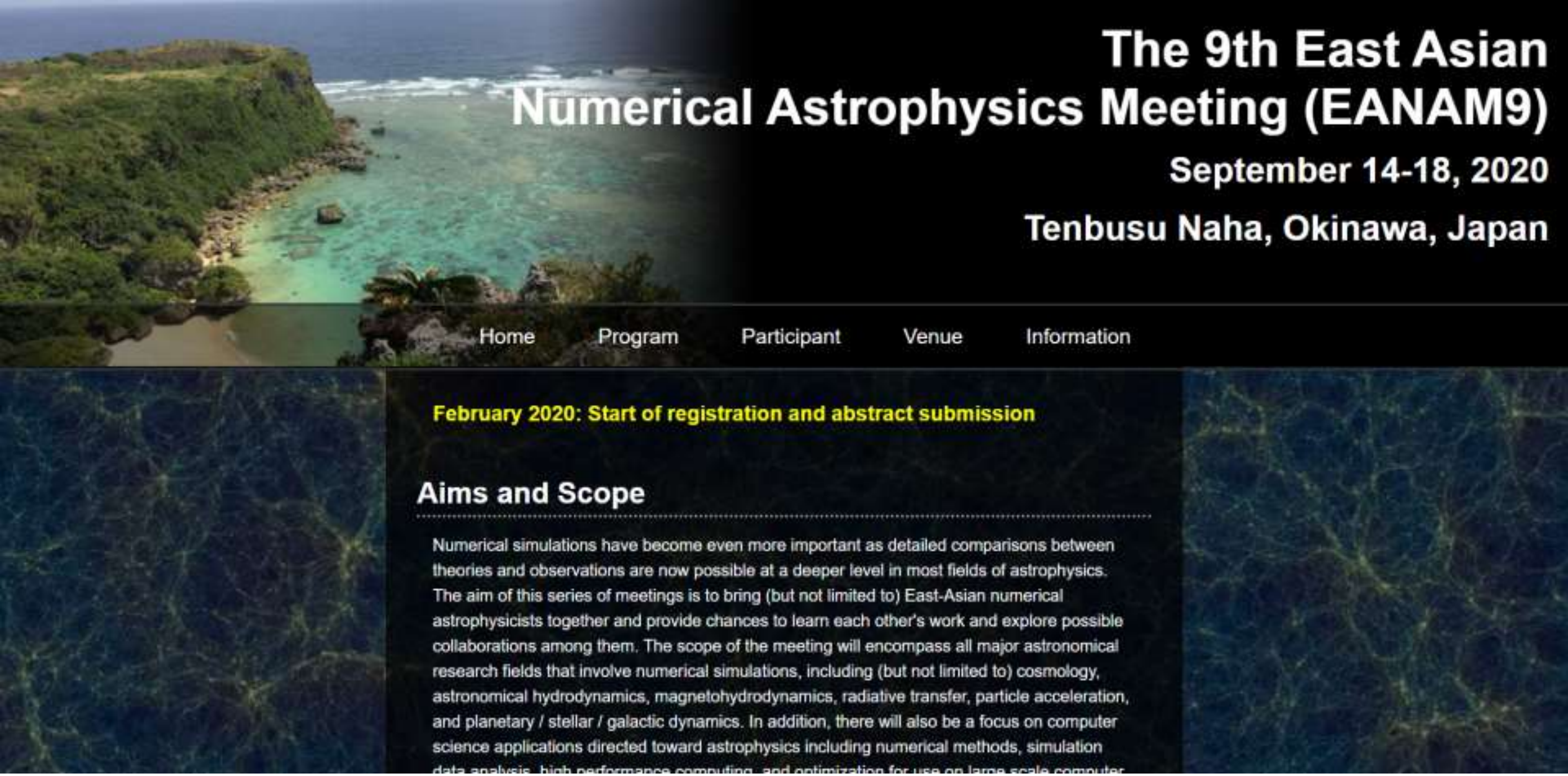
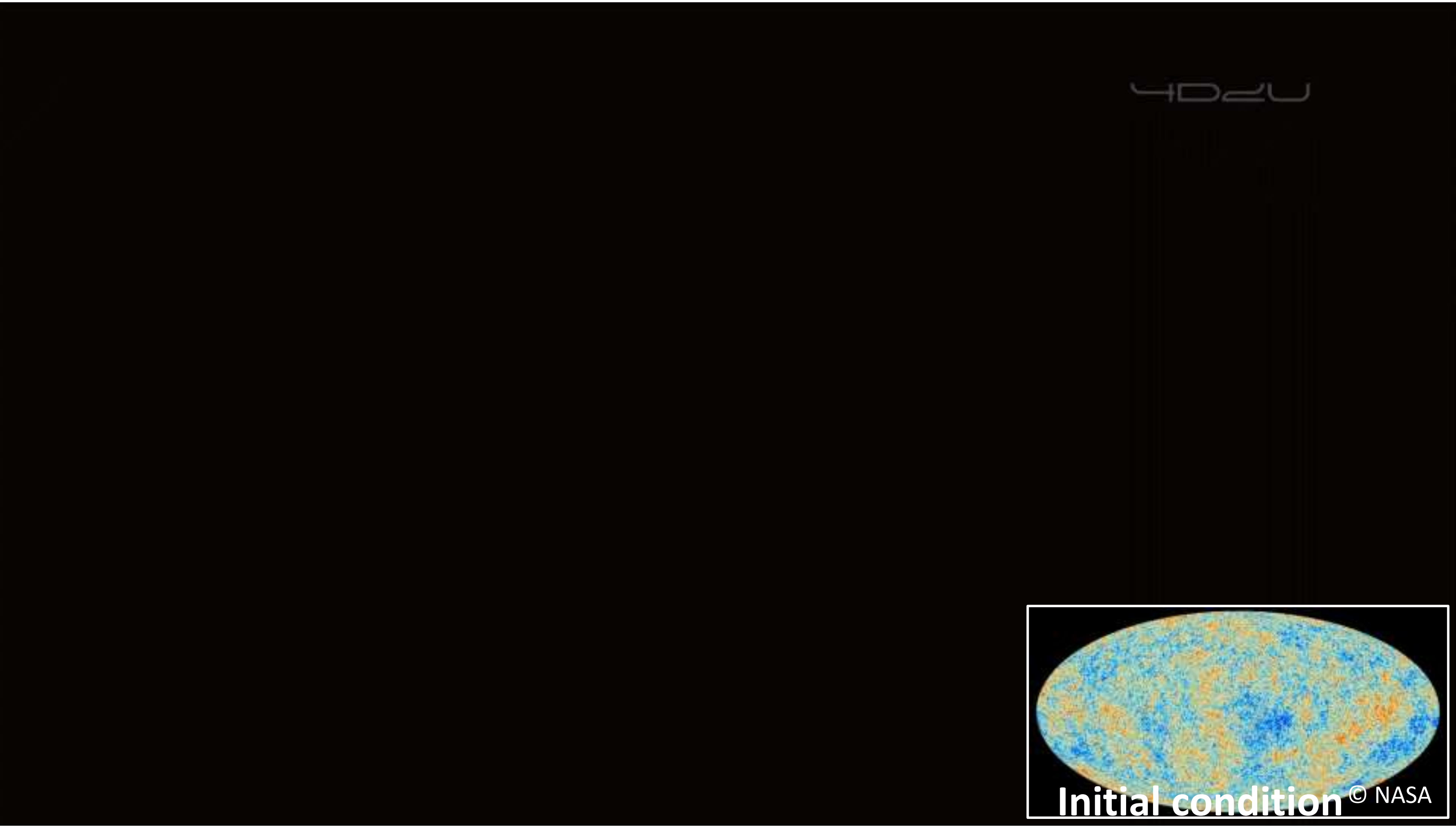
ダークマターの密度揺らぎからはじまる宇宙の天体形成

