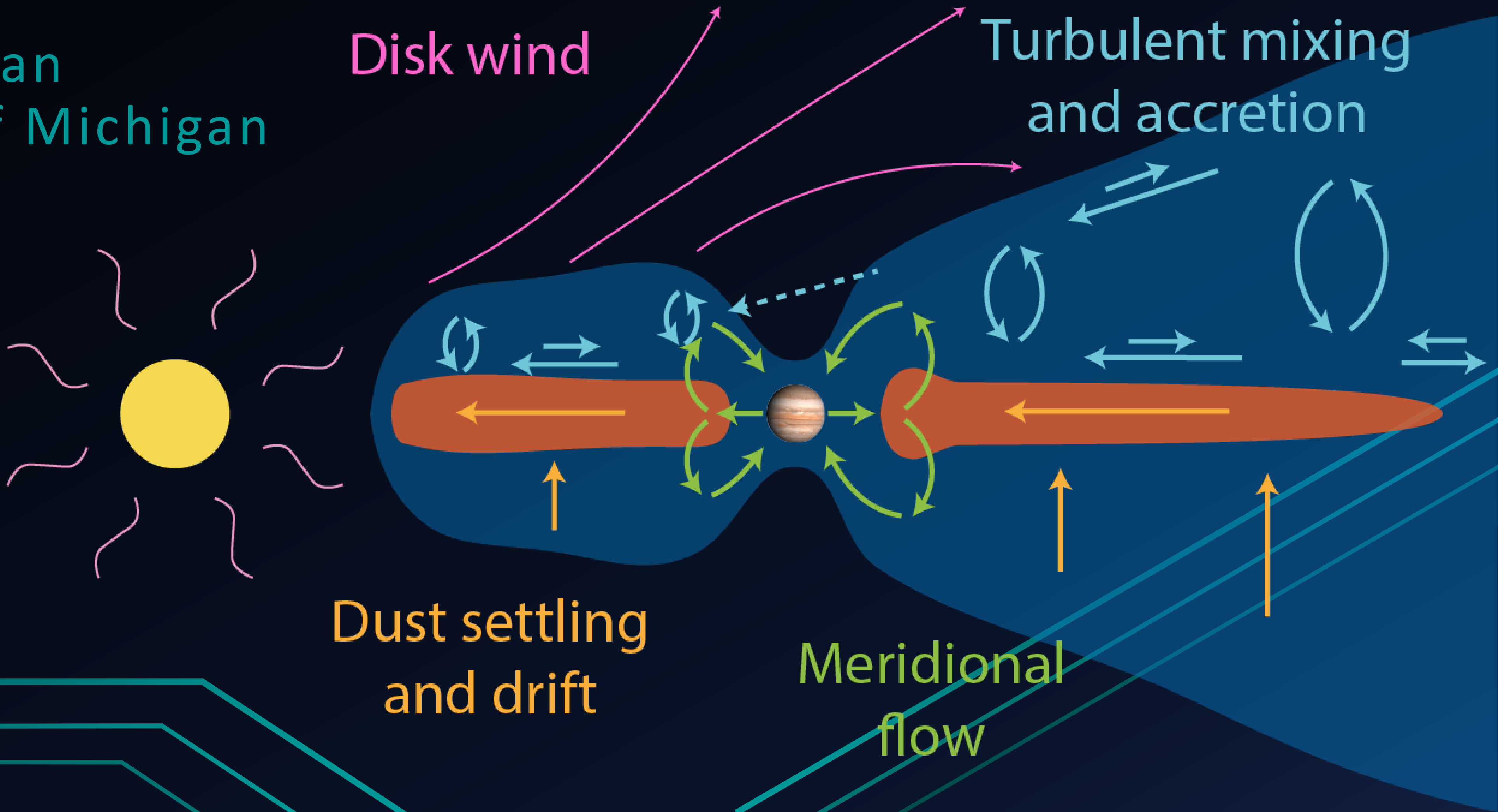
Disks as chemical conveyor belts

Arthur Bosman
University of Michigan

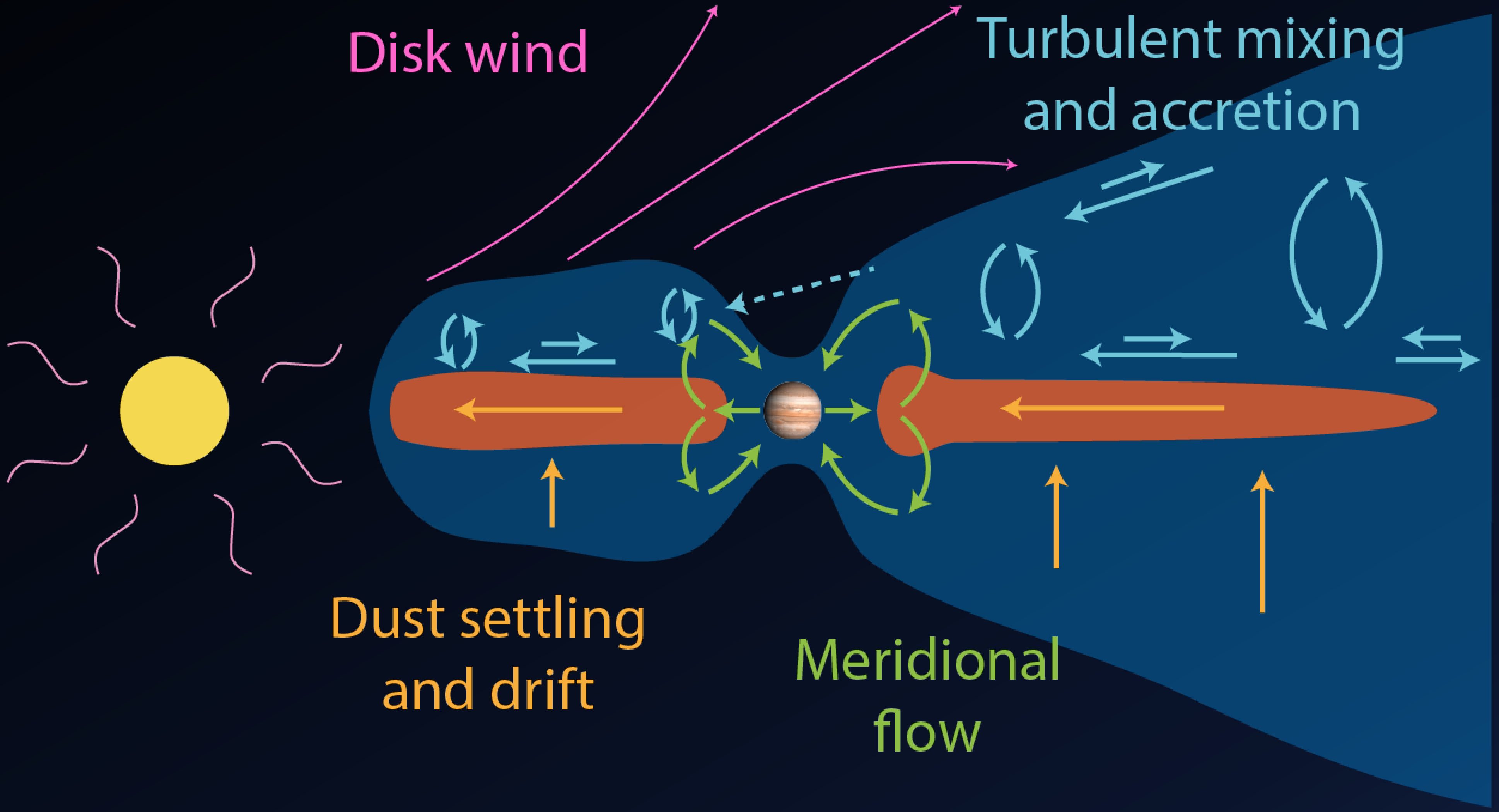


arbos@umich.edu

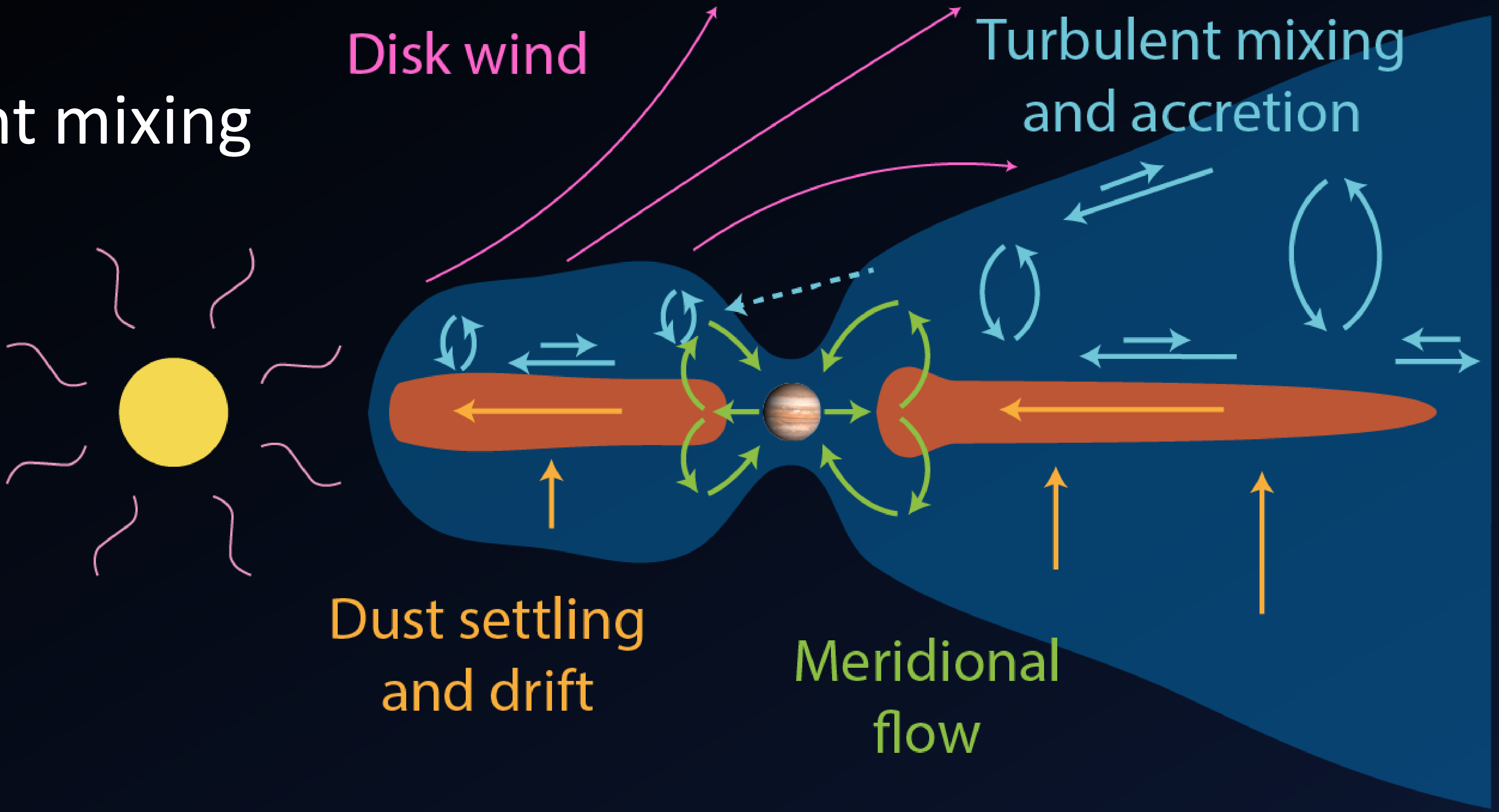
Interactions between transport and chemistry

- Transport species to places they do not form
- Transport changes elemental composition

Disk dynamics



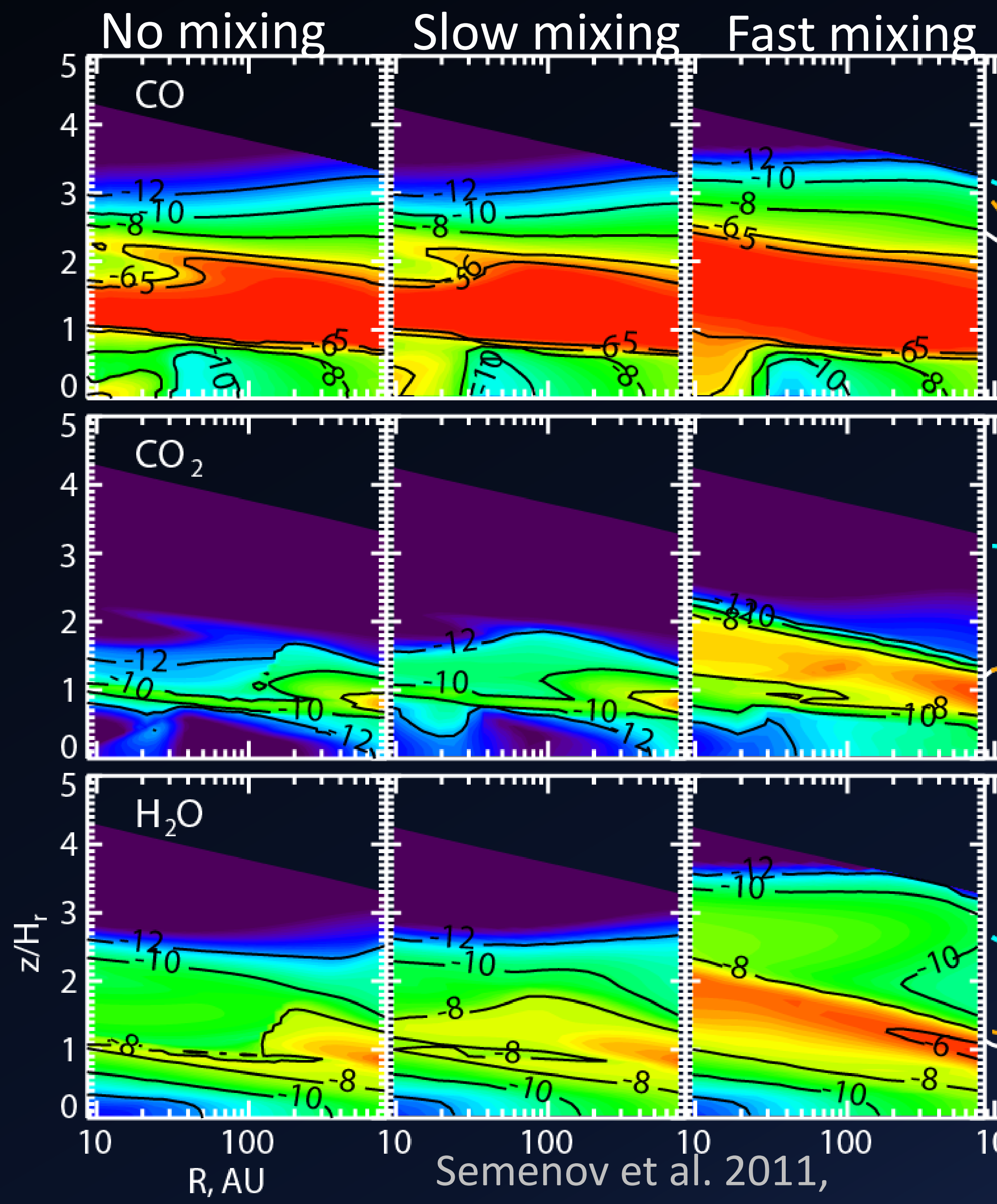
Turbulent mixing



$$\frac{\delta n}{\delta t}(r,z) = -\nabla \cdot \left(D_{turb}(r,z) n_H(r,z) \nabla \frac{n_i(r,z)}{n_H(r,z)} \right)$$

