



# Towards an Accurate Accounting of the Gas Content of Protoplanetary Disks

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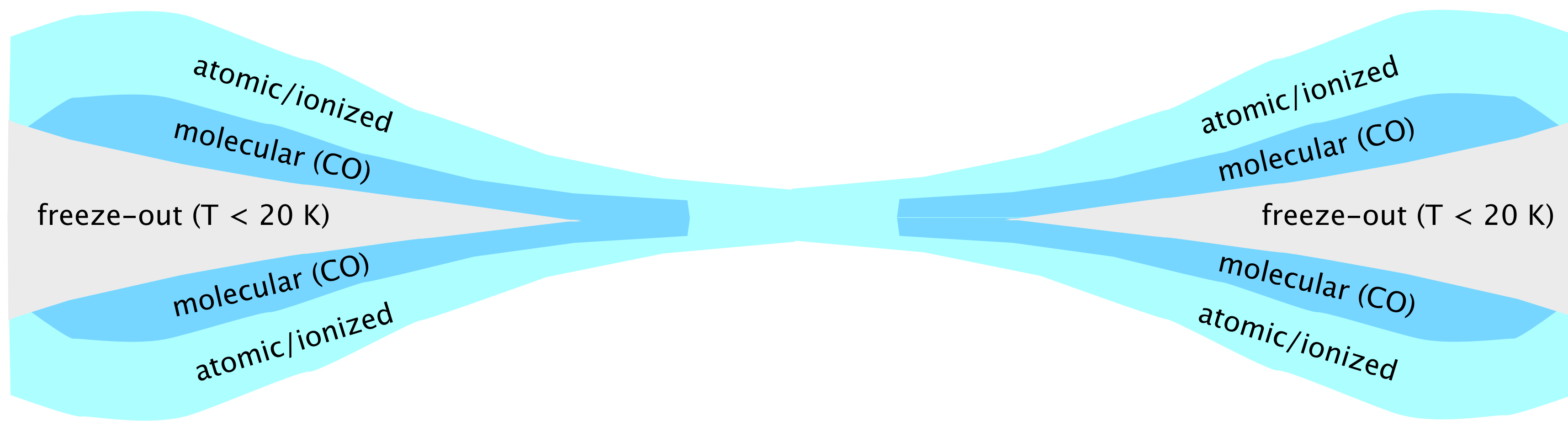
- We seek an observable diagnostic for the mass of the gas in protoplanetary disks.
- A better understanding of the mass and evolution of gas in disks will set constraints on the timescale and mechanisms for giant planet formation.
- The primary gas constituents ( $H_2$  and He) are invisible in disk interiors. We use CO mm-wavelength lines as a tracer.
- Our parametric disk model, rooted in accretion disk theory

and supported by observations, includes geometry, density, temperature, and CO chemistry.

- We calculate the J=1-0, 2-1 and 3-2 emission line strengths for  $^{12}CO$ ,  $^{13}CO$ , and  $C^{18}O$  in model protoplanetary disks.
- We show that  $^{13}CO$  and  $C^{18}O$  (1-0) and (2-1) fluxes correlate well with gas mass, and can potentially constrain the mass to within a factor of 3, a significant improvement over the standard assumption of gas : dust = 100 : 1.

