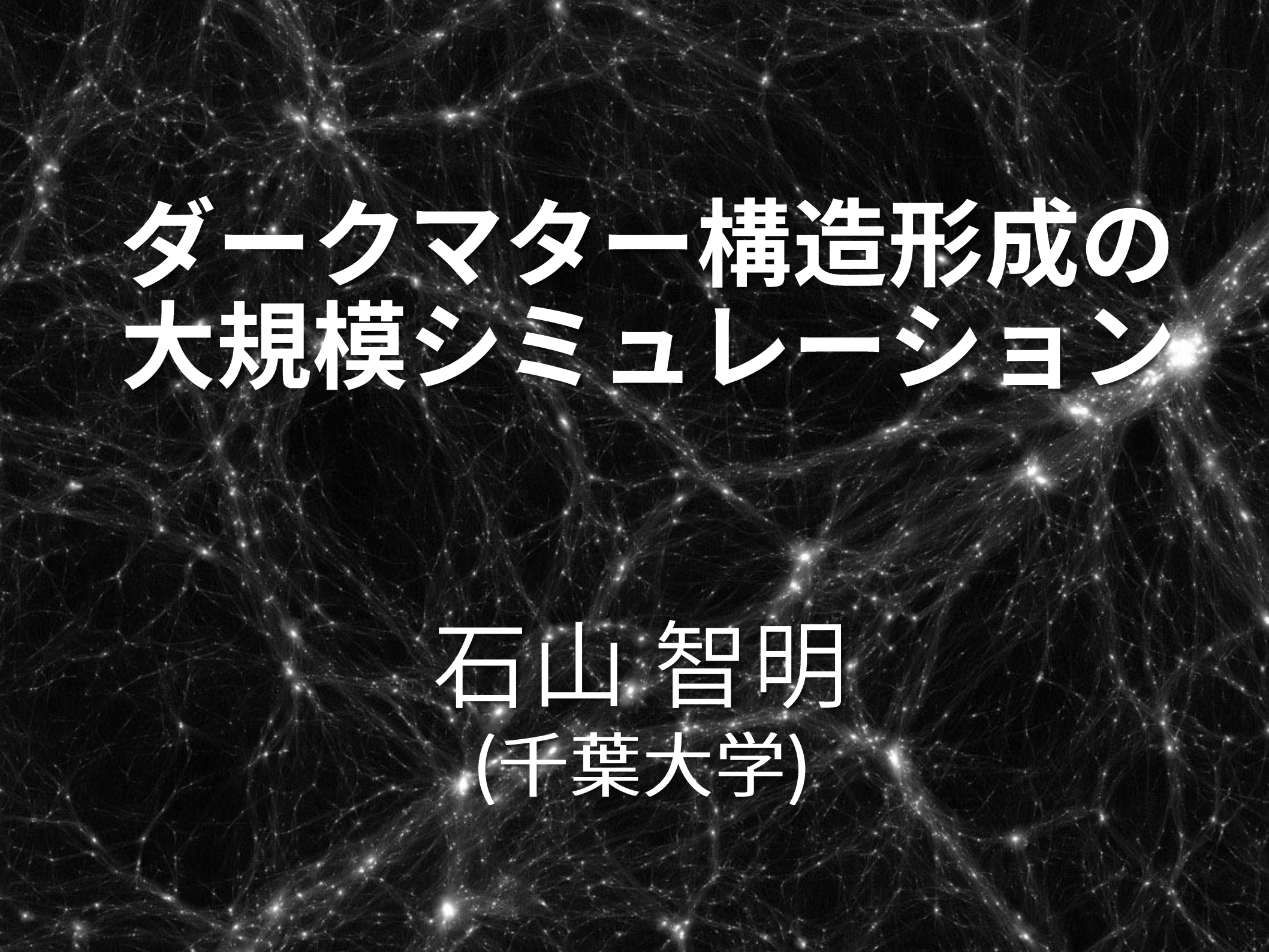


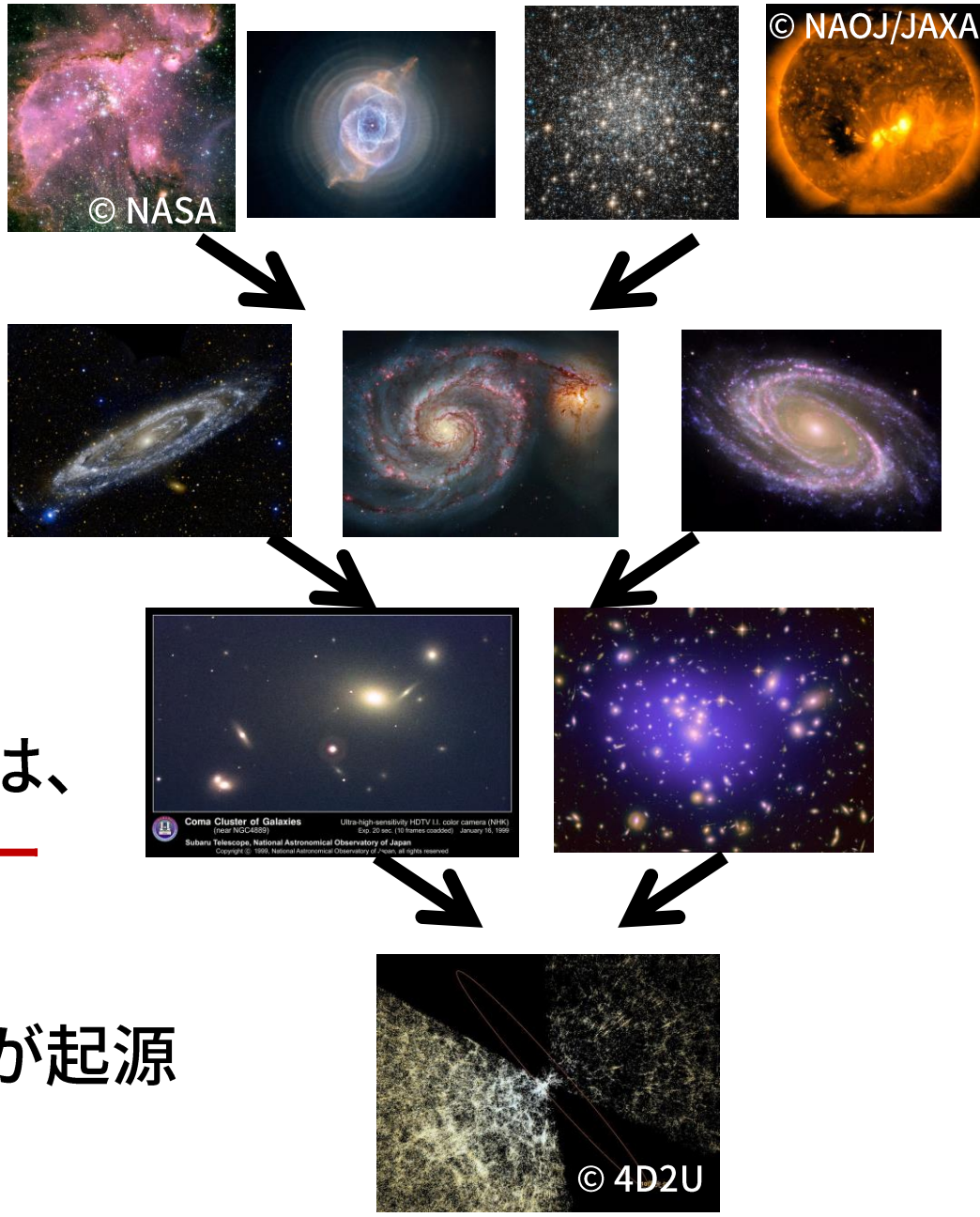
ダークマター構造形成の大規模シミュレーション

石山 智明
(千葉大学)