石山 智明 (千葉大学)



- http://hpc.imit.chiba-u.jp/eanam9/
- 那覇 (国際通り沿い)
- 登録は2月からを予定

Cosmological simulation (dark matter only)

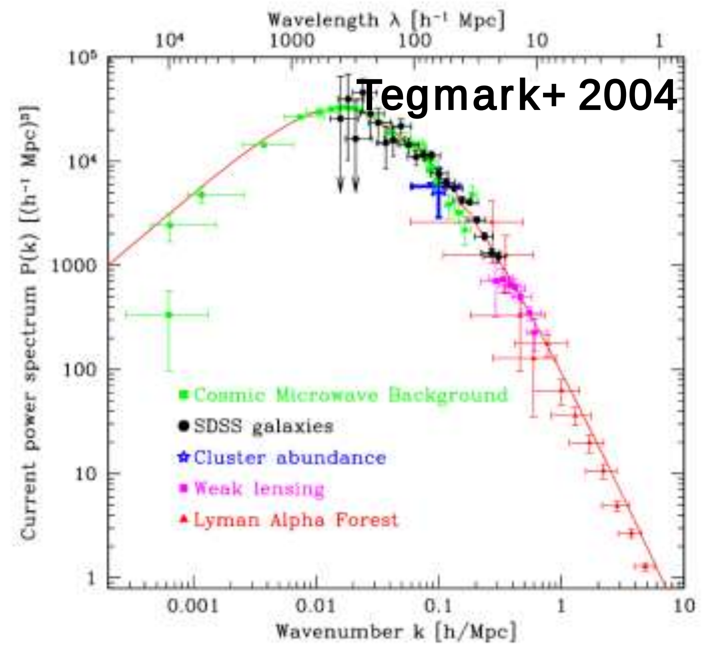


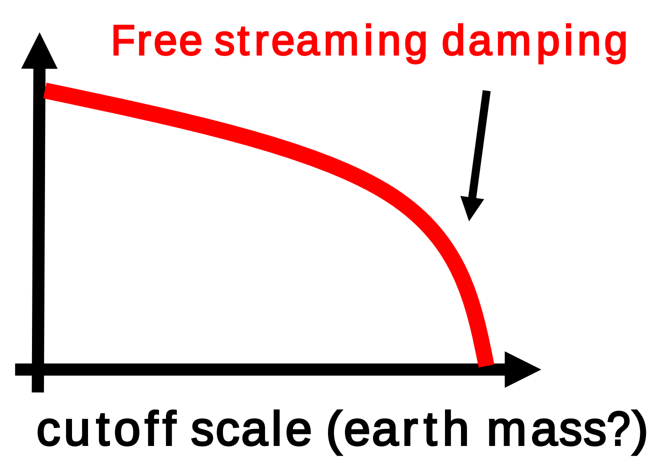
360 degree panoramic video for head mounted display
is available on http://4d2u.nao.ac.jp/English/

最小ハロー質量 ~10⁵Msun
300 kpc

The smallest to the largest

- 100Mpc〜Gpc
  - large scale structure, cosmology
- Galactic halo (~100 Mpc)
  - galaxy formation
  - dark matter detection
- 10^{3-7} Msun halo
  - first star, BH seed?, first galaxy
- The smallest halo (earth mass?)
  - dark matter detection

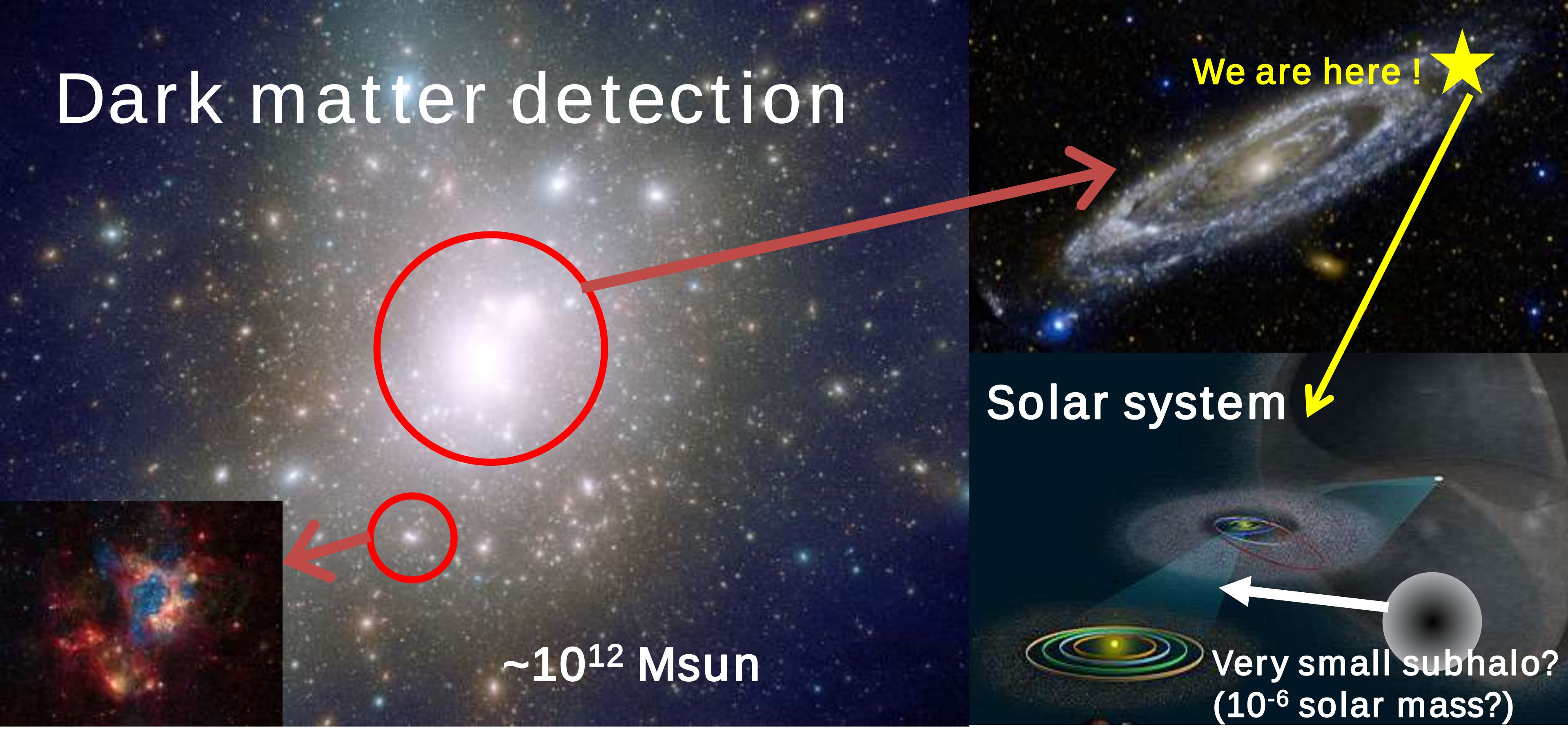




Dark matter?

- Fine structure of dark matter halo
  - Direct detection experiment
  - Indirect detection experiment
- Connection to luminous objects
  - cluster, galaxy, BH?, first star

Dark matter detection



- Numerous subhalos (10^{-6} ~ 10^{10} solar mass)
  - $dn/dm \propto m^{-2 \sim -1.8}$
- Where can we observe gamma-ray flux due to dark matter annihilation ?
  - The center of the Milky Way halo ?
  - Dwarf Galaxy ?
  - Microhalos near Sun ?

