# Complex Molecules in Protoplanetary Disks


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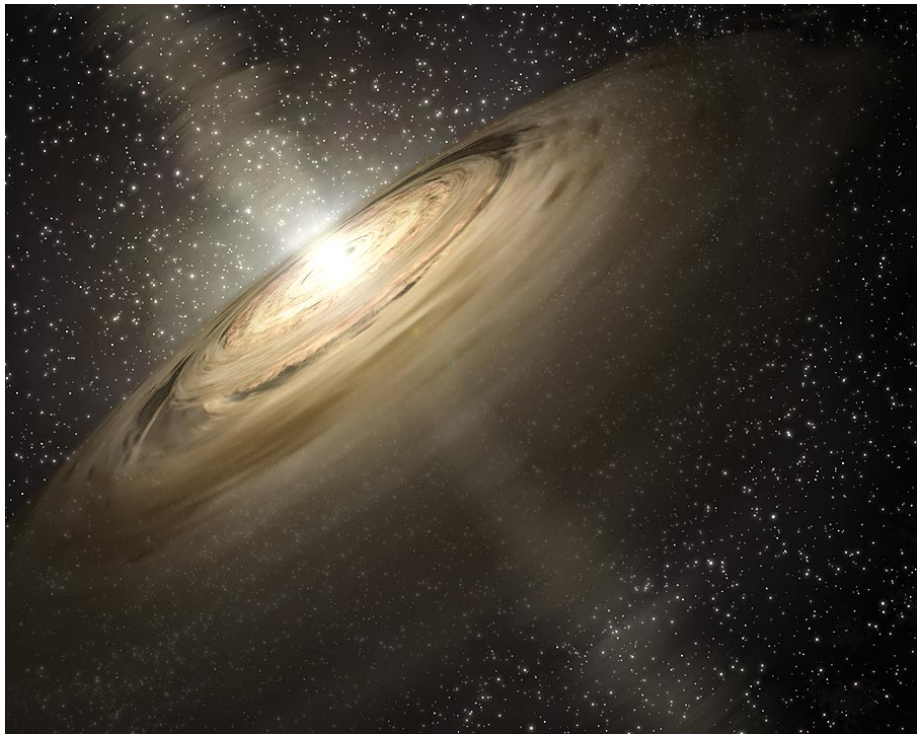
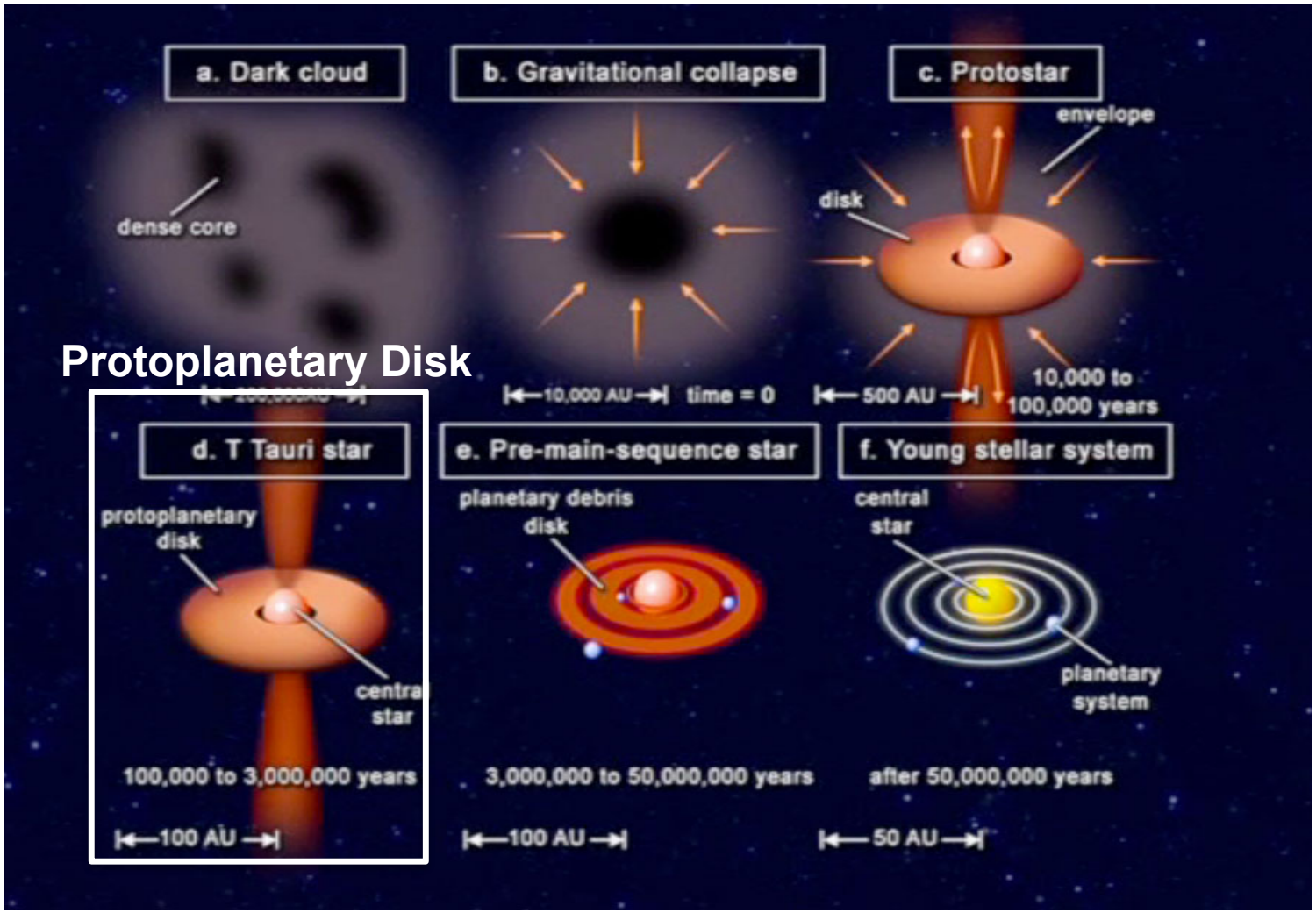
# Outline

