Impact of pebble formation and migration on observable gas-phase volatiles on both sides of the CO snowline

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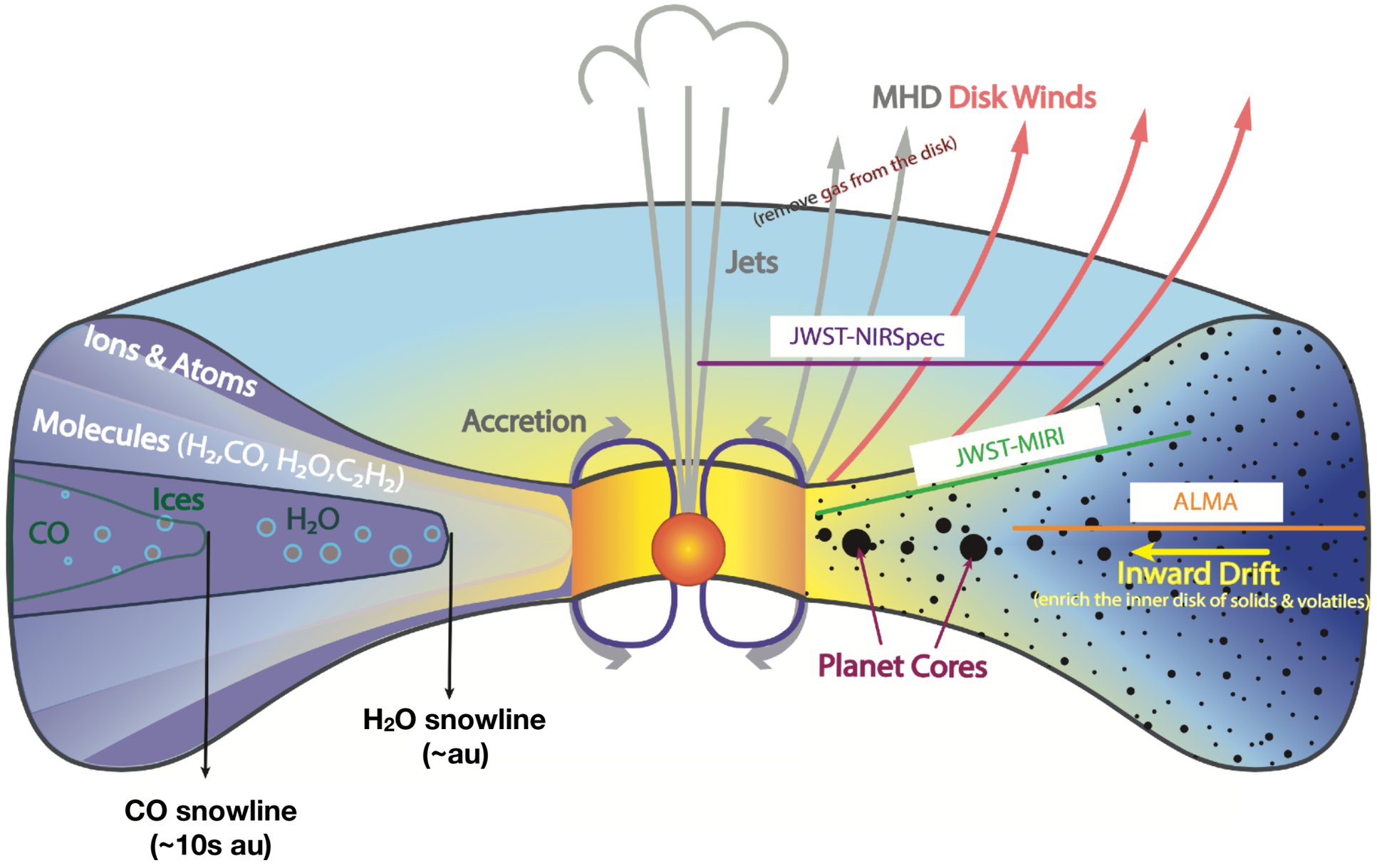
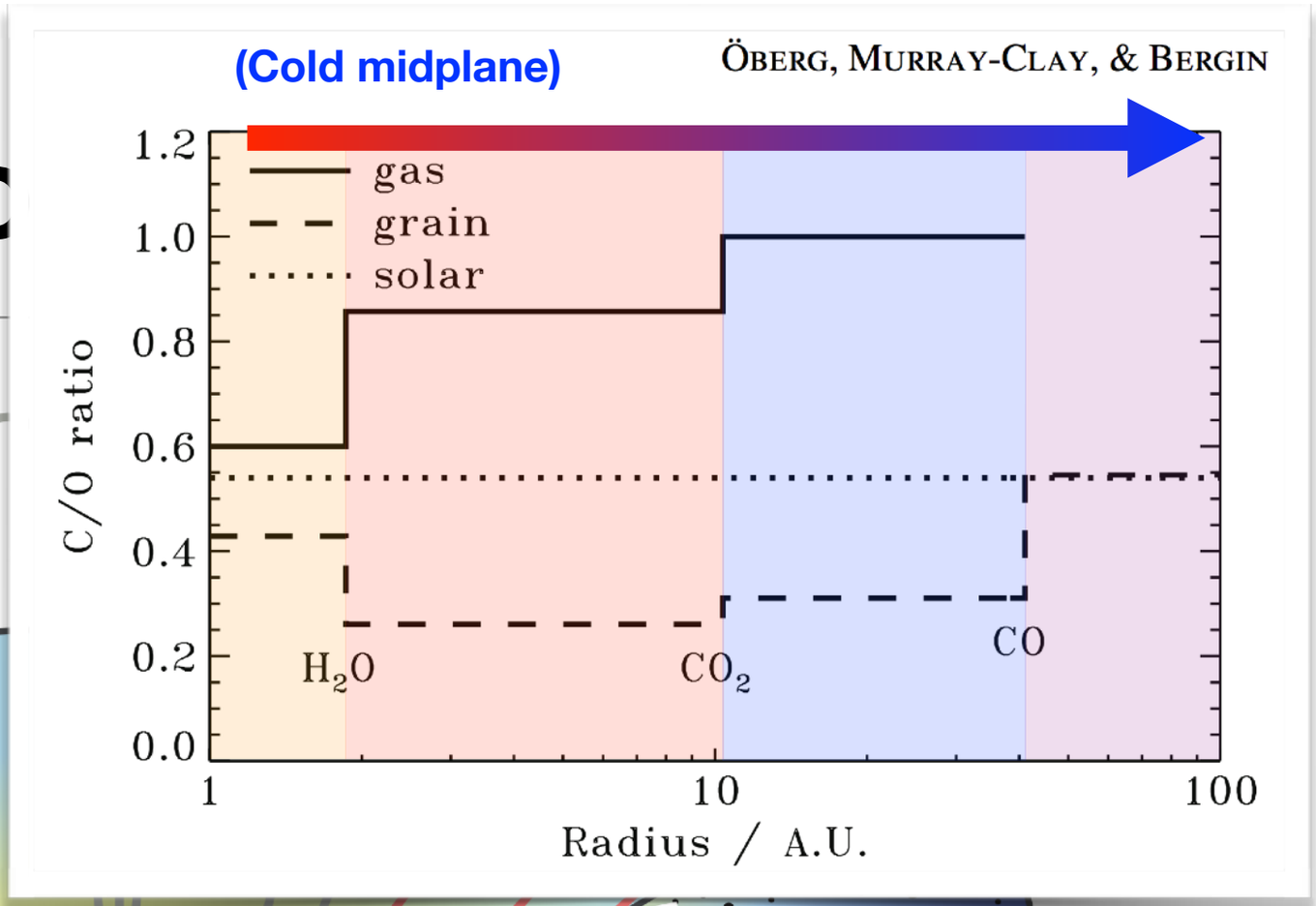
The Protoplanetary Disk

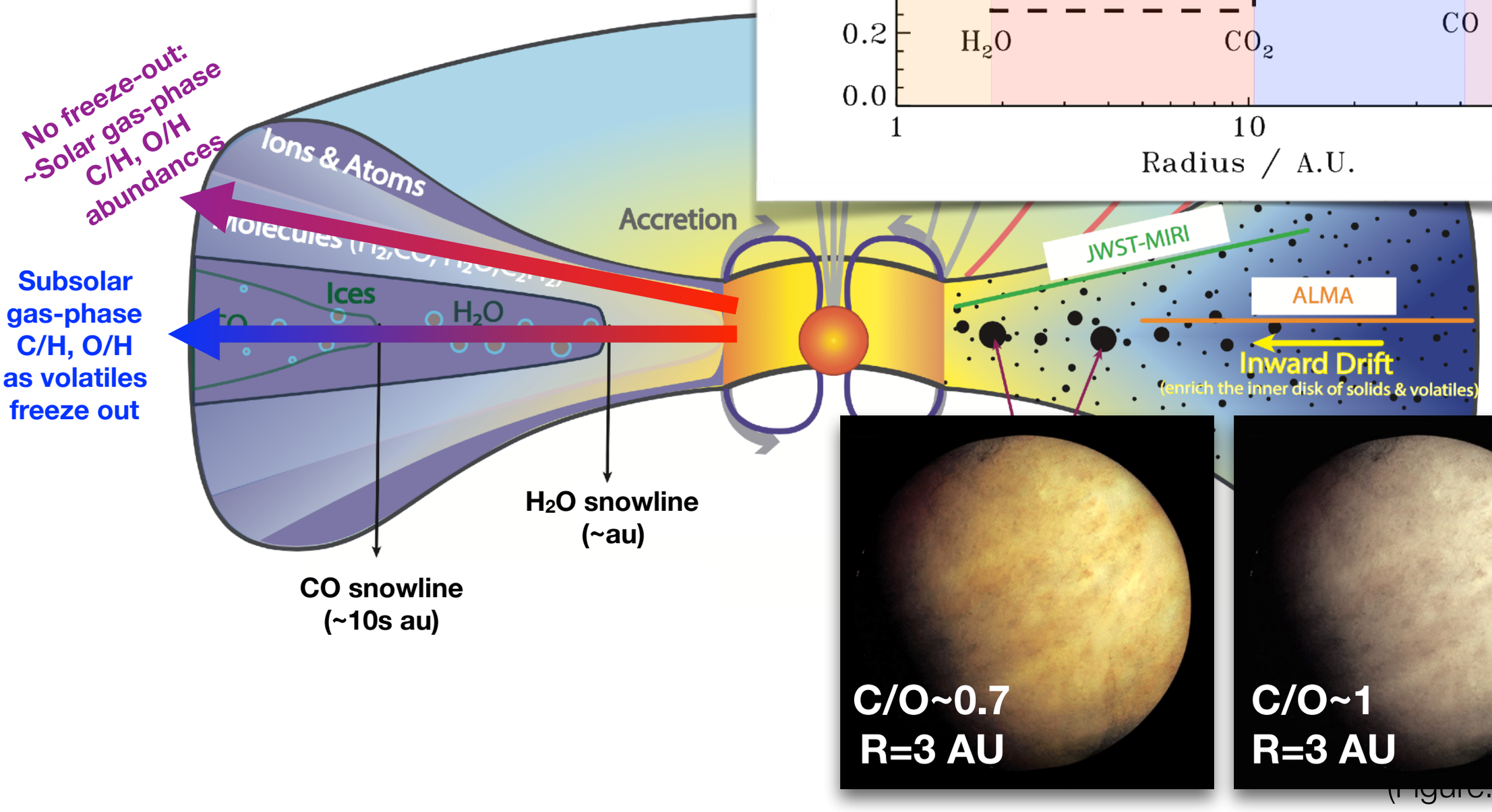


(Figure: L I Cleeves)

The Protoplanetary D

Idealized picture

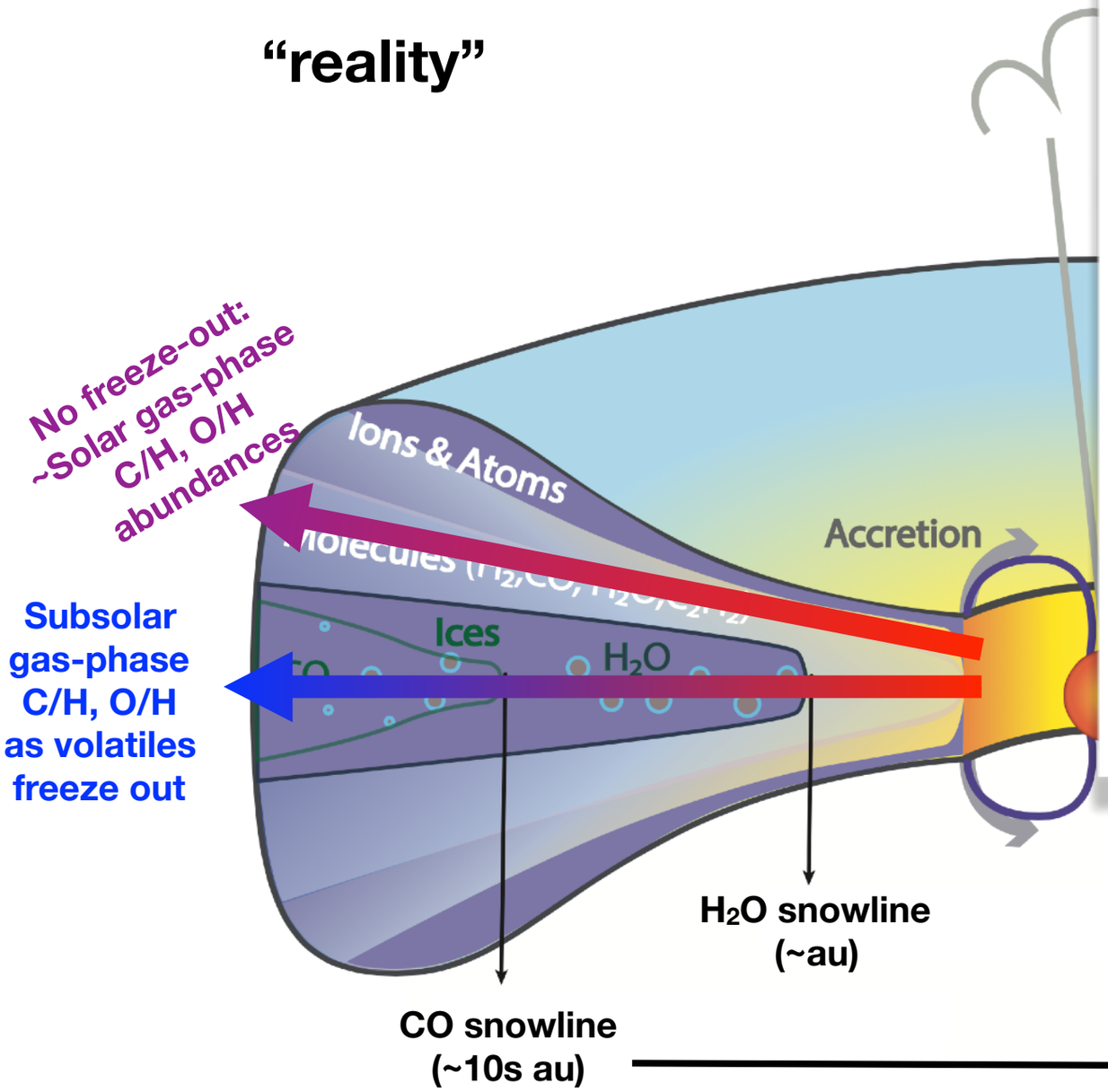




(Figure: E. Sceeves)

