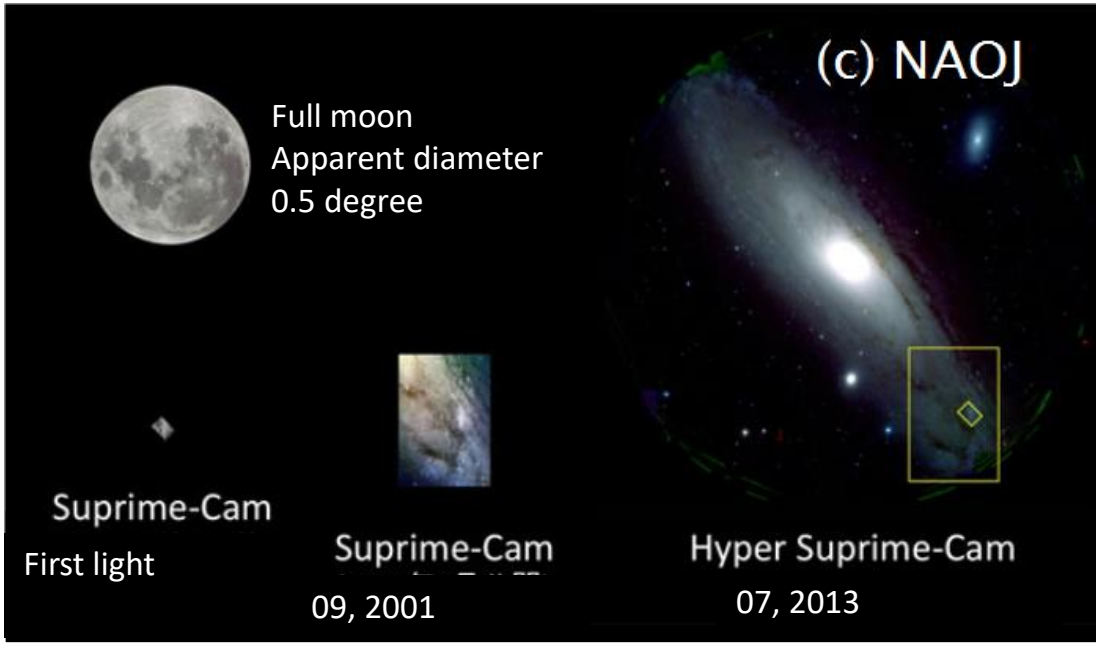
The Uchuu Simulations: DR1の詳細とDR2に向けての状況

石山 智明
(千葉大学)

