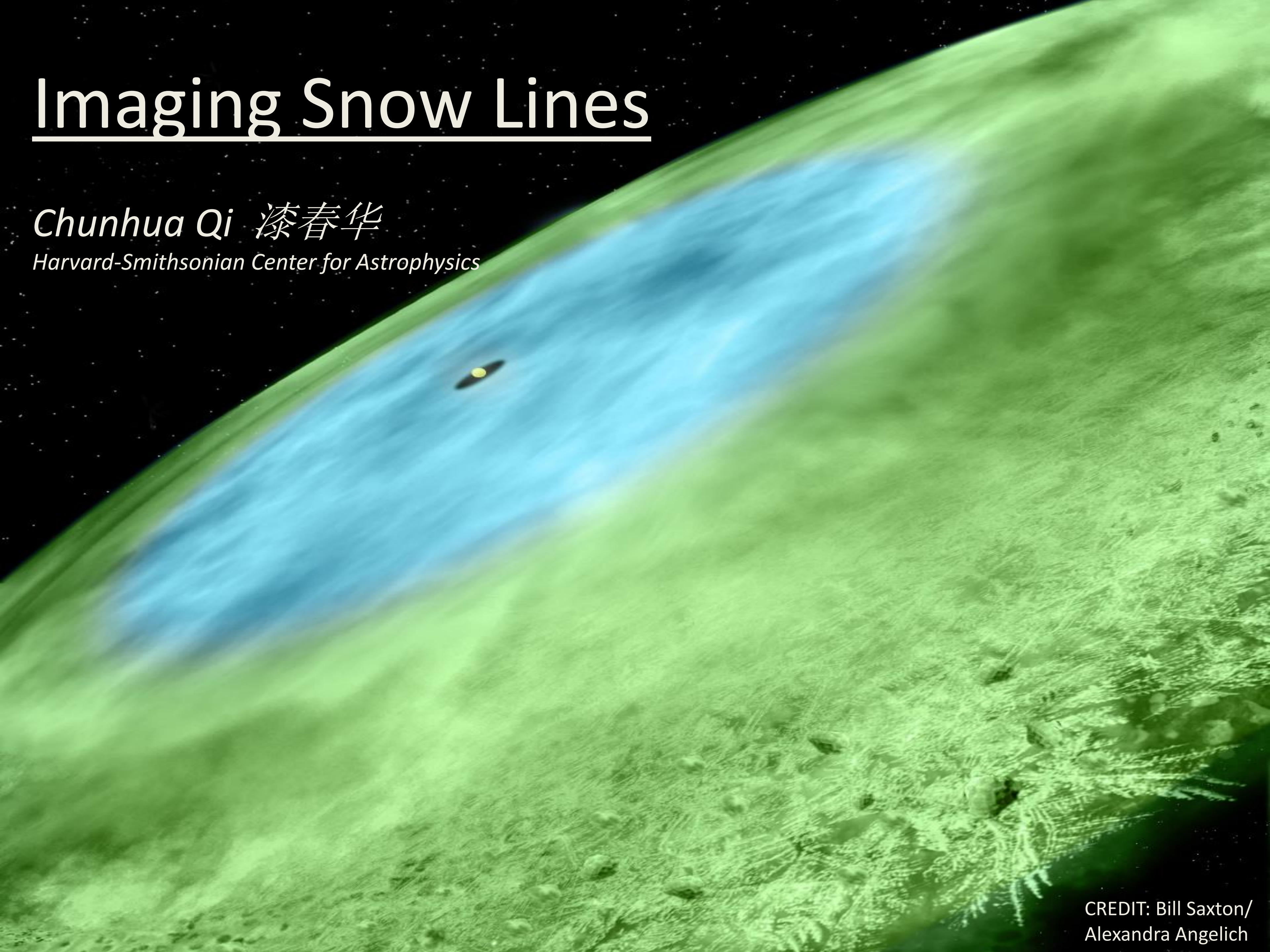
Imaging Snow Lines

Chunhua Qi 漆春华
Harvard-Smithsonian Center for Astrophysics



CREDIT: Bill Saxton/ Alexandra Angelich

SUBMILLIMETER ARRAY (SMA)

8 X 6m dishes

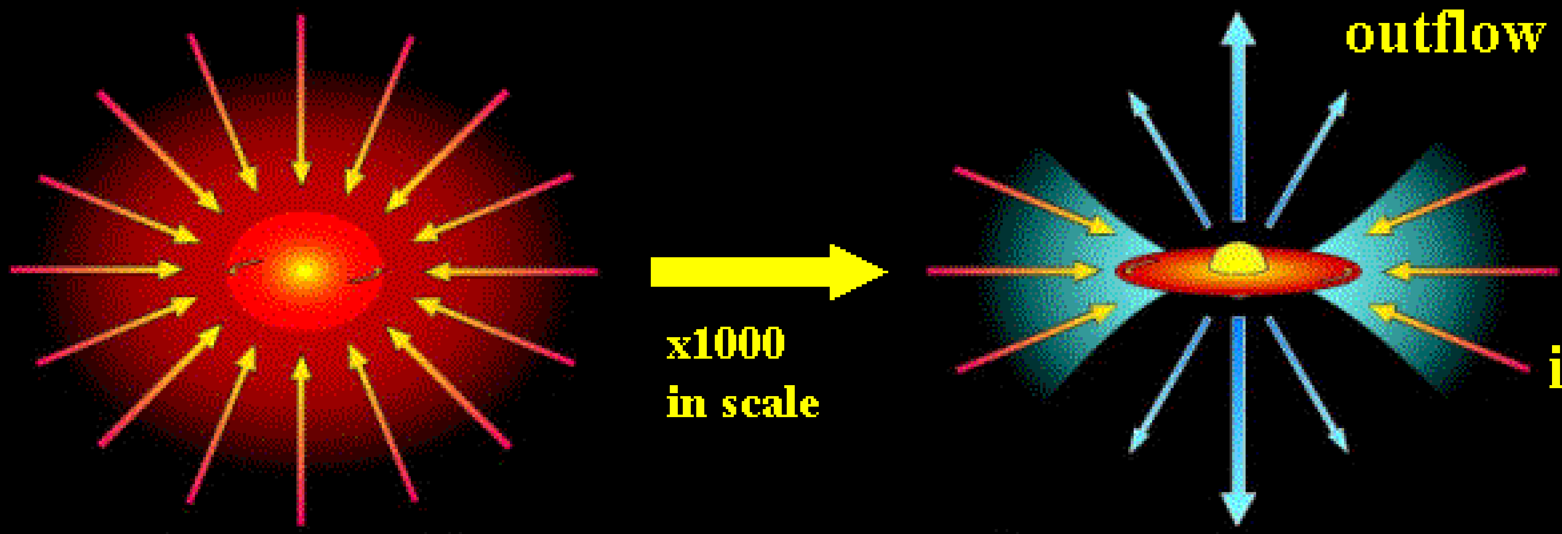
Mauna Kea, Hawaii

ATACAMA LARGE MILLIMETER/SUBMILLIMETER ARRAY (ALMA)

>50 X 12m dishes

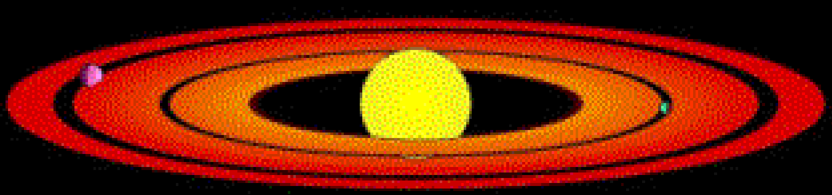
Chajnantor plateau, Atacama Desert, Chile

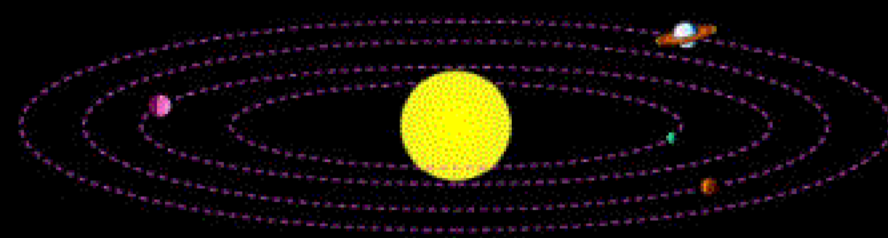
Star (and planet) formation stages



10^4 yrs; $10\text{-}10^4$ AU; 10-300 K

10^{5-6} yrs; 1-1000 AU; 100-3000 K



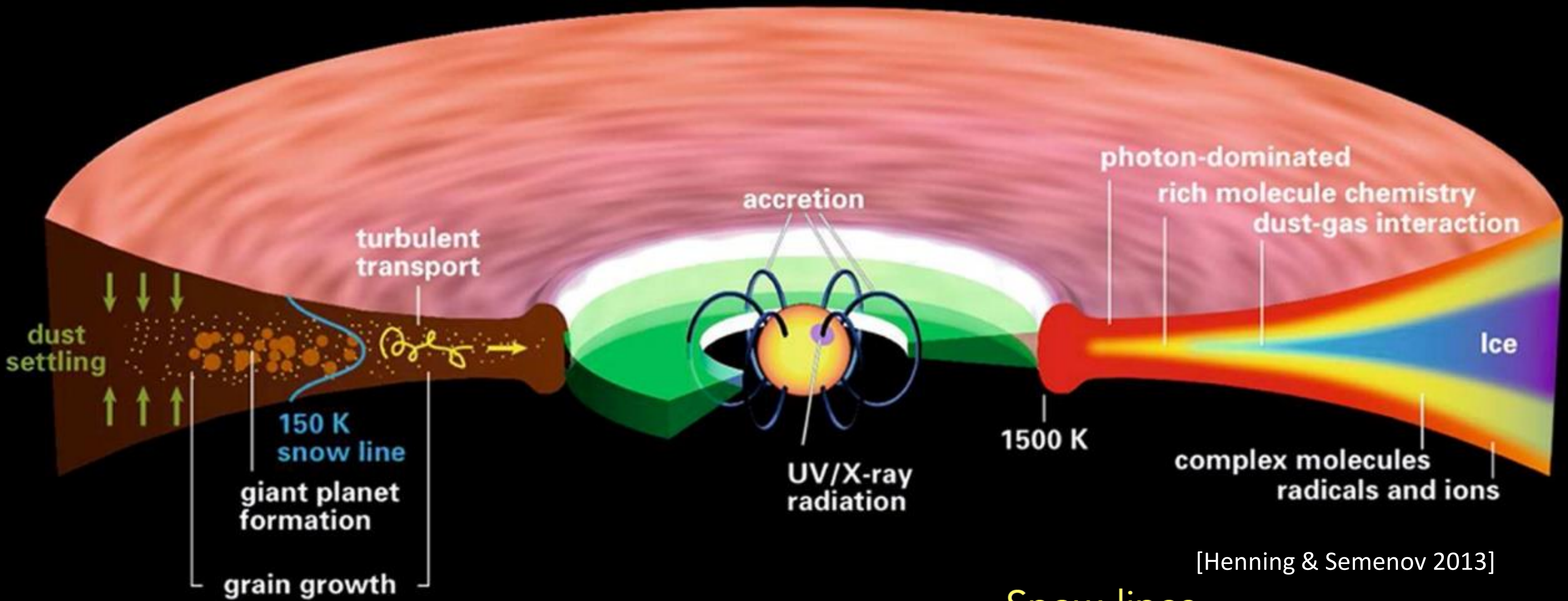


10^{6-7} yrs; 1-100 AU; 100-3000 K

10^{7-9} yrs; 1-100 AU; 200-3000 K

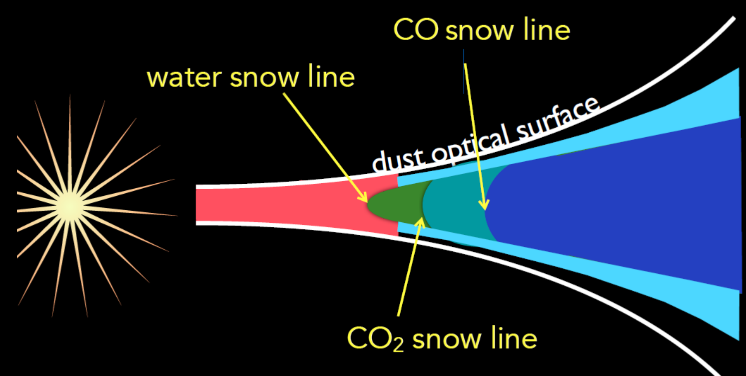
Fig. by McCaughrean

Protoplanetary disk structure



[Henning & Semenov 2013]

