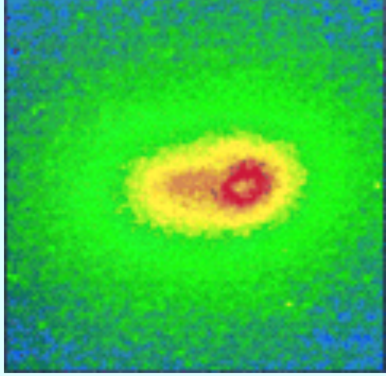
Gas Flows



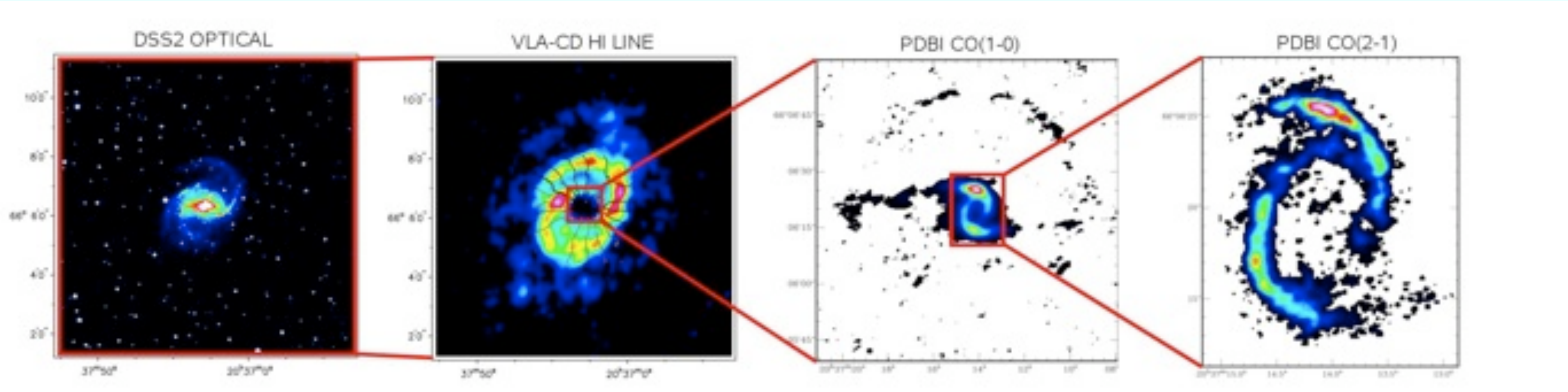
Outline:

➔Gas flows due to bars, m=2

➔ Lopsidedness, m=1, warps, bending

➔Clumps, turbulent viscosity, dyn. friction

➔Feedback, outflows (SF, AGN)



Françoise Combes

Durham, *July 29 2014*

Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique

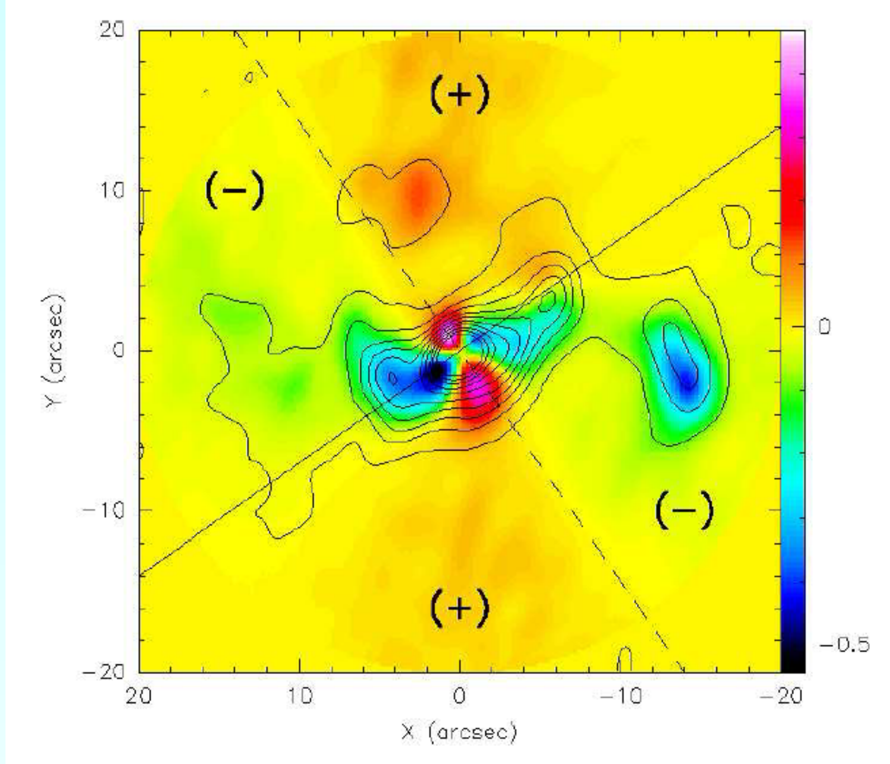
Bar gravity torques

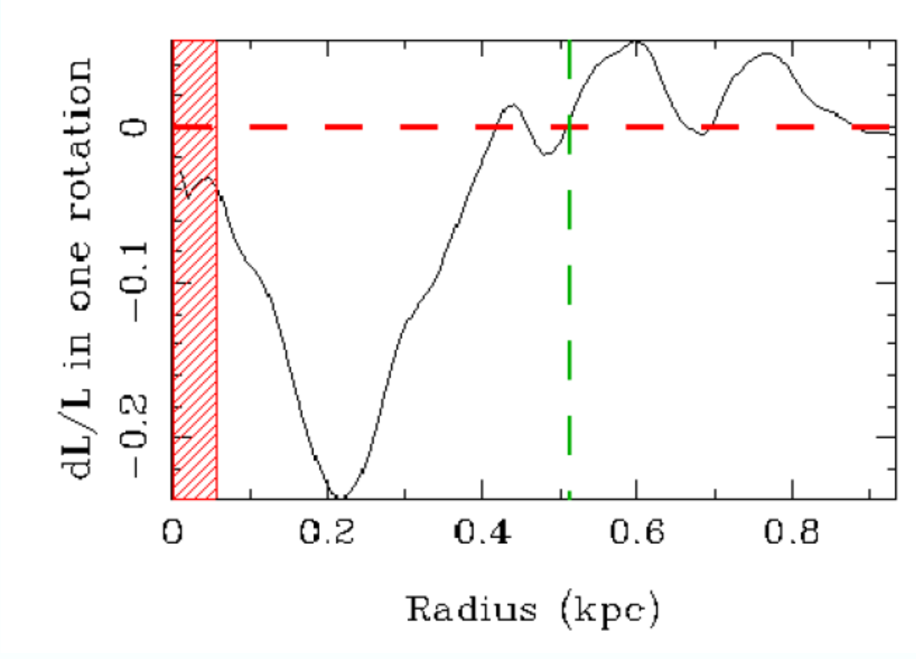
Torque map for NGC 3627
(Casasola et al 2011)

Torques computed from the
red image, on the gas distribution

The gas transfers AM to the stars
➔Weakens or destroys the bar

Correlation between bars and AGN
Schawinski et al 2010
Cardamone et al 2011
And SF Ellison et al 2011



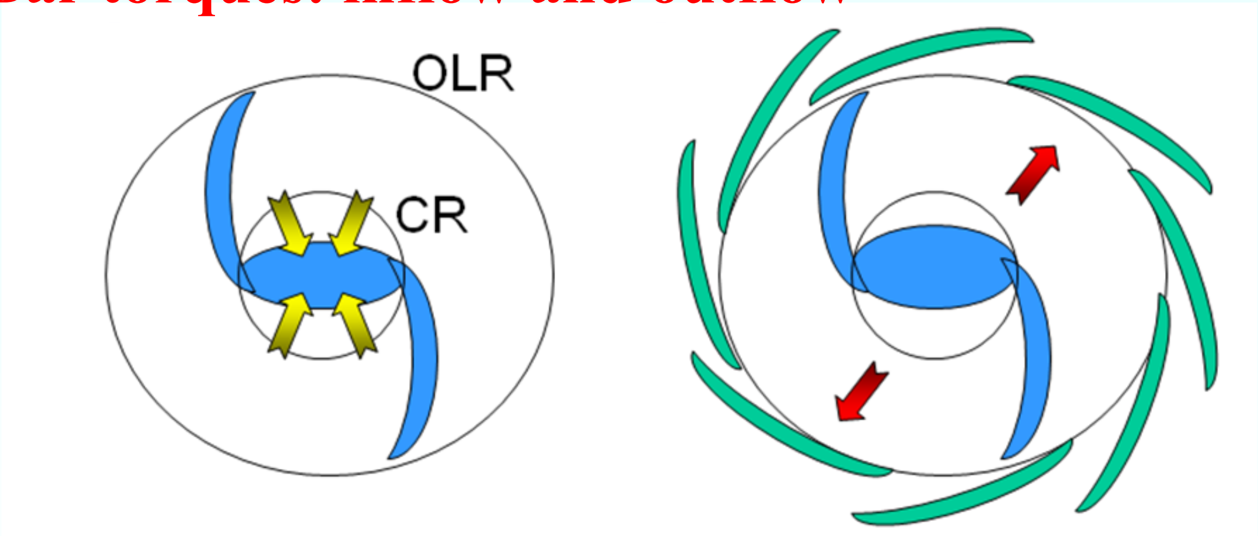


Effect of gas inflow

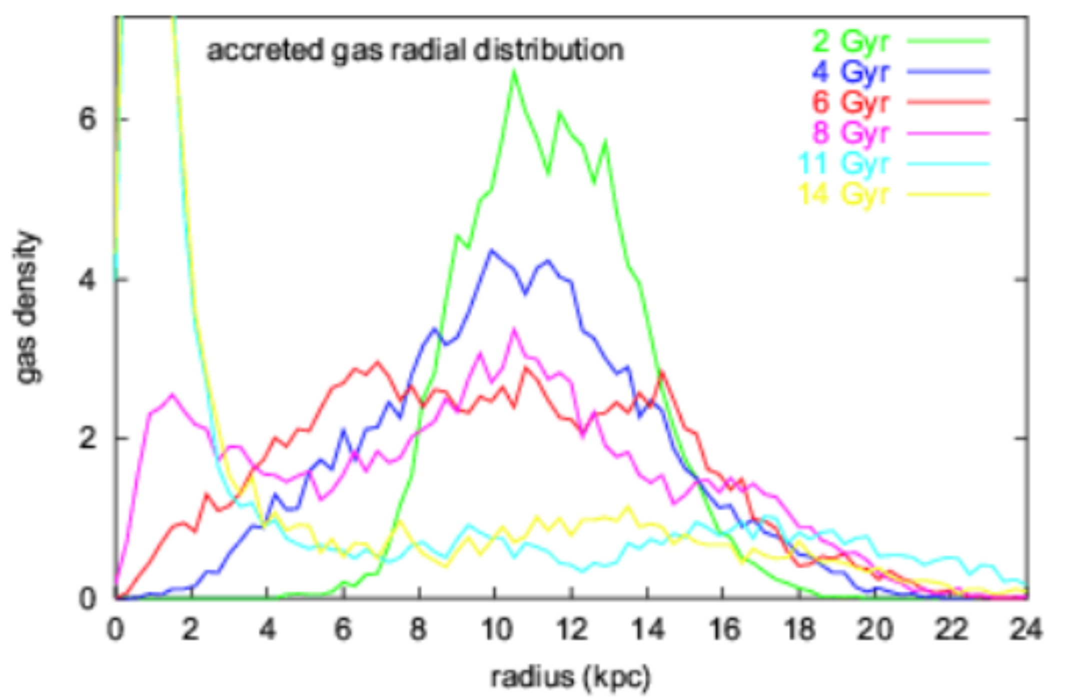
➔Replenish the disk, destabilises it
Generate Star Formation, and bar/spiral at the same time
➔Gravity torques as a consequence
➔Gas inflow rapidly to the center inside corotation
Bulge et Black hole growth

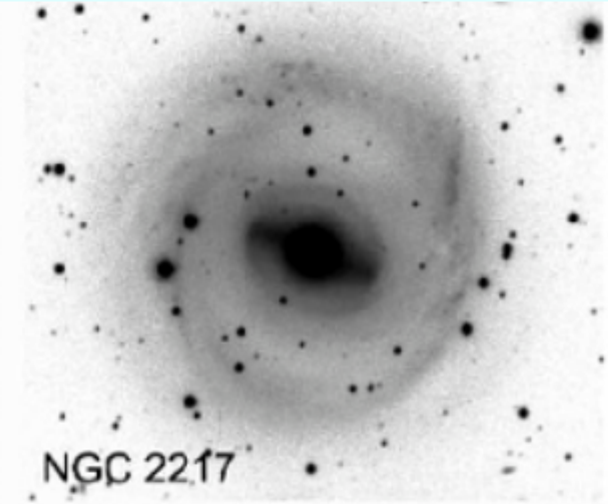
In simulations, the SFR and Q-parameter adjust so that the inflow rate roughly equals the SFR

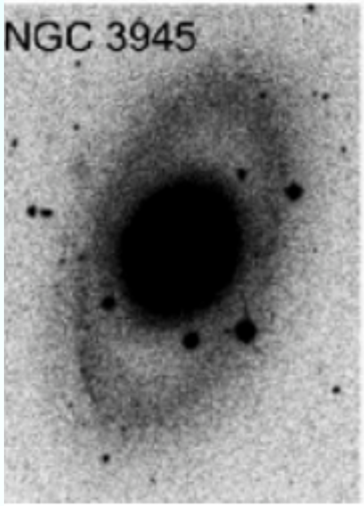
Bar torques: inflow and outflow

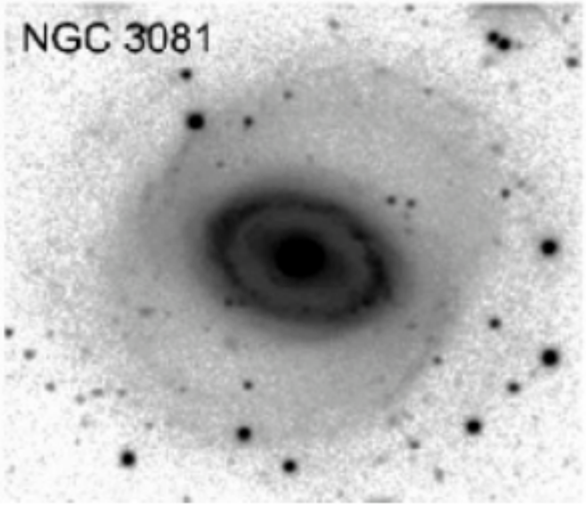


Accretion by intermittence



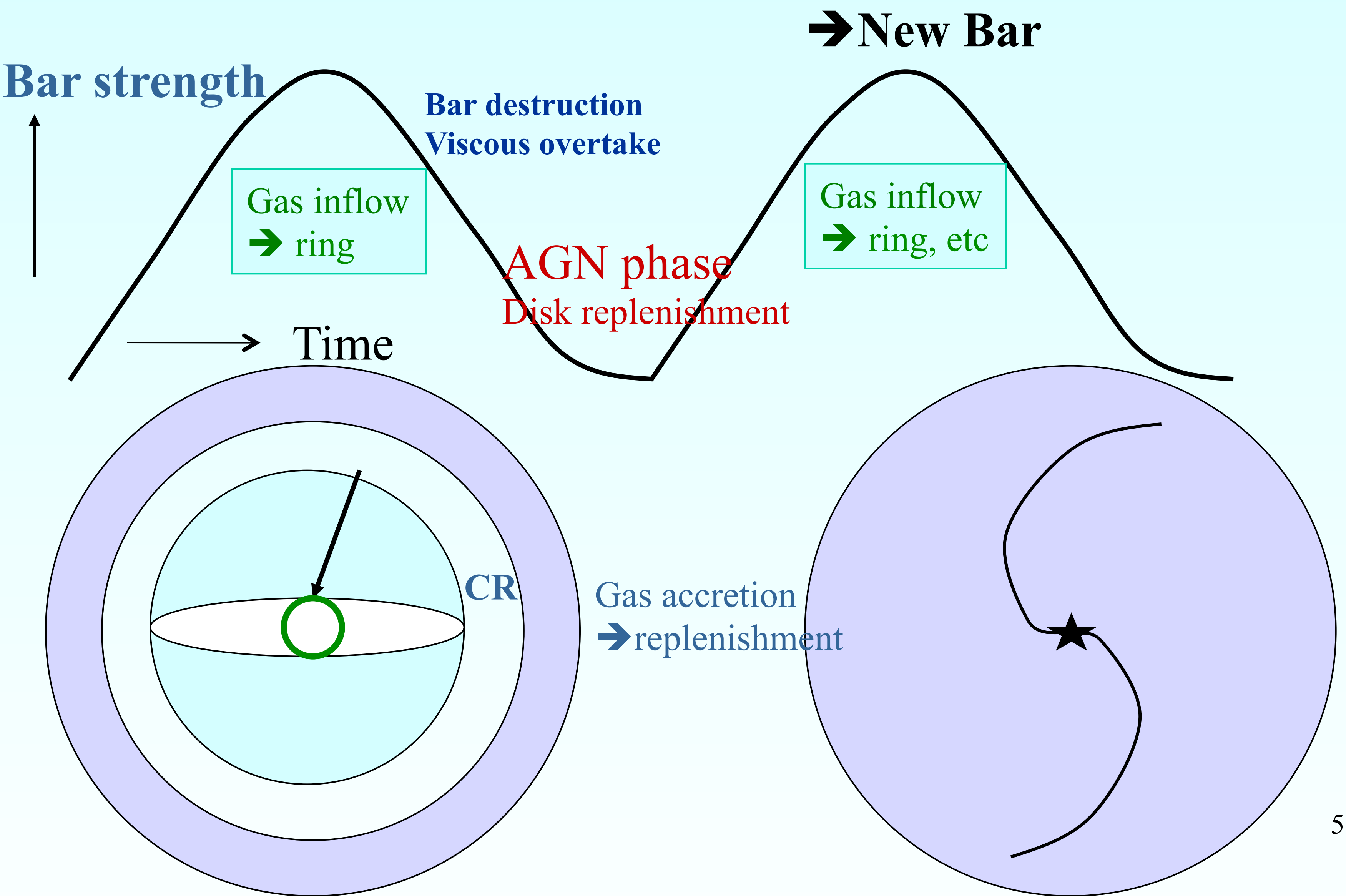




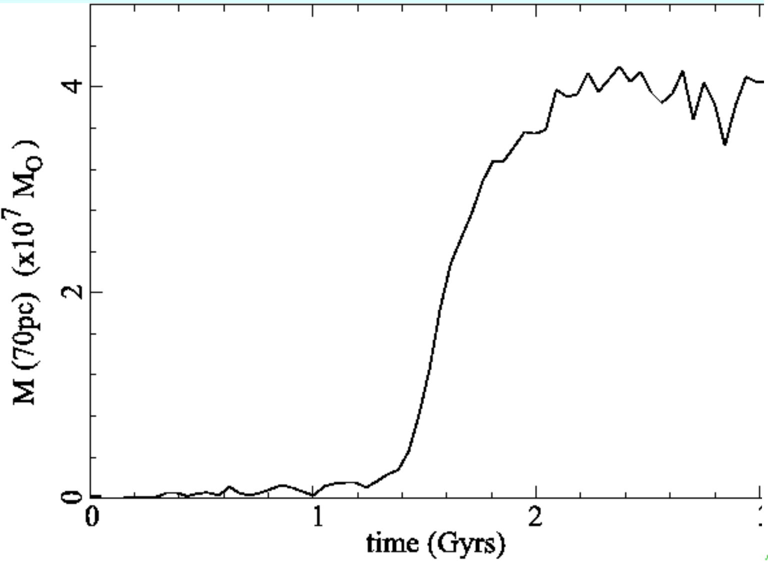


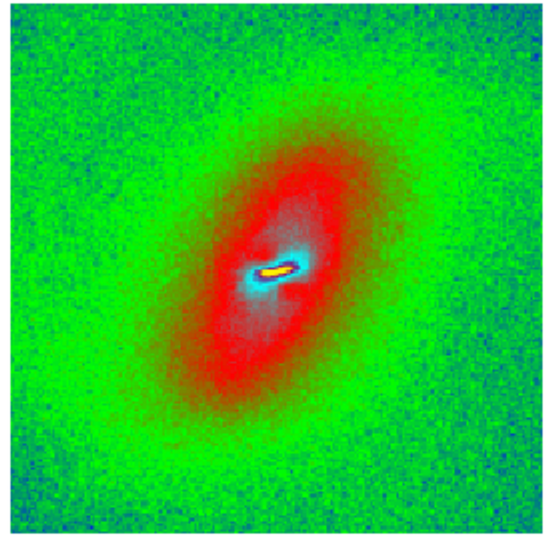
If no continuous accretion
Gas is stalled at OLR
The bar remains strong
(early-types)
Bournaud & Combes 2002

