Evolution of Galaxy Scaling Relations

A Two-Phase Scenario by Redshift

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  - $\sigma - M_*$ Relation
  - $\sigma - z$ Relation

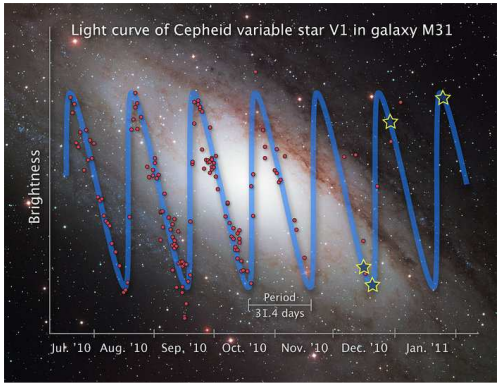
Scaling Relation

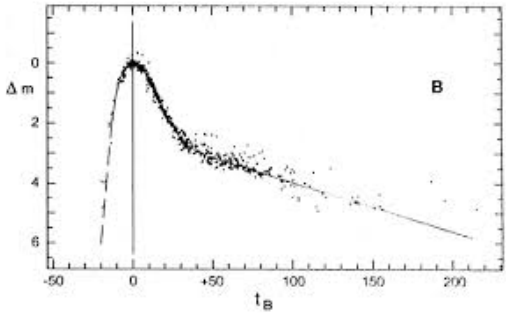
Luminosity Measurement

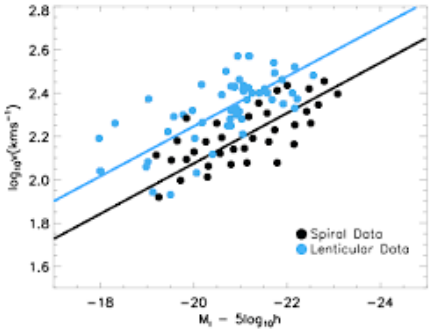
- Luminosity
  - Important Observation Quantity
  → Determination : Distance, Mass

- Standard Candle
  - Cepheid variable
  - Supernova 1a

- Scaling Relation
  - Tully-Fisher relation
  - Faber-Jackson relation







Virial Theorem

- Virialized Condition
  - Equilibrium state : Gravitational Potential Energy & Kinetic Energy

  → No Expansion or No Gravitational Collapse

  → Example) ETGs, Clusters

- Virial Theorem
  - Fundamental relation : $2\langle K\rangle = \langle W\rangle$