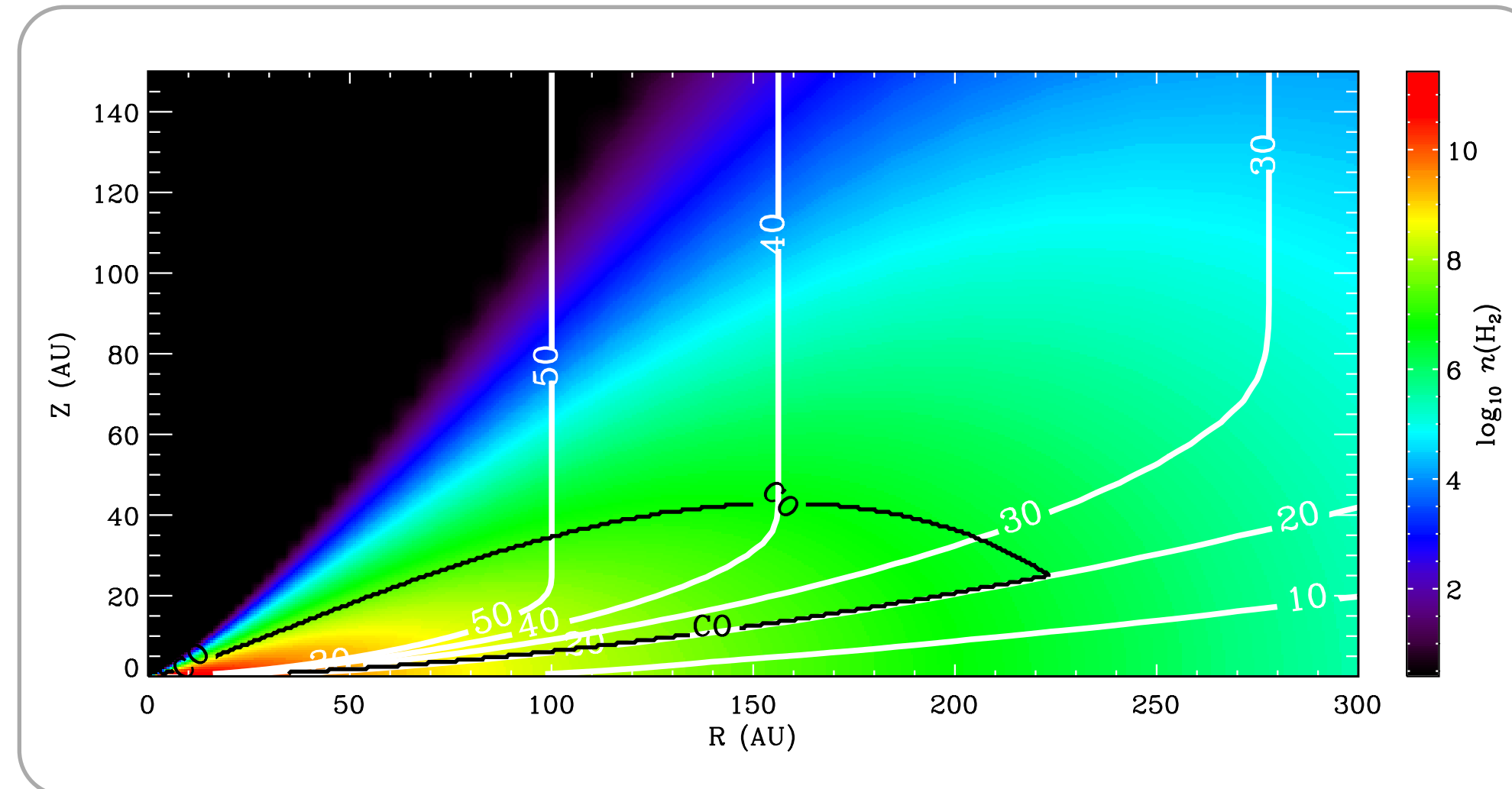
## Parametric Flared Disk Model

We model the protoplanetary disk gas as an axisymmetric three-layer structure (Bergin et al. 2007), flared due to heating from the central star. The outer layer (light blue) is atomic/ionized; molecules are dissociated. The middle layer (dark blue) is molecular; CO emission originates from this layer, which contains most of the gas. In the cold inner zone (grey), CO freezes onto dust grains.



- Our model is based on theoretical expectations (Lynden-Bell & Pringle 1974; Hartmann 2009) and observational verification (Andrews et al. 2012).
- The disks have no gaps or central holes.
- For surface density, we use a tapered power law (Lin & Pringle 1990; Hughes et al. 2008), scaled by the gas mass.
- The midplane temperature follows a power law, with values drawn from thermal simulations of dust (e.g., D'Allesio et al. 1999).
- The vertical temperature profile also follows a radial power law, connected to the midplane temperature by a smooth function (Dartois et al. 2003; Andrews et al. 2012).
- Hydrostatic equilibrium determines the vertical density structure.
- We model the gas independently from the dust; mm-sized grains are decoupled from the gas.
- We calculate the observed emission for a range of disk inclinations.