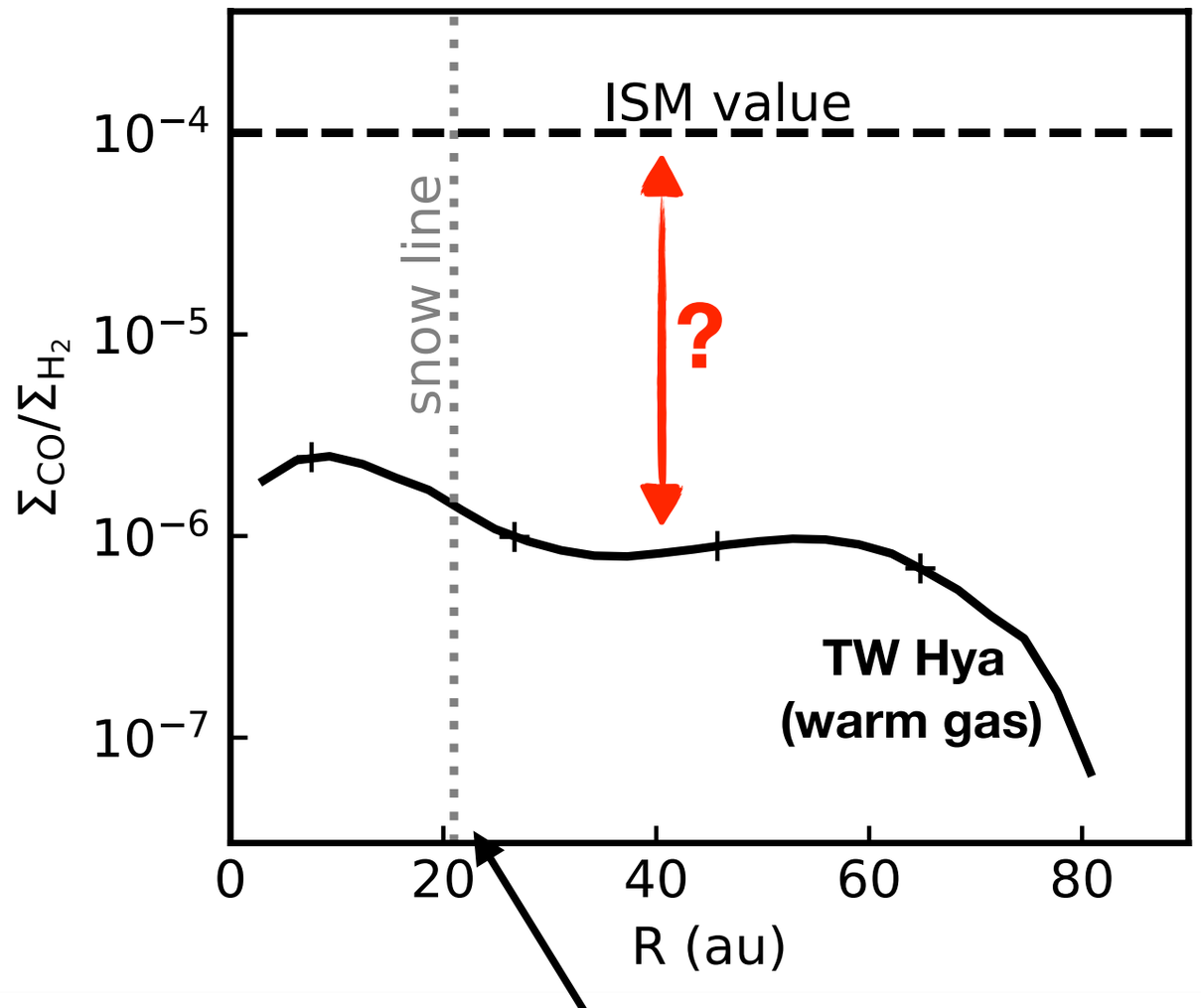
The Protoplanetary Dis

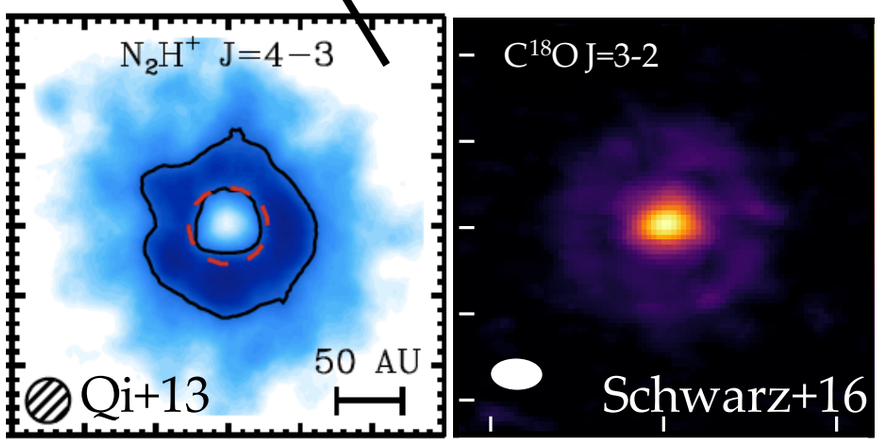
“reality”



(CO & water found to be depleted by 1-2 orders of magnitude in TW Hya and other systems: Meijerink et al. 2009, Favre et al. 2013, Kama et al. 2016, Du et al. 2015, 2017, Schwarz et al. 2016, …)

Schwarz et al. 2016:
CO missing from warm gas is missing



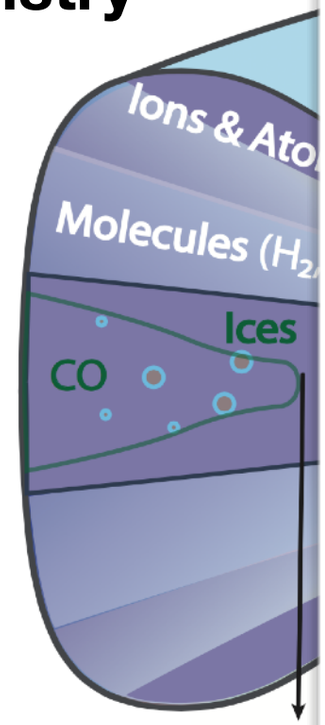


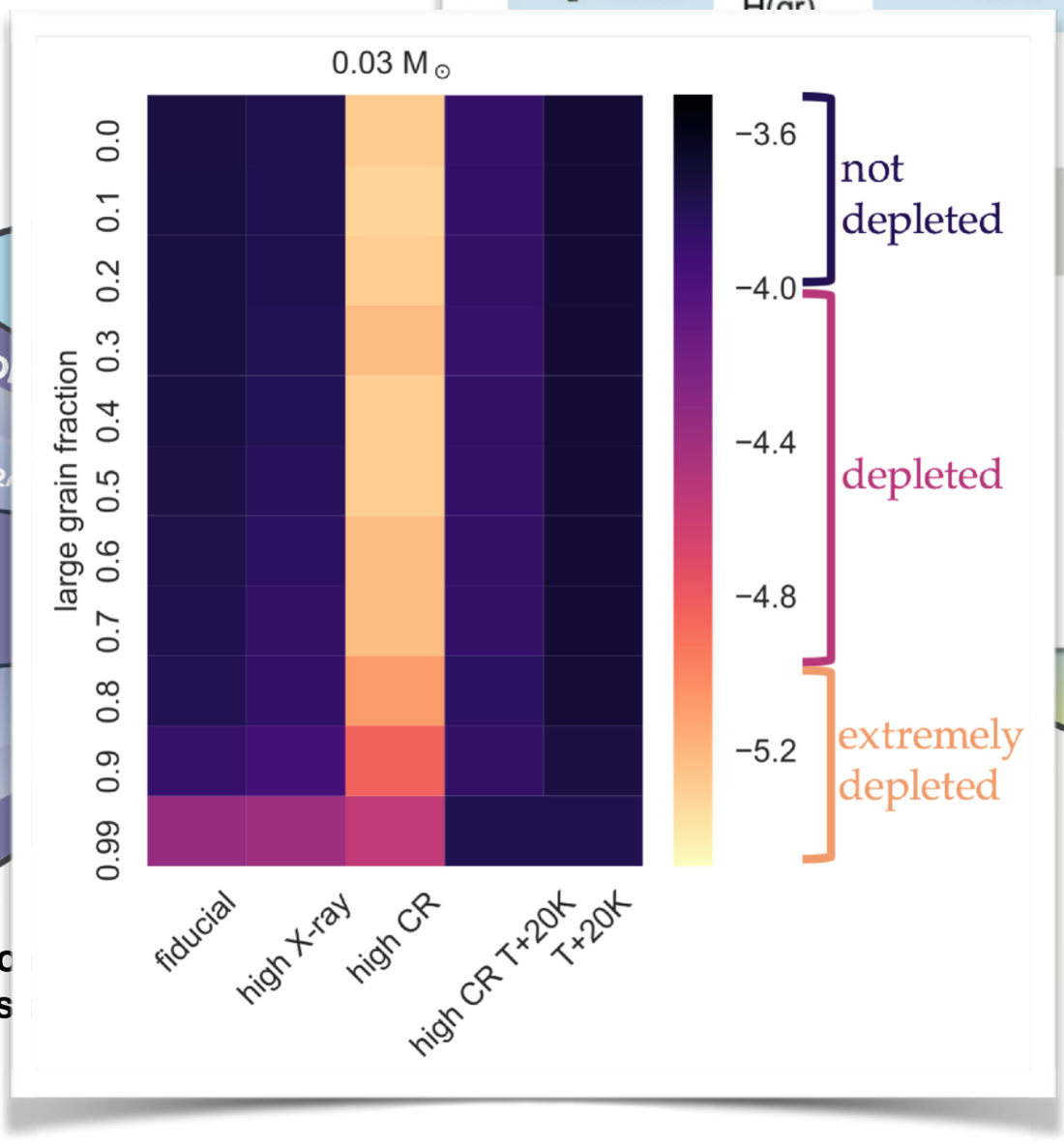
(Figure: E. Sleeves)

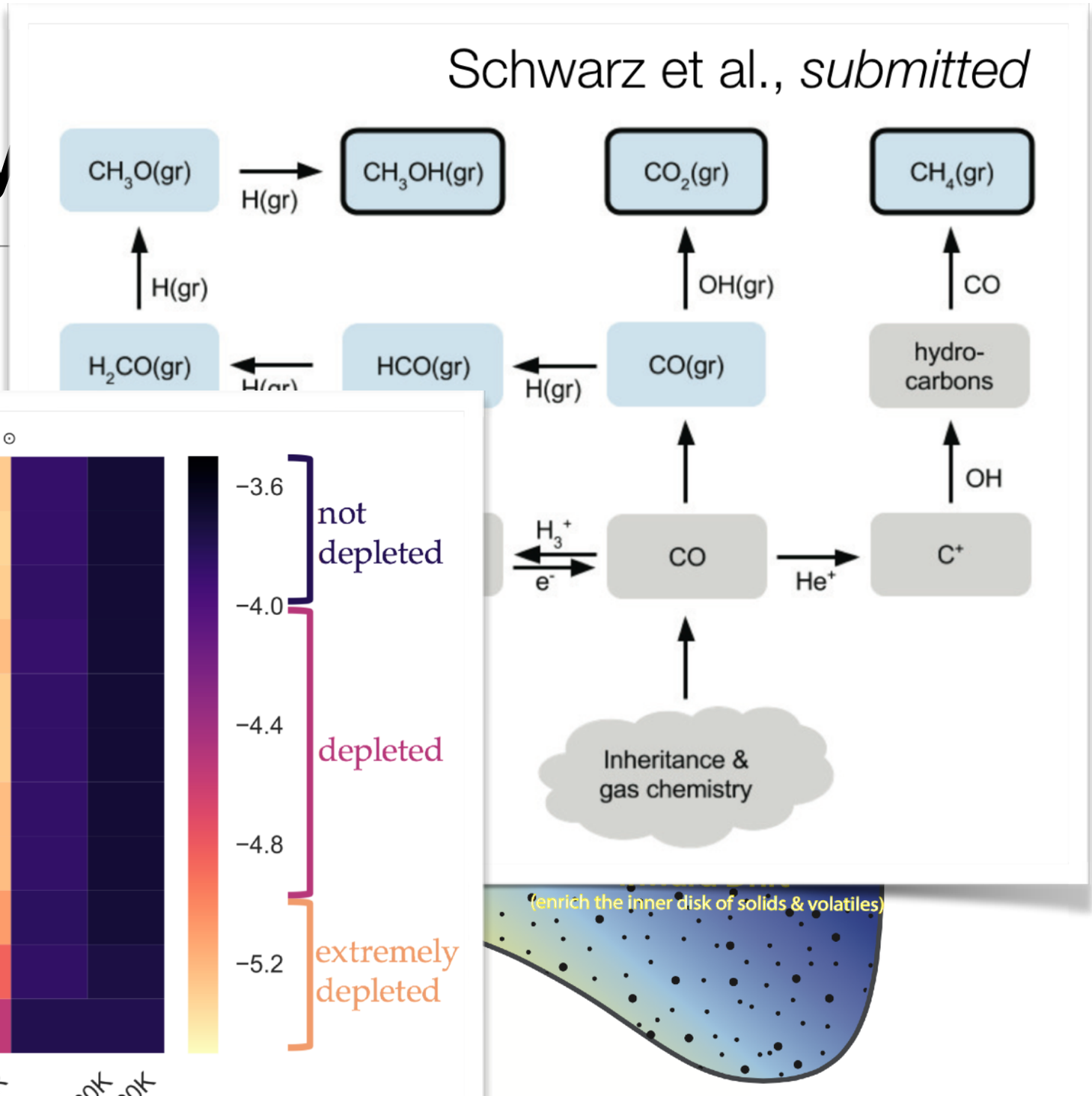
The Protoplanetary

Possible complications

Chemistry







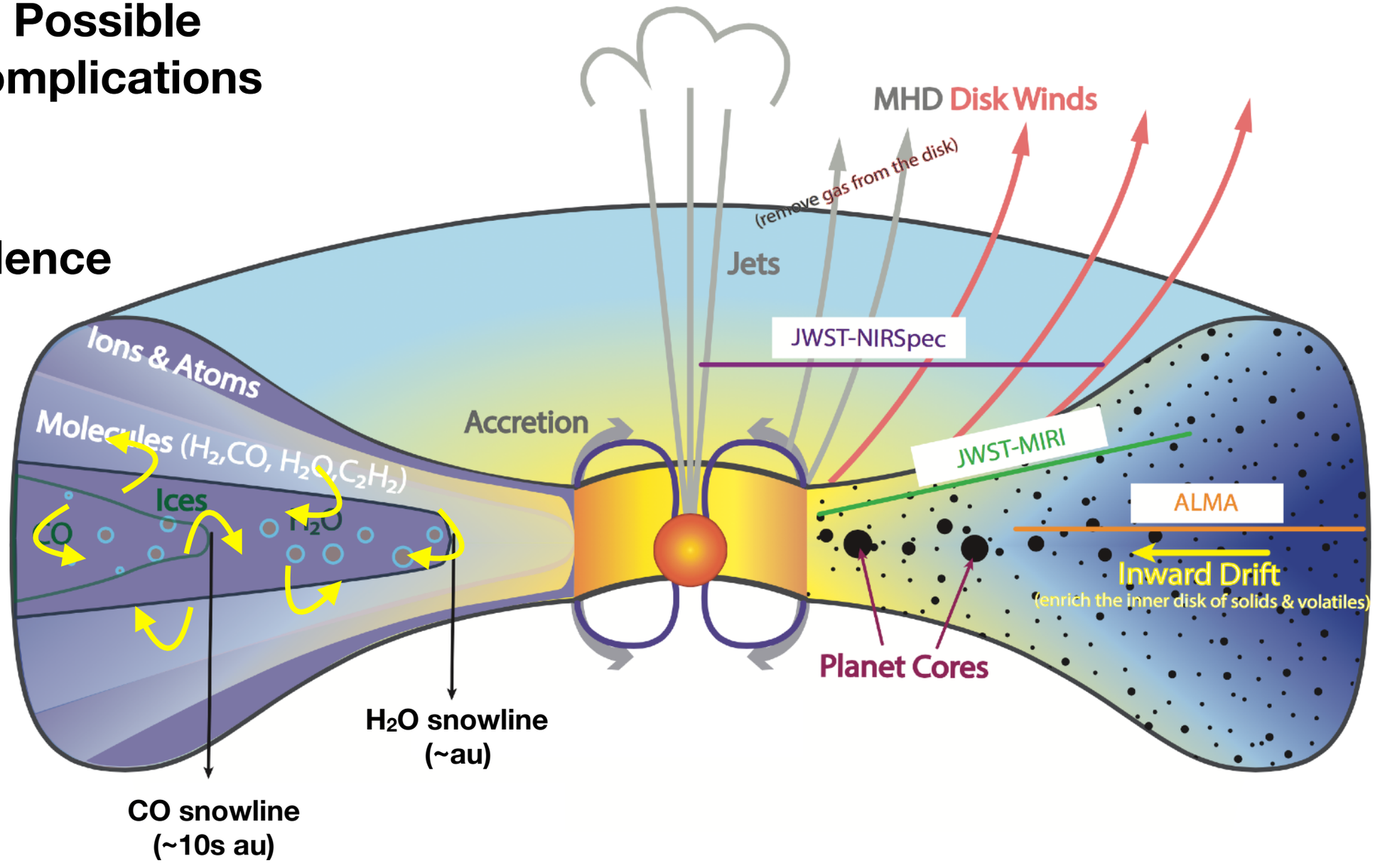
(see also Aikawa & Herbst 1999, Eistrup et al. 2017, Yu et al. 2017)

