CO近赤外線吸収から探る銀河中心pcスケールでのガスの物理状態：あかりとSpitzerによる低分散分光観測

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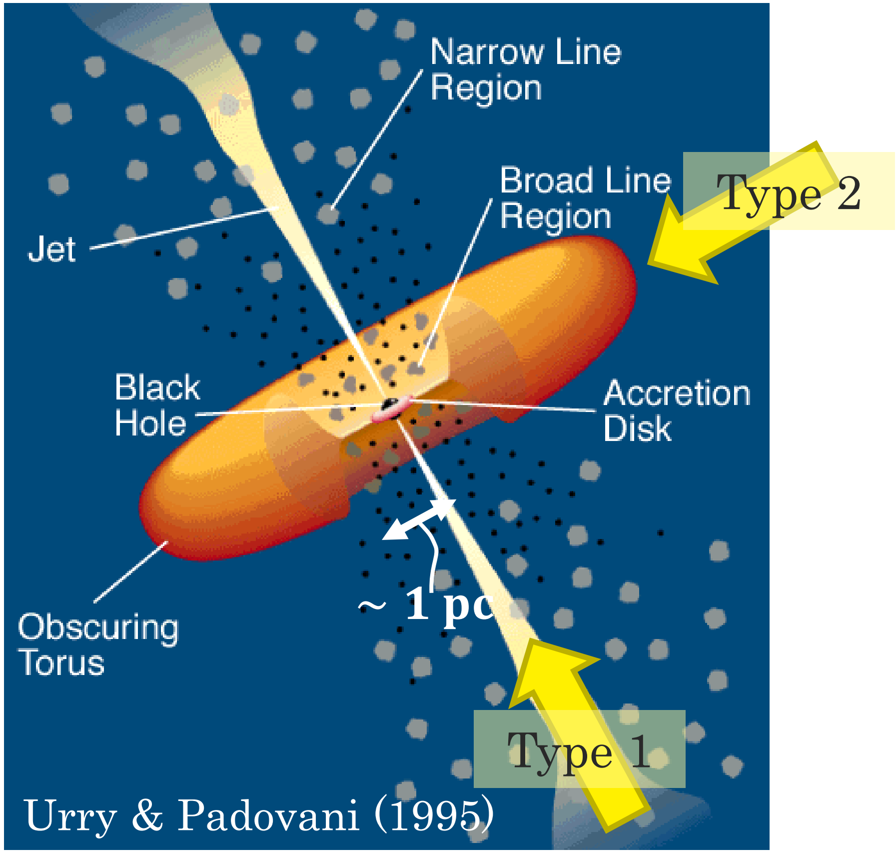
Introduction: Active Galactic Nuclei (AGNs)

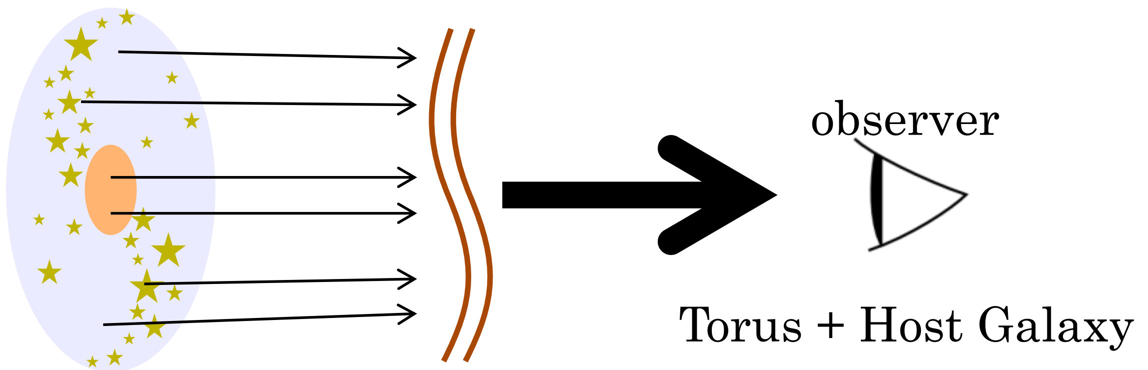
- Classification
  - Broad and Narrow lines -> type 1
  - Only Narrow lines -> type 2
- Unified Scheme
  - Central SMBH, accretion disc
  - Broad Line Regions nearby the center
  - Optically and geometrically thick dusty molecular torus
  - Narrow Line Regions above the torus
  - face-on → type 1
  - edge-on → type 2



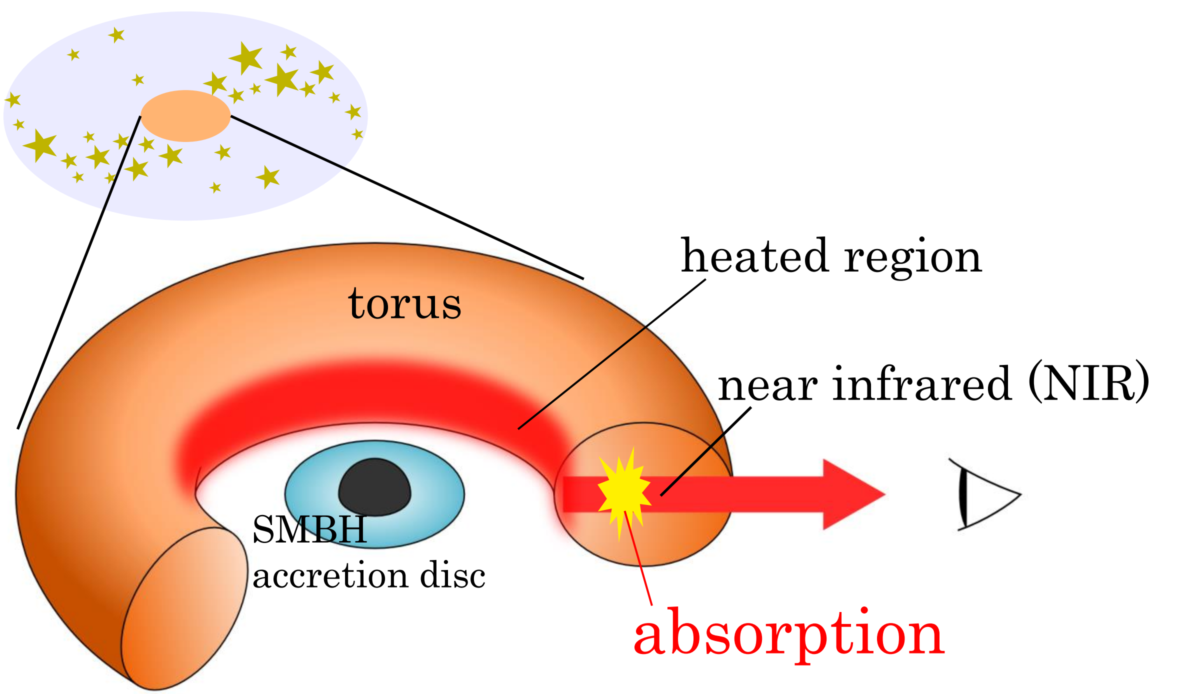
Molecular torus is a key object!

