Bars and Their Impact on Galaxy Evolution over the Last 10 Gyr

Astro 358/Th Feb 24

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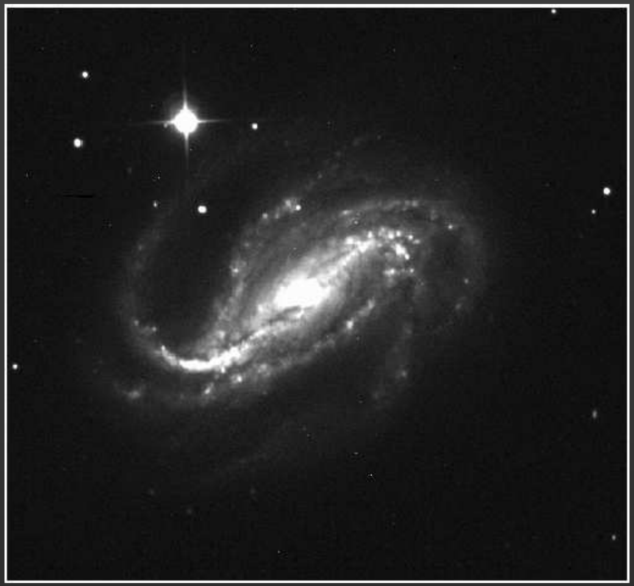
Examples of Barred Galaxies



OUTLINE

Bars: What are they? Why are they important?

Stellar orbits and dynamical resonances in a barred galaxy

How does a bar drive gas inflow and down to what scales ?

Evidence for bar-driven inflow in present-day galalxies

How frequent are bars today ? How do they form? Are they suicidal ?

Are bars a recent phenomenon or were they present in the young Universe 10 Gyrs ago? Latest results from GEMS !

[Can bars funnel gas into a black Hole either directly or indirectly?]

Lecture = Powerpoint (posted as pdf) + In-Class Notes
Pdf at http://www.as.utexas.edu/~sj/a358-sp05

Definition of Bars

Triaxial system where

- a:b:c not equal to 1,
- a>c, b>c : thin in z direction w.r.t. in-plane dimensions
- b/a < 1 : non-axisymmetric

Rotate with a rigid pattern speed Ω_p that can change via interactions with the dark matter halo and interactions with other galaxies (angular momentum exchange)

Made up of a characteristic set of periodic stellar orbits (x_1, x_2, x_3, x_4, chaotic, etc) – see later

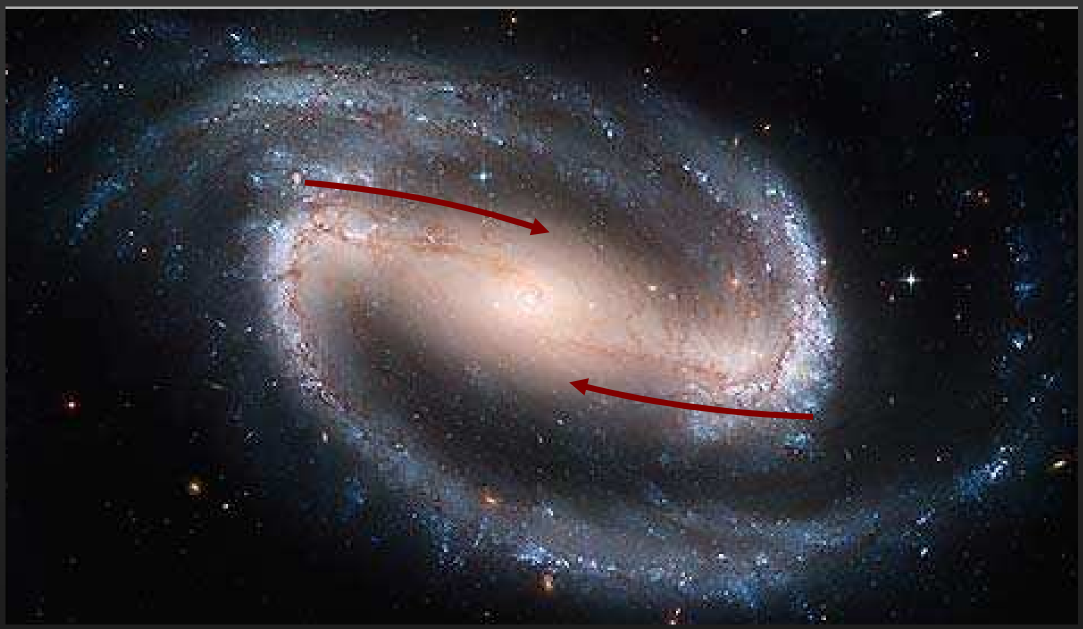
Strong bars often described as having high ellipticity e=1-b/a (thin bars)

Importance of Bars

Importance of bars

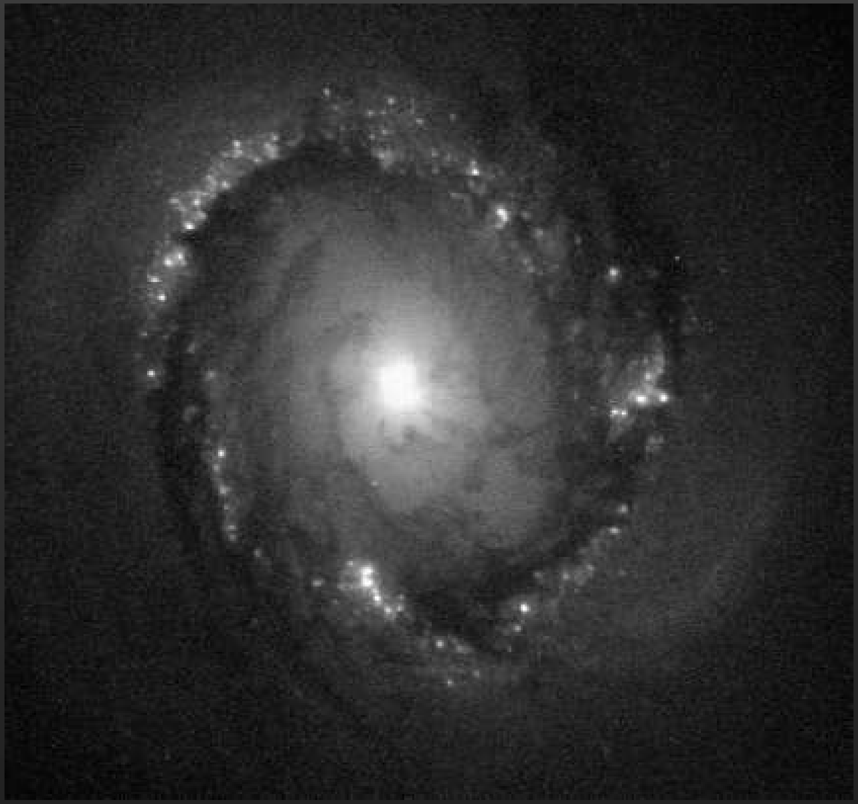
Bars very efficiently drive gas from outer disk of a galaxy into the inner kpc via gravitational torques and dissipation (see later notes)

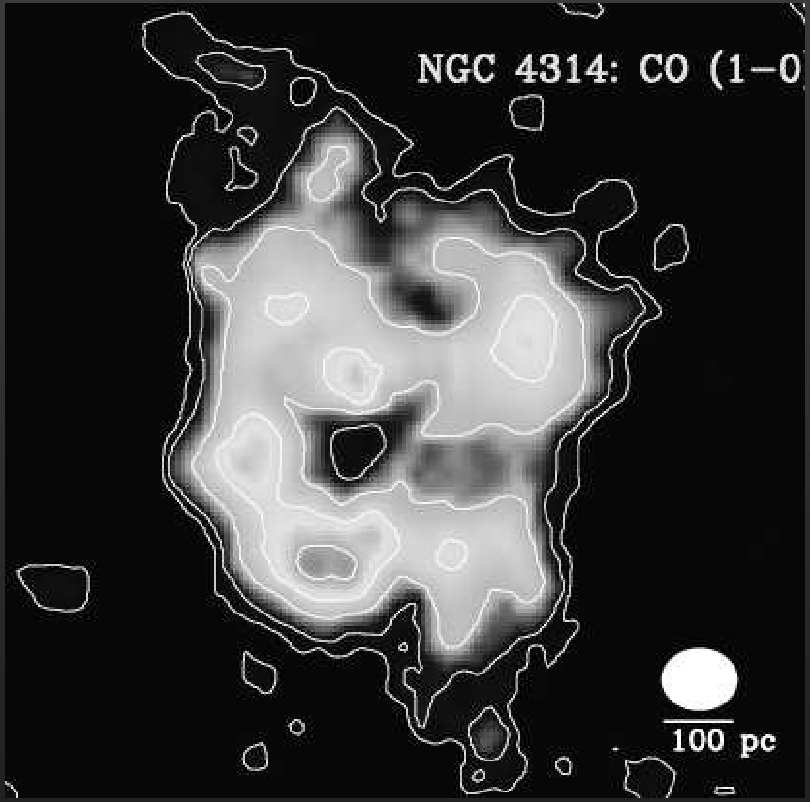
Increase central gas concentration, central mass buildup in galaxies



Importance of Bars

Bar fuel circumnuclear starbursts .. 10 billions L_{sun}!





May indirectly help to feed the central black hole if other fueling mechanisms take over on smaller scales (see later notes).

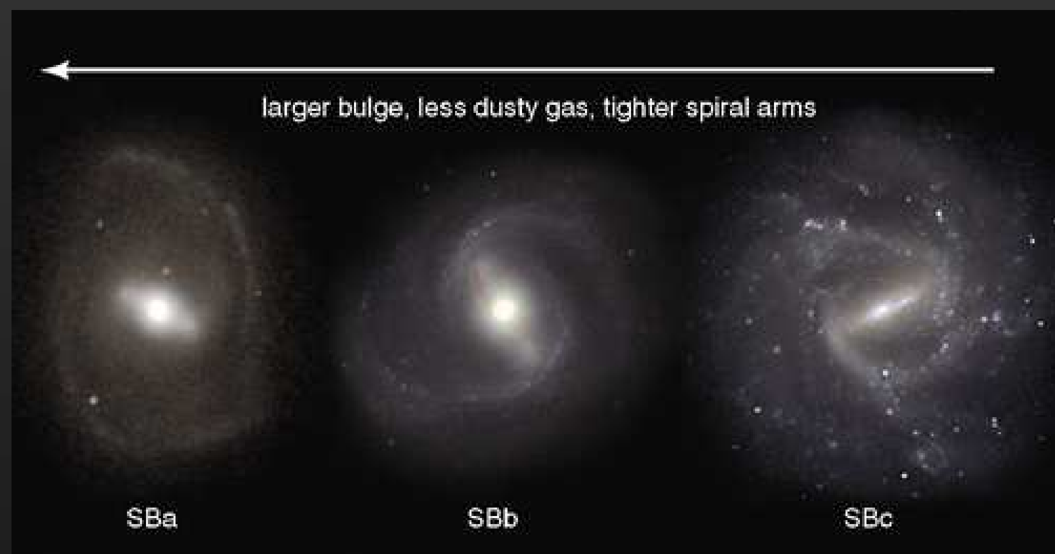
Importance of bars

• **Bars postulated to drive secular evolution along Hubble Sequence (Scd-Sb)?**

Sab Sa	Sb Sbc Sc Scd	Sd
<------------------------------->	< -------------------------------	-------------
z>>1: mergers build BH/bulges?	Structural/secular evolution	Nuclear cluster
SMBH—Bulge correlation		No bulge

Bar-diven gas inflow leads to bulge enhancement in different ways

1) CN stellar disk (high V/σ)
   = ‘pseudo-bulge’
2) Bending instabilites in disk
3) Vertical ILRs in bars
4) Chaotic orbits



Major merger movie

Note: The largest bulges (Sa) probably formed via major merges (merger of 2 disk galaxies of similar mass) rather than via successive secular episodes of bar-driven gas inflow. The latter episodes relevant for less massive bulges in Scd to Sbc.