(Figure: L I Cleeves)

The Protoplanetary Disk

Possible complications

Turbulence

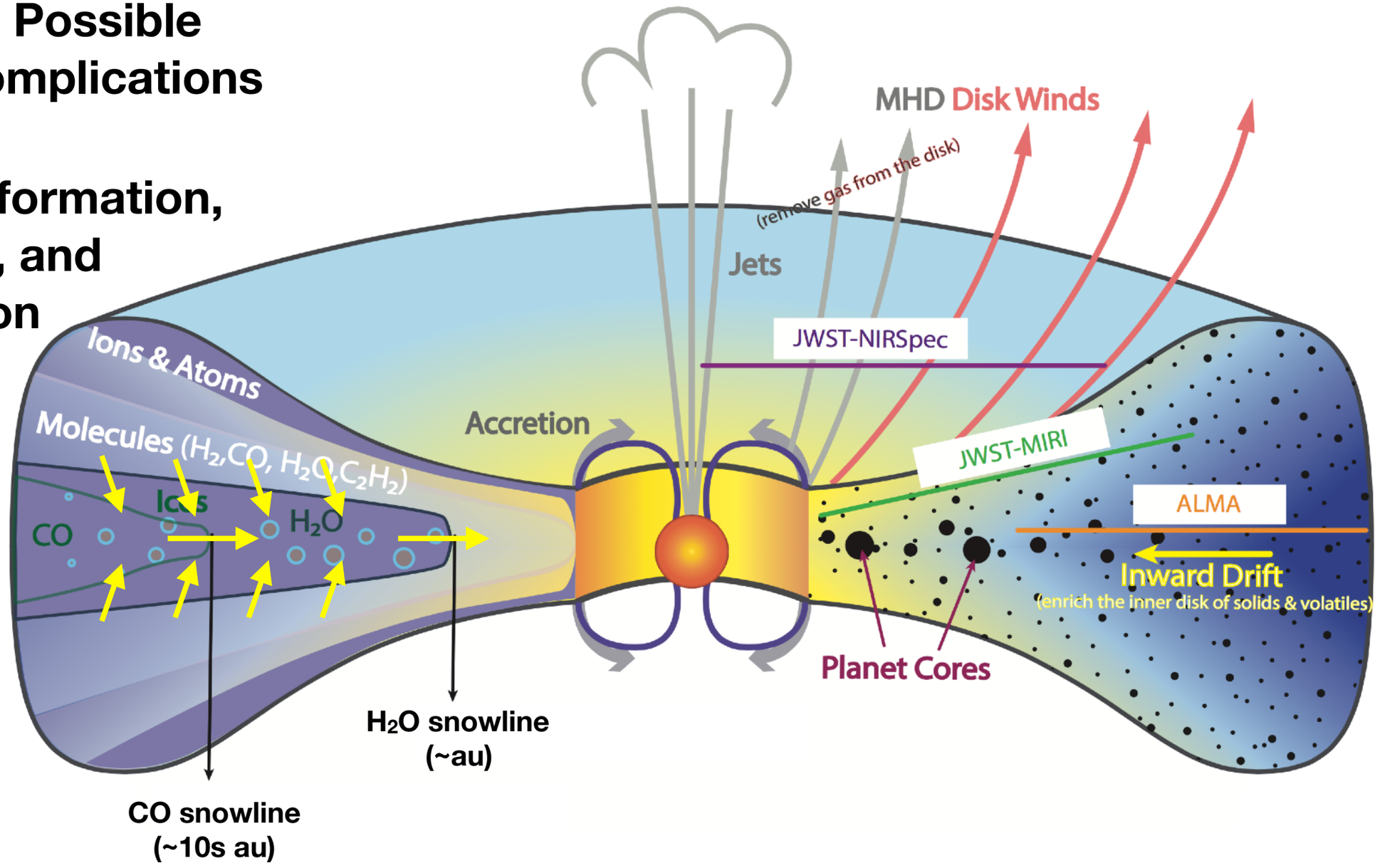


(Figure: L I Cleeves)

The Protoplanetary Disk

Possible complications

Pebble formation, settling, and migration

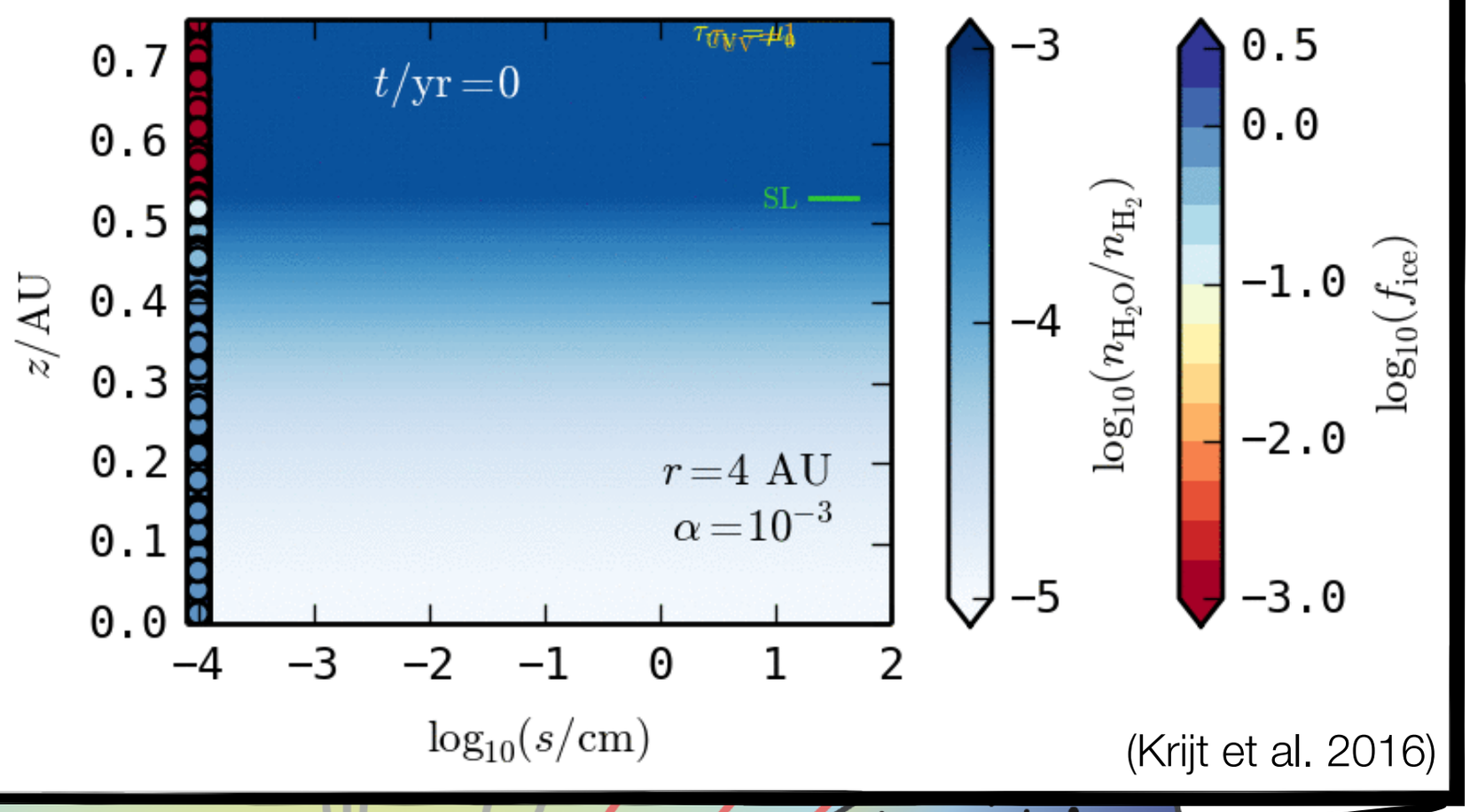


(Figure: L I Cleeves)

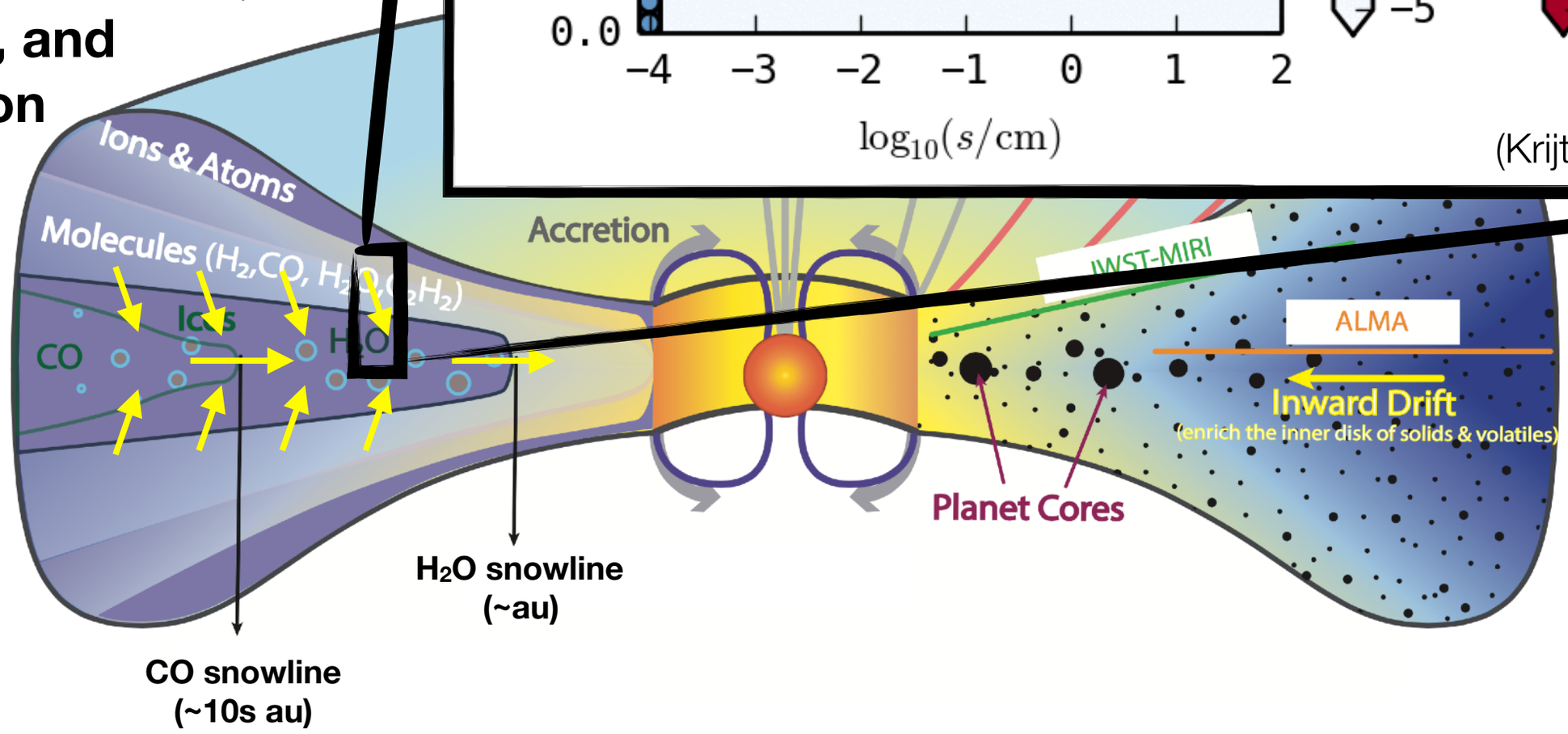
The Protoplane

Possible complications

Pebble formation, settling, and migration



(Krijt et al. 2016)



