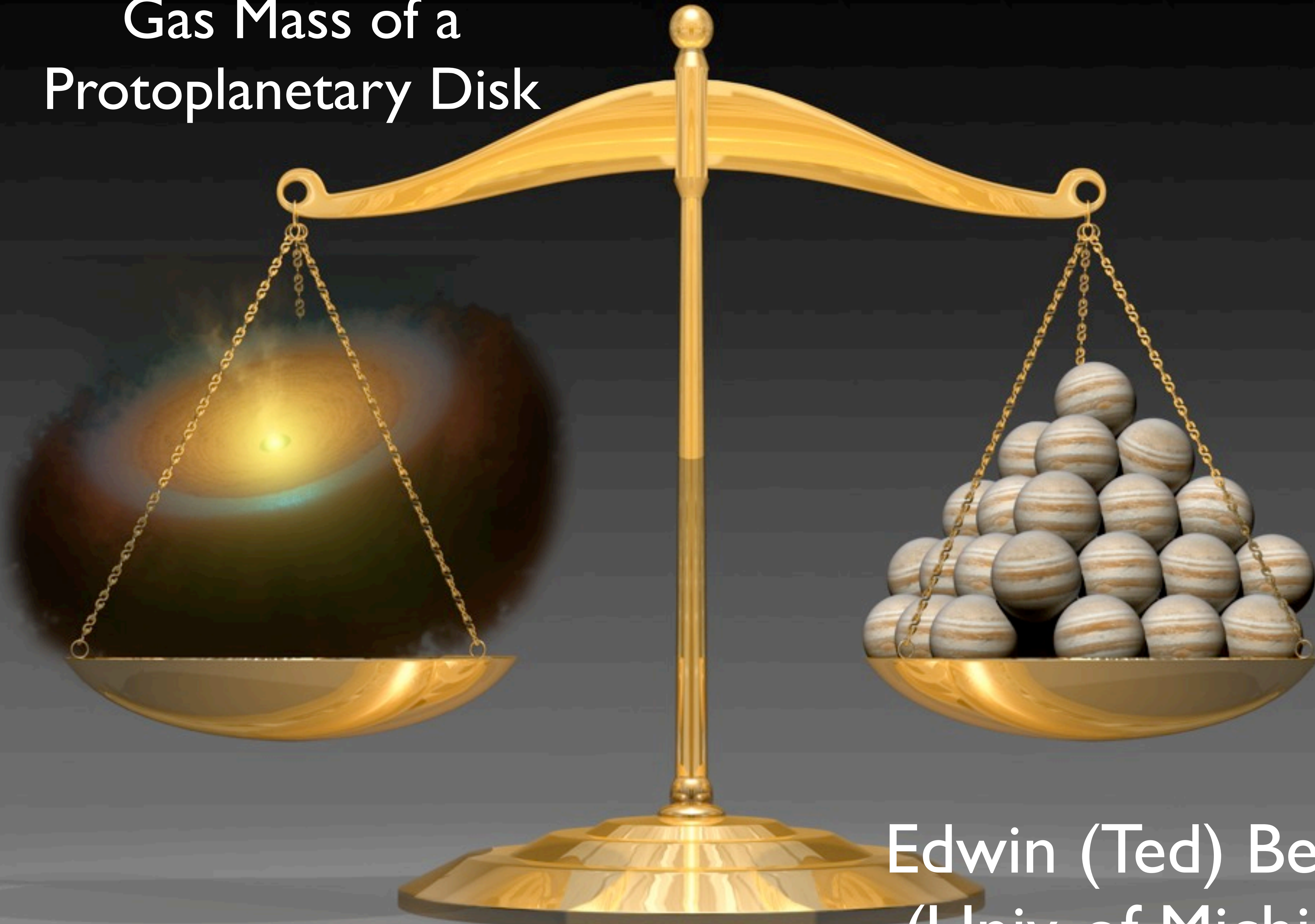
Using HD to Measure the Gas Mass of a Protoplanetary Disk



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HD and Disk Gas Mass

Excellent collaborators:

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- Uma Gorti
- Ke Zhang
- Geoffrey Blake
- Joel Green
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- Thomas Henning
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- Chunhua Qi
- Colette Salyk
- Ewine van Dishoeck

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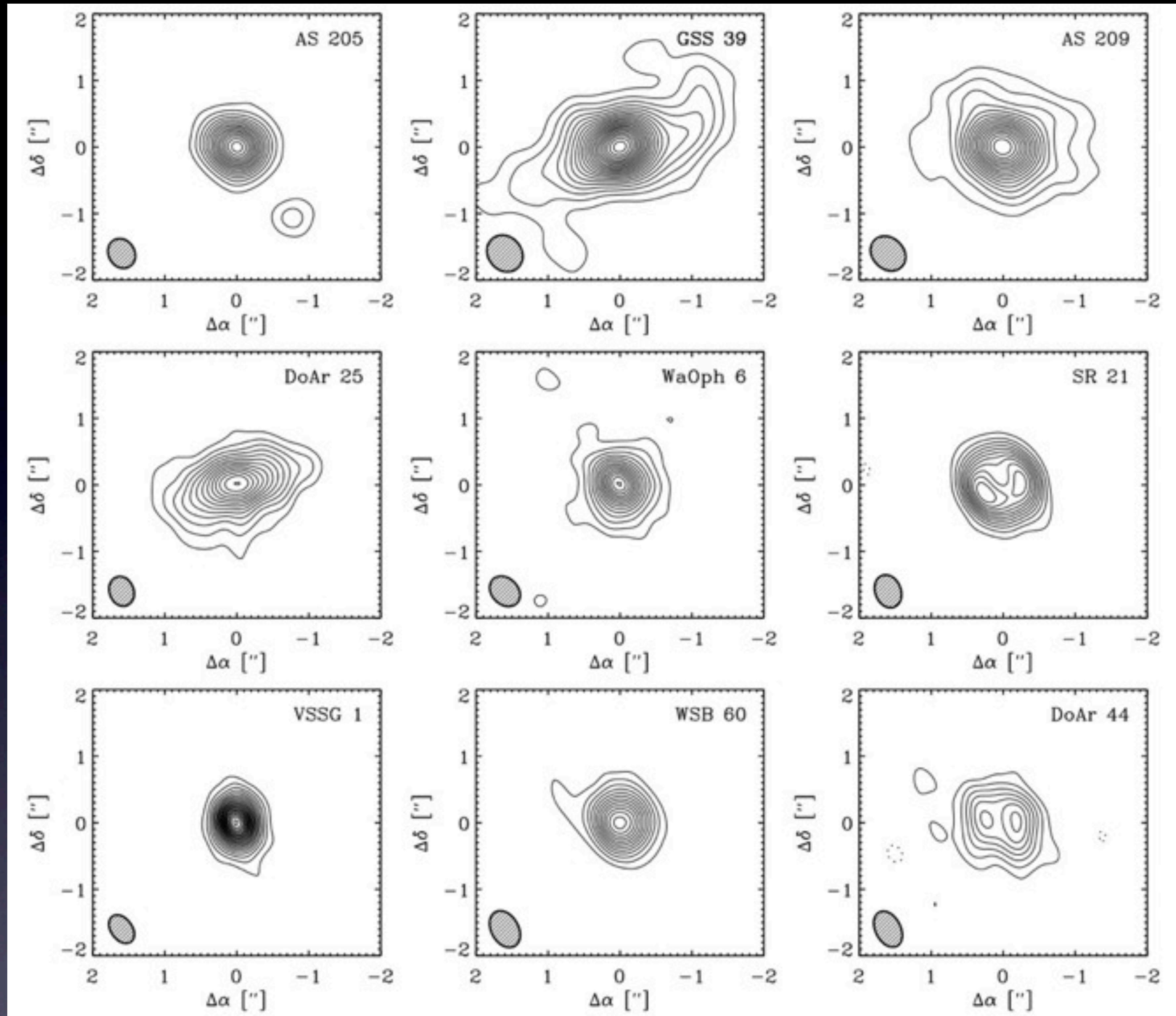
and NSF for chemical modeling

Protoplanetary Disk Gas Mass

- The disk gas mass is the fundamental quantity that determines whether planets can form and on the primary mechanism for gas giant formation.
- For our solar system we have an estimate of the so called minimum mass of 0.01 $M_{\odot}$
- BUT we are clearly detecting exo-planetary systems with more massive planets.

Protoplanetary Disk Gas Mass

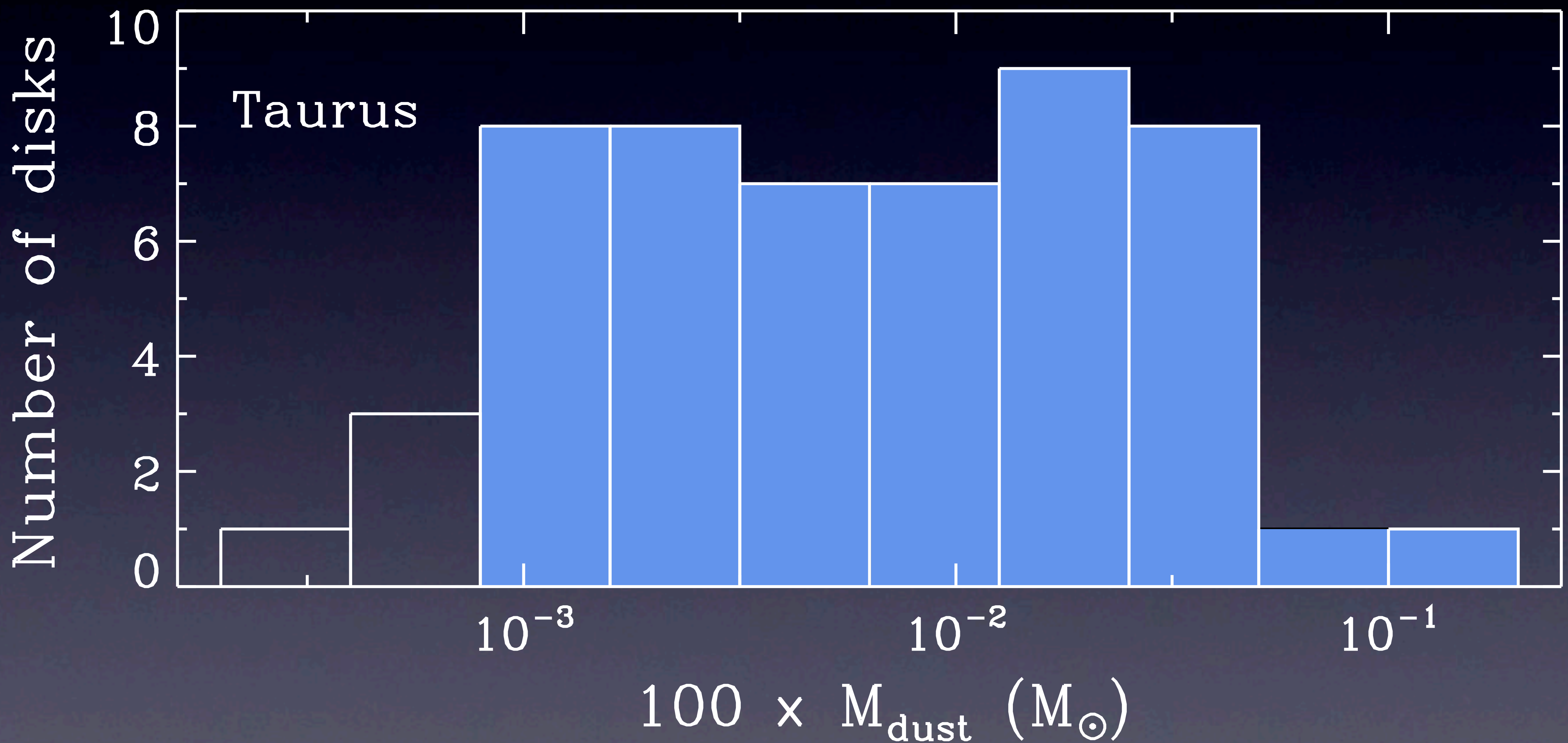
- For protoplanetary disks it is more complicated
  - ➡ H_2 contains all the mass but is unemissive for typical temperatures (20 K) that characterize the disk mass reservoir
- Two proxies are used:
  - ➡ thermal emission from dust grains at mm/sub-mm wavelengths (and a gas to dust ratio)
  - ➡ thermo-chemical modeling of gas emission, primarily CO and isotopologues (and a CO abundance)



