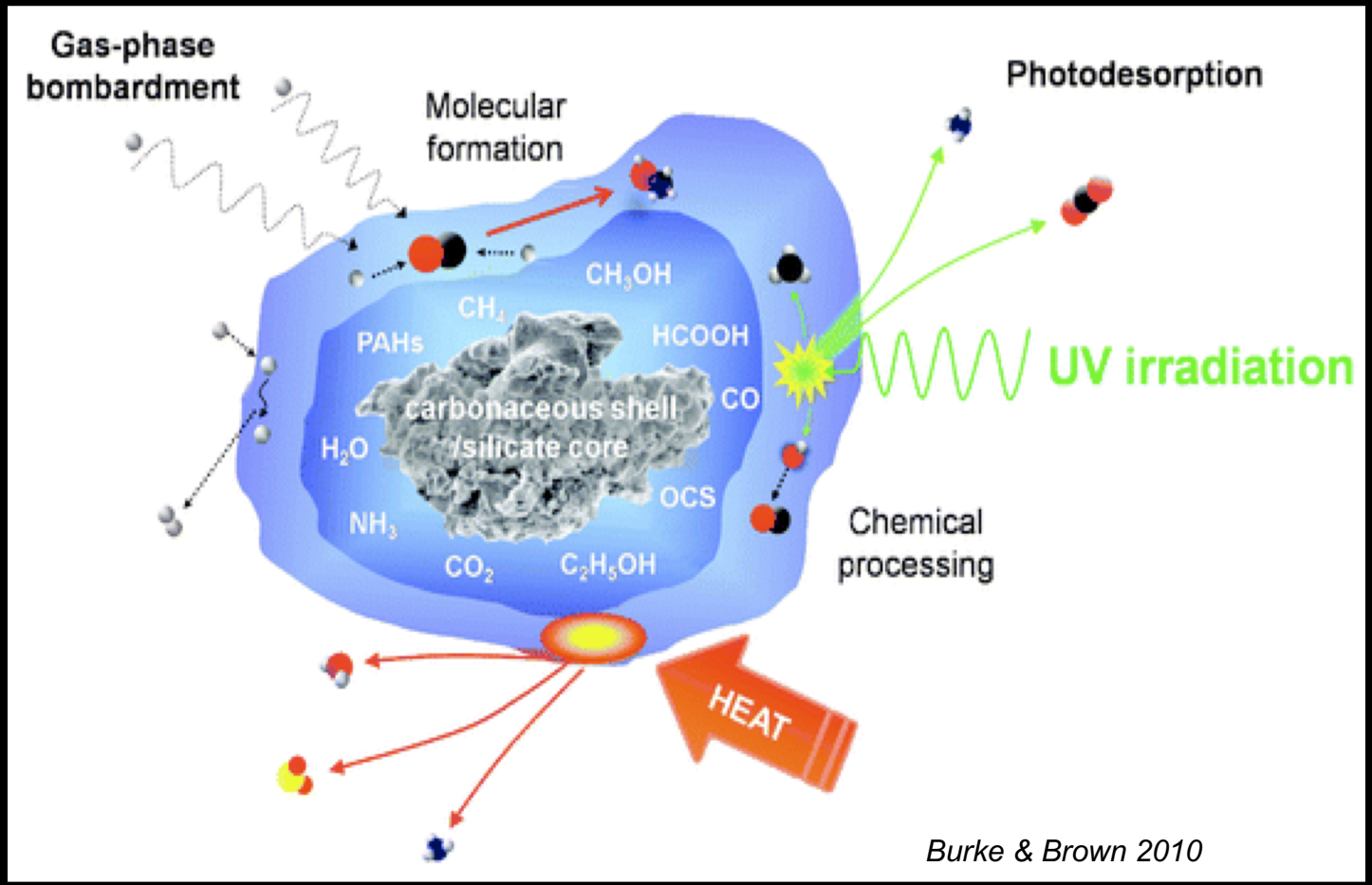
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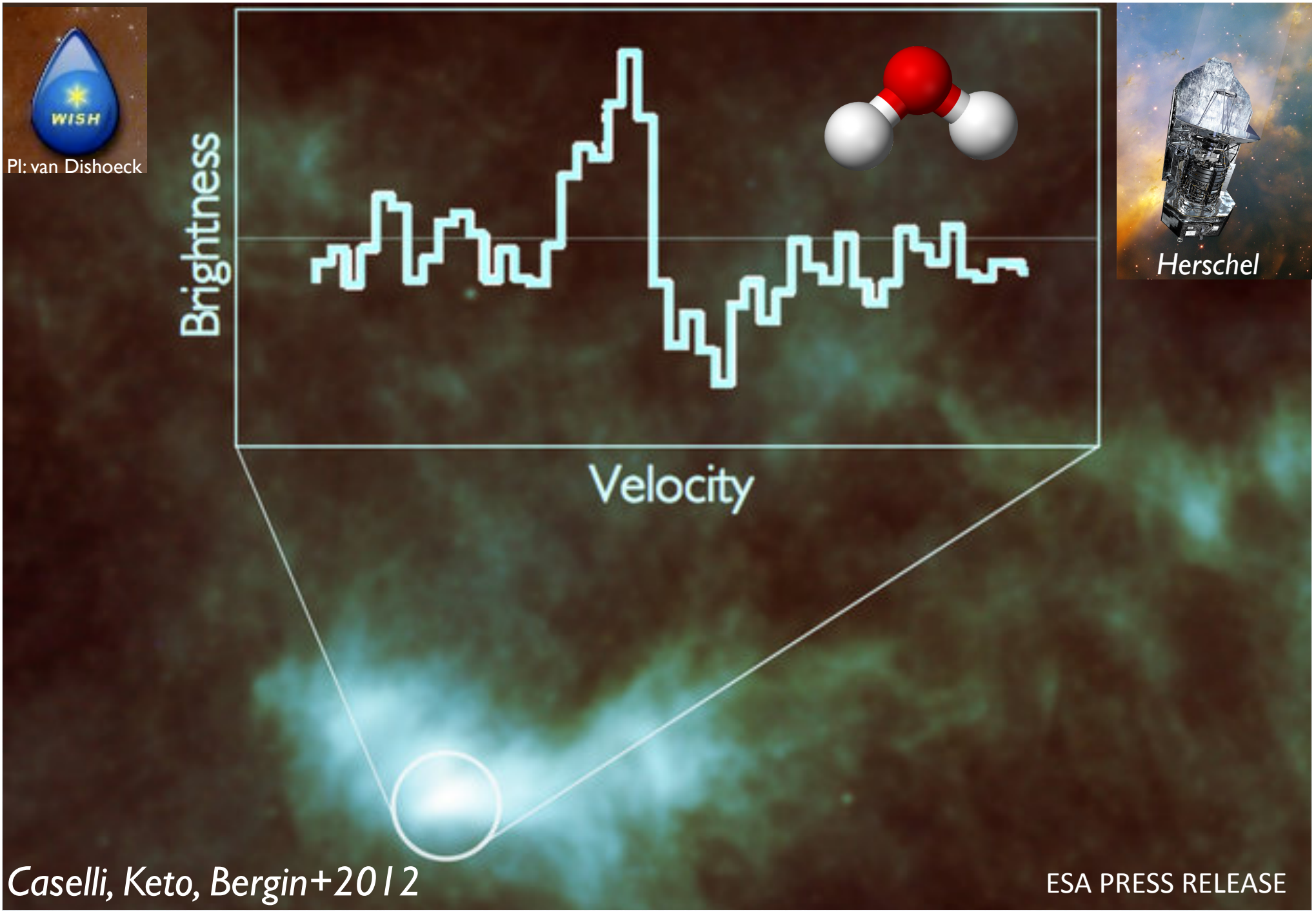
Dust grains are covered with thick icy mantles, storing molecules for the next stages of planet formation.

Image credit: Alves+(2001)

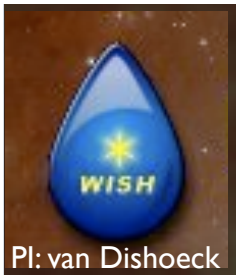
7. The importance of cosmic rays



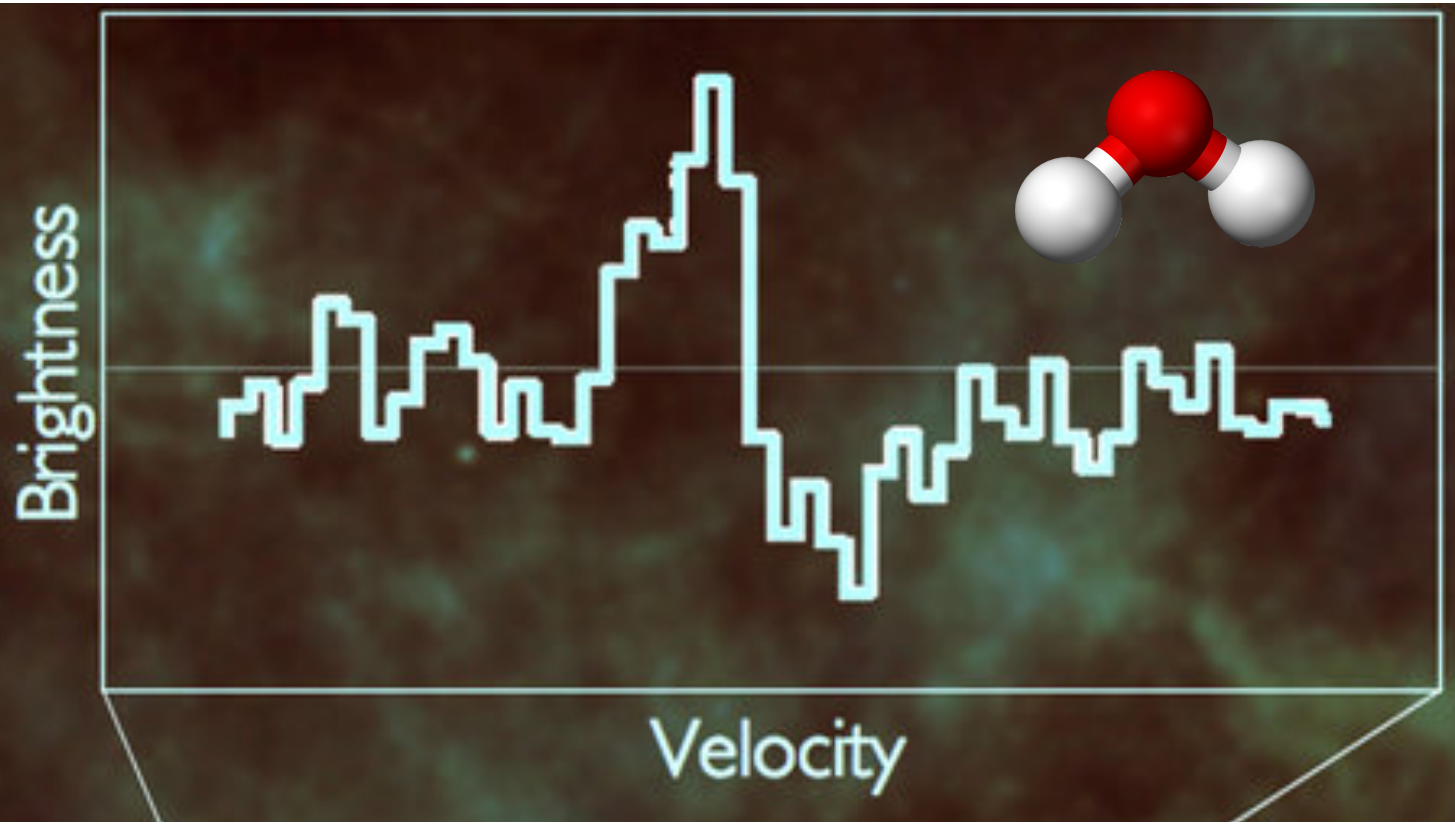
First detection of water vapor in a pre-stellar core