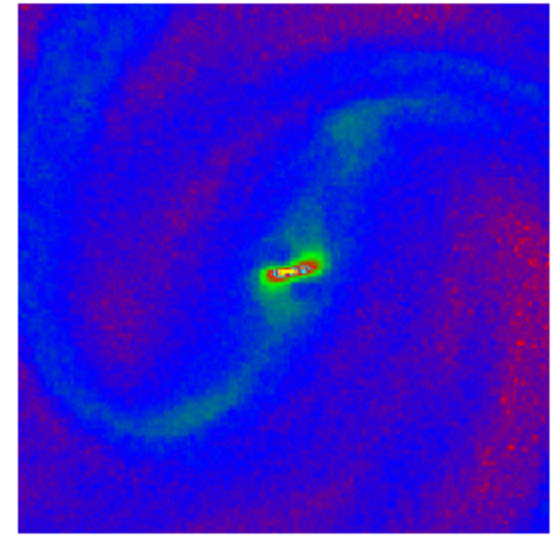
AGN/SB and bar feedback in secular evolution

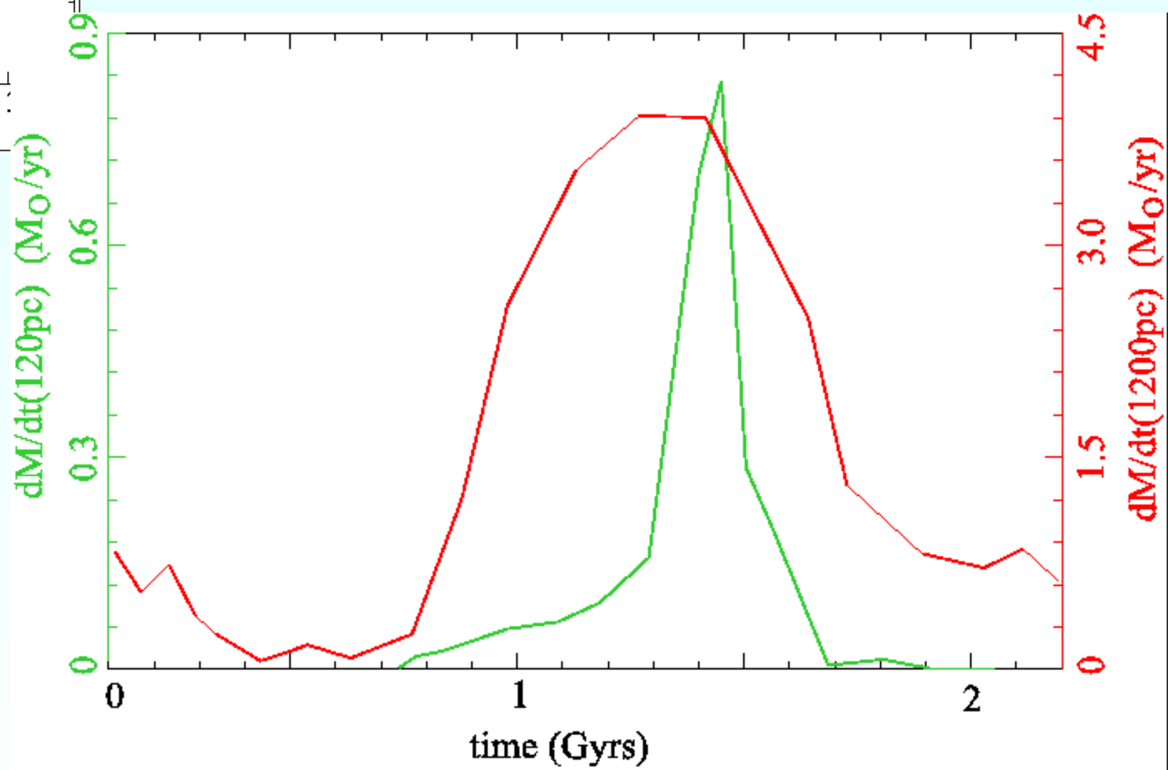


Inflow with two embedded bars









Cumulated gas inflow (70pc)

Inflow rate in 20pc and
in 200pc

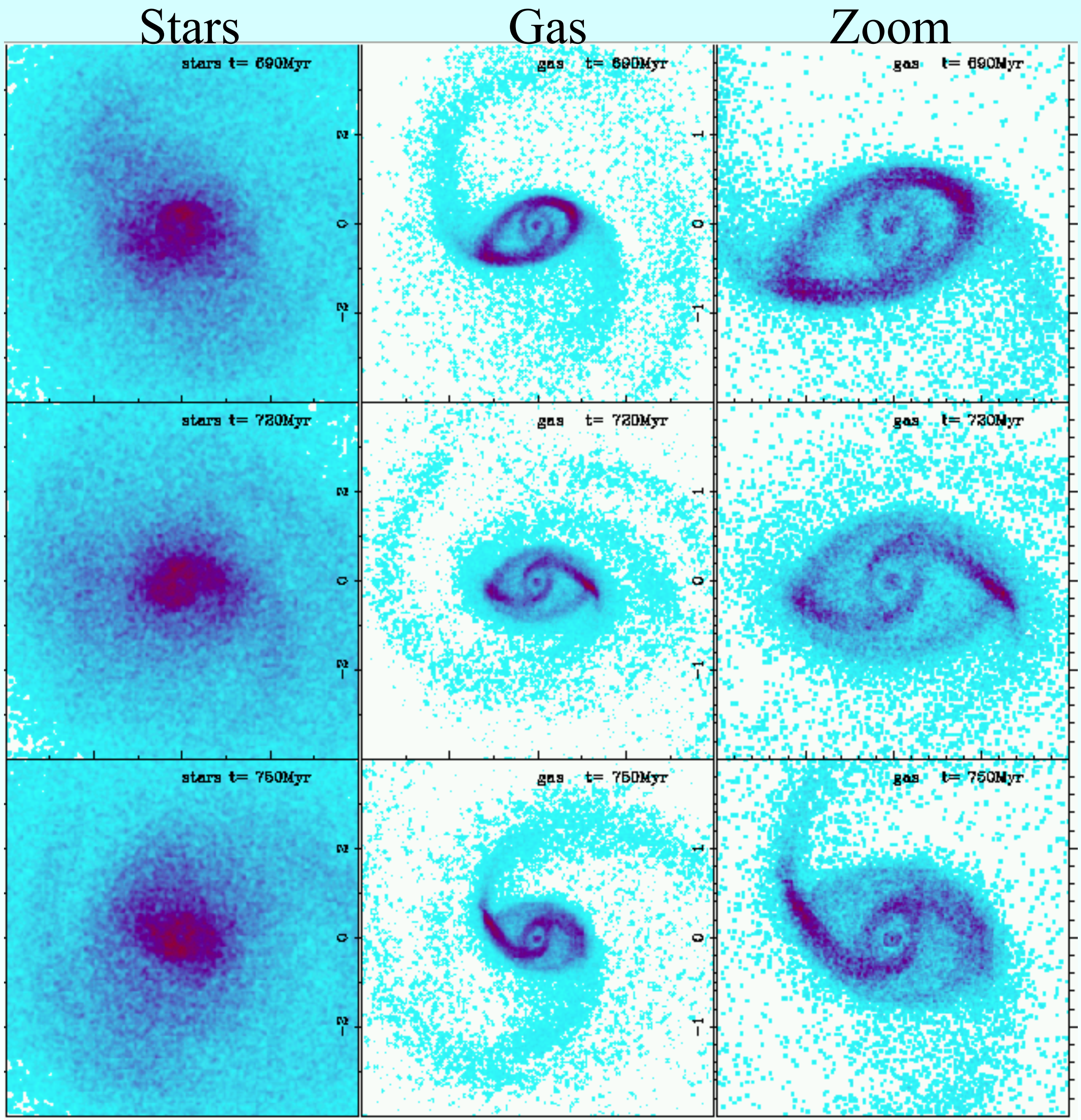
Friedli & Martinet 1993
Bournaud & Combes 2004

A typical case: N2782

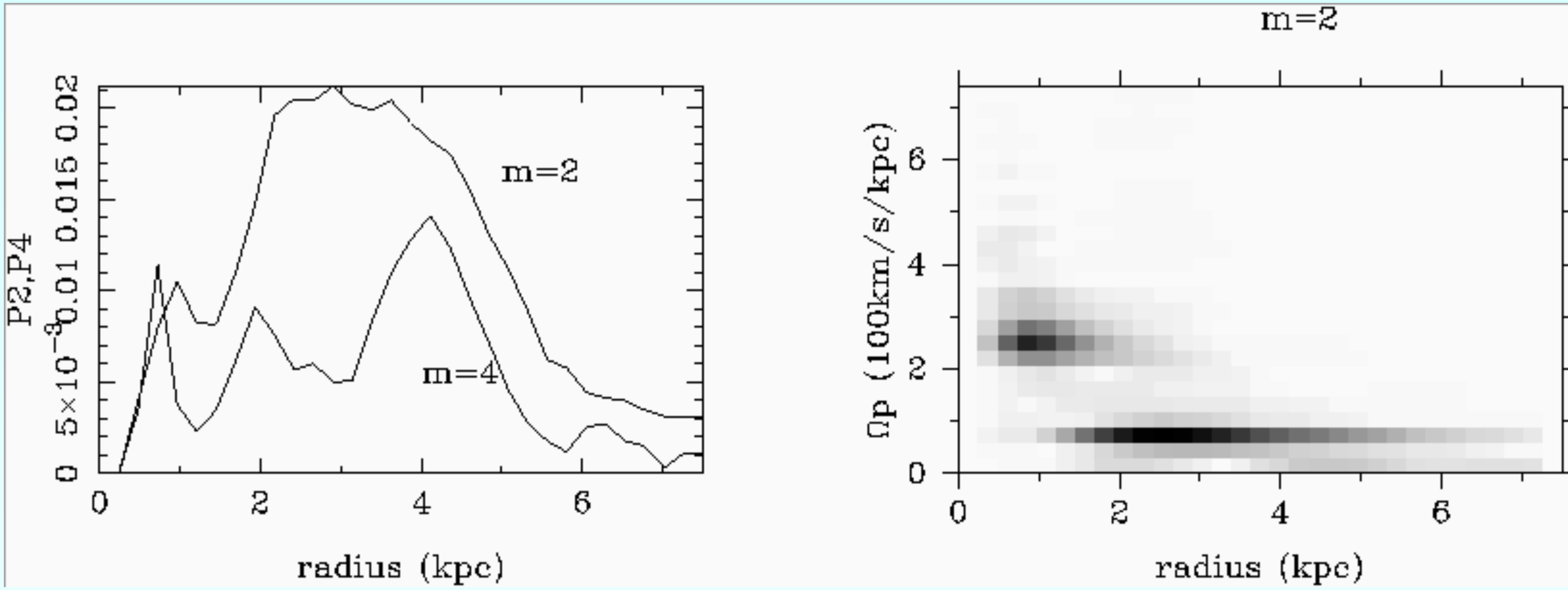
Formation of a primary bar and **decoupled 2nd** bar in N-body+ hydro simulation

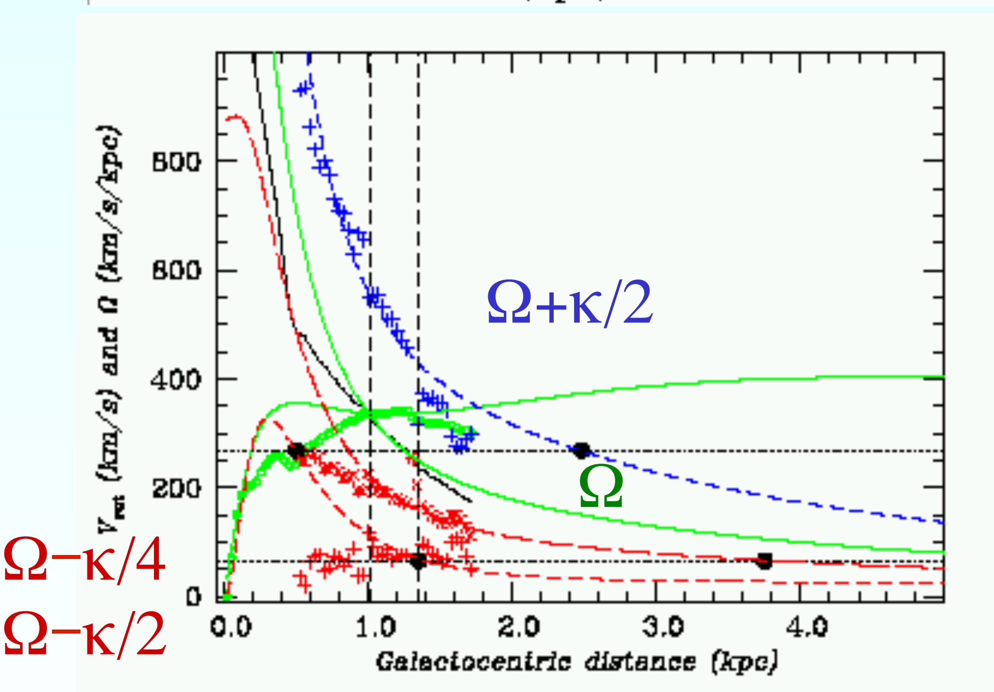
Short phase, when torques are negative down to the very center

Hunt et al 2007



Nested bars in N2782





The CR of the nuclear bar
Is the ILR of the primary bar

Hunt et al 2007

Statistics -- Time-scales
10-100pc fueling

➔ **Only ~35%** of negative torques in the center, scale 1"~50-100pc
6 out of 16 galaxies *(NUGA sample, cf Garcia-Burillo & Combes 2012*
N1961, N2782, N3147, N3368, N3627, N3718, N4321, N4569,
N4579, N4736, N4826, N5248, N5953, N6574, N6951, N7217

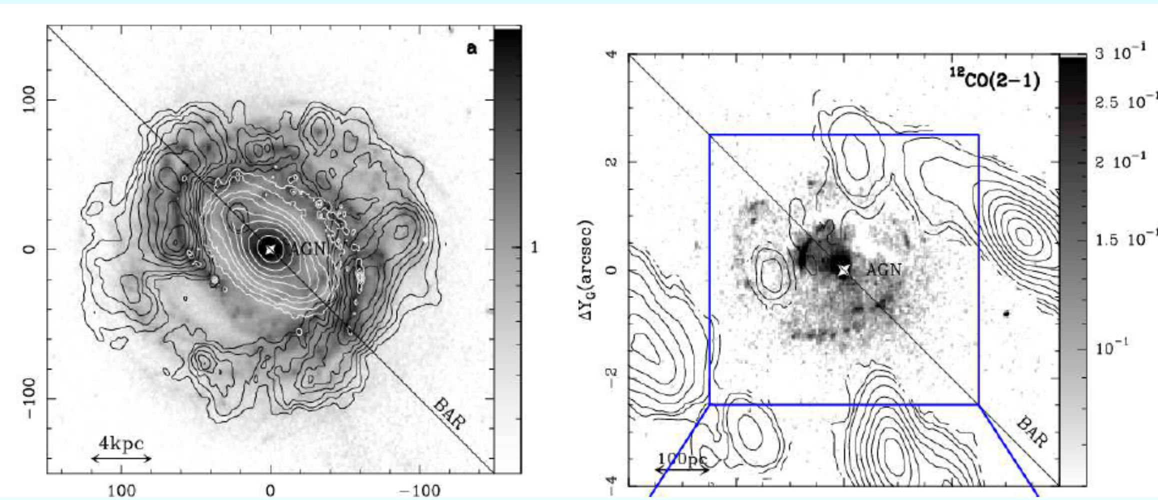
➔ Rest of the times, positive torques, maintain the gas in a ring

