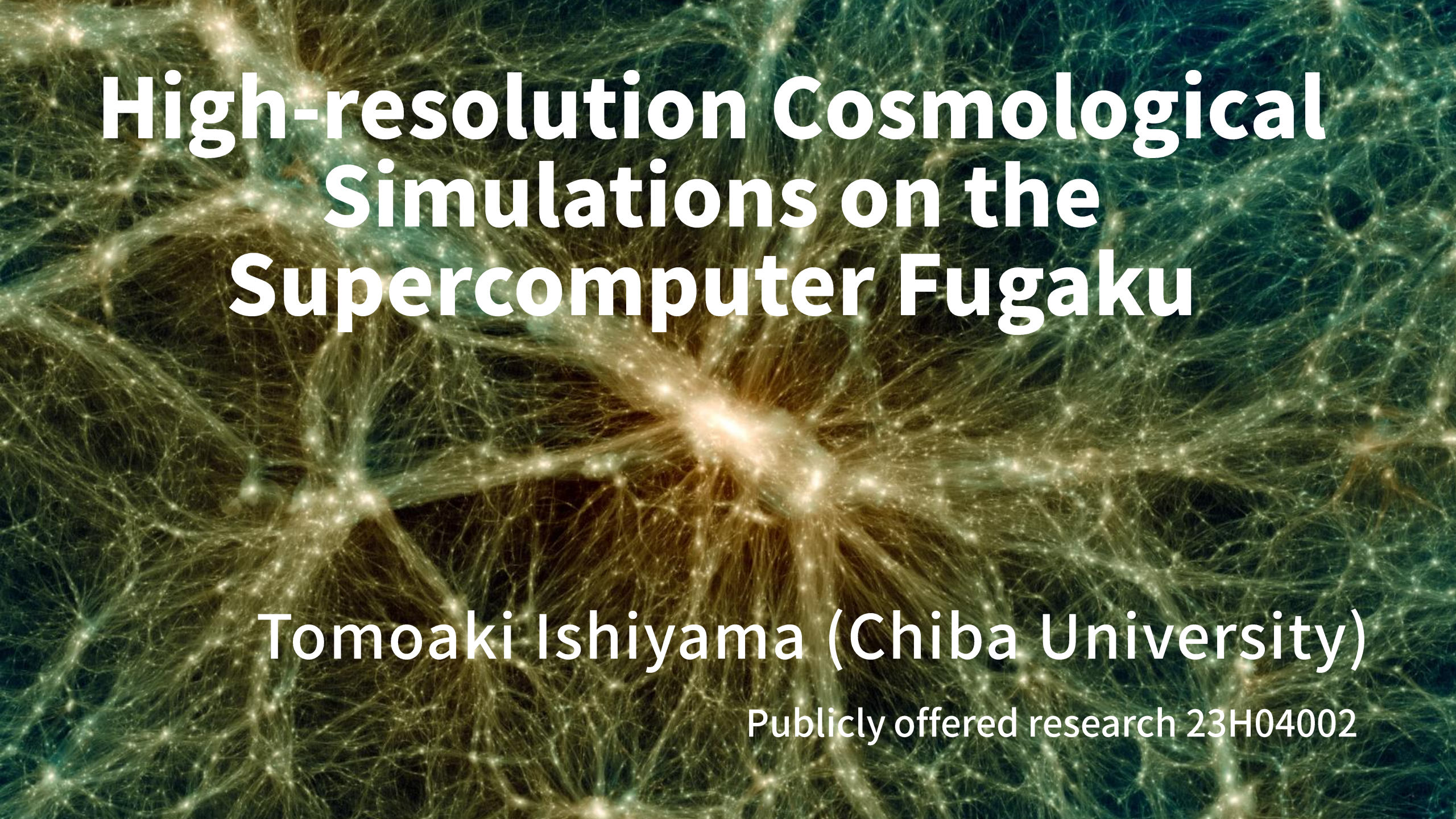
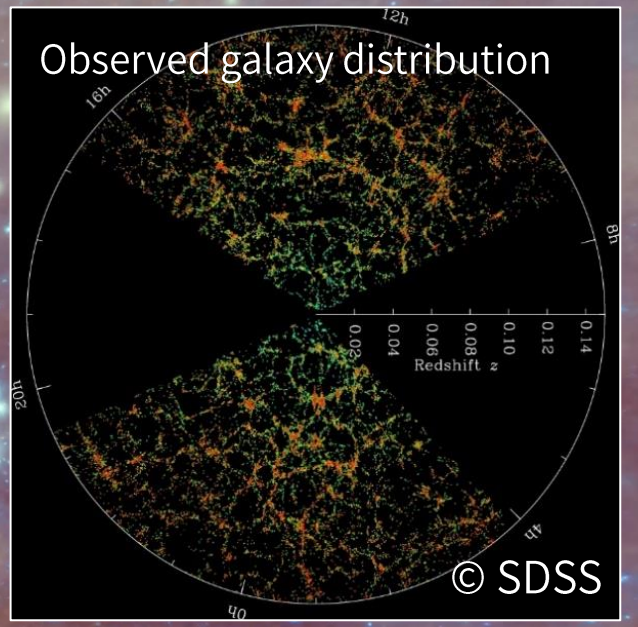


