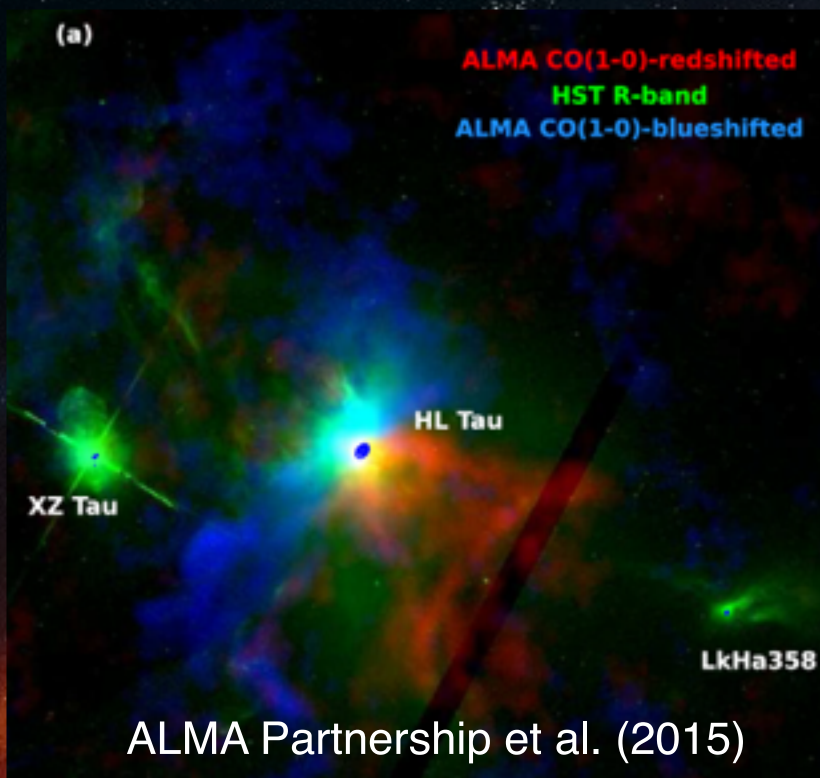
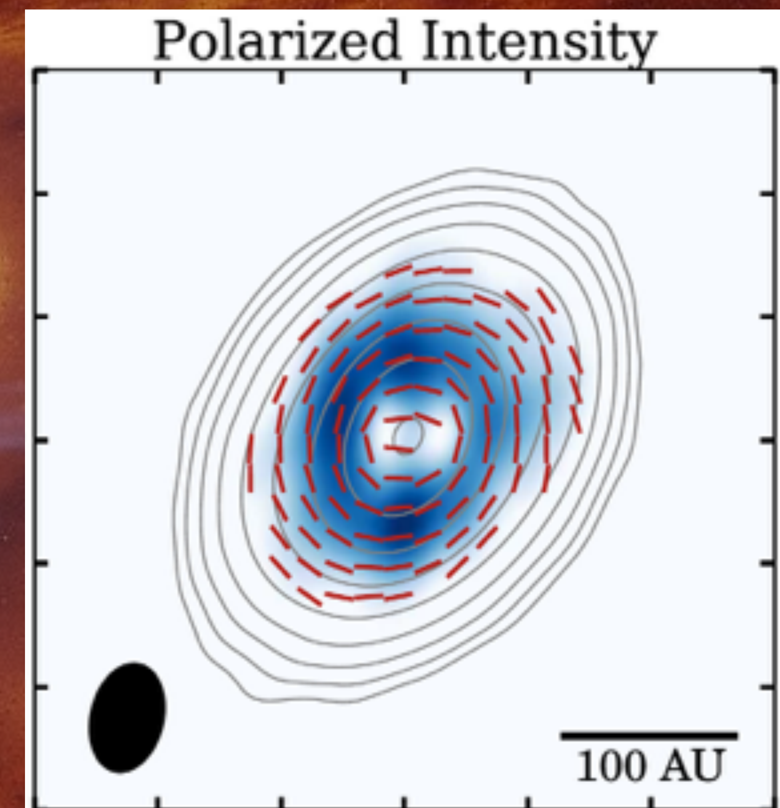
~~Accretion~~ and Dust Evolution in the HL Tau Disk

MHD disk winds might be the main driver of disk accretion.
See Hasegawa, Okuzumi, Flock, & Turner (2017), ApJ, 845, 31!



ALMA Partnership et al. (2015)


ALMA Partnership et al. (2015)

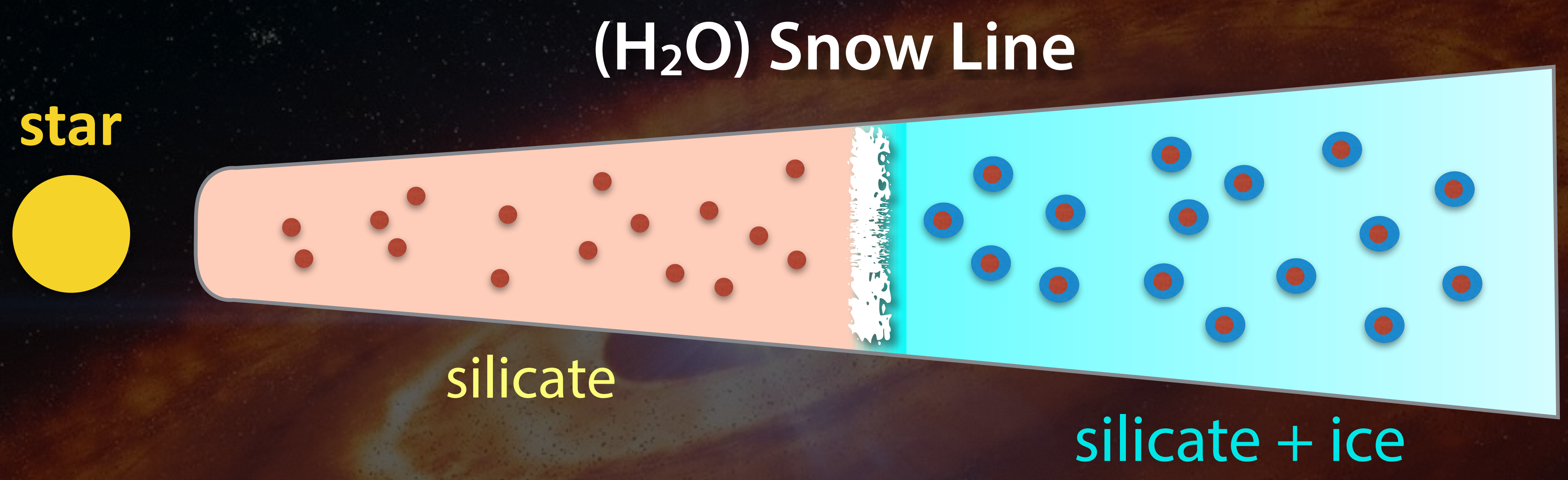


Kataoka et al. (2017)

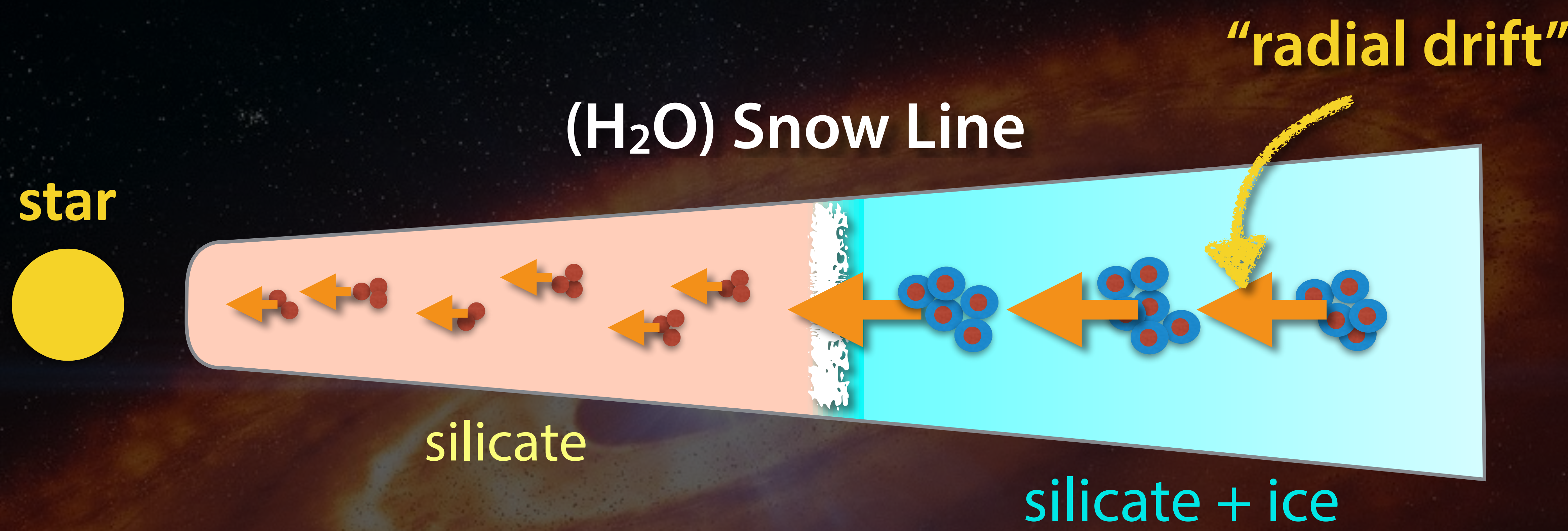
Satoshi Okuzumi (Tokyo Tech)

Yasuhiro Hasegawa, Mario Flock, Neal Turner (JPL/Caltech),
Munetake Momose (Ibaraki Univ.), Hidekazu Tanaka (Tohoku Univ.),
Hiroshi Kobayashi, Sin-iti Sirono (Nagoya Univ.),
Kota Higuchi, Masamichi Nagao (Tokyo Tech)