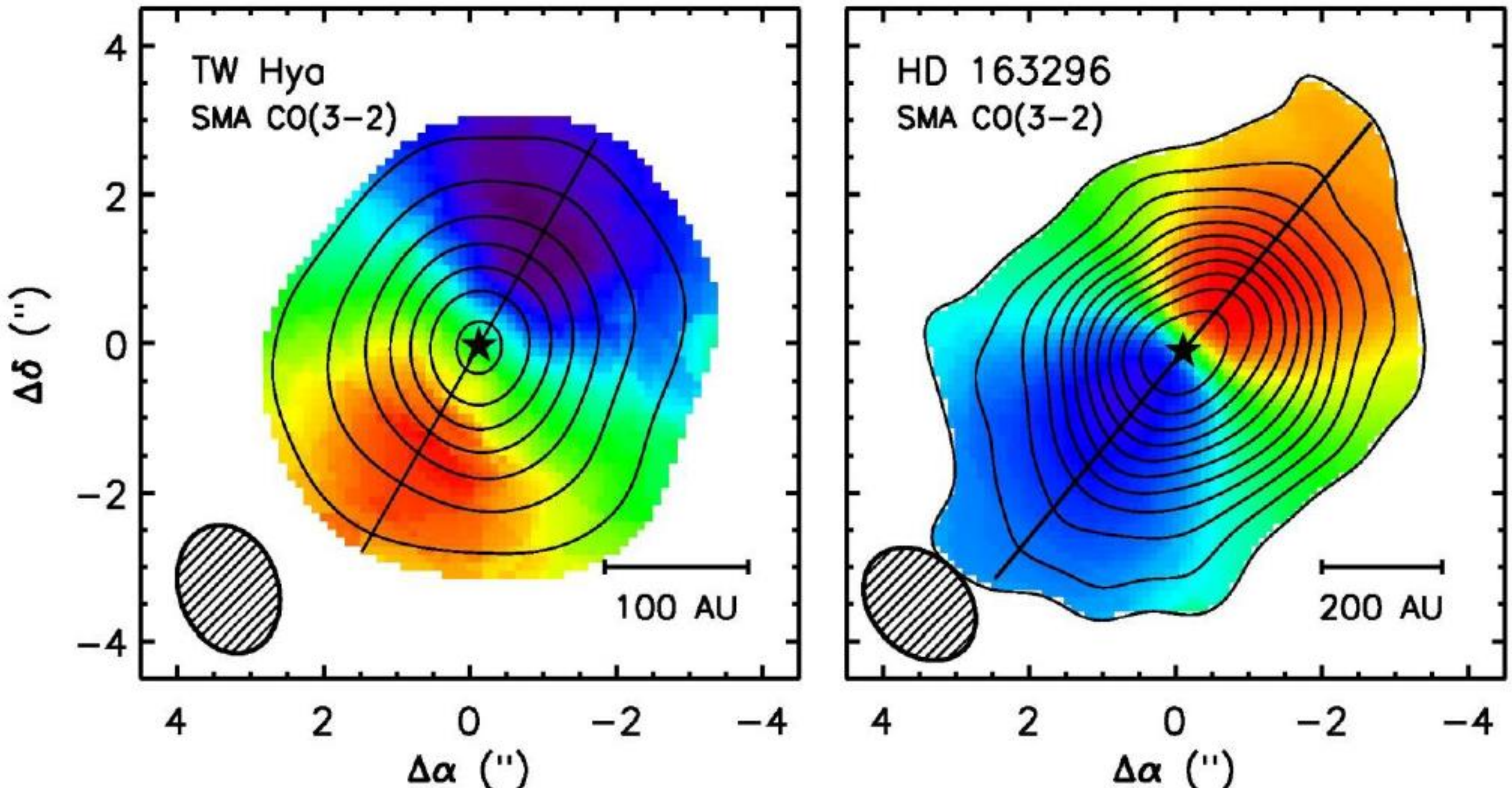
Snow-lines



[Öberg, Murray-Clay & Bergin 2011]

- CO freeze-out/desorption probe ?
- CO snow line location ?

CO disks are “huge”



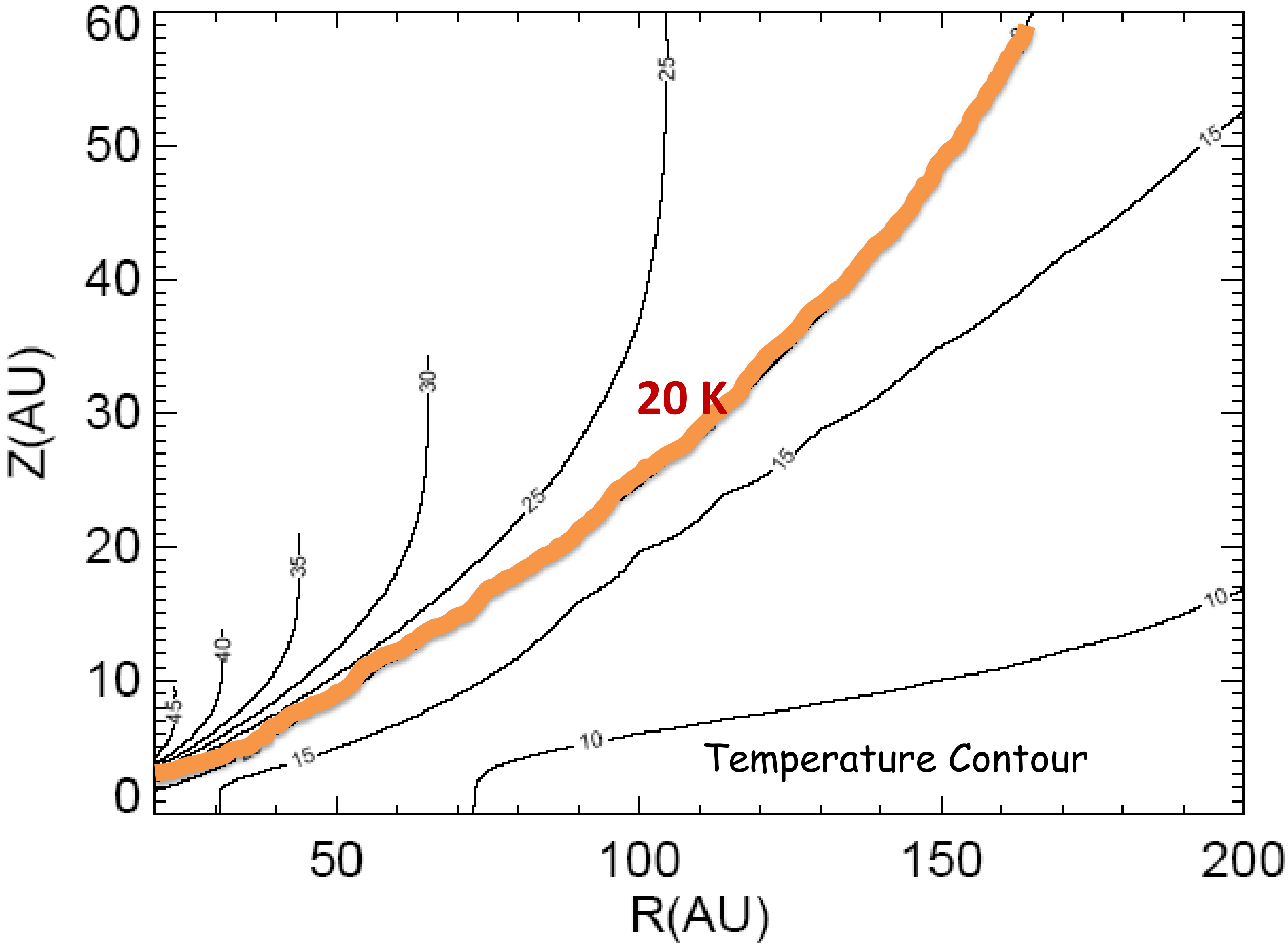
TW Hya

- Classical T Tauri star
- 8-12 Myr old
- Inclination 7^o

HD 163296

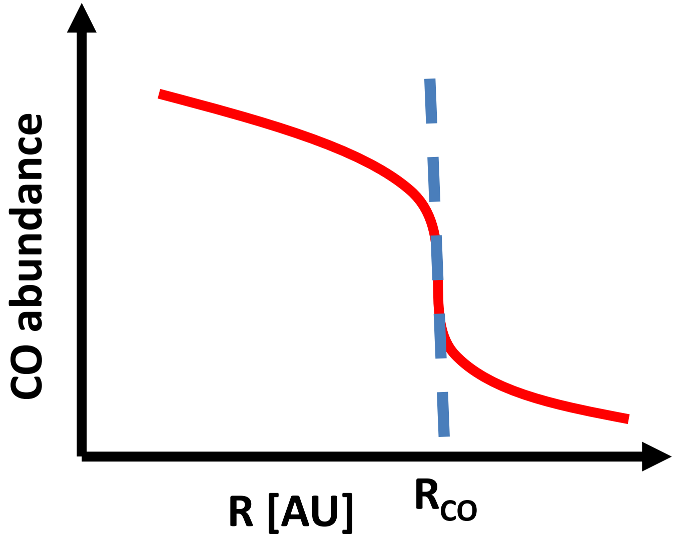
- Herbig Ae star
- 3-5 Myr old
- Inclination 44^o

Disk temperature decreases radially away from the star and vertically toward disk midplane

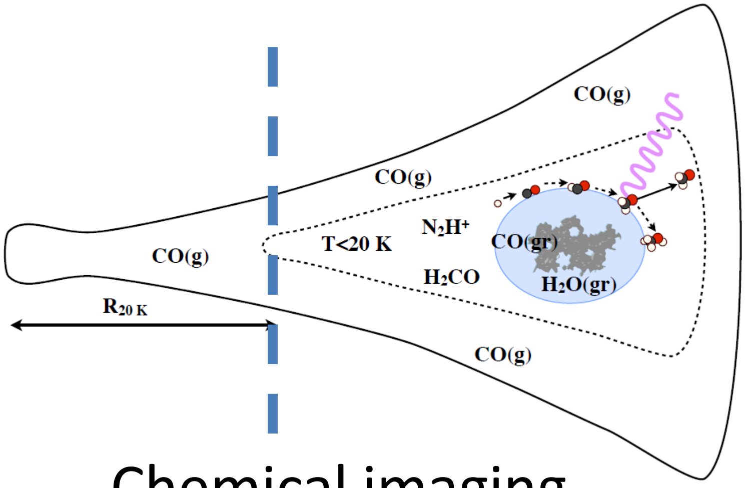


1. CO snow line location

How to locate the CO snow line …

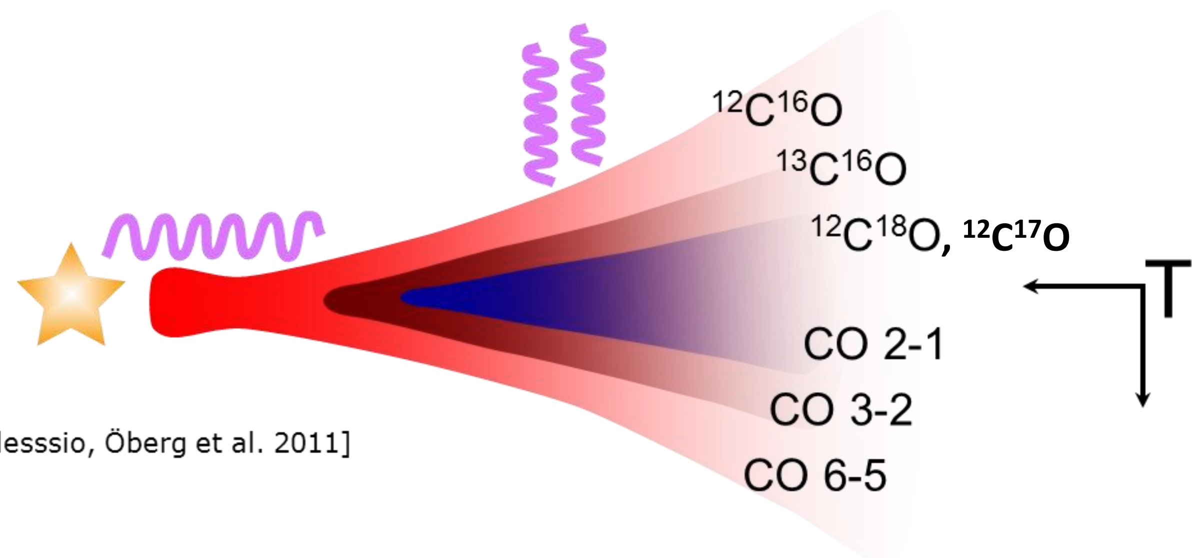


CO abundance drop



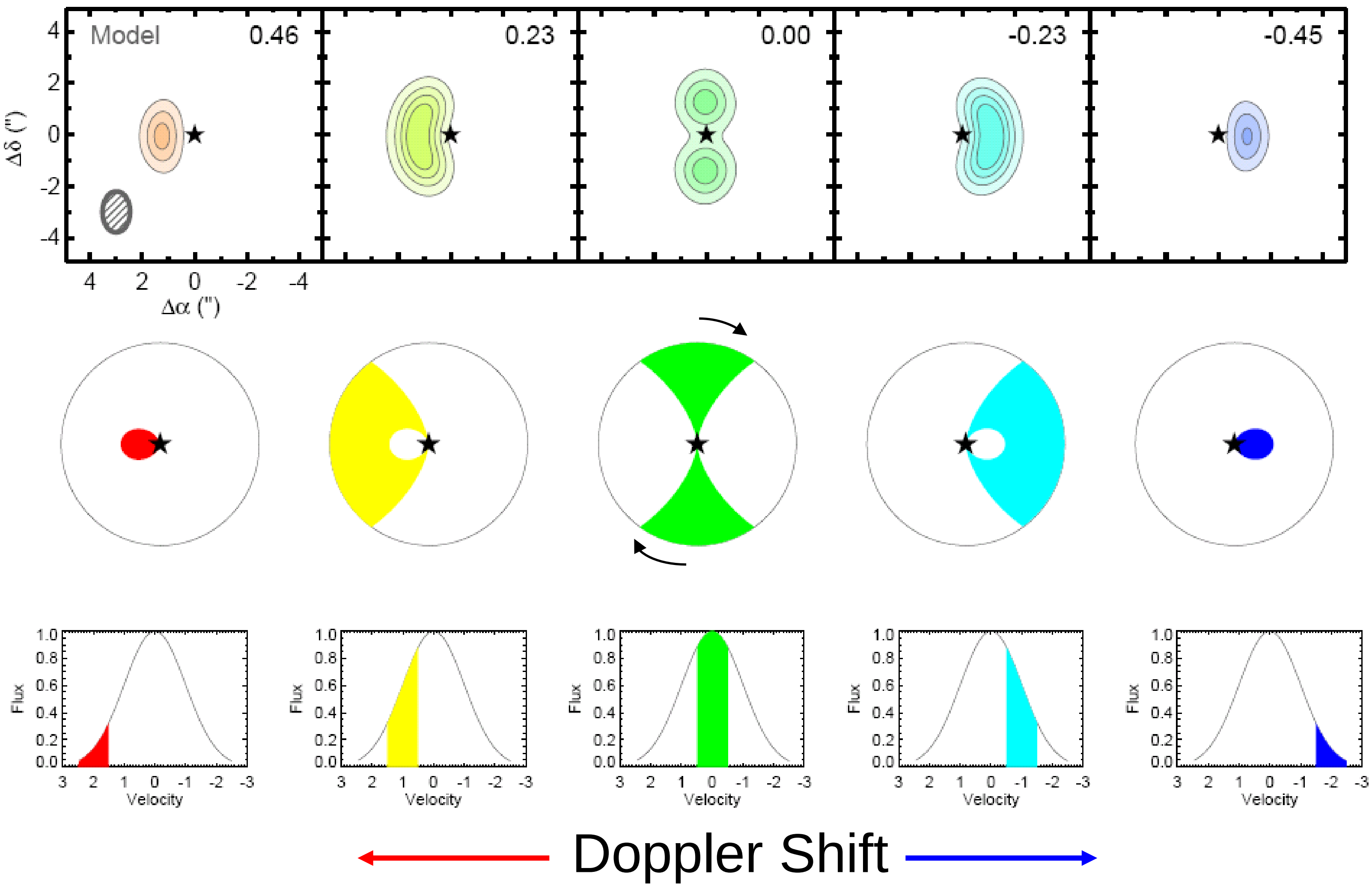
Chemical imaging

Optically thick CO lines on the surface
hide the CO freezeout information at midplane



