The Radial and Vertical Gas Disk Structure in HD163296
1st ALMA Science Verification Results

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Transformational Science with ALMA: From Dust to Rocks to Planets
Formation and Evolution of Planetary Systems

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Outline

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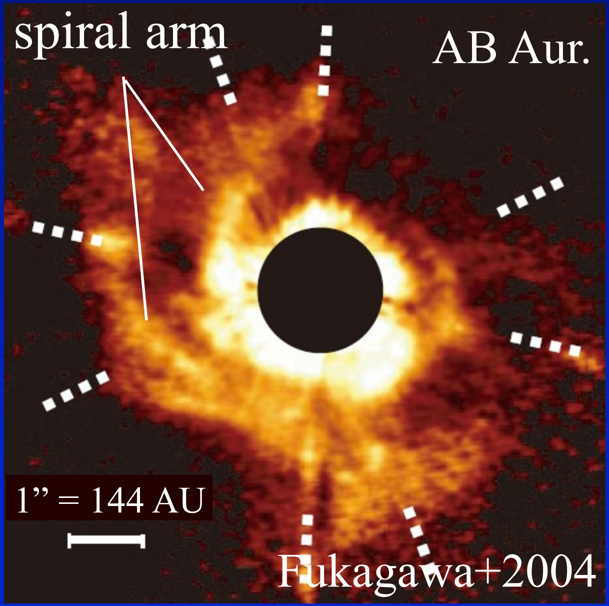
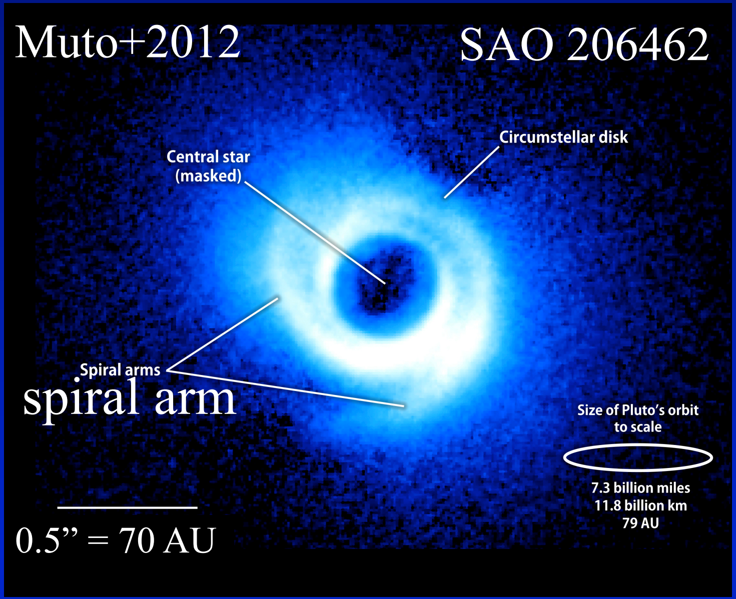
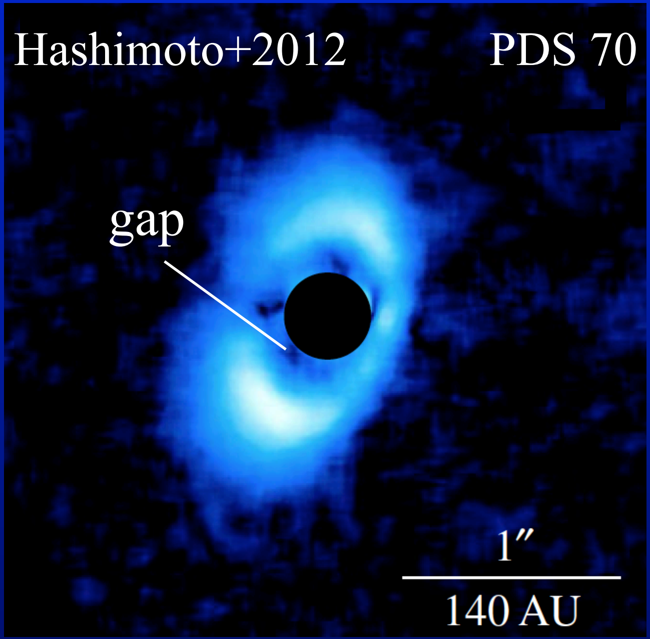
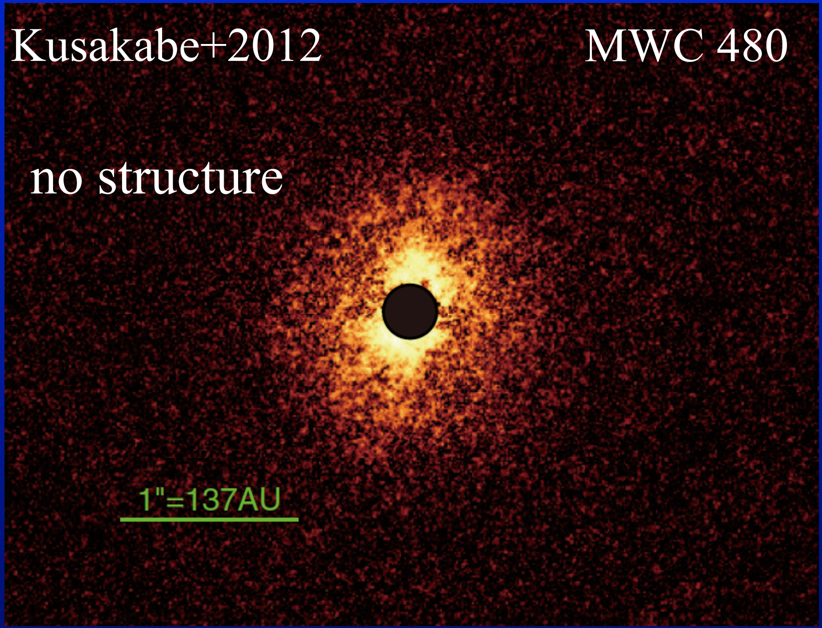
Complex structures of Protoplanetary Disks







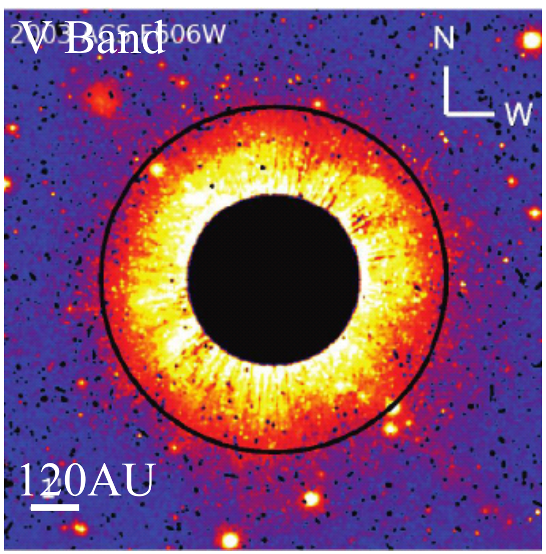


Object Details

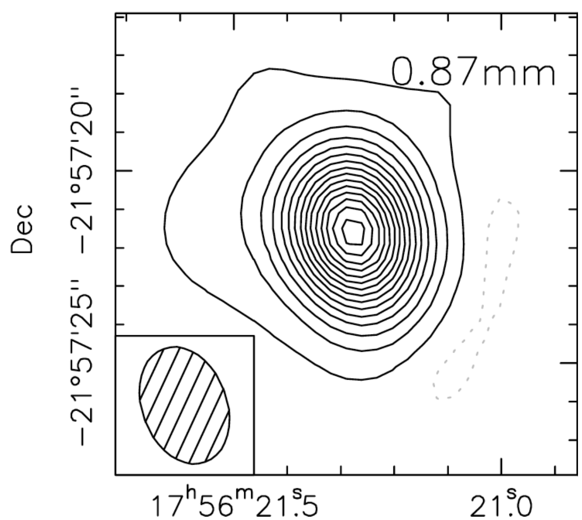
- HD 163296 is very famous Herbig Ae star.
- It has been observed by many people and basic properties are already well known. → We have plenty of observational data!
- No complex structures → easy to analyze

