Barred galaxy formation in the EAGLE cosmological simulation

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Collaborators

Aim:
Search some clues about bar formation in cosmological numerical simulations

Barred galaxies in the EAGLE cosmological hydrodynamical simulation
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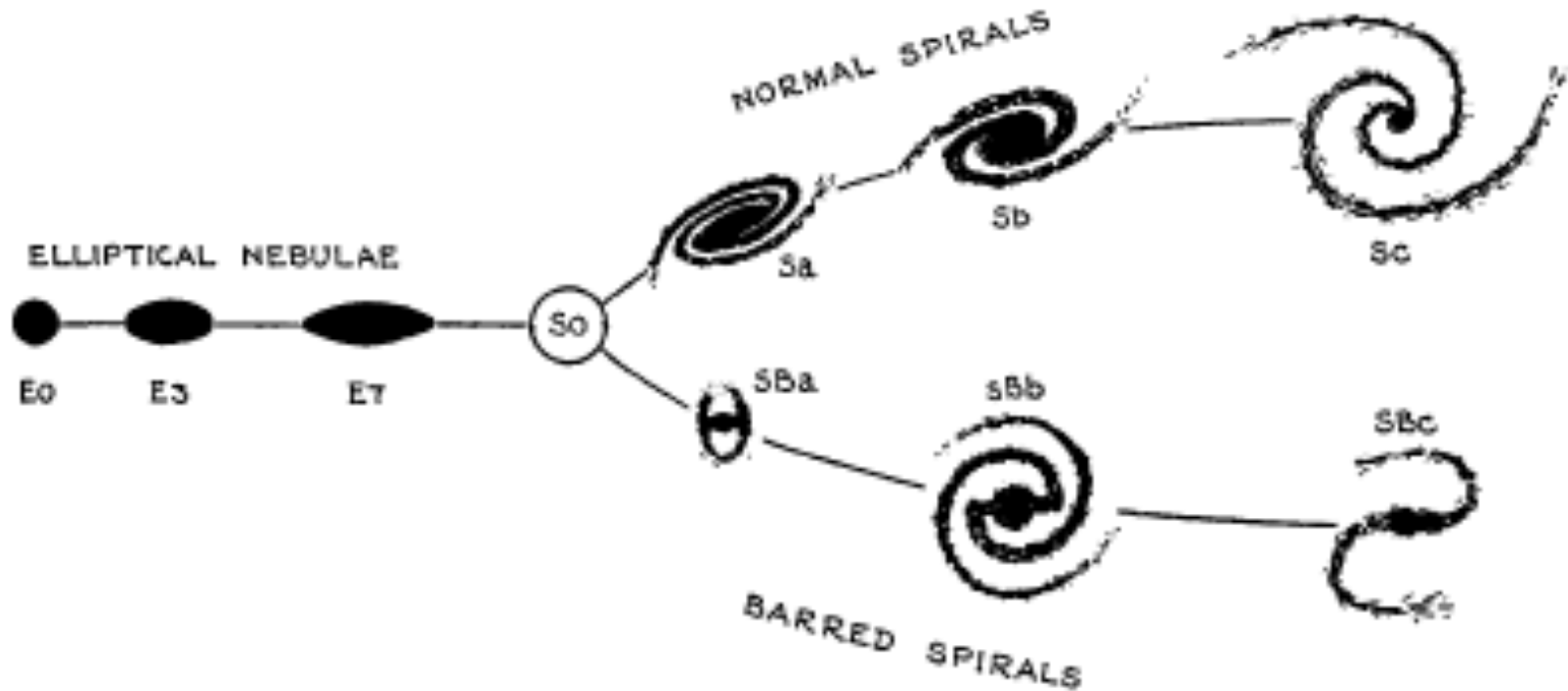
Hubble Morphological Classification

FIG. 1. *The Sequence of Nebular Types.*

The diagram is a schematic representation of the sequences of classification. A few nebulæ of mixed types are found between the two sequences of spirals. The transition stage, S0, is more or less hypothetical. The transition between E7 and SB₂ is smooth and continuous. Between E7 and S₂, no nebulæ are definitely recognized.
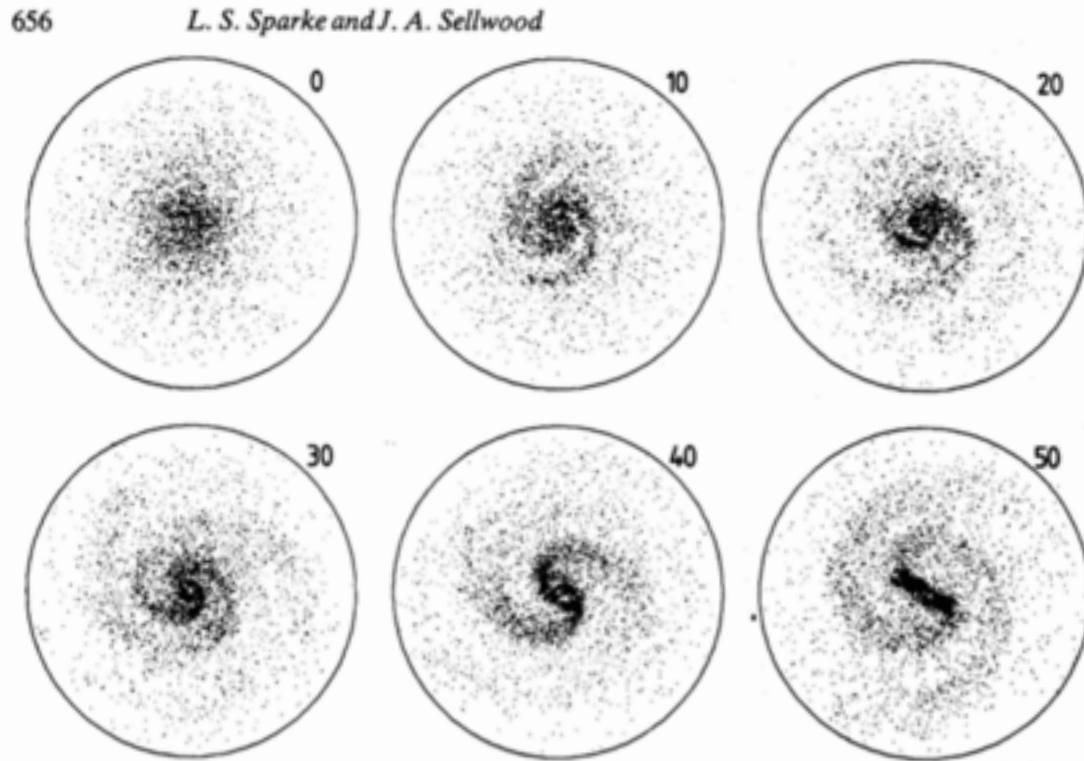
Hubble 1936

Isolated Disk Galaxy Models

656   *L. S. Sparke and J. A. Sellwood*

2 dimensional disk

Self-gravitating particles

Rotation with low velocity dispersion

Numerical and analytical calculations during the past decade have established that cold self-gravitating disks are unstable to the formation of bars (Hohl and Hocknev. 1969; Miller et al., 1970; Kalnajs, 1972; James and Sellwood, 1978).

Combes & Sanders 1981
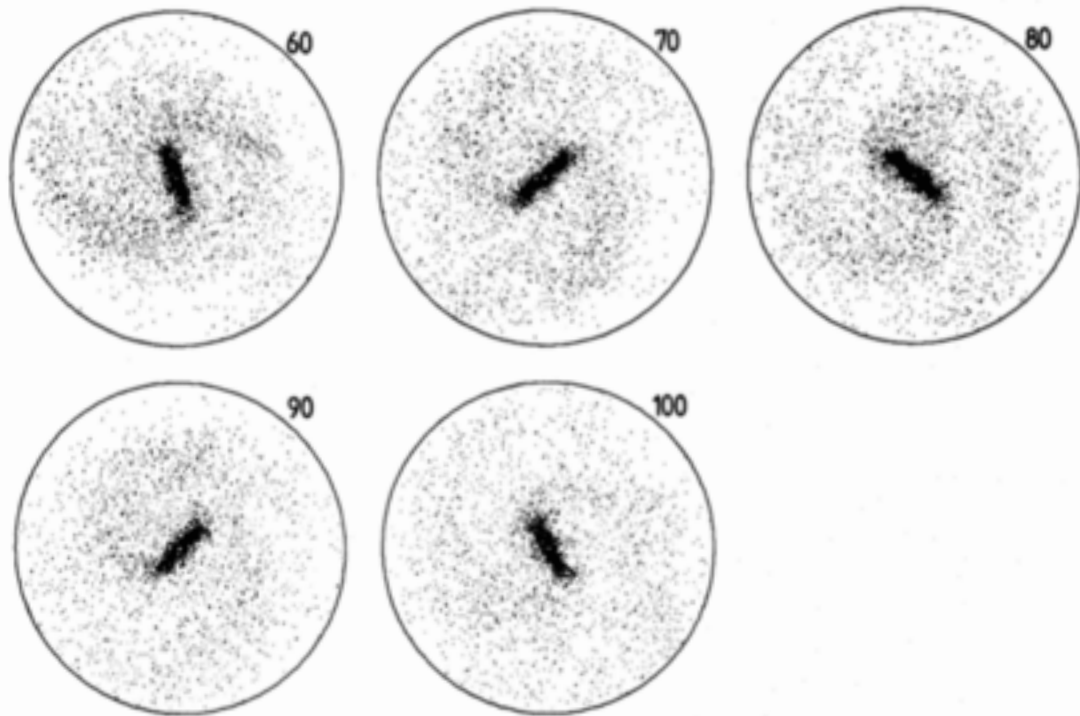
Isolated Disk Galaxy Models

Figure 1. Development of the bar. The times are in natural units and the outer circle marks the boundary of the grid at a radius of 4.57. Only one particle in 10 is included in each frame and the bulge component is not shown.

