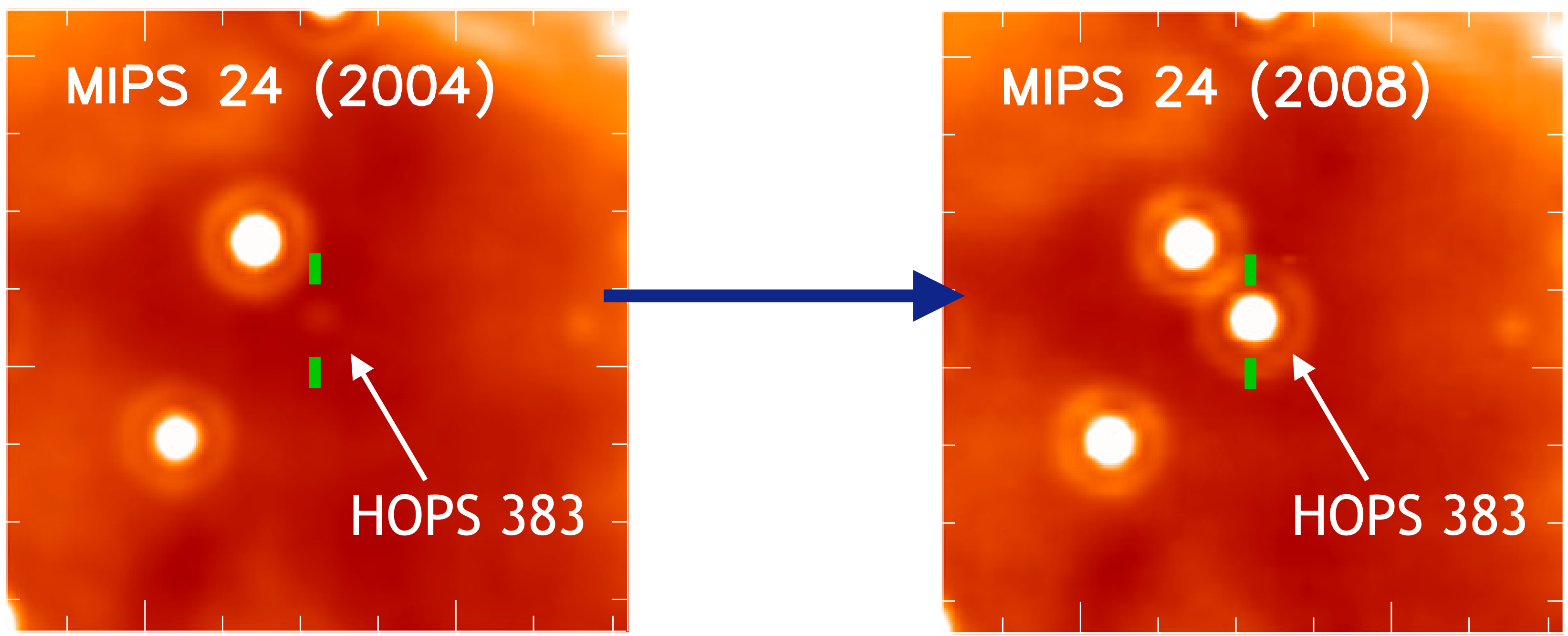
Formation and recondensation of complex organics during luminosity outbursts



Vianney Taquet, Leiden Observatory

Steven Charnley, Eva Wirstrom

KIDA workshop, 07/05/14

Sterrewacht Leiden

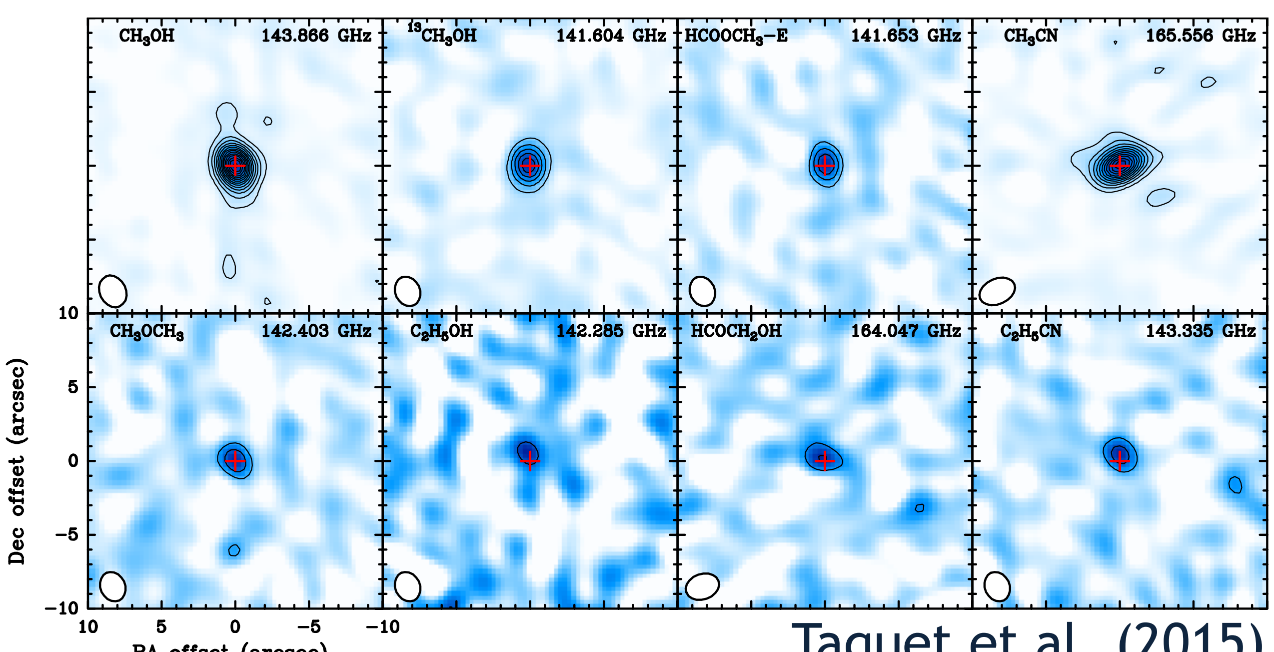
Universiteit Leiden

Complex organics in low-mass protostars

A dozen of N- and O- **complex organics** have been detected in high abundances toward **low-mass protostars** (Cazaux et al. 2003, Bottinelli et al. 2004, 2007)

