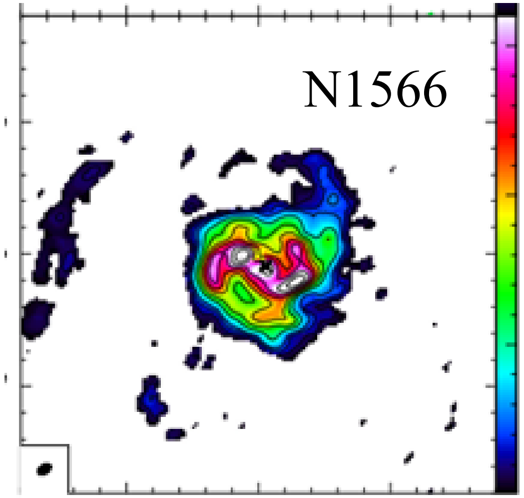
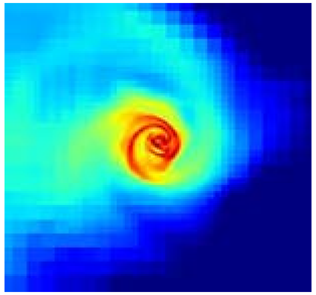
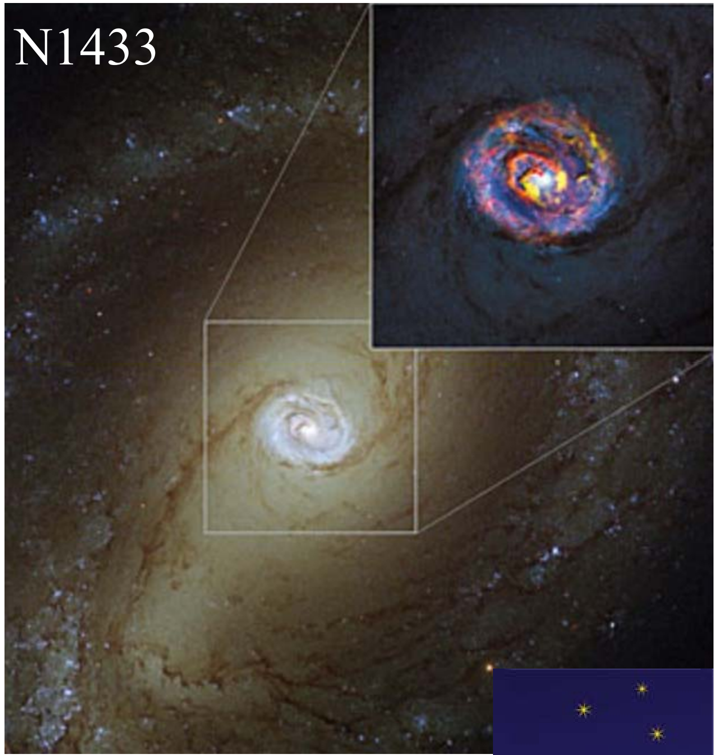
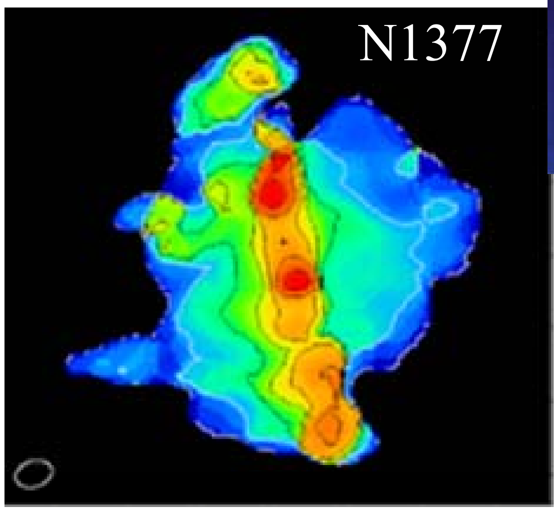
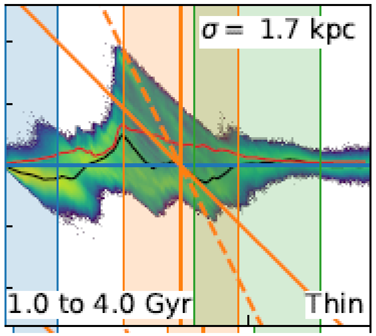






Dynamical processes in Galaxies

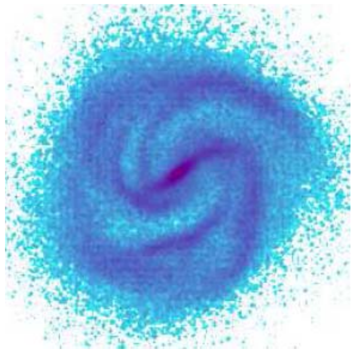




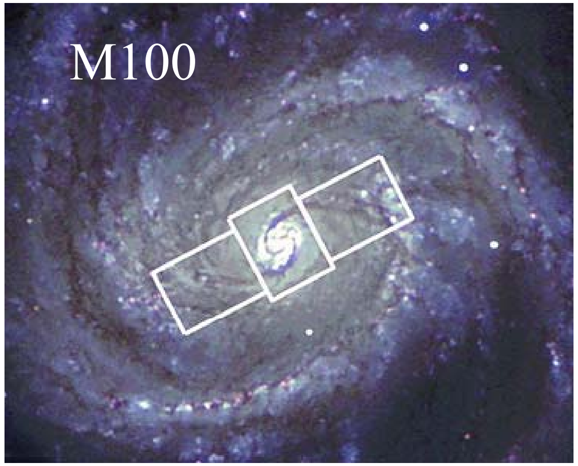
Françoise Combes
Observatoire de Paris

14 April 2018

Outline



➔Angular momentum transfer
➔Dynamical features: nuclear rings, spirals, bars

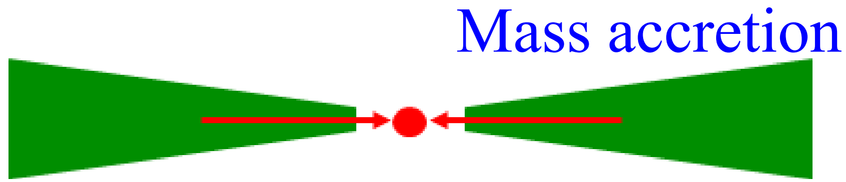


➔Fueling due to gravity torques
➔Feedback, outflows (SF, AGN)

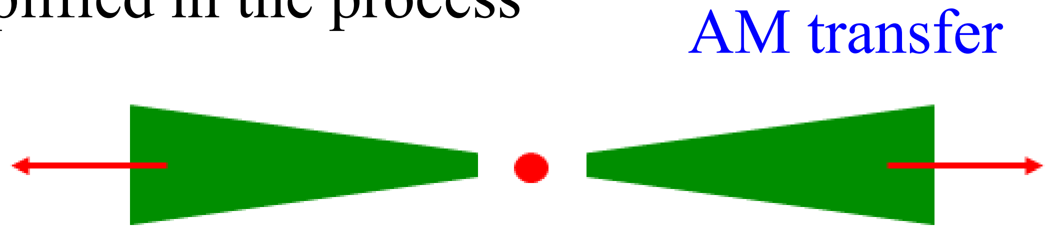
➔Decoupling, different orientations

Angular momentum (AM) transfer

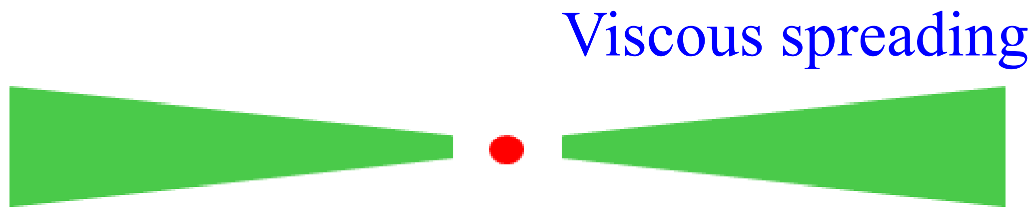
Galaxy disks are **accretion disks**
But viscous torques negligible



Bars, negative AM waves, amplified in the process

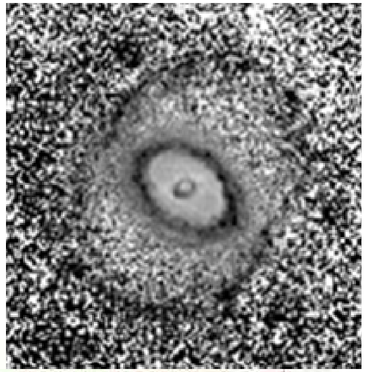


Self-gravity +
Gravity torques for AM transfer

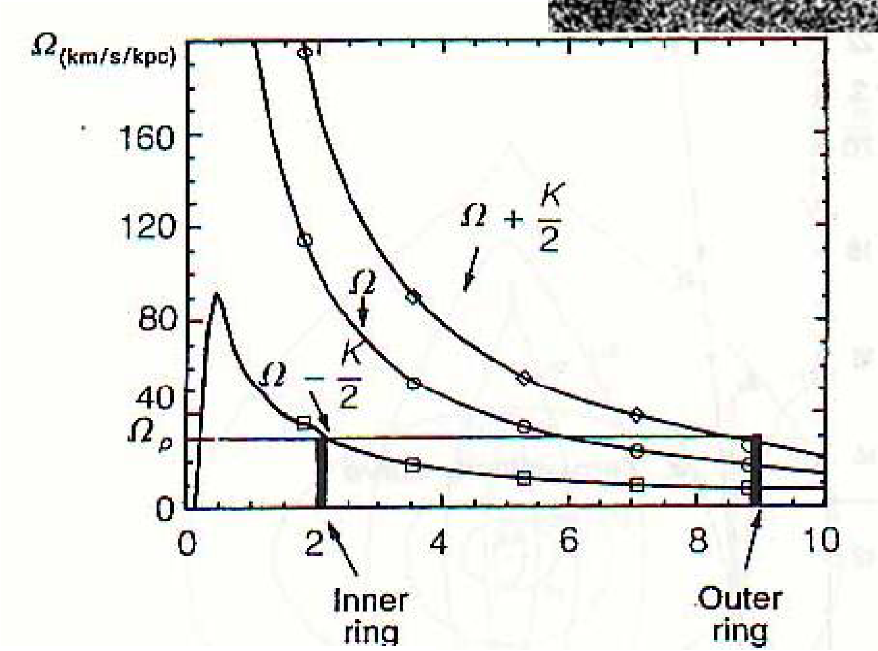


Equivalent « viscosity » from gravitational instabilities (Toomre criterium)
Lin & Pringle 1987

Angular momentum (AM) transfer



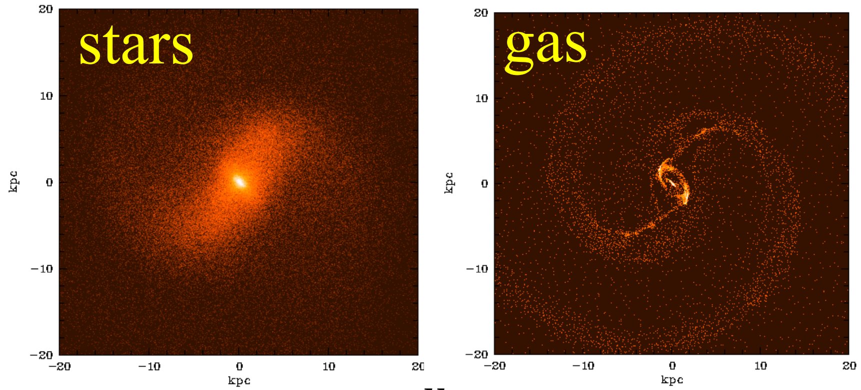
Cold disks form by transferring AM outwards
Bars, more robust than spirals



Decoupling of a secondary bar

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

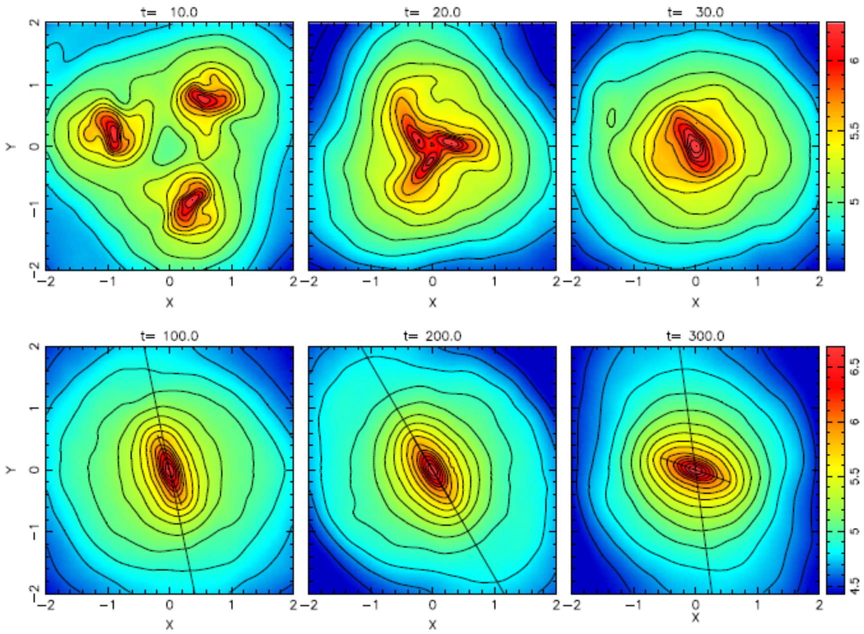
New faster bar inside the ILR ring
+ weakening of the bar, z-resonance
Peanut-shape bulge



