N1097
AAT+
VLT/NACO
(A. Prieto)

# Gas in External Galaxies

## Interstellar Medium -- Lecture 2

Françoise Combes

# The gas component is essential for the star formation and dynamics

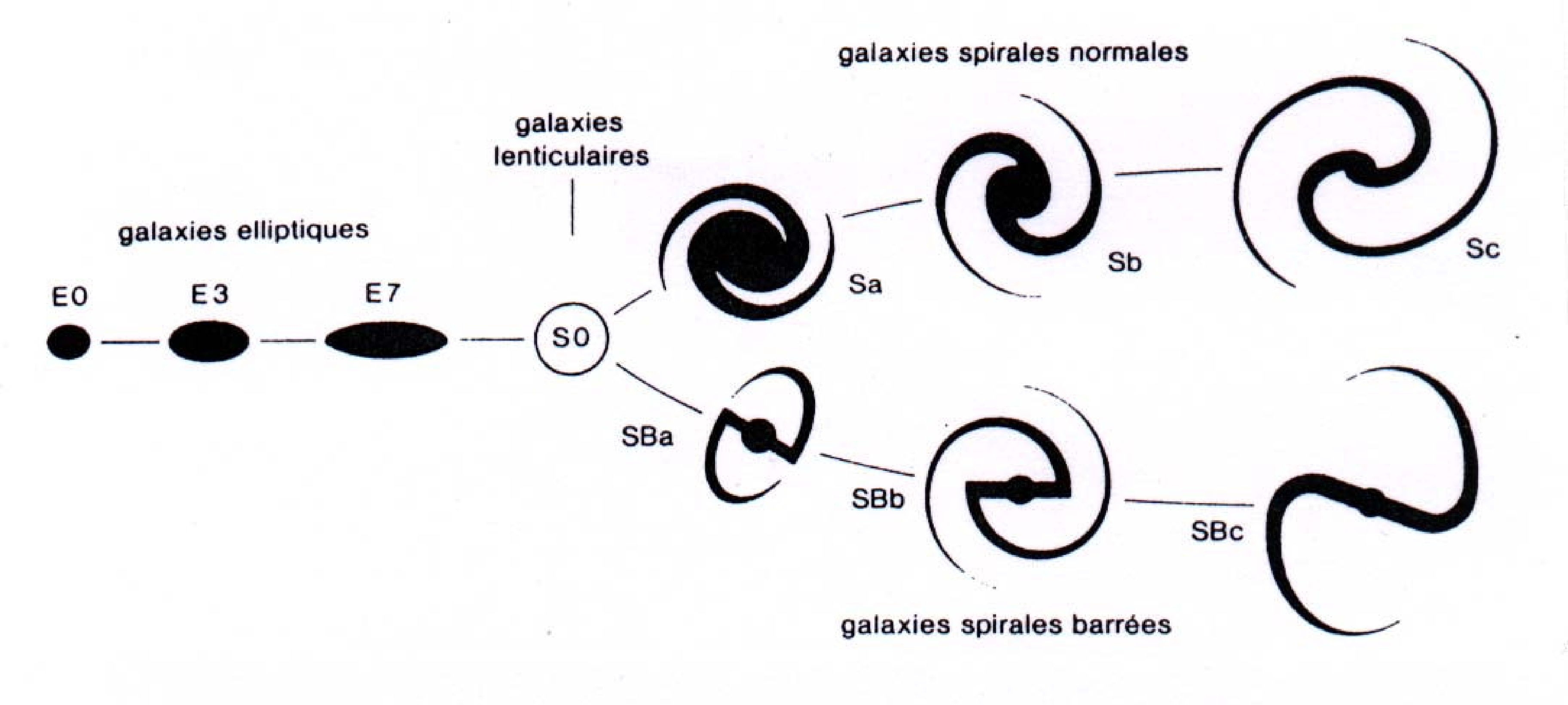
**Morphological type**
**Gas fraction along the Hubble sequence**
**Dwarfs, LSB**

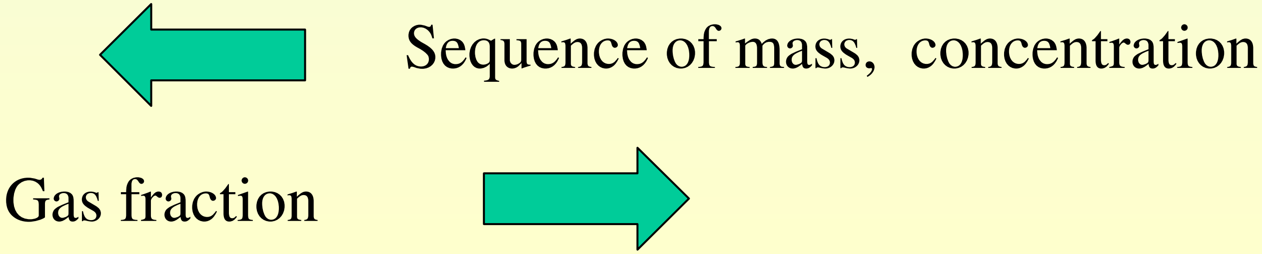
**Radial distribution, spiral structure**
**ISM and bars**
**Fueling of nuclei**

**Polar rings**
**E-galaxies, CO in shells**
**Tidal dwarfs**

**Dynamical triggering of Star Formation**
**AGN feedback**

# Hubble sequence





Sequence of mass,  concentration

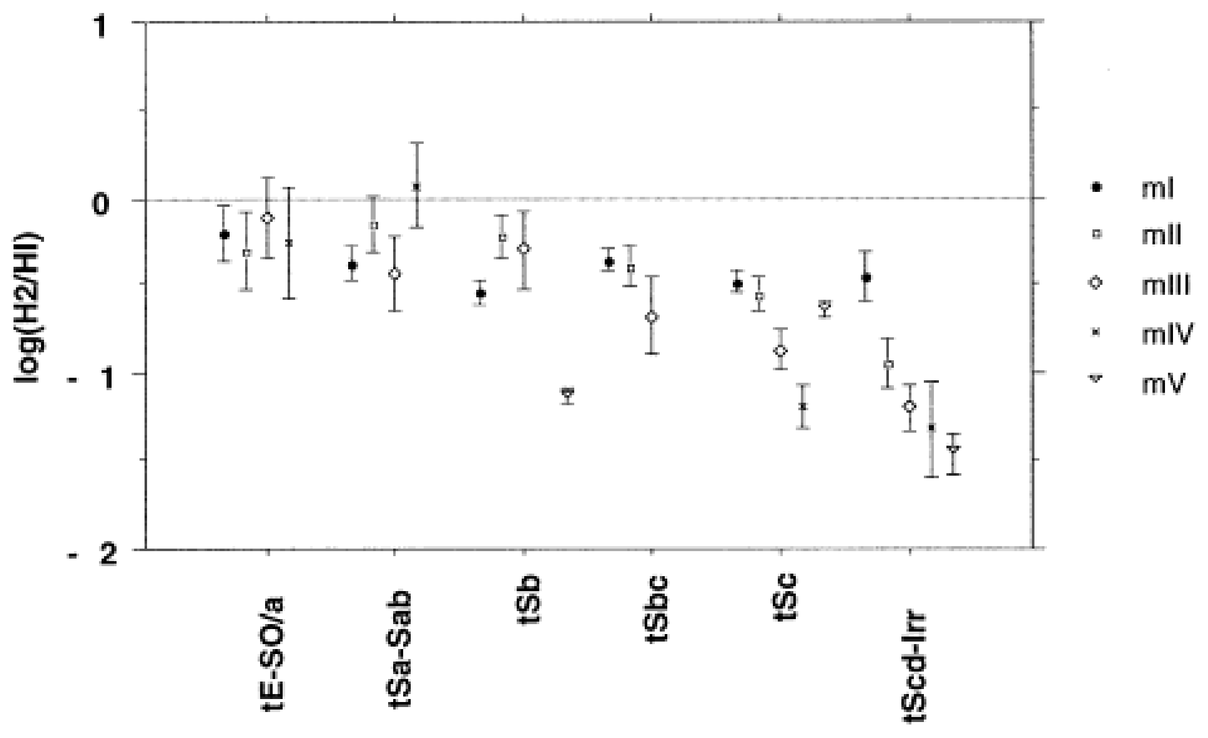
Gas fraction

# HI and $H_2$ content vs morphological types

**HI gas fraction increases for late types**

**The $H_2$ mass is comparable in average to the HI mass in spiral galaxies**

**Varies with morphological type, by a factor ~ 10**



**$H_2$ to HI mass ratios versus type**

**According to mass**

*For galaxies of high masses, there is no trend of decreasing $H_2$/HI with type*

➡ **The dependence on type could be entirely due to metallicity**

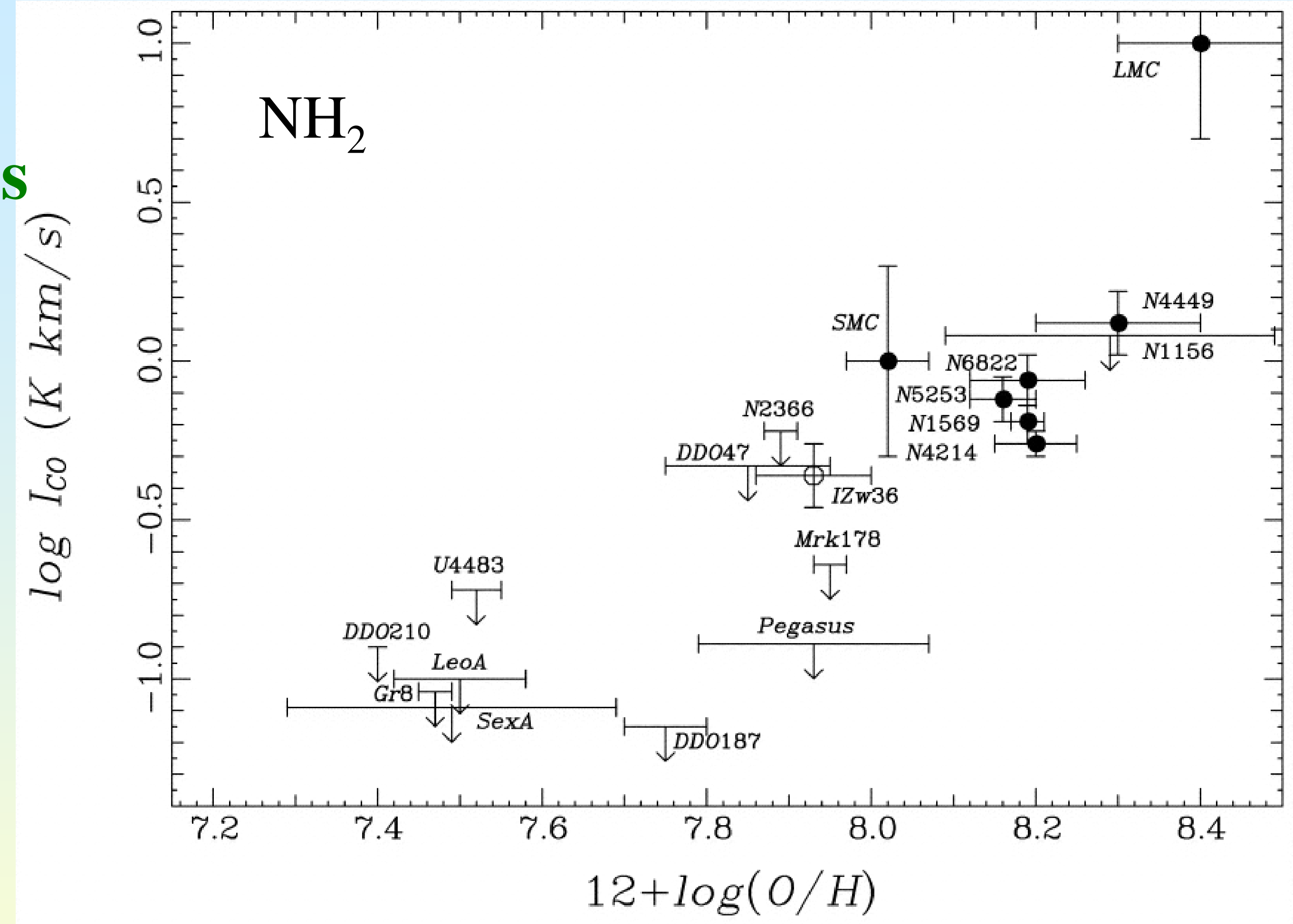
**The conversion factor CO->$H_2$ can vary linearly (or more) with Z**

**Dust depleted by 20 ==> only 10% less $H_2$ but 95% less CO (Maloney & Black 1988)**

**Environment: HI deficient for galaxies in clusters (interactions, ram pressure)**

**There is no CO deficiency in galaxy clusters**

# Dwarf galaxies



**Taylor et al 98**

**O/H is the main factor (below 7.9, galaxies are undetectable)**
**But other factors, too; like the SFR (UV)**
**Barone et al (2000)**

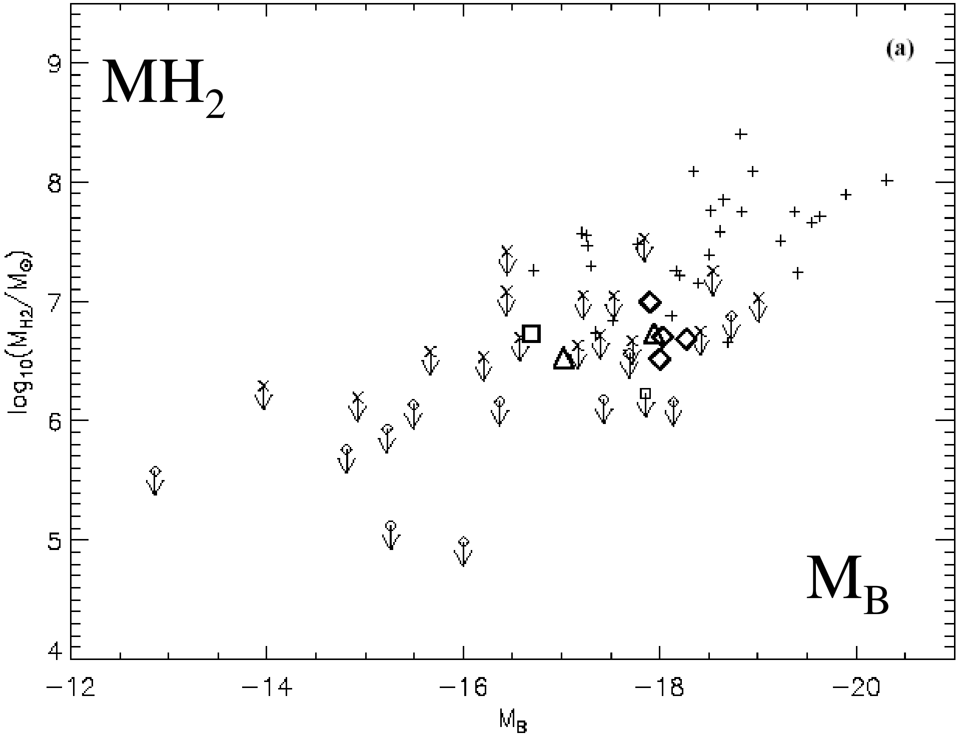
# Low Surface Brightness LSB

**Large gas fraction**
**(up to fg=95% LSB dwarfs Shombert et al 2001)**
**and dark matter dominated ==> unevolved objects**

**Low surface density of HI, too, although large sizes**
**Un-compact**

**Resemble the outer parts of normal HSB galaxies**

15 LSB, Matthews et al 2005



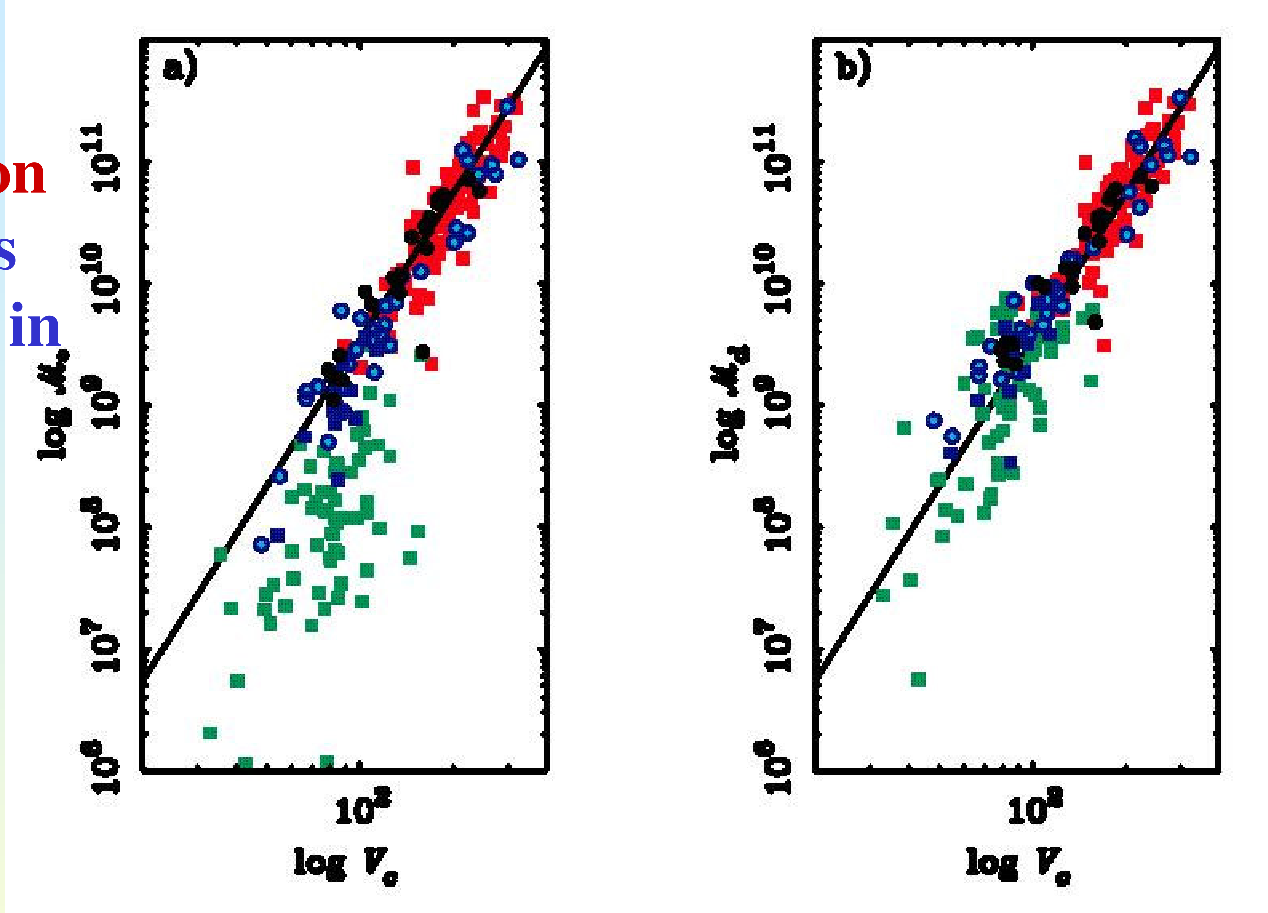
LSB on the same Tully-Fisher relation
(for the same V, galaxies twice as large) $M \sim V^2R$
M/L increases as surface density decreases

Low efficiency of star formation (Van Zee et al 1997)
Gas $\Sigma_g$ below critical

A gas rich galaxy is stable only at very low $\Sigma_g$

Galaxy interaction, by driving a high amount of gas
➔ trigger star formation
LSB have no companions (Zaritsky & Lorrimer 1993)

## Tully-Fisher relation for gaseous galaxies works much better in adding gas mass



Relation $M_{baryons}$ with Rotational V

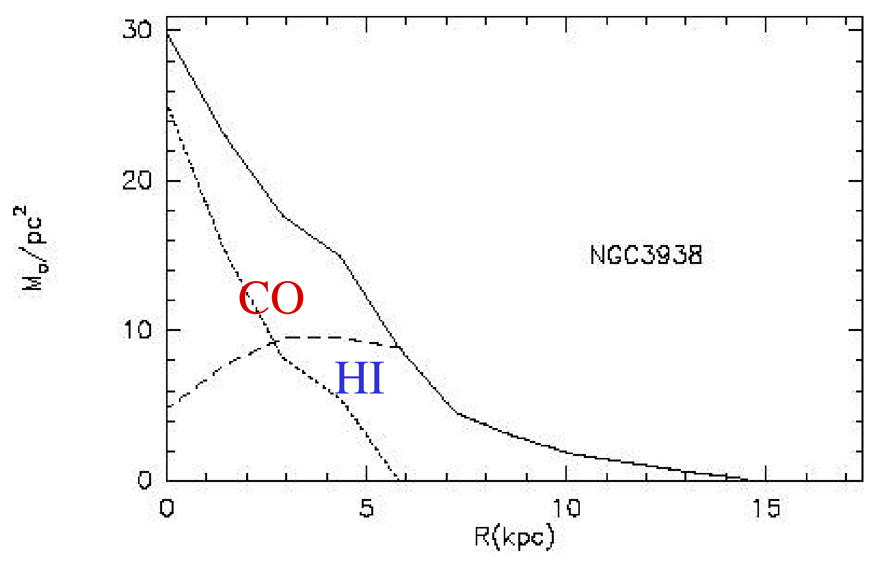
$M_b \sim V_c^4$

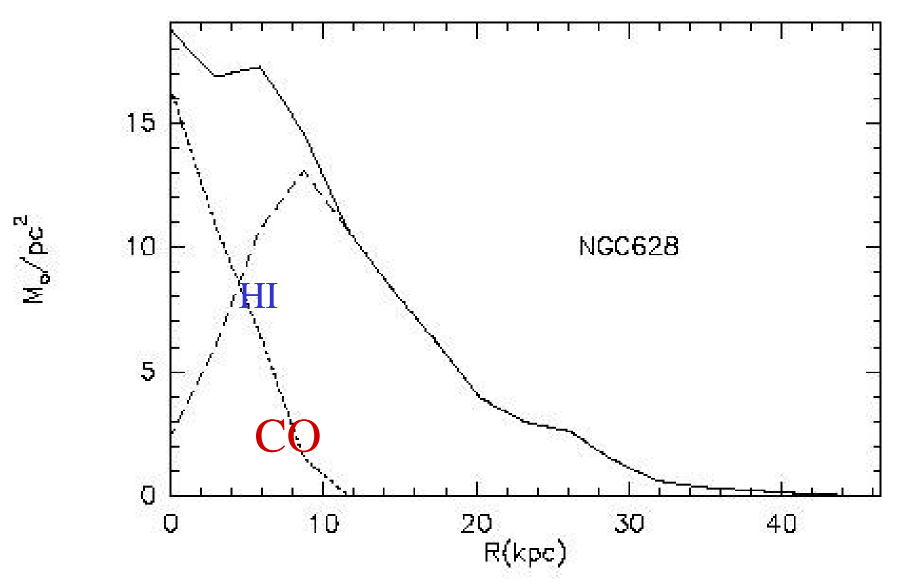
McGaugh et al (2000) ➔ Baryonic TF

# Radial Distribution in Spirals

**HI versus $H_2$**
**The $H_2$ is restricted to the optical disk**
**while the HI extends 2-4 x optical radius**

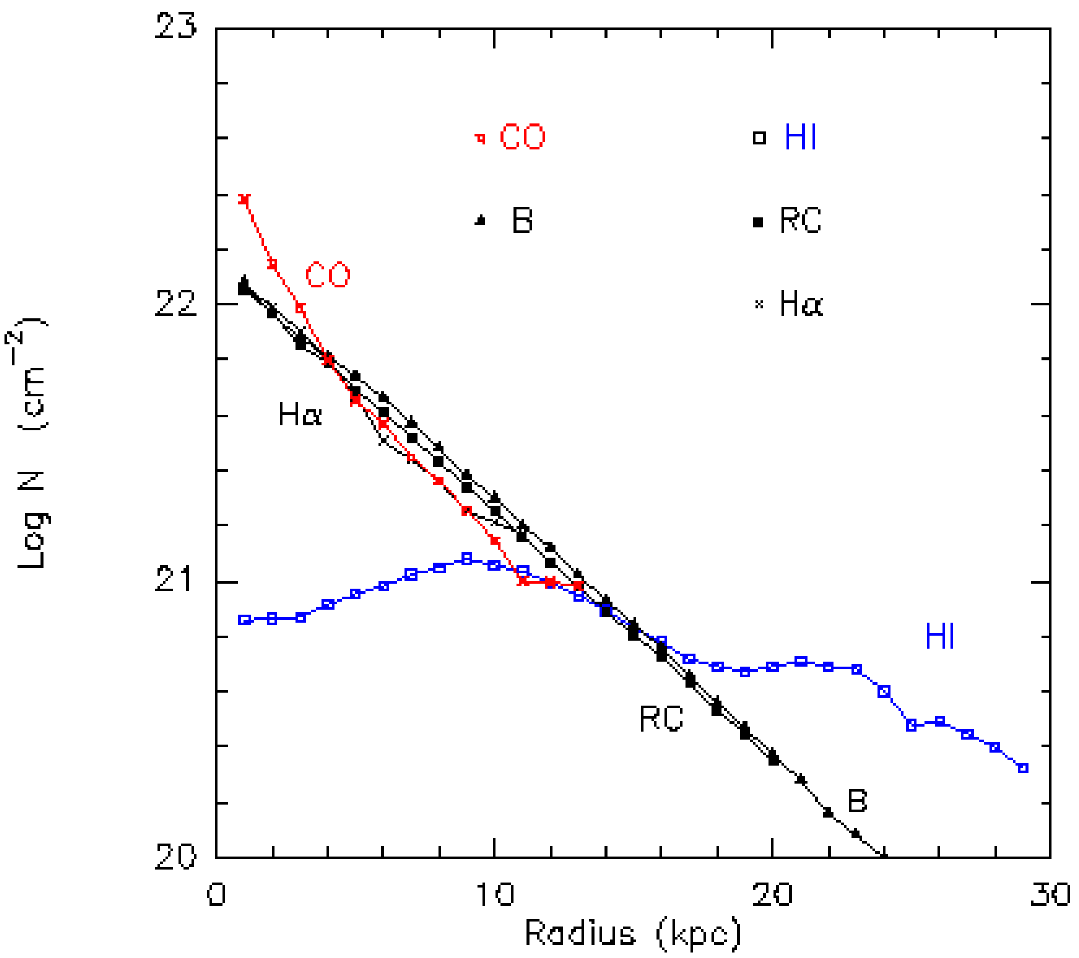
**HI hole or depression in the centers, often compensated by $H_2$**





