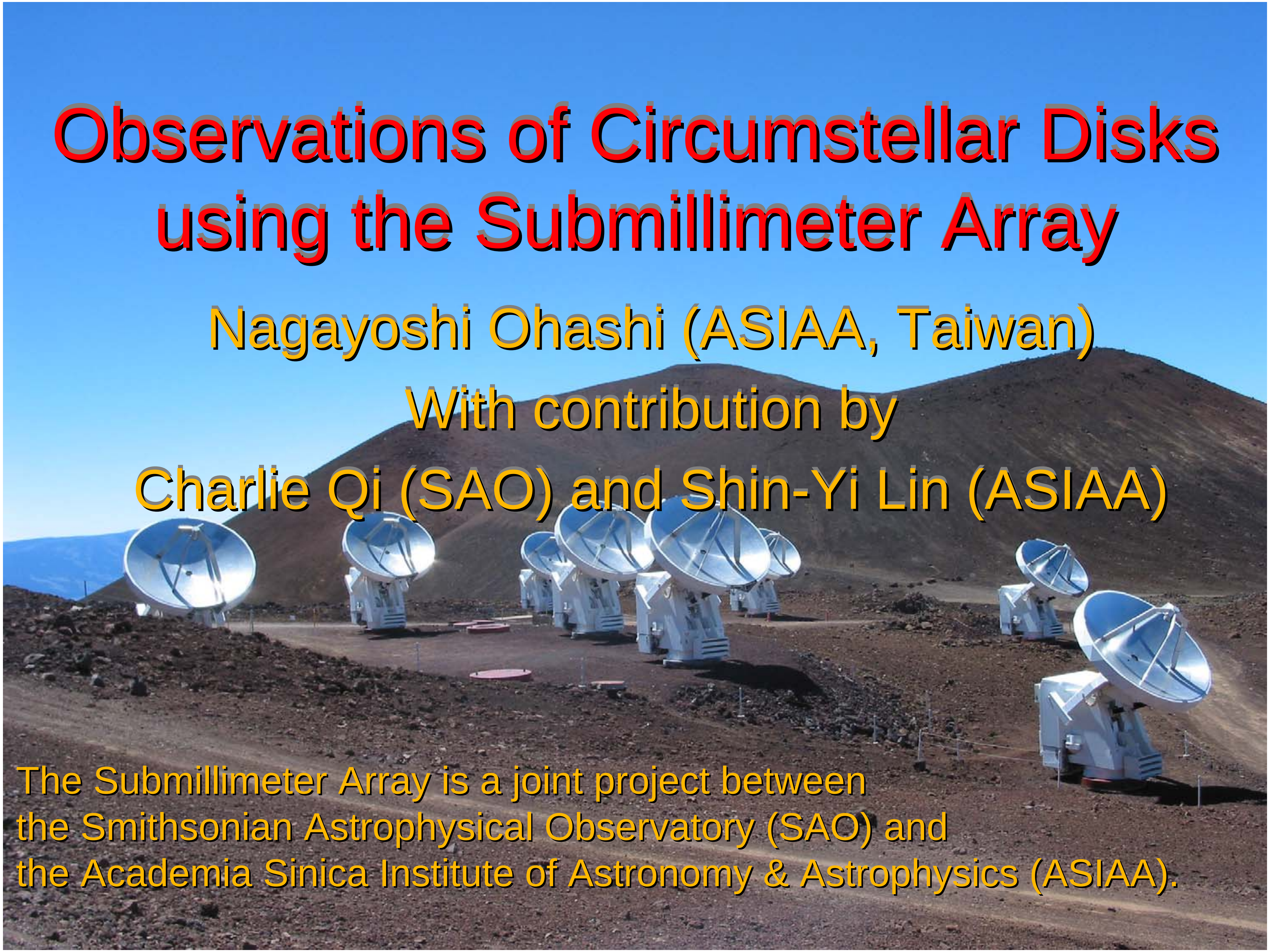


Observations of Circumstellar Disks using the Submillimeter Array

Nagayoshi Ohashi (ASIAA, Taiwan)
With contribution by
Charlie Qi (SAO) and Shin-Yi Lin (ASIAA)

The Submillimeter Array is a joint project between
the Smithsonian Astrophysical Observatory (SAO) and
the Academia Sinica Institute of Astronomy & Astrophysics (ASIAA).

SMA = ~~Smithsonian Millimeter Array~~
Submillimeter Array

Two Taiwanese antennas

Outline of the Talk

- Brief introduction of Circumstellar disks
- What to do for circumstellar disks with the SMA?
- Observations of Circumstellar Disks using the SMA
  - TW Hydrae (Qi et al. 2004, 2006)
  - Herbig Ae stars (Lin, Ohashi et al. 2006)

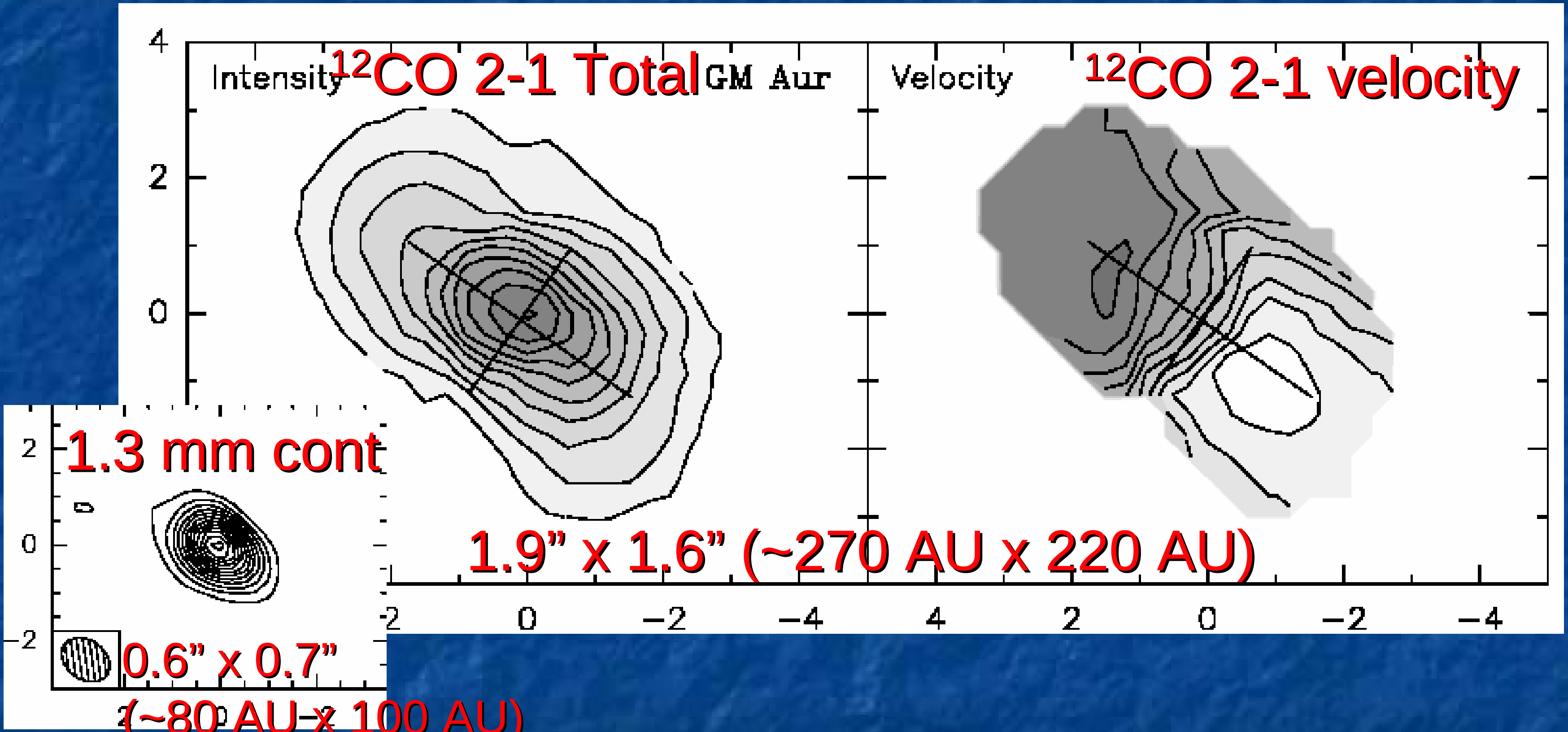
Sorry, No Chemistry, No Complex Molecules!

Why Circumstellar Disks?

- Circumstellar disks (CDs) are most probable sites for planet formation.
  - Important to understand their physical conditions.
  - Common characteristics or more variety?
- More than 150 extra-solar planets have been discovered.
  - More system with hot Jupiters and high eccentricity.
  - How were these extra-solar planets formed?
- High resolution observation is the key to study CDs around Herbig Ae stars.

MM High Resolution Images of CDs

GM Aur (Dutrey et al. 1998)



^{12}CO 2-1 Total

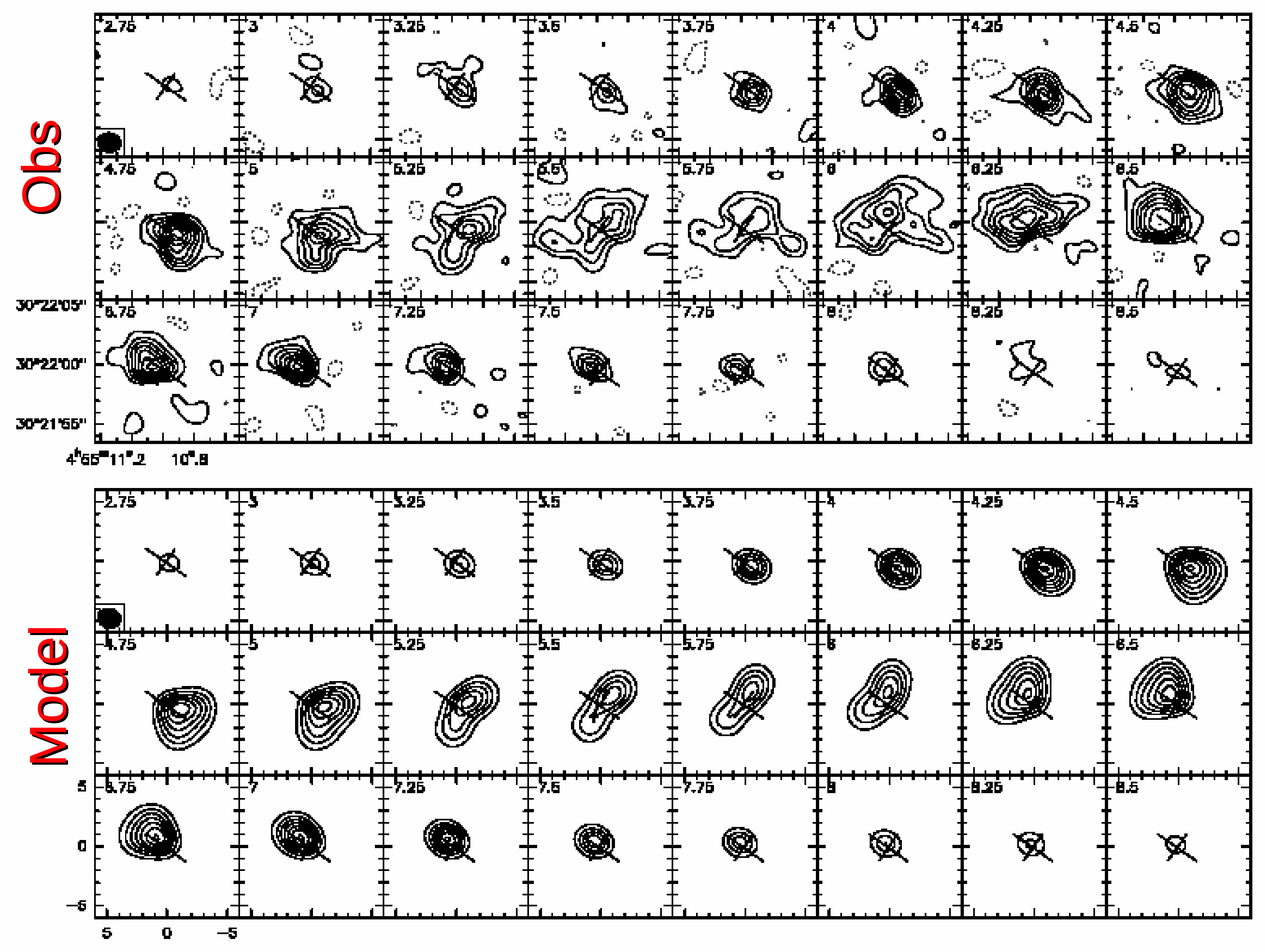
^{12}CO 2-1 velocity

1.3 mm cont

1.9” x 1.6” (~270 AU x 220 AU)

0.6” x 0.7”
(~80 AU x 100 AU)

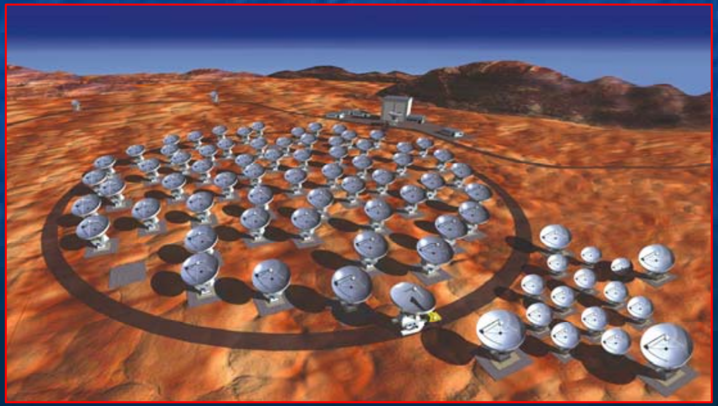
- Geometry: compact, disklike structures
- Kinematics: Kepler motions



- Geometry: compact, disklike structures
- Kinematics: Kepler motions

What to do BEFORE the ALMA?

- It is obvious that the ALMA will help a lot for us to study circumstellar disks in more detail.
- How are we ready to use the ALMA?
- We need to develop good programs to make the best use of the ALMA.

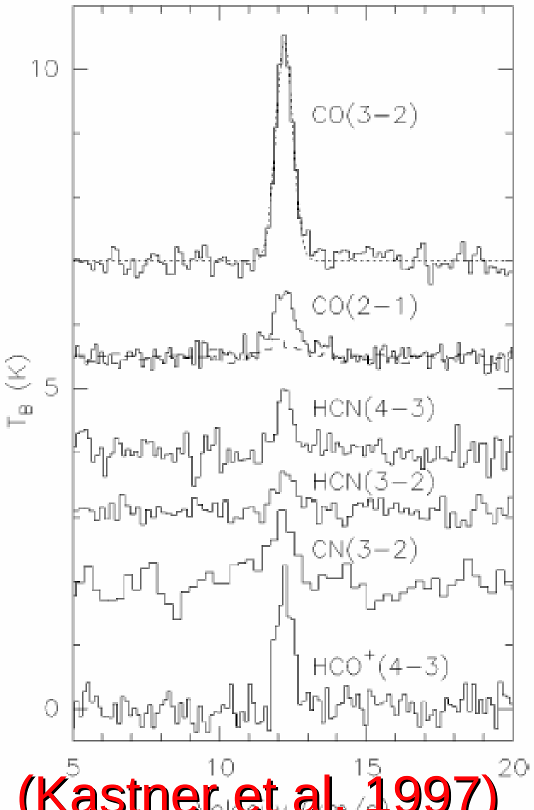


Roles of the SMA

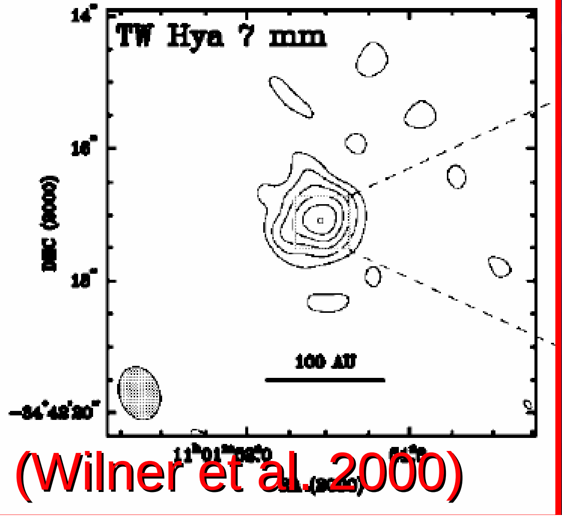
- Forerunner of the ALMA at submm.
- Brings unique observations of CDs at submm.
  - Stronger dust emission, enabling us to study details.
  - High J transitions tracing warmer and denser gas
  - Multi-transition observations to trace different layers of CDs
- Focus on a limited number of sources to make frameworks of CDs, leading future studies using the ALMA.
  - TW Hydrae; closest cTTS with a disk.
  - Herbig Ae stars; bright disks with interesting new features; some of interesting sources in southern sky.

