# High resolution imaging of the molecular torus in NGC 1052 with VLBI

Sawada-Satoh et al. 2016, ApJL 830 L3
Sawada-Satoh et al. 2018, submitted to ApJL

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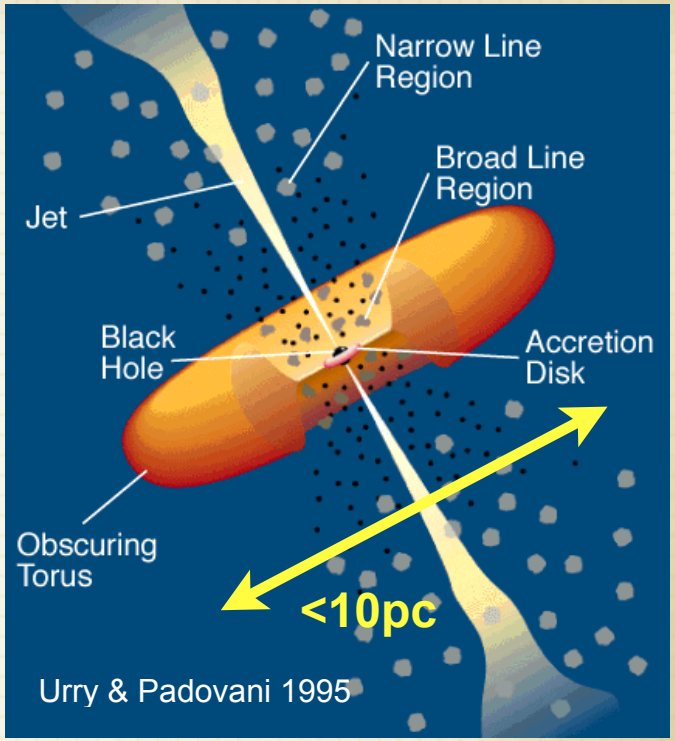
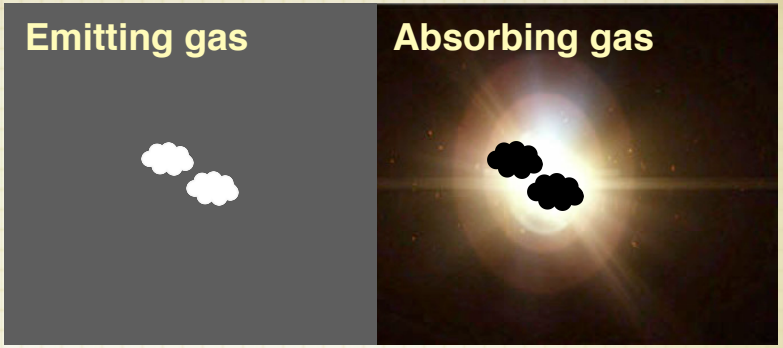
# Motivations & Backgrounds

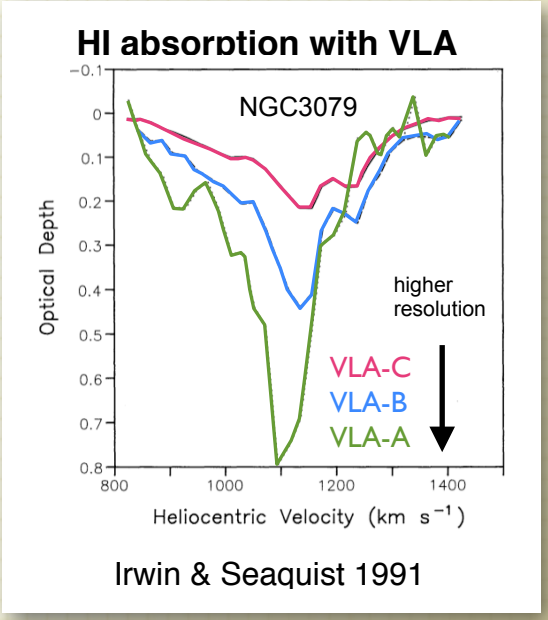
- Circumnuclear torus
  - Fuel tank of mass accretion onto SMBH
  - Invented by astronomers, to explain Seyfert 1 & 2
  - The size : < 10pc
- How can we confirm it ?
  - Requirement of 1 milliarcsec (mas) resolution to image
  - VLBI can acheive it !



# Molecular lines & VLBI

- Molecular gas in AGN region
  - Important clues to study AGN fueling
  - Compact (pc scale)
  - High column density ($10^{23\text{-}24}$ cm$^{-2}$)
- Advantages of VLBI
  - Can display thermal absorption in silhouette against a background synchrtron emission.
  - Sensitive to detect the compact and dense absorbing gas
    - Beam size smaller, filling factor larger