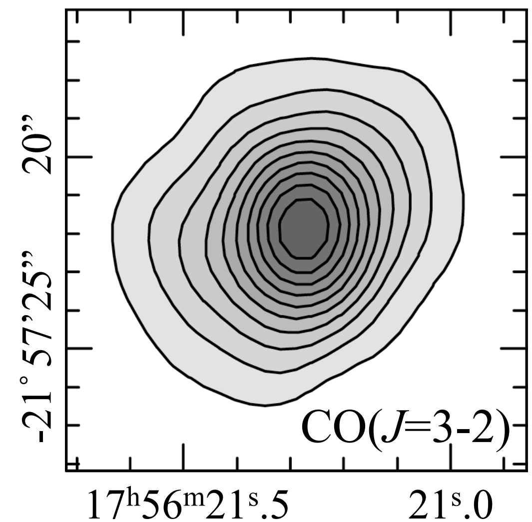
distance [pc]	SP type	M_* [$M_\odot$]	M_{disk} [$M_\odot$]	Age [Myr]	inclination [deg.]
122[a]	A1[b]	2.3[b]	0.024[b]	~5[c]	45[d]

[a] van den Ancker et al. 1998 [b] Mannings et al. 1997 [c] Natta et al. 2004 [d] Isella et al. 2007