Hierarchical Universe

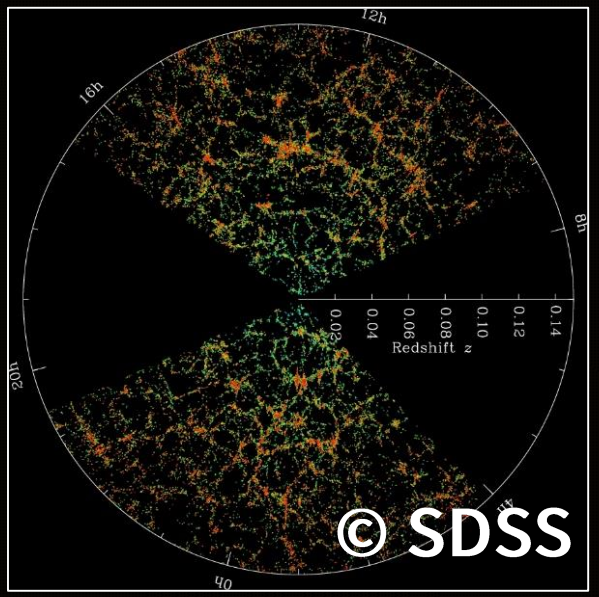
- 星の集団 = 銀河
- 銀河の集団 = 銀河団
- 銀河、銀河団の集合 =
  宇宙の大規模構造

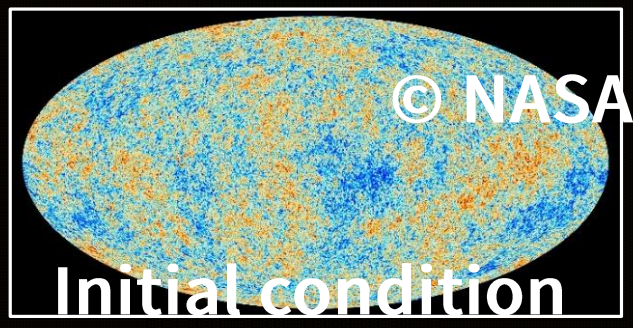
  宇宙の構造は階層的



- これらの階層的な構造形成には、
  重力のみ作用するダークマター
  (暗黒物質)が必要不可欠
- 宇宙初期の微小な密度揺らぎが起源

Large scale structure formation

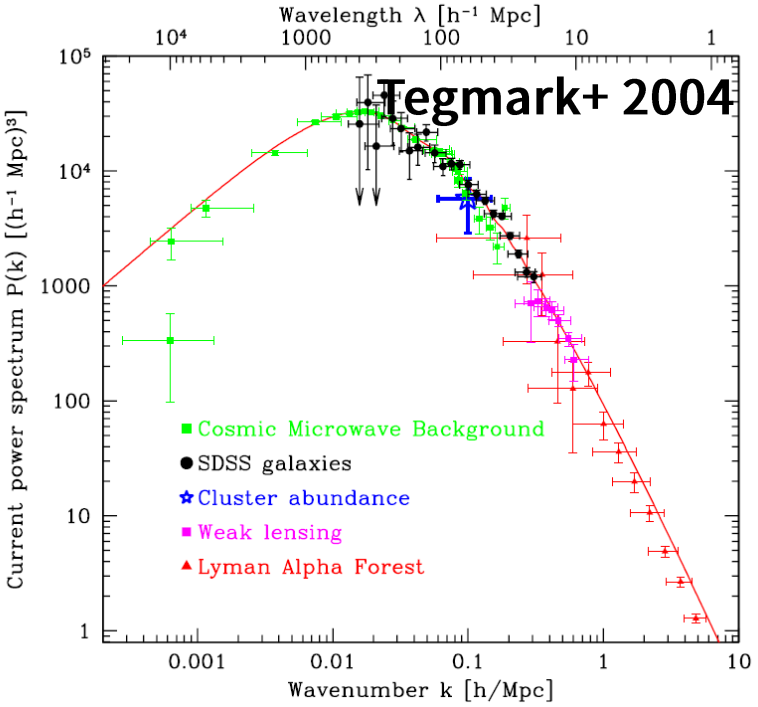


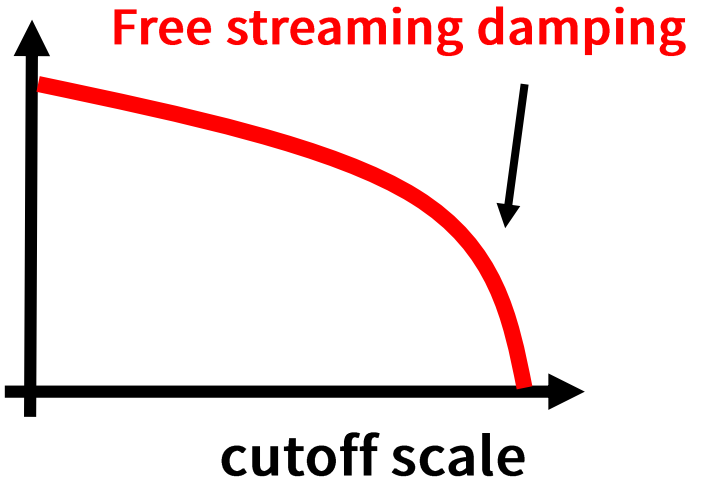


360 degree panoramic video for head mounted display
is available on http://4d2u.nao.ac.jp/English/

Connection to multi scale objects

- 100Mpc～Gpc
  - large scale structure (cosmological information)
- Galactic halo (~10^{12} Msun, ~ Mpc)
  - galaxy formation
  - dark matter detection
- $10^{5\text{-}7}$ Msun halo
  - first star, BH seed?, first galaxy
- The smallest halo
  - Nature of dark matter
  - dark matter detection



