GRAPE-SPH シミュレーションによる楕円銀河の形成と進化

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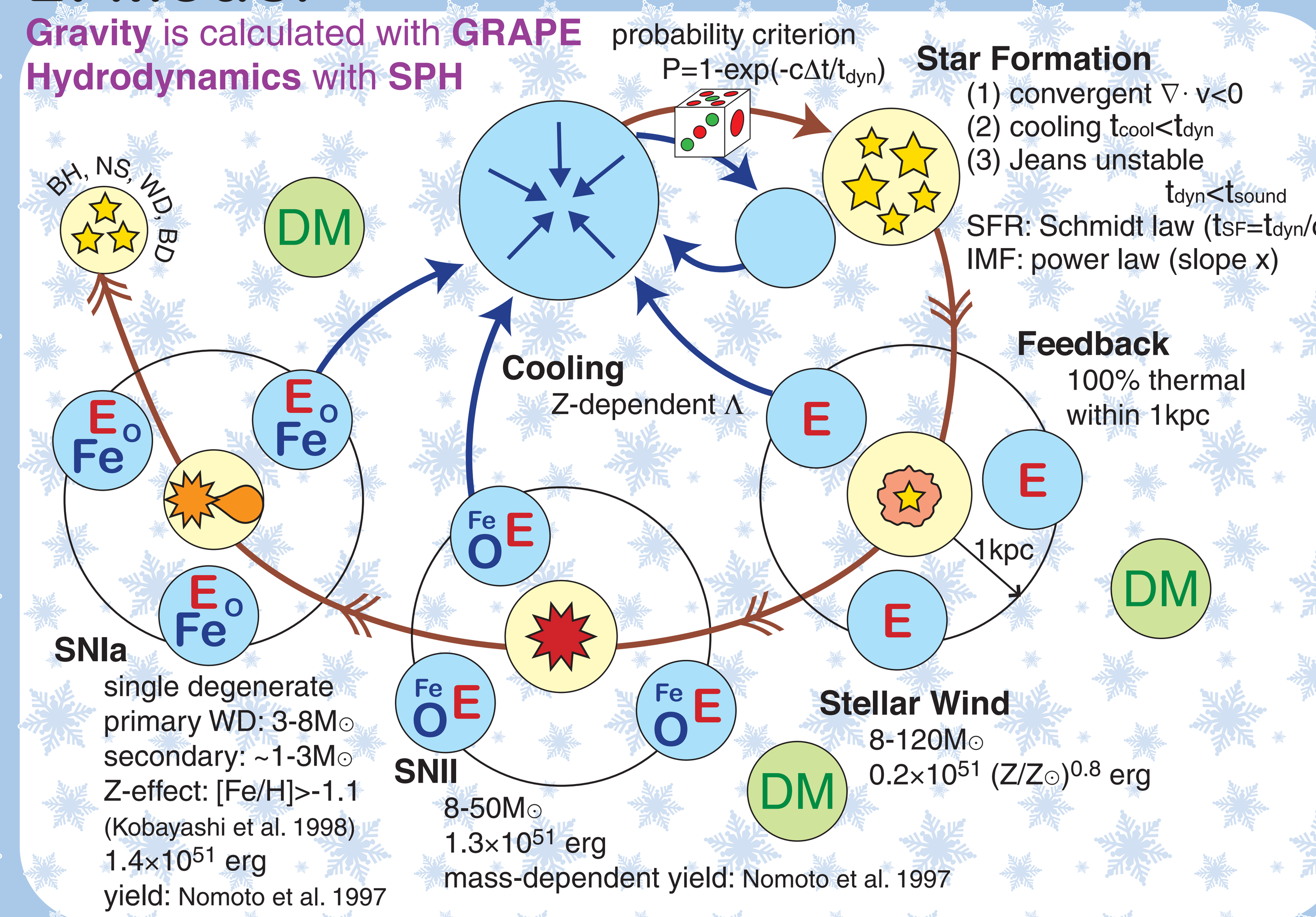
1. Abstract

