Astro 358/Spring 2006 (48915)

Galaxies and the Universe

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Lecture 15+16: Tu Mar 7 + Th Mar 09

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

OUTLINE

What are stellar bars?

Why are bars important for galaxy evolution ?
(Gas inflows, Starbursts, Disky psecudobulges, Secular evolution)

Can bars feed the central black hole? The ang momentum problem.

Dynamical resonances in a barred galaxy

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

Interaction of the bar with the DM halo

Are bars suicidal: do they self destroy?

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

What are Bars ?

1. Stellar bars are triaxial stellar systems, which

→ are flat in z direction compared to their dimensions in the x-y plane,
   a>c and b>c   where (a, b, c) are dimensions in (x,y,z).
→ are non-axisymmetric (elongated or oval) in the x-y plane
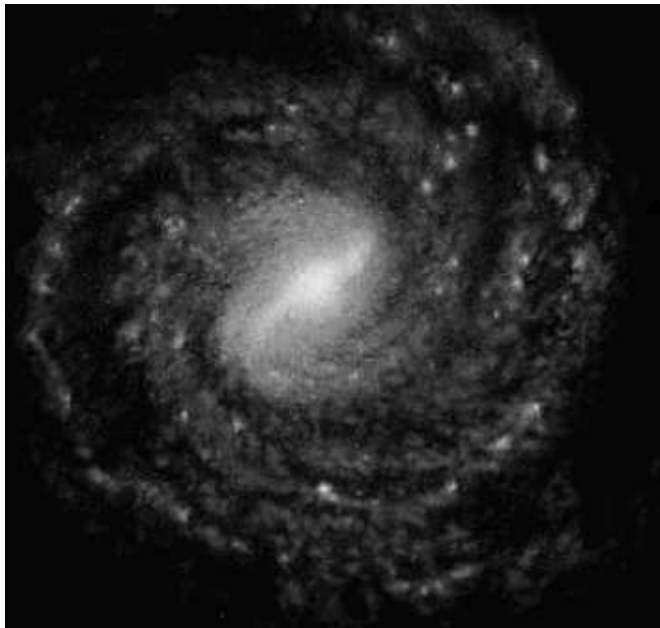   b/a < 1
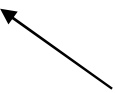

Unbarred spiral (SAab) NGC 4622
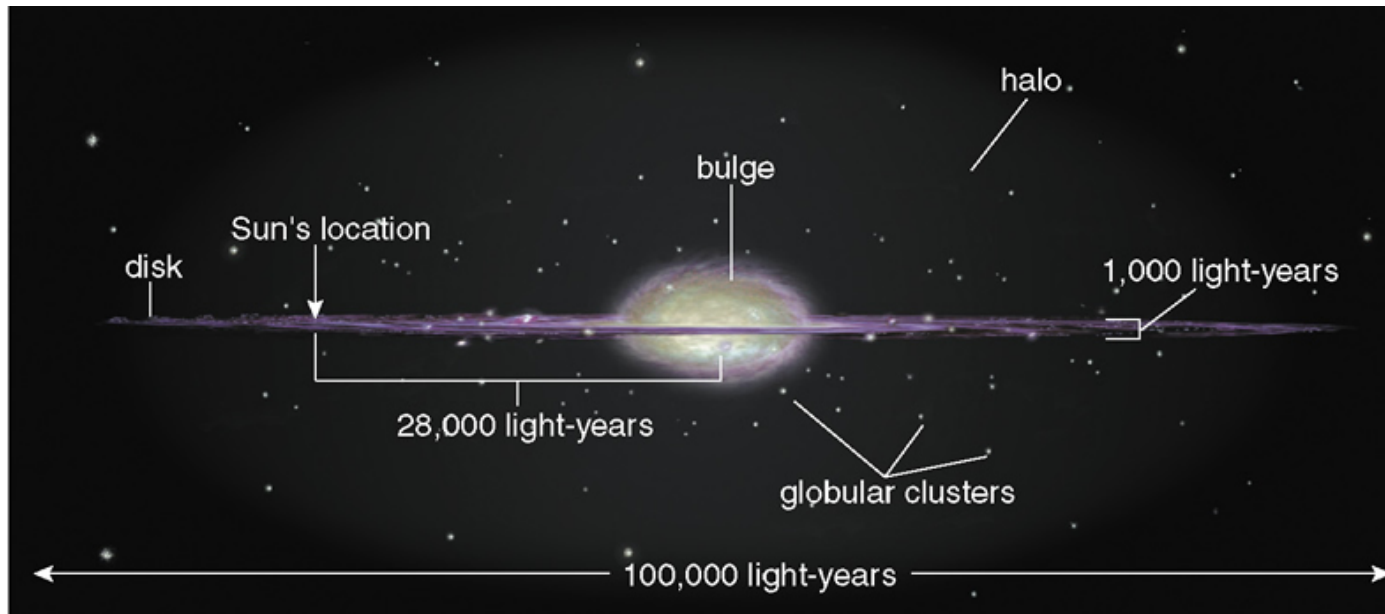

Strongly barred spiral (SB (rs) bc)
NGC 1300

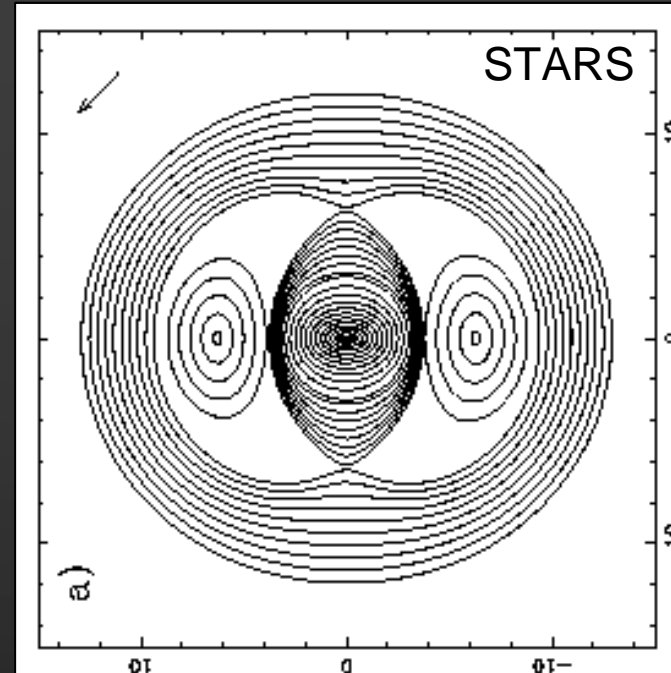# Milky Way = a barred (SBbc) spiral galaxy
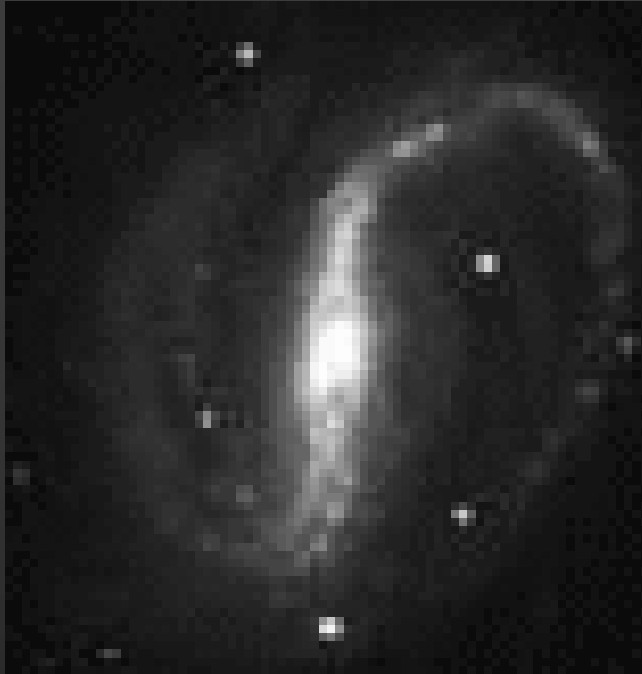

Face-on view
(Artist's conception)

Edge-on view :
Actual infrared image
from COBE satellite

halo

bulge

Sun's location

disk

1,000 light-years

28,000 light-years

globular clusters

100,000 light-years

Edge-on view
(Artist's conception)

Stellar orbits of a bar potential

STARS

Stellar bars are made up of families of periodic stellar orbits (x_1, x_2, x_3, x_4, etc) that conserve the Jacobi integral (E_J = combination of energy and angular momentum)

- Family of x_2 orbits : elongated perpendicular to the bar major axis

- Family of x_1 orbits : elongated along the bar major axis, support the bar

- Near the end of the bar : have chaotic orbits

- Further out: have complex orbits and circular orbits (in the outer disk)

Bar Pattern Speed
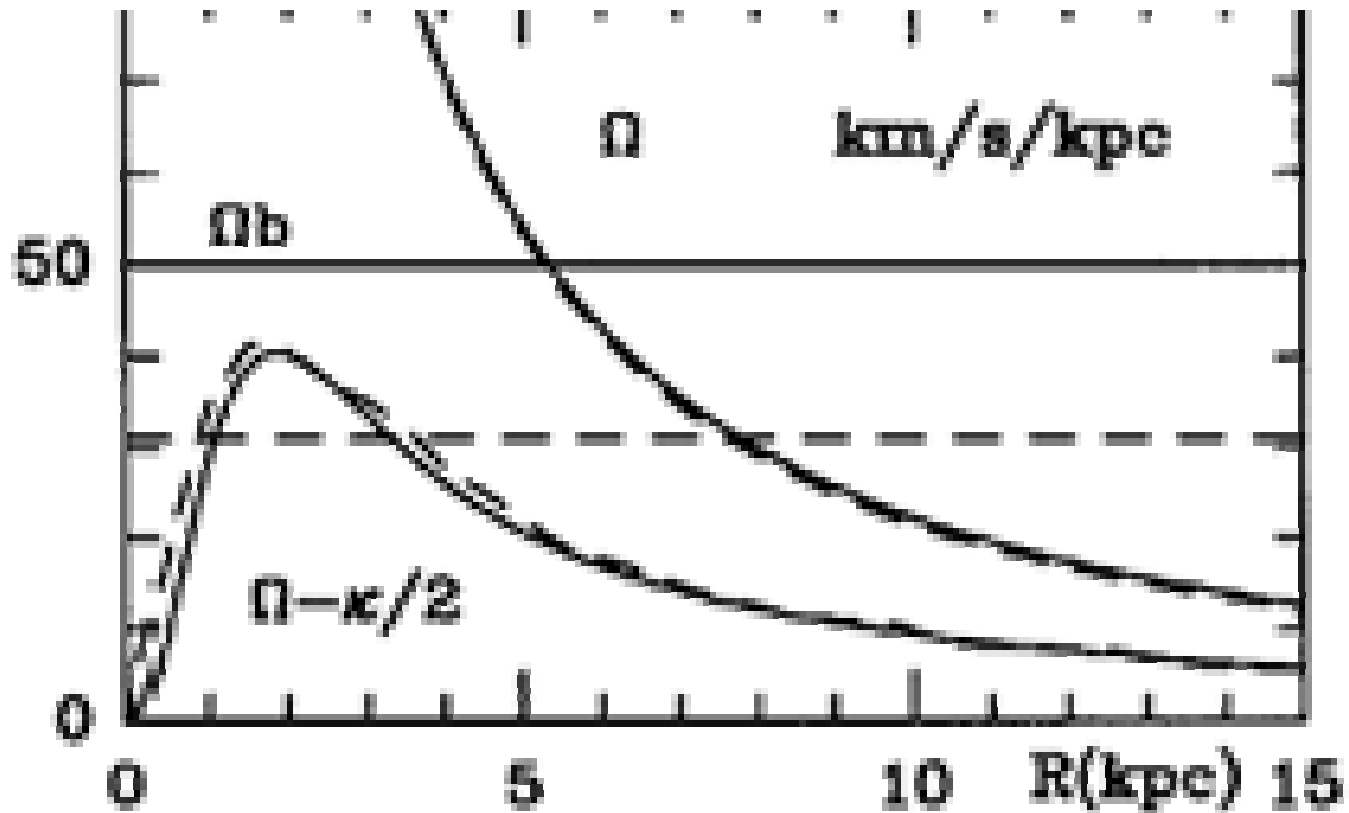
- Bars rotate with a rigid (radius independent) angular frequency called   the bar pattern speed Ω
- See in-class notes