Viscous mixing - Chemistry

Bringing up ices
from the midplane

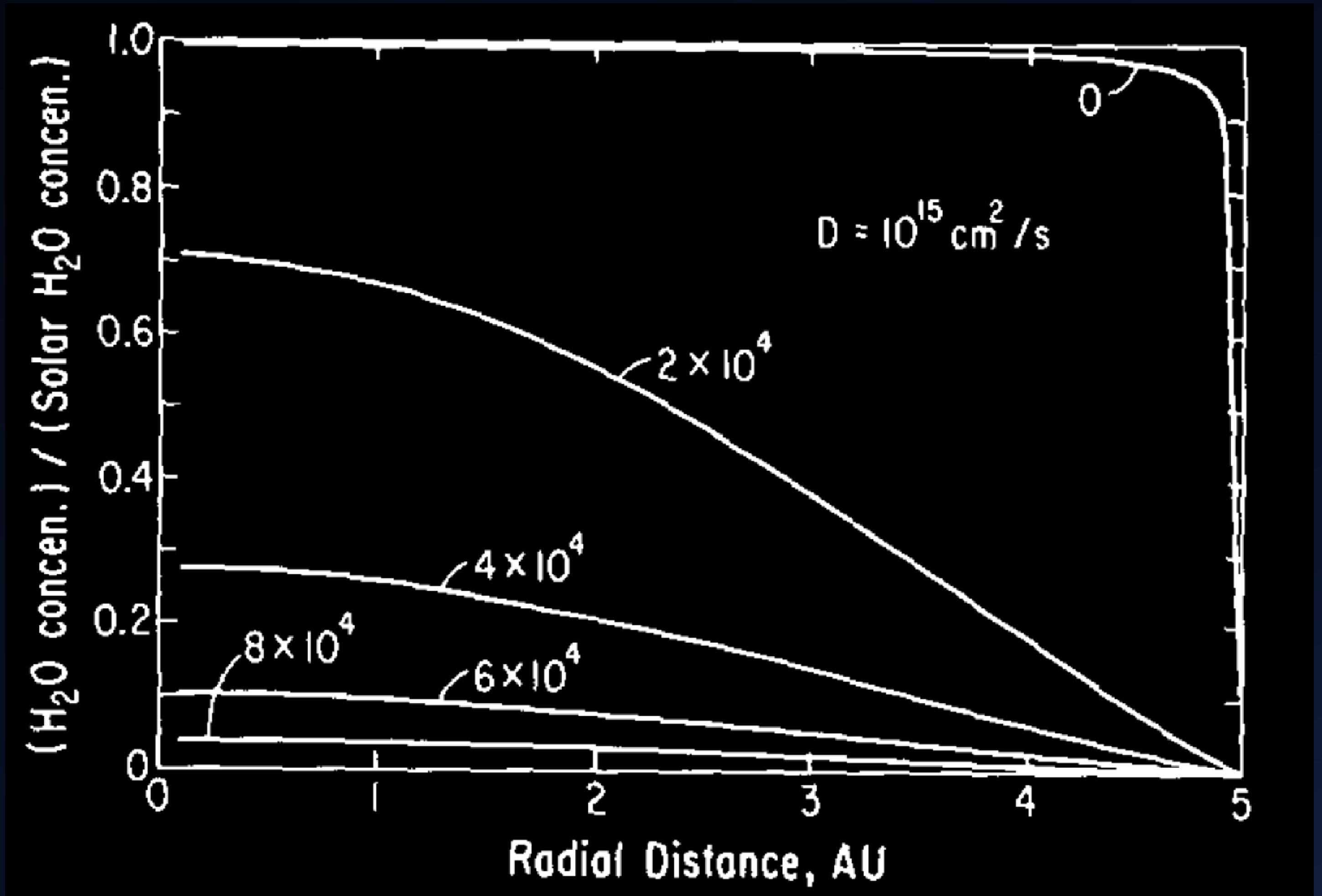


Semenov et al. 2011,
see also Furuya et al 2014

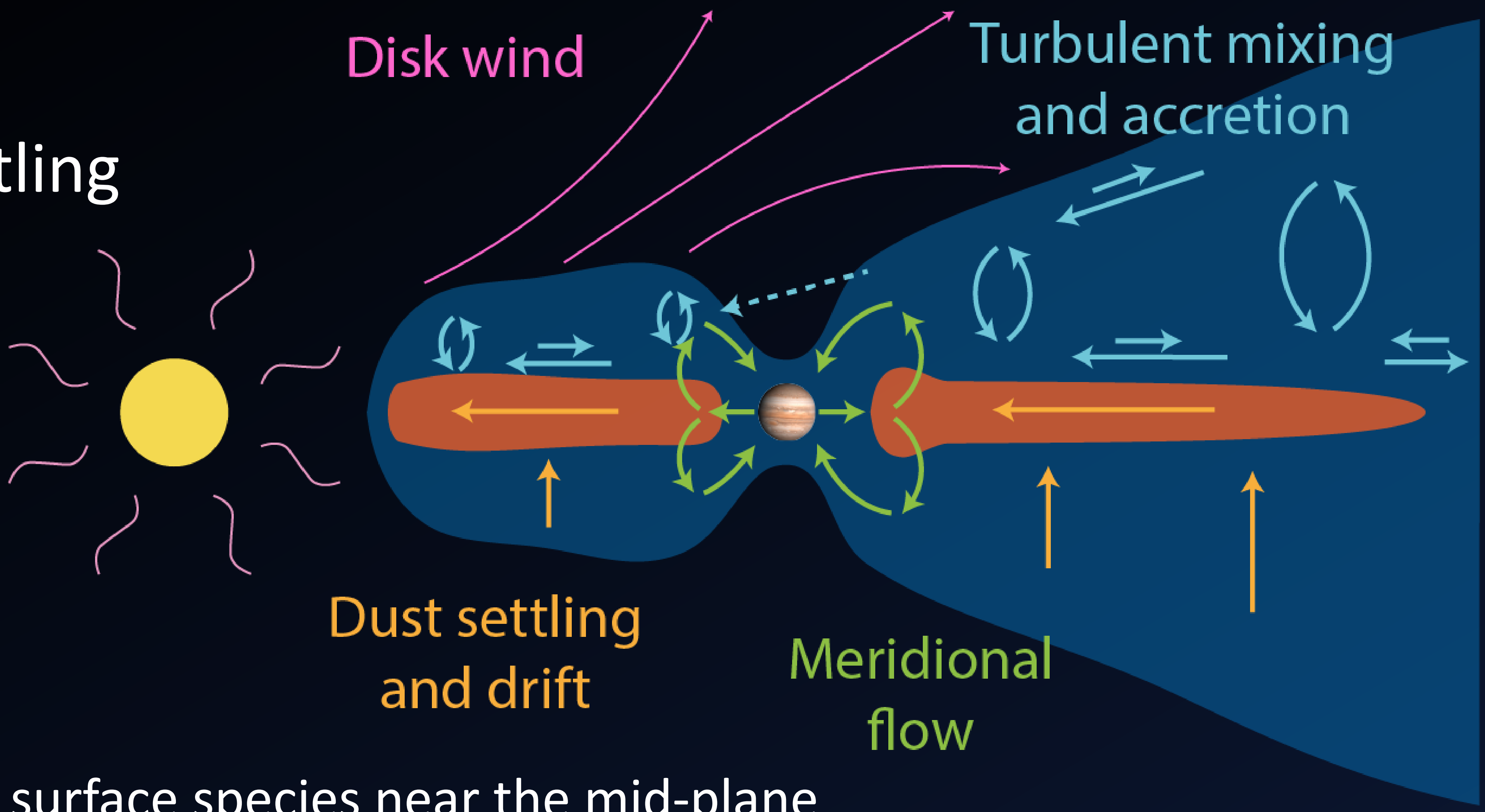
Viscous mixing - Chemistry

Radial cold finger effect

Stevenson & Lunine 1988

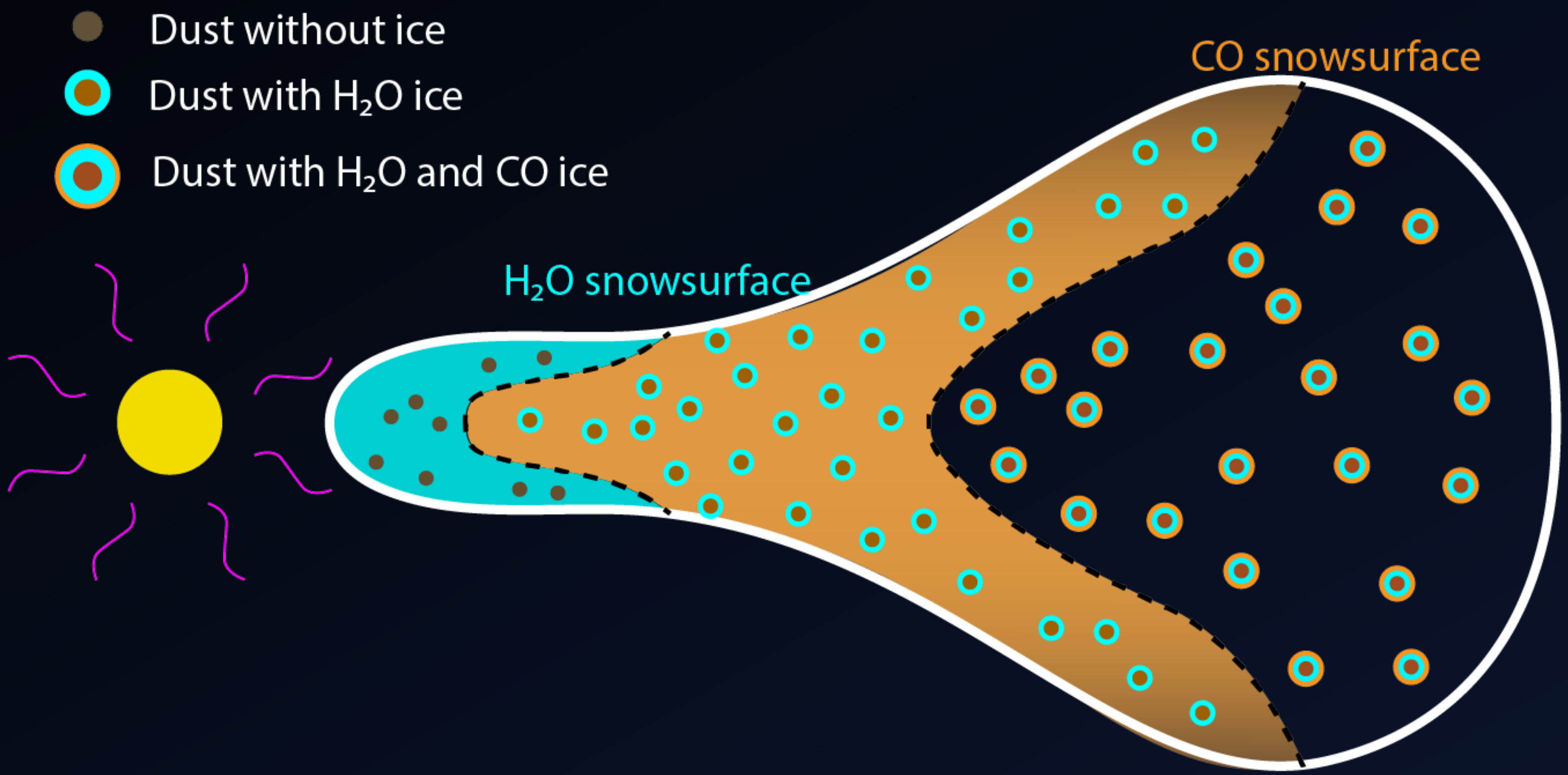


Dust settling



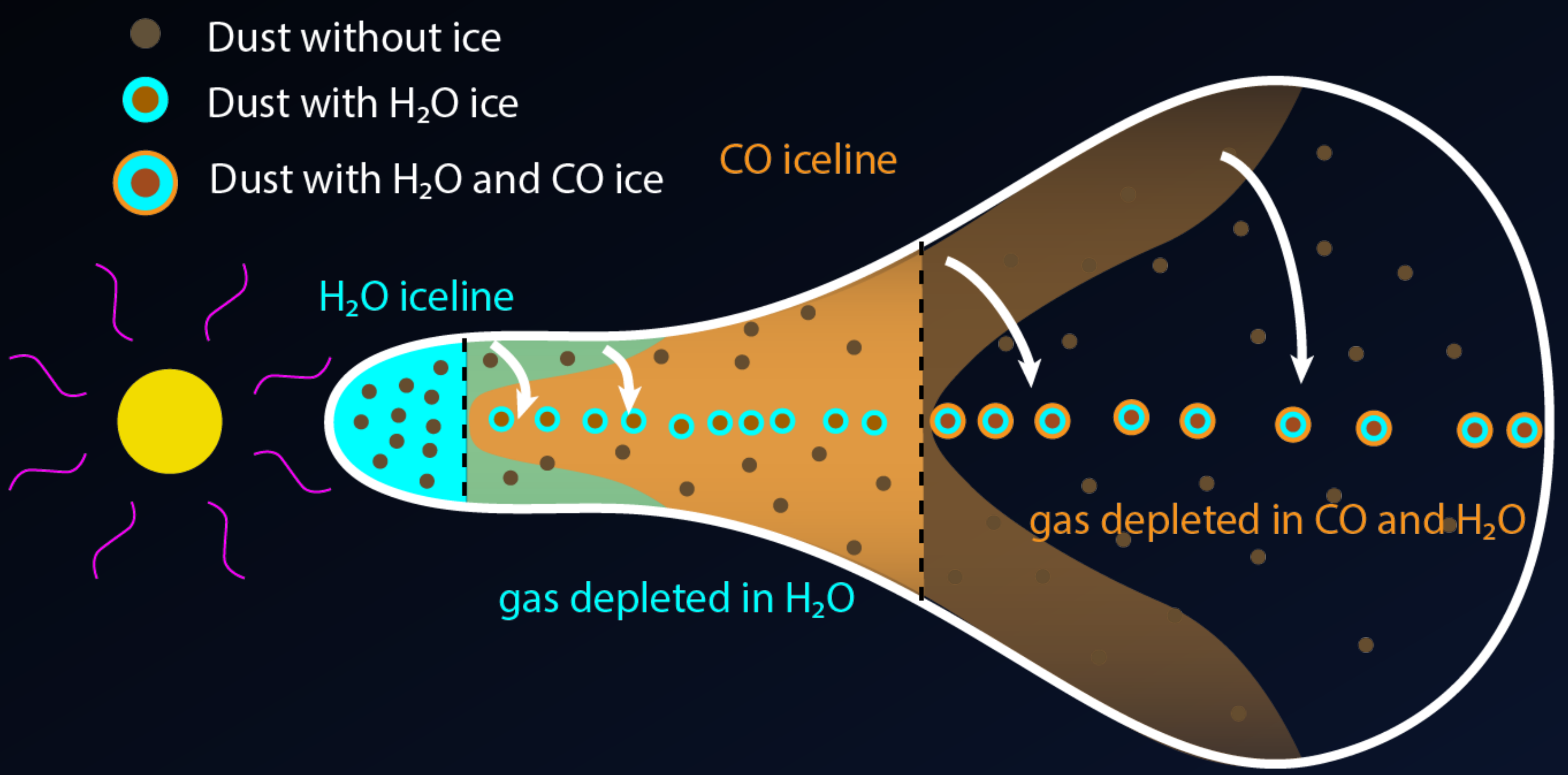
- Trapping surface species near the mid-plane
  - “vertical cold finger effect” Meijerink et al. 2009

Dust settling



Adapted from Bosman & Bergin 2021

Dust settling

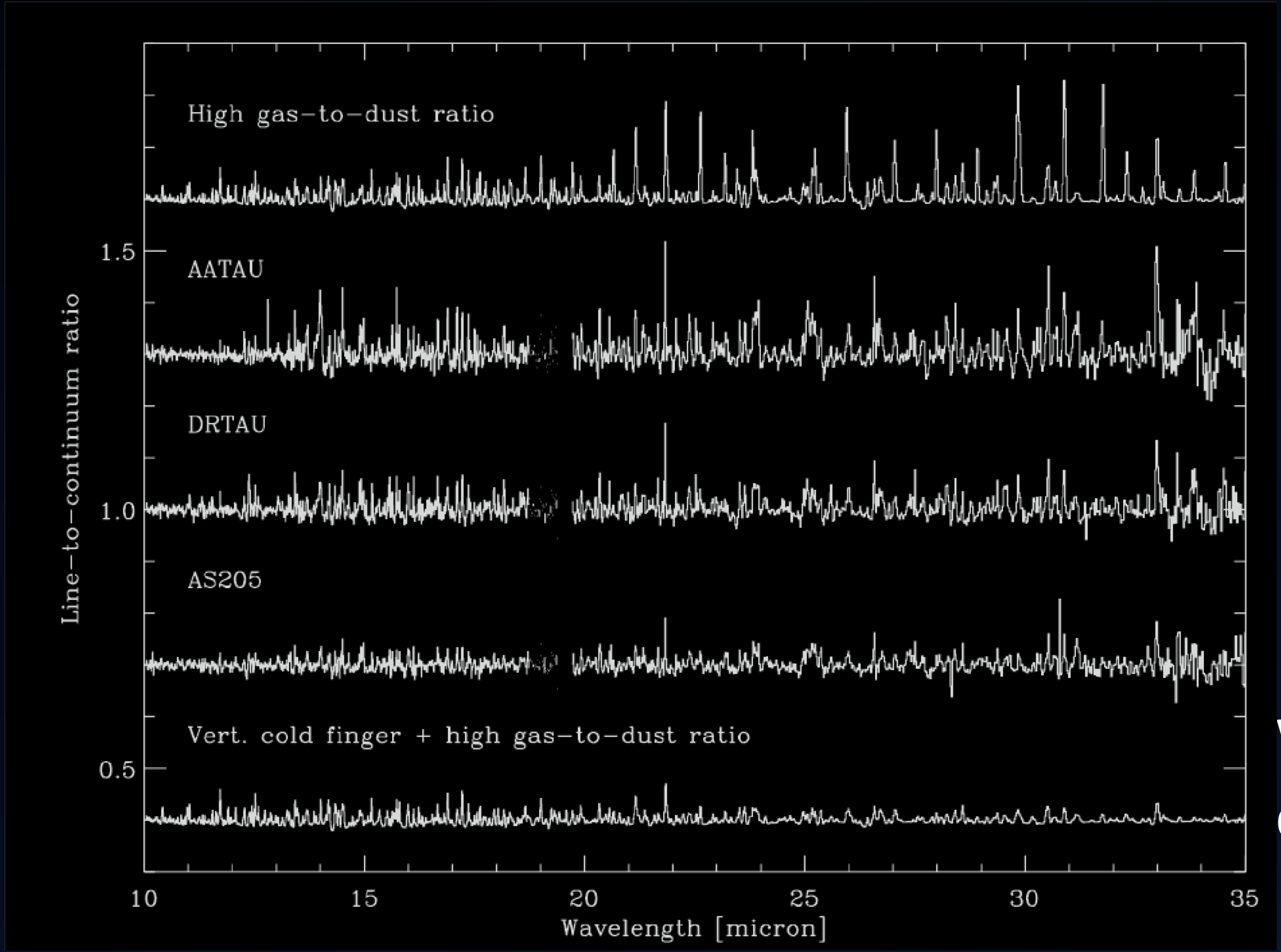


