Fukagawa et al. in prep.

ALMA Observations of the Asymmetrically Gapped Disk around HD 142527

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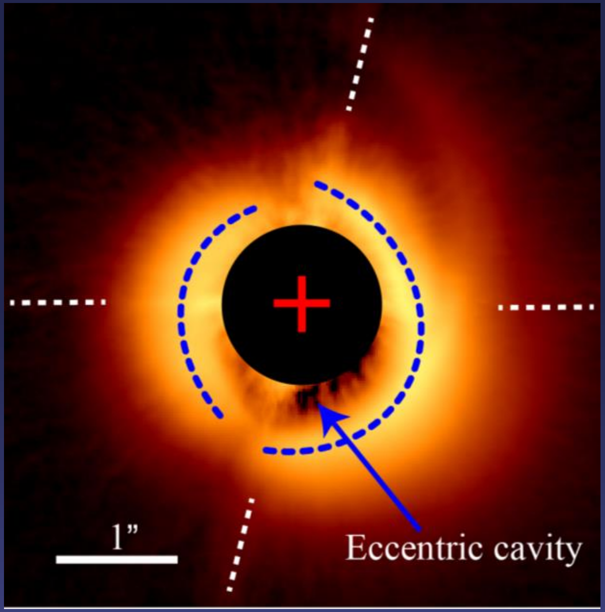
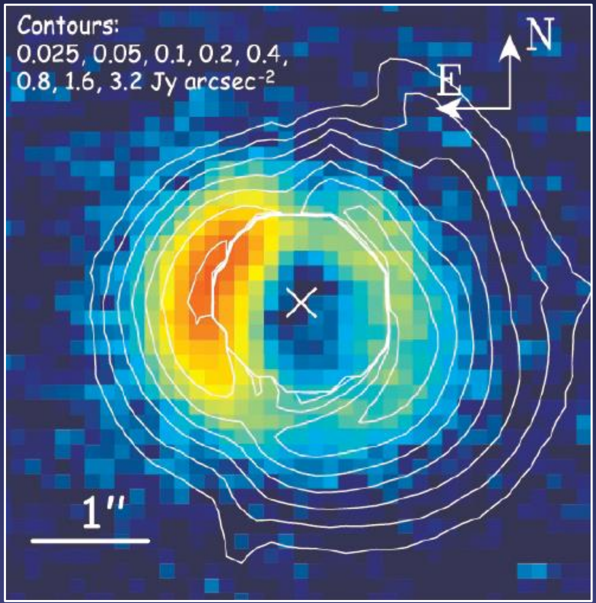
HD 142527

- Herbig Fe star (F6, T_{eff} = 6250 K), D ~ 140 pc
- L = 20 $L_{\odot}$, M = 2.2 $M_{\odot}$, Age ~5 Myr (Verhoeff et al. 2011)
- Abundant IR excess ($L_{IR} \sim L_*$)
- Imaging – one of the peculiar disks



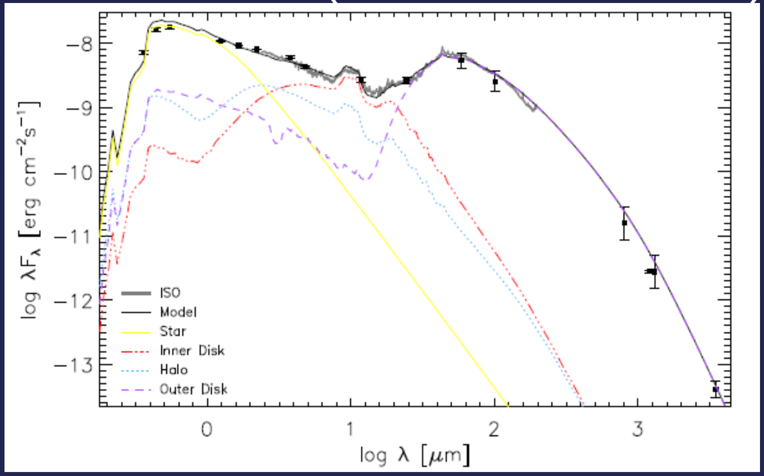
1.6 μm, scattered light
(Fukagawa et al. 2006)