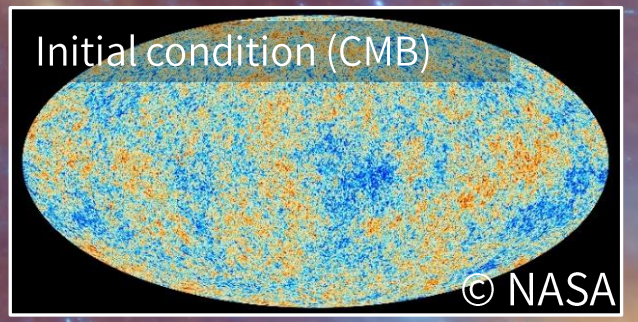
High-resolution Cosmological Simulations on the Supercomputer Fugaku

Tomoaki Ishiyama (Chiba University)

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

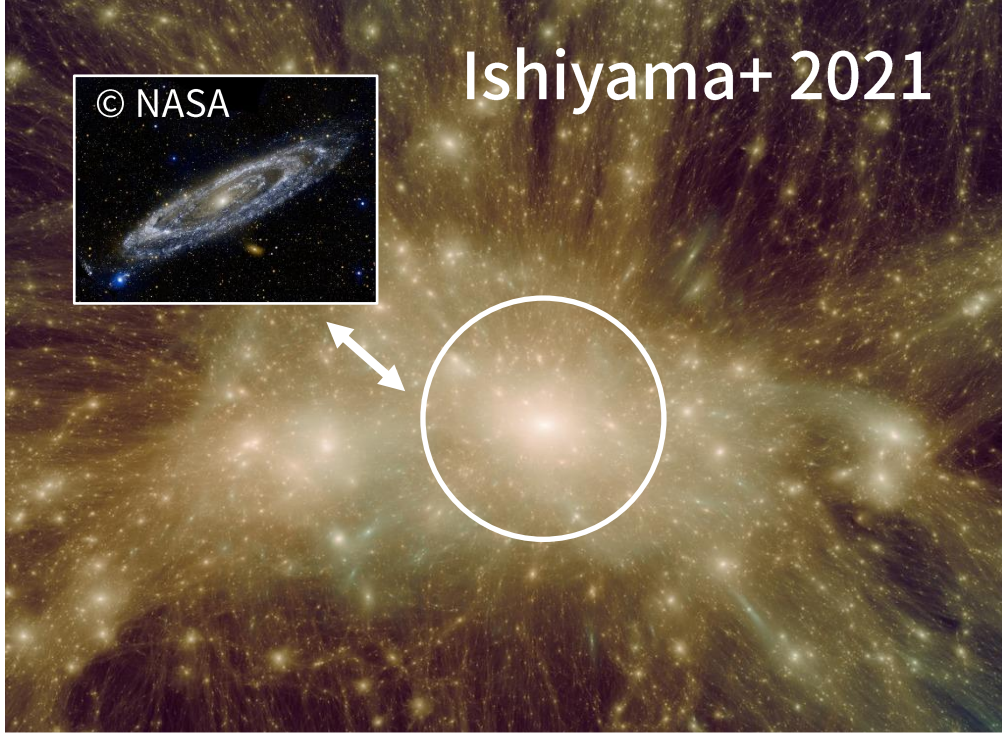
- **Central cusp**
  - Einasto profile or NFW profile

