Formation of Elliptical Galaxies

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Formation and Evolution of Galaxies 2023-2024 Q1
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Elliptical Galaxies

Formation scenarios

- Typically two formation paths are contrasted. In simple terms
  - monolithic collapse
    - stars formed during the rapid collapse of a gas cloud (Eggen, Lynden-Bell & Sandage 1962; Larson 1975)
  - merger scenario
    - stars form in disks which subsequently merge (Toomre 1977)

- In a hierarchical universe

both paths come into play

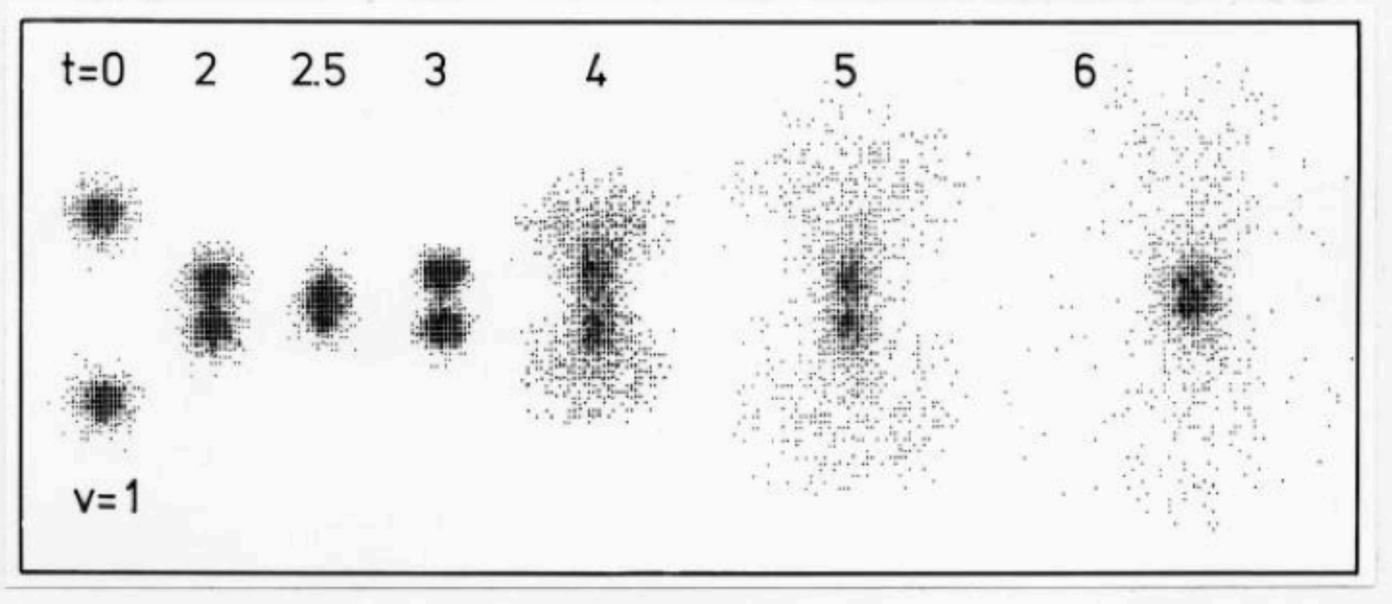


Figure 3 Head-on impact and merger of two stellar-dynamical n = 3 polytropes upon arrival at center with 1.061 times the escape speed U_{esc}. This diagram by van Albada and van Gorkom shows projected densities at seven instants.

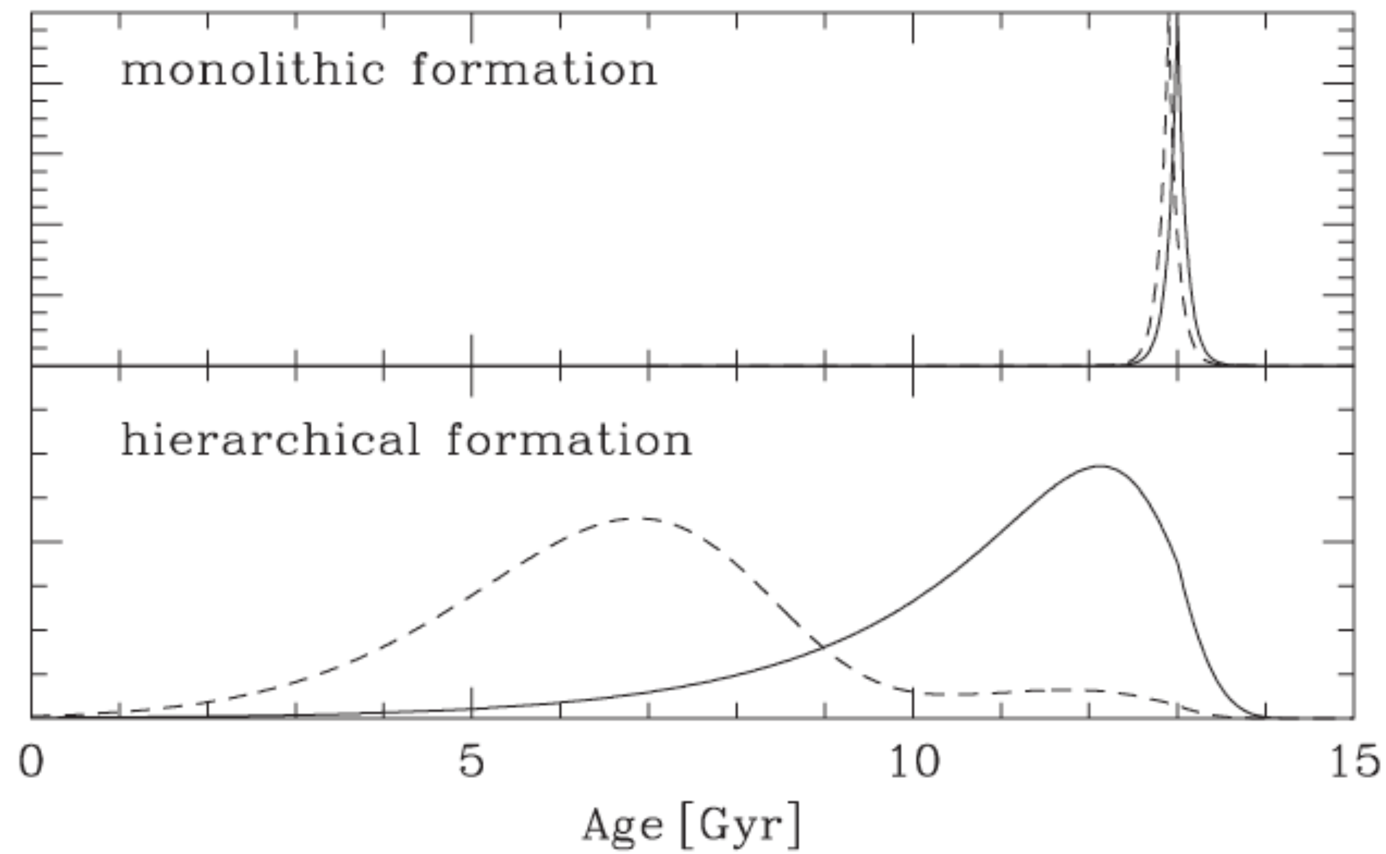


Fig. 13.4. A schematic illustration highlighting the differences between the traditional monolithic collapse (upper panel) and merger (lower panel) scenarios for the formation of the elliptical galaxy population. Solid curves show the mean star-formation history, while dashed curves show the mean rate of increase in the baryonic mass of the largest progenitor. In the monolithic collapse scenario, stars are assumed to form in a single short burst (typically more than 10 Gyr ago), and to assemble into the final galaxy during or shortly after the burst. In the merger scenario, however, the stars are formed over an extended period of time in two or more pre-existing galaxies, which only merge into the final elliptical at a (sometimes much) later time.

<u>Assembly time of the mass does not necessarily correspond to the formation time of the stars</u>

The role of dissipation in galaxy formation

Energy is conserved in dark matter collapse.

Instead, gas typically collapses dissipating energy and conserving angular momentum

Early simple models of bulge/elliptical formation were dissipationless and could explain some basic galaxy properties, but not realistic.

