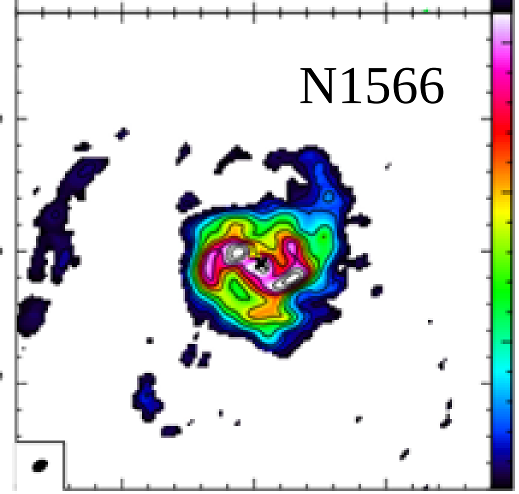
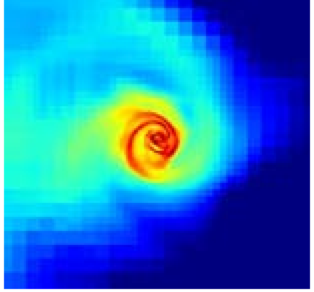
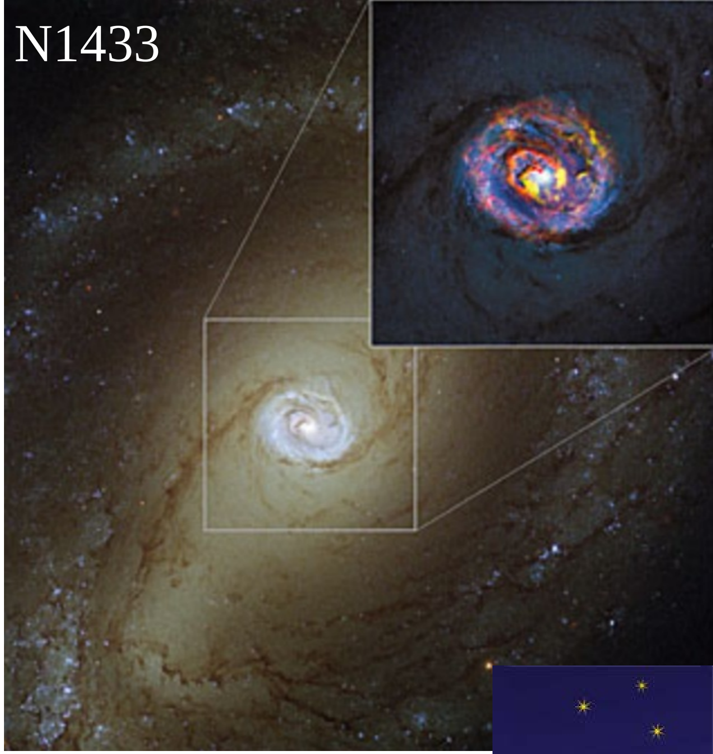
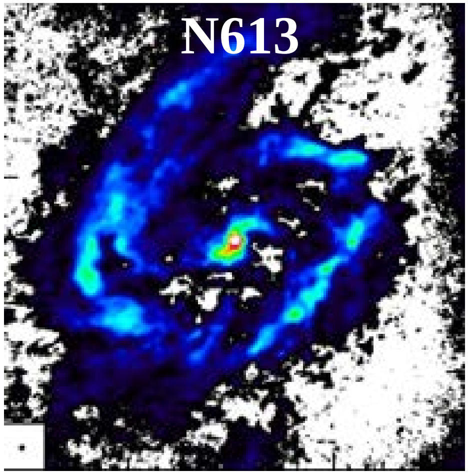






Molecular tori, BH fueling & feedback in nearby AGN

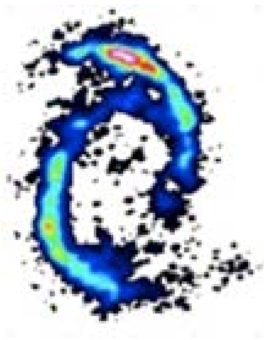


Françoise Combes
Observatoire de Paris

July 2019

Outline

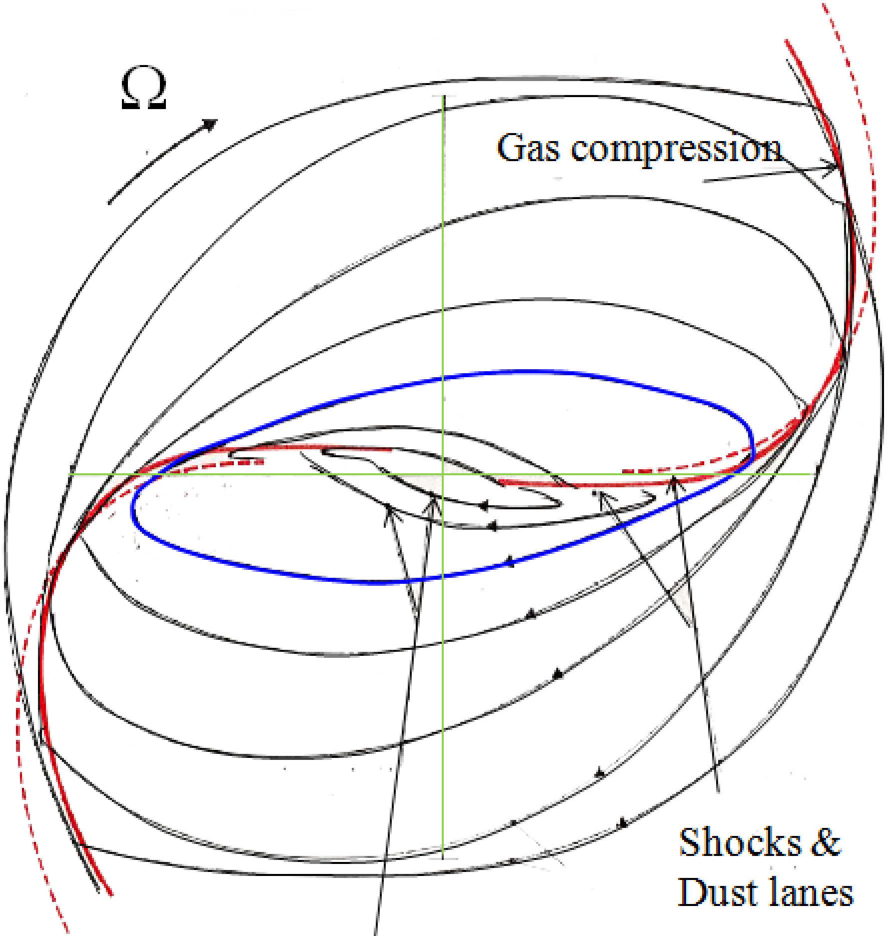
➔ Angular momentum transfer
➔ Dynamical features: nuclear bars & spirals



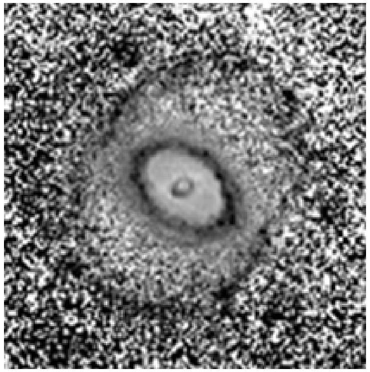
N6951

➔ Fueling due to gravity torques
➔ Feedback, outflows (SF, AGN)

➔ Molecular tori
➔ Decoupling, different orientations

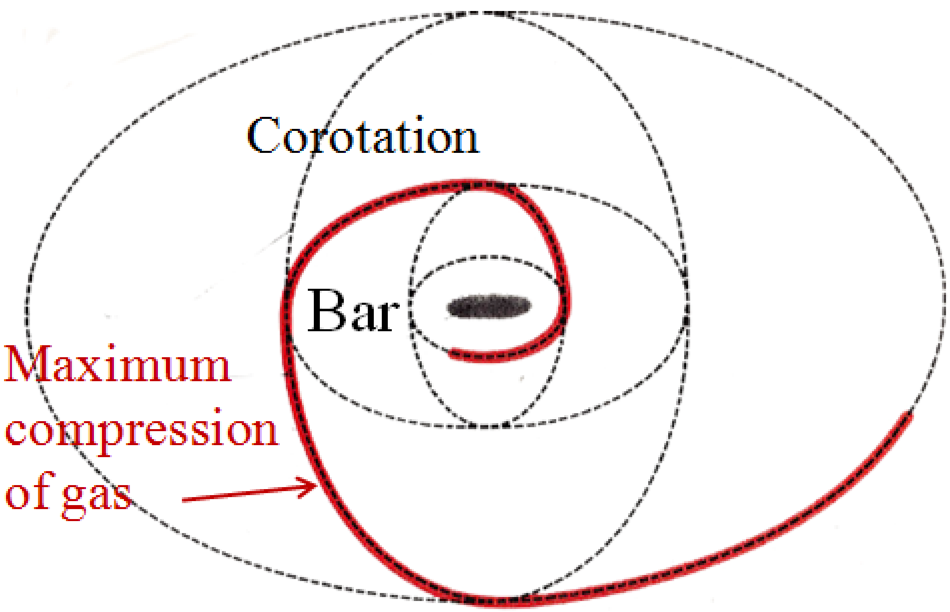


Main features of barred galaxies



N3081

Gas tends to follow periodic orbits
Dissipation, cloud collisions
➔tilt of the ellipses
➔spiral arms

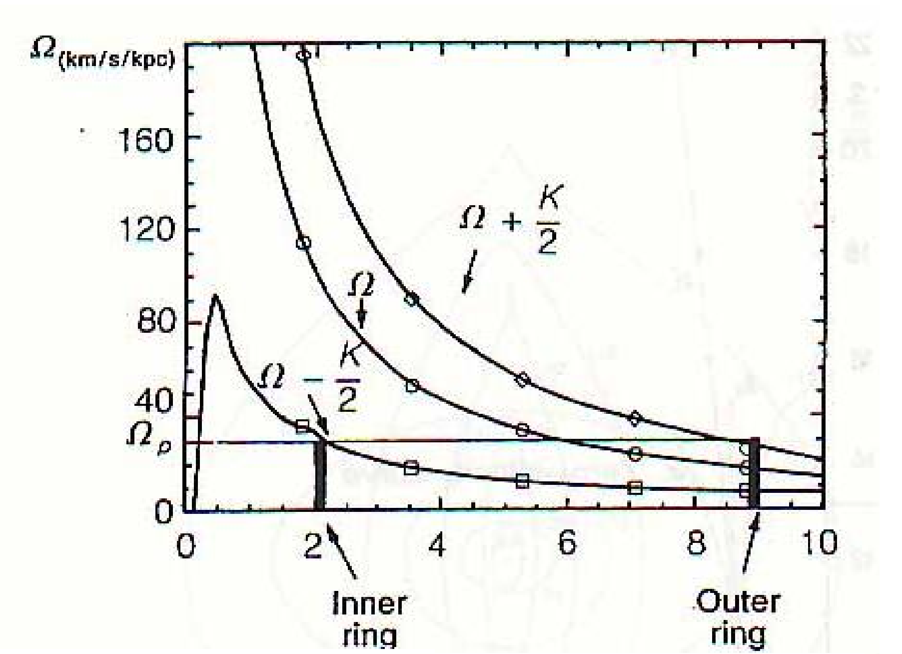


The spiral is open
Rotation of 180-360°

Sanders & Huntley 1976,
Contopoulos, 1980, Athanassoula 1992

Embedded structures

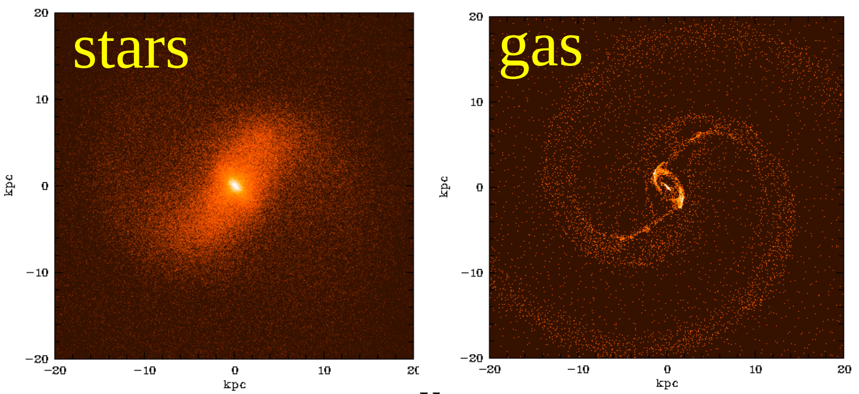
Bars exert a torque on the gas ➔ gas piles up and stalls in a nuclear ring



Decoupling of a secondary bar

In between the two ILR:
perpendicular orbits x2
Do not sustain the bar anymore

New faster bar inside the ILR ring
+ weakening of the bar, z-resonance
Peanut-shape bulge

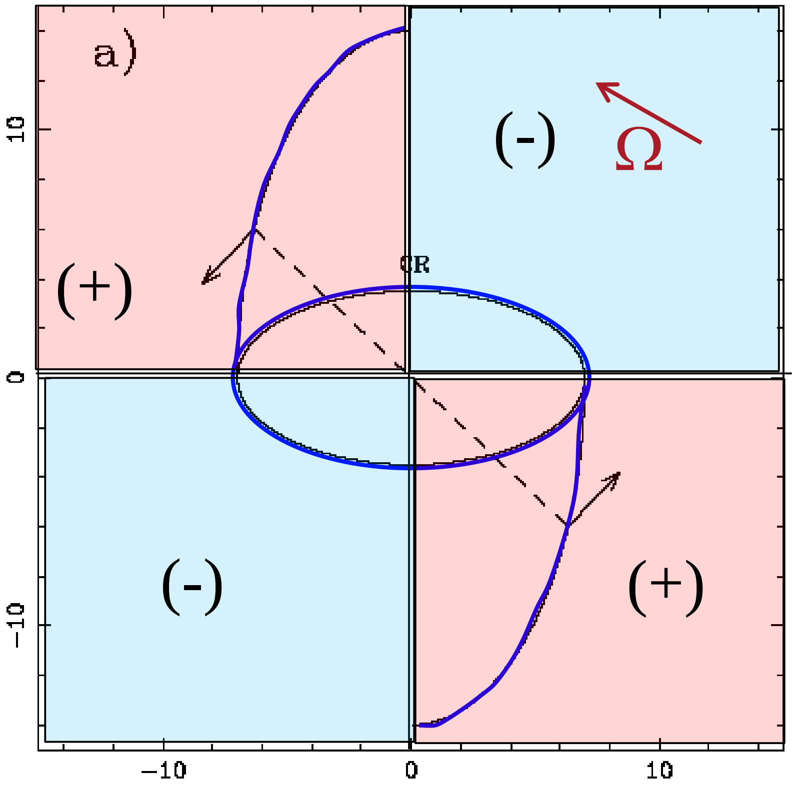


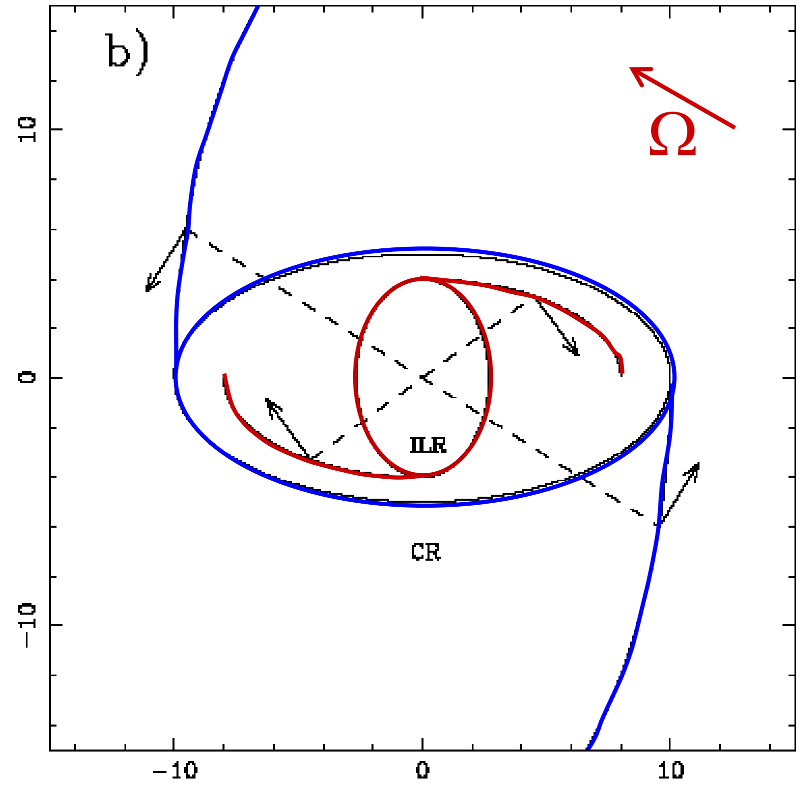
Friedli 1993

Torques exerted on the gas by the bar

Torques change sign at each resonance

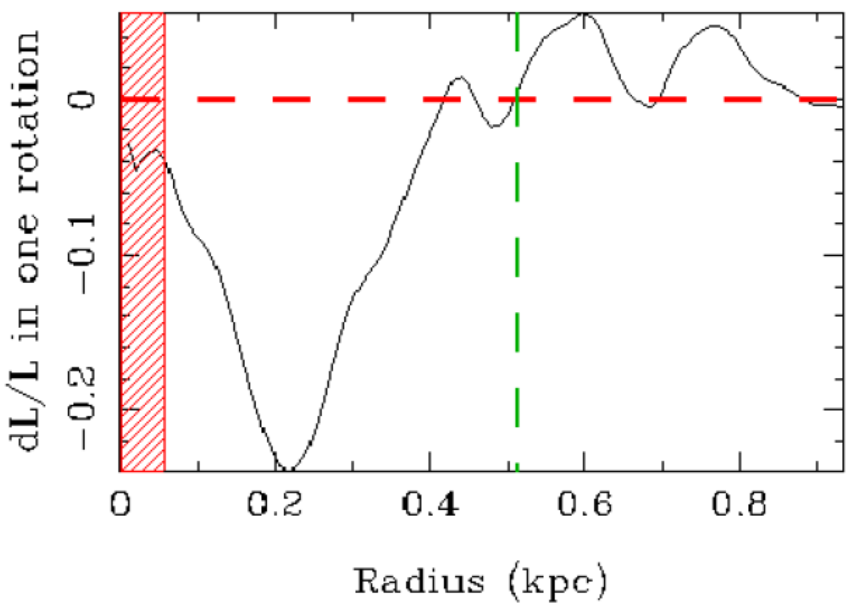
Inside CR, gas loses angular momentum, infalls towards the centre
Outside CR, on the contrary, gas accumulates at OLR

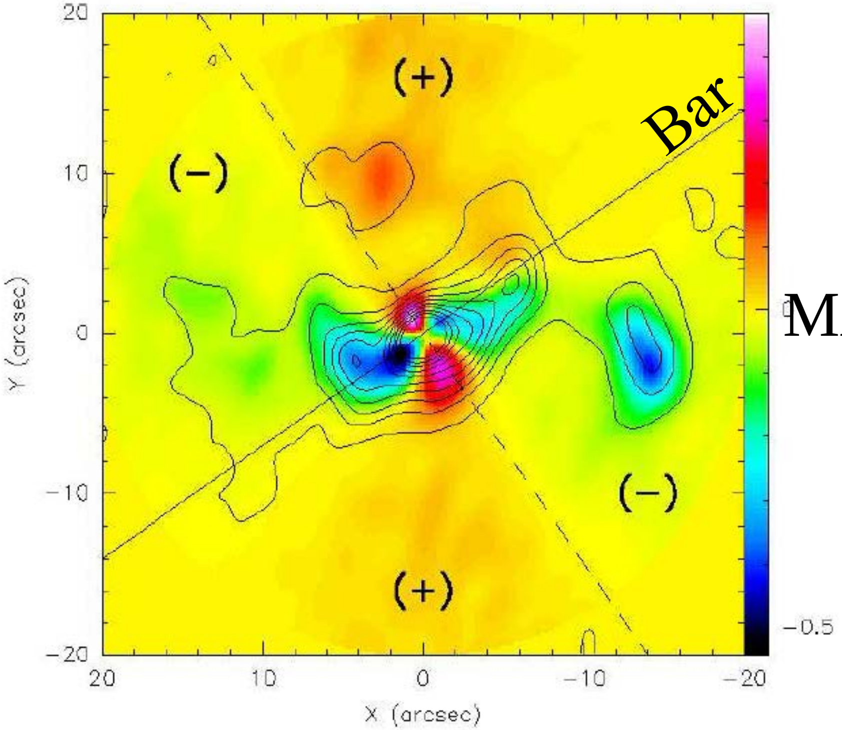




Fueling: Bar gravity torques

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





MA

Torque map for NGC 3627

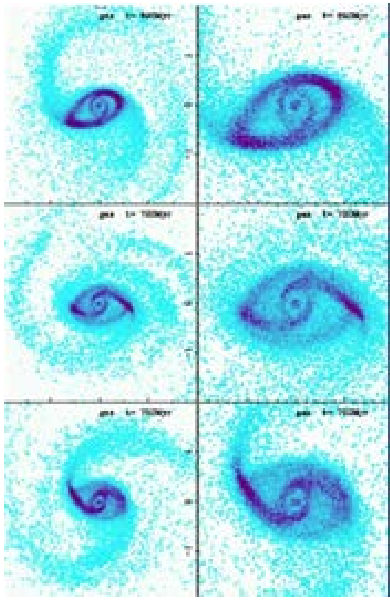
(Casasola et al 2011)

Contours= gas density

Correlation between bars and AGN

Schawinski et al 2010, Masters et al 2011, Cardamone et al 2011, Alonso et al 2014

Statistics -- Time-scales
10-100pc fueling

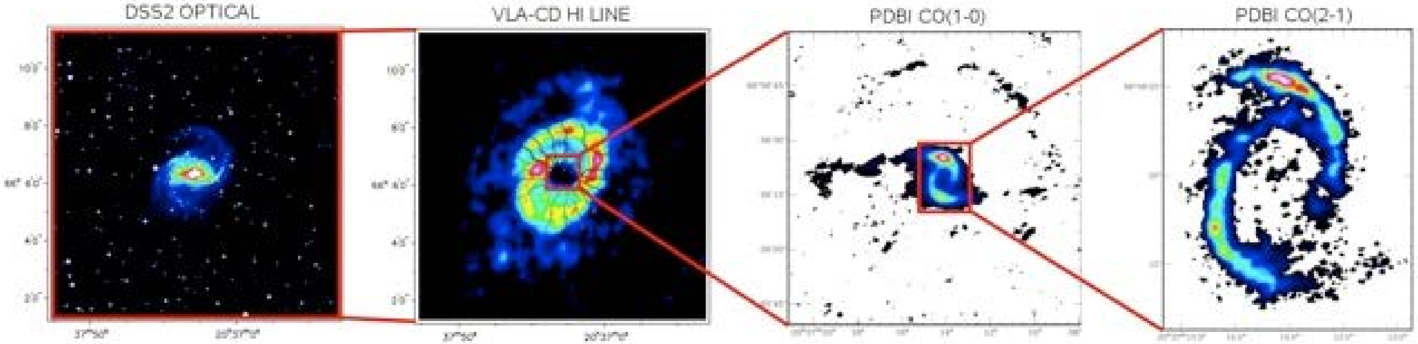


➔ **Only ~35%** of negative torques in the center,
About 20 galaxies *(Garcia-Burillo & Combes 2012)*