How elliptical galaxies form and evolve? Two scenarios, monolithic collapse vs. disk-disk merger, have been debated. We simulate the formation and chemodynamical evolution of 128 elliptical galaxies (Es) from the CDM initial fluctuation, using a GRAPE-SPH code that includes various physical processes that are associated with the formation of stellar systems: radiative cooling, star formation, feedback from Type II and Ia supernovae (SNe II and Ia) and stellar winds, and chemical enrichment. In our CDM-based scenario, galaxies form through the successive merging of subgalaxies with various masses. Their merging histories vary between a major merger at one extreme, and a monolithic collapse of a slow-rotating gas cloud at the other extreme.

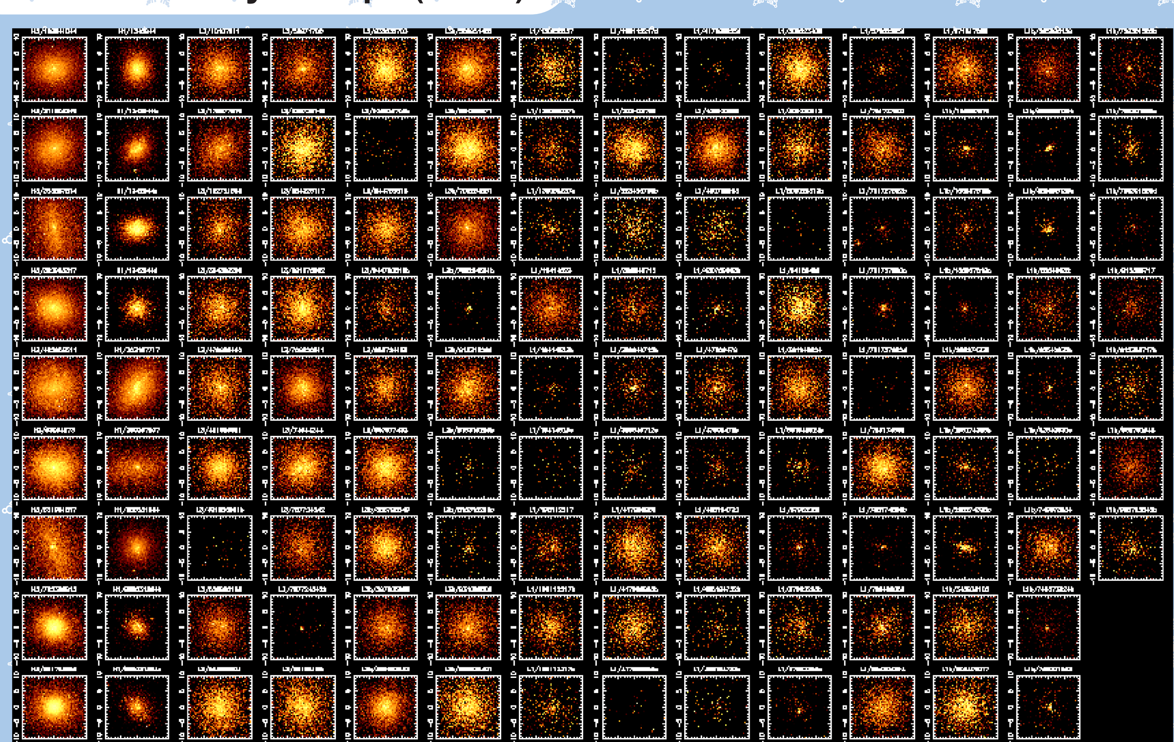
We succeed in reproducing (1) the observed variety of internal structure, e.g., radial metallicity gradients (Kobayashi 2004, MNRAS, 347, 740). The average metallicity gradient $\Delta\log Z/\Delta\log r \cong -0.3$ with dispersion of ± 0.2 and no correlation between gradient and galaxy mass are consistent with observations of Mg2 gradients. The variety of the gradients stems from the difference in the merging histories. Galaxies that form monolithically have steeper gradients, while galaxies that undergo major mergers have shallower gradients.