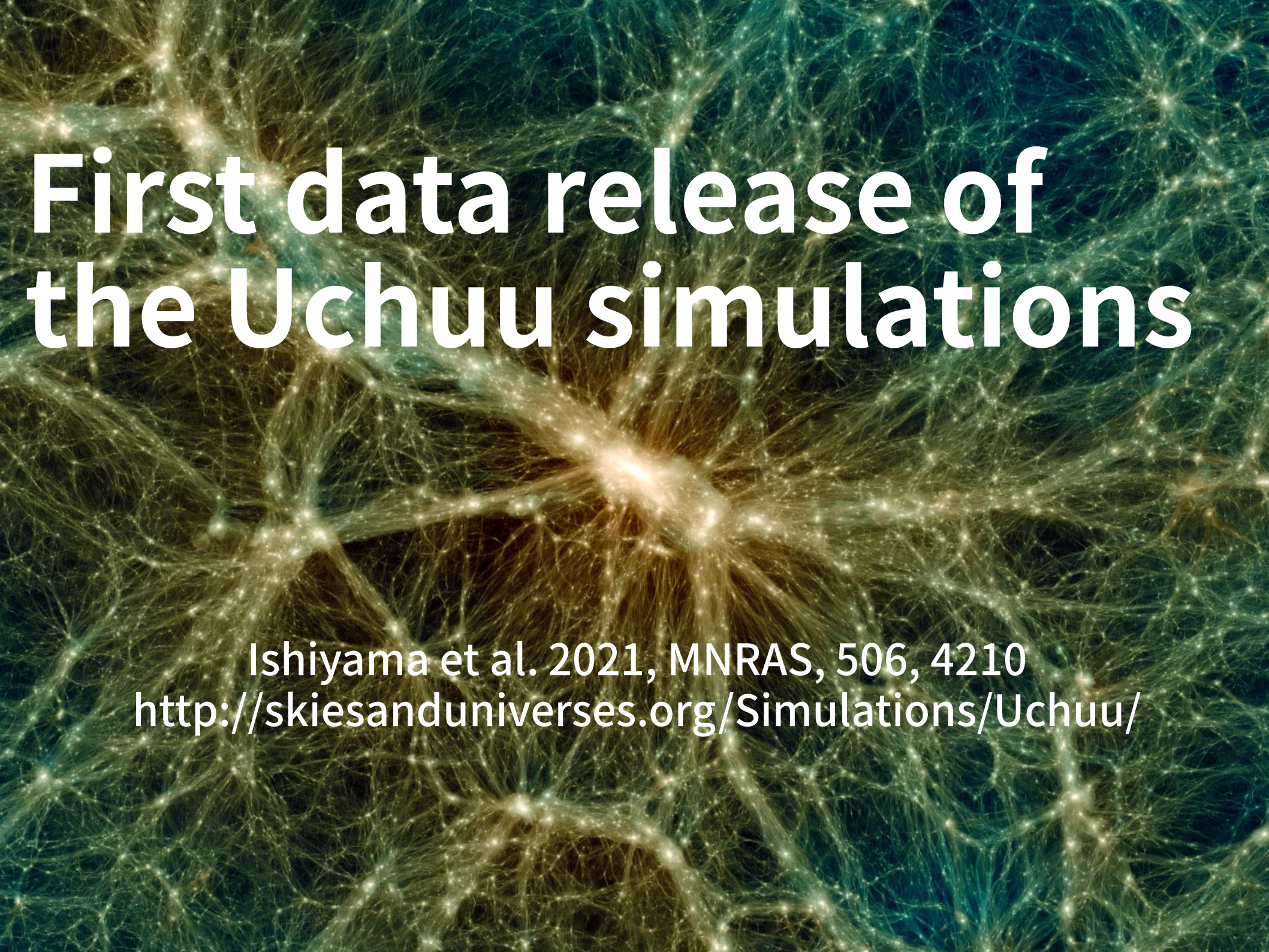


ダークマターシミュレーション

- ダークマターは光学的に直接観測できない

- ハローの内部構造や空間分布を知るにはシミュレーションをするしかない
  - ハローの空間分布 = 観測量である大規模構造、銀河の分布
  - 内部構造はハローの中の天体形成進化そのものに関連し得る

- 宇宙の統計的な初期条件は宇宙マイクロ波背景放射の観測などからよく制限されている



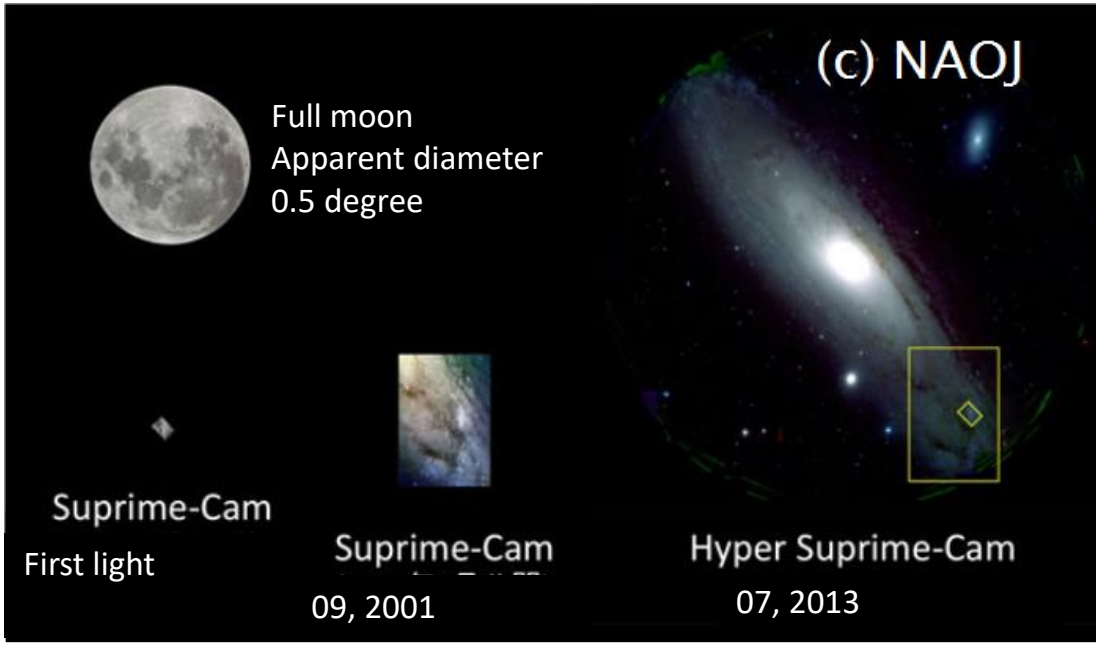
First data release of the Uchuu simulations

Ishiyama et al. 2021, MNRAS, 506, 4210
http://skiesanduniverses.org/Simulations/Uchuu/

Next generation mock galaxy/AGN catalogs

- Ongoing wide/deep surveys (e.g., HSC and PFS on Subaru telescope, Euclid, etc) give extremely large dataset of galaxies/AGNs
  - Survey areas are over 1Gpc
  - Number density of bright AGNs at high redshift
    → < 10^{-6} Mpc^{-3}

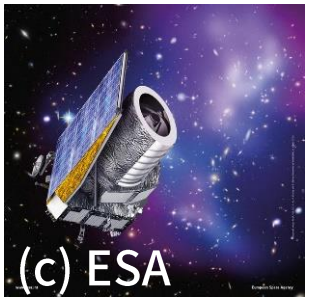
→ Gpc scale mocks



→ **Large numerical simulations** are necessary to construct mocks
  - Cosmological Hydrodynamical simulations (~100 Mpc scale)
  - **Large cosmological N-body simulations (~Gpc scale) with**
    - Empirical models (UniverseMachine, HOD, Abundance matching)
    - Semi analytic galaxy/AGN formation model

Project overview

- Perform huge cosmological N-body simulations
- Provide halo/subhalo catalogs and mock galaxy/AGN catalogs for next-generation wide/deep surveys



- Use several models to construct mock catalogs for community
  - ν^2GC, SAGE, SAG
  - UniverseMachine, HOD, SHAM