Adapted from Bosman & Bergin 2021

Dust settling - observed impact

- “Cold” water is missing

Dust settling - observed impact

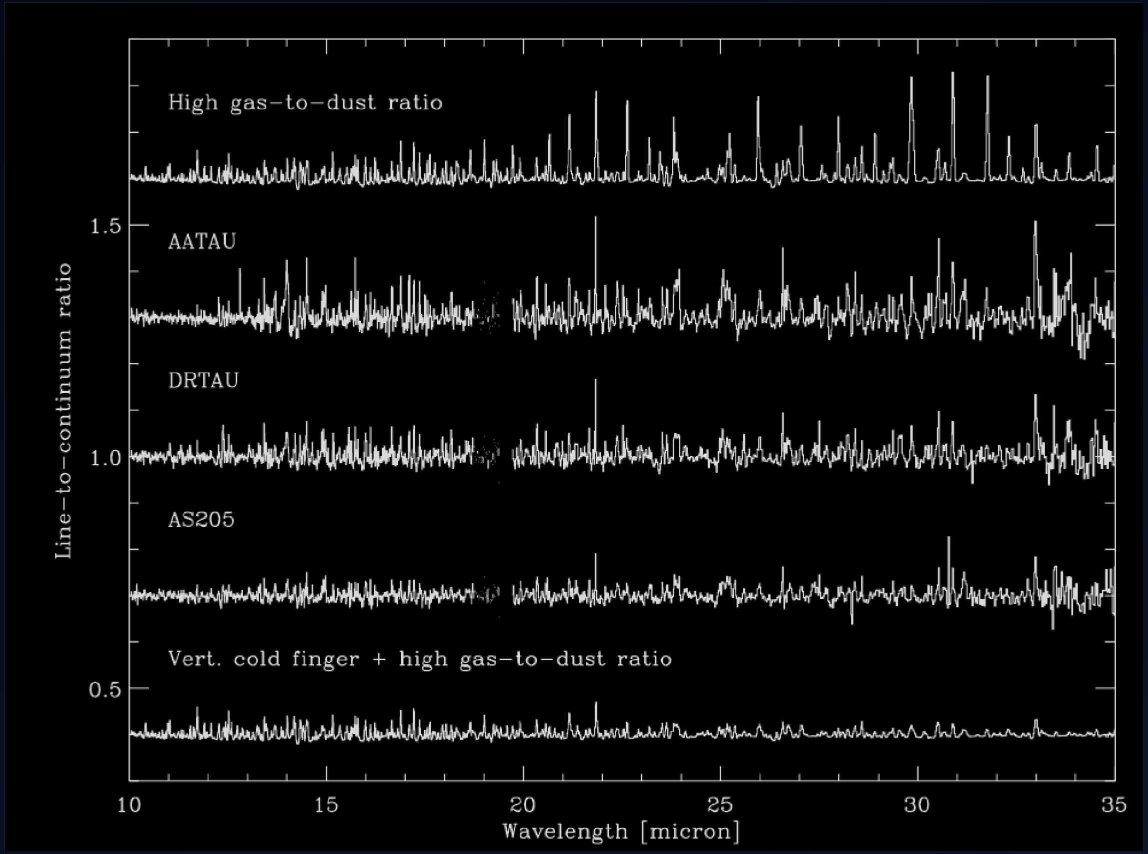


Cold gas dominated

Warm gas dominated

Dust settling - observed impact

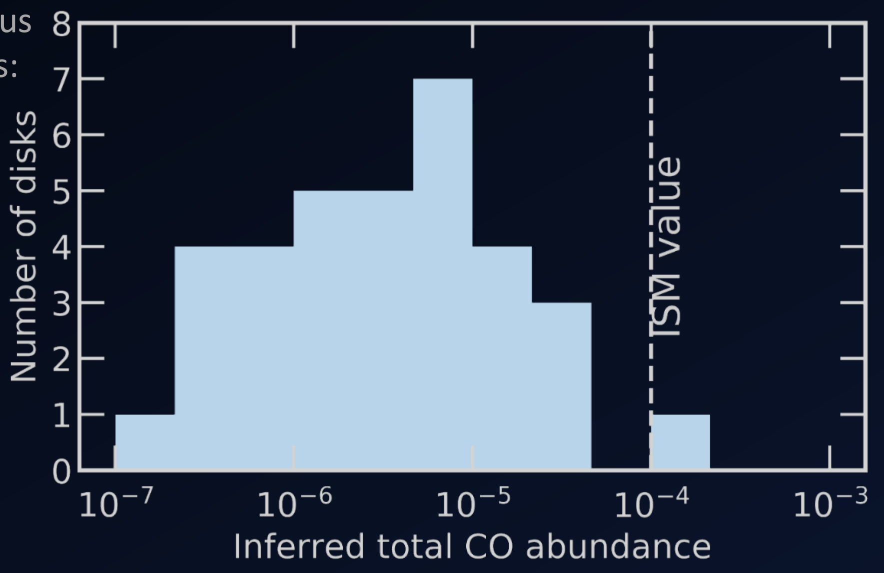
- "Cold" water is missing
- No large reservoir of water outside of the mid-plane snowline
  Meijerink+ 2009, Blevins+2017, Bosman+2021
- No large reservoir of water in the outer disk
  Hogerheijde+ 2011, Du+ 2017



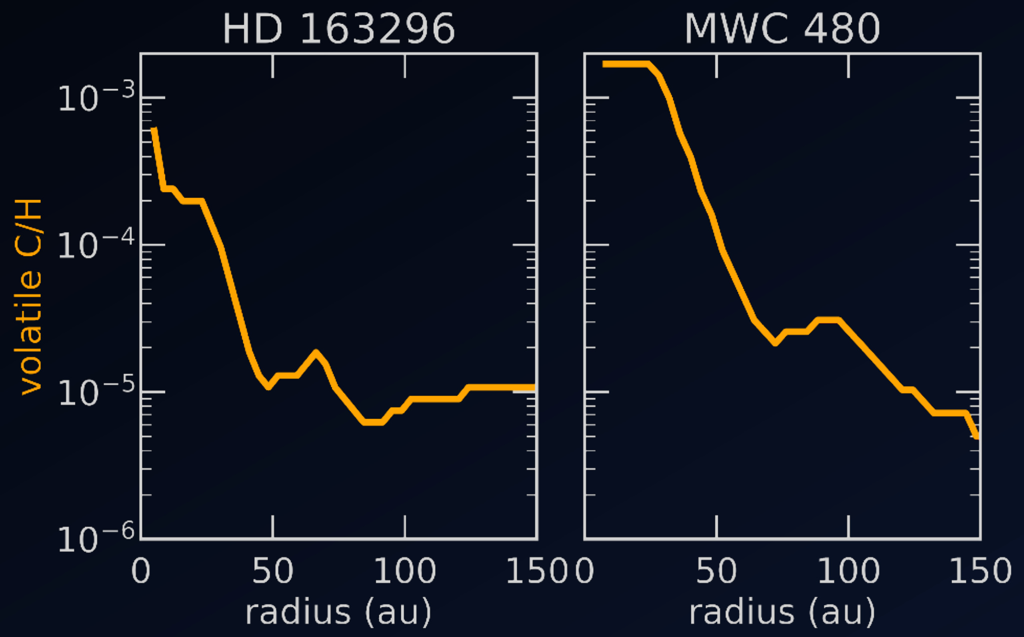
Dust settling - observational constraints