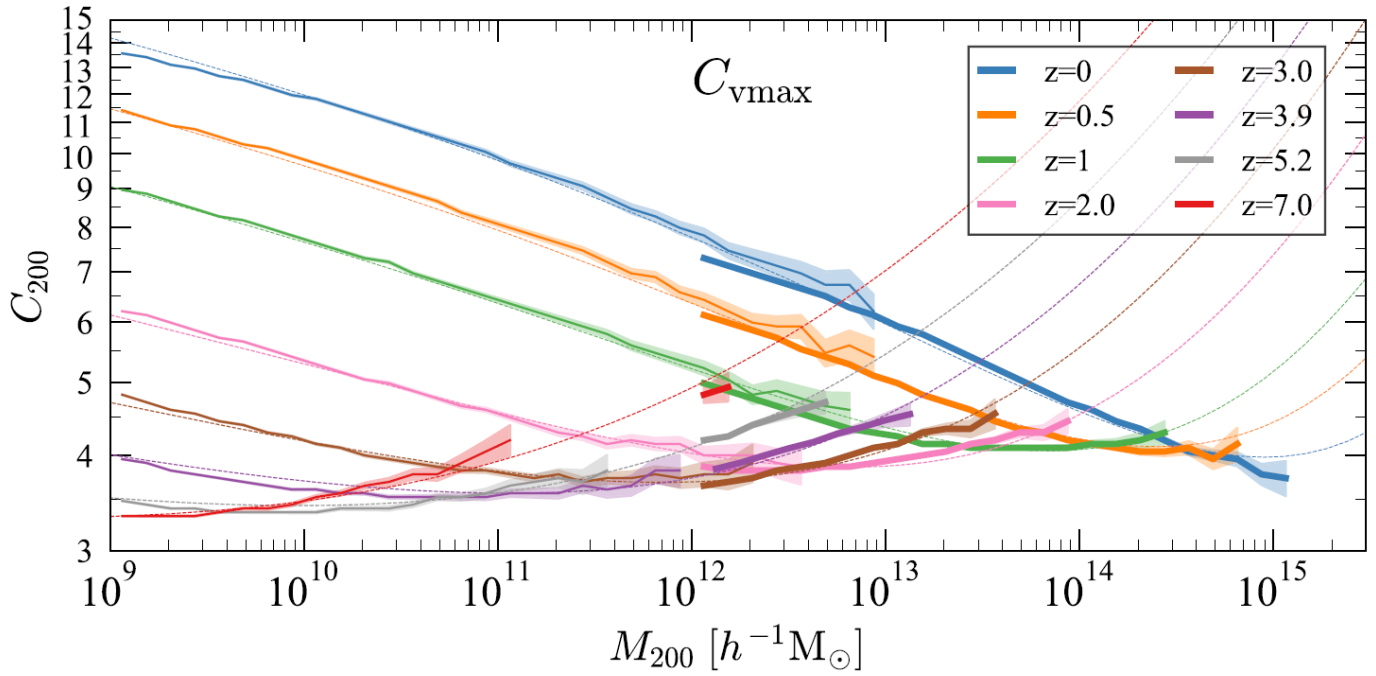
$$\rho(r) = \frac{\rho_{\rm s}}{(r/r_{\rm s})[1+(r/r_{\rm s})]^2}$$

