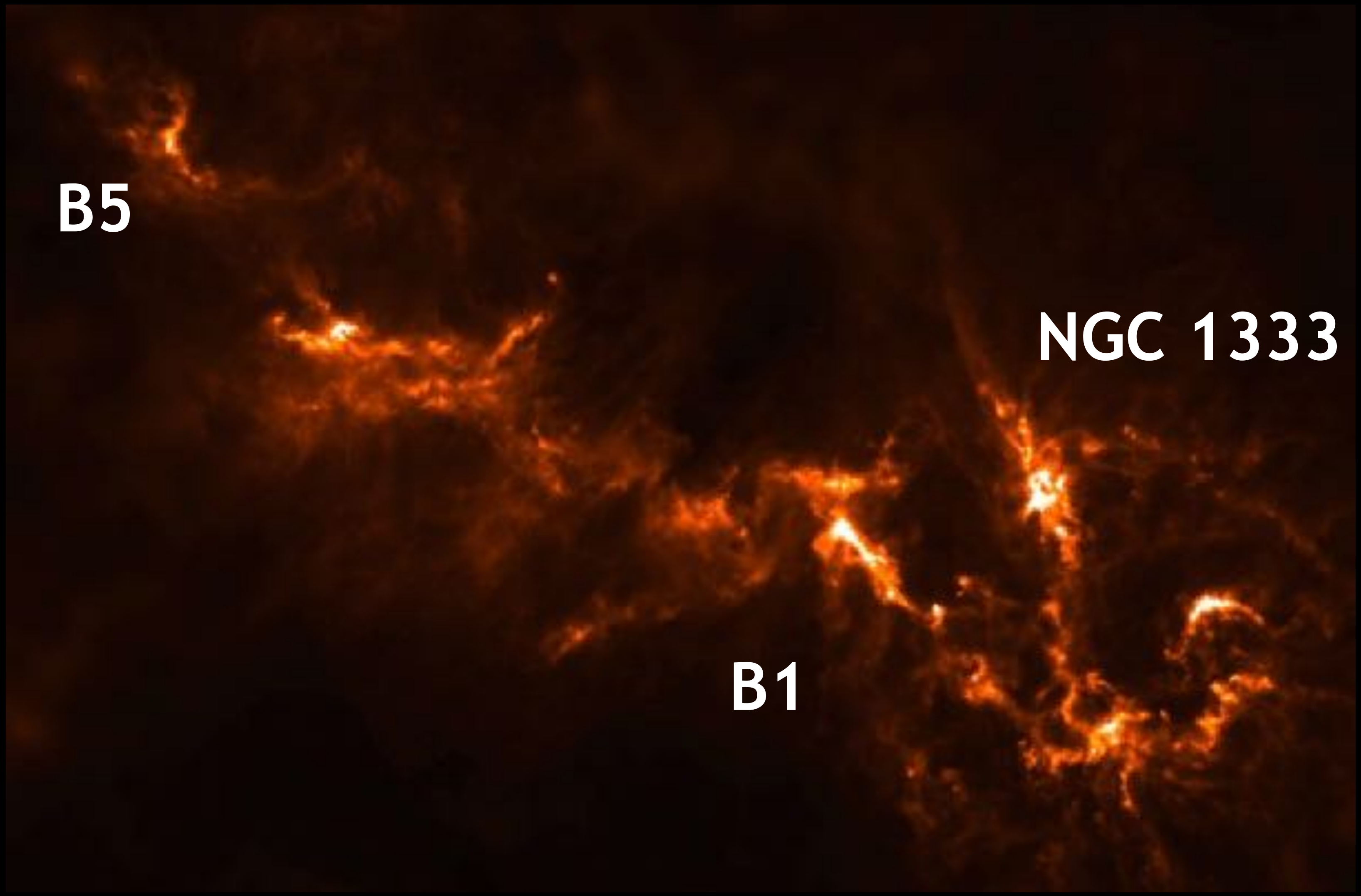
Cold gaseous methanol and non-thermal desorption processes



Perseus molecular cloud as observed with the *Herschel Space Observatory* (Gould Belt Survey, PI: P. André)

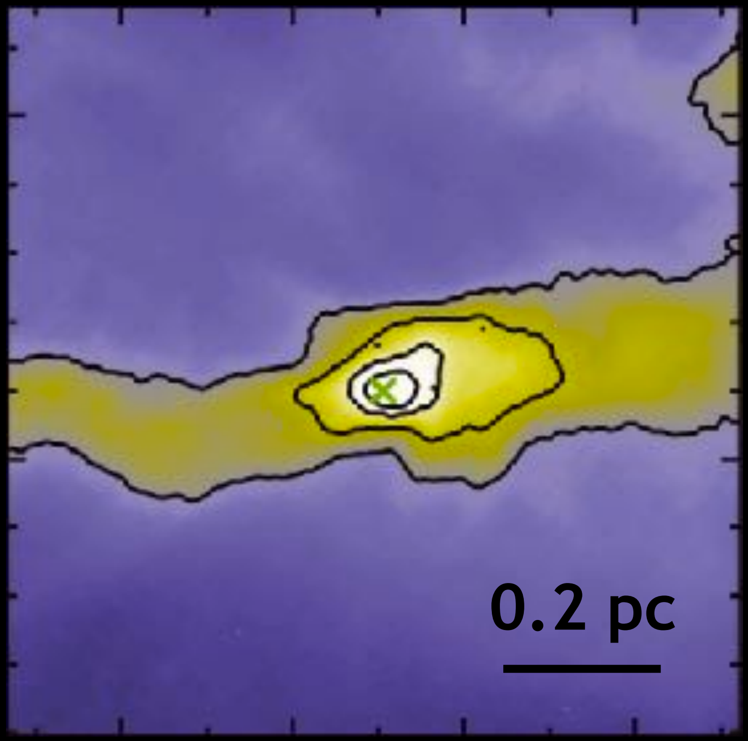
Vianney Taquet
INAF - Osservatorio Astrofisico di Arcetri
Marie Sklodowska-Curie AstroFIt2 fellow

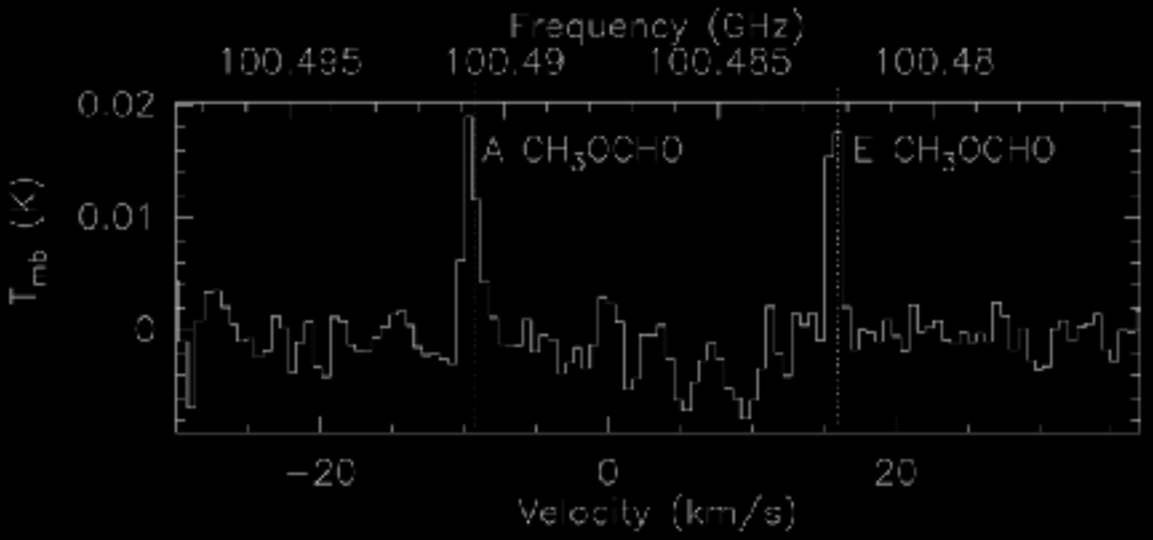
Cold COMs in prestellar cores

First detections of several saturated O-bearing complex organic molecules in nearby prestellar cores: L1689B and L1544

L1689B

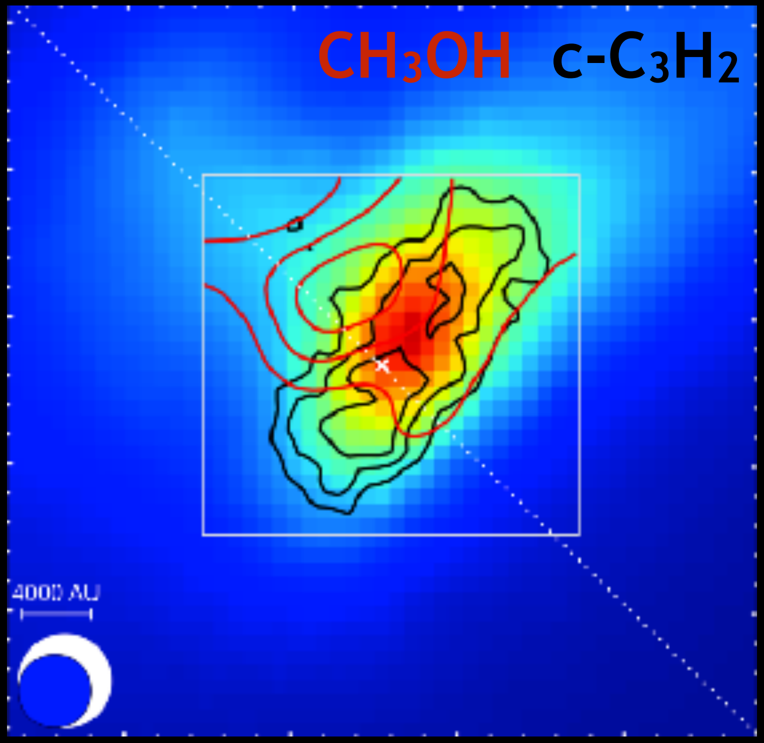
Bacmann et al. (2012)