Introduction: observations of molecular tori

- Face-on
- CO rotational emission (milli, sub-millimeter)
- spatial resolution ~mas ~pc in nearby universe

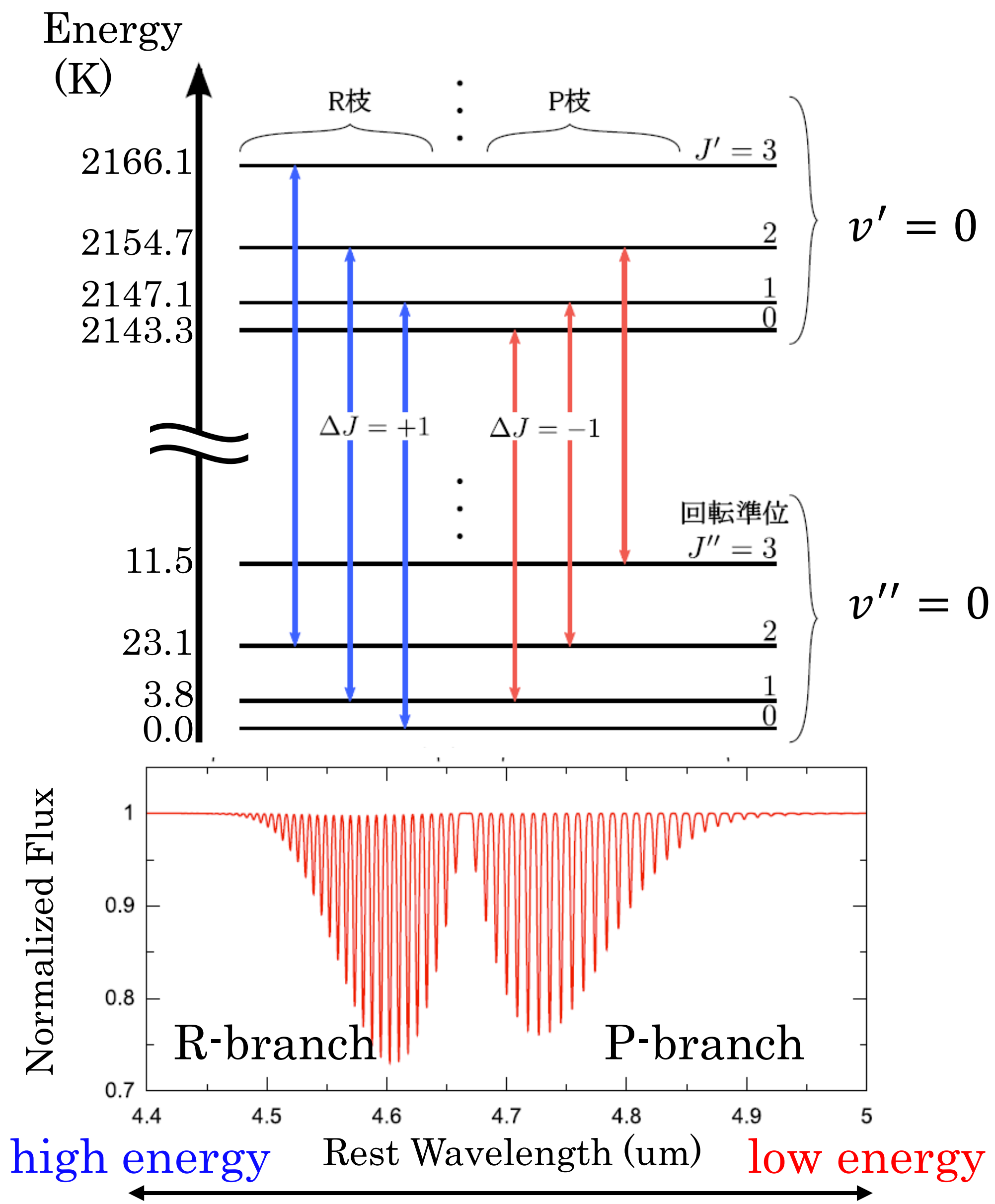


- Edge-on
- near-infrared continuum
  - heated inner edge of tori
- CO ro-vibrational absorption
- gas in the torus absorbs thermal radiation
- NIR emission from host galaxies is negligible



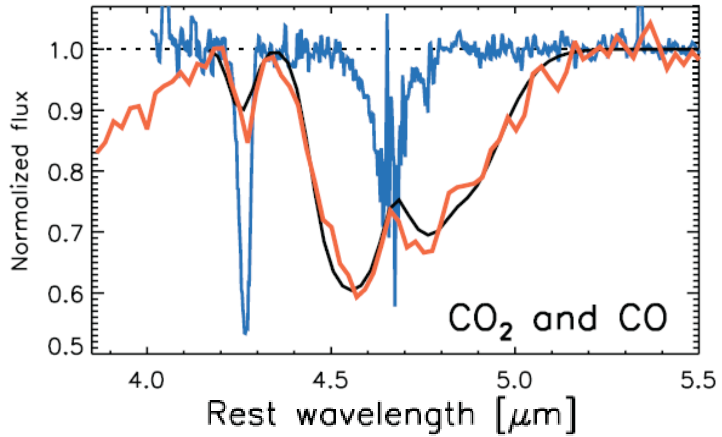
Introduction: CO ro-vibrational transition

