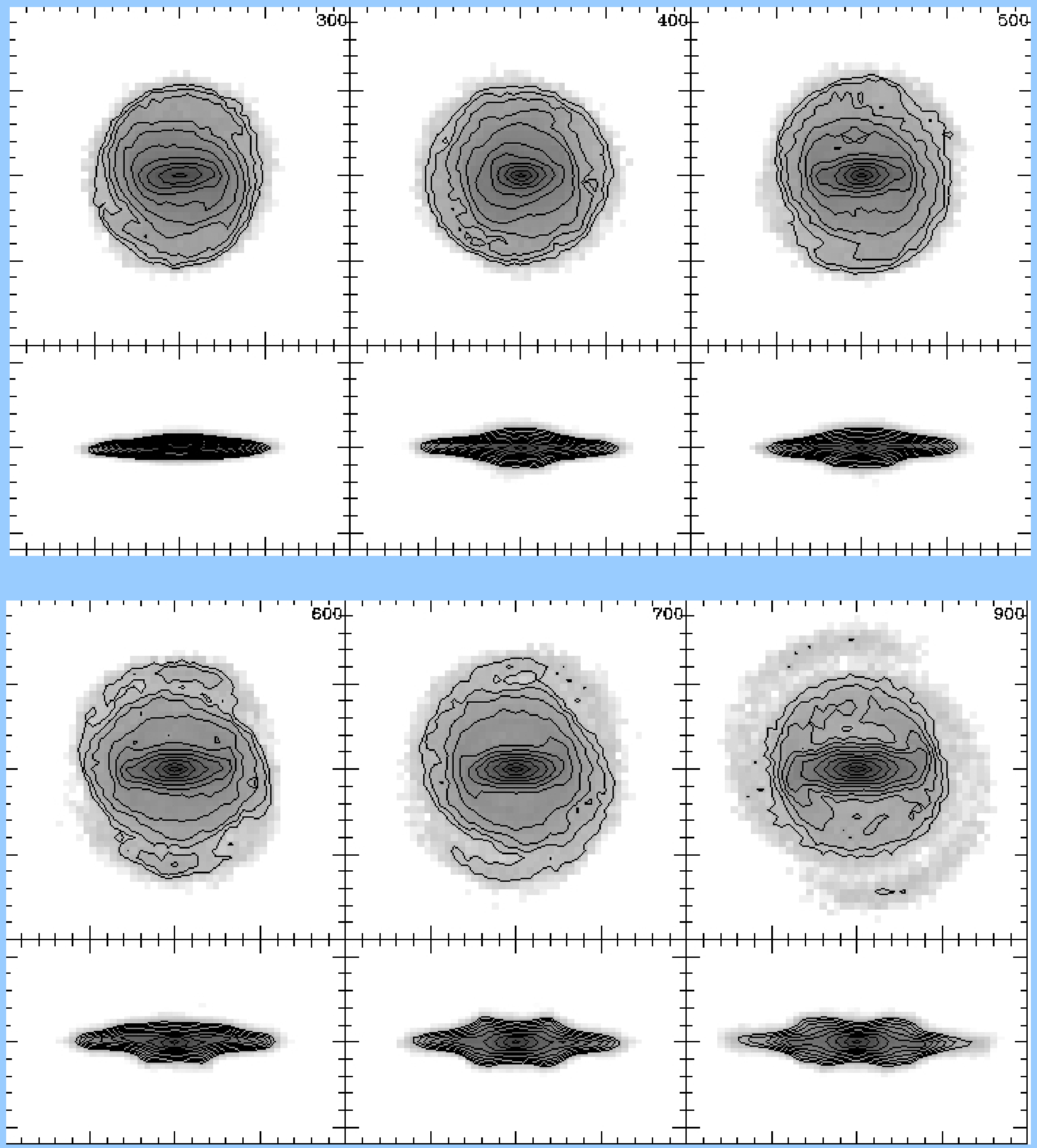
Bars and boxy bulges in the Milky Way and other galaxies

Lia Athanassoula

LAM/AMU/DAGAL/S4G

Bars form spontaneously in disc galaxies



Bars rotate!

Angular momentum redistribution within the galaxy

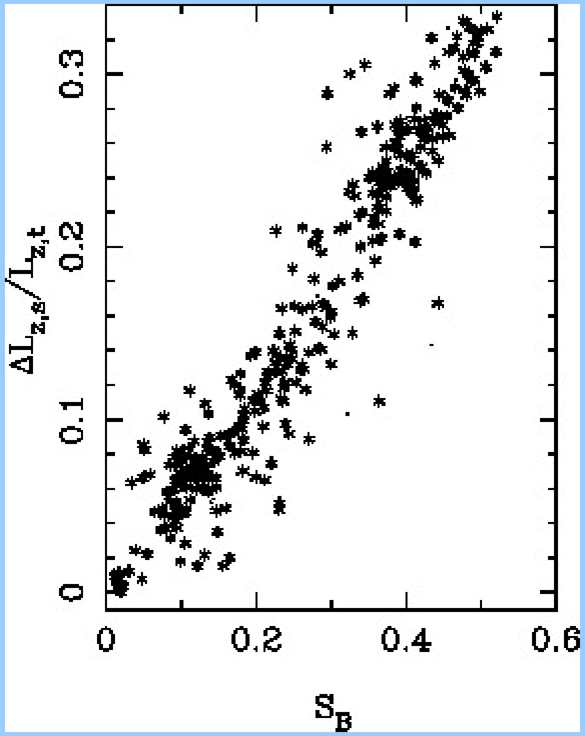
Emitters : (material at near-resonance in the) inner disc
Absorbers : (material at near-resonance in the) outer disc and halo

(Lynden-Bell & Kalnajs 72, Tremaine & Weinberg 85, Weinberg 85, 04 , Athanassoula 03, Fuchs 04, etc)

More angular momentum redistribution should lead to stronger bars and to stronger decrease of their pattern speed

Indeed simulations show that
the strength of the bar correlates well
with the amount of angular momentum
exchanged

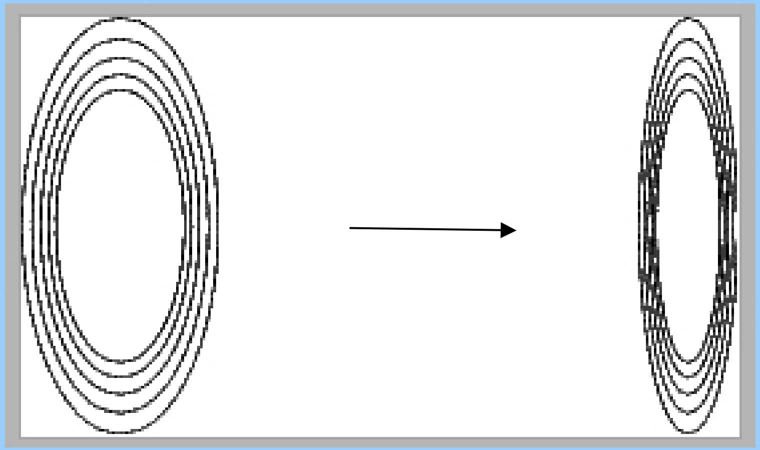
Both for the disc and the halo, there is more angular momentum gained/lost at a given resonance if :
- the density is higher there
- the resonant material is colder



Athanassoula 2013 = EA03

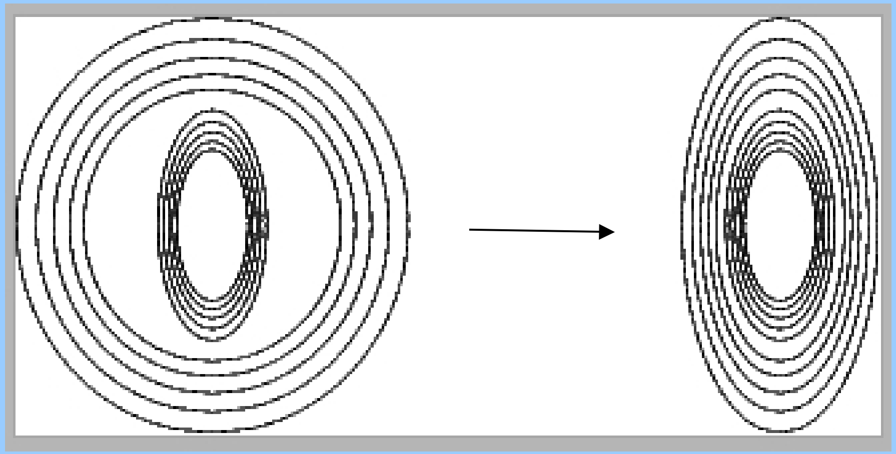
Angular momentum lost by bar: How?

- orbits become thinner



Thinner bar

- bar traps stars which where on near-circular orbits around it, into its outer parts

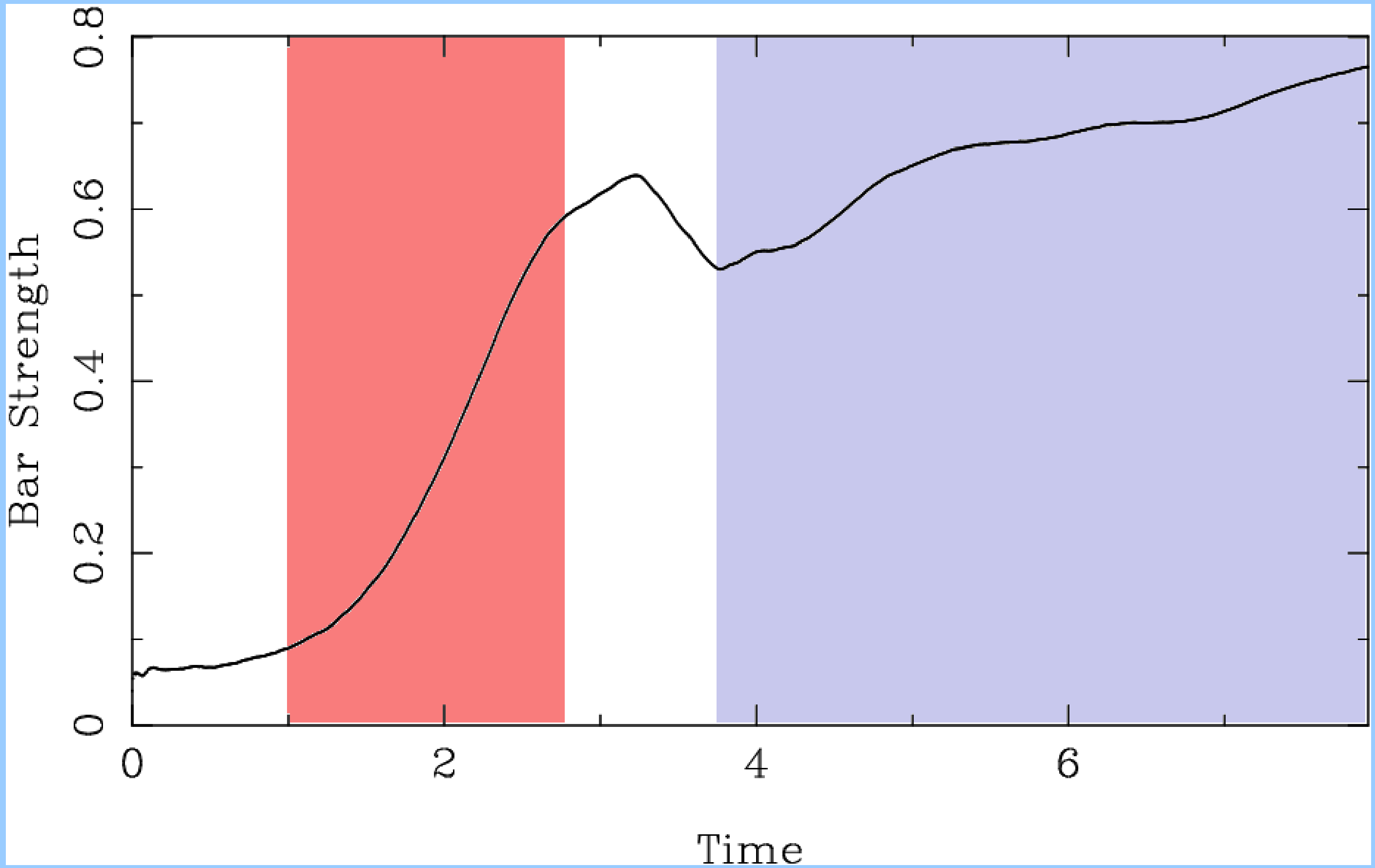


Longer bar

- bar rotates slower

Slower bar

Barred galaxies can not be stationary !! They have to evolve



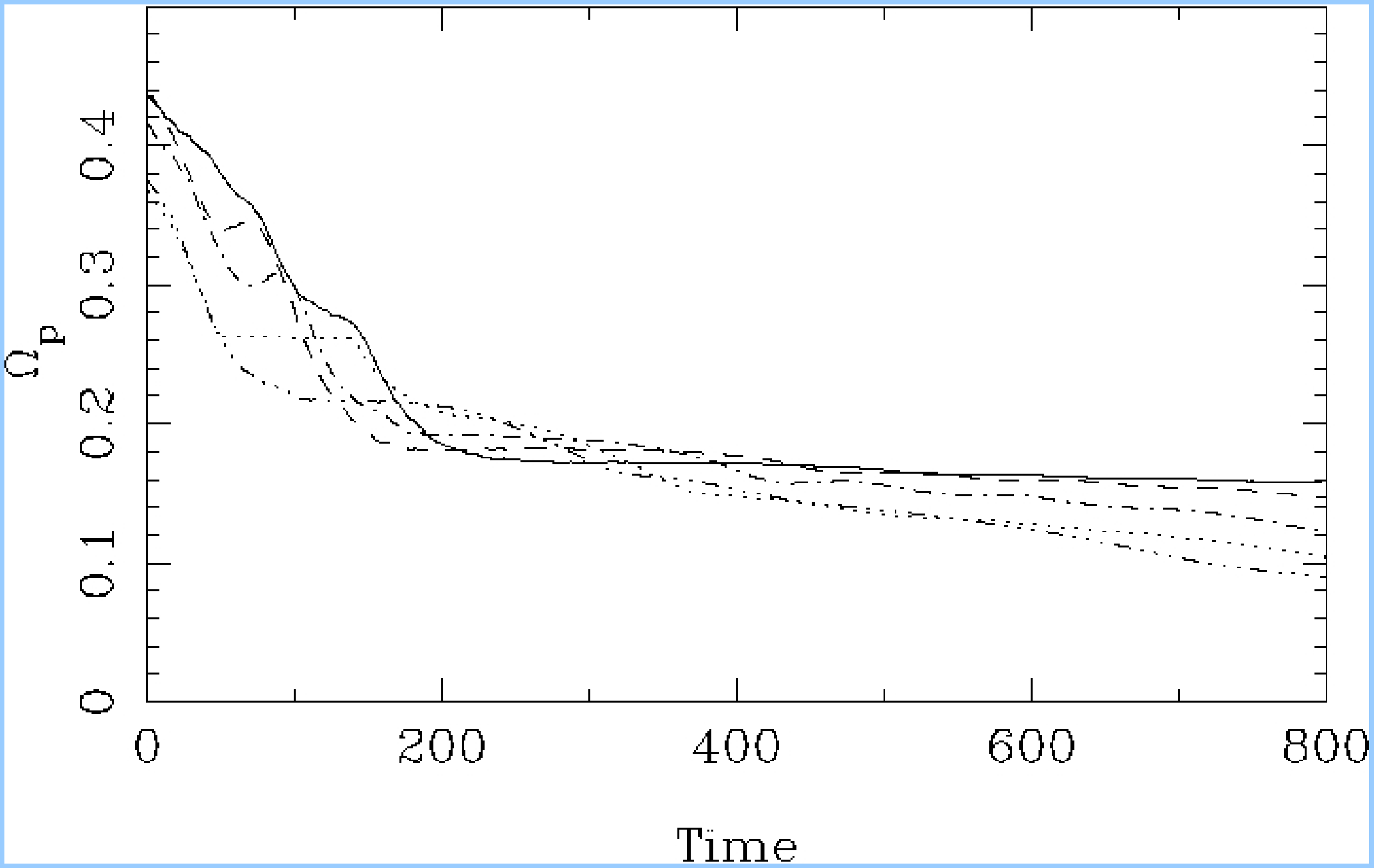
Bar growth

Secular evolution

Bar formation

Bar evolution

Pattern speed decreases with time



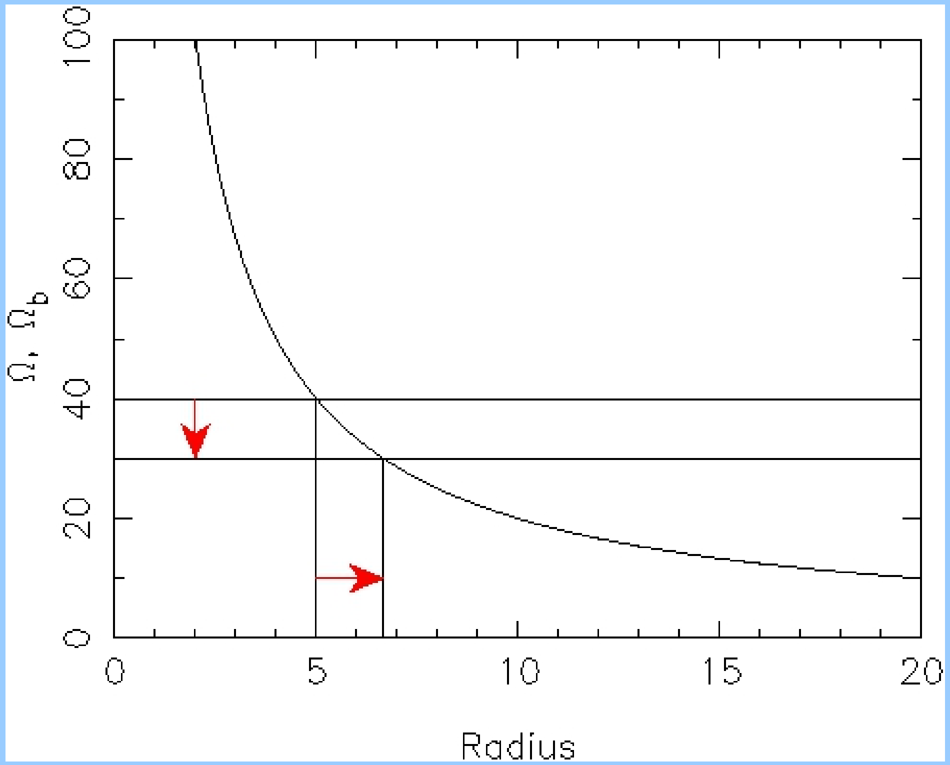
Little and Carlberg 1991, Hernquist and Weinberg 1992, Debattista & Sellwood 2000, Athanassoula 2003, O'Neill and Dubinski 2003, Valenzuela and Klypin 2003, Holley-Bochelmann and Katz 2004, Martinez-Valpuesta et al 2006, Villa-Vargas and Shlosman etc

In order to loose angular momentum, the bar can slow down.