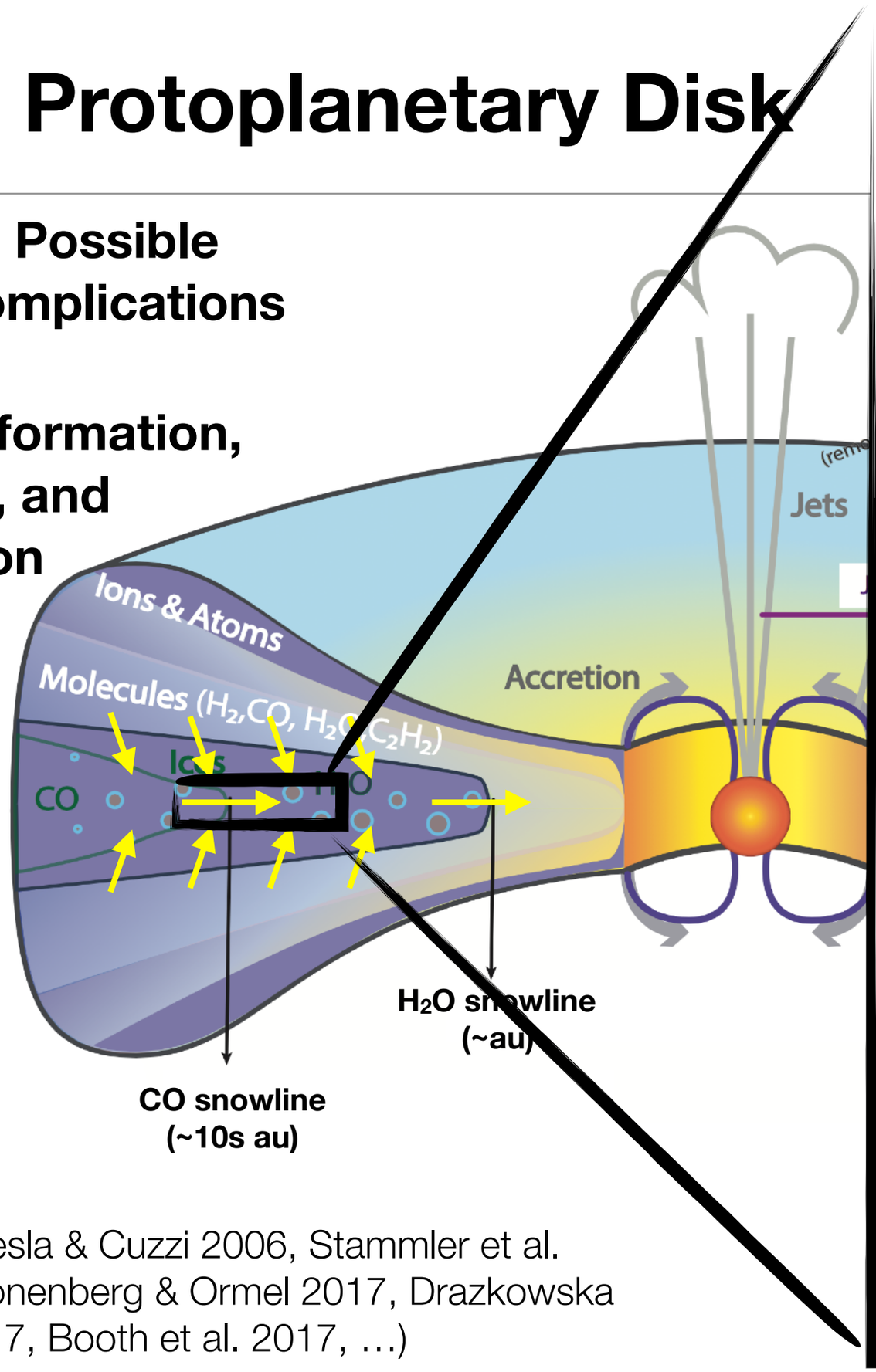
(See also Meijerink et al. 2009, Kama et al. 2016, Xu et al. 2016, …)

(Figure: L I Cleeves)

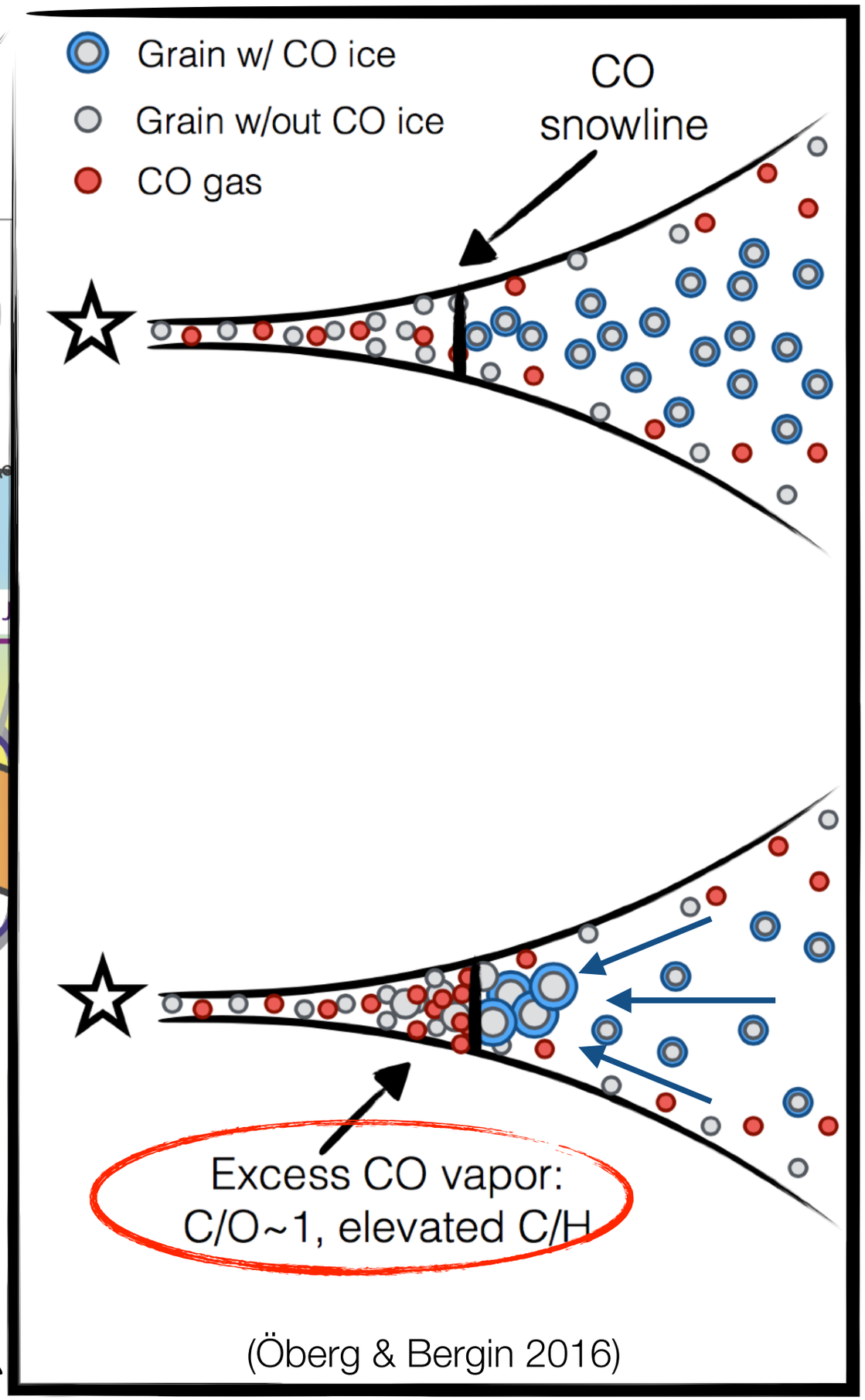
The Protoplanetary Disk

Possible complications

Pebble formation, settling, and migration



(See also Ciesla & Cuzzi 2006, Stammler et al. 2017, Schoonenberg & Ormel 2017, Drazkowska & Alibert 2017, Booth et al. 2017, …)

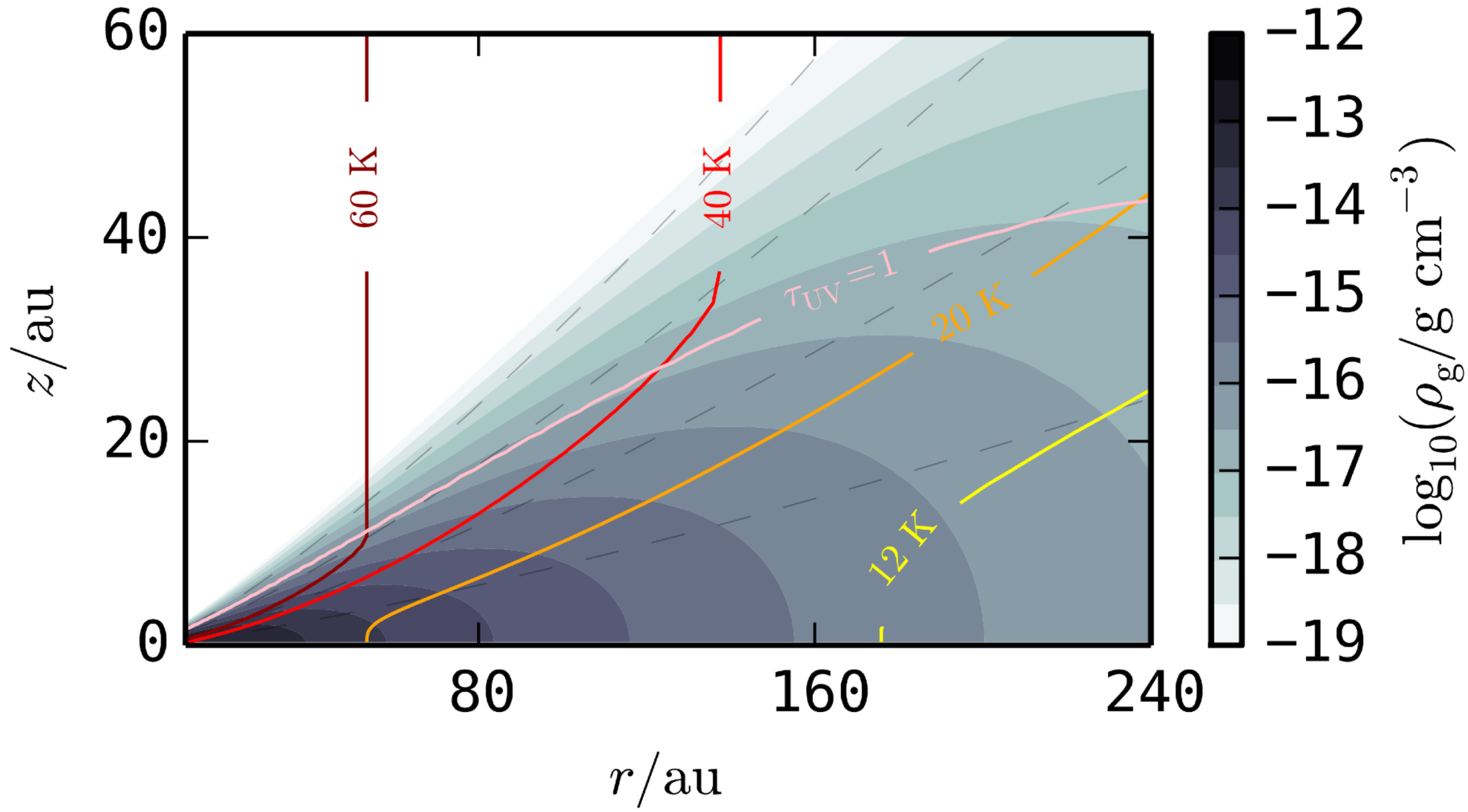


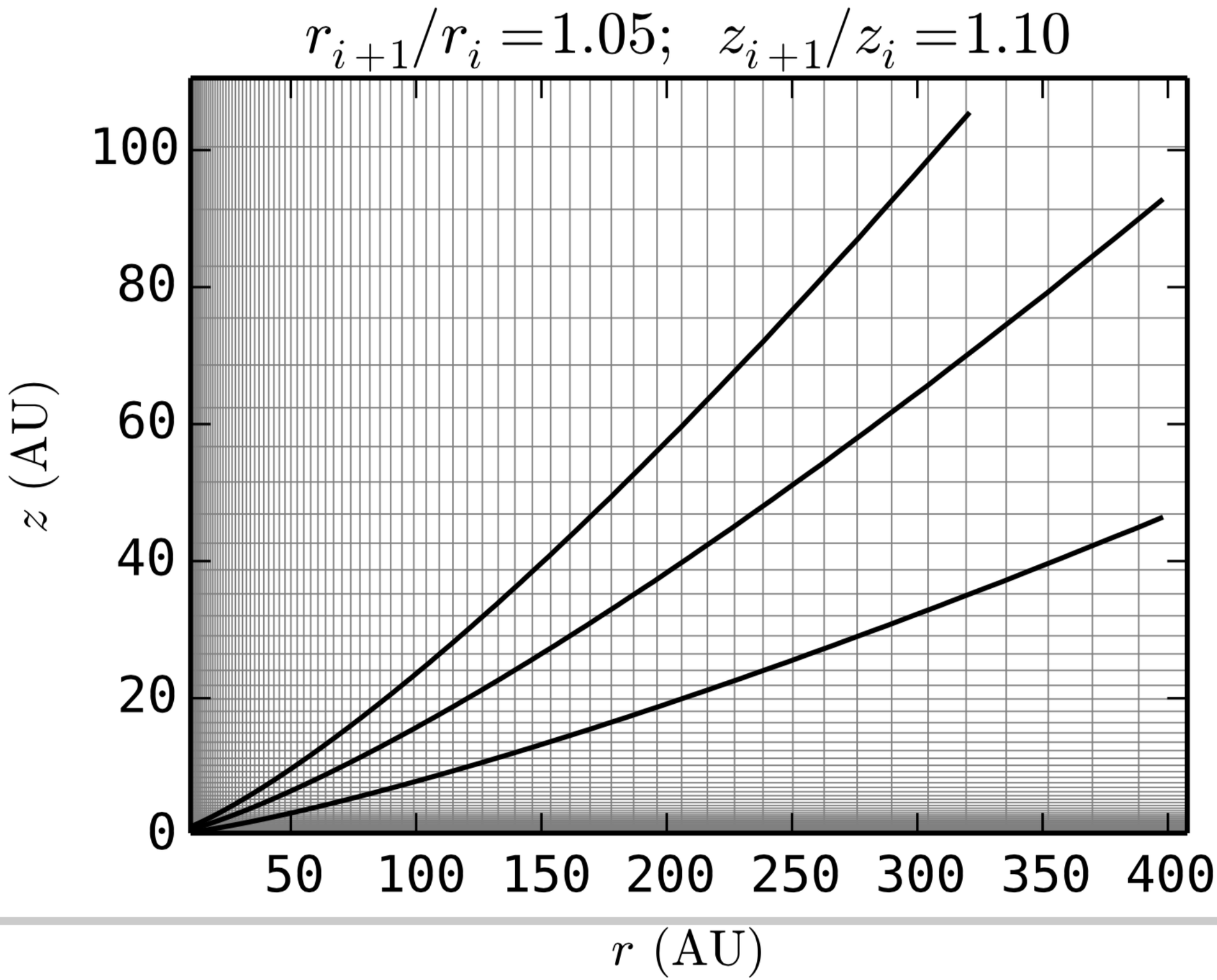
How does large scale pebble formation & migration effect CO abundances; both in the midplane (where planets form) and the disk atmosphere (which we observe)?

(and do we see evidence for these features in nearby disks?)