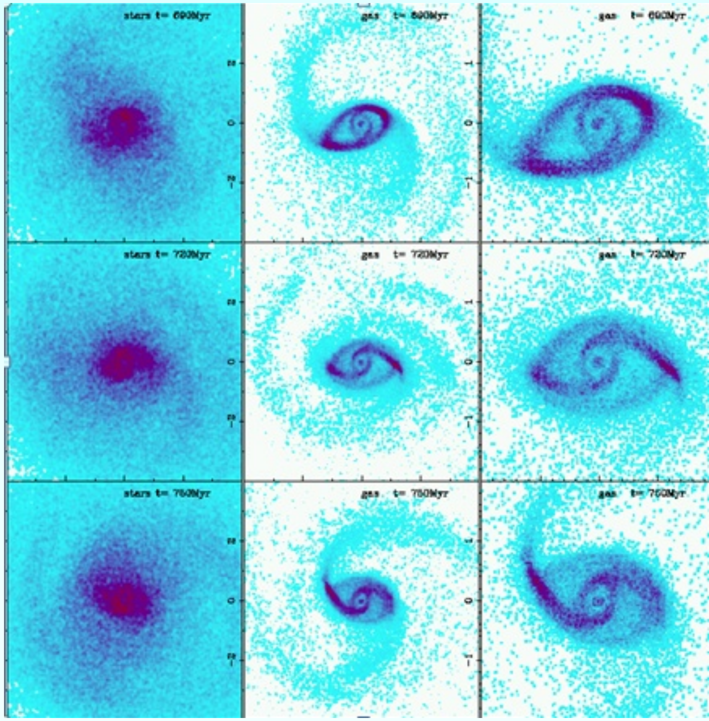
➔ **Short fueling phases, a few 10^7 yrs** (feedback)
Rare to see binary AGN, not fueled at the same time
Difficult to identify the driver: bars have weaken then

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

35% showing gas accretion

➔Galaxies with embedded bars, or bars/ovals
The inner structure takes over the negative torque of the bar beyond the ILR

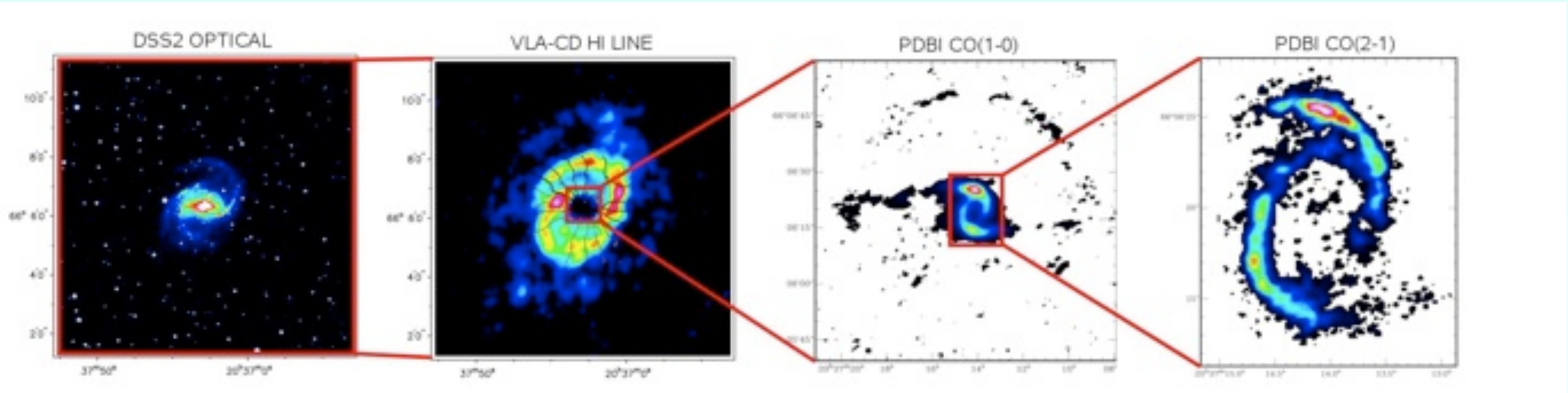




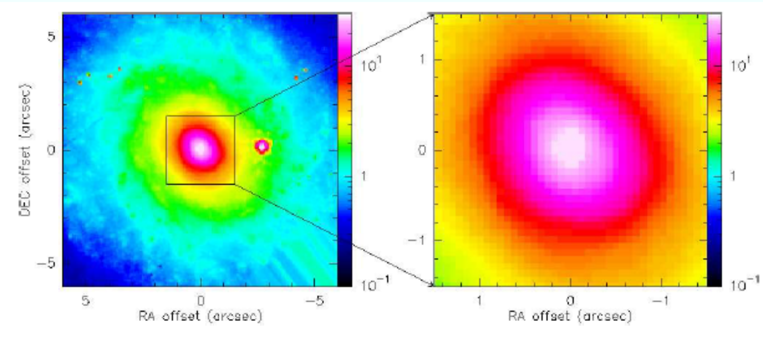
➔Galaxies with no ILR,
and only one primary bar
(case of NGC 3627)

65% showing no central gas accretion

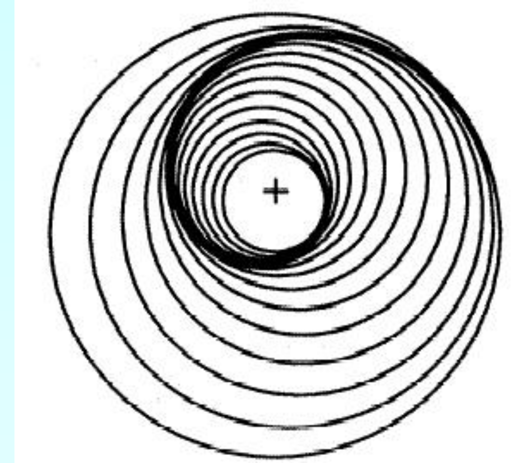
➔Galaxies with embedded bars, or bars/ovals
But the gas is still stalled at an ILR ring (cf N6951, N4321..)



➔Galaxies with no contrasted feature towards the center
Almost axisymmetric, without torques
(case of NGC 7217, N5953..)

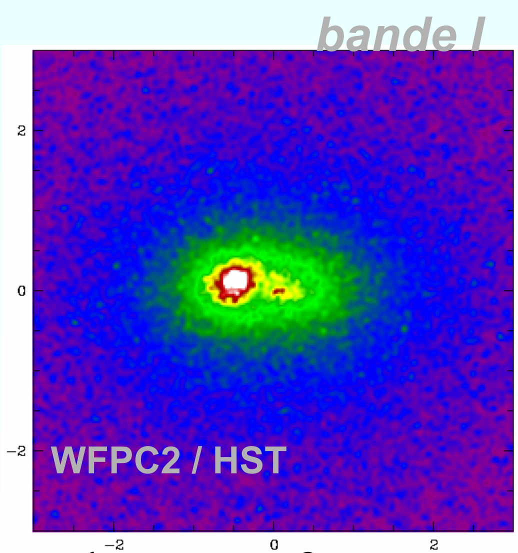


Instabilities m=1

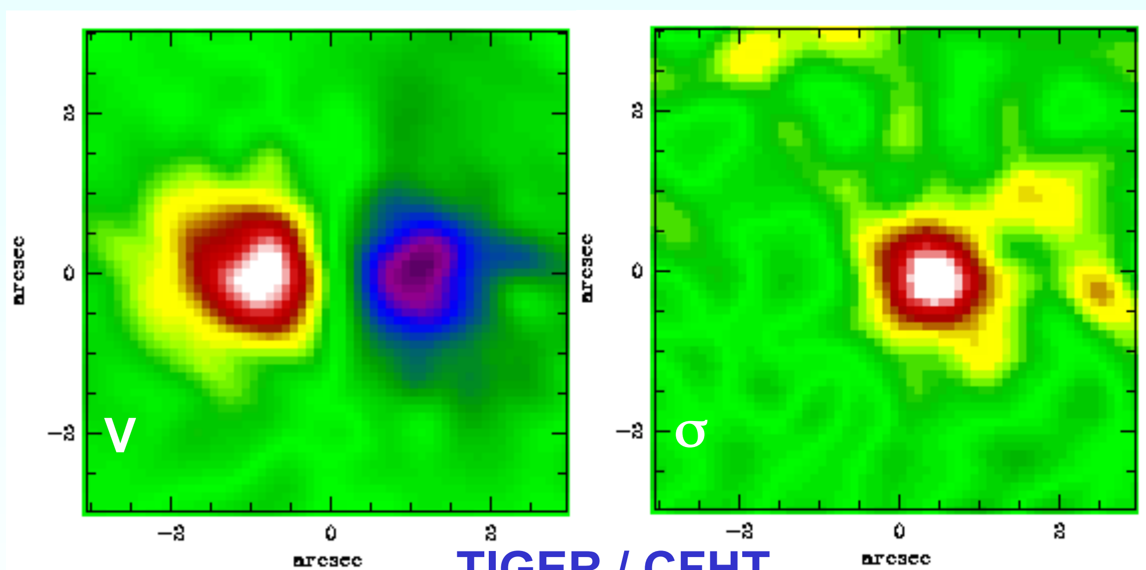


Very rapid differential precession rate Ω - κ
But BH >> purely Keplerian disk, where Ω = κ
m=1 eigen mode, but with a strong self-gravity
➔+ indirect potential, due to the off-centring of the central mass

➔This mode allows the inner disk to lose angular momentum, and to the gas to fall onto the central BH *(cf Reichard et al 2009)*

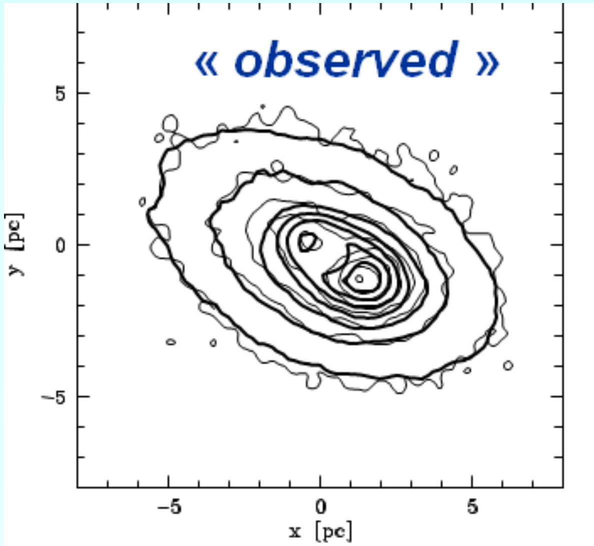


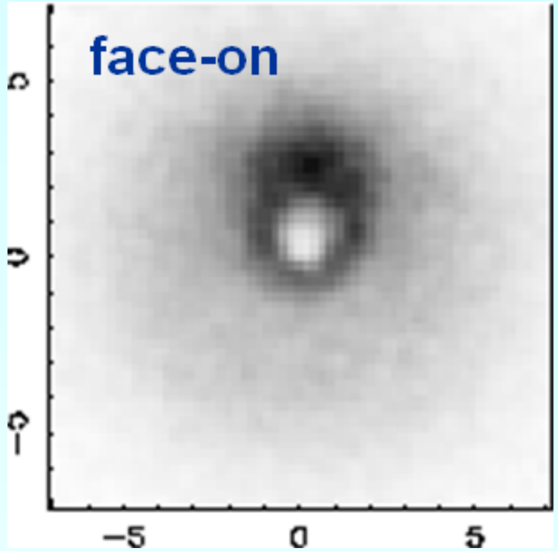
Central 10pc of M31



TIGER / CFHT

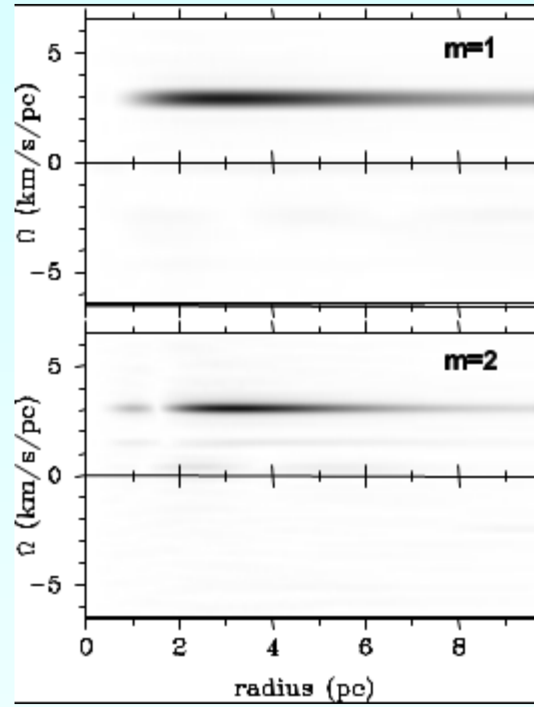
An m=1 keplerian mode ?

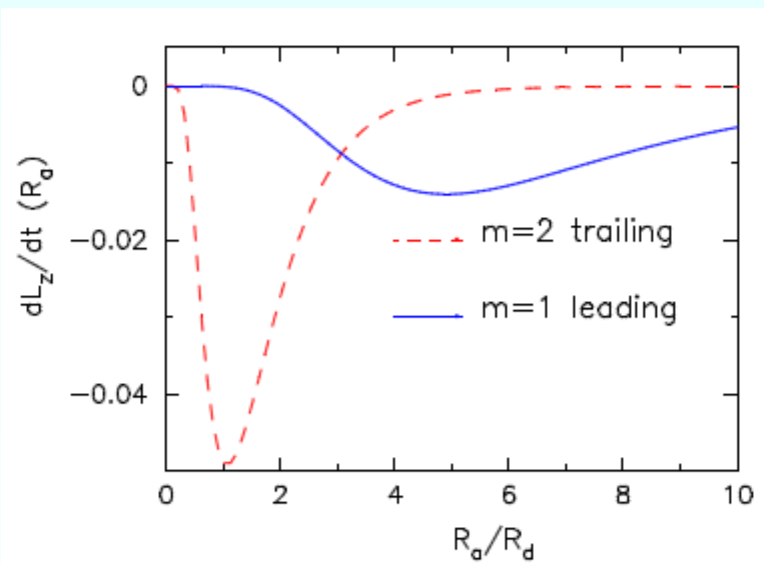




Bacon et al 2001

Pattern speed





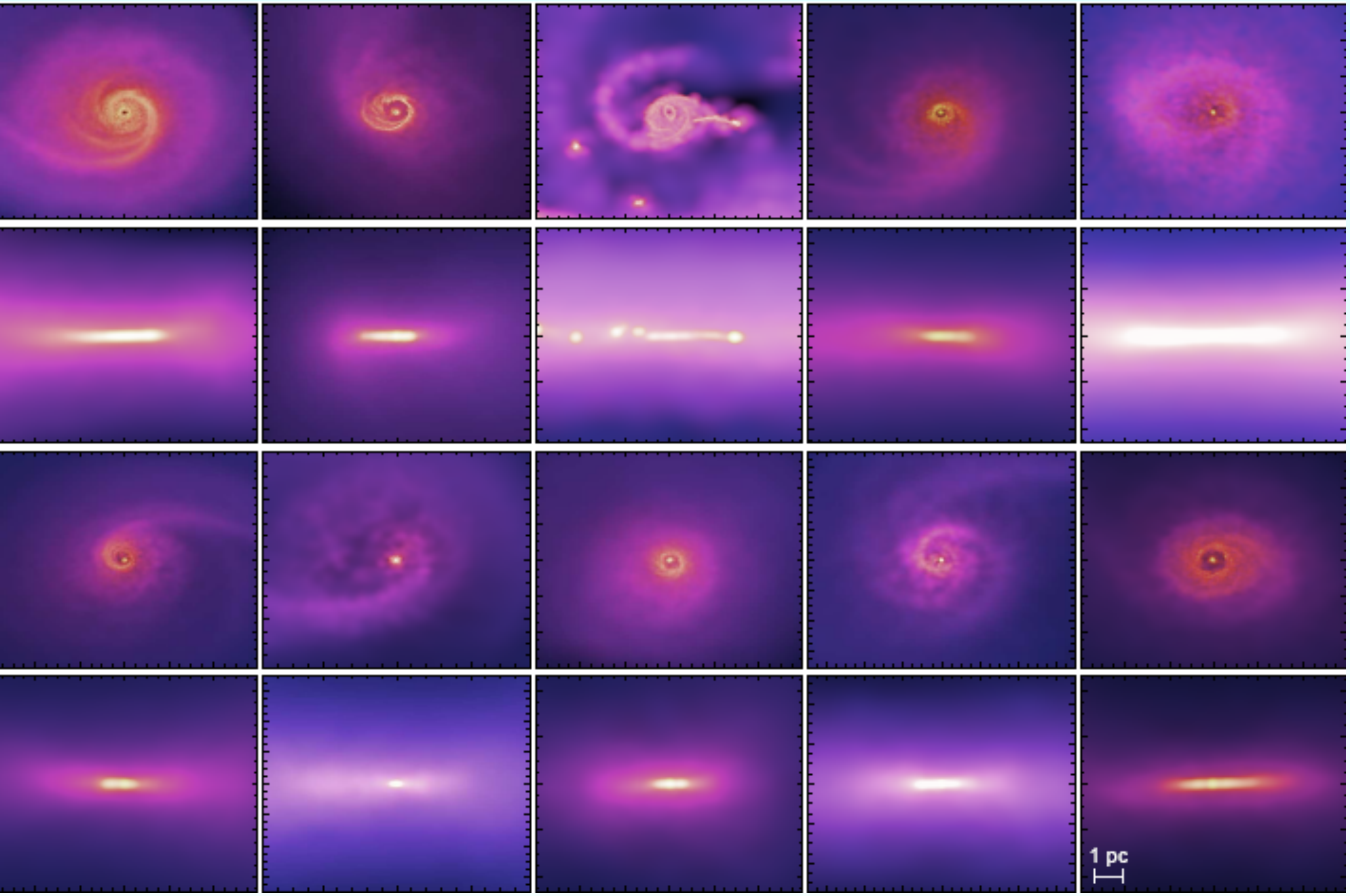
Saha & Jog 2014

- ✓ BH: 7 10^7 M_{sol}
- ✓ Disk: 20-40% of total mass
- ✓ *Pattern speed*: 3 km/s/pc
  (orbital frequency: 250 km/s/pc)
- ✓ *Life-time*: > 3000 rotations
  ~ 4 10^8 yrs