Core member

- Bruno Altieri (ESAC) *
- Sofia Cora (Buenos Aires) *
- Darren Croton (Melbourne) *
- Eric Jullo (Marseille) *
- Tomoaki Ishiyama (Chiba) **
- Anatoly Klypin (Virginia) *
- Ben Metcalf (Bologna)
- David Millan (Granada)
- Taira Oogi (Chiba)
- Francisco Prada (Granada) **
- Manodeep Sinha (Melbourne)
- Sylvain De la Torre (Marseille)
- Cristian Vega (La Serena)
- and many other collaborators

** Co-PI, * core board

Worldwide collaboration based on simulations conducted on Japanese supercomputers

Core member & data mirror

Core member

Marseille

Bologna

Granada

Madrid

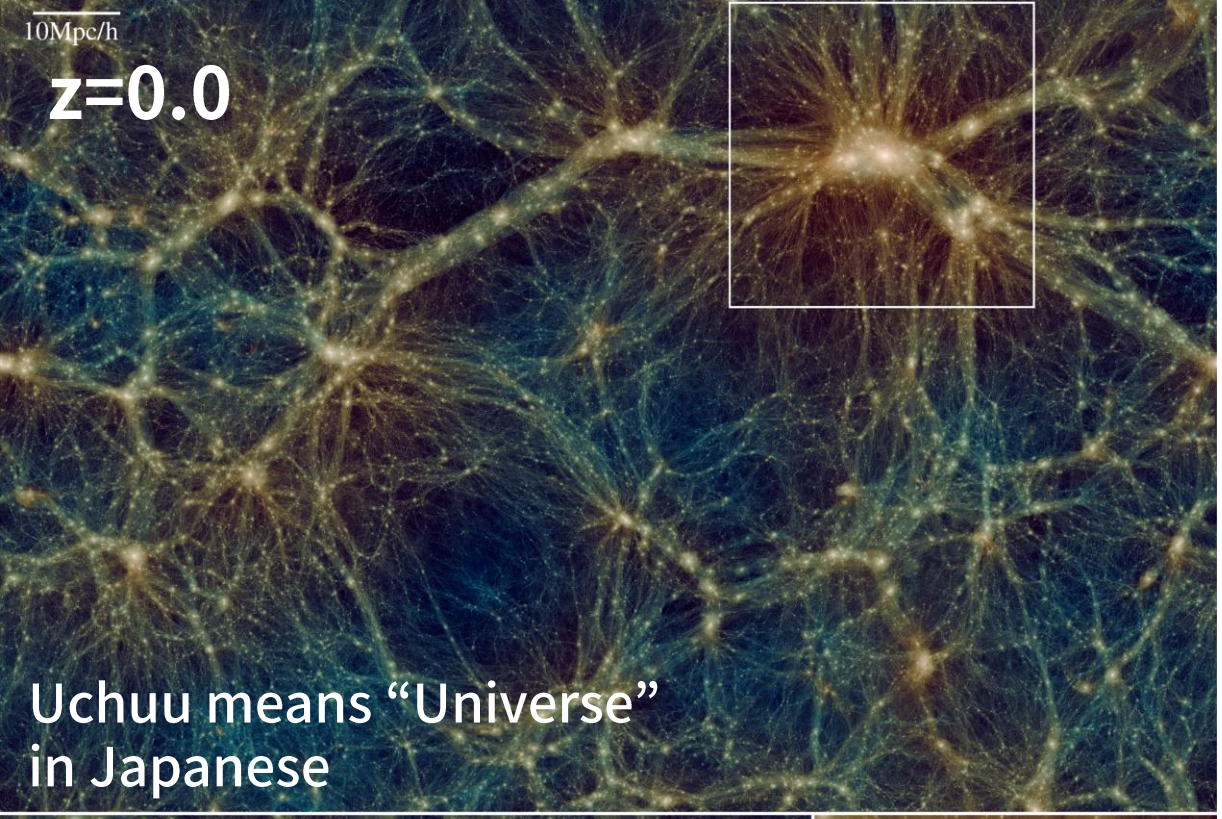
Chiba

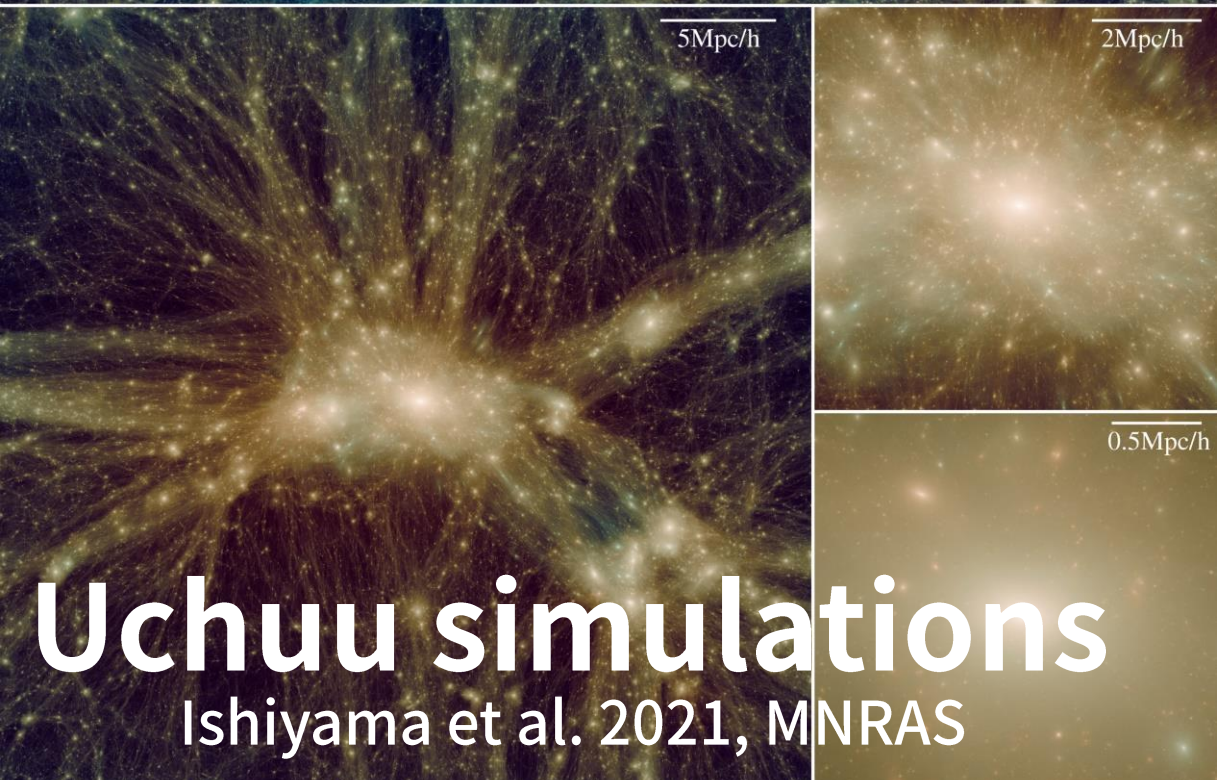
Virginia

La Serena

Buenos Aires

Melbourne





Name	N	L (h^{-1}Mpc)
Uchuu	12800^3	2000.0
mini-Uchuu	2560^3	400.0
micro-Uchuu	640^3	100.0
Shin-Uchuu	6400^3	140.0