First detection of water vapor in a pre-stellar core



PI: van Dishoeck





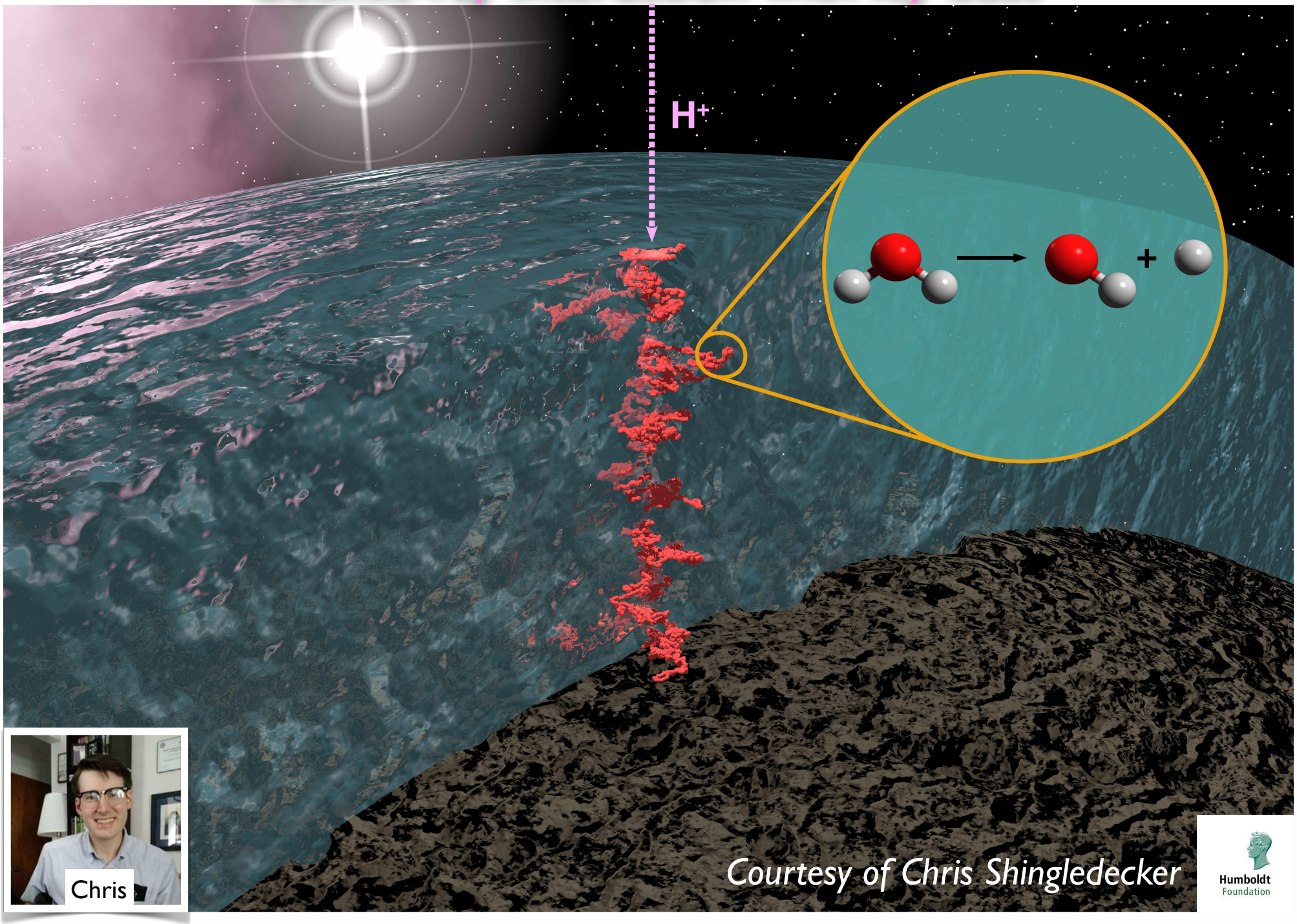
MAIN RESULTS:

1. Unveiled subsonic infall within central 1000 AU;
2. Measured total mass of water vapour: ~0.5 M_{Earth};
3. Deduced total mass of water ice: ~2.6 M_J;
4. Cosmic rays important for water ice desorption.