➔ Rest of the times, positive torques, gas stalled in ring

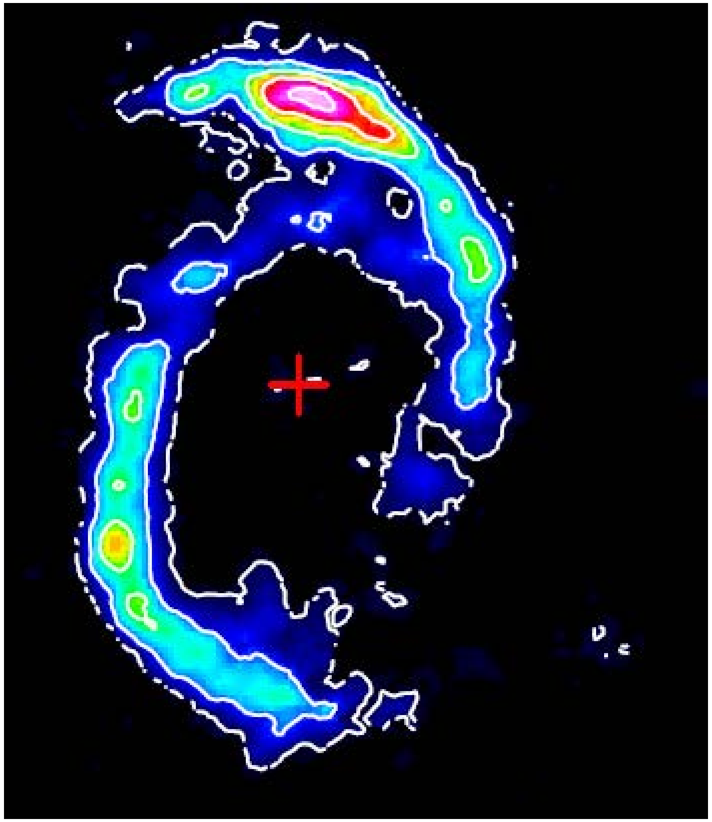
➔ **Fueling phases are short, a few 10^7 yrs** (feedback)

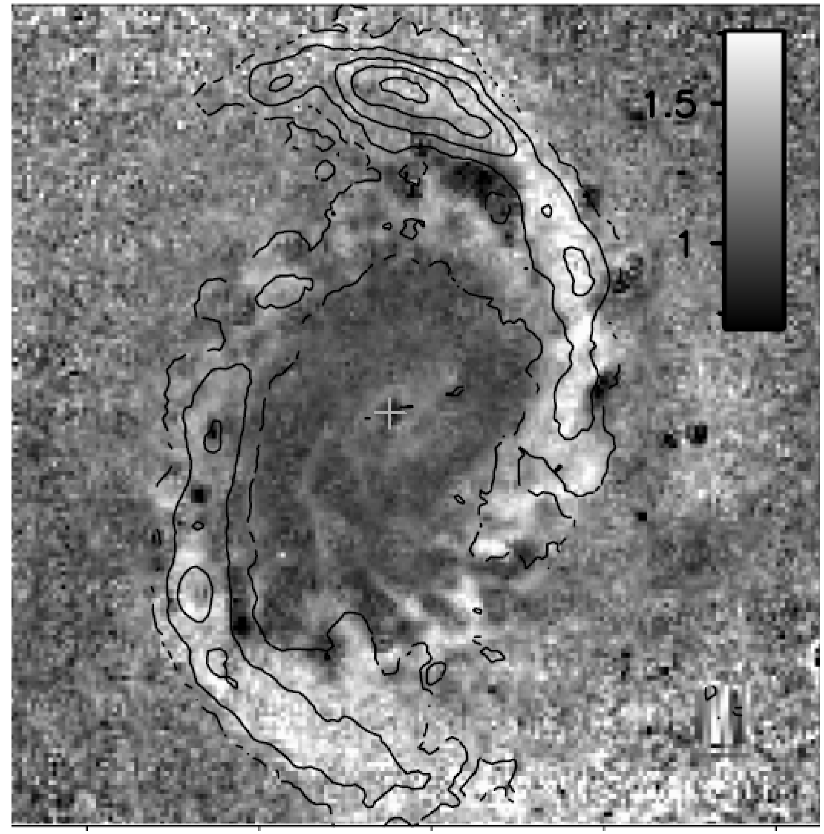
➔ Star formation fueled by the torques, always associated to AGN activity, but with longer time-scales

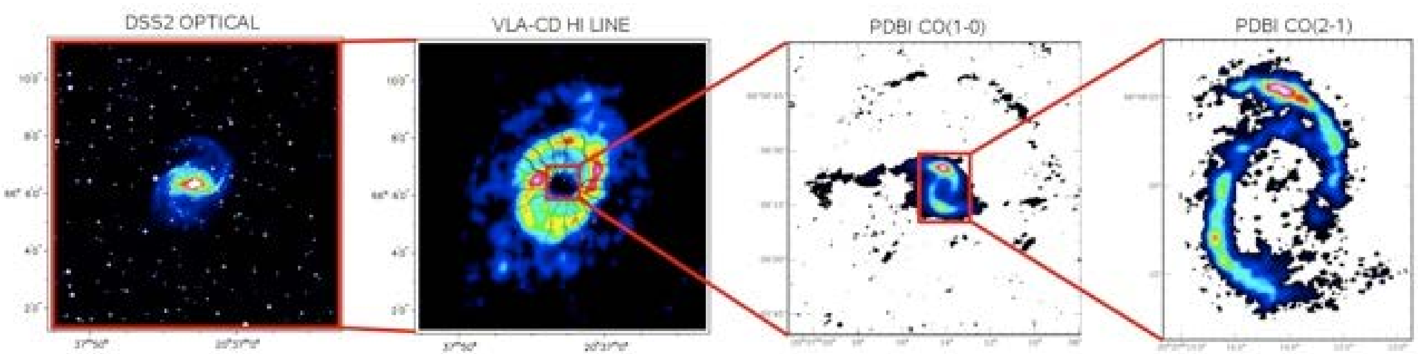


NGC 6951: no gas in the center

Van der Laan 2011



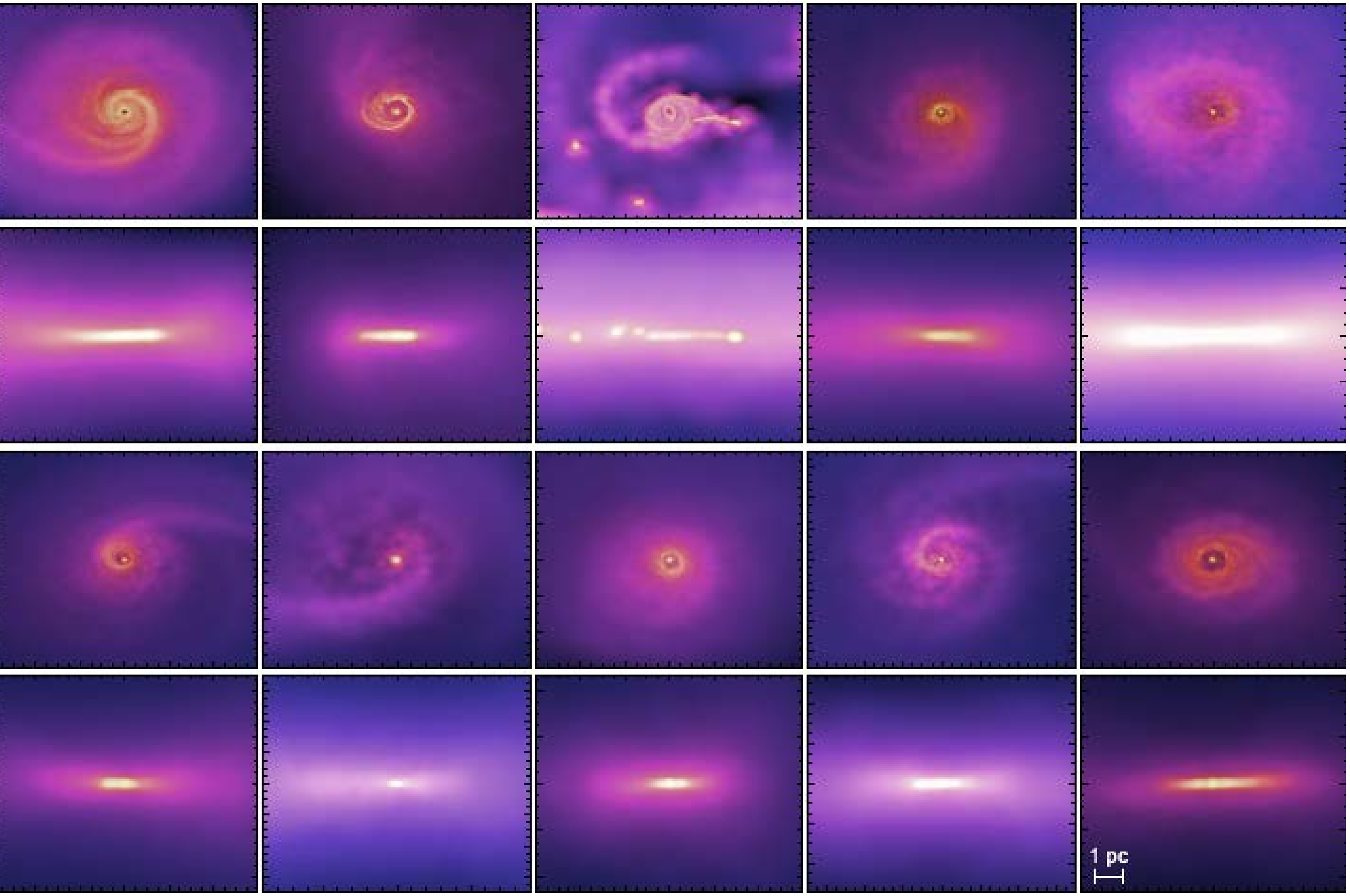




Small-scale accretion

Simulations of gas accretion onto a central BH➔ thick disks (~10pc)

Zoomed simulation: cascade of m=2, m=1, + clumps and turbulence



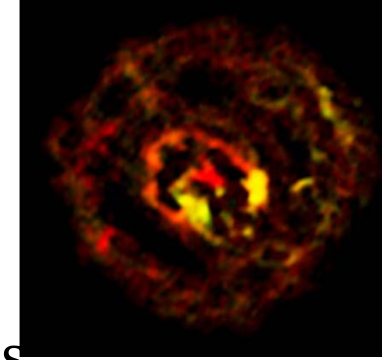
When fgas large
10^{22}-10^{25} cm^{-2}
Clump unstable
Warps, twists
Bending
➔Thick disks

➔Dynamical friction of GMC
If M= 10^6 $M_\odot$
t~80Myr $(r/100pc)^2$
varies in 1/M

Hopkins et al 2011

Gas is piling up in the center: up to f=90%

A second gas rings + outflow



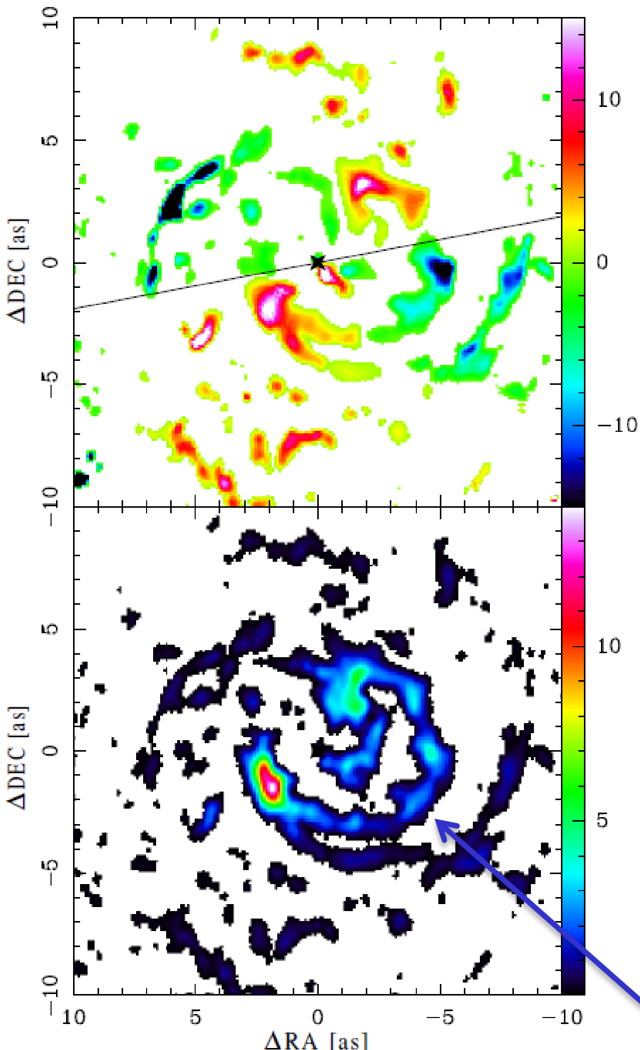
NGC 1433: barred spiral, **CO(3-2) with ALMA**
Molecular gas fueling the AGN, + outflow // the minor axis

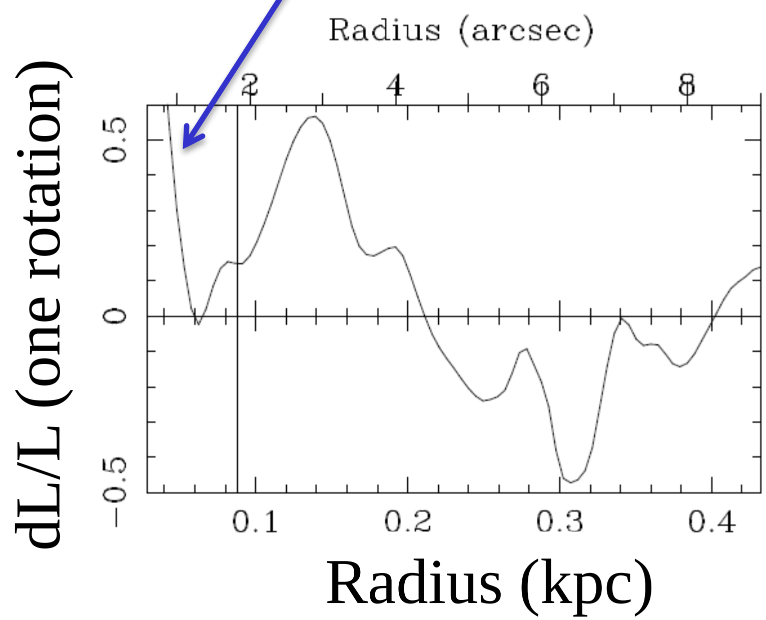
M_{H2}= 5.2 10^7 $M_\odot$ in FOV=18"
100km/s flow
7% of the mass= 3.6 10^6 $M_\odot$
Smallest flow detected

➔ L_{kin}=0.5 dM/dt v^2 ~2.3 10^{40} erg/s
L_{bol} (AGN)= 1.3 10^{43} erg/s
Combes et al 2013

Gravity torques fuel the ring, where gas is stalled
Smajic et al 2014

Torque map in NGC1433





Torques are positive inside 200pc and negative outside

➔ Gas is piling at the 2nd ring

Smajic et al 2014

2nd ring at 200pc= ILR of the nuclear bar

The NGC1566 barred Sy1: feeding phase

N1566 SAB Sy1

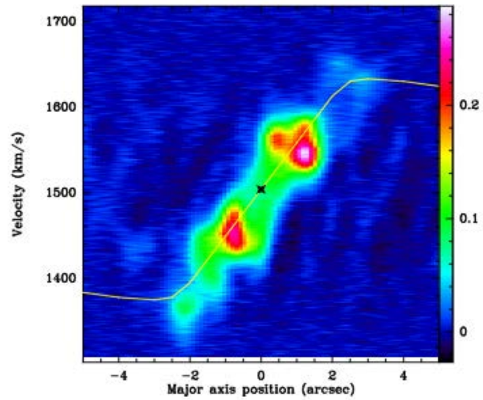
4 arcmin

FOV=18 ’’

Spatial resolution

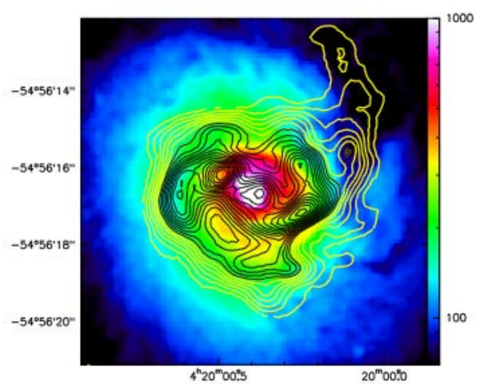
0.5 arcsecond ~25pc

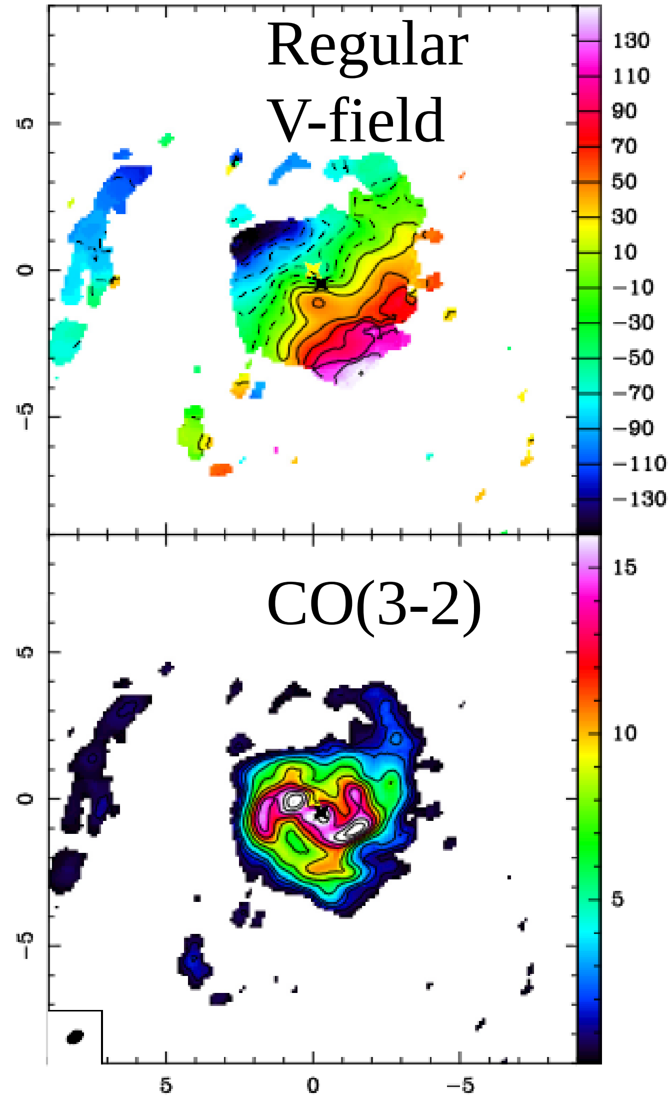
Combes et al 2014



PV major axis

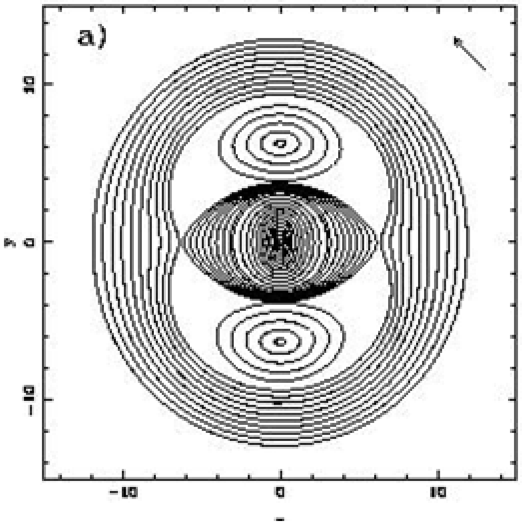
No outflow



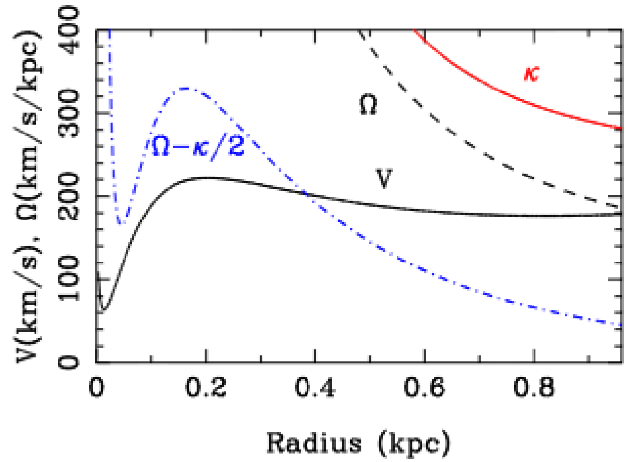


Overlay CO(3-2) contours on HST image

Schematic orbits, and gas behaviour



Stellar periodic orbits



Periodic orbits in a potential in cos 2θ

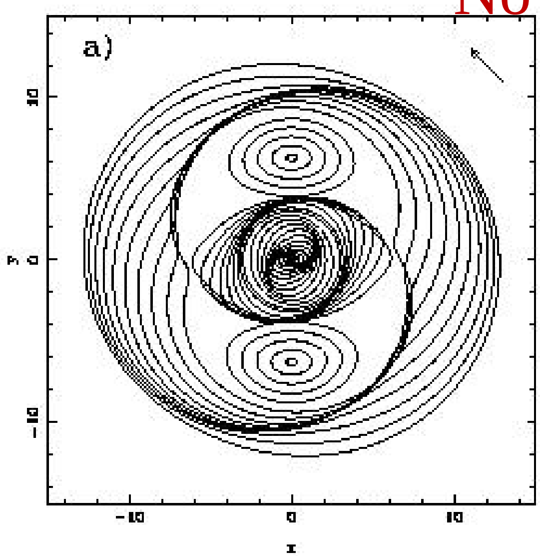
The gas tends to follow these orbits, but rotates gradually by 90° at each resonance