- ★ Introduction to star formation
- ★ Complex organic molecules in hot cores
- ★ Hot core chemistry in protoplanetary disks?
- ★ Results
- ★ Summary

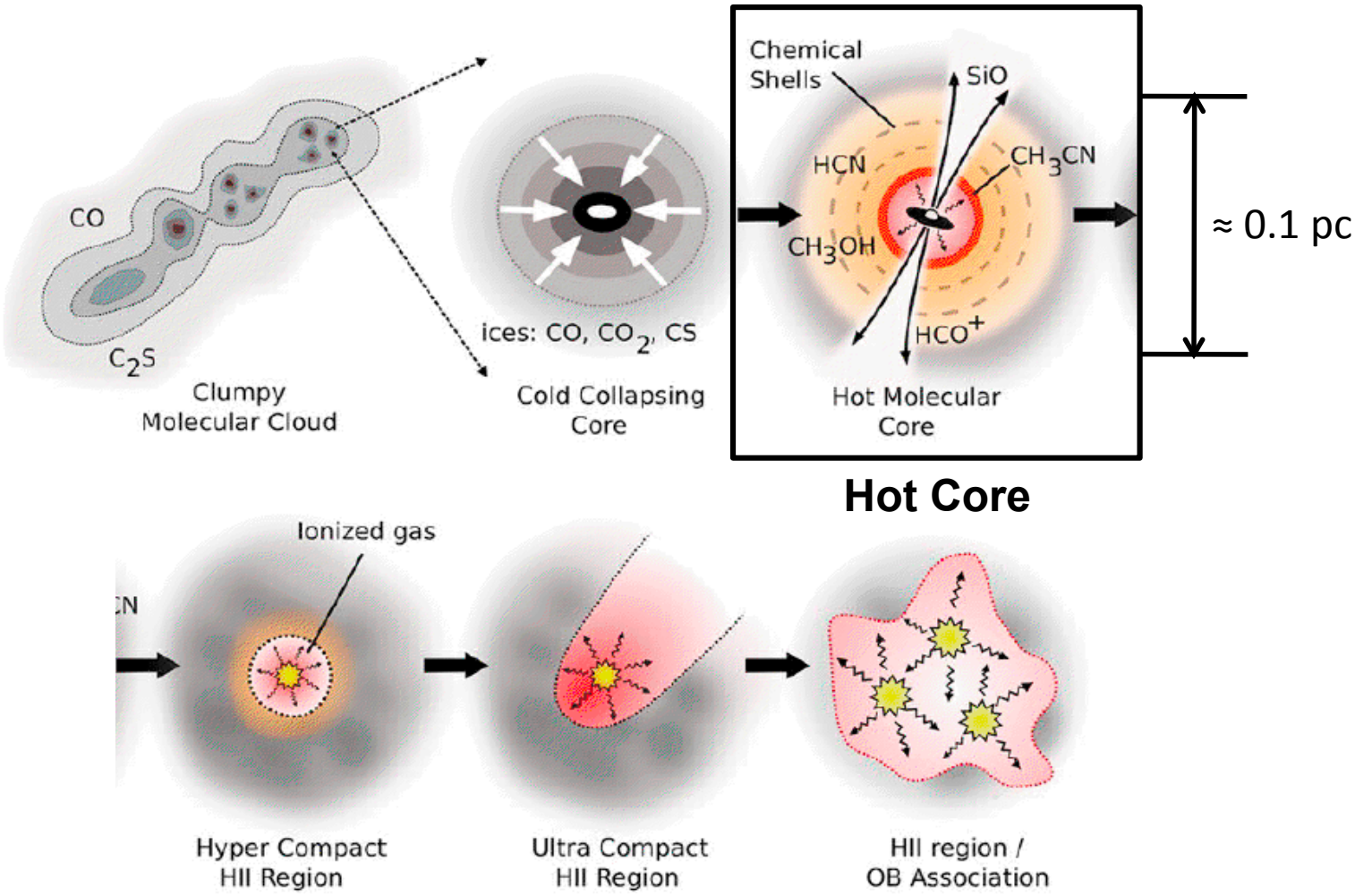


*A dusty disk around a young star. Credit: NASA/JPL-Caltech*

# *Low-mass Star Formation*



# High-mass Star Formation




*www.atnf.csiro.au/research/hypercompact/talks/Purcell.pdf*

# Complex Organic Molecules in Hot Cores

Dense Hot