2 dimensional disk

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Combes & Sanders 1981

Disk + Spherical Halo

A NUMERICAL STUDY OF THE STABILITY OF FLATTENED GALAXIES: OR, CAN COLD GALAXIES SURVIVE?*

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Received 1973 May 29

ABSTRACT

To study the stability of flattened galaxies, we have followed the evolution of simulated galaxies containing 150 to 500 mass points. Models which begin with characteristics similar to the disk of our Galaxy (except for increased velocity dispersion and thickness to assure local stability) were found to be rapidly and grossly unstable to barlike modes. These modes cause an increase in random kinetic energy, with approximate stability being reached when the ratio of kinetic energy of rotation to total gravitational energy, designated t, is reduced to the value of 0.14 ± 0.02. Parameter studies indicate that the result probably is not due to inadequacies of the numerical N-body simulation method. A survey of the literature shows that a critical value for limiting stability $t \simeq 0.14$ has been found by a variety of methods.

Models with added spherical (halo) component are more stable. It appears that halo-to-disk mass ratios of 1 to $2\frac{1}{2}$, and an initial value of $t \simeq 0.14 \pm 0.03$, are required for stability. If our Galaxy (and other spirals) do not have a substantial unobserved mass in a hot disk component, then apparently the halo (spherical) mass *interior* to the disk must be comparable to the disk mass. Thus normalized, the halo masses of our Galaxy and of other spiral galaxies *exterior* to the observed disks may be extremely large.

Disk Instability

Total: Disk+Halo

Disk

The stability and masses of disc galaxies

G. Efstathiou[1,2], G. Lake[1,2,3] and J. Negroponte[4]

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[3] Bell Laboratories, Murray Hill, NJ 07974, USA
[4] Department of Physics, University of California, Berkeley, California 94720, USA

Summary. Using N-body experiments we investigate the global stability of a series of models designed to match the observed photometric and kinematic properties of disc galaxies. The models, therefore, have an exponential surface density profile and rotation curves which are flat at large radii. We find a simple delineator of stability to bar-like modes for a cold disc: $v_m/(\alpha M_D G)^{1/2} = 1.1$, where v_m is the maximum rotational velocity, α^{-1} is the scale length of the exponential disc and M_D is the total disc mass. This is to be compared to a self-gravitating exponential disc for which $v_m/(\alpha M_D G)^{1/2} = 0.63$, thus a hot 'halo' component is required to increase this ratio in a cool disc and provide stability to bar formation. This criterion has been found to apply independent
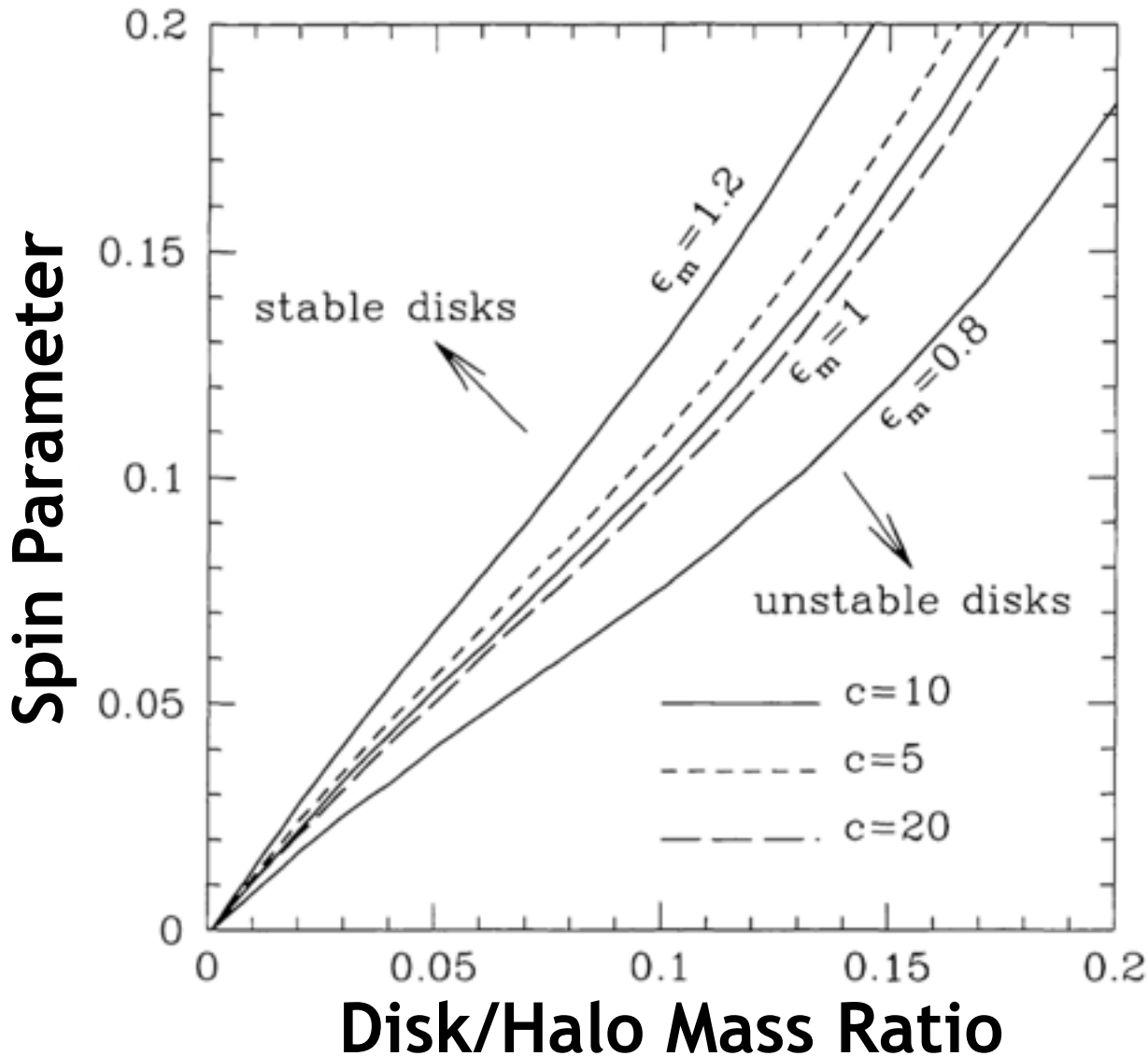
$$\epsilon_m \equiv \frac{V_{max}}{(GM_d/R_d)^{1/2}}$$

Stable disk ϵ_m > 1.1

Unstable disk ϵ_m < 1.1

Isolated disk $\epsilon_m \equiv 0.63$

Semi-Analytical Models

$$\epsilon_m \equiv \frac{V_{max}}{(GM_d/R_d)^{1/2}} \lesssim 1.1$$

Efstathiou et al 1982

$$f_{disc} = \frac{V_c(r_{50})}{\sqrt{GM_{disc}/r_{50}}}$$

Cole et al 2000
Bower et al 2006

Mo Mao & White 1998

Cosmological Simulations

Previous work based exclusively in zoon-in technique:
Curir et al. 2006; **Scannapieco & Athanassoula 2012** and **Okamoto et al 2014** using the Aquarius simulations of individual Milky Way halos study the formation of two barred galaxies in the ΛCDM cosmological model. They show that barred galaxies can form naturally in this model.
Kraljic et al. (2012) using RAMSES study the evolution of bars in a sample of 33 zoom-in simulated galaxies.**Guedes et al. 2013; Goz et al (2015)** two barred galaxies with two different resolution.

Aim:

Extend disk work to a more statistically significant sample.