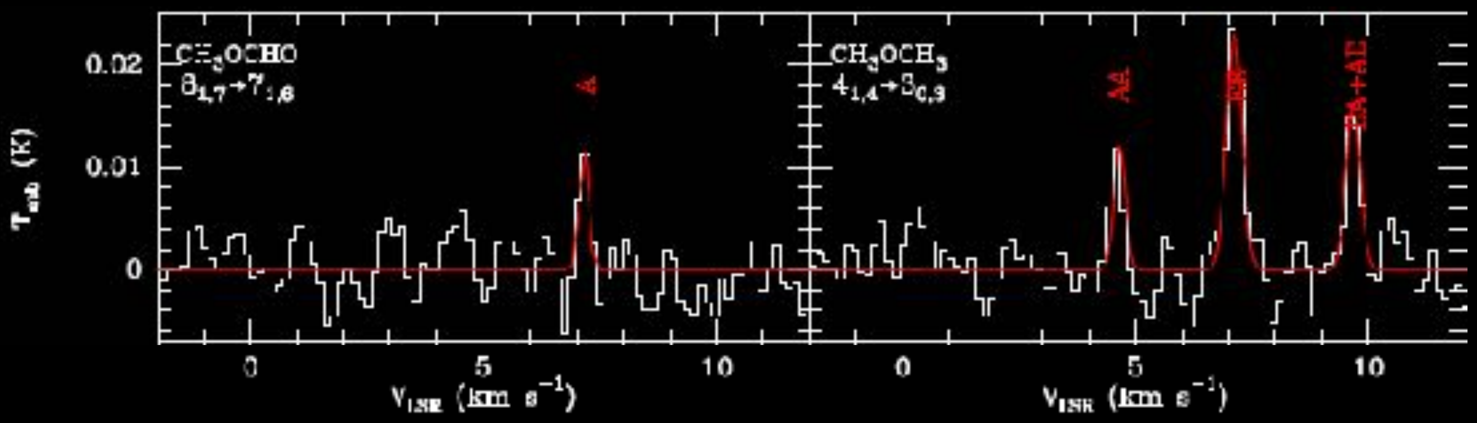




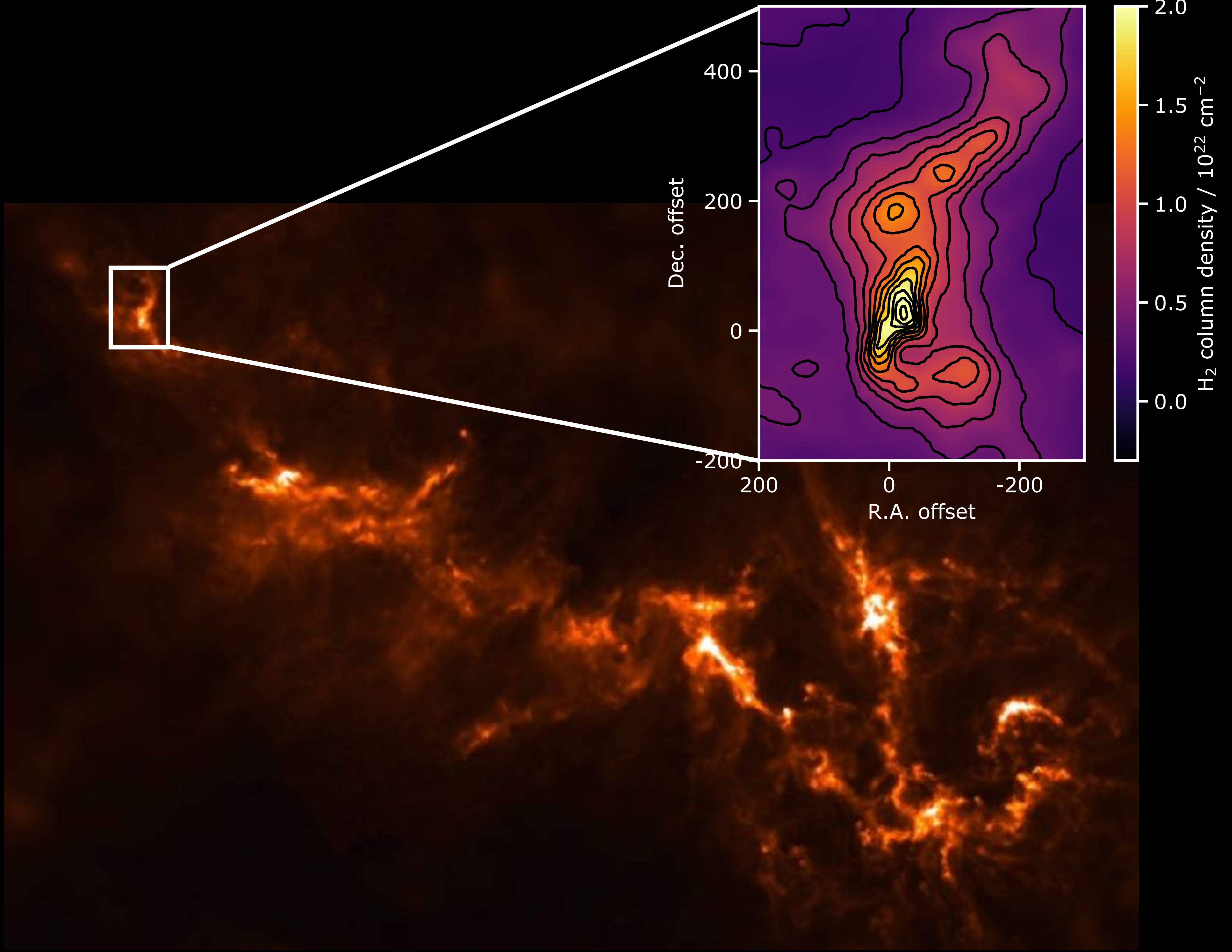
L1544

Vastel et al. (2014), Jimenez-Serra et al. (2016)





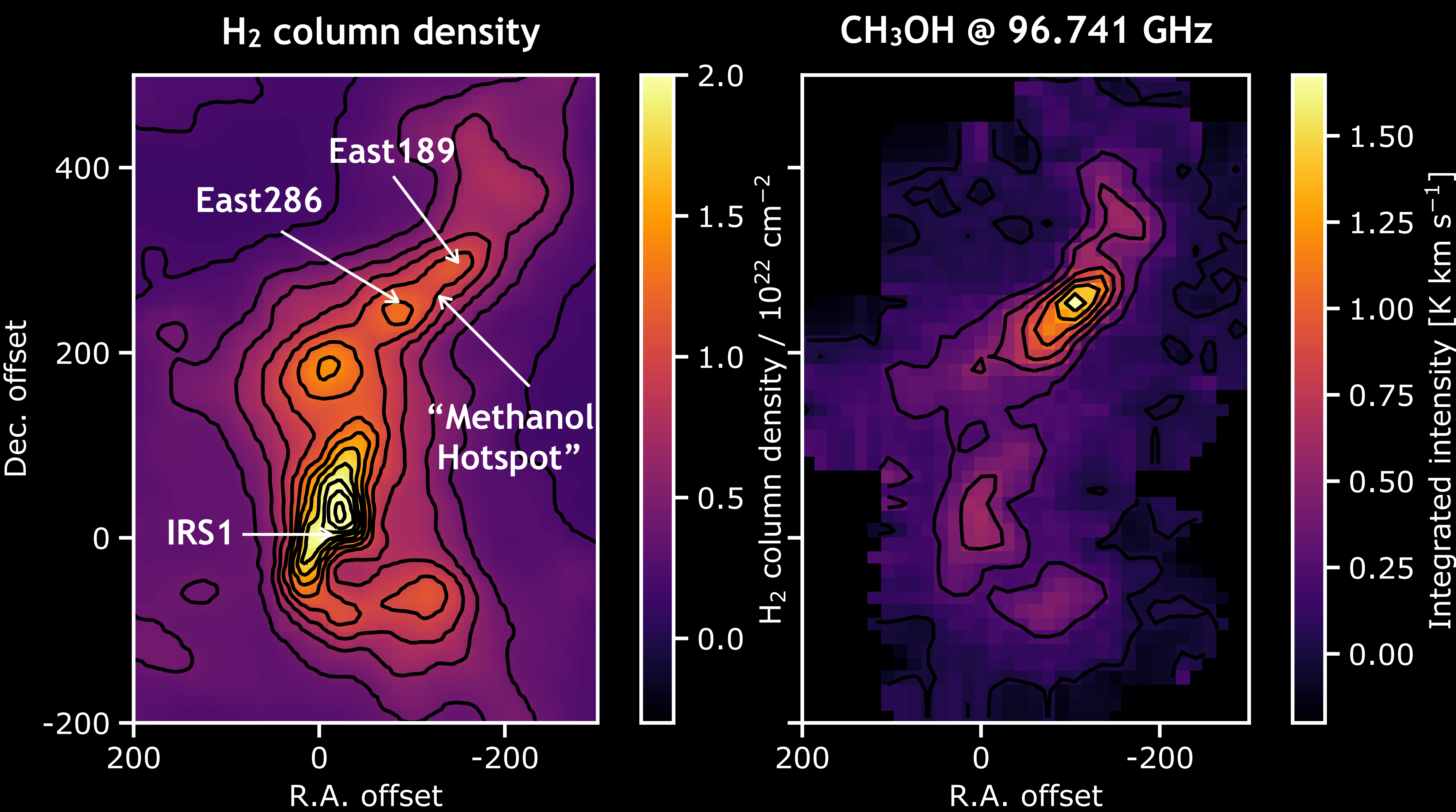
The Barnard 5 molecular cloud



The “methanol hotspot” in Barnard 5

Detection of a “Methanol Hotspot” in the Barnard 5 Molecular Cloud, also showing water emission, located between two cold dense cores

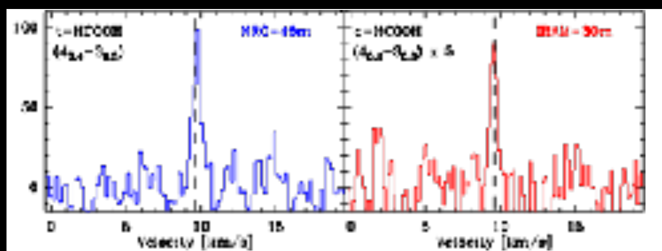
(Wirström et al. 2014)



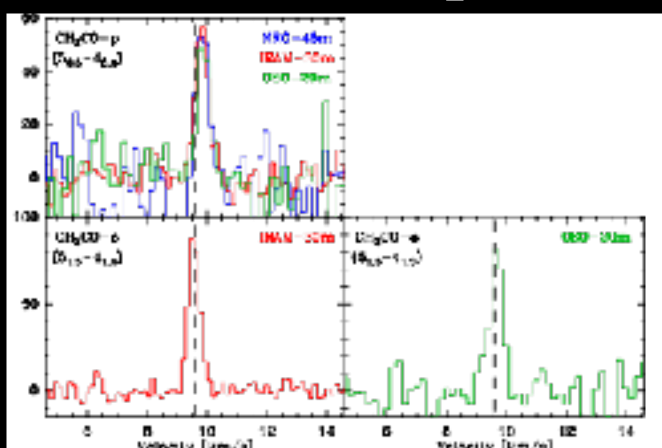
Detection of COMs in Barnard 5

Detection of several O-bearing COMs with the IRAM 30m, NRO 45m, and OSO 20m towards the methanol hotspot