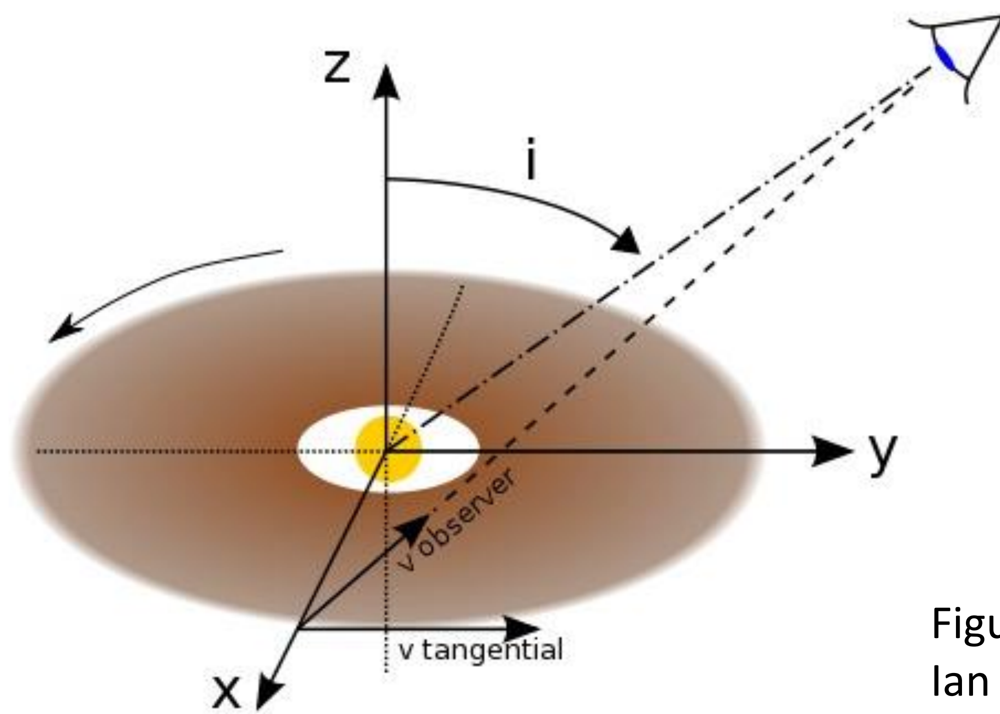
[Qi, d’Alesssio, Öberg et al. 2011]

Channel maps of molecular emission in a Keplerian Disk

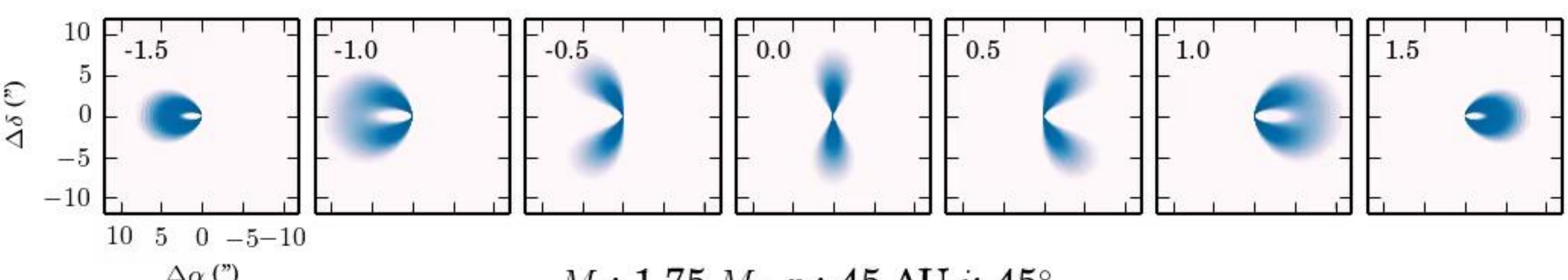


Adapted from Beckwith & Sargent 1993

Resolving protoplanetary disks spatially and spectrally

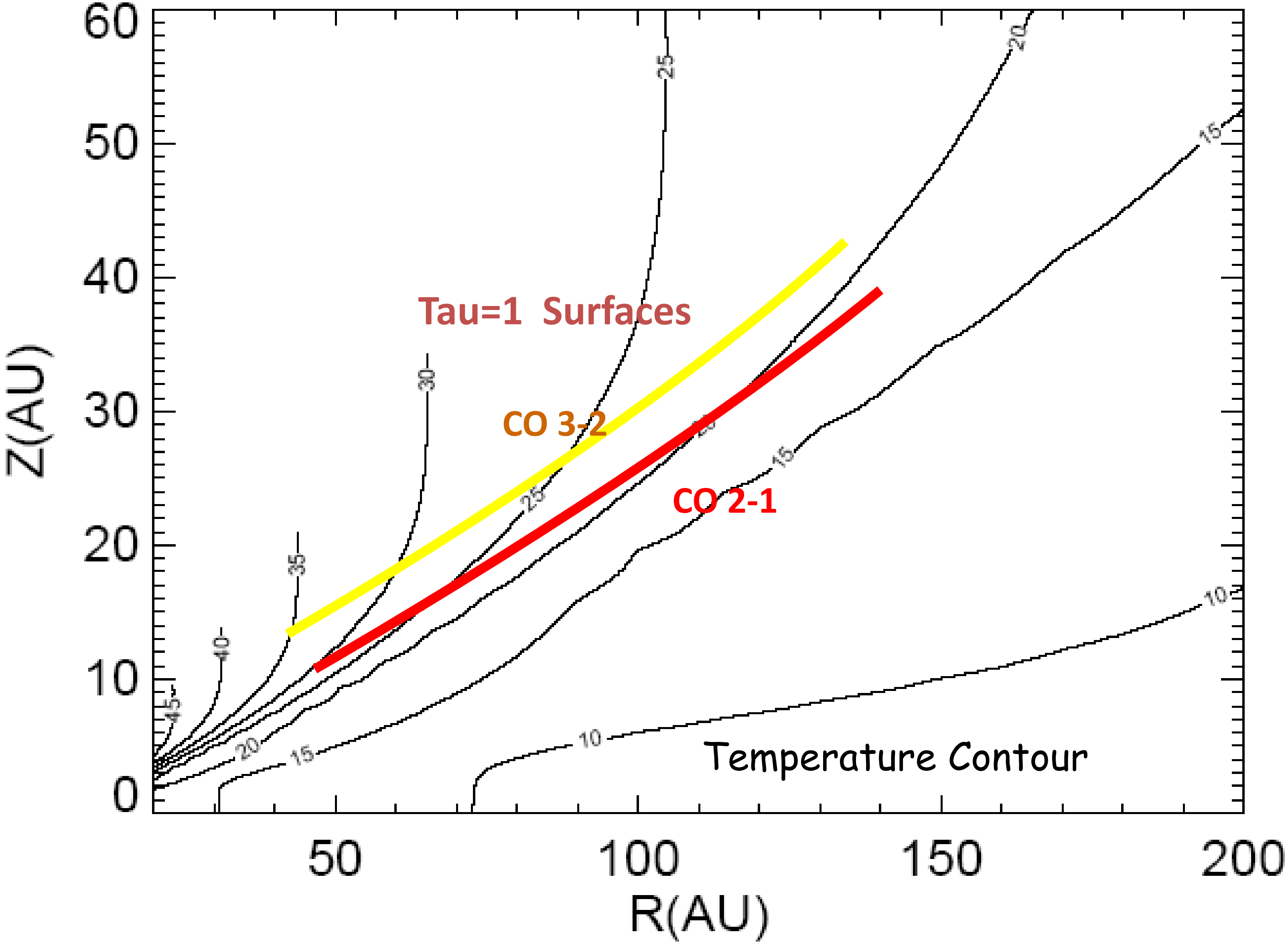


Figure+Movie credit:
Ian Czekala

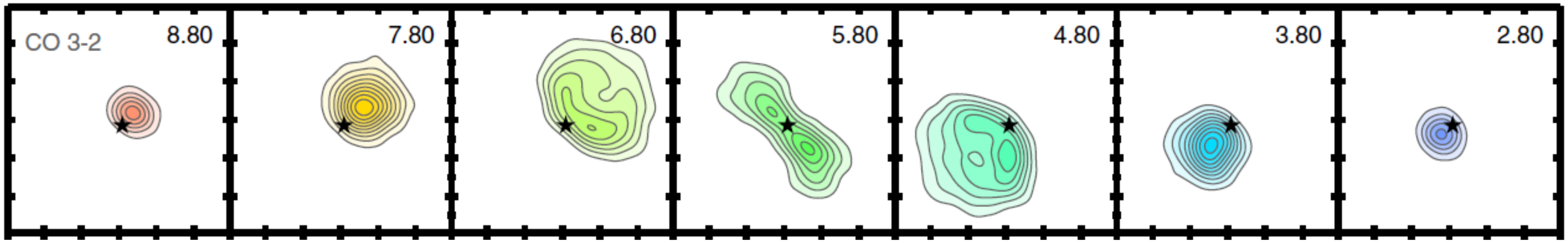


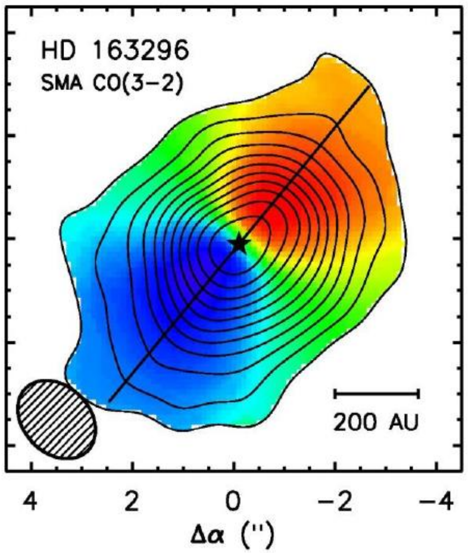
M_*: 1.75 $M_\odot$ r_c: 45 AU i: 45°

Optically thick CO lines and higher Tau=1 surfaces for higher transitions



Resolving the vertical temperature gradient in disks needs sensitive observations and an inclined disk

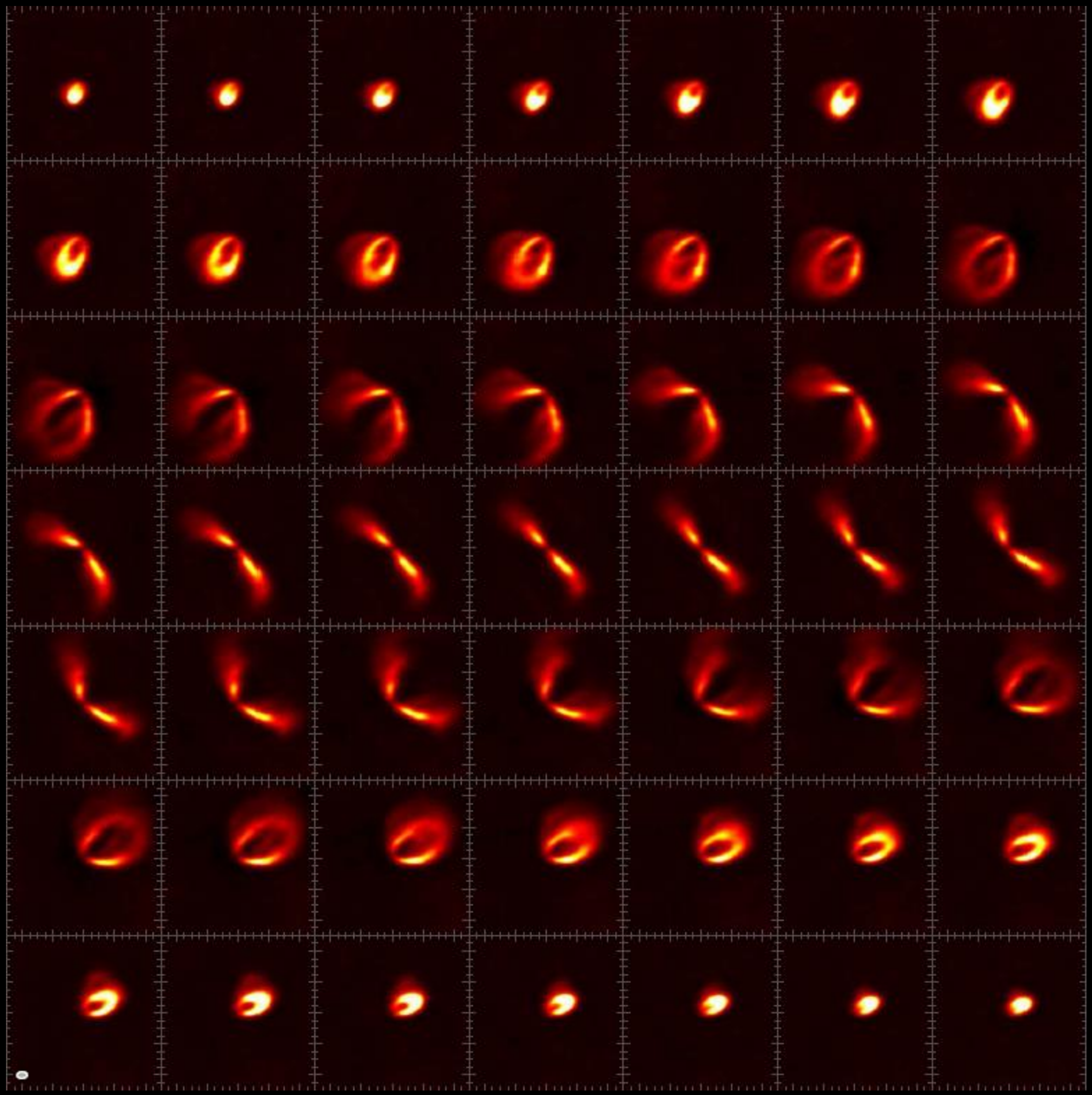




[Qi et al. 2011]