We also reproduce (2) the observed scaling relations among global properties, e.g., the Faber-Jackson relation, the Kormendy relation, and the fundamental plane (Kobayashi 2005, MNRAS, 361, 1216). An intrinsic scatter exists along the fundamental plane, and the origin of this scatter lies in differences in merging history. Galaxies that undergo major merger events tend to have larger effective radii and fainter surface brightnesses, which result in larger masses, smaller surface brightnesses, and larger mass-to-light ratios.

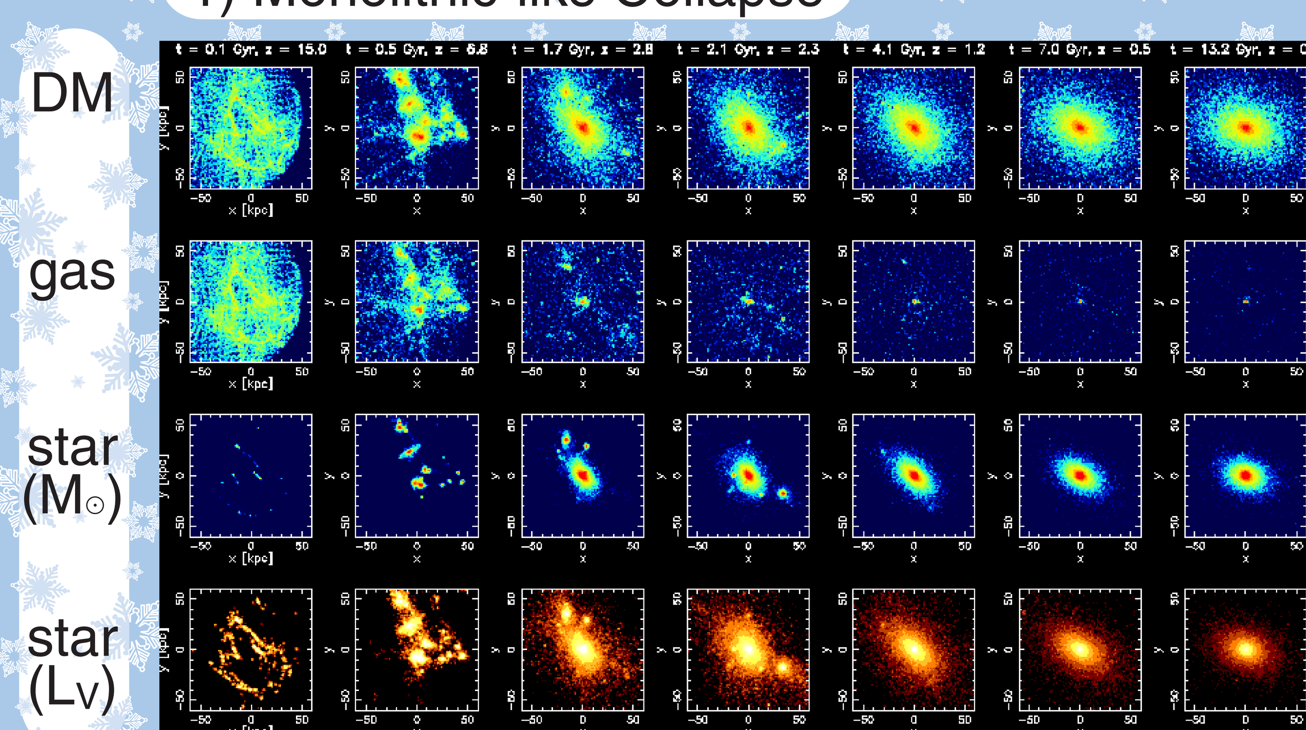
2. Model



