

Highlights of ALMA discoveries in Active Galactic Nuclei

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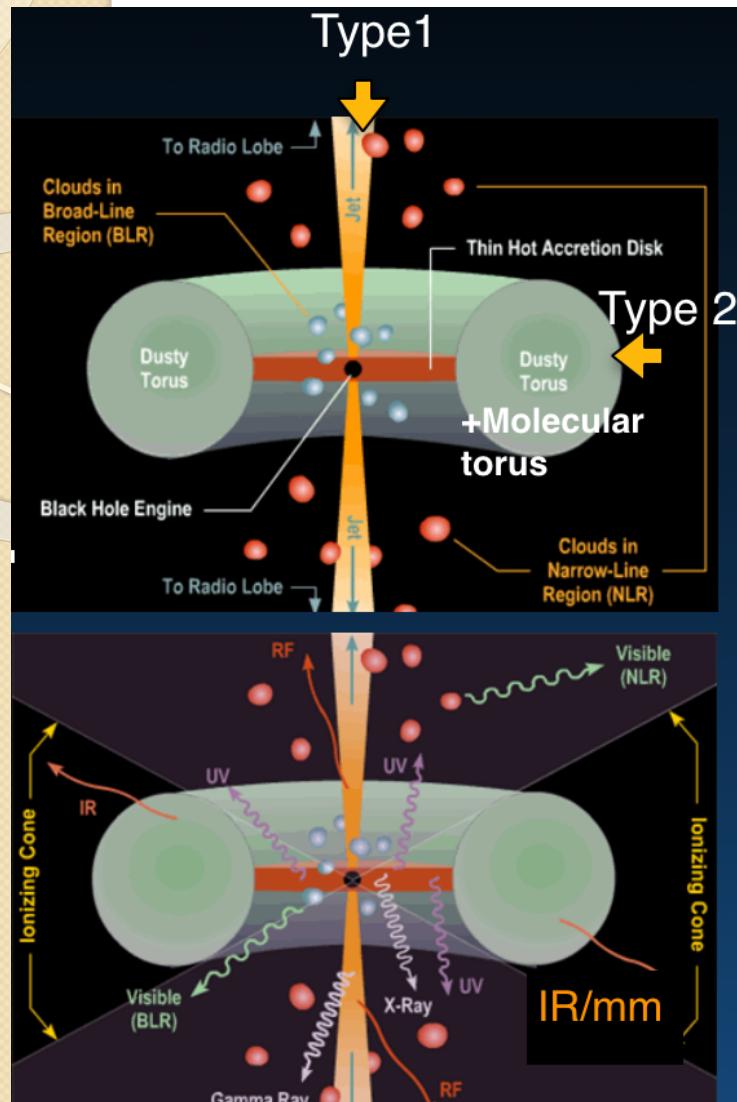


Credit: NRAO/AUI/NSF; D. Berry / Skyworks

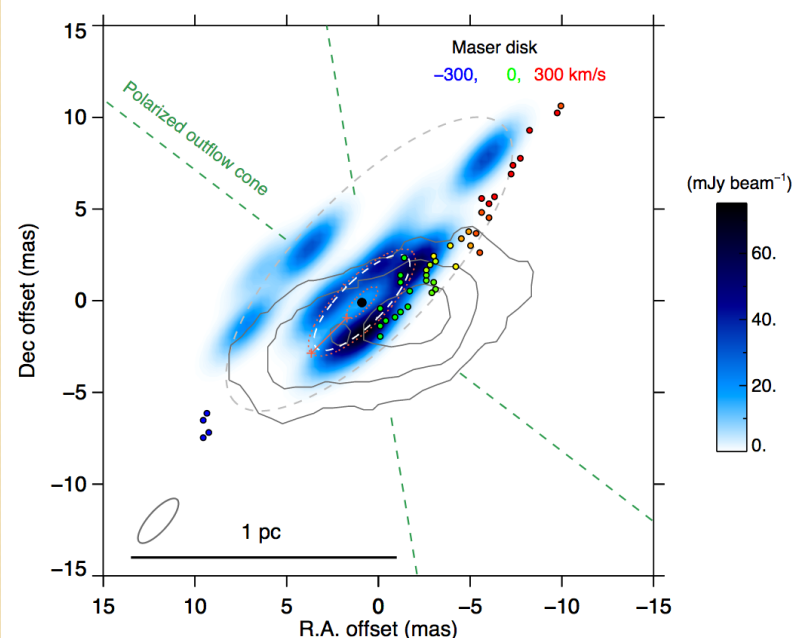
INTRODUCTION

Unified Model for AGN: Antonucci & Miller 1985

- AGN diversity due to nuclear obscuration by dusty/molecular **pc-scale** torus
- AGN tori:
 - absorb UV/optical radiation—>IR
 - contribute to X-ray absorption+reflection



GRAVITY collab, Pfuhl+2019
NGC 1068: VLT NIR K band



- NIR/MIR interferometry (0.05''-0.1'') data

- 1) ~**pc-scale** torus
- 2) >**10-to-a few 10 pc-scale** polar dust

- Few baselines: limited (u,v)-coverage !
- No 'direct' imaging !

The ALMA view of molecular tori in AGN

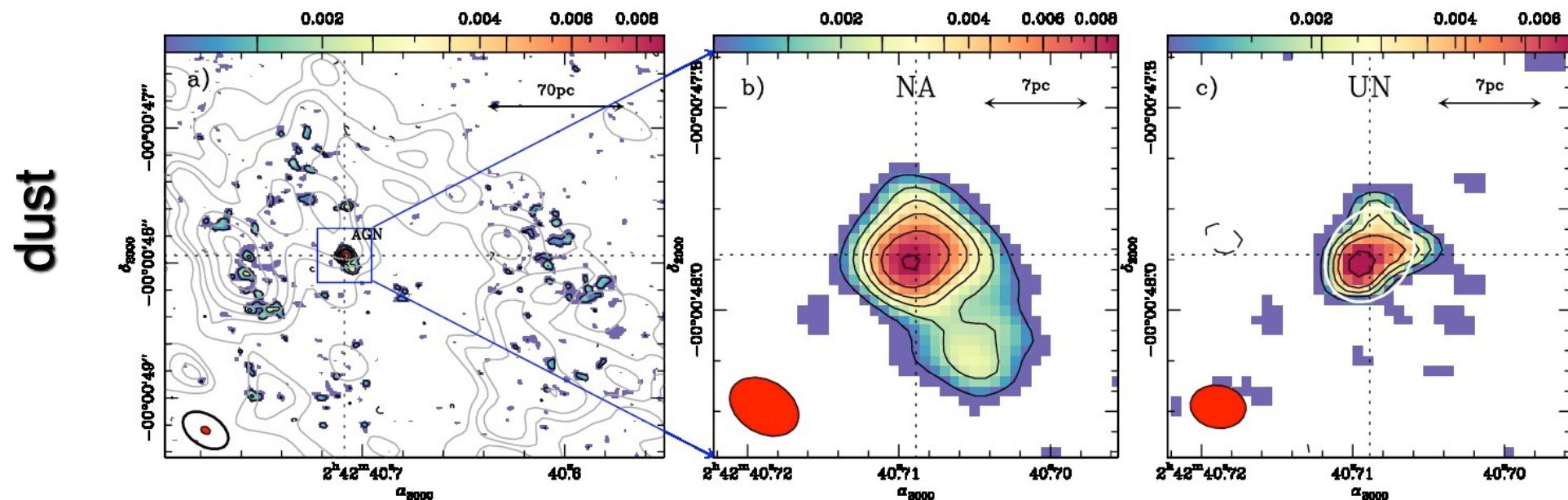
- ALMA can **image directly** dusty/molecular tori in nearby AGN with spatial resolutions of \sim **a few pc** using several frequency bands
- ALMA sensitive to **cold** dust/gas and to wide range of $n(\text{H}_2)$: 10^3 - 10^7 cm^{-3}
- ALMA to probe **internal dynamics** of molecular tori
 - Stationary/rotating doughnut (*Krolik & Begelman+88*) ?
 - Outflowing torus (disk-wind) (*Elitzur & Shlosman+06*) ?
- ALMA can map **connection of torus** with the host: isolated? /inflow?/outflow?