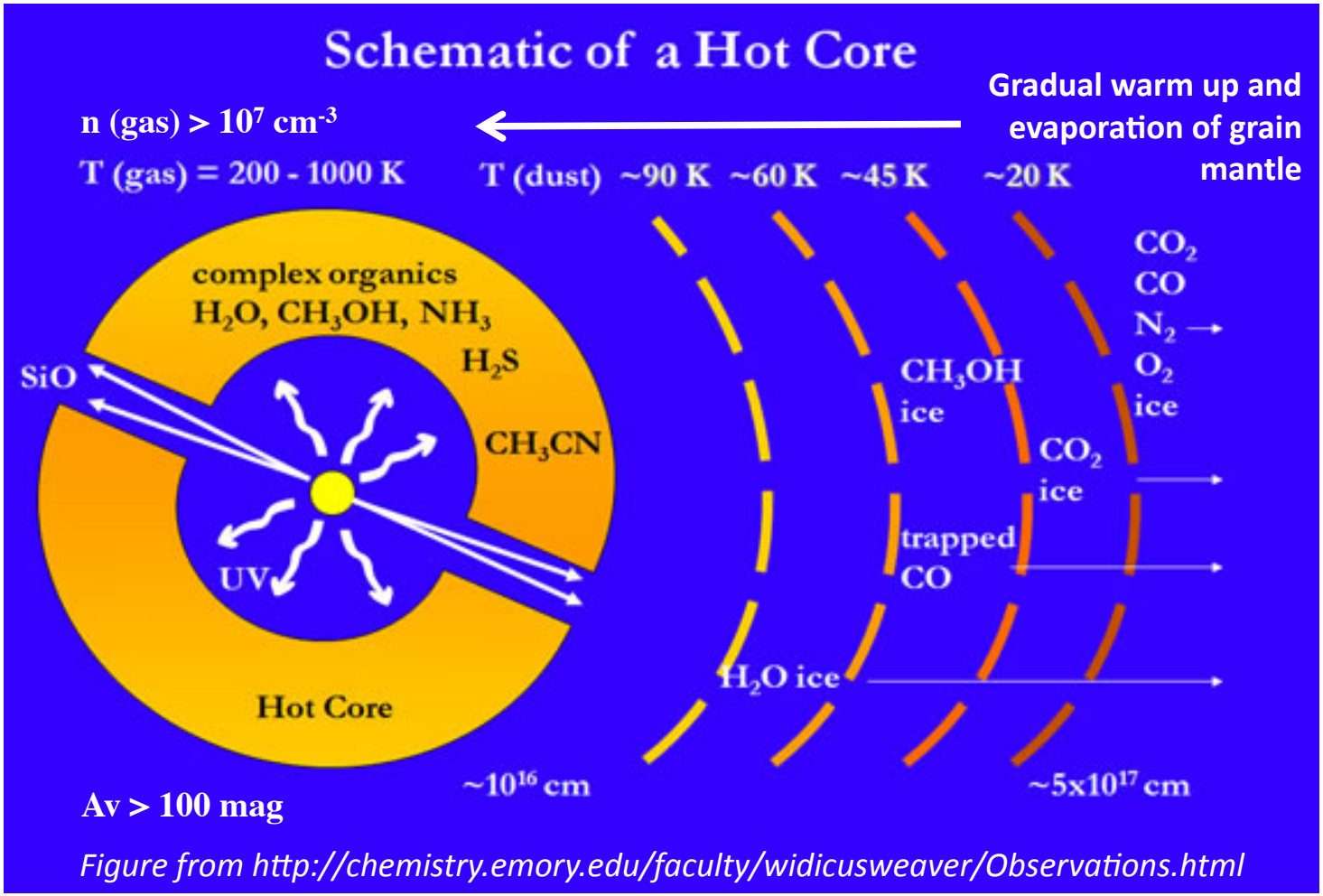



*Figure from http://chemistry.emory.edu/faculty/widicusweaver/Observations.html*

Dark

$CH_3OH$
$HC_2CHO$
$CH_3CHO$
$C_2H_3OH$
$c\text{-}CH_2OCH_2$
$HCOOCH_3$
$CH_3COOH$
$HOCH_2CHO$
$C_2H_5OH$
$CH_3OCH_3$
$CH_3COCH_3$
$HOCH_2CH_2OH$
$C_2H_5CHO$
$HCOOC_2H_5$
$CH_3CN$
$CH_3NC$
$CH_2CNH$
$CH_3NH_2$
$C_2H_3CN$
$NH_2CH_2CN$
$C_2H_5CN$
$n\text{-}C_3H_7CN$
$NH_2CHO$
$CH_3CONH_2$