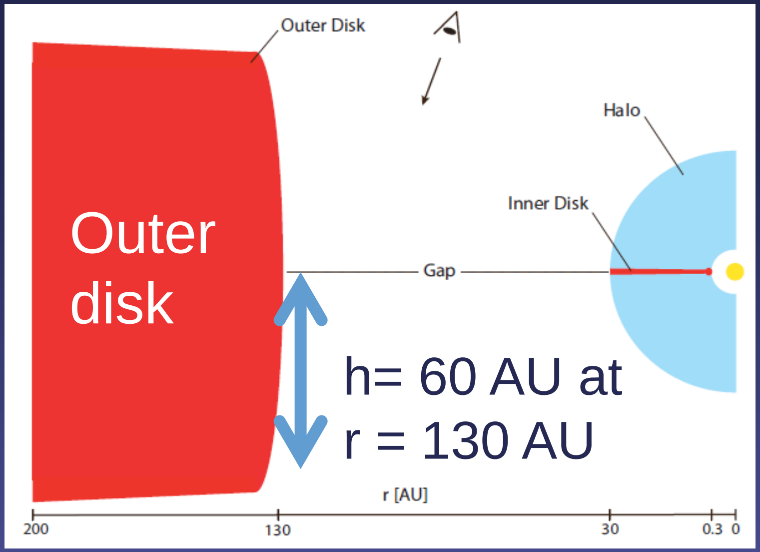
24.5 μm, thermal
(Fujiwara et al. 2006)

The Disk

(Verhoeff et al. 2011)



1. Inner disk (r < 30 AU)
   - High crystallinity, large grains (Bouwman et al. 2001, van Boekel 2004)
2. Gap (Δr ~ 100 AU)
   - Gap seems too wide to be affected by the stellar companion inferred at ~12 AU (Biller+ 2012)
3. Outer disk (r > 100 AU)
   - Multiple spirals + an outer arm



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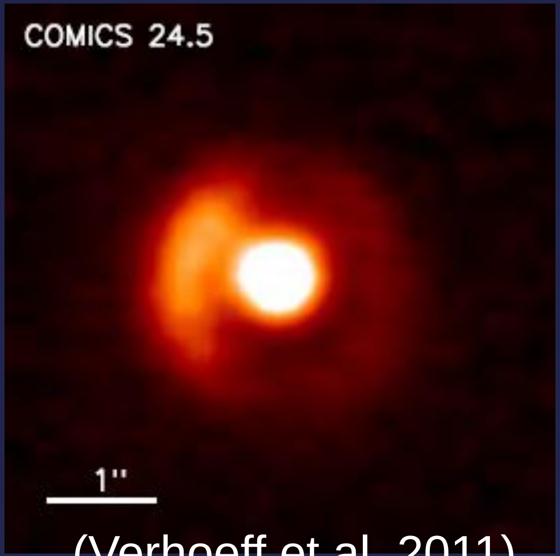
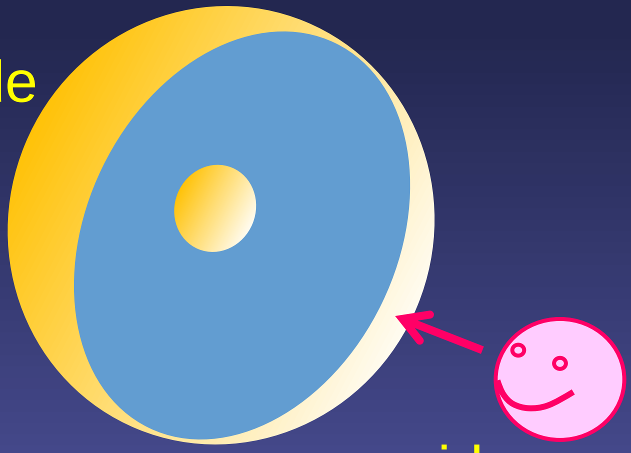


(Verhoeff et al. 2011)



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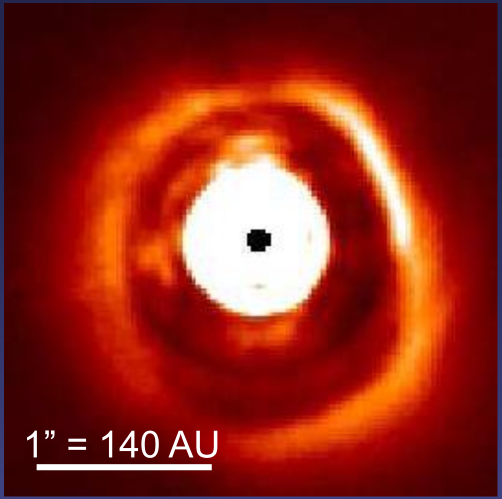
L', H2(1-0)S(1), Ks (Casassus et al. 2012)