## Often exponential disks

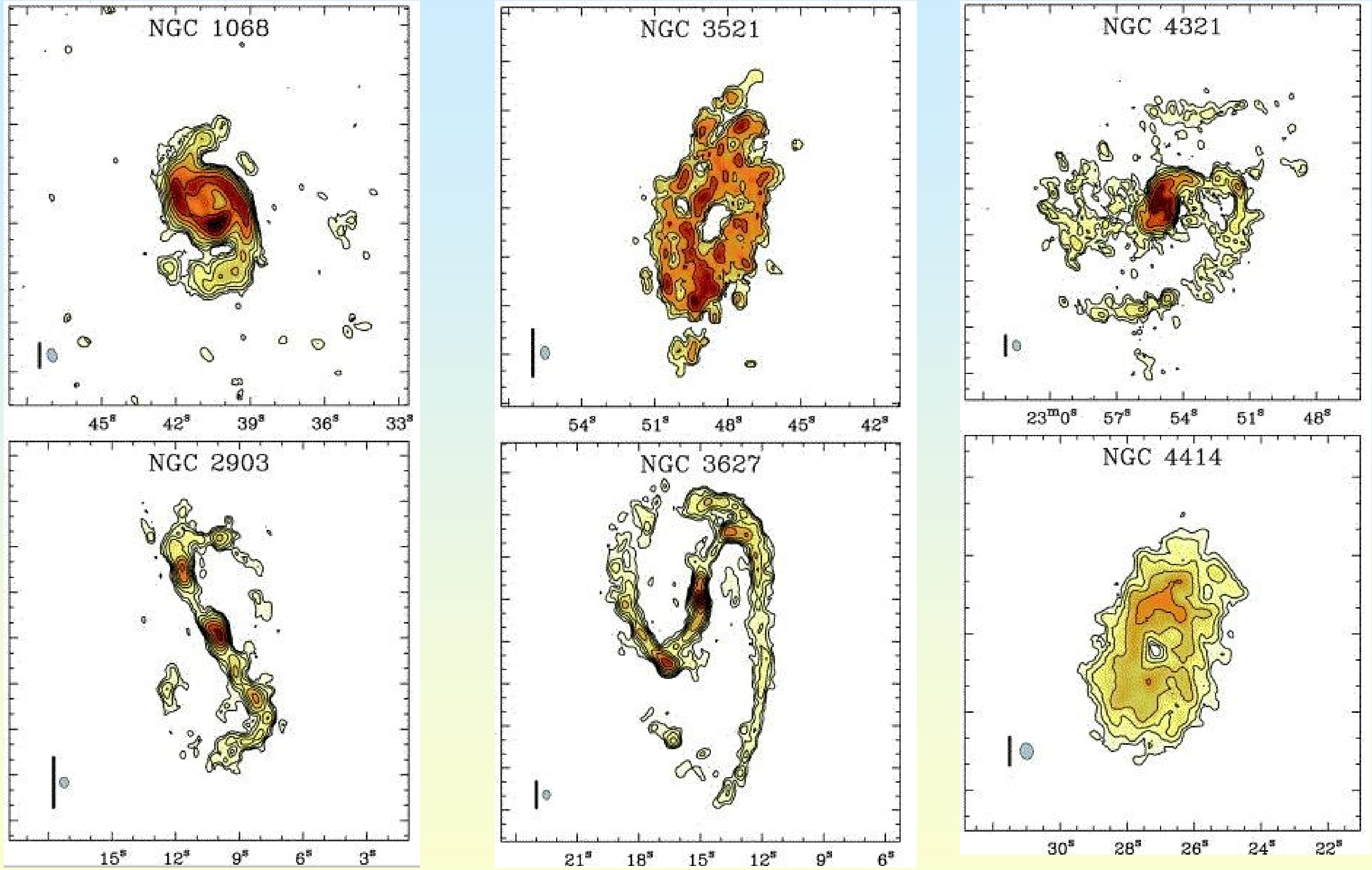
## similar to optical



**Radial distribution in NGC 6946**

**The HI is the only component not following star formation**

# Exp. Scale-lengths optical and CO are similar



**Bima SONG (Regan et al 2001)**

# Spiral Structure

**The $H_2$ component participates even better than the HI and stellar component to the density waves**

due to its low velocity dispersion

**Larger contrast than other components**
**streaming motions, due to the spiral density wave**

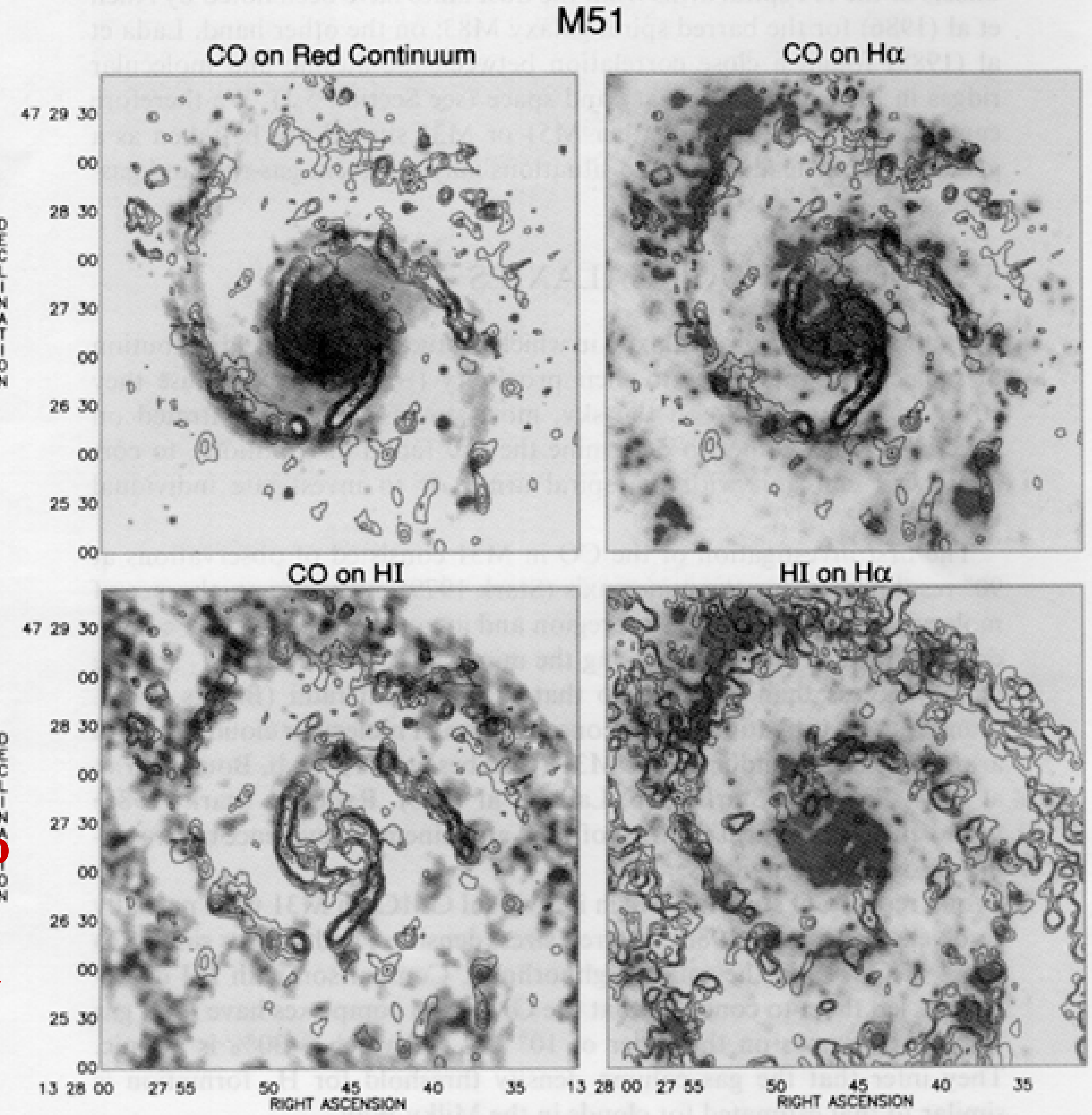
- **Formation of GMC in arms**
- **Formation of $H_2$? Chemical time-scale $10^5$ yrs**
- **HI is formed out of photo-dissociation of $H_2$**
- **CO exist also in the interarms in CO-rich galaxies**

M51 spiral
+ nuclear ring
Tilanus & Allen
1991

Pearls on string

GMC complexes

More recent map
From Aalto,
Hüttemister et al



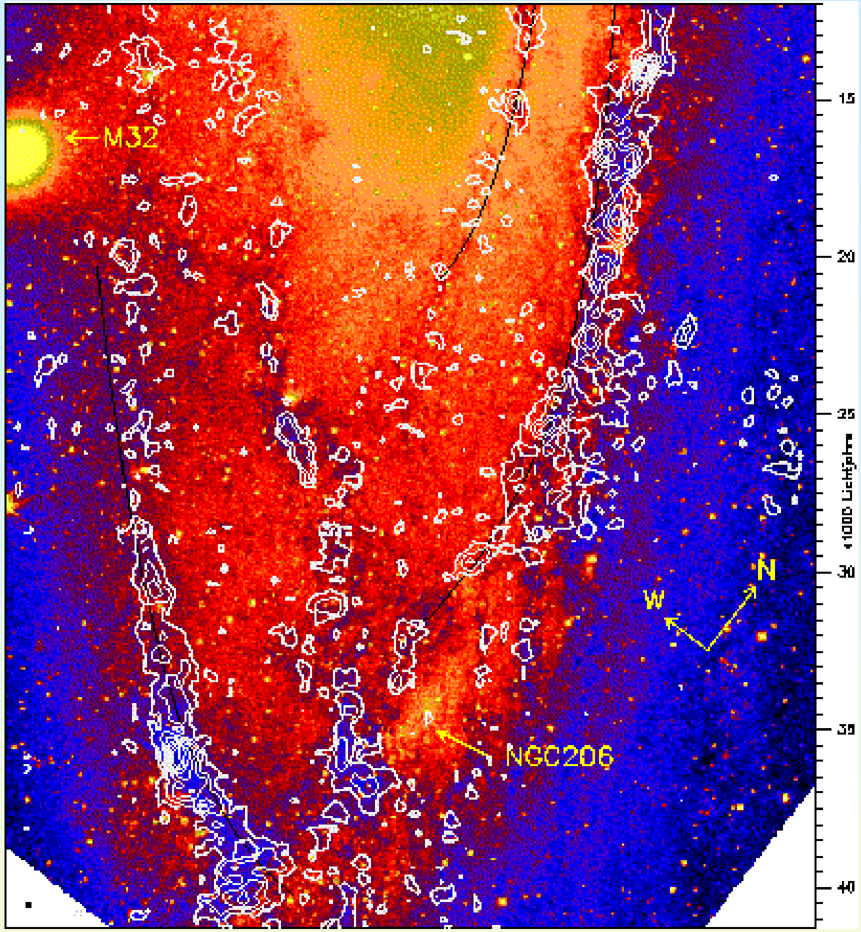
## Full map of M31
## with IRAM 30m

**CO and dust coinciding**

**$M(H_2) \ll M(HI)$**

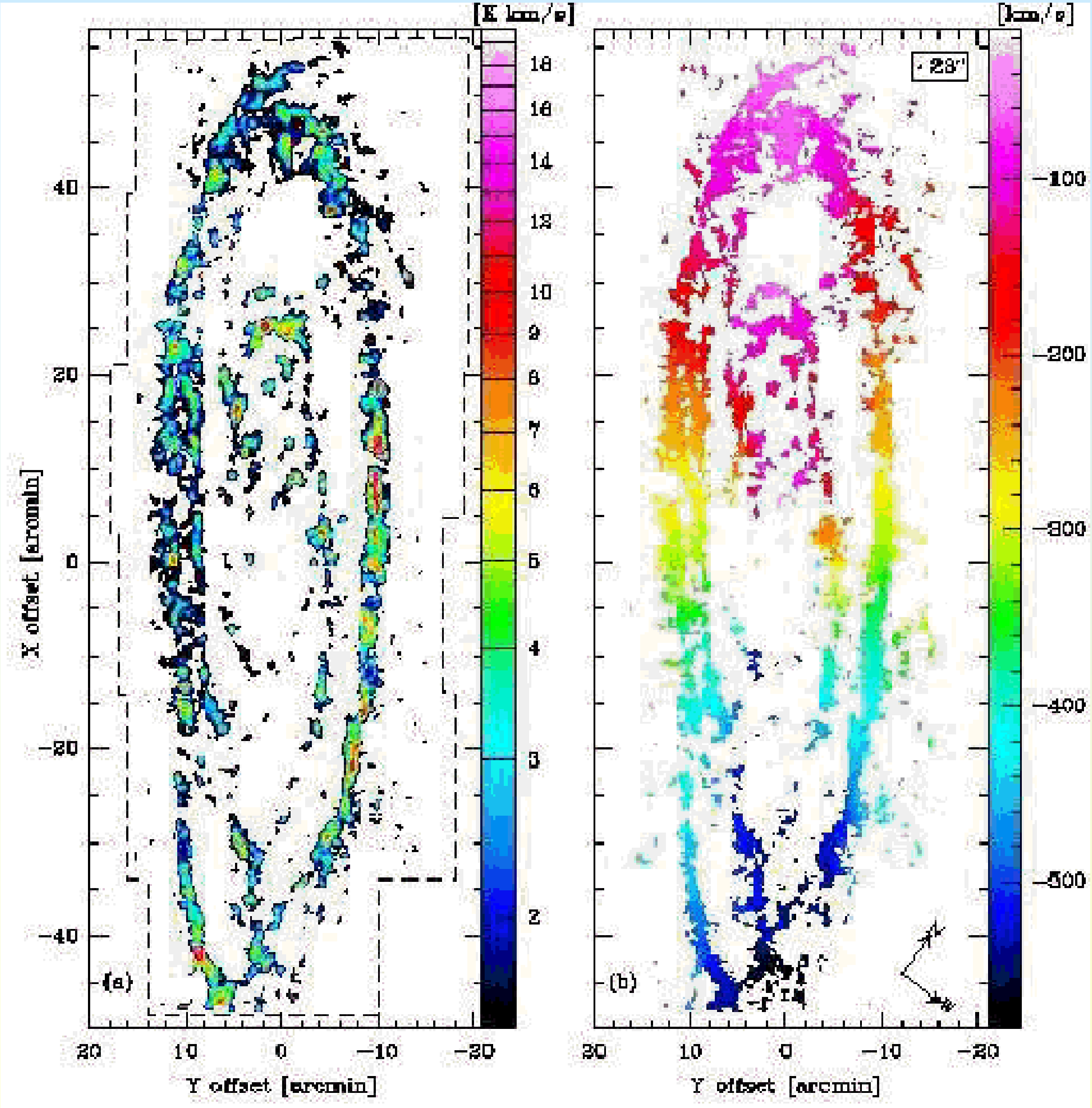
**Mvirial > M(CO)**

**Müller & Guélin 2003**



**On the Fly map of M31 at IRAM 30m, Neininger et al (1998)**

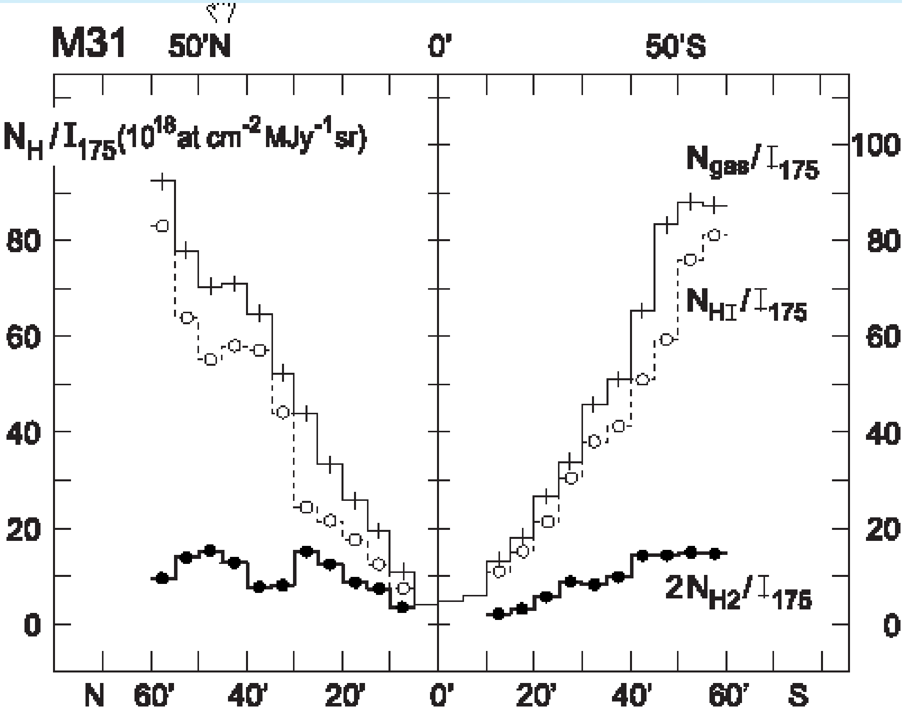
# M31 On the Fly
# IRAM CO
# Nieten et al 2005

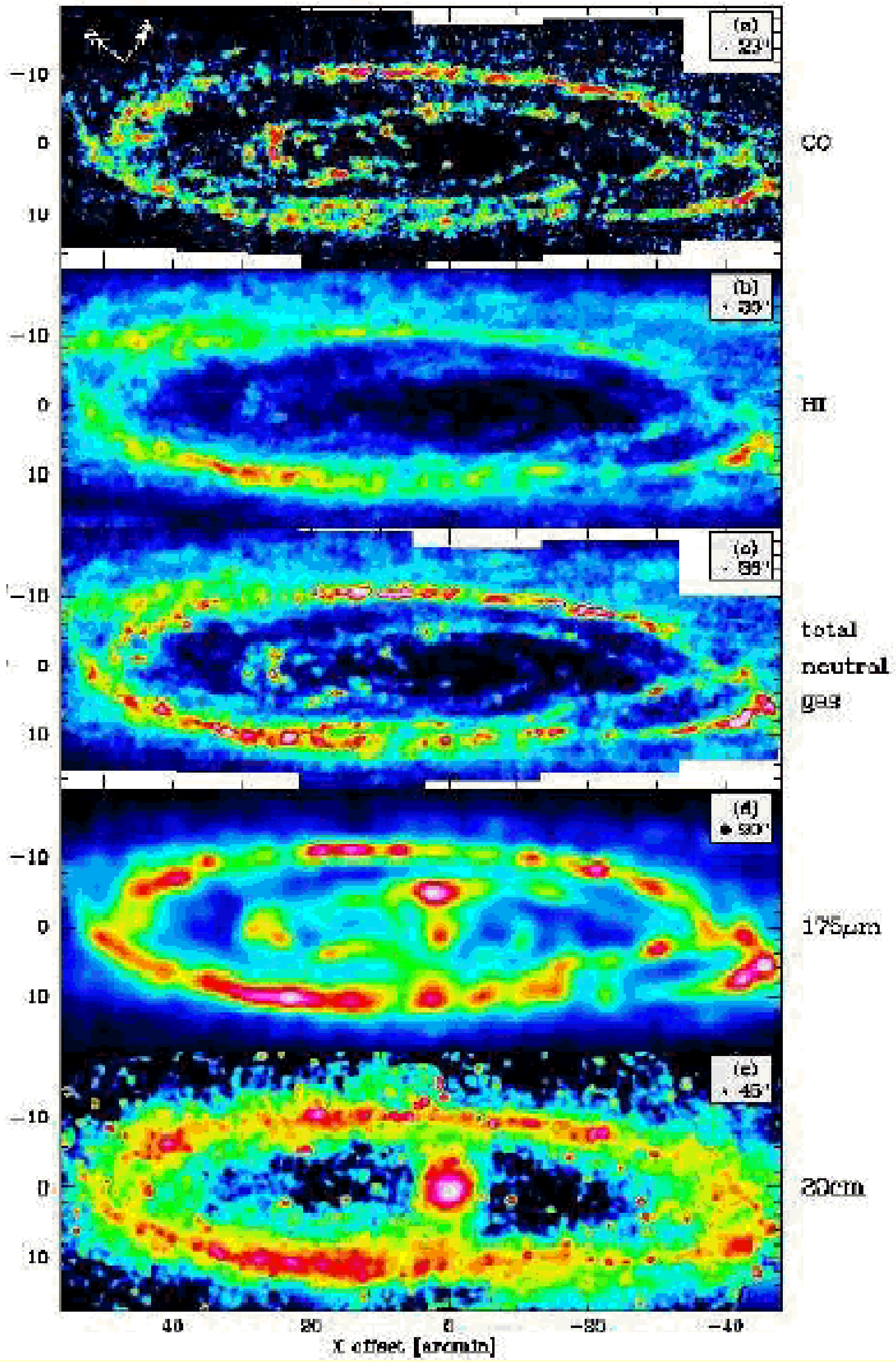


Arm-interarm
Contrast

=20 in CO
=4 in HI

# Gas to dust ratio distribution





CO → H2 yields only 7% of the neutral gas

Nieten et al 2005

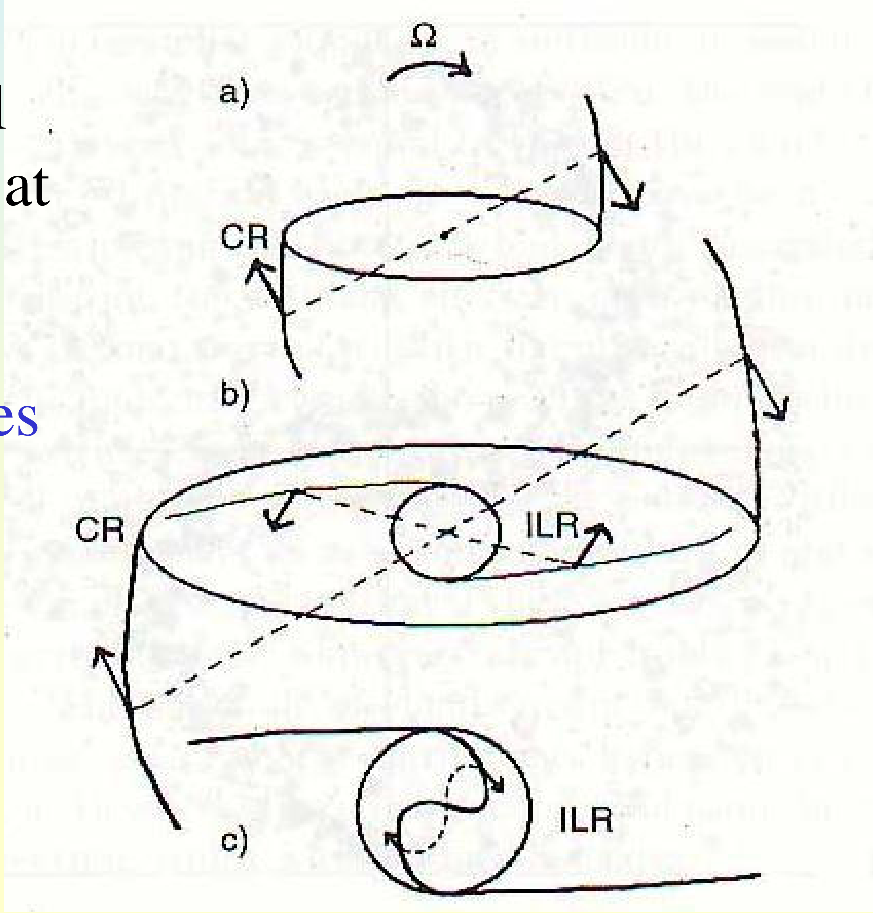
# Gas in Barred Galaxies

**Bars are non-axisymmetric perturbations that create tangential forces and torques on the gas**

The main direction of orbits are parallel or perpendicular to the bar, and change at resonances