- We use RADMC-3D, a publicly available Monte Carlo radiative transfer code (Dullemond 2012), to calculate the CO line emission profiles.



Profile of the upper half of a model disk with  $M_{\text{gas}} = 10^{-2} M_{\odot}$  and  $R_c = 50$  AU. Colors reveal the gas density (scale at right). The white contours are isotherms. The black curves outline the molecular region, which contains most of the gas, and from which the CO emission originates.

## Modeling Results

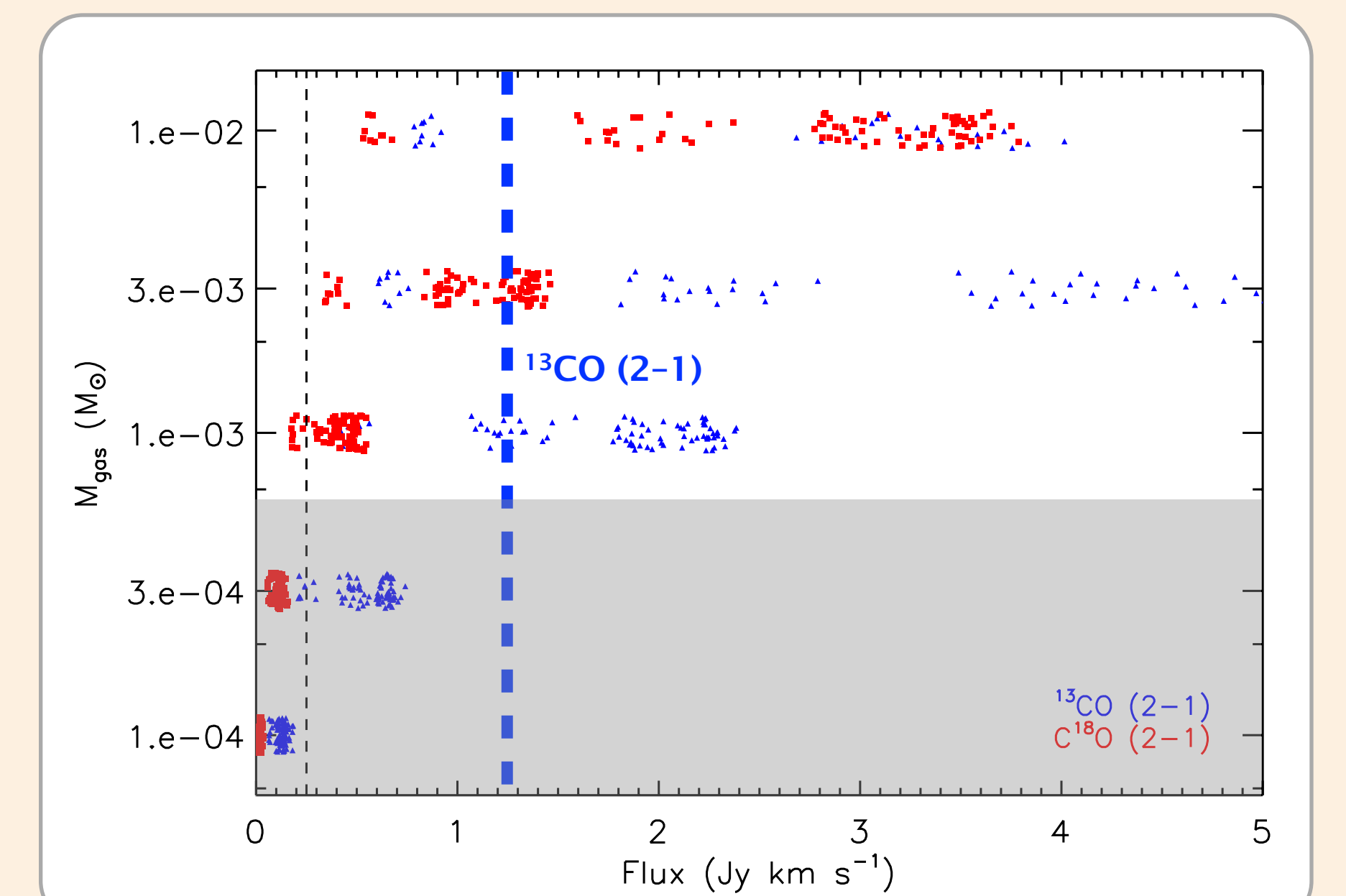
	$^{12}CO(1-0)$	$^{12}CO(2-1)$	$C^{18}O(1-0)$	$^{12}CO(3-2)$	$C^{18}O(2-1)$	$^{12}CO(3-2)$	$C^{18}O(3-2)$
$M_{\text{gas}}$	0.49	0.82	0.92	0.42	0.72	0.86	0.39
$R_c$	0.19	0.15	0.09	0.18	0.16	0.12	0.17
$T_{\text{mid}}$	-0.02	-0.01	0.01	-0.02	-0.02	-0.01	-0.02
$q_m$	0.03	0.02	-0.00	0.03	0.03	0.02	0.03
$T_{\text{at}}$	0.47	0.17	0.02	0.50	0.30	0.14	0.52
$q_a$	-0.32	-0.13	-0.05	-0.35	-0.21	-0.12	-0.36
$i$	-0.10	-0.05	-0.04	-0.11	-0.06	-0.04	-0.12