Wisniewski+ 2008



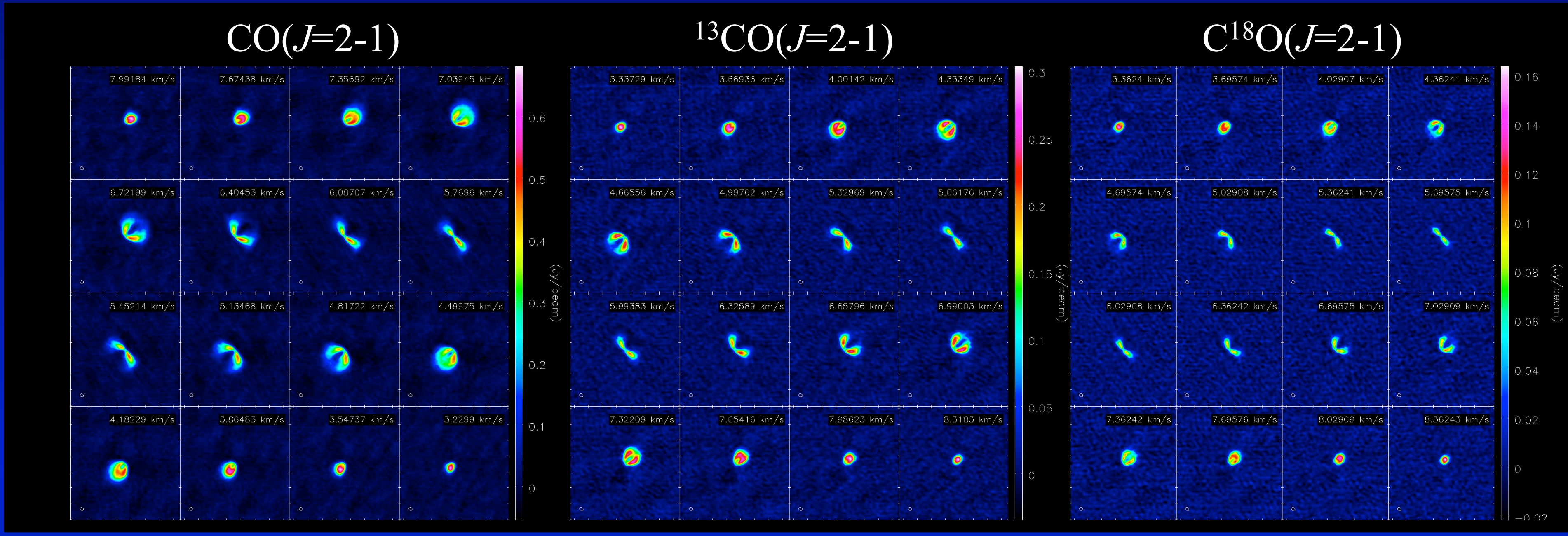


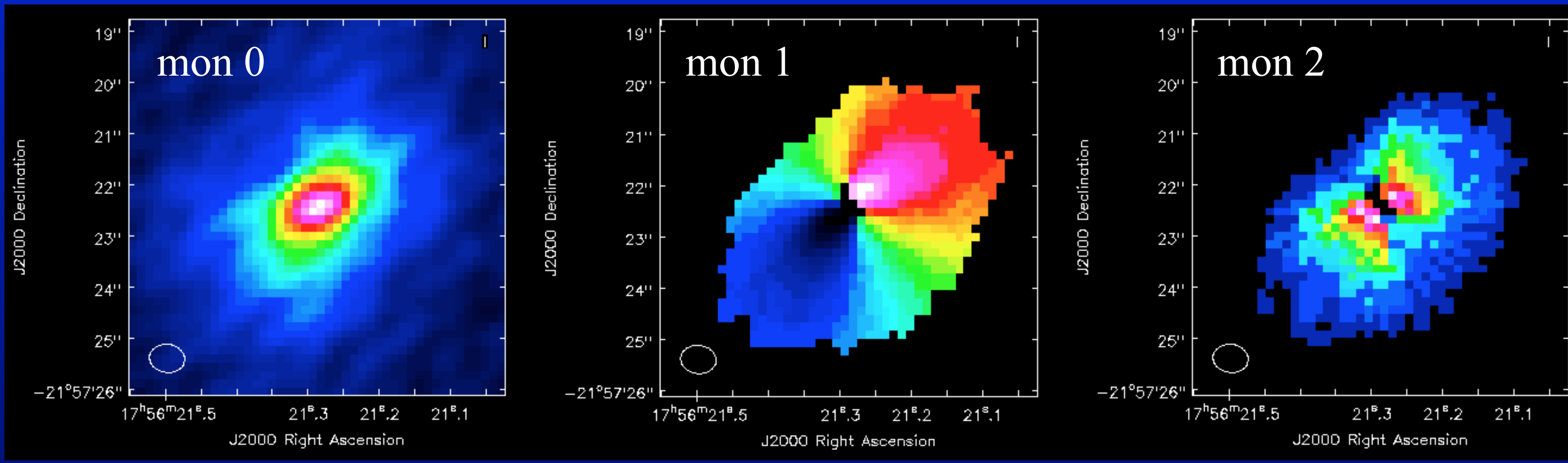
Isella et al. 2007

Observation

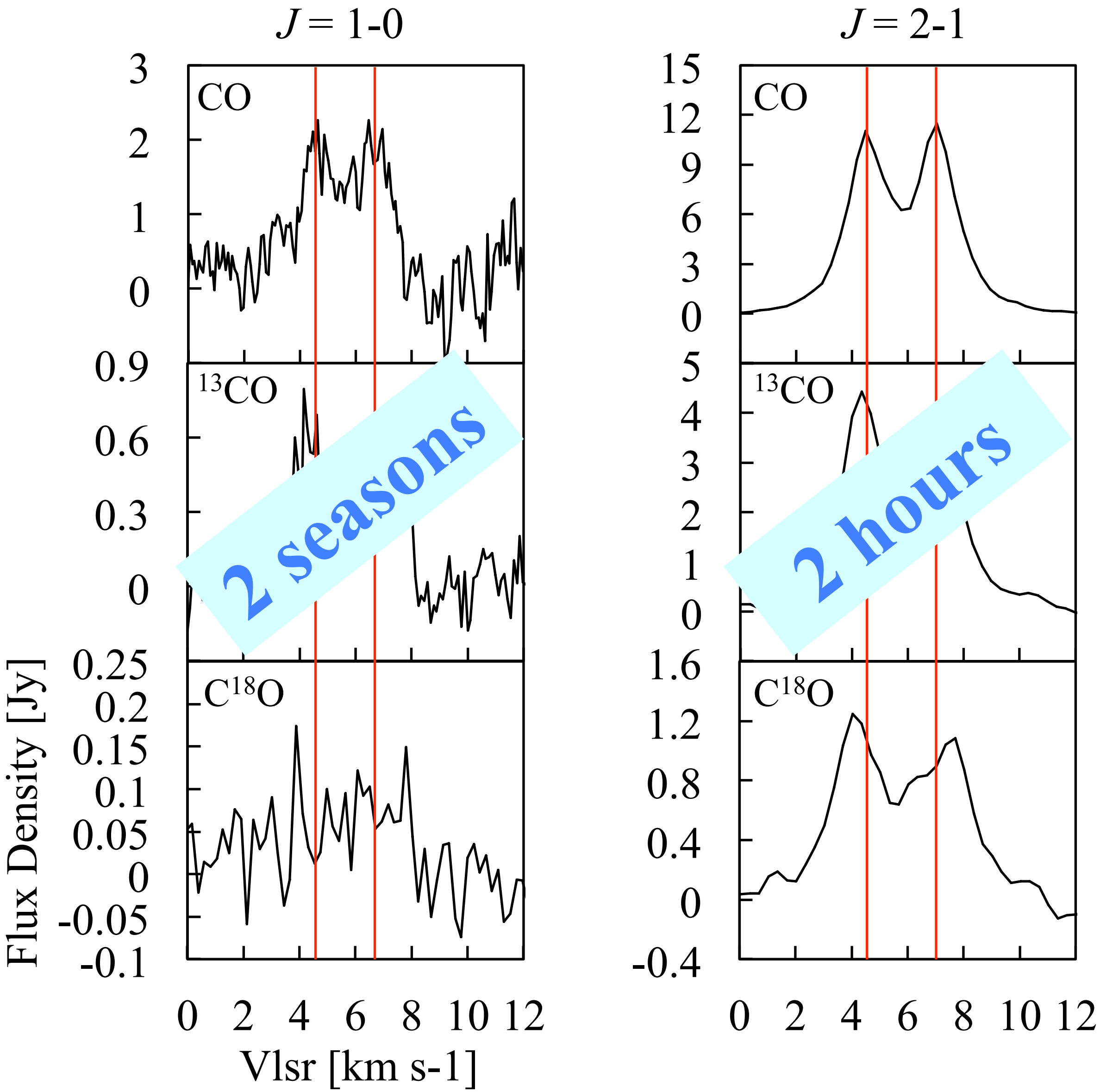
	Interferometer	Single Dish
Lines	CO, ^{13}CO, C^{18}O (J=2-1)	CO, ^{13}CO, C^{18}O (J=1-0) CO, ^{13}CO (J=3-2)
Telescopes	ALMA	J=1-0: NRO 45 m J=3-2: ASTE 10 m
HPBW	0.68” × 0.55”	J=1-0: ~ 15” J=3-2: ~ 23”
Tsys	100 - 250 K	150 - 600 K

Results 1 (ALMA No. 2011.0.00010.SV)





Results 2



Vel. width is wider in optically thin line and narrower in optically thick line. This indicates different Keplerian disk size.

Power-Law Model

- Model description
  - Keplerian disk model (Kitamura et al. 1993)
  - Power-law in temperature and surface density distribution (Hayashi et al. 1981, Beckwith et al. 1990)

$$T(r) = T_0 \left(\frac{r}{100\,AU} \right)^{-q} \qquad \Sigma(r) = \Sigma_0 \left(\frac{r}{100\,AU} \right)^{-p}$$

T_{100} : temperature at 100 AU from a central star

Σ_{100} : surface density at 100 AU from a central star

- Assumption
  - $X(^{12}CO) = 10000$
  - $X(^{12}CO) / X(^{13}CO) = 60$
  - $X(^{13}CO) / X(C^{18}O) = 5$
  - Local Thermal Equilibrium (LTE)
  - Hydrostatic Equilibrium

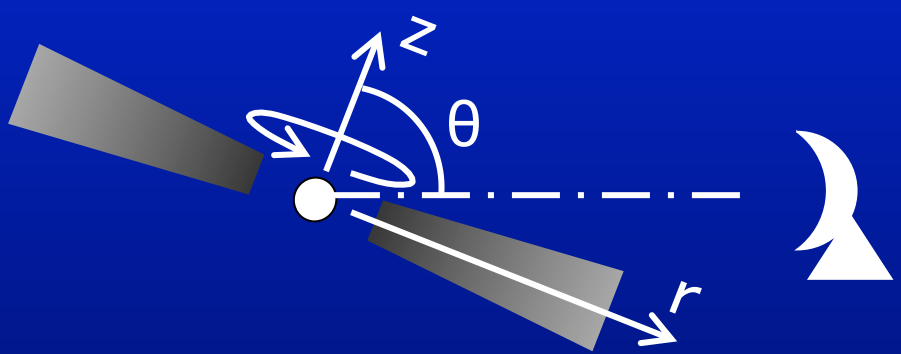


Image of the model

Similarity Solution Model

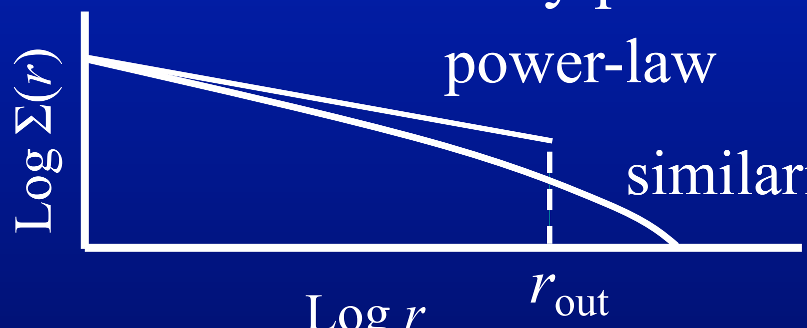
- Similarity solution for the surface density (Hughes et al. 2008)