Flux$\propto \rho^2$ →
Density structures of the halo & subhalos and spatial distribution of subhalos are very important

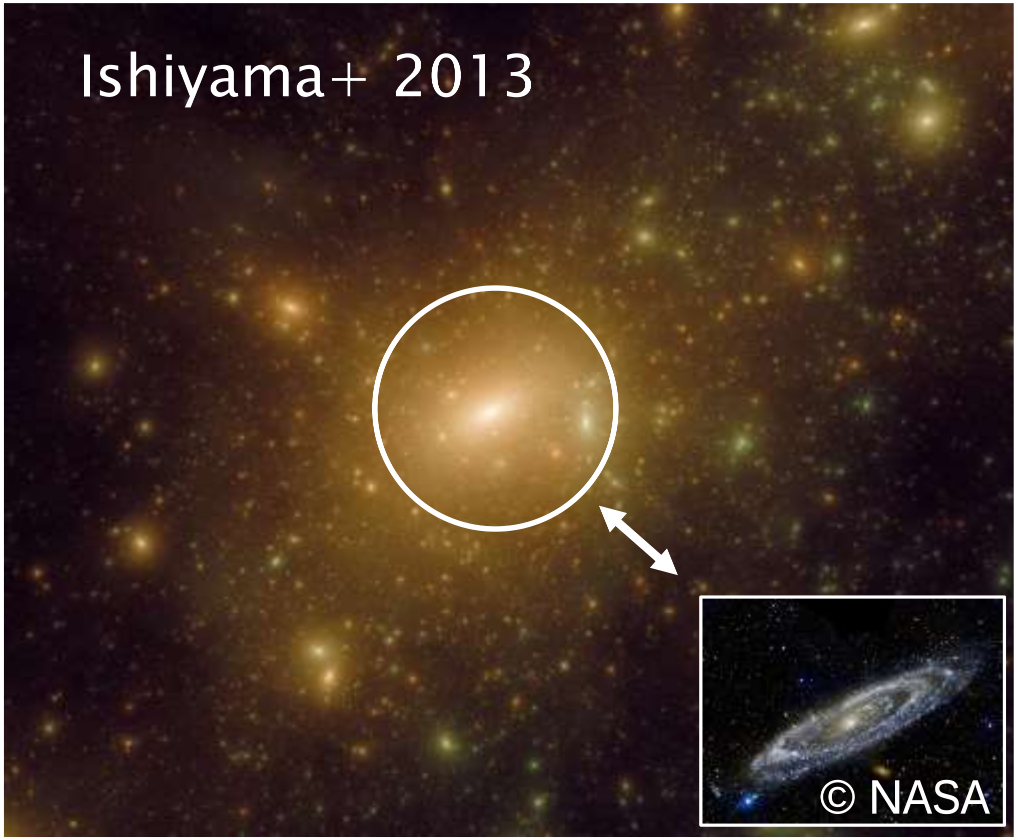
Halo structure

- Central Cusp
  - Einasto profile
  - NFW profile

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

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

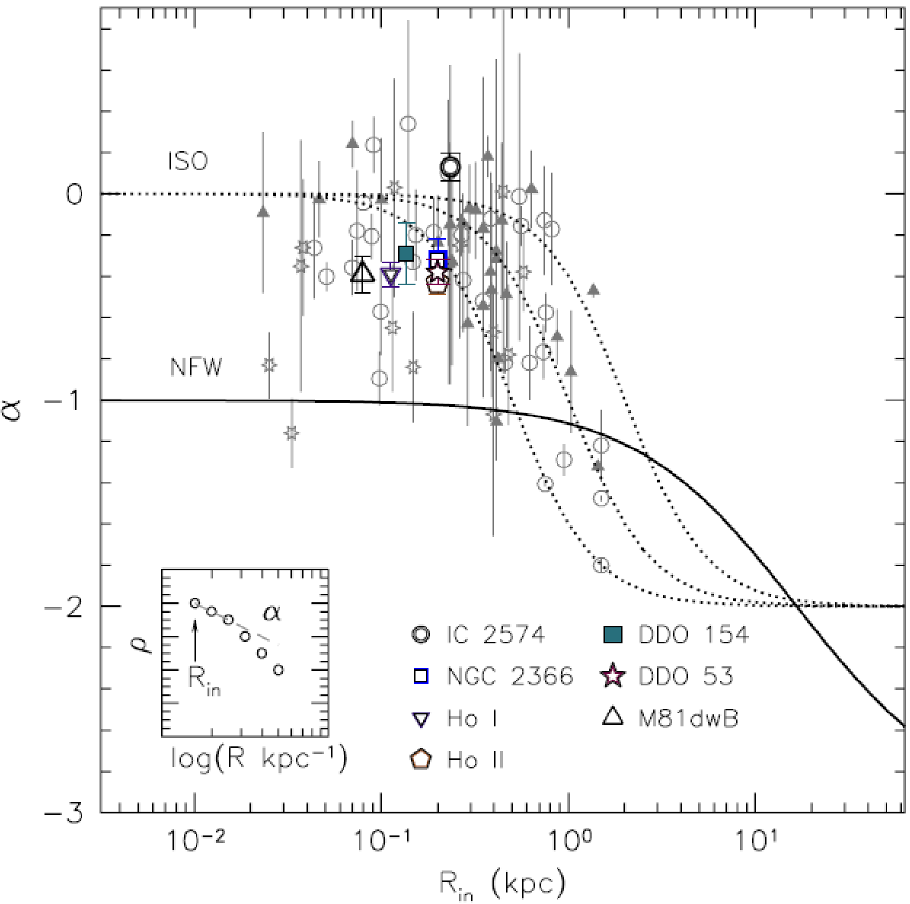
- Numerous subhalo
  - $dn/dm \sim m^{-(1.8\sim2)}$
- Triaxial
- Non Universality
  - Weak dependence on the halo mass
  - halo to halo variation



Impact on the galaxy formation,

Dark matter detection experiment

Observation ?