Friedli 1993

Inside out two-bar formation

Embedded bars in 30% of all barred galaxies



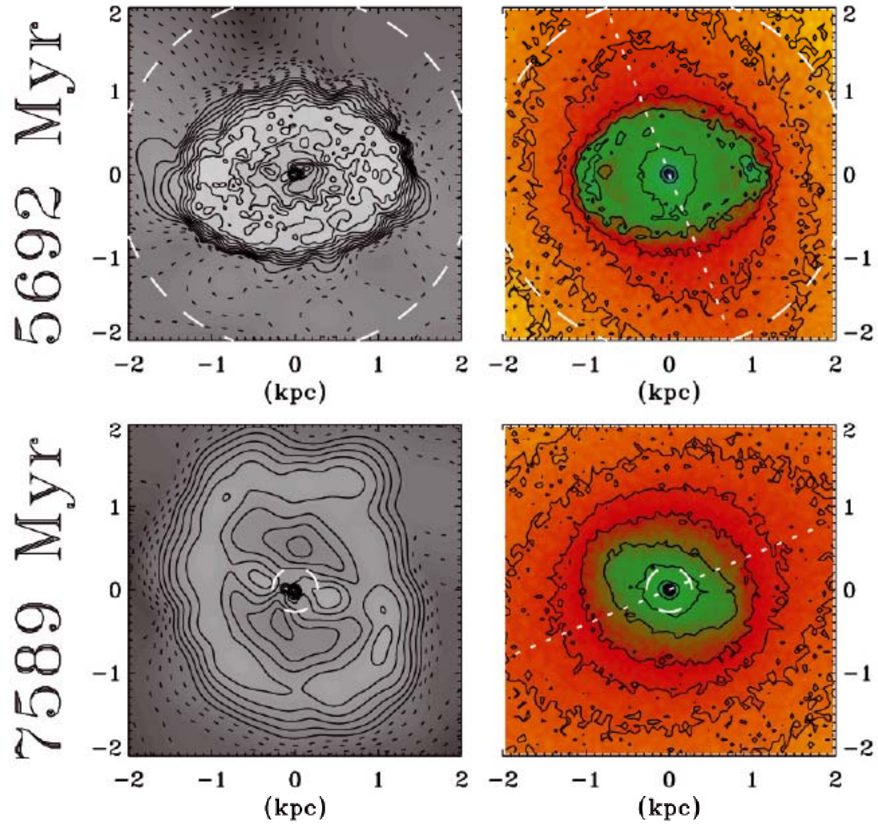
Du et al 2015

From clumpy high-z galaxies

➔ nuclear bar, then a primary bar

Long-lived two-bar galaxies

Wozniak 2015



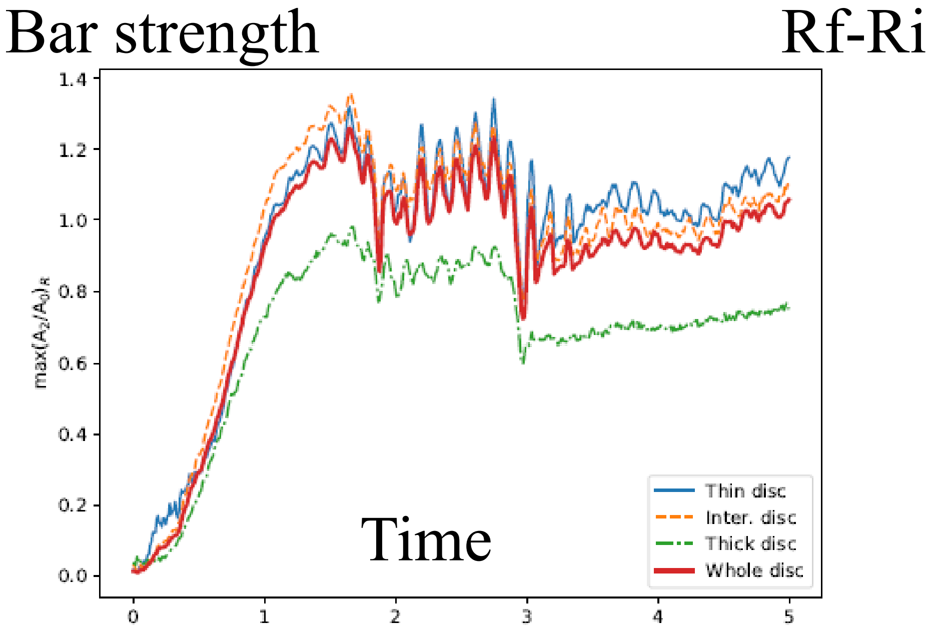
No resonance in common

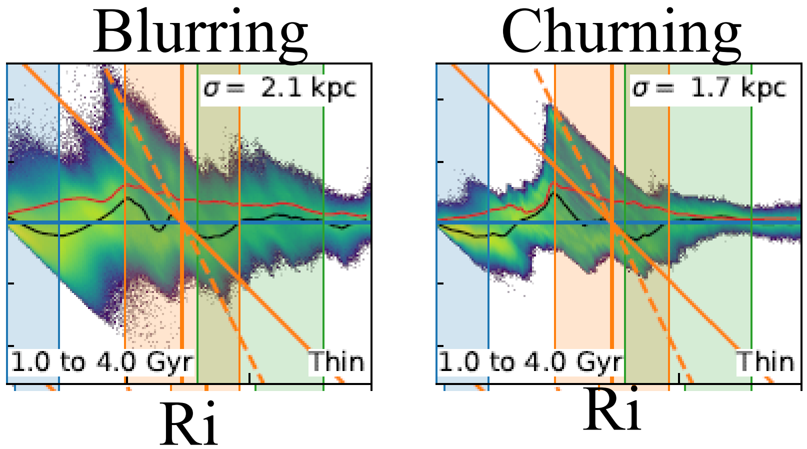
➔No mode coupling

SFR in the gas stabilises the nuclear bar

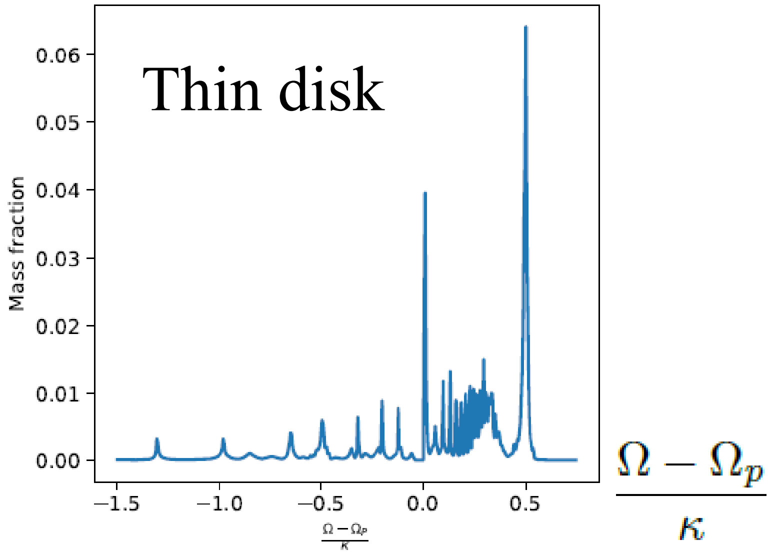
Radial migration

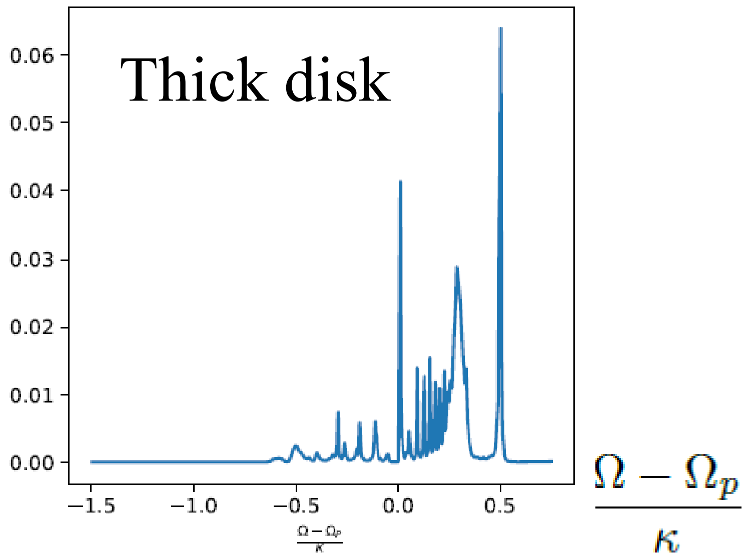
Halle et al 2018





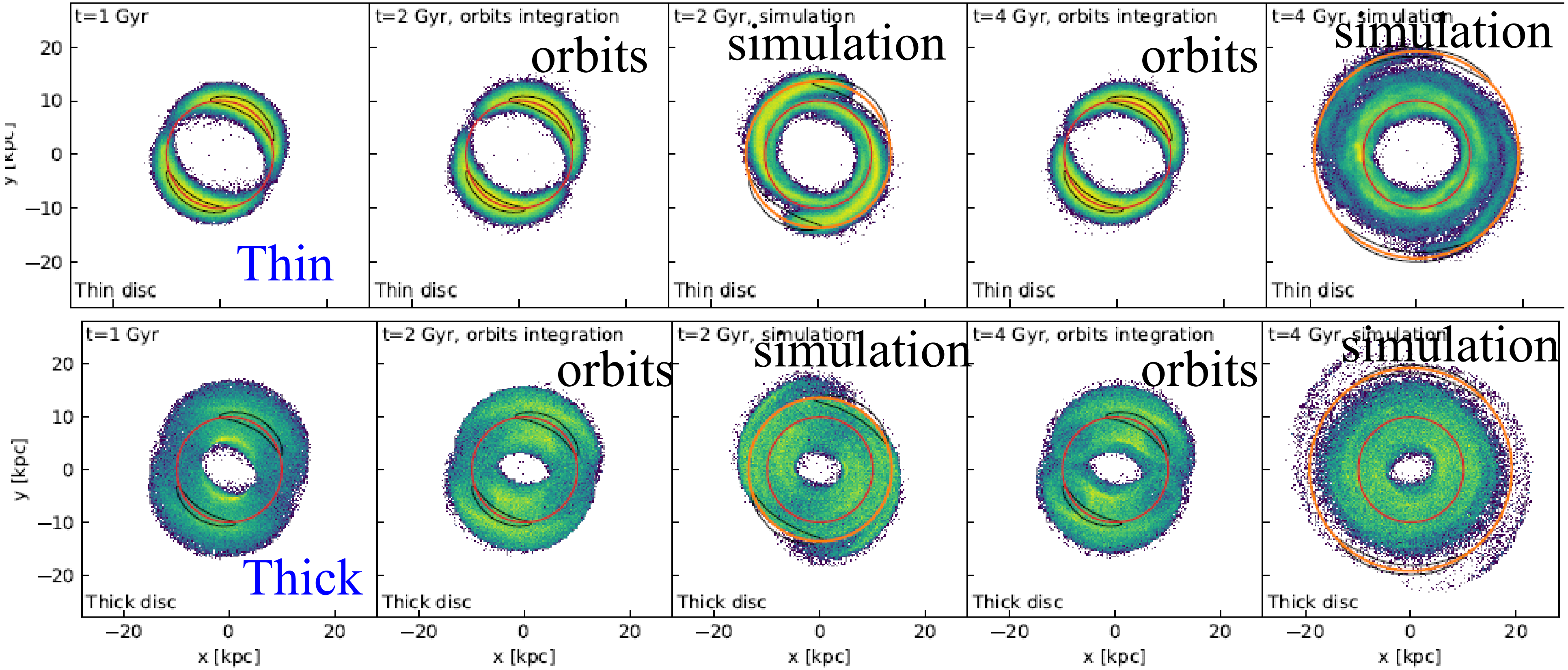
Thin and thick disks are
Equally subject to migration





Thin and thick disk migrations

Orbit integration: with potential and pattern speed fixed

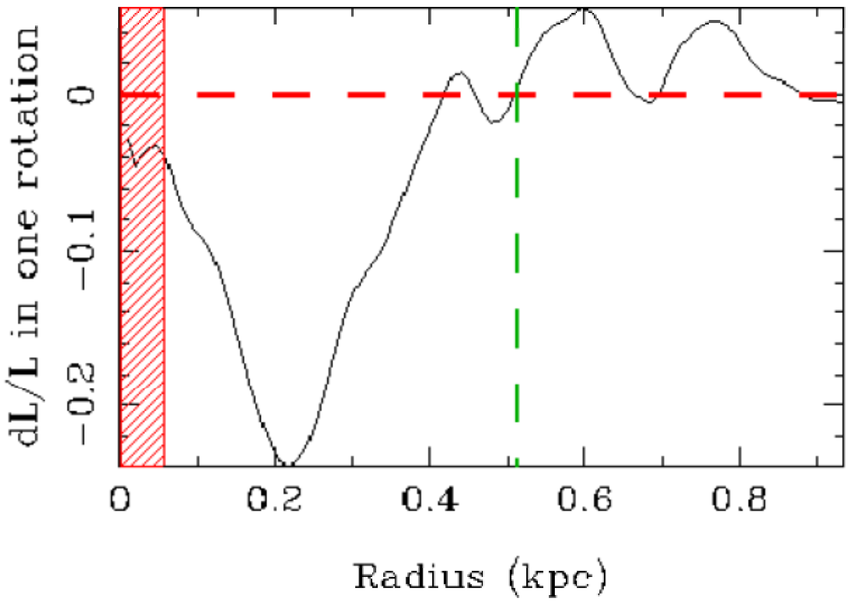


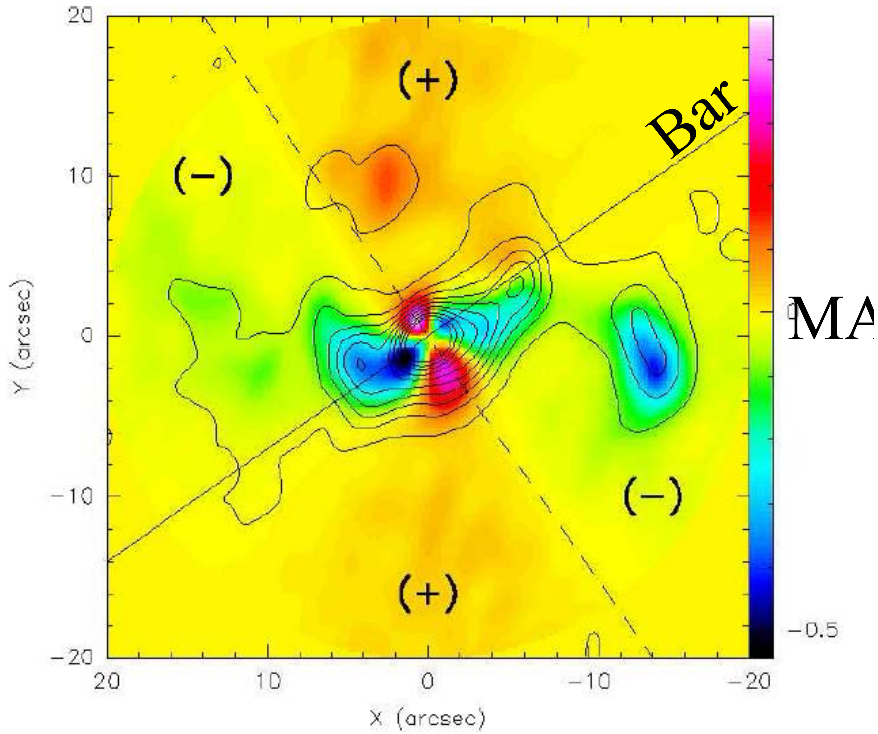
Simulation: potential and pattern speed vary
➔ Real migration