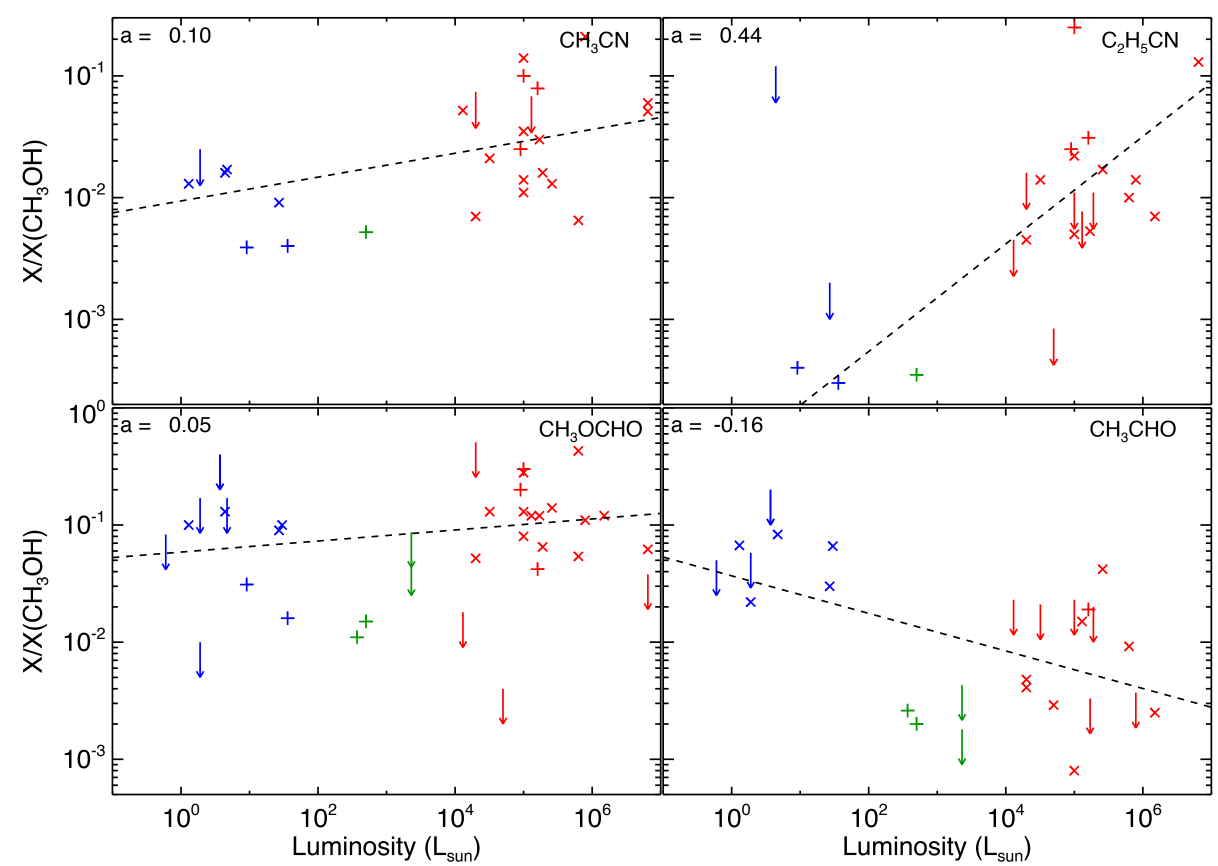
Interferometric observations show that COMs mostly originate from **inner (< 50 AU) regions**

PdBi observations towards NGC1333-IRAS2A

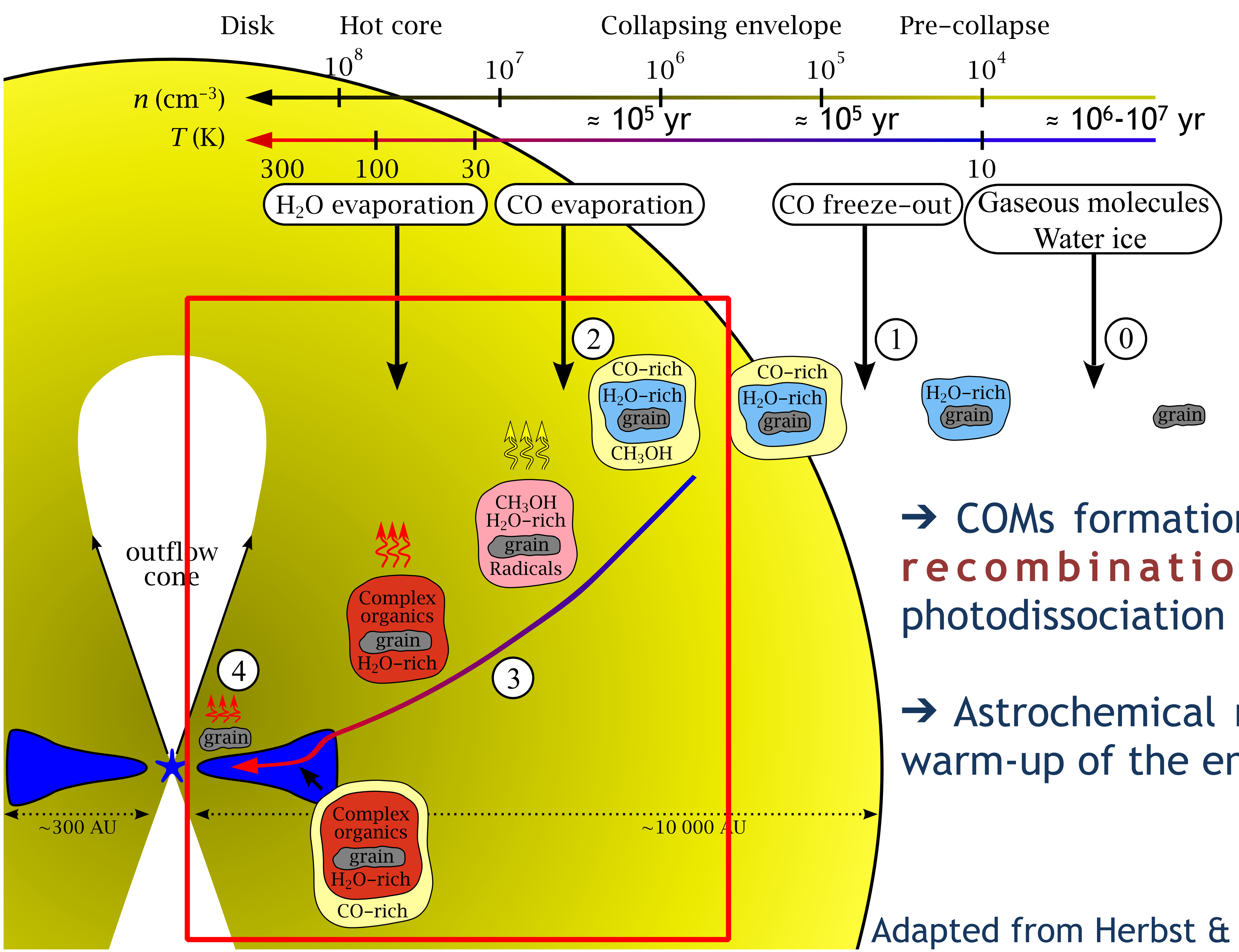


Taquet et al. (2015)