Ellipticity of a bar as a measure of its 'strength'
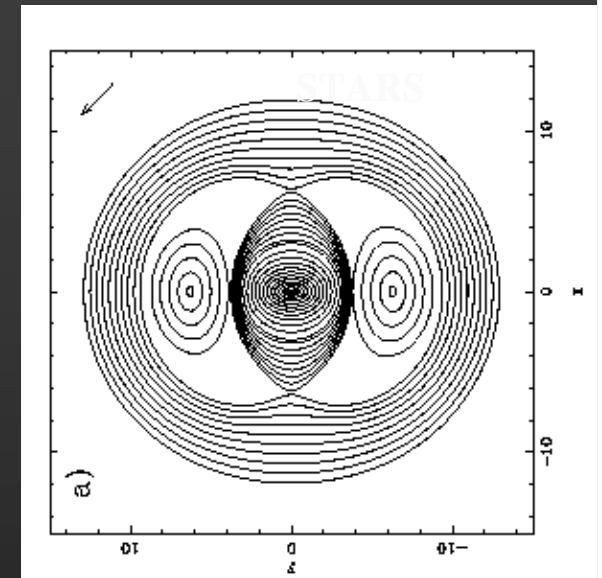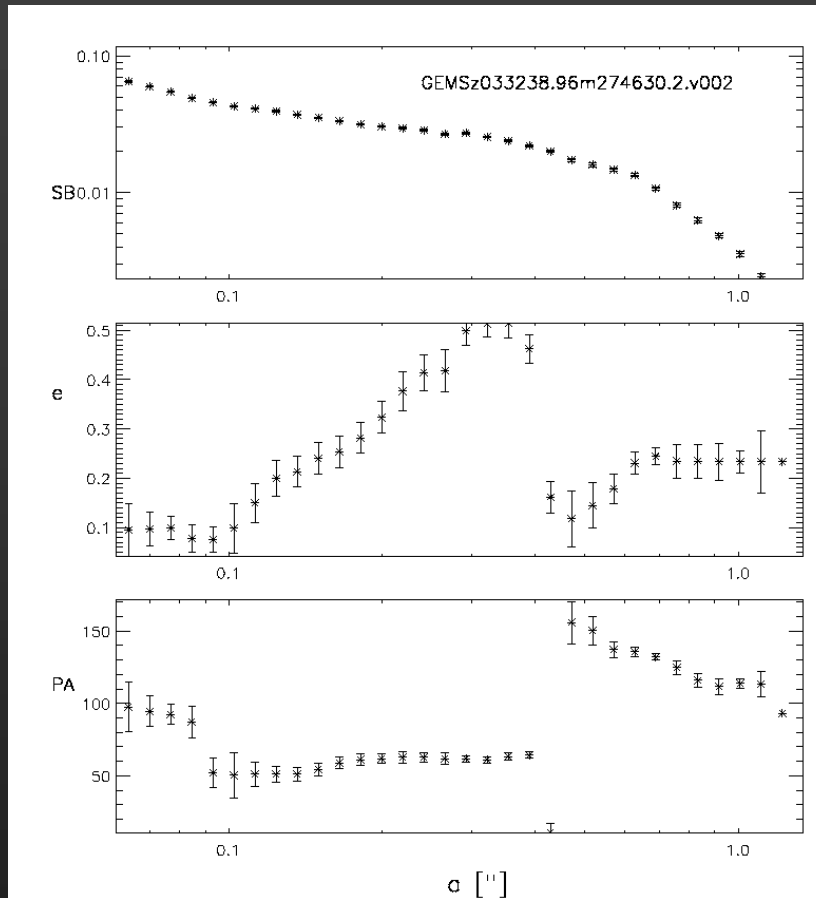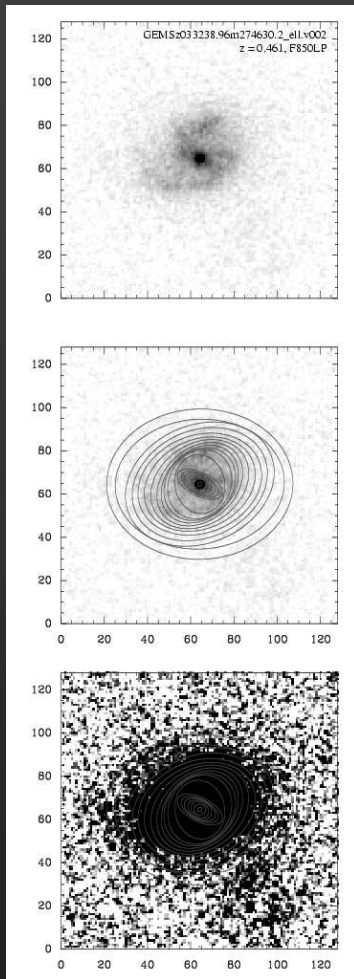
The ellipticity (e_max = 1 –b/a) of the outermost isophote of a bar can be used as a measure of its strength

High e   à Thin or highly elongated bar à 'strong' bar

Low e   à Thick or oval bar à 'weak' bar

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

"Weak" vs. "Strong" Bars

Strongly barred spiral (SB (rs) bc) NGC 1300

Weaky barred spiral (SABc) NGC 674

Why are bars important for galaxy evolution ?

Bars redistribute mass and angular momentum in disk galaxies and thereby drives their dynamical, morphological and structural evolution

1. Bars very efficiently removes angular momentum from gas in the outer disk of a galaxy and drives the gas into the central few 100 pc.

à The gas does *not* go all the way to the center but 'piles up' on scales of r =200-600 pc due to the effect of the gravitational potential and dynamical resonances (see later notes for details)

à The bar increases the central gas concentration and central mass buildup in galaxies.
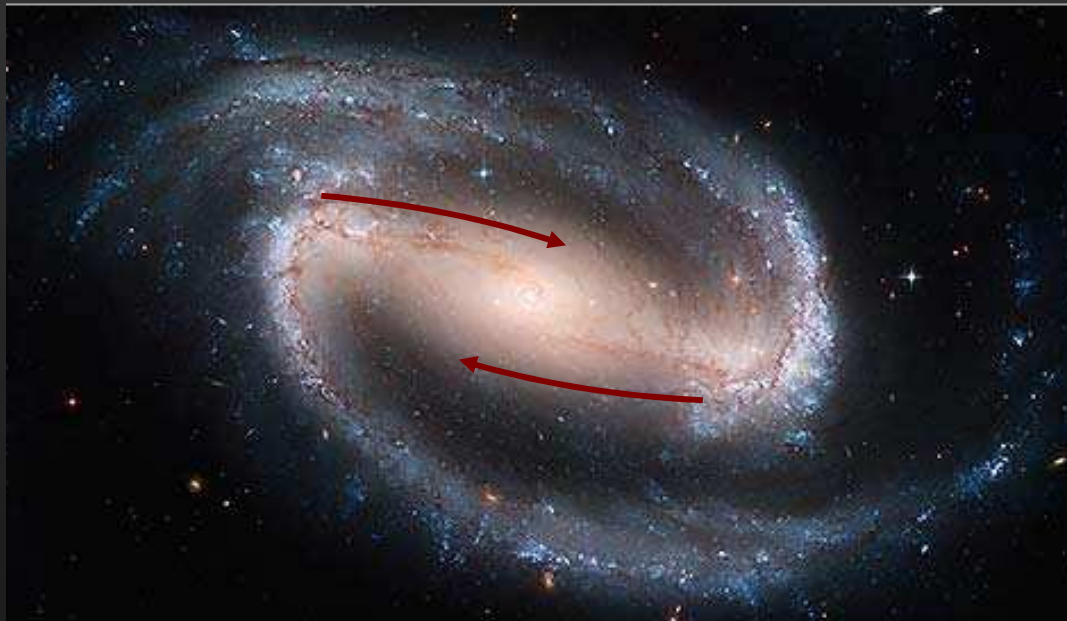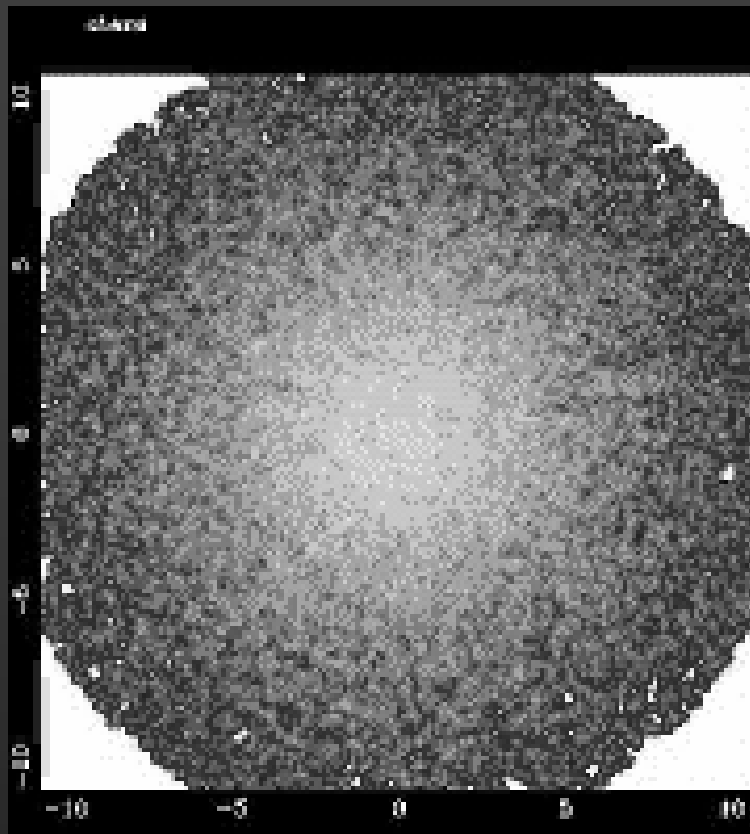
Stars in the disk
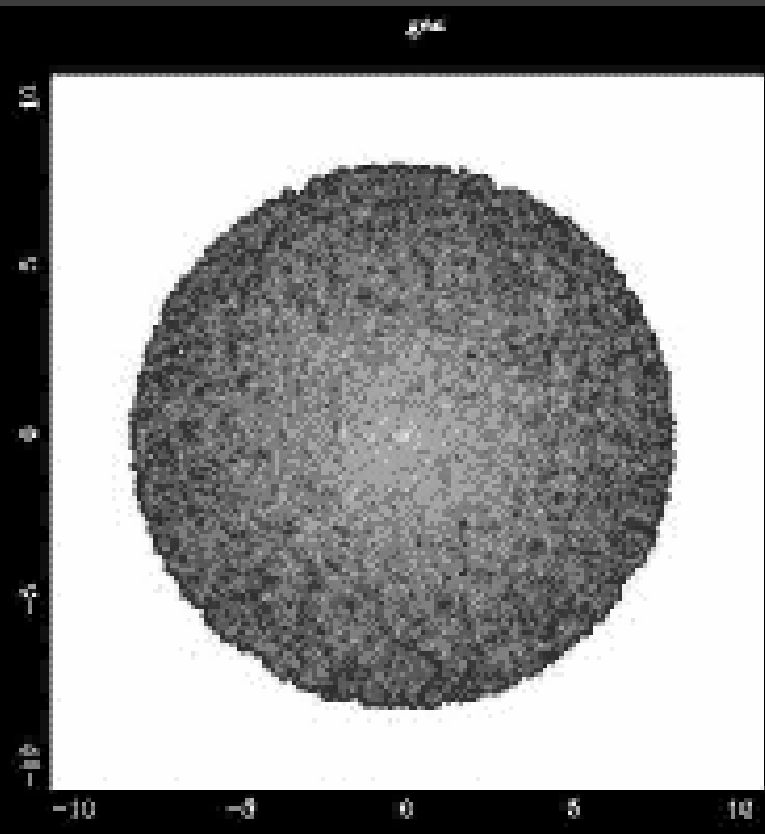
Gas in the disk

Simple simulation of a disk with gas and stars, but no DM halo.