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}

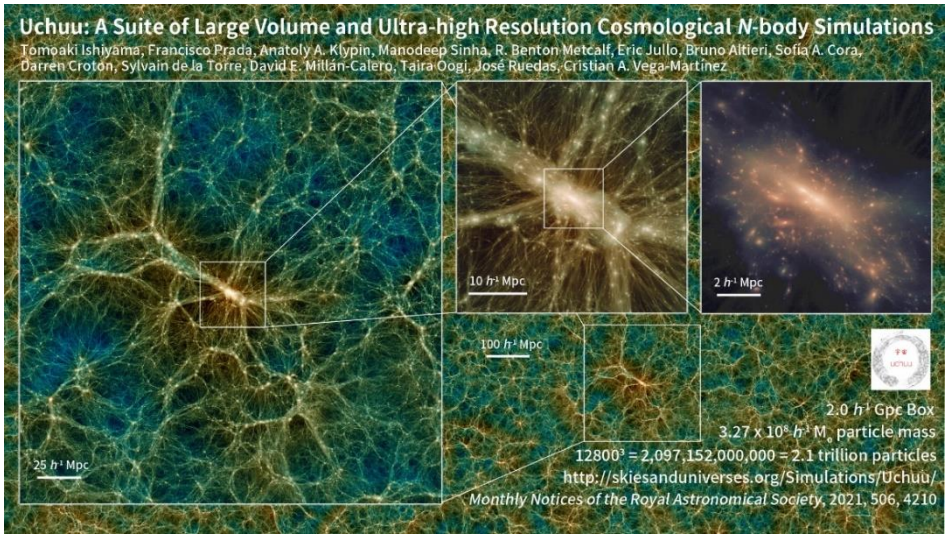
→ Gpc scale mocks



→ **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

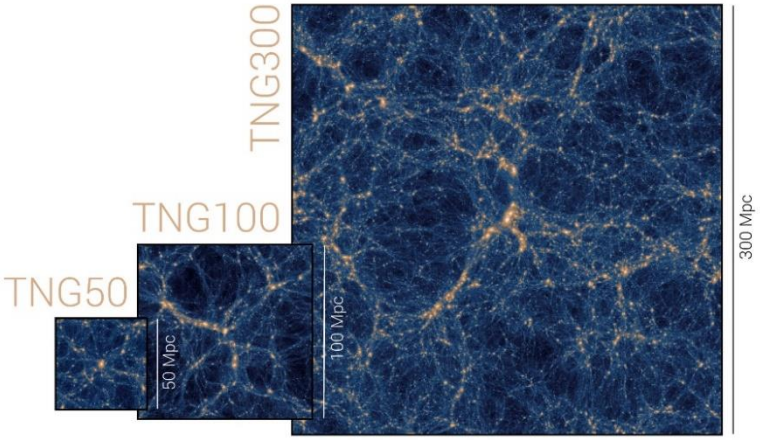
Big numerical challenge

DM only simulations

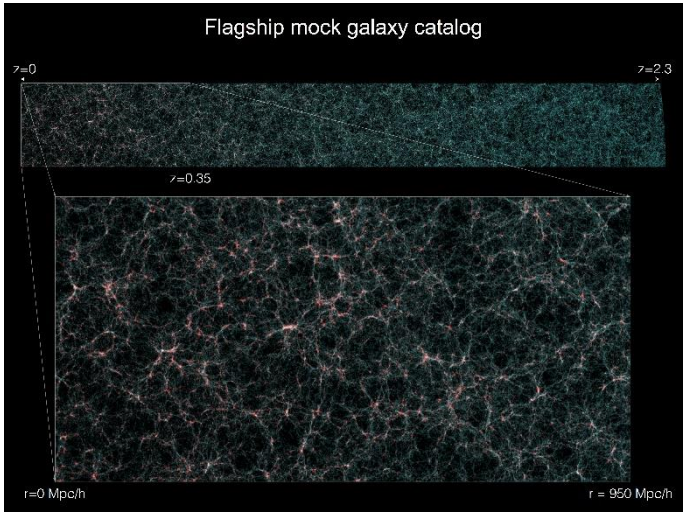


Uchuu simulation

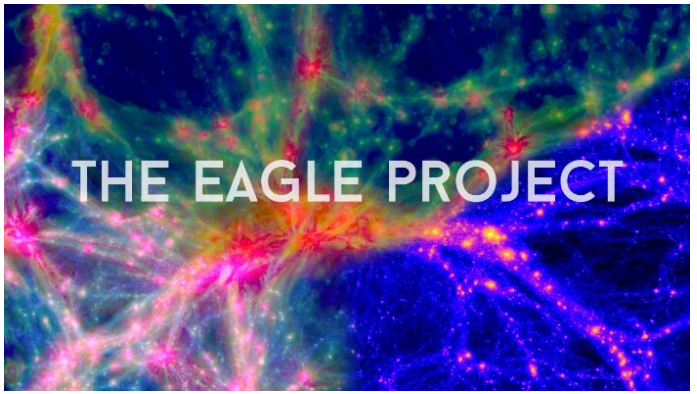
Hydro simulations



Illustris TNG simulation

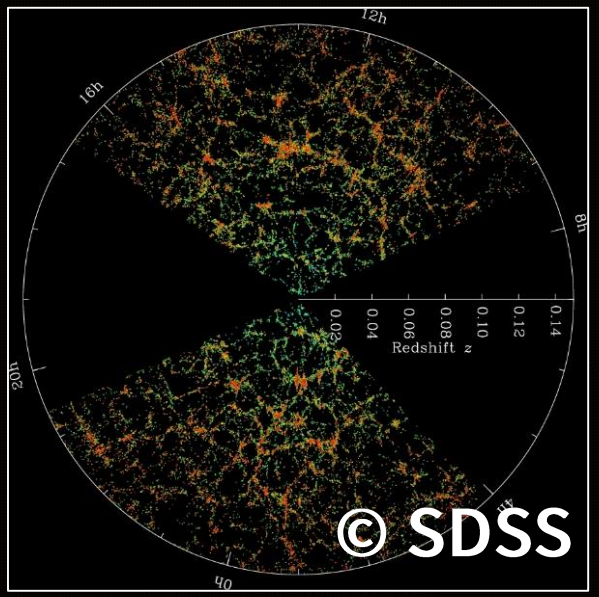


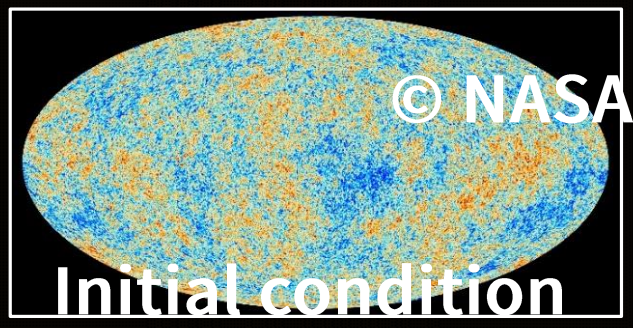
Euclid Flagship simulation



EAGLE simulation

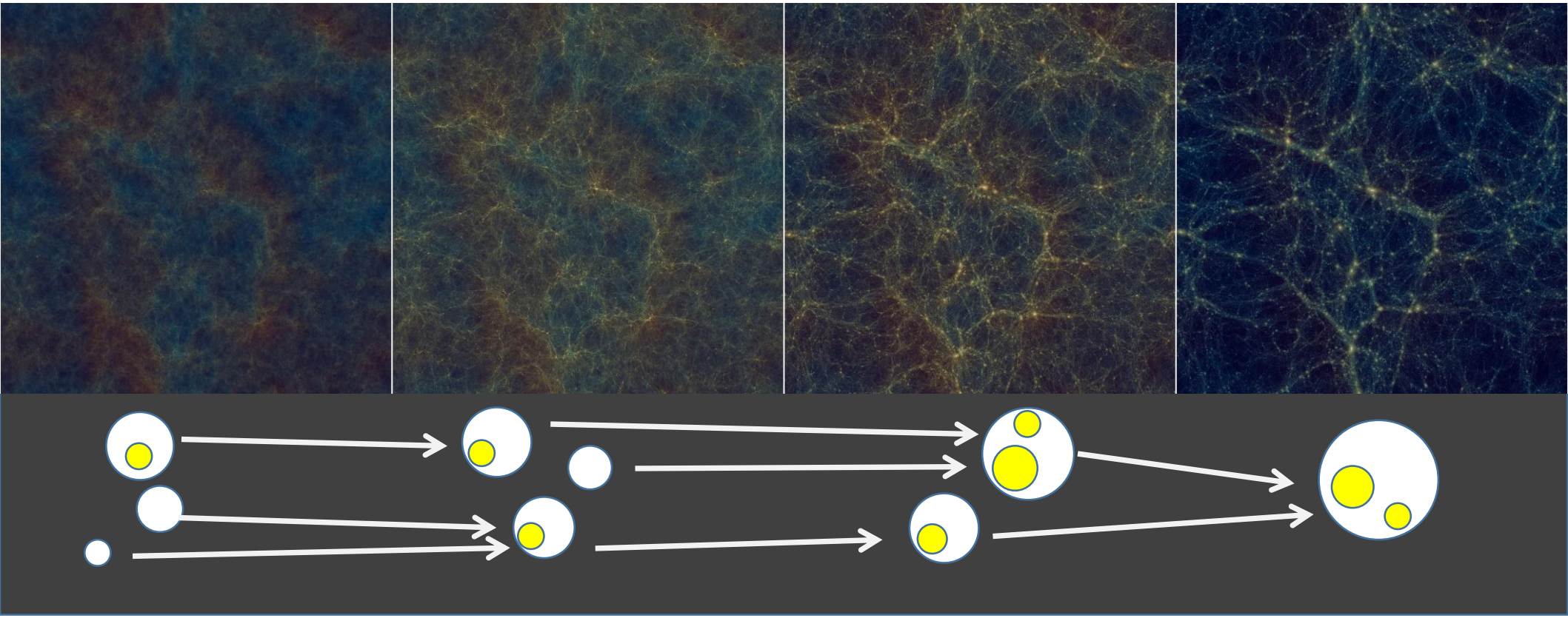
Large scale structure formation





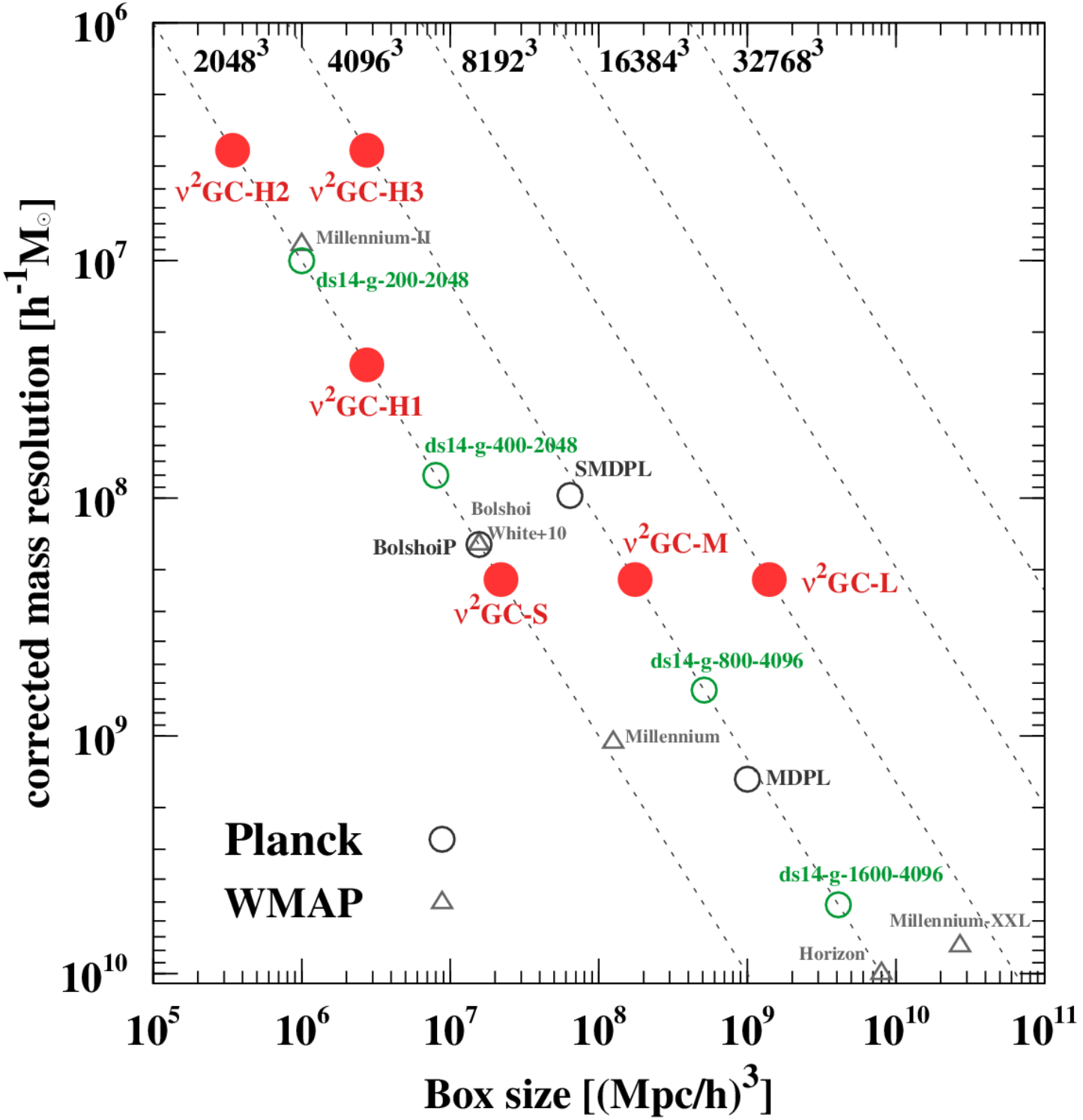
360 degree panoramic video for head mounted display
is available on http://4d2u.nao.ac.jp/English/