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= 10^6Mo

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

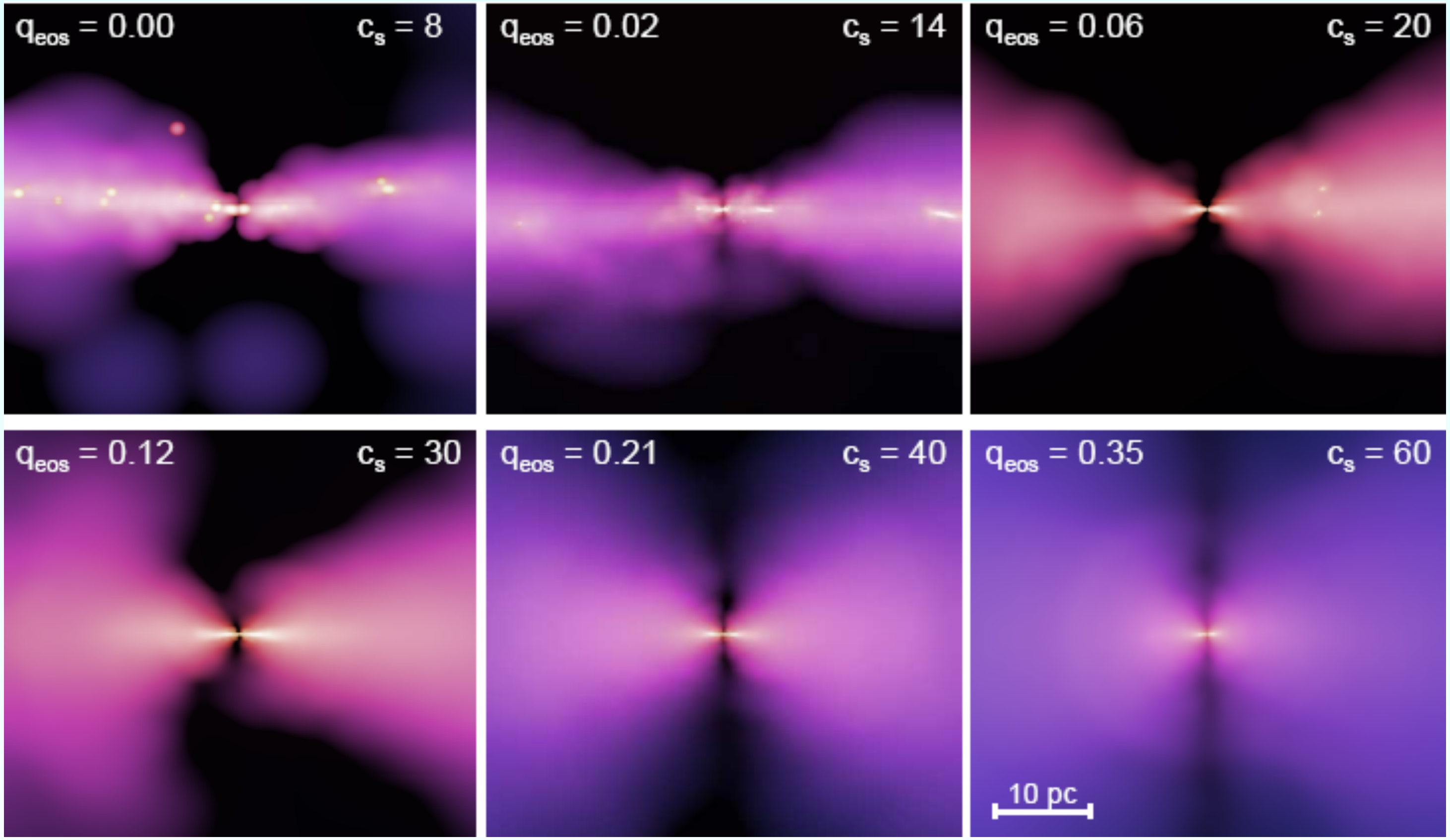
varies in 1/M

Hopkins et al 2011

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

Formation of the torus?

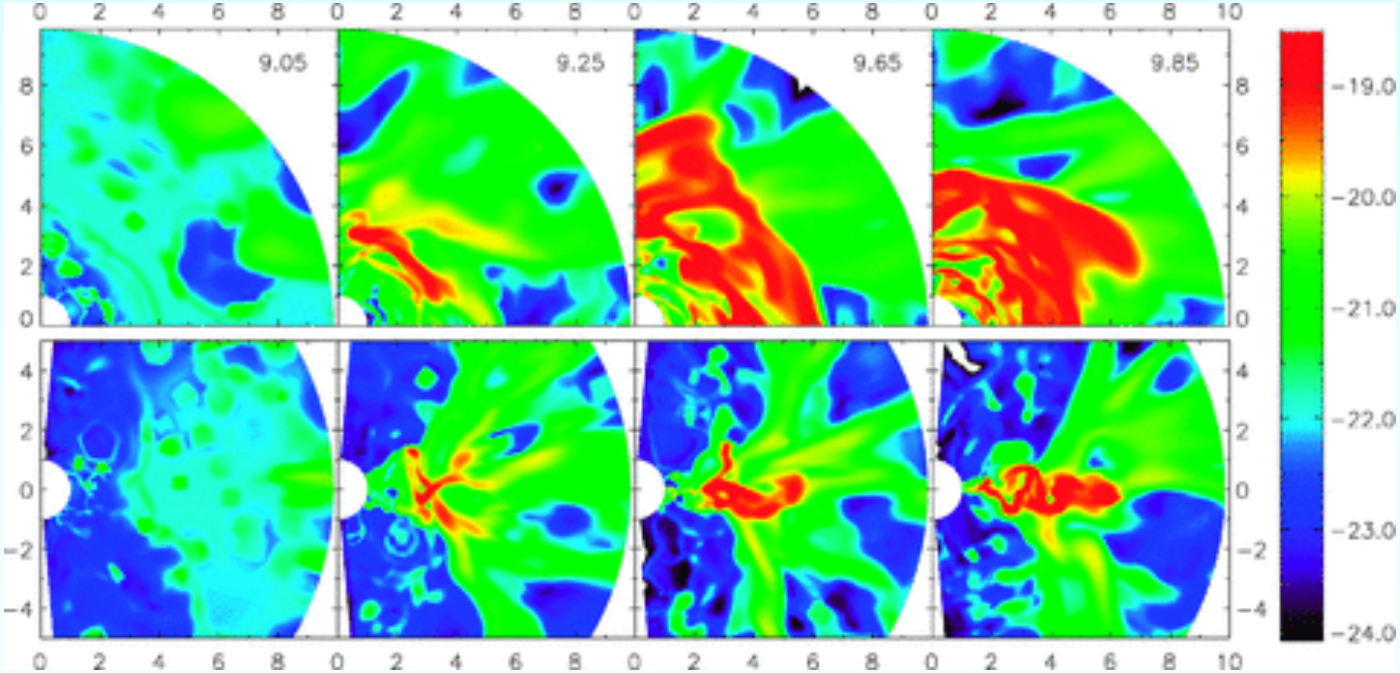
Same simul, but plot in R,z coordinates, variation of Cz, and sub-grid pressure q EOS ➔ reflects the feedback of SF
q EOS= 0 ~isothermal, q EOS =1 ~ adiabatic



Hopkins et al 2011

Thin and thick disks

Both warm thin and cold thick, fluffly, disks/torus could co-exist
Multi-phase under the influence of stellar winds, from
a nuclear stellar cluster –cold filaments, and tenuous hot inter-medium



X-Y

X-Z

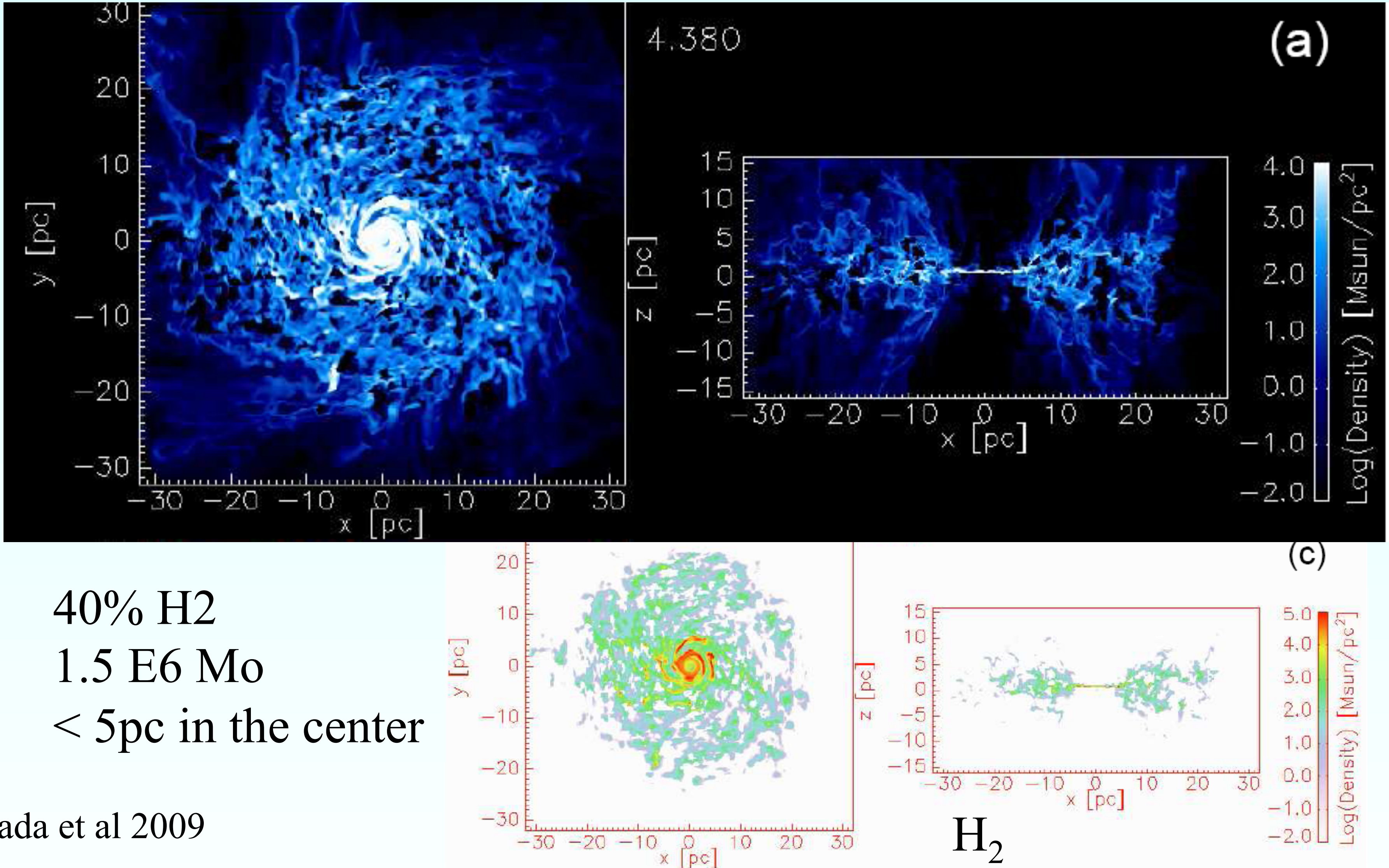
Times in orbits, scales in pc, density in g/cm-3

Schartmann et al 2009

Thinner molecular disks

With more refinement: H_2 formation, and consistent chemistry

UV flux, within a radius of 30pc, SN feedback



40% H2
1.5 E6 Mo
< 5pc in the center

Wada et al 2009

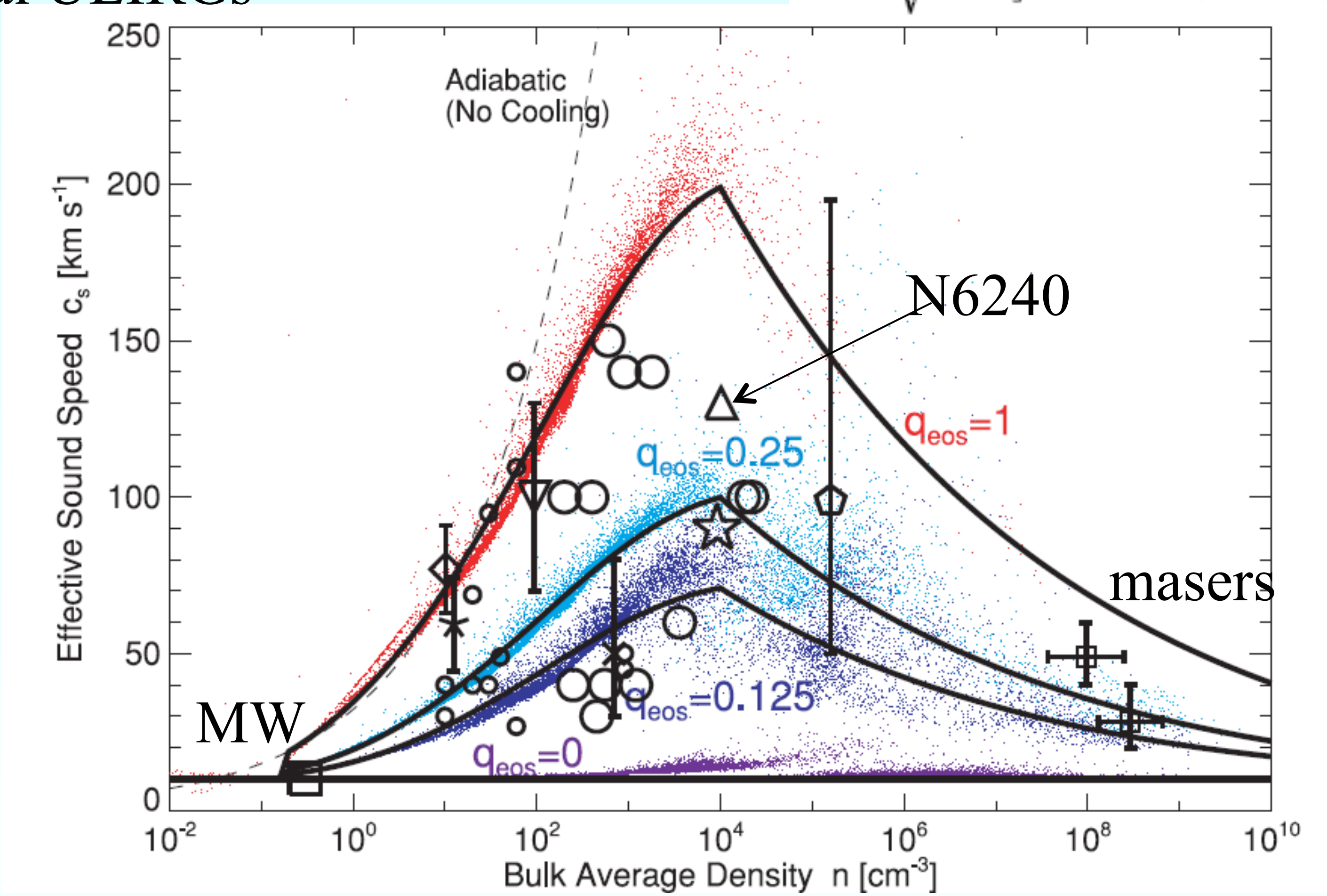
H_2

Influence of stellar feedback

Stellar feedback is included in EOS (subgrid physics)