 **Key to understanding the feeding/feedback cycle of gas**

ALMA resolves NGC1068 torus

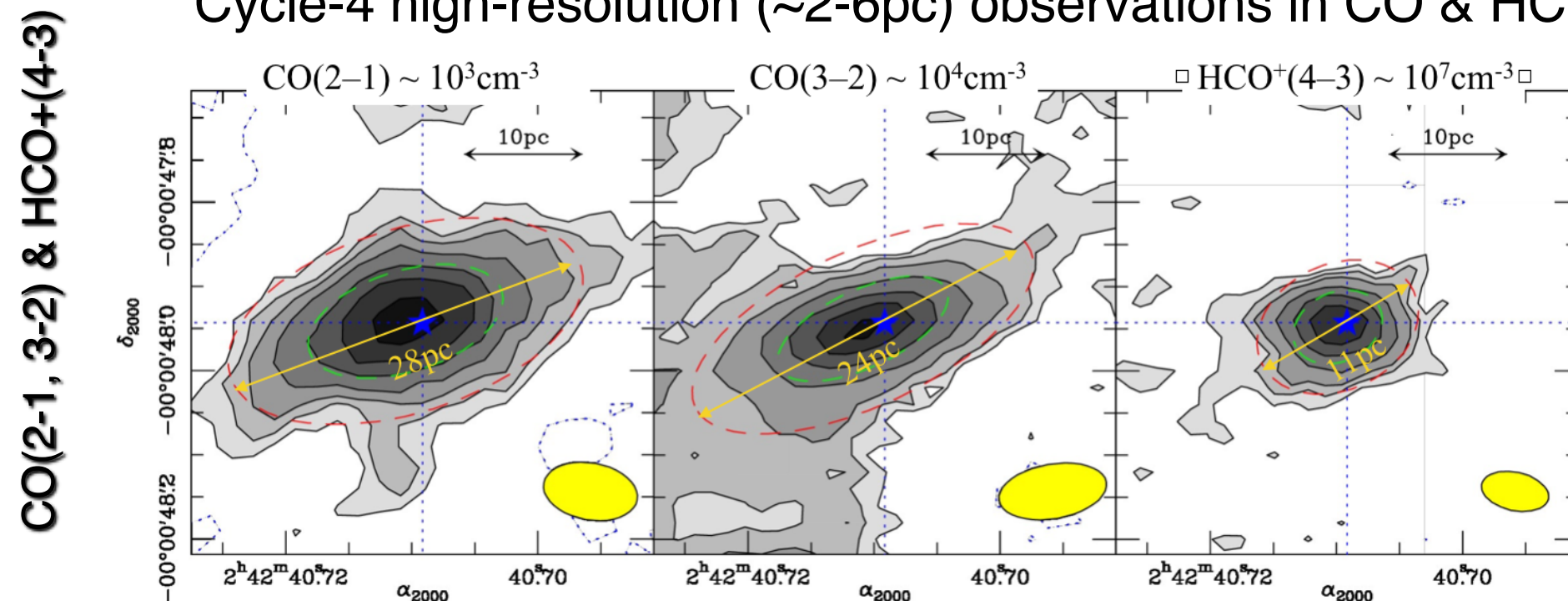
García-Burillo+2016

Cycle-2 observations with resolution: $0.07'' \times 0.05''$ ($\sim 4\text{pc}$)
Dust emission ($432\ \mu\text{m}$) from a $\sim 7\text{pc}$ -diameter 'torus'



García-Burillo+2019

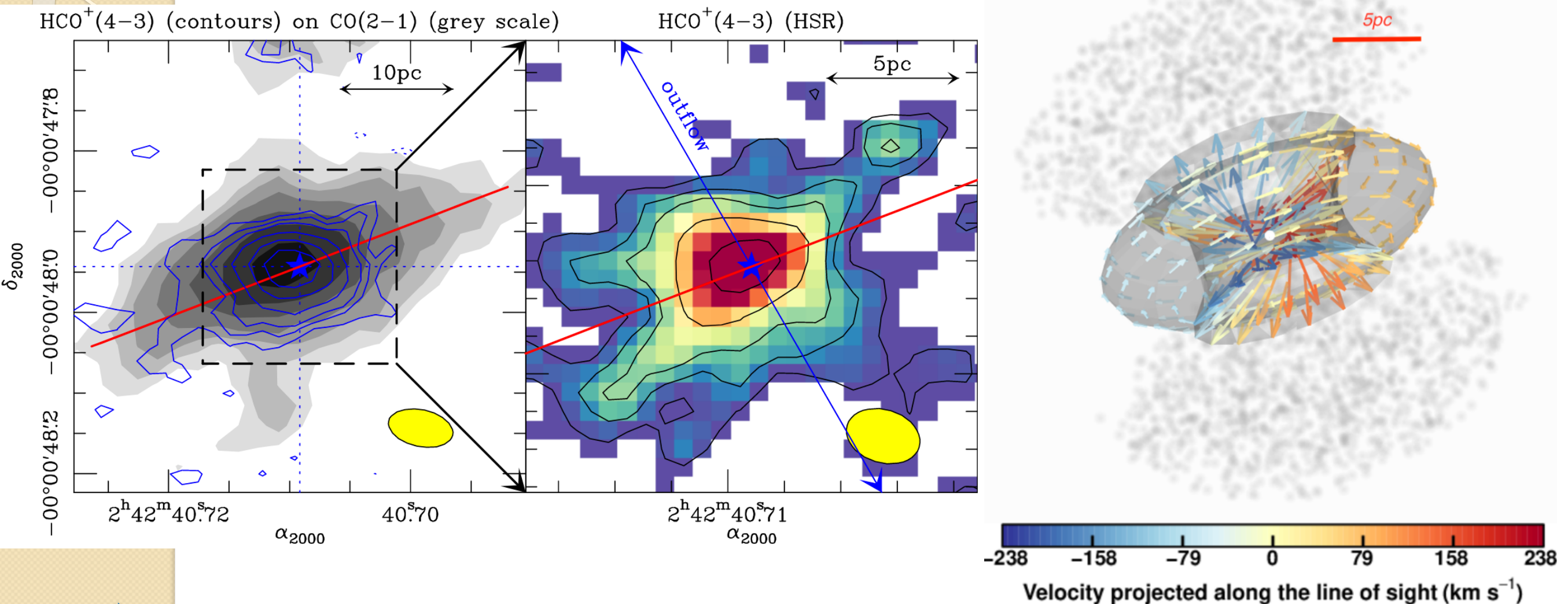
Cycle-4 high-resolution ($\sim 2\text{-}6\text{pc}$) observations in CO & HCO⁺ lines



➡ A big ($\sim 11\text{-}28\text{ pc}$ -diameter) molecular torus with **density radial stratification**

The NGC1068 outflowing torus

García-Burillo+2019

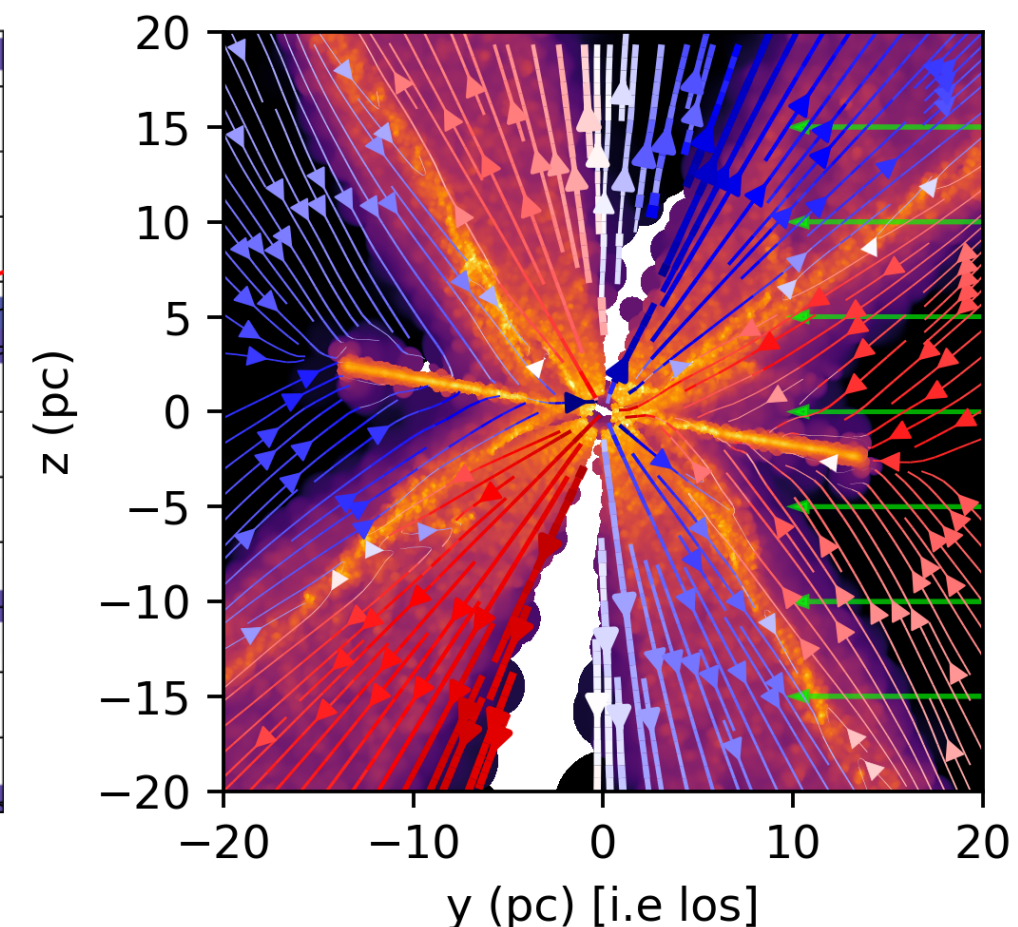
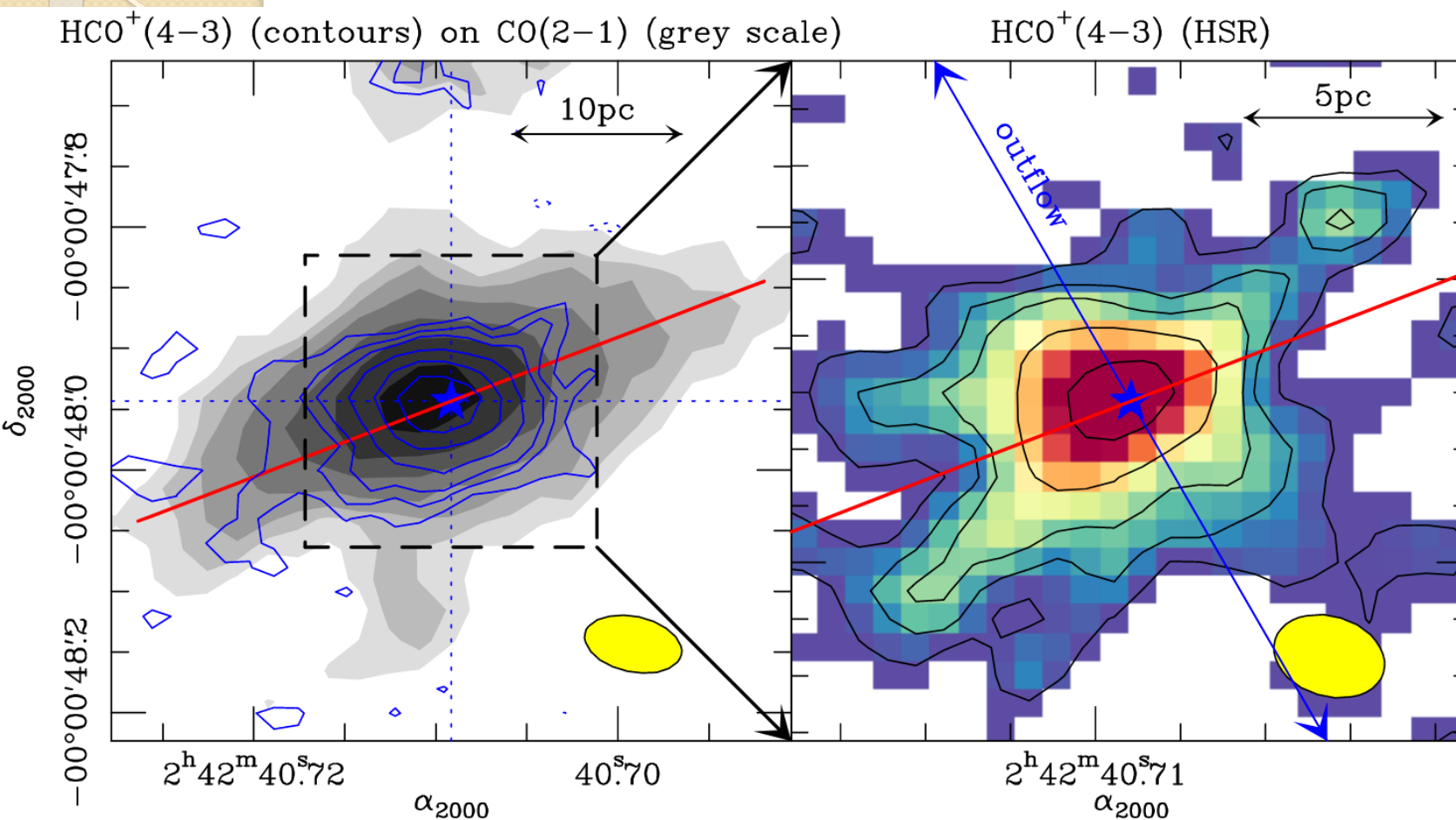


