Investigating dark matter structure by cosmological simulations on the supercomputer Fugaku and machine learning

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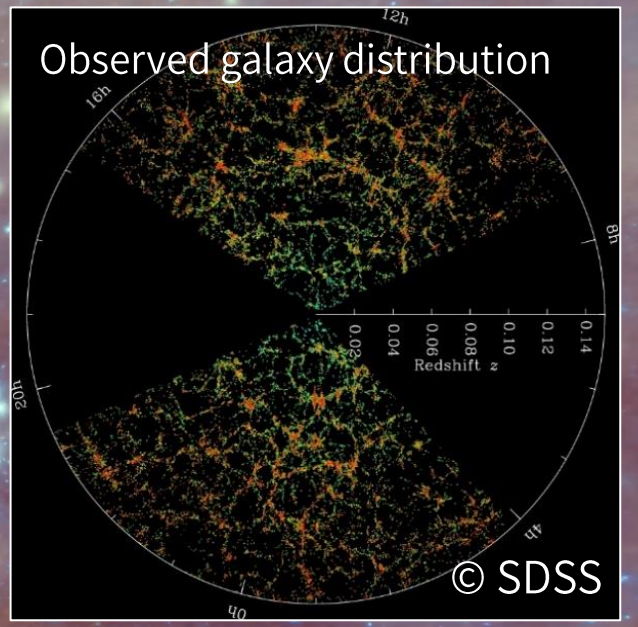
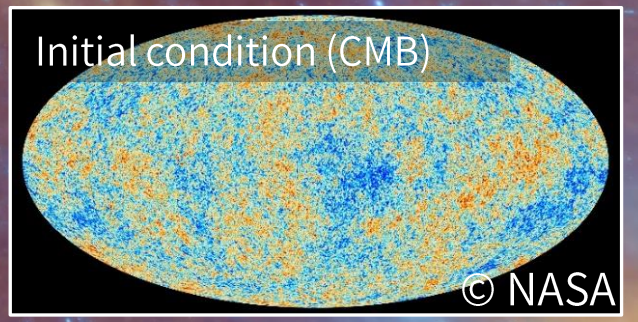
Publicly offered research 23H04002

LCDM cosmological model





4D2U (NAOJ) movie
「Formation and Evolution of Dark Matter Halos (III. Formation of Cosmic Web and Void Structures)」

https://www.youtube.com/watch?v=R7nV6JEMGAo

Halo structure

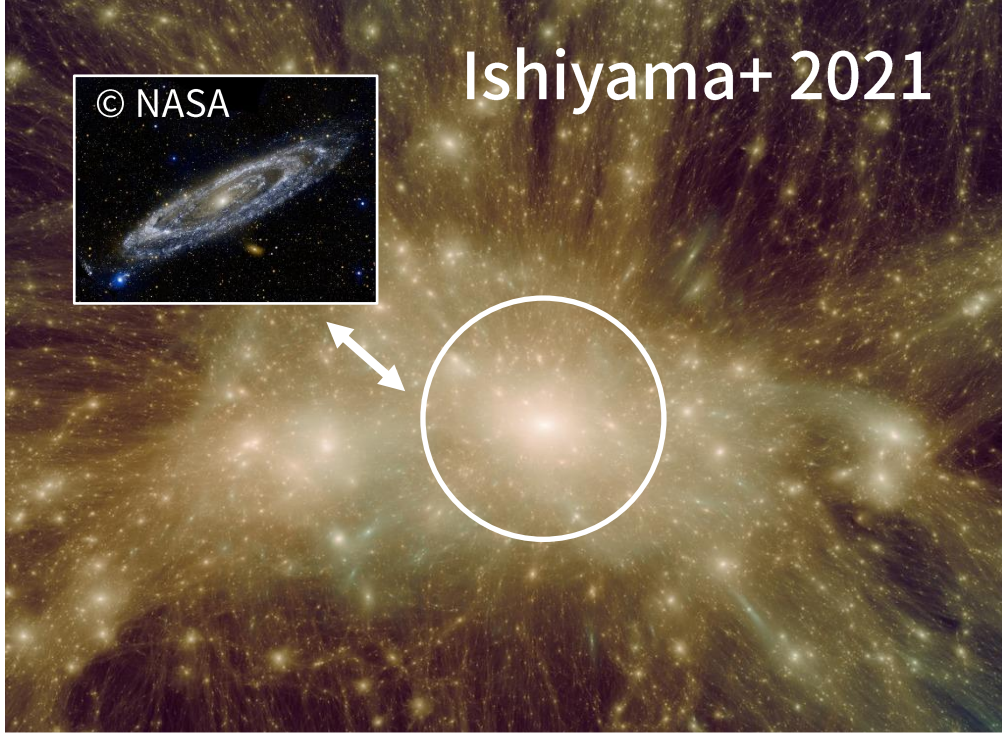
- **Central cusp**
  - Einasto profile or NFW profile

