Evaluating the agreement of cosmological simulation galaxies and observed relations

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Outline

- It's important to study galaxies
- Cosmological simulations need to include everything related to galaxy evolution
- GADGET and KETJU are particle-based simulation codes
- Analysis needs to be tailored
- Galaxy properties show good correlation with observed relations
- Conclusions & future
- Summary

It's important to study galaxies (and I'll tell you why!)

Definition of a galaxy & why and how to study them

Definition of a galaxy

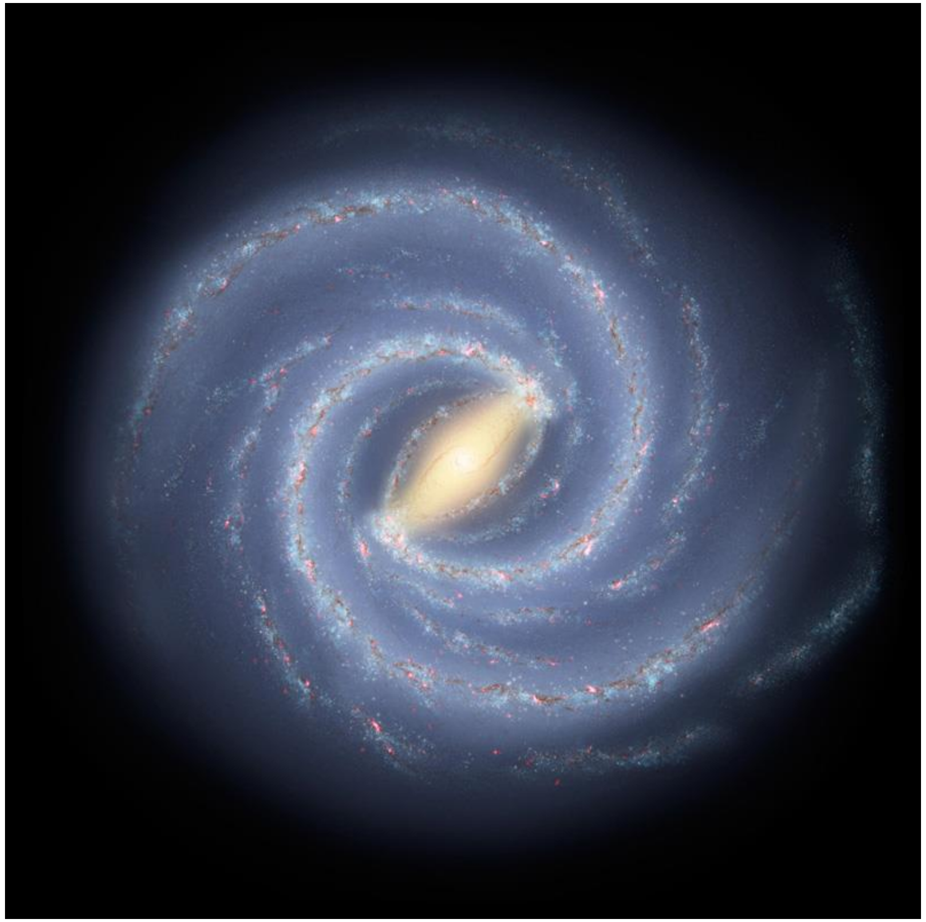


Illustration of the Milky Way.
NASA/JPL-Caltech

- Dynamically bound structure of different components
  - Gas
  - Stars
  - Supermassive black holes (SMHs)
  - Dark matter (DM) halo

Why and how to study galaxies?