à Stellar disk forms a stellar bar (m=2 instability), while gas response forms spiral trajectories.

à Bar drives most of gas into central few 100 pc

2. Bar-driven gas inflows into central few 100 pc lead to luminous (L up to 10 billions Lo) episodes of star formation called starbursts

à   Gas piles up in rings or disks at r ~200 – 600 pc
à Once gas density is high enough, gravity overcomes pressure support and gas on the rings/disk collapses to form stars

NGC 4314: CO (1-0
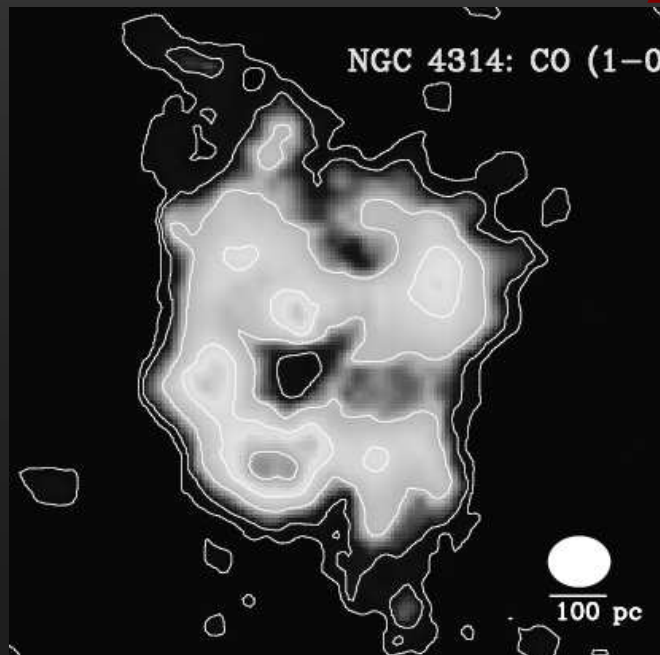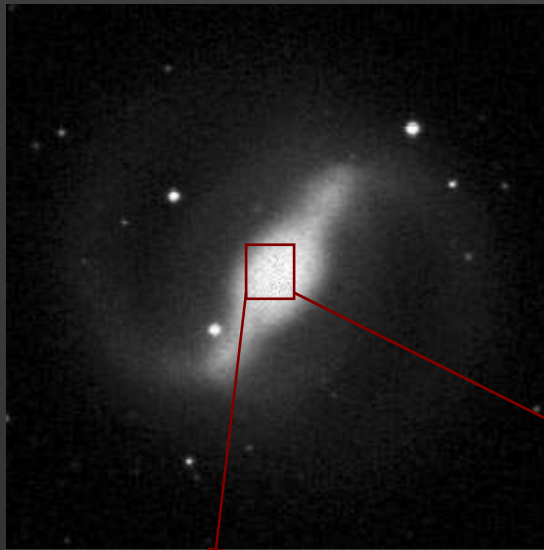
100 pc

Gas ring of r=300 pc

Starburst ring of young new stars is forming in gas ring

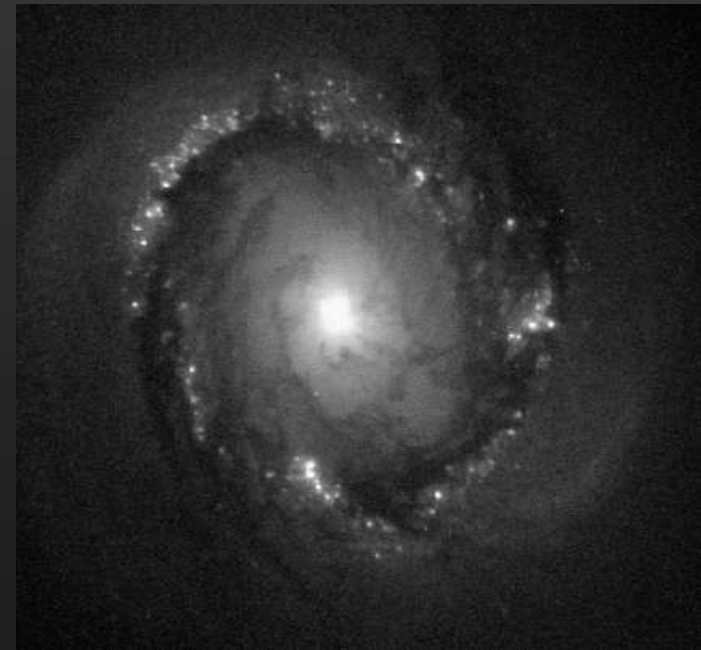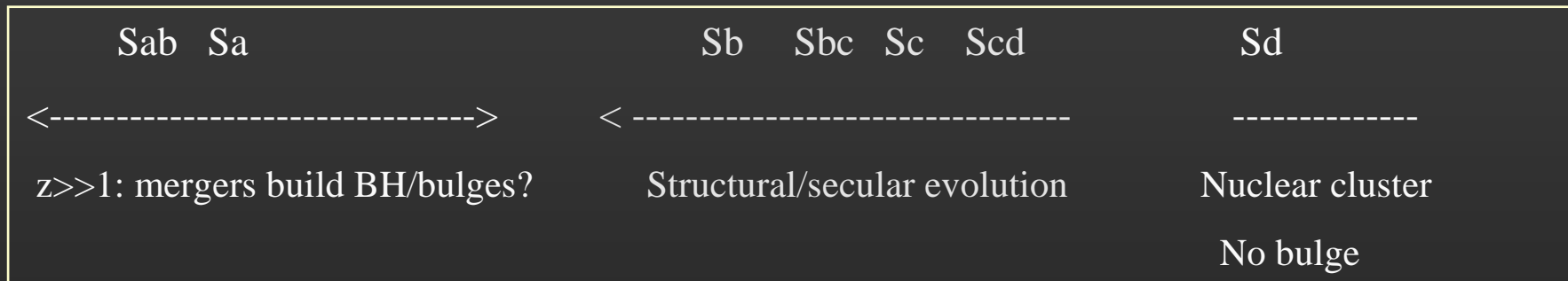3. Bar-driven gas inflow into the central few 100 pc help to build disky (high V/σ) pseudobulges with exponential SB profiles:

à   Gas piles up in rings or disks at r ~200 – 600 pc
     Once gas density is high enough, gravity overcomes pressure support
     and gas on the rings/disk collapses to form stars

à   Disk or rings of young stars form. Vertical instabilities can puff/thicken
      them up. This young stellar component is disky (has high V/σ) and
      have an exponential SB profile : it is called a pseudobulge

à   If an older 3-D de Vaucouleurs bulge already exists, the disky expon
      pseudobulge can sit inside it

à The SB profile for the central kpc of this galaxy will be dominated
     by either a de Vaucouleurs SB profile or by an exponential SB profile
     depending on how luminous the old bulge is w.r.t. the pseudobulge

à See in-class notes

4. It is suggested that bars can drive secular evolution along the Hubble sequence:

à Bars may convert a spiral of late Hubble type (e.g. Sc) into a slightly earlier Hubble type (e.g., Sbc) by driving gas inflows from disk to central regions, building pseudobulges, increasing B/D ratio

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

Note: The largest bulges in (Sa) probably formed via major merges (merger of 2 disk galaxies of similar mass)

larger bulge, less dusty gas, tighter spiral arms

SBa   SBb   SBc
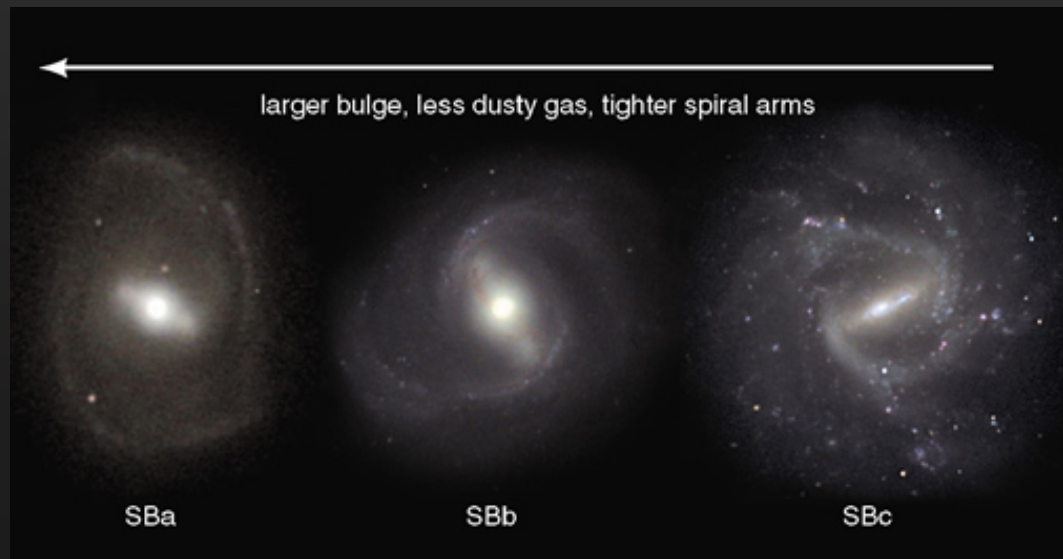
5. Bars or/and tidal pertubations drive spiral arms, especially grand-design spiral arms.

6. Bars exchange angular momentum with the most massive component of a galaxy --- the dark matter halo --- and this interaction can change the shape of the dark matter halo

7. Most present-day spiral galaxies including Milky Way (SBbc) host a bar !

f_{bar} = bar frequency

= % of spiral galaxies that host a large-scale stellar bar.

For present-day galaxies

à At optical λs 30% of spirals have a strong bar, 25% a weak bar

à At near-IR λs, 56% of spirals have a strong bar, 16% a weak bar

	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%

8. Bars are abundant over at least the last 9 Gyr (65% of age of
   the Universe) and can affect a galaxy over most of its lifetime !