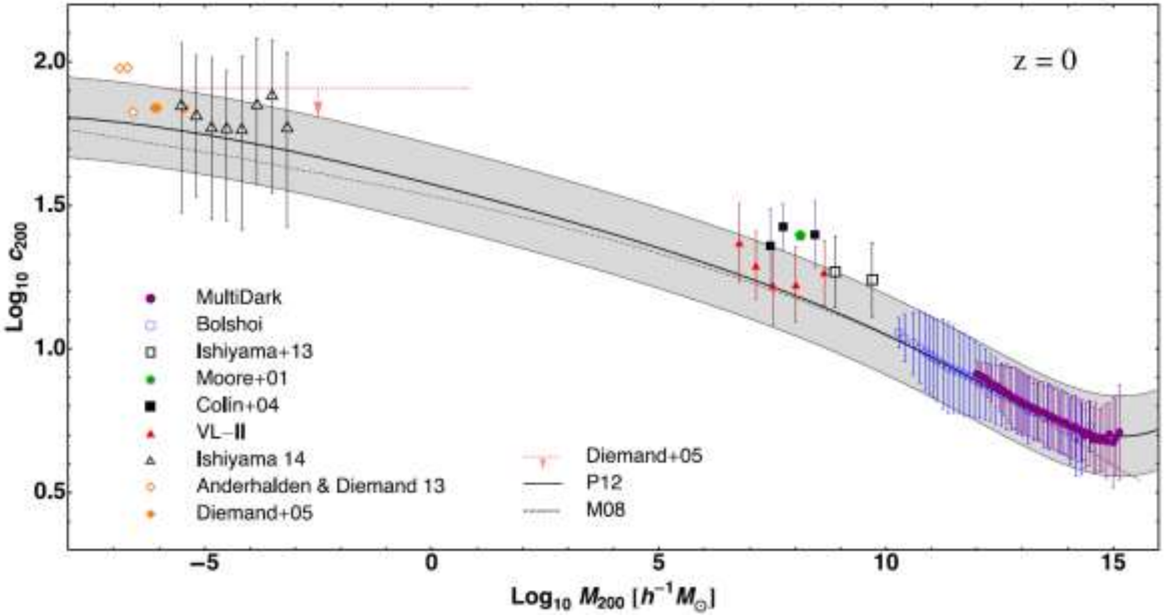


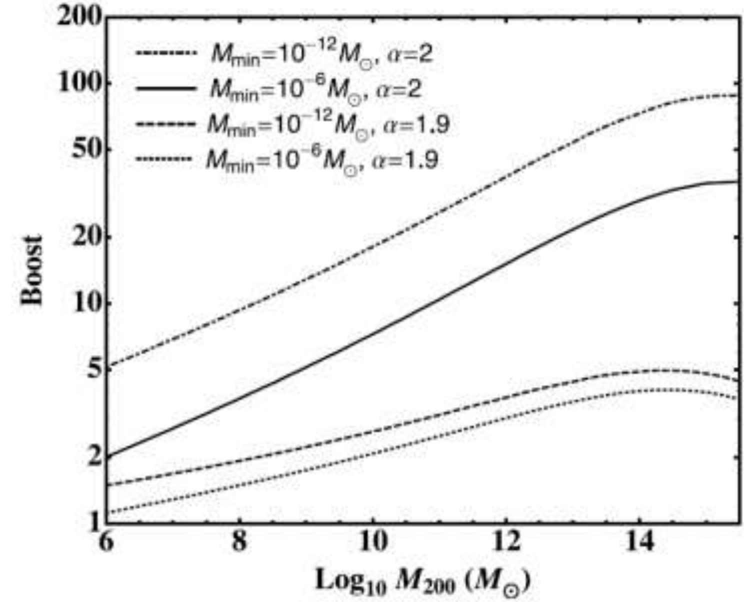
Oh+2011

- The central slopes of LSBs and dwarf galaxies are around -0.2 ~ 0
- Inconsistent with simulations ? (Core cusp problem)
  - Baryonic effect ?
    - e.g., SNe feedback (Governato+ 2012, Teyssier+ 2012, Ogiya+ 2014)
  - CDM Alternative?
  - Sometimes, referred as small scale crisis with missing satellite problem and too big to fail problem

m-c relation and boost factor

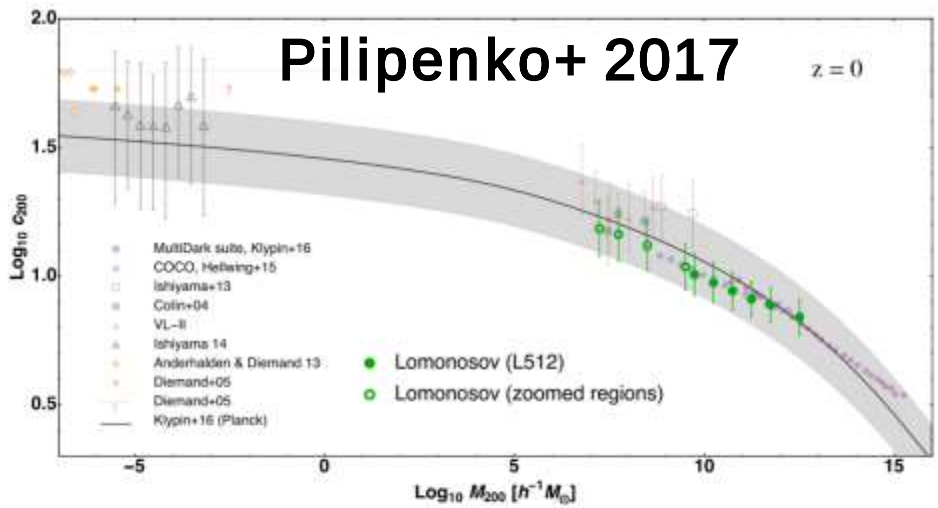
Sanchez-Conde and Prada 2014





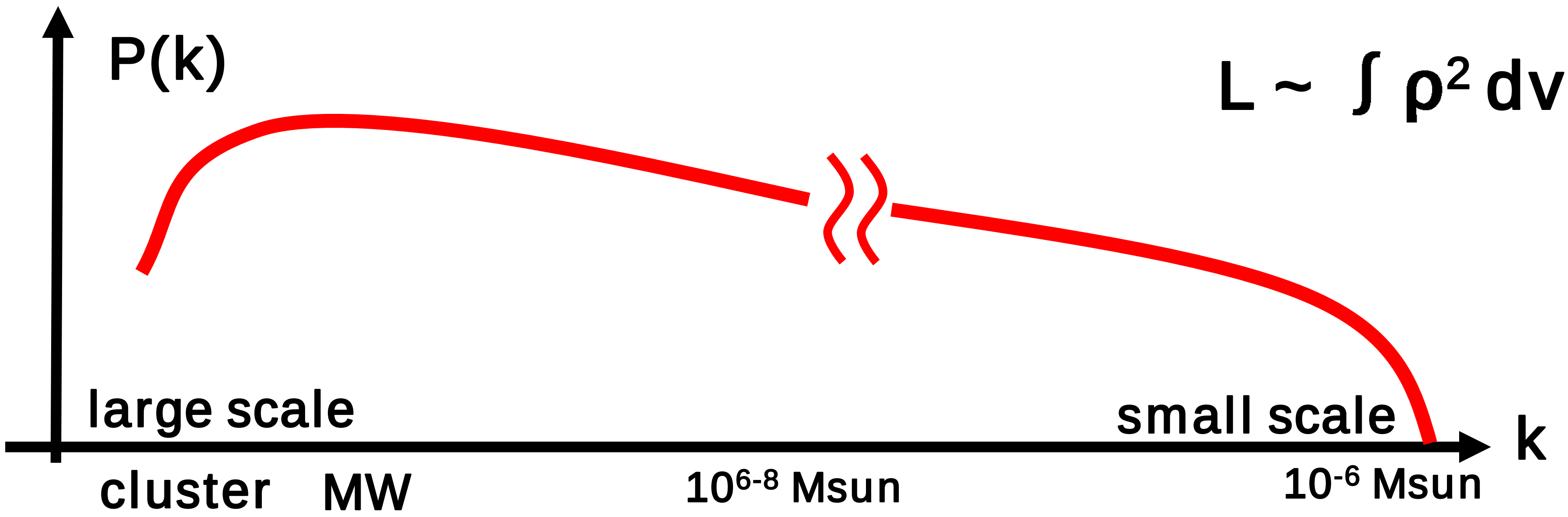
$$B(M) = \frac{1}{L(M)} \int_{M_{\rm min}}^{M} \frac{dn}{dm} \left[1 + B(m)\right] L(m)\, dm$$

Pilipenko+ 2017



So far

$$B(M) = \frac{1}{L(M)} \int_{M_{\min}}^{M} \frac{dn}{dm} [1 + B(m)] L(m) \, dm$$