- Low CO abundances measured

ALMA Survey of Lupus Protoplanetary Disks:
Ansdell+ 2016,
Tazzari+ 2017,
Miotello+ 2017



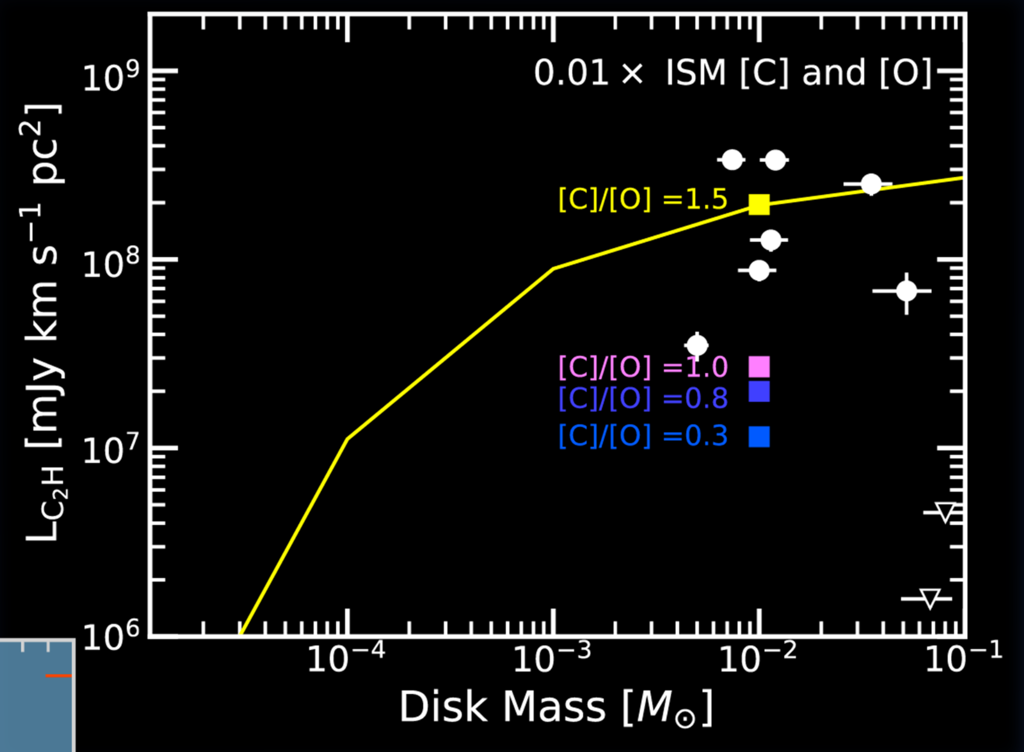
- Low CO abundances confined to outer disk?

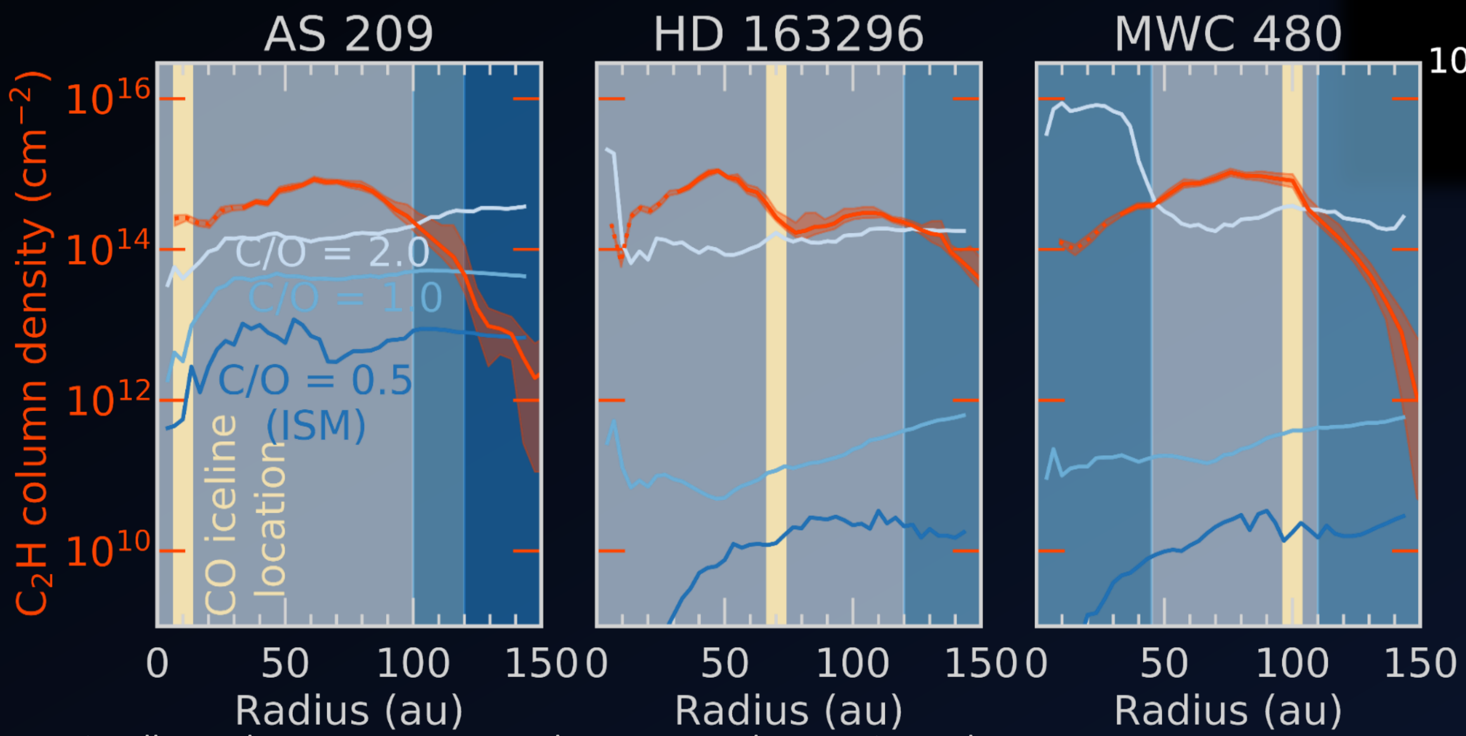


Zhang et al. 2021

C/O observations

C/O ratios ≫ 1





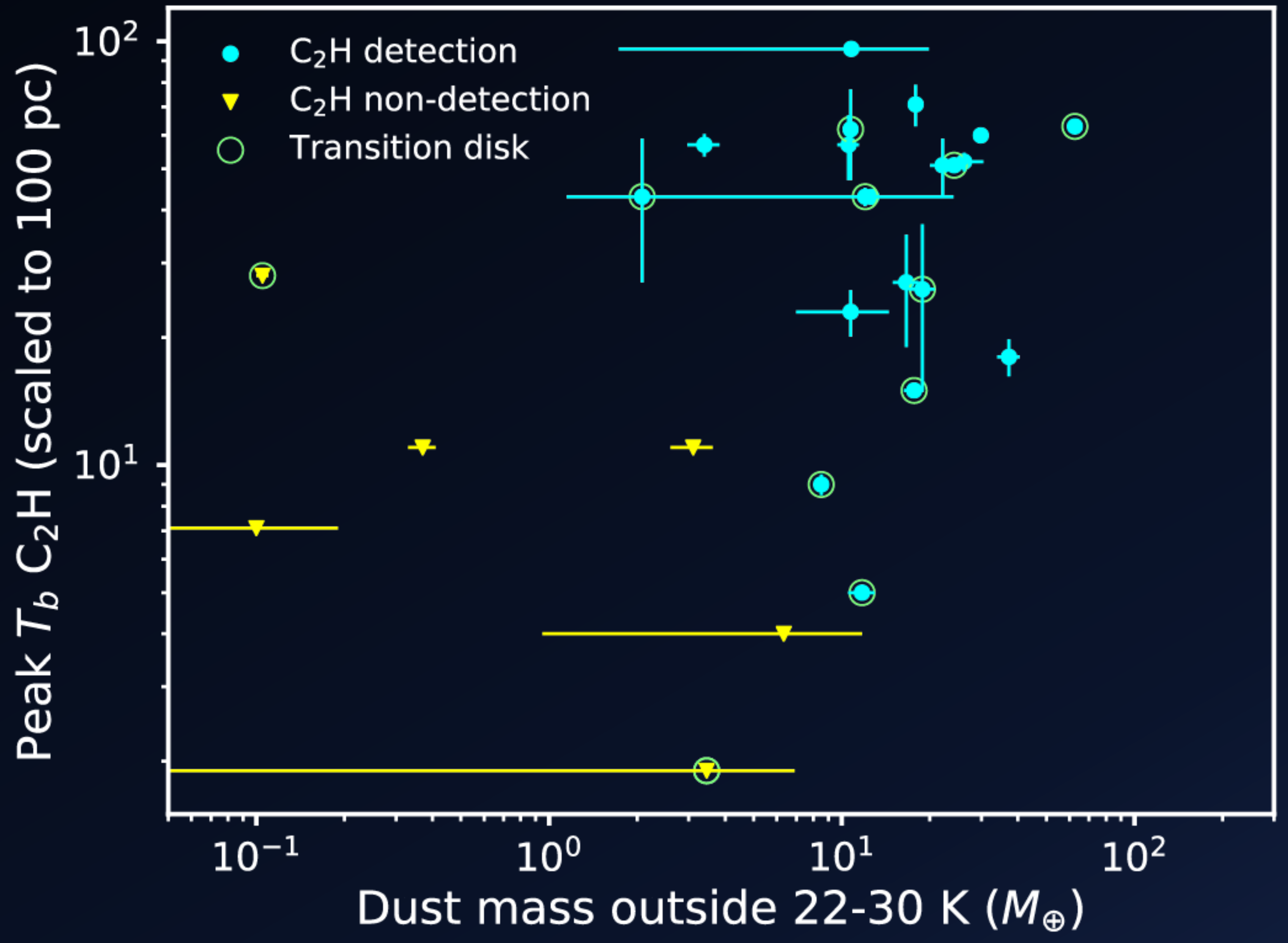
Miotello et al. 2017, Bosman et al. 2021, see also Bergin et al. 2016