Caselli, Keto, Bergin+2012

ESA PRESS RELEASE

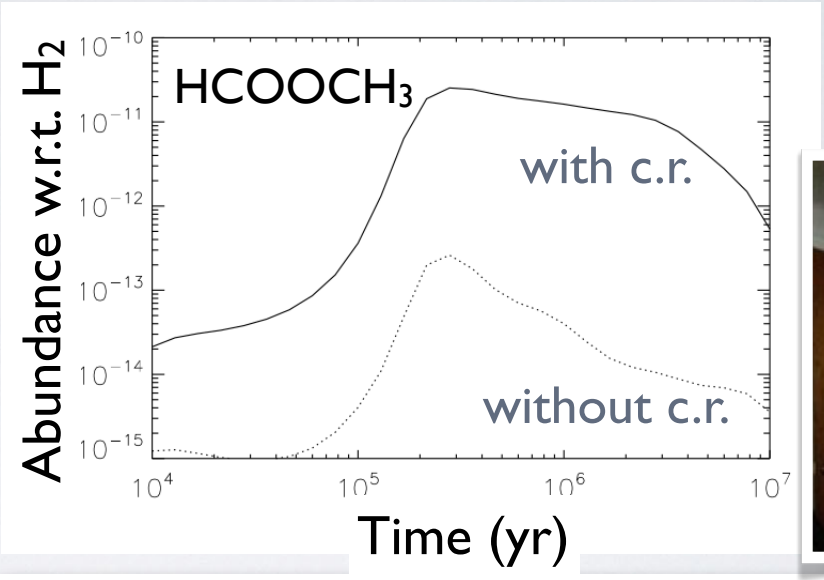
Cosmic-ray interaction with icy dust



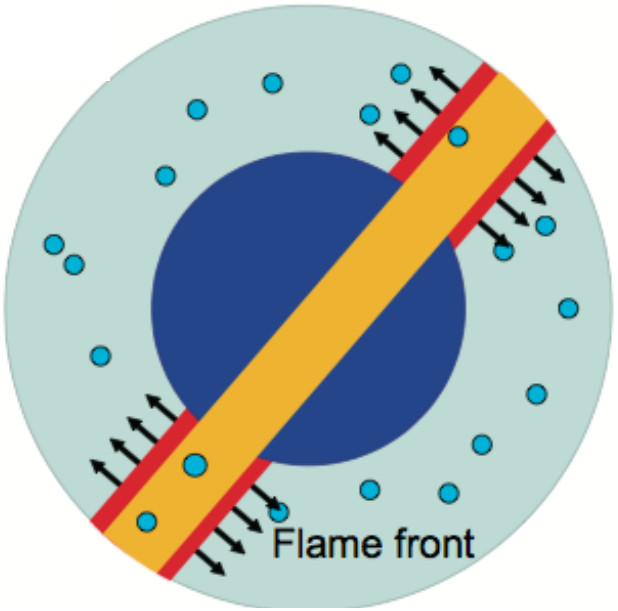
Humboldt Foundation

Cosmic rays affect ice composition

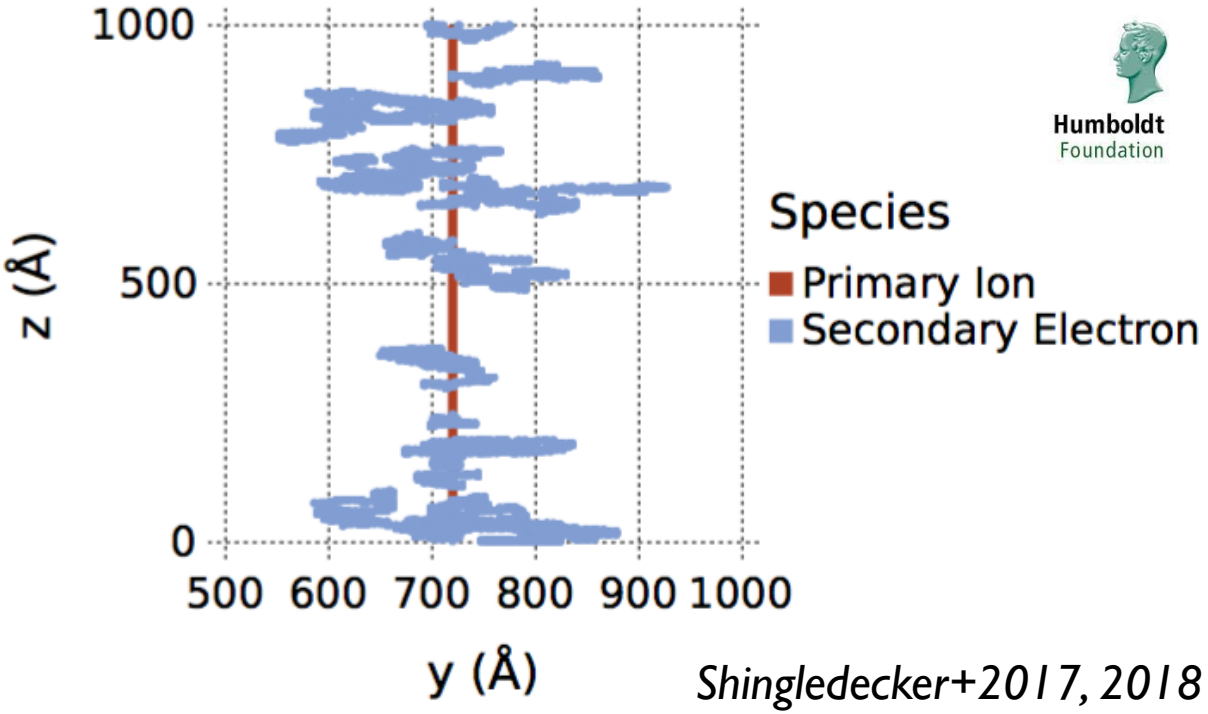








Ivlev+2015a,b and Ivlev+2023

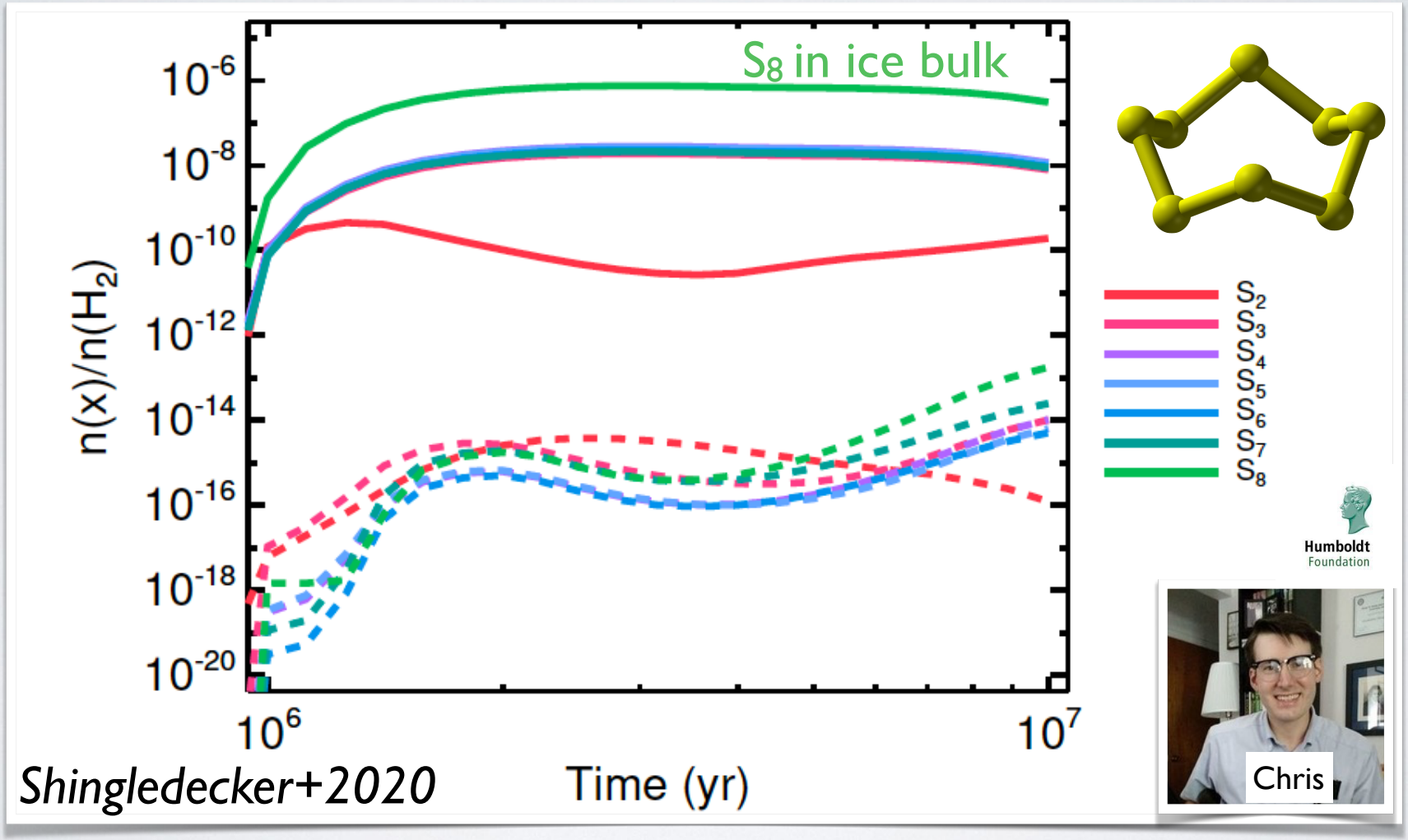


Humboldt Foundation

Shingledecker+2017, 2018

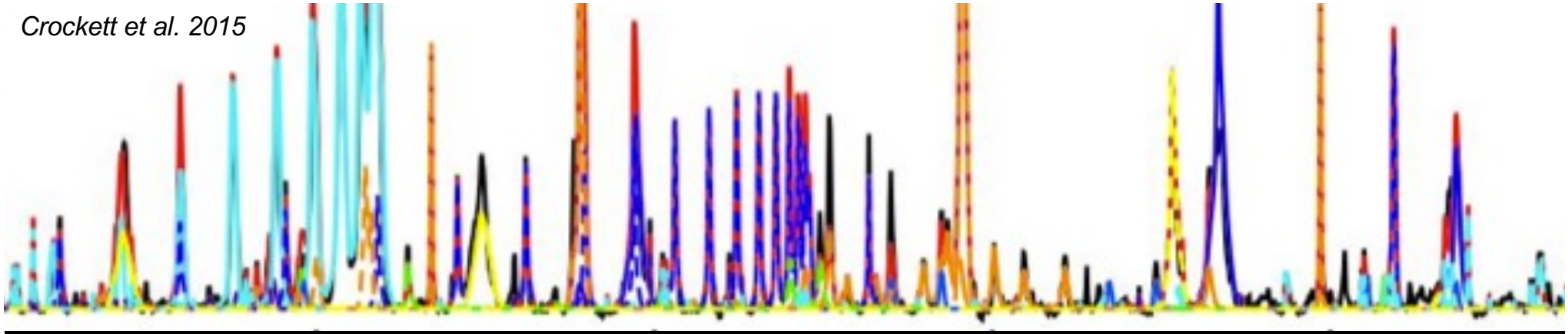
Cosmic rays transform H_2S ice in refractory Sulphur allotropes

(S_2, S_3, S_4 detected in comet 67P/CP coma)



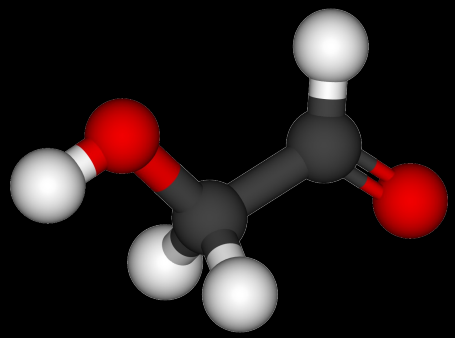
(see also Muñoz Caro 2003; Calmonte+2016; Navarro-Almaida+2020; Cazaux+2021)

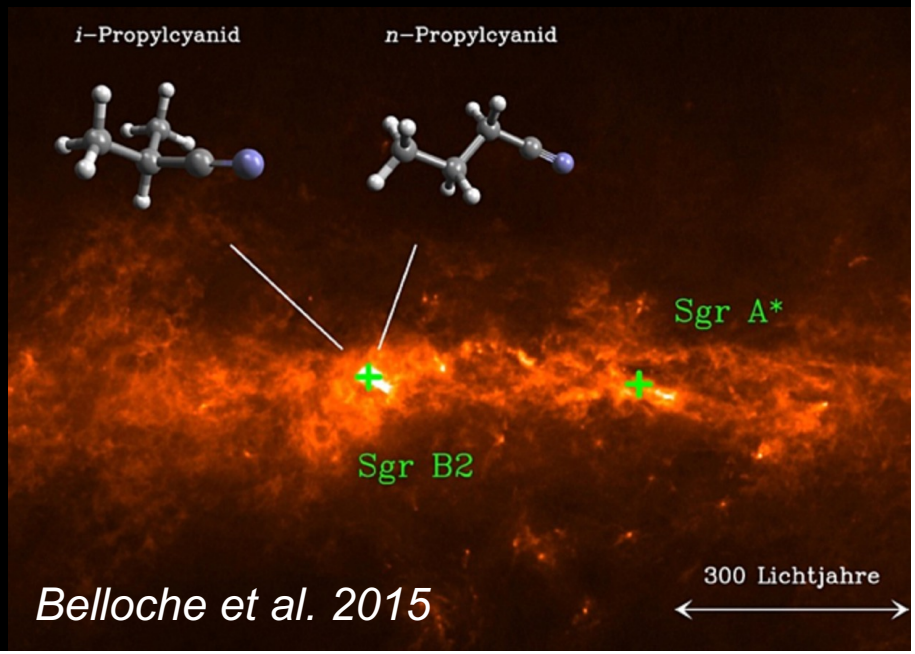
Crockett et al. 2015



9. Complex* Organic Molecules (COMs)







Belloche et al. 2015

* ≥ 6 atoms in size *(Herbst & van Dishoeck 2009)*

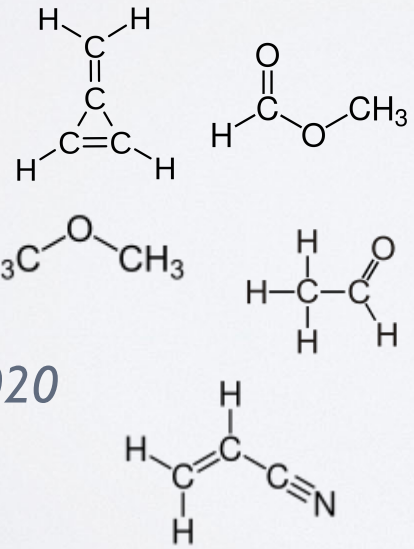
COMs form at the edge of the "catastrophic" CO freeze-out zone

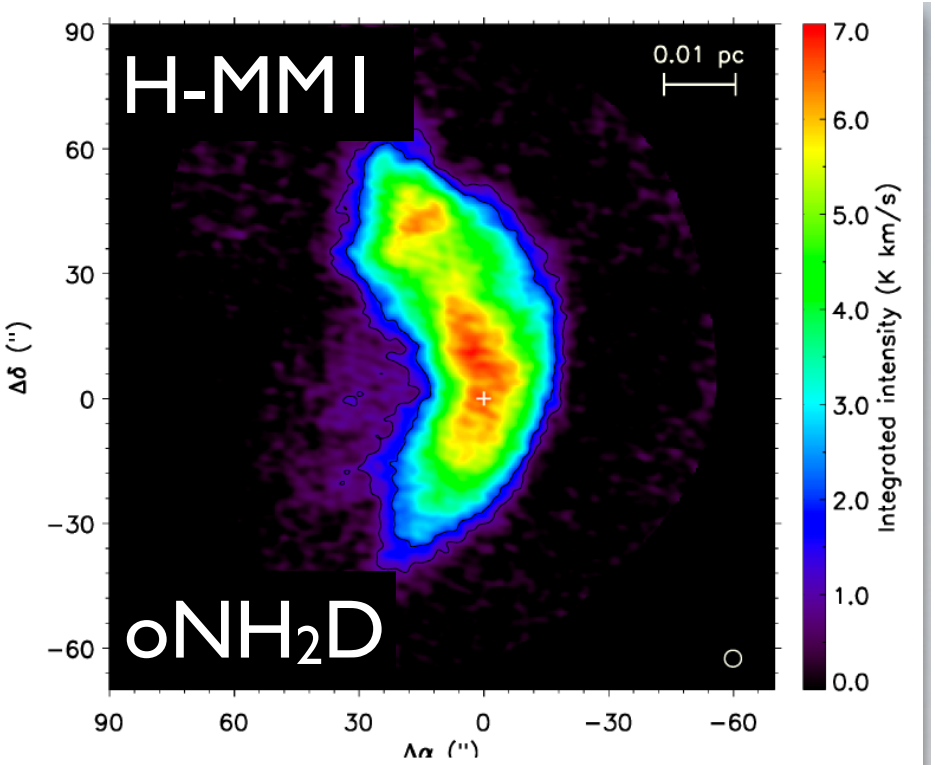
(see theory work by Vasyunin+2017)

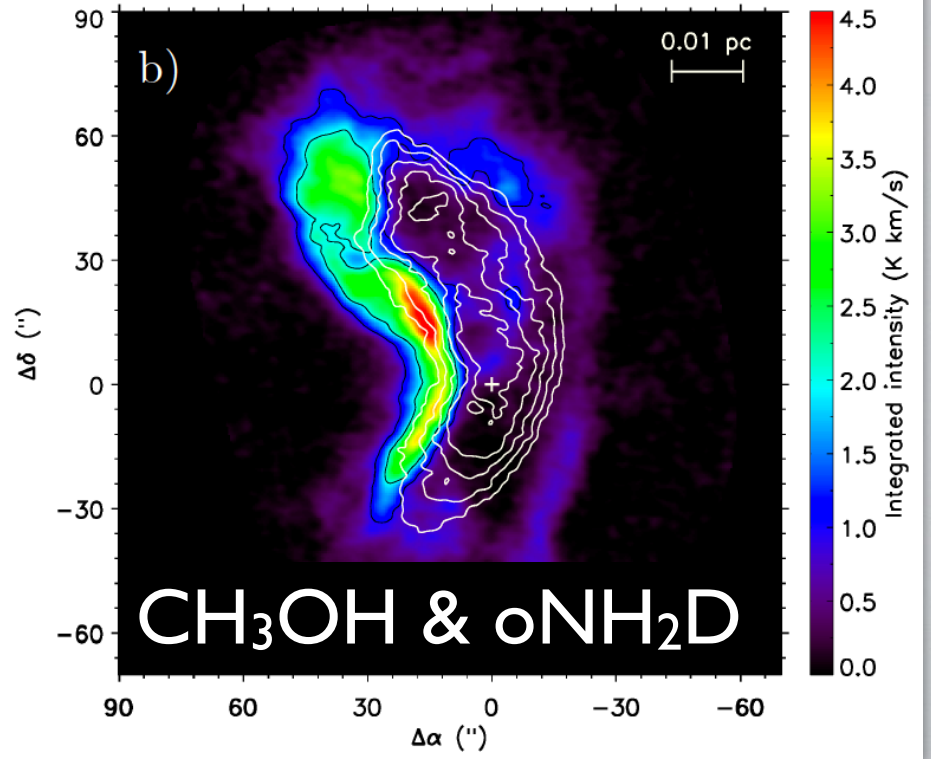
Harju+2020

See also:

Marcelino+2007
Öberg+2010
Bacmann+2013
Bizzocchi+2014
Vastel+2014
Bacmann&Faure 2016
Jiménez-Serra+2016, 2021
Spezzano+2016, 2017, 2020
Scibelli & Shirley 2020
Ambrose+2021
Punanova+2022



