Future Challenges Related to Star and Planet Formation

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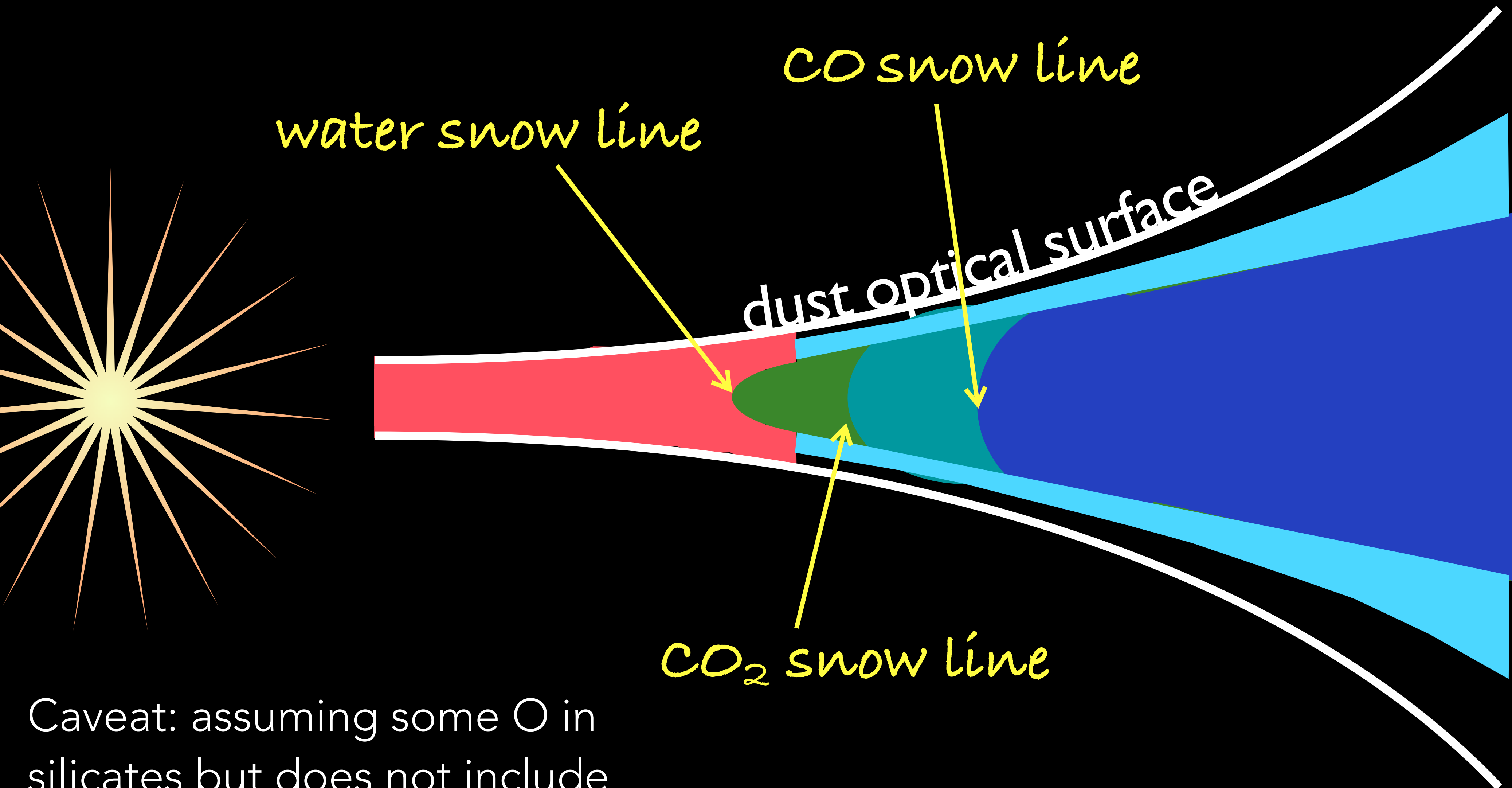
Molecules and Star/ Planet Formation

- We - as a field - need to connect to exoplanets as the largest growth area in astrophysics.
- Two ways to accomplish this
  - ➡ Composition of giant planet atmospheres
  - ➡ Bulk/surface composition of terrestrial planets
- All relate to formation…..
- New capabilities: Space based submm/far-IR, expand VLA, enhance ALMA

Beyond our solar system: C/O Ratio



Caveat: assuming some O in silicates but does not include organics (C-rich + O) and additional unidentified oxygen component

Oberg, Murray-Clay, & Bergin 2011

C/O Ratio

Inside water snow-line: volatiles in gas. C/O = (C/O)$_\odot$ ~ 0.5

CO in gas, water, CO_2 in ice
Gas: C/O ~ 1
Ice: C/O < (C/O)$_\odot$

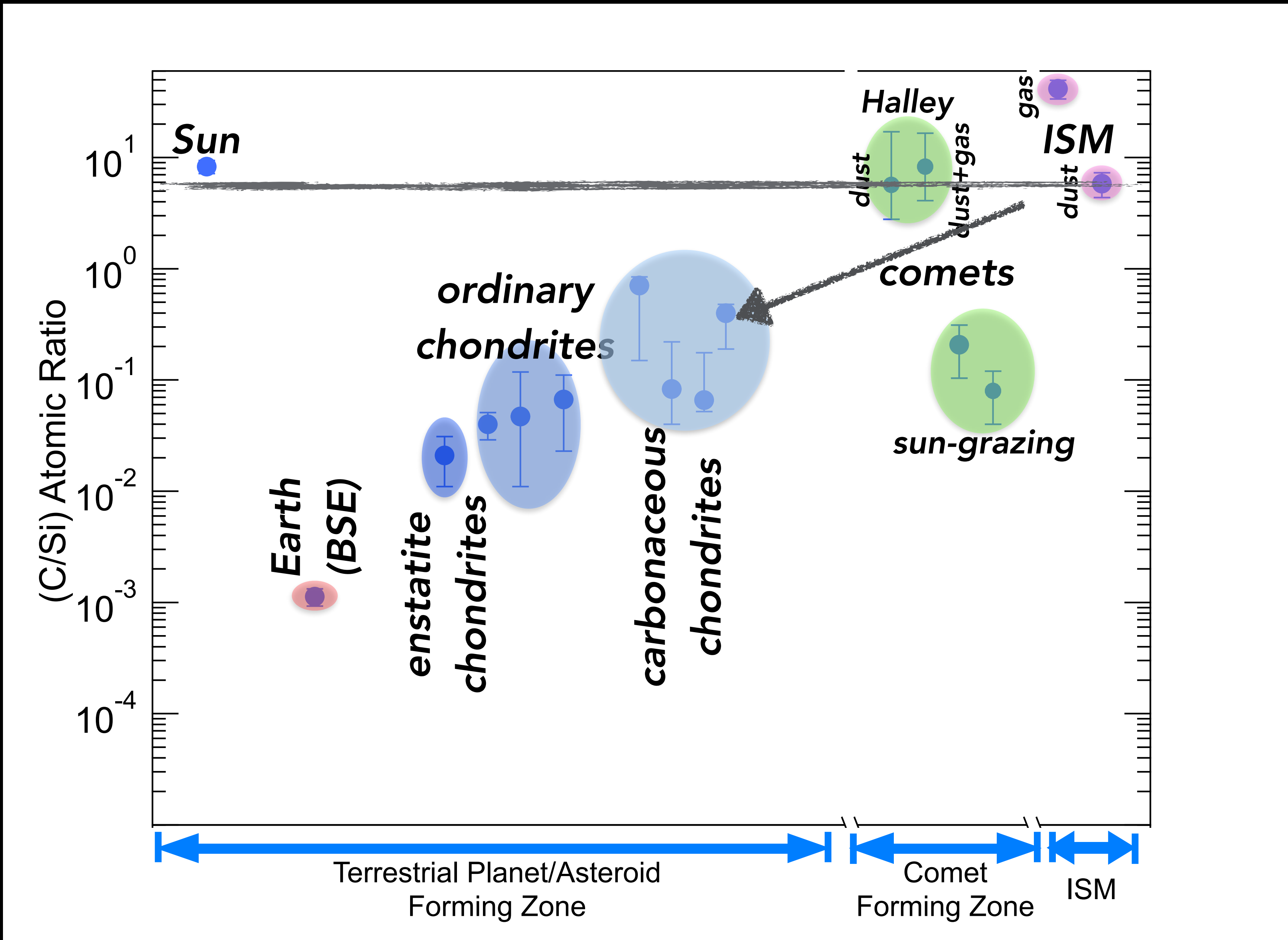
Need to isolate snow-lines of major condensibles:
water, ammonia, carbon monoxide, carbon dioxide, molecular nitrogen

