The Role of Cosmic Rays in Setting the Chemical Content of Protoplanetary Disk Midplanes

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Cosmic Rays – the salt of the star formation recipe
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PlanetS

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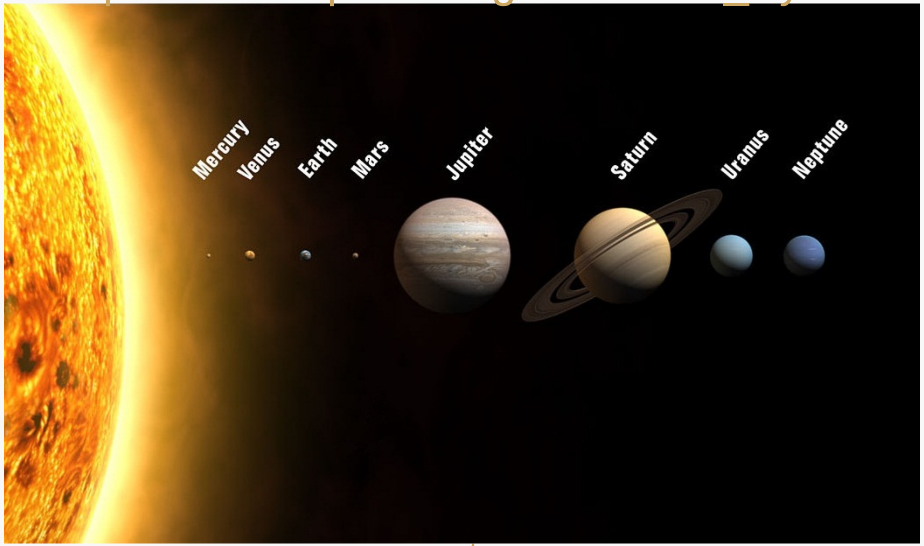
Pillar and Jets HH 901/902

Hubble Space Telescope • WFC3/UVIS

NASA, ESA, and M. Livio and the Hubble 20th Anniversary Team (STScI) STScI-PRC10-13a

https://en.wikipedia.org/wiki/Solar_System



planets & life

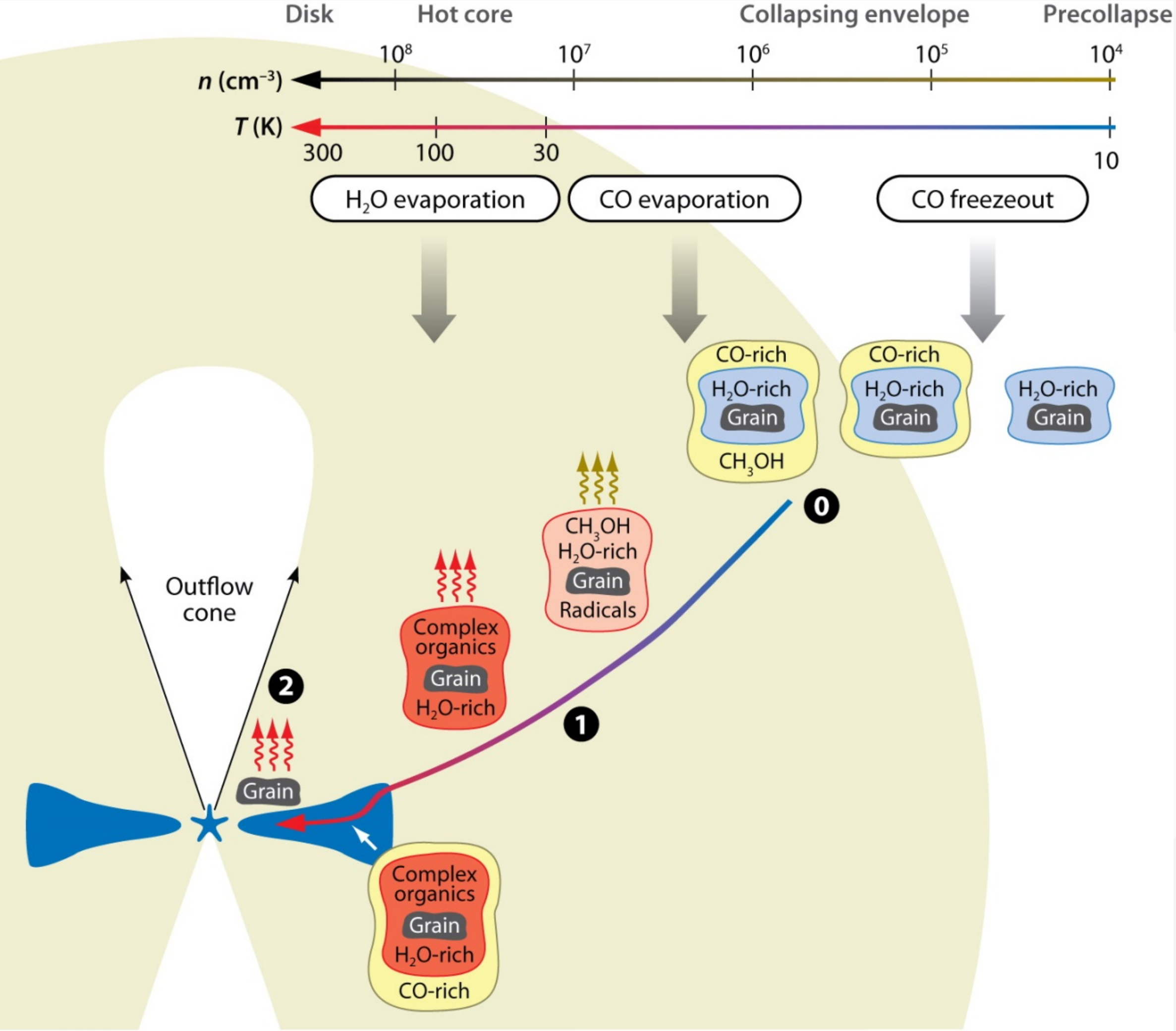
dust & atoms

?