- Band center 4.7 um
- vibration: $v = 1 \leftarrow 0$
- rotation: $\Delta J = \pm 1$
- 2 branches
  - R-branch: $\Delta J = +1$
  - P-branch: $\Delta J = -1$
- Absorption lines of different J come in a small wavelength range.
- Good probe for physical states

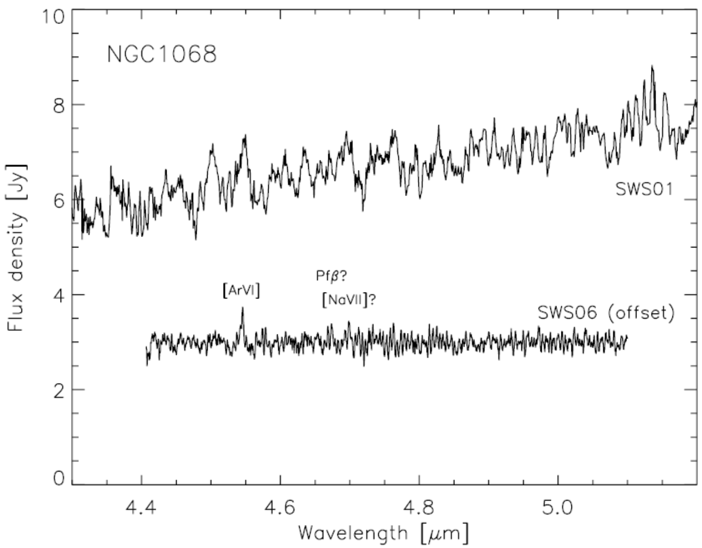


Introduction: other researches

- Spoon et al. 2004, ApJS, 154, 184
  - IRAS F00183-0711
    - LINER
    - Obscured AGN?
  - Spitzer observation
  - Strong CO absorption



- Lutz et al. 2004, A&A, 426, 5
  - Nearby 31 Seyfert galaxies
    - 19 type 1 and 12type 2
  - ISO observations
  - No detection of CO absorption

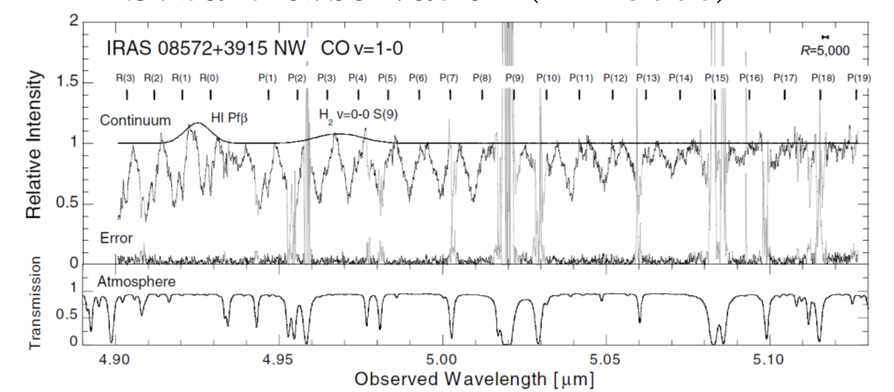


What makes the difference between the two groups ?

Introduction: other researches

- Shirahata (2005), Shirahata et al. (2013)
  - Obscured AGNs
  - High-resolution spectroscopy with Subaru
  - Resolved rotational levels
  - Targets were limited by luminosity and redshift
    - M-band observation → $z < 0.13$

Subaru observation (R = 5000)



- space telescopes enable complementary studies
  - Low-resolution
  - Large sample

In this study, we analyze CO ro-vibrational absorption systematically using AKARI and Spitzer.

Method: space observations

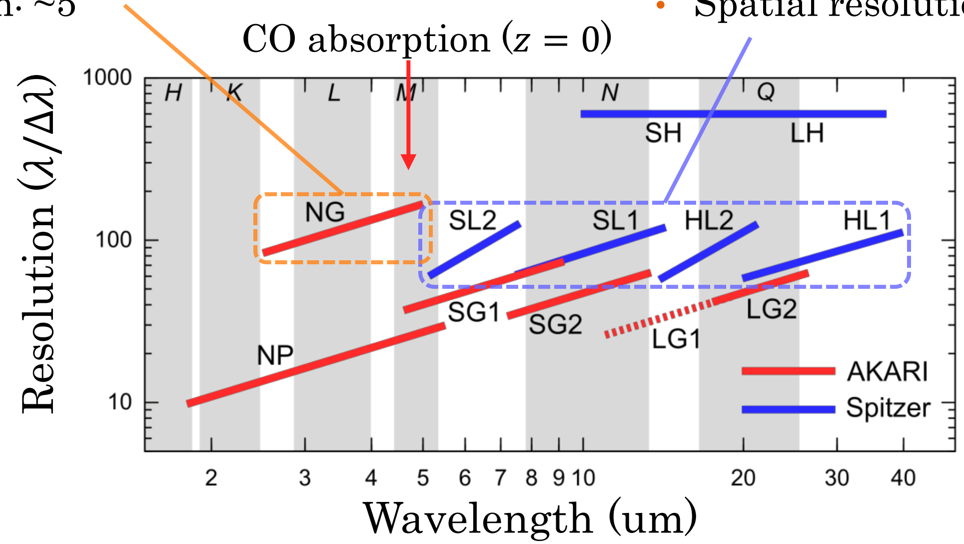
✗ Spectral Resolution	Ground: $\lambda/\Delta\lambda$ ~ 10000 Space: $\lambda/\Delta\lambda$ ~ 100
○ Redshift	Ground: $z < 0.13$ for M-band Space: Not limited by the atmosphere
○ Flux Limit	Ground: > 100 mJy for one-night observations in Subaru Space: > 1 mJy for ten-minute observations with AKARI

AKARI

- NIR grism spectroscopy
- Wavelength: 2.5–5.0 um
  - Redshift $z < 0.07$
- Spectral resolution: $\lambda/\Delta\lambda = 120$ @3.6 μm
- Spatial resolution: ~5”