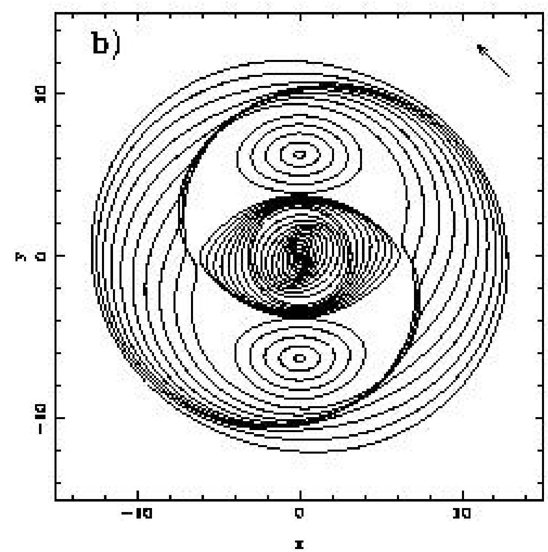
No BH

BH

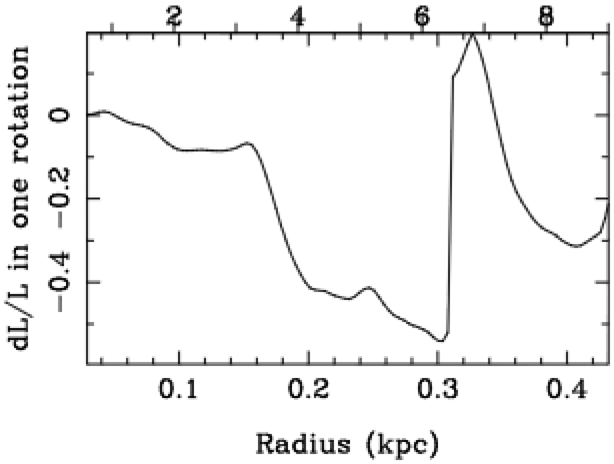
a) without BH, leading

b) with BH, trailing



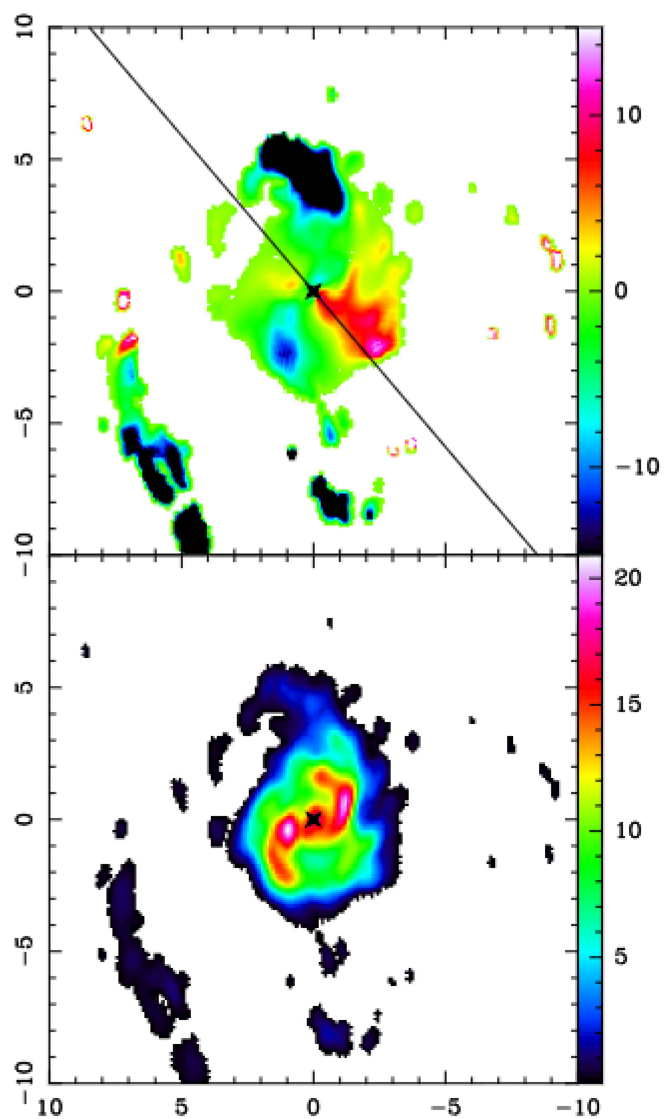


NGC1566: gravitational torques



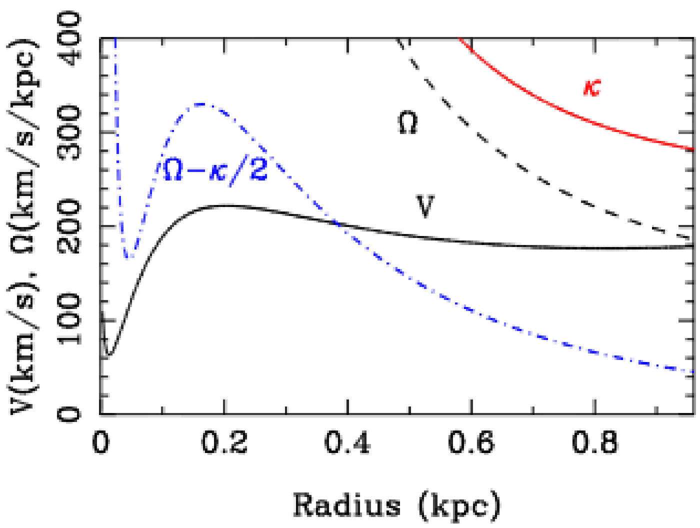
Gas is driven inwards

Torques on deprojected image



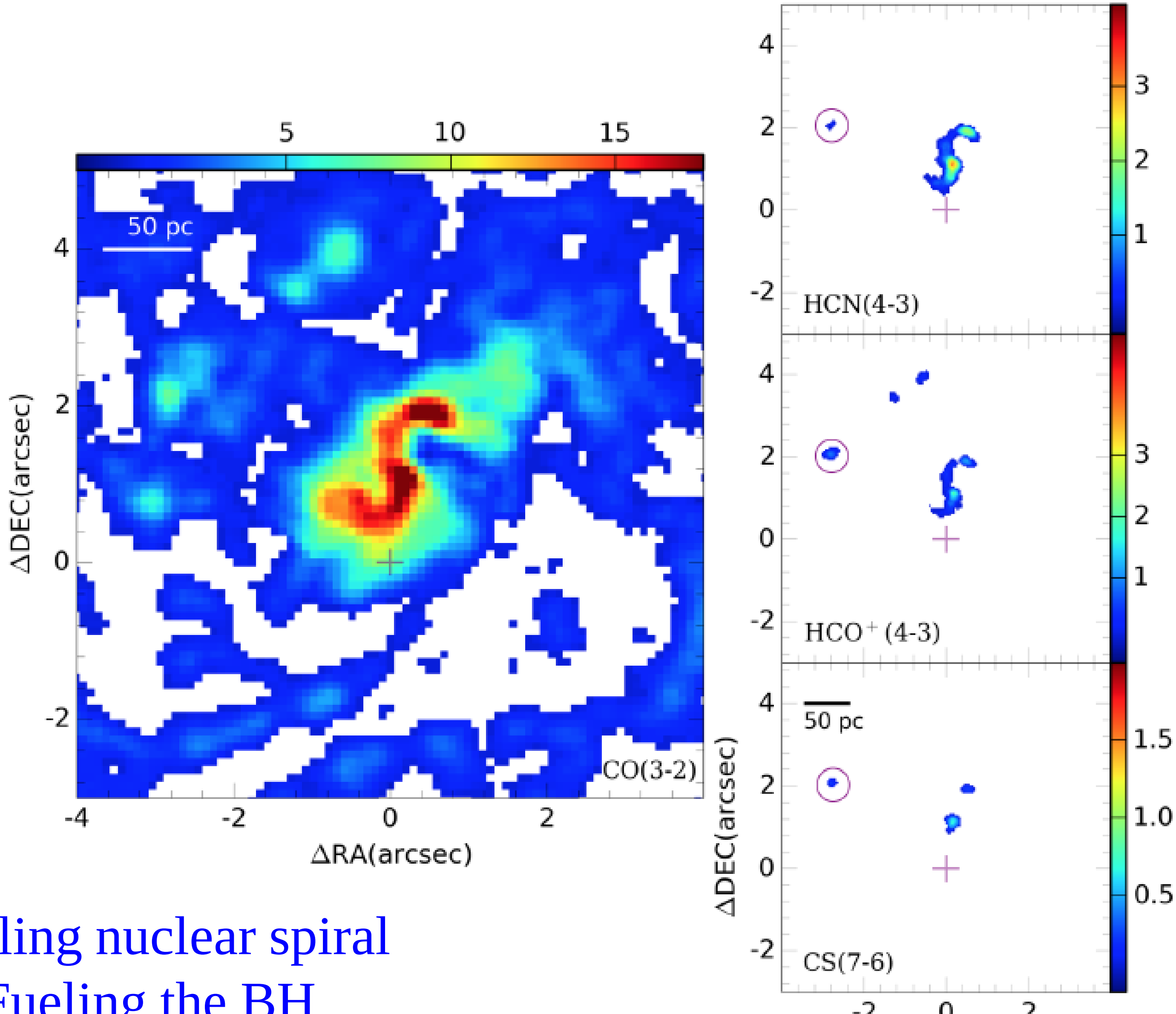
Trailing spiral inside the ILR ring of the bar

➔ BH influence on the dynamics



NGC 1808

Beam 0.08" =4pc



Trailing nuclear spiral

➔ Fueling the BH

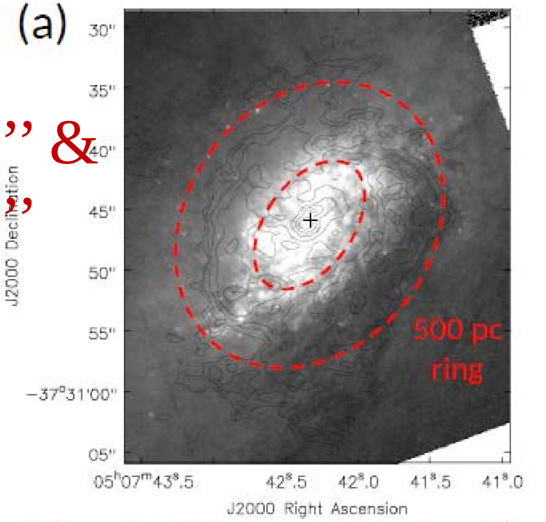
Audibert et al 2019

NGC 1808

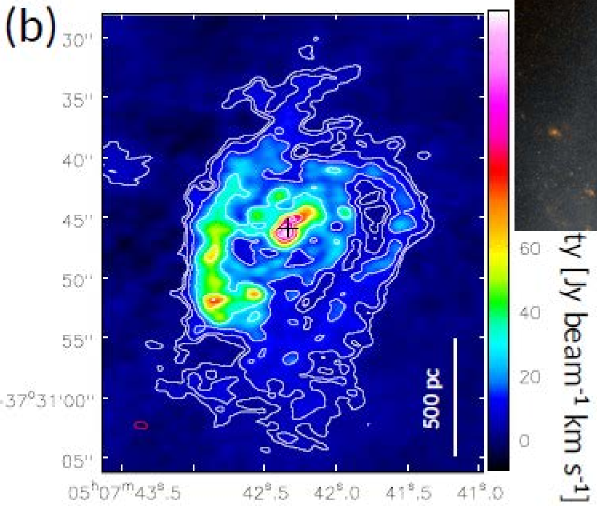
Salak et al 2017

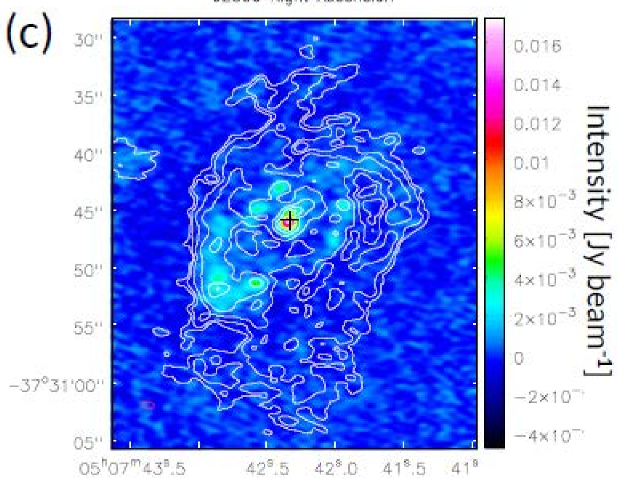
CO32 contours on HST

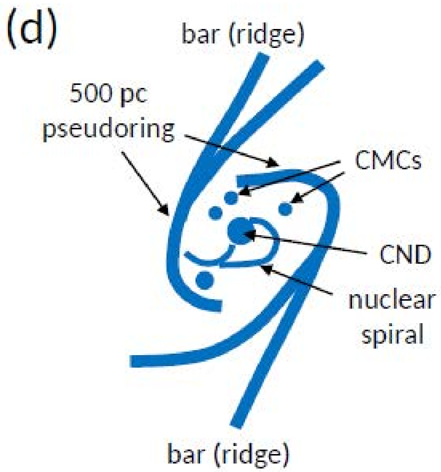
12'' & 25''

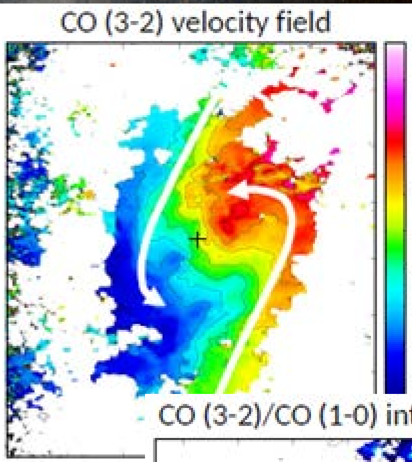


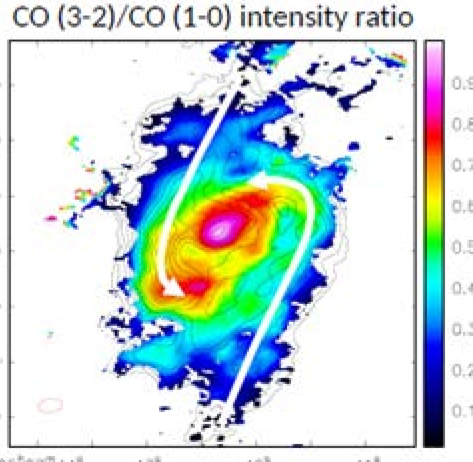
CO32 beam 1''



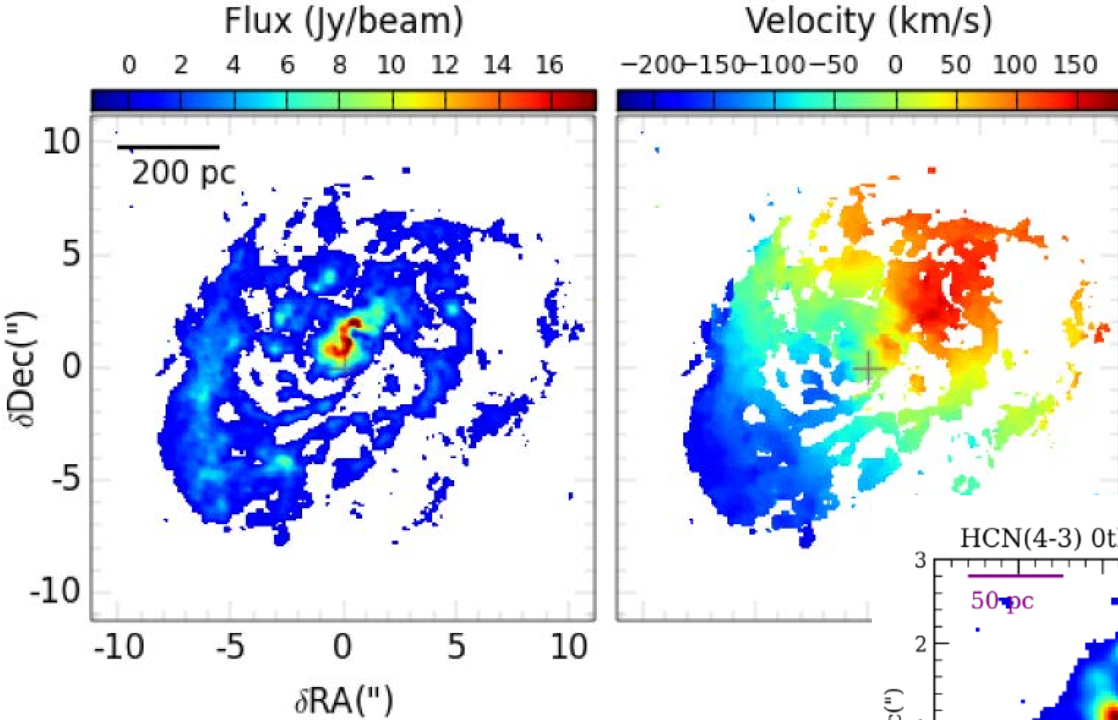








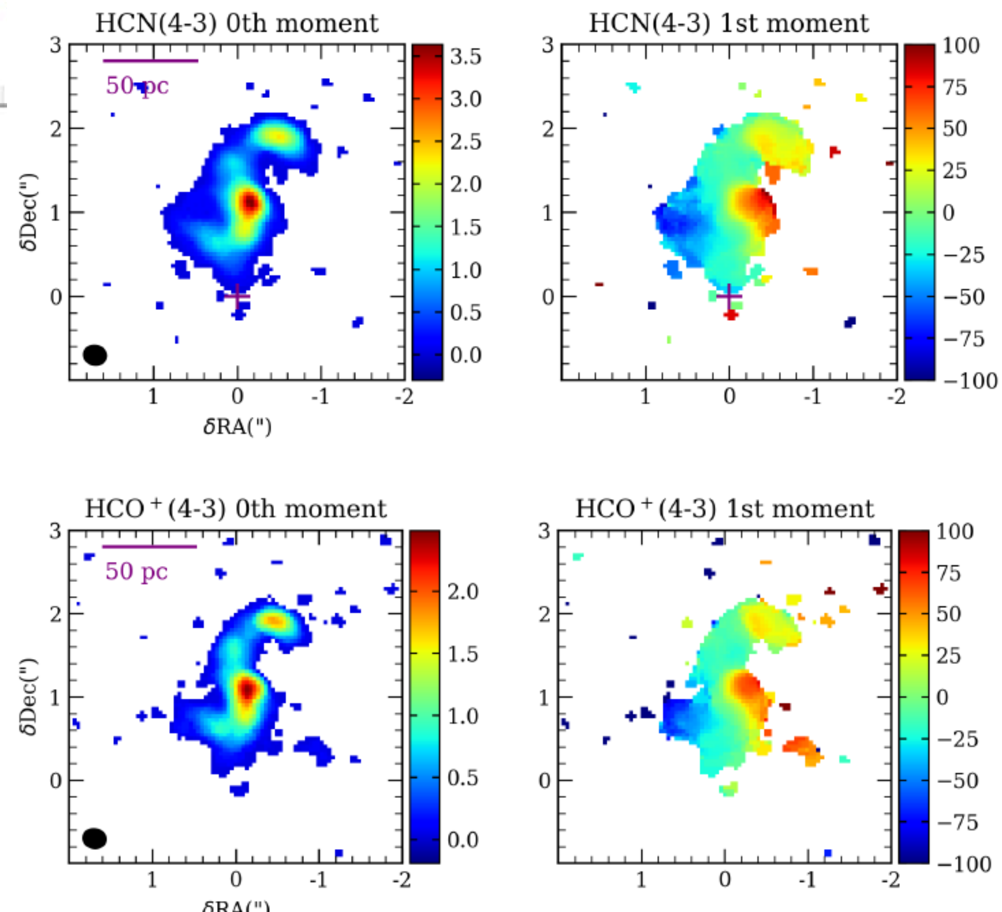
CO32 contours on continuum



PA=323° nuclear disk

Tilted torus PA~270°

R_{torus}=6pc =0.13''



Trailing nuclear spiral
➔ Fueling the BH

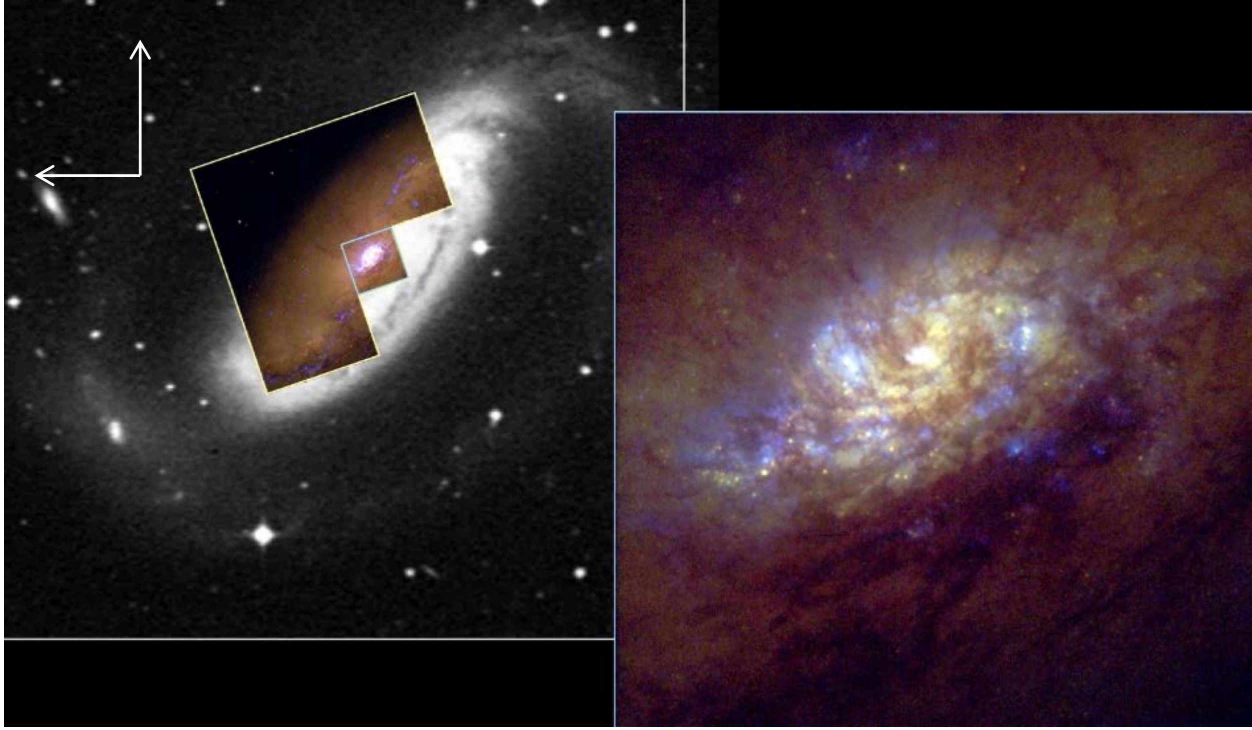
NGC 1808

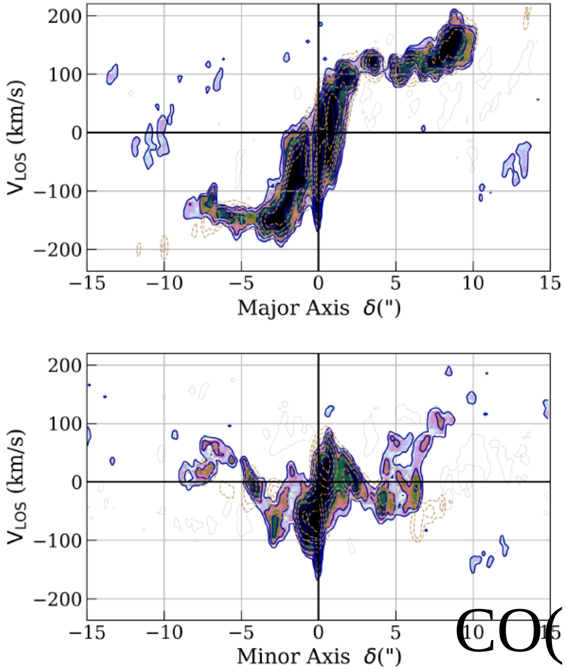
Audibert et al 2019

NGC 1808

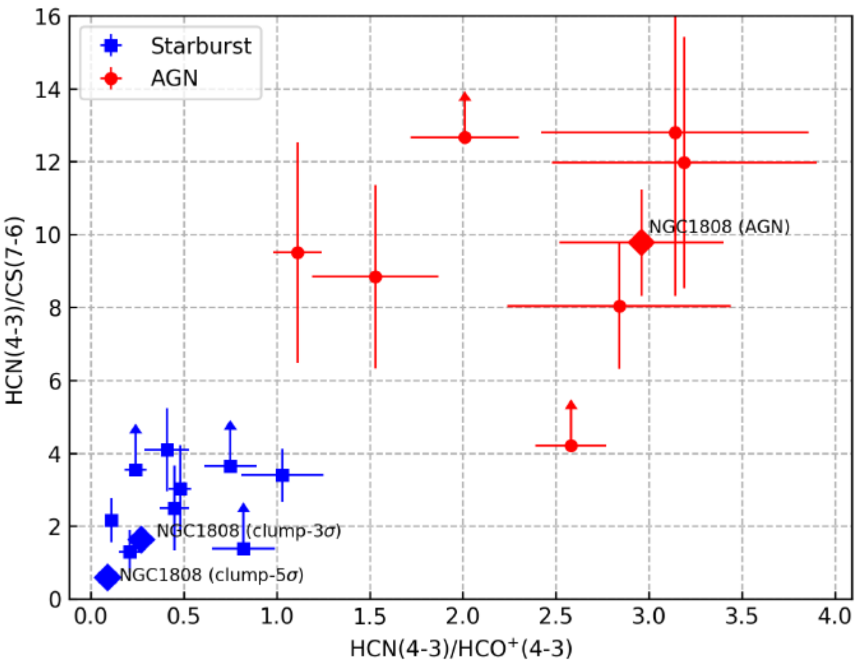
No outflow in CO close to the center

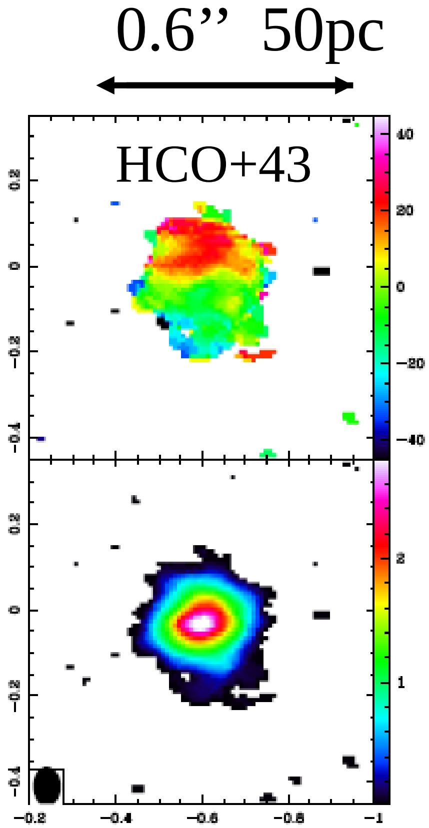
But outflow at larger scale
➔ Due to starburst