Andrews et al. 2009

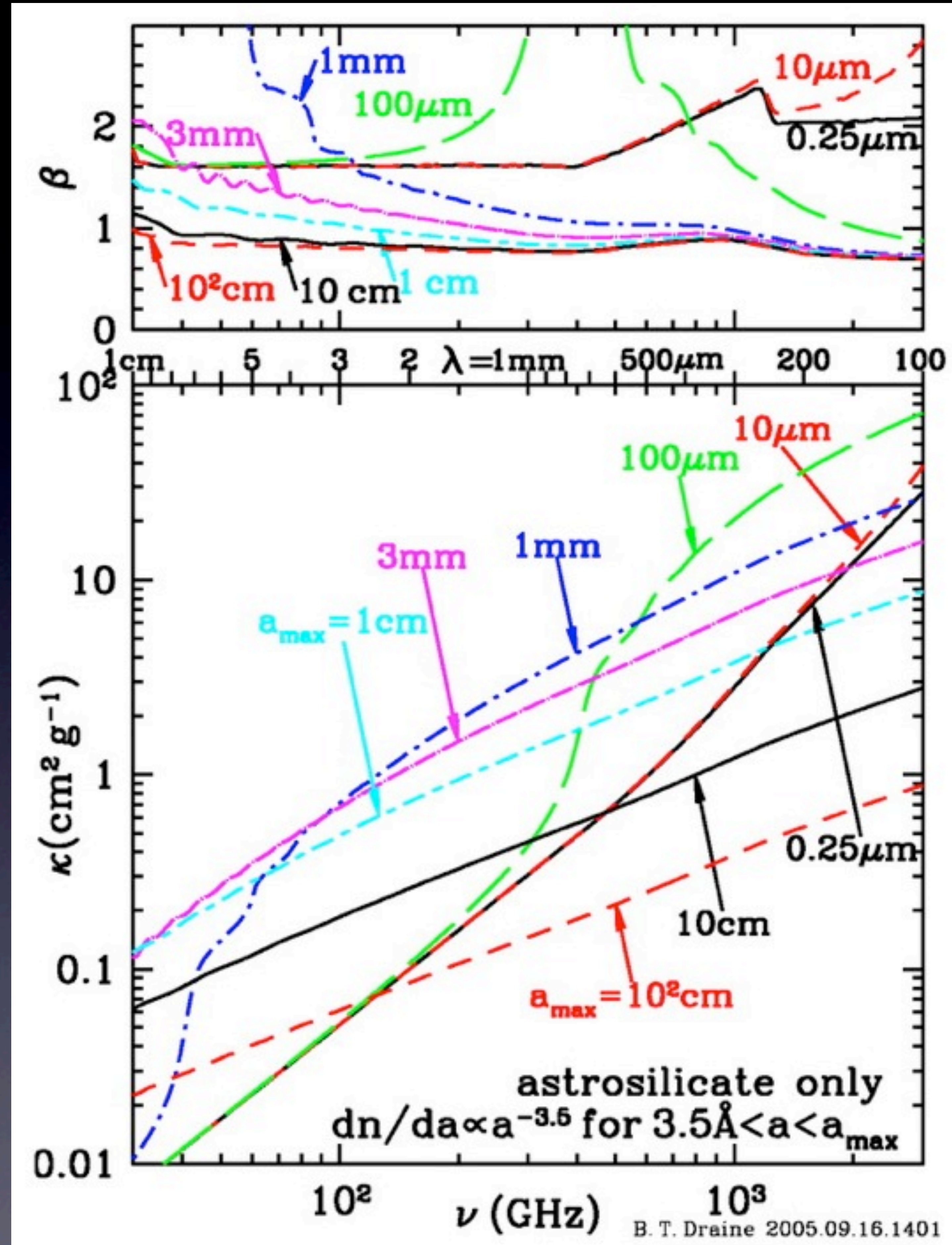
- Mass (gas + dust) = $F_\nu D^2/\kappa_\nu B_\nu[T(r)]$
- at sub-mm wavelengths - Mass $\propto F_\nu/\kappa_\nu T$

Protoplanetary Disk Gas Mass



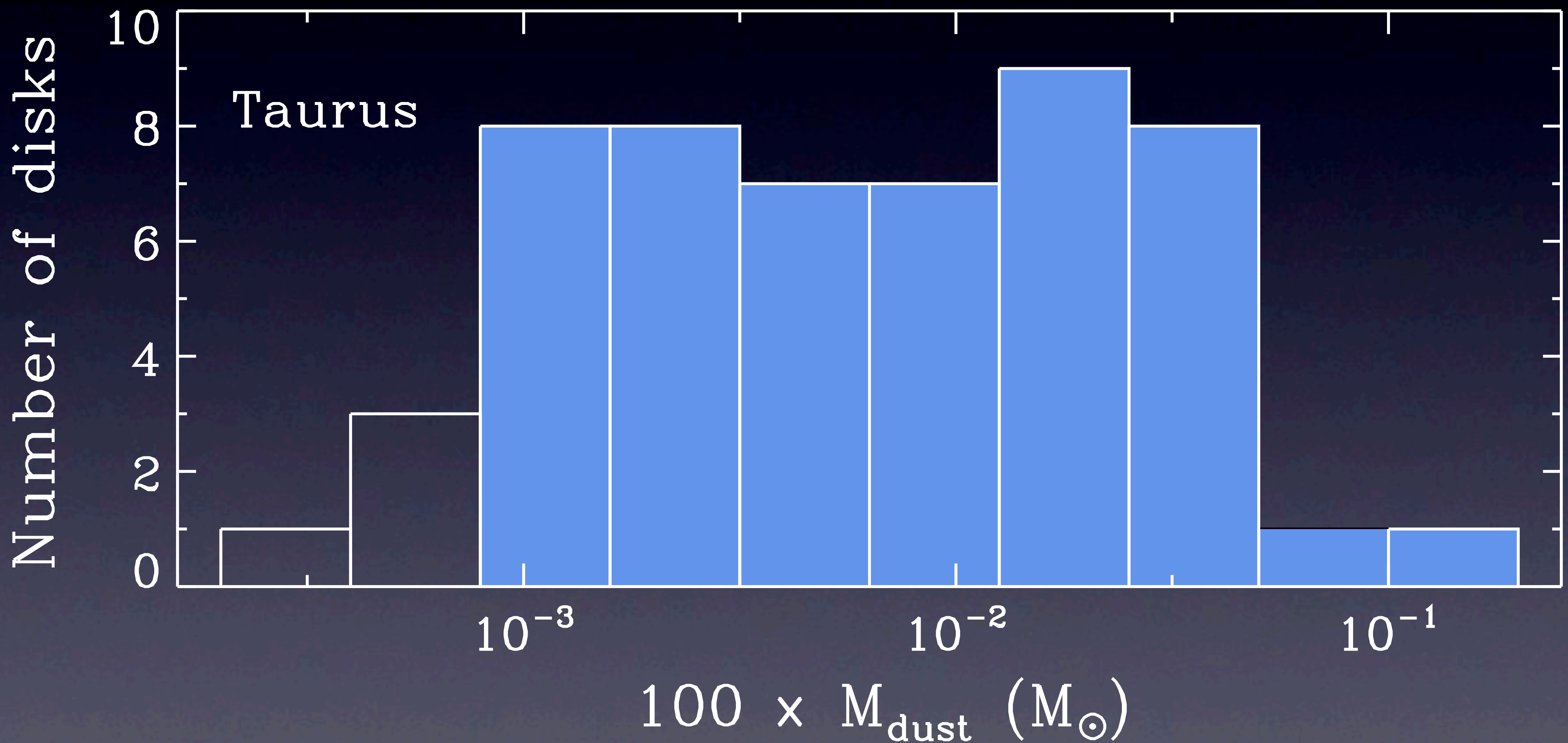
Williams and Cieza 2011

- at submm wavelengths emission proportional to κ (τ = κσ)
- κ = dust mass opacity
- σ = mass column density of grains
- Because of grain growth mass is uncertain - perhaps by a large factor



