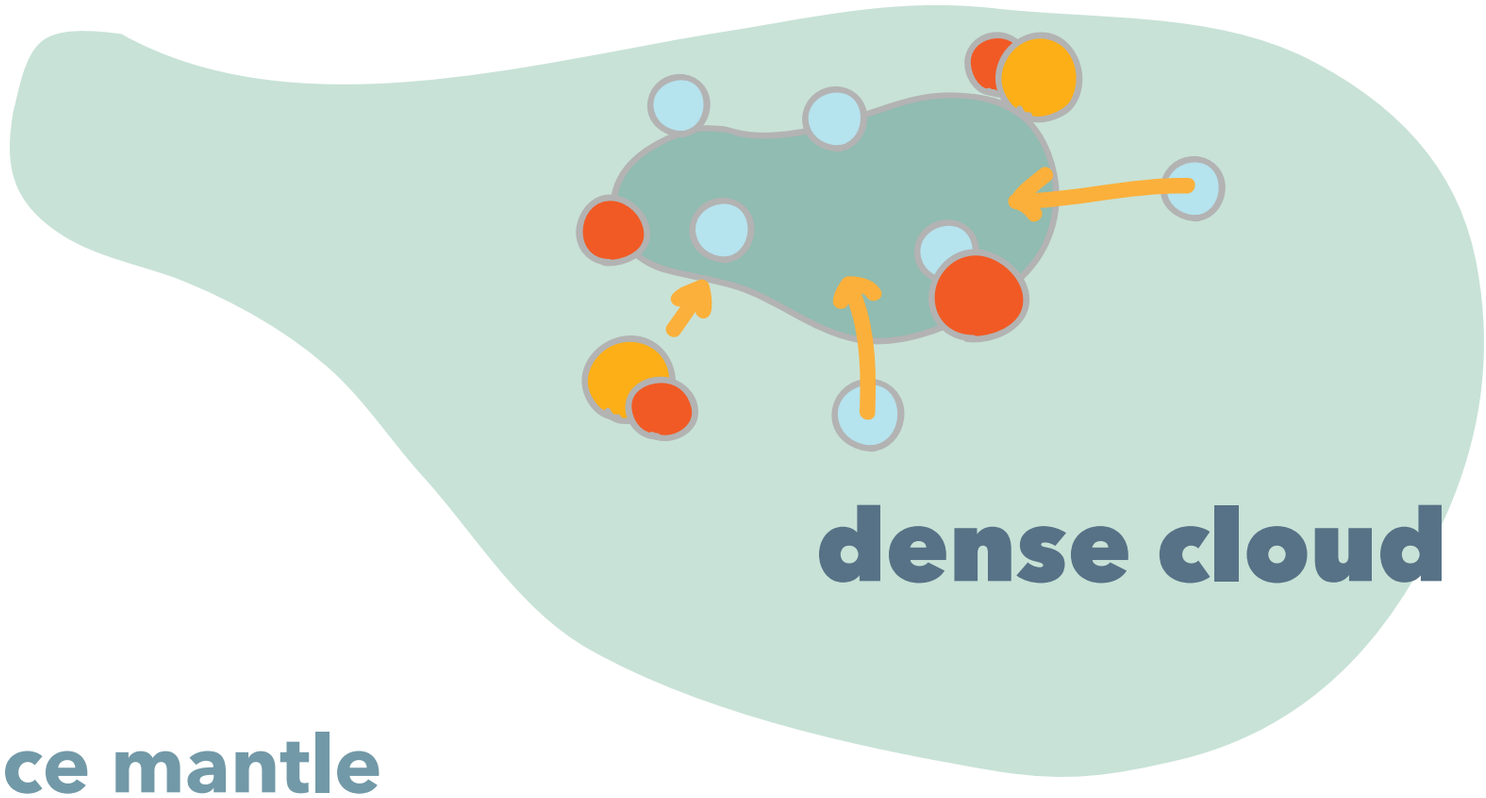
Interstellar ice

diffuse cloud

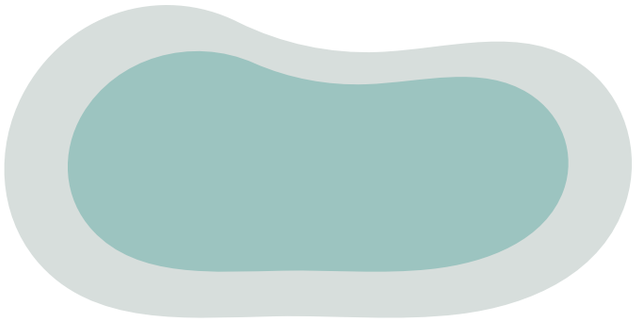
dust grain
silicate / graphite

T_d = 10 K
n > 10^4 cm^{-2}

T_d = 10-30 K
n = 100 cm^{-2}



dense cloud



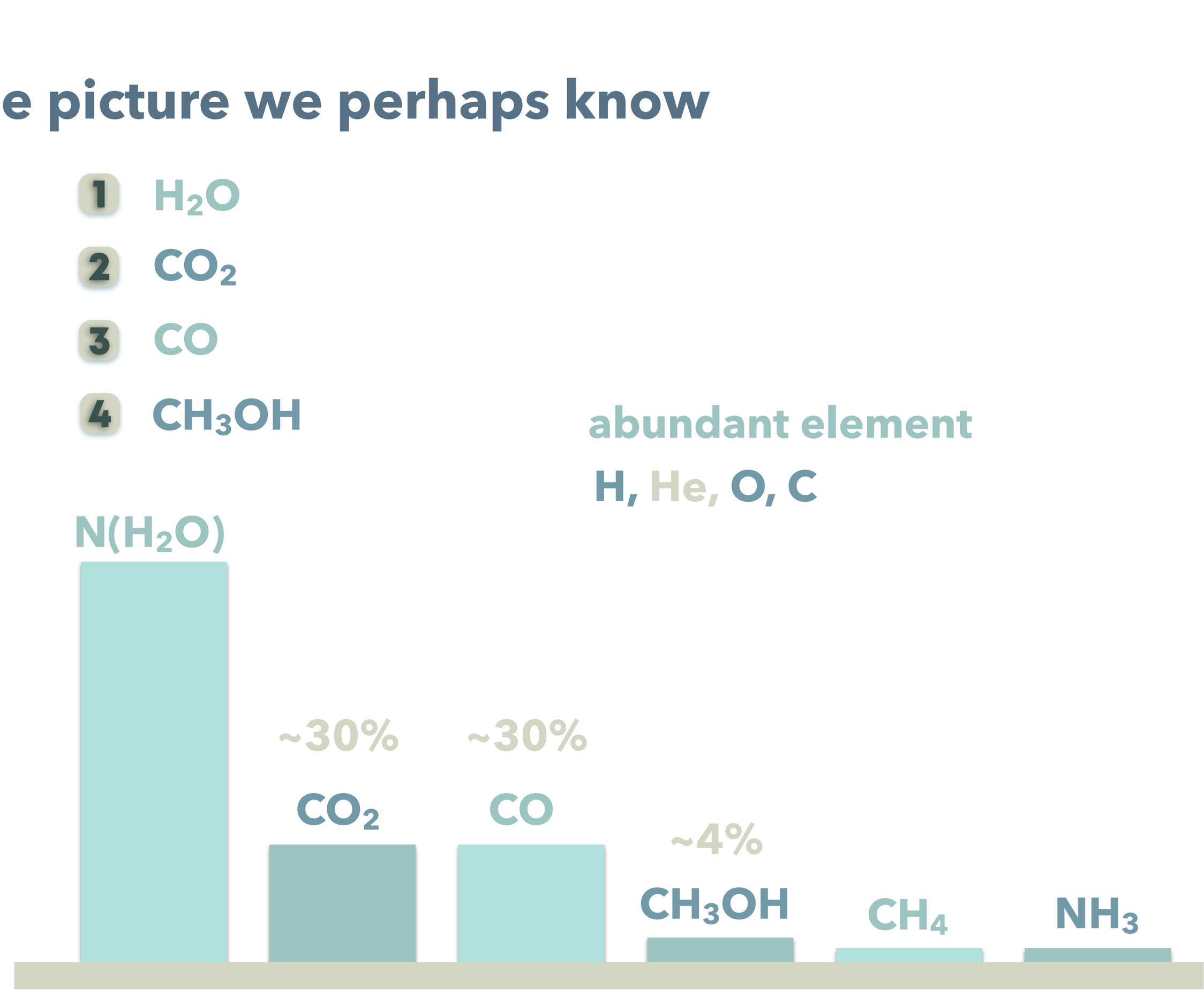
ice mantle
frozen molecules

The picture we perhaps know

1. H_2O
2. CO_2
3. CO
4. CH_3OH

abundant element

H, He, O, C

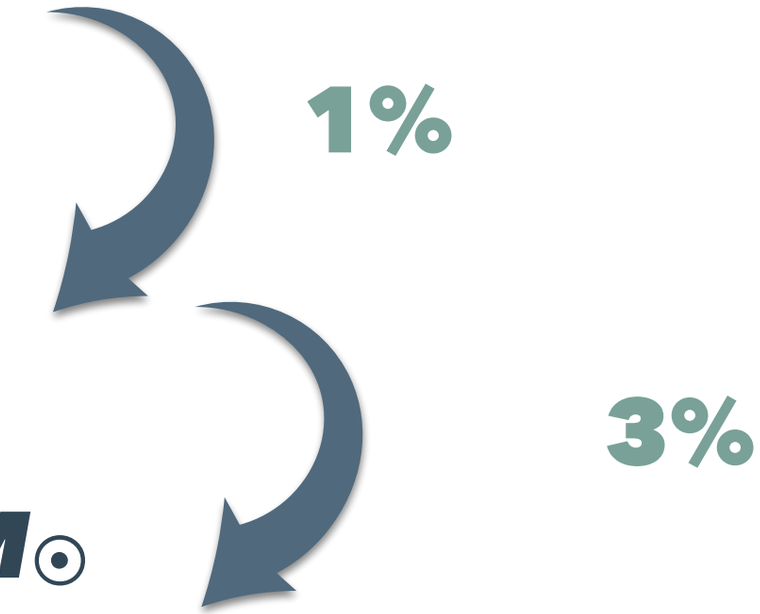


What a Dark Cloud is made of?

