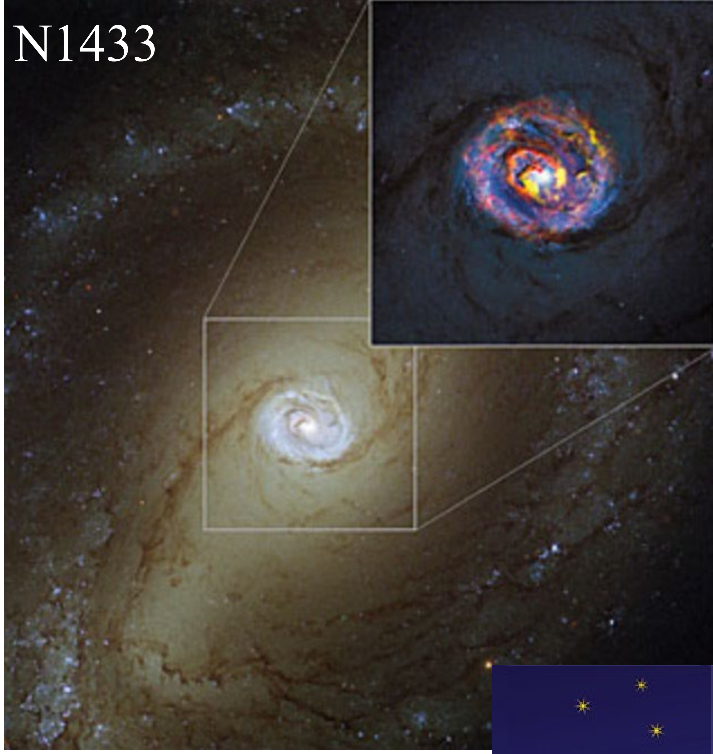
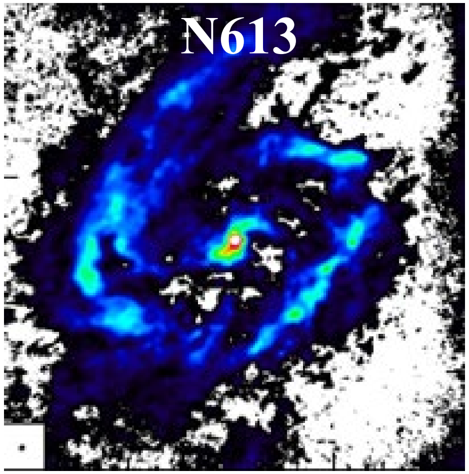
COLLÈGE DE FRANCE 1530

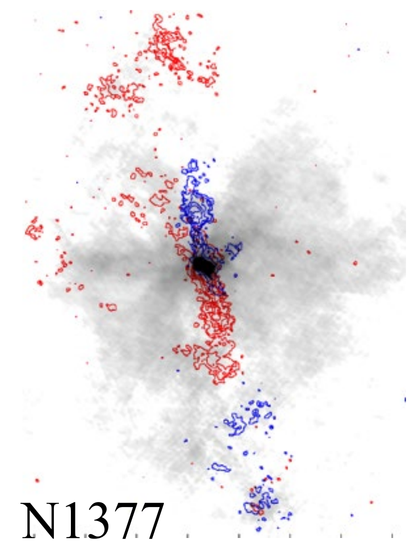



# Galactic Nuclei and GRAVITY+




ALMA

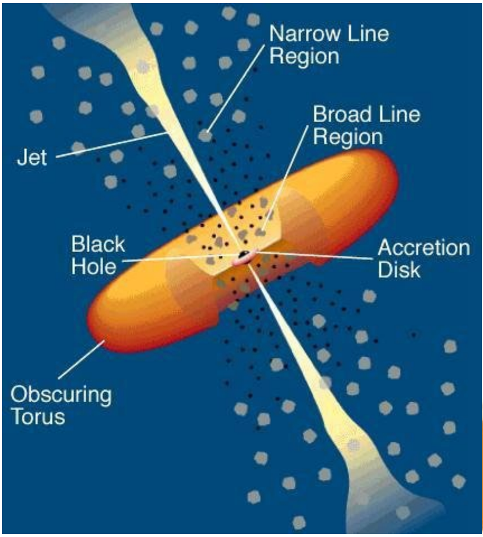
Françoise Combes



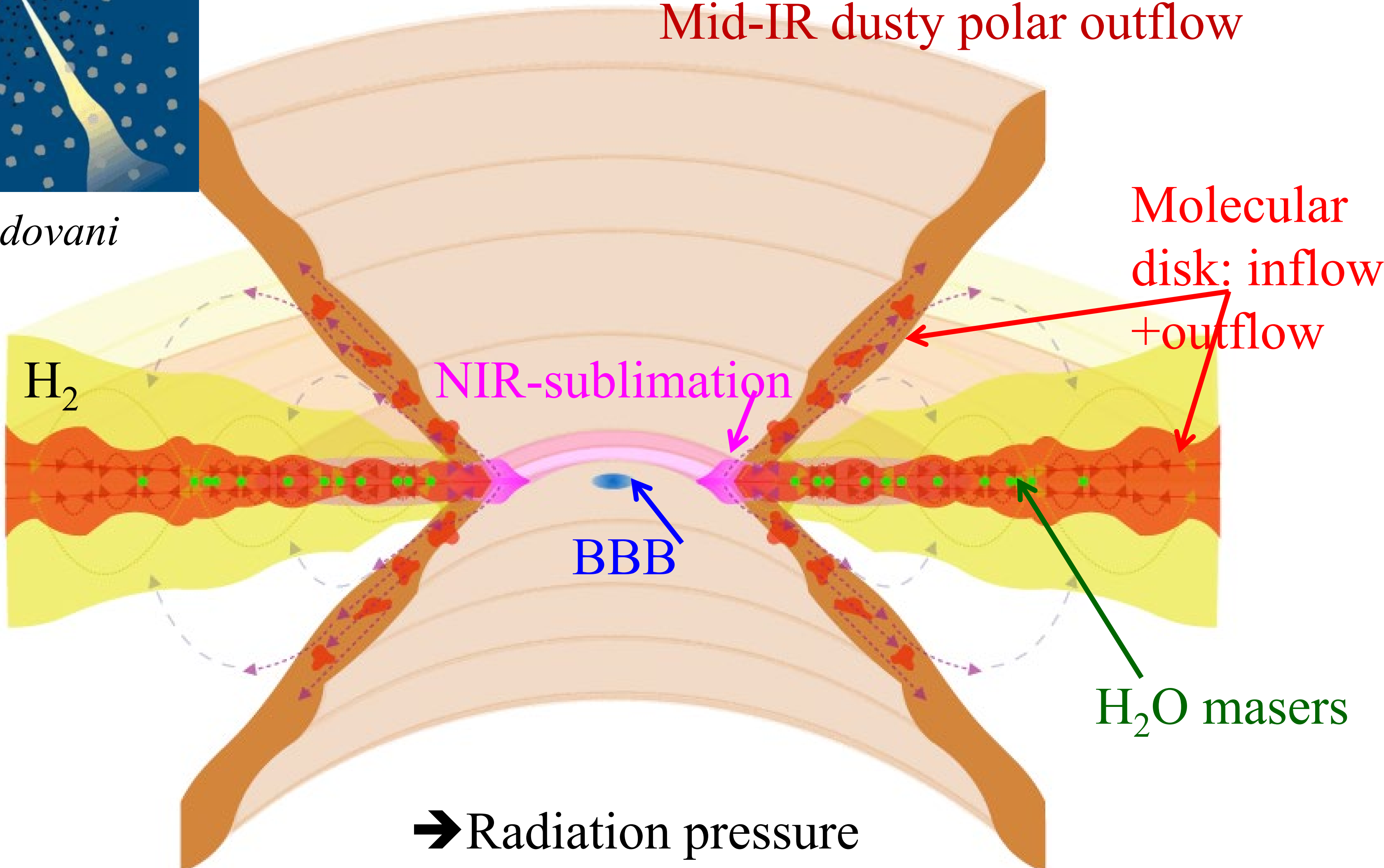

Observatoire de Paris | PSL

# « The dusty torus »
# Types 1 & 2

# Schematic vision: Inflow and outflow

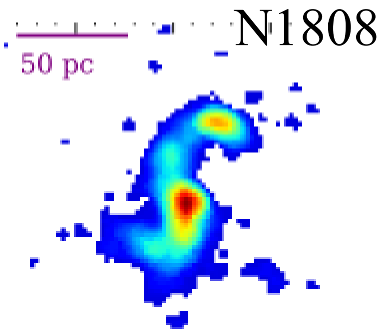



*Urry & Padovani 1995*



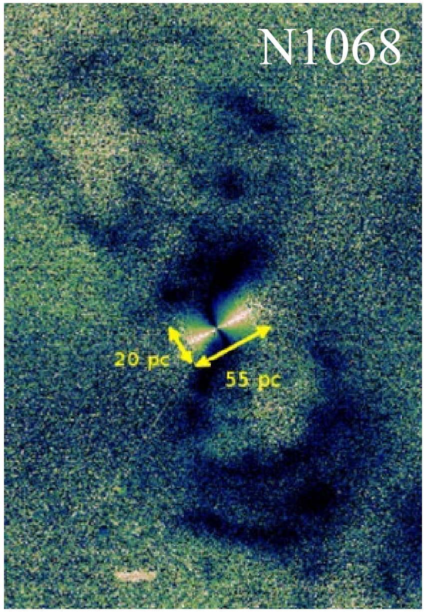

*Hönig 2019*

# Overview




**Feeding the black holes**

➔ Dynamical features: nuclear bars & spirals




**Feedback** from AGN: jets, winds

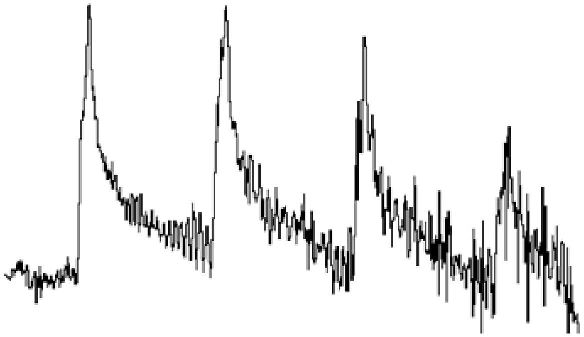
➔ Molecular outflows

**Molecular tori**

➔ Decoupled disk, random orientation

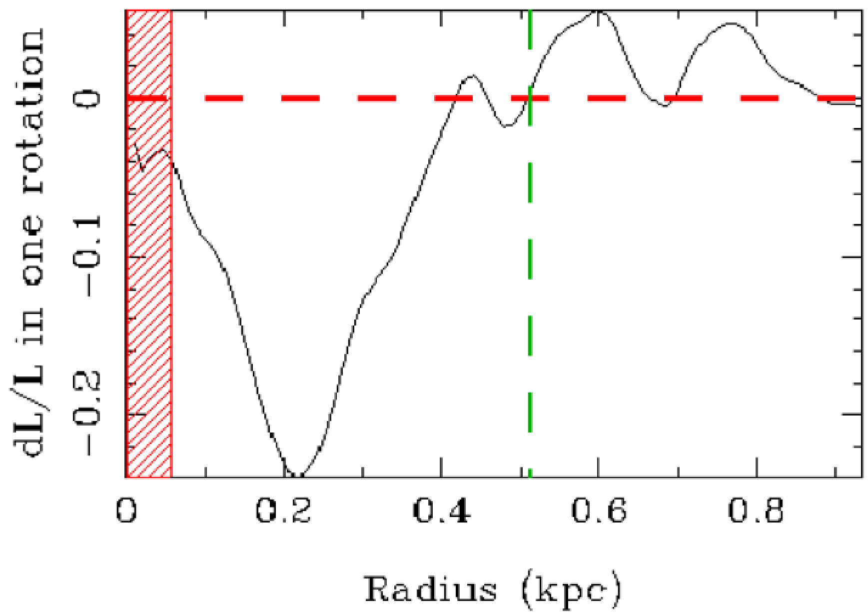
With Gravity+, BLR$^0$

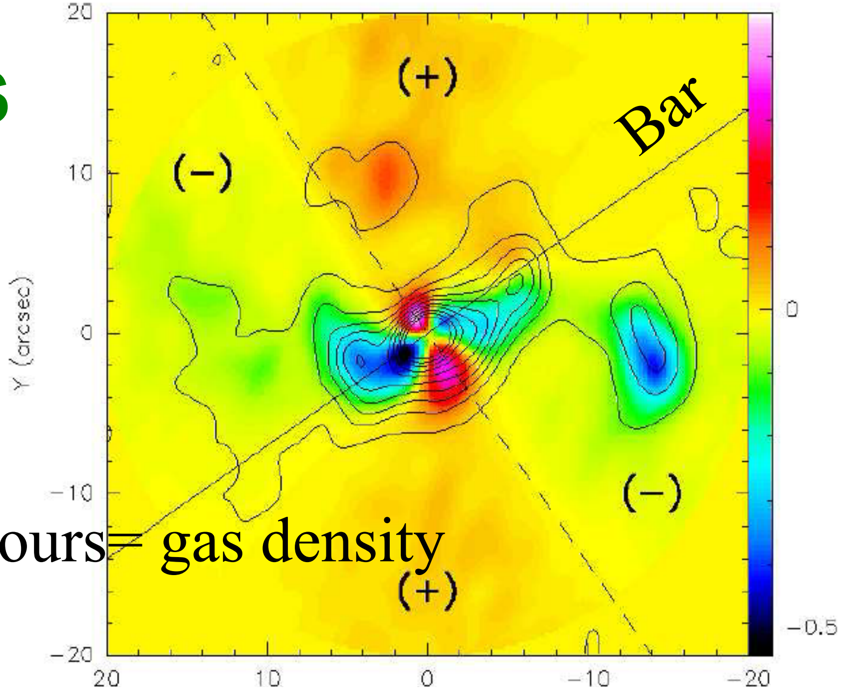
➔ CO hot and dense, too broad? ALMA?