Draine 2006

Protoplanetary Disk Gas Mass

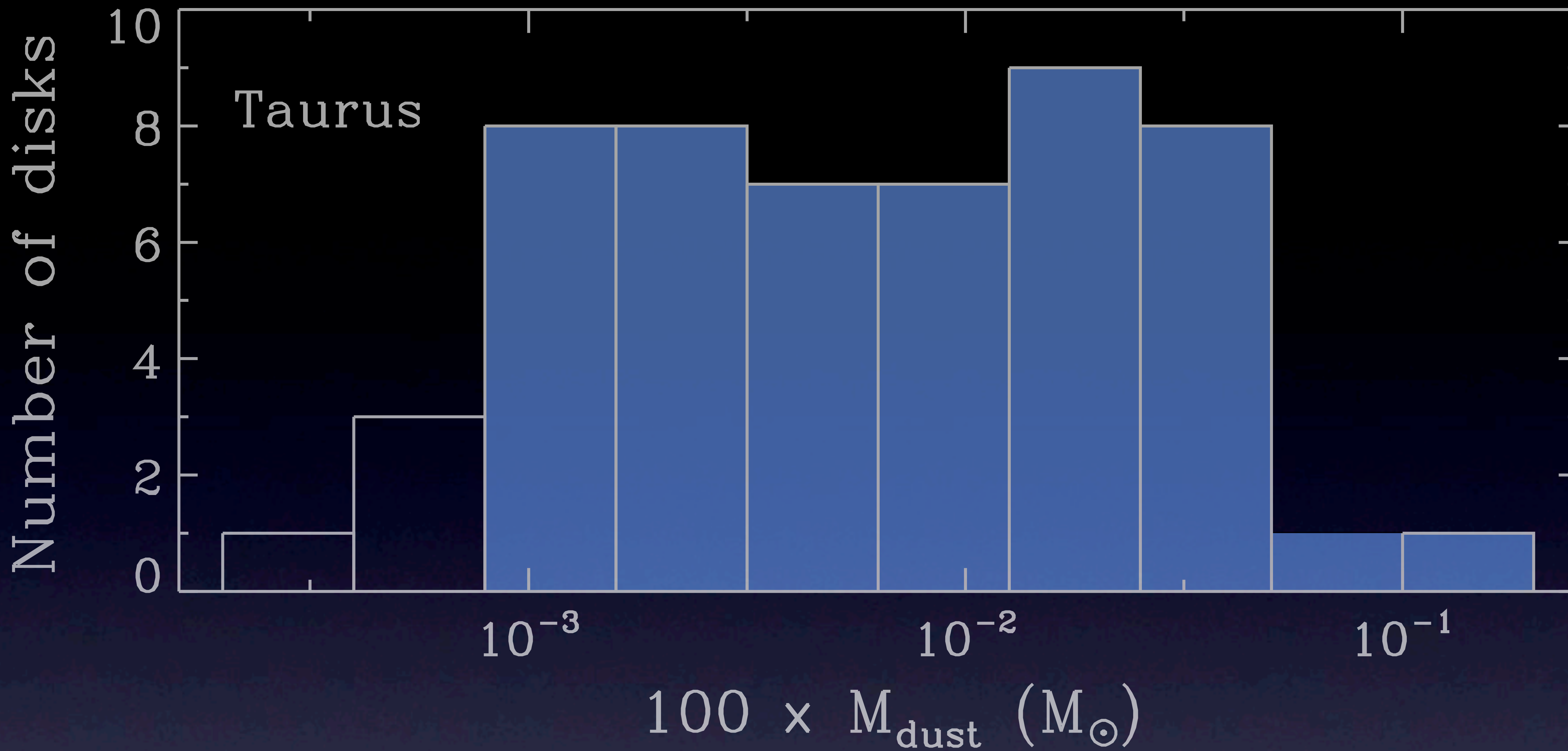


Williams and Cieza 2011

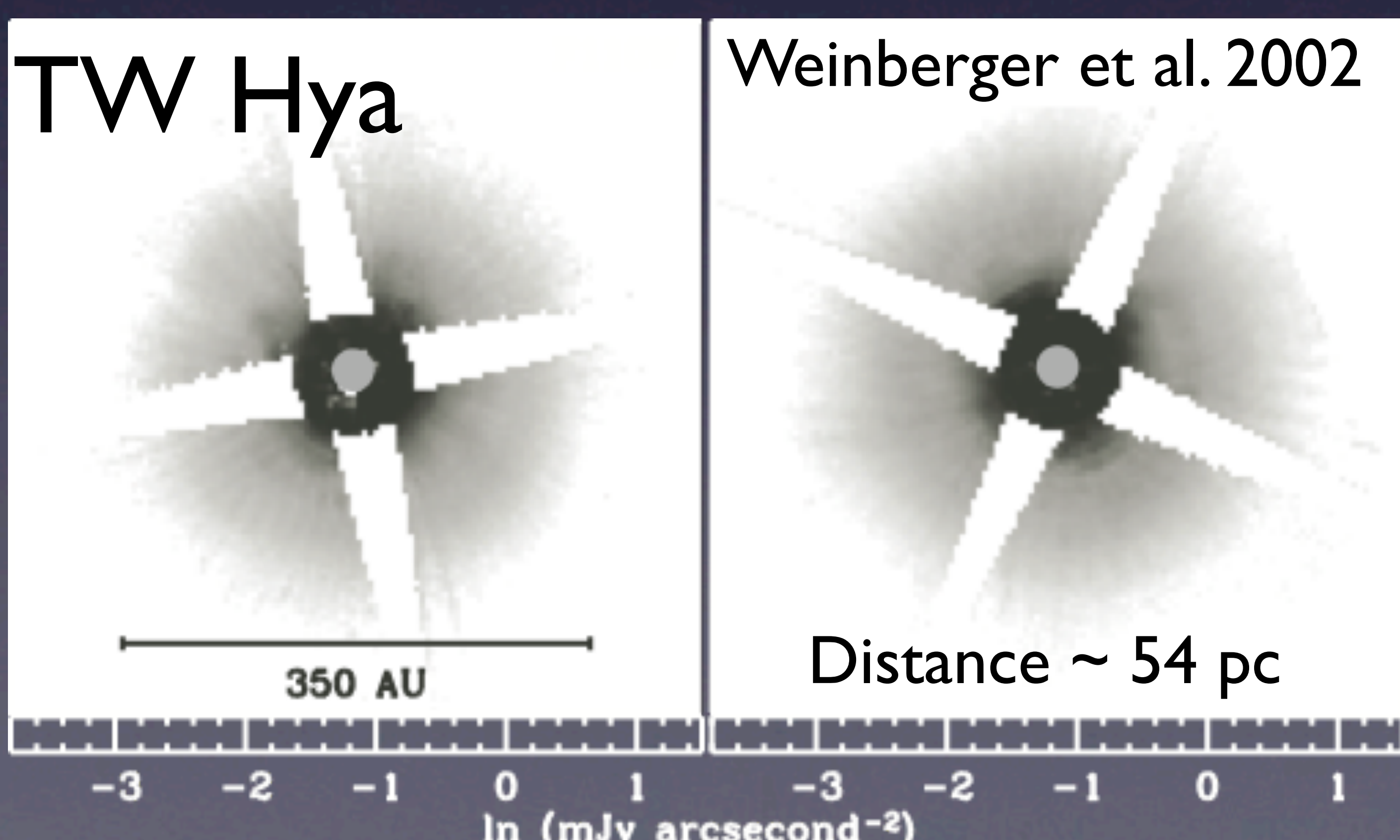
How much of this distribution is due to uncertainty?????

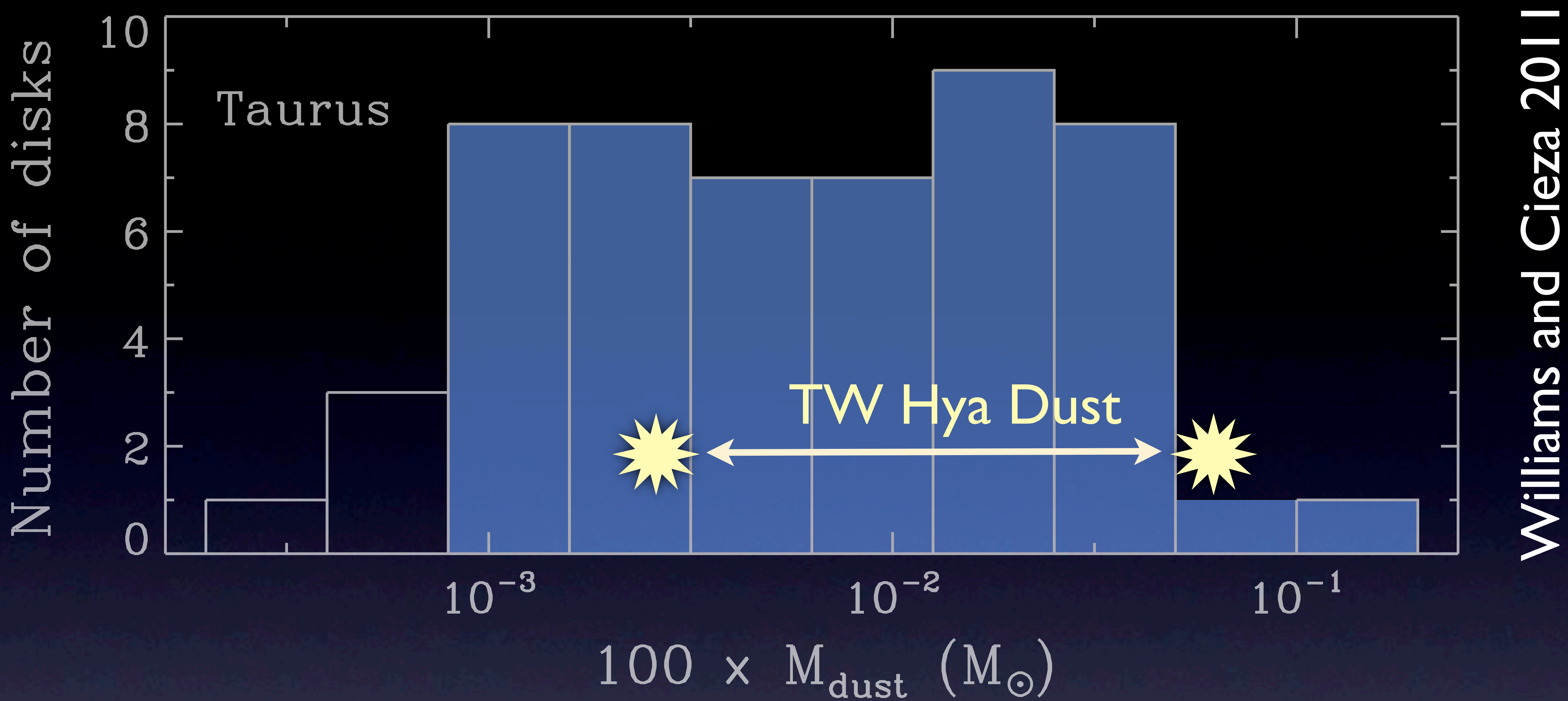
Thermo-chemical Models

- Models of the coupled disk thermal physics and chemistry
- key factor $T_{gas} \neq T_{dust}$
- Include relevant heating, cooling, chemistry as a function of radial and vertical distance
  - ➡ dependent on grain physics (and optical properties), UV + X-ray radiation field, chemical rates, AND DISK MASS
  - ➡ predict line emission of a variety of species (CO, ^{13}CO, O I, …)
- Two models of the closest and best studied object - TW Hya - Gorti et al. 2010, Thi et al. 2010