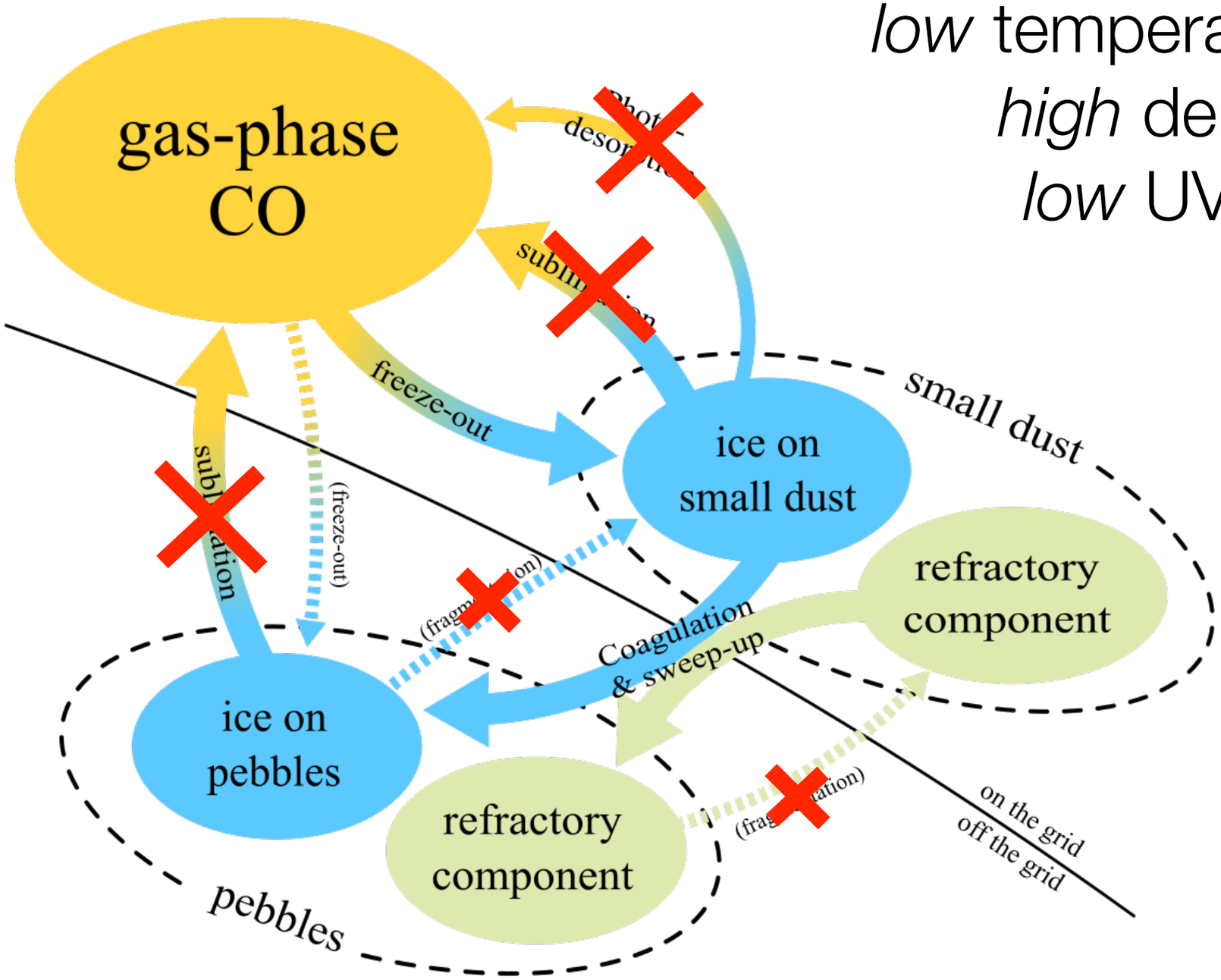
Approach

Imagine a disk with a known bulk gas & temperature distribution

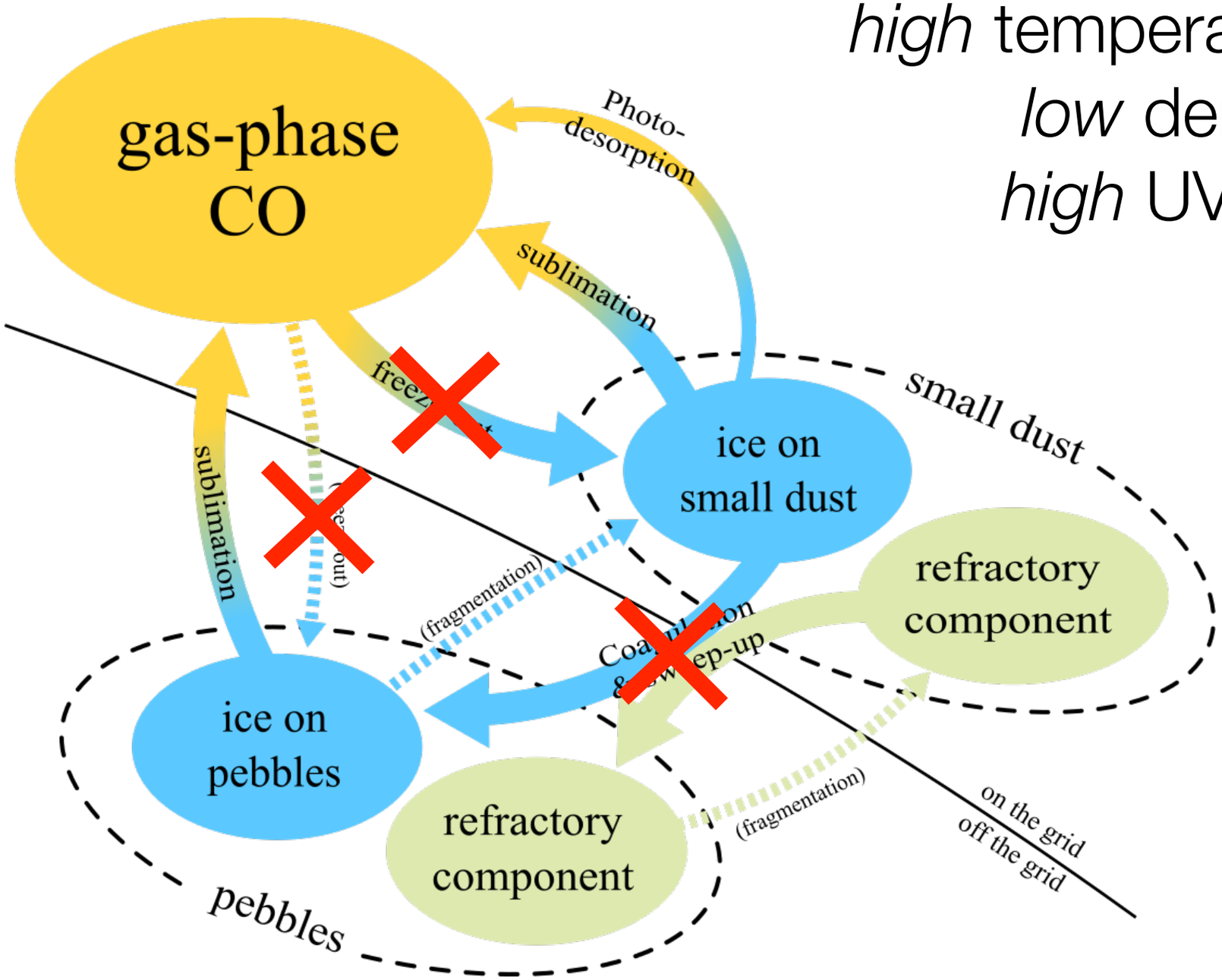



$r_{i+1}/r_i = 1.05; \quad z_{i+1}/z_i = 1.10$
100
80
60
40
20
0
z (AU)
50
100
150
200
250
300
350
400
r (AU)

low temperature
high density
low UV flux



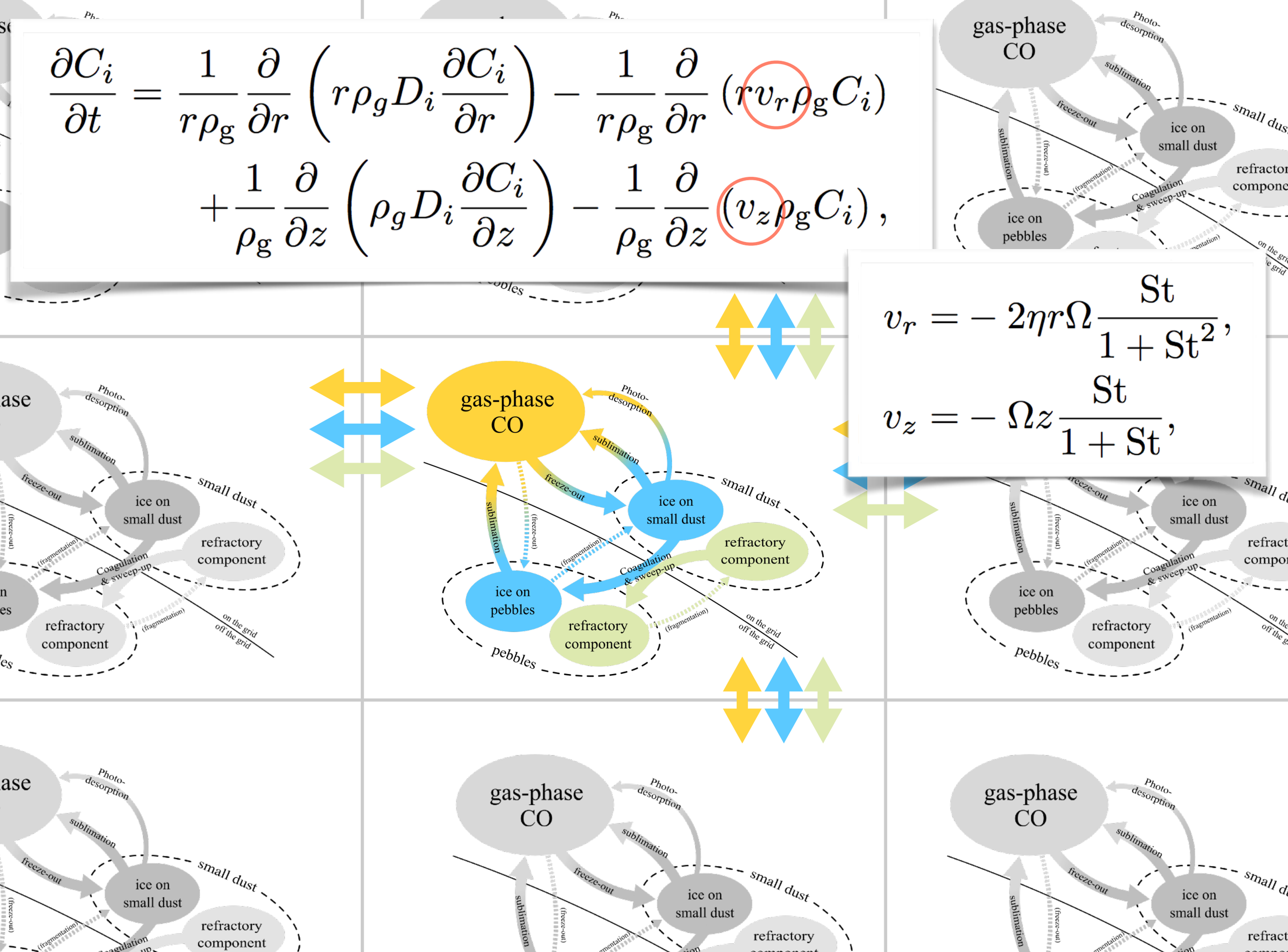
high temperature
low density
high UV flux

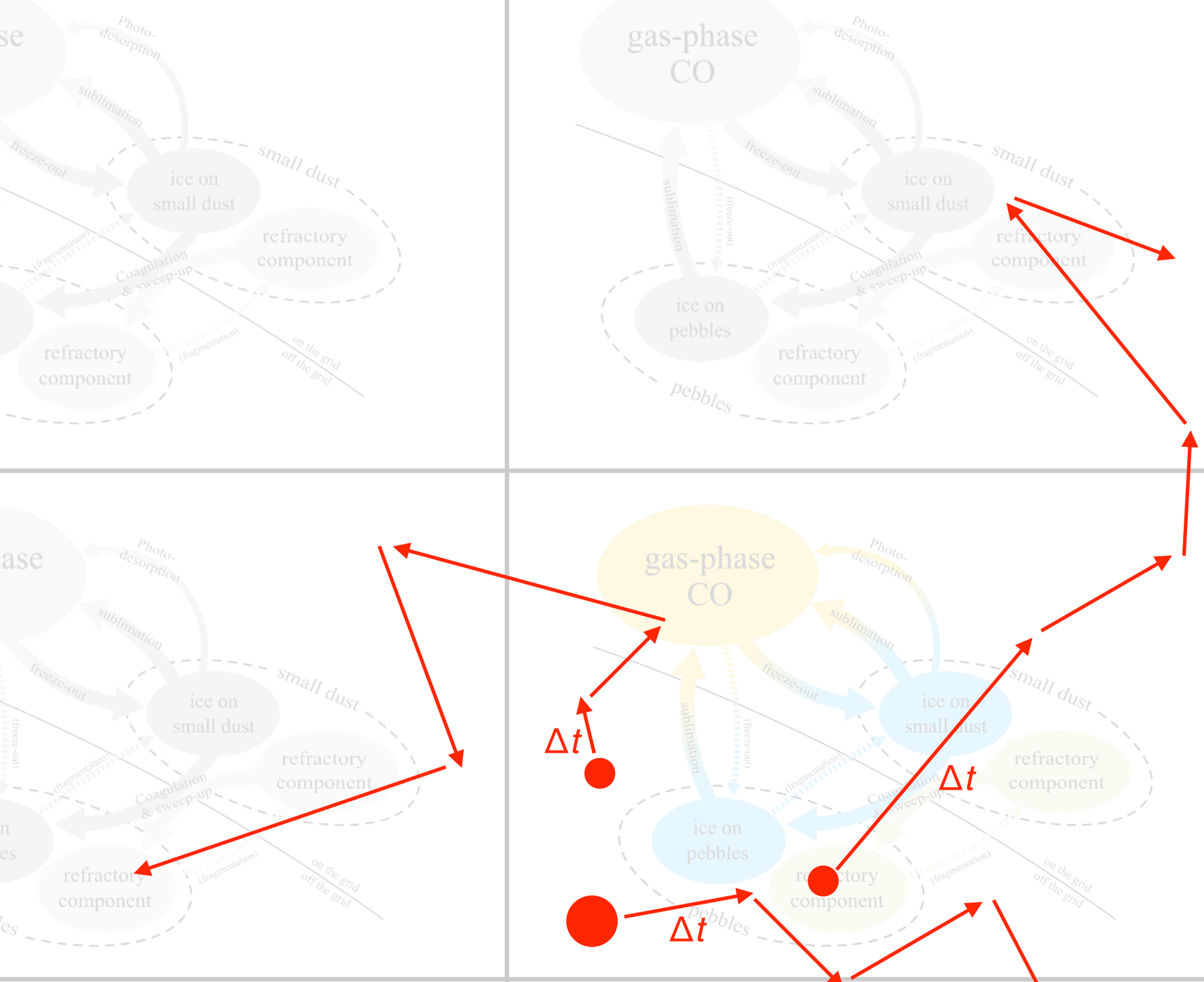


$$\frac{\partial C_i}{\partial t} = \frac{1}{r\rho_{\rm g}}\frac{\partial}{\partial r}\left(r\rho_g D_i \frac{\partial C_i}{\partial r}\right) - \frac{1}{r\rho_{\rm g}}\frac{\partial}{\partial r}\left(r v_r \rho_{\rm g} C_i\right) + \frac{1}{\rho_{\rm g}}\frac{\partial}{\partial z}\left(\rho_g D_i \frac{\partial C_i}{\partial z}\right) - \frac{1}{\rho_{\rm g}}\frac{\partial}{\partial z}\left(v_z \rho_{\rm g} C_i\right),$$

$$v_r = -2\eta r\Omega \frac{\mathrm{St}}{1+\mathrm{St}^2},$$

$$v_z = -\Omega z \frac{\mathrm{St}}{1+\mathrm{St}},$$





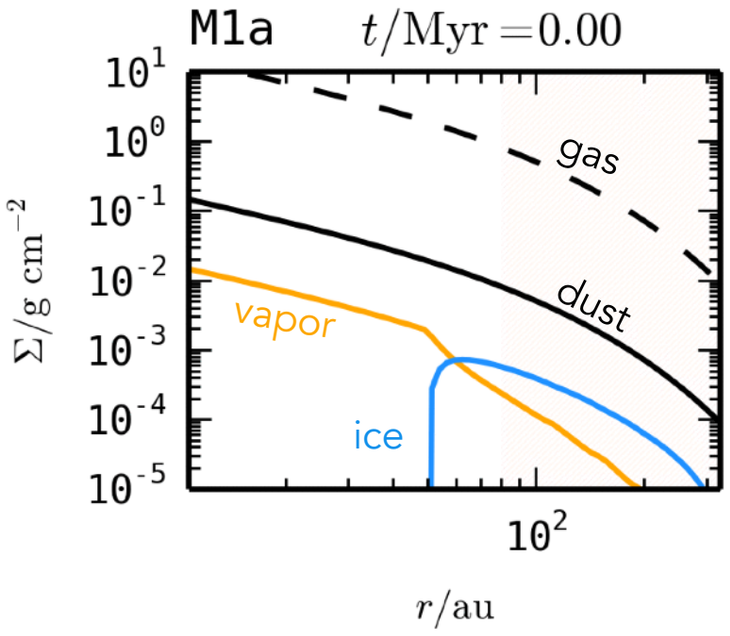
$$r(t+\Delta t) = r(t) + v_r^{\rm eff}\Delta t + R\left(\frac{2}{\xi}D_{\rm p}\Delta t\right)^{1/2},$$