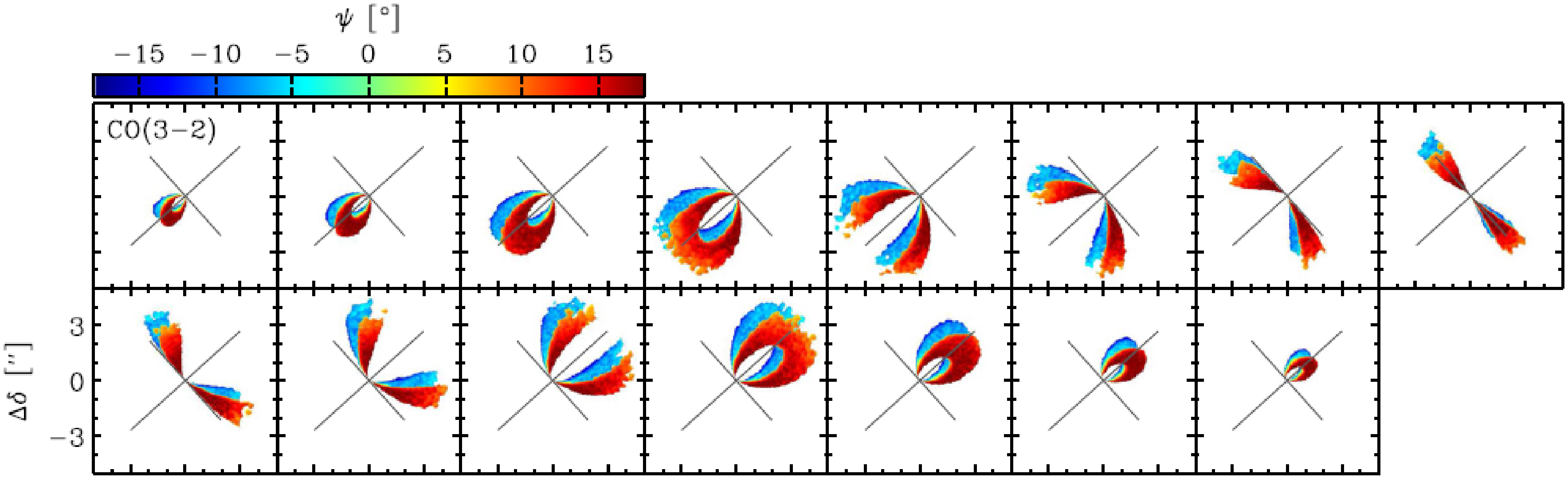
SMA CO 3-2 Observations of HD 163296 (i=44^{o})

Resolving the vertical temperature gradient in disks needs sensitive observations and an inclinded disk



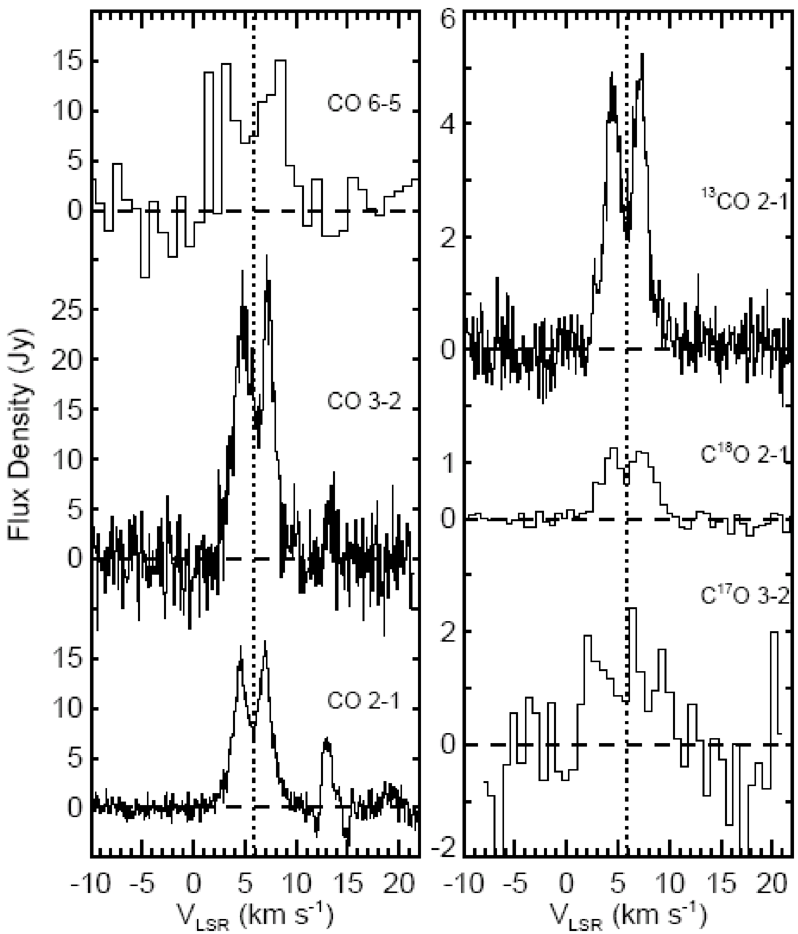
ALMA CO 3-2 Observations of HD 163296 (i=44°) [Rosenfeld et al. 2013]

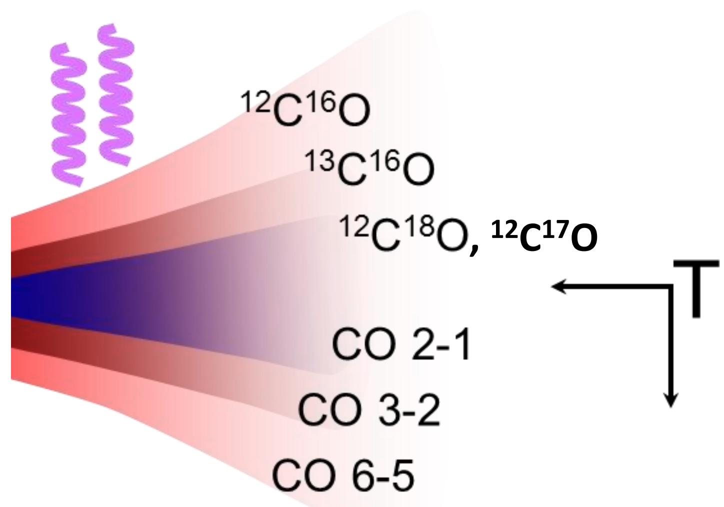
Direct signature of a vertical temperature gradient and layered molecular structure in disk



Resolved τ=1 surfaces of the front and back side of the disk, that was 15 degrees above the midplane. [Rosenfeld et al. 2013]

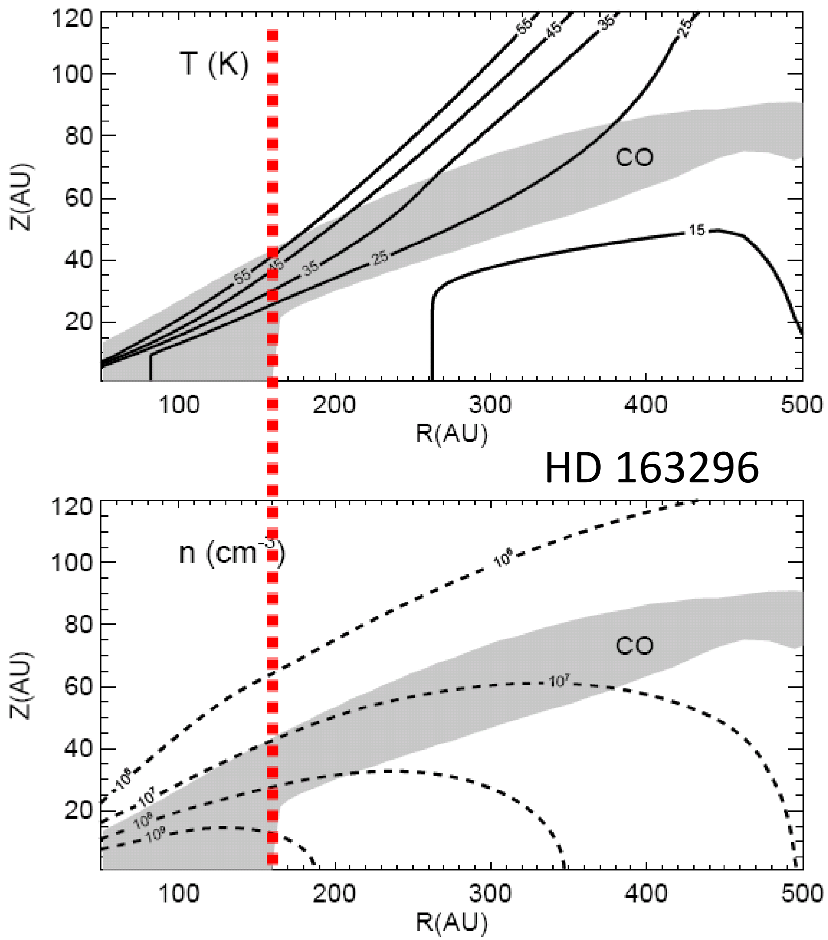
CO (radial and) vertical structure

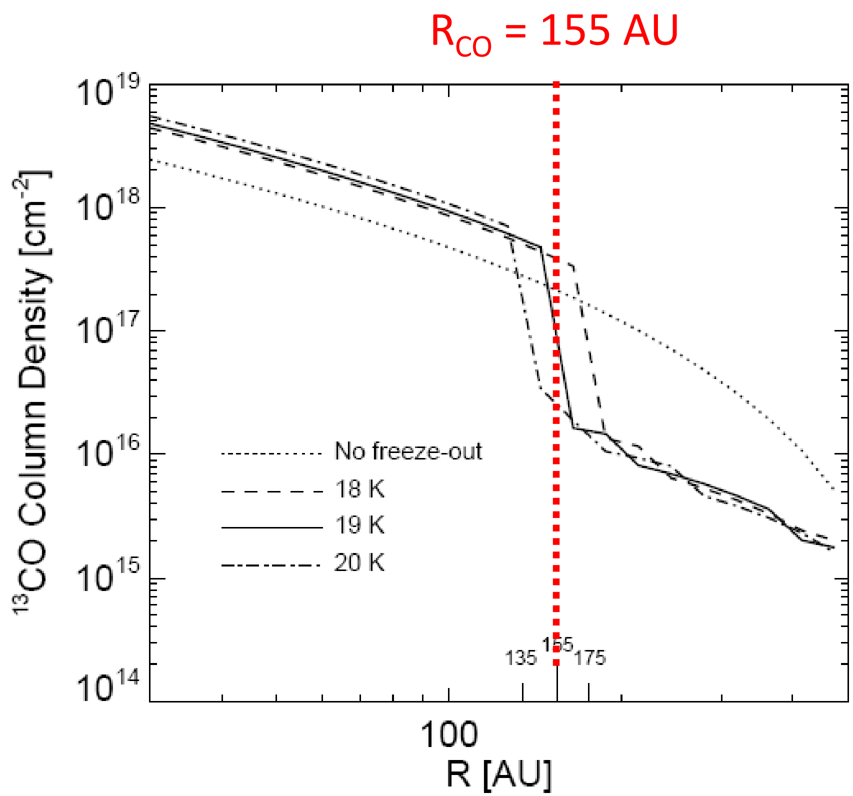




HD 163296 CO studies with SMA [Qi et al. 2011]

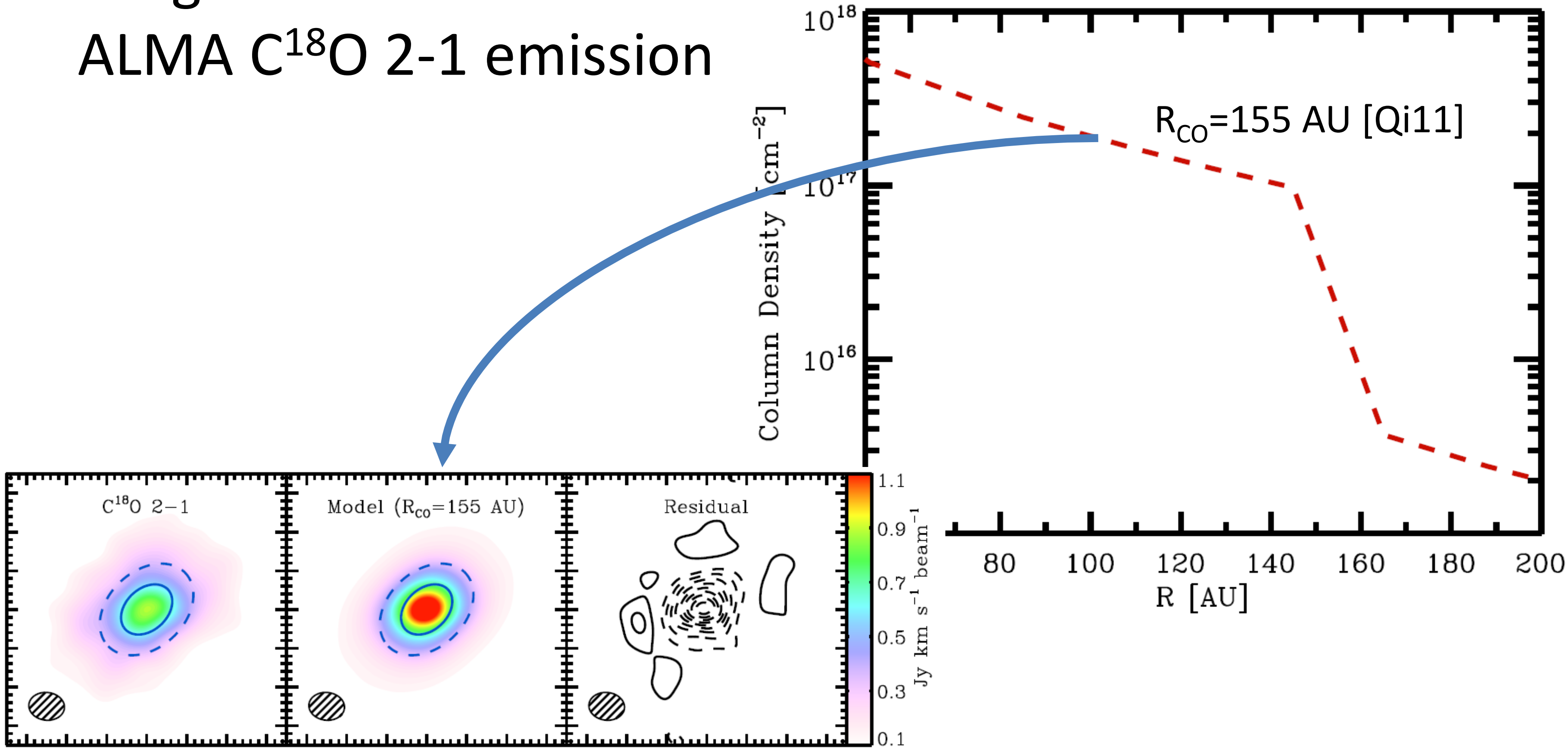
Locating CO snow line based on SMA ^{13}CO 2-1 emission





