Hot corinos: the early organic molecular enrichment of the planet formation zones

Marta De Simone

now ESO Garching Fellow

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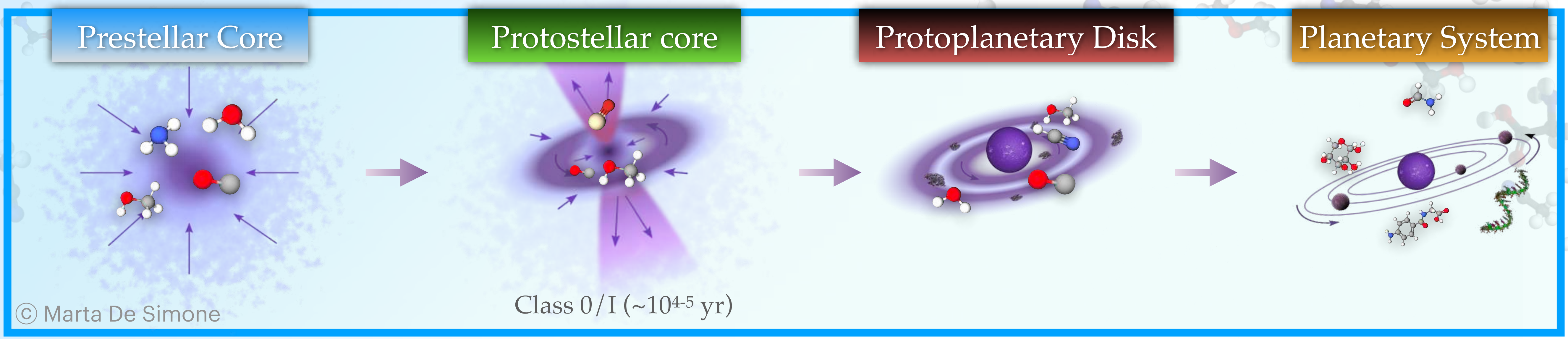
Journées 2023 de la SF2A

22/06/23 Strasbourg

Solar-type star formation process

(e.g. Andre et al. 2000, Caselli & Ceccarelli 2012, Öberg & Bergin 2021)



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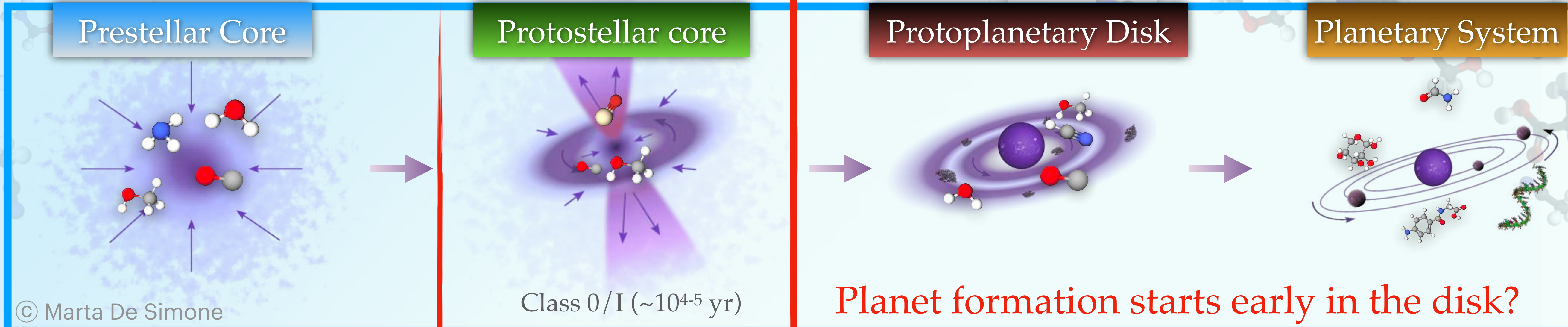
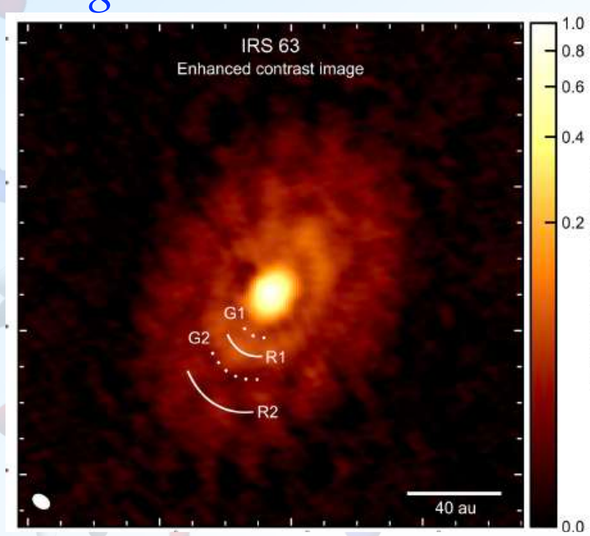
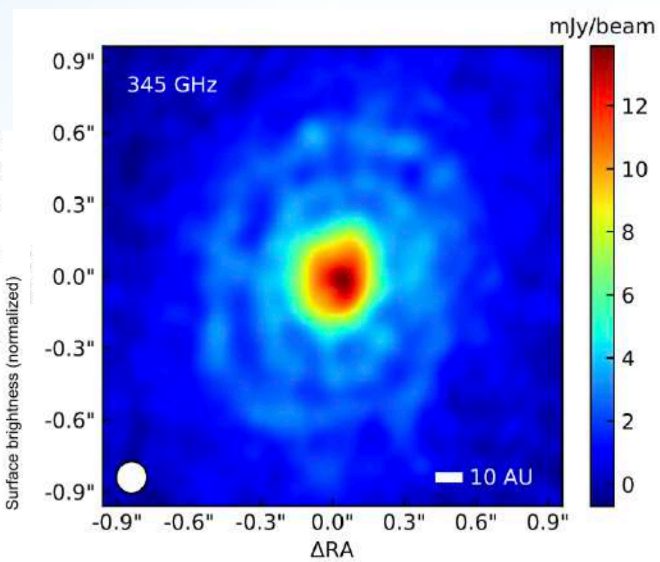


Planet formation starts early in the disk?

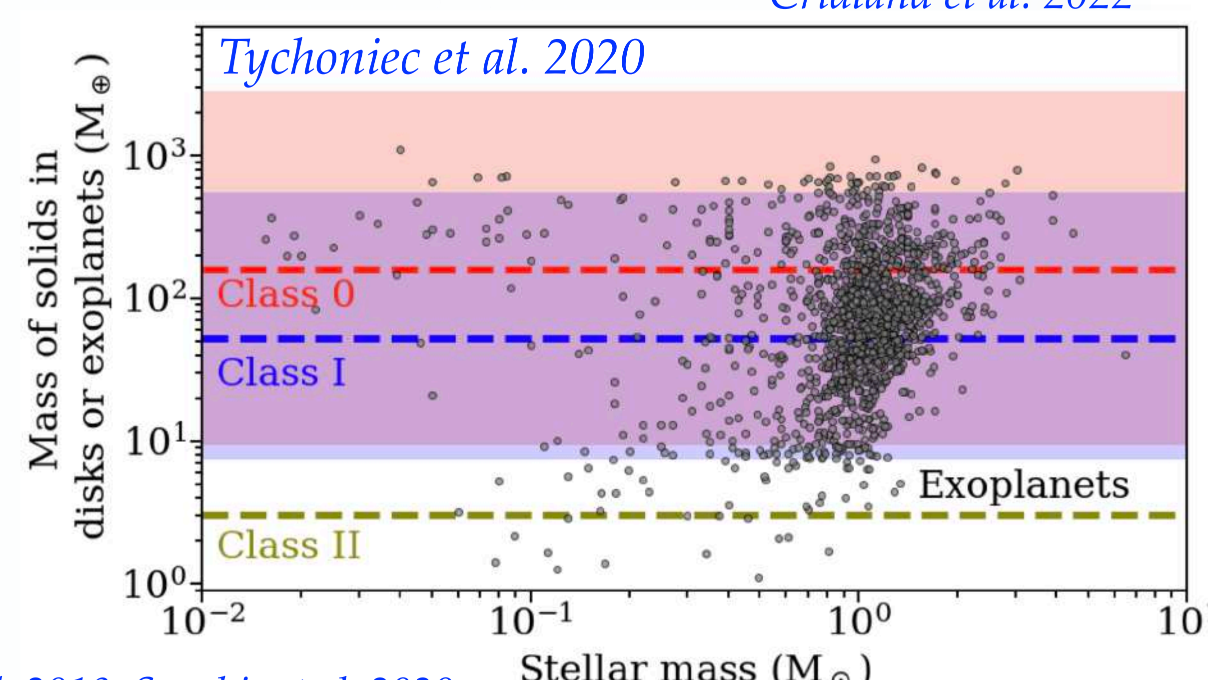
Segura Cox et al. 2020





Sheehan et al. 2018,

Cridland et al. 2022



Harsono et al. 2018; Podio et al. 2020, Manara et al. 2018; Sanchis et al. 2020

The protostellar chemical content can be linked to what forming planets can inherit

Protostellar environments

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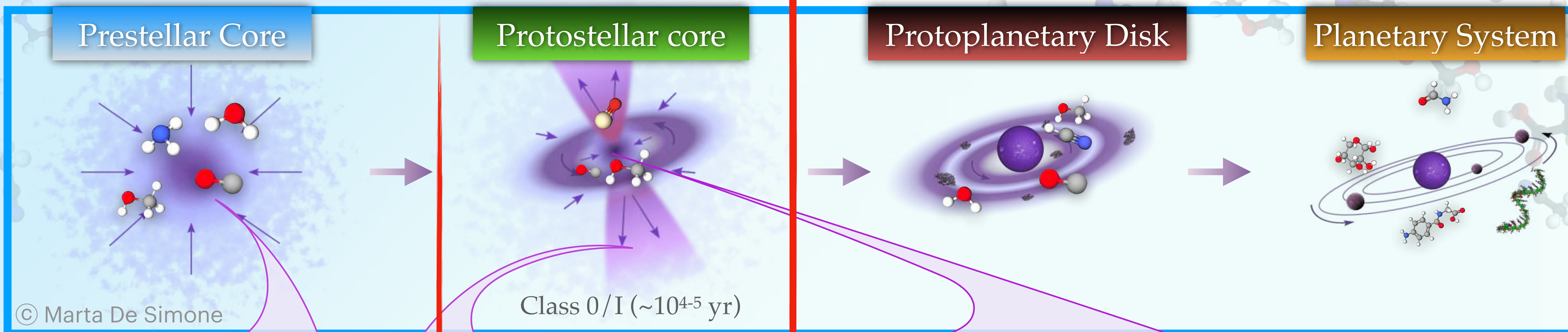
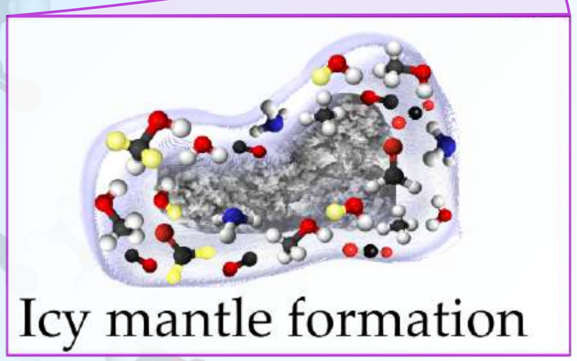
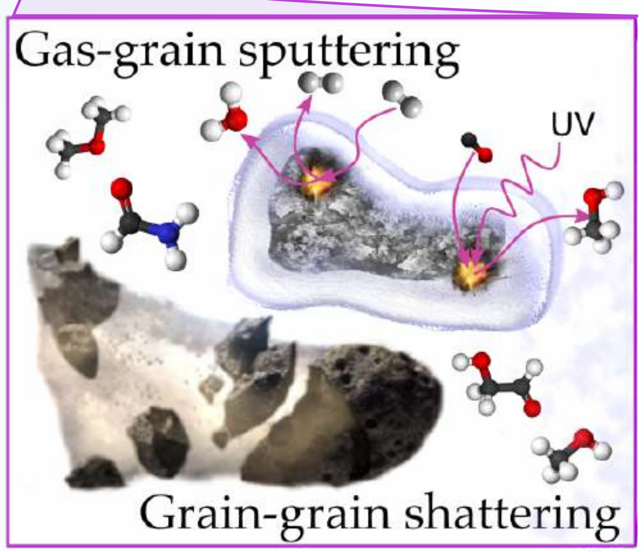
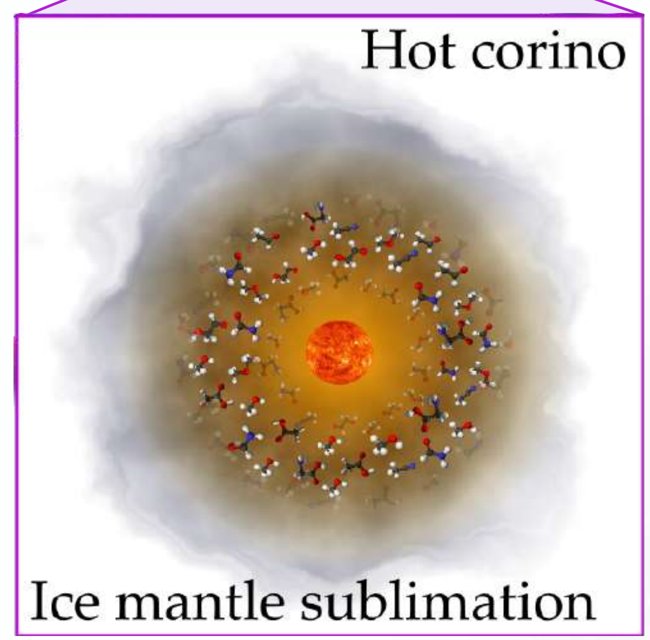






Astrochemical Laboratories



Molecular Retail Shops

Compact (<100 au), hot (>100 K), dense (>10^7 cm^{-3}) region enriched in iCOMs*

Ceccarelli 2004, Ceccarelli et al. 2007

*__iCOMs__: Saturated C-bearing molecules with more than six atoms and containing heteroatoms

(Herbst & Van Dishoeck 2009, Ceccarelli et al. 2017)

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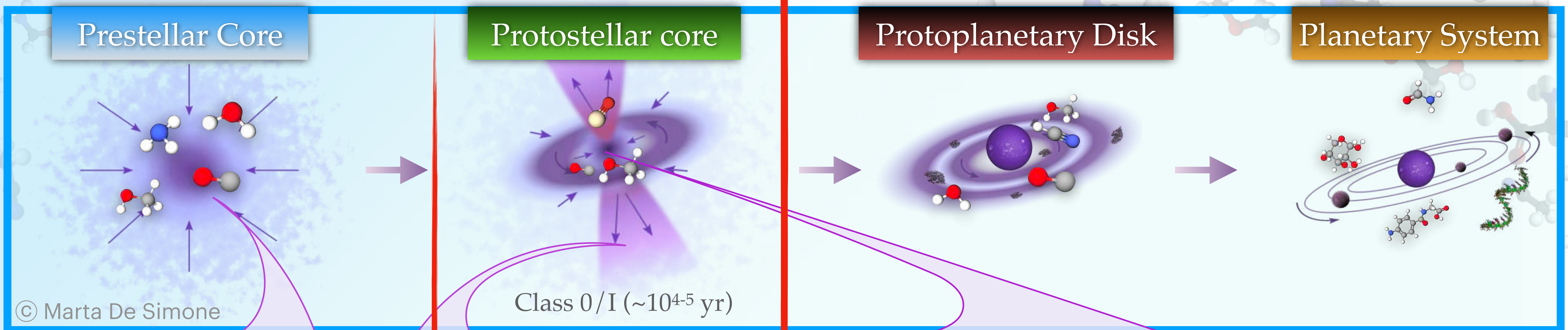
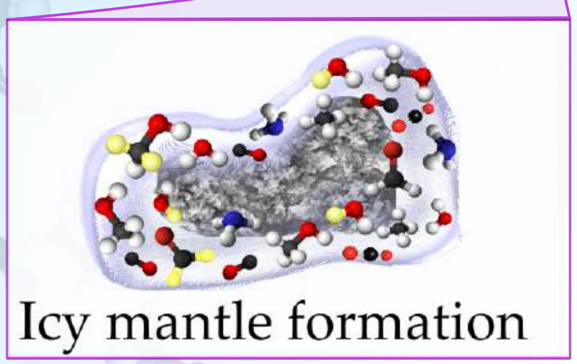
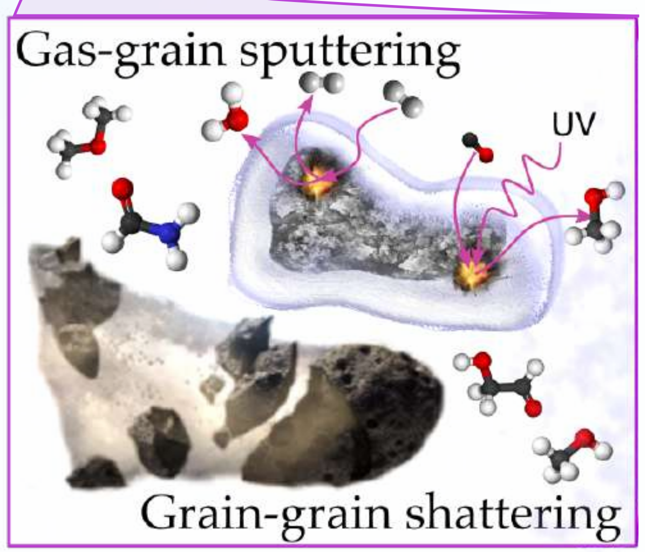




Protostars are far to be fully chemically characterised



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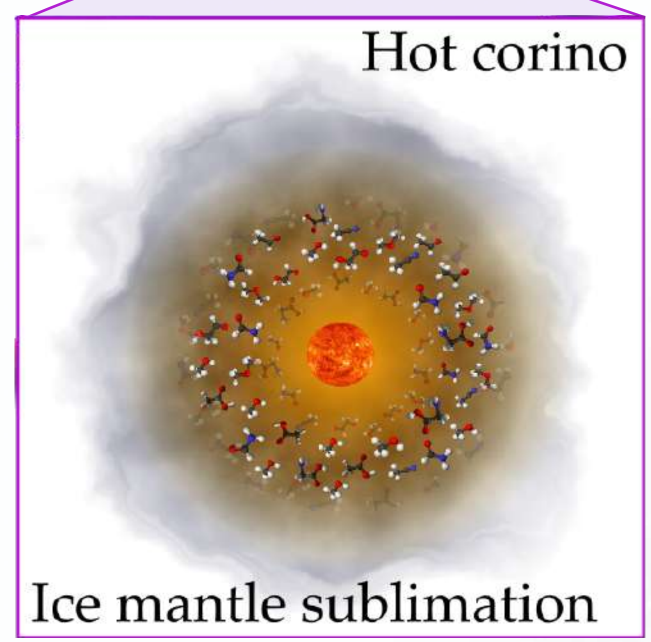