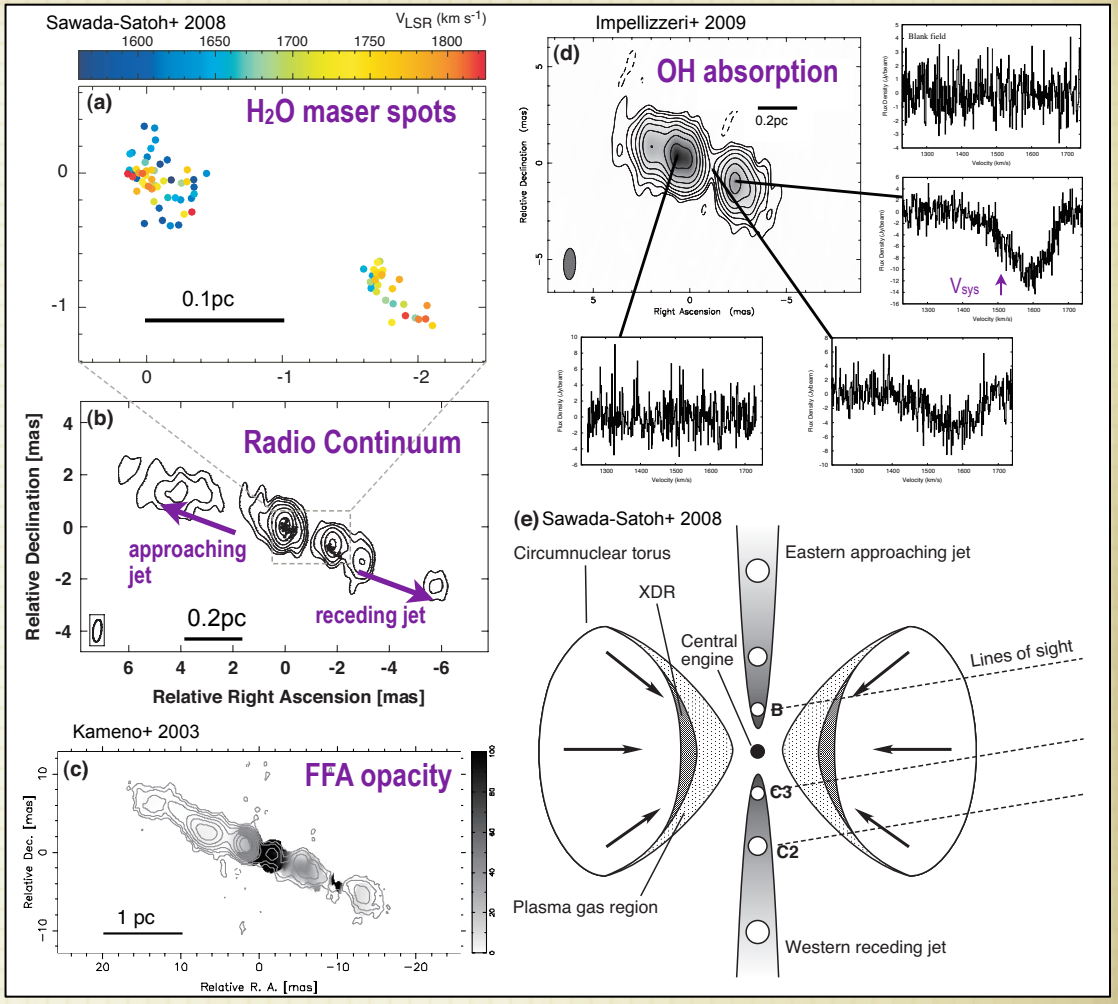



Irwin & Seaquist 1991

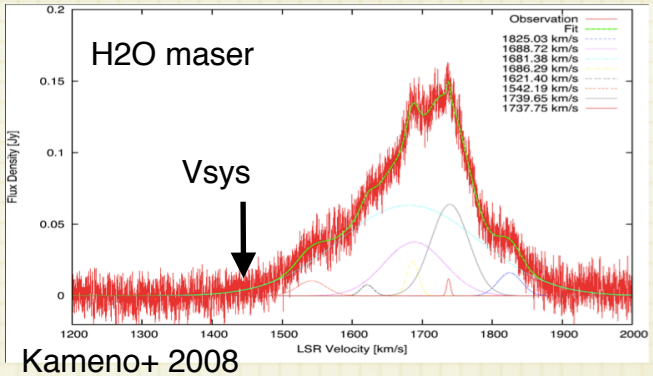
# The target NGC 1052 (1)

- A nearby radio gal.
  - AGN : LINER/Sy2
  - Two-sided radio jet
    - Proper motion with an apparent velocity of 0.26*c*
- AGN torus suggested
  - Several layers
  - Free-free absorption (FFA) due to plasma
  - $H_2O$ maser
  - OH absorption
  - Redshifted from $V_{sys}$
    - Ongoing infall ?