1 **gas** — 1 $M_\odot$

2 **dust** — 0.01 $M_\odot$

3 **ice** — 0.0003 $M_\odot$ = 100 $M_\oplus$



water : enough to fill the ocean 200,000 times

Cycle of Interstellar ice

1 No ice in diffuse cloud

2 water frost grows

3 molecules form on surface

4 other surface processes

5 desorption

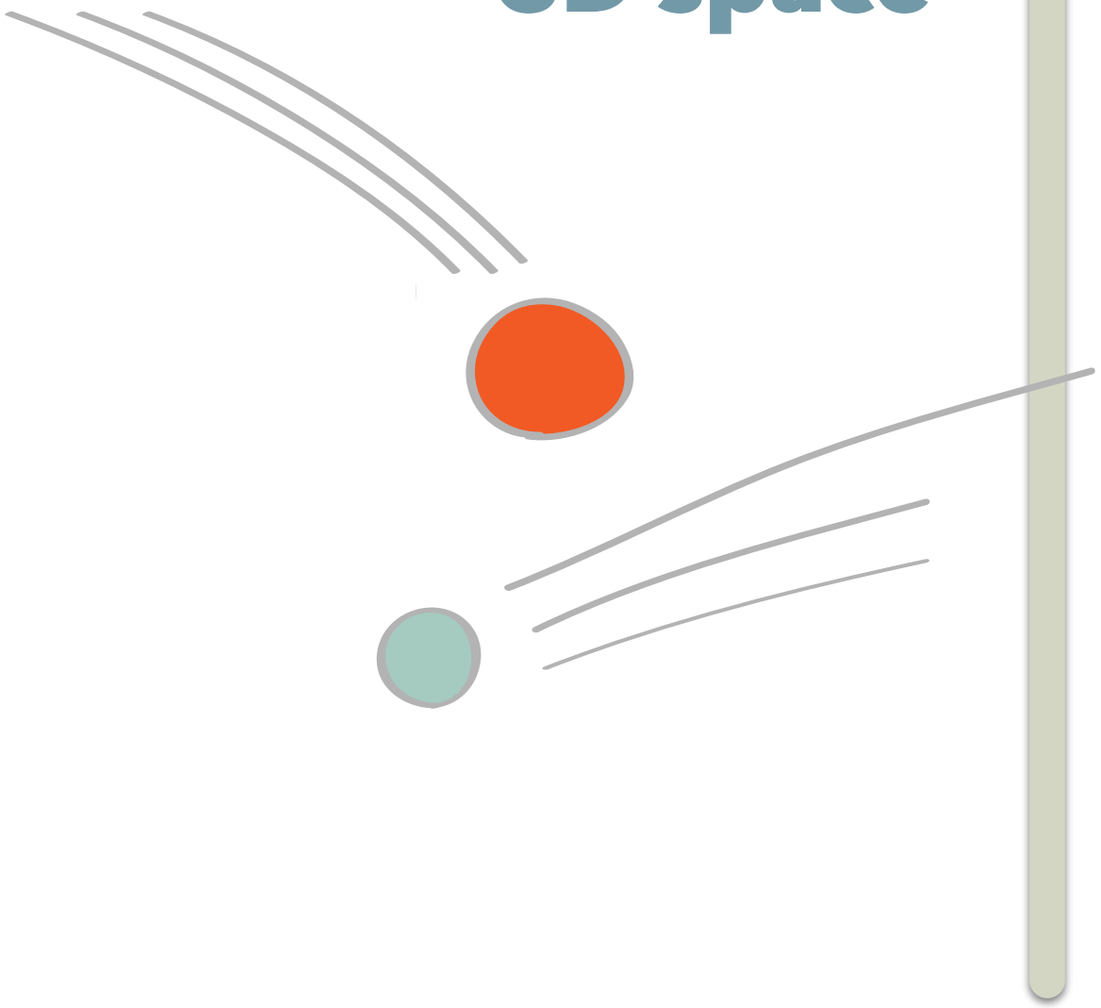
6 transportation

7 some ice stays on planetary crust

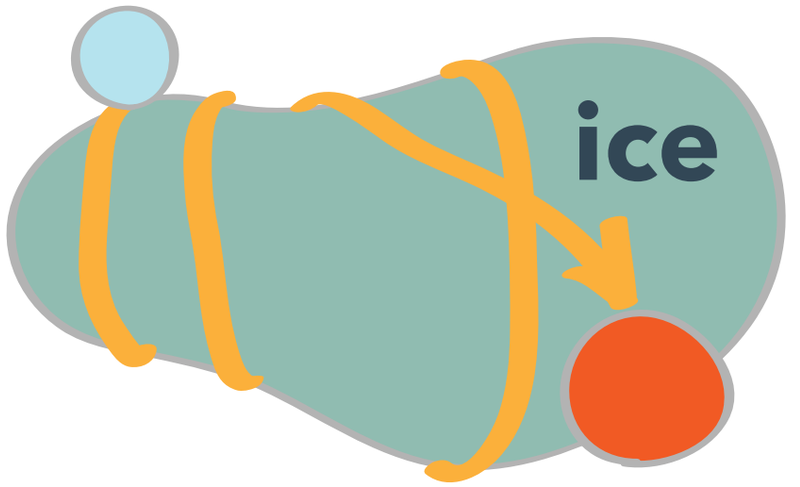
Role of

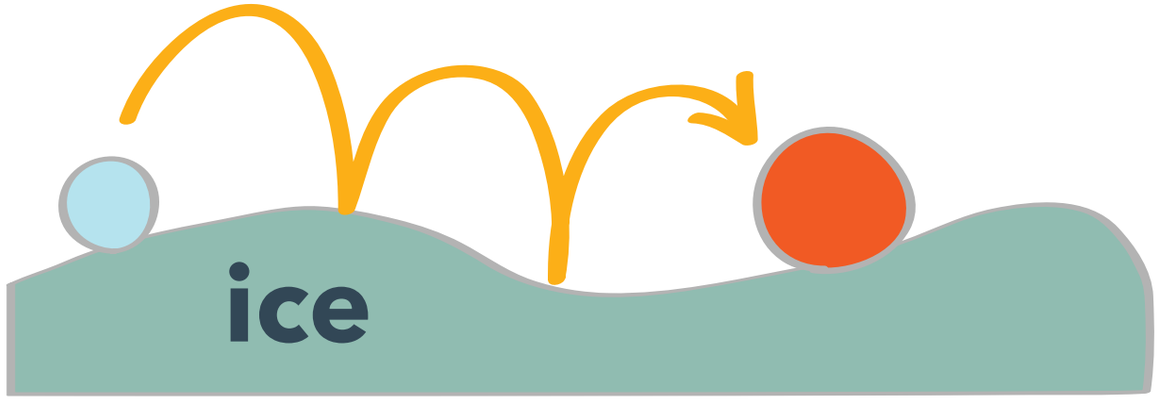
Interstellar ice

3D space



2D surface

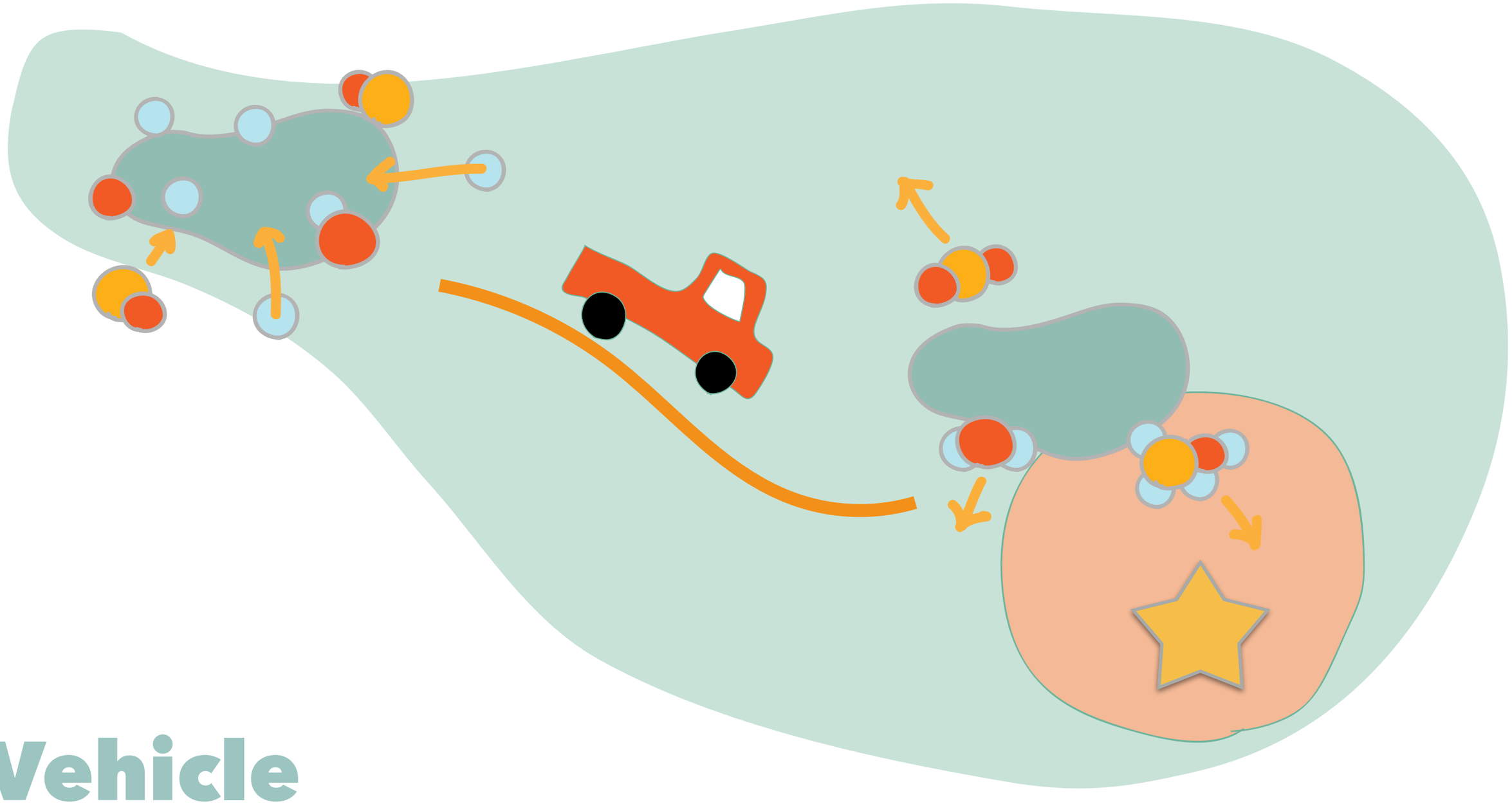




Otherwise
no complex organic molecules in the ISM.