EAGLE Cosmological Simulations

100 Mpc (Gas)
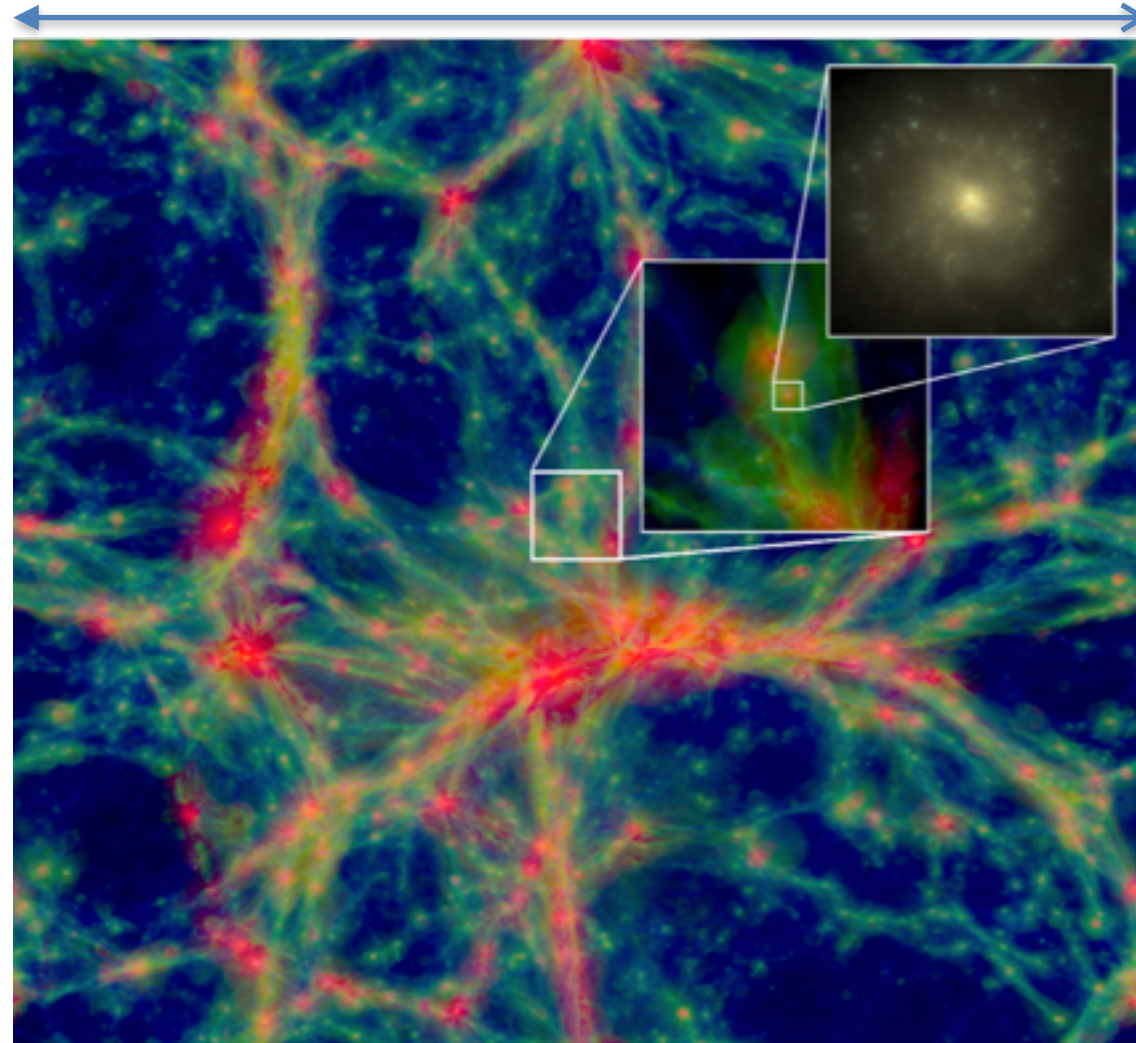
60 kpc (Stars)
$M=3\times10^{10}\ M\odot$

Physical Process:
Gravity, Hydrodynamics, Radiative gas cooling, Star formation, Feedback from Supernovae + AGN Metallicity

Particles:
Gas, stars and dark matter.
$M_{gas}=1.81\times10^6\ M\odot$
$M_{dark}=9.70\times10^6\ M\odot$

Code:
GADGET-3 Springel et al 2005

Cosmological Parameters:
ΛCDM model Plank et al 2014

Schaye et al 2015

Stellar Mass Function

~500 simulated
galaxies

Simulations
Ref–L100N1504
AGNdT9–L050N0752
Recal–L025N0752

Mass of
Milky Way
Galaxy
6x10^10M☉

Observations
● Li & White 09
○ Baldry+ 12

Galaxy Number Density

Stellar Mass

Dwarf   **Stellar Mass**   **Giants**
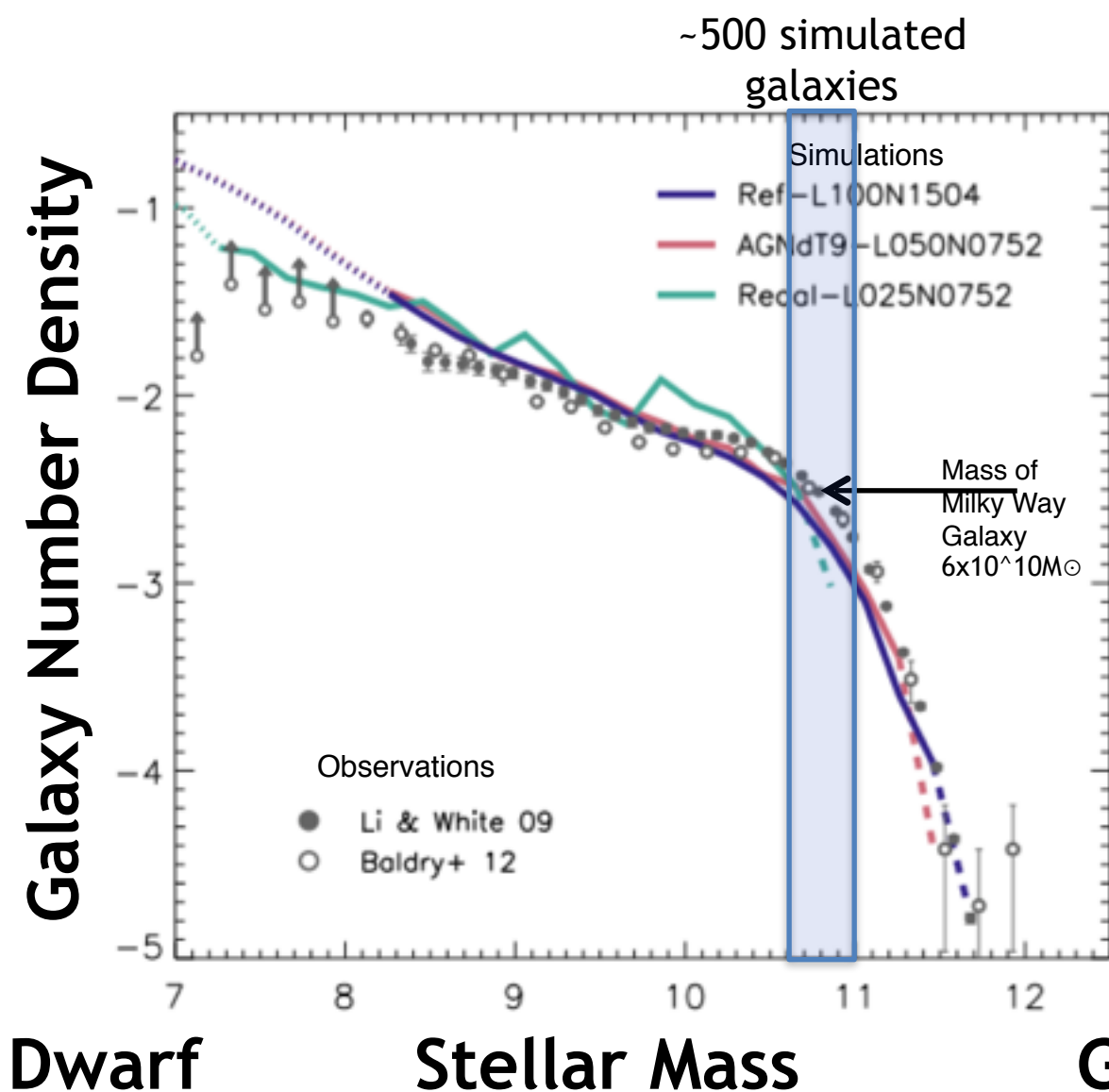
The galaxy stellar mass function at z = 0.1 for the EAGLE simulations compared to observations.

The galaxy number density agrees with the data to <~ 0.2 dex.

High-mass end fewer than 10 objects per (0.2 dex) stellar mass bin.

Low-mass end stellar mass falls below 100 baryonic particles.

GAMA survey (z < 0.06; Baldry et al. 2012) SDSS (z ~ 0.07; Li & White 2009).

Schaye et al 2015

EAGLE Morphological Classification

Normal Spirals

Ellipticals

60 kpc (Stars)
M=5-6x10^10 M☉

Barred Spirals

Disk Galaxy Sample Selection

Disc galaxy sample from EAGLE used in this paper. Left: Galaxy stellar mass, M, as a function virial mass M200. Solid line indicates the prediction of the abundance-matching model of Guo et al. (2010), for reference. Middle: Flattening parameter c=a, measured as the ratio of the eigenvalues of the principal axes of the inertia tensor of the stars. Right: Minor axis stellar velocity dispersion, expressed in units of the total. Vertical dashed lines indicate the conditions required to be selected as "discs" in our analysis. Discs are shown as coloured circles, spheroidal systems as open triangles, and visually identified ongoing mergers or disturbed systems as crosses. The colour scheme denotes the strength of the bar pattern.

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Face-On Galaxies
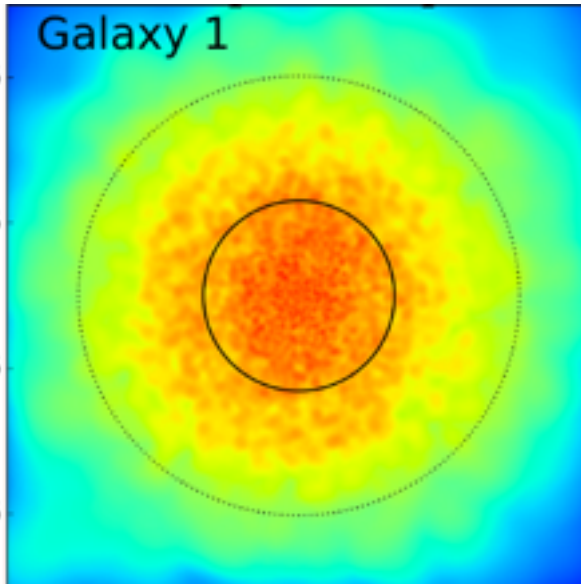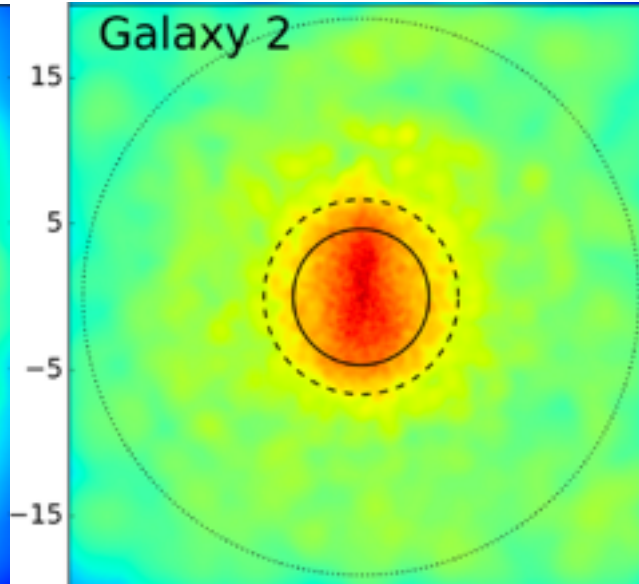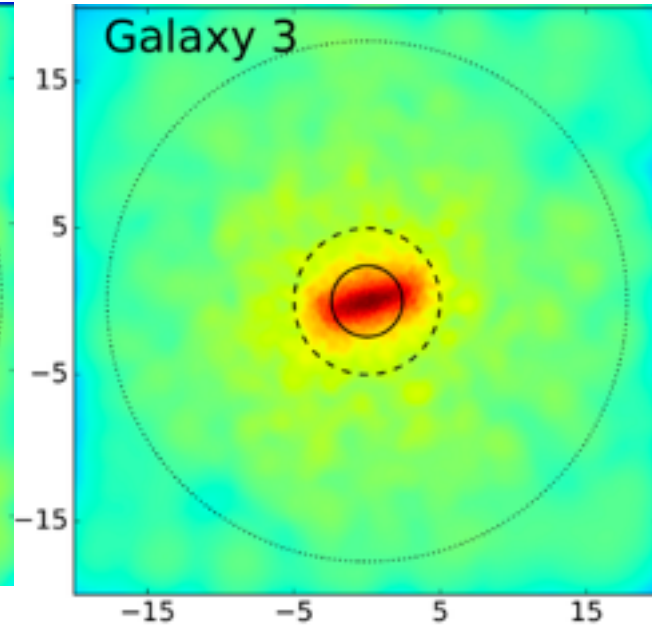
Bar Strength Parameter