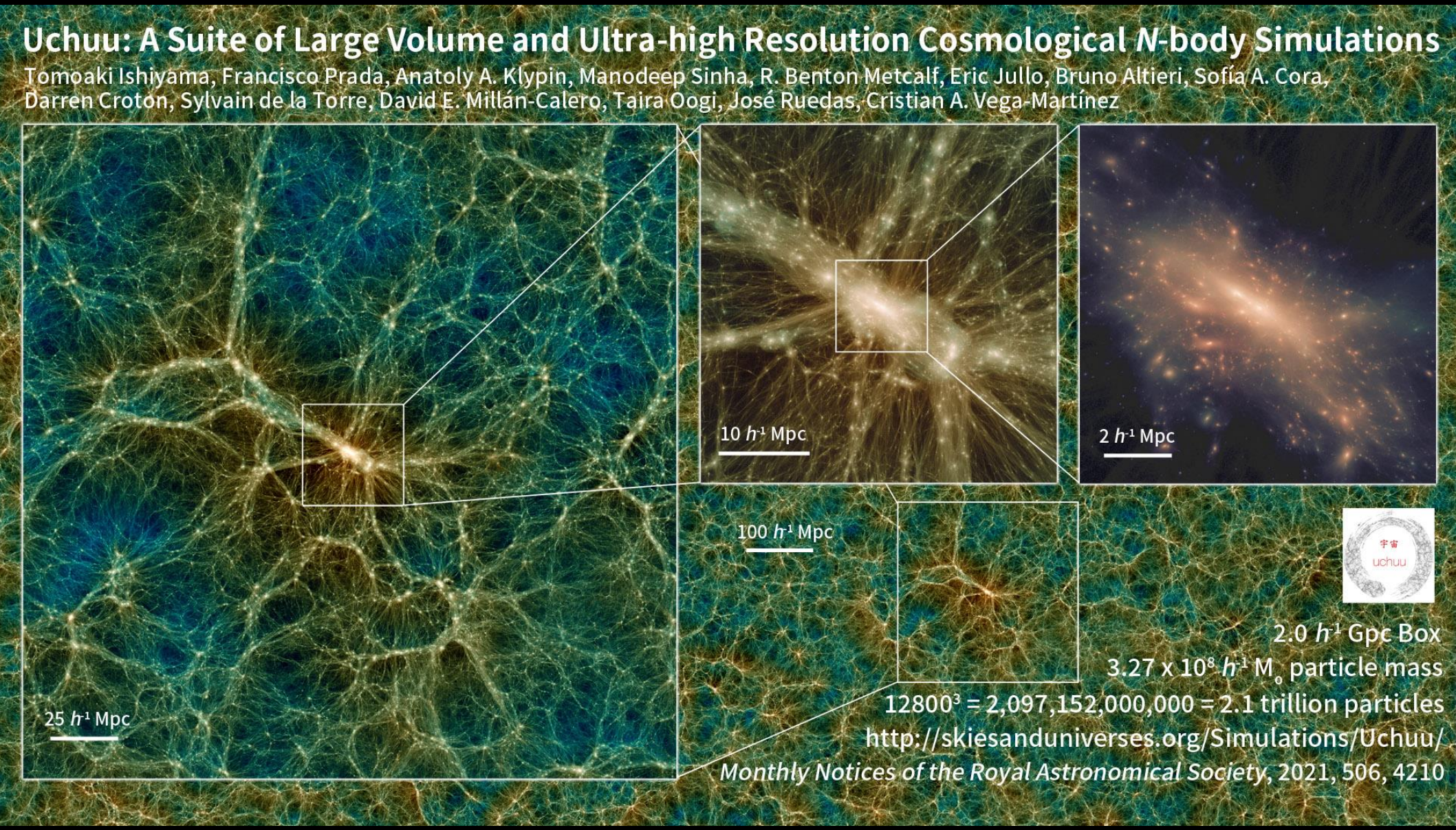
The largest N = $12{,}800^3$ = 2,097,152,000,000

m_{Uchuu} = 3.27 x 10^8 Msun/h
$m_{ShinUchuu}$ = 8.97 x 10^5 Msun/h

Planck Cosmology

Data size (50 snapshots):
Raw particle : ~2PB
Merger tree: ~30TB (HDF5)

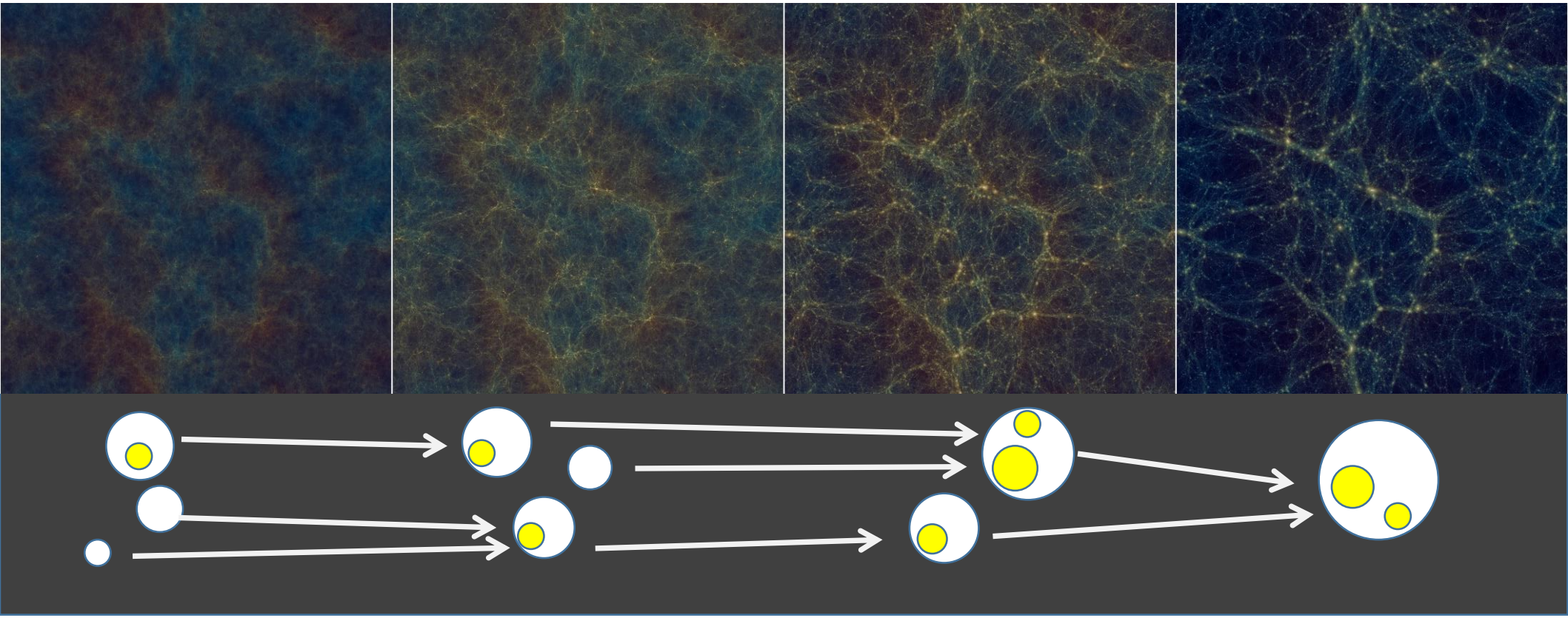
64 x larger volume,
3 x better mass res, compared to Millennium Run
(WMAP1 cosmology)