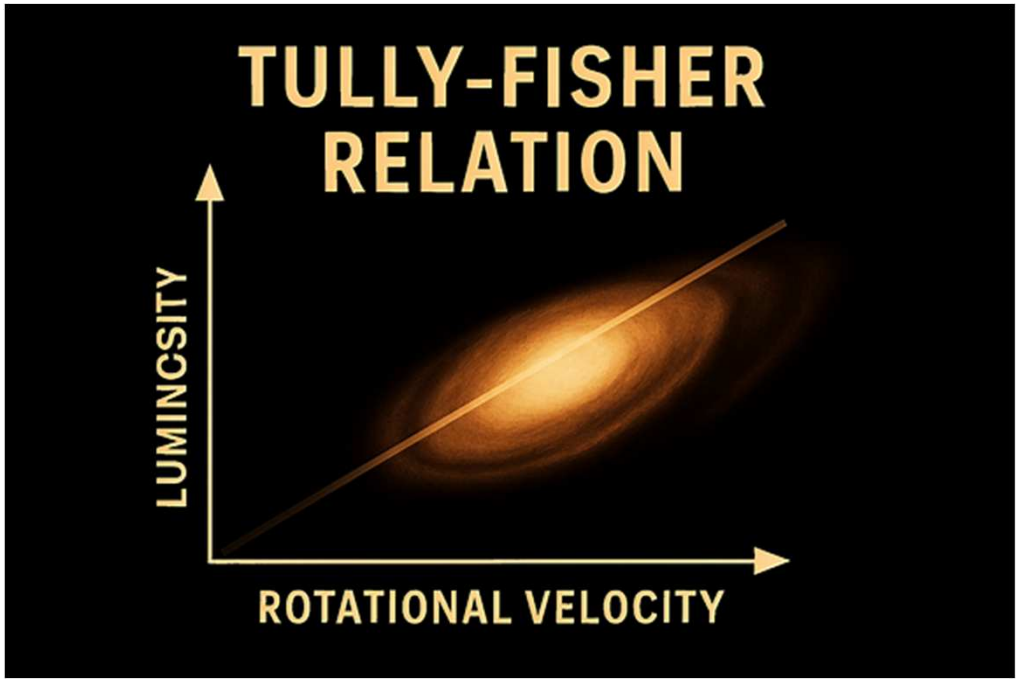
  → $v^2 = \frac{GM}{r}$

- Scaling relation
  - Mass-Velocity Relation by Virial Theorem

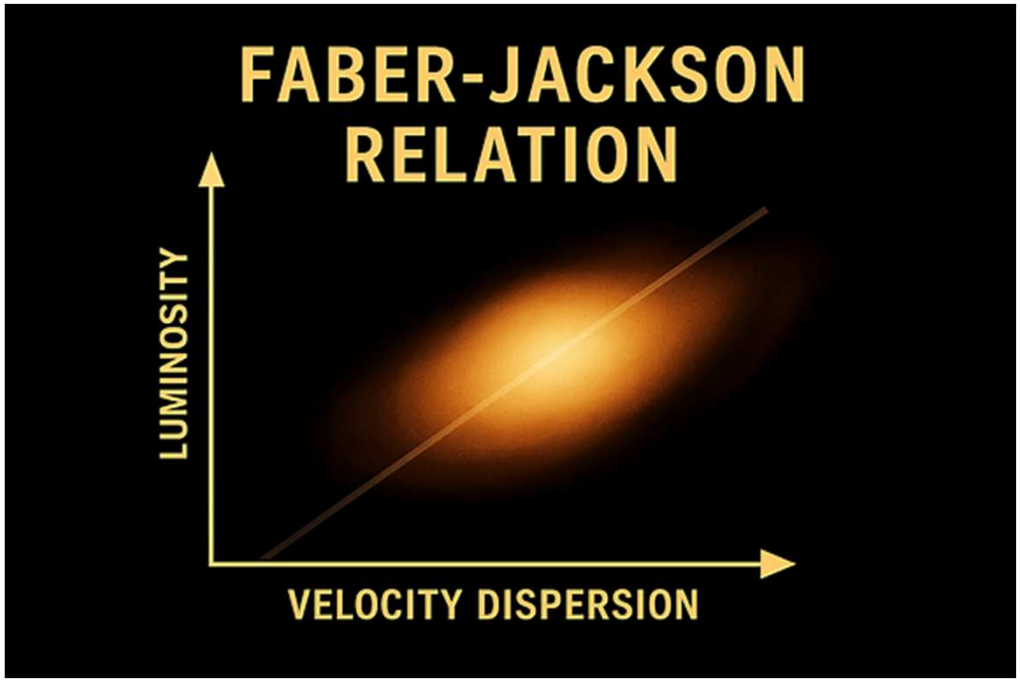
  → Mass to Light ratio : M/L

  → Luminosity-Velocity Relation : Scaling Relation

Scaling Relation



$$\log L \propto \log v_{rot}$$



$$\log L \propto \log \sigma$$

Two-Phase Scenario

Galaxy Formation & Evolution ----------

- Gravitational Collapse
  - Collapse by Density Fluctuation

  → Jeans Instability

- Inflow
  - Baryon Matter

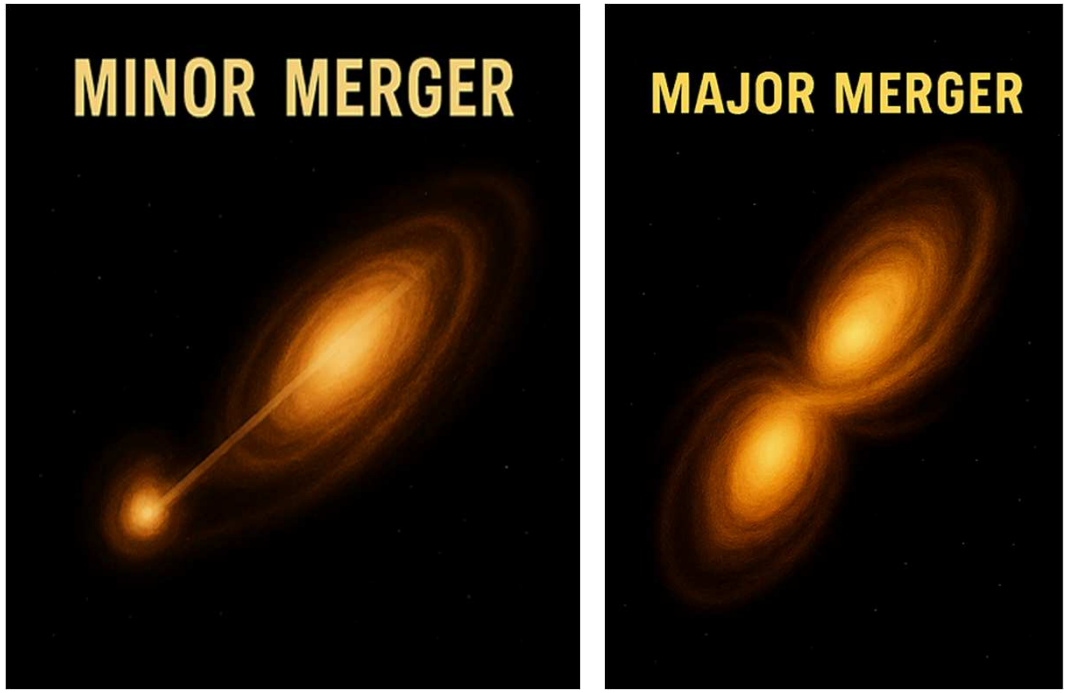
  → Gas
  - Star

- Merger Process
  - Wet Major Merger
  - Dry Minor Merger

Merger Process

- Category
  - By Mass ratio : Major / Minor
  → mass increase ratio : $\eta = \frac{M_a}{M_i}$
  - By Gas fraction : Wet / Dry
  → Effect to Star Formation Rate