→ Torus dynamically perturbed: **rotation & outflow** driven by interaction with AGN wind

The NGC1068 outflowing torus

García-Burillo+2019

Williamson+2020



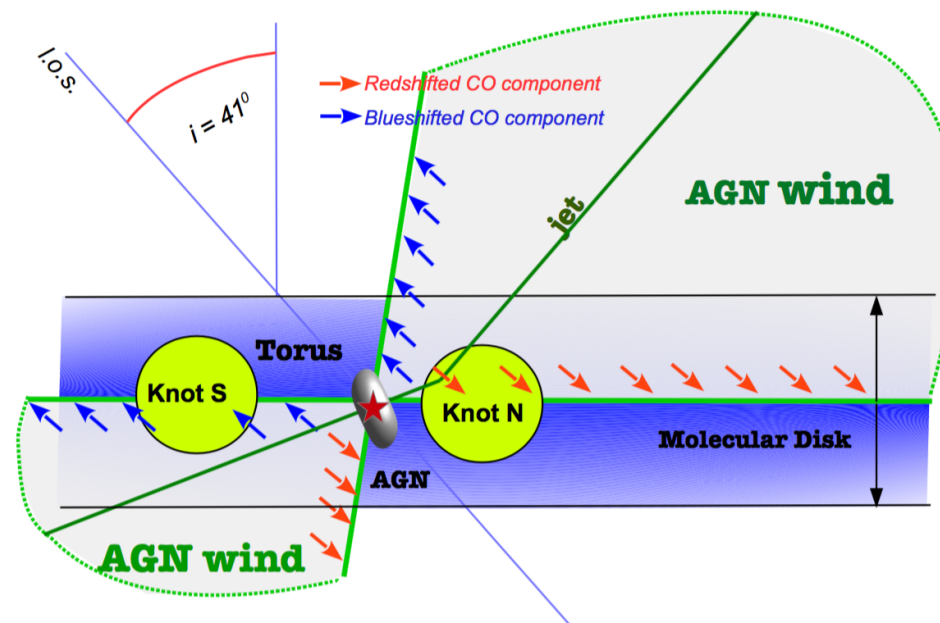
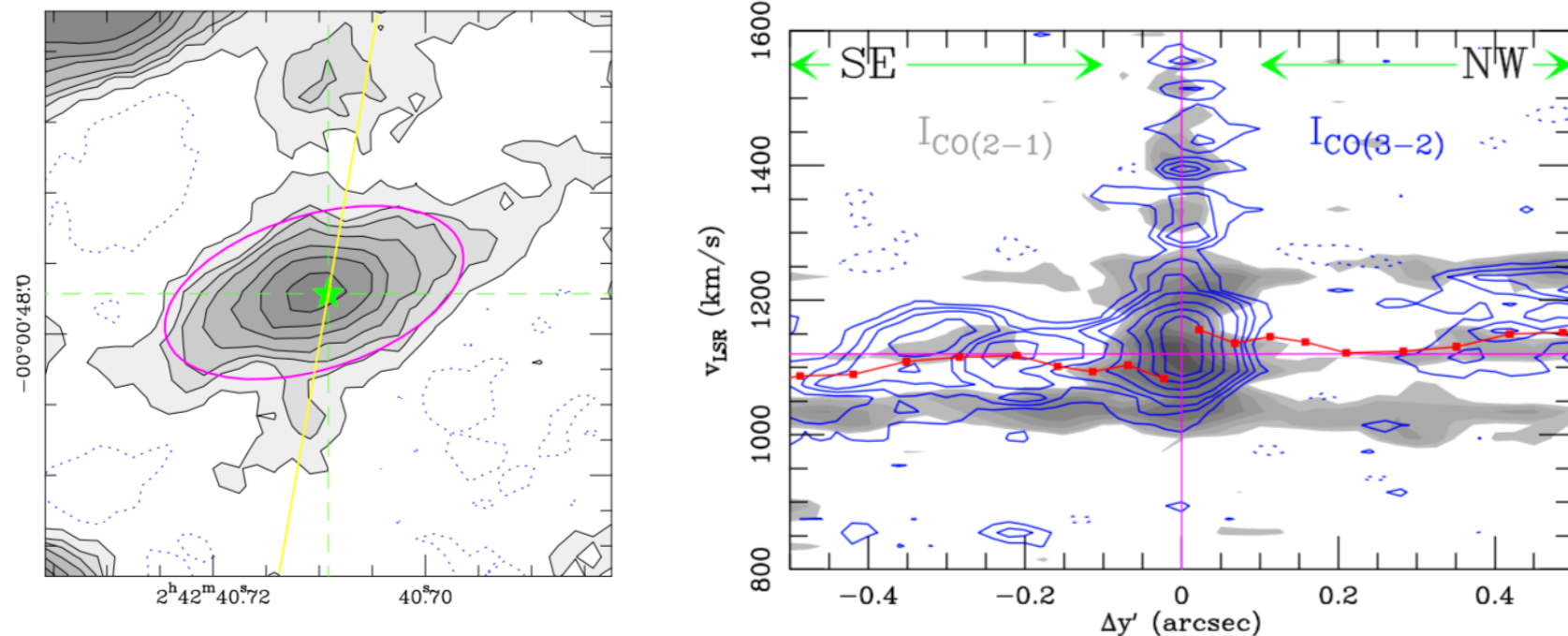
- ➡ Torus dynamically perturbed: **rotation & outflow** driven by interaction with AGN wind
- ➡ Similar to outflowing torus imaged by ALMA in NGC5643 (Alonso-Herrero+2018) and NGC1377 (Aalto+2017, +2017, + 2020)
- ➡ In line with predictions of simulations of radiation-driven dusty/molecular outflowing tori
- ➡ AGN **feedback** helps to regulate the **feeding** in the torus

The torus-host connection in NGC1068

García-Burillo+2019



Torus **connected** to Circumnuclear Disk (CND) by **outflowing gas lanes**



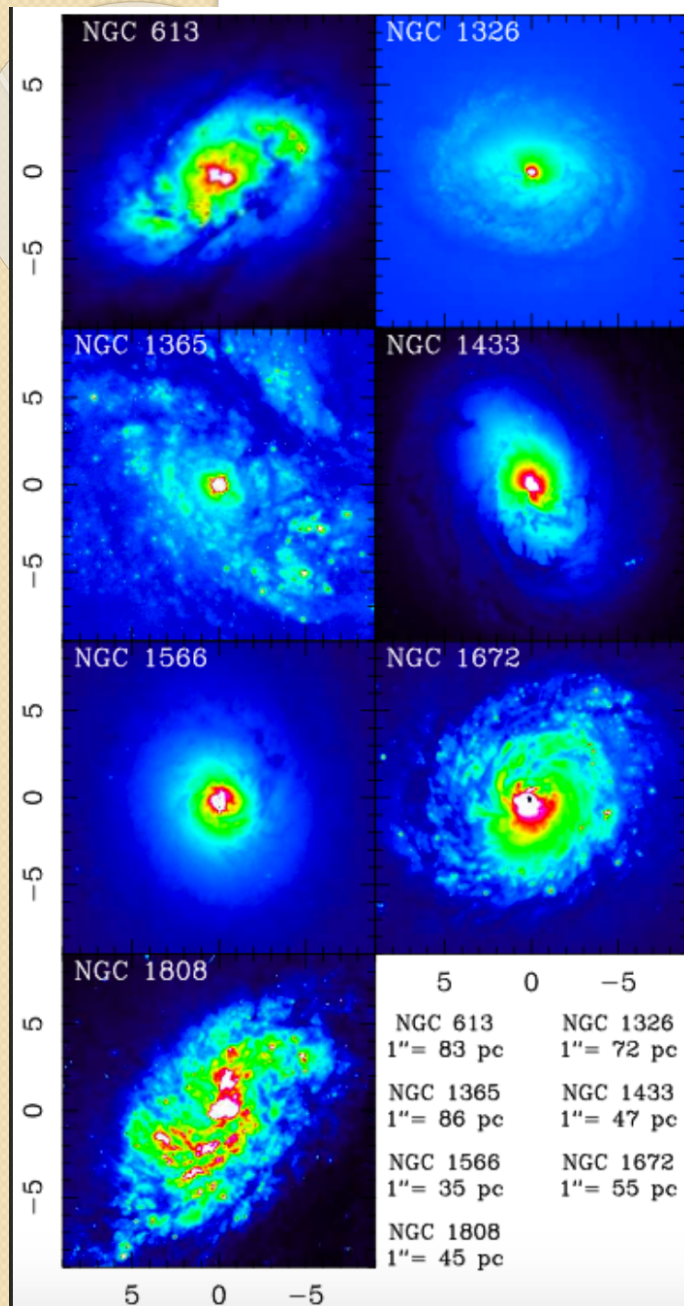
- ➡ A **large-scale molecular outflow** in the torus + CND ($r < 200\text{pc}$) driven by AGN wind
- ➡ ALMA reveals the footprint of AGN feedback on a wide range of spatial scales

