

The line-of-sight velocity variation of CO ro-vibrational lines in the ULIRG IRAS 08572+3915

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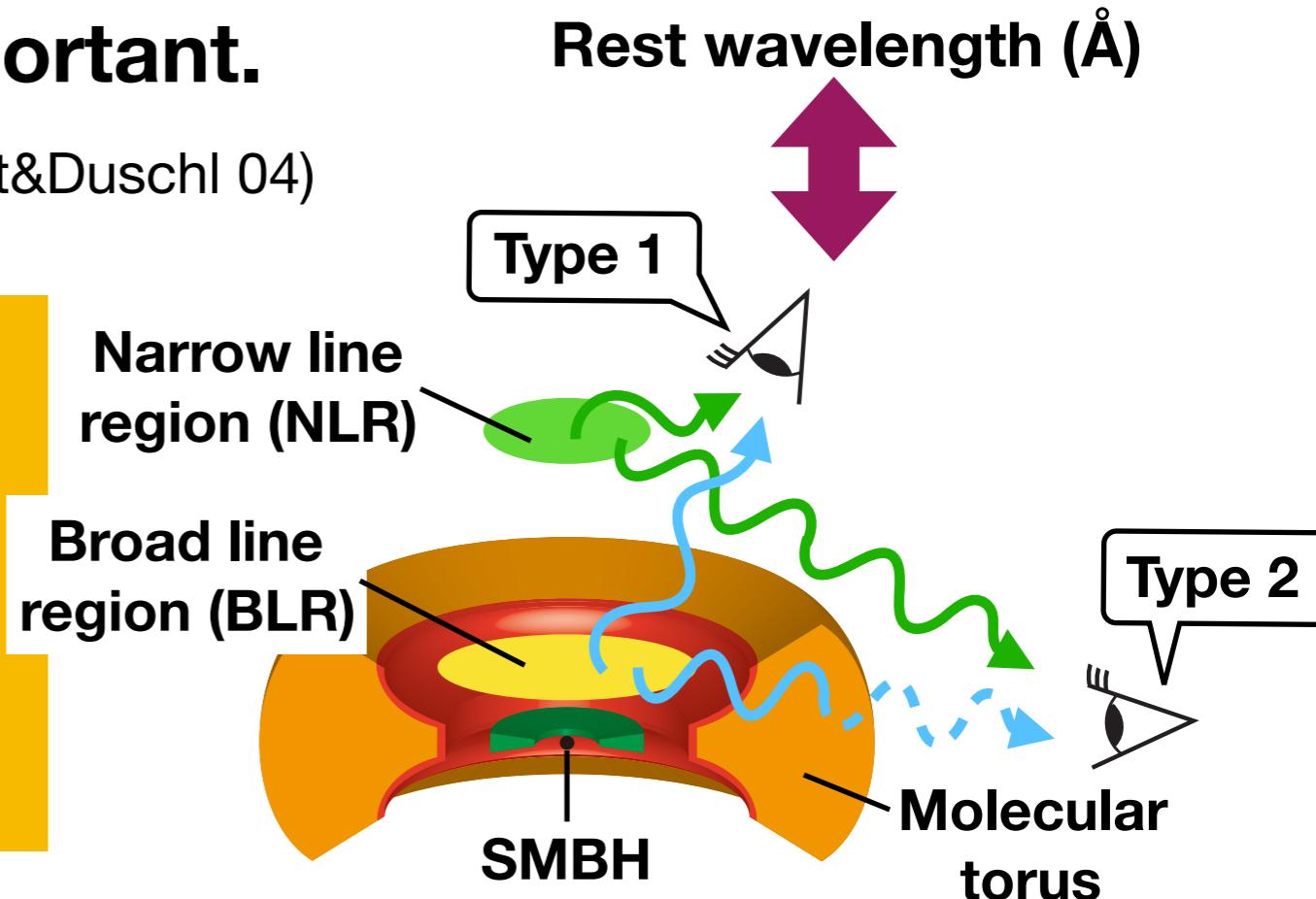
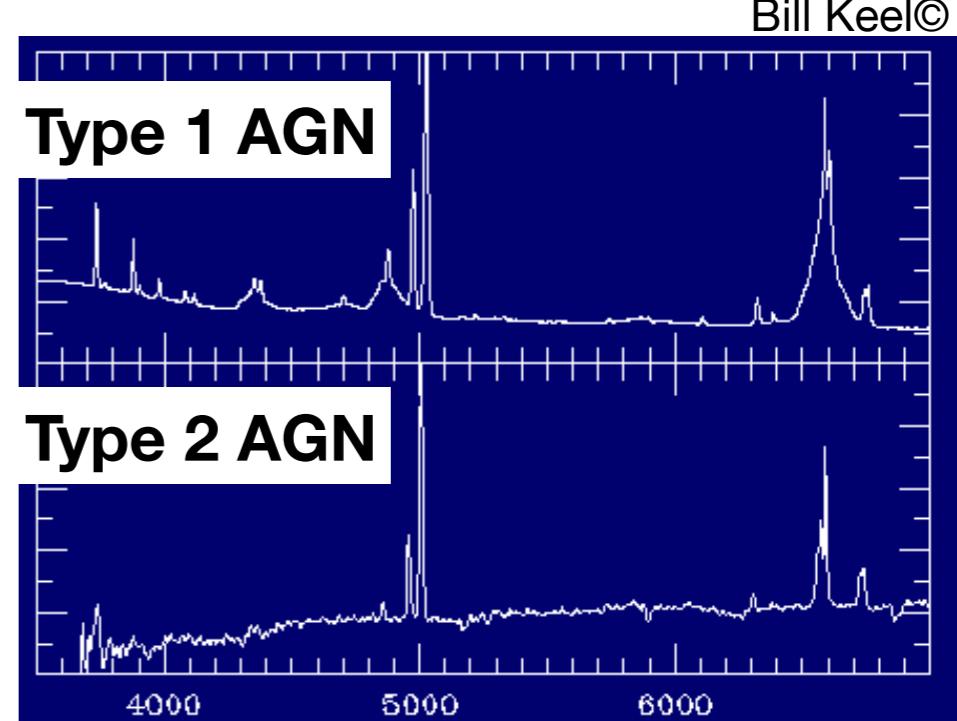
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AGN tori and aims in this work

- Active Galactic Nuclei (AGNs)
 - Central areas of galaxies hosting supermassive black holes (SMBH)
- The unified model of AGNs (Antonucci+85)
 - Intrinsically, type 1 AGNs = type 2 AGNs
 - Obscuration by **molecular tori**
- **Inner structure of tori is important.**
 - ‘Clumpy’ tori models (e.g. Beckert&Duschl 04)

Aims of this work

- To observationally determine ‘clumps’
 - 1) existing regions
 - 2) temperatures, column densities