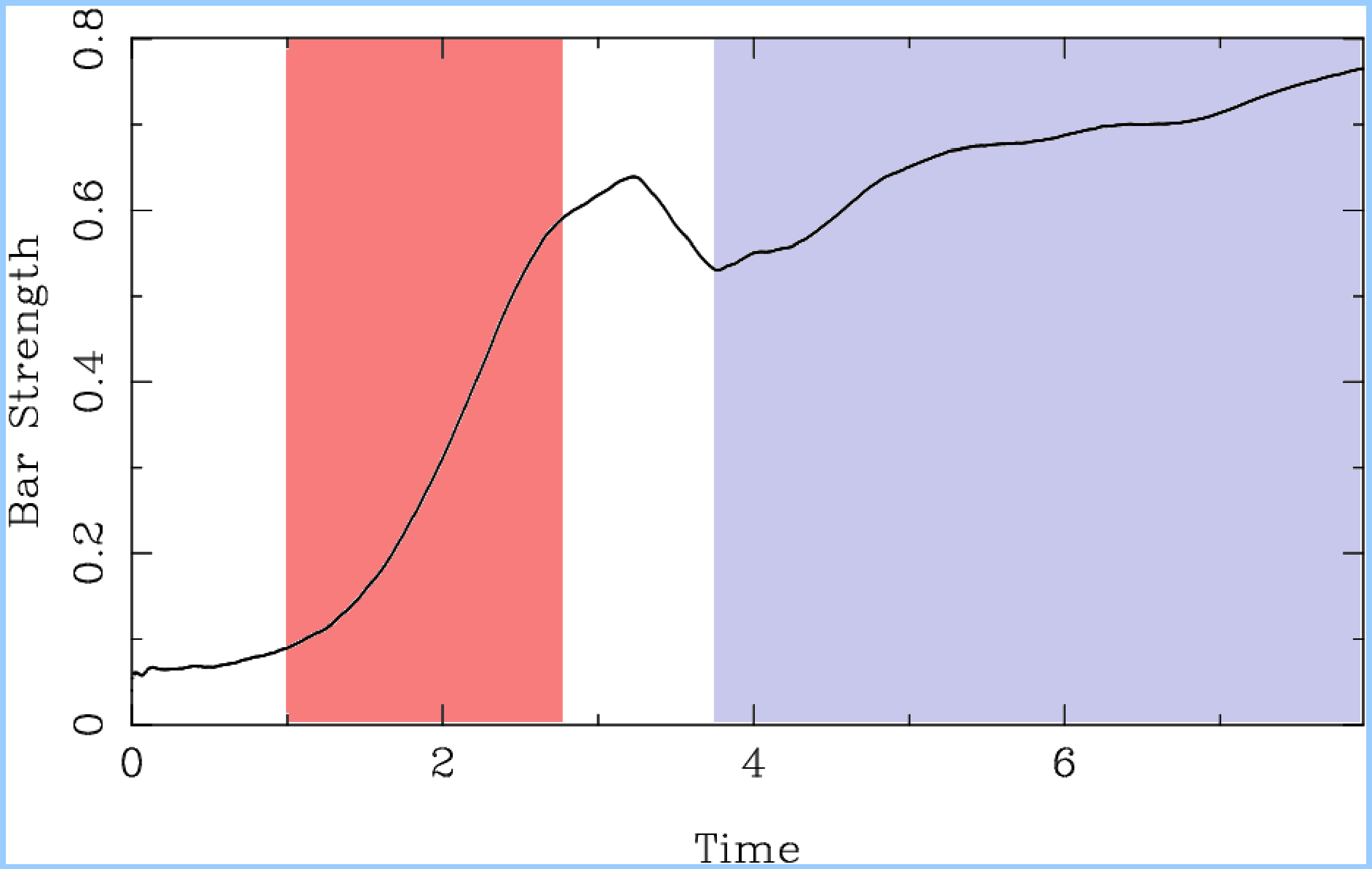
The means that the pattern speed will decrease

The resonances will move further out (to larger radii)

The length of the bar will increase



Corotation radius R_{CR}: the radius at which a star on a circular orbit will corotate with the bar



Bar growth

Secular evolution

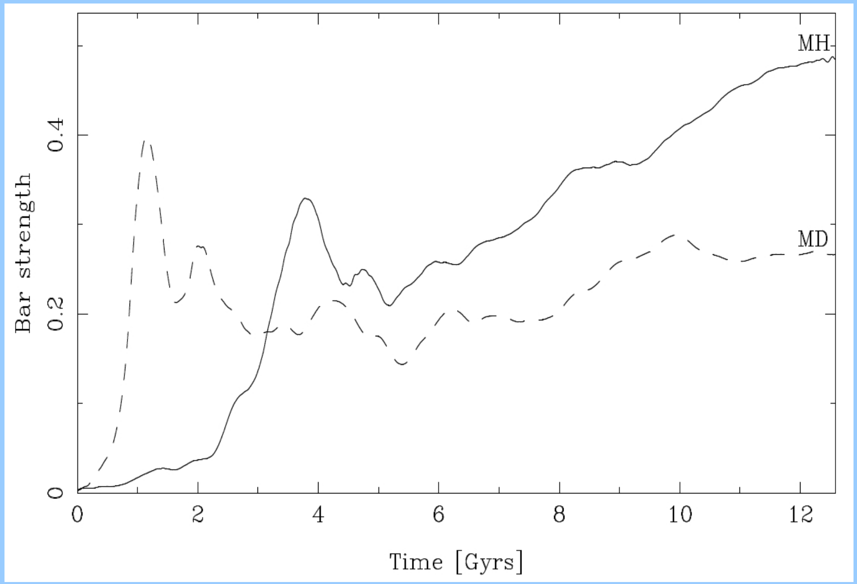
Bar formation

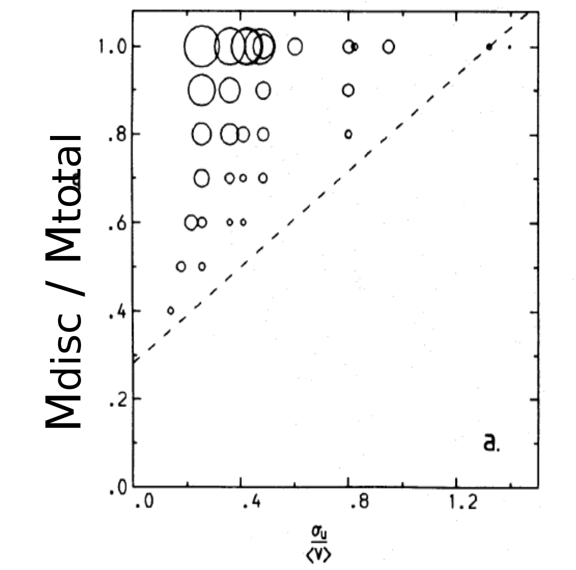
Bar evolution

Effect of halo mass on bar formation and evolution: duality

Haloes slow down bar formation

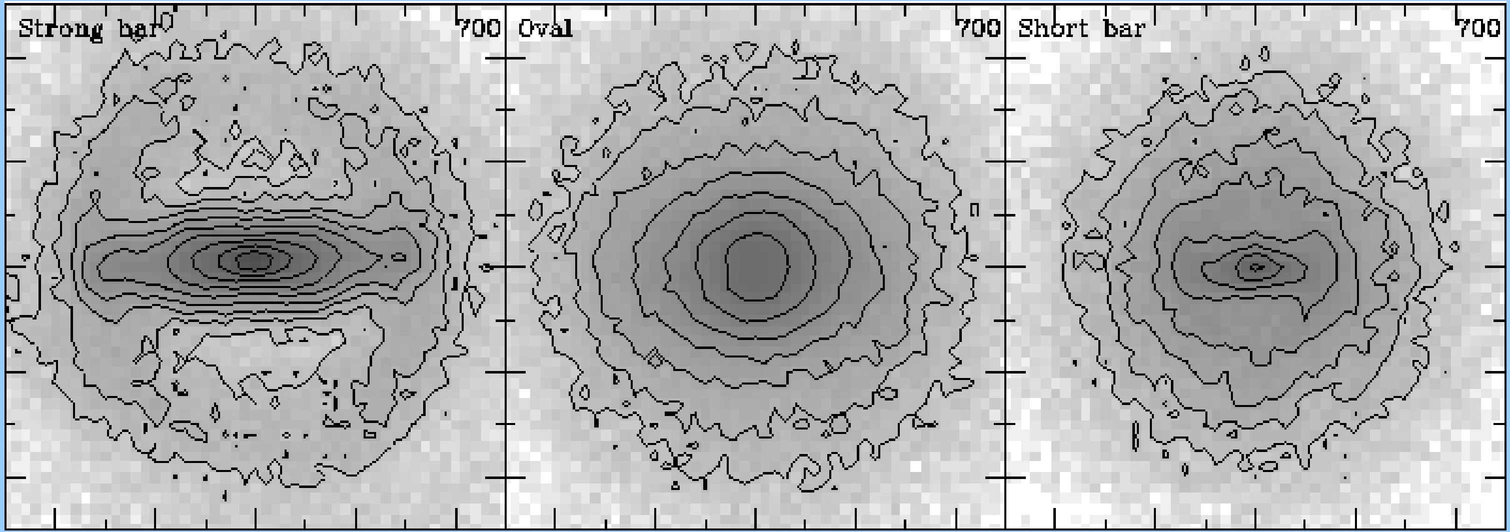
EA02





EA & Sellwood 86
EA03

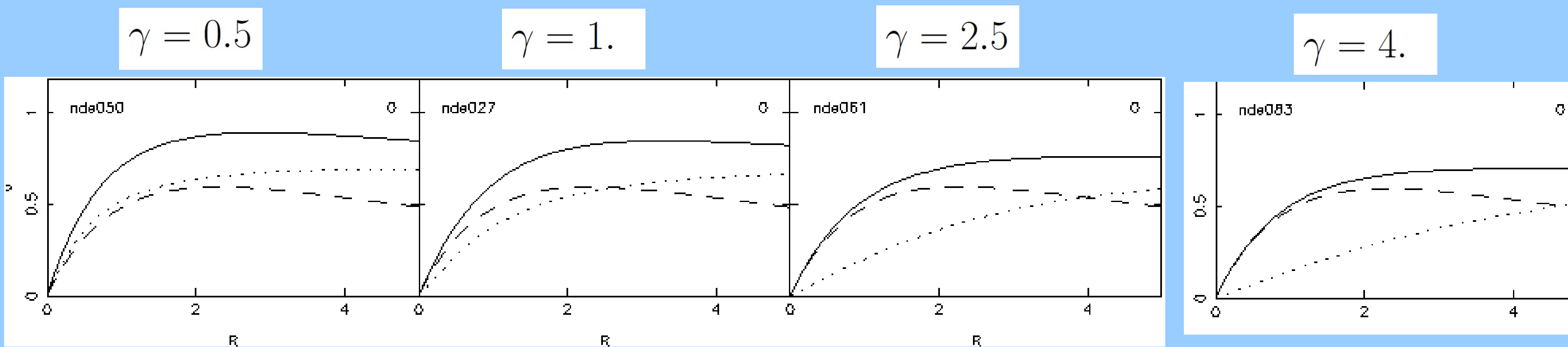
But haloes make bars strong (secular, nonlinear evolution)



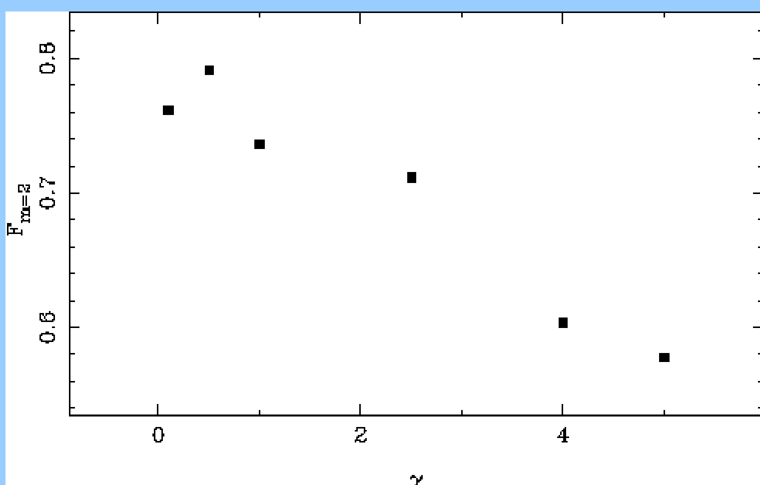
EA03

A series of haloes with different mass in the regions of the main resonance

EA & Misiriotis 02, EA 03

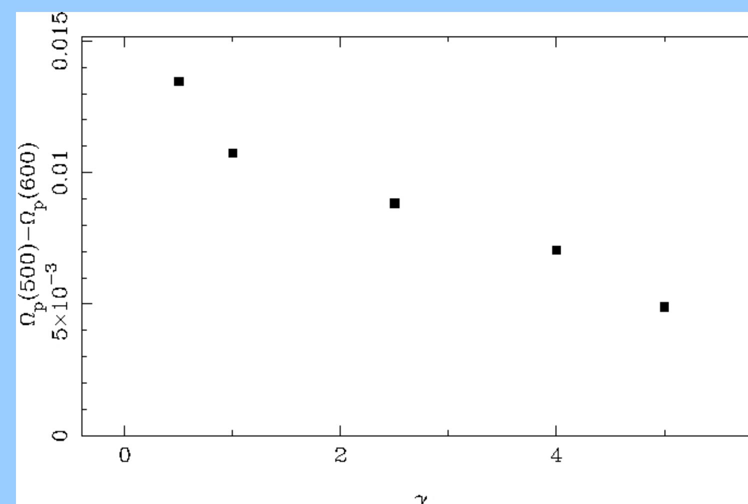


Bar strength



Halo core radius

Pattern speed drop



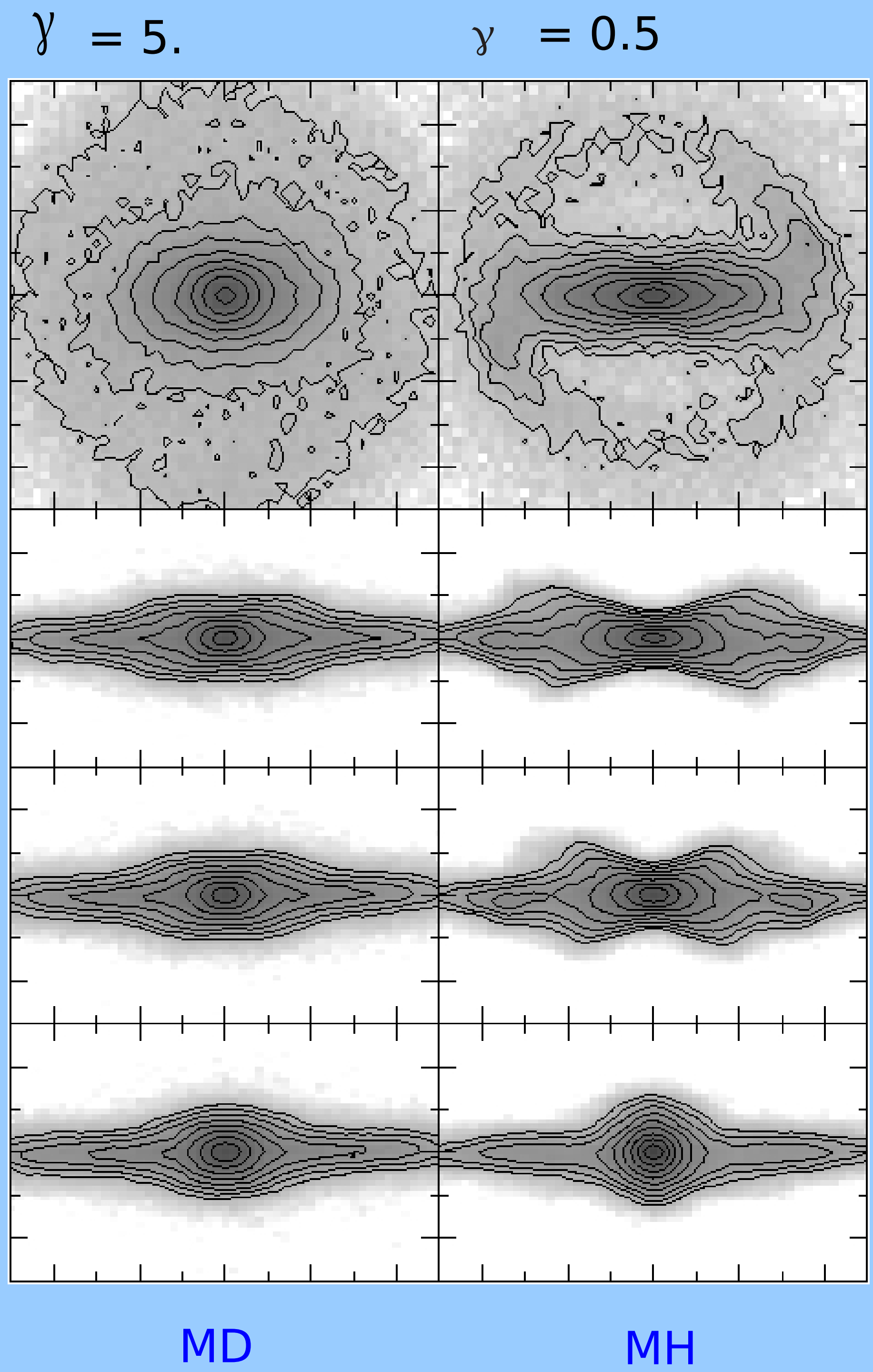
Halo core radius

More concentrated haloes have more mass at resonances and thus can absorb more angular momentum. The bar will emit more angular momentum and grow stronger.