C/O related to disk (sub)-structure

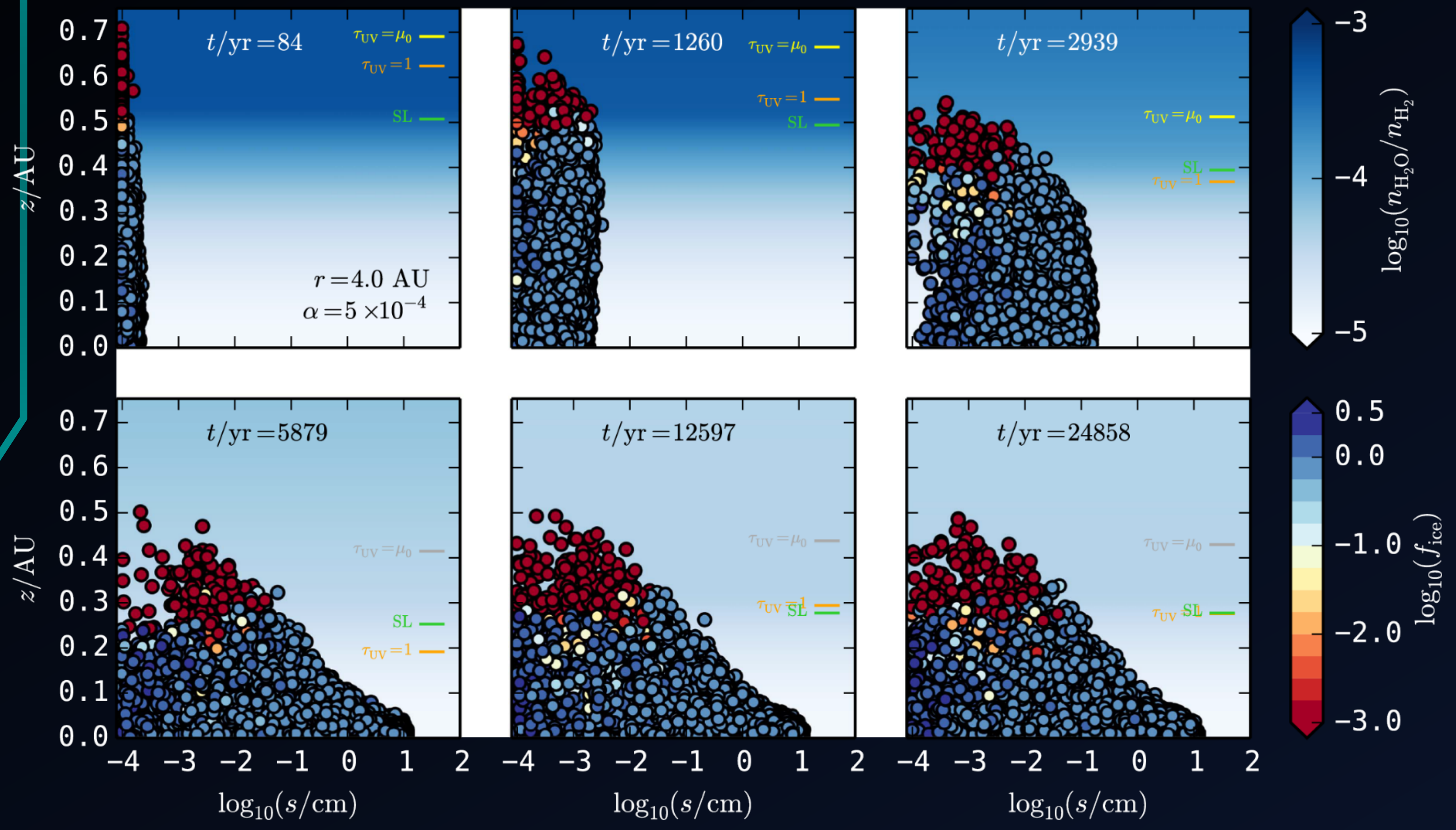
van der Marel et al. 2021

Sufficient cold dust necessary for high C_2H emission

High C/O related to low CO locking in the mid-plane



Trapping in action

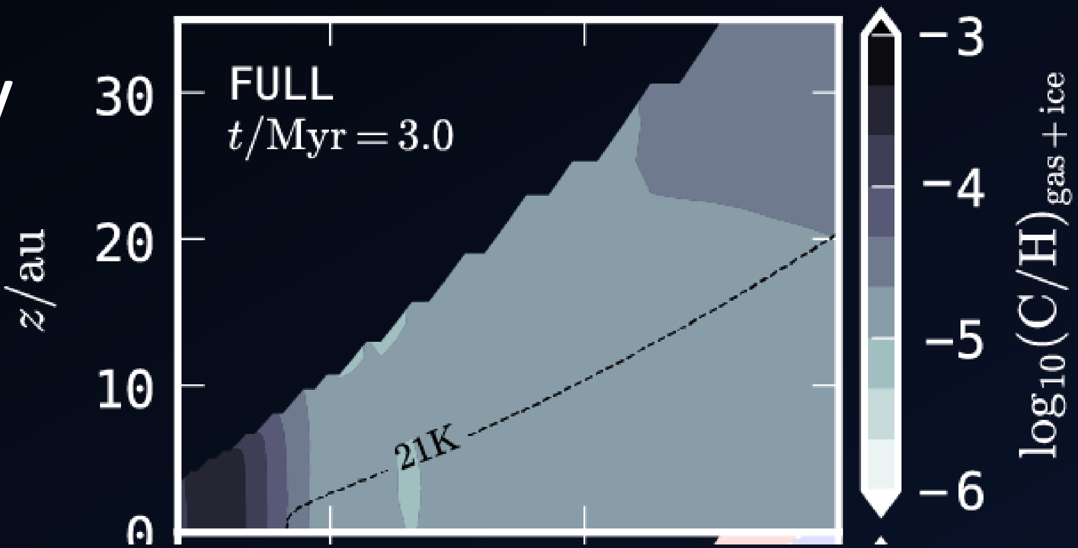


Water diffuses down the gradient

Settled large grains create a ice sink

Krijt et al. 2016

Krijt et al 2020



Trapping and simple chemistry

Same, slower diffusion processes

Chemistry further lowers CO abundance

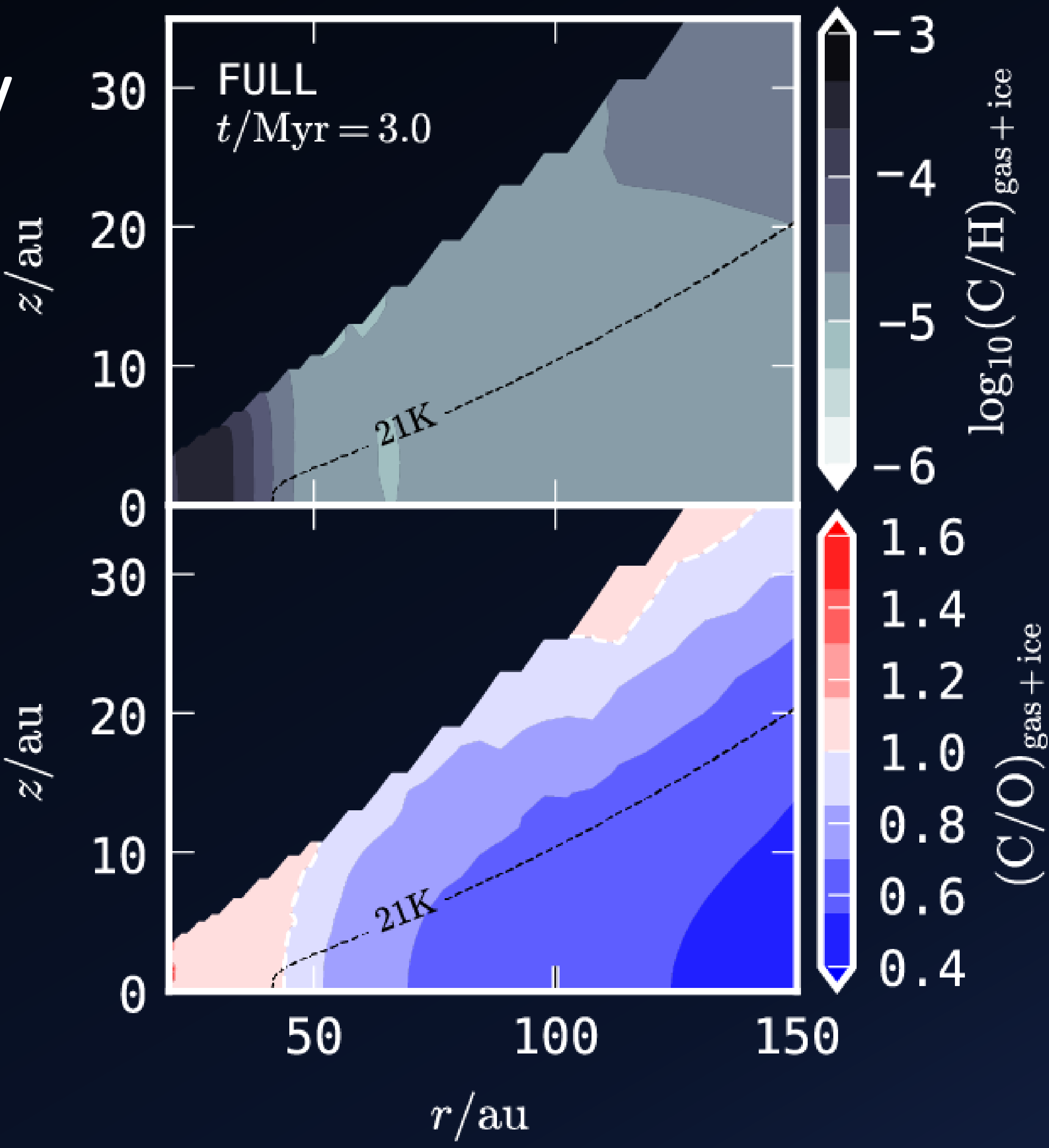
Trapping and simple chemistry

Same, slower diffusion processes

Chemistry further lowers CO abundance

C/O ratios change significantly

Krijt et al 2020

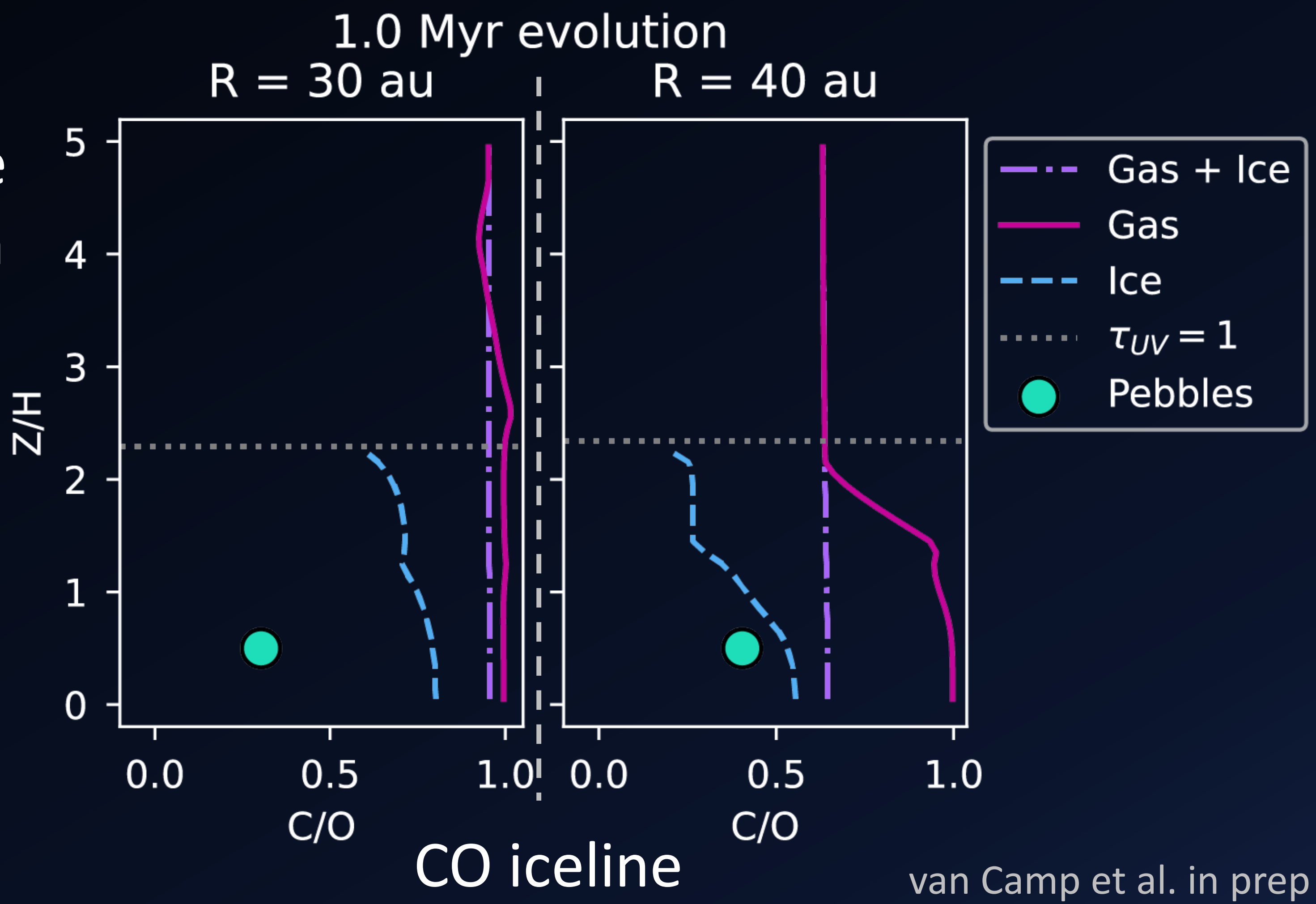


Expanding the chemistry

Including a full gas-phase network and UV reaction

Faster CO depletion

C/O ratios ≤ 1

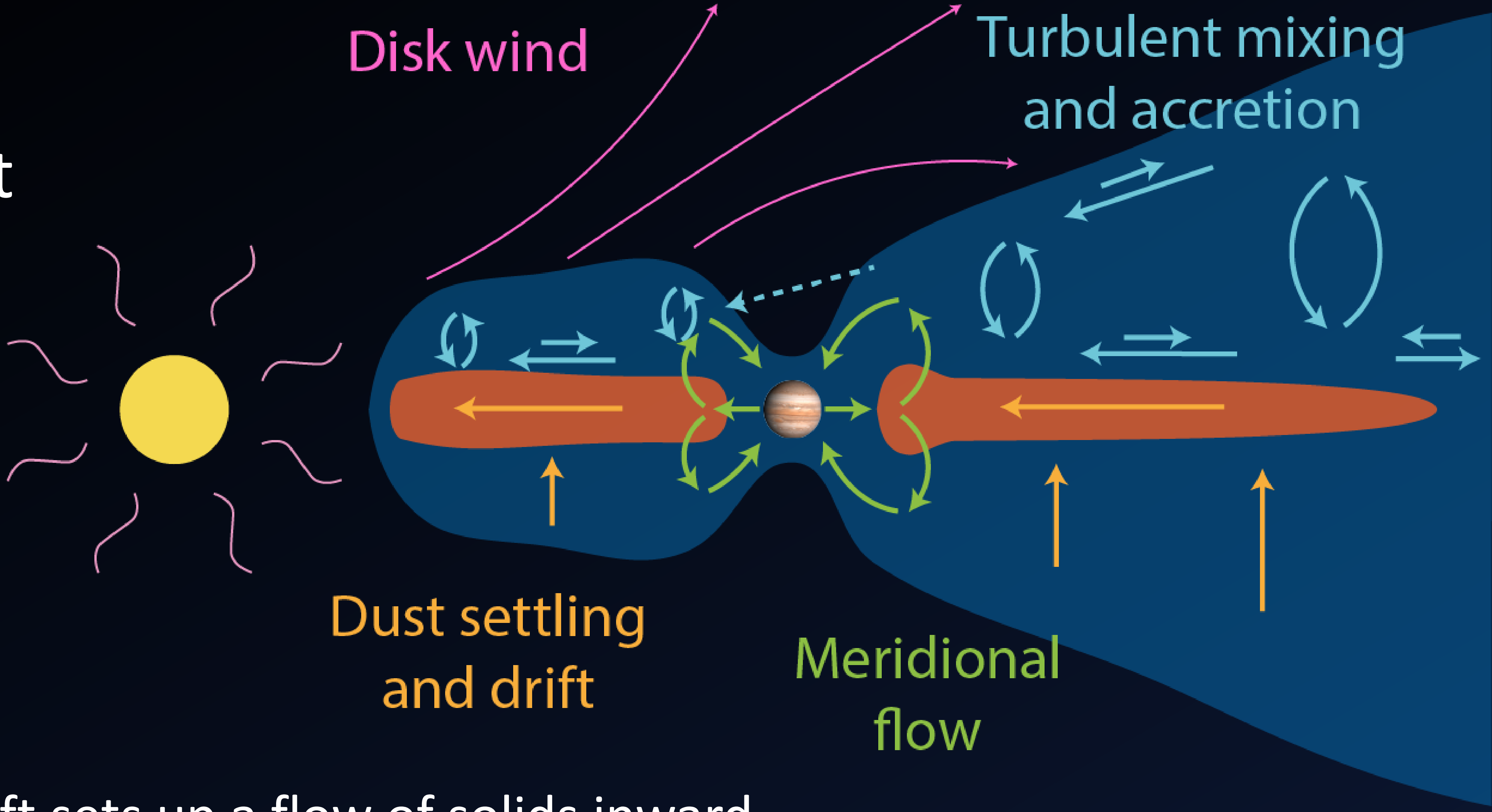


van Camp et al. in prep

Open questions

- C/O ratios
  - Models find it hard to predict values > 1
  - Observations require C/O > 1.5
- Are there limits to concentration?
  - Can you deplete gas stronger than the dust?
  - Can we deplete enough small dust to remove the CO gas?
- What is N_2 doing?
  - Nothing? Cleeves et al 2018

Dust drift



- Radial drift sets up a flow of solids inward
- Enrichment of regions within ice-lines
- (Sub-)structures matter