Earlier studies (Abraham et al 1999; van den Bergh et al 2000) :

à Less than 5% of spirals had strong bars ~9 Gyr go
à barred spiral galaxies, like the Milky Way are practically absent 8 Gyr ago

New studies (Jogee et al 2004; Elmegreen et al 2004)

à   strongly barred spirals are as frequent 9 Gyr ago as they are today.
    The fraction of disks with strong bars remains ~ 30% out to 9Gyr ago
     (see later for details)

à This suggests that bars are likely to be long-lived, hard to destroy, and
    can affect their host galaxy over a large fraction of the galaxy's life
     (Jogee et al 2004)

à This result consistent with new simulations of bar lifetime (e.g., Shen &
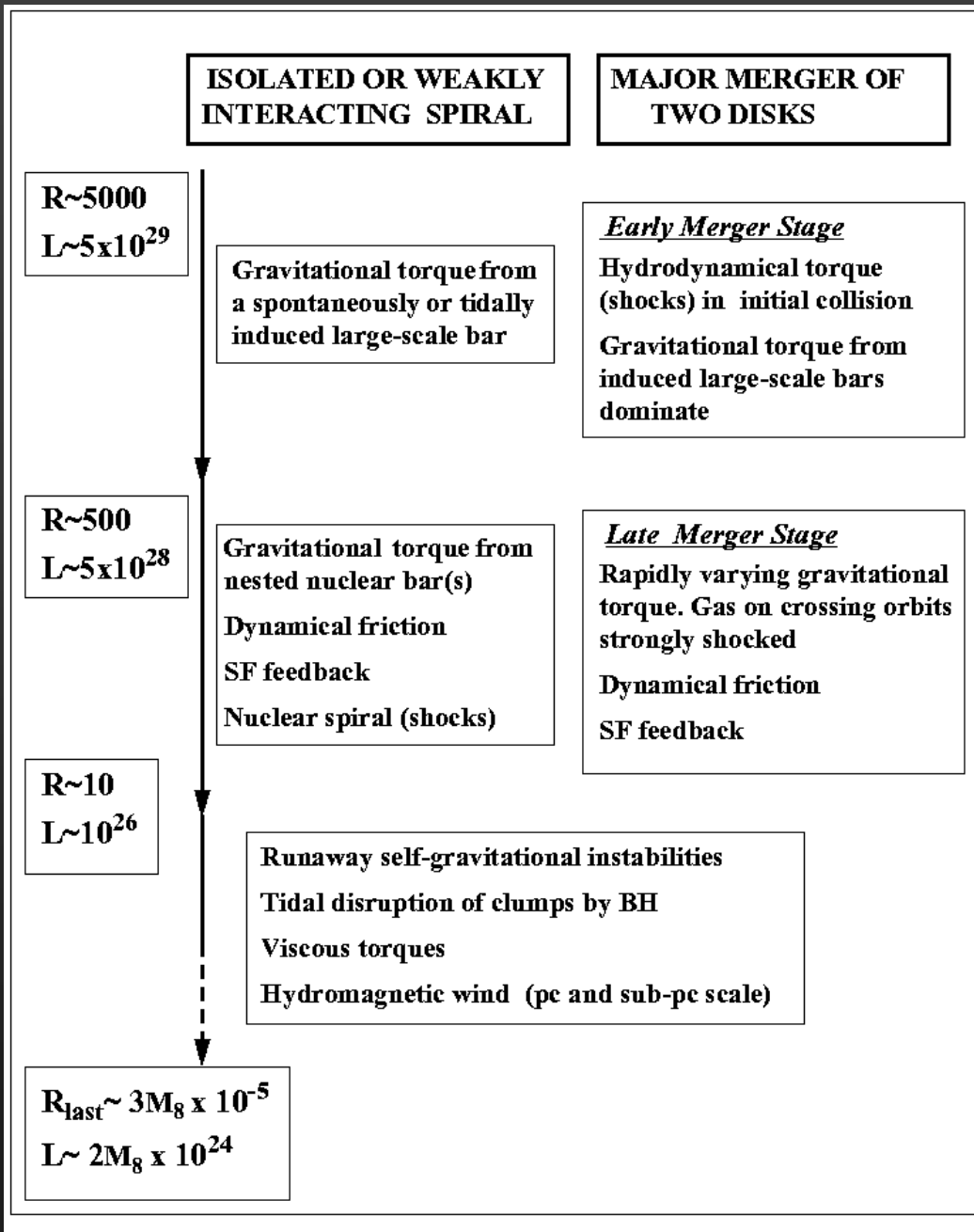   Sellwood 2004) See guest lecture by Shen and paper (SS 2004)
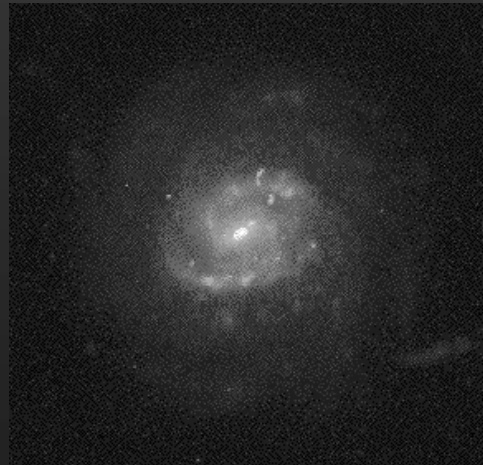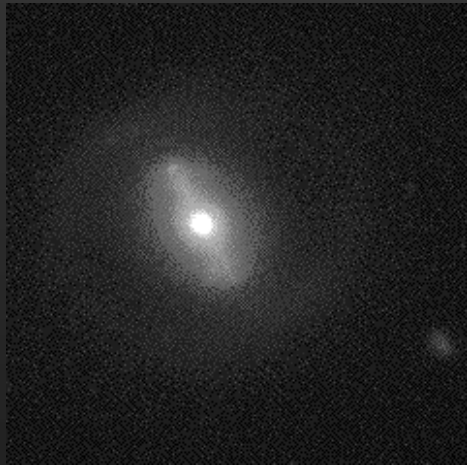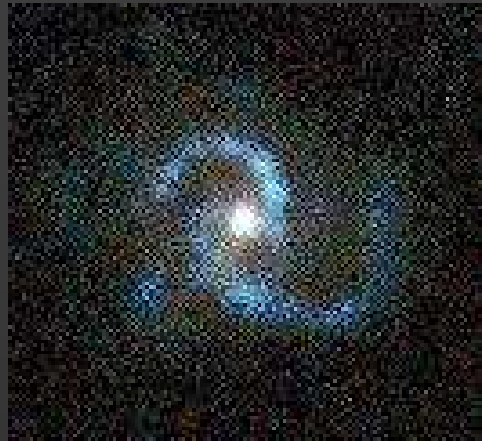
Bars and spirals in disk galaxies   when the Universe was 1/3 to 1/2 of its present age

(Jogee et al. 2004 and the GEMS collaboration)

Can bars feed the central black hole?
The Angular Momentum Problem

Fueling Black Holes The Angular Momentum problem

Location of gas cloud	Ang mom per unit mass $L = r \times v$ 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

ISOLATED OR WEAKLY INTERACTING SPIRAL	MAJOR MERGER OF TWO DISKS

$R\sim 5000$
$L\sim 5\times 10^{29}$

Gravitational torque from a spontaneously or tidally induced large-scale bar

Early Merger Stage
Hydrodynamical torque (shocks) in initial collision

Gravitational torque from induced large-scale bars dominate

$R\sim 500$
$L\sim 5\times 10^{28}$

Gravitational torque from nested nuclear bar(s)

Dynamical friction

SF feedback

Nuclear spiral (shocks)

Late Merger Stage
Rapidly varying gravitational torque. Gas on crossing orbits strongly shocked

Dynamical friction

SF feedback

$R\sim 10$
$L\sim 10^{26}$

Runaway self-gravitational instabilities

Tidal disruption of clumps by BH

Viscous torques

Hydromagnetic wind (pc and sub-pc scale)

$R_{last}\sim 3M_8 \times 10^{-5}$
$L\sim 2M_8 \times 10^{24}$

(Jogee 2005 ,Chapter 6, Textbook "AGN Physics on All Scales")

Stellar Obits and Dynamical Resonances of Bars

Stellar Obits and Dynamical Resonances of Bars

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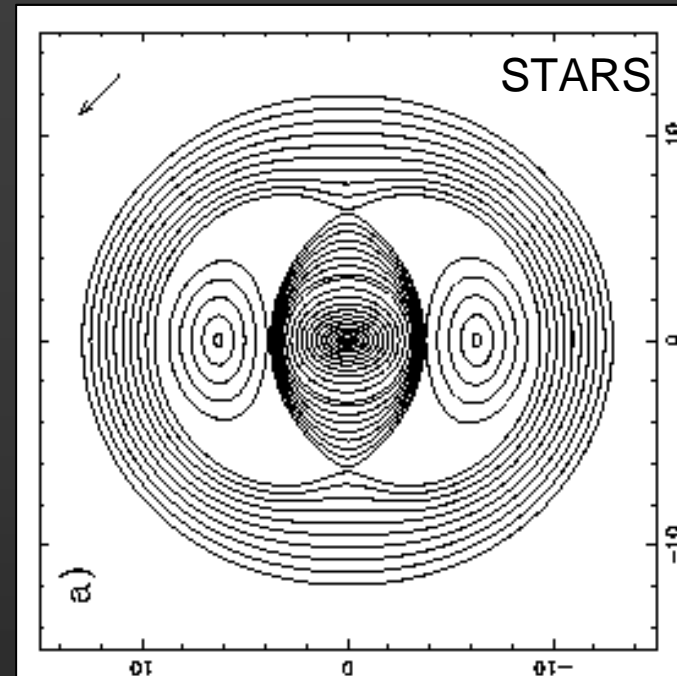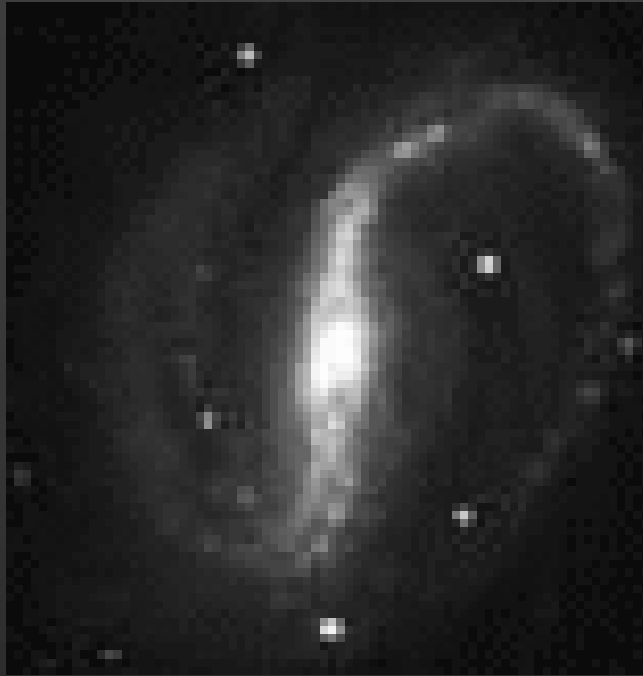
See in-class note : Resonances for both weak and strong bars can be defined in terms of which family of stellar orbits (x_1, x_2, x_3, x_4, chaotic, etc) dominate