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

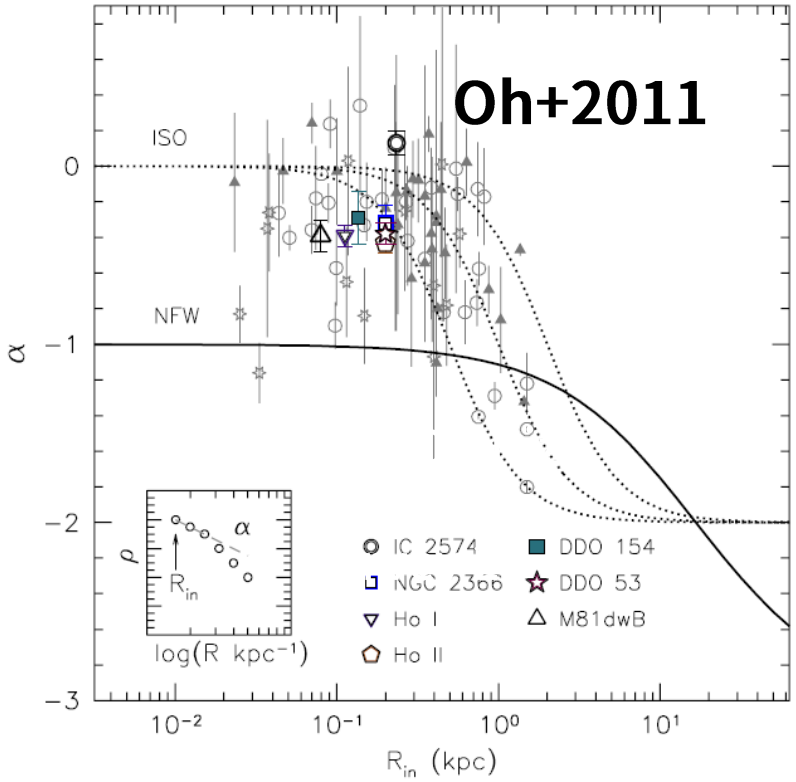
- **Numerous subhalo**
  - $dn/dm \sim m^{-(1.8\sim2)}$
- **Triaxial**
- **Non Universality**
  - Weak dependence on the halo mass
  - halo to halo variation

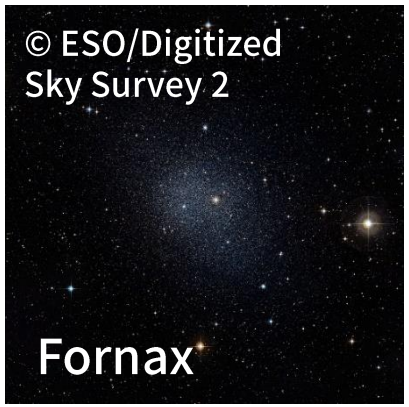
Halo structures can impact on galaxy formation physics