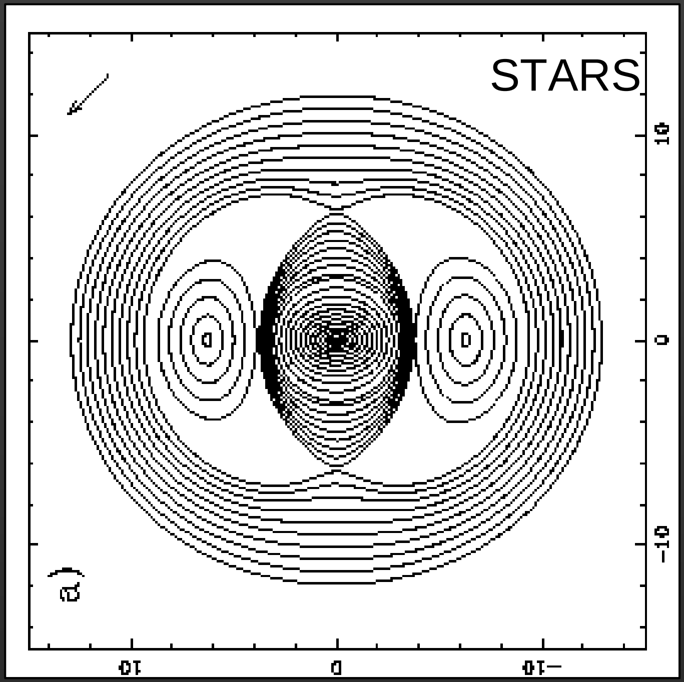
Importance of Bars

Majority (>80%) of present-day disk galaxies host stellar bars . About 1/3 host bars which appear strong at optical wavelengths (Eskridge et al. 2002)

Bars are frequent even at early cosmic epochs, out to lookback times of 8 Gyr when Universe was 40% of its present age (Jogee et al 2004; more on this later) . Thus, bars can impact galaxies over a large fraction of their lifetime.

Stellar Obits and Dynamical Resonances of Bars

Stellar Obits and Dynamical Resonances of Bars



See in-class note : Resonances for both weak and strong bars can be defined in terms of which family of stellar orbits (x_1, x_2, x_3, x_4, chaotic, etc) dominate

à Between Inner Lindblad Resonances (ILRs) dominant orbit family = x_2

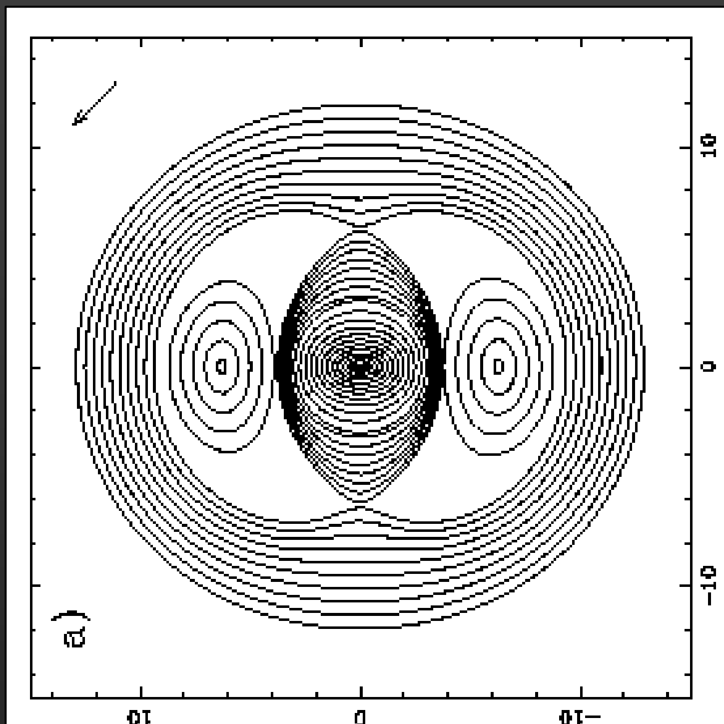
à Between ILRs and Ultra Harmonic resonance, dominant orbit family = x_1

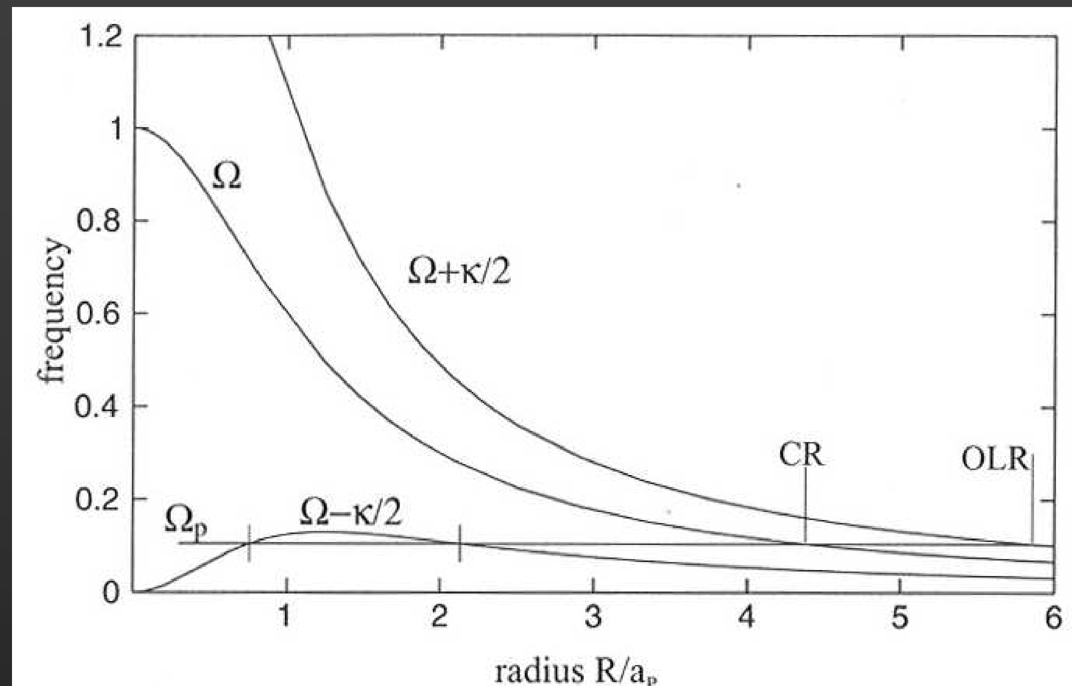
à Between Ultra Harmonic and Corotation resonance have some chaotic orbits

à Between CR and OLR have complex and circular orbits

Stellar Obits and Dynamical Resonances of Bars

STARS

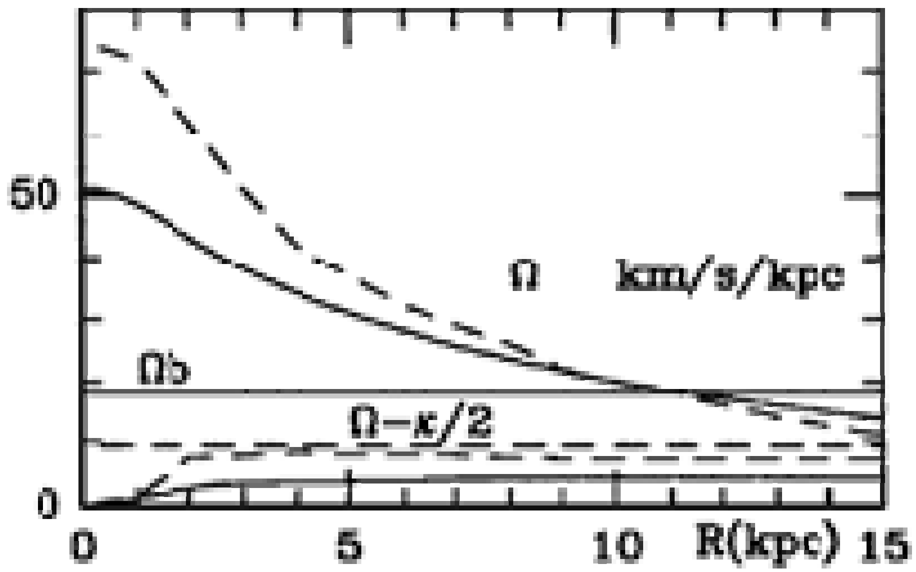




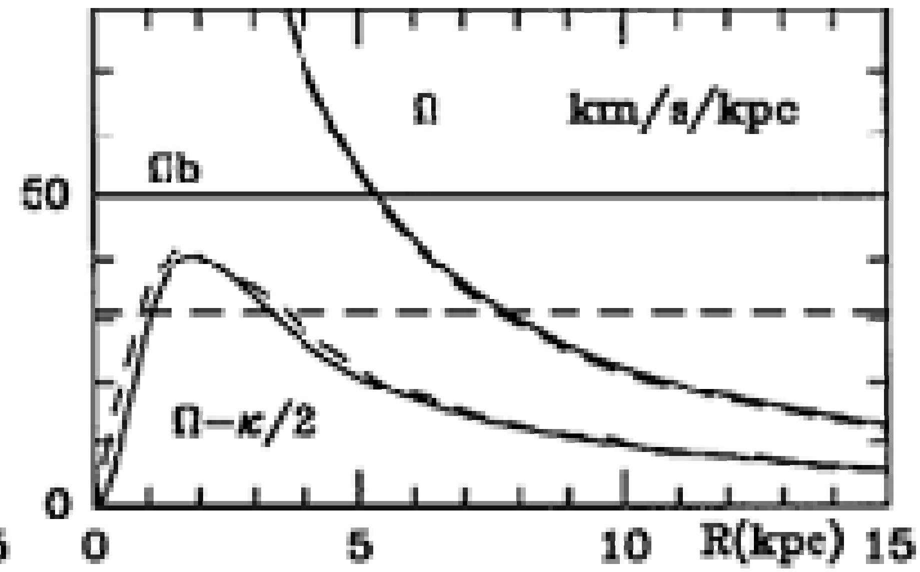
- For a weak bars only : can use the epicyclic approximation and the curve of dynamical frequencies to estimate the location of the bars resonances (OLR, CR, ILR) .

  See in-class notes for equations.

Bars



Weak bar with no ILRs

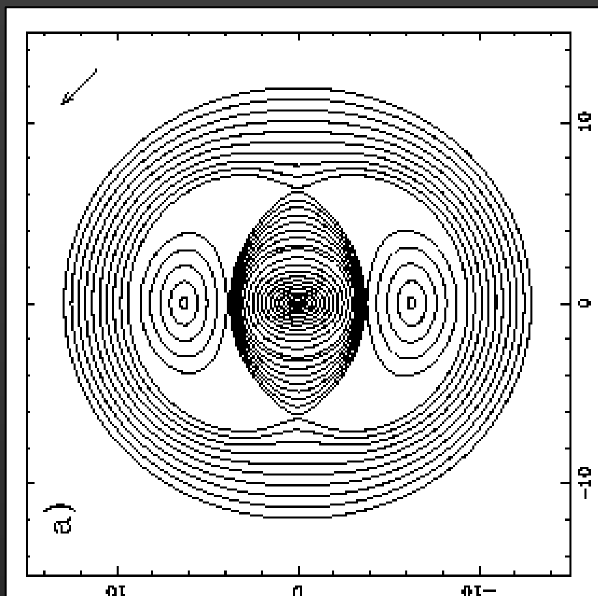


Weak bar with two ILRs

One or more ILRs exist only if central mass concentration is large enough

Ω-k/2 > Ω_b (condition for ILR in a weak bar)

Stellar Obits and Dynamical Resonances of Bars

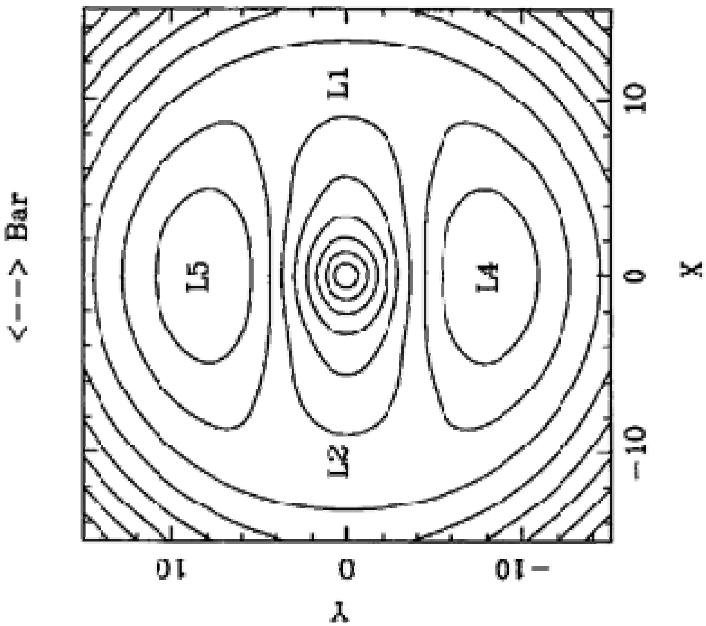


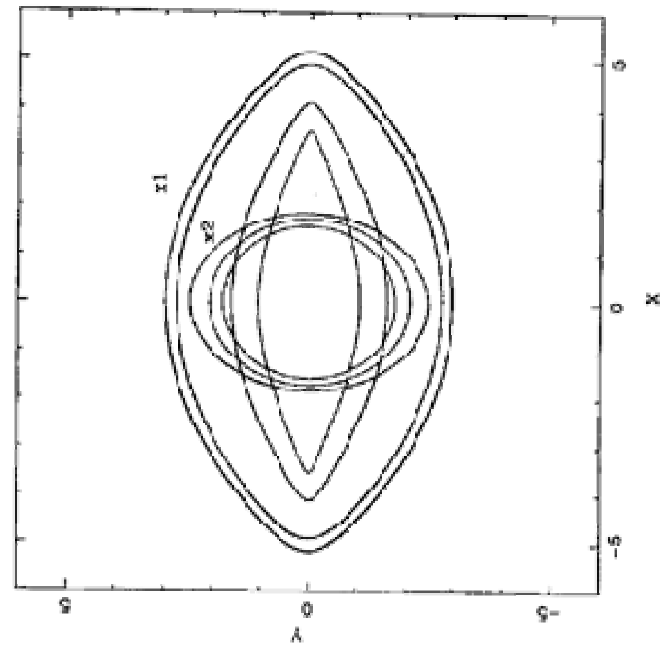
R'1 outer pseudorings
``OLR'' orbit family?