Halle et al 2018

Fueling: Bar gravity torques

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





Torque map for NGC 3627

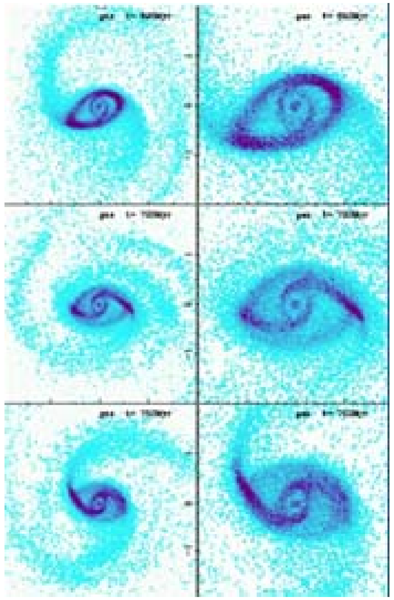
(Casasola et al 2011)

Contours= gas density

Correlation between bars and AGN

Schawinski et al 2010, Cardamone et al 2011

Statistics -- Time-scales
10-100pc fueling

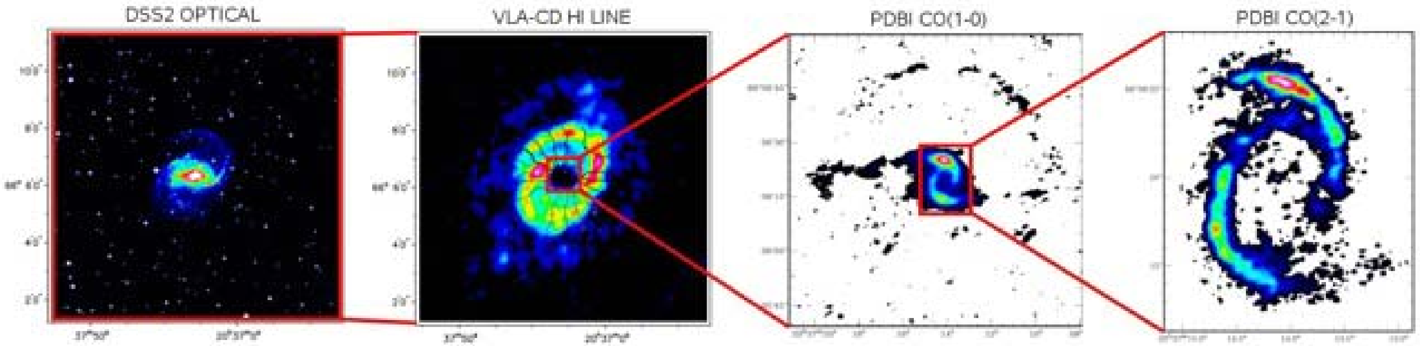


➔ **Only ~35%** of negative torques in the center,
About 20 galaxies *(Garcia-Burillo & Combes 2012)*

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

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

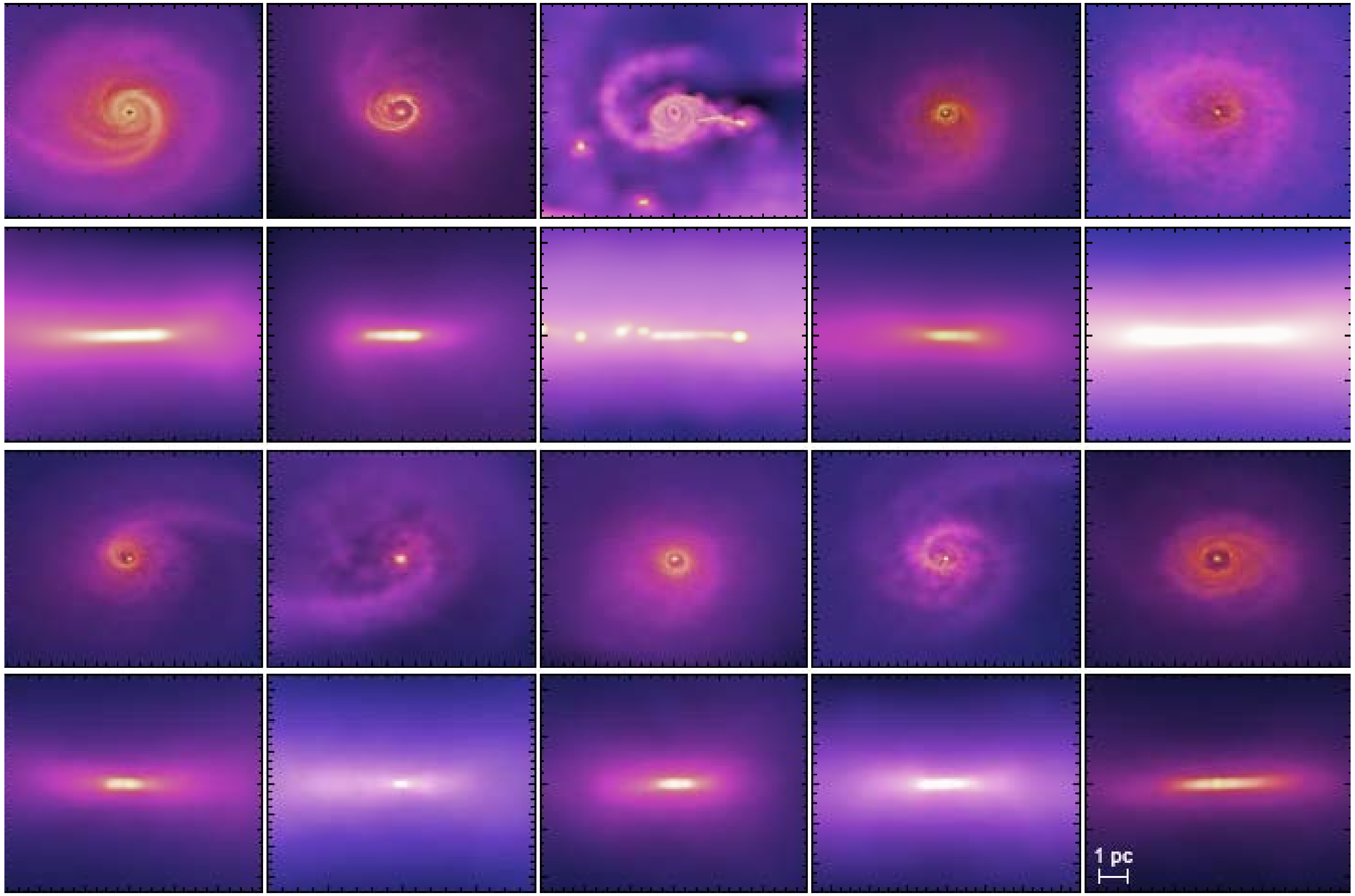
➔ Star formation fueled by the torques, always associated to AGN activity, but with longer time-scales



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 $M_\odot$

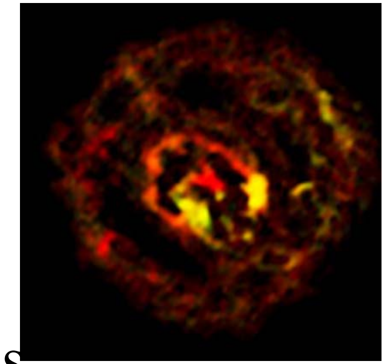
t~80Myr $(r/100pc)^2$

varies in 1/M

Hopkins et al 2011

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

Feedback in low-luminosity AGN



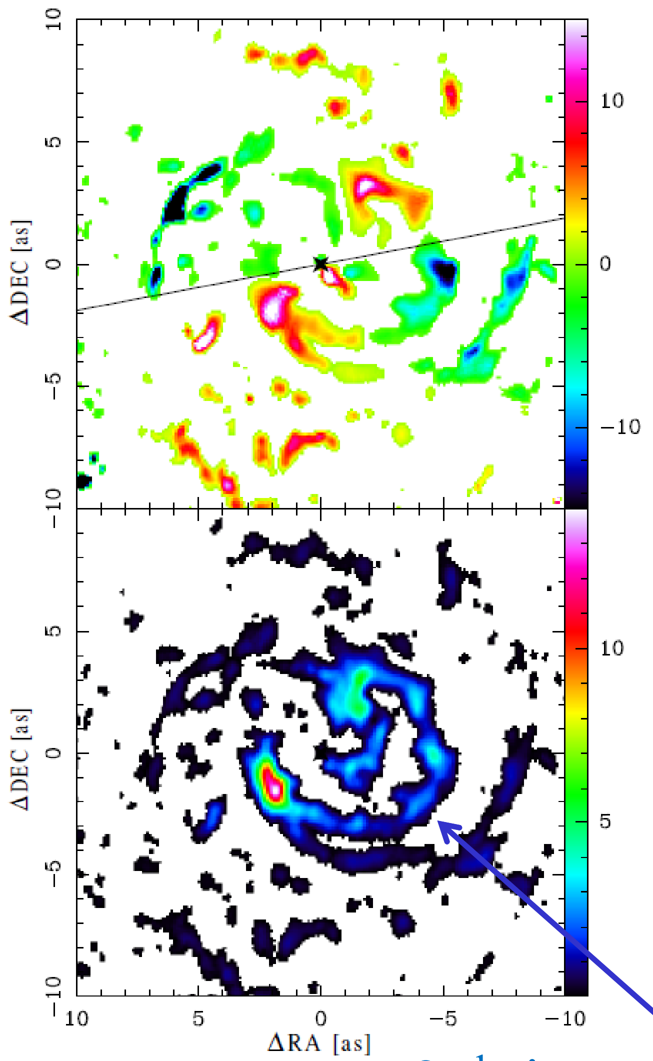
NGC 1433: barred spiral, **CO(3-2) with ALMA**
Molecular gas fueling the AGN, + outflow // the minor axis

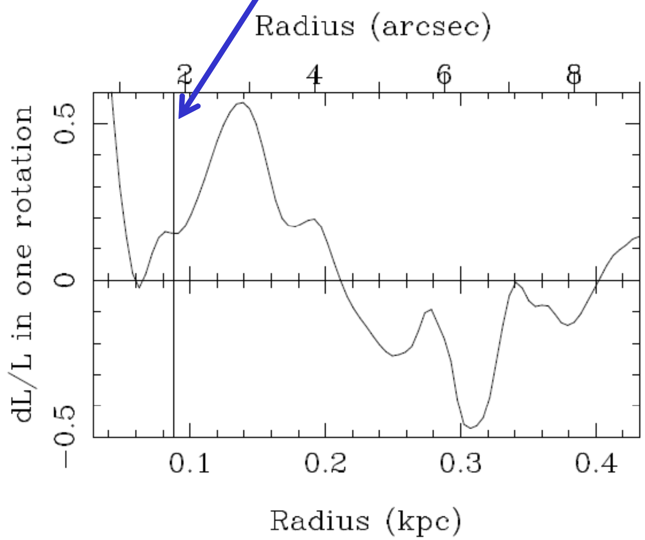
M_{H2}= 5.2 10^7 $M_\odot$ in FOV=18"
100km/s flow
7% of the mass= 3.6 10^6 $M_\odot$
Smallest flow detected

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

Gravity torques fuel the ring
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 nearby barred Sy1

N1566 SAB Sy1

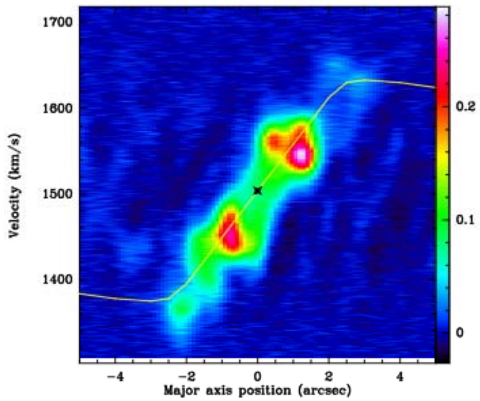
4 arcmin

FOV=18 ”

