The chemical history of young protostars combining mm and cm wavelengths

Marta De Simone

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Collaborators: *C. Codella (IT), C. Ceccarelli (IT), B.E. Svoboda (USA), C.J. Chandler (USA), M. Bouvier (NL), S. Yamamoto (JP), N. Sakai (JP), Y.-L. Yang (JP), A. Lopez-Sepulcre (FR), P. Caselli (DE), L. Testi (IT), L. Loinard (MX), H.B. Liu (TW), B. Lefloch (FR), J.E Pineda (DE), E. Bianchi (DE), N. Balucani (IT), A. Rimola (ES), J. Enrique-Romero (NL), A. Miotello (DE), …*

Fifth Workshop on Millimetre Astronomy in Italy

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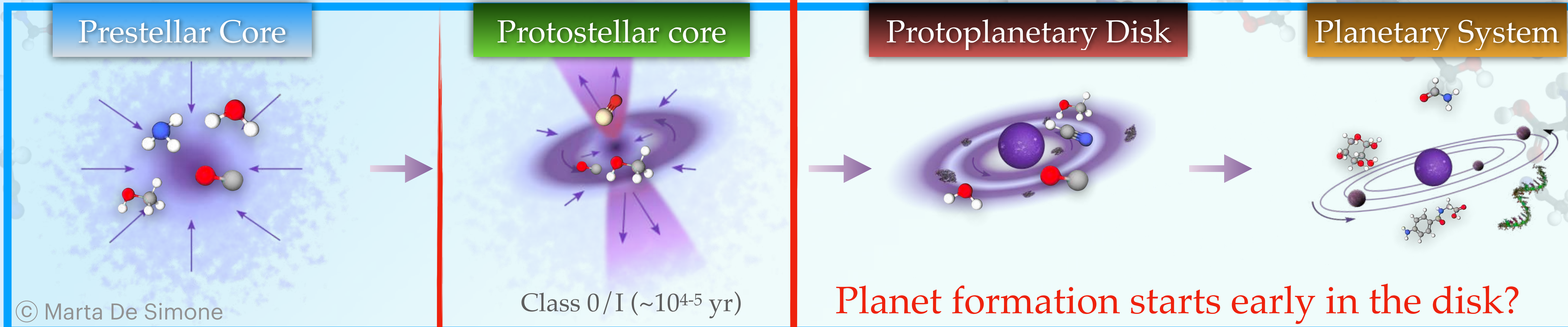
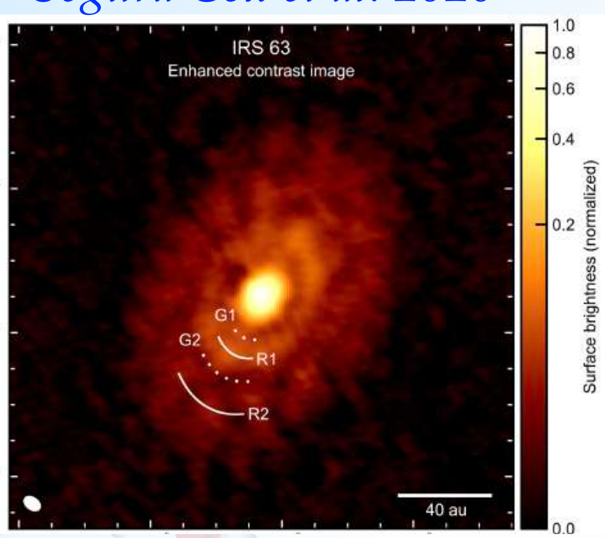
Solar-type protostellar chemistry:

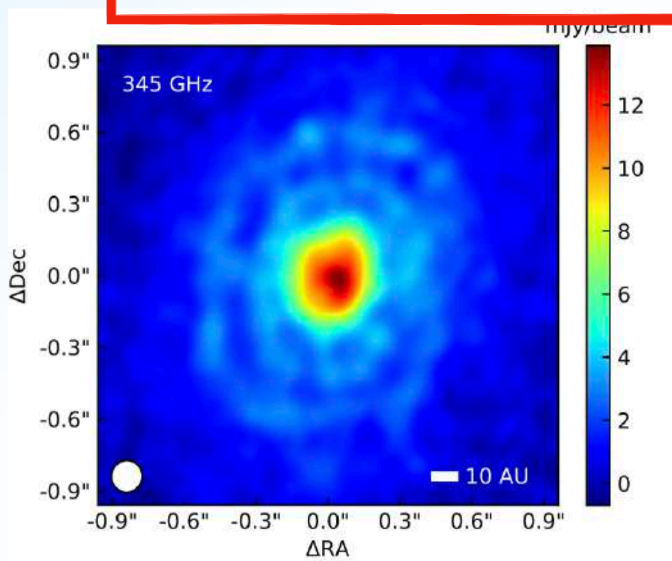
(e.g. Andre et al. 2000, Caselli & Ceccarelli 2012, Öberg & Bergin 2021)



Planet formation starts early in the disk?

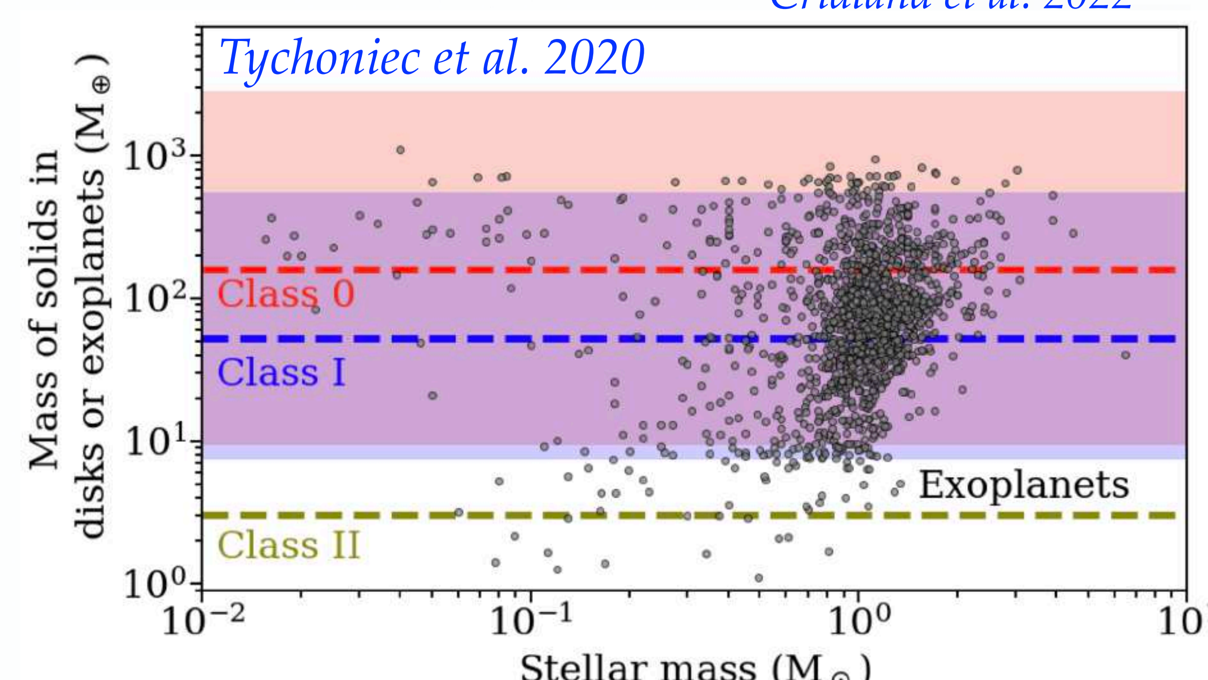
Segura Cox et al. 2020





Sheehan et al. 2018,

Cridland et al. 2022

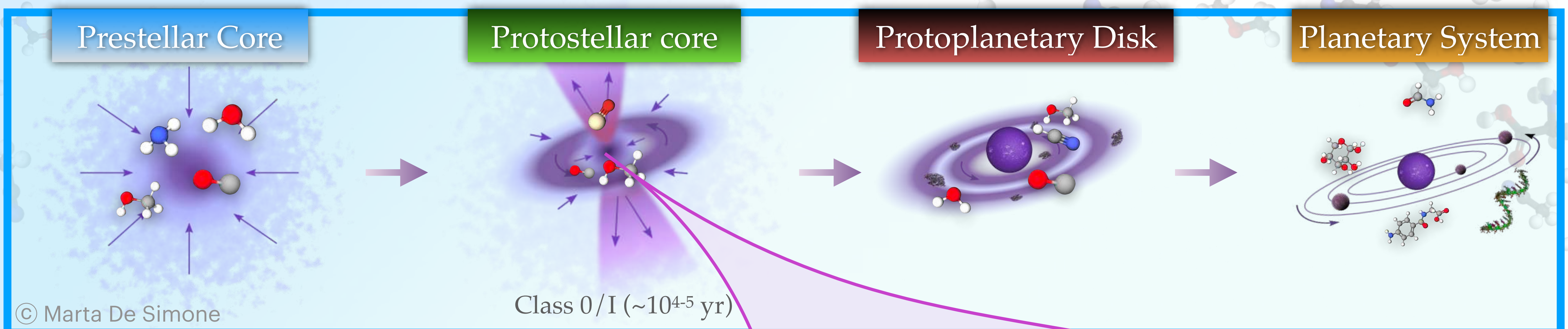


Harsono et al. 2018; Podio et al. 2020, Manara et al. 2018; Sanchis et al. 2020

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

Protostellar chemical nature

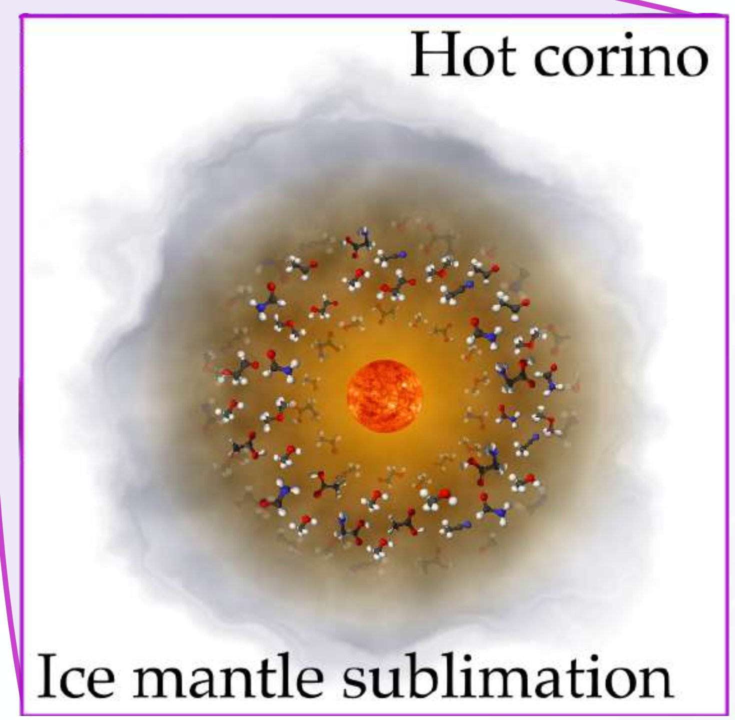
(e.g. Andre et al. 2000, Caselli & Ceccarelli 2012, Öberg & Bergin 2021)



Protostars are far to be fully chemically characterised

Cazaux et al. 2003, Jörgensen et al. 2016, Öberg et al. 2014, Imai et al. 2016, Jorgensen et al. 2016, Coutens et al. 2016, Lee et al. 2017b, De Simone et al. 2017, Oya et al. 2017, Marcelino et al. 2018, Ospina-Zamudio et al. 2018, Manigand et al. 2020, …

always studied at mm wavelengths
(where iCOMs emission is bright)



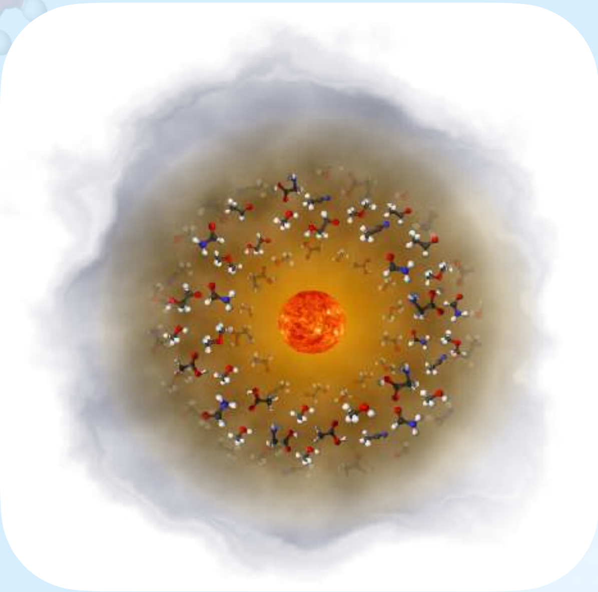
Compact (<100 au), hot (>100 K), dense (>10^7 cm^{-3}) region enriched in iCOMs*

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)

Hot Corinos:
rich chemistry in young Solar-type protostars



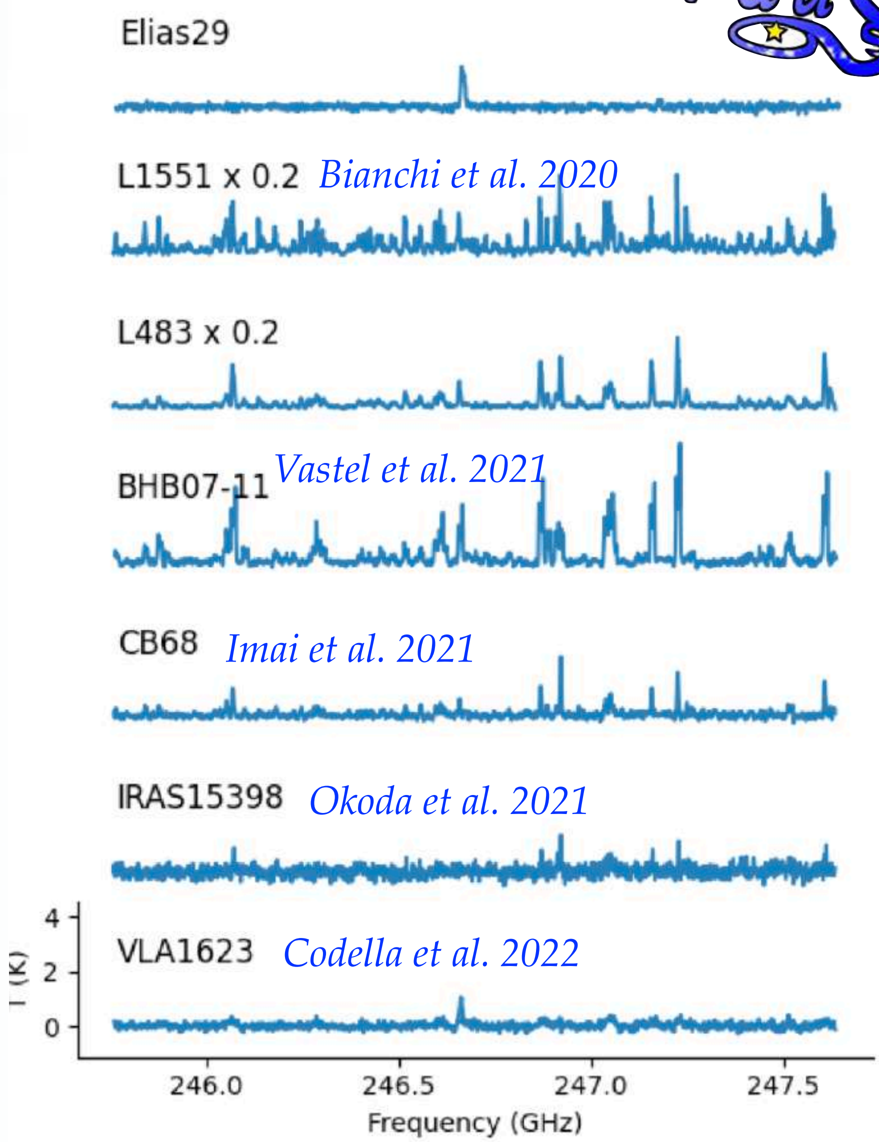
- Not every protostar possesses a hot corino region
- Protostellar systems show different mm molecular spectra

