Disc Galaxies and their Structures: Approach by simulations

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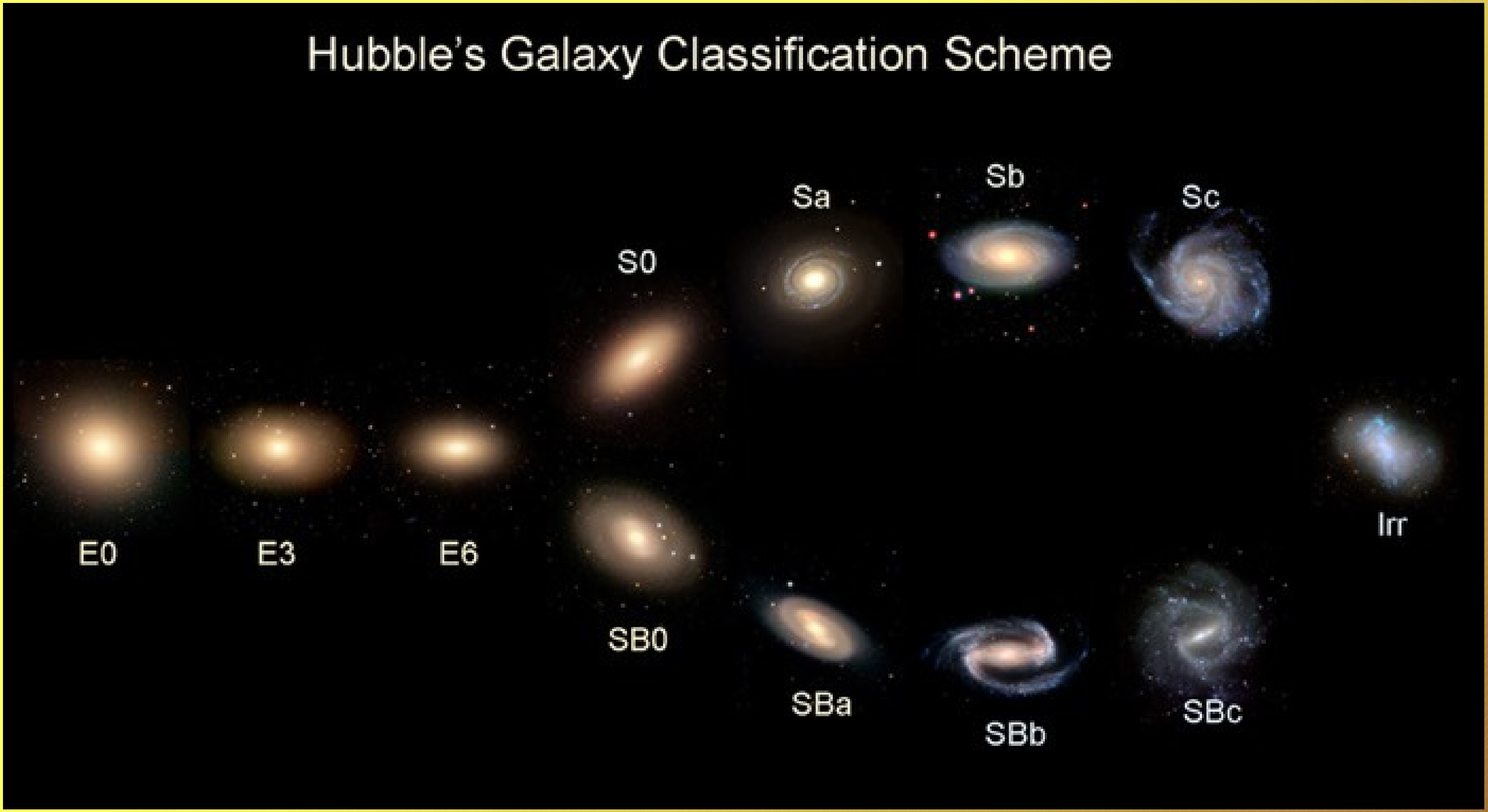
Hubble's tuning fork



Barred Spiral Galaxy NGC 1300

Hubble Heritage

NASA, ESA and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC05-01

NGC 1300 – image from the legacysurvey-dr9

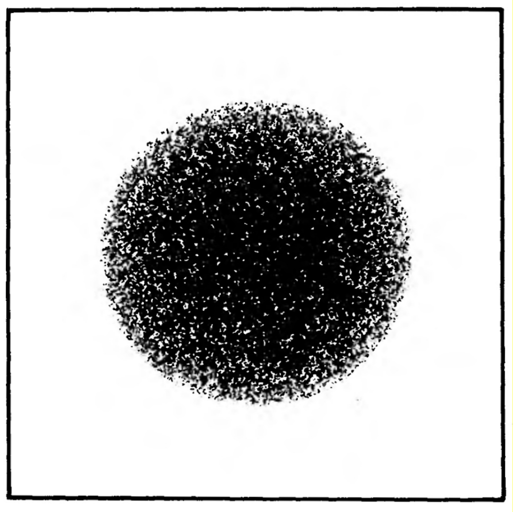
How do we use N-body simulations to study galaxies?

SIMPLEST (early 70s):
– Gravity
– N point masses (particles) // on NASA computer => N=100 000
Calculate the total force on a given particle by summing over the forces from all other particles
– 2D
– Add a halo as a potential (rigid vs self-consistent)
– Particles move due to these forces

NOWDAYS MORE REALISTIC MODELS:
– Big progress in computer technology (hardware)
– Better techniques to calculate forces (software)
– N = several tens or hundreds of millions /billions
– 3D
– All components represented by particles (no rigid components)
– Gas / AGN / Star formation / Feedback / Cooling
– Chemo-dynamics

Hohl 1971 – 2D – used only disc, and found bar instability

Initial conditions



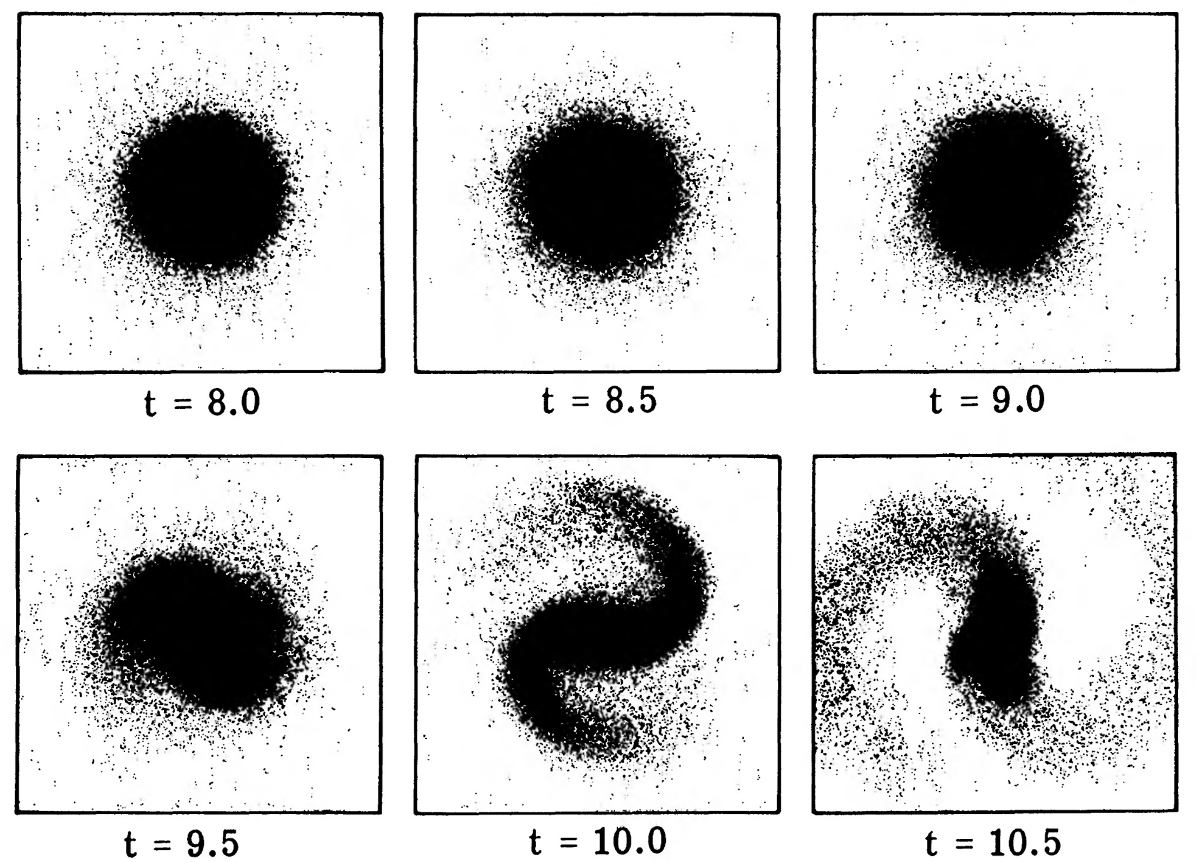


FIG. 3.—Nonaxisymmetric evolution of the disk with an initial condition taken as the disk in Fig. 1 at $t = 8$.

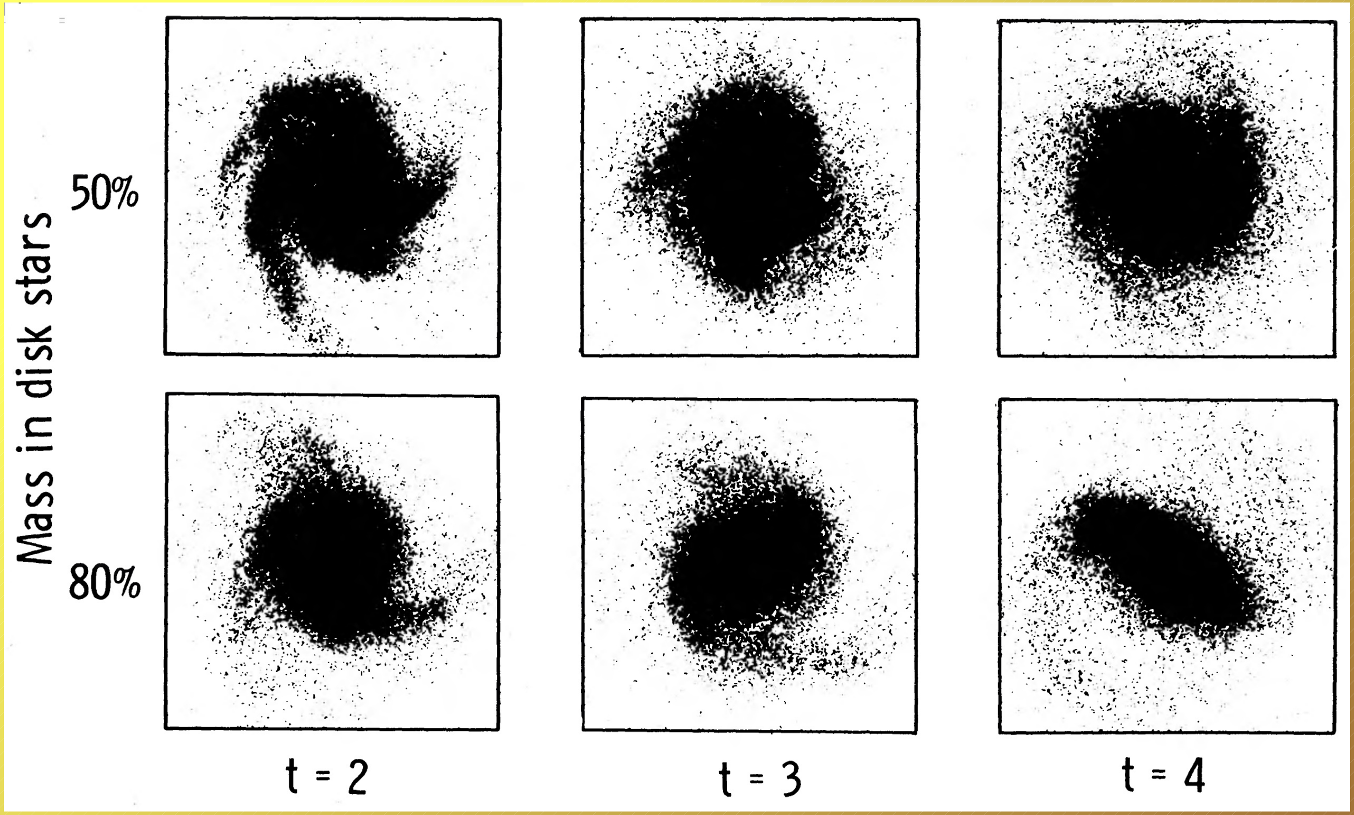
So why are not all galaxies barred?