# Hot Core Chemistry in Protoplanetary Disks?

Observed Molecules: **CO**, CN, CS, OH, SO, $HCO^+$, $N_2H^+$, $\mathbf{H_2O}$, $C_2H$, **HCN**, HNC, $CO_2$, $C_2H_2$, $CH_4$, $H_2CO$ (plus isotopologues e.g. $N_2D^+$, $H_2D^+$, $DCO^+$, DCN, HDO)

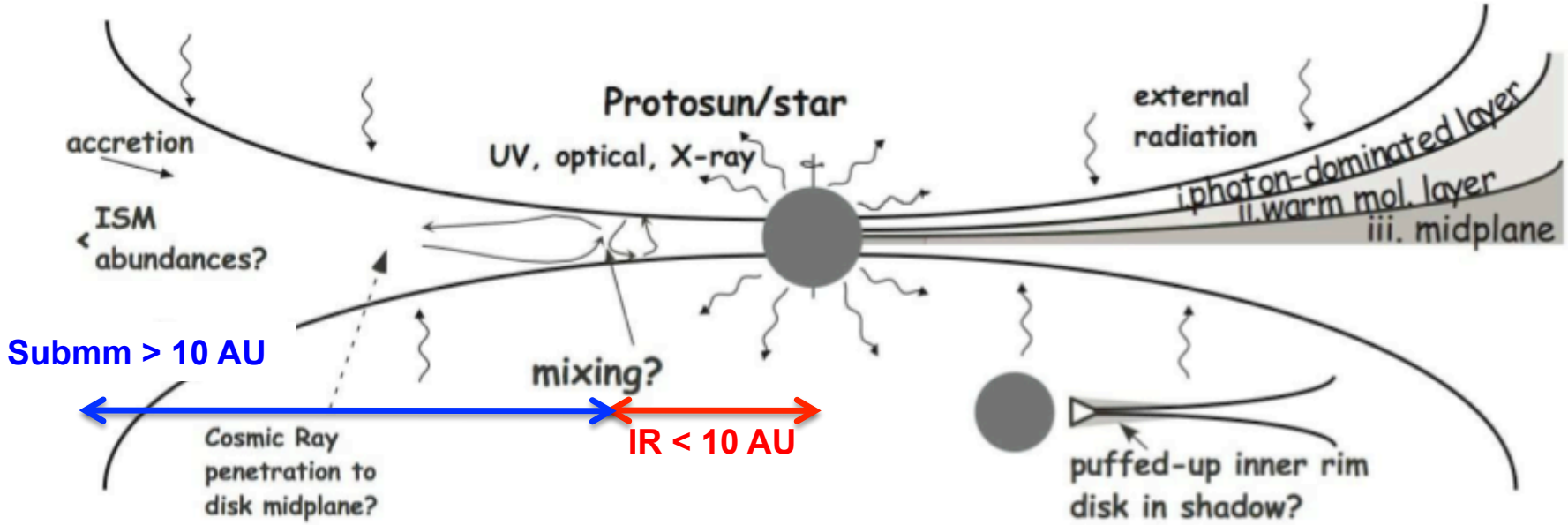


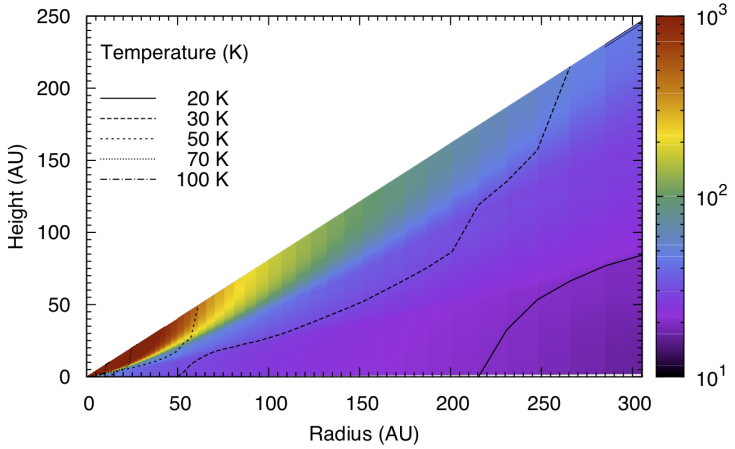

*Figure from Bergin et al. 2007 in Protostars and Planets V, 751*

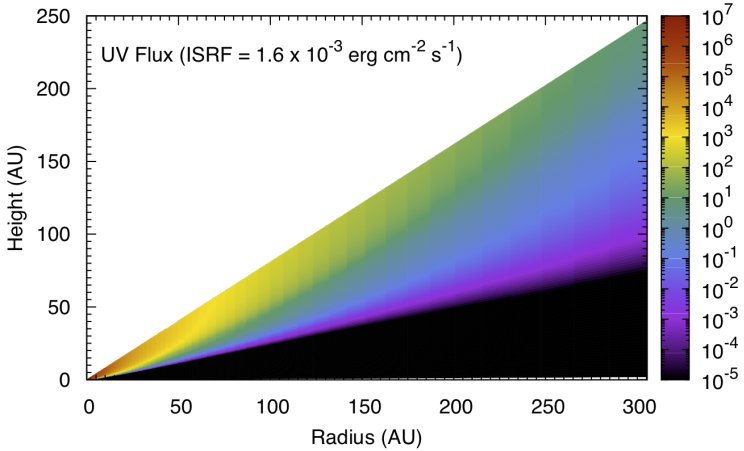
- ⋆Accretion of matter from parent cloud material onto star
- ⋆Dissipation of angular momentum away from the protostellar system
- ⋆Contain all matter, gas and dust, which may form a surrounding planetary system

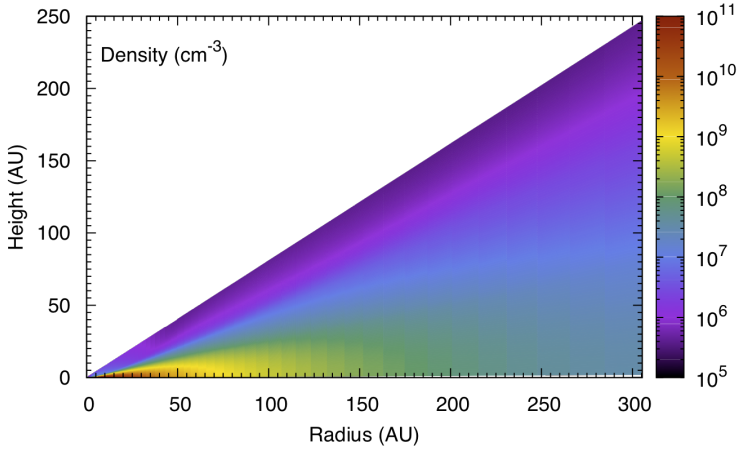
# Hot Core Chemistry in Protoplanetary Disks?

## Disk Model: Protoplanetary disk around a typical T Tauri star

(Nomura & Millar, 2005; Nomura et al. 2007; Walsh et al. 2010, 2011; Heinzeller et al. 2011)