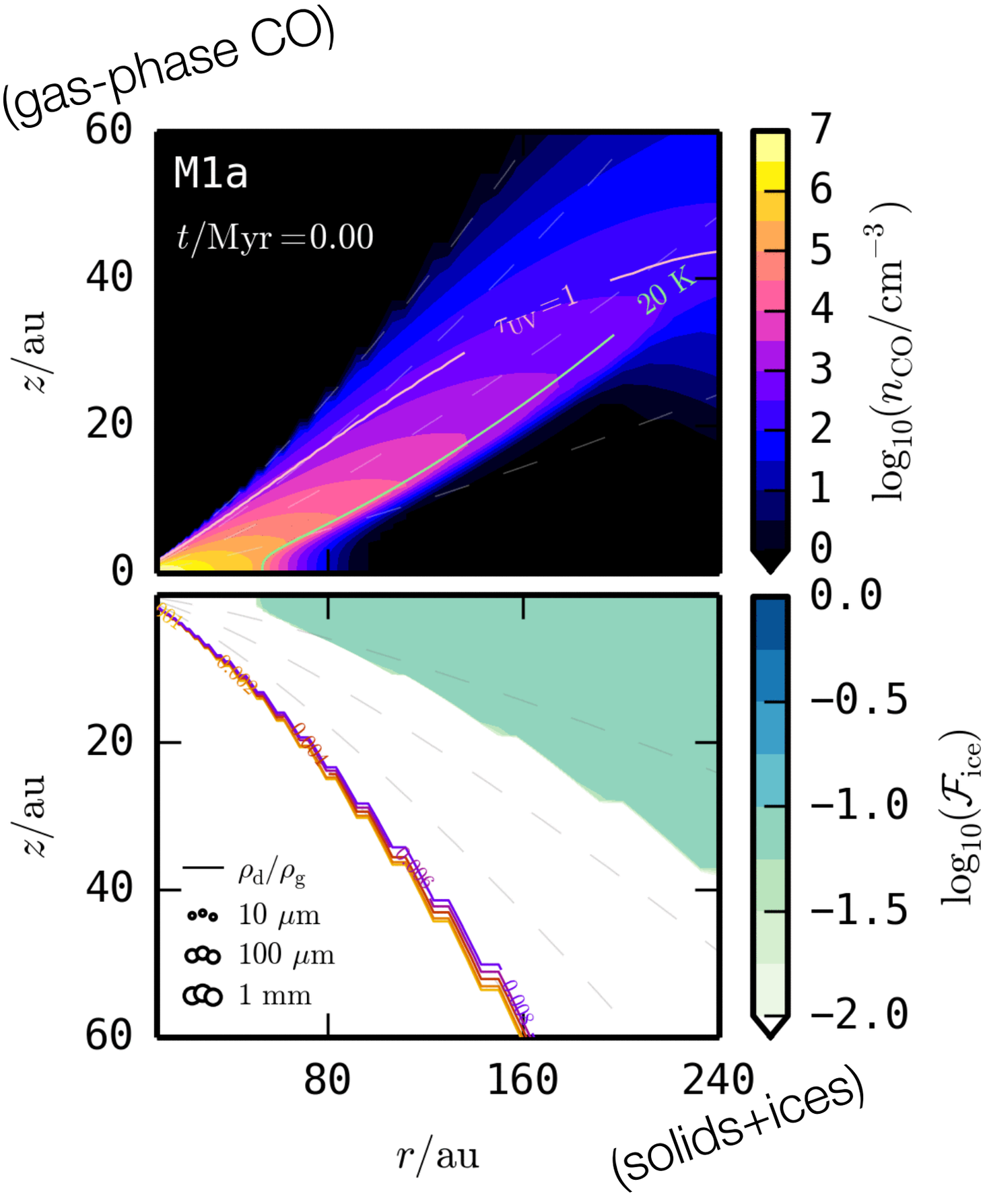
$$z(t+\Delta t) = z(t) + v_z^{\rm eff}\Delta t + R\left(\frac{2}{\xi}D_{\rm p}\Delta t\right)^{1/2},$$

have access to pebble's dynamical histories

Initial conditions

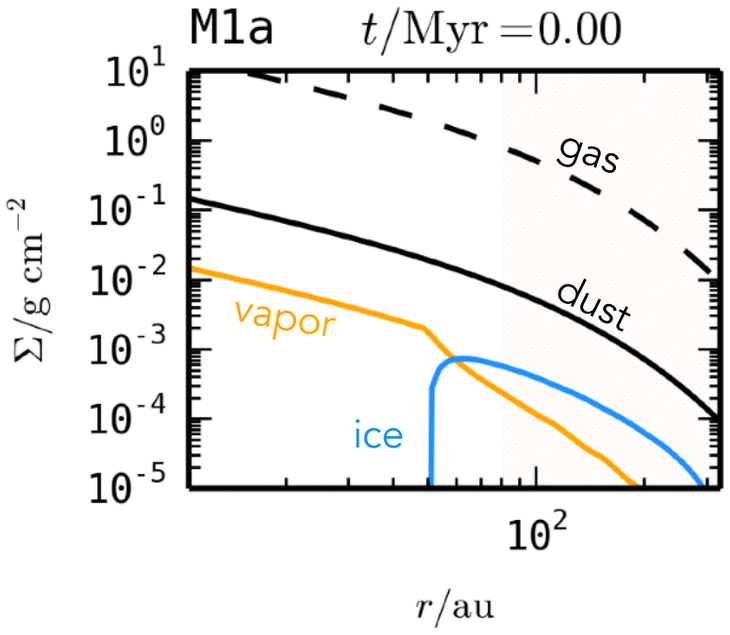
- At *t=0*, everything is in equilibrium
- No pebbles exist (yet)

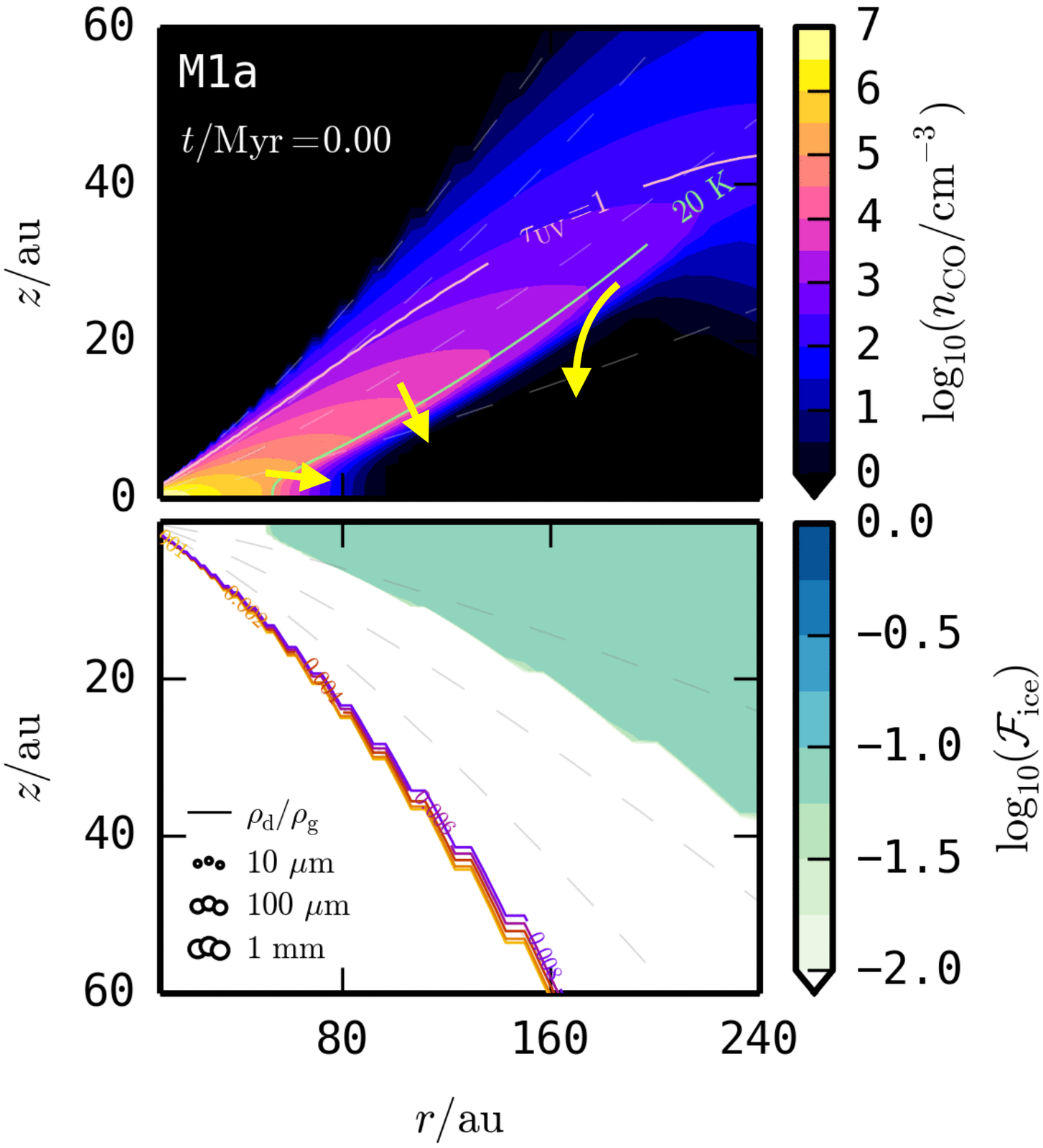




Model M1a

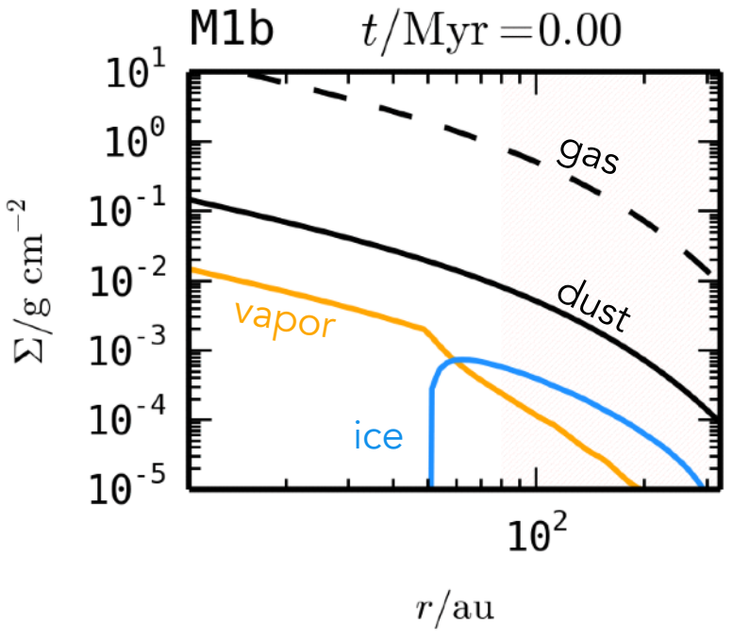
- Vapor allowed to diffuse & freeze-out
- Small dust is **not** allowed to move or form pebbles

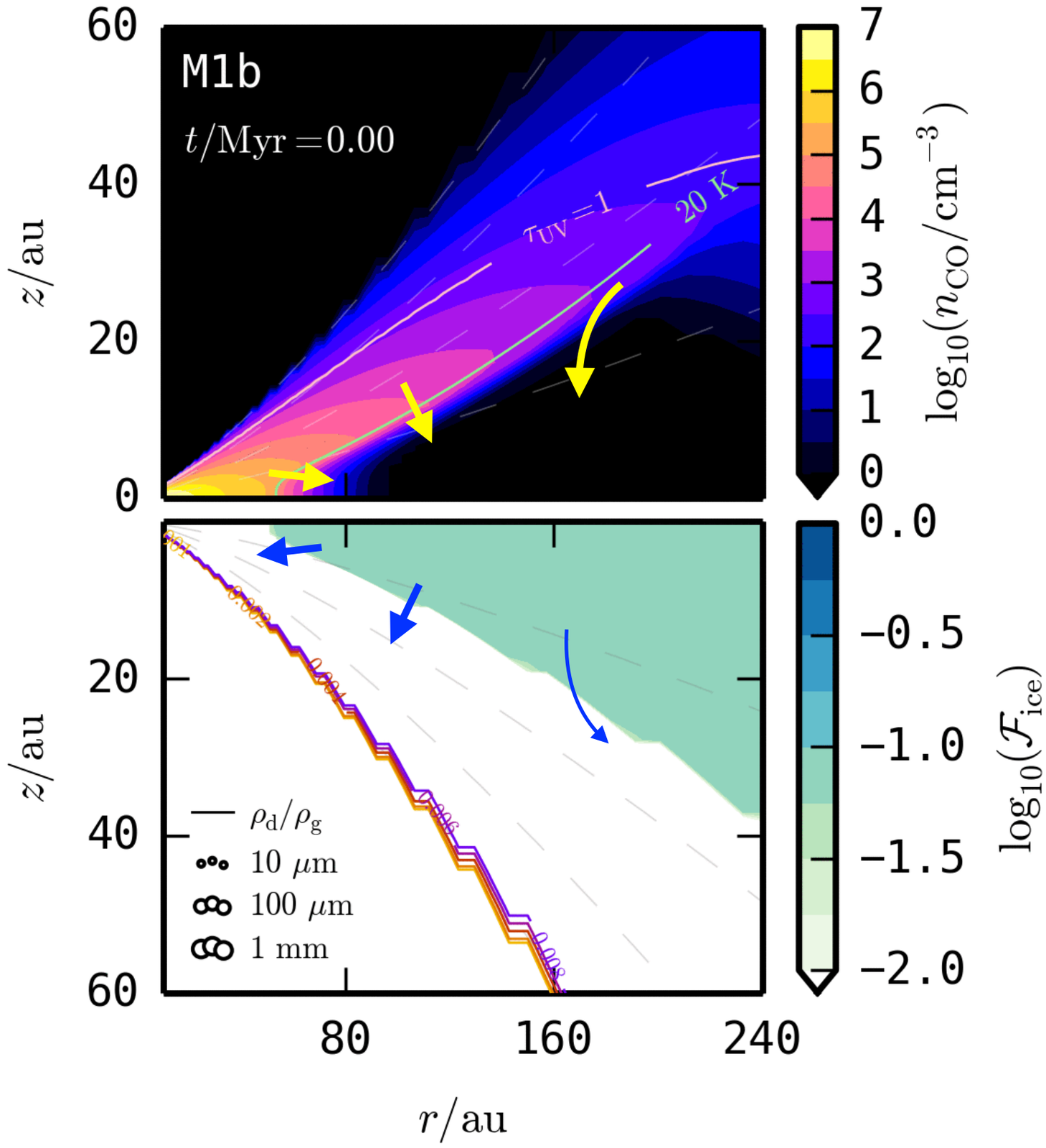




Model M1b

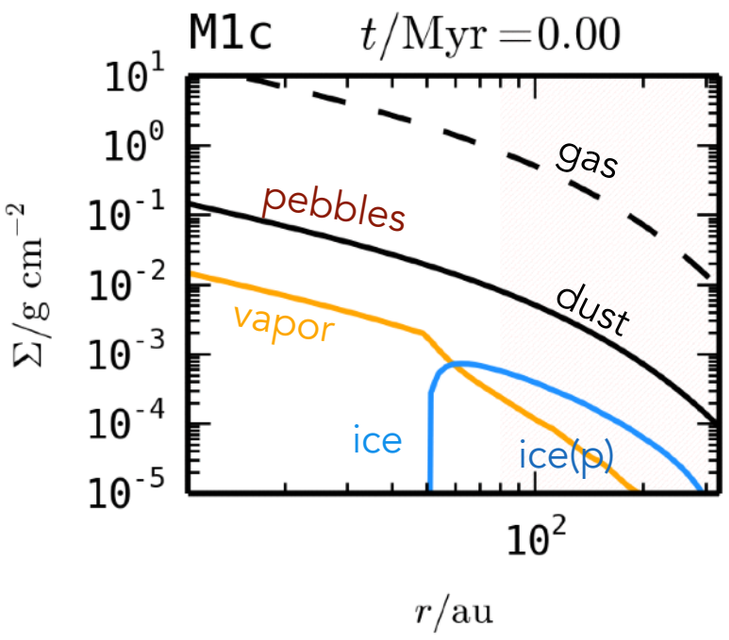
- Like M1a, but now small dust grains can move radially & vertically
- Pebble formation not included