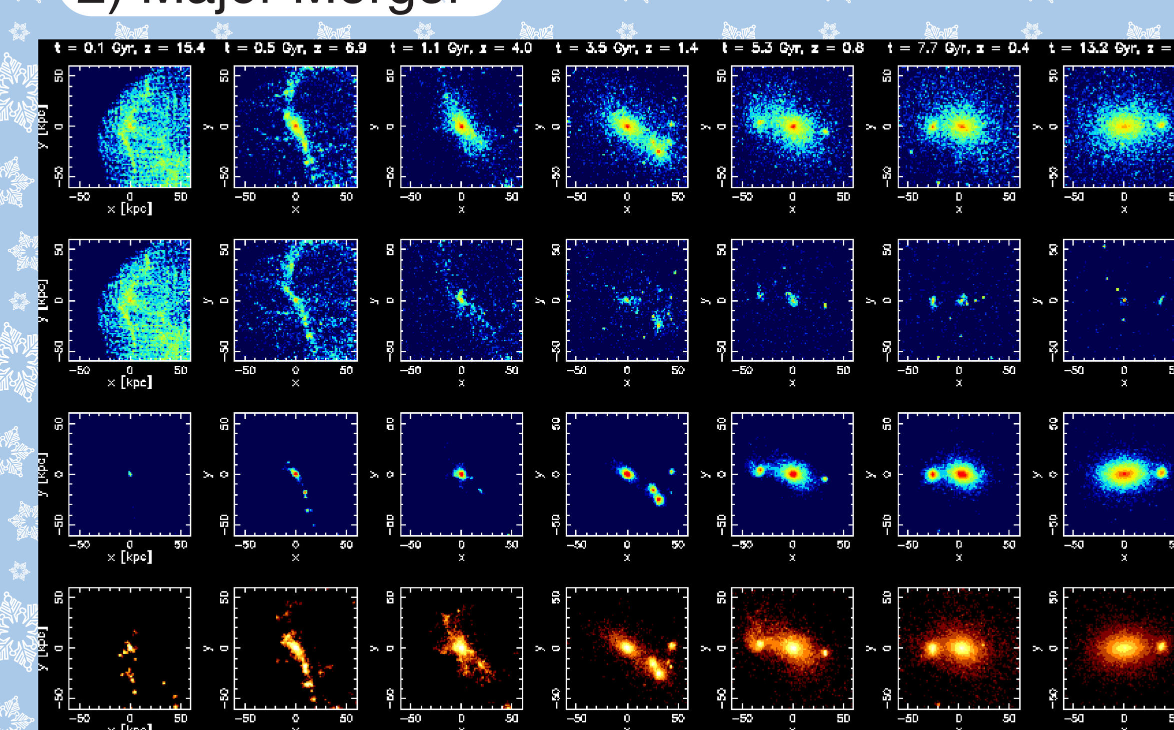
V-luminosity Map (z=0)



1) Monolithic-like Collapse → time



2) Major Merger → time



3. Initial Condition

- cosmological initial condition with GRAFIC (Bertschinger 1995)
- $H_0=50$, $\Omega_0=1.0$, $\lambda_0=0.0$, $\sigma_8=1$, $z_c\sim25$, 1-3σ
- a sphere with r, M_{tot} (baryon fraction=0.1) and N_{tot} (the half for gas)
- $m_{gas}\sim10^{6\text{-}7}$ M⊙, $m_{DM}\sim10^{7\text{-}8}$ M⊙
- small rotation: spin parameter $\lambda\sim0.02$

	r [Mpc]	M [M⊙]	N_{tot}	run
H	1.5	1×10^{12}	60000	13
L	1.5	1×10^{12}	10000	52
cD	3	6×10^{12}	60000	9