n ice
)$_\odot$

Ice: C/O << (C/O)$_\odot$

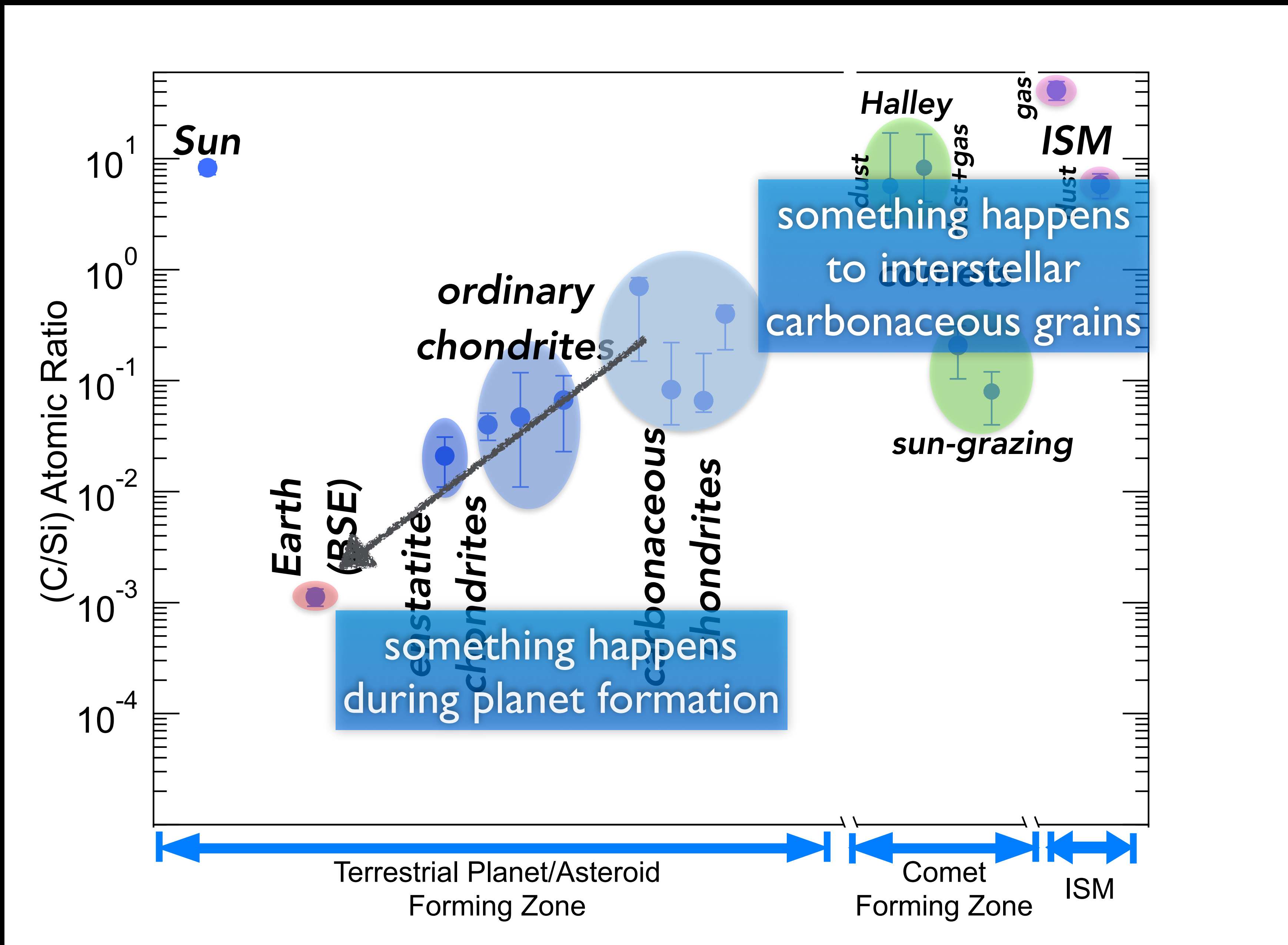
Oberg, Murray-Clay, & Bergin 2011

Carbon



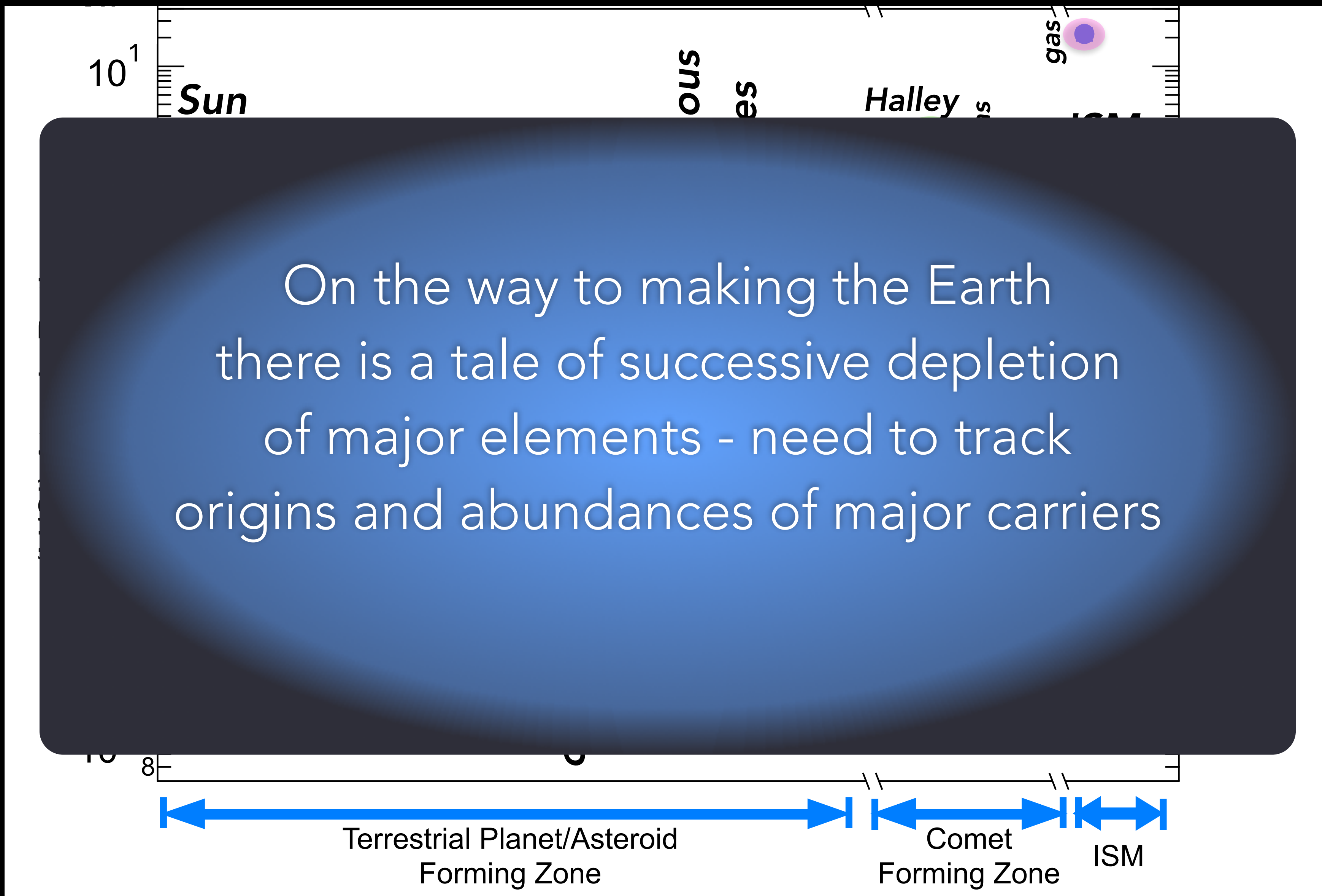
Bergin et al. 2015

Carbon



Bergin et al. 2015

Nitrogen



On the way to making the Earth there is a tale of successive depletion of major elements - need to track origins and abundances of major carriers

Bergin et al. 2015

Locating Snow-Lines

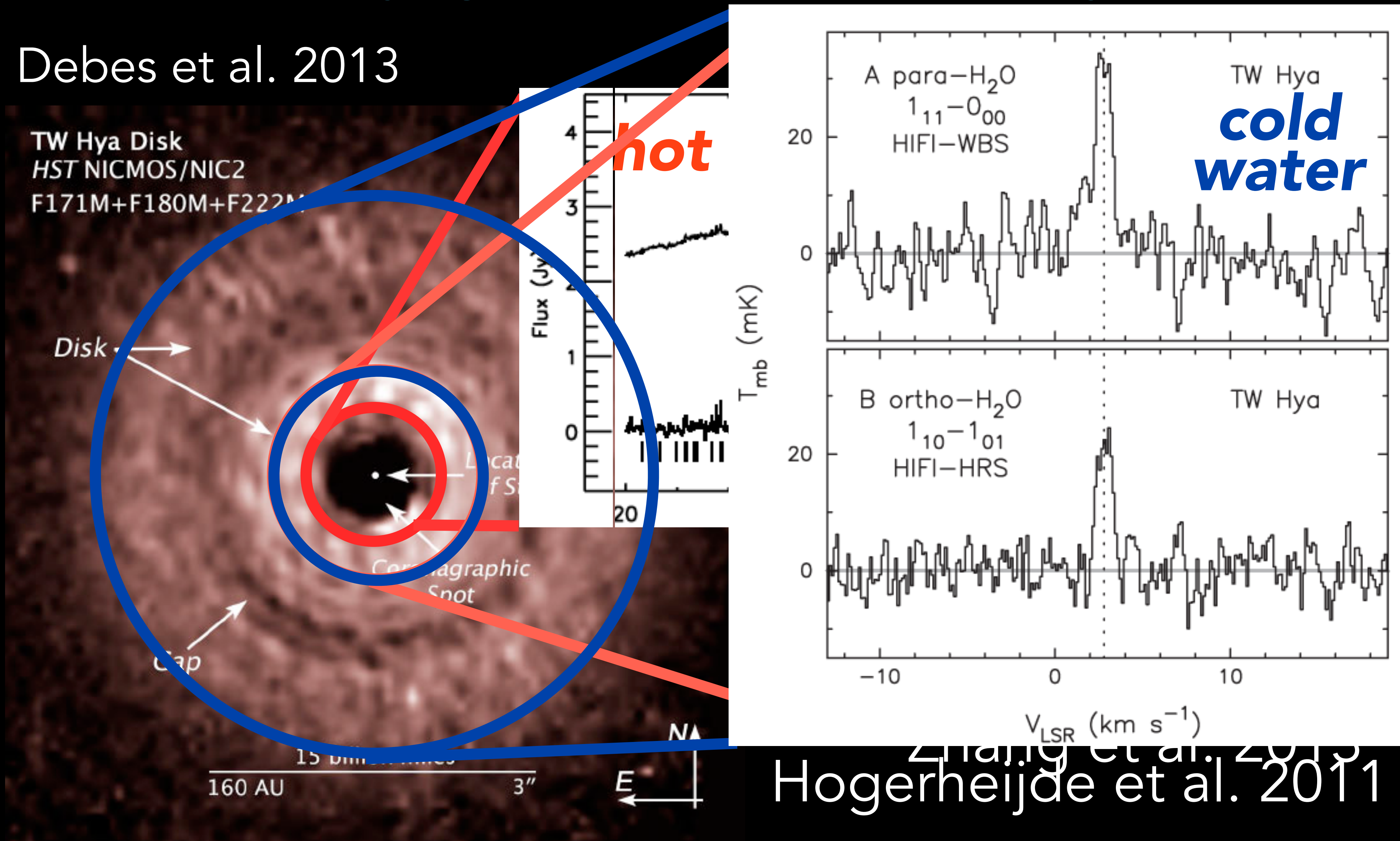
- Methods:
  - ➡ Infer temperature profile and assume ice/vapor transition at sublimation temperature
    - HL Tau
  - ➡ Indirect inference from unresolved data spanning a range of molecular excitation states
    - Spitzer (hot water) + Herschel (cold water)
  - ➡ Direct imaging
    - SMA, NOEMA, ALMA

Water and CO Snow-line

- *H_2O snow-line (T_{dust} ~150 - 200 K)*
    - ➡ close to the star (~1-3 AU)
    - ➡ strongest transitions need space-based observation (e.g. Spitzer/Herschel)
    - ➡ see Zhang+ 2013; Du+ 2015; Blevins+ 2015, in. prep.)