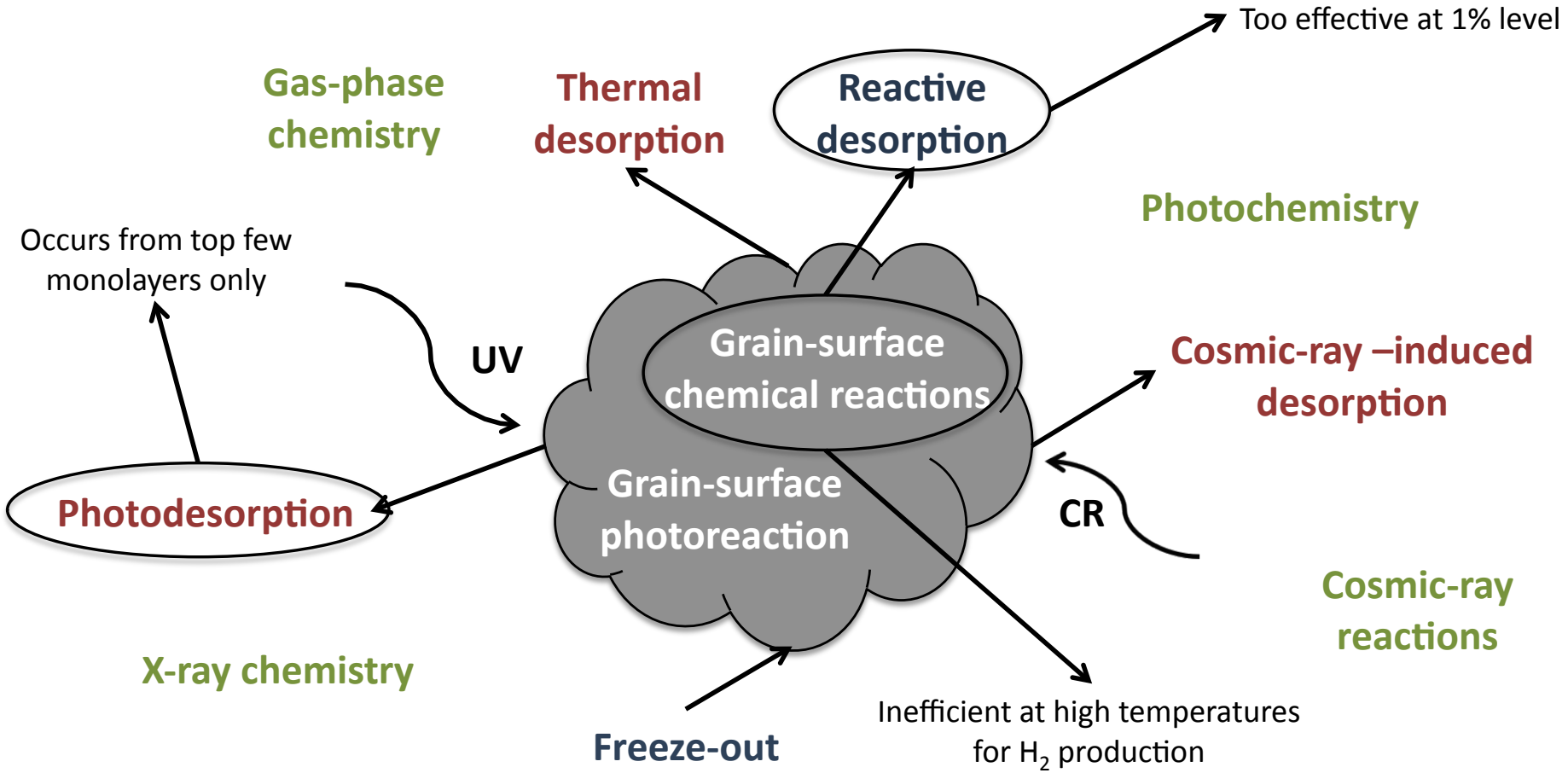




$M_\star$ = 0.5 $M_\odot$, $R_\star$ = 2 $R_\odot$, $T_\star$ = 4000 K
Axisymmetric disk
Steady-state
Hydrostatic equilibrium
X-ray heating