Role of

Interstellar ice

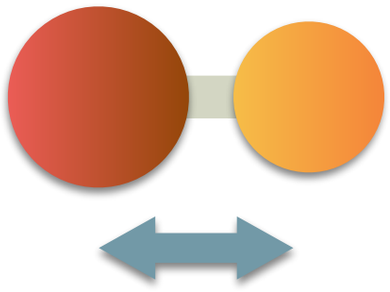


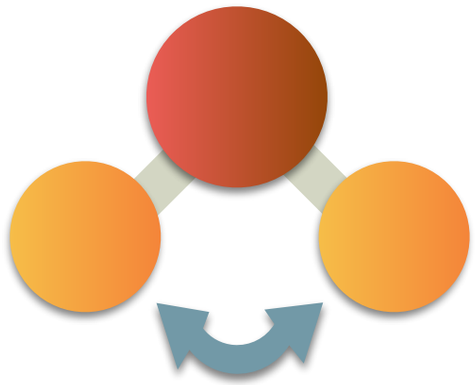
Vehicle

to transport evaporative material across the cloud

What an observer looks at

1 vibrational band → IR





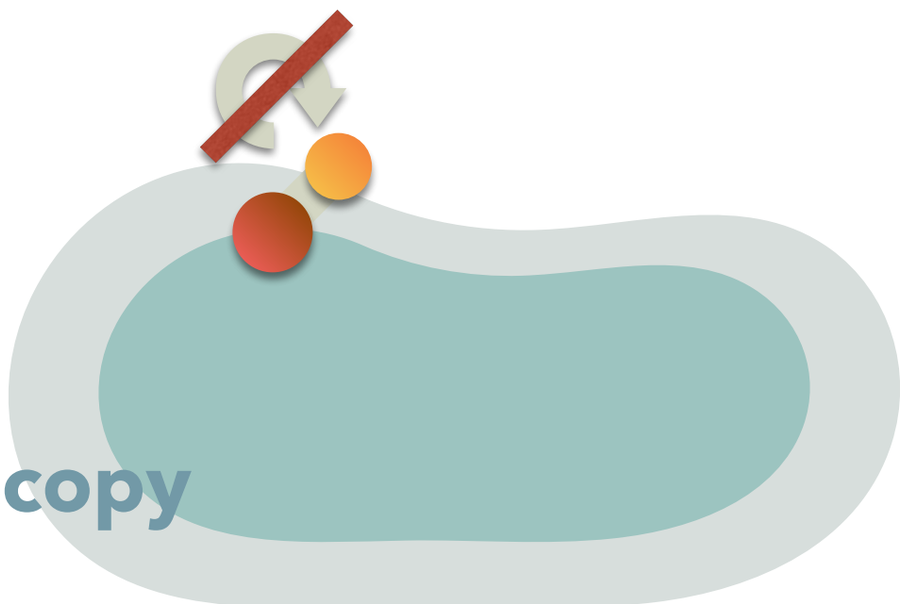
2 rotation quenched → J=0 except H_2

3 vibration restricted → broad + redshifted

4 low temperature

→ no emission except far infrared

→ need continuum star for absorption spectroscopy



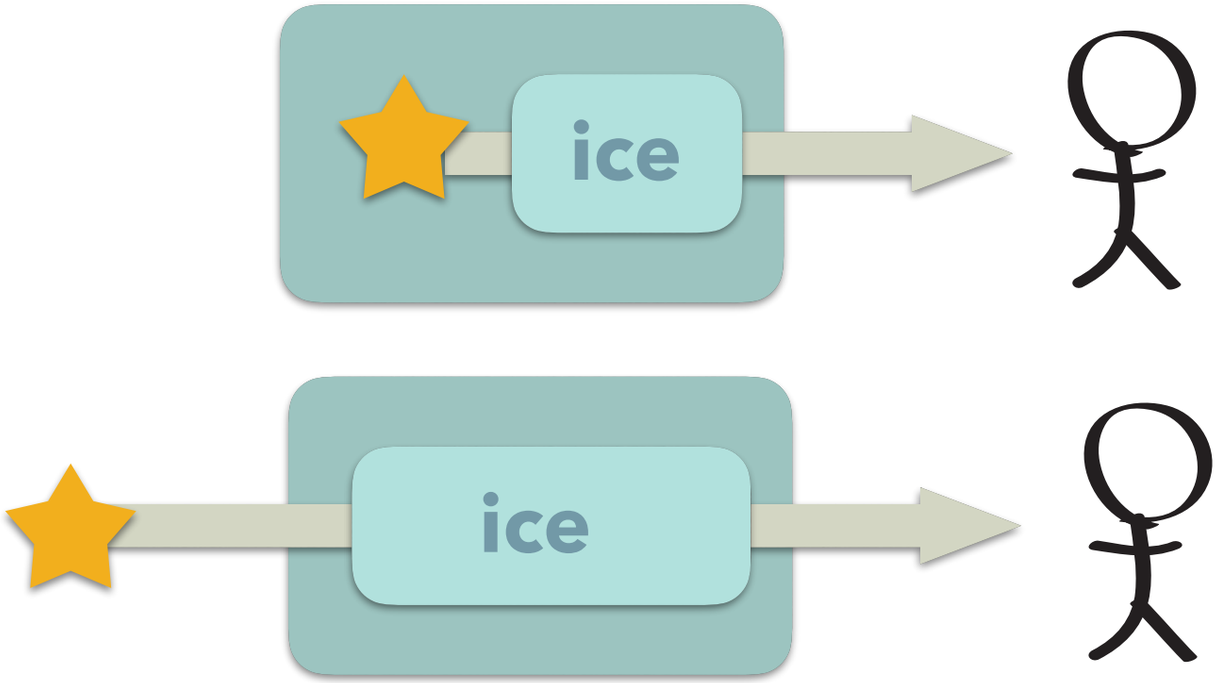
4 low temperature

➡ no emission

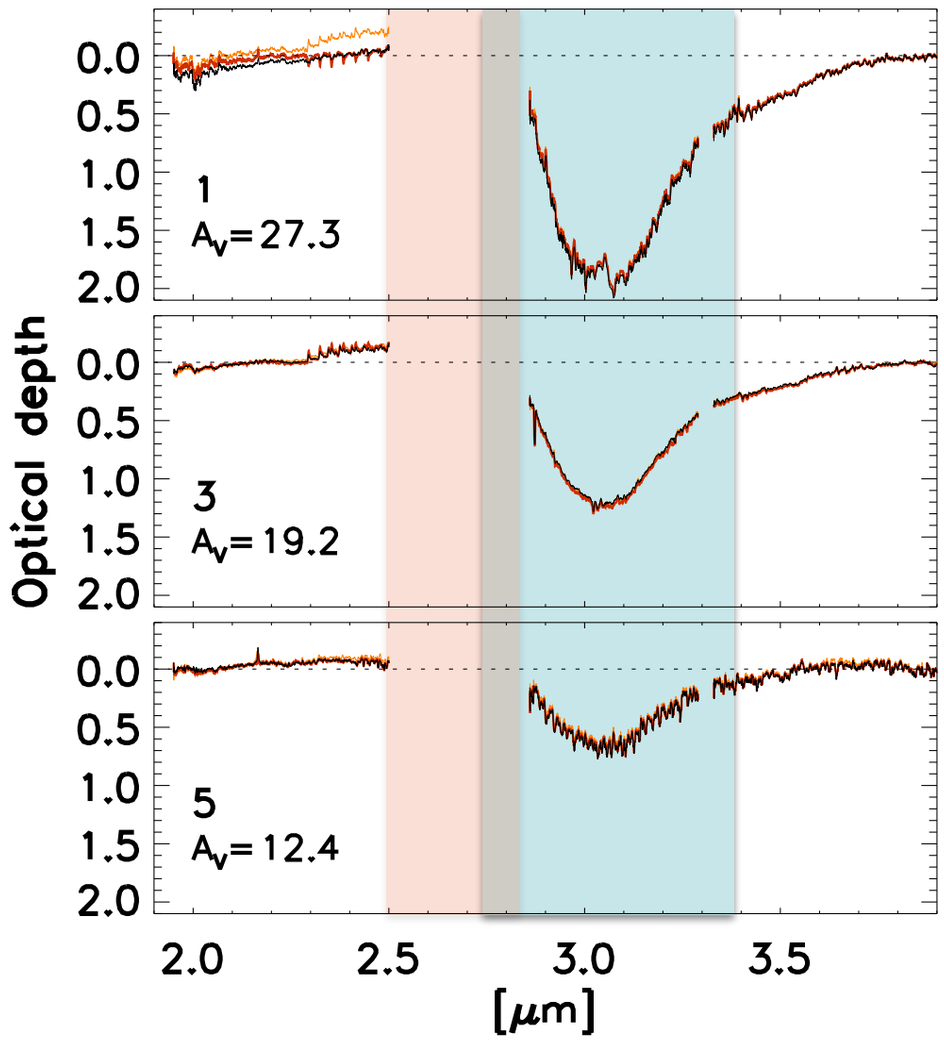
➡ need continuum star

for absorption spectroscopy

except far infrared



atmospheric water vapor



water ice

3 vibration restricted

➡ broad + redshift

Basic surface process

1 accretion
deposition
adsorption

2 diffusion
hop

3 reaction
formation

4 desorption
ejection
evaporation

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1 accretion
deposition
adsorption

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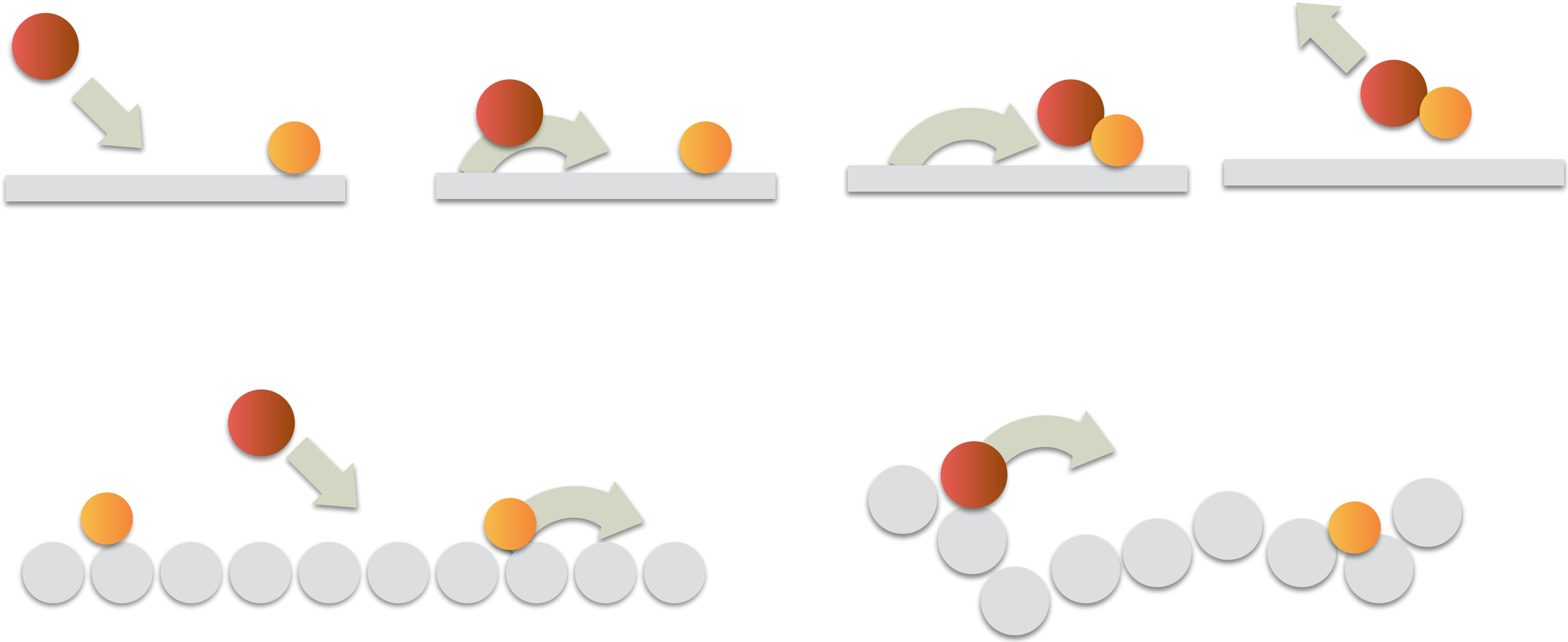


Basic surface process

1 accretion

deposition
adsorption
depletion

layers
island formation
droplet

2 diffusion

hop

thermal diffusion
tunneling diffusion
3D diffusion
segregation
trapping
polar / a polar ice

3 reaction

formation

hydrogenation
deuteration
tunneling reaction
direct reaction (ER)
OH-R stabilization

reaction barrier
reaction energy
branching ratio

4 desorption

ejection
evaporation

thermal desorption
photo desorption
chemical desorption
reactive desorption
co-desorption
surface dependent desorption

transformation

desorption energy
diffusion energy

phase transition
crystalline ice
amorphous ice

porosity
porous amorphous ice
compact amorphous ice
dangling bond

destruction

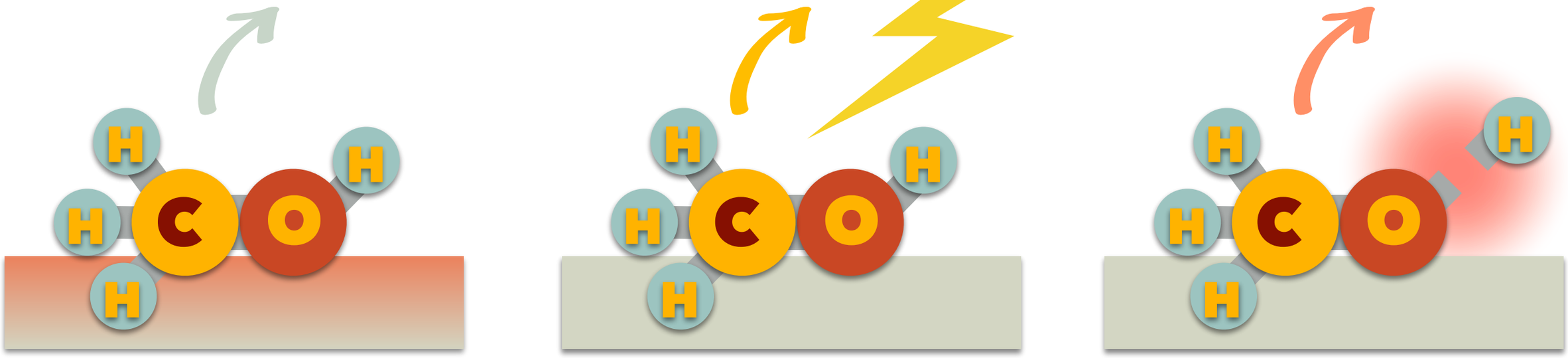
chemical reaction
photolysis
photodissociation
cosmic rays
particle bombardment
shuttering / sputtering
grain grain?

Desorption

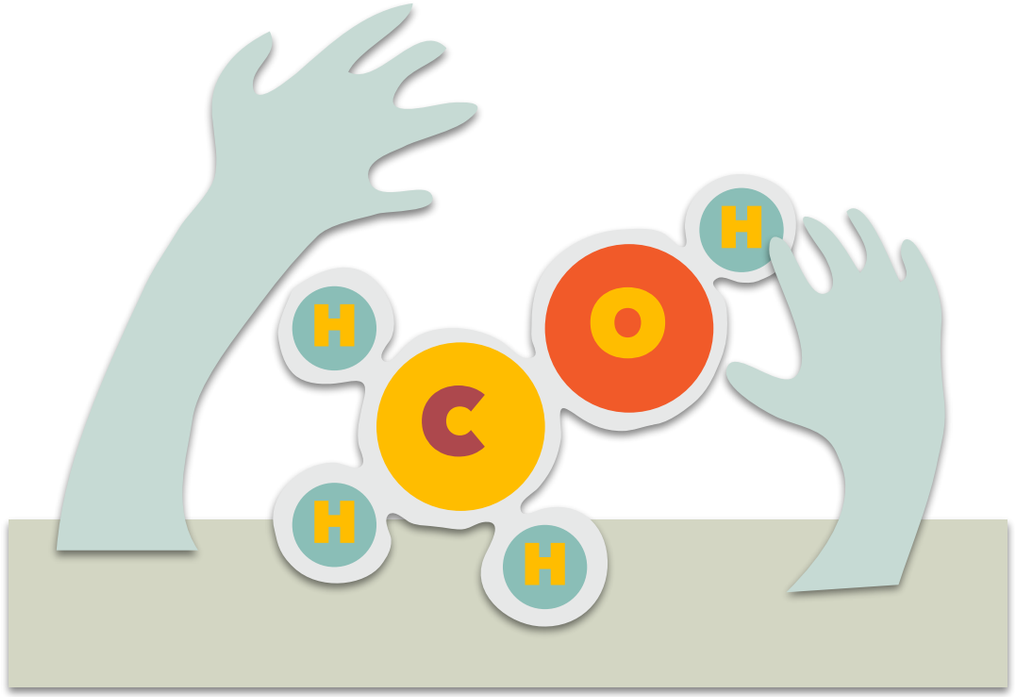
thermal

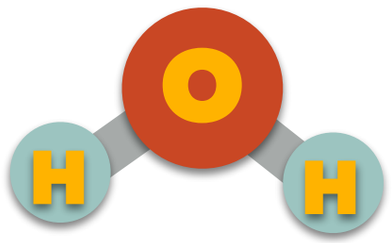
photo

chemical
(reactive)



Desorption depends on surface material



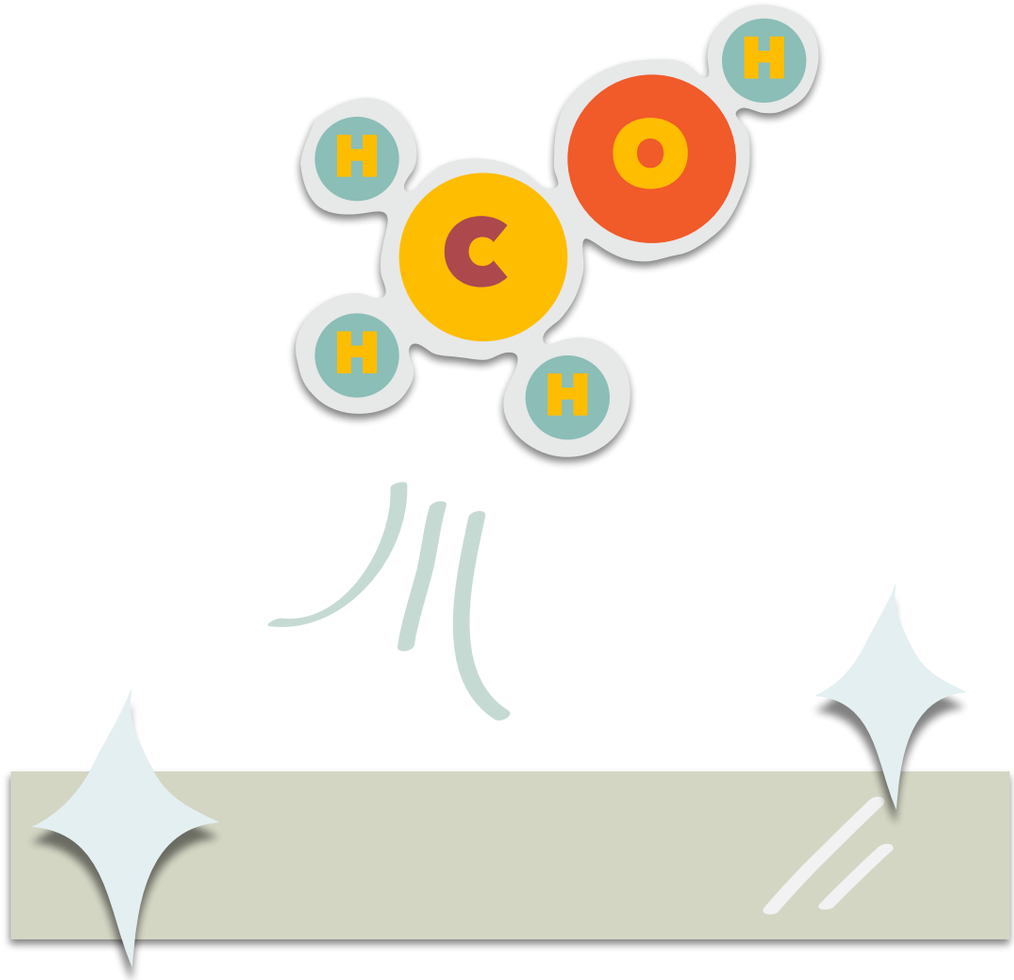


δ-

δ+

Water surface

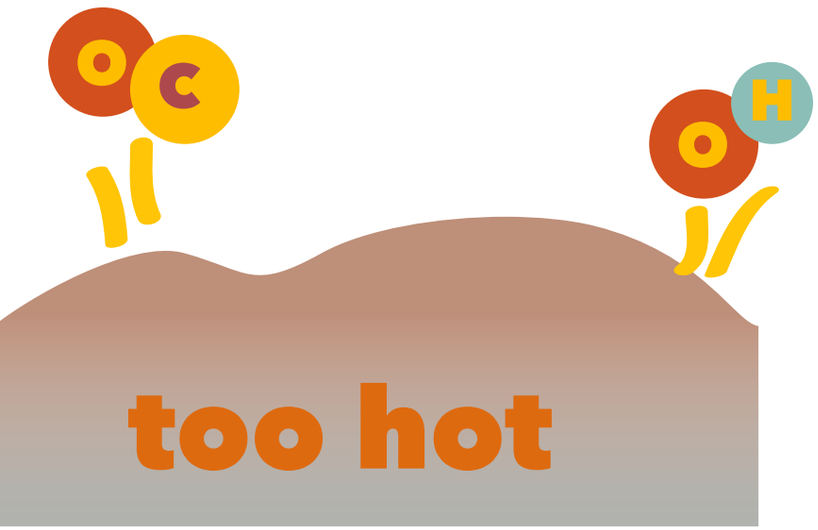
1.5 D (debye)