Less strong bars
Fatter
Never ansae

Elliptical-like
isodensity contours

Boxy edge-on shape



Stronger bars
Longer, thinner and
more massive
Often ansae
Flat radial density
profiles (Elmegreen &
Elmegreen 1985)

Rectangular-like
isodensity contours

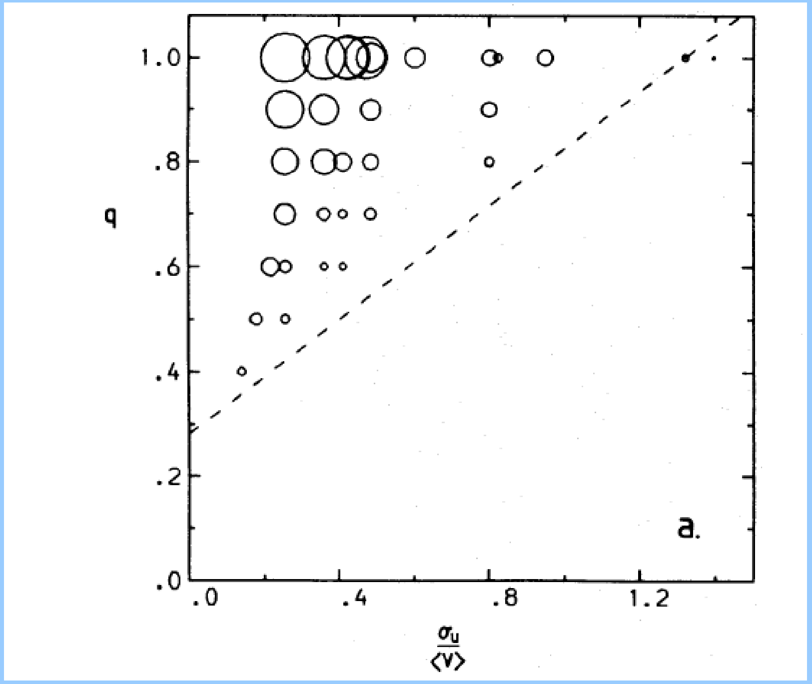
Peanuts or Xs when
seen edge-on

Influence of the disc velocity dispersion

Bar formation phase

Bars form later in hot discs

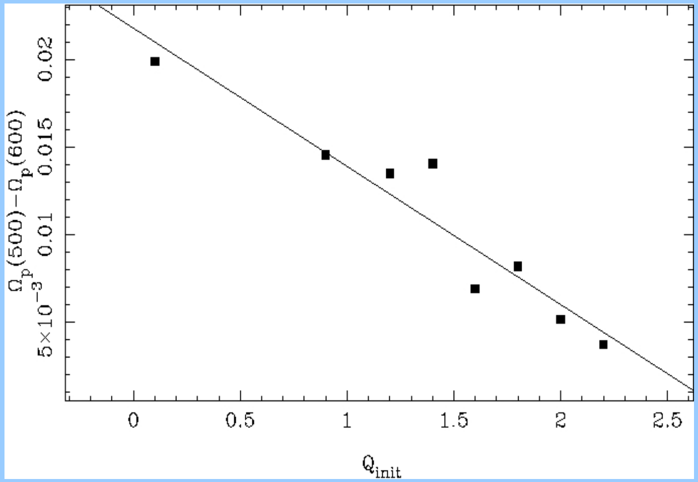
EA & Sellwood 1986



Secular evolution phase

Bars in hotter discs slow down less

Pattern speed drop



Q

EA03

and they are weaker (oval-like)

EA83
EA03

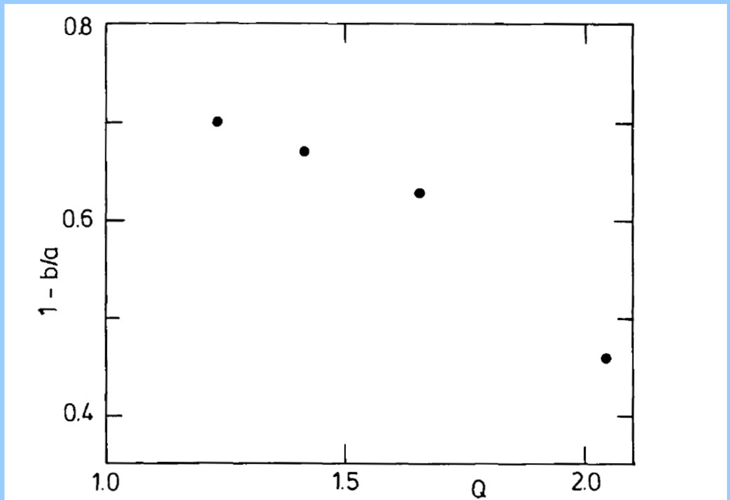
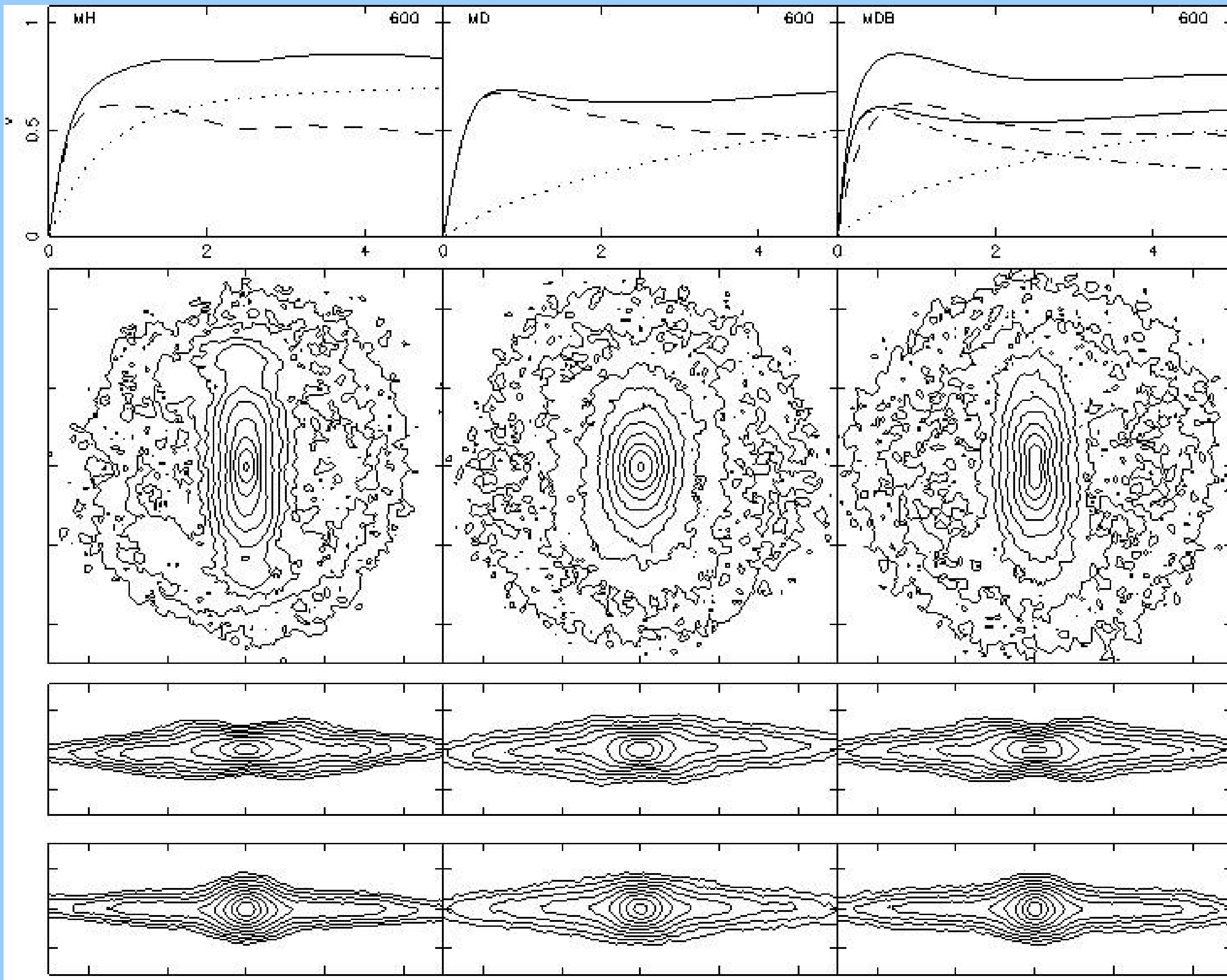


Figure 4. Mean eccentricity of the bar isodensities as a function of the mean mass averaged Q.

A classical bulge

EA & Misiriotis 02
EA 03



BULGES/HALOES

Classical bulges slow down bar formation

In the secular evolution regime they help bars grow stronger

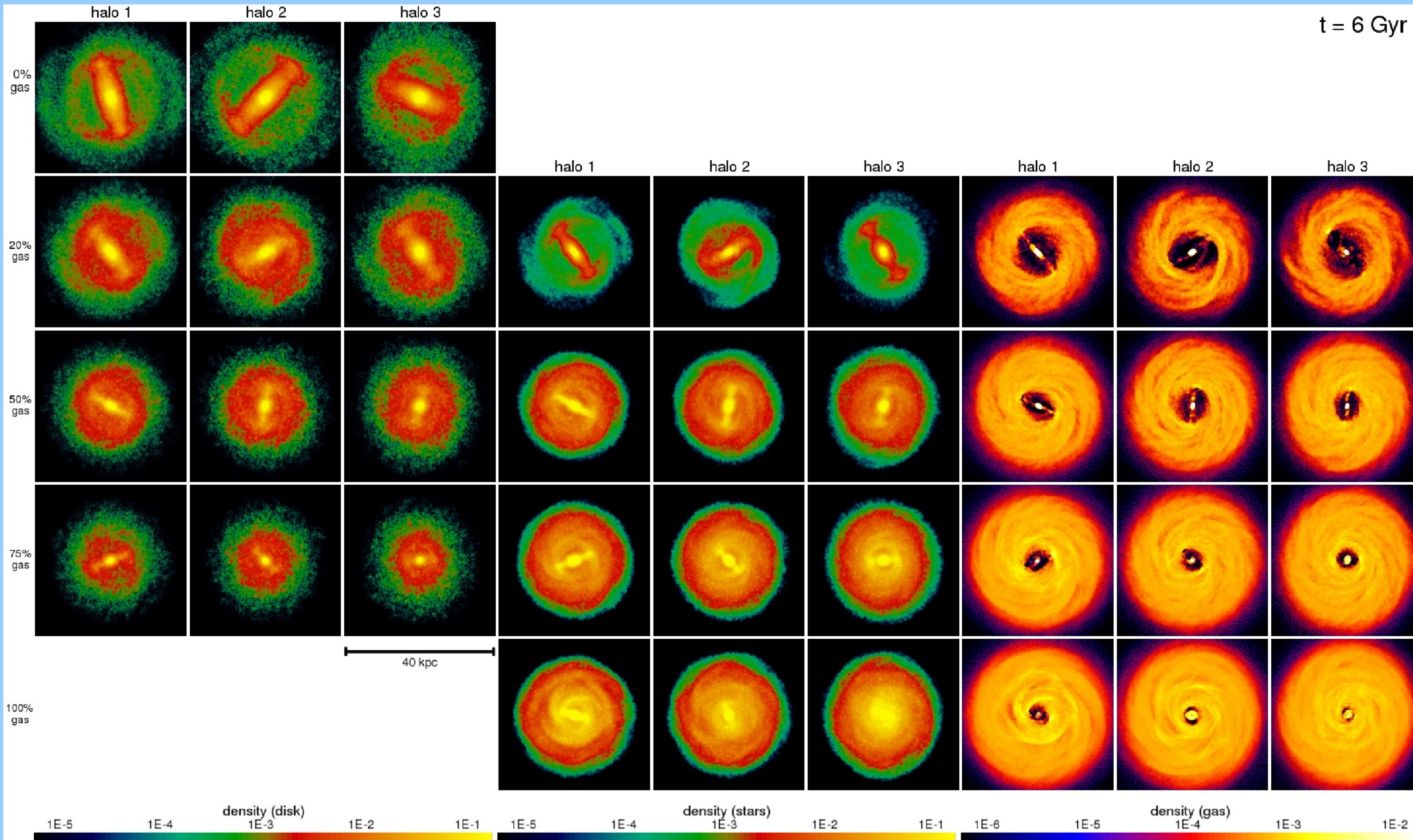
As a result:

Classical bulges flatten (become triaxial) and start spinning (EA & Misiriotis 02, Saha et al 12, Saha & Gerhard 12, 13)

A gaseous component

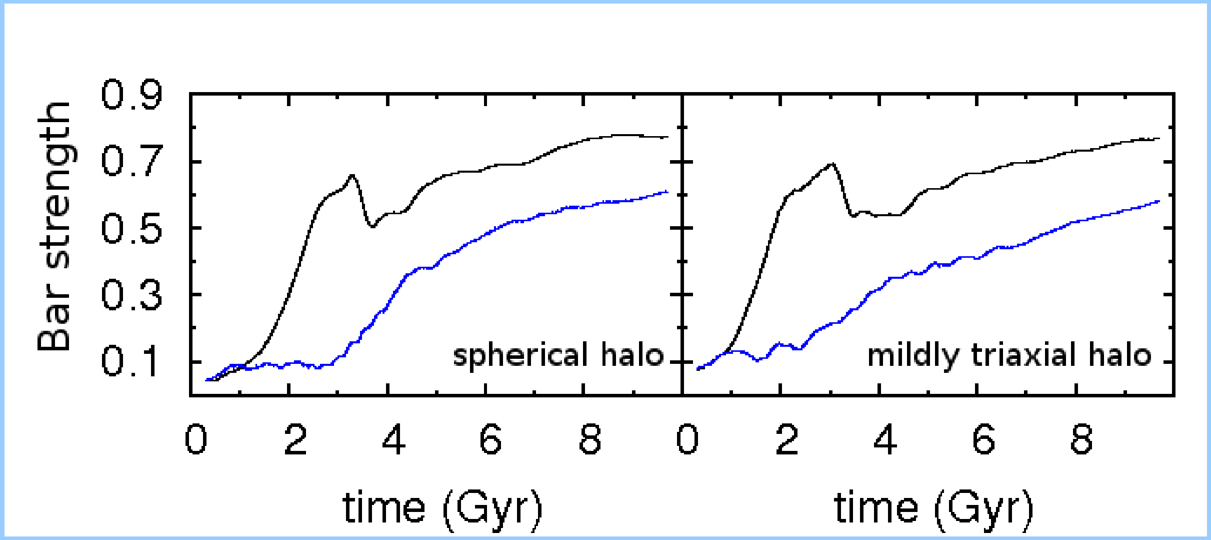
AMR13

t > 6 Gyrs   t < 6 Gyrs   Gas



Athanassoula. Machado & Rodionov 2013 (=AMR13)

Gas slows down bar formation in two ways:



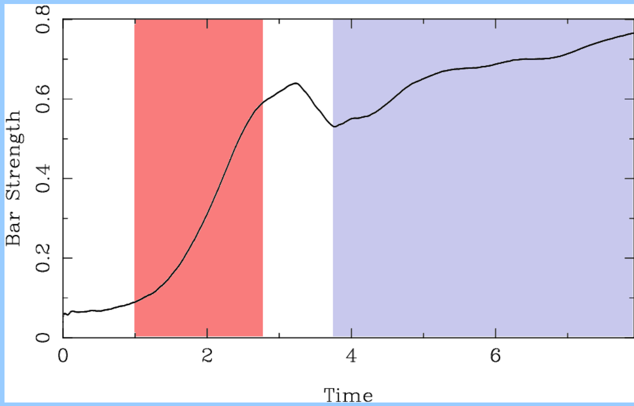
AMR13

Bars are stronger in gas poor than in gas rich cases

Black line: 0% gas
Blue line: Initially 50% of disc mass in gas, drop with time to 5%

Bar formation stage

Relatively heavy haloes (M_h/M_t)	slows down
Hot discs	slows down
Halo triaxiality	speeds up
Increased gas fraction	slows down
Presence of a thick disc component	slows down



What makes bars stronger (secular evolution part)

Maximum angular momentum redistribution, i.e:

Considerable halo and/or bulge contribution	stronger
Cold discs	stronger
Velocity distribution function in halo	stronger/weaker
Halo triaxiality	weaker
Gas poor discs	stronger
Absence of a CMC	stronger

Note: This list is NOT complete
Some of these can not be applied concurrently

What is a bulge ?

Three definitions have been used so far

Morphological : A smooth light distribution that swells out of the central part of a disc seen edge-on

Photometrical (from radial photometric profiles) : The extra light in the central part of the disc, above the exponential profile fitting the remaining (non-central) part

Kinematics : Particularly V/sigma diagram (Binney 1978, 2005)

Bulges

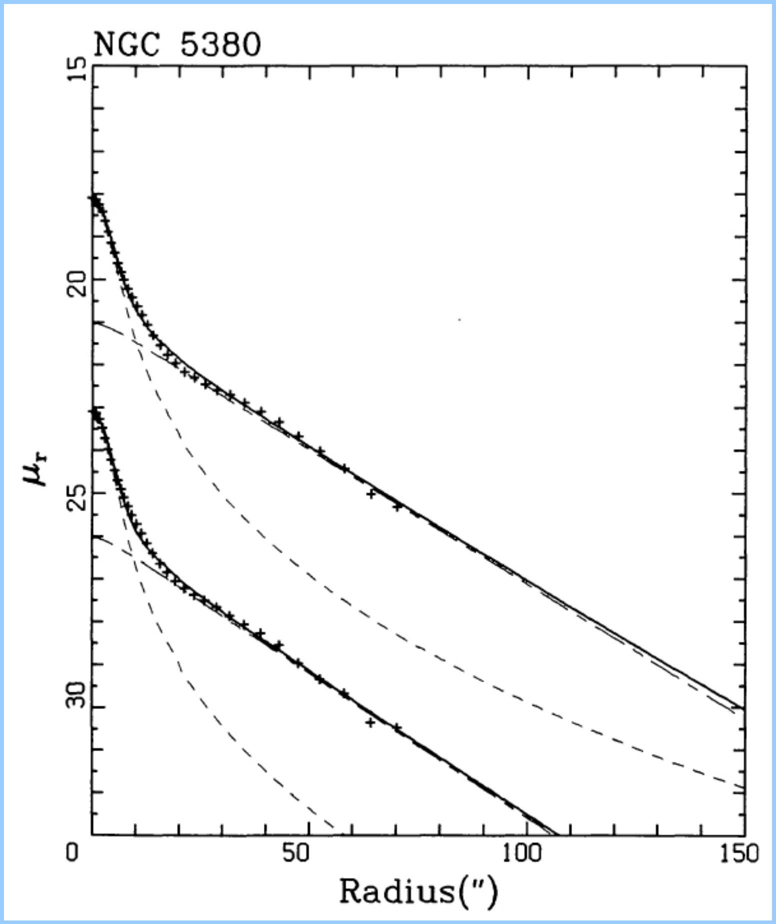
Bulge definitions

Definition 2 :
From photometric profiles

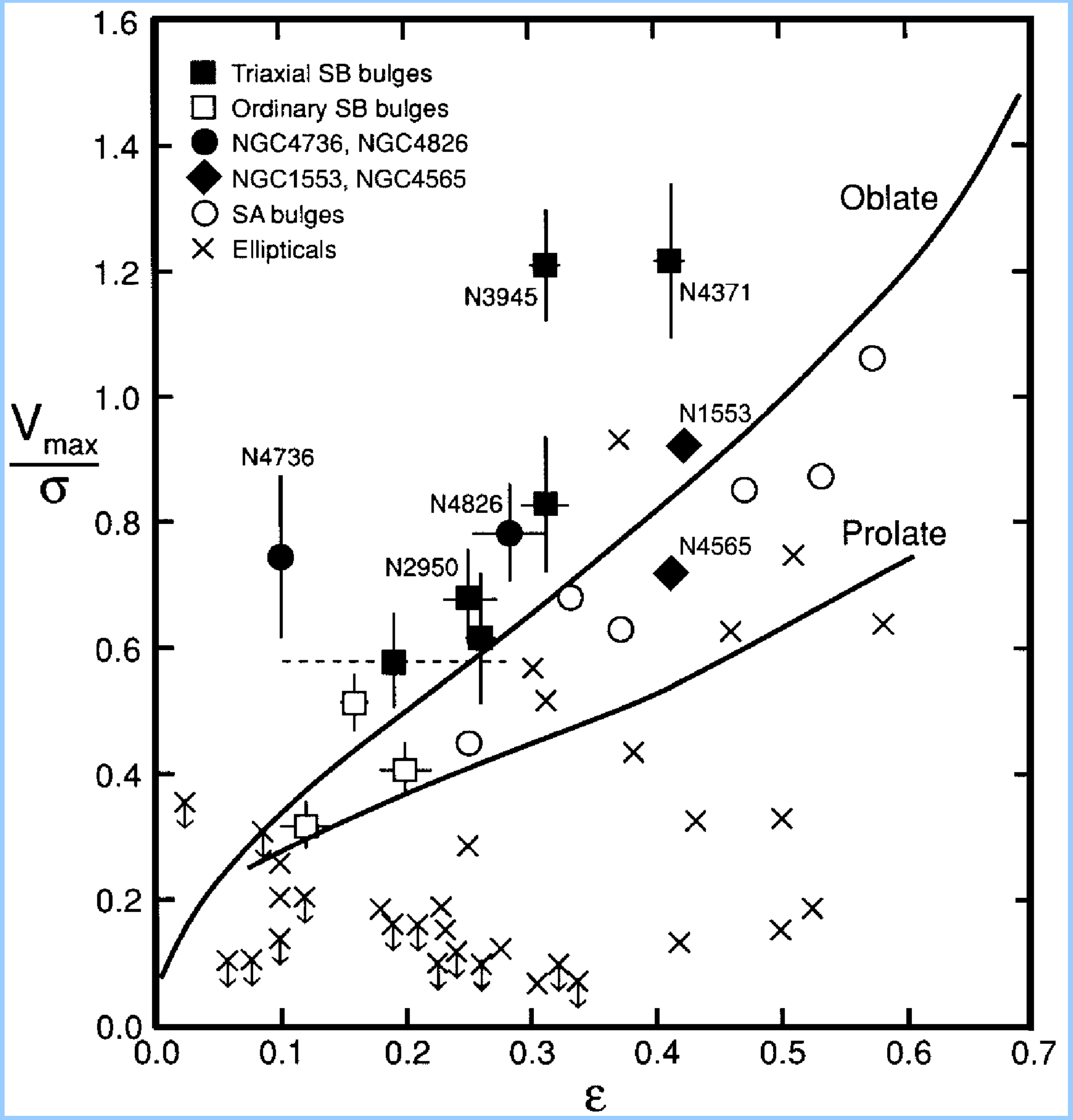
The bulge is identified as the extra light in the central part of the disc, above the extrapolated exponential fitting the remaining (non-central) part.