Spatial resolution

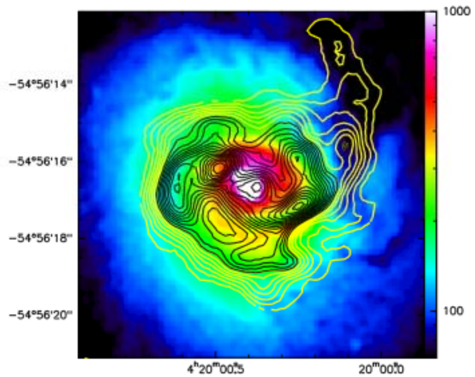
0.5 arcsecond ~25pc

Combes et al 2014

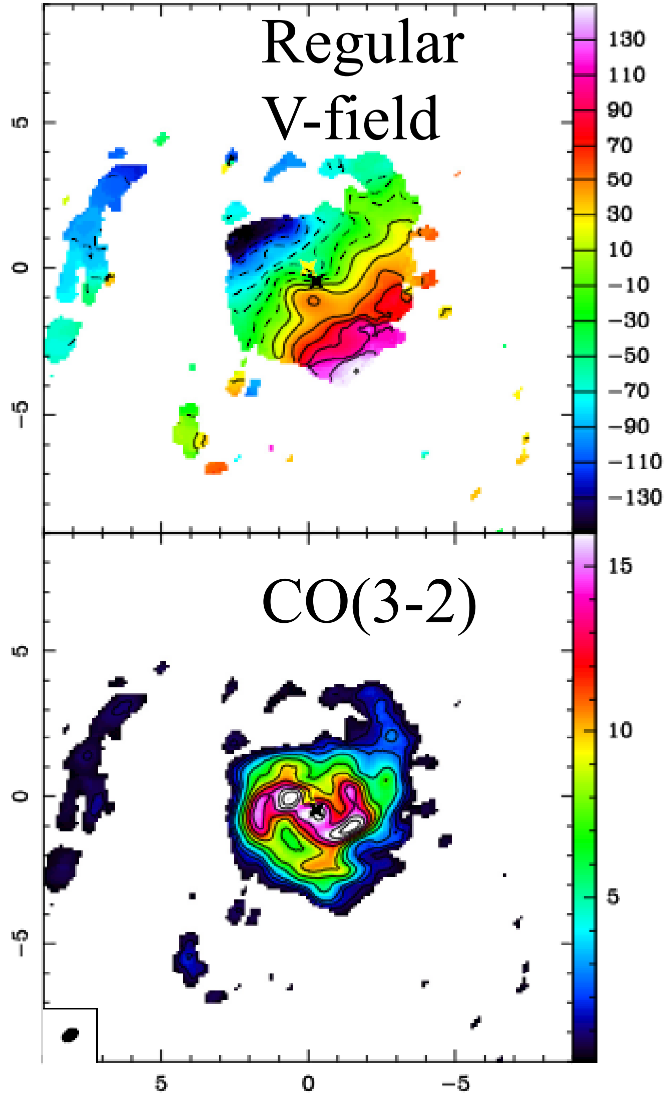


PV major axis

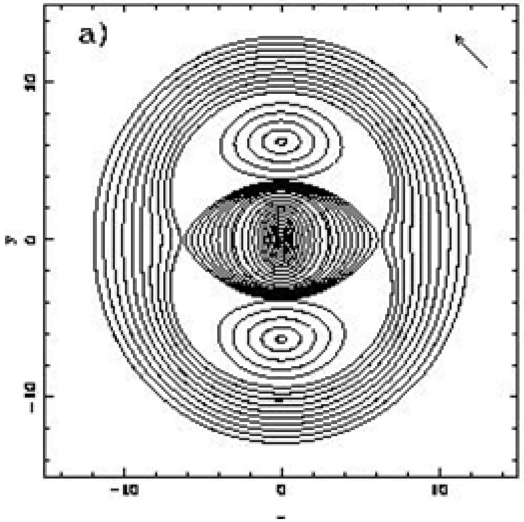
No outflow



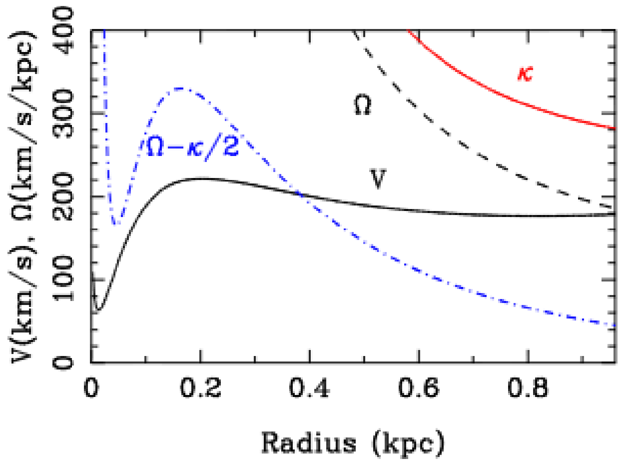
Overlay CO(3-2) contours on HST image



Schematic orbits, and gas behaviour



Stellar periodic orbits



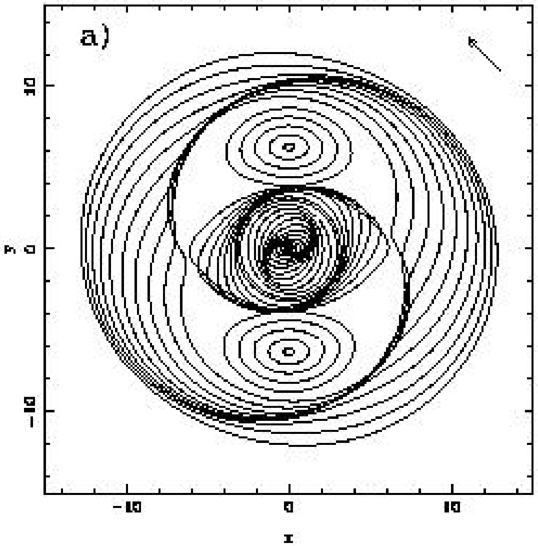
Periodic orbits in a potential in cos 2θ

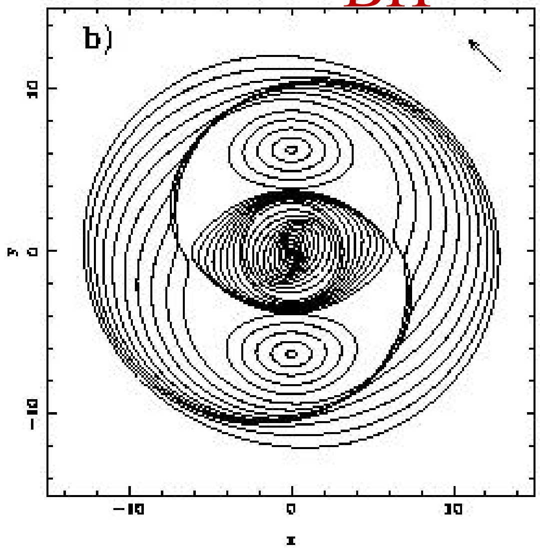
The gas tends to follow these orbits, but rotates gradually by 90° at each resonance

BH

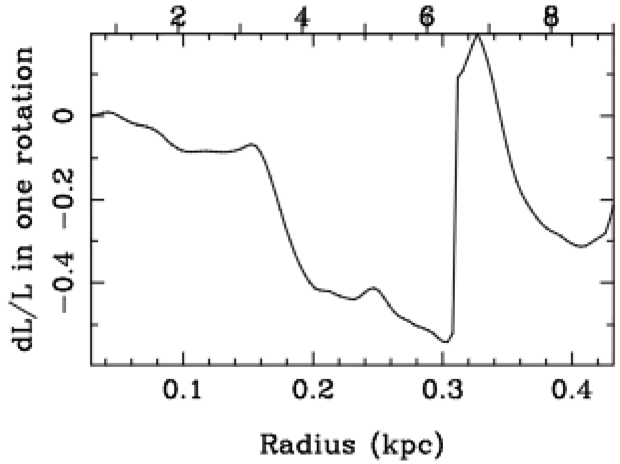
a) without BH, leading

b) with BH, trailing



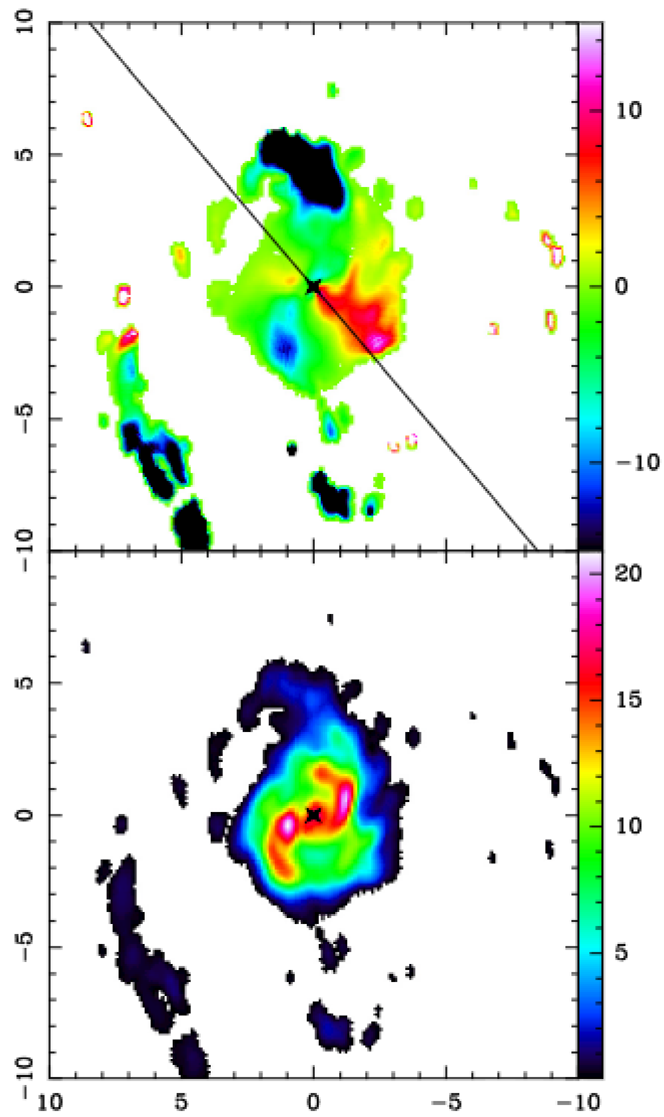


NGC1566: gravitational torques



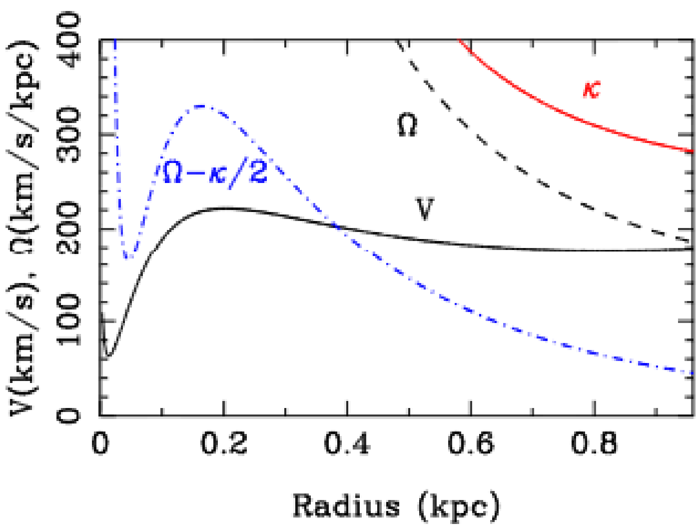
Gas is driven inwards

Torques on deprojected image

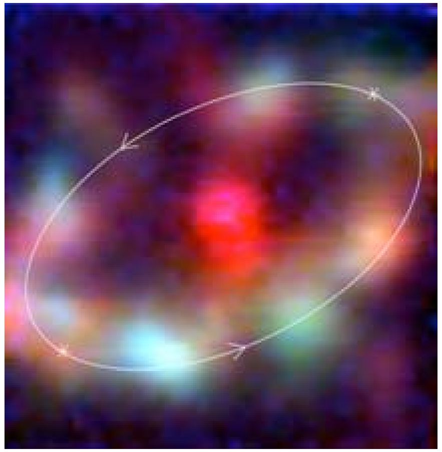


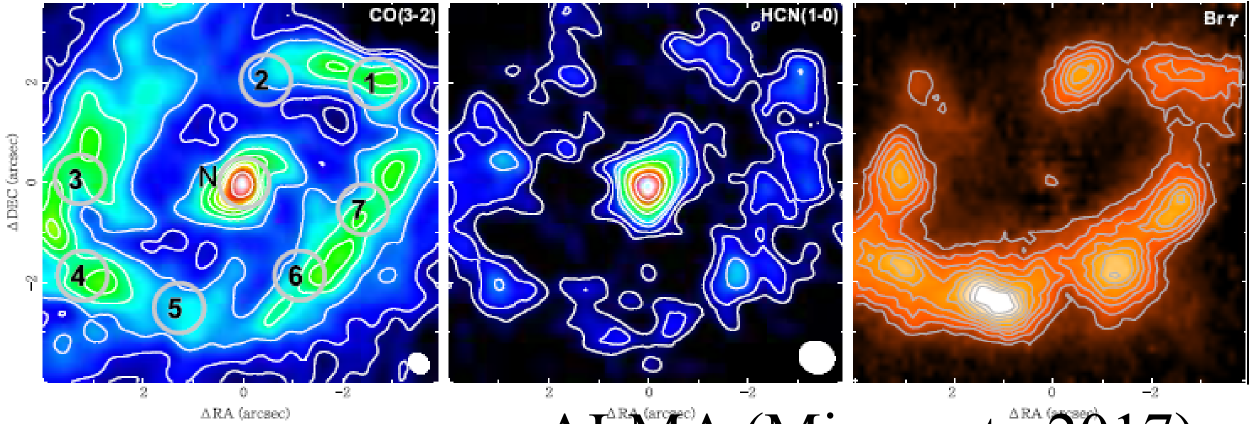
Trailing spiral inside the ILR ring of the bar

➔ BH influence on the dynamics



N613

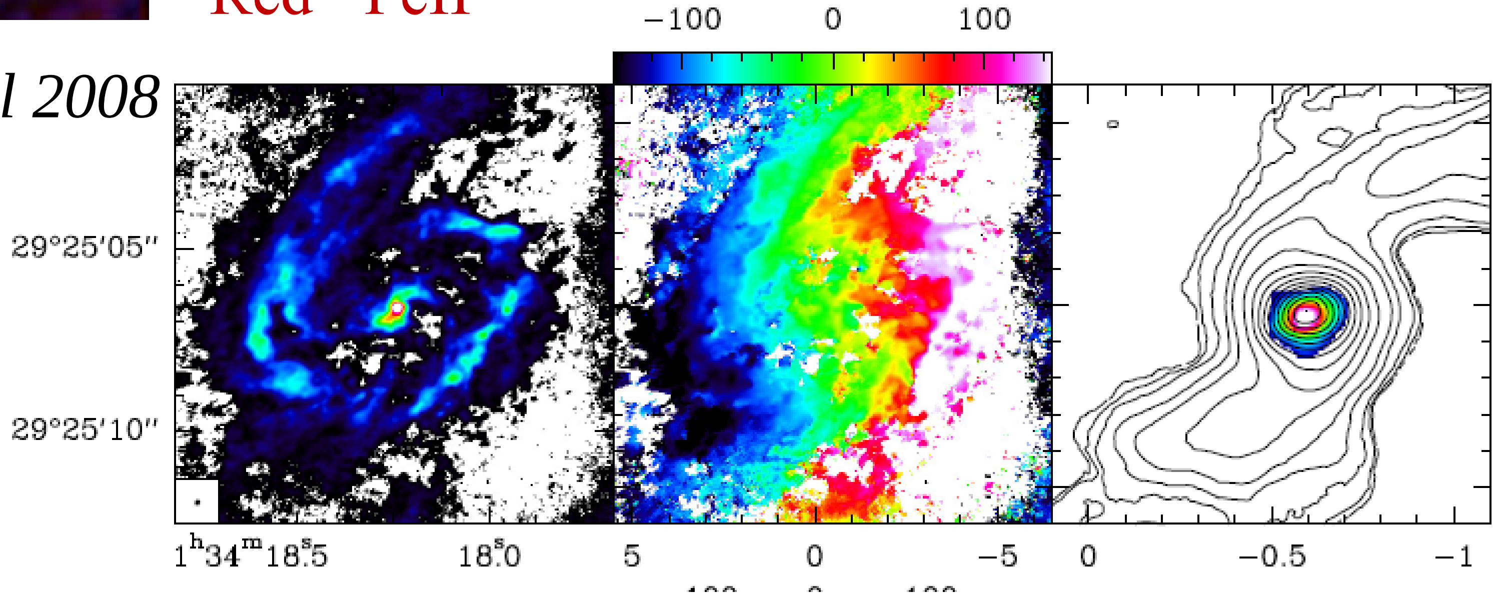




ALMA (Miyamoto 2017)