ALMA Survey of Low-L AGN: NUGA

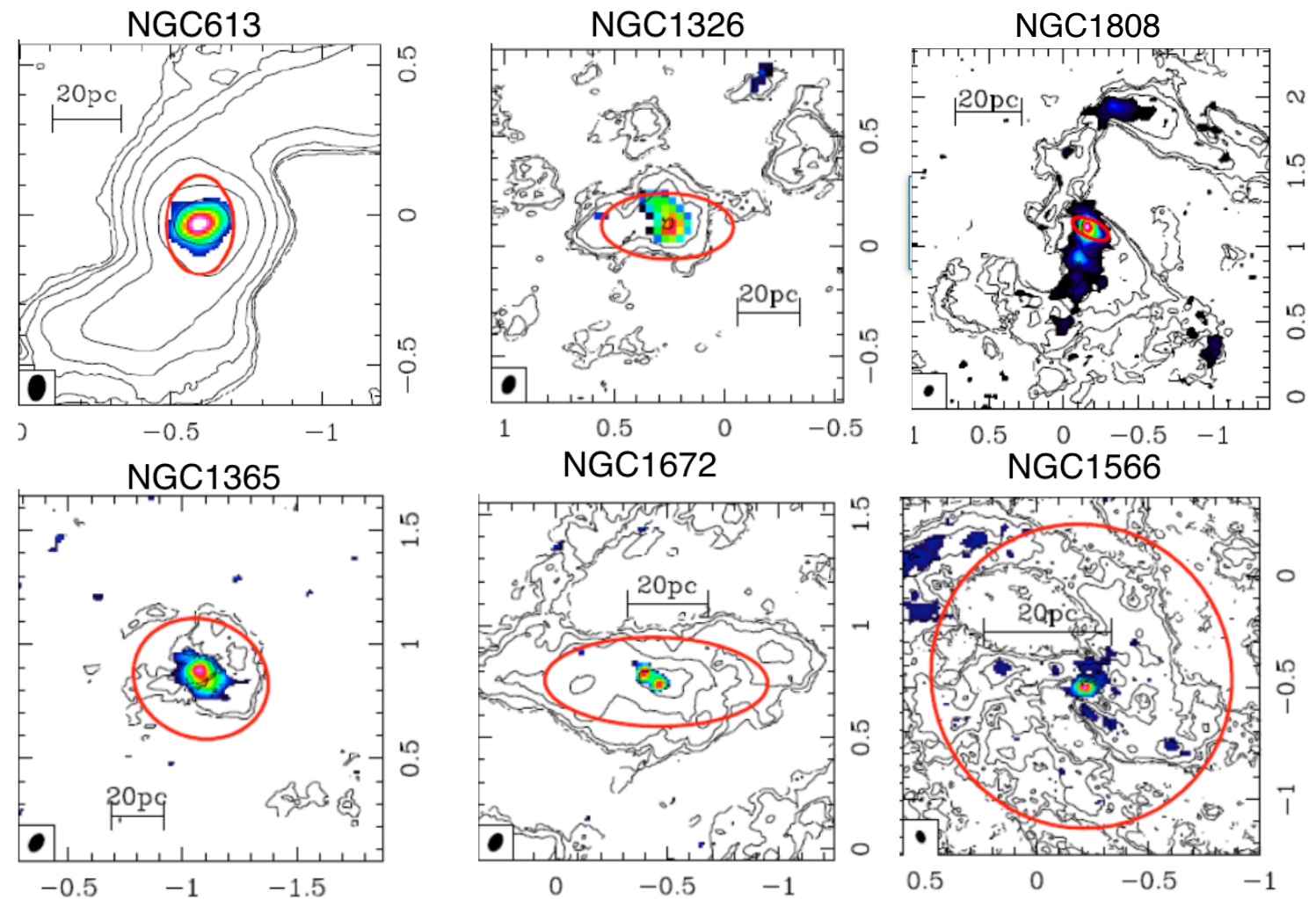
ALMA CO + continuum survey of 7 LLAGN at 4pc resolution (*F.Combes, SGB et al*)

- Imaging AGN disk structures ('tori') on scales \sim a few-100 pc
- Mapping inflow/outflow components in central \sim 1 kpc region

Results: **Combes+19, Audibert+19**



Color: 850 μ m continuum.
Contours: CO(3-2)



- ➔ Molecular tori and AGN-continuum detected in 6 out of the 7 NUGA targets
- ➔ Large sizes + masses: $D \sim 10$ - to- 50 of pc, $M_{\text{gas}} \sim$ up to $>10^6$ - $7 M_{\text{sun}}$
- ➔ Molecular **tori** generally **tilted relative to the hosts**: random orientation

Challenges

❖ **#1:** From single-object studies to representative/complete samples of nearby Seyfert galaxies

- morphologies and kinematics of AGN tori
- properties vs AGN class, luminosity, Eddington ratio, absorption