Importance of the Snow Line in Dust Evolution



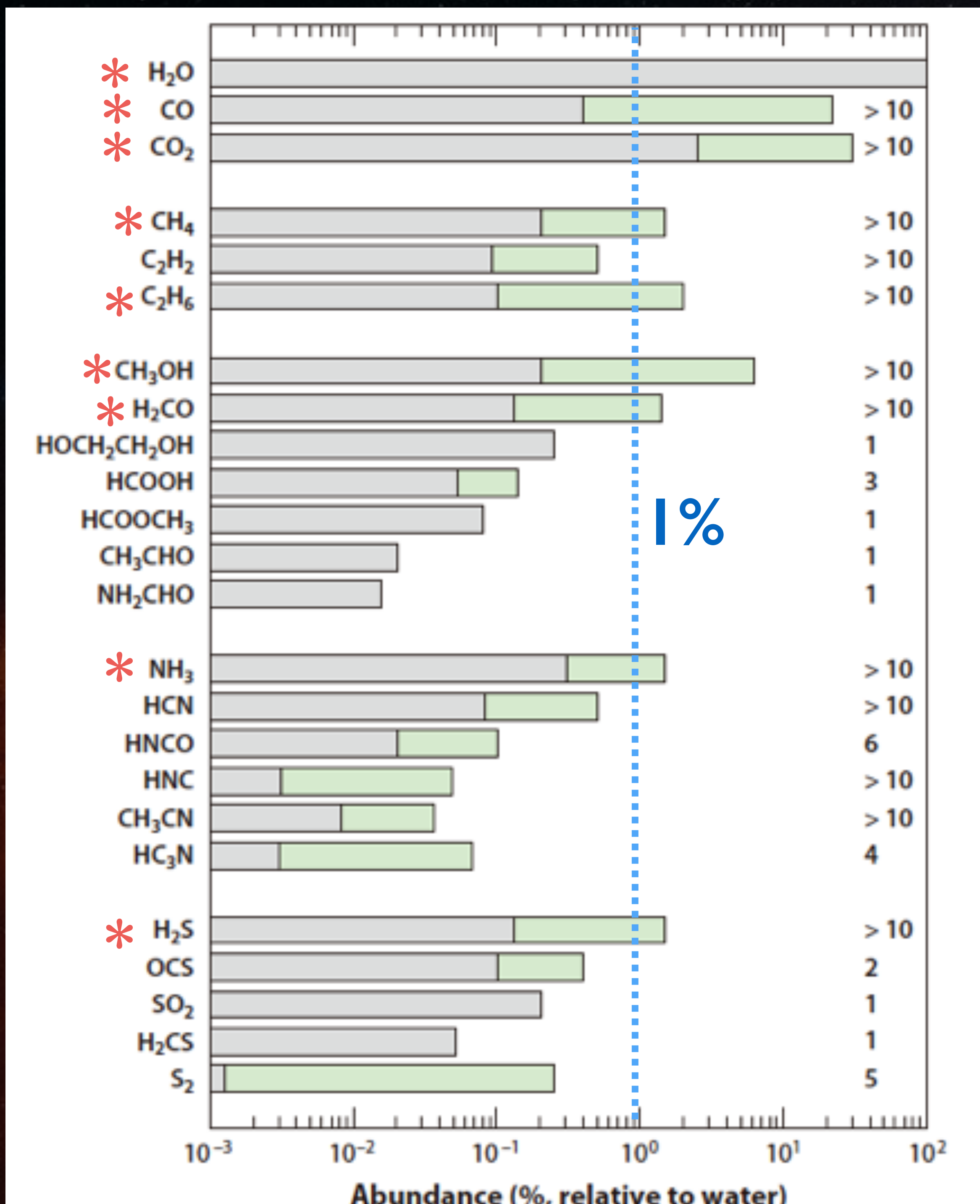
Importance of the Snow Line in Dust Evolution

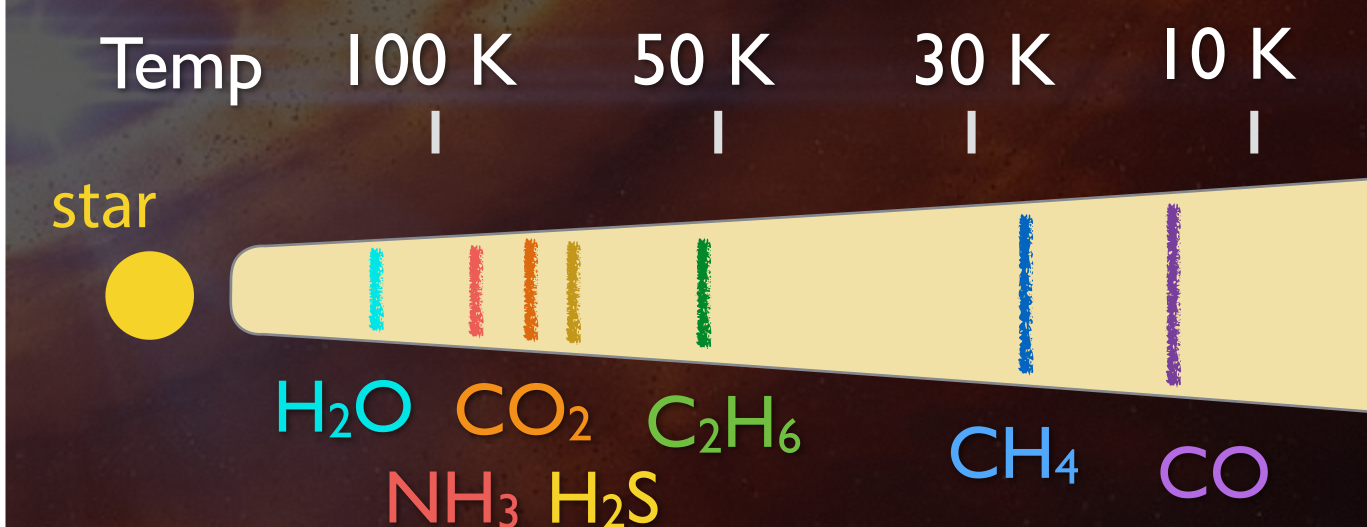


- **Location where particle stickiness changes**
  (particles coated by water ice is sticky. See Wada et al, 2009; Gundlach & Blum 2015)
- **Vapor re-condensation** (Stevenson & Lunine 1988; Ros & Johansen 2013; Schoonenberg & Ormel 2017)
- **Piling-up of silicates** (Saito & Sirono 2011; Ida & Guillot 2011)
- **Sintering** (Sirono 1999,2011a,b; Okuzumi et al. 2016; Sirono & Ueno 2017)

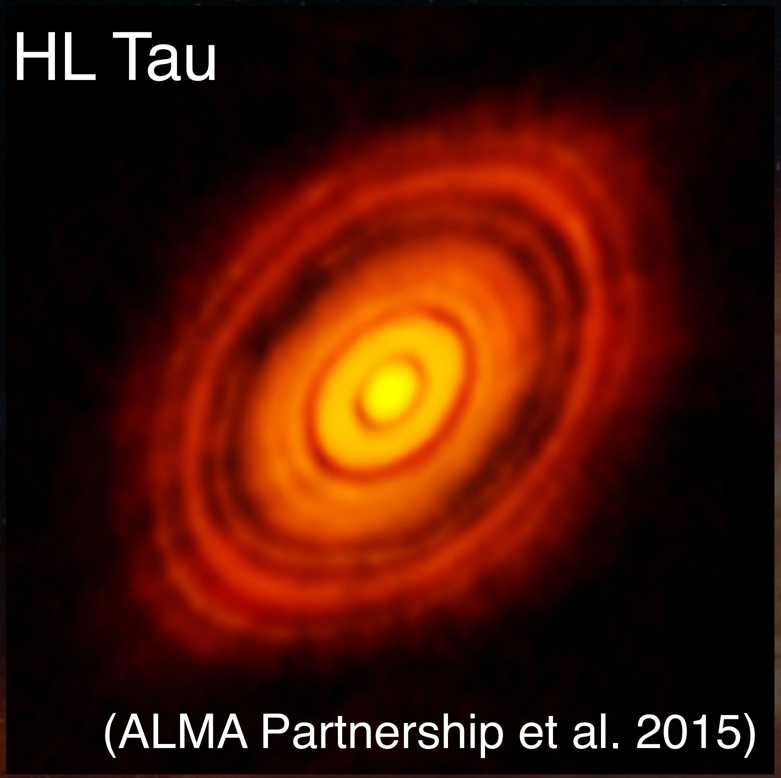
Snow Lines

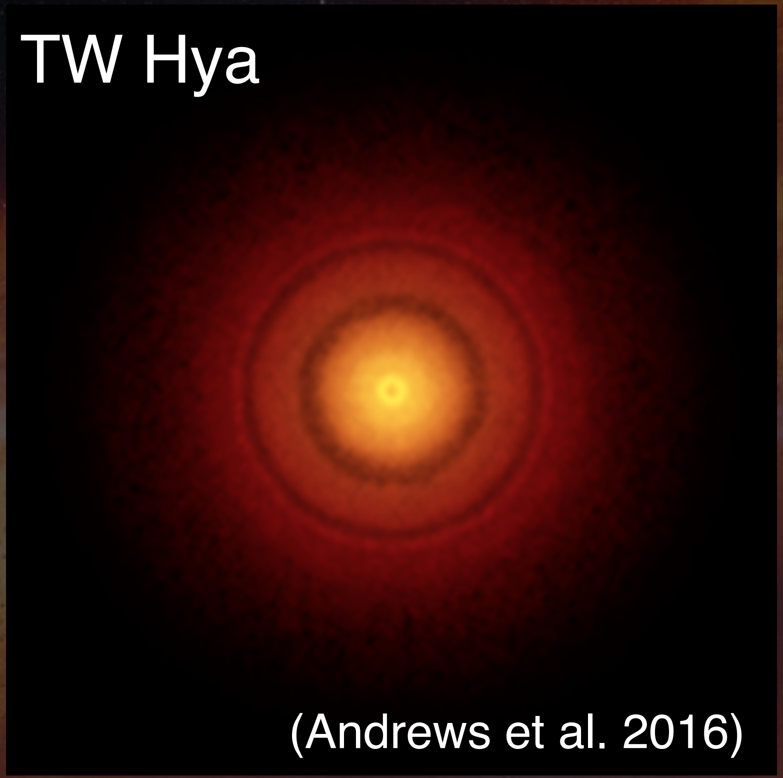
abundances of major volatiles
in comets (Mumma & Charnley 2011)

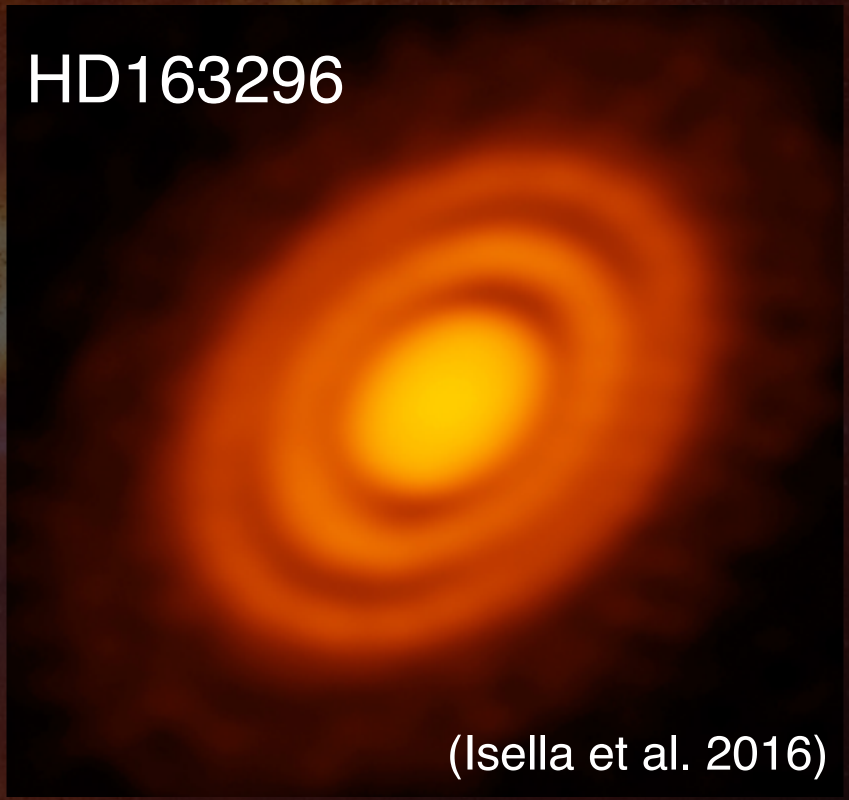




What are the Origins of the Dust Rings/Gaps?