Halo catalogs and merger trees

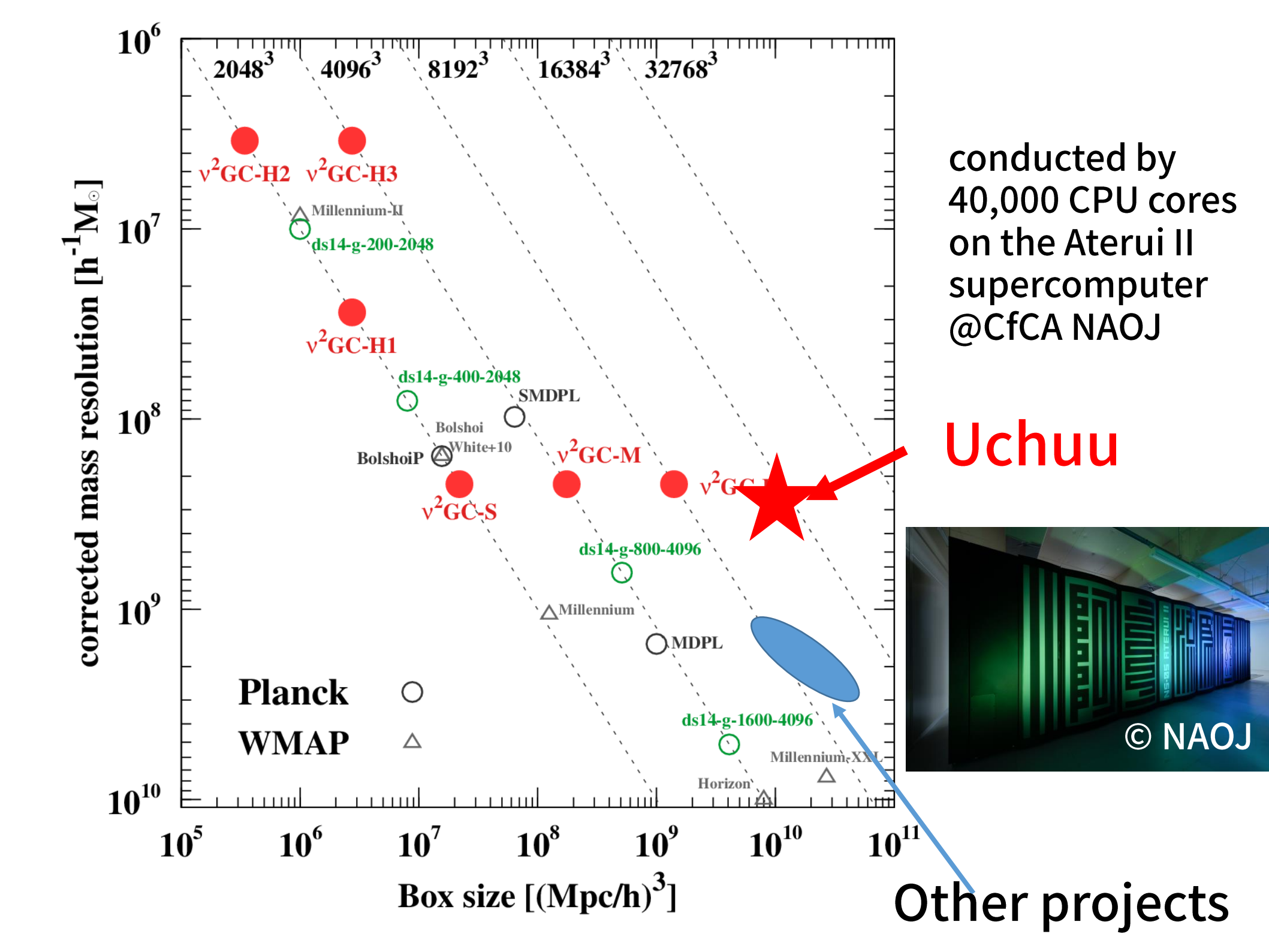


- Identify halos/subhalos at 50 redshifts
  - Halo catalogs: list of halos/subhaloes with many properties such as mass, position, velocity, internal structures (circular velocity peak, scale radius, shape, angular momentum .....)
- Construct progenitor/descendant relationship across redshifts
  - so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

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


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
White+10
BolshoiP
ν²GC-M
ν²GC-L
ν²GC-S
ds14-g-800-4096
Millennium
MDPL
Planck
WMAP
ds14-g-1600-4096
Millennium-XXL
Horizon
corrected mass resolution [h^-1 M⊙]
Box size [(Mpc/h)^3]
10^6
10^7
10^8
10^9
10^10
10^5
10^6
10^7
10^8
10^9
10^10
10^11

Before 2016



conducted by
40,000 CPU cores
on the Aterui II
supercomputer
@CfCA NAOJ

Uchuu

Other projects

Big simulation campaign

Single or a few large simulations

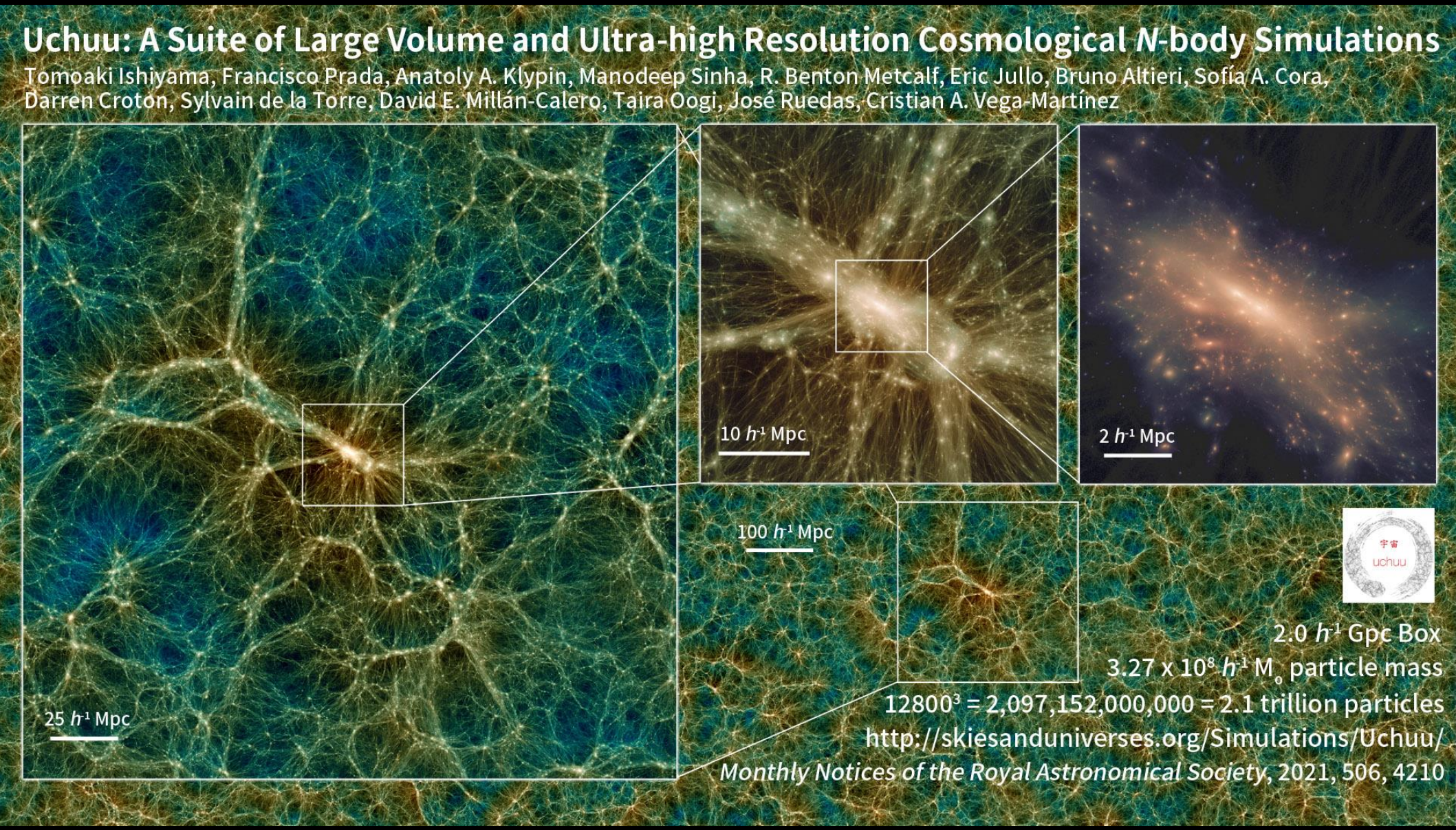
Name	#N	Box (Gpc/h)	particle mass (Msun/h)	cosmology	halo finder	merger tree	data public	code	reference
Uchuu	12800^3	2.0	3.27e8	Planck18	Rockstar	consistent trees	○	GreeM	Ishiyama+ 2021
Darksky	10240^3	8.0	3.9e10	WMAP9	Rockstar	no	△	2HOT	Skillman+ 2014
Euclid flagship	12600^3	3.78	2.4e9	Planck15	Rockstar ?	no	×	PKDGR AV3	Potter+ 2016
Outer Rim	10240^3	3.0	1.9e9	WMAP7	FoF	w/o Subhalo	△	HACC	Heitmann+2019

Large number of runs with a smaller number of particles

e.g., GLAM (Klypin+ 2018), Aemulus (DeRose+ 2019),

Dark Quest (Nishimichi+ 2019), Quijote (Villaecusa-Navarro+ 2020),

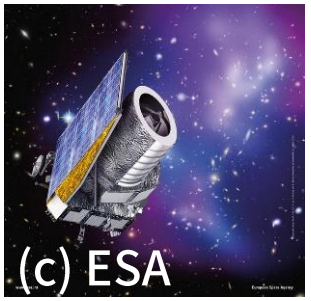
AbacusSummit (Maksimova+ 2021)