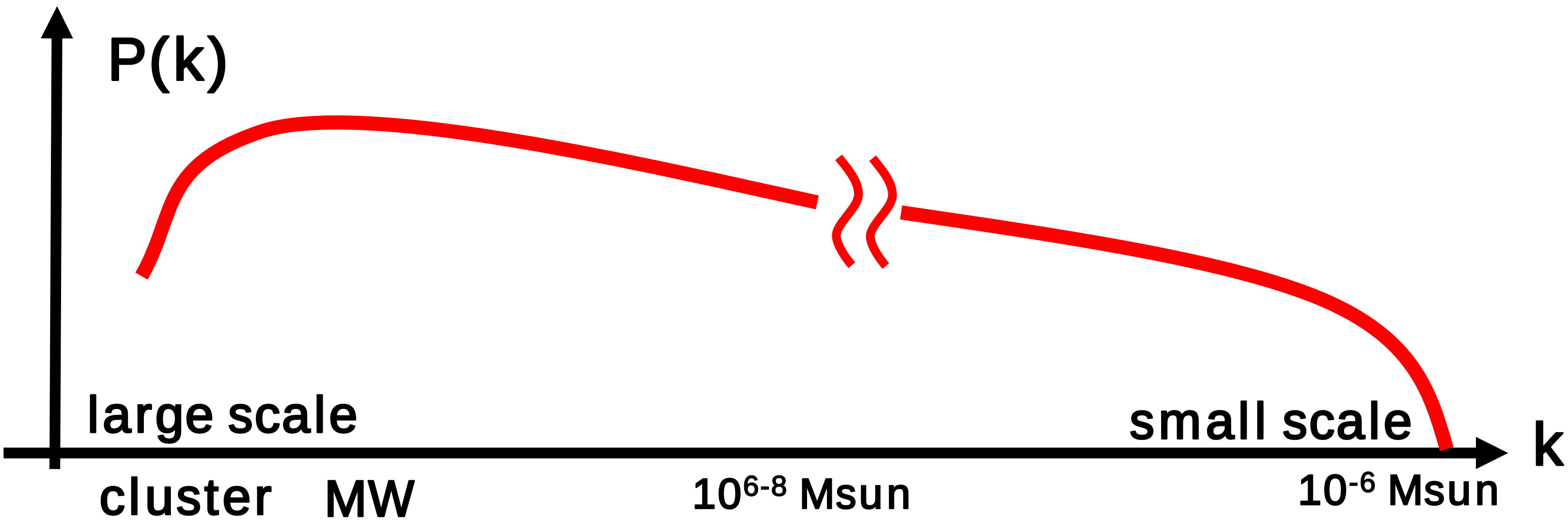
Halo density profile — Extrapolation (w & w/o analytic models)

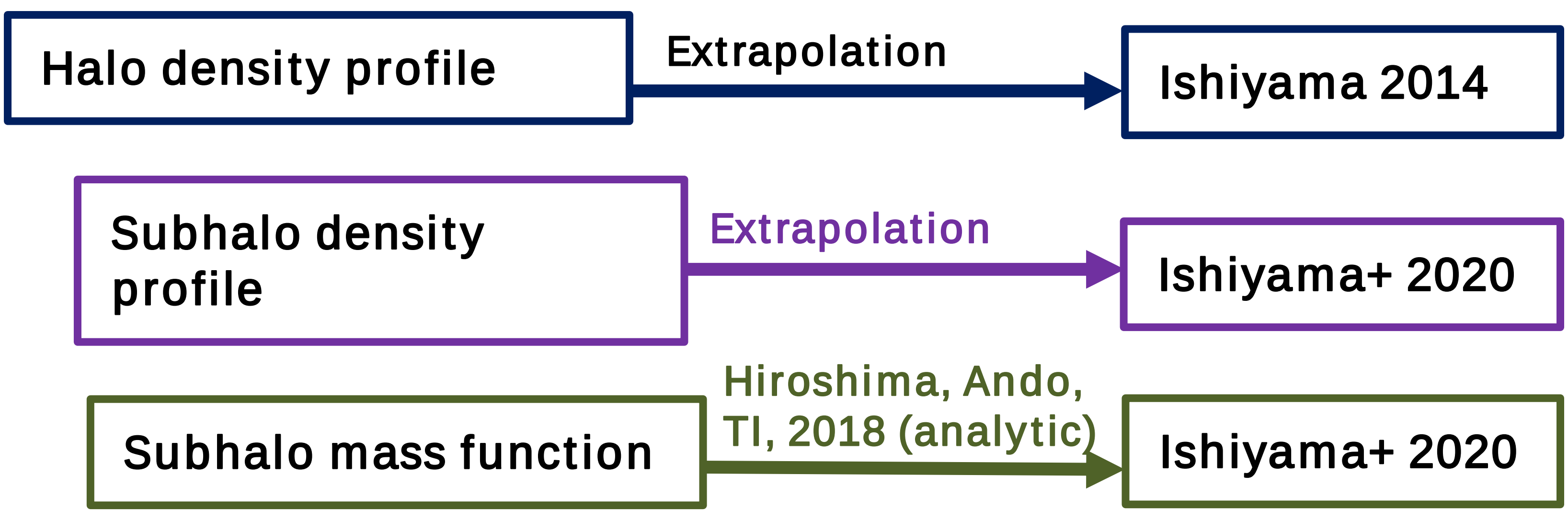
Subhalo density profile — Extrapolation (Moline+ 2017)

Subhalo mass function — Extrapolation

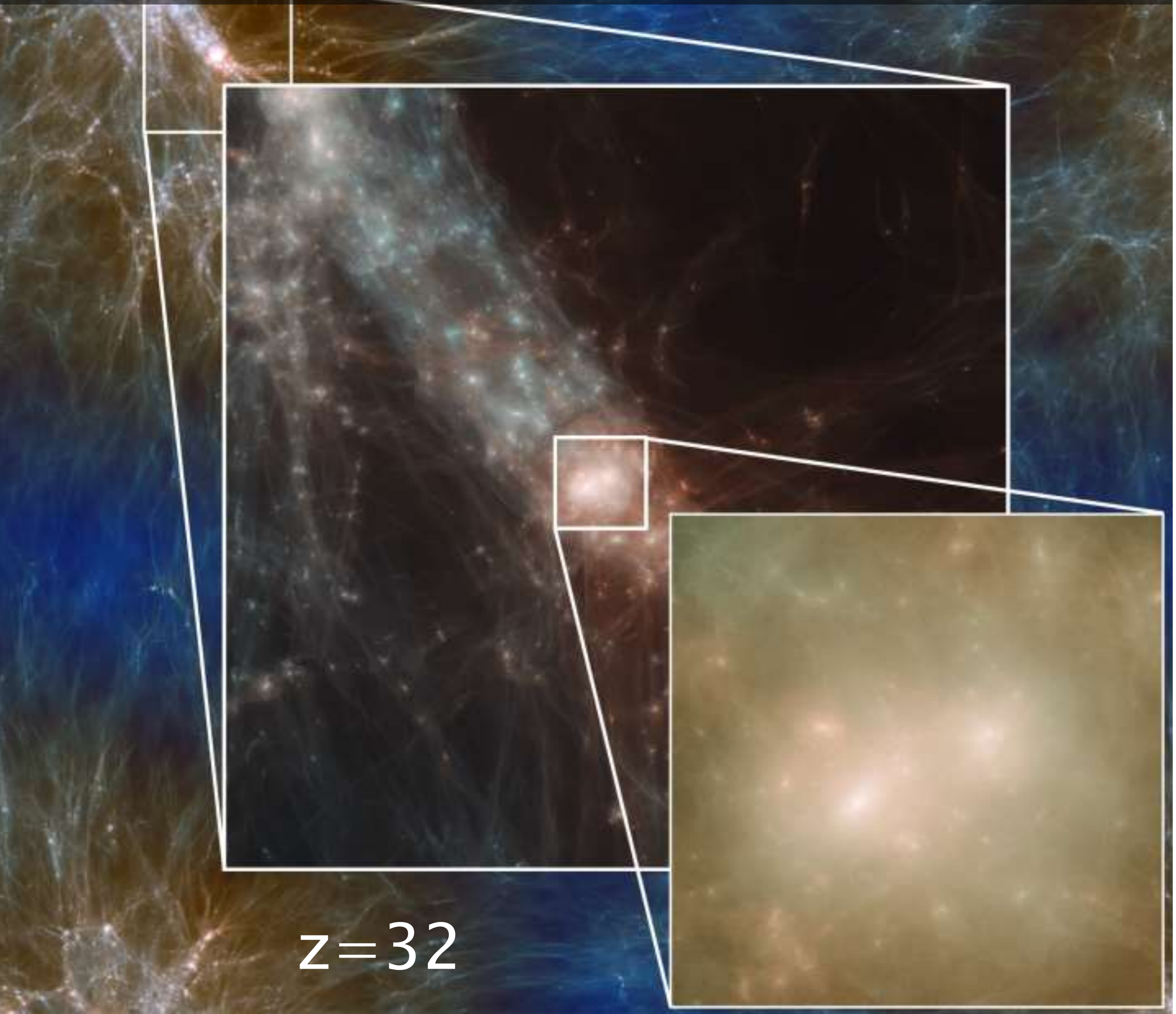
This work

$$B(M) = \frac{1}{L_{\rm host}(M)} \int_{M_{\rm min}}^{M} \frac{dn}{dm} [1 + B_{\rm sub}(m)] L_{\rm sub}(m)\, dm$$