δ+ C O δ-

CO surface

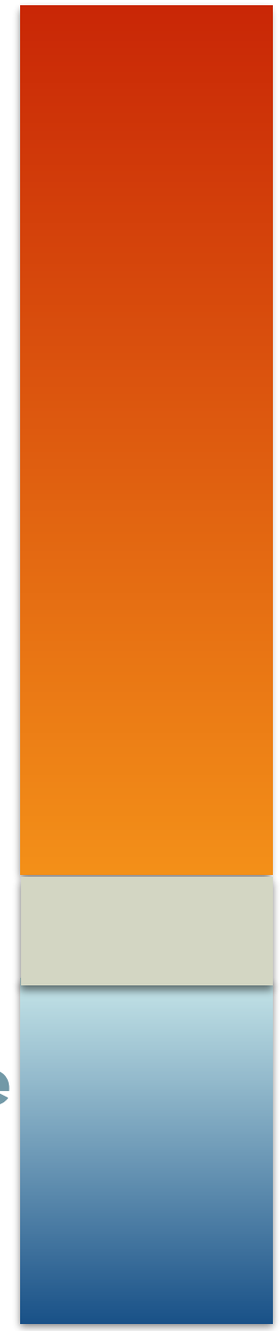
0.12 D (debye)



to hop is not trivial

hopping = tiny desorption

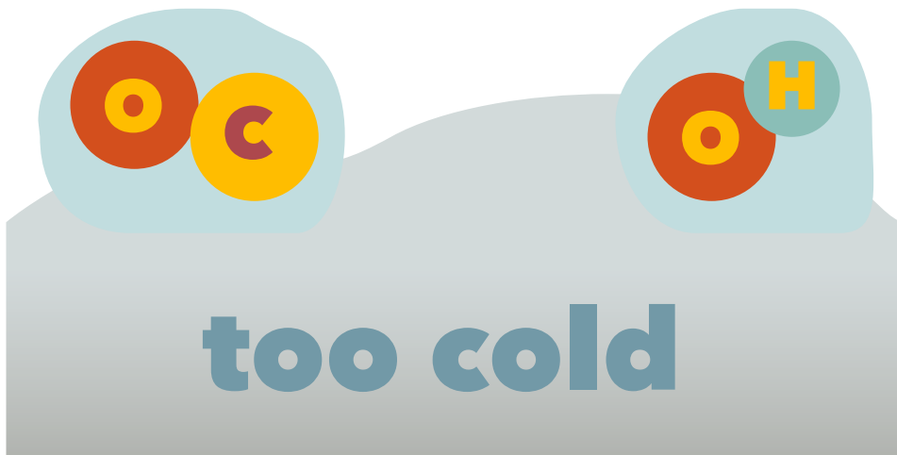
best for large atoms

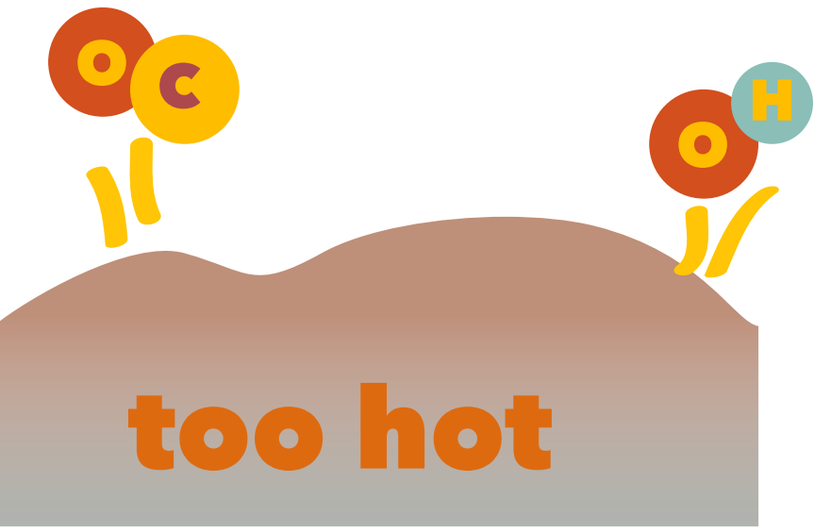


~30-40 K {

starless cores are ~10K

too cold





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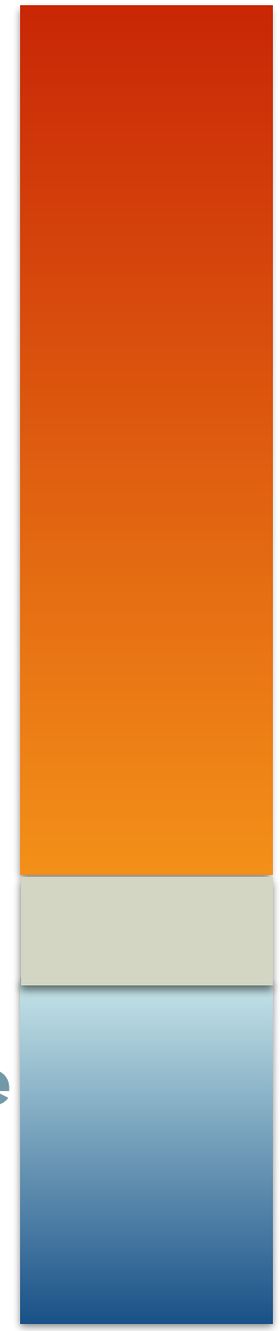

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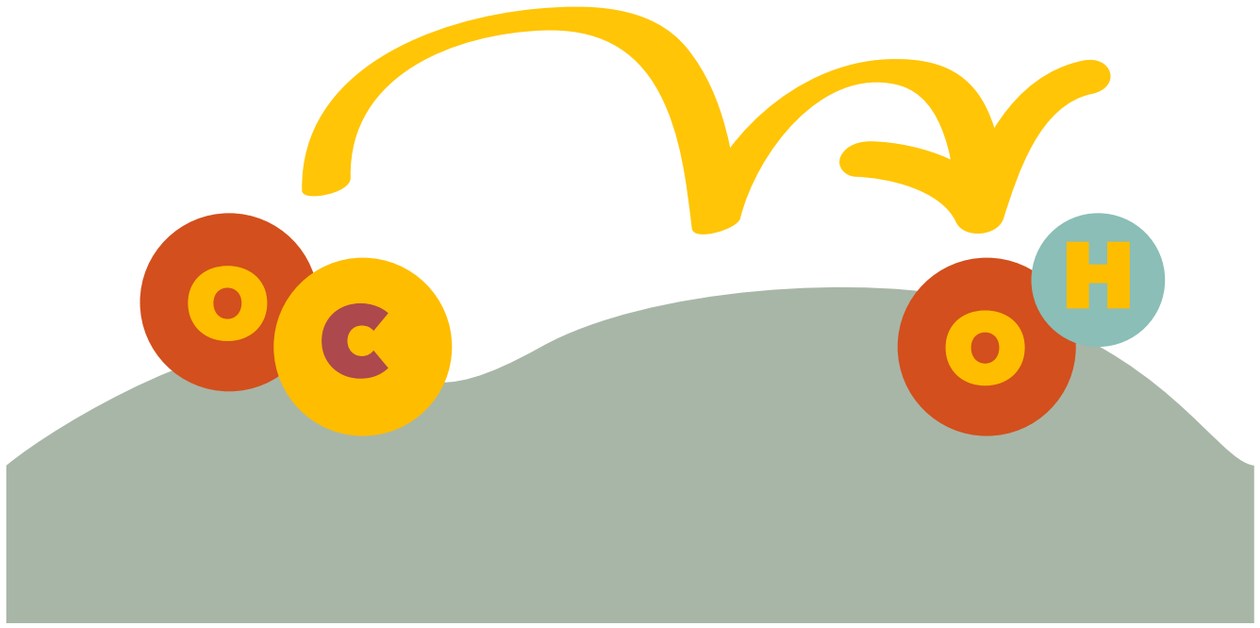
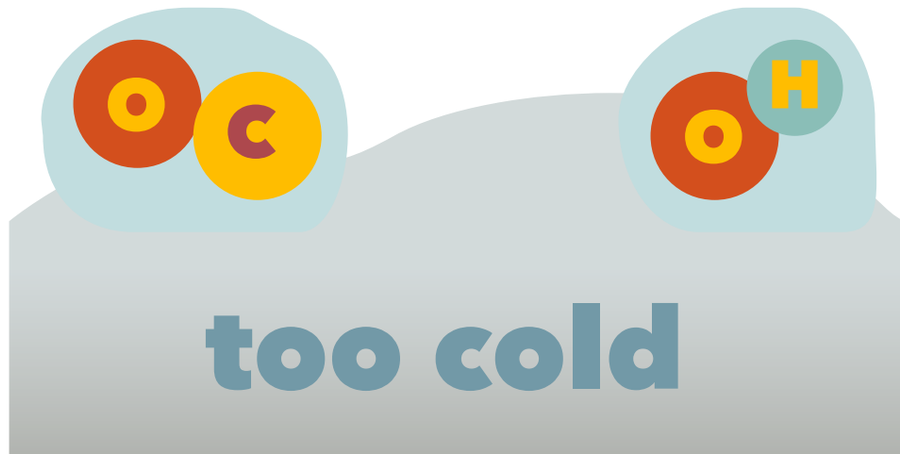
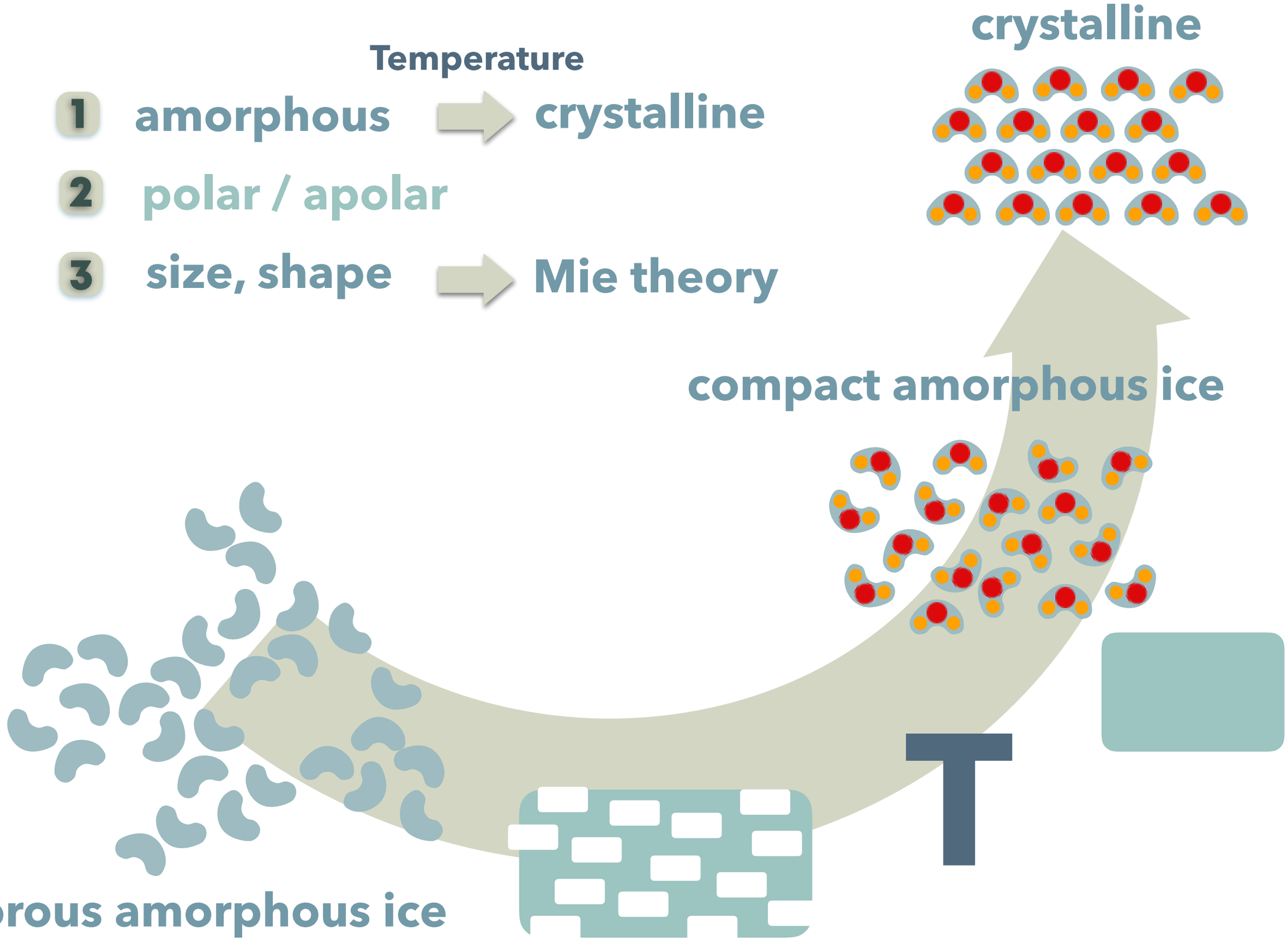