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, …)

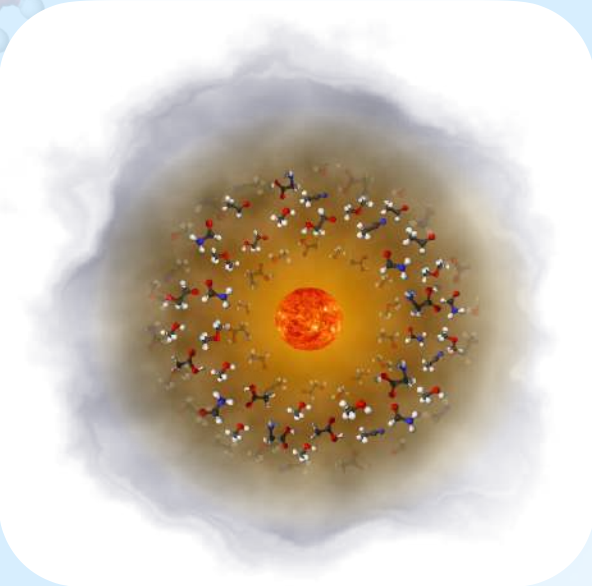
Hot Corinos
Rich in organics
(e.g., CH_3OH, CH_3OCH_3, NH_2CHO, etc.)
Ceccarelli 2004, Ceccarelli et al. 2007

WCCC
(Warm Carbon Chain Chemistry)
Rich in carbon chains
(e.g., C_3H_2, C_xH_x, HC_xN, etc.)
Sakai et al. 2013

Codella et al. 2021



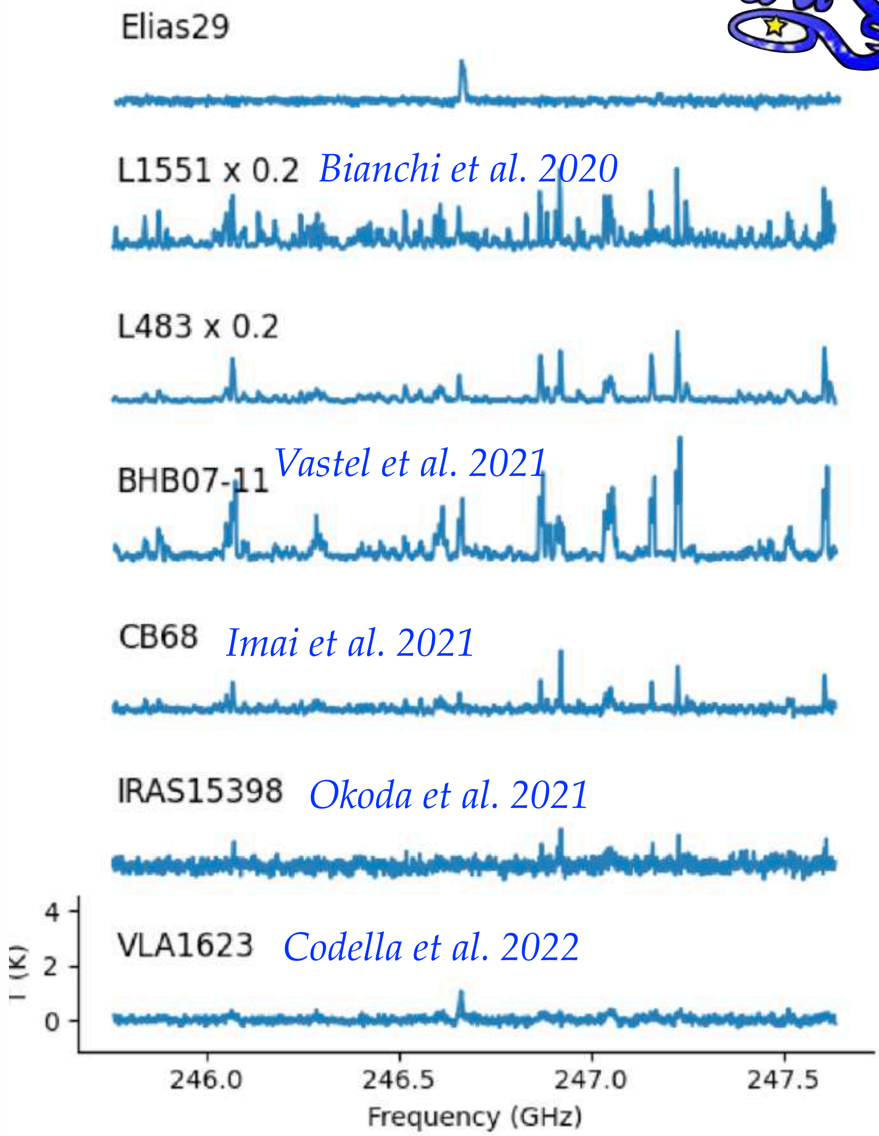
Hot Corinos:
rich chemistry in young Solar-type protostars



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

Why so few Hot Corinos?
Why so different?

Codella et al. 2021



Several possibilities:

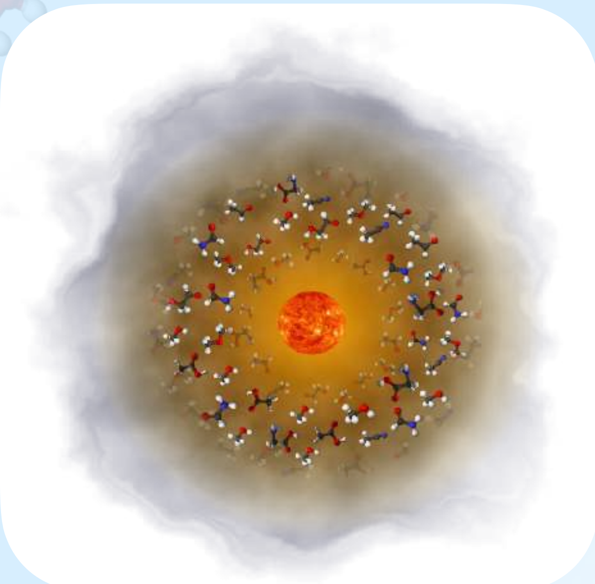
- Observational biases
- presence of small scale structures

(See also Aikawa et al. 2020, Nazari et al. 2022, Van Gelder 2022)

- different grain mantle composition

need for **cm** wavelength observations!!!

Hot Corinos:
rich chemistry in young Solar-type protostars



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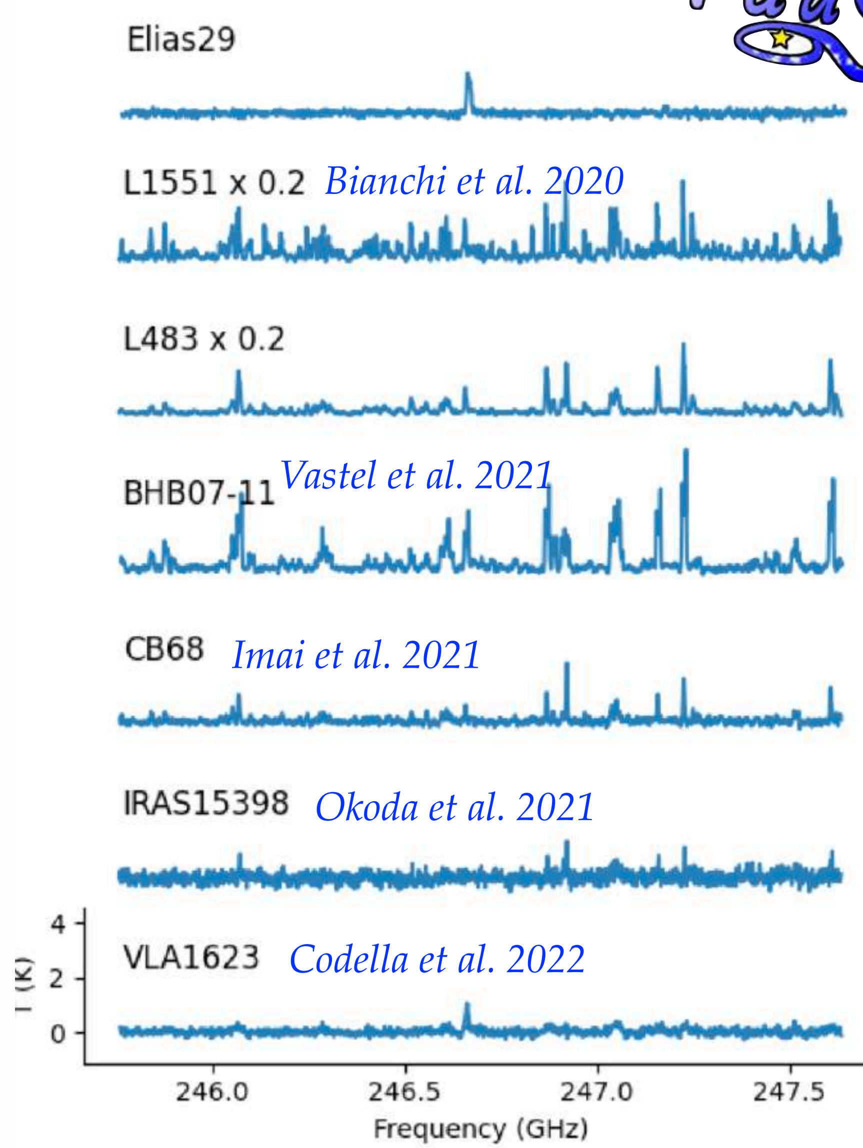
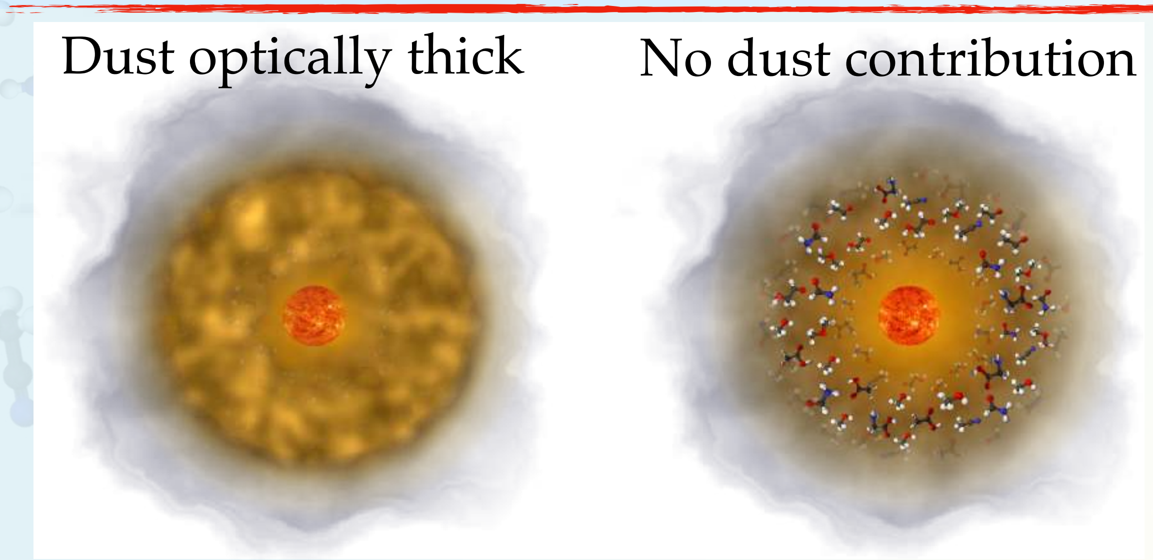
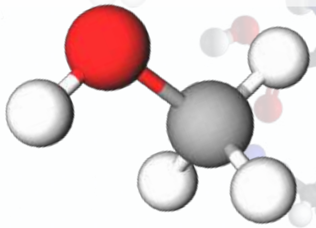