- Galaxy formation and evolution is still an open question
  - Answers improve our understanding of the Universe
- The process can be researched with cosmological simulations
- Realistic results are crucial

→**constant improvements are needed**

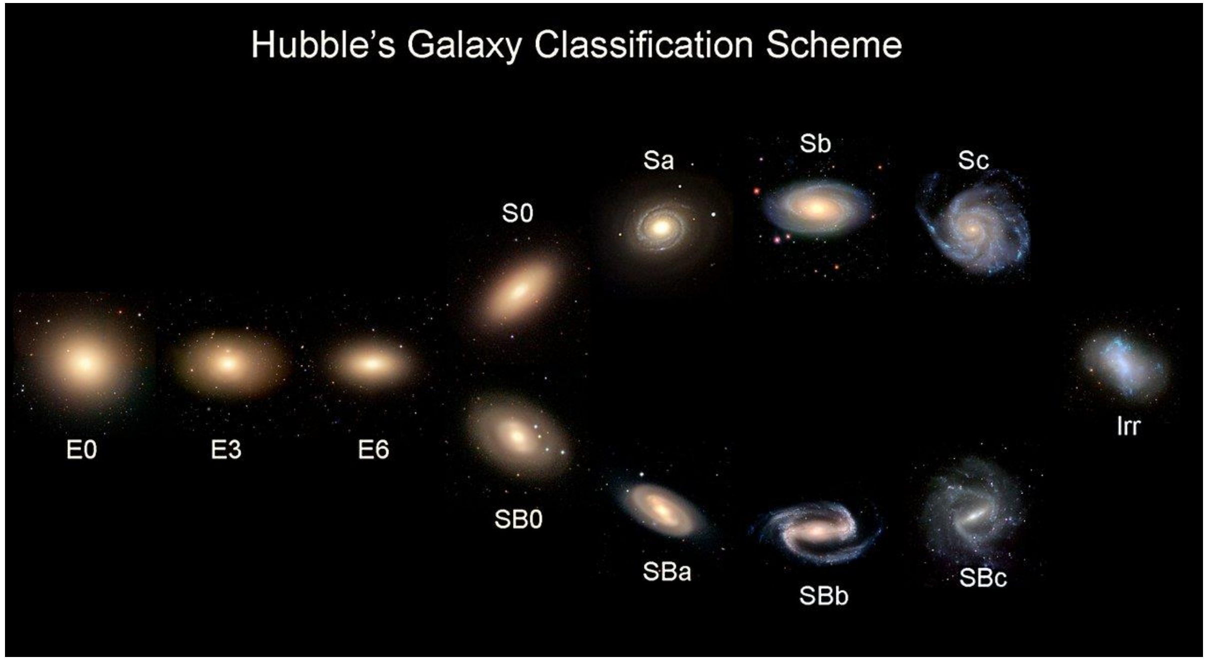
Interacting galaxies as seen by the JWST. Image: NASA/STScI

Cosmological simulations need to include everything related to galaxy evolution

Crash courses to galaxies and cosmological simulations offered by me!