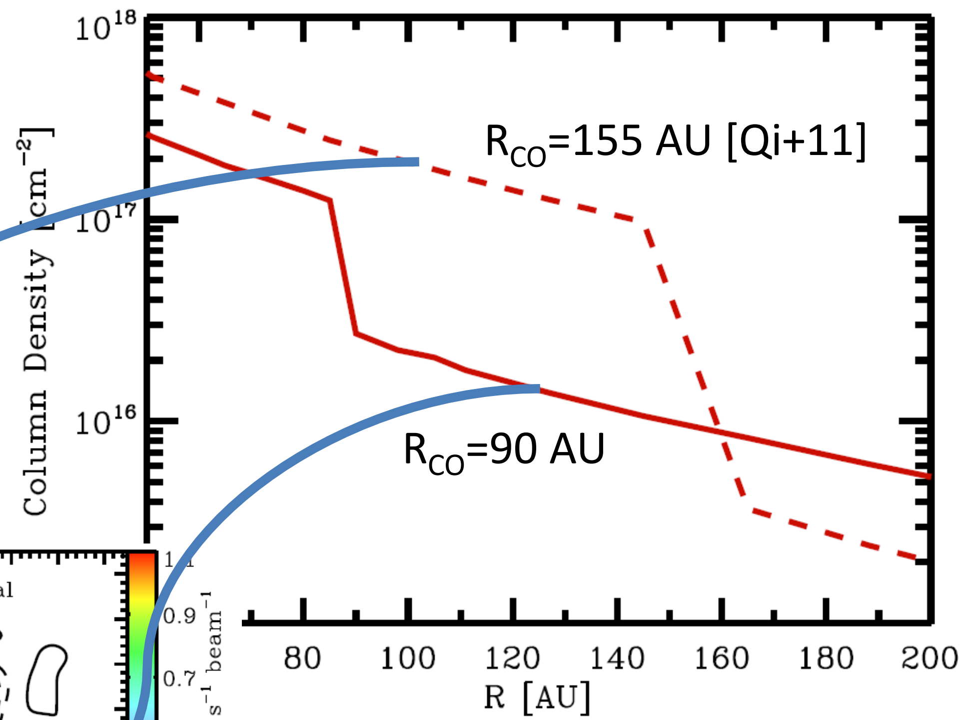
[Qi et al. 2011]

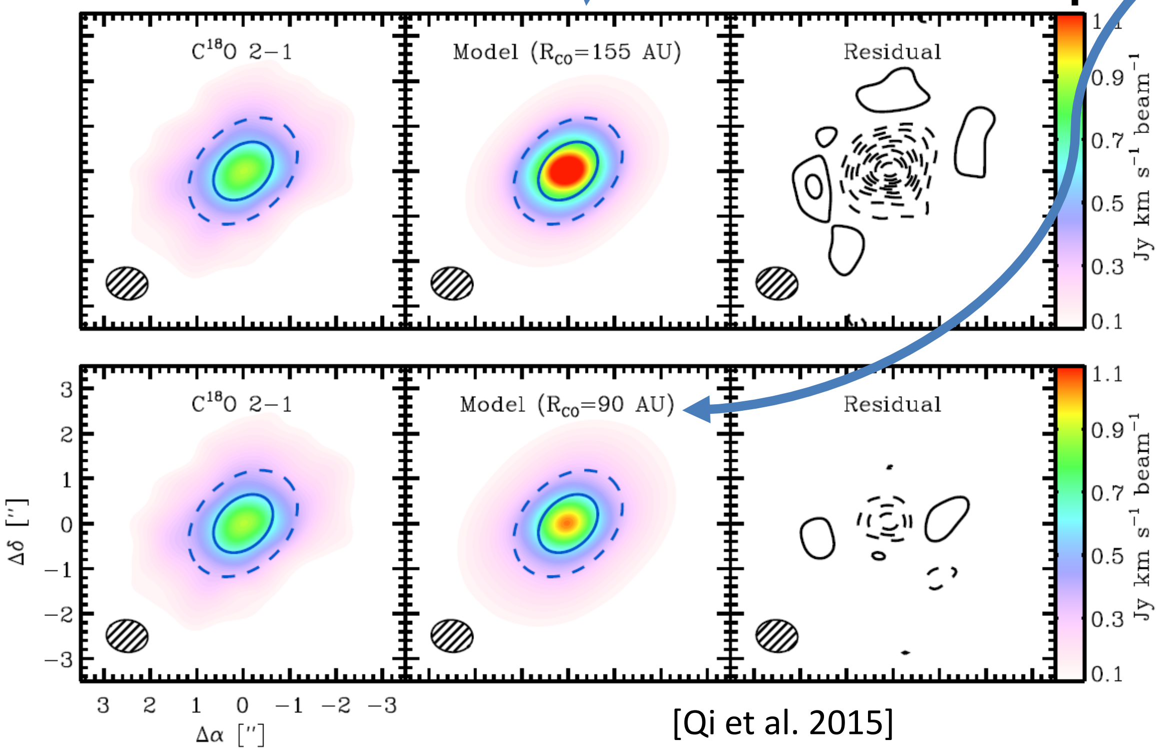
Locating CO snow line based on ALMA $C^{18}O$ 2-1 emission



Locating CO snow line based on ALMA $C^{18}O$ 2-1 emission

✓ CO snow line is at 90 AU in HD 163296 disk



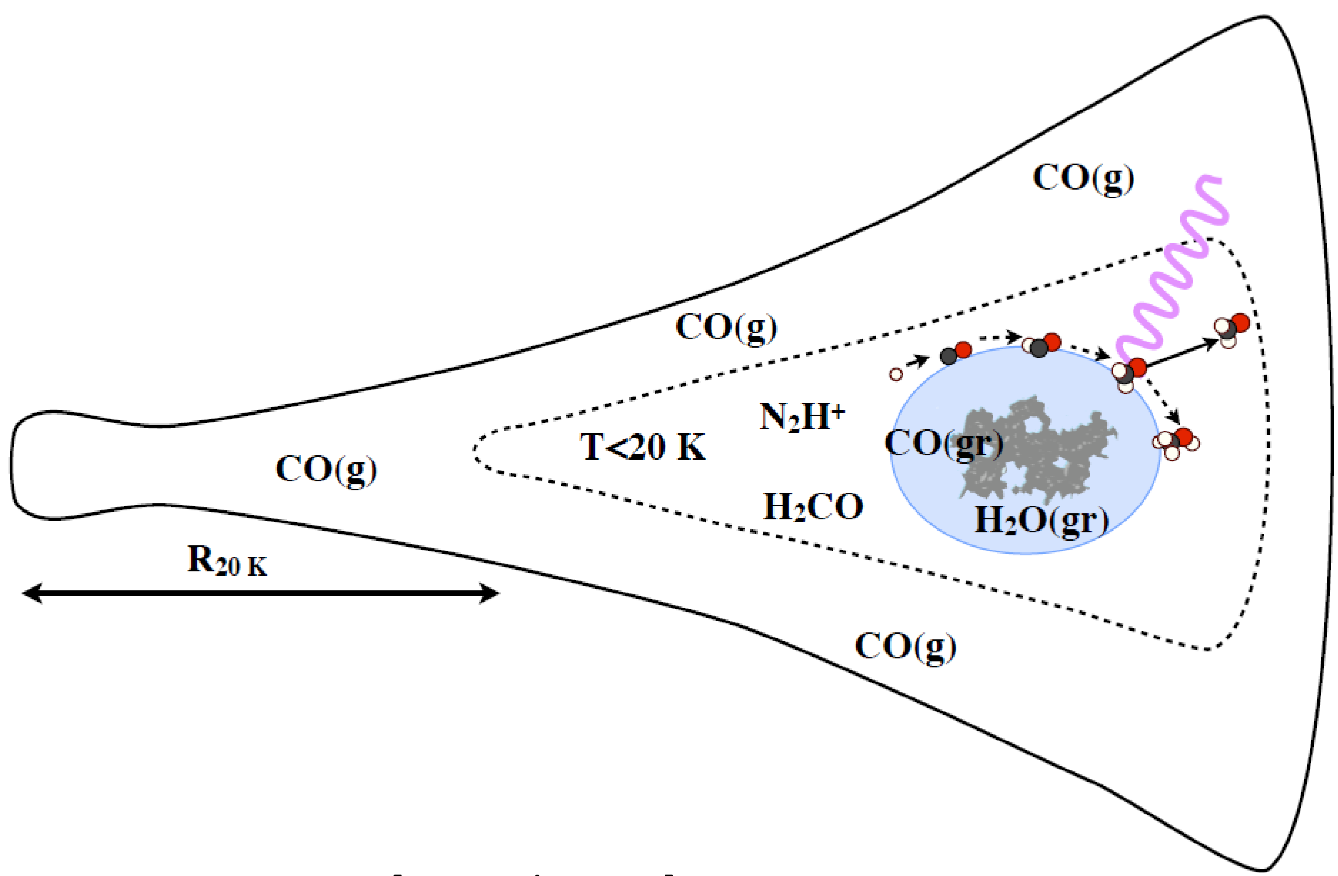


[Qi et al. 2015]

✓ Have to consider the optical depth problem.

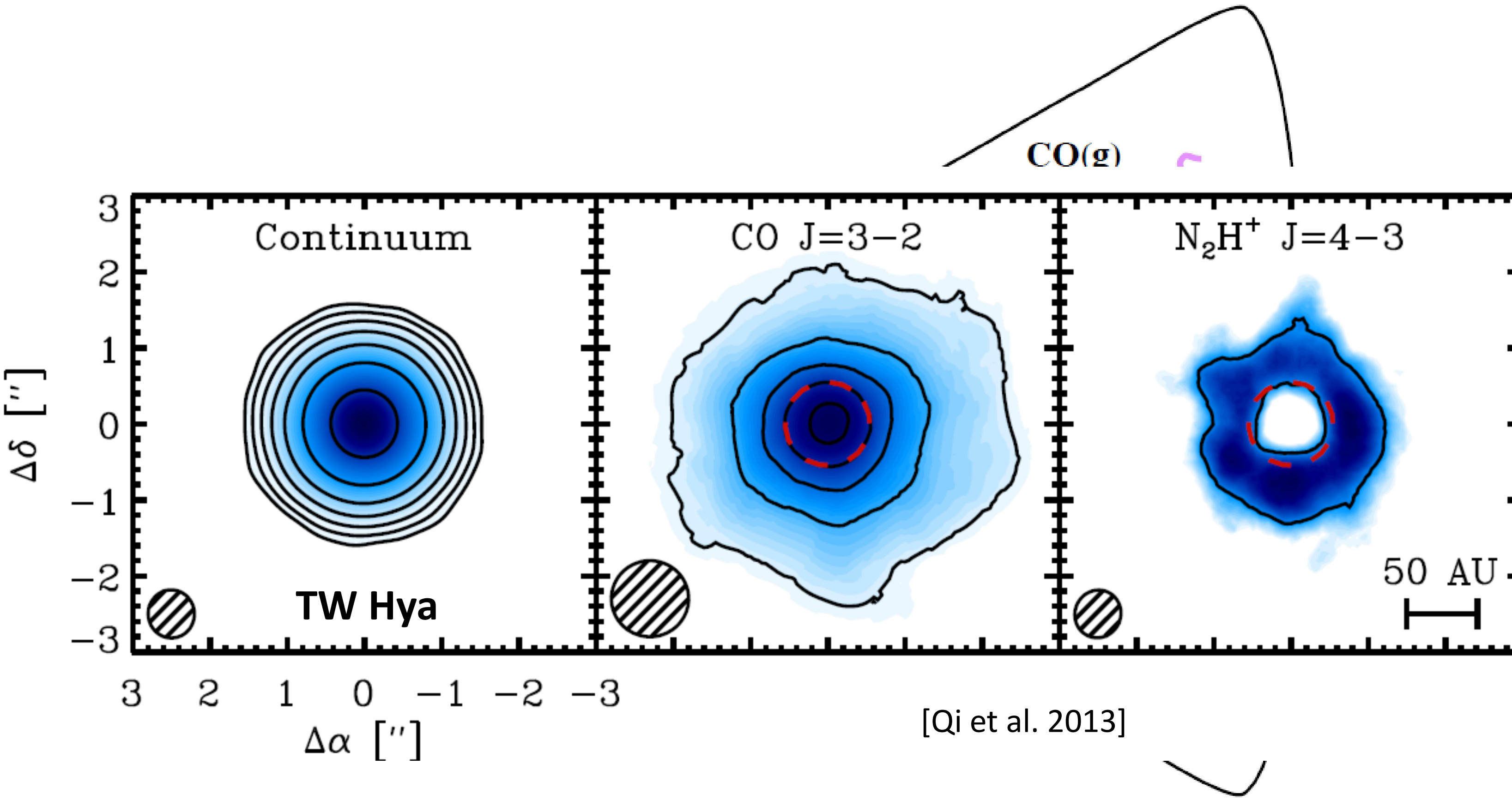
✓ Hard to distinguish from radial profile.