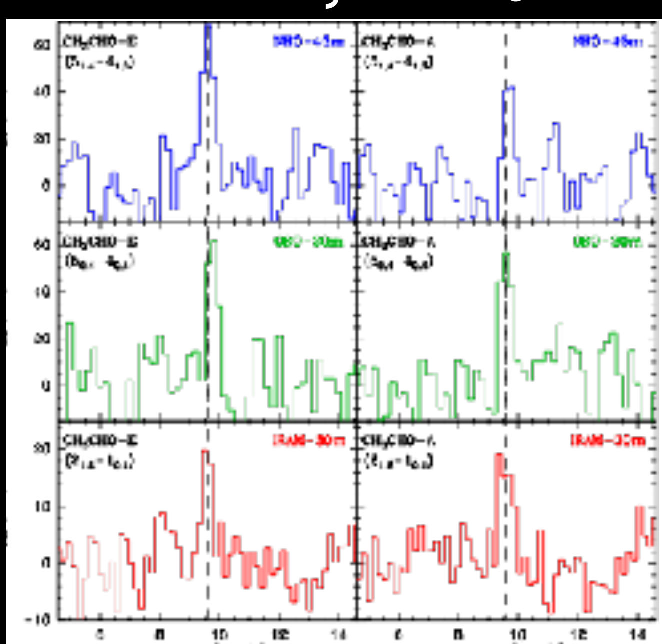
Formic acid HCOOH



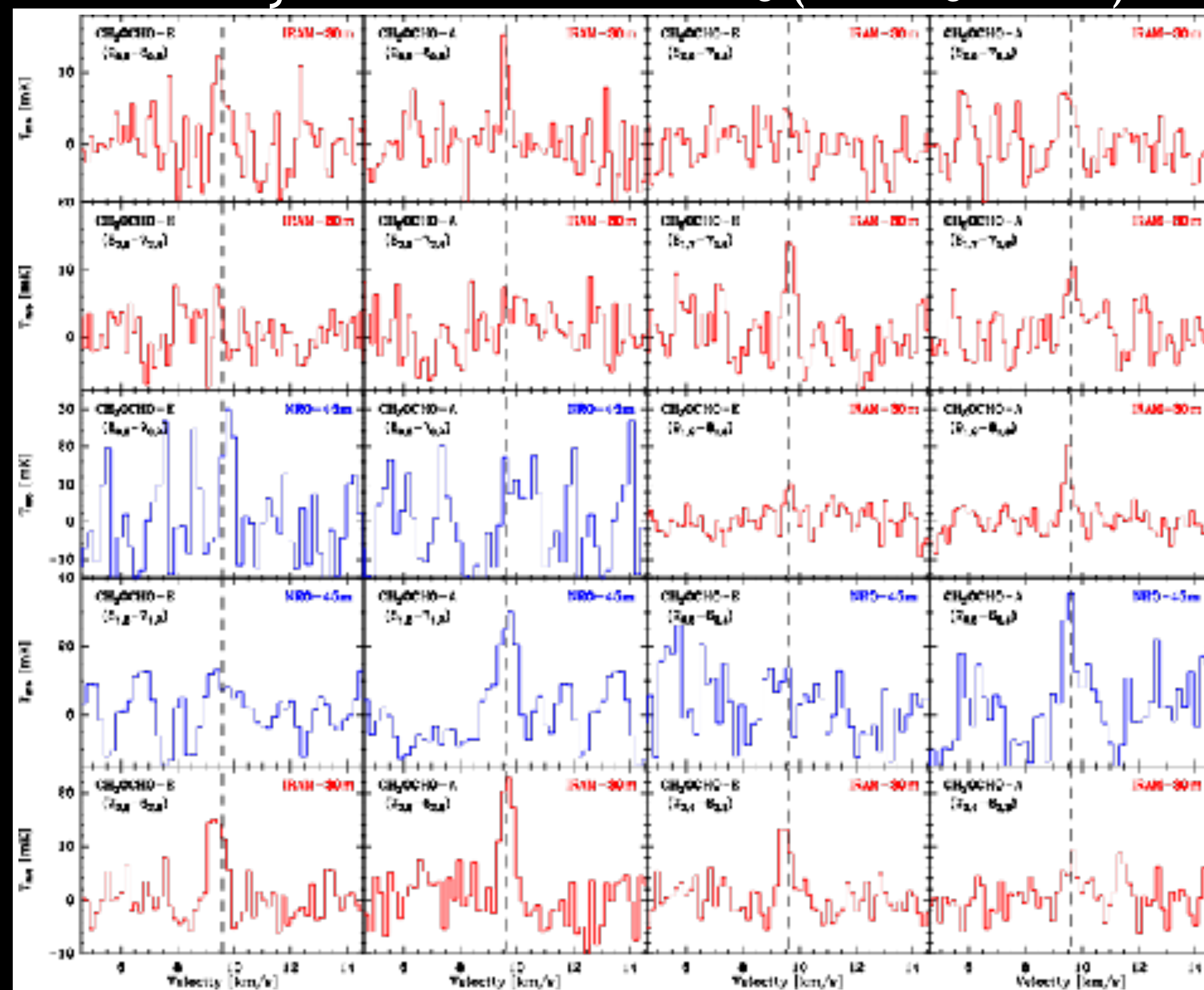
Ketene CH_2CO



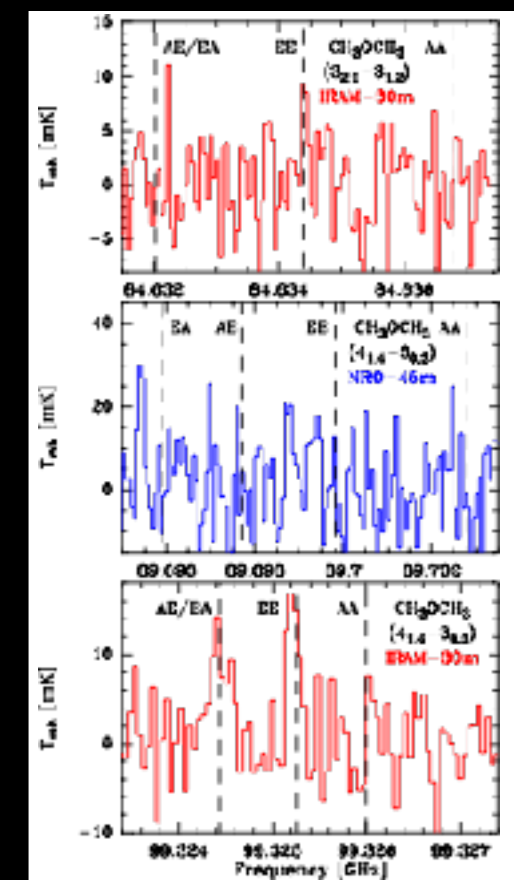
Acetaldehyde CH_3CHO



Methyl formate $HCOOCH_3$ (or CH_3OCHO)



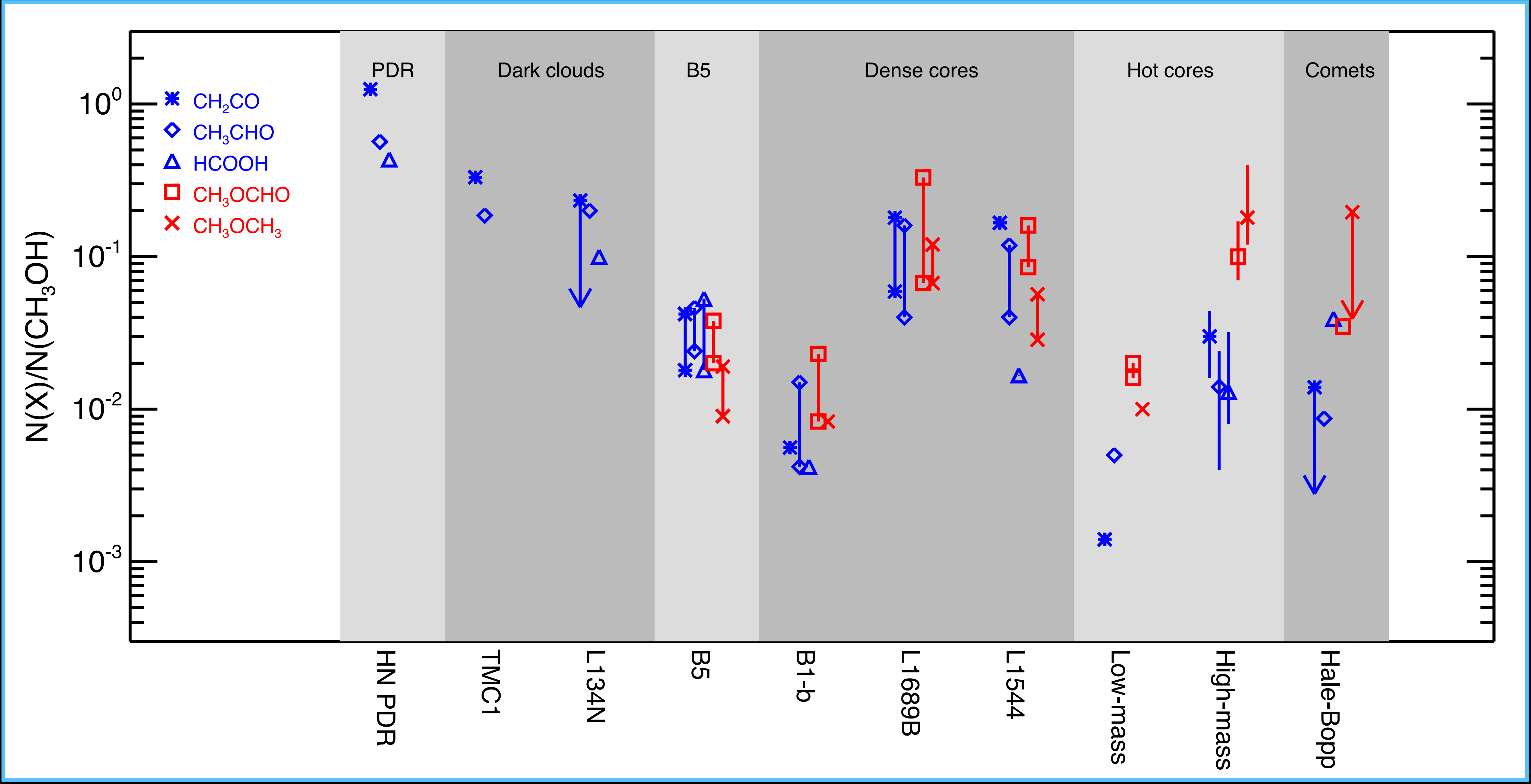
Tentative detection of dimethyl ether CH_3OCH_3