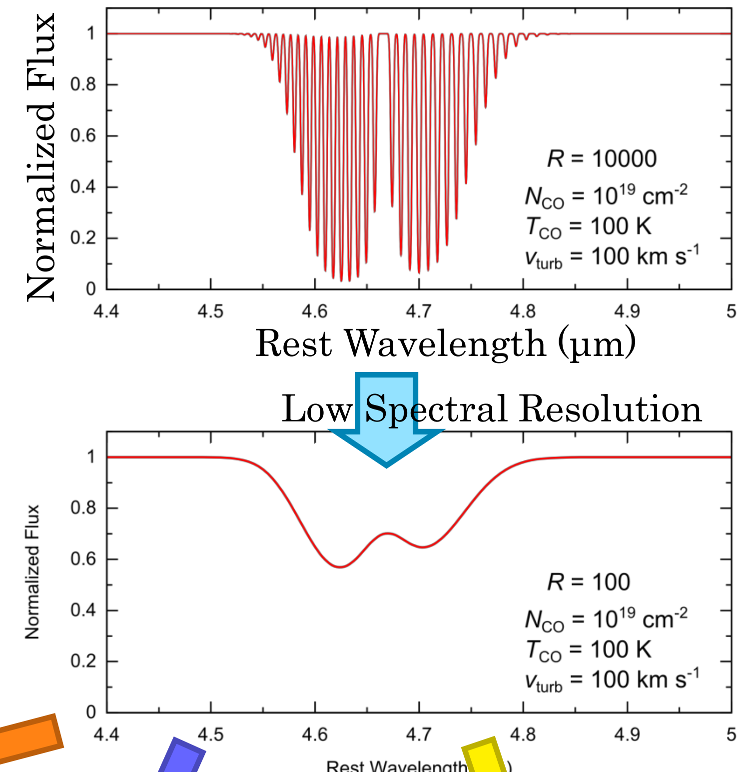
Spitzer

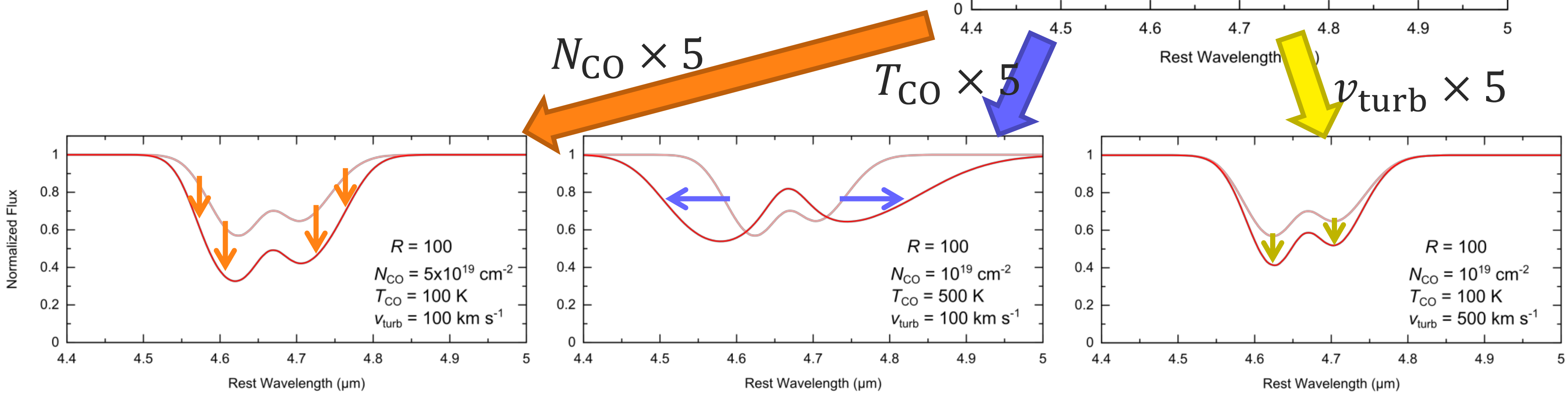
- SL, HL module
- Wavelength: 5.2–40 um
  - Redshift $z > 0.13$
- Spectral resolution: $\lambda/\Delta\lambda = 86$ @5.2 um
- Spatial resolution: ~4”



Method: model fitting

- AKARI and Spitzer observations cannot resolve rotational levels
- Model fitting assuming local thermal equilibrium
  - Cami et al. (2000)
  - Slab geometry and single component
  - Free parameters: column density $N_{\rm CO}$, temperature $T_{\rm CO}$, line width $v_{\rm turb}$





Targets: selection and optical classification

- AKARI
  - Mission Program “AGNUL”
  - Observations during Phase 1 and 2 (LHe + mechanical cooler)
  - 3 targets that show the signature of CO absorption
- Spitzer
  - 4 targets reported by Spoon et al. (2005)

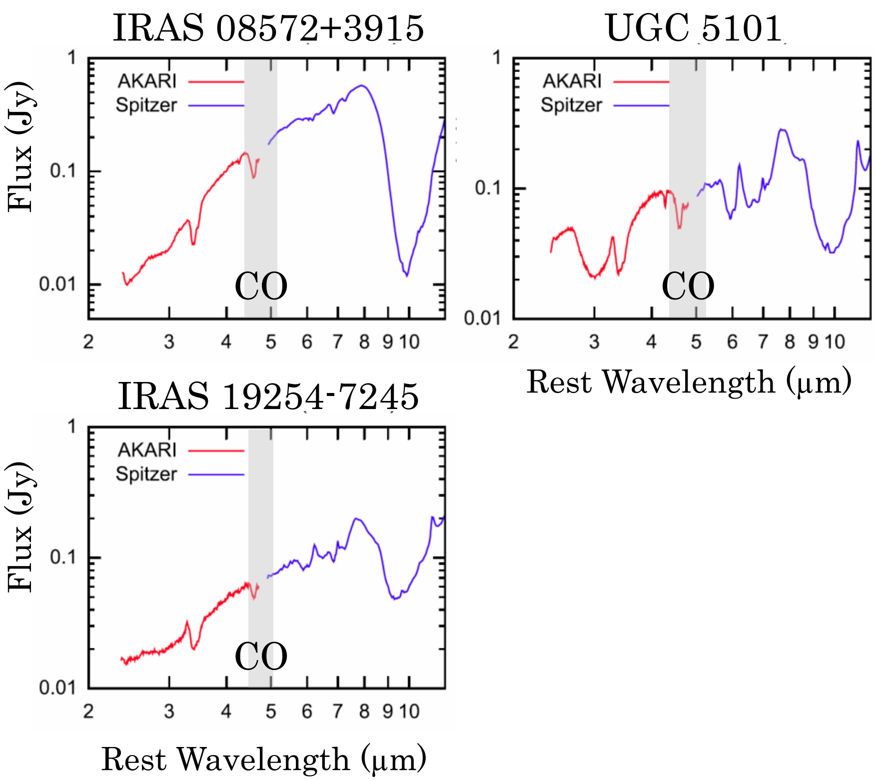
IRAS 08572+3915	z = 0.0583	LINER
UGC 5101	0.0392	LINER
IRAS 19254-7245	0.0617	Seyfert 2
IRAS F00183-7111	0.3270	LINER
IRAS 00397-1312	0.2617	H II
IRAS 00406-3127	0.3424	Seyfert 2
IRAS 13352+6402	0.2370	?