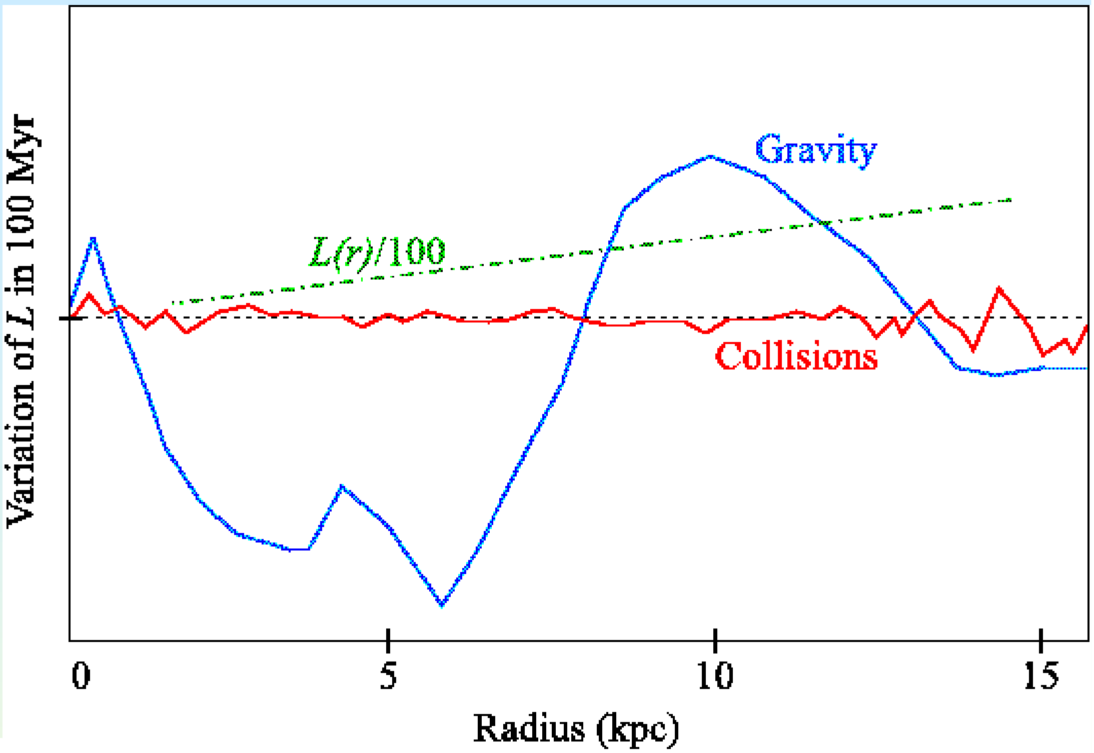
The sign of torques change at resonances

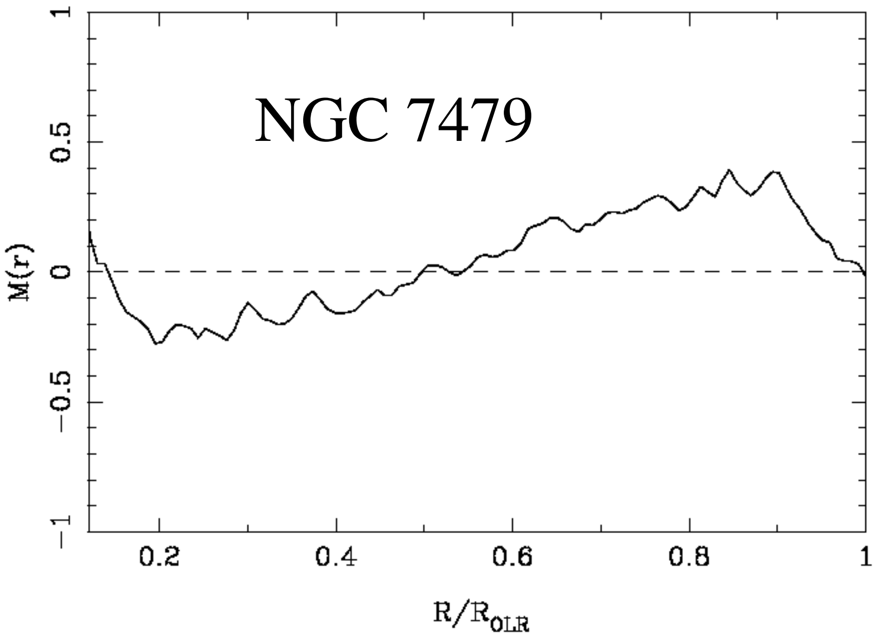
Inside corotation (encircling the bar) the torques are negative, and the gas is driven towards the center



# Gravity Torques

Gravity torques dominate over viscous torques in simulations

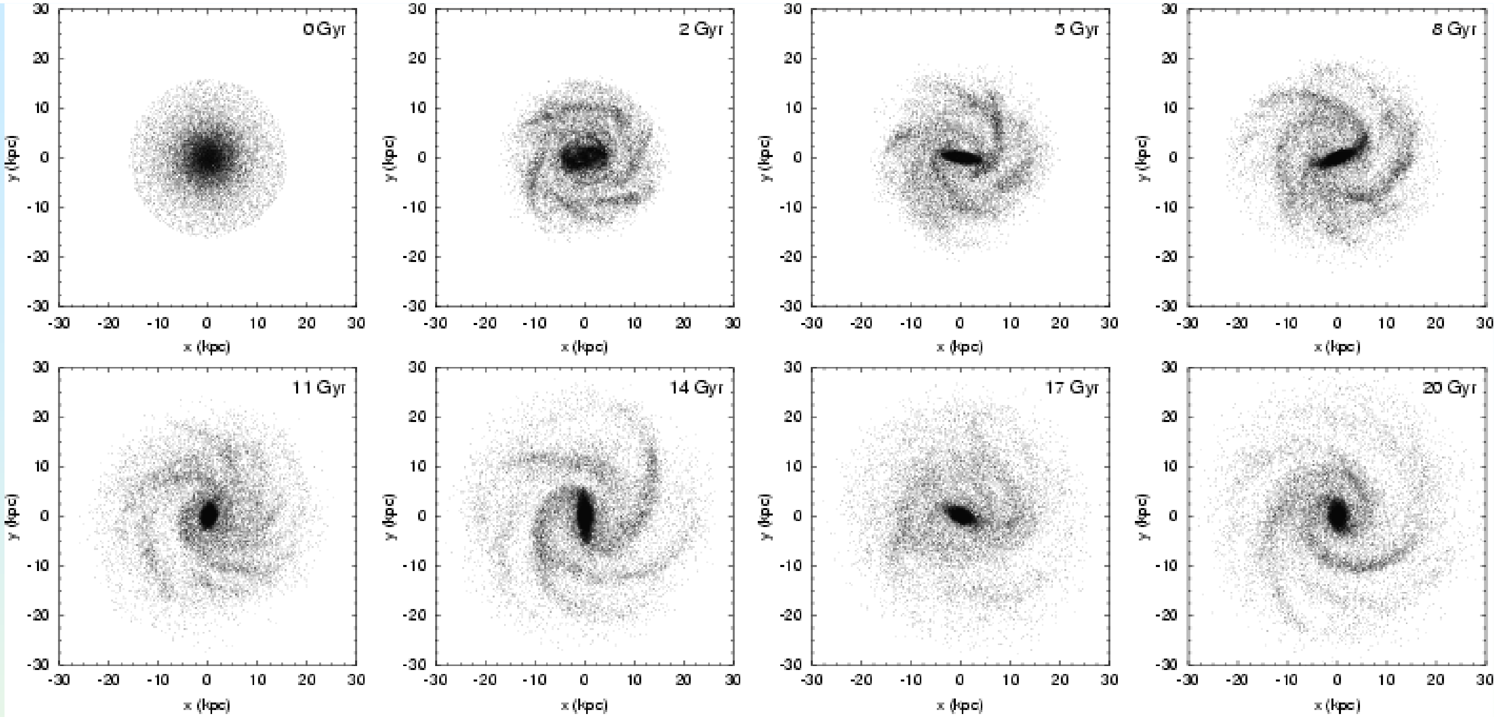




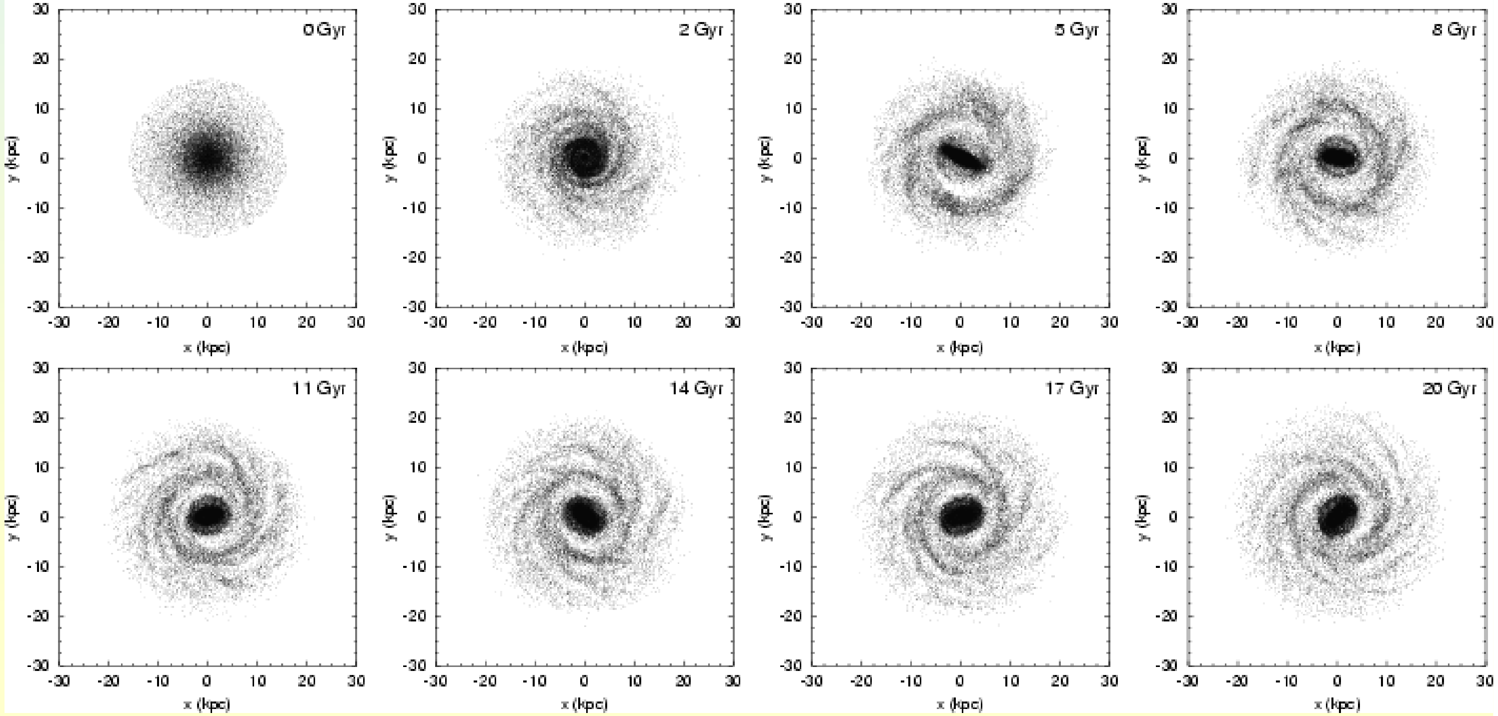
Gravity torques derived from red image (potential) and Hα gas distribution

➔ Rate of gas infall

With gas accretion (and star formation)



Without gas accretion



# Bars destruction and reformation

**Dynamical instabilities are responsible for evolution**

With self-regulation

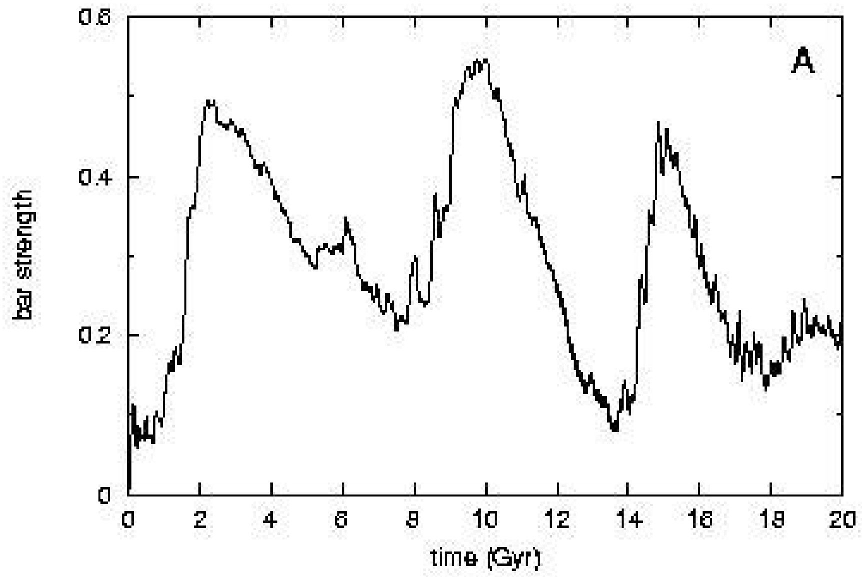
➔Formation of a bar in a cold unstable disk

➔Bar produces gas inflow, and

➔Gas inflow destroys the bar

+gas accretion

Accumulation of mass in the center
creates a
Central Mass Concentration (CMC)
May destroy the bar, through scattering of orbits

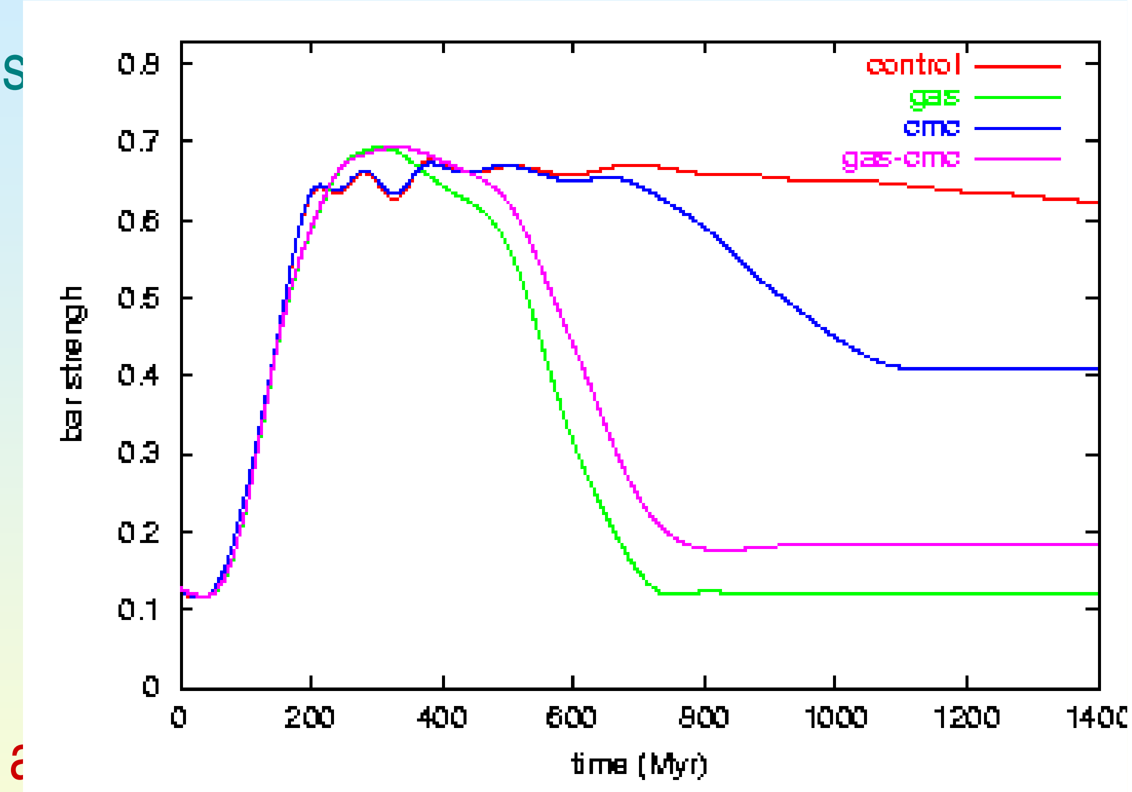


# Role of gas in bar destruction

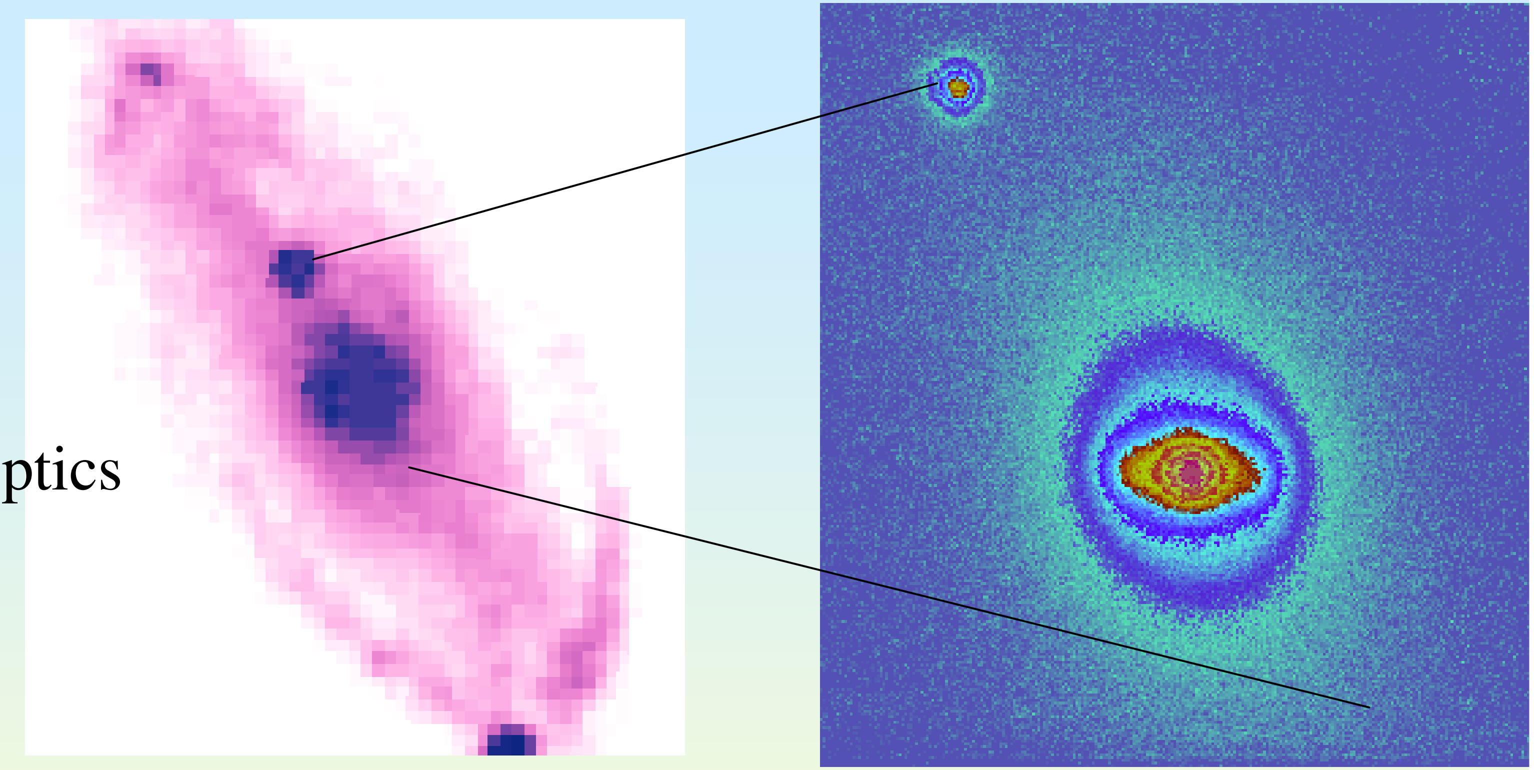
Gas is driven in by the bar torques
The angular momentum is **taken up by the bar wave**

➔ **This destroys the bar**

**Central Mass Concentration,**
**Plays only a small role**
➔ It is then more easy to reform a



(Bournaud & Combes 02, 05)

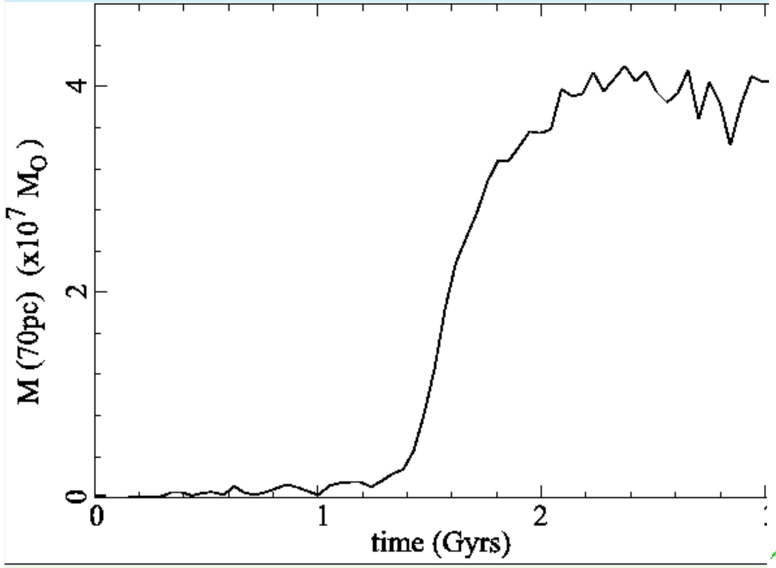


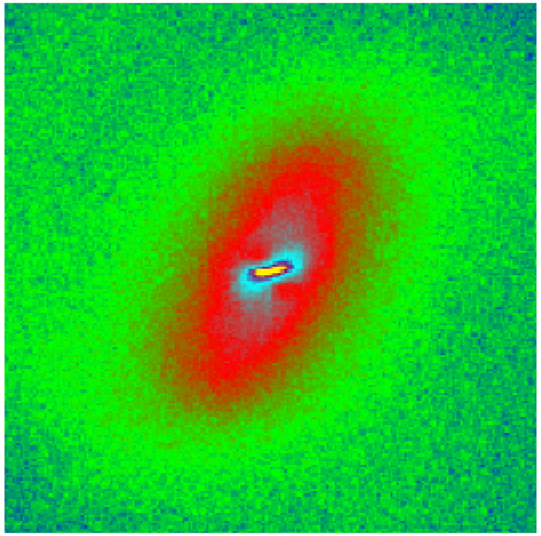
NGC 5728
DSS
+CFH
Adaptive Optics
NIR

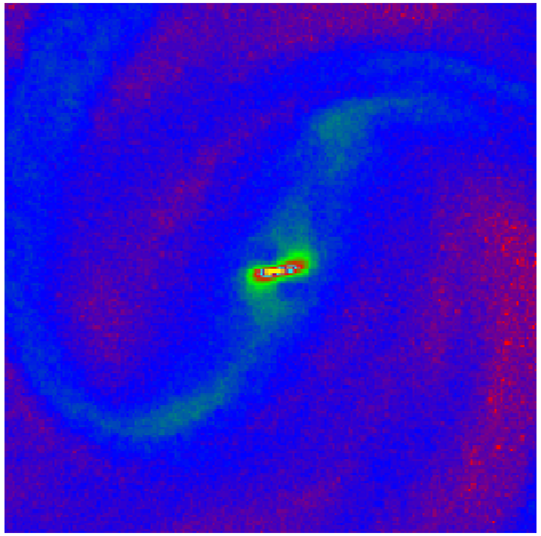
**1/3 of barred galaxies have nuclear bars**

Embedded bars are frequently observed: above a nuclear bar (*right,* field of 36") included inside the primary bar (*left*, field of 108"). The secondary bar rotates faster than the primary bar