Chemical imaging of CO freeze-out: Ring structures



[Qi et al. 2013]

Chemical imaging of the CO snow line: N_2H^+ ring structure

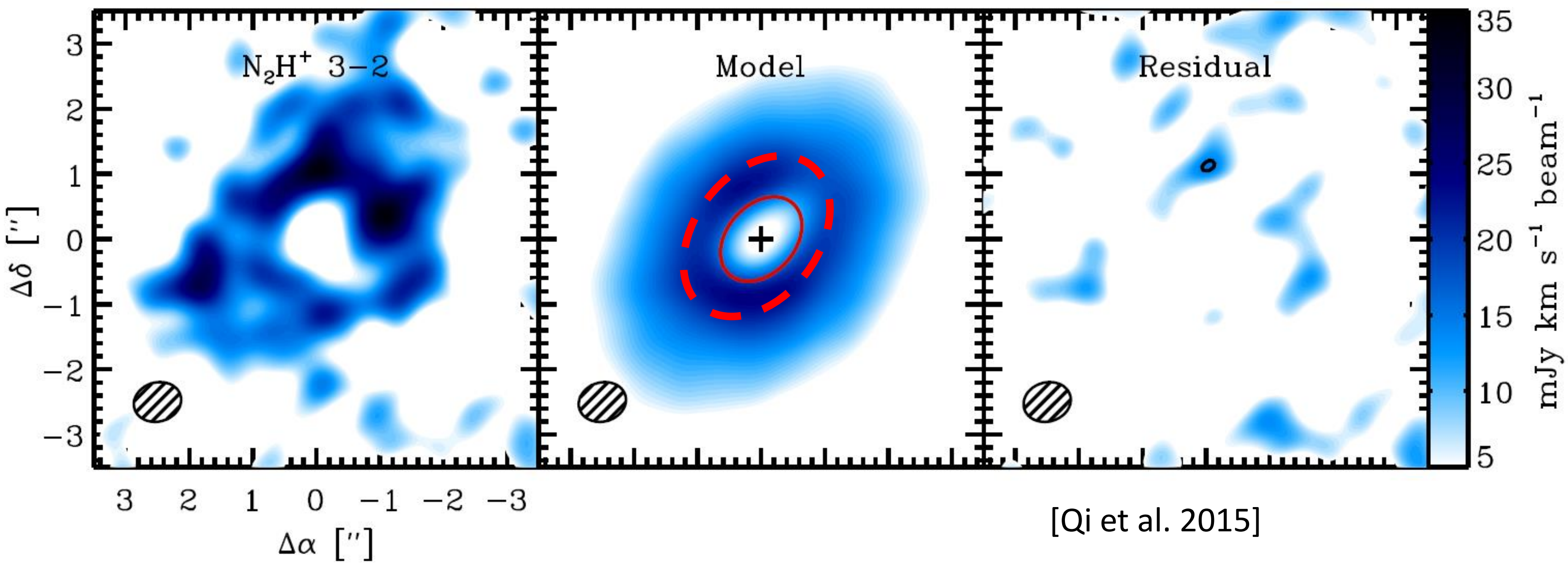


[Qi et al. 2013]

N_2H^+ is destroyed by the gas CO and enhanced by the freeze-out of gas CO

$$\mathbf{N_2H^+ + CO \rightarrow HCO^+ + N_2}$$

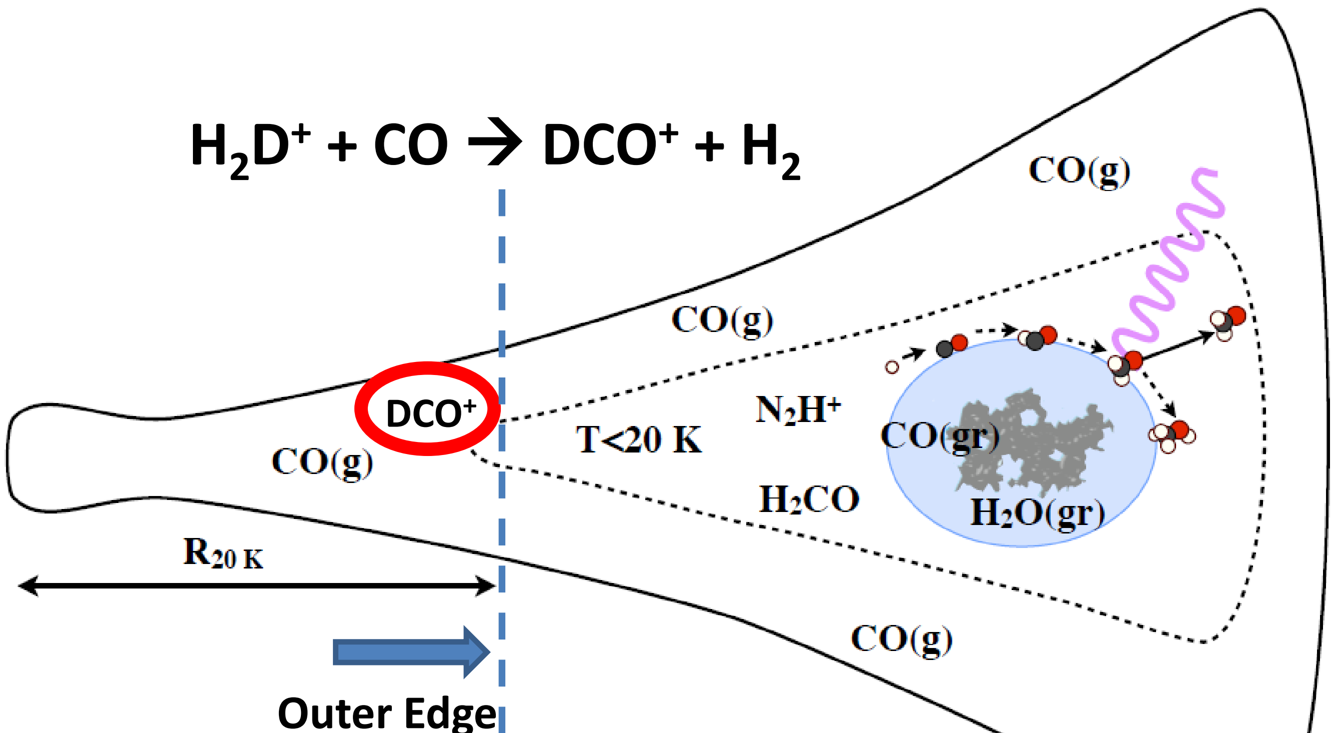
The inner edge of N_2H^+ ring in HD 163296 disk is around 90 AU, consistent with $C^{18}O$ analysis



[Qi et al. 2015]

HD 163296

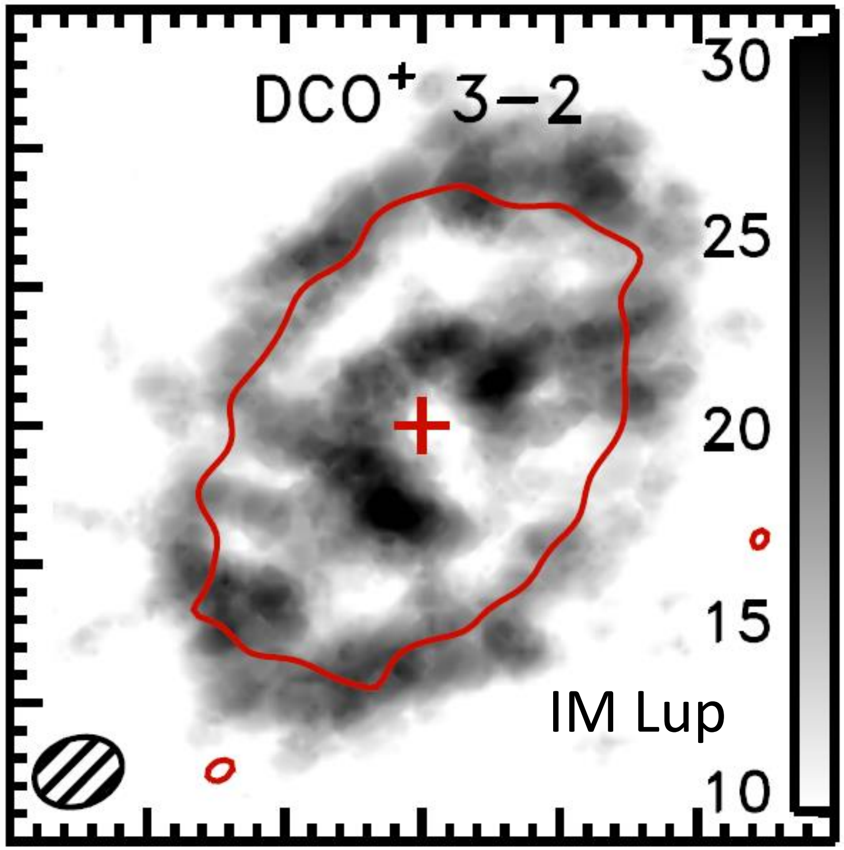
Chemical imaging – DCO^+ ring structure



DCO^+ abundance is balanced by CO freeze-out and temperature-dependent D enhancement

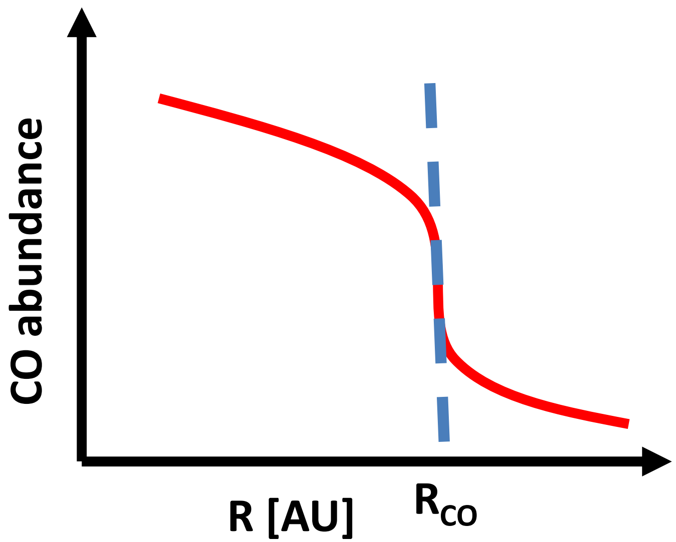
[Mathews et al. 2013]

Probing CO photodesorption



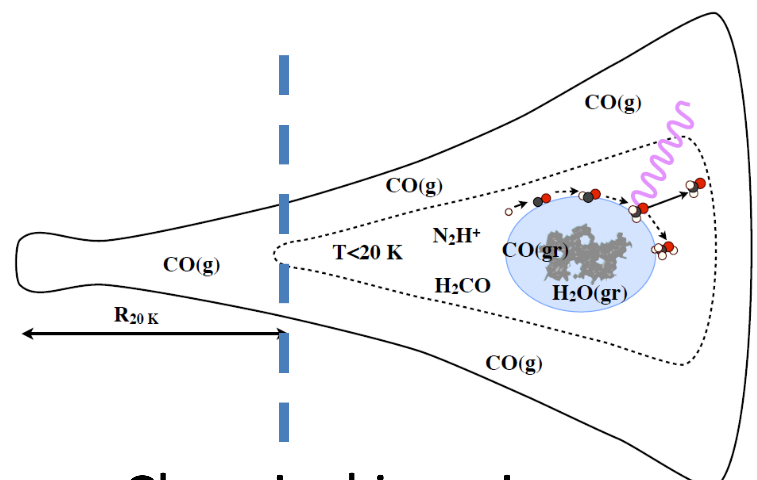
[Öberg et al. 2015]

How to locate the CO snow line …



CO abundance drop

Pro: direct
Con: model dependent;
optical depth, sensitivity issue



Chemical imaging

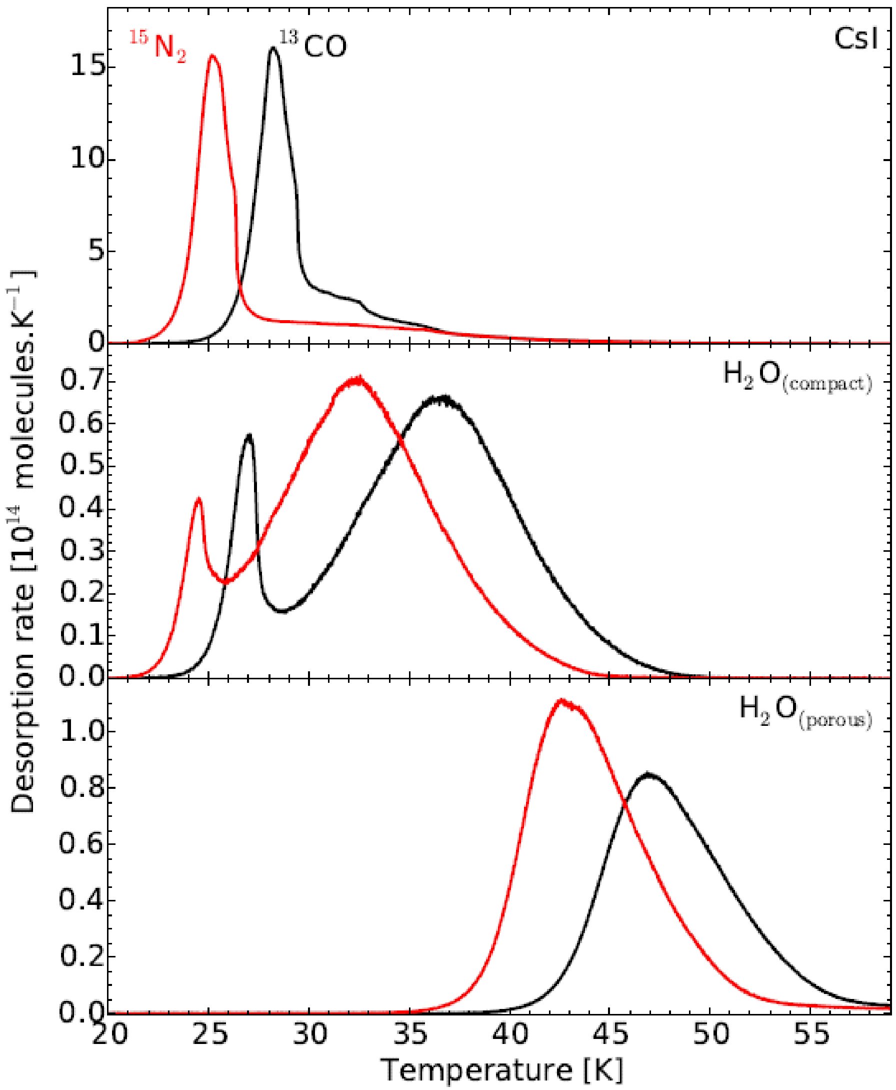
Pro: model “independent”
Con: robust tracer needed;
sensitivity issue

Summary

- N_2H^+ is sensitive to the CO freeze-out but whether it can serve as a robust probe of the CO snow line is still under debate.
- DCO^+ can be used as a probe of the CO desorption, although more works are needed to disentangle the nature of desorption.
- Optically thin CO isotopologue emission can be used locate the CO snow line directly but very tricky due to optical depth and sensitivity issue.

