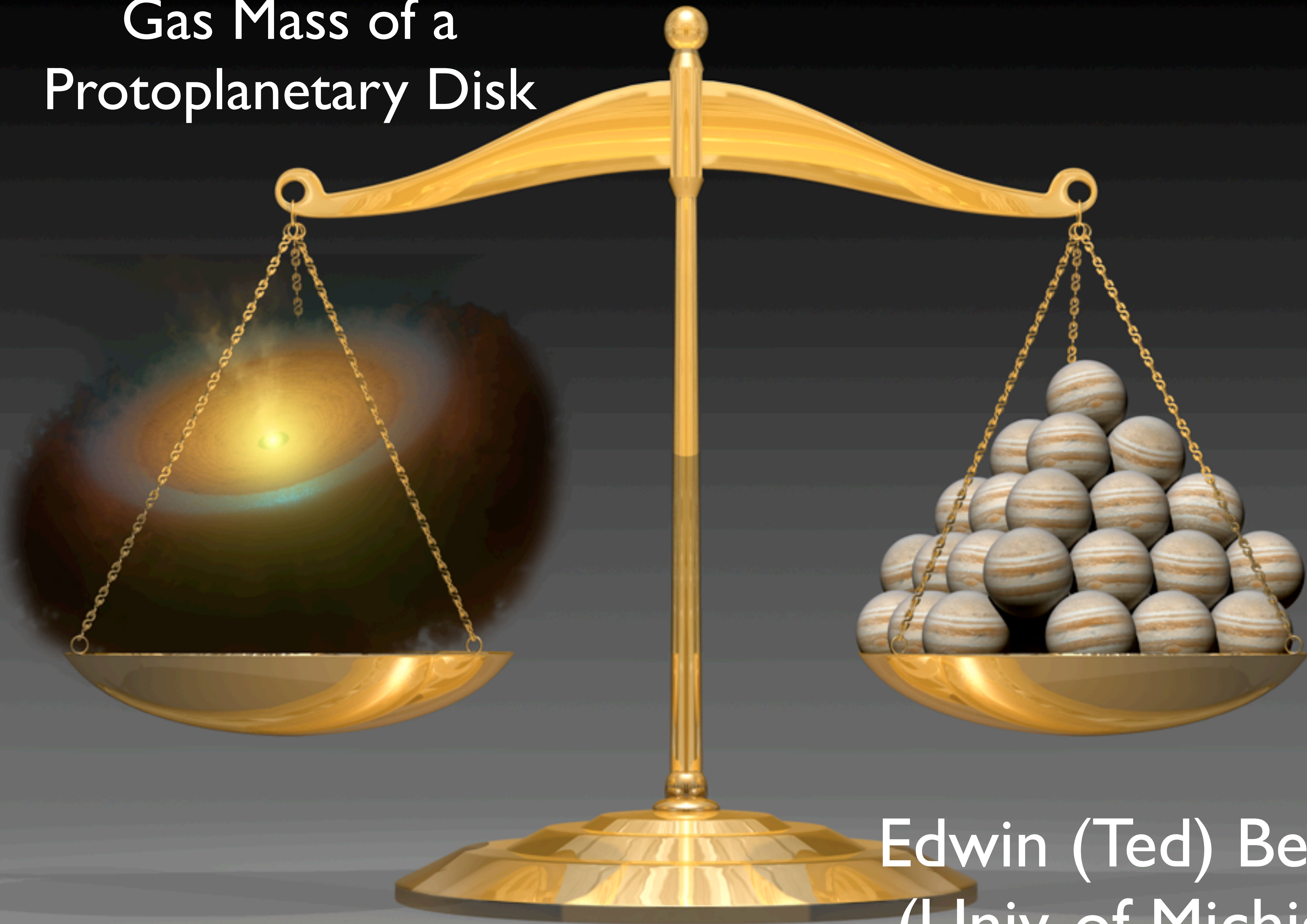
Using HD to Measure the Gas Mass of a Protoplanetary Disk



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(Univ. of Michigan)

HD and Disk Gas Mass

Excellent collaborators:

- Ilsedore Cleeves
- Uma Gorti
- Ke Zhang
- Geoffrey Blake
- Joel Green
- Sean Andrews
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- Thomas Henning
- Karin Öberg
- Klaus Pontoppidan
- Chunhua Qi
- Colette Salyk
- Ewine van Dishoeck

Funding from NASA for Herschel OT

Herschel Space Observatory

- ESA Cornerstone mission covering far-infrared wavelengths 60 - 670 µm
- 3.5m diameter telescope passively cooled to 80 K
- Orbit: Lissajous around L2 - very stable
- 3 instruments:
    - ➡ SPIRE (imaging; FTS R ~ 350-1300)
    - ➡ PACS (imaging; spectrscopy R ~ 1000-5000)
    - ➡ HIFI (heterodyne spectroscopy R > 10^5)

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.

Minimum Mass Solar Nebula

By looking at the mass distribution in the solar system, Hayashi (1981) concluded that the protoplanetary disk of our own solar system had to have (at least) the following mass distribution:

$$\Sigma_{\text{gas}} = 1700 \left(\frac{r}{1\text{AU}} \right)^{-3/2} \text{g/cm}^2$$

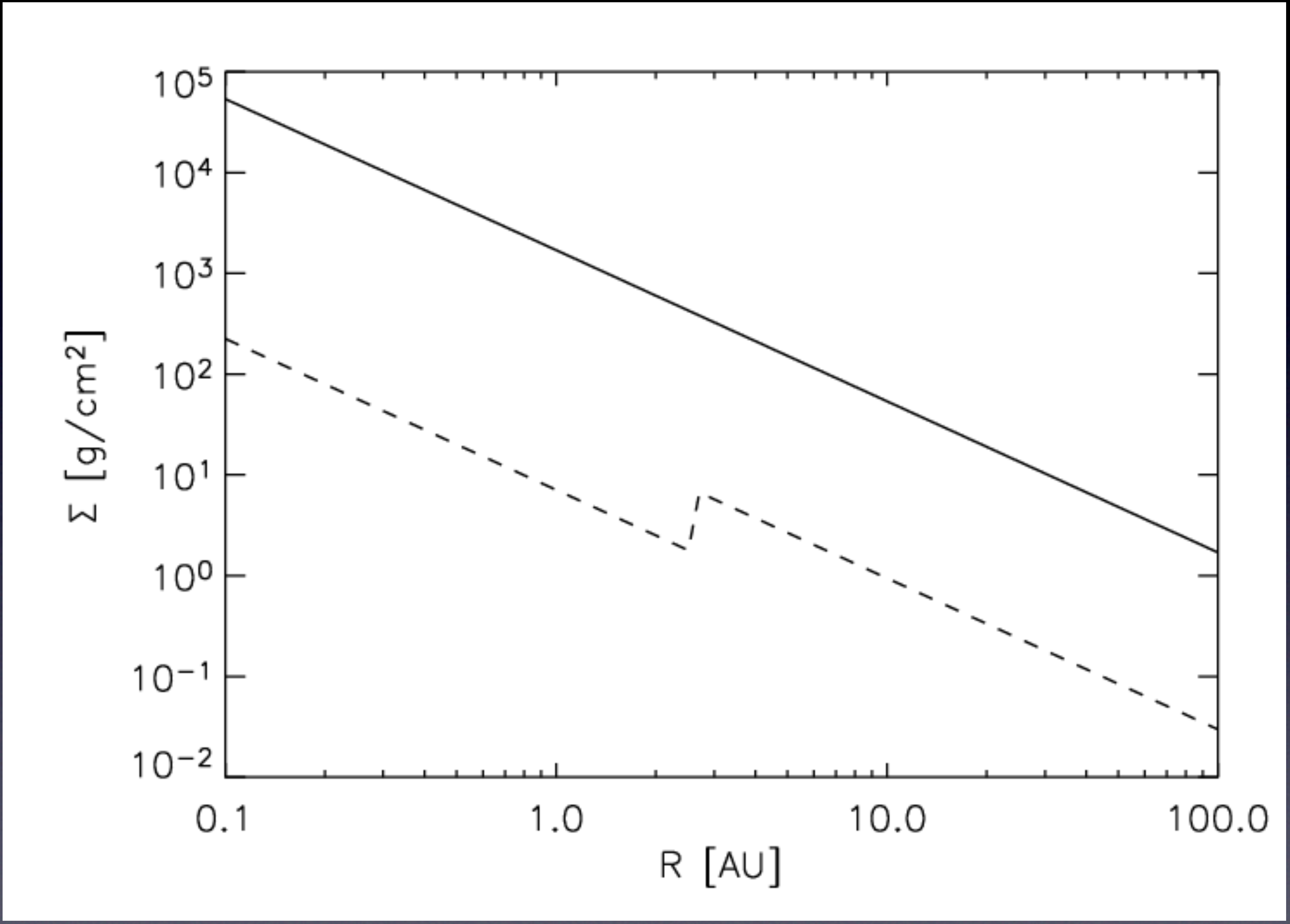
$$\Sigma_{\text{solids}} = 7.1 F_{\text{snow}} \left(\frac{r}{1\text{AU}} \right)^{-3/2} \text{g/cm}^2$$

$$F_{\text{snow}} = \begin{cases} 1, & r < r_{\text{snow}} \\ 4.2, & r > r_{\text{snow}} \end{cases}$$

F_{snow} is the solid mass enhancement due to freeze-out of water onto the grains.