Sersic profile :

effective radius, effective central surface density and, in particular, the Sersic index n



Kinematical definitions : V/sigma plots



Binney 1978, 2005

Open symbols : Classical bulges

Filled symbols :Pseudo bulges

x : ellipticals

Kormendy 1993

Kormendy & Kennicutt 2004

Classical bulges, boxy/peanut bulges and discy bulges

Kormendy : galaxies are not a homogeneous class of objects
(Kormendy 1993, Kormendy & Kennicutt 2004)

Distinction : Classical bulges and pseudo-bulges

Classical bulges

Box/peanut bulges are PARTS of bars and form from a vertical instability.
Disc material that has moved out of the plane

Disc-like bulges form from inflow of (mainly) gas material to the centre
of the galaxy and subsequent star formation

Bulges

Bulge definitions

Definition 2 :
From photometric profiles

The bulge is identified as the extra light in the central part of the disc, above the extrapolated exponential fitting the remaining (non-central) part.

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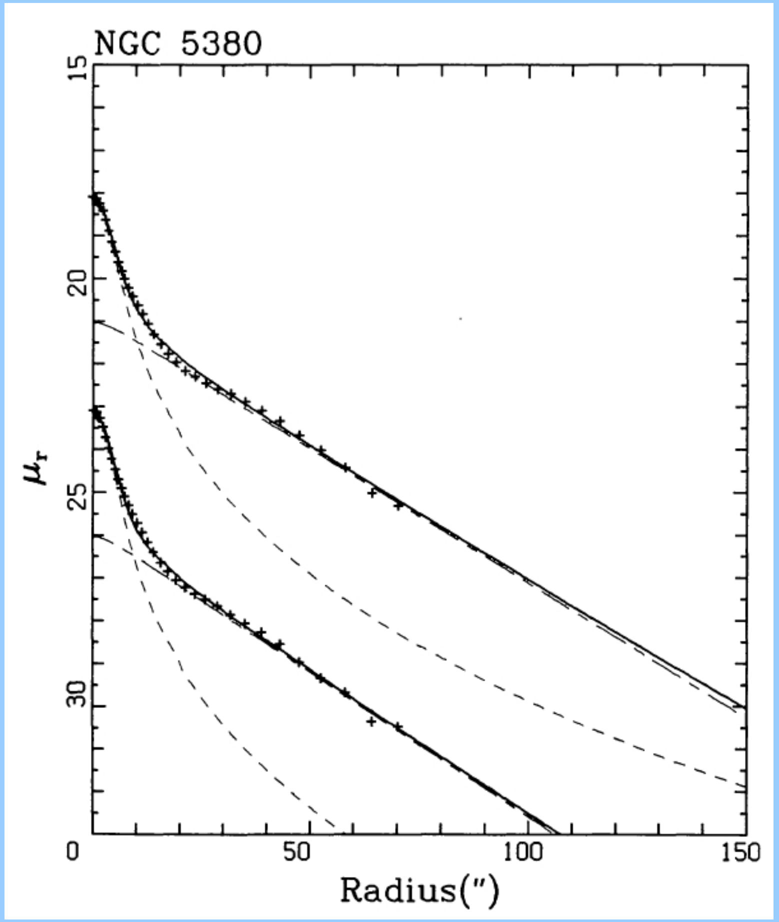
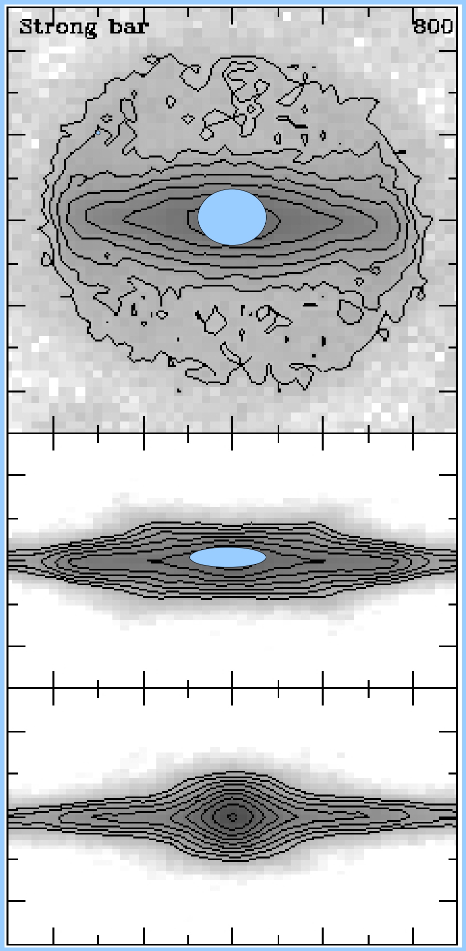
effective radius, effective central surface density and, in particular, the Sersic index n

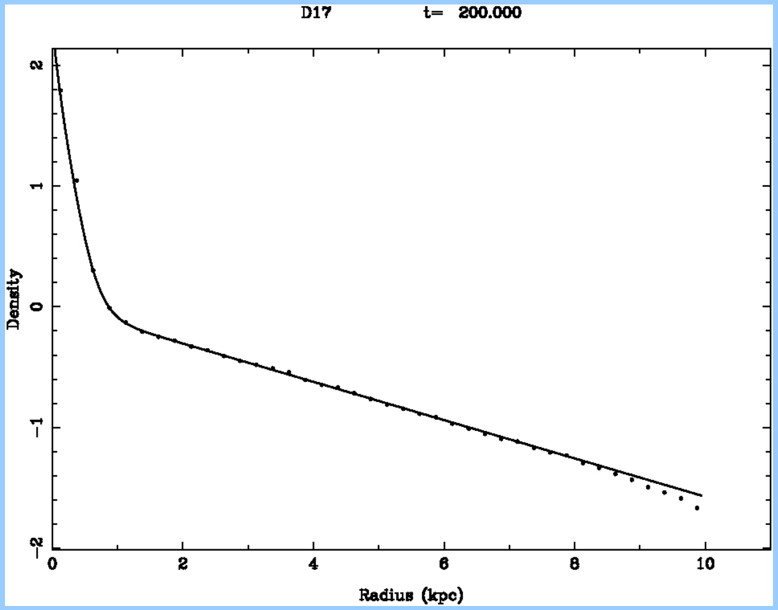
Classical bulges : n of the order of 3 or 4
Discy-bulges : n of the order of 1
Boxy/peanut bulges: n between 0 and 1



Box/peanut bulges are PARTS of bars and form from a vertical instability. Disc material that has moved out of the plane

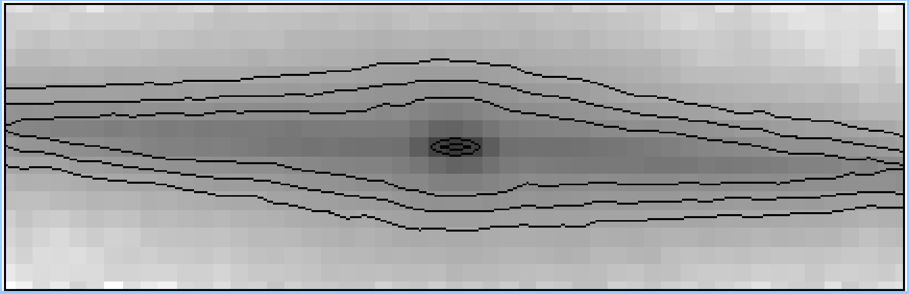
Disc-like bulges form from inflow of (mainly) gas material to the centre of the galaxy and subsequent star formation

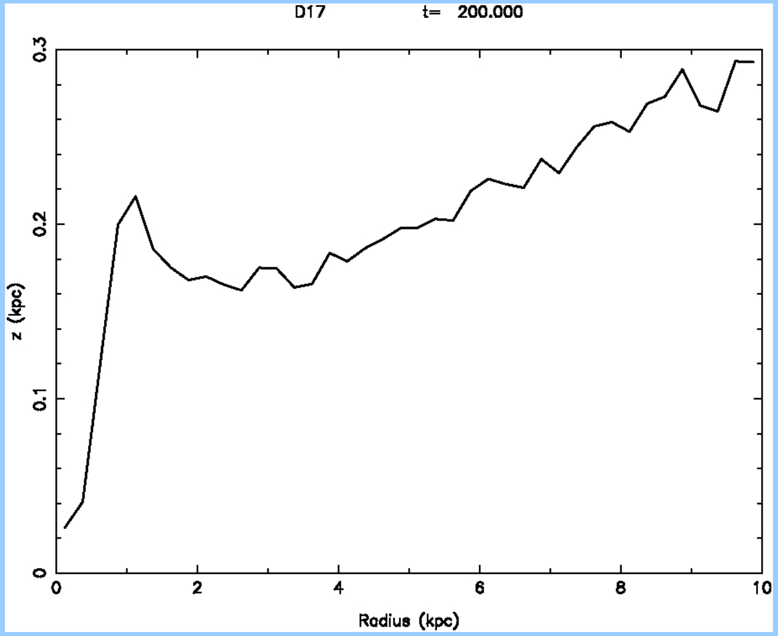




Sersic index = 1

in general Sersic Index < 2

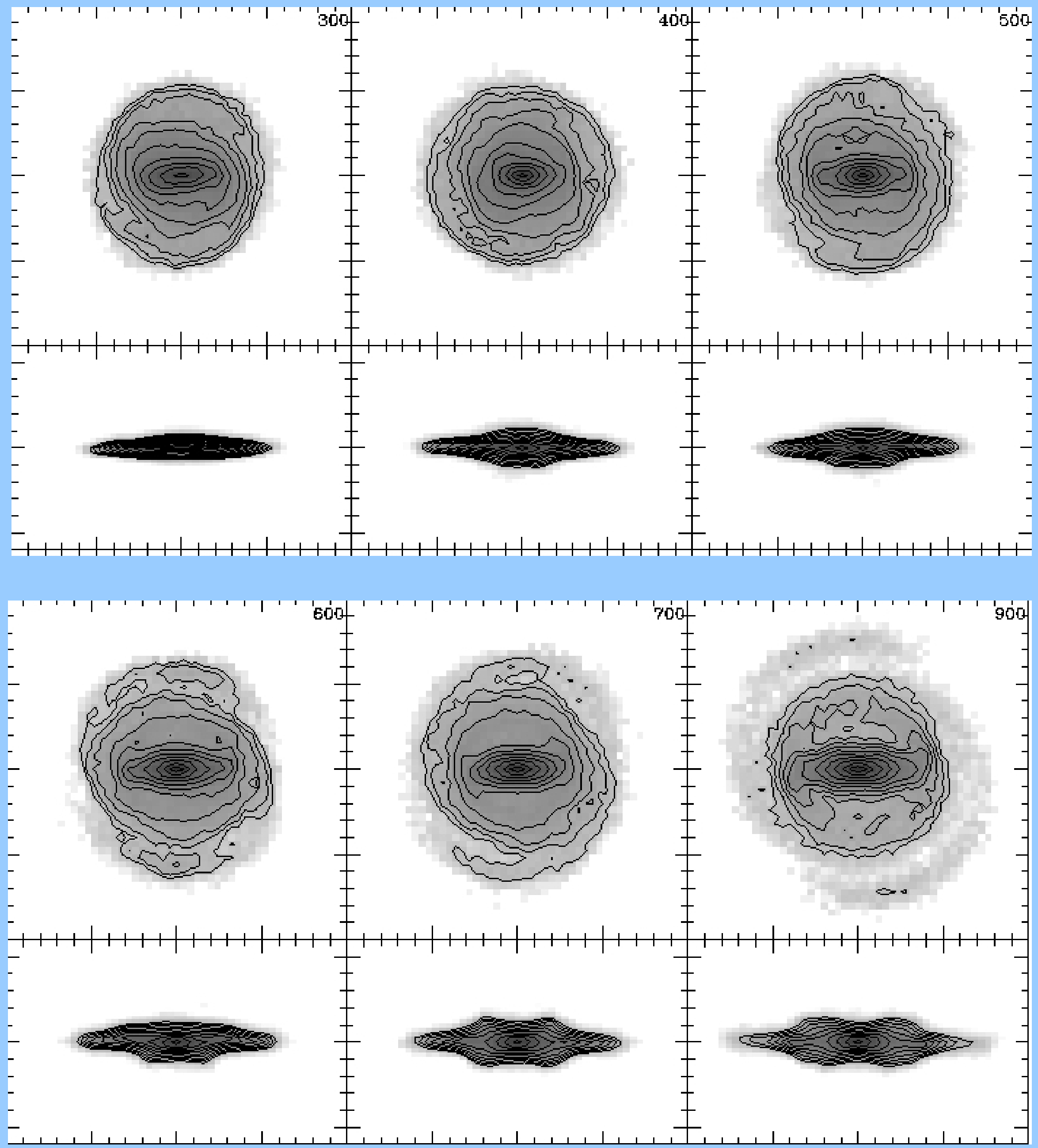




Face-on it often has an oval shape or includes a bar (inner bar)

Athanassoula 08

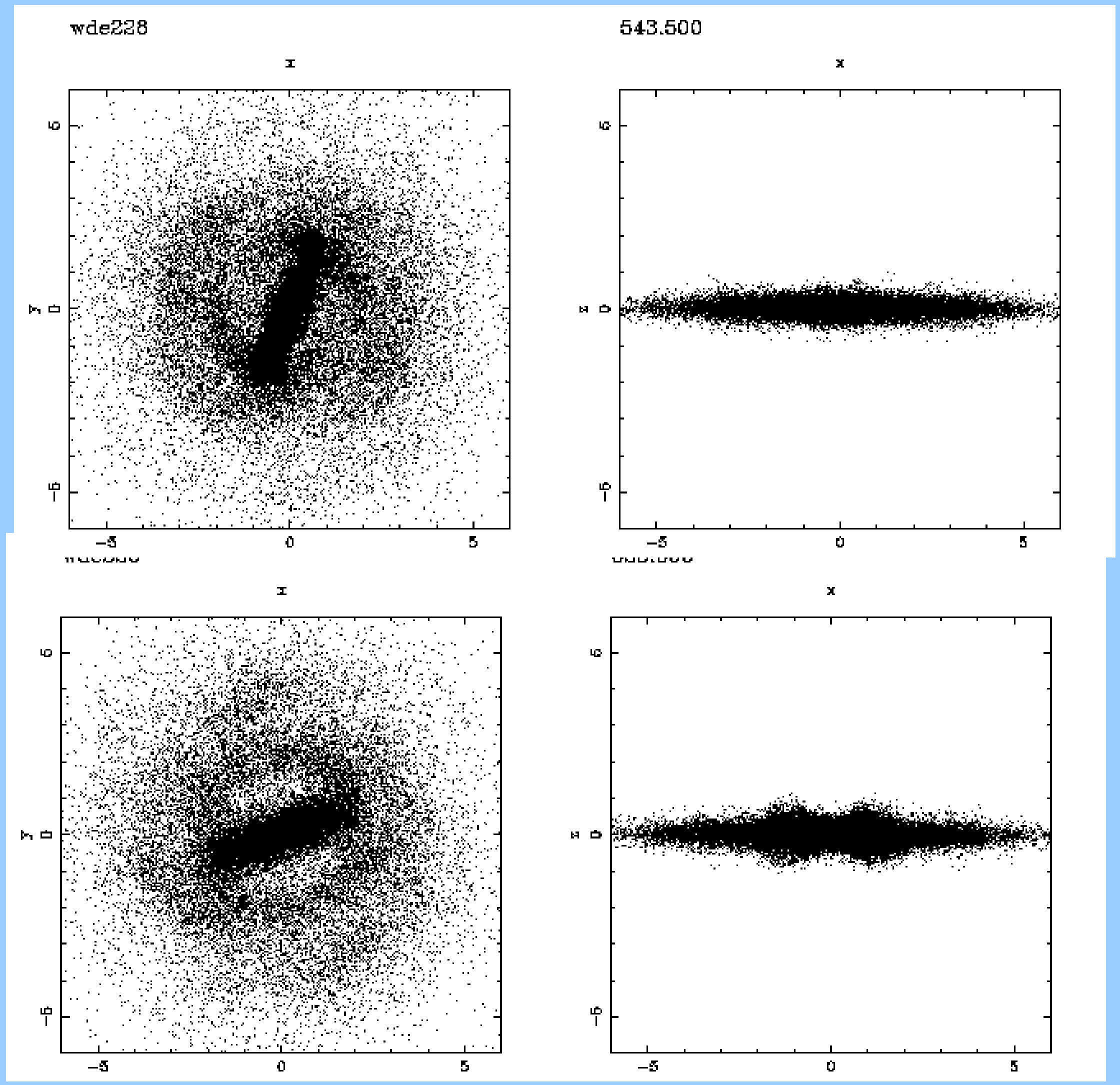
Bars and Boxy/Peanut/X bulges



Bars
rotate!