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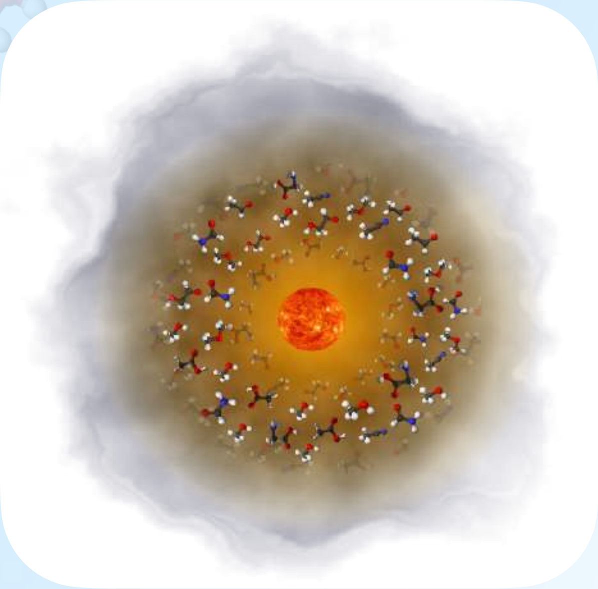
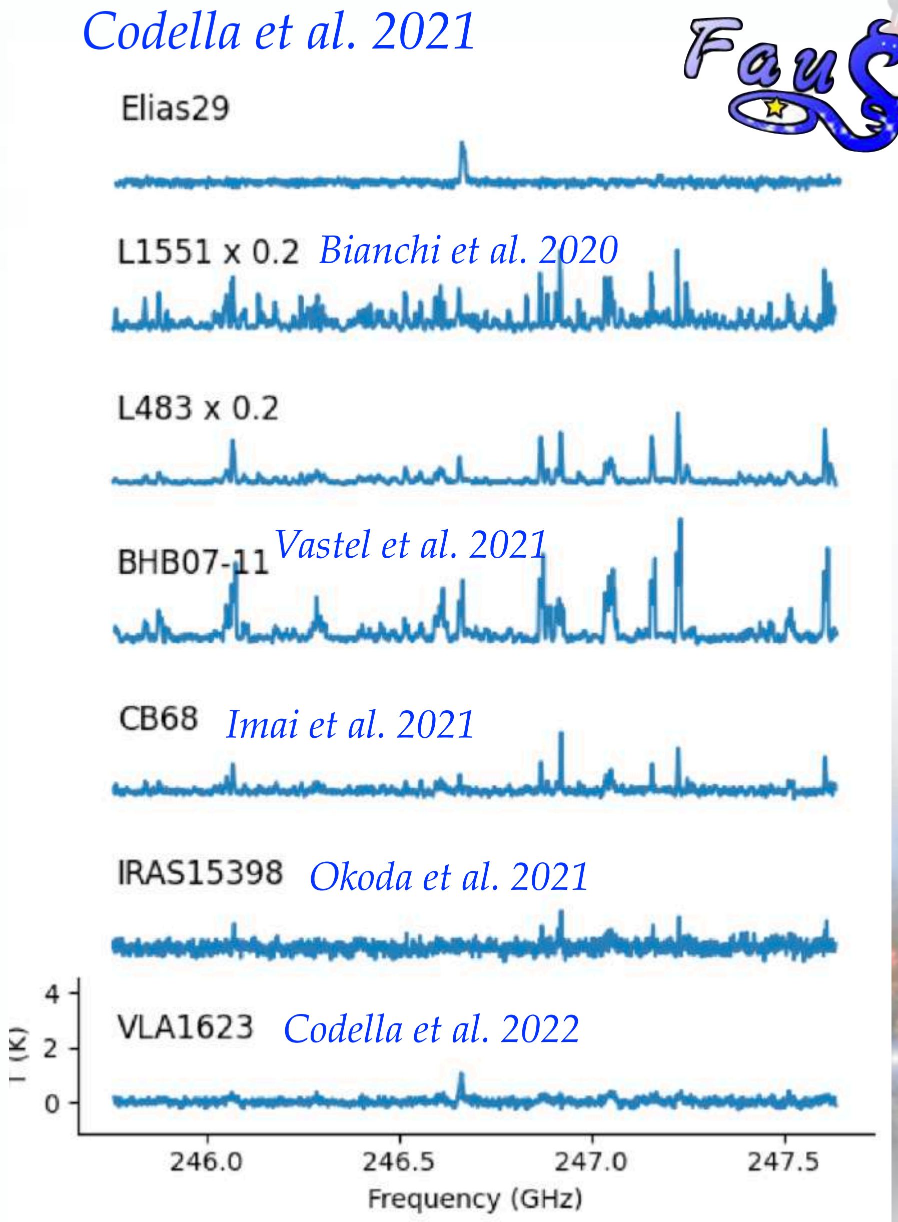
Hot Corinos:
rich chemistry in young Solar-type protostars



- Not every protostar possesses a hot corino region
- Protostellar systems show different mm molecular spectra

At present **25** iCOMs-rich hot corinos (~40 with methanol only) are known
(e.g., De Simone et al. 2017, Belloche et al. 2020, Bouvier et al. 2021, Chahine et al. 2021, Yang et al. 2021, …)



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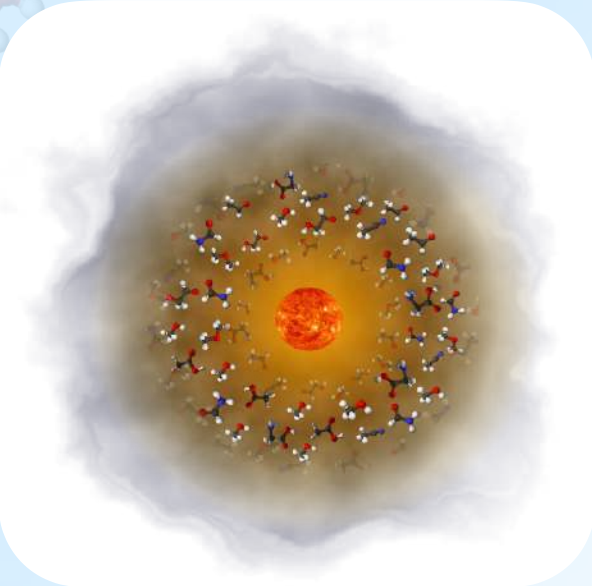

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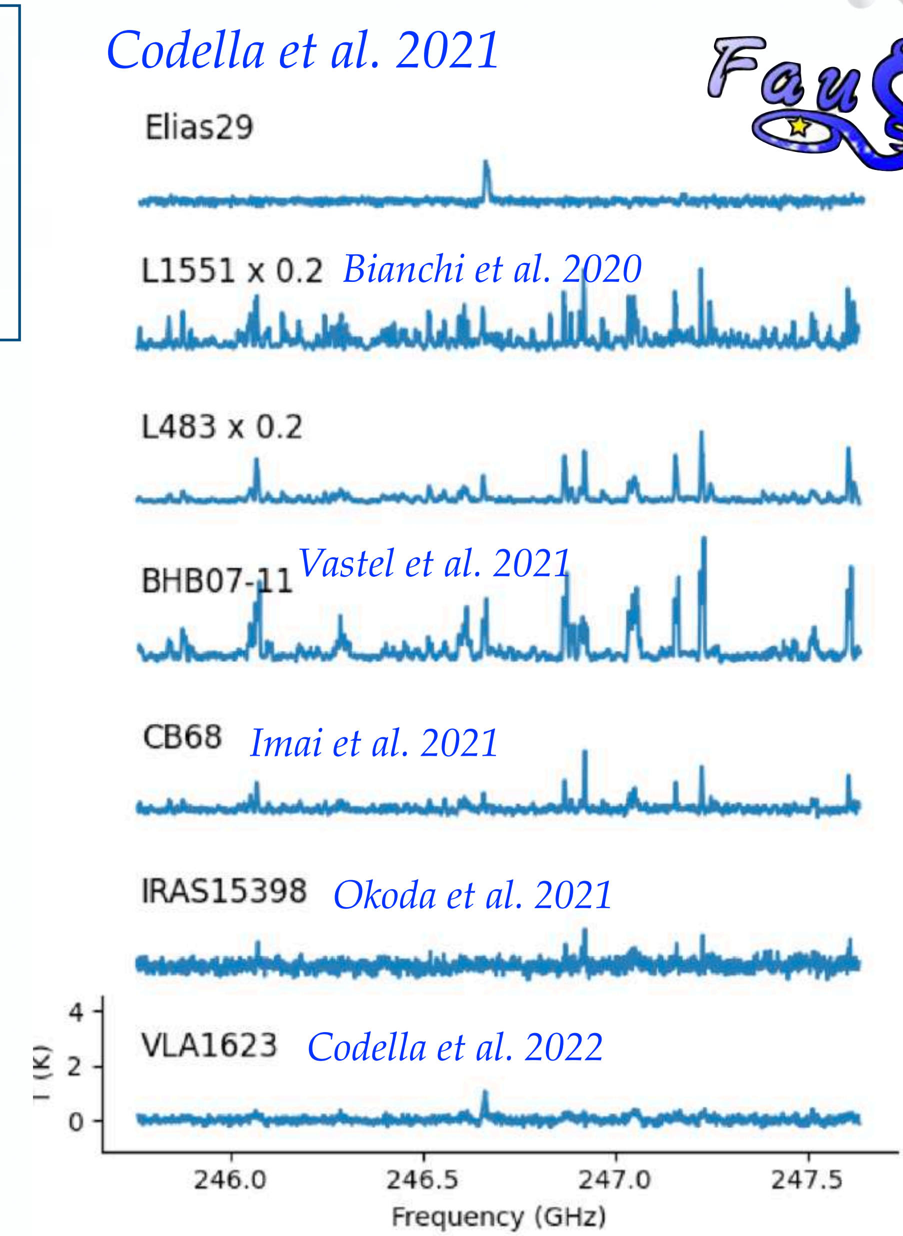
Why so few Hot Corinos?
Why so different?



Several possibilities:

- Observational biases
- presence of small scale structures
  (See also Aikawa et al. 2020, Nazari et al. 2022, Van Gelder 2022)
- different grain mantle composition

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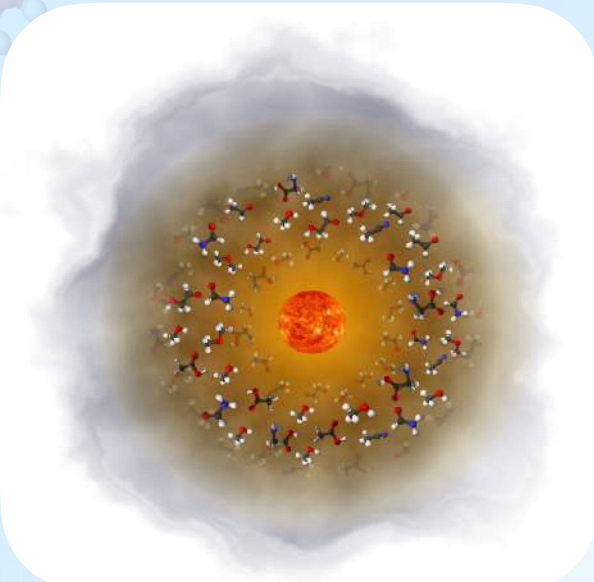

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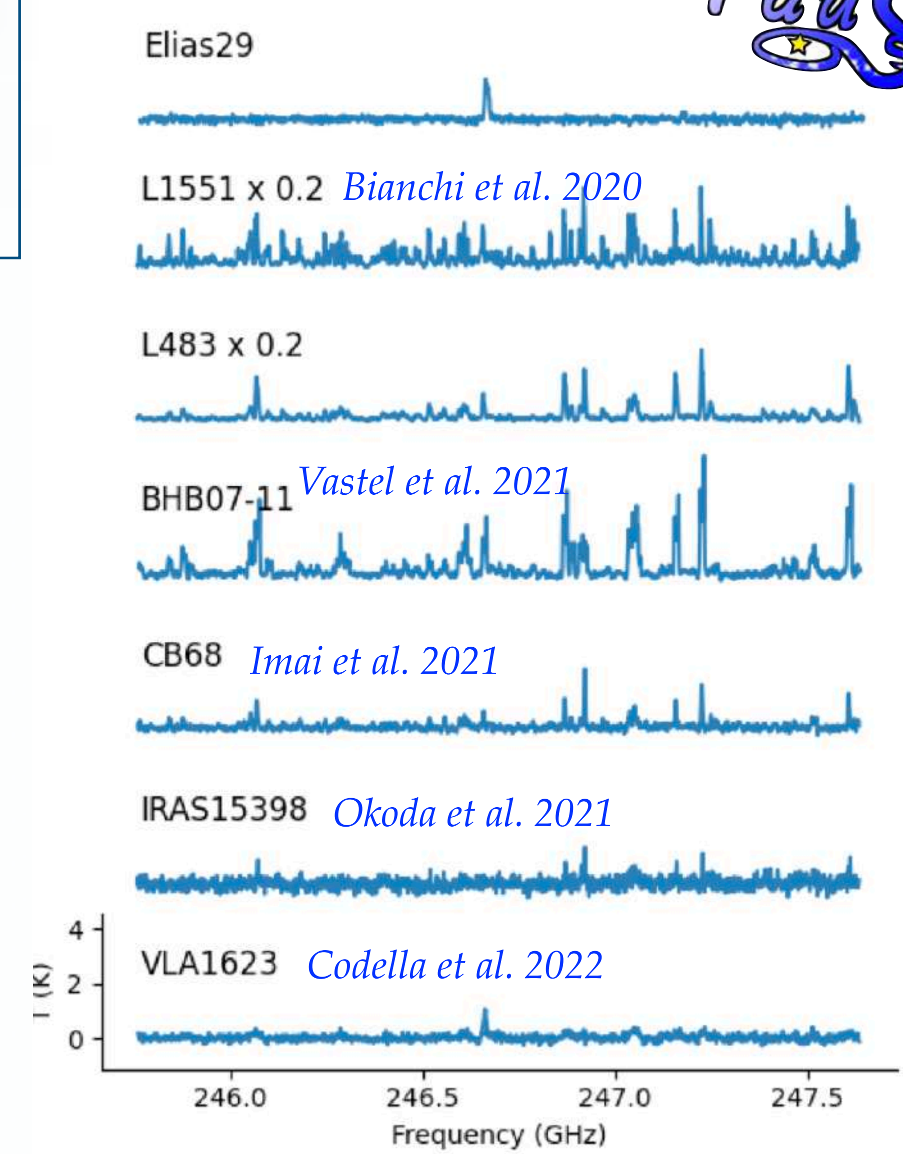
Codella et al. 2021



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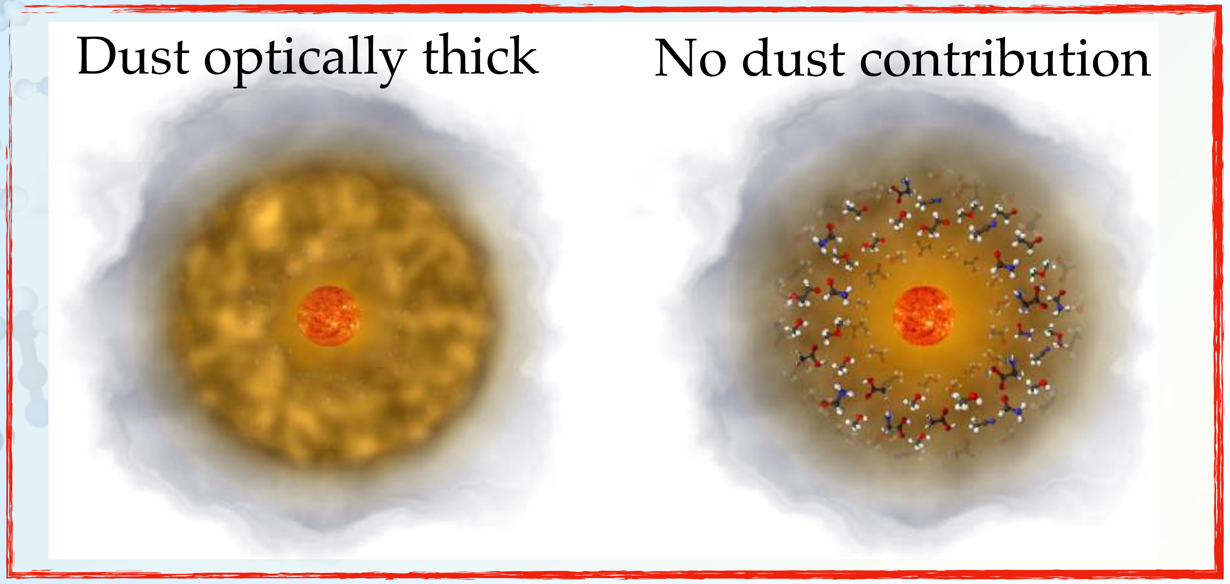
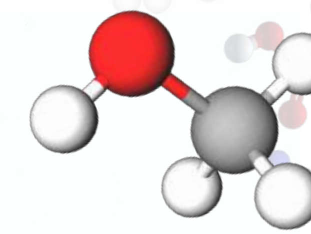
Observational biases: the dust contribution



→ dust opacity effects on iCOMs emission **through mm + cm observations of CH_3OH**



Moving from millimetre to centimetre wavelengths →

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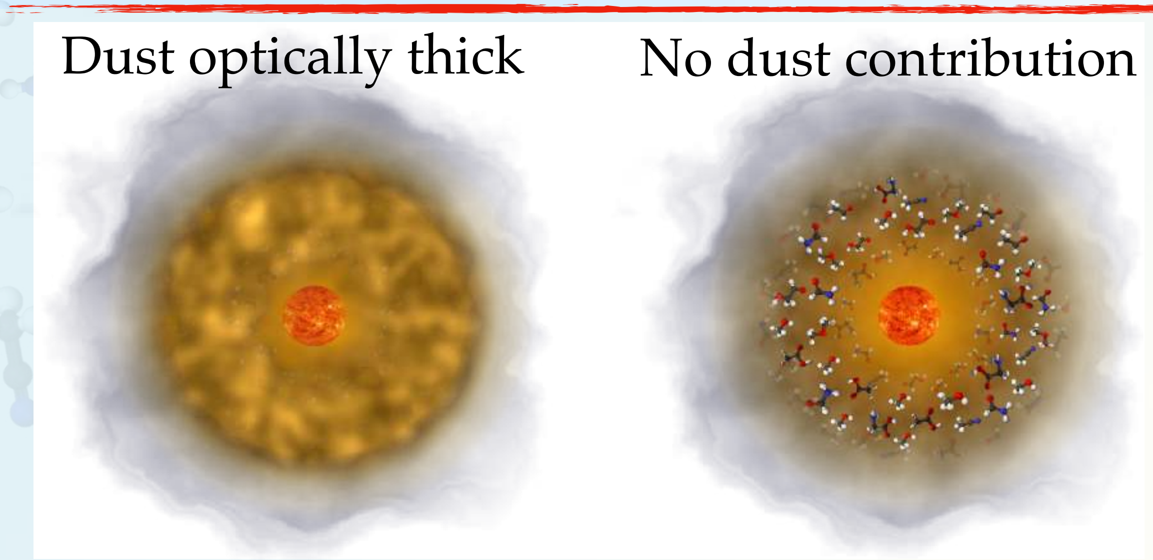

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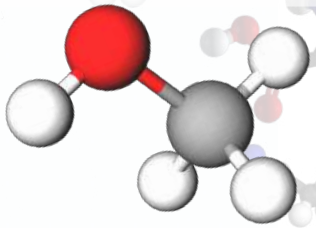
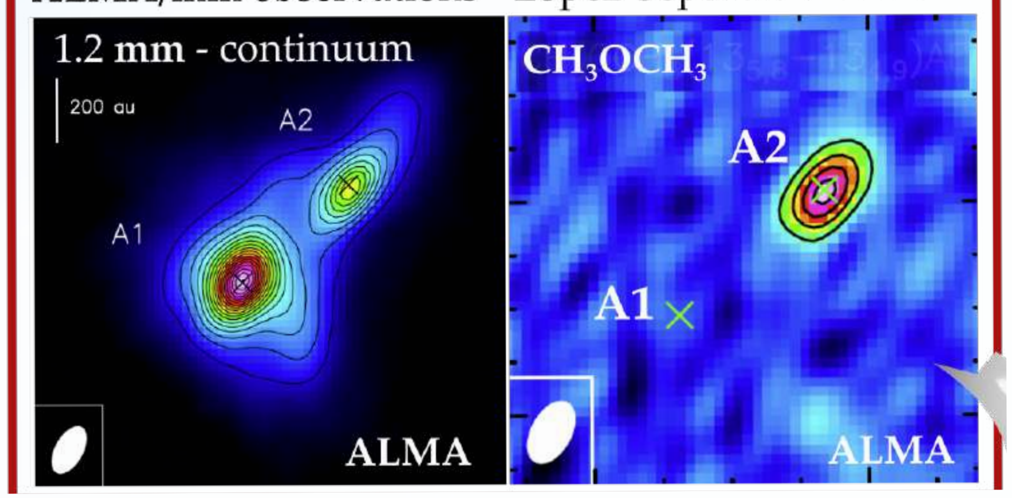