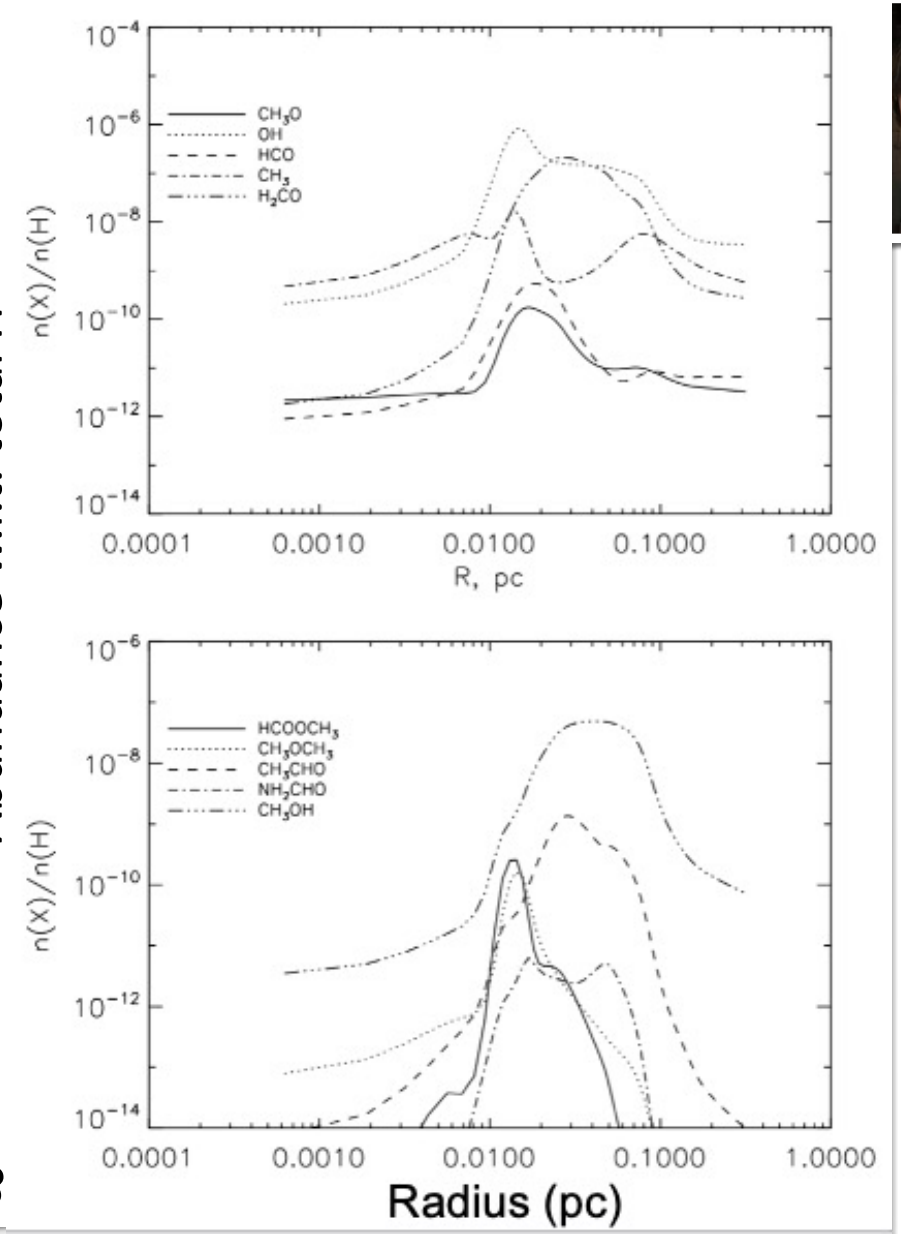




COMs form at the edge of the catastrophic CO freeze-out zone

Vasyunin+2017

Detailed gas-grain chemical network, using measured reactive desorption efficiencies on icy surfaces with different composition *(Minissale+2016)*, photodesorption rates *(e.g. Öberg+2009; Cruz-Diaz+2016; Bertin+2016)* and experimental + theoretical studies on neutral-neutral reactions *(e.g. Shannon+2013; Balucani+2015; Skouteris+2017)*

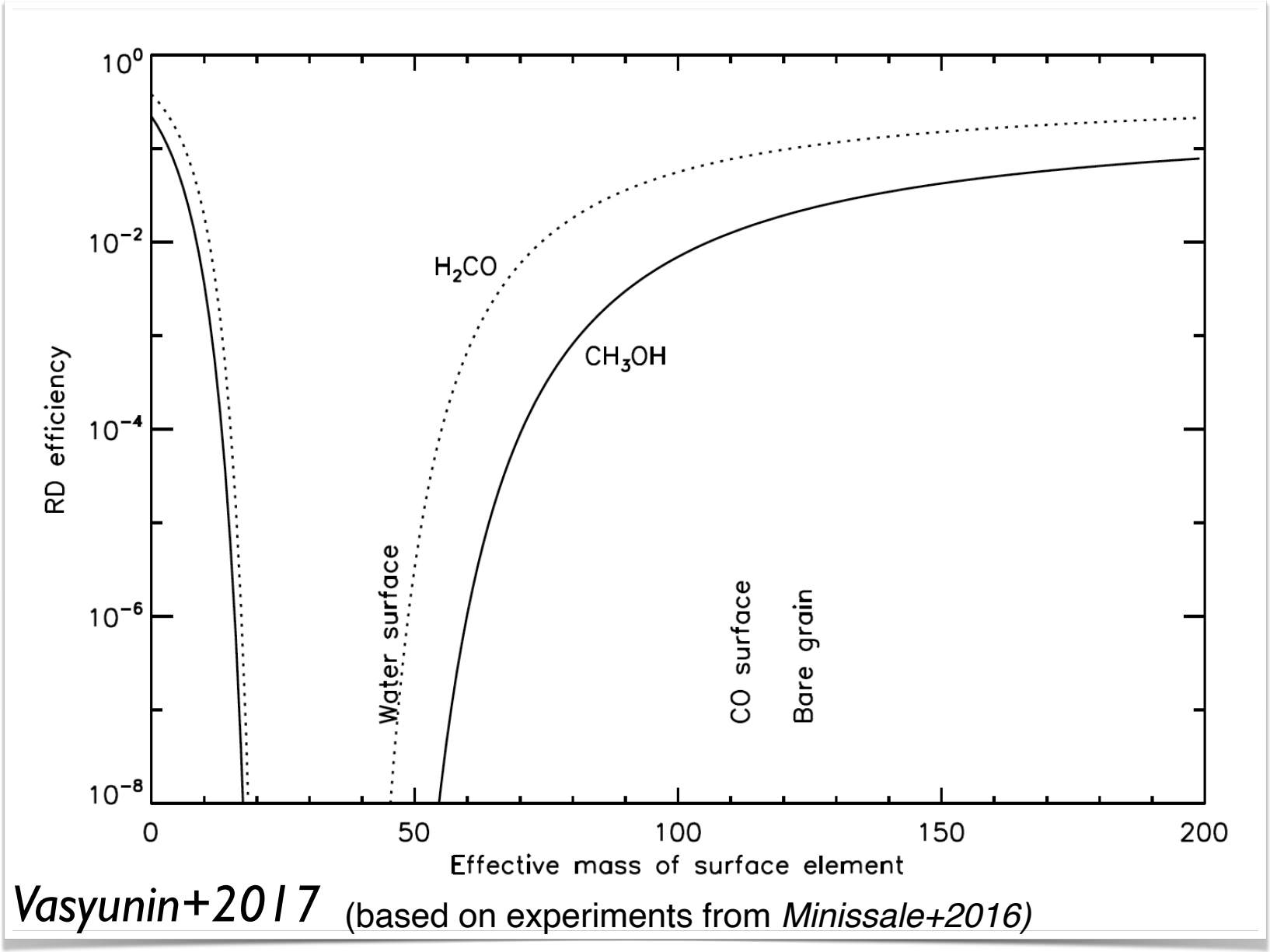




Anton

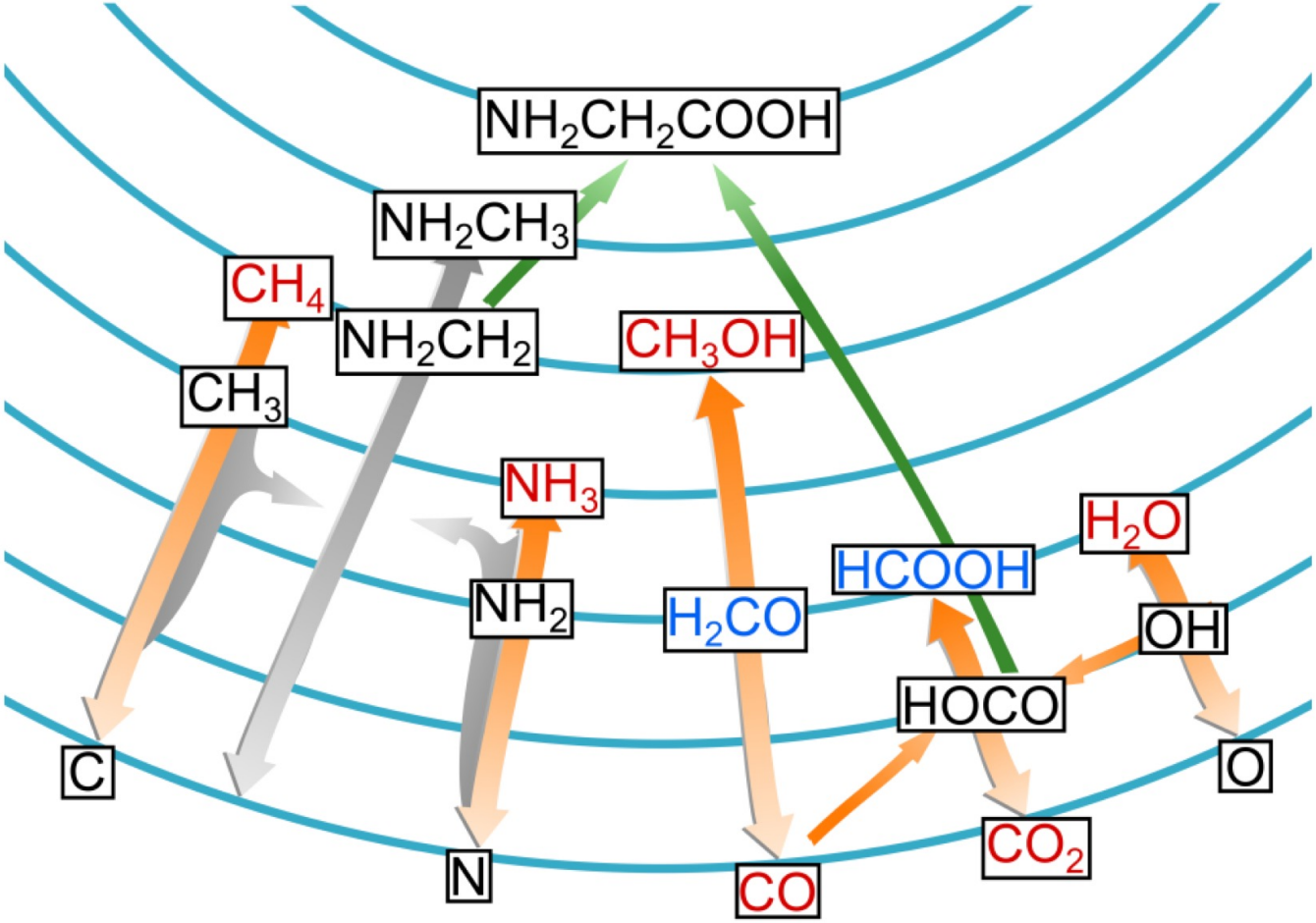
See also: Jin & Garrod 2020; Riedel+2023

Reactive desorption efficiency of CH_3OH and H_2CO dramatically increases when icy mantles are CO-rich (as in cold dense clouds)