Monolithic collapse model in detail

- Stars form in a single burst at high-z, coincident with collapse, and passive evolution afterwards
- Inspired by homogeneity of elliptical galaxies as a class, and by uniformly old stellar populations

- Collapse could not have been purely dissipationless
  - because this would involve also dark matter, and E galaxies are baryon dominated in inner regions
- Therefore collapse must have included significant amounts of gas
  - Gas can segregate, and the very high central stellar densities explained
  - Presence of metallicity gradients of different magnitudes (depending on timescales of star formation and chemical enrichment)

- If dissipational: if halos have spin normally this implies gas settling onto a disk. The solution is to argue that ellipticals would be in low spin halos

Problems with monolithic collapse model

- If dominant population is 10 Gyr old → formation times z ≥ 2, and passive evolution after.

•However the number density of passive massive ellipticals at z ~ 1 is lower by factor 3-4 compared to z = 0

•measured by n(L*) = Φ*

→ smaller for red galaxies at z=1 than at z=0

→ constant for blue galaxies

•These galaxies should be there unless assembly by mass occurs later…

•Another problem is that it predicts a metallicity gradient much larger than observed, and this is hard to avoid.

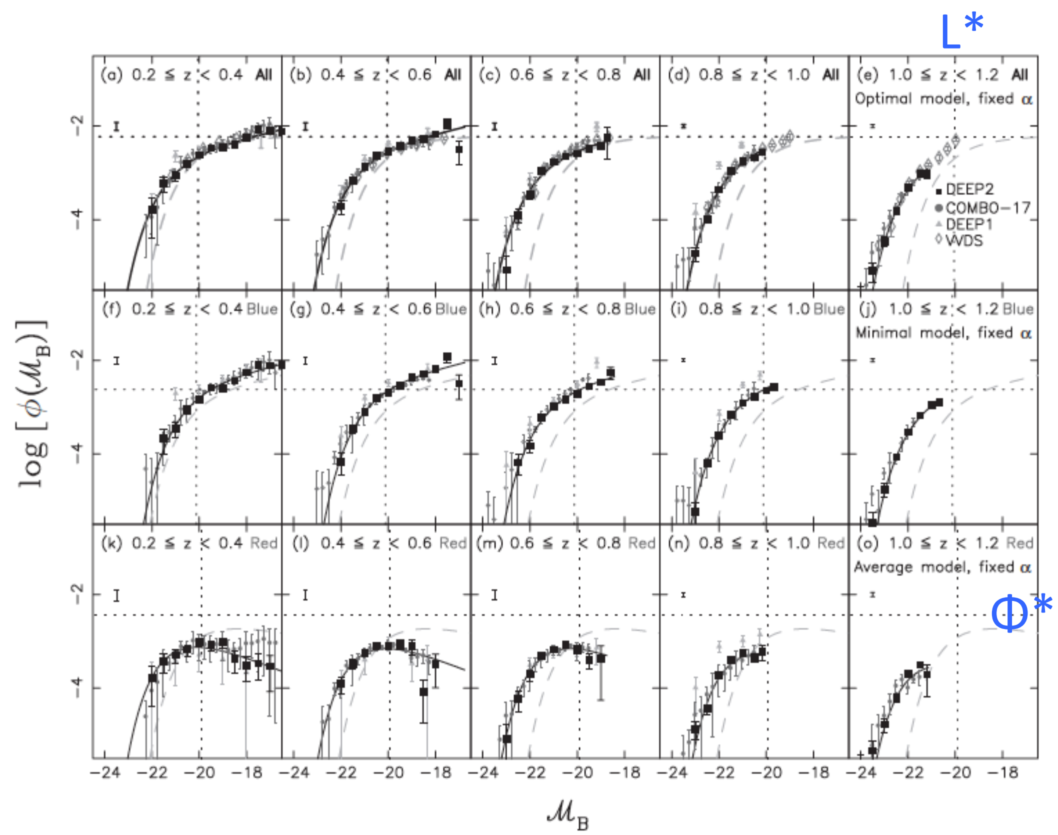
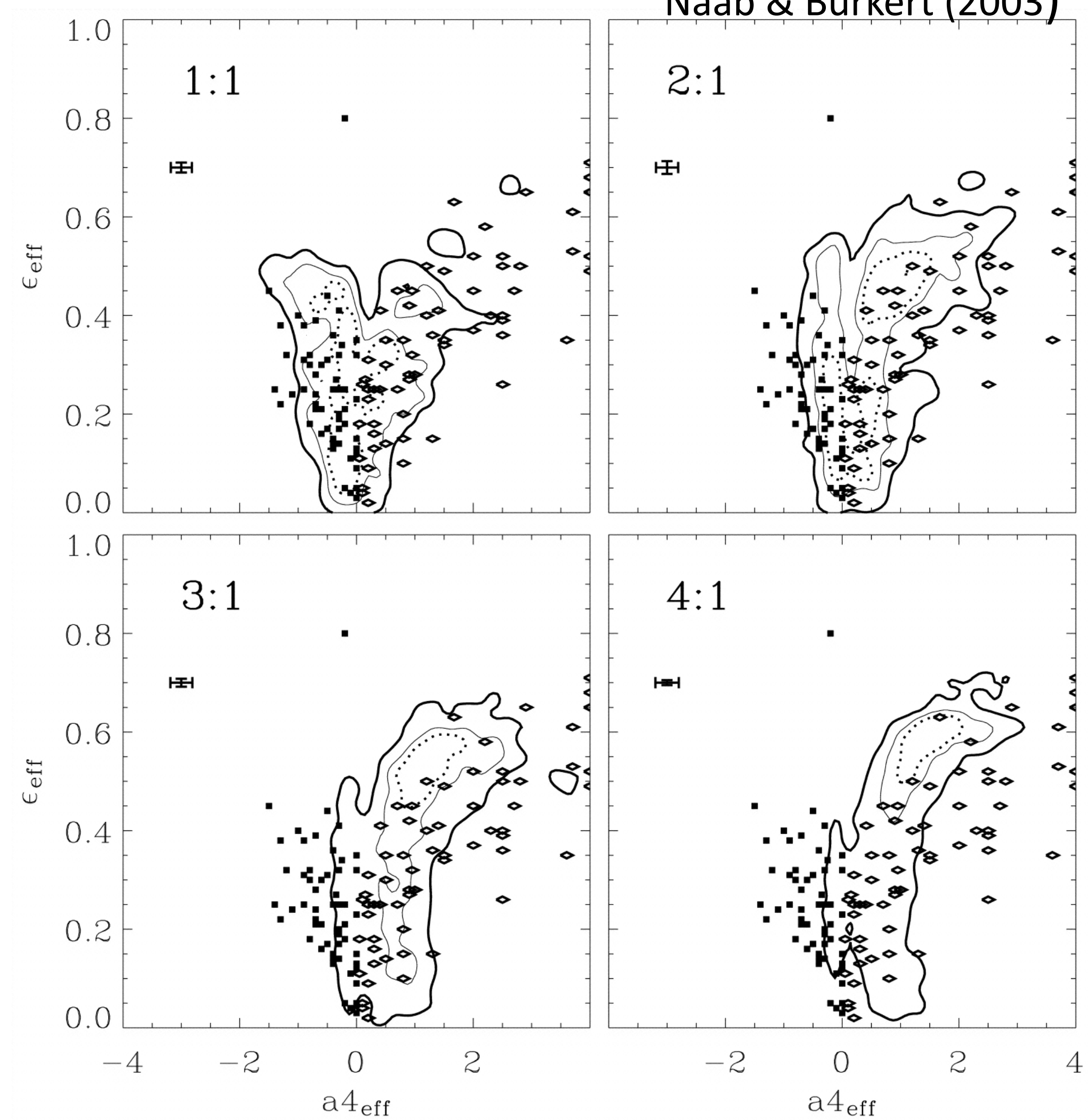


Fig. 2.33. Luminosity functions measured in different redshift bins for 'All' galaxies (top row), 'Blue' galaxies (middle row), and 'Red' galaxies (bottom row). Different symbols correspond to results obtained from different redshift surveys (DEEP1, DEEP2, COMBO-17 and VVDS, as indicated). The solid black lines indicate Schechter functions fitted to the DEEP2 results. For comparison, the dashed gray lines show the Schechter functions for local samples obtained from the SDSS. Overall the agreement between the different surveys is very good. [Adapted from Faber et al. (2007) by permission of AAS]