Taquet et al. (2017)

Abundances of COMs with evolutionary stage

Abundances of "cold" COMs decrease with respect to "warm" species with the evolutionary stage



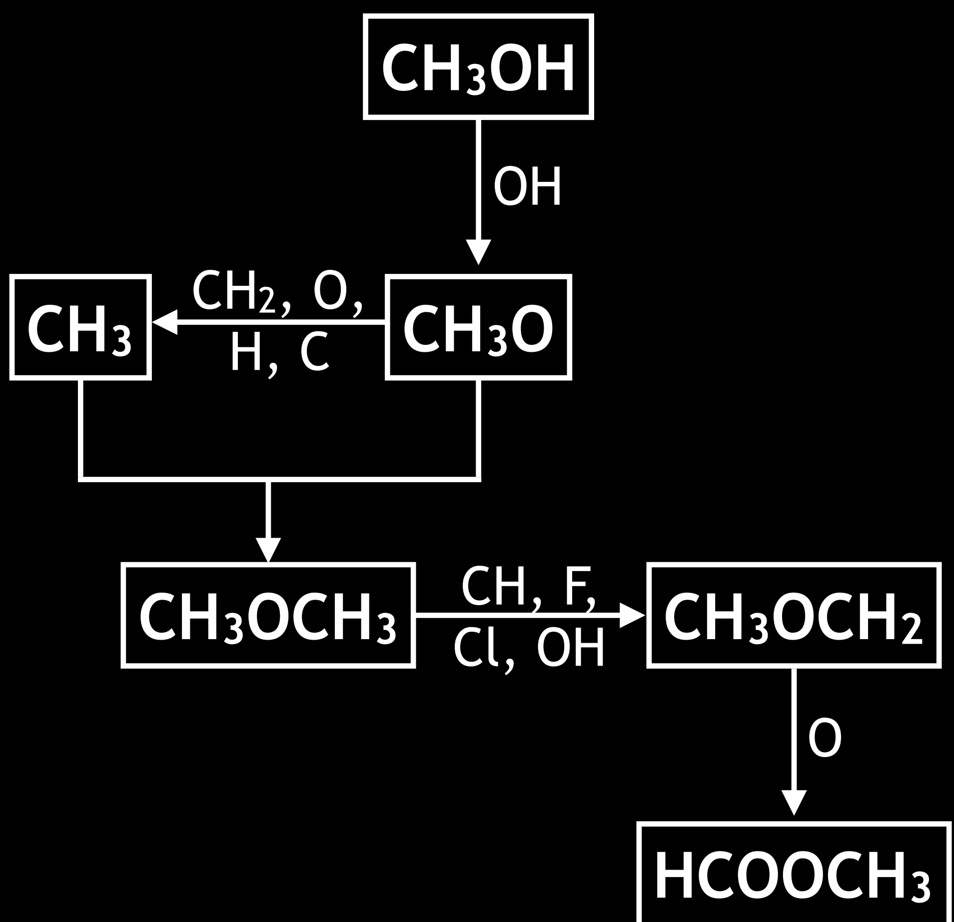
"Warm" species would be mainly produced after the "cold" species (i.e. during the protostar stage) or "cold" species are destroyed

Taquet et al. (2017)

Formation of cold COMs in the gas phase

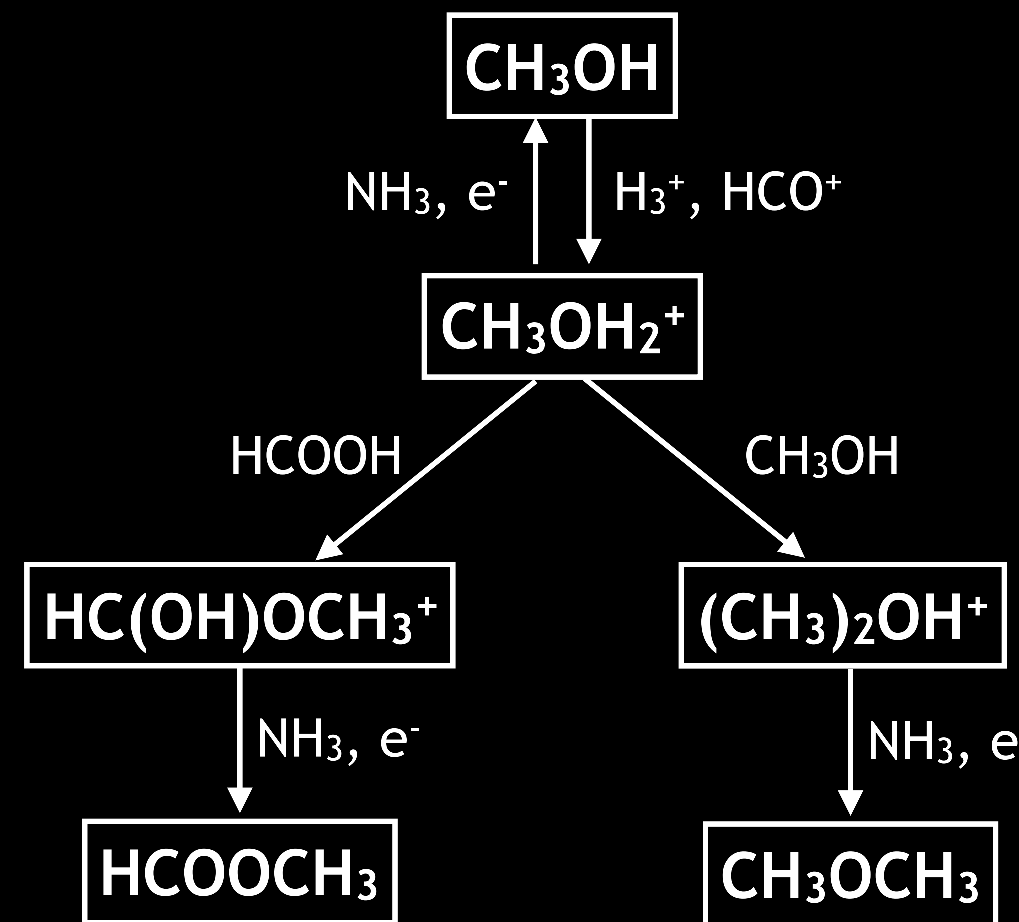
Gas phase formation pathways proposed to explain the detection of cold COMs are based on the presence of gaseous methanol

Neutral-neutral chemistry



Vasyunin & Herbst 2013, Balucani et al. 2015, Vasyunin et al. (2017)

Ion-neutral chemistry



Charnley et al. (1992), Rodgers & Charnley (2001), Taquet et al. (2016)

How to produce methanol in the cold gas phase ?

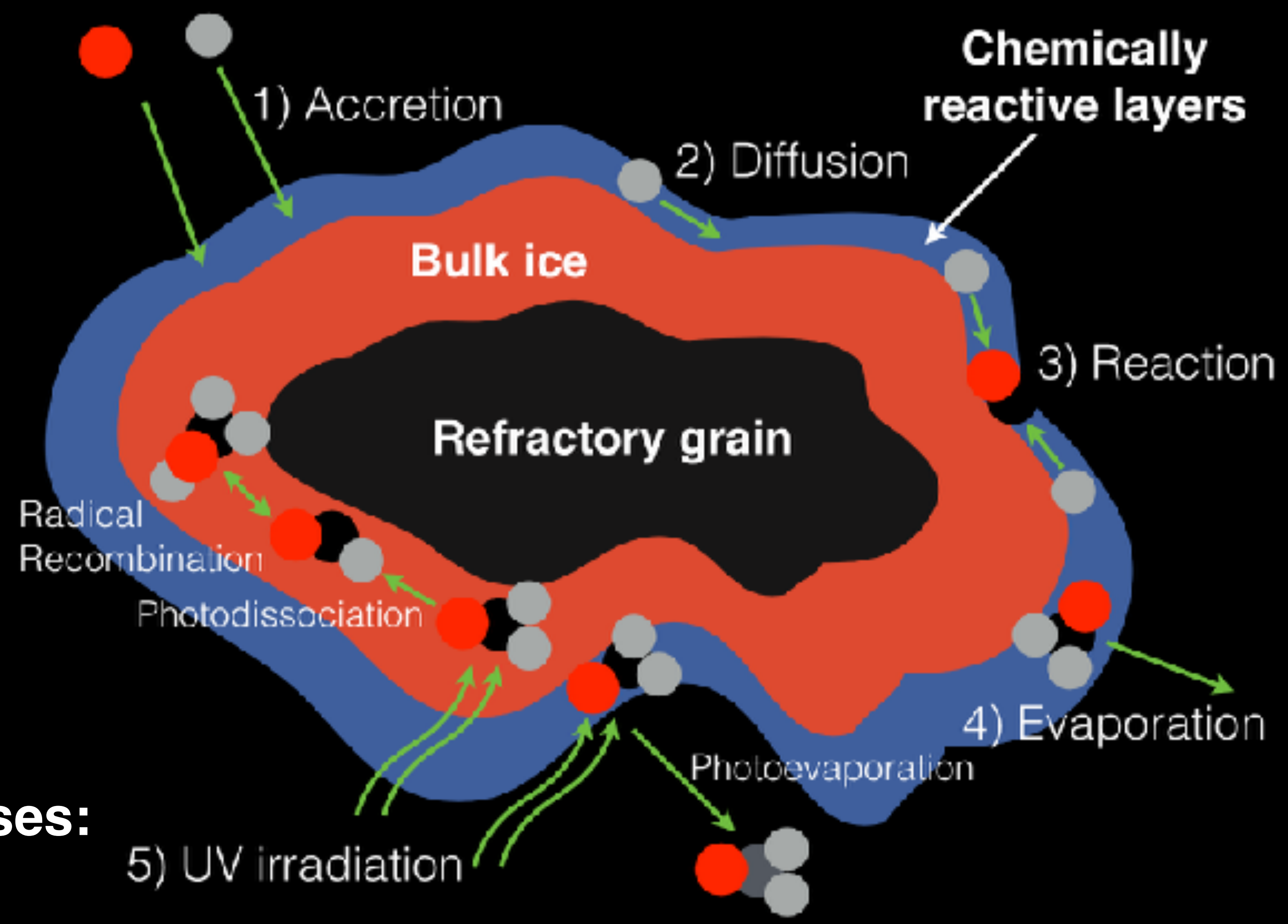
$X(\mathrm{CH_3OH}) \sim 10^{-9} - 10^{-8}$

Modelling the chemical processes in the ISM

Gas phase chemistry

Dissociation, ionisation, ion-neutral, neutral-neutral reactions
(KIDA, or UMIST chemical databases)