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

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 (La Plata) *
- Darren Croton (Melbourne) *
- Sylvain De la Torre (Marseille)
- Tomoaki Ishiyama (Chiba) **
- Eric Jullo (Marseille) *
- Anatoly Klypin (Virginia) *
- Ben Metcalf (Bologna)
- Julia F. Ereza (Granada)
- Taira Oogi (Chiba)
- Francisco Prada (Granada) **
- Manodeep Sinha (Melbourne)
- 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

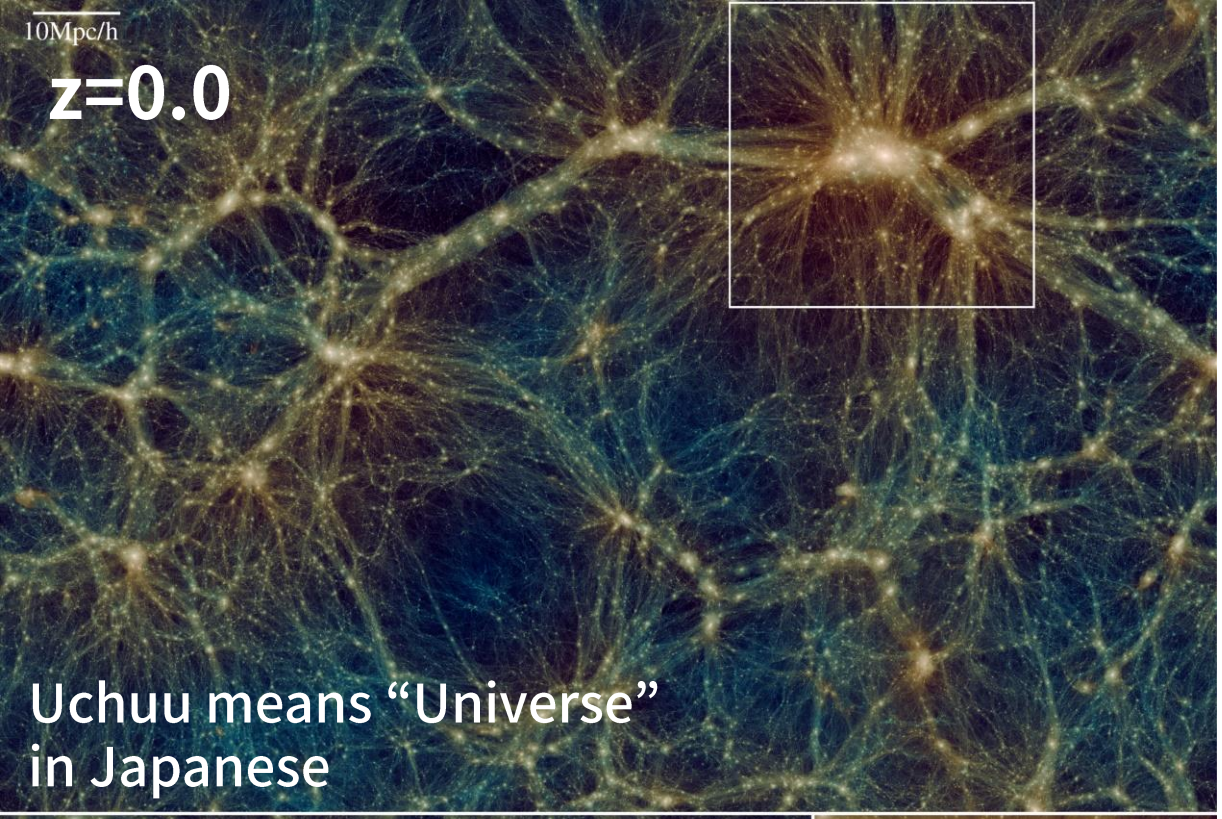
Chiba

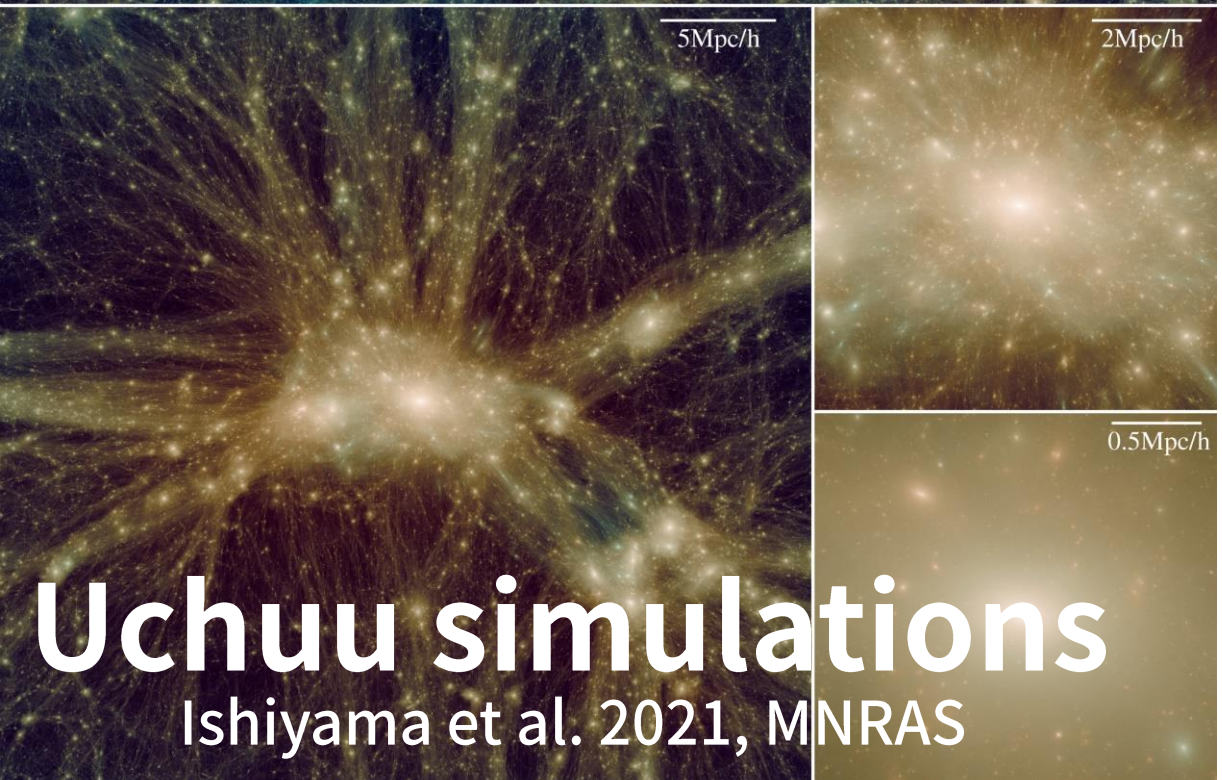
Virginia

La Serena

La Plata

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

Uchuu 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)

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

Snapshots

- Uchuu (64 TB / redshift)
  - 40 at 0<z<6
  - 10 at 6<z<14

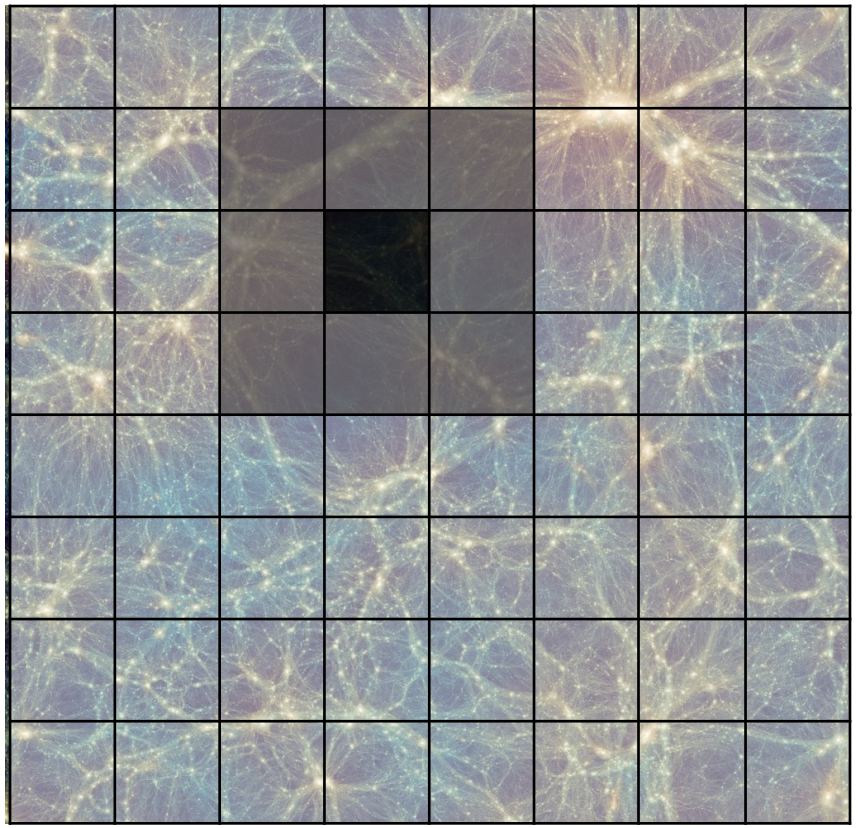
- Shin-Uchuu (8TB / redshift)
  - 40 at 0<z<6 (the same epoch with the Uchuu)
  - 30 at 6<z<20