Outer rings: NGC 1543
(OLR orbit family?)

Note similarity between stellar orbits and observed stellar features in galaxies

Bars



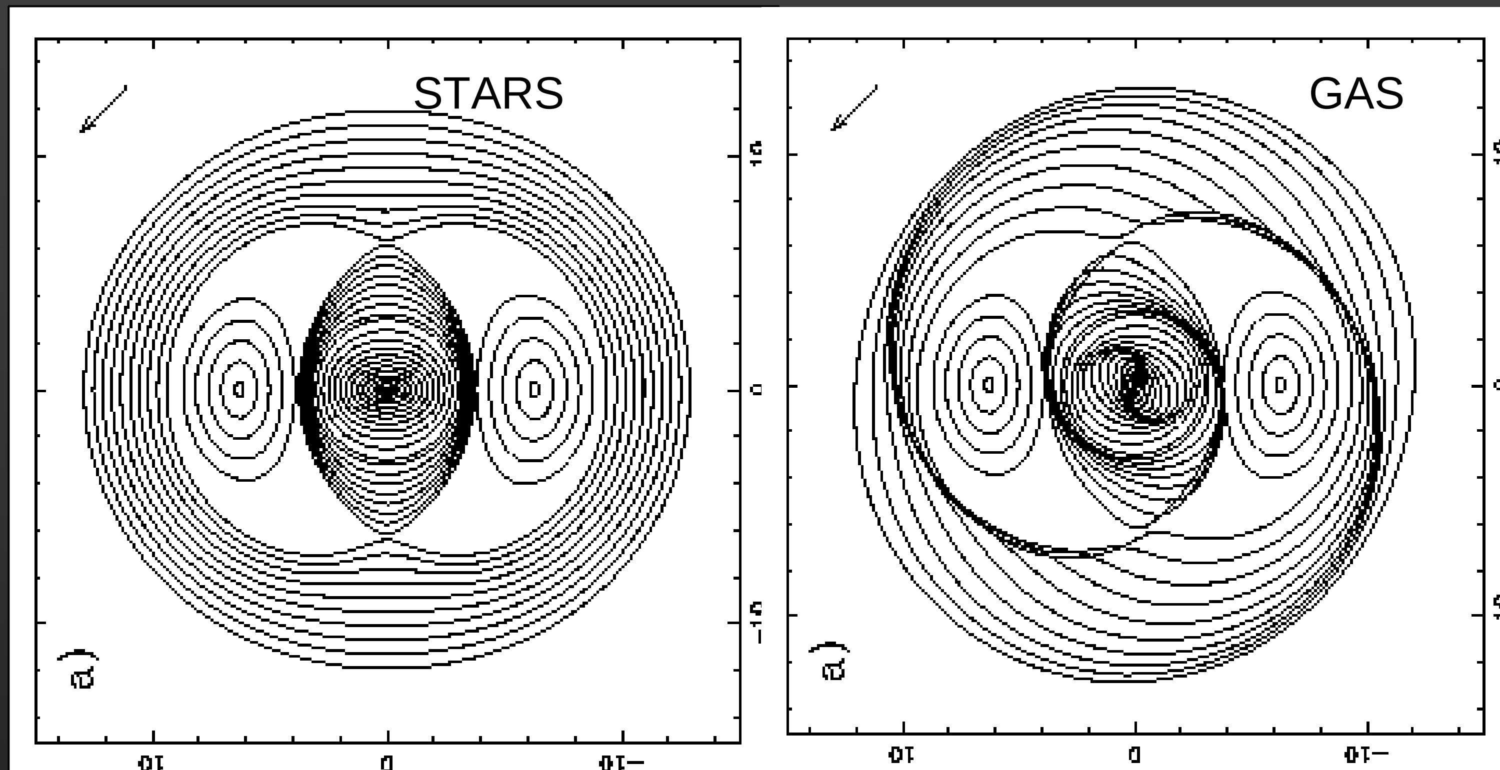


Jacobi Integral (a combination of E and L) is conserved in a rotating non-axisymmetric potential

Can express dynamical resnances in terms of Lagrange points

How Do Bars Drives Gas Inflows?

Bar-Driven Gas Inflow



Family of periodic stellar orbits conserving E_J : e.g., x_1 x_2

ILRs :dominant orbits change from x_1 to x_2

Gas: dissipative and collisional

Phase Shift ---> Spiral response

(Buta & Combes 1996)

Bar-Driven Gas Inflow

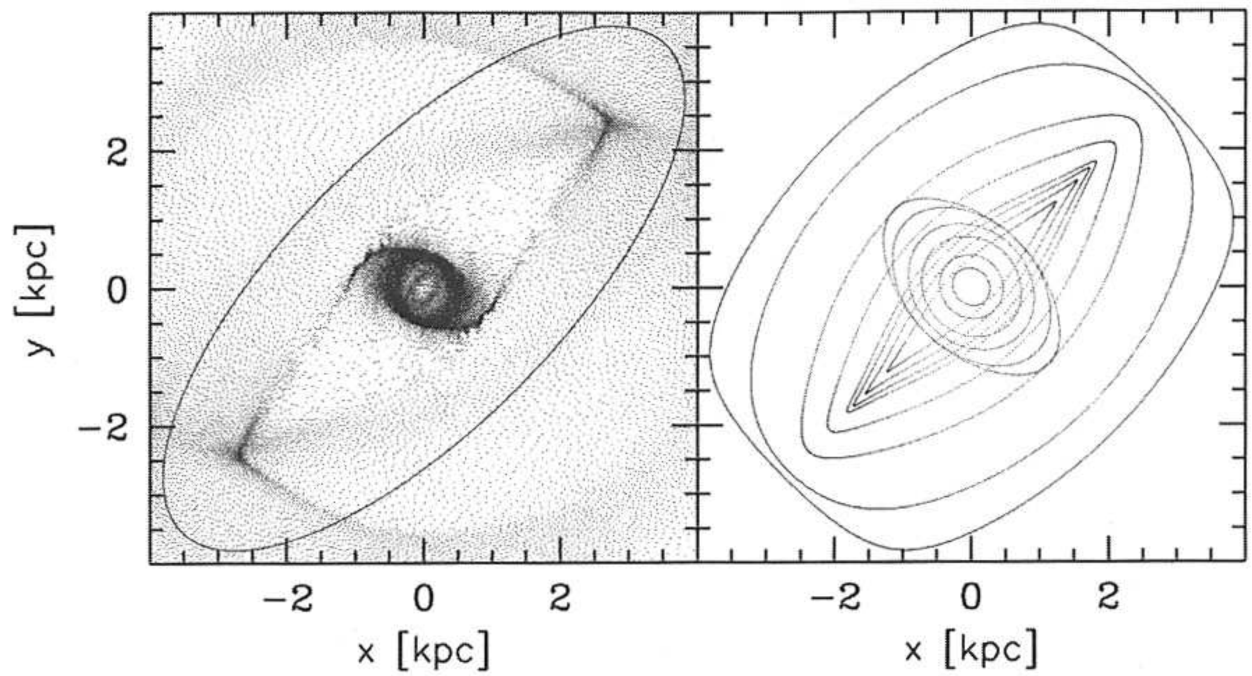
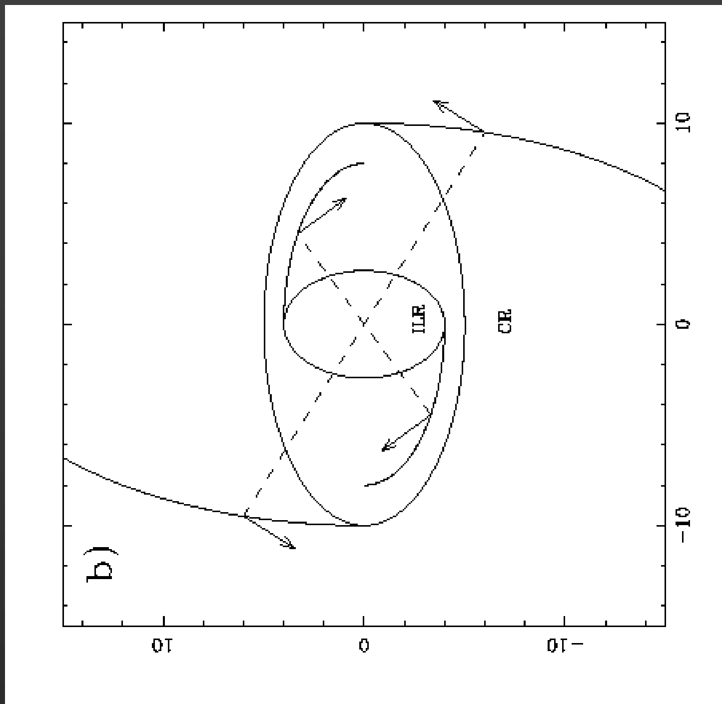


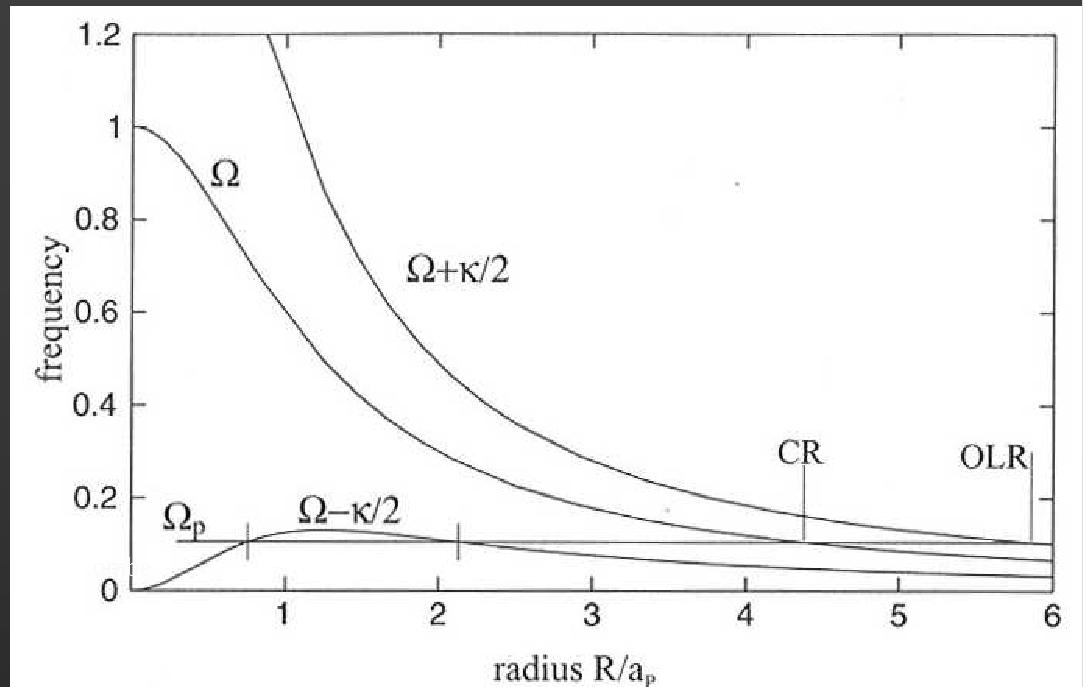
Figure 5.32 Left, gas density from a computer simulation of flow within a bar; the solid curve outlines the bar, rotating clockwise. Right, particle orbits that close on themselves in a frame rotating with the bar. The gas flow is compressed in shocks along the leading edge of the bar – P. Englmaier, after MNRAS 287, 57; 1997.