Merger scenario

- Since star formation occurs mostly in disks, and the merger of disks produces a spheroidal remnant → it has been suggested that massive ellipticals are the remnants of ‘dissipationless’ (also called ‘dry’) mergers of disks

Naab & Burkert (2003)



Mergers between two disks of different mass ratios lead to different types of remnants:

- the more unequal the mass-ratio the more disky the remnant (a4 > 0), perhaps too large ellipticity

- equal mass mergers overlap also with boxy ellipticals but tend to produce remnants that are slightly more elliptical than observed

Symbols are observed boxy and disky ellipticals. Contours indicate the 50% (dotted line), 70% (thin solid line), and 90% (thick solid line) probability of finding a merger remnant in the enclosed area

Merger scenario: remnants

- Merger remnants can merge again, and ellipticals can also result from mergers of ellipticals

- Some support from numerical simulations: remnants of dry (i.e. without gas) mergers between elliptical progenitors of roughly equal mass are typically slow rotating, boxy ellipticals (e.g. Khochfar & Burkert , 2005 ; Naab et al. 2006 ; Cox et al., 2006) that lie on the fundamental plane
- Depending only on relative initial orientation of progenitor discs, almost every observed kinematic peculiarity has been found in equal-mass merger remnants:
    - major axis rotation,
    - kinematic twists,
    - dumbbell features (a feature in the stellar dispersion)
    - counter-rotating cores (Balcells & Quinn 1990; Hernquist & Barnes 1991).
    - Only major disc mergers - depending on the initial disc orientation - can form slow rotators which mostly have counter rotating cores (Jesseit et al. 2009)

→ Dry mergers could be viable mechanism for the formation of *massive* ellipticals.

Gas-poor/rich mergers and the remnants

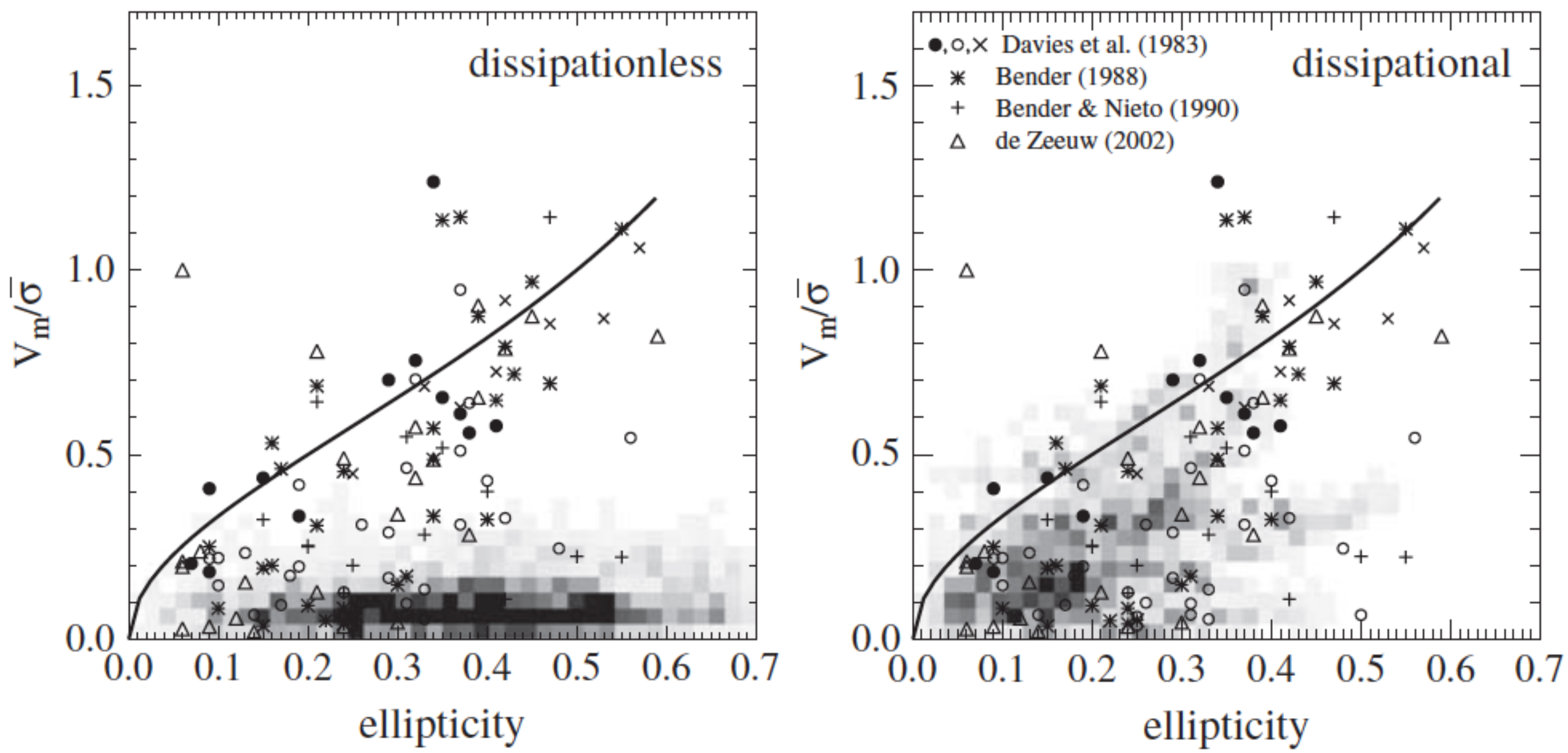


Fig. 13.5. The anisotropy diagram of $v_{\rm m}/\overline{\sigma}$ vs. ellipticity for dissipationless (left-hand panel) and dissipational (right-hand panel) merger remnants obtained from a large suite of hydrodynamical simulations (gray scale). Overplotted, with different symbols, are data for observed ellipticals from Davies et al. (1983), Bender (1988), Bender & Nieto (1990), and de Zeeuw et al. (2002). Note that the dissipational simulations yield remnants in much better agreement with these data. The solid line in both plots corresponds to Eq. (13.25), and indicates the expected relation for an oblate isotropic rotator. [Adapted from Cox et al. (2006) by permission of AAS]

Mergers and the remnants

- Dissipational component has a significant impact on properties of remnant (Barnes & Hernquist, 1996), and is needed for lower luminosity ellipticals
  - Gas makes centers of remnants rounder, less boxy, more centrally concentrated
  - A dissipational component changes asymmetry of the line-of-sight velocity distributions more in agreement with observed rotating early-type galaxies (Naab et al. 2006)
- Kinematics of observed fast rotating early-type galaxies in good agreement with remnants of 'minor' disc mergers with varying mass-ratios (Jesseit et al. 2009; Bois 2011).
- Massive ellipticals apparently could form via dissipationless (‘dry’) mergers, while their less massive counterparts seem to require dissipational (‘wet’) mergers
- Despite successes of binary merger simulations in explaining some photometric and kinematic properties of early-type galaxies, approach has considerable limitations…
  - e.g. we do not know how to reproduce fractions of different types
  - initial conditions: gas fractions, mass ratios, orbits….

Contrasting models in the context of the hierarchical paradigm

- **Star-formation history:**
  - quasi-monolithic collapse assumes stars to form in a single burst
  - hierarchical merging predicts star formation in several different sites and over a more extended period, possibly with merger-induced starbursts.
- **Assembly history**:
  - quasi-monolithic collapse: assembly is coeval with the formation of its stars
  - hierarchical merging: most of stars form in progenitor galaxies well before assembly of final elliptical. Also assembly may involve multiple mergers, and over an extended period of time.
- **Progenitor properties**:
  - quasi-monolithic collapse, the immediate progenitor of an elliptical galaxy is a single starbursting gas cloud
  - hierarchical merging: ellipticals have diverse progenitors (spirals, ellipticals, irregulars, etc.)