cf. NGC 1068（z=0.0038)

Targets: spectra

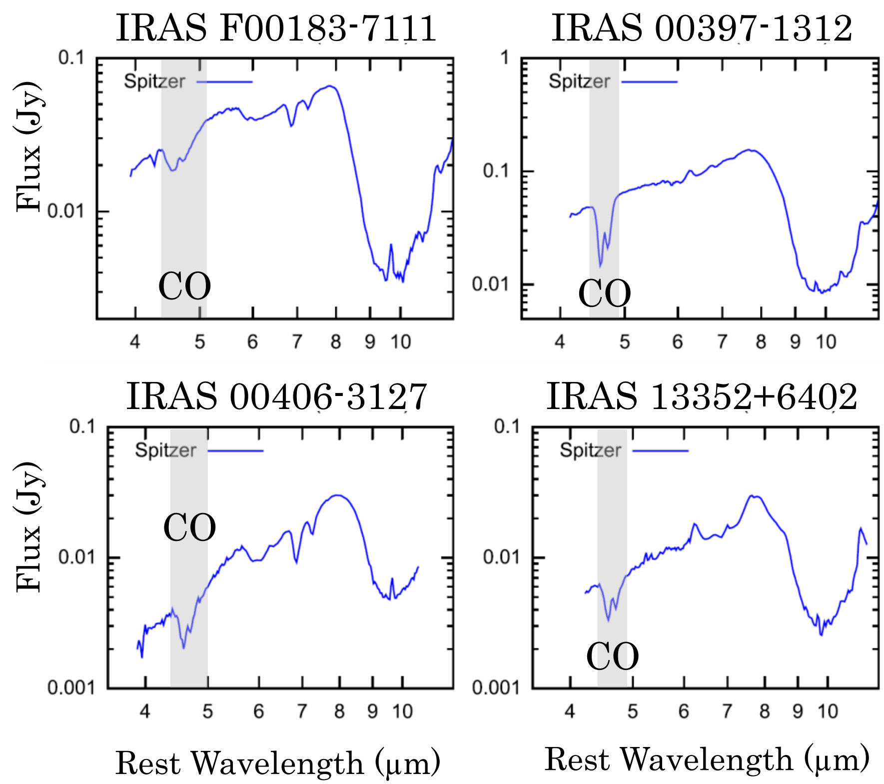
AKARI＋Spitzer

redshift $z < 0.07$

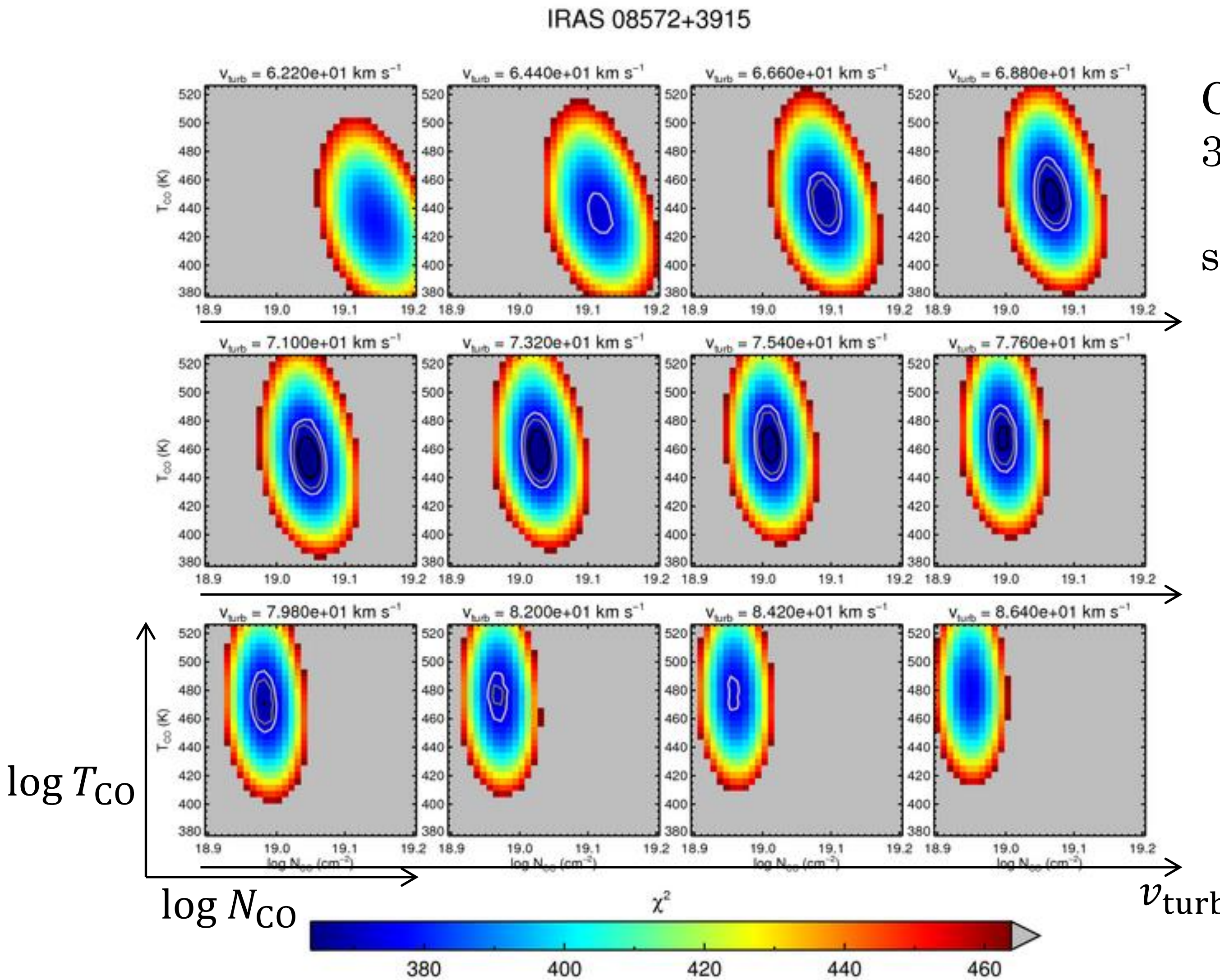


Spitzer

redshift $z > 0.13$



Results: χ^2 in the parameter space

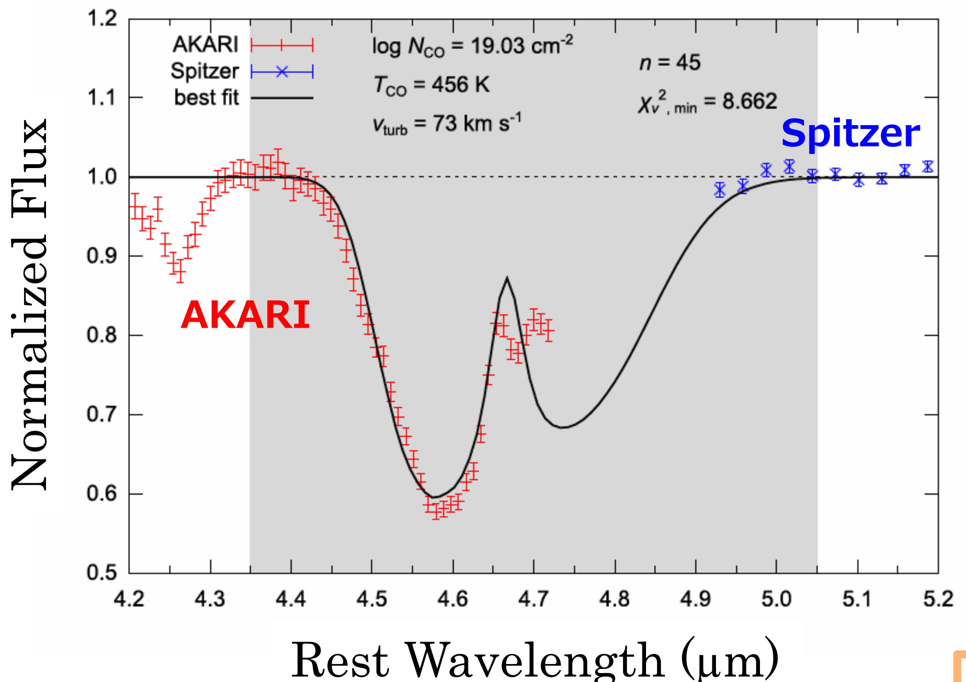