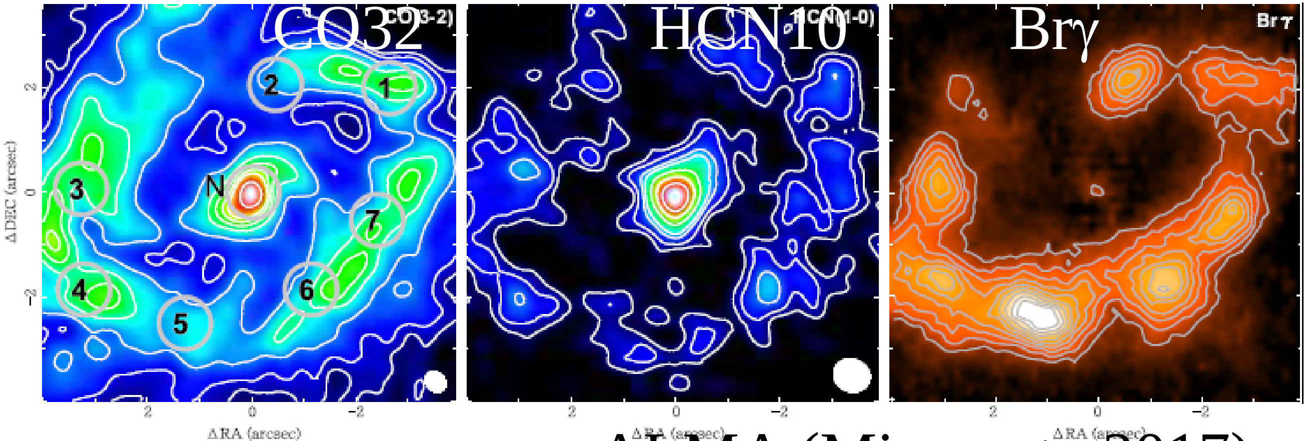




CO(3-2)



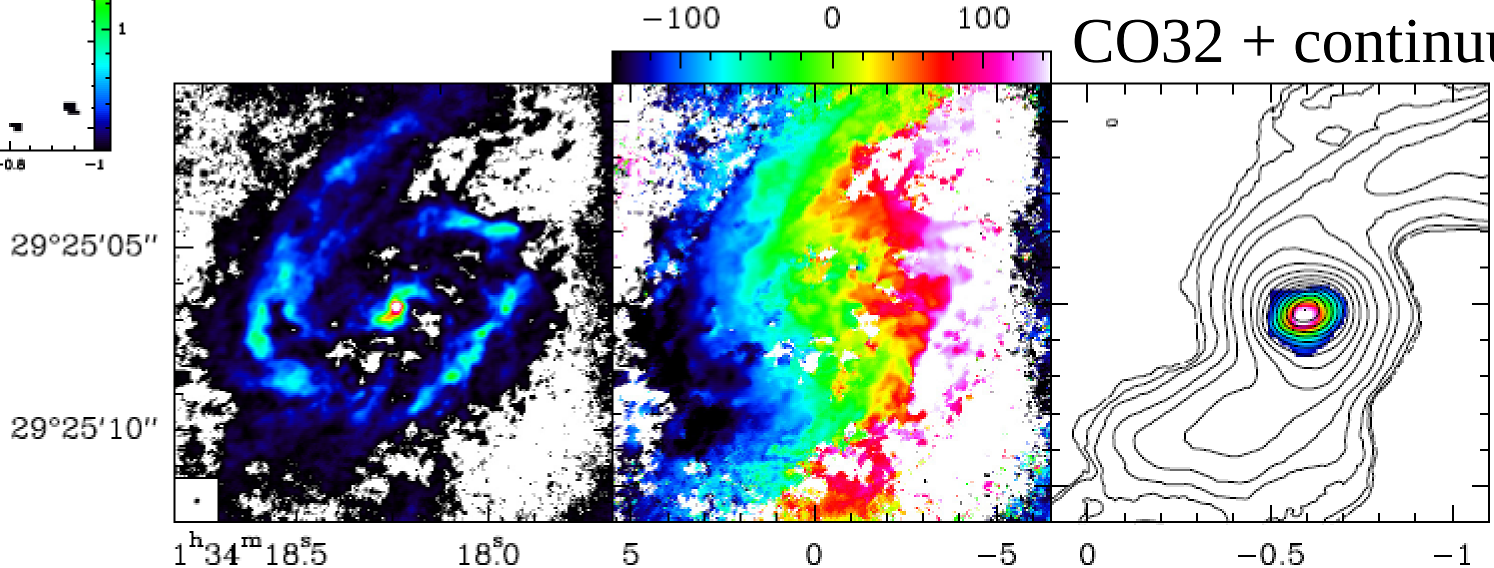




ALMA (Miyamoto 2017)

NGC613

CO32 + continuum

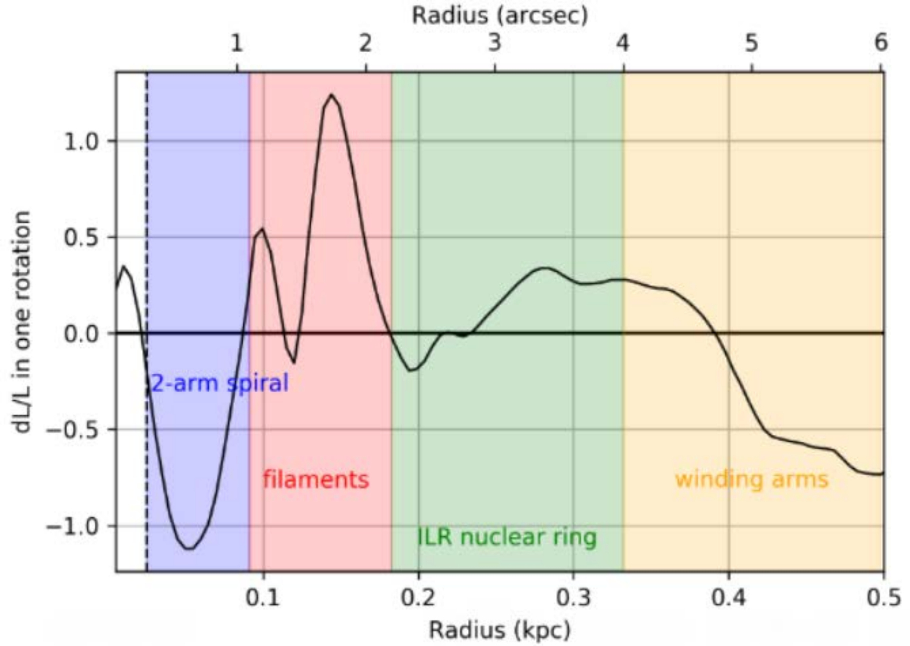


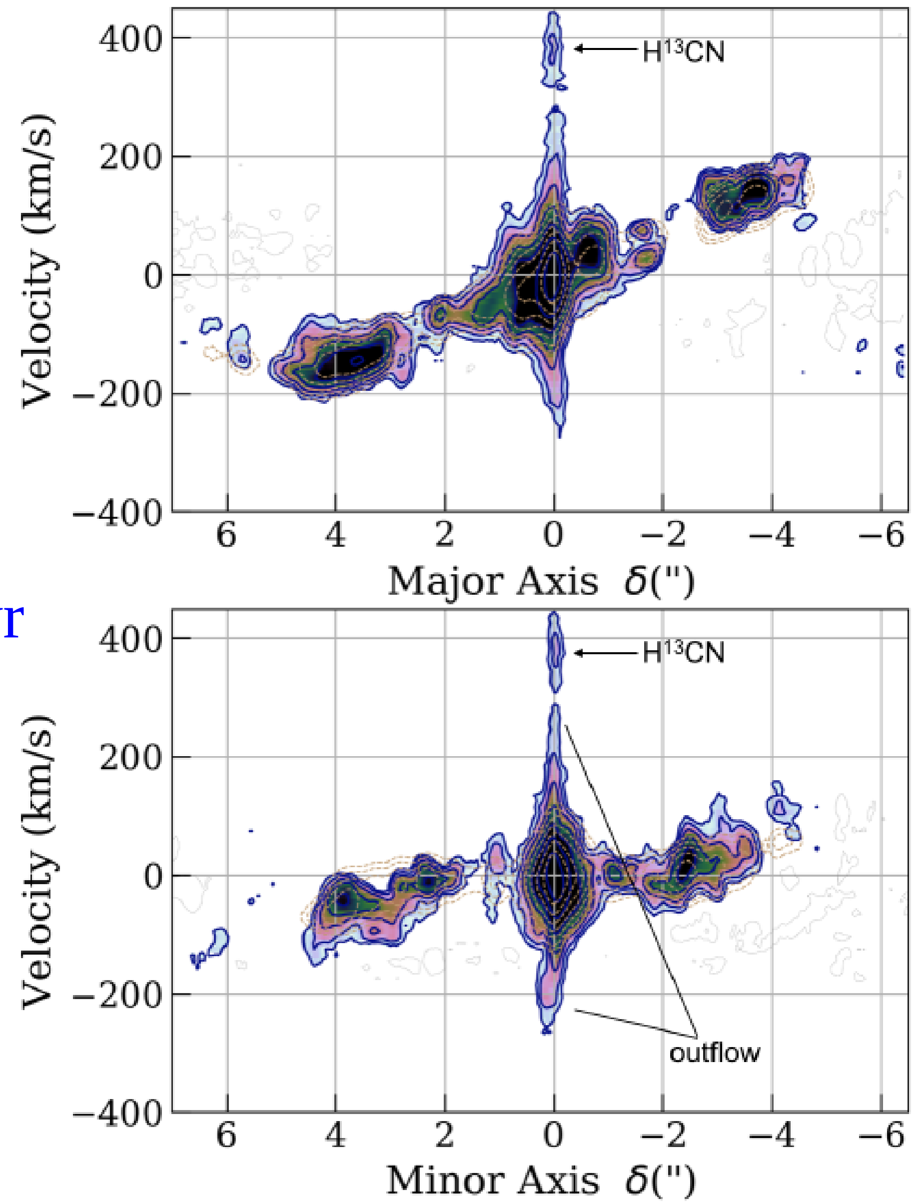
With 0.09'' x 0.06'' resolution (5pc): nuclear spiral +torus

Combes et al 2019

Average gravity torque

NGC 613: Outflow





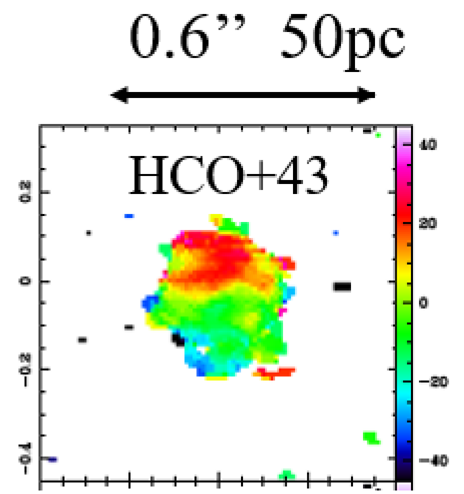
The gas infalls in 1 rotation~10Myr

$M_{out} = 2\ 10^6\ M_\odot$

$\dot{M}_{out} = 15\ M_\odot$ /yr

Audibert et al 2019

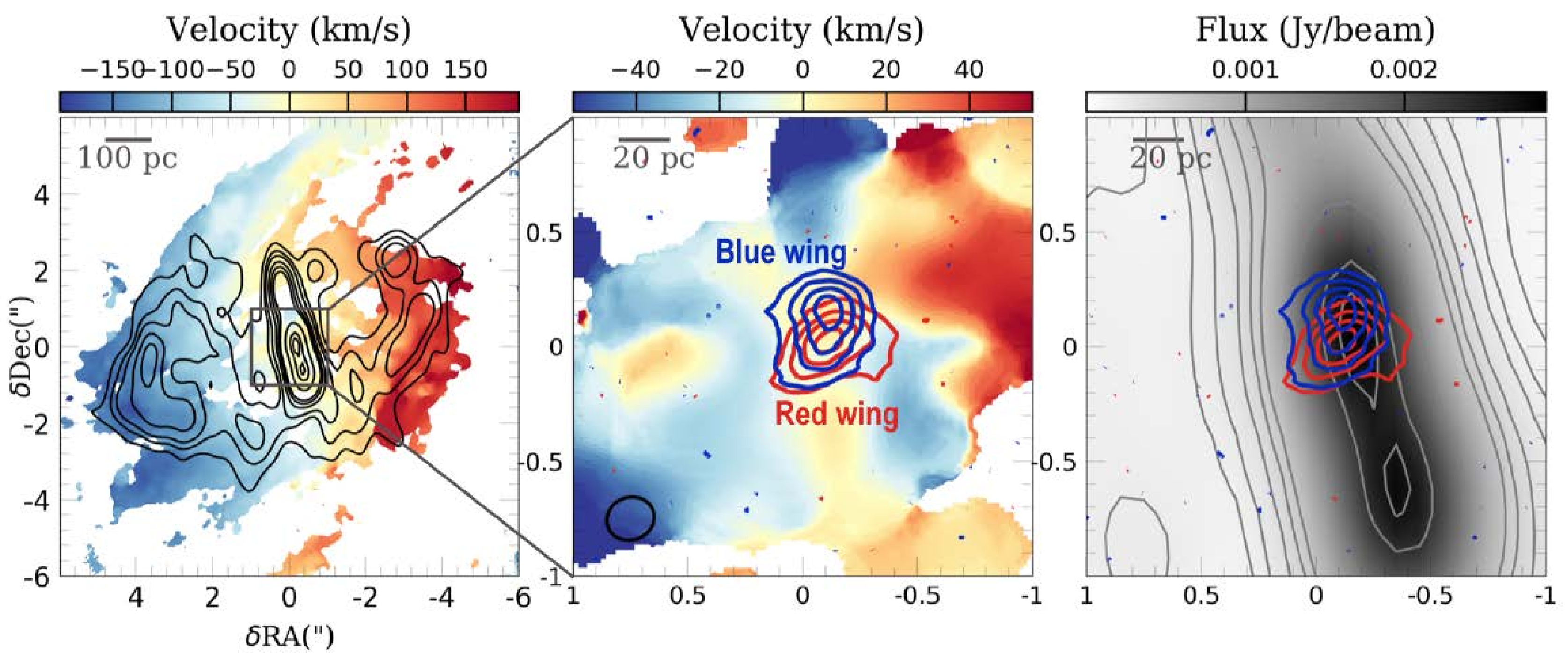
Flow parallel to the radio jet



The molecular torus is R=14pc =0.17”

Difficult to disentangle with the outflow, of size R_{out}=23pc=0.28”, V_{out}=300km/s

But reverse sense!

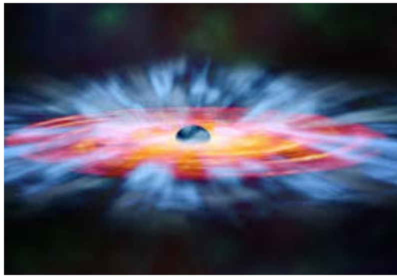


Two main modes for AGN feedback

Quasar mode: radiative or winds

When L close to Eddington, young QSO, high z

L_{Edd} ~M_{BH}/σ_T ➔ M_{BH} ~f $\sigma_T \sigma^4$, f gas fraction



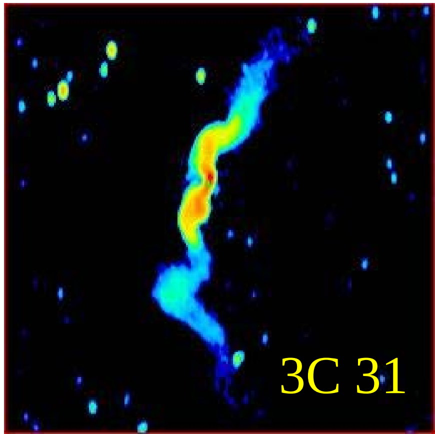
Same consideration with radiation pressure on dust, with σ_d
σ_d / σ_T ~1000, limitation of Mbulge to 1000 M_{BH} ? (e.g. Fabian 2012)

Radio mode, or kinetic mode, jets

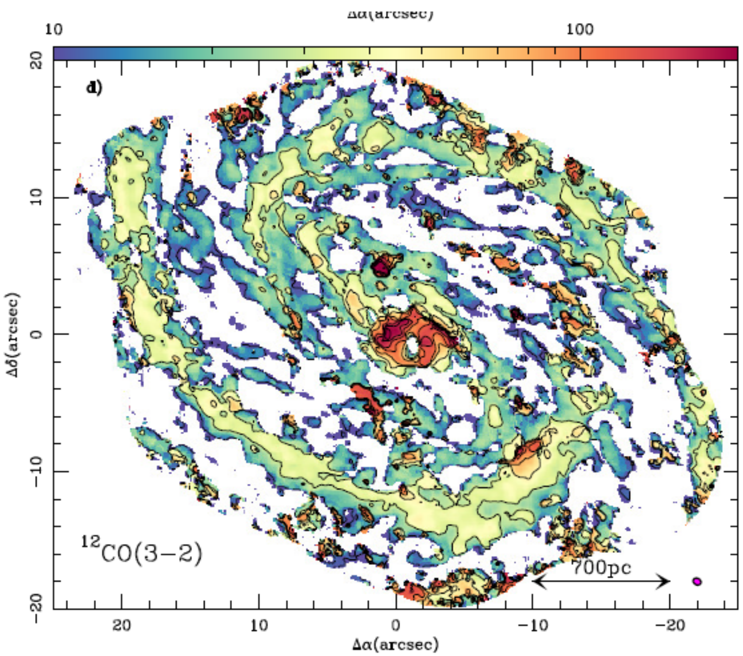
When L < 0.01 L_{edd}, low z, Massive galaxies, Radio E-gal

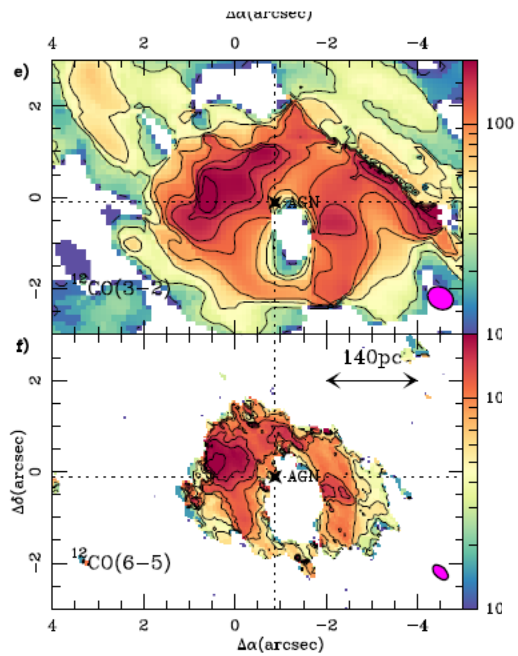
Radiatively inefficient flow ADAF

High frequency of cooling flows in clusters,
Low-luminosity AGN, Seyferts

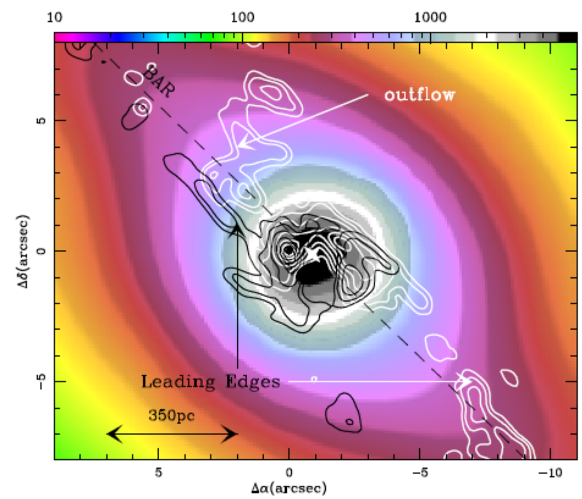


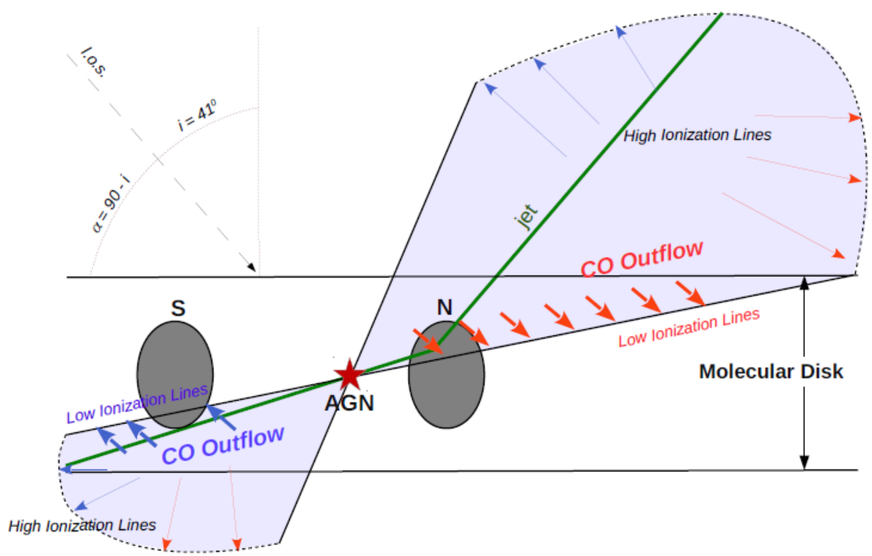
Offcentered nucleus and outflow in NGC1068