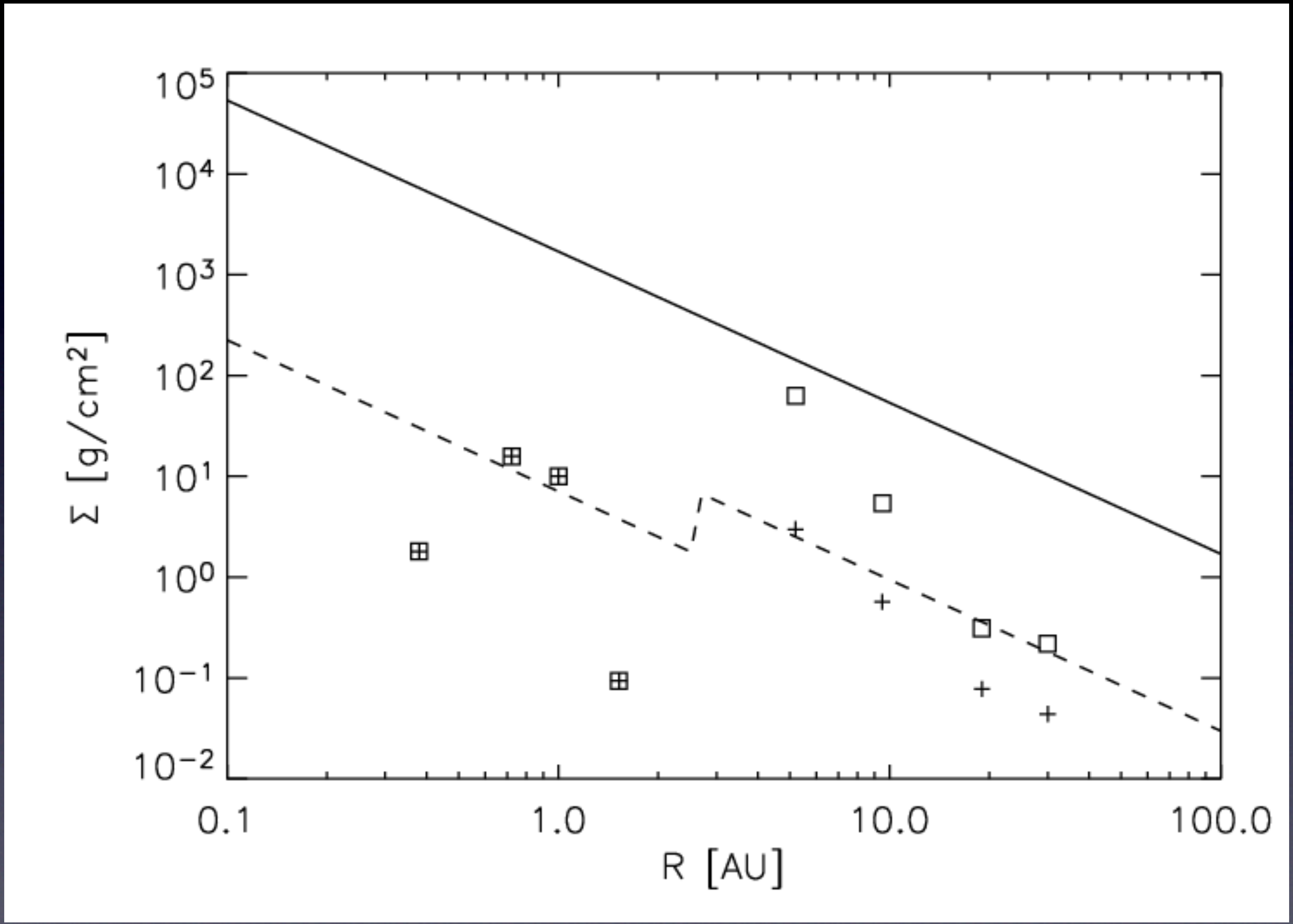
Dullemond

Minimum Mass Solar Nebula



Dullemond

Minimum Mass Solar Nebula: 0.01 $M_\odot$



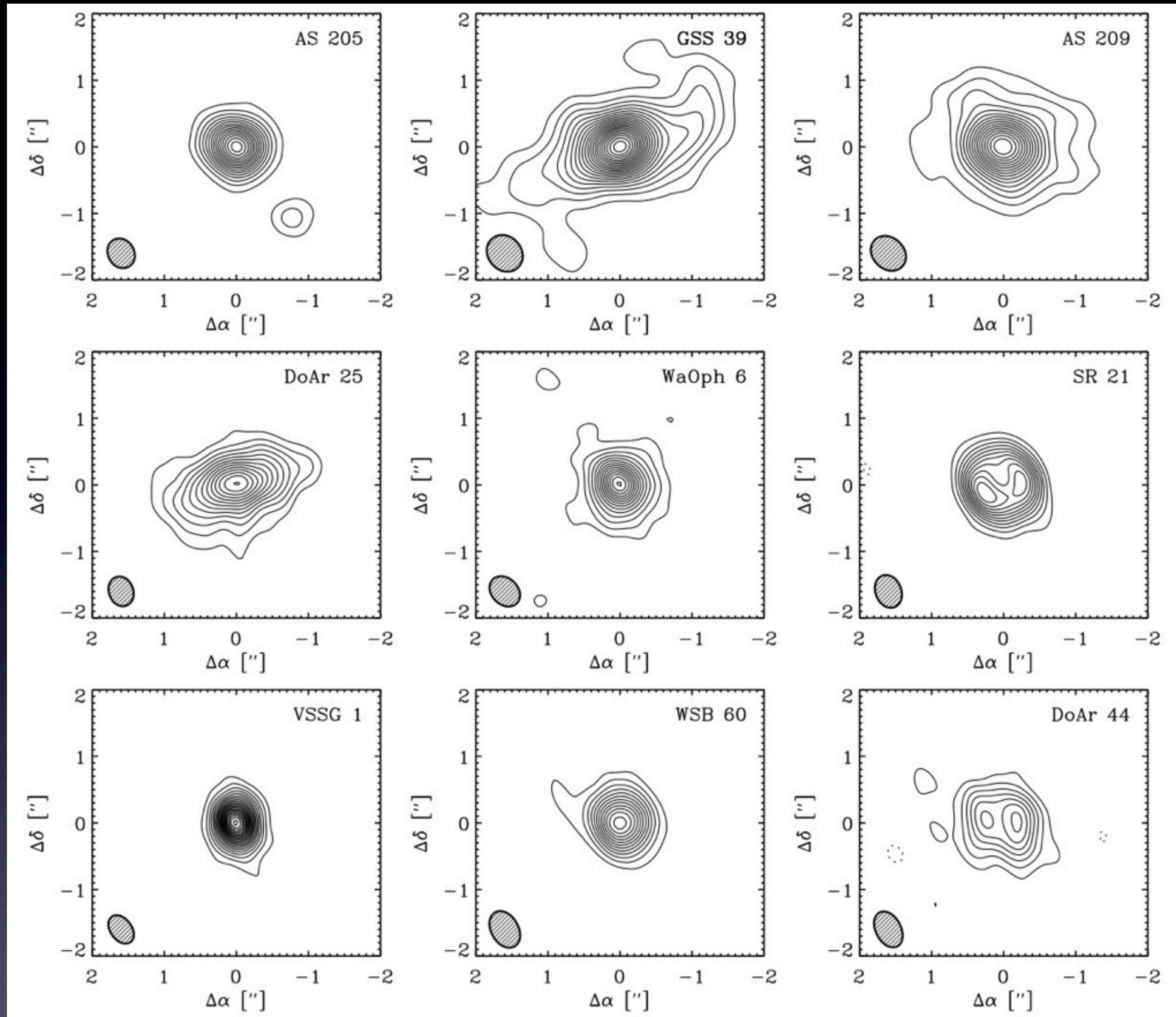
Dullemond

Our planets overplotted: $M_{planet}/\pi\Delta R$

Box = planet, cross = estimated rocky core

Protoplanetary Disk Gas Mass

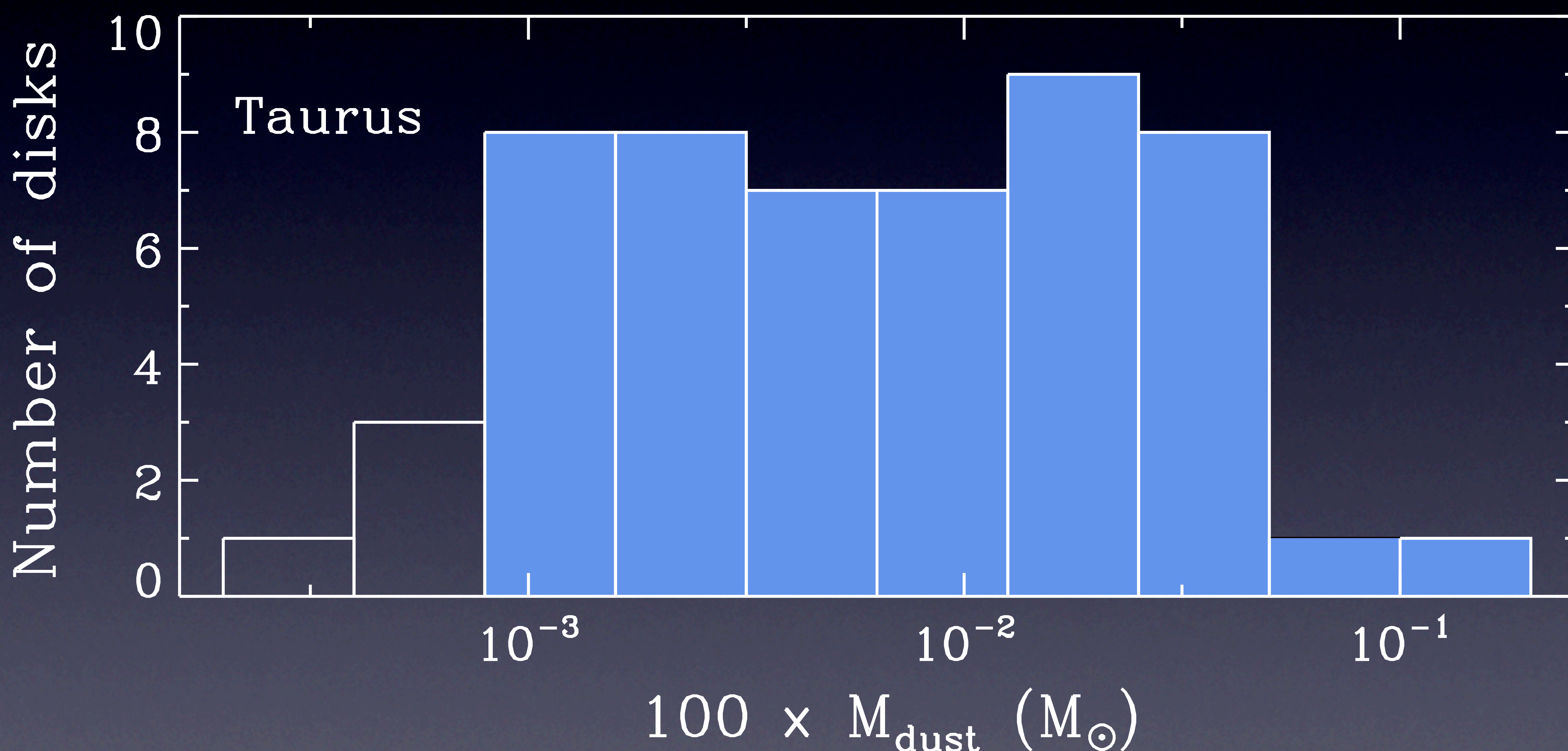
- For protoplanetary disks it is more complicated
  - ➡ H_2 contains all the mass but is unemissive for typical temperatures (20 K) that characterize the disk mass reservoir
- Two proxies are used:
  - ➡ thermal emission from dust grains at mm/sub-mm wavelengths (and a gas to dust ratio)
  - ➡ thermo-chemical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



Andrews et al. 2009

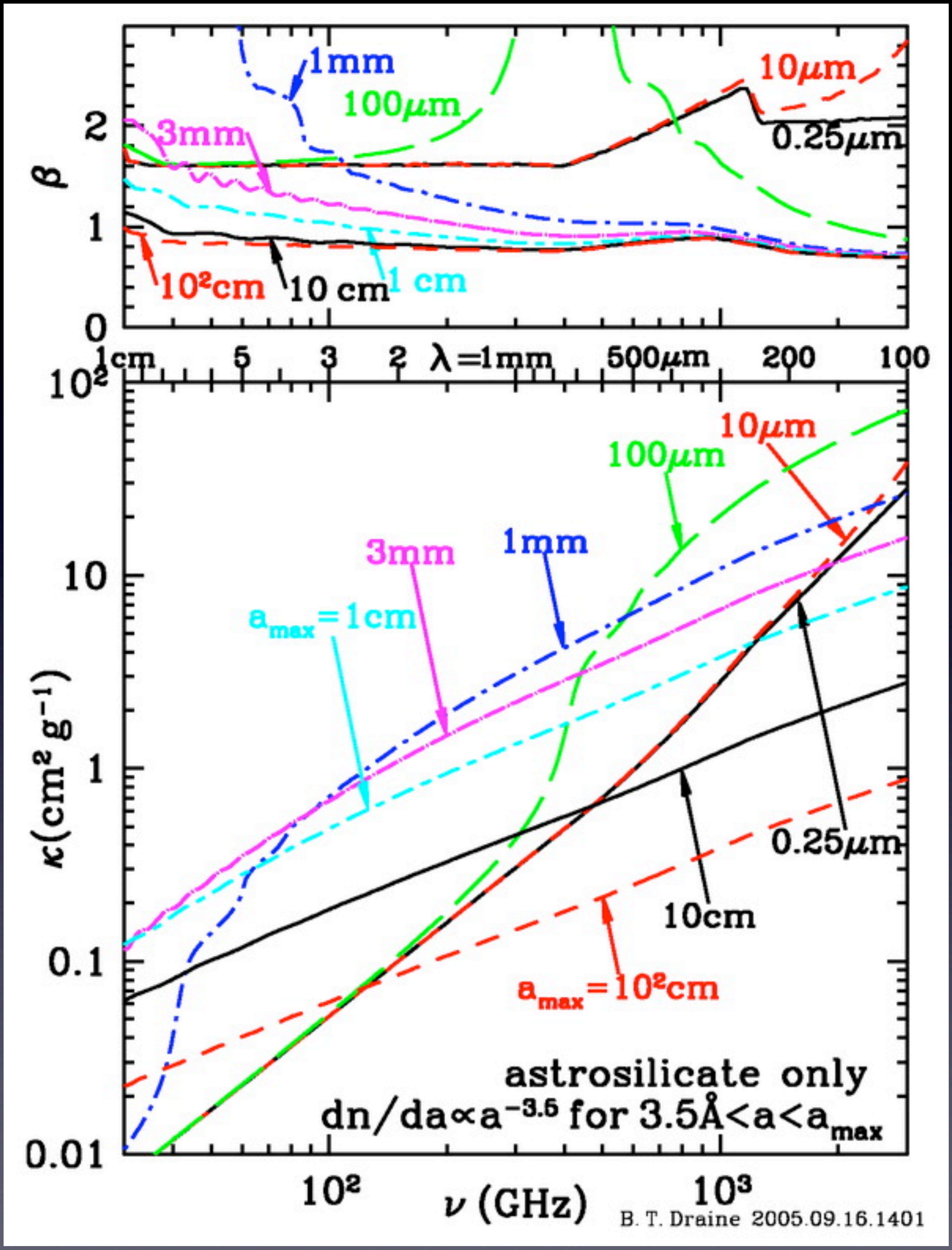
- Mass (gas + dust) = $F_\nu D^2/\kappa_\nu B_\nu[T(r)]$
- at sub-mm wavelengths - Mass $\propto F_\nu/\kappa_\nu T$