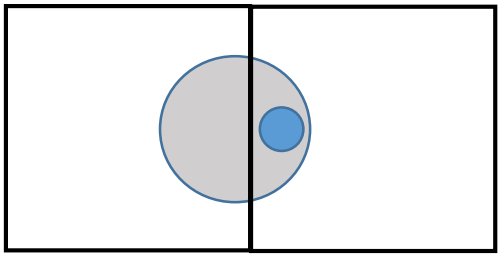
How unique is the Uchuu?

- 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)

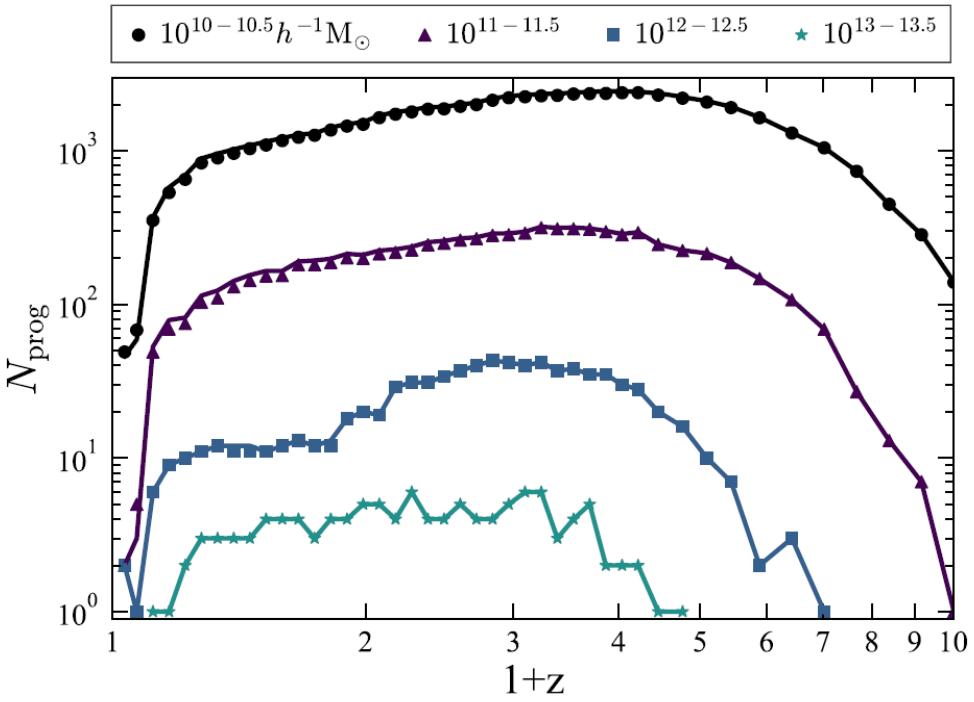
Parallel merger tree construction

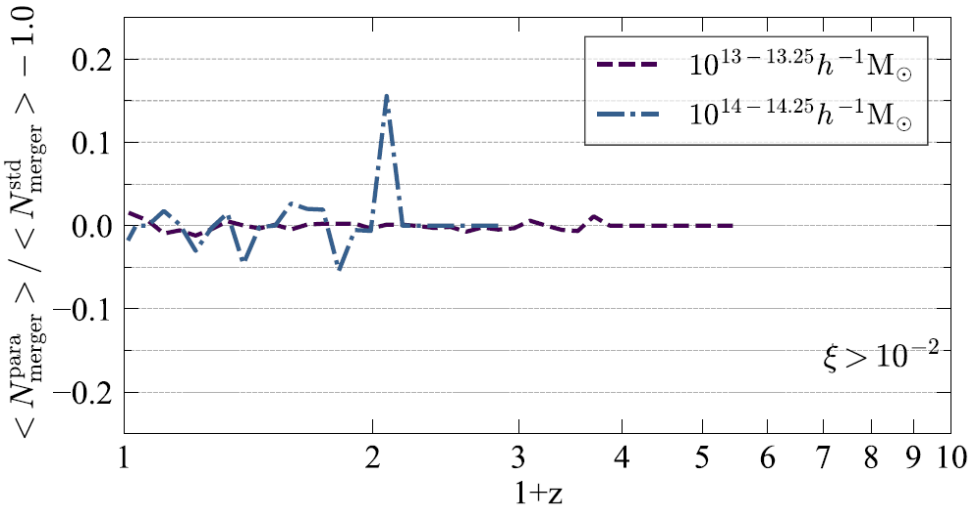


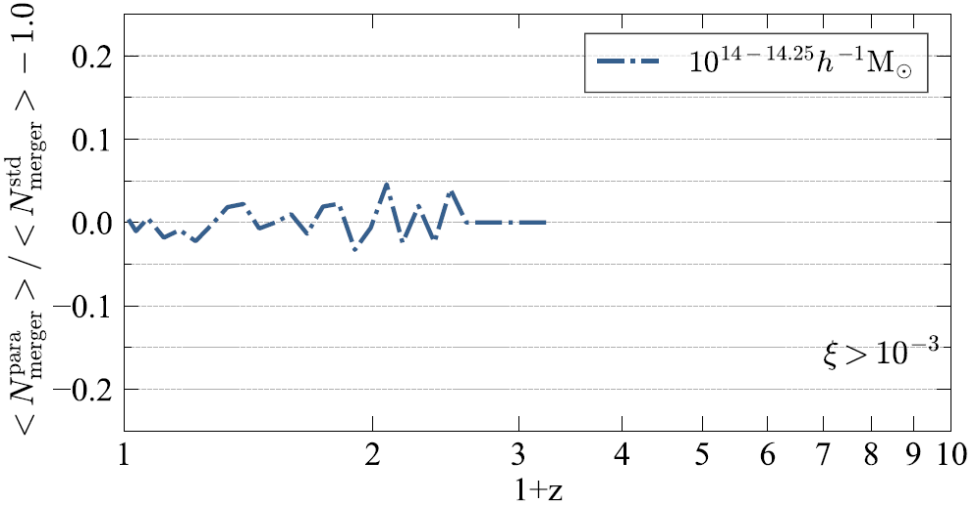


- Split full box at z=0 into n_{sub}^3 subboxes
- To construct merger trees for halos/subhalos in a target subbox (black), 27 subboxes (gray) are used
- After running the consistent trees code, trim halos/subhalos in the target box from the trees
  - Preserve halo/Subhalo hierarchy