$$c_s = \sqrt{q_{eos}\, c_s^2[q=1] + (1 - q_{eos})\, c_s^2[q=0]}\ .$$

O Local ULIRGs

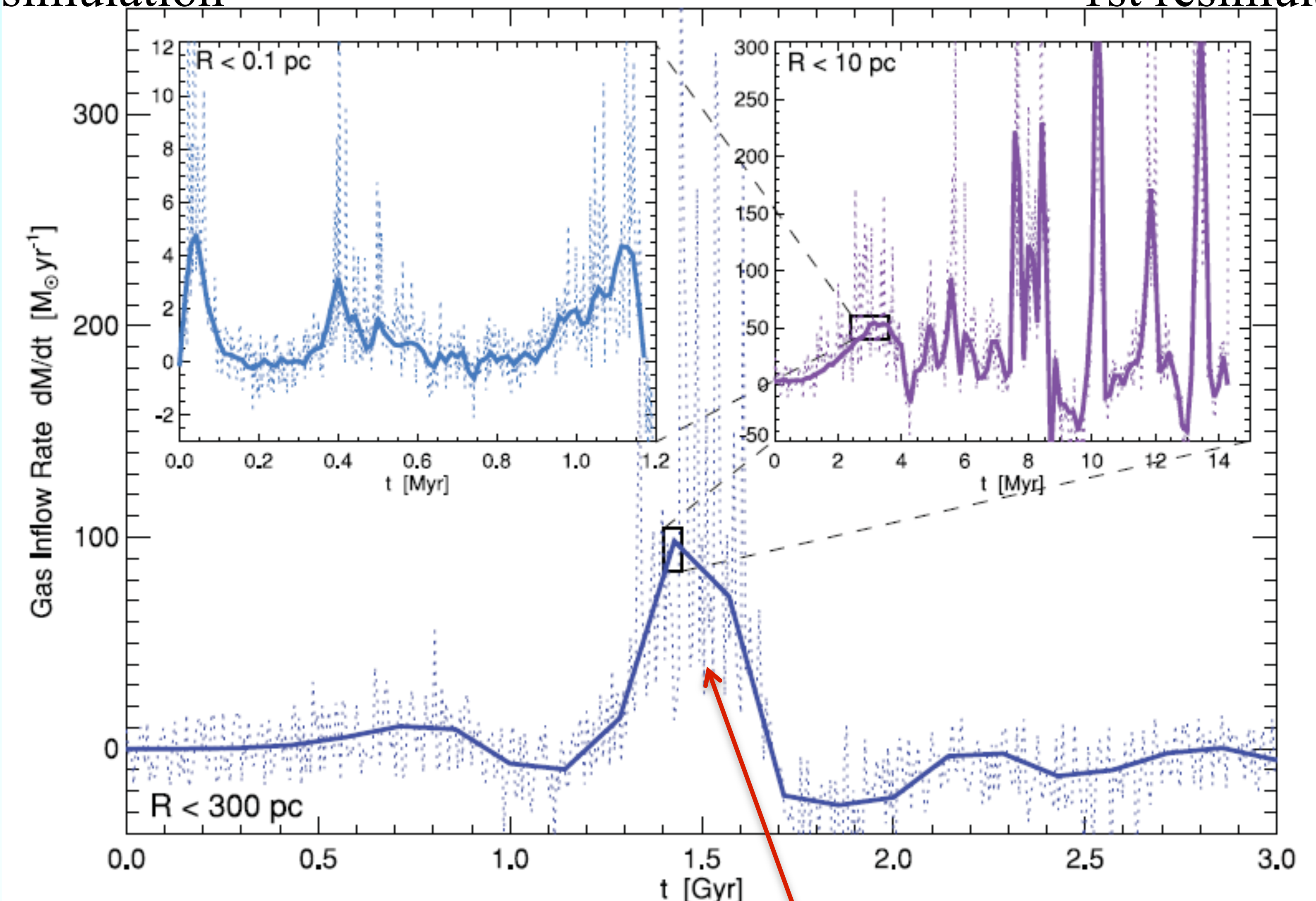


Hopkins & Quataert 2010

Inflow rate, merger

2nd resimulation

1st resimulation

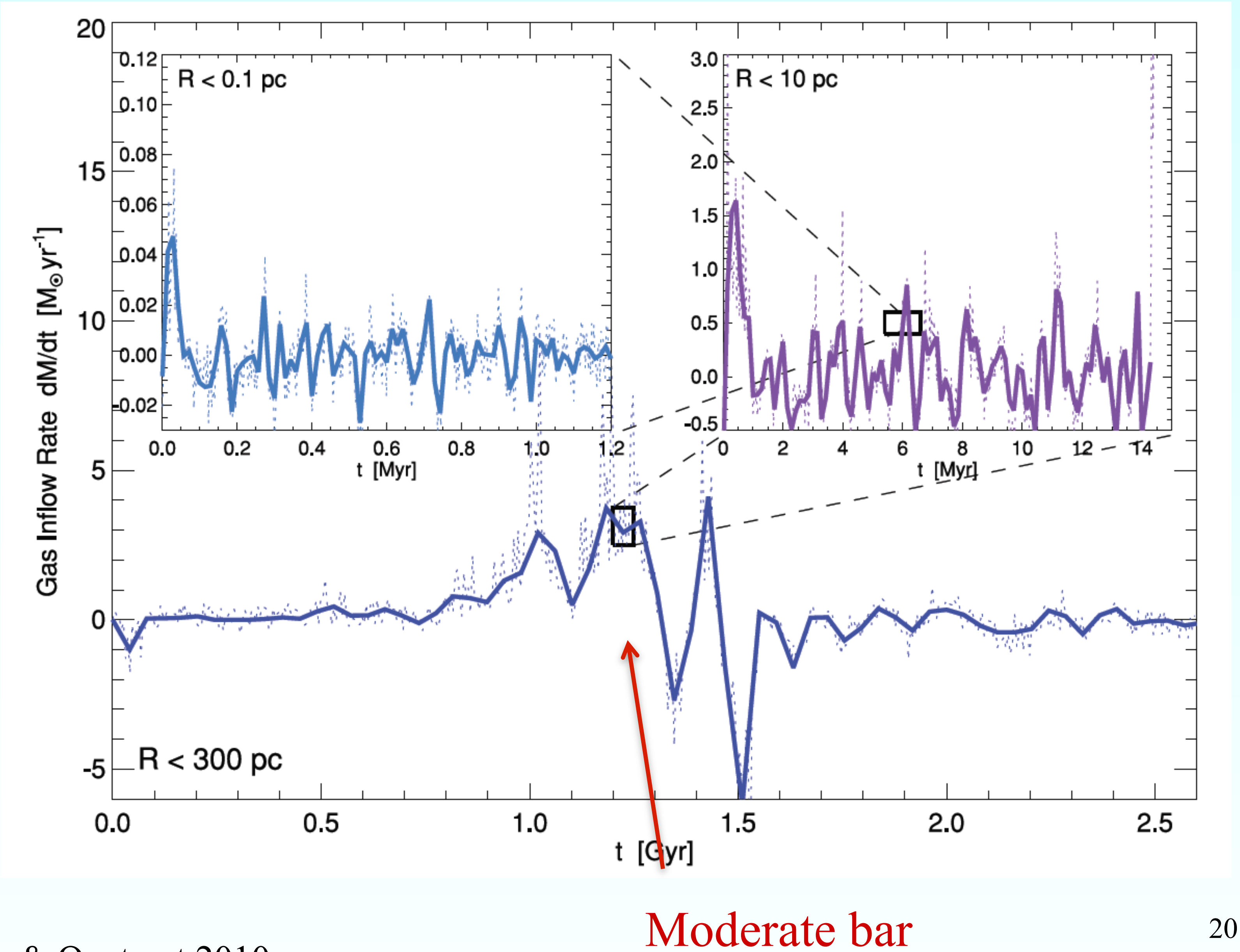


→ Episodic accretion

Coalescence of the 2 nuclei

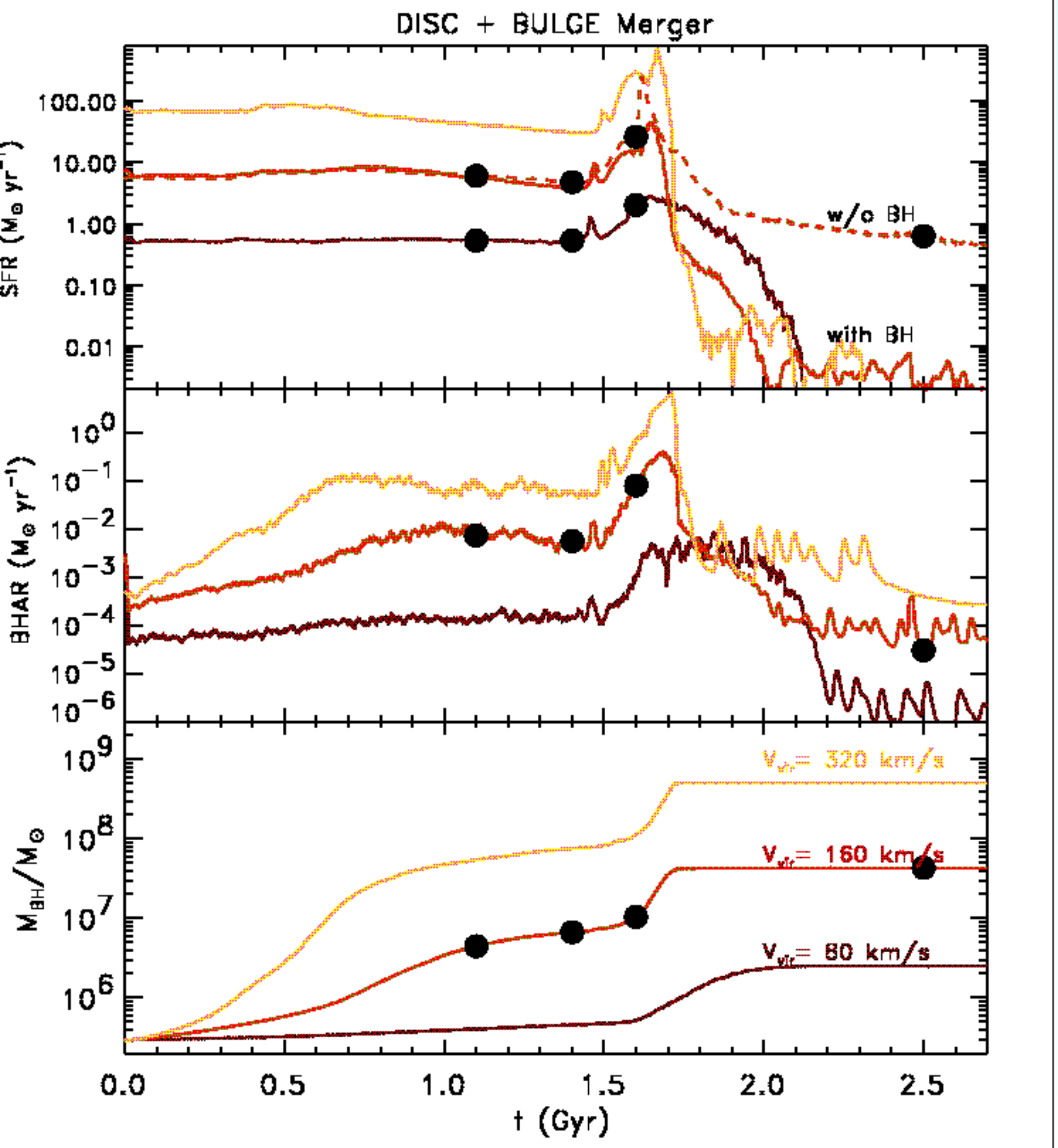
Hopkins & Quataert 2010

Inflow rate, isolated



Hopkins & Quataert 2010

Di Matteo et al (05): Mergers



Quasar feedback

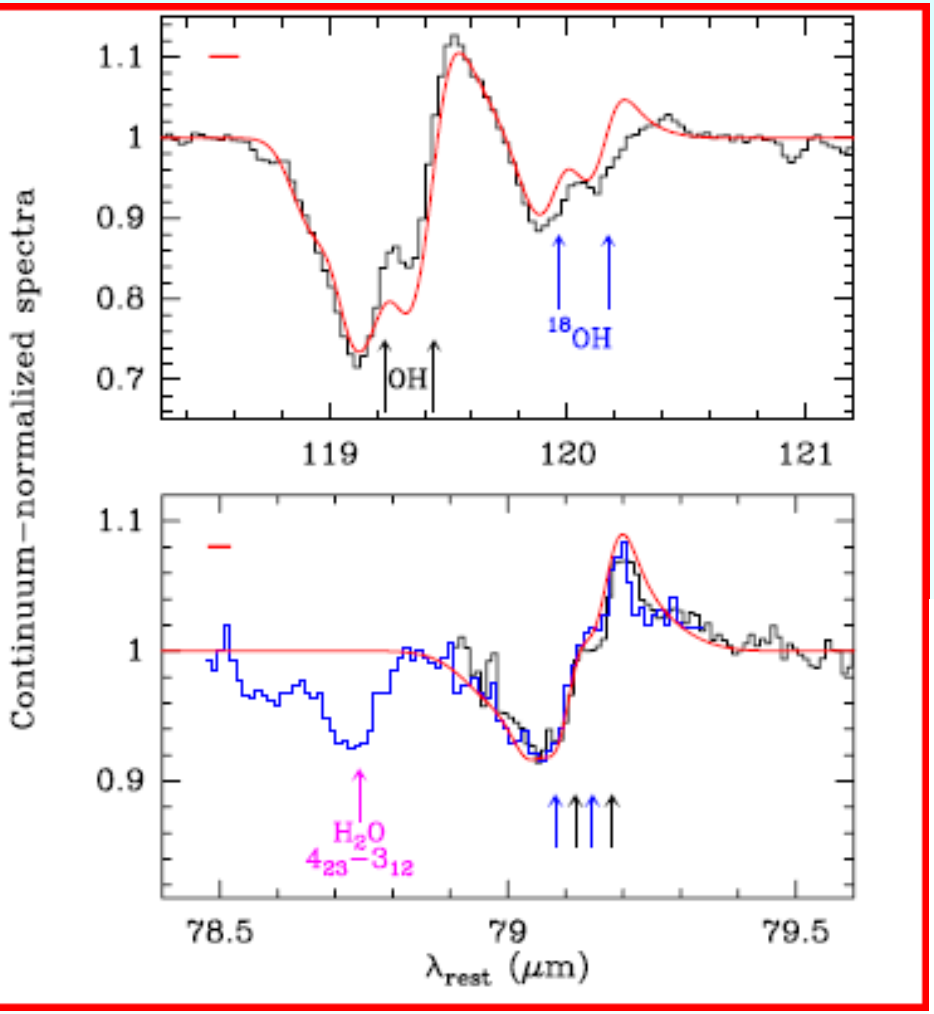
Life-time of a QSO phase ~100 Myr

The energy released by the AGN quenches both SF and AGN growth

Involves only massive galaxies

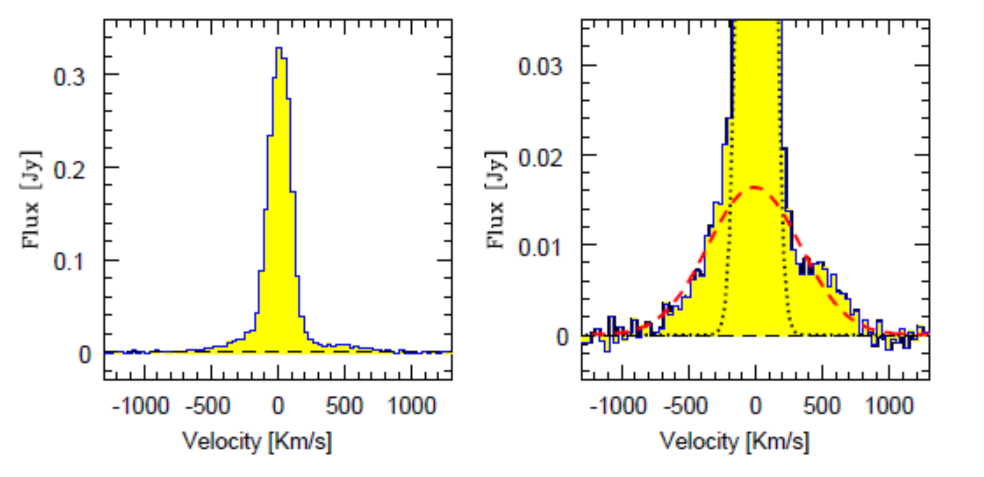
Cf AGN & cooling flows

AGN, SF feedback and outflow

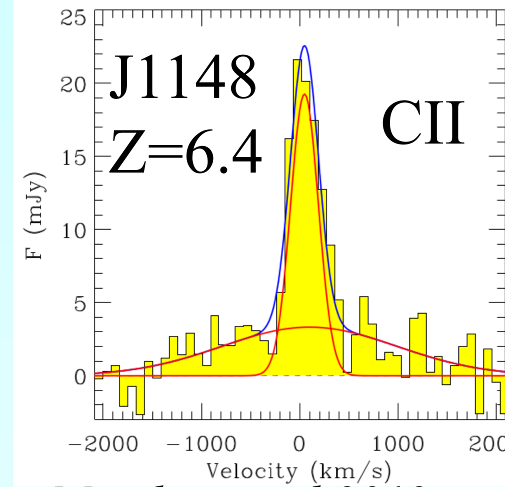


Mrk 231 Fischer et al 2010
Hershel:
OH lines show wide wings

IRAM Ferruglio et al 2010



Molecular outflows



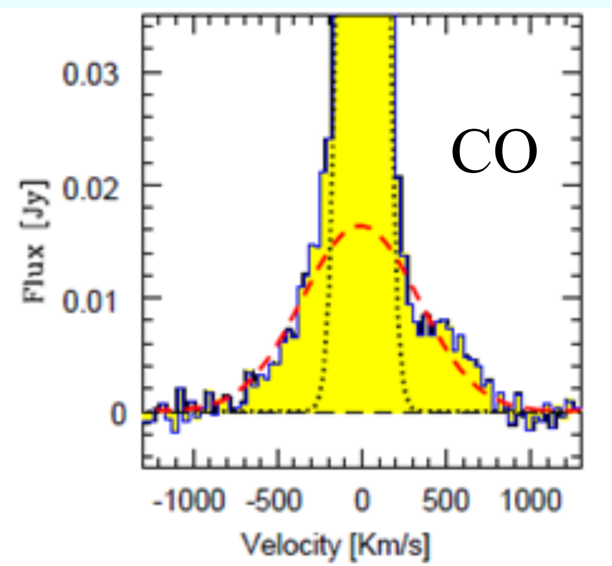
Maiolino et al 2012

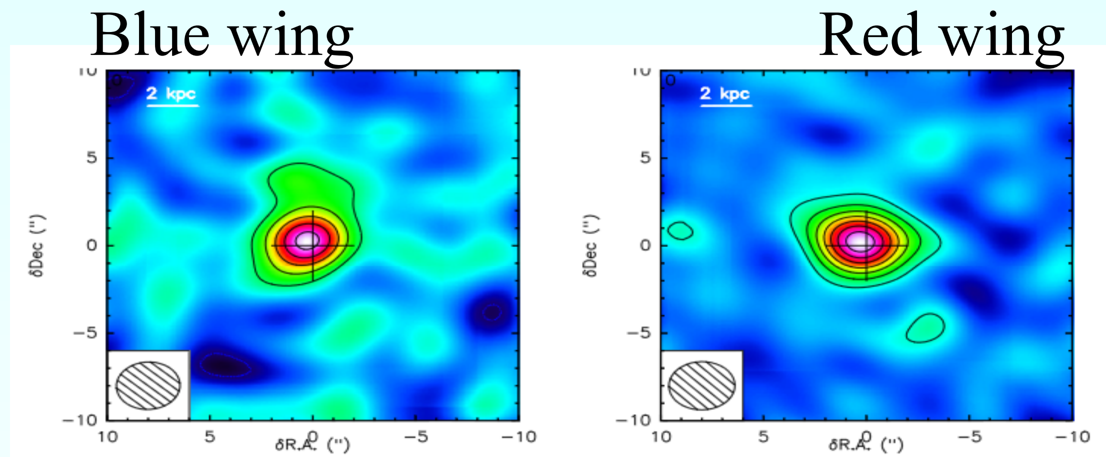
Mrk 231

AGN and also nuclear
Starburst, 10^7-10^8Mo
Outflow 700Mo/yr

On kpc scales, ➔
affects the galaxy, quenches SF

IRAM *Ferruglio et al 2010*



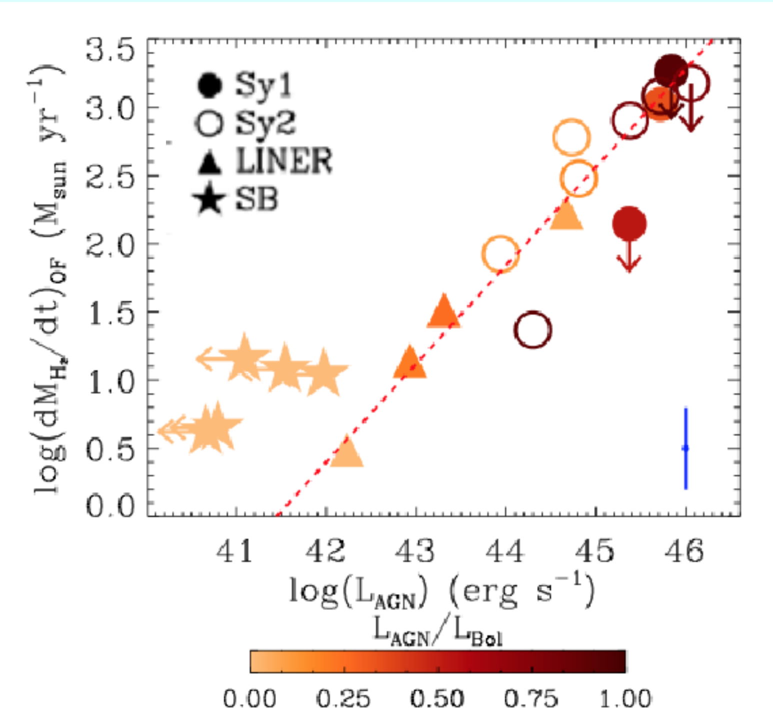


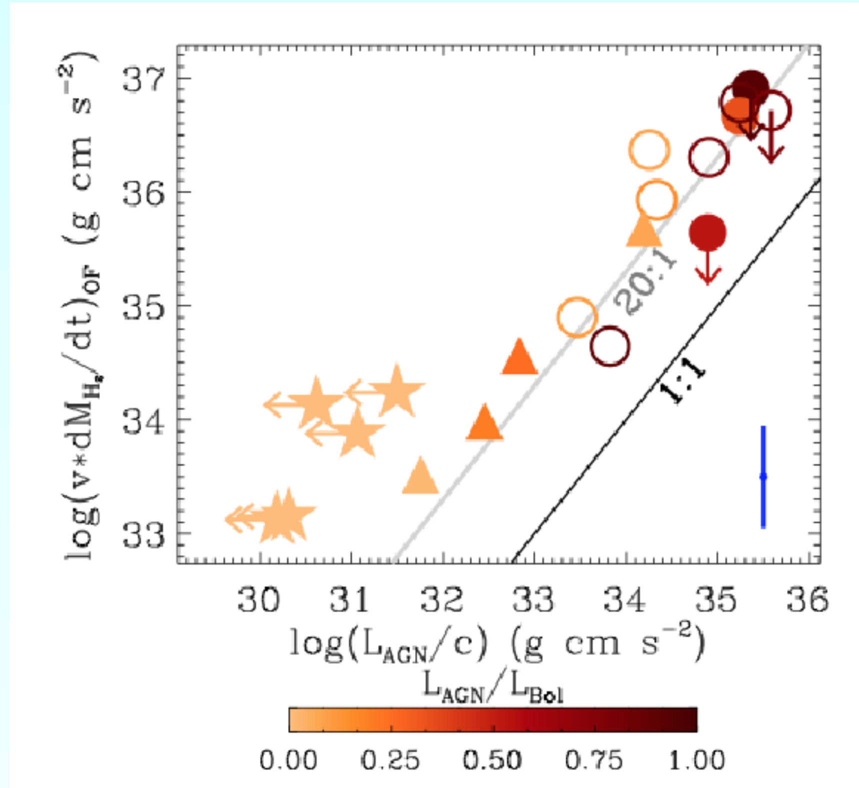
Cicone et al 2012

dM/dt = 3v M_{OF}/R_{OF} ~1000 Mo/yr, (5xSFR)
Kinetic power ~2 10^{44} erg/s ➔ AGN