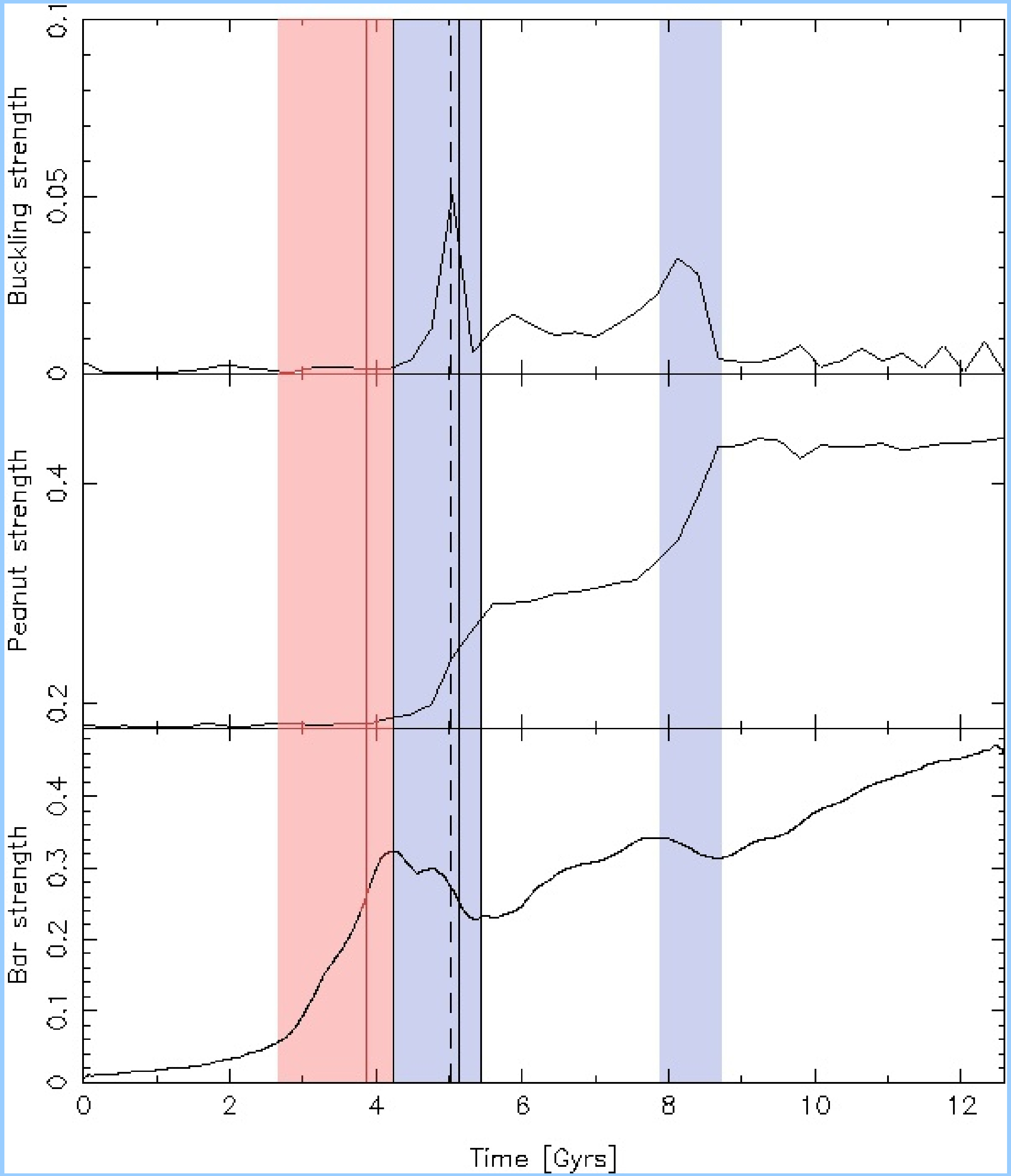
Movie
gtr101

Peanuts form AFTER bars

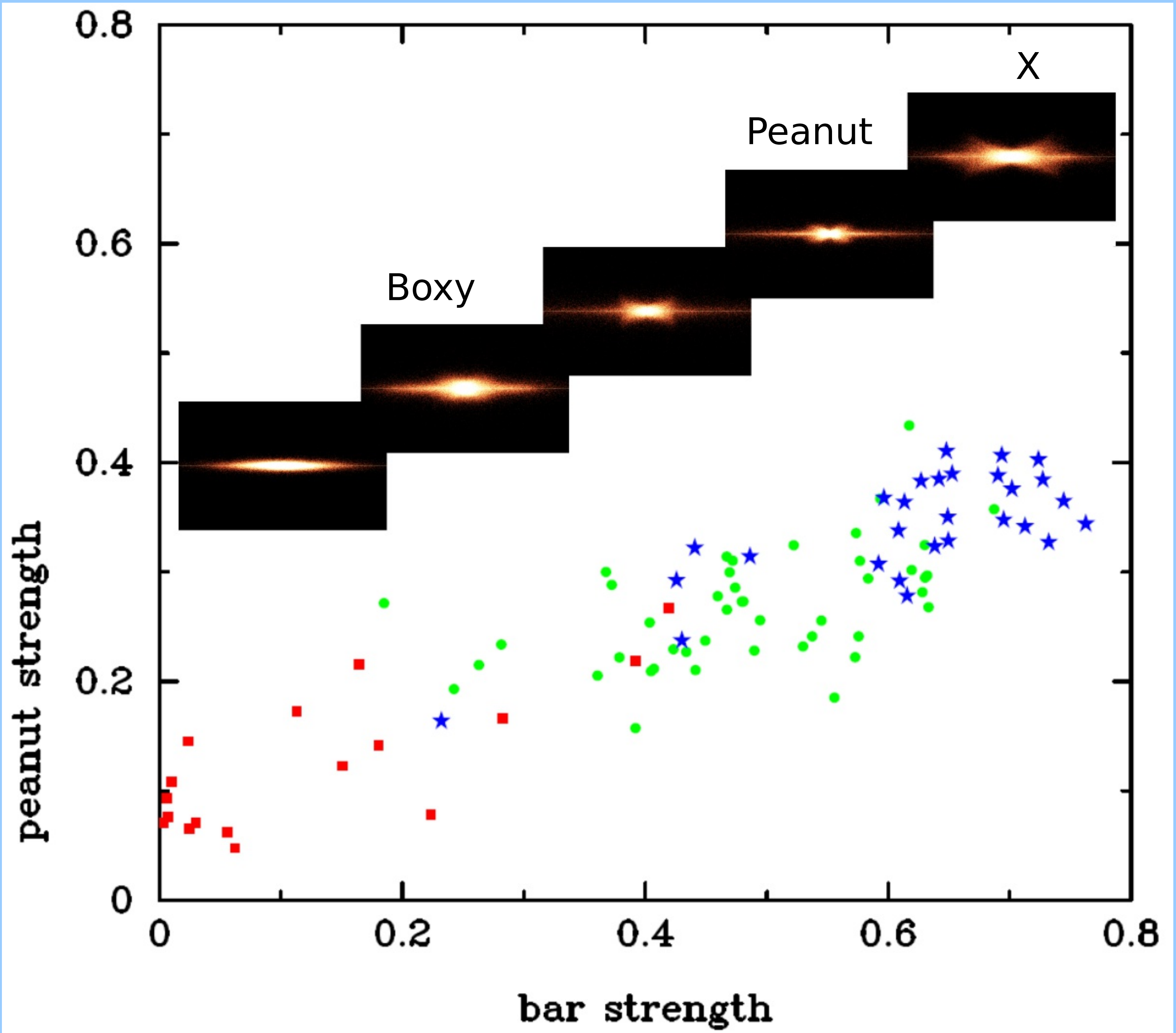


Combes, Debbash, Friedli, Pfenniger 1990
Athanassoula 2005, 2008
Martizez-Valpuesta and Shlosman 2005

Peanuts form AFTER bars

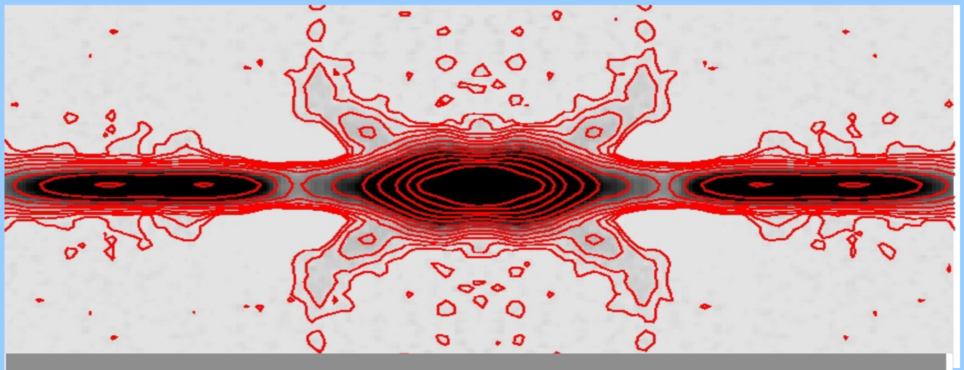


movie



Athanassoula 2008

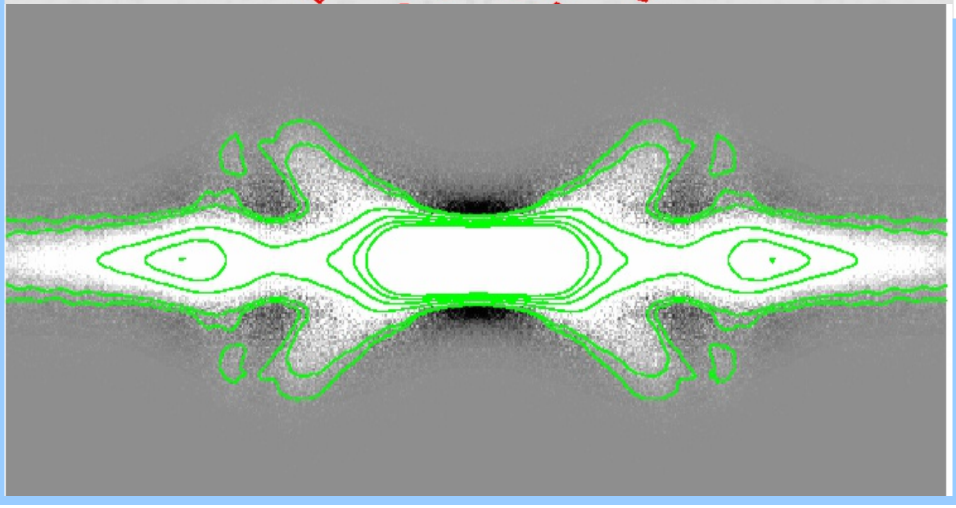
X shapes



NGC 4710 unsharp masked

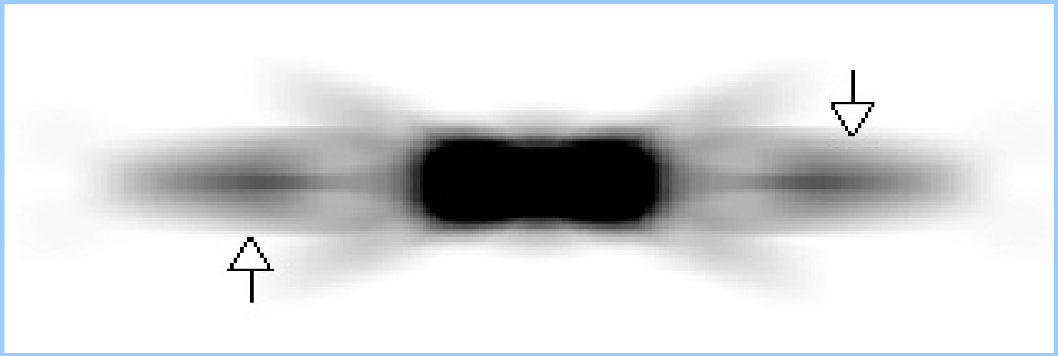
Aronica, Athanassoula, Bureau et al 2003

Bureau, Aronica, Athanassoula et al 2006



N-body simulation

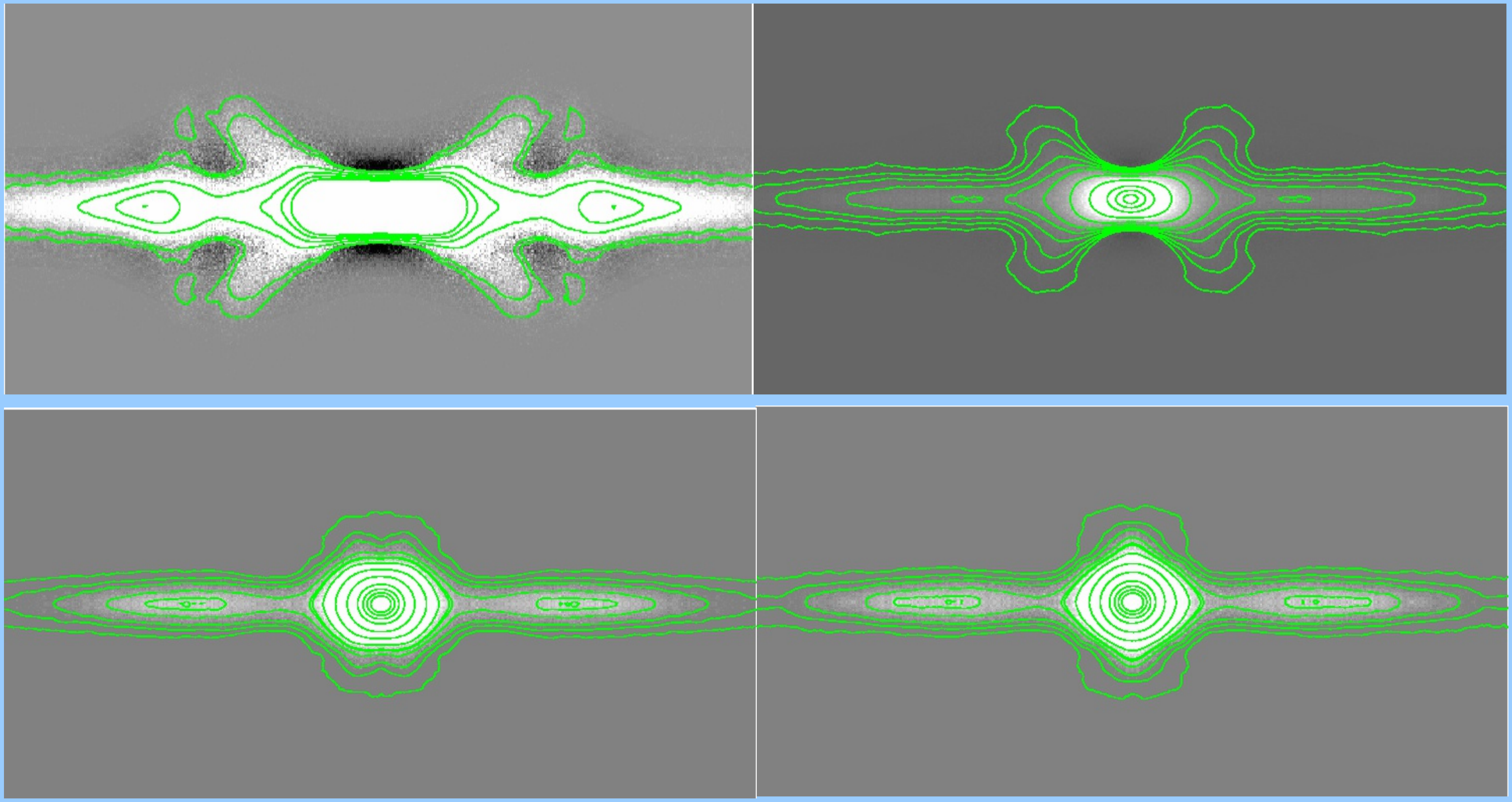
Athanassoula (2005)



3-D periodic orbit calculation

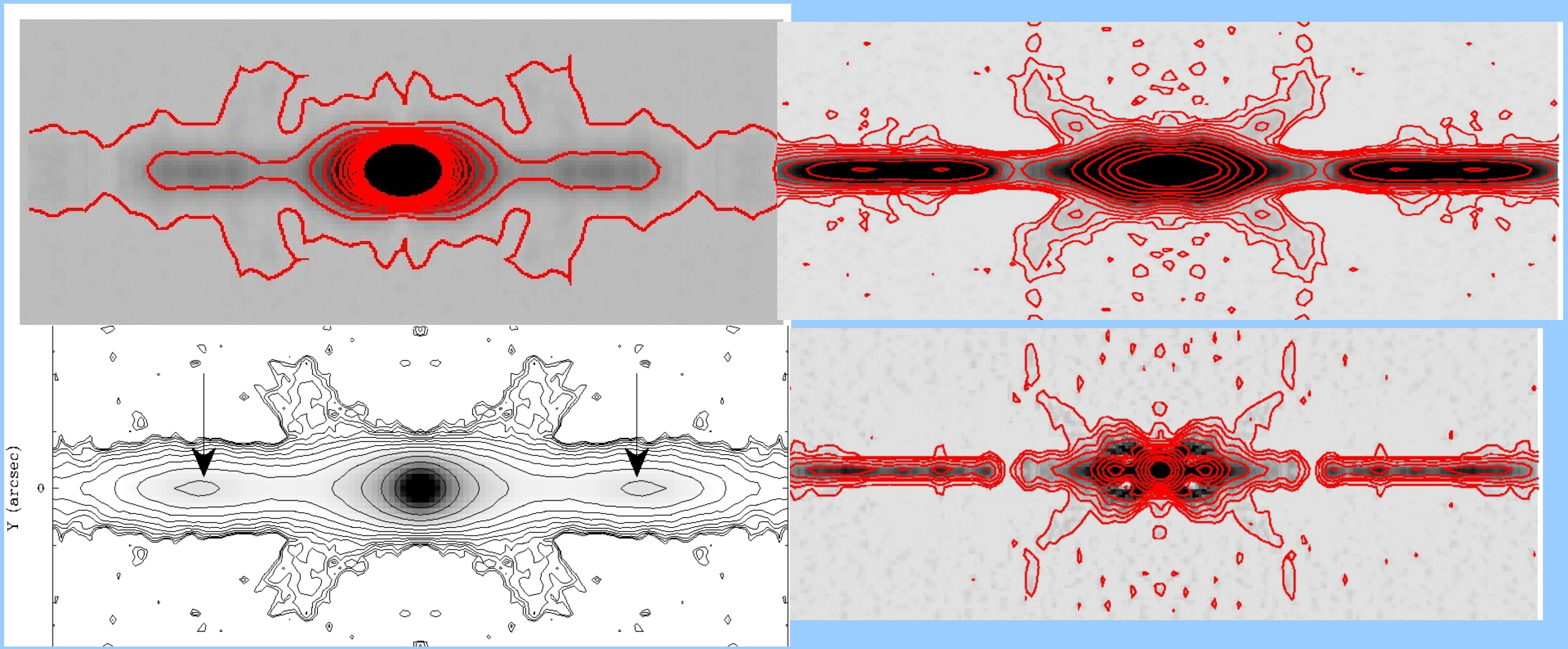
Patsis, Skokos and Athanassoula (2002)

Unsharp masking simulations from different viewing angles



Athanassoula 2005

Observations (unsharp masking)



Aronica, Athanassoula, Bureau, Bosma et al (2003)
Bureau, Aronica, Athanassoula, Dettmar, Bosma, Freeman (2006)

Orbital structure in bars

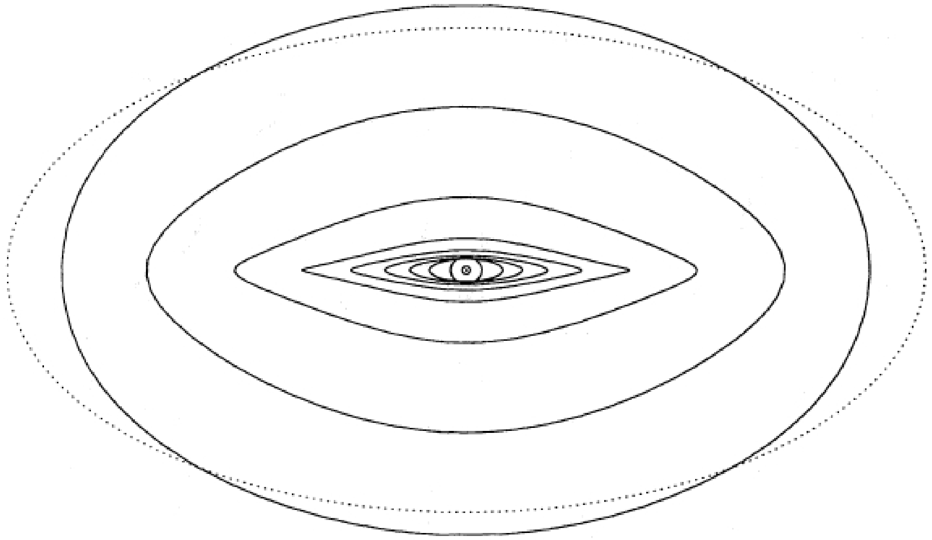
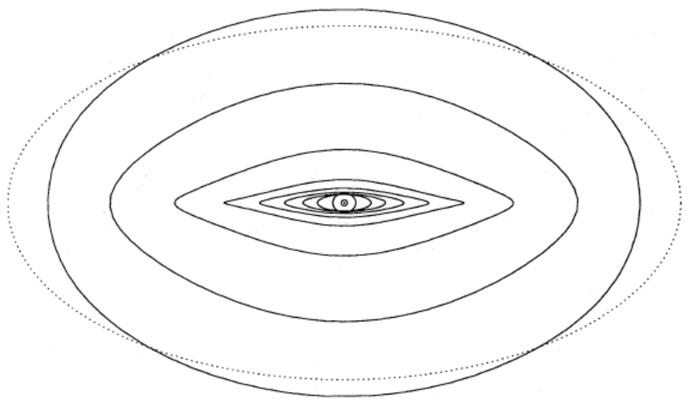


Figure 12. Some periodic orbits of the x_1 family for model 06. The outline of the bar is plotted with a dotted line.