COMs are **as abundant** in low-mass protostars as in high-mass hot cores



Formation of complex organics



➔ COMs formation **on grains** from **radical recombination** triggered by UV photodissociation of ices

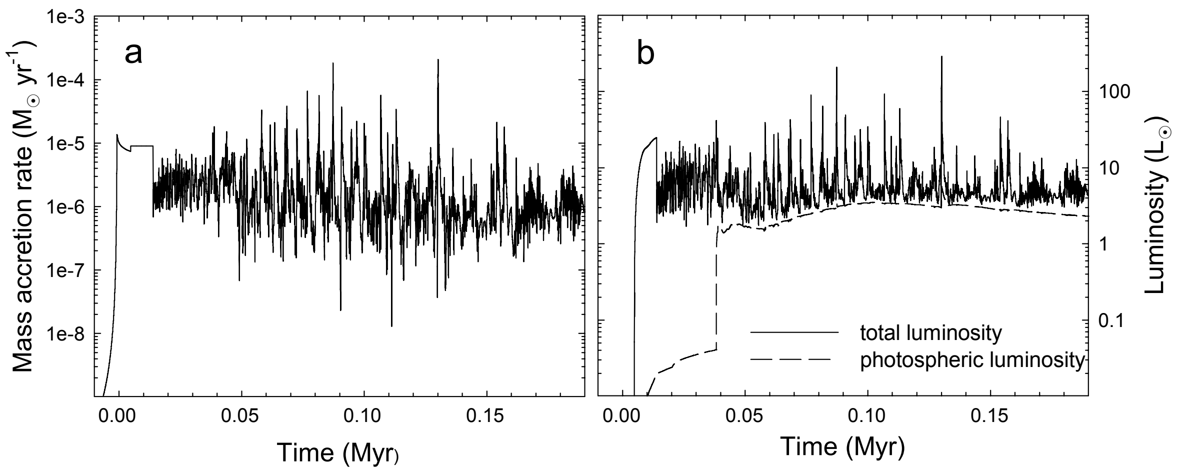
➔ Astrochemical models based on gradual warm-up of the envelope…

Adapted from Herbst & van Dishoeck (2009)

Luminosity outbursts in embedded protostars

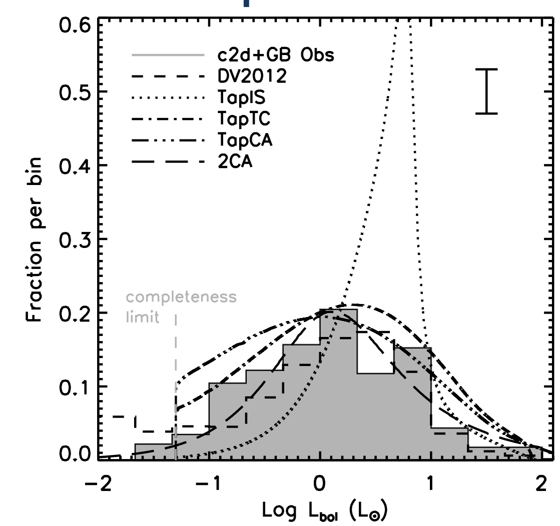
… But the **Early stages of star formation likely undergo episodic luminosity outbursts!**

Hydrodynamical models predict accretion outbursts due to instabilities in circumstellar disk



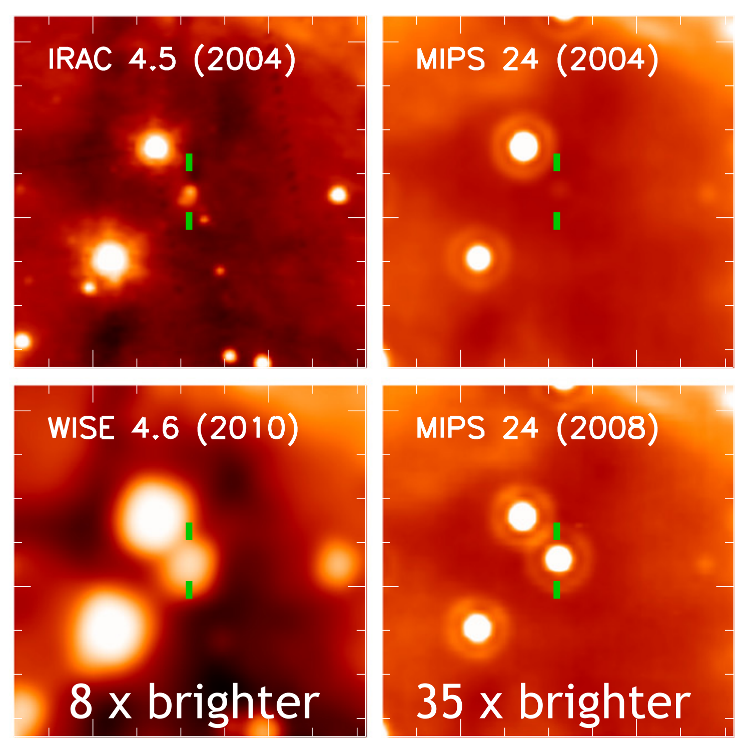
Vorobyov et al. (2013)

Luminosity outbursts can explain observed spread of low-mass protostar luminosities