Gas-grain processes

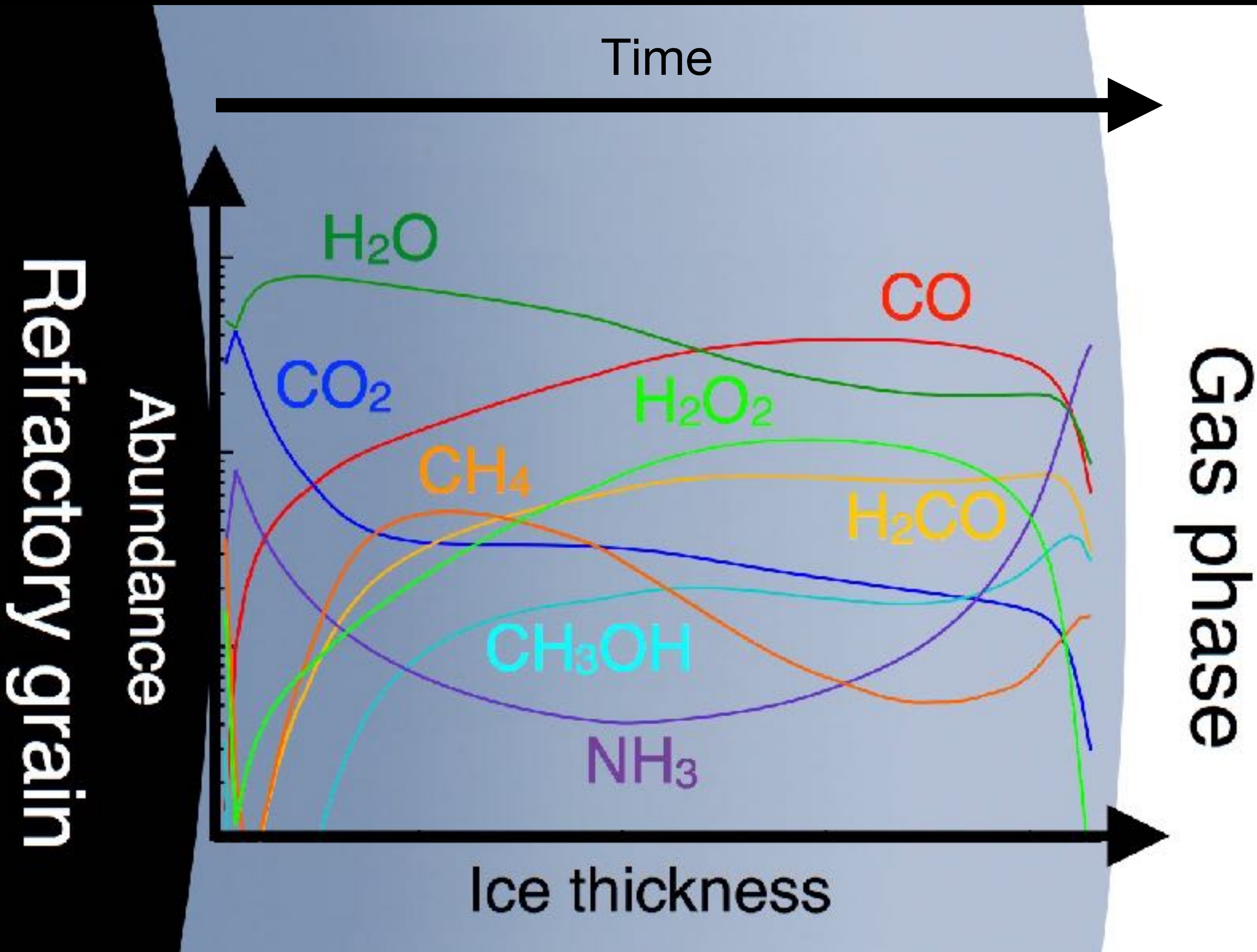


Non-thermal desorption processes:

1) CR-induced grain heating
2) Photolysis
3) CR ice sputterring
4) Chemical desorption
5) Explosive desorption

Ice structure predicted by macroscopic models

Multiphase models predict the chemical heterogeneity of ices induced by the evolution of gas phase abundances physical conditions in dark clouds



Taquet et al. (2014), see also Charnley & Rodgers (2009), Vasyunin & Herbst (2013), Furuya et al. (2016)

Gas phase formation of methanol

Methanol in the gas phase can be formed by the radiative association reaction:

$CH_3^+ + H_2O \rightarrow CH_3OH_2^+$ $k = 2\ 10^{-12}\ cm^3\ s^{-1}$ (Luca et al. 2002)

Followed by electronic recombination

$CH_3OH_2^+ + e^- \rightarrow CH_3OH$ BR = 3 % (Geppert et al. 2005)

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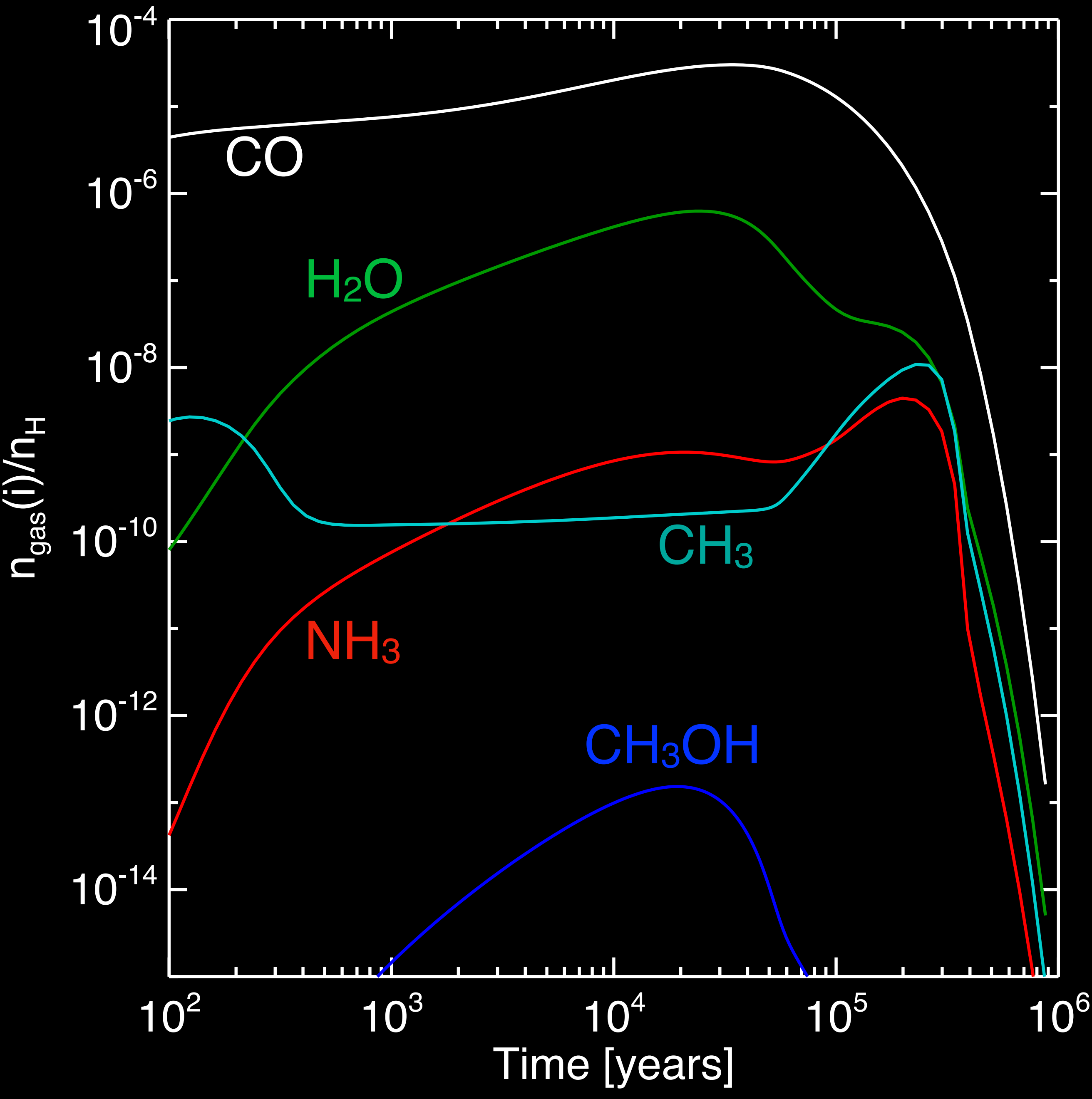

$n_H = 10^5\ cm^{-3}$
$T_d = T_g = 10$ K
$A_V = 20$ mag
$\zeta = 10^{-17}\ s^{-1}$

Desorption by CR-induced grain heating

Cosmic-ray particles with energies between 20-70 MeV / nucleon deposit:
about 0.4 MeV on 0.2 μm grains → grain heating from 10 to 70 K (Léger et al. 1985)

$$k_{CR}(i) = f(70\text{ K})\, k_{ev}(70\text{ K}, i)$$ (Hasegawa et al. 1993)

f(70 K): fraction of time spent at 70 K = $3.2\ 10^{-19}$
= grain cooling time / time interval between two heating events = 10^{-5} s / $3.2\ 10^{13}$ s