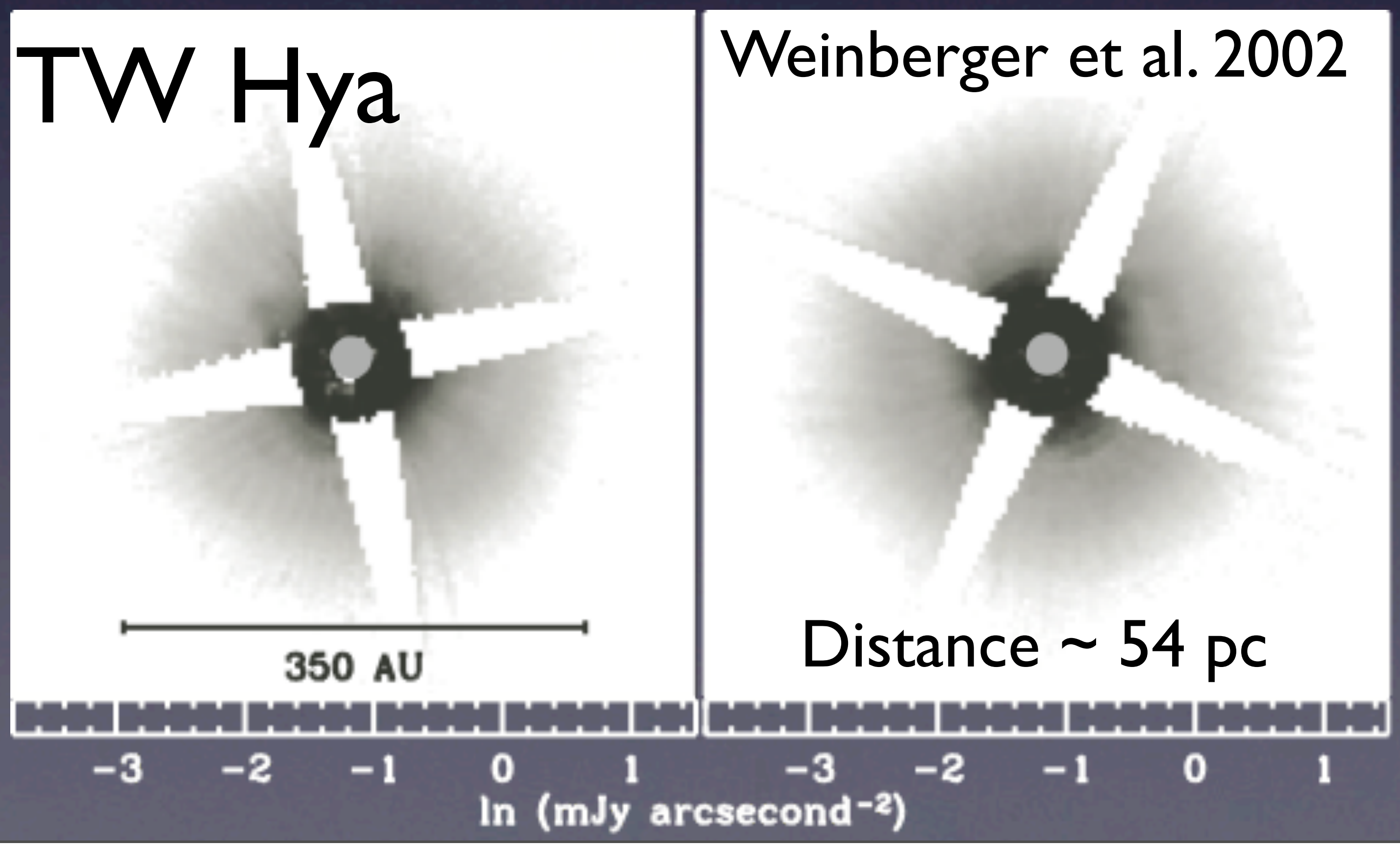


Williams and Cieza 2011

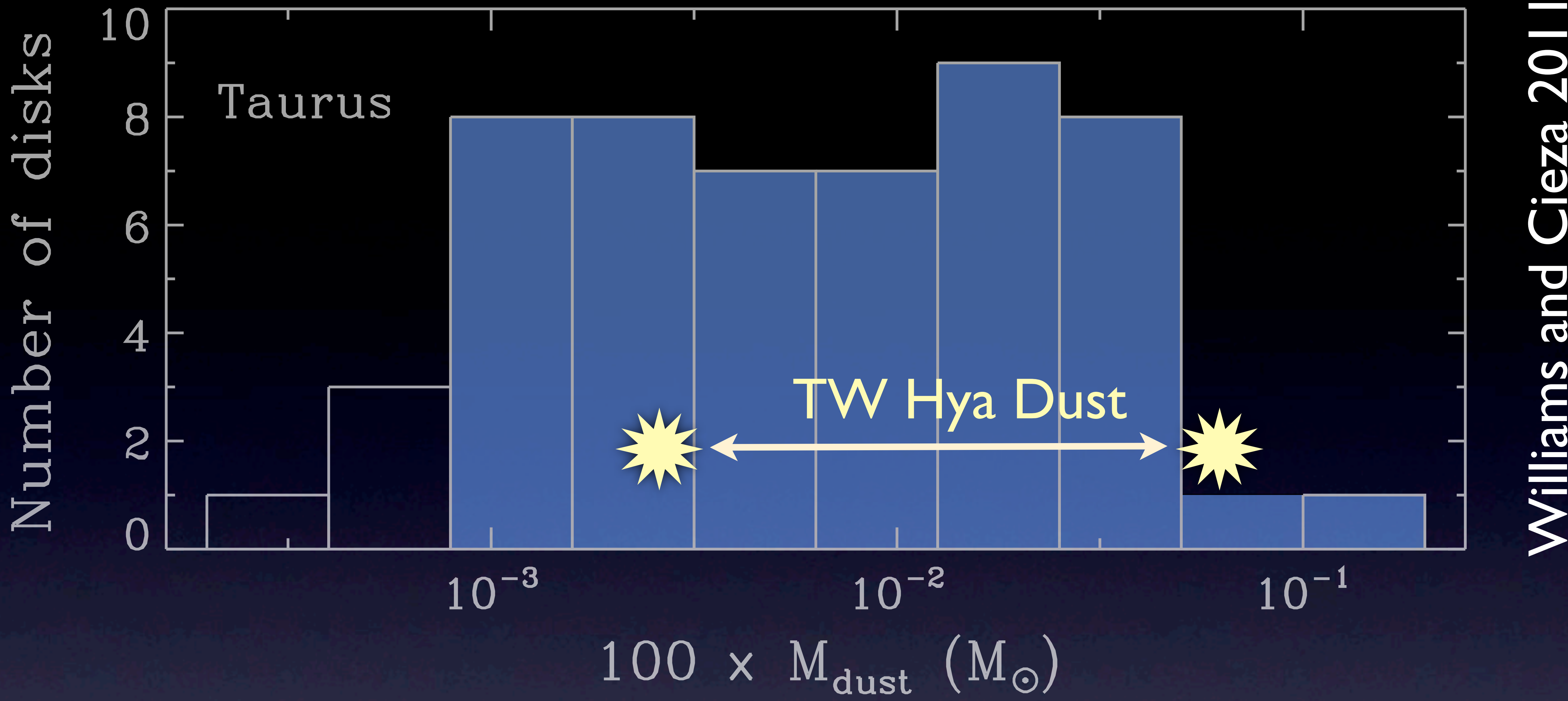


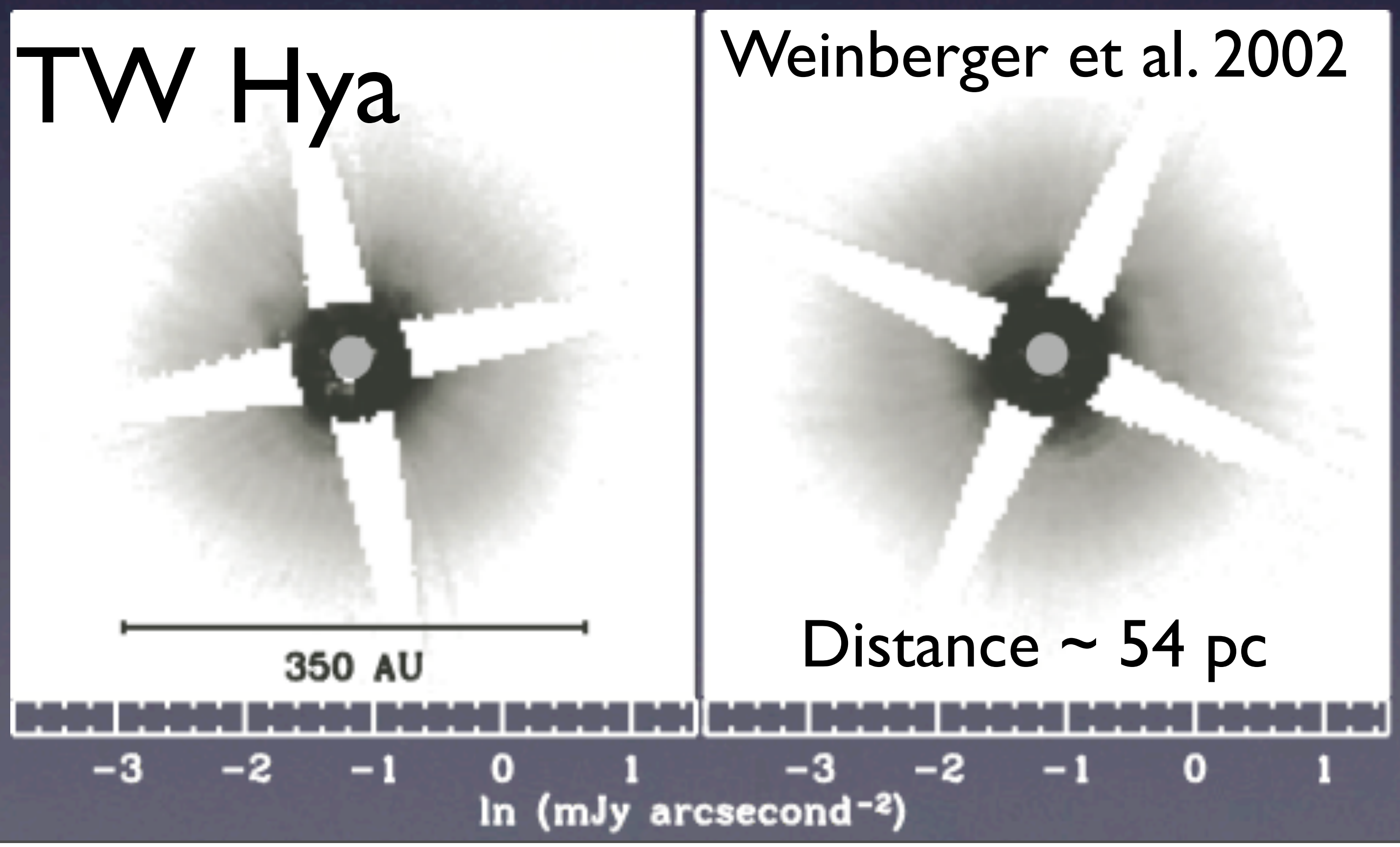


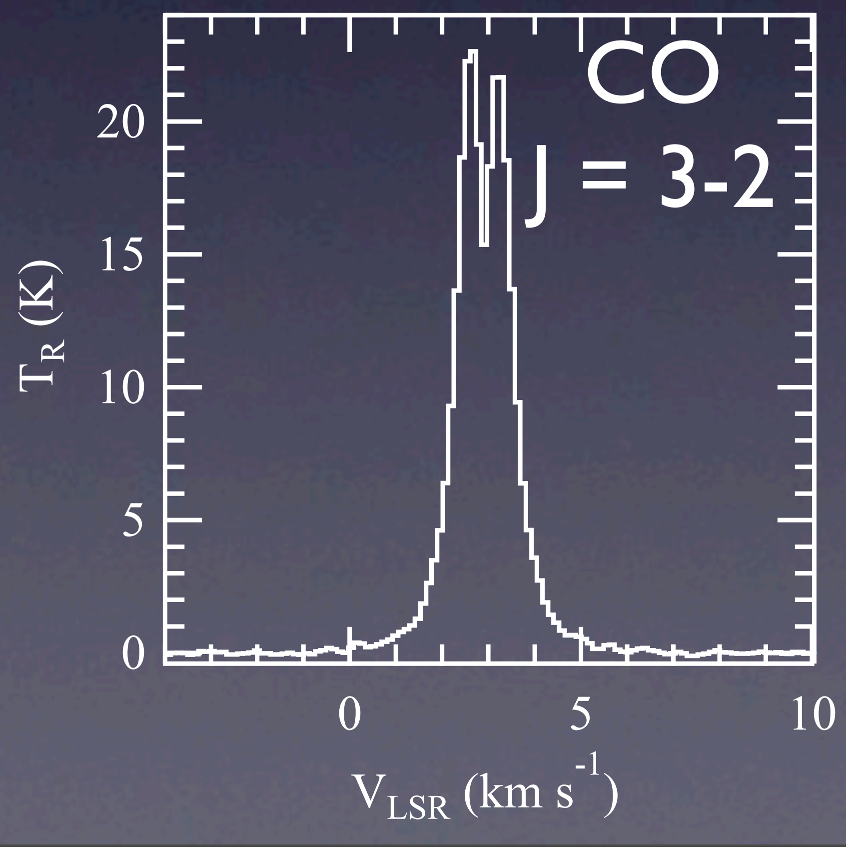
Taurus
TW Hya Dust
Number of disks
100 × M_dust (M_⊙)
Williams and Cieza 2011