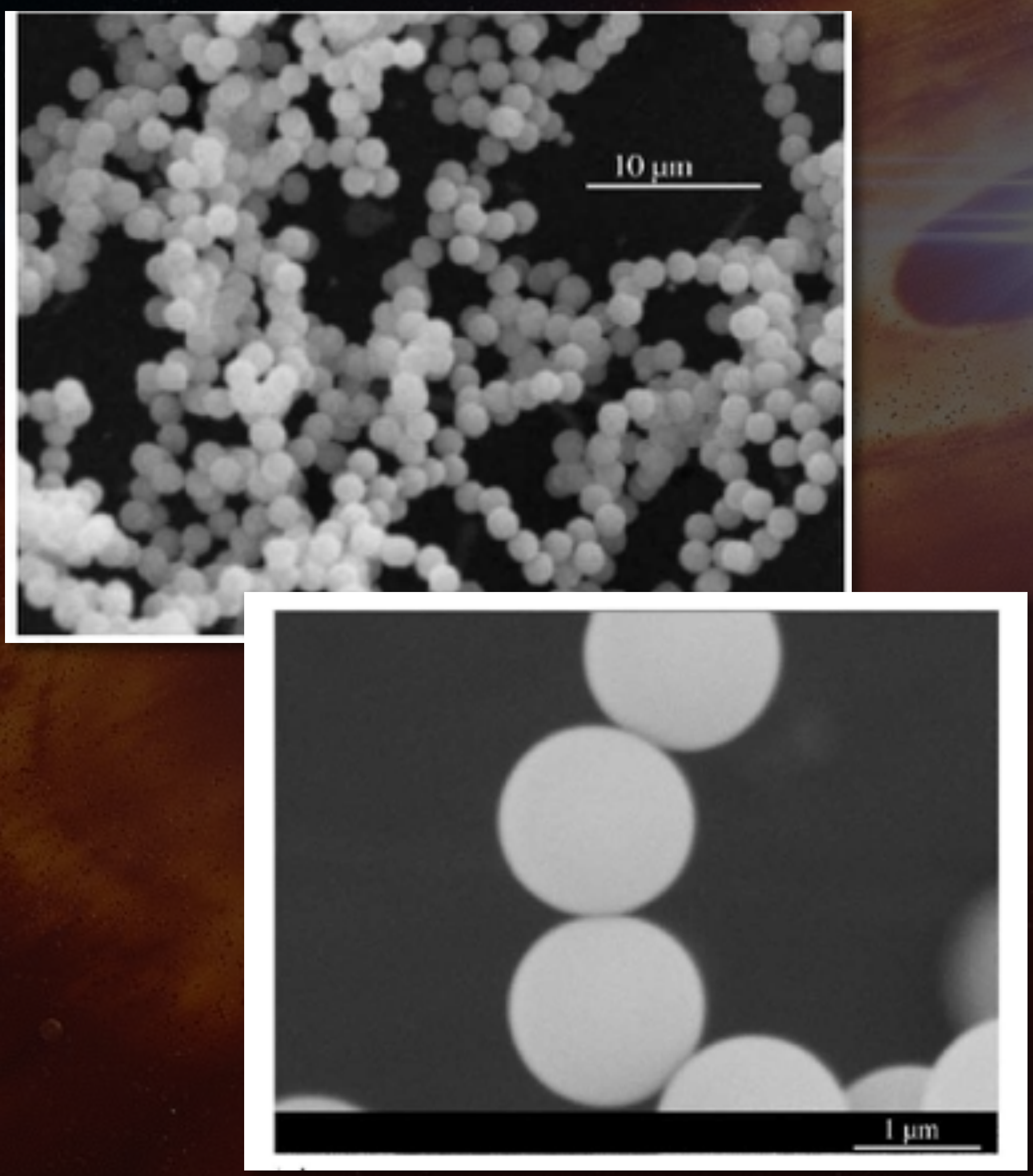


- Planets? (e.g., Dipierro+15; Kanagawa+15; Jin+16; Bae+17)
- Instabilities? (e.g., Takahashi+14; Lorén-Aguilar+15)
- Condensation near the snow lines? (Zhang+15)
- **Sintering near the snow lines? (this work)**

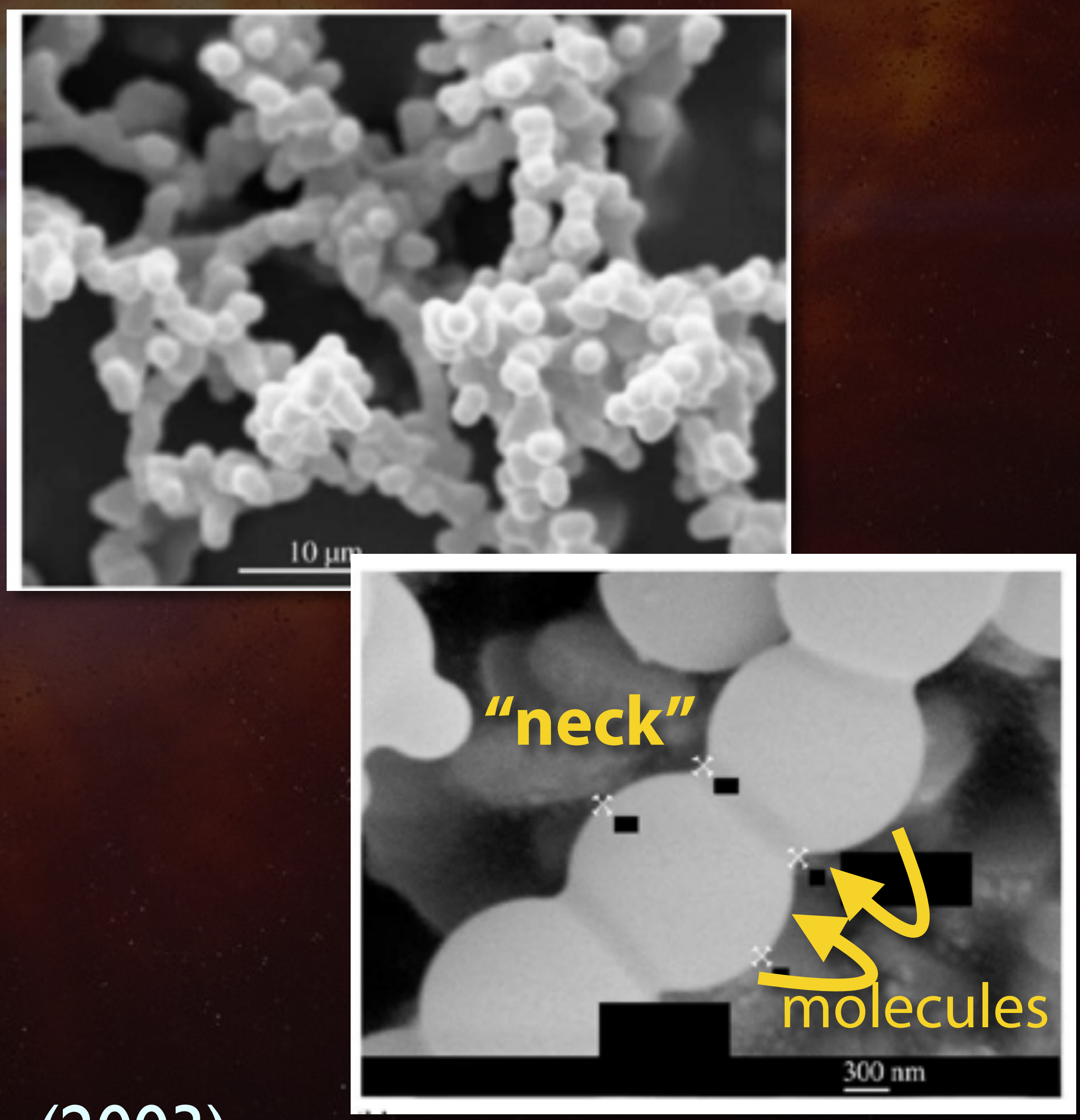
Sintering

Sintering is a grain fusion phenomenon that happens when the temperature is *slightly below* the sublimation/melting temp.:

silica aggregate before sintering



after sintering (1473K, 1hr)



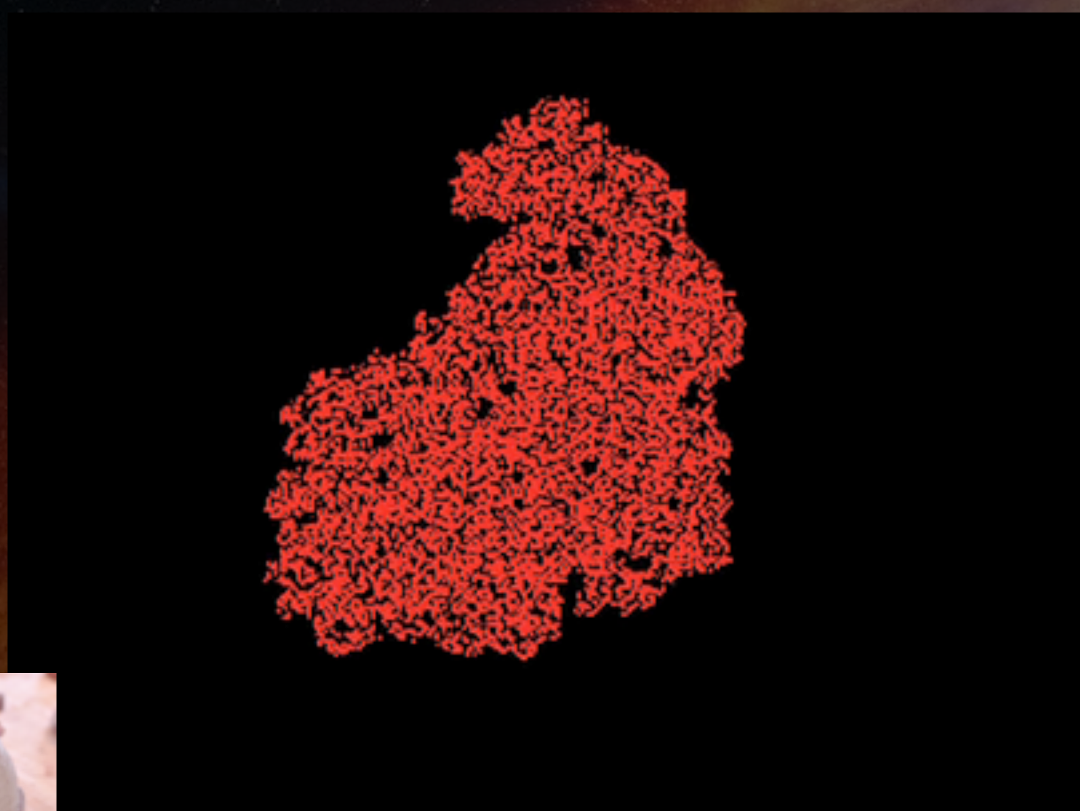
Poppe (2003)