Validation



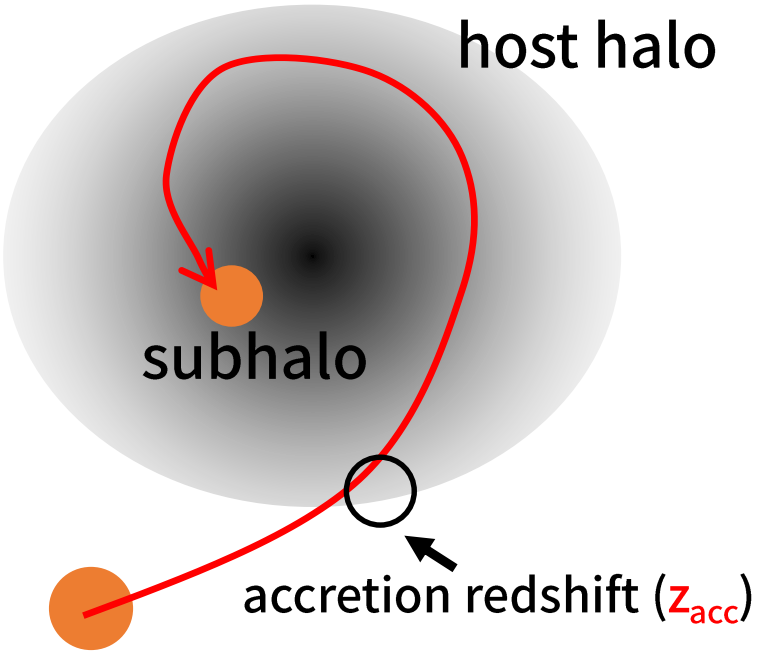


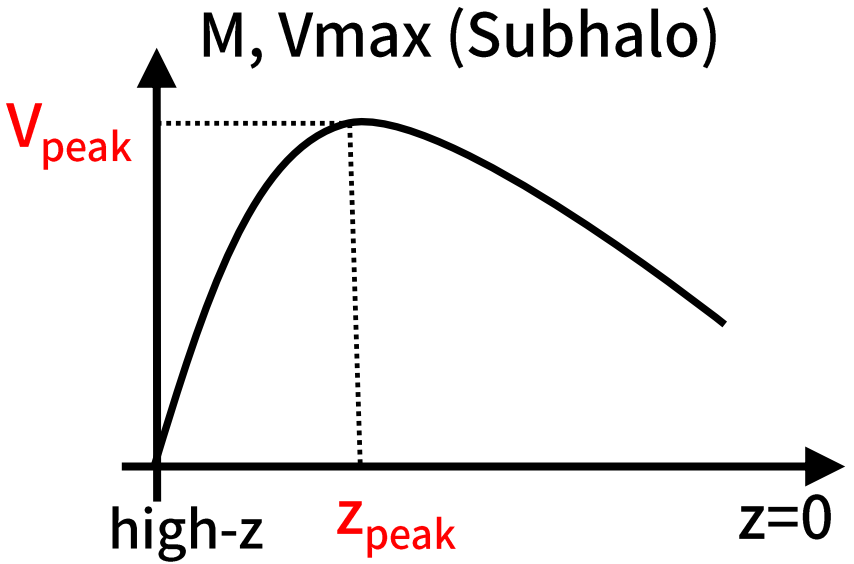


- Comparison between standard and parallel way
- The difference is within 5% level

Extending halo catalogs for easy mock constructions

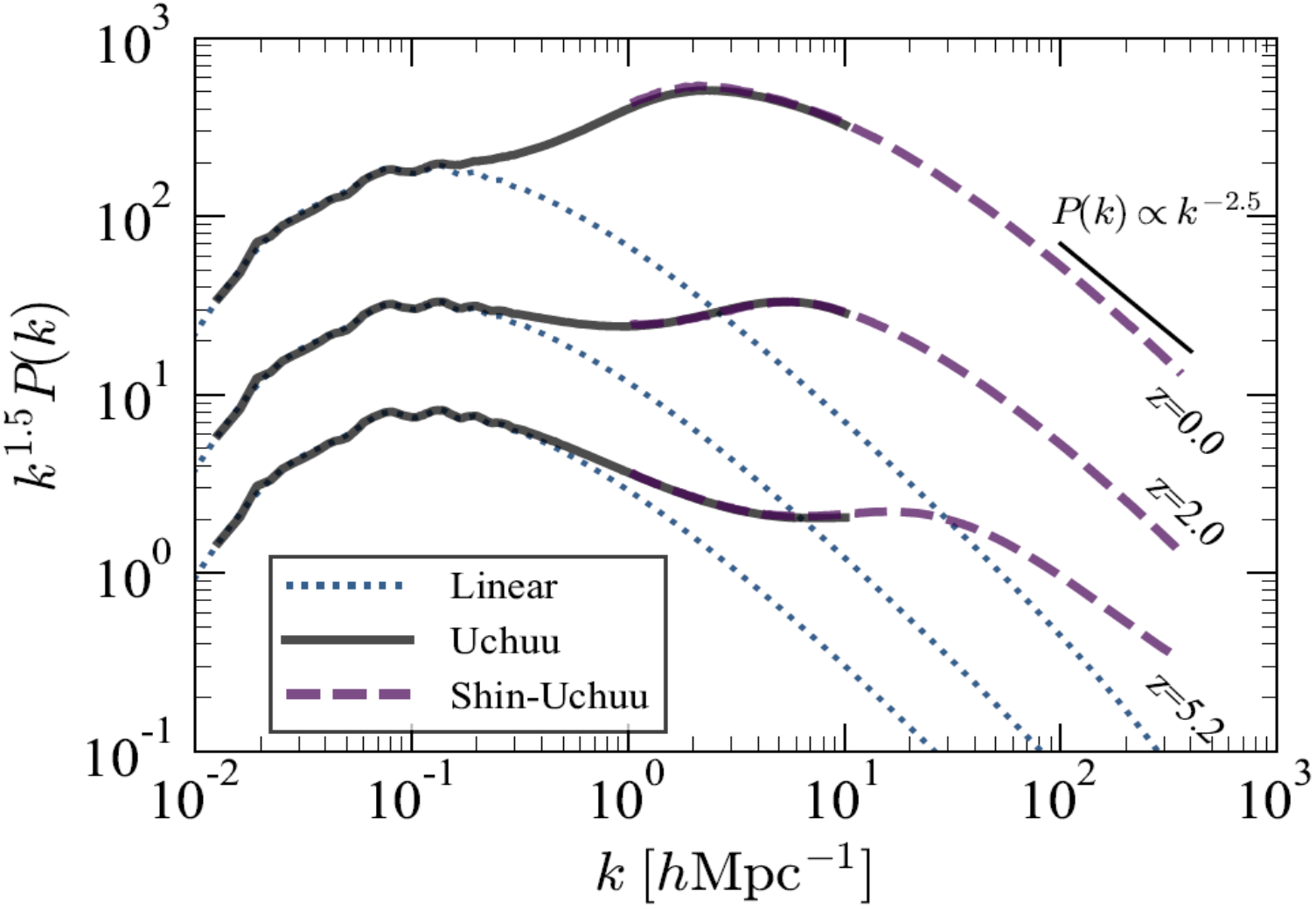
- Most empirical models use subhalo's V_{peak}, M_{peak}, z_{peak}, V_{acc}, M_{acc}, z_{acc} ..... as proxies of galaxy formation
- All these quantities can be derived only analyzing merger trees
- We pre-calculated these important quantities and include them into halo catalogs
  - Drastically reduce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





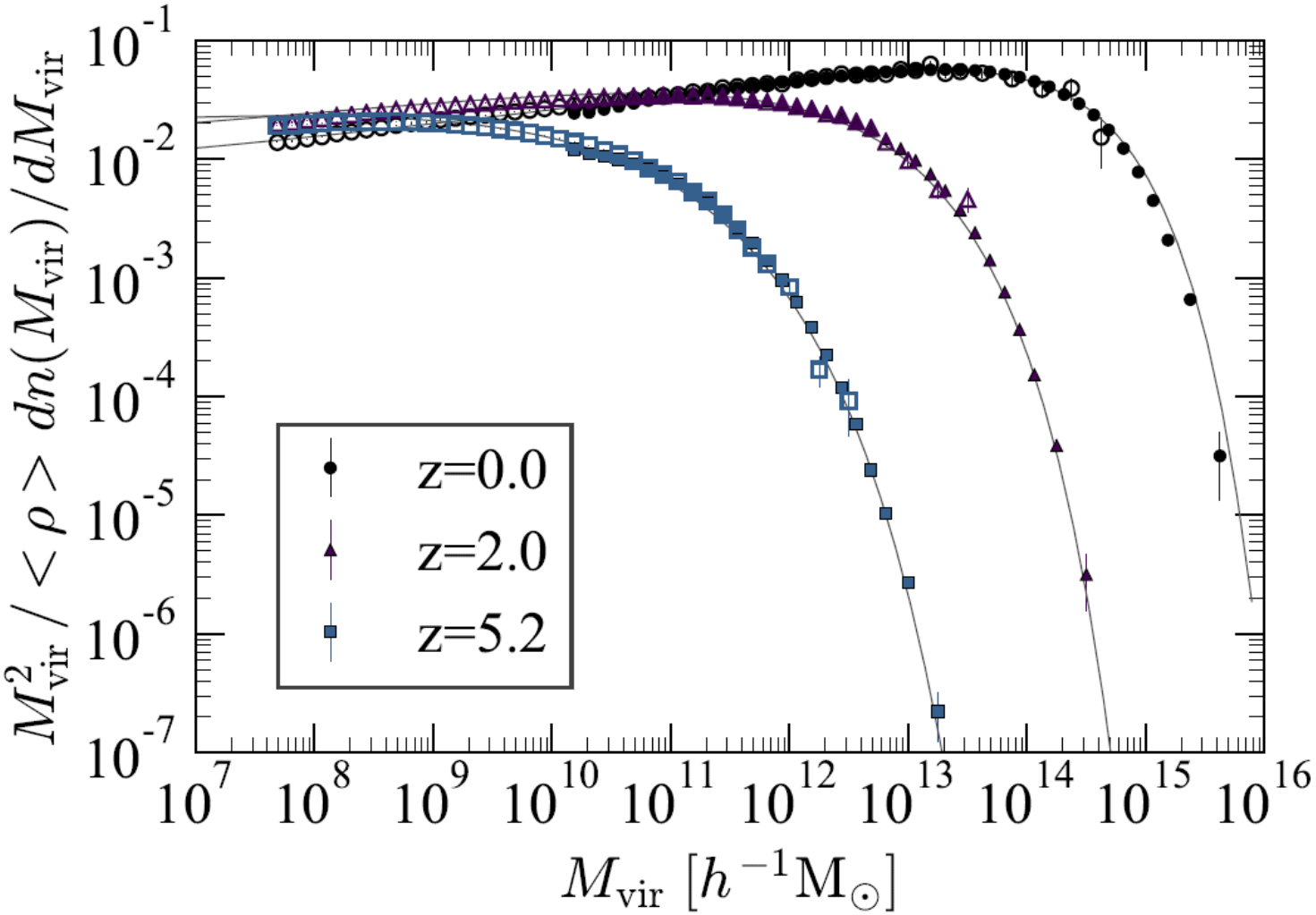
Basic validation of simulations

Matter power spectrum



- Our simulations are accurate enough from the Baryon Acoustic Oscillations up to very small scales