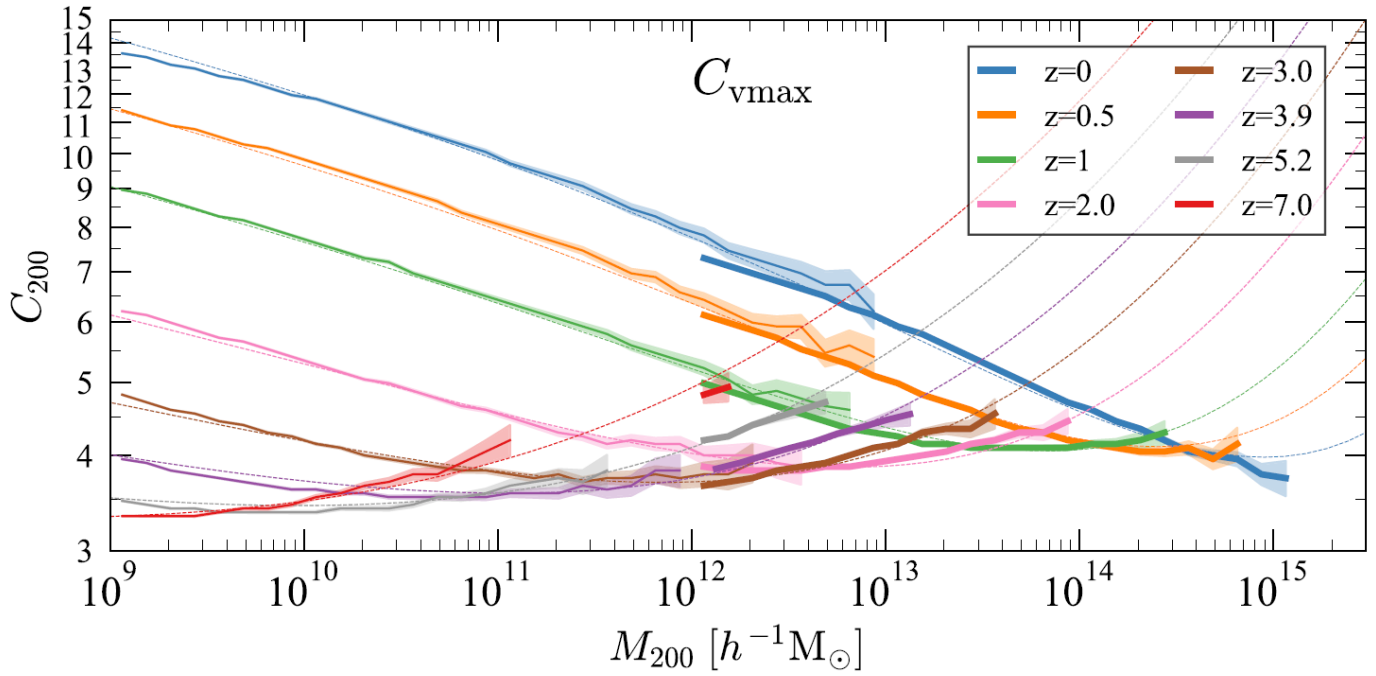
$$\rho(r) = \frac{\rho_s}{(r/r_s)[1+(r/r_s)]^2}$$

Concentration
$c = r_{vir}/r_s$, r_{200}/r_s

- **Numerous subhalo**
  - $dn/dm \sim m^{-(1.8\sim2)}$
- **Triaxial**
- **Non Universality**
  - Weak dependence on the halo mass
  - halo to halo variation

Halo structures have large impact on galaxy formation physics and dark matter detection





Predicting galaxy cluster's mass and concentration using convolutional neural network

- Galaxy clusters are the most massive virialized objects
- The cluster abundance is sensitive to cosmological parameters
- The cluster mass-concentration relation can also be used as a cosmological probe
- Those quantities are not directly observable
- This work: Predicting those quantities using mock galaxy catalogs (Uchuu-UniverseMachine; Aung, TI+ 2023) and convolutional neural network

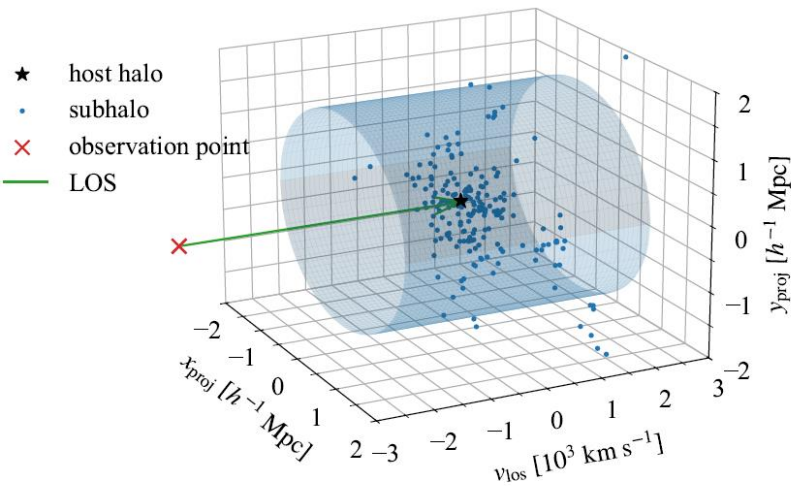
$$\rho(r) = \frac{\rho_s}{(r/r_s)[1+(r/r_s)]^2}$$