What is the chemical compostion of protoplanetary building blocks?

Are cosmic rays important in this context?

Chemistry during collapse



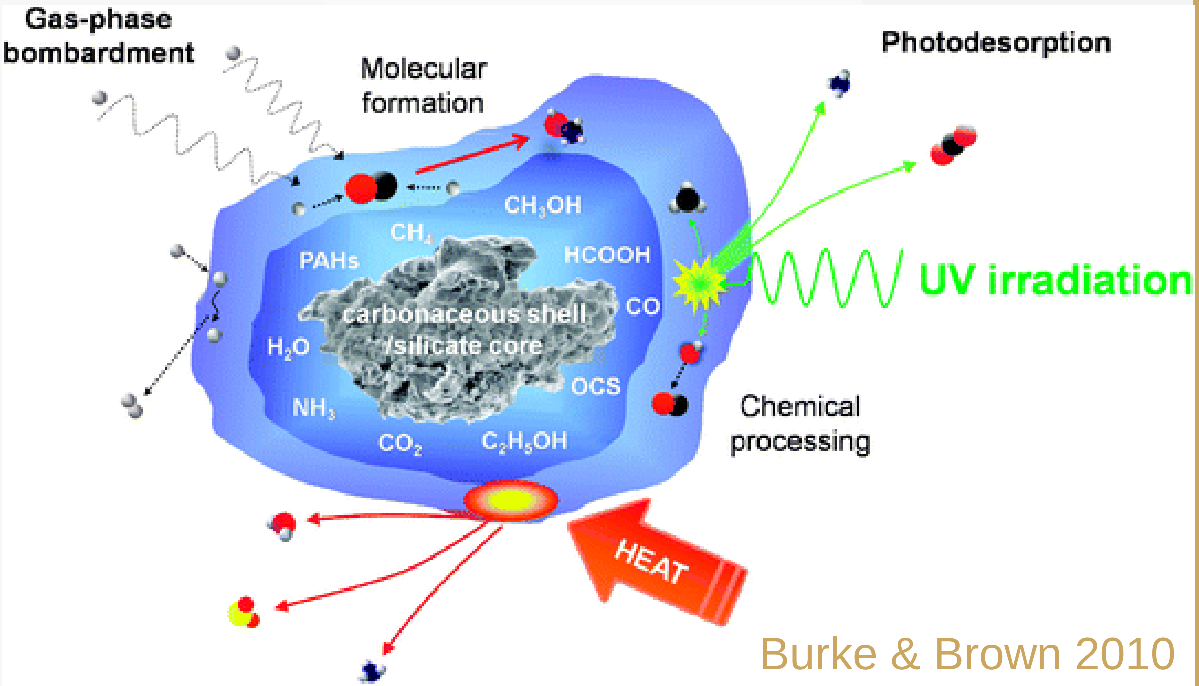
Herbst E, van Dishoeck EF. 2009.
Annu. Rev. Astron. Astrophys. 47:427–80

Chemistry occurs in parallel with the large-scale physical evolution of the system AND with grain growth.

90% of the total disk mass lies below $z = 1$ AU

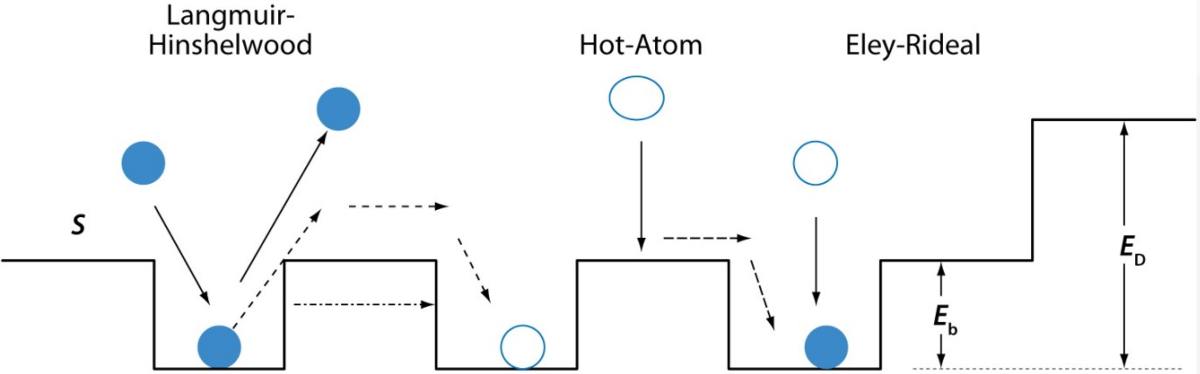
=> protoplanetary disk midplanes are cometary and planetary factories

Interstellar chemical processes



Burke & Brown 2010

Grain-surface chemical processes:



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- Refractories = dust
- Volatiles = gas & ice

Cosmic rays as drivers of chemistry

Photodissociation by the CR-induced UV photons and direct CR ionization the gas

- production of radicals and ions in the gas

Spot heating:

- thermal desorption below T_{des} particularly of weakly bound species (e.g., CO)

Photodissociation and photodesorption by the CR-induced UV photons in the ice

- particularly important for desorption below T_{des} of tightly bound species (e.g., CH_3OH), link with reactive desorption

- production of radicals for COM synthesis

(e.g., Shen+ 2014, Roberts+ 2007)

Typical:

$\zeta = 5 \times 10^{-17}$ s^{-1}

=> 10^4 CR-induced UV photons cm^{-2} s^{-1}

(Prasad & Tarafdar 1983)