Resolving the smallest scale



Max N = 8192^3 = 549,755,813,888

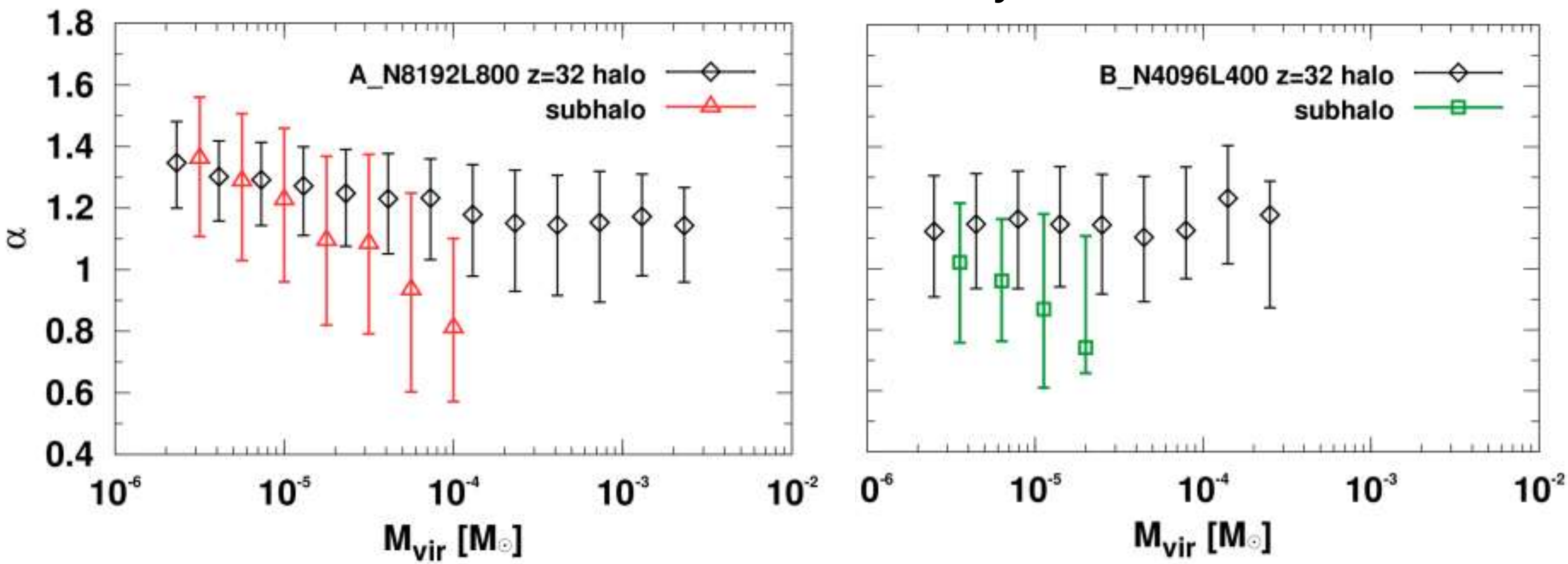
L = 800 pc
m = 3.4×10^{-11} Msun

Analyze
$10^{-6} \sim 10^{-2}$ Msun halos

Ishiyama 2014,
Ishiyama, Ando 2020

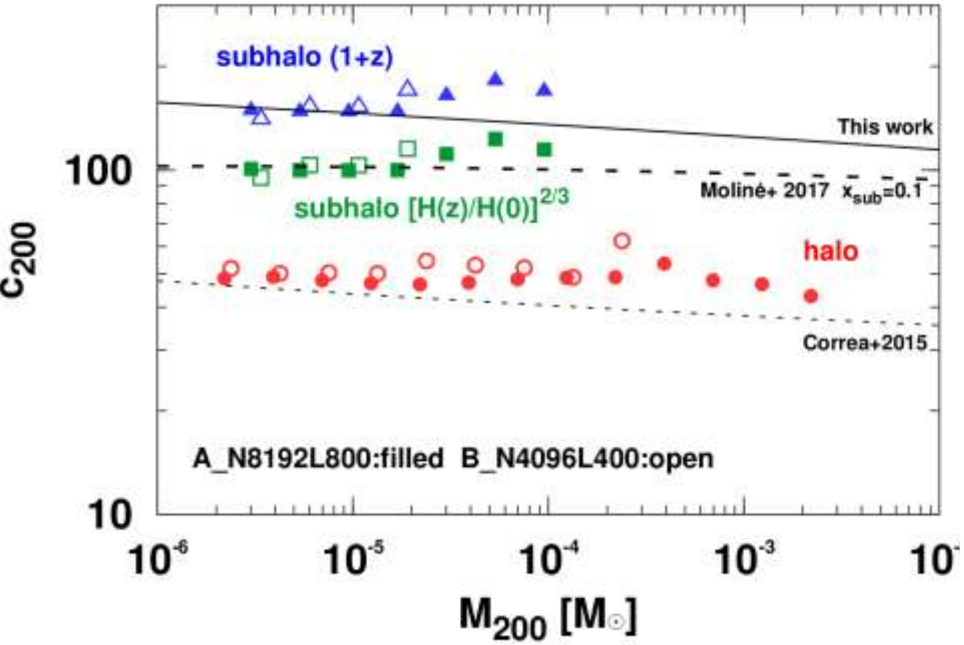
Structure of halos/subhalos near the free streaming scale (z=32)

Ishiyama and Ando, 2020, MNRAS

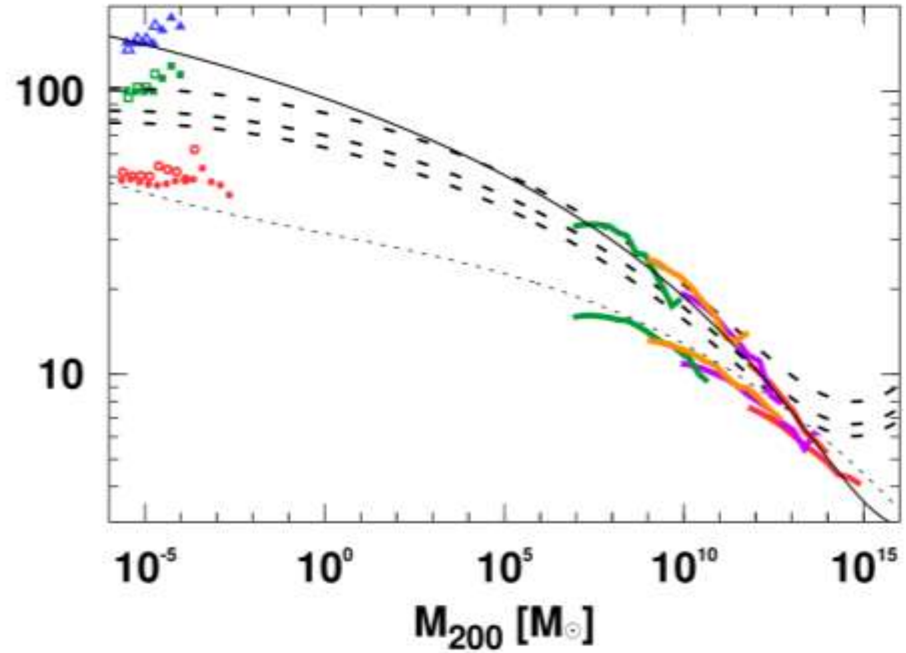


- Fitting function (=NFW when α=1) ➡ $$\rho(r) = \frac{\rho_0}{(r/r_s)^\alpha (1 + r/r_s)^{(3-\alpha)}}$$
- In subhalos, central slopes are considerably shallower than in field halos
  - However, they are still steeper than that of the NFW profile
- Why steeper than -1? See Ogiya and Hahn 2018