# Inflow with two embedded bars

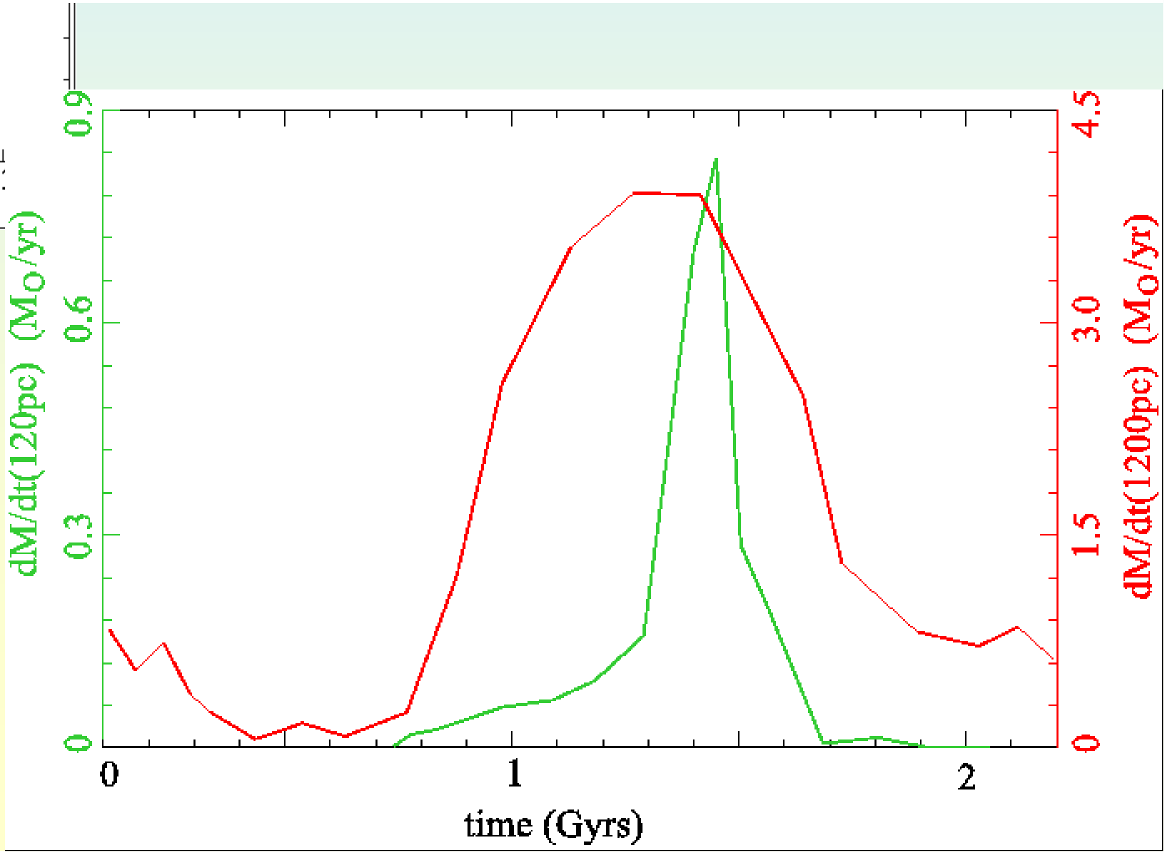




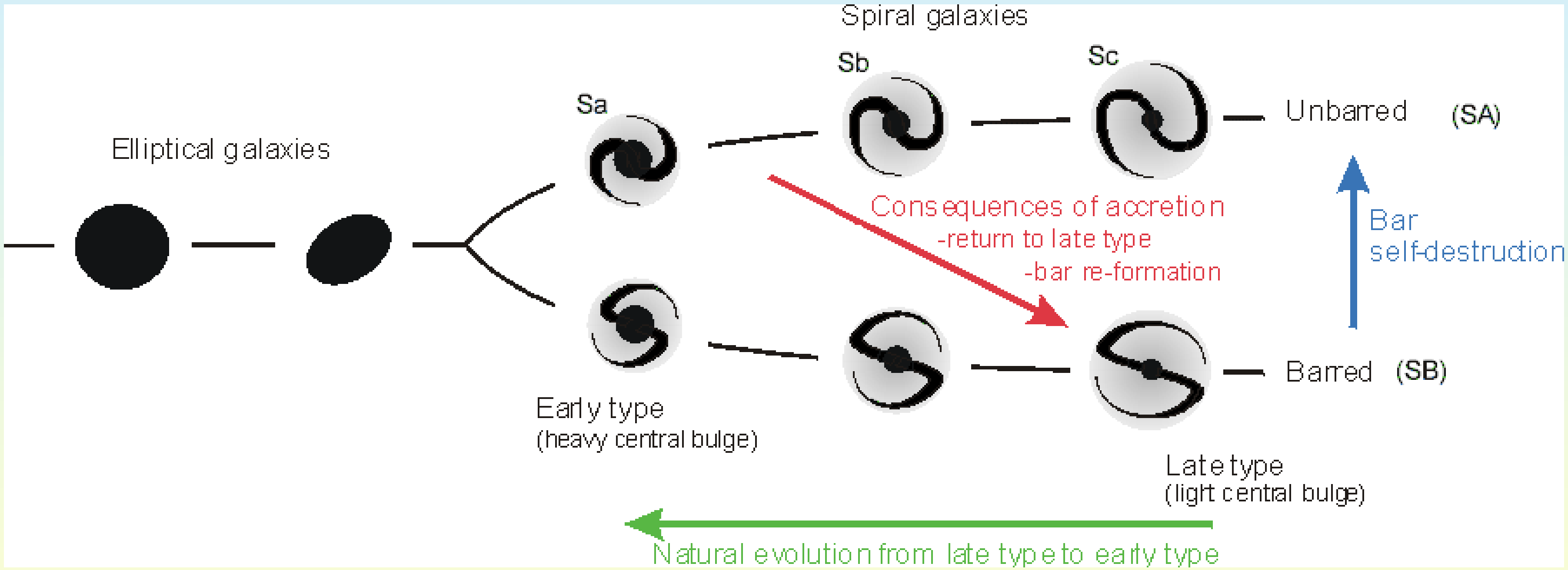


Cumulated gas inflow (70pc)

Inflow rate in 20pc and
in 200pc



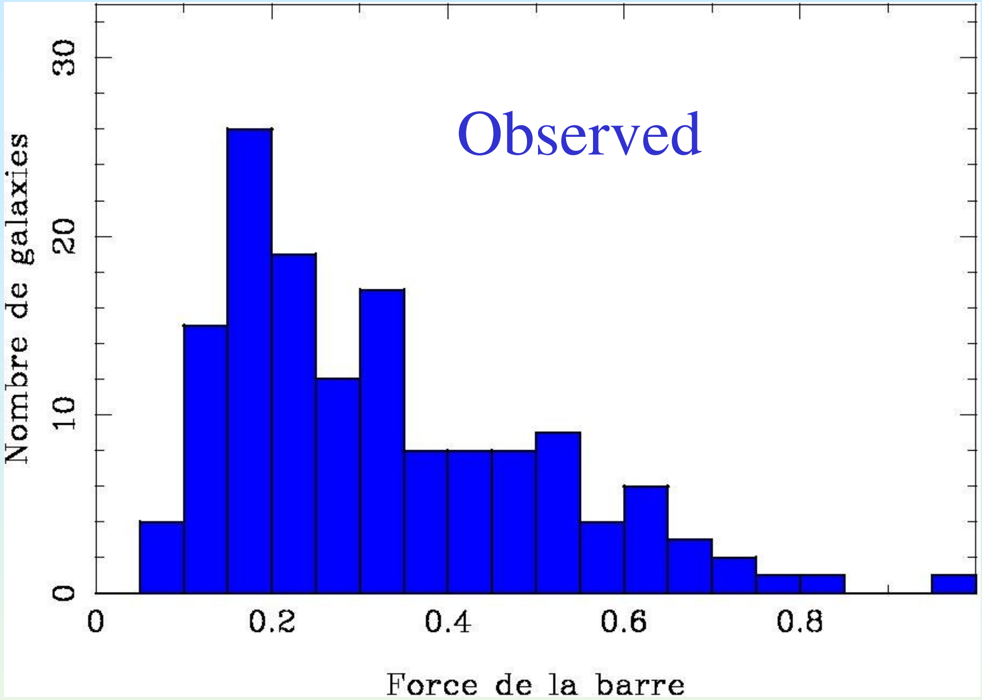
# Evolution along the Hubble Sequence

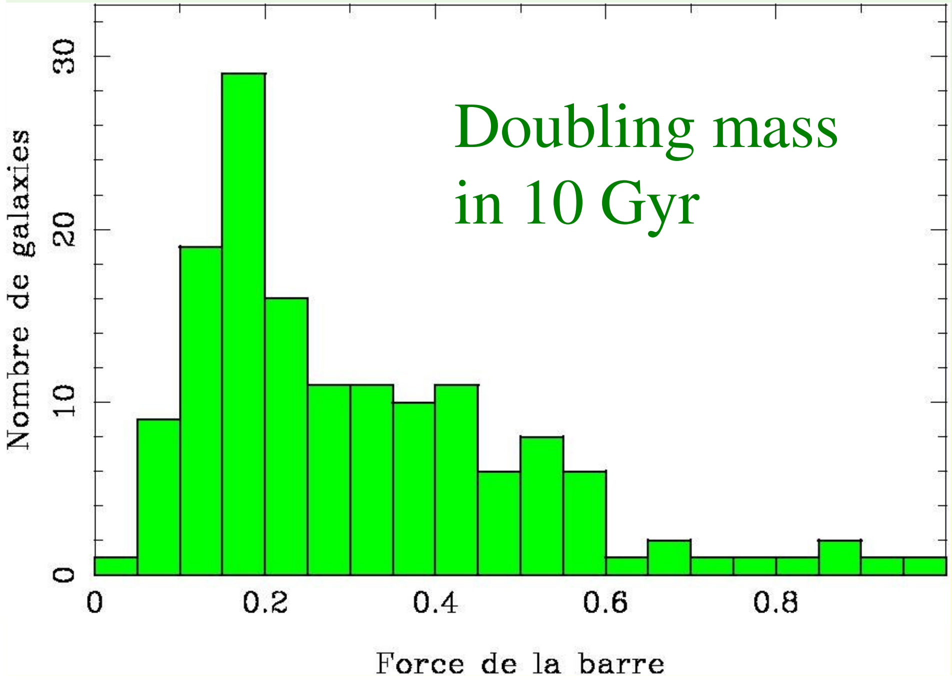


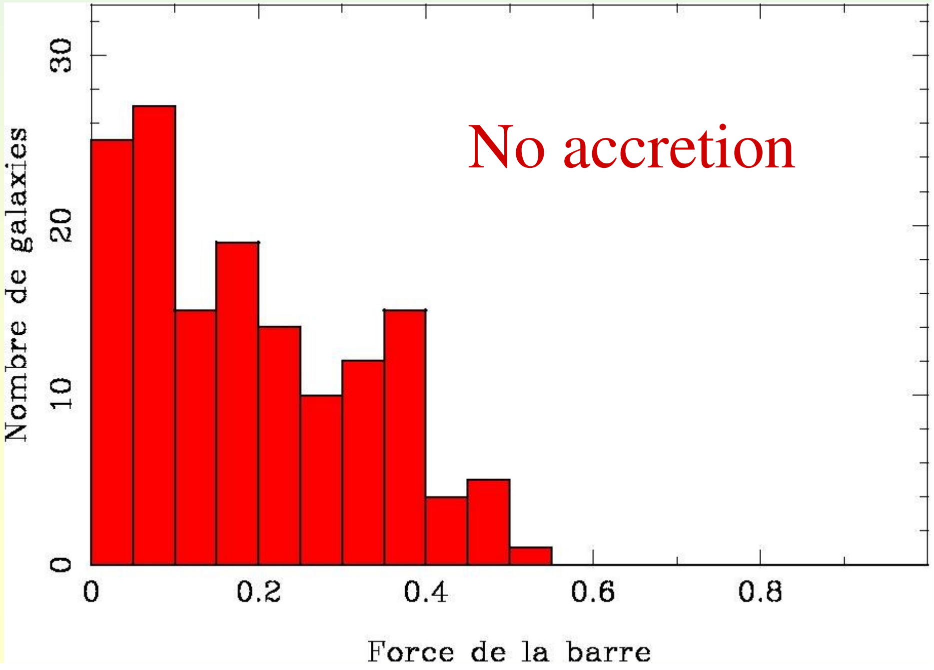
Bulge to disk ratio is an essential parameter of the sequence: although it generally increases through evolution, it can also decrease ➔ **cycle**

# Quantification of accretion rate

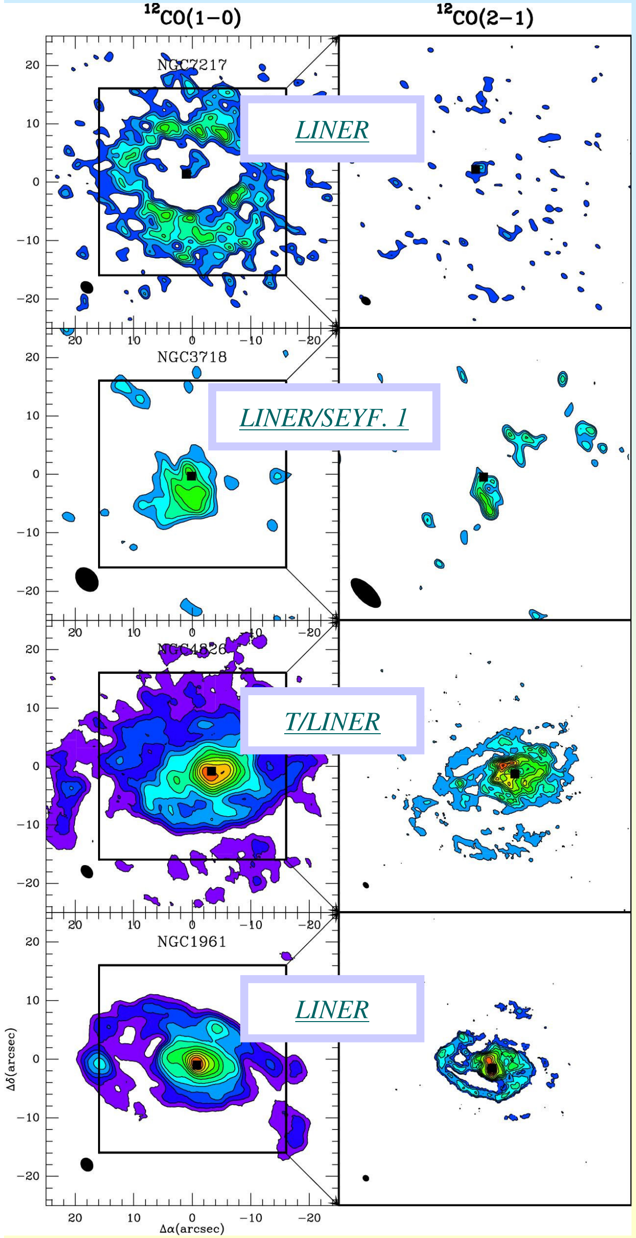
Block, Bournaud, Combes, Puerari,
Buta 2002

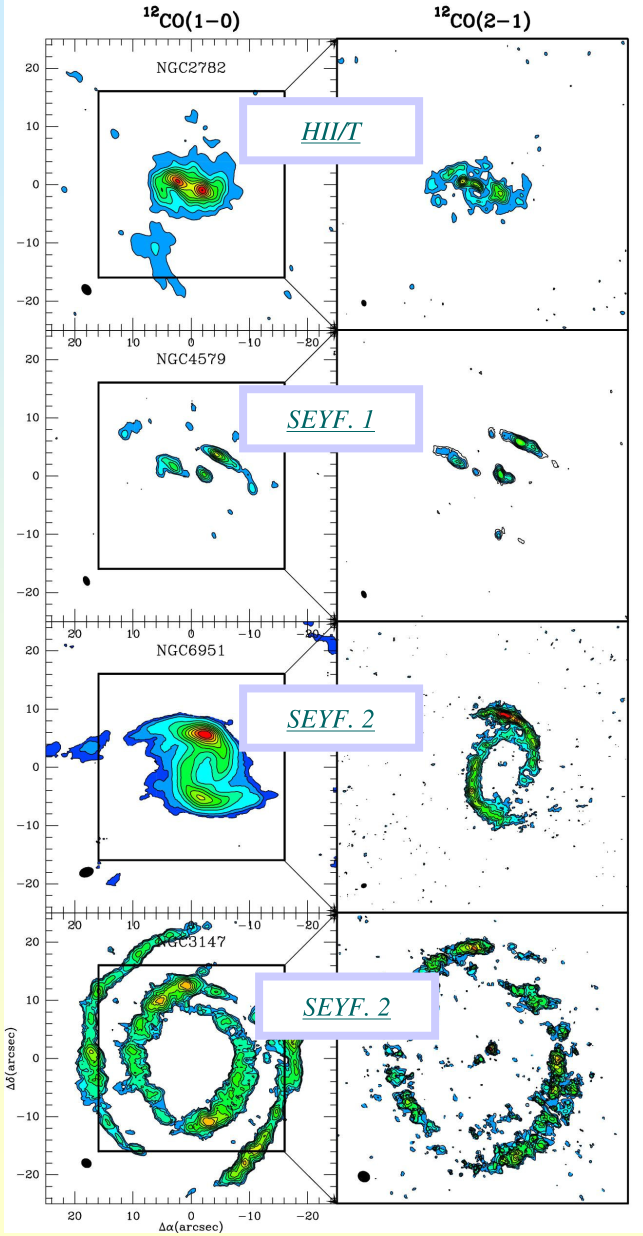


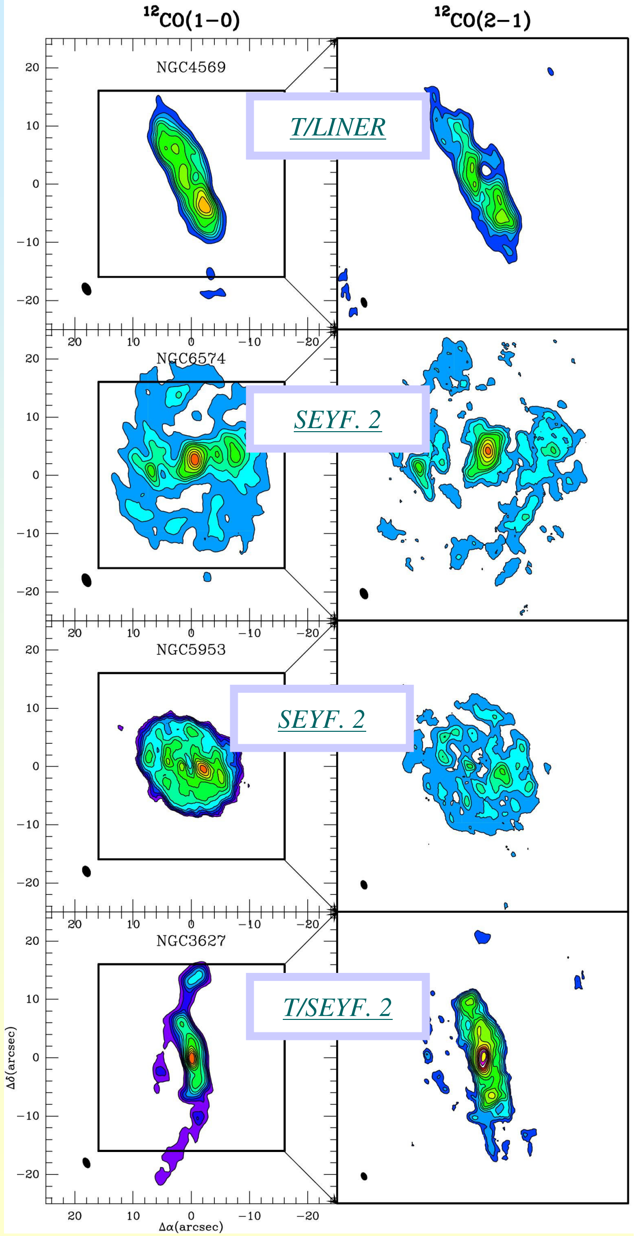




# CO images

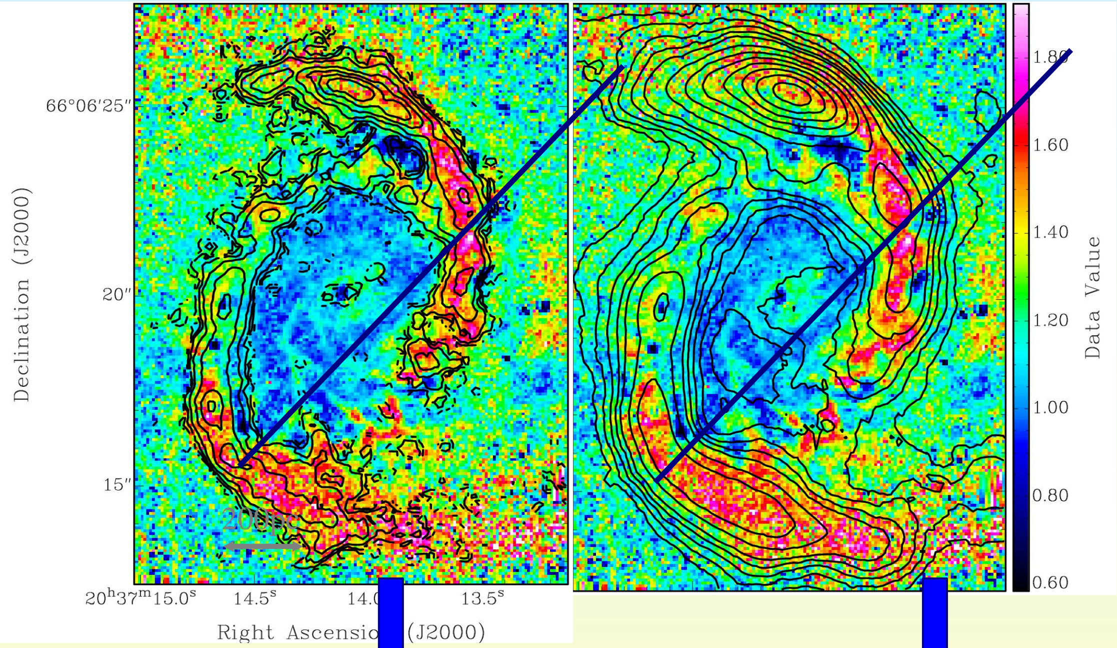

$^{12}$CO(1−0)
$^{12}$CO(2−1)
NGC7217
LINER
NGC3718
LINER/SEYF. 1
NGC4826
T/LINER
NGC1961
LINER
Δδ(arcsec)
Δα(arcsec)
20
10
0
−10
−20


$^{12}$CO(1−0)
$^{12}$CO(2−1)
NGC2782
HII/T
NGC4579
SEYF. 1
NGC6951
SEYF. 2
NGC3147
SEYF. 2
Δδ(arcsec)
Δα(arcsec)
20
10
0
−10
−20

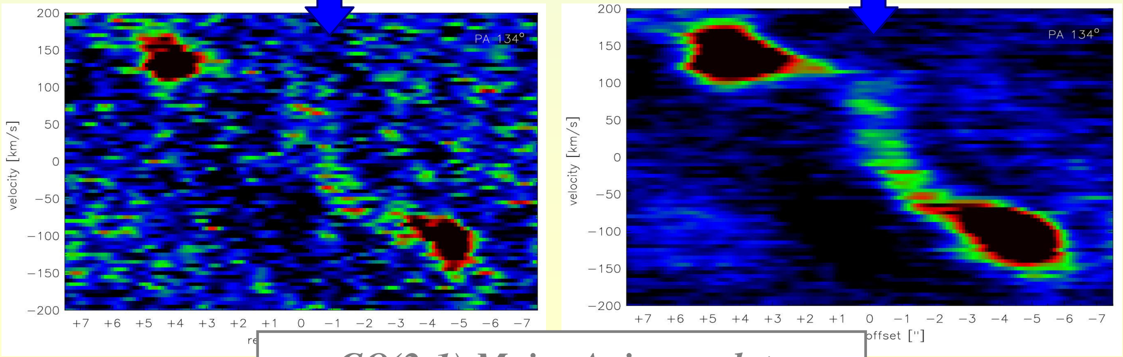

$^{12}$CO(1−0)
$^{12}$CO(2−1)
NGC4569
T/LINER
NGC6574
SEYF. 2
NGC5953
SEYF. 2
NGC3627
T/SEYF. 2
Δδ(arcsec)
Δα(arcsec)
20
10
0
−10
−20

# Searching for observational evidences of ‘ongoing’ feeding...

➔**NGC6951**: barred spiral prototype of Seyfert 2



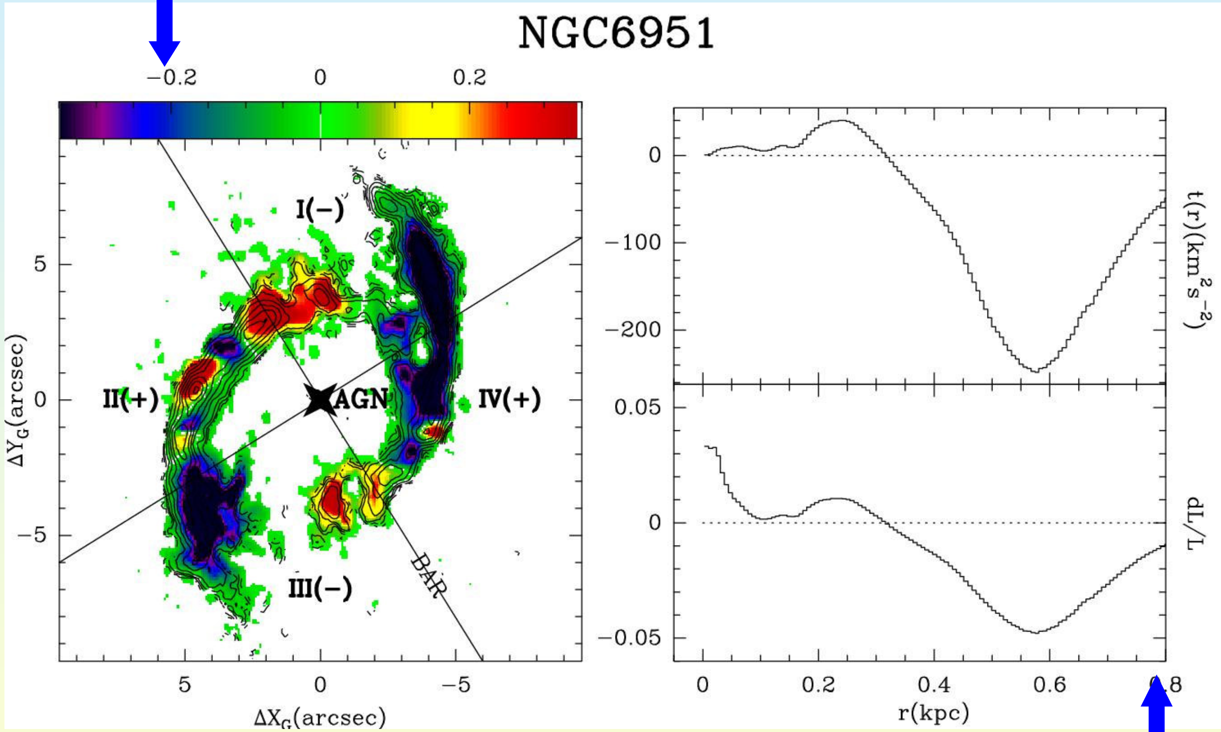
➔***Molecular gas*** distribution inside ***700pc*** suggests gas along ***x2 orbits*** in bar potential: gas piles up in highly contrasted ***nuclear spiral arms*** **(~4x10$^8$ M$_{sun}$)** feeding starburst while **little molecular gas 200 pc from the AGN**.