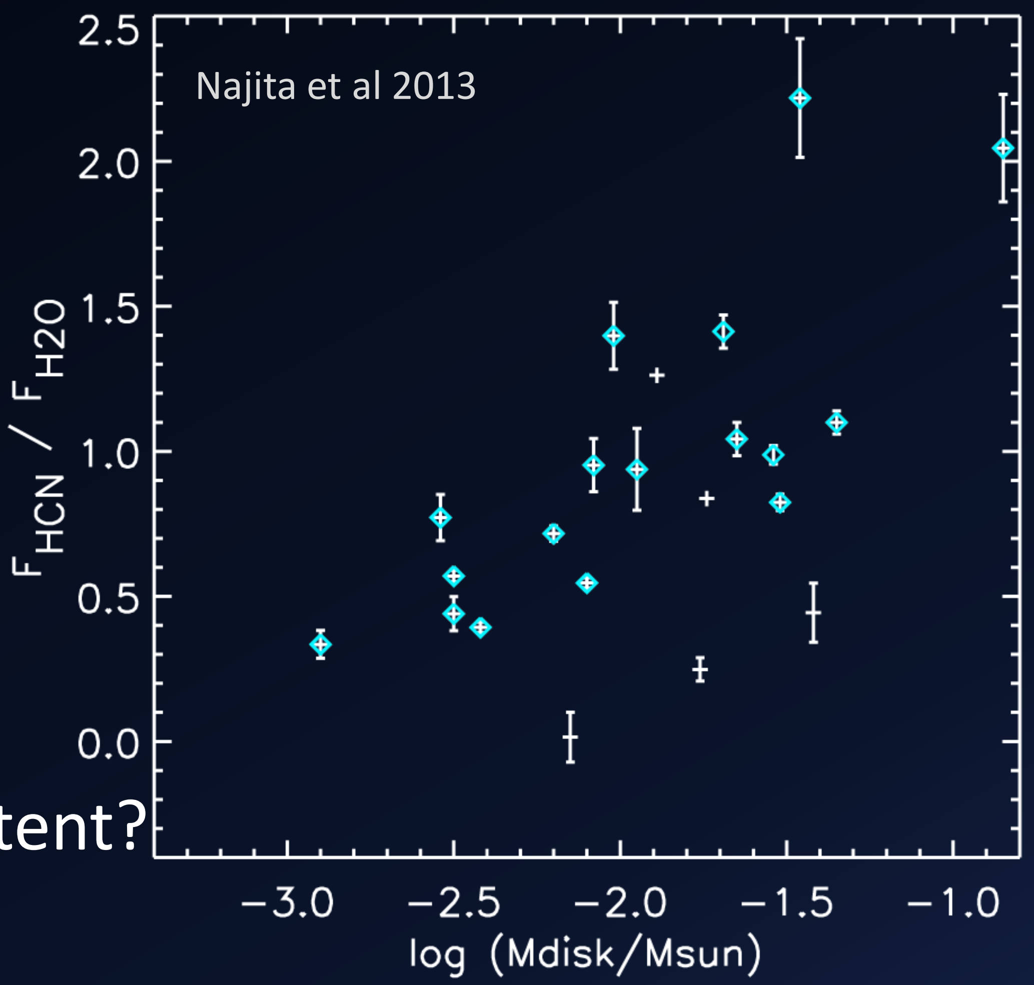
Observational evidence of radial drift

Heavy disks:
low water content?

Relative line strengths of HCN and H_2O correlated with disk dust mass

Locking of ice in planetesimals or…

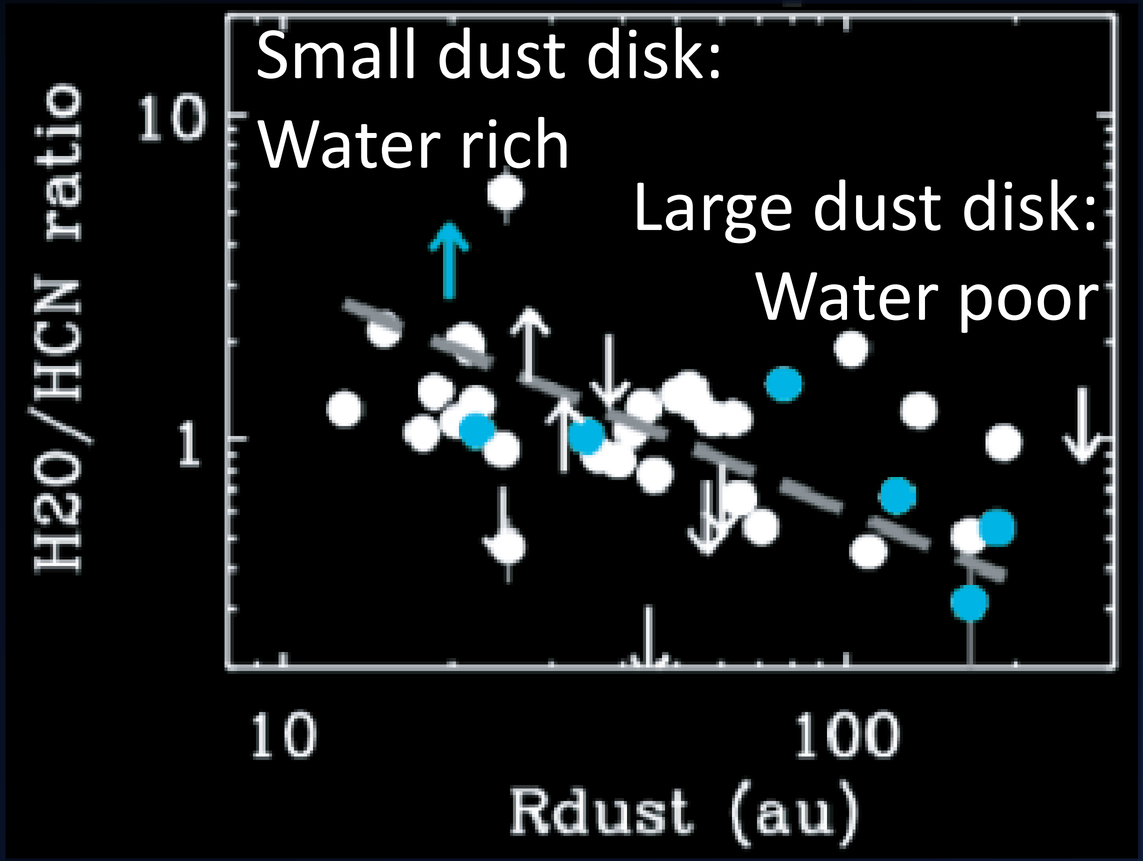
Light disks:
high water content?



Observational evidence of radial drift

… radial drift?

Dust traps hold dust in outer regions:
Large disks have less drift
Lower water abundance