Moving from millimetre to centimetre wavelengths

ALMA/mm observations - Lopez-Sepulcre et al. 2017



IRAS4A at mm
Hot Corino in one of the two companion

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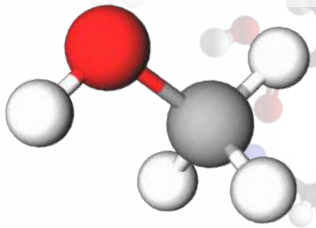
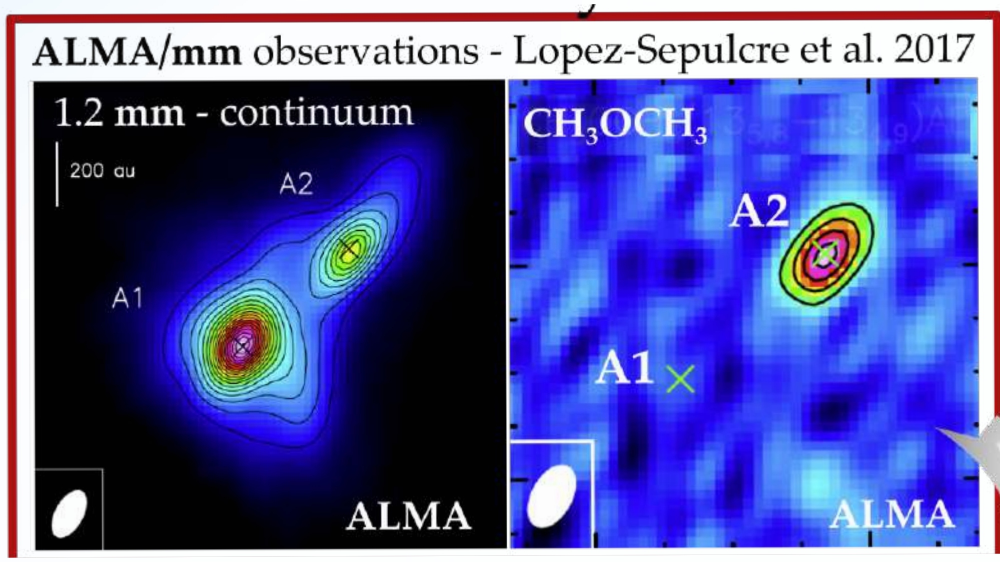


! iCOM abundances at millimeter wavelengths are underestimated

Moving from millimetre to centimetre wavelengths →



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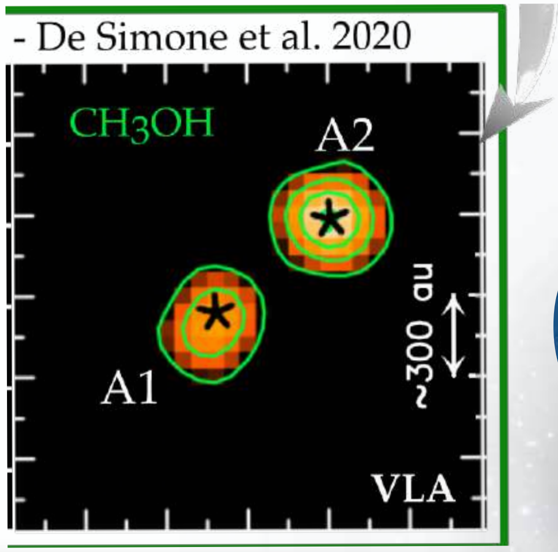
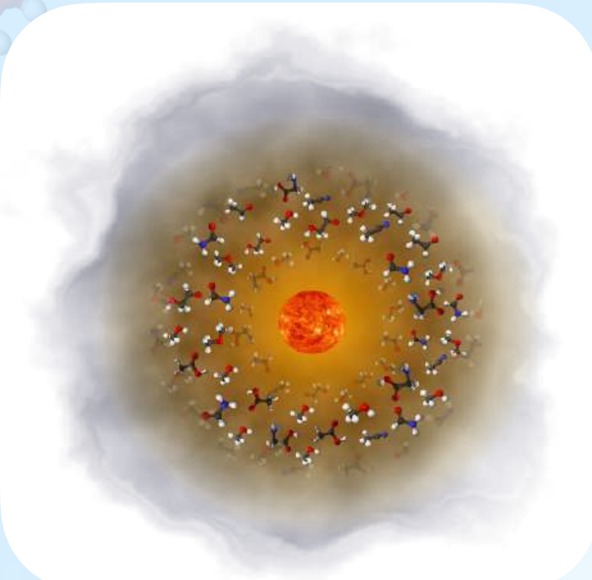


The **dust** is hiding the IRAS 4A1 hot corino

Hot Corinos:
rich chemistry in young Solar-type protostars



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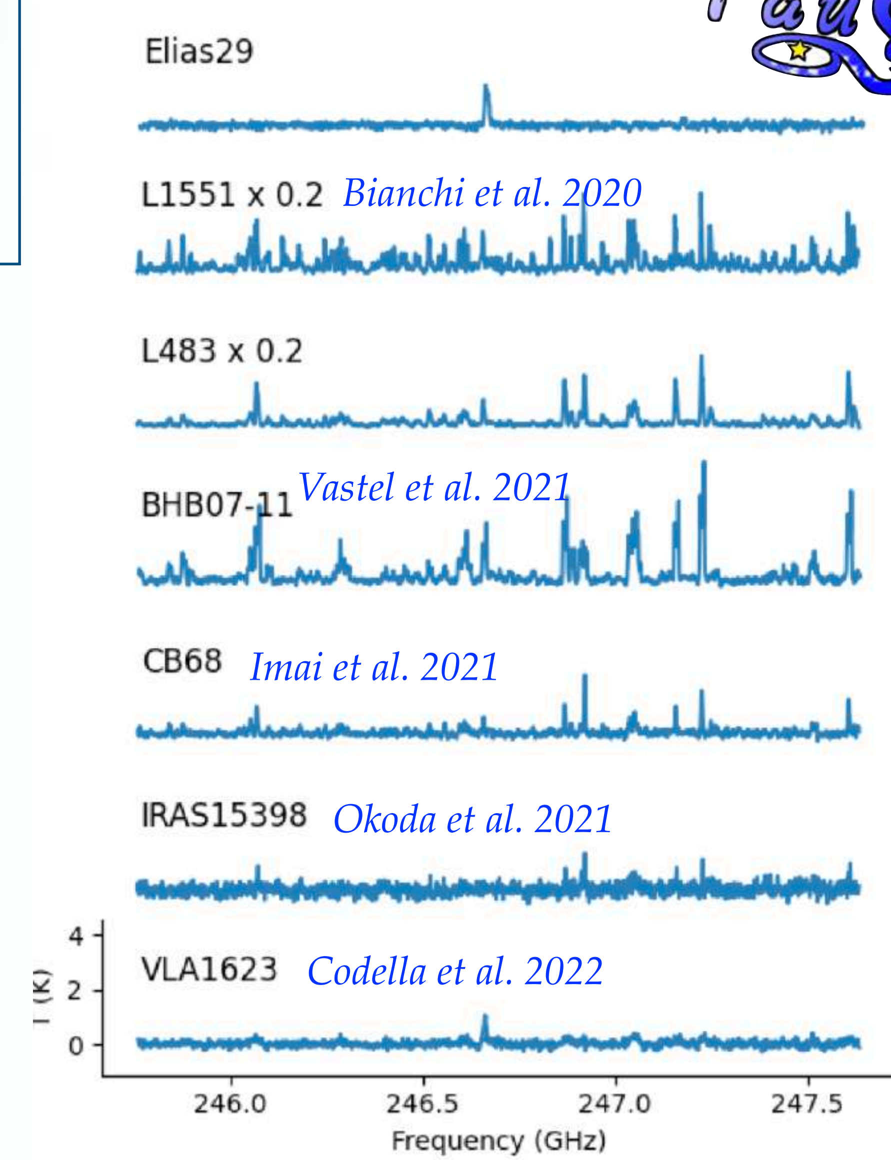

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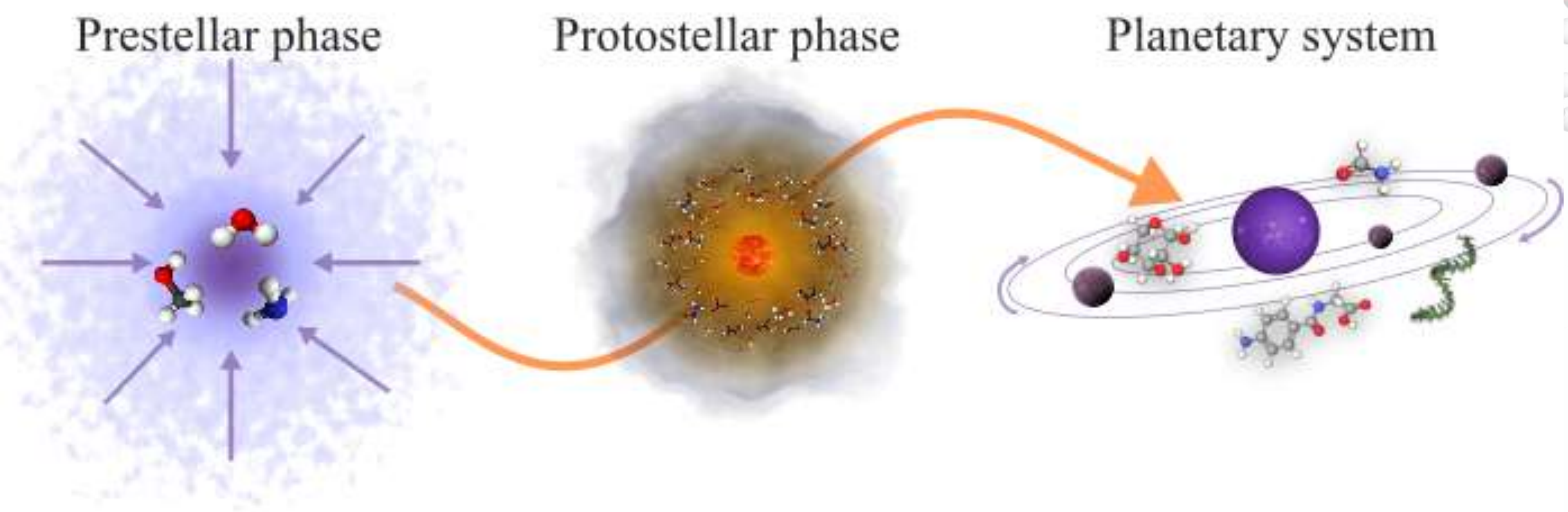
Not all protostars are the same:
Retrieving their ice mantle history



Direct observations of the ice mantle composition for these embedded objects is challenging!

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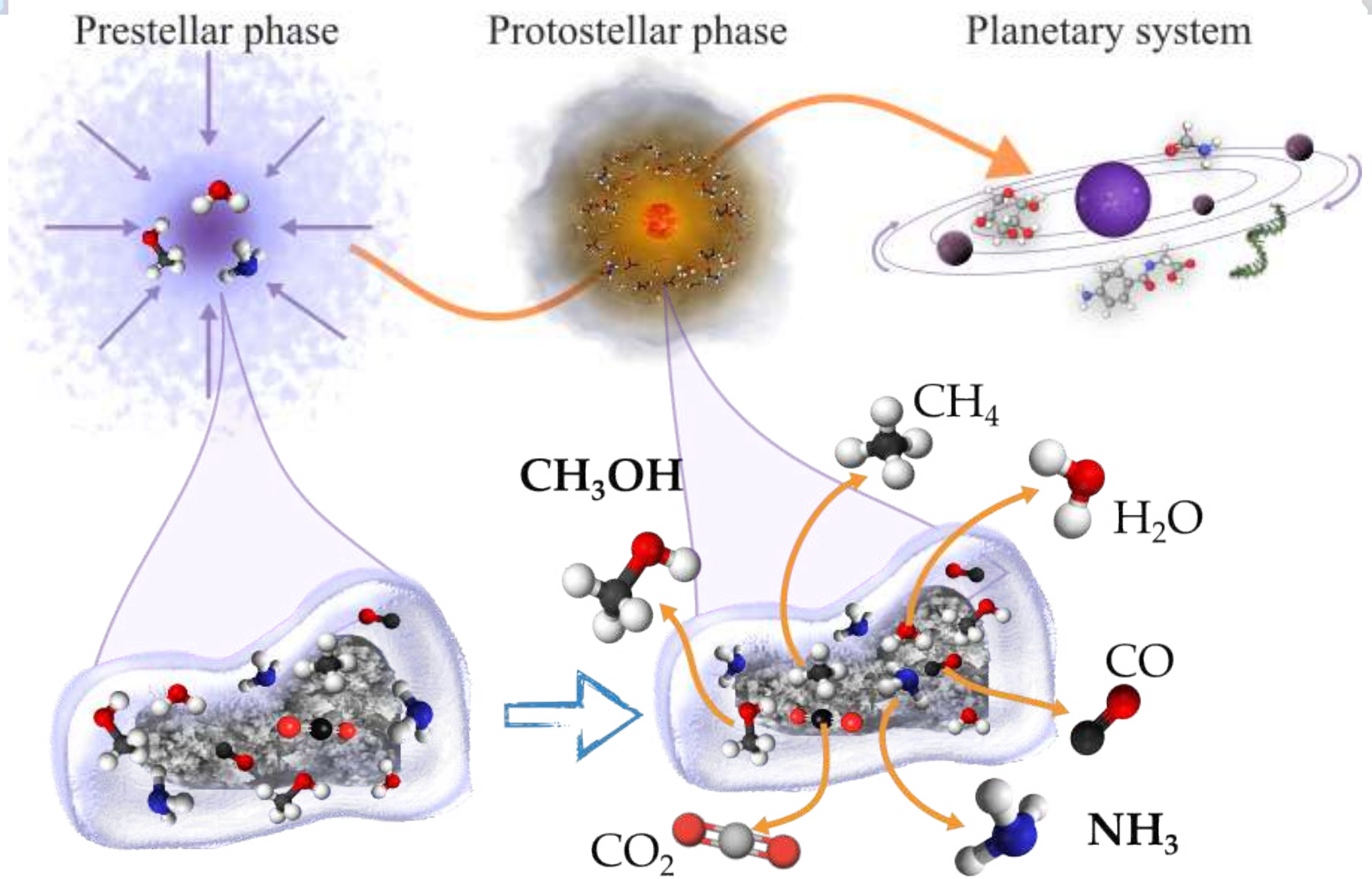


Boogert et al. 2015, McClure et al. 2023

Ice mantle formation

Ice mantle evaporation
--> release species in gas

Retrieve the ice mantle composition indirectly!

Not all protostars are the same:
Retrieving their ice mantle history

NH_3 and CH_3OH best critical tracers of the ice mantle composition

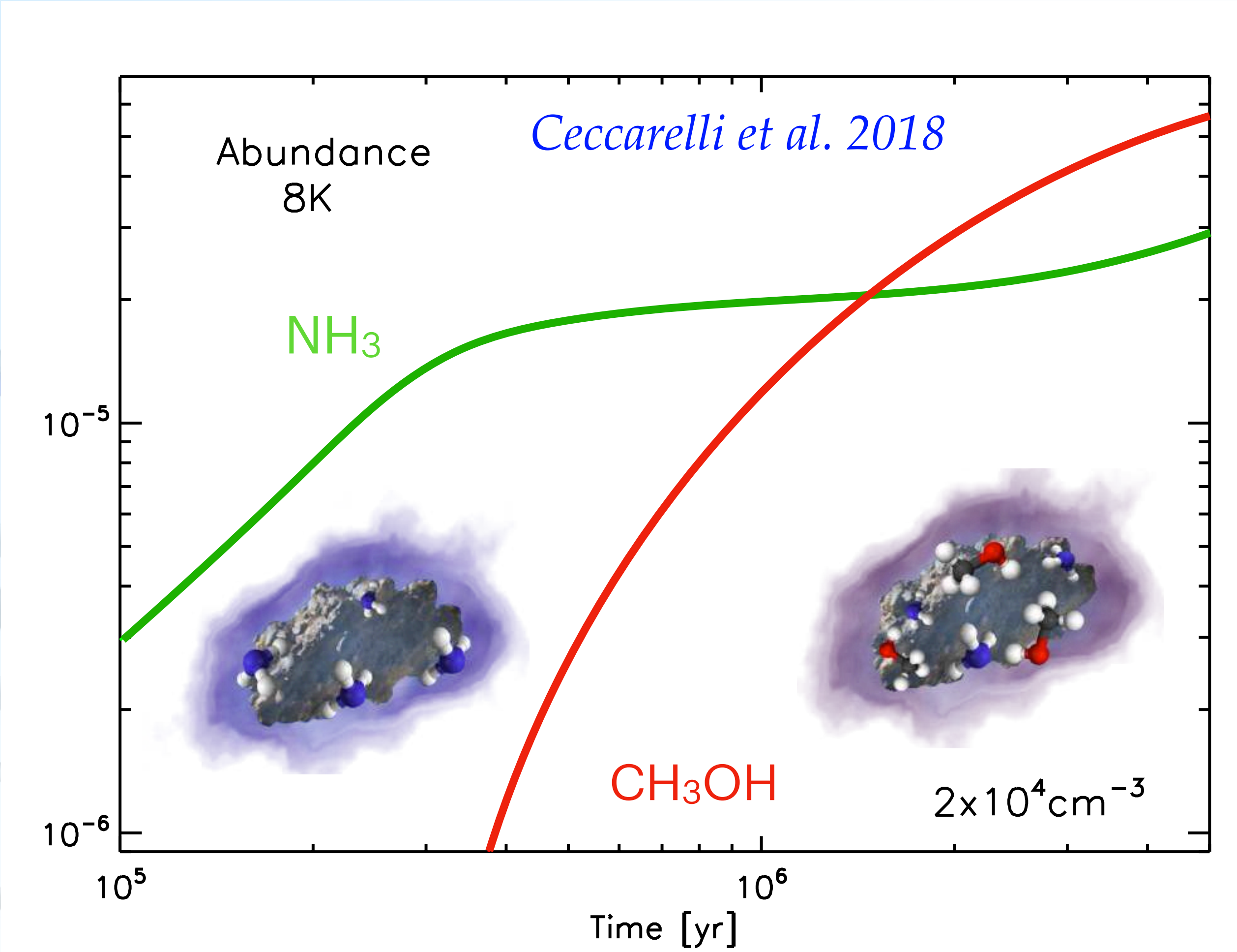
Cm range →

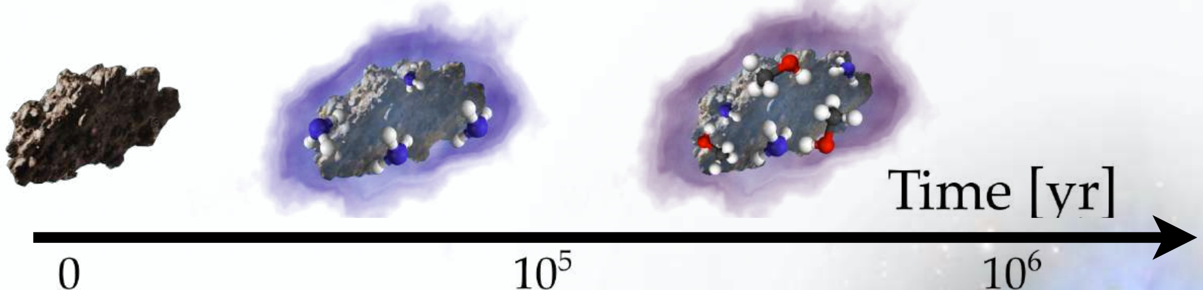
Well known formation paths
(Watanabe & Kouchi 2002; Rimola et al. 2014; Le Gal et al. 2014; Song & Kästner 2017; Jonusas et al. 2020, Tinacci et al. 2022, Ferrero et al. 2023)