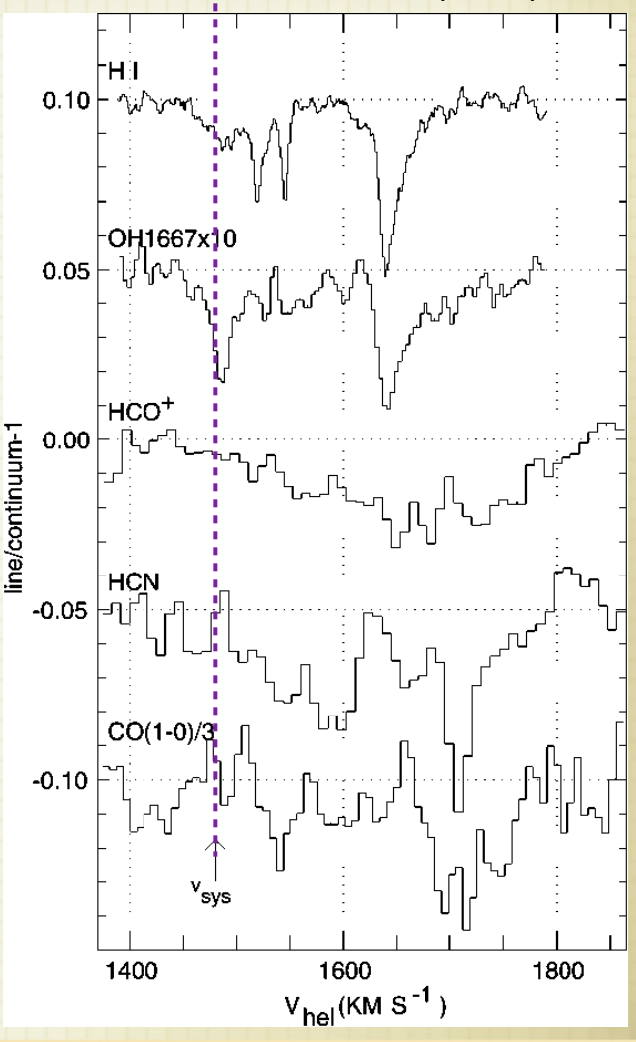
# The target NGC 1052 (2)

- Molecular absorption at mm band
  - $HCO^+$(1-0), HCN(1-0), CO(1-0)
  - Velocity: 1400-1800 km/s
  - Redshifted with respect to $V_{sys}$
    - Similar to OH and $H_2O$
    - Infall from the torus ? or, another motion ?
    - Location of the absorption is a key !



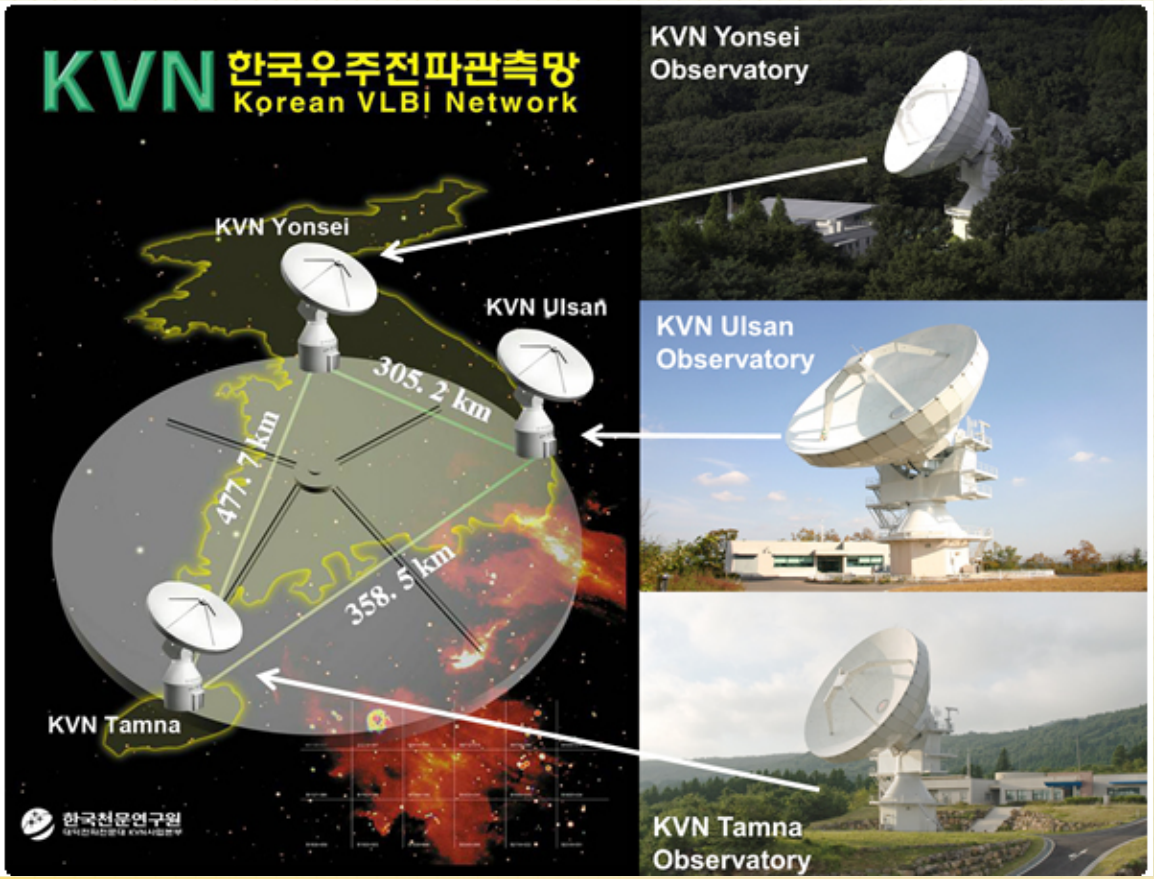
Kameno+ 2008

Liszt & Lucas 2004 (PdBI)