Orbital structure in bars



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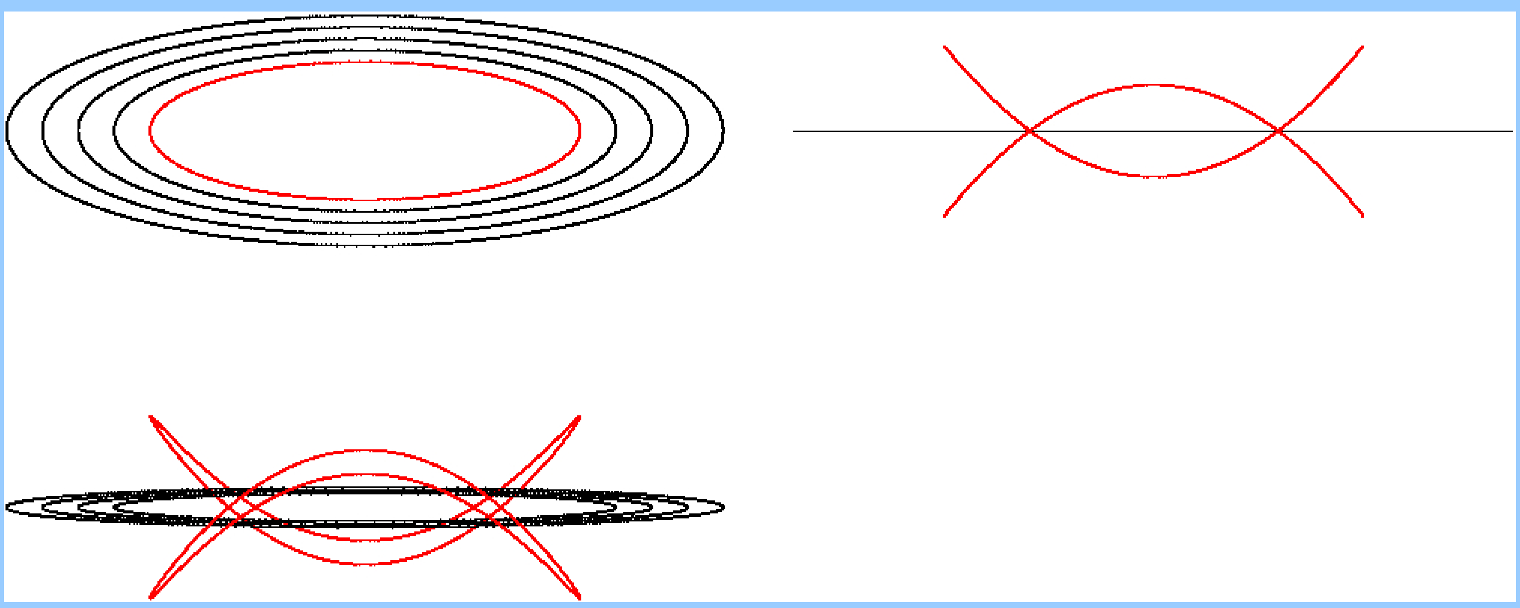
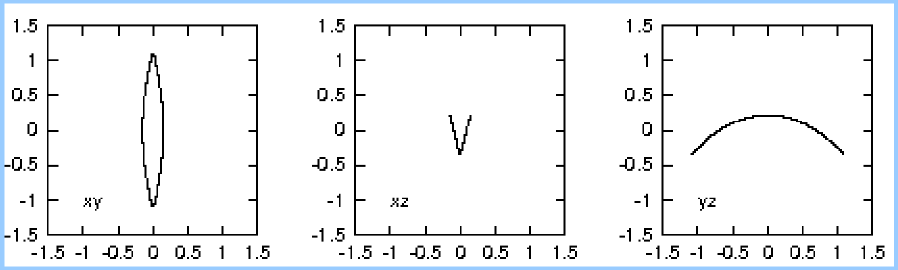
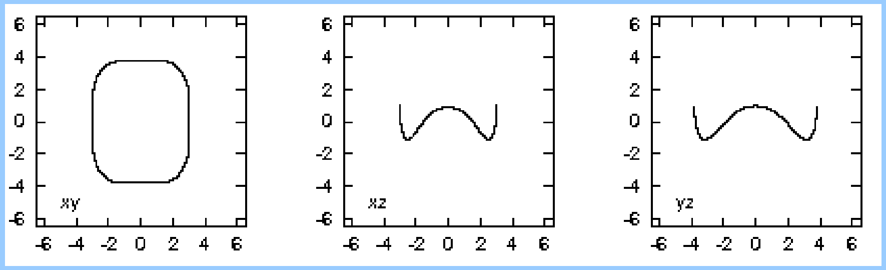
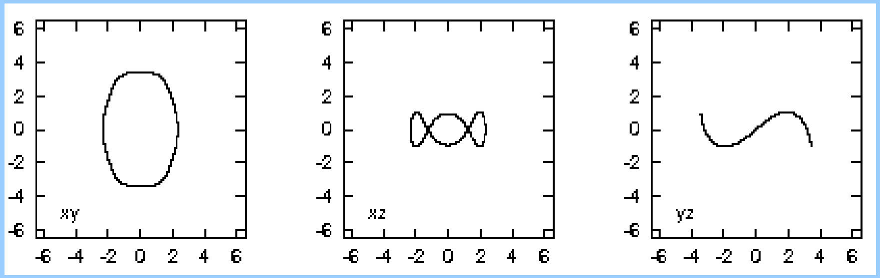


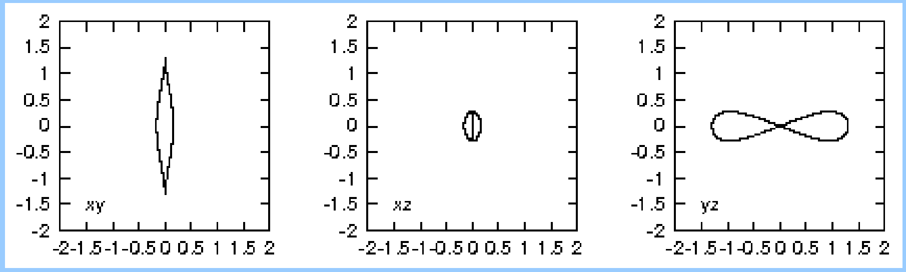
Peanut should have a shape compatible with that of the orbits in the vertical families

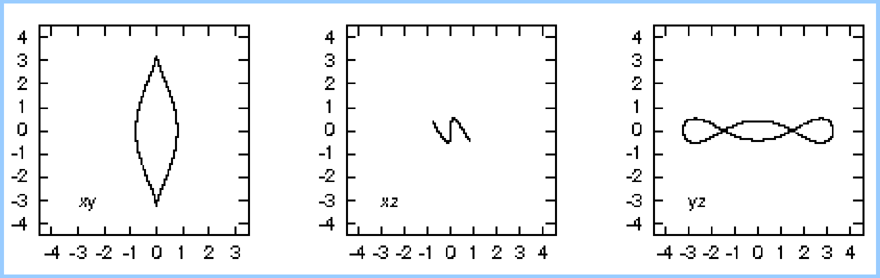
Periodic orbits in 3D



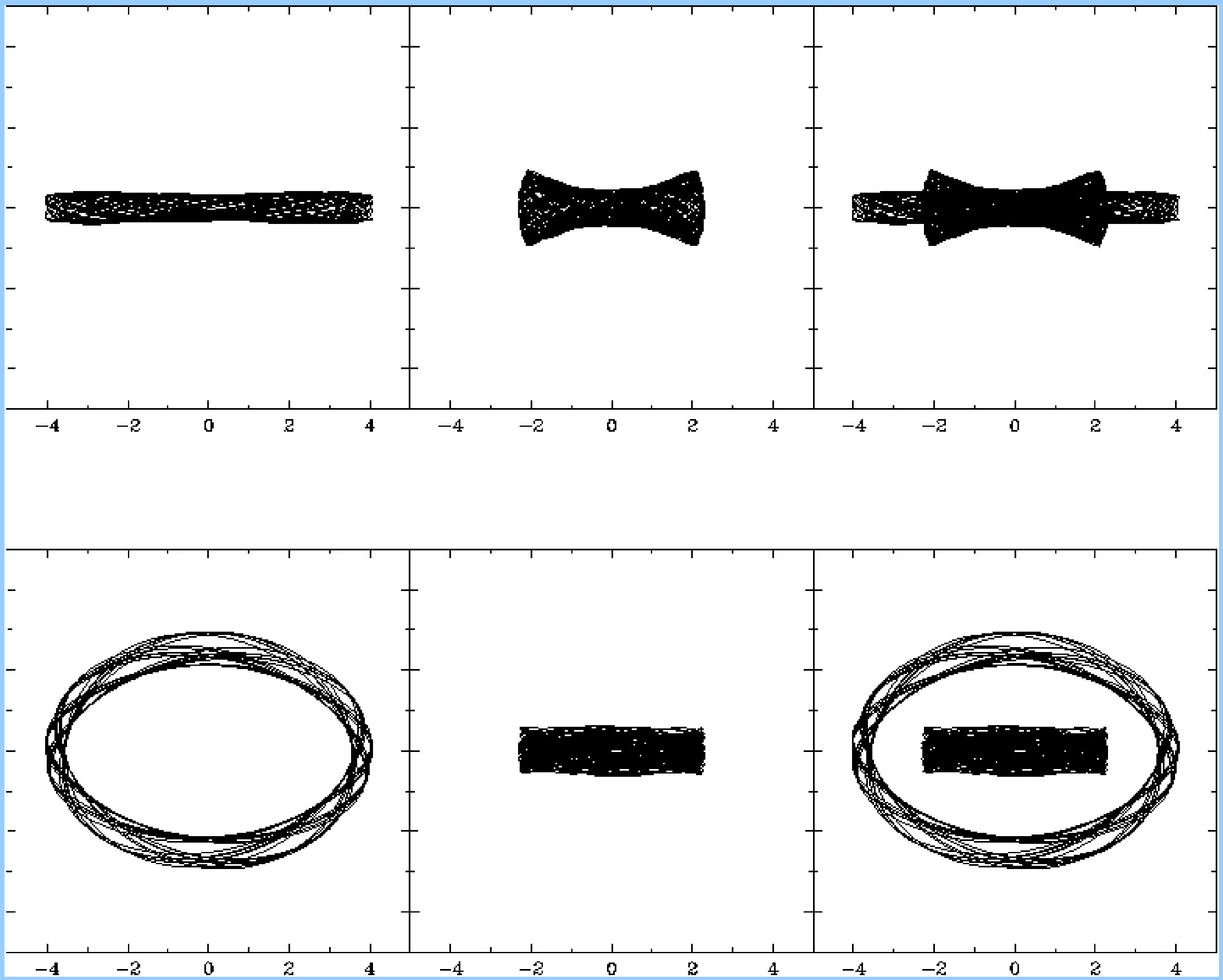








Peanuts should be SHORTER than bars



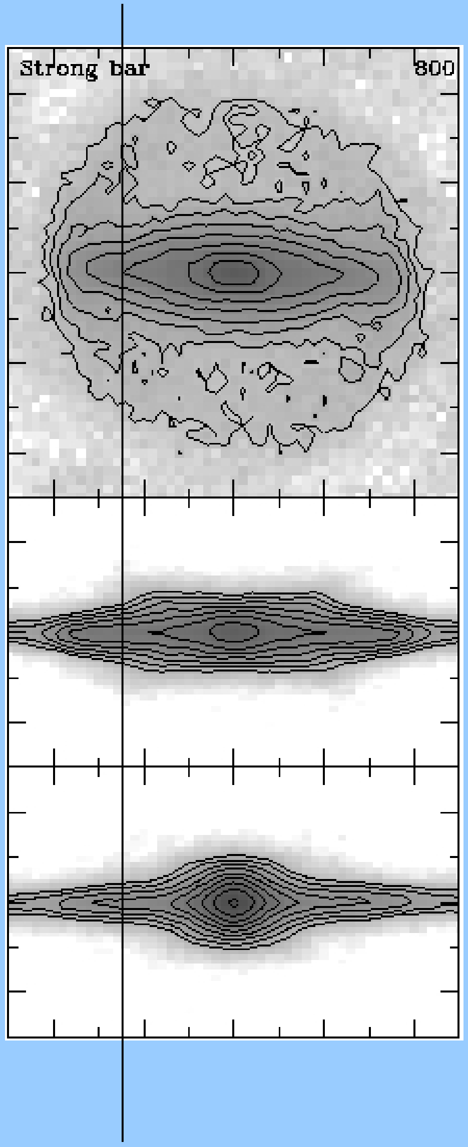
edge-on

face-on

EA 05

Orbital structure theory: peanuts are shorter than bars

Pfenniger 84; Skokos, Patsis, EA 02; Patsis, Skokos, EA 02

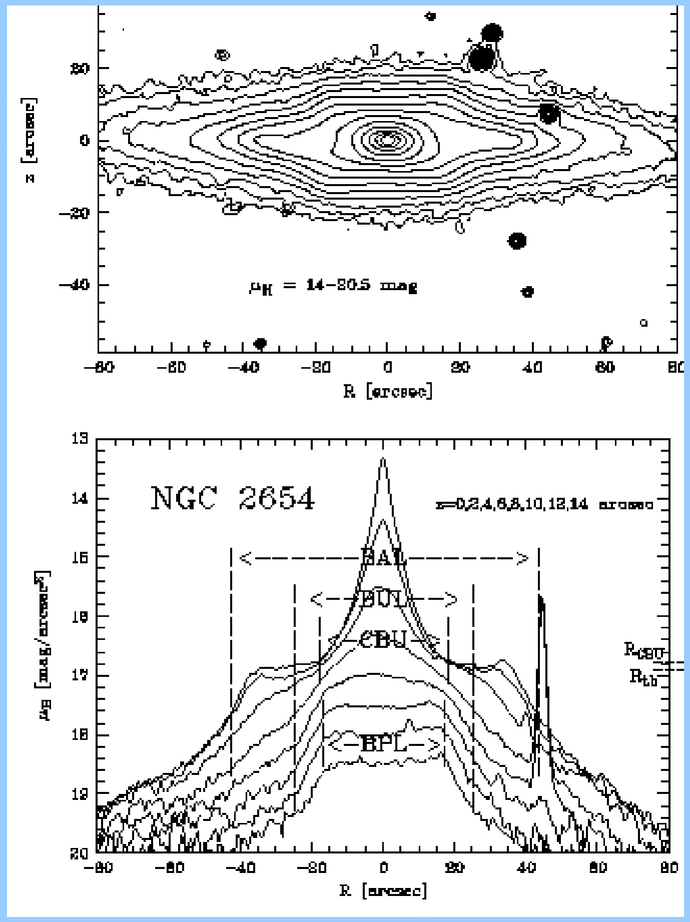


Simulations :

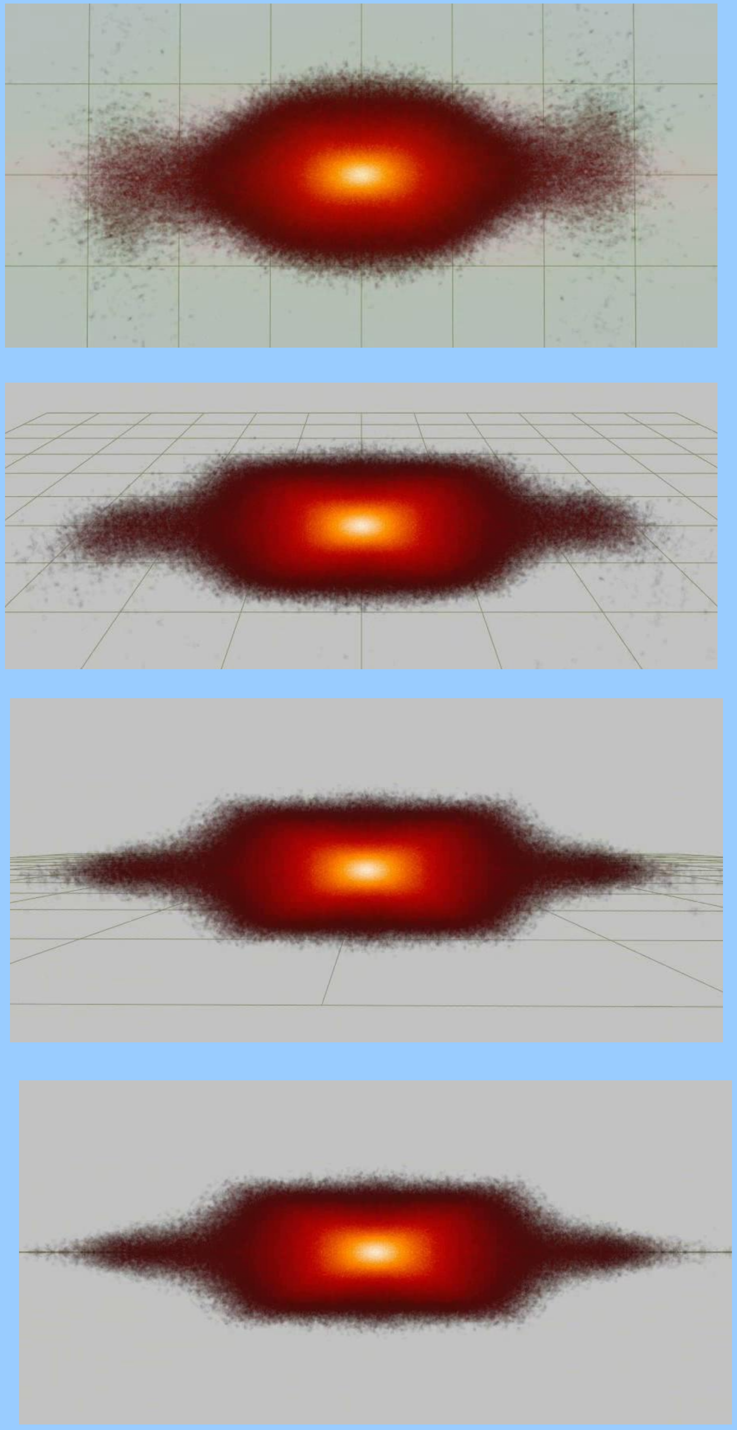
Athanassoula and Misiriotis 2002

Athanassoula 05

Athanassoula and Beaton 2006



Lutticke, Dettmar and Pohlen, 2000
Bureau, Aronica, Athanassoula et al 2006



For a full movie see
http://lam.oamp.fr/research/dynamique-des-galaxies/
scientific-results/milky-way/bar-bulge/how-many-bars-in-mw

Apply to the Milky Way

Signal for 2 bars:

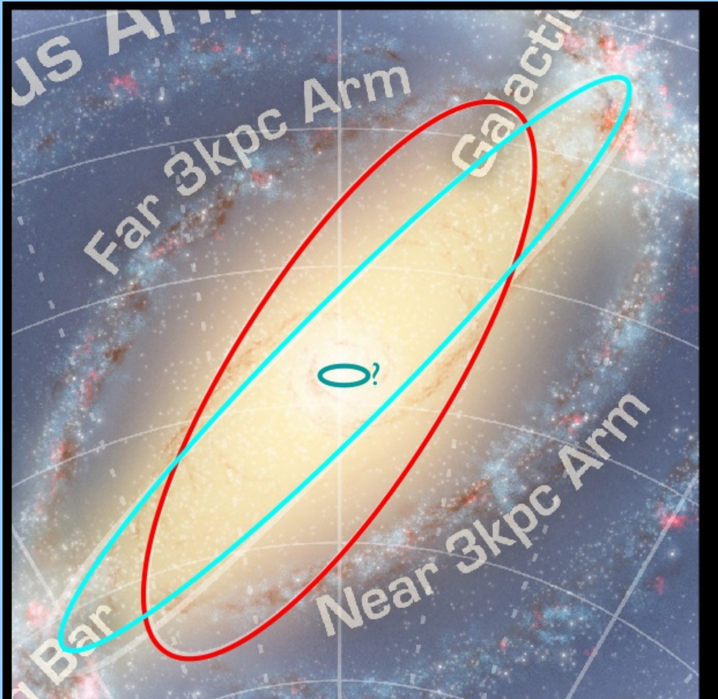
- The COBE/DIRBE bar

Bar semimajor axis 3.1 – 3.5 kpc
Axial ratio 10:4:3
Direction 15 – 30 degrees from the Sun-GC line

- The Long bar

Bar semimajor axis 4 – 4.5 kpc
Axial ratio 10:1.54:0.25
Direction 40 degrees from Sun - GC