Protoplanetary Disk Gas Mass



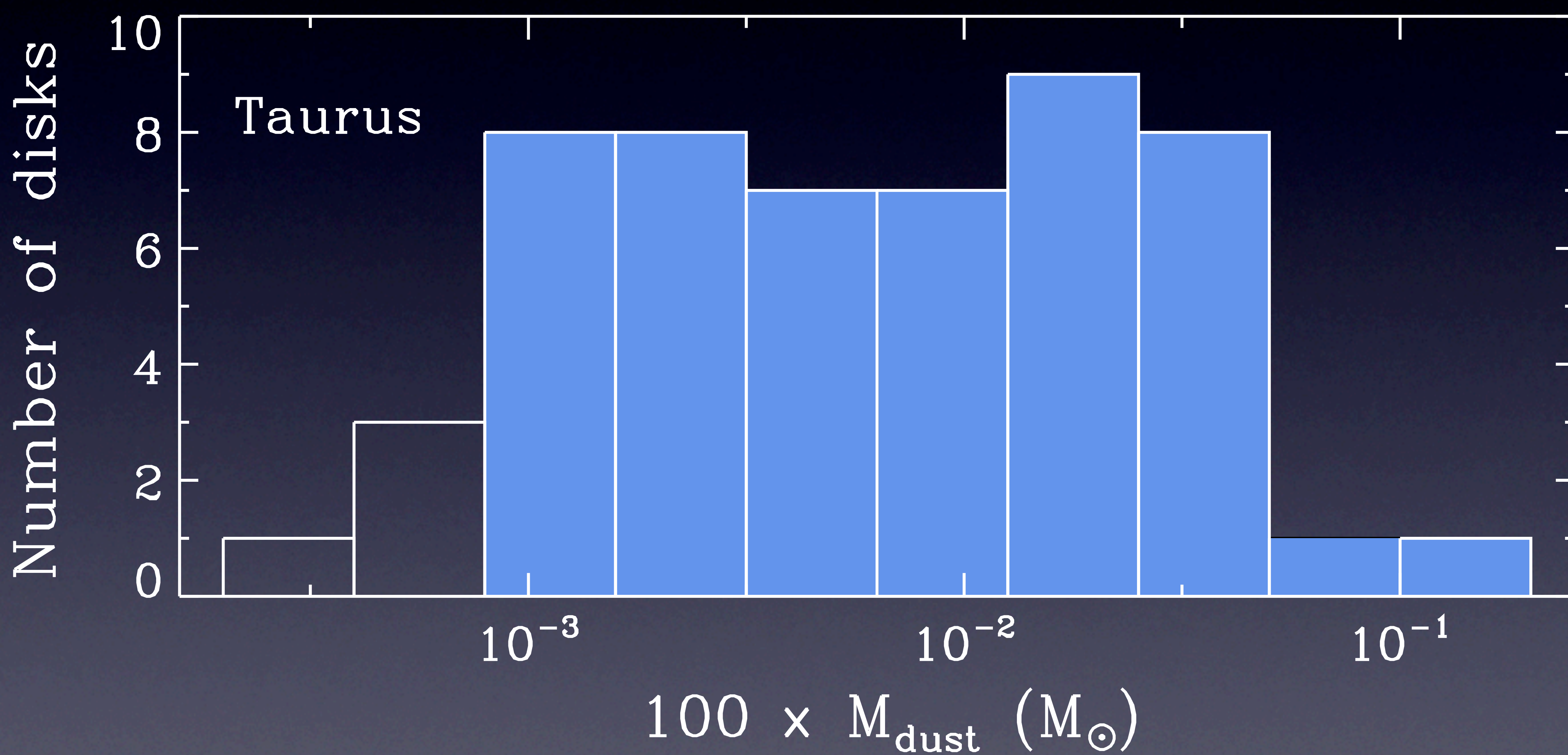
Williams and Cieza 2011

- 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

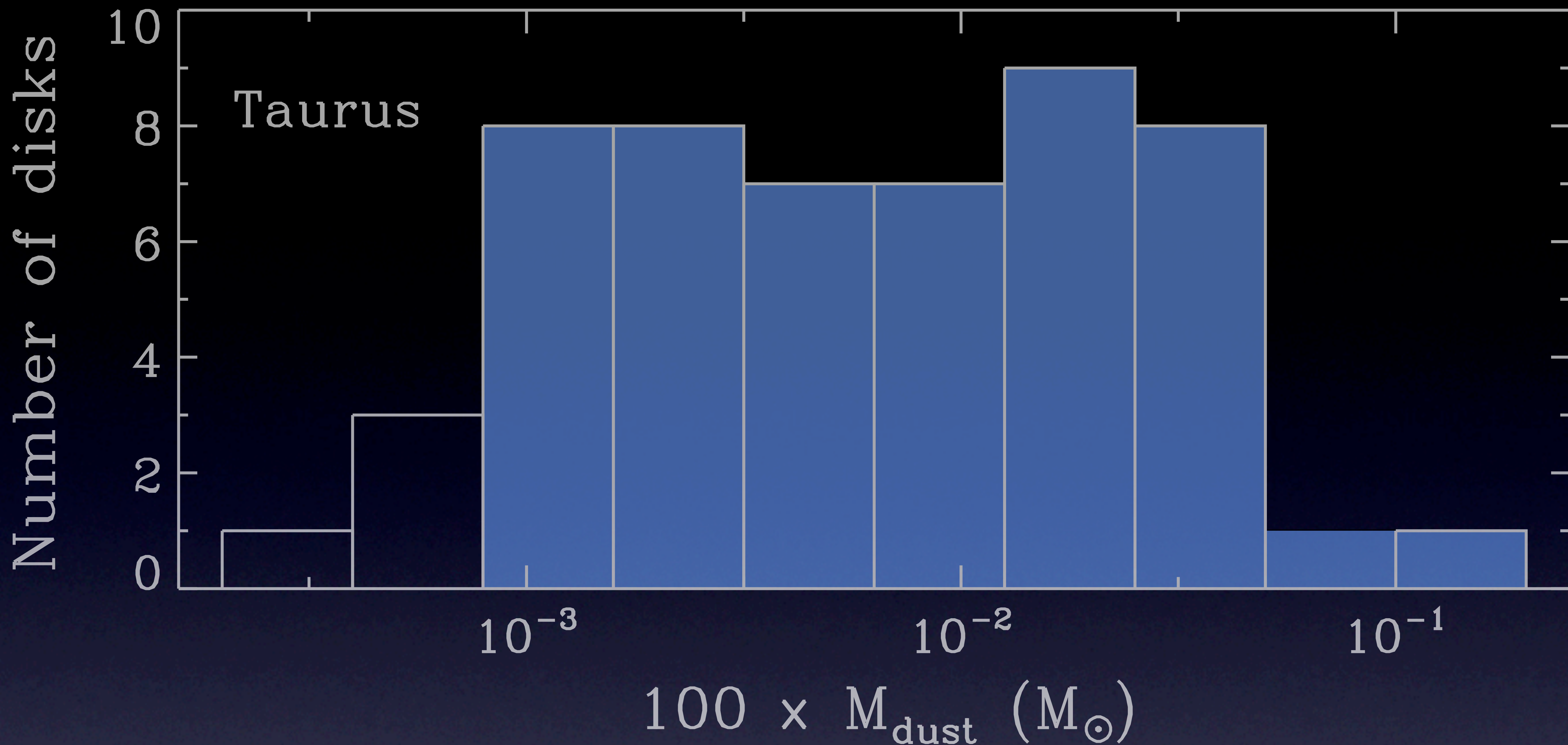


Williams and Cieza 2011

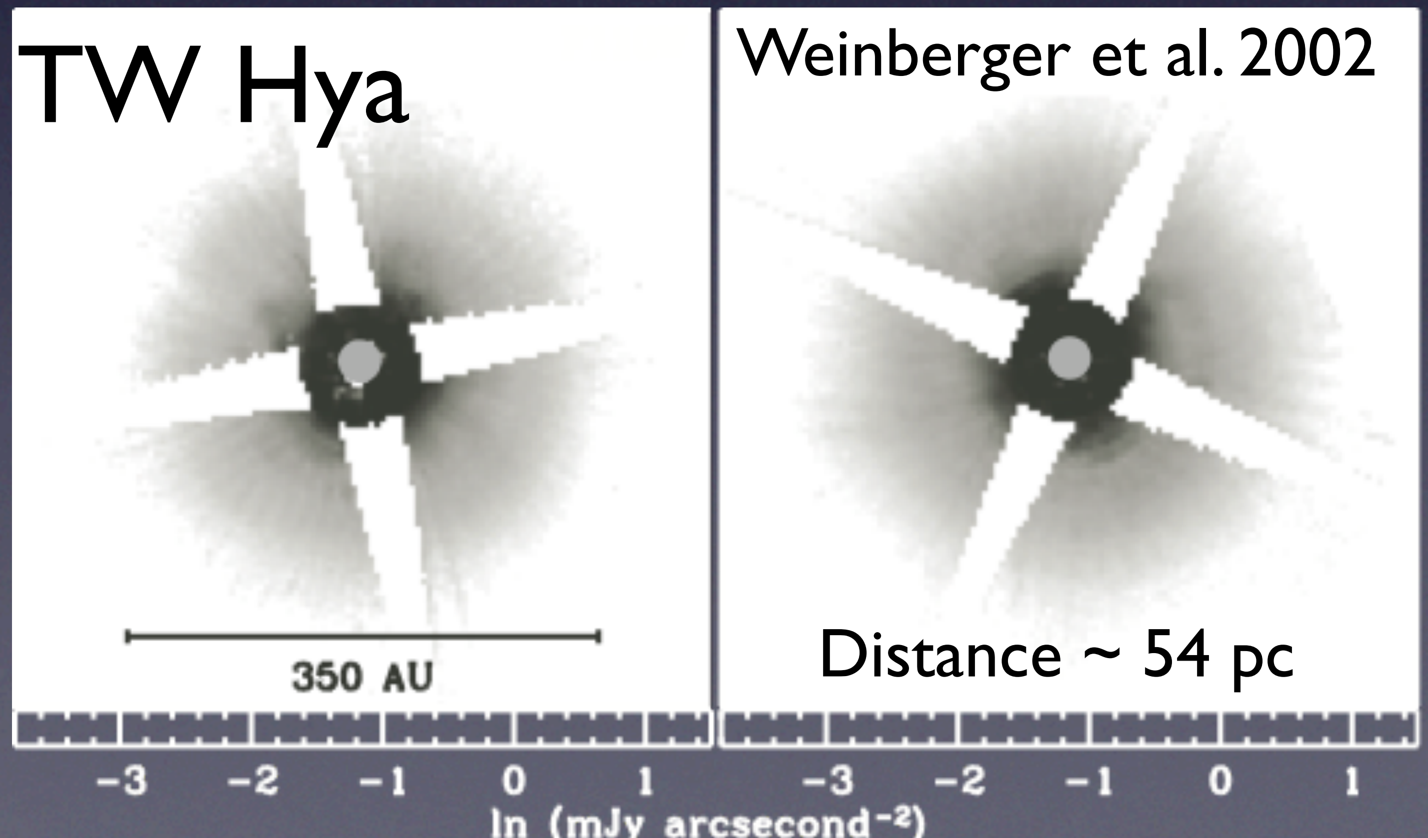
How much of this distribution is due to uncertainty?????

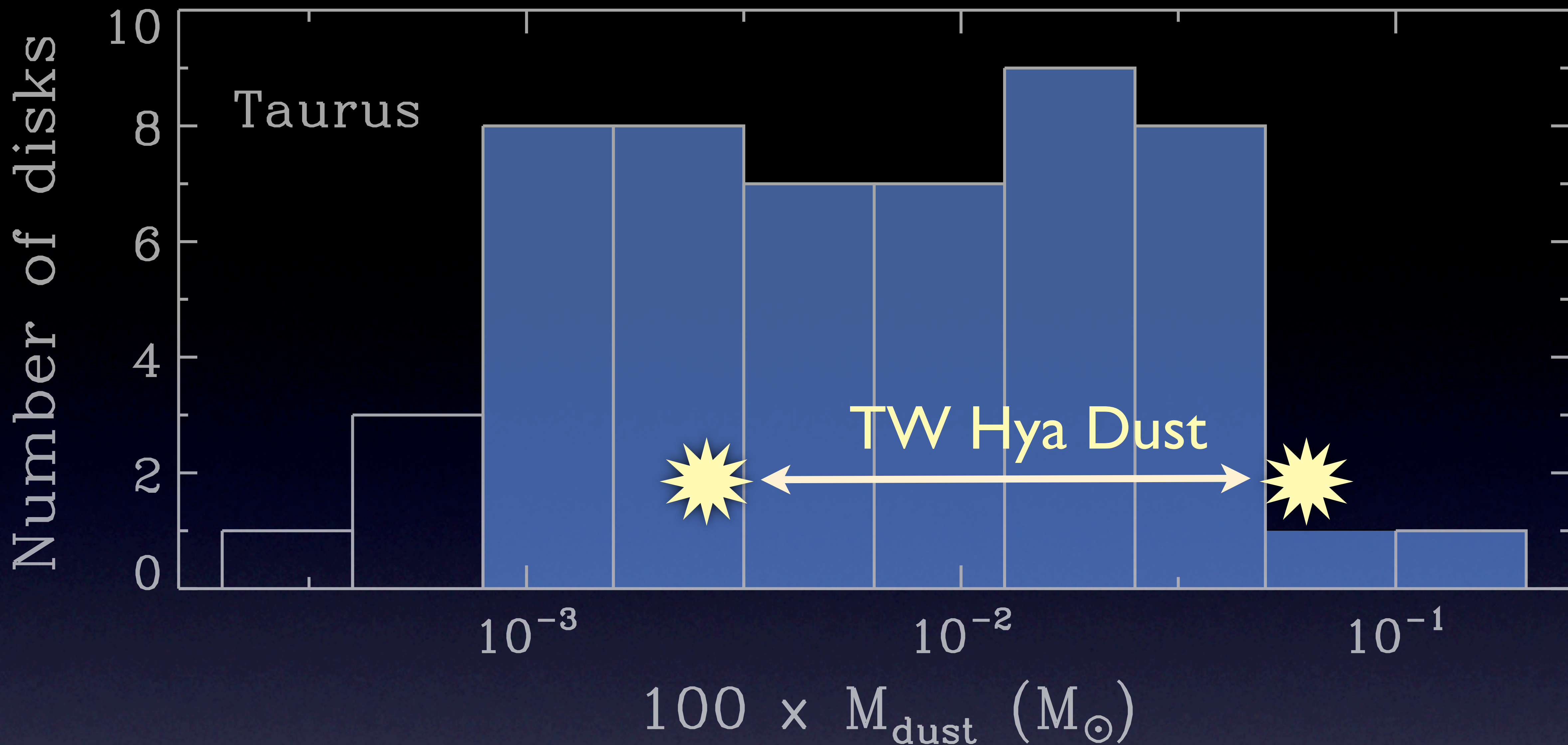
Thermo-chemical Models

- Models of the coupled disk thermal physics and chemistry
- 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