Observational biases: the dust contribution

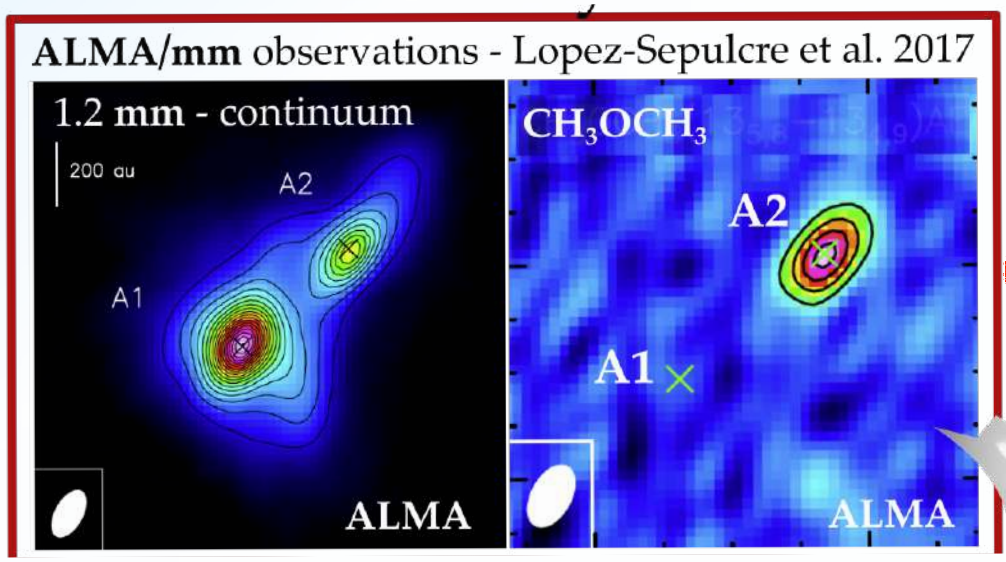


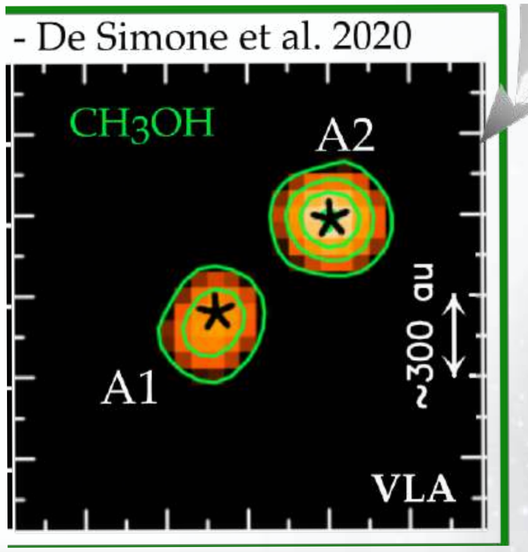
→ dust opacity effects on iCOMs emission
through mm + cm observations of CH_3OH



iCOM abundances at millimeter wavelengths are underestimated

Moving from millimetre to centimetre wavelengths →

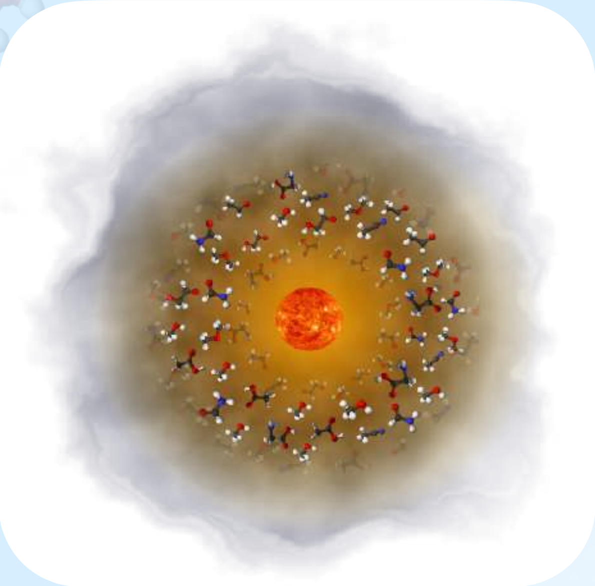




IRAS4A at mm
Hot Corino in one of the two companion

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

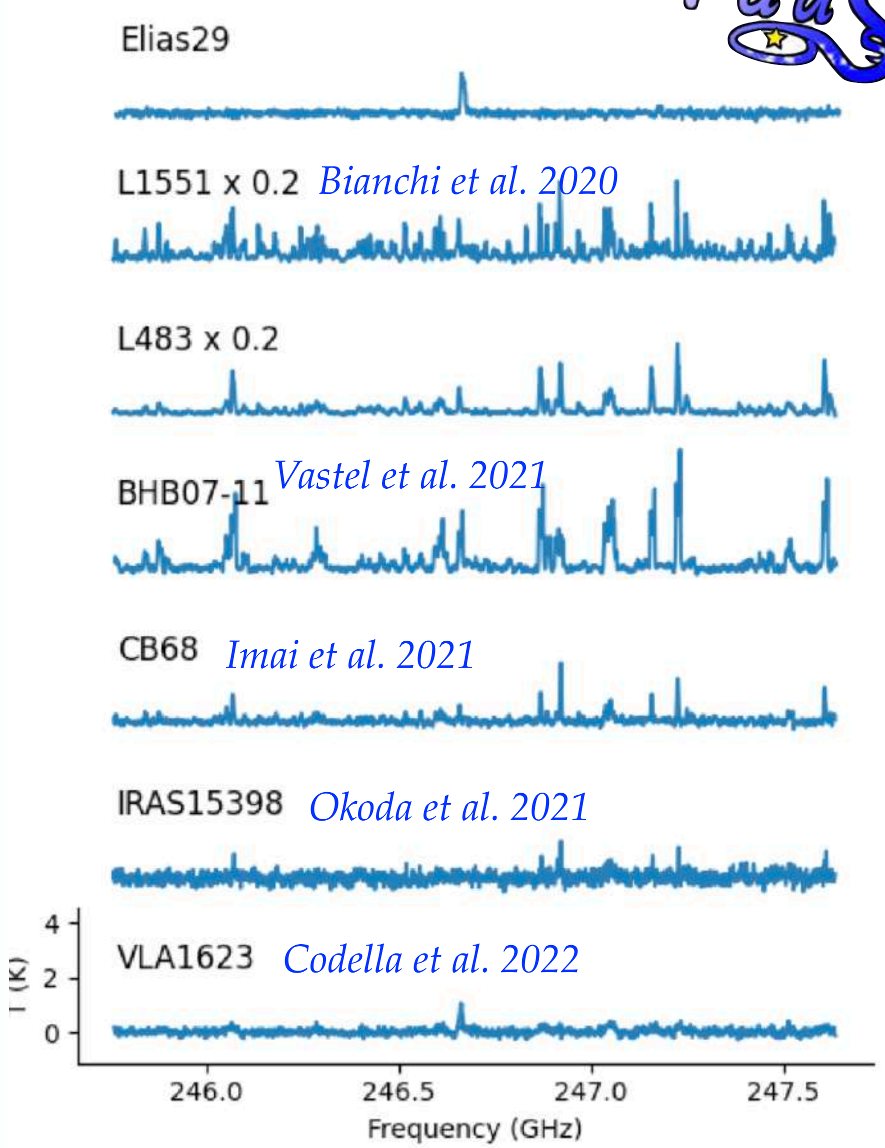
Hot Corinos:
rich chemistry in young Solar-type protostars



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

Why so few Hot Corinos?
Why so different?

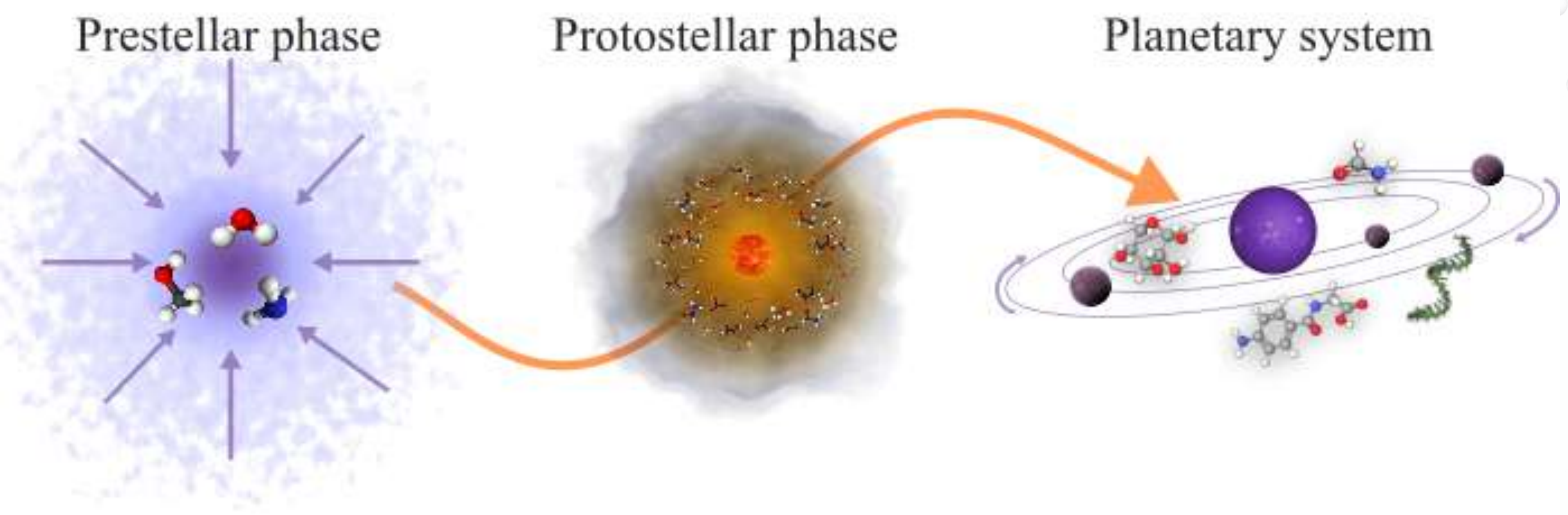
Codella et al. 2021



Several possibilities:

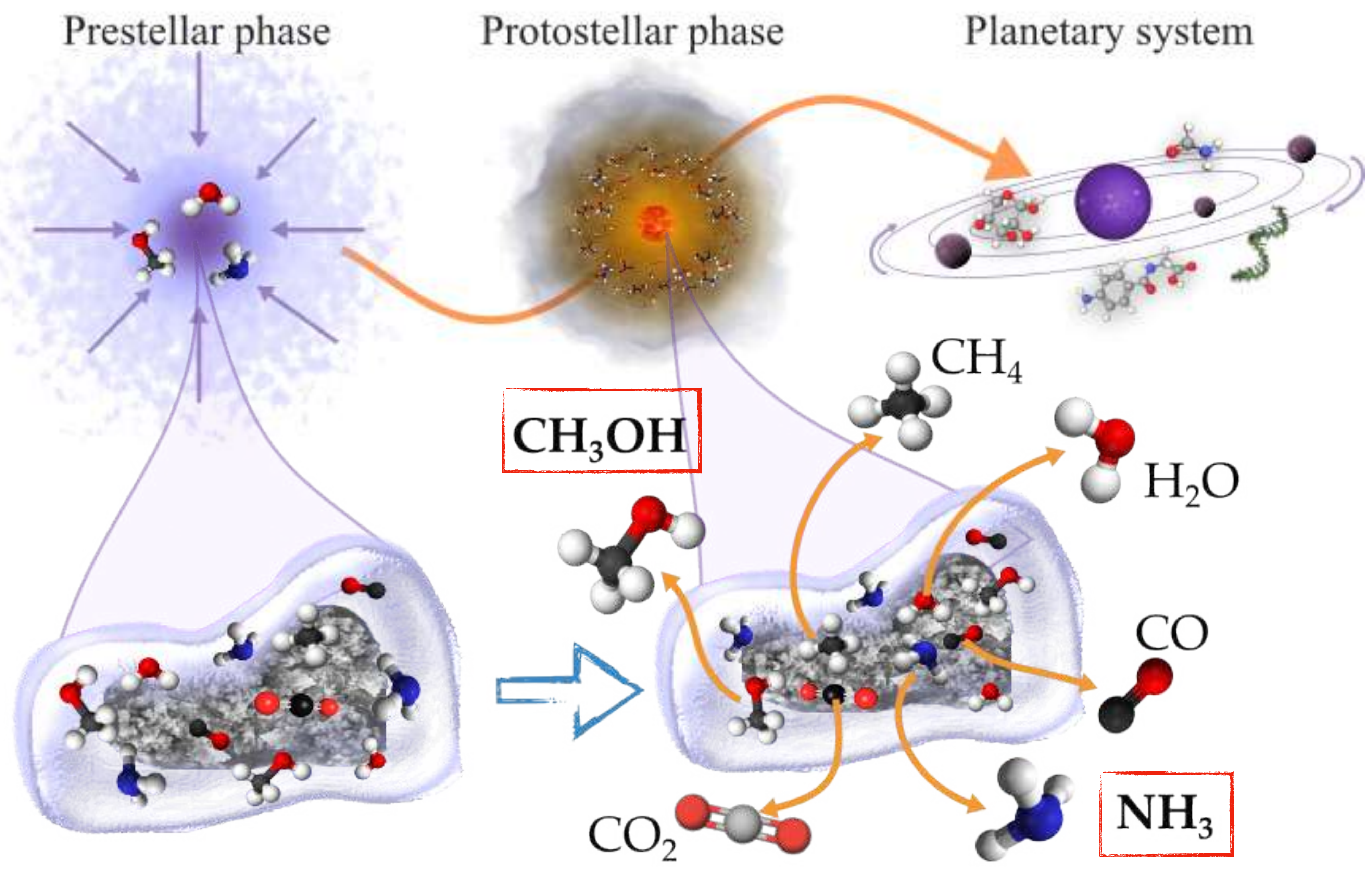
- Observational biases ✔
- presence of small scale structures
  (See also Aikawa et al. 2020, Nazari et al. 2022, Van Gelder 2022)
- different grain mantle composition

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



Direct observations of the ice mantle composition is challenging!