Black V=-50km/s
White V=50km/s



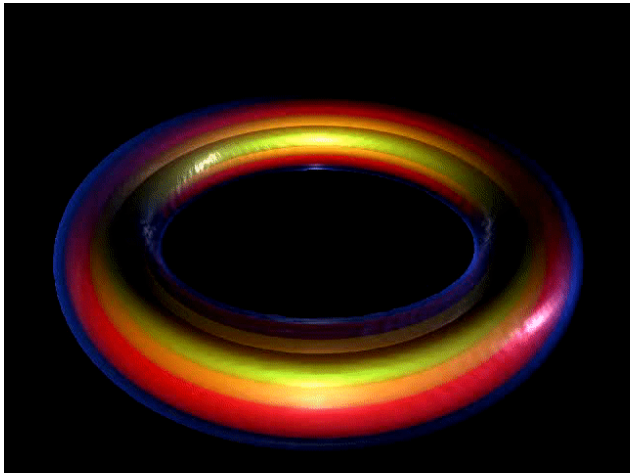


Outflow of $63 M_{\odot}$/yr
10x the star formation rate
in this region

Garcia-Burillo, Combes, Usero et al 2014

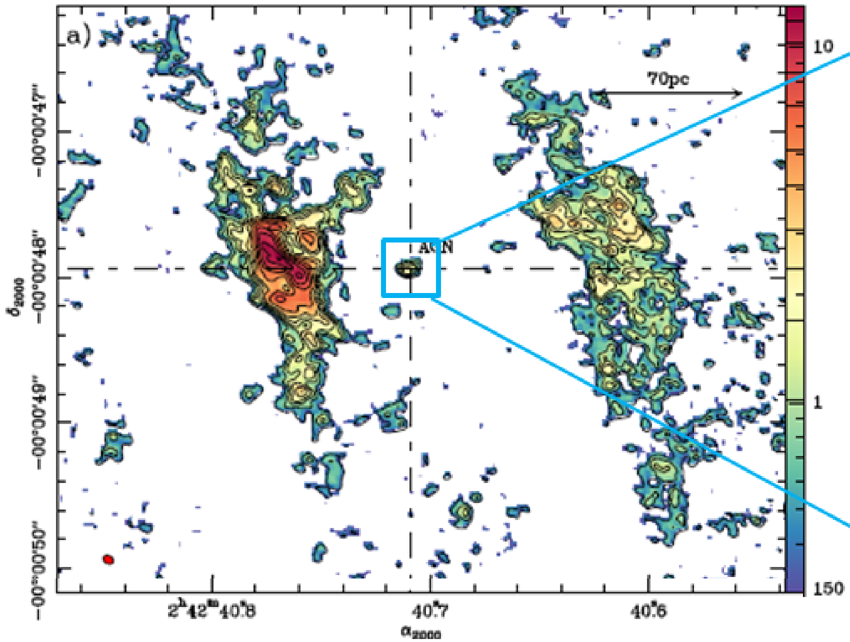
Detection of molecular tori

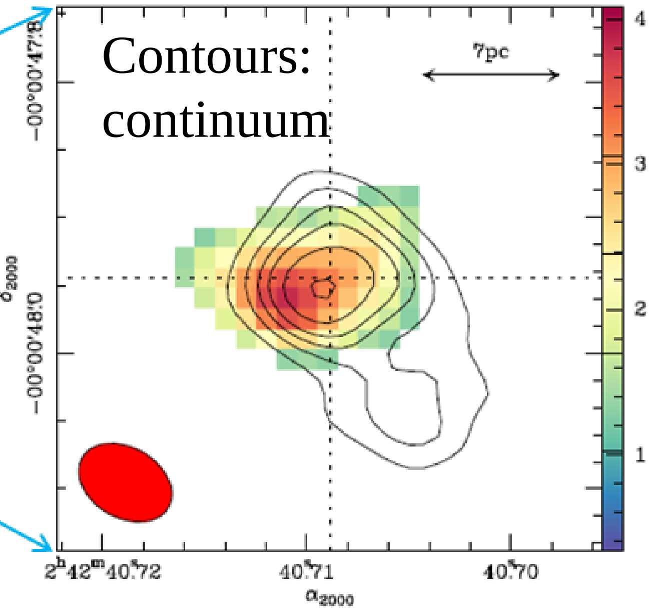
J. Tohline



ALMA CO(6-5) and 432μm dust emission
➔Torus of 7-10pc in diameter in NGC1068

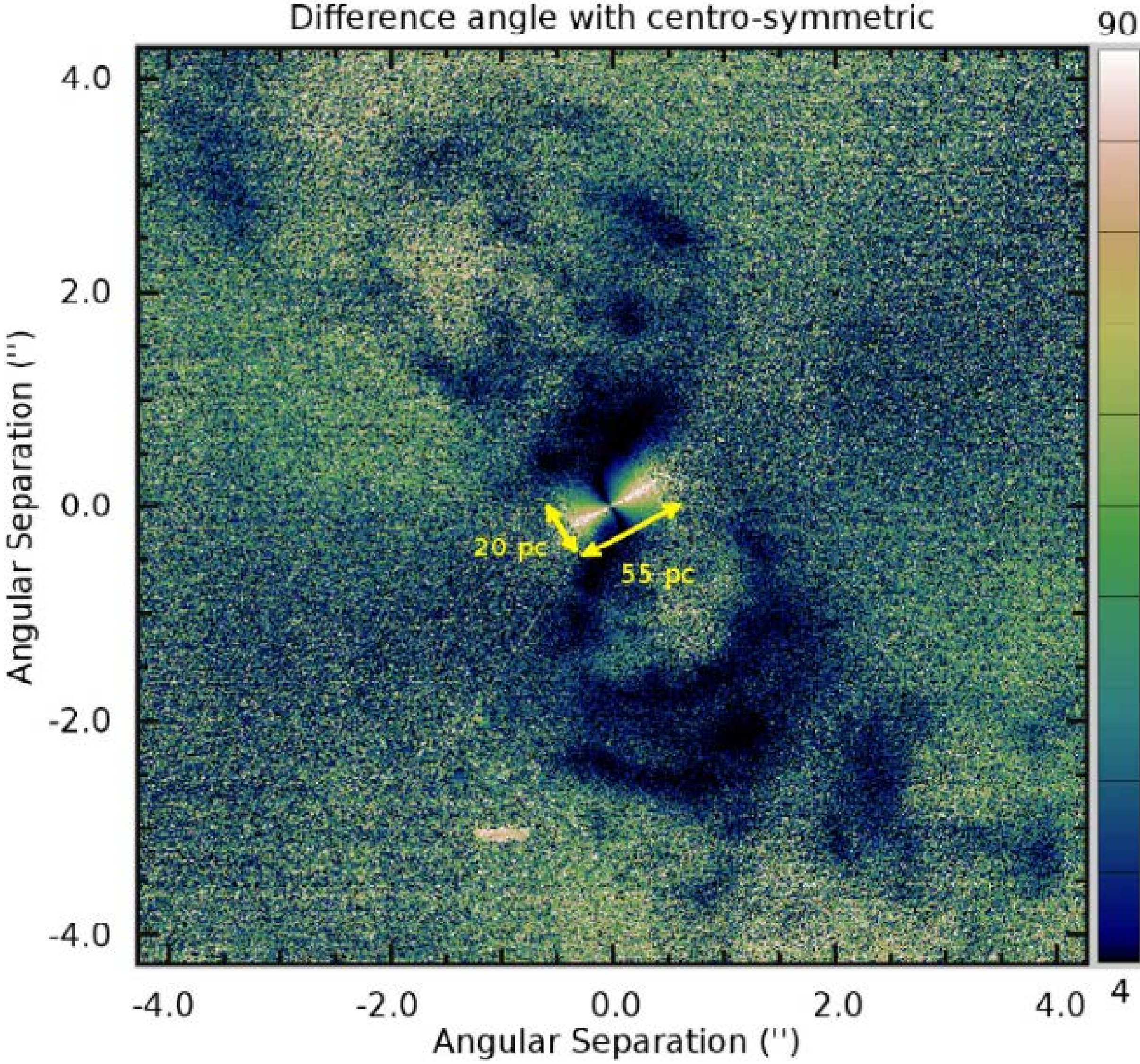
More inclined than the H_2O maser disk
Papaloizou-Pringle instability

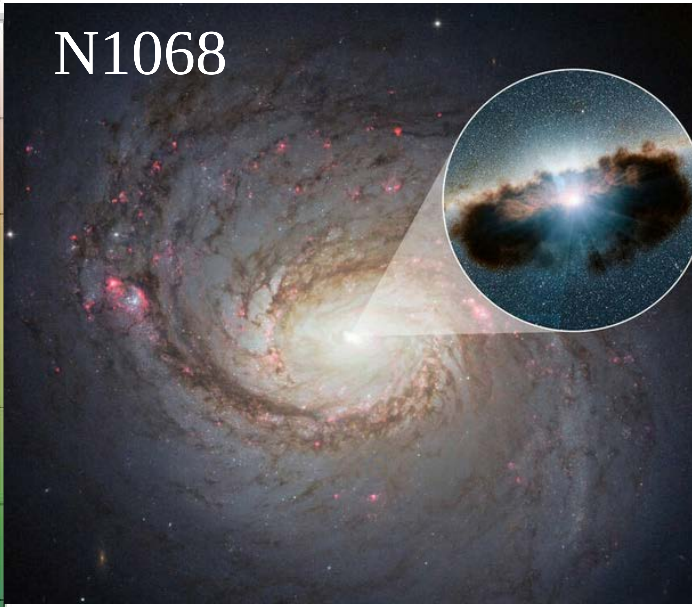




Garcia-Burillo, Combes, Ramos-Almeida et al 2016, **R=3.5pc torus**

Molecular torus inside a polar dusty cone



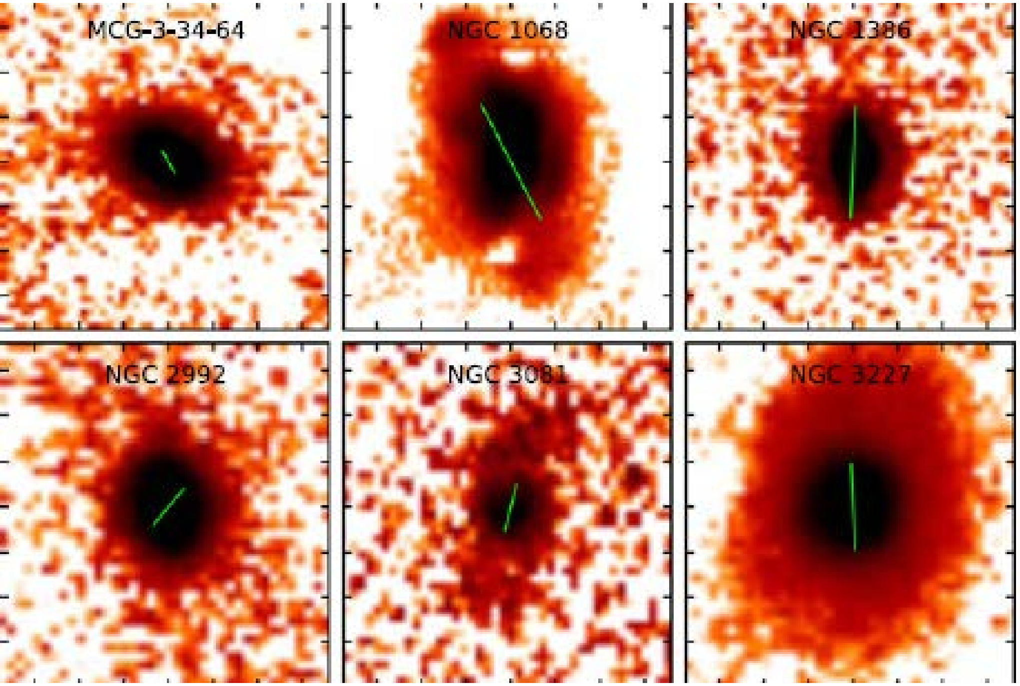


X-rays, XMM, Nustar
Several components
From 10^{23} cm^{-2}
up to $10^{25}$$cm^{-2}$
➔Compton-thick
~up to 100pc scale
Bauer et al 2015
Marinucci et al 2016

1''=50pc, *Gratadour et al 2015 SPHERE NIR*

Polar dust distribution

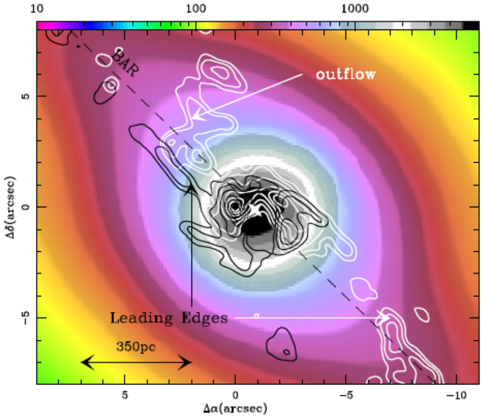
N1068



149 AGN, 21 show extended dust distribution, 18 on the polar axis (MIR)
Aligned with [OIII], [OIV] radio, masers, etc..

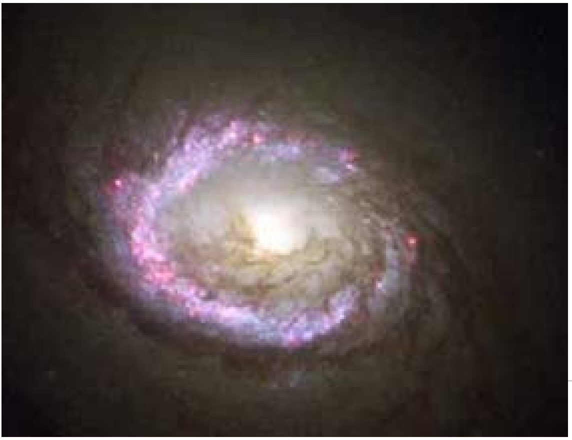
Dusty winds, associated to the molecular outflows?