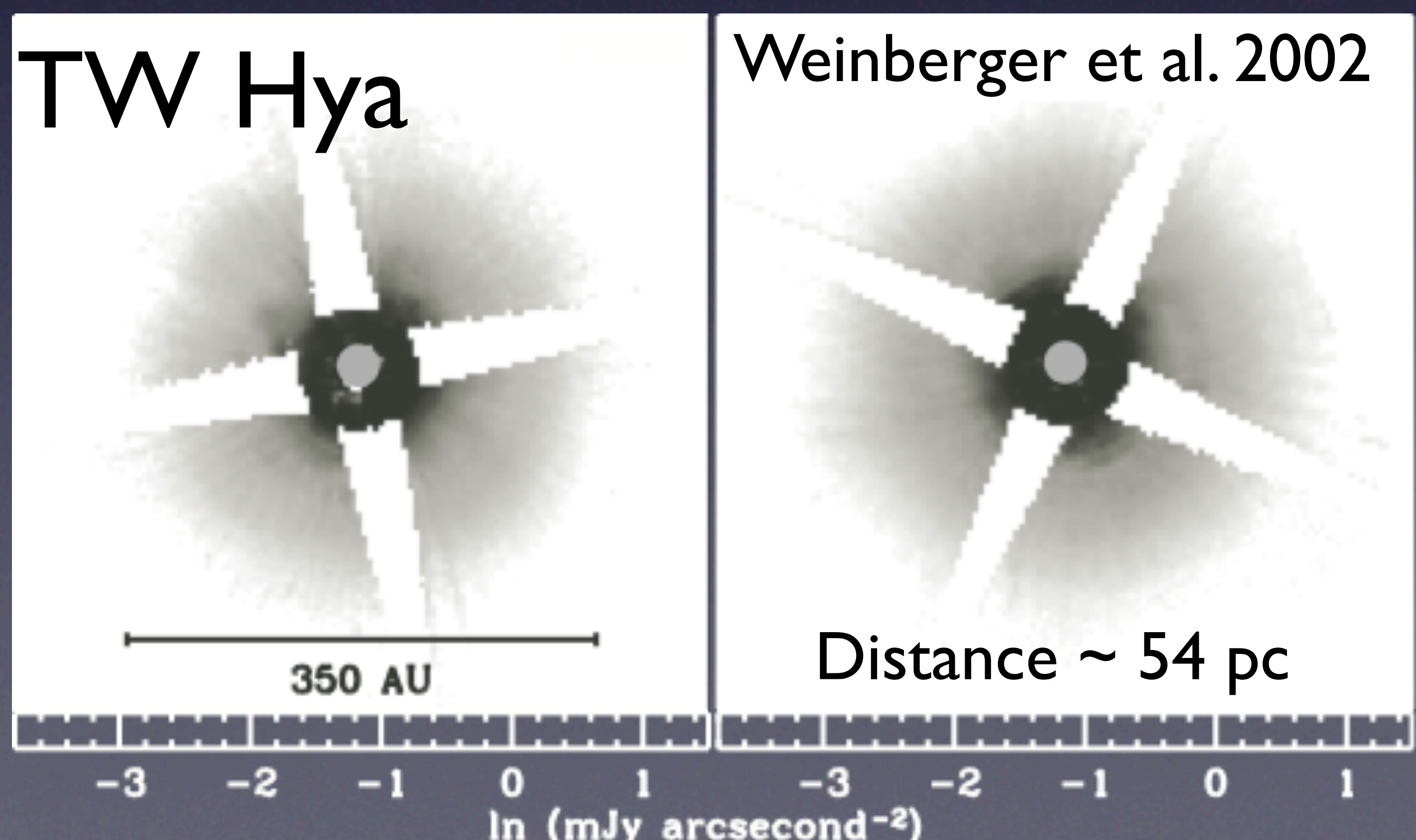


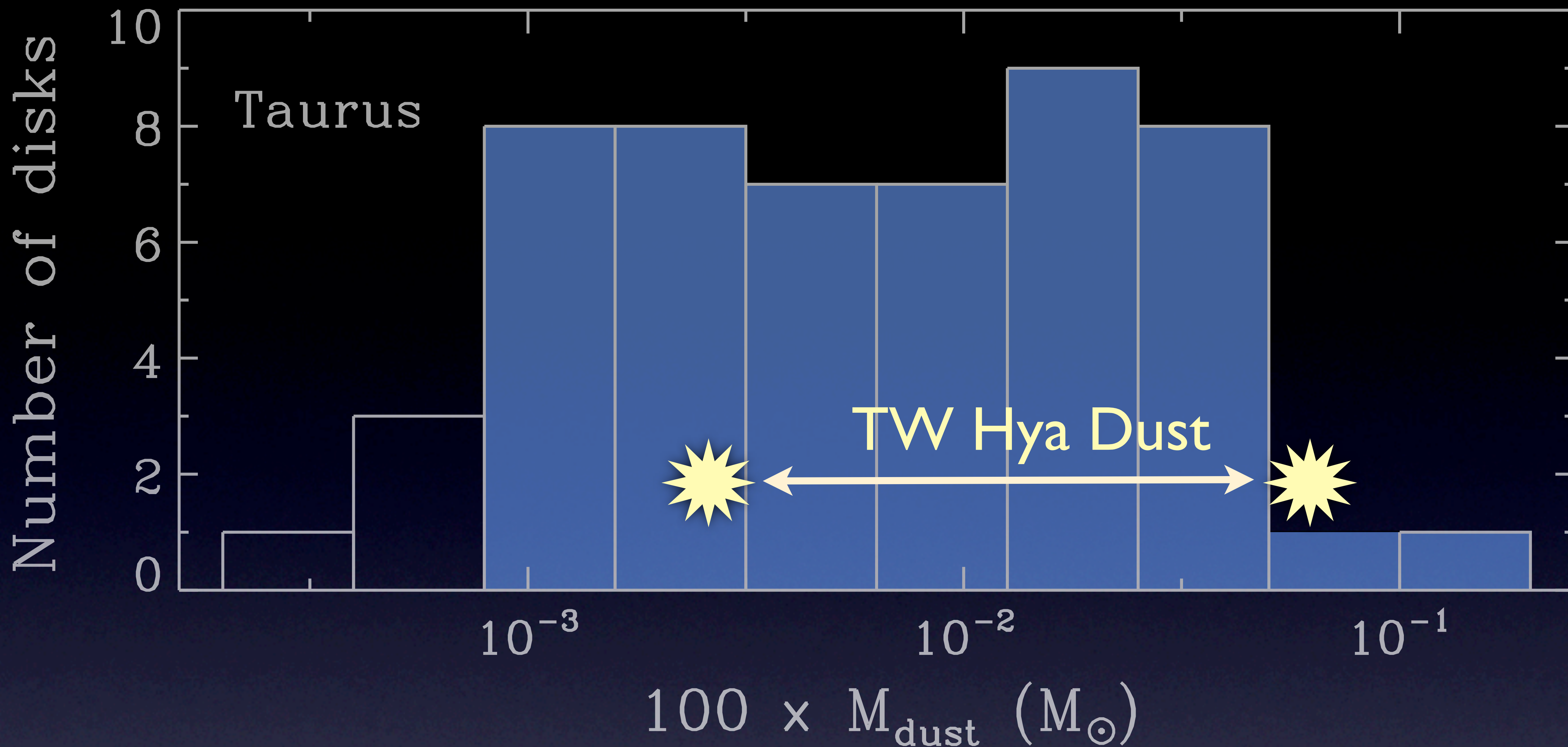
Williams and Cieza 2011



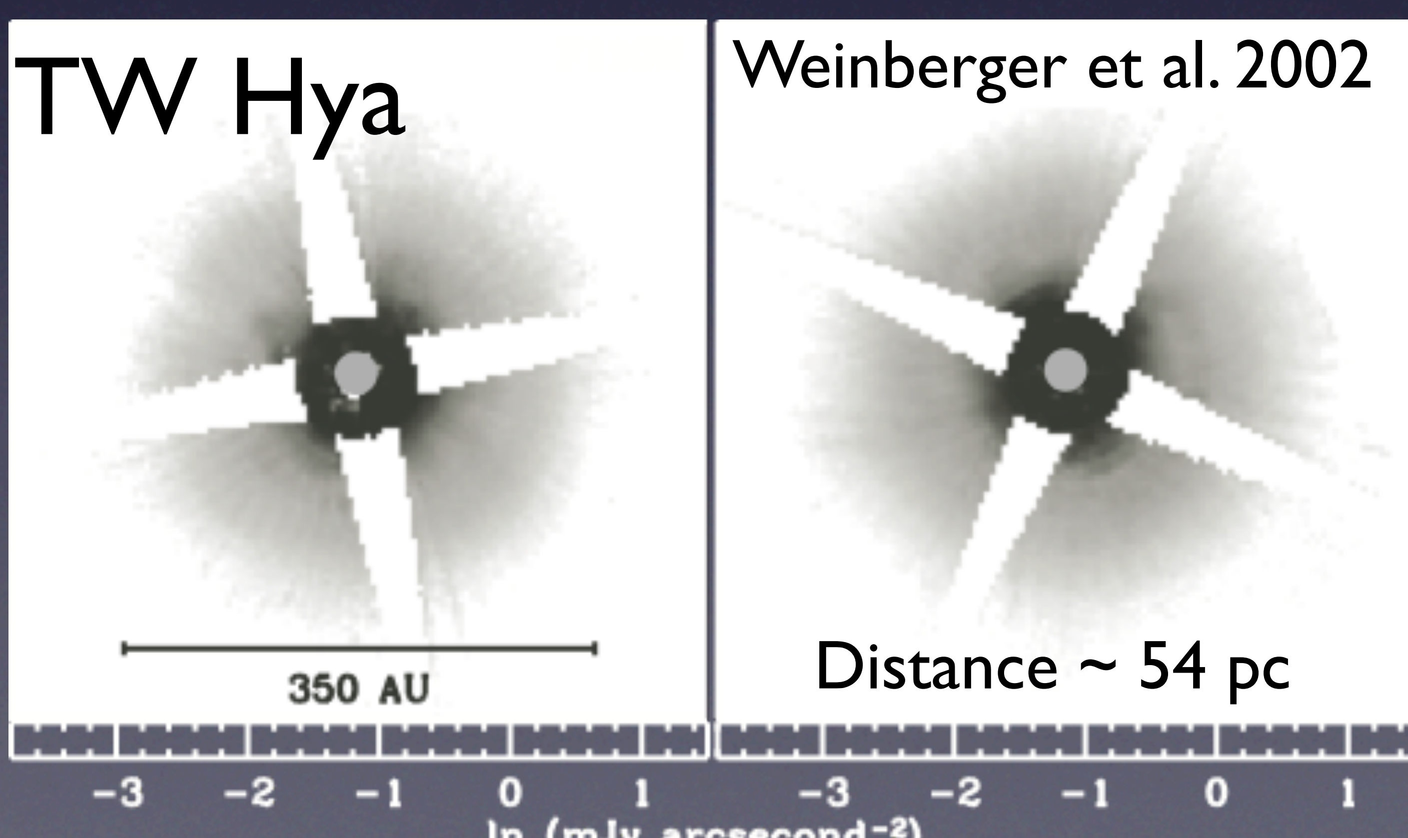


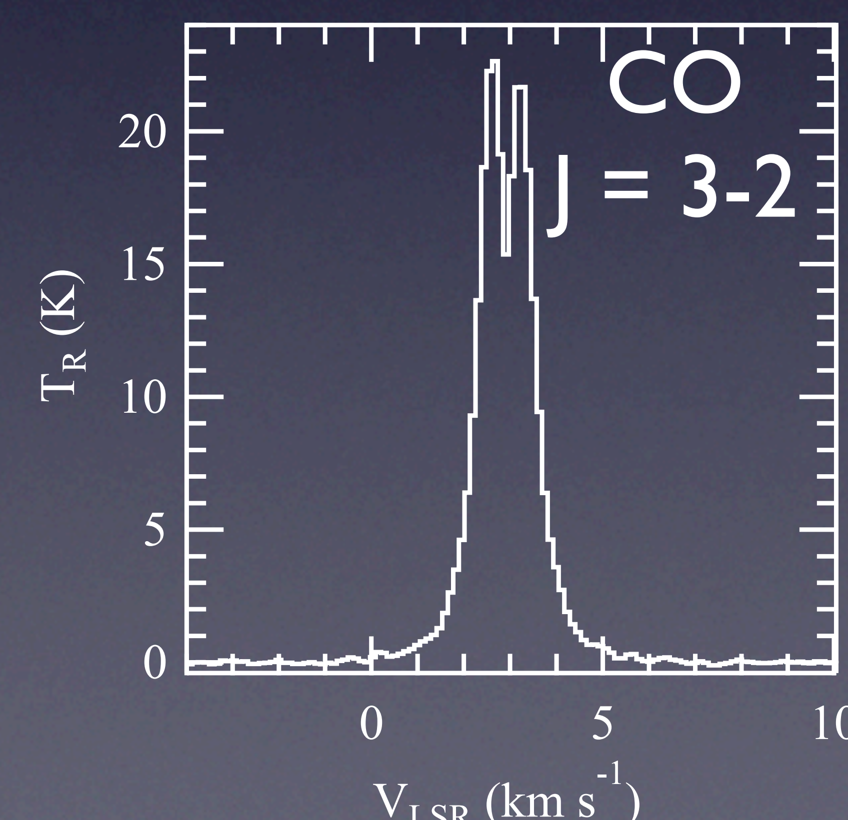
Williams and Cieza 2011

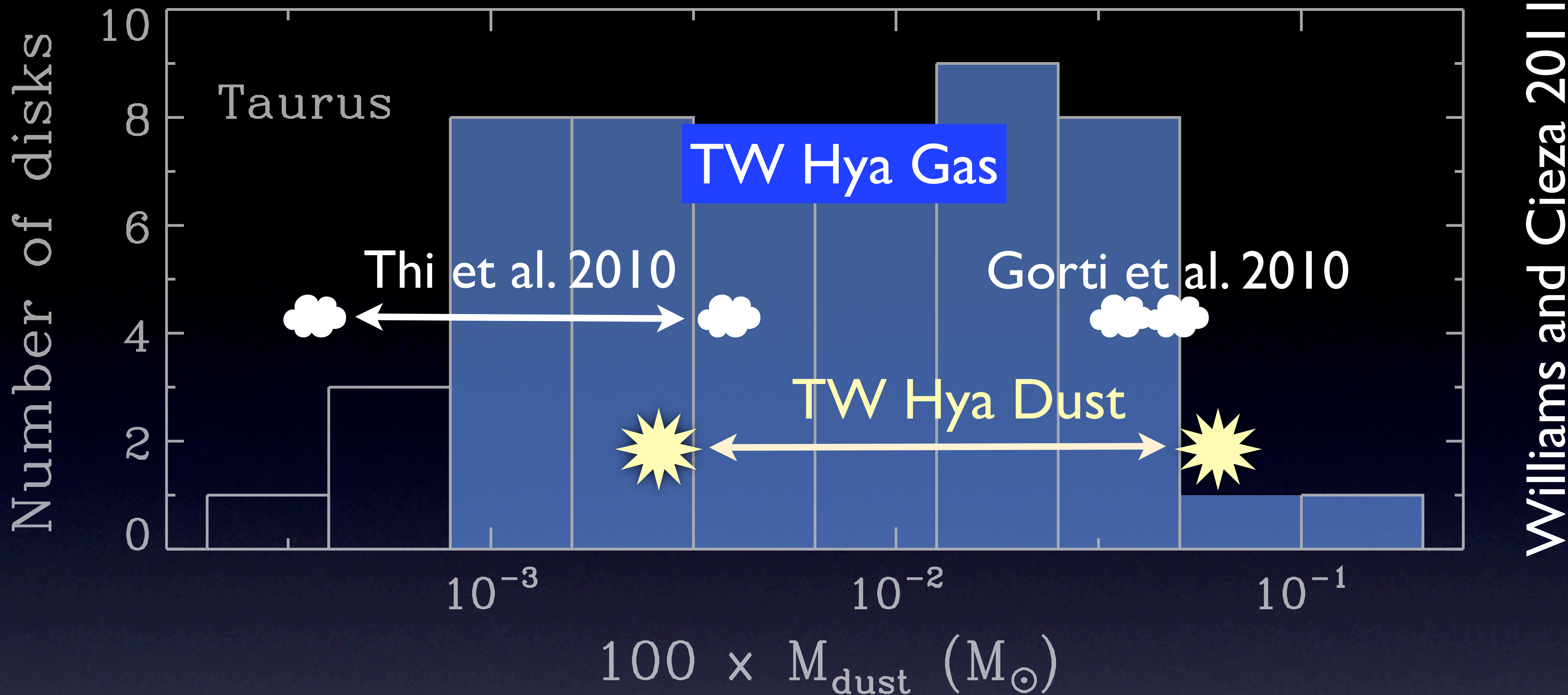