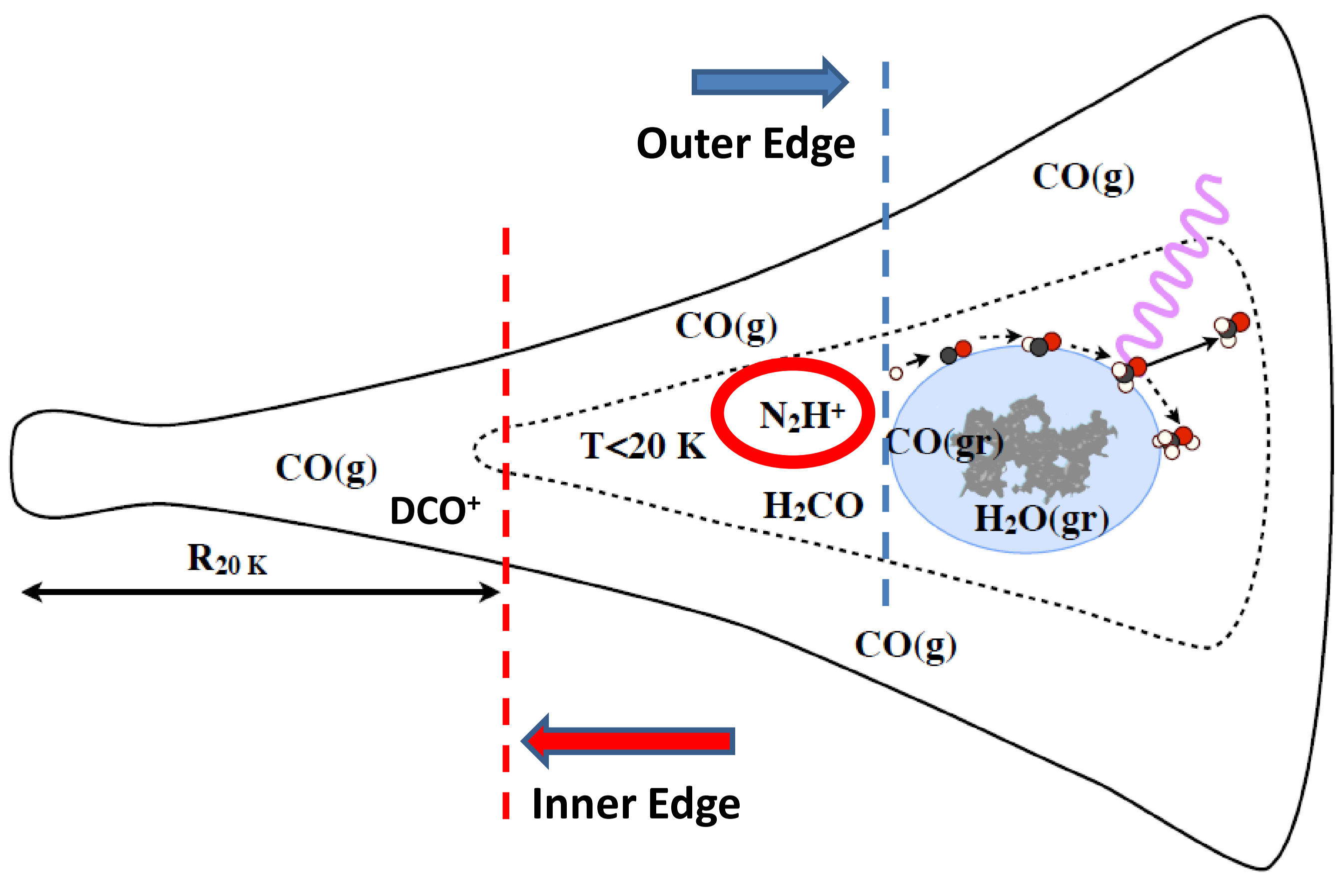
2. N_2 snow line

N_2 and CO freezeout temperature only differ by about 3-4 K



[Fayolle et al. 2015]

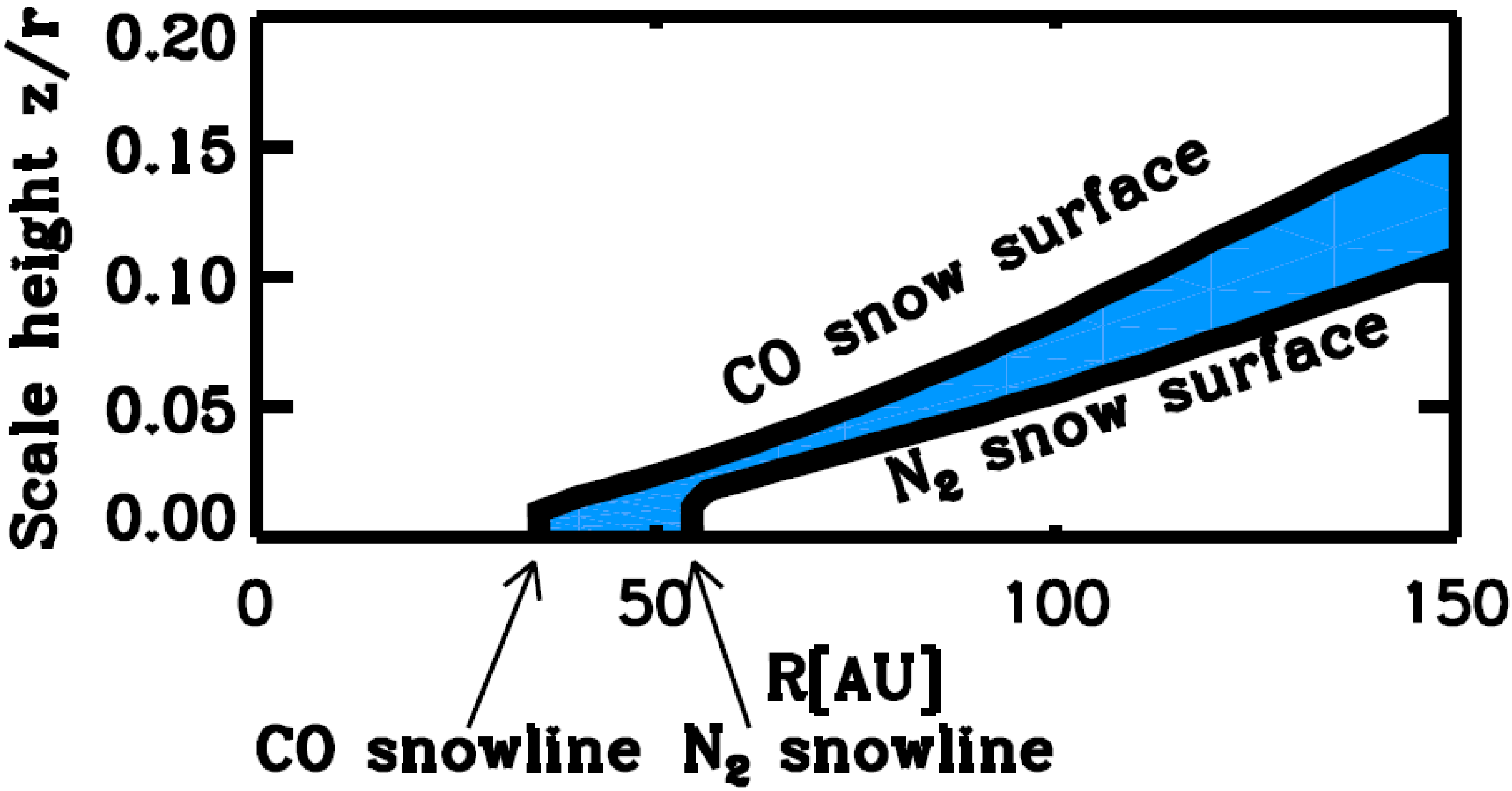
Chemical imaging of the CO snow line: N_2H^+ ring structure



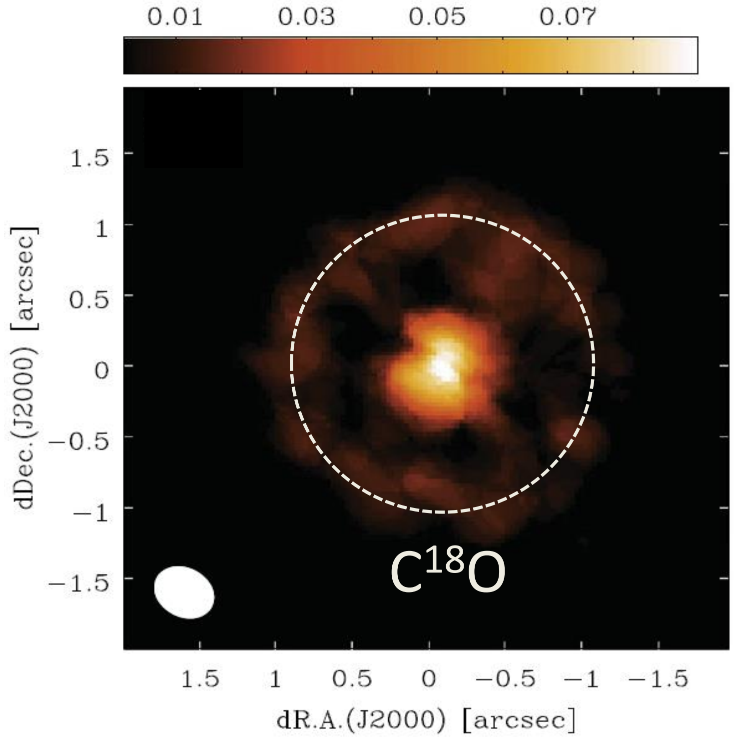
N_2H^+ is destroyed by the gas CO and formed through proton transfer from H_3^+ to N_2

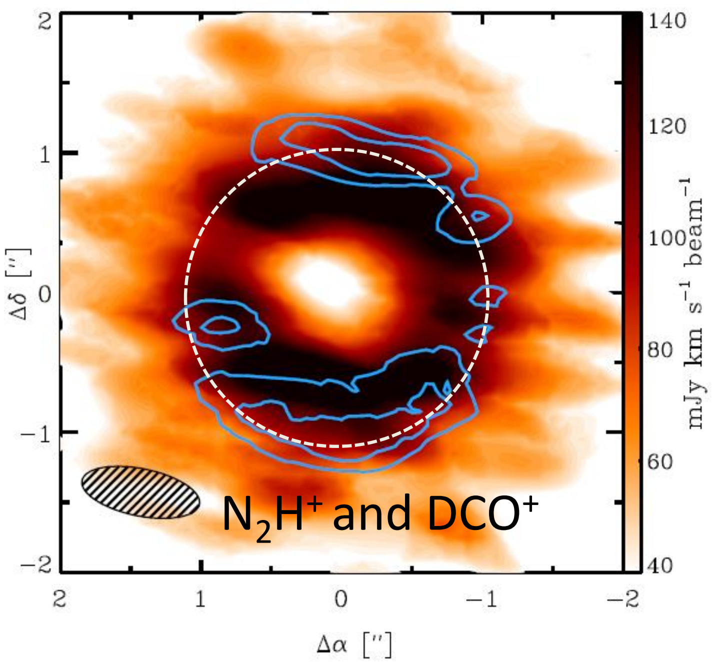
$$\mathbf{N_2 + H_3^+ \rightarrow N_2H^+ + H_2}$$

N_2 Snow line ?


Scale height z/r
0.20
0.15
0.10
0.05
0.00
CO snow surface
N2 snow surface
0
50
100
150
R[AU]
CO snowline
N2 snowline

CO desorption vs N_2 freezeout

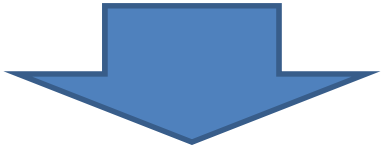




[Qi et al. in prep]

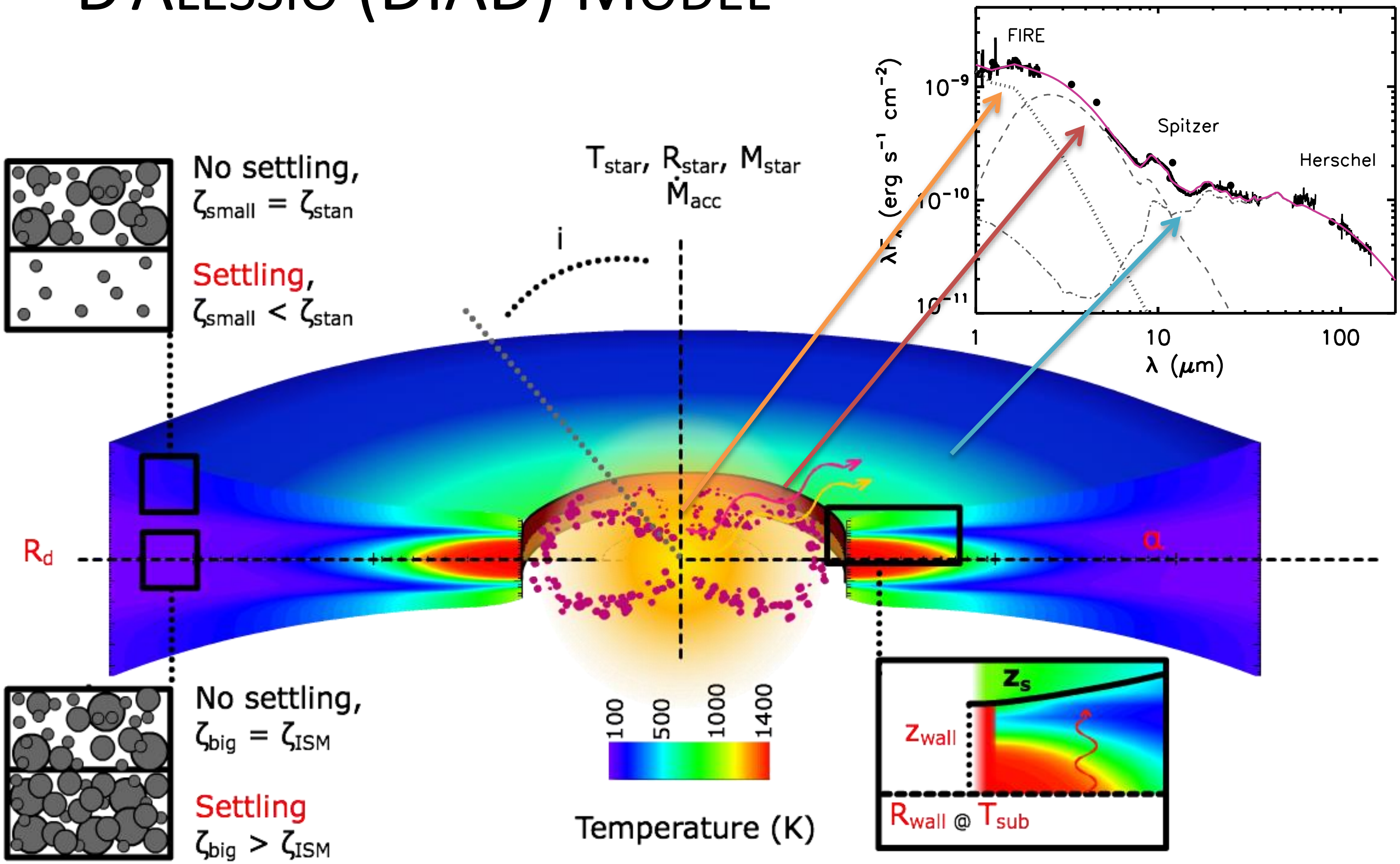
[Nomura et al. 2016]

