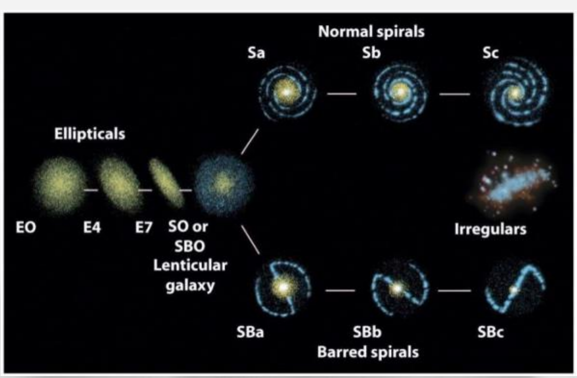
Galactic dynamics and models of galaxies

Tirawut Worrakitpoonpon

at IF-SUT School, Phitsanulok
19th February 2023

Hubble sequence



Galaxy can be classified by ***Hubble sequence*** (or Hubble's tuning-fork diagram). From left to right, galaxies are identified as ***early type*** to ***late type***.

- E = Elliptical
- S = Spiral
- S0, SB0 = Lenticular
- Irr = Irregular

cr: https://www.physast.uga.edu/~rls/

Elliptical galaxies

Surface brightness of elliptical galaxies along the axis can be fitted by ***de Vaucouleurs law*** (or ***R***$^{1/4}$ ***law***)

$$I(R) = I_e e^{\{-7.67[(R/R_e)^{1/4}-1]\}}$$

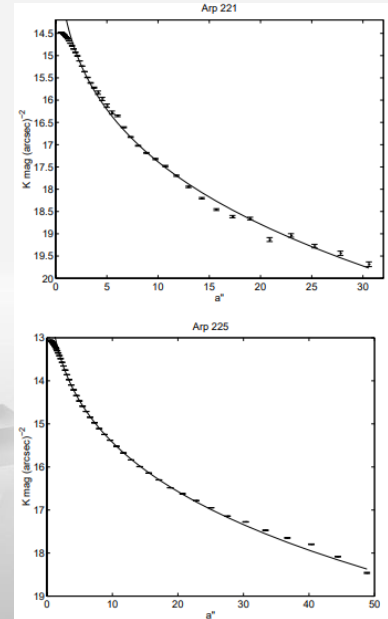
where R_e= effective radius

I_e= constant.

de Vaucouleurs profile can be generalized to ***Sersic profile***

$$I(R) = I_e e^{\{-b_n[(R/R_e)^{1/n}-1]\}}$$

where $b_n \approx 2n - \frac{1}{3}$. Note that the situation for cD or dwarf galaxies is different.



Surface brightness and de Vaucouleurs profile

cr: Chitre & Jog (2002) A&A

Elliptical galaxies

Central velocity dispersion of massive elliptical galaxies exhibits simple scaling known as ***Faber-Jackson relation***

$$L \propto {\sigma_0}^4$$

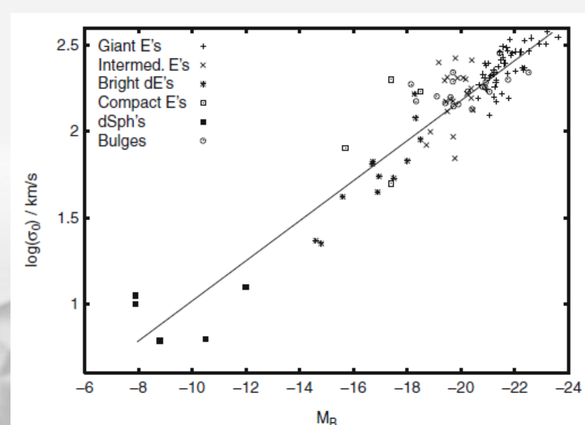
where L = luminosity

σ_0 = central velocity dispersion.

Note that

$$\mathcal{M} \propto \log(L)$$

where $\mathcal{M}$ = absolute magnitude.



Faber-Jackson relation in various elliptical systems

cr: Bender et al. 1992, ApJ

Elliptical galaxies

Elliptical galaxies exhibits great varieties in size, spectrum, luminosity due to different origins. Rough classification is as follow

- Normal elliptical (E or gE)
- Dwarf elliptical (dE): small mass and low luminosity
- cD elliptical: very luminous and large in the center of galaxy cluster
- Blue compact dwarf elliptical (BCD): with many young blue star.
- Dwarf spheroidal elliptical (dSph): dwarf close to spheroidal

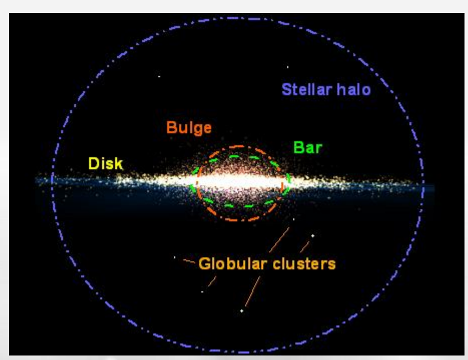
Table 3.1 Characteristic values for early-type galaxies