Gas shocked on leading edges of bar + torque inside CR drive it inward

Bar-Driven Gas Inflow



(Buta & Combes 1996)



Torque on gas

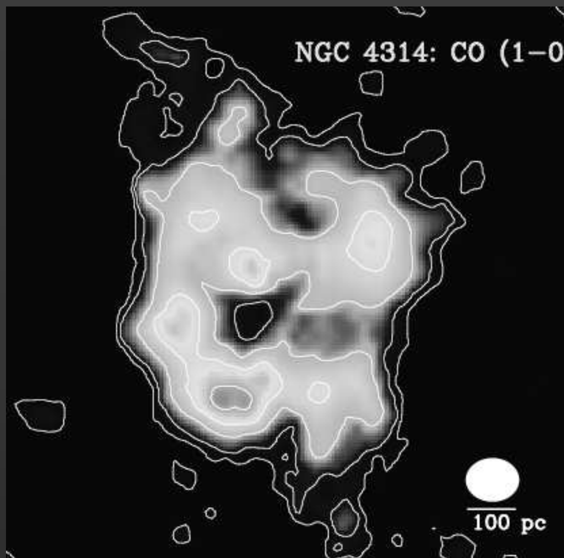
IILR OILR CR OLR

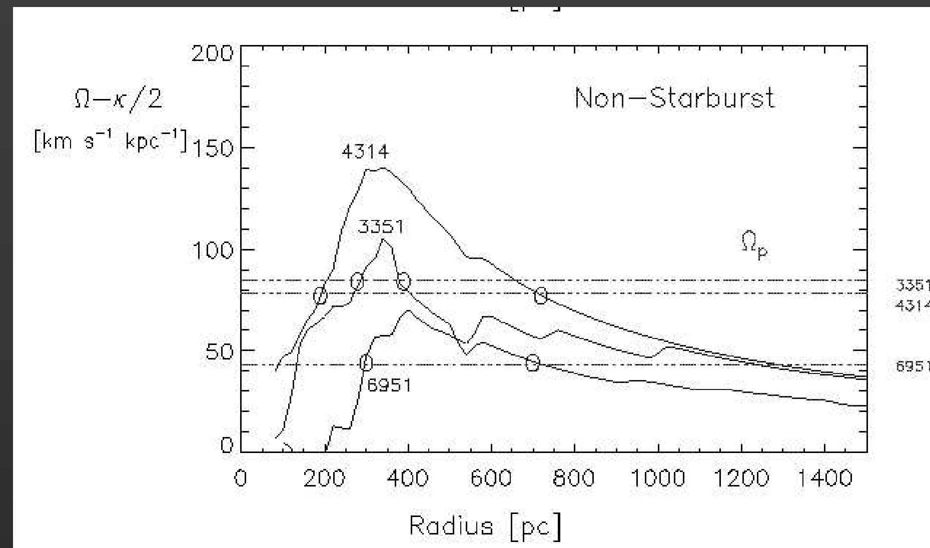
Gravitational torque on gas (T = **r** x **F**) varies near different resonances. Can remove or add angular momentum (L = **r** x **v**) -- see class notes

Gas shocked on leading edges of bar + torque inside CR drive it inward

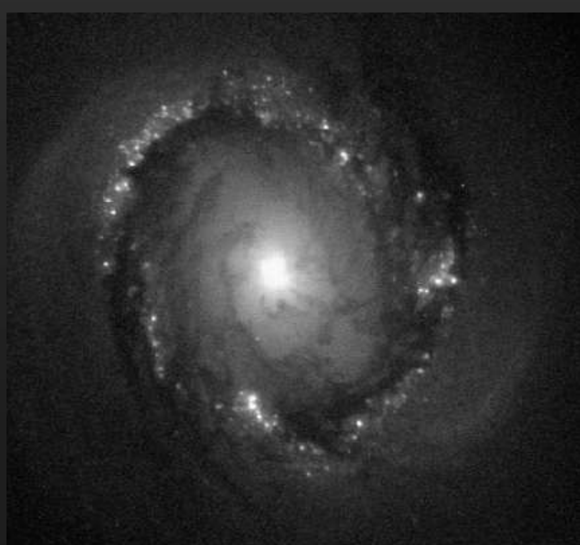
Near ILRs, shocks weaken, torque weaken/reverse à Gas piles up in rings

Bar-Driven Gas Inflow



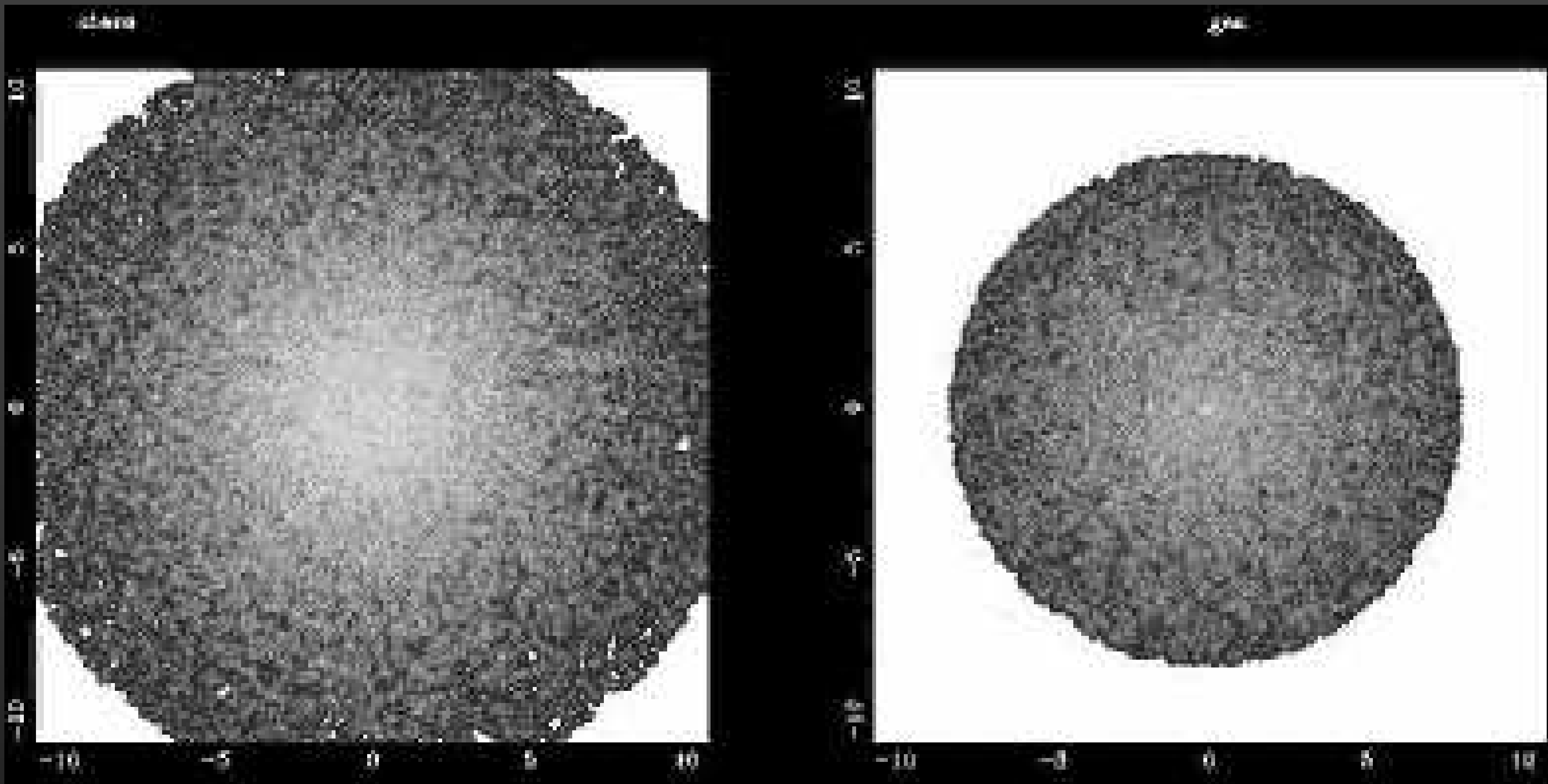


(Jogee, Scoville & Kenney 2005)



Example of gas and SF in rings inside OILR and often between OILR and IILR

Bar-Driven Gas Inflow



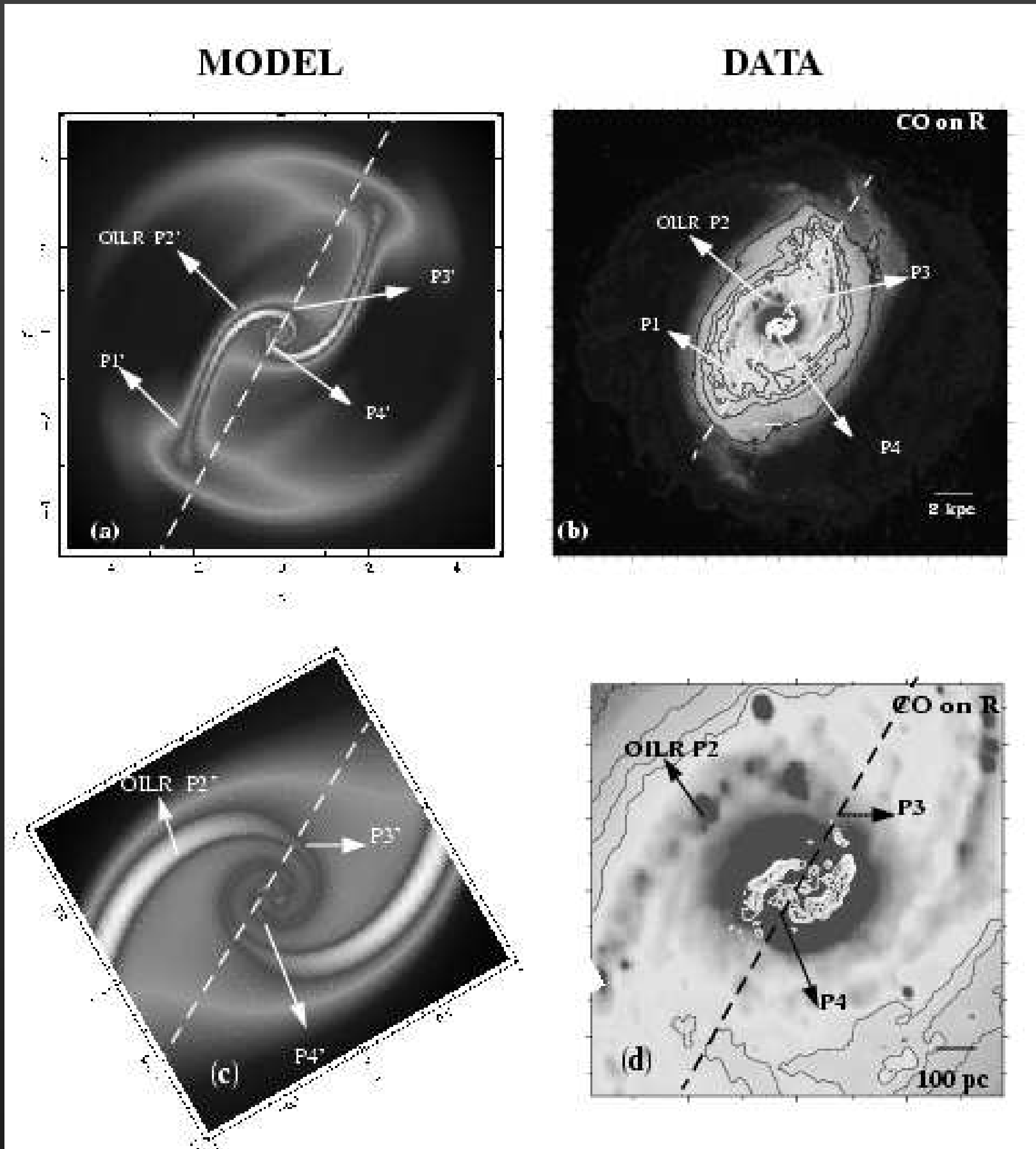
Stars Gas

Simple movie

- B/D=1:3, N-body. Gas as sticky particles . T= 6 bar periods= few 100 Myr
- Limitations: No dark matter halo. Shocks in the gas are not modeled

Note formation of gas spiral trajectories and final central gas concentration

Bar-Driven Gas Inflow



Model = SPH simulations with DM halo of gas inflow driven by a bar. Notice the curved shocks on the leading edge of the bar.