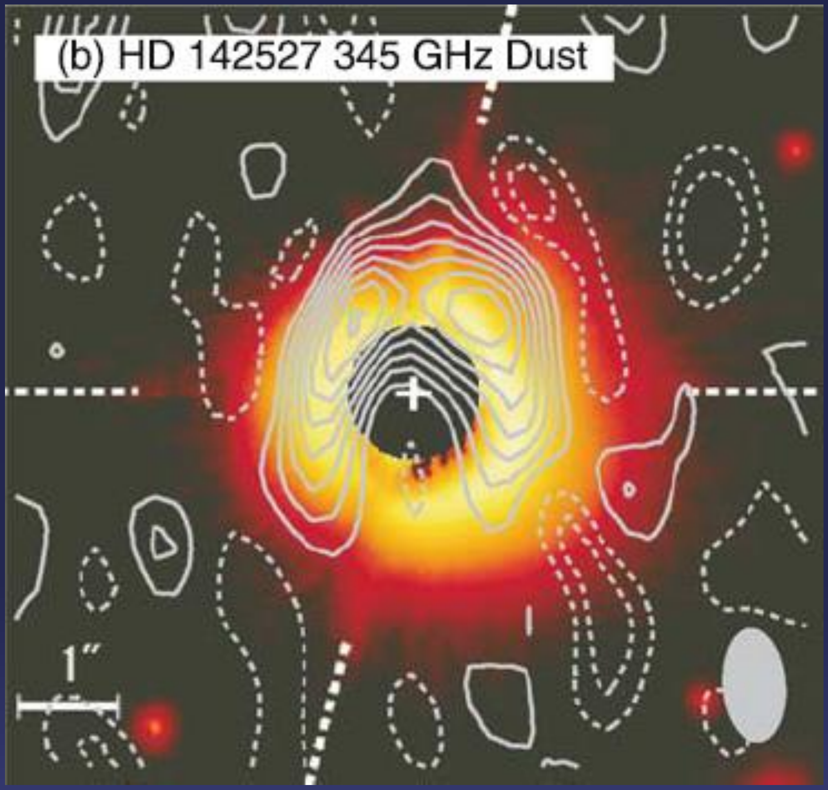


L' band (3.8 μm) (Rameau et al. 2012)

Another Motivation toward ALMA

- Strong non-axisymmetry: "horseshoe" disk
  - (1) Very wide (~1") cavity
  - (2) Enhancement in the northern area

→ One of the best protoplanetary disks for ALMA early science



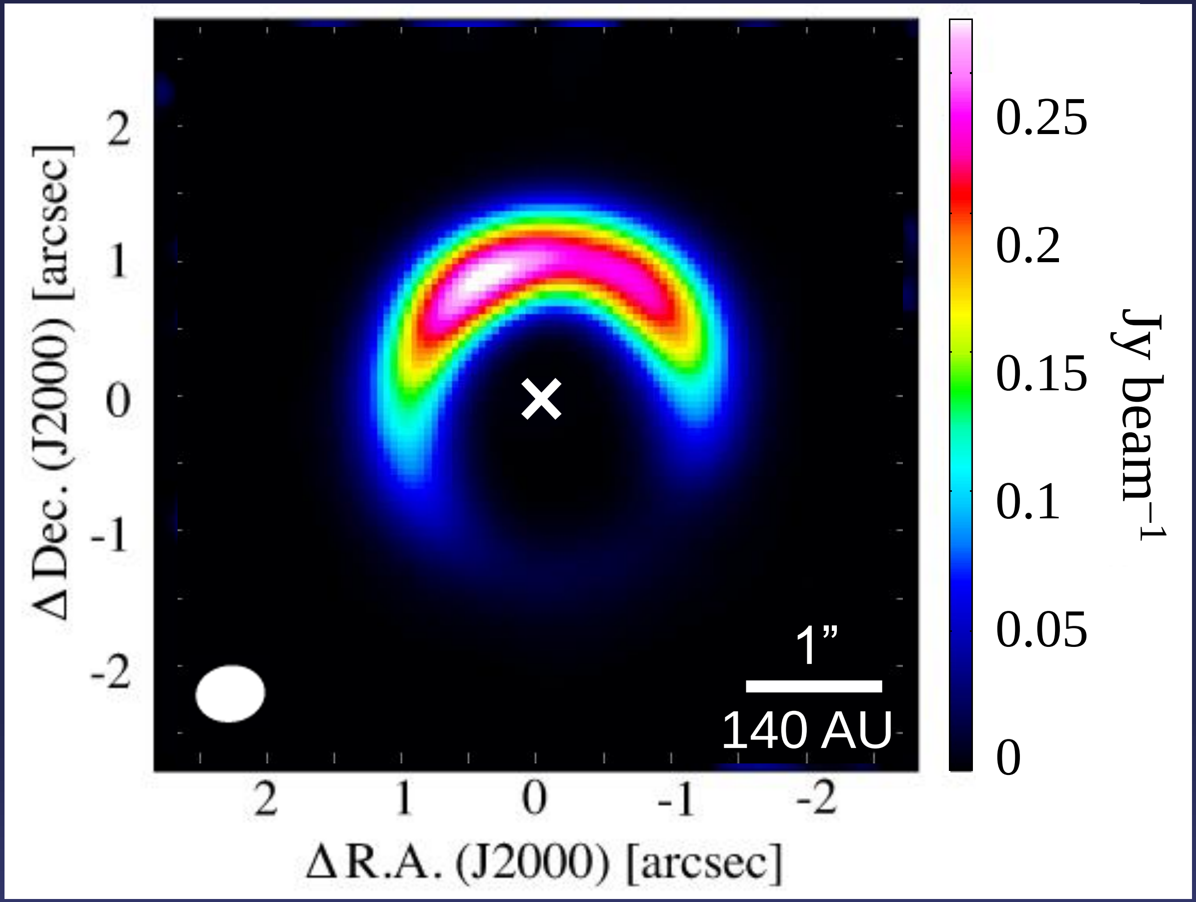
Contours: SMA 880 μm continuum (from 2σ, spacing of 2σ) (Ohashi 2008)