→

The NH_3/CH_3OH depends on the cloud **temperature** and **density**, and the ice mantle formation **timescale**

Taquet et al. 2012a, Aikawa et al. 2020



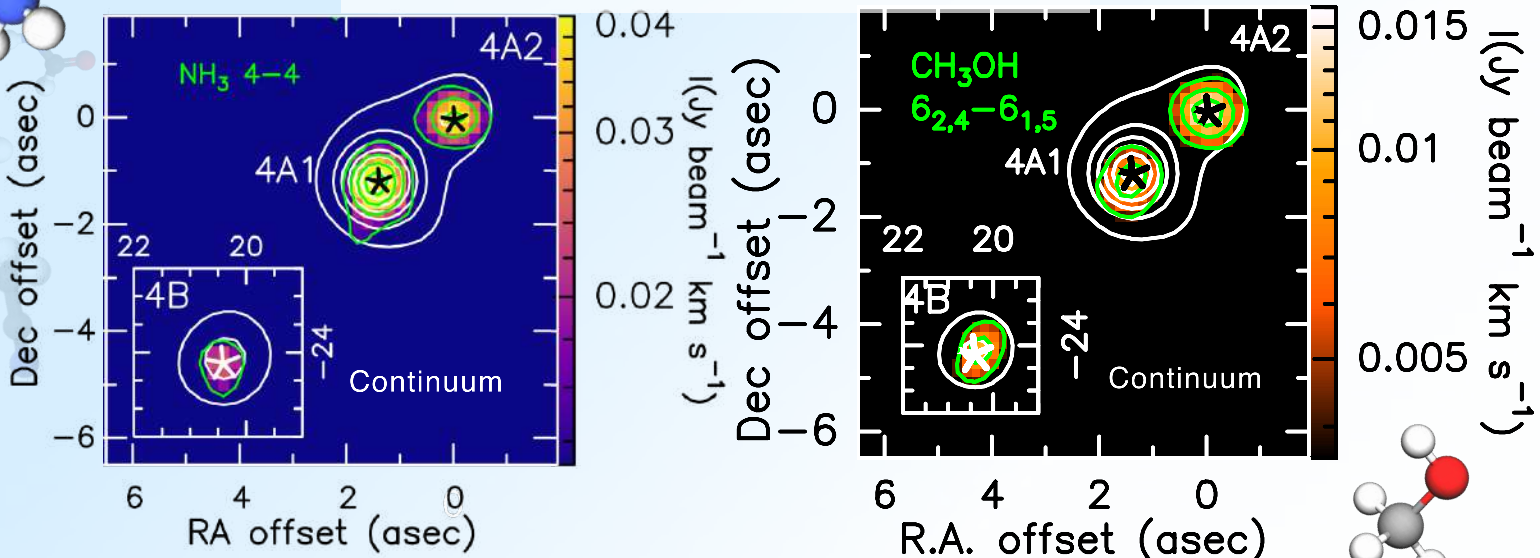


e.g, an old grain mantle would likely be enriched in CH_3OH

Not all protostars are the same:

Retrieving their ice mantle history -> the IRAS 4A case

De Simone et al. 2022, ApJL



Abundance ratio $\frac{NH_3}{CH_3OH}$ *(non-LTE LVG)*:

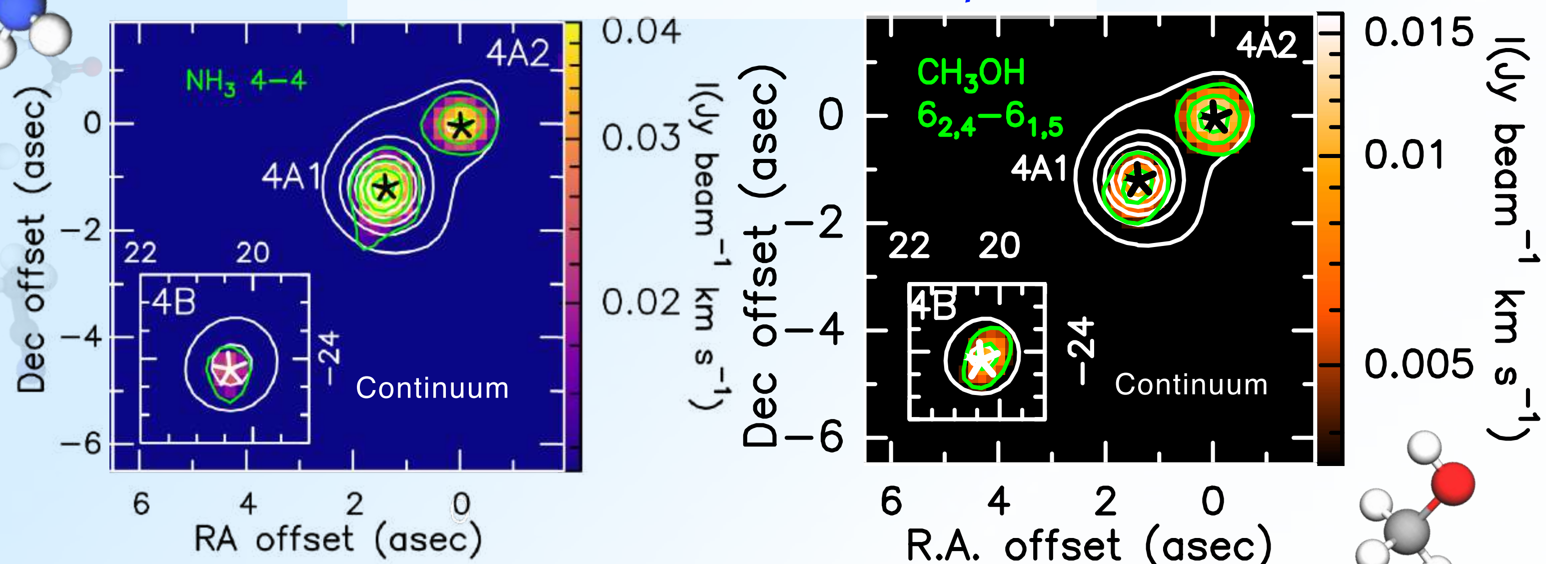
IRAS 4A1	IRAS 4A2	IRAS 4B
< 0.5	0.015 – 0.5	0.003 – 0.3

The three protostars have the same chemical history:

They were formed from pre-collapse material with **similar physical conditions**

Not all protostars are the same:
Retrieving their ice mantle history -> the IRAS 4A case

De Simone et al. 2022, ApJL



$\frac{NH_3}{CH_3OH}$	Abundance ratio *(non-LTE LVG):*	
IRAS 4A1	**IRAS 4A2**	**IRAS 4B**
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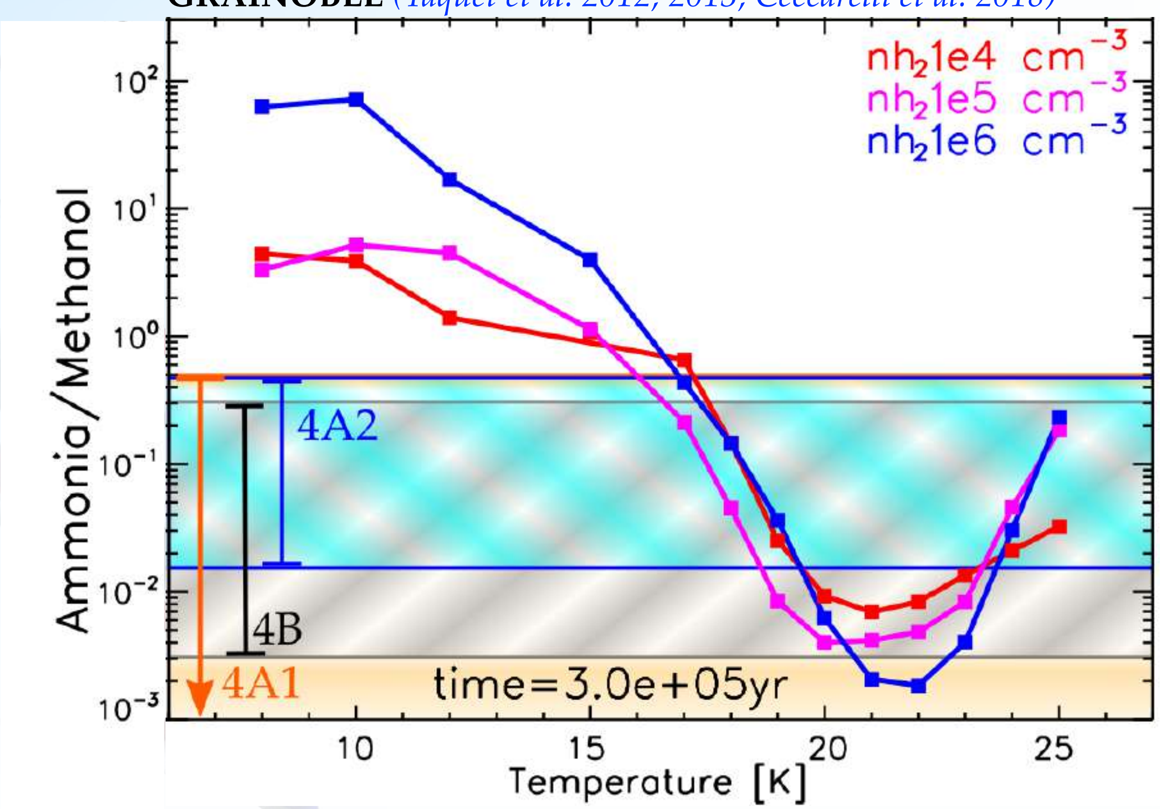
Astrochemical model (gas+grain)

GRAINOBLE *(Taquet et al. 2012, 2013, Ceccarelli et al. 2018)*



Pre-Collapse conditions

$T \geq 17$ K

Too warm for a prestellar core at 60 au!

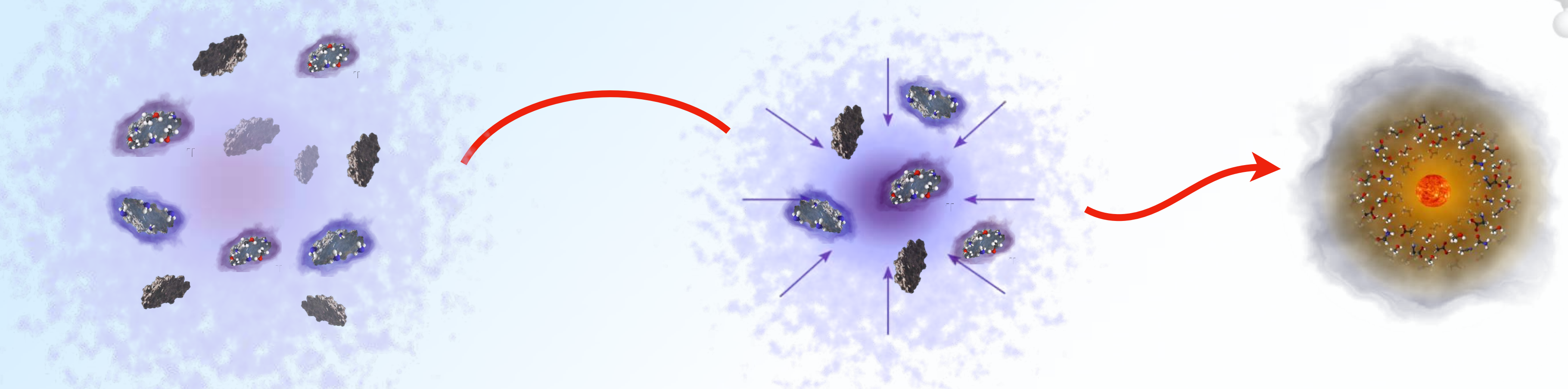
Typical of the less dense material in NGC 1333 south

Zari et al. 2016; Zhang et al. 2022

Premature collapse!

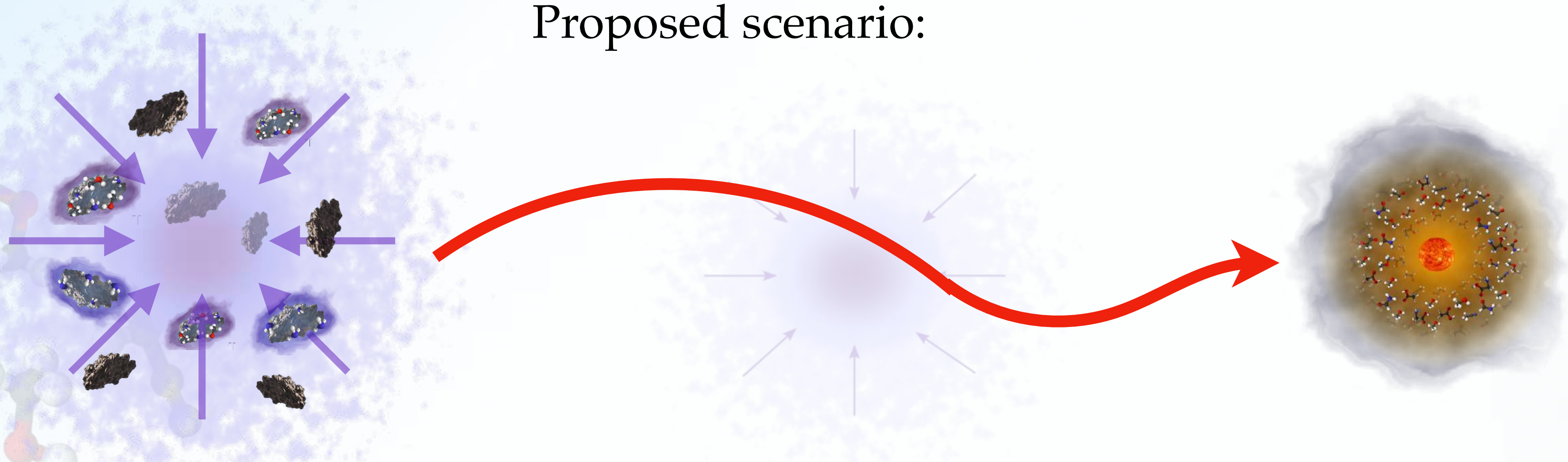
Not all protostars are the same:
Retrieving their ice mantle history -> the IRAS 4A case

Typical scenario:



Warm ~ 17 K	Cold ~ 8 K	Hot ~100 K
Less dense ~10^4 cm^{-3}	Dense ~10^6 cm^{-3}	More dense ~10^7 cm^{-3}

Proposed scenario:



IRAS 4A1, 4A2, 4B did not experience the usual prestellar core phase

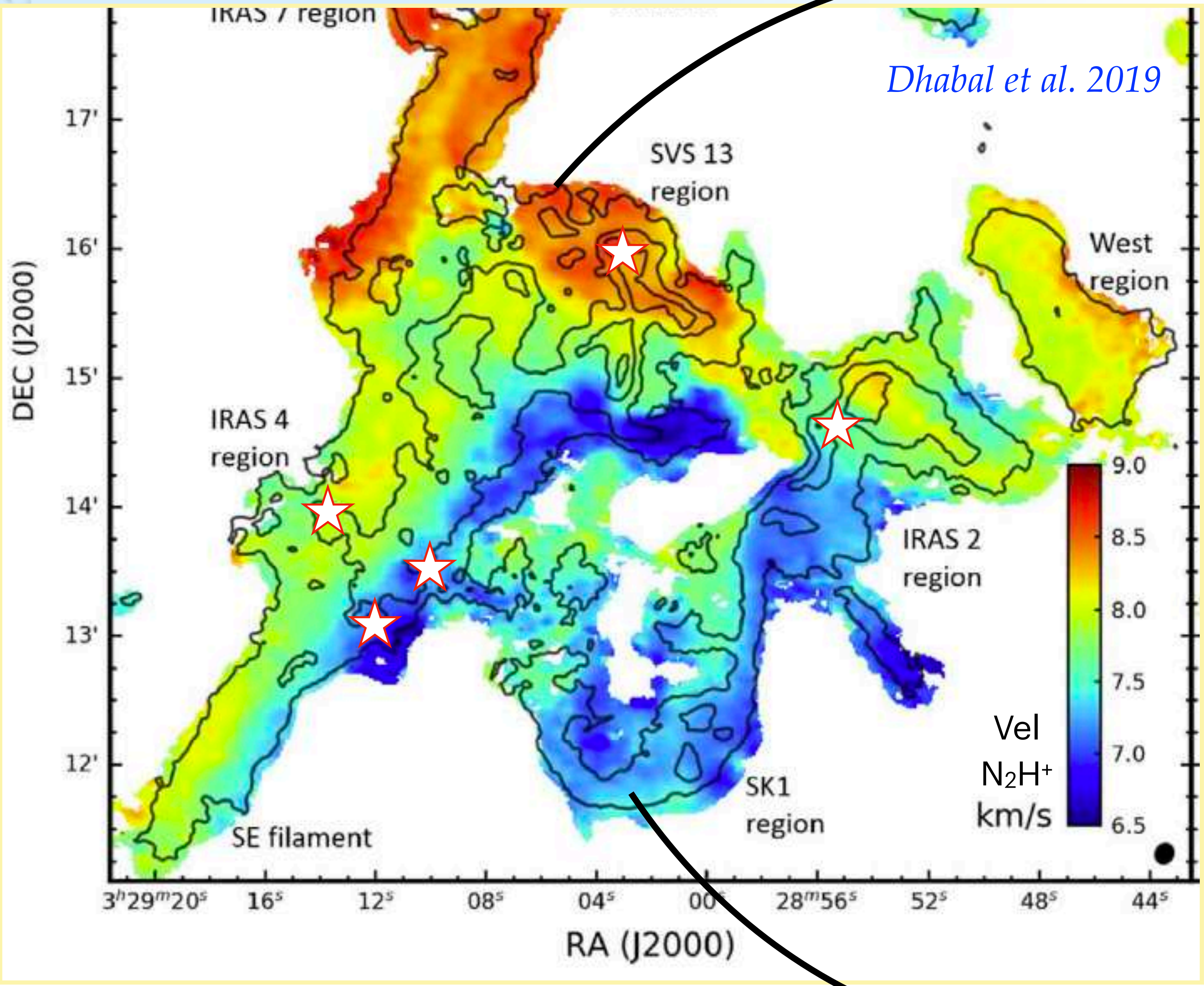
De Simone et al. 2022

External Triggers?