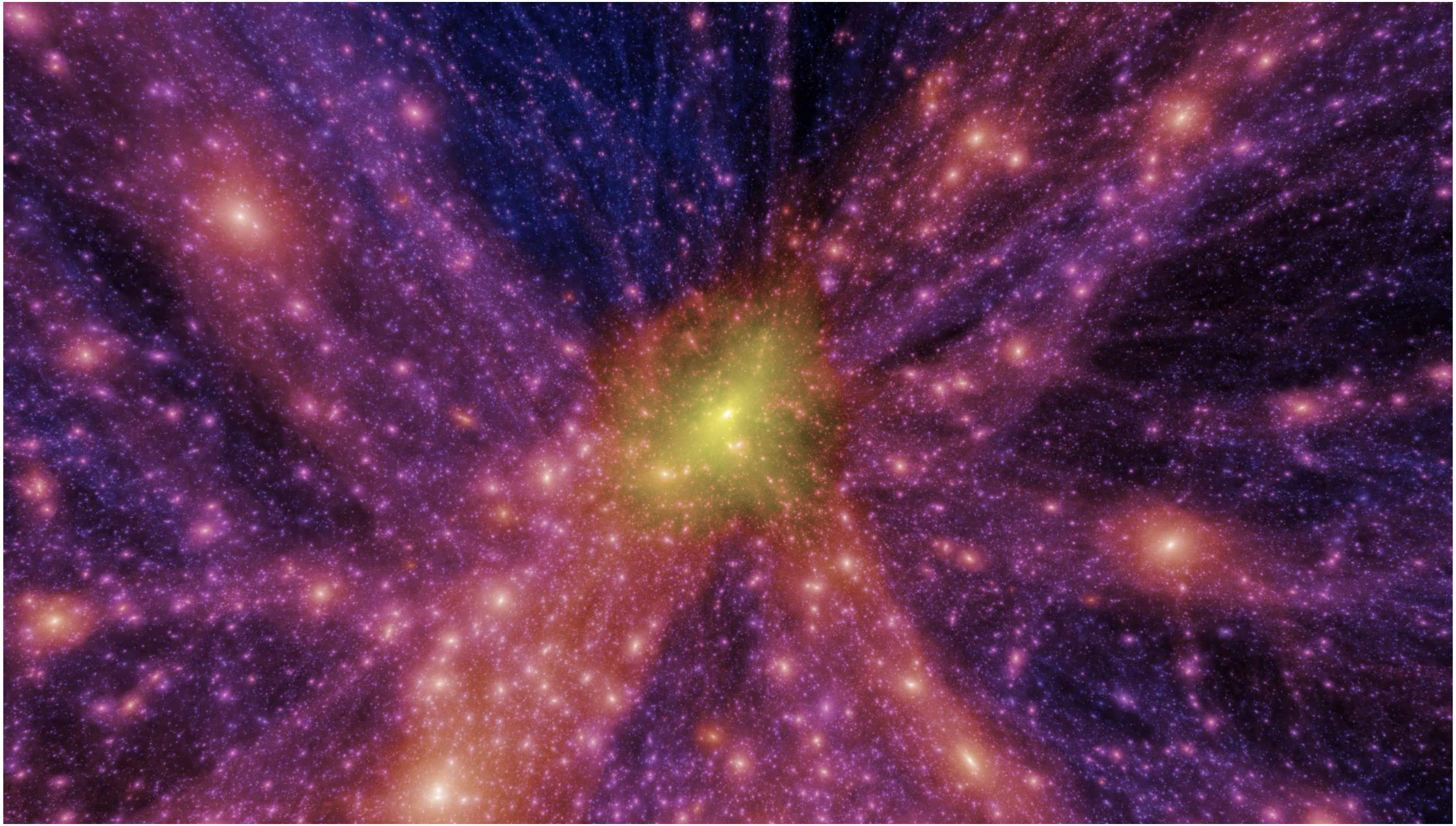
Galaxies are constantly evolving

- Can be classified based on their morphologies
  - Early-type and late-type galaxies
- Start as density perturbations
- Evolve following physical phenomena
  - Gas cooling, star formation, feedback...
- Interact and merge



Classic Hubble's galaxy classification
Credit: Zooniverse

→ Cosmological simulations need to capture all of it!



Credit: Stuart McAlpine

Cosmological simulations consider physics on various scales

- N-body & hydrodynamical simulations
  - grid or particle based
- Gravity (stars, SMBHs, DM) and hydrodynamics (gas)
  - Are evolved with physical equations at every time step
- Subgrid-physics
  - Gas cooling, star formation, feedback, SMBH accretion etc.

The beginner's guide to zoom-in simulations

1) Generate initial conditions (ICs) using only DM
2) Run with low resolution
3) Identify a region of interest
4) Generate ICs for that region using both DM and baryons
5) Run the small region with high resolution and all physics

→ **Saves computing resources**

GADGET and KETJU are particle-based simulation codes

Introduction to numerical simulation codes

GADGET – a flexible code for various uses

- Dark matter only / hydrodynamical simulations
- Particle based: **particles are not strictly physical!**
  - Masses ~10^5 $M_\odot$
- Softened gravity
- Small scale physics
  - Gas cooling, stellar feedback, SMBH feedback and accretion etc.