Challenges for hierarchical model

- Ellipticals formed via mergers → expect stars of different ages that formed in each of the progenitors
  - apparent contradiction with E that are SSP and “generically observed to be old”

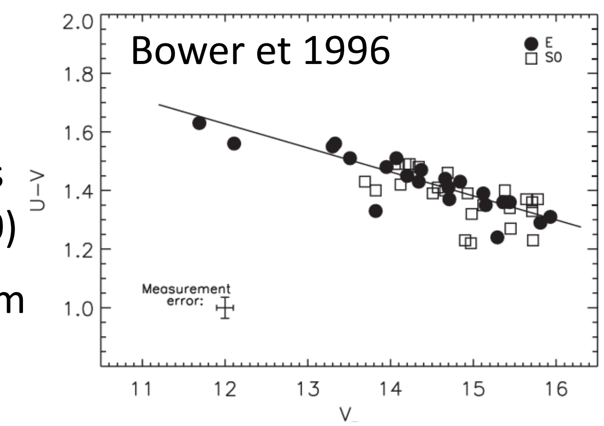
•tight color-magnitude diagram (a “SSP”): tricky to disentangle age from metallicity

•however the trend is apparently result of luminosity-metallicity relation (Kodama & Arimoto 1997) and small scatter due to old ages/passive evolution

•Use of Lick-indices (rather than broad band colours) can help break some degeneracies between age and metallicity → indicate relatively large scatter in age (Trager et al. 2000)

•Some care needed as indices are sensitive to a small amount (few %) of recent star form

•Differences between ellipticals in low and high density environments are real.



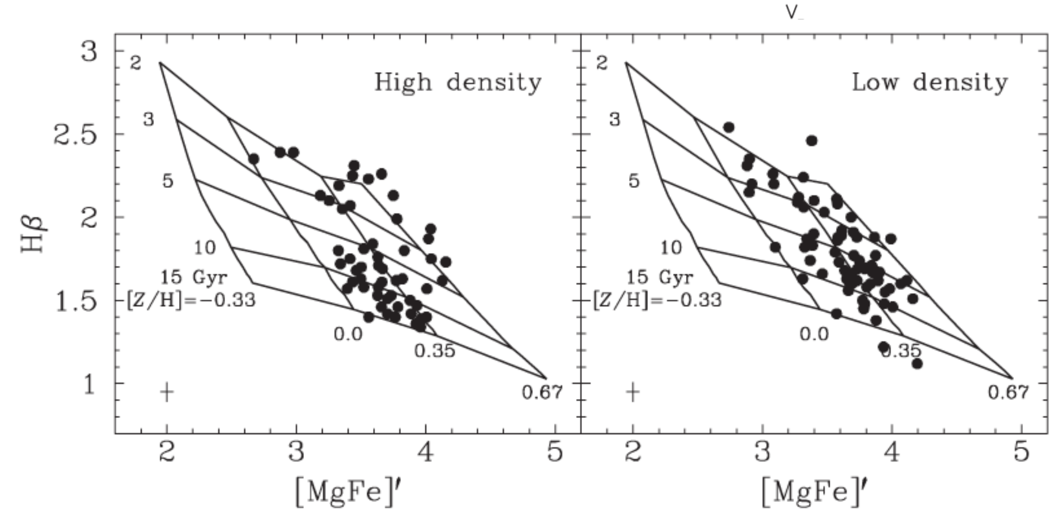
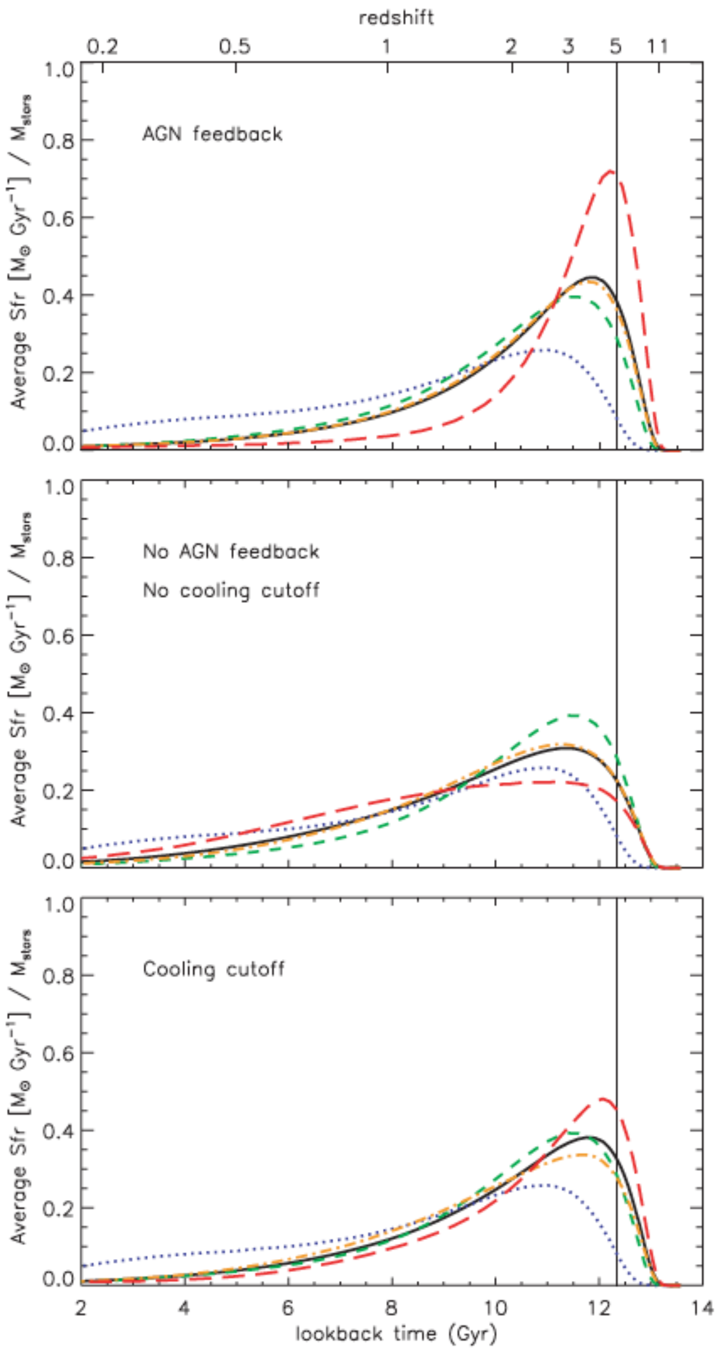


Fig. 13.8. The Lick indices Hβ vs. [MgFe]′ for a sample of ellipticals, lenticulars and cD galaxies with overplotted a grid of SSP models of Thomas et al. (2003) for metallicities of [Z/H] = 0.0, 0.35 and 0.67, and ages of 2, 3, 5, 10 and 15 Gyr. The median 1σ error bars of the data points are shown in the lower-left corner. Results are shown separately for galaxies in high- and low-density environments (left and right panels, respectively). [Adapted from Thomas et al. (2005) by permission of AAS]

Why the hierarchical model works

- This has been solved by
  - LCDM model
  - introduction of AGN feedback (needed anyhow for the LF)
  - Models are able to reproduce the trends with age and mass
  - predict that more massive ellipticals form their stars over shorter timescale, in agreement with observations

- Feedback and winds lead to chemical enrichment, and to a good mass metallicity relation for ellipticals
- Gradients would naively not be expected if mergers would erase all information
  - but they do not: stars that are most bound, remain more bound, and so gradients are preserved to some degree in the merger product



De Lucia et al. 2006, Croton et al. 2006

Why the hierarchical model works

- Earlier models predicted ellipticals should have young stars, following the mass assembly of the halos
- Ages of the stellar populations have to be decoupled from dynamical/assembly age
  - age-mass relationship is antihierarchical
  - although more massive halos are assembled later, the progenitors formed earlier