Benjamin



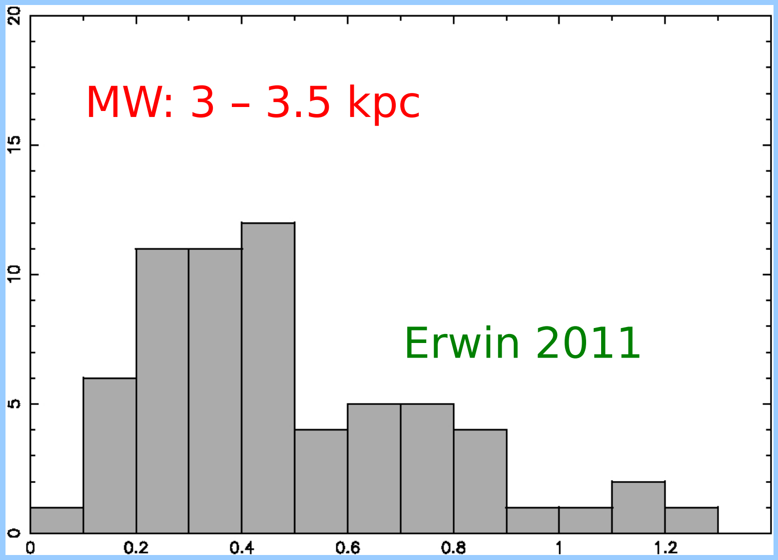
Artist's conception of MW (Robert Hurt, SSC/IPAC/JPL)
http://ipac.jpl.nasa.gov/media_images/ssc2008-10b1.jpg

Hammersley et al 2000, Benjamin et al 2005
Lopez-Corredoira et al 2005, 2007

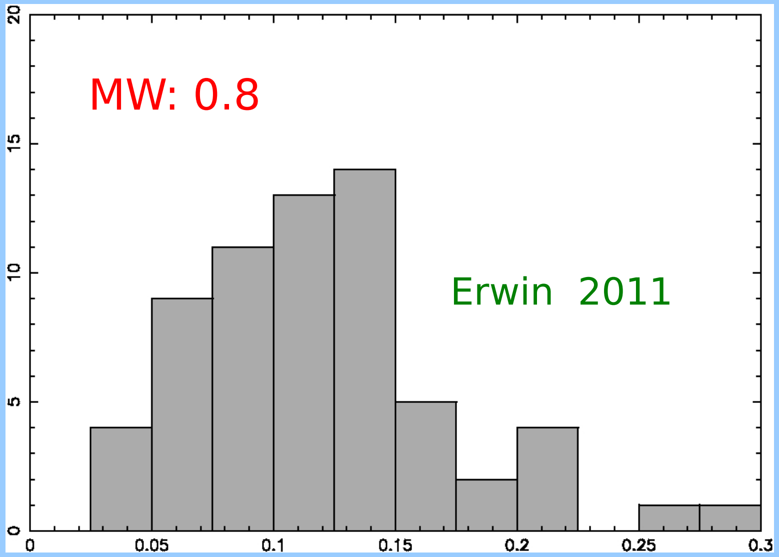
So what is the structure of the bar/bulge system in our Galaxy?

Summarise arguments from
Romero-Gomez, EA et al 2011

Double bar systems in external galaxies



Semi-major axis length [kpc]



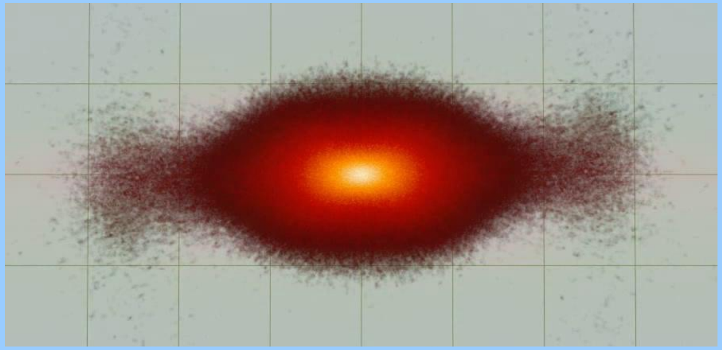
Length ratios (secondary/primary)

The bar lengths of the COBE/DIRBE bar and the Long bar show clearly that these two together do not form a double bar system.

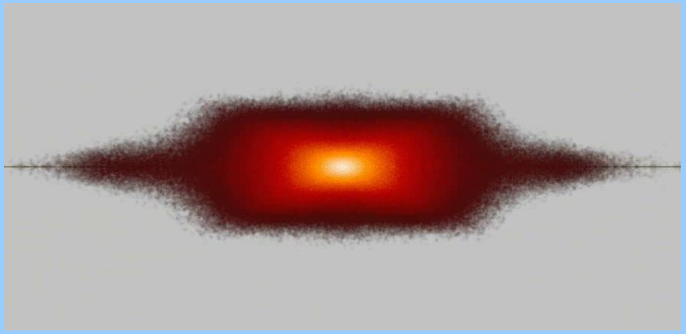
Also there are limits to these length ratios from resonant interaction driven chaos and morphology in simulations (Maciejewski and Sparke 2000, Maciejewski and Athanassoula 2008, Shen and Debattista 2009, Heller et al 2009)

(but the MW may well have a double bar Alard 01)

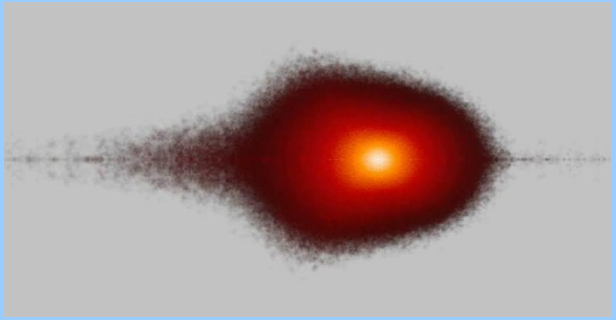
Romero-Gomez et al 2011

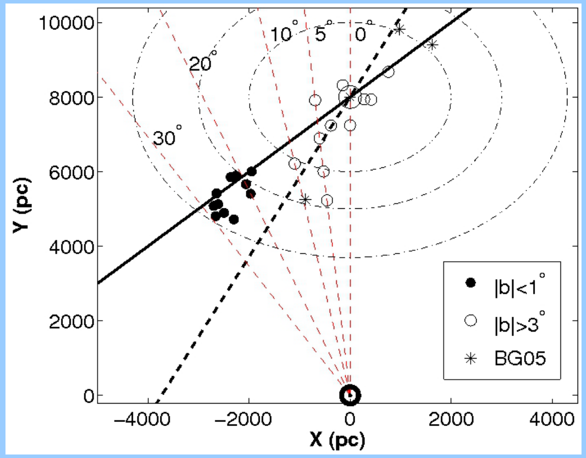


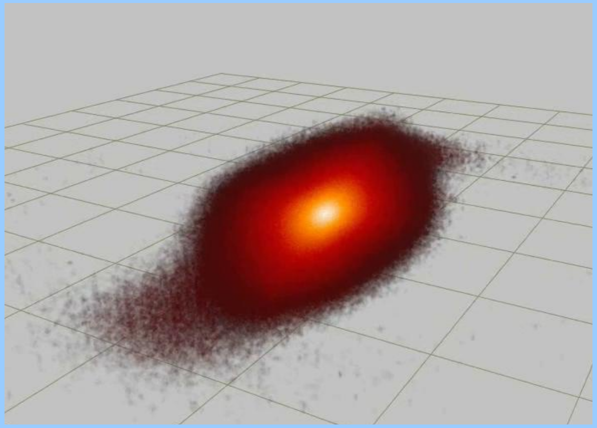
How are the COBE/DIRBE bar and the Long bar related?
Clue 1: Long bar is vertically very thin, COBE/DIRBE bar is very thick.
Clue 2: Long bar is longer than the COBE/DIRBE bar



Athanassoula (2006): There is a single bar of which the COBE/DIRBE bar is the boxy/peanut part and the Long bar is the thin outer parts. Tested by Cabrera-Lavers et al (2007).







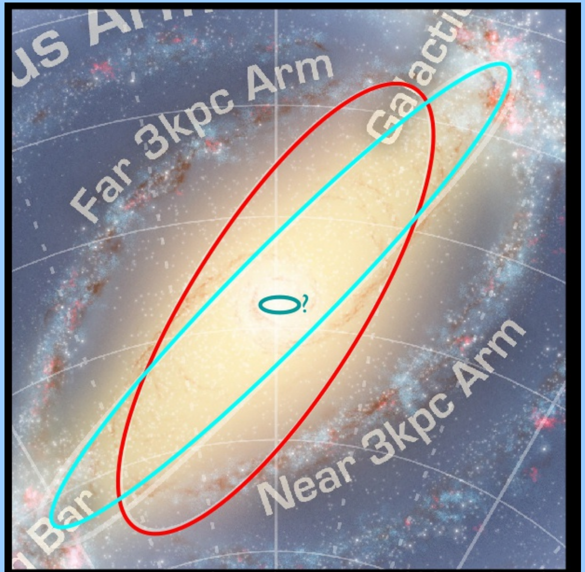
See also Romero-Gomez et al (2011) and Martinez-Valpuesta and Gerhard (2011)

For a full movie see
http://lam.oamp.fr/research/dynamique-des-galaxies/scientific-results/milky-way/bar-bulge/how-many-bars-in-mw

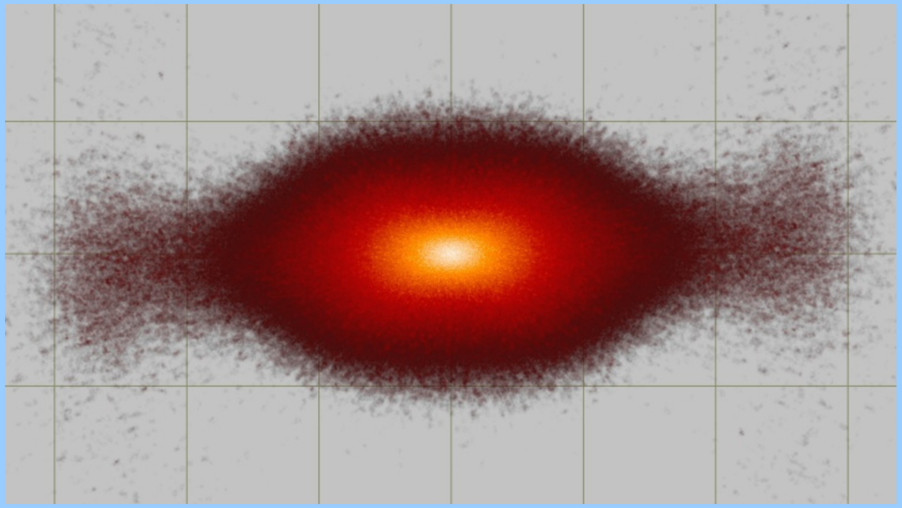
But:

The difference in position angles? (15 - 30 degrees for COBE/DIRBE bar and 40 degrees for the long bar)

Arguments presented in Romero-Gomez, EA et al (2011).
See also Martinez-Valpuesta and Gerhard (2011). Good agreement



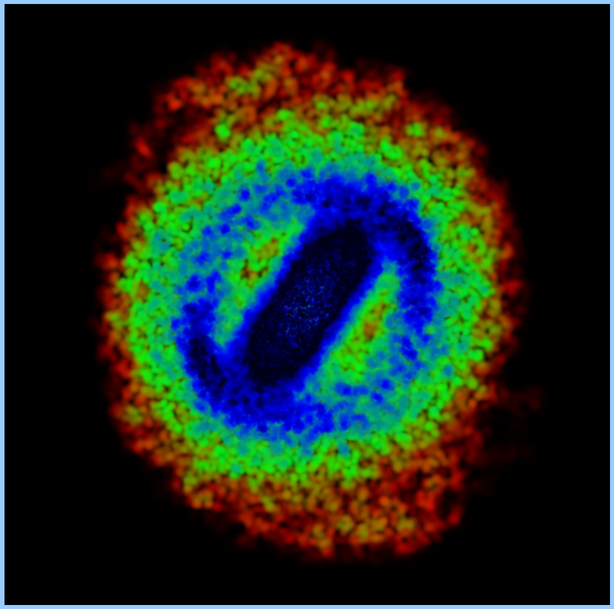
Artist's conception of MW (Robert Hurt, SSC/IPAC/JPL)
http://ipac.jpl.nasa.gov/media_images/ssc2008-10b1.jpg

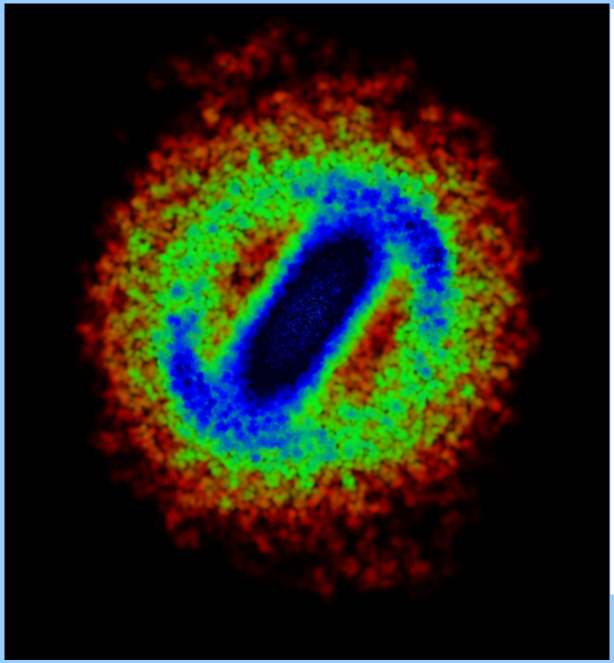


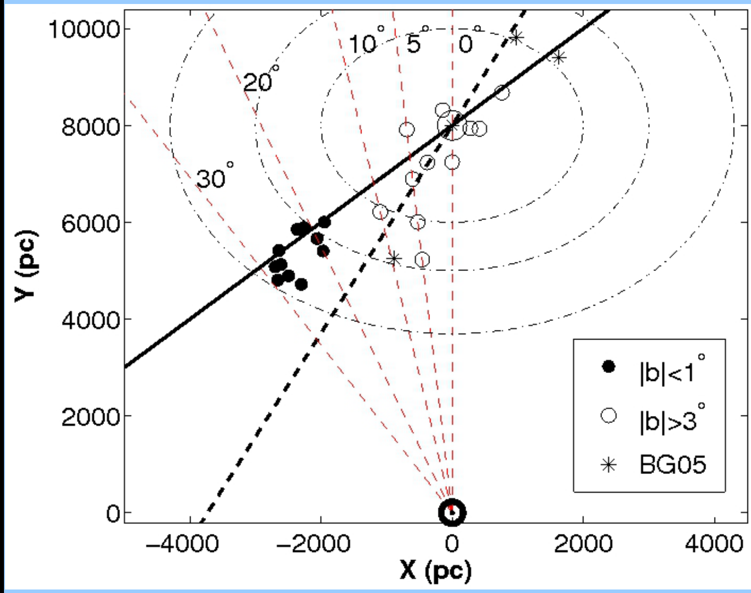
Zasowski, Benjamin and Majewski (2011)

The long bar is at 25 – 35 degrees

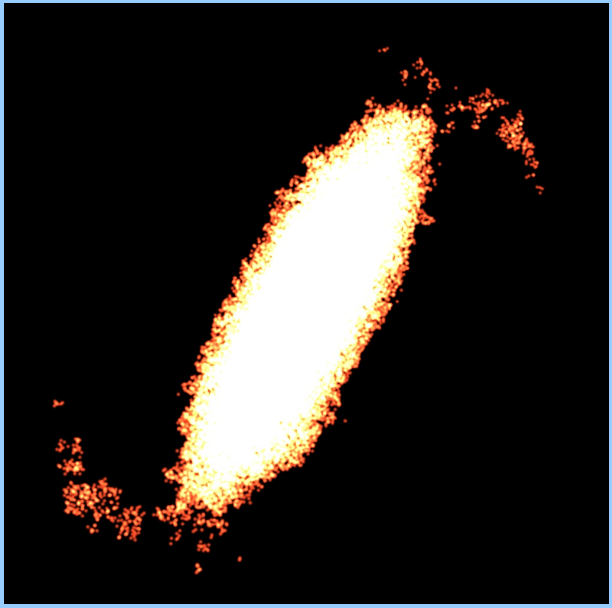
Face-on view of the bar: The B/P part is thicker than the outer part. This can contribute to the angle difference between the Long 'bar' and the COBE/DIRBE 'bar'

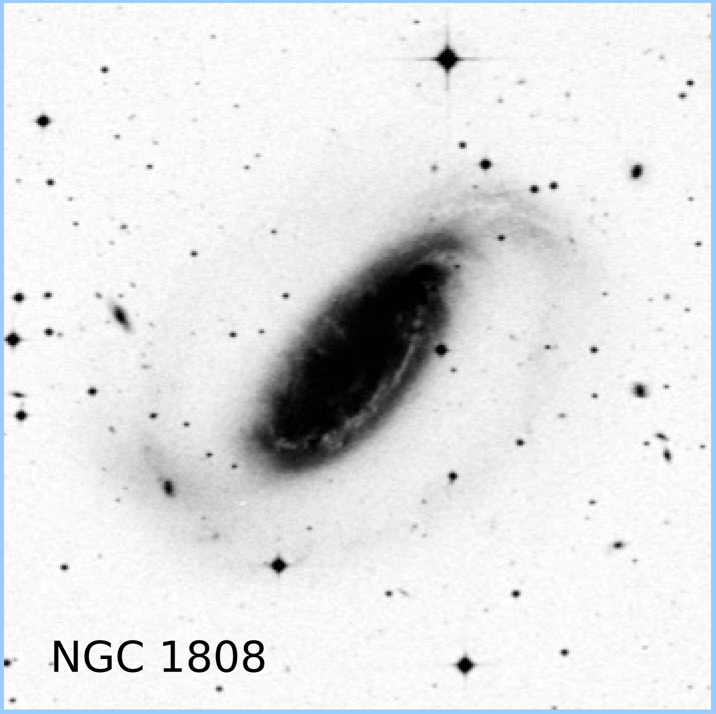






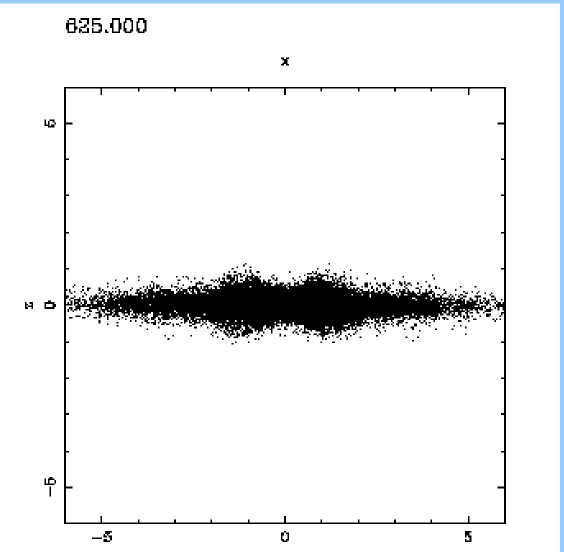
A leading extension in the ring: This may be the reason that we see the long bar at a larger angle than the COBE/DIRBE bar (or may contribute substantially to it).