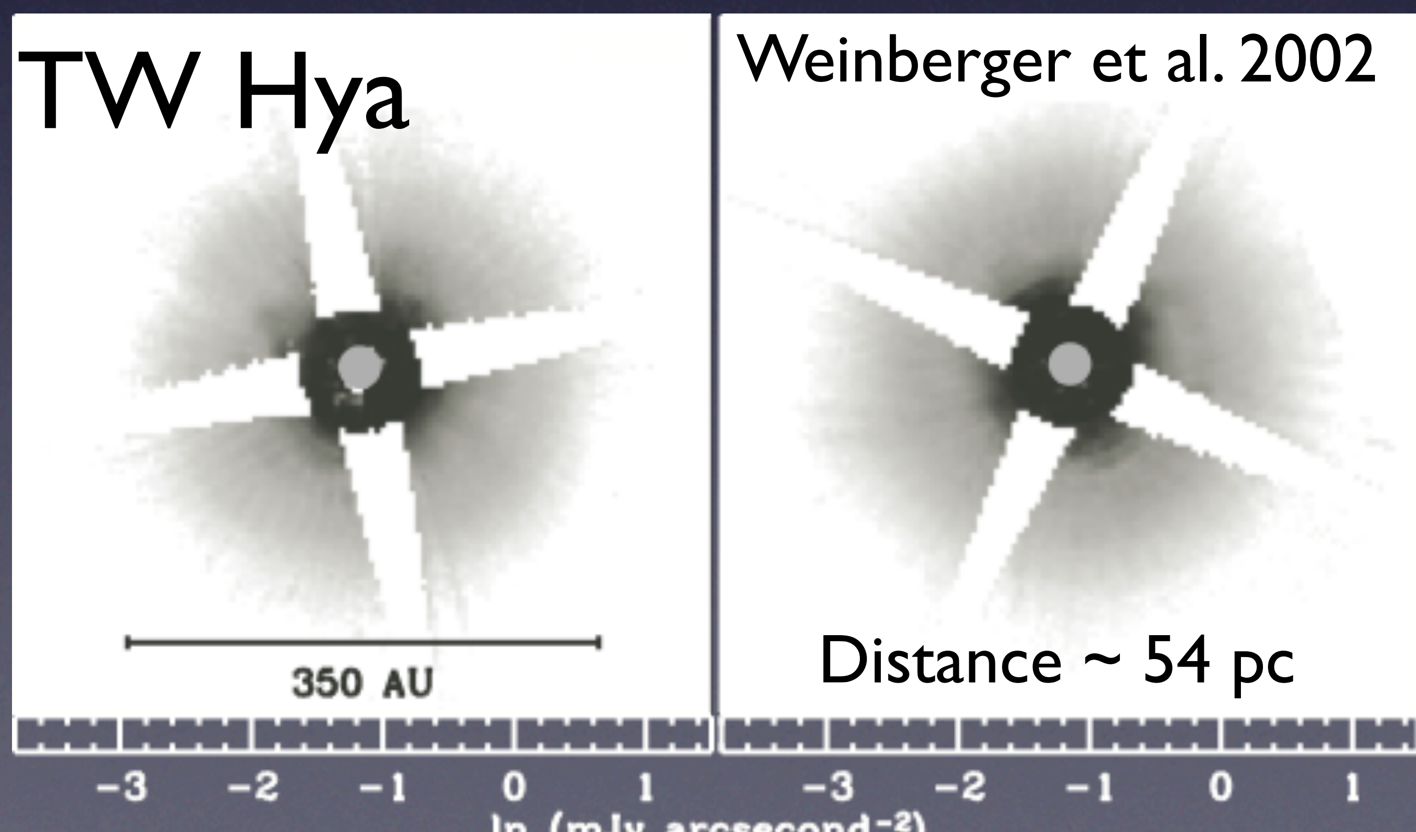
Williams and Cieza 2011



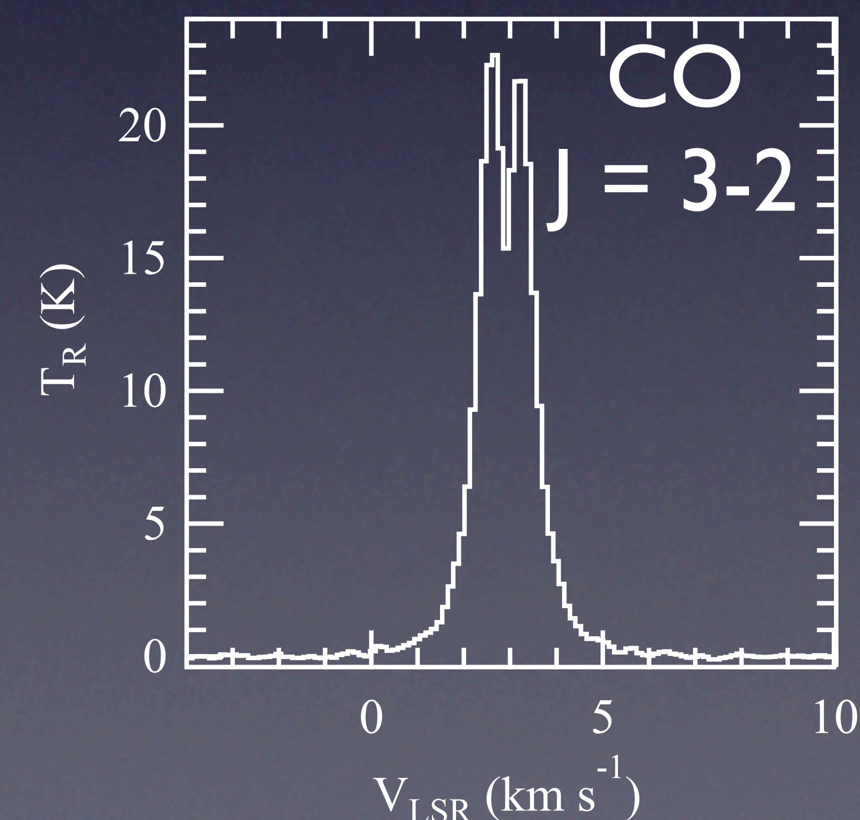




Number of disks
10
8
6
4
2
0
Taurus
TW Hya Gas
Thi et al. 2010
Gorti et al. 2010
TW Hya Dust
10^{-3}
10^{-2}
10^{-1}
$100 \times M_{dust}$ ($M_{\odot}$)
Williams and Cieza 2011