Oxygen in TW Hya

Debes et al. 2013



Hogerheijde et al. 2011

Water and CO Snow-line

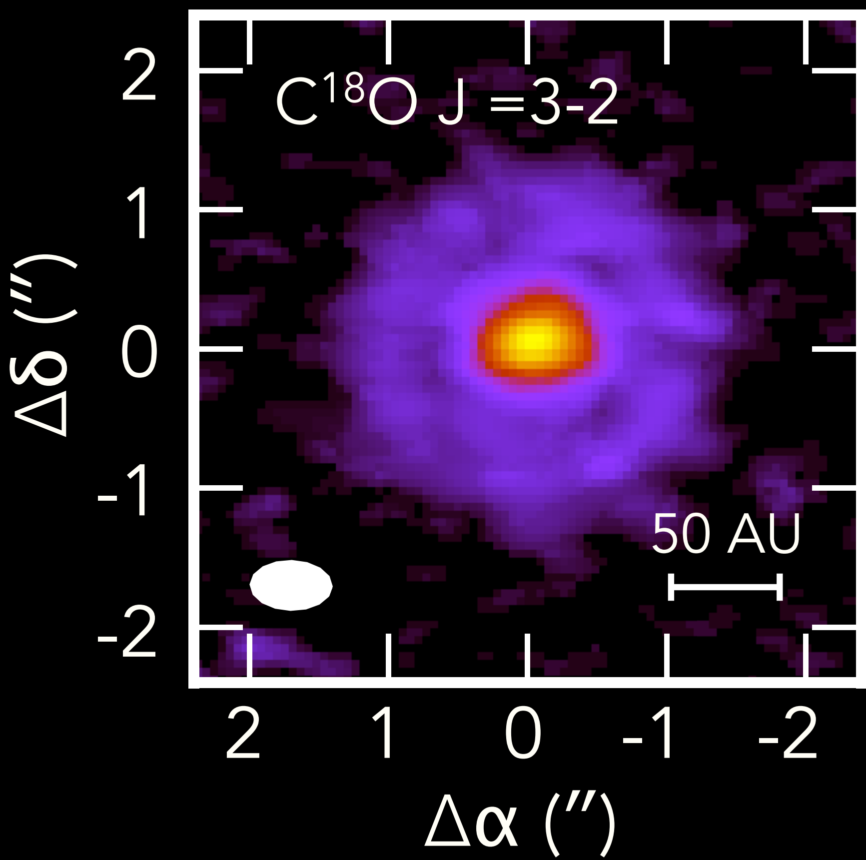
- *H_2O snow-line (T_{dust} ~150 - 200 K)*
  - ➡ close to the star (~1-3 AU)
  - ➡ *JWST cannot do this alone!! need access to cold transitions from space*
  - ➡ *OR!!!! could add dishes to ALMA to increase sensitivity —- ALMA 2.0 — resolve the most important chemical transition!*

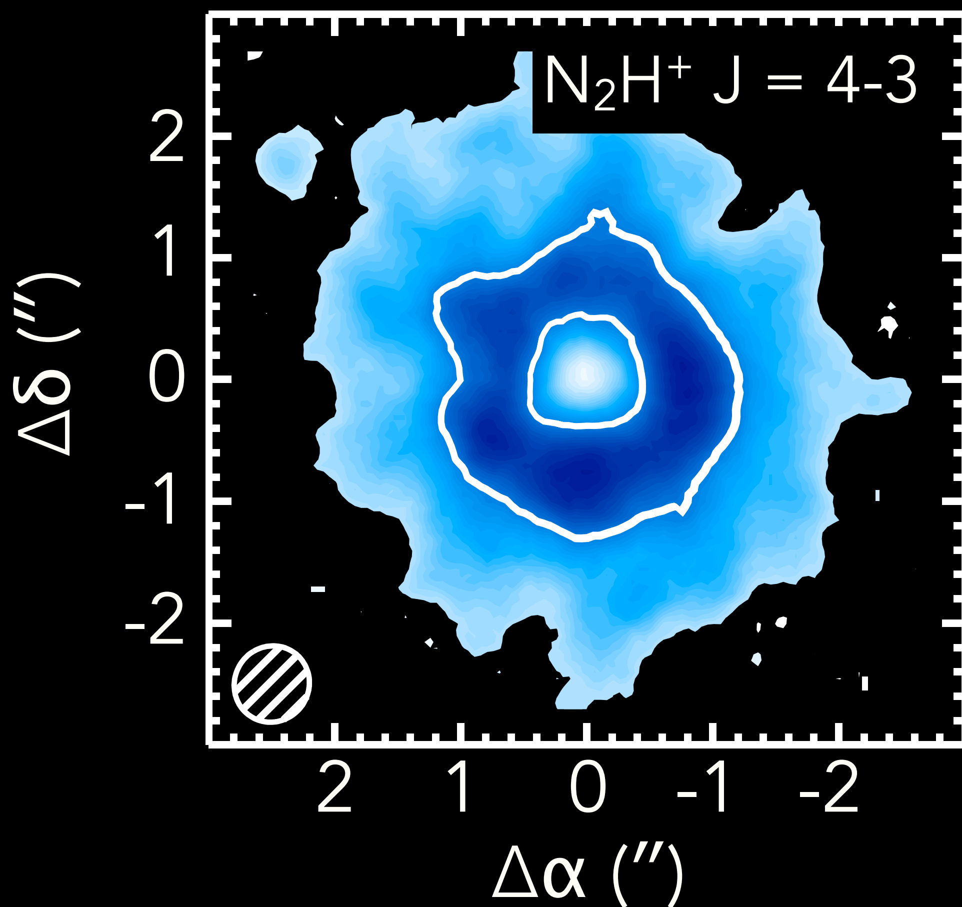
Water and CO Snow-line

- *CO snow-line (T_{dust} ~ 20 - 40 K)*
  - ➡ greater distances from star (tens of AU)
  - ➡ can be resolved with ground-based telescopes
  - ➡ numerous stable C and O isotopes to reduce optical depth ($^{12}C^{16}O$, $^{13}C^{16}O$, $^{12}C^{18}O$, $^{12}C^{17}O$, $^{13}C^{18}O$, $^{13}C^{17}O$)