So why are not all galaxies barred?

Ostriker & Peebles 1973 (150 -500 particles)

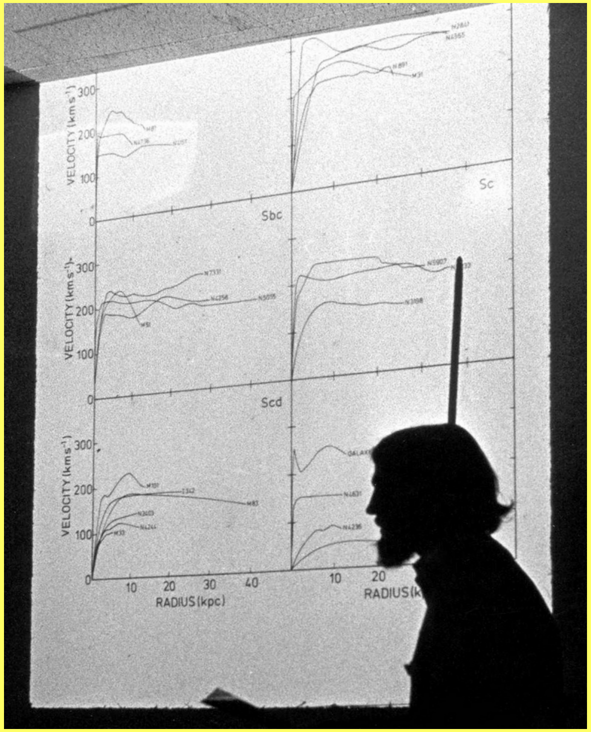
Cure the bar instability using a halo potential (sufficiently strong)

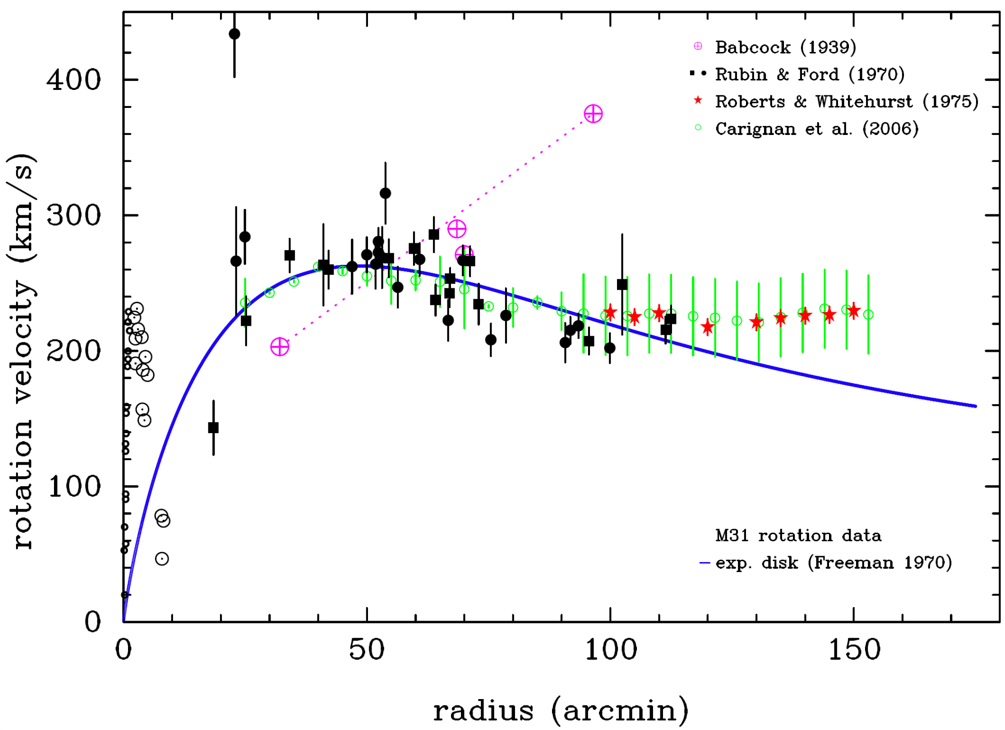
This was the beginning of all the work on dark matter (DM)

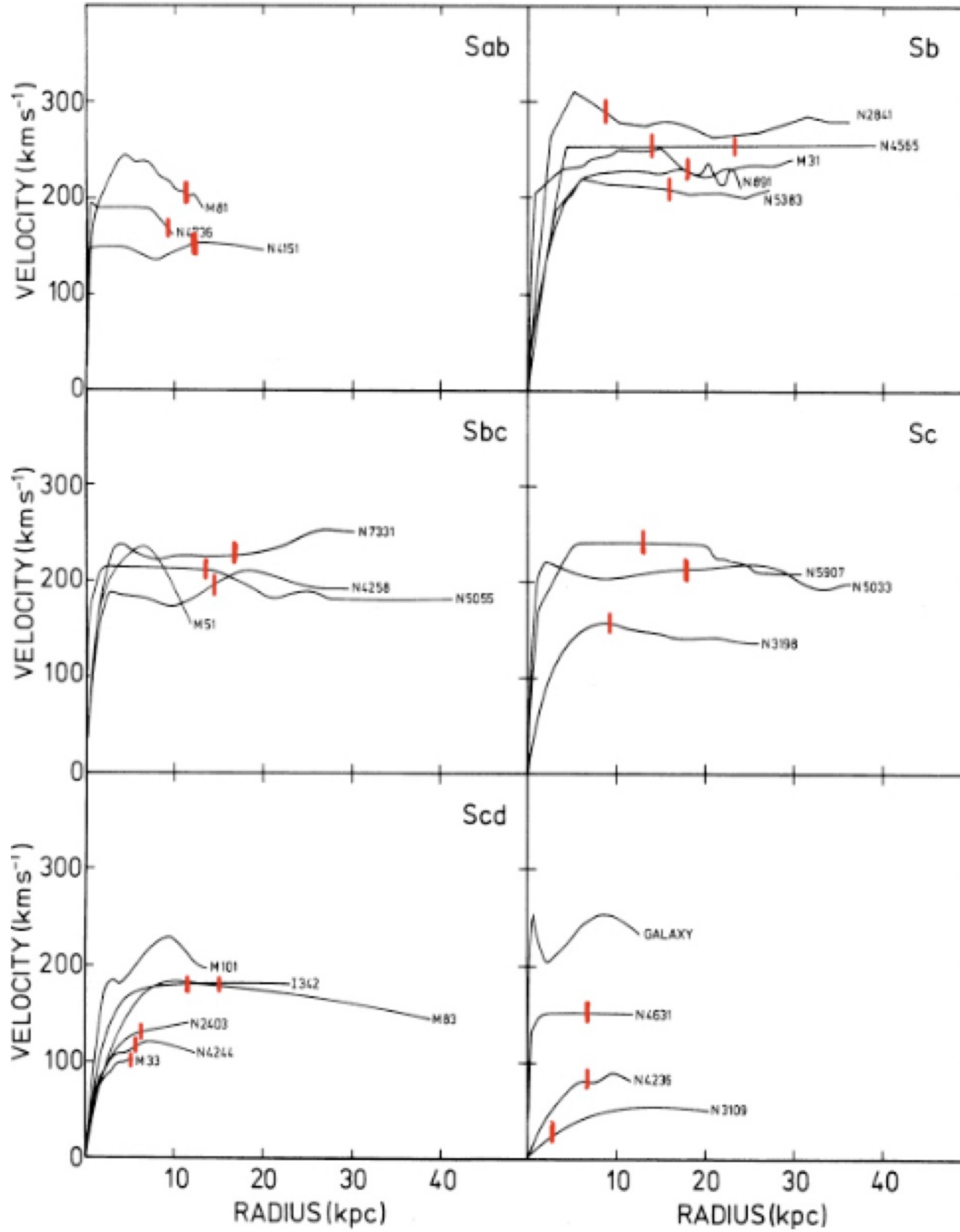


Hohl 1976

Bosma, 1978, 1981a,b







Reproduced in Faber & Gallagher ARAA 1979

How do we use N-body simulations to study disk galaxies?

– Big progress in computer technology (hardware)
– Better techniques to calculate forces (software)
– N = several tens of millions

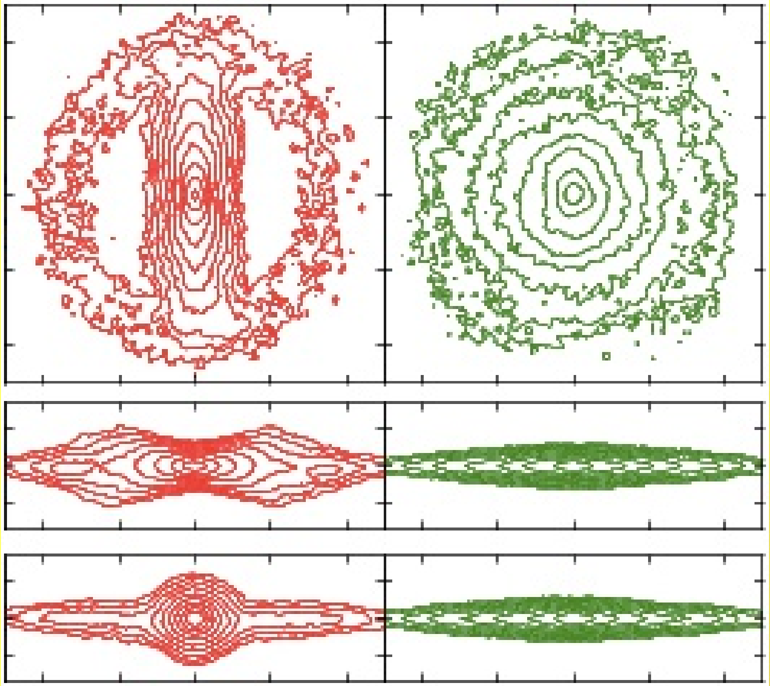
NOWDAYS MORE REALISTIC MODELS:
– All components represented by particles (no rigid components)
– 3D
– Gas / Star formation / AGN / Feedback / Cooling
– Chemo-dynamics (MW and GAIA)