Observations

- Band 7 (336 GHz), covering $^{13}CO(J=3\text{-}2)$, $C^{18}O(J=3\text{-}2)$
  - Optically thinner lines than ^{12}CO
- 20–26 12-m antennas
- Beam size = 0.5” x 0.4” (70 x 60 AU)
- Effective velocity resolution ~0.2 km/s
  (Channel width of 0.11 km/s)

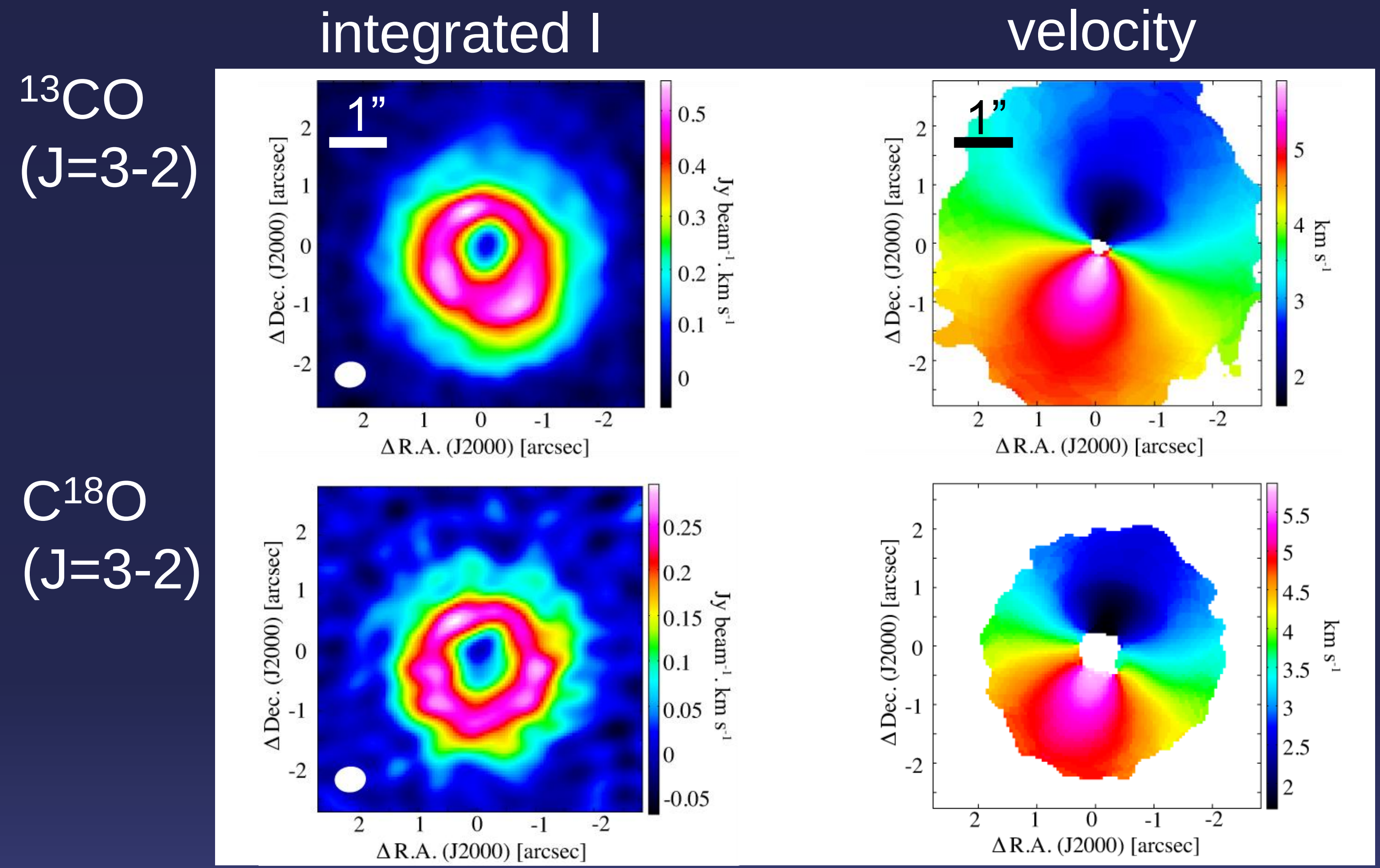
	Continuum	**13CO (3-2)**	**C18O (3-2)**
Beam size	0.50” x 0.41”	0.52” x 0.43”	0.53” x 0.43”
Rms noise (mJy/beam)	0.2	10 (per channel)	11 (per channel)