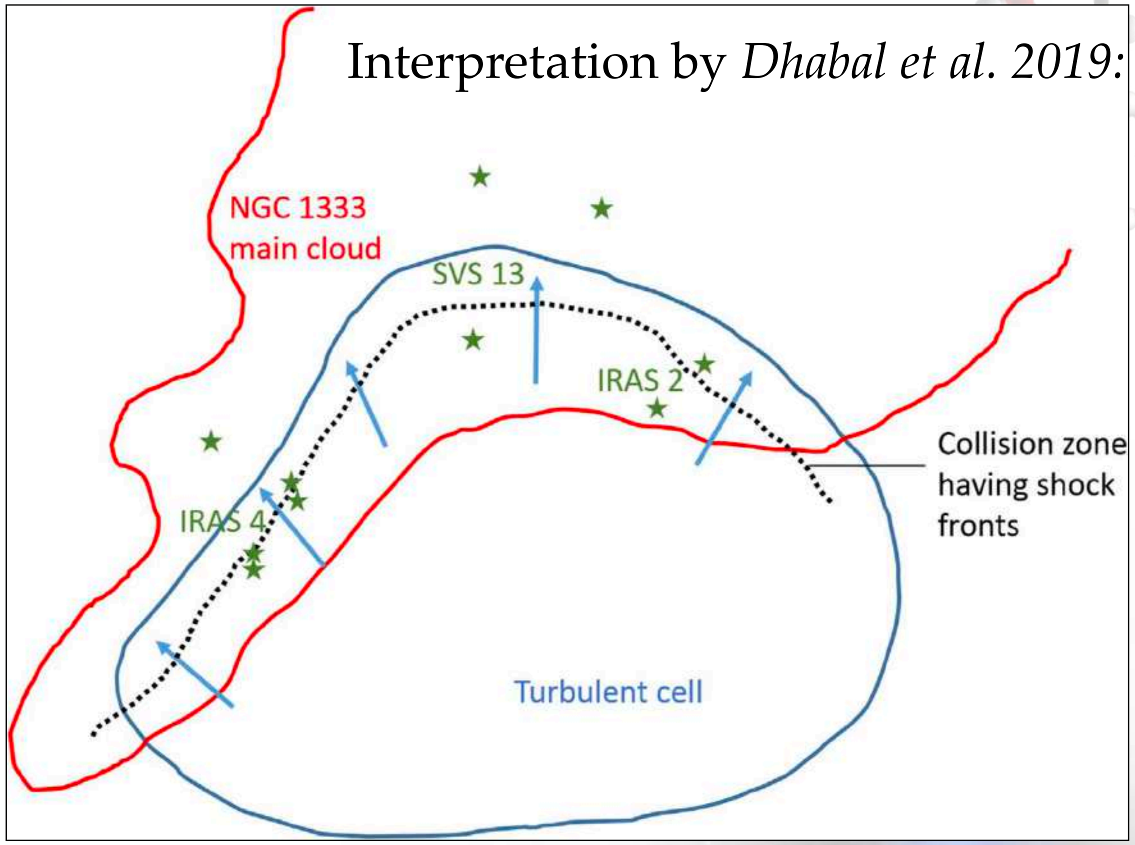
Could have been the expanding **bubbles** that shaped NGC 1333?
(Dhabal et al. 2019; De Simone et al. 2022)

A premature collapse has been triggered where no prestellar core existed

Zoom out of the Perseus/NGC 1333 region



Red-shifted zone: moving away from us

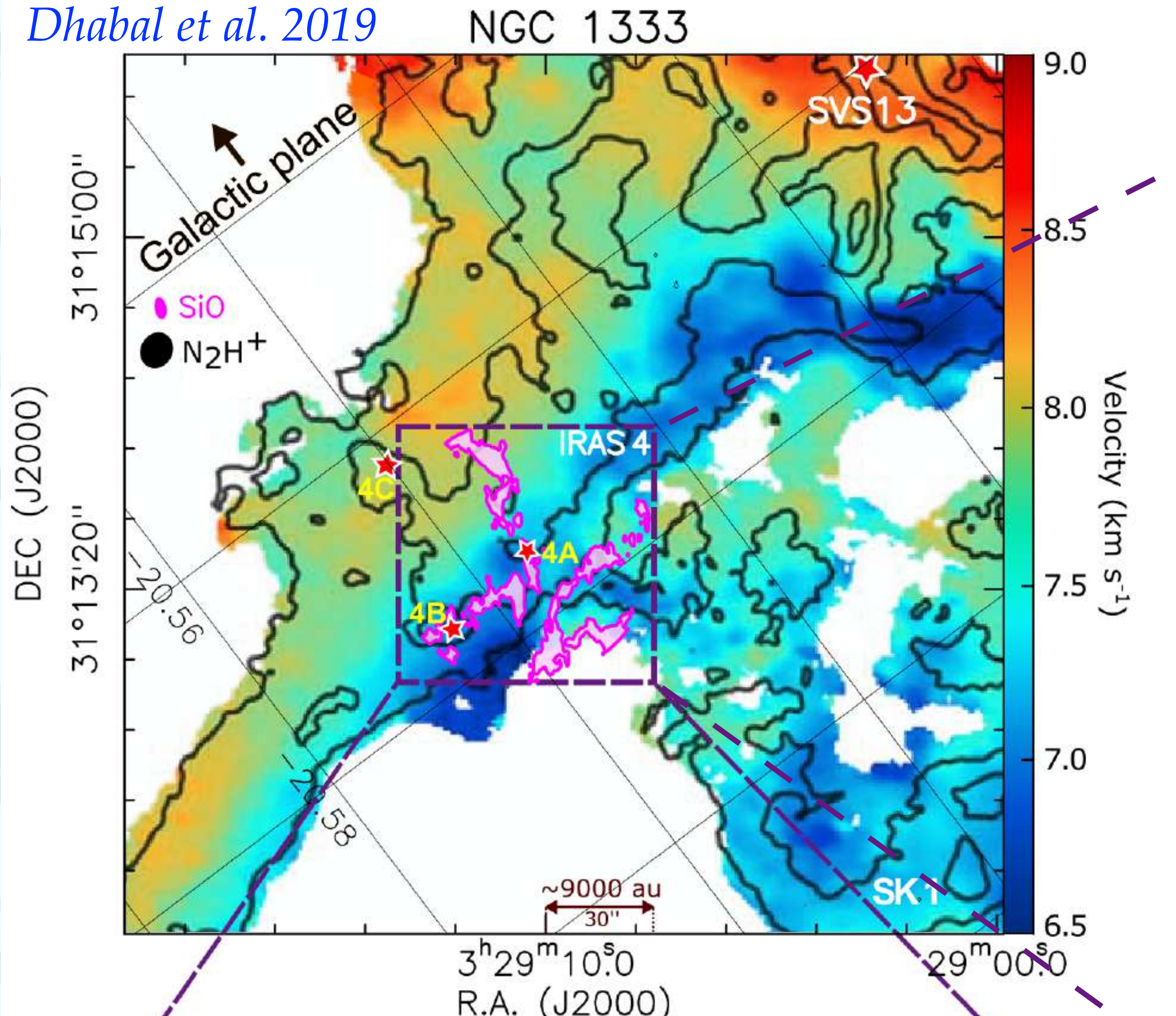


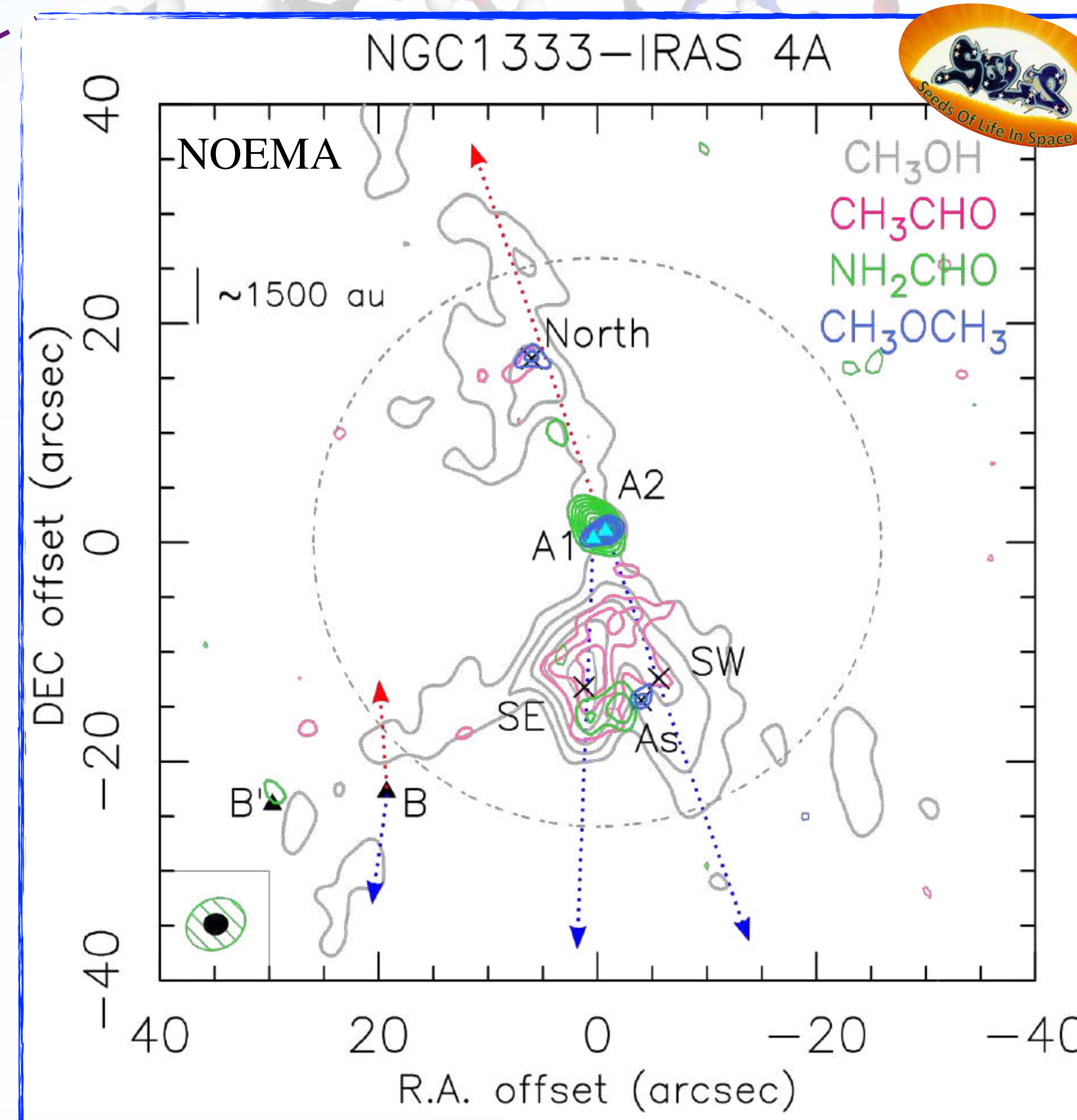
Blue-shifted zone: moving toward us

Are there any signatures of this interaction?

The IRAS 4A surroundings: outflows and shocks

Dhabal et al. 2019





First imaging of iCOMs in the IRAS 4A Outflows

De Simone et al. 2020b A&A

Constrain iCOMs formation routes?
(gas phase vs grain surface)

↑

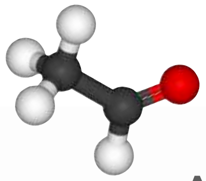
Evidence of Chemical Differentiation along IRAS 4A outflows

The IRAS 4A surroundings: outflows and shocks

acetaldehyde formed in gas phase?

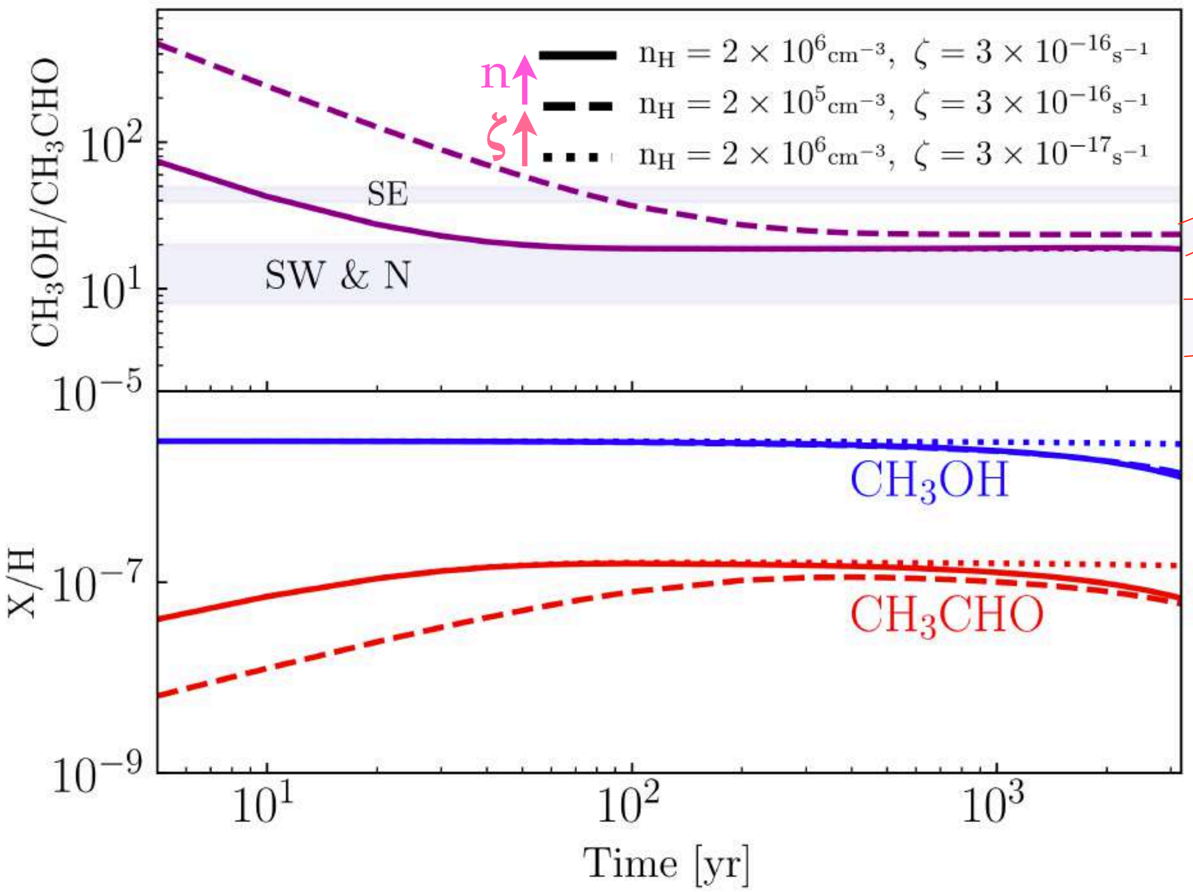
$$CH_3CH_2 + O \rightarrow CH_3CHO + H$$

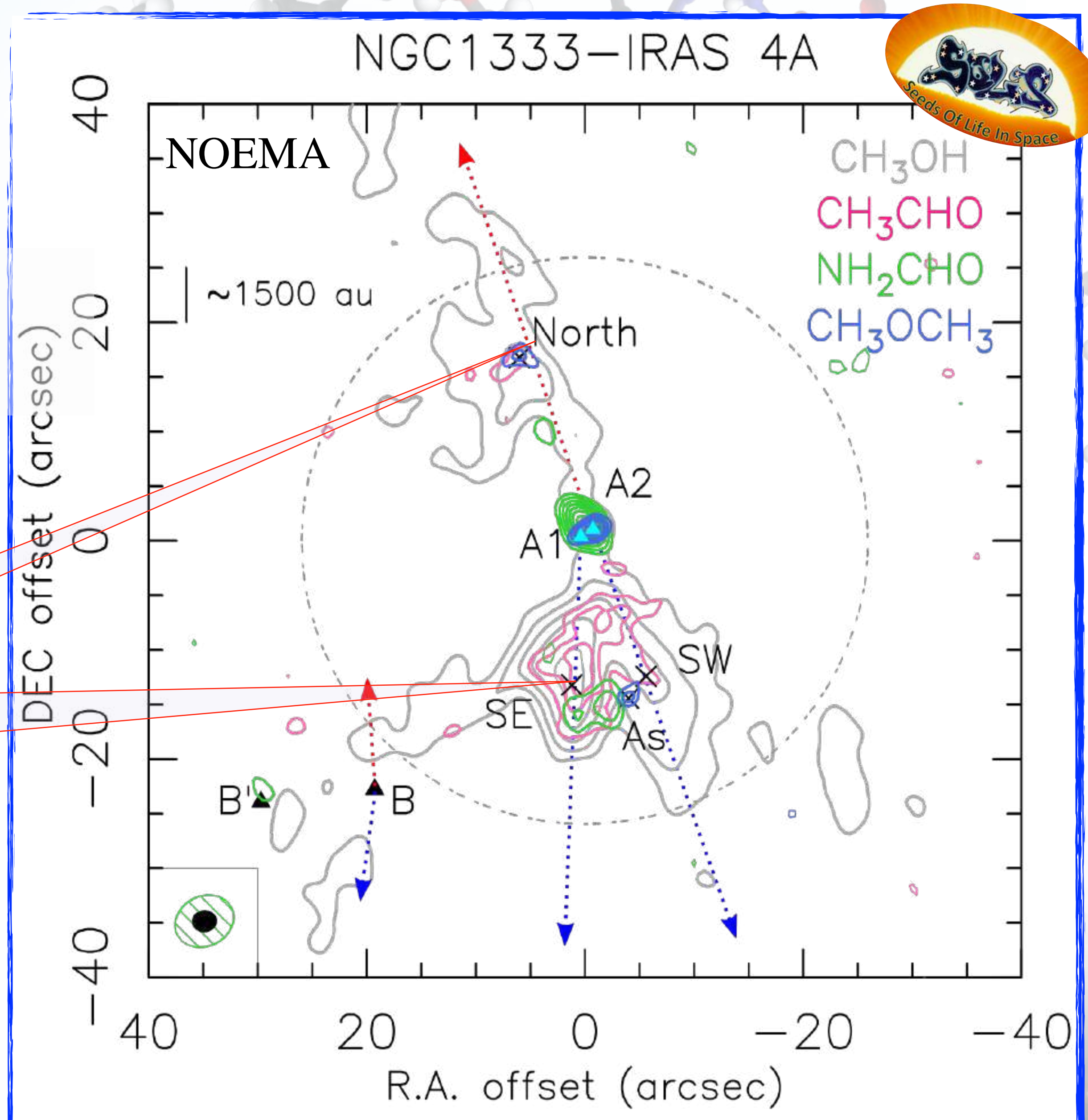
Charnley 2004, Vazart et al. 2020



Astrochemical Model (gas-phase)

GRAINOBLE+ (*Taquet et al. 2012, Witzel et al. in prep*)





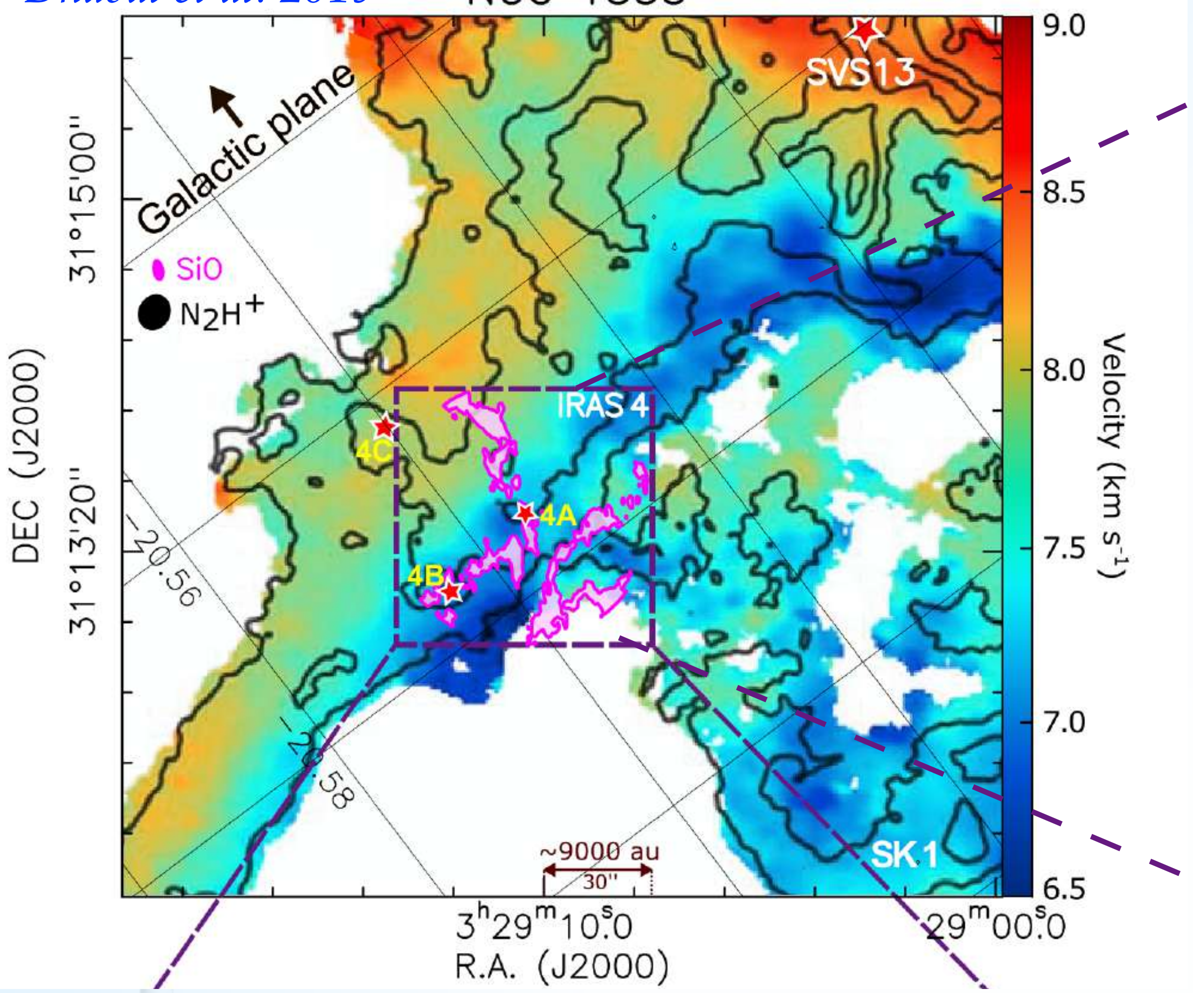
First imaging of iCOMs in the IRAS 4A Outflows