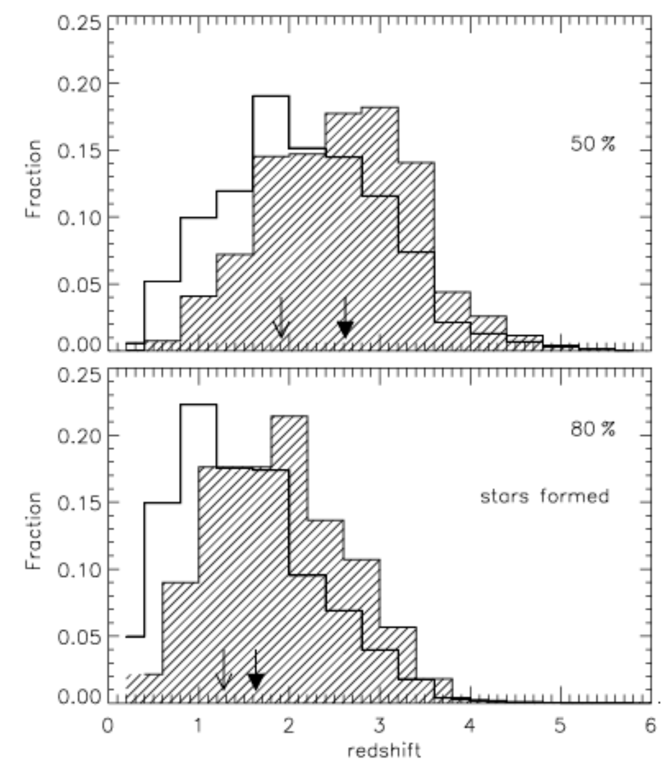


Figure 4. Distribution of the formation redshifts of model elliptical galaxies. In the upper (lower) panel, the formation redshift is defined as the redshift when 50 per cent (80 per cent) of the stars that make up the elliptical galaxy at redshift $z = 0$ are already formed. The shaded histogram is for elliptical galaxies with stellar mass larger than 10^{11} $M_{\odot}$, while the open histogram is for all the galaxies with mass larger than 4×10^{9} $M_{\odot}$. Arrows indicate the medians of the distributions, with the thick arrows referring to the shaded histograms. Note that more massive ellipticals typically form their stars earlier.

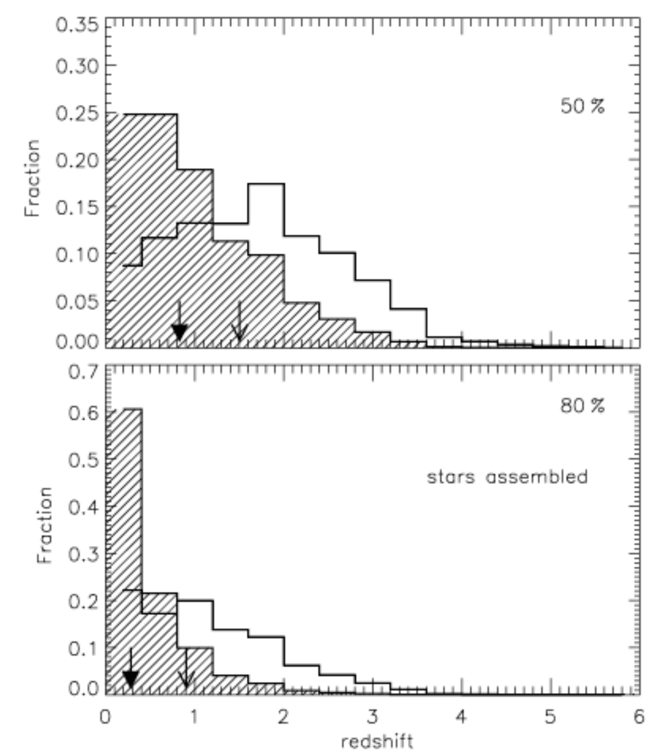


Figure 5. As in Fig. 4, but for the assembly redshifts of model elliptical galaxies. We define the assembly redshift as the time when 50 per cent (80 per cent) of the stars that make up the galaxy at redshift zero are already assembled in one single object. Note that more massive ellipticals typically assemble their stars later (cf. Fig. 4).

De Lucia et al (2006)

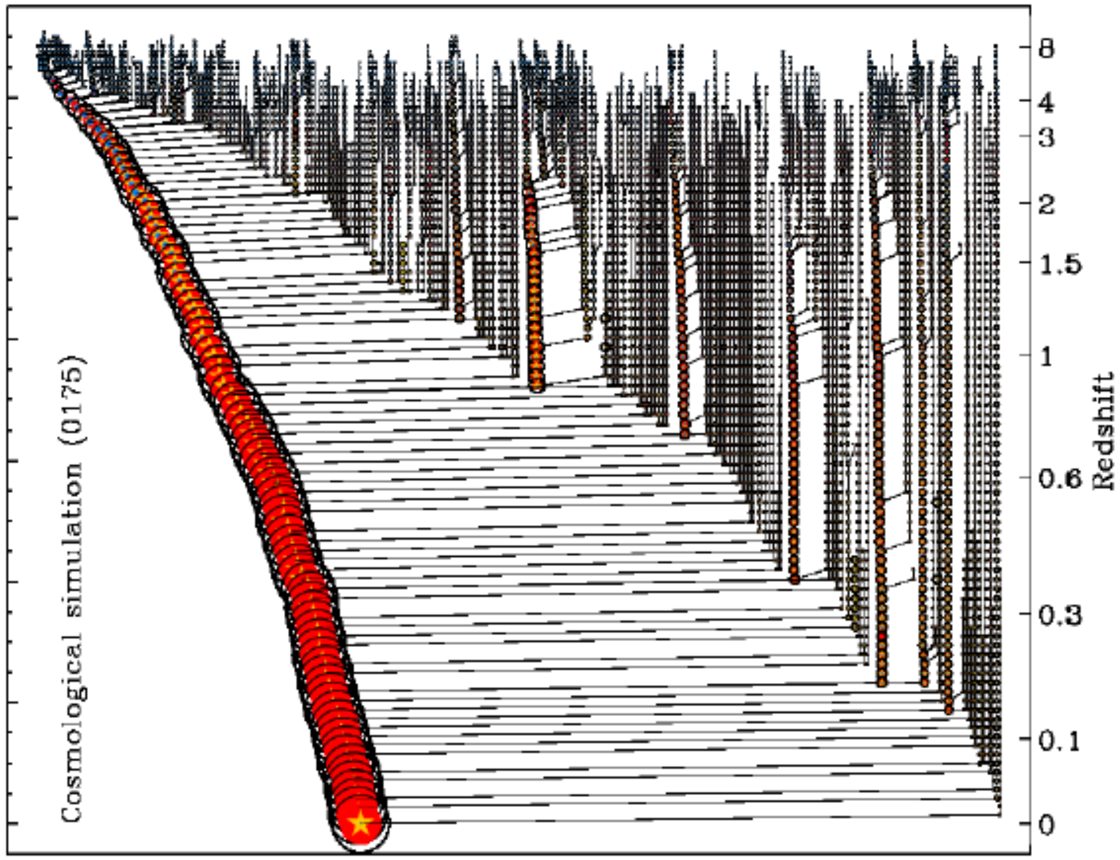
Formation paths: simulations in LCDM

- Recent high-resolution cosmological zoom-in simulations on formation of massive galaxies mix of both the 'monolithic' dissipative collapse models of early 70's and merger scenario of the 80's and 90's.

•Massive early-type galaxies appear to grow in two main phases:

•<u>Early evolution</u> ($2 < z < 6$) is dominated by significant gas in flows (Keres et al. 2005; Dekel et al. 2009) and in-situ star formation

•<u>Late evolution</u> is dominated by assembly of stars which have formed in other galaxies and have then been accreted onto the system at lower redshifts ($3 < z < 0$)



Naab et al (2013)