KETJU – solving SMBH dynamics

- Extension of GADGET
- Adds regions around SMBH
  - Gravity is unsoftened

→Solves SMBH dynamics accurately

ie. has a very specific focus and use!

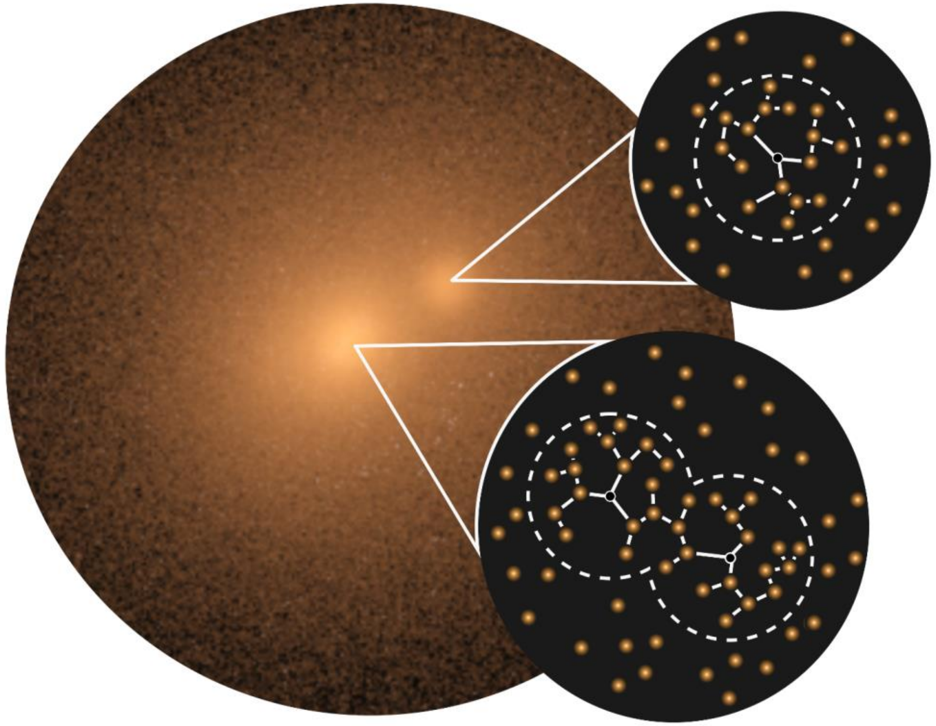


Illustration of the KETJU regions around SMBHS.
Figure reproduced from Mannerkoski et al. 2023

Analysis needs to be tailored

Details of the used zoom-in simulation and my analysis

Zoom-in simulation details

- Data from a zoom-in simulation (from z=50 to today)
- Focused on a galaxy group
  - $2\times10^{13}M_\odot$
- 410^3 particles
- Comoving size of $(\sim15Mpc)^3$