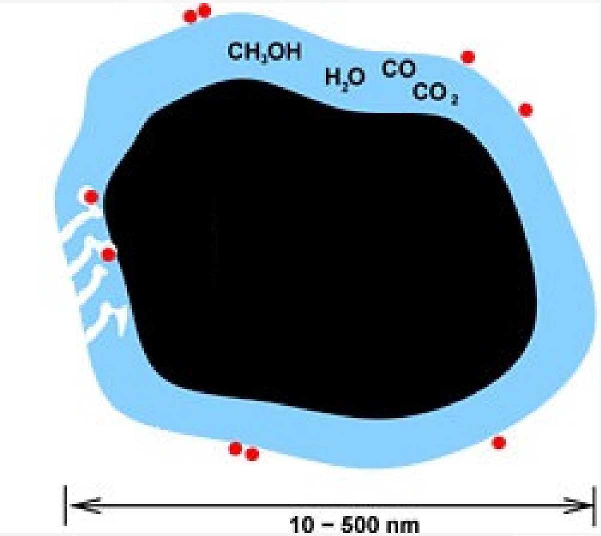
Account for attenuation:

$$\zeta = \zeta_0 \exp(\frac{-\Sigma_{(R,z)}}{96\ g\ cm^{-2}})$$

Lower limit: 7.3×10^{-19} s^{-1} from ^{26}Al radionuclide decay

(Umebayashi & Nakano 1981; Cleeves+ 2013)

Non - equilibrium chemical model



2-phase model (rate equations method), incl.:

coupling

gas phase ⟷ solid phase

& large gas-grain chemical network

McElroy et al. 2013; Garrod & Herbst 2006; Walsh et al. 2014a,b

1. chemical simulation of the dark, quiescent precollapse phase for 3×10^5 yr

→ initial chemical conditions across the system

2. chemical modeling per point/trajectory in 2D

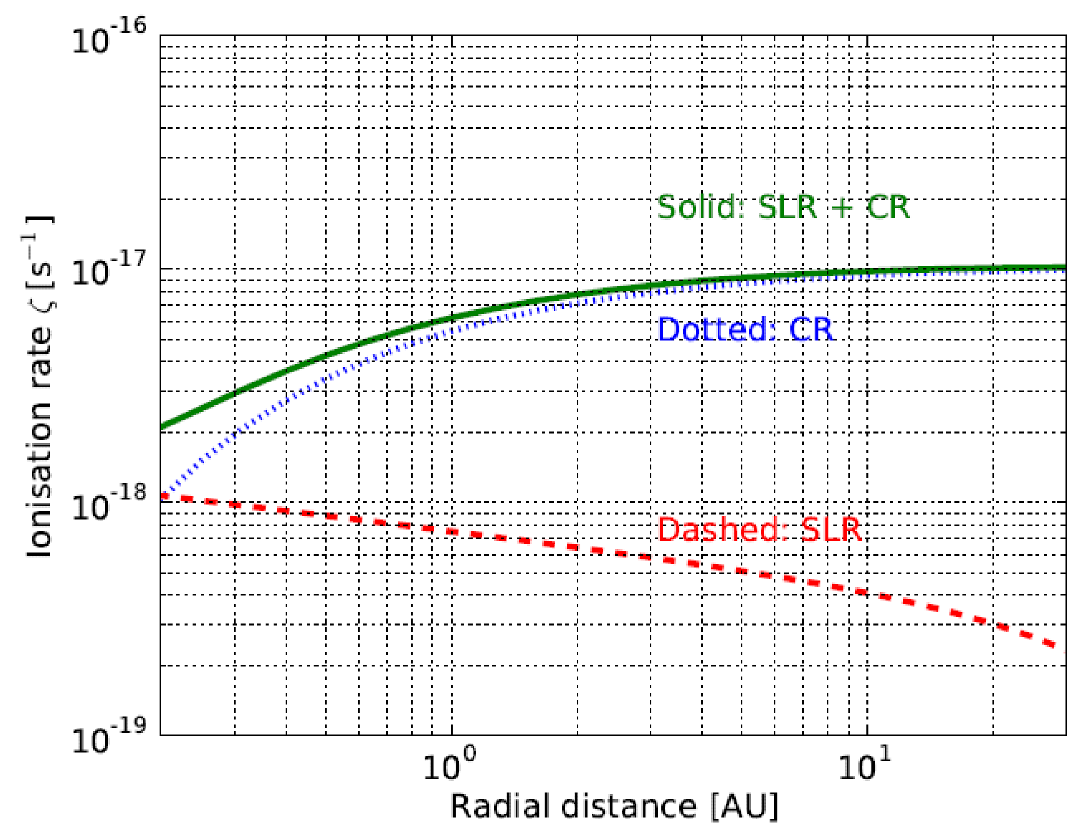
Static protoplanetary disk models

After 1 Myr:

- If CRs are neglected, then volatile abundances are unaltered
- CRs enhance CO_2 abundance at the expense of CO and H_2O
- CRs also destroy CH_4 gas in the inner disk (< 20 AU), but enhances CH_4 gas in the outer disk

At longer times the effects are stronger ($\sim 10^4 - 10^5$ yr).

Midplane chemistry is ionization-driven!