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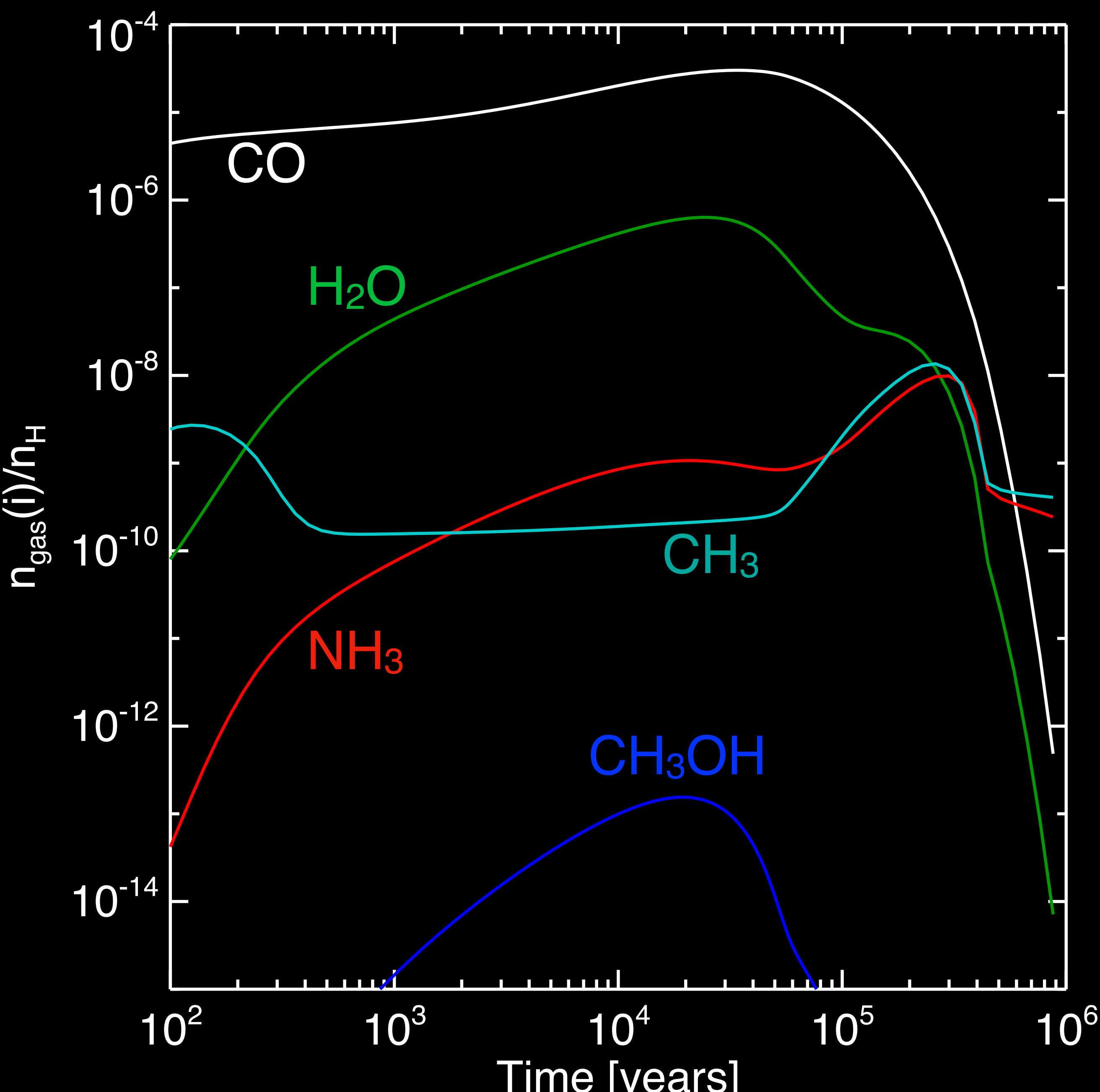

$n_H = 10^5$ cm^{-3}
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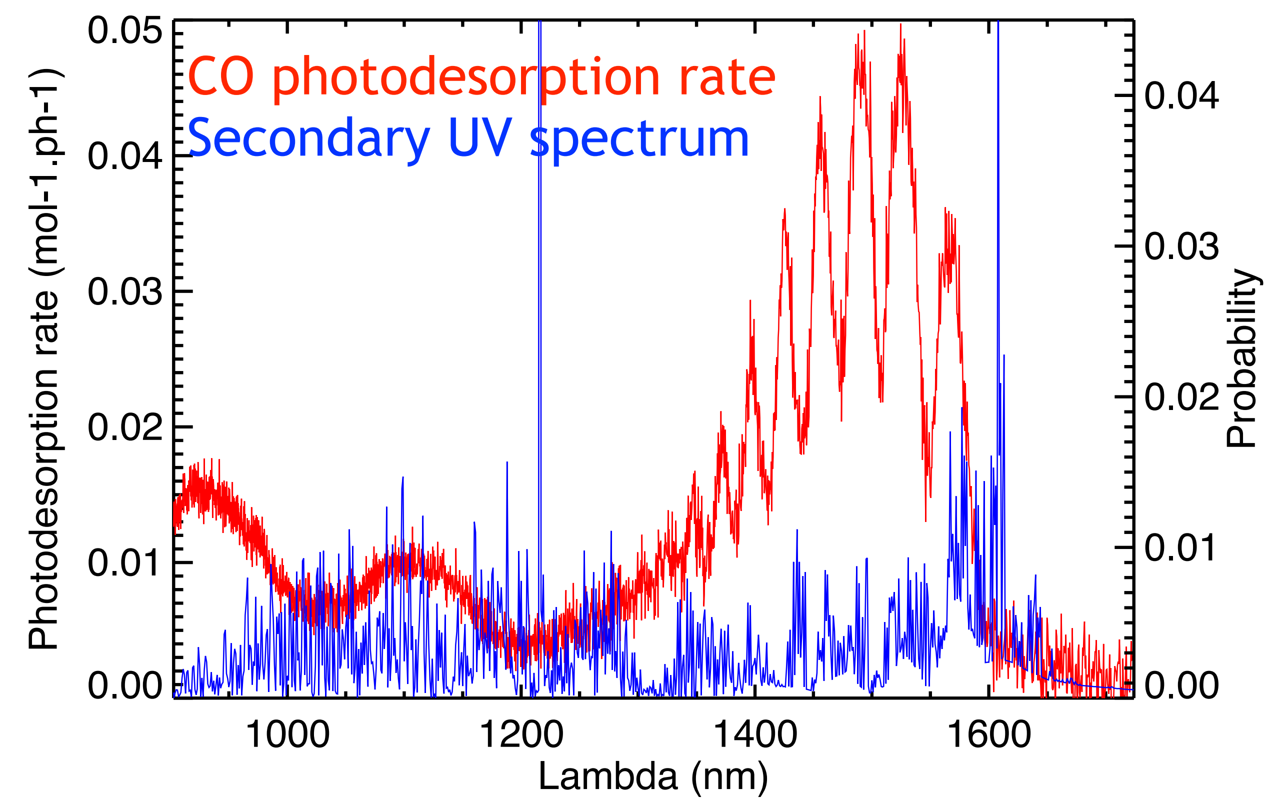
Desorption by UV photolysis

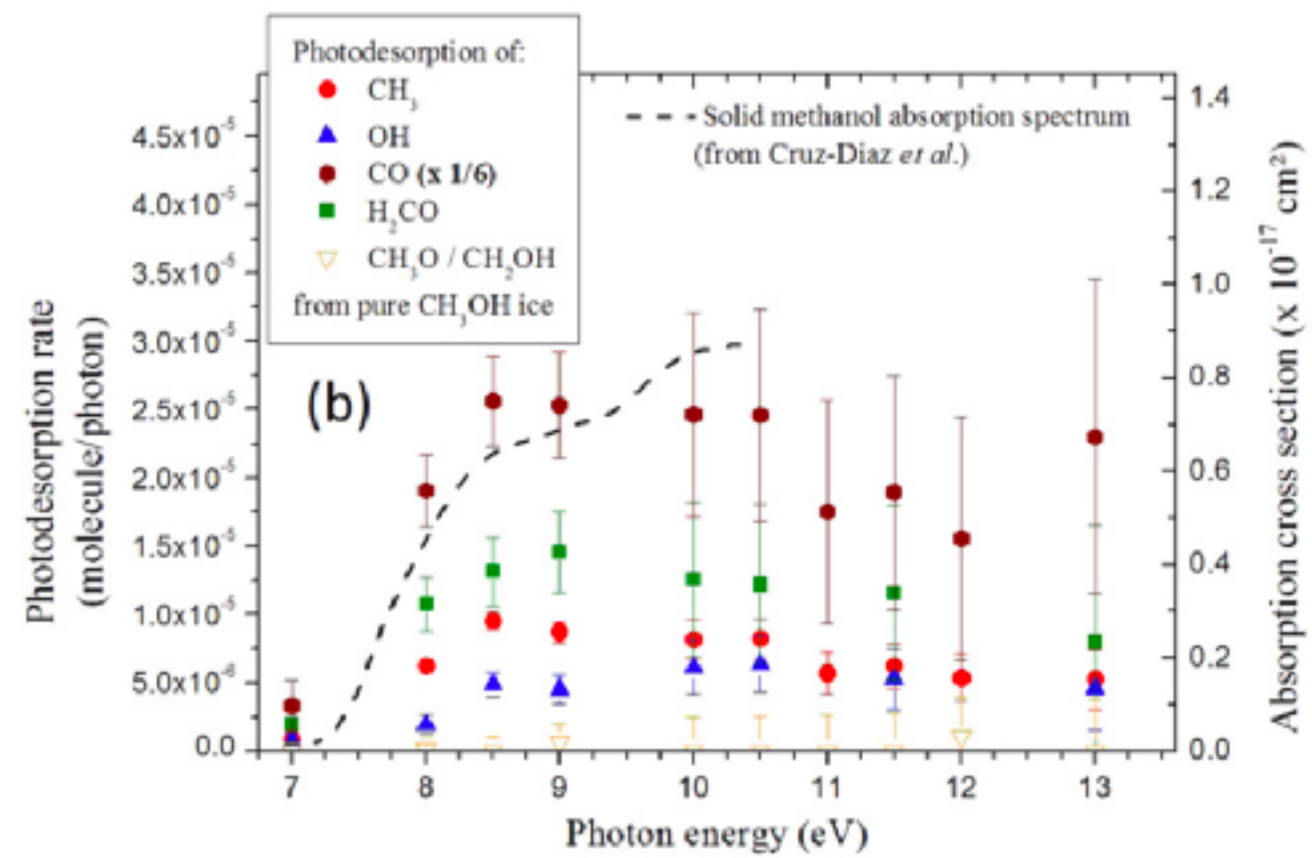
Flux of UV photons (≃ 10^4 photons cm^{-2} s^{-1}) produced by the relaxation of H_2 excited by secondary electrons formed through ionisation of H_2 by CRs
(Prasad & Tarafdar 1983, Sternbeg et al. 1987, Shen et al. 2004)

→ Need for wavelength-dependent studies of UV photolysis of ices

Pure CO ice



Pure CH_3OH ice



Yield(CO photodesorp.) ~ 10^{-2} mol photon^{-1}

Yield(CH_3OH photodesorp.) ~ 10^{-5} mol photon^{-1}

Fayolle et al. (2011)

Bertin et al. (2015)
See also Cruz-Diaz et al. (2016)

Desorption by UV photolysis

Incorporation of measured or computed absorption cross sections and photo-dissociation / photo-evaporation yields

$$k_{UV}(i) = (F_{\mathrm{UV,ext}}\, Y_{\mathrm{UV,ext}}(i) + F_{\mathrm{UV,CR}}\, Y_{\mathrm{UV,CR}}(i))\, \sigma_{\mathrm{d}}/N_{\mathrm{s}}$$

(Andersson & van Dishoeck 2008, Fayolle et al. 2011, Bertin et al. 2013, 2015, etc)