***CO(2-1) Major Axis p-v plots***

# Gravitational Torques in NGC6951

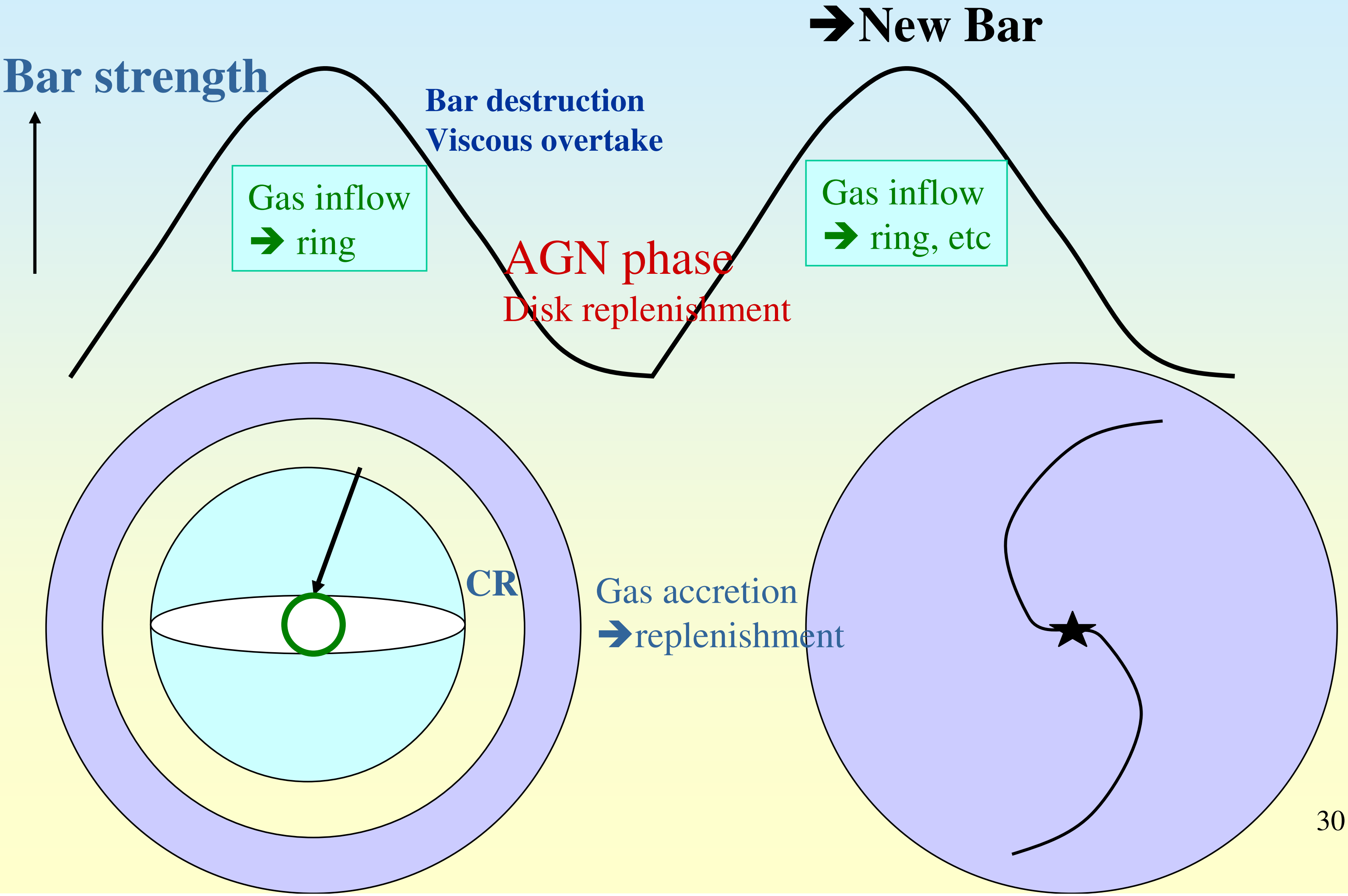
**Torques Map**



**Efficiency of Torques**

**->Efficiency of stellar torques**

# Schematics of secular evolution



**➔New Bar**

**Bar strength**

**Bar destruction**
**Viscous overtake**

Gas inflow
➔ ring

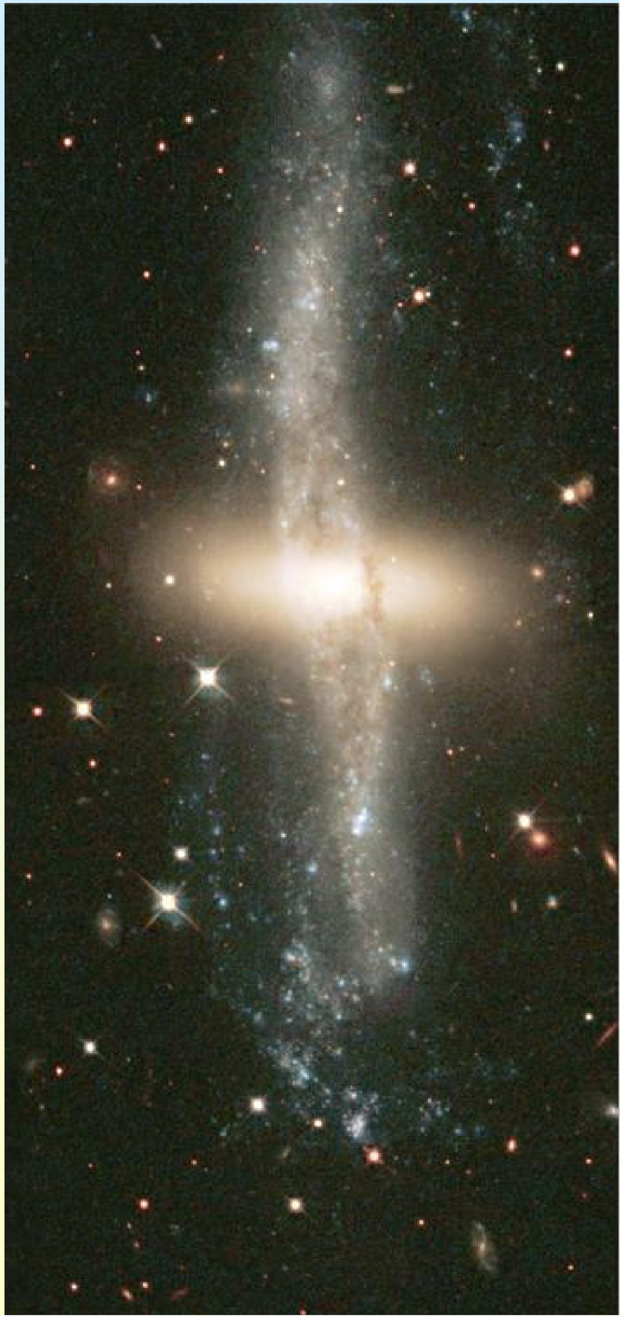
Gas inflow
➔ ring, etc

AGN phase
Disk replenishment

**CR**

Gas accretion
➔replenishment

# Polar Ring Galaxies (PRG)



**Good examples of gas accretion**

**PRG are composed of an early-type host surrounded by a gas+stars perpendicular ring**

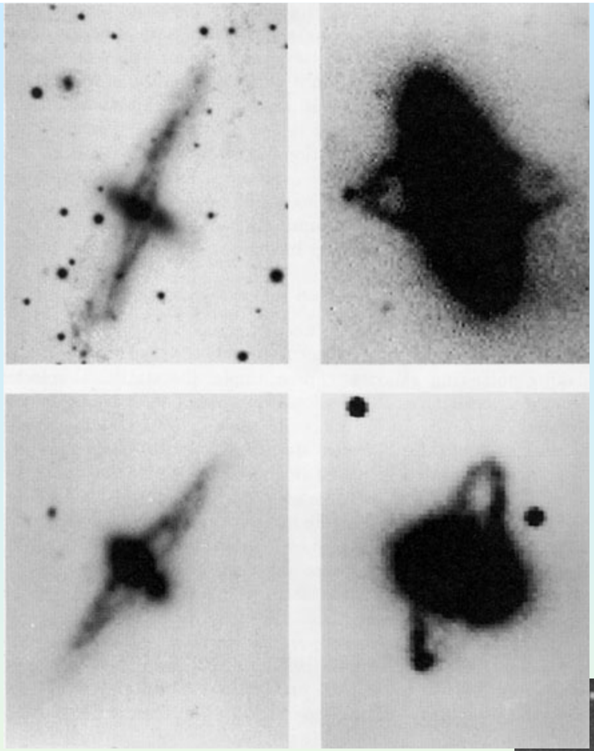
**The polar ring is akin to late-type galaxies large amount of HI, CO, young stars, blue colors**

**Unique opportunity to check the shape of dark matter halo**

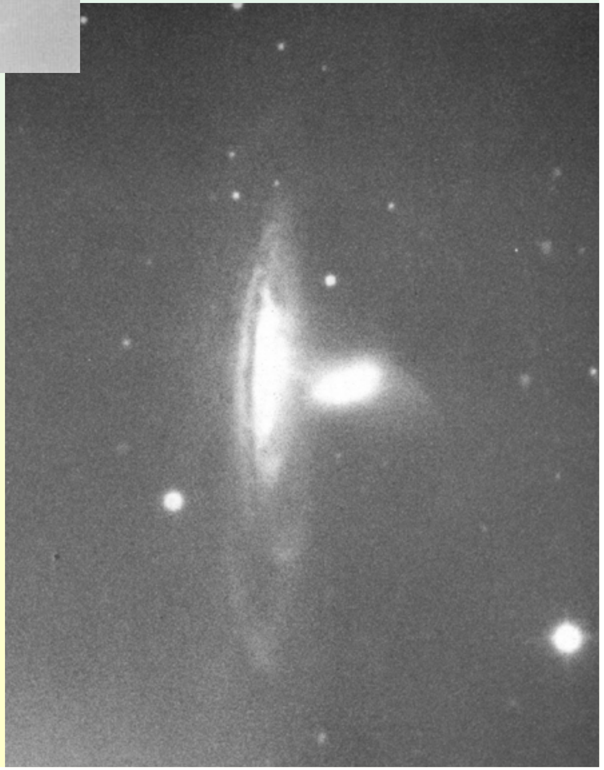
⇨ **Formation scenarios**

# Formation of Polar Rings

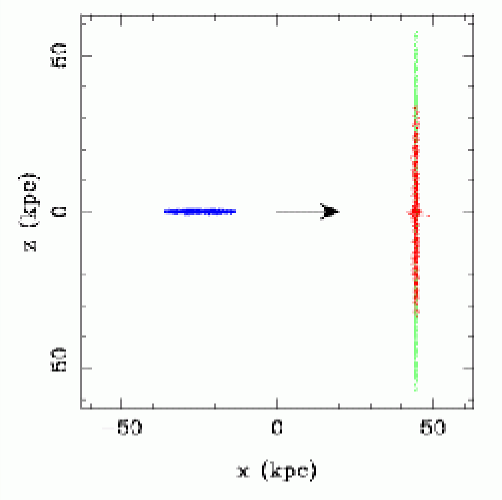
By accretion?



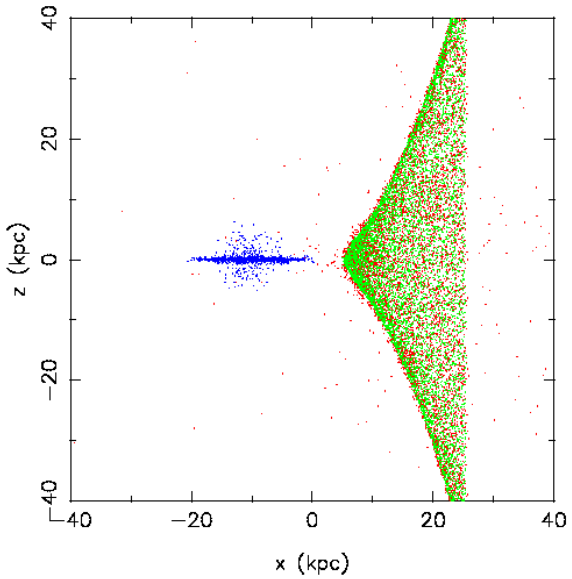
By collision?



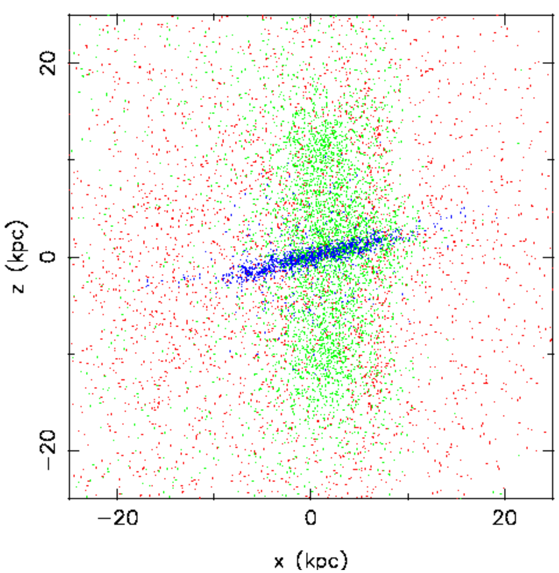
# Formation of PRG by collision



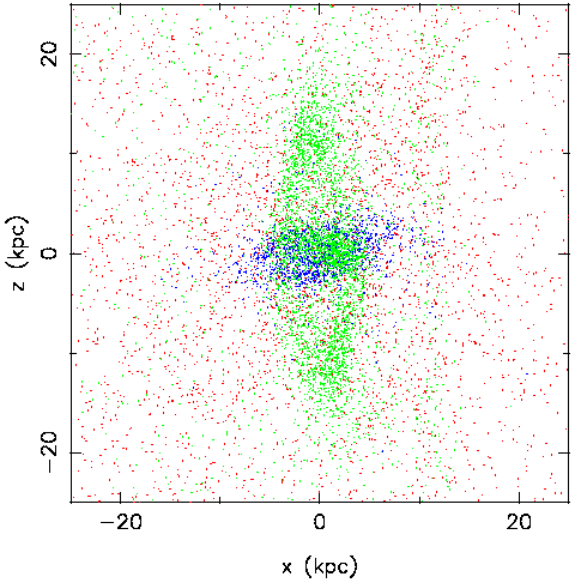
0.3Gyr



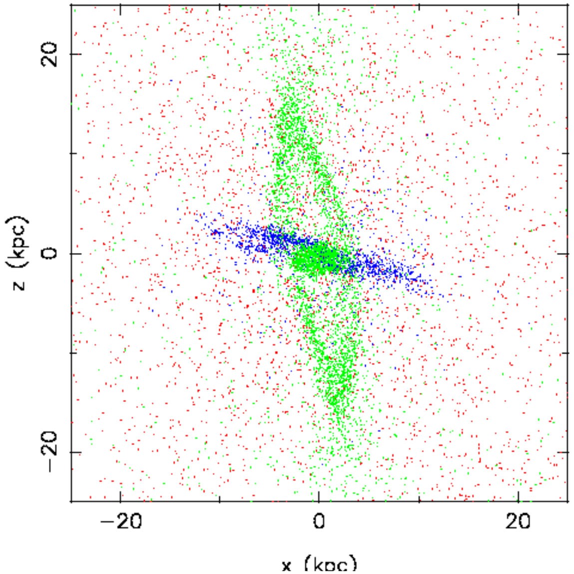
1.5Gyr



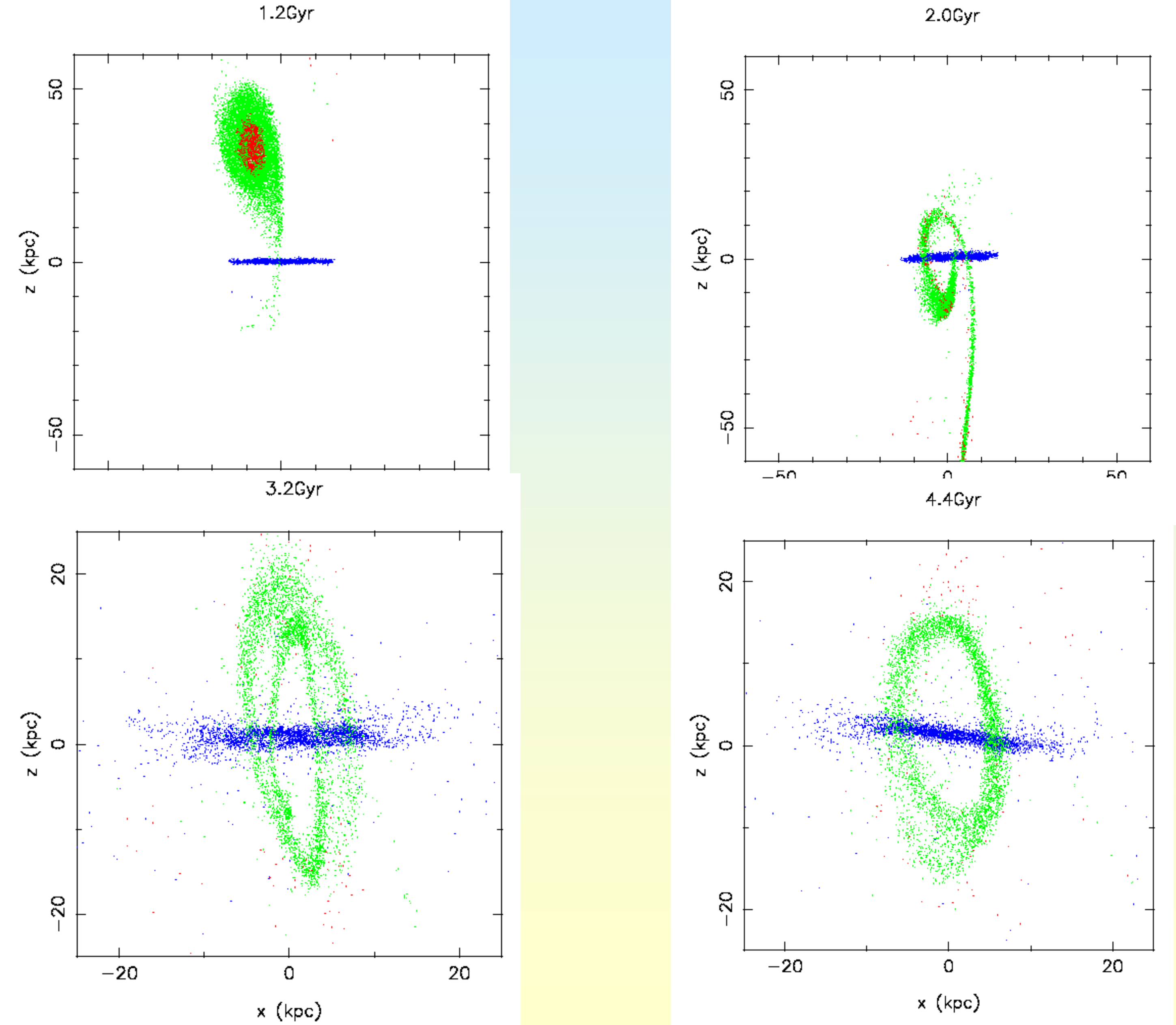
2.1Gyr



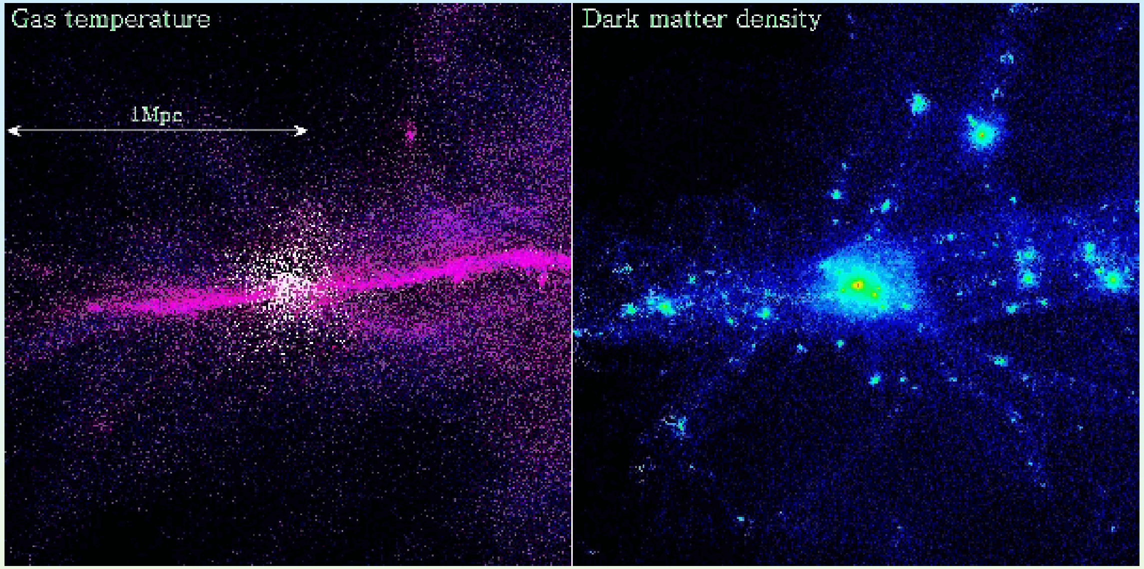
3.0Gyr

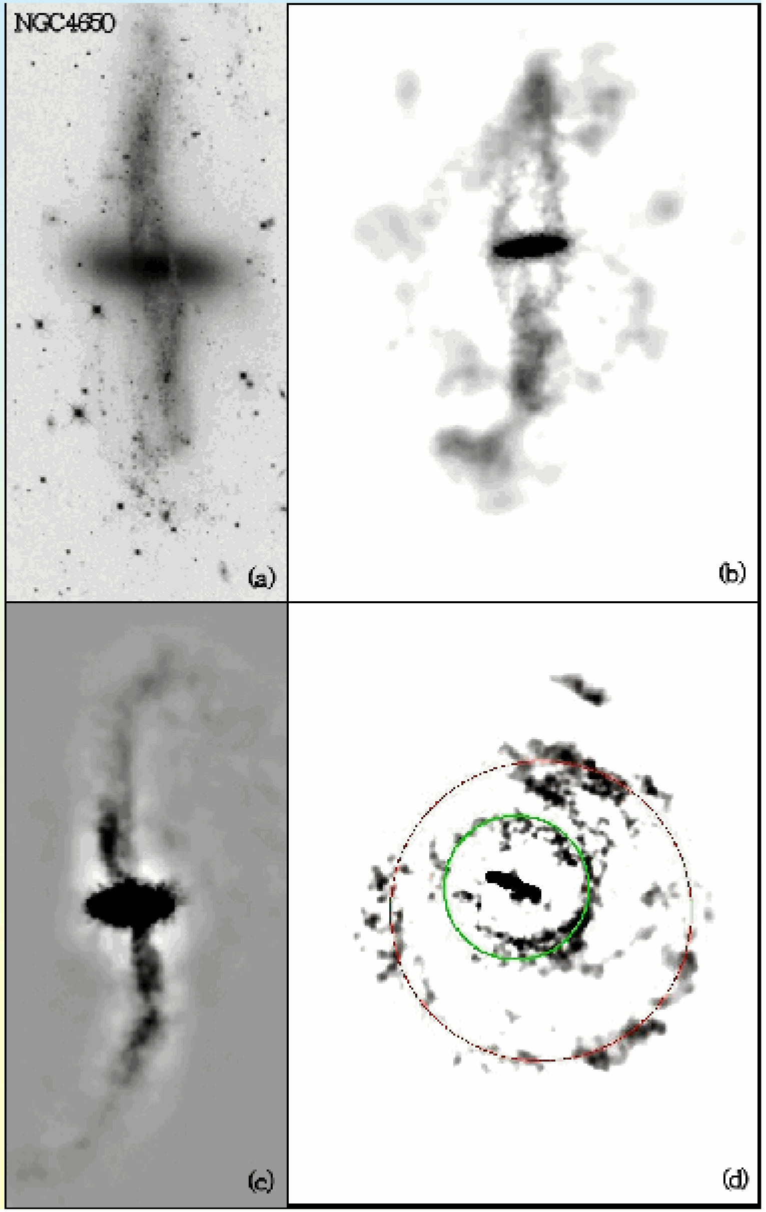


# Formation of PRG by accretion



# Cold accretion from cosmic filaments





Maccio & Moore 2005

# Molecular gas in Ellipticals

**Most E-galaxies possess accreted gas, already detected in HI (van Gorkom et al 1997)**

**Either the remnant of the merger event at their birth, or accretion of small gas-rich companions**

**No correlation with the stellar component → accretion**

**Elliptical galaxies have a lot of gas, but in the hot phase (heated by shocks in the merger, emitting X-rays)**

# Shells around ellipticals

**The merging events giving birth to ellipticals are also forming shells**

**Stellar shells discoverd by Malin & Carter (1983)**
**Ripples like waves generated by the collision**

**HI gas detected in shells (Schiminovich, 1994, 95)**
**Normally, the diffuse gas condenses to the center in the merger**