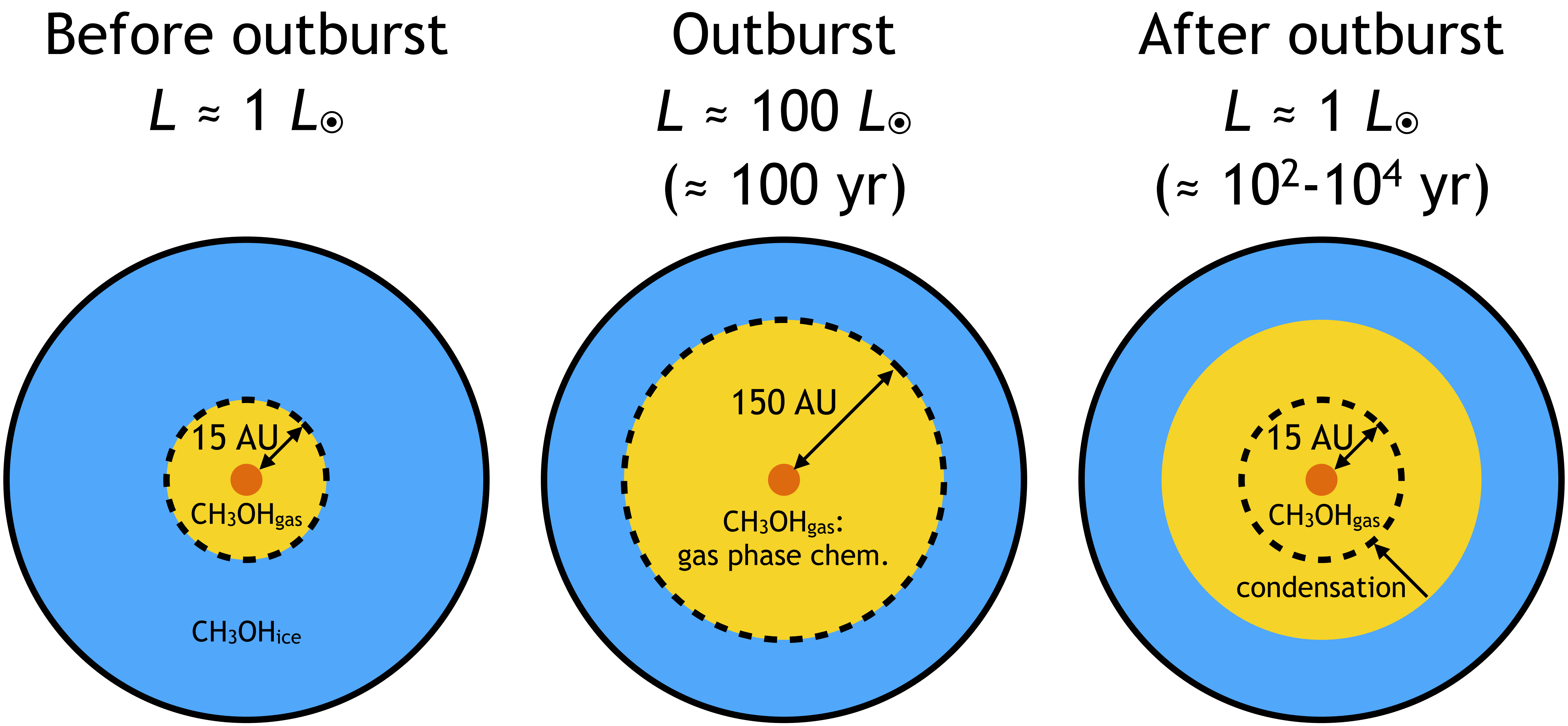
Dunham & Vorobyov (2012)

Luminosity variability observed toward embedded sources



Class 0 protostar HOPS 383 (Safron et al. 2015)

Luminosity outbursts and chemical evolution



Gas phase chemical network

Update of the gas phase chemical network from Rodgers & Charnley (2001) including rates of key reactions recently measured or computed:

- Methyl formate now formed from $HCOOH + CH_3OH_2^+ \longrightarrow HC(OH)OCH_3^+ + H_2O$
(Neill et al. 2011 and Cole et al. 2012)

- Electronic recombination measured for several protonated COMs
(Geppert et al. 2006, Hamberg et al. 2010, Vigren et al. 2010)
$XH^+ + e^- \longrightarrow X + H$ BR ≈ 5 - 10 %

- Highly exothermic proton transfer reaction between protonated COMs and NH_3
(not included in KIDA/OSU/UMIST databases ?)
$XH^+ + NH_3 \longrightarrow X + NH_4^+$ (rate of ≈ 10^{-9} $cm^3 \cdot s^{-1}$ taken from similar reactions)

Binding energies and initial abundances

Species	$X_{\rm ini}$	E_b	Ref(E_b).
H_2O	1×10^{-4}	5775	1
CO	3.8×10^{-5}	1150	2
N_2	1.6×10^{-5}	790	3
CO_2	3.0×10^{-5}	2690	4
CH_4	5.0×10^{-6}	1090	5
NH_3	5.0×10^{-6}	3075	6
H_2CO	2.5×10^{-6}	3260	7
CH_3OH	7.0×10^{-6}	5530	2
HCOOH	1.6×10^{-6}	5570	2
C_2H_5OH	1.6×10^{-6}	6795	8
CH_3OCH_3	0	4230	8
CH_3OCHO	0	4630	8
CH_3CN	0	4680	2
CH_3CHO	0	3800	9

NOTE. — [1]: Fraser et al. (2001); [2]: Collings et al. (2004); [3]: Bisschop et al. (2006); [4]: Noble et al. (2012a); [5]: Herrero et al. (2010); [6]: Sandford & Allamandola (1993); [7]: Noble et al. (2012b); [8]: Lattelais et al. (2011); [9]: Öberg et al. (2009);

- **Initial abundances** taken from **IR observations of ices** towards low-mass and high-mass protostars (see Tielens et al. 1991, Oberg et al. 2011)

Suffer from high uncertainties due to contamination from other tertiary species/mixtures