CO ro-vibrational absorption lines

Issues in torus observations

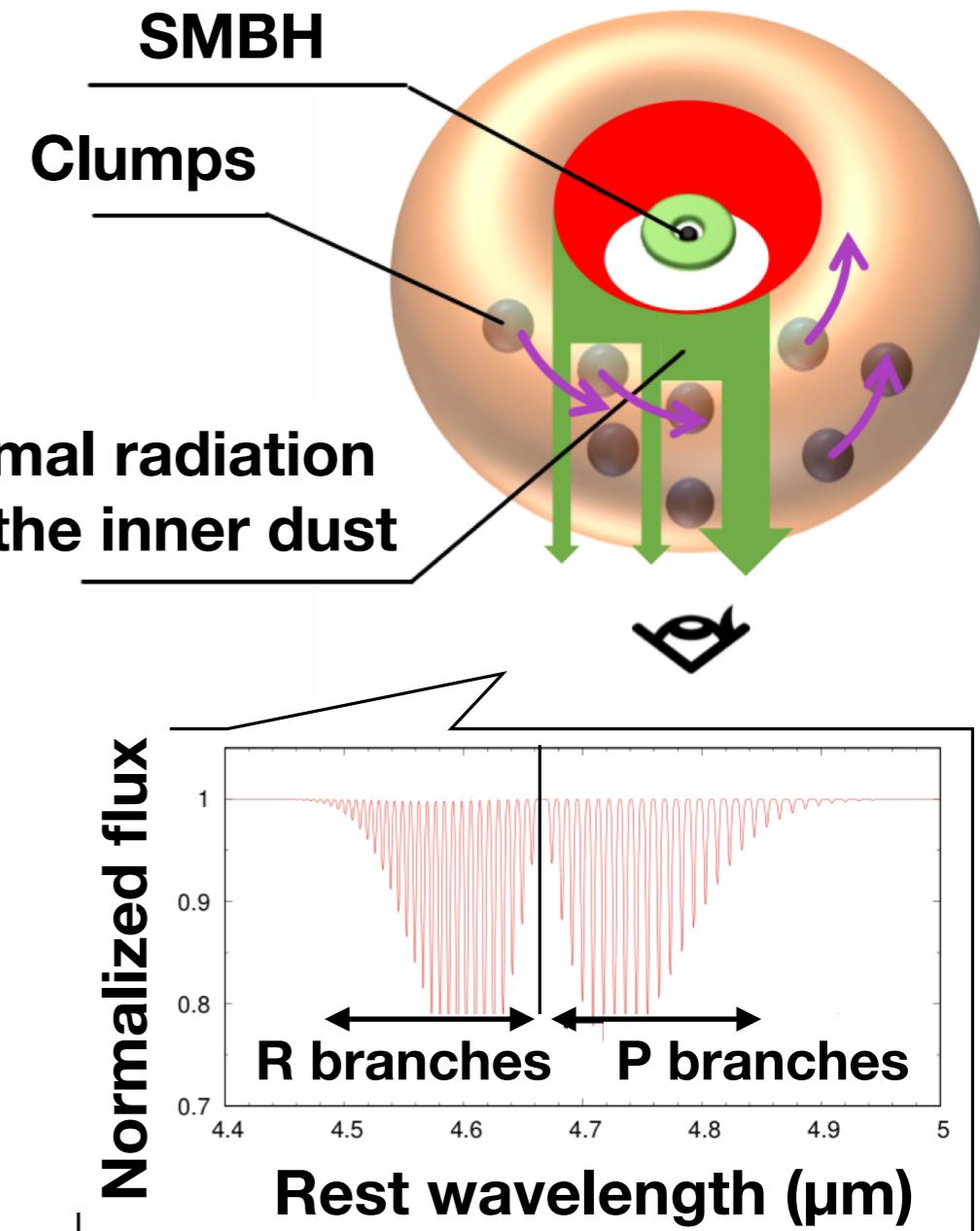
- Size of a molecular torus is \sim pc.
- A torus is difficult to be spatially resolved even with ALMA, except very nearby AGNs.



• CO ro-vibrational absorption lines

($v = 1 \leftarrow 0, \Delta J = \pm 1, \sim 4.7 \mu\text{m}$)

- Radiation source is inner dust of molecular torus. (Prieto+10)
- AGN emission is dominant at $\sim 4.7 \mu\text{m}$.
 - Less affected by the host galaxy
- Absorption lines with various J levels are observed simultaneously.
 - CO gas temperatures, column densities



Detectability of time variations

- By measuring accelerations of CO lines, **we can estimate clumps' orbit radii**, assuming Keplerian motions.
- If $R_{\text{orb}} = 1 \text{ pc}$ (typical value from models), and $R_{\text{in}} = 0.5 \text{ pc}$ are assumed, predicted velocity variations are:

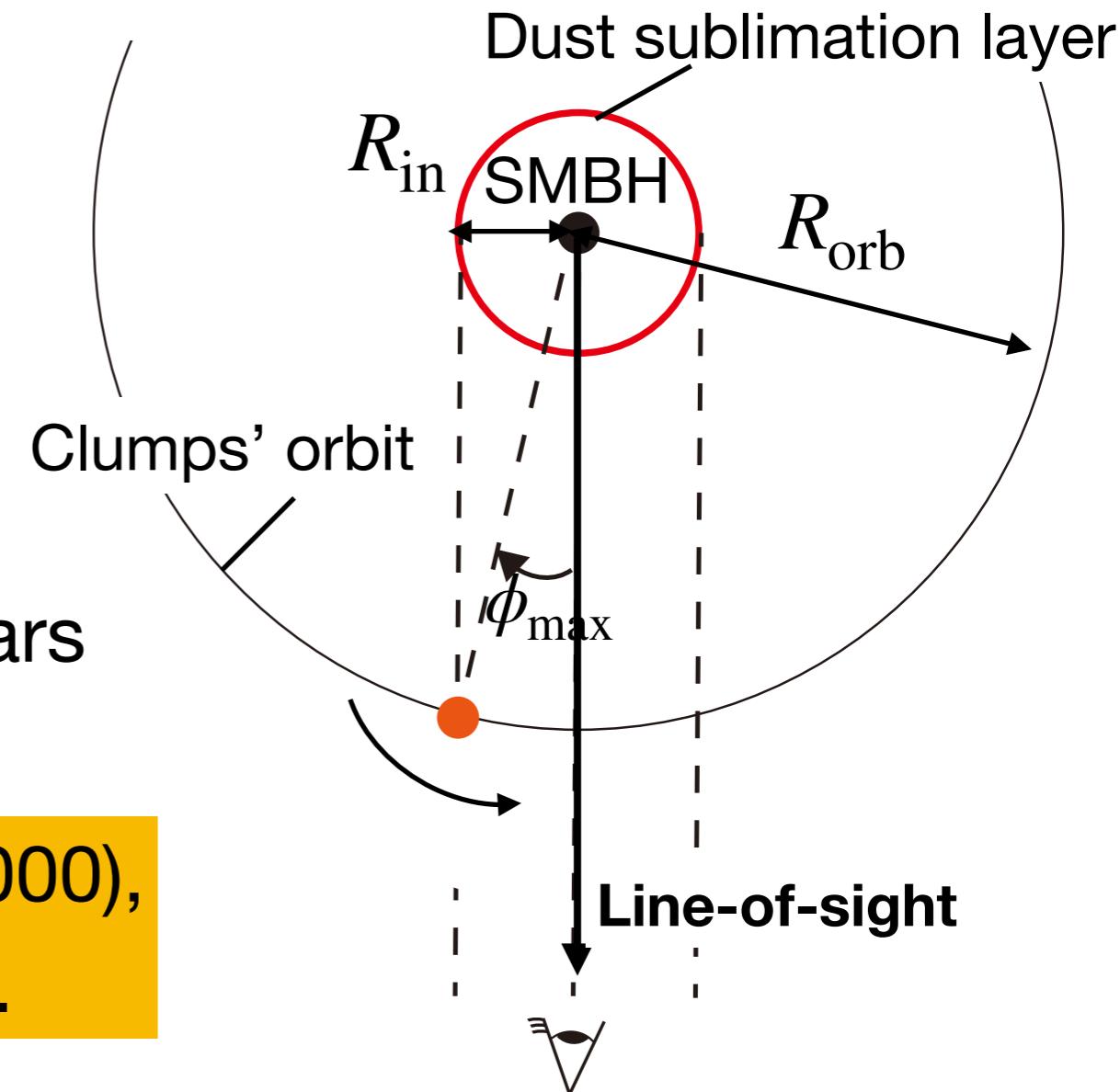
$$\frac{dV_{\text{LOS}}}{dt} = \frac{GM_{\text{BH}}}{R_{\text{orb}}^2} \sin i \cos \phi$$