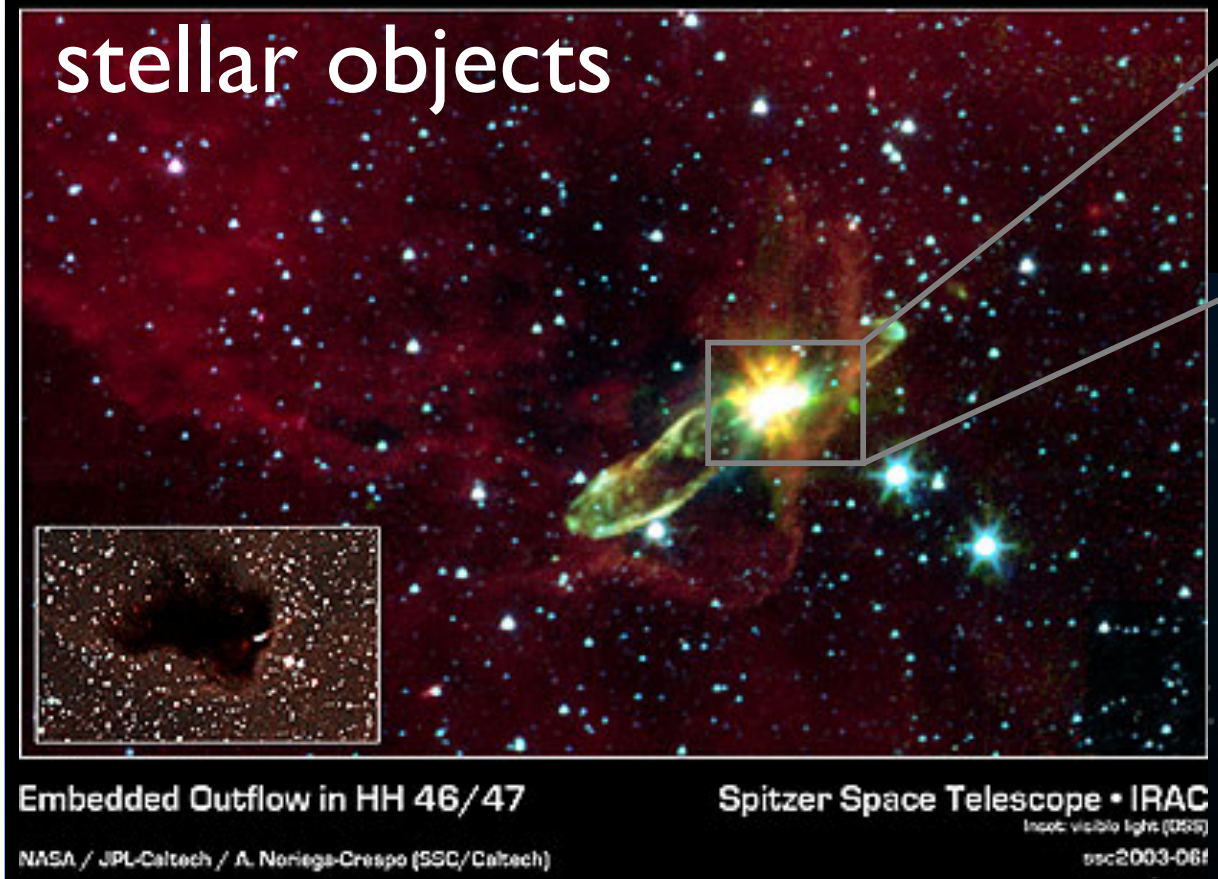
Vasyunin+2017 (based on experiments from *Minissale+2016)*

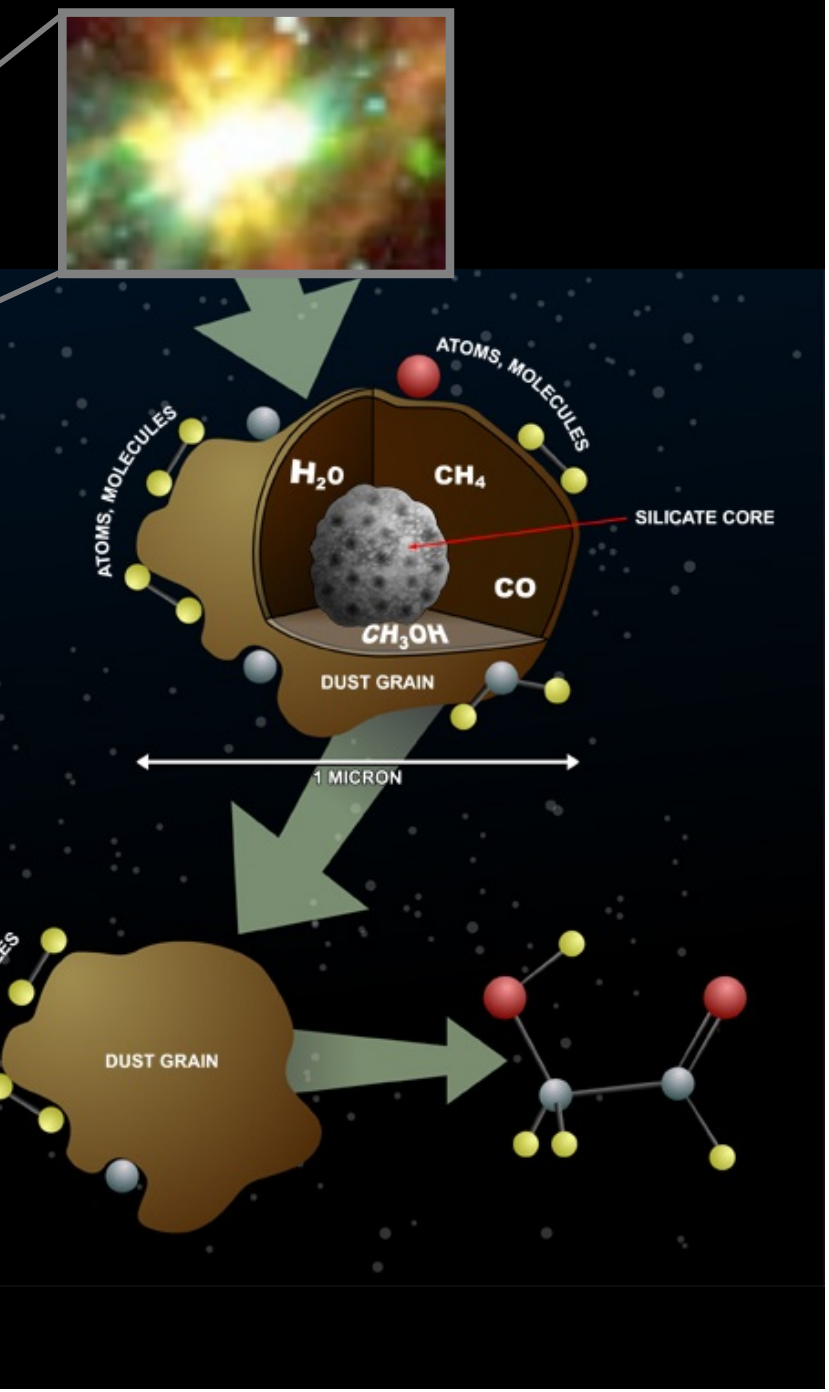
Formation of glycine in a water-rich ice at low T



Laboratory experiment: *Ioppolo+2021, Nature Astronomy*
see also Krasnokutski+2022, Nature Astronomy

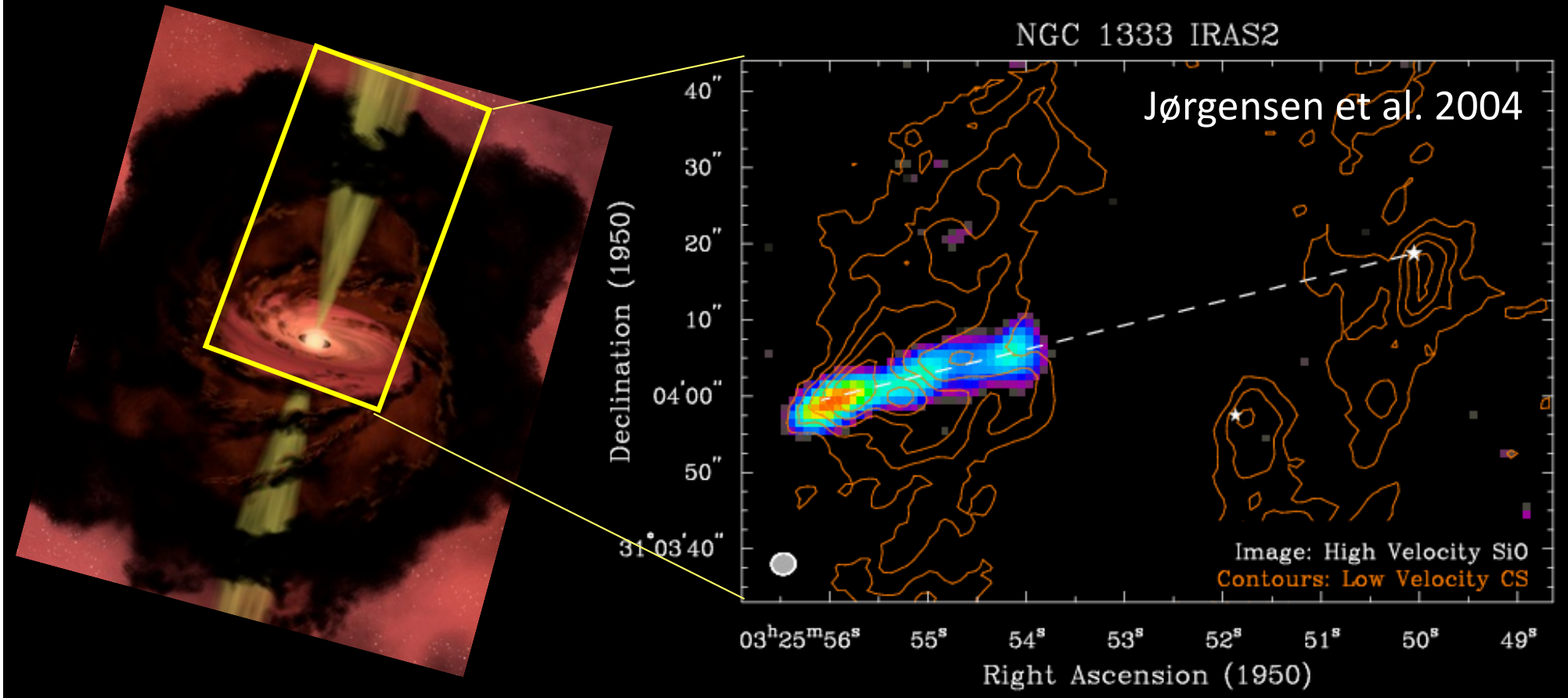
Icy species can return in gas phase nearby young stellar objects





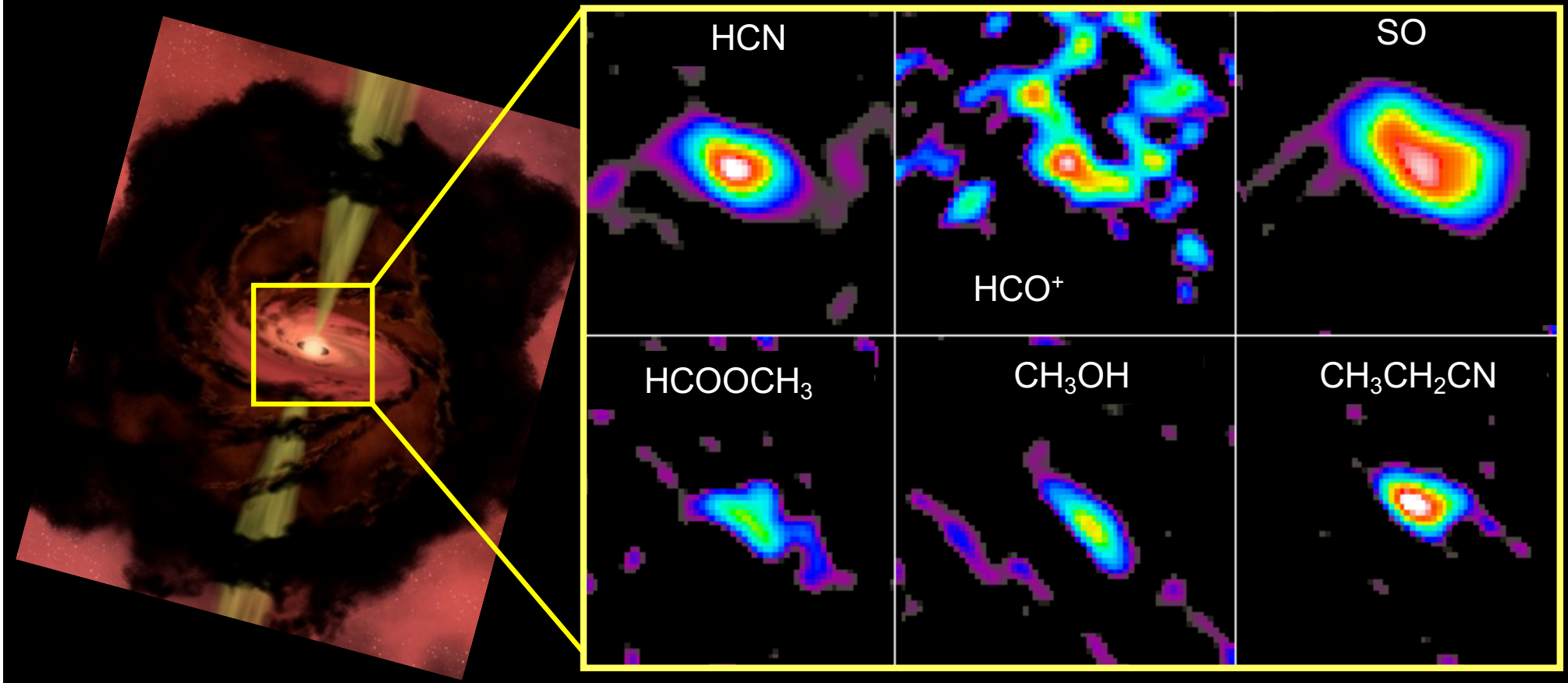
- Dust heating + energetic particles nearby protostars (icy mantle processing and evaporation; e.g. Viti+2004, Garrod+2008)
- Dust (icy mantles and cores) sputtering + vaporisation along outflows (e.g. Caselli+1997, Jiménez-Serra+2008)

Strong H_2O, SiO, CH_3OH, NH_3, emission (e.g. Bachiller 1996) and complex molecules (e.g. C_2H_5OH, $HCOOCH_3$, NH_2CHO: Arce+2008; De Simone+2020) along outflows driven by young stellar objects.