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



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

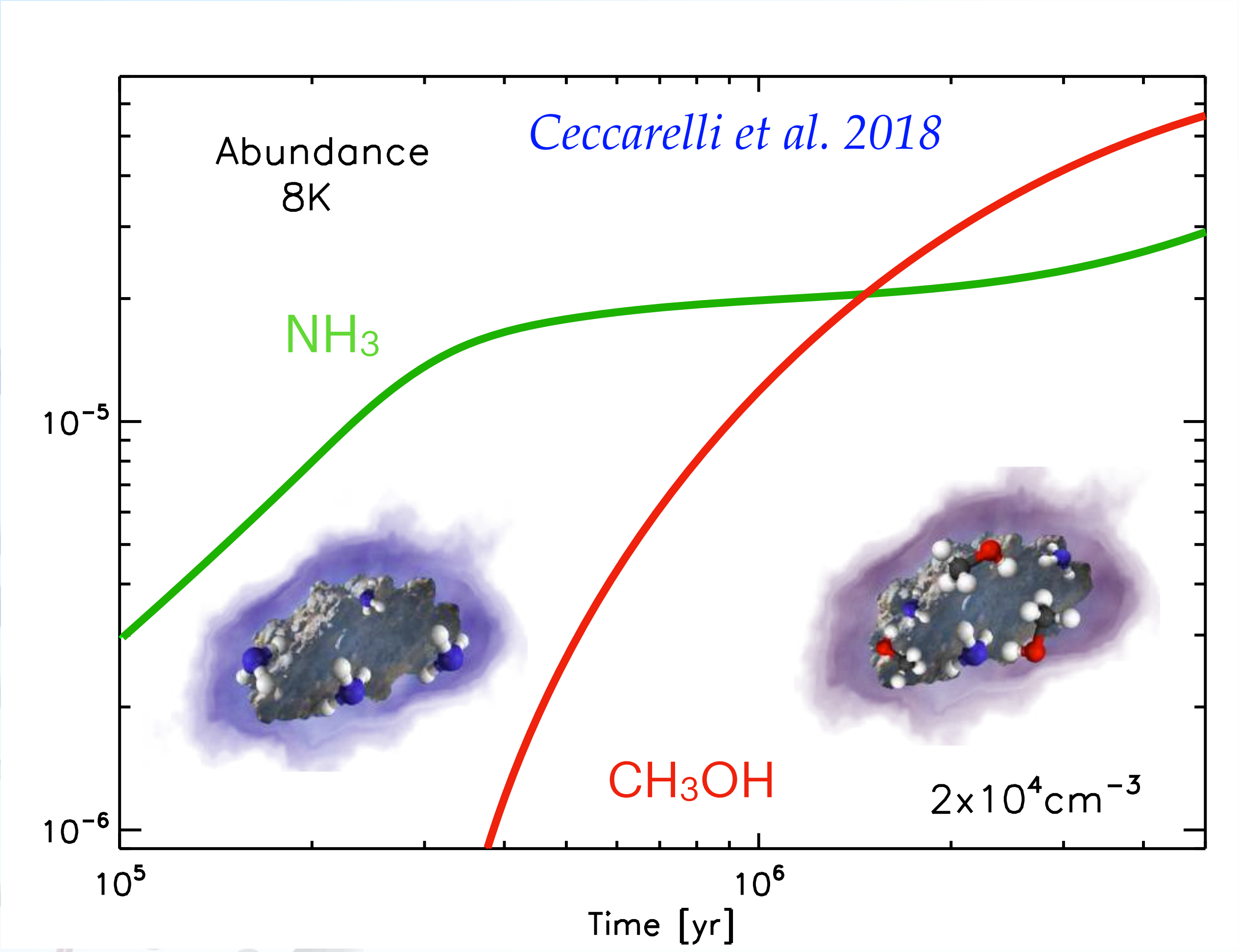
Cm range → VLA NRAO

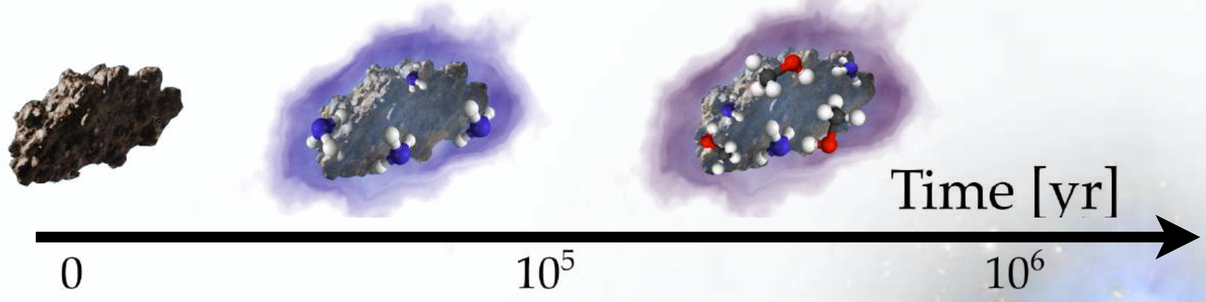
Well known formation paths
(Watanabe & Kouchi 2002; Rimola et al. 2014; Le Gal et al. 2014; Song & Kästner 2017; Jonusas et al. 2020, Tinacci et al. 2022, Ferrero et al. 2023)

→

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

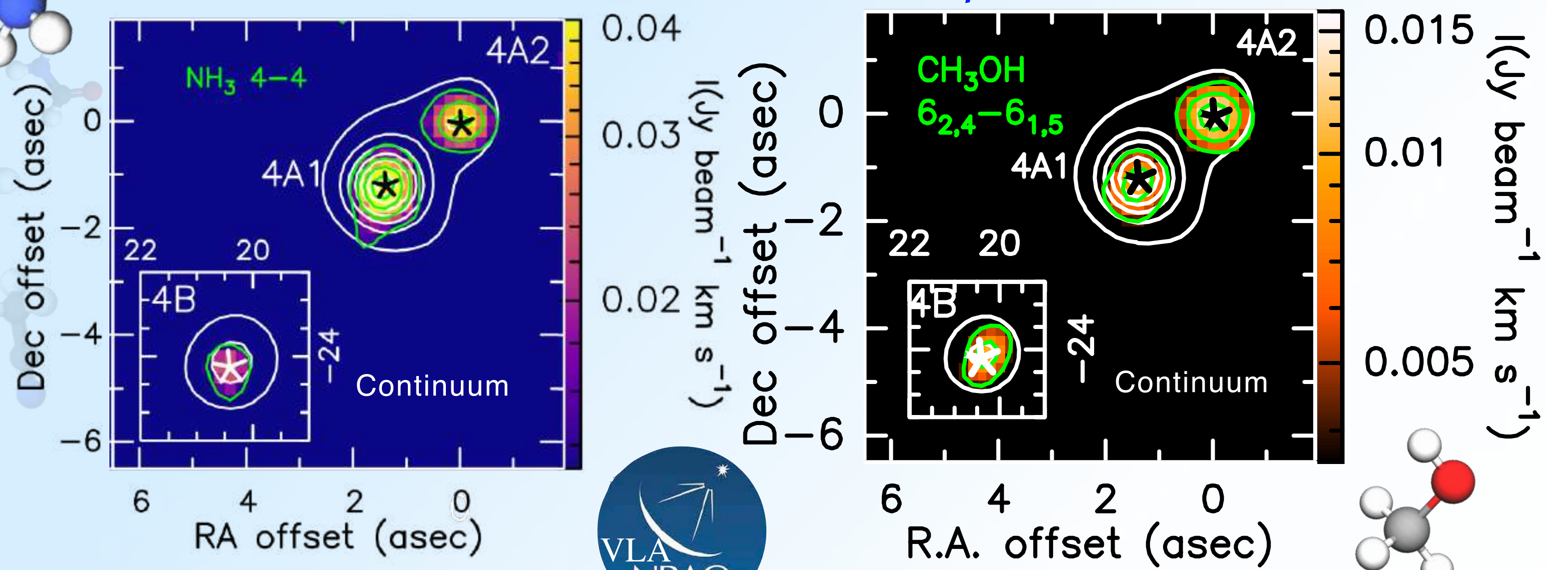




e.g, an old grain mantle would likely be enriched in CH_3OH

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

De Simone et al. 2022, ApJL



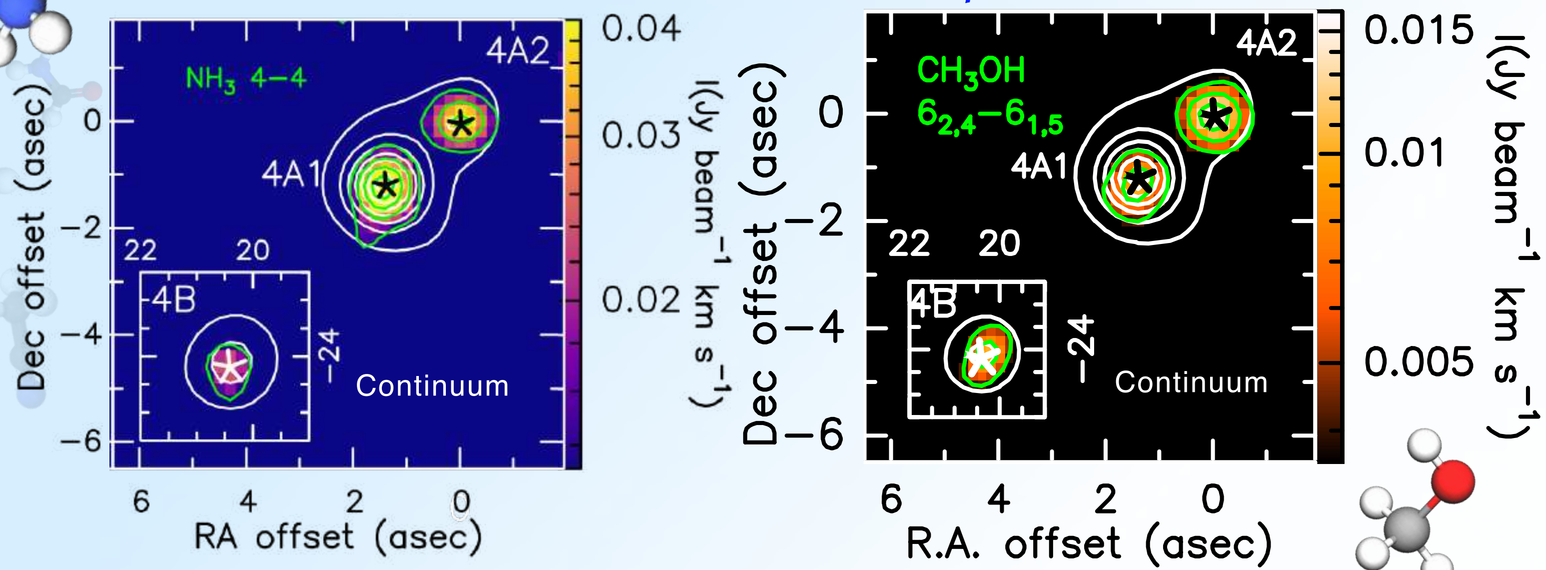
$\frac{NH_3}{CH_3OH}$ Abundance ratio *(non-LTE LVG):*		
IRAS 4A1	**IRAS 4A2**	**IRAS 4B**
< 0.5	0.015 – 0.5	0.003 – 0.3

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 case of IRAS 4A

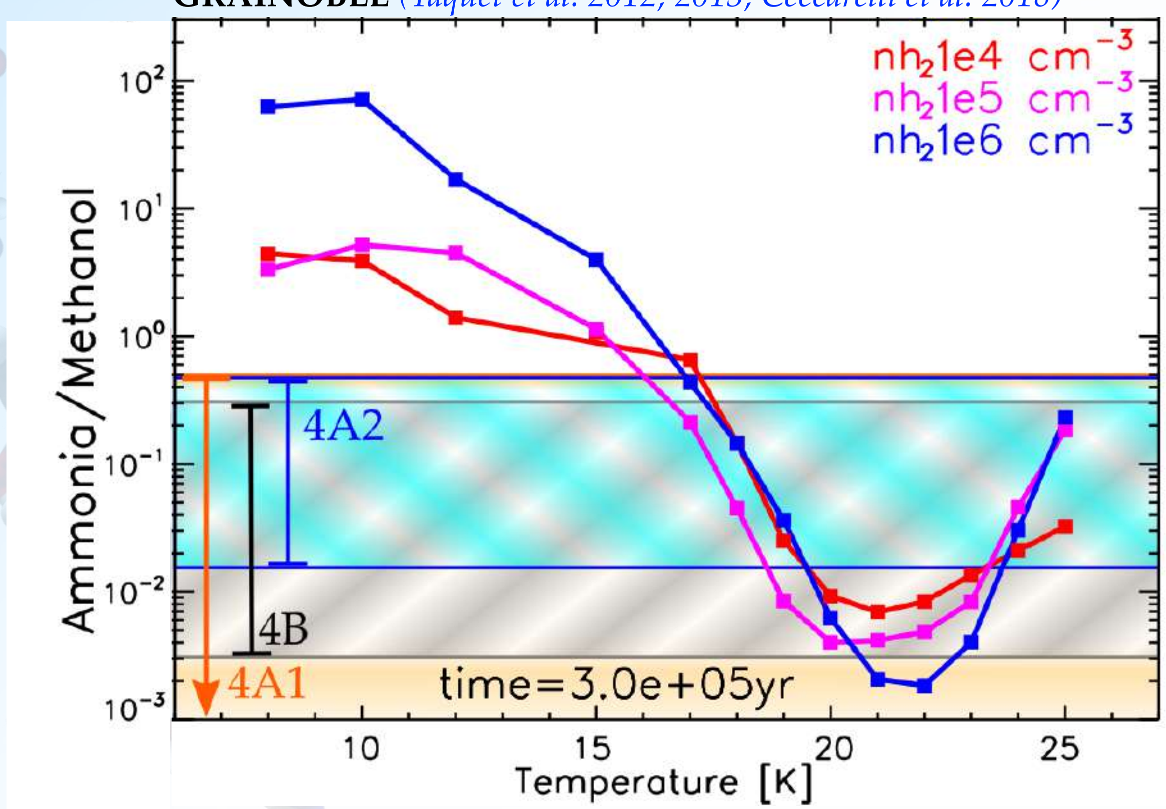
De Simone et al. 2022, ApJL



$\frac{NH_3}{CH_3OH}$	Abundance ratio *(non-LTE LVG):*	
IRAS 4A1	IRAS 4A2	IRAS 4B
< 0.5	0.015 – 0.5	0.003 – 0.3

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!

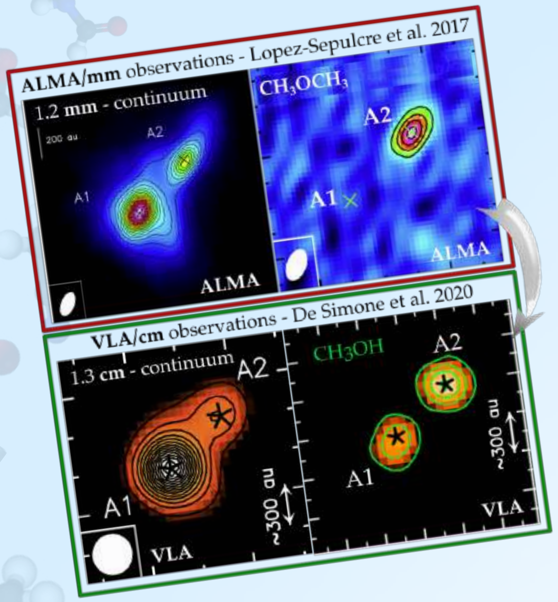
Typical of the less dense material in NGC 1333 south

Zari et al. 2016; Zhang et al. 2022

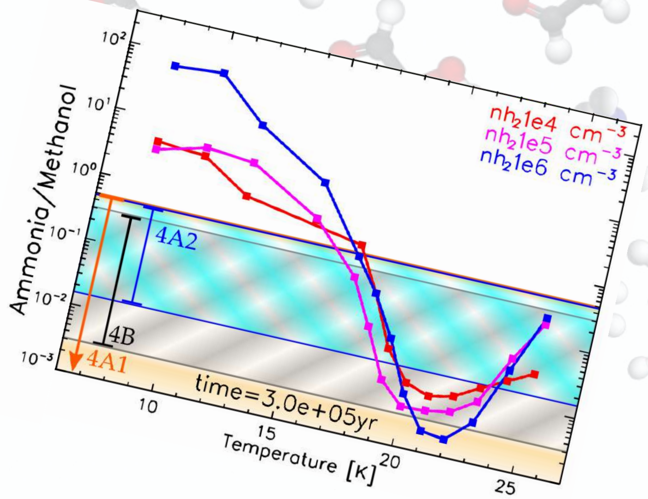
Premature collapse!

Take home messages
Looking to the future…

Cm + mm observations are crucial for the correct study of hot corinos



We constrained the **chemical** and **dynamical** history of the IRAS 4 protostars without being biased by dust opacity effects



What next?