Spectral profile / depth affected by

Temperature

1. amorphous ➡ crystalline
2. polar / apolar
3. size, shape ➡ Mie theory

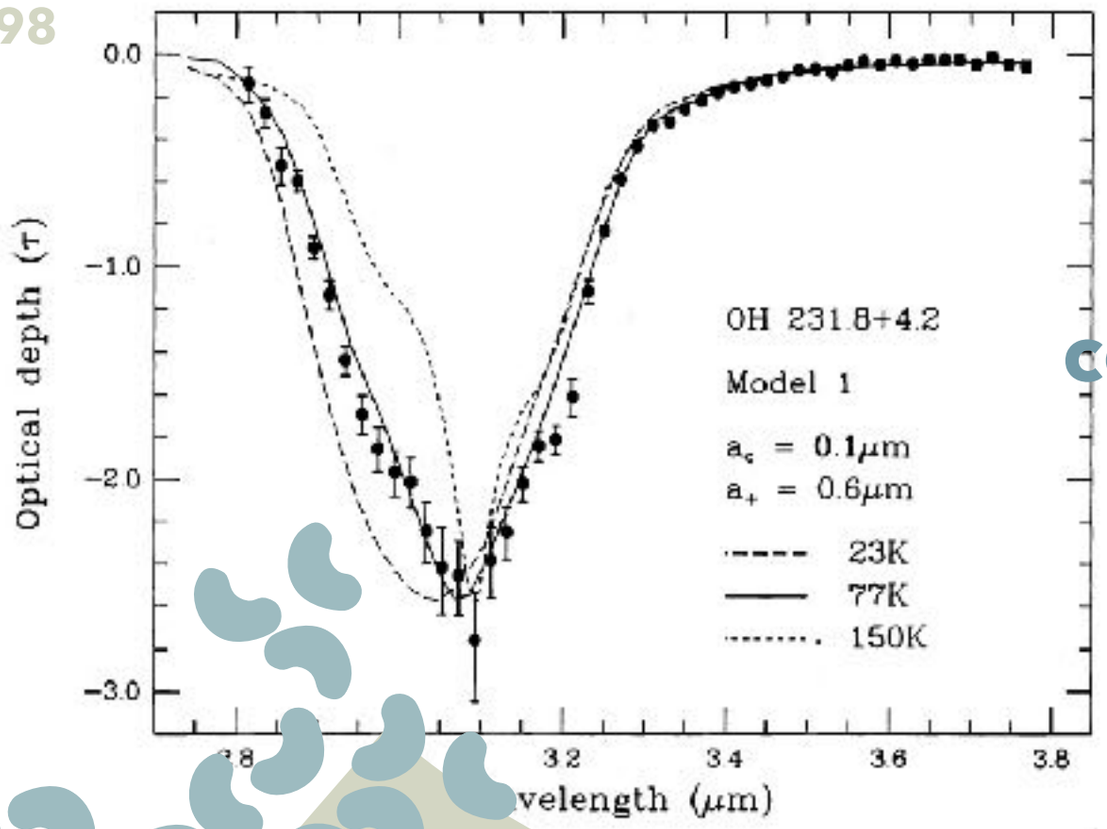


Spectral profile / depth affected by

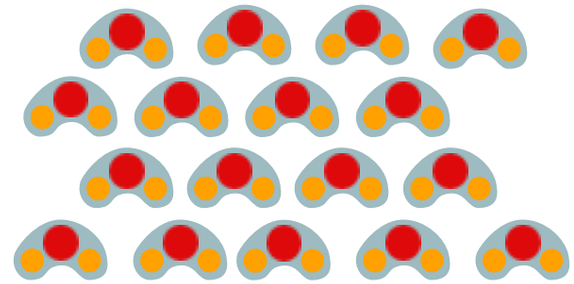
Temperature

1 **amorphous** ➡ **crystalline**

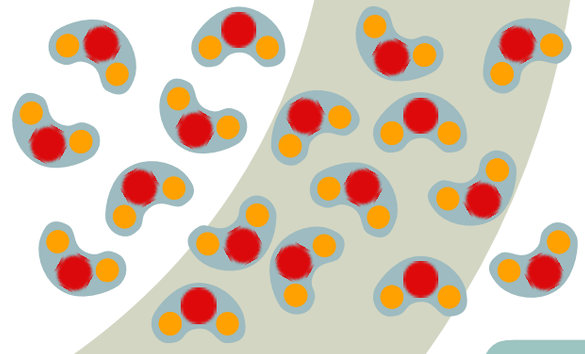
Smith et al. 1998
ApJ, 334, 209

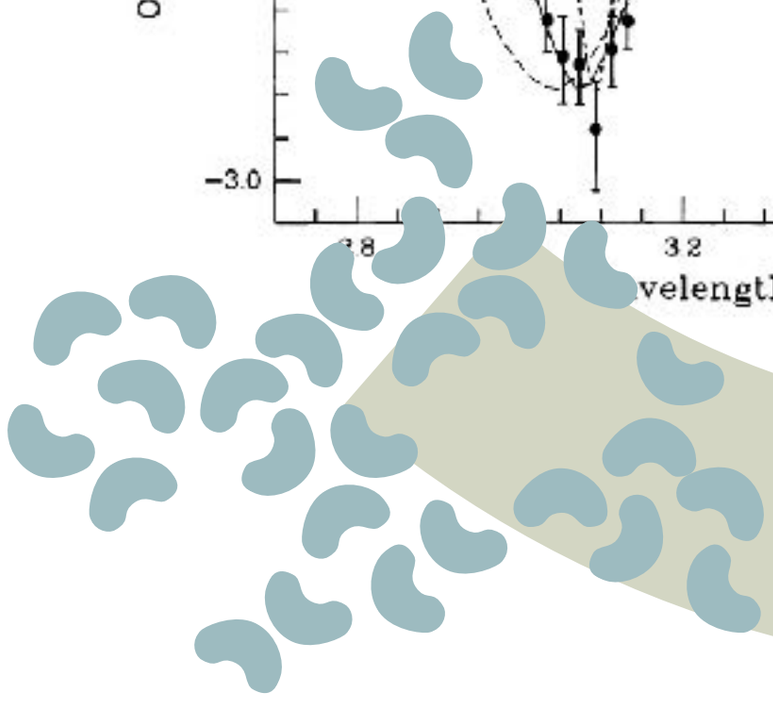


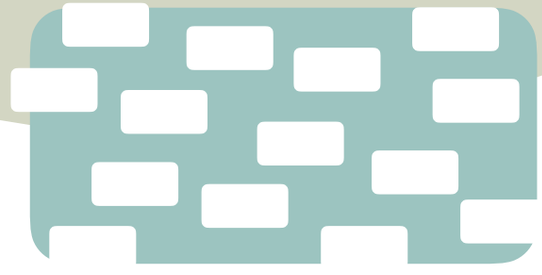
crystalline



compact amorphous ice







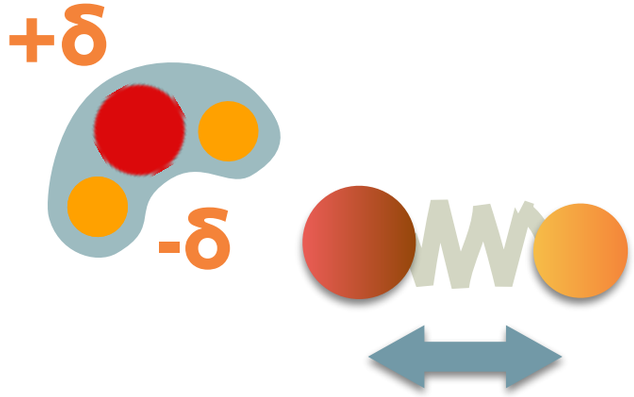
porous amorphous ice

Spectral profile / depth affected by

2 polar / apolar

surrounded by water ice
water - rich environment

not surrounded by water ice
water - poor environment

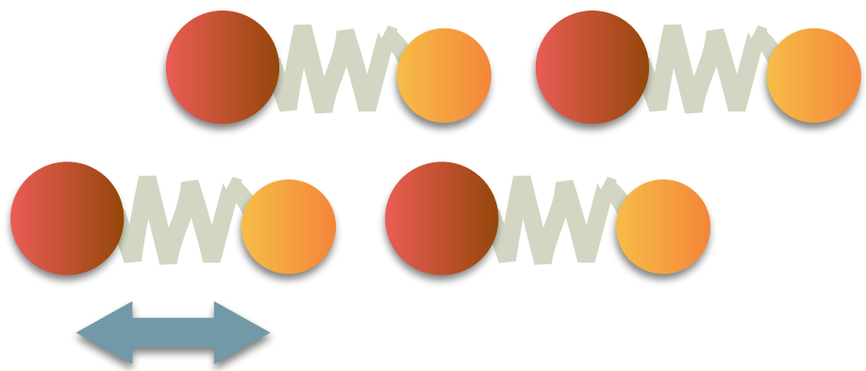