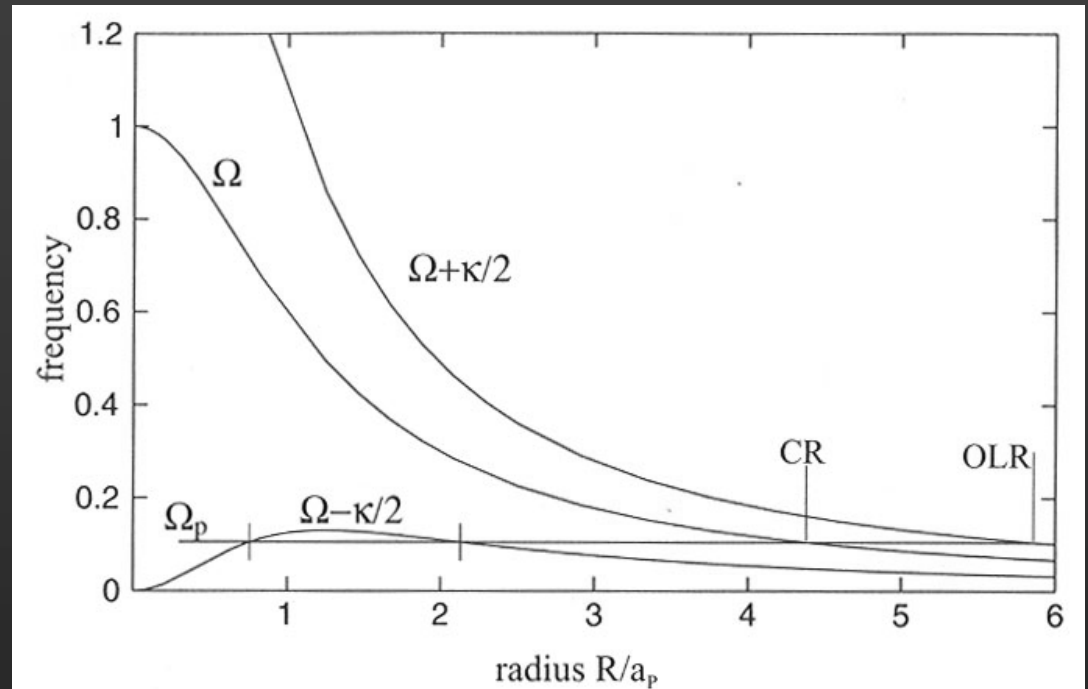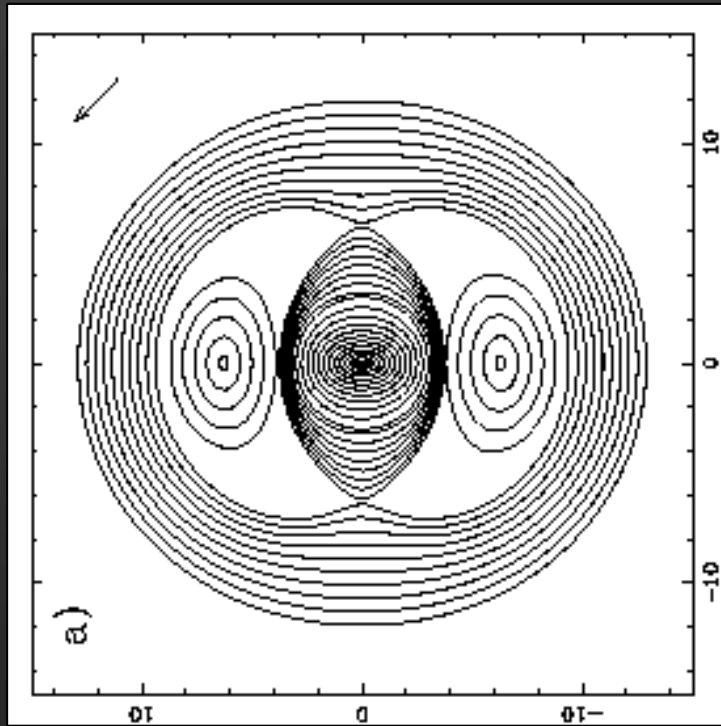à Between Inner Lindblad Resonances (ILRs) dominant orbit family = x_2

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

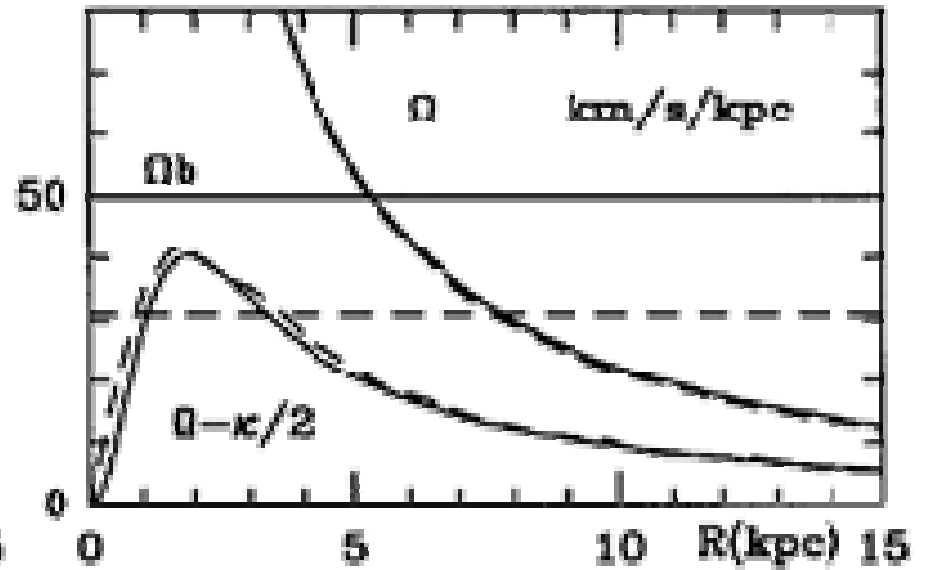# *Stellar Obits and Dynamical Resonances of Bars*

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) .

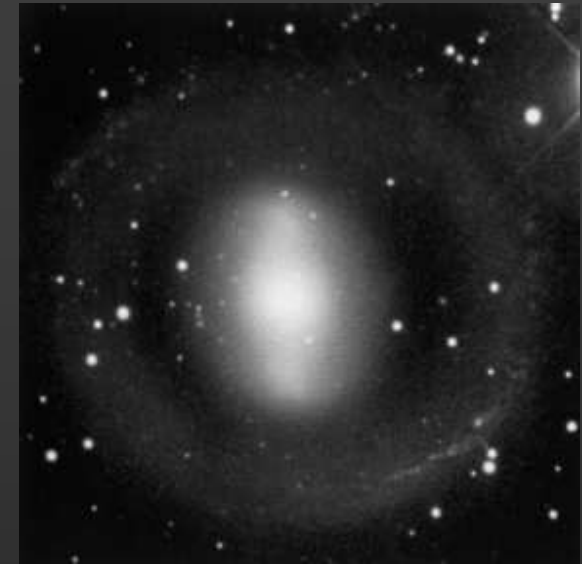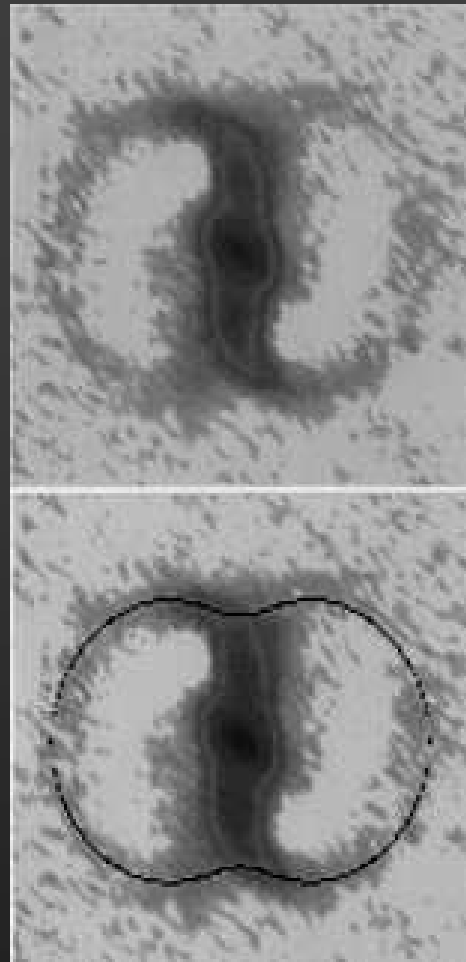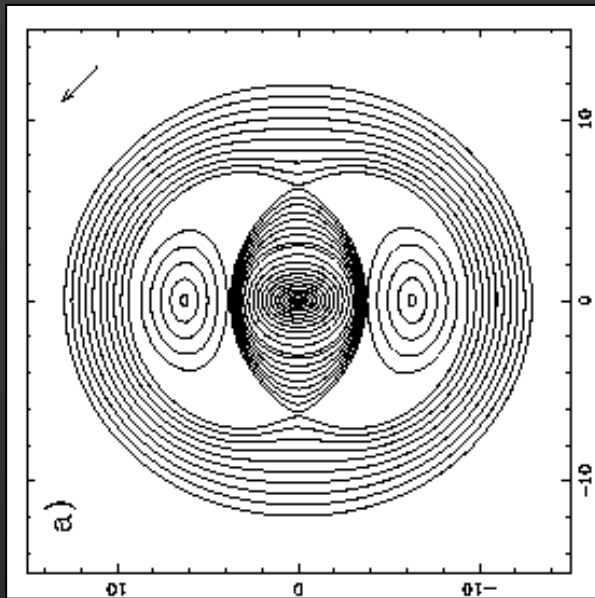See in-class notes for equations.