Sintered Aggregates are Brittle

(Sirono 1999; Sirono & Ueno 2017)

Example: aggregates of 0.1-μm icy grains, colliding at 20m/s

w/o sintering



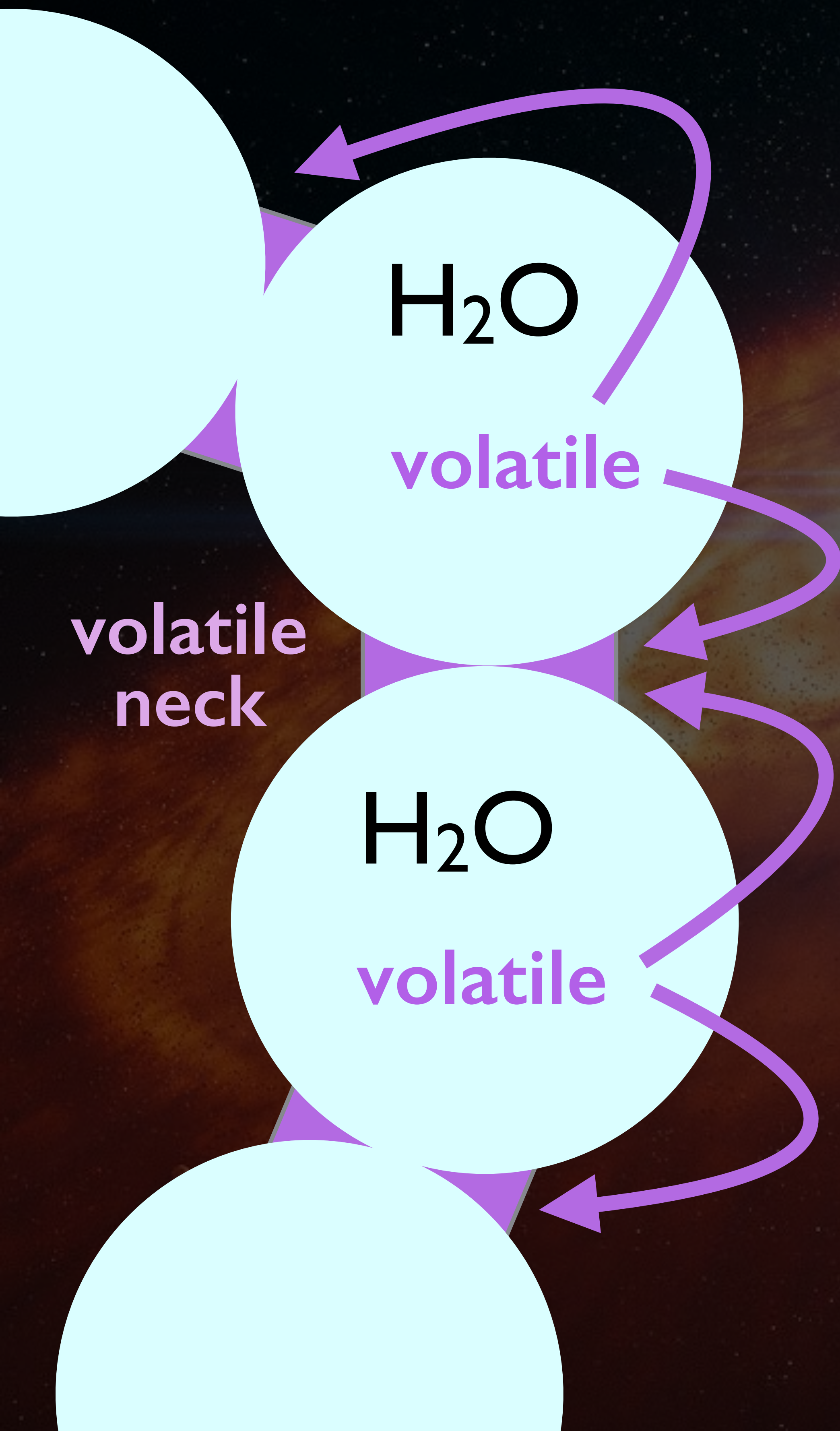
disruption at ≳ 50 m/s

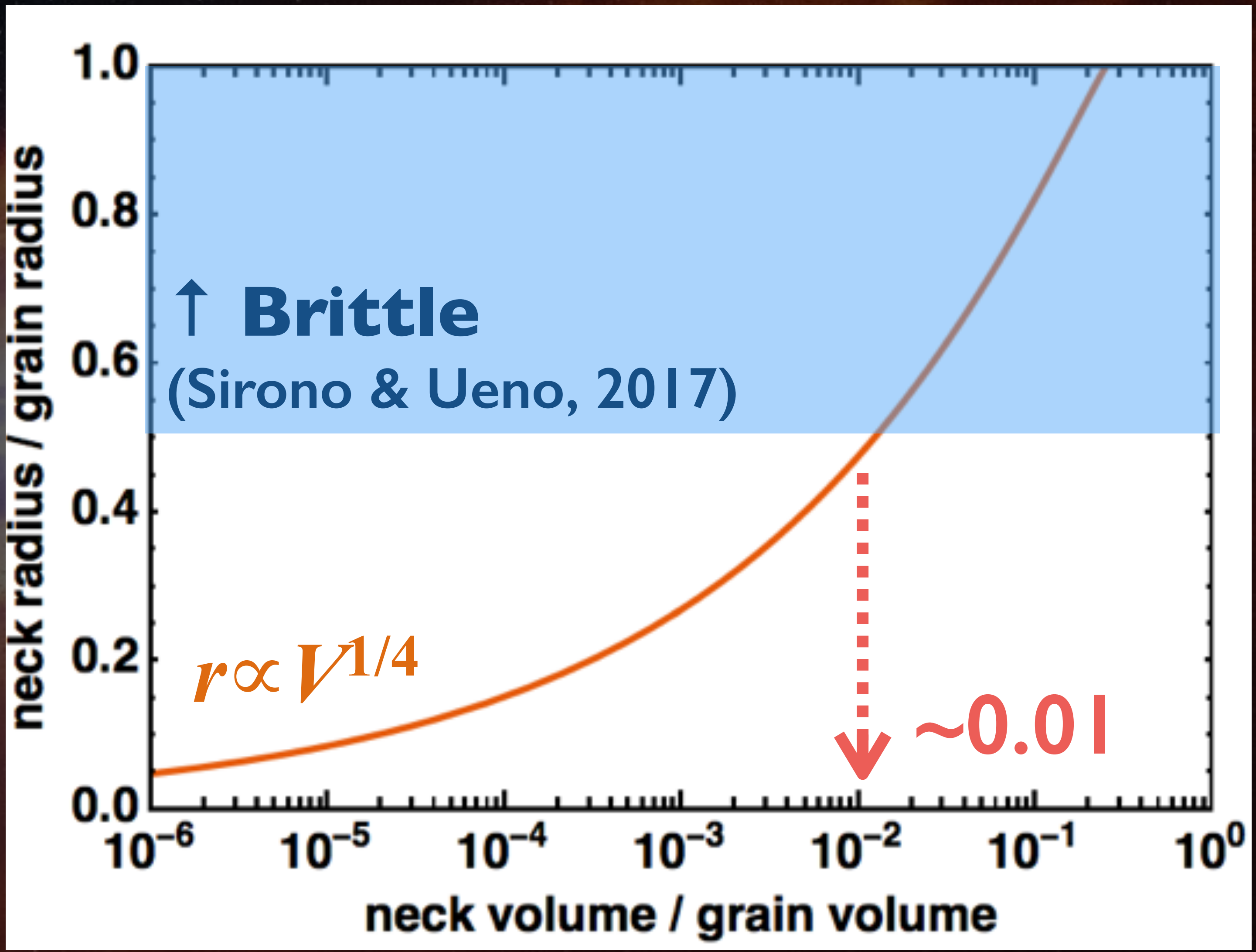
(see also Wada et al. 2009)

w/ sintering

disruption at ≳ 20 m/s

Minor Volatiles Can Cause Sintering

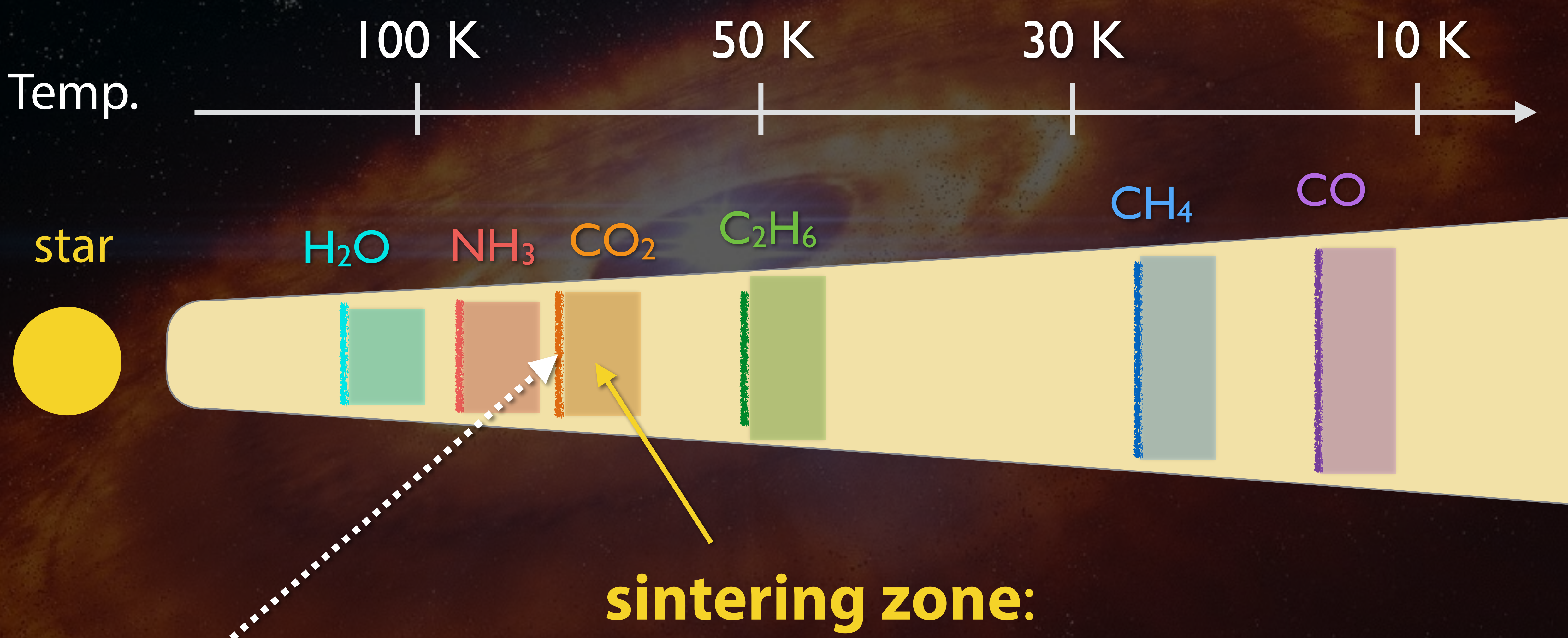




Even minor volatiles (of volume faction ~1%) **are able to produce thick necks!**