Continuum at 340 GHz



- Outer “Horseshoe” : N-S brightness contrast ~ 25
  - Peak = 280 mJy/beam, T_b ~ 22 K (!)
- Inner disk + gap (non-detection) + outer disk

Molecular Lines



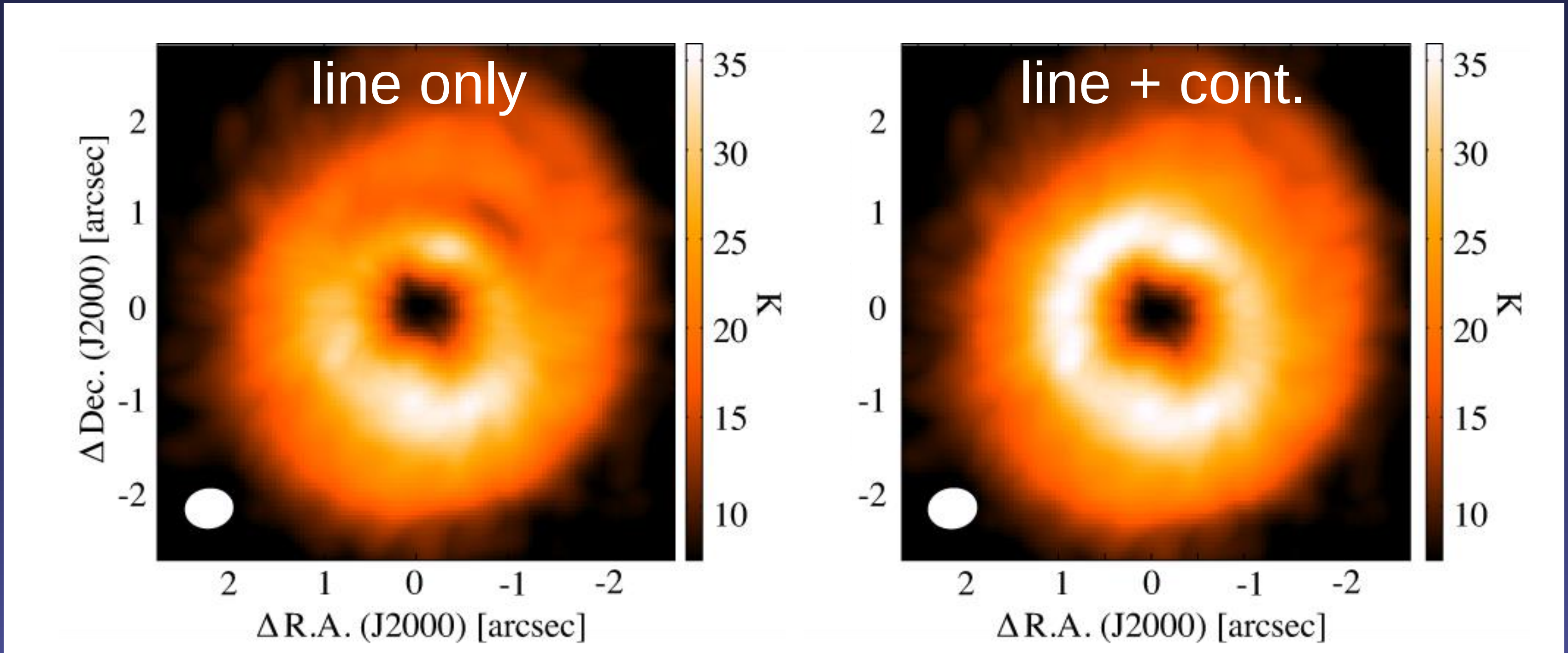
- Integrated I: ring-like distribution
- Velocity field follows Keplerian rotation; (major-axis PA = –19°, i = 27° ± 2° for M_* = 2.2 $M_\odot$)