❖ **#2:** Moving to high luminosities

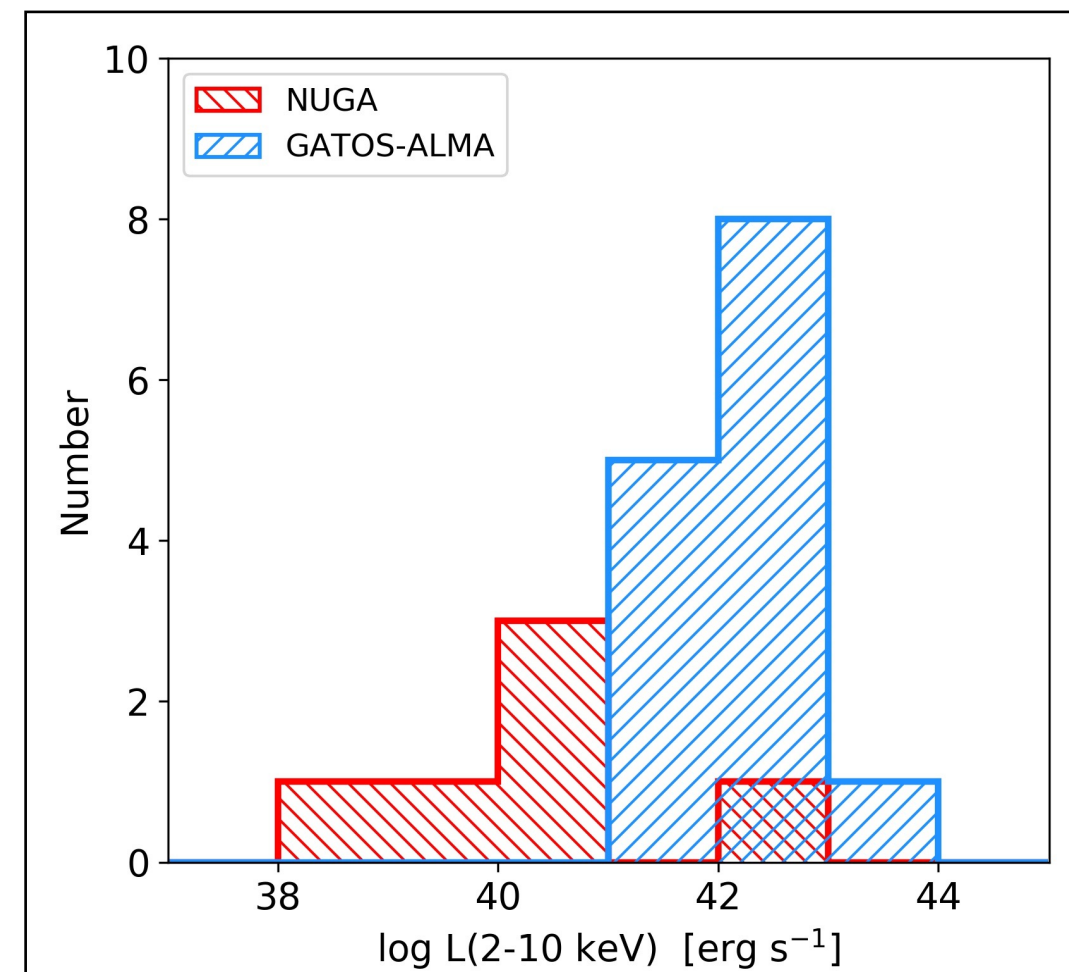
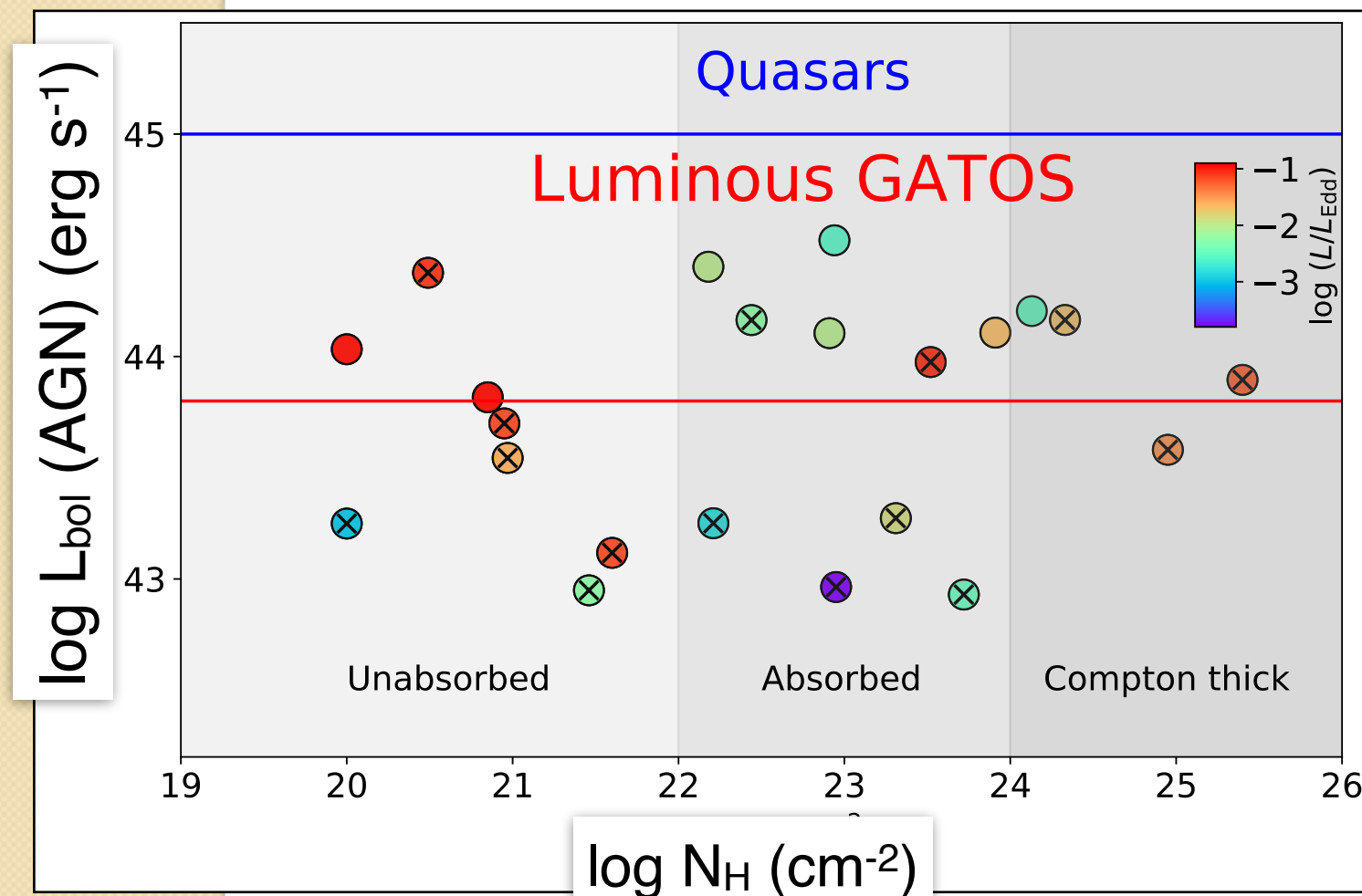
- few studies of nearby QSO mostly associated with ULIRGs
- QSO are more distant than Seyferts and torus not resolved
- connection with the host galaxy - molecular/ionized outflows and circumnuclear star formation activity

❖ **#3:** Torus models

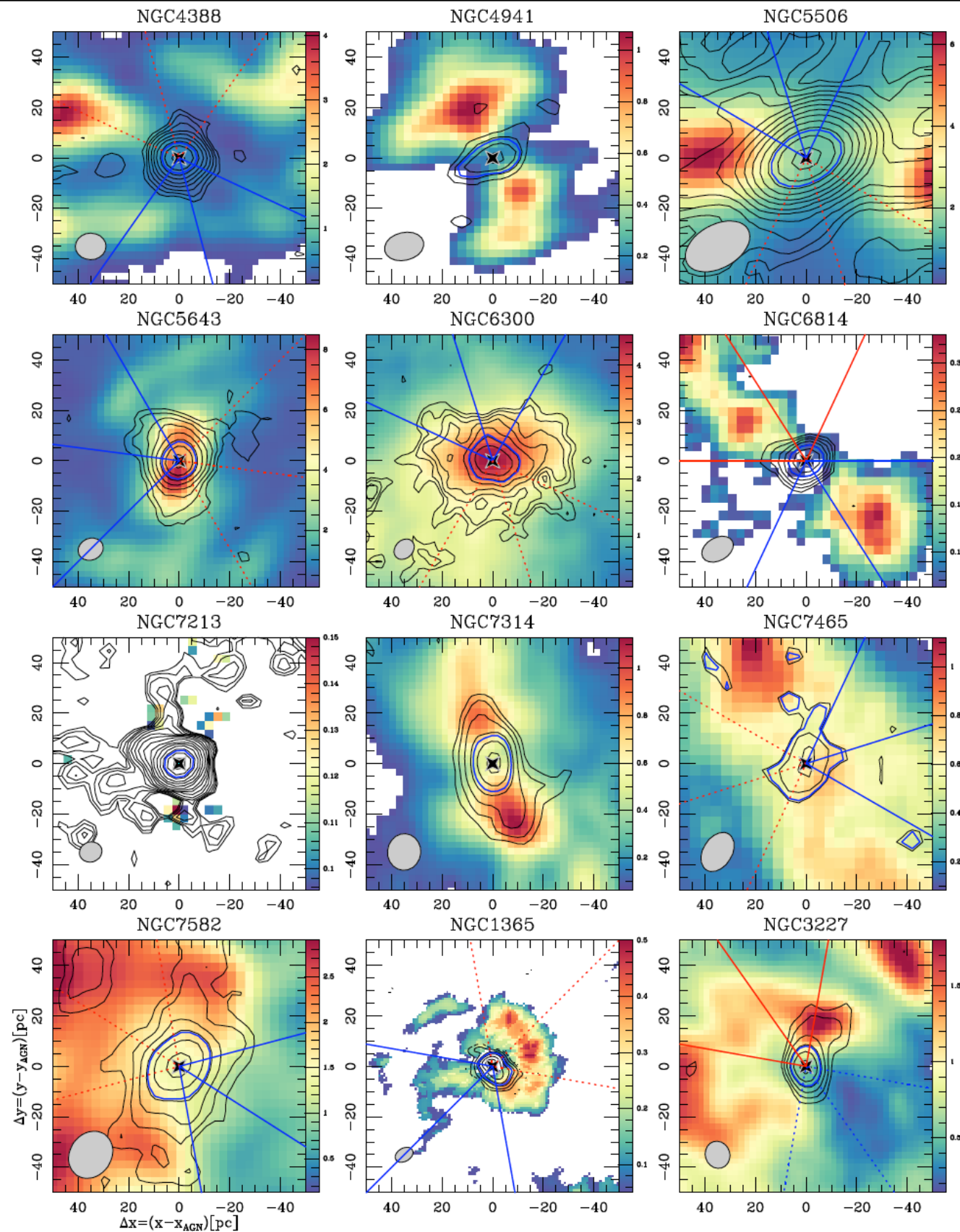
- comparison with observations
- refinement of models for application to intermediate and high-z AGN (torus unresolved)

GATOS Survey

- ✧ Volume-limited sample (distances $< 40\text{Mpc}$) of Seyfert galaxies selected in **ultra-hard X-rays (14-195keV)** from the all-sky Swift/BAT catalog
- ✧ Range of AGN luminosities, column densities and Eddington ratios
- ✧ **ALMA CO(3-2) + 870 μm observations at 7-10pc resolution**
- ✧ NOEMA, optical IFU GTC/MEGARA and VLT/MUSE and future JWST