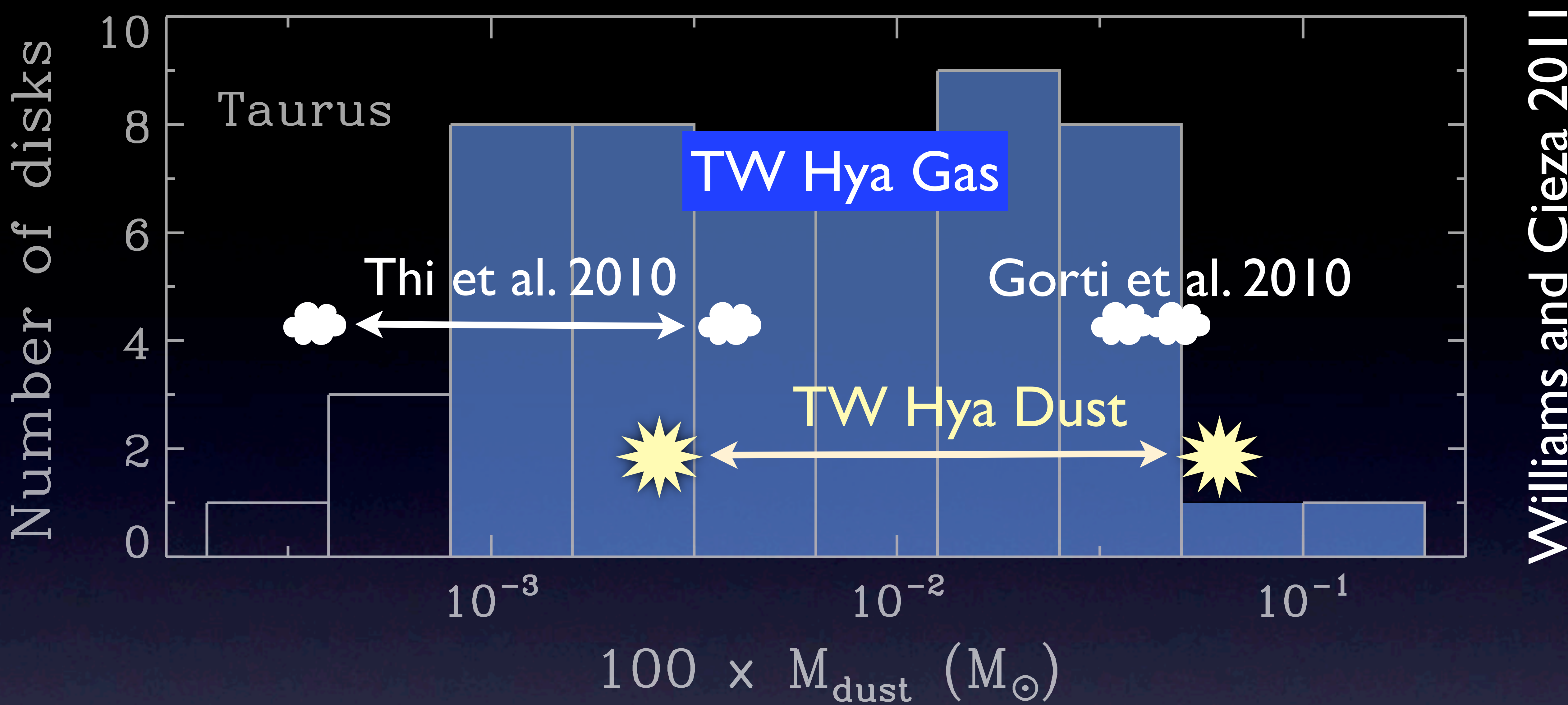


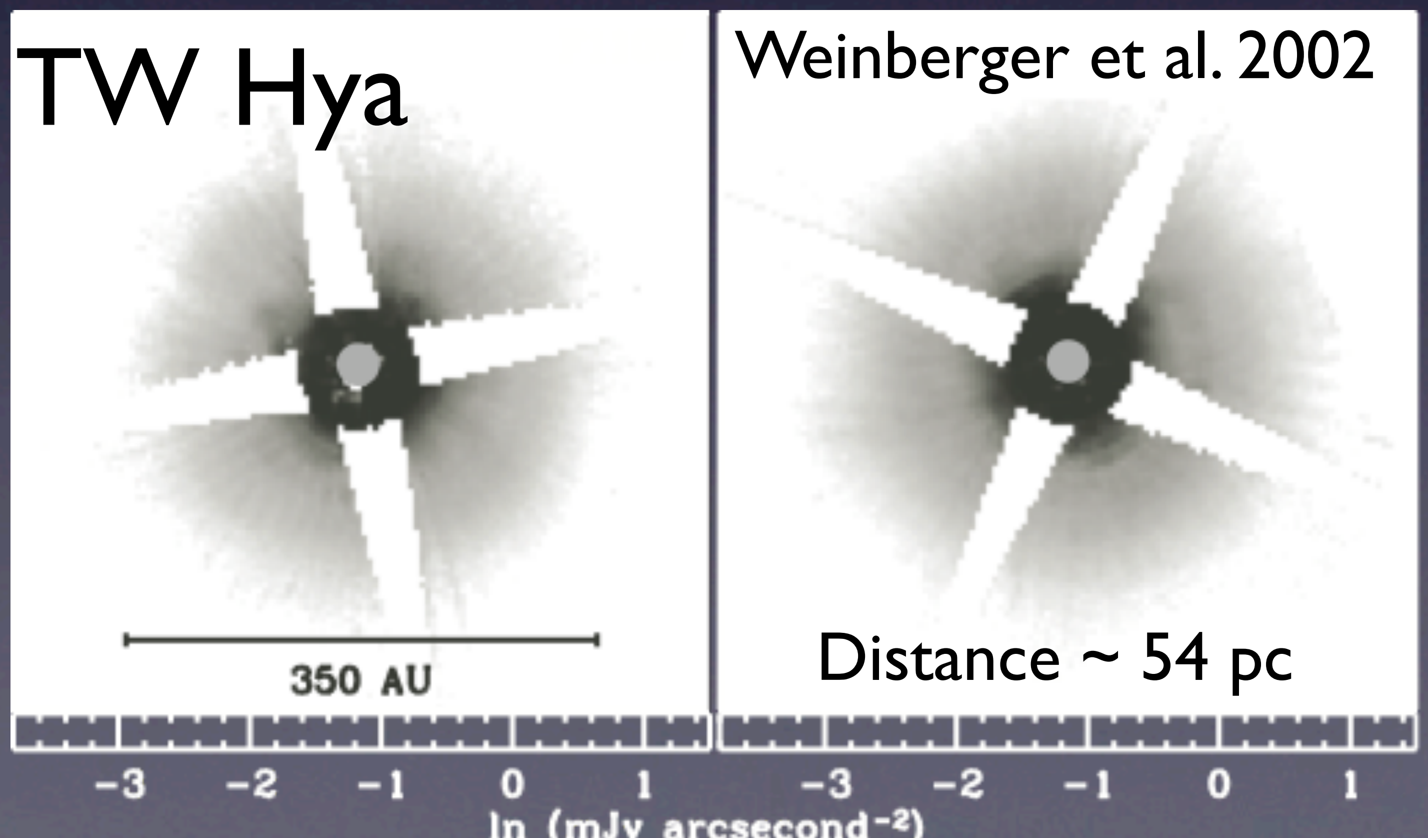
TW Hya
Weinberger et al. 2002
350 AU
Distance ~ 54 pc
ln (mJy arcsecond^-2)

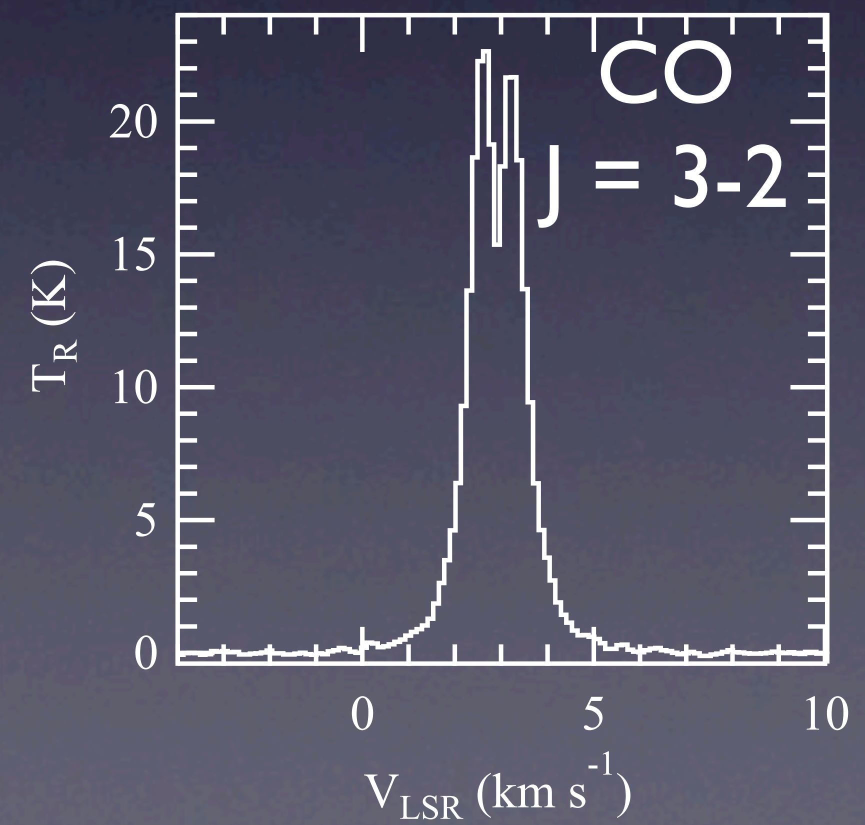

Taurus
Number of disks
0
2
4
6
8
10
10^{-3}
10^{-2}
10^{-1}
$100 \times M_{dust}$ ($M_\odot$)
TW Hya Dust
Williams and Cieza 2011