TW Hydrae

- Nearest (56 pc) cTTS with a circumstellar disk.
- Relatively strong molecular emissions were detected (Kastner et al. 1997, Thi et al. 2001, van Dishoeck et al. 2003).
- Quite low declination (-34 deg).
- A disk of ~5 x 10^{-3} Mo was imaged in dust emission at 7mm (Wilner et al. 2000).
- L_X ~ 2 x 10^{30} erg s^{-1} (Kastner et al. 1999)

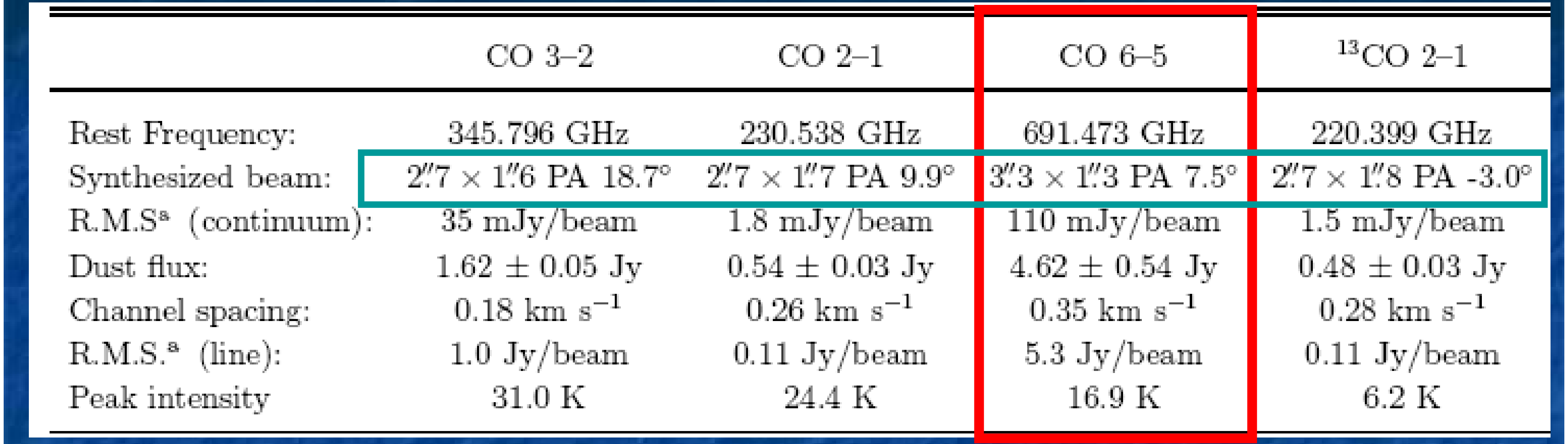


(Kastner et al. 1997)

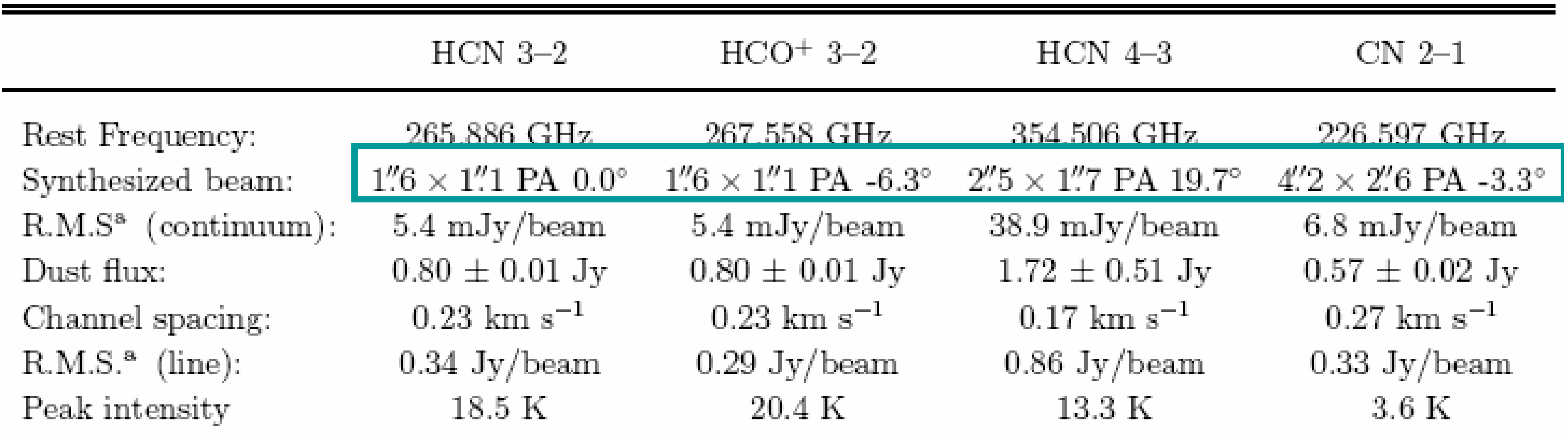


(Wilner et al. 2000)

SMA Observations



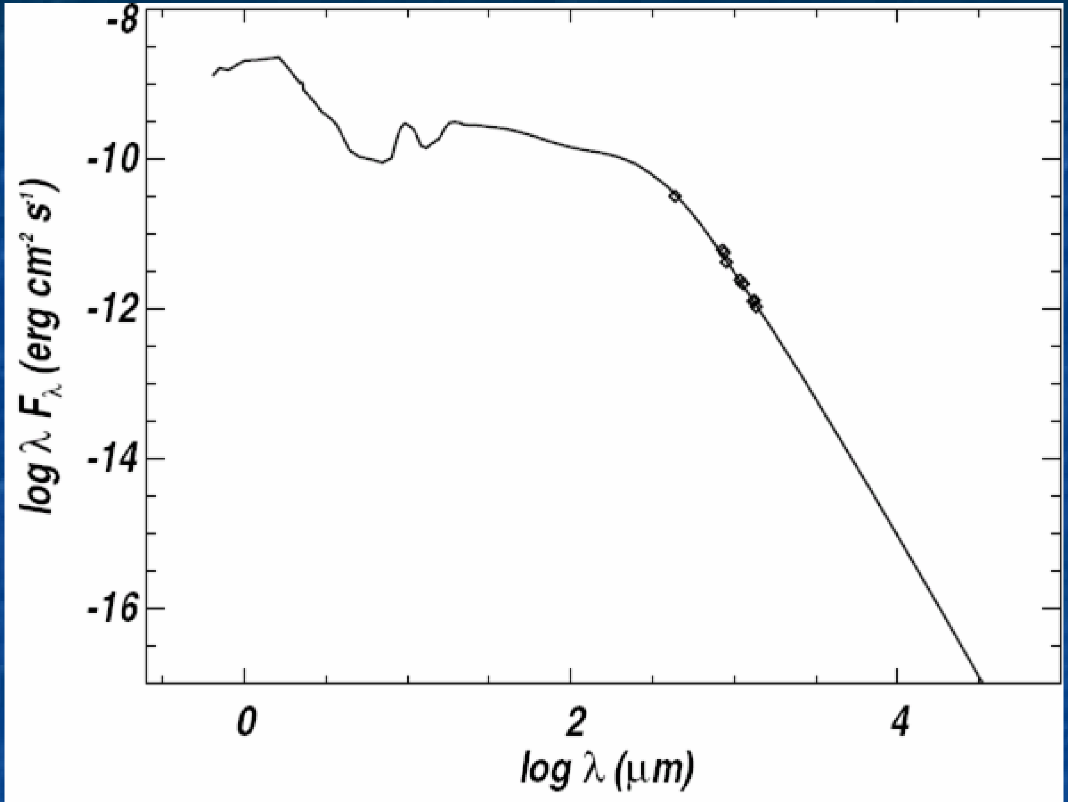
	CO 3–2	CO 2–1	CO 6–5	^{13}CO 2–1
Rest Frequency:	345.796 GHz	230.538 GHz	691.473 GHz	220.399 GHz
Synthesized beam:	2″.7 × 1″.6 PA 18.7°	2″.7 × 1″.7 PA 9.9°	3″.3 × 1″.3 PA 7.5°	2″.7 × 1″.8 PA -3.0°
R.M.S^a (continuum):	35 mJy/beam	1.8 mJy/beam	110 mJy/beam	1.5 mJy/beam
Dust flux:	1.62 ± 0.05 Jy	0.54 ± 0.03 Jy	4.62 ± 0.54 Jy	0.48 ± 0.03 Jy
Channel spacing:	0.18 km s^{-1}	0.26 km s^{-1}	0.35 km s^{-1}	0.28 km s^{-1}
R.M.S.^{a} (line):	1.0 Jy/beam	0.11 Jy/beam	5.3 Jy/beam	0.11 Jy/beam
Peak intensity	31.0 K	24.4 K	16.9 K	6.2 K



	HCN 3–2	HCO$^+$ 3–2	HCN 4–3	CN 2–1
Rest Frequency:	265.886 GHz	267.558 GHz	354.506 GHz	226.597 GHz
Synthesized beam:	1″.6 × 1″.1 PA 0.0°	1″.6 × 1″.1 PA -6.3°	2″.5 × 1″.7 PA 19.7°	4″.2 × 2″.6 PA -3.3°
R.M.S^a (continuum):	5.4 mJy/beam	5.4 mJy/beam	38.9 mJy/beam	6.8 mJy/beam
Dust flux:	0.80 ± 0.01 Jy	0.80 ± 0.01 Jy	1.72 ± 0.51 Jy	0.57 ± 0.02 Jy
Channel spacing:	0.23 km s^{-1}	0.23 km s^{-1}	0.17 km s^{-1}	0.27 km s^{-1}
R.M.S.^{a} (line):	0.34 Jy/beam	0.29 Jy/beam	0.86 Jy/beam	0.33 Jy/beam
Peak intensity	18.5 K	20.4 K	13.3 K	3.6 K

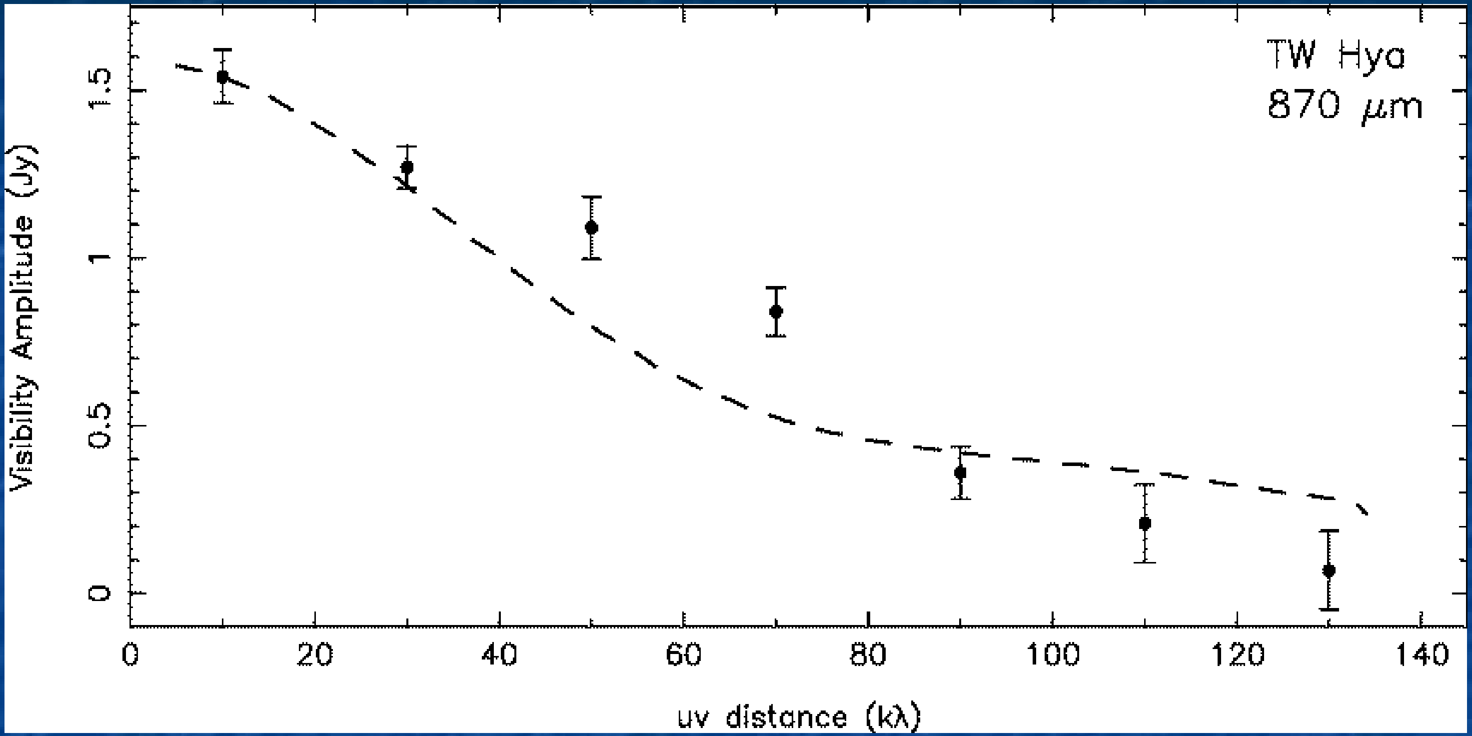
See more details in Qi et al. 2004, 2006

TW Hya Continuum



- The SMA continuum measurements agree well with the predictions of the physically self-consistent irradiated accretion disk model for TW Hya (Calvet et al. 2002)
- The radial brightness distribution of the disk observed at 345 GHz is also consistent with Calvet's model.

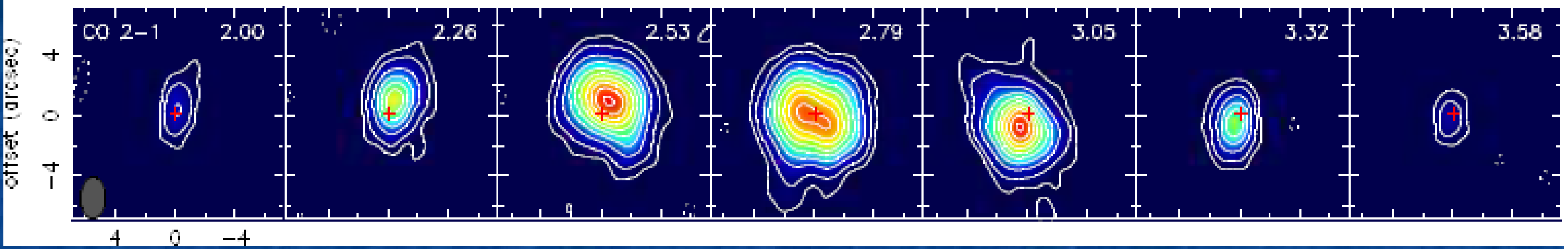
TW Hya Continuum



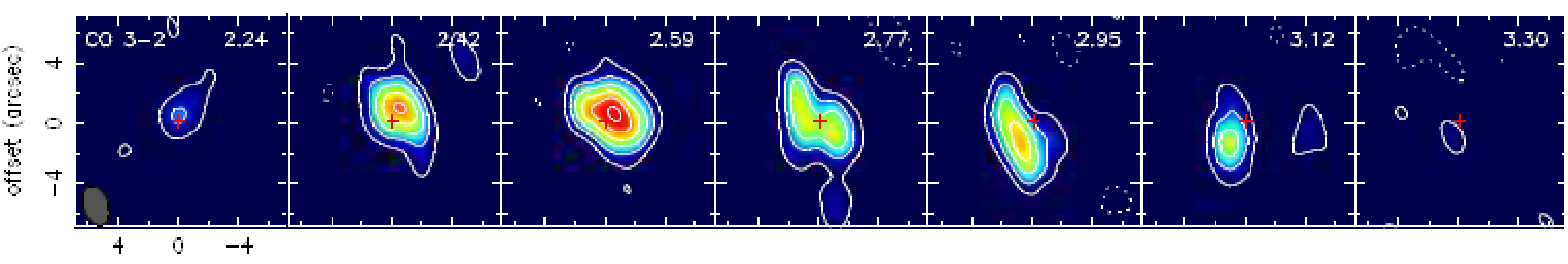
- The SMA continuum measurements agree well with the predictions of the physically self-consistent irradiated accretion disk model for TW Hya (Calvet et al. 2002)
- The radial brightness distribution of the disk observed at 345 GHz is also consistent with Calvet’s model.