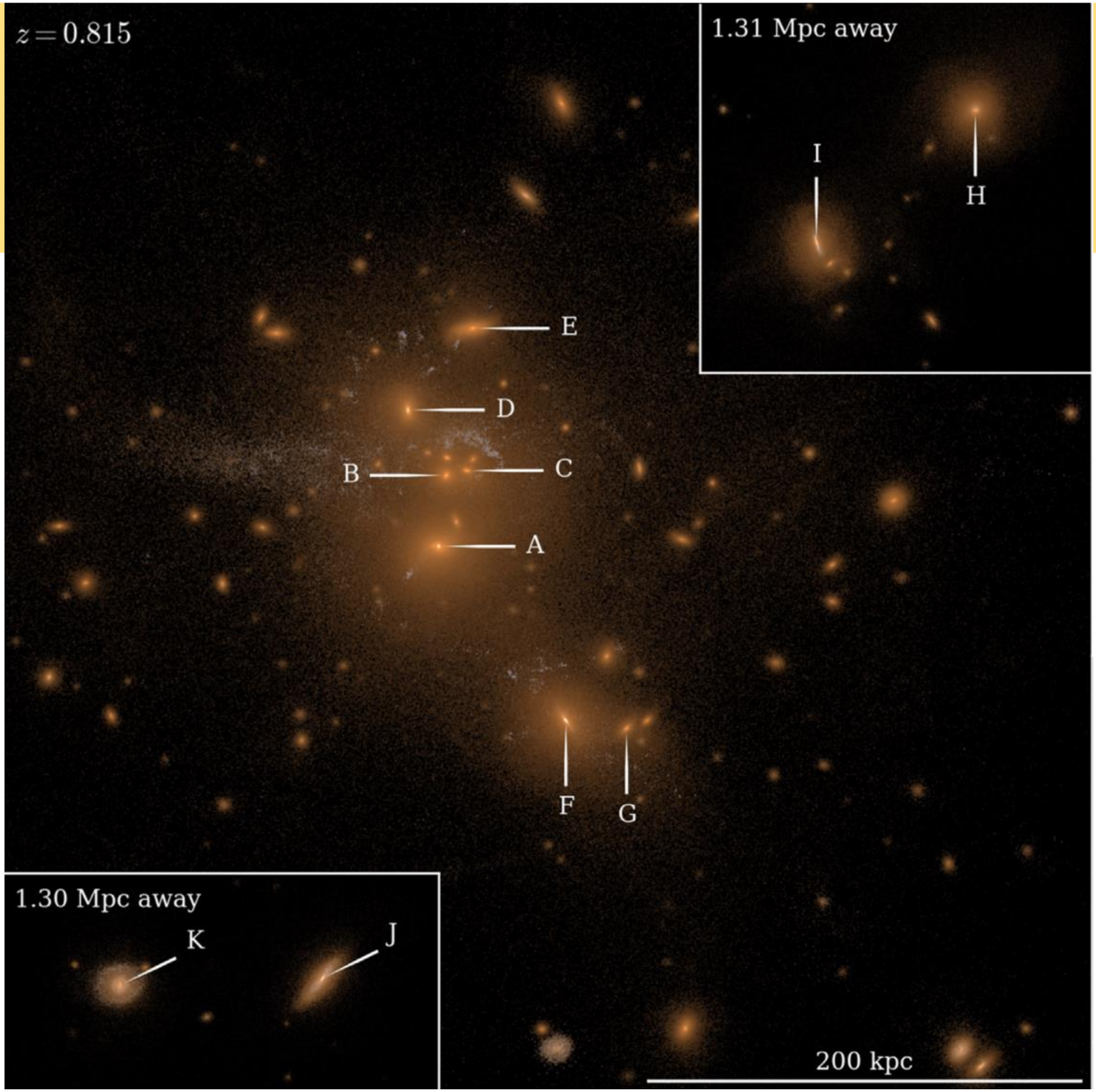


Illustration of the simulation volume. Figure reproduced from Mannerkoski et al. 2022.