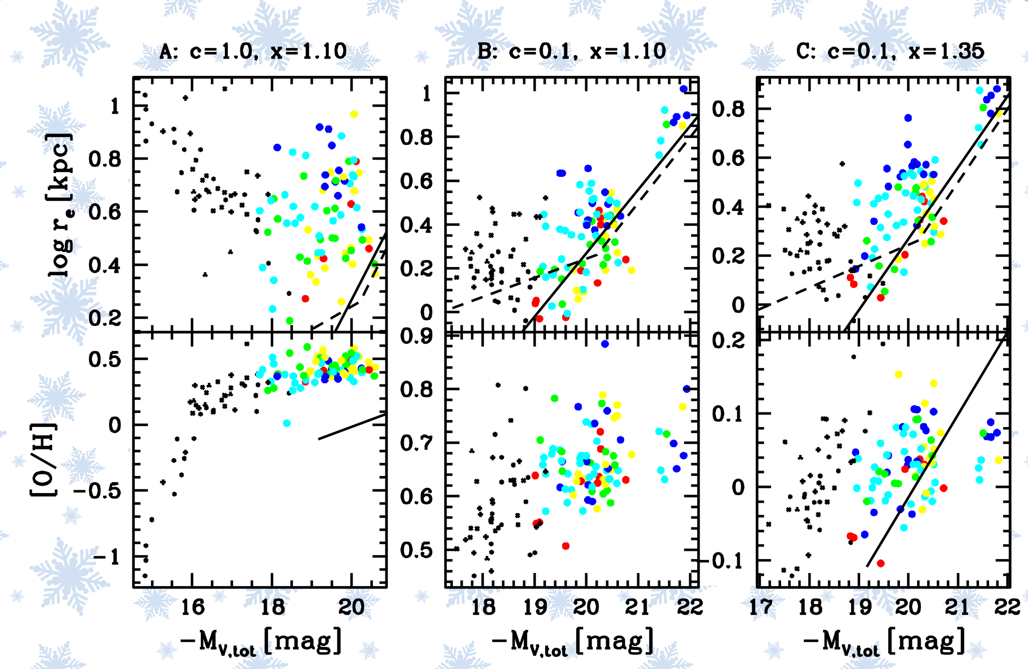
All Es formed by the starburst at z>2, and have de Vaucouleurs SB profiles.
Note that Es formed by a major merger with large λ are not included in our sample.

4. Scaling Relations

We simulate 3 sets of parameters for all run.
- star formation timescale ($t_{SF}=t_{dyn}/c$)
- initial mass function (slope x)

The obtained galaxy numbers and merging histories are slightly different.

model	c	x	Ellipticals	Dwarfs
A:	1.0	1.10	78	46
B:	0.1	1.10	91	53
C:	0.1	1.35	86	43