Linear correlation coefficients for gas disk parameters (rows) with CO isotopologue line strengths (columns).

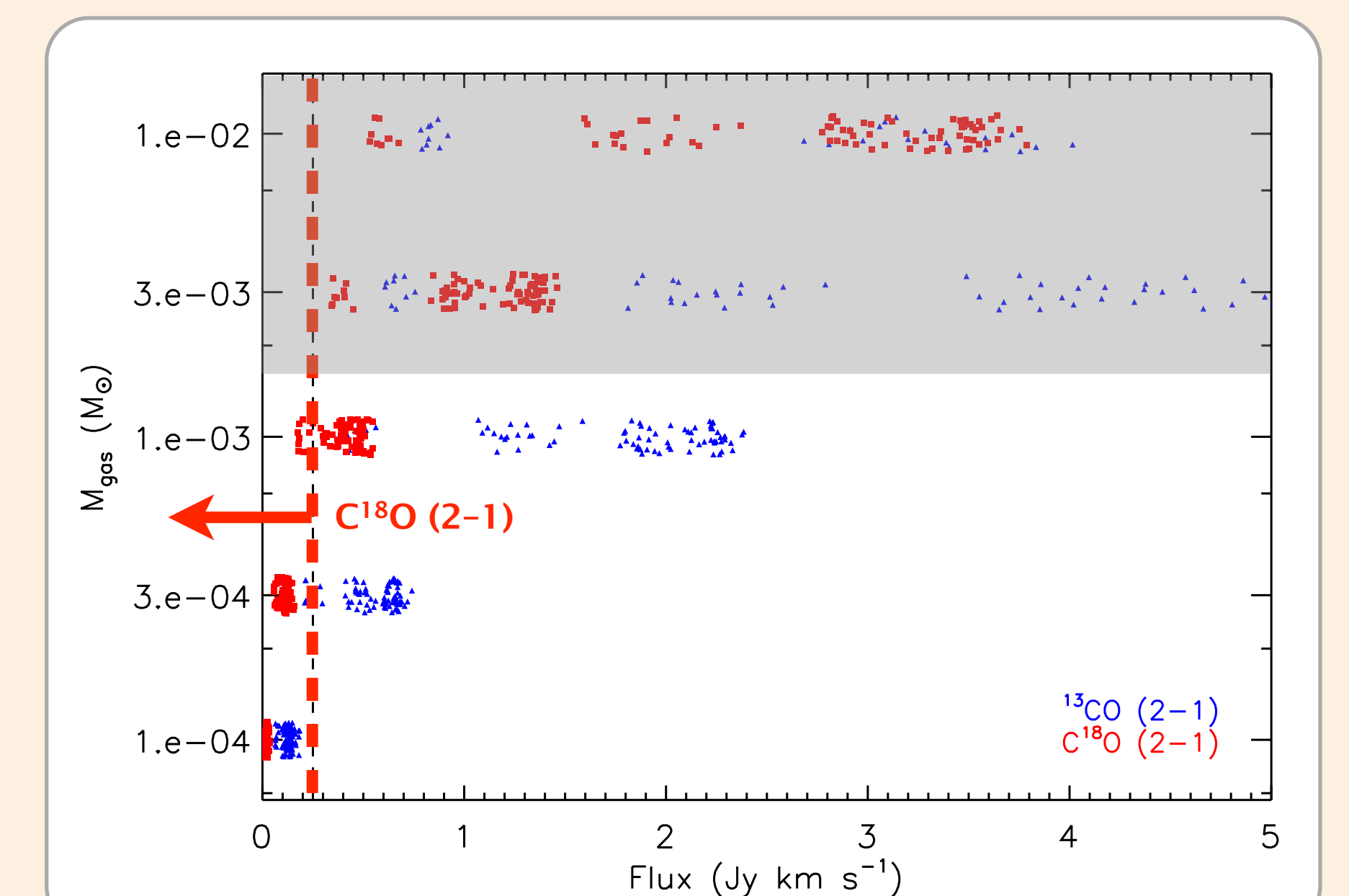
- $^{12}CO$  lines and all (3-2) lines are optically thick, and thus provide poor measures of gas mass.
- For optically thinner  $^{13}CO$  and  $C^{18}O$  (1-0) and (2-1) lines, flux correlates strongly with  $M_{\text{gas}}$ .
- Disk radius ( $R_c$ ) and vertical temperature structure ( $T_{\text{at}}$ ,  $q_a$ ) have some influence on line fluxes.
- Midplane temperature structure, disk inclination, and column depth for photodissociation (not shown) have little influence on line fluxes.