Green: 100pc along the polar axis
Asmus et al 2016

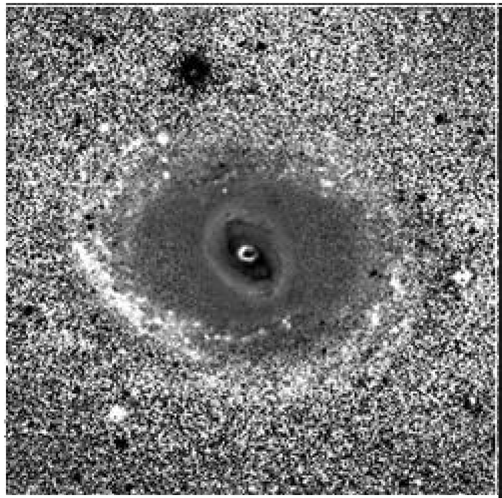


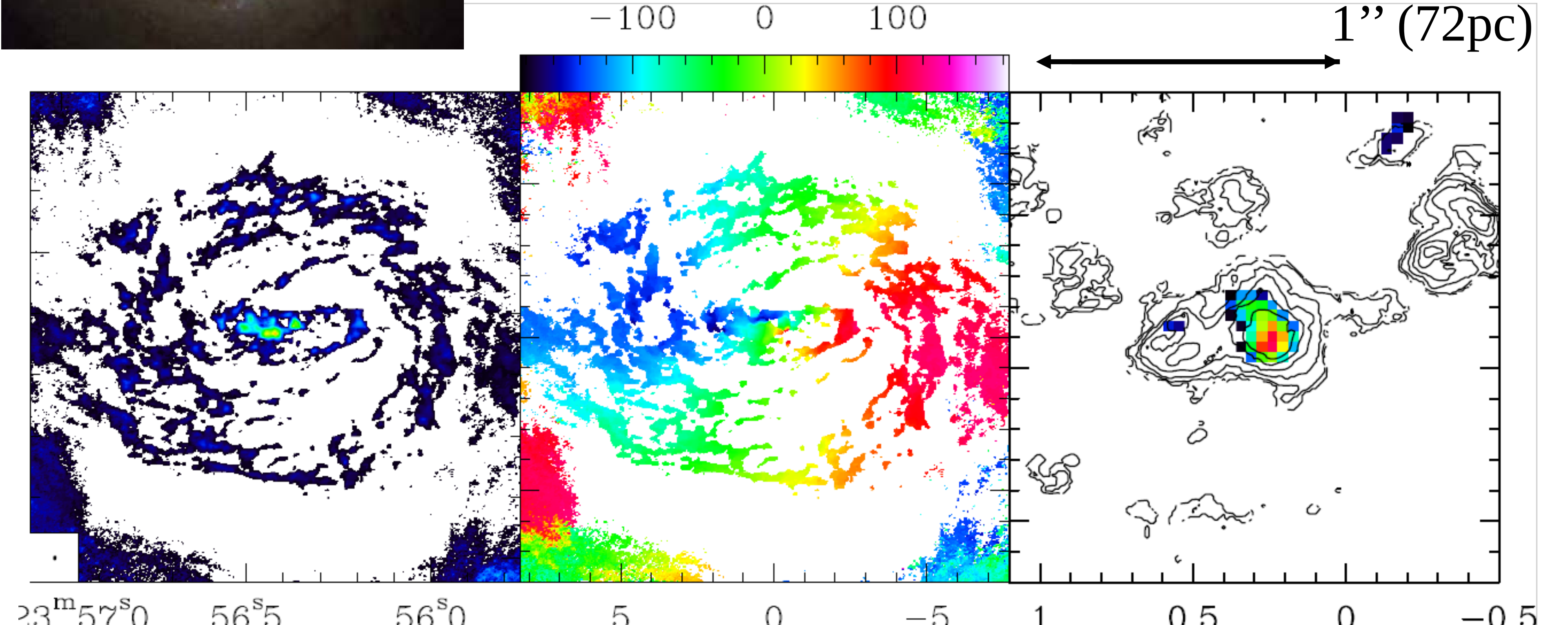
NGC1326

Liner, (R1)SB(rl)0/a



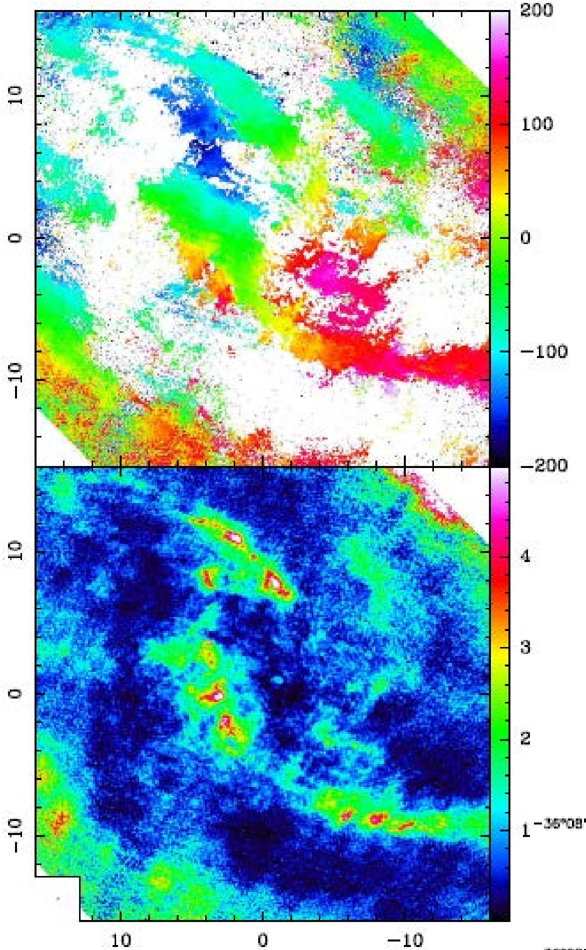
10''
720pc



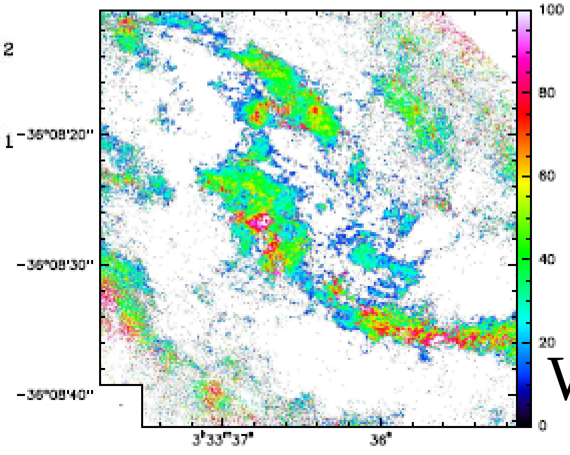


NGC 1365

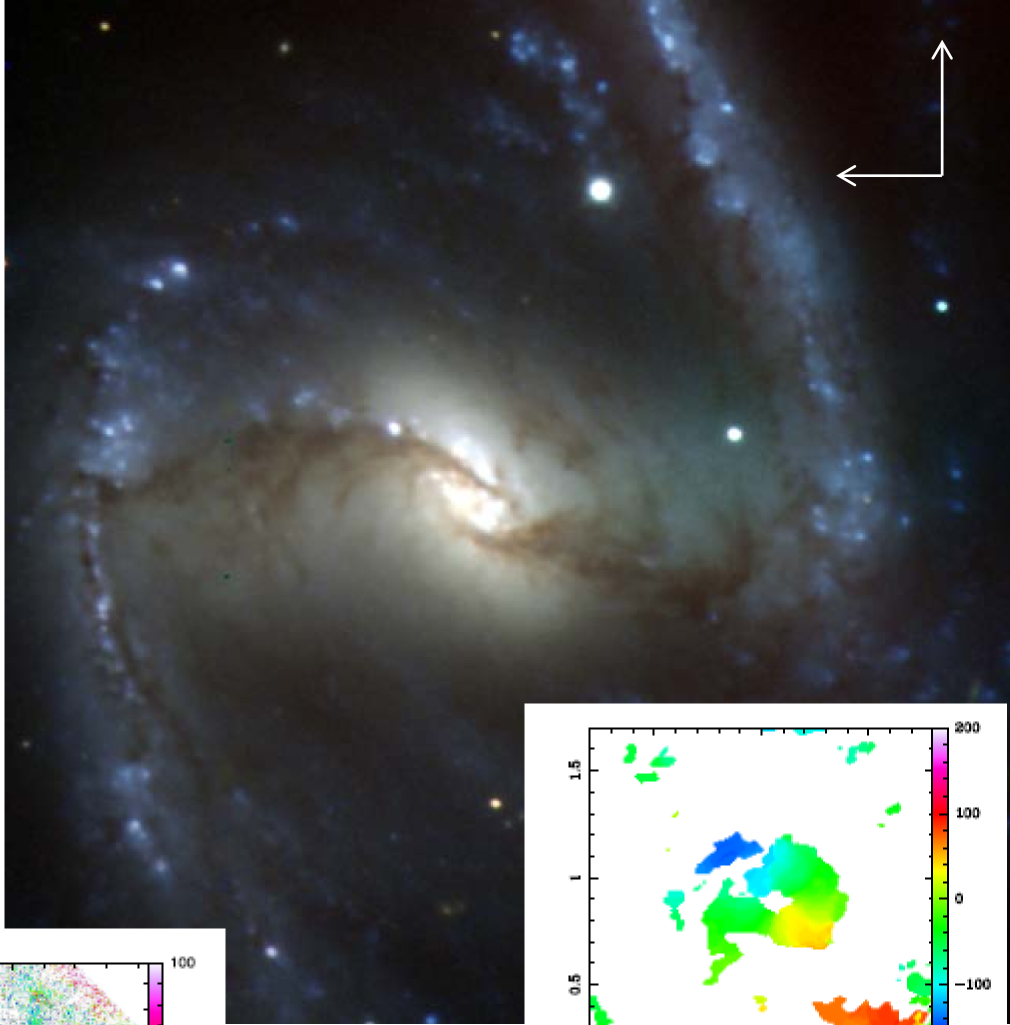
Sy 1.8, (R')SB(s)b

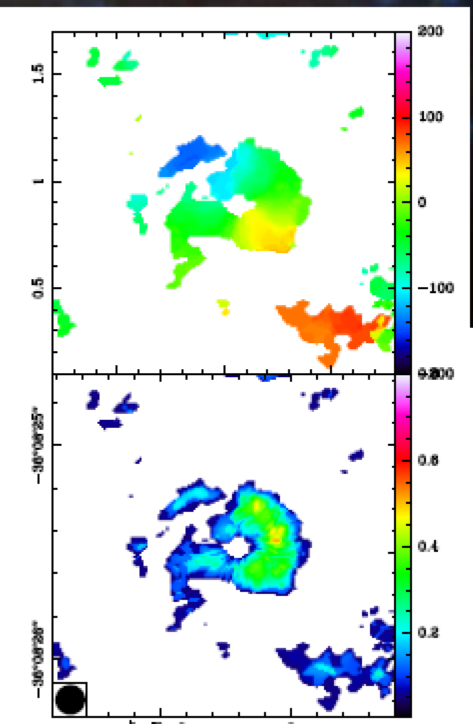


CO32, moderate resolution

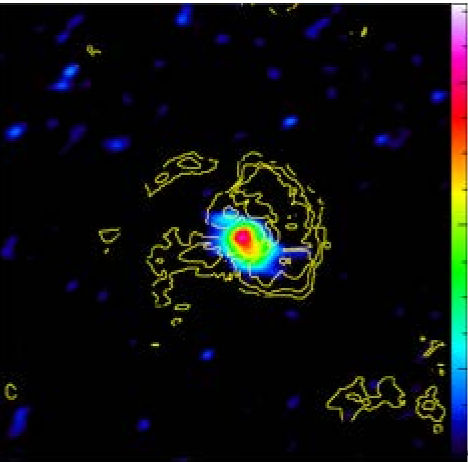


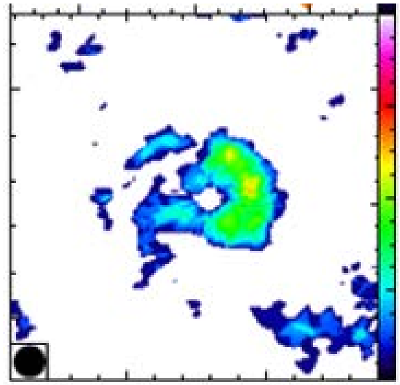
Width

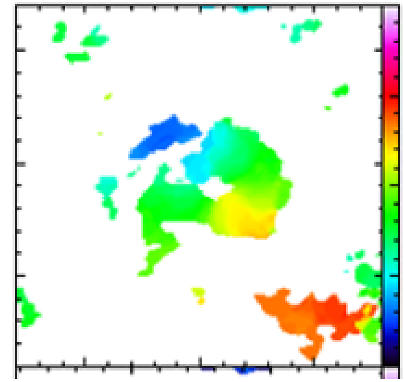




Frequency of « molecular tori » : 7/8





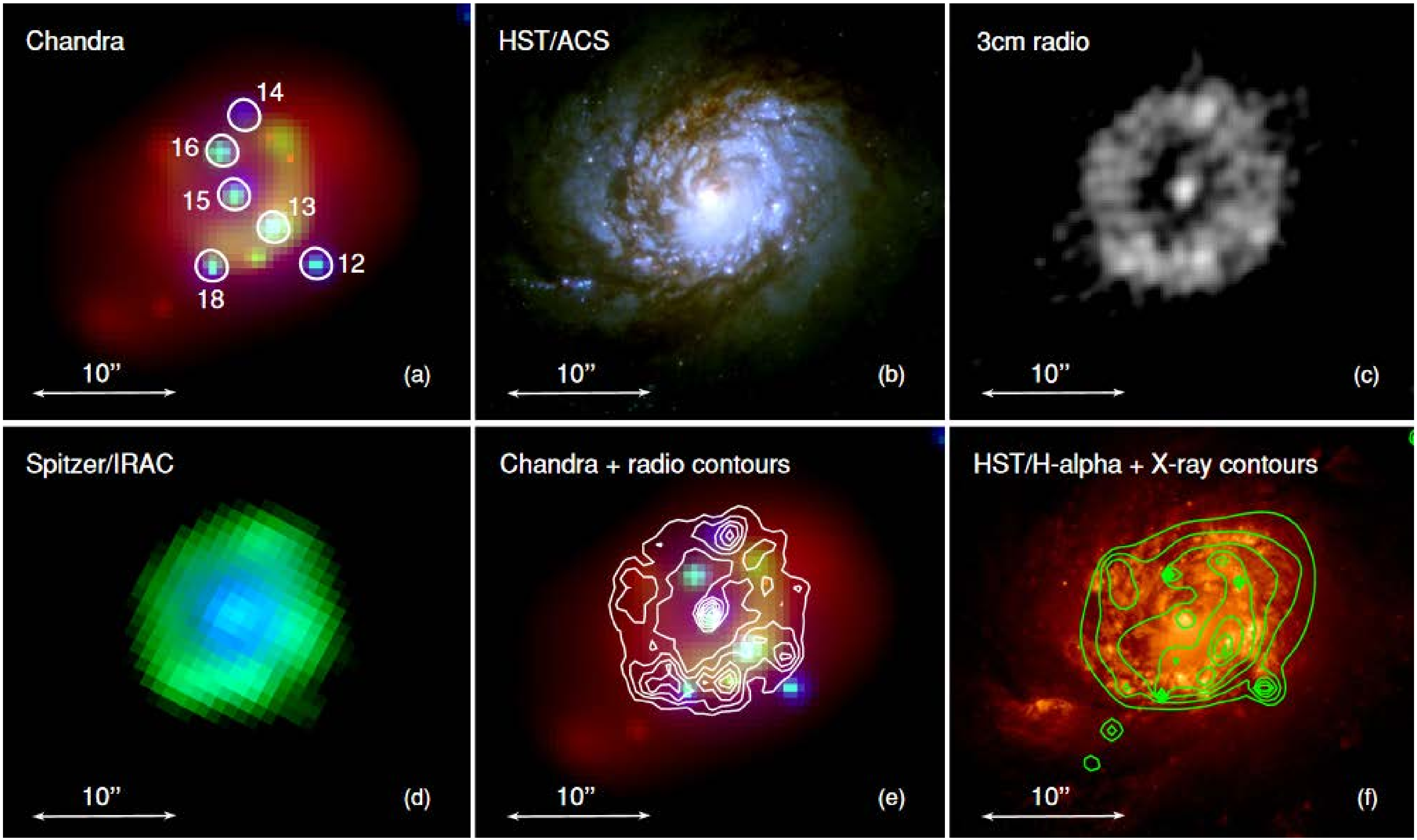


NGC 1365

Galaxy	Radius (pc)	$M(H_2)^a$ $10^7 M_\odot$	inc(°) torus	inc(°)[b] gal
NGC 613	14±3	3.9±1.4	46±7	36
NGC 1326	21±5	0.95±0.1	60±5	53
NGC 1365	26±3	0.74±0.2	27±10	63
NGC 1433	–	–	–	67
NGC 1566	24±5	0.88±0.1	12±12	48
NGC 1672	27±7	2.5±0.3	66±5	28
NGC 1808	6±2	0.94±0.1	64±7	84
NGC 1068	3.5	0.01	80	24

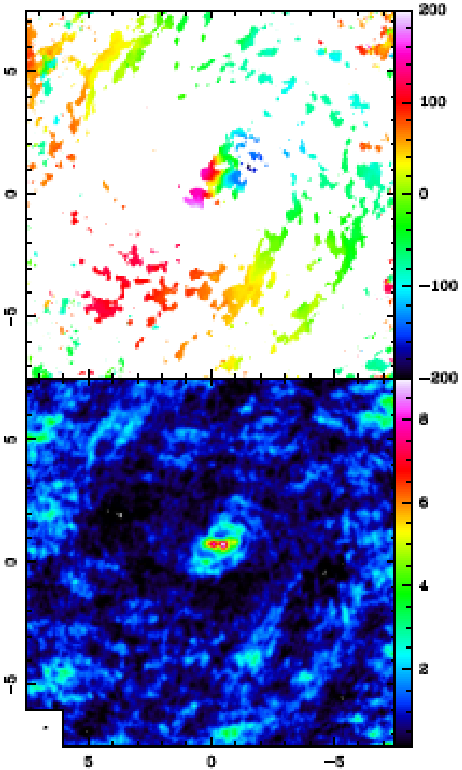
NGC 1672 *(Jenkins et al 2011)*

Sy 2, SB(s)b   SF in the ring at ILR R=300pc

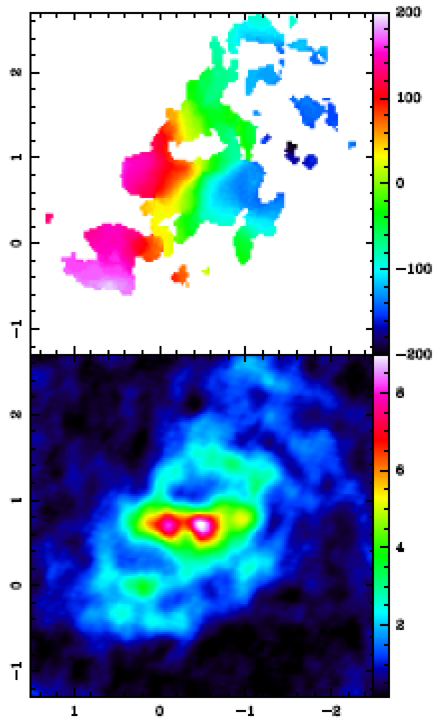


NGC1672

- Sy 2, SB(s)b
- 11.4 Mpc, i~30°
- 3pc resolution



15'' (820pc) CO32



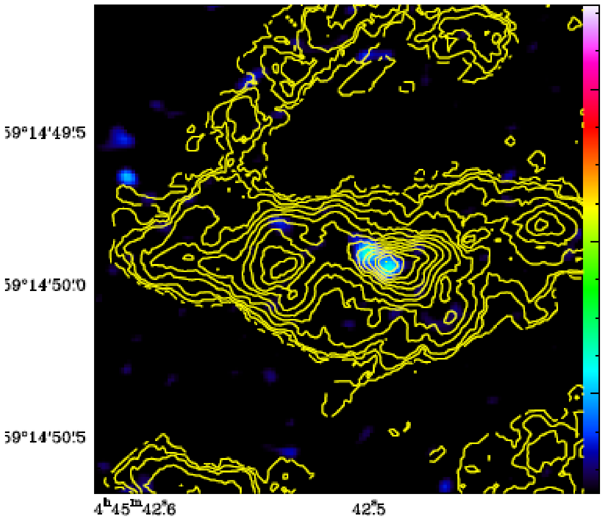
4'' (220pc)

Torus edge-on R=16pc

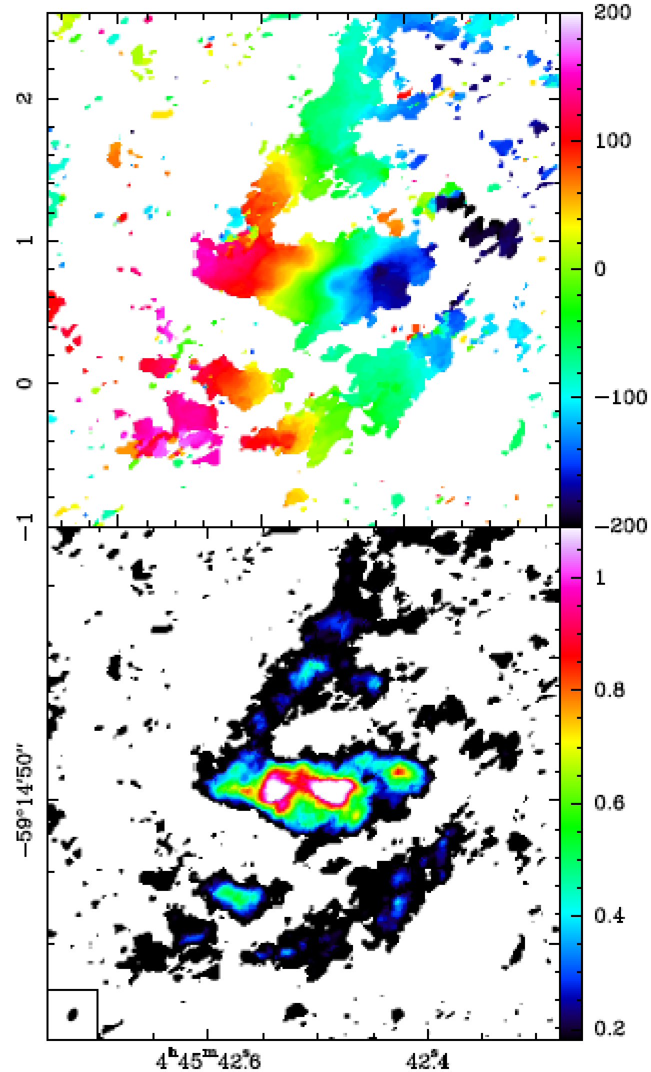
Beam 0.09'' x 0.06''