TW Hya CO Snow-line

$N_2H^+ + CO \Rightarrow N_2 + HCO^+$



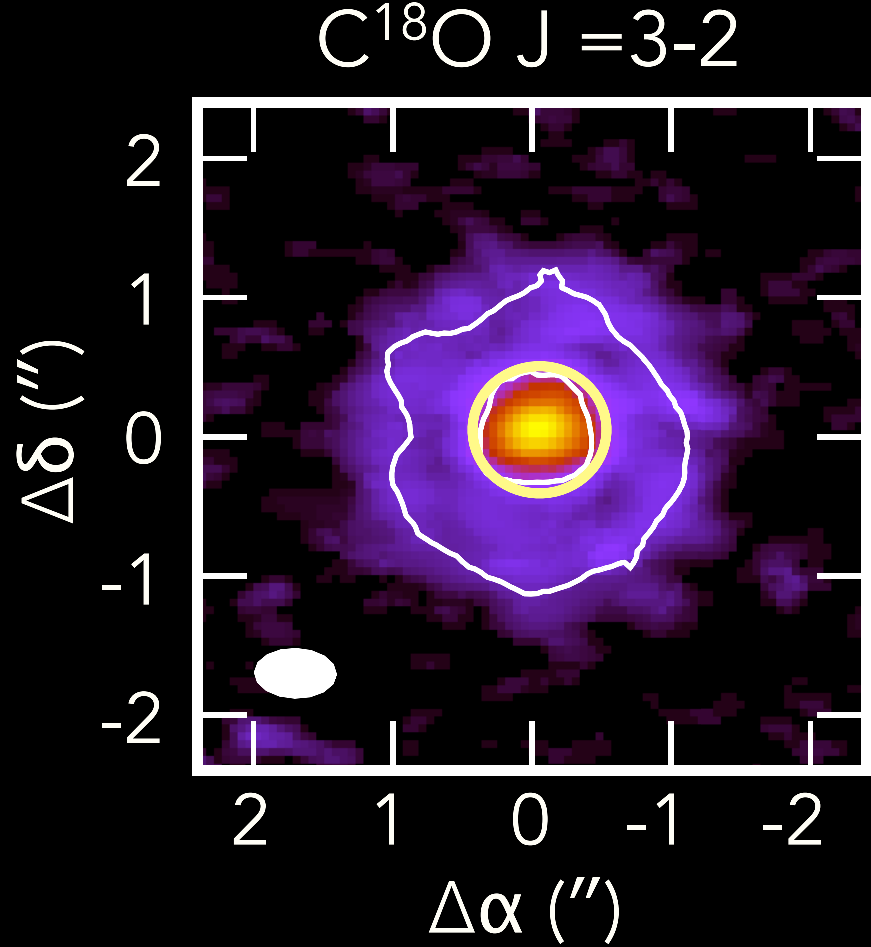


Schwarz+ 2015, in prep.

Qi+ 2013

TW Hya CO Snow-line

Schwarz+ 2015, in prep.



^{13}CO 6-5, 3-2, $C^{18}O$ 6-5, 3-2 & abundance analysis

CO surface snow-line = 25 - 30 AU; midplane ~20 -25 AU

Protoplanetary Disk Gas Mass

- Linchpin for determination of chemical abundances
- Cannot trace H_2 directly - need to use proxies
  - ➡ thermal emission from dust grains at mm/sub-mm
  - ➡ thermo-chemical modeling of CO gas emission

important question: If we measure abundance in emissive layers (excluding freeze out zone) - is it low gas mass or low abundance?

Missing C,O or H_2?

- Low CO/dust & CI/dust

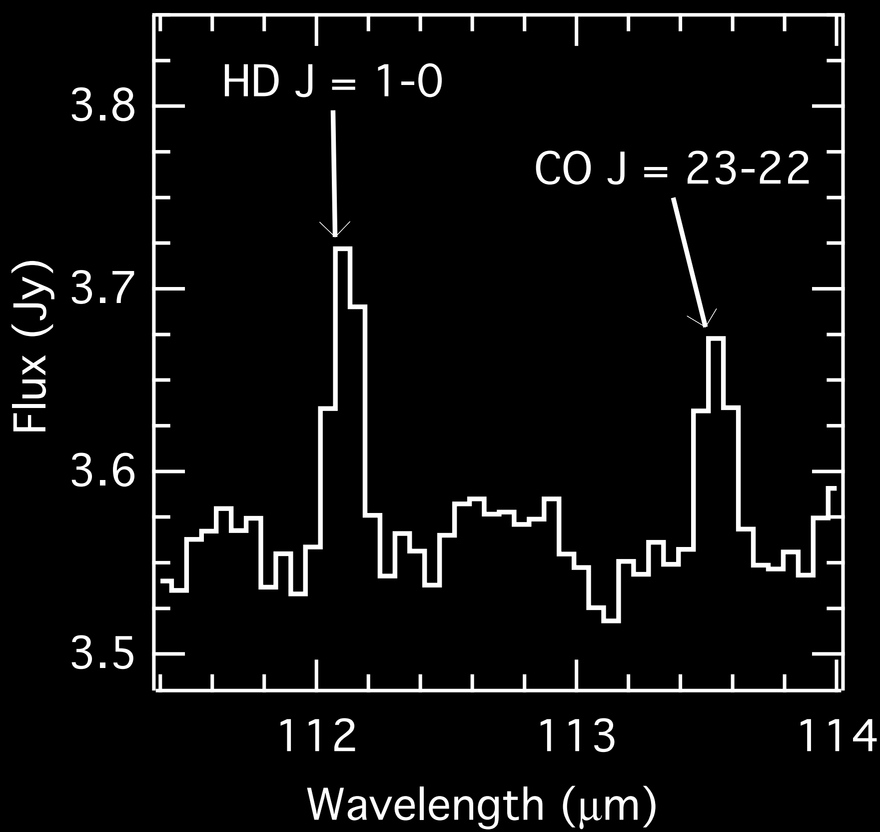
  (Chapillon+ 2008; Dutrey+ 2003; Tsukagoshi+2015; Kama + 2015)

- Cold water emission survey - no detections beyond TW Hya and HD100546 (Hogerheijde+ 2011; Du et al., in prep.)

- C^+ detected in 27% of 47 T Tauri stars (Dent et al. 2013)

- O I less emissive compared to continuum in 21 disks (Keane et al. 2014)