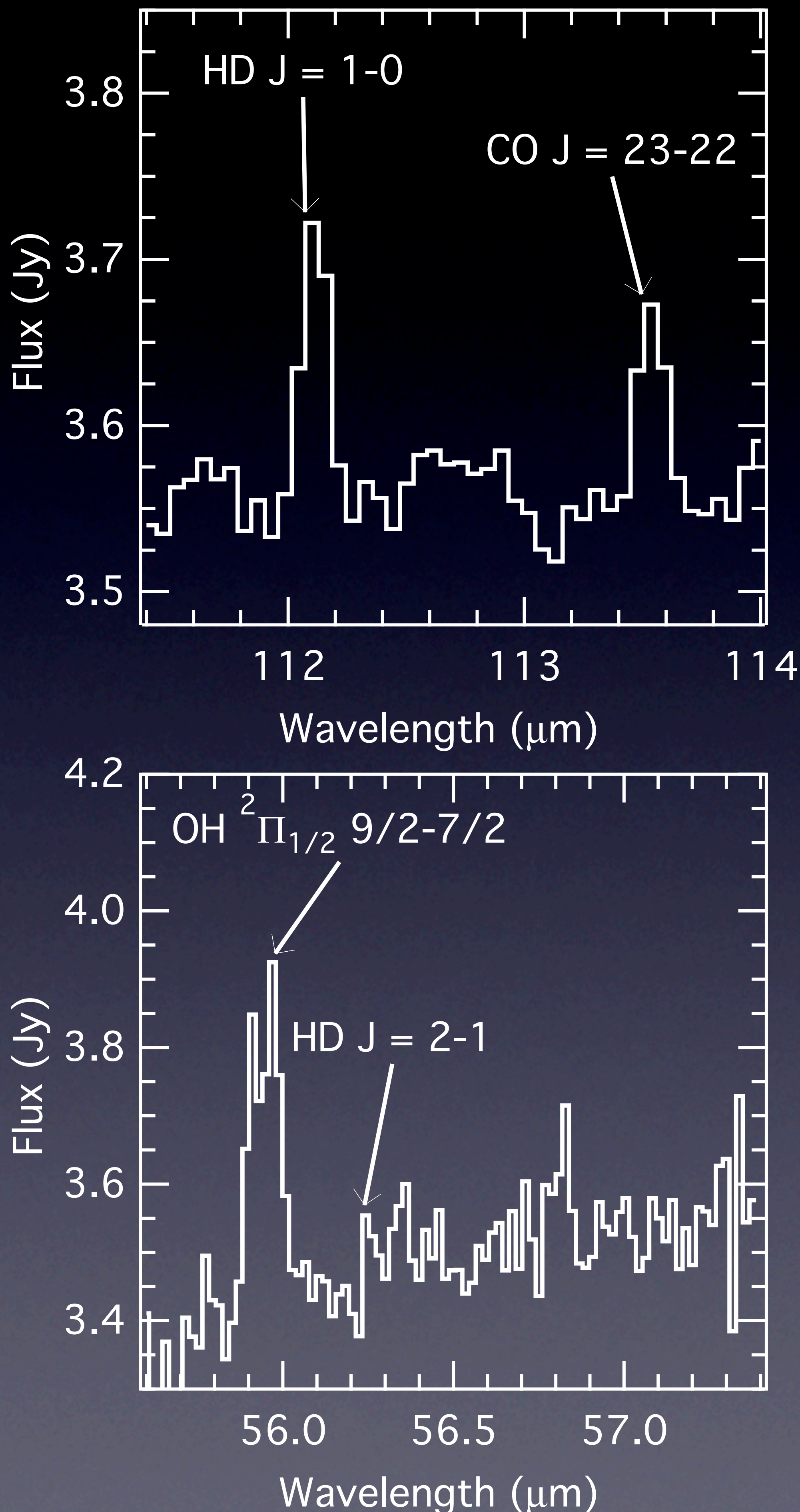


TW Hya
Weinberger et al. 2002
350 AU
Distance ~ 54 pc
−3 −2 −1 0 1
−3 −2 −1 0 1
ln (mJy arcsecond^{-2})



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

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

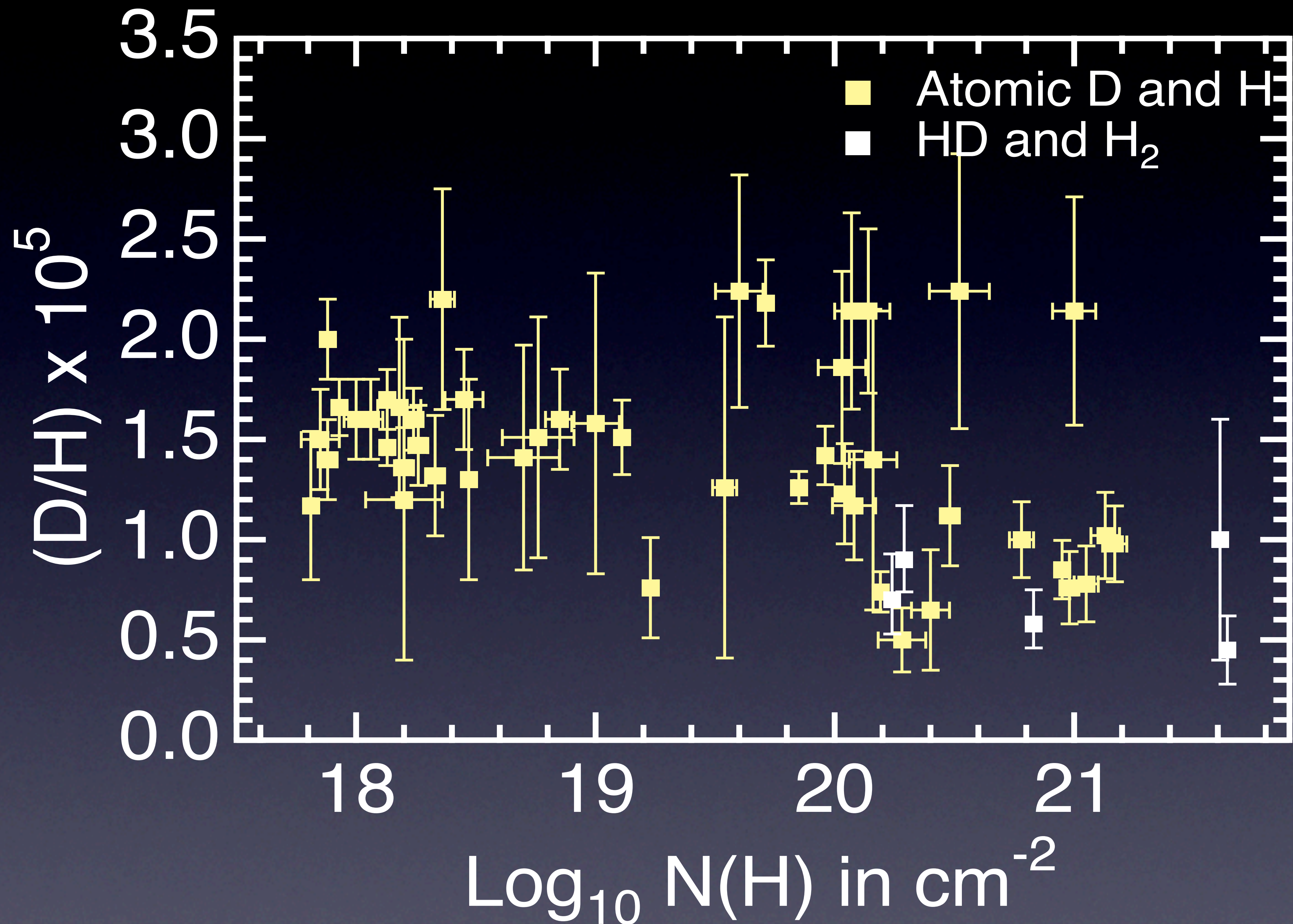
HD and the Disk Gas Mass

- 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

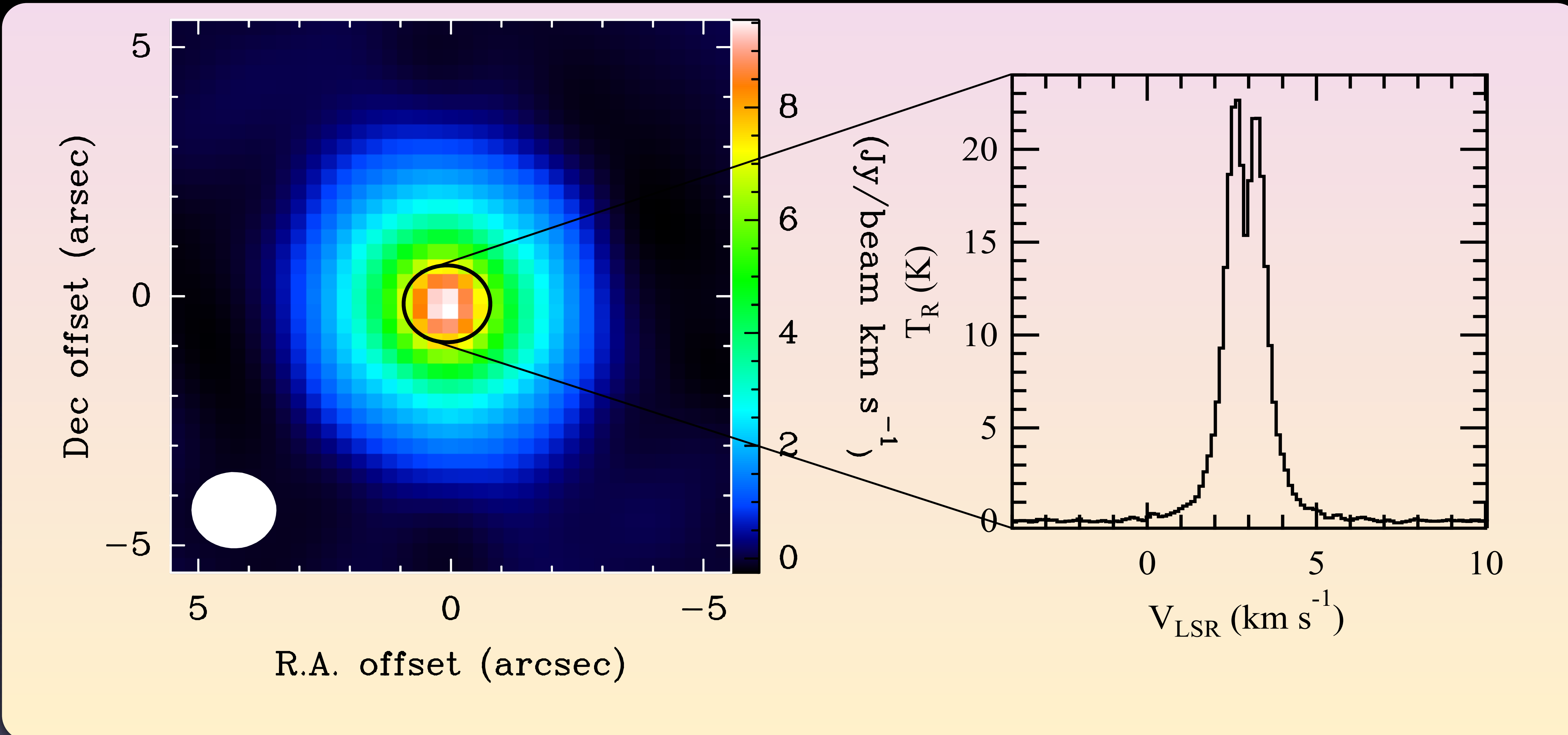
Deuterium Abundance



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

from HD & H_2 (Neufeld et al. 2006)

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

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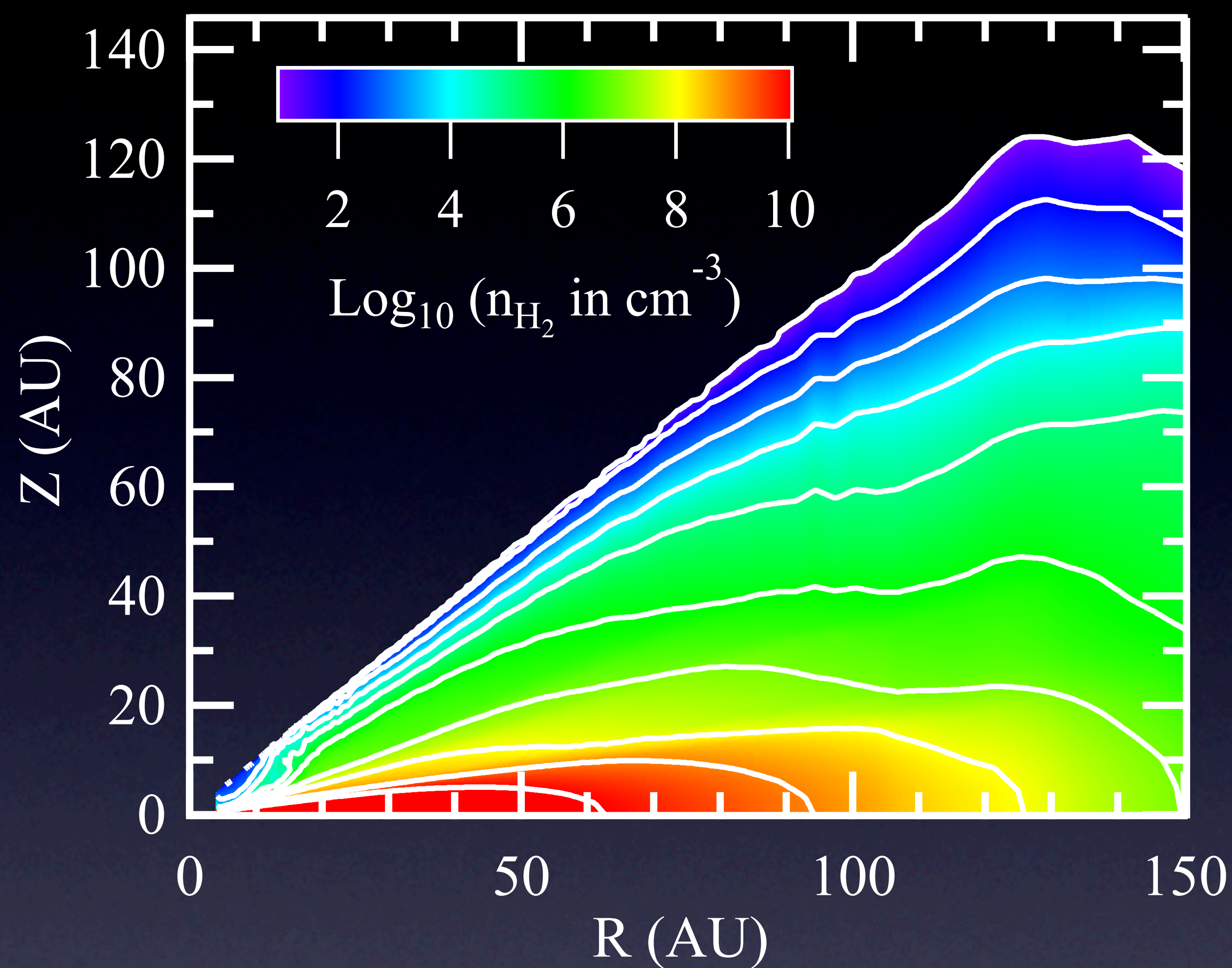