- **Multi-wavelength approach** (mm + cm and IR): unveil the hot corinos nature with a strong multiline analysis
- **Surveys** at high sensitivity and angular resolution: observe iCOMs less abundant than methanol at < 10 au in different sources in the same/different regions

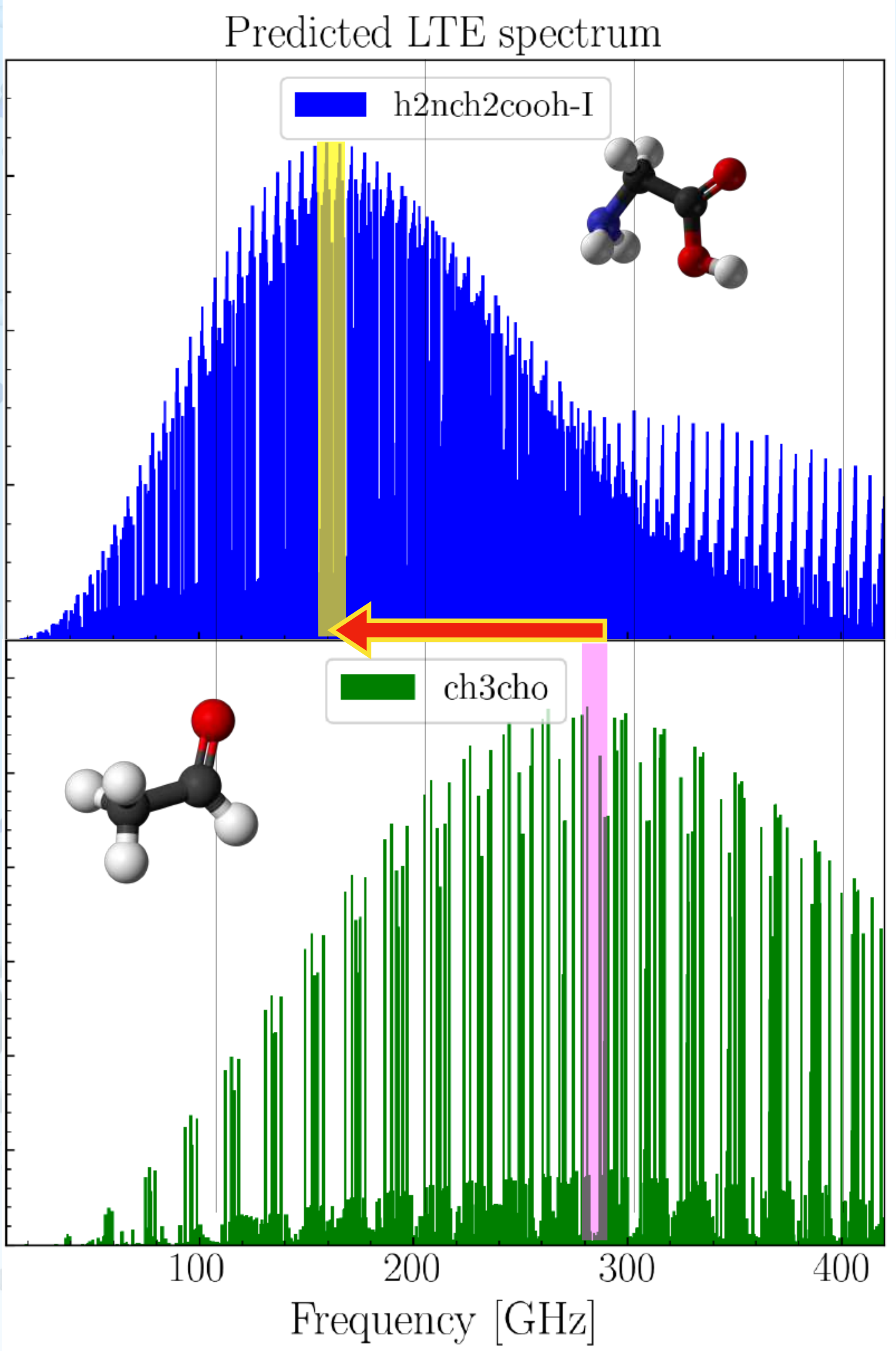
ALMA
BAND 1
35-50 GHz

ngvla
SKA
SQUARE KILOMETRE ARRAY
Cm -facilities

IR -facilities

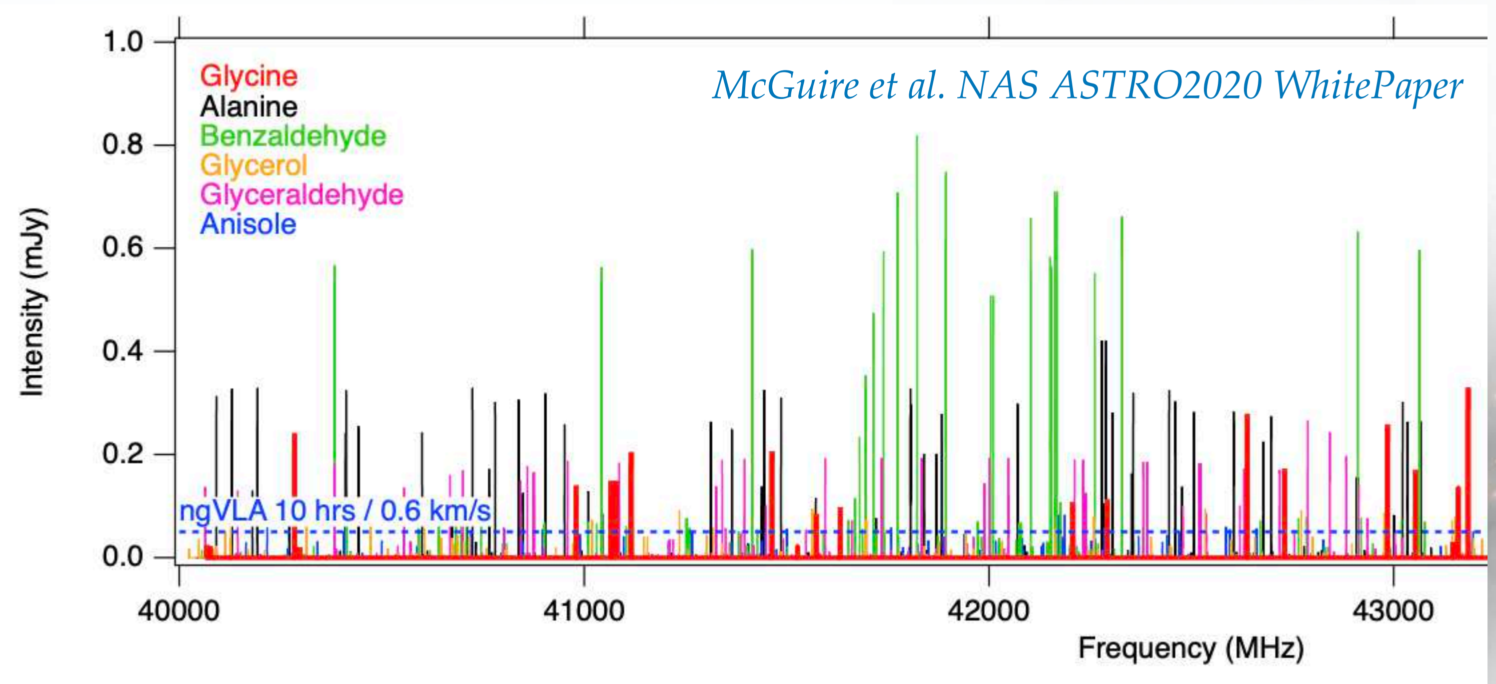
Full coverage of the entire sky, large frequency coverage

Multiwavelength approach
centimiter + millimeter



More complex is the species, at much lower frequency is its emission peak

cm	- No dust absorption - Complex species in less crowded spectra - Mantle history (with NH_3 and CH_3OH)
mm	- Bright simple species + deuterated
cm+mm	- Correct dust absorption factor - Complete chemical census - Strong multiline analysis



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Thank you

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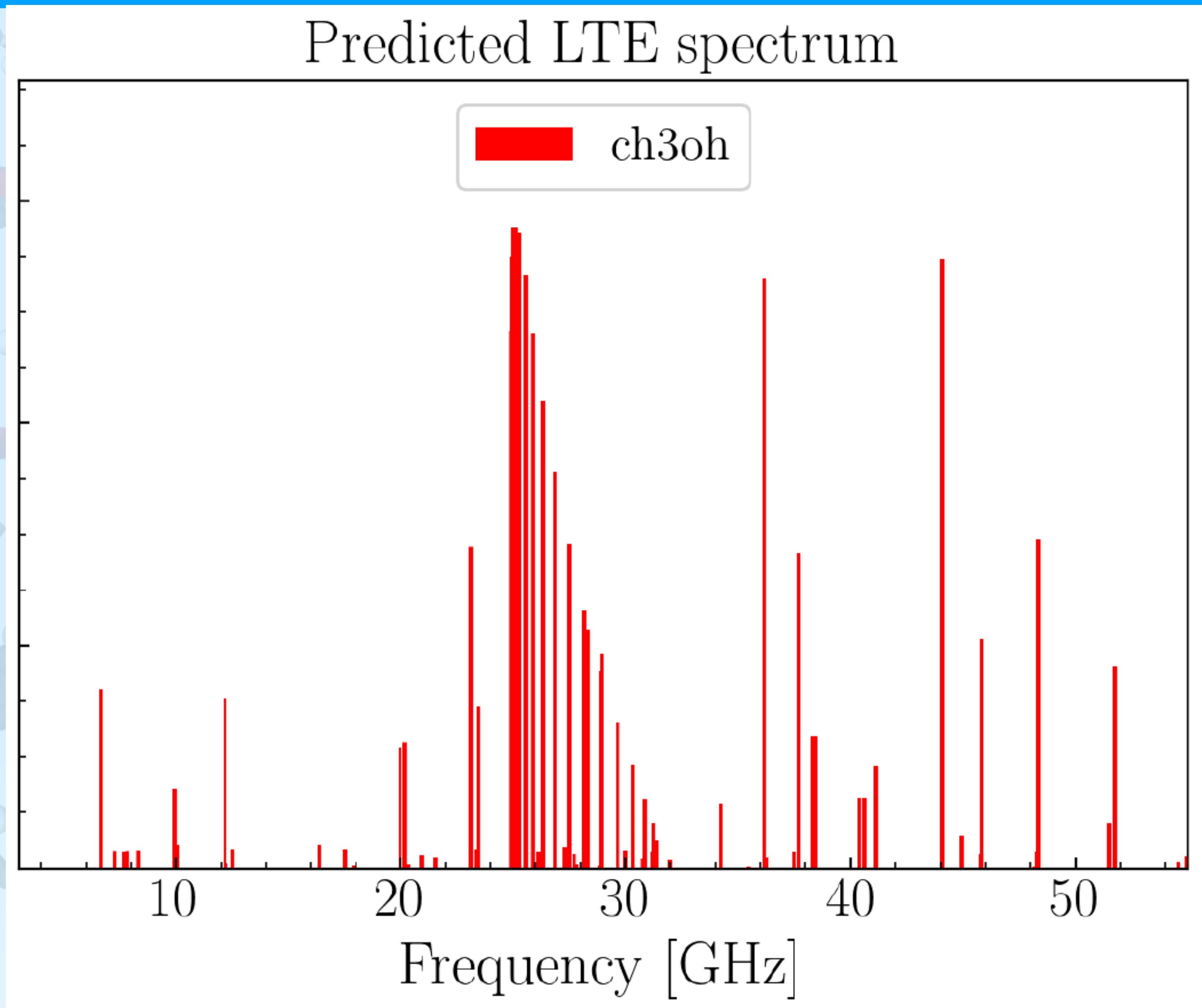
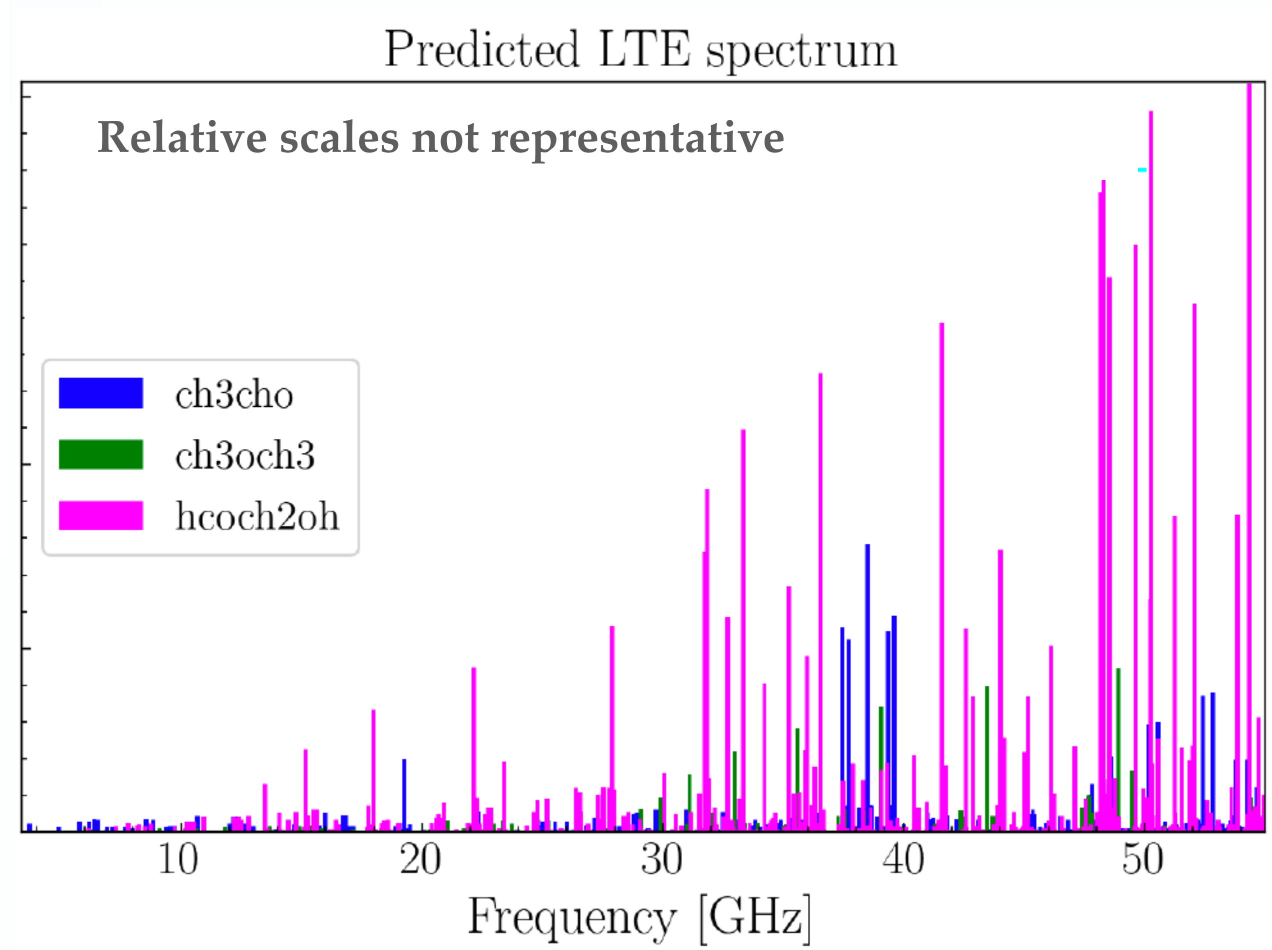
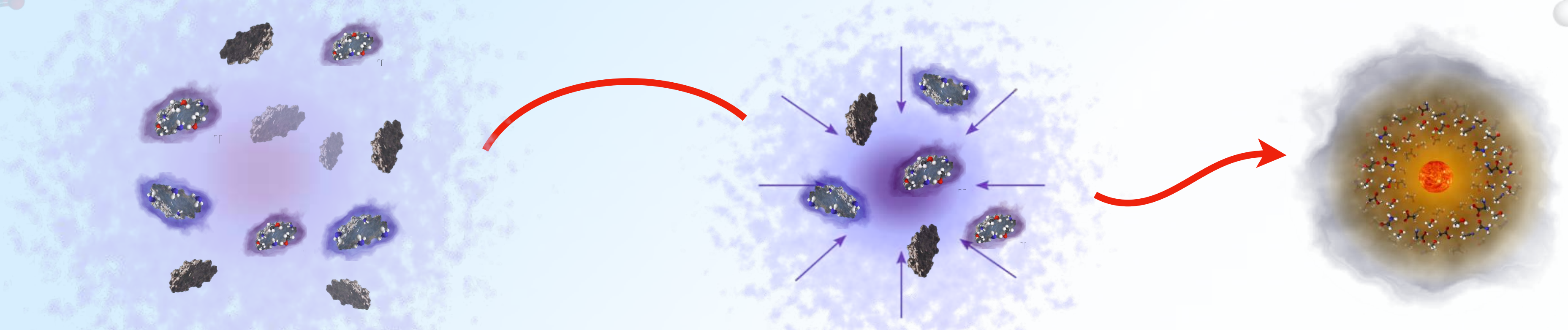
Predicted spectrum of some iCOMs at 5 - 50 GHz