TW Hya Images I

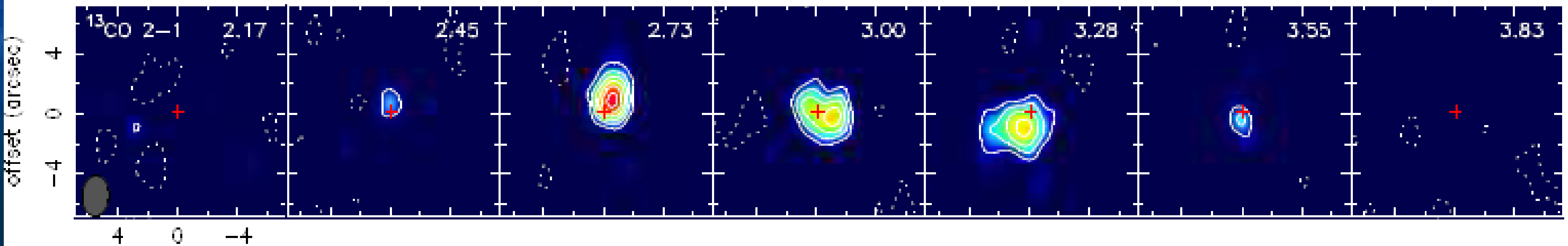
CO 2-1



CO 3-2

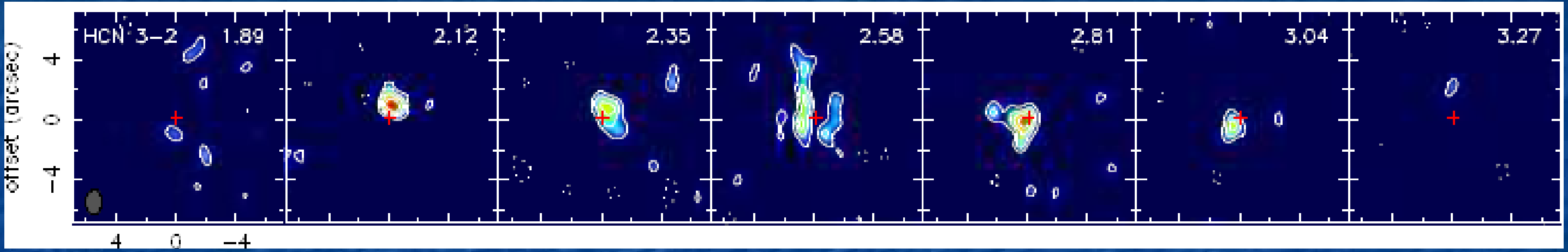


^{13}CO 2-1

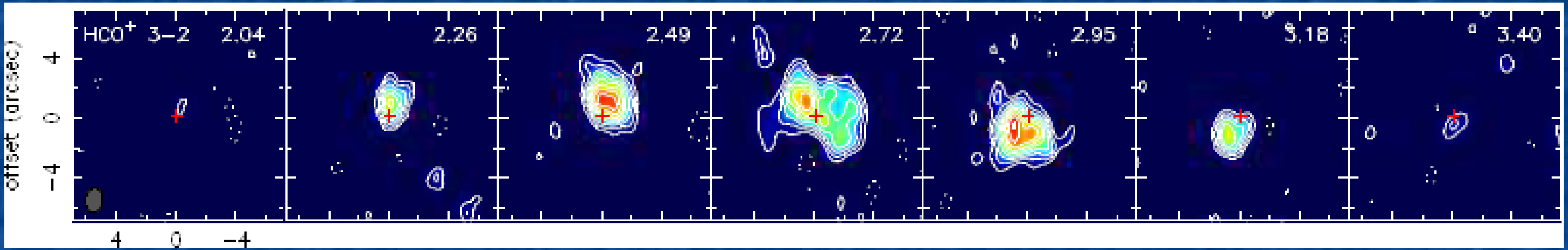


TW Hya Images II

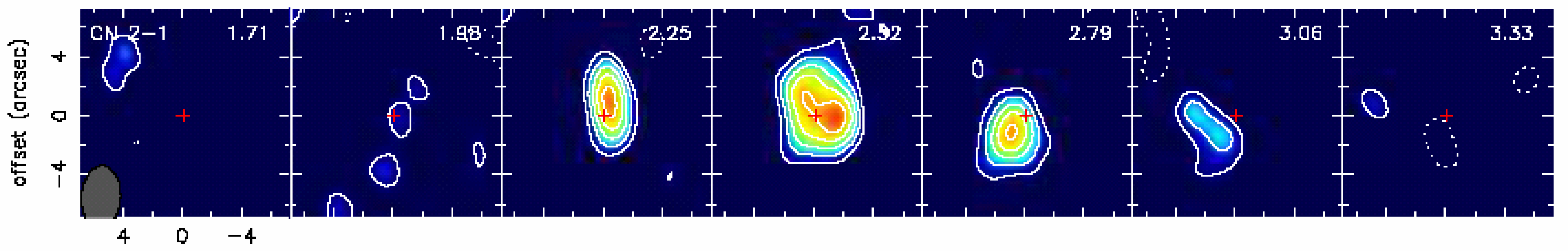
HCN 3-2



HCO$^+$ 3-2



CN 2-1

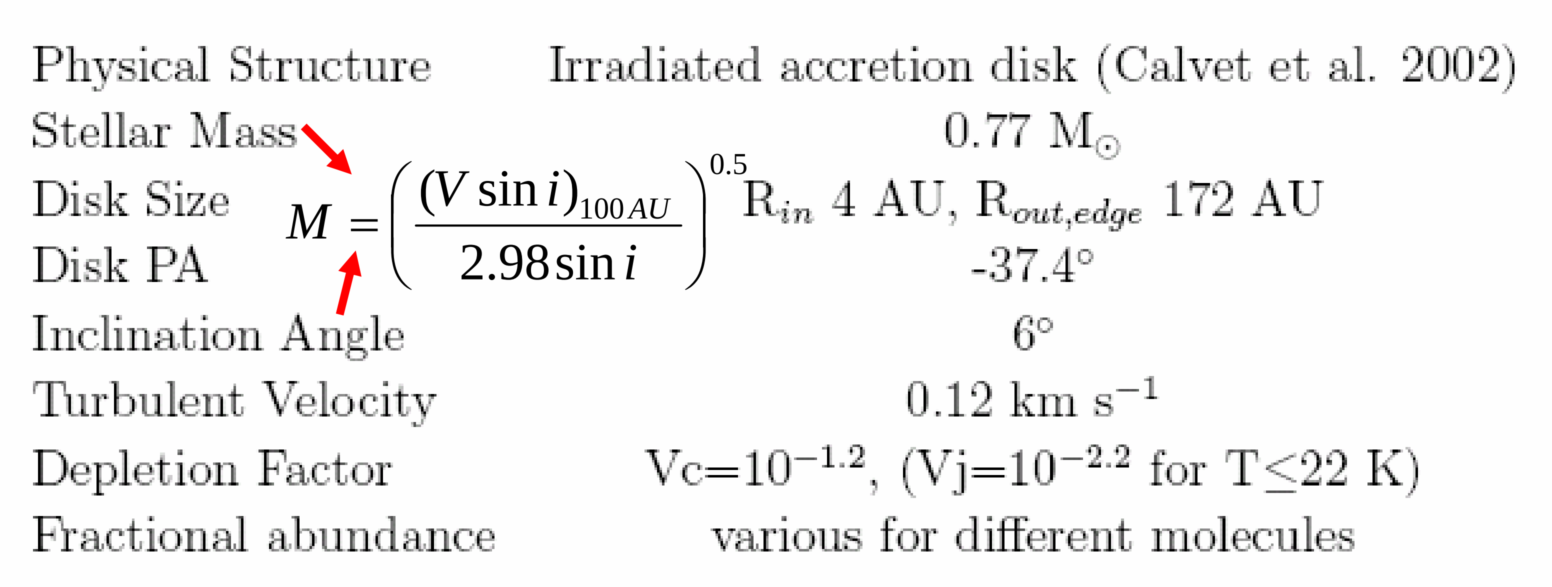


Data Analysis

- We use a 2-D accelerated Monte Carlo model (Hogerheijde & van der Tak 2000) to calculate the radiative transfer and molecular excitation for CO emissions.
- Chi-square analysis

$$\chi^2 = \Sigma_n\Sigma_i(Re(mod_{i,n}) - Re(obs_{i,n}))^2 \times W_i + \Sigma_n\Sigma_i(Im(mod_{i,n}) - Im(obs_{i,n}))^2 \times W_i$$

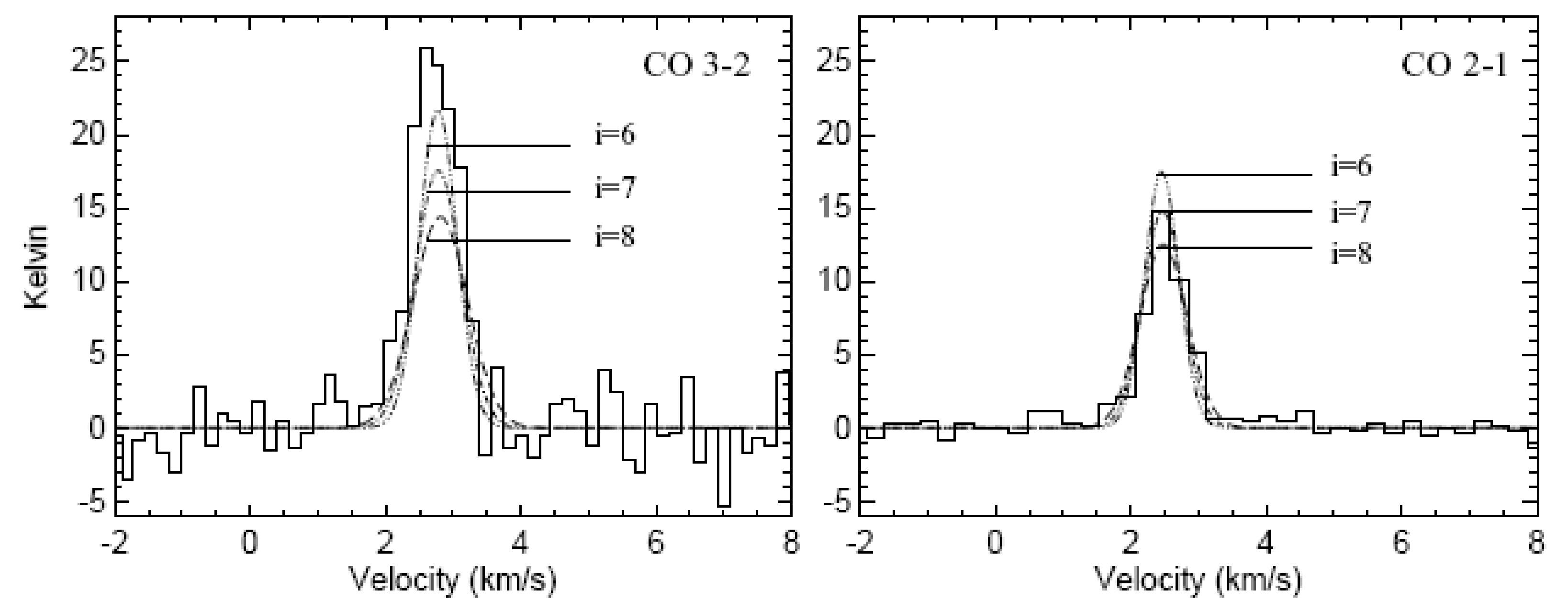
$$W_i = \frac{1}{\sigma_i^2} \quad \text{with} \quad \sigma_i = \frac{\sqrt{2}kT_{sys}}{A_{eff}\eta\sqrt{\tau\Delta\nu}}$$

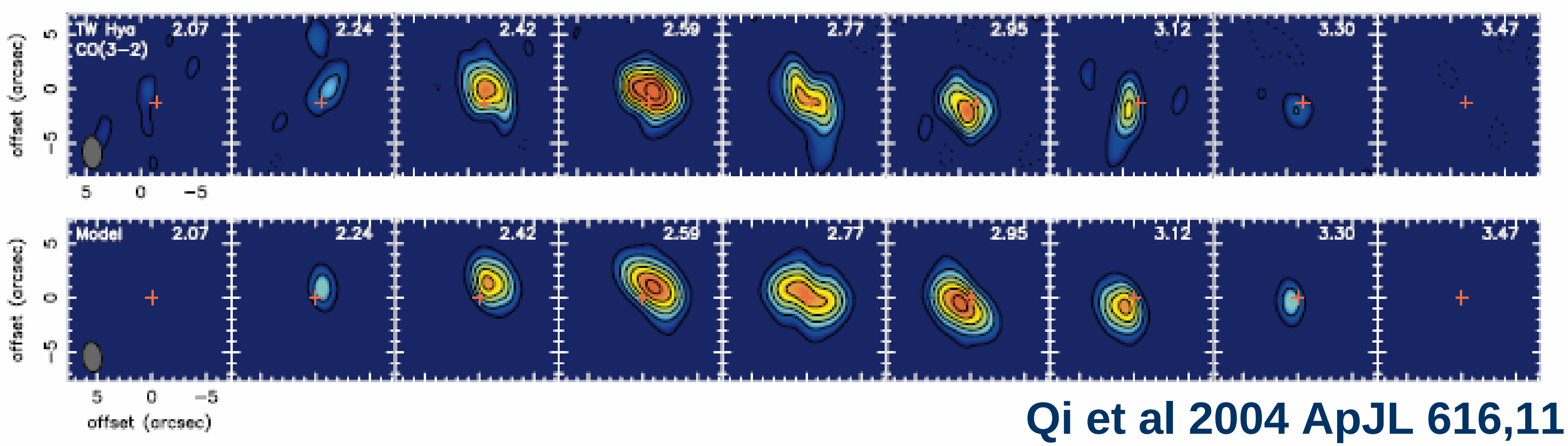


Physical Structure	Irradiated accretion disk (Calvet et al. 2002)
Stellar Mass	0.77 $M_\odot$
Disk Size	R_{in} 4 AU, $R_{out,edge}$ 172 AU
Disk PA	-37.4°
Inclination Angle	6°
Turbulent Velocity	0.12 km s^{-1}
Depletion Factor	Vc=$10^{-1.2}$, (Vj=$10^{-2.2}$ for T$\leq$22 K)
Fractional abundance	various for different molecules