Accretion rate: $dM/dt = 10^{-8}\ M_\odot\ yr^{-1}$
Viscosity: $\alpha = 0.01$; $v \approx \alpha c_s H$

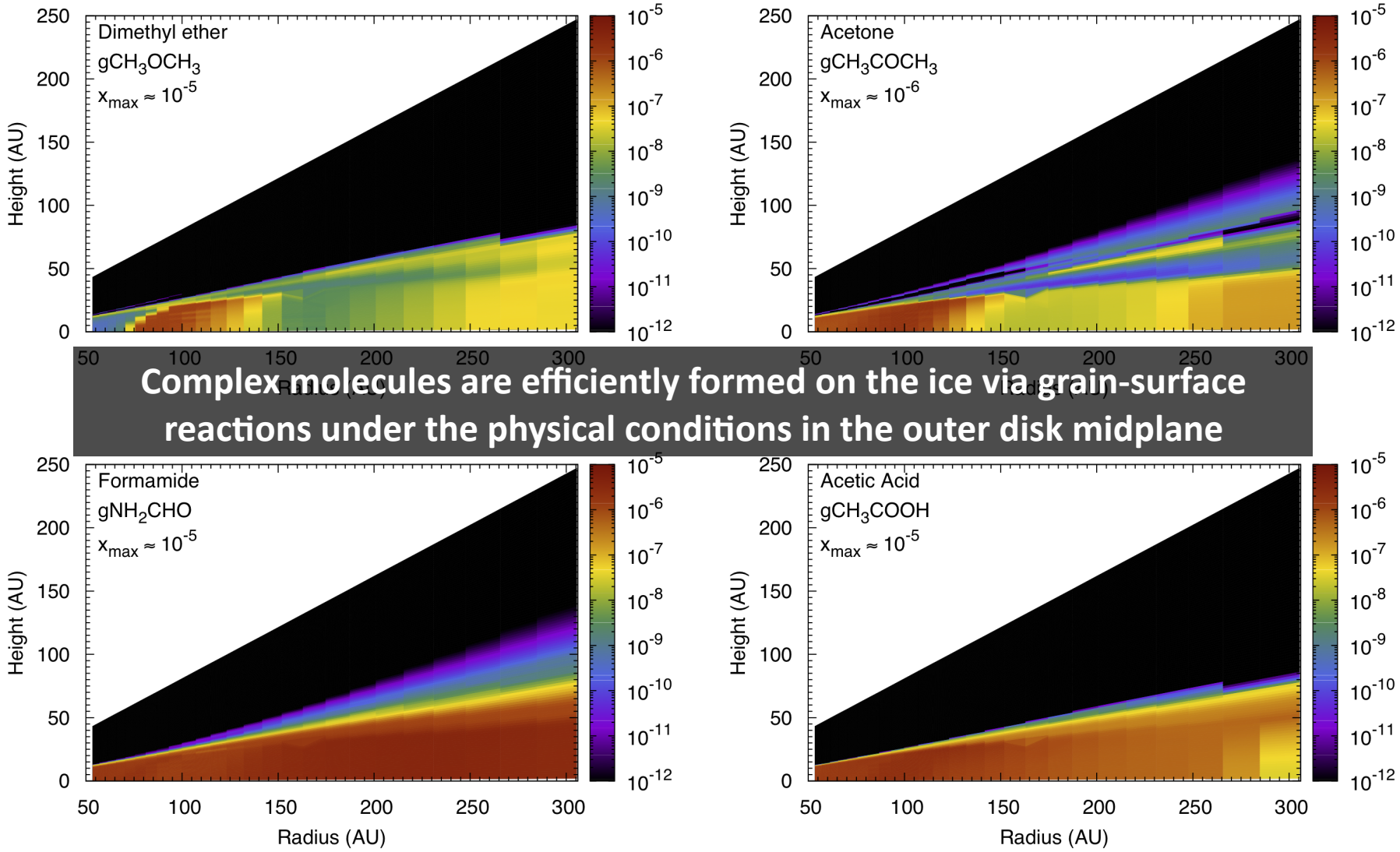
# *Hot Core Chemistry in Protoplanetary Disks?*