TW Hya
Weinberger et al. 2002
350 AU
Distance ~ 54 pc
−3
−2
−1
0
1
ln (mJy arcsecond^{-2})

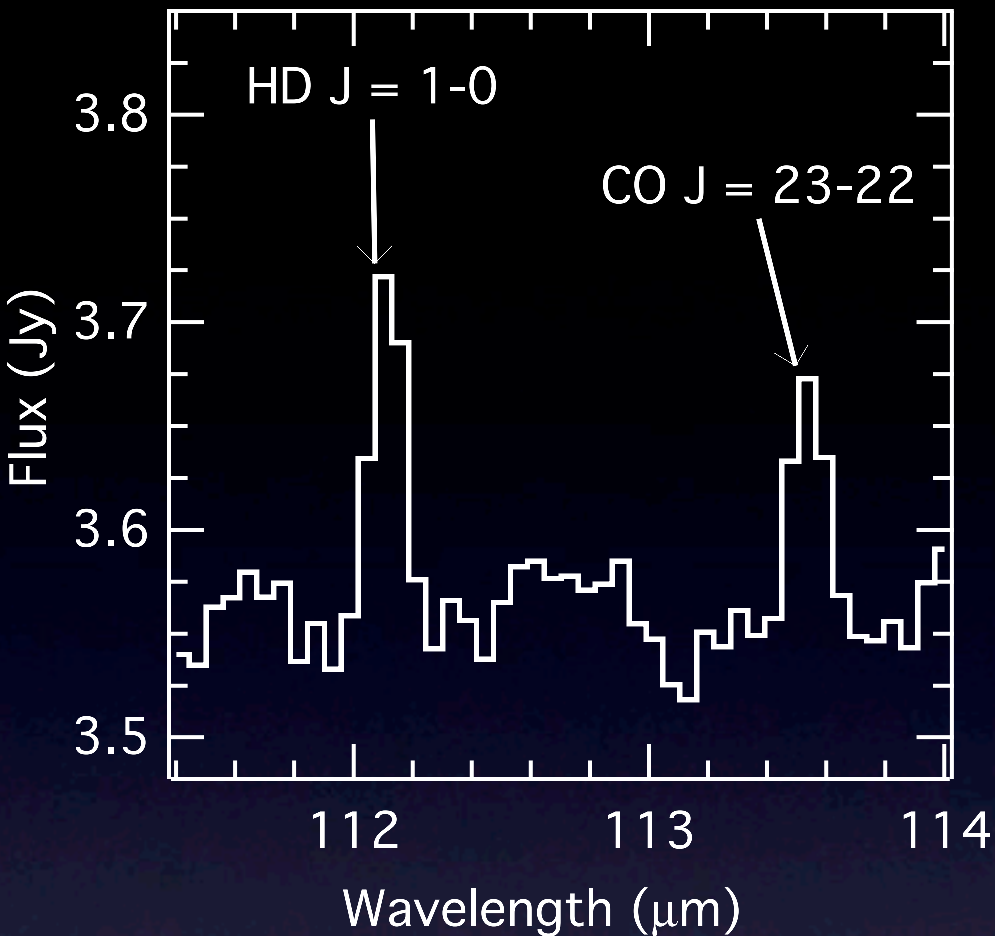

CO
J = 3-2
T_R (K)
0
5
10
15
20
V_{LSR} (km s^{-1})

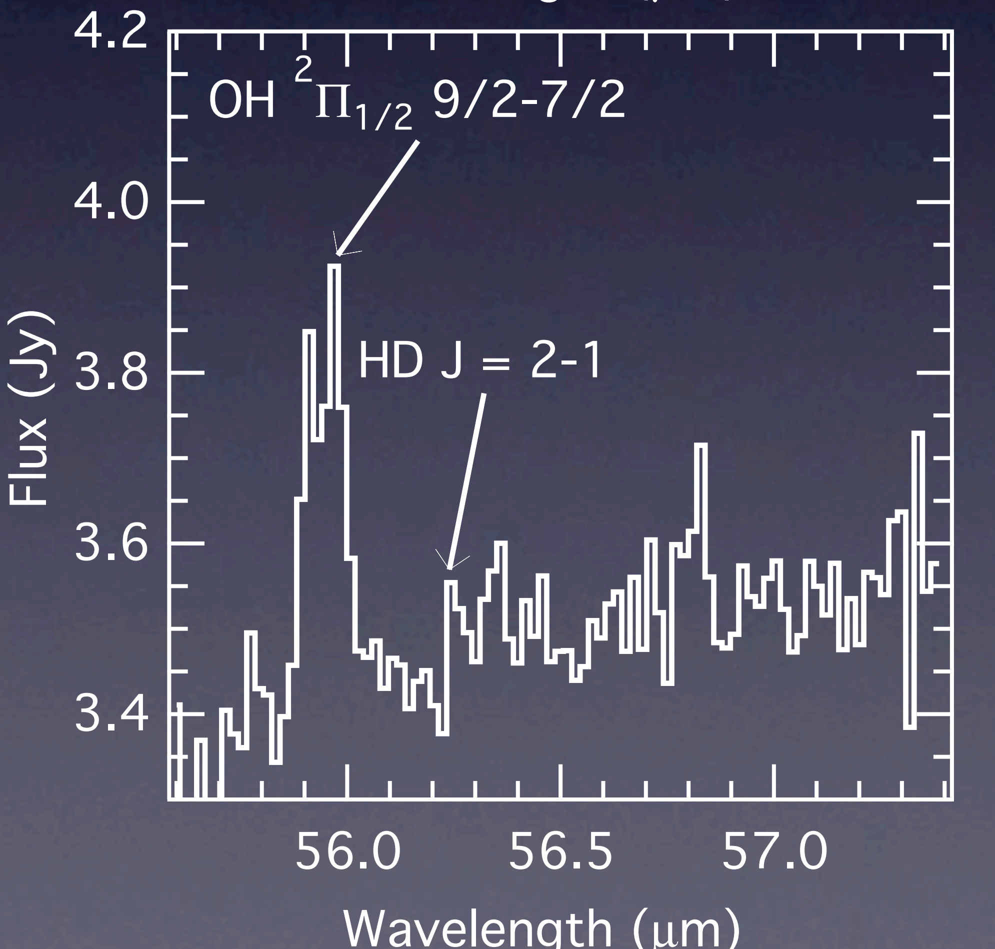






Tuesday, May 14, 13



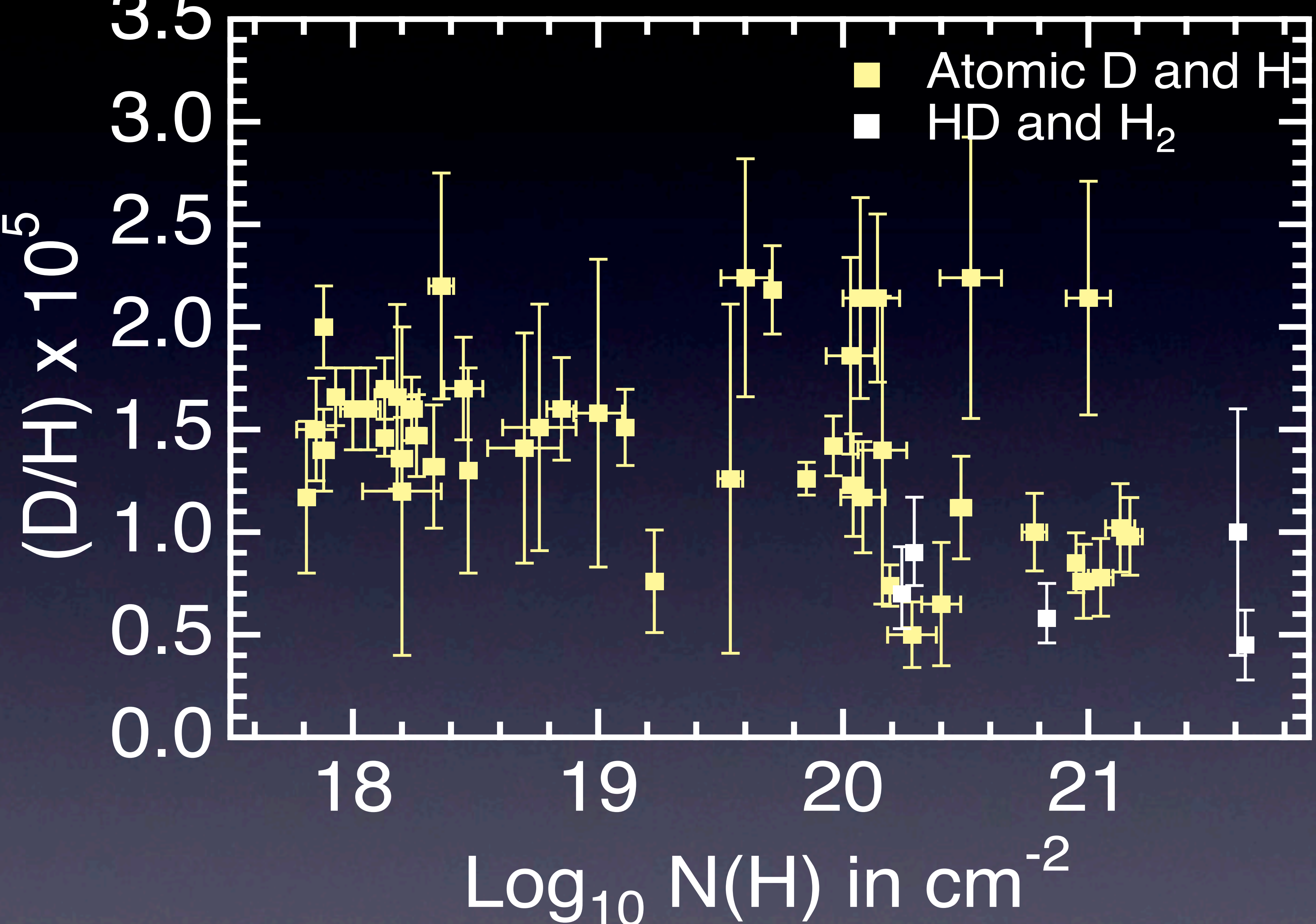


Herschel Detection of HD towards TW Hya

- 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 (~1.5 x 10^{-5})
- HD will follow H_2 in the gas
- New probe of gas mass

Bergin et al. 2013, Nature, 493, 644

Deuterium Abundance



from atomic D & H (Friedman et al. 2006)

from HD & H_2 (Neufeld et al. 2006)