$$M = \left(\frac{(V\sin i)_{100AU}}{2.98\sin i}\right)^{0.5}$$

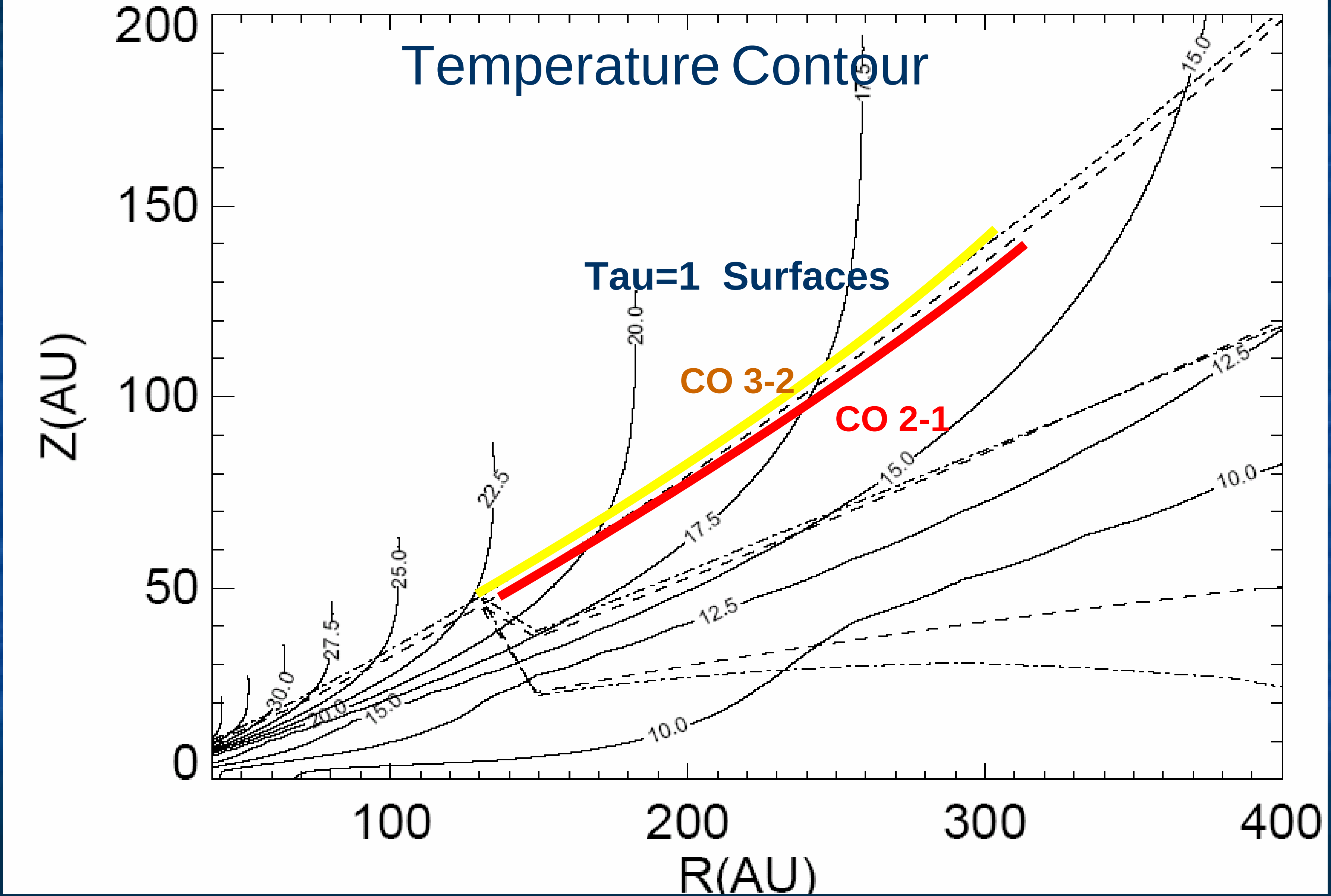
TW Hya CO 2-1 and 3-2





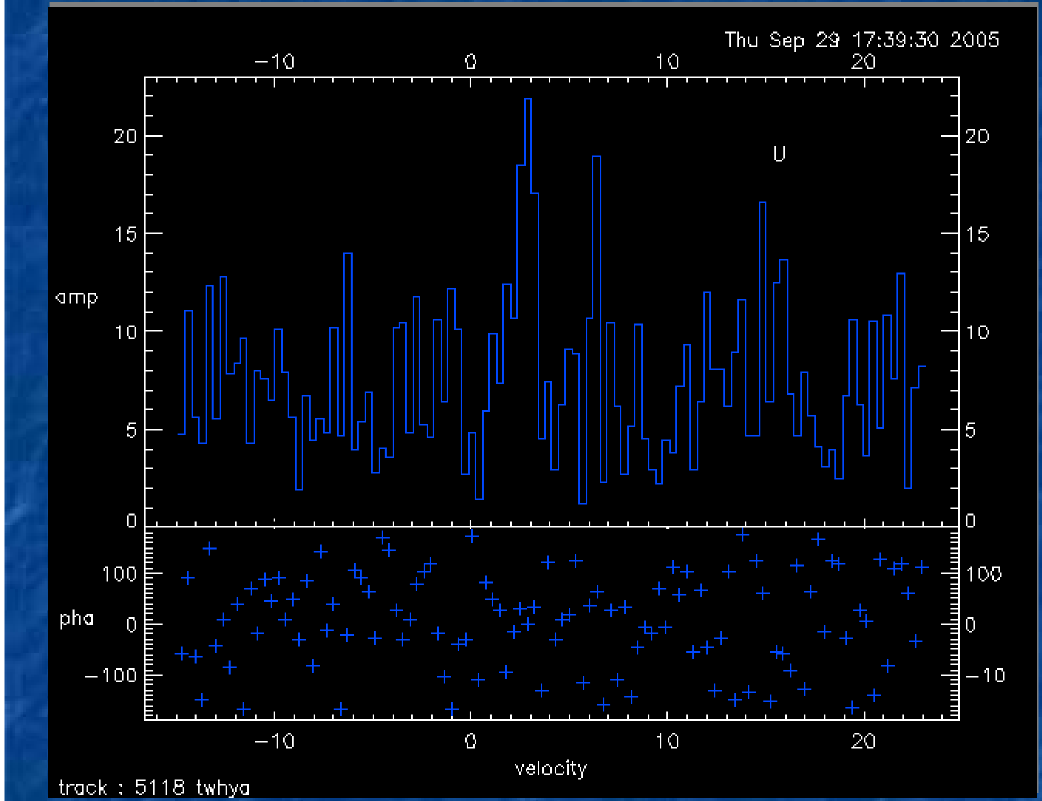
Qi et al 2004 ApJL 616,11

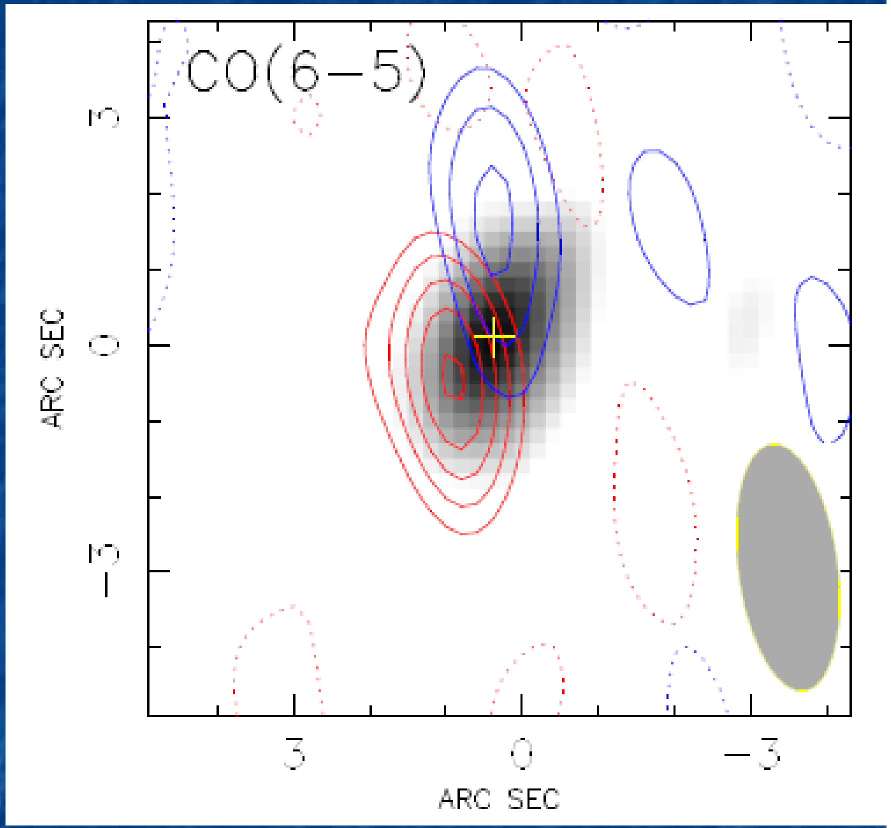
TW Hya CO 2-1 and 3-2



Qi et al 2004 ApJL 616,11

TW Hya CO 6-5





Deviation between observations and the model is even more in CO6-5 (show later), suggestive of a steeper vertical gas temperature profile.

The Effects of X-Rays

- The heating by X-rays

Mean heating energy
per ionization

$$\Gamma_X = 4.8\times10^{-11} erg\,\varsigma_X \left(\frac{\Delta\varepsilon_h}{30eV}\right)\left(\frac{AU}{r}\right)^2 n$$

$$where \quad \varsigma_X = 6\times10^{-9} s^{-1} \left(\frac{AU}{r}\right)^2 \; for\ TW\ Hya$$

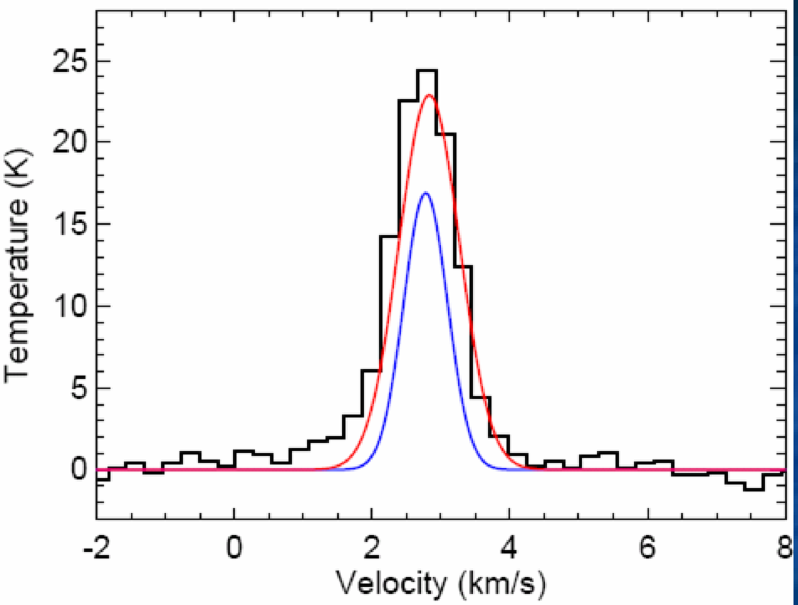
- The dust-gas cooling

$$\Lambda_{dg} = 2\times10^{-33} erg\, cm^3 s^{-1} \left[\frac{\rho_d}{\rho_g}\frac{50nm}{a}\frac{\alpha}{0.5}\right] T^{0.5} \boxed{(T - T_d)}\, n^2$$

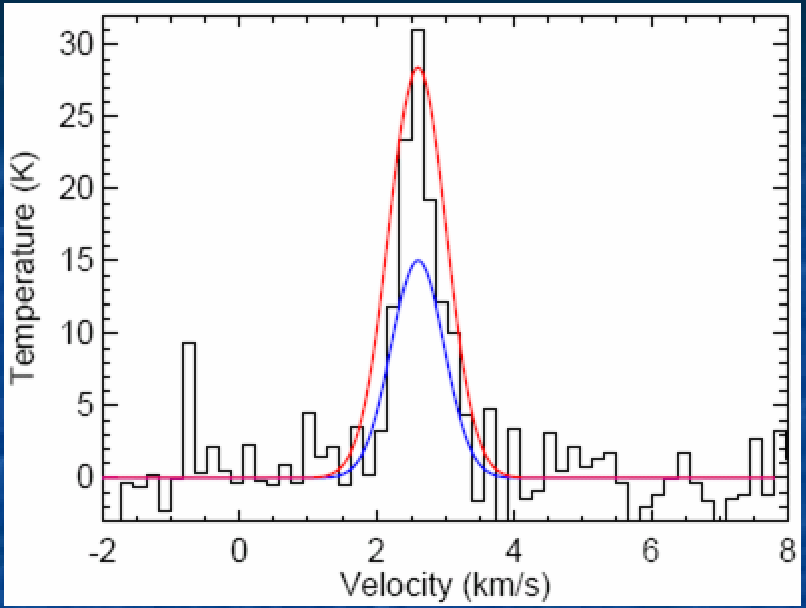
Mean dust radius

Glassgold & Najita 2001
Glassgold et al. 2004

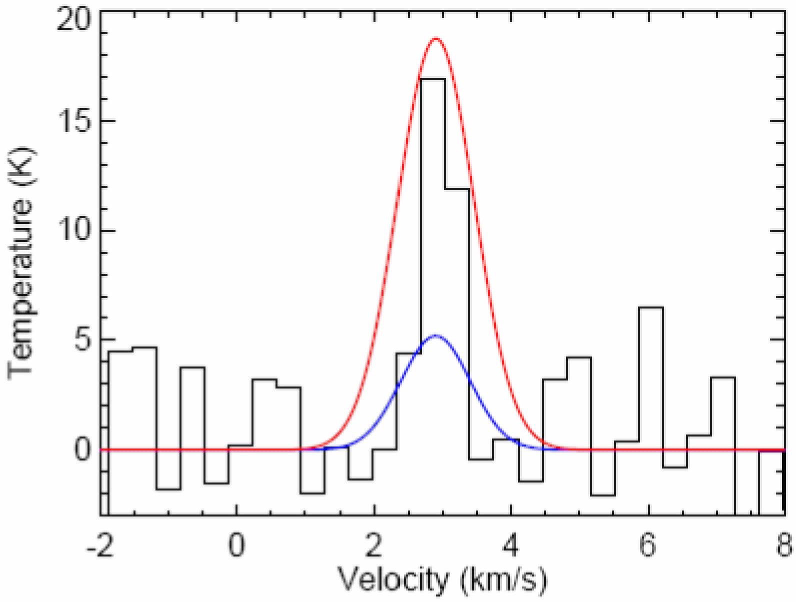
CO 2-1



CO 3-2



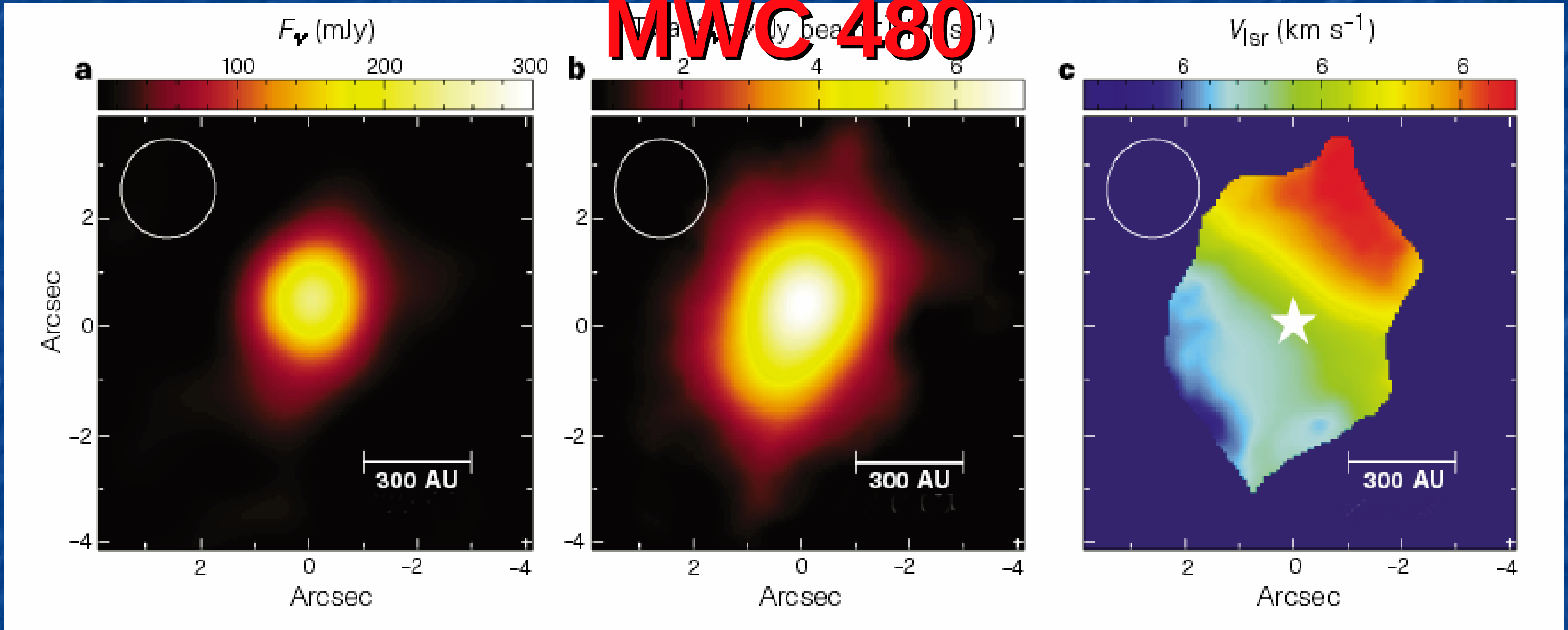
CO 6-5



Blue: Canonical Model
(Calvet et al. 2002,
Qi et al. 2004)
Black: SMA data
Red: Model with X ray heating
(Qi et al. 2006)

Observations of Herbig Ae stars

Observations of Herbig Ae stars using mm-interferometers



MWC 480

1.3 mm dust **^{12}CO 2-1 integrated** **^{12}CO 2-1 mean velocity**

Manning, Koerner, & Sargent 1997, Nature

- Geometry: compact, disklike structures
- Kinematics: Kepler motions

High Resolution Observations of CDs around Herbig Ae stars

- Hebig Ae stars as well as T Tauri stars have been observed using mm-interferometers in the 1990's (e.g., Mannings et al. 2000)
  - Geometry: Compact, disklike structures
  - Kinematics: Keplerian motions.
- Recent high resolution observations at Opt/IR have revealed more complicated structures of disks around Herbig Ae stars (e.g., HD 141569; Clampin et al. 2003, AB Aur; Fukagawa et al. 2004).
  - How were these complicated structures created?
  - What kind of effect do these complicated structures have on planetary formation?