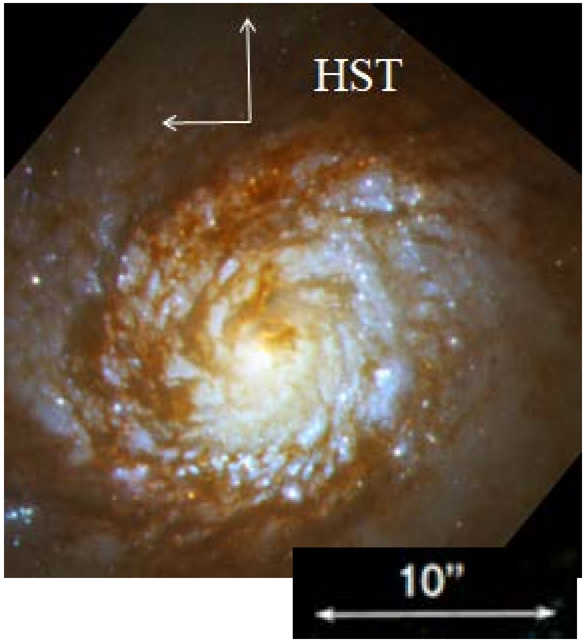
Combes et al 2019

NGC 1672



1 arcsec = 55pc

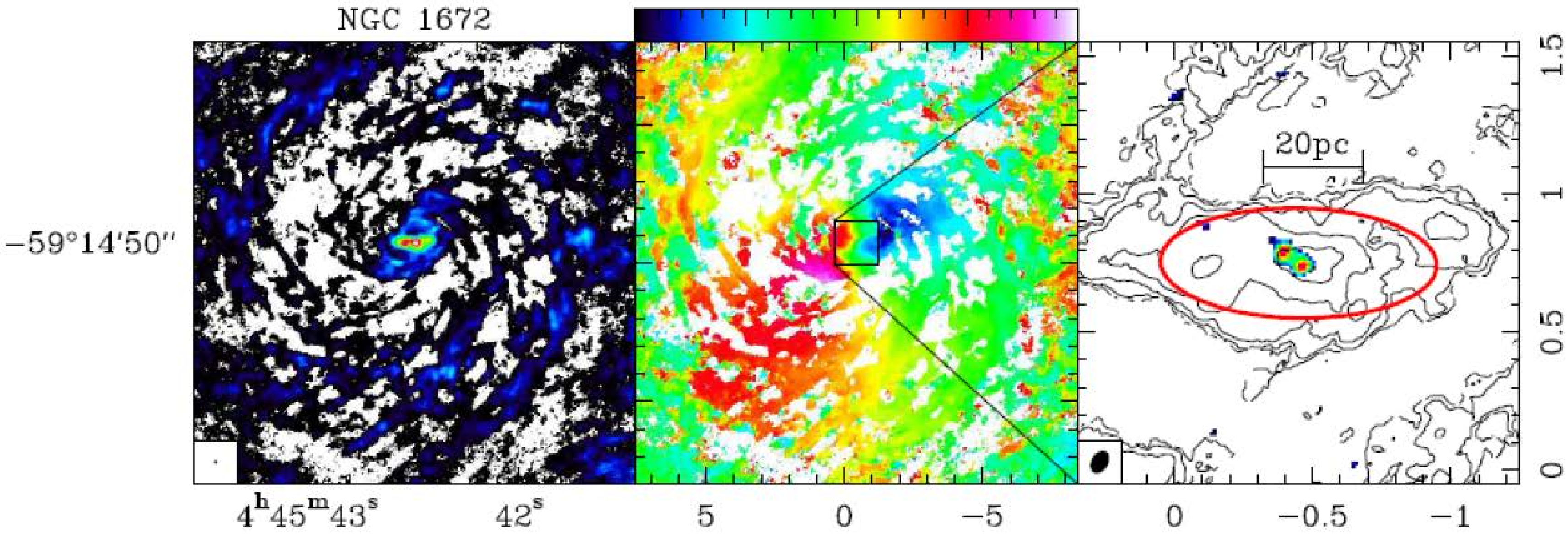




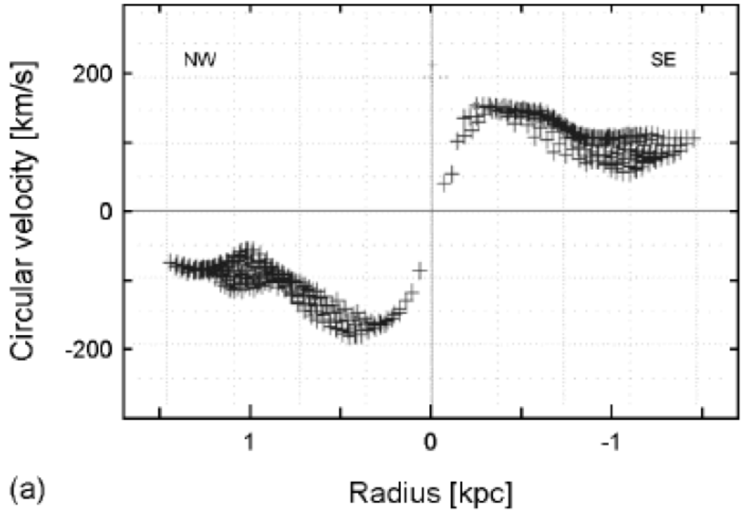
CO32-contours on continuum

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

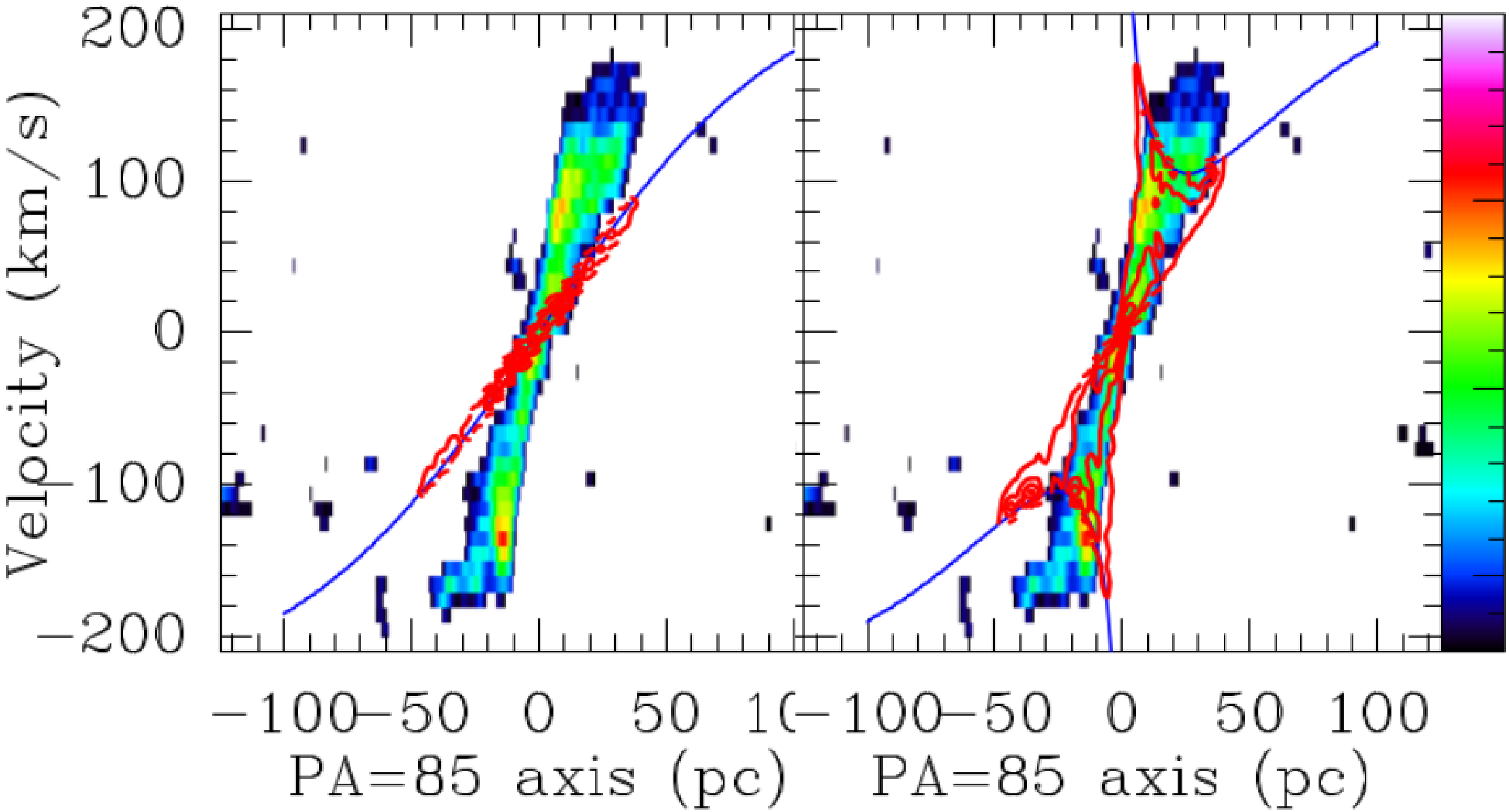
NGC 1672



Diaz et al 1999: Hα velocity field, at kpc scale



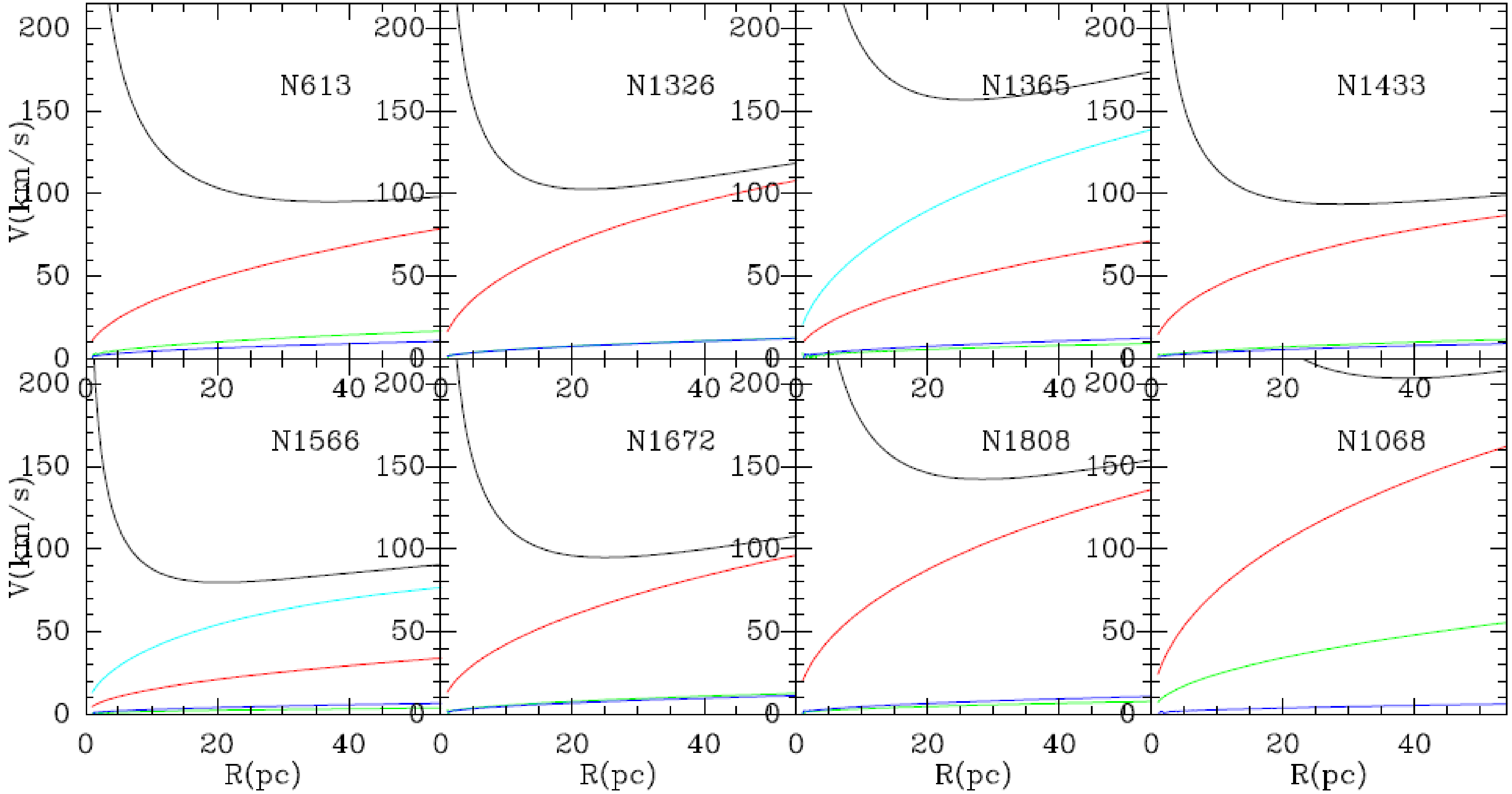
N1672: Black hole mass



Without BH

With BH, of
M= 5 10^7 $M_\odot$

Potential from NIR galfit, Sersic components

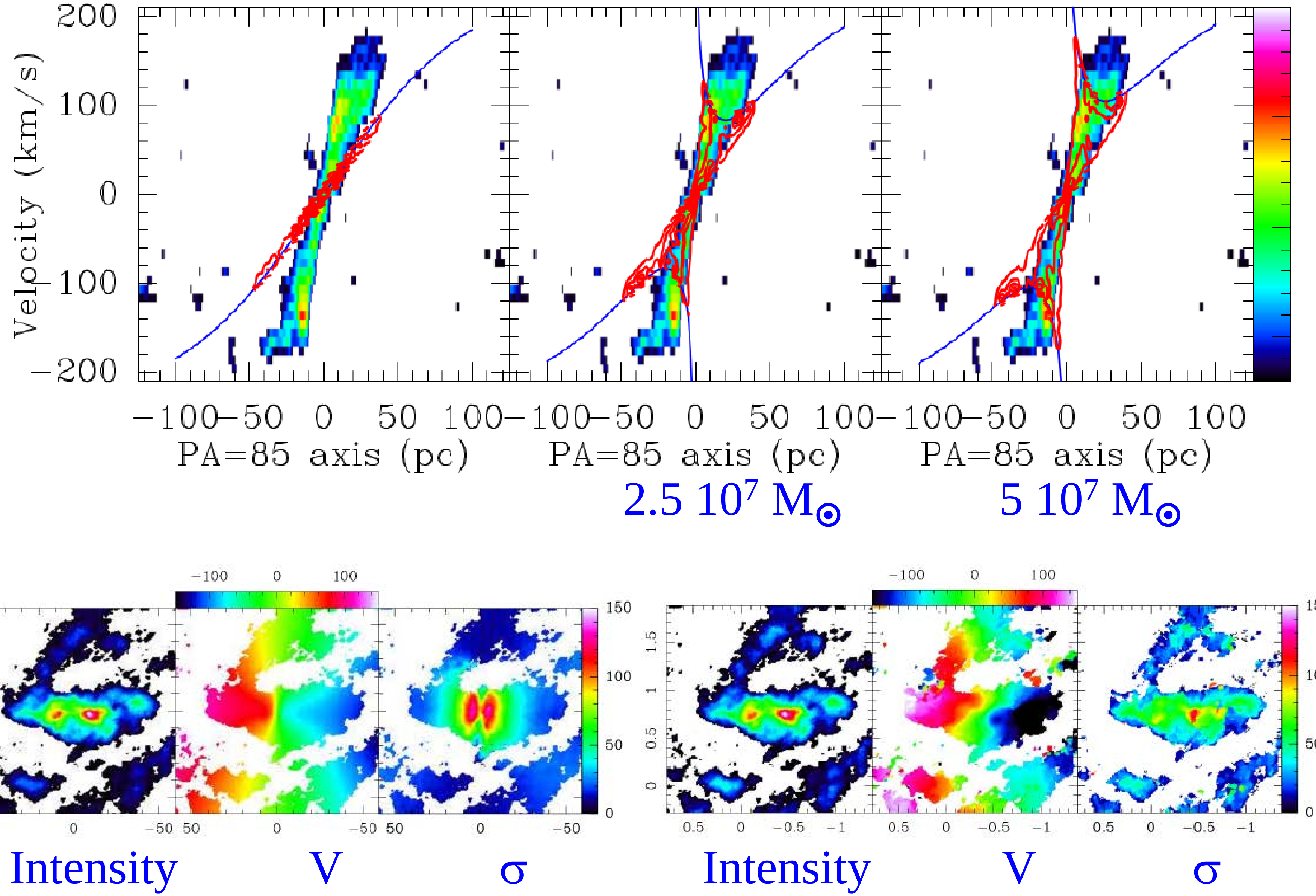


the bulge in red, the disk in green, the bar in blue, nucleus in cyan

Simulations of gas in the potential, with possibility of varying incl, PA

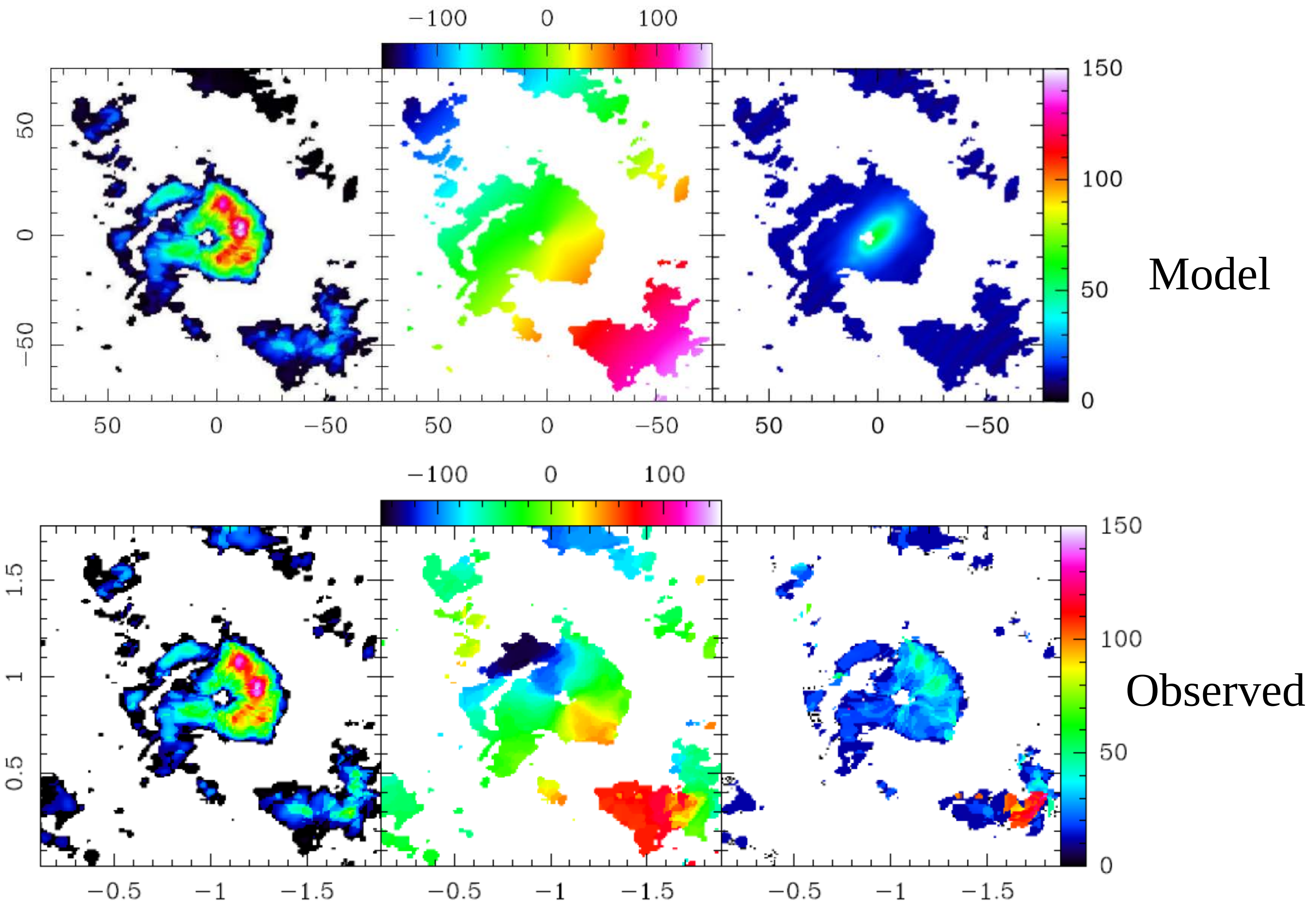
Rotational V with Q_{toom}=1. Building a data cube, and projecting

Normalised to the 2D moment-0 CO map, at each pixel



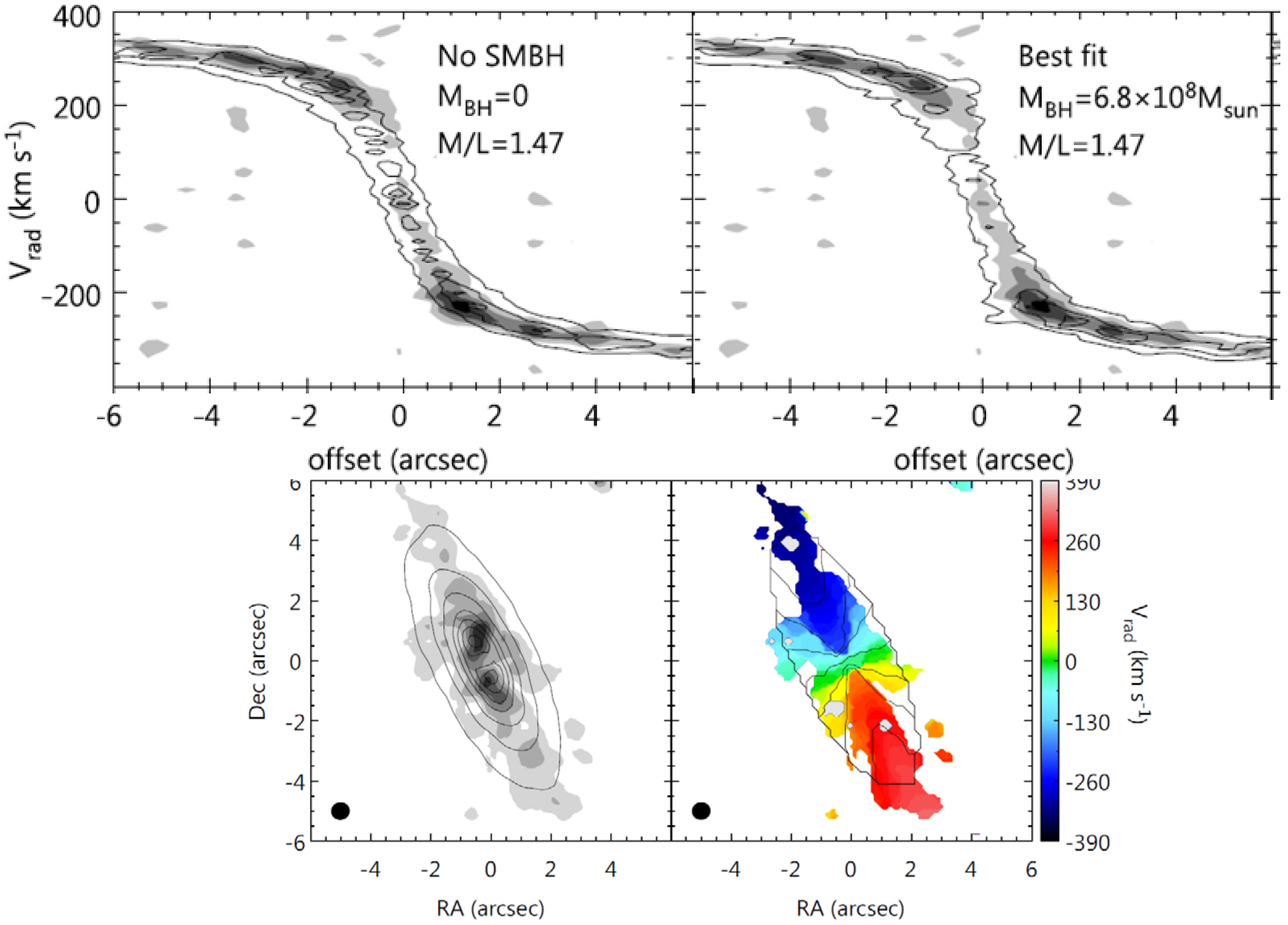
Model Observations

Modelisation of NGC 1365



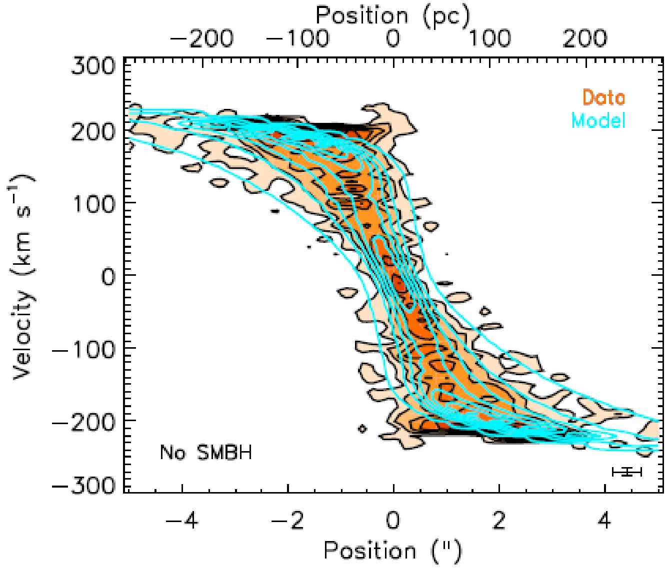
WISDOM project: NGC 3665 *Onishi et al 17*

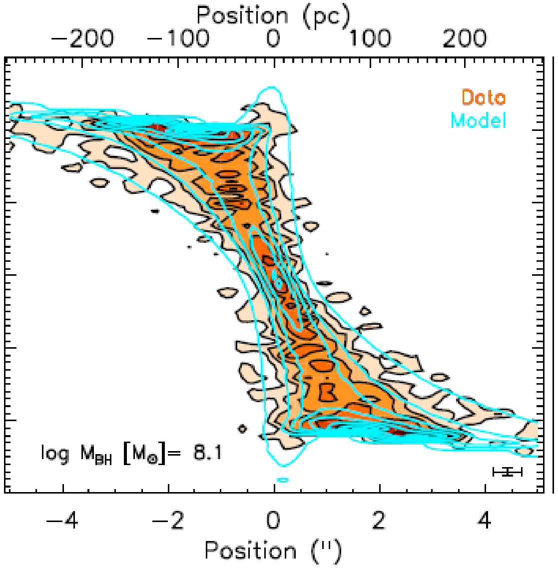
CO(2-1) , Beam 0.60x0.56'' = 100x93pc   1'' =167pc

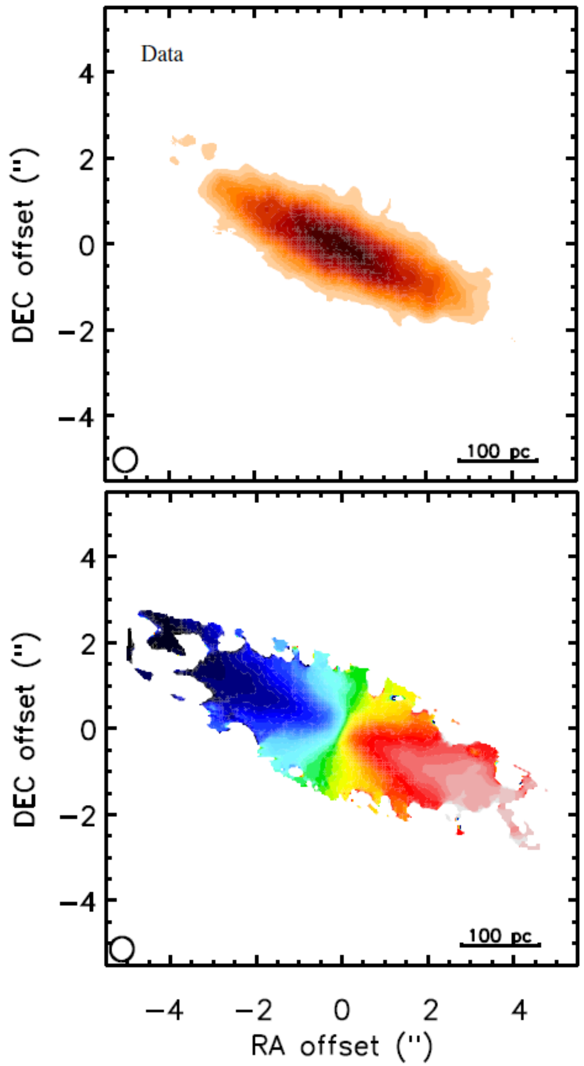


WISDOM project: NGC 4697 *Davis et al 17*

CO(2-1) , Beam 0.54x0.52" = 30x 29pc







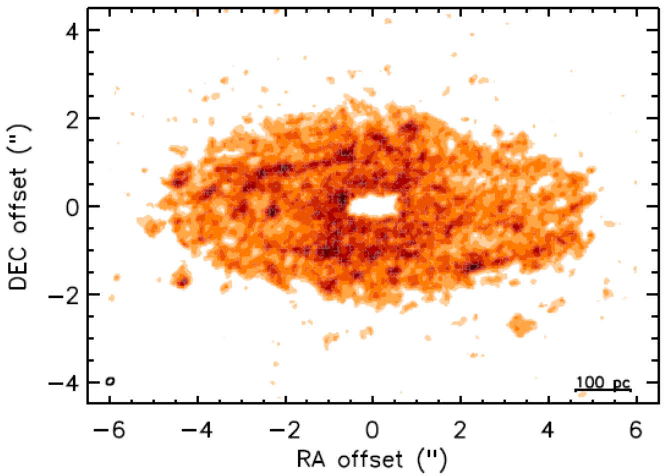
No BH

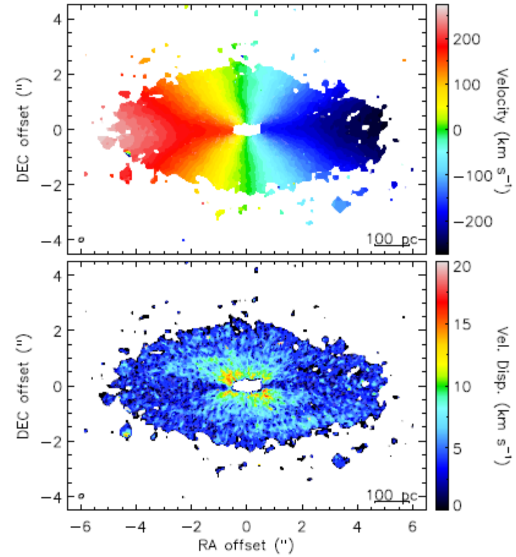
$1.2\ 10^8\ M_\odot$

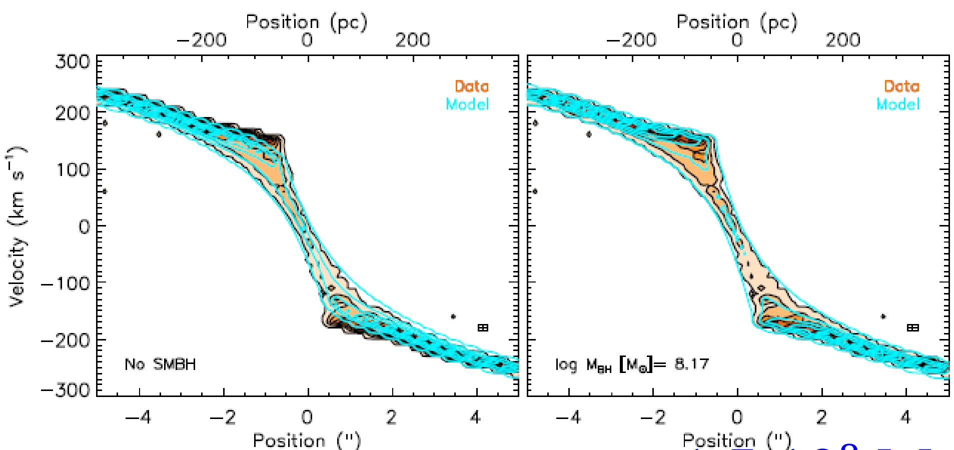
Best Fit

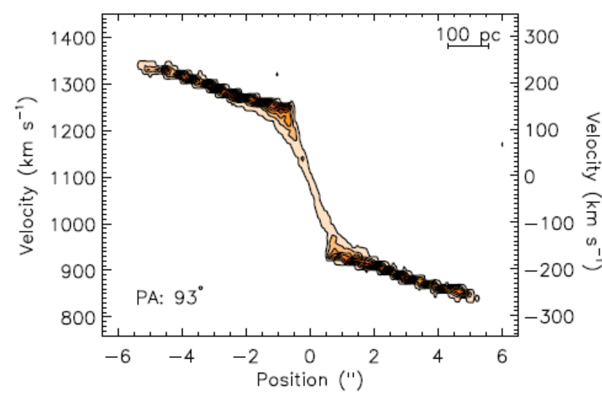
WISDOM project: NGC 4429 *Davis et al 17*