# Observations

- Korean VLBI Network (KVN) https://radio.kasi.re.kr/kvn/main_kvn.php
  - The first dedicated mm-band VLBI array



# Observations

- KVN observation : HCN J=1-0

| | | | |
|---|---|---|---|
| Correlator | KJCC | Target | NGC 1052 |
| Rest Frequency | 88.632 [GHz] | Transition | HCN J=1-0 |
| Beam size | 1.5x0.9 [mas] (0.1pc) | Obs. date | 2015/03/05 |
| Bandwidth | 128 [MHz] | On-source time | 7.5 hr |

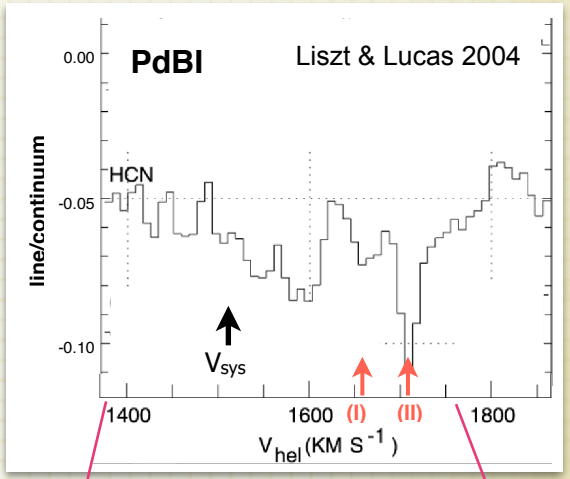
Time gap : 27 months

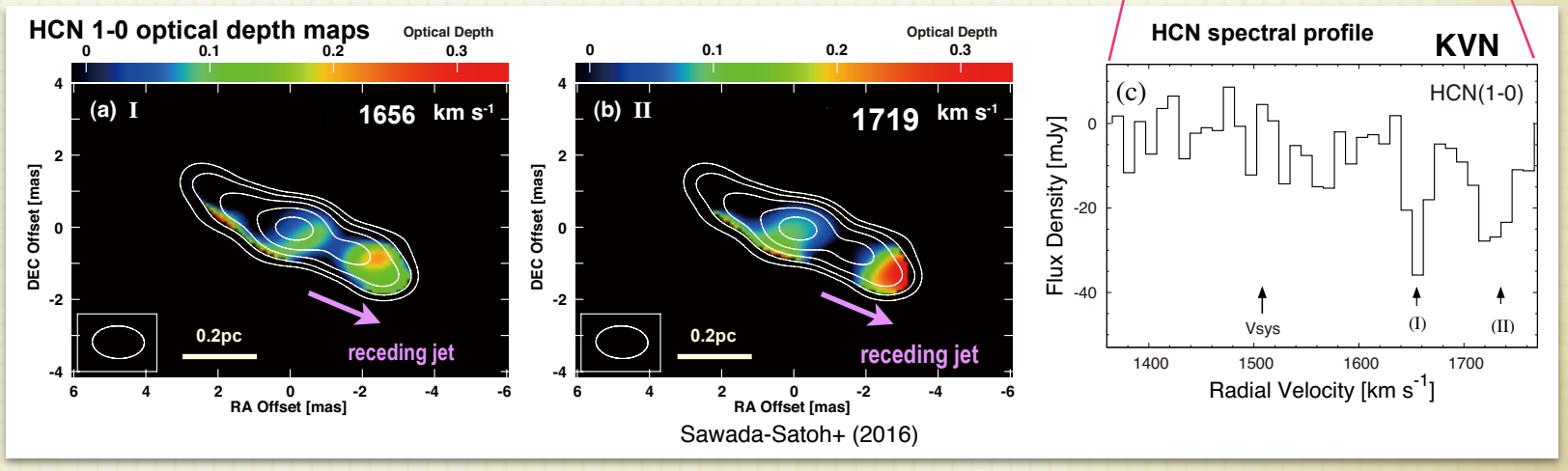
- KVN observation : $HCO^+$ J=1-0

| | | | |
|---|---|---|---|
| Correlator | KJCC | Target | NGC 1052 |
| Rest Frequency | 89.188 [GHz] | Transition | $HCO^+$ J=1-0 |
| Beam size | 1.5x0.9 [mas] (0.1pc) | Obs. date | 2017/06/17 |
| Bandwidth | 512 [MHz] | On-source time | 7.5 hr |