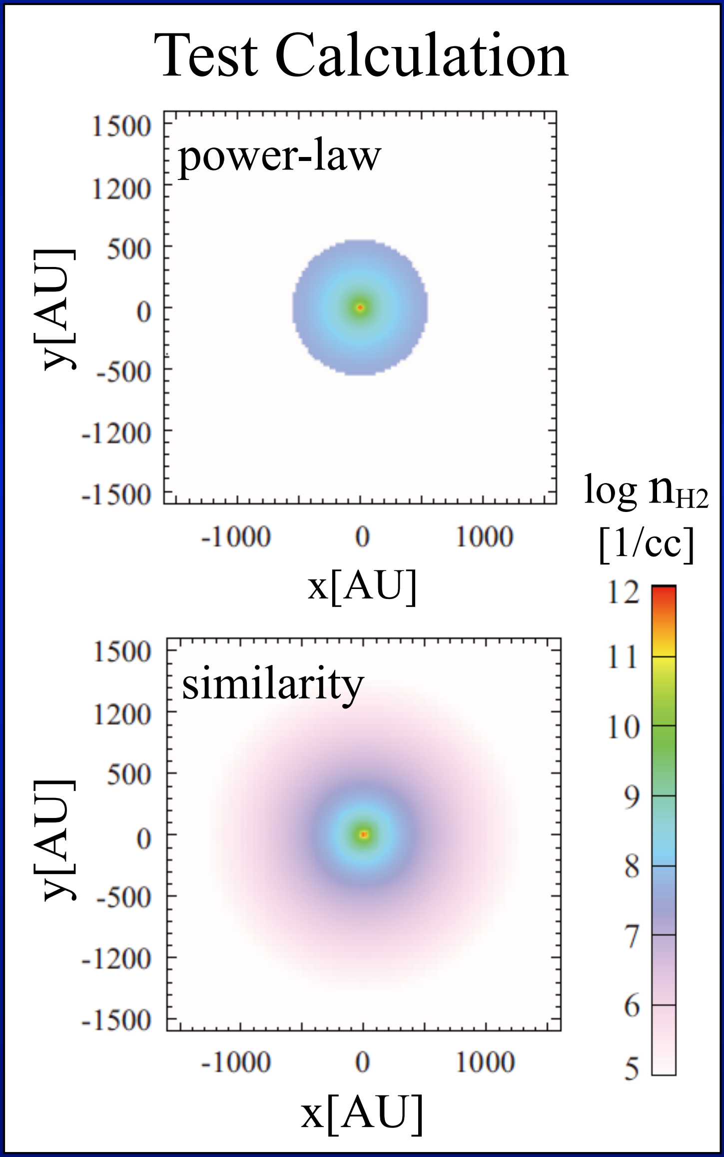
$$\Sigma(r) = \frac{C_1}{r^p} \exp\left[-\left(\frac{r}{C_2} \right)^{2-p} \right]$$

C_1 normalized surface density

C_2 distance where $\Sigma(r)$ starts decreasing exponentially

- Vertical density distribution
  Hydrostatic equilibrium
- Uniform temperature is assumed
- Difference between the two models
  truncation caused by power-law





Model Parameters

- Fixed parameters : The results obtained by other observations applied

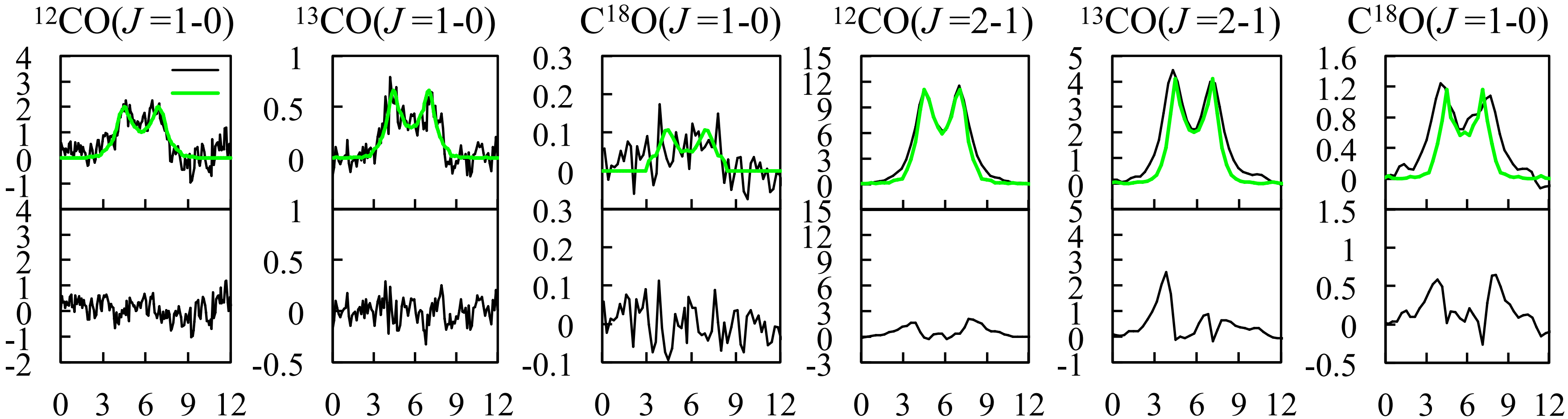
	distance [pc]	M_* [$M_\odot$]	inclination [deg.]	p	q
HD163296	122	2.3	45	1.0	0.5

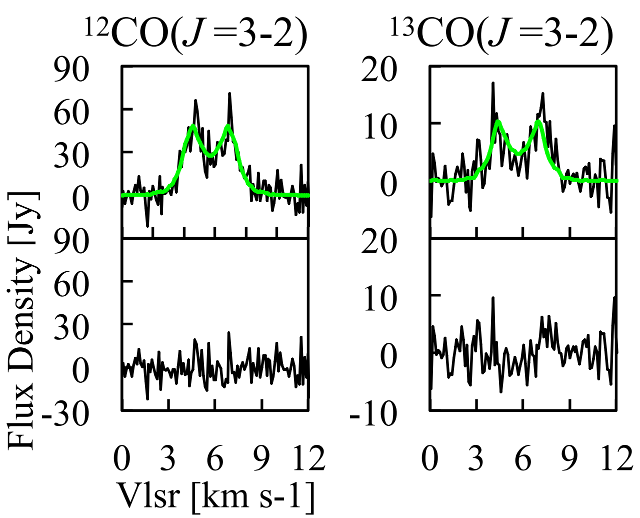
- Free parameters : Best fit parameters are searched

  - Outer radius : $r_{\mathbf{out}}$, C_2
  - Temperature : $T_{\mathbf{100}}$
  - Surface density : $\Sigma_{\mathbf{100}}$, C_1