	S0	cD	E	dE	dSph	BCD
M_B	-17 to -22	-22 to -25	-15 to -23	-13 to -19	-8 to -15	-14 to -17
M ($M_\odot$)	10^{10}–10^{12}	10^{13}–10^{14}	10^{8}–10^{13}	10^{7}–10^{9}	10^{7}–10^{8}	$\sim 10^{9}$
D_{25} (kpc)	10–100	300–1000	1–200	1–10	0.1–0.5	<3
$\langle M/L_B \rangle$	~ 10	>100	10–100	1–10	5–100	0.1–10
$\langle S_N \rangle$	~ 5	~ 15	~ 5	4.8 ± 1.0	–	–

Spiral galaxies

In general, major components of elliptical galaxies include

- Disk: flattened component where spiral arms or bar reside.
- Bulge: central ellipsoidal component.
- Halo: extended envelop.



Components of spiral (or lenticular) galaxy

cr: https://kof.zcu.cz/st/dis/schwarzmeier/

Spiral galaxies

Galactic bulge follows de Vaucouleurs profile similar to elliptical galaxy, i.e.

$$I_{bulge}(R) = I_e e^{\{-7.67[(R/R_e)^{1/4}-1]\}}.$$

where R_e= effective radius

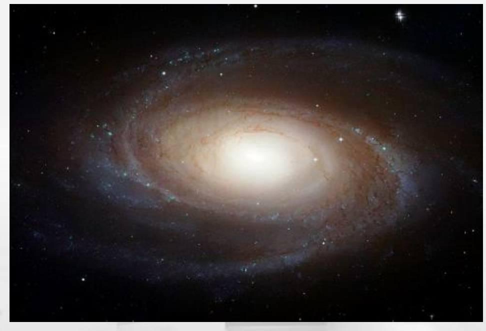
I_e= constant.

Galactic disk brightness follows exponential profile, i.e.

$$I_{disk}(R) = I_d e^{-(R/R_d)}$$

where R_d = disk scale length

I_d = constant.



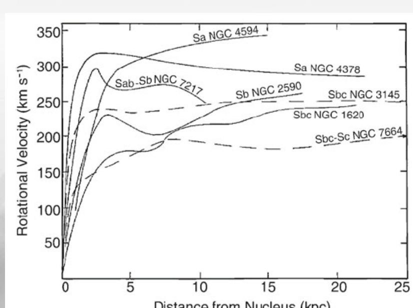
M81

cr: https://kof.zcu.cz/st/dis/schwarzmeier/

7

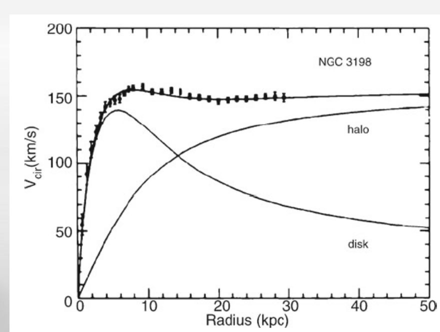
Spiral galaxies

Rotation curve of spiral galaxies is flat at large distance. This implies the embedding dark matter.



Rotation curve of spiral galaxies

cr: Rubin et al. (1978) ApJ



Reconstruction of rotation curve

cr: van Albada et al. (1985) ApJ

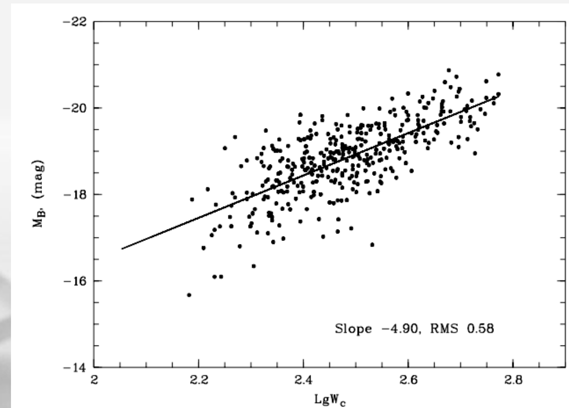
8

Spiral galaxies

Maximum rotational velocity correlates with luminosity (i.e. ***Tully-Fisher relation***)

$$L \propto {v_{max}}^{\alpha}$$

where $\alpha \sim 4$.



Tully-Fisher relation

cr: Karachentsev et al. (2002) A&A

9

Spiral galaxies

Distinction from Sa to Sc is mainly from bulge fraction and opening angle of spiral arms.