# HCN (1-0) absorption with KVN

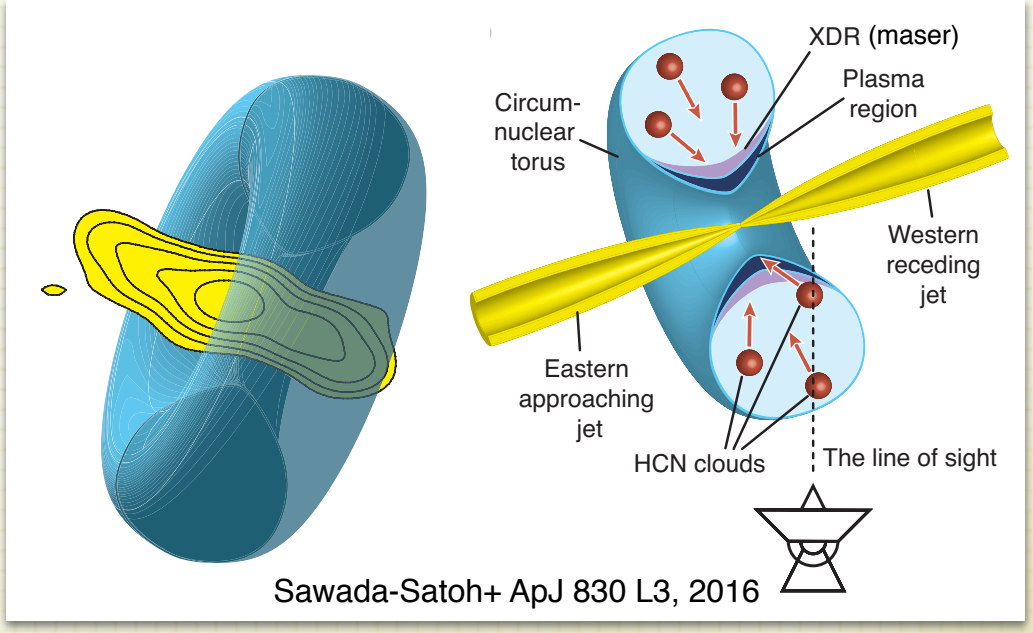
- The first VLBI map of HCN (1-0) (Sawada-Satoh+ ApJ 830 L3, 2016)
  - Two redshifted features, detected.
  - The features around $V_{sys}$, not detected.
  - Localized on the receding jet side.
  - A depth of >10%, deeper with PdBI



# A possible model

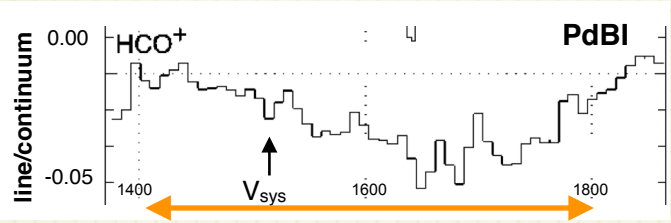
- Several layers + clumpy HCN clouds (Sawada-Satoh+ 2016)
  - High opacity localized on the receding jet => Inclined torus
  - At least two narrow absorptions => Inhomogeneous, clumpy
  - Redshifted velocity => Ongoing infall onto SMBH