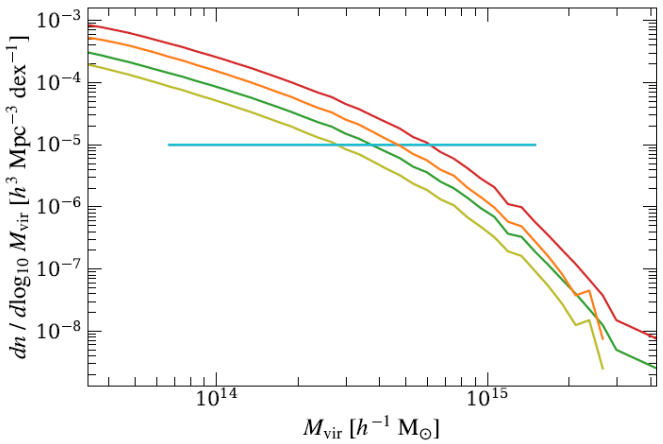
Concentration
$c = r_{vir}/r_s$, r_{200}/r_s

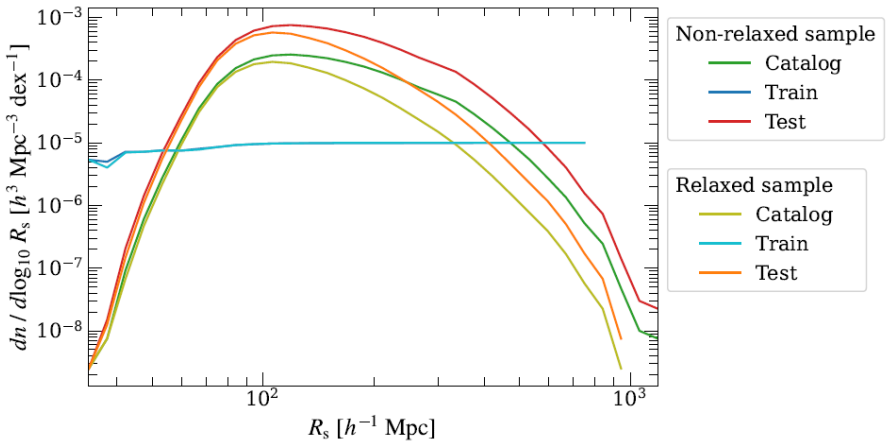
Tominaga, Nakamura, TI, Abdullah, in prep

Data and method

- Galaxy clusters at z=0.09 and member galaxies in Uchuu-UniverseMachine mock catalogs (Aung, TI+ 2023)
- Input for CNN: 2D histogram of member galaxies' observable quantities, observed by observers at z=0.0
  - Projected distance from the center of cluster
  - Line of sight velocity
- Mimicking observations taking interloper galaxies into account
- Flattening the data distribution by down- and upsampling (multiple projections)