Choices must be made to complete the analysis

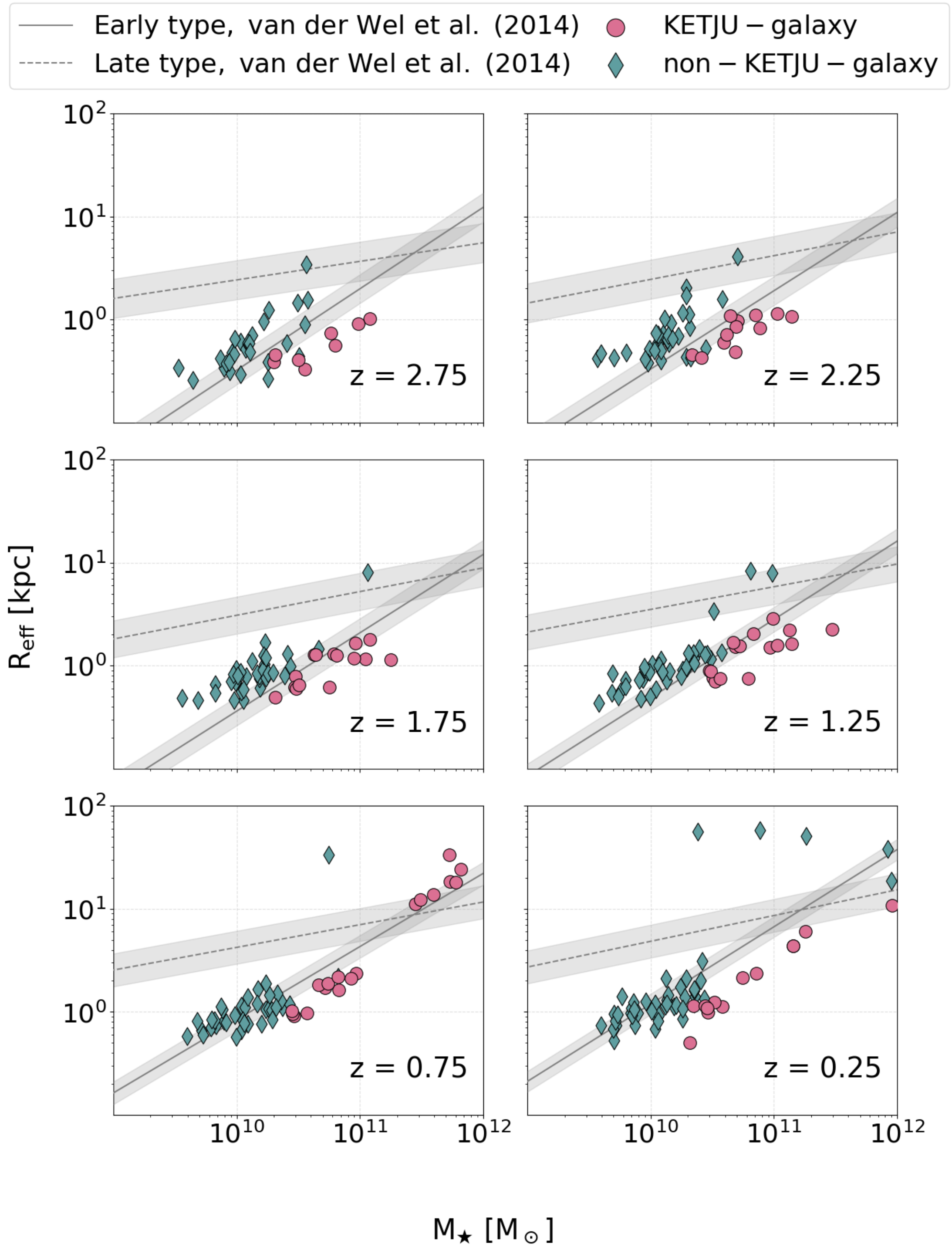
- Definition of a galaxy: R=0.1virial radius
- All information of the particles is available in the data files
  - Other properties can be derived from them
- Split into KETJU- and non-KETJU-galaxies
  - Central SMBH mass $7.4\times10^{7}M_{\odot}$ as a divider

$$\rho(< R_{200}) = \Delta_c \frac{3H^2(t)}{8\pi G}$$

Density at the virial radius. Δ_c is the overdensity constant (=200), *H* Hubble parameter and *G* gravitational constant.