Halos should be adequately modeled

Live halo

Halo can receive angular momentum

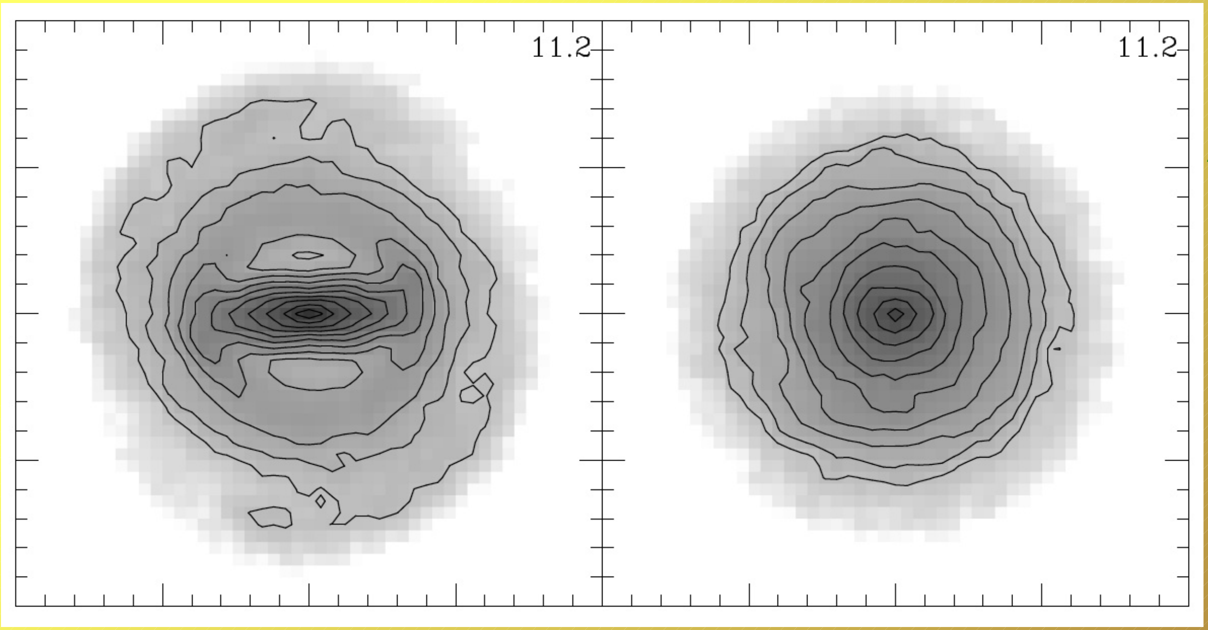
Strong bar develops



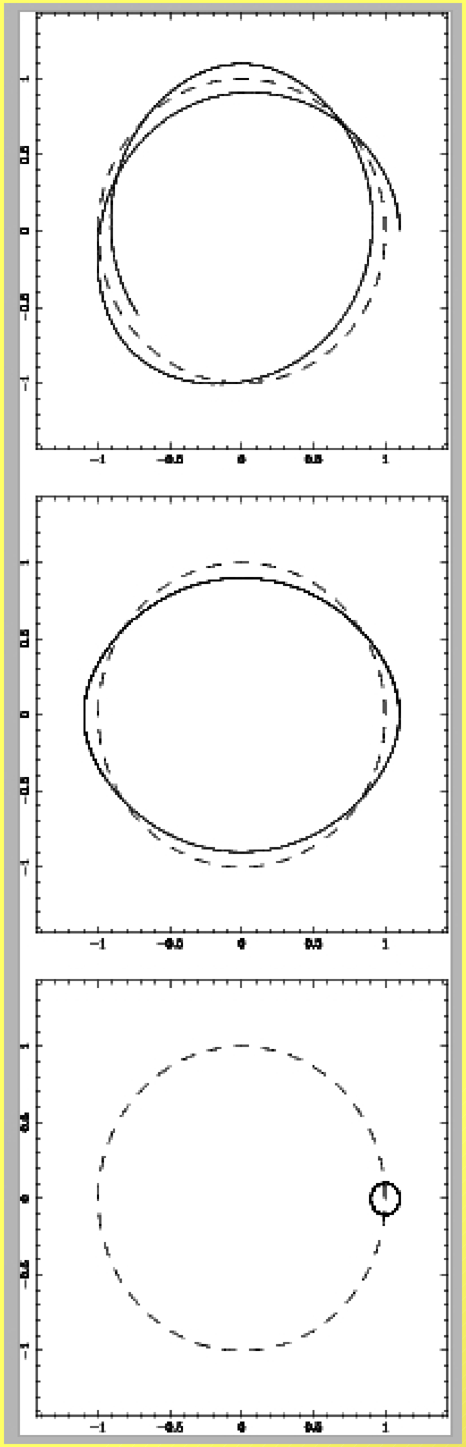
Rigid halo

Halo can not receive angular momentum

No bar develops



Athanassoula 2002



$\Omega - \Omega_p$

κ

$(\Omega - \Omega_p)/\kappa = 0.5$

$\Omega = \Omega_p$

Angular frequency
Radial (epicyclic) frequency

Inner Lindblad resonance

Corotation resonance

Analytical Predictions I

Bars drive the redistribution on mass and angular momentum within the galaxy: Inner parts loose, outer parts gain

Emission and absorption occur principally at near-resonance

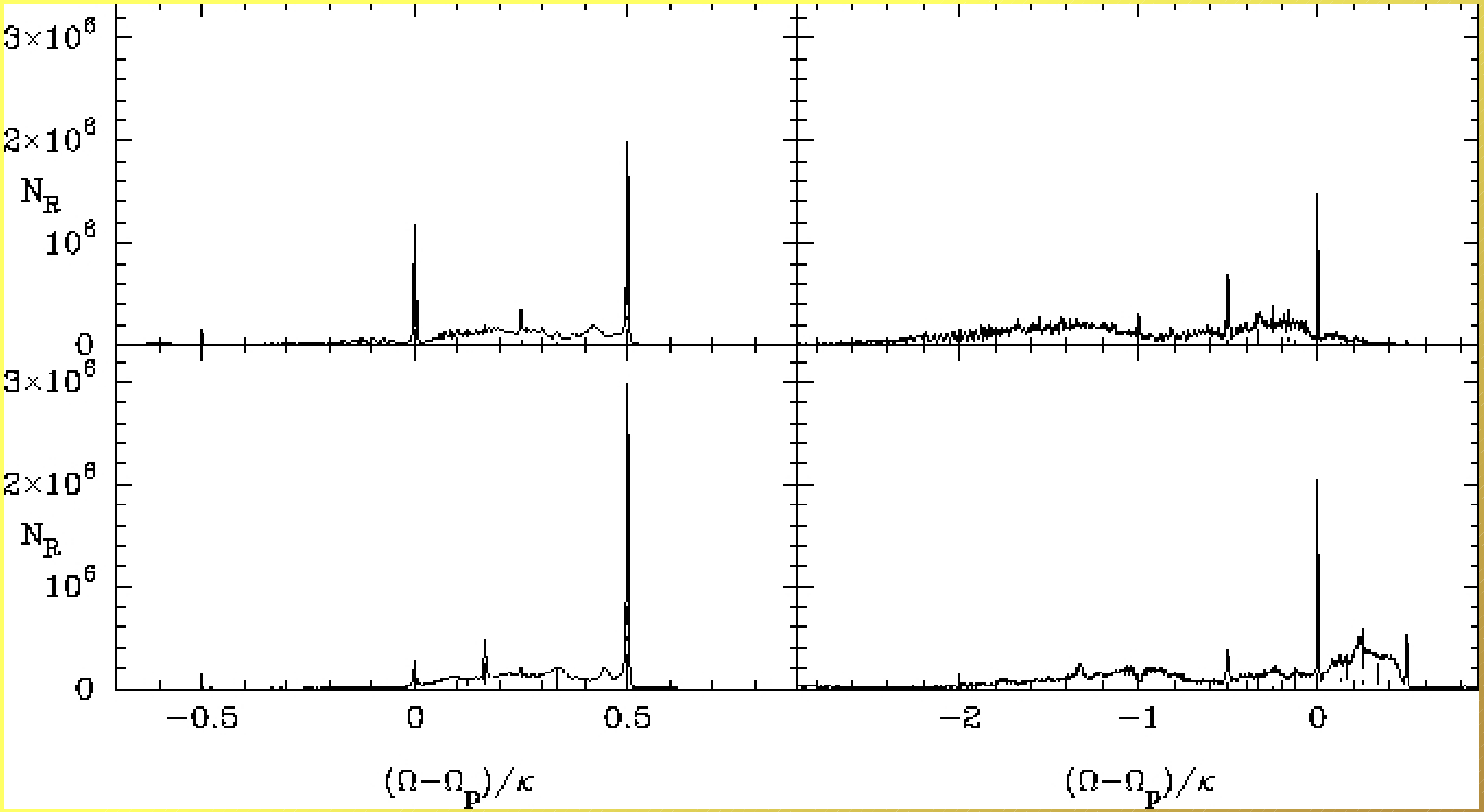
inner disc --------------------> outer disc
(bar region) Lynden-Bell & Kalnajs 1972

inner disc --------------------> halo
(bar region) Tremaine and Weinberg 1984, Weinberg 1985

inner disc --------------------> outer disc + halo
(bar region) Athanassoula 2003, Fuchs 2004, Weinberg 2004 etc

Resonances

OLR CR ILR OLR CR ILR

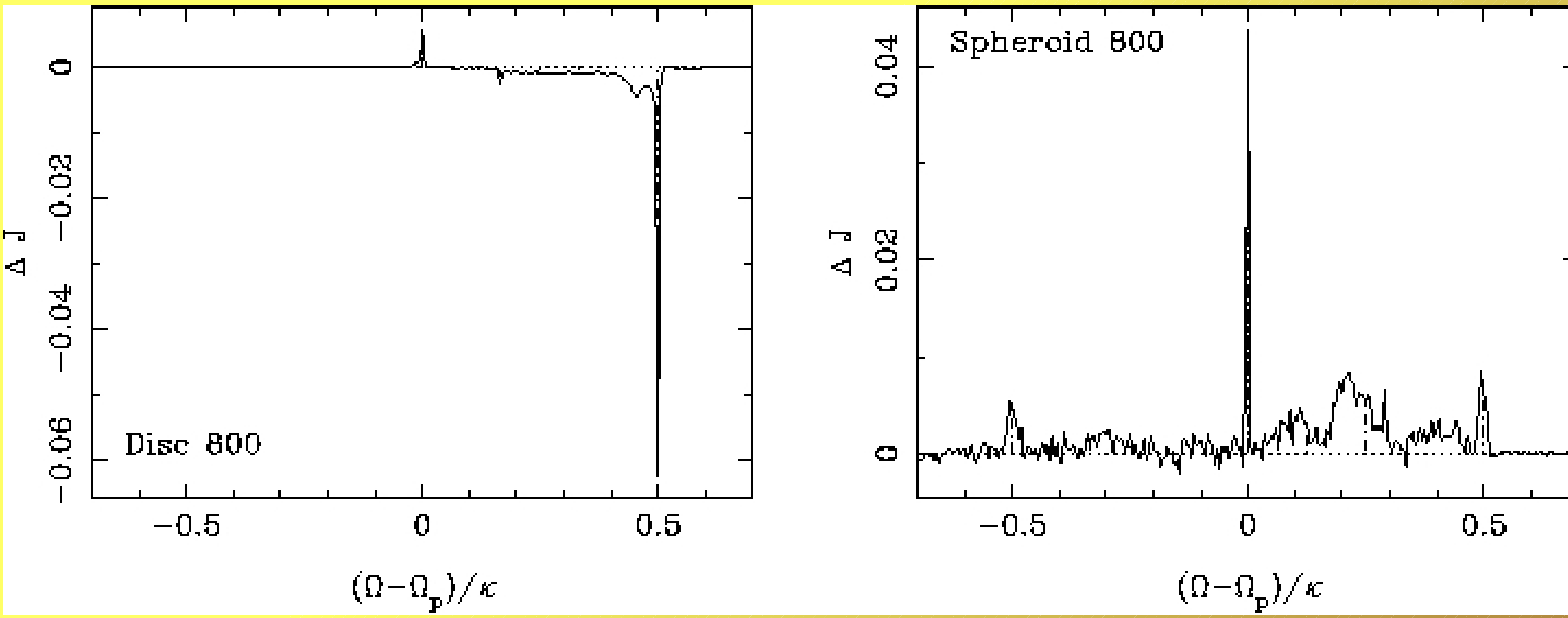


Athanassoula 2002, 2003

Confirmed by Martinez-Valpuesta+ 2006, Ceverino+ 2007, Saha+ 2011, Fragkoudi+ 2020, etc.