# Fueling: Bar gravity torques

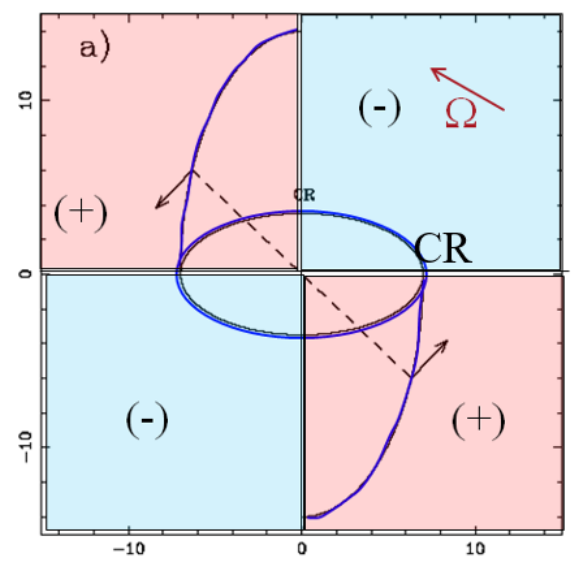
Torques computed from the HST red image, on the gas distribution




**Torque map for NGC 3627**

*(Casasola et al 2011)*




➔ **Only ~35%** of negative torques in the center,

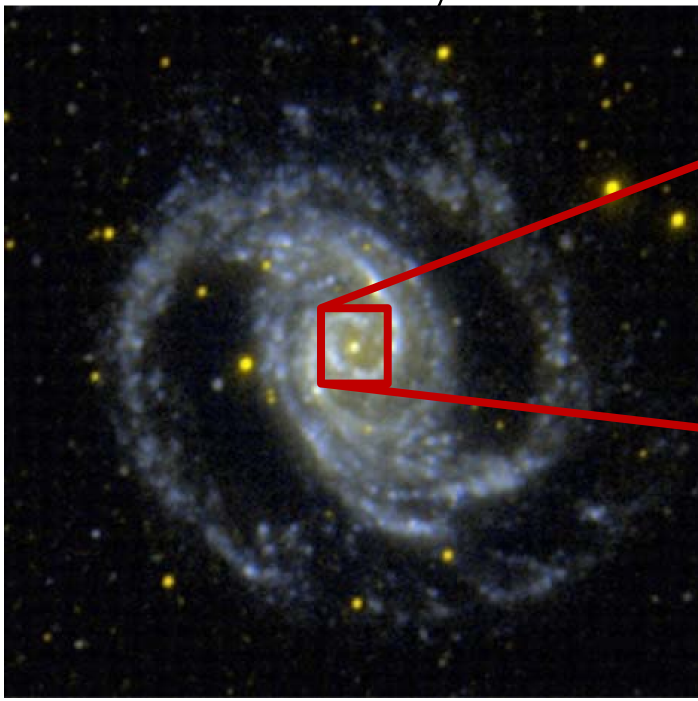
**About 20 galaxies** *(Garcia-Burillo & Combes 2012)*

At 10-100pc scales

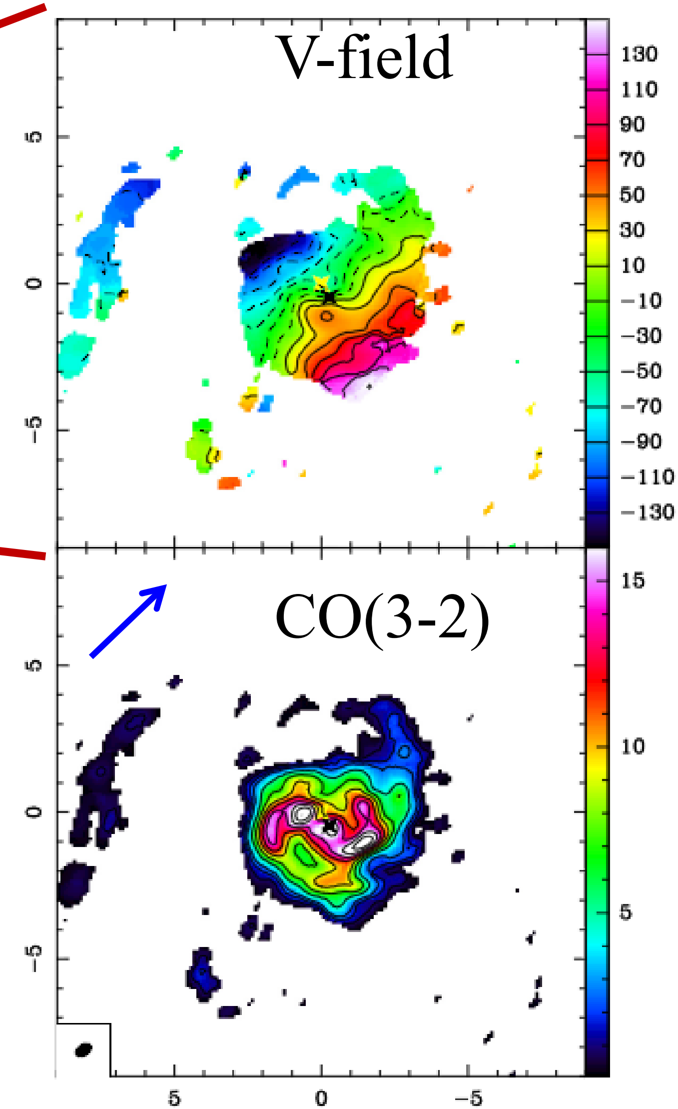
➔ **Fueling phases ~a few $10^7$ yrs**

# The NGC1566 barred Sy1: feeding phase

N1566 SAB Sy1



4 arcmin

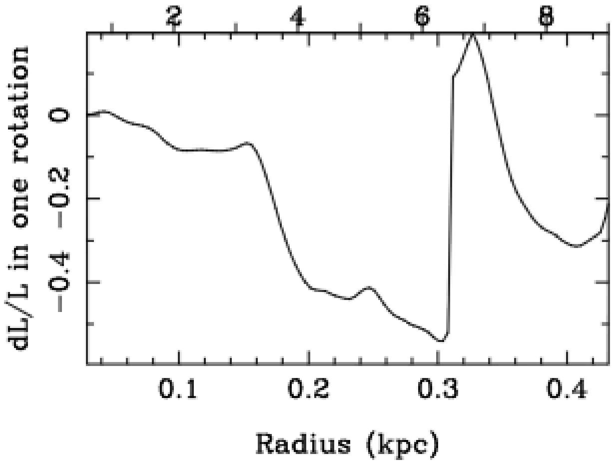



FOV=18 ”