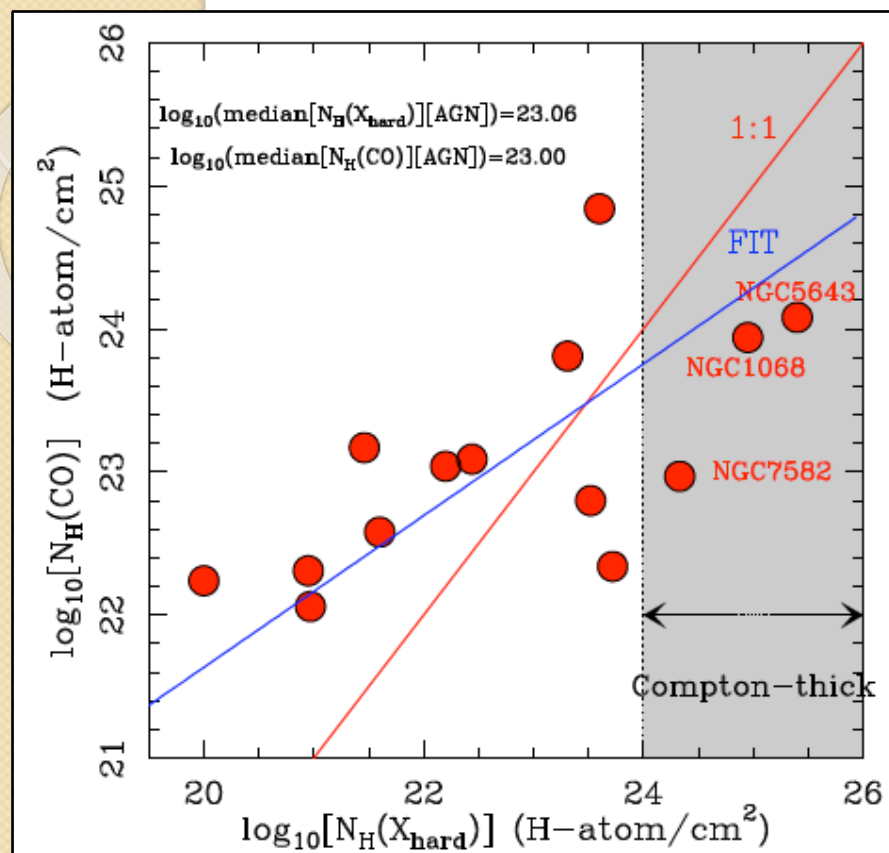


Tori in GATOS Survey

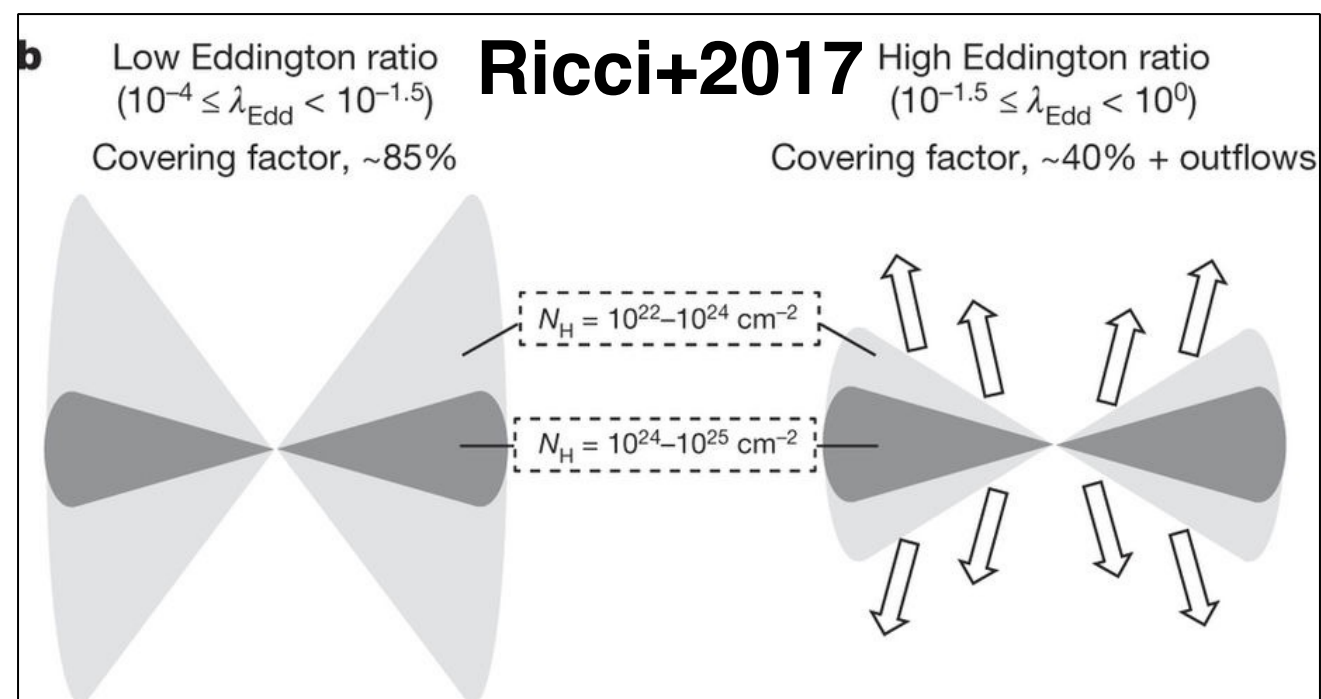
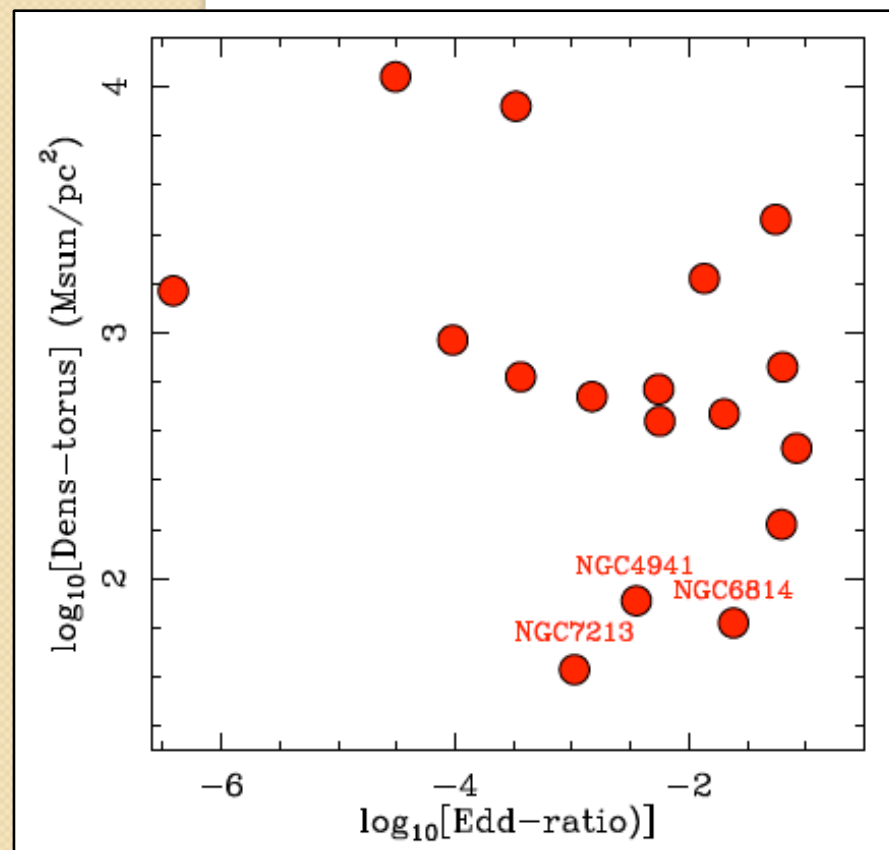


- ❖ CO(3-2) emission (in color) is detected at and around the AGN on scales $r < 50$ pc
- ❖ Continuum at $850\mu\text{m}$ with a bright point source (prob. synchrotron emission) + extended emission (cold dust emission)
- ❖ Large tori with diameters 20-100 pc and masses 10^5 - $10^7 M_\odot$
- ❖ In most cases dusty/molecular tori connected with host galaxy but kinematically & morphologically decoupled and perpendicular to ionization cones