Uchuu high-resolution images:
http://hpc.imit.chiba-u.jp/~ishiymtm/UchuuPress/

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

Halo catalogs and merger trees



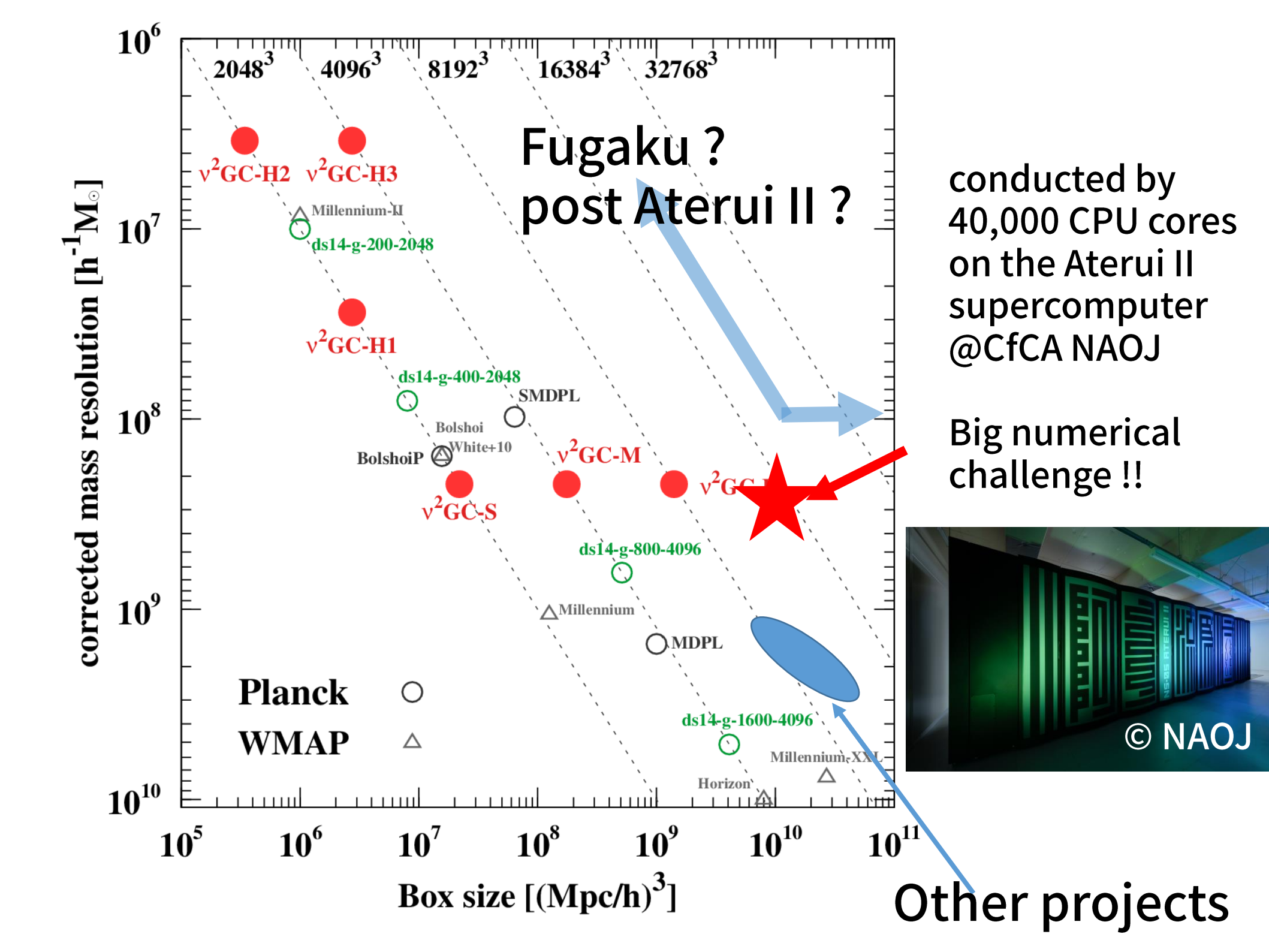
- Identify halos/subhalos at 50 redshifts
  - Halo catalogs: list of halos/subhaloes with many properties such as mass, position, velocity, internal structures (circular velocity peak, scale radius, shape, angular momentum .....)
- Construct progenitor/descendant relationship across redshifts
  - so called merger tree

Enable to reduce data size (by a factor of ~100) and get halo/subhalo information easier !!!

How unique is the Uchuu?

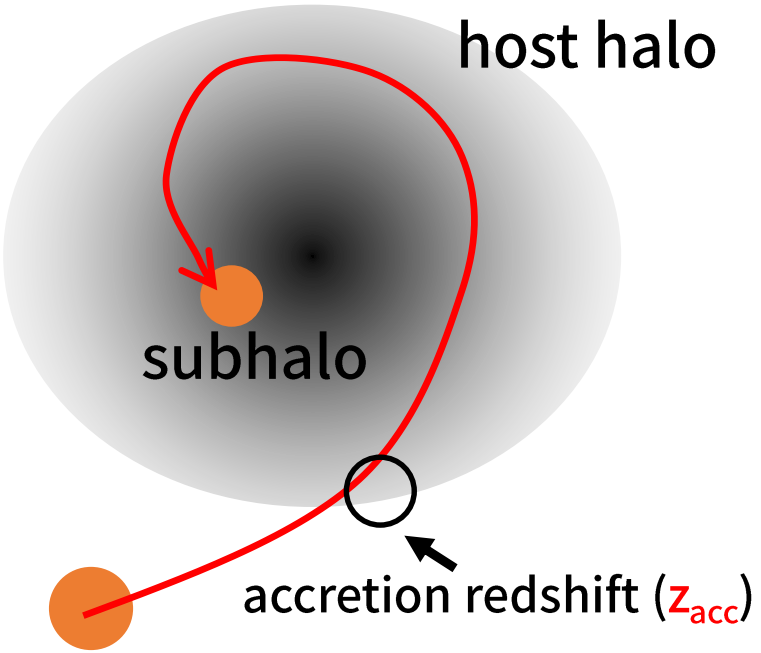
- Only the Uchuu satisfies both conditions
  - Mass resolution is high enough to resolve small galaxies
  - Simulation volume is comparable to next-generation surveys volume