**Chemical Network: 8573 reactions involving 808 species**

(Garrod & Herbst, 2006; Garrod et al. 2008; Harada & Herbst 2010; Laas et al. 2011)

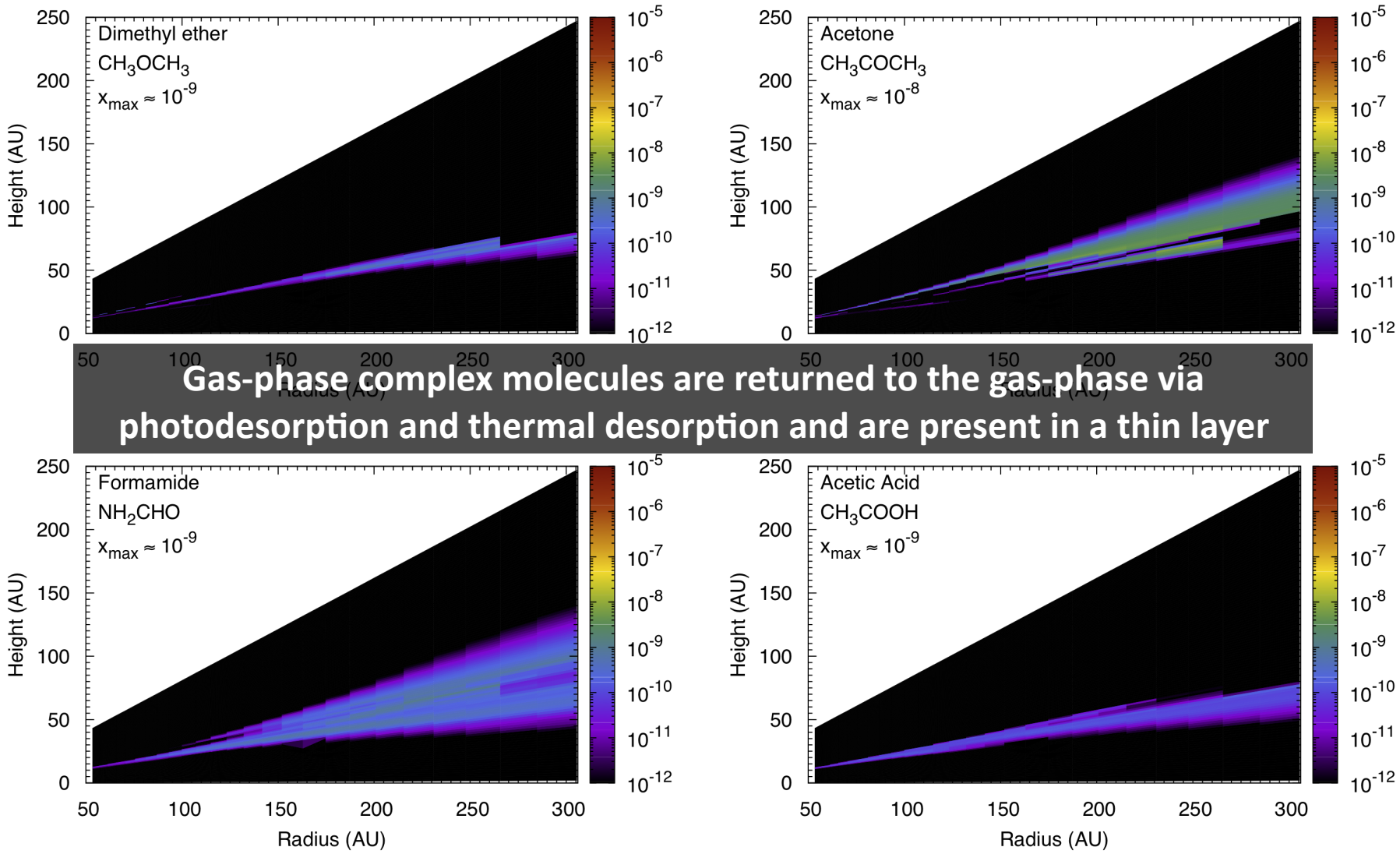


# Results: Ice-mantle Species



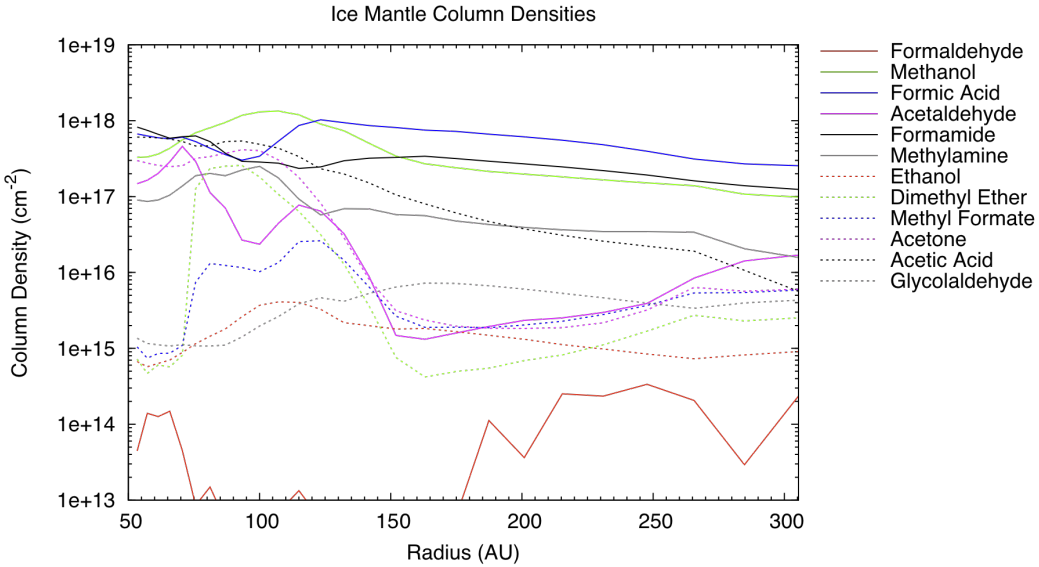

**Complex molecules are efficiently formed on the ice via grain-surface reactions under the physical conditions in the outer disk midplane**

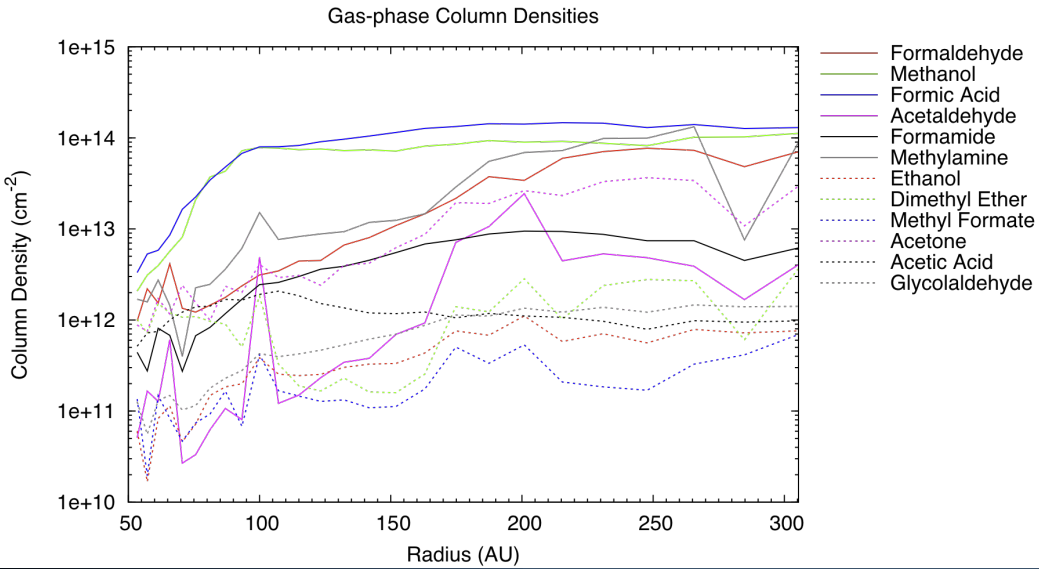
# Results: Gas-phase Species




**Gas-phase complex molecules are returned to the gas-phase via photodesorption and thermal desorption and are present in a thin layer**

# Results: Column Densities




**Most abundant ice-mantle species:**

- HCOOH
- $NH_2CHO$
- $CH_3OH$
- $CH_3NH_2$
- $CH_3CHO$
- $CH_3COOH$

**IMPLICATIONS ON COMETARY ICE COMPOSITION?**

**Most abundant gas-phase species:**

- HCOOH
- $CH_3OH$
- $H_2CO$
- $CH_3NH_2$
- $CH_3COCH_3$
- $NH_2CHO$
- $CH_3CHO$

**POSSIBLE CANDIATES FOR ALMA FULL SCIENCE?**

# *Summary*

- ★ Can 'hot core' chemistry form complex organic molecules (COMs) in protoplanetary disks?
- ★ COMs formed in ice (≈ 1 %) – linked to cometary composition?
- ★ Ices are processed by UV photons, X-rays and cosmic rays allowing build up of complexity via radical-radical surface reactions (e.g. Garrod et al 2008)
- ★ Release into gas-phase via thermal desorption and photodesorption – may be observable with ALMA full operations
- ★ To be investigated: sensitivity to initial ice conditions, $H_2$ production, photodesorption from top monolayers only