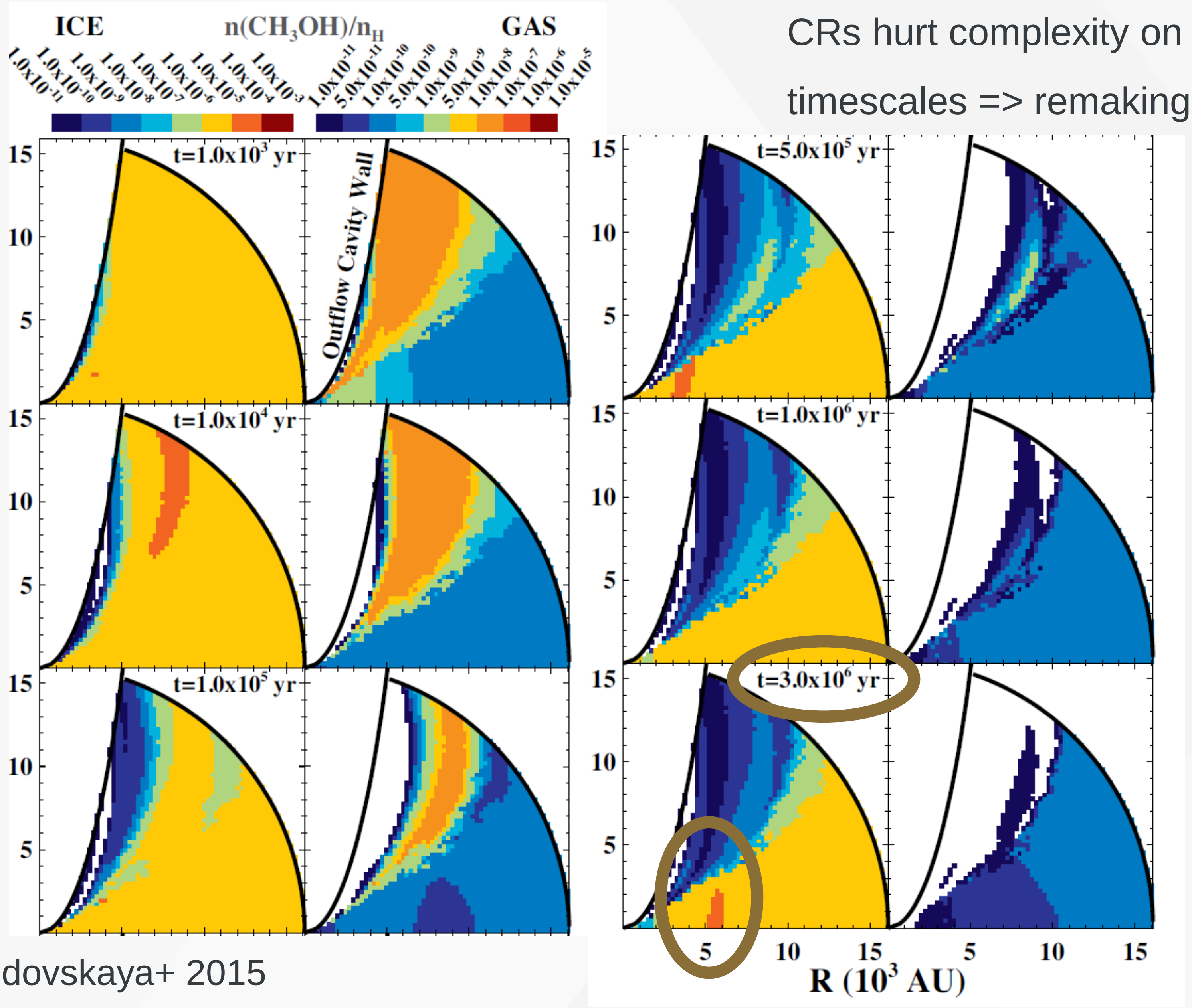


(SLR: short-lived radionuclides)

Eistrup+ 2016, 2017

On large scales in the envelope

CRs hurt complexity on the longest timescales => remaking of CH_3OH.



Drozdovskaya+ 2015

Dynamical physicochemical model

2D, semi-analytic computation

Visser et al. 2009, 2011

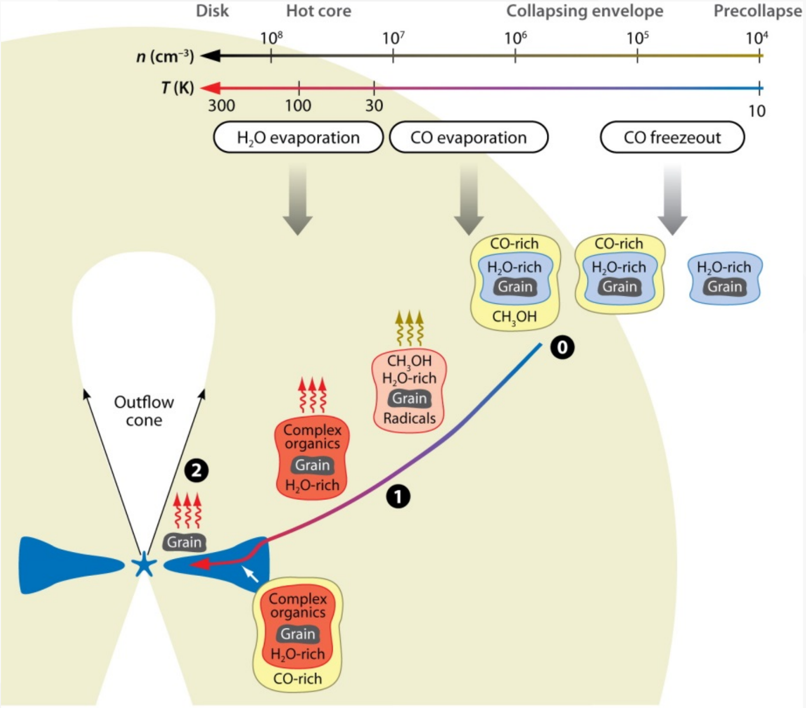
1. pre-stellar core to protostar & protoplanetary disk (2.46×10^5 yr)

⇨ density(R, z, t) & velocity(R, z, t)

2. λ-dependent radiative transfer with RADMC3D

⇨ $T_{dust}(R, z, t)$ & $F_{UV}(R, z, t)$

3. compute trajectories & the physical conditions along them
4. run the chemistry