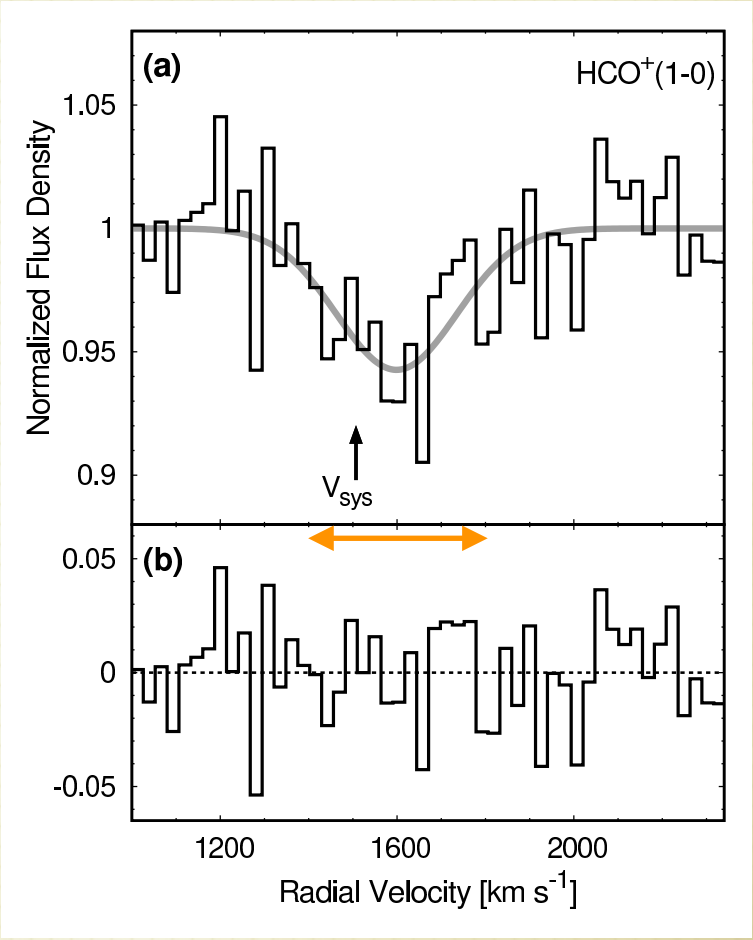


# $HCO^+$ (1-0) absorption with KVN

- The first VLBI detection of $HCO^+$ (1-0) absorption line

Sawada-Satoh+ 2018, submitted

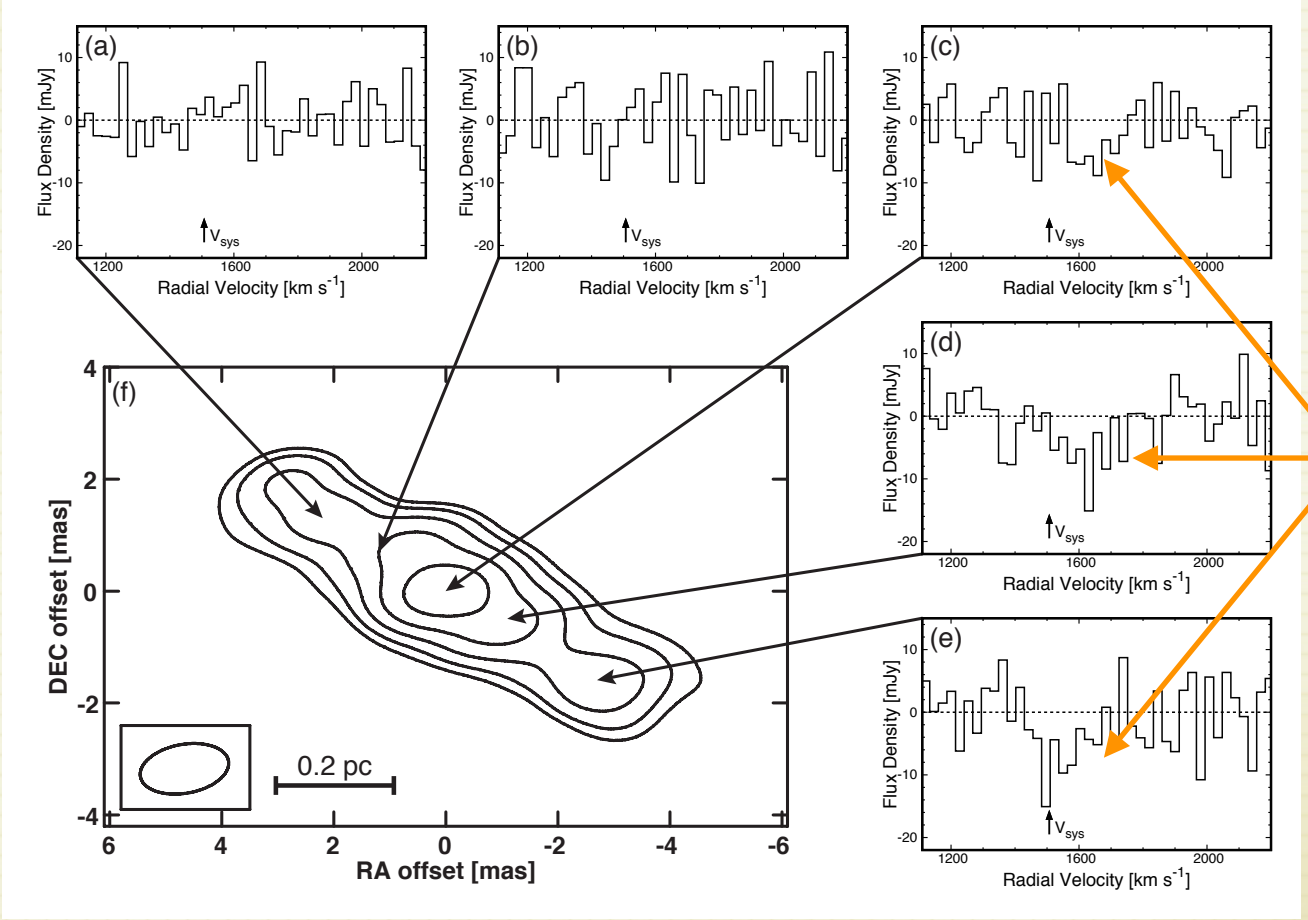



- Broad (~500km/s) ! unlike HCN
  - Slightly asymmetric with a blueshifted wing
- A gaussian fit :
  - FWHM : 272+-25km/s
  - maximum depth : 0.06