ALMA: mapping inside the nuclear ring

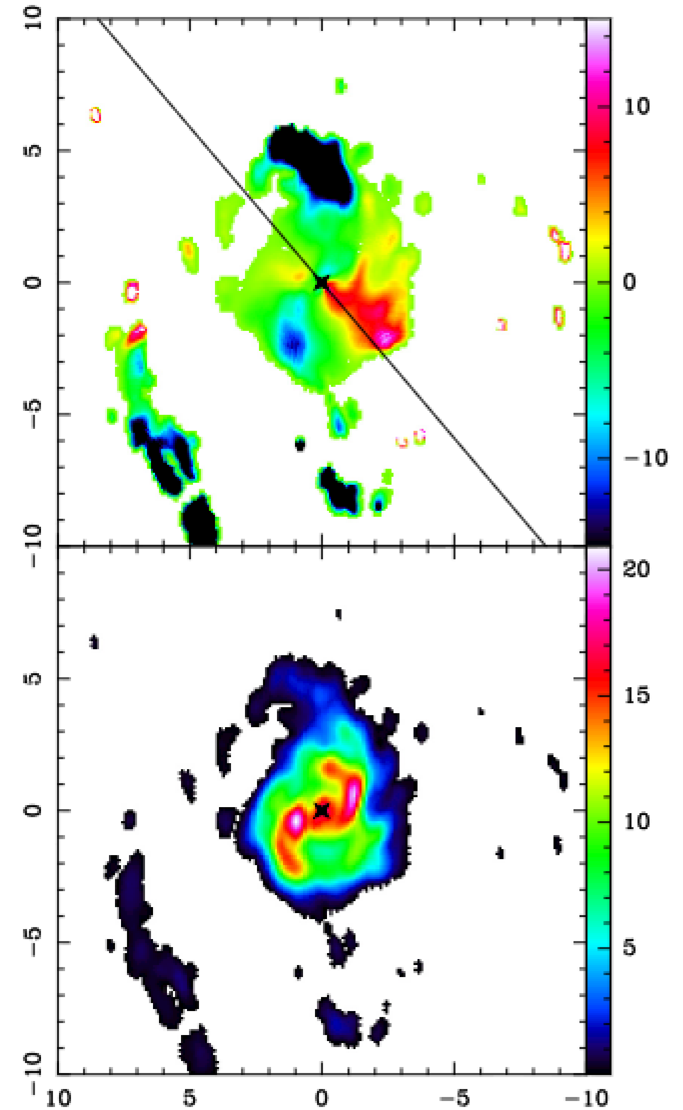
*Combes et al 2014*

# NGC1566: gravitational torques

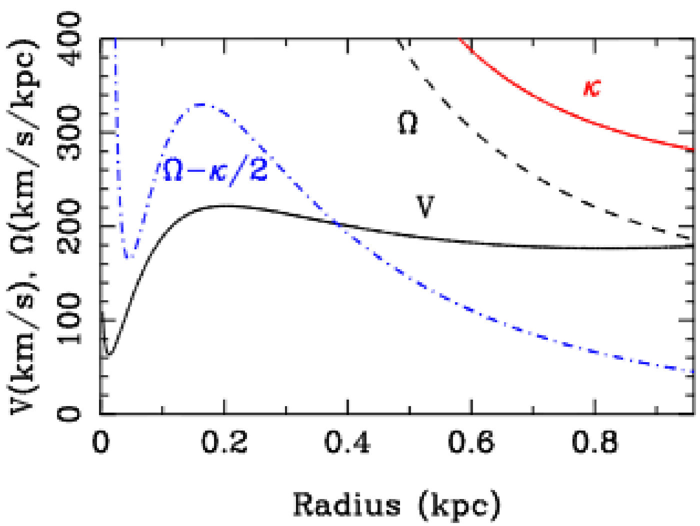



Torques on deprojected image

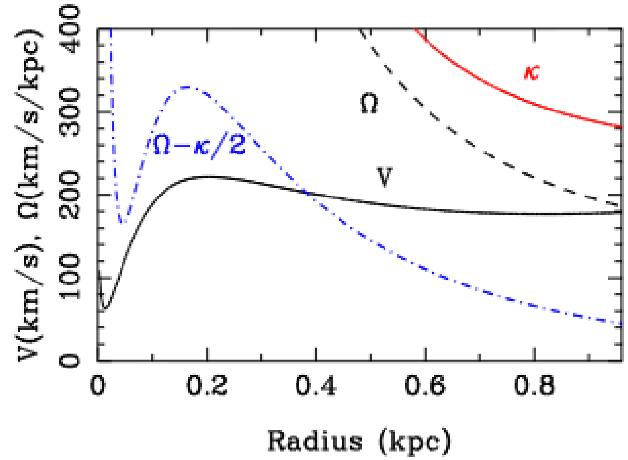
Gas is driven inwards




Trailing spiral inside the ILR ring of the bar
➔ BH influence on the dynamics



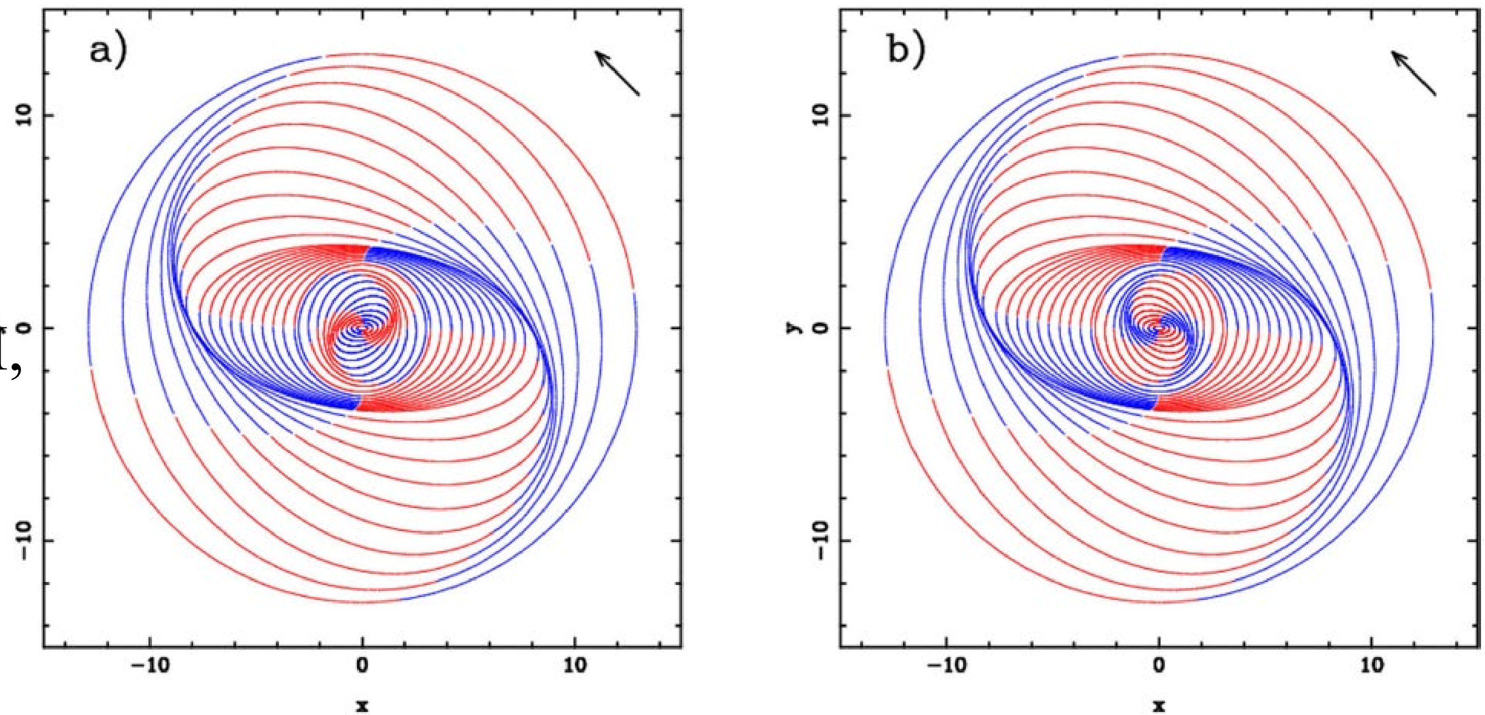
# Influence of the black hole potential




Winding sense of the inner spiral

Without BH

With BH

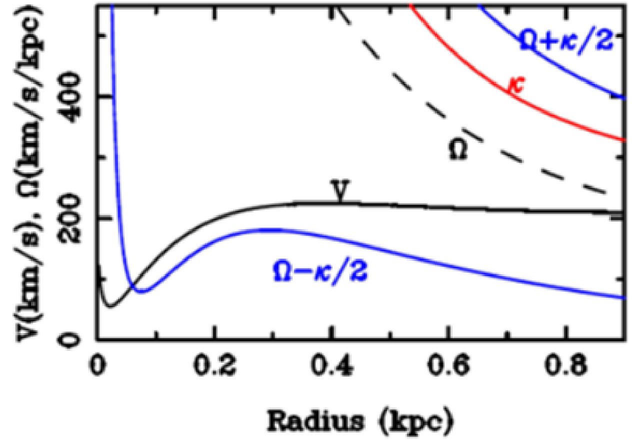


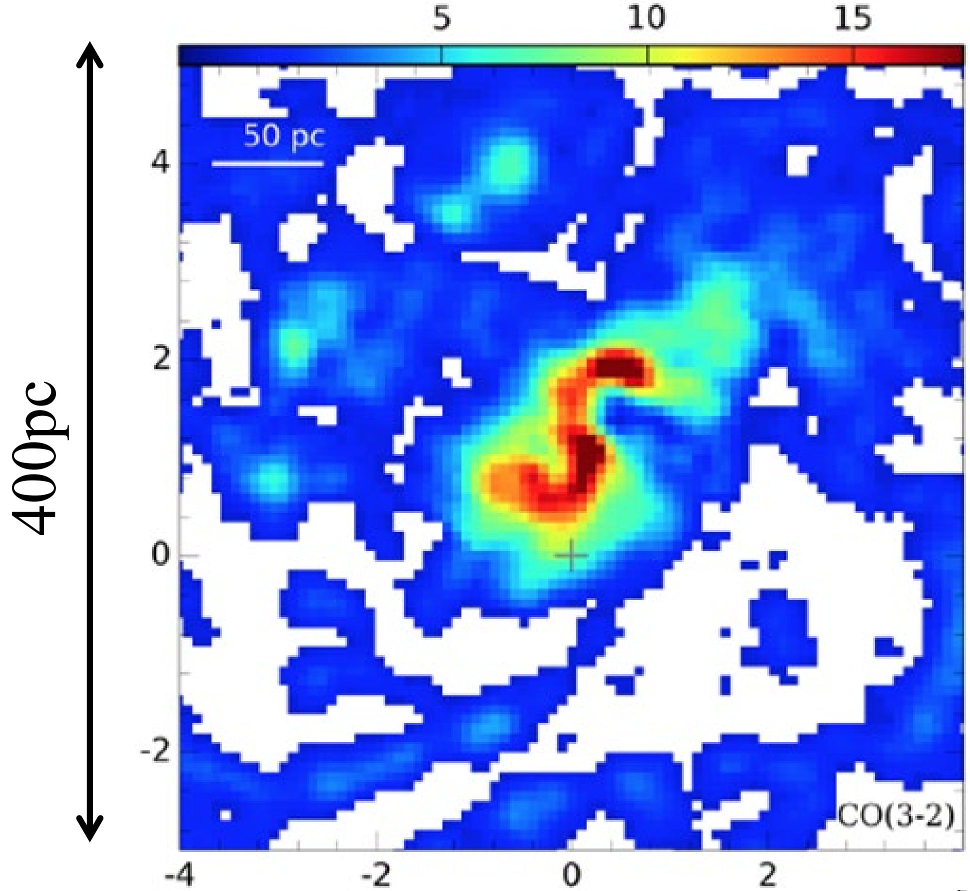

a) without BH, leading

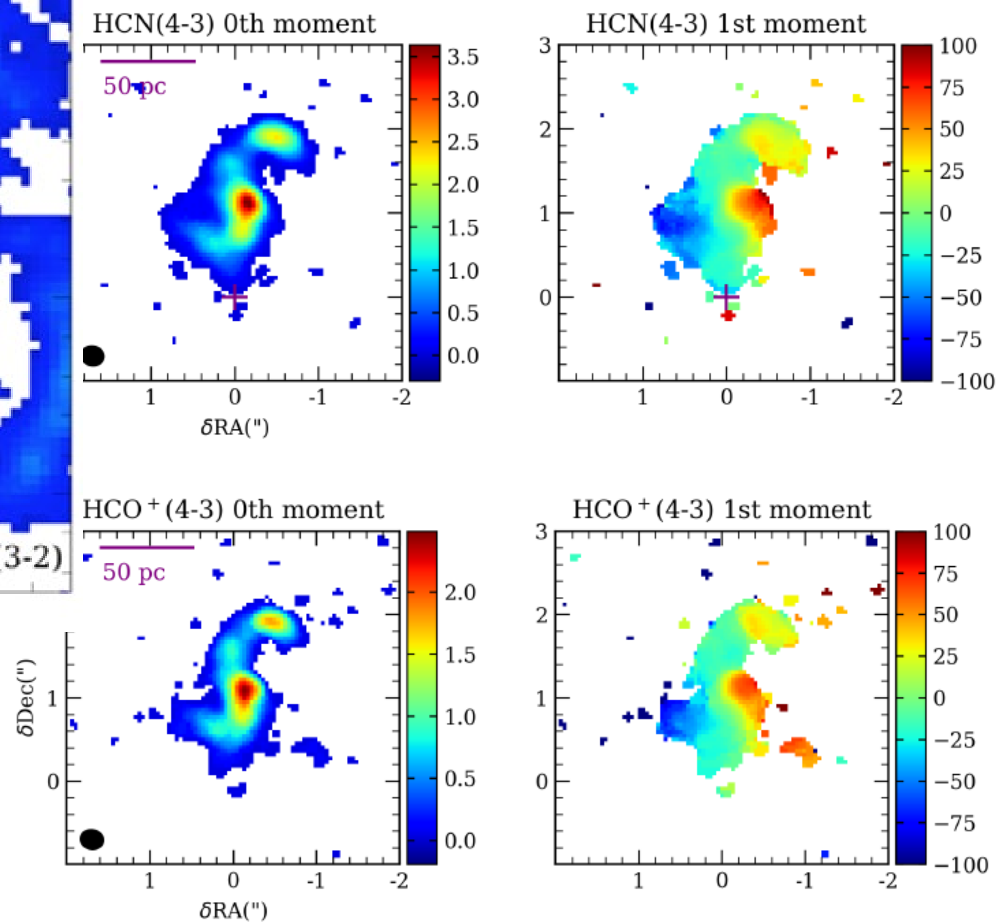
b) with BH, trailing

# also in NGC1808

*Audibert et al 2020*



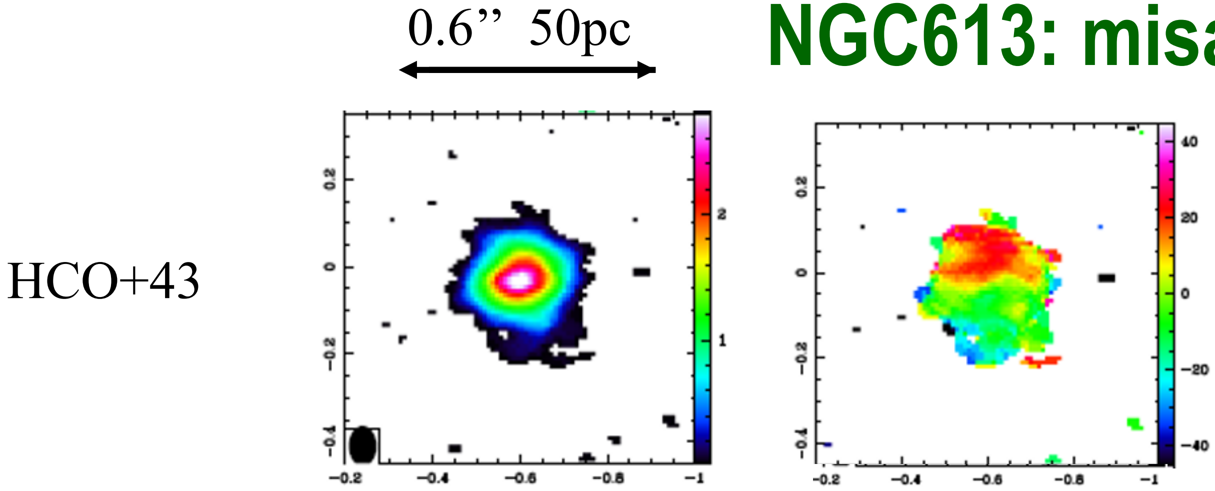



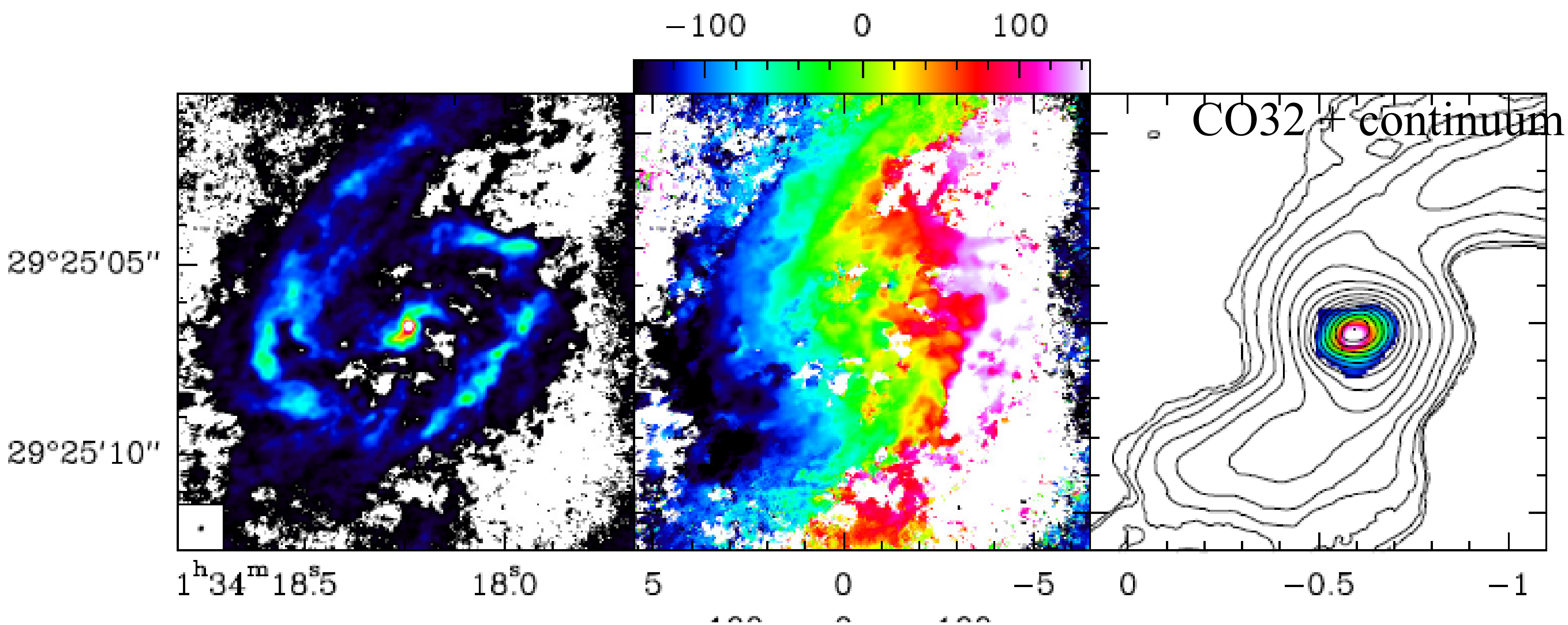




Trailing nuclear spiral in N1808
➔ Fueling the BH

**Beam 0.08" =4pc**

# NGC613: misaligned torus



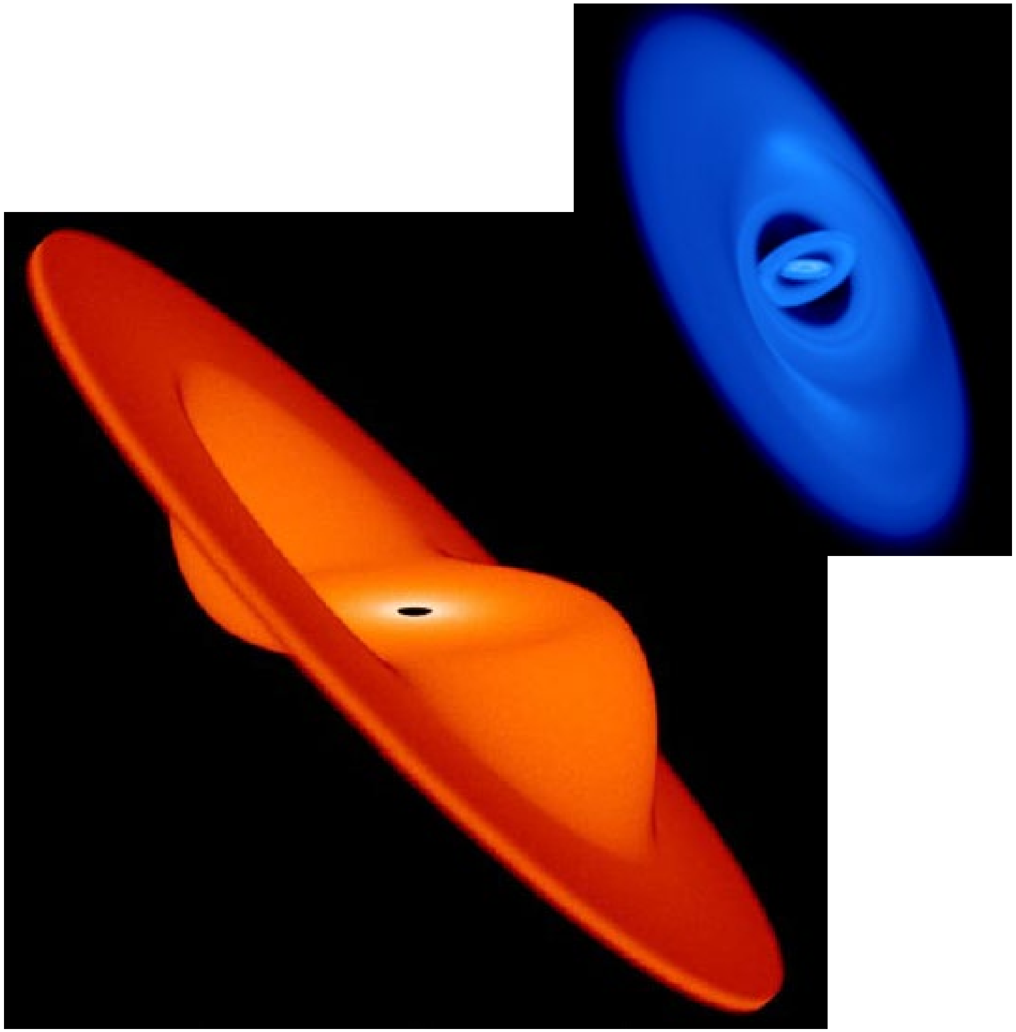

With 0.09” x 0.06” resolution (5pc): nuclear spiral +torus