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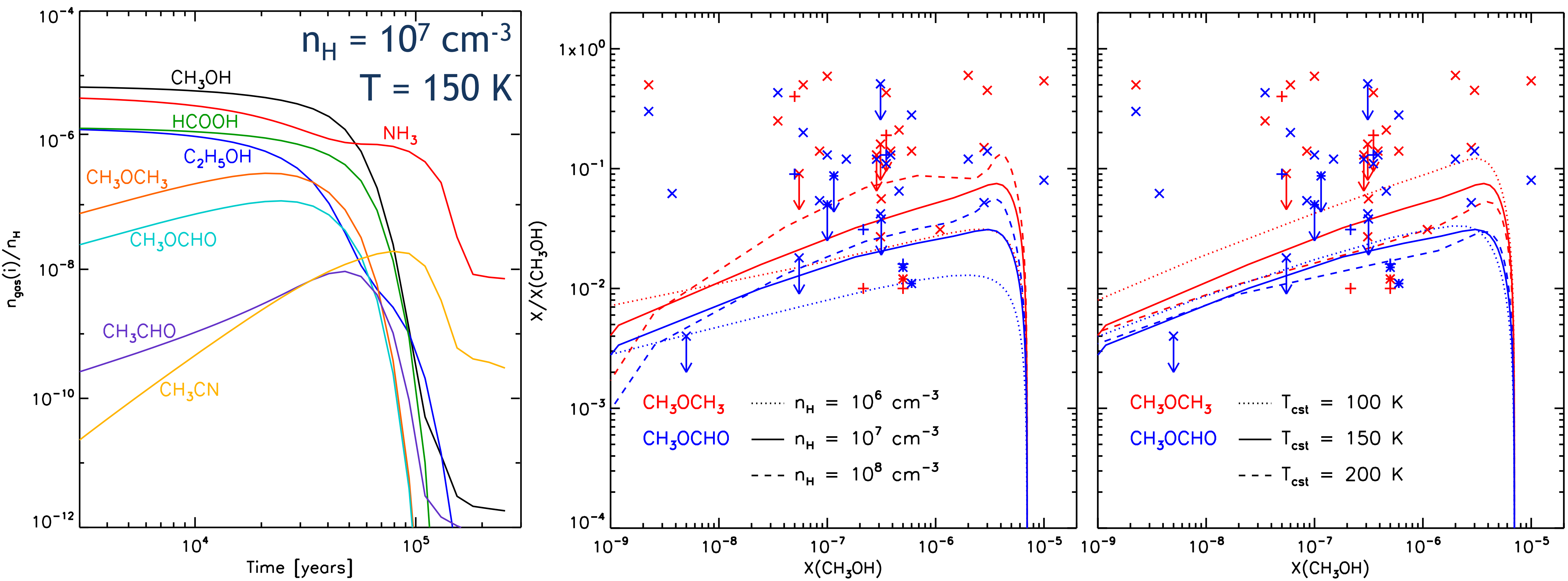
- **Differences in binding energies** between methanol and COMs
→ different temperatures of sublimation

COMs formation for static physical conditions

Gas phase chemistry produces high abundances of COMs !

➔ Abundances > 10^{-7} can be reached for methyl formate and dimethyl ether



Importance of NH_3 in COMs abundance

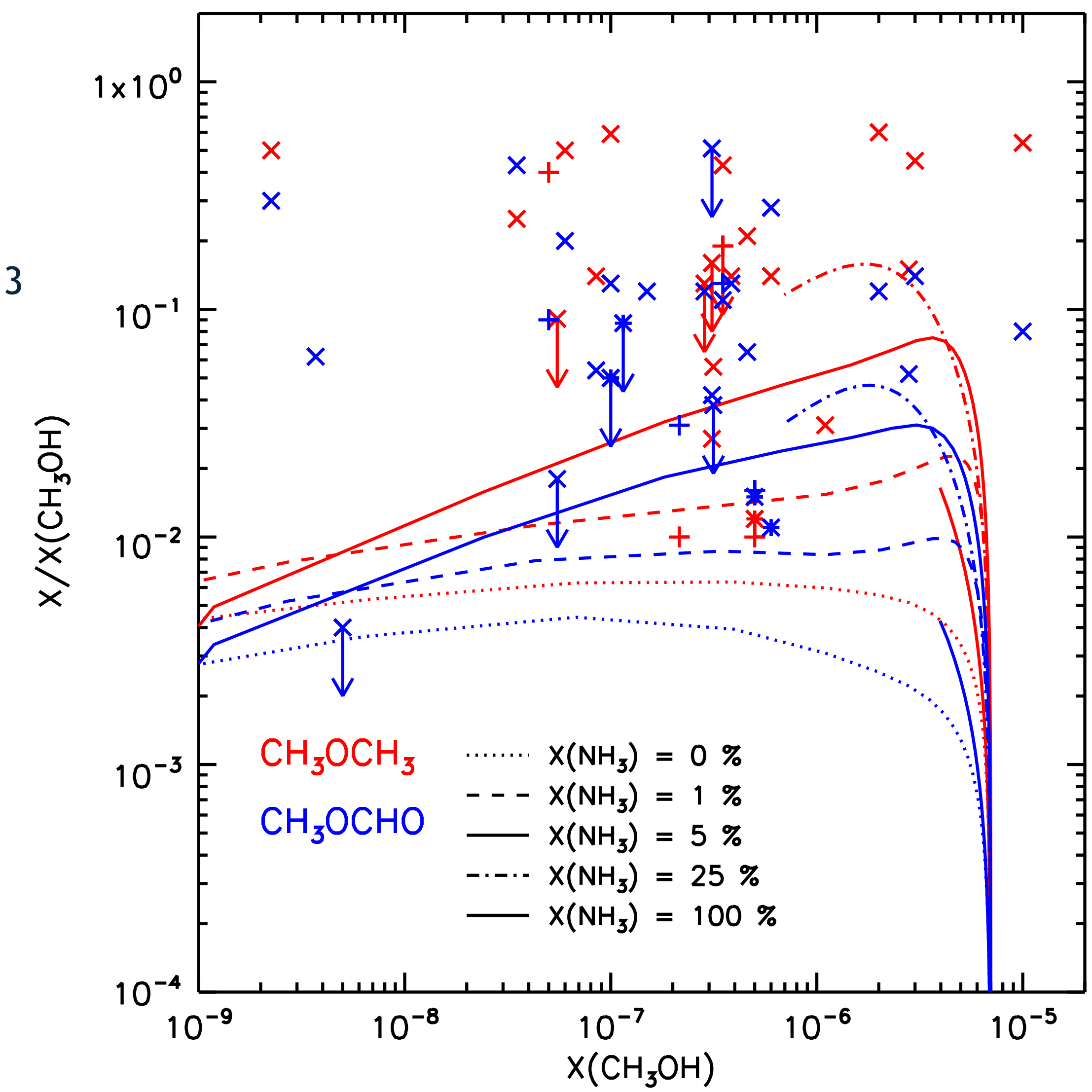
NH_3 abundance governs the formation efficiency of COMs:

- Low NH_3 abundance ➔ efficient protonation of methanol but low formation of COMs from protonated ions
- High NH_3 abundance ➔ efficient formation of COMs from ions but low protonation of methanol

Example for dimethyl ether:

$$CH_3OH \underset{e^-,\ NH_3}{\overset{H_3O^+,\ HCO^+}{\rightleftarrows}} CH_3OH_2^+ \xrightarrow{+\ CH_3OH} CH_3O(H)CH_3^+ \xrightarrow{e^-,\ NH_3} CH_3OCH_3$$

Abundances of COMs reach their maximum for X(NH_3) ≈ 10-20 %
➔ similar to NH_3 abundances of 5-15 % observed around protostars (see Oberg et al. 2011)