Unbarred   **Weak Bar**   **Strong Bar**
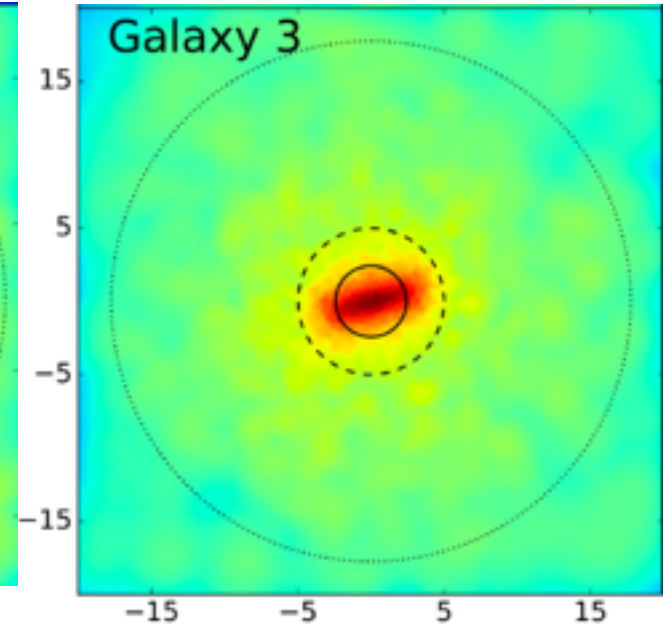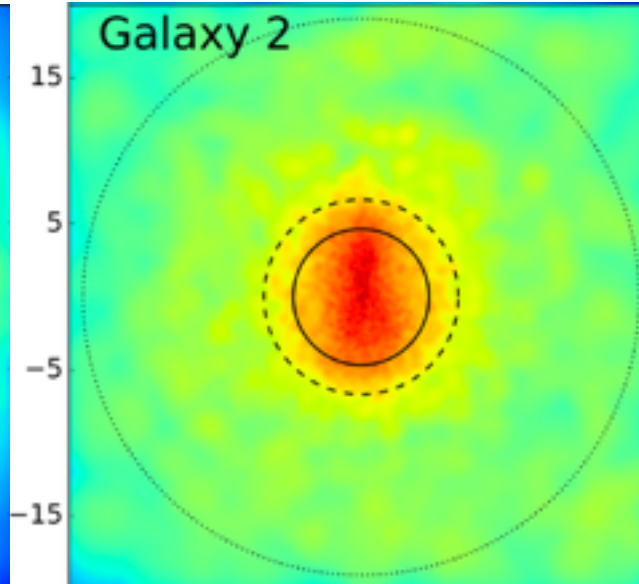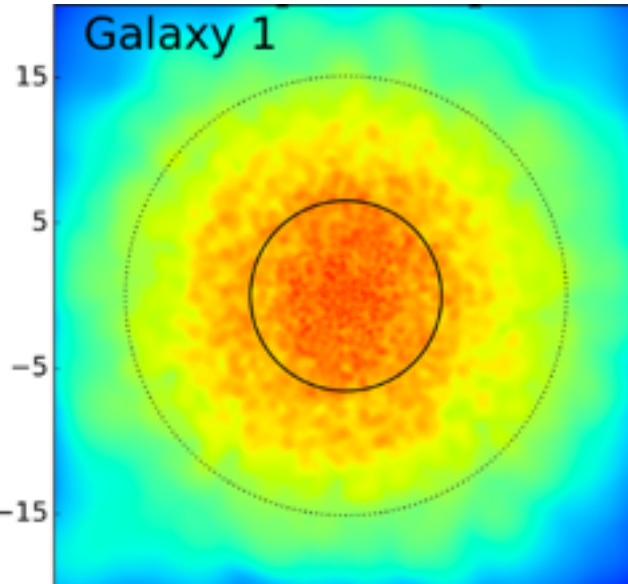
A2=0   A2=1

$$a_m(R) = \sum_{i=1}^{N_R} m_i \, cos(m\theta_i)$$

$$\mathbf{I}_m(R) = \sqrt{a_m^2 + b_m^2}$$

$$A_2(R) = \frac{I_2}{a_0}$$
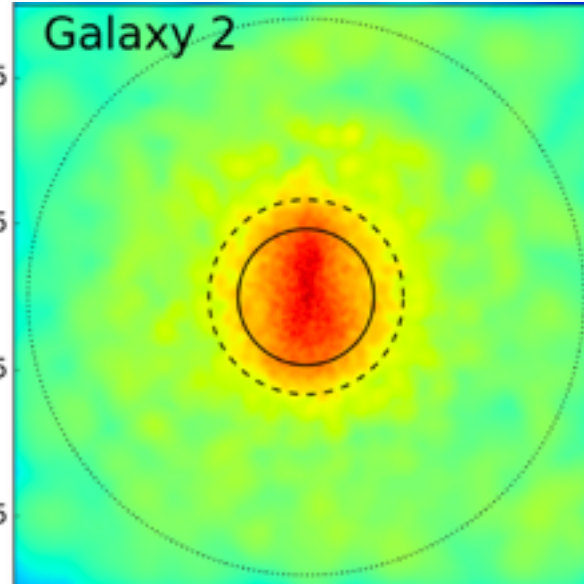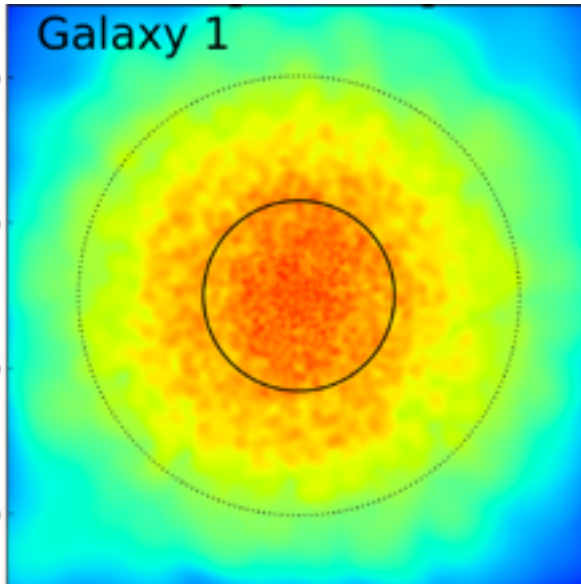
$$b_m(R) = \sum_{i=1}^{N_R} m_i \, sin(m\theta_i)$$
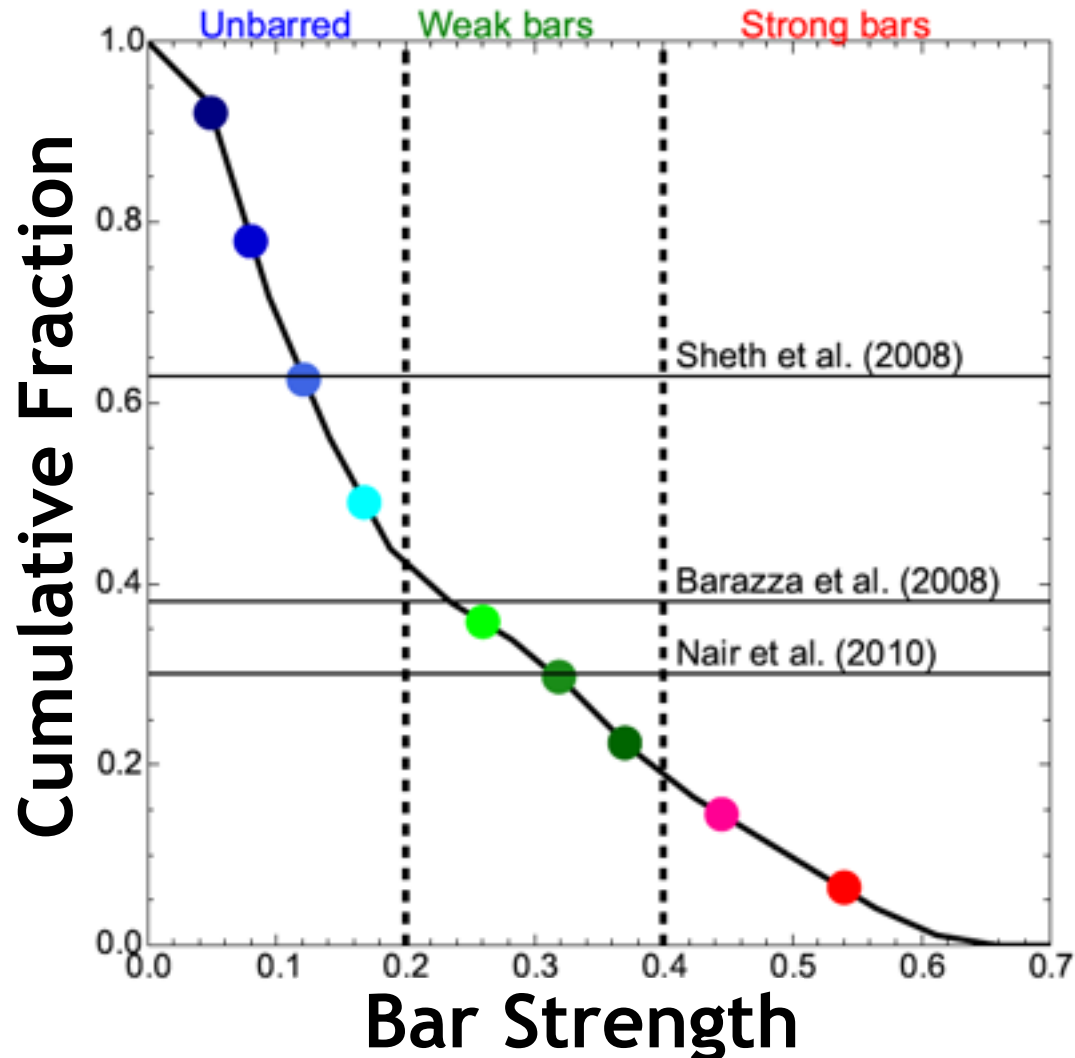
Bar Strength Radial Profile