Resonances and angular momentum redistribution

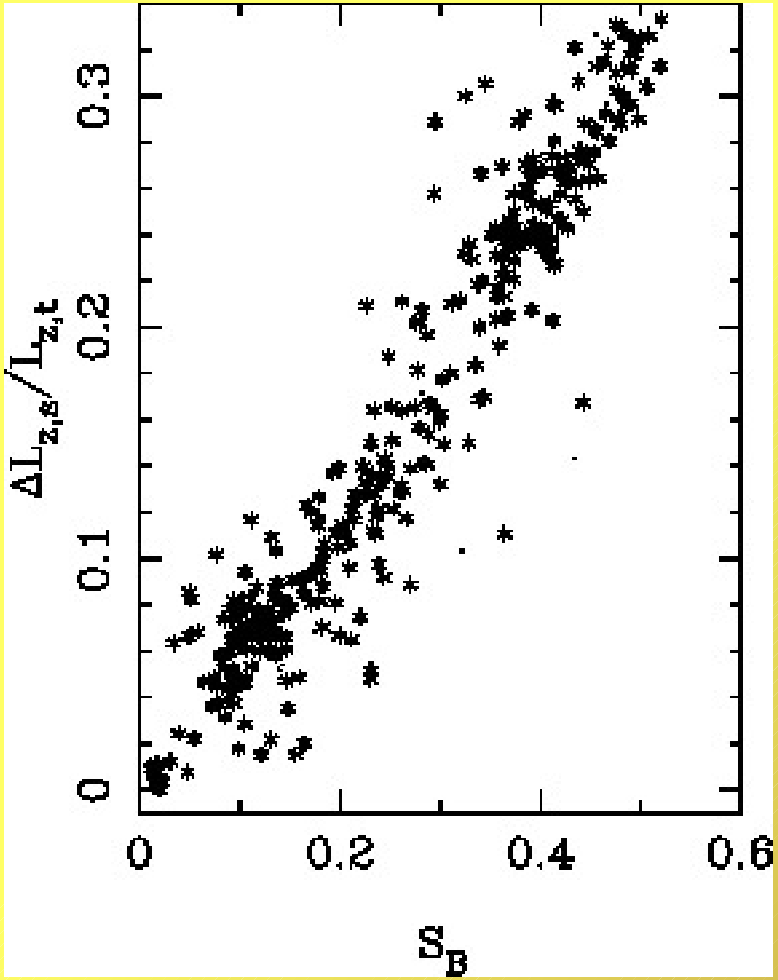
CR ILR OLR CR ILR



Absorb Lz Emit Lz (loose)

Absorb Lz everywhere

Athanassoula 2002, 2003



Athanassoula 2003

Excellent agreement between results from analytic work, and results from simulations

Emitters : (material at near-resonance in the) inner disc
(bar region)

Absorbers: (material at near-resonance in the) outer disc
and mainly the halo – (density/mass)

As the bar loses angular momentum
- it will grow stronger
- it will slow down (i.e. its pattern speed will decrease)

(Kalnajs 1970, Lynden-Bell and Kalnajs 1972, Athanassoula 2003)

Angular momentum exchange drives the dynamical evolution of barred galaxies

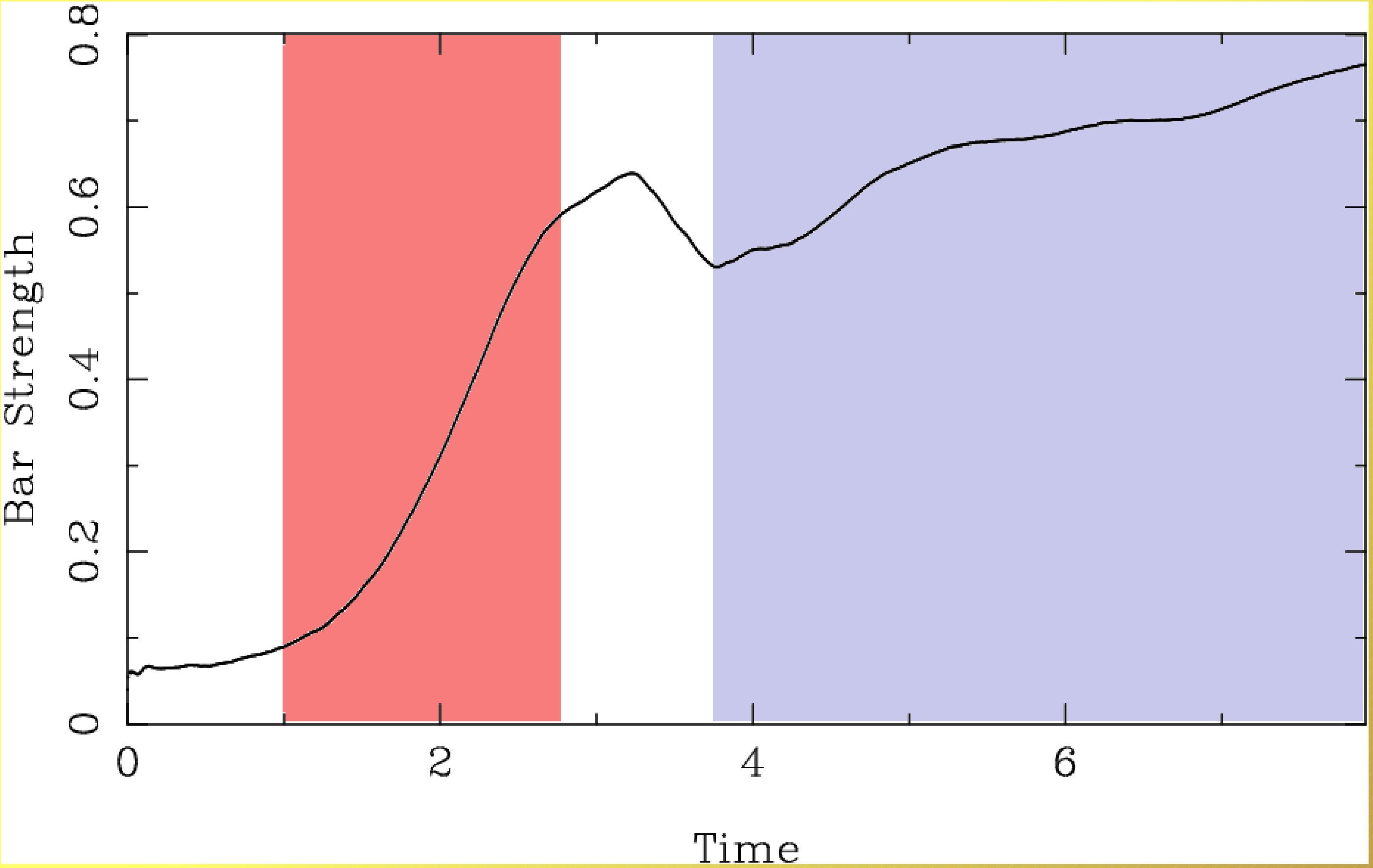
Excellent agreement between results from analytic work, and results from simulations

Emitters : (material at near-resonance in the) inner disc

Partners:
The inner disc wants to get rid of its angular momentum
The outer disc and halo want to absorb it

Additional partners/complications
- Gas
- Companions

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



Bar growth

Secular evolution

Bar formation

Bar evolution

Why are not all disc galaxies barred?

Bars in three dimensions

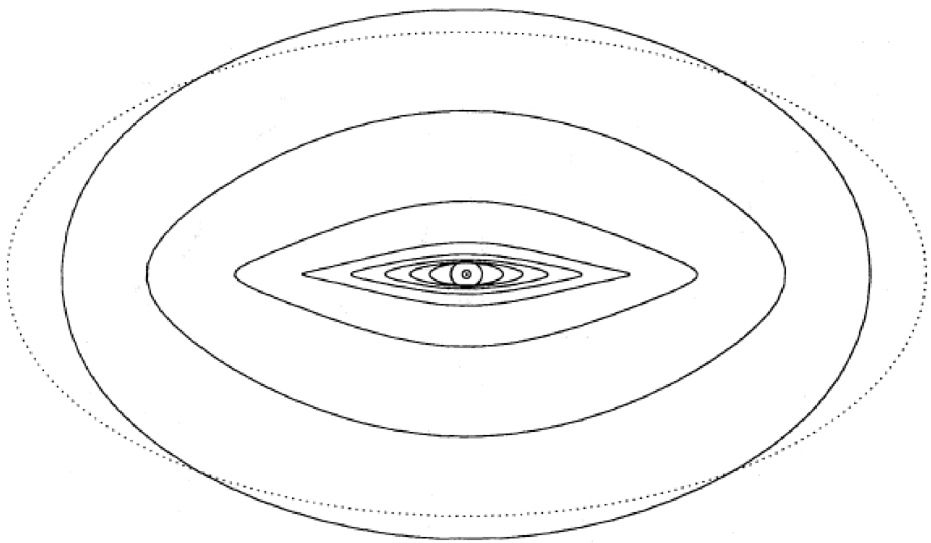
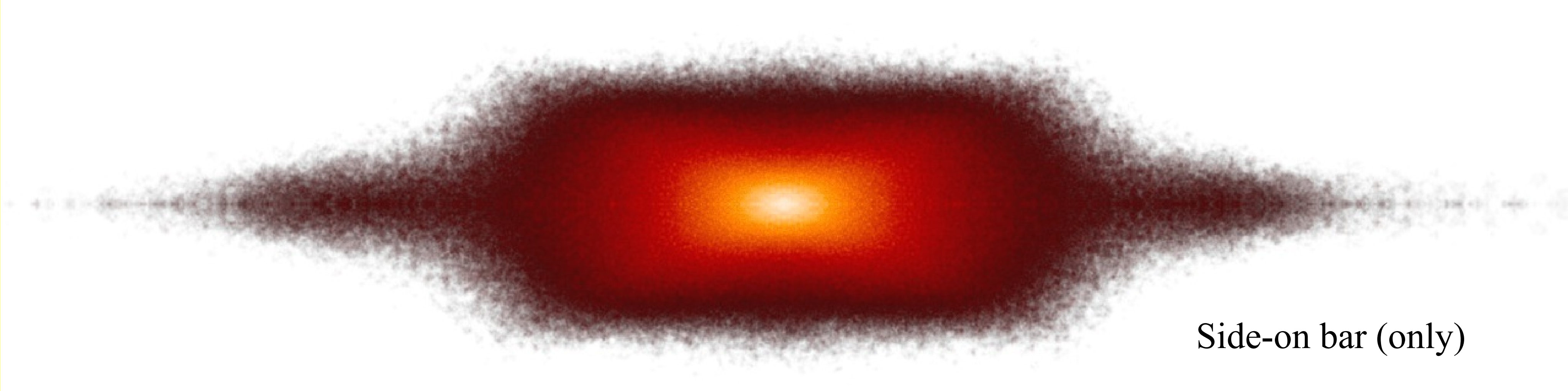
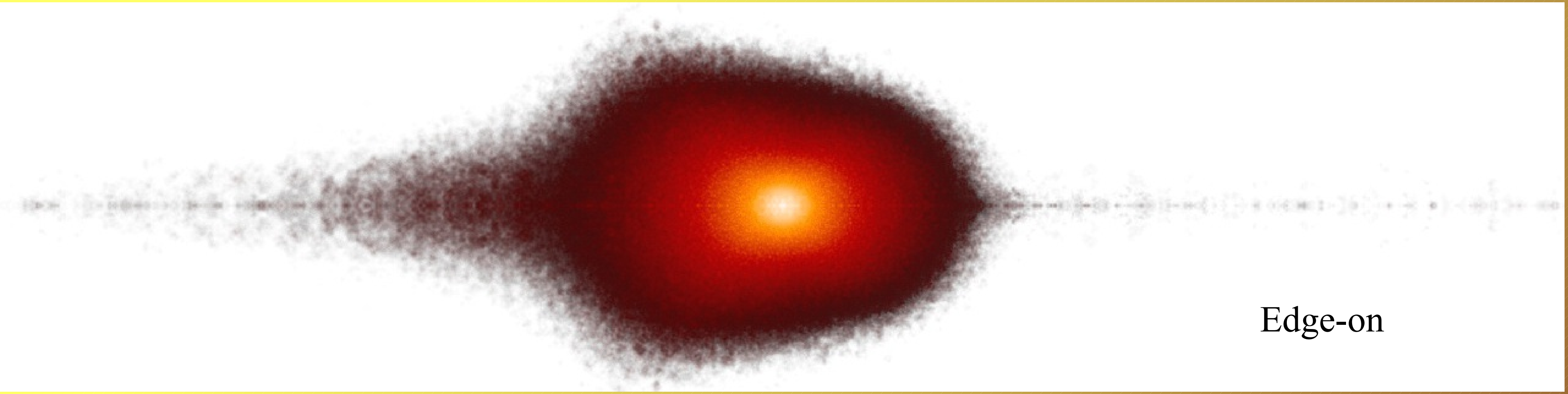


Figure 12. Some periodic orbits of the x_1 family for model 06. The outline of the bar is plotted with a dotted line.