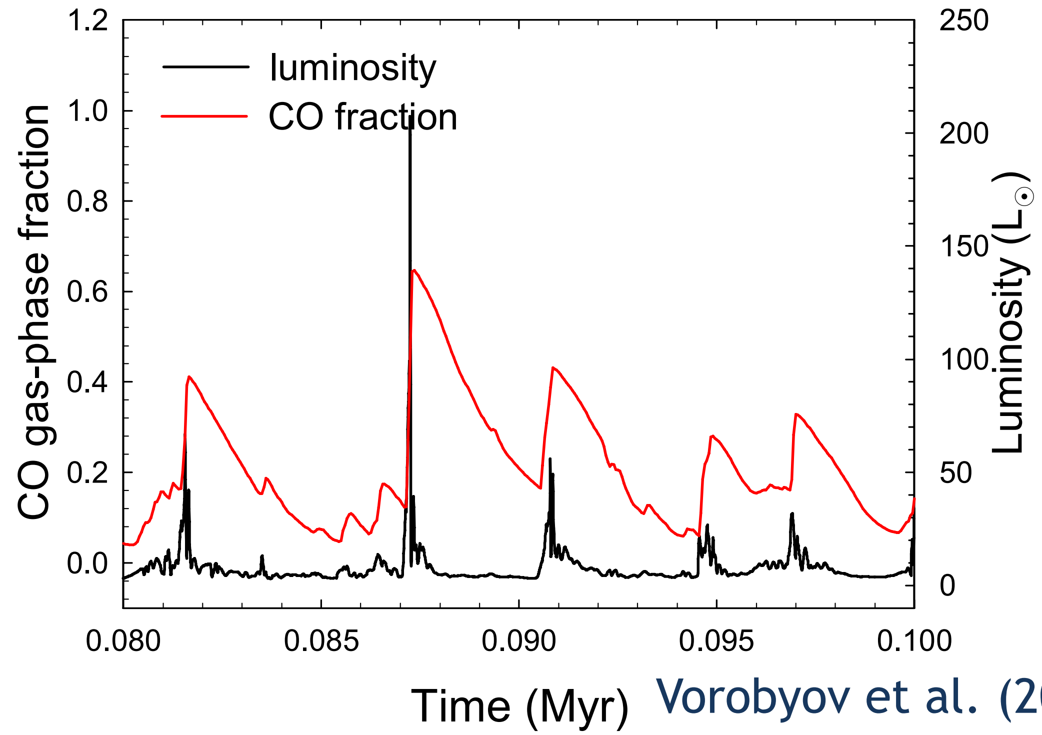
Physical conditions

- **Luminosity evolution**

$$L(t) = (L_{\rm max} - L_{\rm min})\exp(-t/\tau) + L_{\rm min}$$

$$T(t) = T_{\rm min} \times (L_\star(t)/L_{\rm min})^{1/4}$$

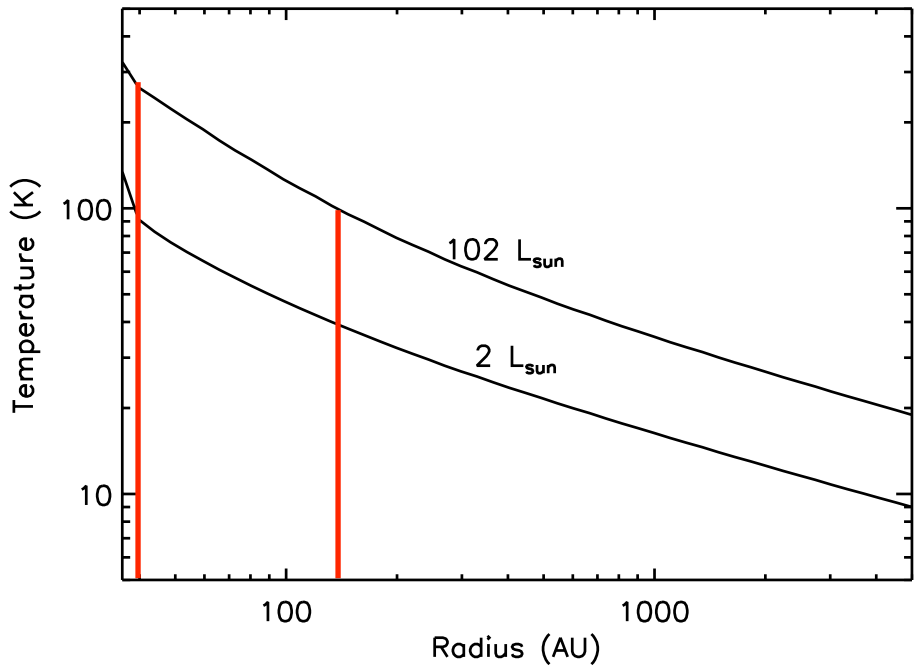
L_{min} = 2 $L_\odot$ and L_{max} = 100 $L_\odot$
τ = 100, 300, 500 yr



Vorobyov et al. (2013)

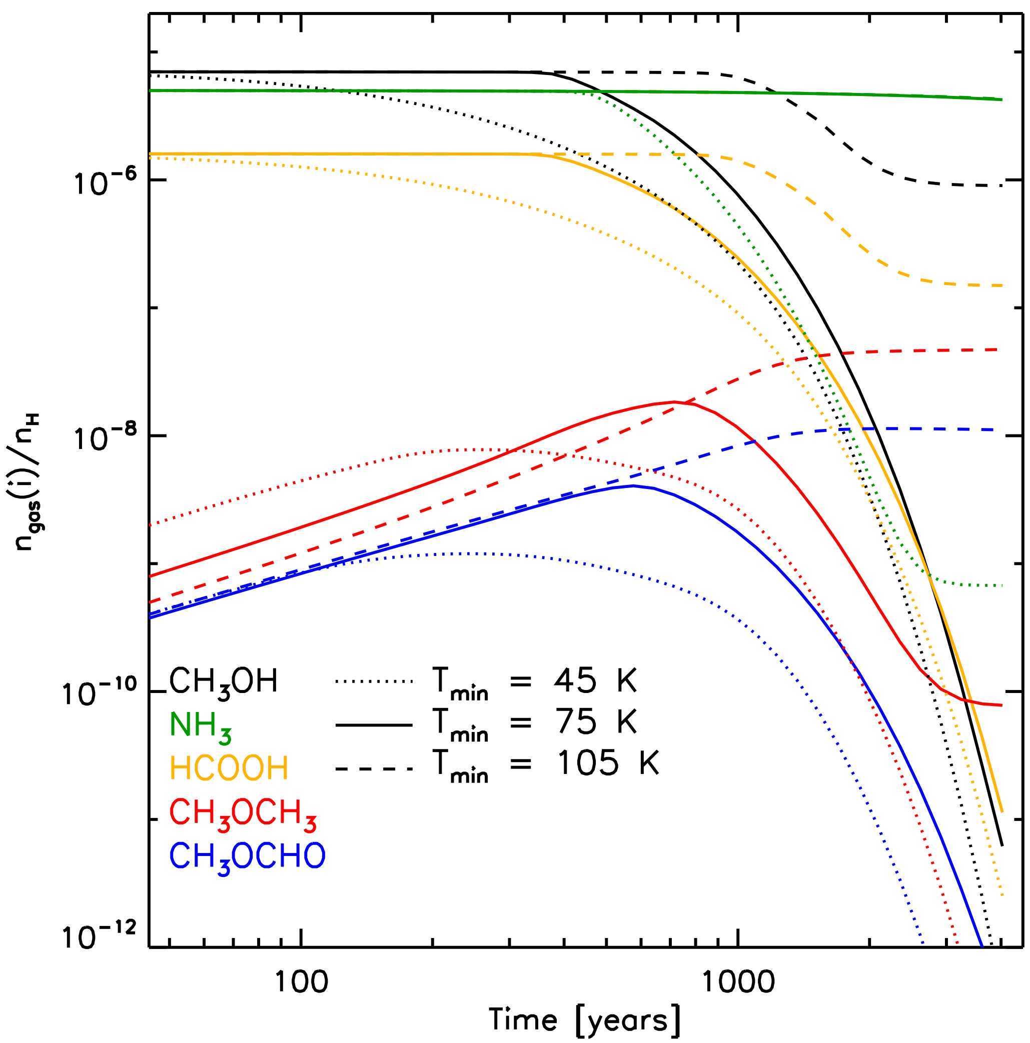
- **Physical conditions at snow lines during/after luminosity outburst**