Unbarred   **Weak Bar**   **Strong Bar**
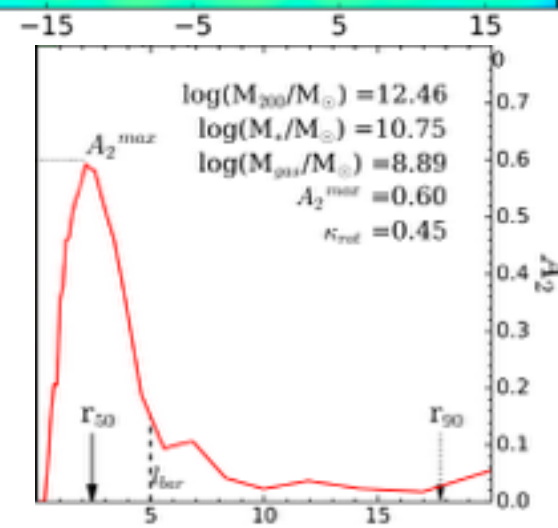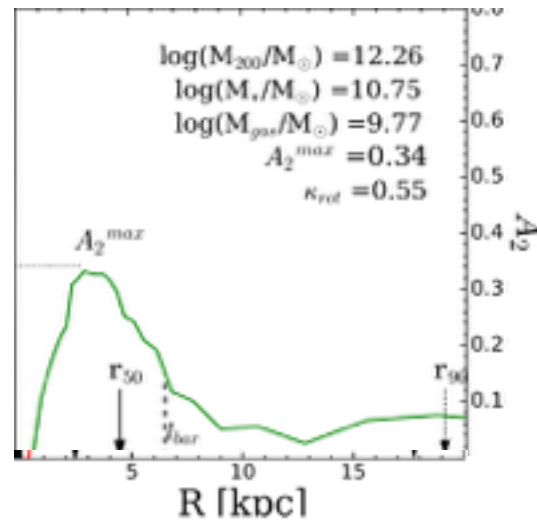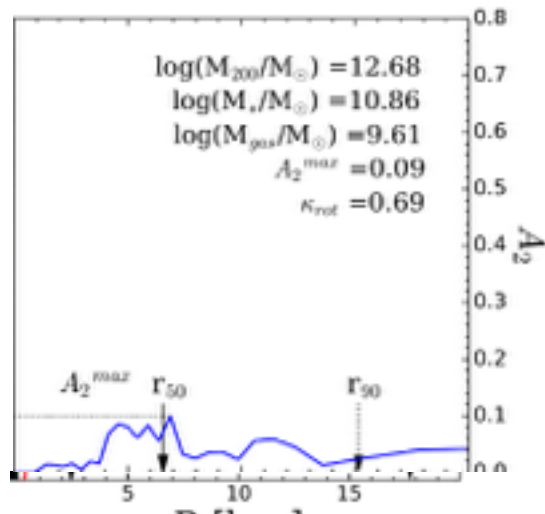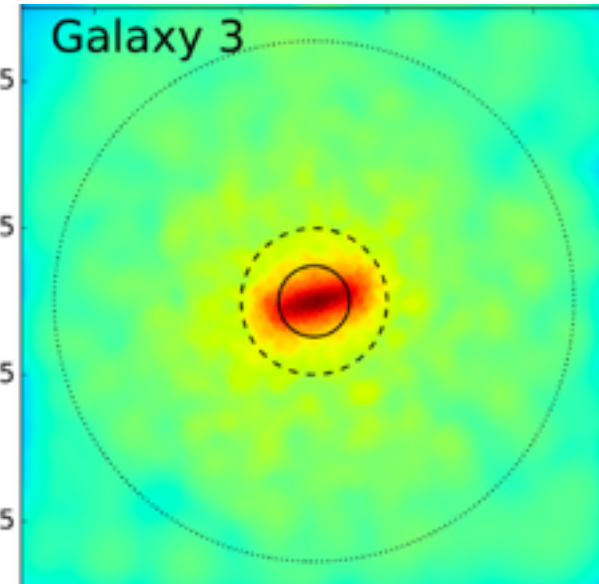
Abundance of Barred Galaxies

Cumulative galaxy fraction as function of bar strength parameter A2_max in the local Universe.

About 40% of EAGLE discs have bars (weak or strong) seems quite consistent with observations: Barazza et al. (2008) ~38%, Sheth et al. (2008) ~ 62% Nair & Abraham (2010) ~ 30%.
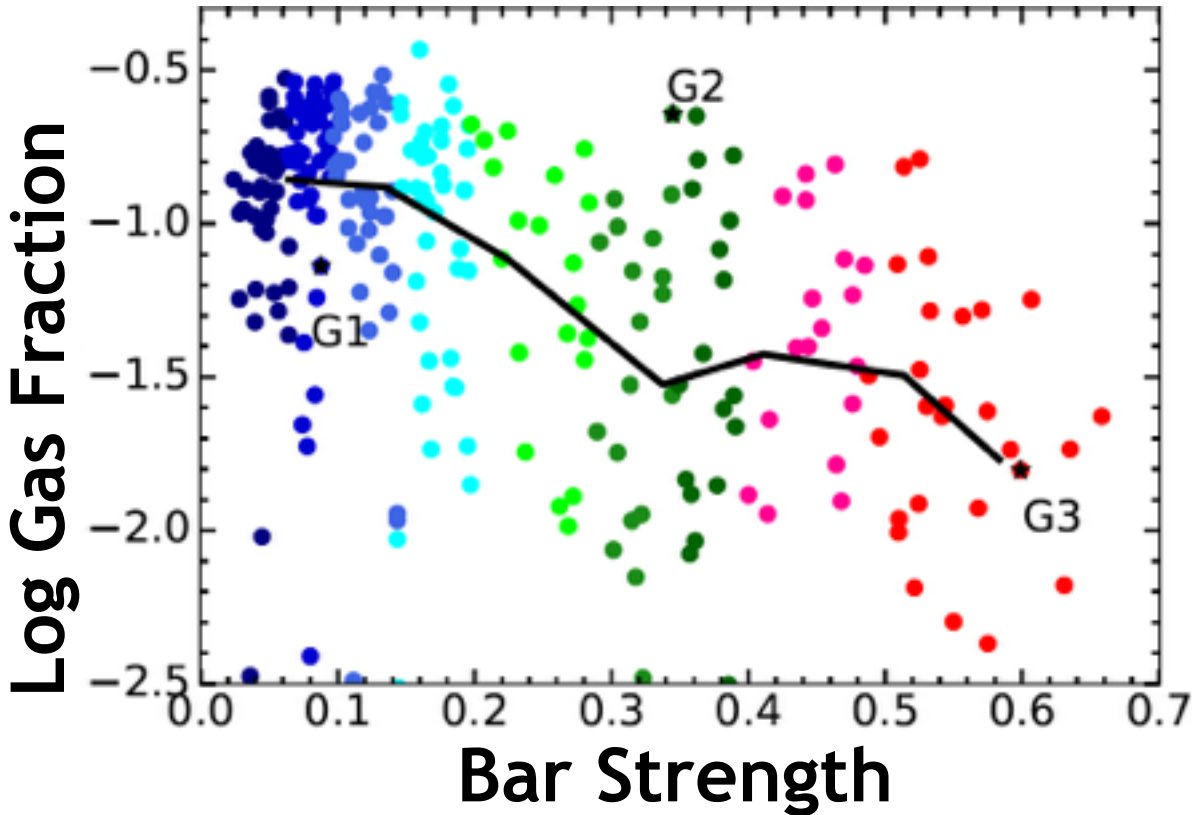
No standard definition of a bar. Bar prominence depends on the photometric band (stronger in the infrared), morphological type (longer in early-type spirals), galaxy mass (decreasing with increasing mass) and redshift (less frequent at early times).