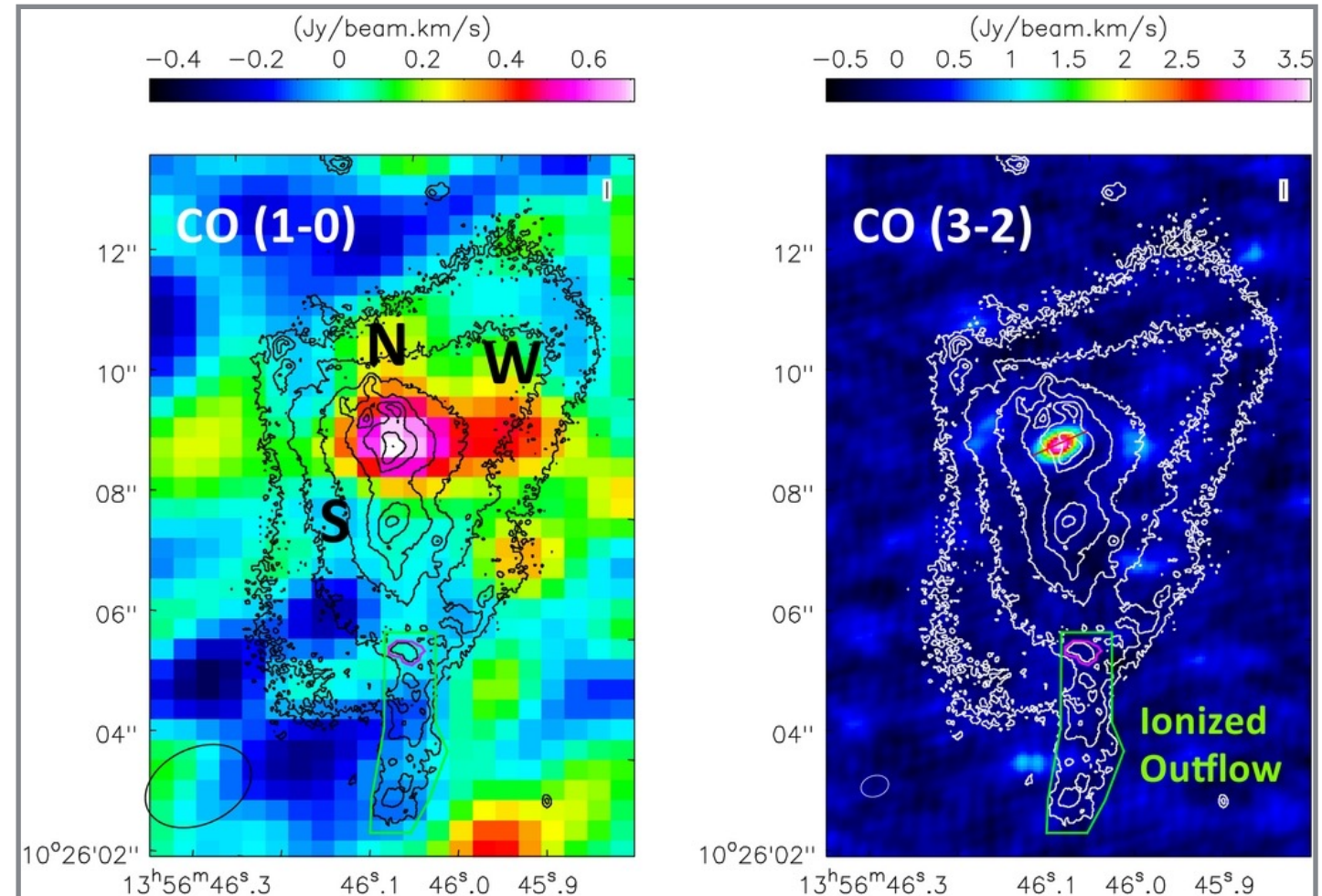
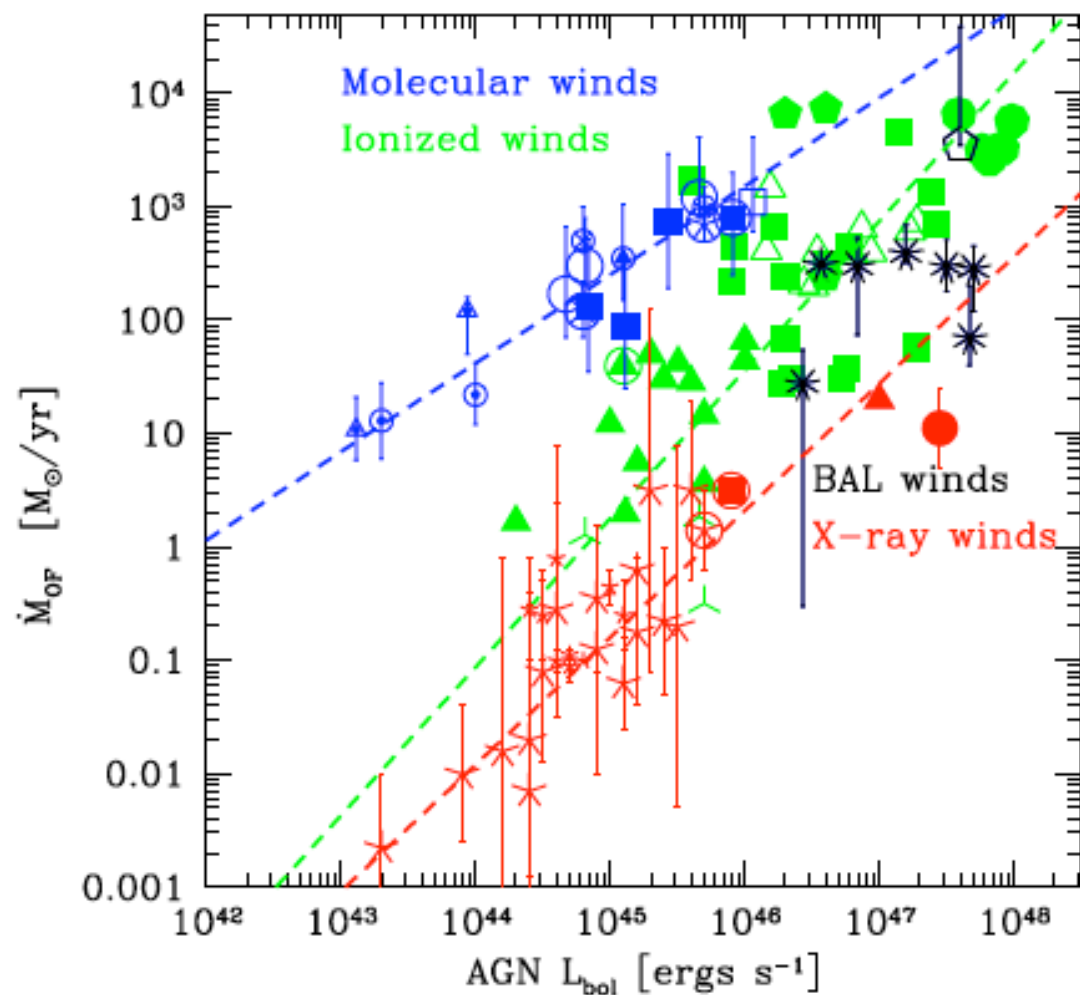
Scaling relations in GATOS Survey



- Column densities derived from CO(3-2) at AGN location correlated with column densities derived from hard X-rays
- ALMA (scales 3 to 10pc) is already resolving the bulk of the absorbing material around the SMBH
- Decreasing molecular gas surface densities at higher Eddington ratios



Molecular outflows in luminous AGN



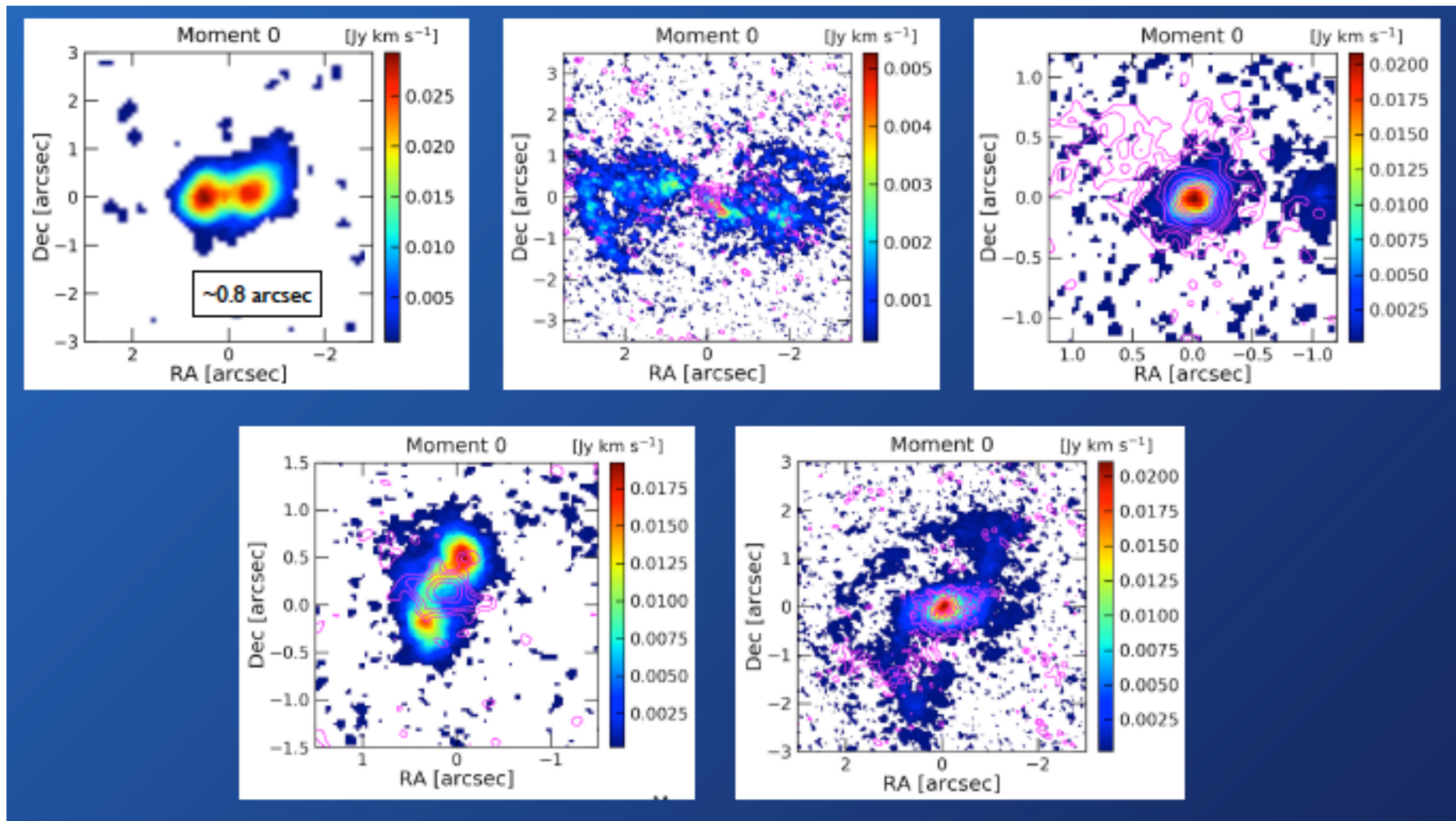
SDSS J1356+1026 (Sun+2014):

Compilation (Fiore+2017):

- ❖ Molecular phase dominates the outflow rate at least out to $L_{\text{AGN}} \sim 10^{45} \text{ erg/s}$ and then comparable to ionized phase

- ❖ QSO/ULIRG at $z=0.1$
- ❖ Large ionized outflow but compact CO(3-2) emission
- ❖ 500km/s outflow detected probably associated to AGN