Connect to large scales



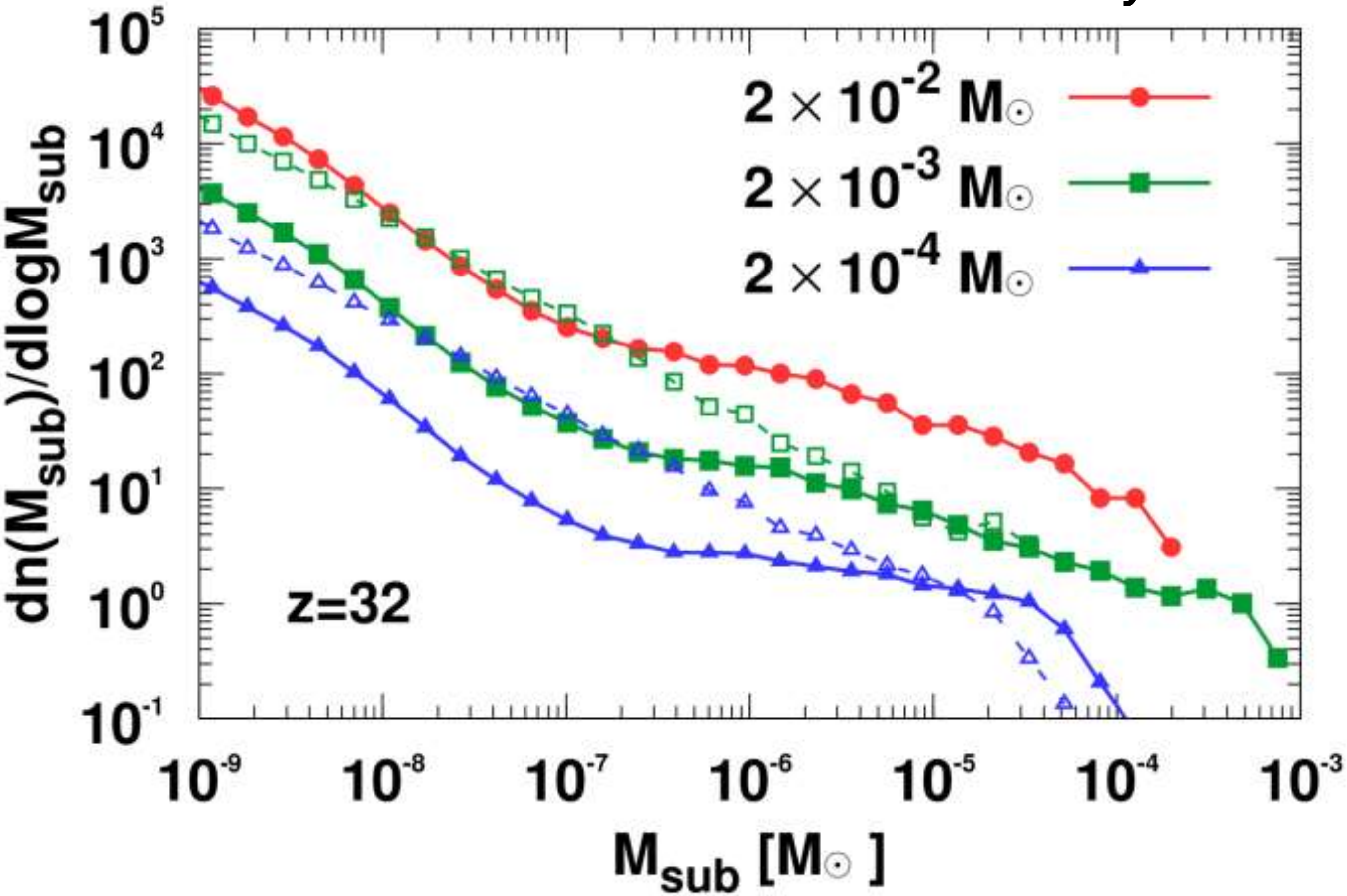
Ishiyama and Ando, 2020, MNRAS



- Different m-c relation between halos and subhalos
- Intermediate scales are still missing

Stacked subhalo mass function (z=32)