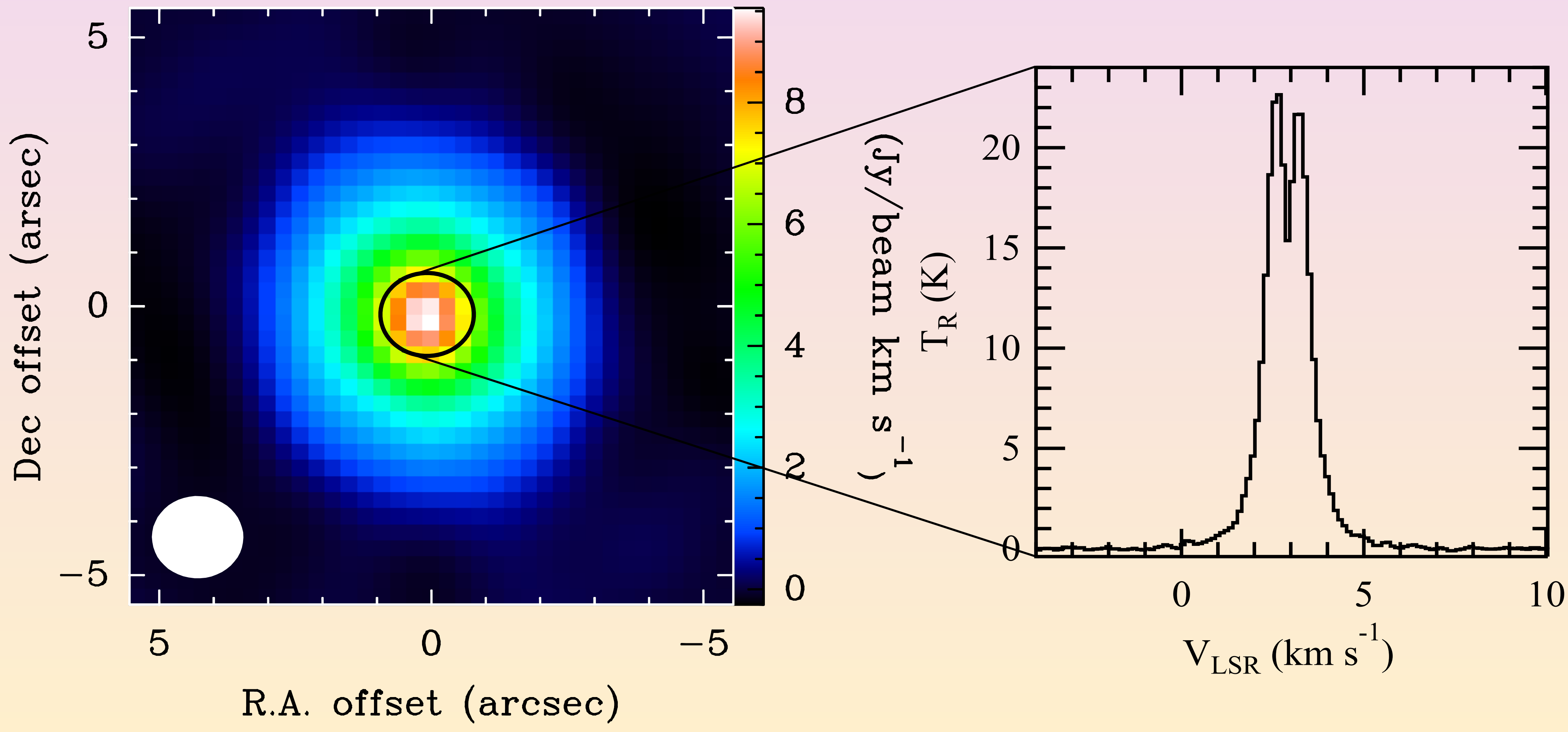
HD and the Disk Gas Mass

- Emission is strongly sensitive to gas temperature:

$$M_{gas} \propto \frac{F_l}{x(\mathrm{HD})} D^2 \exp\left(\frac{128.5\mathrm{K}}{T_{gas}}\right)$$

- Does not trace $T_{gas} < 20$ K because J = 1 state is not populated
- Non-detection of HD J = 2 → 1 implies $T_{gas} < 80$ K for HD -- stringent limit is then $M_{gas} > 2.2 \times 10^{-4}\ M_{\odot}$

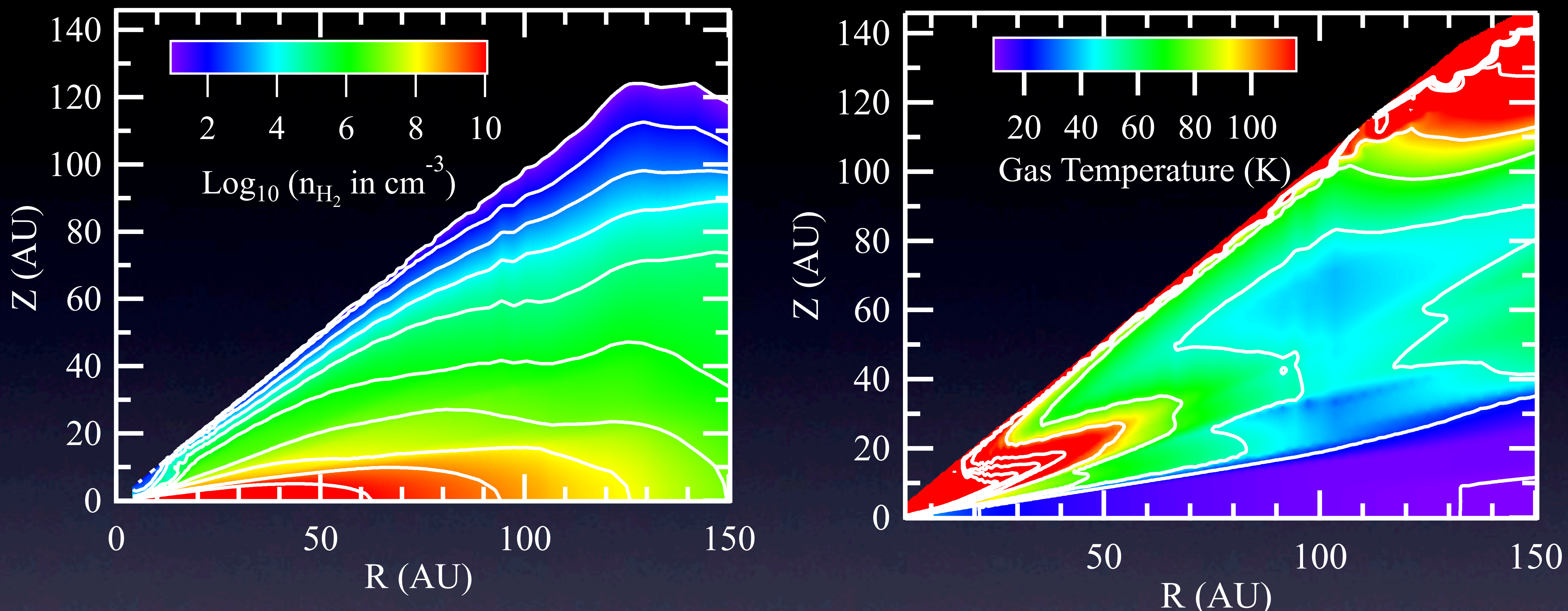
HD and the Disk Gas Mass



- Use ALMA observations of optically thick CO to constrain T_{gas} ~ 30 K inside of R = 43 AU.
- TW Hya minimum gas mass is > 4 x 10^{-3} $M_{\odot}$

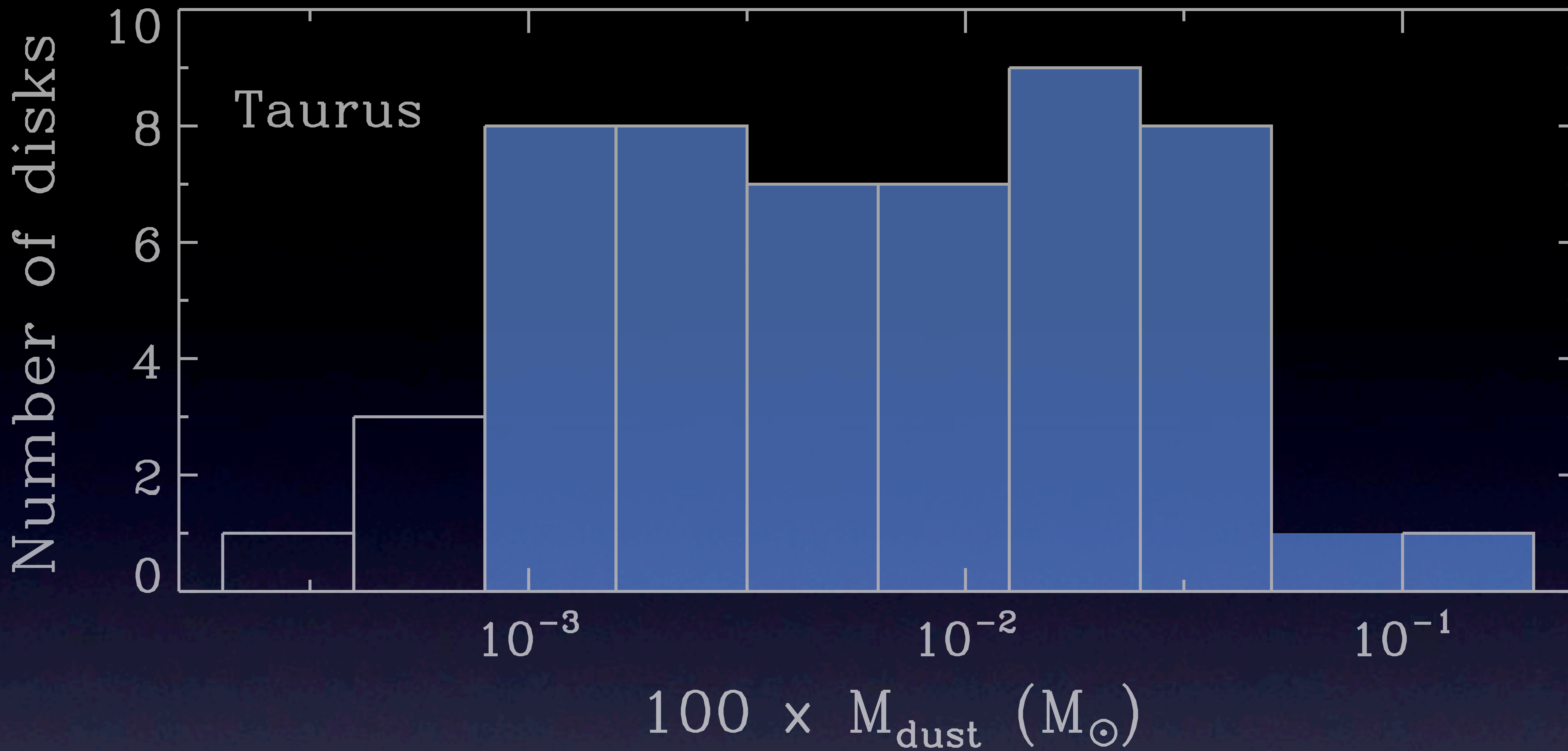
Bergin et al. 2013, Nature, 493, 644

HD and the Disk Gas Mass



- Thermochemical models with M_{gas} = 3 x 10^{-3} $M_{\odot}$ (Thi et al. 2010) -- predict HD line flux a factor of 20 too low
- Thermochemical models with M_{gas} = 0.06 $M_{\odot}$ (Gorti et al. 2010) -- are a factor of 2 below observed HD J = 1-0 emission