Blue= HeI
Green = Brγ
Red= FeII

Böker et al 2008
SINFONI



With 0.09" x 0.06" resolution: nuclear spiral +torus
Combes et al 2018

UFO+ molecular outflow Mrk231

V_{UFO} = 20 000 km/s

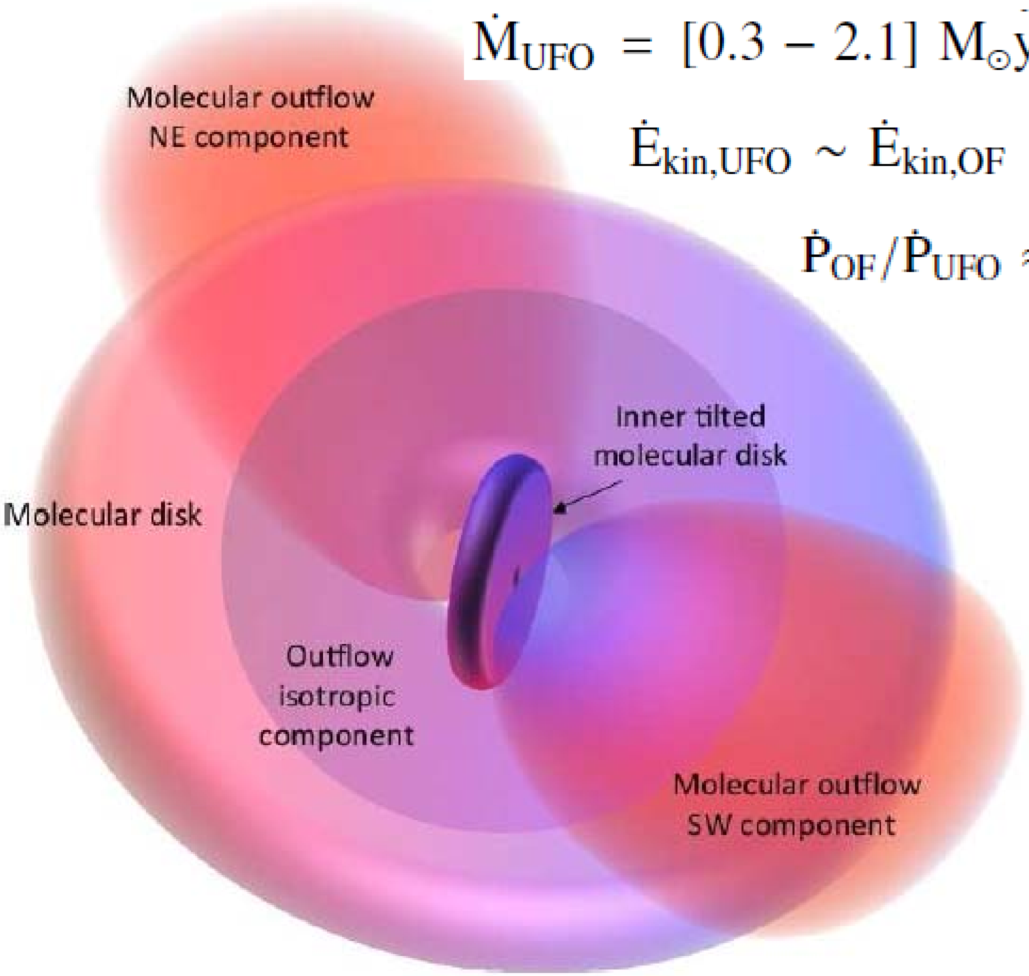
1kpc in molecules, 3kpc in atomic gas

(Rupke & Veilleux 2011) **Loading factor η > 2.5**

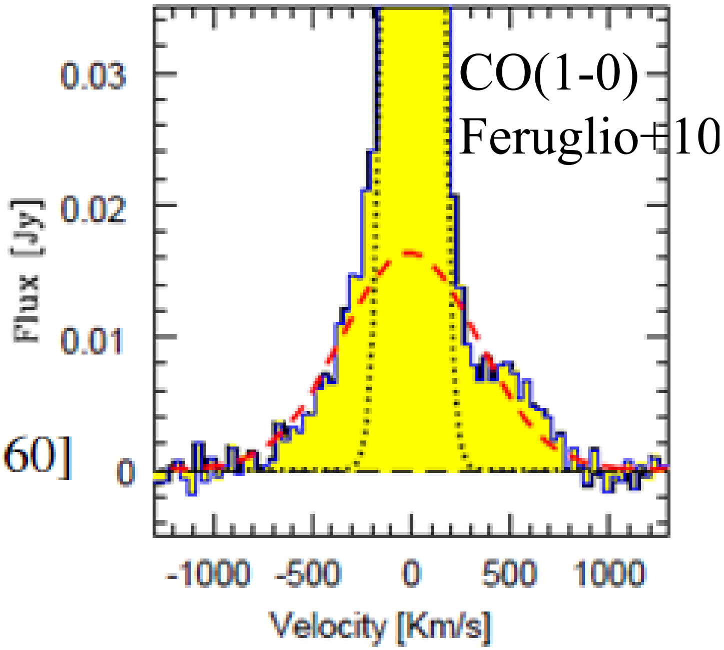
$\dot{M}_{UFO} = [0.3 - 2.1]\ M_{\odot} yr^{-1}$

$\dot{E}_{kin,UFO} \sim \dot{E}_{kin,OF}$

$\dot{P}_{OF}/\dot{P}_{UFO} \approx [30 - 60]$



+HCN
Aalto +12



+ Radio jet in the N
+ SB wind in the S

Ejected gas 10^7-10^8 $M_{\odot}$

Outflow of 700 $M_{\odot}$ /yr

Feruglio et al 2015

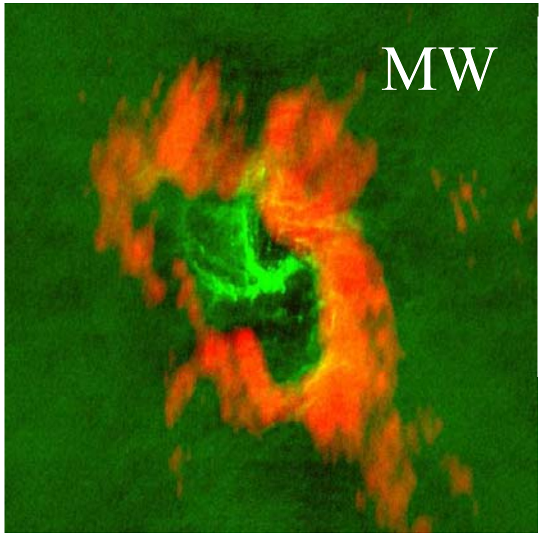
Non-alignment with host disk

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

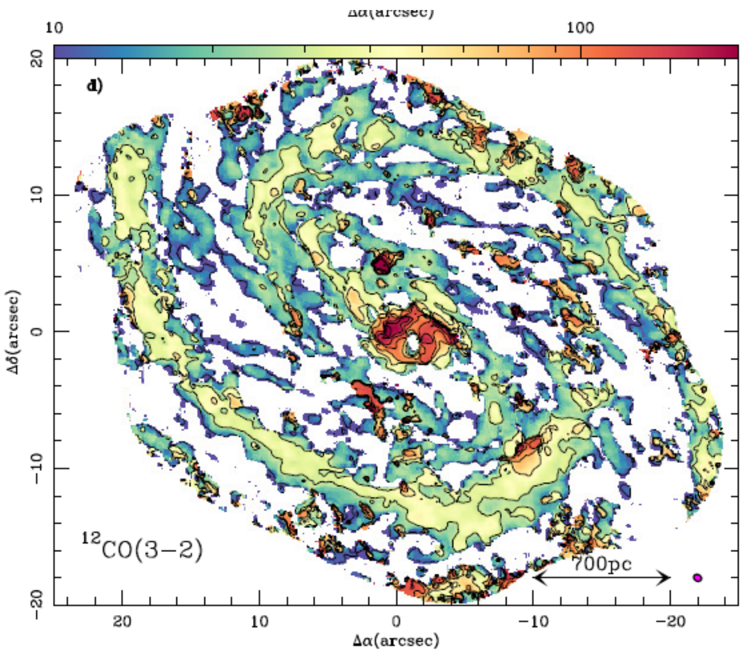
Many Seyfert have their jet not perpendicular to the main disk
(Schmitt & Kinney 2002; Jog & Combes 2009)

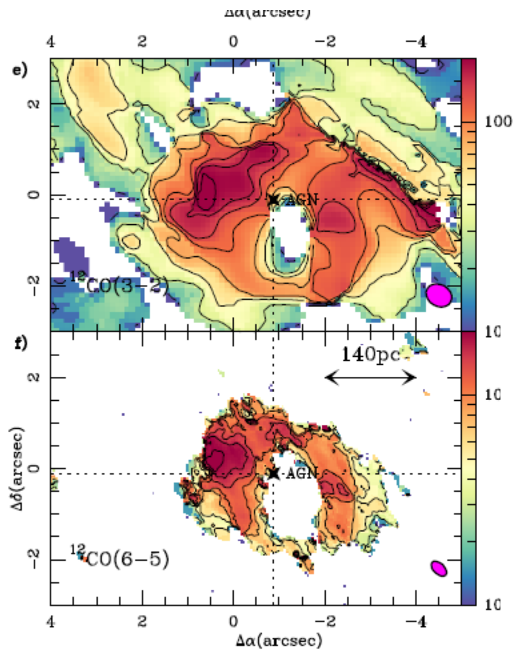
CNR: circumnuclear ring
2-3pc in radius
HCN in orange
Ionized gas in green
Inclination of 20° /plane



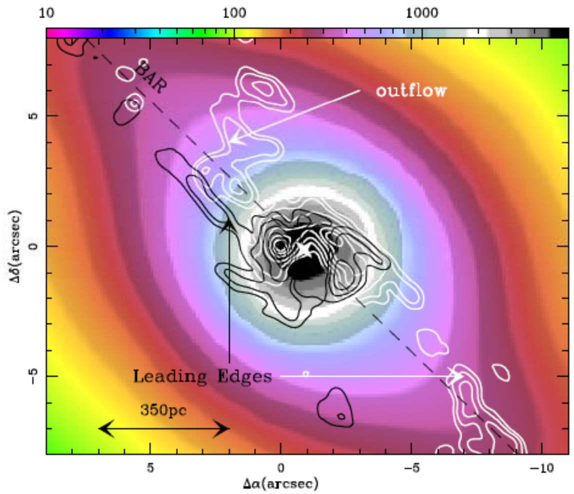
Mini-spiral $60 M_\odot$
Cavity $200 M_\odot$
CNR $10^6 M_\odot$
$7\ 10^4$ cm^{-3}
300K

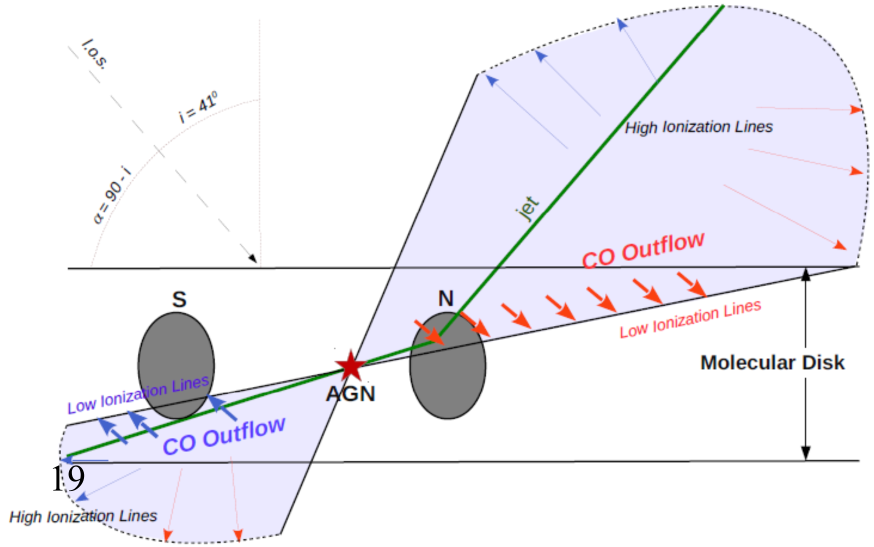
Offcentered nucleus and outflow in NGC1068