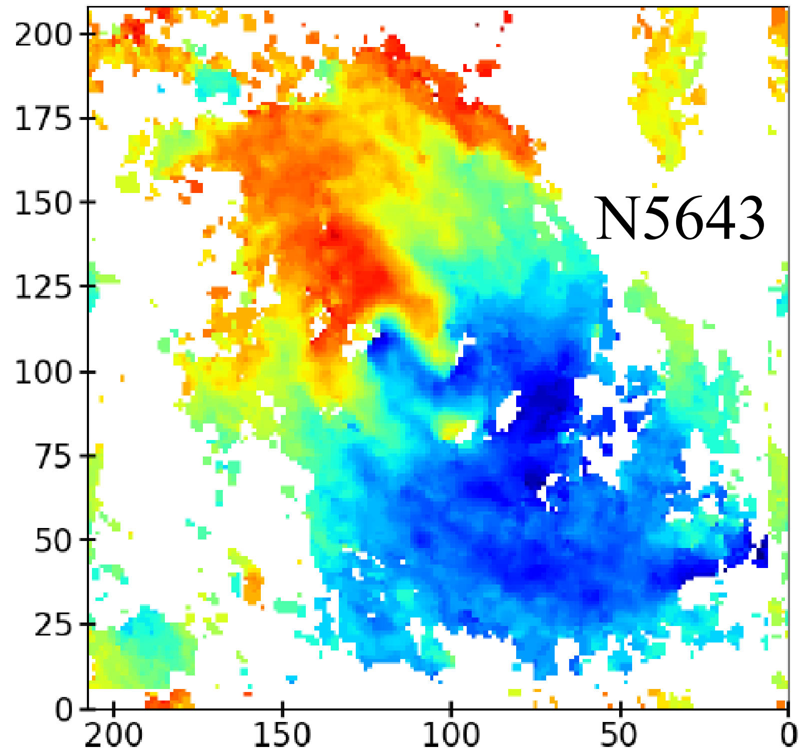
*Combes et al 2019*

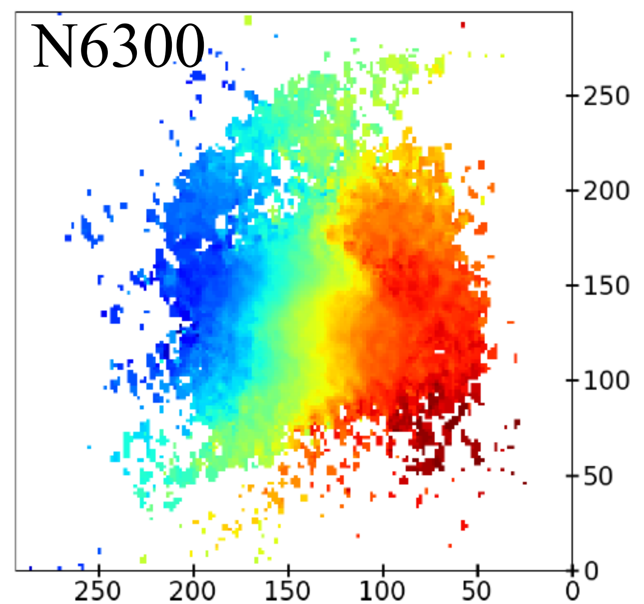
# Tilted planes

NGC 5643, NGC 6300

Poitevineau, Combes, Garcia-Burillo  et al 2022





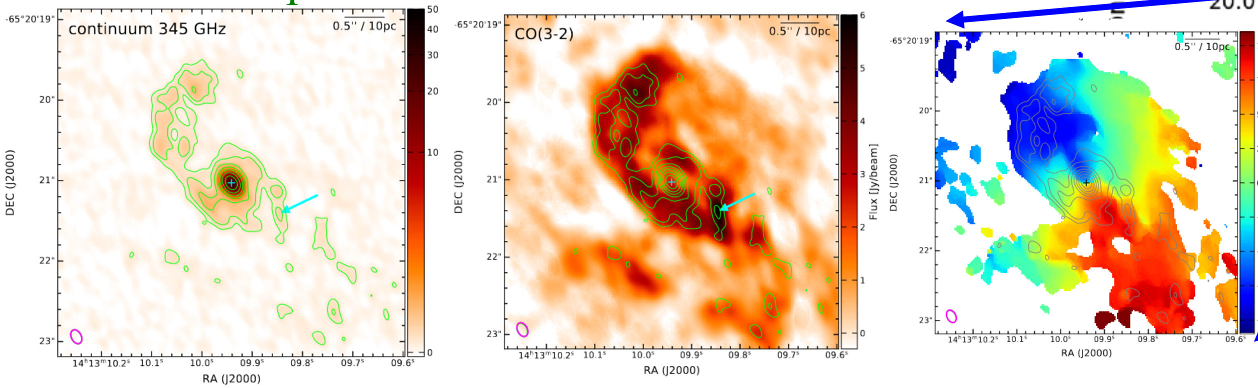



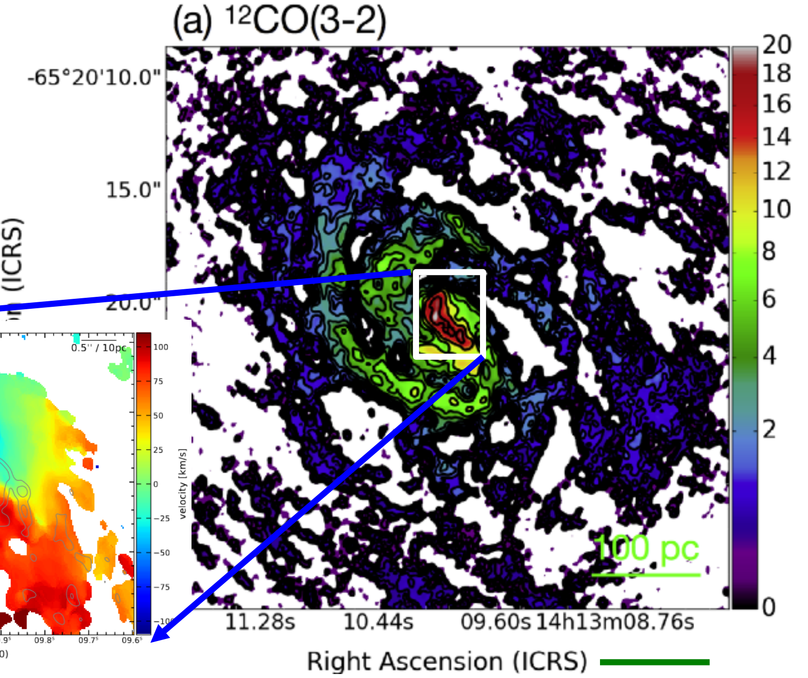

GATOS project Garcia-Burillo et al 2021

# Circinus, 3.8pc resolution

*Tristram et al 2022*

100pc

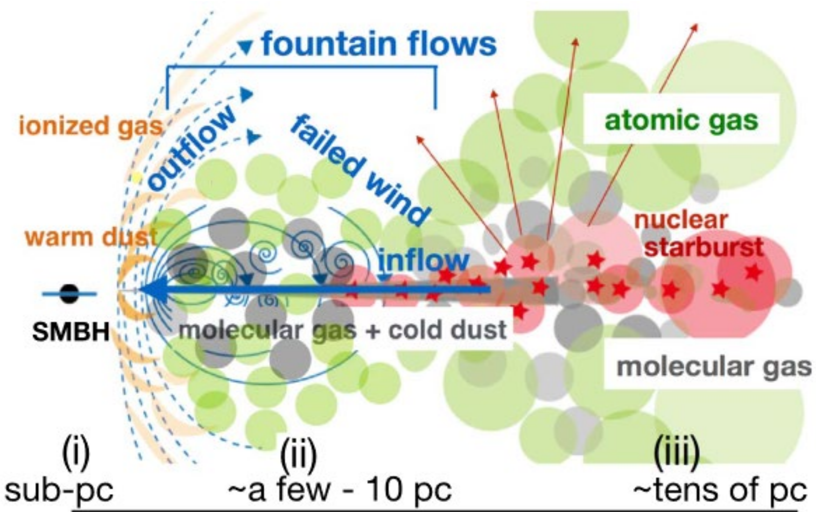


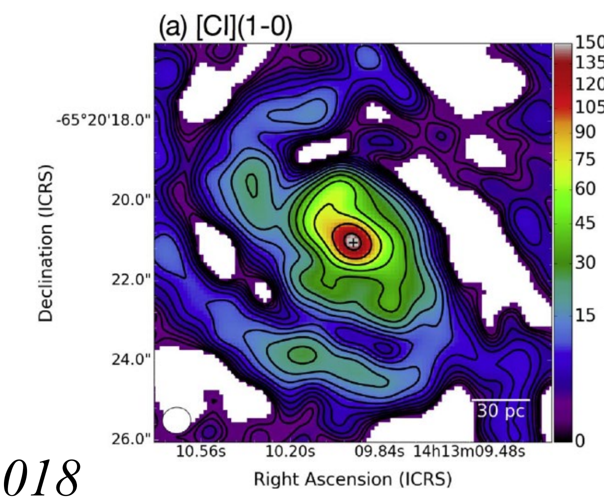




100pc

Nuclear spiral, of 20-30pc, and inside another circum-nuclear disk, which can be the molecular torus (edge-on, type 2)

A hole in CO(3-2) but not HCO+ → CI



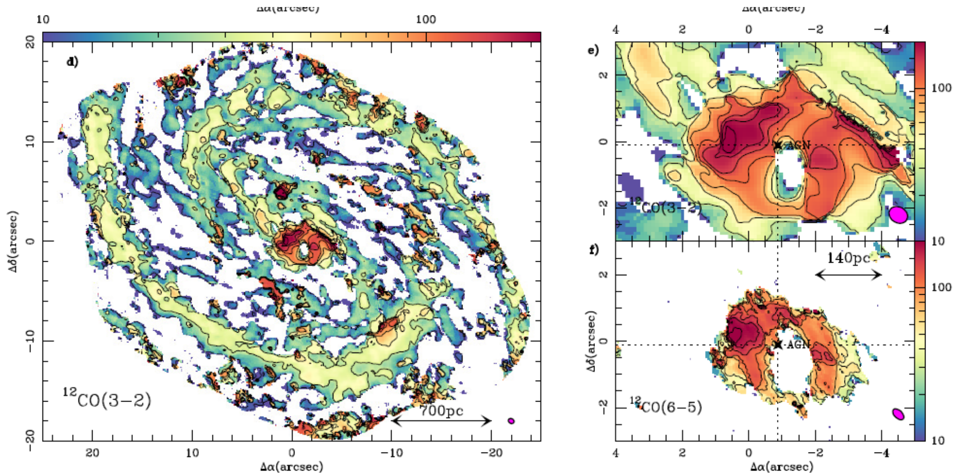




*Izumi et al 2018*

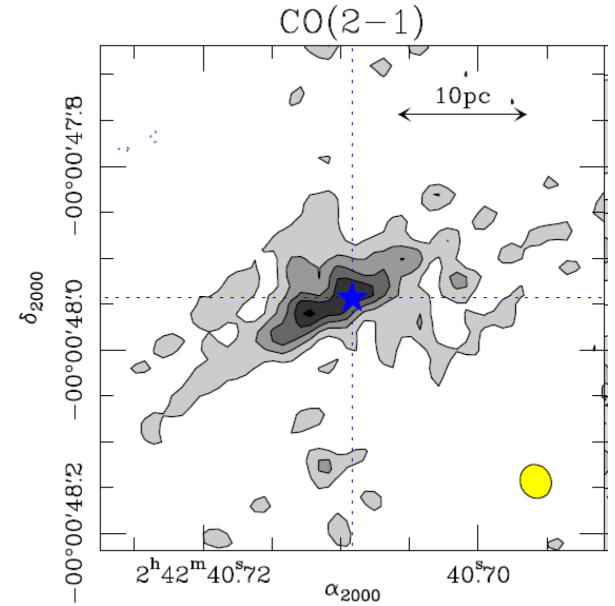
# 2 Feedback

# Molecular torus with ALMA

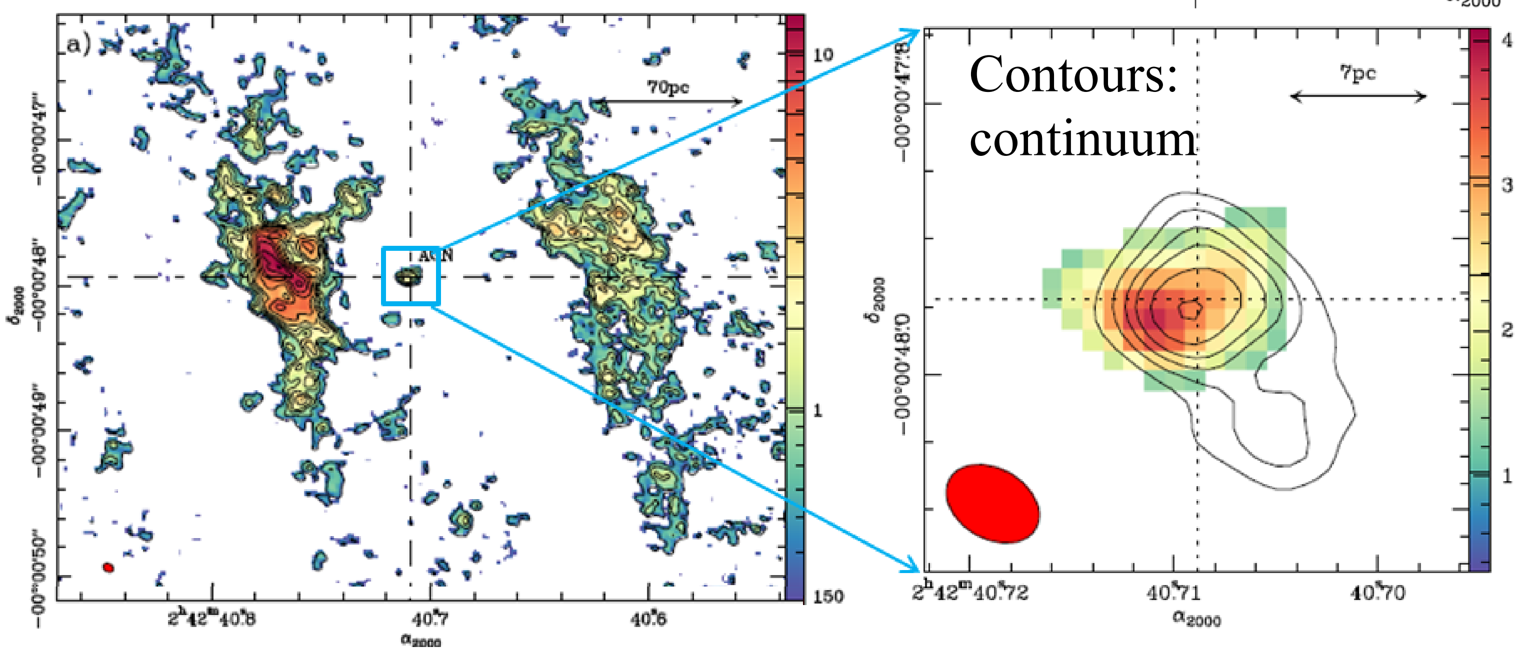
*Garcia-Burillo et al 2019*




Beam
0.05”



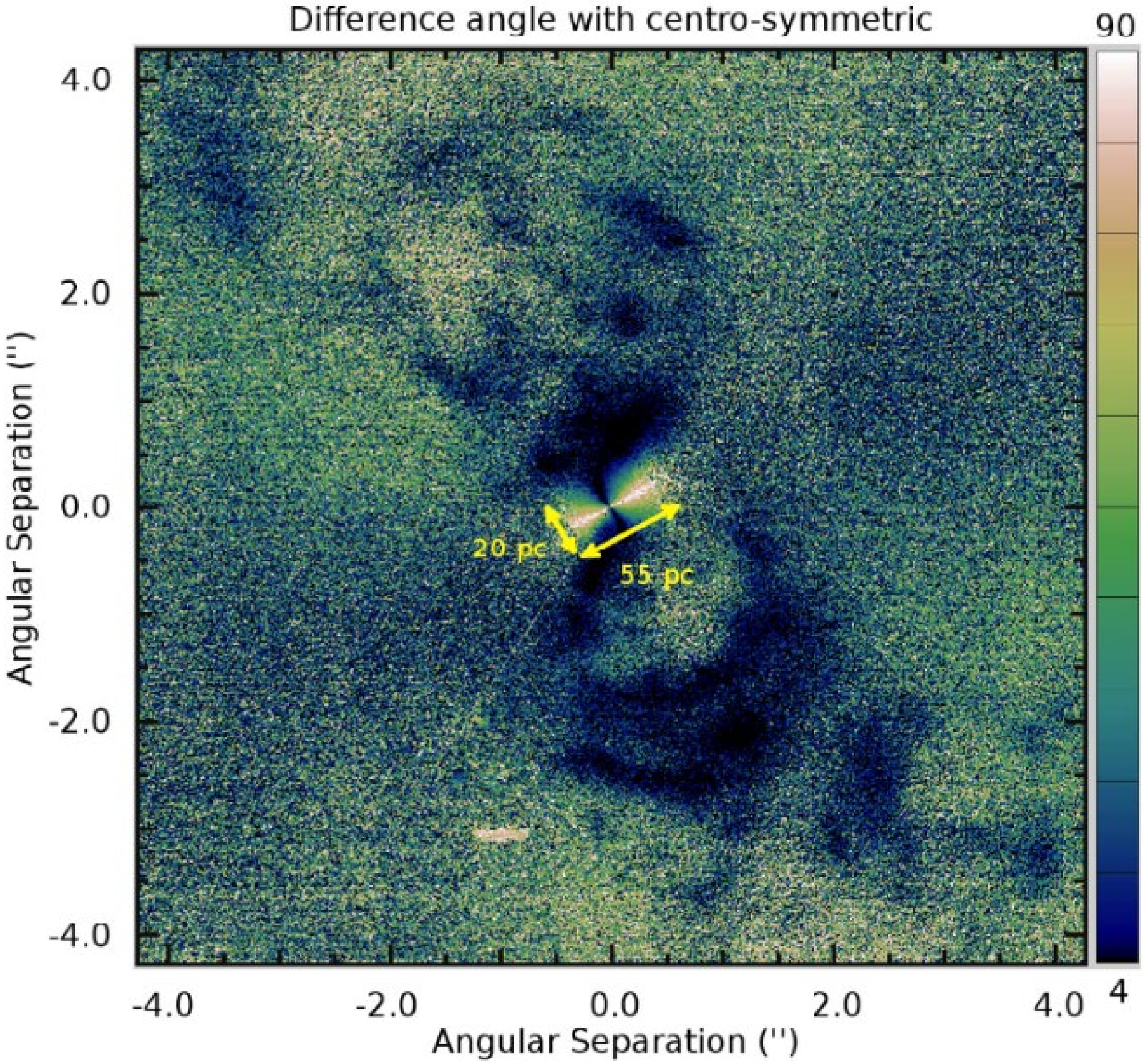

NGC1068

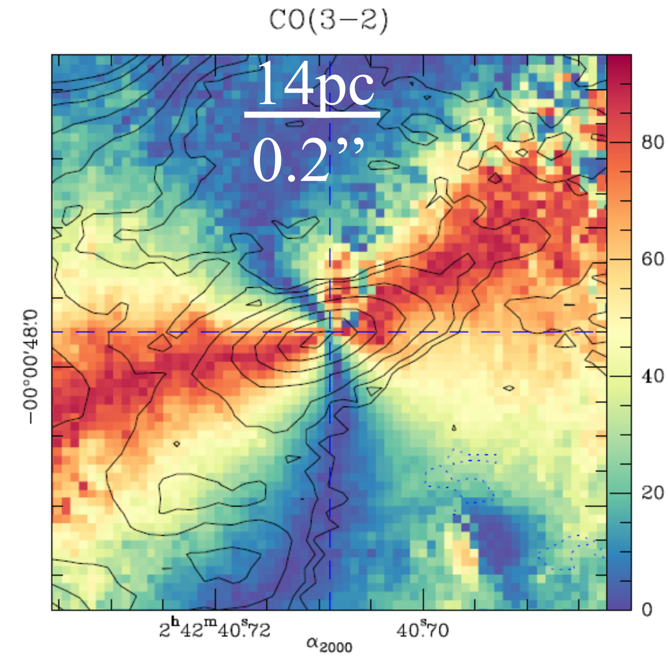



CO(6-5)