- Galaxy Evolution by Merger
  - Velocity Evolution
  : $\frac{{v_f}^2}{{v_i}^2} = \frac{1+\eta\epsilon}{1+\eta}$ $(\epsilon = \frac{{v_a}^2}{{v_i}^2})$
  - Size Evolution
  : $\frac{{r_f}^2}{{r_i}^2} = \frac{1+\eta\epsilon}{1+\eta}$
  → Evolution Change by Merger



Merger Process

- Major Merger
  - Mass ratio = 1 : 4
  - Galaxy Evolution
    : same velocity merge ($\epsilon \approx 1$)

  → Size decrease

  → Velocity Dispersion increase

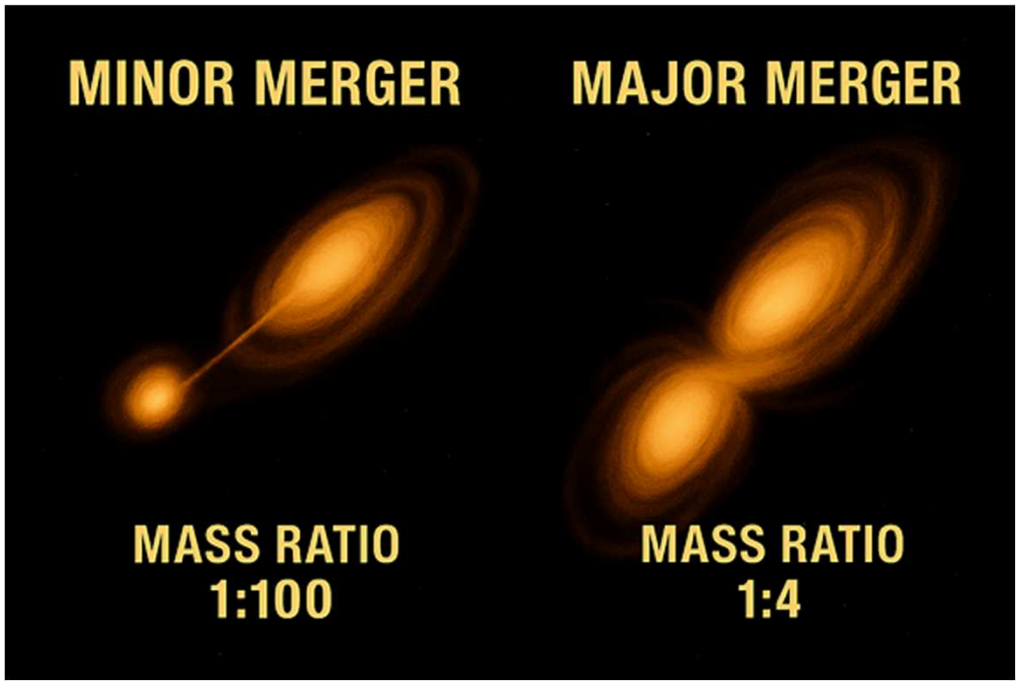
  (for same mass)

- Minor Merger
  - Mass ratio = 1 : 100
  - Galaxy Evolution
    : different velocity merge ($\epsilon \ll 1$)

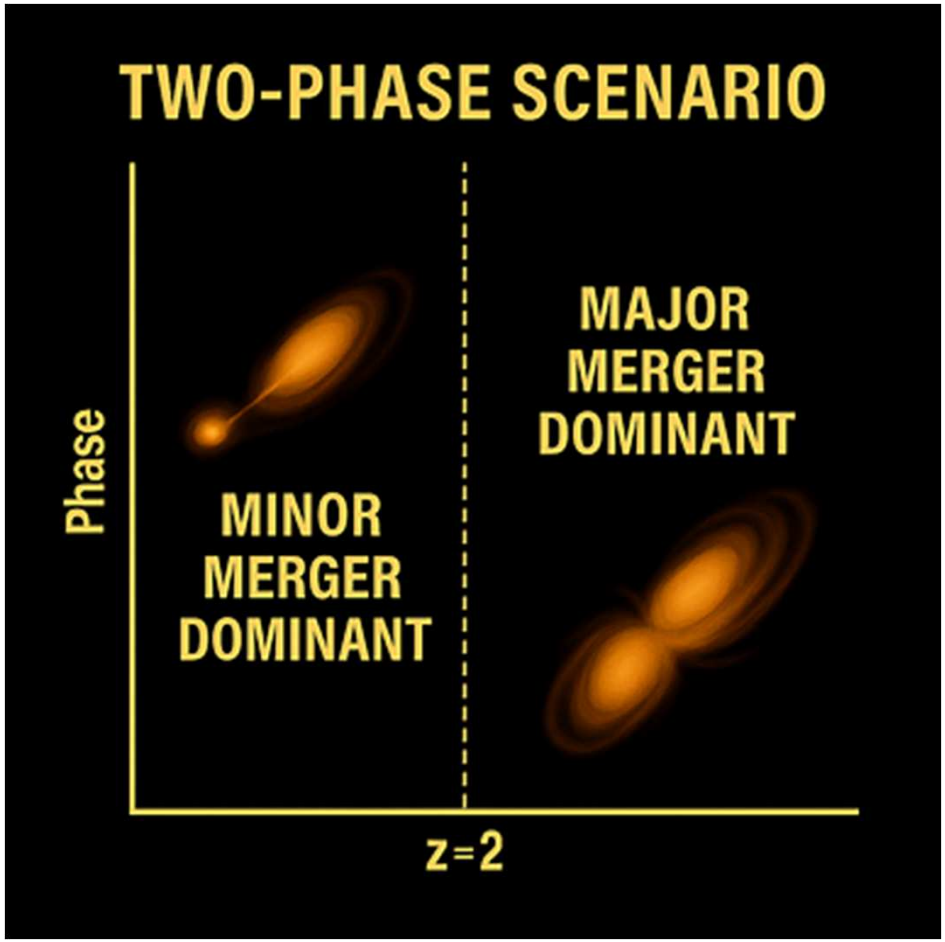
  → Size increase

  → Velocity Dispersion decrease

  (for same mass)