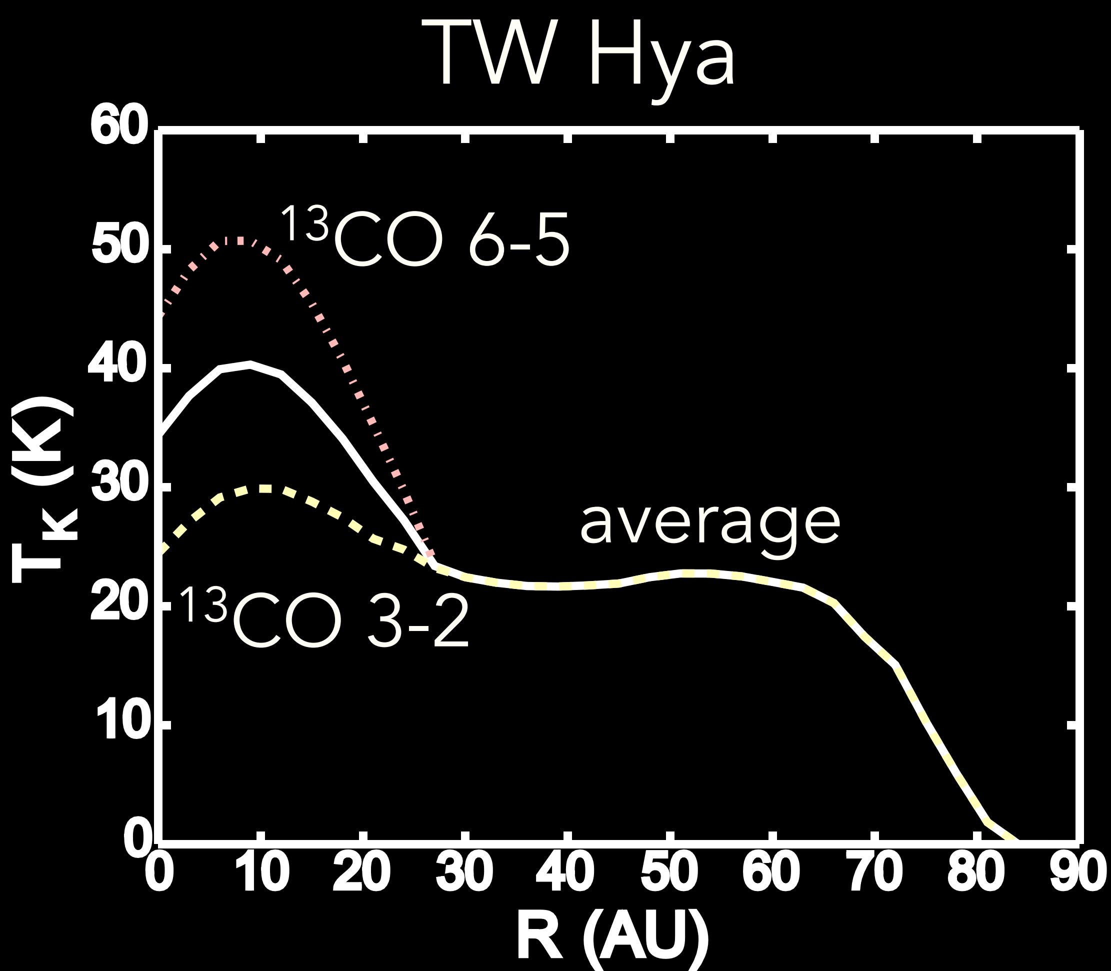
Herschel Detection of HD towards TW Hya



Bergin et al. 2013

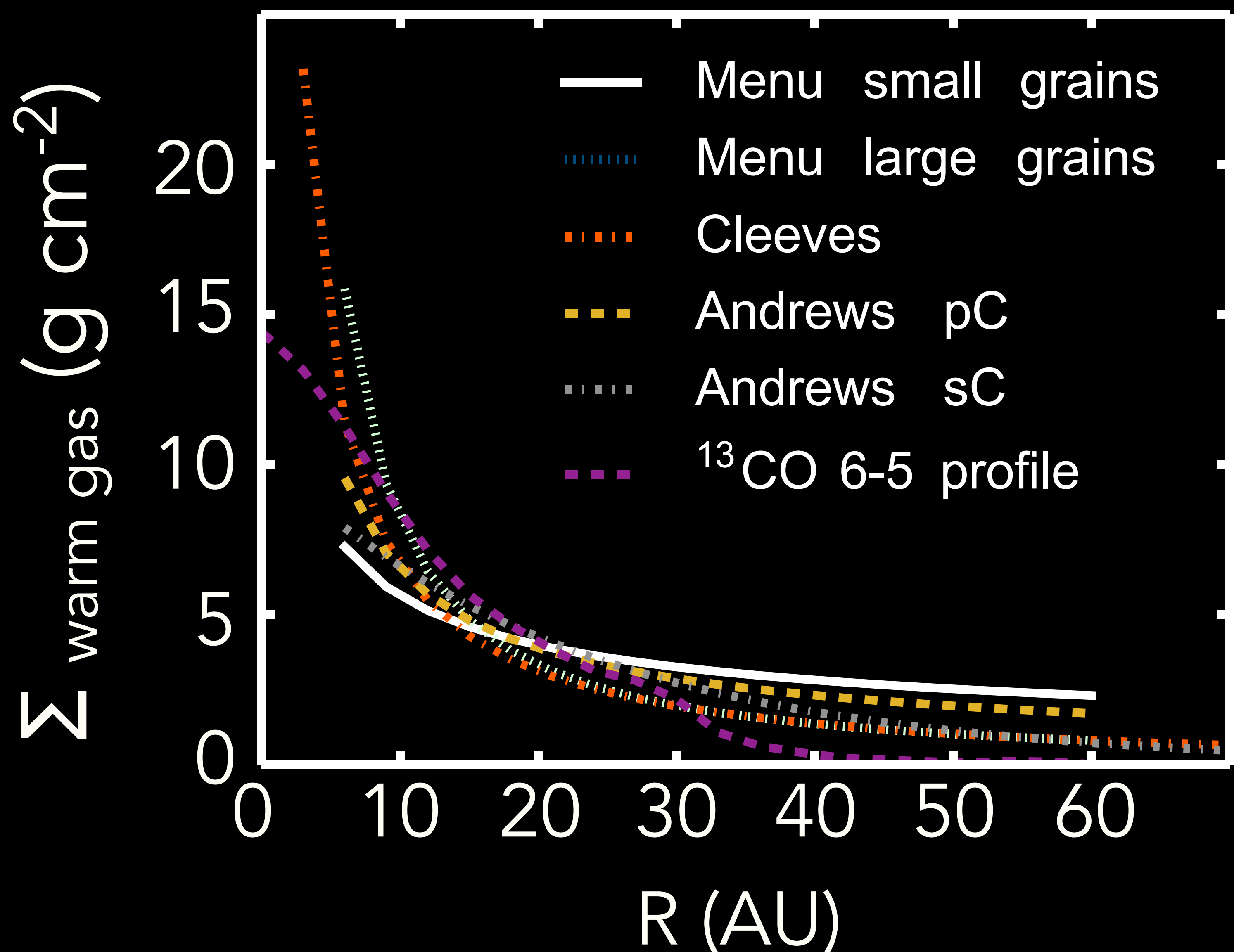
- ➡ HD is a million times more emissive than H_2 at T ~ 20 K.
- ➡ Atomic D/H ratio inside the local bubble is well characterized ($\sim 1.5 \times 10^{-5}$)
- ➡ More direct measurement of disk gas mass ($\sim 0.05\ M_{\odot}$)
- ➡ Caveat: strong T dependency

Surface CO Snow-line



Schwarz et al. 2015, in prep.