Calculated χ^2 in the 3D parameter space

searched the best fit

Results: best fit

IRAS 08572+3915



$$\log N_{CO} = 19.03\,^{+0.30}_{-0.08}\ \mathrm{cm}^{-2}$$

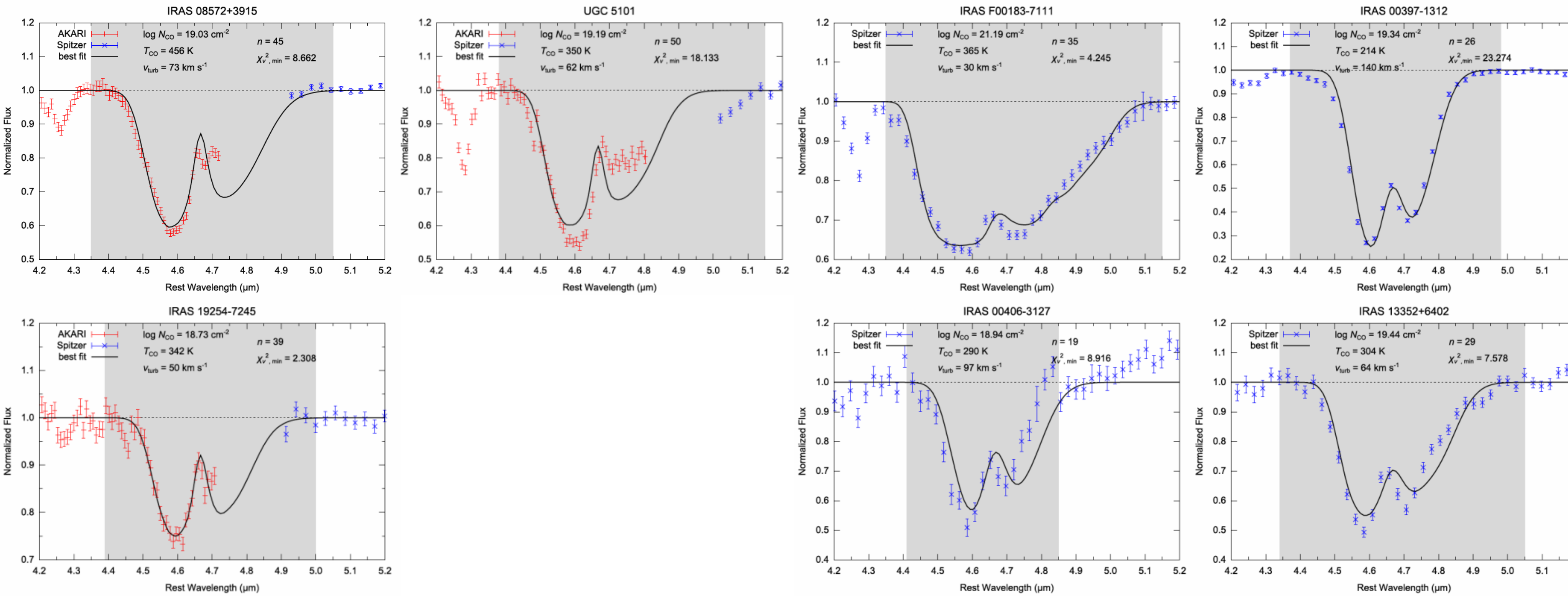
$$T_{CO} = 456\,^{+38}_{-34}\ \mathrm{K}$$