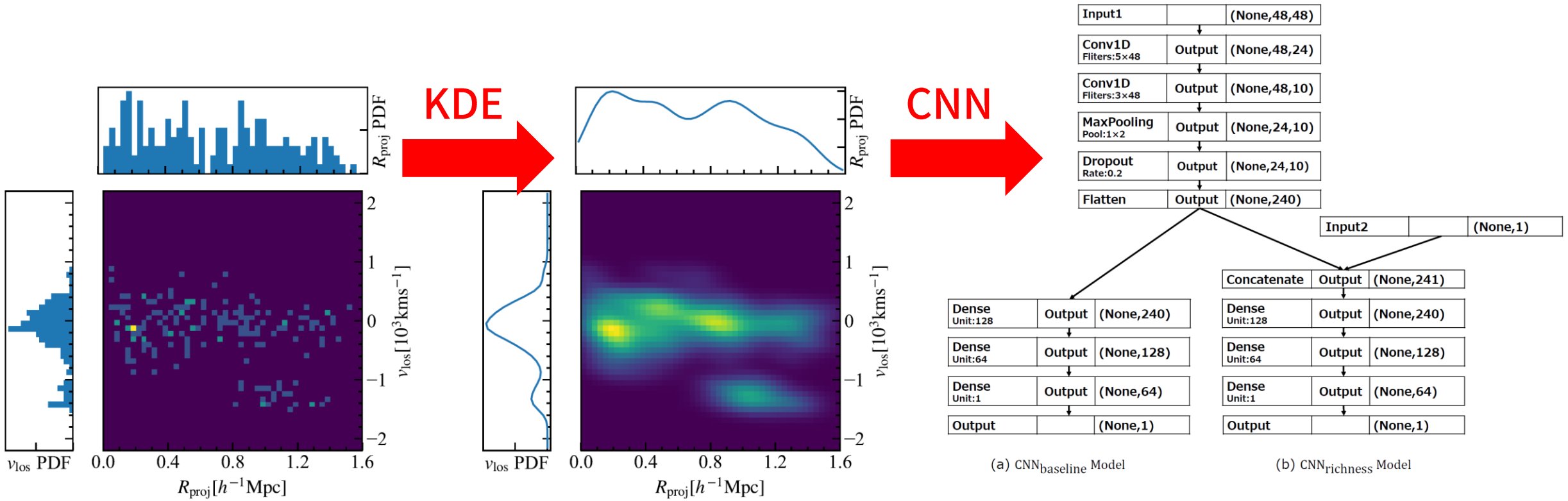




Tominaga, Nakamura, TI, Abdullah, in prep

CNN

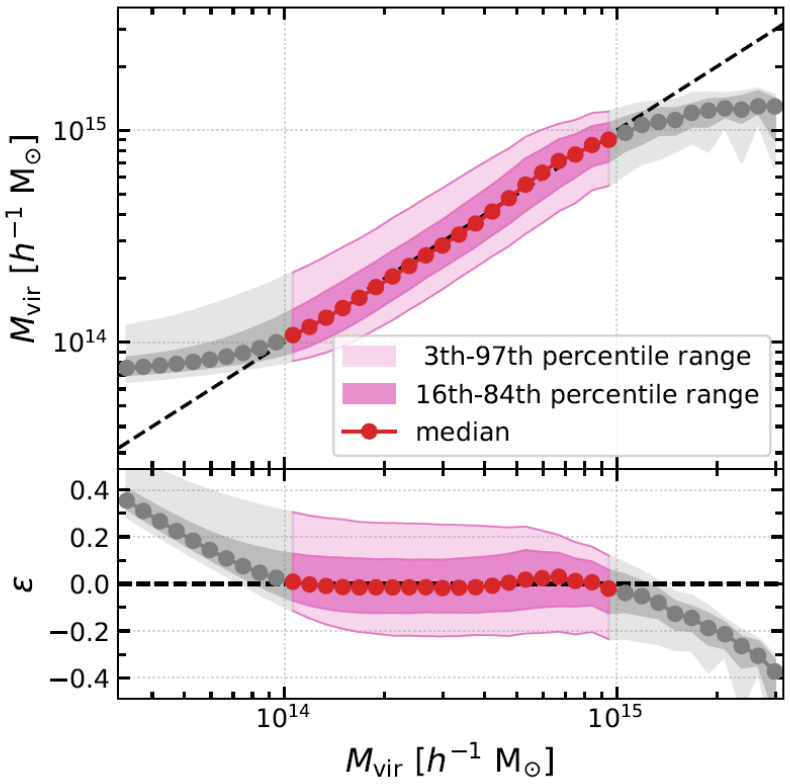
- Input: 2D histogram of member galaxies' observable quantities projections, taking interloper galaxies into account
- Smoothed by kernel density estimation (KDE)
- Richness can also be used as additional input parameter for a dense layer



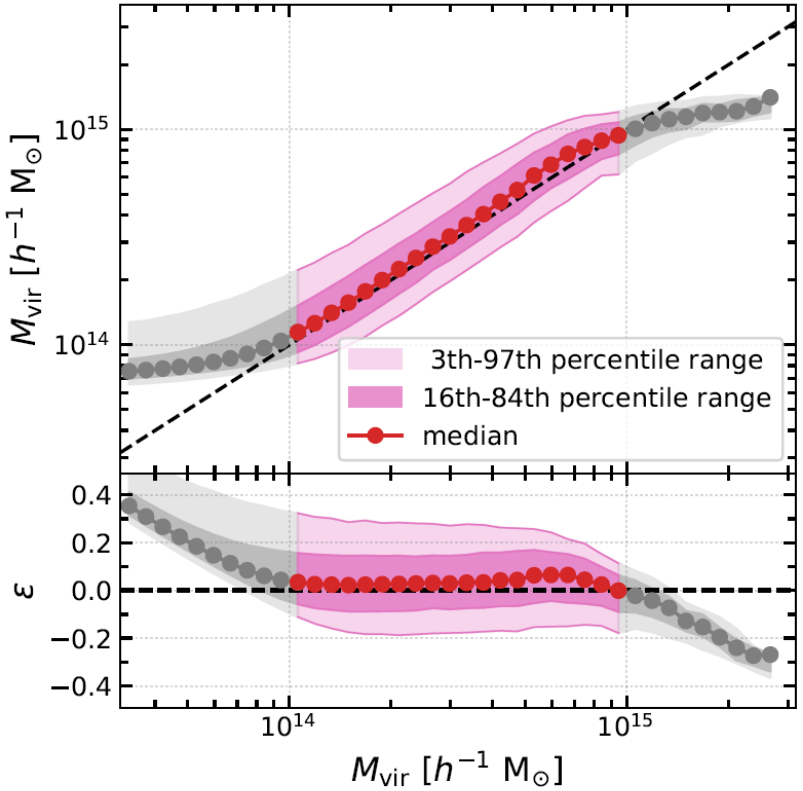
Halo mass

ε = log10 (Predict/true)