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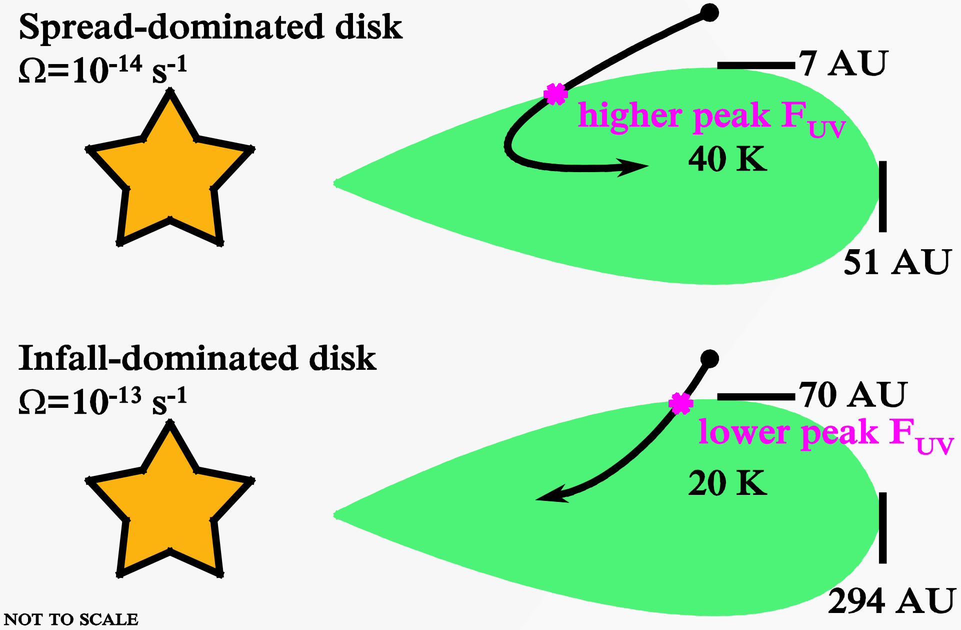
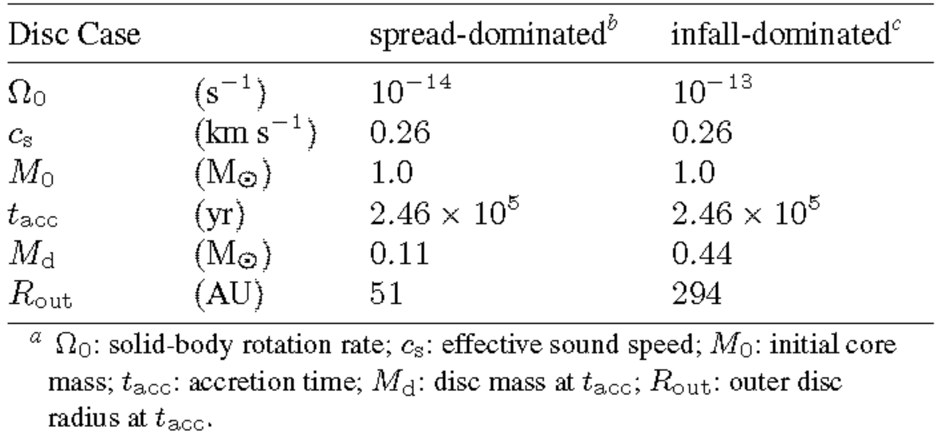
Two cases

CRs will also be crucial in setting the abundances and gas/ice-partition of the initial prestellar abundances.



Several hundred trajectories per case!



Disc Case		spread-dominated[b]	infall-dominated[c]
Ω_0	(s^{-1})	10^{-14}	10^{-13}
c_s	$(\mathrm{km\,s}^{-1})$	0.26	0.26
M_0	$(\mathrm{M}_\odot)$	1.0	1.0
t_acc	(yr)	2.46×10^5	2.46×10^5
M_d	$(\mathrm{M}_\odot)$	0.11	0.44
R_out	(AU)	51	294

[a] Ω_0: solid-body rotation rate; c_s: effective sound speed; M_0: initial core mass; t_acc: accretion time; M_d: disc mass at t_acc; R_out: outer disc radius at t_acc.

Stronger CR-attenuation in the infall-dominated disk.

=> less efficient midplane chemistry

Drozdovskaya+ 2016

Global Physical Conditions

Parcels encounter different physical conditions en route.

Critical steps of T_{dust}:

20 K: loss of CO ice

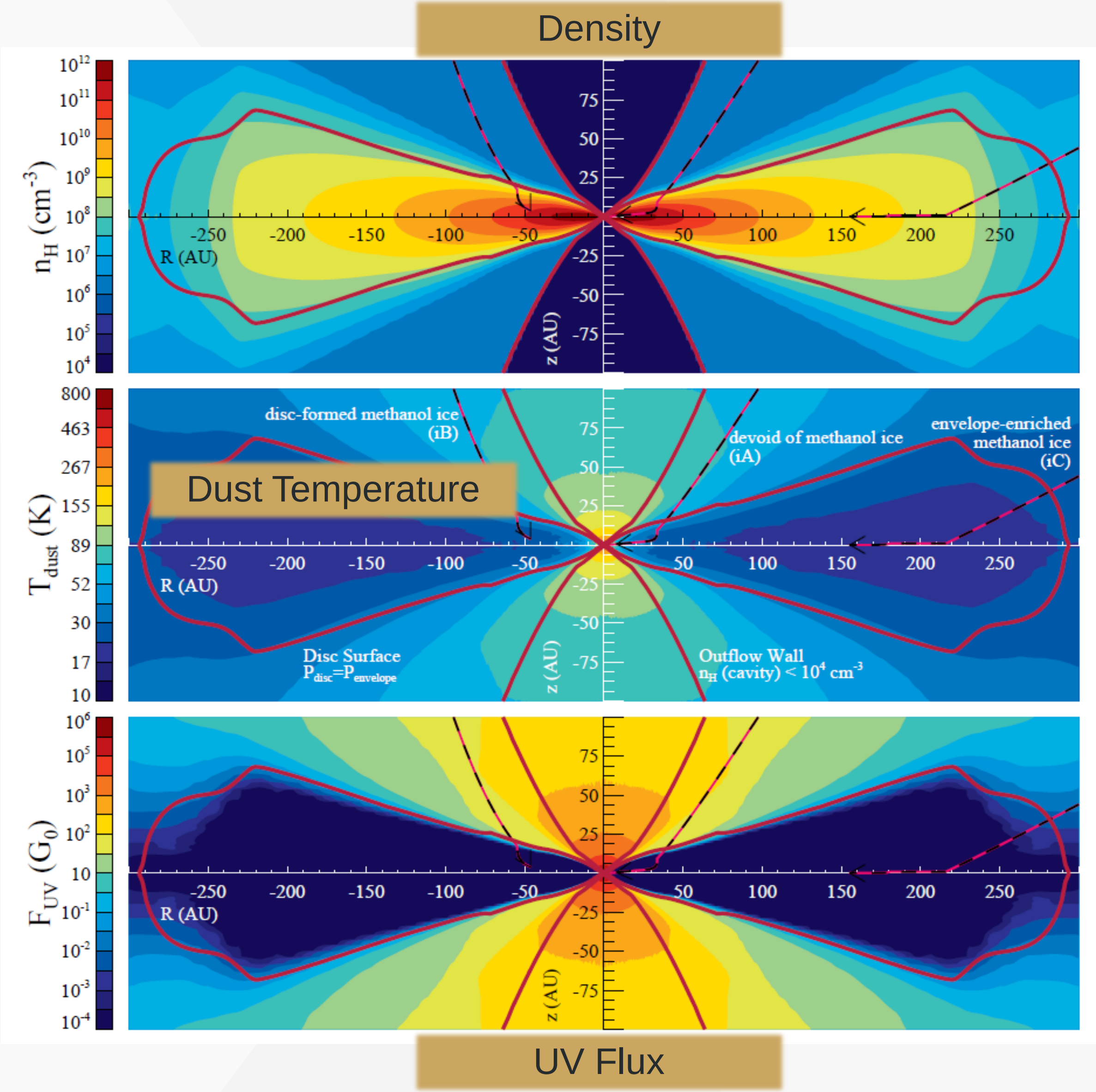
100 K: loss of H_2O

& CH_3OH ices

40 – 80 K: optimal mobility of radicals

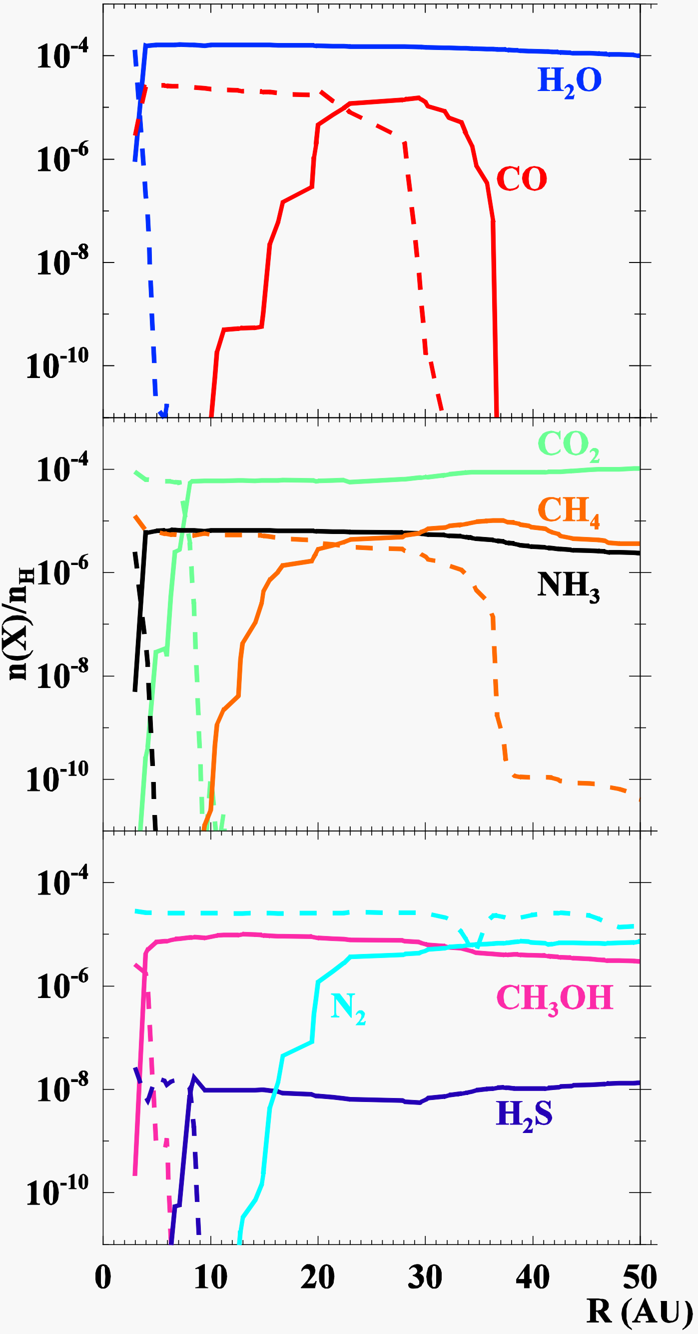
F_{UV} is also important!

At 3×10^5 yr:



Disk chemistry is CR-dominated.