Bars
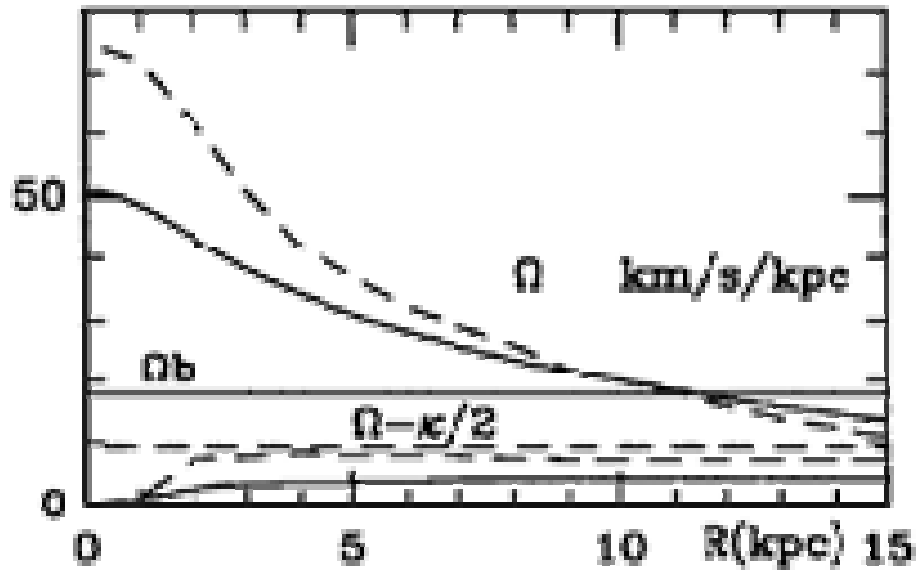
Weak bar with no ILRs

Weak bar with two ILRs

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

$$\Omega - k/2 > \Omega_b \quad \text{(condition for ILR in a weak bar)}$$

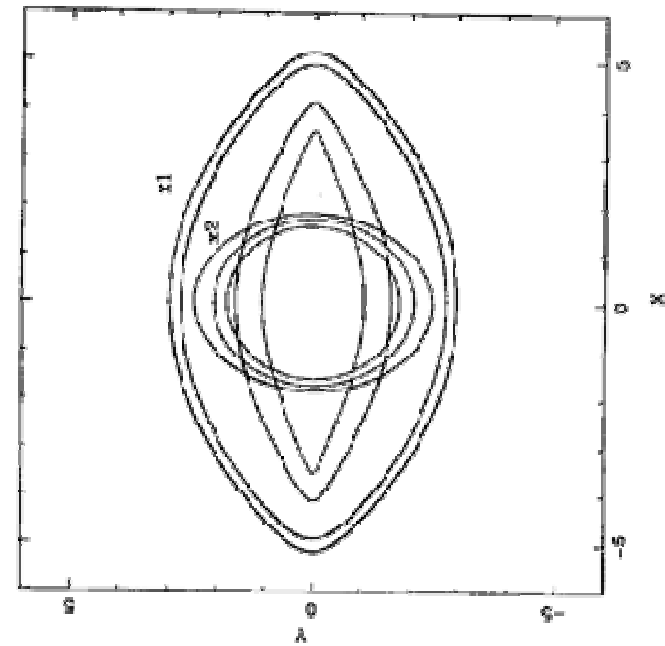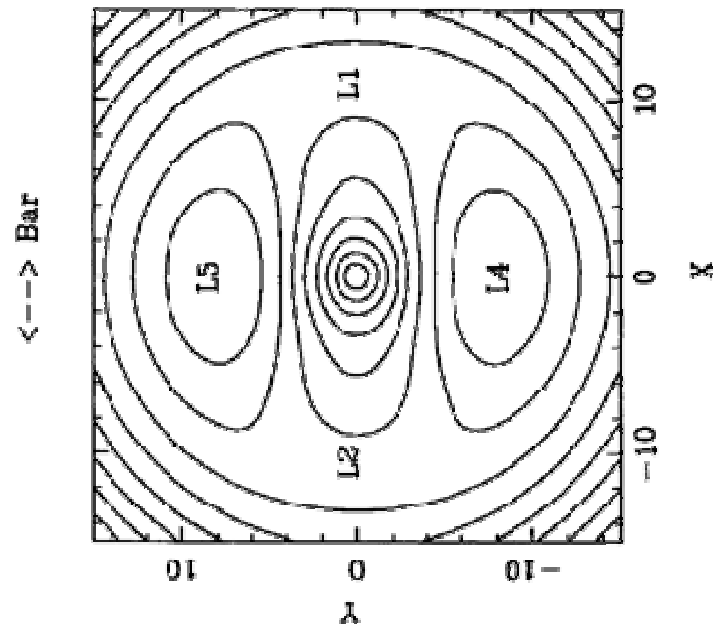# *Stellar Obits and Dynamical Resonances of Bars*

Outer rings: NGC 1543
(OLR orbit family?)

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

Note similarity between stellar orbits and observed stellar features in galaxies
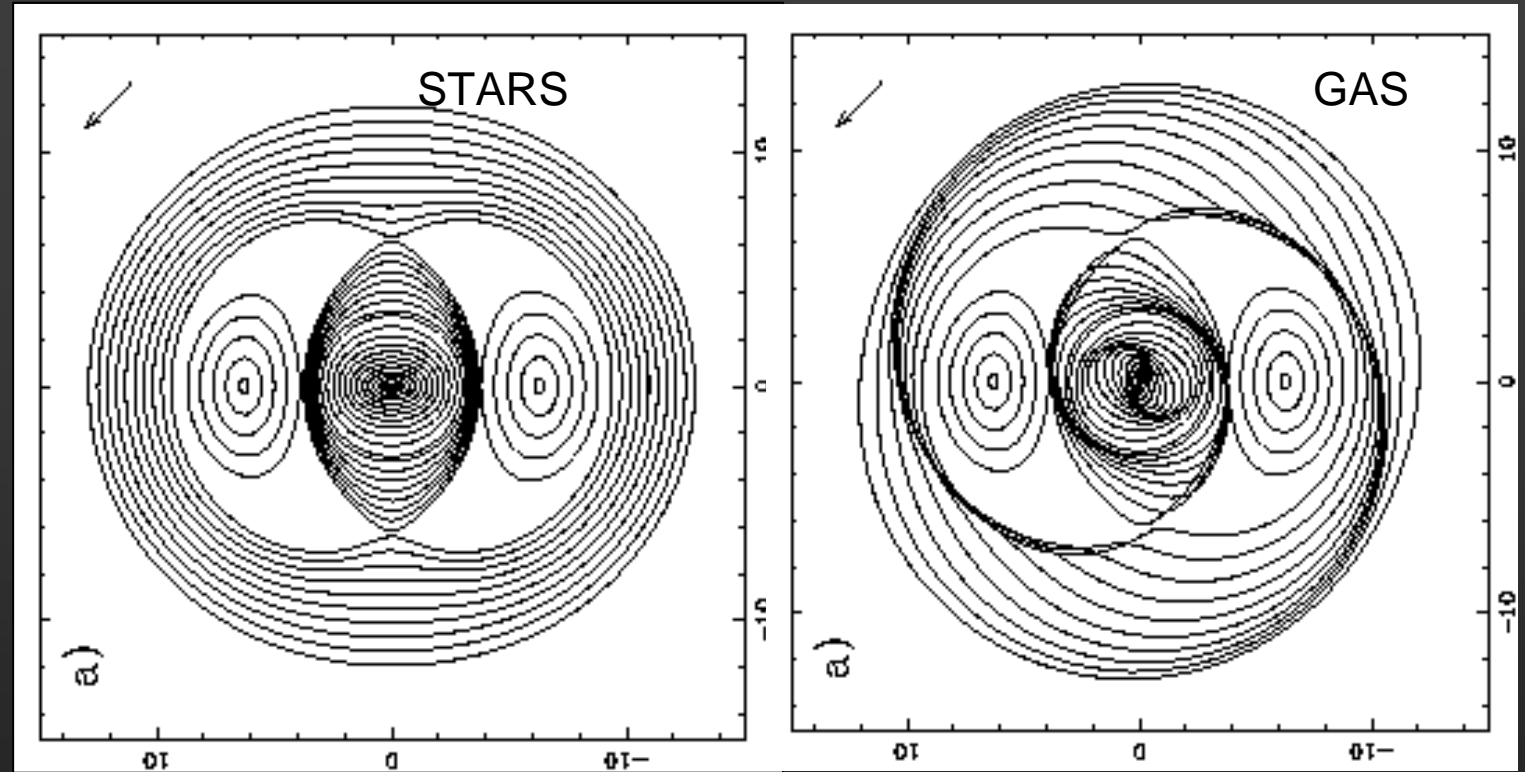
Bars

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

Can express dynamical resonances in terms of Lagrange points

How Do Bars Drives Gas Inflows?

Bar-Driven Gas Inflow

STARS

GAS

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)
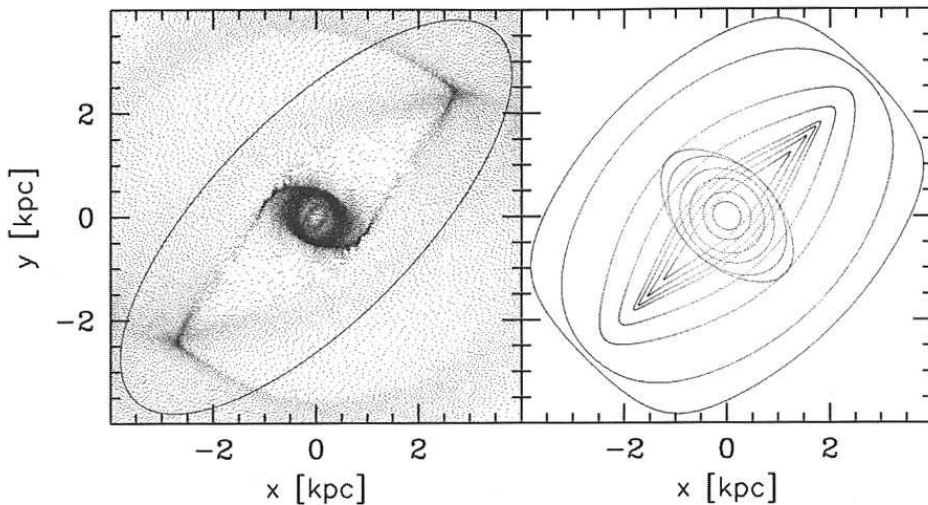
Bar-Driven Gas Inflow

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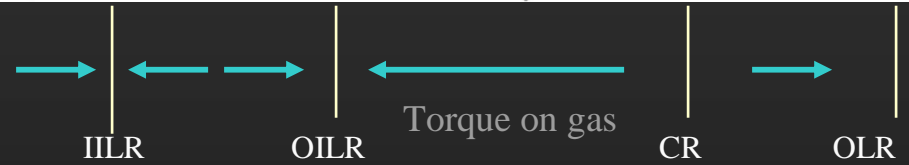
Gas shocked on leading edges of bar
+ torque inside CR drive it inward

Bar-Driven Gas Inflow

(Buta & Combes 1996)

Torque on gas

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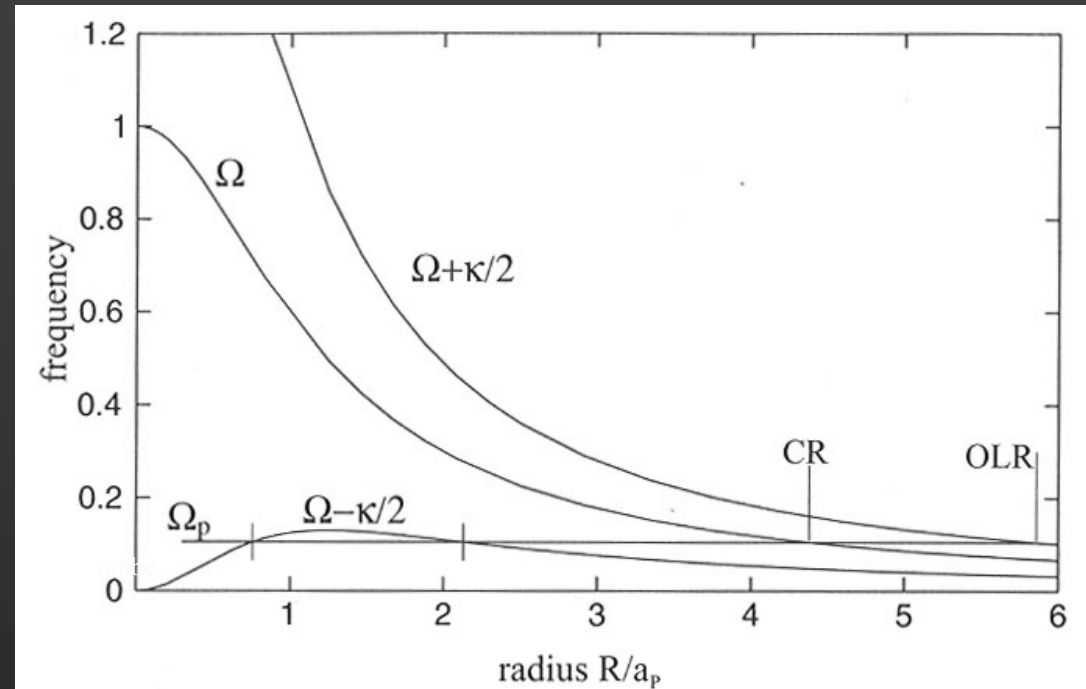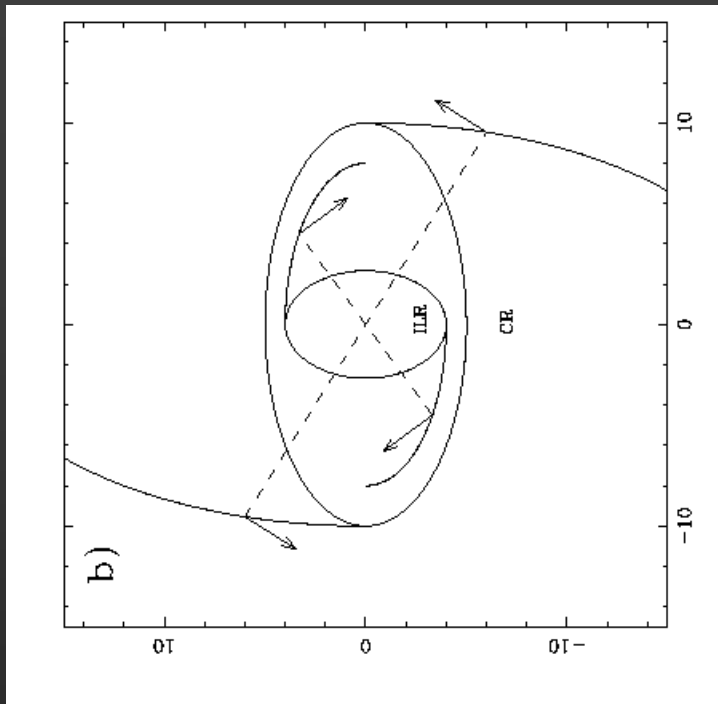
Gravitational torque on gas (T = **r** x **F**) varies near different resonances. Can remove or add angular momentum (L = **r** x **v**) -- see class notes