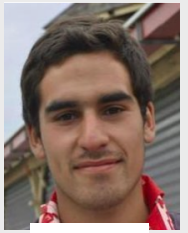


Complex organic molecules in hot cores and hot corinos

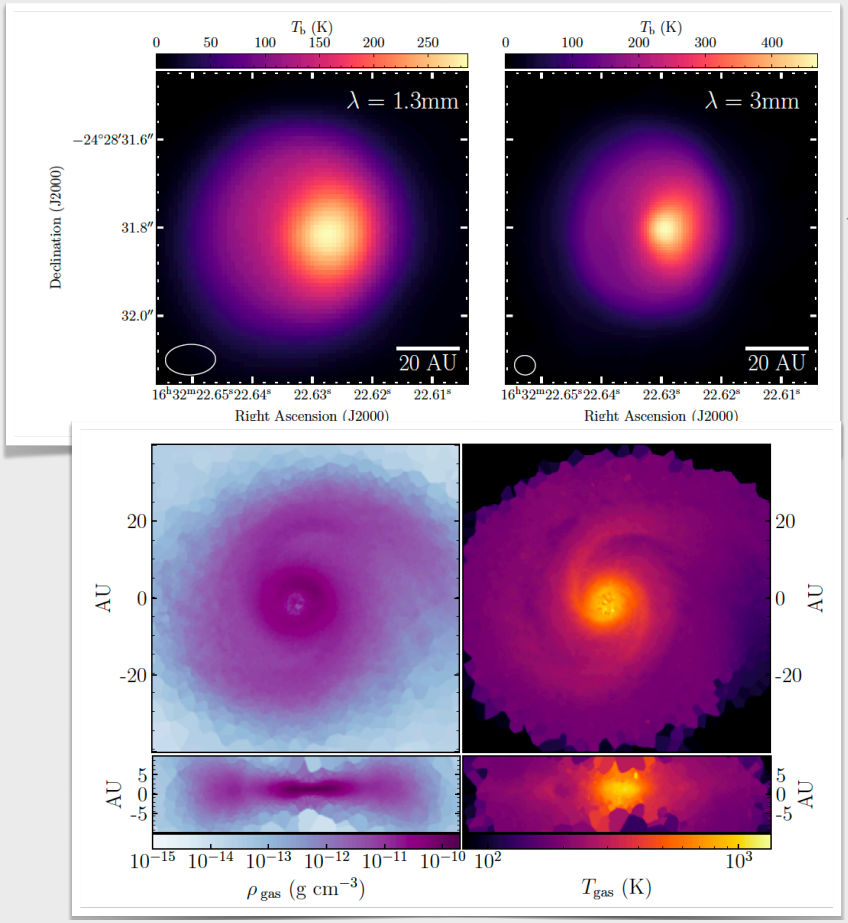
(e.g. Wright et al. 1996; Cazaux et al. 2003; Bottinelli et al. 2004, 2008; Kuan et al. 2004; Belloche+2009; Widicus-Weaver&Friedel 2012; Jørgensen+2016; Ceccarelli+2022, PPVII)



Protostellar disks can be hot and gravitationally unstable



Joaquin



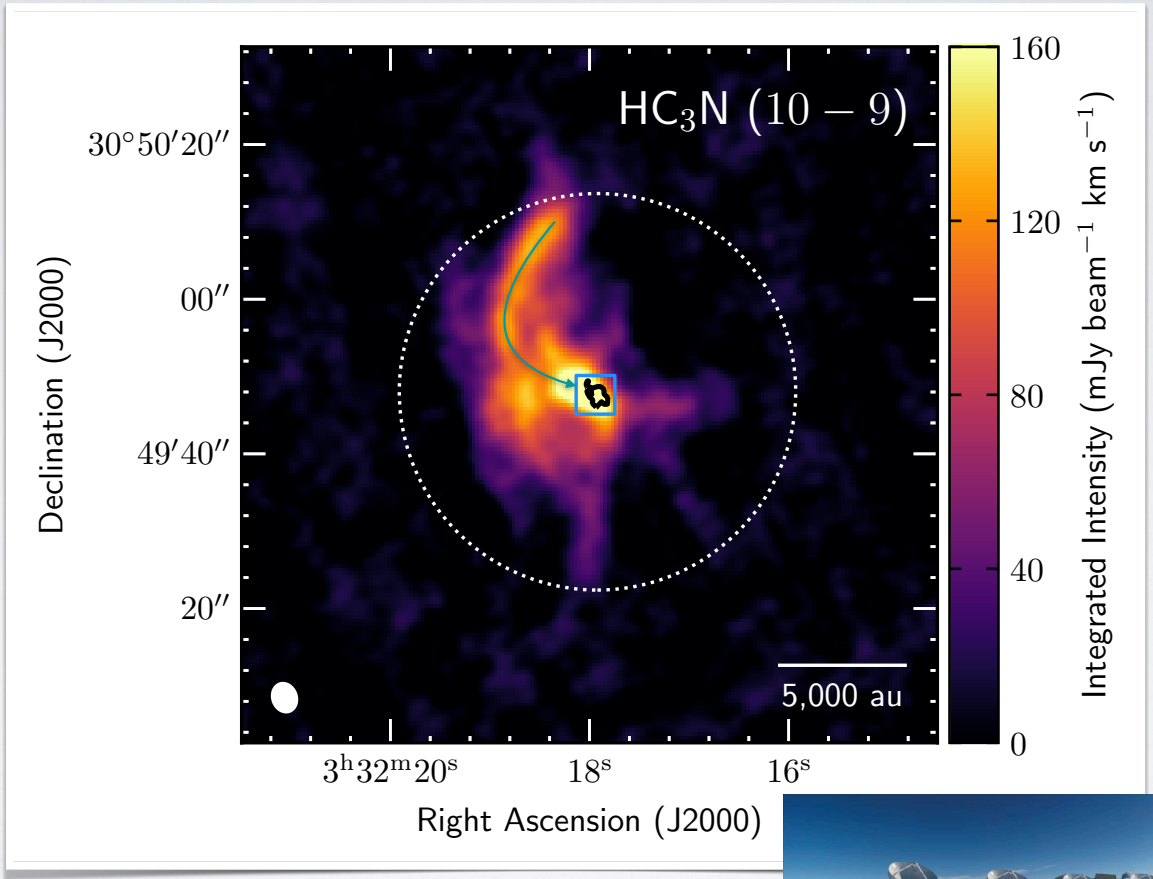
IRAS16293B ALMA observations: high brightness temperatures with T_b(3mm) > T_b(1mm), indicative of hot mid-plane.

Simulations of a gravitationally unstable disk, which reproduce ALMA observations: all icy mantles should evaporate + dust processing.

Zamponi, Maureira, Liu+2021

Not all ice is lost! Protostars accrete directly from the surrounding cloud through streamers



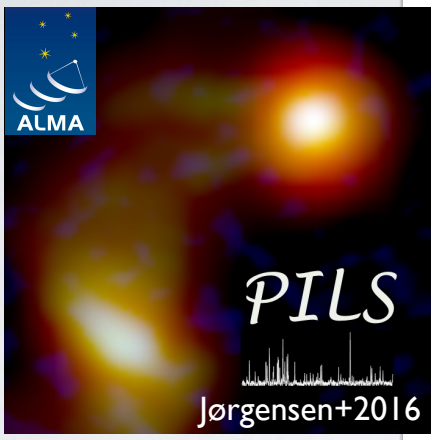


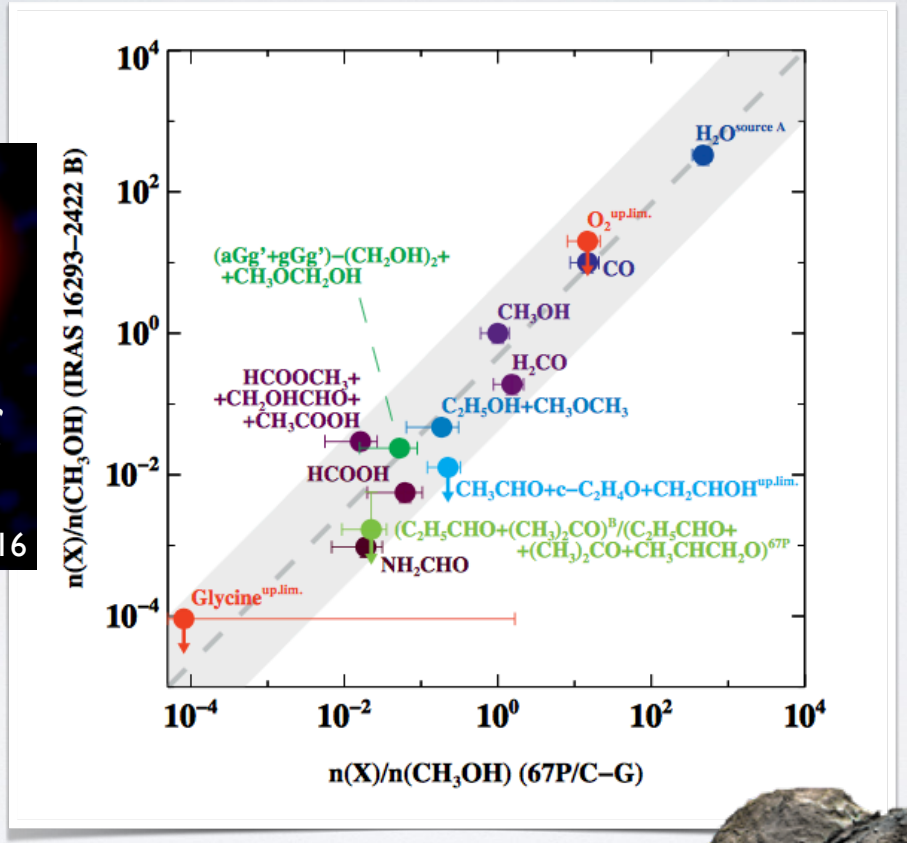
Pineda+2020, Nature Astronomy



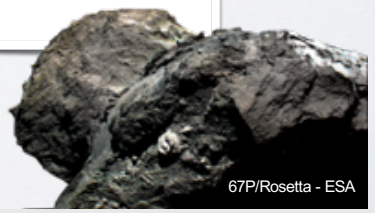
(See also, e.g., Valdivia-Mena+2022, Hsieh+2023, Flores+2023)

Similar complex organic abundances in comets and star-forming regions





"The volatile composition of cometesimals and planetesimals is partially inherited from the pre- and protostellar phases of evolution."