Mass Distribution

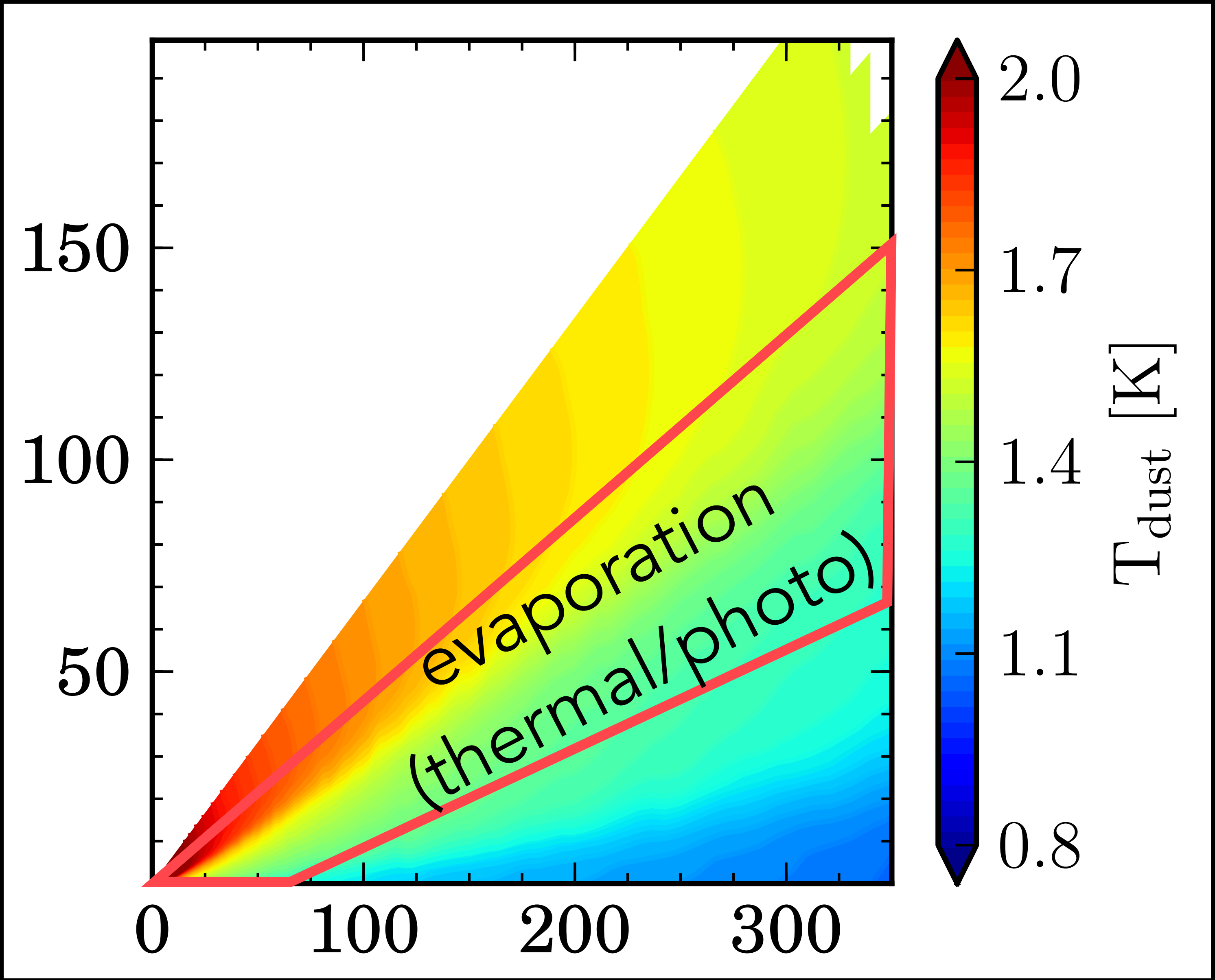


Schwarz et al. 2015, in prep.

HD and $C^{18}O$ in TW Hya

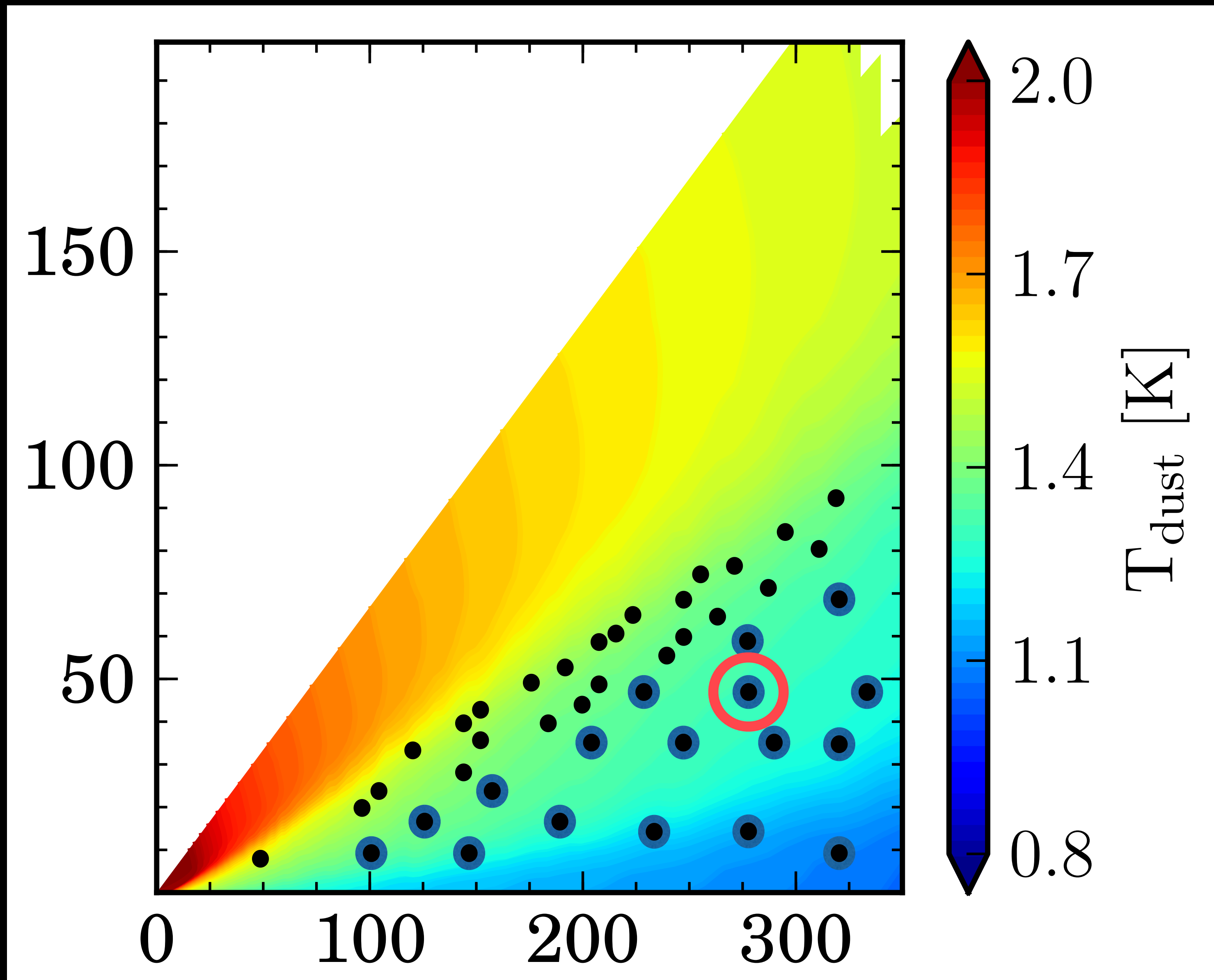
- Favre et al. 2013
  - ➡ Emission ratio $F_{J=2\text{-}1}(C^{18}O)/F_{J=1\text{-}0}(HD)$ is proportional to the CO abundance
  - ➡ Excitation
    - — HD will not emit if $T_{gas} < 20$ K
    - — CO freezes onto grains if $T_{gr} < 20$ K
  - ➡ CO Abundance $< 10^{-5}$ (+ confirmed by ALMA observations - Schwarz et al. 2015, in prep.)
  - ➡ Same result for water (Du et al. 2015).