Bergin et al. 2013, Nature, 493, 644



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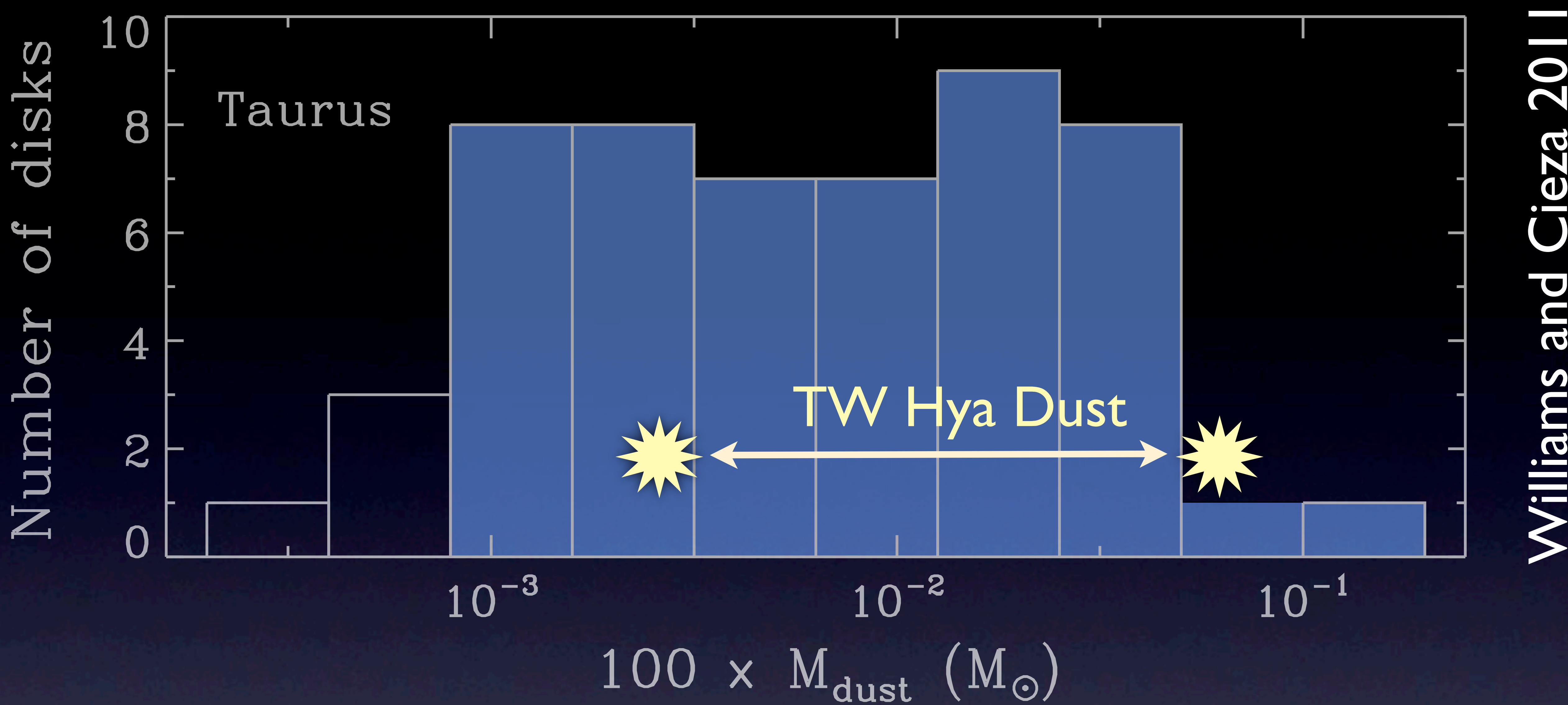

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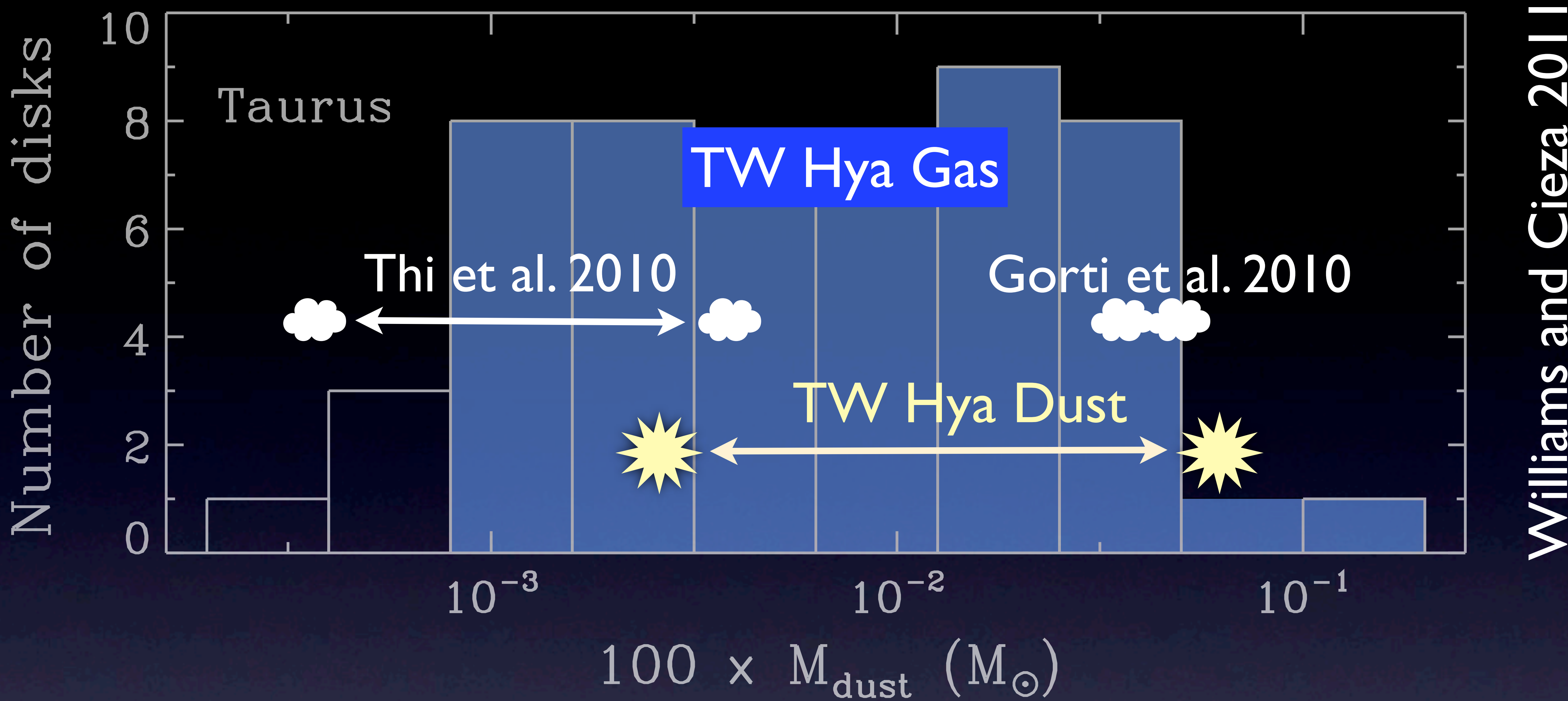

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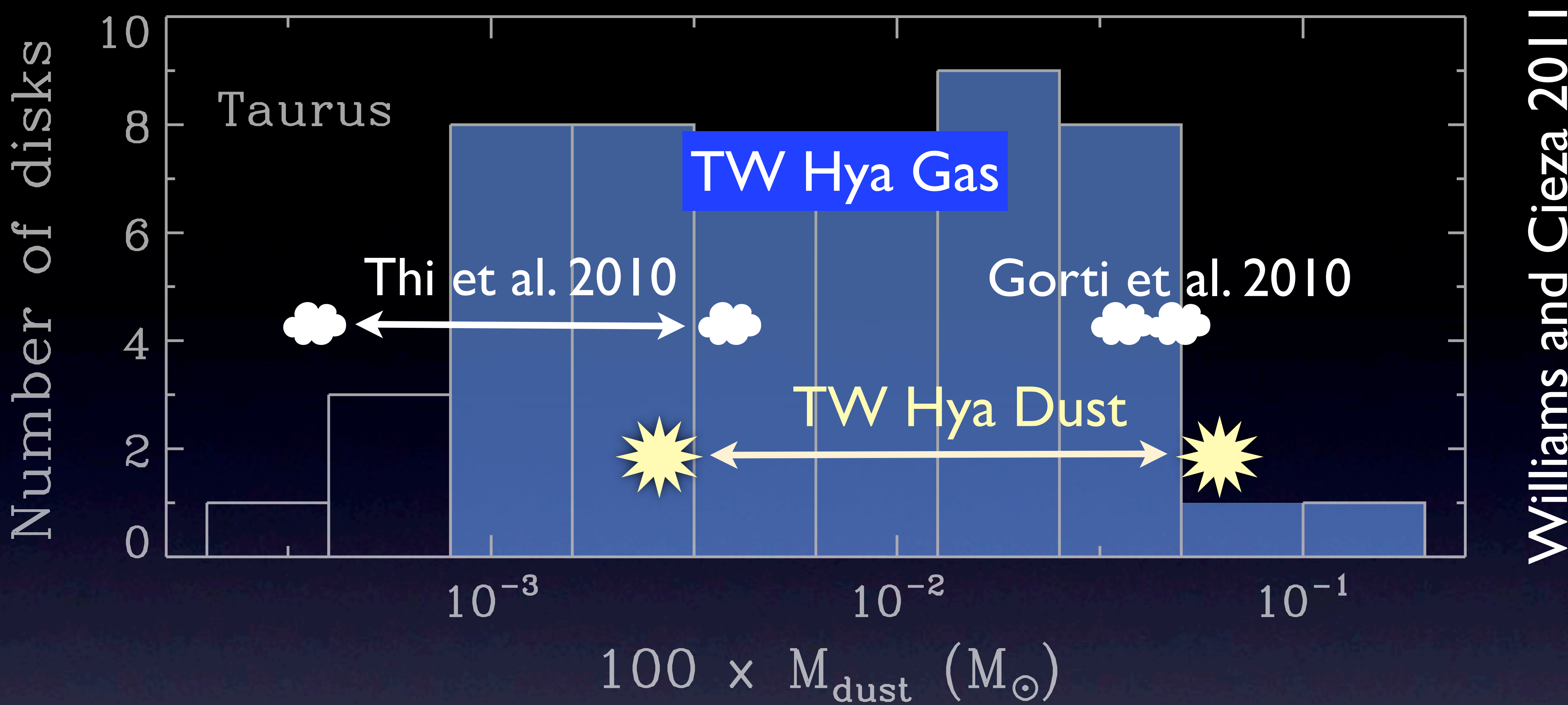

- TW Hya has a massive gas disk
- many times MMSN
- other systems are underestimated?

Bergin et al. 2013, Nature, 493, 644

Summary

- First detection of HD fundamental transition in a protoplanetary disk
- New estimate of disk gas mass in TW Hya from HD detection implies mass is greater than the minimum mass solar nebula.
- Current survey of 5 systems -- 1.5 additional HD detections.
  - ➡ other objects at greater distance and lower sensitivity
  - ➡ also did not discuss midplane optical depth