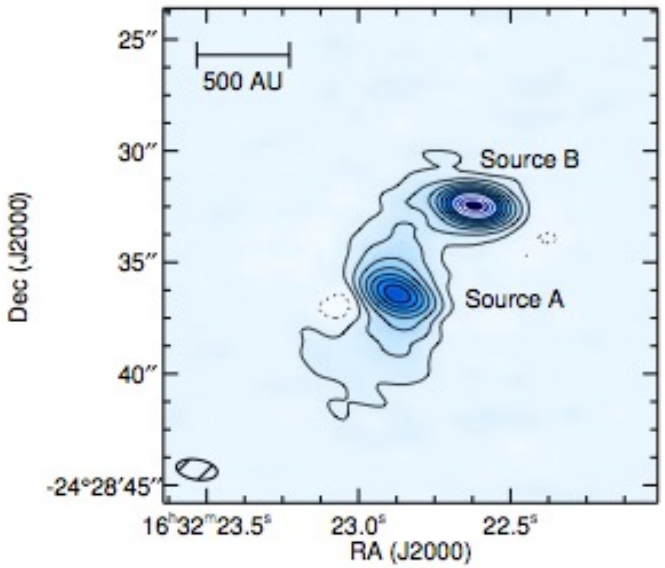
Drozdovskaya+2019, 2021

See also Biver+2015, Rivilla+2020, Drozdovskaya+2022

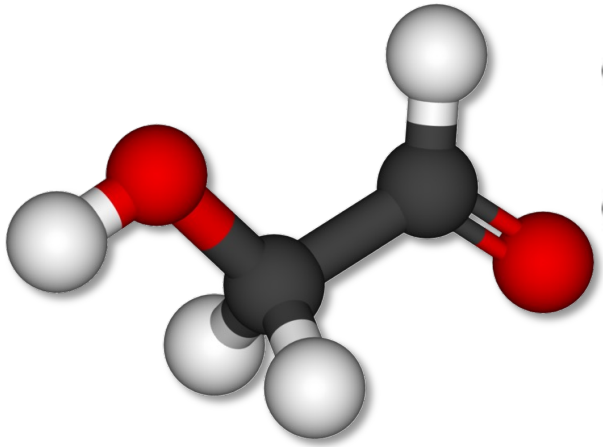
The simplest sugar detected with ALMA in a Solar-type protostellar source

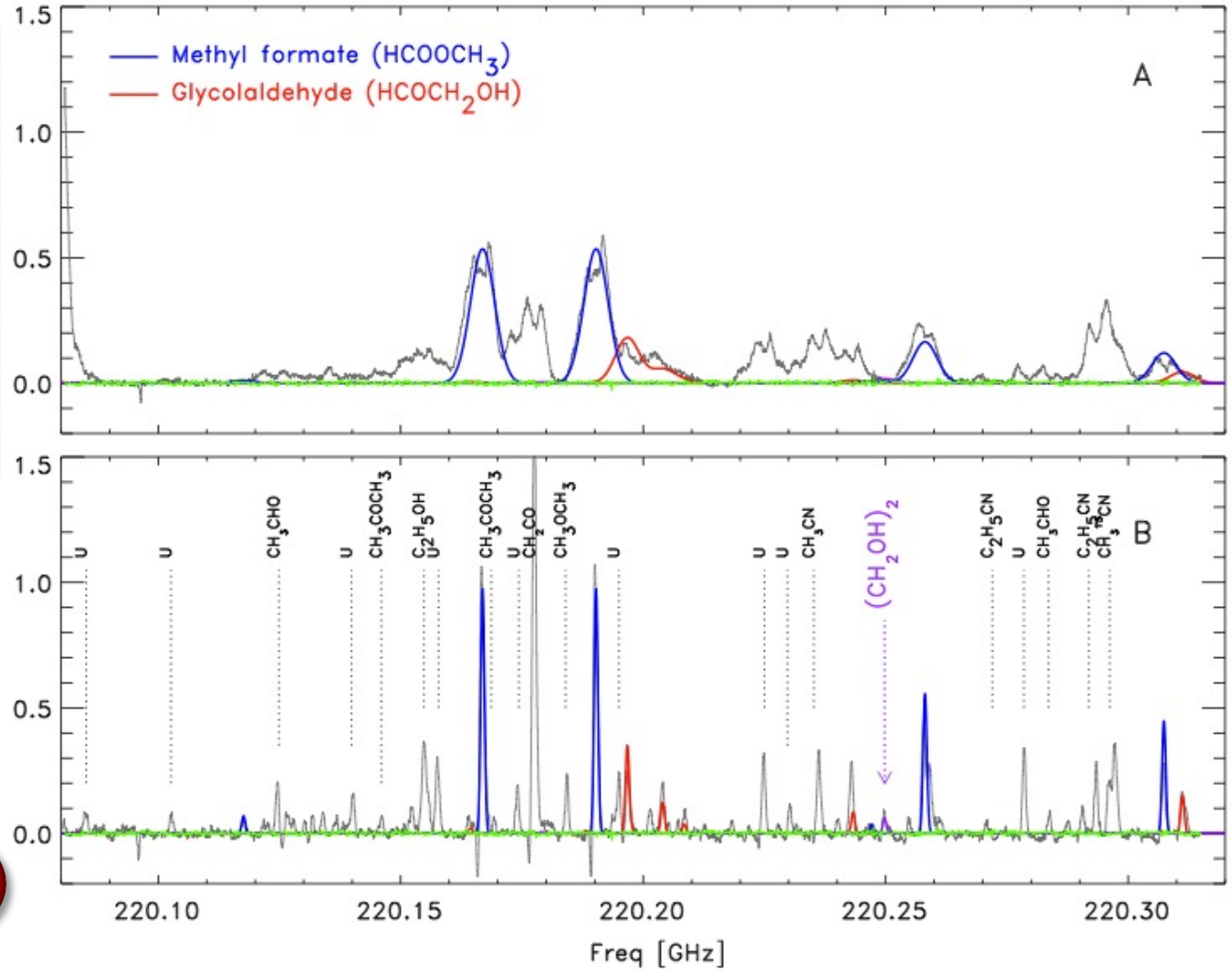


1mm continuum map



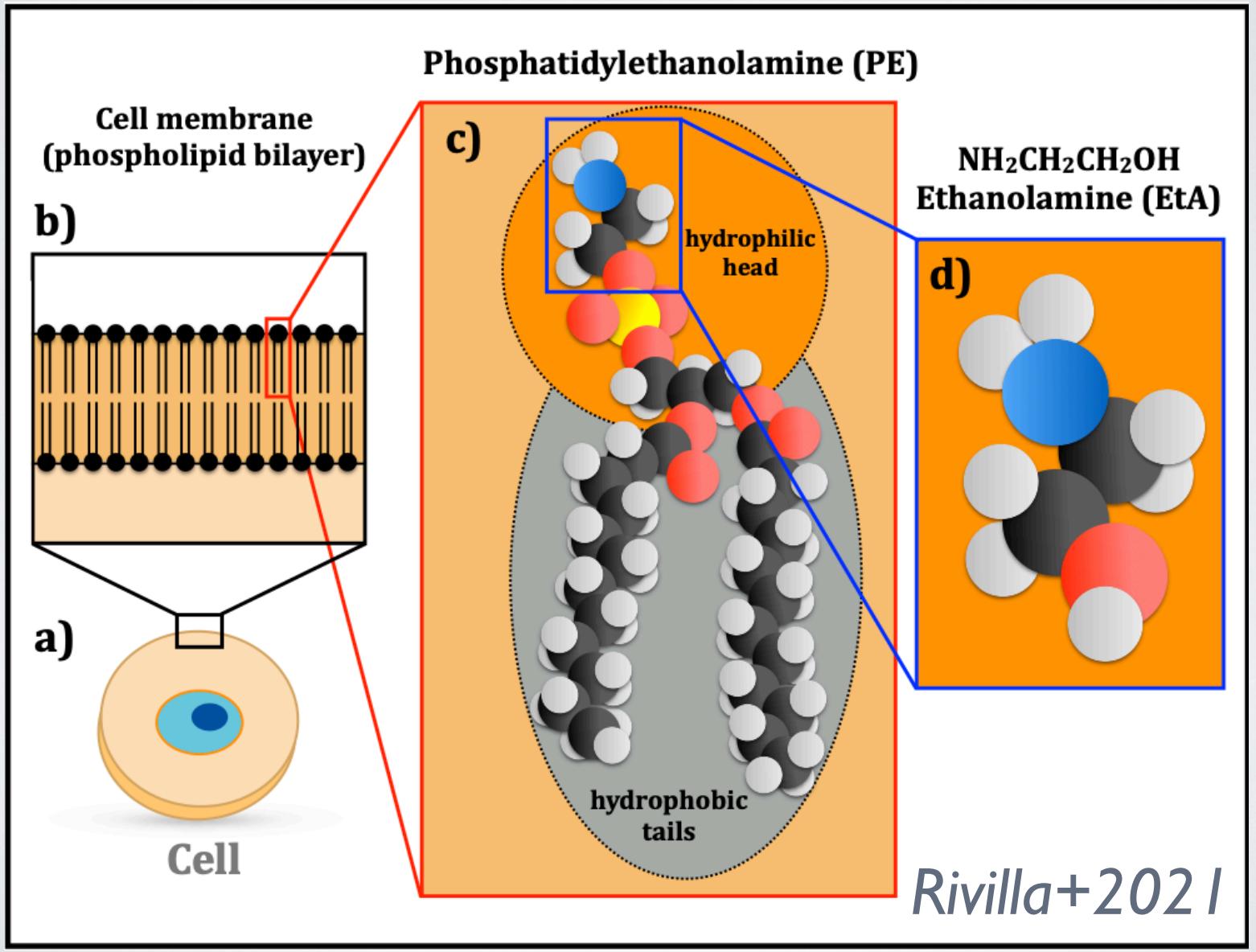
Pineda et al. 2012





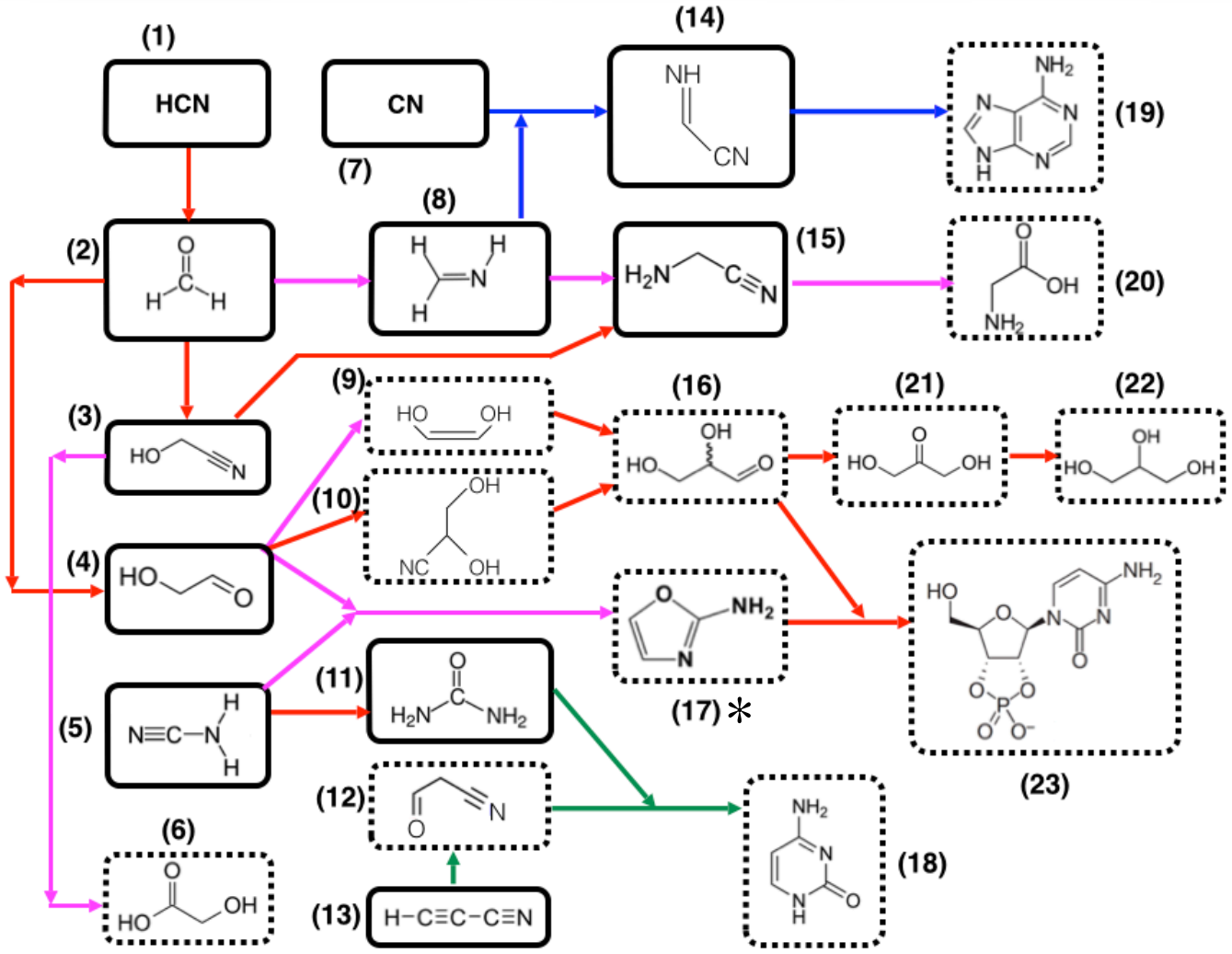
Jørgensen et al. 2012

Discovery in space of ethanolamine, the simplest phospholipid head group



Towards the RNA-world in the ISM

(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)