Where is the O and C



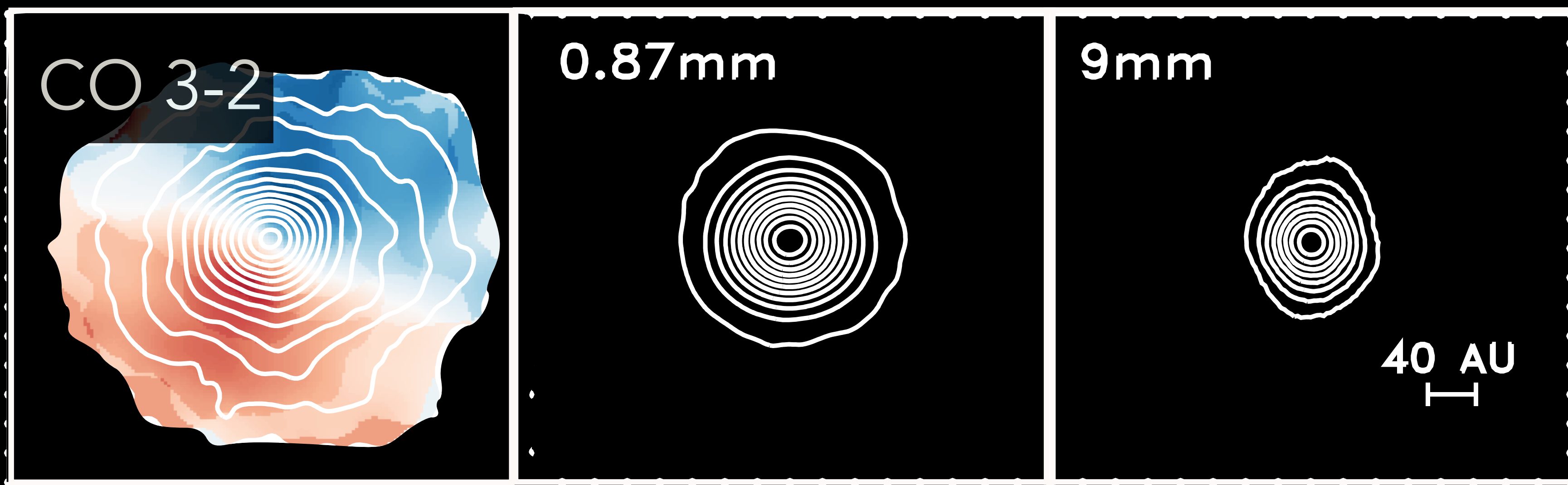
Possible Mechanism

- radial + vertical pressure gradients
- dust settling + growth + radial drift
- sequesters volatiles in midplane ***(more water than CO)***
- particles must be large enough to frustrate feedback



Du+ 2015; but see Chapillon+ 2008

Evidence for Radial Drift



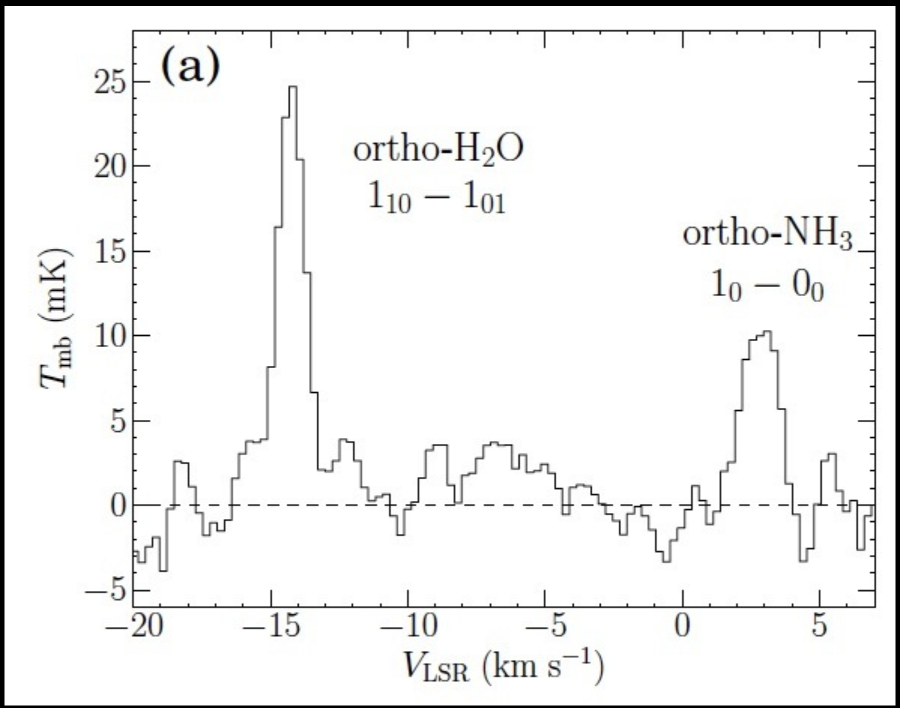
Andrews 2015

Consequences:

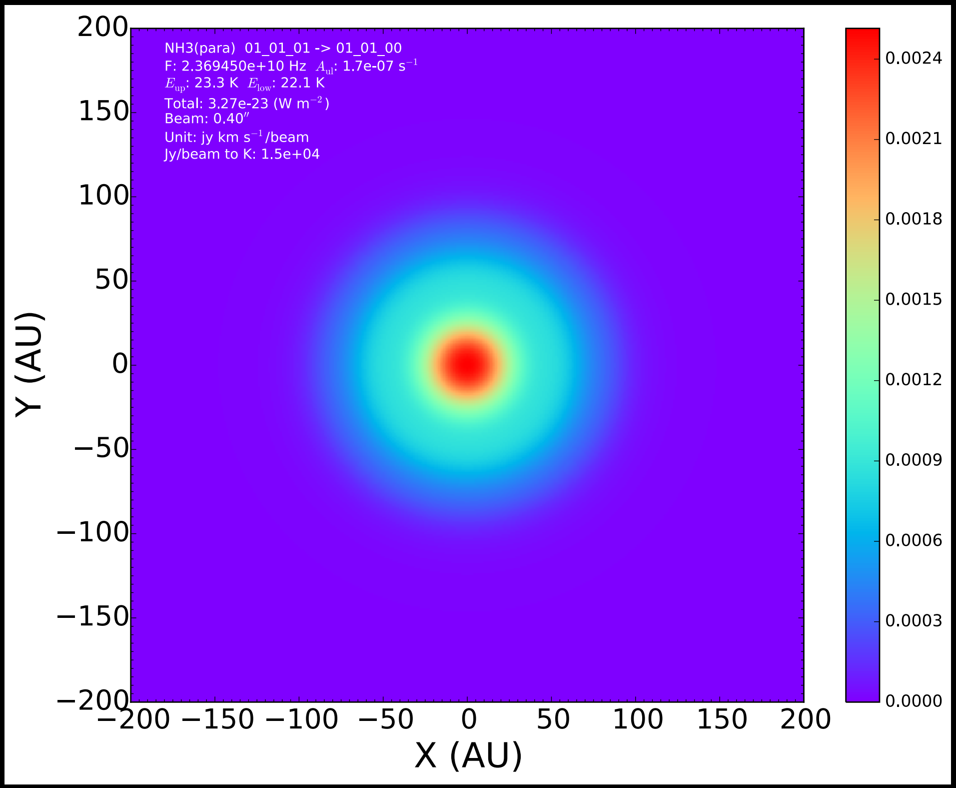
1. Dust mass and surface density concentrated vertically and radially
2. Ices must follow
3. What about larger grains - expanded VLA!

We are tracking the implantation of ices that seed terrestrial worlds!

What about Nitrogen?



Salinas et al. 2015, in prep.



- Trace N_2 via N_2H^+ - cannot measure inside CO snow-line!
- Cannot get NH_3 - we will NOT know what is going on with N
- emission is very weak — need expanded VLA

Summary

- Far-IR/Space:
  - ➡ Survey of HD emission in disks using a sensitive Far-IR telescope is central to science case for a future instrument
  - ➡ Could survey hundreds of systems and obtain real statistics.
- Expanded VLA:
  - ➡ ONLY way to set any constraints on nitrogen - the 5th most abundant element, a key biogenic element, major constituent of our atmosphere
  - ➡ needed to probe dust evolution
- ALMA 2.0
  - ➡ Could resolve water snowline - most important chemical/physical transition in the disk