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
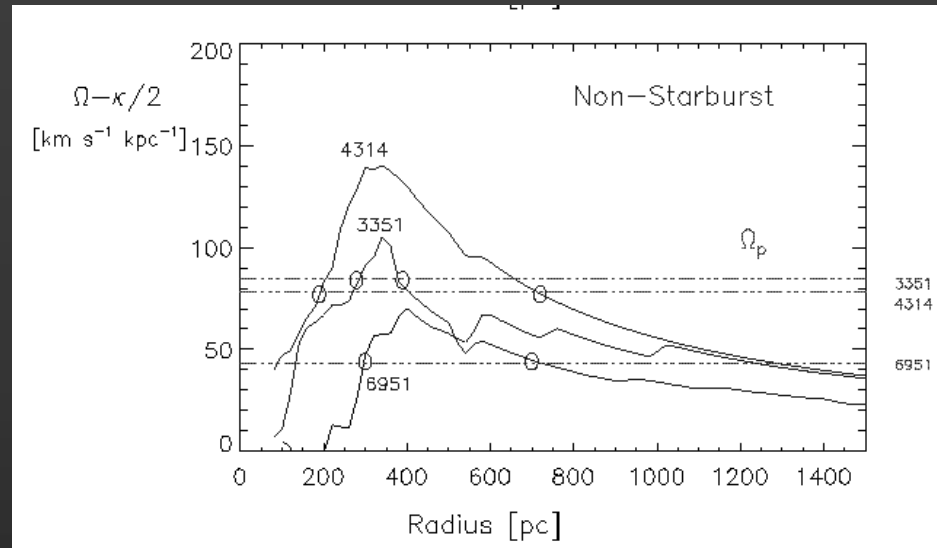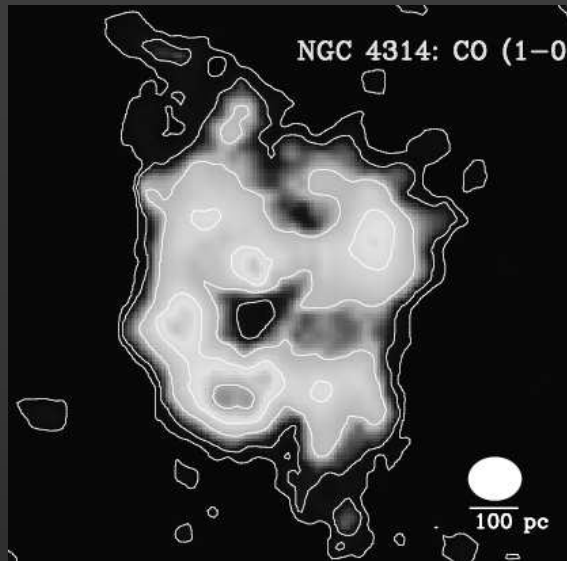
(Jogee, Scoville & Kenney 2005)

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

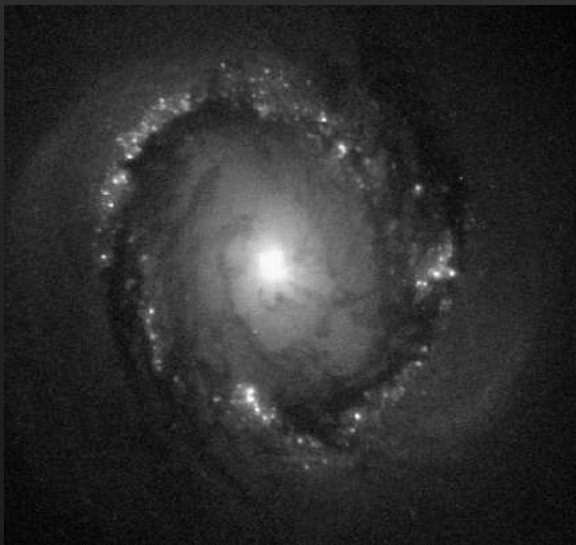# *Interaction of Bar with DM halo*

- 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)

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

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

C) Athanassoula (2003) used <u>live axisymmetric</u> DM halos
     - A massive DM halo can make a bar stronger due to resonant interactions
       and angular momentum exchange

(D) 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
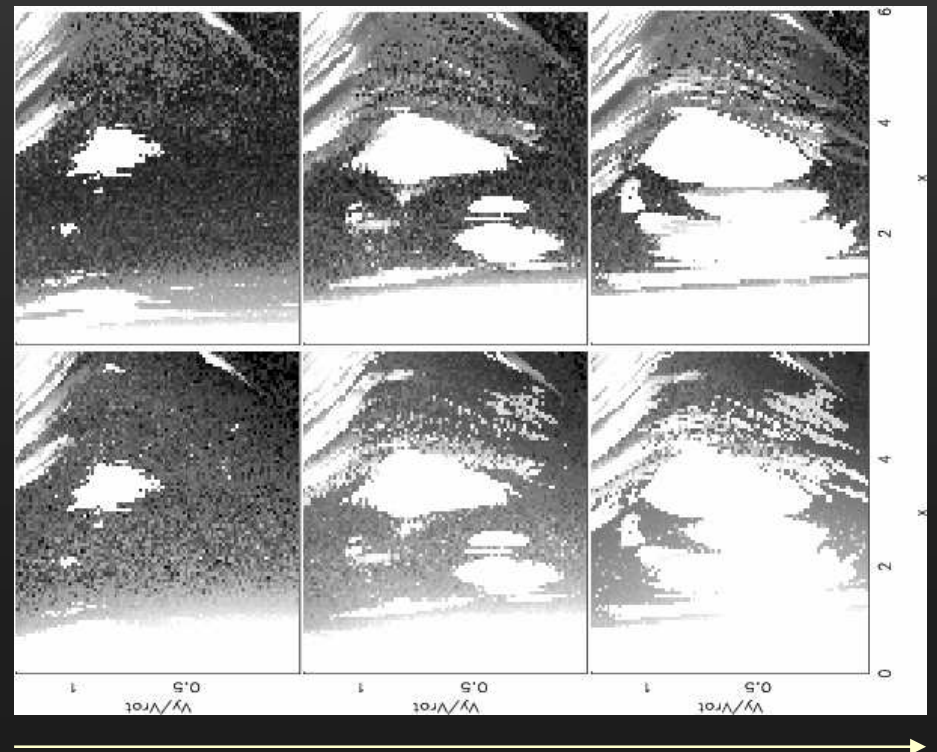
Are bars suicidal: do they self destroy?

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 <u>present-day</u> disk galaxies host bars. One third host strong bars

- Bars can shape the evolution of these <u>present-day</u> 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 <u>Are bars long-lived features that influence a galaxy over its lifetime</u>
      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
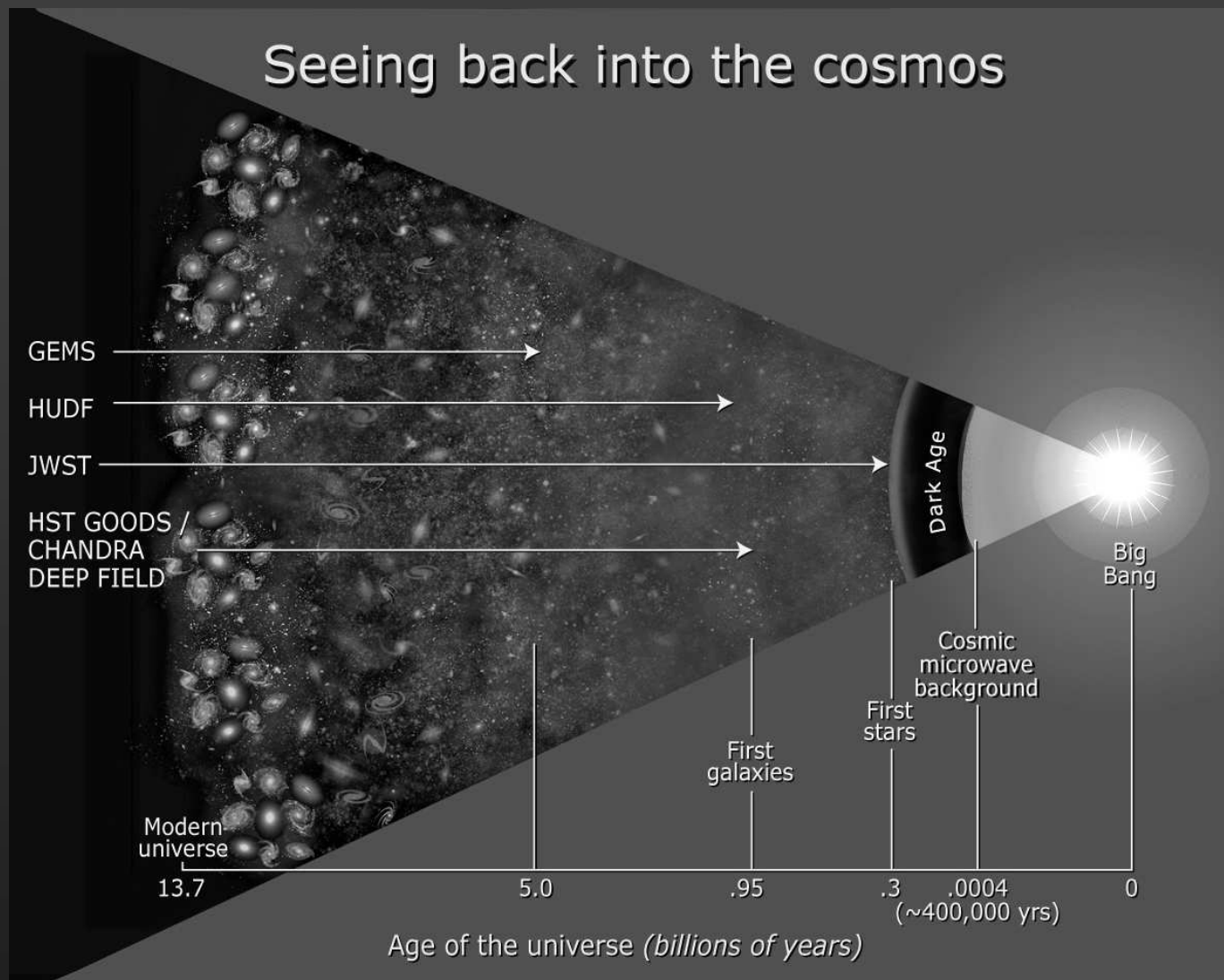
　　à　observe a large area in the sky