Complicated Structures in CDs around Herbig Ae stars

AB Aur @ 1.6 micron

Fukagawa et al. 2004

HD 142527 @ 1.6 micron

Fukagawa et al. 2006

What is the actual distributions of the circumstellar material?

SMA Observations of Herbig Ae Stars

Spectral Type	Group I			
Source	AB Aur		HD 142527	HD 169142
Line	CO 3-2	CO 2-1	CO 3-2	CO 2-1
Angular Resolution (arcsec)	1.0 x 0.7 PA = -58	1.1 x 0.8 PA = 80	2.4 x 1.5 (cont: 1.2x0.6) PA = 22	1.6 x 1.0 PA = 20

Spectral Type	Group II		
Source	HD 163296		MWC 480
Line	CO 3-2	CO 2-1	CO 2-1
Angular Resolution (arcsec)	3.1 x 2.1 PA = 16	4.9 x 3.1 PA = 80	4.7 x 2.2 PA = -65

^{12}CO 6-5 was also observed recently.

See more details in Lin et al. 06 (AB Aur CO3-2) and Raman et al. 06 (HD 169142).

AB Aur

- AB Aur is a nearby, bright, single Herbig Ae star.
  - d ~ 144 pc, Sp = A0 Ve, M_* ~ 2.4 Mo, age ~ 4 Myr
- Extended reflection nebulosity in optical.
  - AB Aur is associated with abundant envelope material.
- ^{13}CO (1-0) and 2.7 mm continuum images using the OVRO mm-array (Mannings & Sargent 1997).
  - A CD around AB Aur was clearly demonstrated.
  - Detailed structures were not revealed because of a low angular resolution (~5”).
- 1.6 μm coronagraphic image using the Subaru telescope (Fukagawa et al. 2004).
  - Spiral arm-like structures in the CD were revealed.

SMA Results:
345 GHz Dust Continuum

QuickTimeý Ç²
TIFFÅiLZWÅj êLí£ÉvÉçÉOÉâÉÄ
Ç™Ç±ÇÃÉsÉNÉ`ÉÉÇ¾å©ÇÈÇžÇ½Ç…ÇÕïKóvÇ-Ç ÅB

- The dust continuum disk was clearly resolved at ~1” angular resolution .
- Two peaks; one at 1” SW and the other at 1” NE to the star, but no clear peak at the stellar position.
  - Size of the ringlike structure ~ 150 AU or less.
- Mass ~7.5 M_J (gas + dust)
- See also Pietu et al. 2005.

The structure of the dust disk seems to be very different from those of CDs around other Herbig Ae/T Tauri stars.

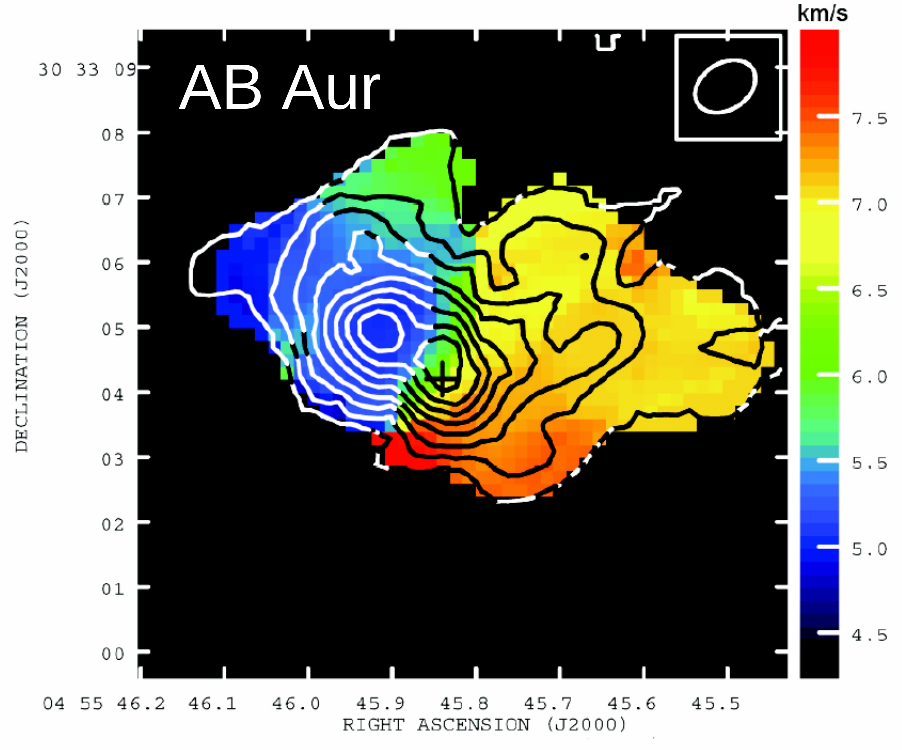
SMA Results: ^{12}CO (3-2)

AB Aur

- An elongated disk structure, consistent with other observations.
  - Overall dimension: ~530 ´ 330 AU
- Two peaks; one at the stellar position, and the other at the most prominent spiral arm.
  - A part of the ^{12}CO 3-2 emission seems to trace the spiral arm.
  - PdBI ^{12}CO 2-1 map shows only one peak at the stellar position.
- Additional extended structures.
- See also Corder et al. 2005 for ^{13}CO 1-0 images.

Structures of the gaseous disk seems to be very different from those around other Herbig Ae/T Tauri stars.

SMA Results:
^{12}CO velocity structure



- Clear velocity gradient along the major axis.
  - Kepler rotation.
- There seems to be some additional structures, which deviates from simple rotation.

Comparison with a toy model

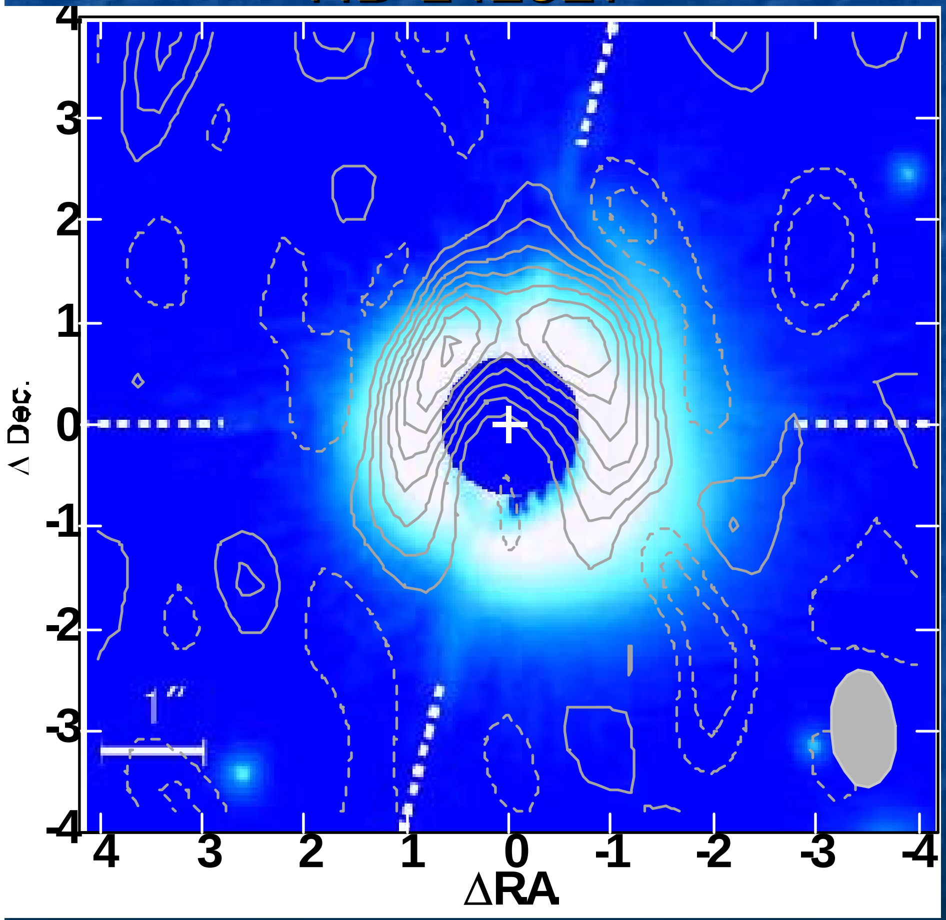
- Color:obs
- Cont: model
- M*=2.2 Mo
- I= 42 deg
- R= 530 AU
- $T_b \propto r^{-0.47}$

HD 142527

- Bright Herbig Ae star
  - d ~ 140-200 pc; Sp = F6 IIIe; M_* ~1.9 Mo; age ~ 2 Myr
- Categorized as Group I source (same as AB Aur)
- Very low declination (-42 deg); no high resolution observations were done before.
- Subaru coronagraphic image shows spiral “banana-split” structures (Fukagawa et al. 2005).
- ^{12}CO & ^{13}CO 3-2 observations with ASTE at a low angular resolution.
  - Extended ^{12}CO 3-2 emission
  - Compact ^{13}CO3-2 emission

SMA Results:
345 GHz Continuum

HD 142527

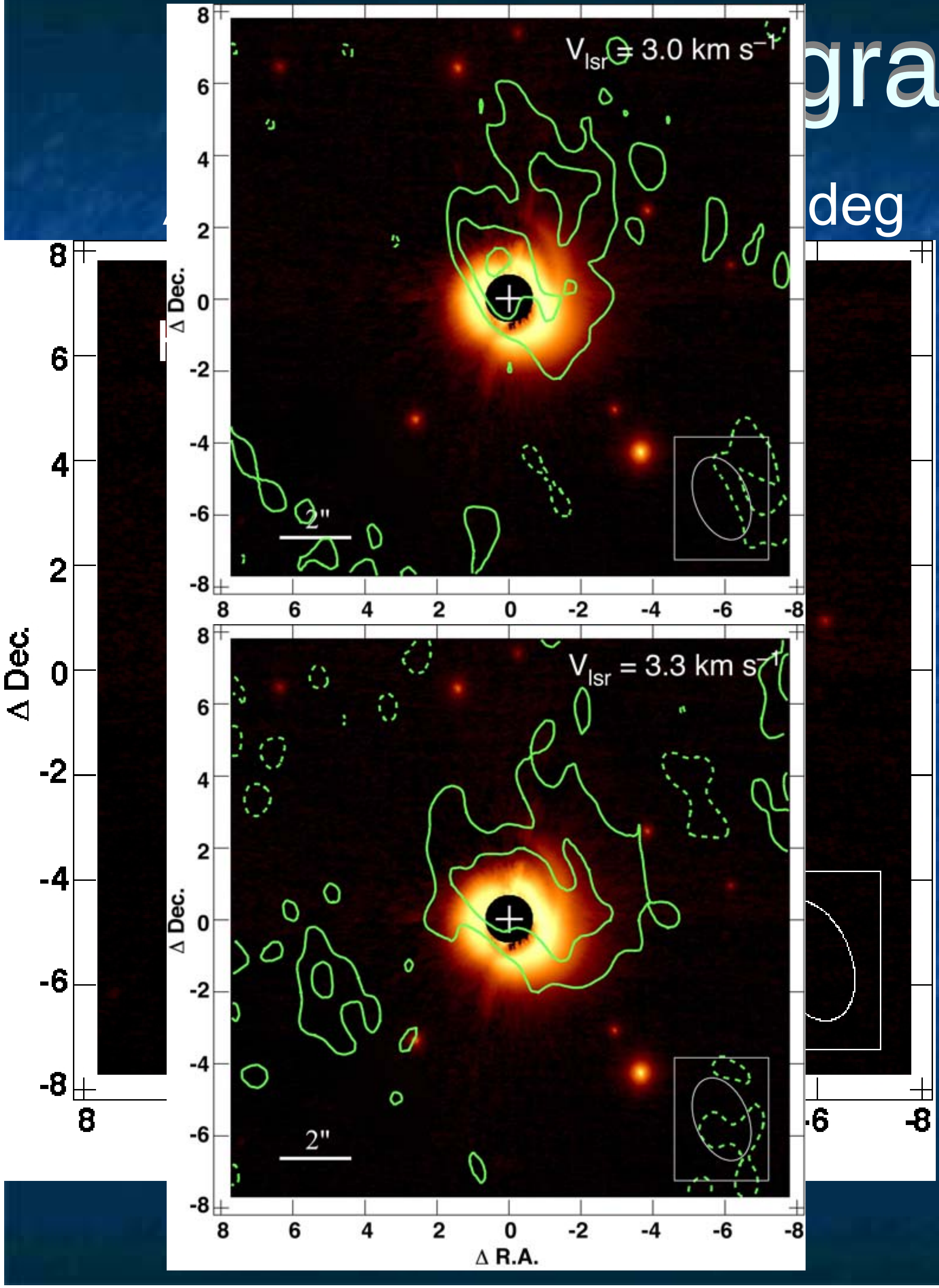


- 345 GHz continuum distribution resembles to the 1.6 μm scattered emission.
  - An arc-like structure enclosing the central star
  - two peaks; one at the NE and the other at the NW.
  - Peak positions are shifted to the N as compared to those seen at 1.6 μm.
  - No clear emission on the southern side.
  - Total flux density ~1.2 Jy

-> ~ 0.03 Mo (gas + dust).