Core cusp problem

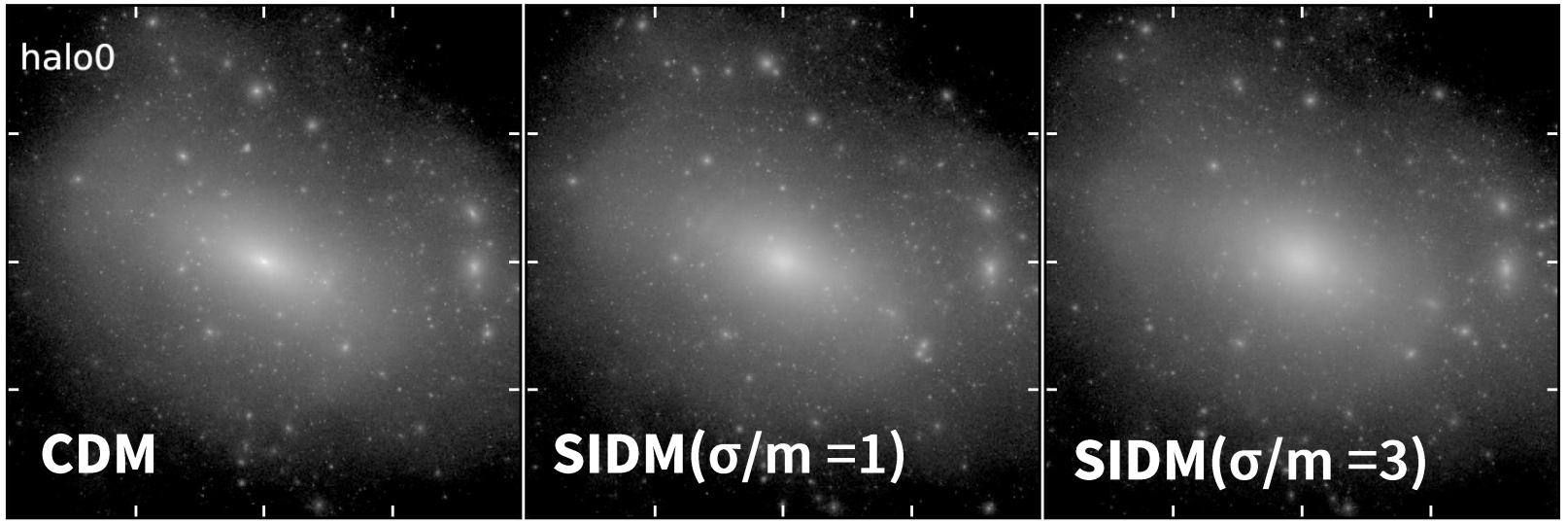




- The central slopes of low surface brightness and dwarf galaxies are around -0.2 ~ 0
- Inconsistent with simulations ? (Core cusp problem)
  - Baryonic effect ?
  - CDM Alternative?
    - Self-Interacting dark matter (SIDM)
    - Warm dark matter (WDM)
    - Fuzzy dark matter (FDM)

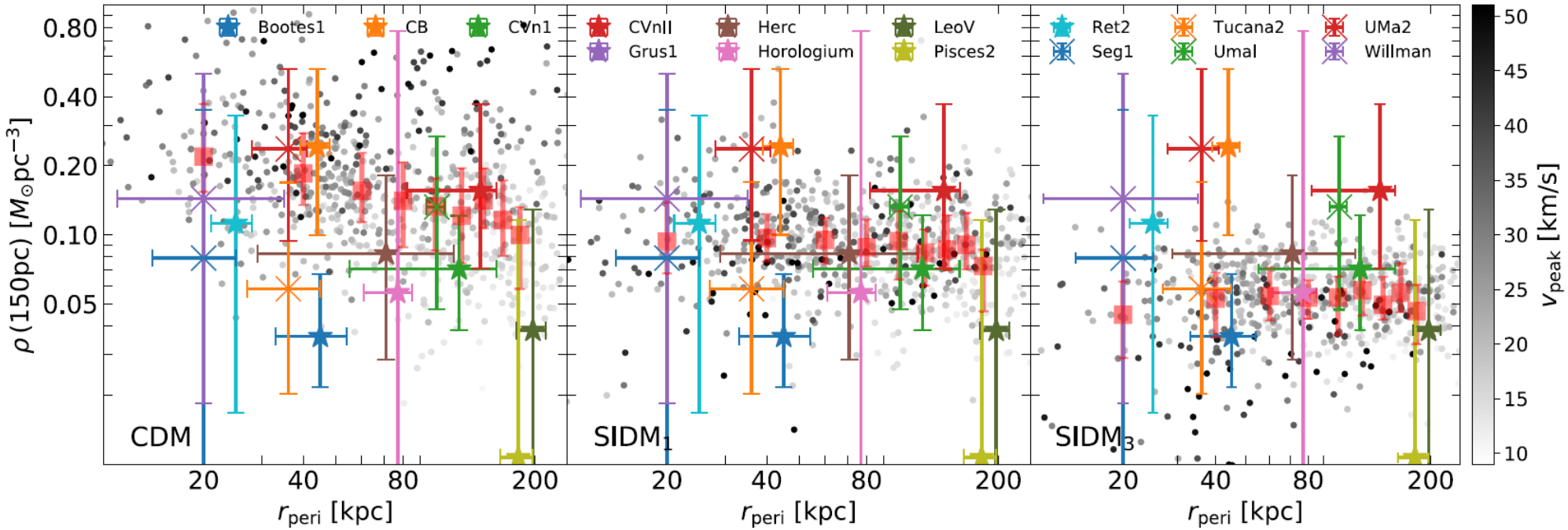
Both mechanisms can coincide and interplay. To remove this degeneracy, it is ideal to study dark matter dominated system such as dwarf spheroidal (dSph) and ultra faint (UFD) galaxies