$$\Rightarrow 30 \text{ km s}^{-1} \lesssim \Delta V_{\text{LOS}} \lesssim 65 \text{ km s}^{-1}$$

$$M_{\text{BH}} = 10^9 M_{\odot}, \text{ in 15 years}$$



Using Subaru IRCS ($R \sim 5000-10000$), these variations can be detected.



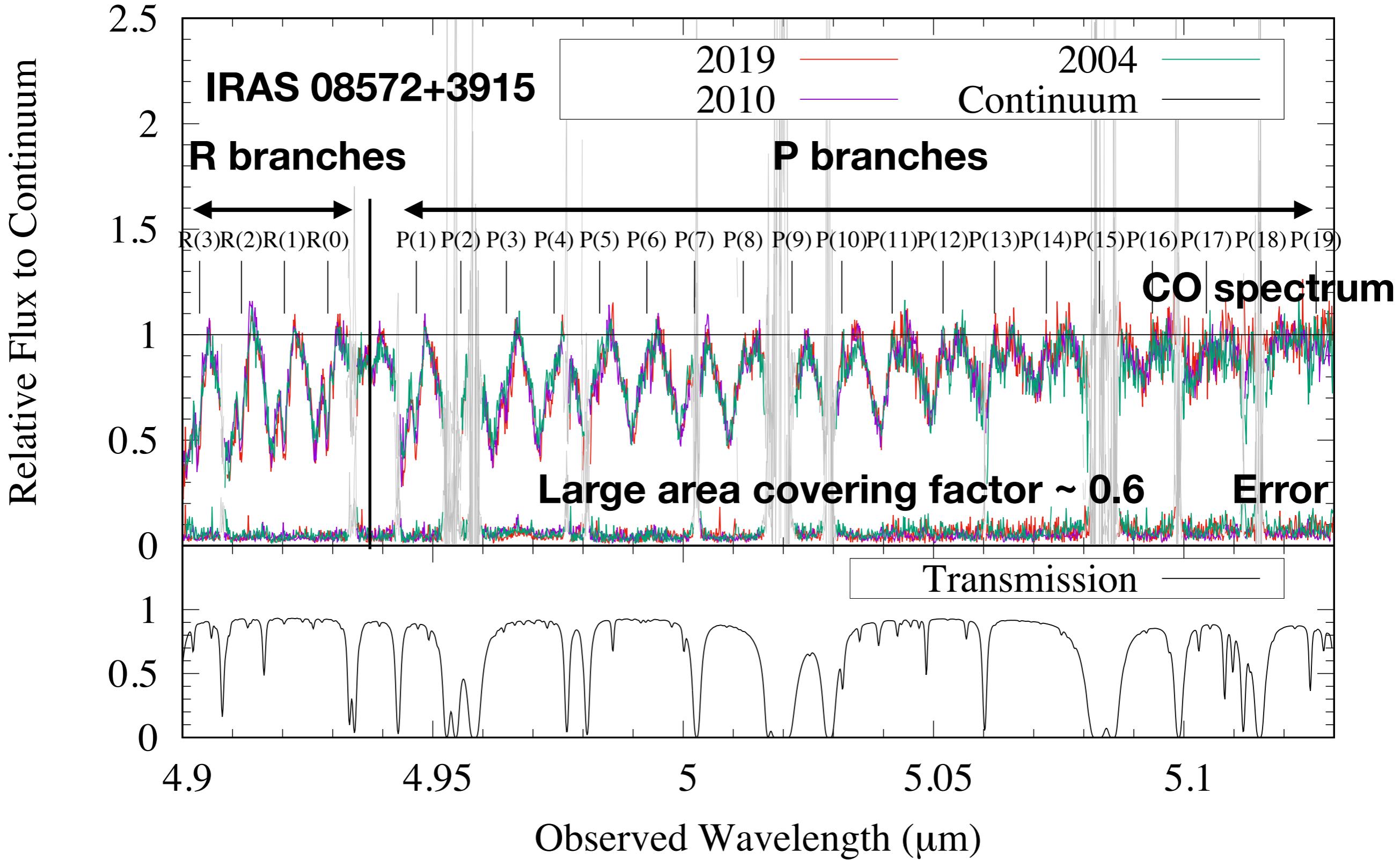
Targets and observations

- IRAS 08572+3915 NW (z=0.0583)
 - Ultra Luminous InfraRed Galaxy (ULIRG), AGN
 - $L_{\text{AGN}} \sim 10^{46} \text{ erg s}^{-1} \rightarrow M_{\text{BH}} \sim 10^9 M_{\odot}$ ($\lambda_{\text{Edd}} = 0.1$)
- Subaru, IRCS @ M-band

	Date (UT)		Wavelength resolution	Wavelength (μm)	Adaptive Optics
15 yr	2004	Jan. 15 Feb. 4	5,000 (~60 km s ⁻¹)	5.00–5.13 4.90–5.04	No
9 yr	2010	Feb. 28	5,000 (~60 km s ⁻¹)	4.90–5.04 5.00–5.13	No
	2019	Jan. 19	10,000 (~30 km s ⁻¹)	5.00–5.13	Yes
		Jan. 20		4.90–5.04	