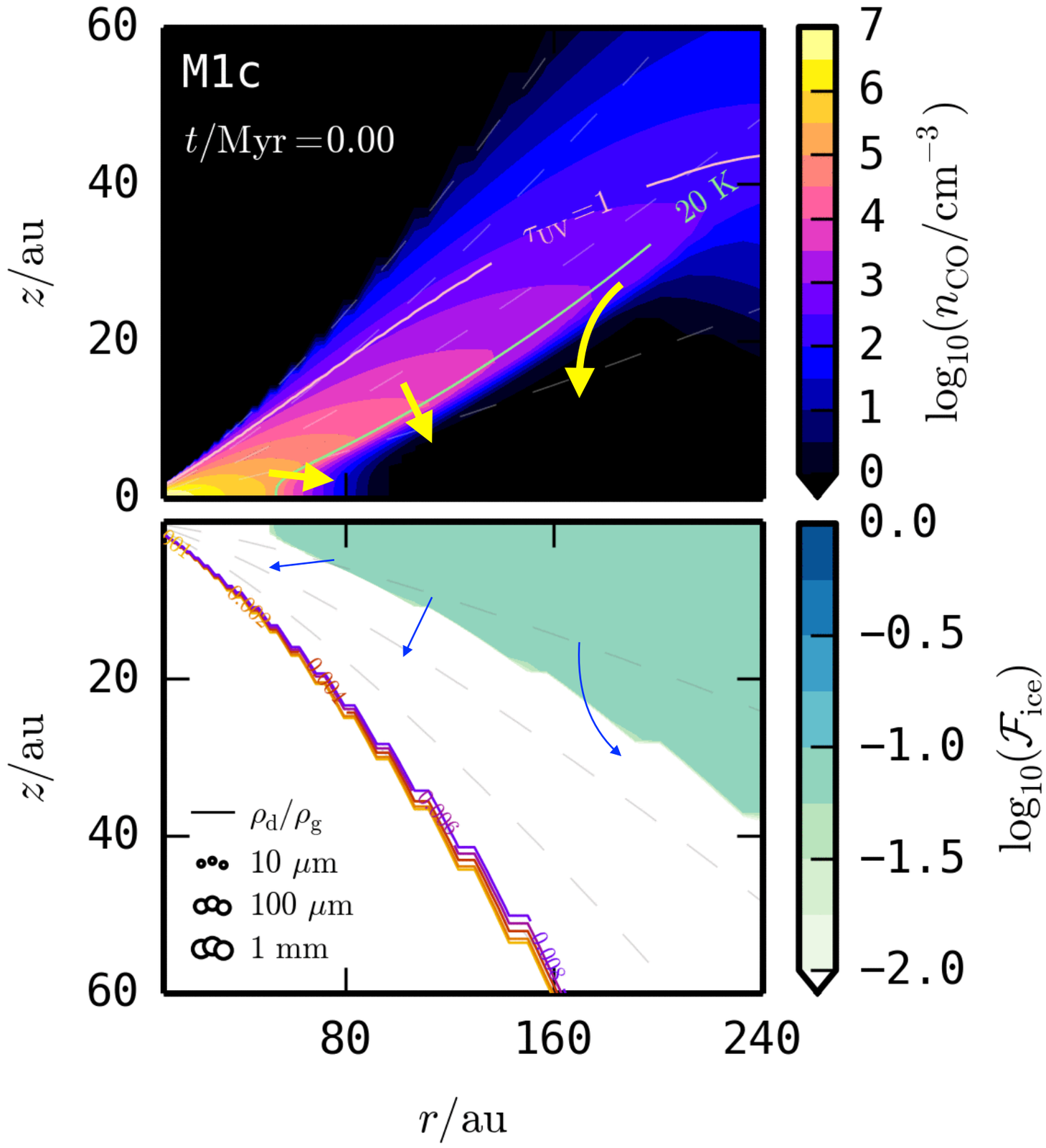




Model M1c

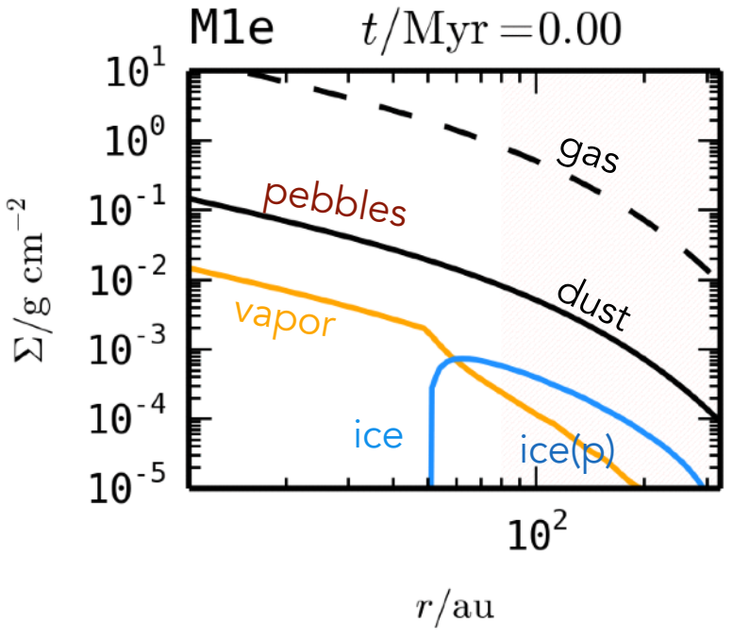
- Like M1b, but now pebbles can form (their sizes are limited by the `bouncing barrier')
- However, pebbles are **not** allowed to move

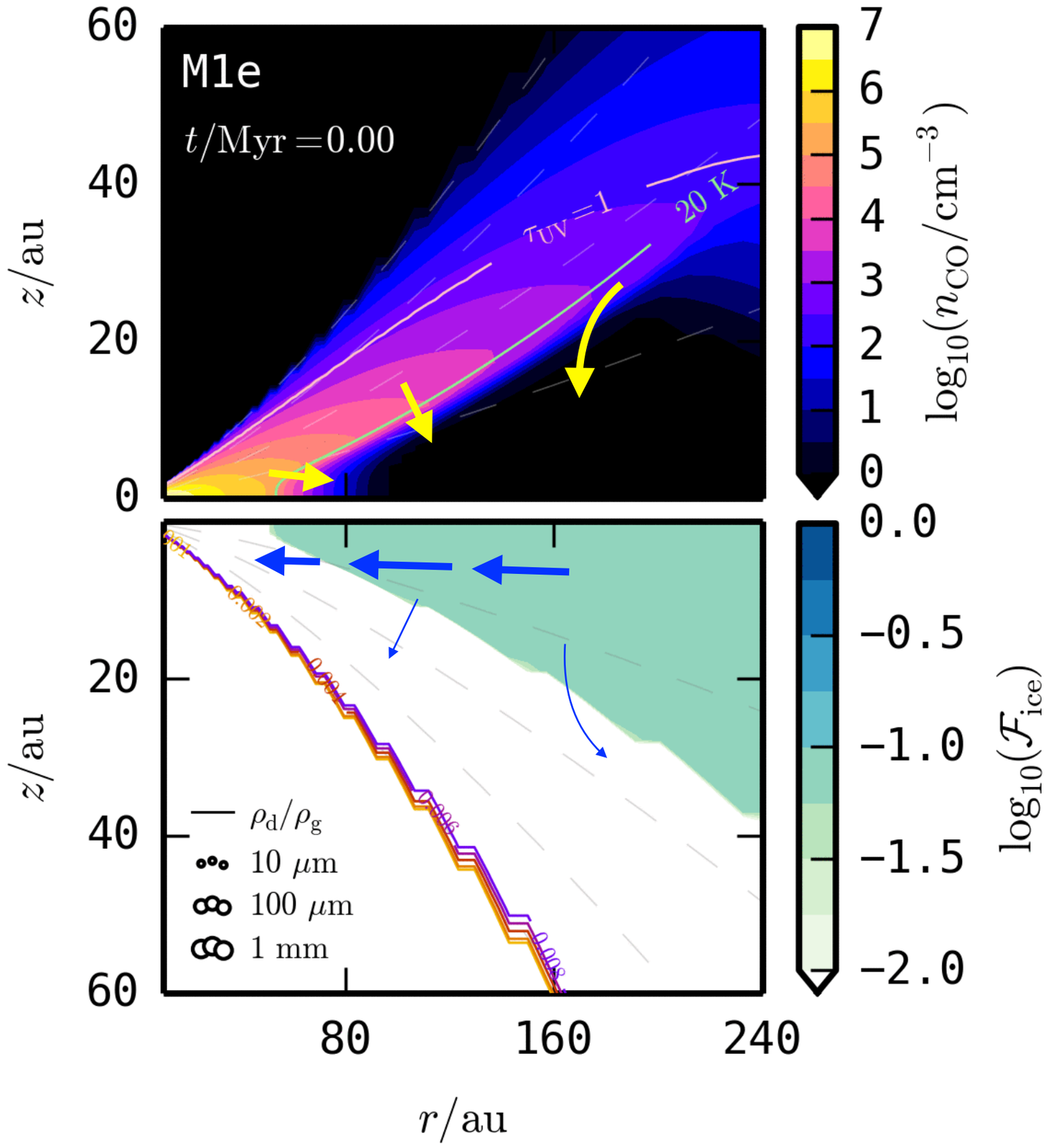




Model M1e

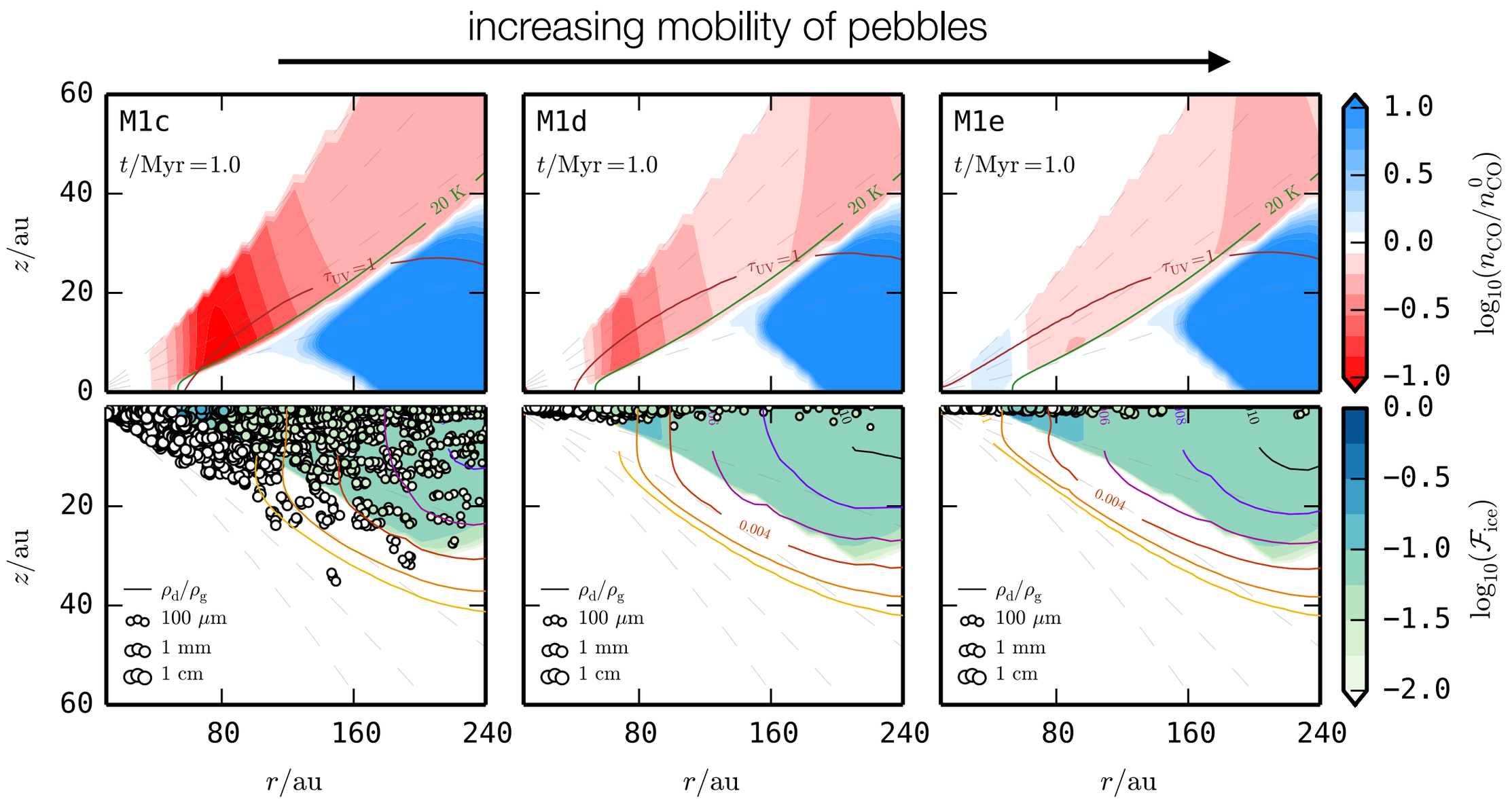
- Like M1c, but now pebbles can move settle & drift radially
- (They also grow by colliding amongst themselves)





Comparison after 1Myr

Pebbles alter the gas-phase CO/H_2 in complex and time-dependent way, usually resulting in depletion of CO in the warm molecular layer, and enhancement inside the midplane snowline