High-resolution cosmological SIDM simulations



Ebisu, Ishiyama, Hayashi, 2022, PRD

N	1024^3
box size	8 Mpc/h
mass res	4.1 x 10^4 Msun/h
force	100 pc/h



Our project

- New data is coming soon by Subaru PFS

- Higher resolution simulations are necessary
  - Directly resolving density structure at 150 pc
  - We are going to perform such simulations using Fugaku supercomputer by summer 2024

- However, the number of particles of a MW halo exceeds 10^9

⬇

- Public halo/subhalo finders can not handle such ultrahigh resolution halos
  - Memory requirement for such halos > memory of computational node
  - We are now developing a new massively parallel halo/subhalo finder

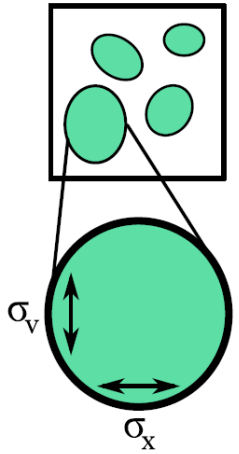
Necessary functions of a new finder

- MPI + OpenMP parallelization for modern supercomputers
- Good parallel scaling beyond 10,000 parallel processes
- Finding subhalos of a halo using multiple computational processes to overcome the memory issue
  - In public finders, a halo can not be distributed into multiple processes
- Providing more halo properties, such as the halo intermediate axis
- Making public
- (desirable) Can run on the fly
- (desirable) Can also find galaxies for cosmological galaxy formation simulations

- We decided to modify Rockstar (Behroozi+2013) halo/subhalo finder
  - One of the most commonly used finder
  - Using phase space information, namely, accurate

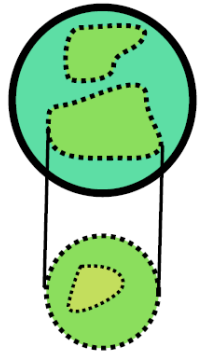
Rockstar algorithm

- 3D parallel FoF
  - A FoF group (consists of halos and subhalos) can distribute into multiple processes
- Re-distribute particles on all processes as all particles of a FoF group are in the same process
- Halo/subhalo finding for each FoF group
  - A FoF group can't be analyzed by multiple processes
- The parallelization is implemented using a socket library, not standard MPI and OpenMP
  - Without collective communication. Slow
  - Depending on machines, the number of simultaneous connections is limited



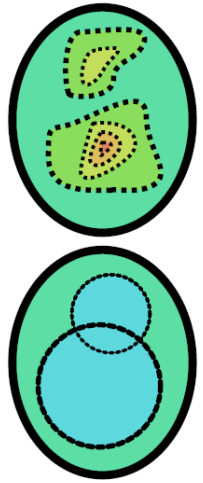
1. The simulation volume is divided into 3D Friends-of-Friends groups for easy parallelization.

2. For each group, particle positions and velocities are divided (normalized) by the group position and velocity dispersions, giving a natural phase-space metric.



3. A phase-space linking length is adaptively chosen such that 70% of the groups particles are linked together in subgroups.

4. The process repeats for each subgroup: renormalization, a new linking-length, and a new level of substructure calculated.



5. Once all levels of substructure are found, seed halos are placed at the lowest substructure levels and particles are assigned hierarchically to the closest seed halo in phase space.

6. Once particles have been assigned to halos, unbound particles are removed and halo properties (positions, velocities, etc.) are calculated.