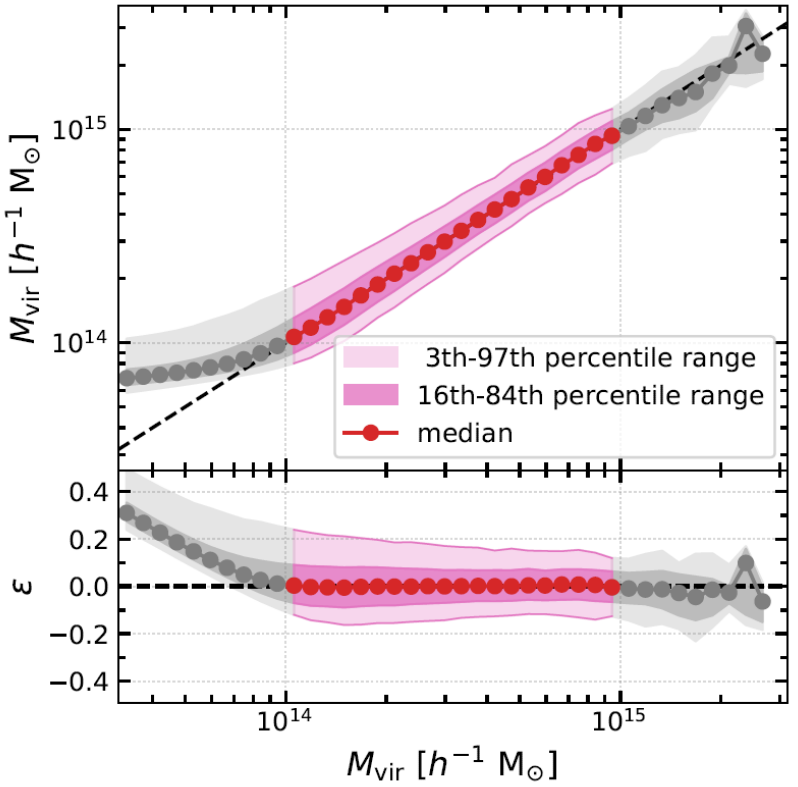
All clusters



relaxed



relaxed + richness

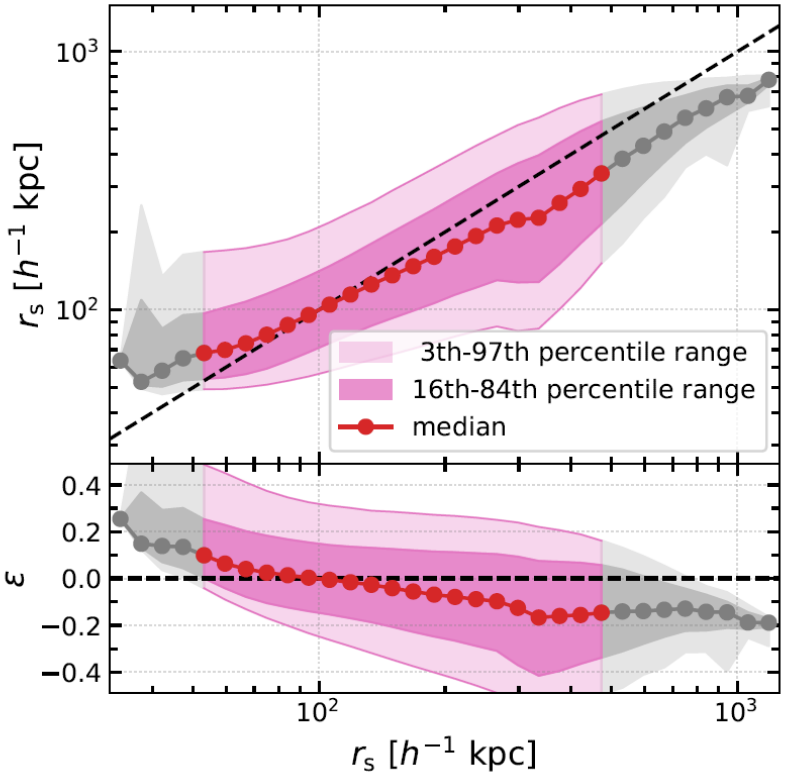


- The median error and 1sigma scatter are less than ~0.03 and ~0.15 dex, respectively
- Including richness can further decrease scatter down to ~0.1 dex
  - Larger effect than using only relaxed clusters