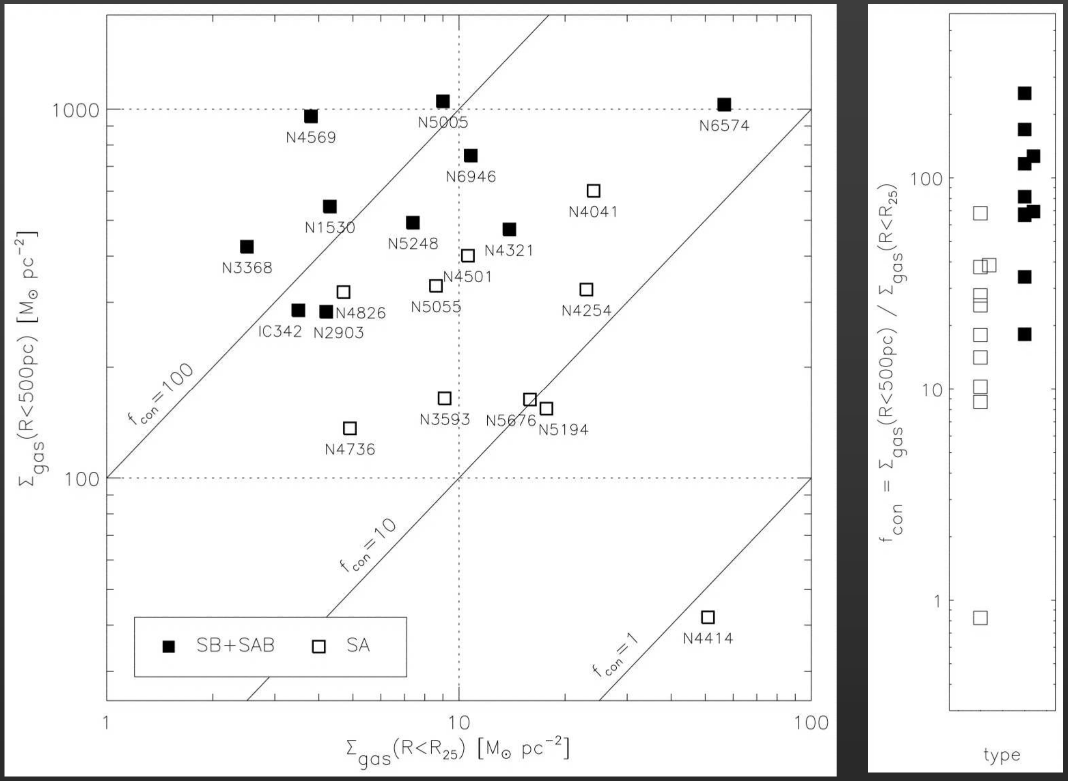
Data : R image over entire galaxy and CO in central few kpc of the galaxy

Data and model suggest that the bar drives shocks and a gaseous spiral density wave which can travel deep inside the OILR if the central mass concentration is low

(Jogee, Shlosman, Laine et al. 2002)

Evidence for bar-driven gas inflow in local present-day galaxies

Evidence for bar-driven gas inflow

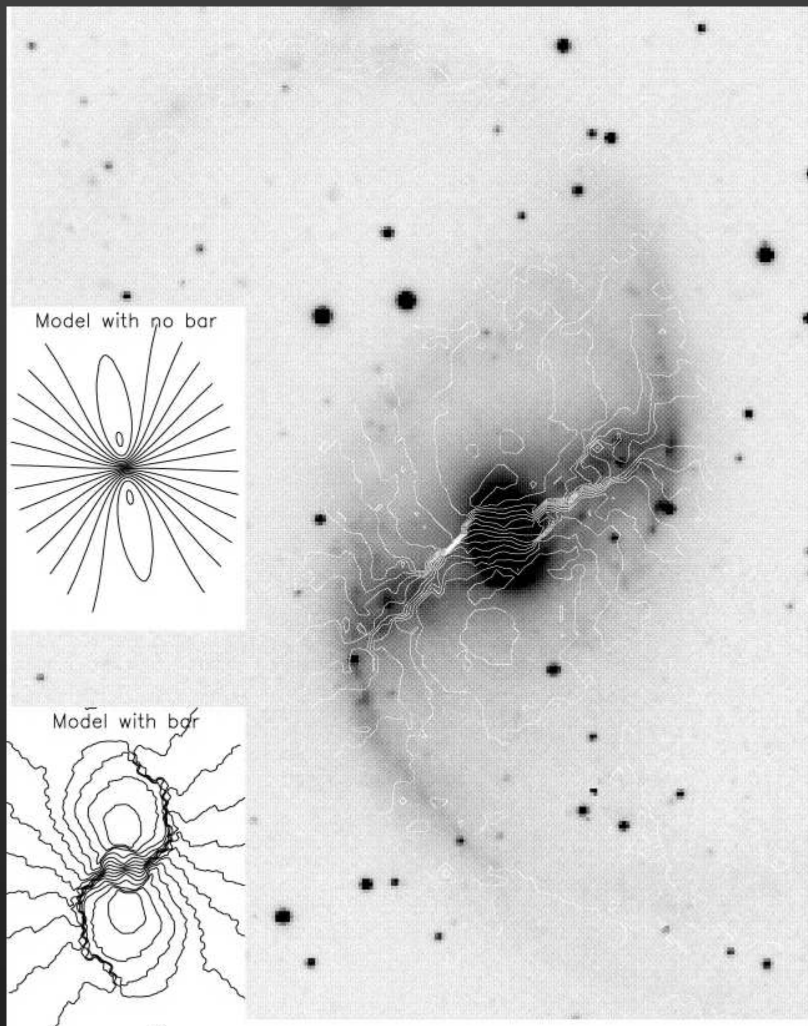


(Sakamoto et al 1999)

- Gas central concentration f_{con} in r<500 pc is larger in barred than unbarred spirals

f_{con} = [Σ_{gas} within 500 pc] / [Σ_{gas} within (R<R$_{25}$)] (e.g., Sakamoto et al. 1999; Sheth et al. 04)

Evidence for bar-driven gas inflow



Velocity field of ionised gas along bar of NGC 1530 à velocity pinching and non-circular motions (Regan, Teuben, & Vogel 1997)

Estimated inflow rates : a few M_o yr^{-1}

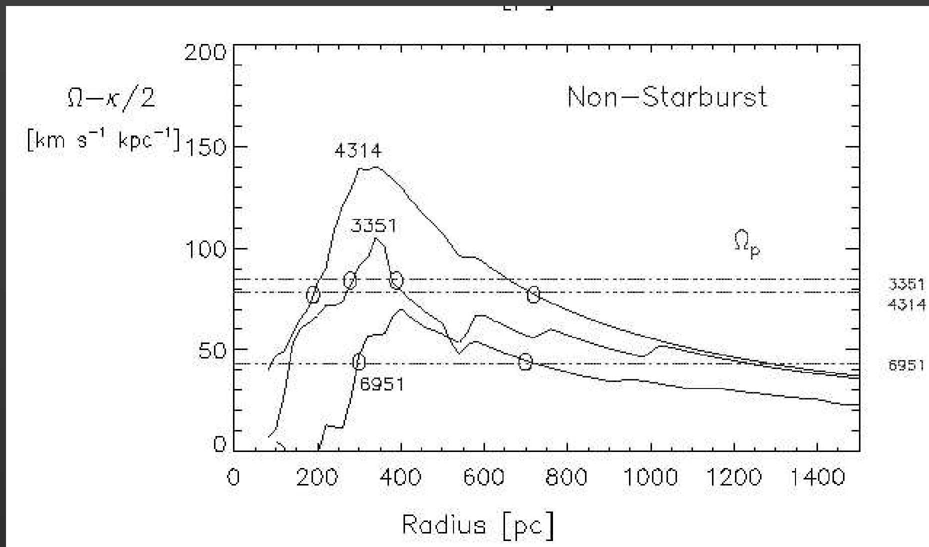
à 4 +- 2: along bar of NGC 7479
(Quillen et al. 1995)

à 4 to 6 : at 1 kpc radius in NGC 7479
(Laine et al. 1998)

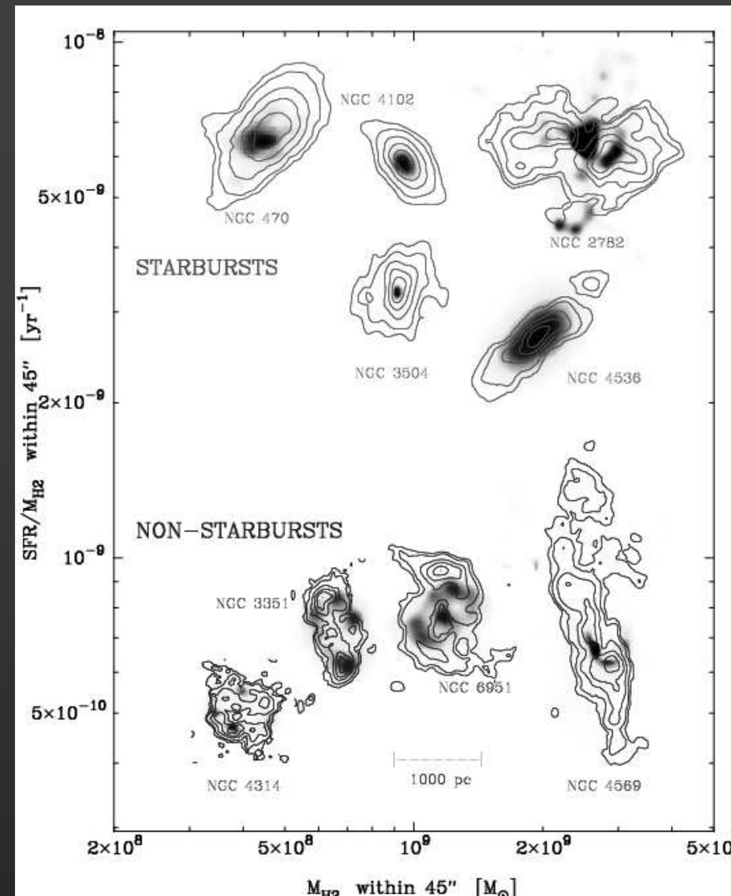
à ~1 : into 1 kpc ring in NGC 1530
(Regan et al 1997)

Global abundance [0/H] gradient is shallower in barred than in unbarred spirals
(Martin & Roy 1994)

Evidence for bar-driven gas inflow



(Jogee, Kenney & Scoville 2005)