The Sintering Zones

Sirono (2011b); Okuzumi et al. (2016)



snow line:
where ice sublimates

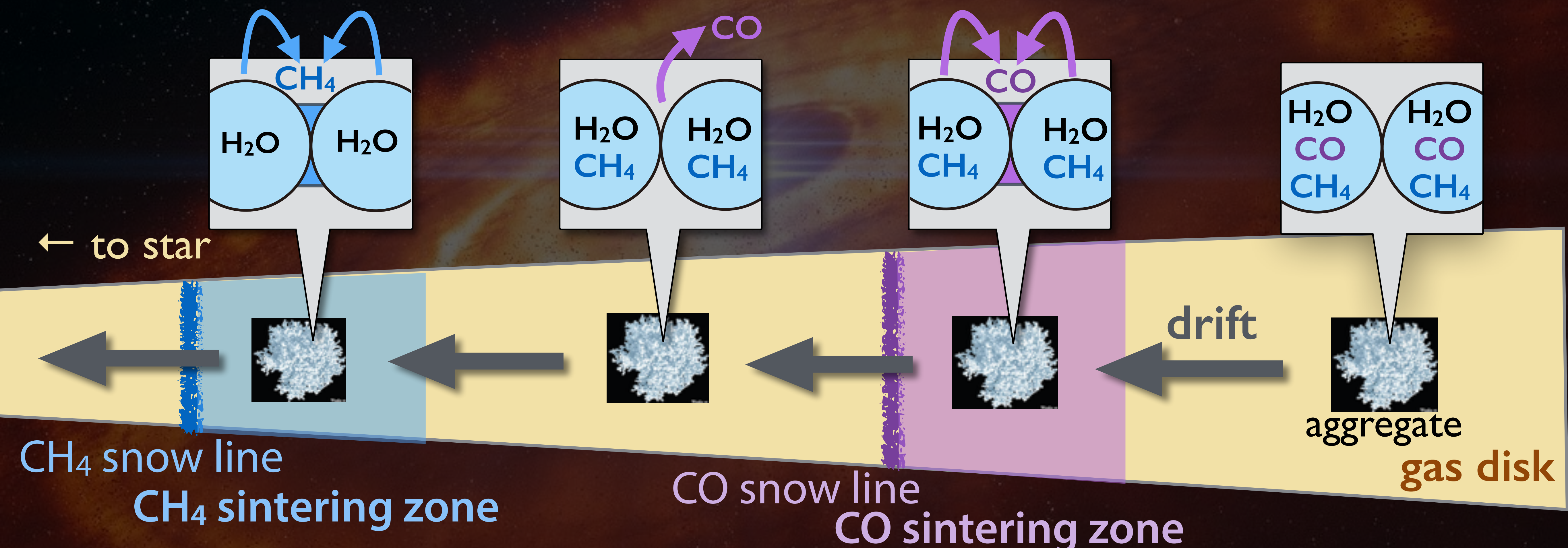
sintering zone:
where icy aggregates get sintered
(sintering timescale < collision timescale)

1D Dust Evolution Model with Sintering

Okuzumi et al. (2016)

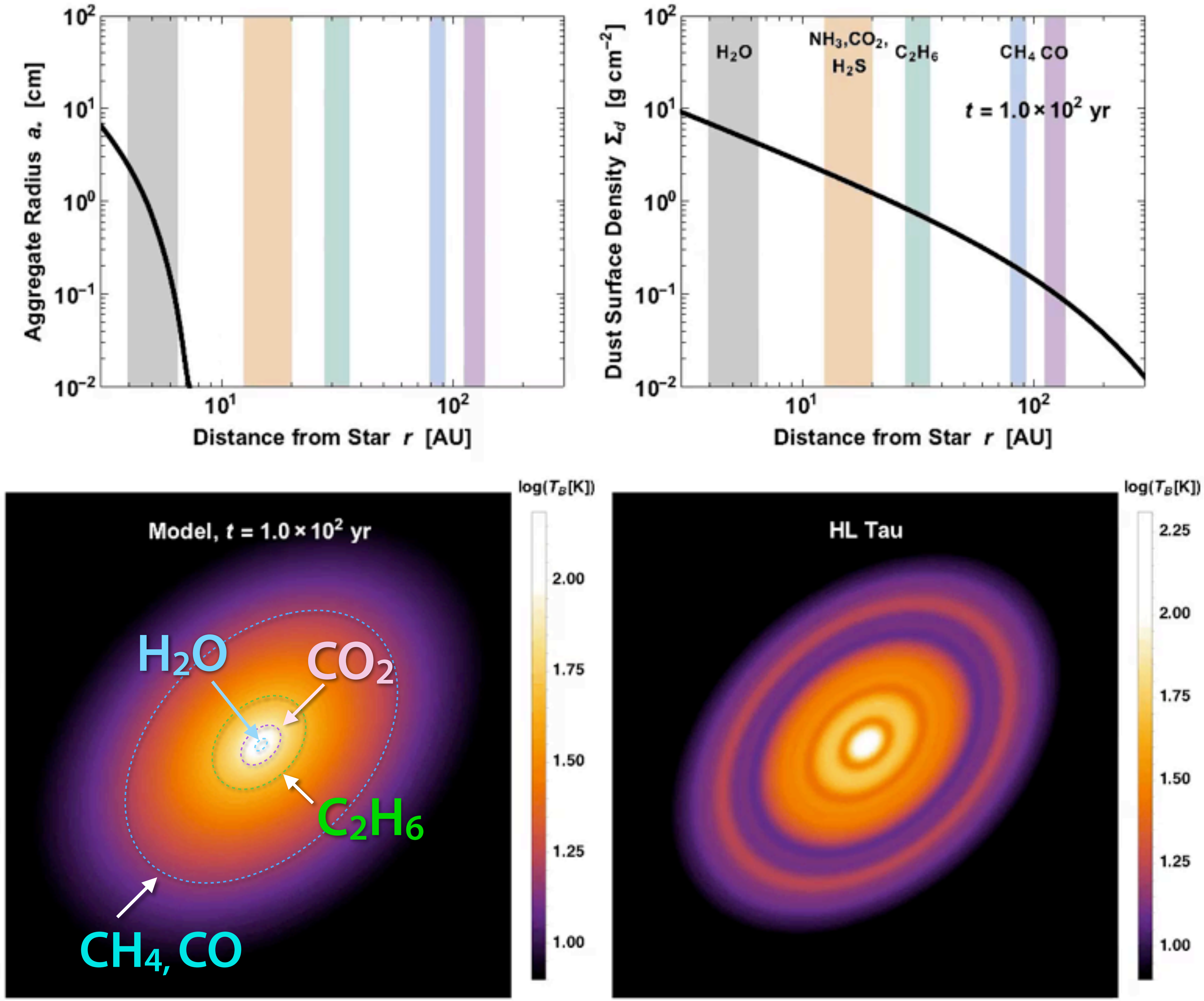
Consider aggregates of silicates and ices

(H_2O, CO, CO_2, CH_4, C_2H_6, NH_3, H_2S; Mumma & Charnley 2011)

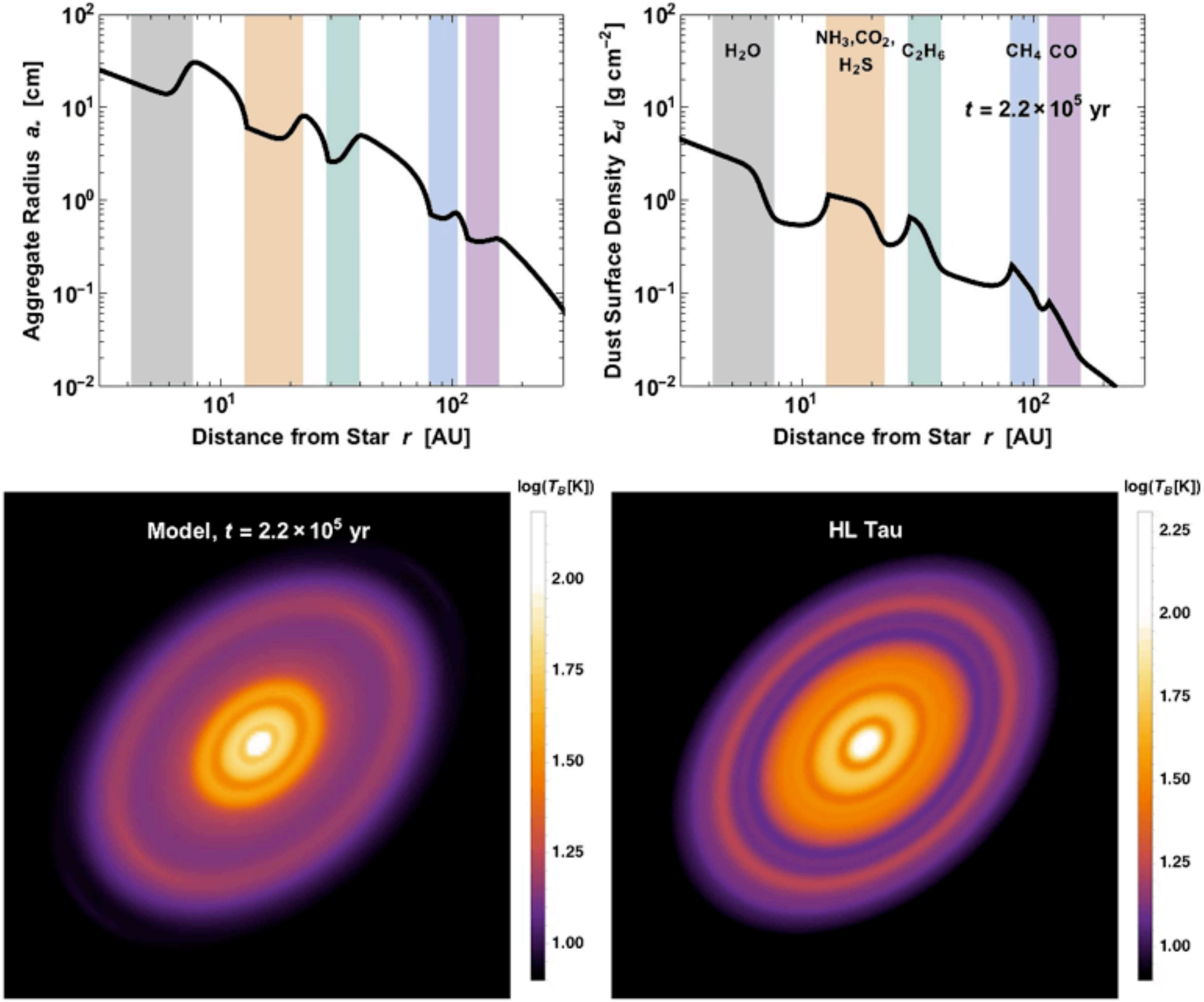


v_{frag} (normal) = **50 m/s** $(a_{monomer}/0.1\,\mu m)^{-5/6}$ (Wada et al. 2009)

v_{frag} (sintered) = **20m/s** $(a_{monomer}/0.1\,\mu m)^{-5/6}$ (Sirono & Ueno, 2017)