Infall-dom. disk; Drozdovskaya+ 2016

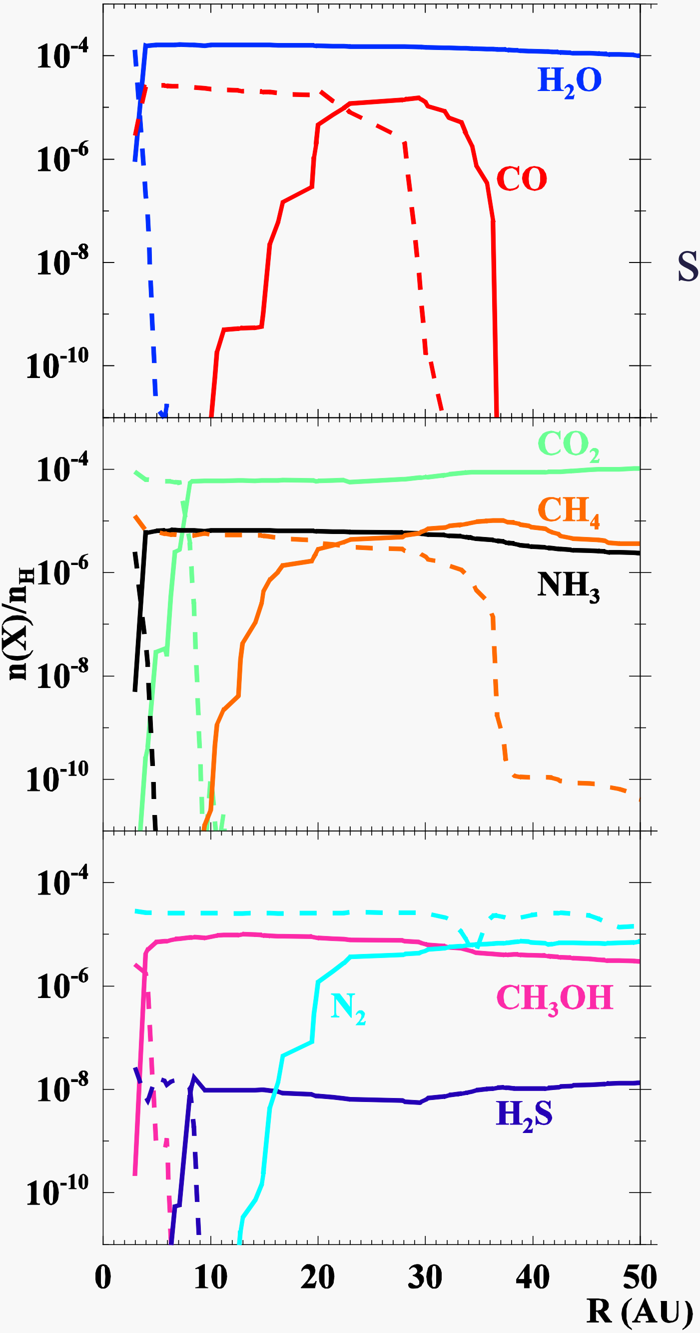


Infall-dom. disk; Drozdovskaya+ 2016

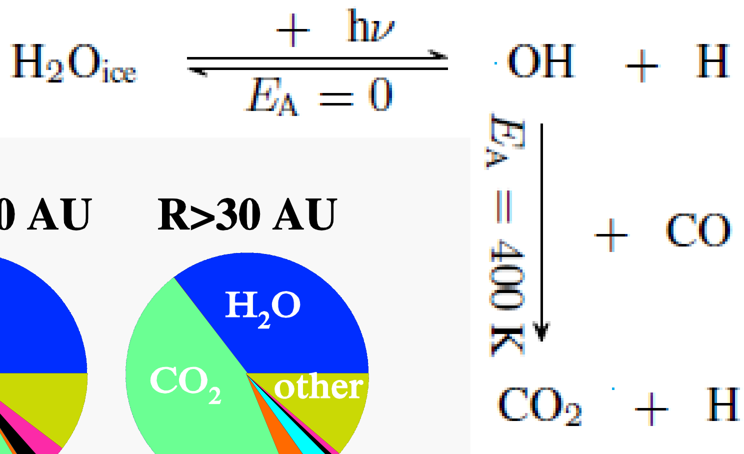
Simple Volatiles in Midplanes

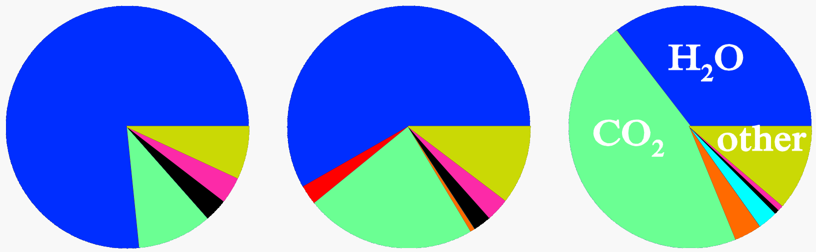
- Inner disk: gas-rich
- Outer disk: ice-rich
- Midplane snowlines recovered

Simple Volatiles in Midplanes



Cloud to disk inheritance is species-dependent!





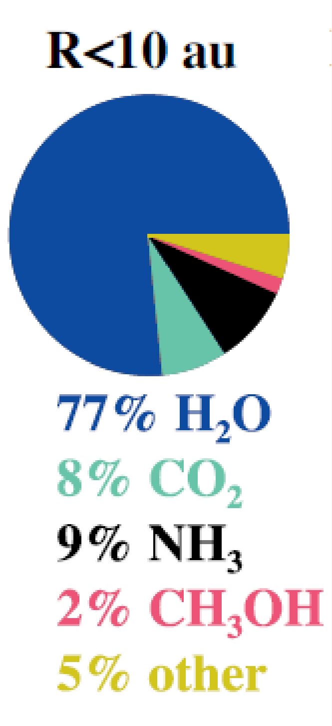
R<10 AU	R: 10–30 AU	R>30 AU
77% H_2O	58% H_2O	35% H_2O
	3% CO	
10% CO_2	23% CO_2	46% CO_2
	1% CH_4	4% CH_4
		3% N_2
3% NH_3	2% NH_3	1% NH_3
4% CH_3OH	3% CH_3OH	1% CH_3OH
7% other	10% other	11% other

Extra CO_2 formed!