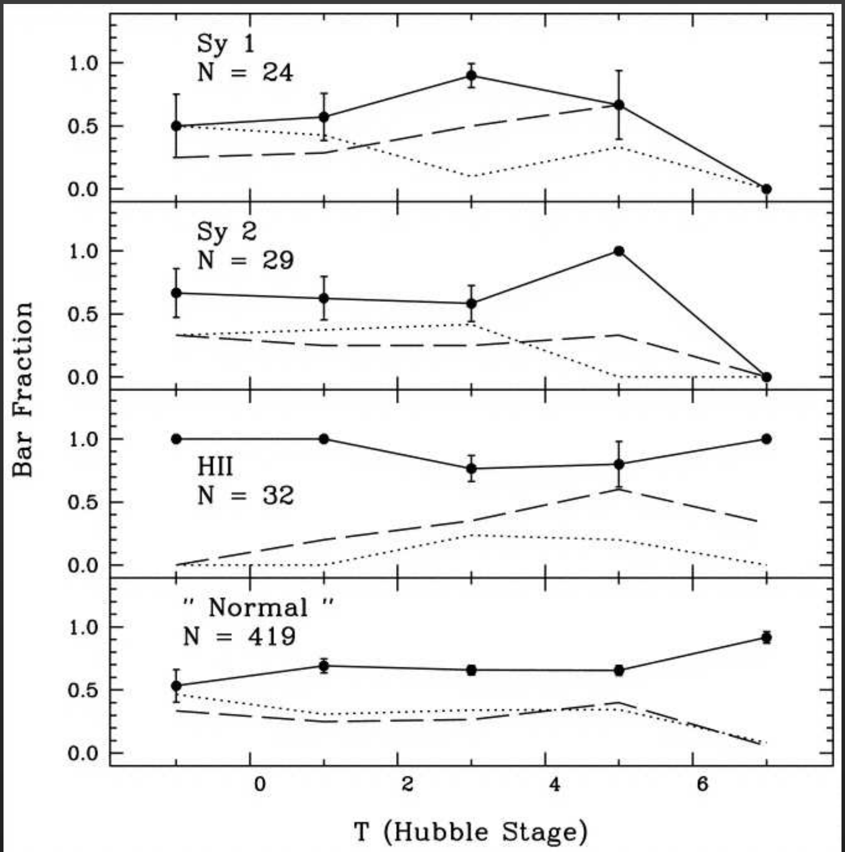


High resolution (2”) observations of molecular gas in the inner few kpc of barred galaxies show a range in gas morphology and a range in SFR per unit mass of gas, which is broadly consistent with different evolutionary stages of bar-driven inflow:

- à Early stages : most of the gas is still along the bar : there is large shear and little SF
- à Later stages : large gas concentrations (few 100 –few 1000 $M_o\,pc^{-2}$) inside OILR of bar
- à Where gas density is above a critical value, see intense star formation (3 to 11 $M_o\,yr^{-1}$)

Evidence for bar-driven gas inflow

• Starburst/HII galaxies have a larger fraction of bars than quiescent galaxies



0=S0/a 1~Sab 3~Sbc 5~Scd 6=Sd

E12MGS (Hunt & Malkan 1999)
- 891 galaxies ; 116 Sy
- Bar + optical type from RC3
- Nuclear type from NED : Sy LINER HII normal

Fraction of galaxies with bars
- "Normal" (quiescent) : 61-68 %
- HII/Starburst : 82-85 % ;excess
- AGN : 61-68 % ; no excess

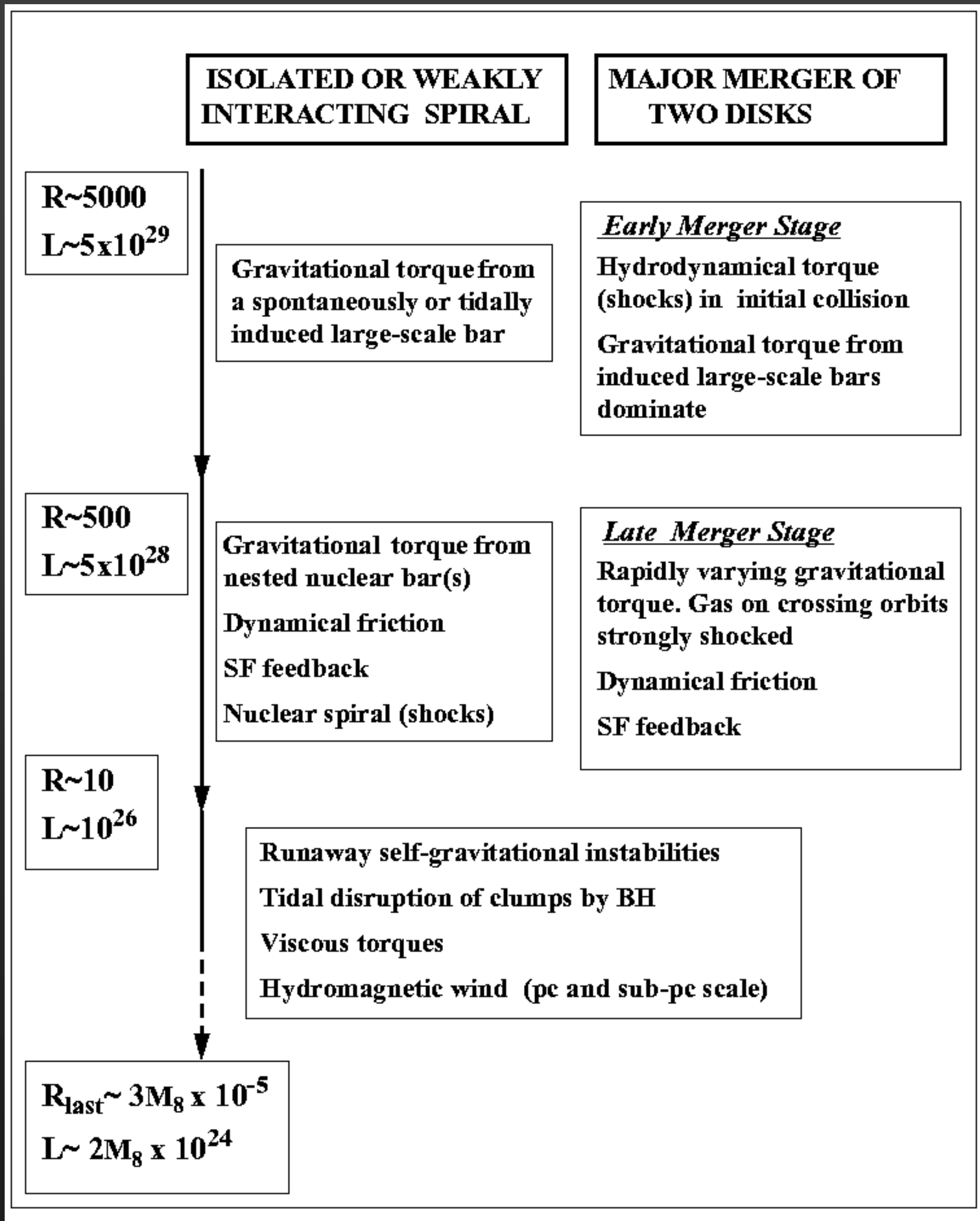
Fueling Black Holes The Angular Momentum problem

Location of cloud in disk	$L = r \times v$ in $cm^2\,s^{-1}$
At r=10kpc	3e29
At r=200 pc	4e27
At last stable orbit of BH ($10^8 \times M_8$)	2e24 M_8

à Gravitational torques: most efficient way of reducing
L at r= few kpc –few 100s pc

Gravitational torques vs dynamical friction & viscous torques

r	M	v	T_{gra}	T_{DF}	T_{visc}
pc	M_o	km s^{-1}	Myr	Myr	Myr
1000	1e7	300	20	1020	1000
200	1e7	300	4	30	-



(Jogee 2004, AGN Physics on All Scales, Chapter 6)

Do bars fuel black holes directly or indirectly ?

- Large gas inflows into r=1 kpc are primarily driven by an induced bar

à During many minor mergers

à during early stages of major (1:1) or intermediate (1:3) mergers

(Mihos & Hernquist 95; Noguchi 1988; Hernquist & Mihos 95; Heller & Shlosman 94; Hernquist 96; Naab & Burkert 01)

<u>How frequent are bars in present-day galaxies?</u>

<u>How do bars form and dissolve?</u>

<u>Are they suicidal?</u>

How frequent are bars in present-day galaxies?

- Bar fraction or bar frequency f_{bar} means the fraction of spiral galaxies that host a large-scale stellar bar.
- f_{bar} from optical images : 30% of spirals host strong bars

	f_{bar} in optical	f_{bar} in NIR (H)
Strong (e>=0.4) bars	30%	56%
Weak bars	25%	16%
All bars (weak+strong)	55%	72%

(Eskridge et al. 02; Jogee et al 2004)

• In galaxies w/ lots of dust and SF, some bars are not revealed in optical images (B, R , I) or may appear weaker than they truly are.

• Due to the lower extinction at near-IR wavelengths, NIR images better trace the underlying stellar mass distribution and reveal bars.

à f_{bar} higher in NIR

How do bars form and dissolve?

- In order for a disk to undergo a bar (m=2) instability
  - à disk must have a large gas mass density Q<2
  - à system of (disk + bar + dark matter halo must be dynamically cold (ordered motion dominate over random motion)

- Early works assumed a rigid (non-responsive) axisymmetric DM halo which does not interact with the barred disk . They derived unrealistic criteria for bar formation (e.g., Ostriker Peeble criteria) and claimed that a massive bulge or DM halo always suppresses bars

- BUT… real disks are embedded in live (responsive) DM halo which may be axisymmetric or triaxial!
  - à Bar exchanges angular momentum with DM halo
  - à Bar experiences dynamical friction from DM halo

Athanassoula (2003) used live axisymmetric DM halos

- à A massive DM halo can make a bar stronger due to resonant interactions and angular momentum exchange

How do bars form and dissolve?

- Recent work/simulations with live triaxial_ DM halos show that if the halo is triaxial and centrally concentrated, then
  - à Either it rapidly destroys the bar
  - à Or its triaxiality is reduced by the halo-disk- bar interaction

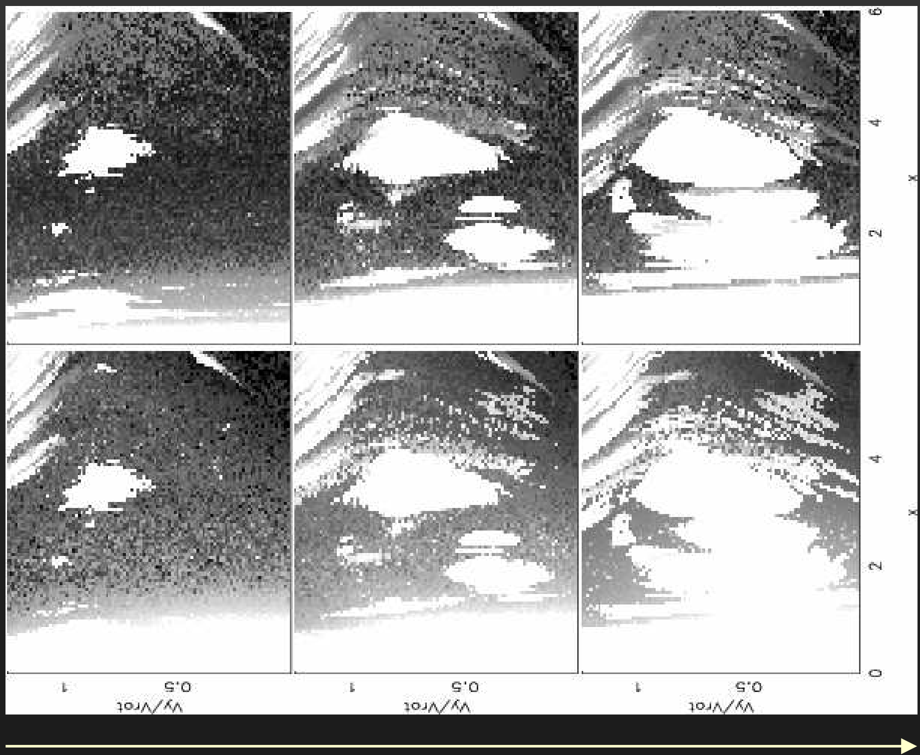
    (El Zant & Shlosman 2002; Berentzen, Shlosman, \& ,Jogee 2005)

Stability of a bar embedded in cold dark matter halos of different triaxiality

Halo b/a : Left=1.0 Right=0.95

Orbits: white= chaotic blue = regular

As triaxiality of DM halo rises, the fraction of disk stellar chaotic orbits increases, causing bars to weaken or dissolve



Do bars self-destroy? Do they reform?

Controversial topic… simulations make widely different predictions!

à Suicidal bars ? Bars produce a high central mass concentration. The latter then destroys the bar by inducing chaotic orbits and increasing the relative importance of x2-like orbits wrt x1-like orbits.

à Destruction of a bar is easy according to early work
Need mass inside r=100 pc to be ~1-2 % of mass inside CR of bar (e..g., Pfenniger & Norman 1990; Norman, Sellwood & Hasan et al. 1996)

à Destruction: less easy if DM halo is live versus rigid (e.g., Athanassoula 2003)

à Destruction: if it happens, it takes place much more slowly than thought earlier
(e.g., Shen & Sellwood 2004)

à Reformation of a bar once it is destroyed is difficult: it requires cooling of the disk as a destroyed bar leaves behind a lot of chaotic and dynamically hot orbits.