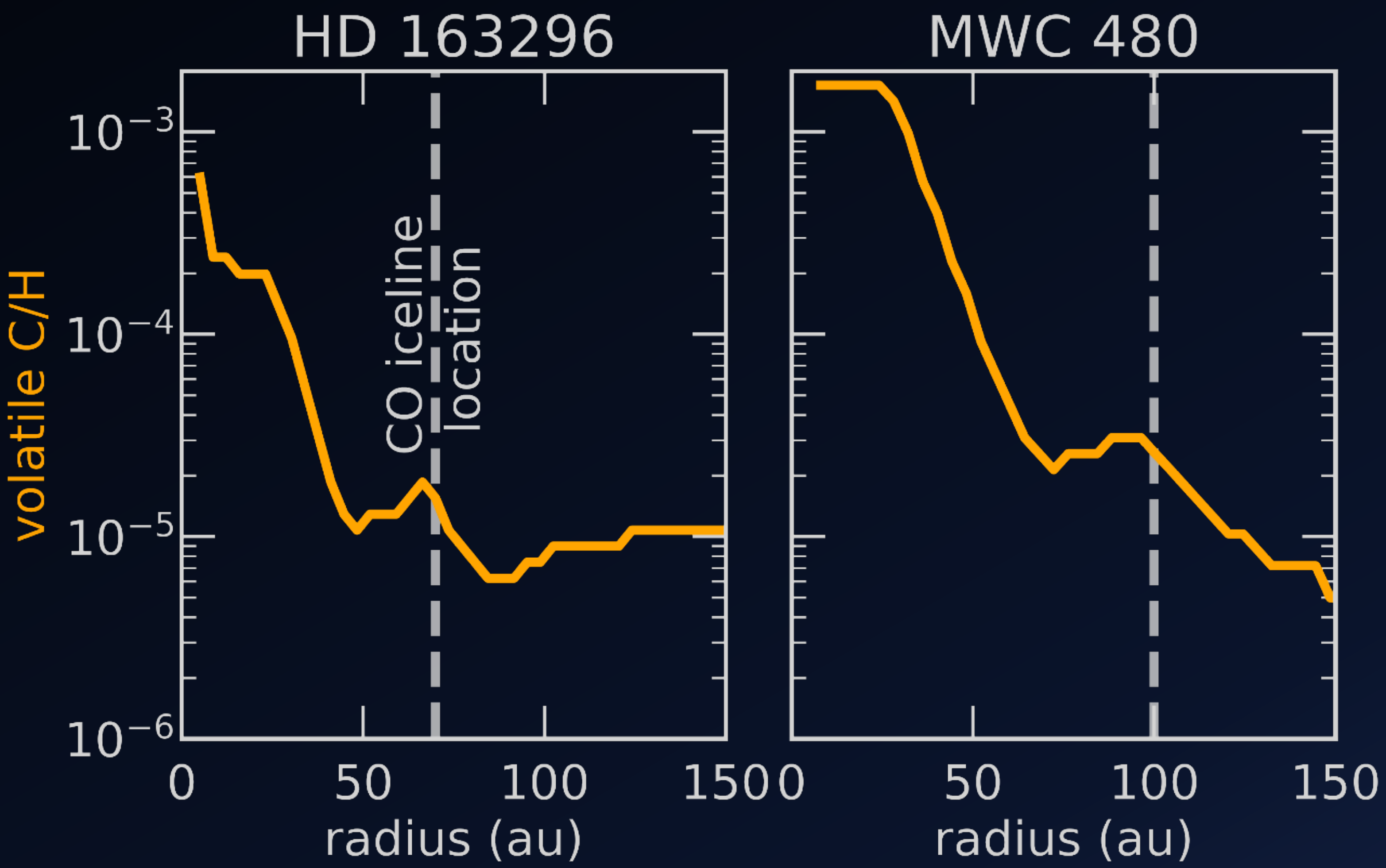


Banzatti et al. 2020

Observational evidence of radial drift

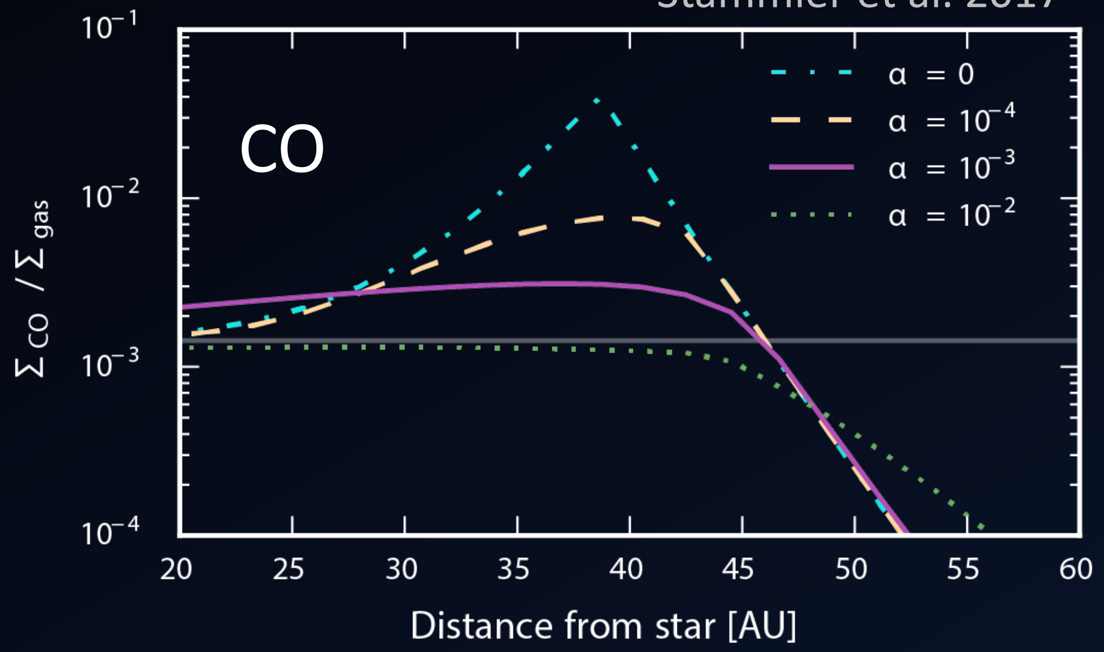
Abundance jumps inside of the iceline

Super ISM C/H

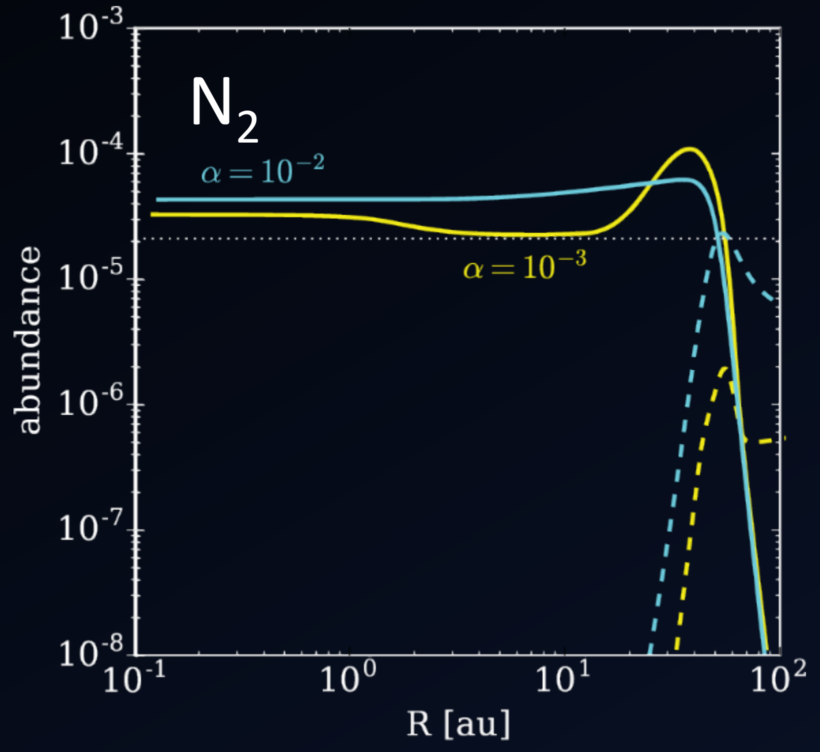


Zhang et al. 2021

Drift affecting the outer disk



Stammler et al. 2017



Booth et al. 2019

Peak created at ice line for low viscous α

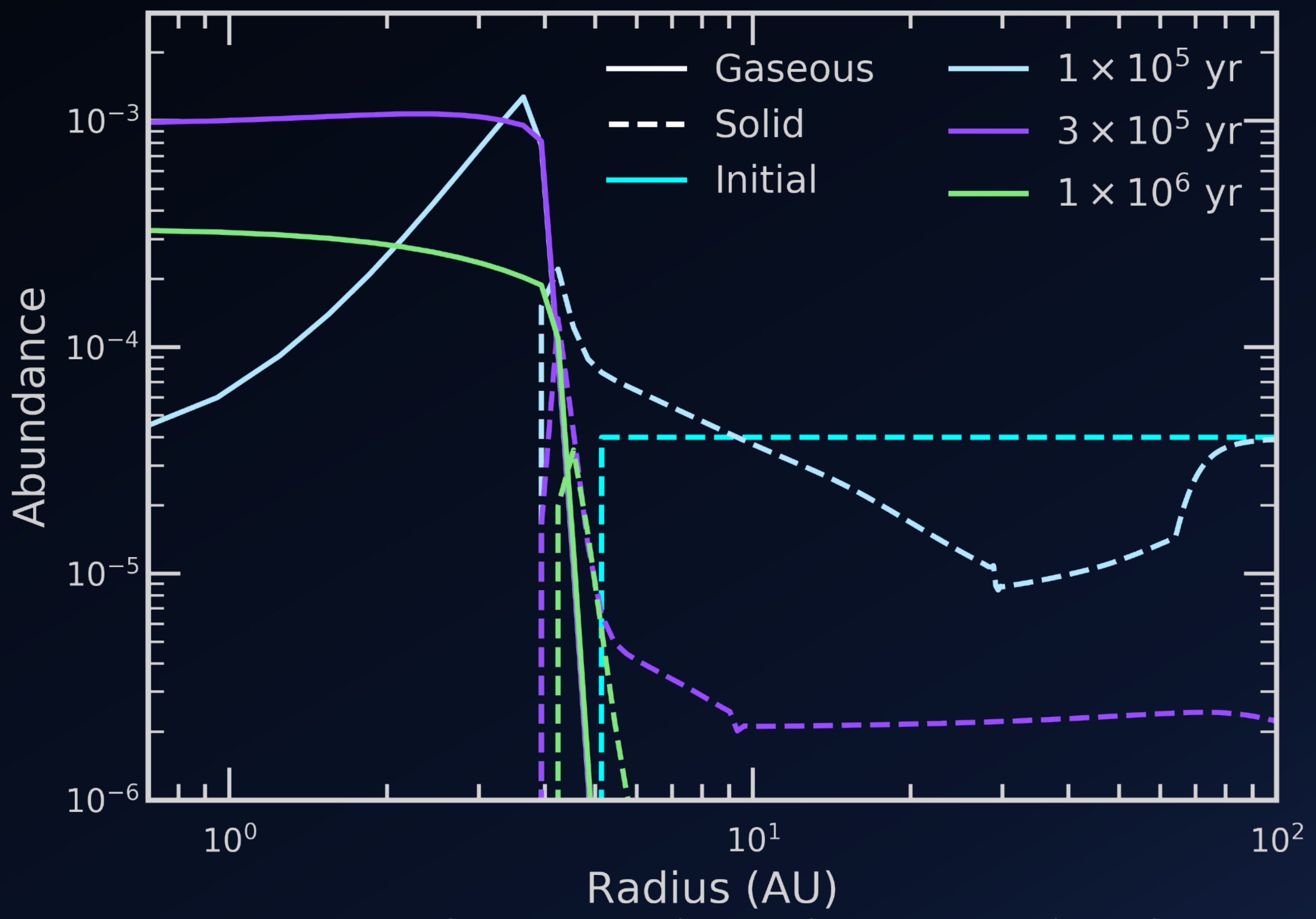
Abundance increase modest for high α

Drift affecting the inner disk

Abundance peak only at early times

Abundance proportional to drift rate

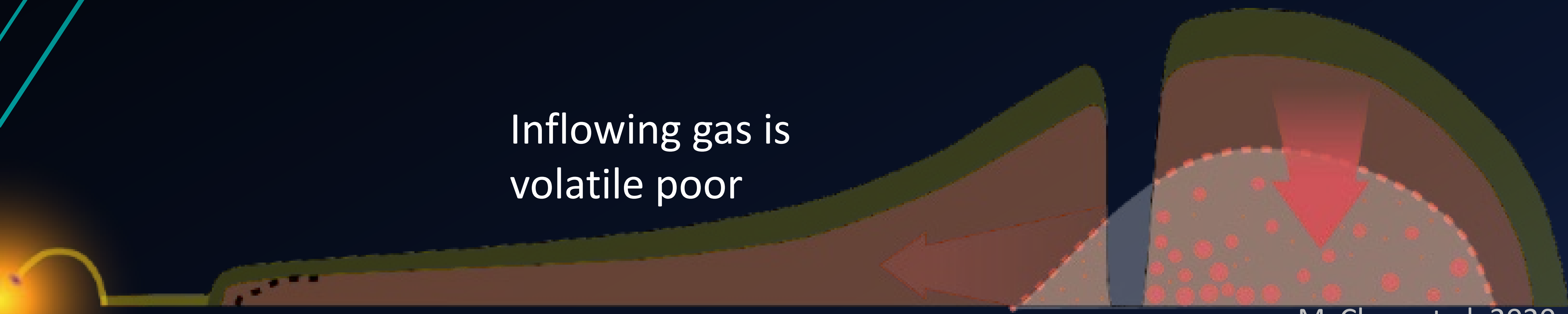
CO_2



Bosman et al. 2018, see also Ciesla+2006, Booth et al 2017, 2019

Absence of drift: ice locking

- Traps hold back dust significantly

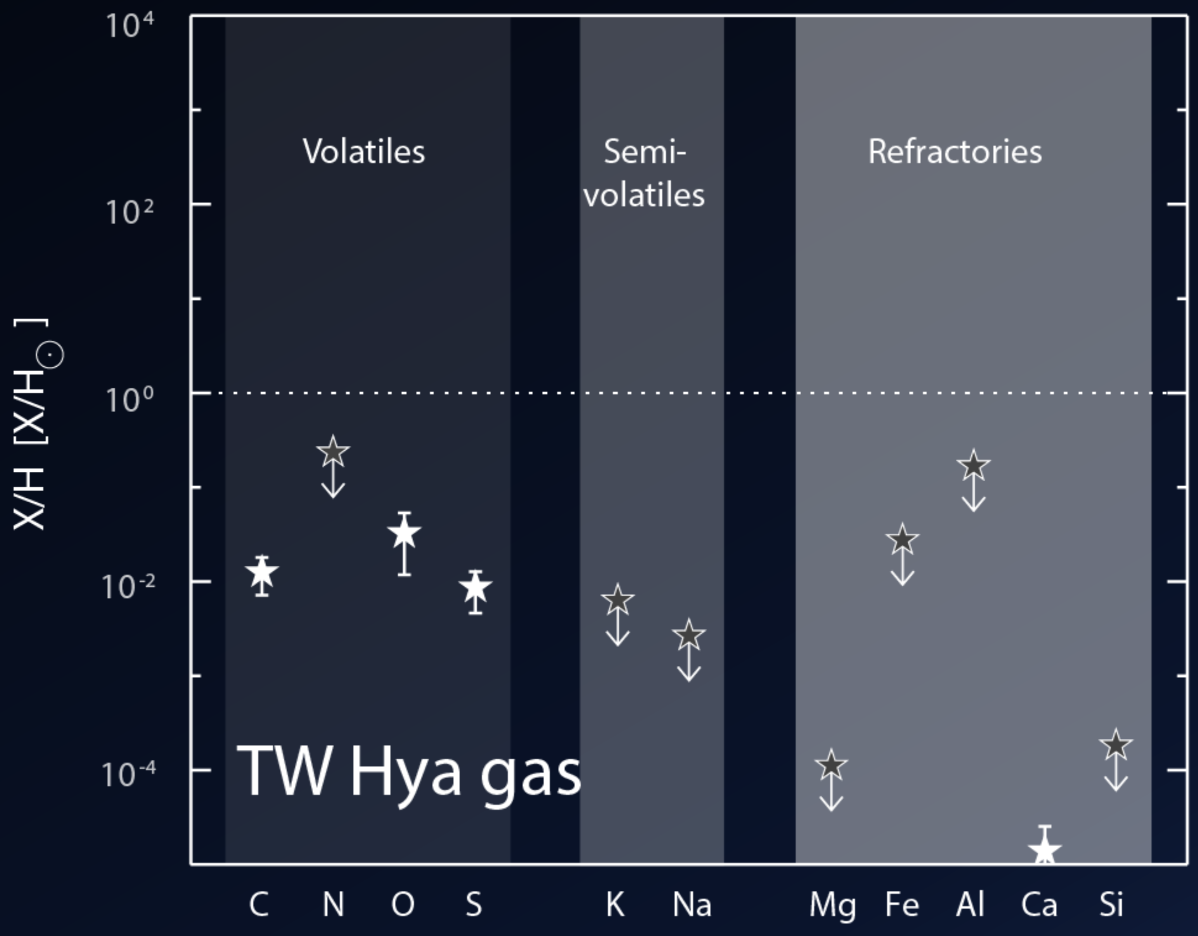


McClure et al. 2020

Ice locking

Evidence of locking seen in gas accreting unto TW Hya

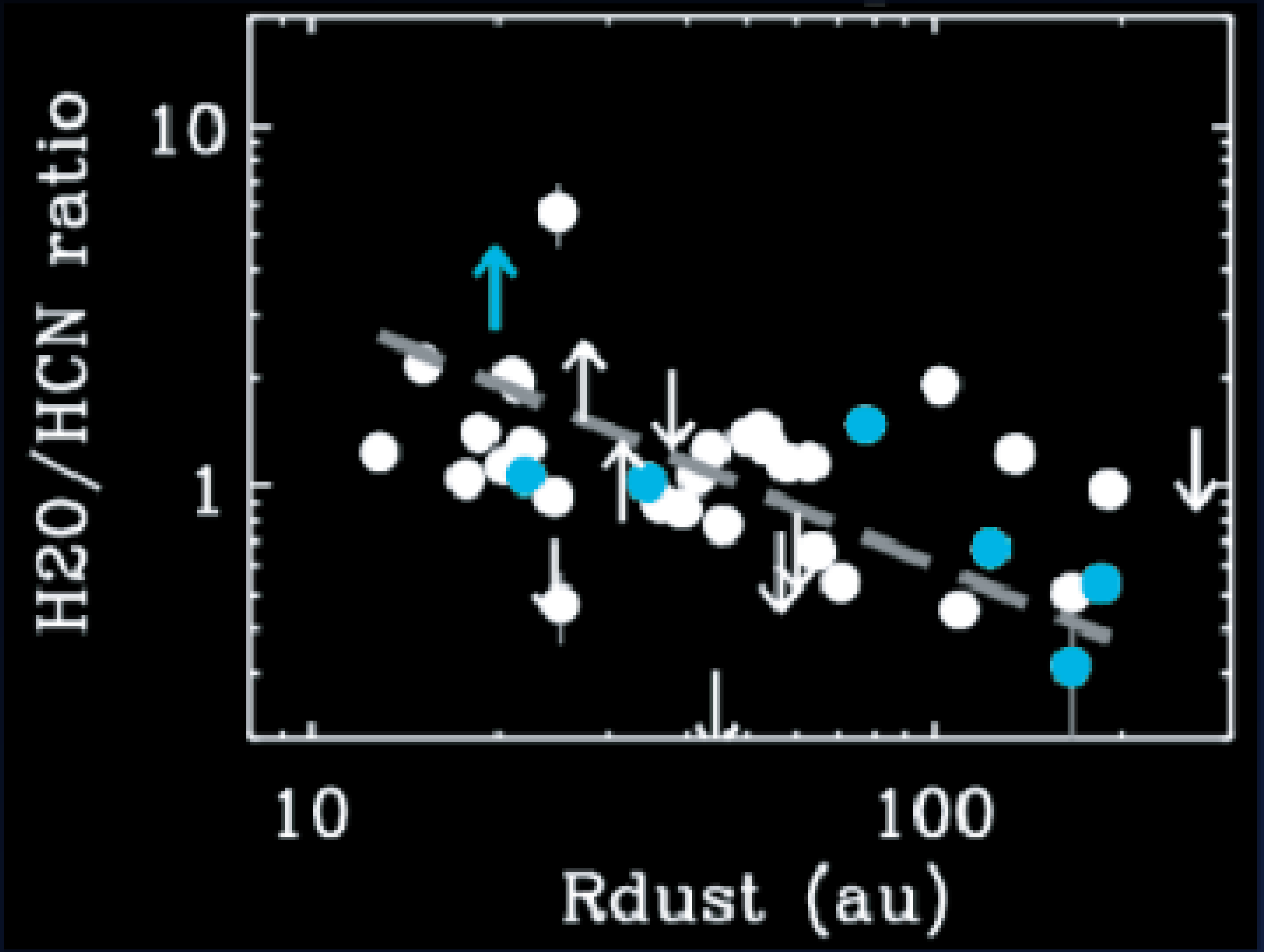
Carbon locking also seen in 5 other disks