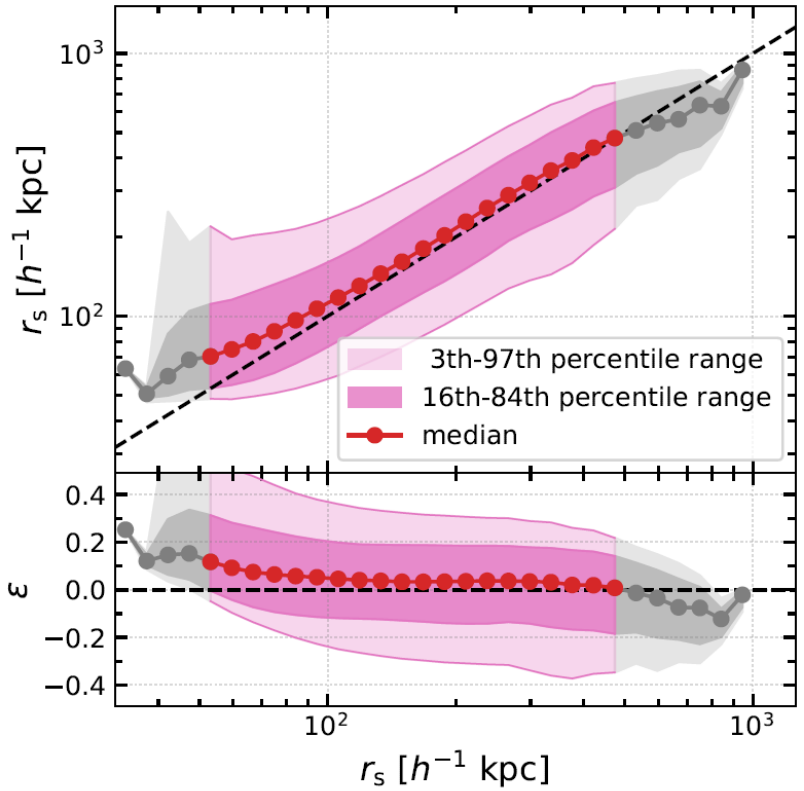
Scale radius (concentration)

ε = log10 (Predict/true)

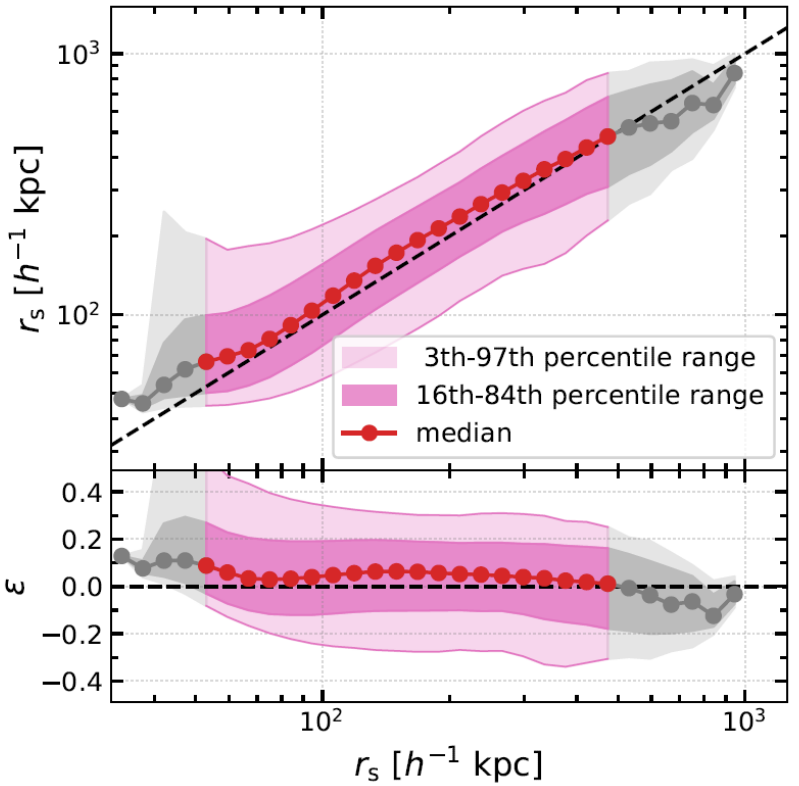
All clusters



relaxed



relaxed + richness



- The median error and 1sigma scatter are less than ~0.04 and ~0.17 dex, respectively
- Using only relaxed clusters can modifiy the overall slope to the true one
- Including richness doesn’t have much effect