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

Typical scenario:

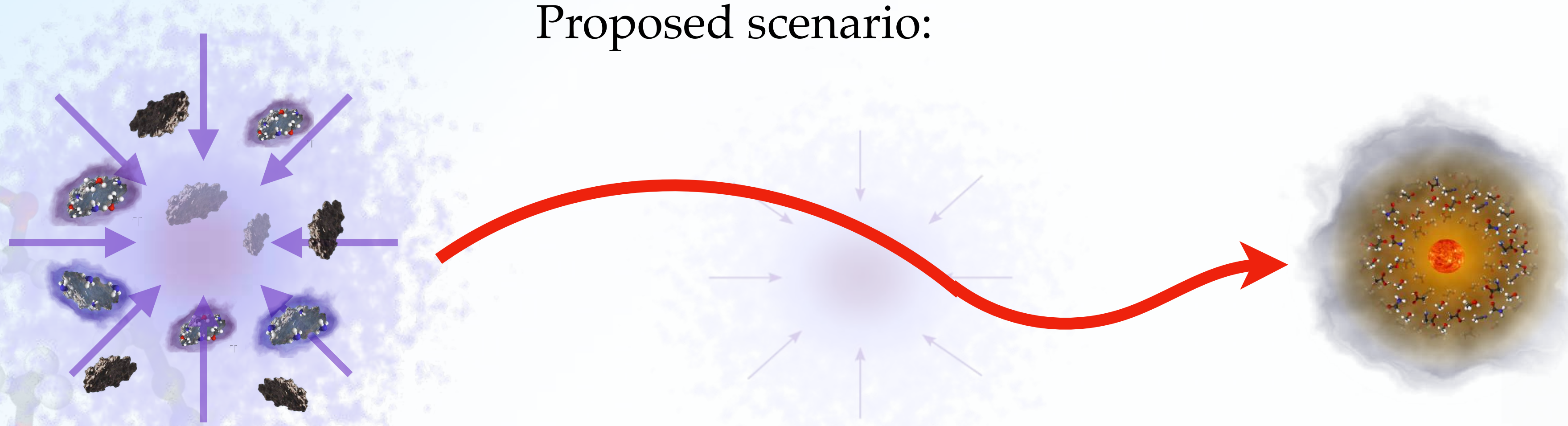


Warm ~ 17 K
Less dense ~10^4 cm^{-3}

Cold ~ 8 K
Dense ~10^6 cm^{-3}

Hot ~100 K
More dense ~10^7 cm^{-3}

Proposed scenario:



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

External Triggers?

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

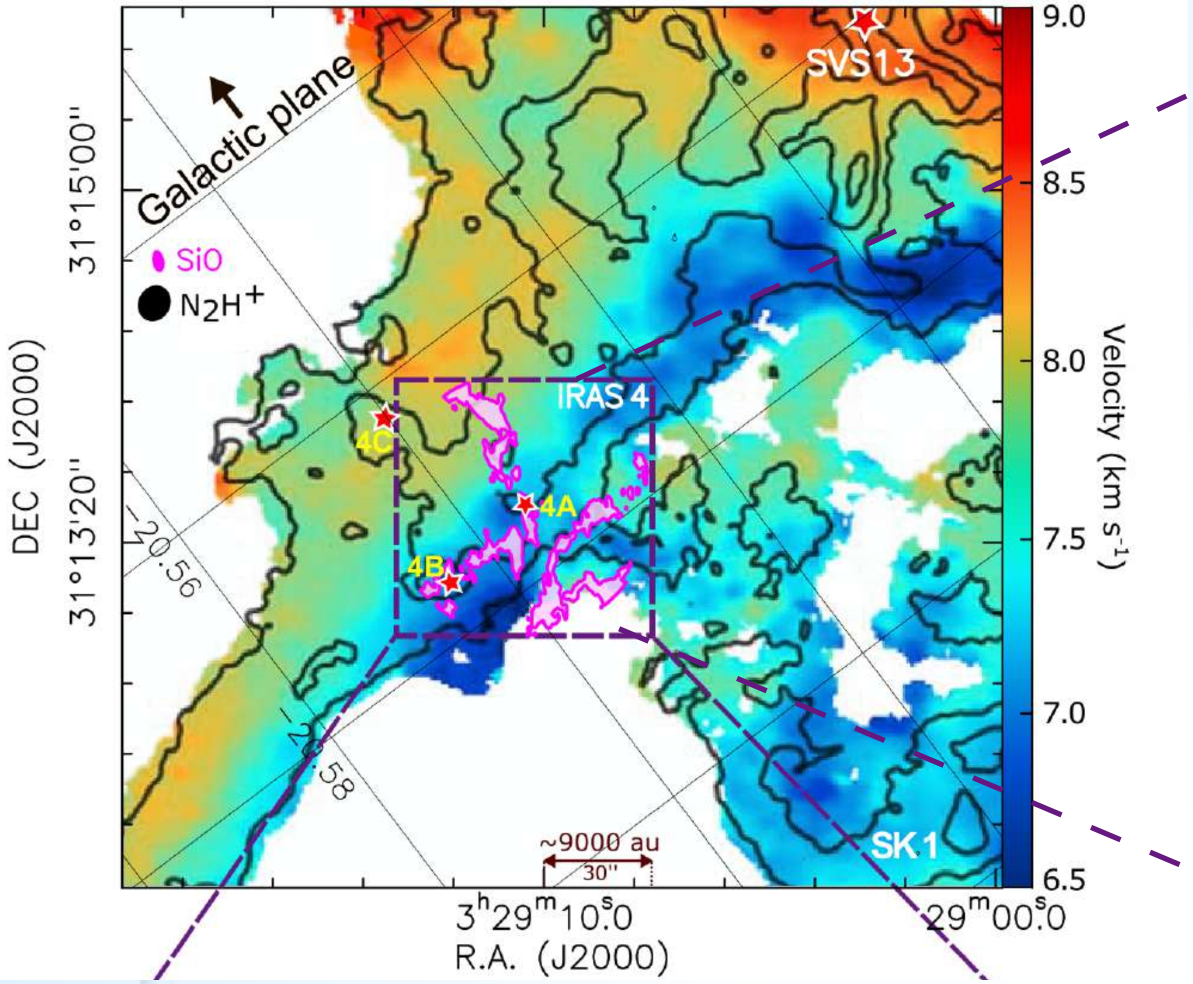
A premature collapse has been triggered where no prestellar core existed

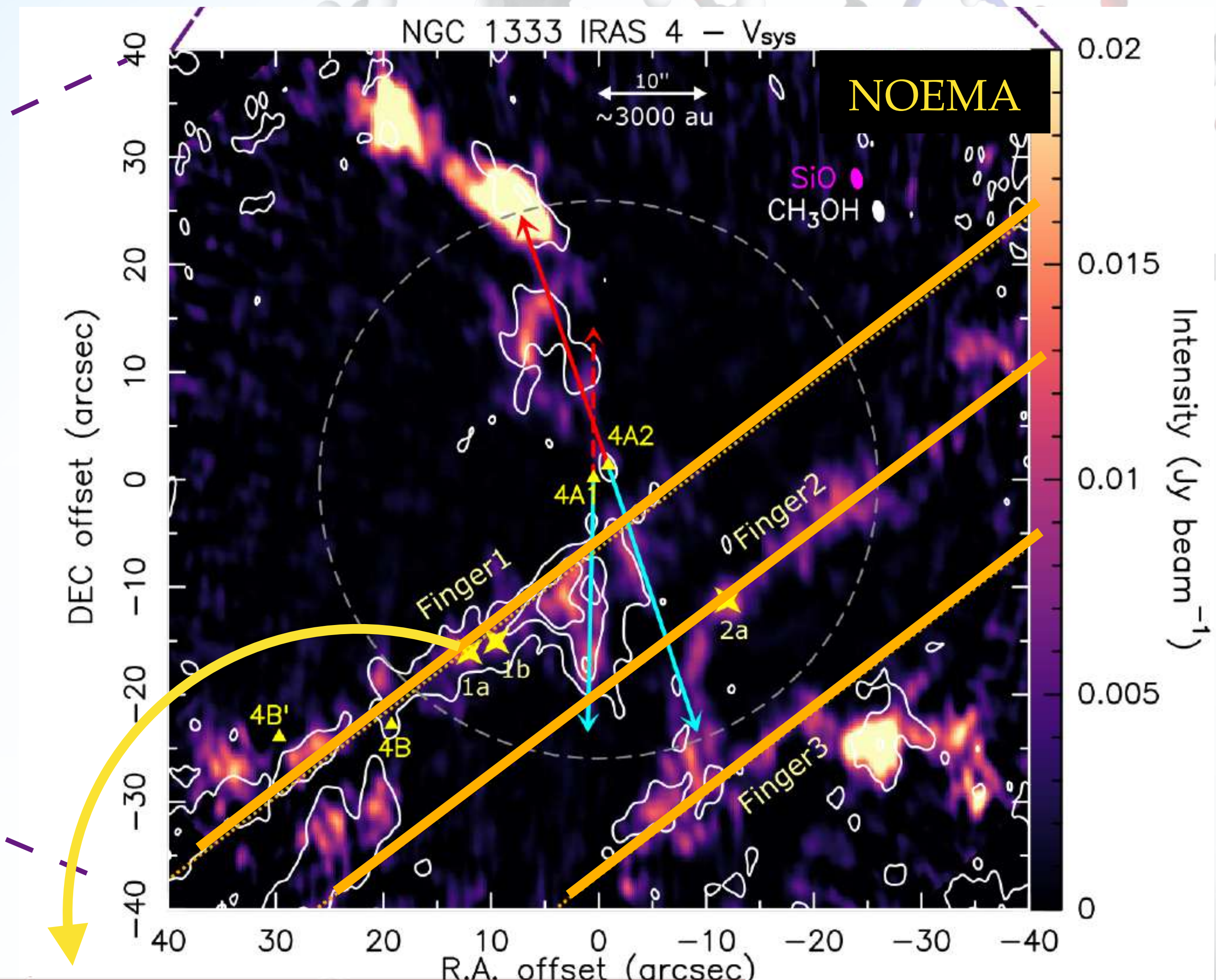
De Simone et al. 2022

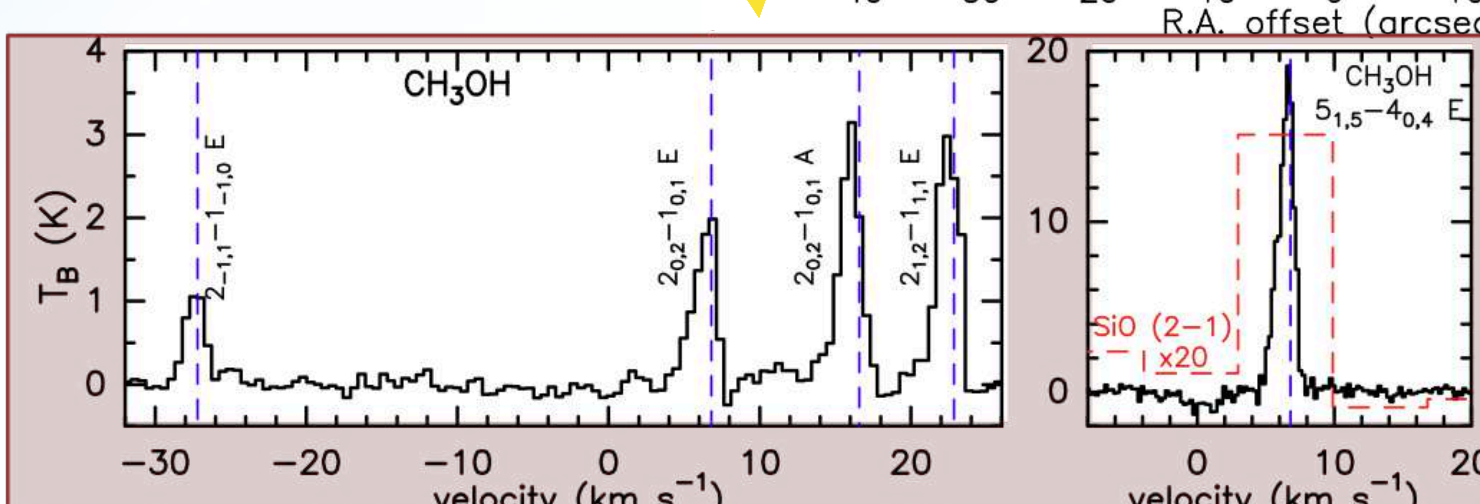
Shock as result of cloud collisions:
the case of the NGC1333 IRAS 4 system