Two-Phase Scenario



Evolution of Scaling Relations Change by Phase

The assembly of stars in massive galaxies

	In-situ	Accreted
Epoch	$6 \gtrsim z \gtrsim 2$	$3 \gtrsim z > 0$
Baryonic mass source	cold gas flows	minor & major mergers
Size of region	$r_{1/2} \approx 2kpc$	$r_{1/2} \approx 7kpc$
Energetics	Dissipational	Conservative

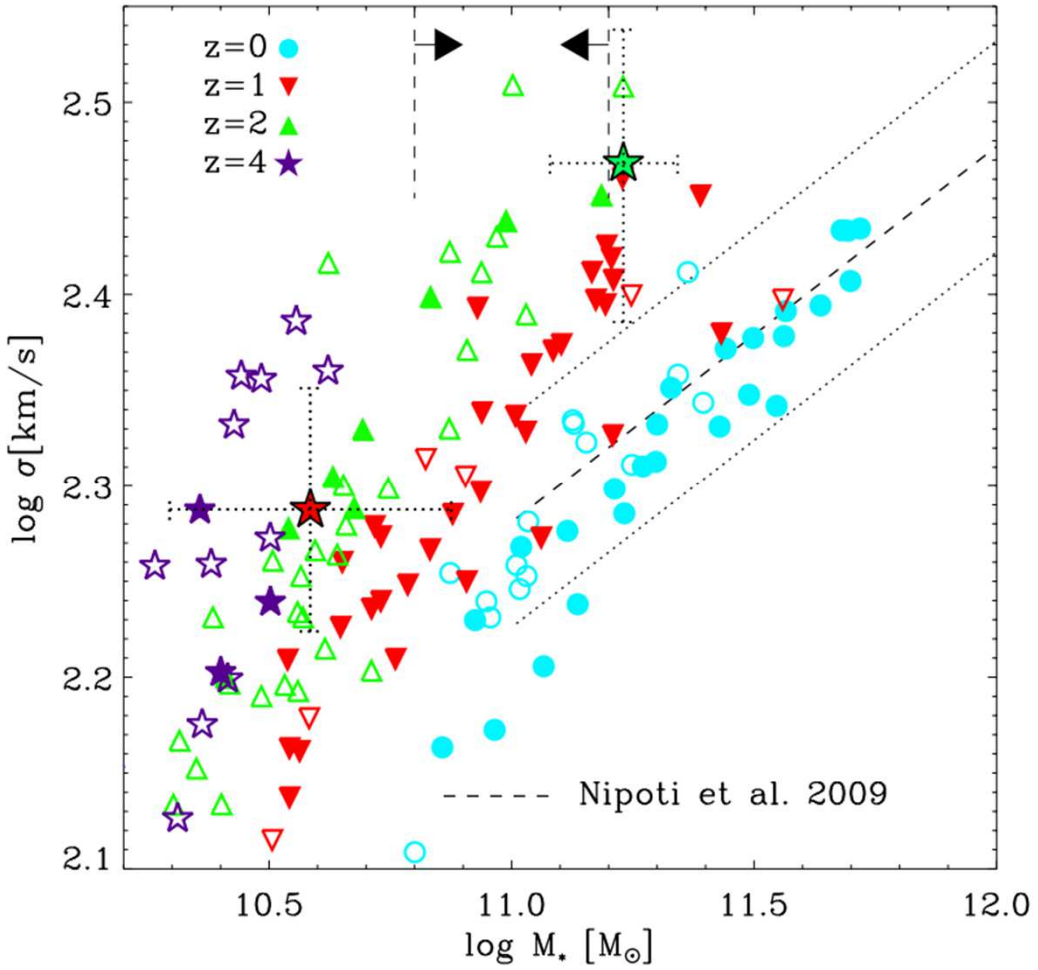
Reference : THE TWOPHASES OF GALAXY FORMATION, Ludwig Oser, 2018

Velocity Dispersion

Data Analysis

- Simulation Results
  - 30 elliptical galaxies
- Observation Results
  - Ludwig Oser's Research
  - Carlo Nipoti's Research
- Replication Study
  - Represent : Ludwig Oser's Research