How dense the disk can be in the northern area of the horseshoe?

T_b for $^{13}CO(J=3\text{-}2)$

- ^{13}CO emission should be optically thick
  - $^{13}CO/C^{18}O$ << canonical value (~7; ISM, HD 163296; Qi et al. 2011)
  - $T_b(^{13}CO) - T_b(C^{18}O) = 5$ K; in N, $130 < r < 300$ AU

→ T_b reflects temperature, not column density



Surface Density of the Horseshoe

How massive does the disk at the horseshoe peak?

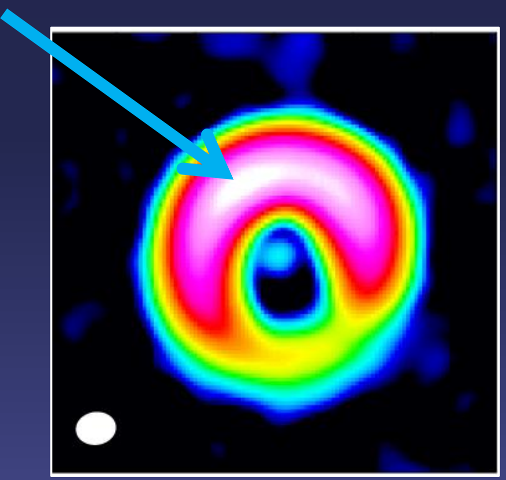
- Peak T_b = 36 K of ^{13}CO provides the upper bound for temperature of dust grains emitting in submm
  - ^{13}CO should be located in the upper layer

→ Σ(dust) = 0.22 g cm^{-2} at the peak

→ Σ(dust) = 0.087 g cm^{-2} at 161 AU, azimuthally-averaged

→ $M_{disk} = 0.08\ M_{\odot}$

- T = const. = 36 K
- opacity = 0.034 cm^2/g (β = 1.0)
- optical depth estimated for 36 K

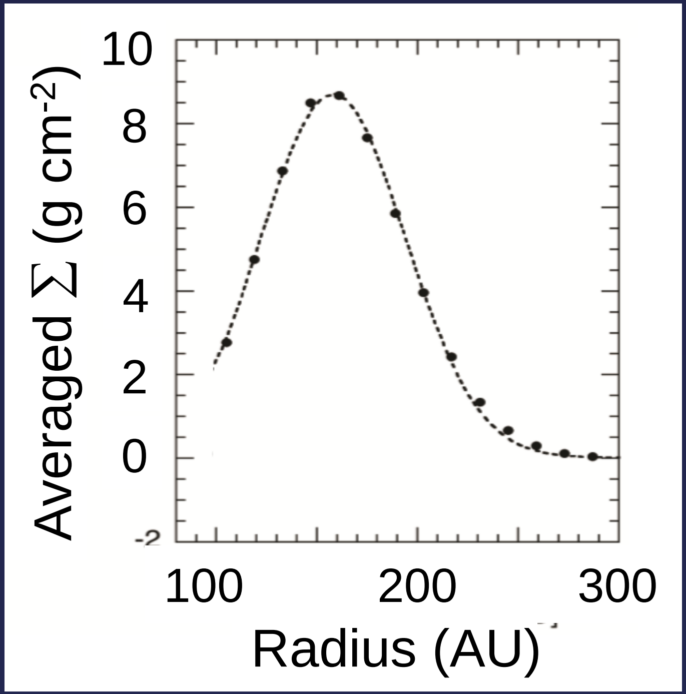


Structure

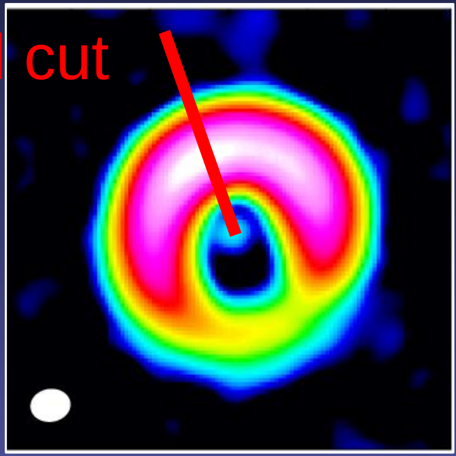
- Radial brightness distribution is well represented by Gaussian