polar

vibration restricted
broad + redshift

Palumbo & Strazzulla
1993, A&A 269, 568

CO
CO_2



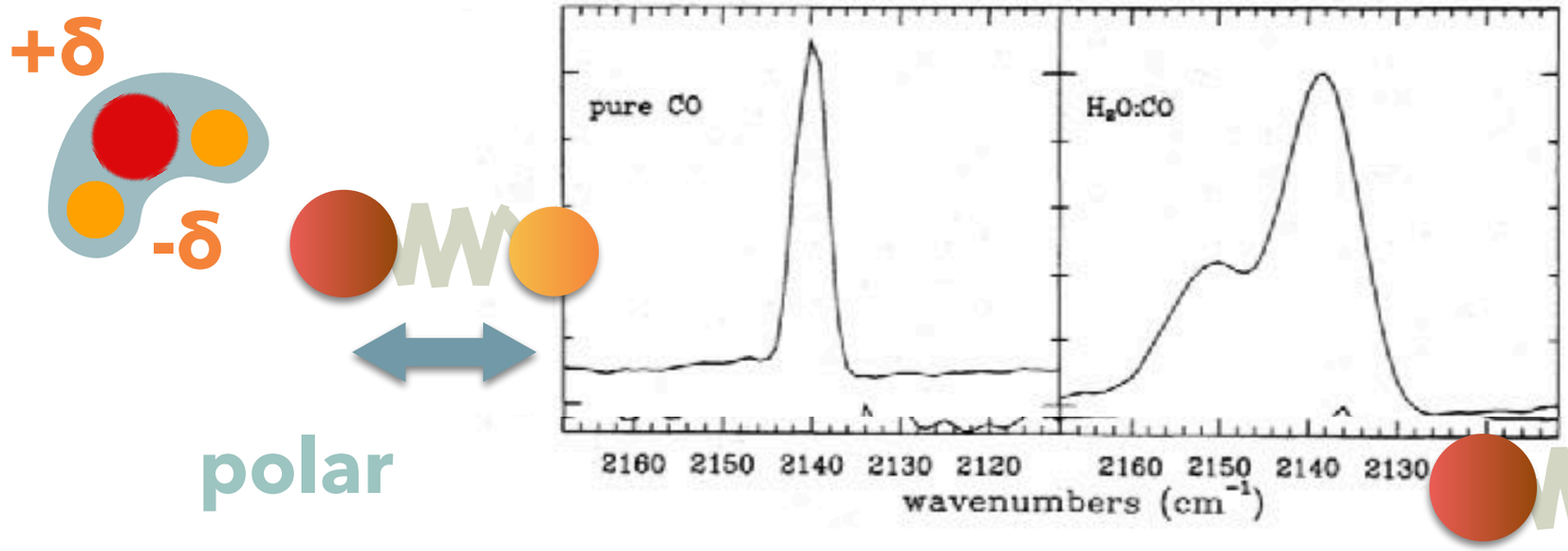
apolar sharp + blue

Spectral profile / depth affected by

2 polar / apolar

surrounded by water ice
water - rich environment

not surrounded by water ice
water - poor environment

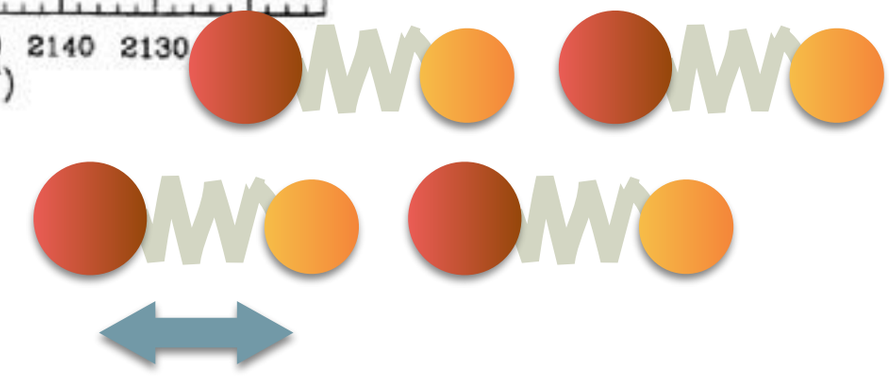


Palumbo & Strazzulla
1993, A&A 269, 568

CO
CO_2

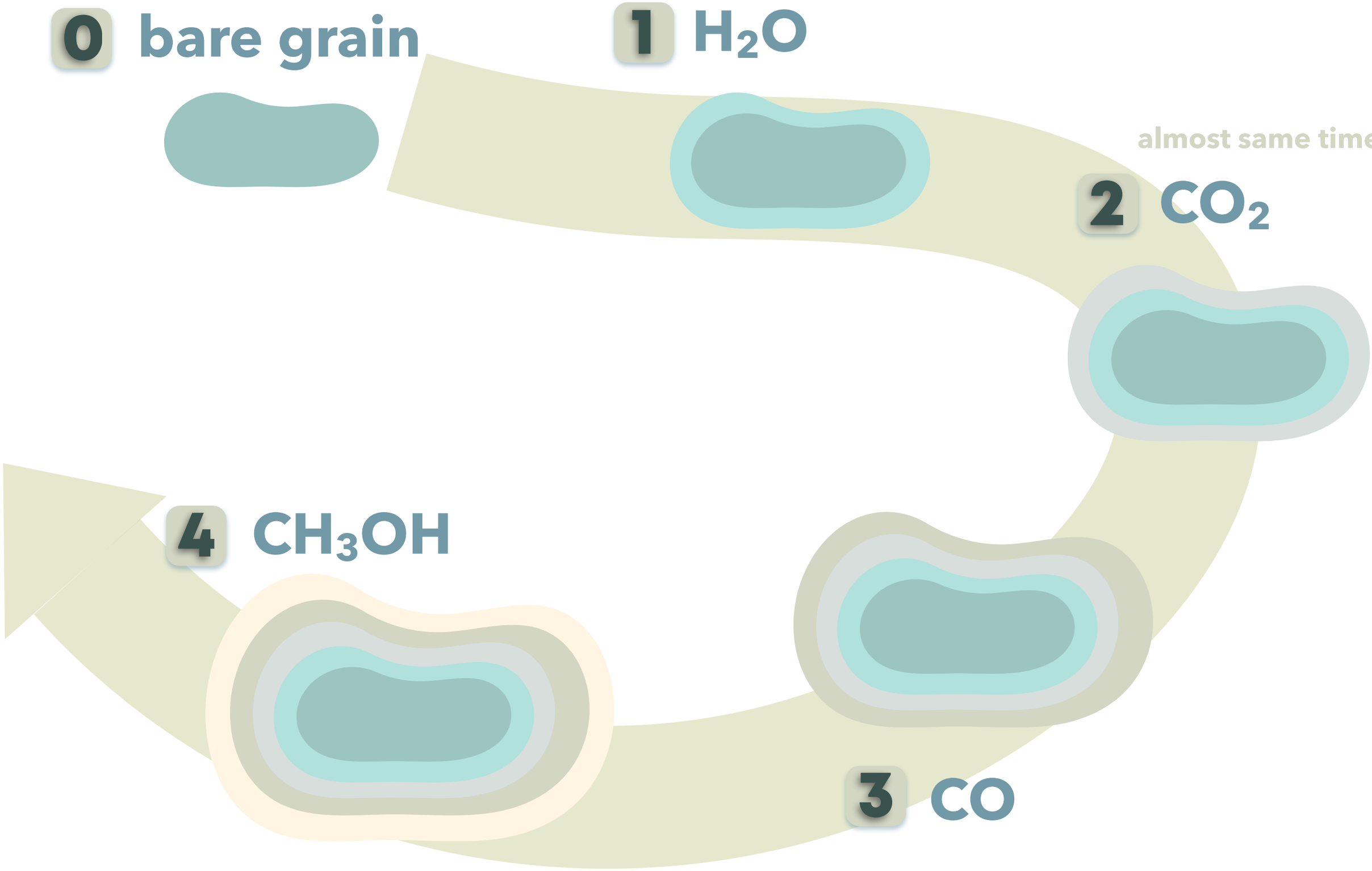
polar

vibration restricted
⇒ broad + redshift

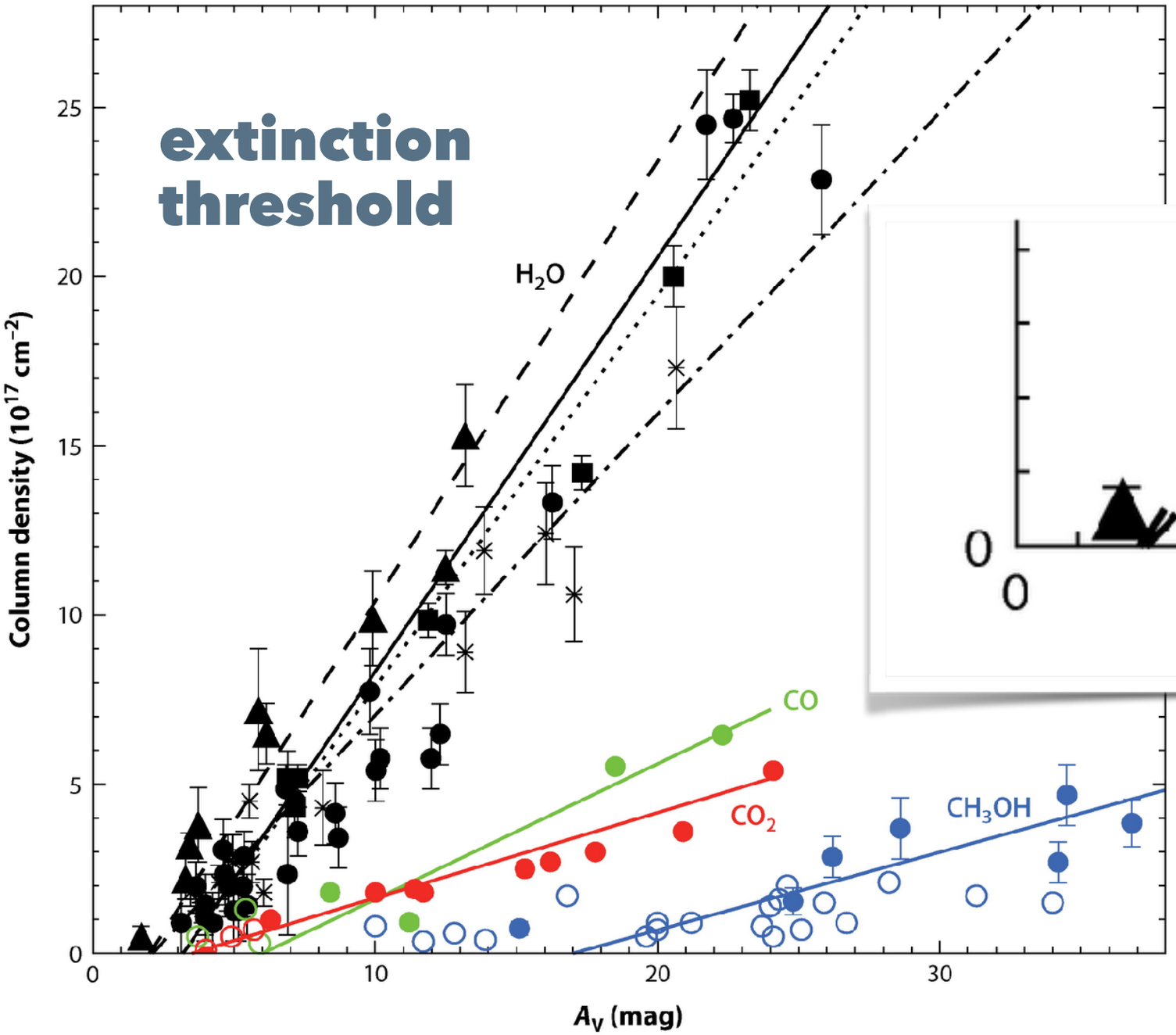


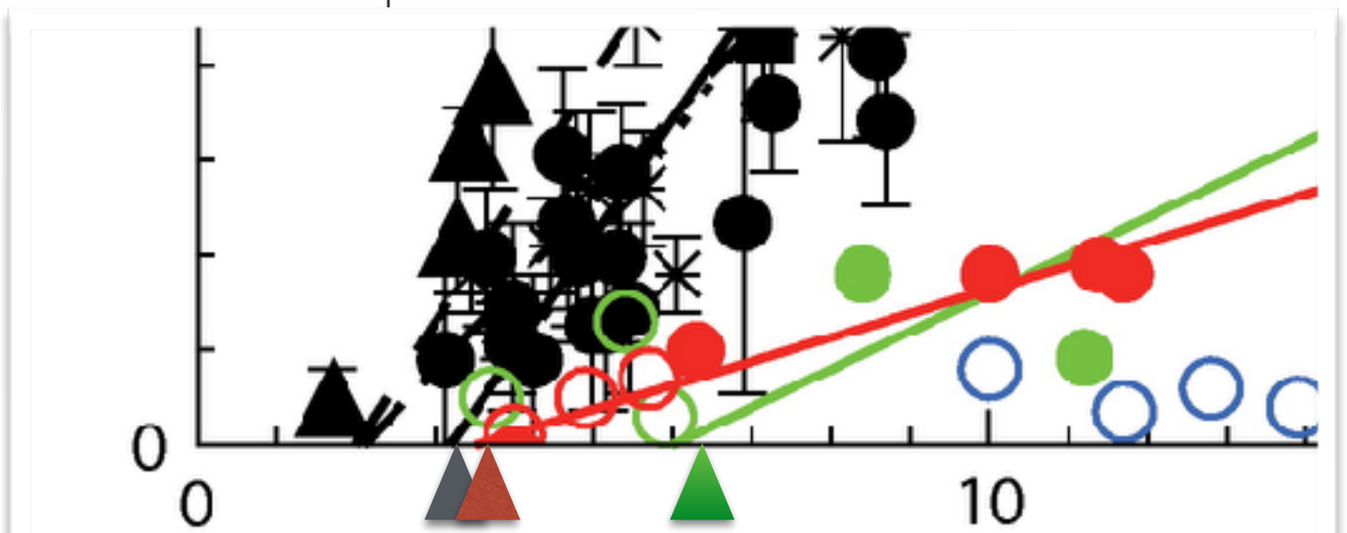
apolar sharp + blue

What happens when a **bare grain** enters a **dark cloud**



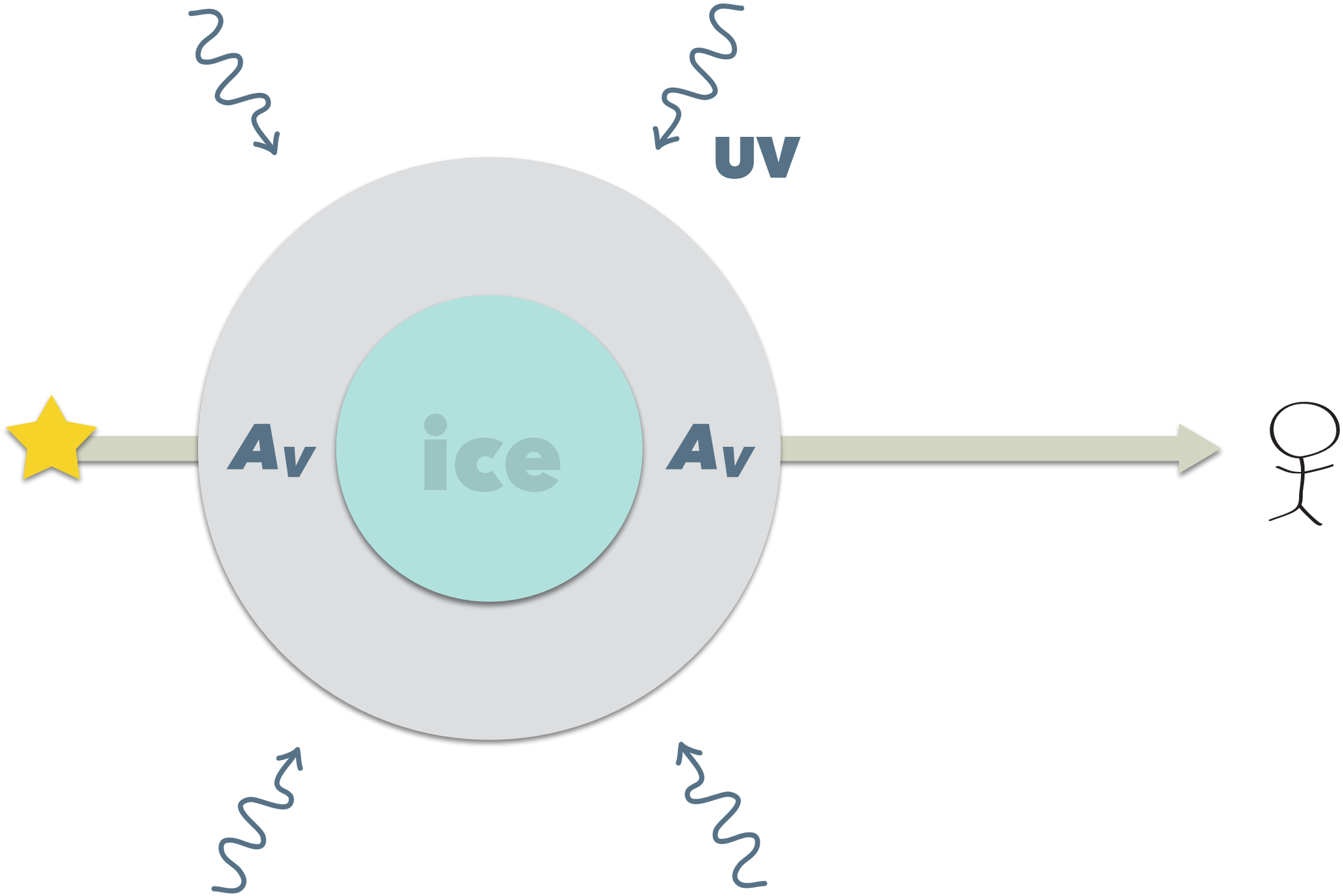
How do we know that?