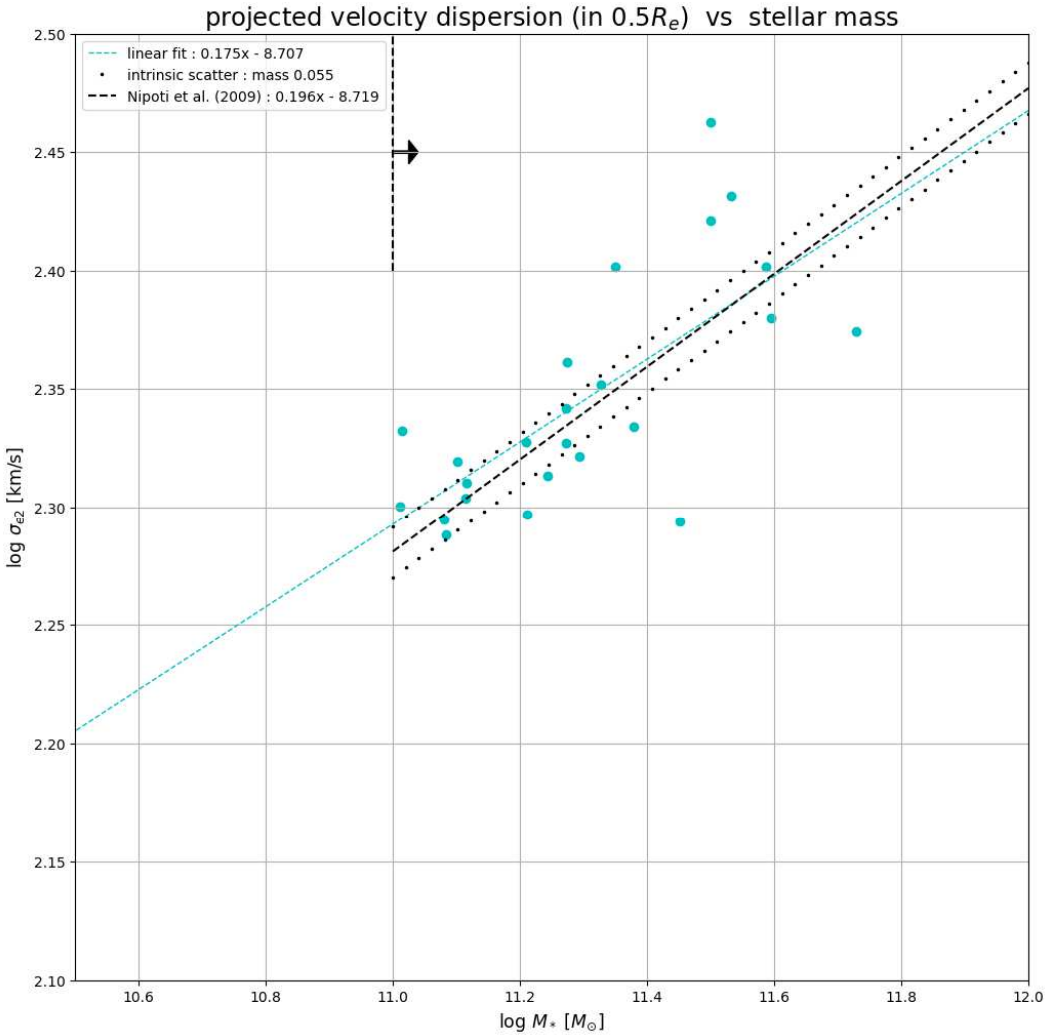
  → 'velocity dispersion – stellar mass' relation evolution



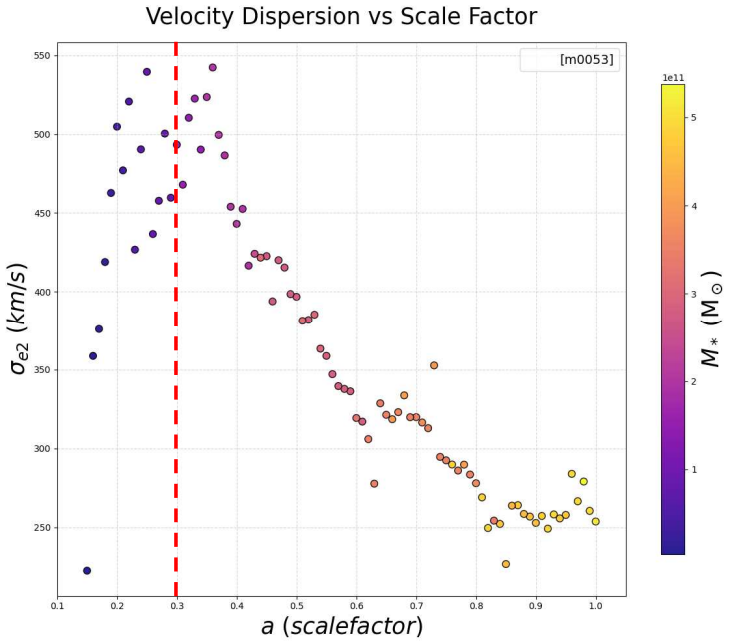
Reference : THE TWOPHASES OF GALAXY FORMATION, Ludwig Oser, 2018