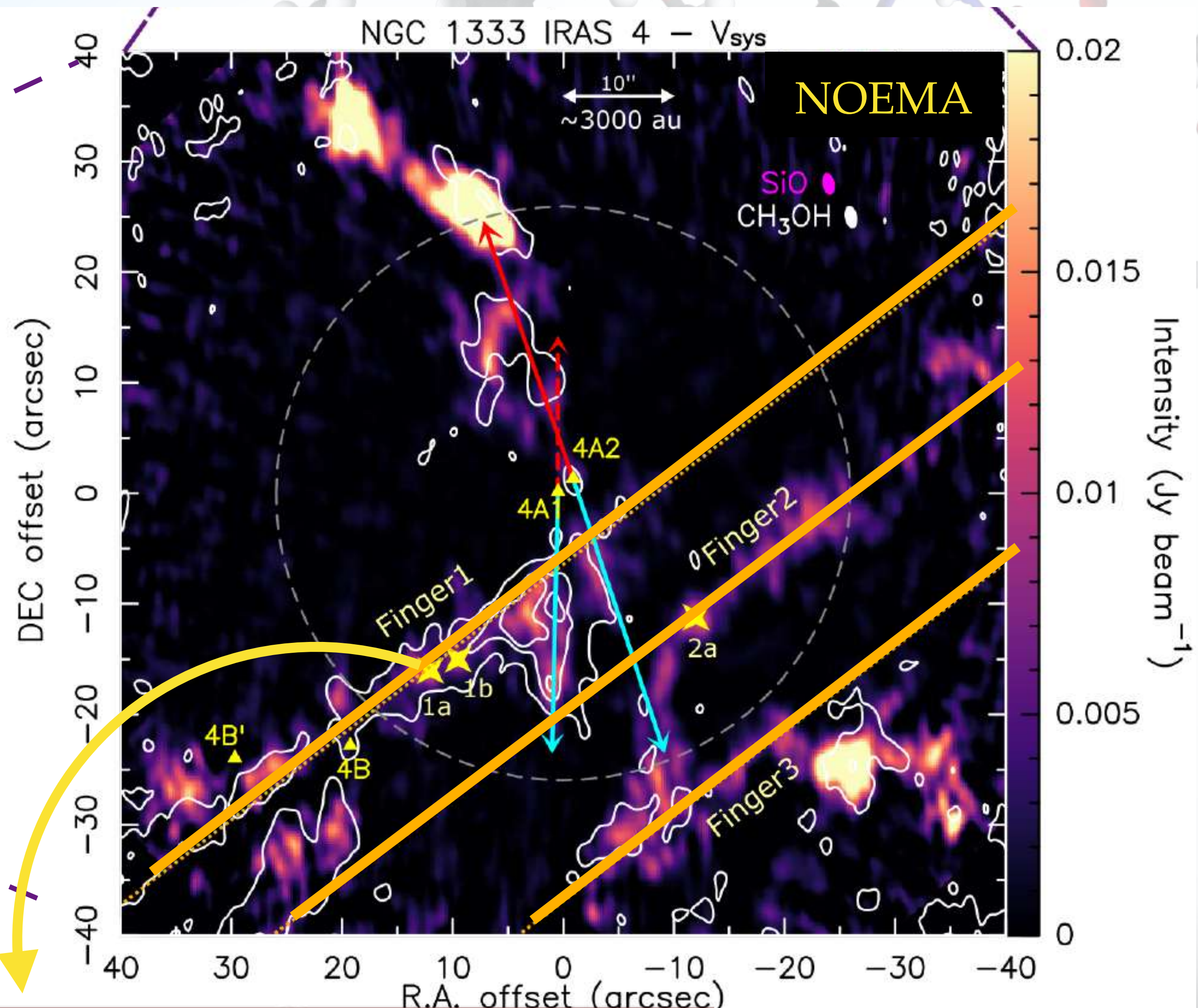
(i) Acetaldehyde gas phase product,
(ii) 4A1 Outflow younger or less dense than the 4A2 one

De Simone et al. 2020b A&A

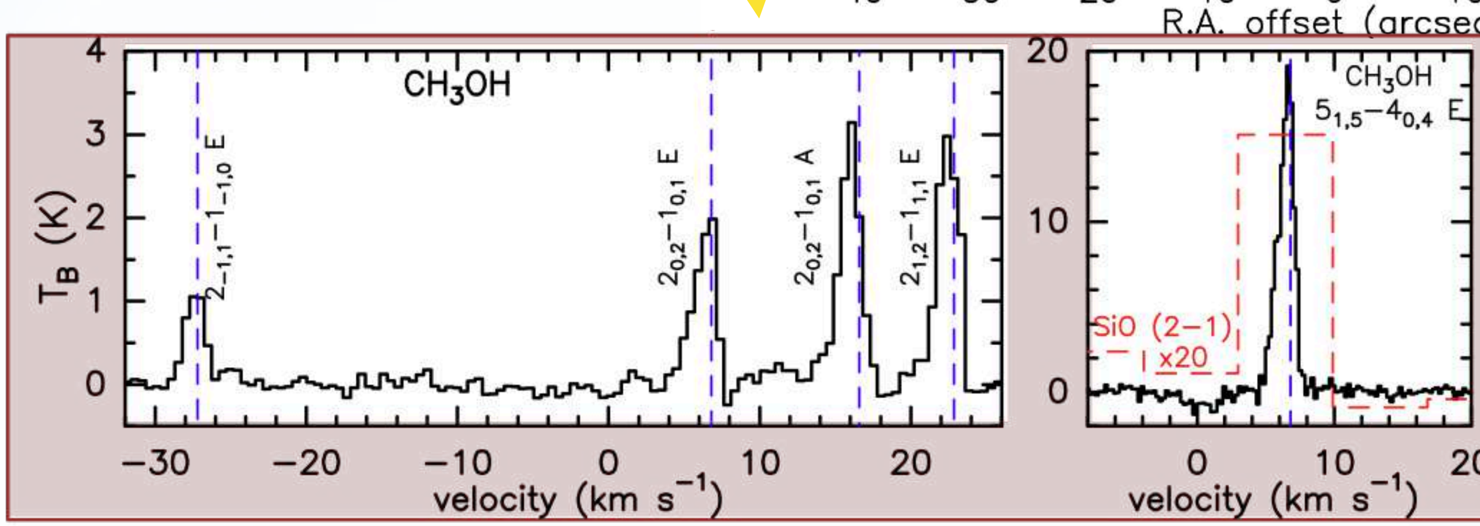
The IRAS 4A surroundings: outflows and shocks

Dhabal et al. 2019



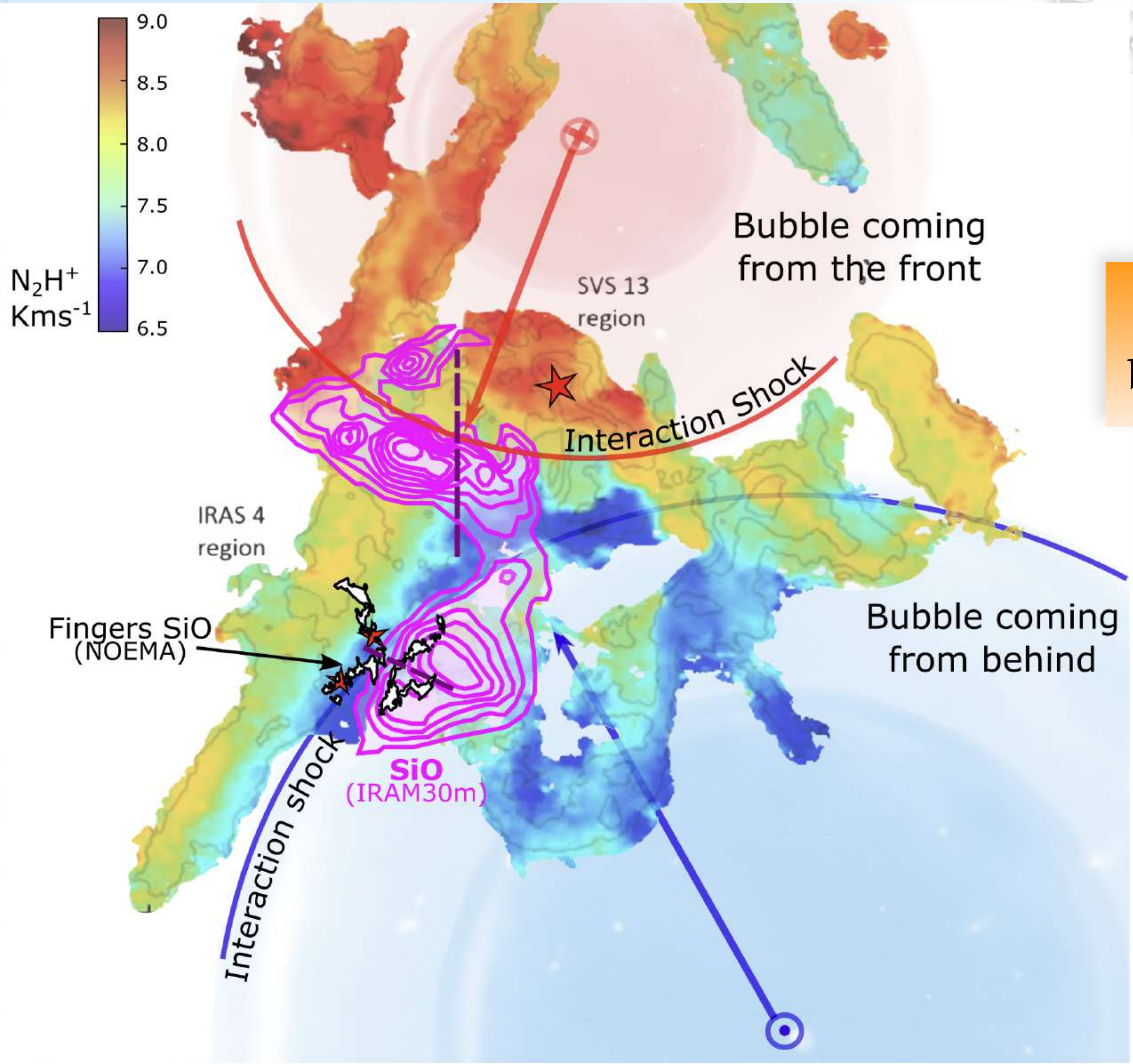


Narrow (~1.5 km/s) elongated structure around the systemic velocity (~6.7 km/s)



De Simone et al. 2022 MNRAS

Shock as result of cloud collisions:
the case of the NGC1333 IRAS 4 system



NGC 1333 could have been shaped by two clashing expanding bubbles.

Could this clash have **triggered the formation** of the protostars on the filament?

Stay tuned…

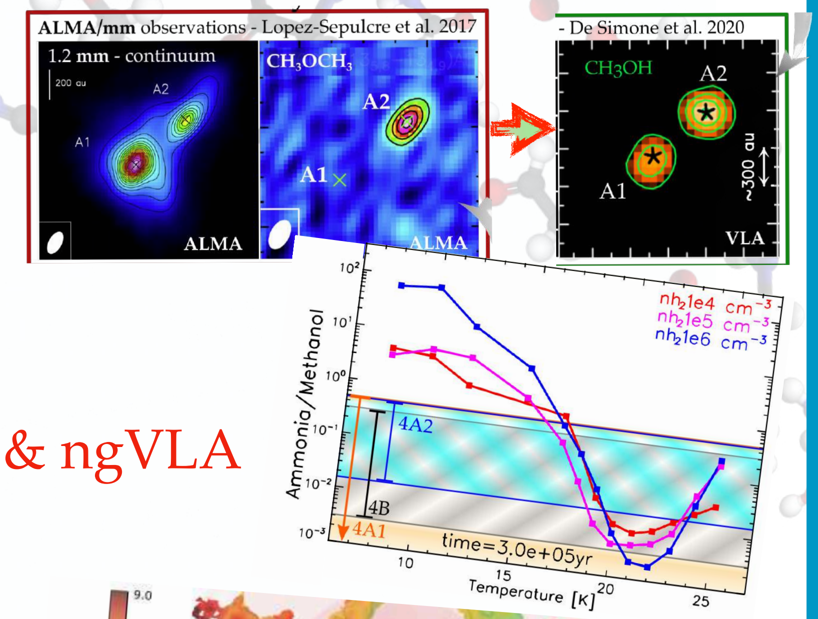
De Simone et al. 2022 MNRAS

Final remarks

What is the origin and nature of hot corinos?

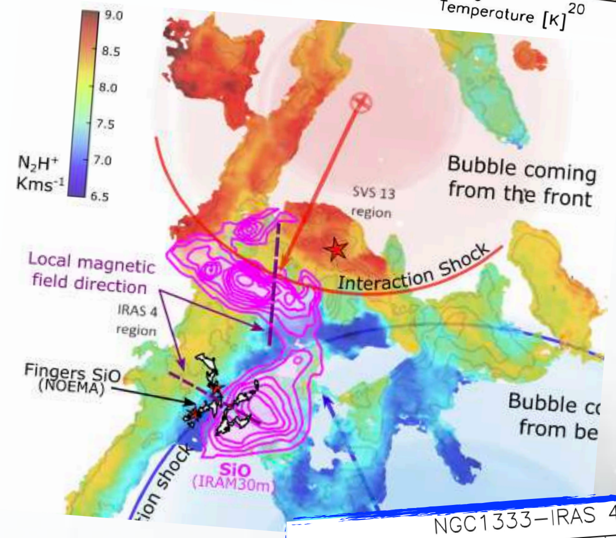
- Dust can absorb hot corino emission at mm wavelength.
- The NH_3/CH_3OH ratio can be used to constrain the pre-collapse clump conditions

—> multi wavelength approach
pave the way for future SKA & ngVLA



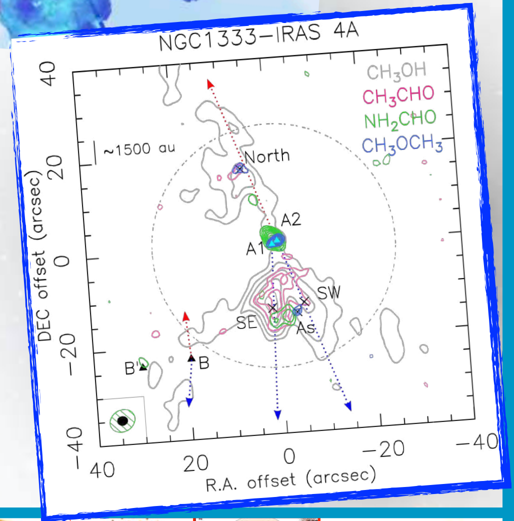
What is the impact of external events on star forming regions?

Arcsec observations of shock tracers as CH_3OH and SiO can help to reconstruct the dynamical history of NGC 1333



How interstellar Complex Organic Molecules are synthesized?

Outflows are powerful astrochemical laboratories when the iCOMs spatial distribution is resolved!



Hot corinos: the early organic molecular enrichment of the planet formation zones

Marta De Simone
ESO Garching Fellow

Thank you

PhD supervisors: *C. Ceccarelli (IT), C. Codella (IT),*

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Journées 2023 de la SF2A
22/06/23 Strasbourg