De Simone et al. 2022 MNRAS

Dhabal et al. 2019



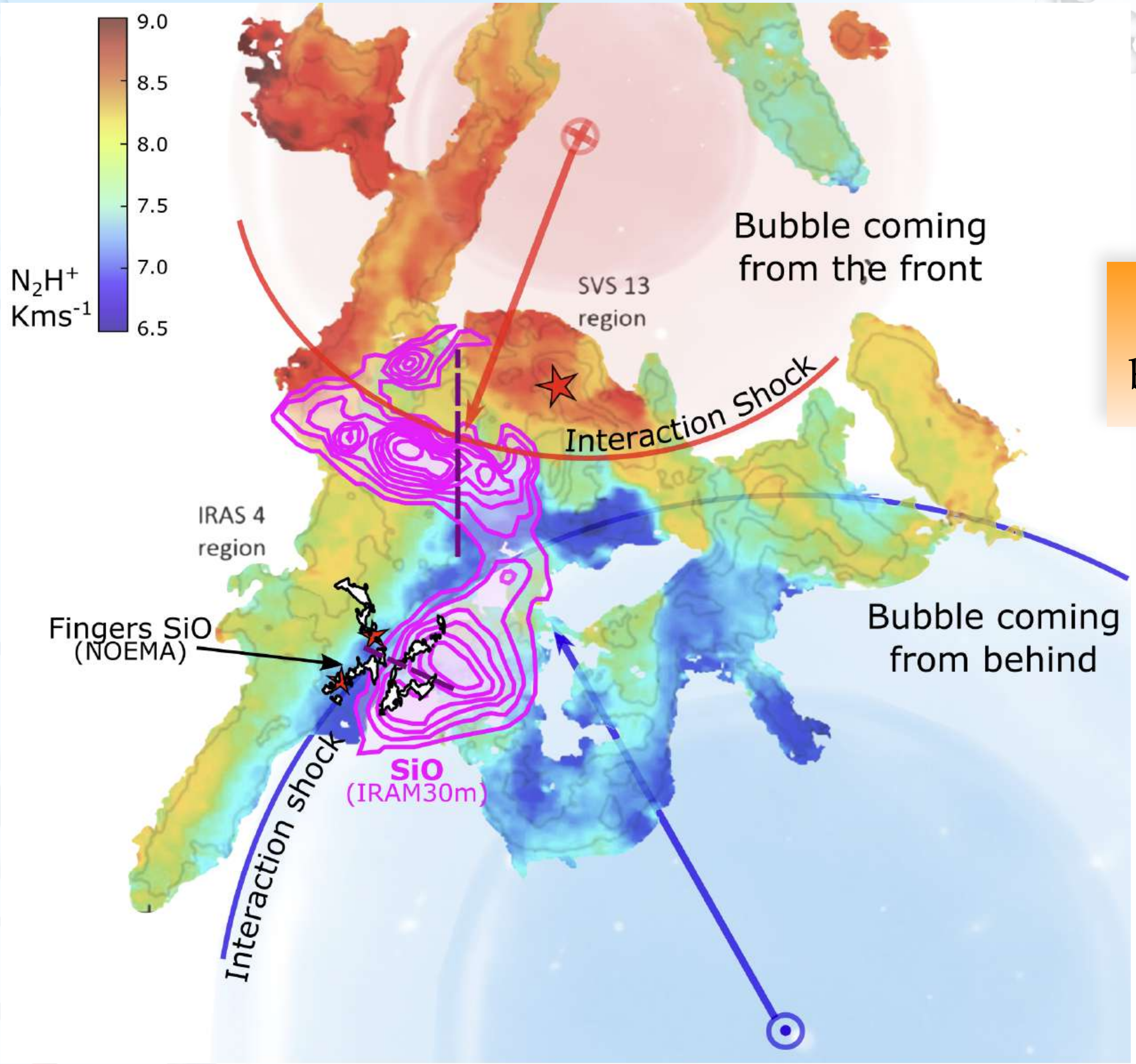




Narrow (~1.5 km/s) elongated structure around the systemic velocity (~6.7 km/s)

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

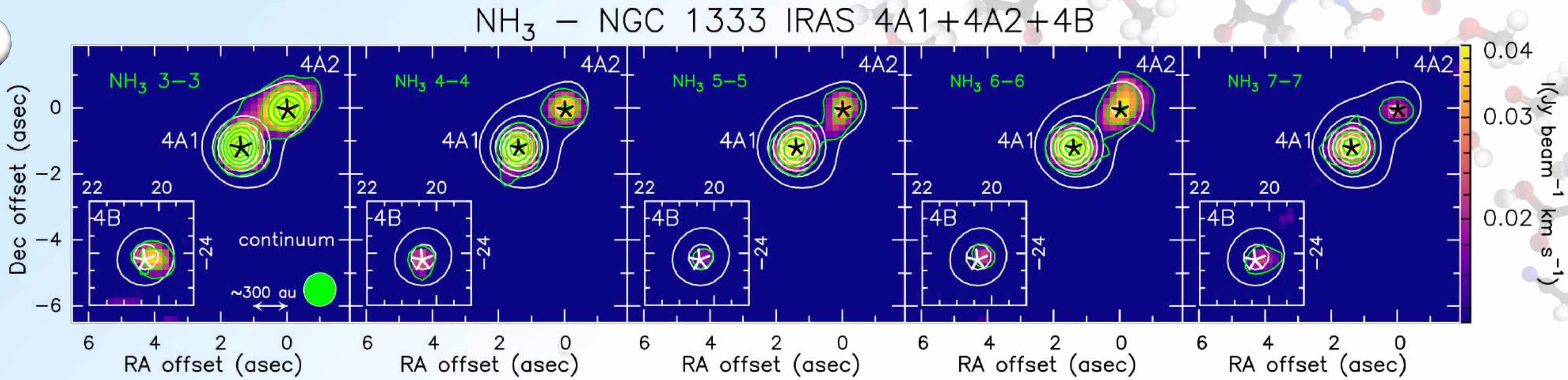
De Simone et al. 2022 MNRAS

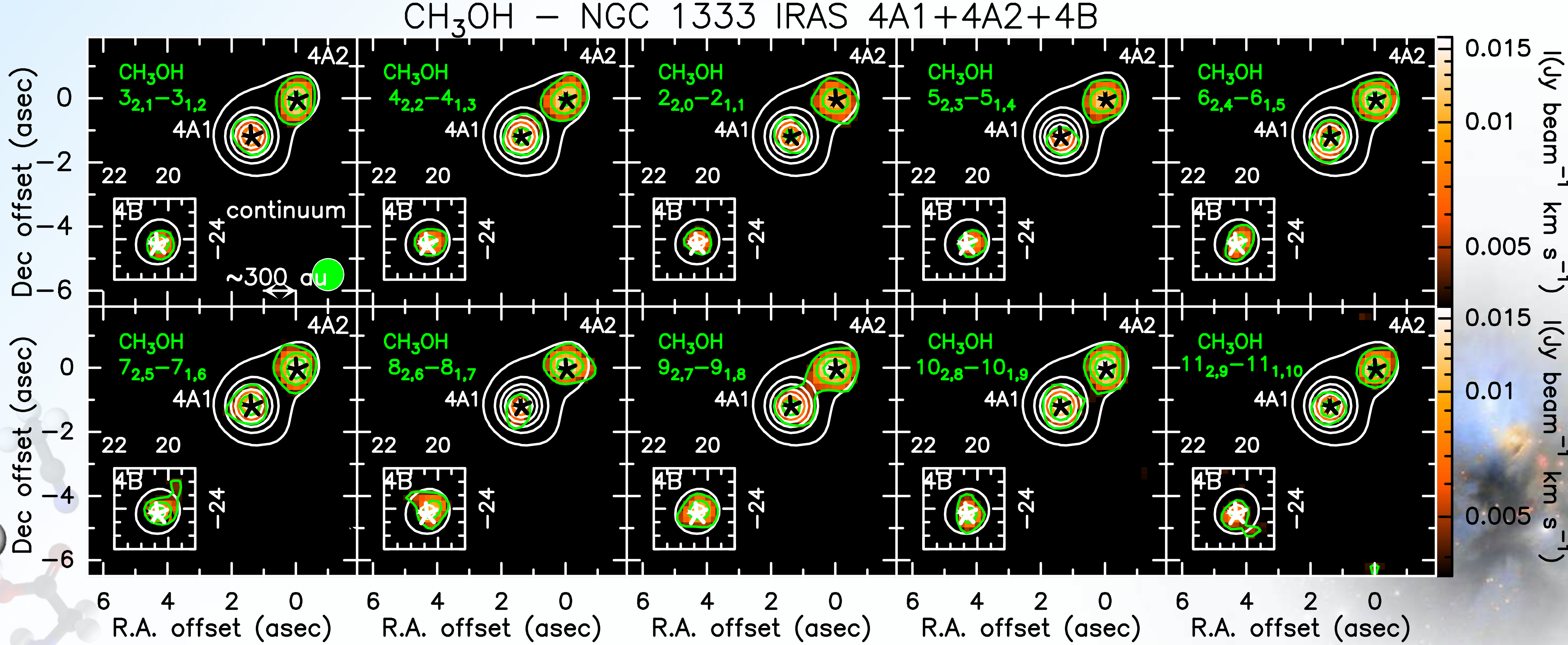


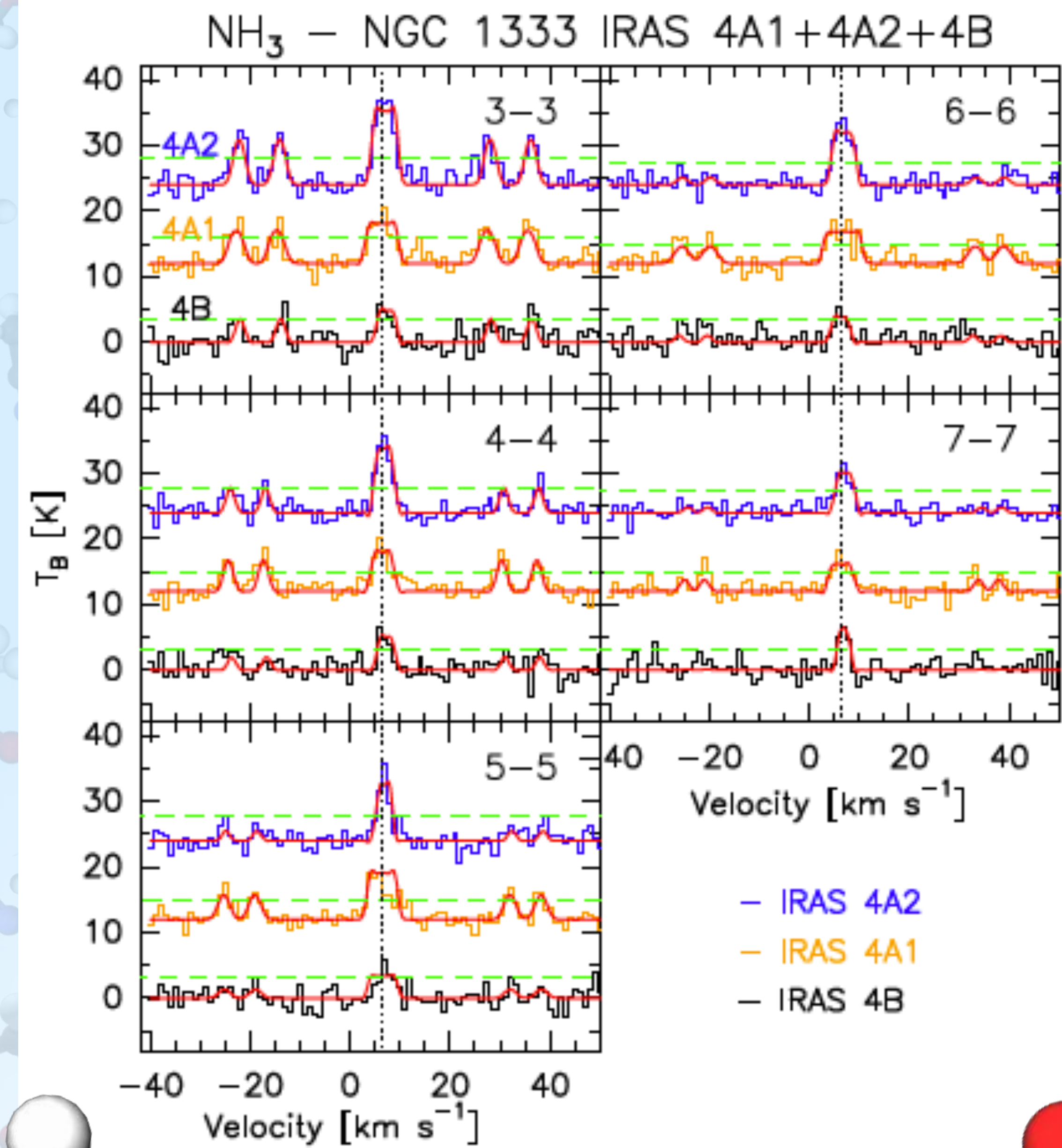
NGC 1333 could have been shaped by two clashing expanding bubbles.

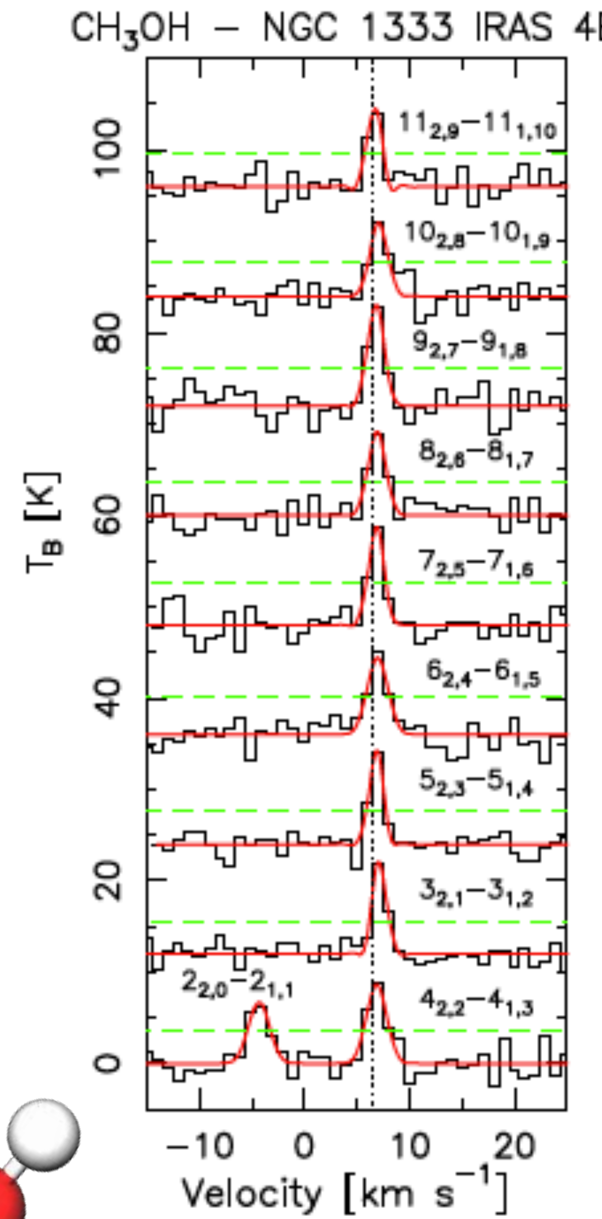
Could this clash have **triggered the formation** of the protostars on the filament?