Gas Mass vs Bar Strength

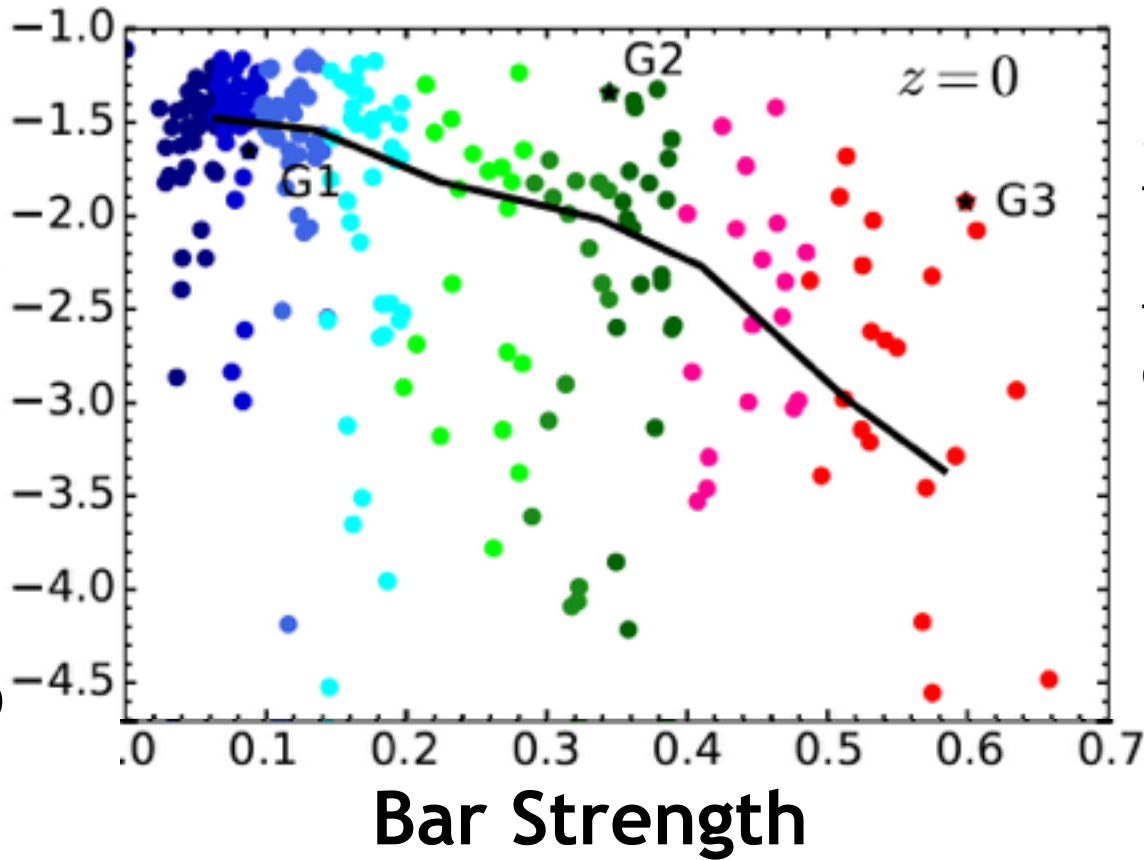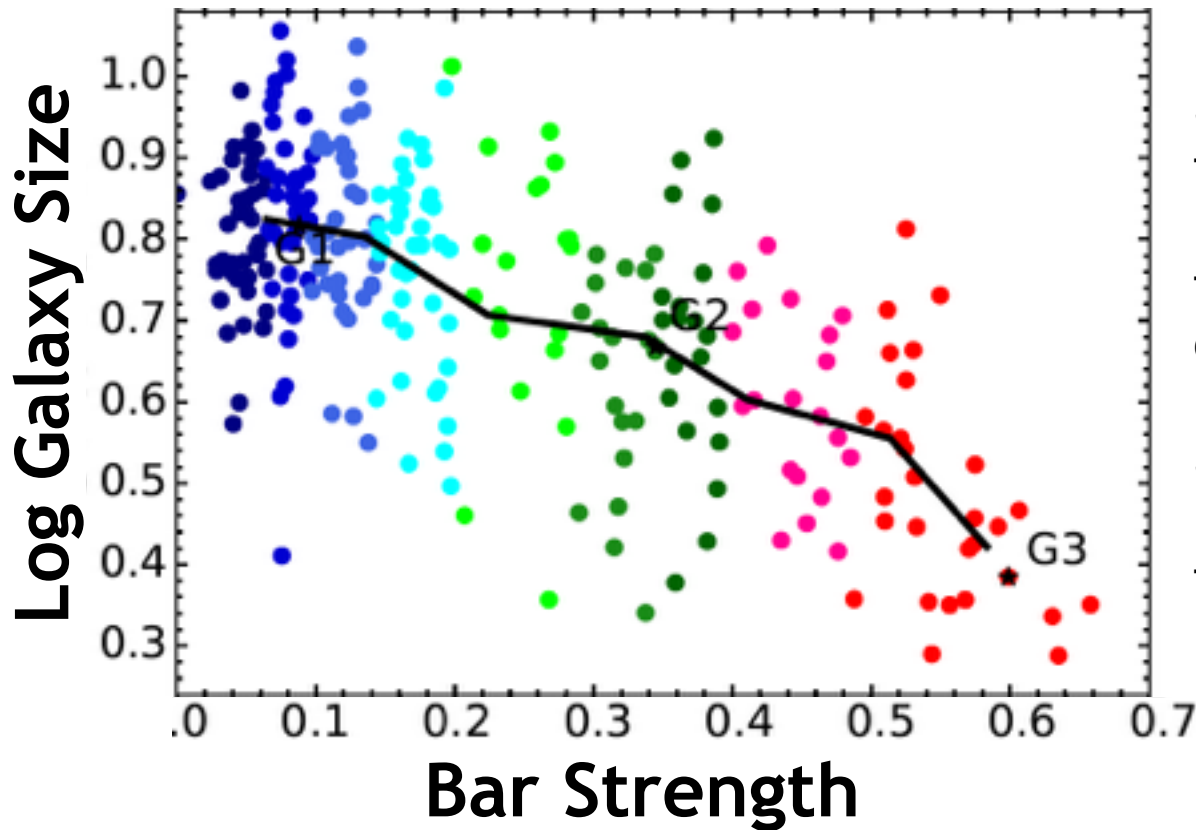# Star Formation vs Bar Strength

Bars are relatively gas poor

Star formation rates ~ 40% of their past average for unbarred galaxies, decreasing to 1% for strongly barred ones.
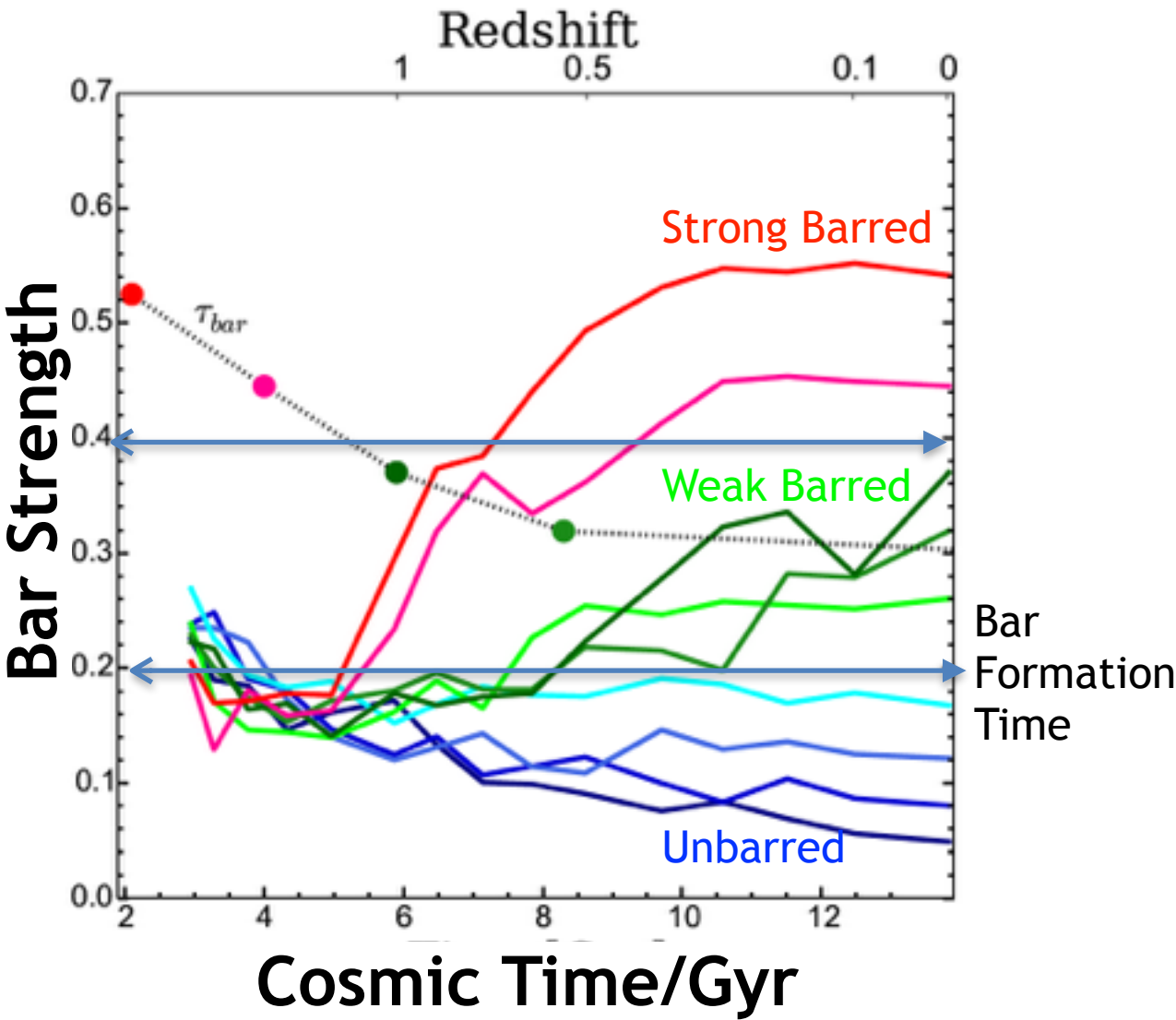
Size vs Bar Strength

Bars are relatively gas poor

Star formation rates ~ 40% of their past average for unbarred galaxies, decreasing to 1% for strongly barred ones.