High density, HCN, HCO+, *Aalto et al 2012*

Relations outflows with AGN

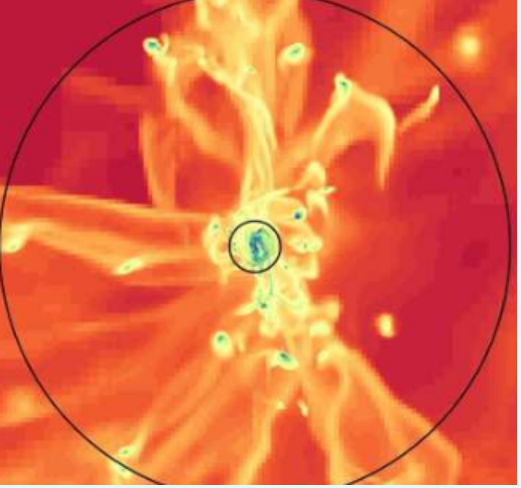




For AGN-hosts, the outflow rate
Correlates with the AGN power

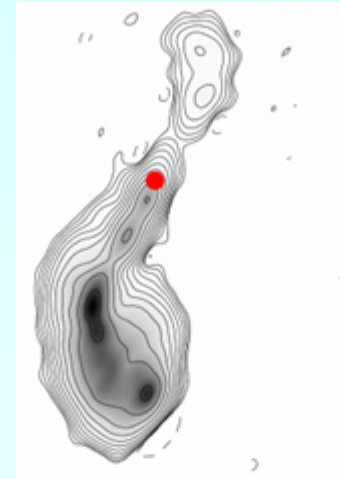
Cicone et al 2014

dM/dt v ~20 L_{AGN}/c
Can be explained by
energy-driven outflows
(Zubovas & King 2012)

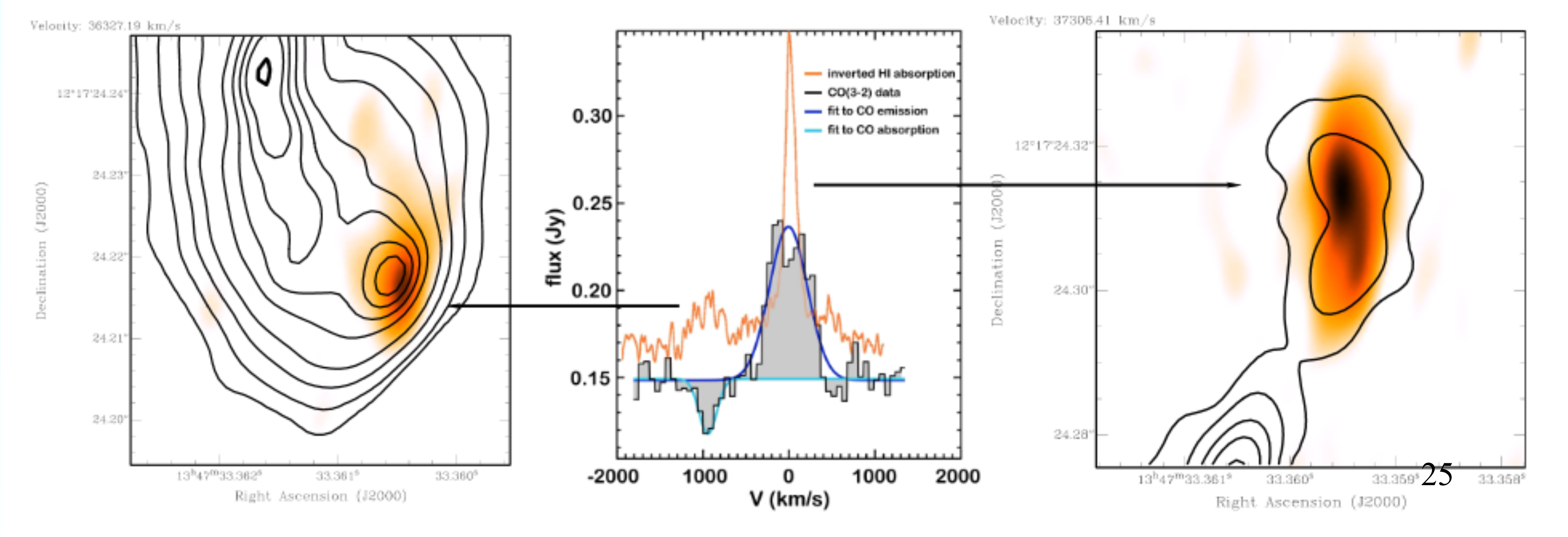


Positive AGN feedback
Radio jets triggered SF

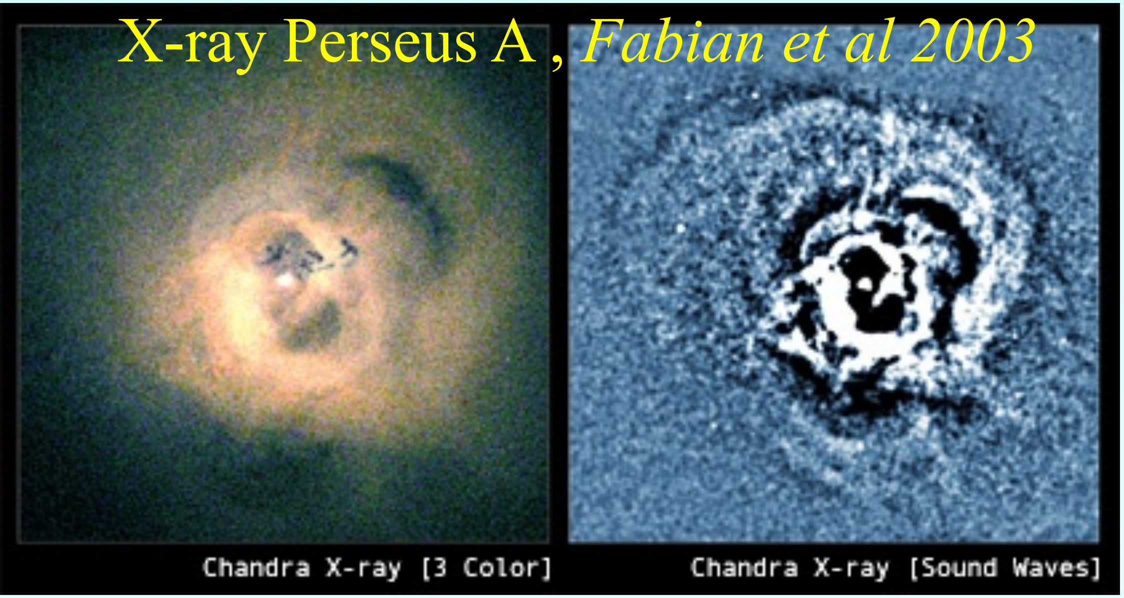
Silk 2005, Dubois et al 2013



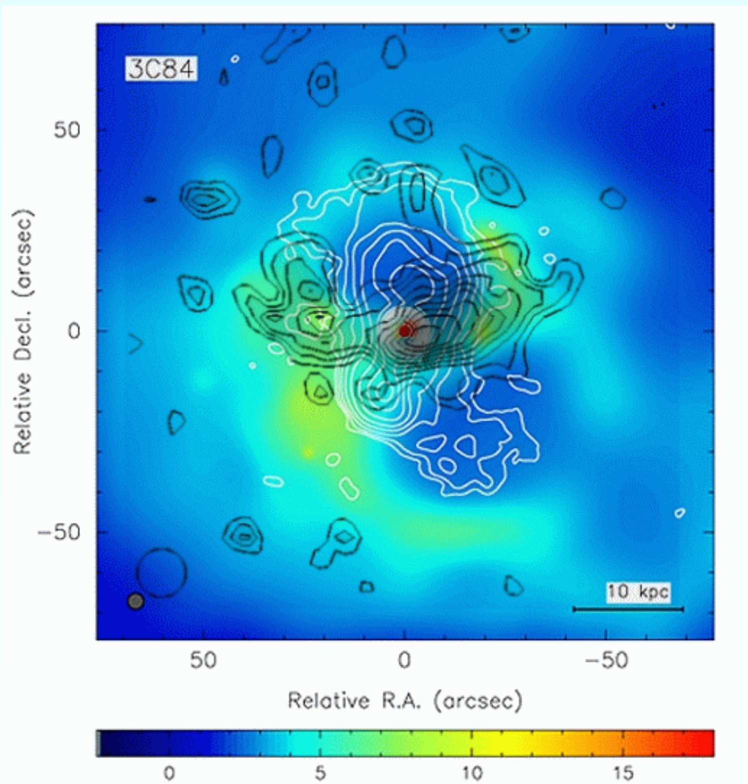
Young, restarted radio loud AGN 4C12.50
The outflow is located 100 pc from the nucleus
where the radio jet interacts with the ISM
Morganti et al 2013, Dasyra & Combes 2012



Gas flow in cool core clusters

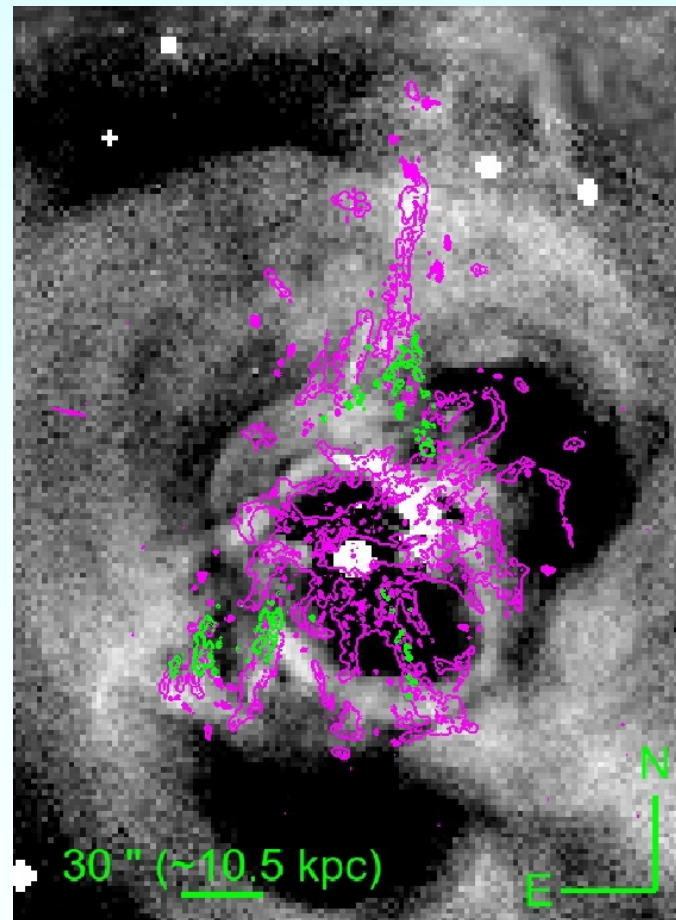


X-ray Perseus A , *Fabian et al 2003*



Molecular Gas Salomé et al 2006

Star formation (green)
Canning et al 2014



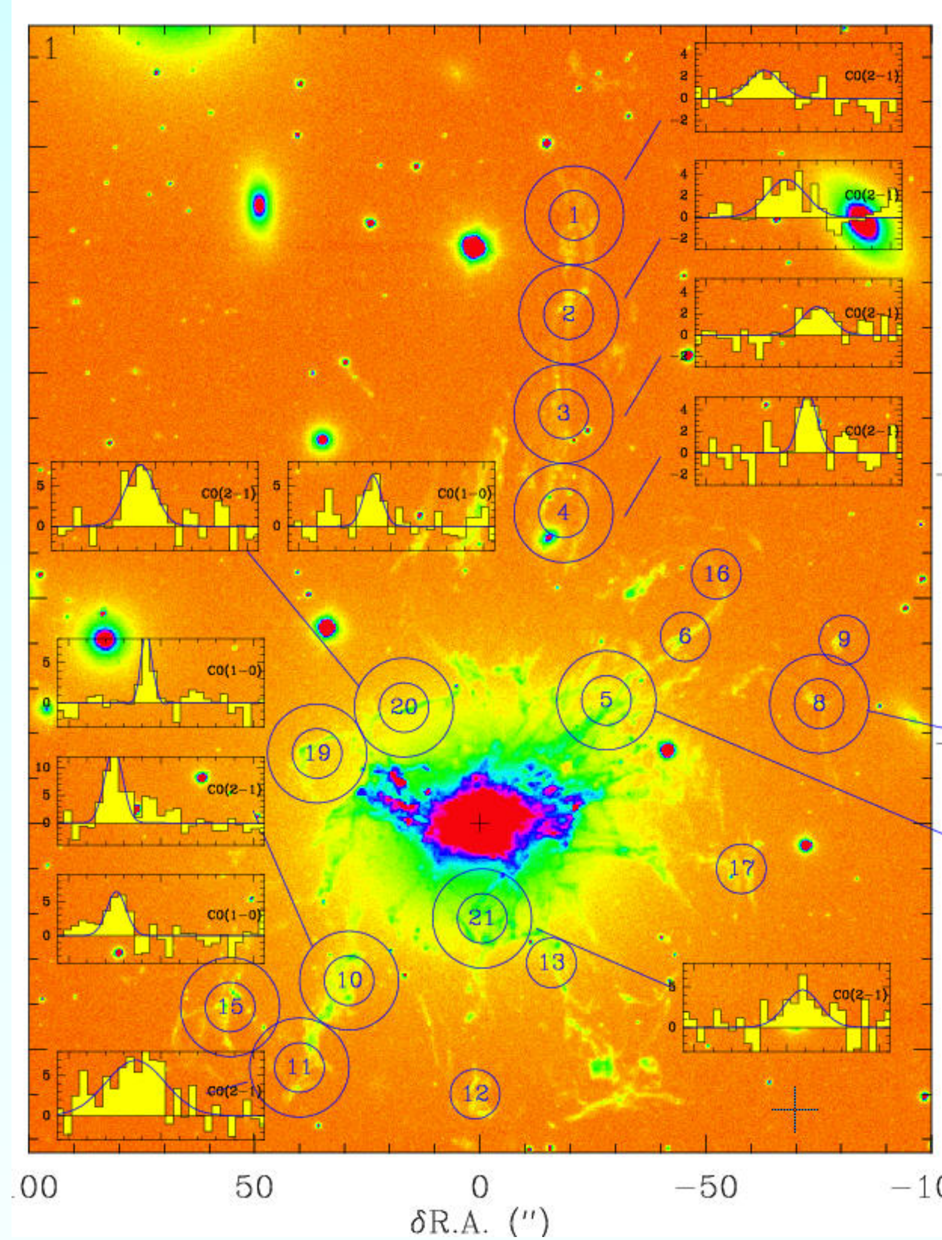
Cold CO in filaments

Here also, inflow and outflow coexist

The molecular gas coming from previous cooling is dragged out by the AGN feedback

The bubbles create inhomogeneities and further cooling

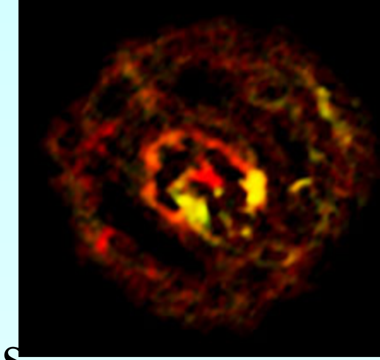
The cooled gas fuels the AGN



Velocity much lower than free-fall

Salome et al 2008

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_o in FOV=18"
100km/s flow
7% of the mass= 3.6 10^6 Mo
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 AGN
Smajic et al 2014

The NGC1566 nearby barred Sy1

N1566 SAB Sy1

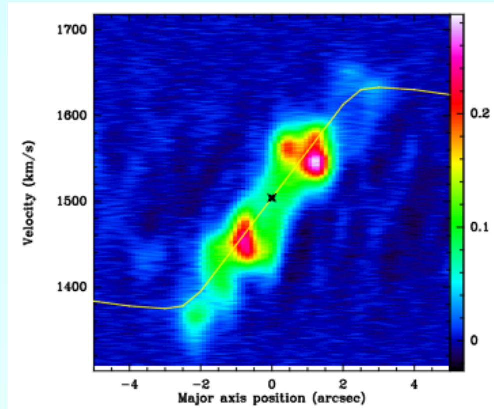
4 arcmin

FOV=18 ”