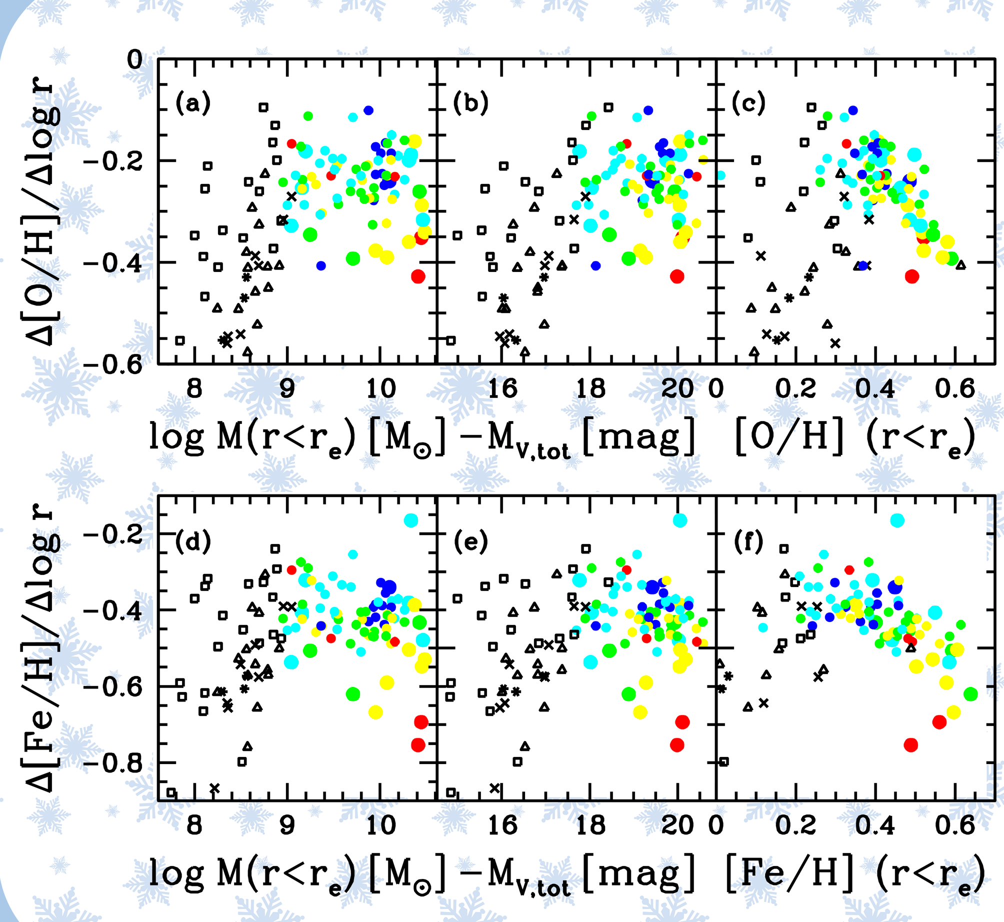


With model A (left), galaxies are too extended and too metal-rich. With model B (middle), the radius becomes smaller by a factor of 3, which agrees with the observation. But the metallicity is still too high. With model C (right), the radius-magnitude relation remains good, and the metallicity decreases to meet the observations.

The hydrodynamical simulation including star formation involves an uncertainty that is how to determine the star formation parameter c. We show here that it can be constrained from the scaling relation. Because the star formation timescale controls when and where stars form in a contracting gas cloud in a dark matter halo, the star formation timescale determines not only the ages of stars, but also the size of the galaxy.

From the observed radius-magnitude relation, the local star formation timescale is constrained to be ten times longer than the dynamical timescale. The global star formation timescale is found to be 1-2 Gyr, which is longer than 0.1 Gyr commonly adopted in one-zone models.

5. Metallicity Gradients

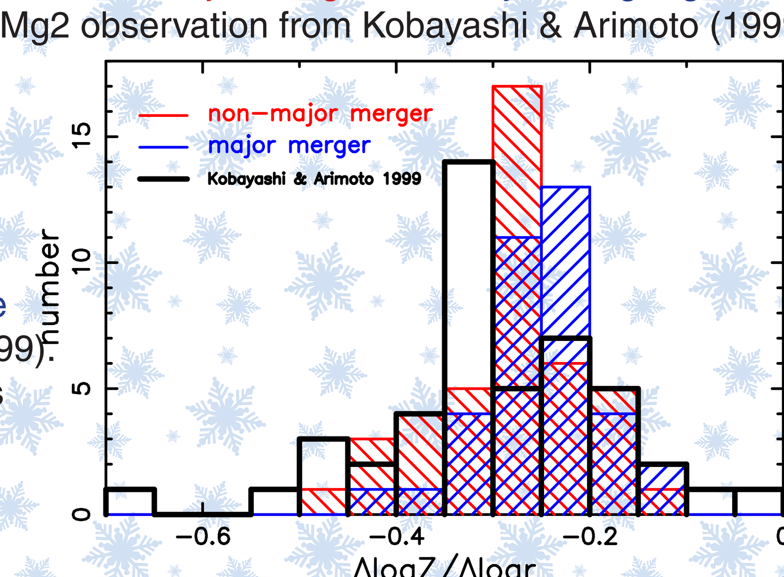


The basic processes during merging events driving the evolution of the metallicity gradients are:
i) destruction by mergers to an extent dependent on the progenitor mass ratio, which means merger galaxies have flatter gradients.
ii) regeneration when strong central star formation is induced at a rate dependent on the gas mass of the secondary, which is not effective.
iii) slow evolution as star formation is induced in the outer regions through late gas accretion.