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



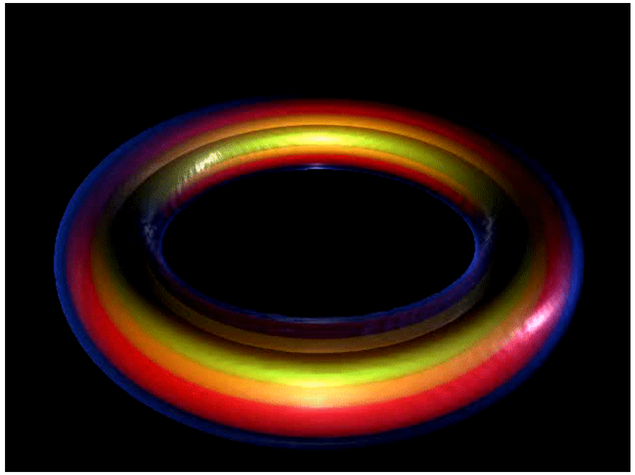


Outflow of $63M_{\odot}$/yr
10x the star formation rate
in this region

Garcia-Burillo, Combes, Usero et al 2014

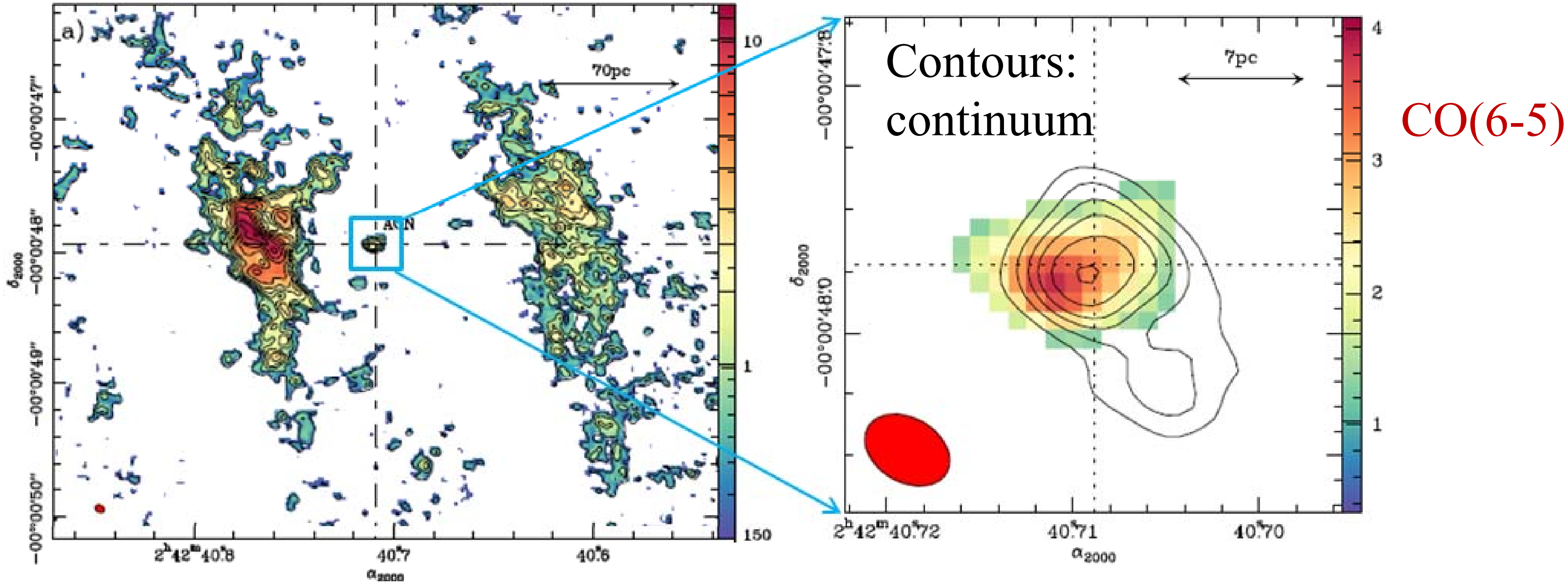
Detection of molecular tori

J. Tohline



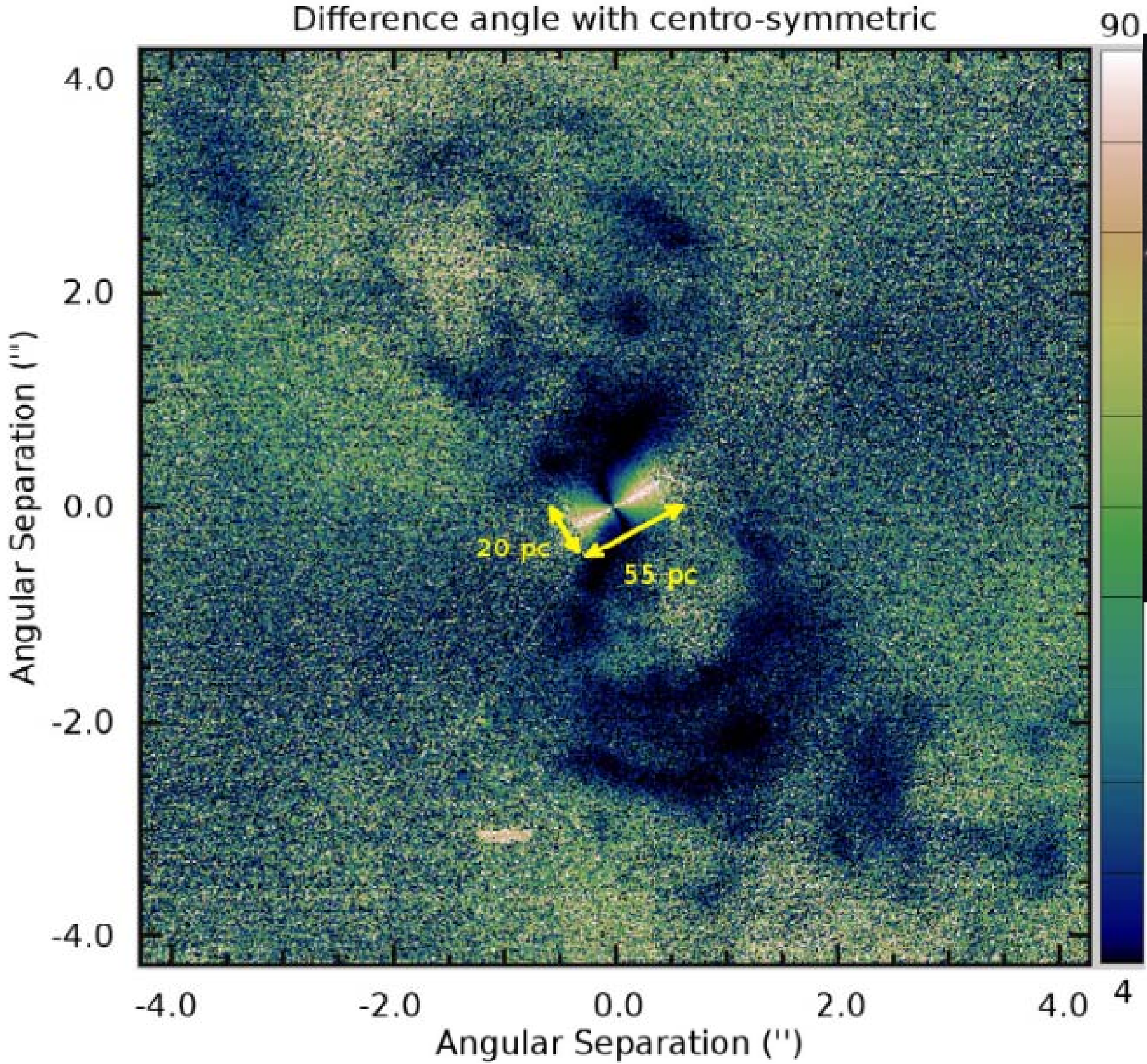
ALMA CO(6-5) and 432μm dust emission
➔Torus of 7-10pc in diameter in NGC1068

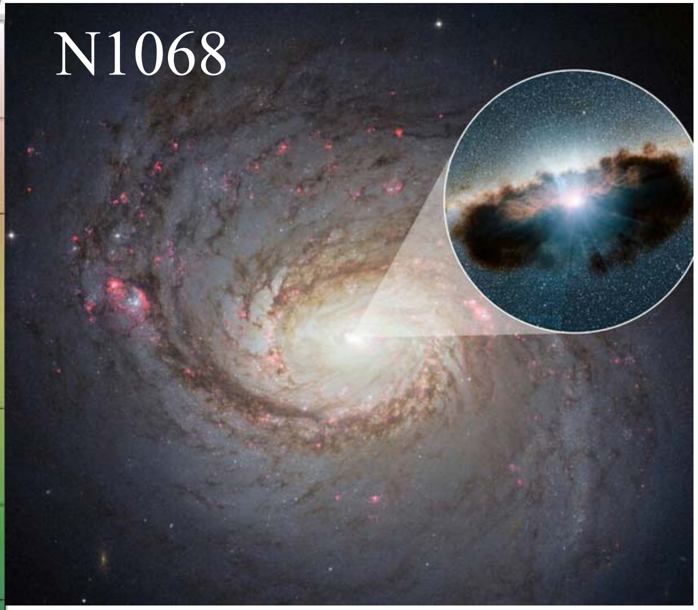
More inclined than the H_2O maser disk
Papaloizou-Pringle instability



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

Molecular torus inside a polar dusty cone



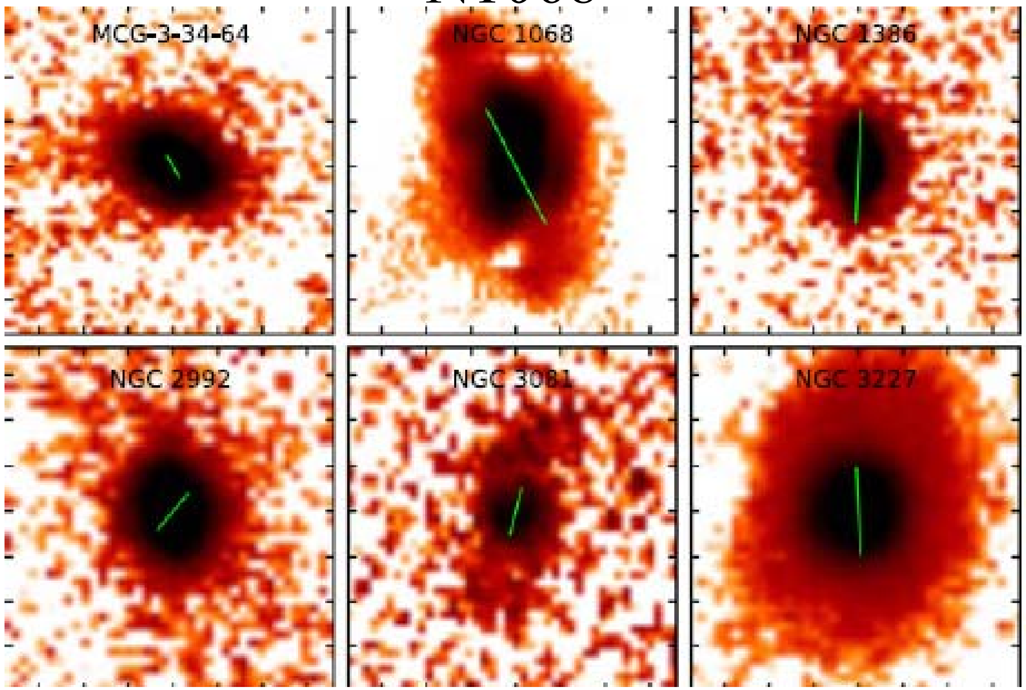


X-rays, XMM, Nustar
Several components
From 10^{23} cm^{-2}
up to 10^{25}cm^{-2}
➔Compton-thick
~up to 100pc scale
Bauer et al 2015
Marinucci et al 2016

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

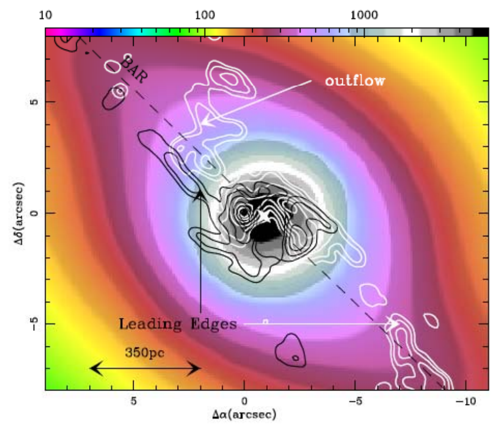
Polar dust distribution

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?



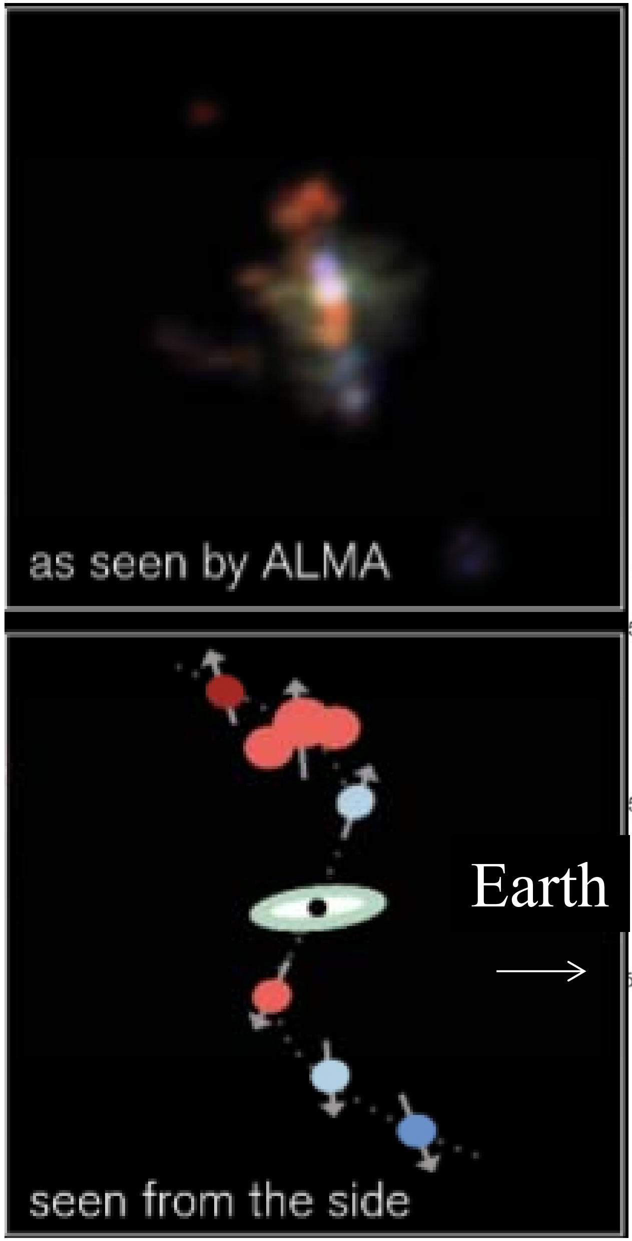
Green: 100pc along the polar axis
Asmus et al 2016