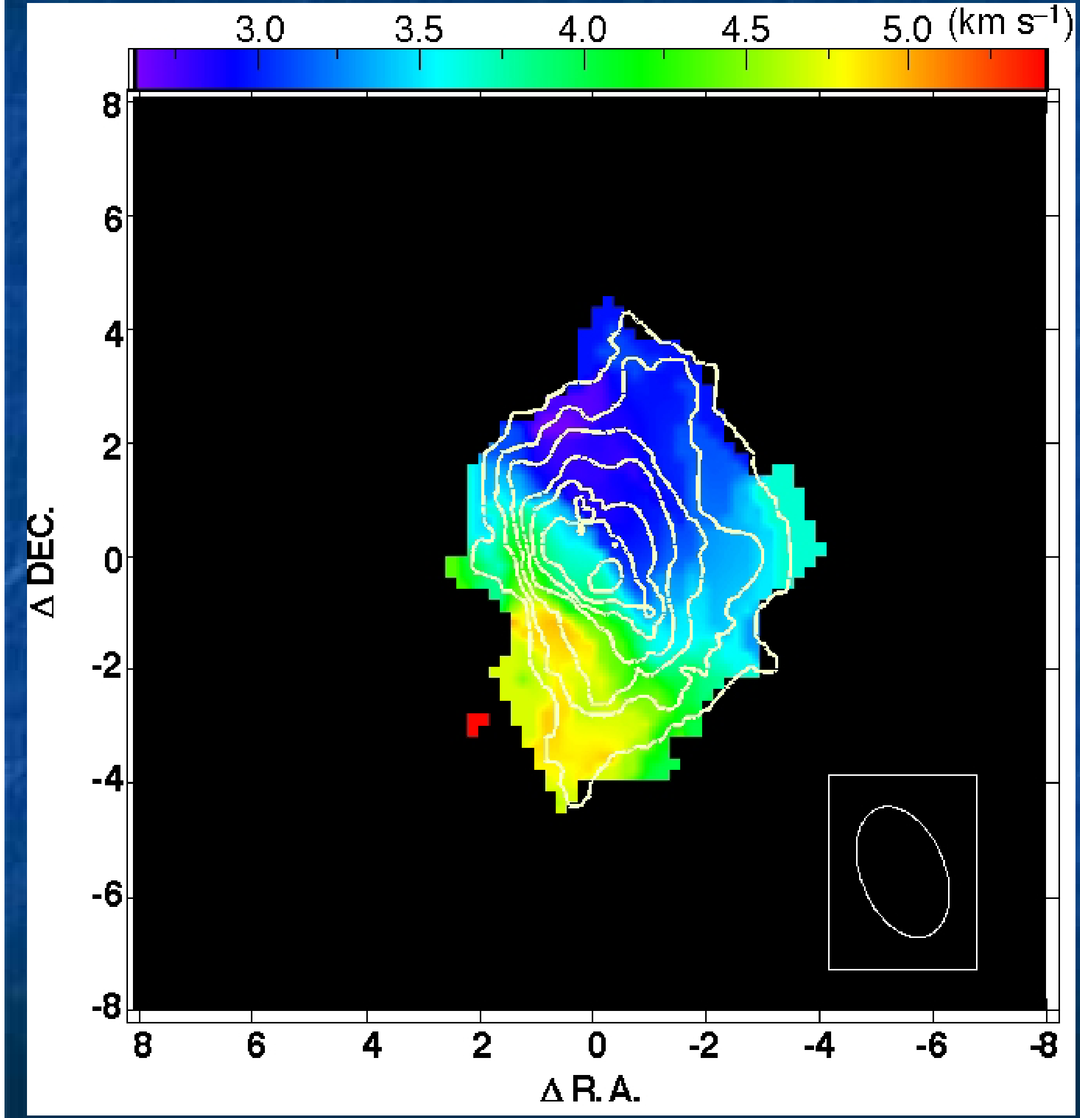
grated Intensity

deg



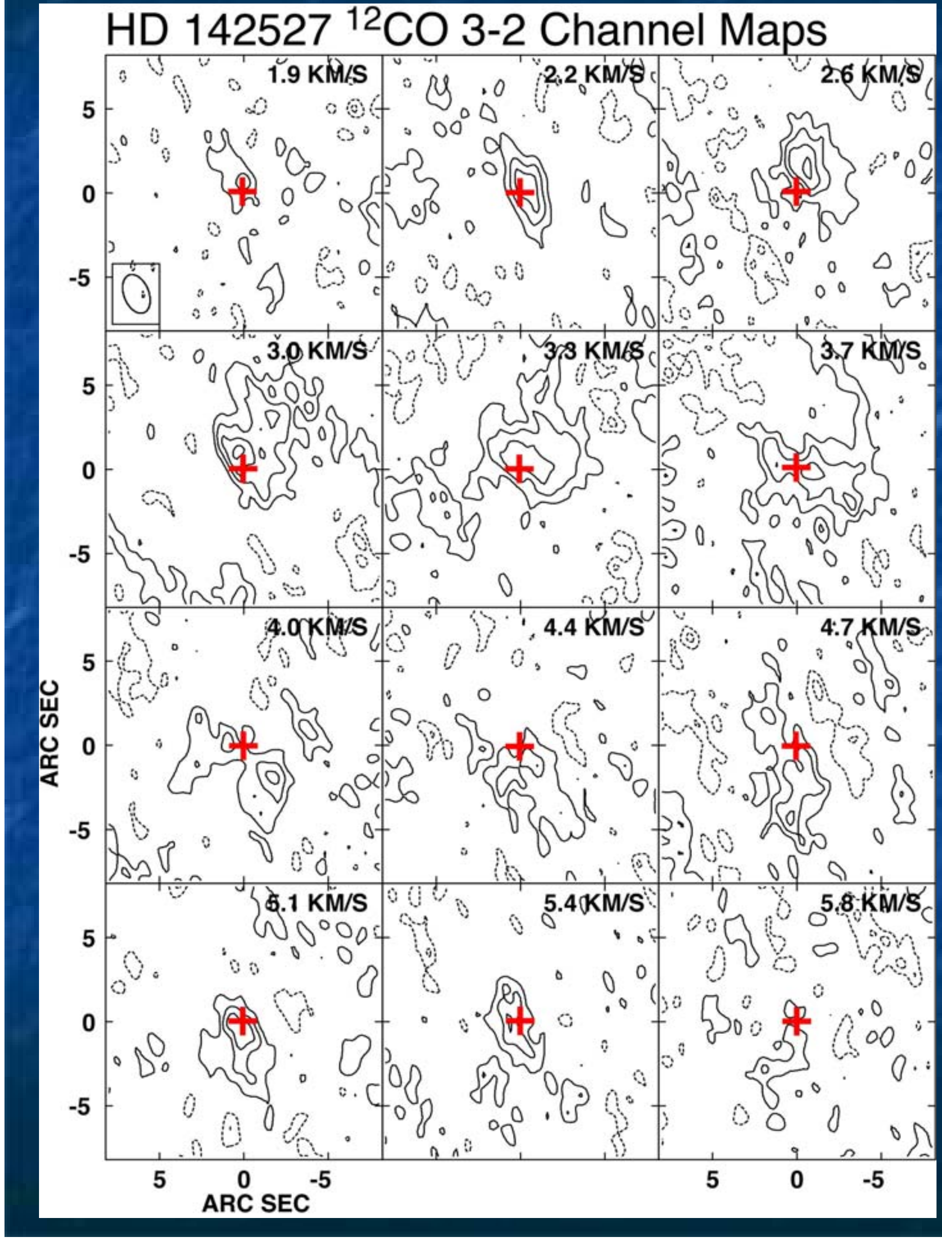
- Elongated structures with a single peak at the stellar position.
  - NE to SW elongation at higher contours.
  - NNW to SSE elongation at lower contours.
  - Size ~ 3.4" x 2.5" (480 AU x 350 AU); PA~8 deg
  - Any gaseous component possibly associated with the spiral arm?

^{12}CO 3-2 Mean Velocity

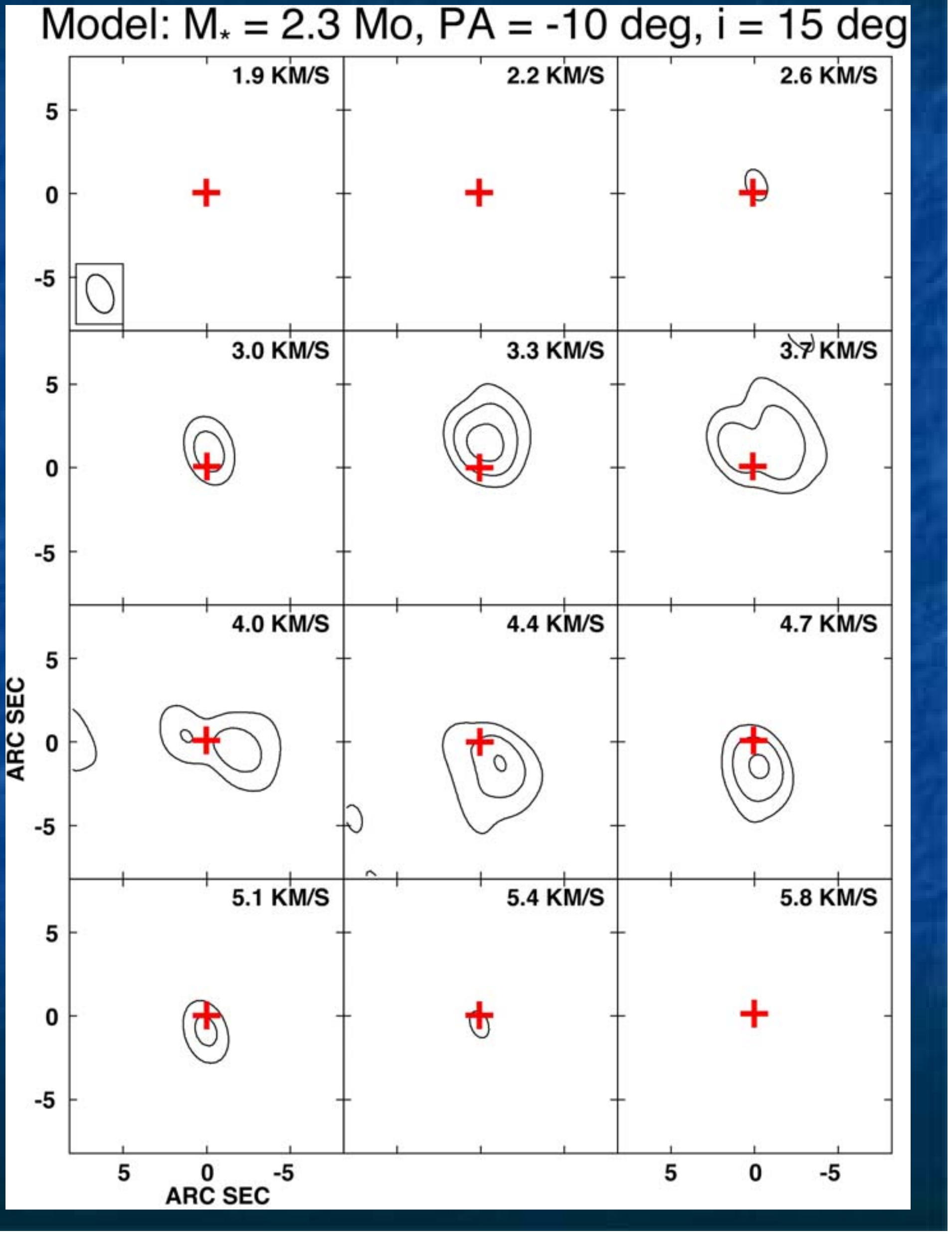


- Clear velocity gradient from NW to SE, which is probably due to rotation.
  - Roughly consistent with Kepler rotation around a 2Mo star.
  - Disk axis is from NE to SW?
- Additional velocity gradient suggestive of non-circular motion.
  - Any relationship with gas possibly associated with the spiral arm?

^{12}CO 3-2 Channel Maps



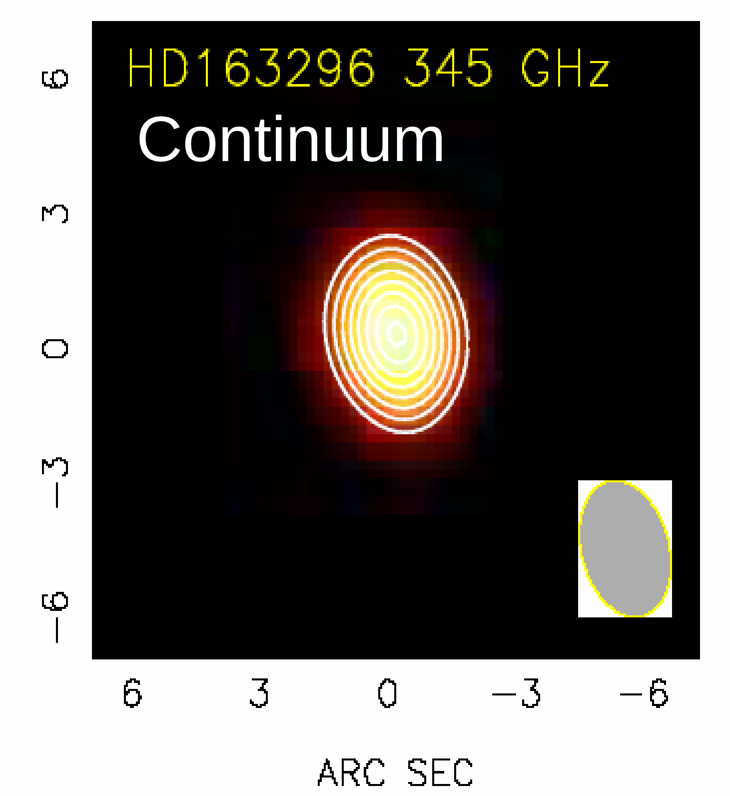
HD 142527 ^{12}CO 3-2 Channel Maps

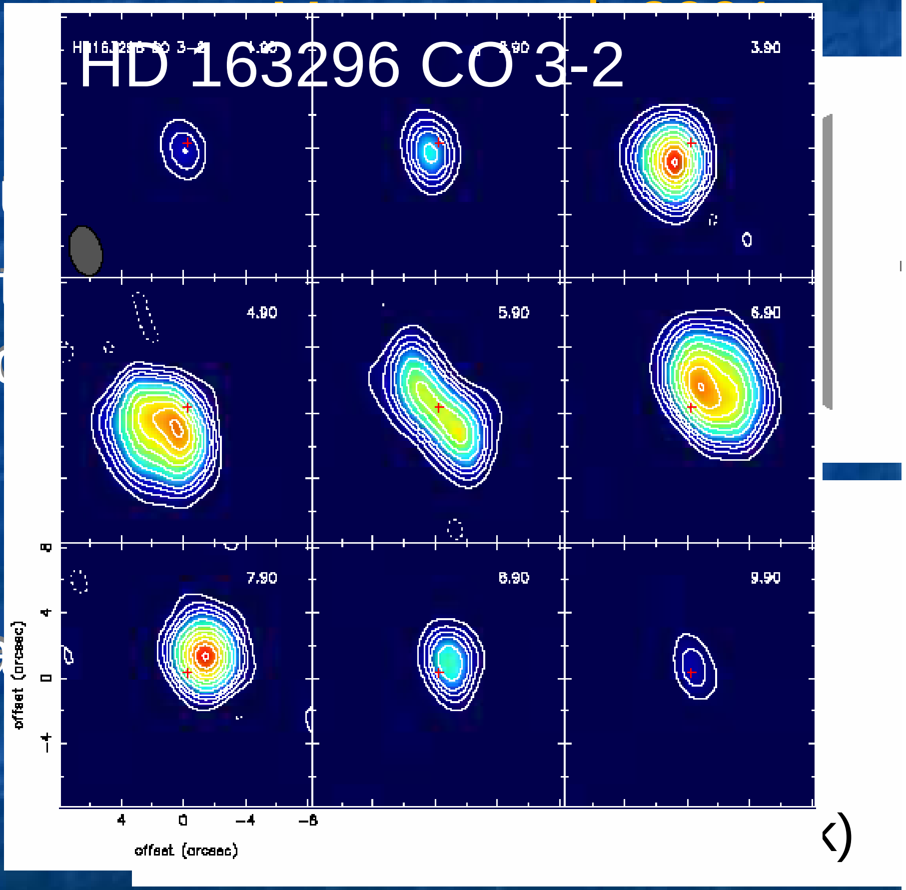


Model: M$_*$ = 2.3 Mo, PA = -10 deg, i = 15 deg

Comparison between Group I and II

- Gr
  - ructu
  - tructu
    notic
- Gr
  - aks
  - ks a





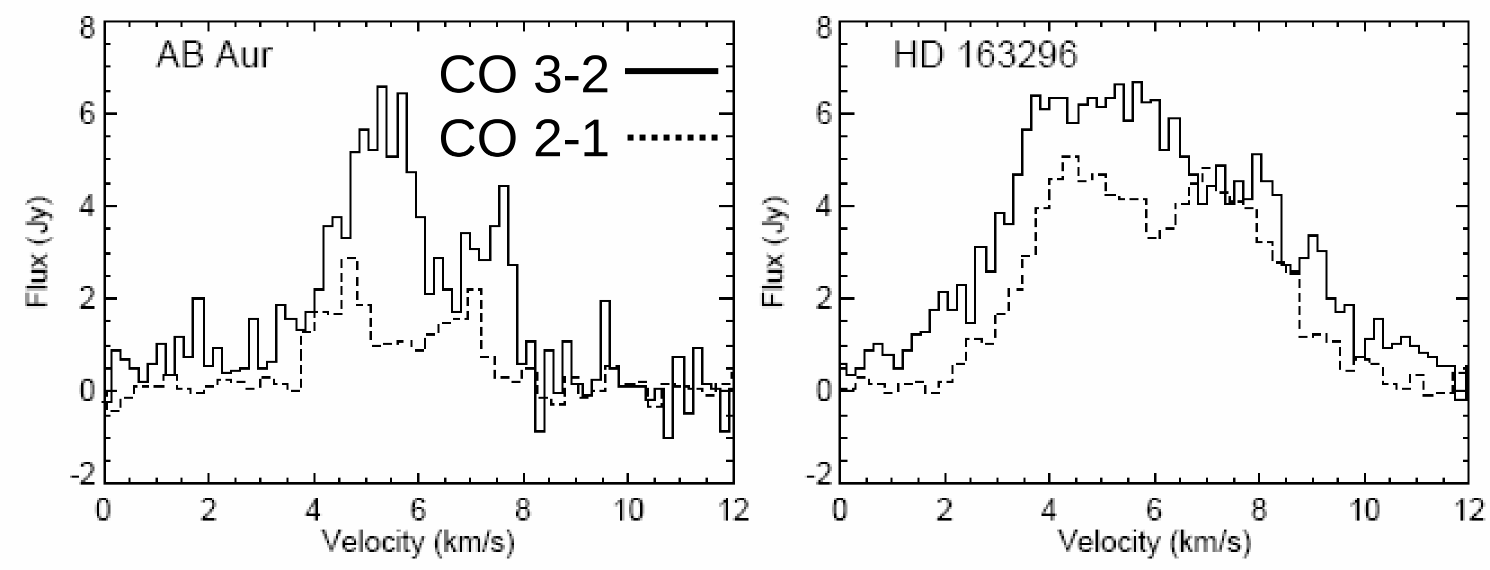
C. Qi et al.