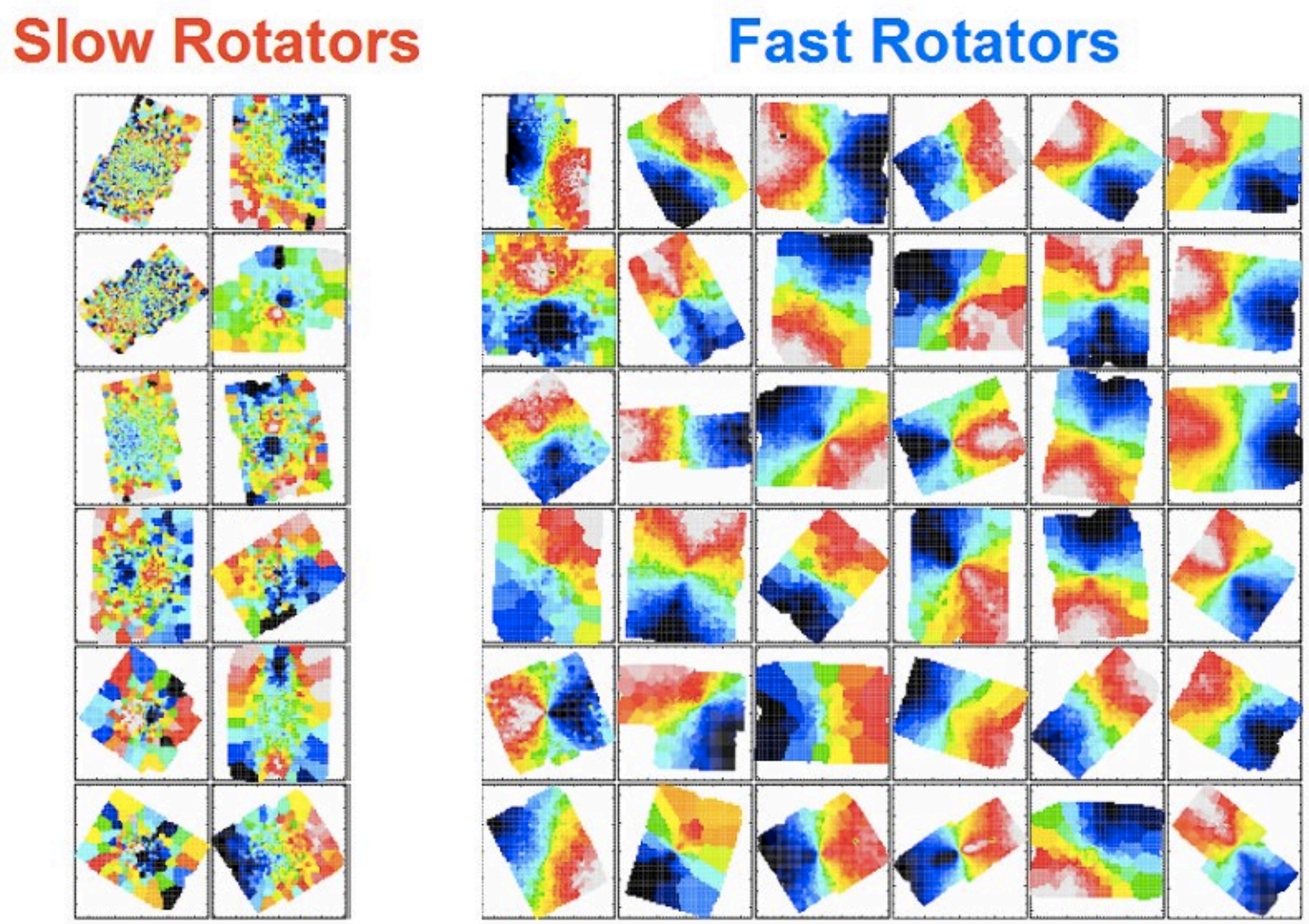
Zooming into the dynamics of E galaxies

•SAURON survey of nearby ellipticals led to classification into <u>slow rotators and fast rotators</u> (Bacon et al. 2001)

•based on λ_R-parameter:
$\lambda_R = \langle R\ |V|\rangle / \langle R(V^2 + \sigma^2)^{1/2}\rangle$

a measure of specific angular momentum of galaxies from their 2D line-of-sight velocity field (Emsellem et al. 2007)

•$\lambda_R > 0.1$: fast rotator
• $\lambda_R < 0.1$: slow rotator



Zooming into the dynamics of E galaxies

•Fast rotators: low- and intermediate-mass field population (Cappellari 2011); family of flattened, oblate systems with regular velocity fields.

•Slow rotators: in high density environments, most massive and round galaxies, and have peculiar properties such as kinematic twists and kinematically decoupled components (Krajnovic et al. 2011; Emsellem et al. 2011).

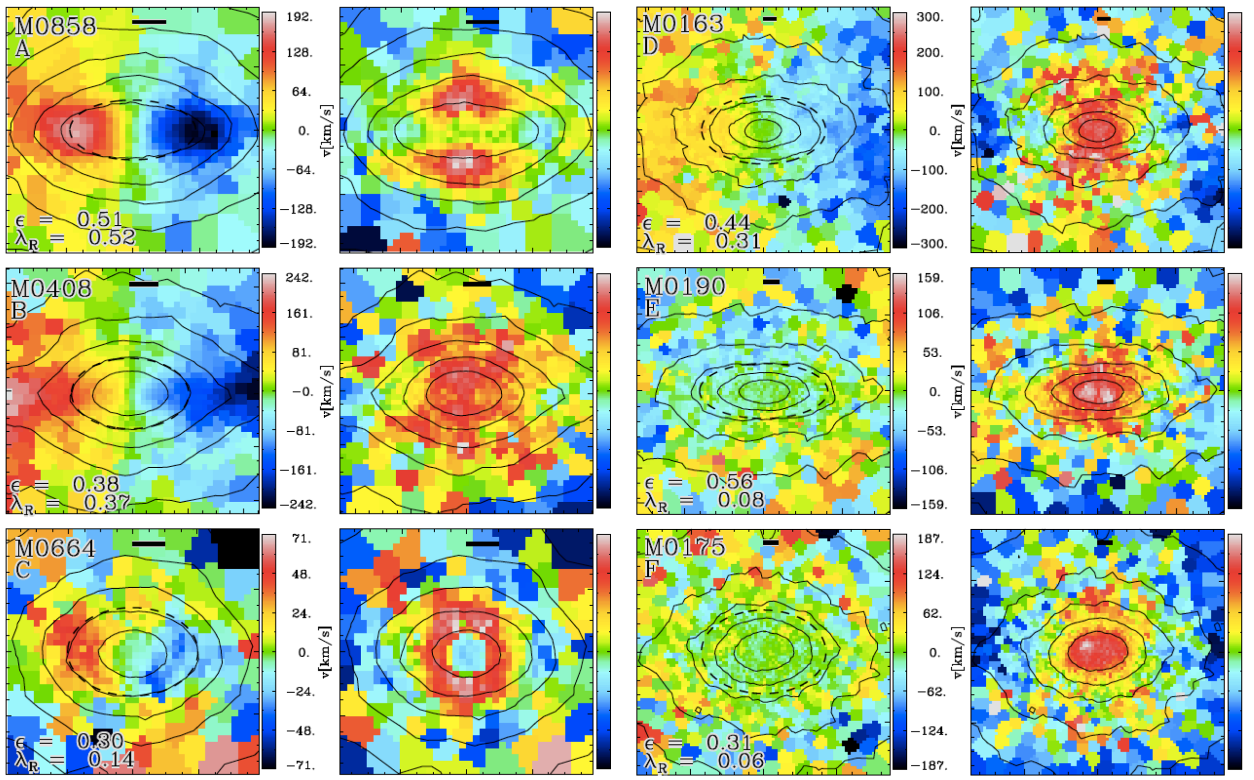
•ATLAS3D: unbiased survey of early type galaxies in the nearby Universe.

•Some important results:

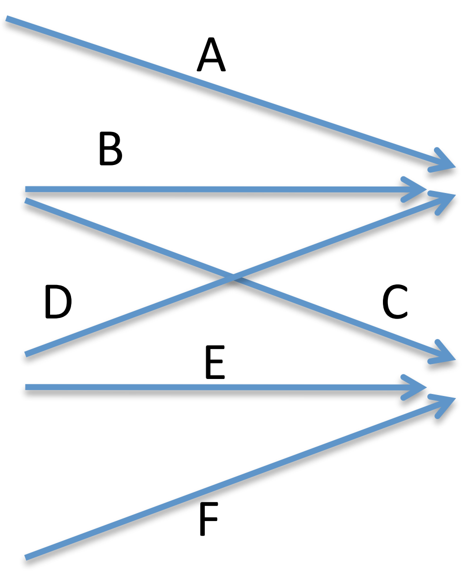
- •only a small fraction (12%, 32/260) of E galaxies rotate slowly.
- •the majority (86%, 224/260) of early-type galaxies shows significant (disc-like) rotation with regular velocity fields (Krajnovic et al. 2011; Emsellem et al. 2011).