*Garcia-Burillo, Combes, Ramos-Almeida et al 2016,* **R=3.5pc torus**

# Molecular torus inside a polar dusty cone




*Garcia-Burillo et al 2019*

X-rays, from $10^{23}$ $cm^{-2}$ up to $10^{25}cm^{-2}$

➔Compton-thick

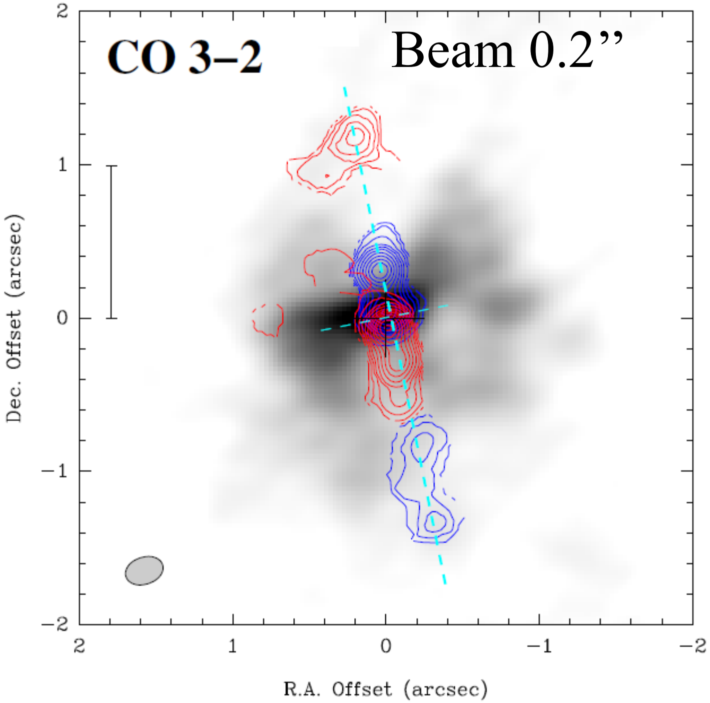
~up to 100pc scale

*Bauer et al 2015*

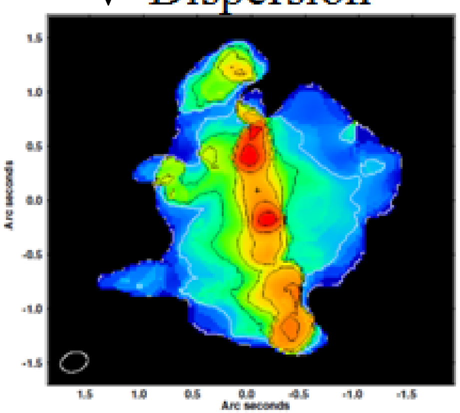
*Marinucci et al 2016*

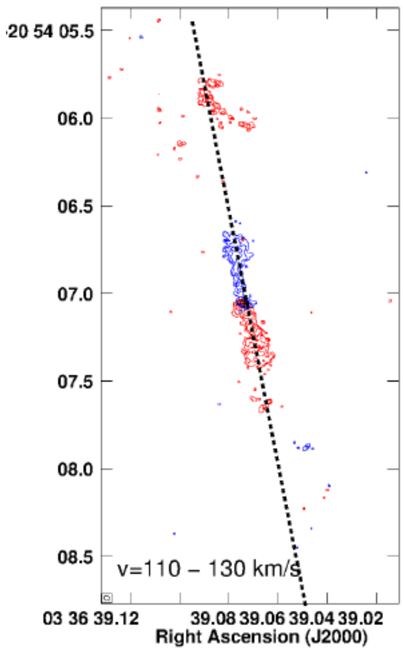
1''=70pc, *Gratadour et al 2015 SPHERE NIR*

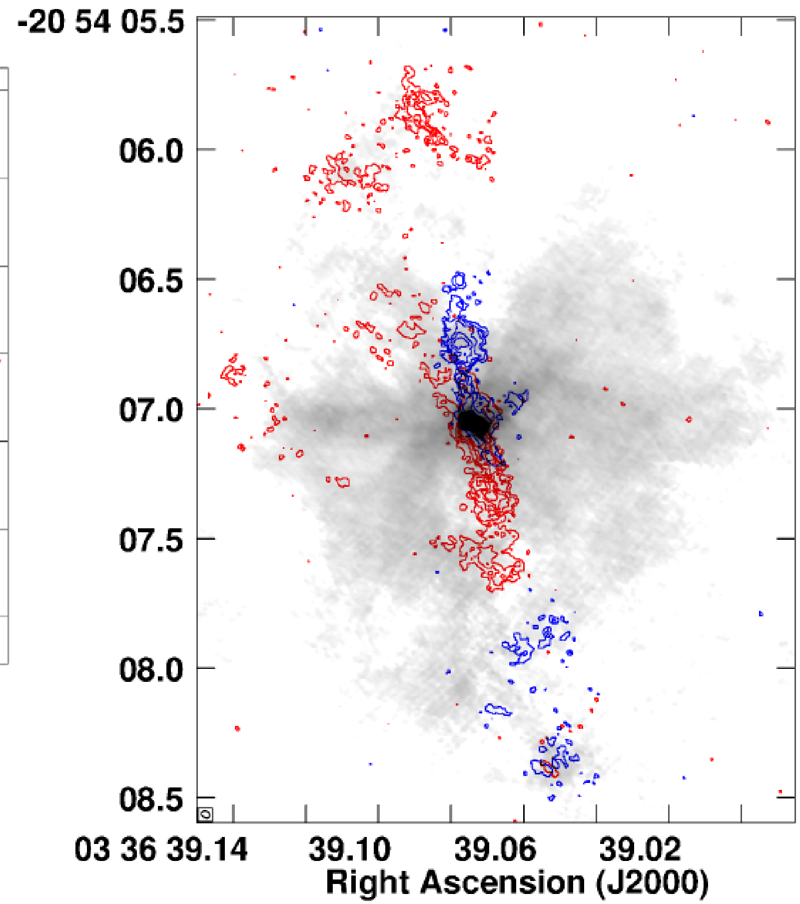
# Radio mode or MHD model in NGC1377?




The most radio quiet galaxy!



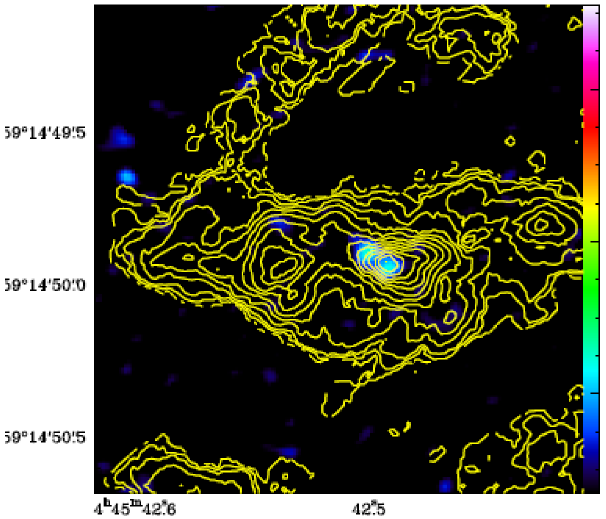




$MH_2$ in the cone
$10^8\ M_\odot$
In the jet $10^7\ M_\odot$

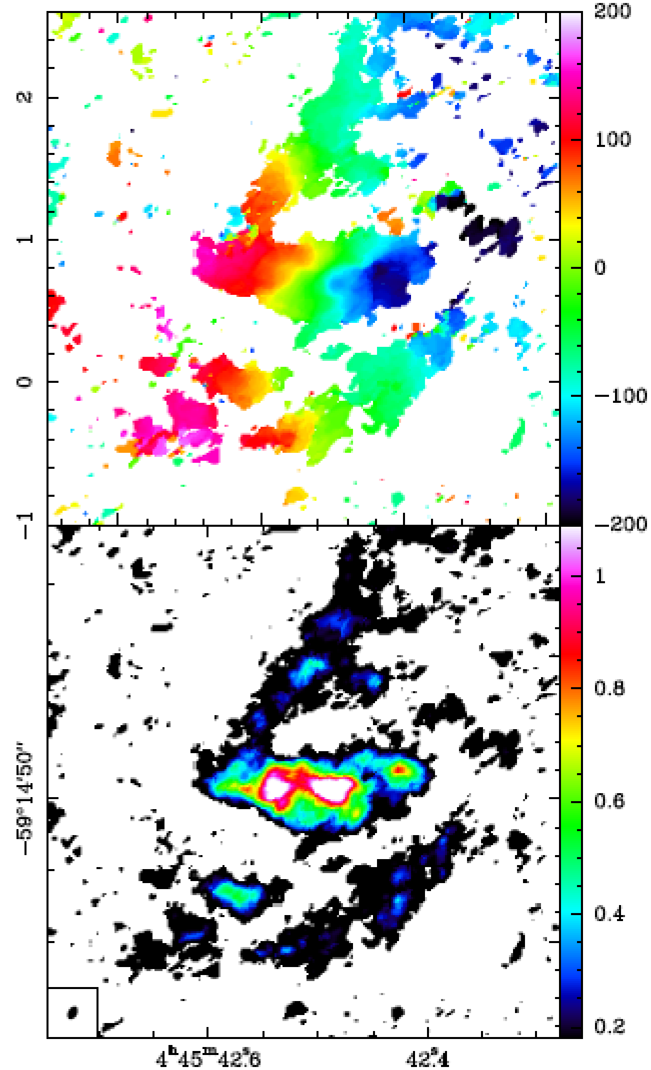
*Aalto et al 2016, 2019*

# 3 Molecular tori

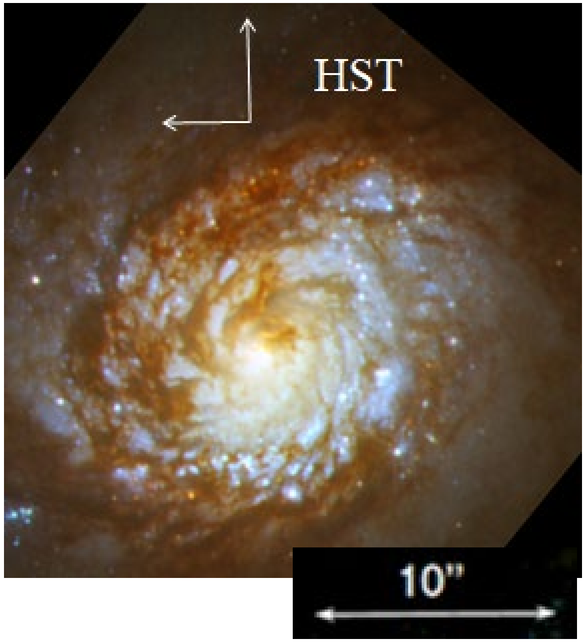
# NGC 1672




1 arcsec = 55pc




# Misalignment



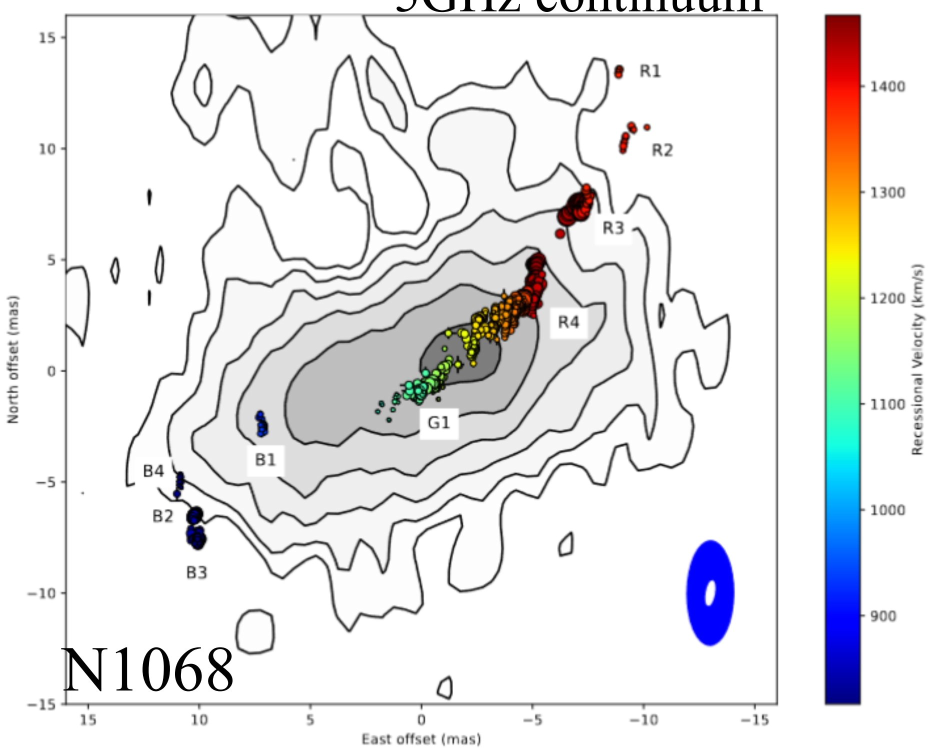

CO32-contours on continuum

HCN(4-3) & HCO+(4-3) just detected in the center

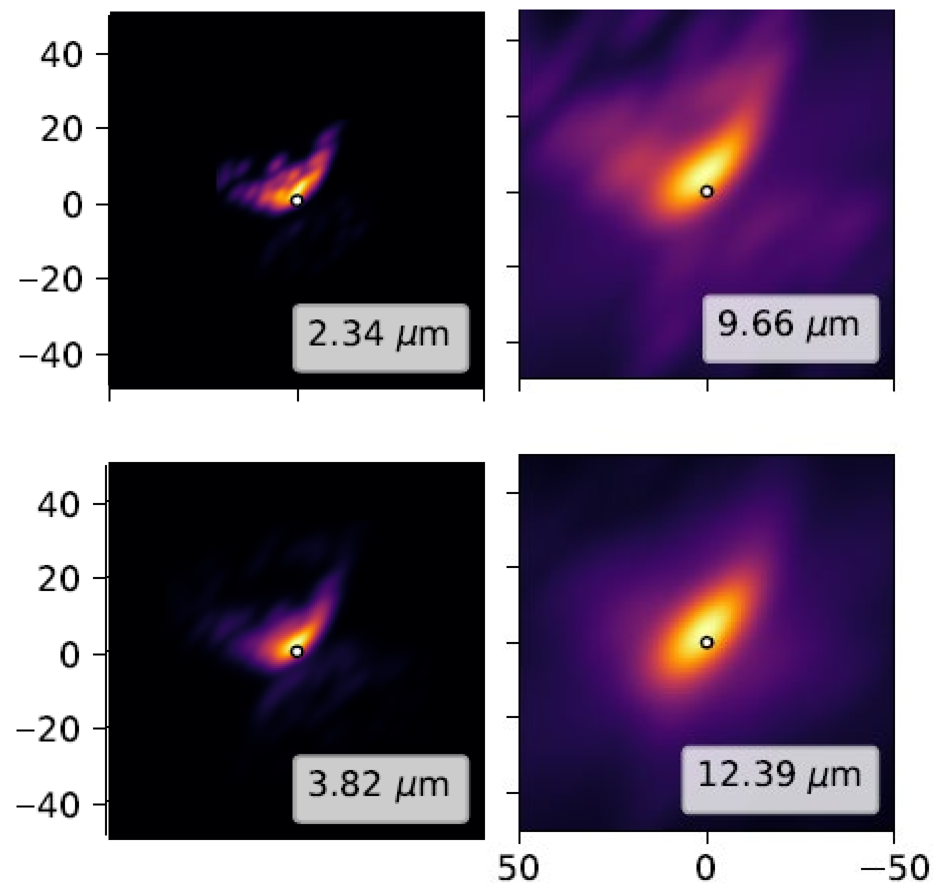
# Warped disk and wind


$H_2O$ masers on 0.3-0.8pc warped discs
Best represented by Lense-Thirring effect
➔ also heat the disk
GRAVITY+MATISSE *Leftley et al 2024*