Strongly-barred discs are roughly three times smaller than unbarred systems
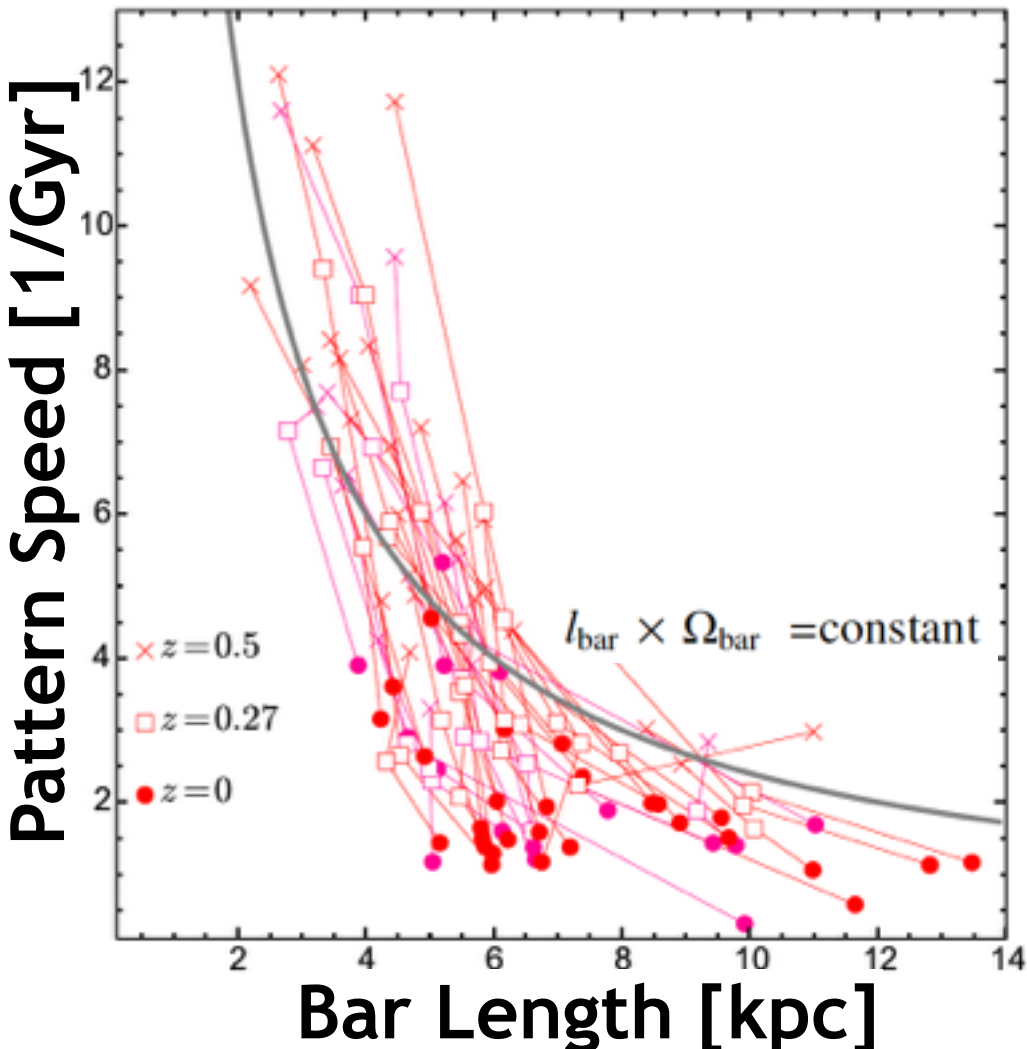
Bar Growth

Strong bars develop quickly and saturate

Weak bars are still growing at z = 0.

Few unbarred galaxies have had bars in the past.

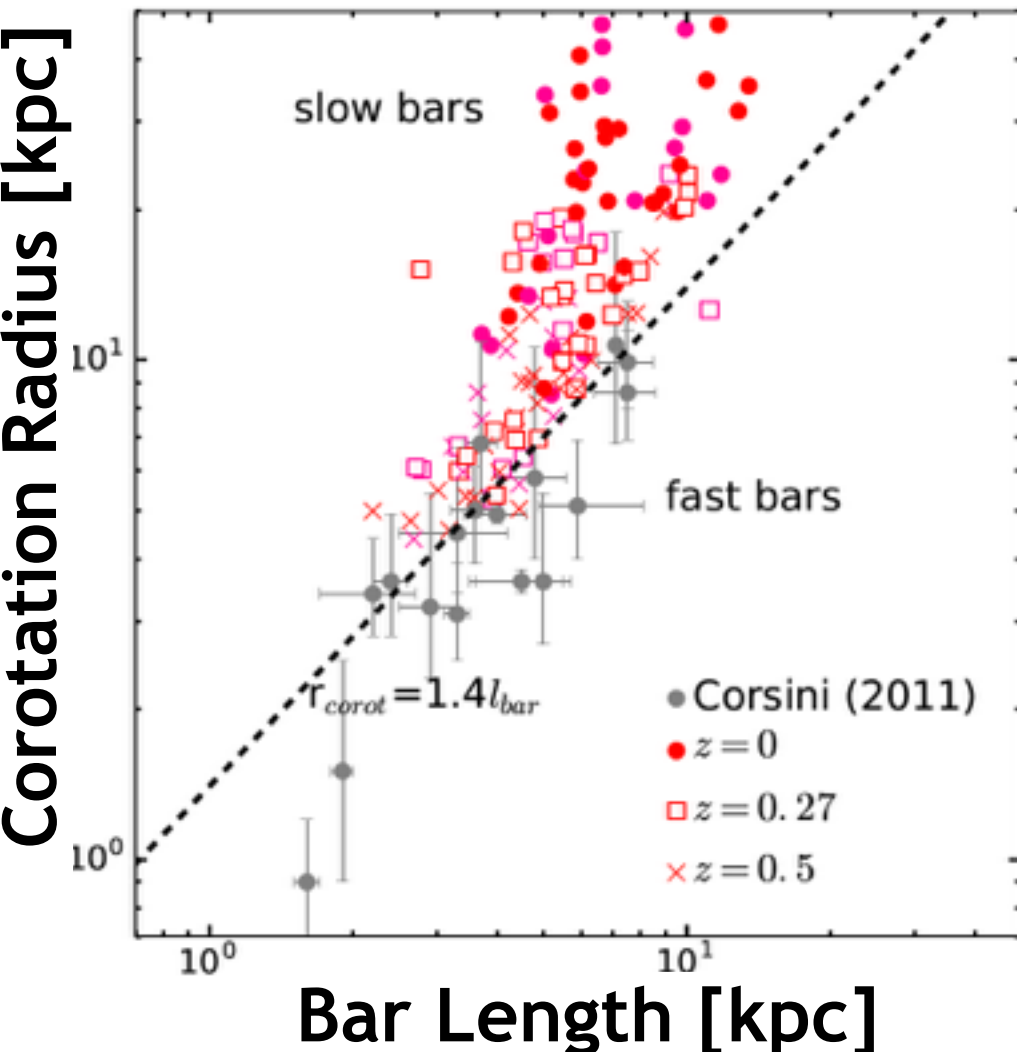Timescale for bar growth is clearly a strong function of final bar strength.

Bar Growth and Slowdown
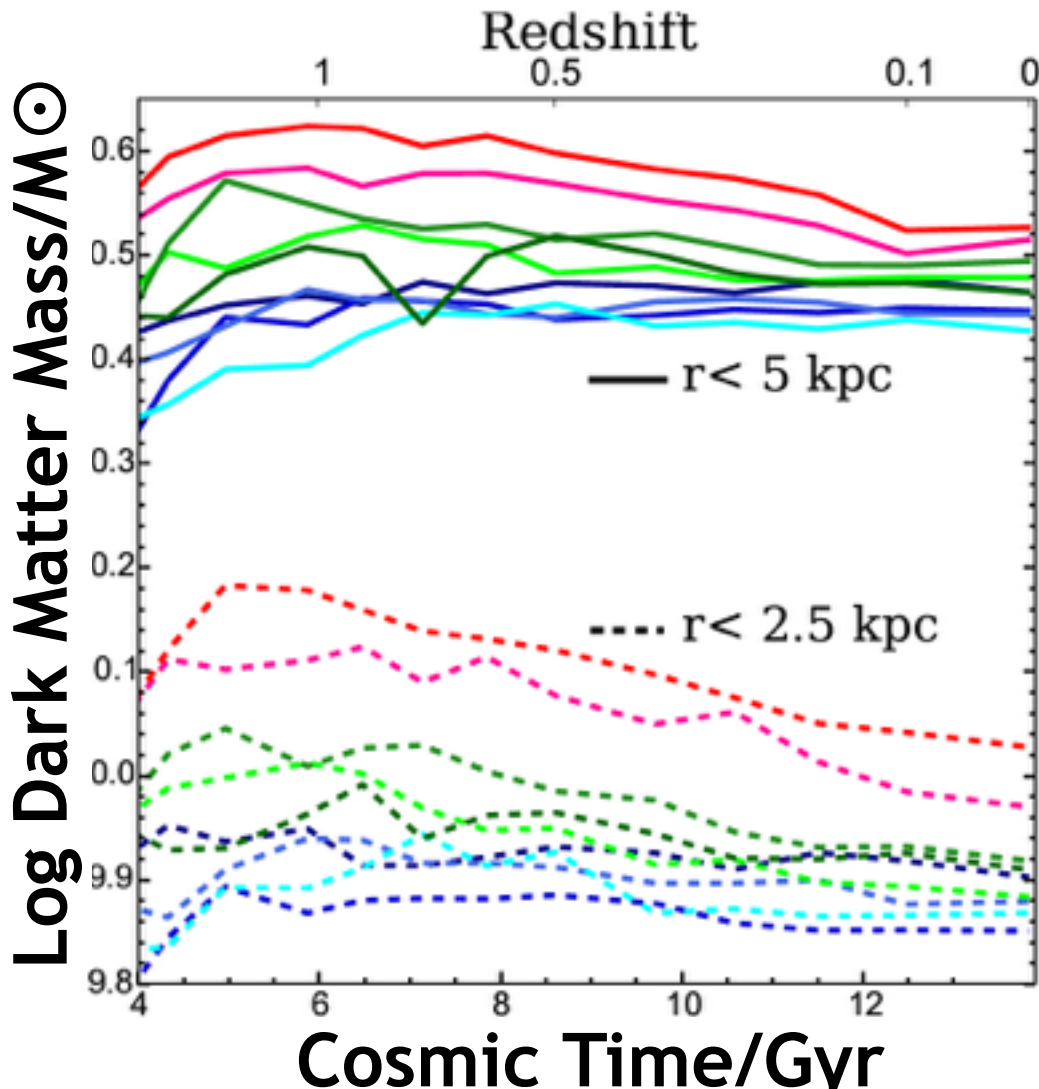

Bars slow down as they grow.