Feature found in:
Athanassoula and Misiriotis 02

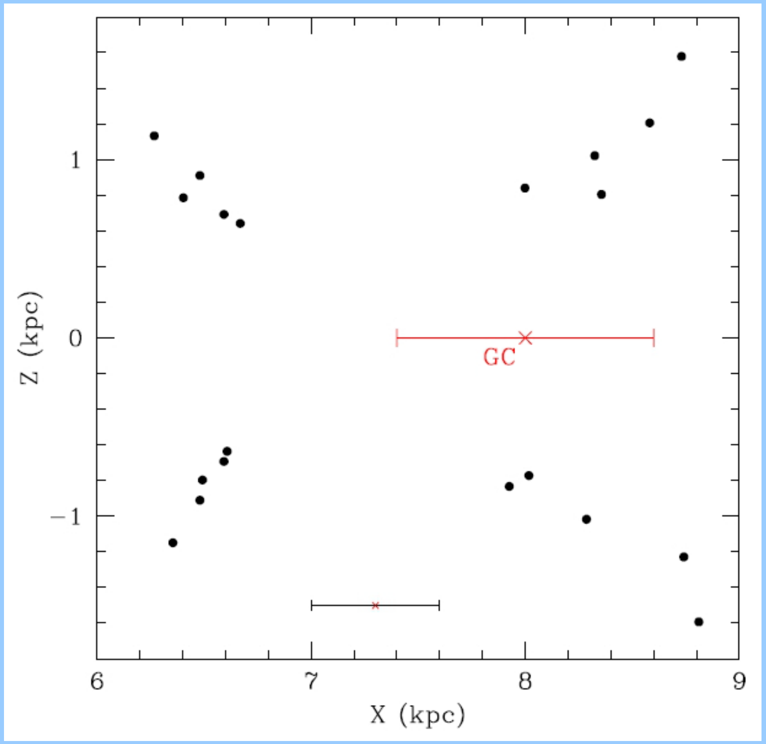
Use for the MW:
Romero-Gomez, EA et al 2011
Martinez-Valpuesta & Gerhard 2011



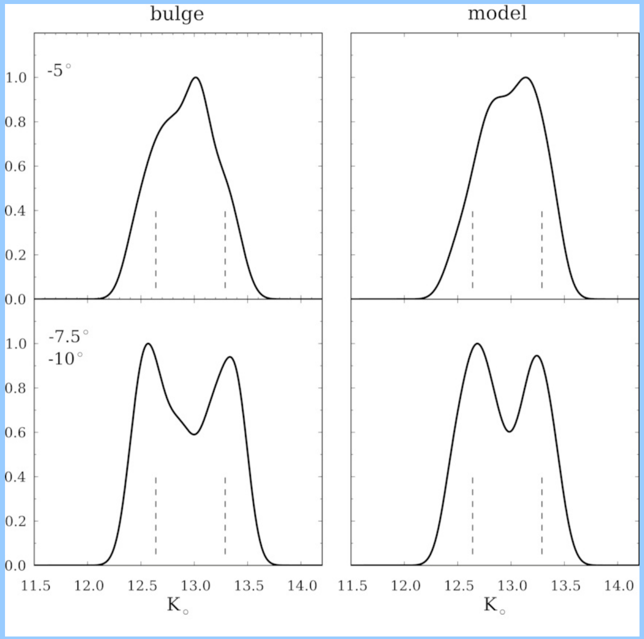
McWilliam & Zoccali 2010

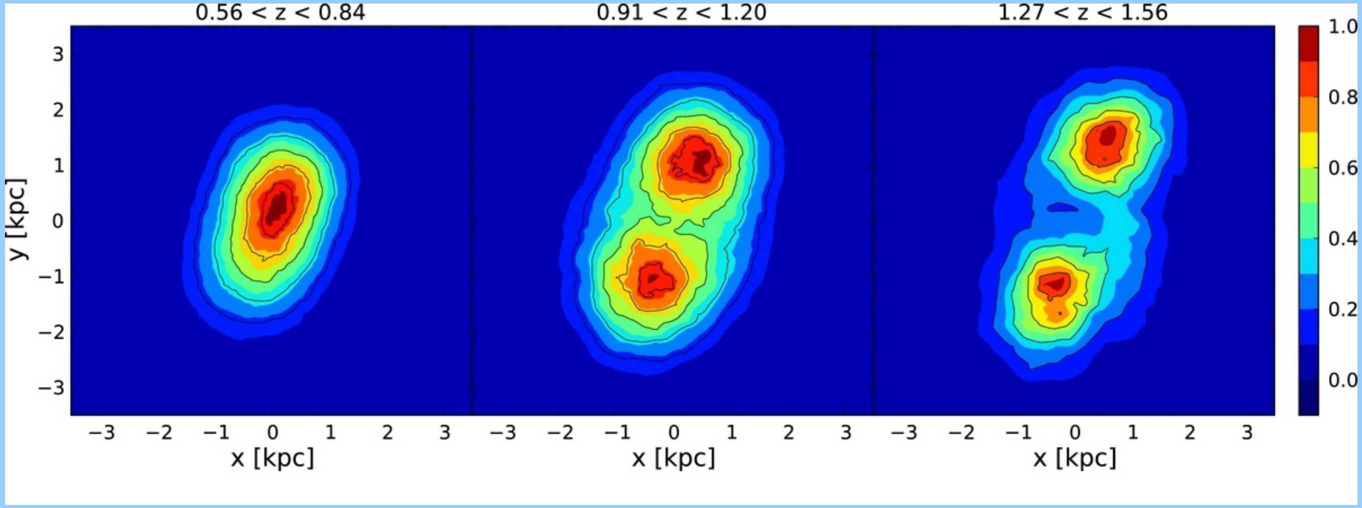
Nataf et al 2010

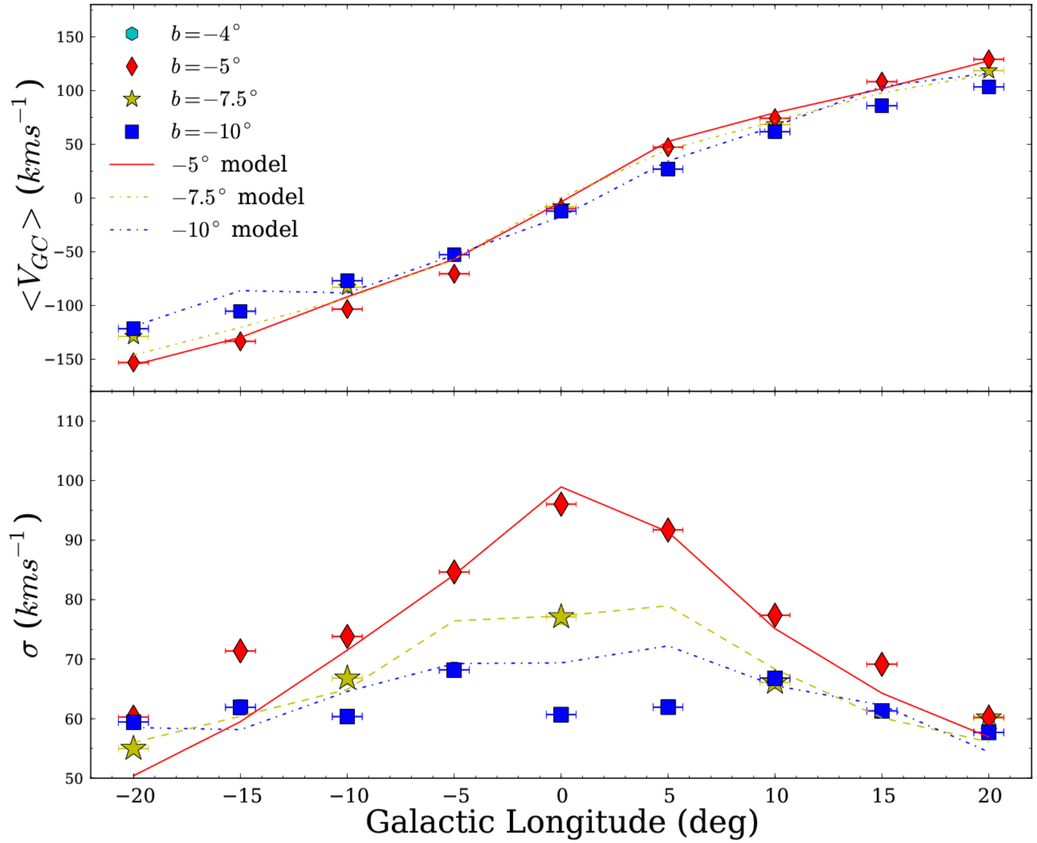
etc



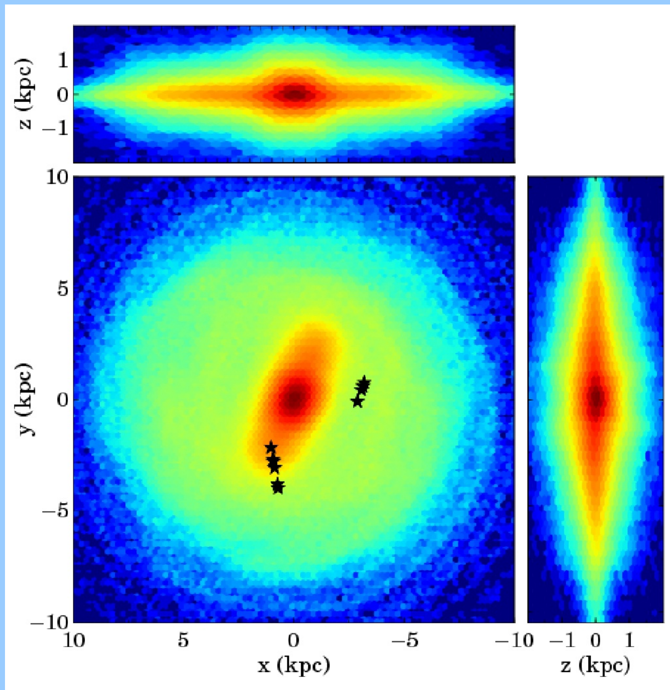
ARGOS: Ness et al 2012, 2013a, 2013b



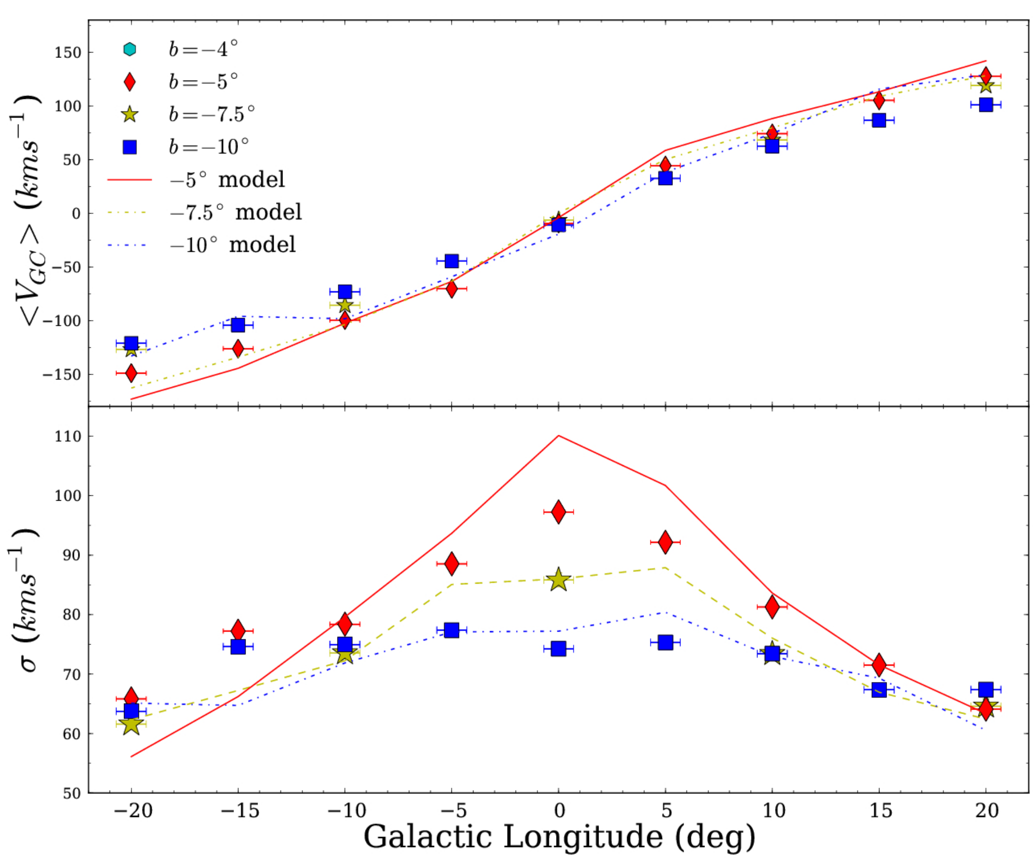




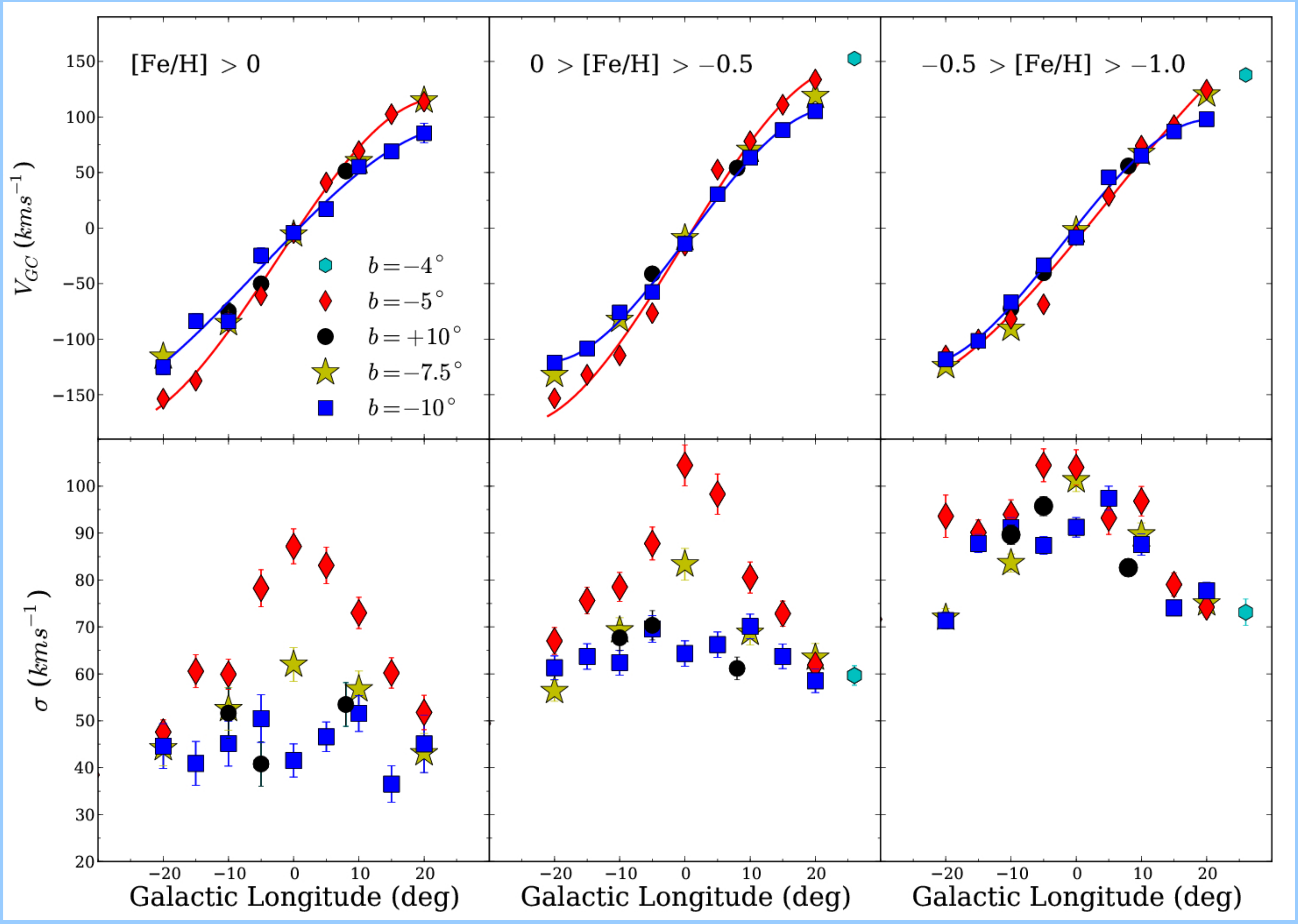
$b=-4°$
$b=-5°$
$b=-7.5°$
$b=-10°$
$-5°$ model
$-7.5°$ model
$-10°$ model
$<V_{GC}>$ (kms^{-1})
σ (kms^{-1})
Galactic Longitude (deg)



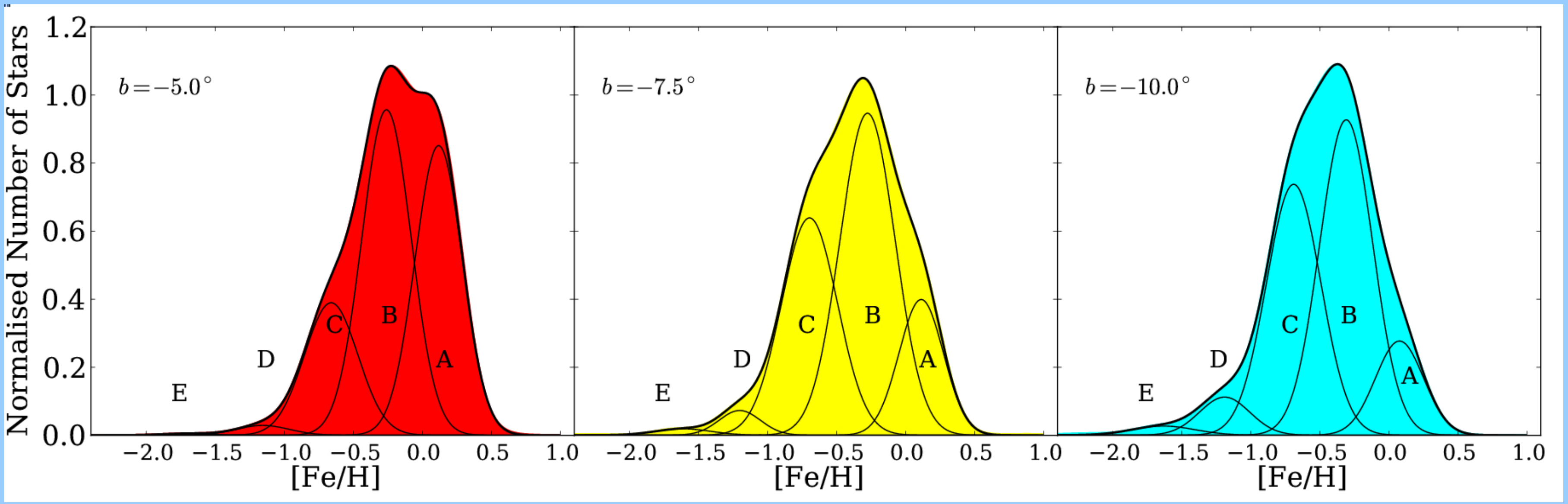
z (kpc)
y (kpc)
x (kpc)
z (kpc)



$b=-4°$
$b=-5°$
$b=-7.5°$
$b=-10°$
$-5°$ model
$-7.5°$ model
$-10°$ model
$<V_{GC}>$ (kms^{-1})
σ (kms^{-1})
Galactic Longitude (deg)



[Fe/H] > 0
0 > [Fe/H] > −0.5
−0.5 > [Fe/H] > −1.0
$b = -4°$
$b = -5°$
$b = +10°$
$b = -7.5°$
$b = -10°$
V_{GC} (kms^{-1})
σ (kms^{-1})
Galactic Longitude (deg)
Galactic Longitude (deg)
Galactic Longitude (deg)


Normalised Number of Stars
$b = -5.0^\circ$
$b = -7.5^\circ$
$b = -10.0^\circ$
A
B
C
D
E
[Fe/H]
0.0
0.2
0.4
0.6
0.8
1.0
1.2
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0

The end