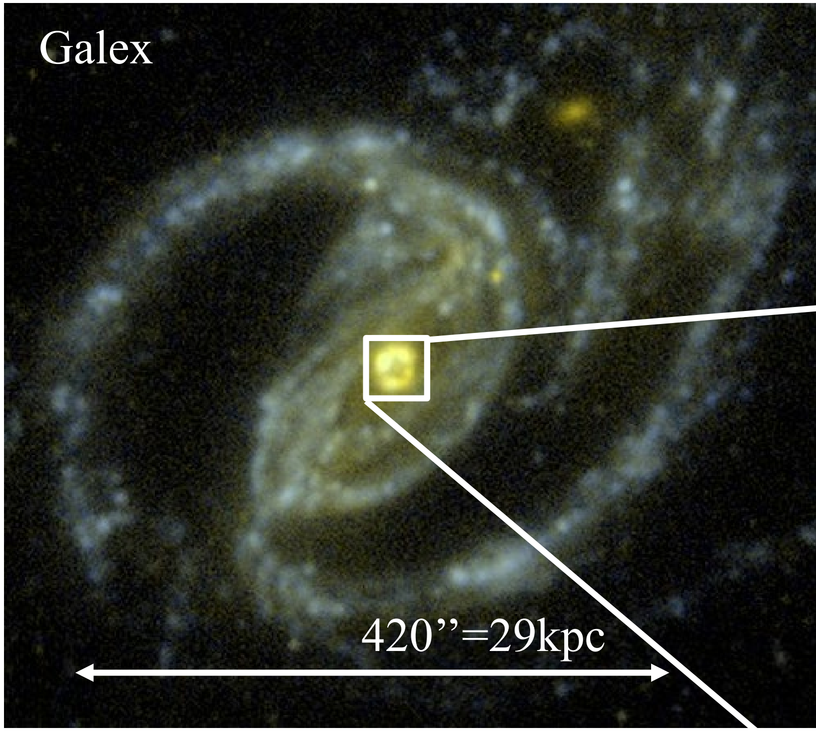
5GHz continuum



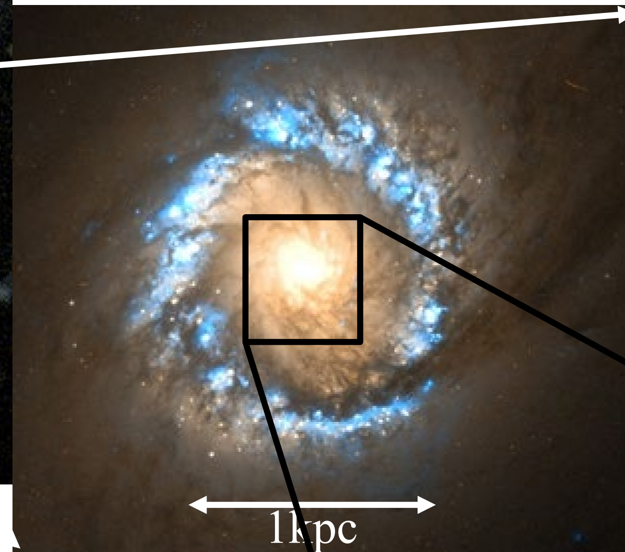

*Gallimore et al 2023*



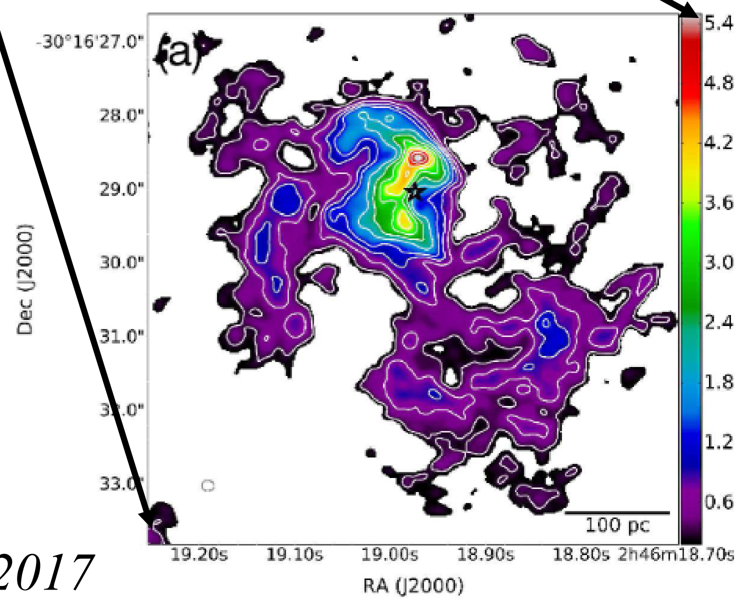
# NGC 1097




*Fathi et al 2006*




$\lambda$Edd =7$10^{-4}$




*Izumi et al 2017*

ALMA with 10pc resolution reveals a nuclear spiral inside the ILR ring, but no apparent central torus

No torus in 10-20% of LLAGN

More with $\lambda$Edd ?

*Garcia-Burillo et al 2021*

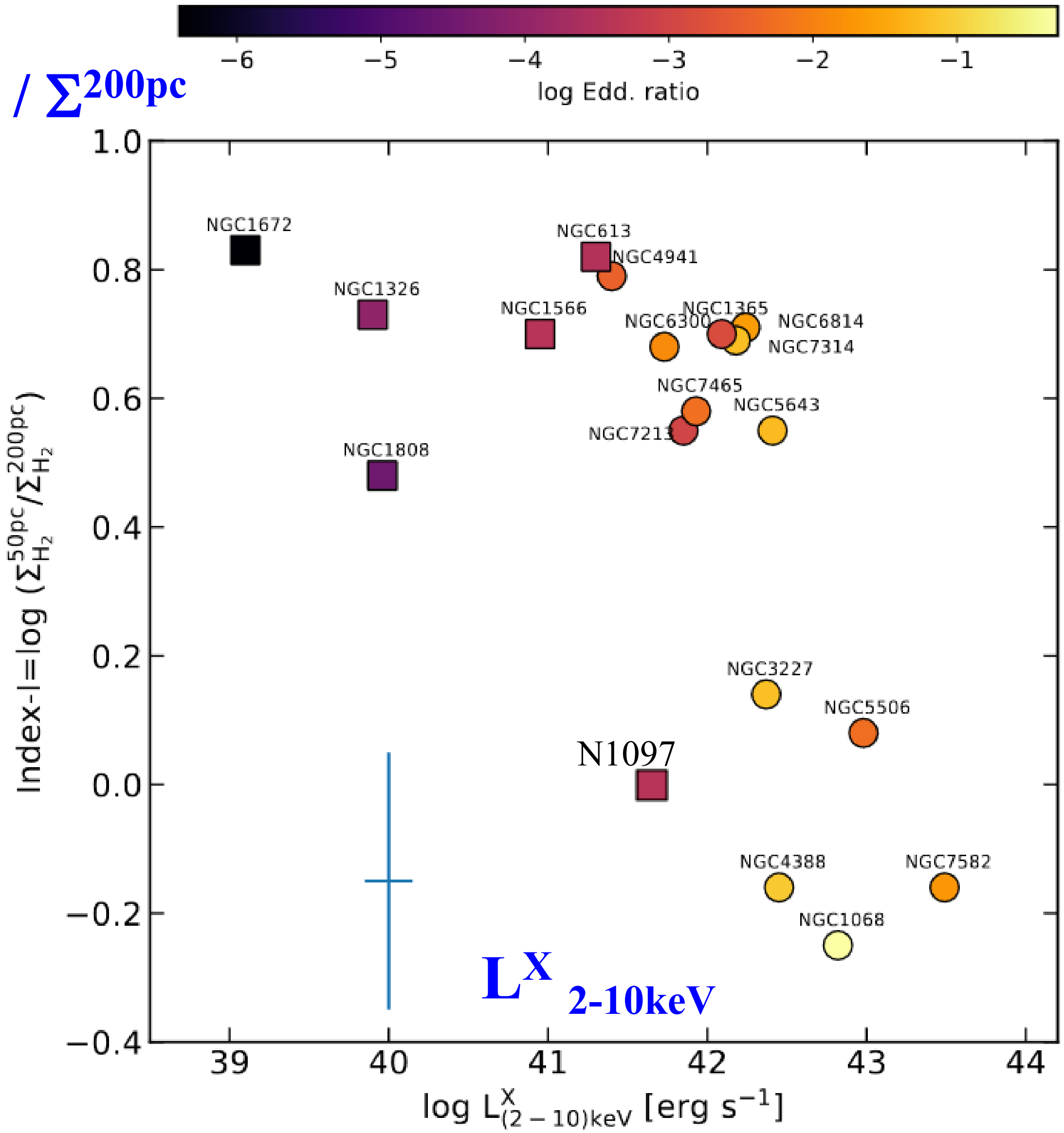
# Influence of AGN

$\Sigma^{50pc} / \Sigma^{200pc}$

The most active AGN
have less $H_2$ concentration

Drops for Lx> $10^{42.5}$ erg/s

And also $E_{dd} > 10^{-3}$




*Garcia-Burillo et al 2021*

④ **GRAVITY+**

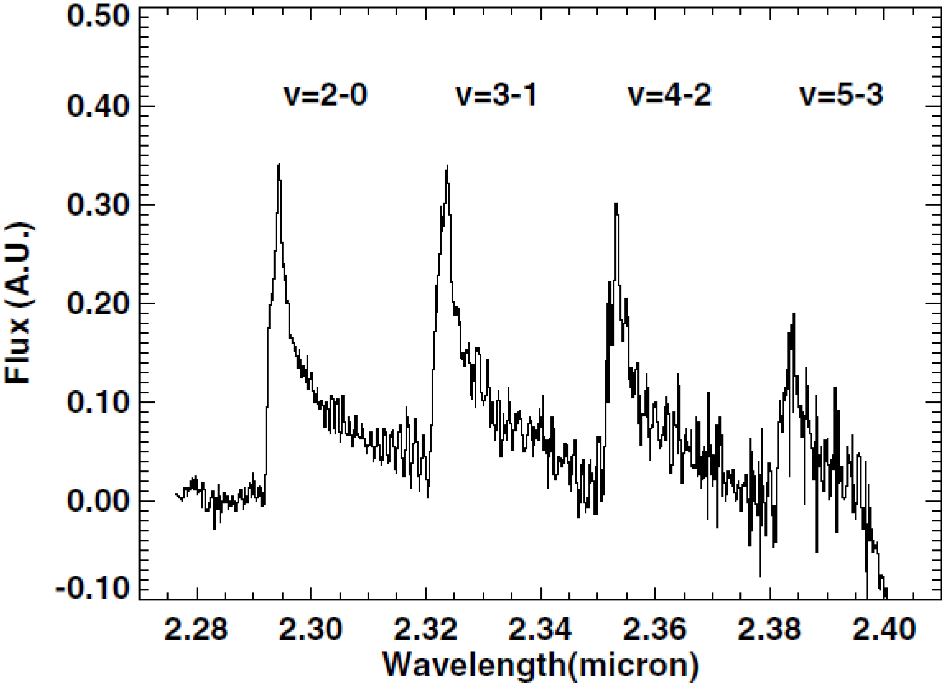
# CO bandhead around stars

*W Thi et al 2005*

Hot dust-free inner **disk around 51 Oph**

R=10 000  ISAAC/VLT   CO $\Delta v=2$
Molecular disk in Keplerian orbit
T=2000-4000K, $n(H_2) > 10^{10} cm^{-3}$
Inner AU, between the $R_{trunc}$ and $R_{sublim}$
i=88°, N(CO) $\sim 10^{20} cm^{-2}$

$R_{trunc}$= 0.15 AU, $R_{max}$=0.35 AU
$R_{sublim}$ =0.6 AU  T= 1500K




ISO/SWS  N(CO) $\sim 10^{21} cm^{-2}$
Cooler T= 500-900K
$V_{rot}$= 267km/s  $R(cor)=GM_*/V^2_{rot}$
**R(cor)** =0.05AU   < $\mathbf{R_{sublim}}$

# Resolved hot CO around 51 Oph Be star

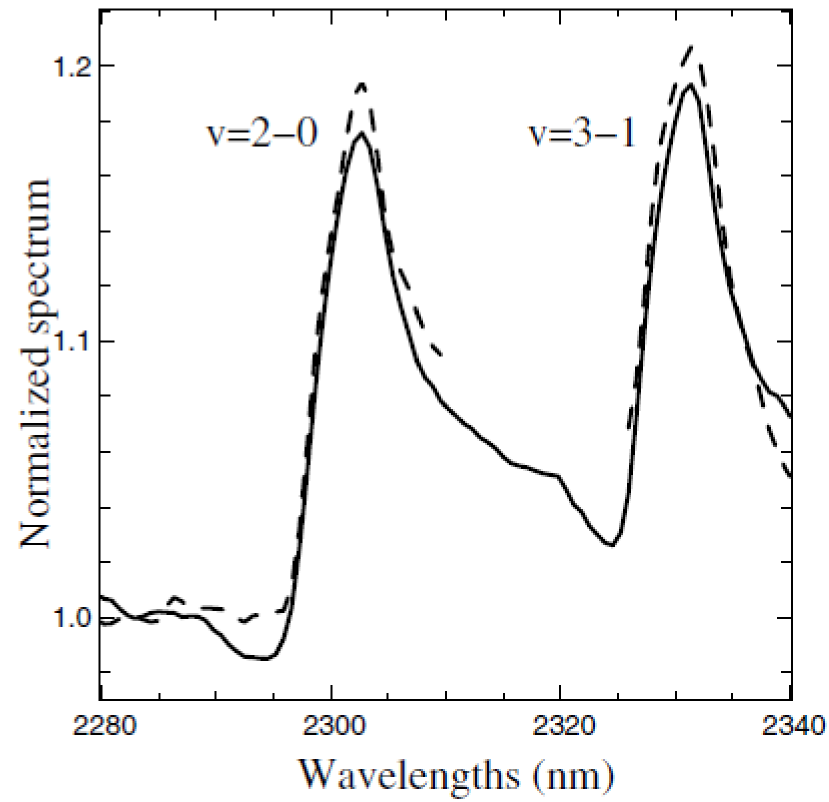
AMBER VLTI R=35 and 1500 *Tatulli et al 2008*