Athanassoula 1992

Bar only (exclude halo and disc). 2 edge-on views:

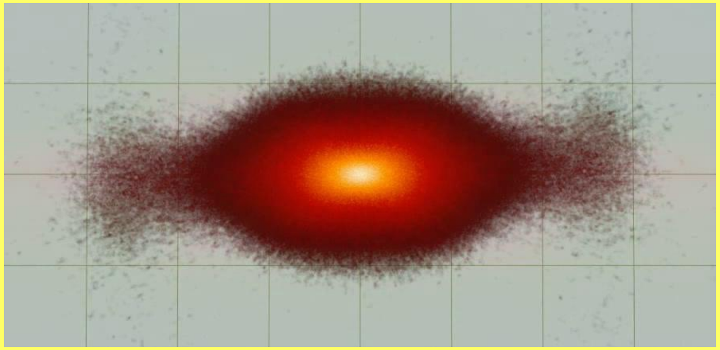


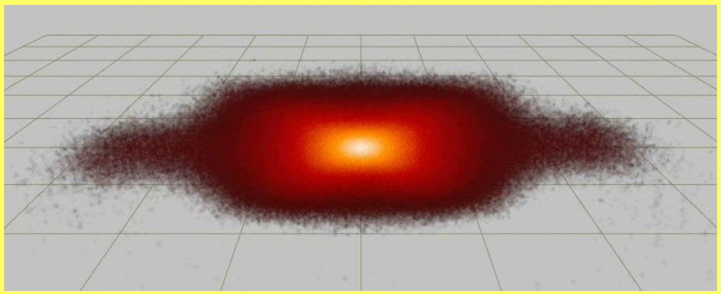


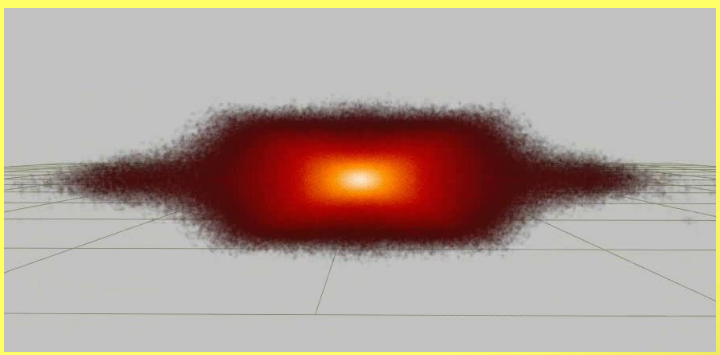
Shape of bars

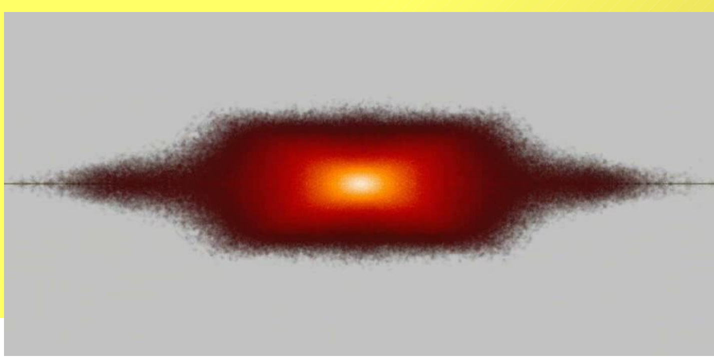
Boxy/Peanut Bulges

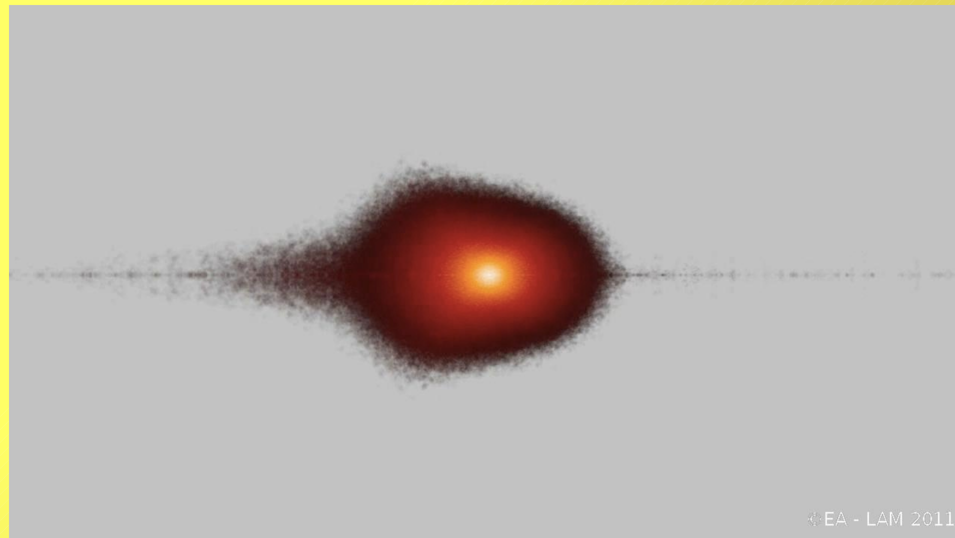
•

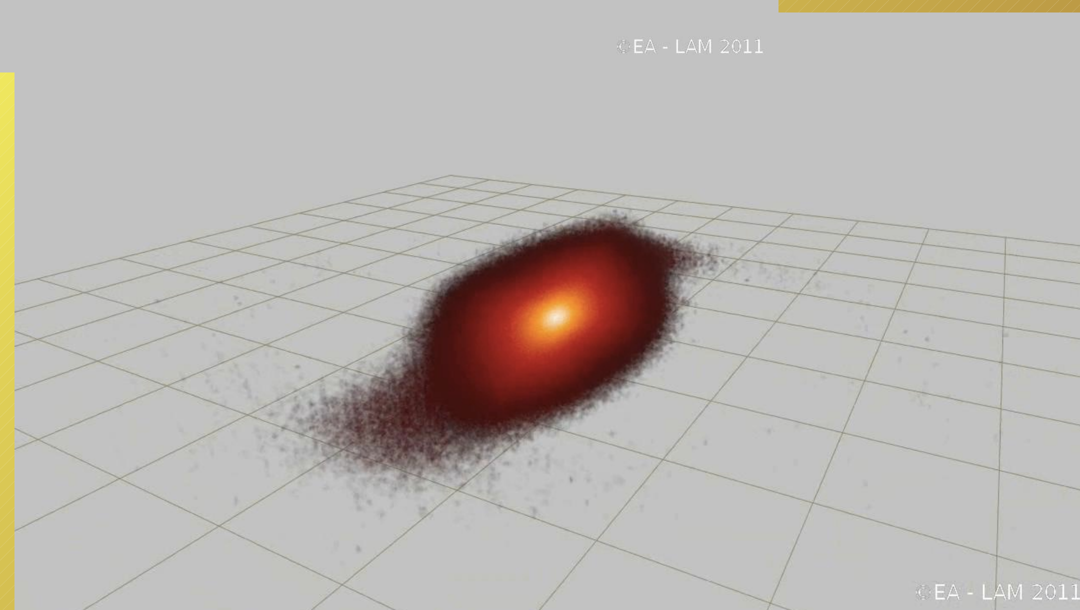






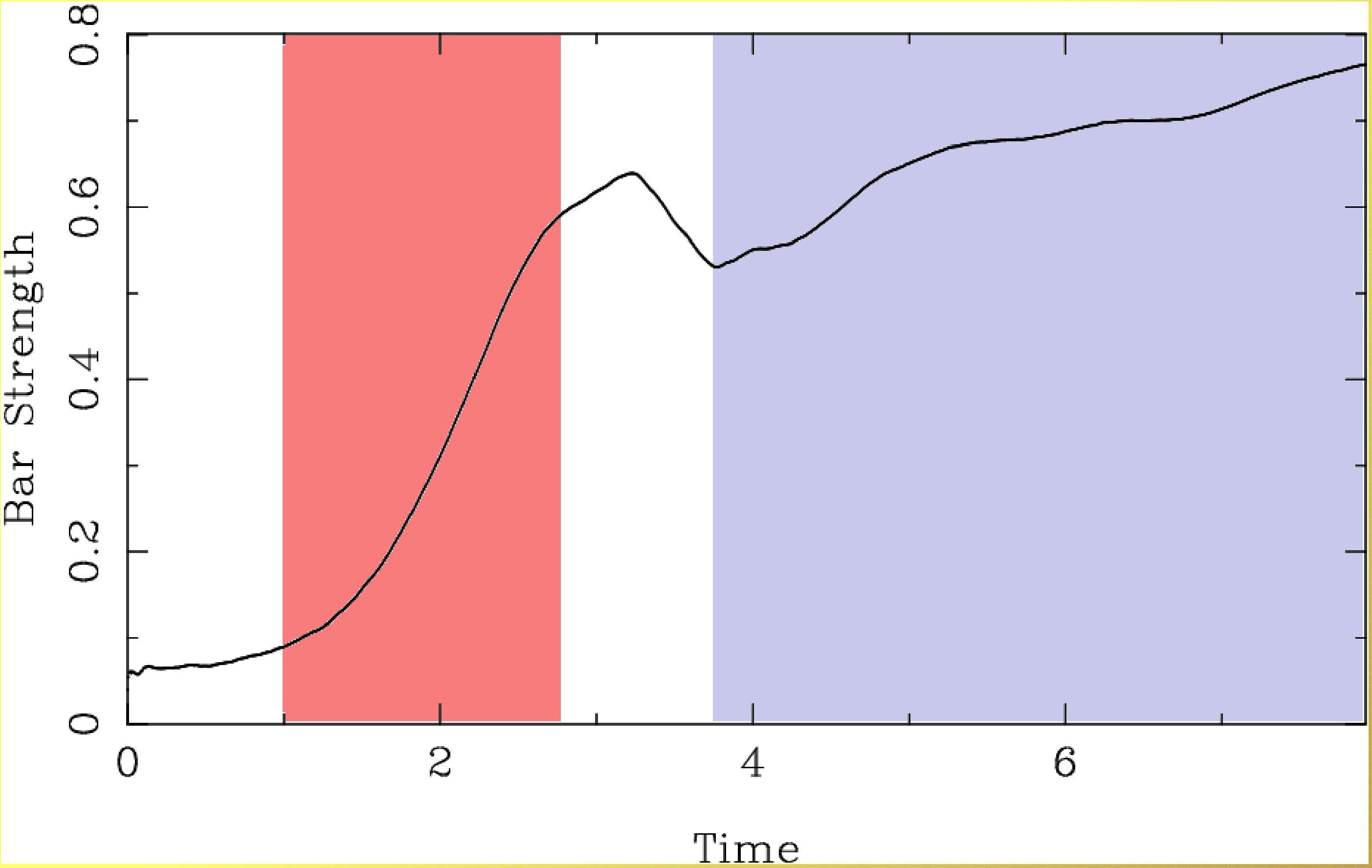






EA2005

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



Bar growth

Secular evolution

Bar formation

Bar evolution

Why are not all disc galaxies barred?