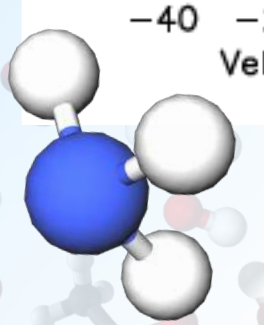
Stay tuned…

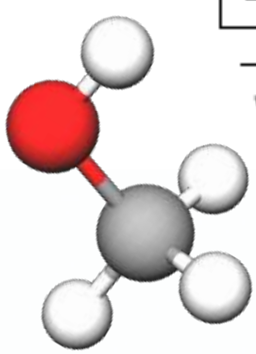

NH3 — NGC 1333 IRAS 4A1+4A2+4B
NH3 3-3
NH3 4-4
NH3 5-5
NH3 6-6
NH3 7-7
4A1
4A2
4B
continuum
~300 au
Dec offset (asec)
RA offset (asec)
I(Jy beam−1 km s−1)


CH3OH — NGC 1333 IRAS 4A1+4A2+4B
CH3OH 3_{2,1}−3_{1,2}
CH3OH 4_{2,2}−4_{1,3}
CH3OH 2_{2,0}−2_{1,1}
CH3OH 5_{2,3}−5_{1,4}
CH3OH 6_{2,4}−6_{1,5}
CH3OH 7_{2,5}−7_{1,6}
CH3OH 8_{2,6}−8_{1,7}
CH3OH 9_{2,7}−9_{1,8}
CH3OH 10_{2,8}−10_{1,9}
CH3OH 11_{2,9}−11_{1,10}
4A1
4A2
4B
continuum
~300 au
Dec offset (asec)
R.A. offset (asec)
I(Jy beam−1 km s−1)

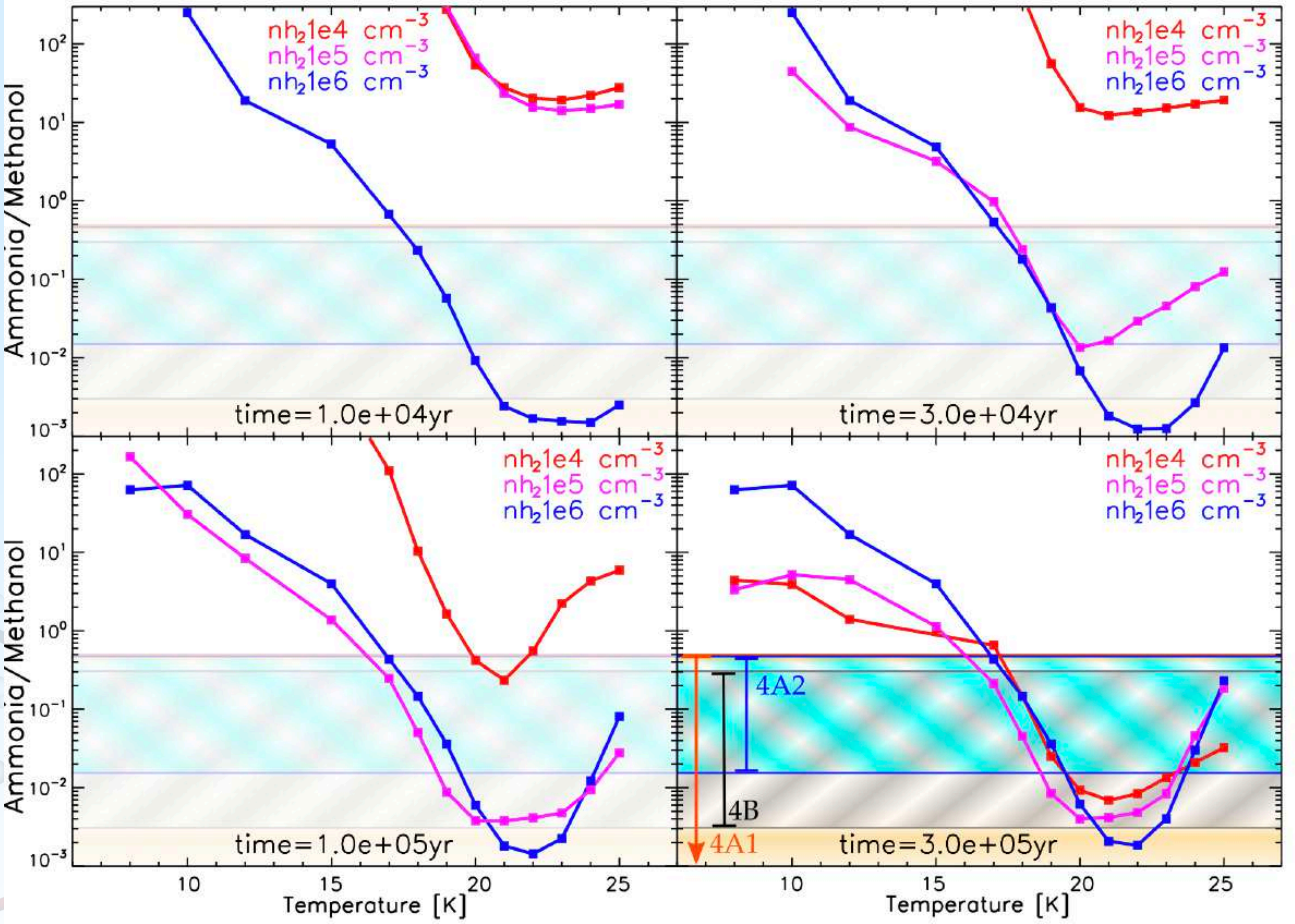




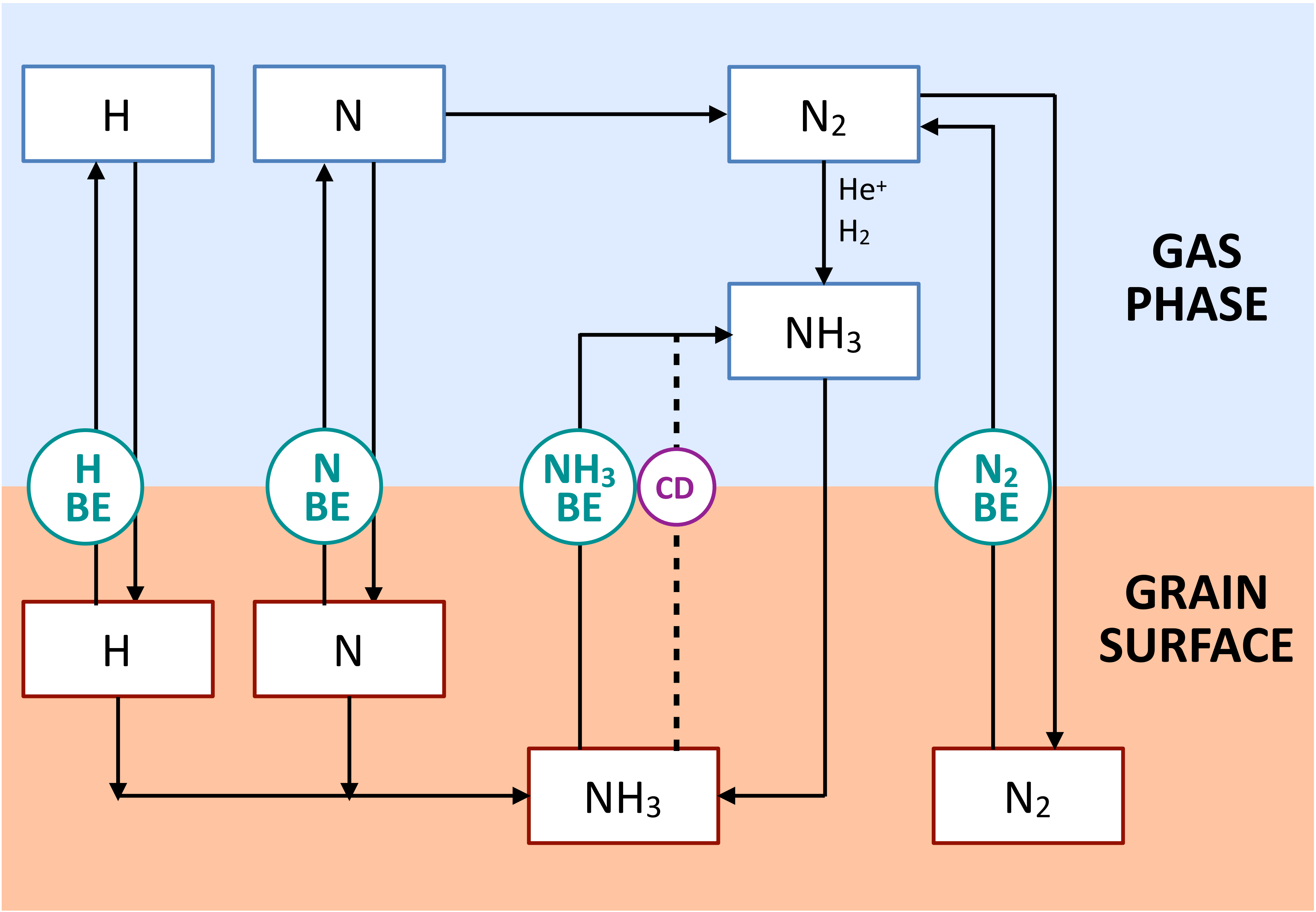


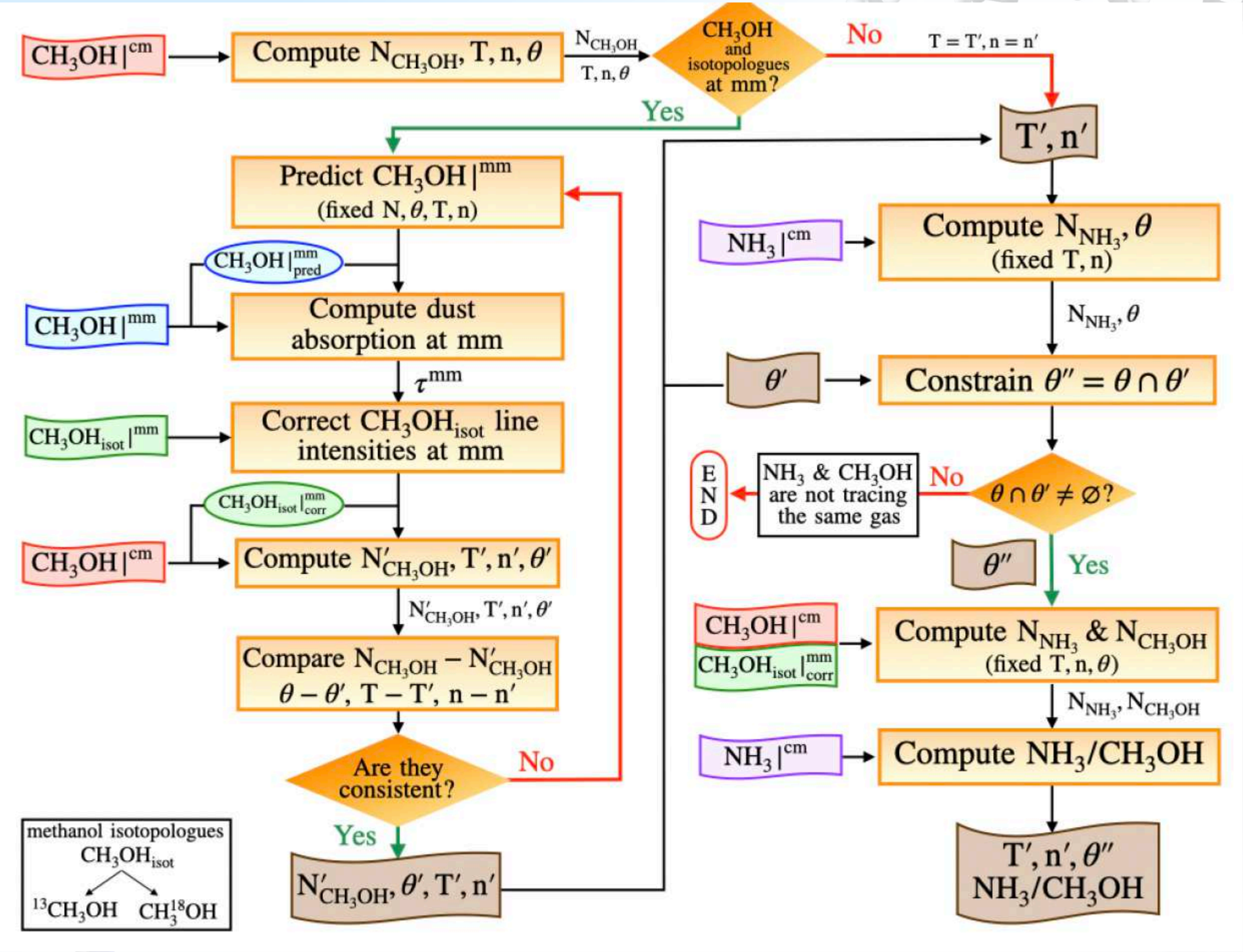


Transition	Frequency[a] [GHz]	$E_{up}^{(a)}$ [K]	$\log A_{ij}^{(a)}$
	CH_3OH		
3(2,1)-3(1,2) E	24.92871	36	-7.2
4(2,2)-4(1,3) E	24.93347	45	-7.1
2(2,0)-2(1,1) E	24.93438	29	-7.2
5(2,3)-5(1,4) E	24.95908	57	-7.1
6(2,4)-6(1,5) E	25.01812	71	-7.1
7(2,5)-7(1,6) E	25.12487	87	-7.1
8(2,6)-8(1,7) E	25.29442	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



nh$_2$1e4 cm^{-3}
nh$_2$1e5 cm^{-3}
nh$_2$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


CH3OH|cm
Compute NCH3OH, T, n, θ
NCH3OH
T, n, θ
CH3OH and isotopologues at mm?
No
T = T′, n = n′
Yes
T′, n′
Predict CH3OH|mm
(fixed N, θ, T, n)
CH3OH|mm pred
CH3OH|mm
Compute dust absorption at mm
τmm
CH3OHisot|mm
Correct CH3OHisot line intensities at mm
CH3OHisot|mm corr
CH3OH|cm
Compute N′CH3OH, T′, n′, θ′
N′CH3OH, T′, n′, θ′
Compare NCH3OH − N′CH3OH
θ − θ′, T − T′, n − n′
Are they consistent?
No
Yes
N′CH3OH, θ′, T′, n′
methanol isotopologues
CH3OHisot
13CH3OH
CH3 18OH
NH3|cm
Compute NNH3, θ
(fixed T, n)
NNH3, θ
θ′
Constrain θ″ = θ ∩ θ′
θ ∩ θ′ ≠ ∅?
No
NH3 & CH3OH are not tracing the same gas
END
θ″
Yes
CH3OH|cm
CH3OHisot|mm corr
Compute NNH3 & NCH3OH
(fixed T, n, θ)
NNH3, NCH3OH
NH3|cm
Compute NH3/CH3OH
T′, n′, θ″
NH3/CH3OH