Galaxy properties show good correlation with observed relations

Chosen highlights of my thesis results

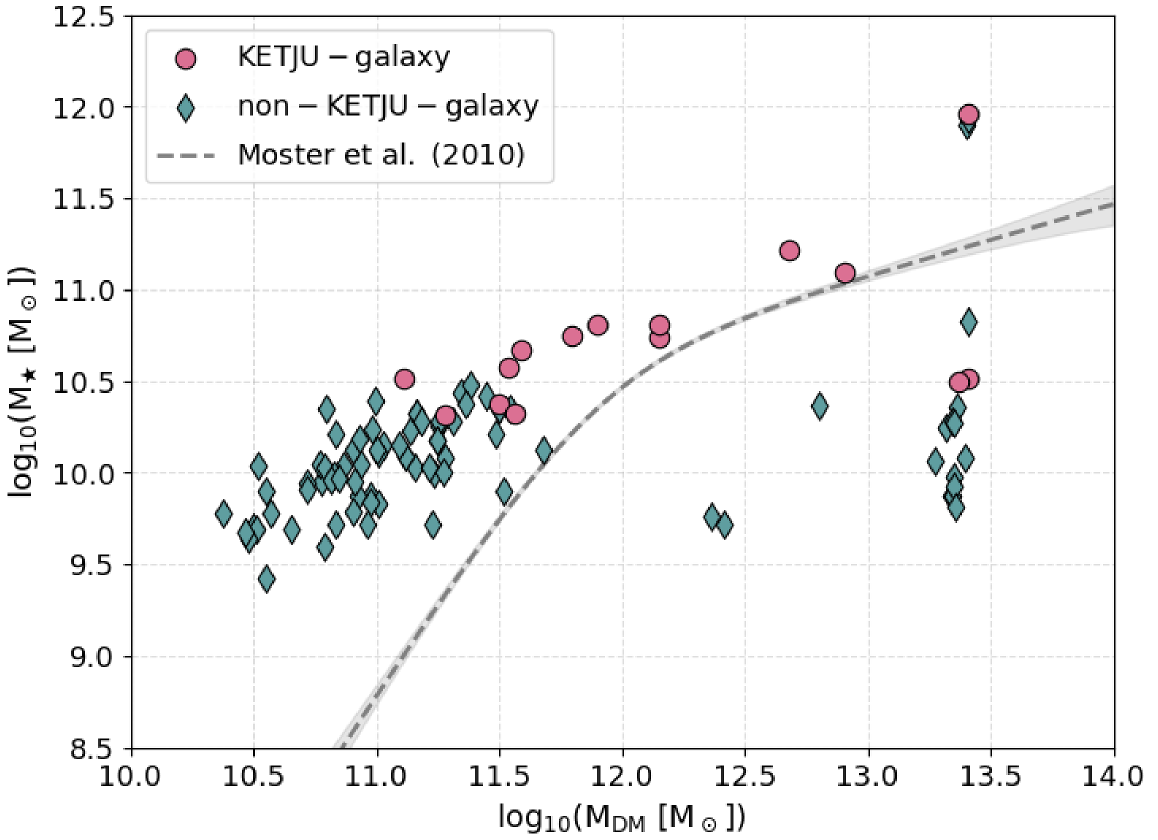


Sizes and masses evolve expectedly

- Evolution of the size-mass relation follows observed relations
- Most simulation galaxies are late type-galaxies
  - Also seen in other results
- Interacting galaxies lie above the relations