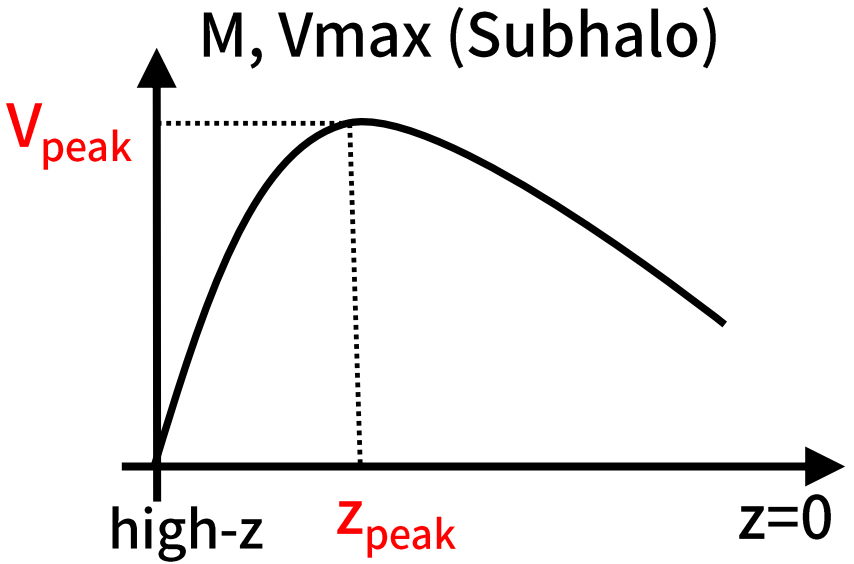
- Merger trees are available
  - Similar projects have never been able to provide merger trees because merger tree construction for big simulations is also numerically challenging
  - To do it, we develop an extention of the Rockstar halo/subhalo finder and the consistent trees code (Behroozi+ 2013)


2048^3
4096^3
8192^3
16384^3
32768^3
ν²GC-H2
ν²GC-H3
Millennium-II
ds14-g-200-2048
ν²GC-H1
ds14-g-400-2048
SMDPL
Bolshoi
BolshoiP
White+10
ν²GC-M
ν²GC-S
ds14-g-800-4096
Millennium
MDPL
Planck
WMAP
ds14-g-1600-4096
Millennium-XXL
Horizon
corrected mass resolution [h⁻¹M⊙]
Box size [(Mpc/h)³]
Fugaku ?
post Aterui II ?
conducted by
40,000 CPU cores
on the Aterui II
supercomputer
@CfCA NAOJ
Big numerical
challenge !!
© NAOJ
Other projects

Extending halo catalogs for easy mock constructions

- Most empirical models use subhalo's V_{peak}, M_{peak}, z_{peak}, V_{acc}, M_{acc}, z_{acc} ..... as proxies of galaxy formation
- All these quantities can be derived only analyzing merger trees
- We pre-calculated these important quantities and include them into halo catalogs
  - Drastically reduce analysis cost and data size
  - Easy construction of mock catalogs using SHAM





http://skiesanduniverses.org/Simulations/Uchuu/

Data products and release schedule

- DR1 data (~125 TB in total) : **released on July 28th, 2020**
  - **Rockstar halo/subhalo catalogs (including Vpeak, Vacc, Mpeak)**
  - **Merger trees**
  - **Random sample of particles (0.5%)**
  - **Codes for analysis (python)**

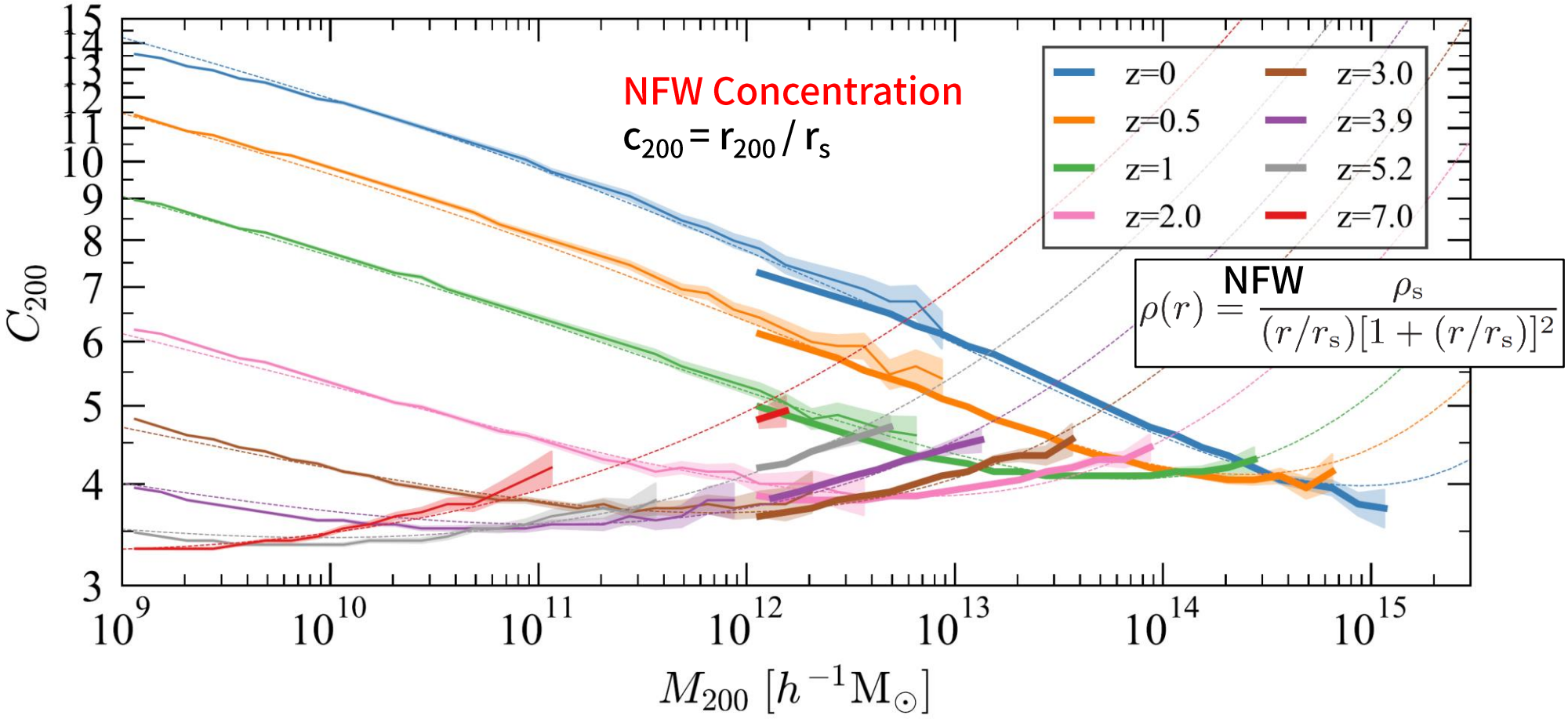
- DR2: **late 2021 ~ early 2022**
  - Uchuu + UniverseMachine mock (empirical model)
  - Uchuu + ν^2GC mock (semi-anatlytic)
- DR3?
  - Uchuu + SAGE mock (semi-anatlytic)