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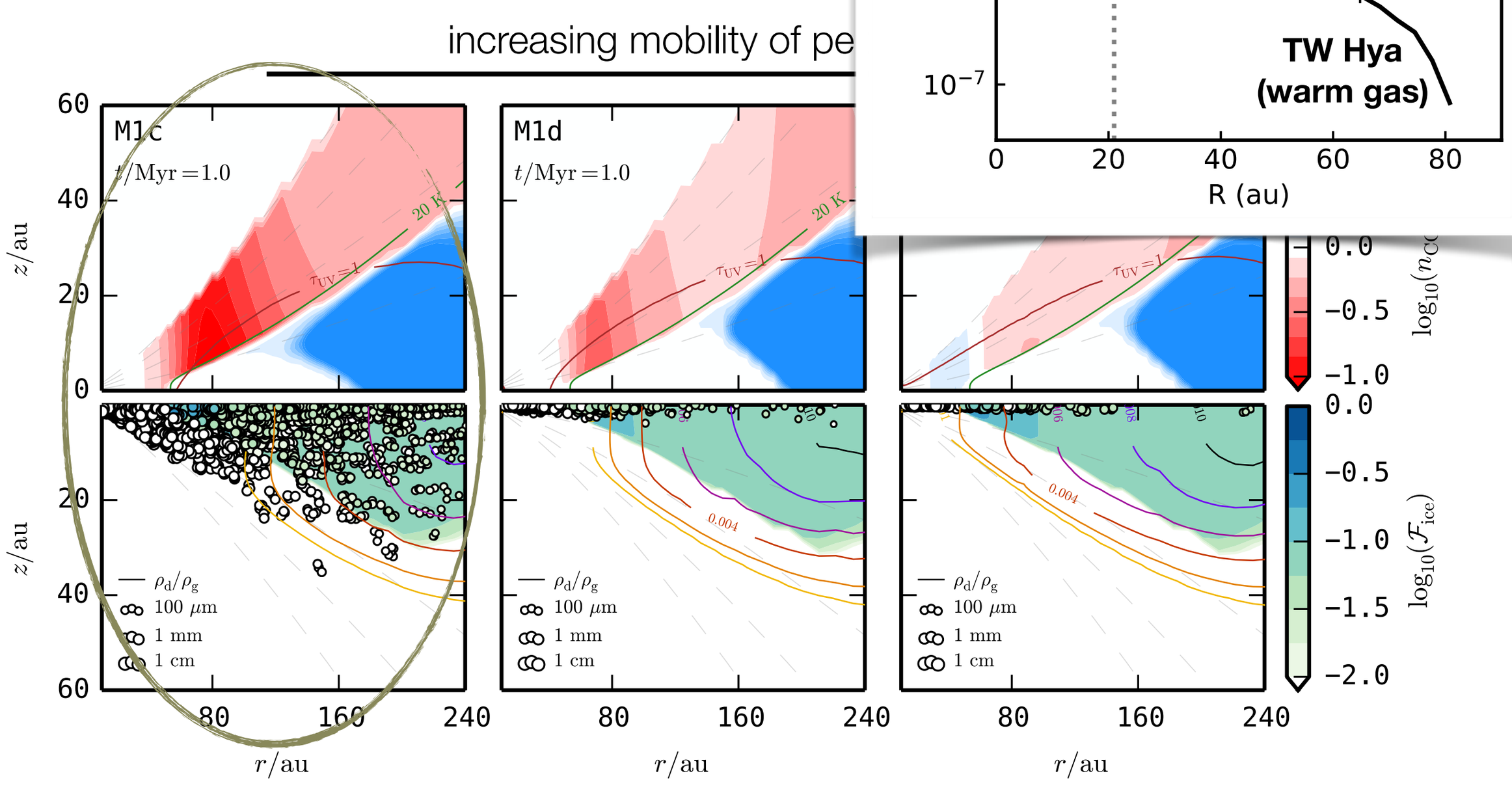
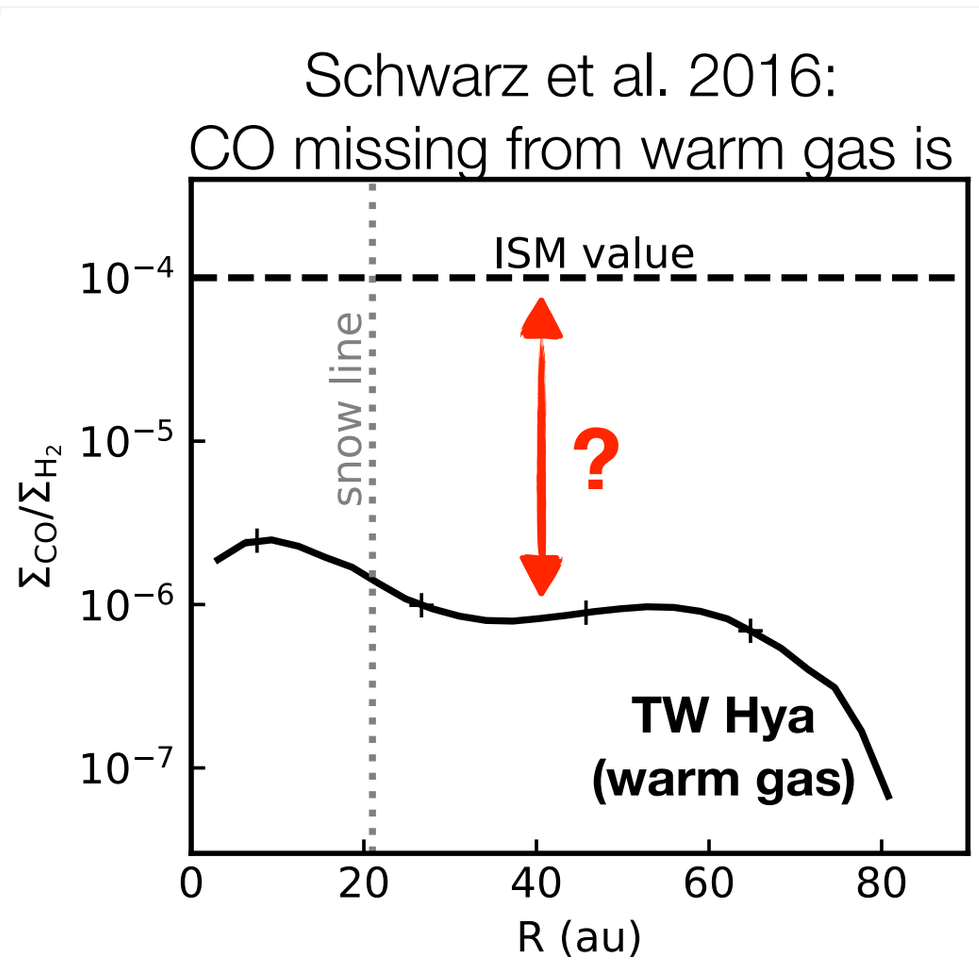
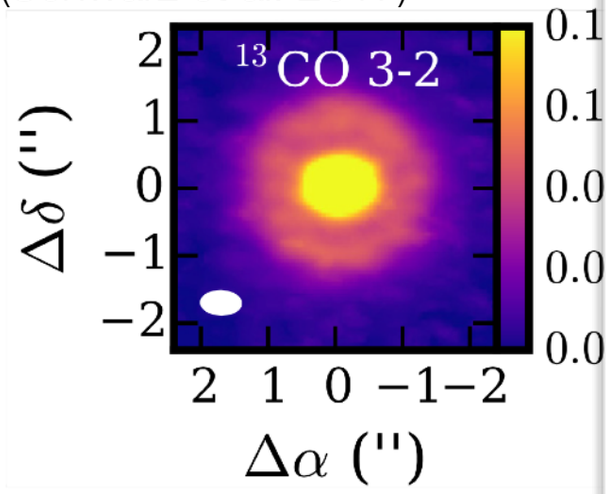
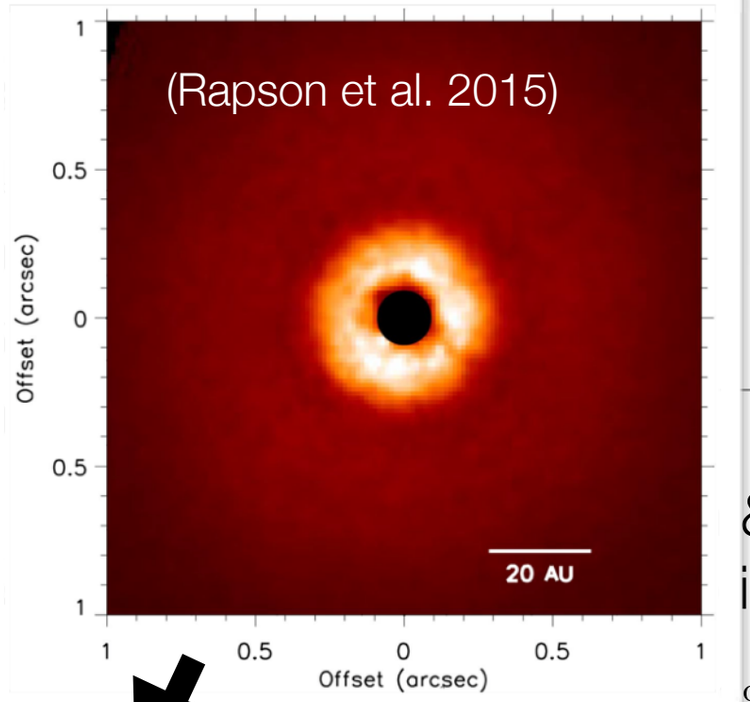
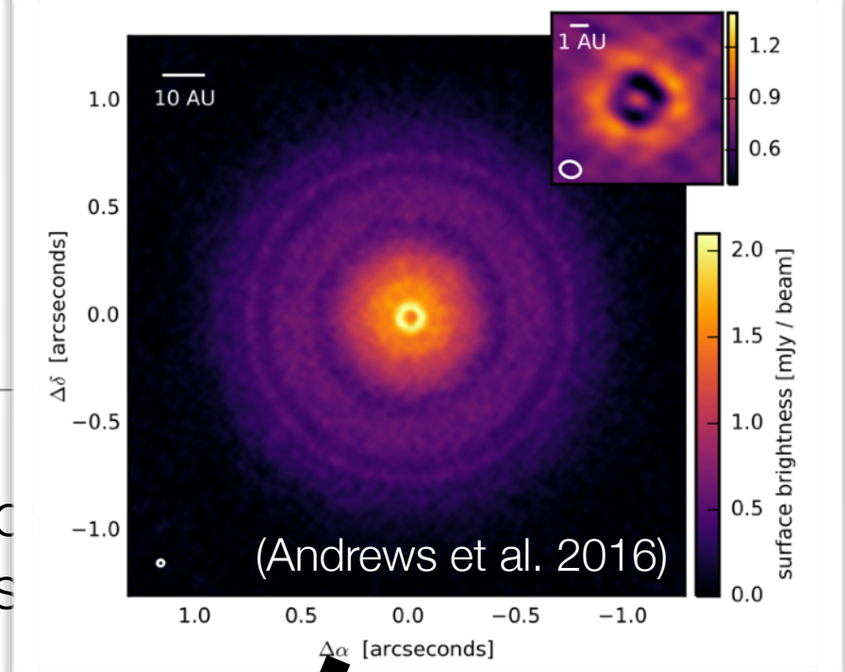




(Schwarz et al. 2017)







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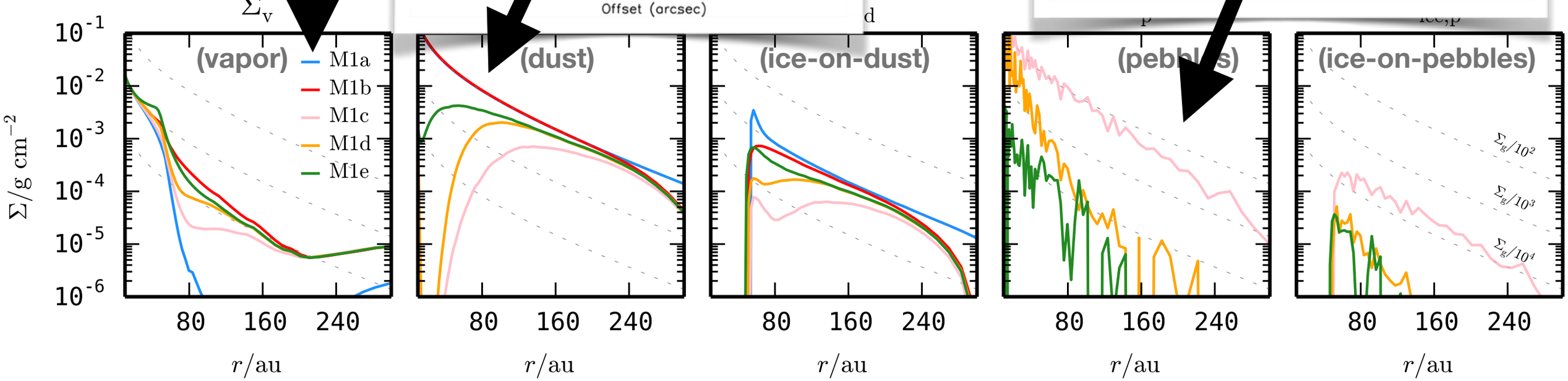
in PP disks



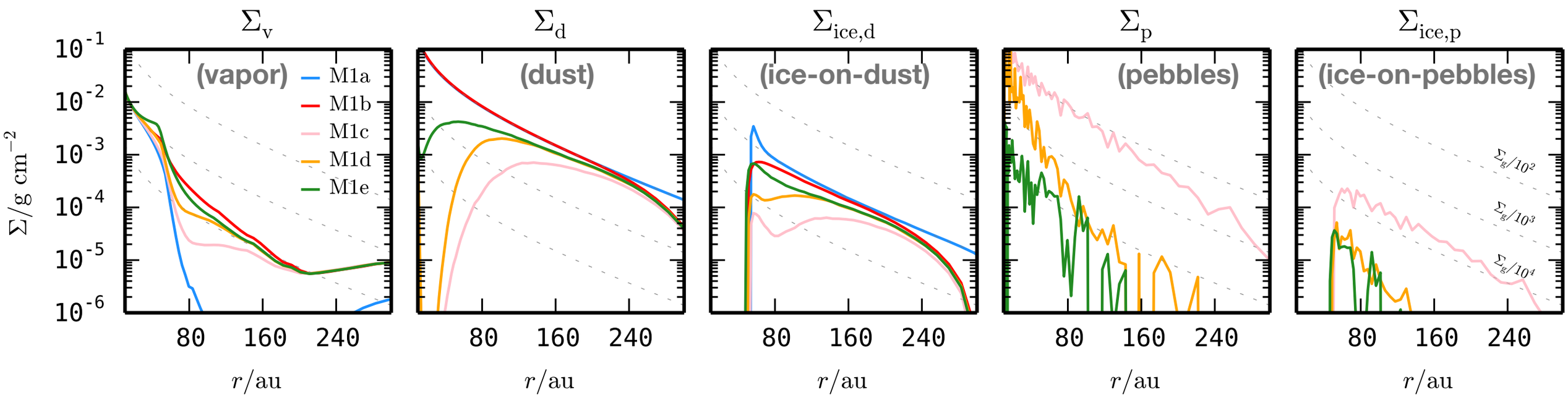
Next steps:

By comparing different models to a suite of multi wavelength observations (CO isotopologues, mm continuum, scattered light, …) we hope to constrain magnitude & timing of large scale pebble migration

Comments/help welcome!

Summary / outlook

Our model can resolve time-dependent evolution & interaction of different gas-phase and solid components (CO molecules, dust, pebbles) in PP disks



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