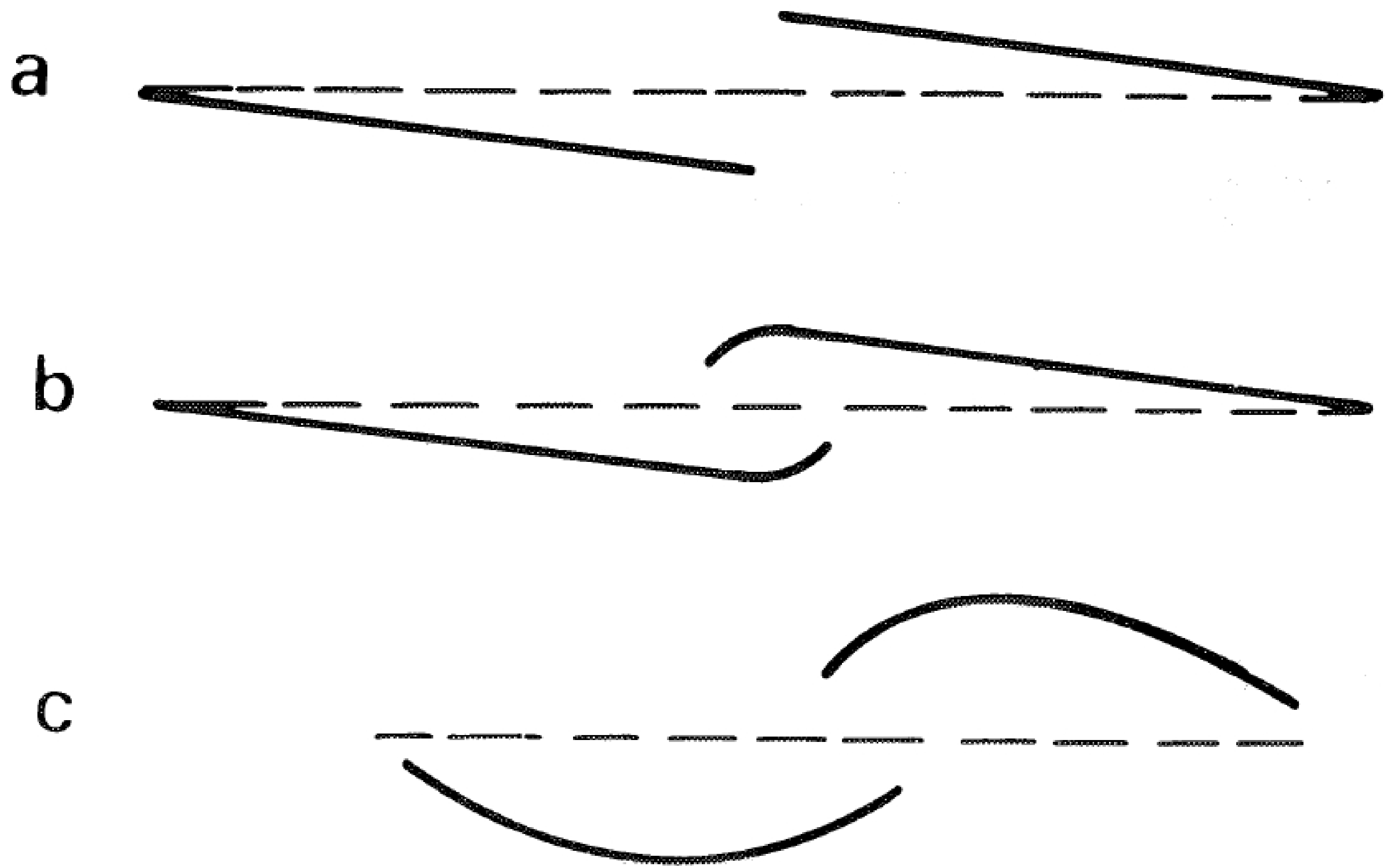
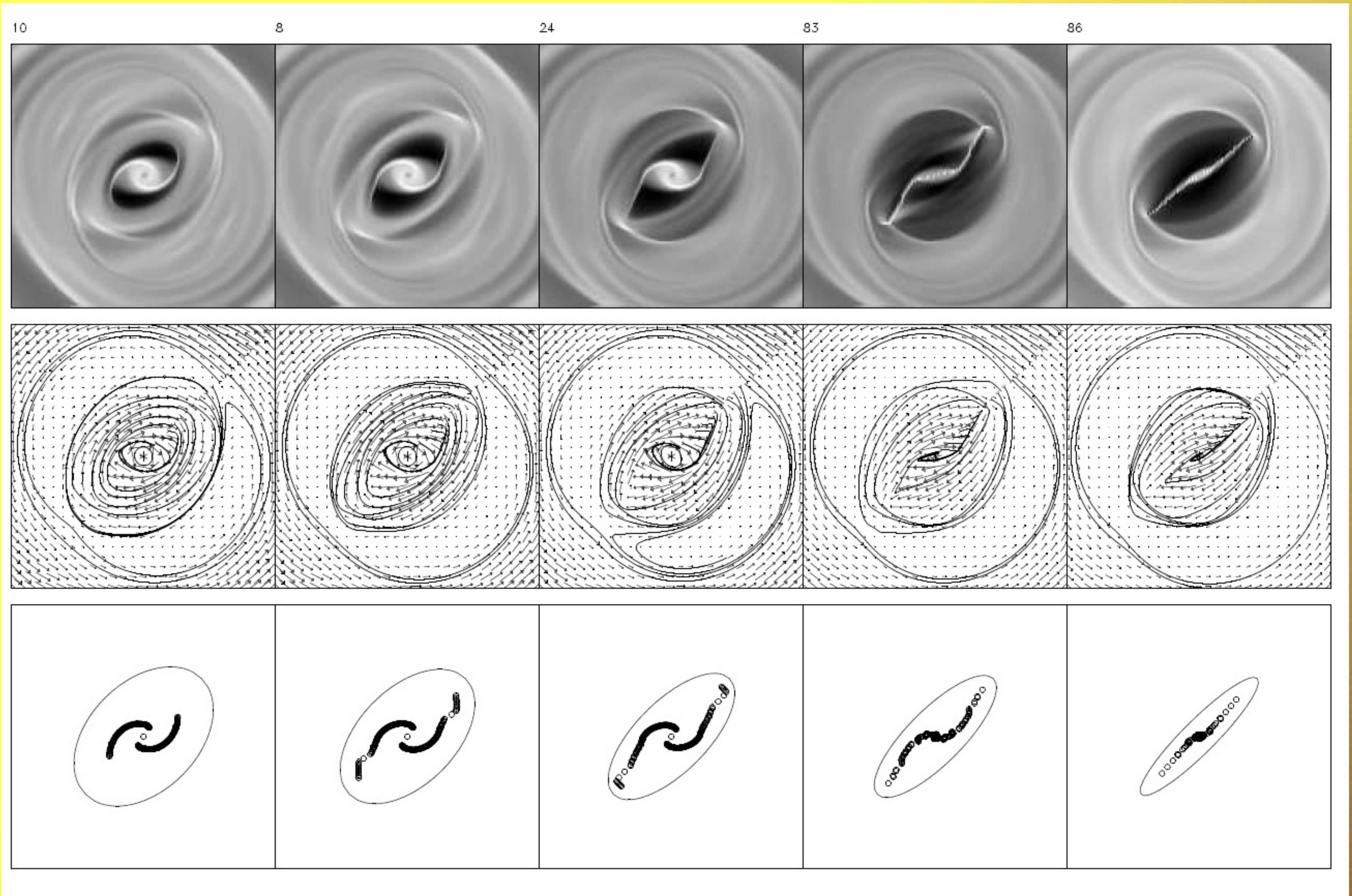


Figure 1. Schematic drawing of the shapes of dust lanes in bars (solid lines). The dashed lines give the position of the bar major axis. Reproduced, with permission, from Athanassoula (1984).

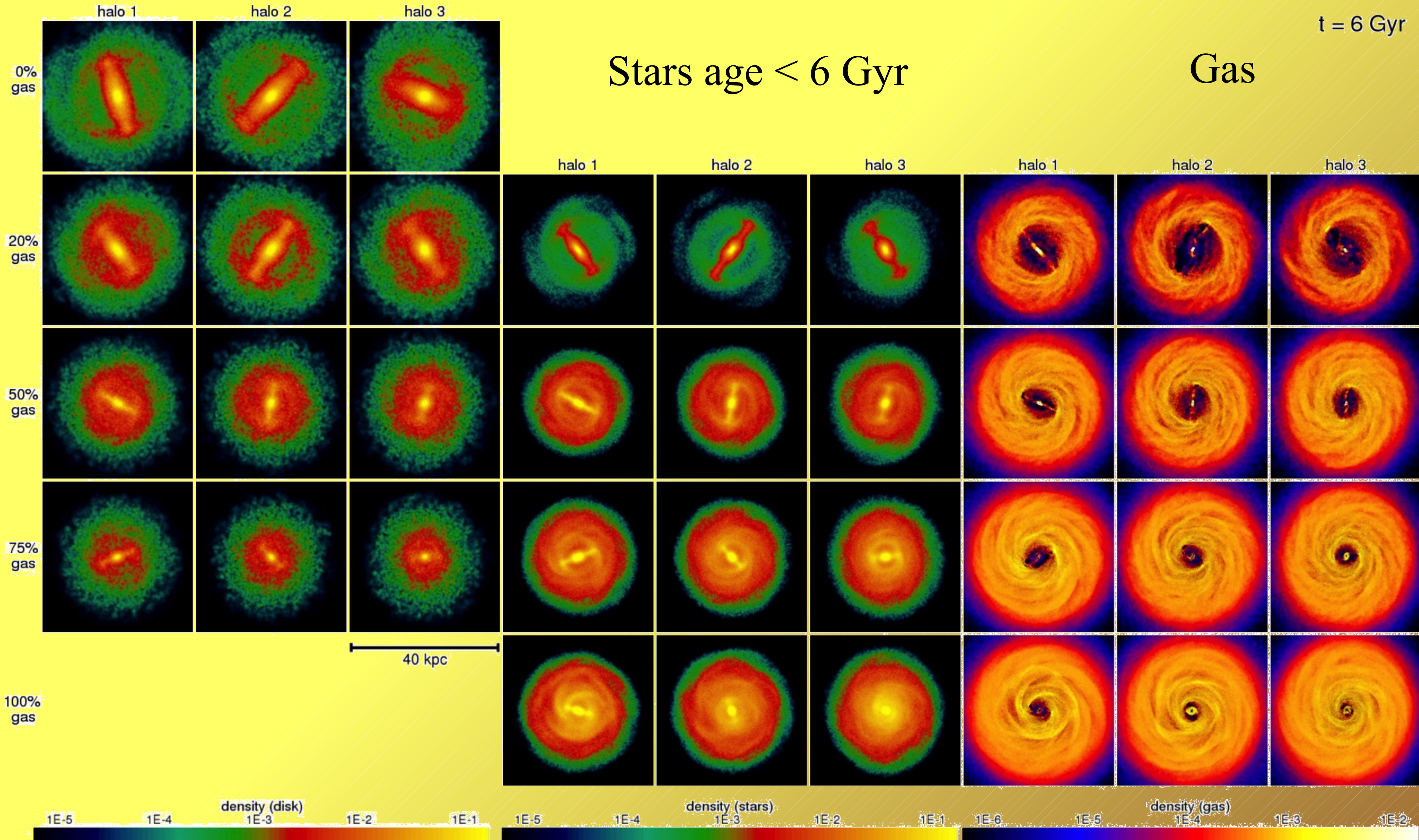
Athanassoula 1992

Axis ratio

a/b = 1.5 1.7 2.3 3.0 5.0



Stars age > 6 Gyr



Athanassoula + Machado + Rodionov 2013

Formation and evolution of galactic discs: starting with the last major/intermediate merger