Fitting by Power-Law Model

r_{out} = 550AU, p=1.0, q=0.5

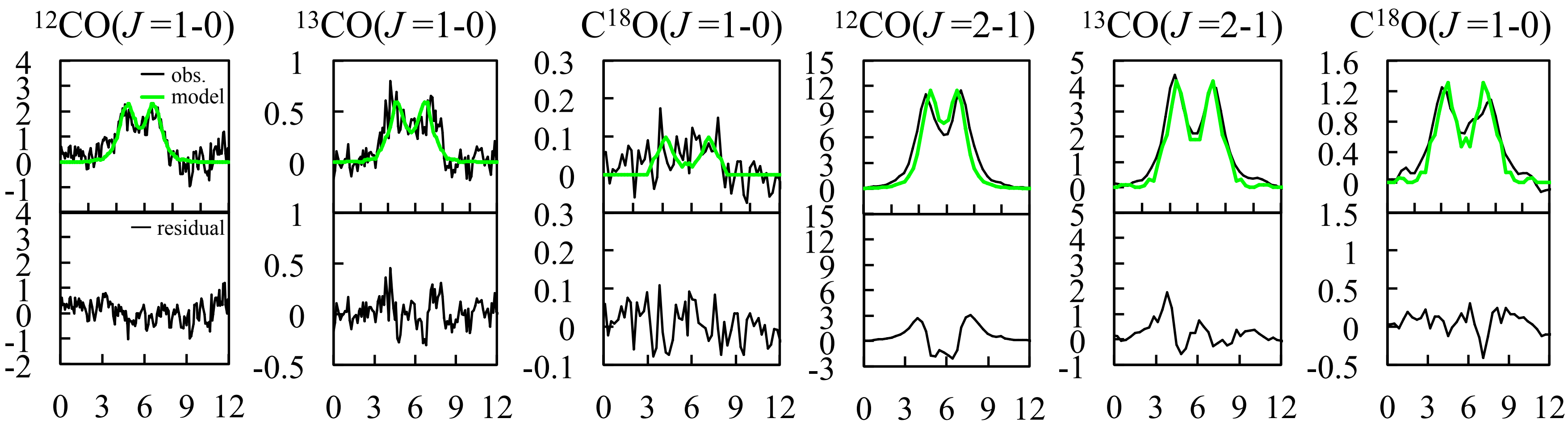


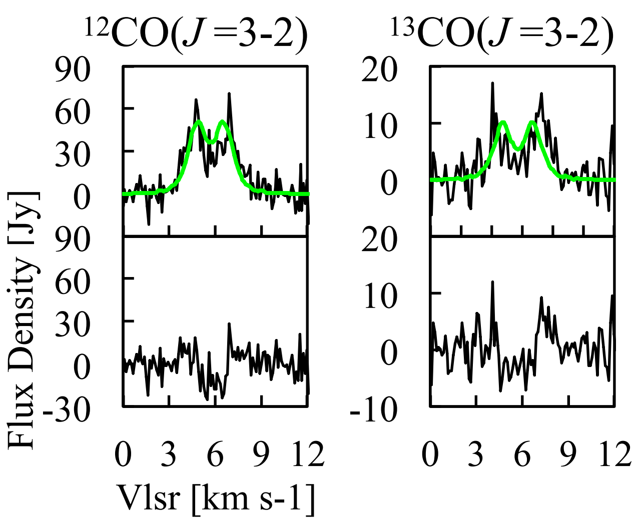


Σ_{100} [gm s^{-1}]	T_{100} [K]		
1	^{12}CO(J=3-2)	^{12}CO(J=2-1)	^{12}CO(J=1-0)
	55^{+5}_{-3}	49±1	30±3
	^{13}CO(J=3-2)	^{13}CO(J=2-1)	^{13}CO(J=1-0)
	30±5	31±1	19±5
		C^{18}O(J=2-1)	C^{18}O(J=1-0)
		20±1	16^{+8}_{-6}

Fitting by Similarity Solution Model

r_{out} = 700AU, p=1.0, q=0.5





Σ_{100} [gm s^{-1}]	T_{100} [K]		
1	^{12}CO(J=3-2)	^{12}CO(J=2-1)	^{12}CO(J=1-0)
	34^{+4}_{-3}	30±1	18±3
	^{13}CO(J=3-2)	^{13}CO(J=2-1)	^{13}CO(J=1-0)
	18±4	20±1	14±5
		C^{18}O(J=2-1)	C^{18}O(J=1-0)
		16±1	10^{+10}_{-7}

Vertical Location of the Photosphere

Optical depth of rotational transition emission from rigid rotor molecules such as CO（Scoville et al.1986）

$$\tau_{\nu_0} = \frac{8\pi^3 B\mu^2}{3kT_{ex}\Delta V_{gas}}(J+1)N\exp\left[-\frac{hBJ(J+1)}{kT_{ex}}\right]\left[1-\exp\left(-\frac{h\nu_0}{kT_{ex}}\right)\right]$$

B : rotational constant

μ : permanent dipole moment

J : rotational quantum number

N : column density

h : Plank constant

k : Boltzman constant

T_{ex} : excitation temperature

ΔV_{gas} : velocity width

ν_0 : transitional frequency

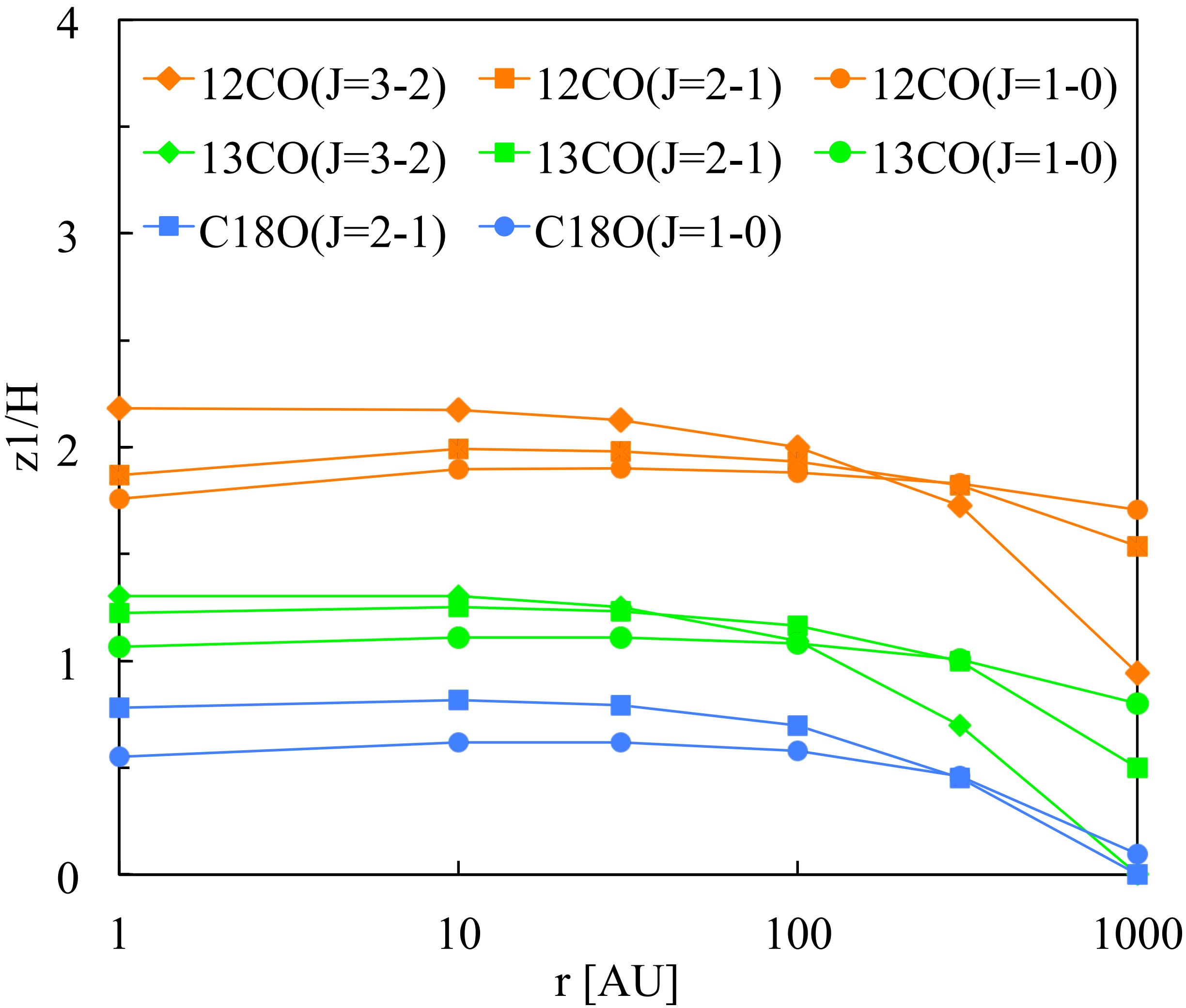
Optical depth expressed by surface density