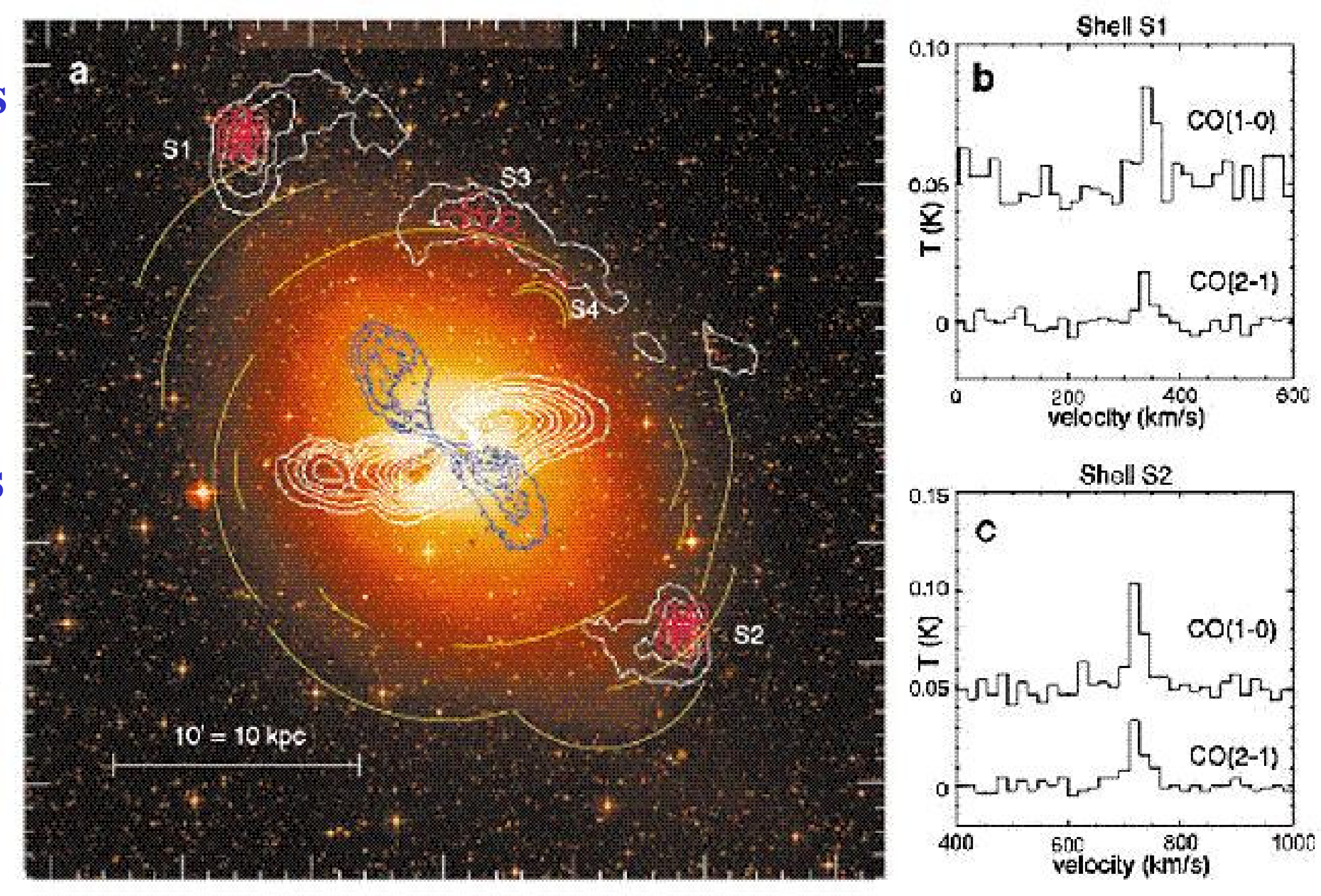
**CO is now also detected in shells (Charmandaris et al 2000)**

**Star shells in yellow**

**HI white contours**

**CO points in red**

**Radio jets in blue**



**Charmandaris, Combes, van der Hulst 2000**

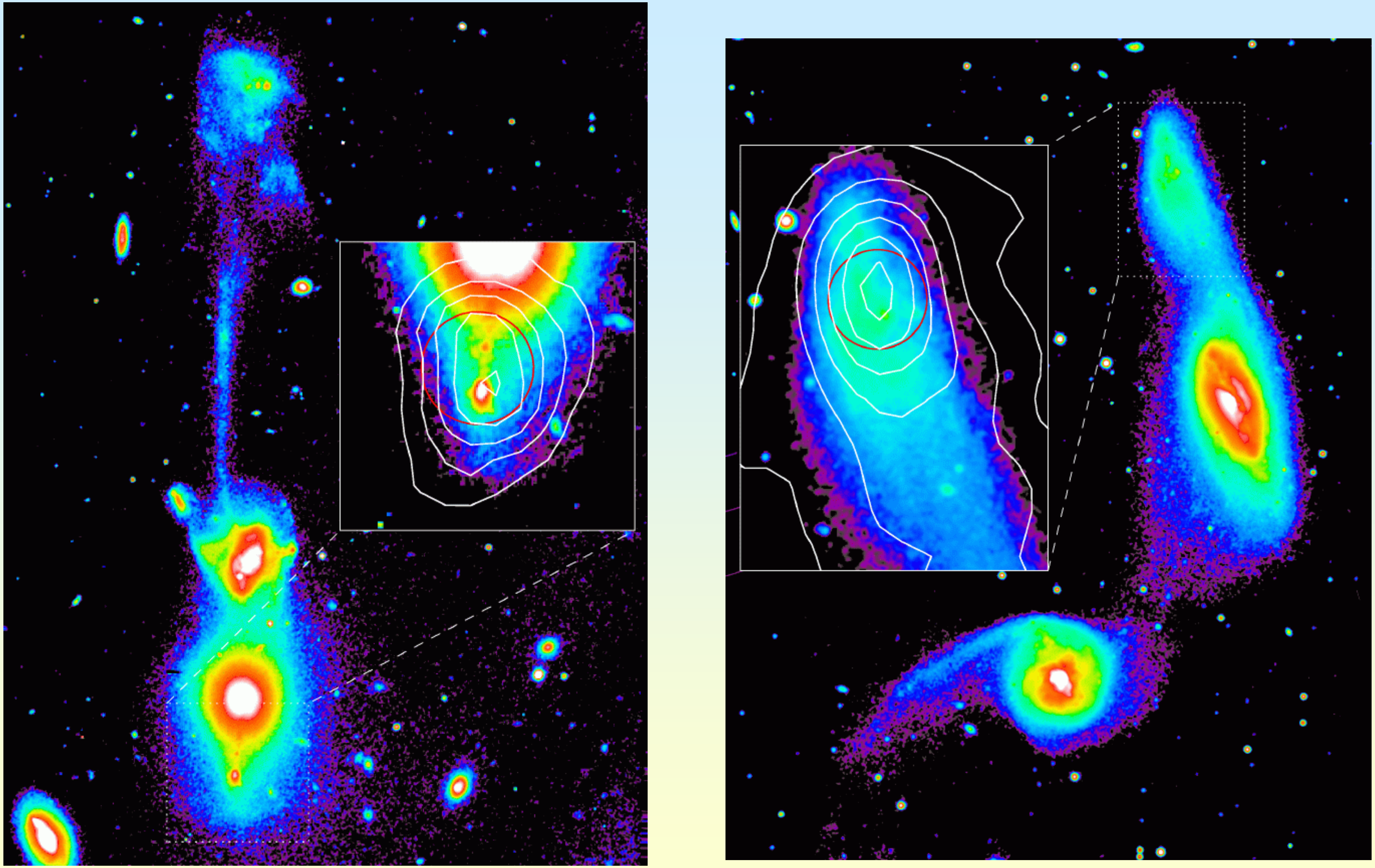
# Gas dragged outside galaxies

**Interactions of galaxies, formation of tidal tails**
**Gravitational collapse in the tail ➔ tidal dwarfs**

**CO detected in these small dwarfs, supposed to be formed in the interaction**

**Is the molecular gas dragged with the tidal tail gas and reclump in the tidal dwarf, or the molecular gas re-formed in the collapse?**
**Trigger some star formation, but in general insufficient to have solar metallicity**
**More likely that the gas and metals come from the main galaxies**

**Fate of these tidal dwarfs? In general, they are re-accreted and merge**



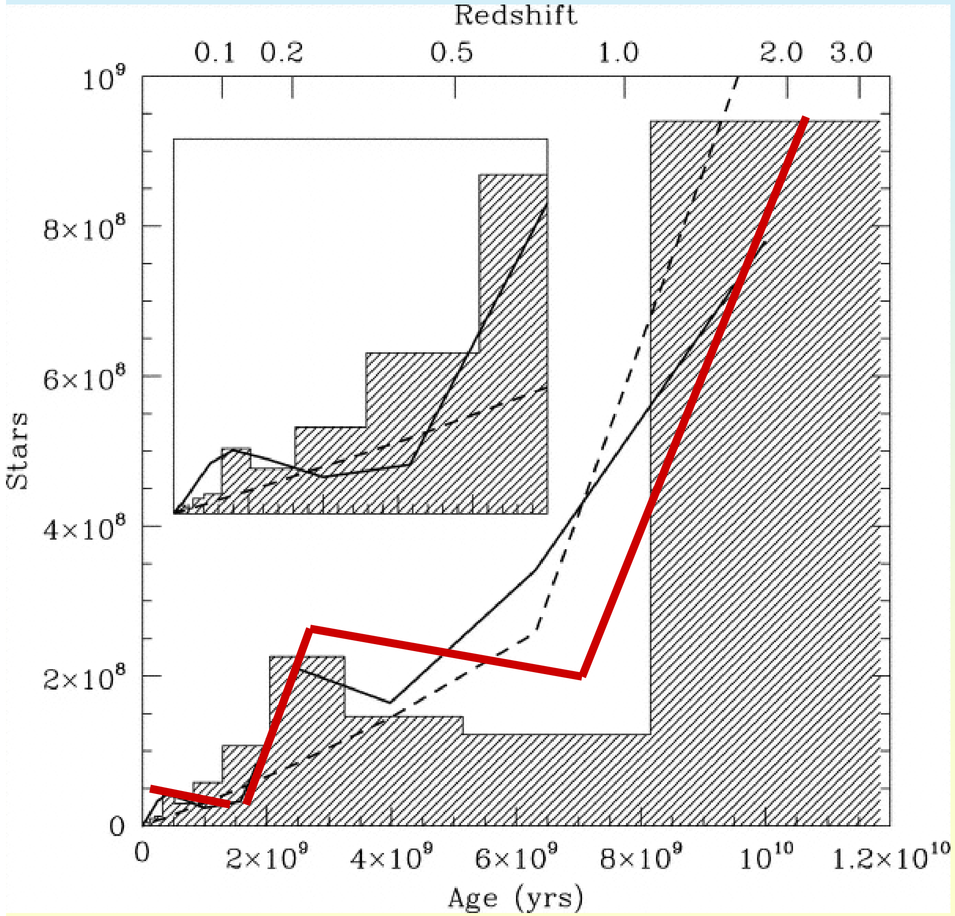
**Braine et al 2000, 01**

# Star formation
# Is it triggered by the dynamics?

The biggest starbursts (ULIRGs, 1000 Mo/yr)
are all mergers of galaxies *(e.g. Sanders & Mirabel 1996)*
*but they are rare (more gas, dust, young stars)*

Interacting galaxies don't show intense starbursts
*(Bergvall et al 03),* or **only in their centers**
➔**Interactions: necessary condition, but not sufficient**
Another necessary condition: the presence of gas

# Star Formation History in SMC

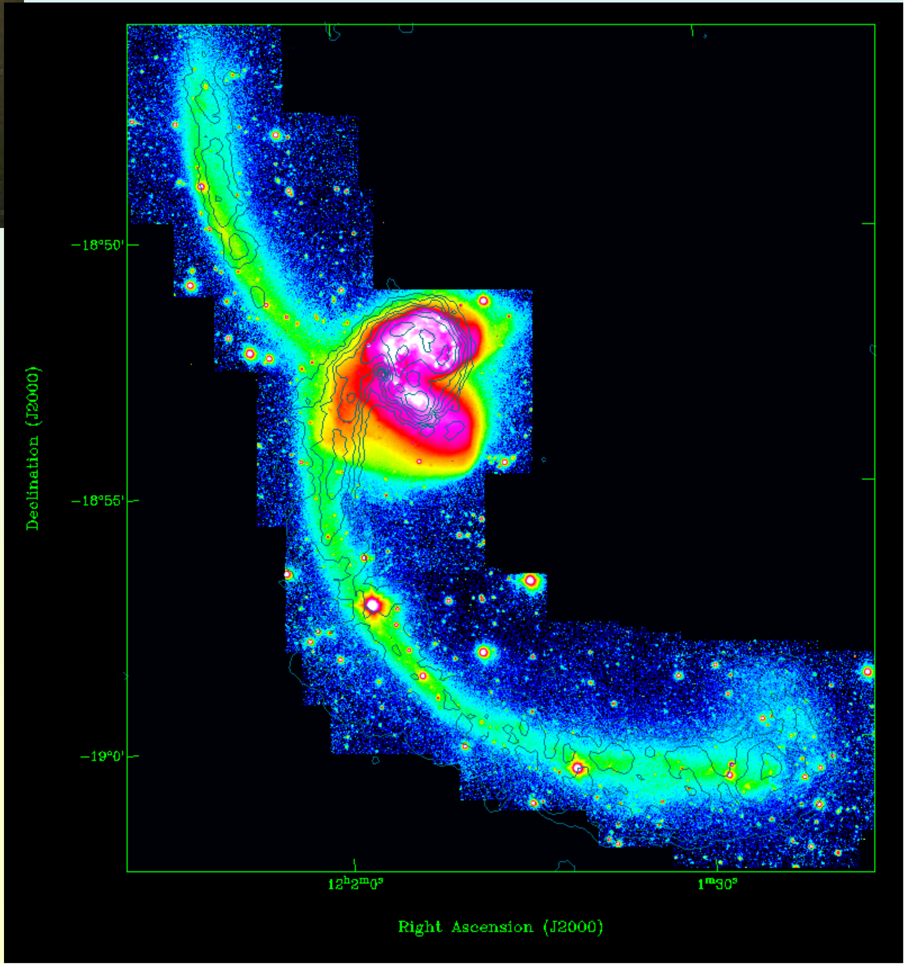


Star formation history in SMC reveals some bursts corresponding to pericenters with the Milky Way *(Zaritsky & Harris 2004)*

Between 10-70% tidal

➔*fit possible with gas infall at least 50%*

# The Antennae HST
# SSC formation
# (Super Star Clusters)



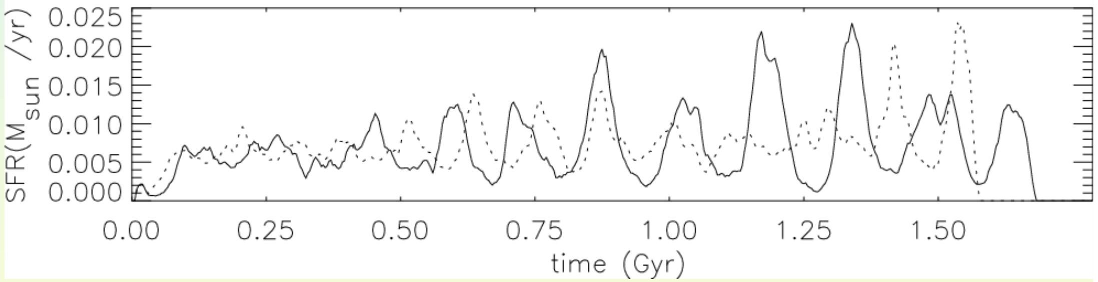
The Antennae, HI

Contours obtained with VLA
+BVR colors

# Dynamical processes

SFR/area ~ $\Sigma^n$ n=1.5 (global, not local, Schmidt law)
➔Same for interacting and non-interacting

**Processes:** Jeans instability, dynamical time $\rho^{3/2}$
or Cloud-cloud collisions *(Elmegreen 1998)*
+SF contagion + Feedback (➔ chaotic conditions..)



**Without dynamical trigger**,
episodic bursts with feedback
*(Köppen et al 1995; Pelupessy et al 2004)*

**Radial gas flows due to bars, or spirals**
Molecular gas concentrations, and circumnuclear starbursts

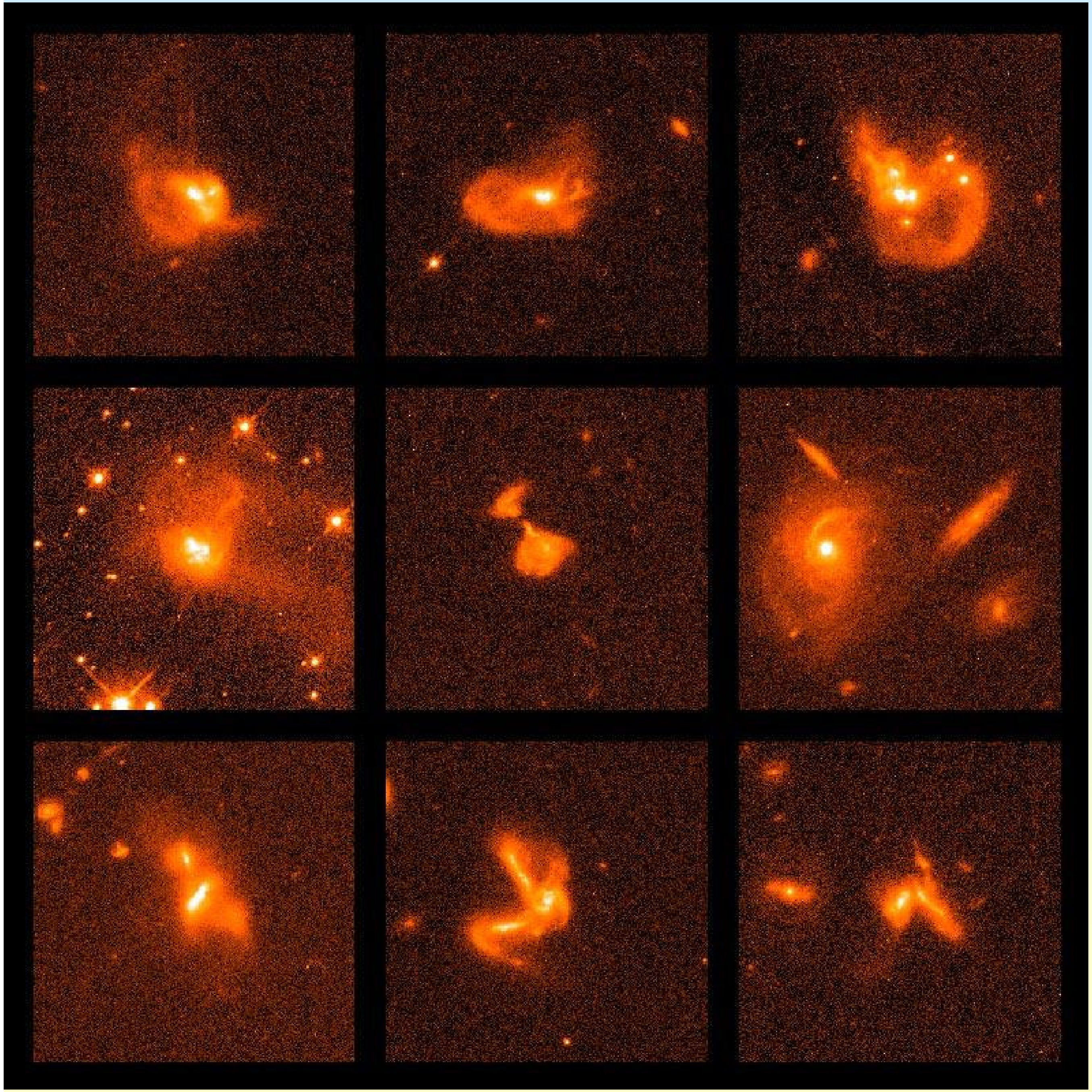
# Ultra-Luminous Galaxies

ULIRGs have enhanced amounts of gas (CO-rich), $10^{11}$ Mo
but also enhanced star formation efficiency (SFE)
**Most of their light is in the Far Infrared**

SFE= $L_{FIR}/M(H_2)$

This can be explained by the gravitational torques of the interactions driving gas very quickly to the centers
Gas is concentrated in central nuclear disks or rings*(Downes et al 98)*

The condition of starburst: accumulating gas in a time short enough that feedback mechanisms have no time to regulate



Interactions between galaxies

Ultra-luminous galaxies
are always mergers

# Compressive tidal forces

For a spherical density profile in a power-law $\rho(r) \sim r^{-\alpha}$, then the acceleration is in $r^{1-\alpha}$, so the attraction can increase with distance, if $0 < \alpha < 1$

➔ the tidal force is compressive $F_{tid} \sim (1-\alpha)\, r^{-\alpha}$

In particular, for a core density (rotation curve V is in $r^{1-\alpha/2}$)

Molecular clouds inside the core are then compressed, and SF can be triggered

Can also explain the formation of nuclear starbursts and young nuclear stellar disks

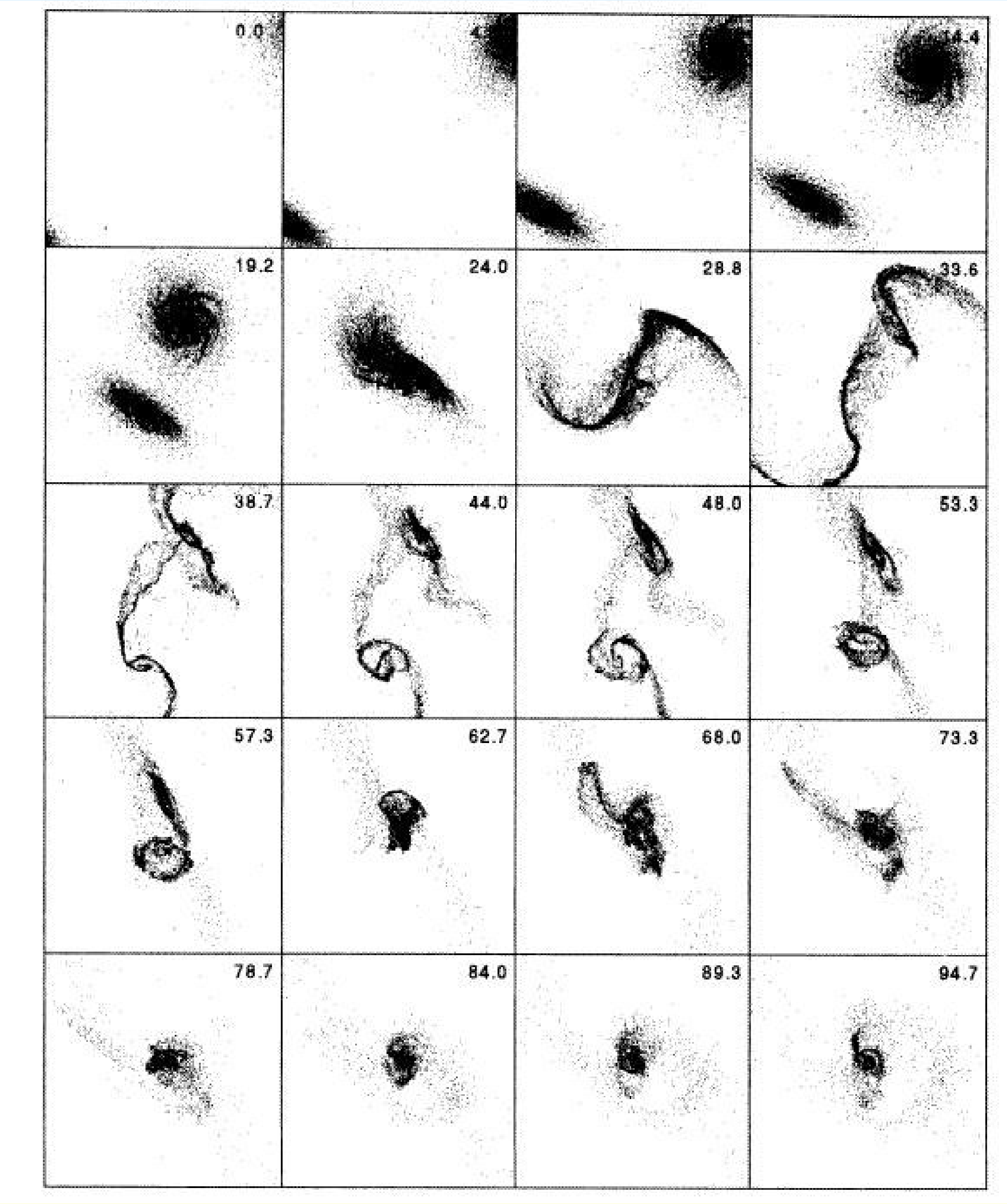
**Revealed by velocity drops at galaxy centers**