n_H = 10^6, 10^7, 10^8 cm^{-3}
T_{min} = 45, 75, 105 K

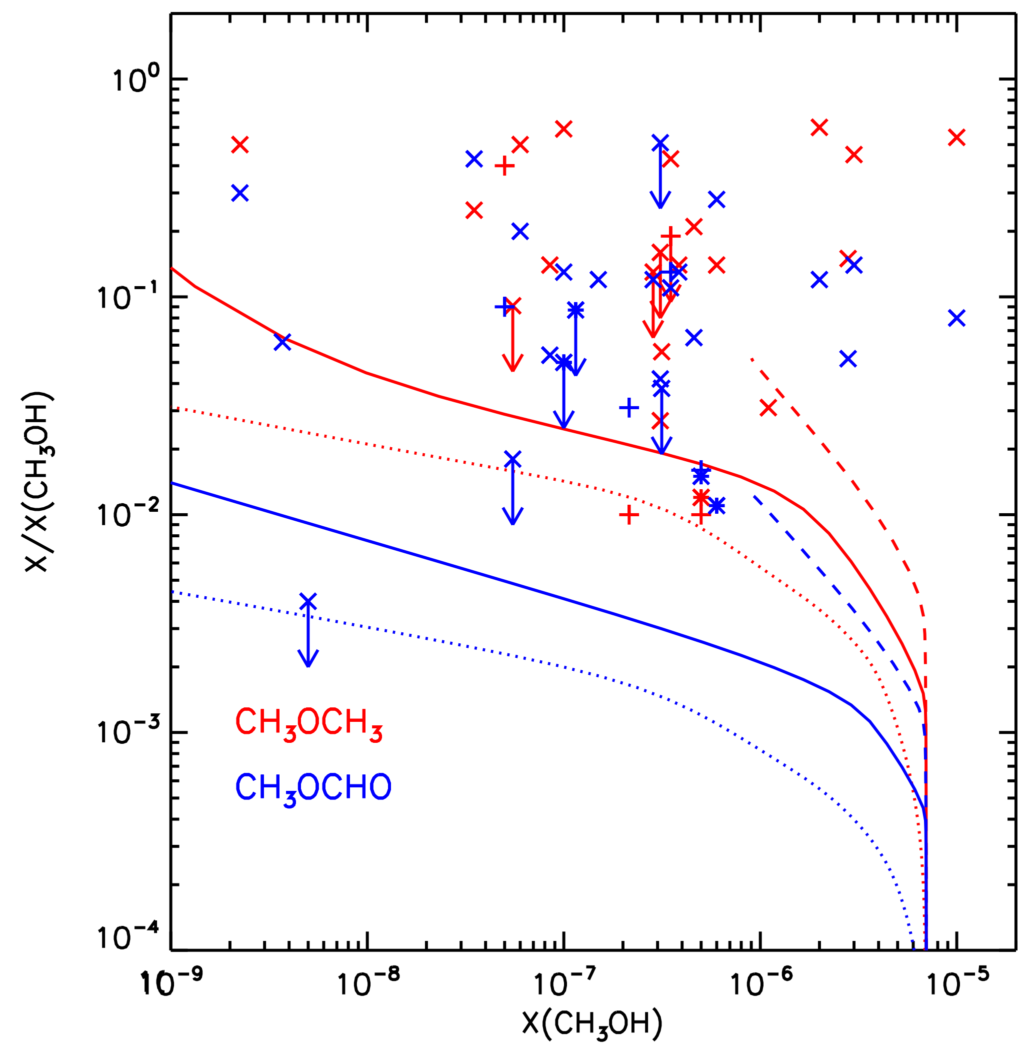


COMs formation during luminosity outbursts

Gas phase chemistry can produce significant amount of COMs **(10^{-8})** in one outburst