Table 3.2 Characteristic values for spiral galaxies

	Sa	Sb	Sc	Sd/Sm	Im/Ir
M_B	−17 to −23	−17 to −23	−16 to −22	−15 to −20	−13 to −18
M ($M_\odot$)	10^9–10^{12}	10^9–10^{12}	10^9–10^{12}	10^8–10^{10}	10^8–10^{10}
$\langle L_{bulge}/L_{tot}\rangle_B$	0.3	0.13	0.05	–	–
Diam. (D_{25},kpc)	5–100	5–100	5–100	0.5–50	0.5–50
$\langle M/L_B\rangle$ ($M_\odot/L_\odot$)	6.2 ± 0.6	4.5 ± 0.4	2.6 ± 0.2	∼ 1	∼ 1
V_{max} range(km s^{-1})	163–367	144–330	99–304	–	50–70
Opening angle	∼ 6°	∼ 12°	∼ 18°	–	–

10

Introduction – Long-range interacting system

Given a *d*-dimensional pair-potential in the form

$$V \propto \frac{1}{r^{\alpha}}$$

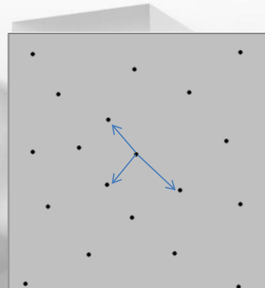
the interaction is classified as

- Short-range interaction (SRI) if $\alpha > d$
- Long-range interaction (LRI) if $\alpha \leq d$

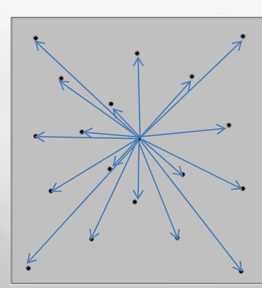
11

Introduction – Long-range interacting system

Potential energy of long-range interacting system diverges as system size goes to infinity, with constant density.



short range



long range

12

Introduction – Long-range interacting system

Current understanding suggests the following relaxation scheme for systems governed by gravity

Initial Condition

→ *Collisionless (or violent) Relaxation*

→ *Dynamical time scale*

Quasi-Stationary State (QSS)

→ *Collisional Relaxation*

→ *Time scale diverging with N*

Thermal Equilibrium

Introduction – Long-range interacting system

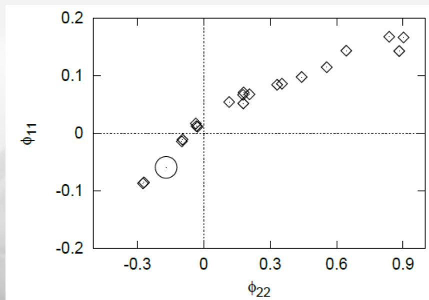
Estimate of violent relaxation time scale using the rate of mean-field fluctuation gives

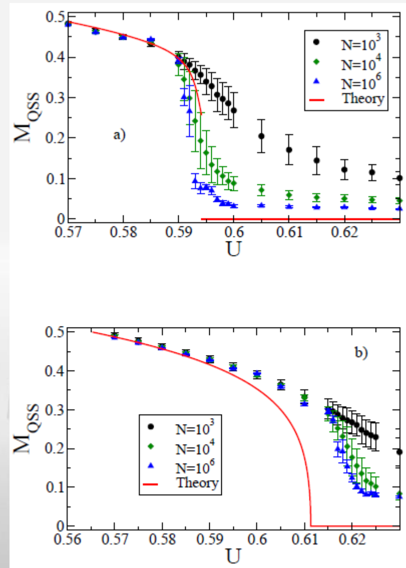
$$\boxed{t_{relax} = \frac{3}{4}\left[\frac{\dot{\Phi}^2}{\Phi^2}\right]^{-\frac{1}{2}} = \frac{3}{\lambda}\sqrt{\frac{3}{32\pi G\bar{\rho}}}}$$

which is of order free-fall time and does not depend on particle number, N.

Typical galaxies have free-fall time of order 10^7-10^8 years.

Diversity of the QSSs





(Antoniazzi et al. 2007)

Introduction – Long-range interacting system

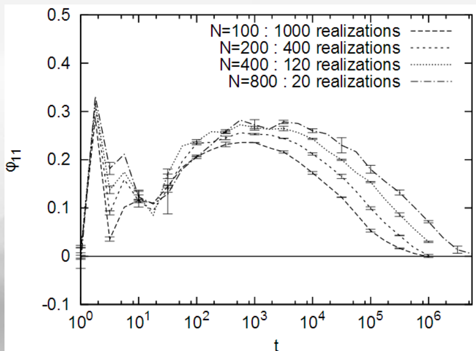
Estimate of collision rate demonstrates that relaxation time scale to thermal equilibrium diverges with particle number, *N*, as

$$t_{relax} \sim \frac{N}{8 \ln N} t_{cross}$$

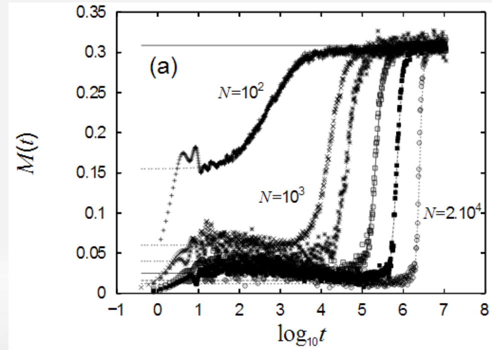
(see Chandrasekhar 1943)

Massive galaxies are currently in quasi-stationary states

Collisional relaxation to thermal equilibrium



1D gravity
(Joyce & Worrakitpoonpon 2010)



HMF model
(Yamaguchi et al. 2004)

17