Previous simulations:

Sp + Sp ===> E

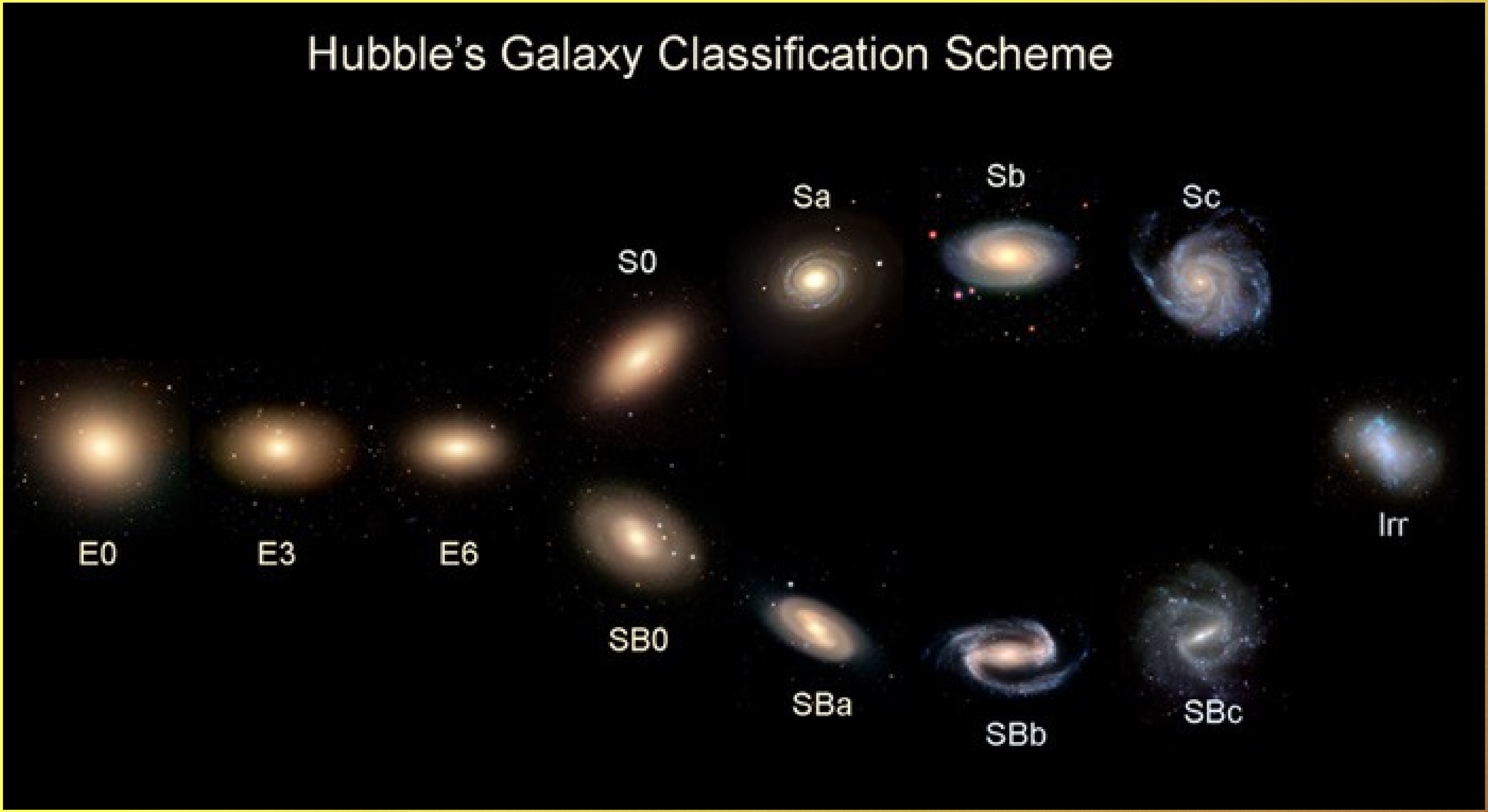
This work:

Sp + Sp ===> Sp

Athanassoula et al. 2016, 2017, Rodionov et al. 2016, Peschken et al. 2017

Toomre A. + Toomre J. (1972), Toomre A (1977) : Spiral + Spiral => Elliptical

EA+Rodionov+Peschken+Lambert (2016) Spiral + Spiral => Spiral !! (or elliptical ?)



– Include gas, SF ===> e.g.: gas flow, age of stars
– Start off a few Gyr before the last major (or intermediate) merger
– The ICs do not assume the pre-existence of any fully developed disc structure(s). The disc forms and evolves during the simulation
– Include chemical evolution (chemo-dynamics, no proxy, 12 elements, could add more)
– High resolution
(# of particles: 5M - 30M, linear resolution of 25 pc – 50 pc)

– Include hot gaseous haloes

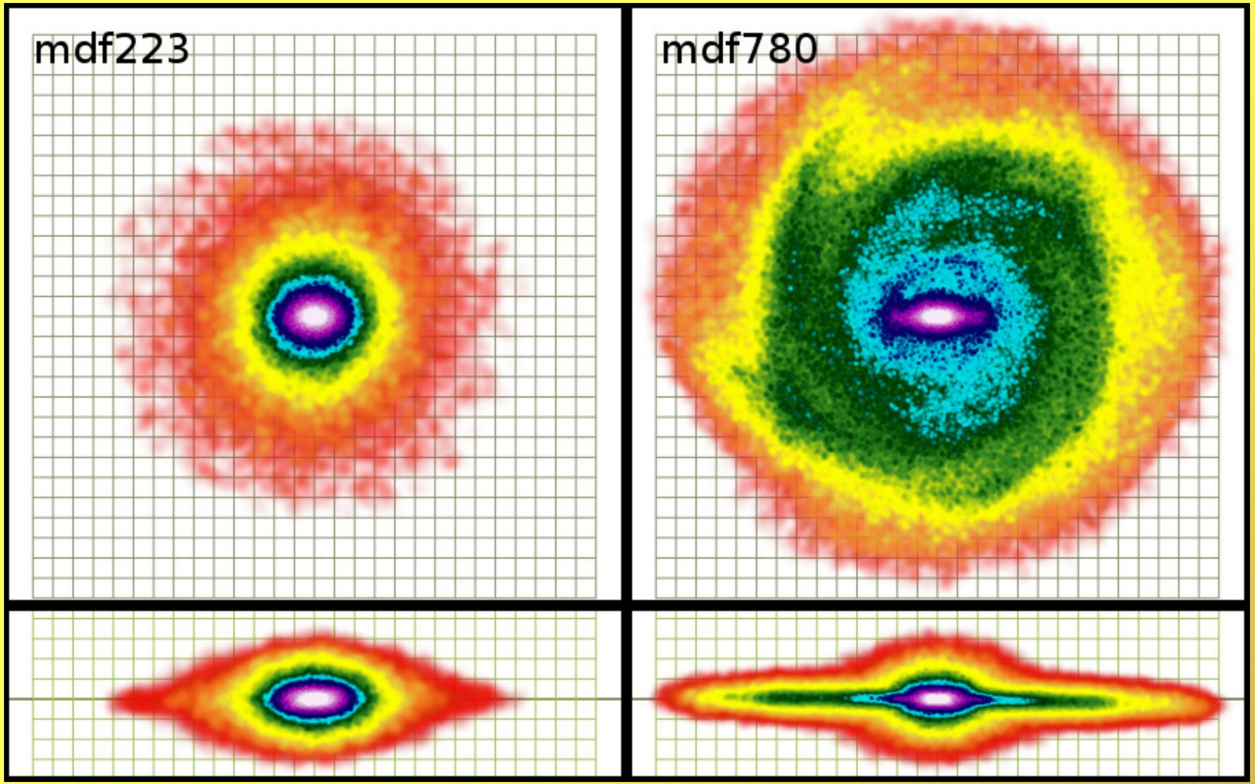
– For more information: EA, Rodionov, Peschken, Lambert 2016

– Include feedback (SN and AGN), cooling etc.

– We include a more complete comparison of simulation results with nearby galaxy properties (morphology, kinematics, photometry, ages, chemical abundances, metallicity, metallicity gradients, etc.)

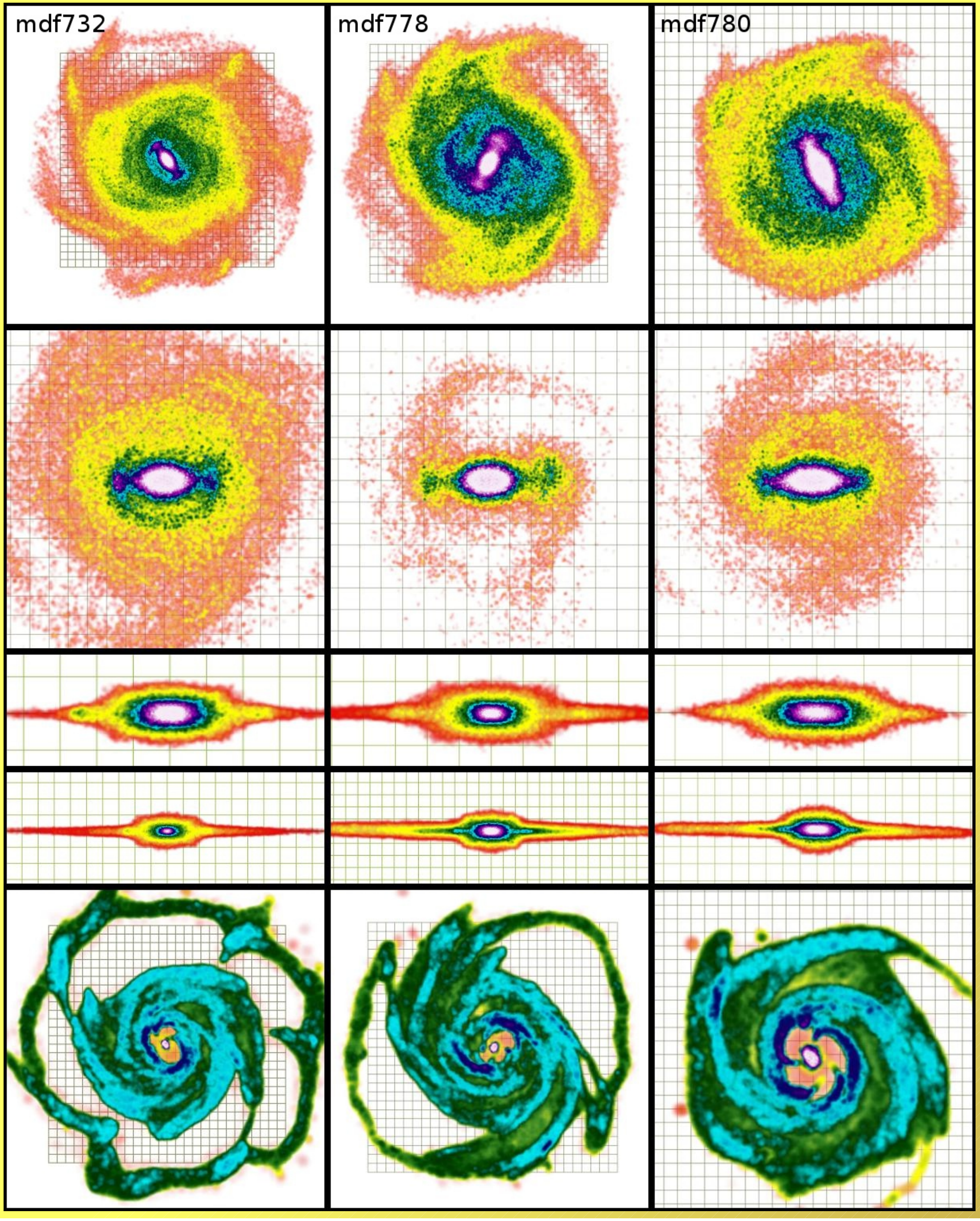
The effect of gas in the halo
Note the difference in morphology and size