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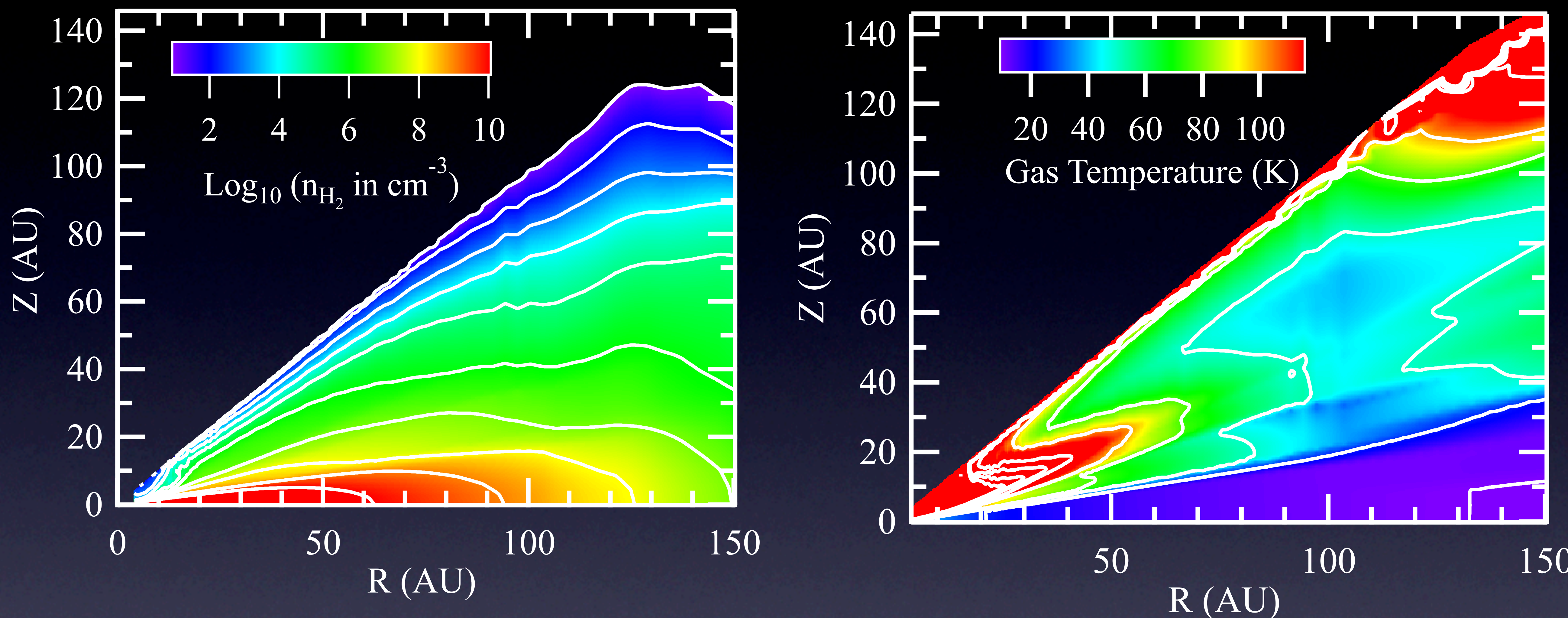

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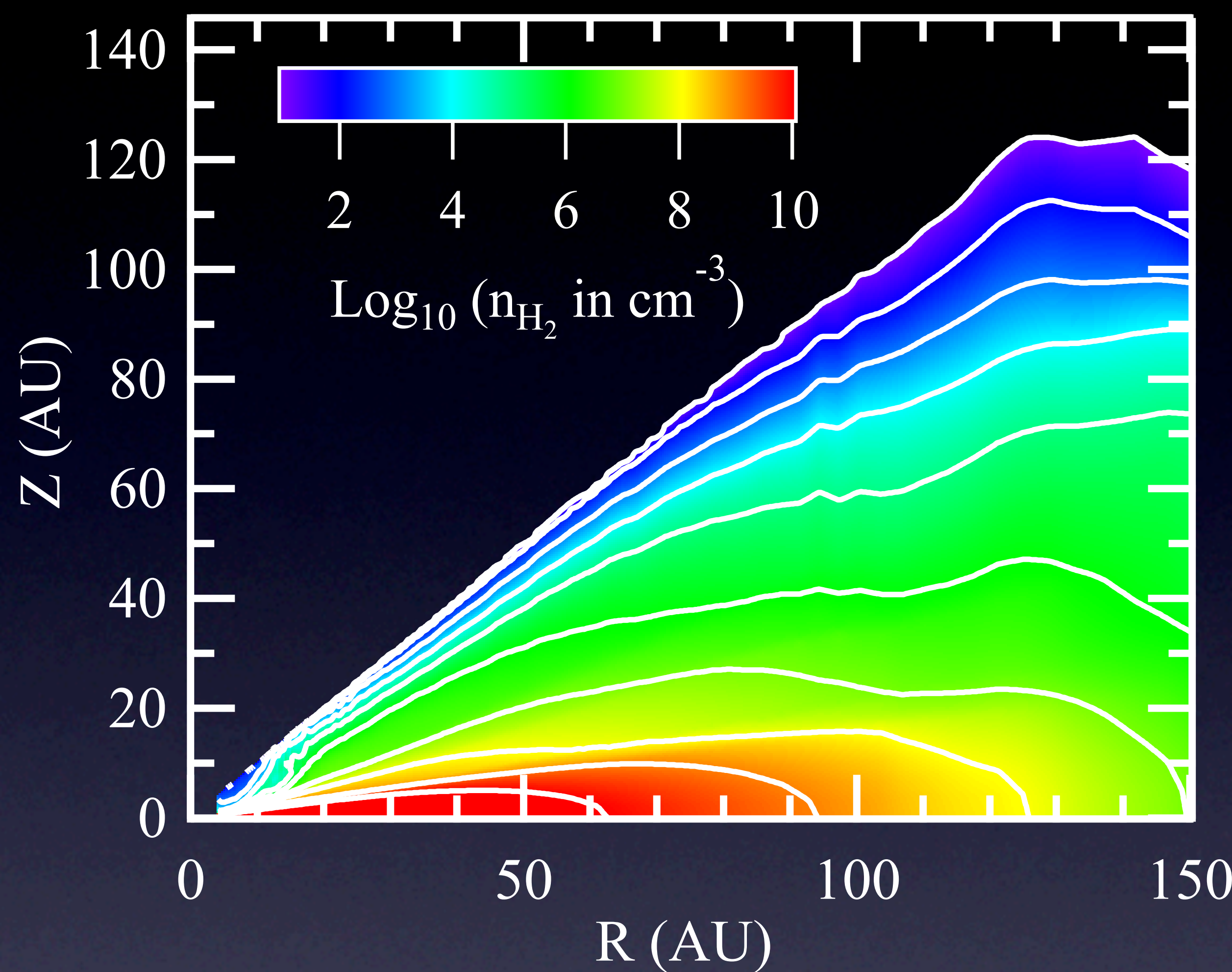
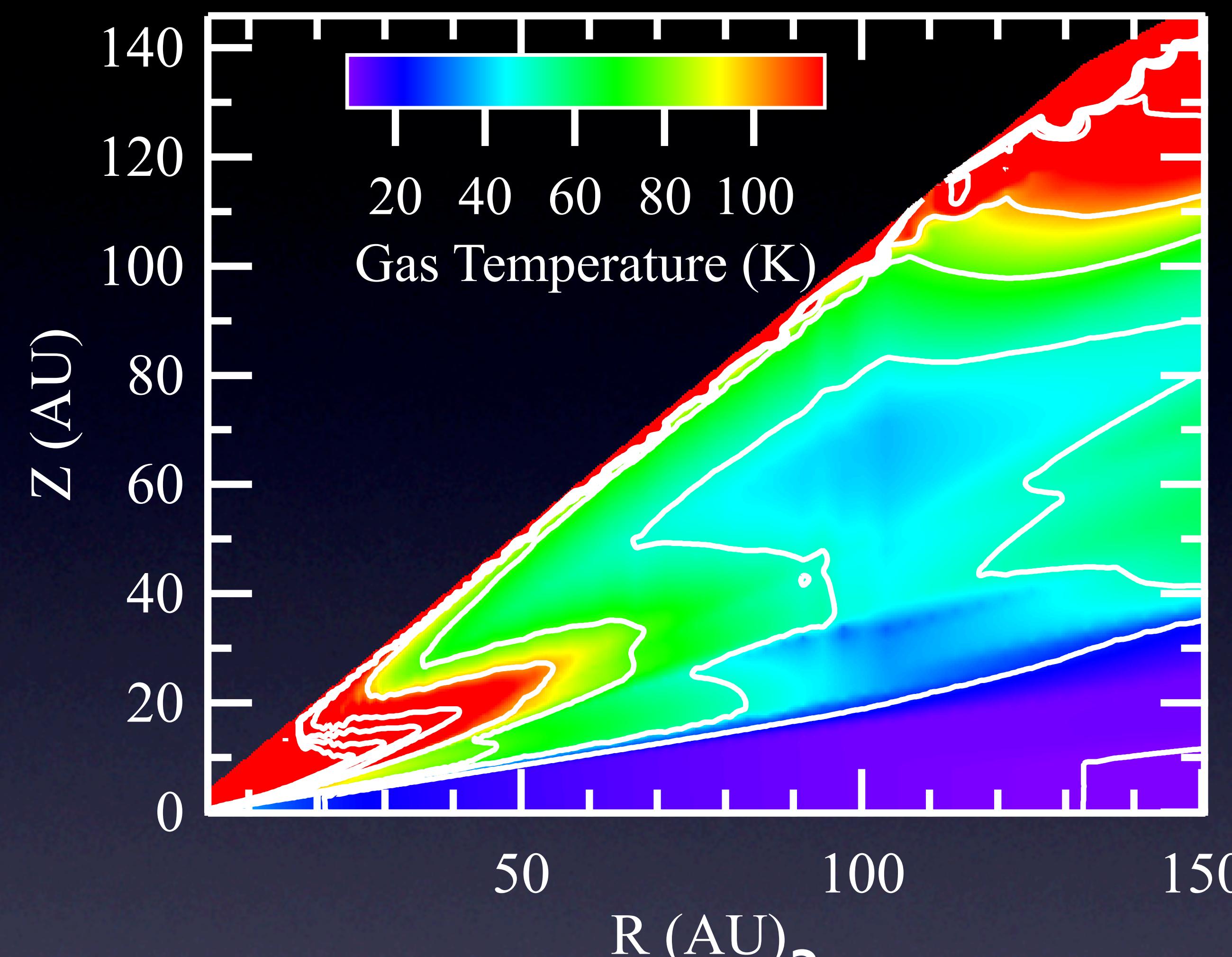
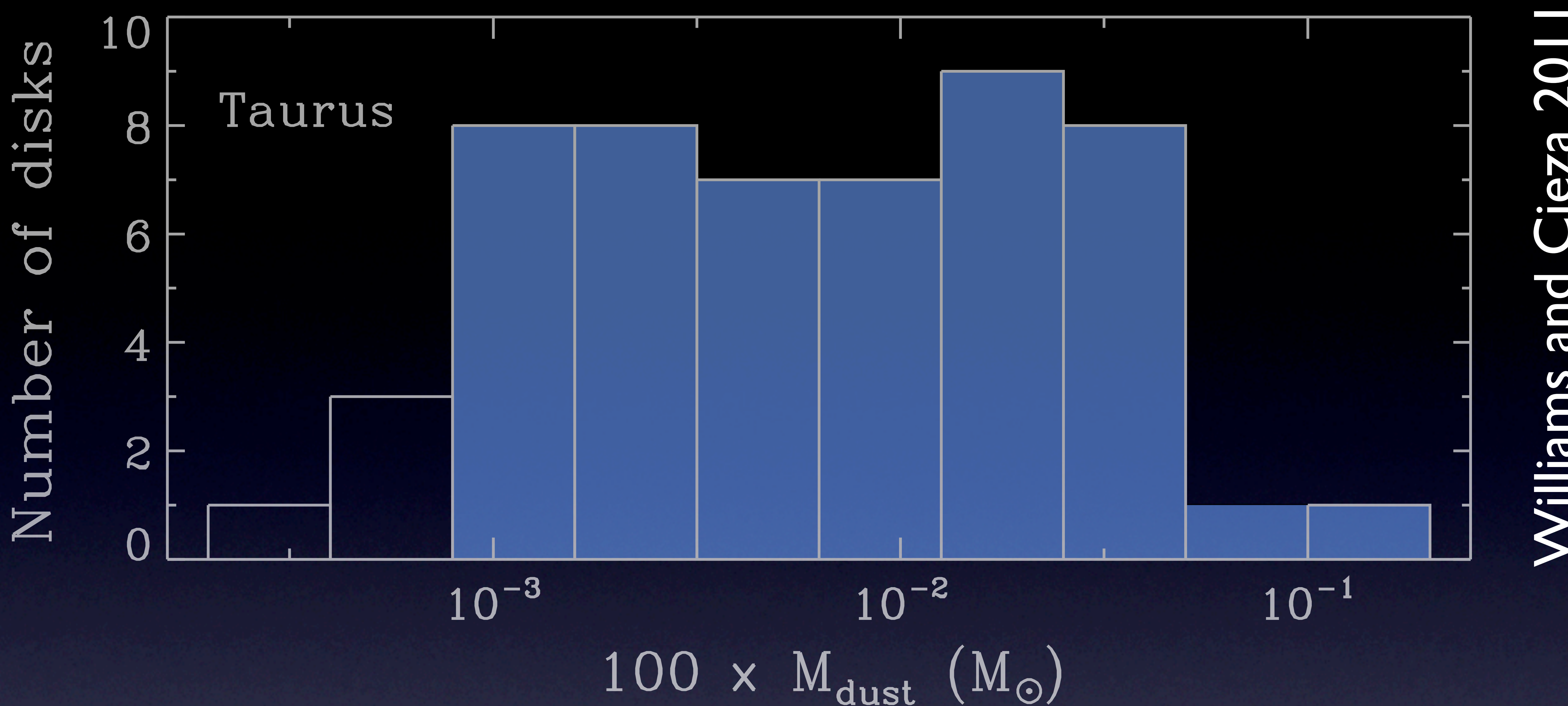
HD and the Disk Gas Mass