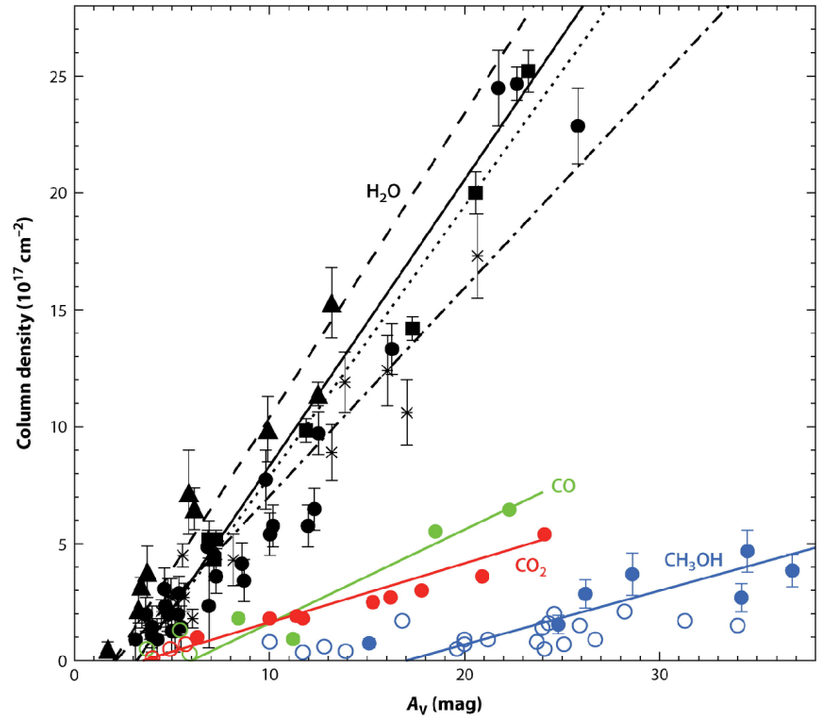


H_2O	3.1 mag
CO_2	4.3 mag
CO	6.7 mag

Boogert ACA, et al. 2015.
Annu. Rev. Astron. Astrophys. 53:541–81


UV
Av
ice
Av

UV



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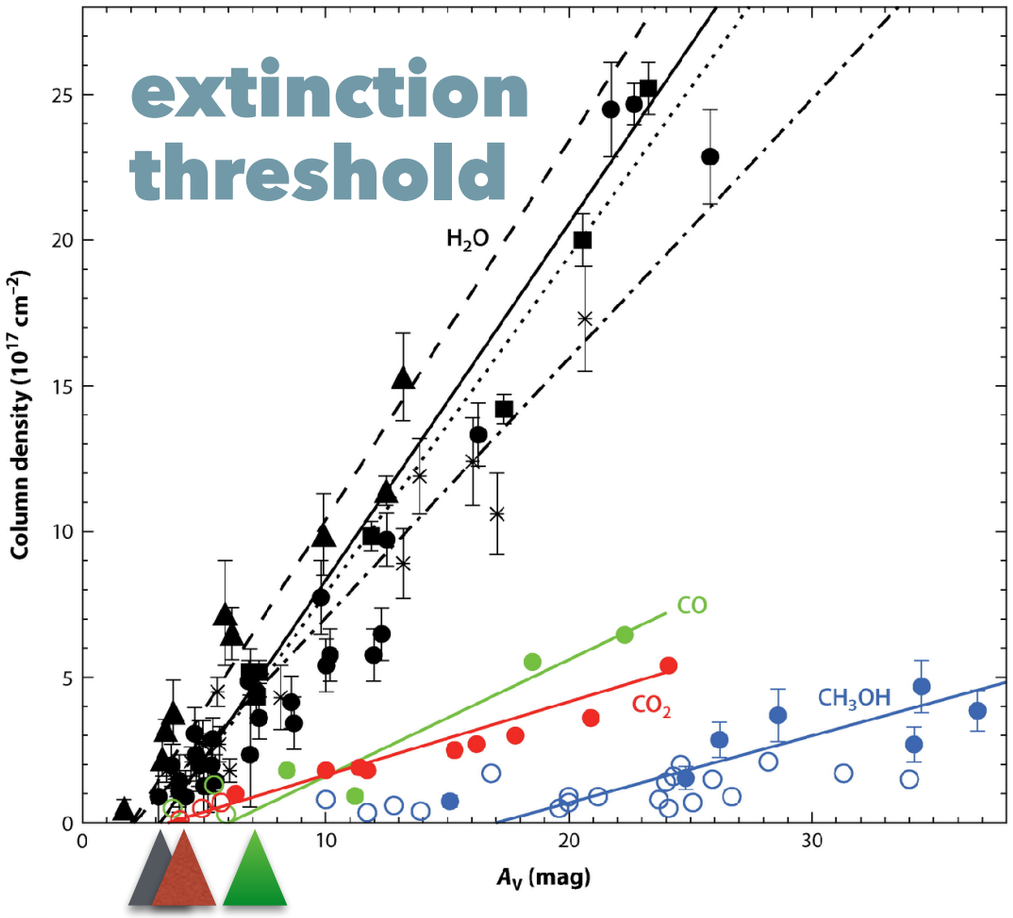
What happens when a bare grain enters a dark cloud



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H_2O	3.1 mag
CO_2	4.3 mag
CO	6.7 mag

why water ice forms before CO ice does?

1 Dust is cold in Diffuse cloud

T_k ~ 80 K

T_d ~ 10–15 K

2 CO is more stable than H_2O

C=O 90000 K

O-H 55000 K

3 CO_2 forms with H_2O

... and main path requires CO on surface

Explanations available

1 **CO_2 formation without CO on the surface**

irradiation — Mennella et al. Palumbo et al.

2 **CO accretion takes time**

$t_{acc} \propto n^{-1} \rightarrow$ slow in diffuse cloud

3 **all CO on surface converted to CO_2**

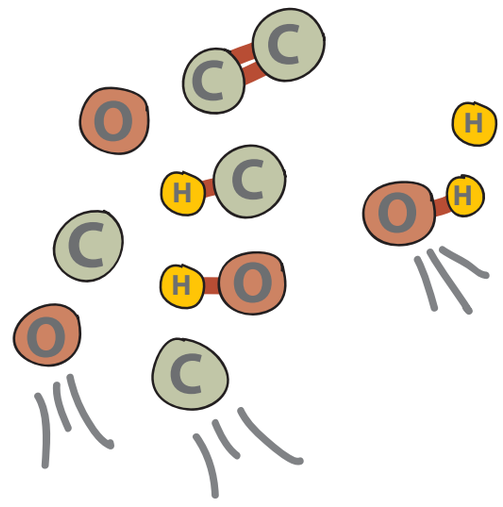
4 **or all the way to CH_3OH**

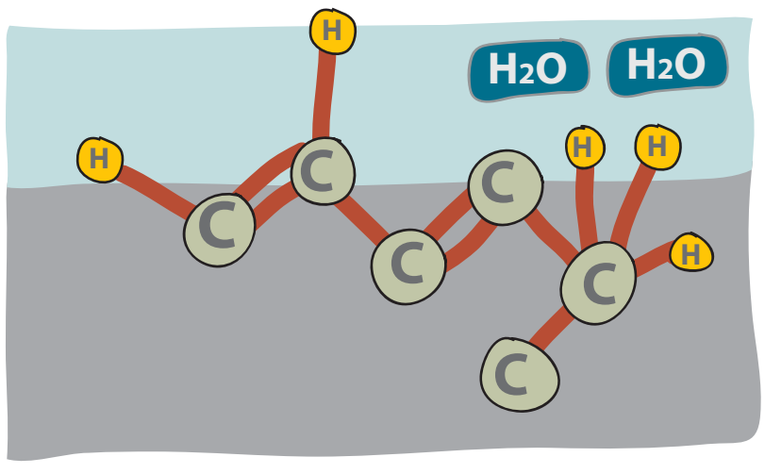
Explanations available

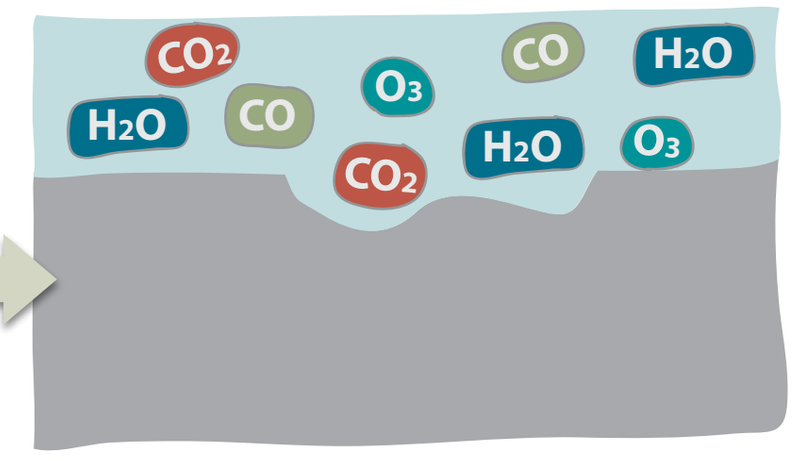
1 CO_2 formation without CO on the surface

irradiation — Mennella et al. Palumbo et al.

cosmic ray







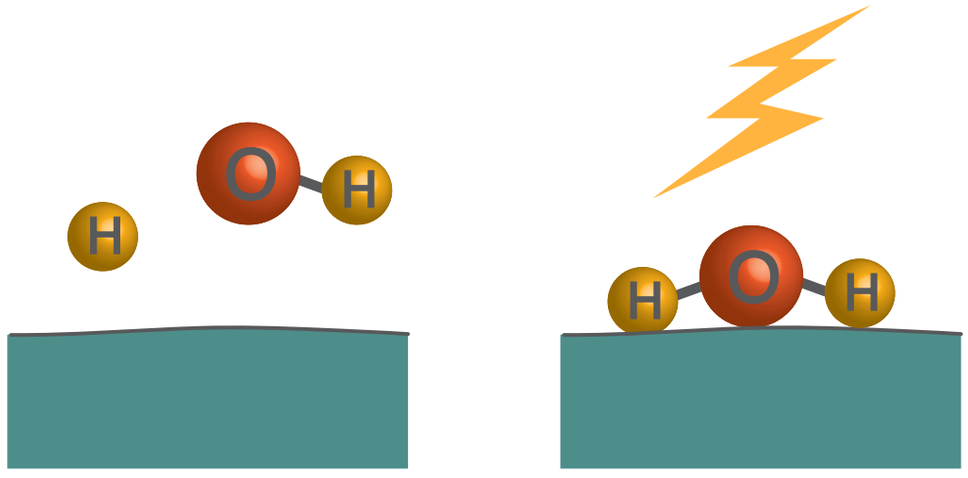
bombardment — taken apart — frozen again