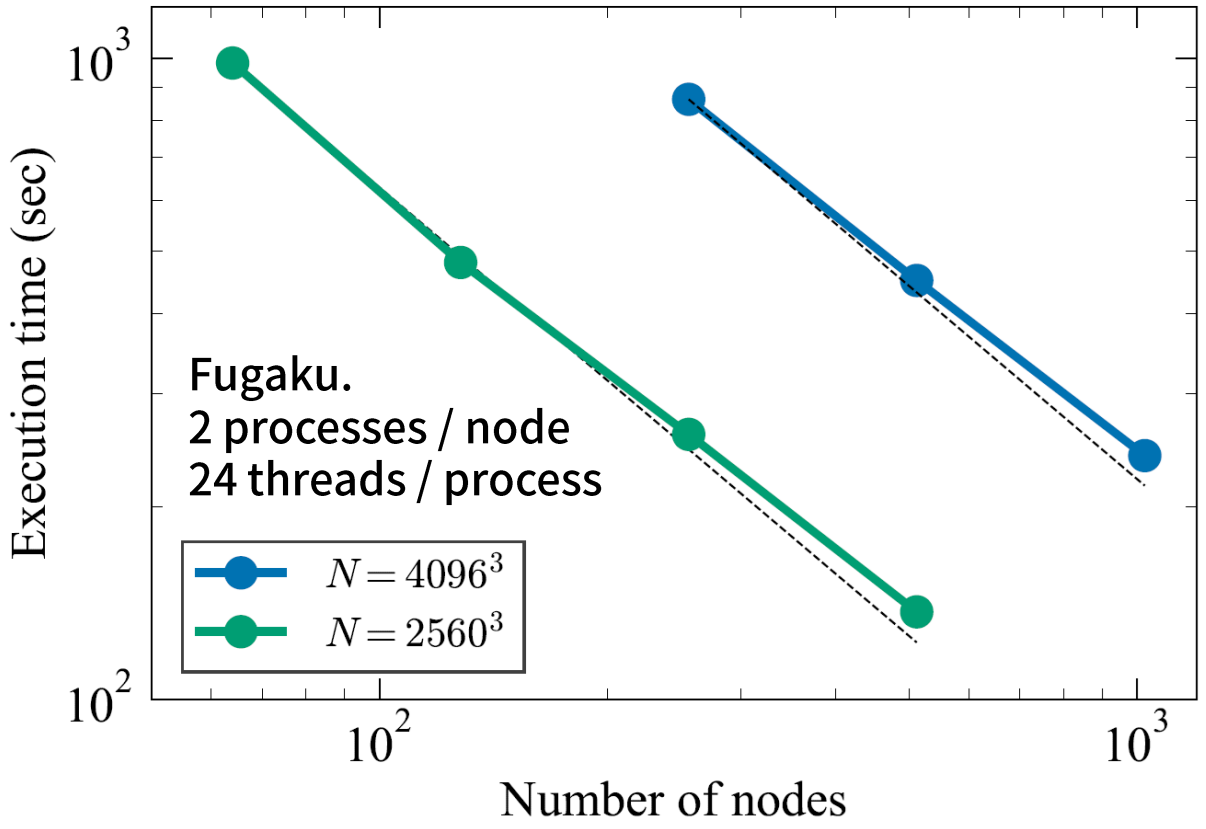
Other achivements (digest)

MPI-Rockstar: a Hybrid MPI and OpenMP Parallel Implementation of the Rockstar Halo finder

Tokuue, Ishiyama, Osato, Tanaka, Behroozi, arXiv: 2412.18629, submitted to JOSS

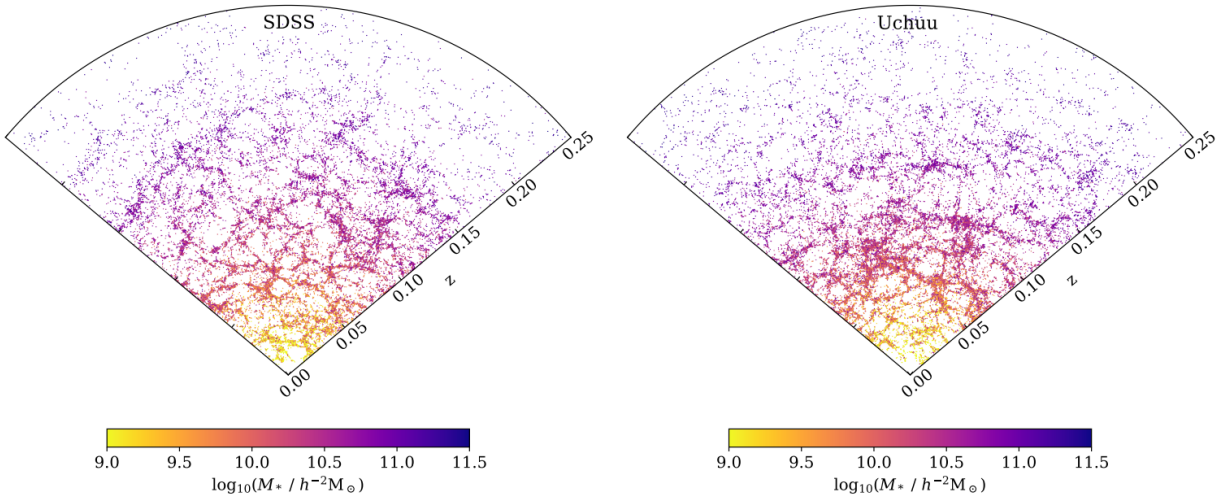
https://github.com/Tomoaki-Ishiyama/mpi-rockstar