　　à　observe at high spatial resolution (HST)

GEMS survey conducted with the Advanced Camera for Surveys on HST
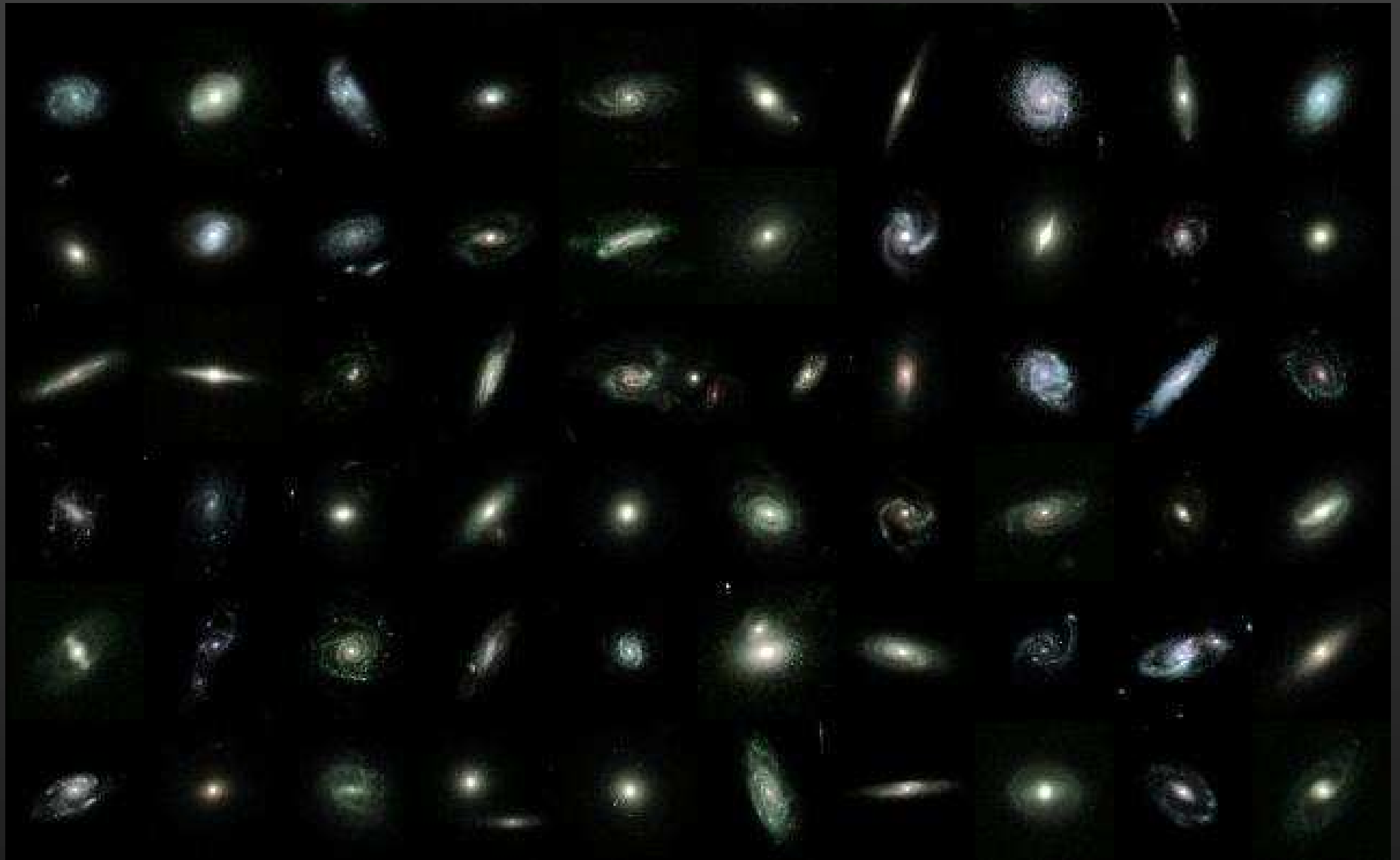
　　à　**Largest-area ever imaged in 2 filters with HST** (120 x HDF)

　　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!!**
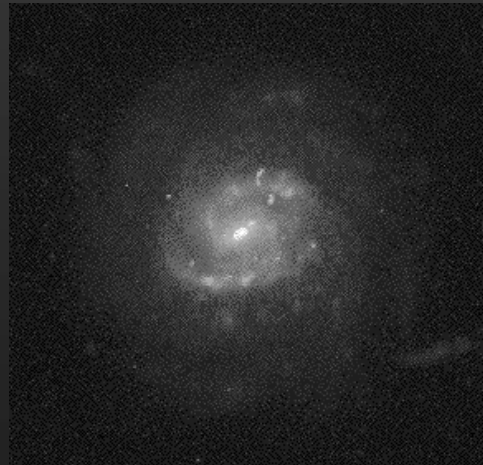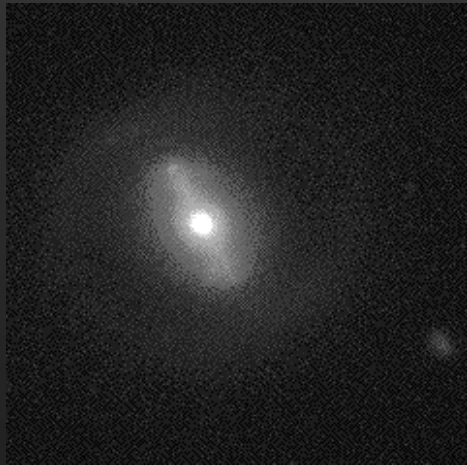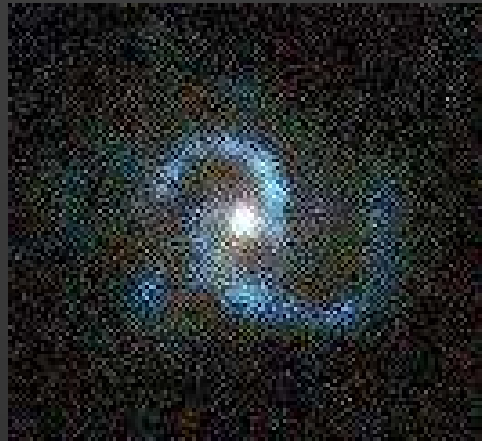
Seeing back into the cosmos

GEMS: 10,000 galaxies present over last 9 billion years…… out to epochs when the Universe was only 1/3 of its present age
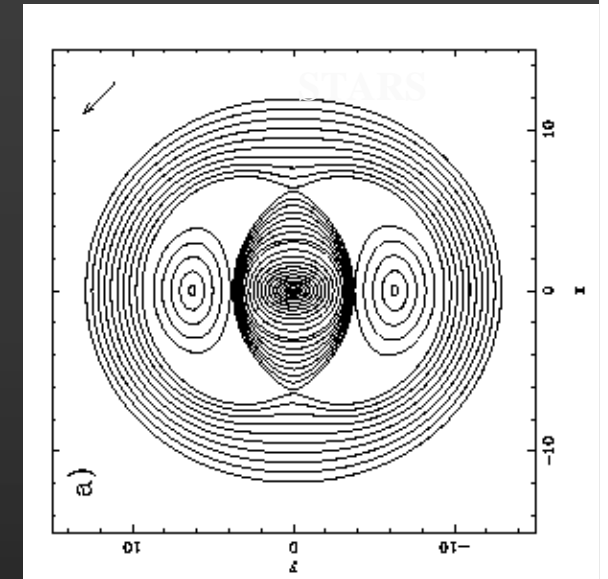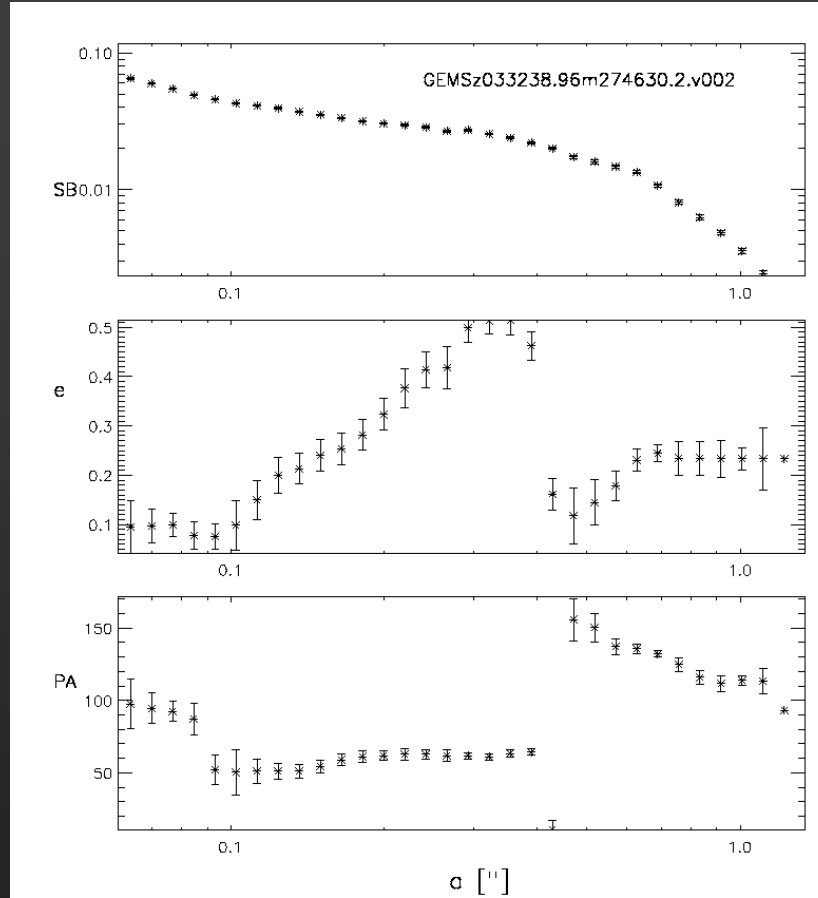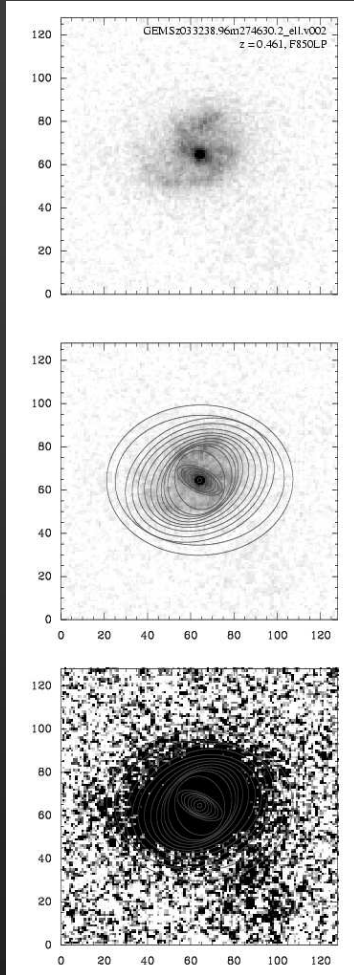
Diversiy of galaxies 9 Gyr ago, when Universe was only 30% of its present age!
The family album of how galaxies looked in their 'thirties'

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)