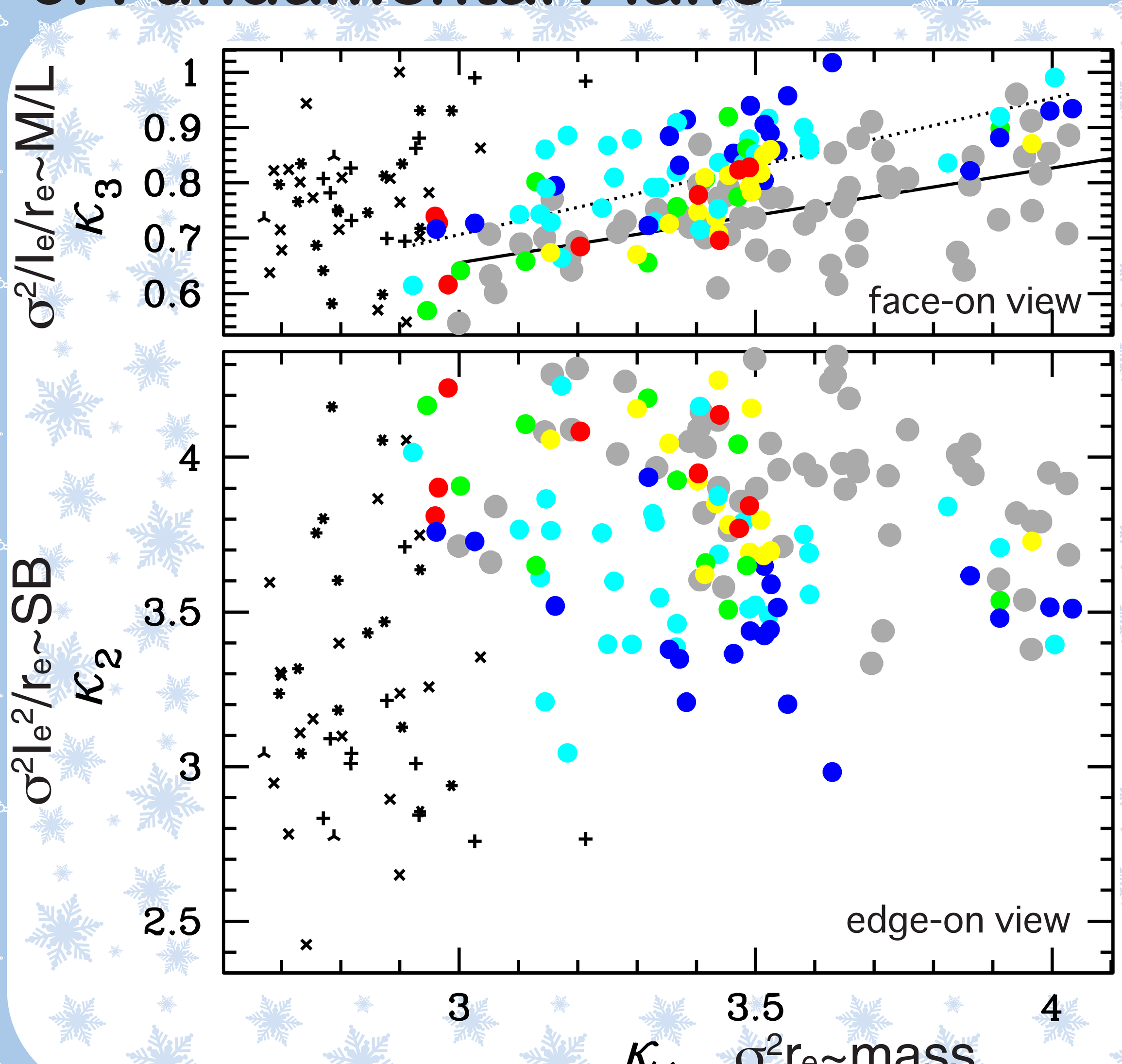
- monolithic
- assembly
- semi-merger
- merger
- double merger
- dwarfs