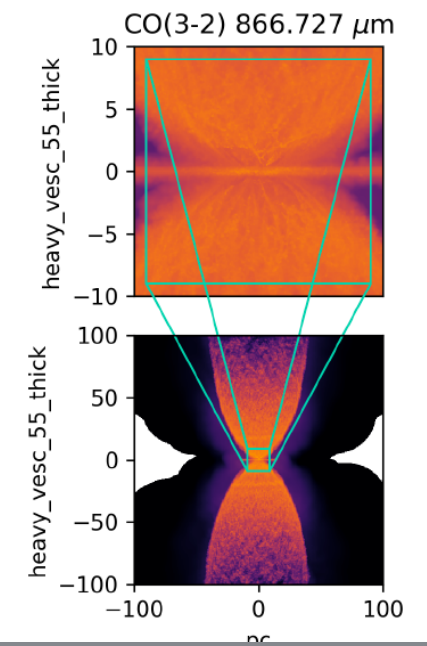
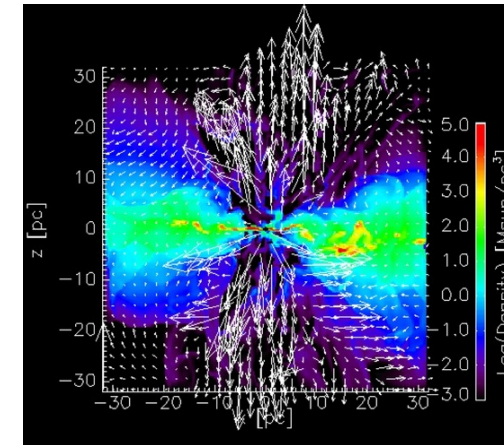
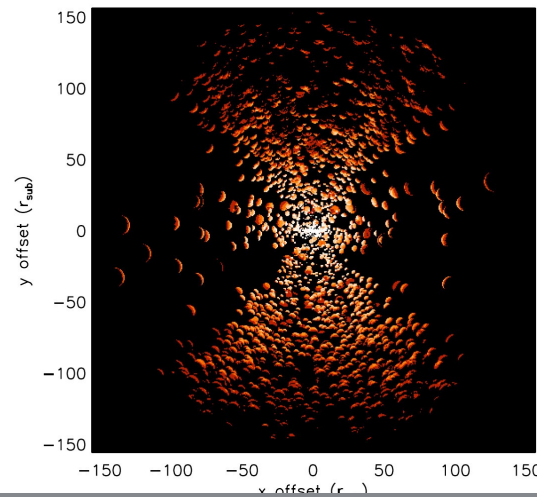
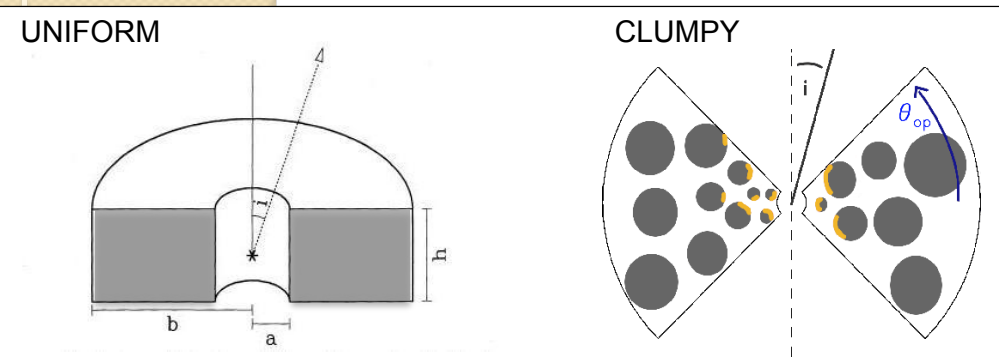
Molecular outflows in luminous AGN



Ramos Almeida +2020 (in prep)

- ❖ Pilot study of 7 QSO 2s with ALMA at 0.2'' resolution (~ 370 pc)
- ❖ 5/7 detected in CO(2-1) with diverse morphologies
- ❖ Non-circular motions detected in all 5 with kinematics consistent with outflows but less extreme than molecular outflows in ULIRGs

Torus models

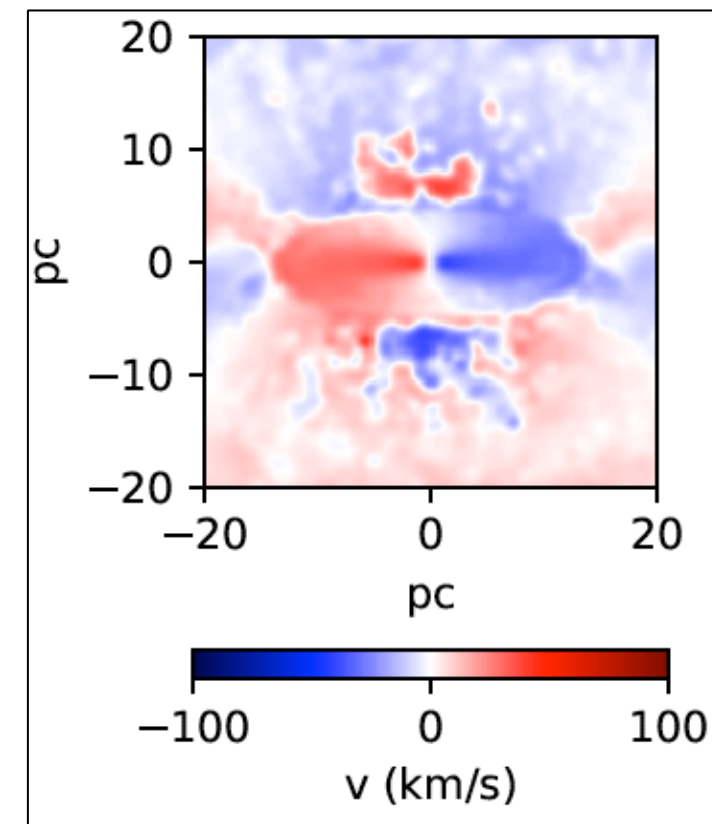


Static torus models: homogenous, **clumpy** (Pier & Krolik 1992, Nenkova+2008, Schartmann+2008)

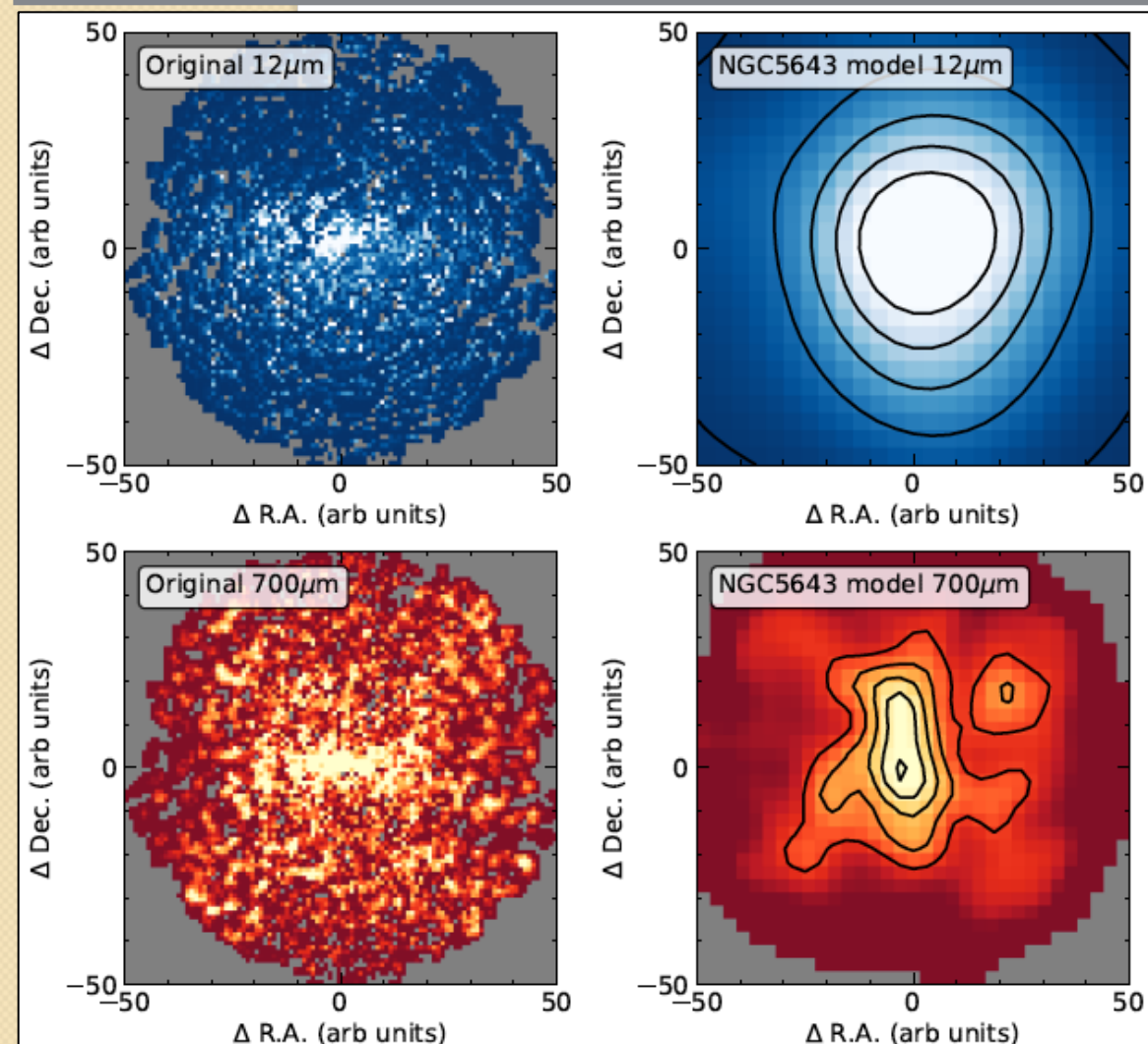
Static disk+wind **models** (Hönig & Kishimoto 2017)

Radiative hydrodynamical **models** (Wada+2012, Williamson+2019, 2020)

Comparison of mid-IR and far-IR morphologies and kinematics with model predictions



Alonso-Herrero
+2020 (in prep)



Summary of ALMA discoveries

- Tori are *surprisingly* large $r=10\text{-}40\text{pc}$, massive $M(\text{H}_2) \sim 10^5\text{-}10^7 M_\odot$ (with some fraction outflowing), and account for the bulk of AGN obscuration
- Tori are perpendicular to ionization cones, morphologically connected to the host galaxy but generally decoupled kinematically
- Molecular outflows in luminous AGN and QSO still to be fully understood



Torus (disk+wind) is the central structure in the gas flow cycle:

- gas is brought in from the host galaxy for SMBH growth: **feeding**
- driven out by the AGN in a wind: **feedback**