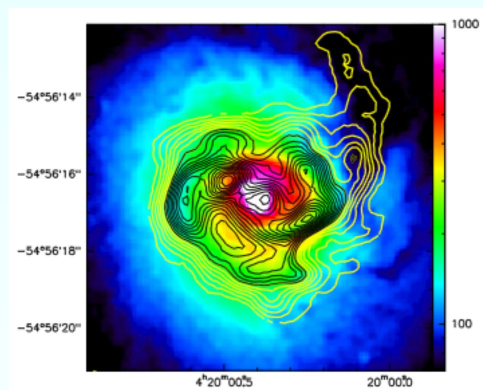
Spatial resolution

0.5 arcsecond ~25pc

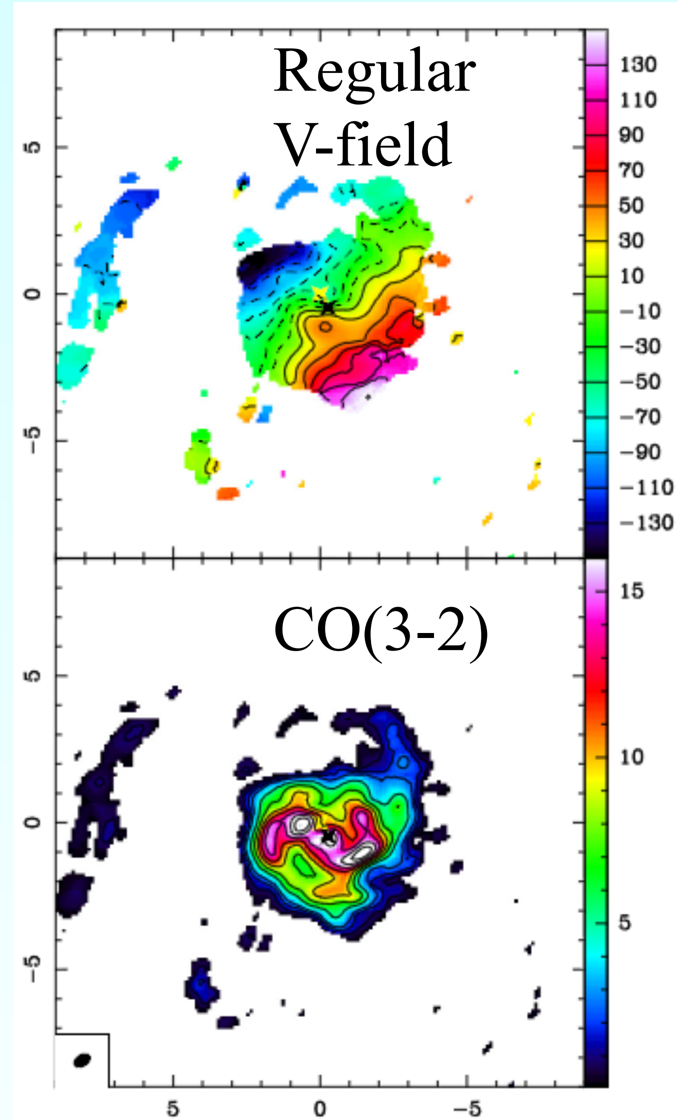
Combes et al 2014



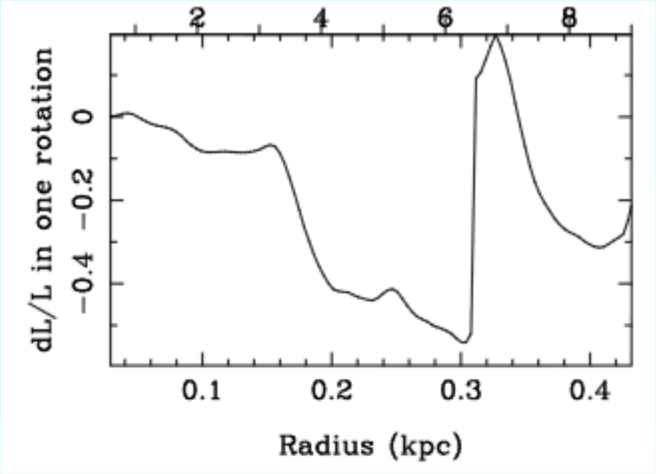
PV major axis
No outflow



Overlay CO(3-2) contours
on HST image

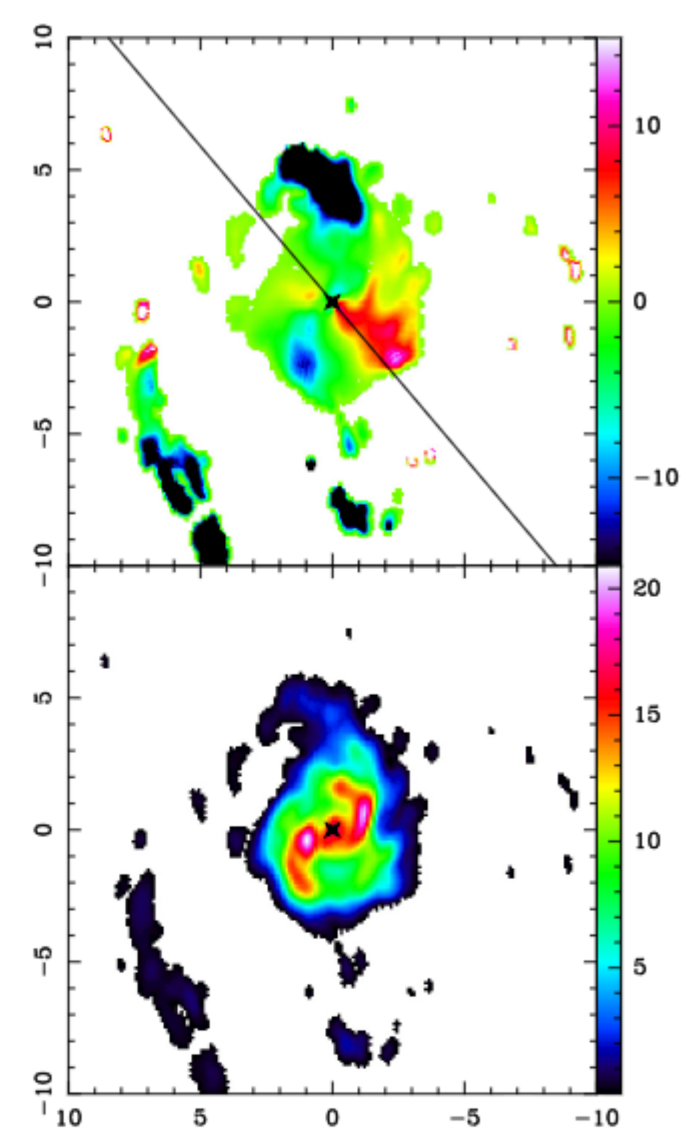


NGC1566: gravitational torques



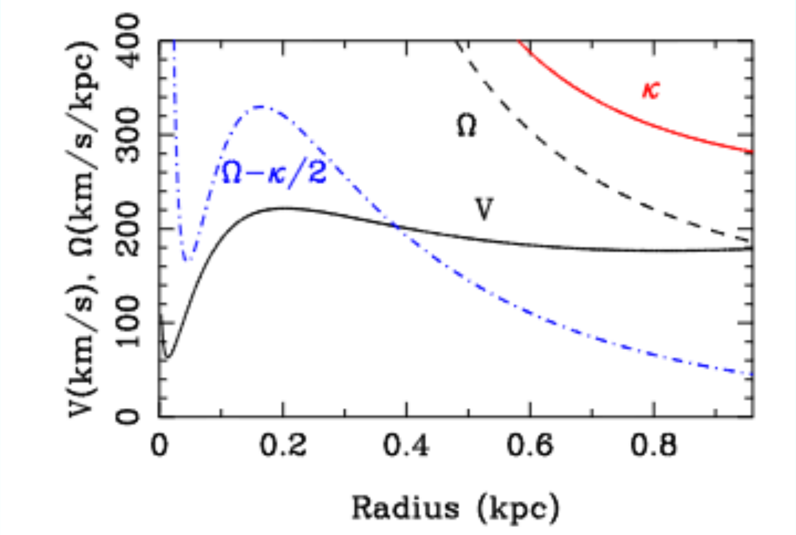
Gas is driven inwards

Torques on deprojected image

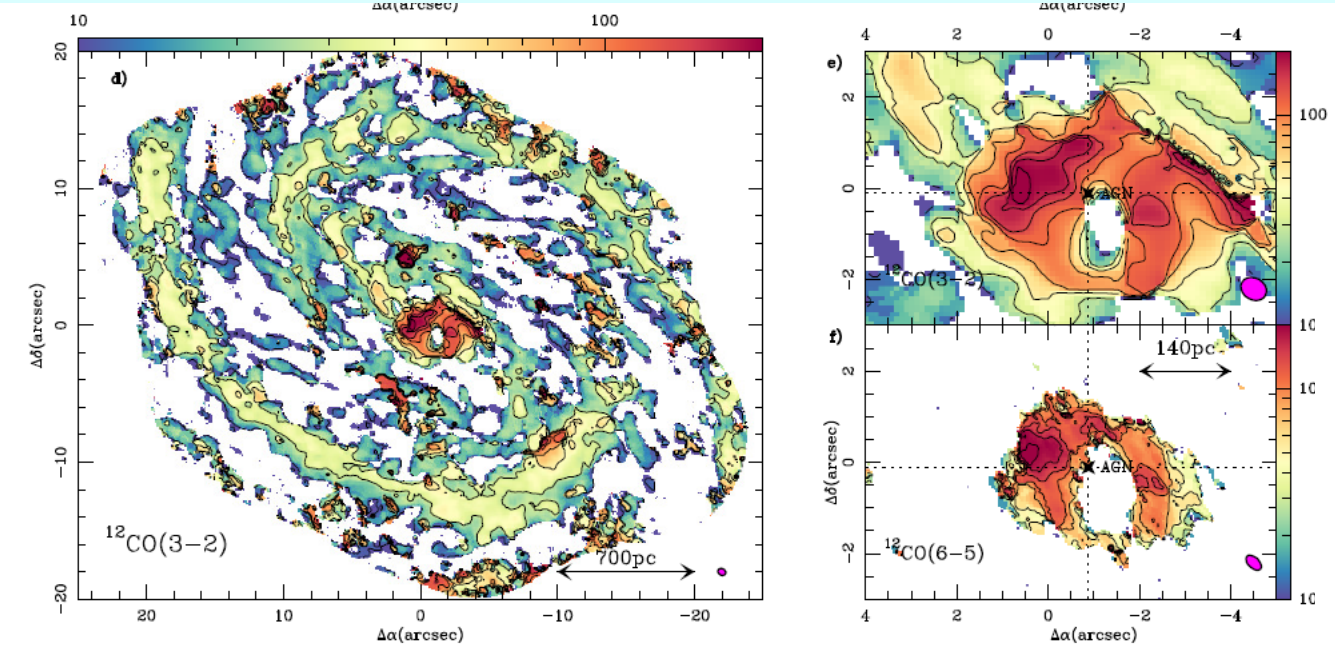


Trailing spiral inside the ILR ring of the bar

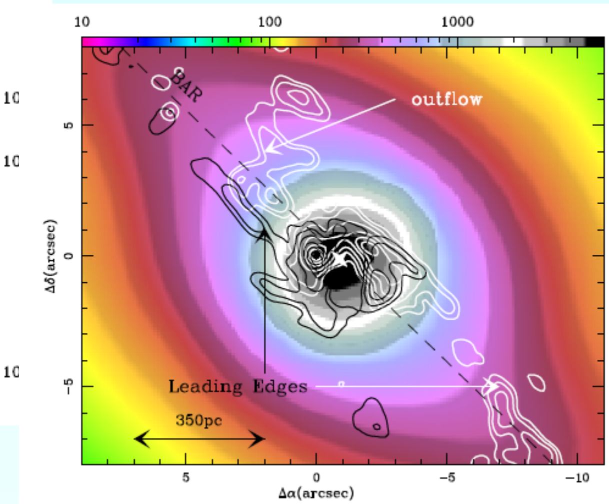
➔ BH influence on the dynamics

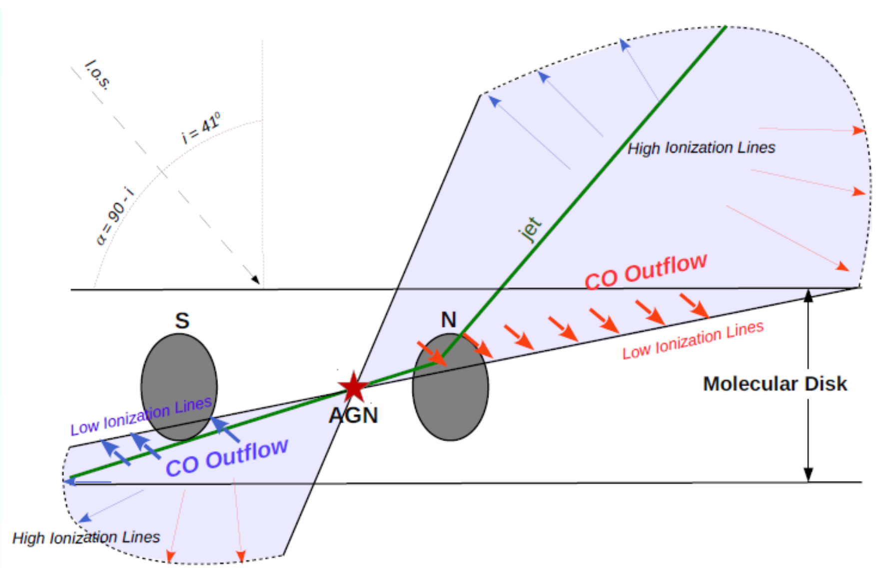


Off-center AGN and outflow in N1068



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

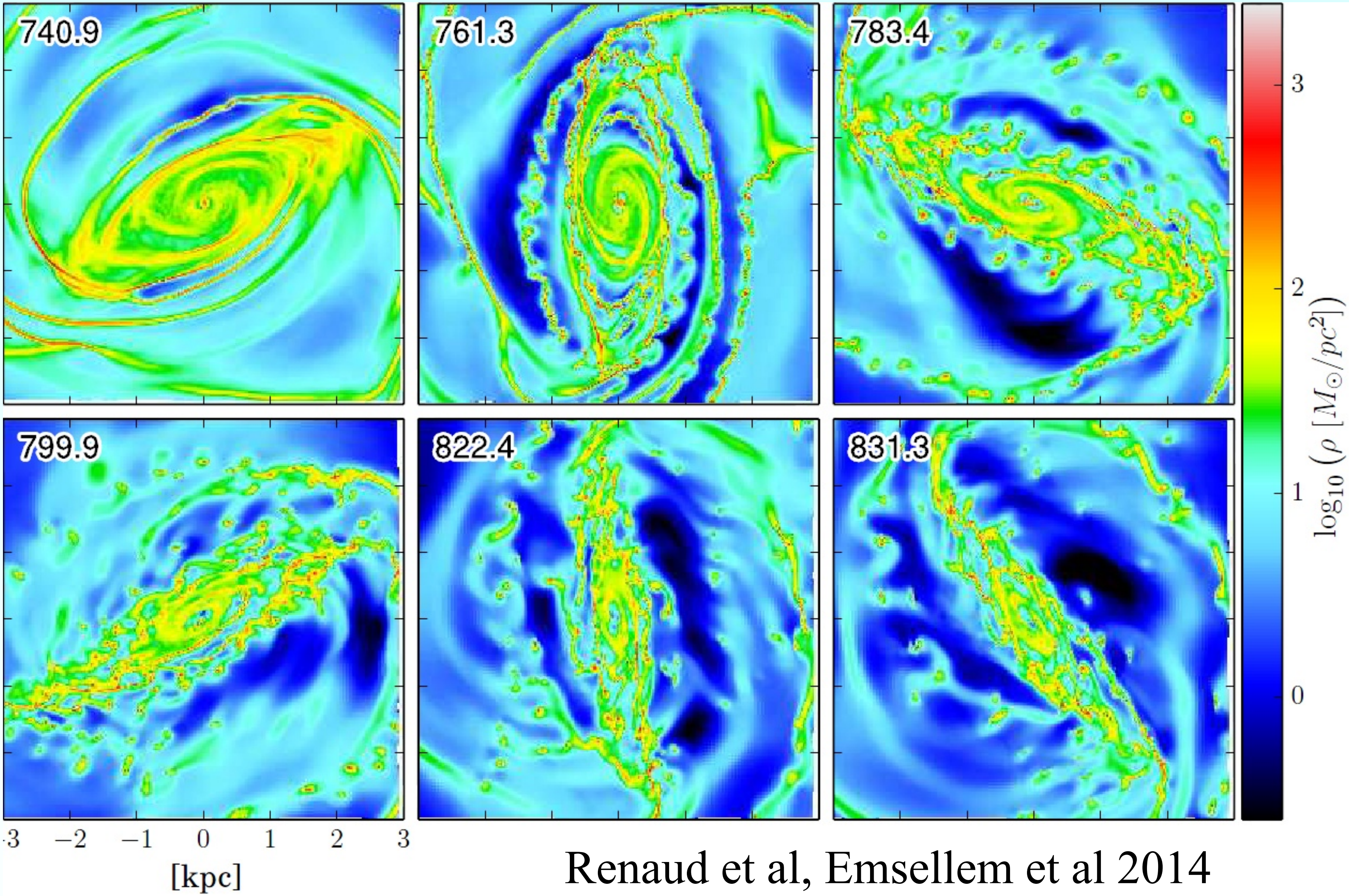




Outflow of 63Mo/yr
About 10 times the SFR in this CMD region

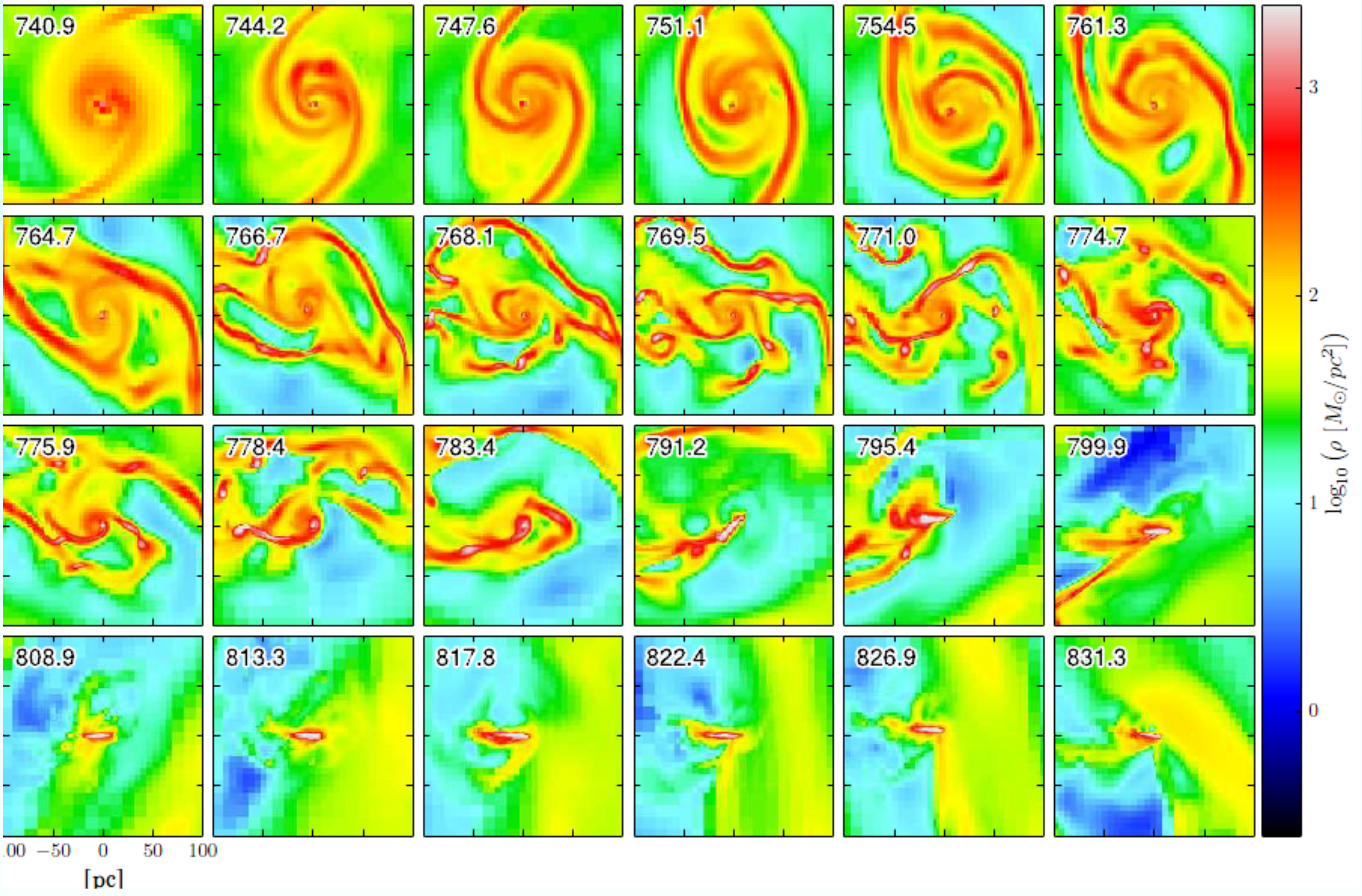
Garcia-Burillo et al 2014

High-resolution simulation: MW

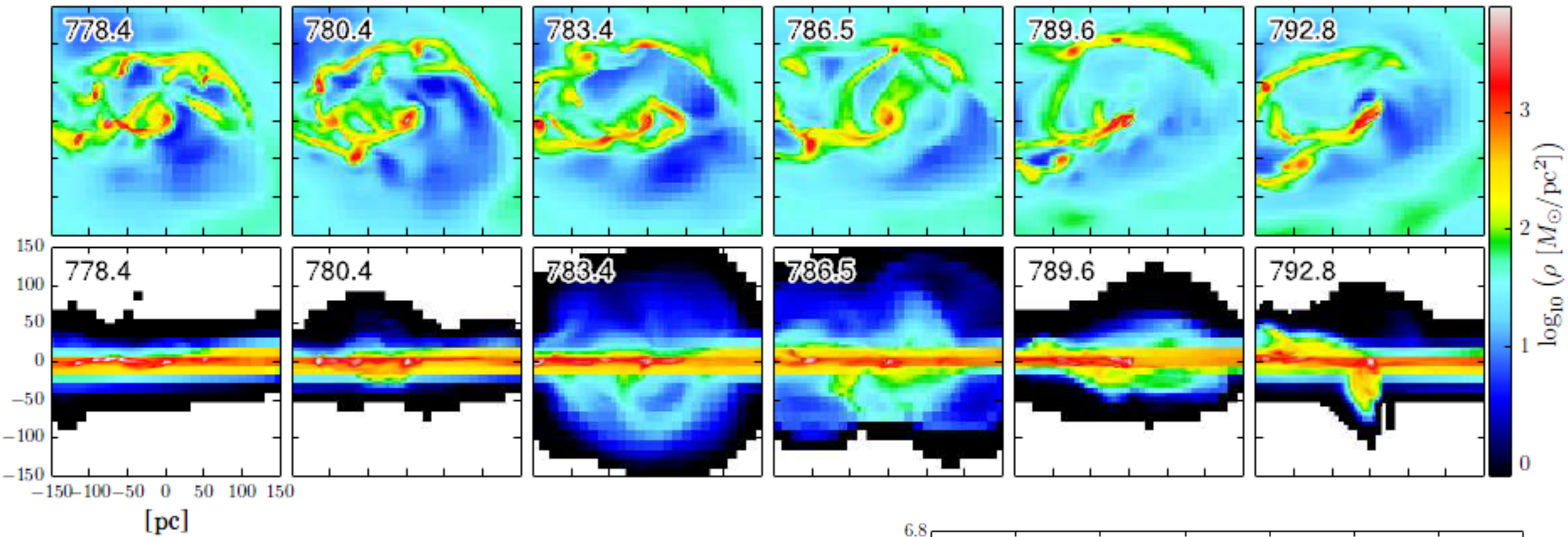


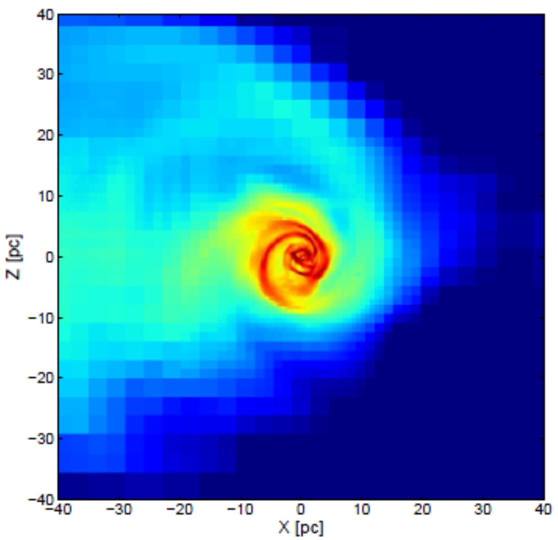
Renaud et al, Emsellem et al 2014

Zoom in the central 200pc region



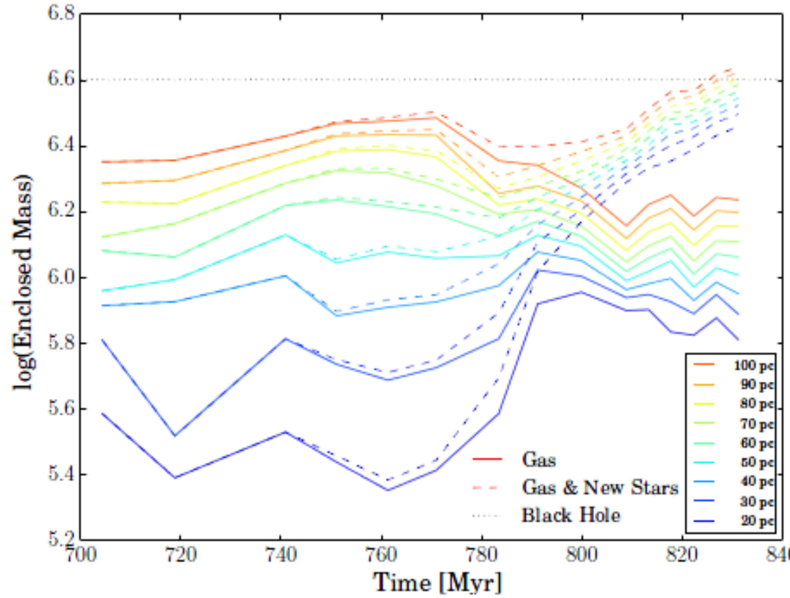
How the gas is accreted





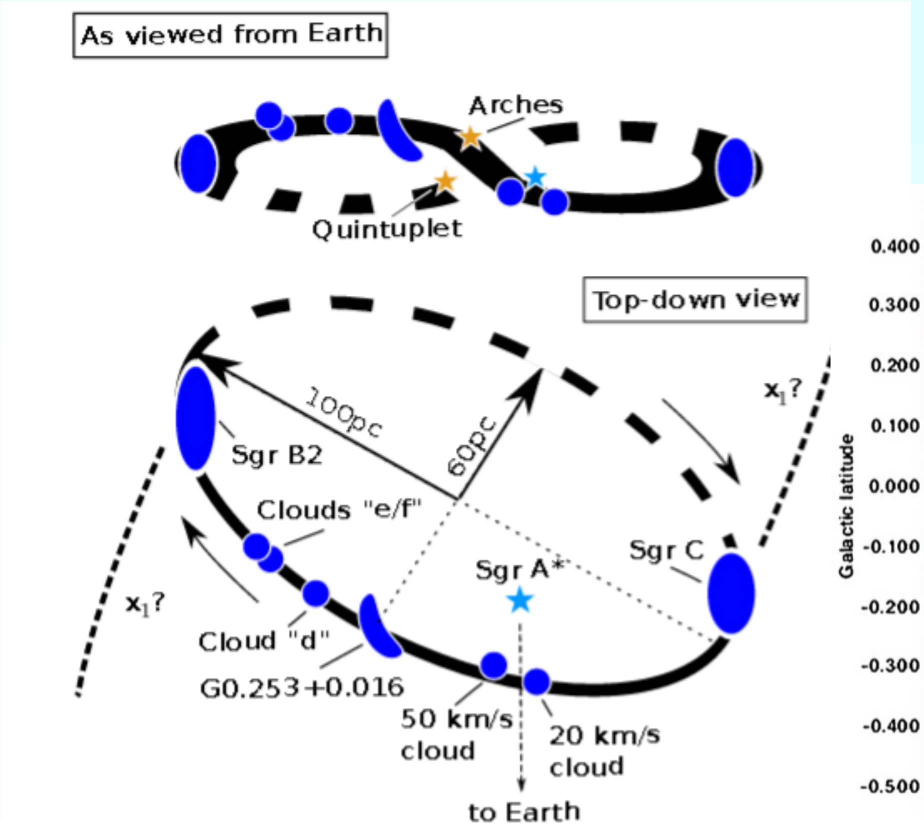
Strong SN Feedback
➔Gas in the Perpendicular plane

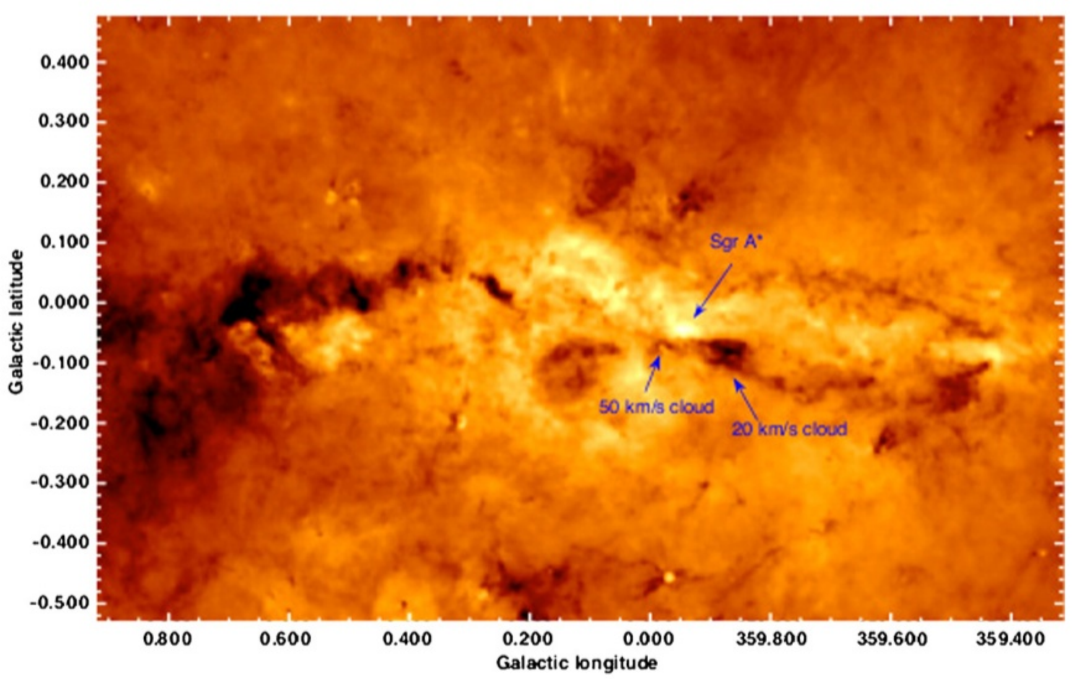
Emsellem et al 14



CMZ in the Milky Way

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





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