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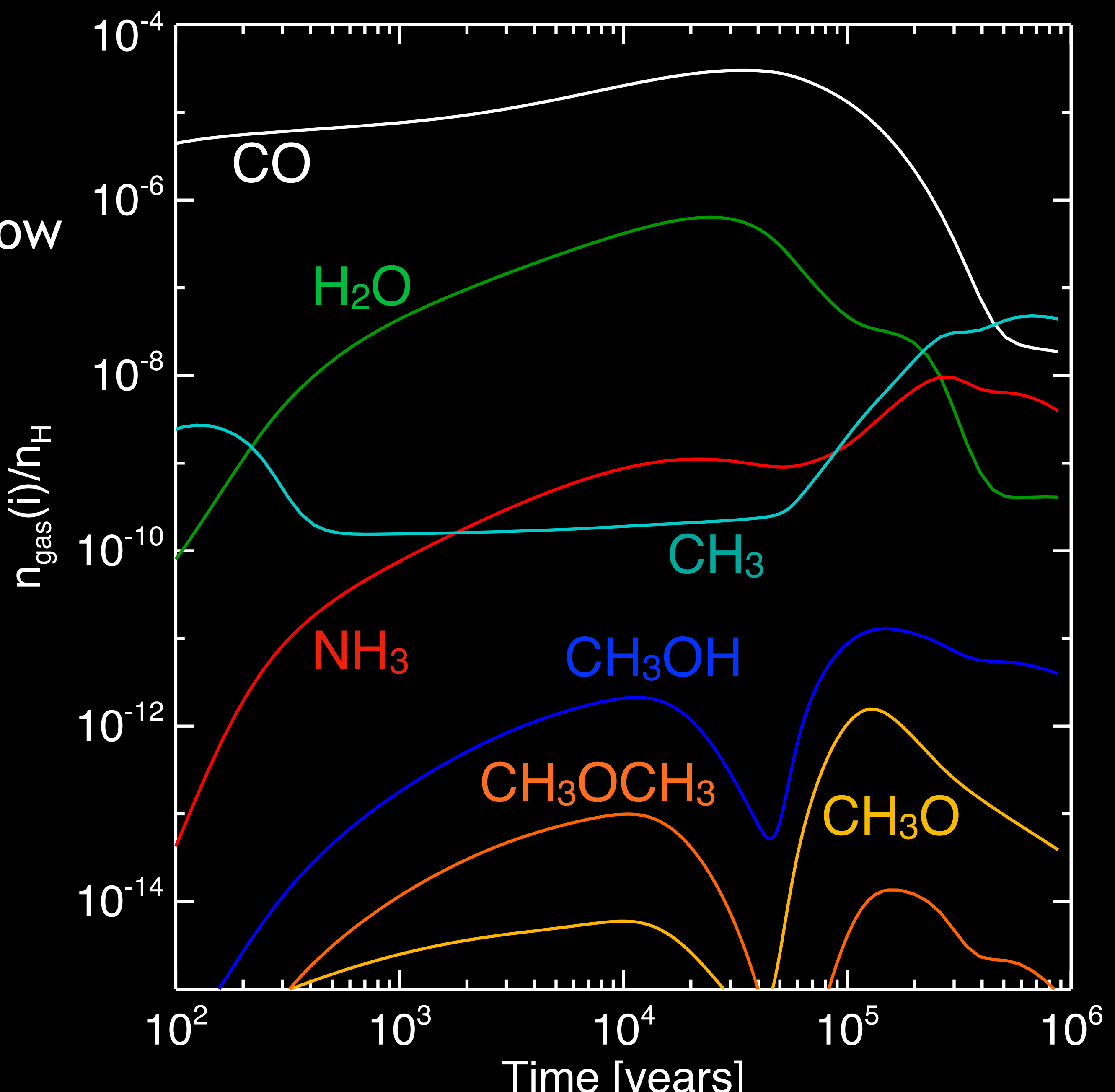
(Andersson & van Dishoeck 2008, Fayolle et al. 2011, Bertin et al. 2013, 2015, etc)

2 CH_3OH peaks:
1) CH_3+O triggered by low CH_3 binding energy
2) CO hydrogenation



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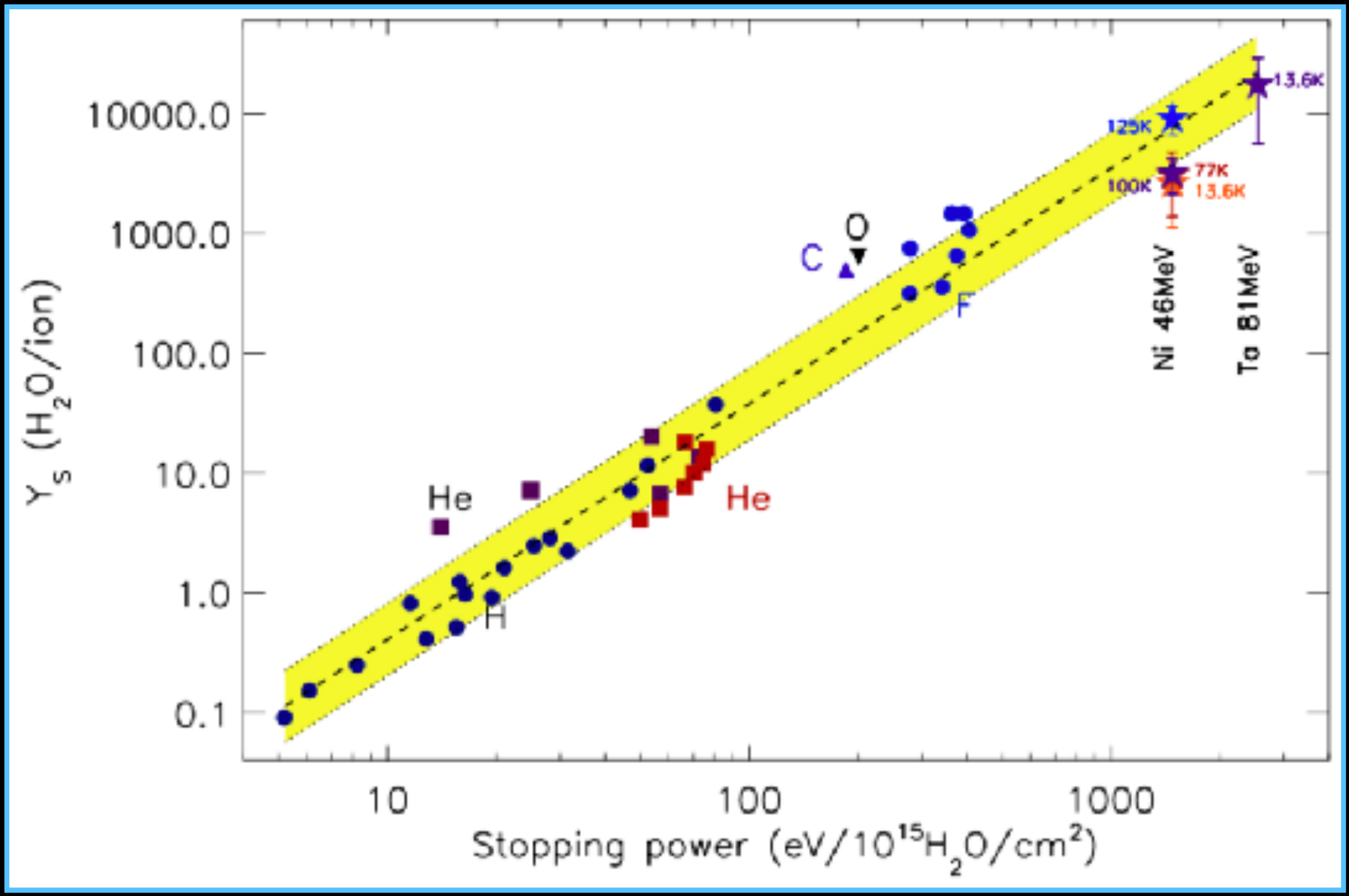
Ice sputtering by cosmic rays

In addition to crystallisation, cosmic-rays can sputter interstellar ices as shown by laboratory experiments
(Brown et al. 1984, Dartois et al. 2015)



	GCR		
E_0(MeV)	200	400	600
ζ(s^{-1})^a	3.34(−16)	5.89(−17)	2.12(−17)
η^{GCR}(H_2O/cm^2/s)^b	27.0^{+26}_{-13}	$8.3^{+8.2}_{-4.1}$	$4.1^{+4.1}_{-2.1}$

Y ~ 10^{-3} (vs ~10^{-5} for UV photodesorption of CH_3OH)

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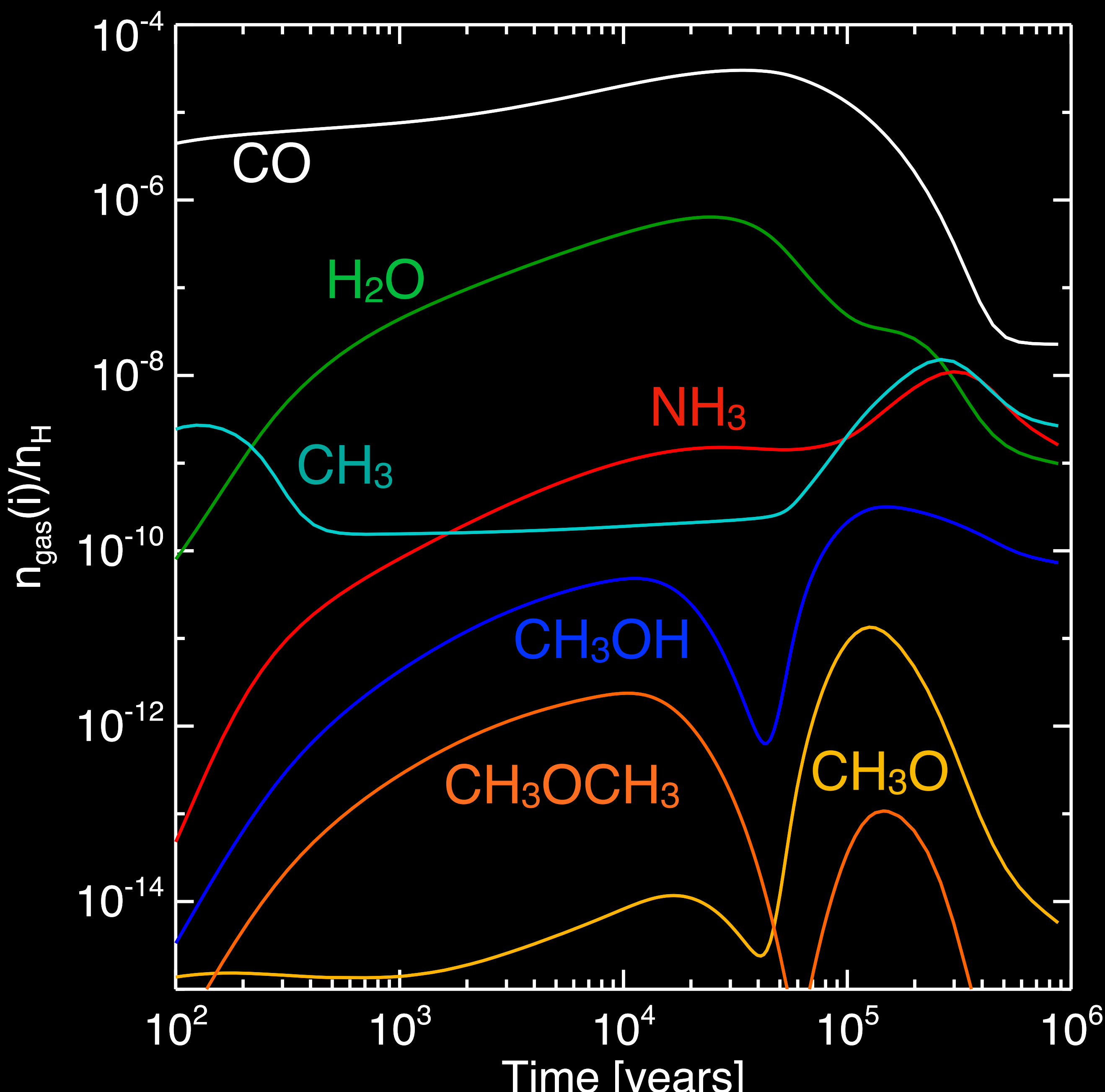