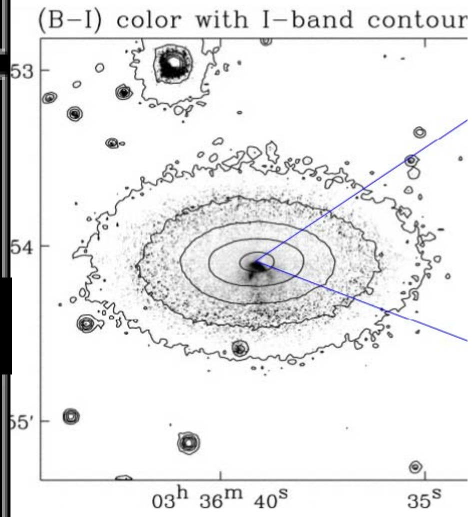
ALMA observations of NGC 1377

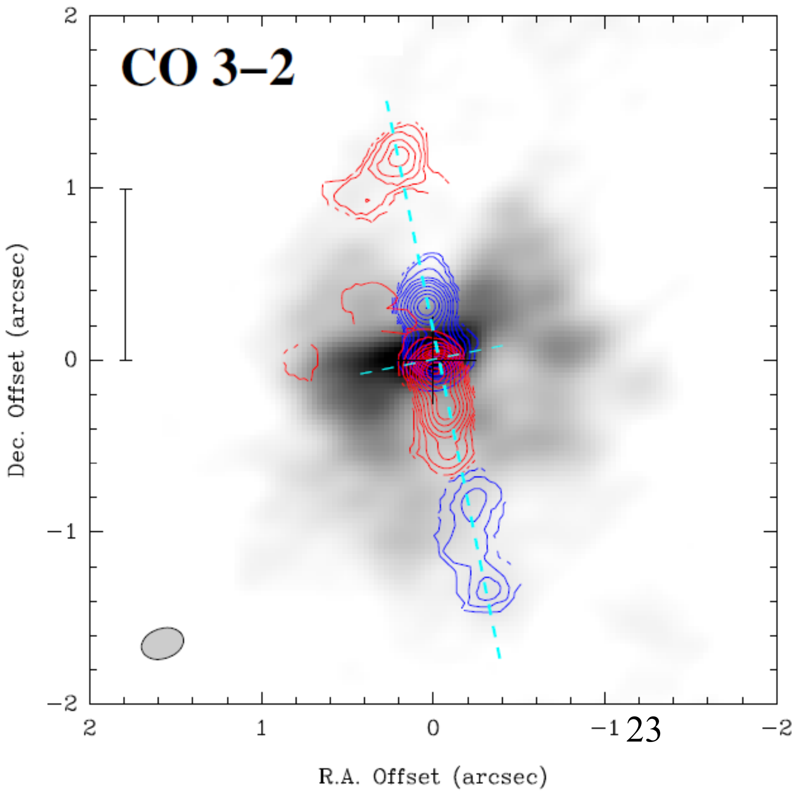
Beam 0.2 arcsec

Aalto et al 2016

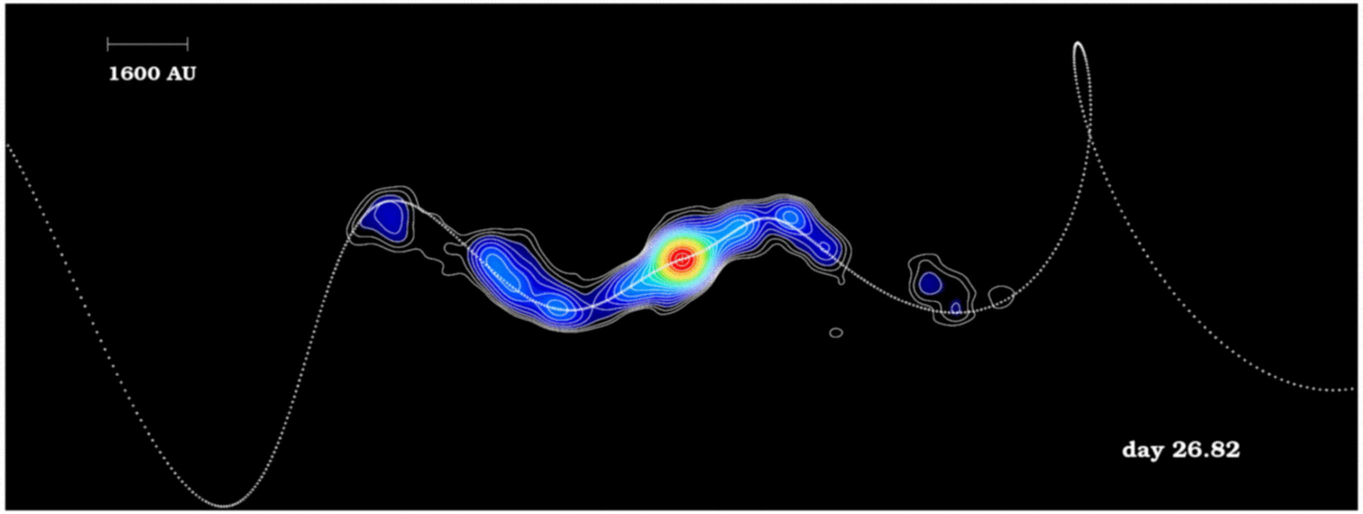
MH_2 in the cone 10^8 $M_\odot$
In the jet 10^7 $M_\odot$



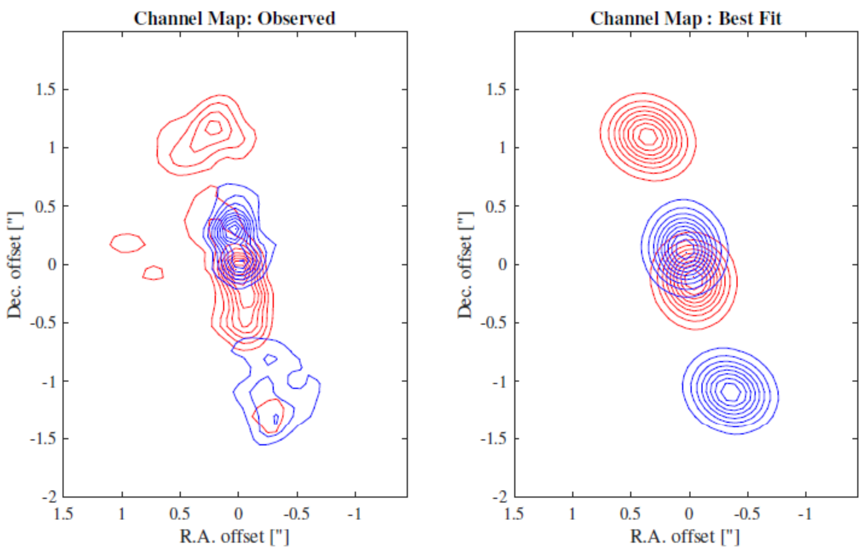




Precessing jets in N1377: as in micro-quasars



SS433 VLBA 15GHz,
1mas= 3AU
Mioduszewski et al. 2006
Inner jet 5mas
Motion 7-10mas/day

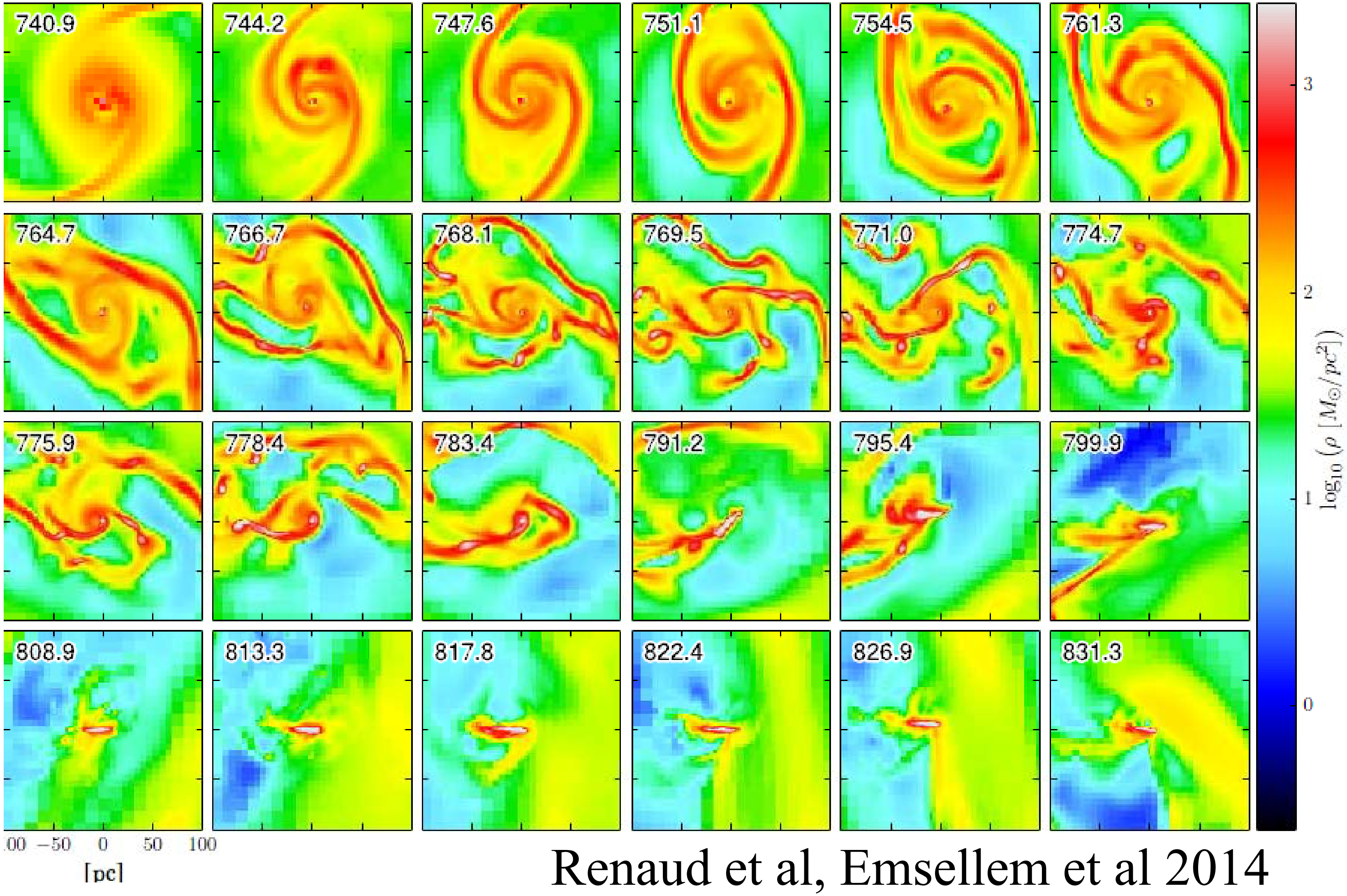


Model of a simple precession
The jet changes sign symmetrically North/South
Vflow= 250-600km/s
Launched r < 10pc