Relationship between disk characteristics and SEDs?

Difference in Vertical Structures between Two Groups?

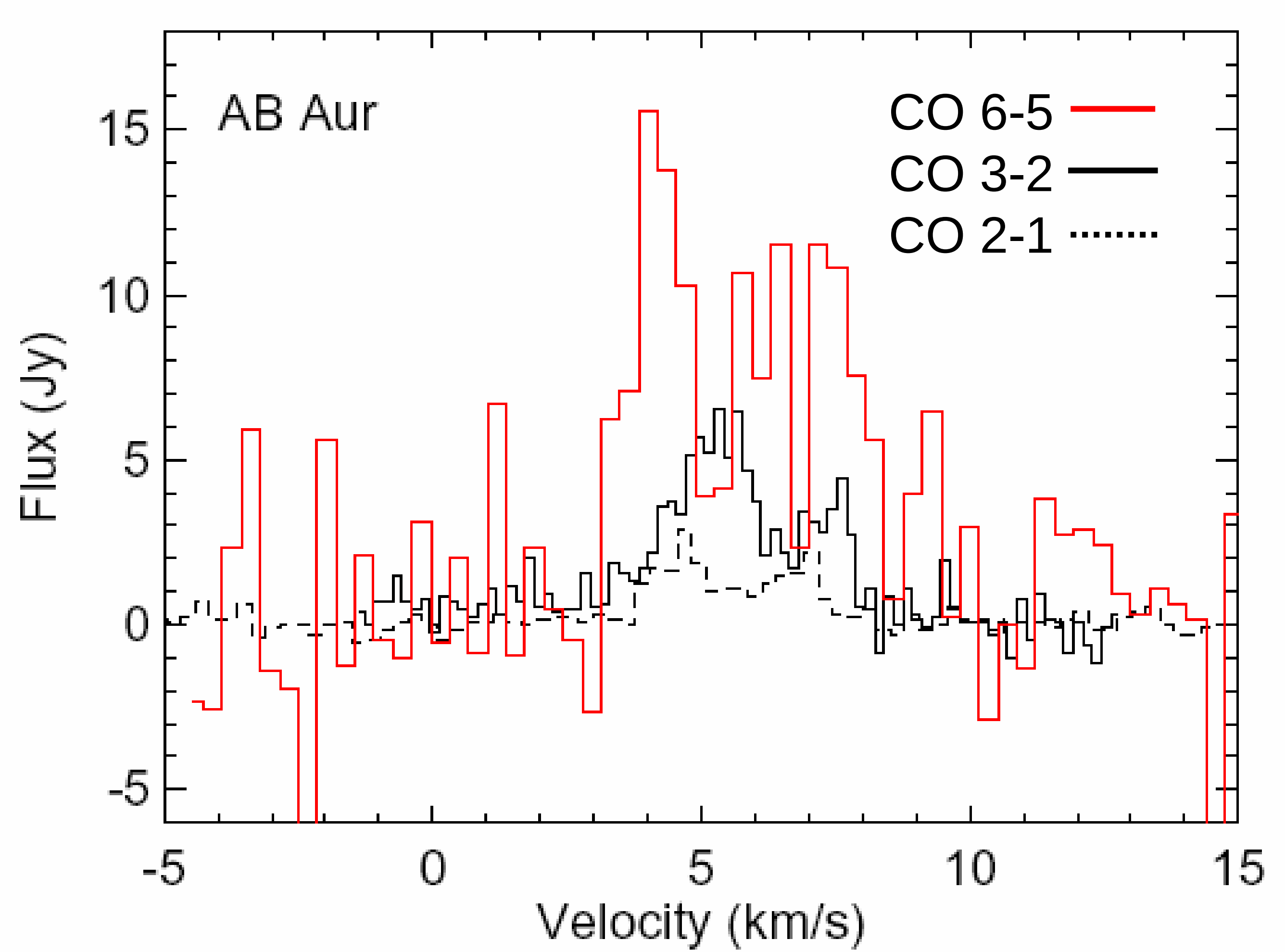
Group I

Group II



Group I sources may have more vertical structures than Group II sources, which is consistent with their SEDs.

Difference in Vertical Structures between Two Groups?



SUMMARY

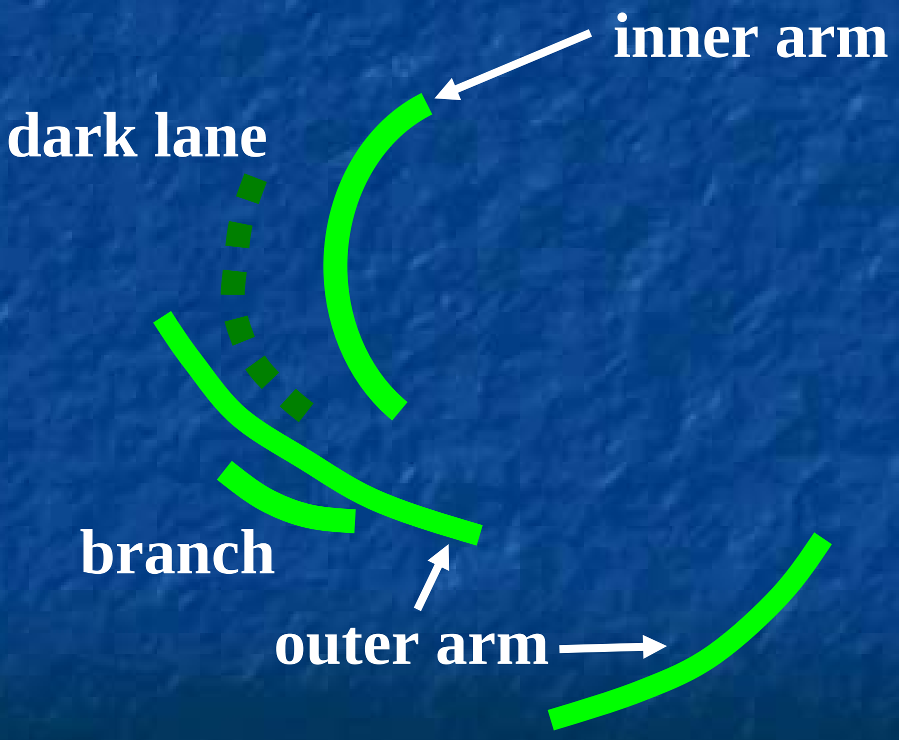
- The SMA plays a crucial role to study CDs around TTSs and Herbig Ae stars at submm.
- TW Hya; closest cTTS with a disk.
  - X ray heating is important to explain the vertical gas temperature gradient.
  - Chemical structures can be studied in detail.
- AB Aur and HD 142527; disks with spiral arms.
  - Both dust continuum and CO emissions shows material showing spiral-like (or ring-like) structures.
  - There seems to be non-Keplerian motions, which could be related to spiral structures.
  - Vertical structures may be important to explain these characteristics.

SMA results will lead future observations using the ALMA at submm.

Origin of the Central Cavity in the Dust Disk of AB Aur

- Irregularity in dust temperature and/or dust surface density.
  - The SED of AB Aur has a large mid IR excess, which may be due to the disk geometry such as flaring. Such structures might make an irregular dust temperature distribution?
  - Is it possible to crate such flaring structures by gravitational instability.
- Dust particles at the disk center might grow up, decreasing the dust opacity.

AB Aur:
1.6 μm Coronagraphic Image

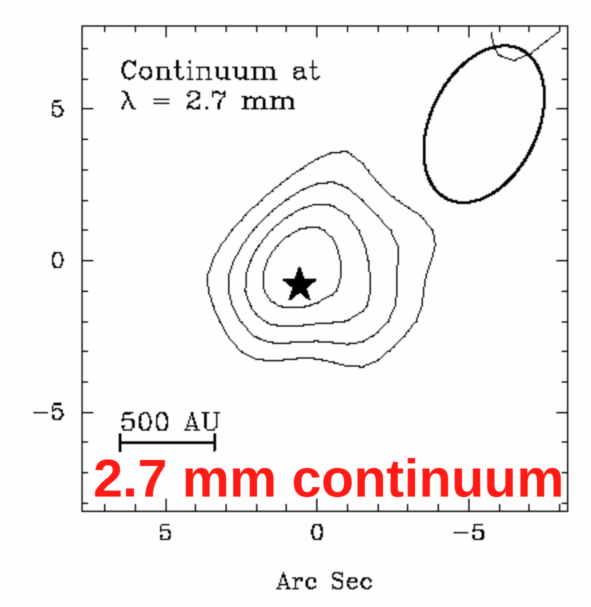


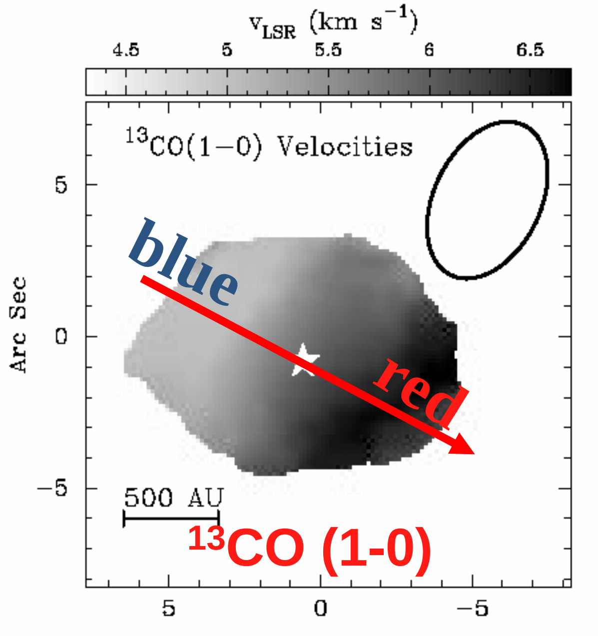
- The CD is detected in scattered light.
  - P.A. = 58° ± 5°, inc. = 30°±5°
- 4 major spiral arms are identified.
  - An HST optical image also shows similar structures (Grady et al. 1999).
- Weak gravitational instability would be the source of the spiral structures.

What is the actual disk structure?

AB Aur: 2.7 mm Continuum and ^{13}CO (1-0) maps

(Mannings & Sargent 1997)





- 5.5" x 3.5" beam unresolved the dust disk.
- The upper limit of the $R_{\text{dust disk}}$ ~ 250 AU.

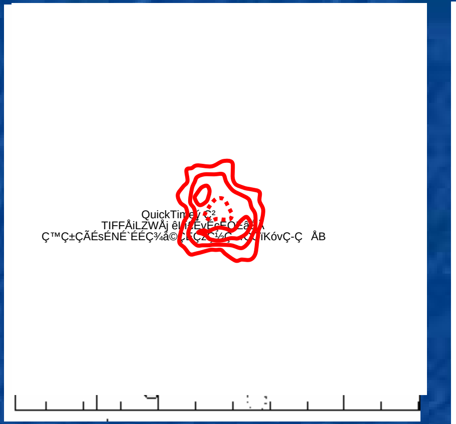
- The gas disk was resolved
  - R_{disk} ~ 390 AU, P.A. ~ 79°, inclination ~ 76°
- Clear velocity gradient along the major axis.
  - rotation consistent with Kepler motion.

^{12}CO 3-2 Channel Maps

Several channel maps trace the spiral arms seen in the Subaru image.

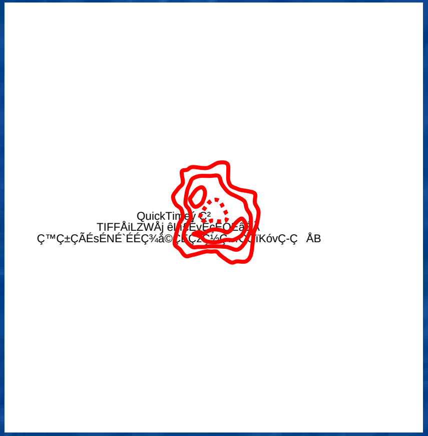
Comparison of dust maps at different frequencies

PdBI 2.8 mm



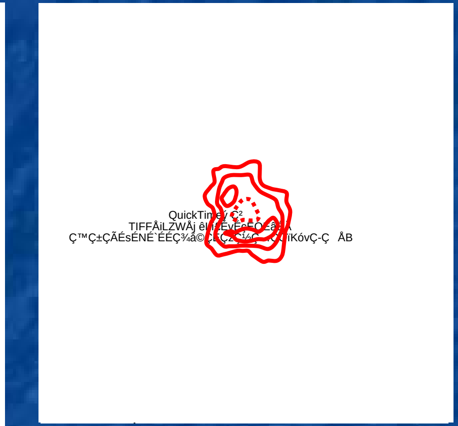
1.4" x1.1"

NMA 2mm



2.1"x1.6"

PdBI 1.4 mm



0.85" x 0.59"

SMA 850 μm

Comparison of Dust Maps at Different Frequencies

PdBI 2.8 mm

1.4" × 1.1"

NMA 2mm

2.1" × 1.6"

PdBI 1.4 mm

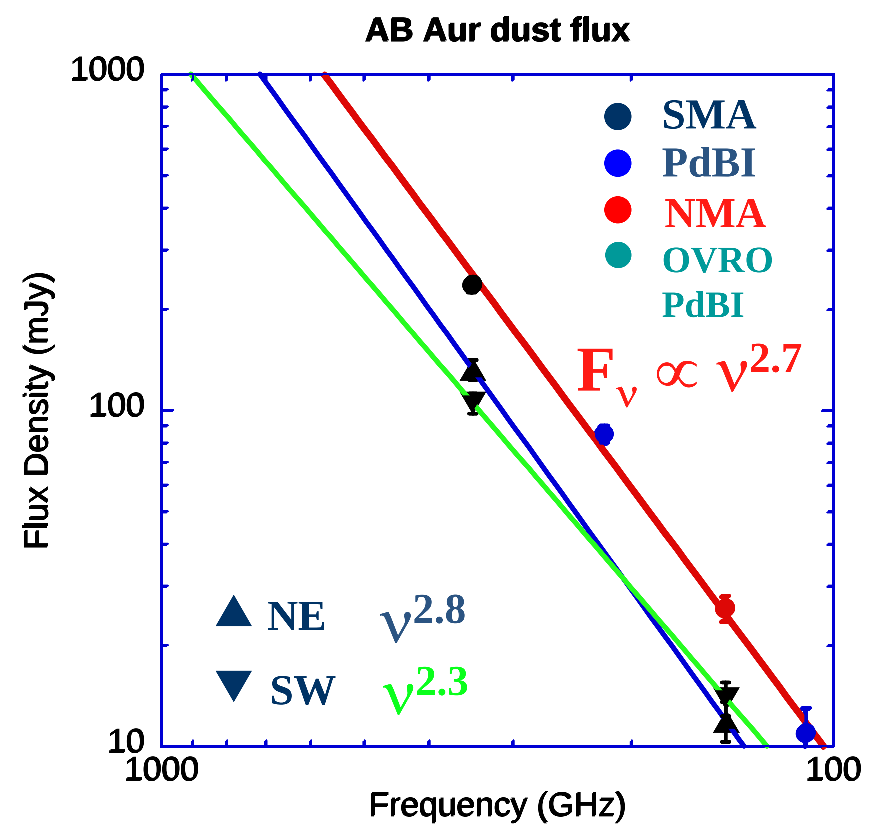
0.85" × 0.59"

SMA 850 μm

1.0" × 0.72"