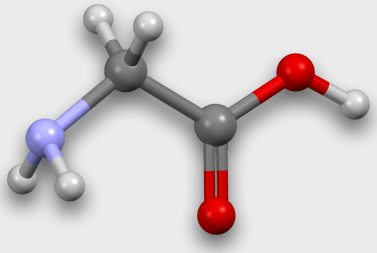
Jiménez-Serra+2020

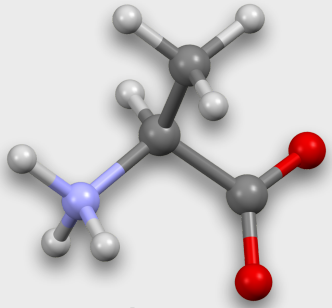
Pre-biotic molecules at the dawn of our Solar System

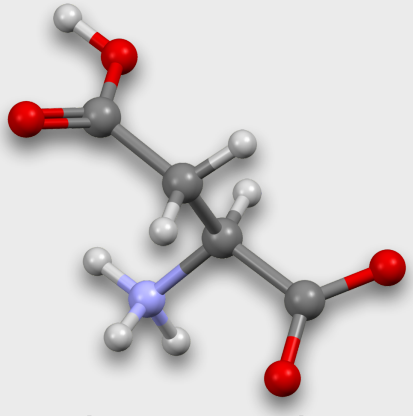


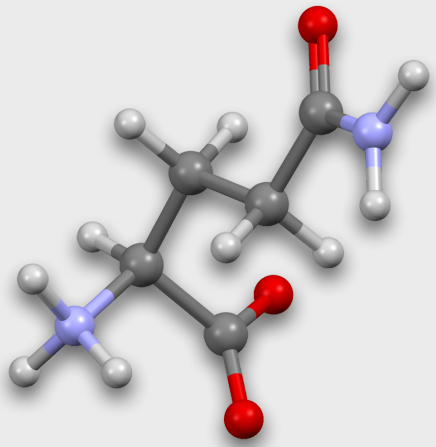



>200 amino acids (20 are used by all living beings on Earth), fatty acids, all bases in RNA and DNA (adenine, cytosine, guanine, thymine, uracil), ribose have been identified in primitive meteorites (e.g. *Oba+2022, Nature communications*).


Glycine

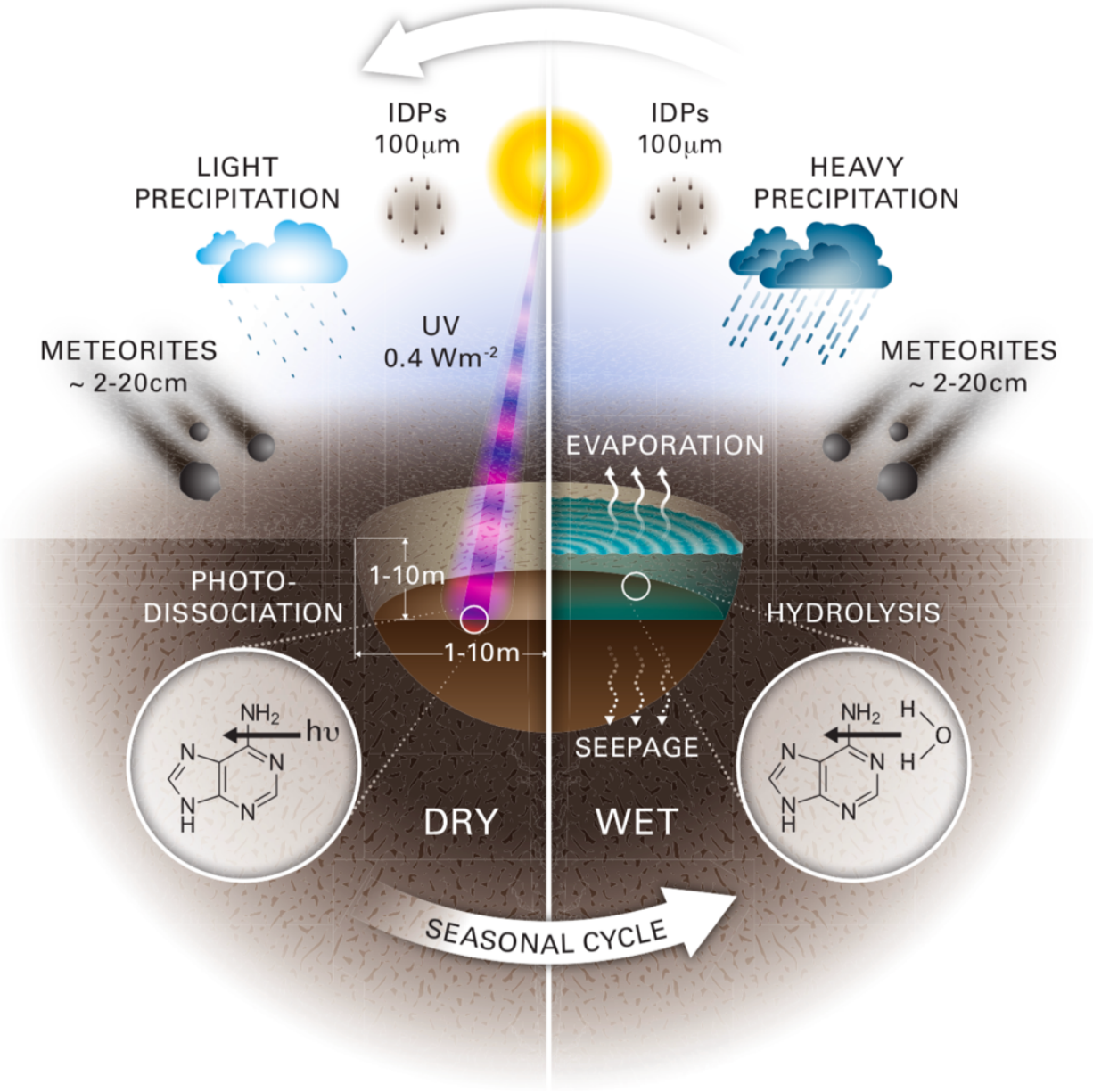

L-Alanine


L-Aspartic Acid

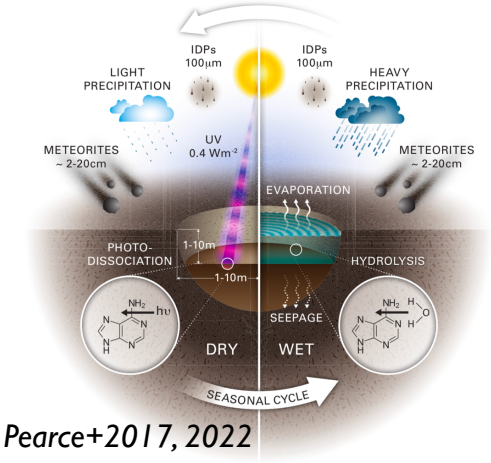

L-Glutamine

The delivery of pre-biotic molecules on habitable planets could trigger the origin of life!

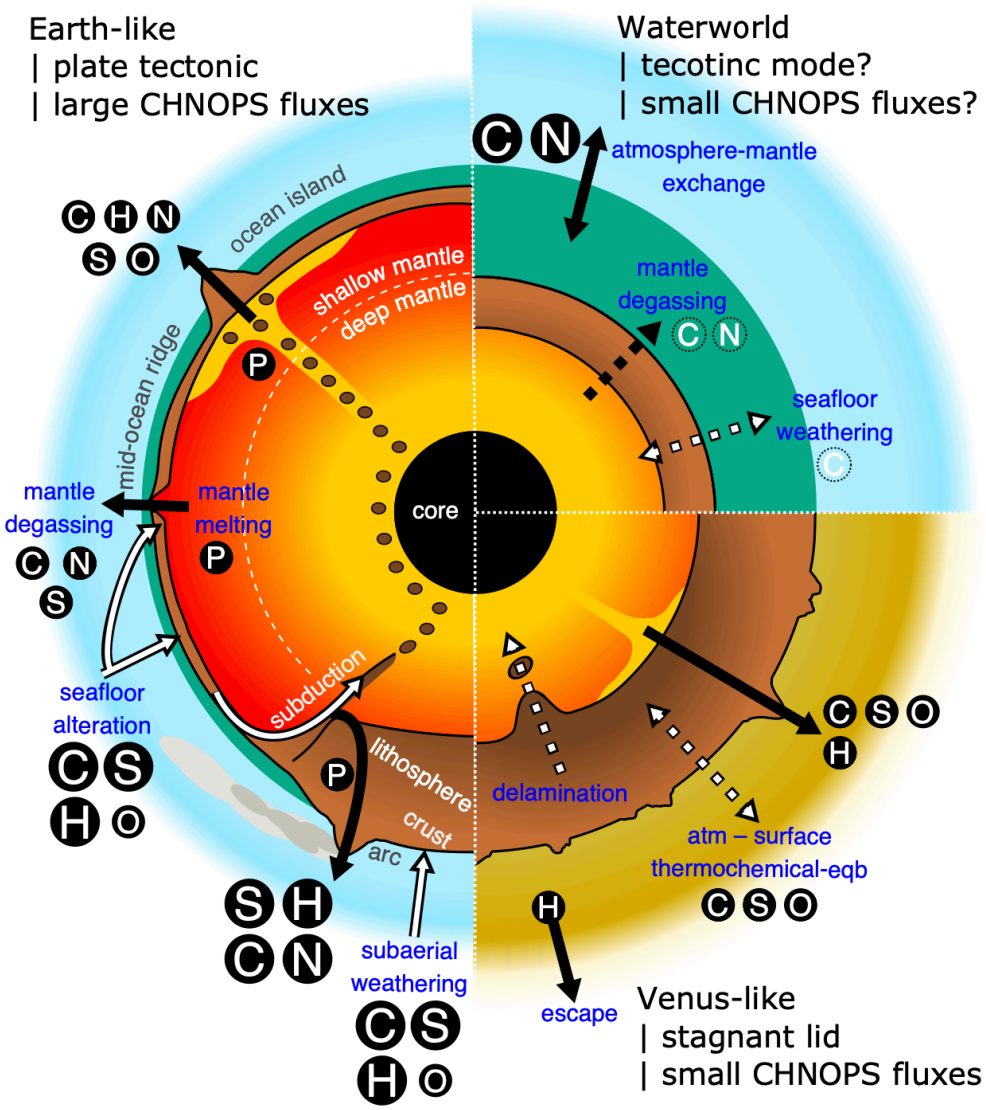
RNA can be produced within ~200 Myr of the Moon-forming impact (Pearce+2017, 2022)



Planetesimal composition affects the geo- and biochemical evolution of habitable planets



Pearce+2017, 2022



Krijt, Kama, McClure+2022, PPVII

THE END