Producing galaxies too efficiently

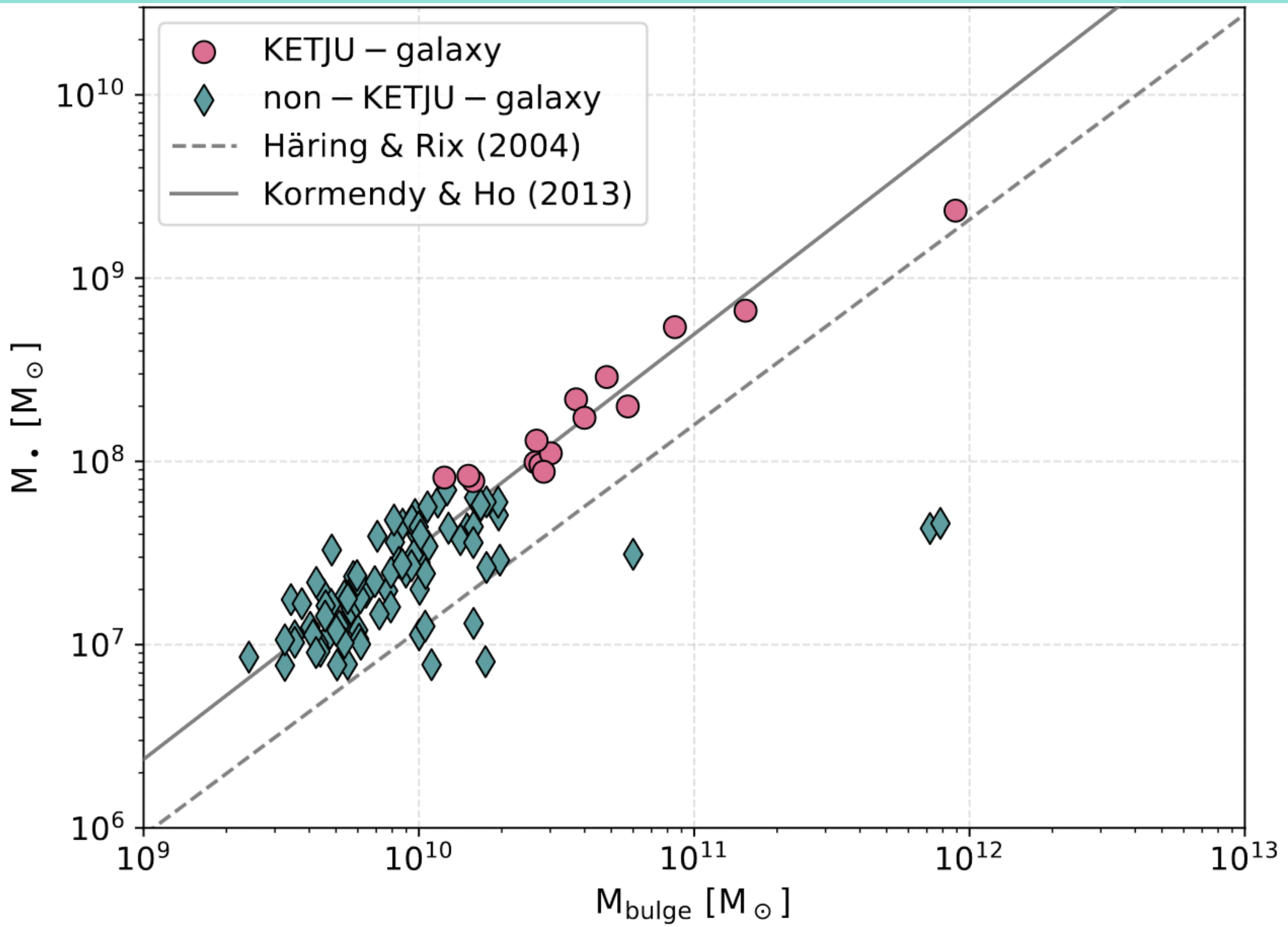
- The galaxy formation efficiency
- Above the relation = more stellar mass than expected
- Clumped galaxies are within each other's virial radii R_{200}.



Stellar masses of the galaxies against their DM halo masses.

Reproducing observed relations

- BH-mass as a function of the bulge mass also has an observed relation
- Especially good correlation with observed relation from Kormendy & Ho 2013



Black hole masses against the stellar bulge masses of galaxies.

Conclusions & what the future holds

- Relatively good agreement with observed relations
- In depth analysis of galaxy formation efficiencies and needed corrections
- Adding more physics to the simulation
    - Binary feedback model and accretion discs

Summary: what I'd like you to remember

- Galaxy formation and evolution still needs to be studied
- Cosmological simulations are powerful tools for that
- We need realistic simulation galaxies to study the Universe
- The KETJU-code mainly reproduces observed relations in cosmological simulations
- No simulation code is perfect, and KETJU has room for development

Thank you!

Questions?