→ *ring, torus*…

Sharp outer/inner edges in transitional disks (e.g., Isella et al. 2010, Andrews et al. 2011, Tang et al. 2012)



- FWHM in *r* is narrower at the northern horseshoe peak
- Δr = 50 AU ~ 2 × scale height (36 K) after beam deconvolution

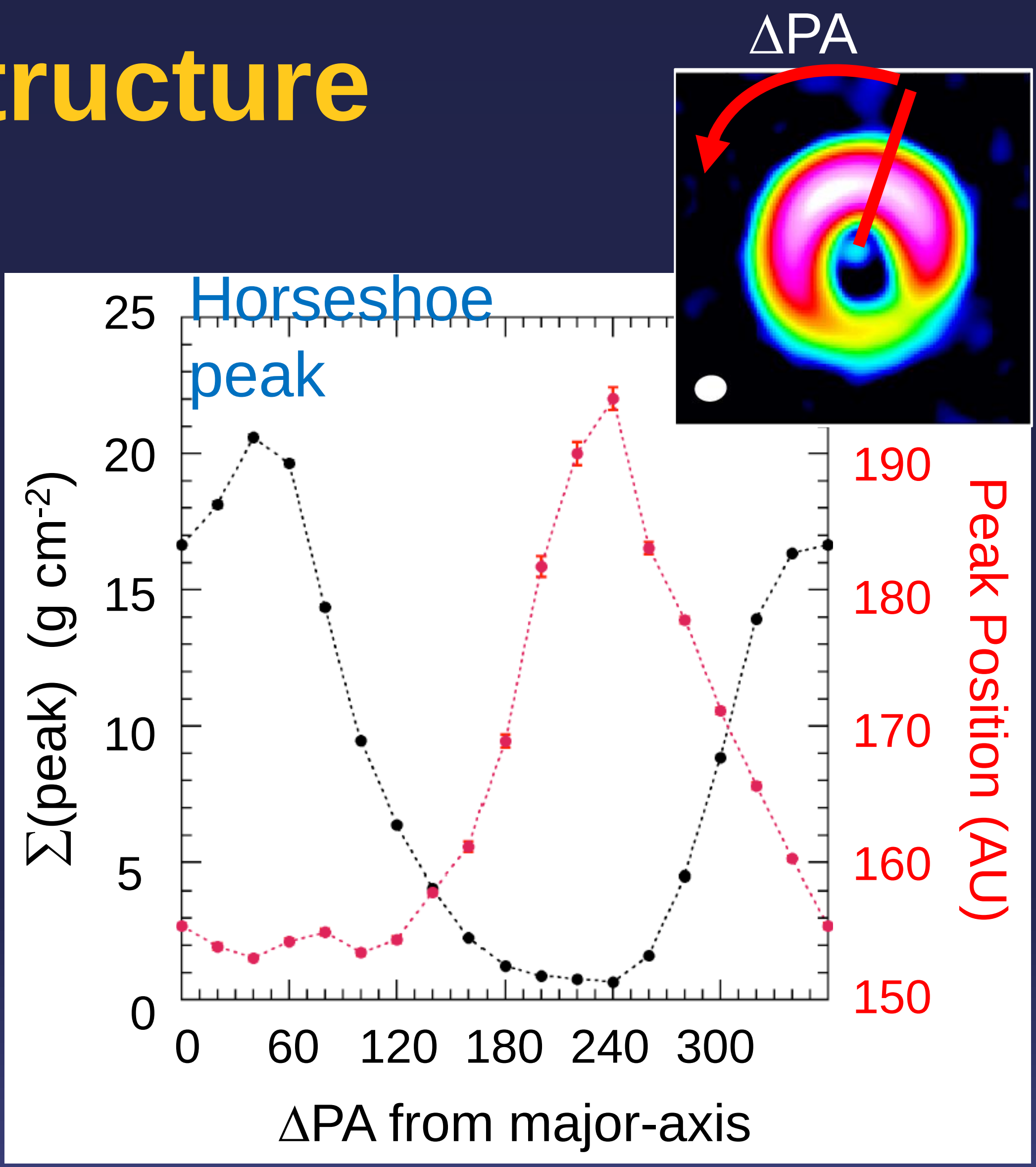


Structure

- Anti-correlation between the peak intensity *versus* peak position for the fitted Gaussian