CO gas temperatures,
column densities

Spectra of IRAS 08572+3915



Velocity components in CO lines

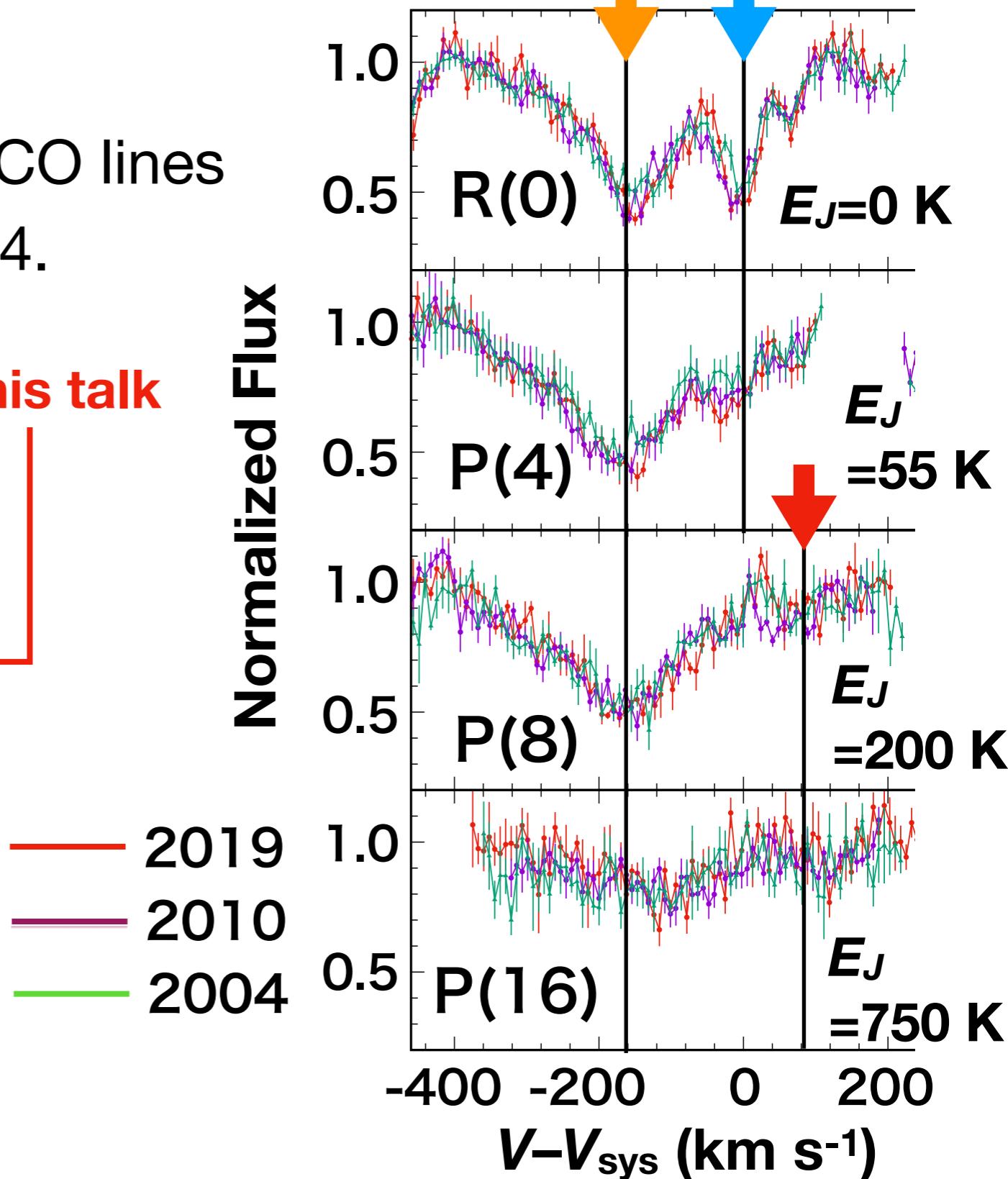
- Shirahata+13 found 3 velocity components in the CO lines using spectra obtained in 2004.

Attributed to ... **Focus in this talk**

 : Molecular torus
(centered at
 $V-V_{\text{sys}} \sim -160 \text{ km s}^{-1}$)

 : Host galaxy
(centered at
 $V-V_{\text{sys}} \sim 0 \text{ km s}^{-1}$)

 : Hot Inflow
(centered at
 $V-V_{\text{sys}} \sim +80 \text{ km s}^{-1}$)