Behroozi+2013

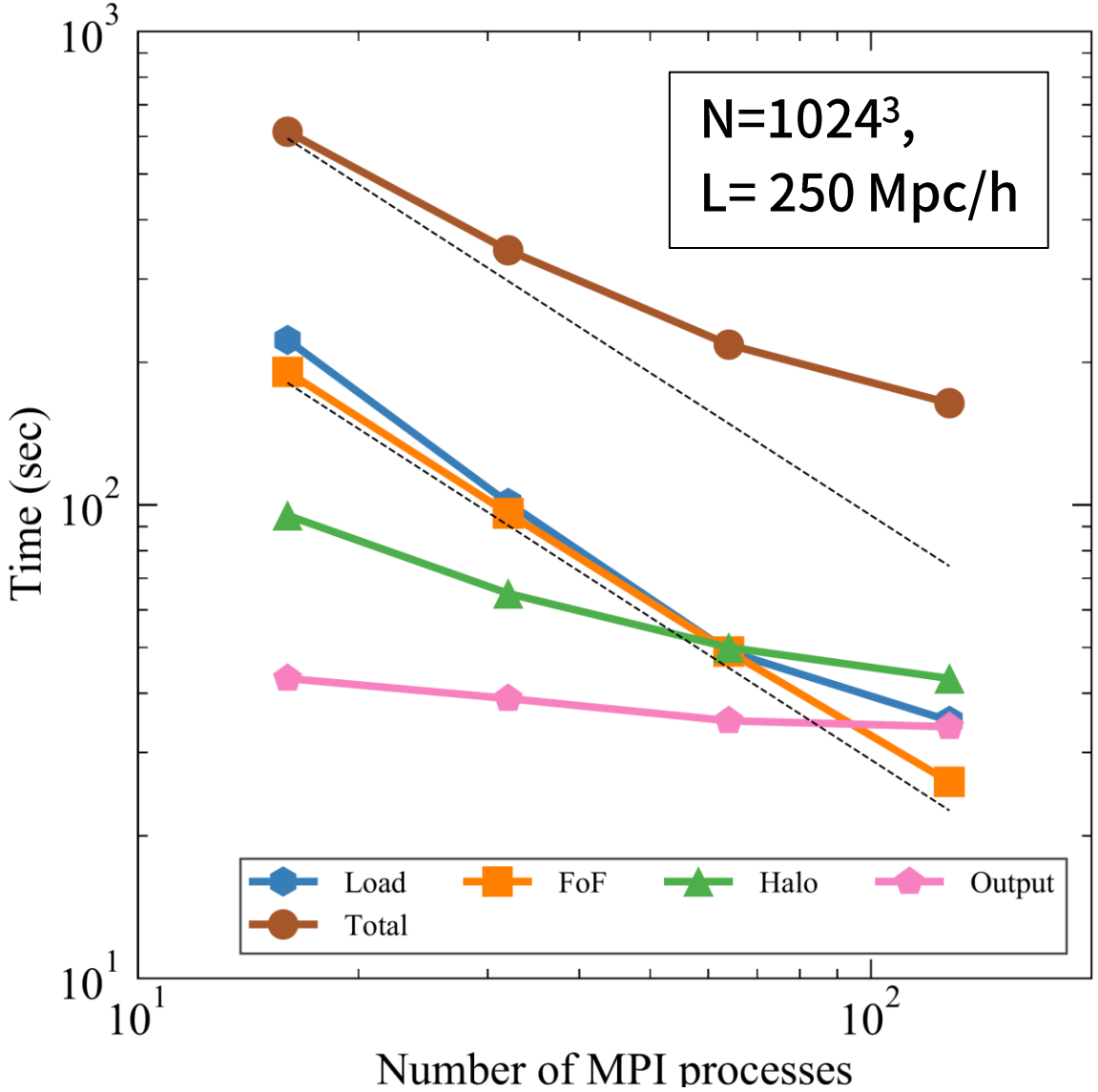
MPI+OpenMP Hybrid parallelization

Mainly done by Tomoyuki Tokuue (M2 at Chiba University)

- 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
  - Each MPI process can simultaneously perform the halo/subhalo finding for *p* FoF groups, where *p* is the number of threads
  - Currently, a FoF group can’t be analyzed by multiple processes as the original Rockstar