Halo mass function



- The mass range spans approximately eight orders of magnitude, reflecting the power of our very large simulation set
- The convergence between both simulations is remarkably good, within a few per cent, ensuring the accuracy of our simulations

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

DR1

- **Uchuu (~100TB)** **released on July 28th, 2020**
  - Rockstar halo/subhalo catalogs (including Vpeak, Vacc, Mpeak)
    - No mass cut (36 TB)
    - Only halos/subhalos with $M_{200c} > 10^{11}$ Msun/h (5.5 TB)
    - Only halos/subhalos with $M_{200c} > 10^{12}$ Msun/h (508 GB)
  - Merger trees (26 TB)
  - Random sample of particles (0.5%, 320GB/redshift, Gadget-2)

- **Shin-Uchuu (~16TB)**
  - Rockstar halo/subhalo catalogs (including Vpeak, Vacc, Mpeak)
    - No mass cut (4.3 TB)
    - Only halos/subhalos with $M_{200c} > 10^{9}$ Msun/h (189 GB)
  - Merger trees (2.7 TB)
  - Random sample of particles (1.6%, 131GB/redshift, Gadget-2)

HDF5 files are provided

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

How to access the data fast

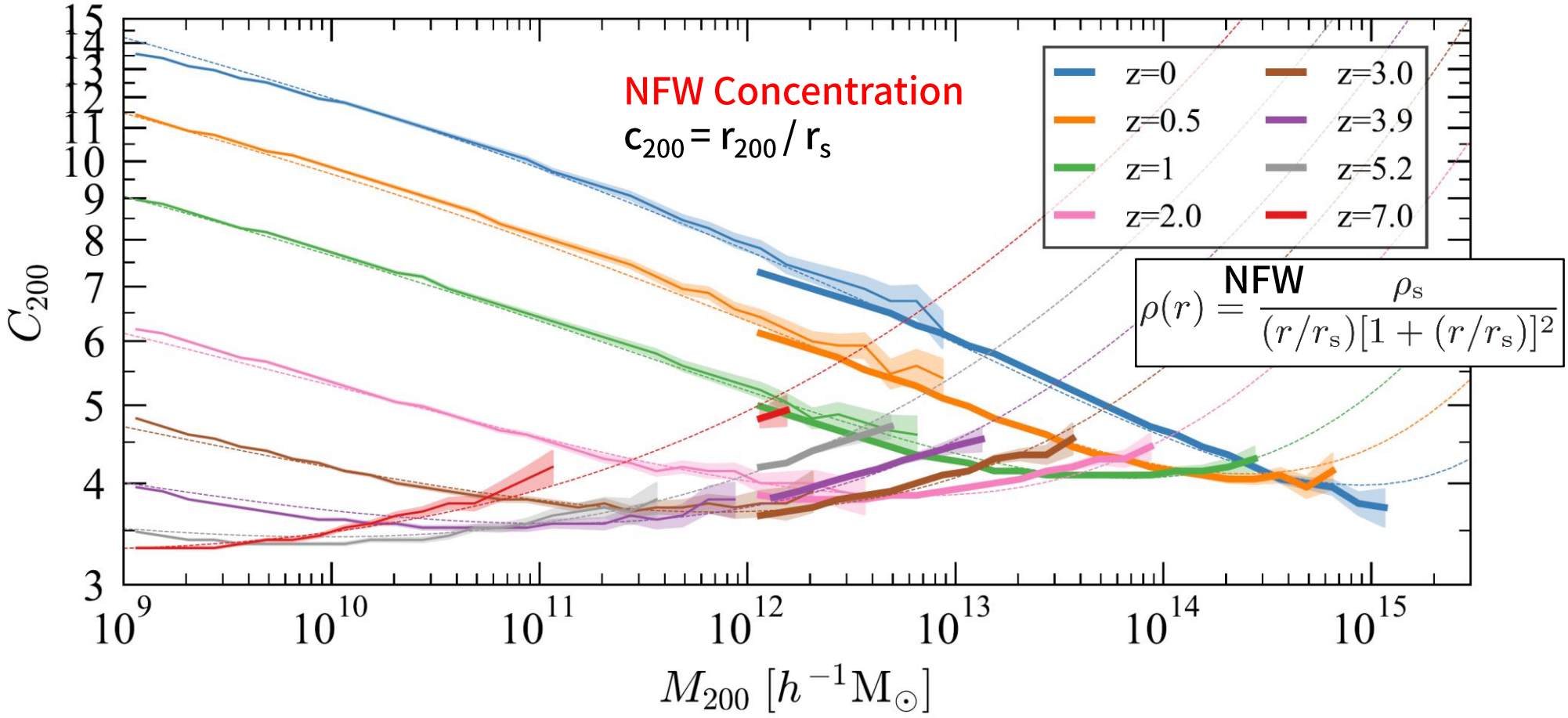
- http or ftp (wget, browser)
  - Slow (maximum ~10-20 MB/s per stream)
  - Can be accelerated by multiple streams
- RedIRIS High Speed Data Transfer Service
  - Very fast: Can be accelerated up to the maximum network speed
  - Dedicated software is necessary (free, easy to install)
- Ask me

- Uchuu-BigData platform @ CESGA
  - Hadoop / spark cloud service
  - Users do not have to care about data managements
  - Just log-in the server and run Jupyter Notebook

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

Ishiyama et al. 2021, MNRAS, 506, 4210

Single fitting function

- Re-calibrated model by Diemer and Joyce (2019)

$$c(\nu, n_{\rm eff}, \alpha_{\rm eff}) = C\,(\alpha_{\rm eff}) \times \tilde{G}\left(\frac{A\,(n_{\rm eff})}{\nu}\left[1 + \frac{\nu^2}{B\,(n_{\rm eff})}\right]\right),$$

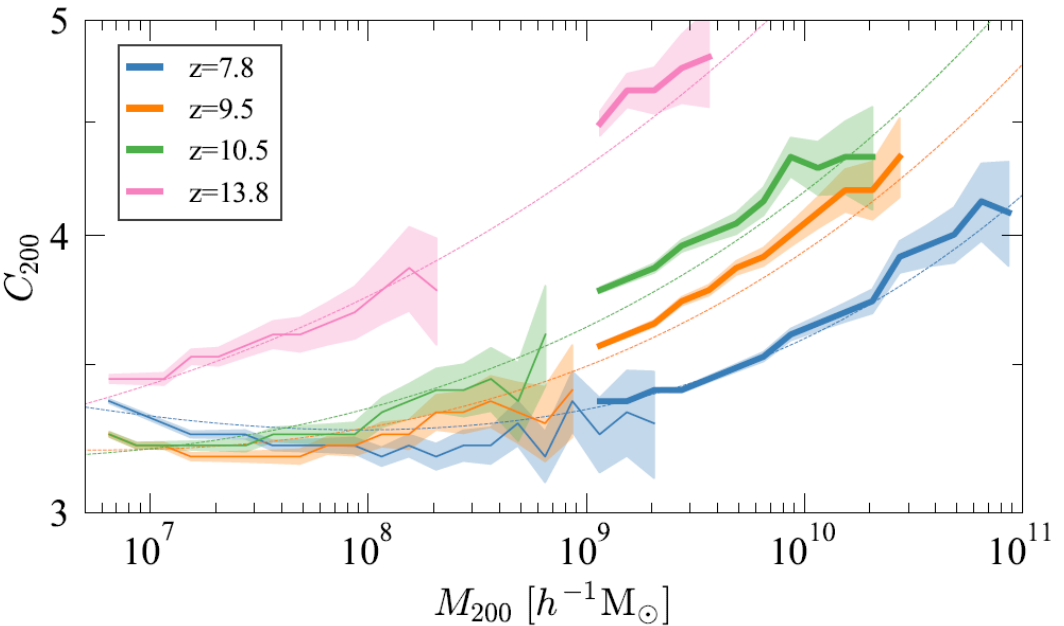
- Provides parameter sets for M_{vir}, M_{200c}, M_{500c}
  - Both for relaxed and unrelaxed halos
- Already implemented in Colossus code (Diemer+2018)