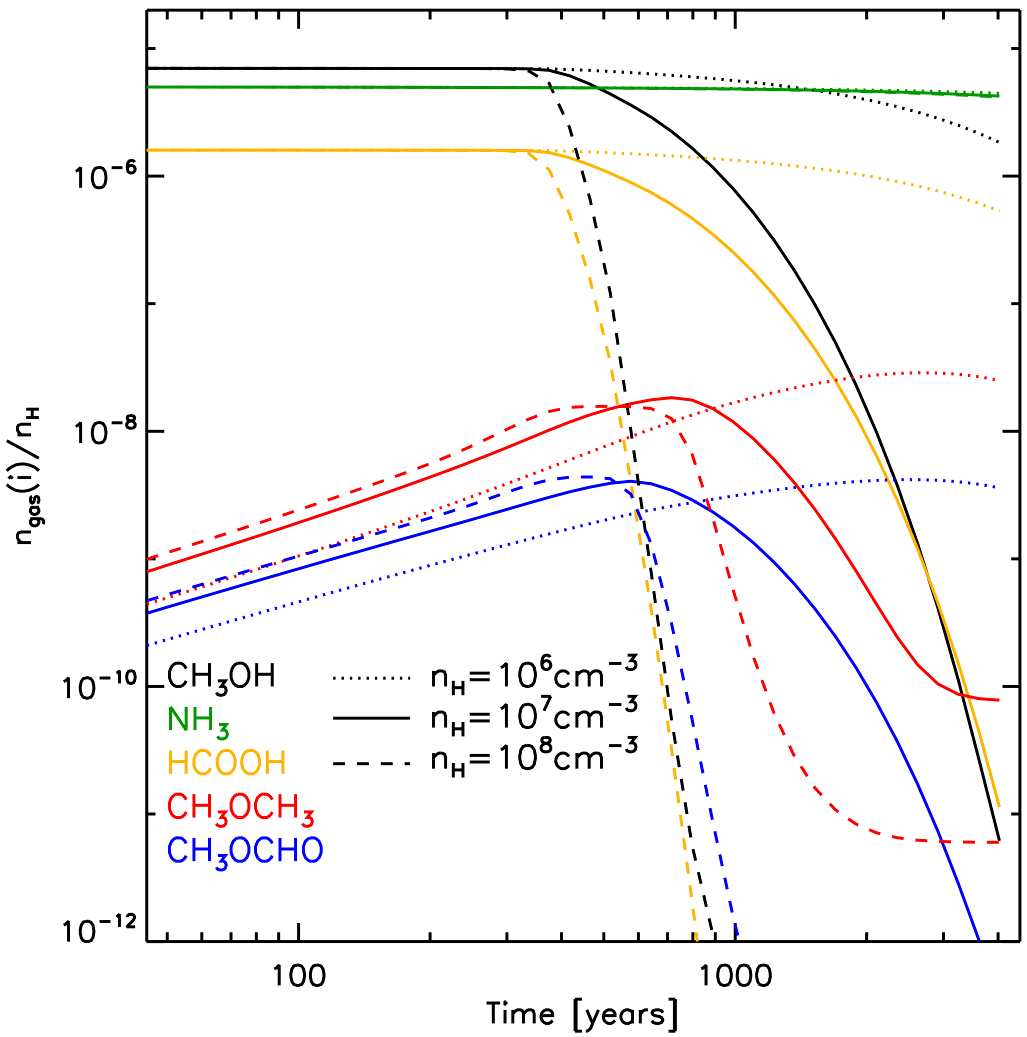
Low COM binding energies increase their abundance ratios during the recondensation

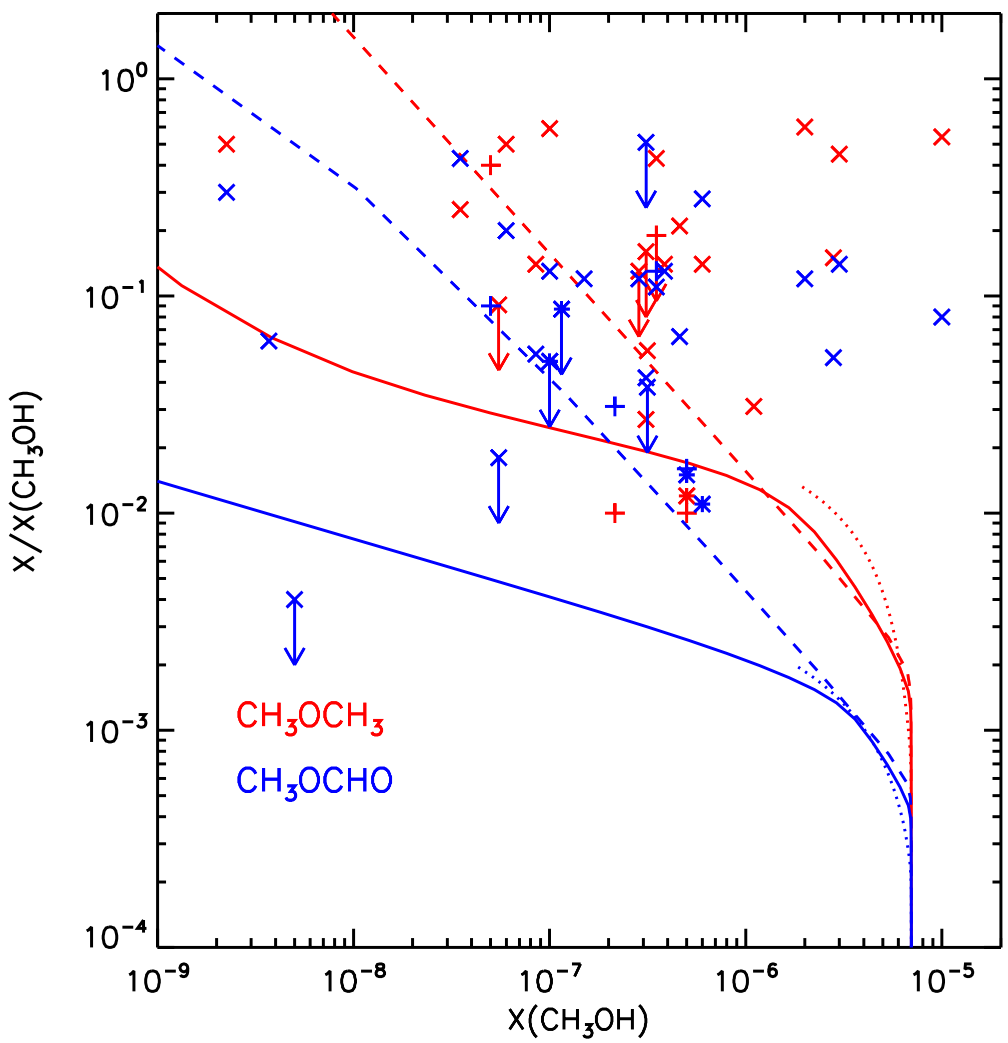


$n_H = 10^7$ cm^{-3}; τ = 300 yr

COMs formation during luminosity outbursts

- **High abundance** ratios are predicted in **dense envelopes** (n_H = 10^8 cm^{-3})
- In **low-density envelopes**, COMs **stay in the gas phase** long after the end of the outburst





T_{min} = 75 K; τ = 300 yr

Conclusions and Perspectives

✓ Significant contribution of gas phase chemistry to the formation of some complex organics → importance of ammonia

✓ Abundance ratios of COMs relative to methanol increase as the envelope cools down after a luminosity outburst because of their low binding energy

✓ In spite of their low-luminosity (≈ 1 $L_\odot$), most low-mass protostars might be able to produce COMs in the gas on 100-200 AU scales due to outbursts

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→ Extension to other species showing higher/lower binding energies

→ Coupling with grain surface chemistry and with more realistic physical models