$$\tau_{\nu_0} = \int_{z_1}^{\infty} \frac{\Sigma(r)\kappa_\nu}{\sqrt{\pi}H(r)}\exp\left[-\left(\frac{z}{H(r)}\right)^2\right]dz$$

z_1 : distance from the mid-plane to the photosphere

κ_ν : opacity

Location of the Photospheres



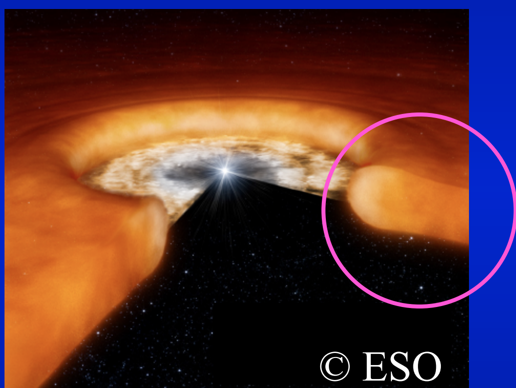
12CO upper layer

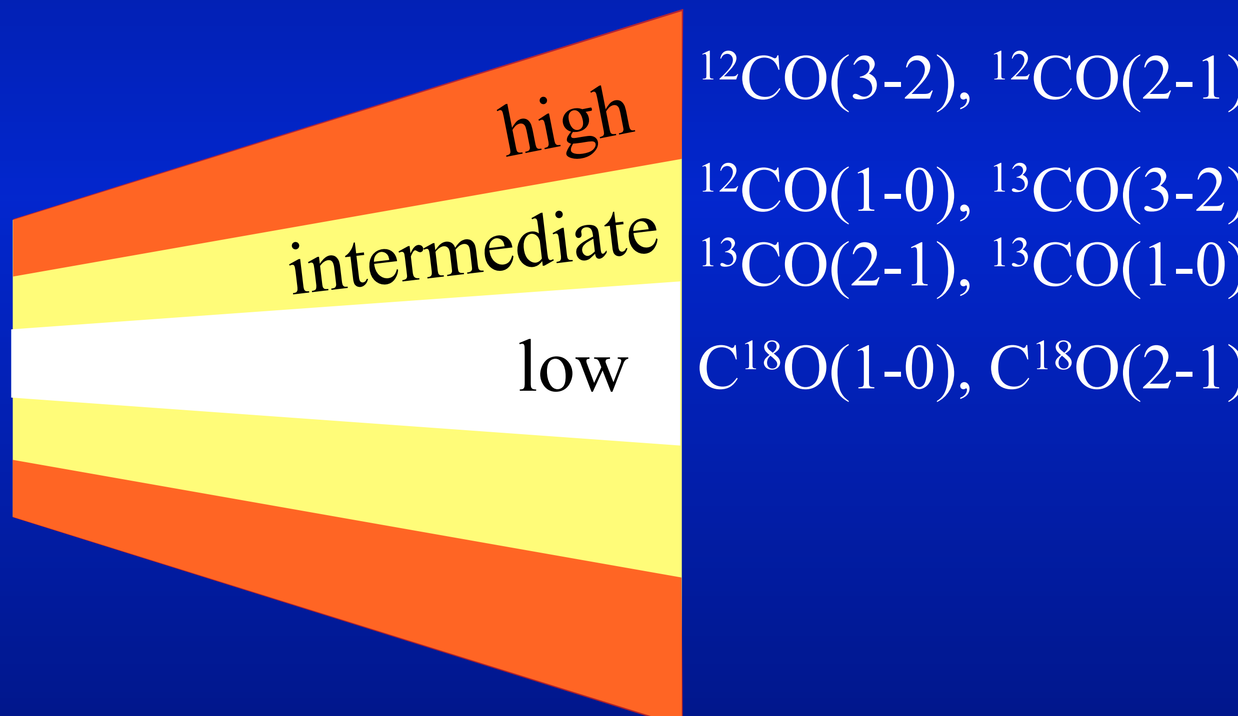
13CO middle layer

C18O lower layer

Vertical temperature structure

- The upper layer is warm and interior is cold.
- Vertical temperature distribution presents near the scale height.





Summary

- HD163296 was observed by 8 CO isotopologue lines.
- The velocity width is wider in optically thin line and narrower in optically thick line.
- The upper layer is warm and interior is cold.
- We compared power-law and similarity solution disk models.
  - → Similarity solution is better at reproducing gas emission simultaneously.
  - → Surface density tapers off gradually in the outer edge of the disk.

Discrepancy between Dust & Gas Emission

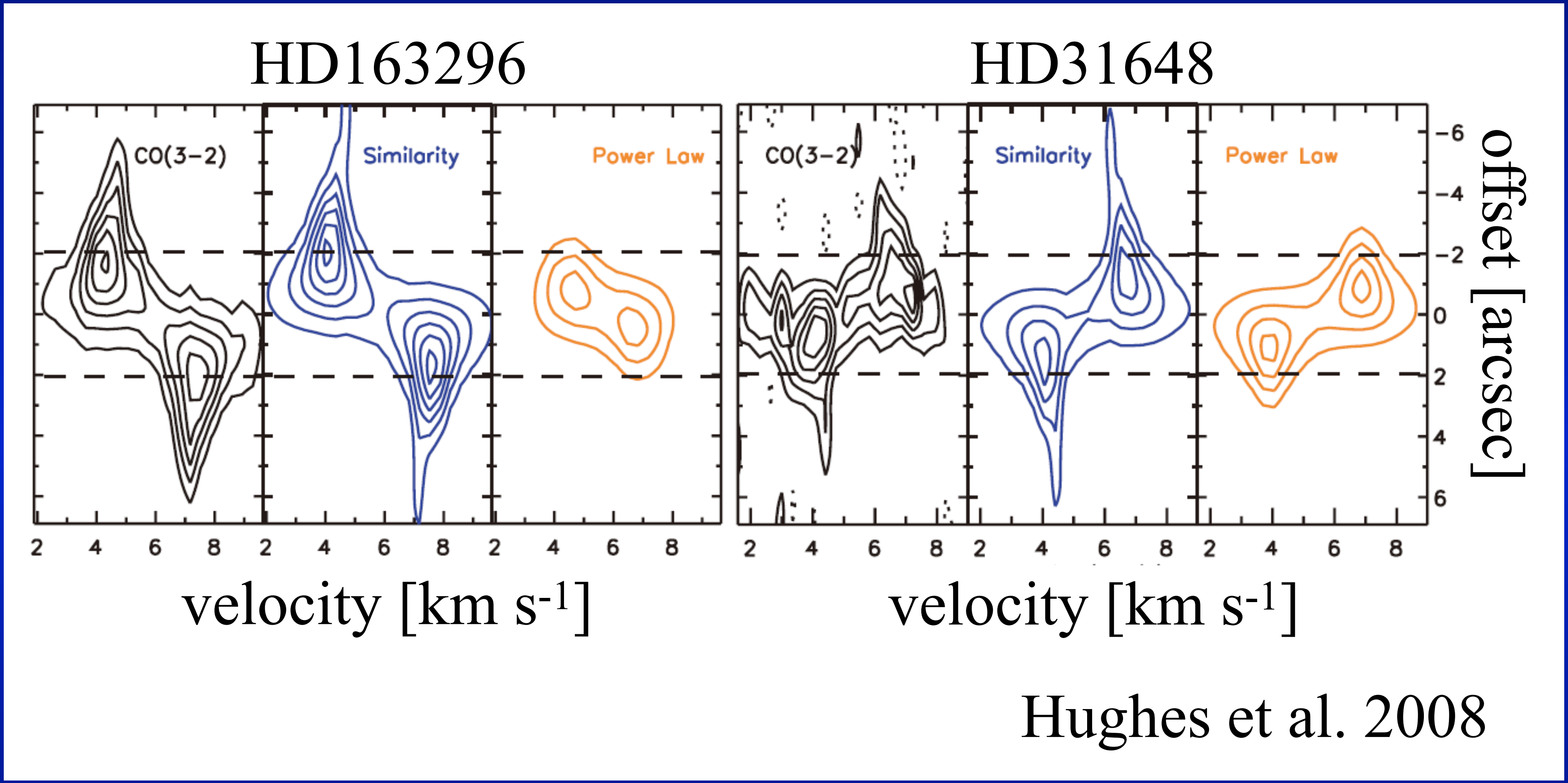
Discrepancy in disk size has emerged between the extent of the dust continuum and molecular gas emission.