Disk vertical temperature profile



Radial distribution of the N_2H^+ ring

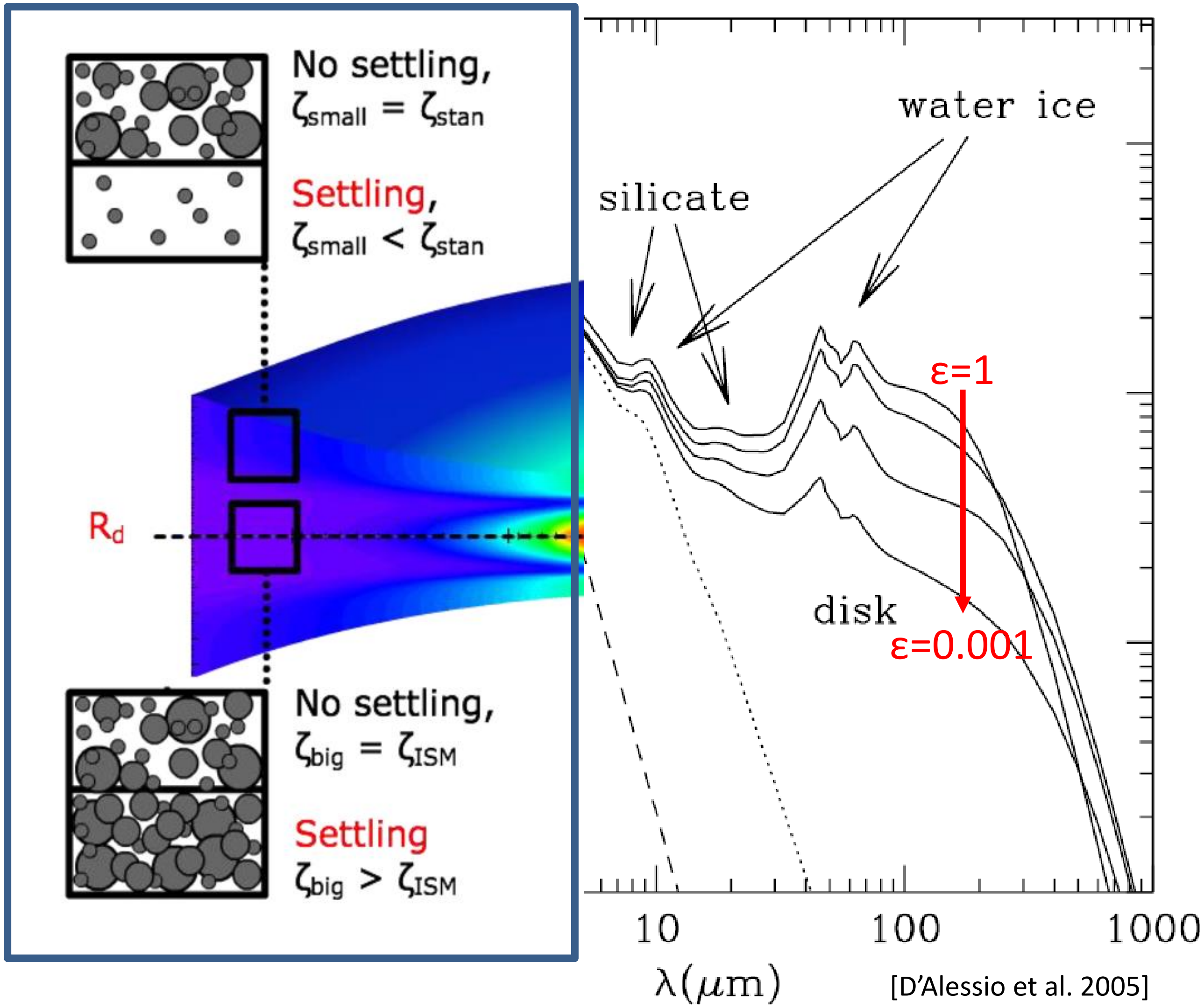
D'ALESSIO (DIAD) MODEL



(D'Alessio et al. 2006)

[Slide courtesy: Melissa McClure]

SEDs of disk models with different degrees of settling



[D'Alessio et al. 2005]

$$\epsilon = \frac{\zeta_{small}}{\zeta_{std}}$$

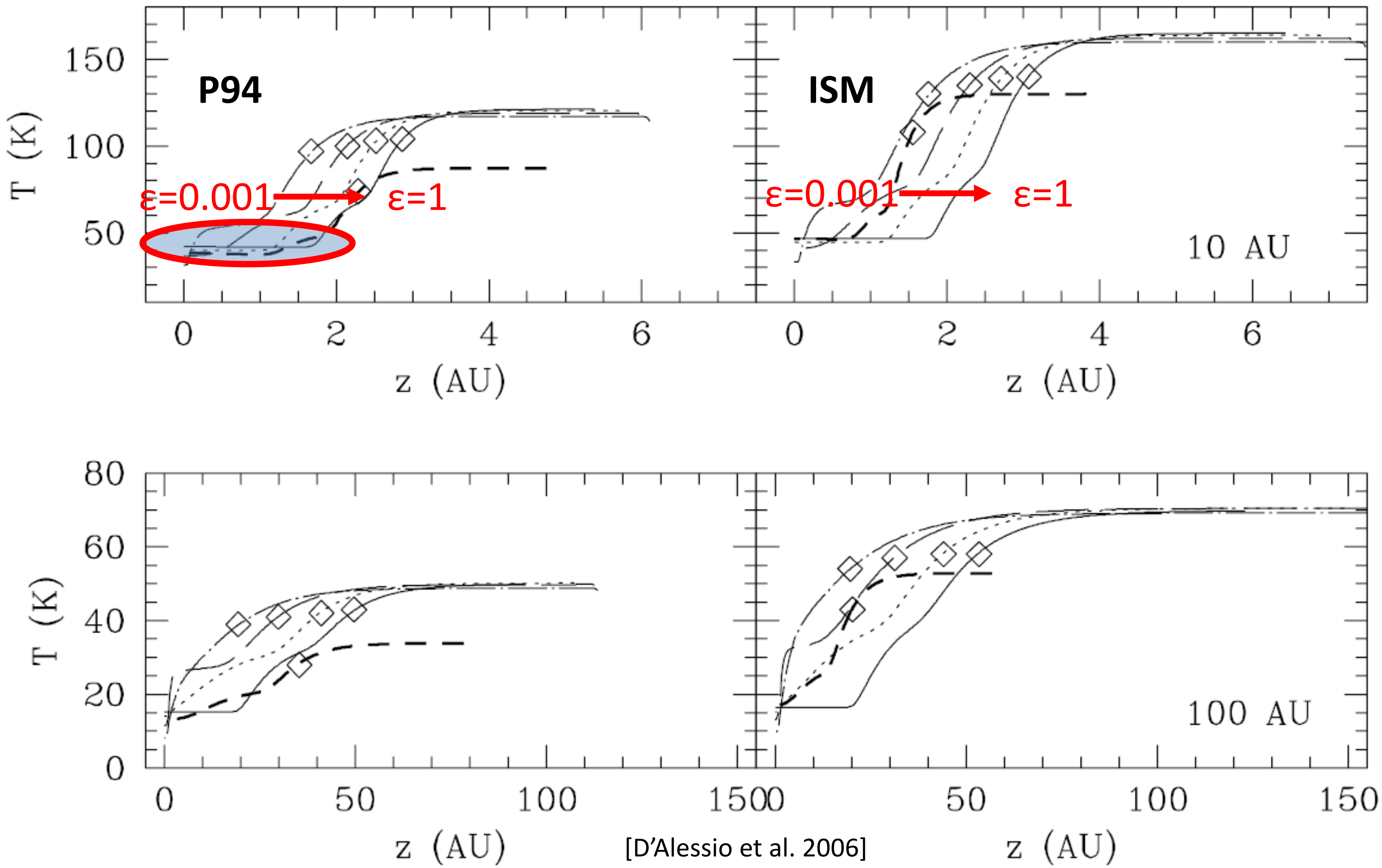
ζ_{small}

depleted dust-to gas mass ratio of the small grains

ζ_{std}

standard dust-to gas mass ratio in the ISM

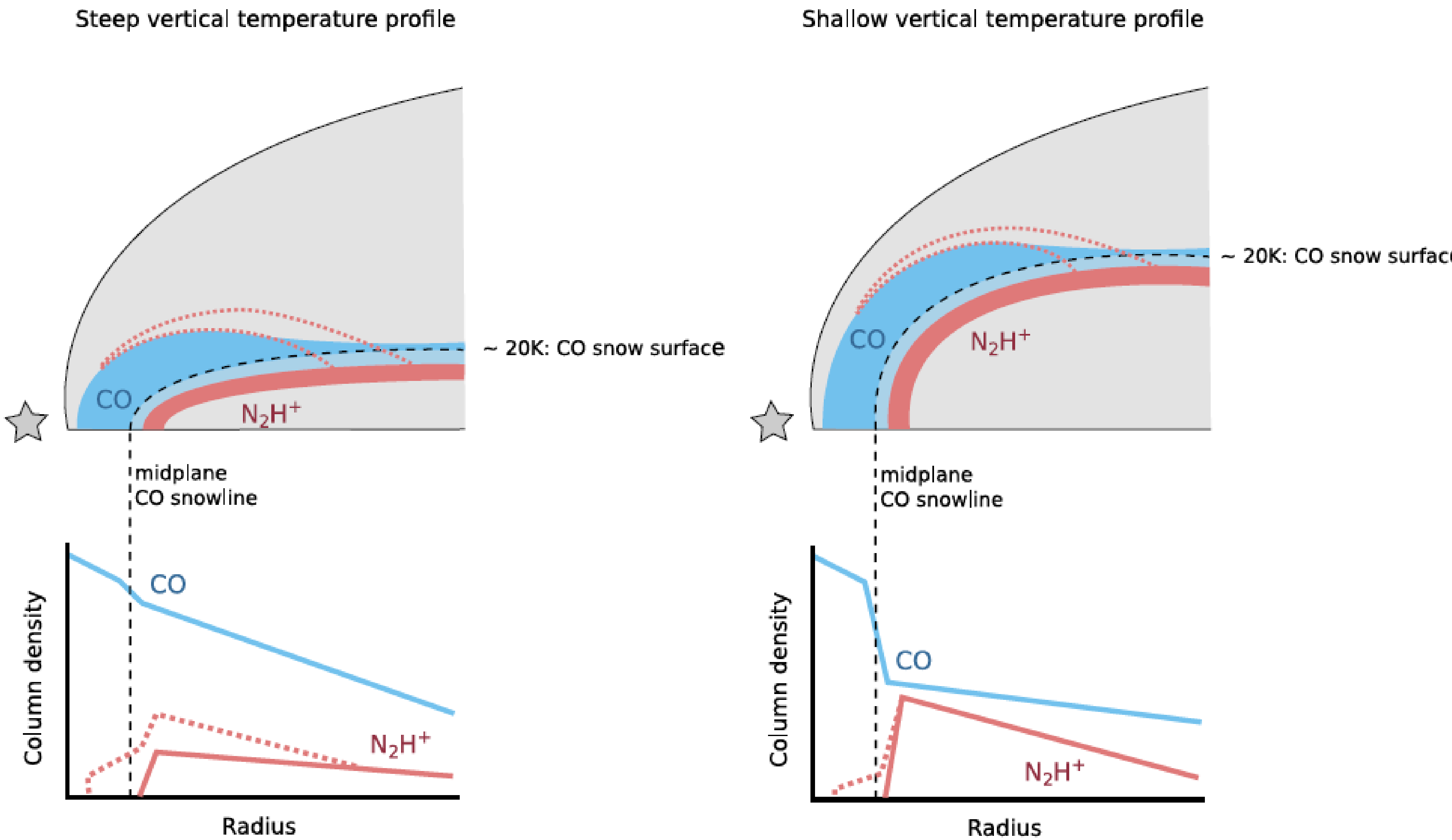
Effects of Dust Settling on Temperature Profiles



[D'Alessio et al. 2006]

P94: dust mixture following Pollack et al. 1994 ; ISM: dust mixture following Draine & Lee 1984

Robustness of N_2H^+ as tracer of the CO snow line depends on the disk temperature structure



[van't Hoff et al. 2017]

Summary

- N_2H^+ is found to trace the layers between the CO and N_2 freezeout temperature.
- If there is a substantial layer of constant temperature plateau near the disk midplane, N_2H^+ can be used as a tracer to both the CO and N_2 snow lines.

Collaborators: K. Öberg, D. Wilner, S. Andrews, L.I. Cleeves (CfA);
C. Espaillat (Boston U.); E. Bergin, N. Calvet (U. Michigan);
G. A. Blake (Caltech)

END