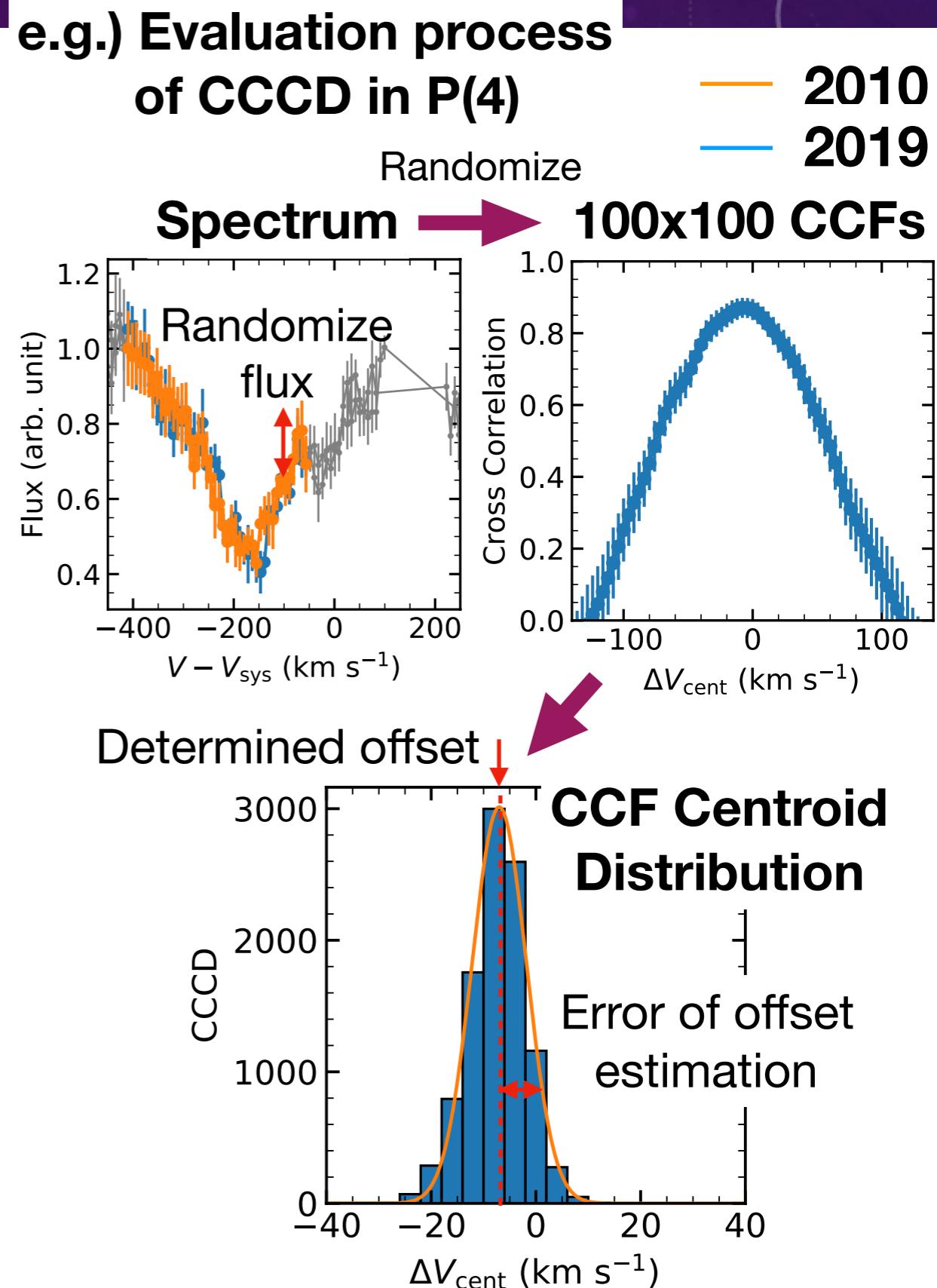
Results

1. Analyses on time variations in CO line velocity

Evaluation of velocity variations

Flux Randomization (Peterson+98)

- A method to evaluate velocity offsets with cross-correlation functions (CCF), propagating flux errors
- The velocity offsets and their errors are determined from probability distribution of CCF centroids.



Upper limits on velocity variations

- Velocity variations were estimated **for the first time** in the periods: 2004–2019, and 2010–2019.
 - ΔV_{CO} : Error-weighted means of the CO velocity variations
 - ΔV_{cal} : Error-weighted means of velocity offsets due to the errors of wavelength calibrations

→ **Velocity variations are tightly constrained as:**

$$\begin{aligned} |\Delta V_{\text{CO}} - \Delta V_{\text{cal}}|_{2004-2019} &< 10 \text{ km s}^{-1} \\ |\Delta V_{\text{CO}} - \Delta V_{\text{cal}}|_{2010-2019} &< 7 \text{ km s}^{-1} \end{aligned} \quad (\text{3-sigma limits})$$

Period	Wavelength (μm)	$\Delta V_{\text{cal}} (\text{km s}^{-1})$	$\Delta V_{\text{CO}} (\text{km s}^{-1})$
2004-2019	4.90–5.04	-5 ± 2	-8 ± 4
	5.00–5.13	$+1 \pm 1$	$+4 \pm 4$
2010-2019	4.90–5.04	-10 ± 2	-7 ± 3
	5.00–5.13	$+5 \pm 2$	$+4 \pm 2$

Lower limit on clumps-BH distance

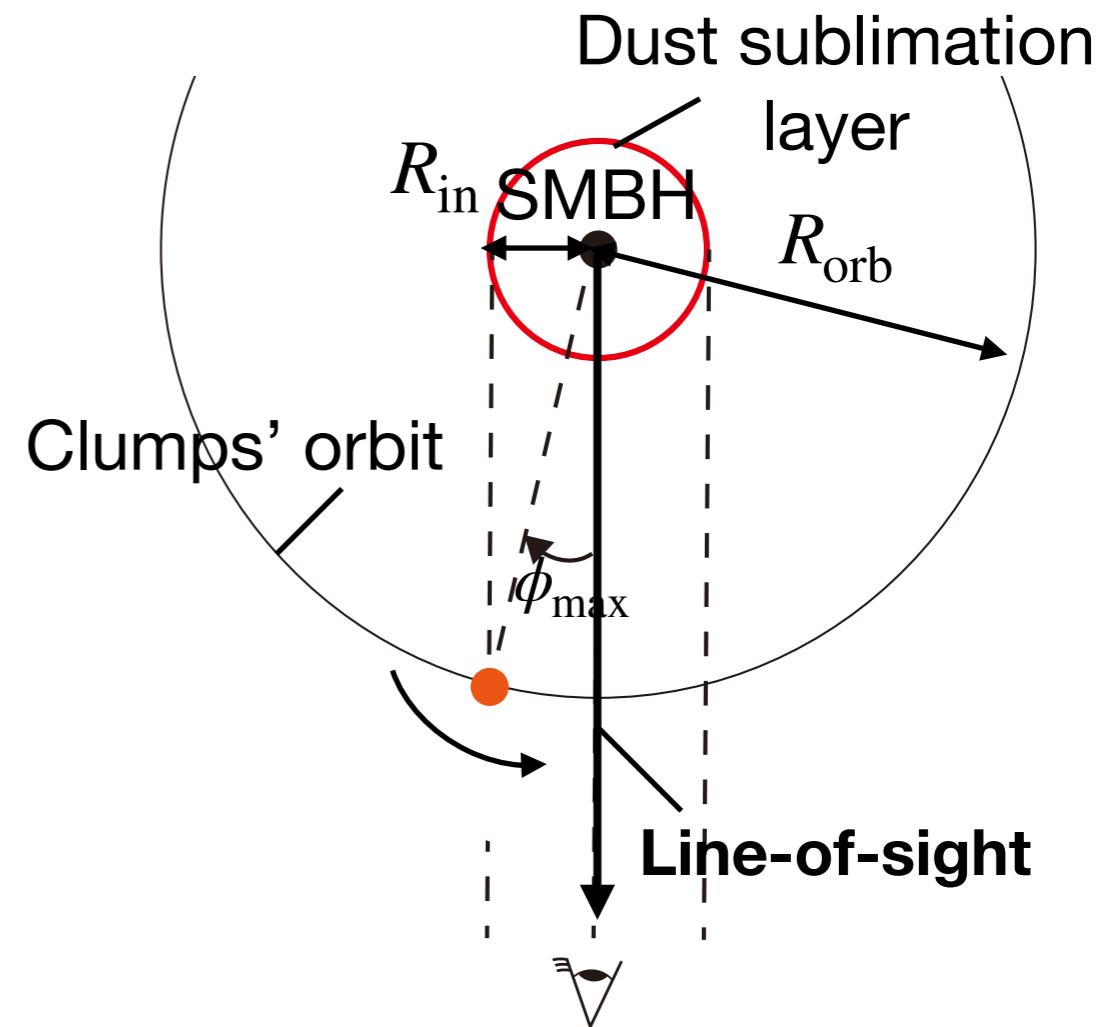
- Assuming that gravitational force is dominant in the molecular torus, and clumps are in circular Keplerian orbits, we evaluate their orbital radii as:

$$\frac{dV_{\text{LOS}}}{dt} = \frac{GM_{\text{BH}}}{R_{\text{orb}}^2} \sin i \cos \phi \leq a_{\text{up}}$$

$$\Rightarrow R_{\text{orb}} \geq \sqrt{\frac{GM_{\text{BH}}}{a_{\text{up}}} \sin i \cos \phi_{\text{max}}}$$

$$\Rightarrow R_{\text{orb}} \gtrsim 2.5 \text{ pc} \left(\frac{M_{\text{BH}}}{10^9 M_{\odot}} \right)^{0.5} (\sin i)^{0.5}$$

→ Clumps are likely to exist farther from BH than models typically predict ($\sim 1 \text{ pc}$).