- Fully refactoring Rockstar using MPI+OpenMP instead of the socket library
- Most communications (e.g., particle re-distribution) is replaced by fast collective (e.g., MPI_Alltoallv) communication
- Halo/subhalo finding is done by MPI+OpenMP hybrid way
- Additional halo properties: Inertial tensor, intermediate axis, chi square of the NFW fitting
- N>10^{12} can be analyzed



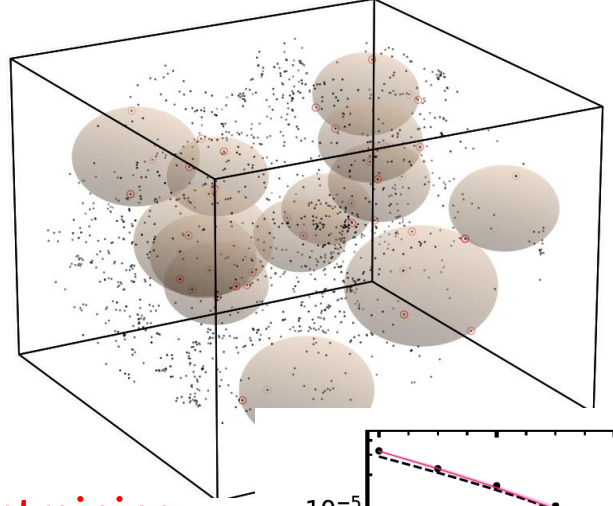
Uchuu lightcones

- Lightcones mock catalogs based on Uchuu simulation
- Abundance matching (V_{peak} – luminosity function) + color assignment
- Reproduce statistics of SDSS main galaxy survey

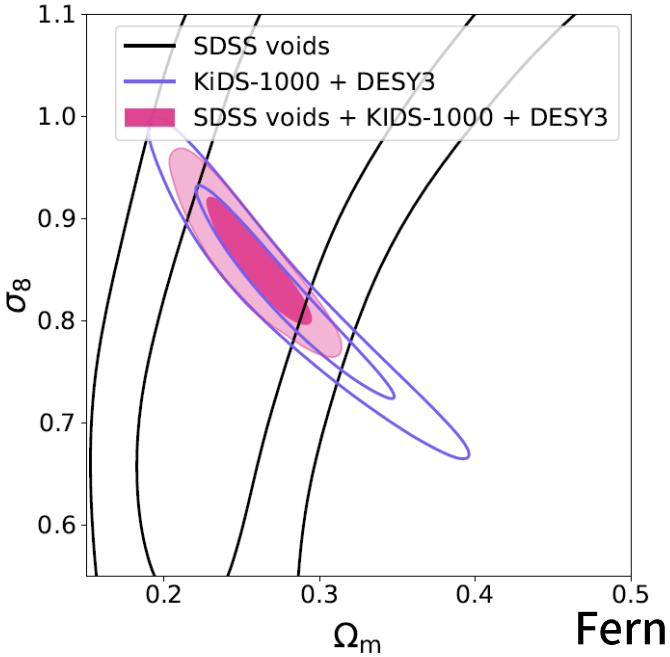


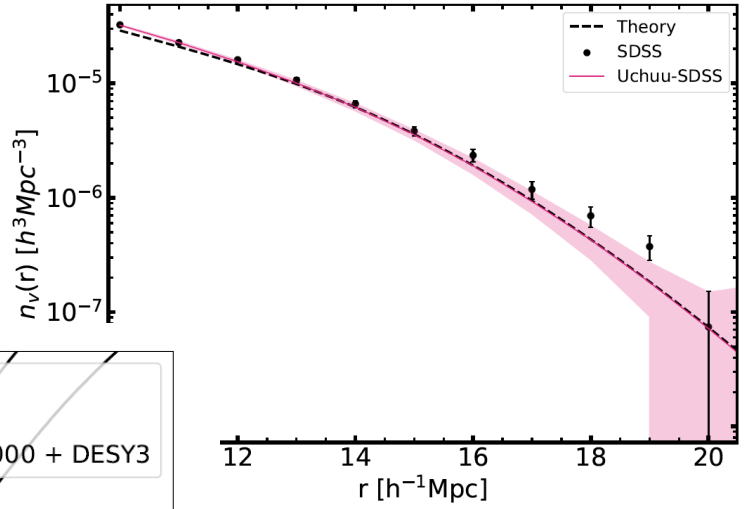
Dong-Páez, TI+ 2024, MNRAS

Uchuu-BOSS lightcones are also available (Ereza, TI+ 2024, MNRAS)



Constraining cosmological parameter using SDSS void





Fernández-García, TI+ 2025

Summary

- Predicting galaxy cluster’s mass and concentration using mock galaxy catalogs and convolutional neural network
- The accuracy is quite well
  - Including richness increases the accuracy for mass prediction
  - Using only relaxed sample increases the accuracy for concentration prediction
- Caveat: rely on Planck18 cosmology