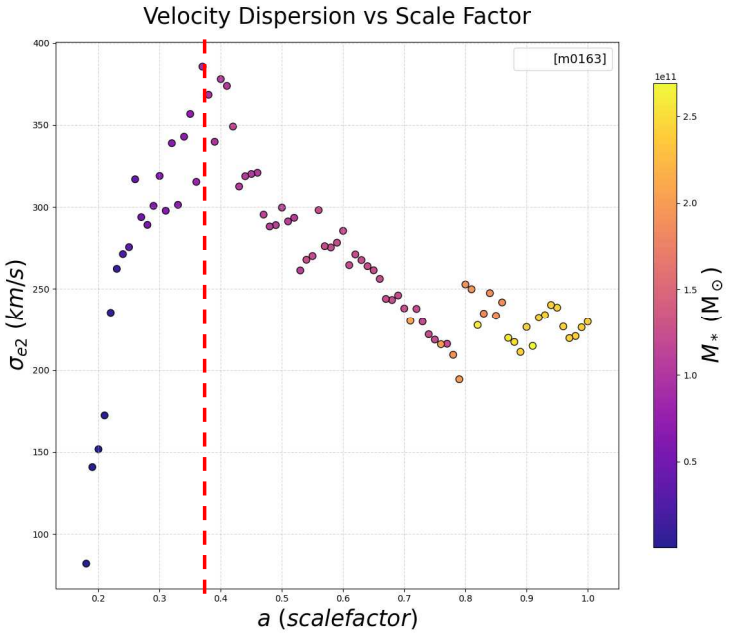
Faber-Jackson Relation (z = 0)

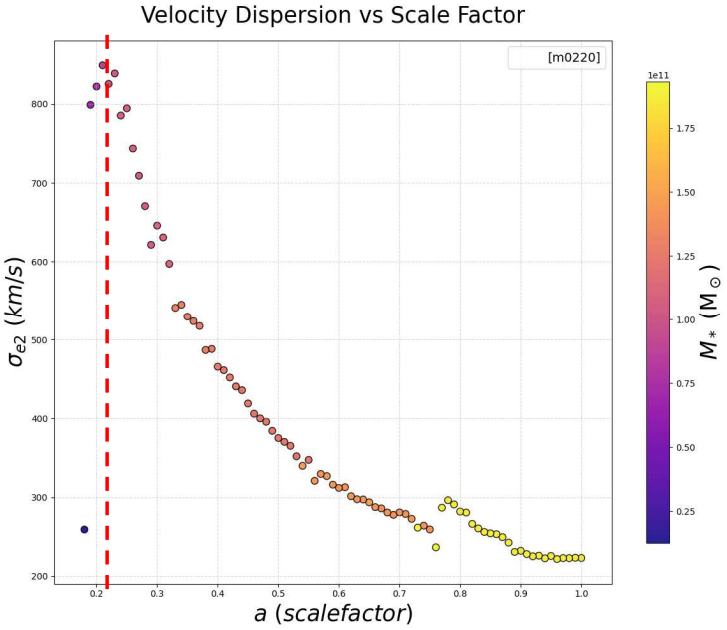
- Simulation Data
  - Linear Proportional relation
    : $\log\left(\frac{\sigma_{e2}}{km\ s^{-1}}\right) = 0.175 \times \log\left(\frac{M_*}{10^{11} M_\odot}\right) - 0.707$
- Observation
  - Nipoti's results
    : $\log\left(\frac{\sigma_{e2}}{km\ s^{-1}}\right) = (0.196 \pm 0.033) \times \log\left(\frac{M_*}{10^{11} M_\odot}\right) + 2.281 \pm 0.021$
- Error for Virial Theorem
  - Incomplete virialized state
  - Only Stellar Mass (Ignore Dark Matter)