CO(3-2) , Beam 0.18x0.14" = 14x 11pc D=16.5Mpc 1" = 80pc



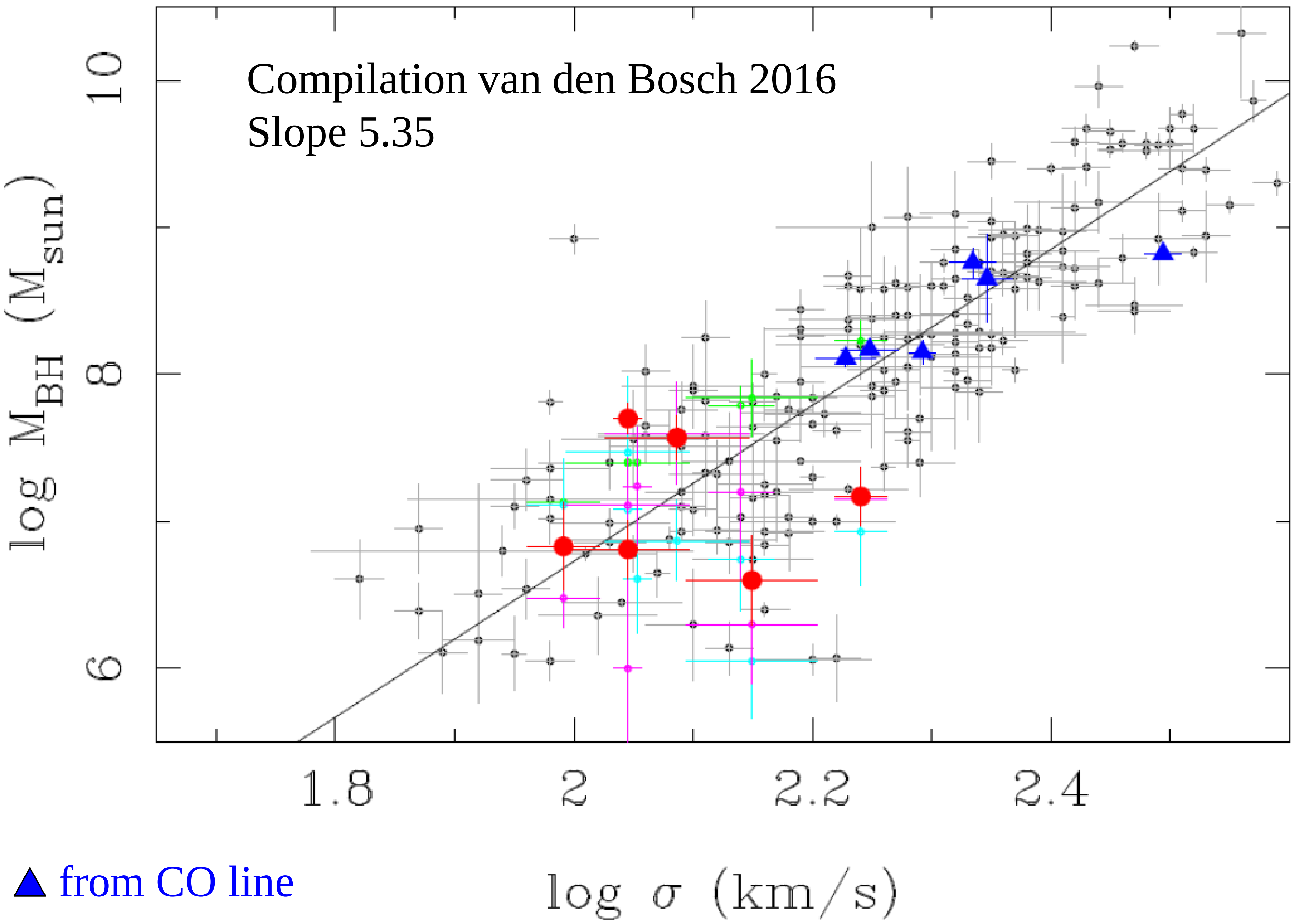






No BH

1.5 10^8 $M_\odot$
Best Fit


Compilation van den Bosch 2016
Slope 5.35
log M_BH (M_sun)
10
8
6
1.8
2
2.2
2.4
log σ (km/s)
from CO line

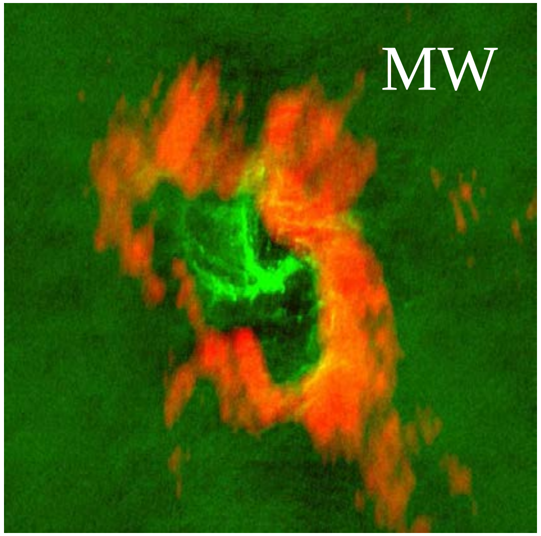
Non-alignment with host disk

Like in the MW, the nuclear disks are not aligned with the galaxy, nor the ISM nuclear disks

In NGC 4258, the maser disk 0.2pc in size is misaligned by 119° from the galaxy disk, the jet is in the plane

Many Seyfert have their jet not perpendicular to the main disk (Schmitt & Kinney 2002; Jog & Combes 2009)

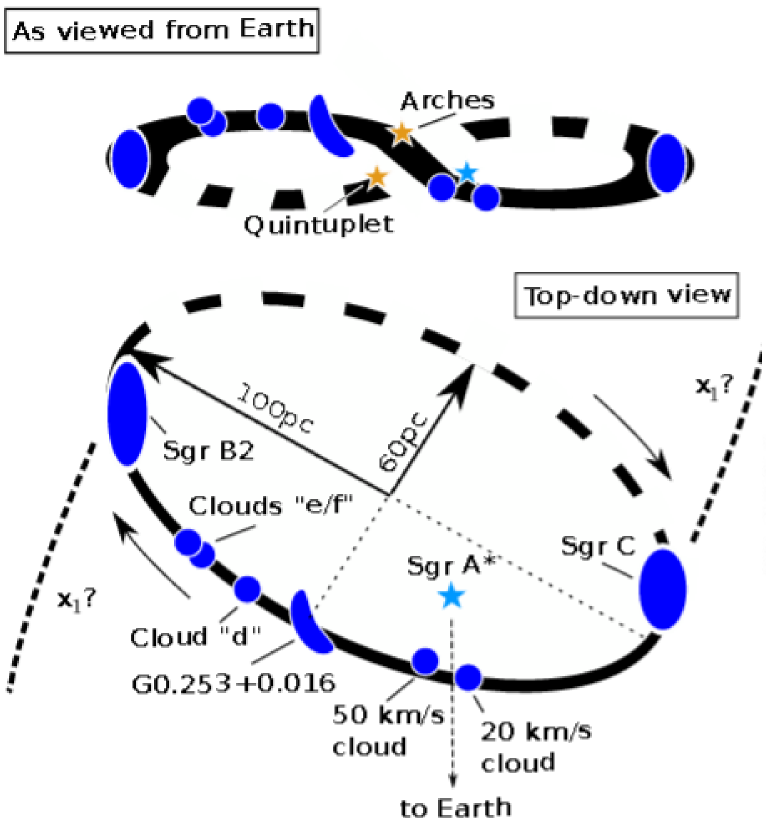
CNR: circumnuclear ring
2-3pc in radius
HCN in orange
Ionized gas in green
Inclination of 20° /plane



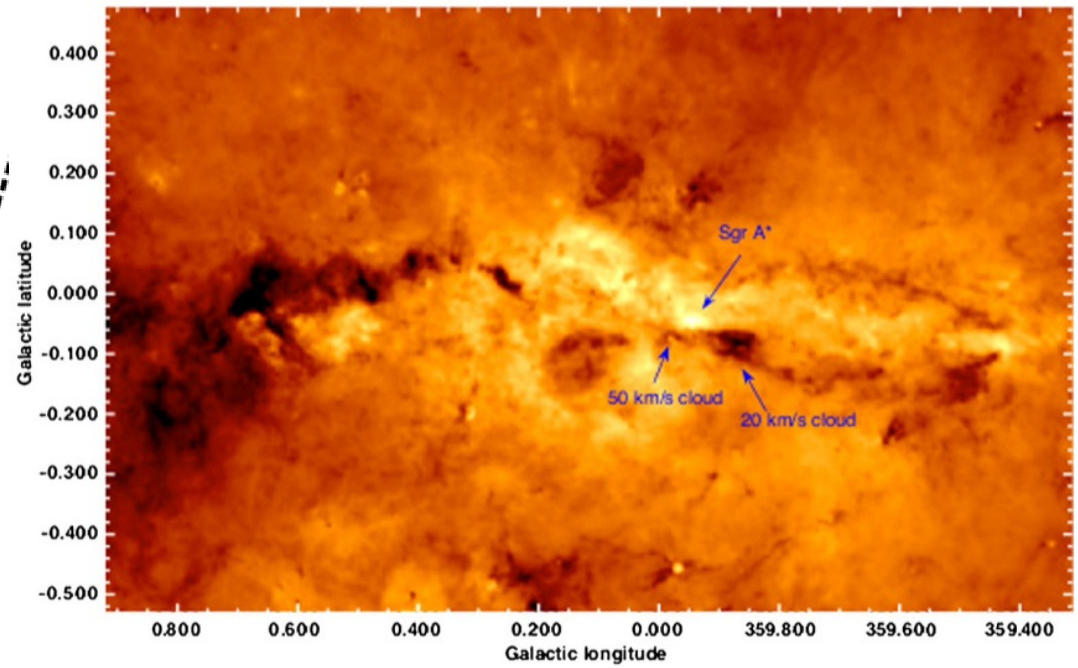
Mini-spiral 60$M_\odot$
Cavity 200$M_\odot$
CNR $10^6 M_\odot$
$7\ 10^4\ cm^{-3}$
300K

CMZ in the Milky Way

3 10^7Mo cold gas, 60x100pc, x2 orbit, SgrA* off-centered➔ m=1



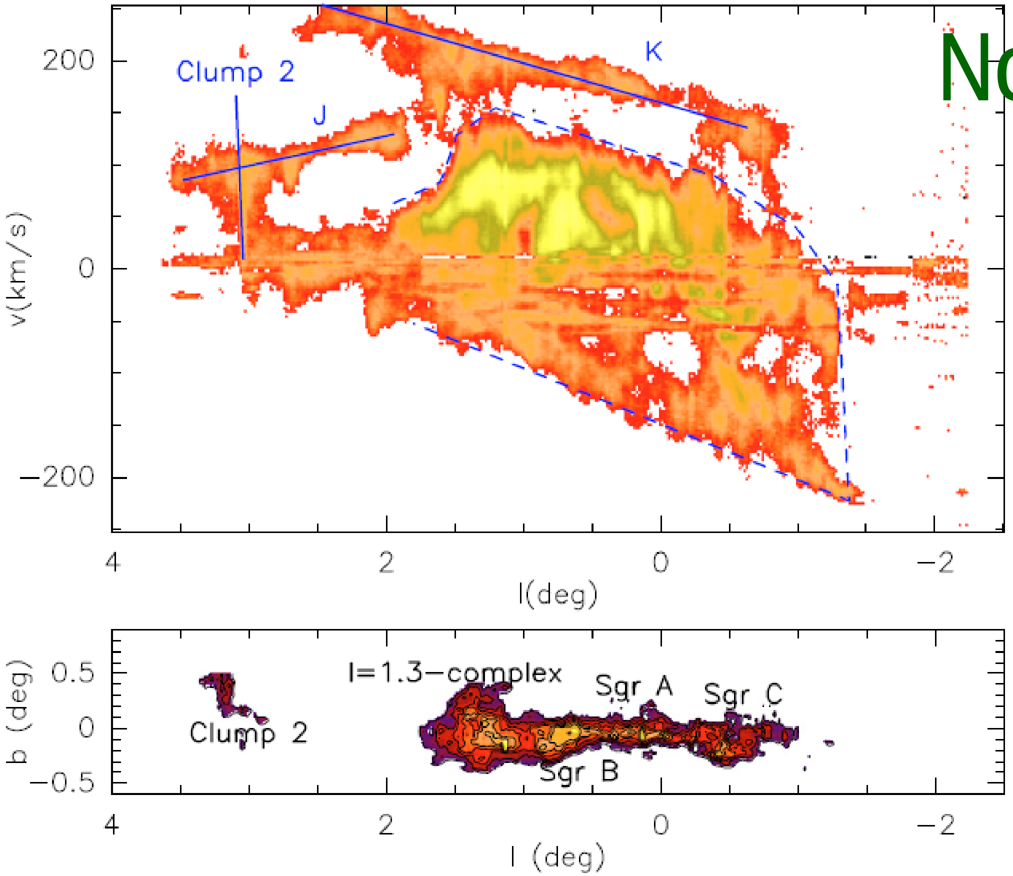
Resonant ring R=100pc

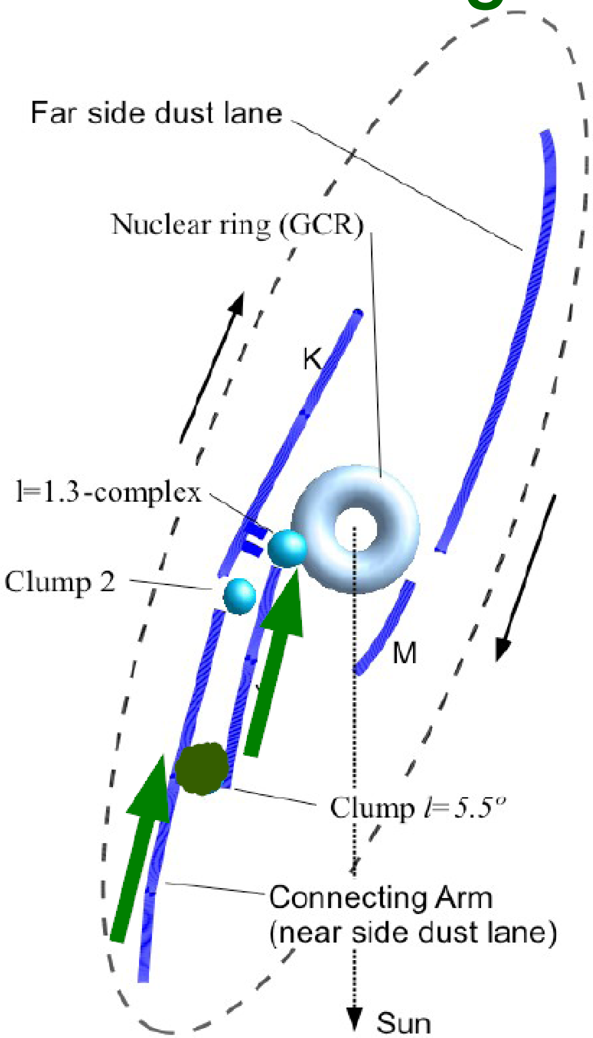


Why no SFR in the 500pc-center?
Kruijssen et al 2014

Herschel
Molinari et al 2011

Non-alignment of rings





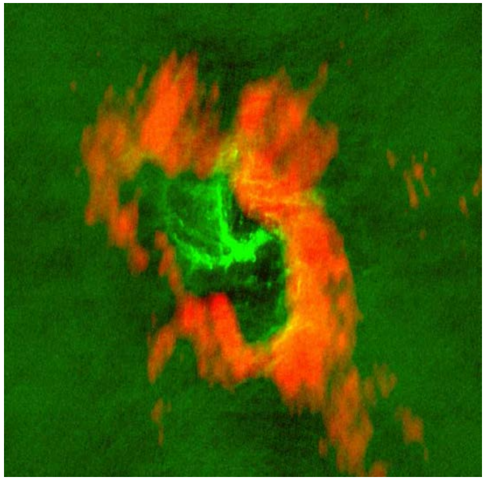
CNR: circumnuclear ring

R=2-3pc

orange = HCN

Green= Ionized gas

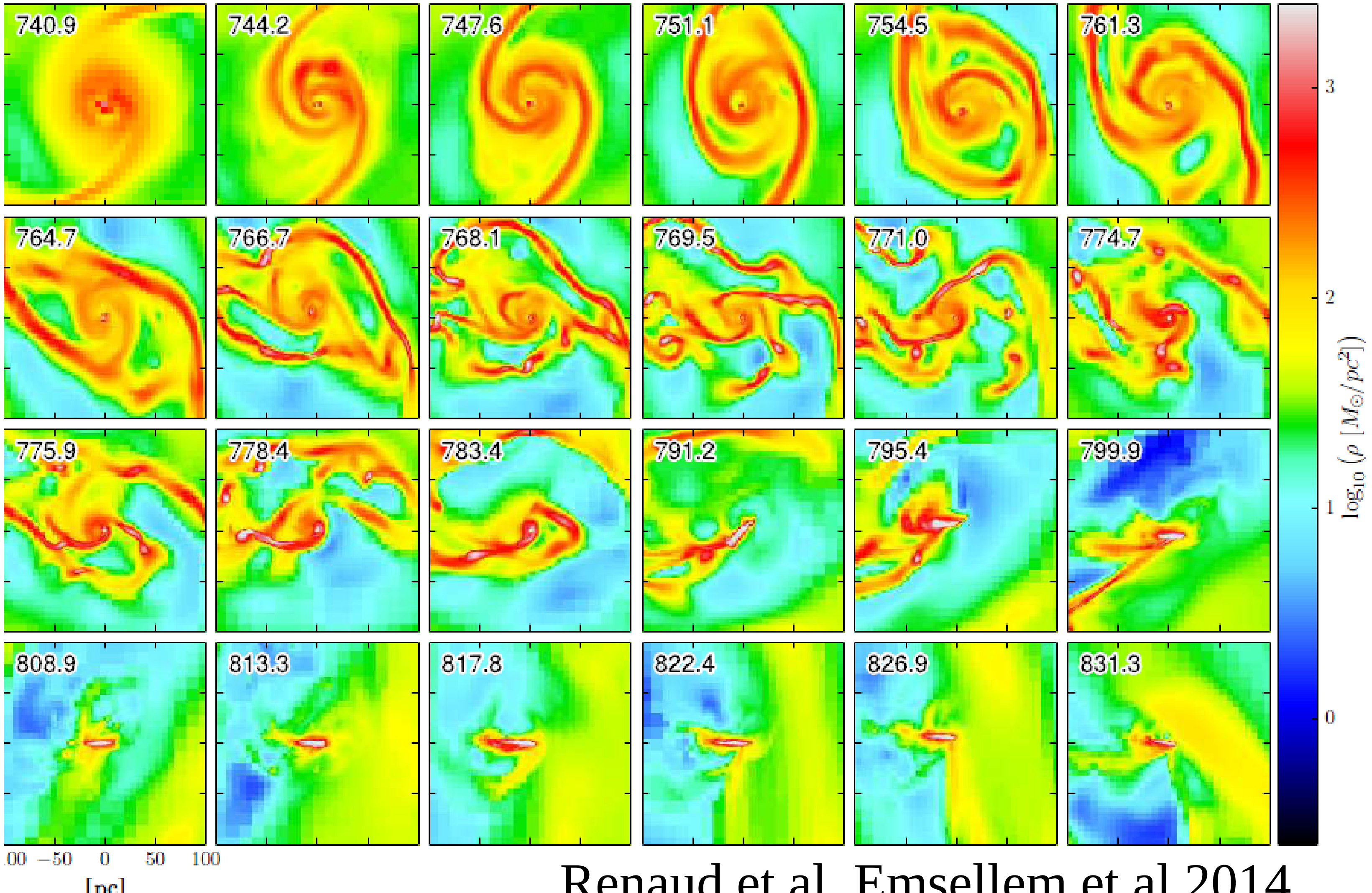
Inclination of 20° /plane



Rodriguez-Fernandez & Combes 2008

High-resolution simulation of the Milky Way
Zoom in the central 200pc region

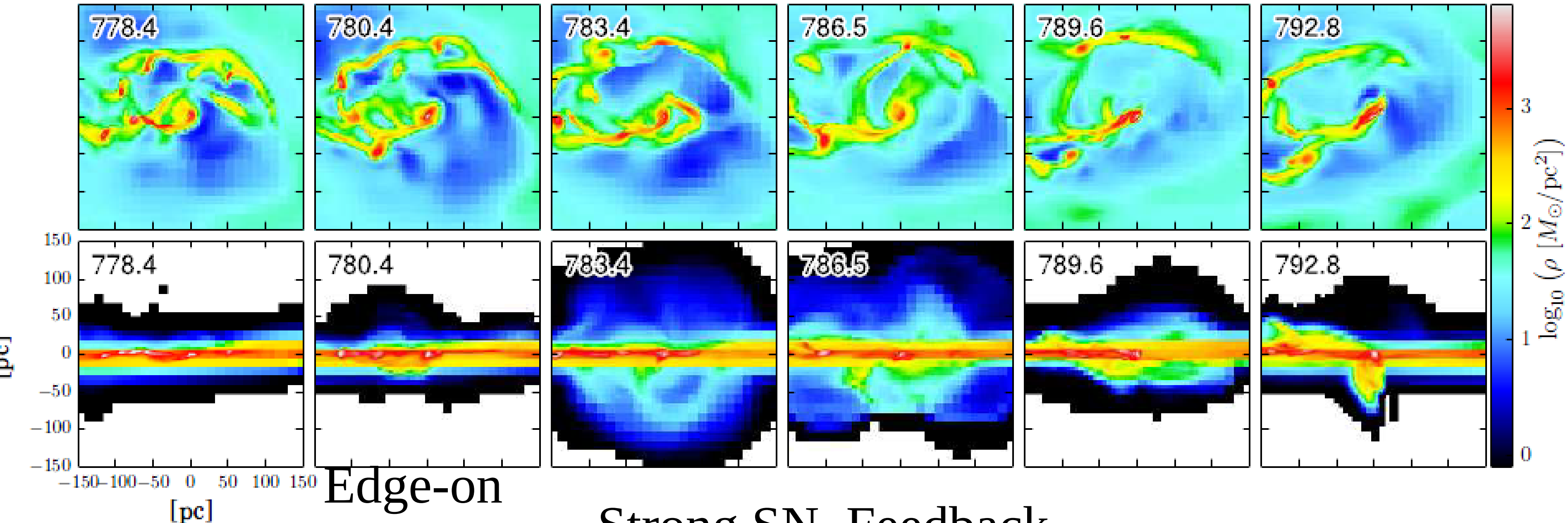
Face-on



Renaud et al, Emsellem et al 2014

How the gas is accreted

Face-on

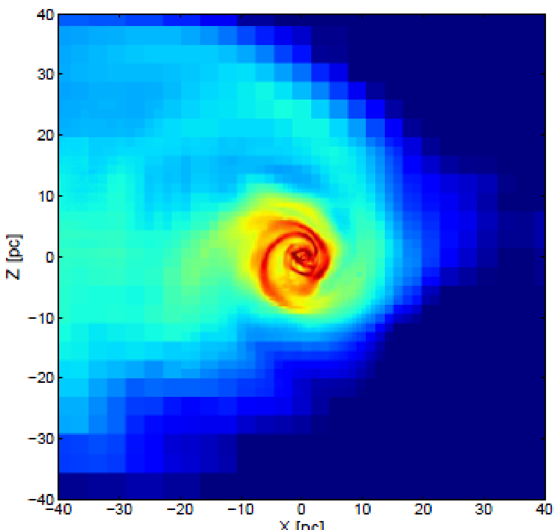


Edge-on

Strong SN Feedback

➔Gas in the perpendicular plane

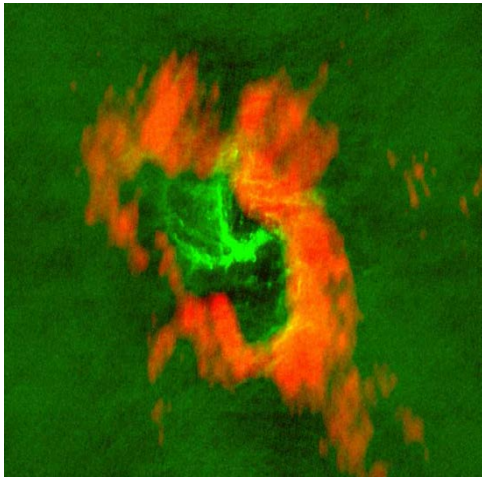
Emsellem et al 15



Polar disk face-on

Inclined

Circumnuclear ring



SUMMARY

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

➔ **At scales ~1-10pc,** macro-turbulence, clumps, warps, dynamical friction, formation of **thick disks/torus**

➔ **Feedback:** outflows due to starbursts and to AGN
Strong coupling due to mis-alignment

➔ **Mis-alignment between small scales and large scales due to accretion, and different dynamical time-scales,**