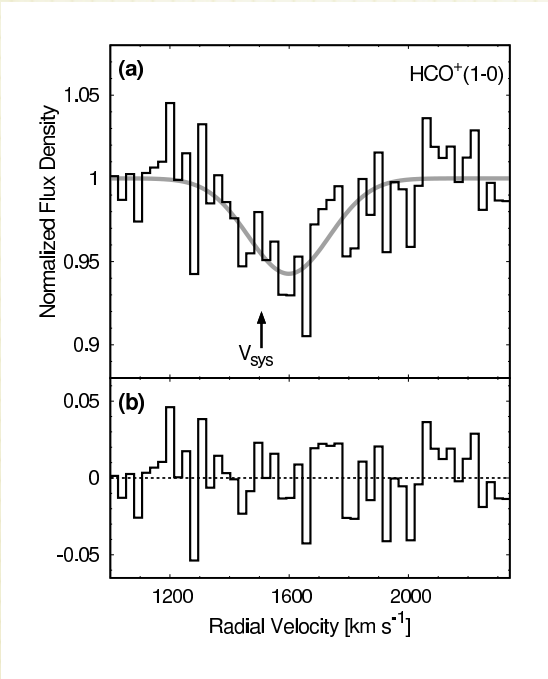
# HCO+ (1-0) absorption with KVN

- Spectra of $HCO^+$ (1-0) absorption at different locations

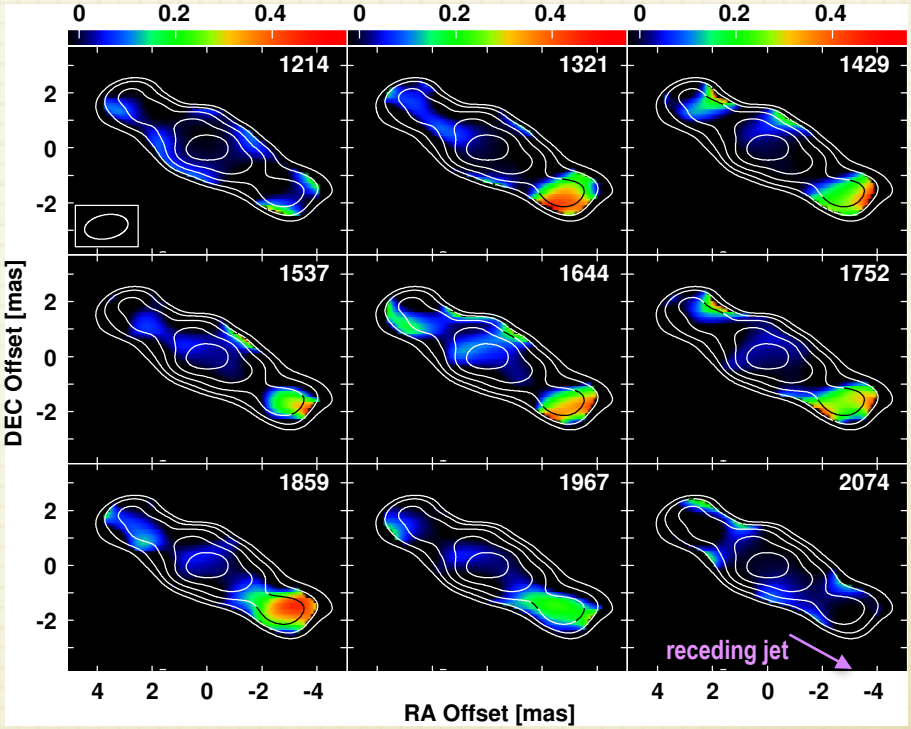


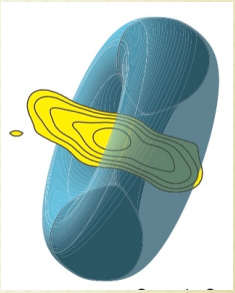
# HCO+ (1-0) absorption with KVN

- Channel maps of HCO+ absorption
  - Located on the receding jet side => support the torus model