à Reccurent destruction/formation of bars via gas accretion (Bournaud & Combes 2004)
Gas accretion inside r<5 kpc of 4-5 M_o/yr over Hubble time
Destroy bar when gas is torqued in and stars gain L from gas inside CR
Reform bars via gas accretion which lowers B/D, lowers velocity dispersion
Bar lifetime <= 3-4 Gyr with gas accretion

Bars in the Young Universe
How long do bars live?

- Many present-day disk galaxies host bars. One third host strong bars

- Bars can shape the evolution of these present-day galaxies by redistributing mass, igniting central starbursts, helping to build bulges, etc

- Yet many fundamental unknowns…

à The Universe today is 13.7 billion years old.
When did barred spirals like our Milky Way form?
Were they present in the young Universe, 10 Gyr ago?
How did they evolve ?

à Are bars long-lived features that influence a galaxy over its lifetime or are they transient features that are easily destroyed?

How to study disk galaxies over the last 10 billion years?

Light from distant galaxies takes billions of years to reach us

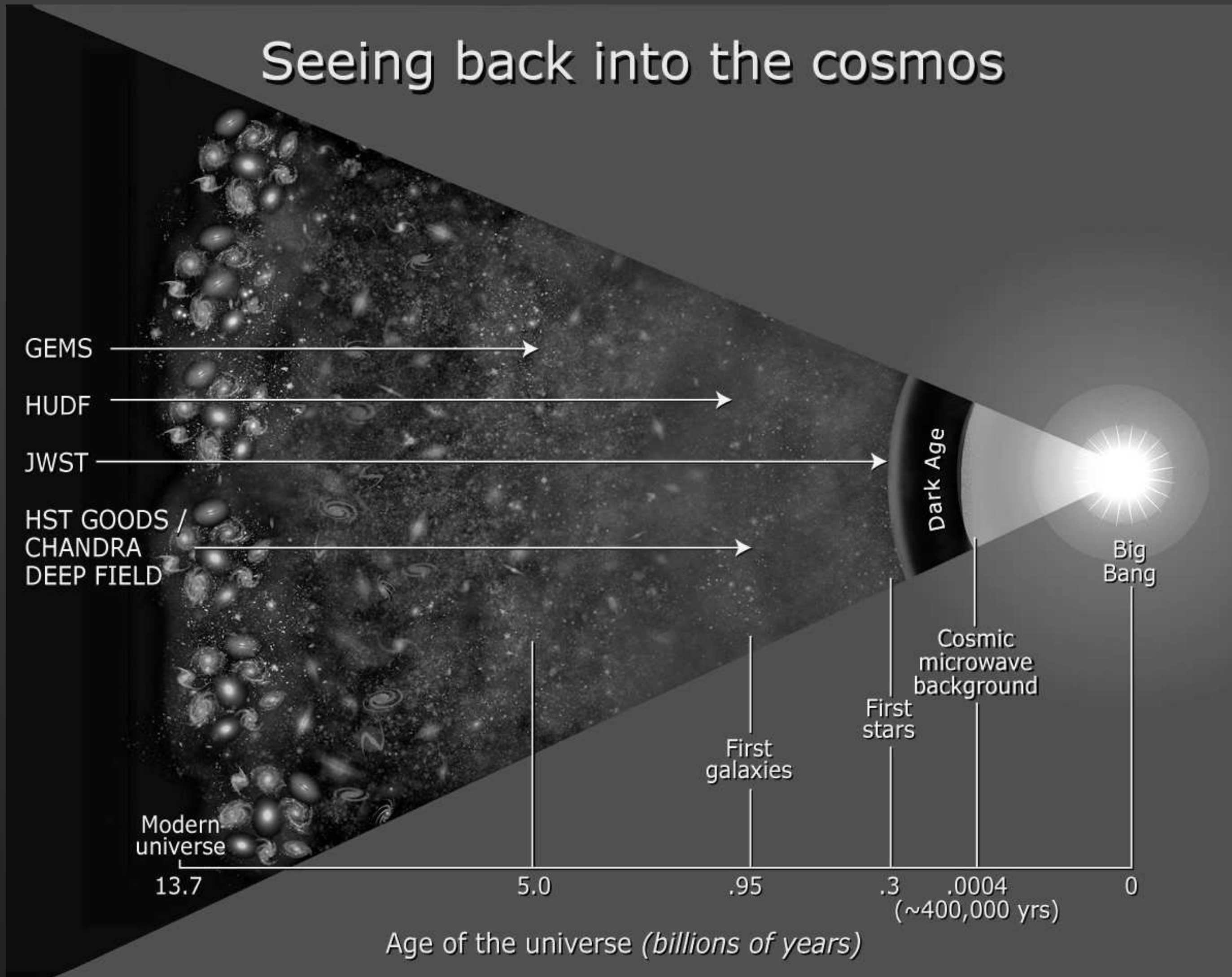
- à ***images of distant galaxies allows us to look back in time***
- à ***the larger the distance….the larger the lookback time***

To study the evolution of disk galaxies over last ~10 Gyr

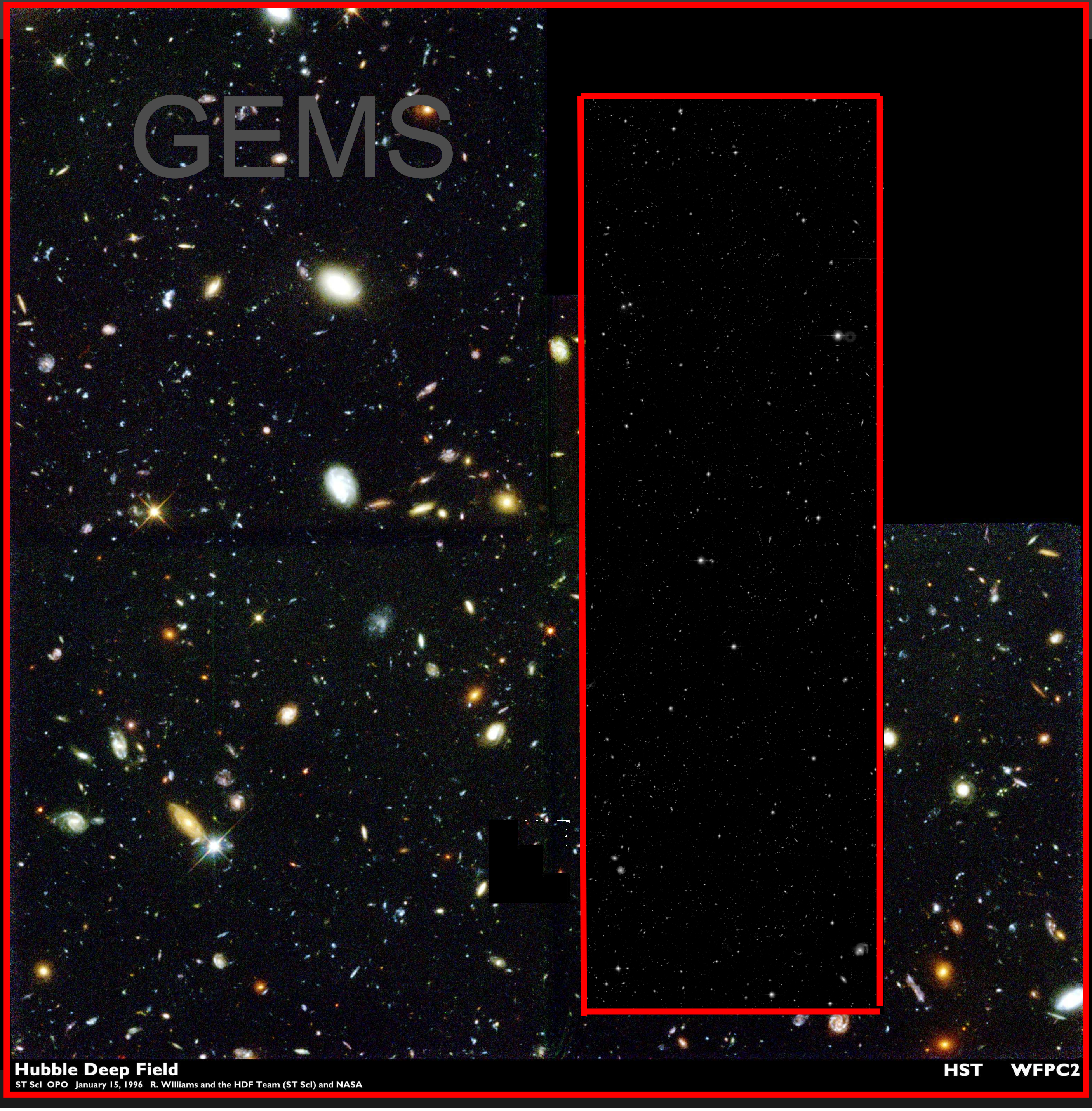
- à observe distant galaxies located up to 10 billion light years away
- à observe a large area in the sky
- à observe at high spatial resolution (HST)

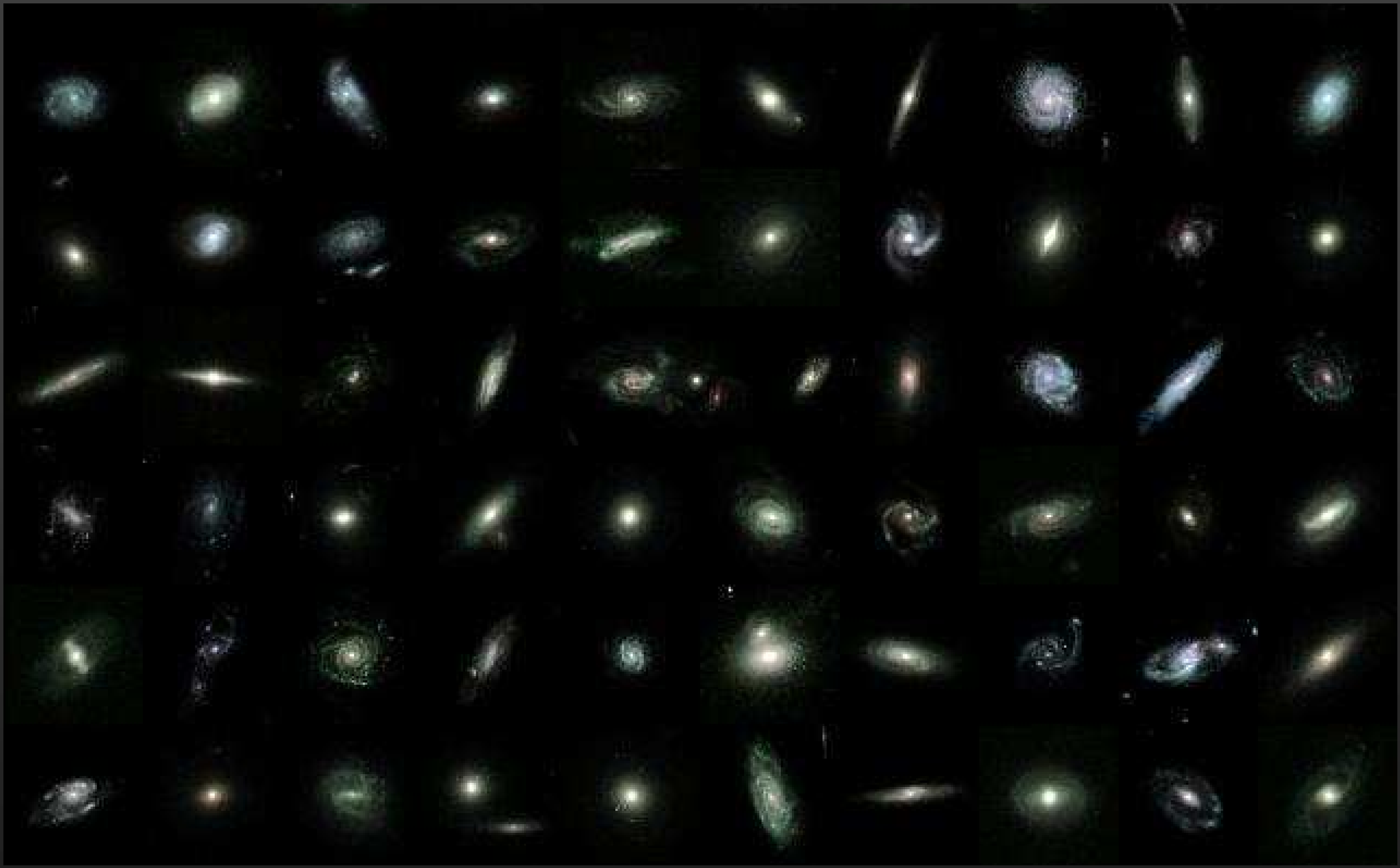
GEMS survey conducted with the Advanced Camera for Surveys on HST