Simulations: different formation paths

Remnants/ellipticals can be classified into 6 different types depending on history



- Gas-rich minor mergers
- Gas-rich major mergers
  - differences in inclin.
- Gas-poor major mergers
  - differences in inclin.
- Gas-poor minor mergers



- Fast rotators
- Slow rotators

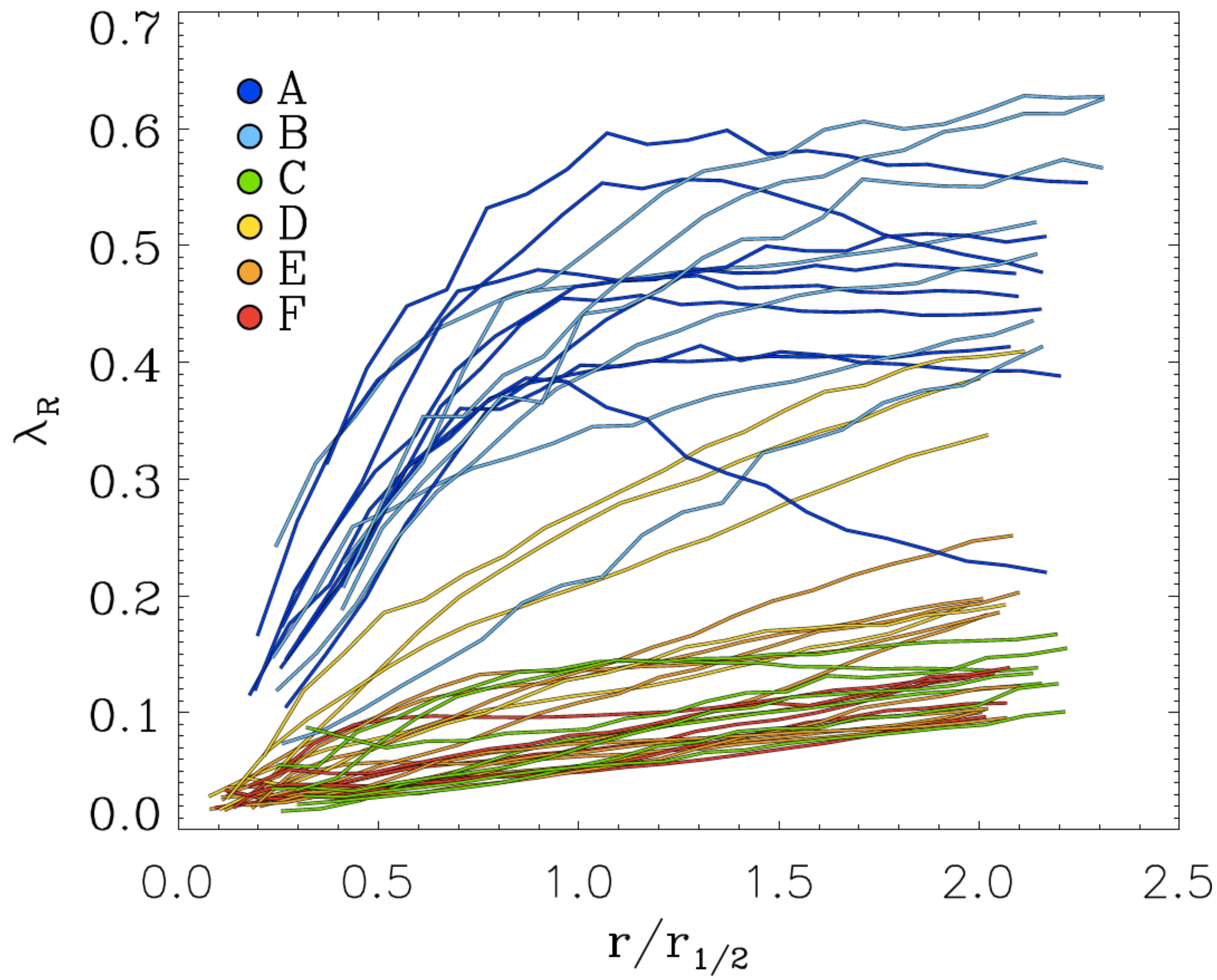


Figure 5. λ_{R} profiles for the simulated central galaxies up to two half-mass radii sorted by their assembly class. The profiles of class A (dark blue) peak at radii $\lesssim r_{\mathrm{e}}$ with no further increase whereas class B profiles (light blue) continuously increase, similar to class D. The slow rotators (classes C: green, E: orange F: red) have flat or slowly rising profiles. The amplitudes of λ_{R} as well as the characteristic profile shapes are in agreement with observed early-type galaxies (Emsellem et al. 2004, 2011).

Naab et al. 2013

Simulations: different formation paths

- Remnants/ellipticals can be classified into different types depending on history

- **Class A**: Fast rotators resulting from *gas-rich minor mergers* and gradual dissipation.
  - Late ($z < 2$) assembly histories dominated by minor (occasionally early major) mergers and a significant amount (up to 40 per cent) of central in-situ, dissipative, star formation
  - Regular fast rotators with $0.26 < \lambda_R < 0.6$ and edge-on ellipticities: 0.3 - 0.55 .

- **Class B**: Fast rotators with *late gas-rich major mergers*
  - Similar to class A, in class B has involved significant in-situ star formation
  - Galaxies have experienced a late gas-rich major merger leading to a net spin-up of the merger remnant or leaving a previously rapidly rotating system unchanged
  - λ_R values and ellipticities in same range as class A but λ_R profiles are rising beyond $r_{1/2}$

- **Galaxies of class A** and **class B** have the youngest mass-weighted stellar populations (9.5 Gyrs)

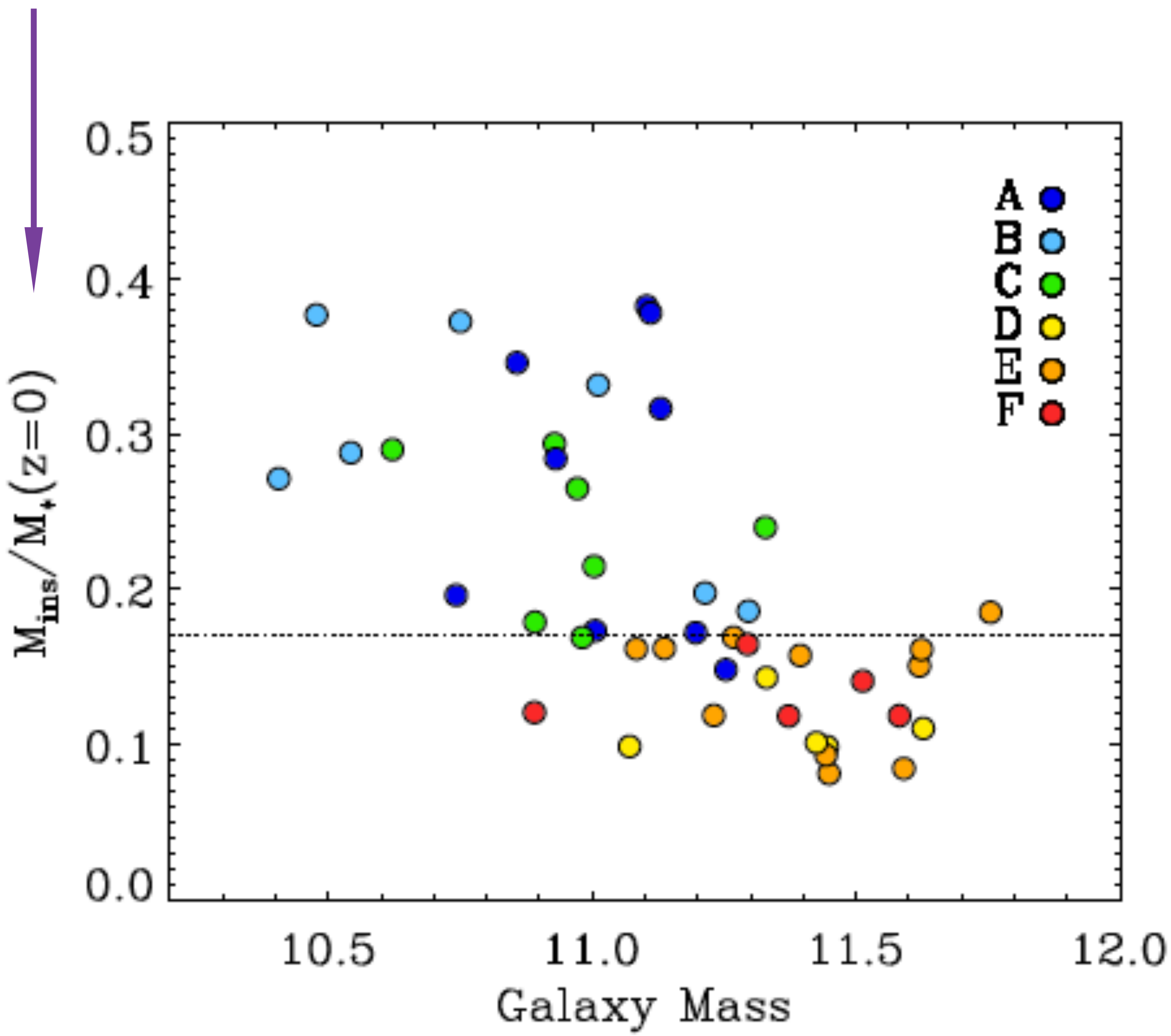
- **Class C**: Slow-rotators with *late gas-rich major mergers*.
  - All galaxies that have experienced a late gas-rich major merger leading to a spin-down of remnant or leaving spin of a slowly rotating progenitor unchanged.
  - High in-situ fractions (similar to classes A and B) with typical central depressions in the stellar velocity dispersion. This feature originates from stars that have formed from gas driven to the center of the galaxy during the merger