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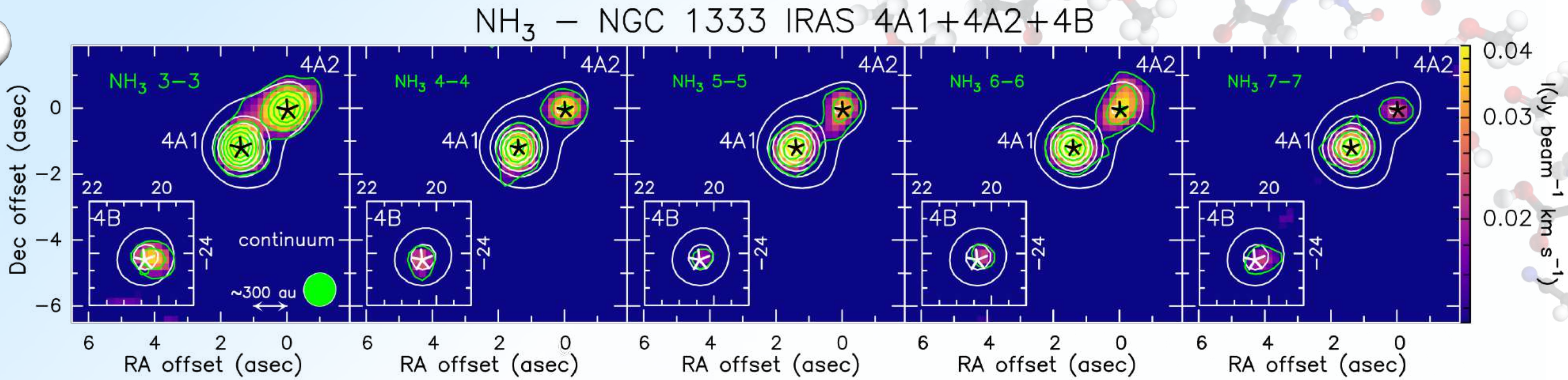
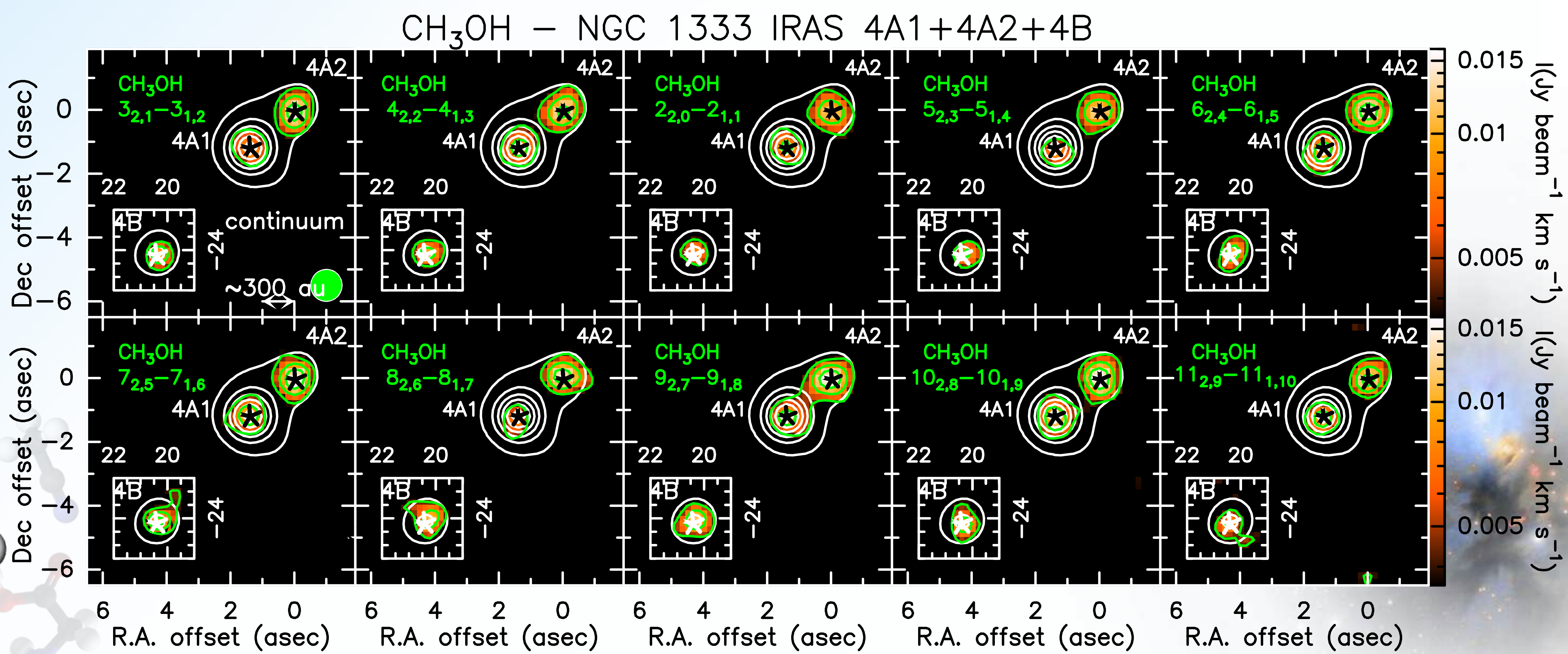
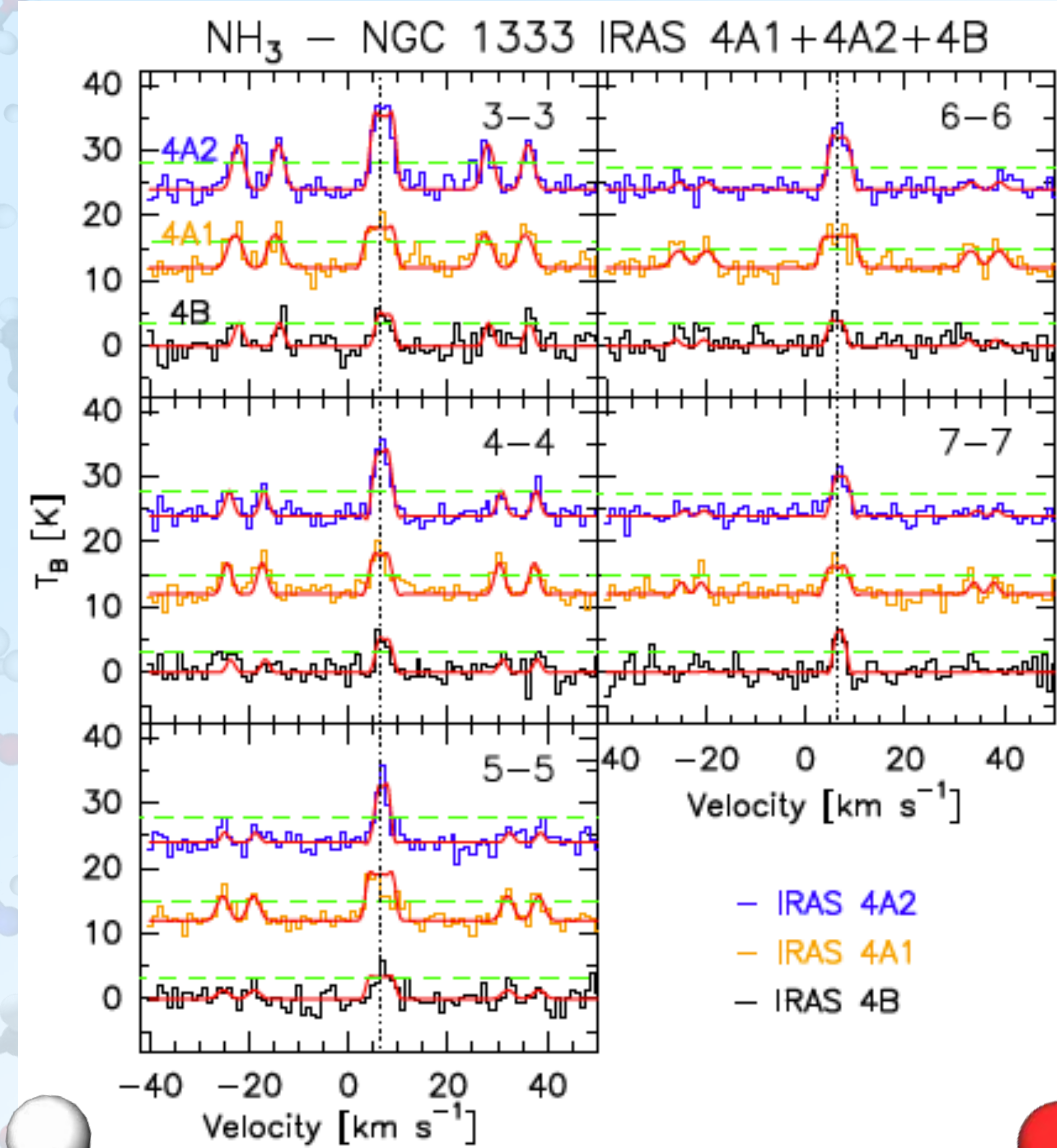
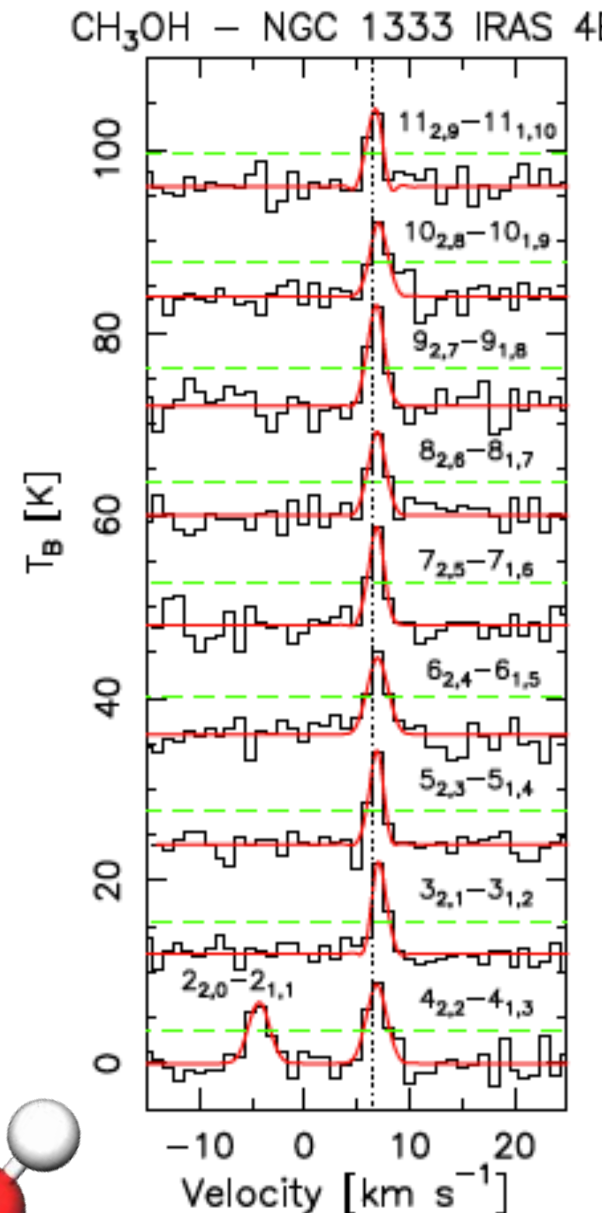


NH$_3$ – NGC 1333 IRAS 4A1+4A2+4B
NH$_3$ 3–3
NH$_3$ 4–4
NH$_3$ 5–5
NH$_3$ 6–6
NH$_3$ 7–7
4A1
4A2
4B
continuum
~300 au
Dec offset (asec)
RA offset (asec)
I(Jy beam^{-1} km s^{-1})

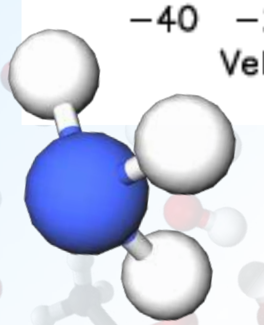


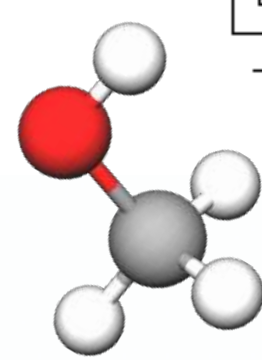
CH$_3$OH – NGC 1333 IRAS 4A1+4A2+4B
CH$_3$OH $3_{2,1}-3_{1,2}$
CH$_3$OH $4_{2,2}-4_{1,3}$
CH$_3$OH $2_{2,0}-2_{1,1}$
CH$_3$OH $5_{2,3}-5_{1,4}$
CH$_3$OH $6_{2,4}-6_{1,5}$
CH$_3$OH $7_{2,5}-7_{1,6}$
CH$_3$OH $8_{2,6}-8_{1,7}$
CH$_3$OH $9_{2,7}-9_{1,8}$
CH$_3$OH $10_{2,8}-10_{1,9}$
CH$_3$OH $11_{2,9}-11_{1,10}$
continuum
~300 au
Dec offset (asec)
R.A. offset (asec)
I(Jy beam^{-1} km s^{-1})

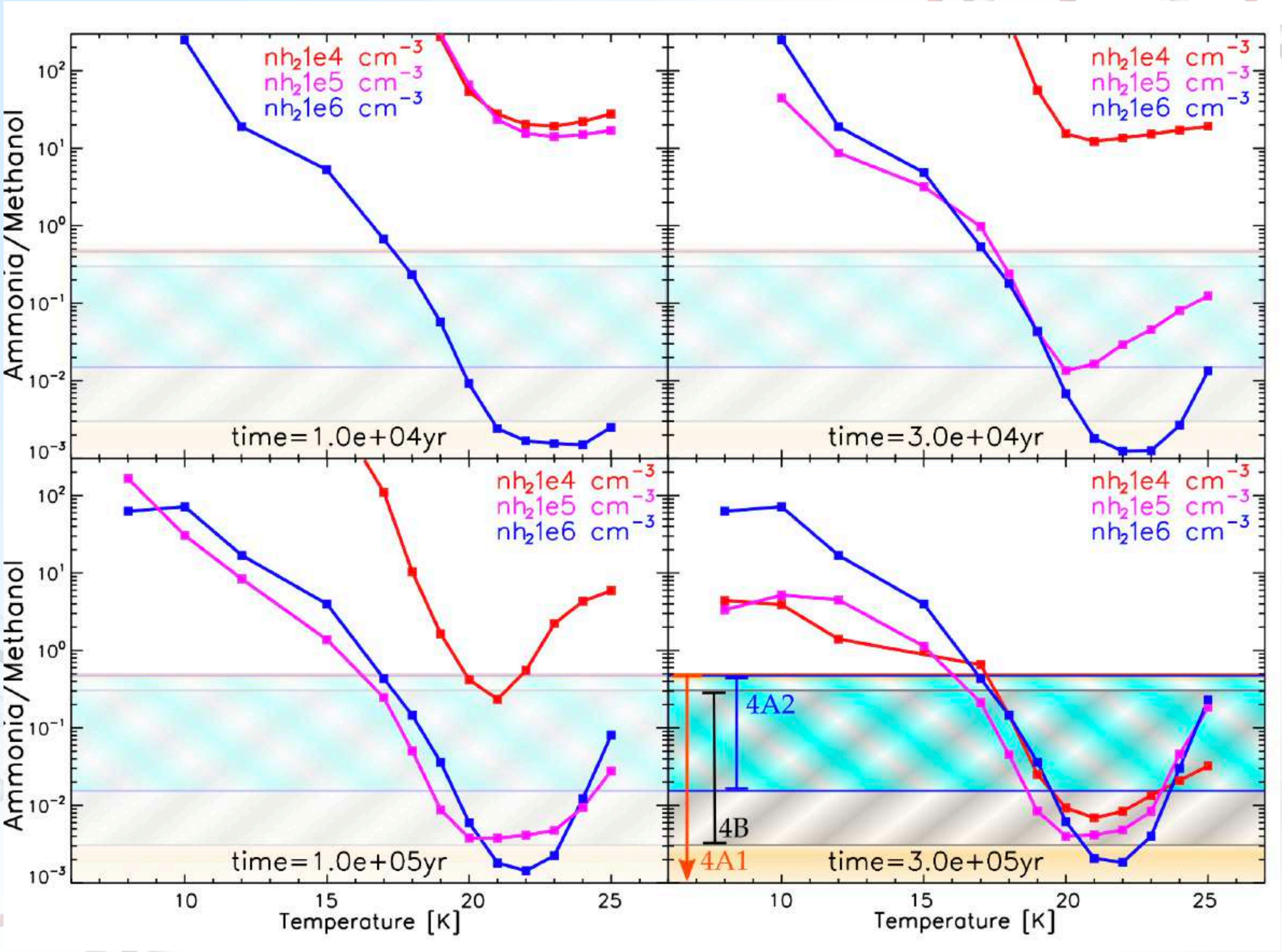




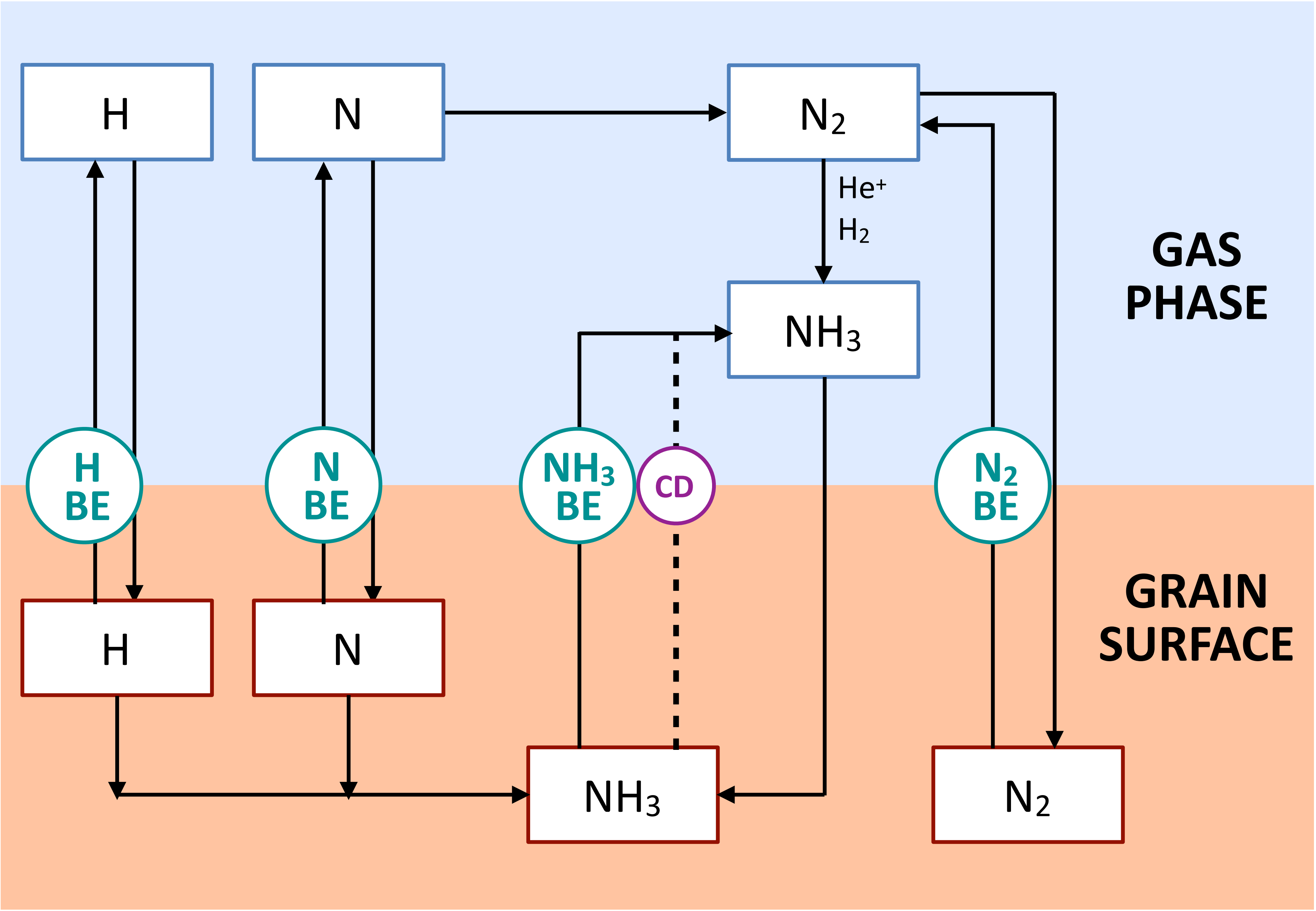
Transition	Frequency[(a)] [GHz]	$E_{up}^{(a)}$ [K]	$\log A_{ij}^{(a)}$
CH_3OH			
3(2,1)-3(1,2) E	24.92871	36	-7.2
4(2,2)-4(1,3) E	24.93347	45	-7.1
2(2,0)-2(1,1) E	24.93438	29	-7.2
5(2,3)-5(1,4) E	24.95908	57	-7.1
6(2,4)-6(1,5) E	25.01812	71	-7.1
7(2,5)-7(1,6) E	25.12487	87	-7.1
8(2,6)-8(1,7) E	25.29442	106	-7.0
9(2,7)-9(1,8) E	25.54140	127	-7.0
10(2,8)-10(1,9) E	25.87827	150	-7.0
11(2,9)-11(1,10) E	26.31312	175	-6.9
NH_3			
3-3	23.87013	124	-6.6
4-4	24.13942	201	-6.5
5-5	24.53299	296	-6.5
6-6	25.05602	409	-6.5
7-7	25.71518	639	-6.4