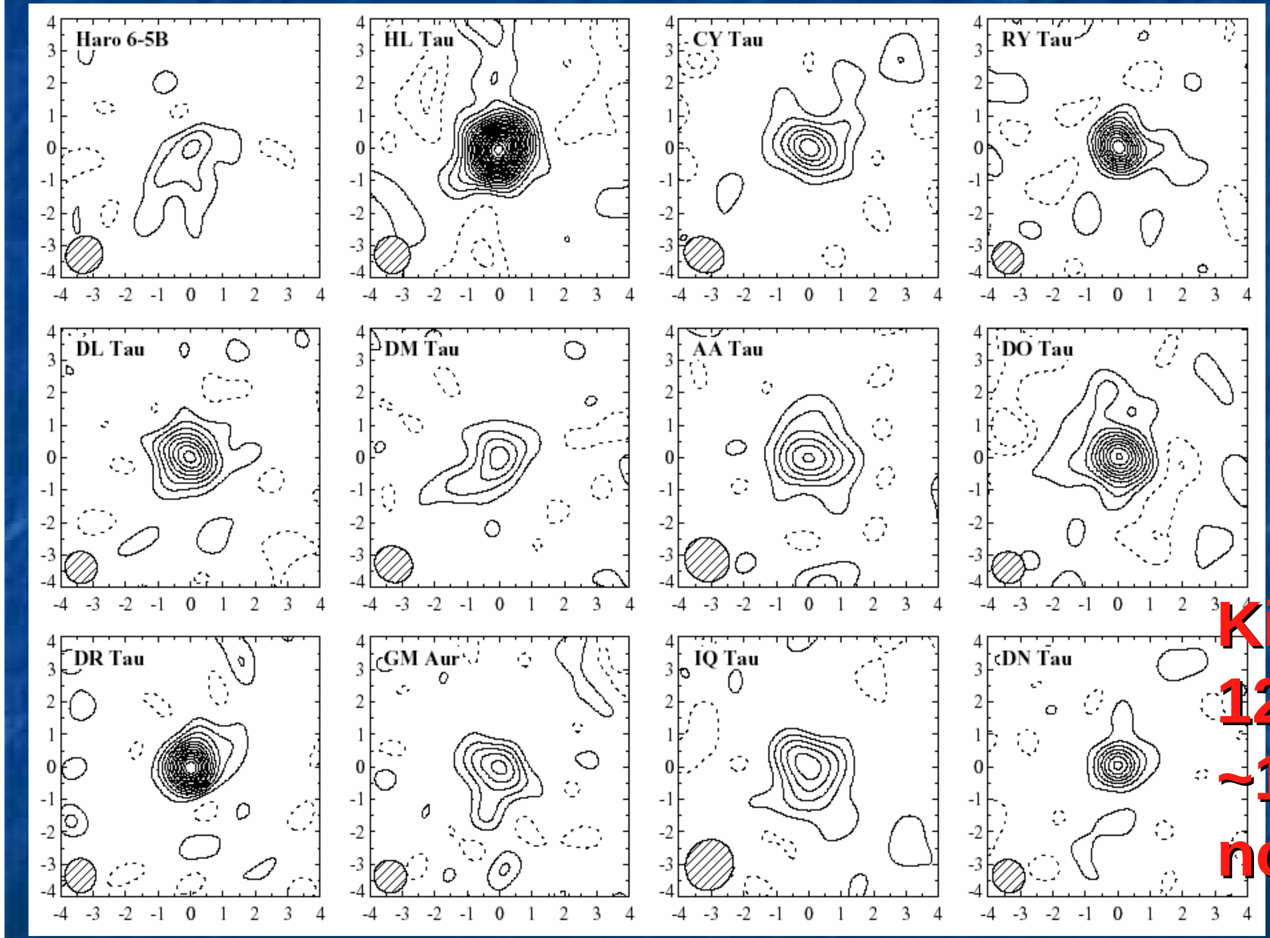
- Dust continuum has no peak at the stellar position at all the frequencies.
- Two peaks (NE and SW to the stellar position) or a ringlike structure is obvious at 850 micron, while the NE peak is not very clear at lower frequencies.

SED of AB Aur Dust Emission



- The SMA measurement @ 850 μm is consistent with others @ mm-wavelengths.
- The NE part might have a larger spectral index (larger β?) than the SW part?
  - Characteristics of dust particles, such as size, might be different between NE and SW?

Are there any ring-like structures in other CDs?



Kitamura et al. 2002
12 maps of CDs at ~1" resolutions show no ring-like structures.

AB Aur disk has irregularity in dust surface density and/or dust temperature distribution

Spirals around Herbig Ae/Be Stars

Group II

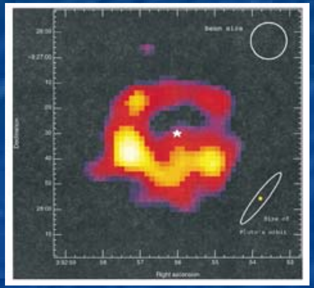
Group I

Group I

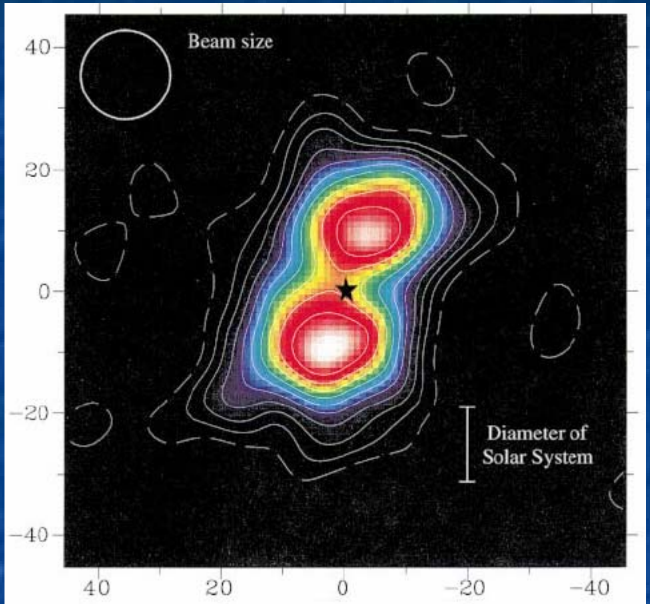
HD 142527
(Fukagawa et al. 2005

Any relationship between the SED and the spiral structures? Further observations of these sources with interferometrs are important.

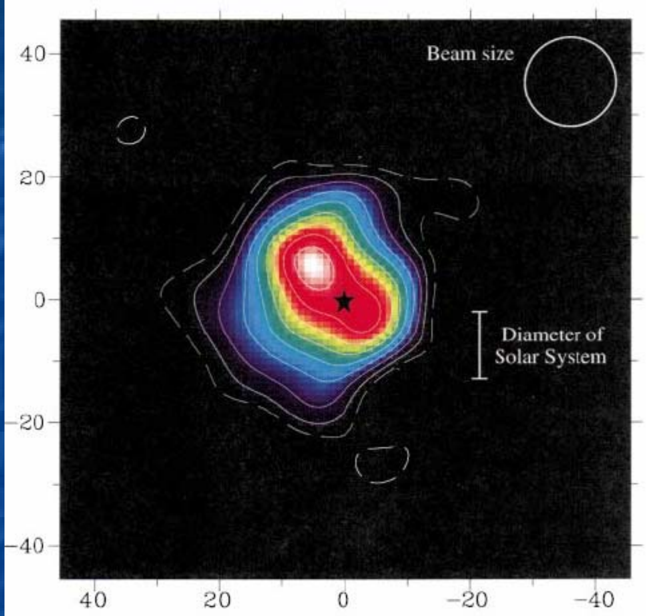
Evolution to Debris Disks?



εEridani 3.22 pc
Greaves et al.



Fomalhaut 7.7 pc
Holland et al. 1998



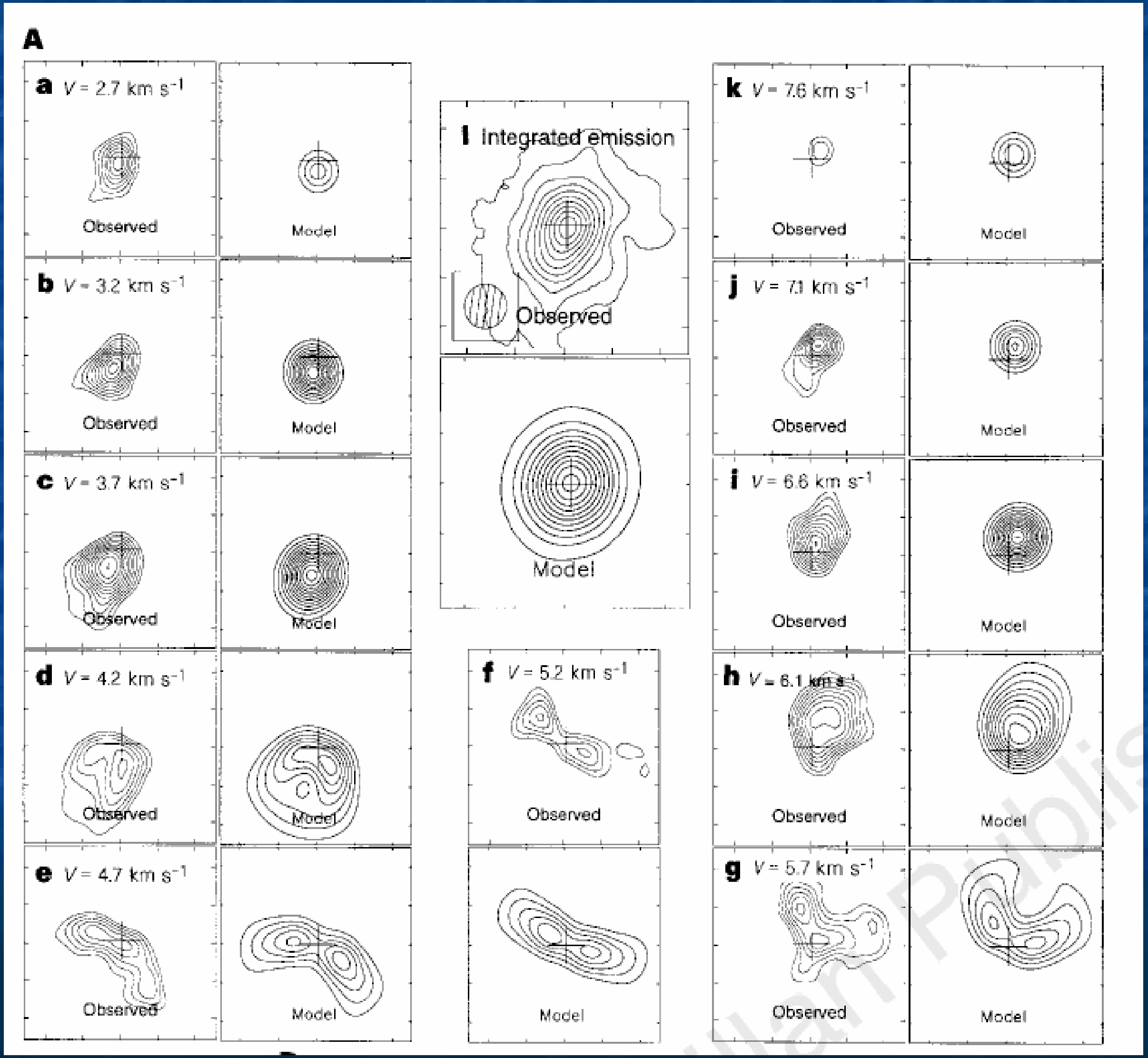
Vega 7.8 pc
Holland et al. 1998

The size scale of the central cavity in the AB Aur disk is similar to those in debris disks. Any relation between them?

Future works

- More detailed modeling of the 345 GHz dust and ^{12}CO (3-2) disks of AB Aur.
  - LVG modeling to derive the gas temperature and density
- ^{12}CO (2-1) observations of AB Aur using the SMA.
- 150 GHz dust observations of AB Aur using the NMA and the rainbow.
  - Derive the disk surface density more accurately and investigate gravitational stability using Toomre's Q parameter.
  - Invesigate the dust spectral index (β) at the center of the disk to see possible dust growth
- Observe other Herbig Ae stars with and without spiral structures using mm and submm interferometer.

MWC 480:
^{12}CO 2-1 channel maps

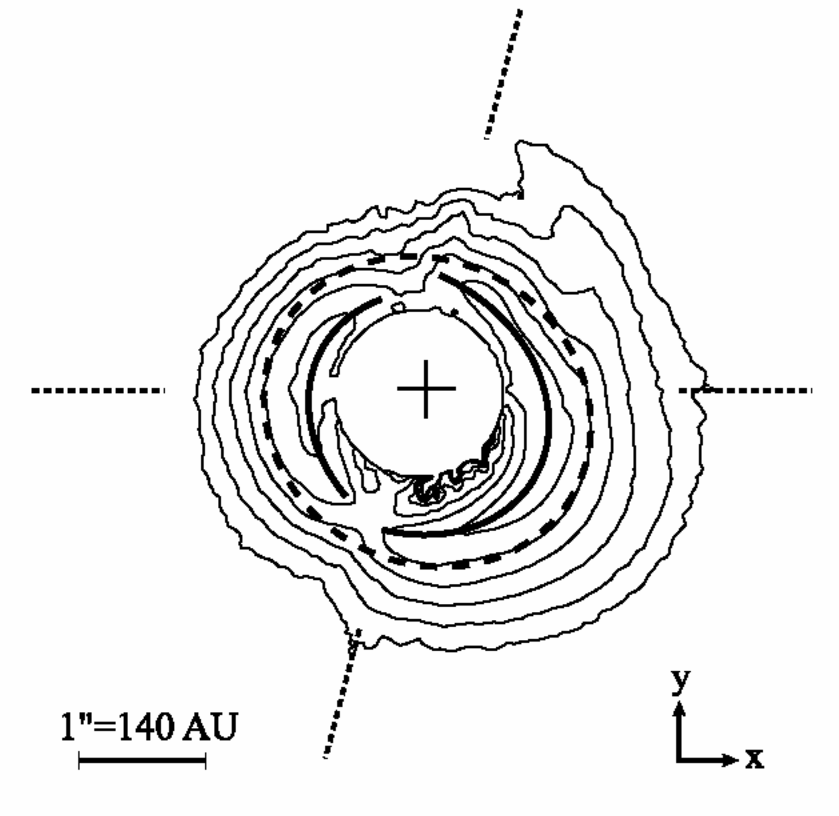


Manning et al. 1997

Circumstellar Disks around Herbig Ae stars

- Herbig Ae stars are:
  - PMSs with intermediate stellar masses (~2 Mo), counterparts of T Tauri stars.
  - known to be accompanied with circumstellar disks (CDs), which are considered to be sites of planets formation.
  - Possible progenitors of Vega-type stars with debris disks, some of which are believed to have already formed planets.
- High resolution observation is the key to study CDs around Herbig Ae stars.
- Good and important targets for mm- and submm-interferometers.

Subaru Coronagraphic Image at 1.6 micron



- Circumstellar material was clearly detected and spatially resolved.
  - Banana-split arc
  - Spiral arm
  - Inner hole
- Observation was made in scattered light.

What is the geometric and kinematical structures of the circumstellar material?

SMA 345 GHz Continuum map

$\Delta\theta$=1.2"x 0.63" PA=4 deg

Summary

- Herbig Ae star, HD 142527 was observed using the SMA.
  - 345 GHz continuum emission revealed an arc-like structure enclosing the central star. The emission is clearly depressed at the stellar position.
    - Possible companion?
  - ^{12}CO 3-2 emission, on the other hand, shows a single peak at the stellar position. While the emission shows a clear velocity gradient suggesting disk rotation, the direction of the disk is not morphologically clear.
- Further observations at higher angular resolutions and in different transitions are absolutely necessary.
- SMA is very important to study planetary formation.

SUMMARY

- The CD around AB Aur was imaged in ^{12}CO 3-2 and 345 GHz continuum using the SMA, revealing details of structures of the CD.
- The dust disk was clearly resolved, showing a ring-like structure around the central star.
  - The ring-like structure is most likely due to enhancement of the disk surface density.
  - The NE part of the dust disk might have a larger dust spectral index than the SW part.
- ^{12}CO 3-2 emission shows geometrical and kinematical structures, which strongly deviate from simple Keplerian disks.
  - It would be difficult to create such structures by only gravitational instability; need simulations with detailed models.