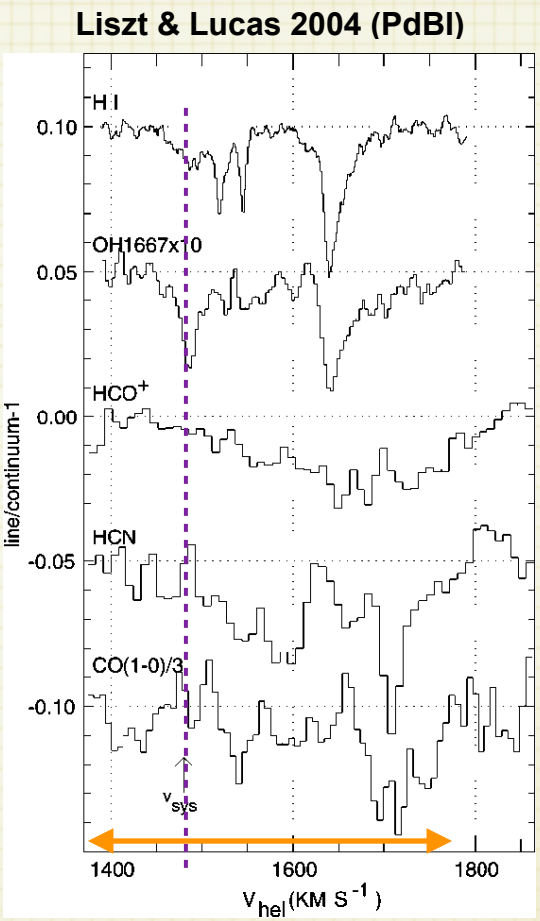

Contour: 88GHz continuum
Color: Optical depth of $HCO^+$ absorption

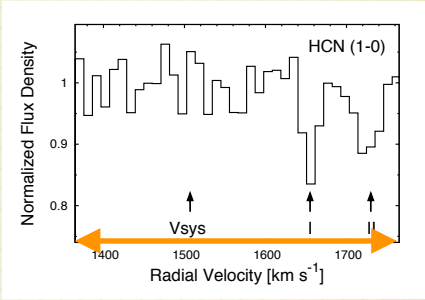


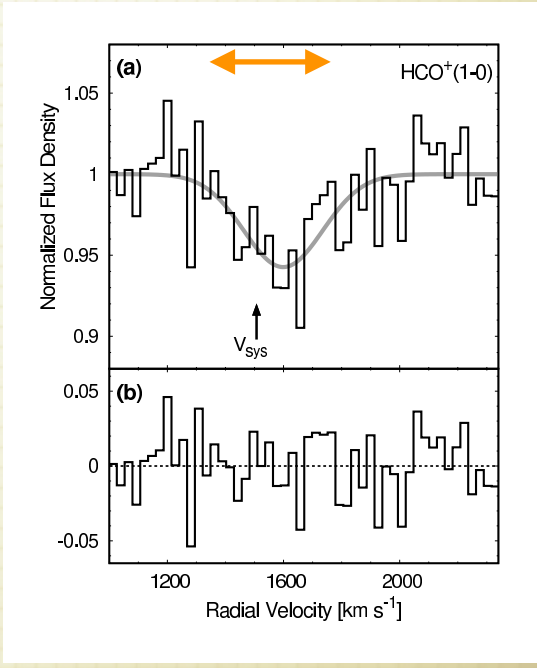



# What the $HCO^+$ spectrum tells

- Redshifted from $V_{sys}$
  - Ongoing infall
  - Same as HCN, OH, $H_2O$
- Broad width
  - Not thermal broadening
  - A complex of several clumps or structures with various difference velocities
  - Infall + turbulence + interaction + etc.



# Physical properties from HCN

**Column density of HCN 1-0 absorption**

Sawada-Satoh+ ApJ 830 L3, 2016

| Label | $V_p$ [km/s] | $V_p$-$V_{sys}$ [km/s] | $\Delta v$ [km/s] | $N_{HCN}$(T=100K) [$10^{14}$ cm$^{-2}$] | $N_{HCN}$(T=230K) [$10^{14}$ cm$^{-2}$] |
|---|---|---|---|---|---|
| I | 1656 | 149 | 31.7 | 9.5 | 50 |
| II | 1719 | 212 | 52.9 | 20 | 101 |

- $N(H_2)$ : $10^{24}$-$10^{25}$ cm$^{-2}$ (HCN/$H_2$ ratio of $10^{-9}$; Smith & Wardle 14)
  - 1-2 order higher than N(e) by FFA opacity (~$10^{23}$; Kameno+ 01)
- Infall rate : ~0.05-0.5 $M_{sun}$/yr $\dot{M} = f_v R_{\rm in} N_{\rm H} m_{\rm H} V_{\rm in} \Omega$
  - Comparable to the rate estimated from X-ray luminosities (~0.04 ; Wu & Cao 06)

# Physical properties from $HCO^+$

**Column density of $HCO^+$ 1-0 absorption**

Sawada-Satoh+ 2018, submitted

| HCO+ | $V_p$ [km/s] | $V_p$-$V_{sys}$ [km/s] | $\Delta v$ [km/s] | $N_{HCN}$(T=100K) [$10^{14}$ $cm^{-2}$] | $N_{HCN}$(T=230K) [$10^{14}$ $cm^{-2}$] |
|---|---|---|---|---|---|
| | 1658 | 151 | 272 | 8.8 | 46 |

- $N(H_2)$ : $10^{24}$-$10^{25}$ $cm^{-2}$ ($HCO^+/H_2$ ratio of 2-3x$10^{-9}$; Liszt & Lucas 00)
  - Consistent with $N(H_2)$ estimated from the HCN absorption.
- The column density ratio between HCN & $HCO^+$ integrated over frequency : ~3.3
  - $R_{HCN/HCO+}$ (~2.5) in CND knots of NGC1068 (García-Burillo+ 14)
  - $R_{HCN/HCO+}$ (~2.0) in AGN of NGC1097 (Izumi+ 13)
  - Note that the background jet component can move with an apparent velocity of 0.26*c* (Vermeulen+ 03)

**0.18 pc (almost 1 beamsize) during 27 months !**

# Summary

- Conducted KVN observations of the HCN(1-0) & $HCO^+$(1-0) absorption in NGC 1052.
- Our HCN results are naturally explained by an AGN torus
  - Two HCN absorption features are identified at redshifted velocities.
  - Reached a depth of >10%, deeper than that of PdBI.
  - Found N($H_2$) of $10^{24}$--$10^{25}$ $cm^{-2}$ (HCN-to-$H_2$ ratio of $10^9$), assuming a Tex of 100--200 K
  - High opacity of HCN absorption localized on the receding jet
  - HCN gas is clumpy, and traces ongoing infall onto SMBH.
- The first VLBI detection of $HCO^+$(1-0) absorption
  - A broad absorption feature (~500km/s). Infall + turbalence ?
  - Localised on the receding jet side.  Torus ?