## Example: AA Tau

We calculated  $^{13}CO$  and  $C^{18}O$  (2-1) fluxes for model disks with  $M_{\text{star}} = 0.6 M_{\odot}$ ,  $R_c = 100$  AU,  $i = 60^\circ$ . We compared these to SMA observations of AA Tau, known to have a disk with  $M_{\text{dust}} \sim 0.1 M_{\text{Jup}}$ .



$^{13}CO$  (2-1) is detected at  $1.26 \text{ Jy km s}^{-1}$  (blue dashed line), setting a lower limit of  $M_{\text{gas}} \gtrsim 10^{-3} M_{\odot}$ .



The black dashed line is the  $3\sigma$  SMA detection limit at 1.3 mm.  $C^{18}O$  (2-1) is not detected (red dashed line), setting an upper limit of  $M_{\text{gas}} \lesssim 10^{-3} M_{\odot}$ .

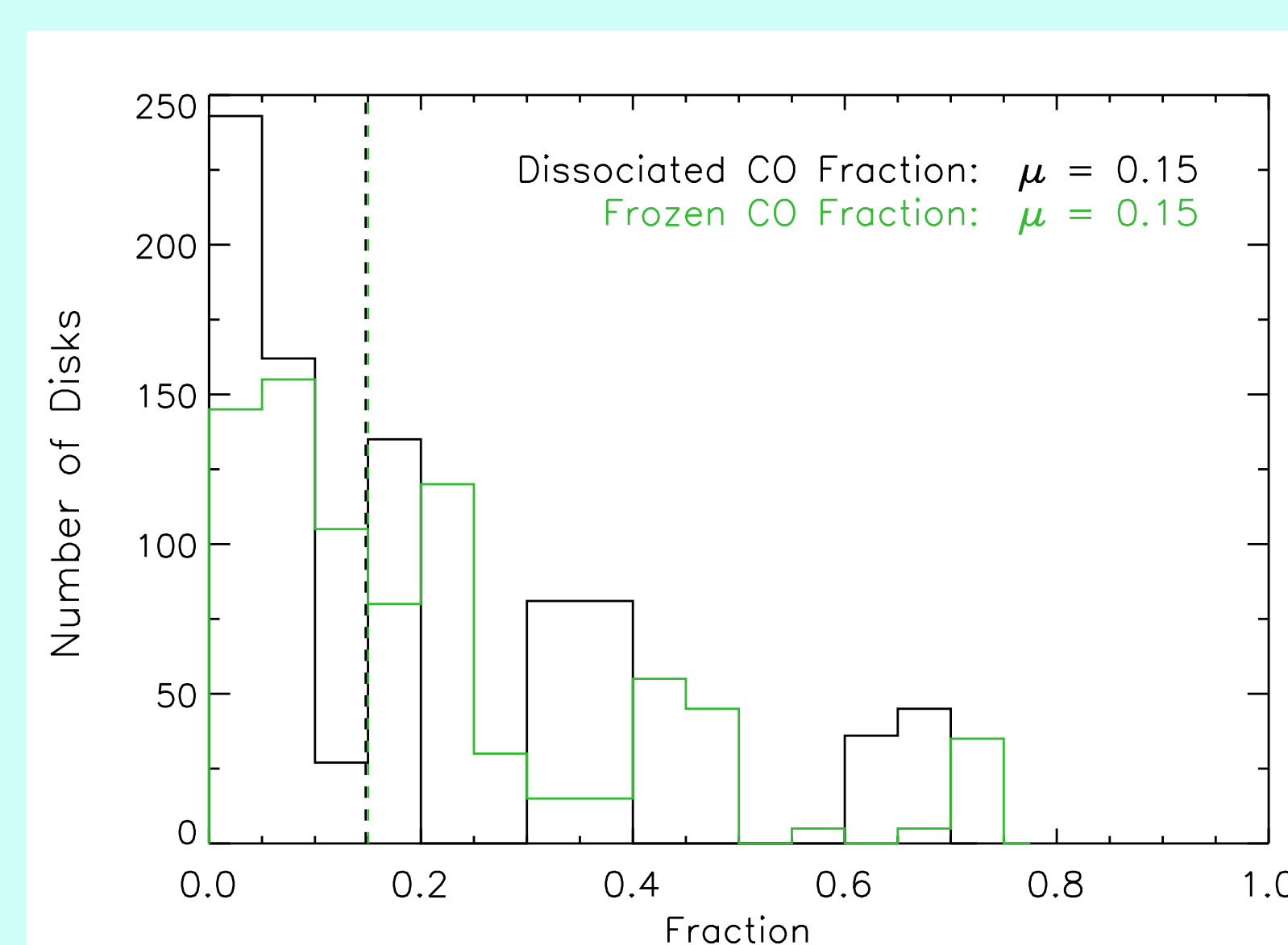
Together, these observations constrain the AA Tau disk to have  $M_{\text{gas}} \sim 10^{-3} M_{\odot} \approx 1 M_{\text{Jup}}$ , to within a factor of 3.

## Gas In Disks

- $H_2$  is a symmetric molecule with no dipole transitions, so it has no emission lines at the cold temperatures of disk interiors ( $\lesssim 100$  K). Only trace molecules like CO can be observed in millimeter emission at these temperatures.
- As disks evolve, the gas photoevaporates, freezes out, or accretes onto the star and planets, leaving a debris disk with essentially no gas. So we cannot assume that the gas-to-dust mass ratio is the same as in the ISM (i.e., 100:1).
- Millimeter-sized dust grains decouple from the gas in disks, so dust cannot be used to trace the gas at millimeter wavelengths.
- In cold quiescent disk interiors, the gas is in LTE.
- CO remains well-mixed with  $H_2$  where it is not depleted (see box at right).
- CO emission depends on chemistry and disk structure as well as mass. All of these qualities must be modeled.
- We use  $[^{12}CO] / [H] = 10^{-4}$  based on observations of molecular clouds in the local galaxy.
- We assume  $^{13}CO$  and  $C^{18}O$  are 70 and 500 times less abundant than  $^{12}CO$ , respectively.
- At millimeter wavelengths, CO emission in disks is resolved with interferometry.

## CO Depletion

- CO is dissociated in outer layers of disks by cosmic rays and radiation from the central star.
- CO remains shielded and intact in disk interiors.
- CO freezes out where  $T \lesssim 20$  K (Qi et al. 2011).



Histogram of the fractions of CO gas that are dissociated (black) and frozen out (green) in 810 model disks. The median fractions are indicated by the vertical dashed lines (both at 0.15). In most of the disks,  $\gtrsim 80\%$  of the gas remains in gas phase.

## References

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