HDF5 files are provided

Applications

Ishiyama et al. 2021, MNRAS, 506, 4210

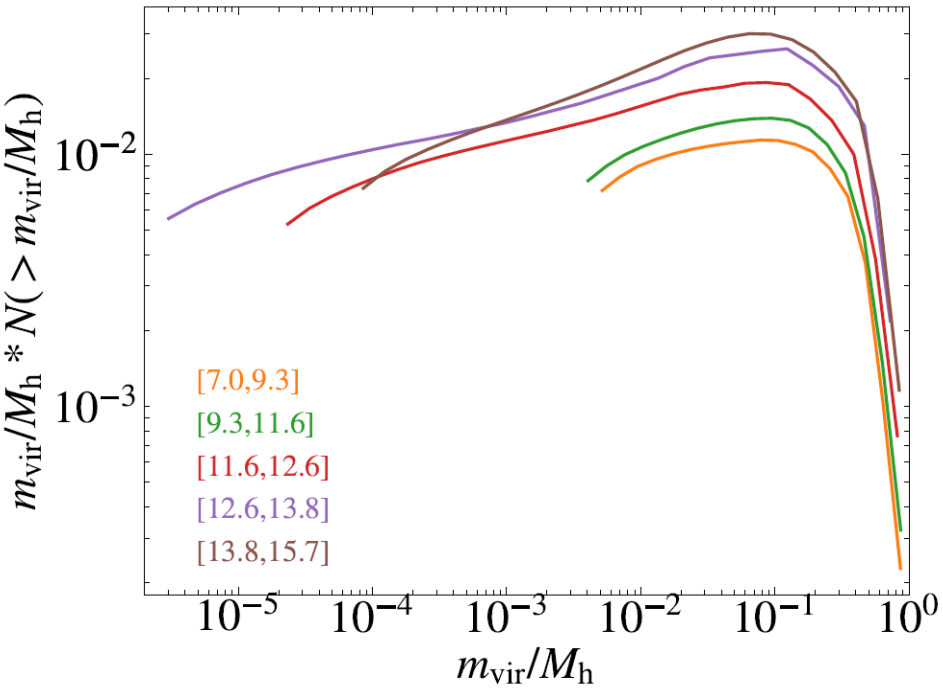
mass-concentration relation

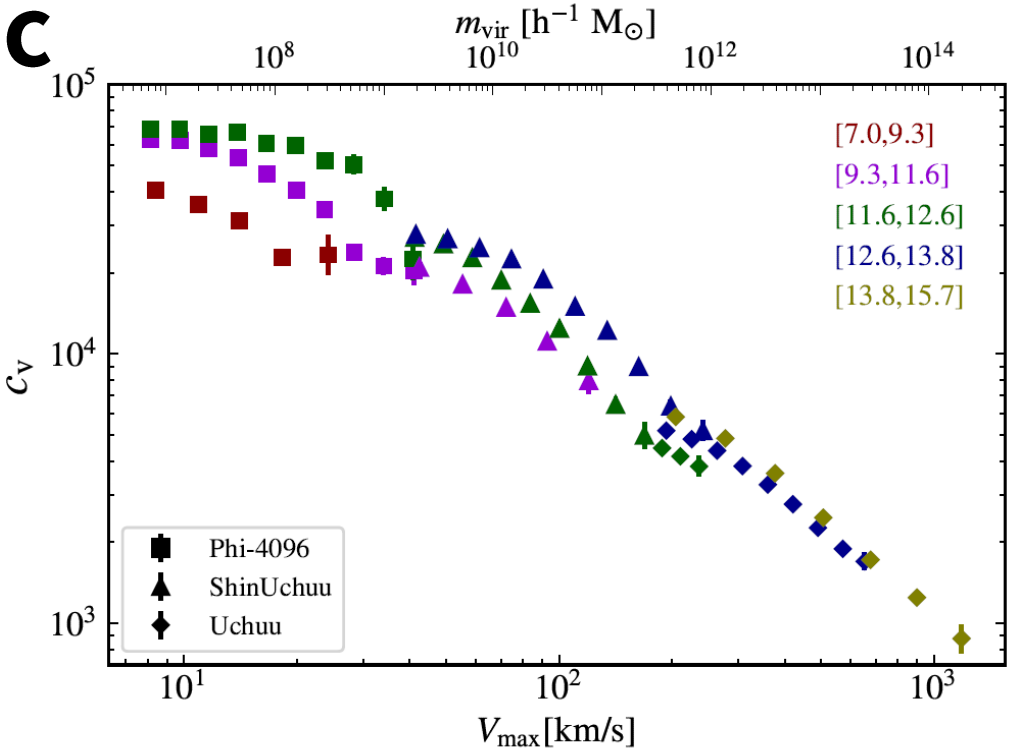


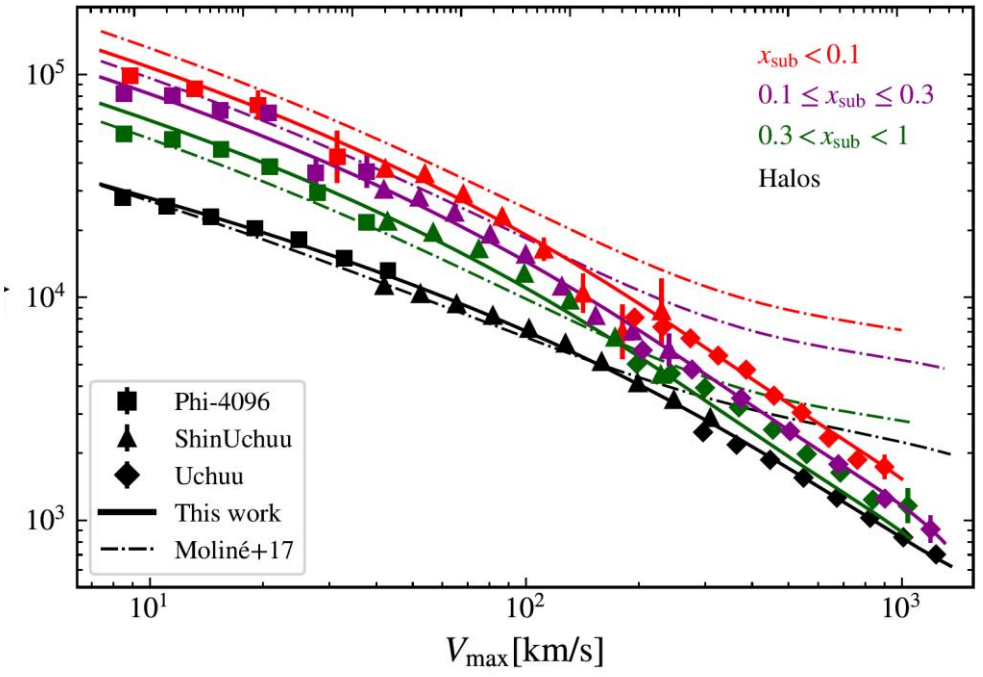
- We provide a mass-concentration model, which reproduces data within 5% error for haloes with $10^{7\text{-}15}$ M_{sun} at $0<z<14$
- Traditional power law fitting is very bad at high mass end in each redshift

Moline, Ishiyama et al., 2021, arXiv: 2110.02097

Subhalo demographic







Name	N	L (h^{-1}Mpc)	m (h^{-1} M$_\odot$)	ε (h^{-1}kpc)
Uchuu	12800^3	2000	3.27×10^8	4.27
ShinUchuu	6400^3	140	8.97×10^5	0.40
Phi-4096	4096^3	16	5.13×10^3	0.06

Ishiyama et al. 2021, MNRAS, 506, 4210

Summary and future

- We are going to provide mock galaxy/AGN catalogs with comparable volume and resolution of next-generation wide/deep surveys

- As DR1, halo/subhalo catalogs, merger trees, and analysis tools (python) are published (~125TB)
  - http://skiesanduniverses.org/Simulations/Uchuu/
  - Including pre-calculated halo evolutional information (Vpeak, Vacc, and so on)

- DR2 will be late 2021 ~ early 2022, which includes galaxies/AGNs constructed by various models