**Confirmation R= 0.15 AU**

Also the CO gas contributes to the $2\mu m$ continuum inside $R_{sublim}$

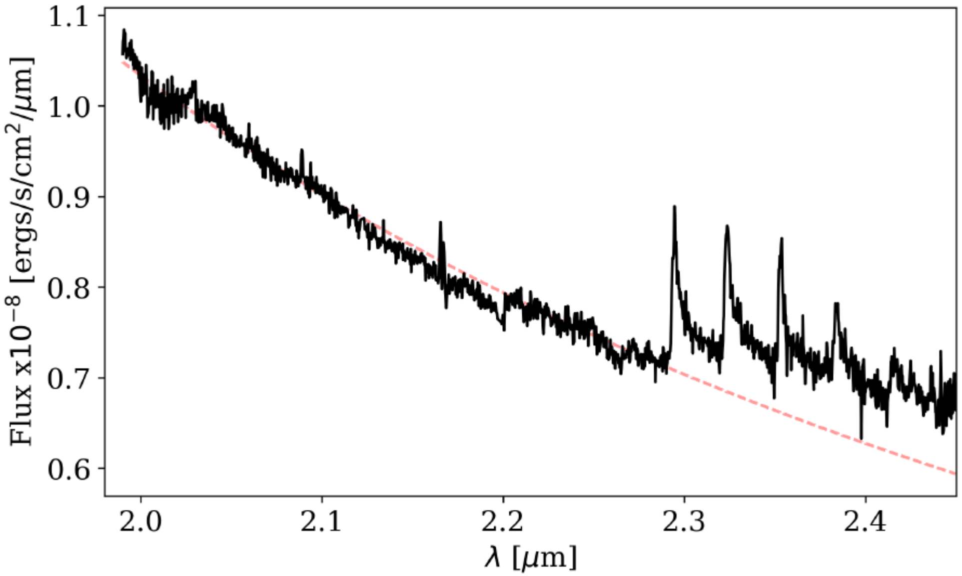
PA=126°, i=82°

CO self-shielding,
and reformation
$C + OH \rightarrow CO + H$
If $N(CO) > 10^{15} cm^{-2}$



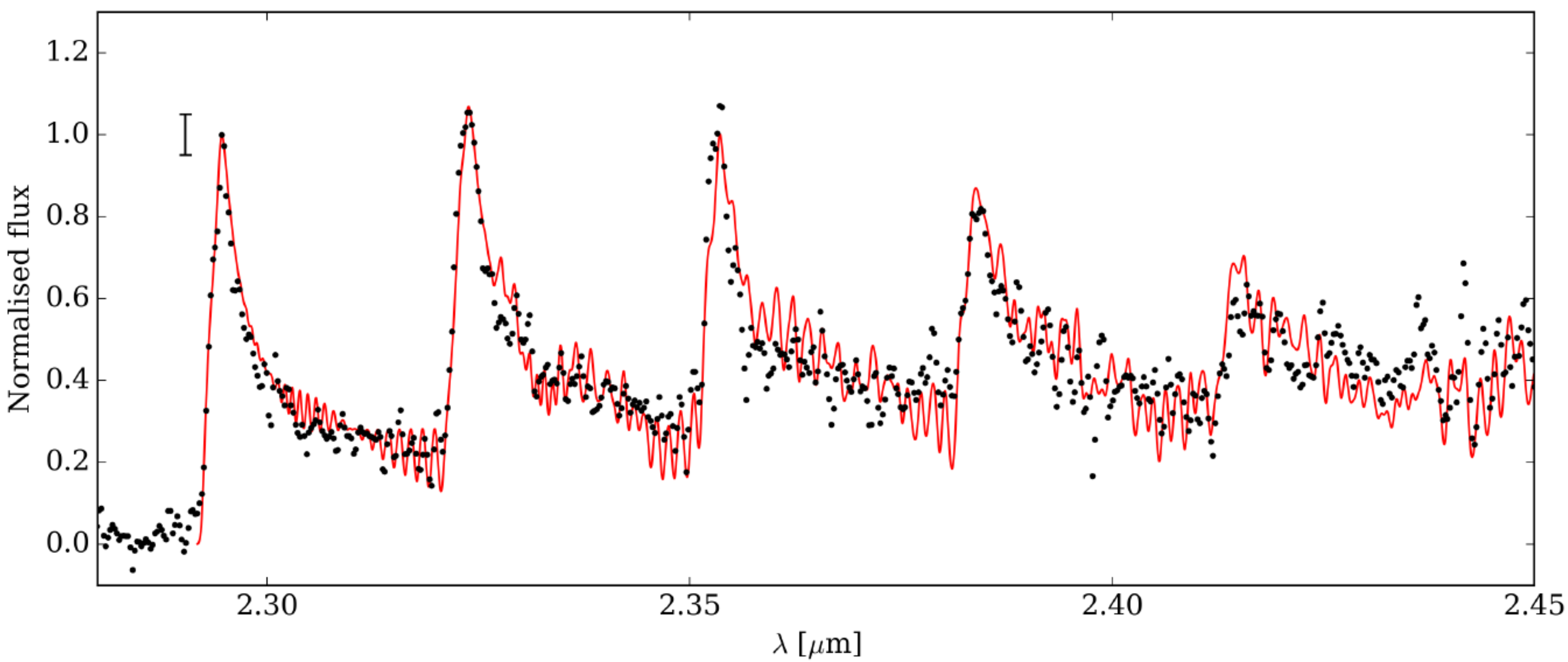

D=130pc, 1mas = 0.12 AU

# GRAVITY: 51 Oph



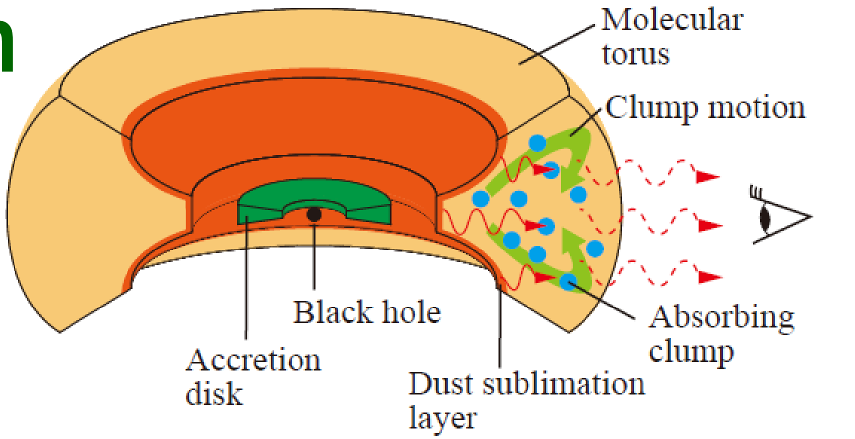

Continuum: 80% T= 10 000K
20% T=1500K dust 0.5AU
12 baselines
*Koutoulaki et al 2021*

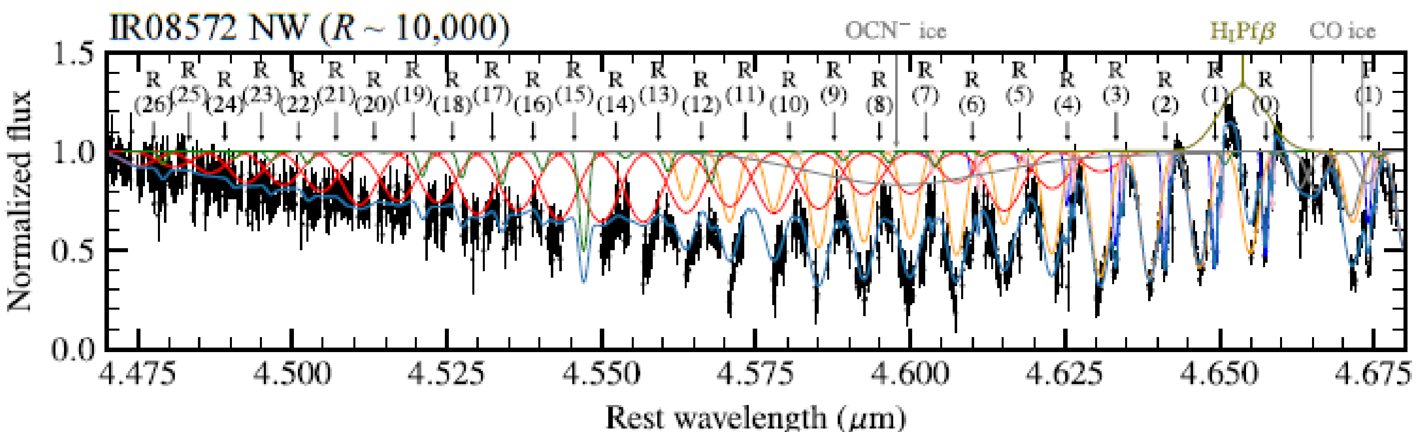
PA=116°, i=63°, CO at 0.1 AU < $R_{sublim}$

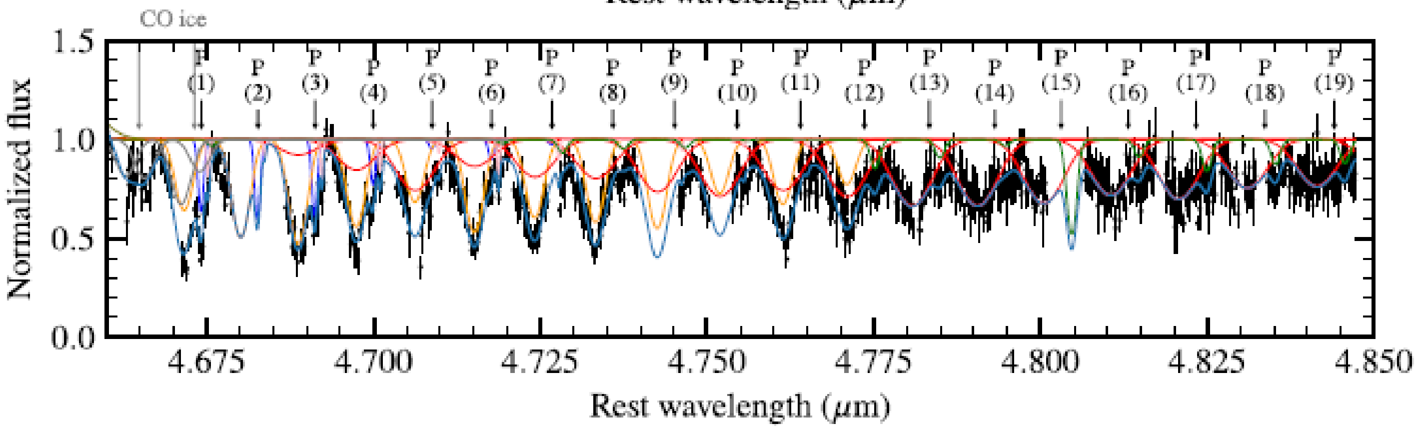


# CO bandhead in absorption

ULIRGs, with molecular torus
CO v=0→1, 4.67μm, R=10 000
SUBARU
*Onishi et al 2024*




4-5 clumps
at each los

Inner outflow
V~240km/s
Denser, hotter

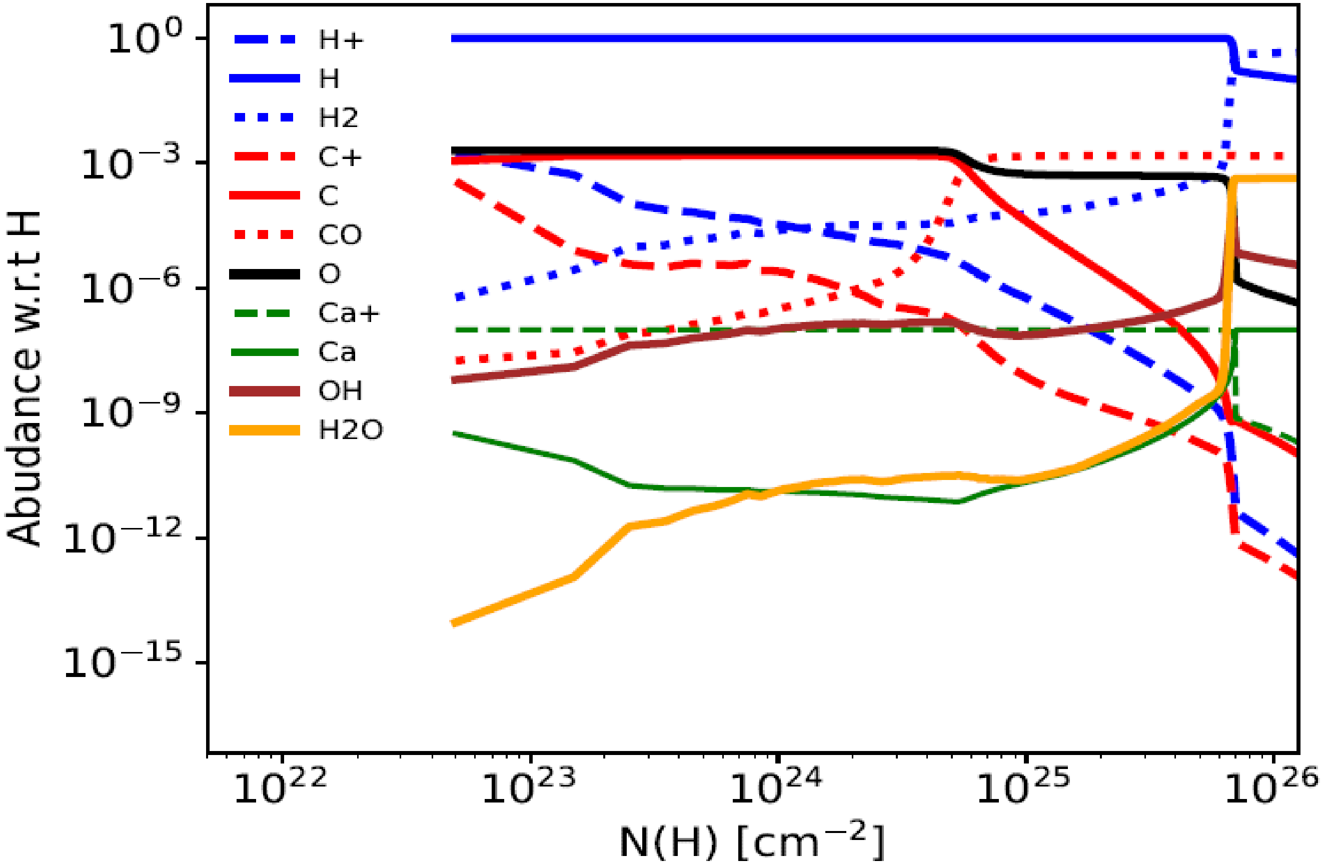
Outer low-V
V < 100km/s

# Predictions of CO bandhead in BLR

BLR sizes = $10^2$-$10^3$ Rs  $BLR^+$ 10-100 $M_\odot$, $BLR^0$ $10^5$-$10^6$ $M_\odot$