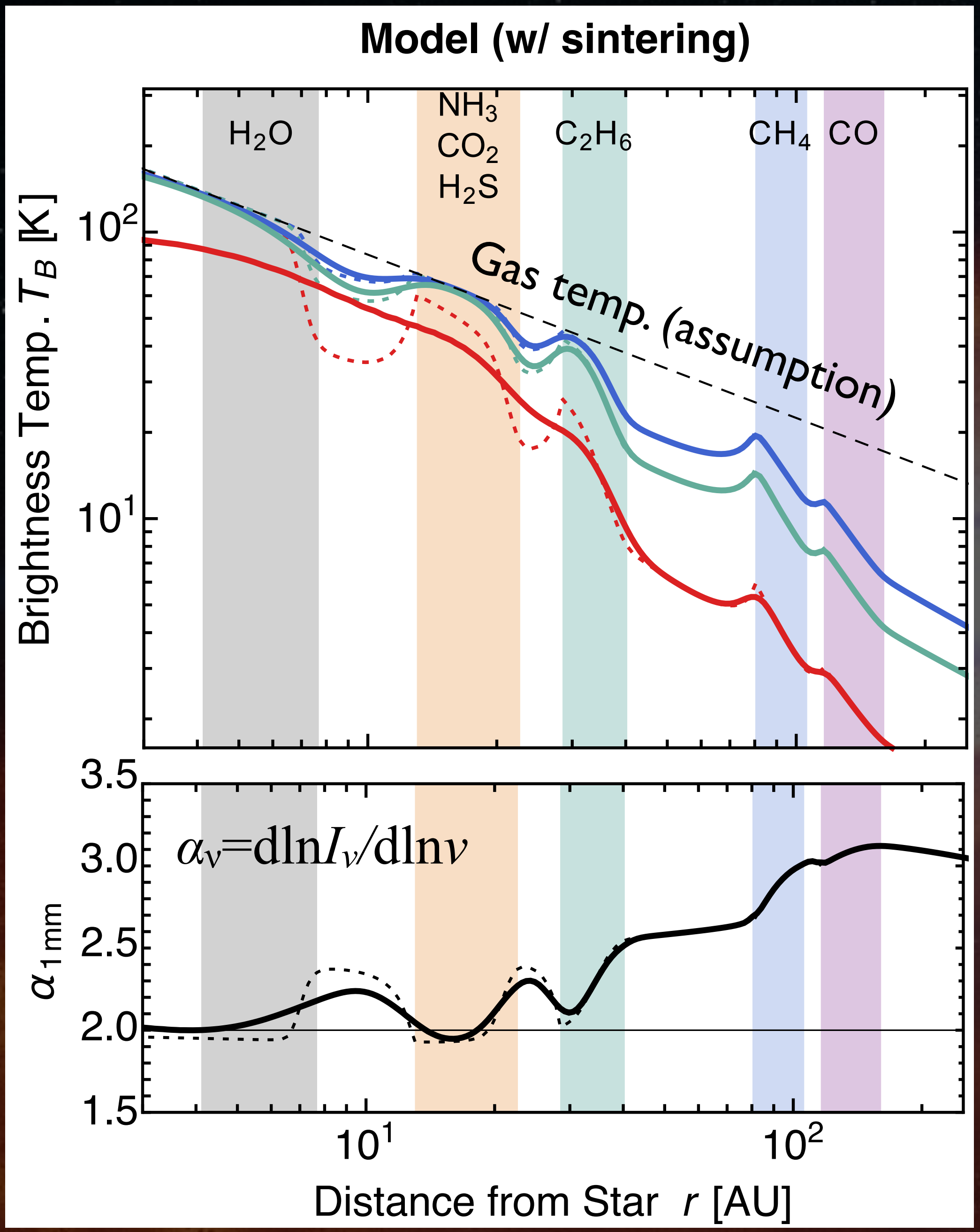


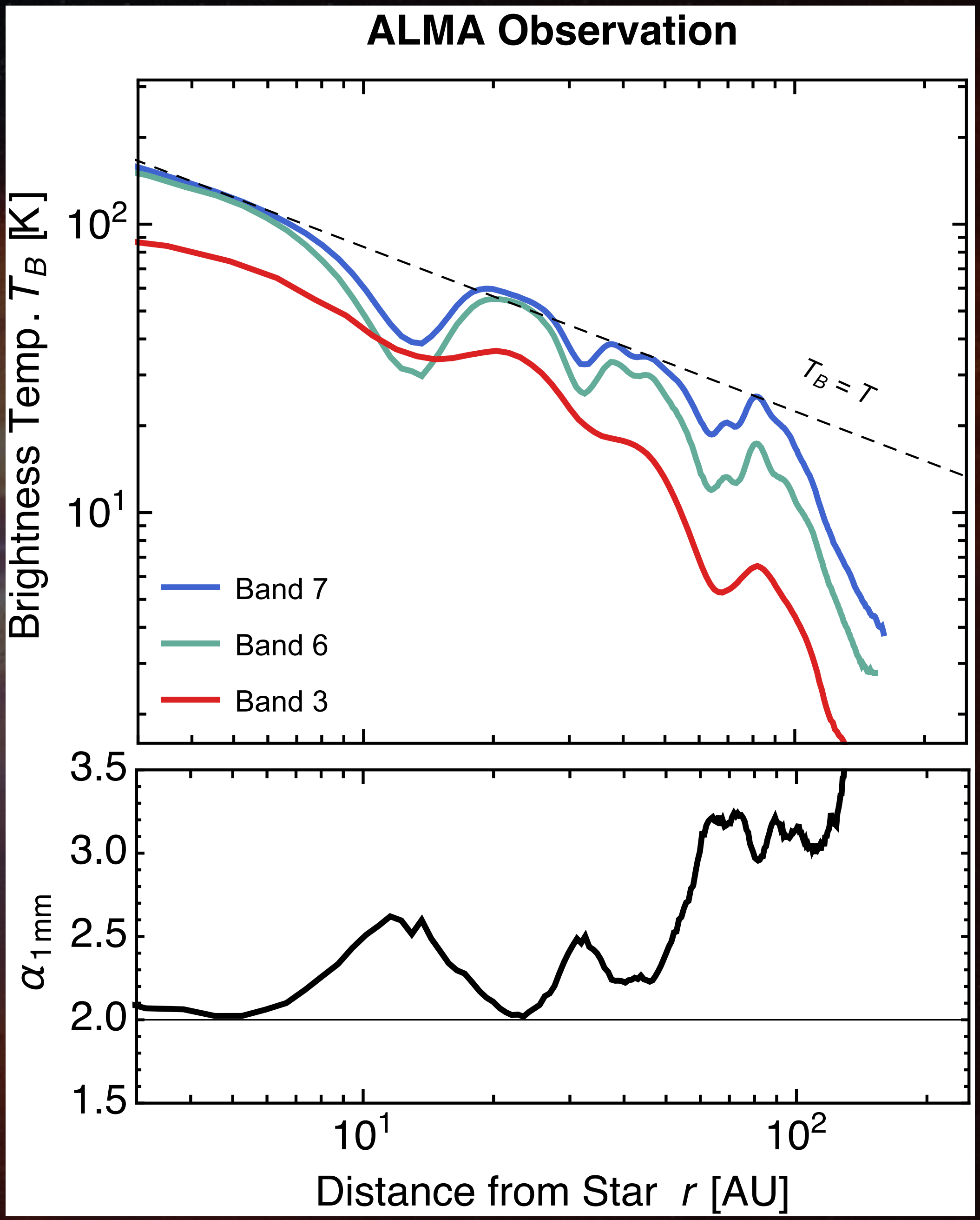
10^2
10^1
10^0
10^{-1}
10^{-2}
Aggregate Radius a_* [cm]
Distance from Star r [AU]
H_2O
$NH_3, CO_2,$ H_2S
C_2H_6
CH_4 CO
$t = 1.0 \times 10^2$ yr
Dust Surface Density Σ_d [g cm^{-2}]
Model, $t = 1.0 \times 10^2$ yr
H_2O
CO_2
C_2H_6
CH_4, CO
log(T_B[K])
2.00
1.75
1.50
1.25
1.00
HL Tau
log(T_B[K])
2.25
2.00
1.75
1.50
1.25
1.00



Aggregate Radius a_* [cm]
Distance from Star r [AU]
Dust Surface Density Σ_d [g cm^{-2}]
H_2O
NH_3, CO_2, H_2S
C_2H_6
CH_4 CO
$t = 2.2 \times 10^5$ yr
Model, $t = 2.2 \times 10^5$ yr
HL Tau
log(T_B[K])

Detailed Comparison with HL Tau





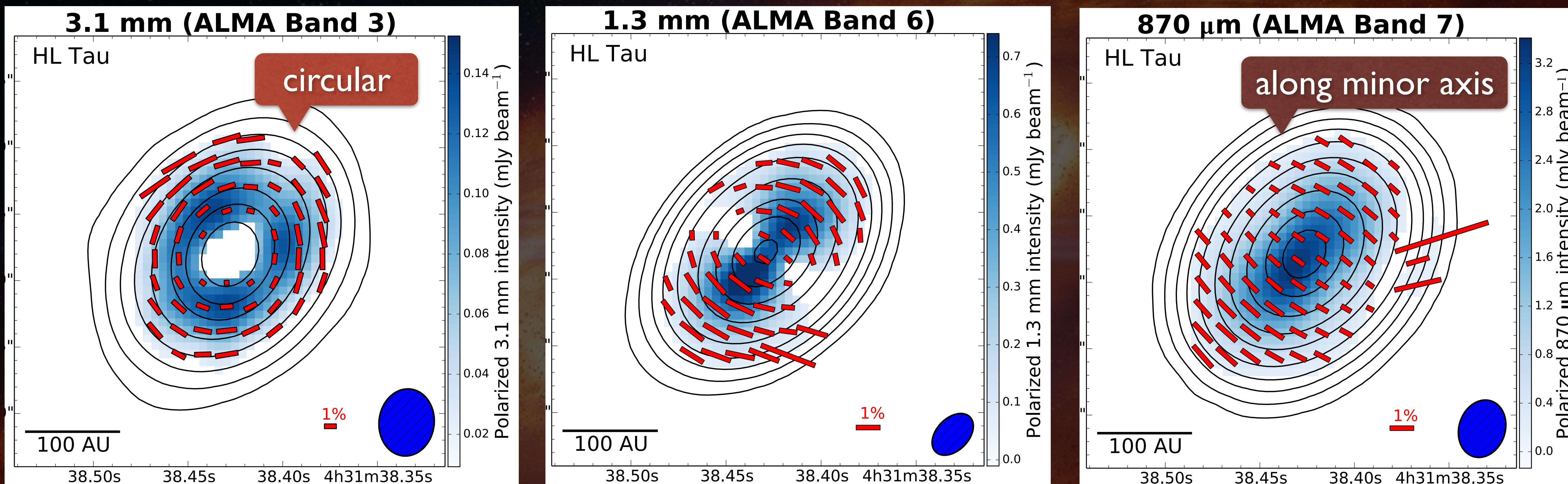
The sintering model reproduces :