$$v_{turb} = 73\,^{+13}_{-8}\ \mathrm{km\,s}^{-1}$$

High Temperature
and
Large Column Density

Cf: molecular clouds in star-forming regions, $T < 50$ K

Results: best fit



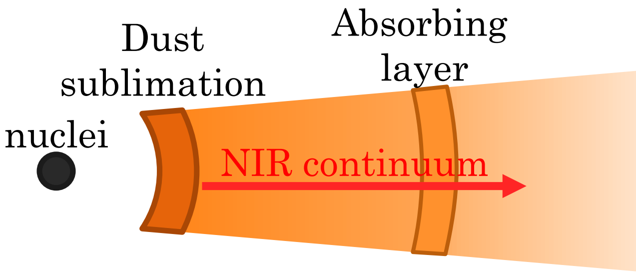
		Median	Each Unc.
Column Density	N_{CO}	$1 \times 10^{19}\ \mathrm{cm}^{-2}$	40%
Temperature	T_{CO}	350 K	10–40%
Line Width	v_{turb}	70 km/s	10–30%

$N_{\mathrm{H}} \sim 1 \times 10^{23}\ \mathrm{cm}^{-2}$

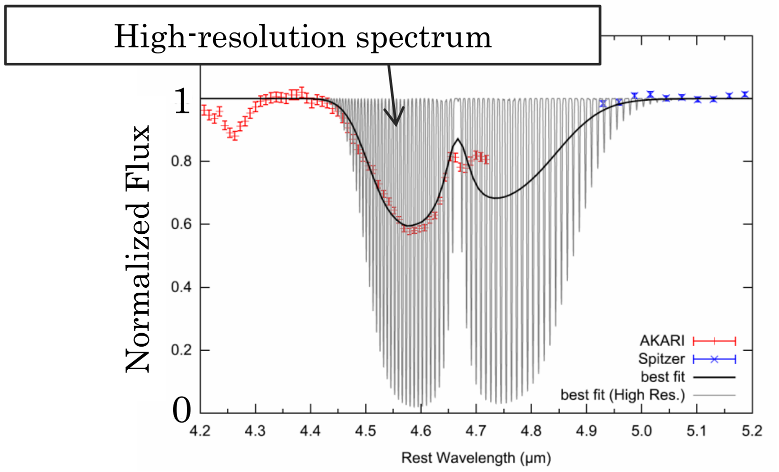
Warm and **Abundant**

Discussion

- Origin of NIR continuum
  - NIR continuum (~5 μm) -> Thermal radiation ($\gtrsim 10^3$ K)
  - Heated by central nuclei
  - Dust sublimation temperature is ~ 1500 K
    → inner edge of the torus is a good candidate

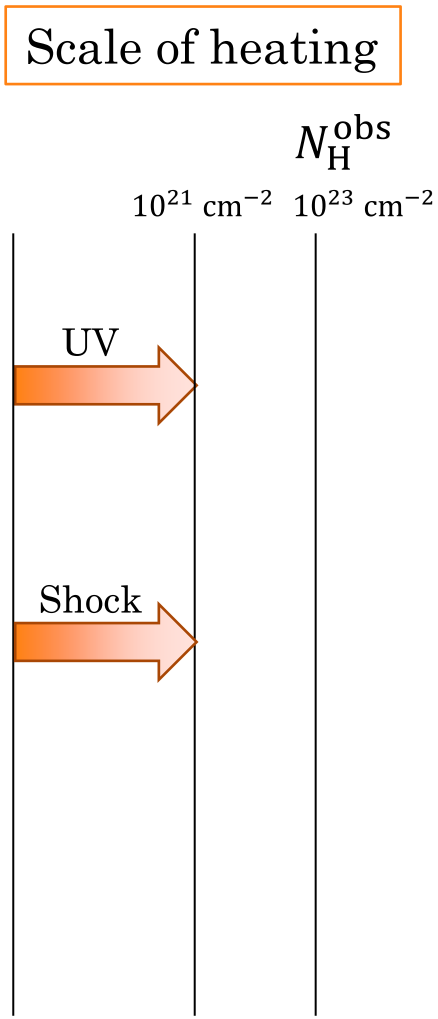


- Absorber
  - Absorption line of each J is almost saturated
  - Molecular clouds in star-forming regions distribute randomly and cannot cover the background entirely
  - Molecular cloud of systematic geometry surrounding the nucleus



Discussion

- Heating mechanism
  - Observed gas has high temperature (350 K) and large column density ($N_{\mathrm{H}}^{\mathrm{obs}} \sim 10^{23}\ \mathrm{cm}^{-2}$)
  - 3 candidates are examined
- 1. Photo Dissociation Region (PDR)
  - The accretion disk emits UV light and heats surrounding gas up to 10^4 K (Tielens & Hollenbach 1985).
  - But UV flux is attenuated by neutral gas and penetrates column density of only $N_{\mathrm{H}} \sim 10^{21}\ \mathrm{cm}^{-2} \ll N_{\mathrm{H}}^{\mathrm{obs}}$ (Diplas & Savage 1994).
  - PDR can hardly explain the observed large column density.
- 2. Shock Heating
  - Shock layers caused by such as outflows can be heated up to ~ 1000 K.
  - But the scale of shock layers is only $N_H \sim 10^{21}\ \mathrm{cm}^{-2} \ll N_{\mathrm{H}}^{\mathrm{obs}}$ (McKee et al. 1984)
  - The observed large column density cannot be explained by shock heating.