Dust continuum: smaller size
Gas emission: larger size

Examples

- AB Aur (Pietu et al. 2005)
  - Continuum (2.8, 1.4mm) : 350±30 AU
  - $^{12}CO(J=2\text{-}1)$: 1050±10 AU
- HD 163296 (Isella et al. 2007)
  - Continuum (0.87-7mm) : 200±15 AU
  - $^{12}CO(J=3\text{-}2)$ etc : 540±40 AU

Successful Examples of Similarity Solution



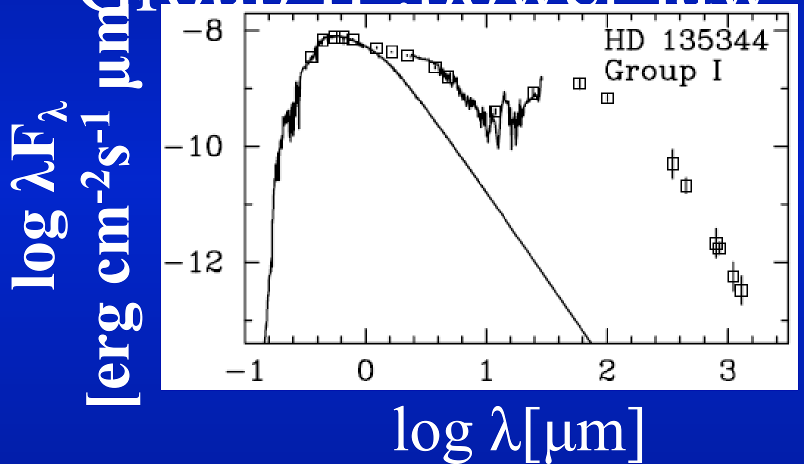
Similarity solution model is better at reproducing both dust continuum and gas emission simultaneously.

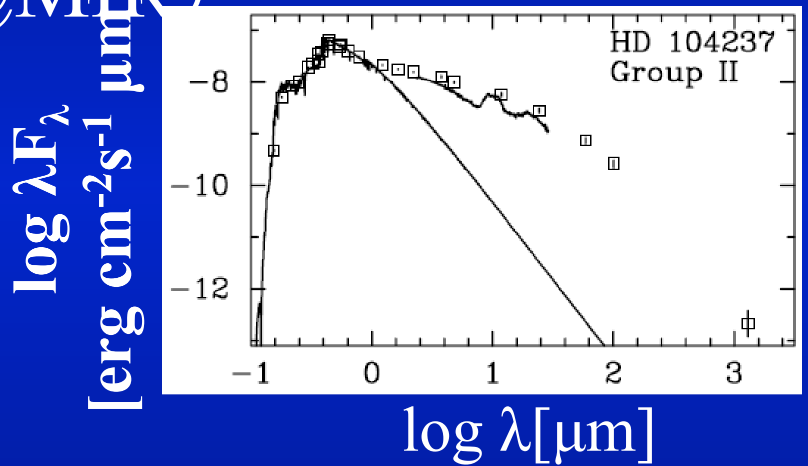
Disk Classification

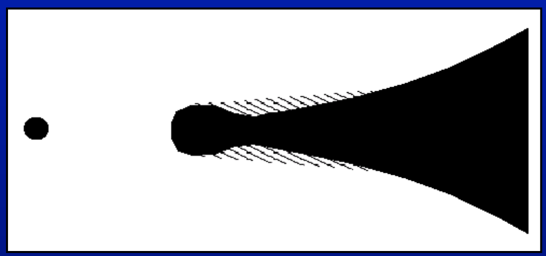
- SED Classification (Meeus +2001, Dullemond +2002)

  Group I :power law＋black body (@MIR)

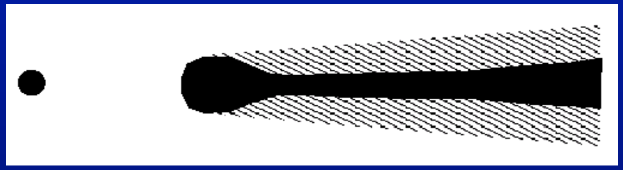
  Group II :power law（@MIR）







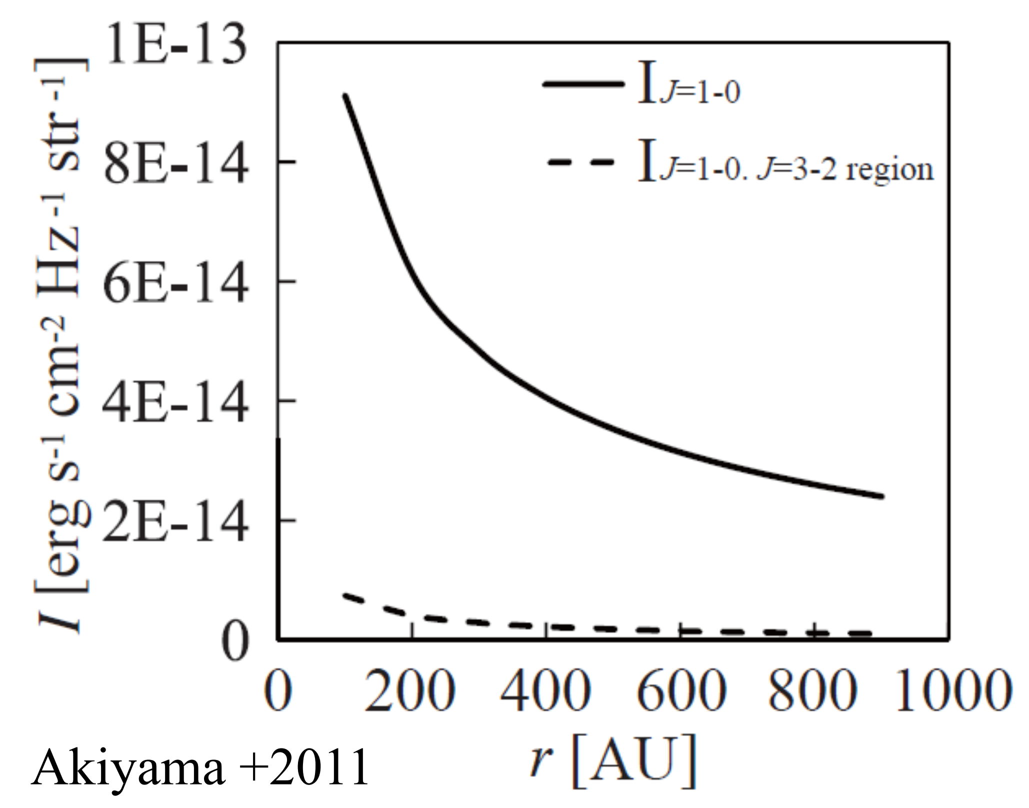
Group I (flared)