*(Emsellem et al 2001, Wozniak et al 2003)*

Mihos & Hernquist 96

Simulations of
disk/halo galaxies

Gas and young stars
are plotted

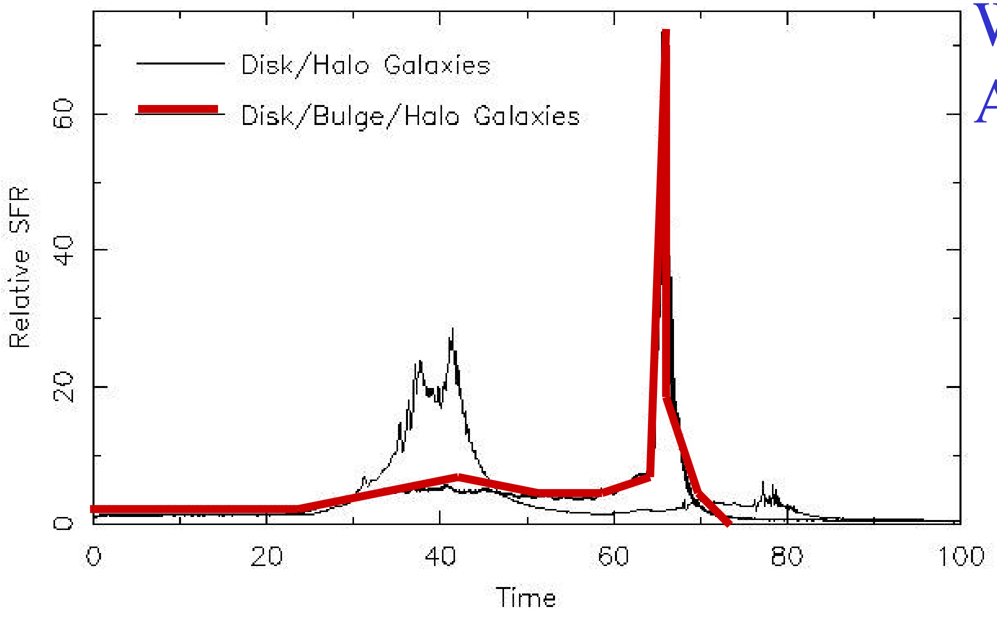


# Star formation Recipes

Numerical simulations use recipes, for the sub-grid physics

Schmidt law with threshold, with **exponent n=1.5**

**Results depends on disk stability**



Without bulge, disk more unstable

At the end, the same SFR

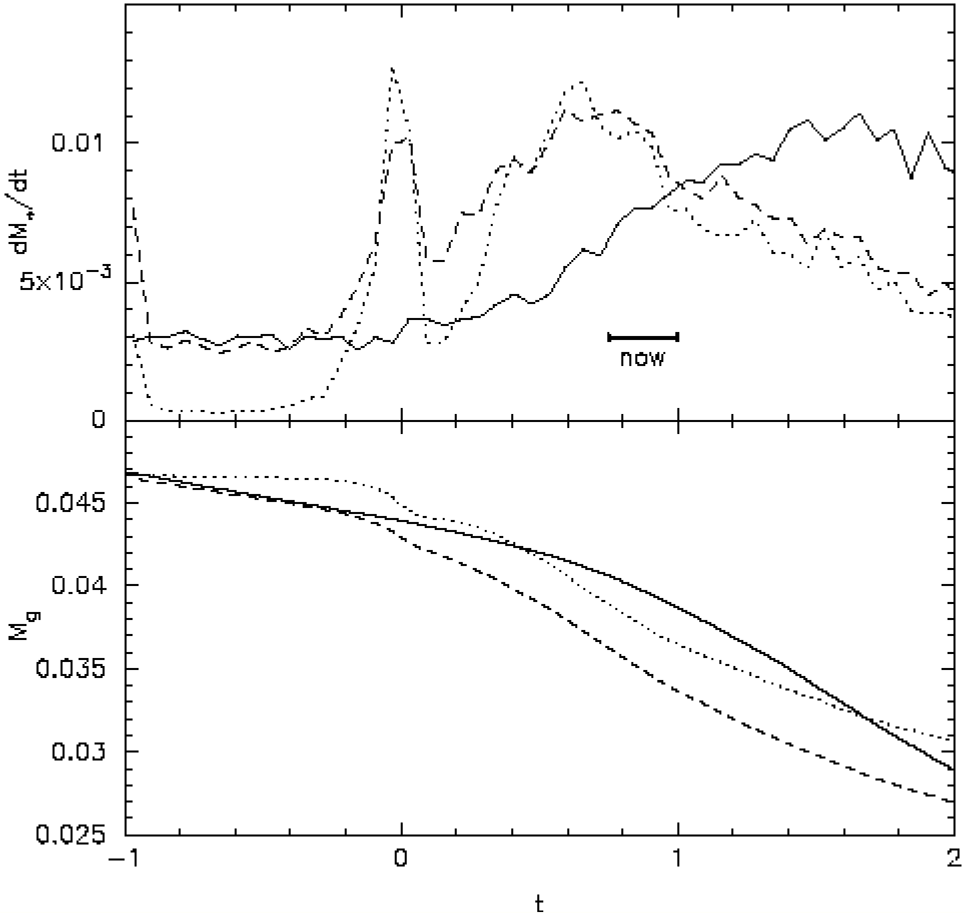
# Influence of velocity dispersion

Star formation in $\rho^{n} \ \sigma^{\beta}$
could take into account shock-induced SF

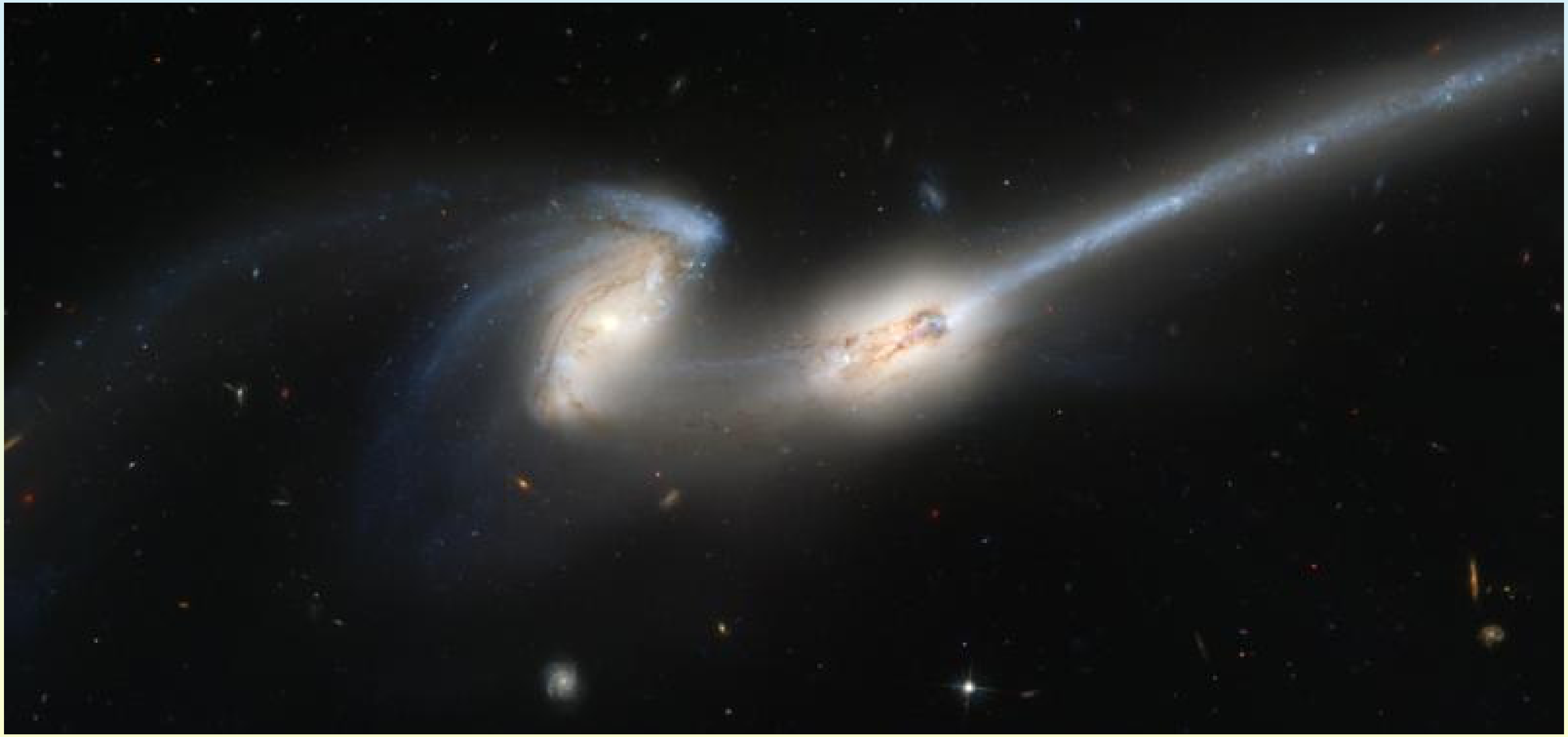
Applied by Barnes (2003) to the Mice simulations
Better match of the observations, when $\beta = 0.5$

Star formation
and Mgas remaining
**solid** line n=1.5 $\beta$ =0
**dash** n=1 $\beta$ =0.5
**dotted** n=1 $\beta$ =1

t=0= pericenter



# The Mice

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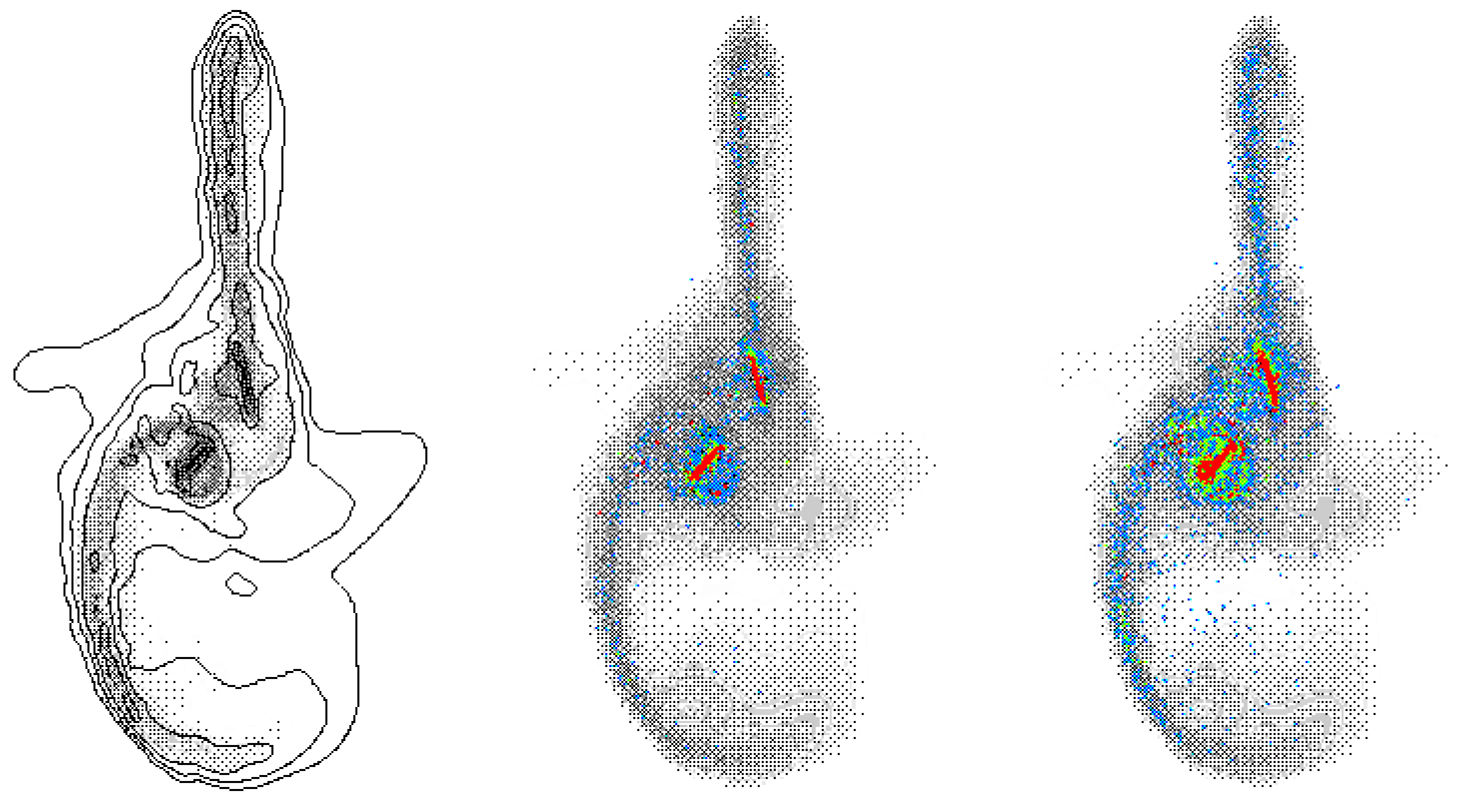


Contours: old stars
grey scale: gas

Points= New stars
Red: youngest age, then green, blue

β=0 β=0.5

*(Barnes 2004)*

# Importance of gas infall: Constant SFR for intermediate Hubble types

Galaxies in the middle of the Hubble sequence have about constant Star formation rate
(Kennicutt et al 1994, Brinchmann et al 04)

➔ Galaxies must accrete large amounts of gas mass along their lives

Required for bar reformation:
a source of continuous cold gas accretion
from the filaments in the near environment of galaxies

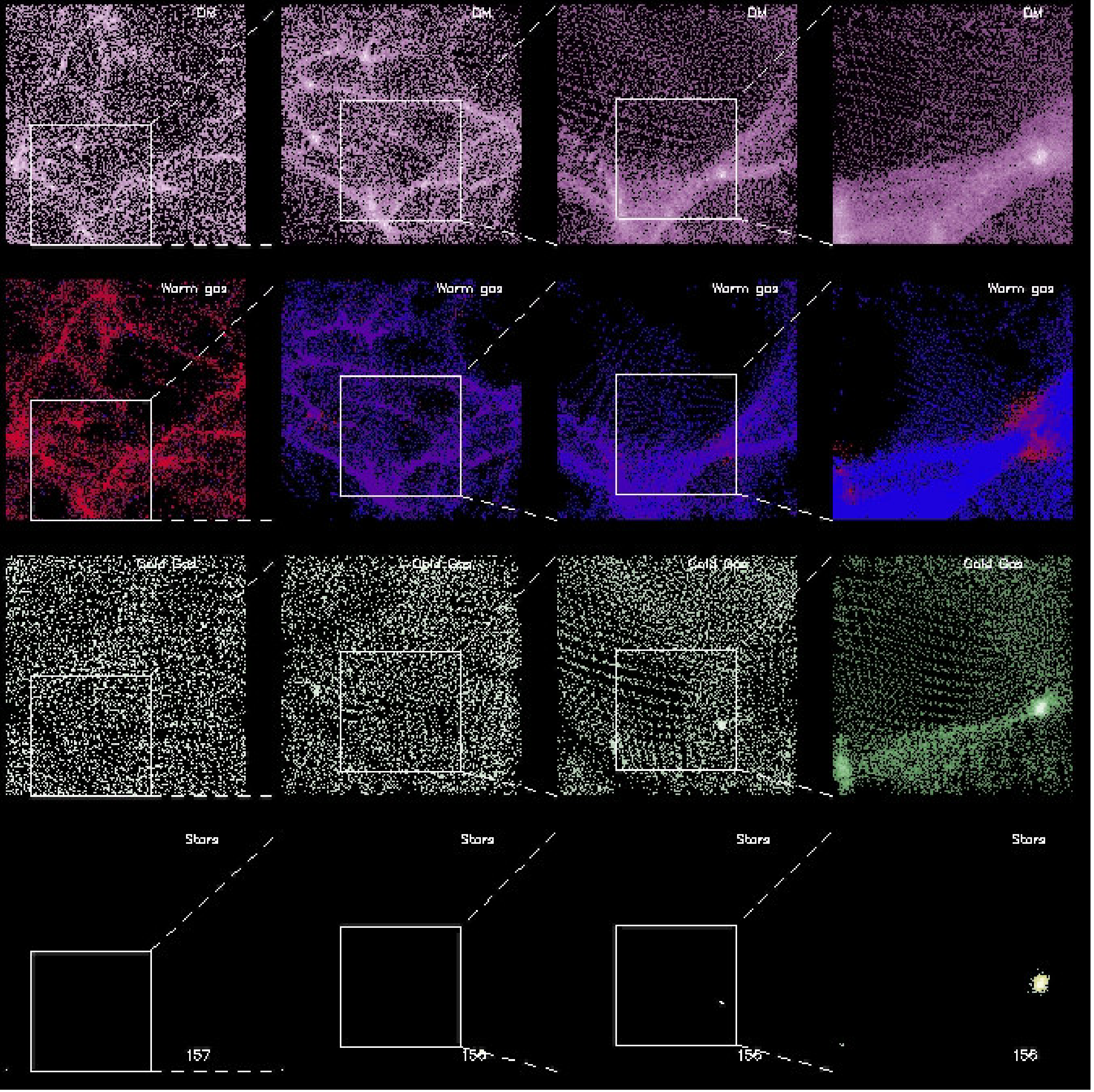
➔ Cosmological accretion can explain bar reformation

4 « phases »

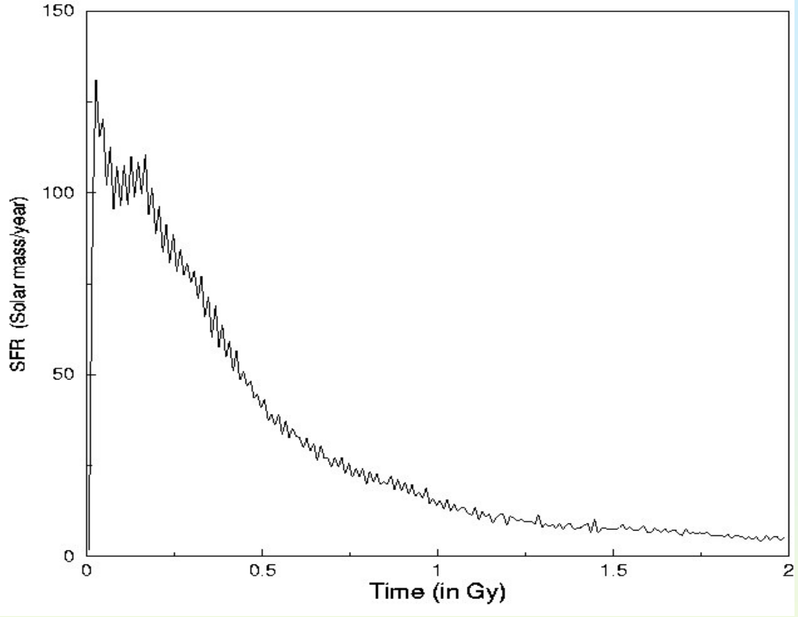
4  Zoom levels

from 20 to 2.5 Mpc.

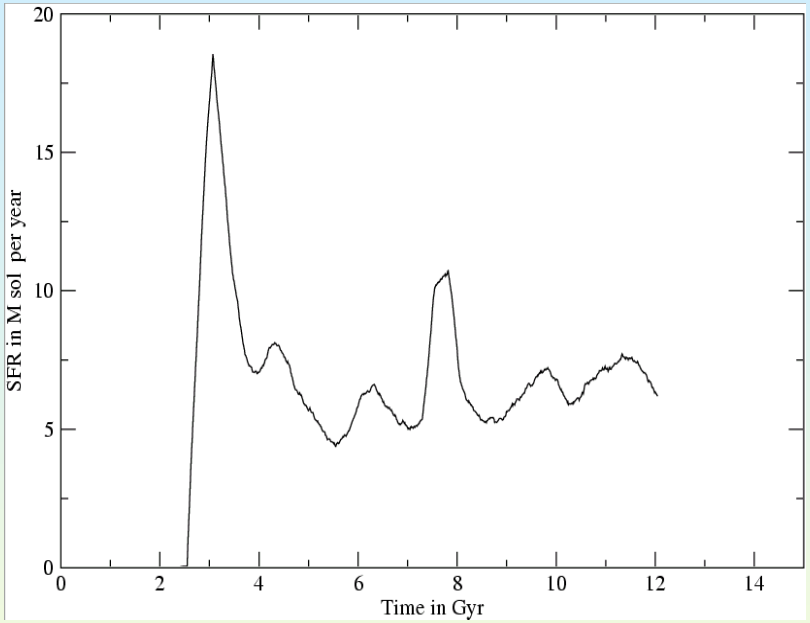
z = 3.  (from. z=10.)



# History of star formation



Isolated galaxy

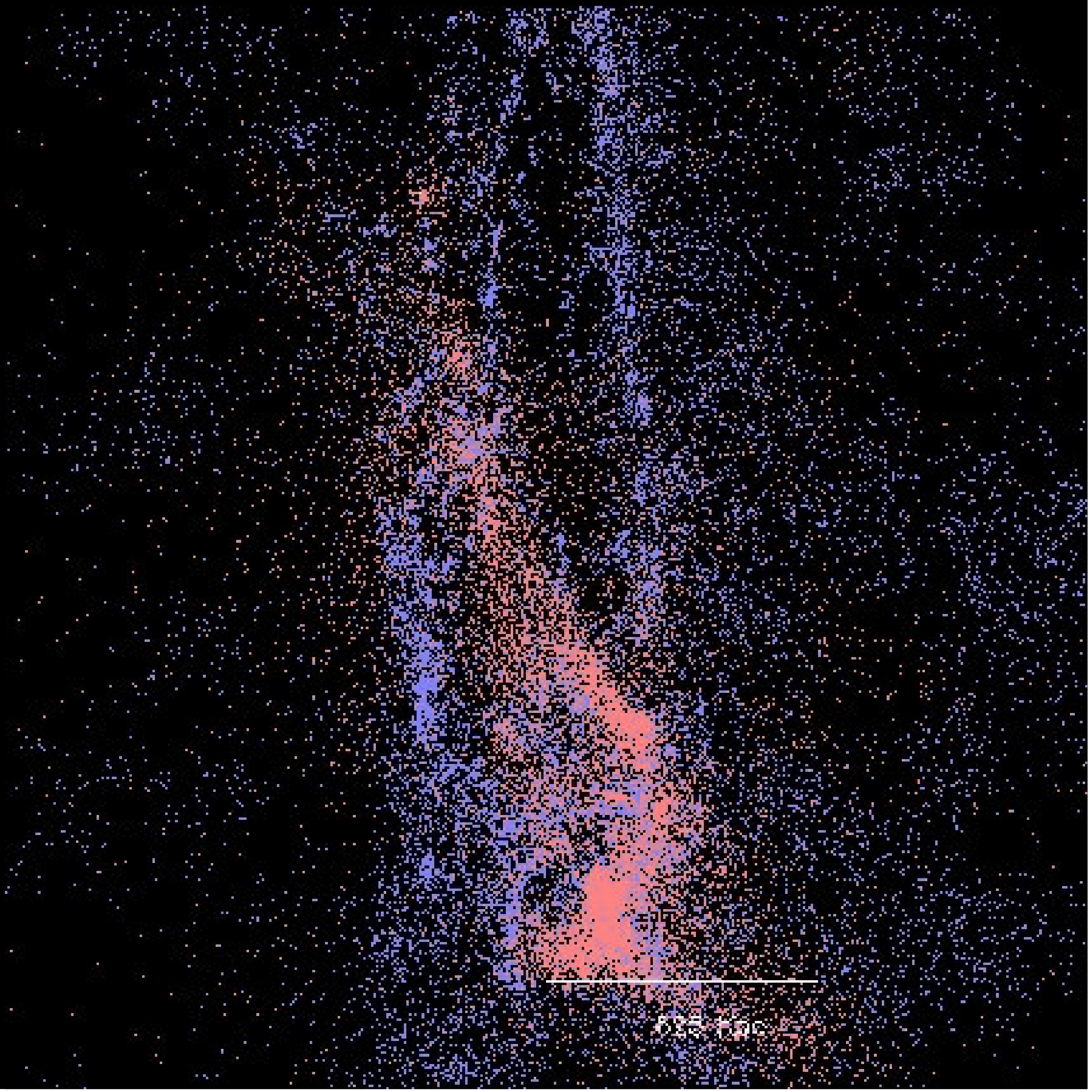


Galaxy with **accretion and mergers**

**→Accretion is compatible with doubling the mass in 10 Gyr**

# Galaxies and Filaments

Gas is accreted from the Cosmic filaments



Multi-zoom
(Semelin & Combes 2003)