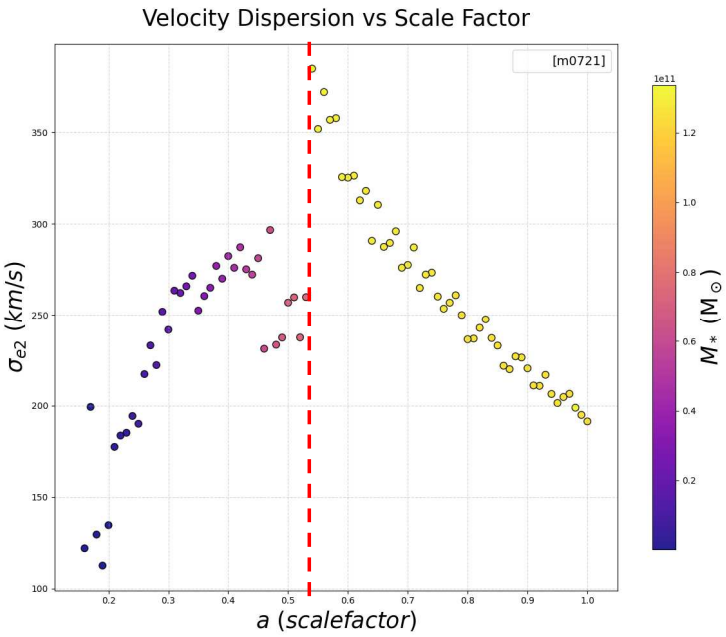
Velocity Dispersion Evolution

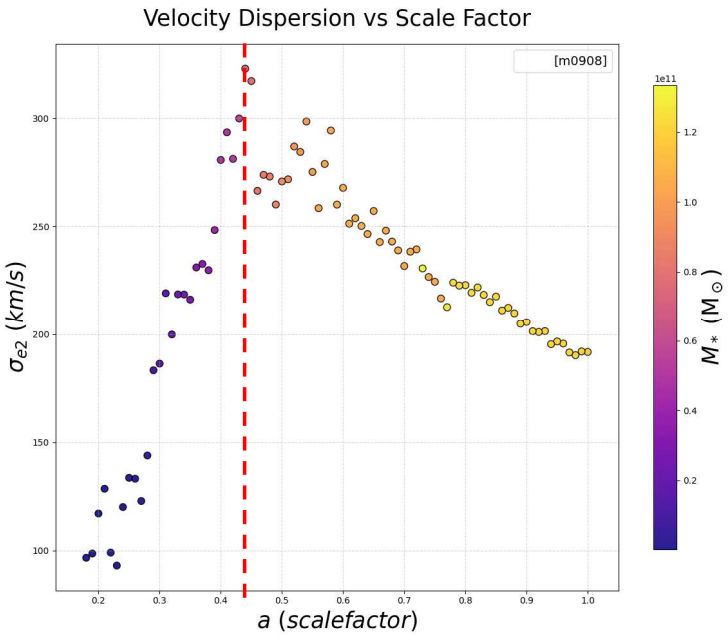


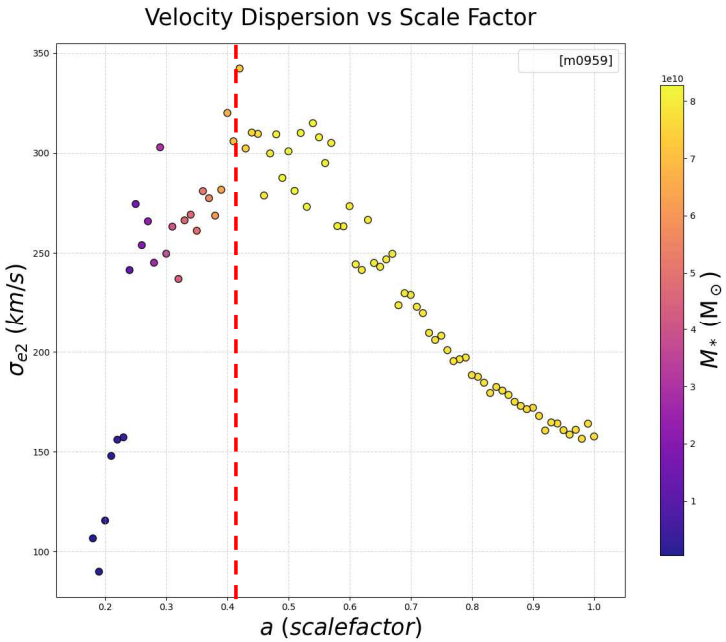




Velocity Dispersion Evolution







Velocity Dispersion by Stellar Mass

- Evolution of Faber-Jackson Relation
  - Reduced Velocity Dispersion Overall

  → Effect of Minor Merger

- Two-Phase Scenario
  - Slope

    z = 0.0 : 0.252
    z = 1.0 : 0.353
    z = 2.0 : 0.463
    z = 3.0 : 0.359
    z = 4.0 : 0.355

  → 4.0 < z < 2.0 : Slope increase

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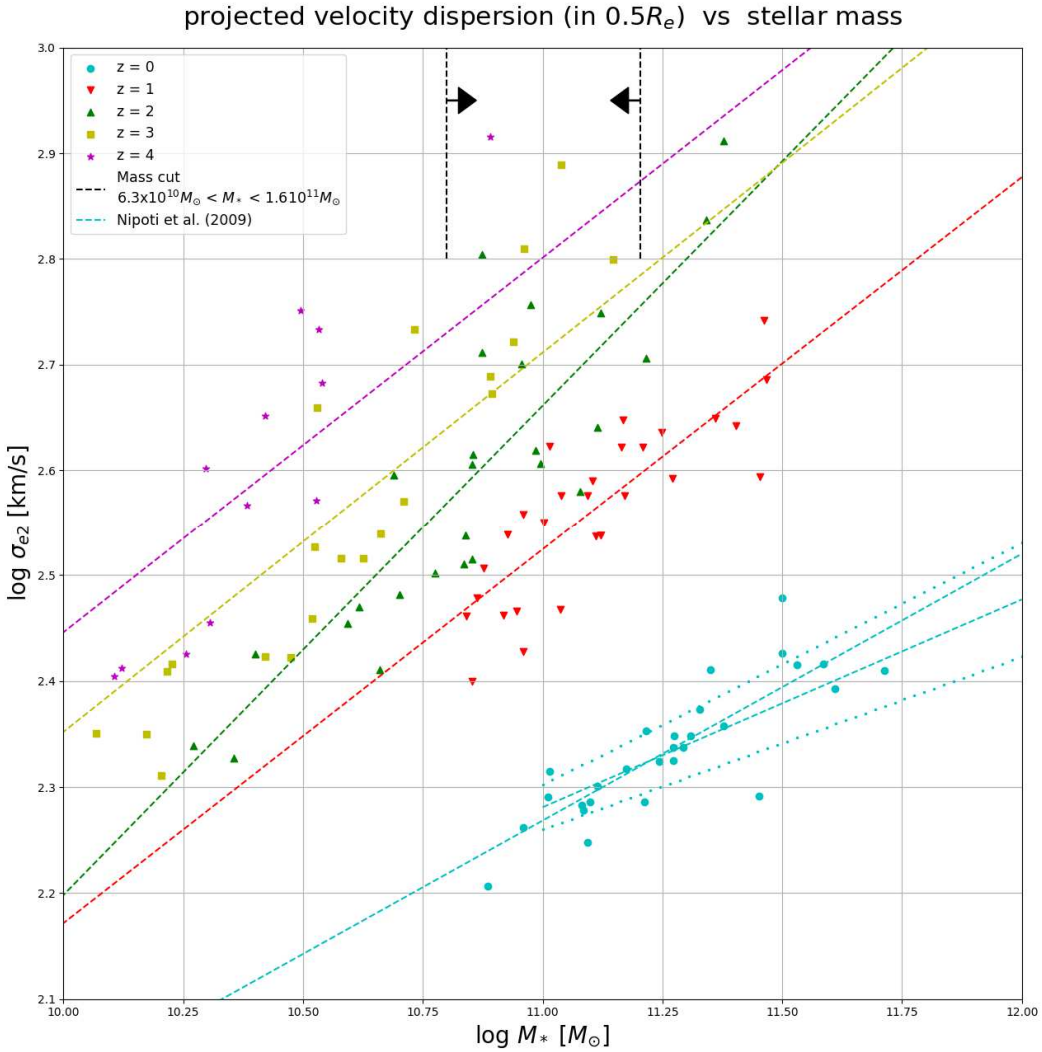