ν: peak height

n_{eff}: effective slope of the power spectrum

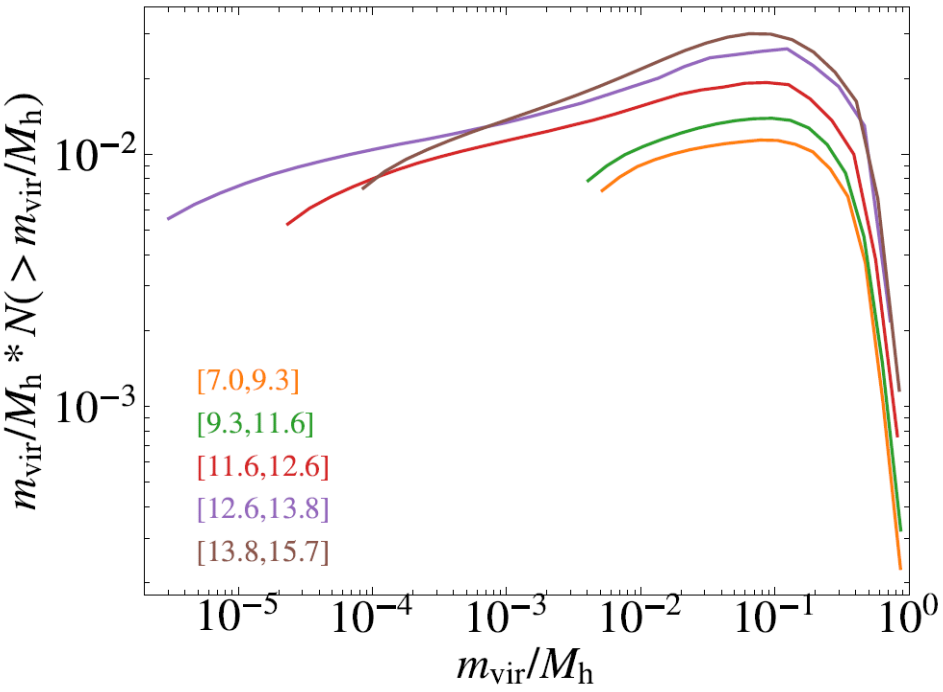
α_{eff}: effective exponent of linear growth

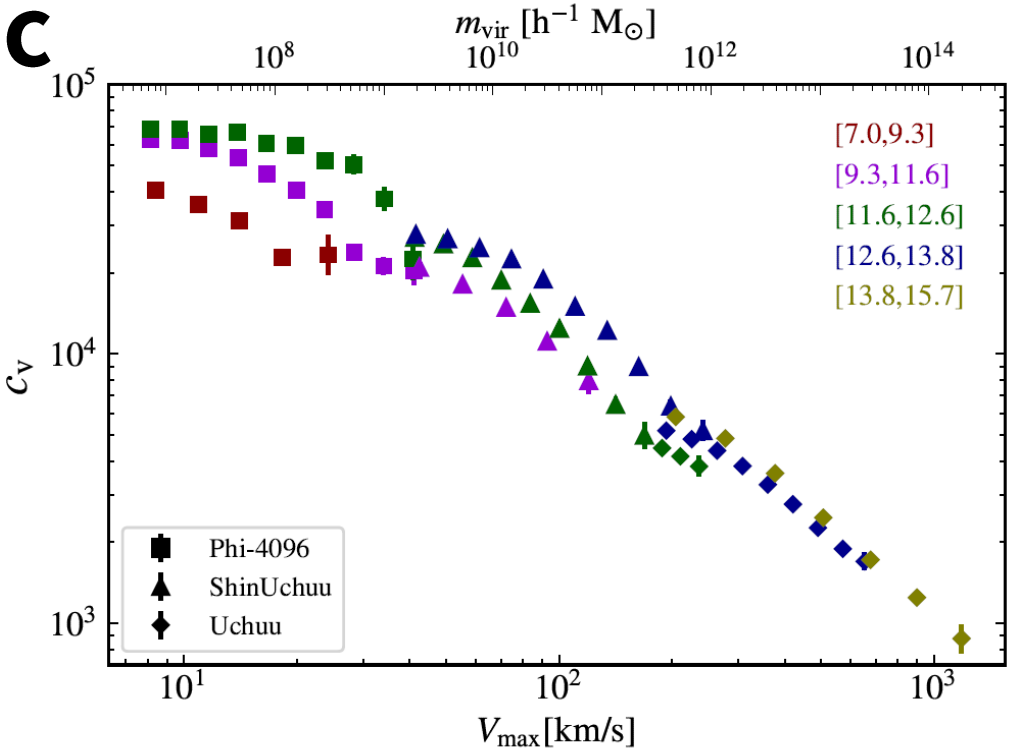
Name	N	L (h^{-1}Mpc)	m ($h^{-1}\,M_\odot$)	ε (h^{-1}kpc)
Uchuu	12800^3	2000	3.27×10^8	4.27
ShinUchuu	6400^3	140	8.97×10^5	0.40
Phi-4096	4096^3	16	5.13×10^3	0.06

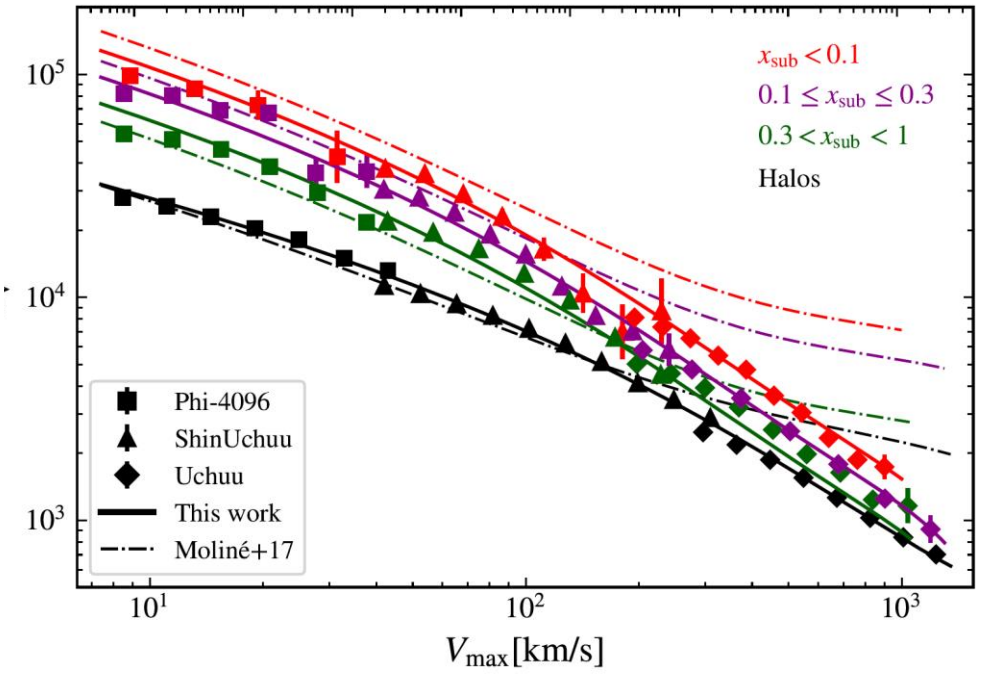


Moline, Ishiyama et al., 2021, arXiv: 2110.02097

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

DR2

- Uchuu +

empirical

- UniverseMachine (Behroozi+ 2019)

galaxy

early 2022

- ν^2GC (Makiya+ 2016, Shirakata+ 2019)
- SAGE (Croton+ 2016)
- SAG (Cora+ 2018)

galaxy + AGN

late 2022

semi-analytic

Aung et al. in prep

Uchuu + UM catalogs

- Catalogs are already available (thanks to Peter Behroozi)
- Early data access is possible upon request
- Shin-Uchuu + UM is currently processing

Other data

- Gravitational lensing map with lightcone catalogs (led by Ben Metcalf and Eric Jullo)
  - In 2022?

- (not sampled) particles around cluster halos
  - Currently available at z=0, 0.5, 1.0

他のデータのリクエスト、既存の公開データの
カスタマイズなどは随時受け付けております

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

- DR2 (Uchuu+UniverseMachine) is coming soon!
  - Catalogs by SAMs will be available in 2022