Histograms of the metallicity gradients.
The red and blue area are for non-major merger and major merger galaxies.
The thick lines show the Mg2 observation from Kobayashi & Arimoto (1999).

We succeed in reproducing the observed average (-0.3) and dispersion (-0.8 to 0) of the metallicity gradients (Kobayashi & Arimoto 1999). No correlation between gradients and masses or luminosities. The origin of scatter lies in differences of merging histories.



6. Fundamental Plane



An intrinsic scatter exists along the fundamental plane, and the origin of the scatter in the simulation lies in differences in merging history. Galaxies that undergo major mergers tend to have larger effective radii and fainter surface brightnesses, which result in larger κ_1 (mass), smaller κ_2 (surface brightness), and larger κ_3 (mass-to-light ratio).

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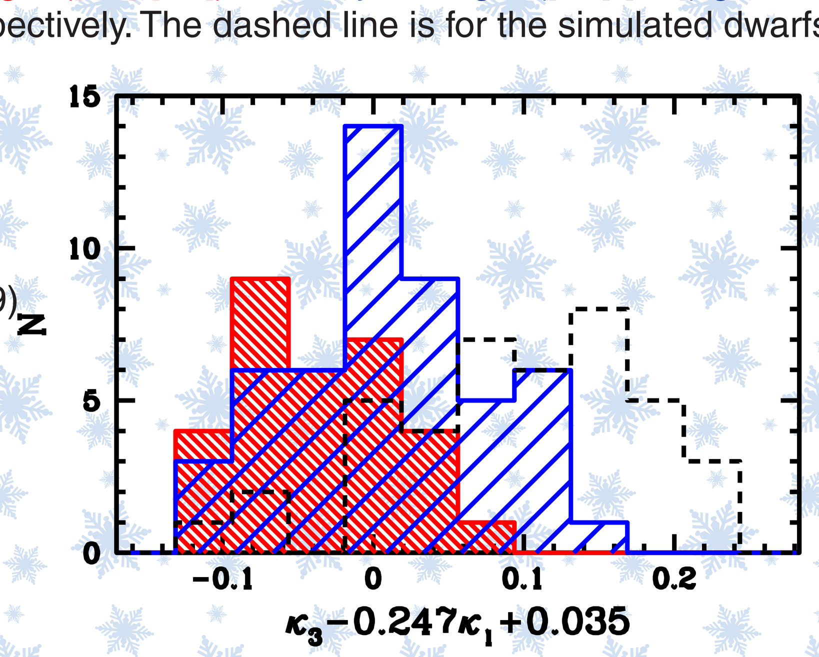
gray points & solid line: observation (Pahre 1999)

Histograms of the deviations from the fundamental plane. The red and blue areas are for the simulated non-major merger ([E1]-[E3]) and major merger ([E4]-[E5]) galaxies, respectively. The dashed line is for the simulated dwarfs



7. Origin of Ellipticals

The origin of elliptical galaxies can be understood under the CDM picture. Galaxies form through the successive merging of subgalaxies with various masses. Their merging histories vary between a major merger at one extreme, and a monolithic collapse of a slow-rotating gas cloud at the other extreme.

The majority of stars formed in a initial star burst at z>2, and the star formation during merging events is small.

Internal structure such as metallicity gradients is greatly affected by merging histories, while the global properties are determined from overall masses according to the scaling relations.

Merging histories can, in principle, be inferred from the observed metallicity gradients of present-day galaxies.

The small scatter along the fundamental plane is caused by the differences in merging history.