✓Positions of major rings (within an accuracy of <30%)

✓Radial distribution of mm spectral index $\alpha = d\ln I_\nu / d\ln \nu$

A New Particle-size Constraint from mm Polarization

- ALMA has revealed that HL Tau's mm polarization pattern changes drastically with wavelength (Kataoka et al. 2017; Stephens et al. 2017)



Kataoka et al. (2017) Stephens et al. (2017)

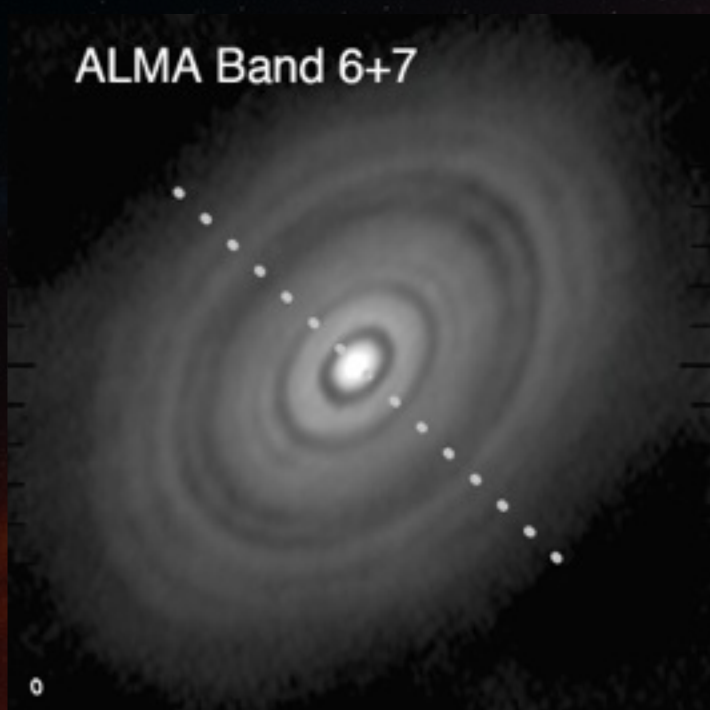
- One possibility: the size of dust particles producing the polarized emission is **~ 100 μm** (~λ/2π) (Kataoka et al. 2017).
- This size is much smaller than expected for sticky H_2O particles (~ 1mm…1cm at 100 au) ⇒ Strong turbulence?

Weak Turbulence in the HL Tau Disk

Pinte et al. (2016)

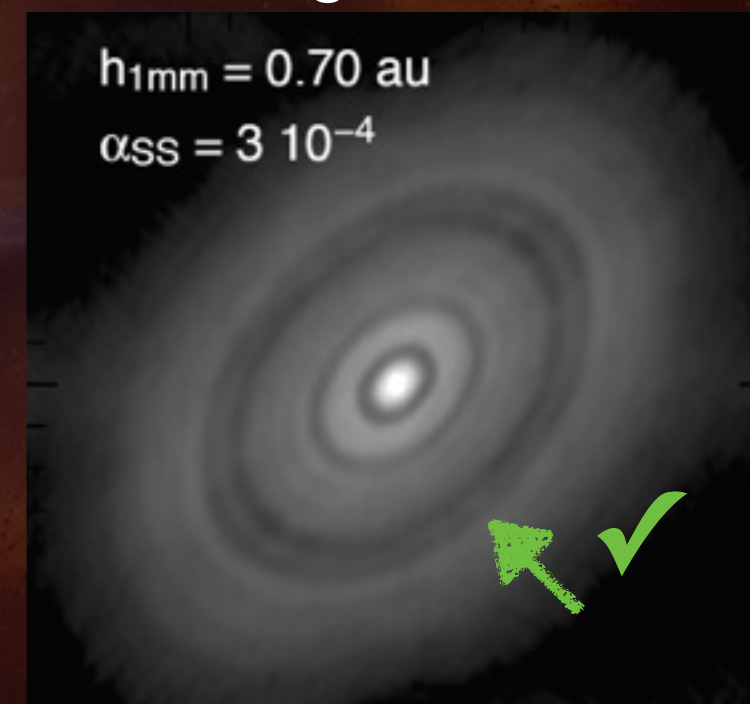
The well-defined morphology of the rings indicates that the dust is concentrated at the midplane:

ALMA image



model image (no settling)

model image (with settling)



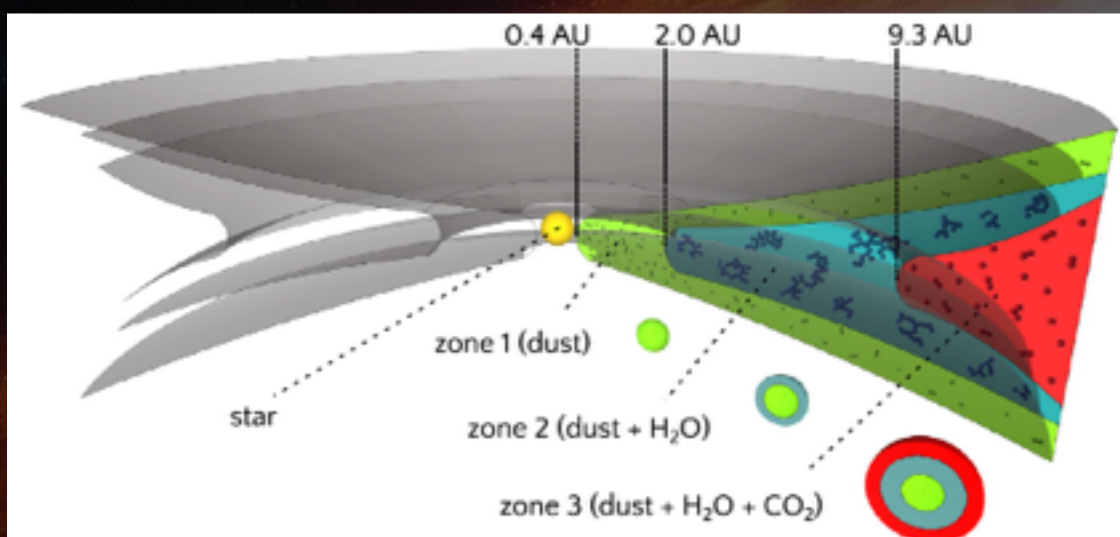
This strongly suggests that disk turbulence is very weak:

($\alpha \equiv D_{\rm diff}/c_s H_{\rm gas} \lesssim 10^{-3} \ldots 10^{-4}$ in the outer disk)

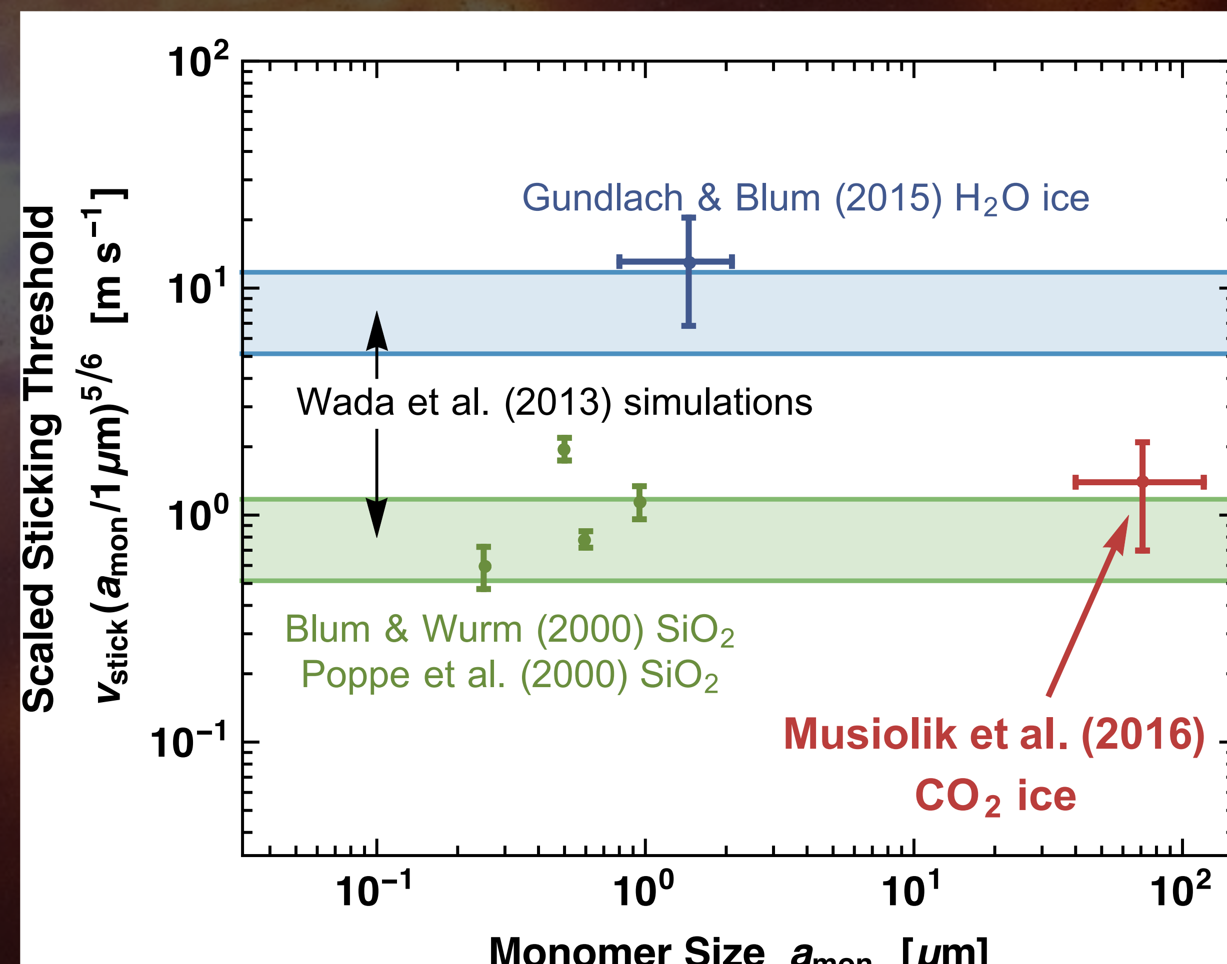
Then why the particles in the outer disk are so small?

Evidence for Non-sticky CO_2 Mantle?