→ Not an eccentric disk (higher density expected at apastron)

- "Ring + gaseous floor" (^{13}CO out to ~450 AU ↔ ~300 AU for dust)



(G/D = 100 is assumed in Σ)

Enhancement toward North: Implications

Discussion using the *lower limit* of Σ

1. Self-gravitating?

- Gas-to-dust = 100
- Toomre Q for a Keplerian disk

$\rightarrow$ Q ~ 3 for Σ = 8.7 g cm^{-2} azimuthally-averaged (160AU)

$\rightarrow$ Q ~ 1 for Σ = 22 g cm^{-2} at the density peak

…Gravitationally unstable

Enhancement toward North: Implications

2. Dust accumulation that lowers gas-to-dust

- Gas-to-dust < 100, at least ~10 makes Q >> 1
- Particle trapping at pressure maxima

  Instability caused in a disk with Q >>1

  e.g., large-scale vortices (e.g., Birnstiel et al. 2013, Ataiee et al. 2013, talk by T. Birnstiel, F. Menard)
- Constraints based on Rayleigh criterion

  $\Omega \propto r^{-n}$, n should be < 2

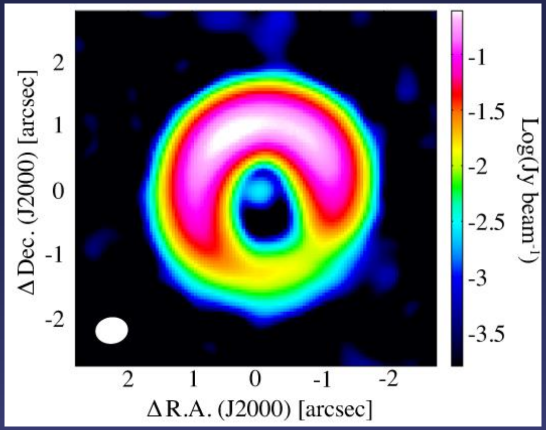
In either case, the enormous pile-up of disk material beyond 100 AU from the star $\rightarrow$ planet forming site?

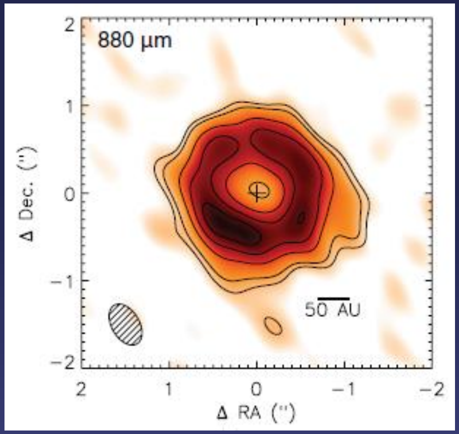
Uniqueness?

- Azimuthal asymmetry; x 10 compared to other ring-like disks

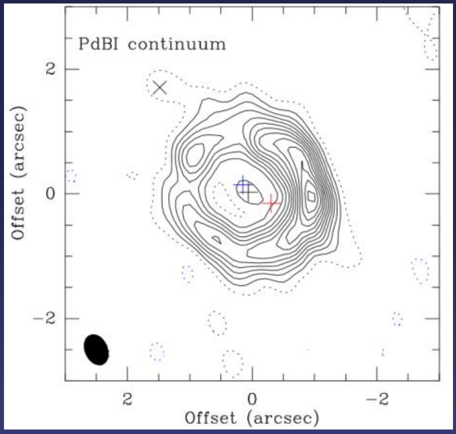
  (x 100 for the “peanut”; talk by N. van der Marel)
- Relatively massive disk

  (>~4% of the stellar mass)





J1604-2130
(Mathews et al. 2012)



AB Aur
(Tang et al. 2012)

etc…

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Summary

- ALMA observations revealed the horseshoe-shaped disk which is surprisingly bright at its northern area in dust emission at 336 GHz.
- To evaluate the density there, it is essential to constrain the grain temperature, which was estimated from the ^{13}CO (J = 3—2) line data.
- The peak surface density was then calculated as 21 g cm^{-2} assuming the canonical gas-to-dust mass ratio of 100. This indeed implies that the region is locally too massive to stand against self-gravity.
- Alternatively, accumulation of grains is expected to lower the gas-to-dust ratio by one order of magnitude or more and make the region stable against dynamical gravitational collapse.