- à **Largest-area ever imaged in 2 filters with HST** (120 x HDF)
- à **Images 10,000 galaxies present over last 9 billion years…… out to epochs when the Universe was only 1/3 of its present age!!**



GEMS: 10,000 galaxies present over last 9 billion years…… out to epochs when the Universe was only 1/3 of its present age


GEMS
Hubble Deep Field
ST ScI OPO January 15, 1996 R. Williams and the HDF Team (ST ScI) and NASA
HST WFPC2



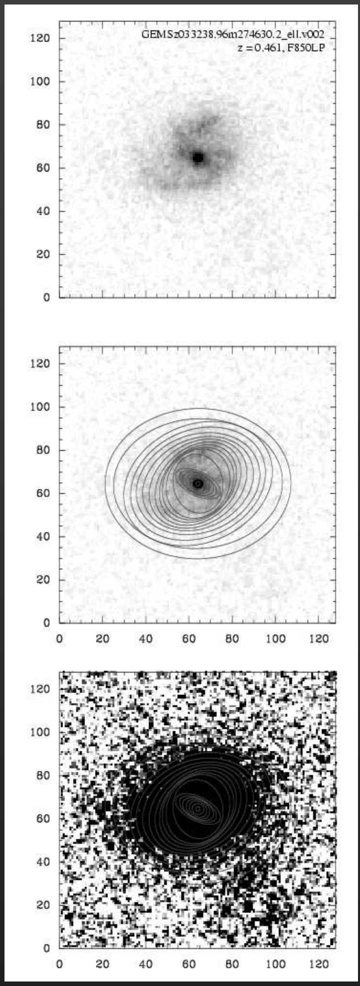
Diversiy of galaxies 9 Gyr ago, when Universe was only 30% of its present age!

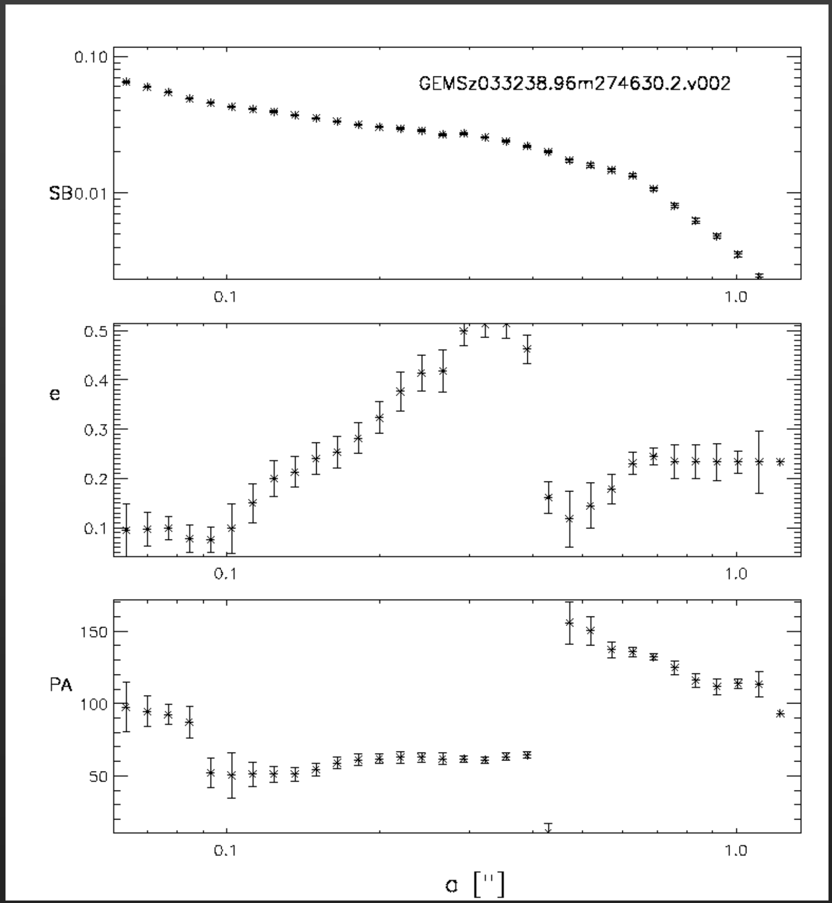
The family album of how galaxies looked in their ‘thirties’

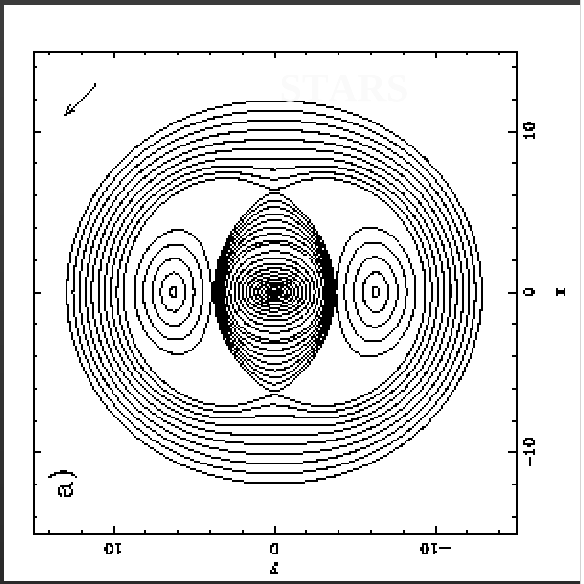
Bars and spirals in disk galaxies   when the Universe was 1/3 to 1/2 of its present age

(Jogee et al. 2004 and the GEMS collaboration)

Isophotal fits to identify bars/disks at z~1







Family of periodic stellar orbits conserving E_J : e.g., x_1 x_2

* Isophotes = guide to underlying stellar orbits.
* Bar = [Rise in e to a global max > 0.25 along with a plateau in PA]
  followed by
  [a drop in e >= 0.1 + generally a change in PA in the disk]

Selected Results

Earlier studies claimed that barred spiral galaxies were practically absent 8-9 Gyr ago (bar fraction <5%)

But we find that strongly barred spirals are as frequent 9 Gyr ago as they are today. The fraction of disks with strong bars remains ~ 30% over a wide range of epochs from 8-9Gyr ago to the present day. (Jogee et al . 2004)

Bars must have lifetimes well above 2 Gyr. They are therefore long- lived features of disk galaxies, persisting over most of the galaxy's life. (Jogee et al . 2004)

How do bars interact with a live triaxial dark matter halo?

Recent work/simulations (El Zant & Shlosman 2002; Berentzen, Shlosman, \& ,Jogee 2005) with live triaxial DM halos show that if the halo is triaxial an centrally concentrated, then

à Either it rapidly destroys the bar

à Or its triaxiality is reduced by the halo-disk- bar interaction

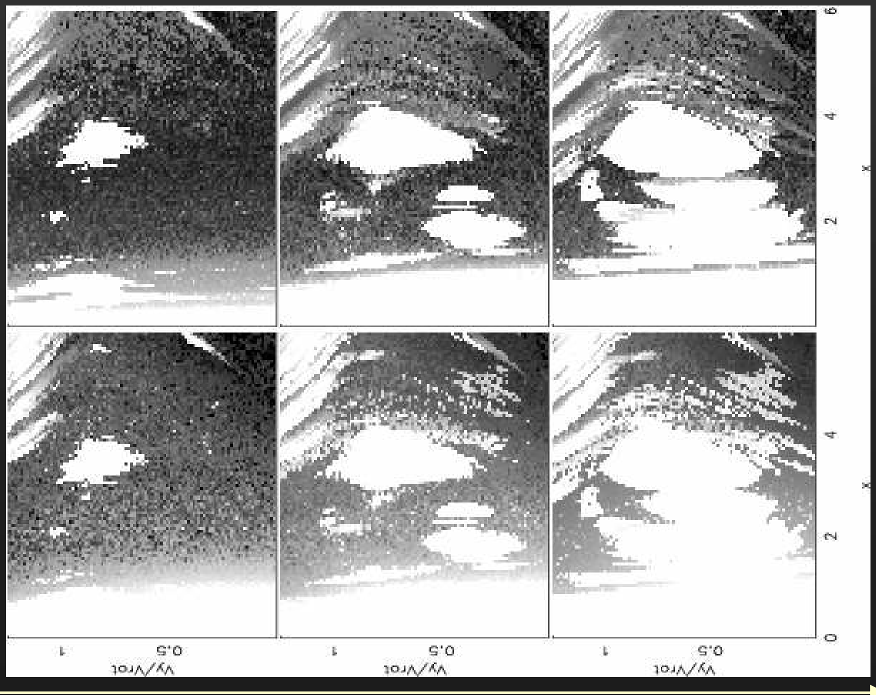
Conversely, abundance of bars at z~1 and their inferred long lifetime implies that DM halos at z~1 have low triaxiality left

Stability of a bar embedded in cold dark matter halos of different triaxiality

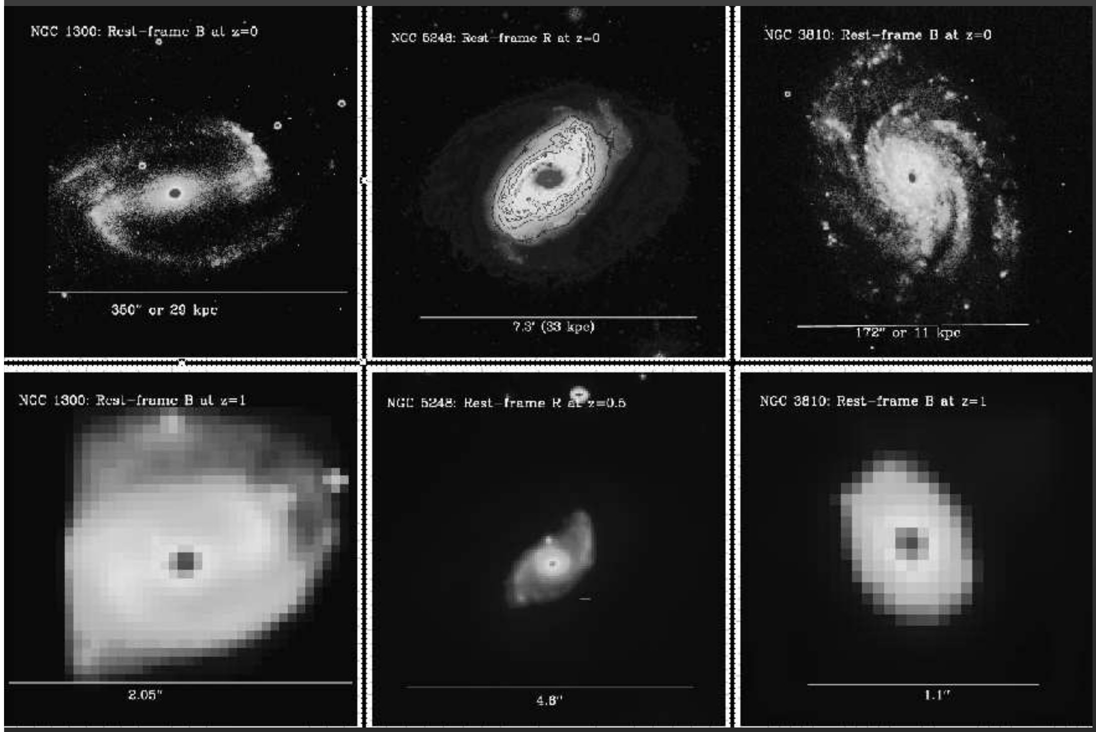
Halo b/a : Left=1.0 Right=0.95

Orbits: white= chaotic blue = regular

As triaxiality of DM halo rises, the fraction of disk stellar chaotic orbits increases, causing bars to weaken or dissolve



Artificial Redshifting of nearby galaxies to address systematics



From
z=0

To
z=0.6 (R)
z=1 (B)

- Need to understand/correct for redshift-dependent systematic effects

    Cosmological dimming, Loss in spatial resolution, [Bandpass shifting]

- Artificially redshift local "standard" sample of spirals : OSU,S2, SDSS

    à most weak small a<1.5 kpc bars not detectable in ACS images

    à weak bars with SF in very faint disks may be mistaken for disks with spirals

Open Issues/Ongoing Research

(Research Projects)