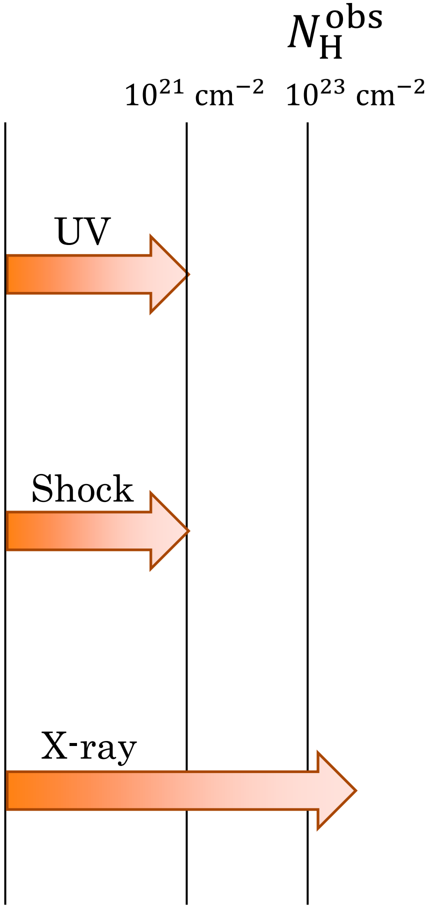


Discussion

- 3. X-ray Dissociation Region (XDR)
  - AGN nucleus emits hard X-ray photons (2—10 keV) and heats surrounding gas.
  - The temperature of the gas can reach ~ 10^4 K.
  - Hard X-ray can penetrate neutral gas of $N_{\rm H} \sim 10^{24}\ {\rm cm}^{-2} \sim N_{\rm H}^{\rm obs}$ before photoelectrically absorbed (Meijerink & Spaans 2005).
  - XDR can explain the observed large column density.

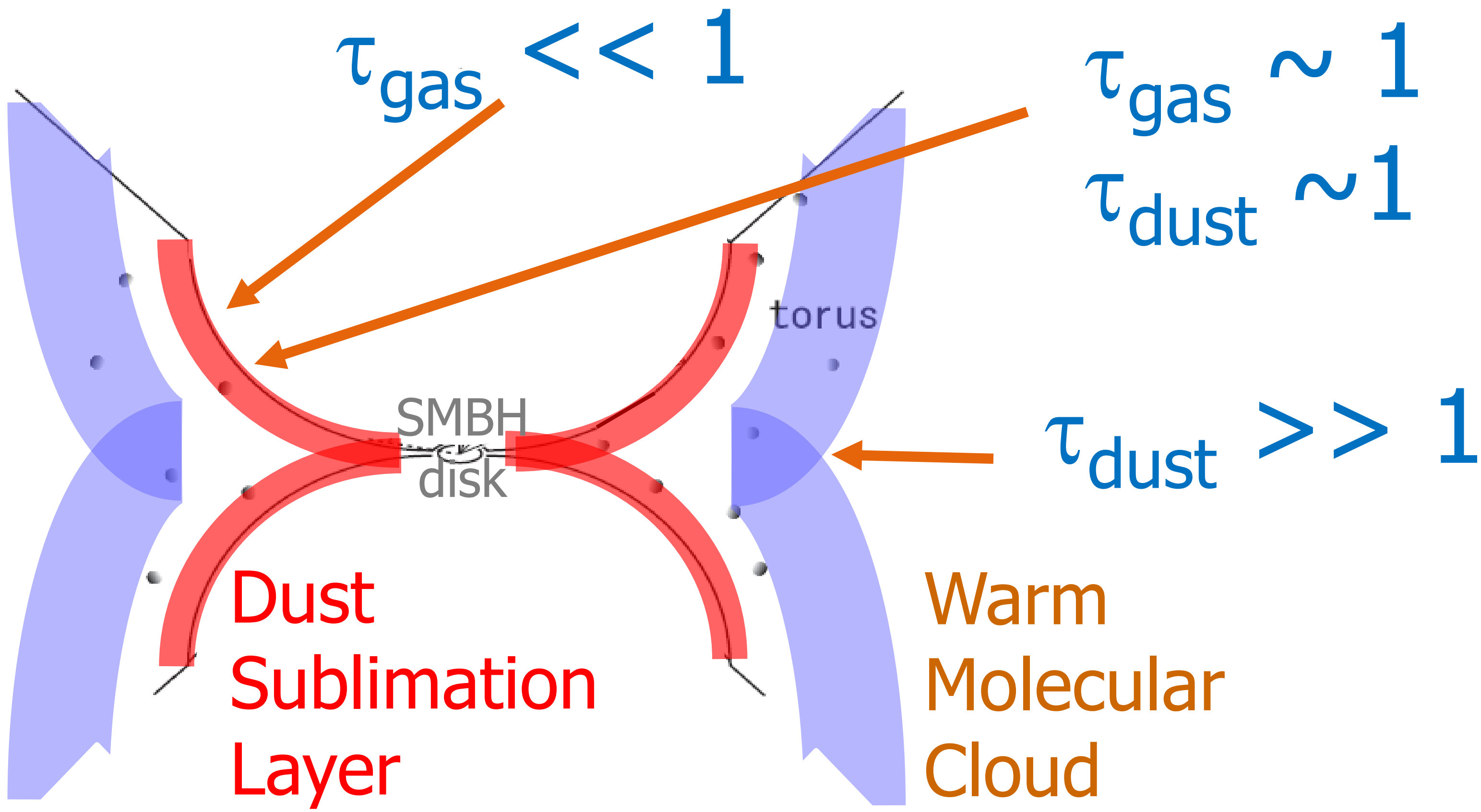
→ XDR is a good candidate as the heating mechanism

Scale of heating



Discussion

- When CO absorption is observed?
  - Geometrical effects?



Kawaguchi et al. 2010, 2011

Summary

- We observed CO ro-vibrational absorption (4.7 um) to study the physical state of molecular tori.
- From observations by AKARI and Spitzer, we obtained spectra of low resolution and wide wavelength range for 7 targets.
- CO absorptions were almost saturated and implied background emitters heated by the nuclei and molecular clouds of systematic geometry surrounding them.
- From the model-fitting analysis, in spite of low-resolution spectra that does not resolve rotational levels, we succeeded to obtain column densities, temperatures, and line widths with uncertainties of (several) × 10%.
  - Medians of them were, $N_{\mathrm{CO}} = 1 \times 10^{19}\ \mathrm{cm}^{-2}$, $T_{\mathrm{CO}} = 350\ \mathrm{K}$, $v_{\mathrm{turb}} = 70\ \mathrm{km\ s}^{-1}$
- The result indicates warm and abundant gas.
- XDR is a good candidate of the heating mechanism