- Thermochemical models with $M_{gas} = 3 \times 10^{-3}\ M_\odot$ -- predict HD line flux a factor of 20 too low
- Thermochemical models with $M_{gas} = 0.06\ M_\odot$ -- are a factor of 2 below observed HD J = 1-0 emission

Bergin et al. 2013, Nature, 493, 644



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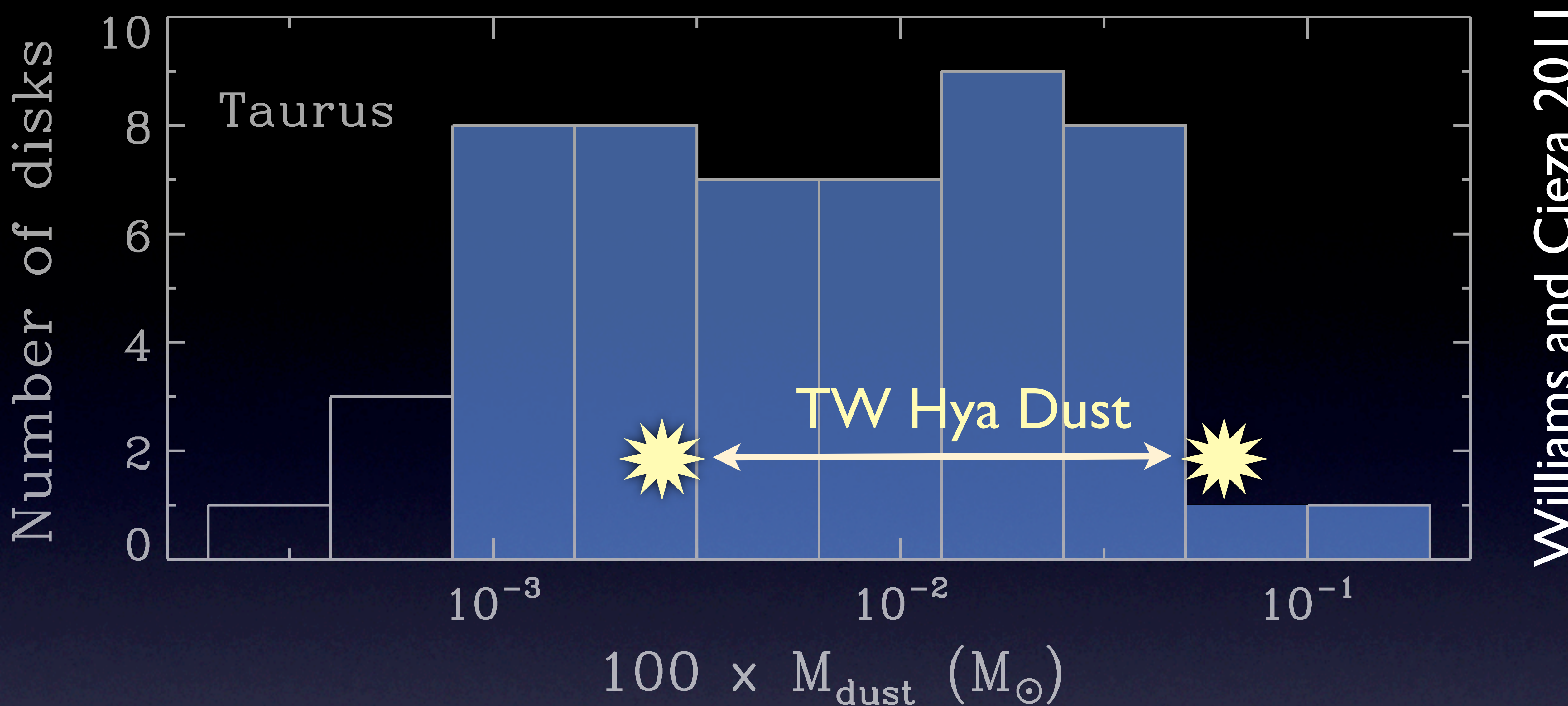

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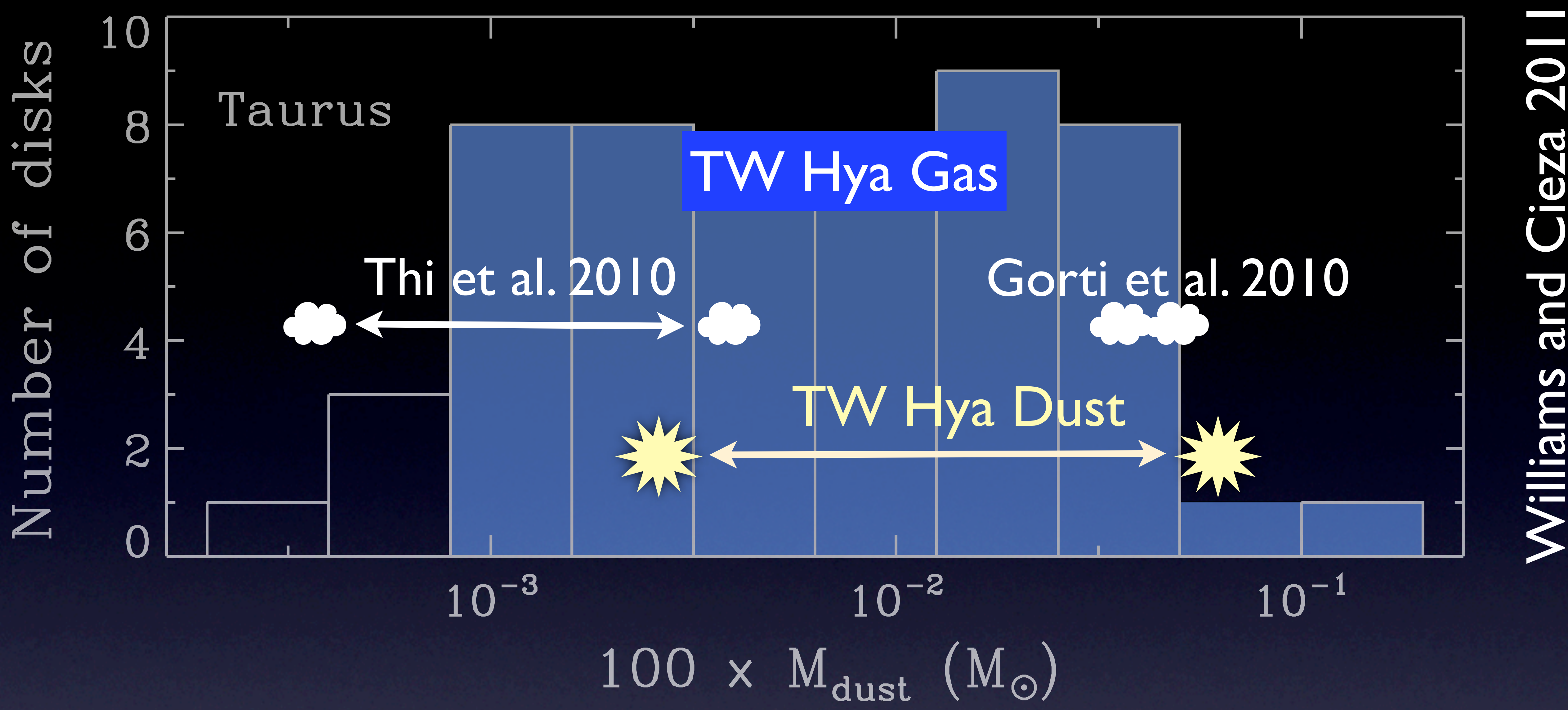

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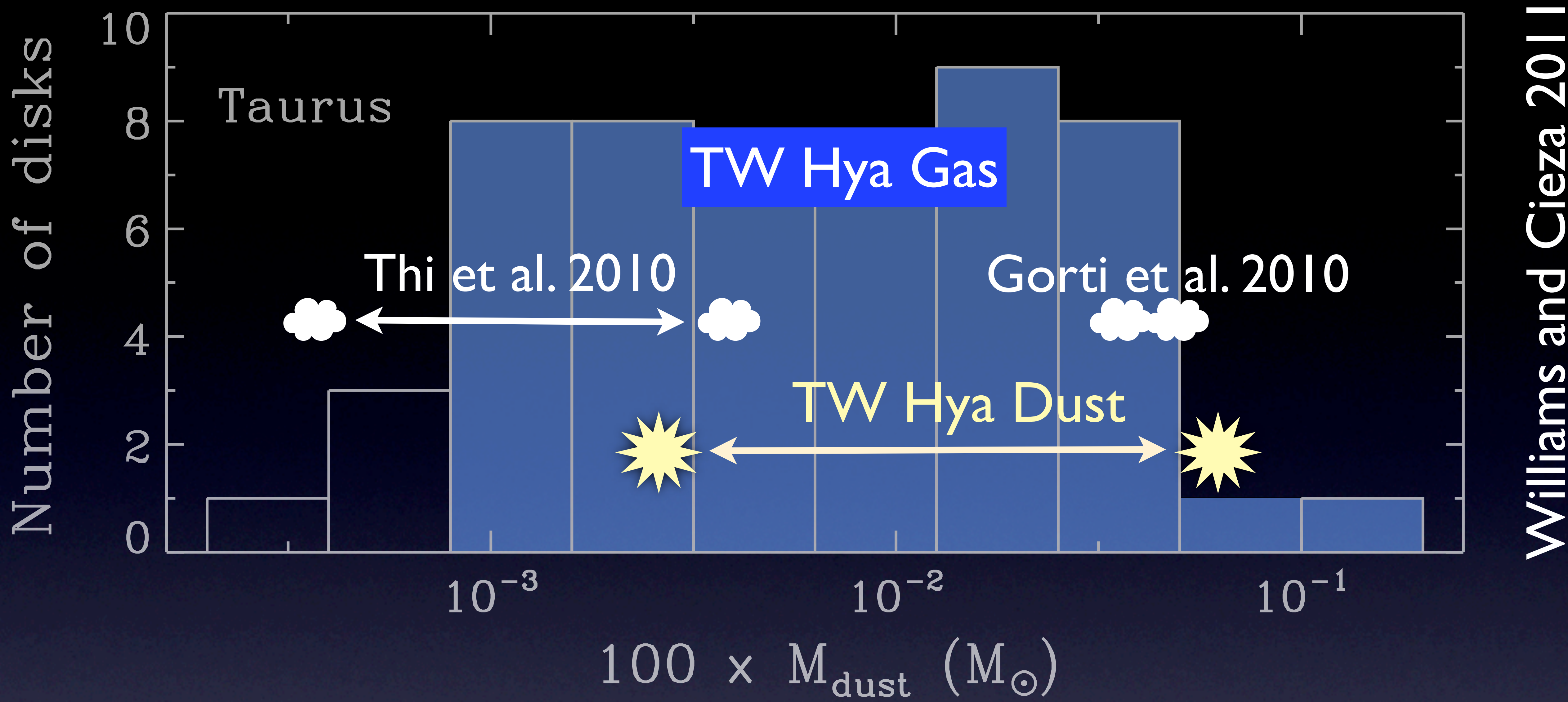

- TW Hya has a massive gas disk
- many times MMSN
- other systems are underestimated?

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 -- no other HD detections.
  - ➡ other objects at greater distance and lower sensitivity
  - ➡ also did not discuss midplane optical depth
- Future -- detection is right at limit for SOFIA (AND requires southern deployment).
- BUT current RX is not near the quantum limit -- much more room for hope.