- **Class D**: Fast-rotators with *late gas-poor major mergers*.
  - All galaxies in this class have, in addition to minor mergers, experienced a recent collisionless major merger leading to significant spin-up of remnant or leaving the properties of a previously fast rotating galaxy unchanged
  - $0.1 < \lambda_R < 0.3$

- **Class E**: Elongated slow-rotators with *late gas-poor major mergers*.
  - Galaxies have, in addition to minor mergers, undergone at least one recent recent major merger which has lead to a significant spin-down of the remnant or has only mildly changed the properties of a previously slowly rotating galaxy
  - Their late assembly involved little dissipation
  - Slowly rotating $\lambda_R < 0.19$ with slowly rising profiles.
  - Ellipticities are significantly higher than for galaxies in class C (which have similar merger histories but more dissipation) with values from 0.3 to 0.55.
  - The properties are consistent with results from binary collisionless major merger simulations with remnants that are slowly rotating but have a prolate shape and, occasionally, show strong kinematic twists

- **Class F**: Round slow-rotators with *gas-poor minor mergers only*.
  - The $z < 2$ assembly history is dominated by stellar minor mergers without any major mergers
  - little in-situ star formation
  - Galaxies of this class have the lowest angular momentum $\lambda_R < 0.09$ with almost featureless velocity fields
  - Among the roundest galaxies with values < 0.27

Stellar mass fraction formed in situ



Naab et al. 2013

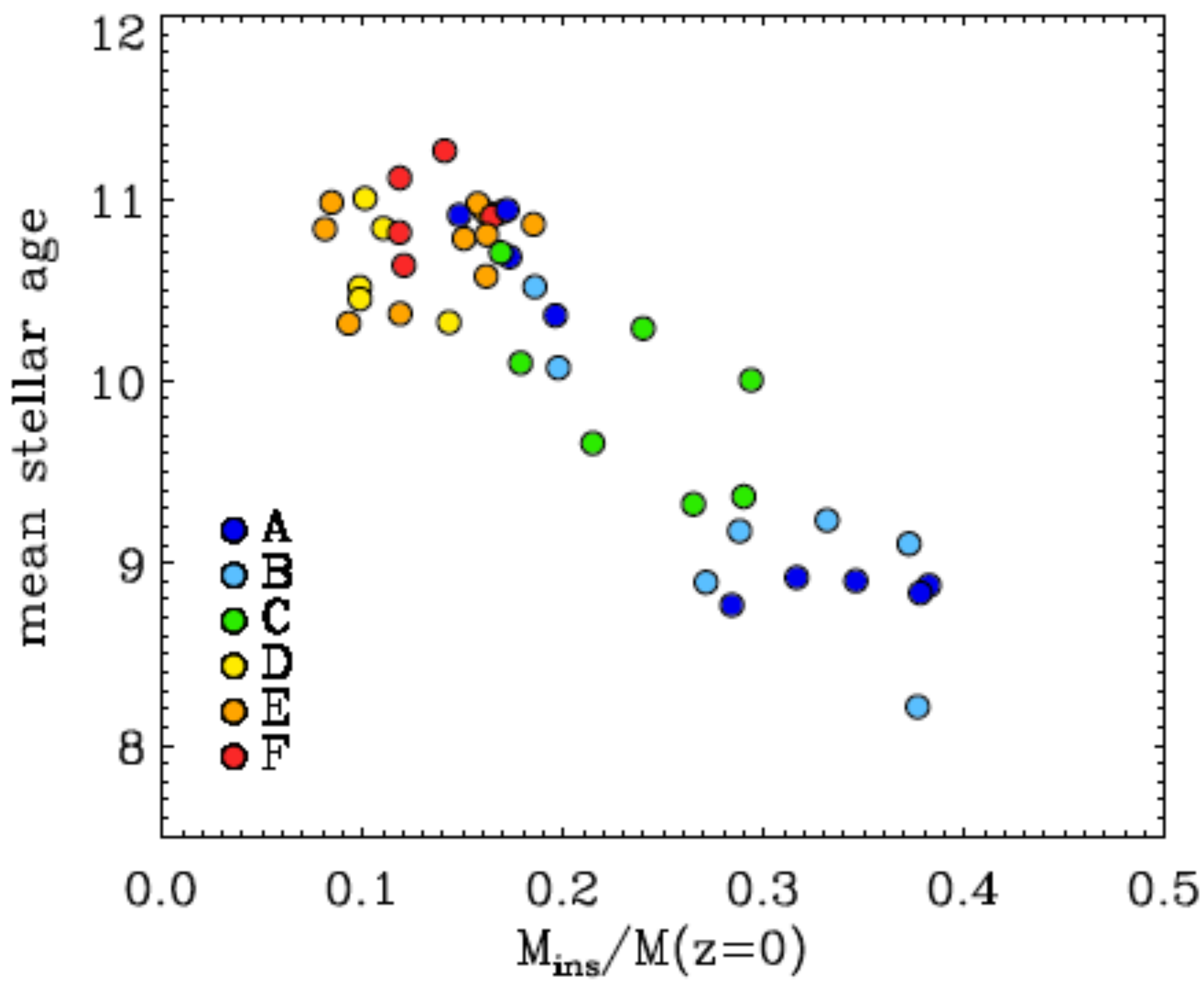


Figure 8. Mass-weighted stellar ages of the central galaxies versus the fraction of stars formed in-situ, $M_{\rm ins}$, since $z = 2$. Galaxies of assembly classes D, E, and F with predominantly dissipationless recent assembly histories (see Fig. 4) are consistently old (~ 10.7 Gyrs). As expected galaxies of classes A, B, and C (whose late assembly involves more dissipation, see Fig. 4) in general are younger and show a larger spread in age (some have ages similar to classes D, E, and F, some are as young as ~ 8.5 Gyrs).

Table 2. Properties of galaxy classes

Class (1)	M_* (2)	λ_R (3)	λ_R-profile (4)	ϵ (5)	M_{ins}/M_* (6)	$\langle age \rangle$ (7)	Mergers (8)	h_3 - v/σ (9)	map-features
A	11	0.45	peaked	0.45	0.27	9.7	mj & mi	strong	dumbbell
B	8.7	0.47	rising	0.45	0.29	9.3	mj & mi	strong	discs
C	10	0.10	flat	0.31	0.24	9.9	mj & mi	no	dispersion dip
D	26	0.23	rising	0.36	0.11	10.6	mj & mi	very weak	fast rotation
E	29	0.11	slowly rising	0.43	0.14	10.7	mj & mi	no	slow rotation
F	24	0.08	flat	0.27	0.13	10.9	mi only	no	no rotation

Note. — (1): Assembly class as discussed in the text. (2): Mean stellar mass inside R_{10} in $10^{10} M_\odot$. (3): Mean value of λ_R. (4): Shape of the λ_R-profile. (5): Mean ellipticity. (6): Mean in-situ mass fraction; dissipative assembly for galaxies with a fiducial value larger than 18 per cent. (7): Mean mass-weighted stellar age in Gyrs. (8): Mergers relevant for galaxy assembly; mj: major mergers, mi: minor mergers. (9): Strength of the anti-correlation between h_3 and v/σ. (10): Special features in the kinematic maps.