$BLR^+$ as an outer layer,  bulk in $BLR^0$ with neutral H and $H_2$

Inside the $R_{sublim}$, **dense and hot molecules → CO**




CLOUDY model

$n_H = 10^{14}$ cm$^{-3}$

log(U) = -5

V = 250 km/s

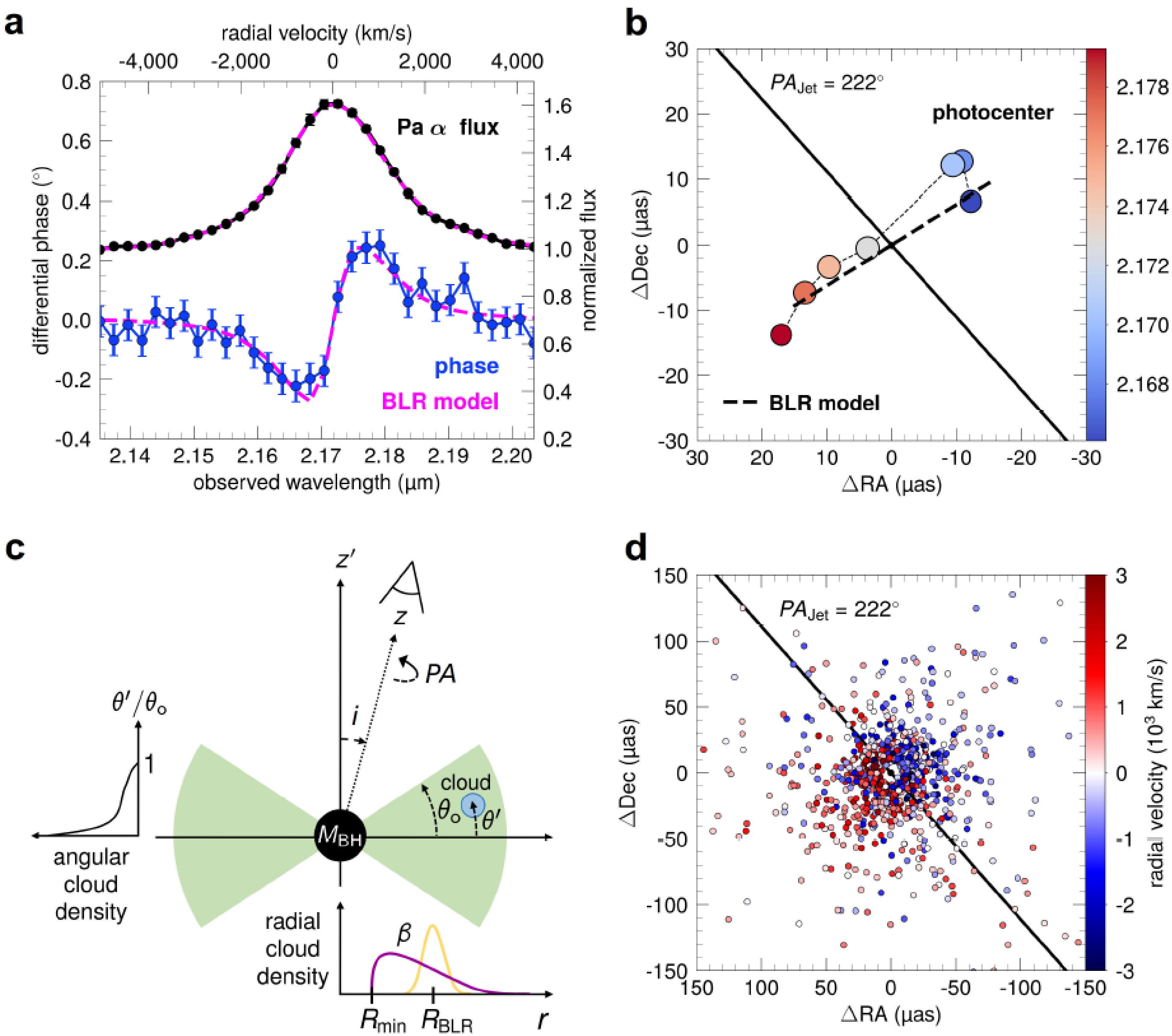
Rs = 2 $GM_{BH}/c^2$

Broad lines expected

*Thi & Papadopoulos 2024*

# 3C273 BLR with GRAVITY

*Sturm et al 2018*



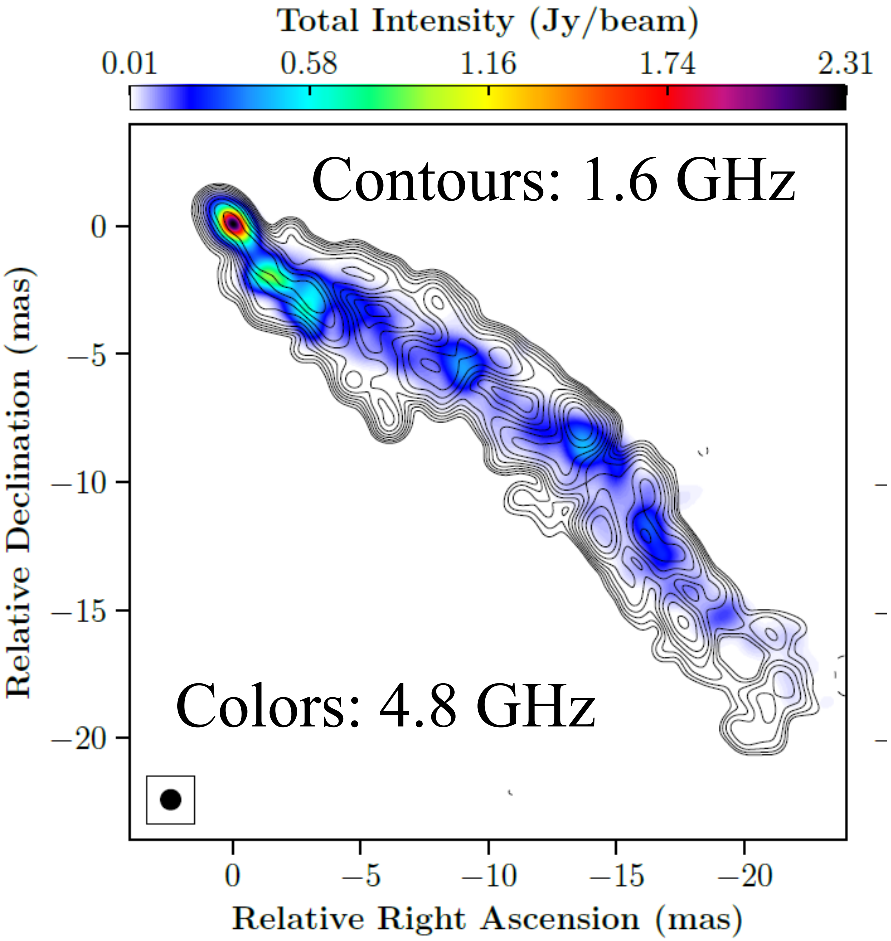

Pa α
Astrometry
10μas
Blue-red shifts
of the BLR

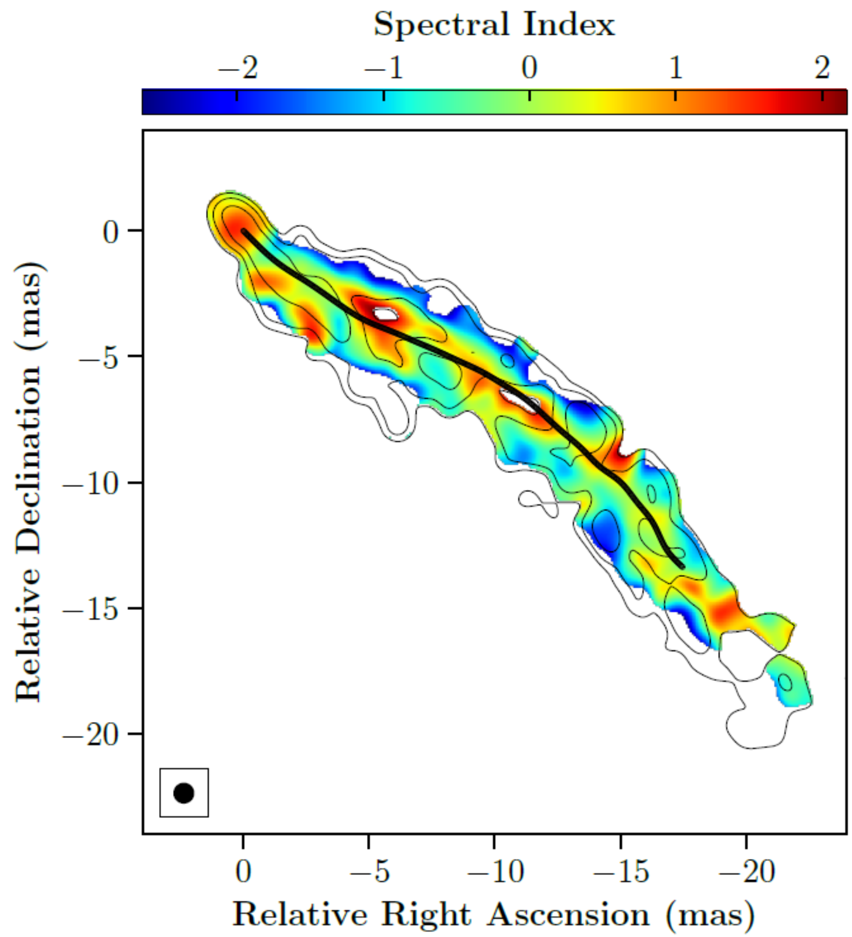
BLR < 0.1mas
D=550 Mpc
z=0.158
$M_{BH}$ =2.6 $10^8 M_\odot$

$R_{BLR}$ = 40μas
2700km/s FWHM

# 3C273 with Radio -Astron

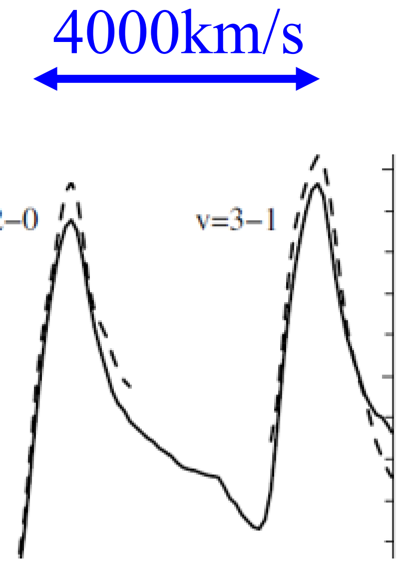
*Bruni et al 2021*
1mas at 1.6GHz,
0.5mas at 4.8 GHz




Spine/sheath structure in the jet,
Limb-brightened at 1.6GHz

# GRAVITY+: BLR CO bandhead




Quite difficult, since the various bands will blend,
if FWHM > 4000 km/s, **or with low inc?**
Cannot separate blue and red-shift like with Pa$\alpha$
S/N lower, but more sensitivity?

$R_{BLR}$ = 0.12 pc in 3C273
With more nearby AGN, D=20Mpc, could be 1mas

Outflow and
BLR rotation?

Could be possible to detect CO v=1-1 and J=3→2
for instance with ALMA
At least spectrally, searching for a broad lines

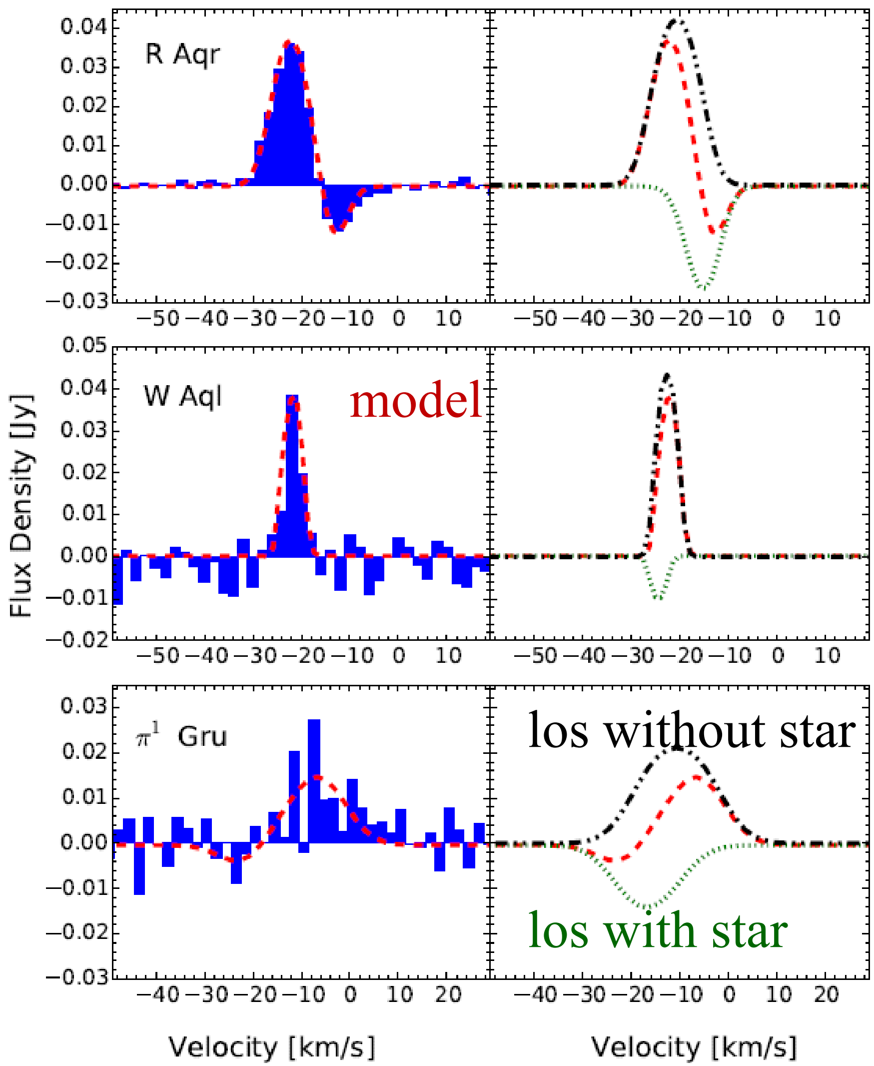
We have observed (40mas) the v=1, J=3-2 line in a parallel band
while looking at molecular tori ➔First look: nothing
Wait for **WSU** Wideband Sensitivity Upgrade?

# ALMA detection of CO v=1: AGB stars

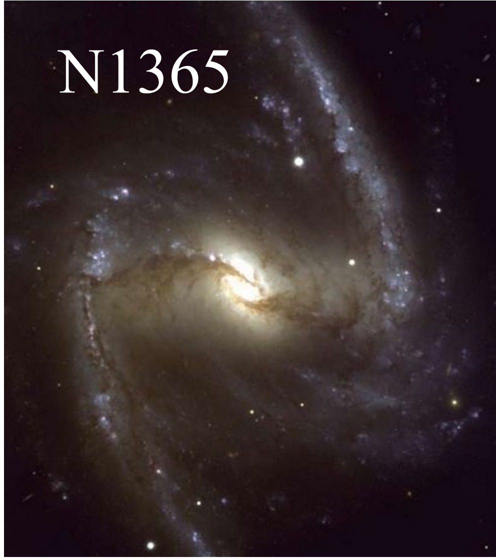
CO v = 1 J = 3 → 2 in 5 AGB stars
Region between the surface and the wind starting place
*Khouri et al 2016*

| | v=1 | v=0 |
|---|---|---|
| CO(1-0) | 114.221752 | 115.271201 |
| CO(2-1) | 228.439074 | 230.537990 |
| CO(3-2) | 342.647636 | 345.795989 |
| CO(4-3) | 456.842977 | 461.040770 |
| CO(5-4) | 571.020677 | 576.267904 |
| CO(6-5) | 685.176392 | 691.473090 |
| CO(7-6) | 799.305677 | 806.651806 |
| CO(8-7) | 913.404136 | 921.799700 |

*Gendriesch et al 2009*



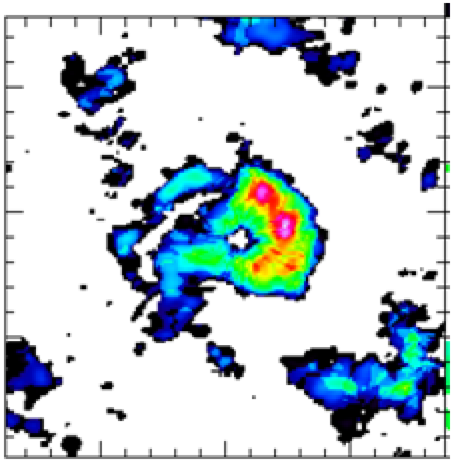
# SUMMARY




➔ **Fueling: Primary bar** drives gas to ILR→ **100pc**
**Then nuclear bar from 100pc to 10pc**

➔ **Feedback: molecular** outflows due to AGN
Radio jets or winds (or both)

N1365 torus



➔ **Molecular tori: decoupling**

➔ **GRAVITY+: try to detect a hot and dense $BLR^0$, with broad lines, $10^5$-$10^6$ $M_\odot$**