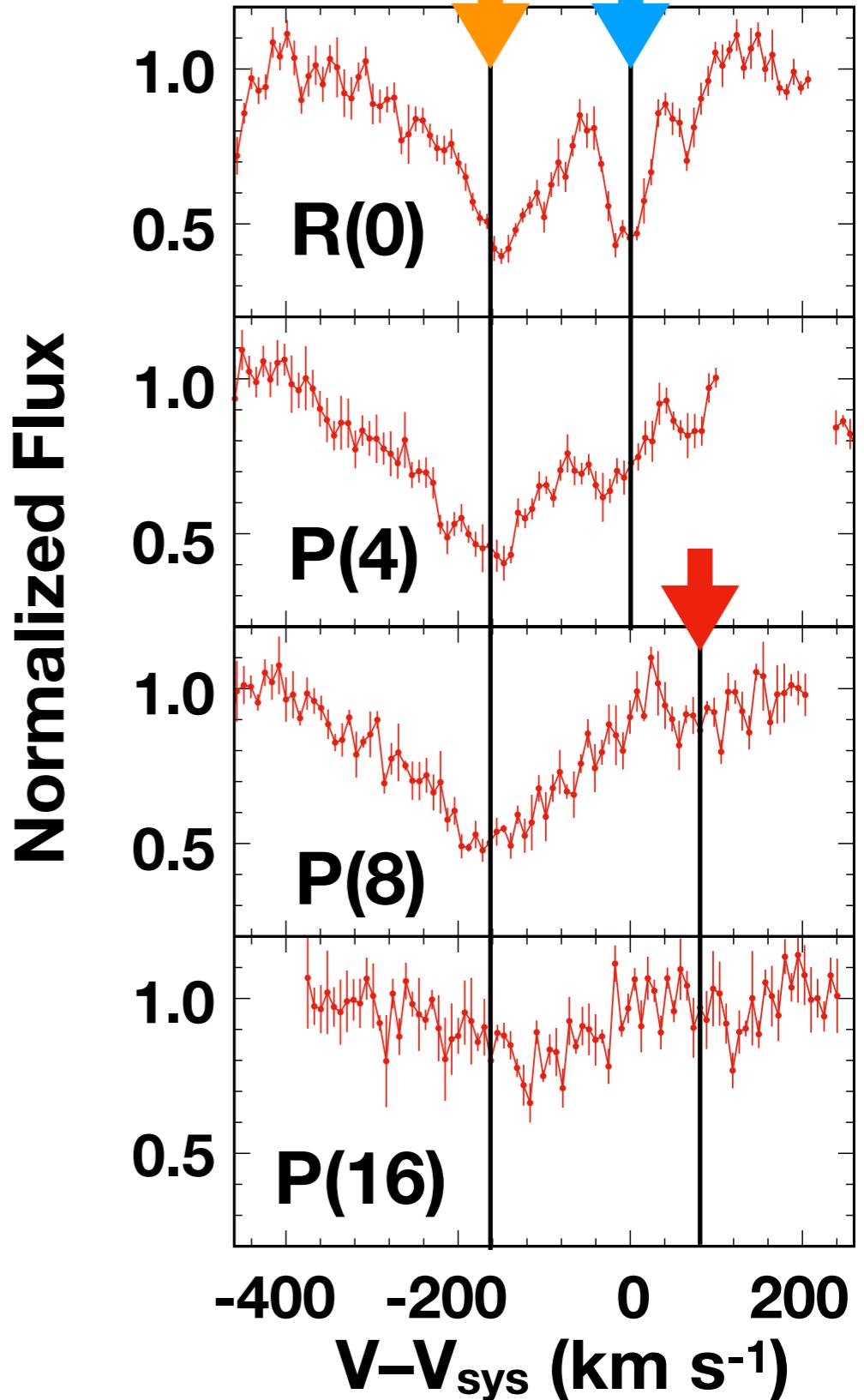
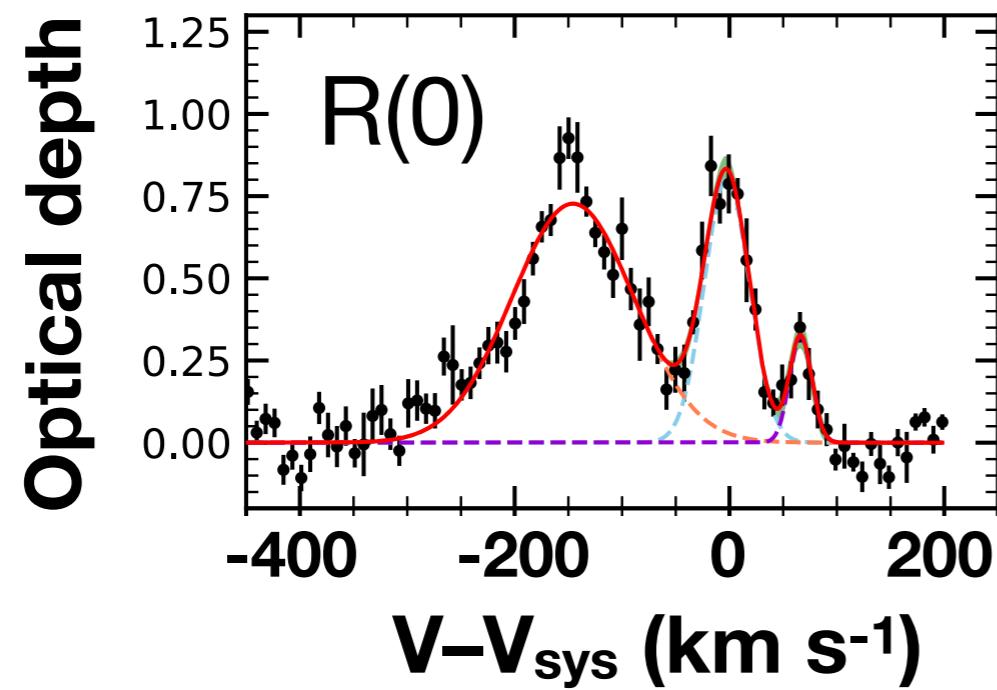
a_{up} : An upper limit of acceleration
 i : Inclination angle (90° =edge-on)