McClure et al. 2019, see also Bosman et al. 2019

Ice locking or drift

H2O/HCN Banzatti et al 2020,
C-depletion: McClure 2019



Ice locking or drift

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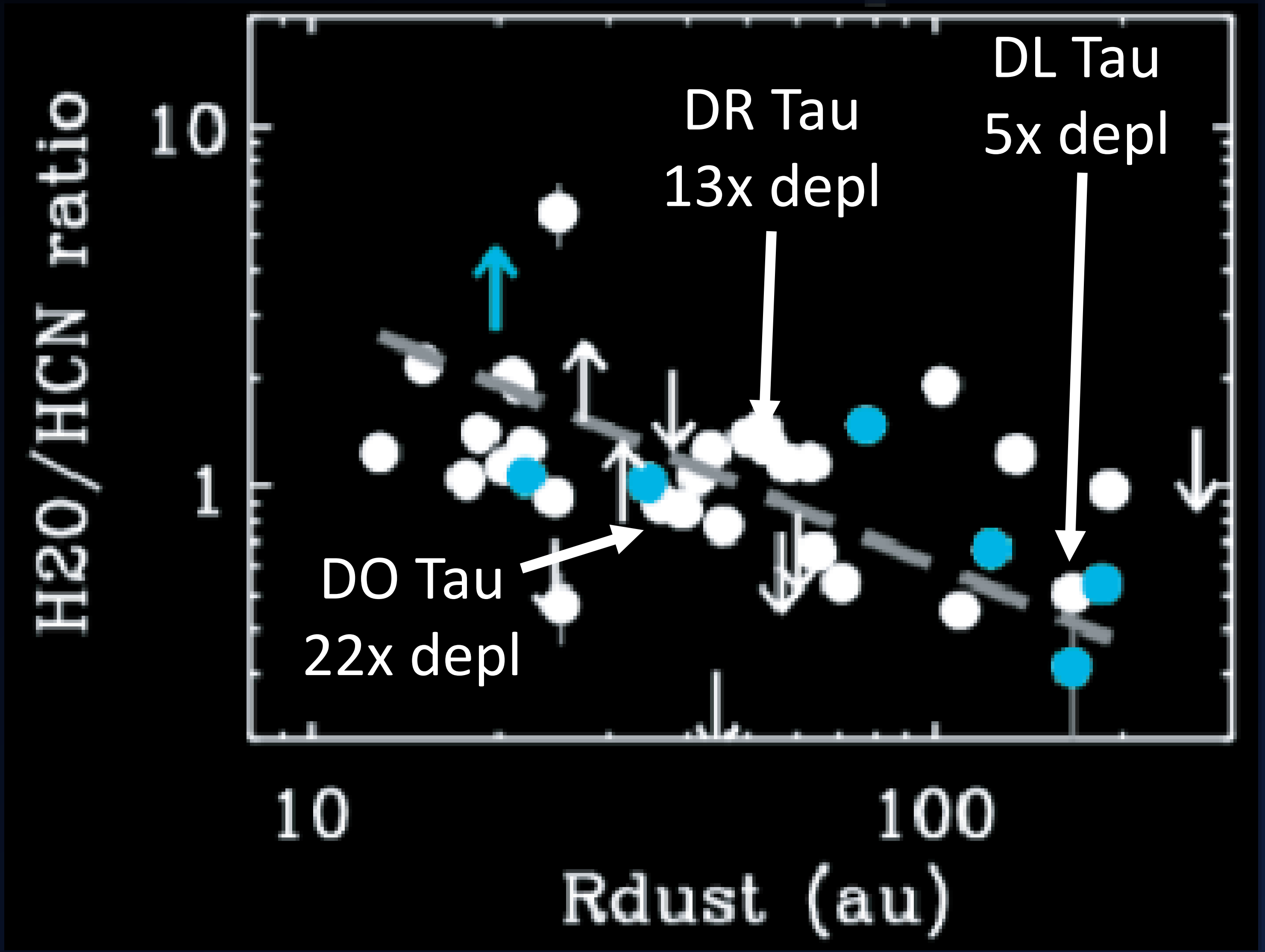
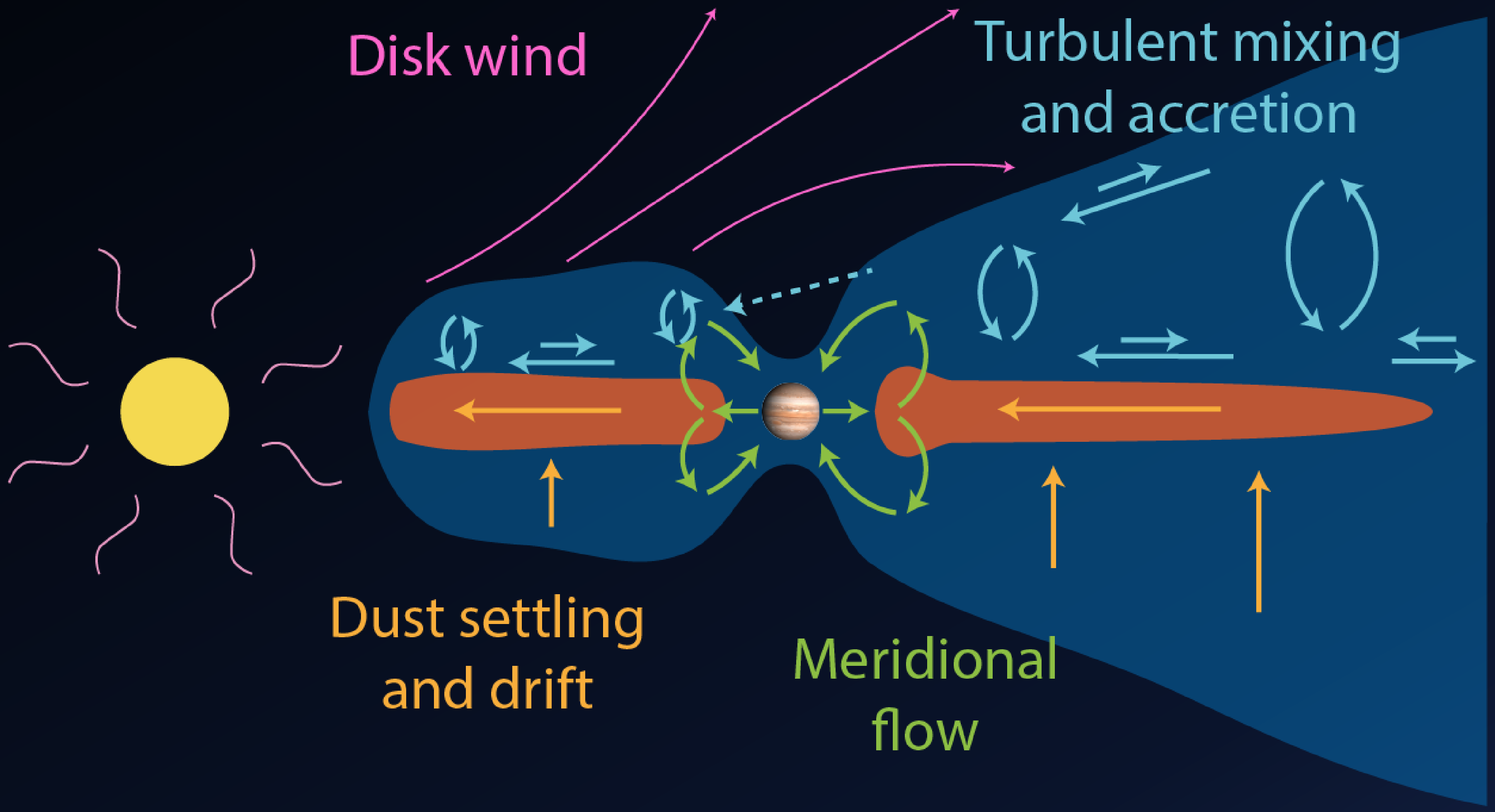
Contradictory evidence?



Open question

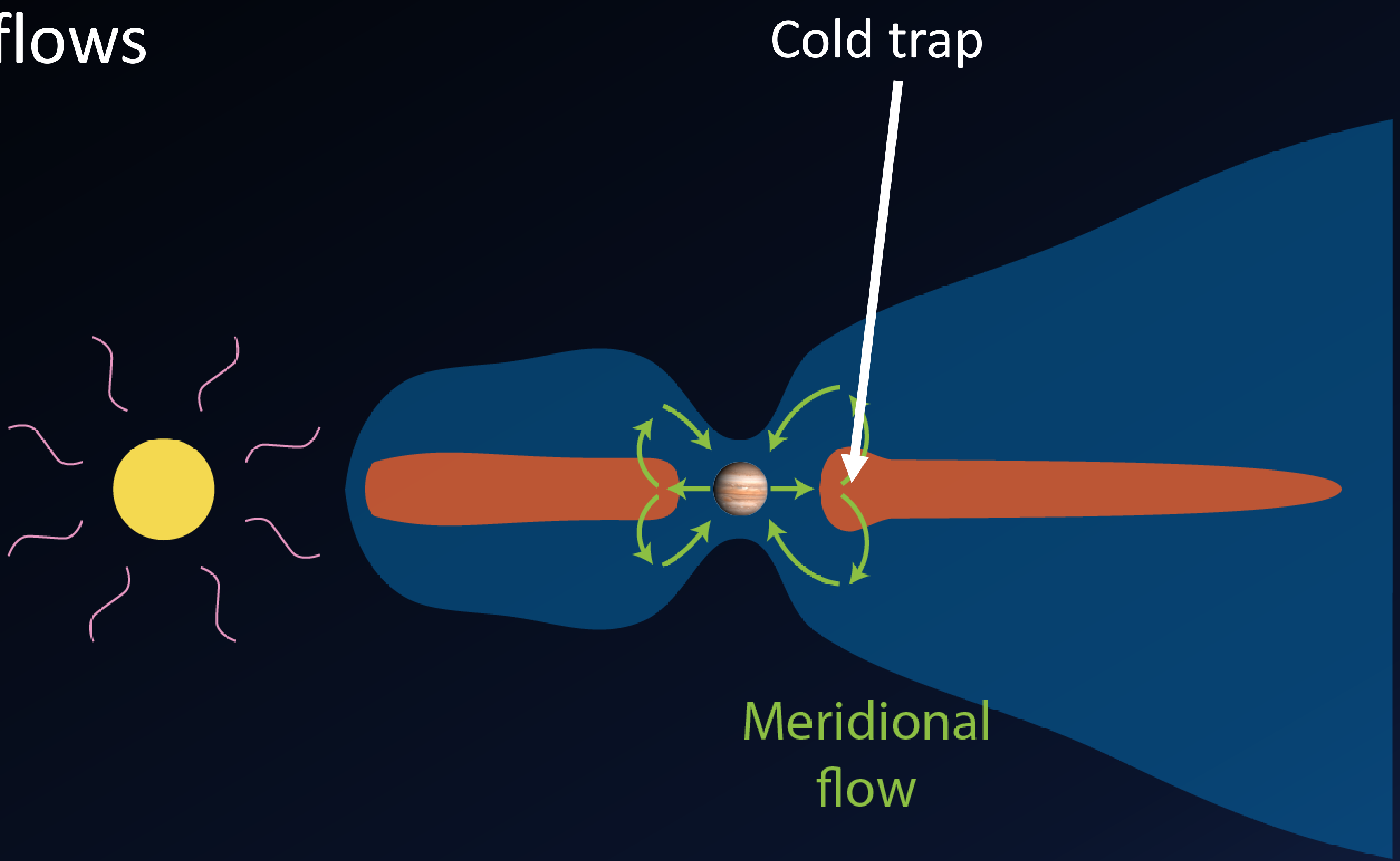
- How fast is drift?
  - How effective are gaps at stopping drift?

Meridional flows



Meridional flows

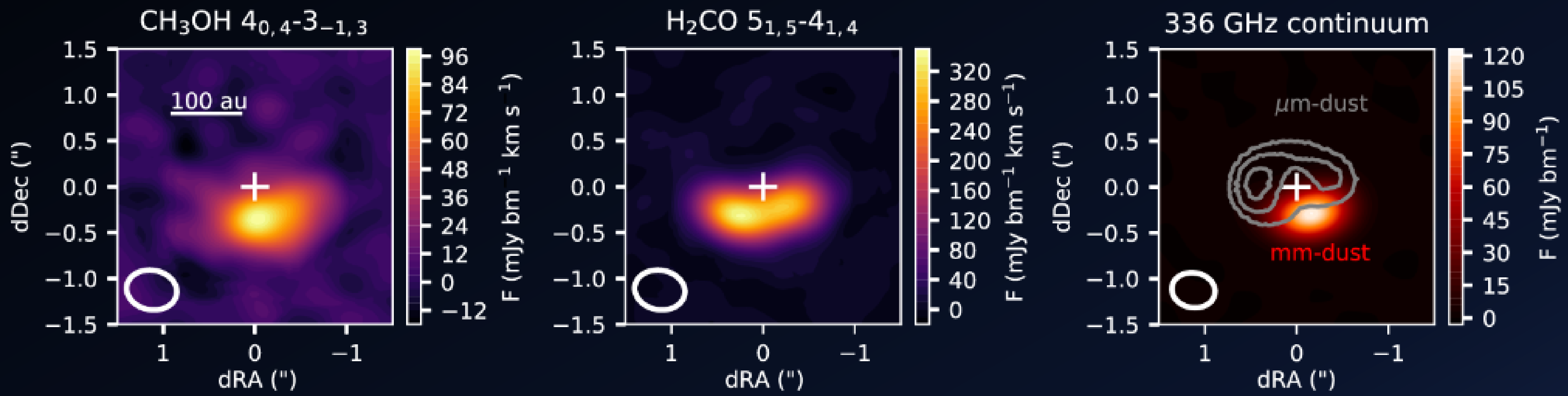
Progressive locking of volatiles in the dust trap?



Alarcon et al. 2020

Meridional flows

or a source of ice bound species?



van der Marel et al. 2021, Booth et al 2021a, 2021b

Conclusions

- Settling and diffusion impact the abundance structure
  - Effects seen, but not quantitatively predictable
  - High C/O ratios not explained yet

- Links between (sub)-structures and inner disk abundances
  - Strongly reduced solid transport?