Bar Slowdown

z = 0.5 (triangles), z = 0.27 (squares), and z =0 (circles). Grey symbols with error bars are observational data from the compilation of Corsini (2011).

"Fast bars" are those below the dotted line delineating rcorot = 1:4 lbar. Most strong bars in our simulation are "slow" at z = 0, in contrast with observational estimates.

Dark Matter Halo Evolution

Bar slowdown clearly reduces the central density of dark matter within the region of the bar.

By contrast, the central dark matter densities of unbarred galaxies remain unchanged during the past 5-6 Gyr.

Conclusions

1) 20% strong bars, 20% weak bars, 60% unbarred. This bar frequency seems in reasonable agreement with observational estimates

2) Bars develop preferentially in systems where the disc is gravitationally important

3) Stronger bars develop in systems that are less gas-rich, and that have formed the bulk of their stars earlier than unbarred discs.

4) Strong bars develop relatively quickly before saturating but weak bars are still growing in strength

5) Strong bars slow down quickly as they grow

6) Bar slowdown induces an expansion of the inner regions of the dark matter halo
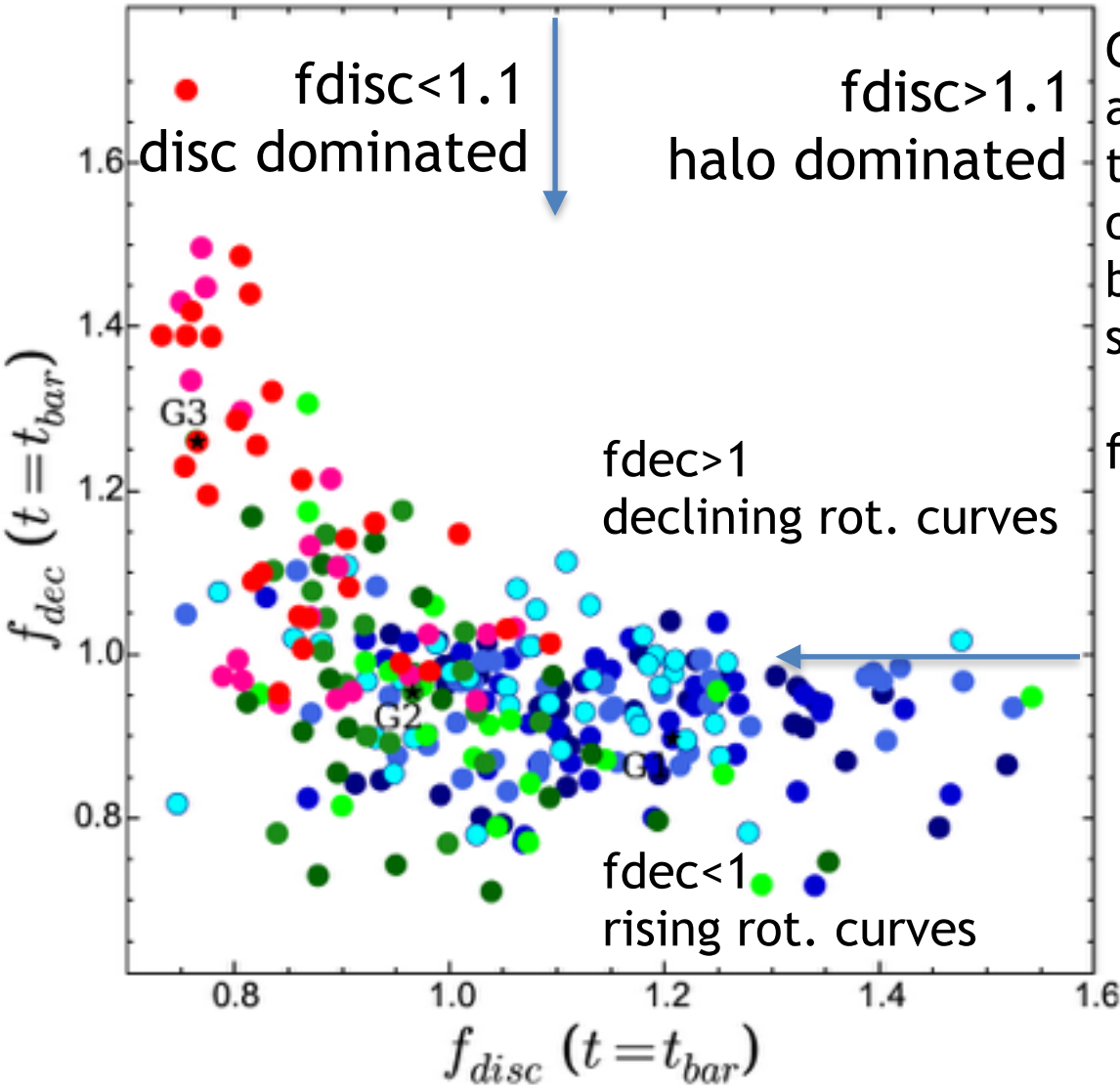
Bar Length
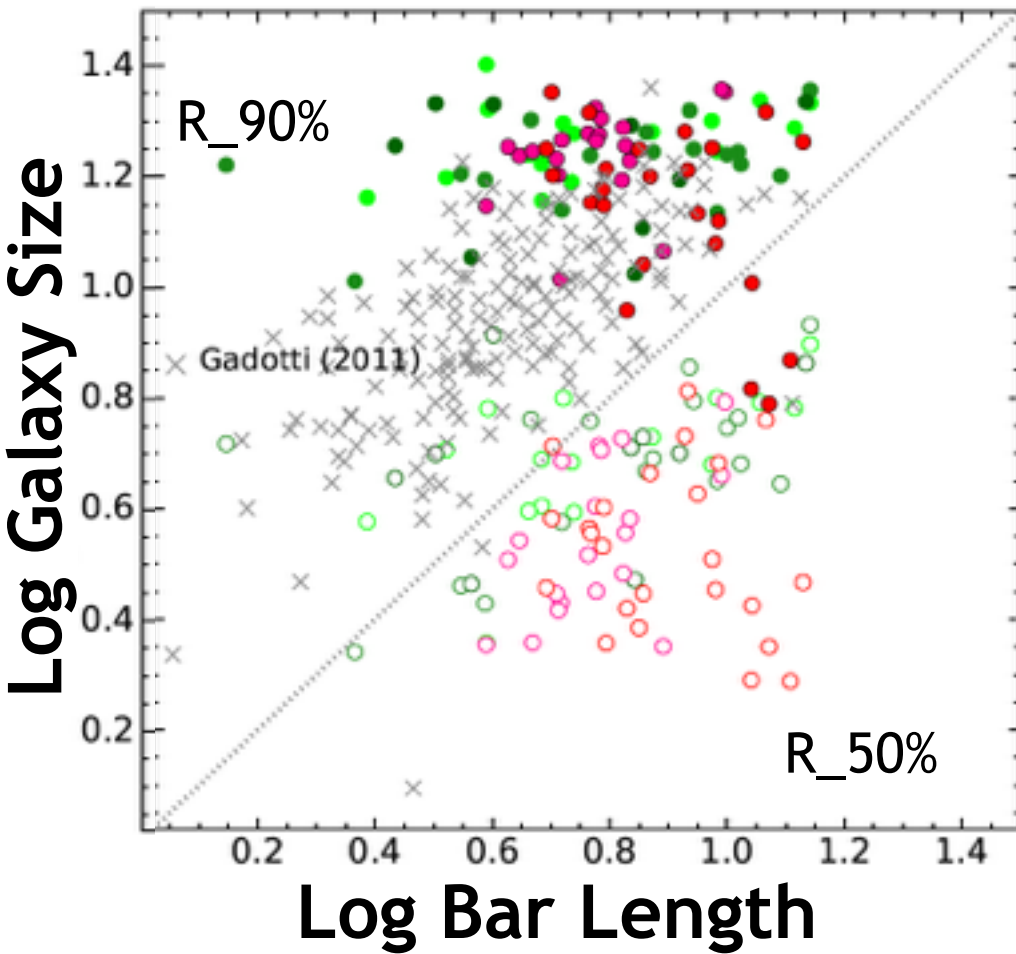
Distribution of bar lengths of nearly 1,000 SDSS (less massive and smaller than our sample) galaxies (Gadotti 2011).

There is no obvious discrepancy between observations and simulations in the regime where they overlap

Bar Formation Prediction

$$f_{disc} = \frac{V_c(r_{50})}{\sqrt{GM_{disc}/r_{50}}}$$

fdisc<1.1
disc dominated

fdisc>1.1
halo dominated

fdec>1
declining rot. curves

fdec<1
rising rot. curves

Galaxies that remain unbarred are predominantly those where the disc is less important, not only within their half-mass radii but also in relation to their surrounding halos.

fdec= Vcirc(R50%)/Vmax,halo