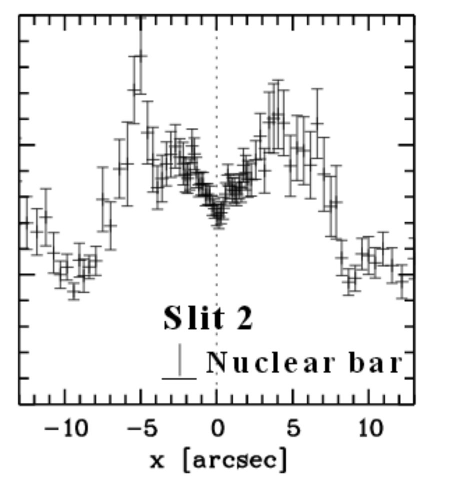
Herschel
Molinari et al 2011

Accumulation of gas and stars

Differences between Seyfert and non-active galaxies *(Hicks et al 2013)*

(1) more centrally concentrated nuclear stellar surface brightness
(2) lower stellar DV within 200 pc,
(3) elevated H2 1–0 S(1) luminosity
(4) more centrally concentrated H2

N1097



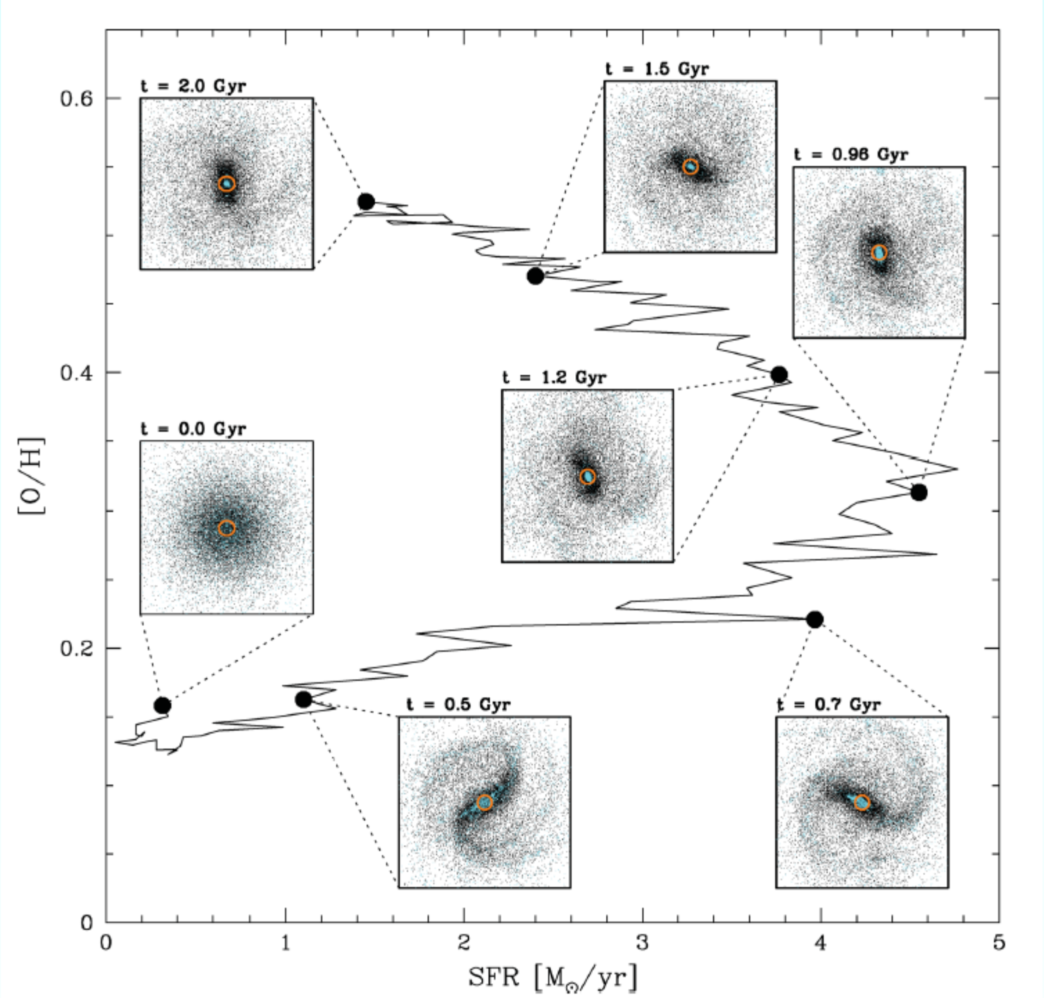
Inflow and outflow of H2 in the center of AGN
Not outflow, but more chaotic in non-active galaxies
with counter-rotation

σ−drop
Emsellem et al 01

Davies et al 2014

SFR and metallicity gradients

Martel et al 2013



Gas flows due to bars
(no gas flow without)

Enrichment in metals
Due to the flow of gas
Enriched by SFR all along the bar

In situ enrichment small

CONCLUSION – Scale is important!

➔ **Primary bars** are essential to drive gas from **10kpc to R ~ 100pc**
Then nuclear bars from 100pc to 10pc
Bars + asymmetries, tidal interaction, mergers, and **embedded** structures at the various scales **fuel nuclear starbursts and AGN:**
Mainly m=2, but also m=1, or companions

➔ **At scales ~1-10pc,** viscous turbulence, clumps, warps, bending, dynamical friction, formation of thick disks/torus, **when there is gas** (afterwards, vestige nuclear stellar disks remain, cf M31)

➔ feedback, outflows are present, due mainly to Starburst, and to AGN when violent

➔ **Alignment between small scales and large scales not expected**