- Outside the CO_2 snow line , icy grains might be covered by CO_2 ice.
- Recent experiments (Musiolik et al. 2016a,b) confirmed that CO_2 ice is less sticky than H_2O ice.
- Reason: CO_2 is non-polar (having zero dipole moment)



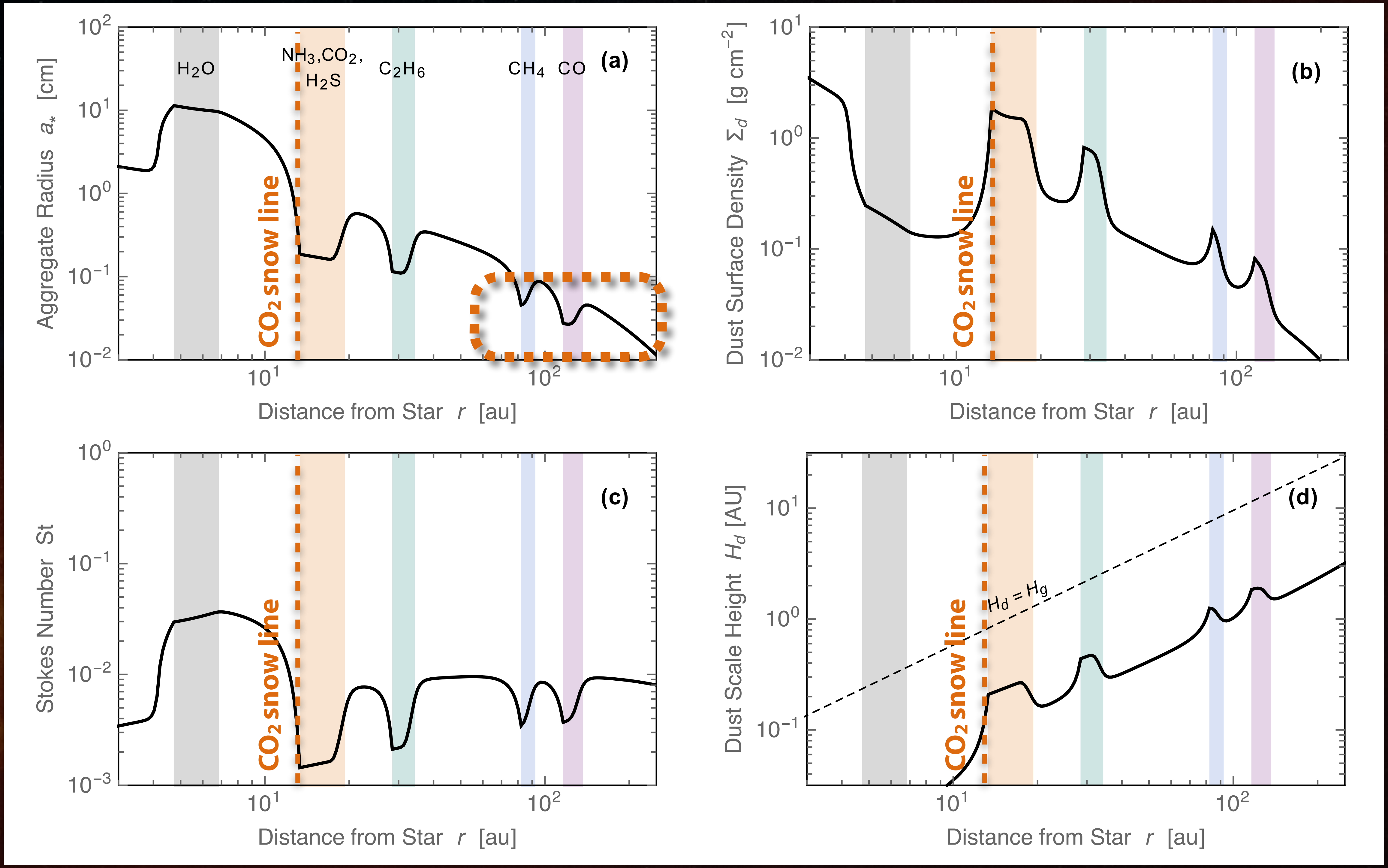
Musiolik et al. (2016)



Question: Can this effect explain the small particle size in the outer part of the HL Tau disk?

Including the non-stickiness of CO_2 Mantle

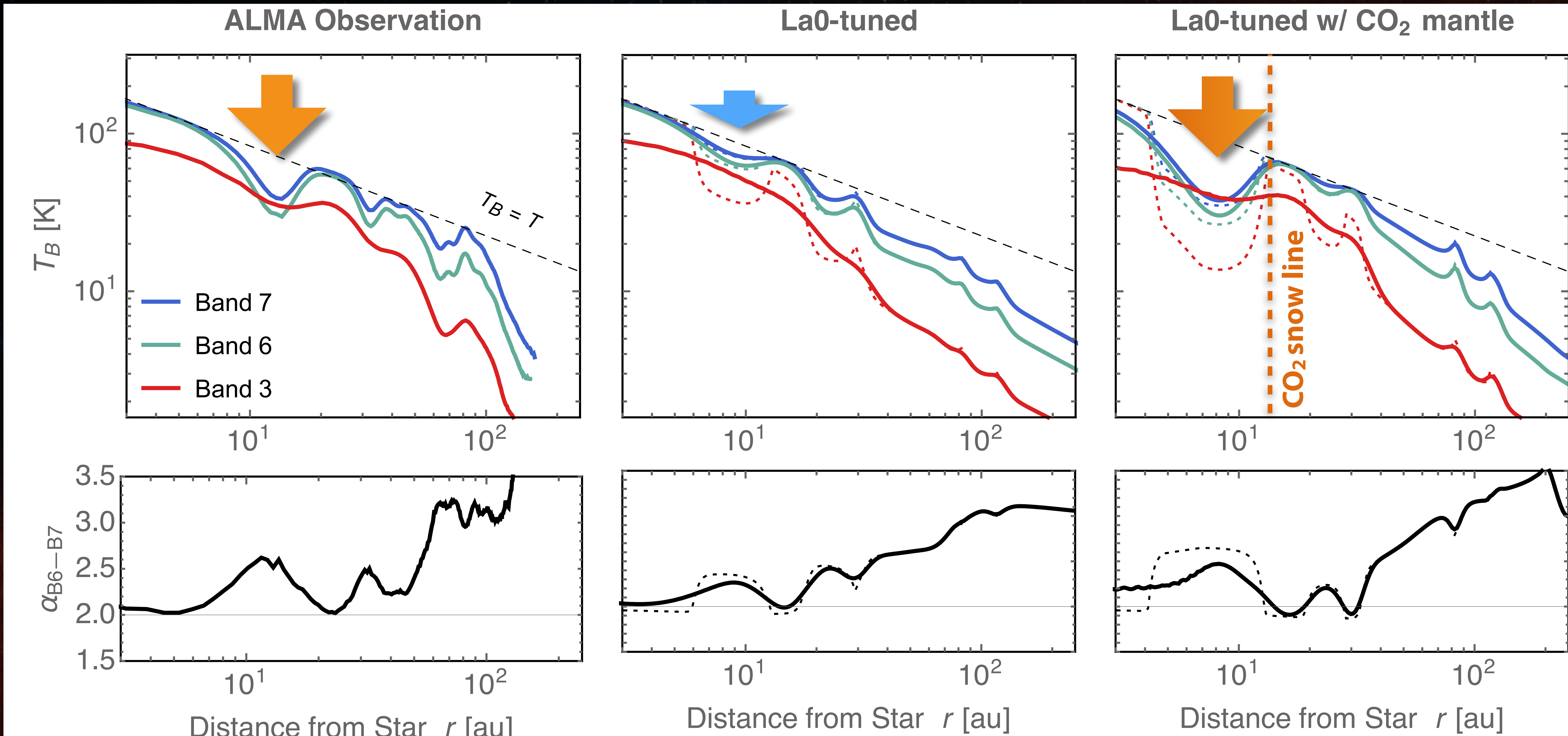
Snapshot at 1.4 Myr for $\alpha_{diff} = 10^{-4}$ (Okuzumi & Higuchi, in prep.)



- As expected, particle size of ~ 0.1 mm is realized in the outer disk
- If α_{diff} is low (~ 10^{-4}), dust settling is also realized.

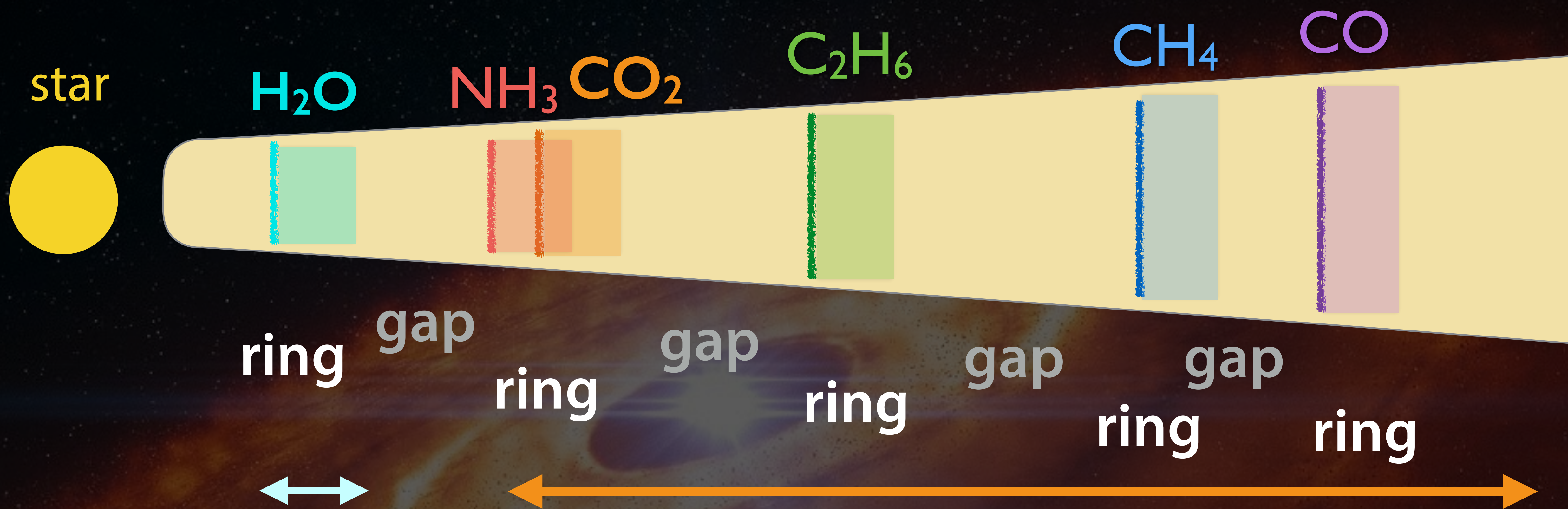
Including the non-stickiness of CO_2 Mantle

Okuzumi & Higuchi, in prep.



With CO_2 mantle, the dust gap just interior to the CO_2 snow line tends to become deep, because the small particles outside the CO_2 snow line slowly drift in.

Summary: A Picture of HL Tau form the Snow-Line Scenario



- Dust ring formed through H_2O sintering

- Dust rings formed through sintering
- Additional fragmentation caused by CO_2 mantle (origin of polarization pattern)

Particles grow efficiently thanks to sticky H2O mantle
⇒ A sweet spot for planetesimal formation via dust coagulation?