Aalto et al 2016

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

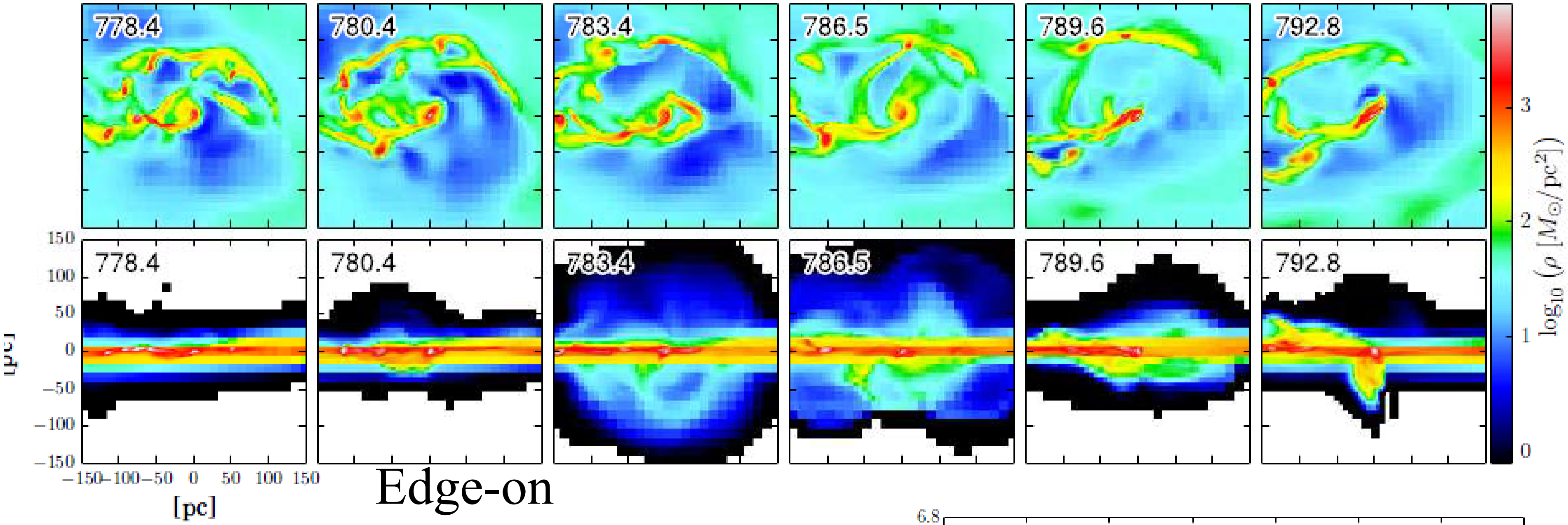
Face-on

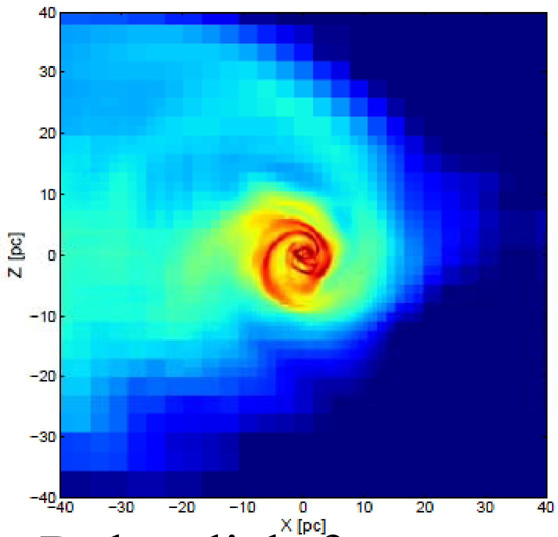


Renaud et al, Emsellem et al 2014

How the gas is accreted

Face-on

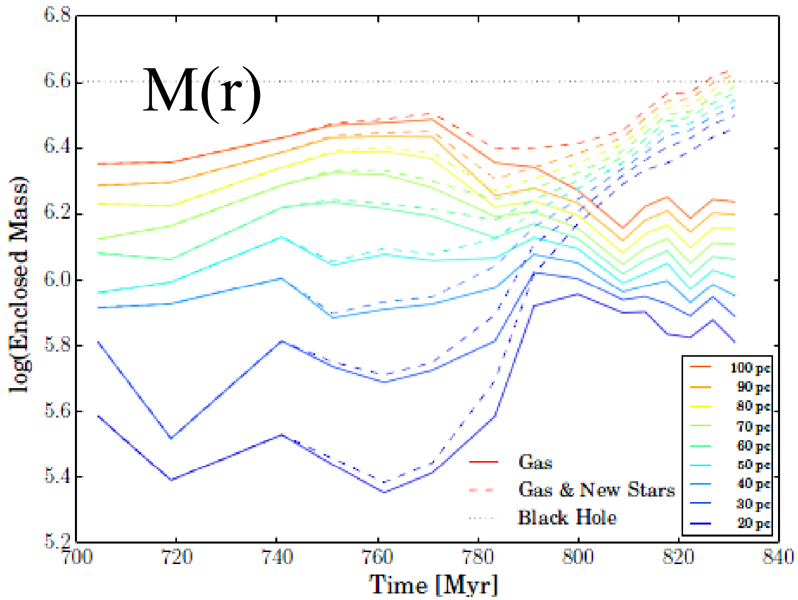




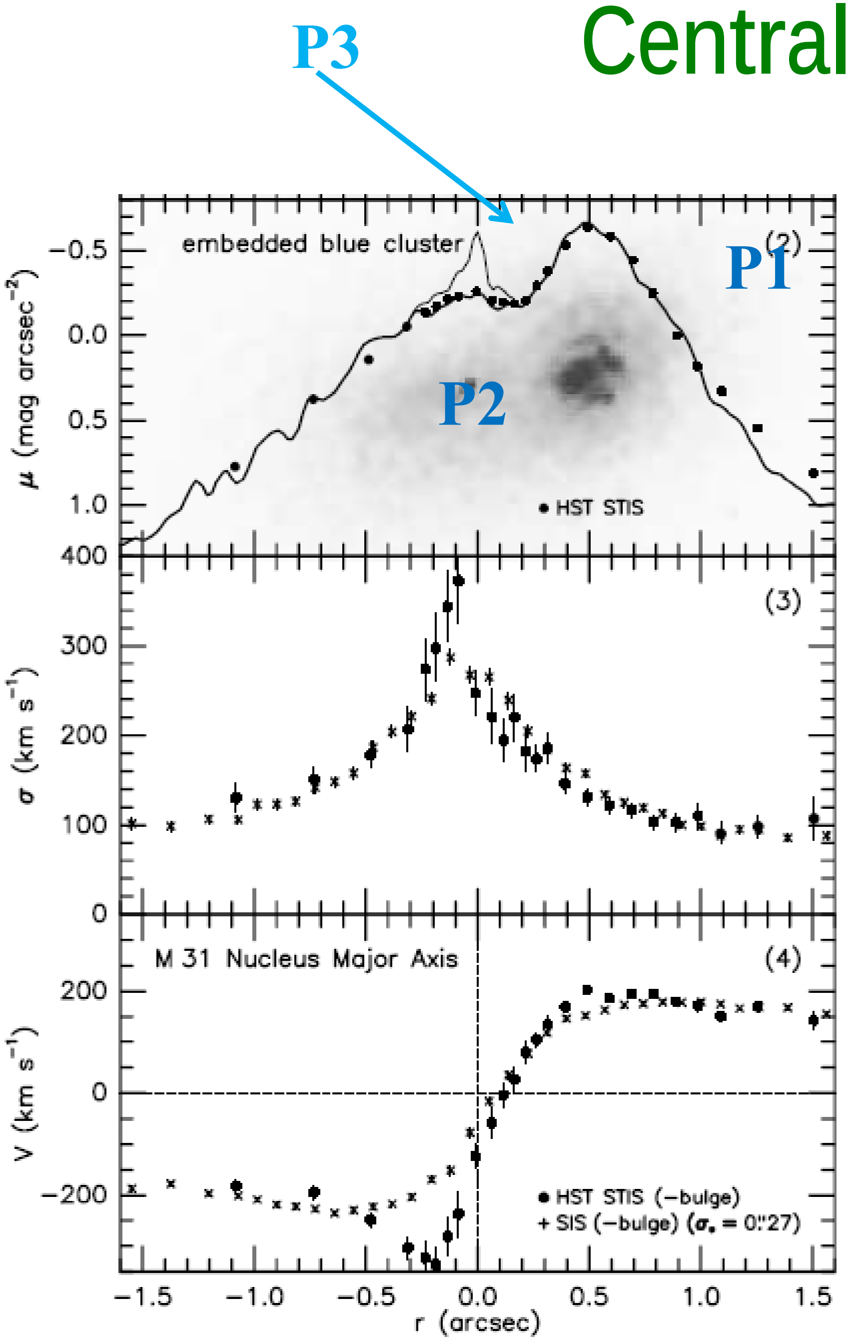
Polar disk face-on

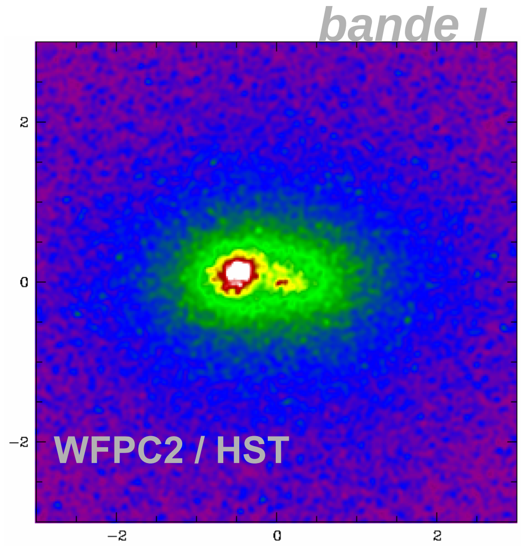
Strong SN Feedback
➔Gas in the Perpendicular plane

Emsellem et al 15



Central 10pc of M31





Existence of two disks of stars

-- P1+P2, excentric old stars

-- P3, star burst 200 Myr old

Different inclination, more face-on than M31 (77°)

P3 σ=670km/s, Vcir=1700km/s

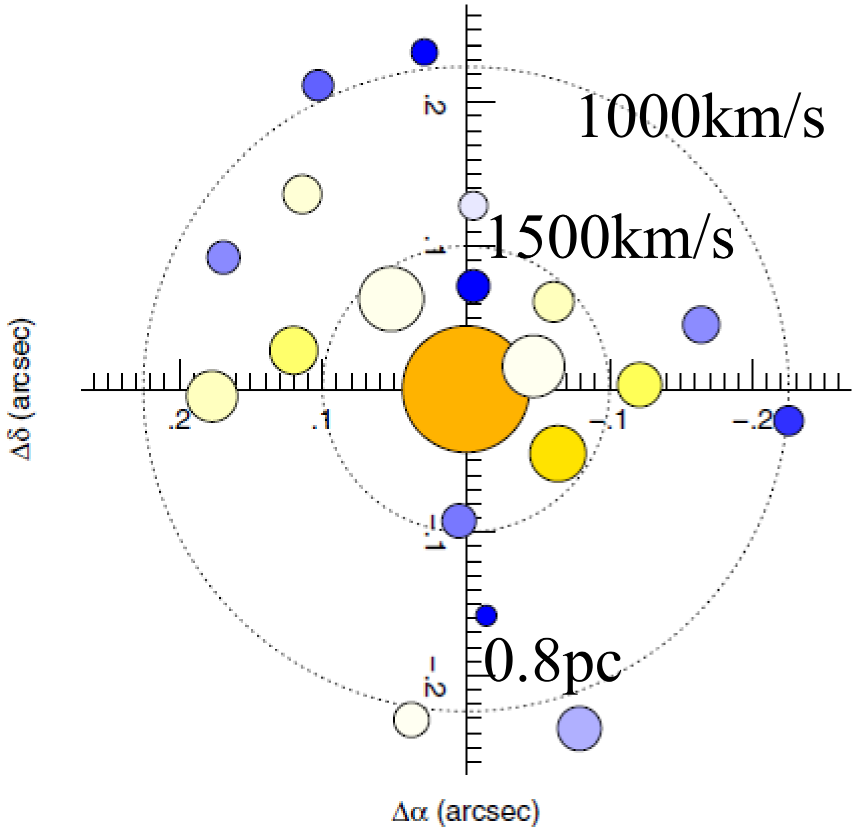
M_{BH}= 1.5 10^8 $M_\odot$

Bender et al 2005

Slow mode: Tremaine 2001

Triple nucleus in M31

P3: young star cluster, of age 100-200 Myr
How this cluster could have formed?



Surprising high compactness
Cannot be only BH-stripped giants
➔it is possible to form stars in the strong tidal field of a BH

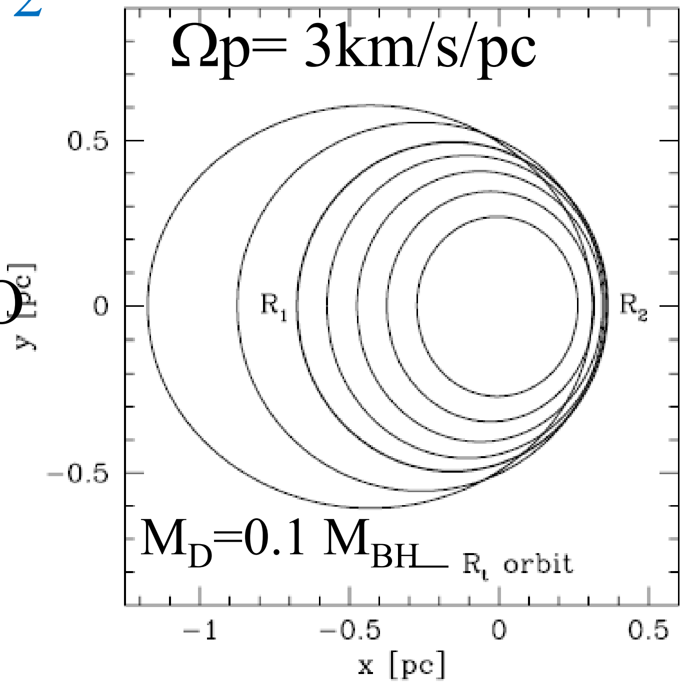
Lauer et al 2012

Formation of the young P3 cluster

In situ, r <1pc, age 100-200Myr (similar to MW?)

Stellar mass loss from the P1+P2 disk, if pattern speed <3-10 km/s/pc
fixes the size of P3
Gas cloud orbits➔ crossing, dissipation and infall r< 1pc
R1 the last non-crossing orbit
Gas mass for P3: $10^5 M_\odot$ << $10^7 M_\odot$ of P1+P2

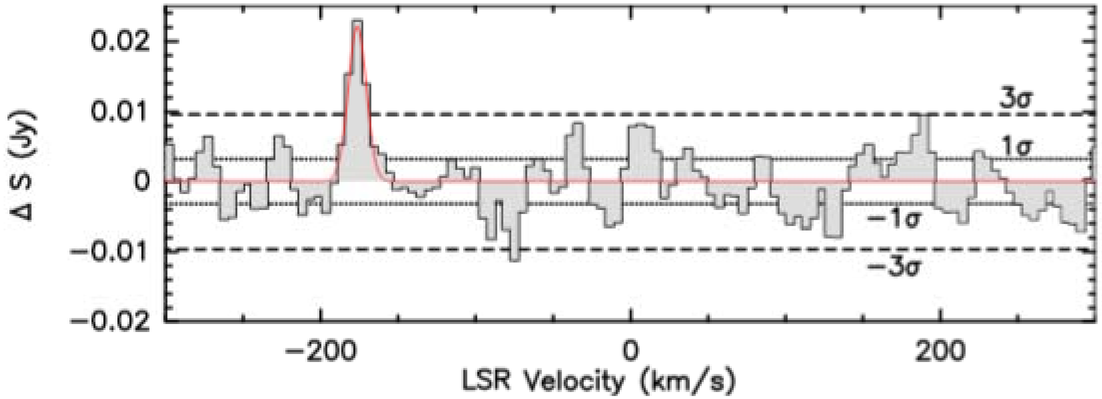
Winds at 10^{-4} $M_\odot$/yr, fills P3 in ~500Myr
Should produce repeated star bursts
a CND of a few $10^4 M_\odot$ might be visible in CO
(ΔV ~1000km/s)



P. Chang et al 2007

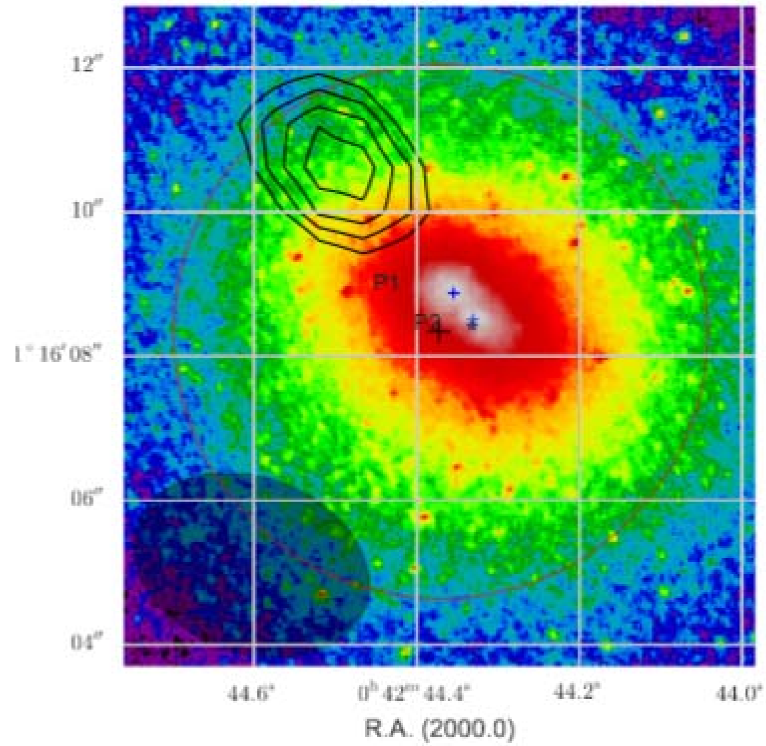
Upper limits on the gas accretion

A few $10^4 M_\odot$ might be visible in CO ($\Delta V \sim 1000$km/s)



NOEMA
3σ upper limit of 4300 $M_\odot$
for a line width of 1000 km s

Only a small clump seen in projection



Melchior & Combes 2017

SUMMARY

➔ **Fueling: Primary bar** drives gas → **100pc**
Then nuclear bar from 100pc to 10pc
Accretion 1/3rd of the time

➔ **At scales ~1-10pc,** viscous turbulence, clumps, warps, bending, dynamical friction, formation of thick disks/torus, **when there is gas**
Frequent m=1 in stellar disks

➔ Feedback, outflows are present, due to Starburst, and to AGN
Precession, strong coupling due to mis-alignment

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