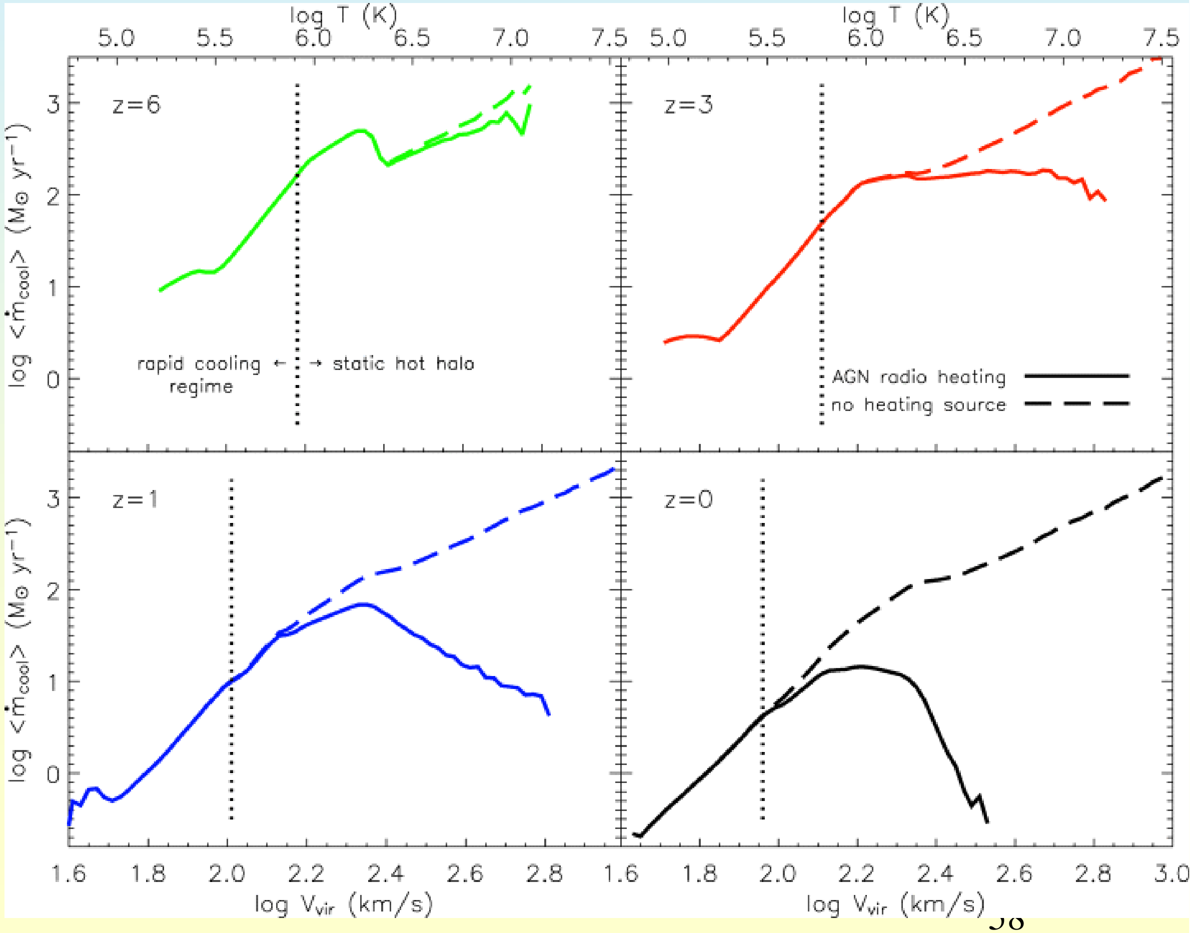
# Active Galactic Nuclei feedback

Supermassive black holes exist in every galaxy
When they accrete mass, they can inject large energies in the surrounding

**Feedback due to the AGN:**
**Reheating processes,**
**schocks, jets,**
**acoustic waves, bubbles...**

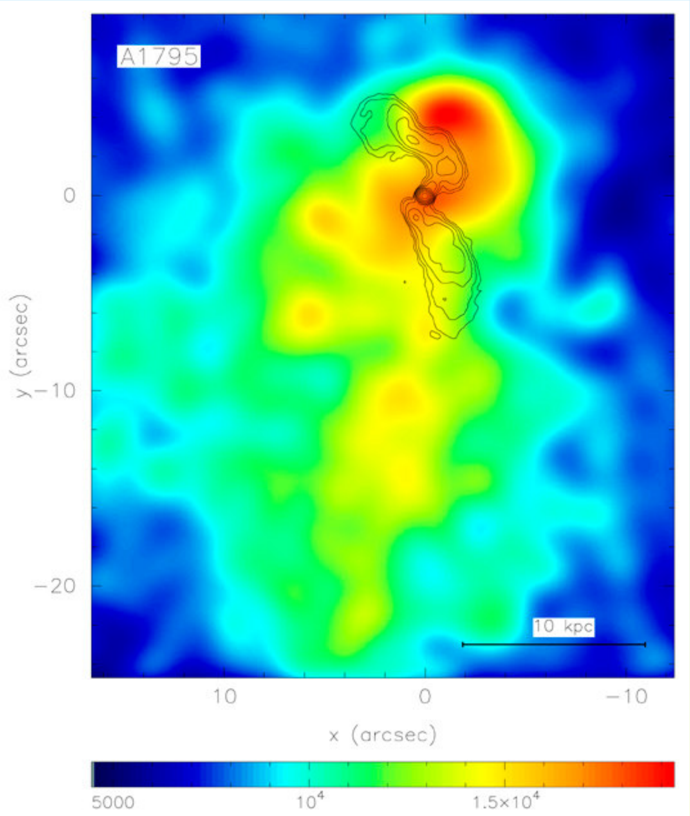
**Works only for the largest masses**

**In particular Clusters**
**Self-regulated to**
**a lower cooling rate**



Croton et al 05

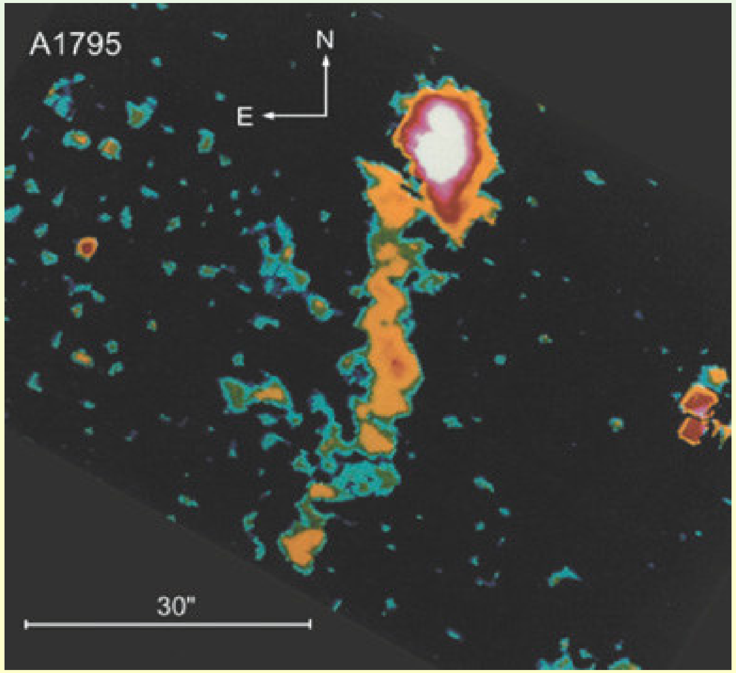
# Abell 1795 cooling flow



Very hot gas dominates the visible mass in galaxy clusters

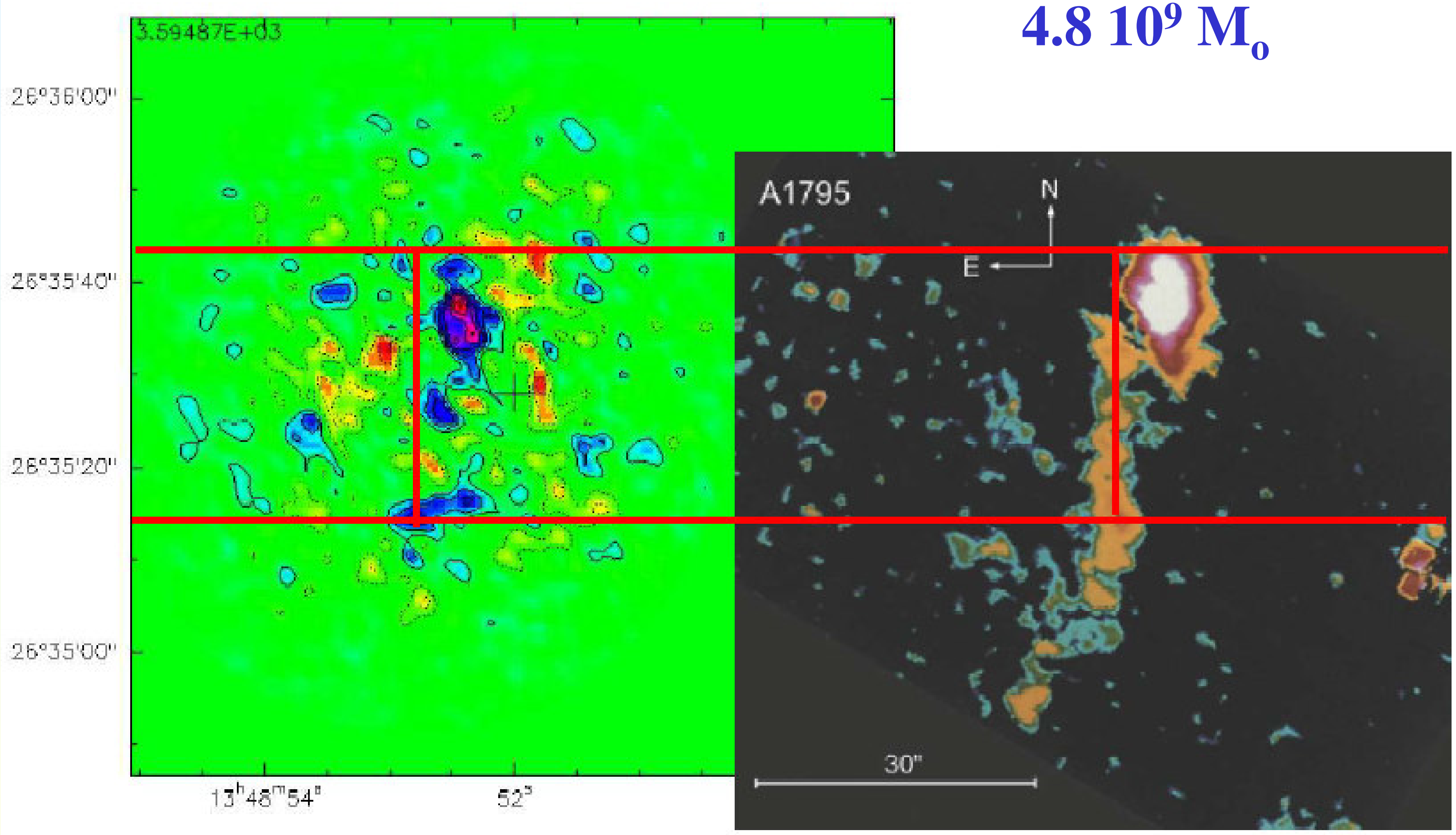
**Should be cooling only in the center, where the density is sufficient**

Cooling time  300 Myr
200 Mo/yr  in R < 200kpc



60kpc Hα filament at V(cluster)
➔Cooling wake
The cD has V=374km/s w/o cluster

# Abell 1795: CO with IRAM interferometer



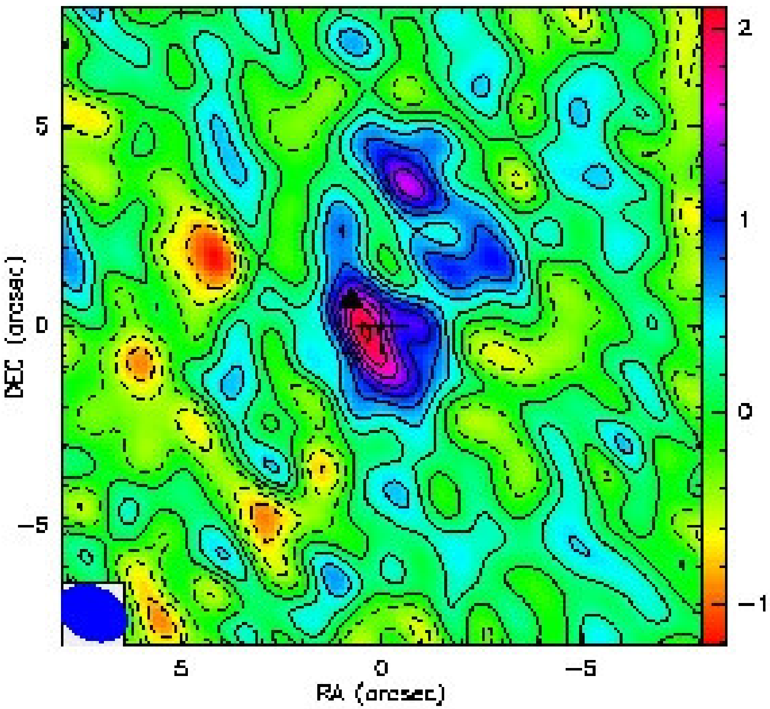
**$4.8\ 10^9\ M_o$**

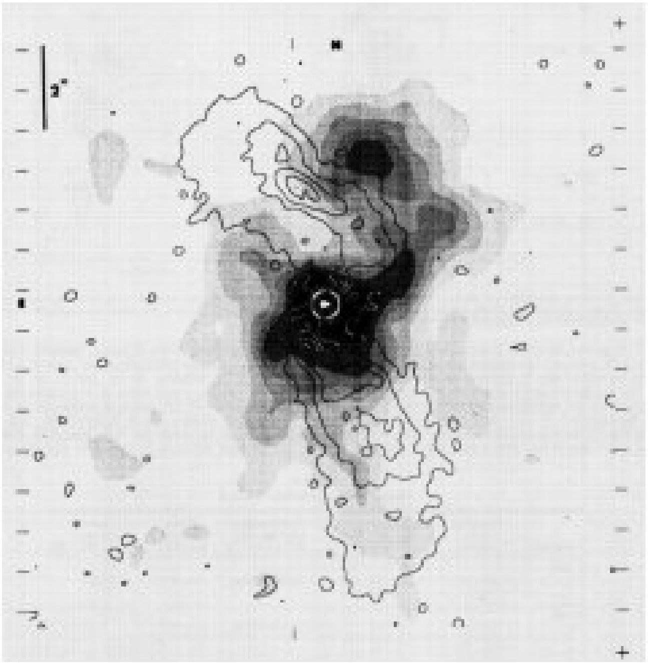
CO(1-0) 3.8 ’’ IRAM PdB CO(2-1) 1.8’’

Cold gas coincident with cooling flow, not with any galaxy

(Salomé & Combes 2003) z=0.06326 Cont-3mm = 7mJy

# CO(2-1) integrated map





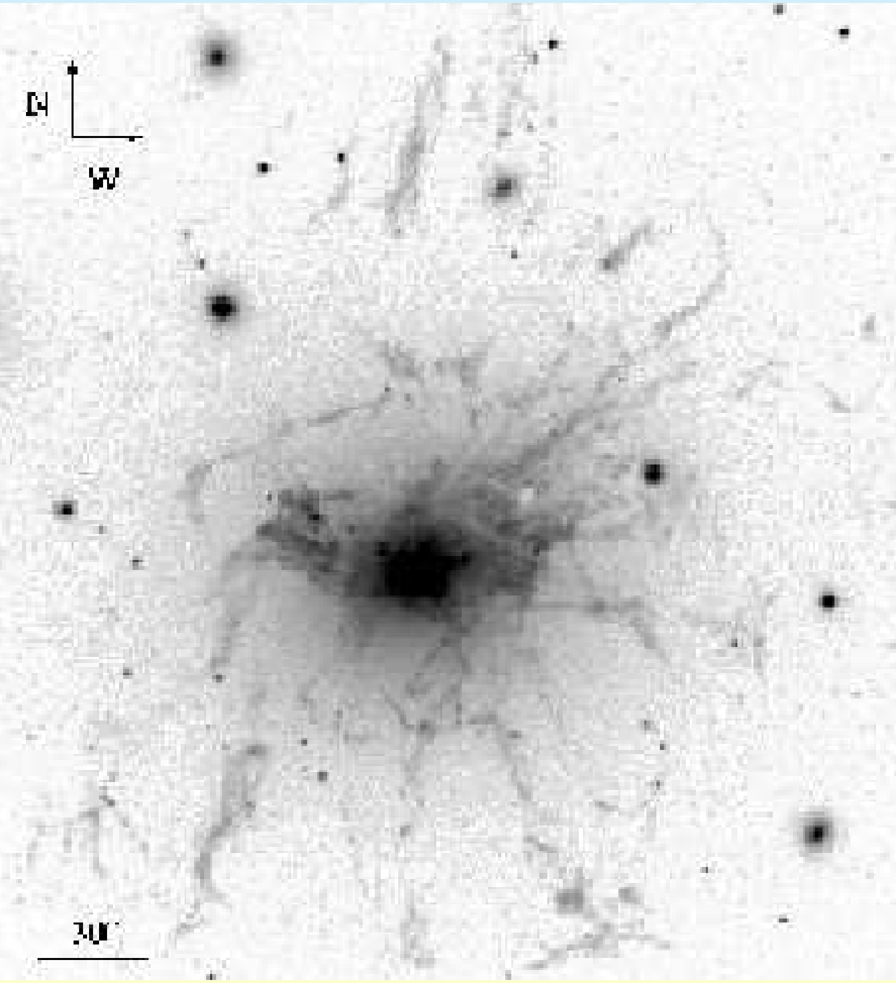
**Close correspondance** between the CO(2-1) emission and the Hα +[NII] line emission (gray scale)

6cm contours van Breugel et al 1984

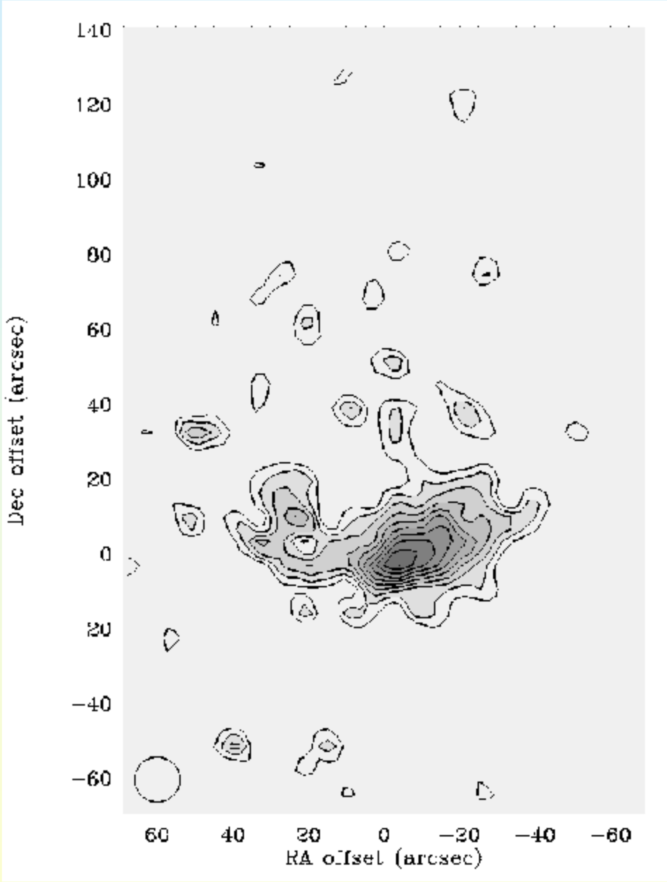
Cold gas may have deflected the expanding radio lobes?

➔The jet creates a hole (bubble) in the hot gas, which is compressed at the boundaries, and cools

# NGC 1275 Hα (WIYN) and CO (IRAM)



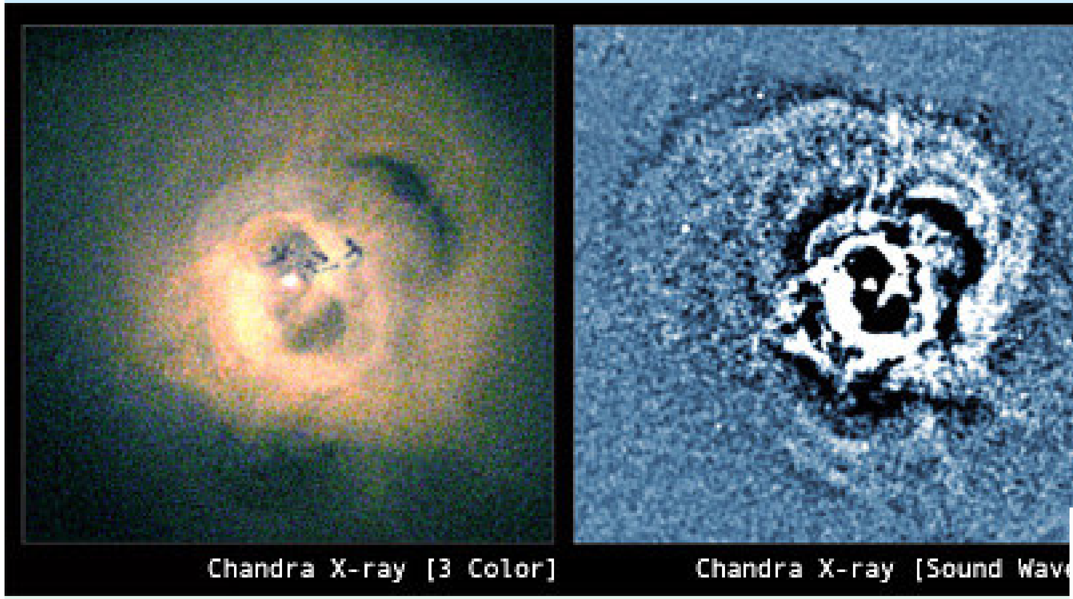
Hα, Conselice 01

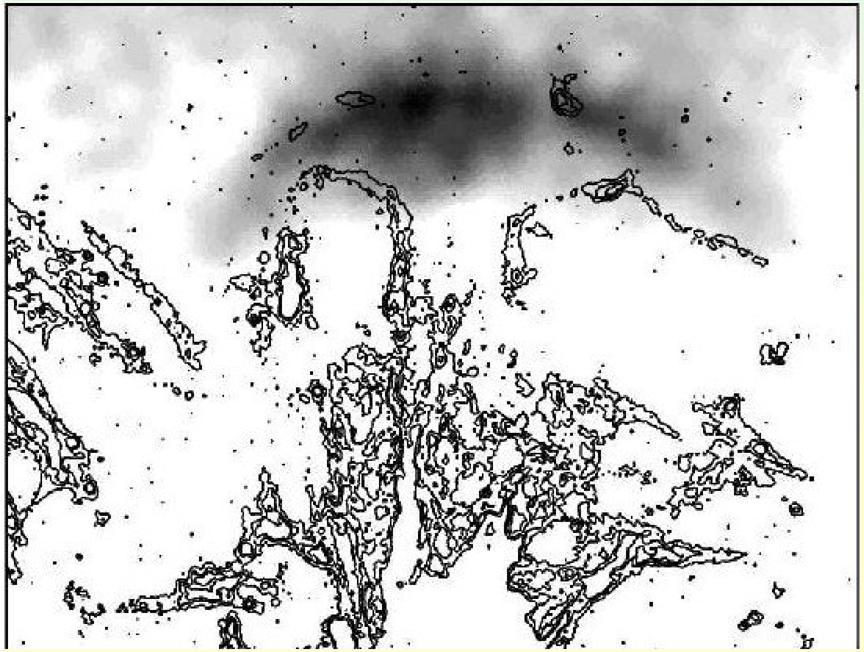


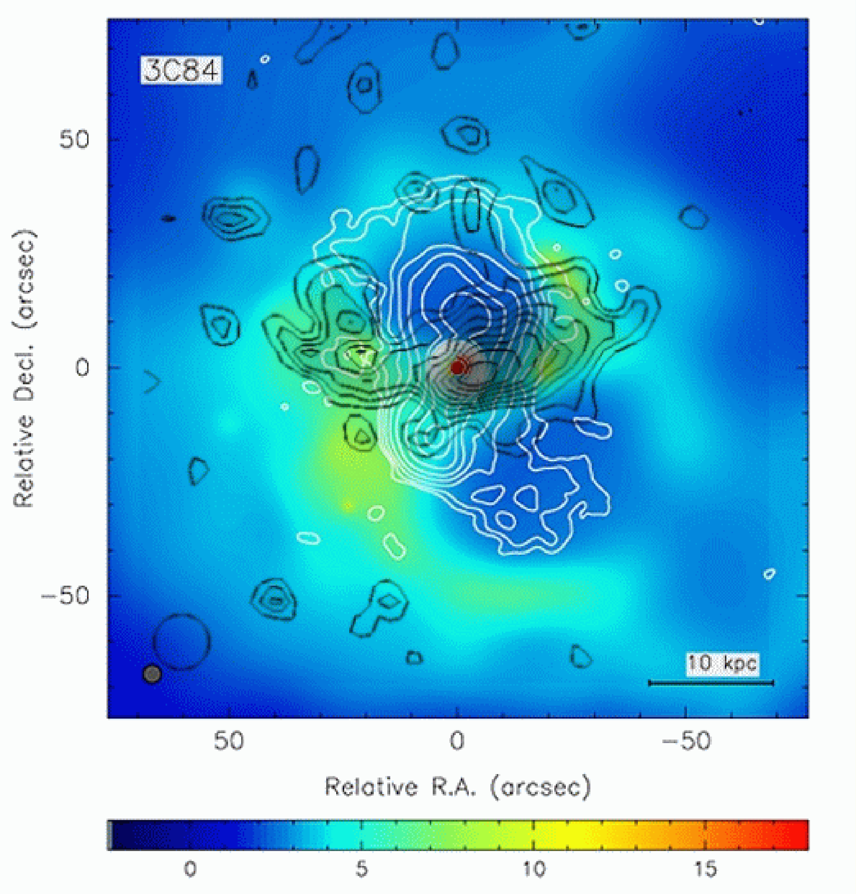
Salome, Combes, Edge et al 05

# Perseus Cluster

Salome et al 2006







# Some conclusions

Star formation depends **essentially on the gas supply**
Gas accretion is essential for the efficiency of dynamics

Galaxy interactions help to drive the accreted gas radially inwards and trigger central starbursts

➔In the field, accretion is dominant, and explain bars and spirals, and the *constant star formation* rate for intermediate types

➔In rich environments: quicker evolution, much more importance of mergers, secular evolution of galaxies is halted at z~1, since galaxies are stripped from their gas