Results

**2. Estimates on CO temperatures
and column densities
with spectra obtained in 2019**

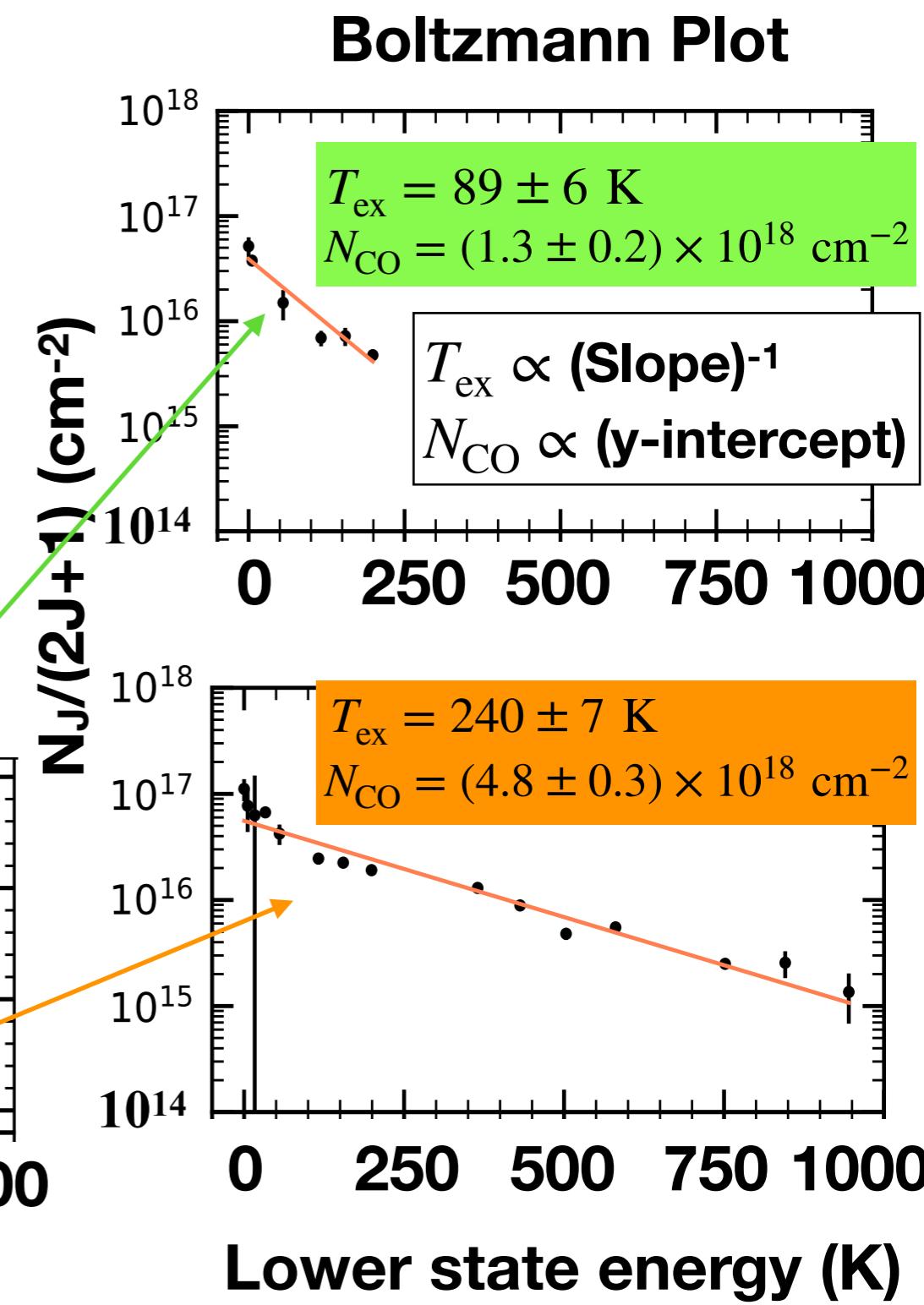
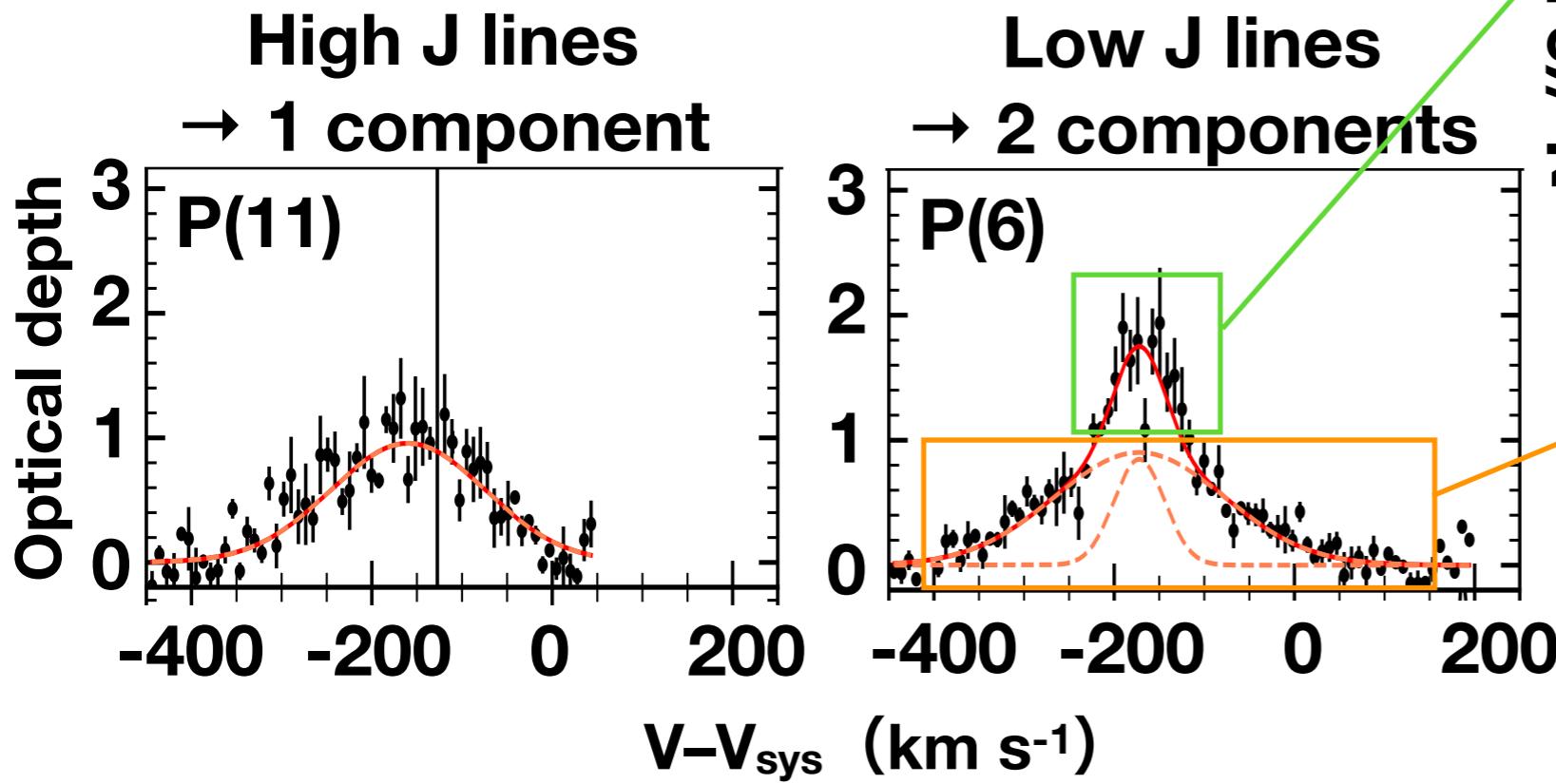
Multi-component study of absorption lines