whatever CO landed on grain, are converted to CO_2

$$CO + OH \rightarrow CO_2 + H$$

this stops, because

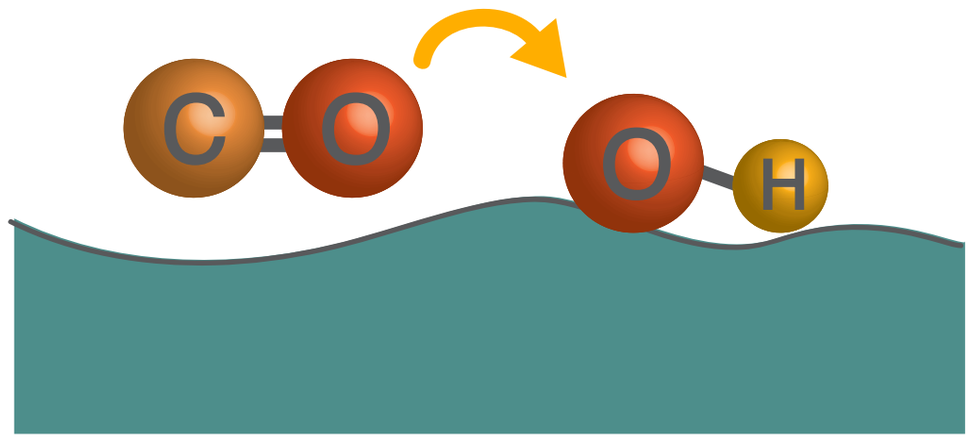
1 A_V is too large



OH not available as it is locked in H_2O

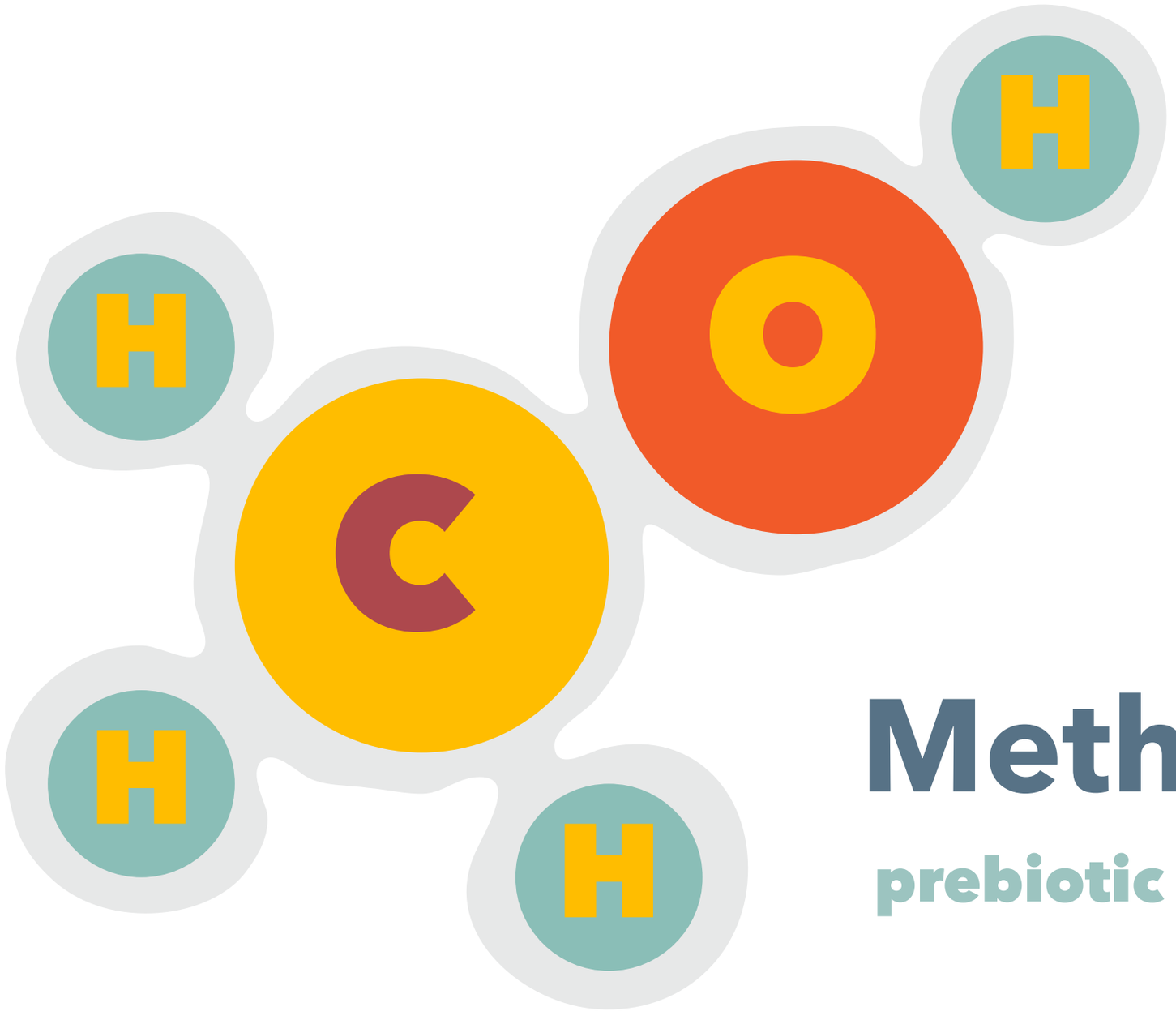
Vasyunin & Herbst 2013

2 T_d is too low



CO does not hop any more to meet OH (OH immobile)

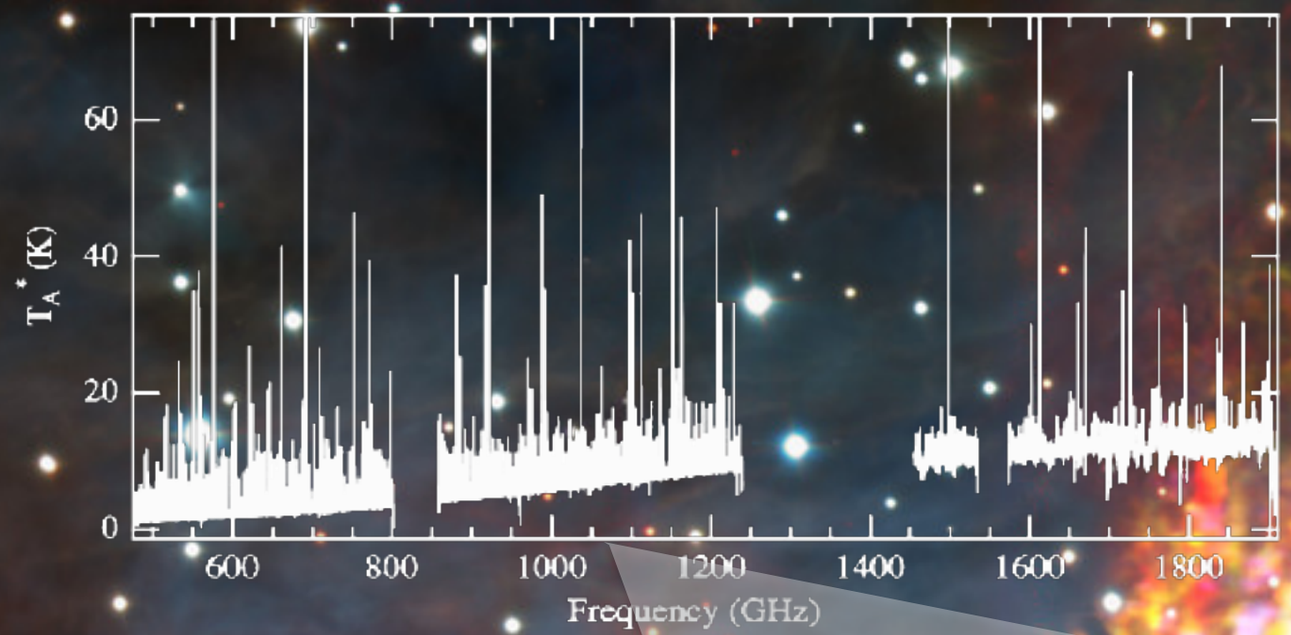
Garrod & Pauly 2011



Methanol

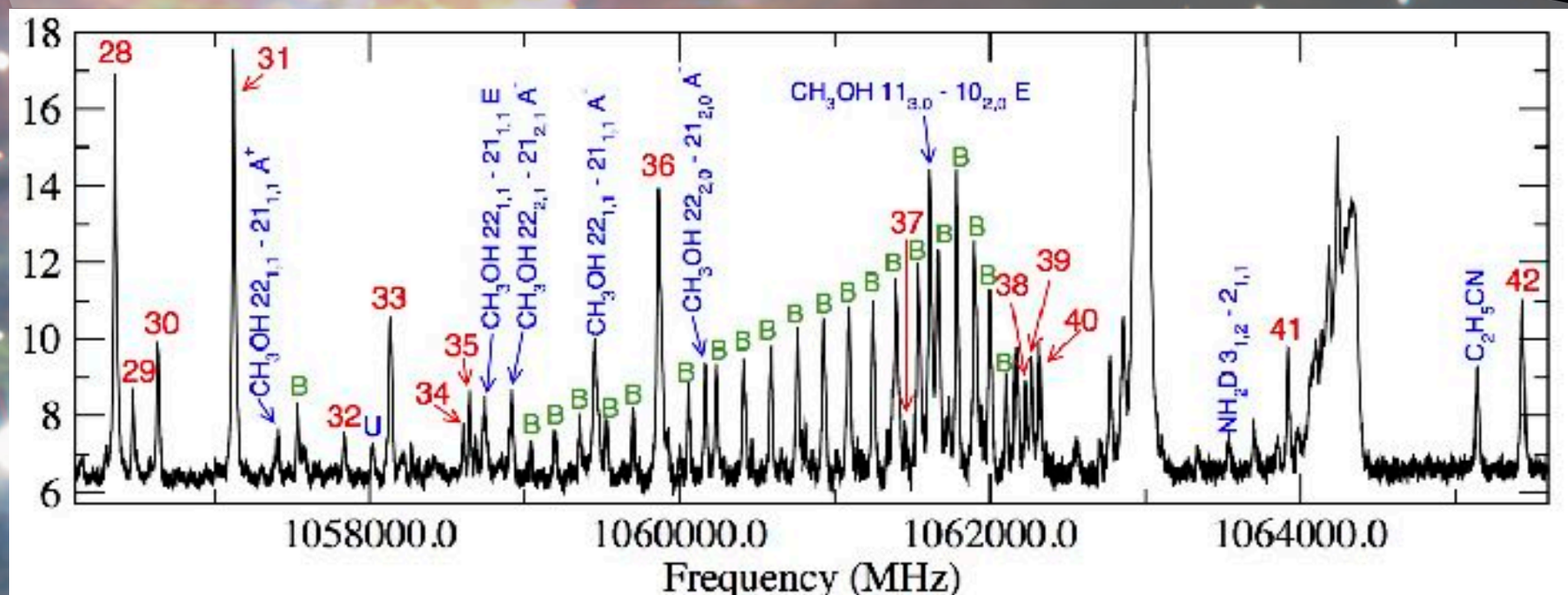
prebiotic molecule

Methanol forests



Bergin et al. HEXOS

HIFI Orion KL



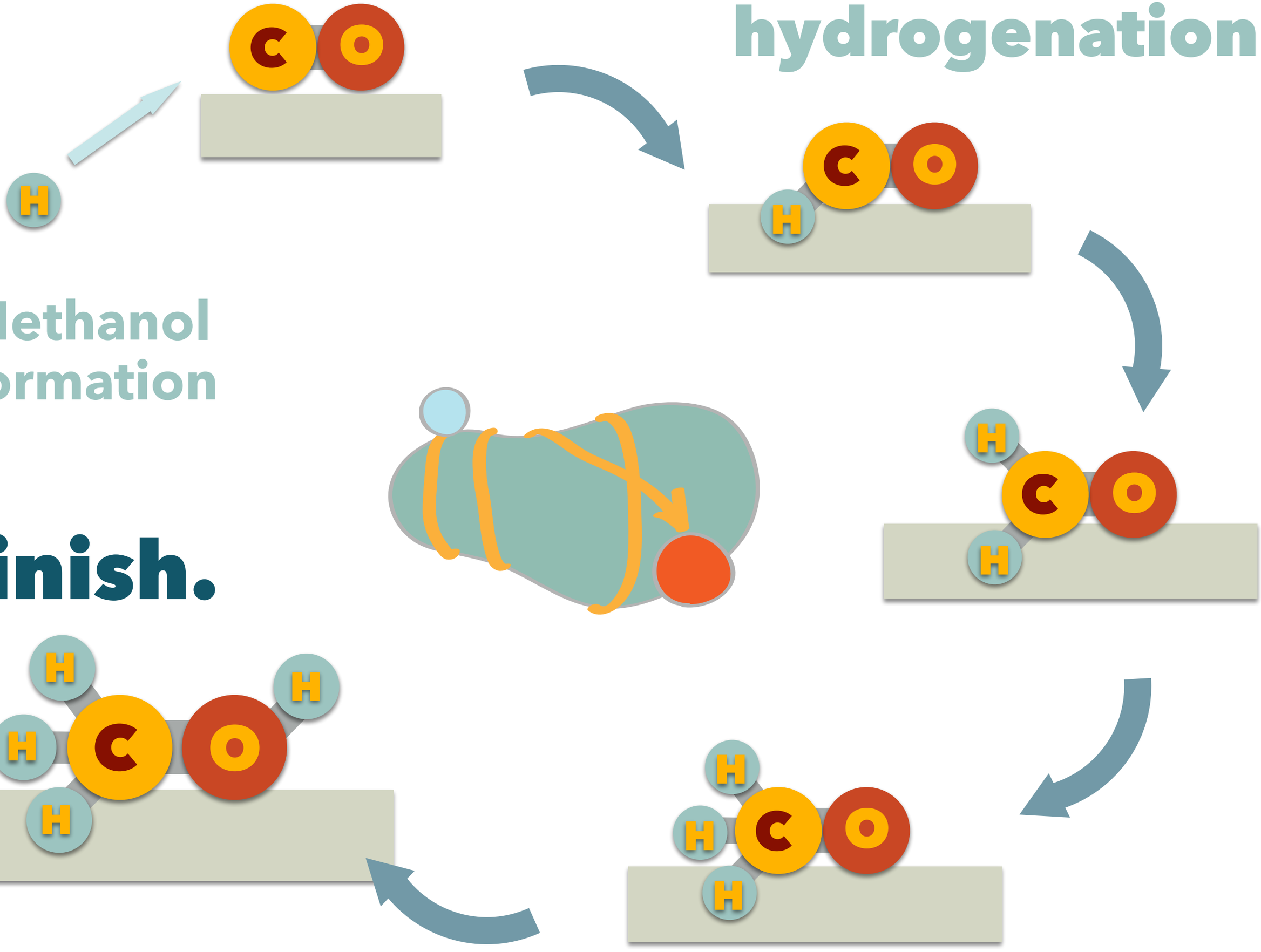
Wang et al. 2011

image: Bally et al.

hydrogenation

Methanol formation

finish.



What happens

when a bare grain enters a dark cloud

0 bare grain

surface is ready
: 10 - 15K

1 H_2O

surface formatiom dominant
main destruction process : photodissociation

almost same time
with H_2O ice

2 CO_2

$N(CO_2) \propto N(H_2O)$

CO_2 ice : mostly polar

3 CO

gas phase formation

after H_2

$t_{acc} \sim 10^9 / n$ [yr]

shows up when CO_2
formation ceased

T? or A_V?

direct
formation by
cosmic ray
bombardment?

4 CH_3OH

sequential
hydrogenation of CO

star formation
desorption

ice is
molecular factory