Group II (self-shadow)

高温層による他の輝線への影響

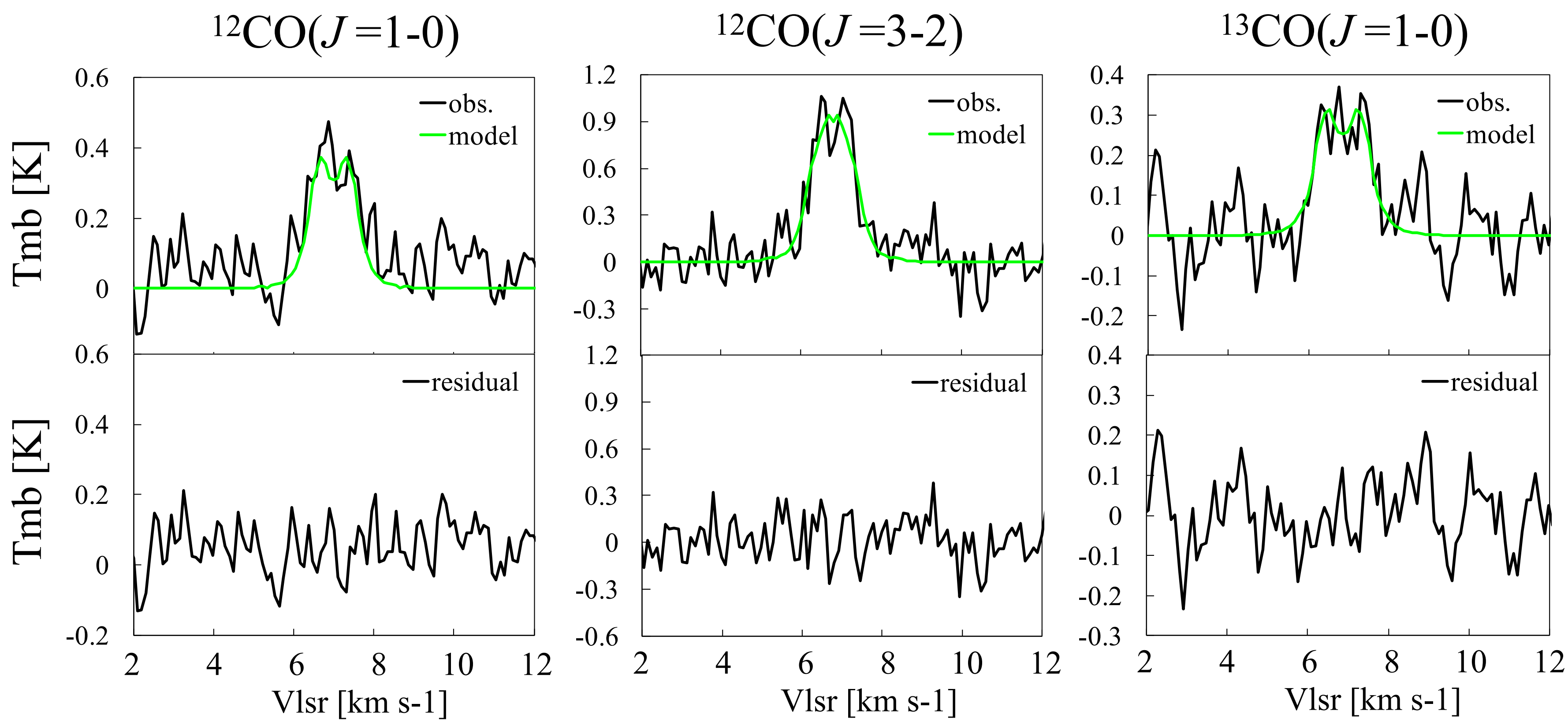
^{12}CO(J=3-2)の高温層が他の輝線に著しく寄与していると温度構造が破綻する。



J=3-2領域からのJ=1-0の強度は、低温層からのJ=1-0強度の1/10程度。ほとんど影響はない。

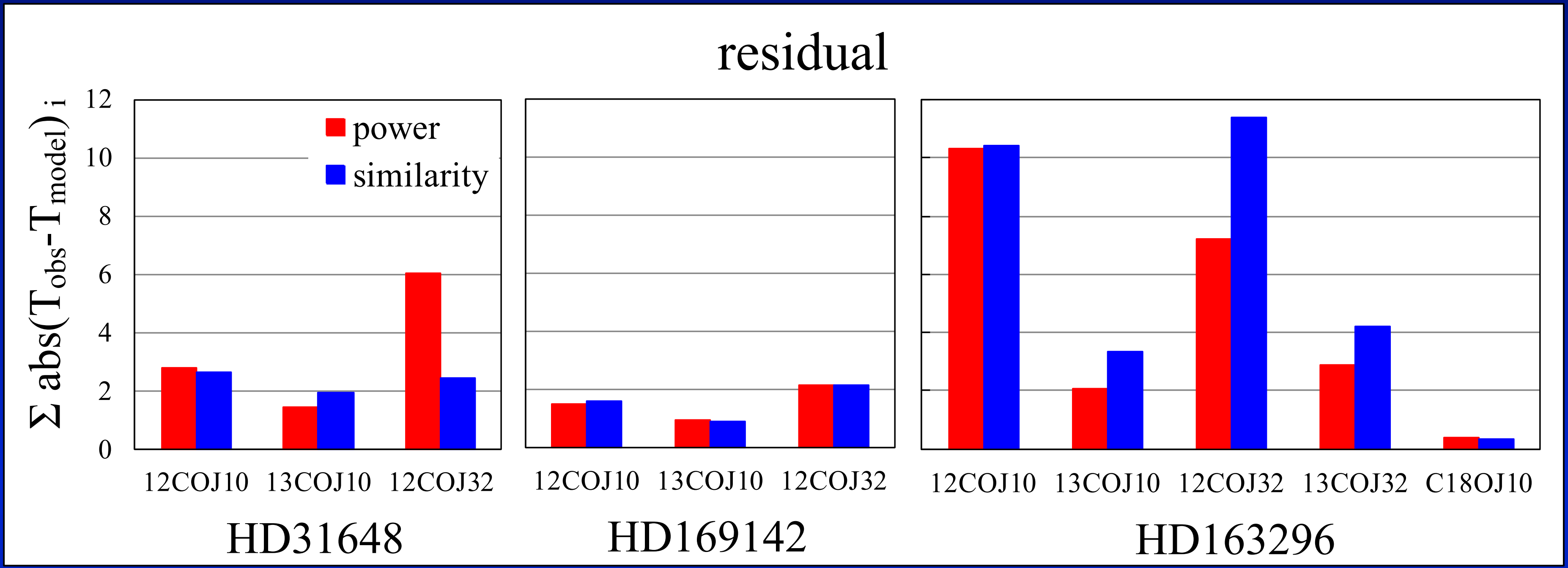
HD169142 Fitting by SS model

r_{out} = 800AU, p=1.5, θ=13°



	T_{100} [K]		
Σ_{100} [gm s^{-1}]	$^{12}CO(J=3-2)$	$^{12}CO(J=1-0)$	$^{13}CO(J=1-0)$
0.1	30	11	11

Residuals after Model Fitting



Similarity solution disk model shows better fitting than the power-law disk model

→ Surface density tapers off gradually in the outer edge of the disk

Previous talk: Vertical temperature structure