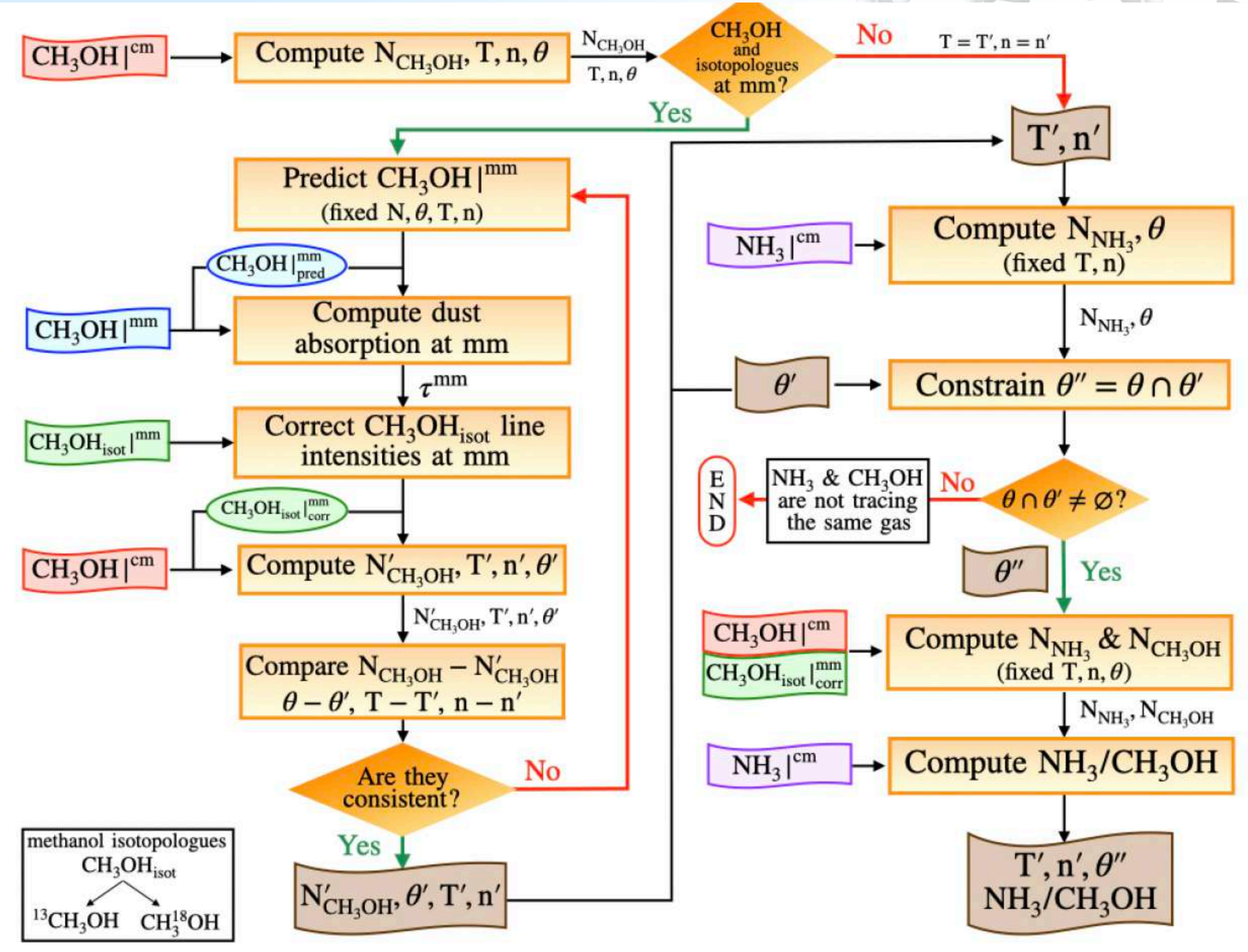




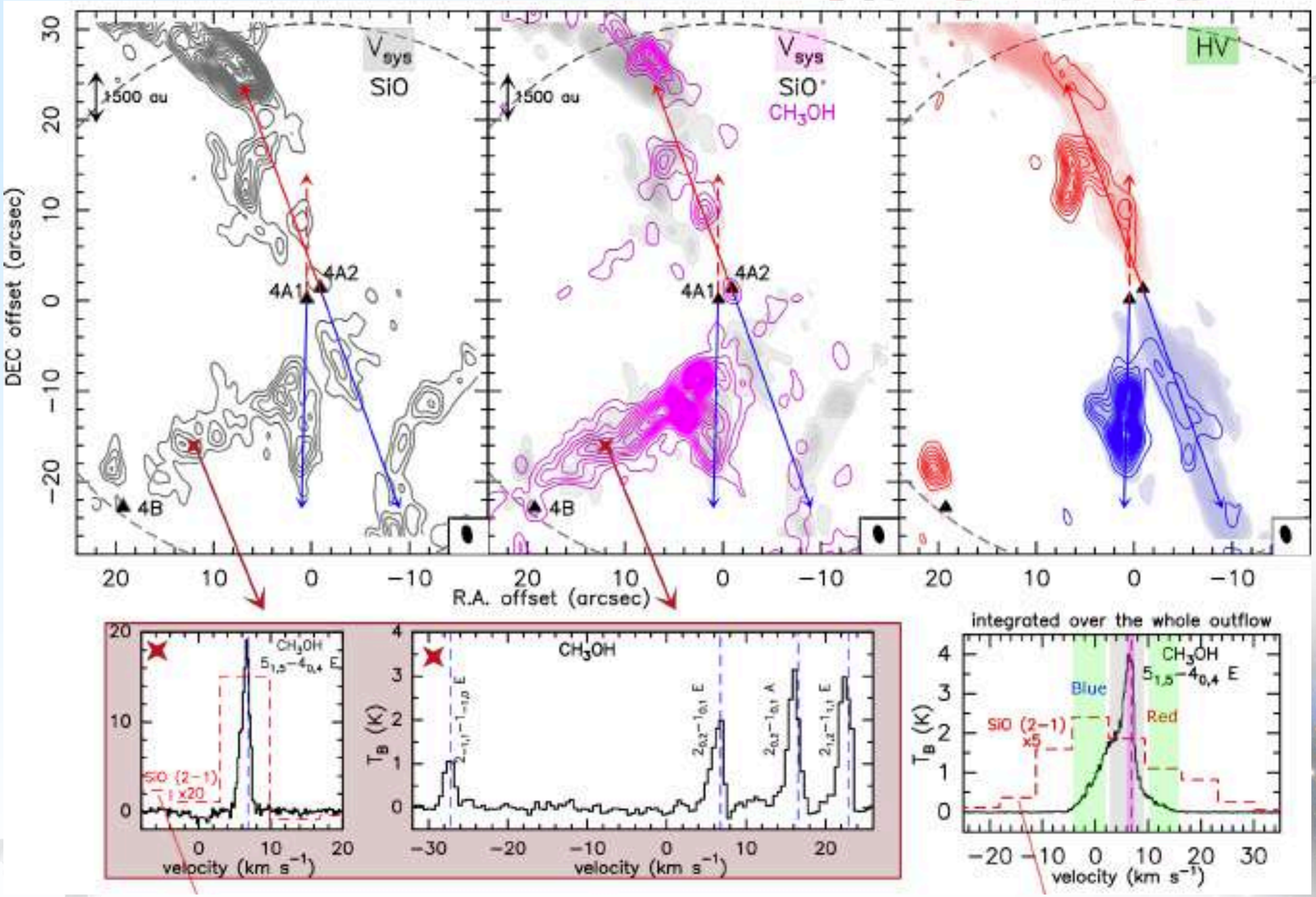
nh2 1e4 cm-3
nh2 1e5 cm-3
nh2 1e6 cm-3
Ammonia/Methanol
time=1.0e+04yr
time=3.0e+04yr
time=1.0e+05yr
time=3.0e+05yr
4A2
4B
4A1
Temperature [K]



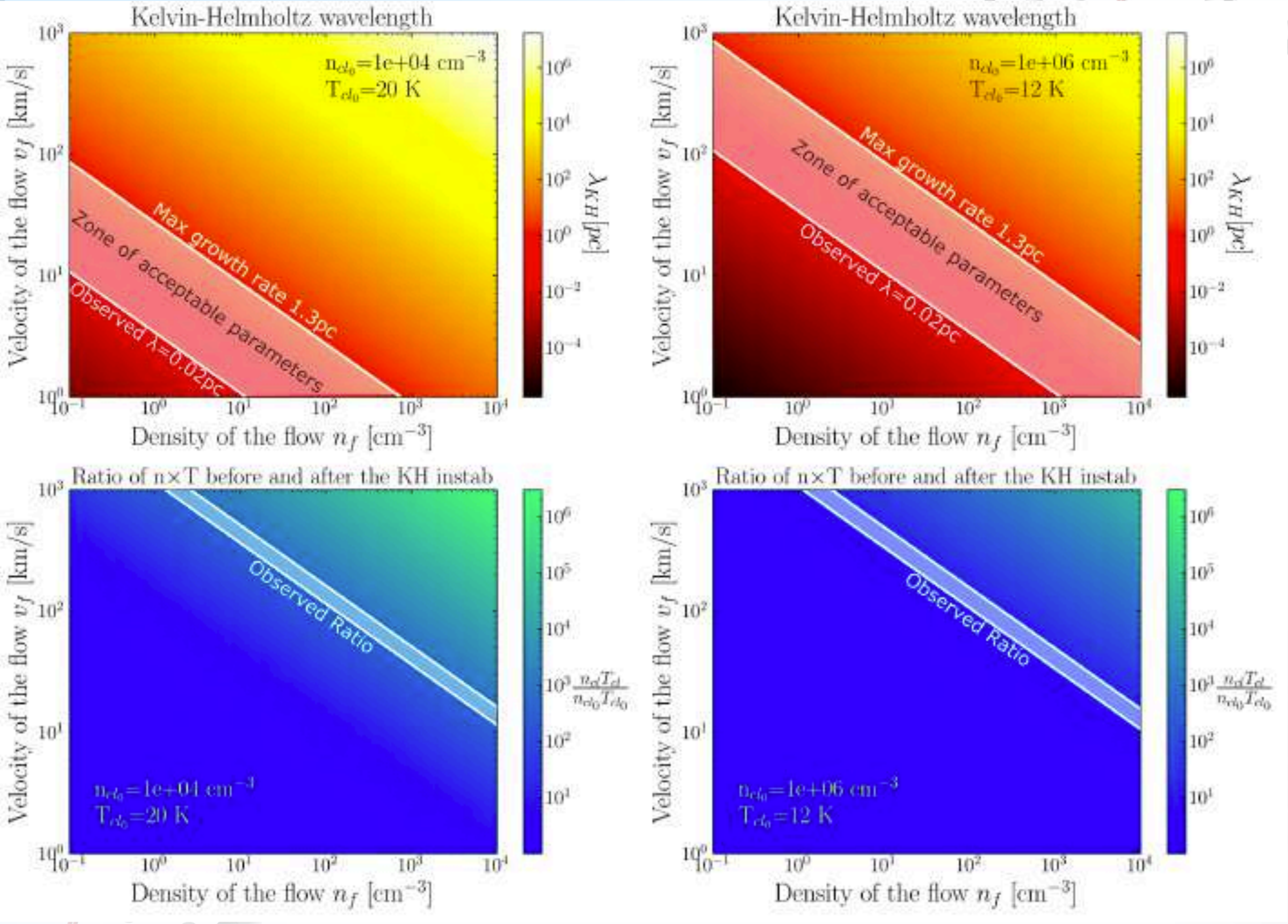
H
N
N_2
He^+
H_2
NH_3
GAS PHASE
H BE
N BE
NH_3 BE
CD
N_2 BE
GRAIN SURFACE
H
N
NH_3
N_2



$CH_3OH|^{cm}$
Compute N_{CH_3OH}, T, n, θ
N_{CH_3OH}
T, n, θ
CH_3OH and isotopologues at mm?
No
T = T′, n = n′
Yes
T′, n′
Predict $CH_3OH|^{mm}$ (fixed N, θ, T, n)
$CH_3OH|^{mm}_{pred}$
$CH_3OH|^{mm}$
Compute dust absorption at mm
τ^{mm}
$CH_3OH_{isot}|^{mm}$
Correct CH_3OH_{isot} line intensities at mm
$CH_3OH_{isot}|^{mm}_{corr}$
$CH_3OH|^{cm}$
Compute N'_{CH_3OH}, T′, n′, θ'
N'_{CH_3OH}, T′, n′, θ'
Compare $N_{CH_3OH} - N'_{CH_3OH}$ $\theta - \theta'$, T − T′, n − n′
Are they consistent?
No
Yes
N'_{CH_3OH}, θ', T′, n′
methanol isotopologues
CH_3OH_{isot}
$^{13}CH_3OH$ $CH_3^{18}OH$
$NH_3|^{cm}$
Compute N_{NH_3}, θ (fixed T, n)
N_{NH_3}, θ
θ'
Constrain $\theta'' = \theta \cap \theta'$
E N D
NH_3 & CH_3OH are not tracing the same gas
No
$\theta \cap \theta' \neq \varnothing$?
θ''
Yes
$CH_3OH|^{cm}$
$CH_3OH_{isot}|^{mm}_{corr}$
Compute N_{NH_3} & N_{CH_3OH} (fixed T, n, θ)
N_{NH_3}, N_{CH_3OH}
$NH_3|^{cm}$
Compute NH_3/CH_3OH
T′, n′, θ'' NH_3/CH_3OH



V_sys
SiO
1500 au
V_sys
SiO
CH3OH
HV
4A1
4A2
4B
DEC offset (arcsec)
R.A. offset (arcsec)
CH3OH
SiO (2-1) x20
velocity (km s-1)
CH3OH
TB (K)
velocity (km s-1)
integrated over the whole outflow
CH3OH
Blue
Red
SiO (2-1) x5
TB (K)
velocity (km s-1)

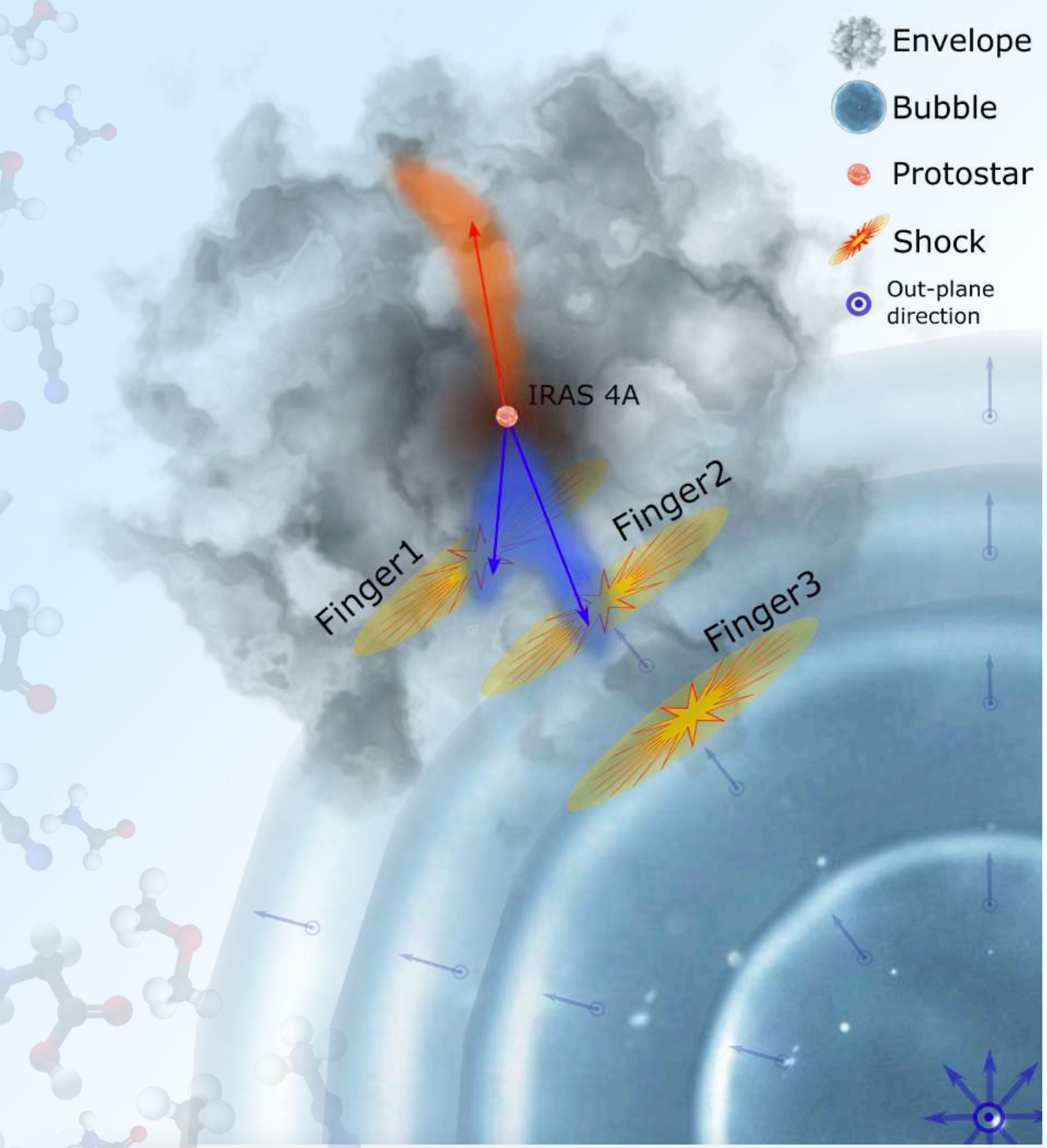


$$\lambda_{KH} = \frac{2\pi}{g_{cl}} v_f^2 \frac{n_f}{n_{cl}}$$

$$g_{cl} = \pi \; G\mu \; m_H \; N_H$$

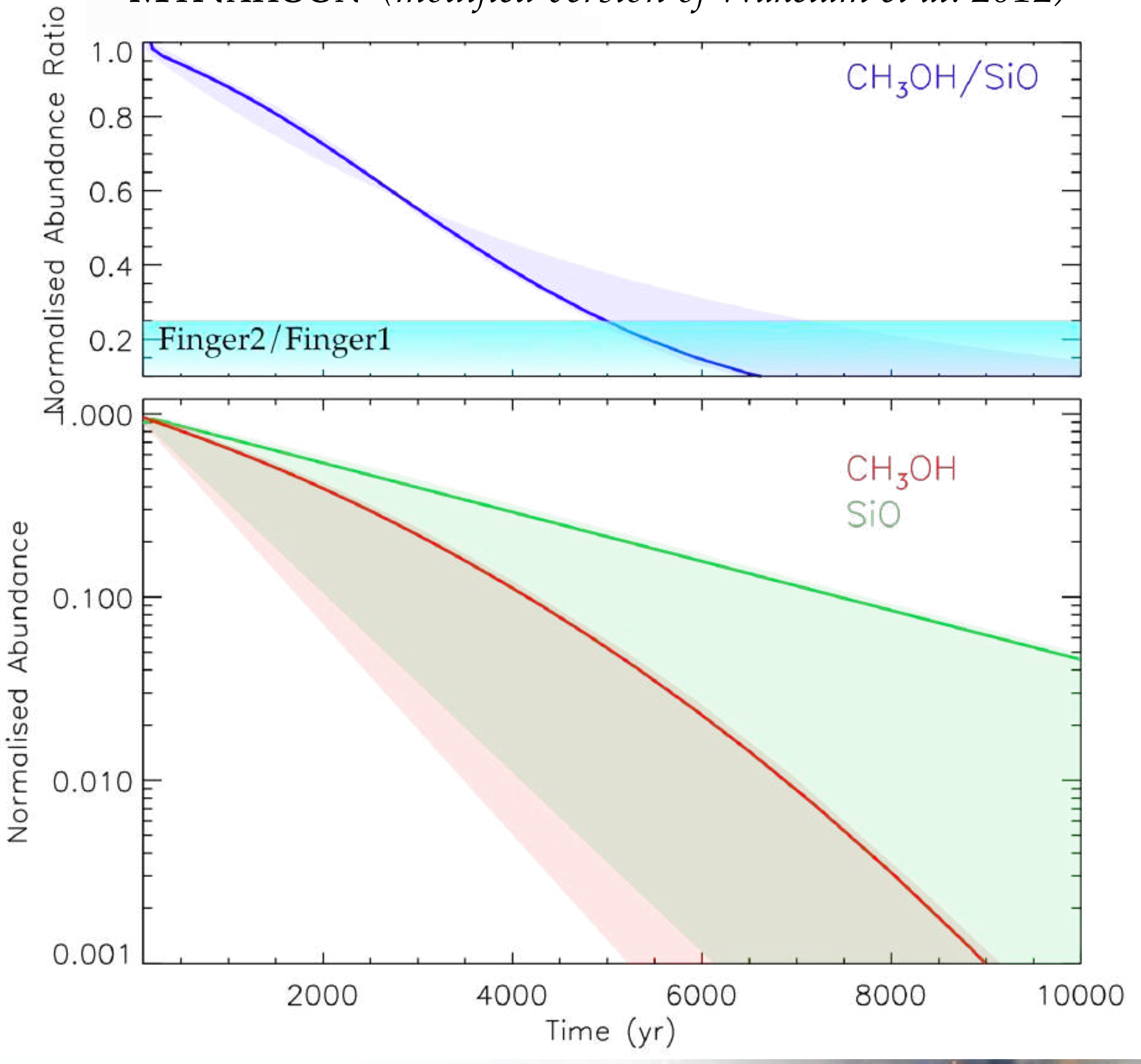
$$\frac{n_{cl}T_{cl}}{n_{cl_0}T_{cl_0}} = \frac{m_H n_f v_f^2}{2 n_{cl_0} k_B T_{cl_0}} + 1$$

Finger1 is younger than Finger2 by at least 5000 yr



Astrochemical model (gas-phase)

MyNahoon *(modified version of Wakelam et al. 2012)*



The fingers trace a train of shocks due to an expanding bubble coming from south-west