- We separated each velocity component by fitting multiple gaussians **for the first time.**



Detections of another torus component

- In low J lines, torus components **excess** a single gaussian around the peaks.
- Narrower component's $T_{\text{ex}}, N_{\text{CO}}$ < Wider component's $T_{\text{ex}}, N_{\text{CO}}$
- $T_{\text{ex}} = 240 \text{ K} > T_{\text{ex}}$ of starbursts, which supports CO lines are from AGNs.



Possible origin of the components

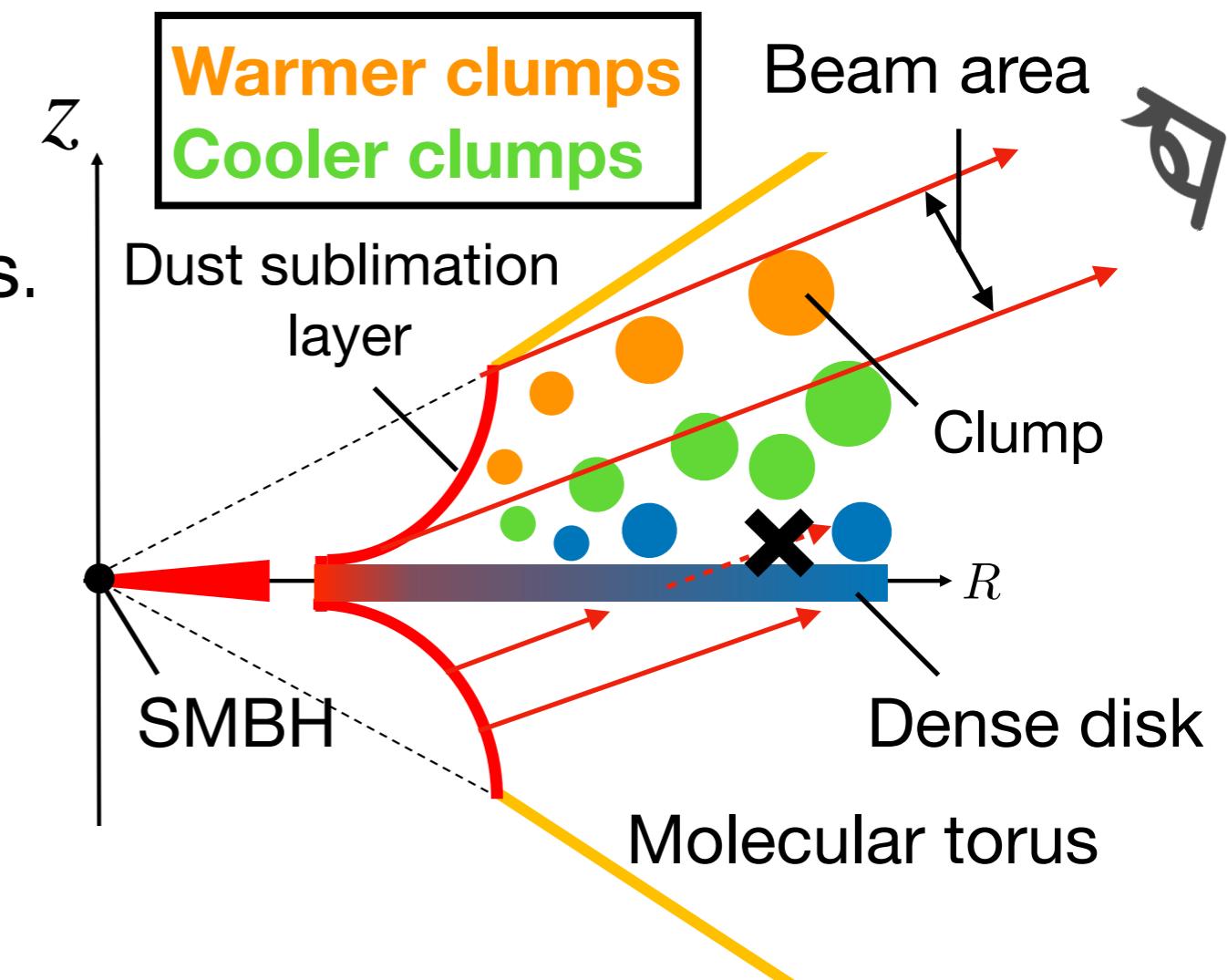
- Cooler component: $T_{\text{ex}} \approx 90 \text{ K}$, $N_{\text{CO}} \approx 1 \times 10^{18} \text{ cm}^{-2}$
- Warmer component: $T_{\text{ex}} \approx 240 \text{ K}$, $N_{\text{CO}} \approx 5 \times 10^{18} \text{ cm}^{-2}$
- The column density of warmer CO > cooler CO
- 2 components are NOT in the pressure equilibrium.

- Their central velocities are equivalent.

→ These are from similar regions.



- These are likely to be from clumps with different temperatures.



Summary

- Time variations in velocity of CO ro-vibrational lines in AGN IRAS 08572+3915 have been measured between 3 epochs.
- Velocity variations are tightly constrained, or $< \sim 10 \text{ km s}^{-1}$, which leads the lower limit on clumps' orbital radii to be $\sim 2.5 \text{ pc}$, **greater than typical value in the models ($\sim 1 \text{ pc}$)**.
- It has been found that the velocity component attributed to a molecular torus actually consists of 2 components with different velocity widths.
- In the molecular torus, a cooler component ($T_{\text{ex}} \approx 90 \text{ K}, N_{\text{CO}} \approx 1 \times 10^{18} \text{ cm}^{-2}$) and a warmer component ($T_{\text{ex}} \approx 240 \text{ K}, N_{\text{CO}} \approx 5 \times 10^{18} \text{ cm}^{-2}$) are NOT in the pressure equilibrium, and **likely to be from individual clumps**.