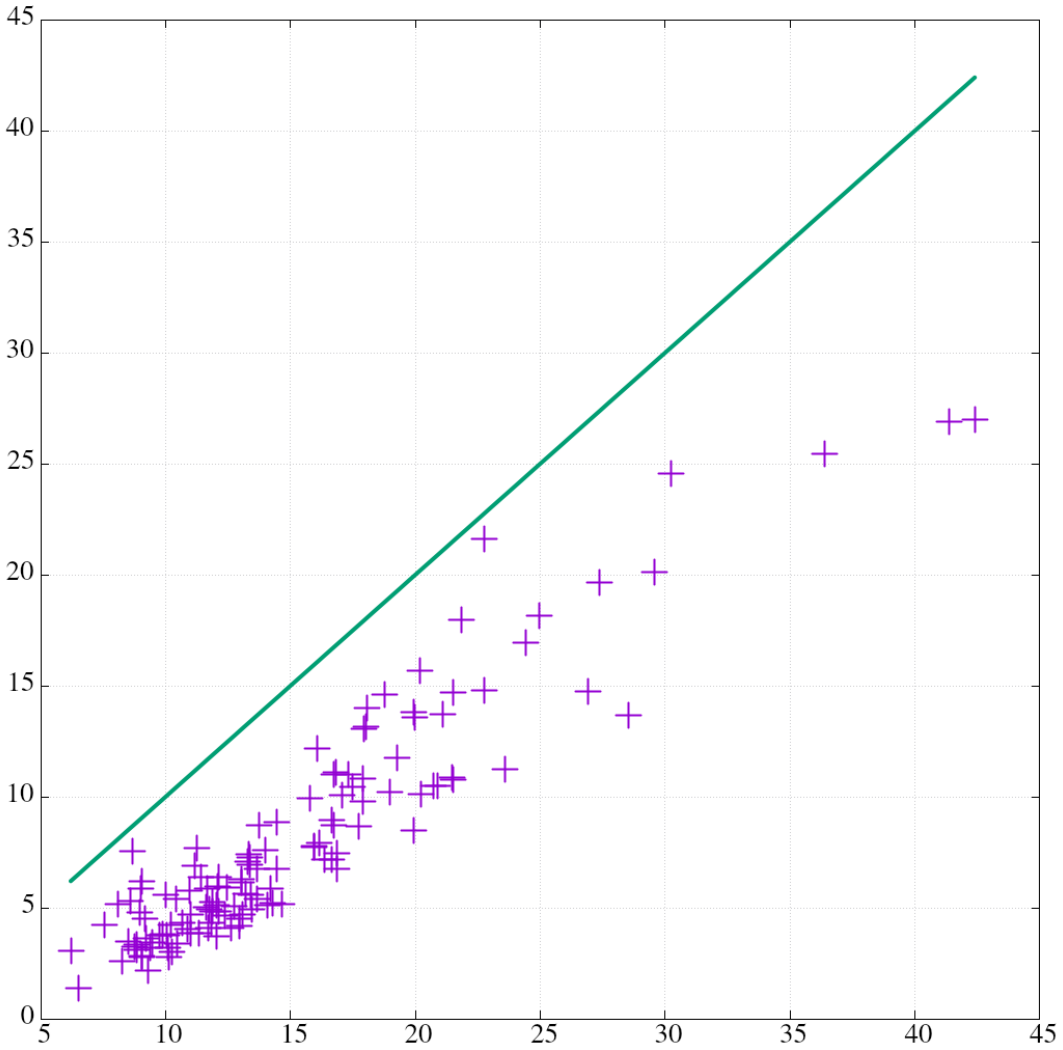
Current status and Performance on Fugaku

- It's actually running on Fugaku by MPI+OpenMP hybrid way !
- Can run up to N=2560^3 due to a memory issue
  - A node of Fugaku has only 32 GB memory per node
  - Can be solved soon
- Load balance is good if the number of particles per process is > 16M



(12 threads (CPU cores) per MPI process)

The reason of load imbalance



- The total time of halo/subhalo finding on each process (x-axis) versus the maximum time of finding for a FoF group in the process (y-axis)
- The most of time is occupied by analysis of a part of big groups
- The original Rockstar has the same issue
- Can be reduced by hierarchical parallelization

Summary

- MPI + OpenMP parallelization for modern supercomputers, **DONE**
- Good parallel scaling beyond 10,000 parallel processes, under development
- Finding subhalos of a halo using multiple computational processes to overcome the memory issue
  - In public finders, a halo can not be distributed into multiple processes, start to work soon
- Providing more halo properties, such as the halo intermediate axis, **DONE**
- Making public, hopefully by summer