$n_H = 10^5$ cm^{-3}
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$\zeta = 10^{-17}$ s^{-1}

Chemical desorption

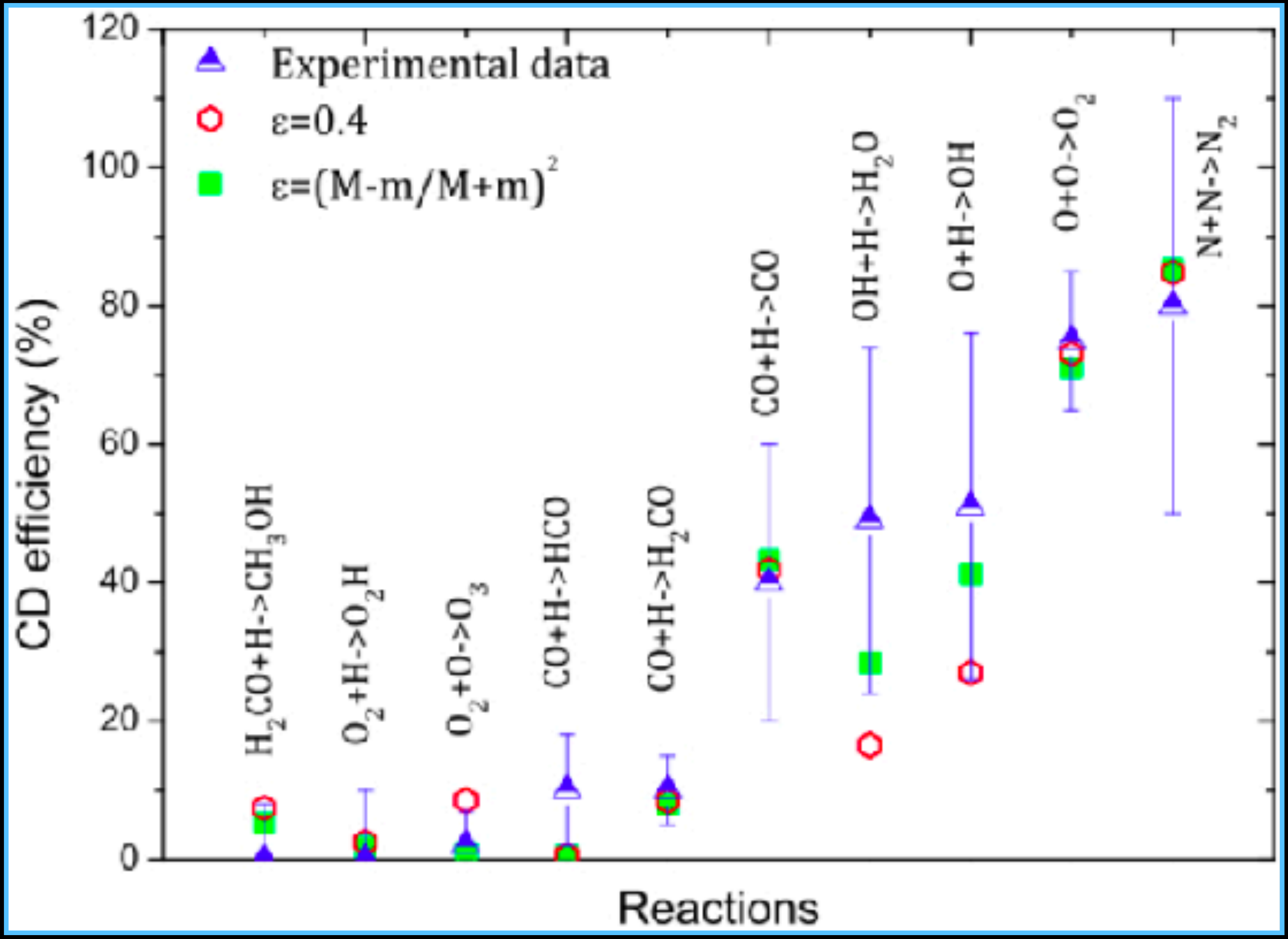
Energy released by exothermic surface reaction can break binding energy of product through the so-called "chemical desorption" process

Efficiency of product ejected in the gas estimated to be ~ 1 - 2 % (Garrod et al. 2007)

Experiments show that this fraction depends on product, reaction, and substrate:

$$\mathrm{CD} = e^{-\frac{E_{\mathrm{binding}}}{\epsilon \Delta H_R / N}}$$

Minissale & Dulieu (2014), Minissale et al. (2016)



See
A. Vasyunin's talk

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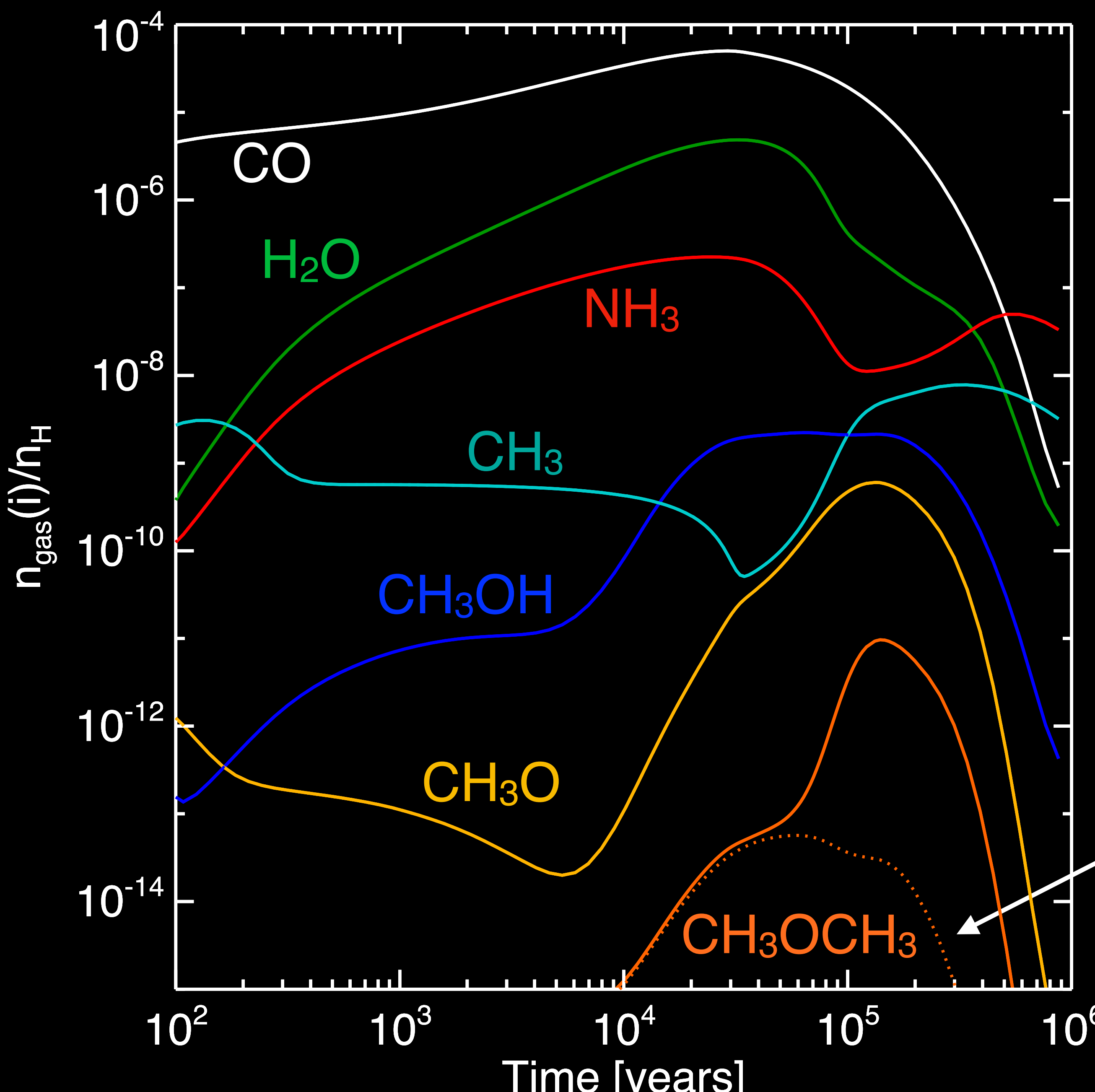

Without CH_3O+CH_3 reaction

$n_H = 10^5\ cm^{-3}$
$T_d = T_g = 10\ K$
$A_V = 20\ mag$
$\zeta = 10^{-17}\ s^{-1}$

Conclusions

Several desorption processes have been proposed during the last four decades to explain the detection of volatile (CO, CH_3OH) species in cold gas:

- Efficiency of all processes highly depends on substrate, and specific species

- Chemical desorption on bare or CO surfaces seems to be the most efficient way to explain the abundance of CH_3OH in dark clouds

Cold neutral-neutral gas phase chemistry can explain the presence of COMs in cold dense clouds with abundances of a few percents / CH_3OH

Can this neutral-neutral chemistry important around protostars ?