Without With

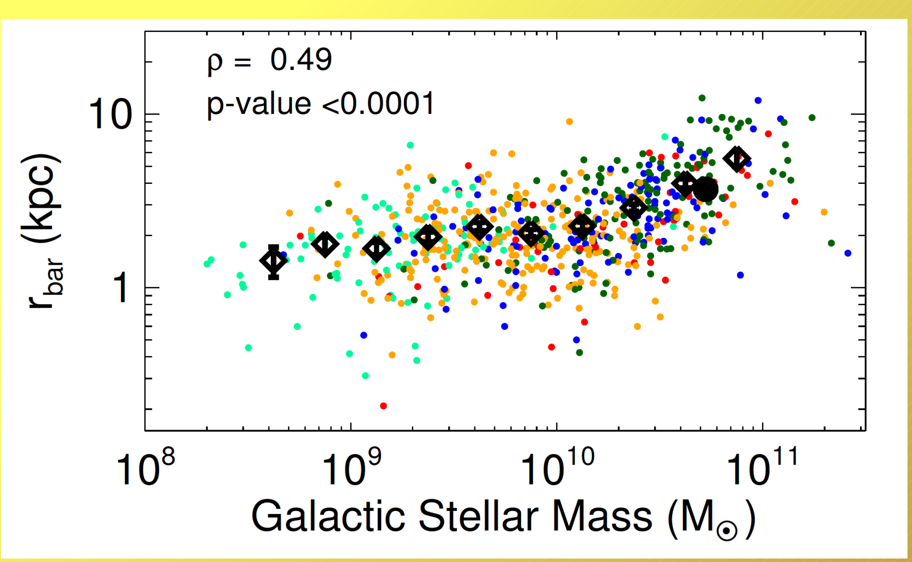


Athanassoula + Rodionov + Peschken + Lambert 2016

Morphologies



Bar length



Observations : S4G,
Diaz-Garcia et al. 2015

Our 3 fiducial simulations :
Black filled circle

Good agreement with local universe galaxies

Athanassoula, Rodionov, Peschken, & Lambert 2016

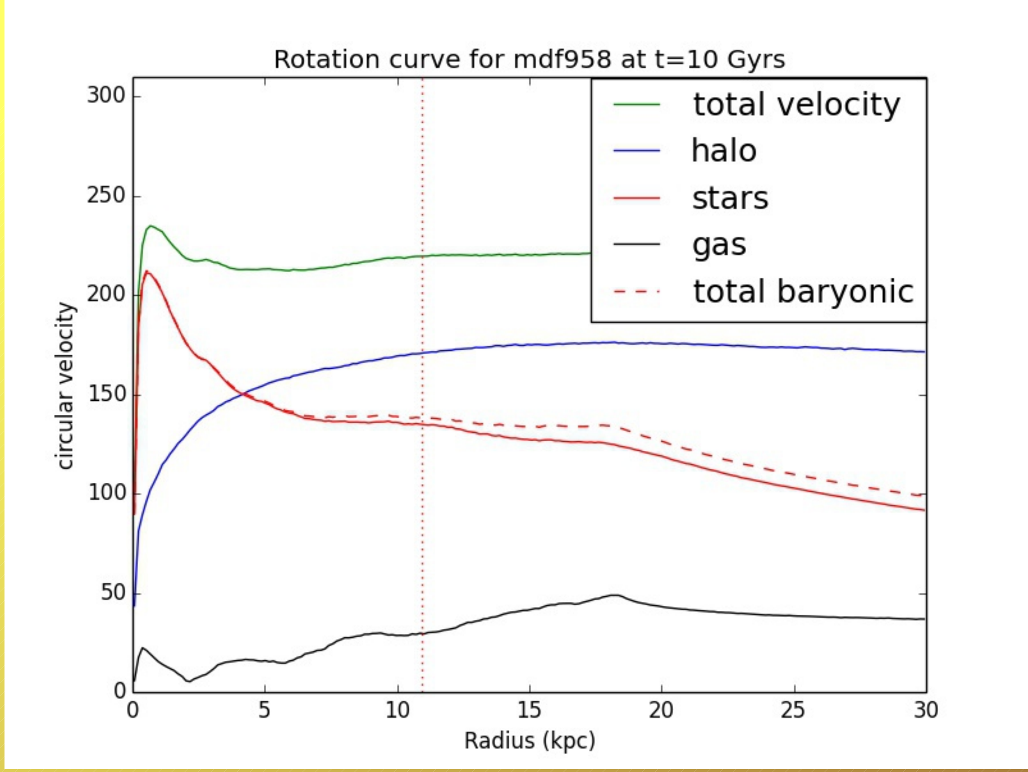
Morphology (bars, ansae, B/P/X structure, discy pseudo bulges, rings, spirals ….)

3 types of « bulges » can co-exist : classical, discy pseudo-bulges, B/P/X

Minimum mass ratio of classical bulge mass to total stellar mass : 10-20%

Chemical abundances (in progress, comparison with MW)

Disc surface density
- Type I, II and III
- Rinner, Router, Break radius
- As a function of population age
- Evolution with time



Thin/Thick disk properties

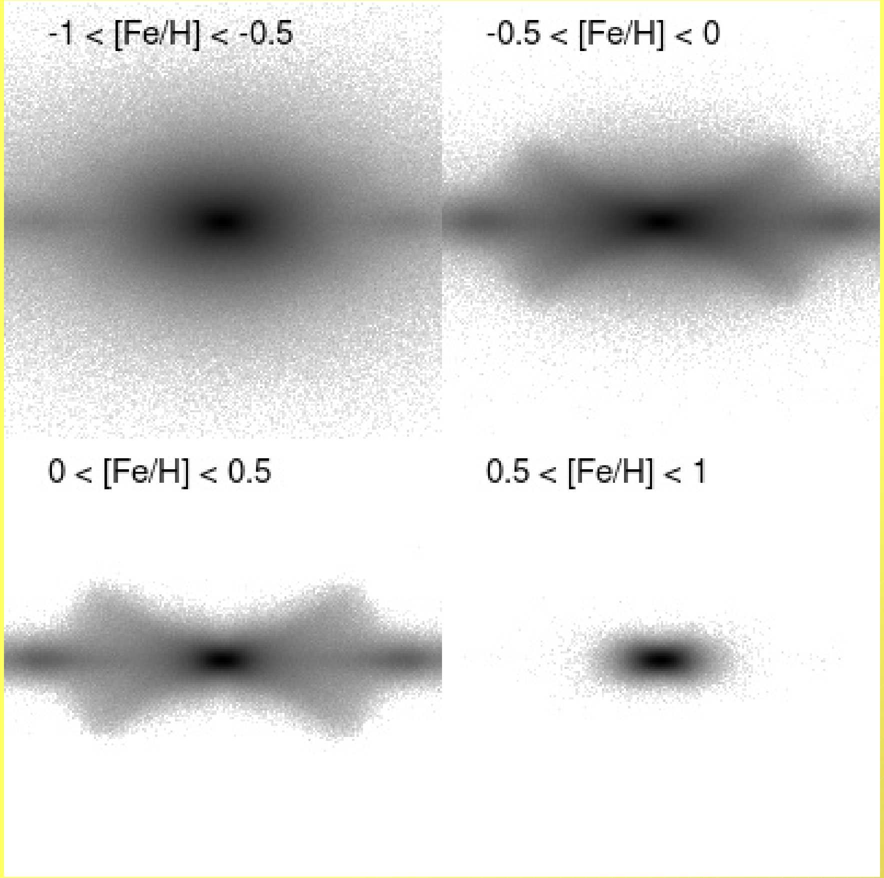
Kinematics

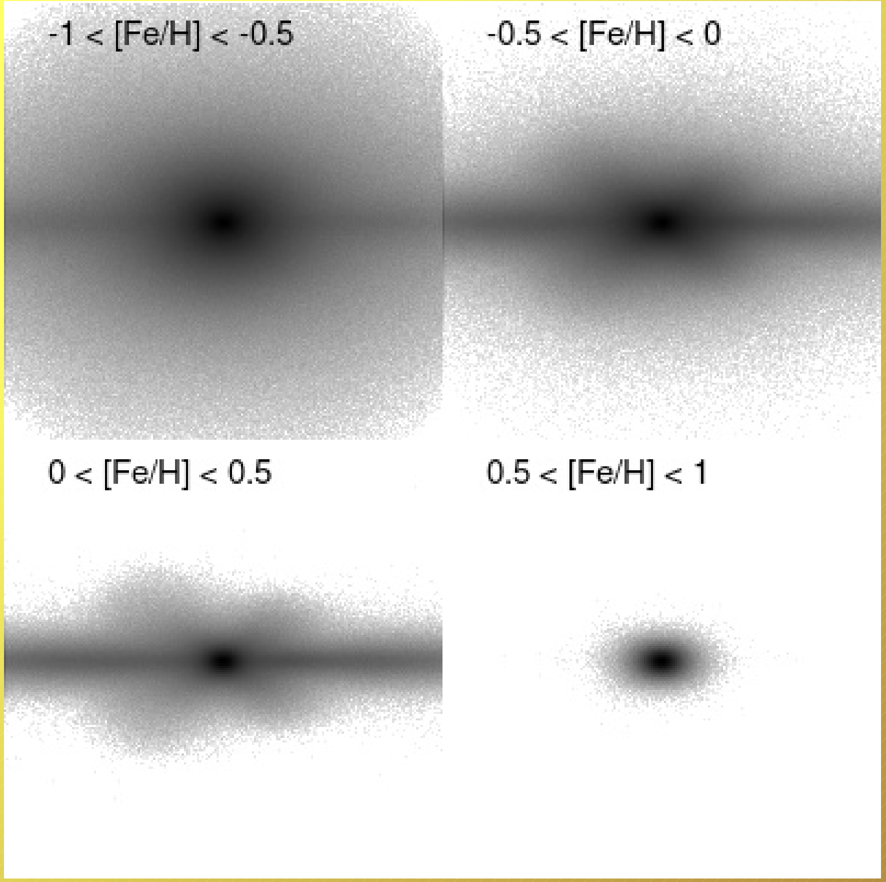
Rotation curves

So far fine / More tests in progress

Shape of bars as a function of stellar age (metallicity)

Metal poor (old)





Metal rich (young)

Metallicity

EA, Rodionov, Prantzos 2017

The end .... or the beginning