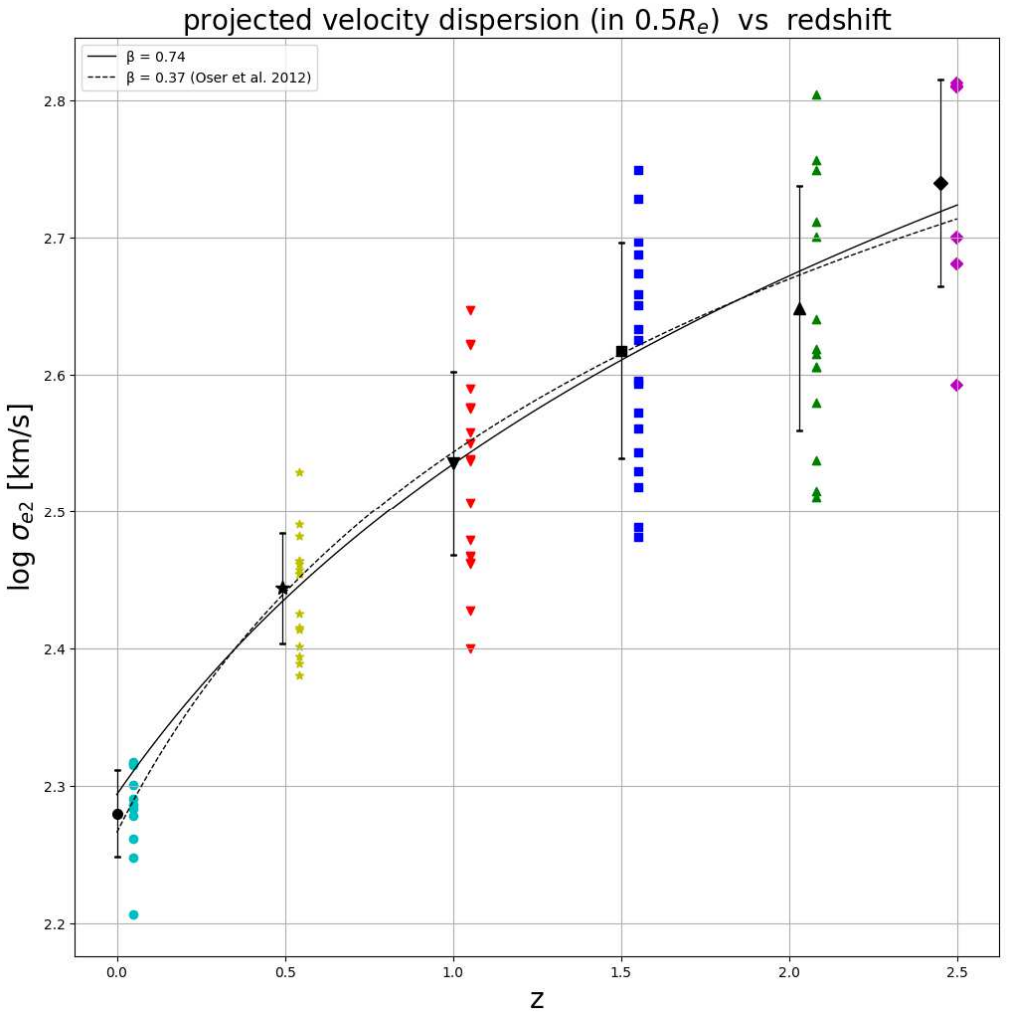
Velocity Dispersion by Redshift

- Velocity Dispersion Decrease
  - Average values

    z = 0.0 : σ = 190.44km/s
    z = 0.5 : σ = 277.89km/s
    z = 1.0 : σ = 342.86km/s
    z = 1.5 : σ = 414.45km/s
    z = 2.0 : σ = 445.34km/s
    z = 2.5 : σ = 549.37km/s

    → decrease of about 2.34 times

- Compare
  - results : $\sigma = 217.10 \times (1+z)^{0.74} - 20.53$
  - oser's : $\sigma = 486.05 \times (1+z)^{0.37} - 291.07$



Thank you for listening