Infall-dom. disk; Drozdovskaya+ 2016

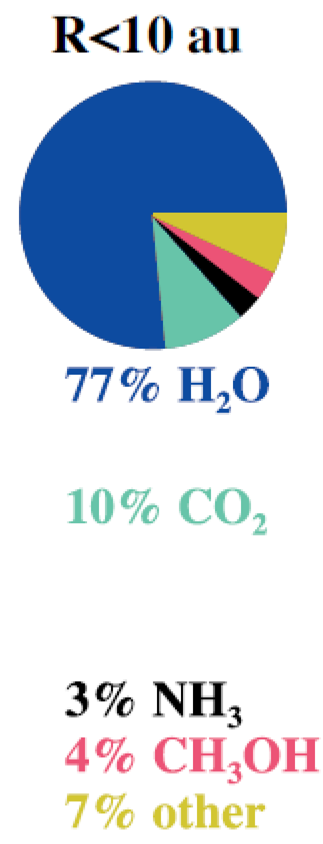
The two cases again

Less CR attenuation



Spread-dom. Disk

More CR attenuation



Infall-dom. disk;

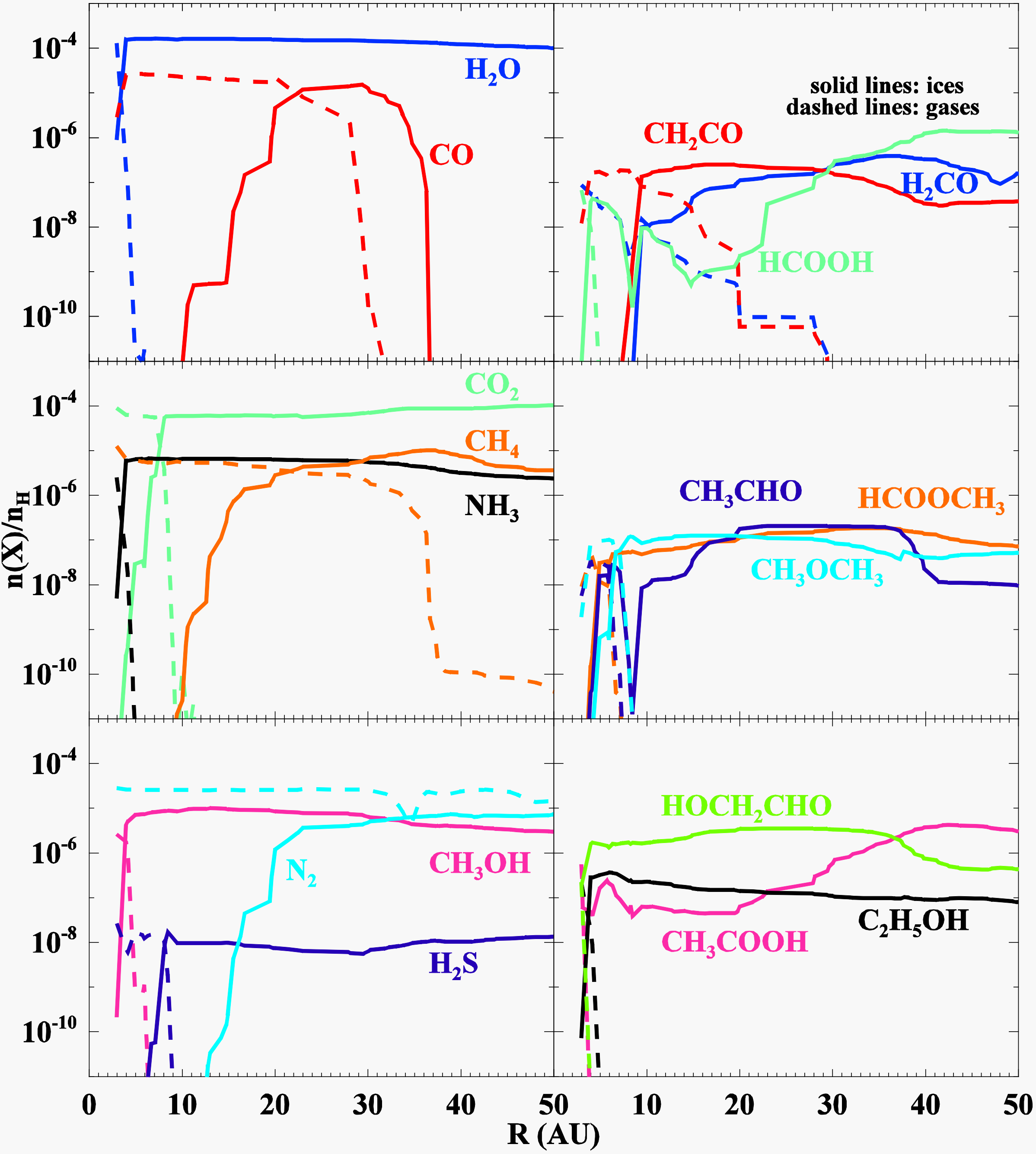
Drozdovskaya+ 2016

Higher ionization =>

- less CH$_3$OH & COMs
- more NH$_3$

(opposite to Eistrup+ 2016)

Complex Volatiles in Midplanes



Infall-dom. disk; Drozdovskaya+ 2016

- complex organic ices are on the order of methanol ice

~1% of water ice

- Comparable to 67P!

(Le Roy+ 2015; Goesmann+ 2015)

- total COMs ~10% of mantle
- transport enhances the abundance of complex organic molecules in protoplanetary disks
- CRs will set the consequent chemical evolution in the midplane

Take-home messages

- Prestellar core volatiles are not simply inherited by the disk.
  - H_2O & CH_3OH down; CO_2 & complex organics up
- Dynamic infall and the chemistry en route are non-negligible for the composition of the protoplanetary disk and the planetesimals therein.
- **Cosmic rays dictate protoplanetary disk midplane chemistry and its initial composition.**