Ishiyama and Ando, 2020, MNRAS



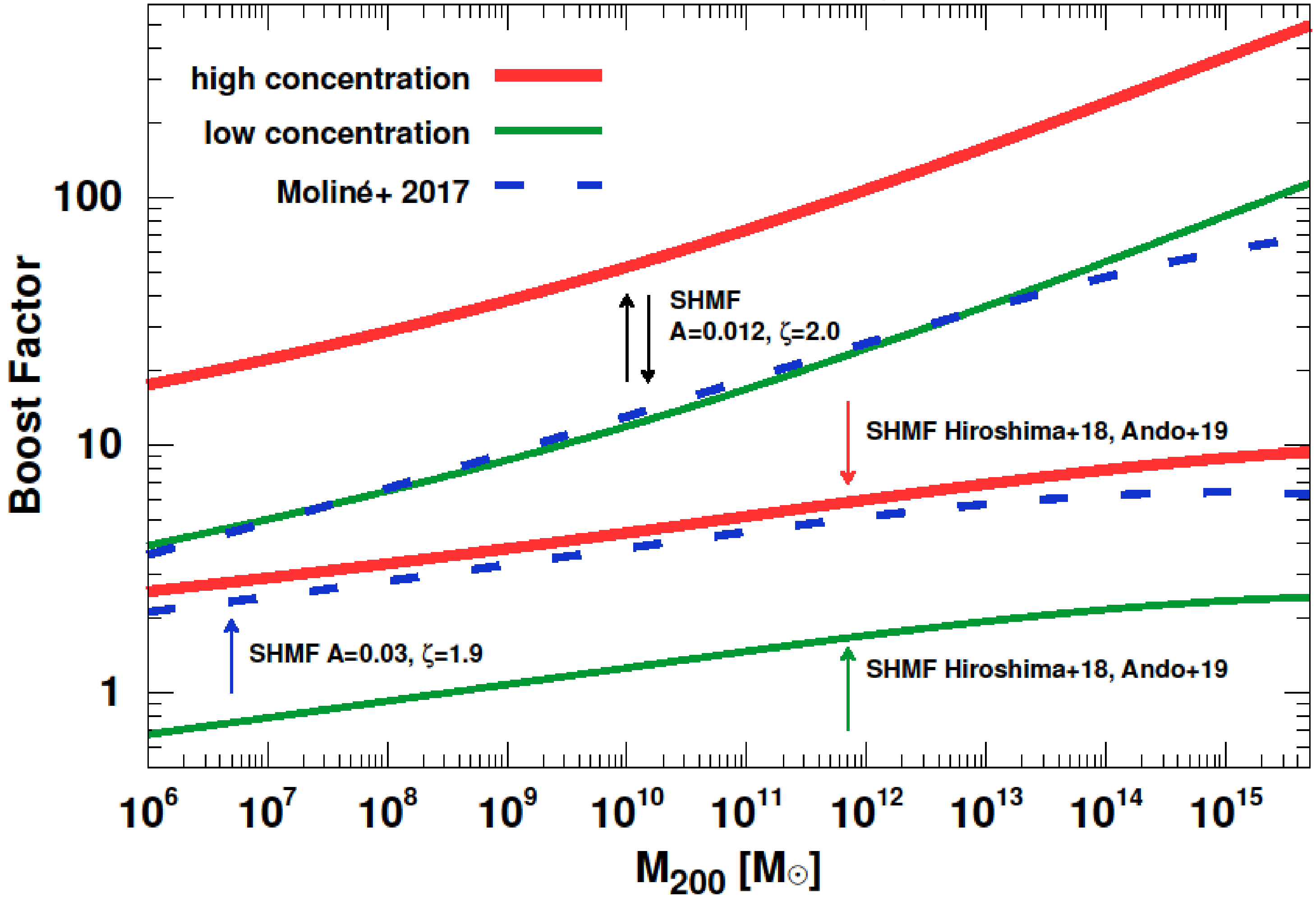
Solid:
w/ cutoff
$N=8192^3$
800pc box

Dashed:
w/o cutoff
$N=4096^3$
400pc box

- The subhalo abundance is suppressed below the free streaming scale, however, artificial fragmentation exists
  - Weaken annihilation signals

Annihilation boost factor

Ishiyama and Ando, 2020, MNRAS



- Steeper cusp and suppressed subhalo mass function compensate each other
- Subhalo m-c relation and the slope of subhalo mass function have more impact

Structure of the smallest halo

- We study the abundance and structure of halos/subhalos near the free streaming scale using a suite of large cosmological N-body simulations

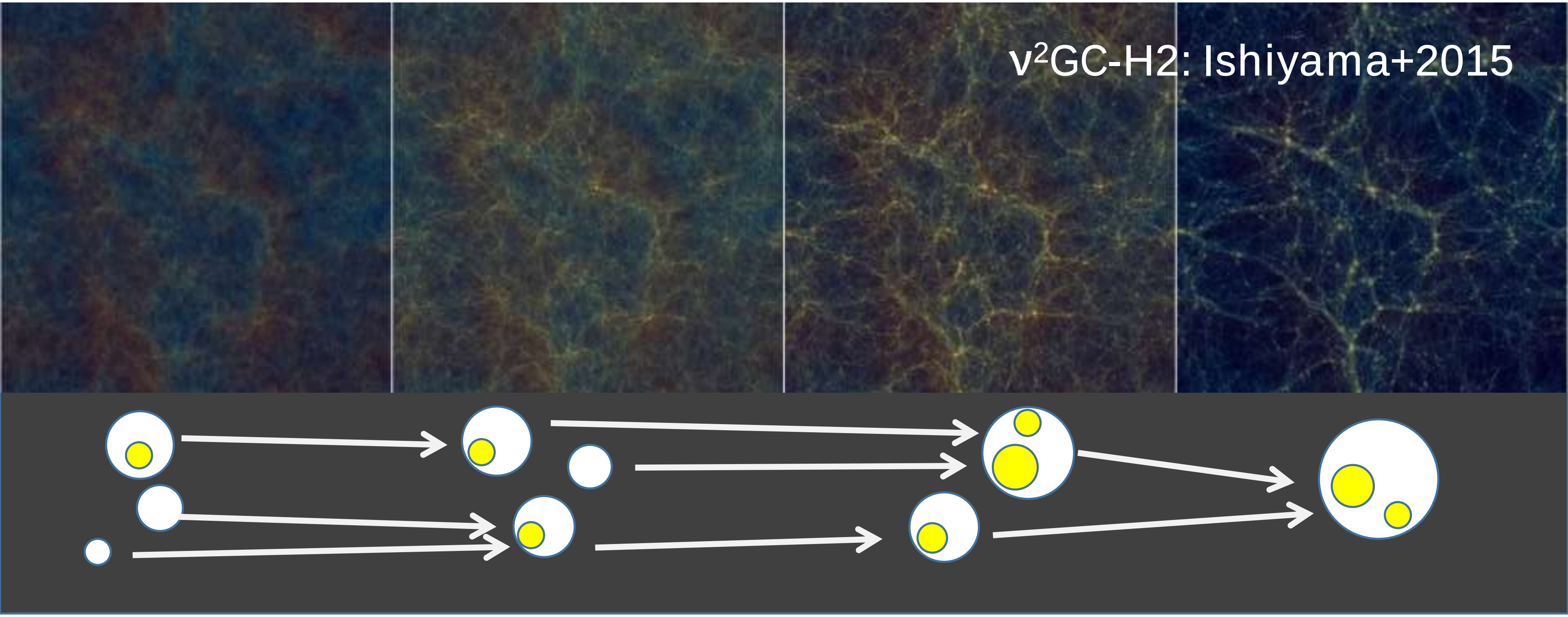
- The central cusps are much steeper than that of the NFW profile
  - Becomes gradually shallower as the halo mass increases
  - Shallower in subhalos than in halos
- Concentrations significantly increase in subhalos (tidal effect)

- The subhalo abundance is suppressed strongly below the free streaming scale
  - The ratio between in the cutoff and no cutoff simulations is well fitted by a single correction function regardless of the host halo mass and the redshift

- The effects of steeper cusps and suppression of the subhalo abundance could compensate each other in annihilation signals

Dark matter and luminous objects

Cosmological N-body simulations



- ダークマター密度揺らぎの非線形成長を有限のボリューム、質量分解能の下でシミュレーション
  - 各時刻におけるハロー/サブハローの質量、内部構造、運動といった特徴を記述する多数のパラメータに縮約した情報 (ハローカタログ)
  - それらを時刻間でつなぎ合体など進化の情報を記述する merger tree

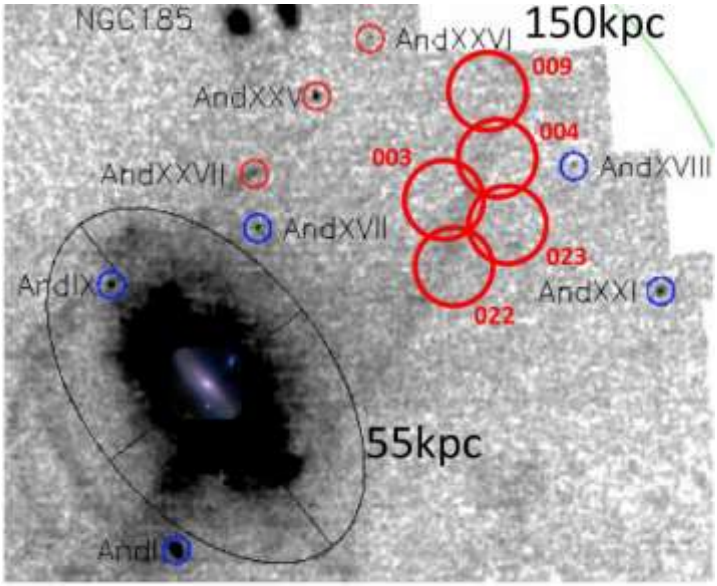
Public simulations

Name	#particles	L(Mpc/h)	m (Msun/h)	Consistent tree	Rockstar	redshifts
ν^2GC-L	8192^3	1120.0	2.20×10^8	×	☺	z=0,1,2,3 4,4.57,6,7
ν^2GC-M	4096^3	560.0	2.20×10^8	upon request	···	table
ν^2GC-S	2048^3	280.0	2.20×10^8	☺	···	table
ν^2GC-H1	2048^3	140.0	2.75×10^7	☺	···	table
ν^2GC-H2	2048^3	70.0	3.44×10^6	☺	···	table
Phi-1	2048^3	32.0	3.28×10^5	☺	···	table
ν^2GC-SS	512^3	70.0	2.20×10^8	☺	···	table

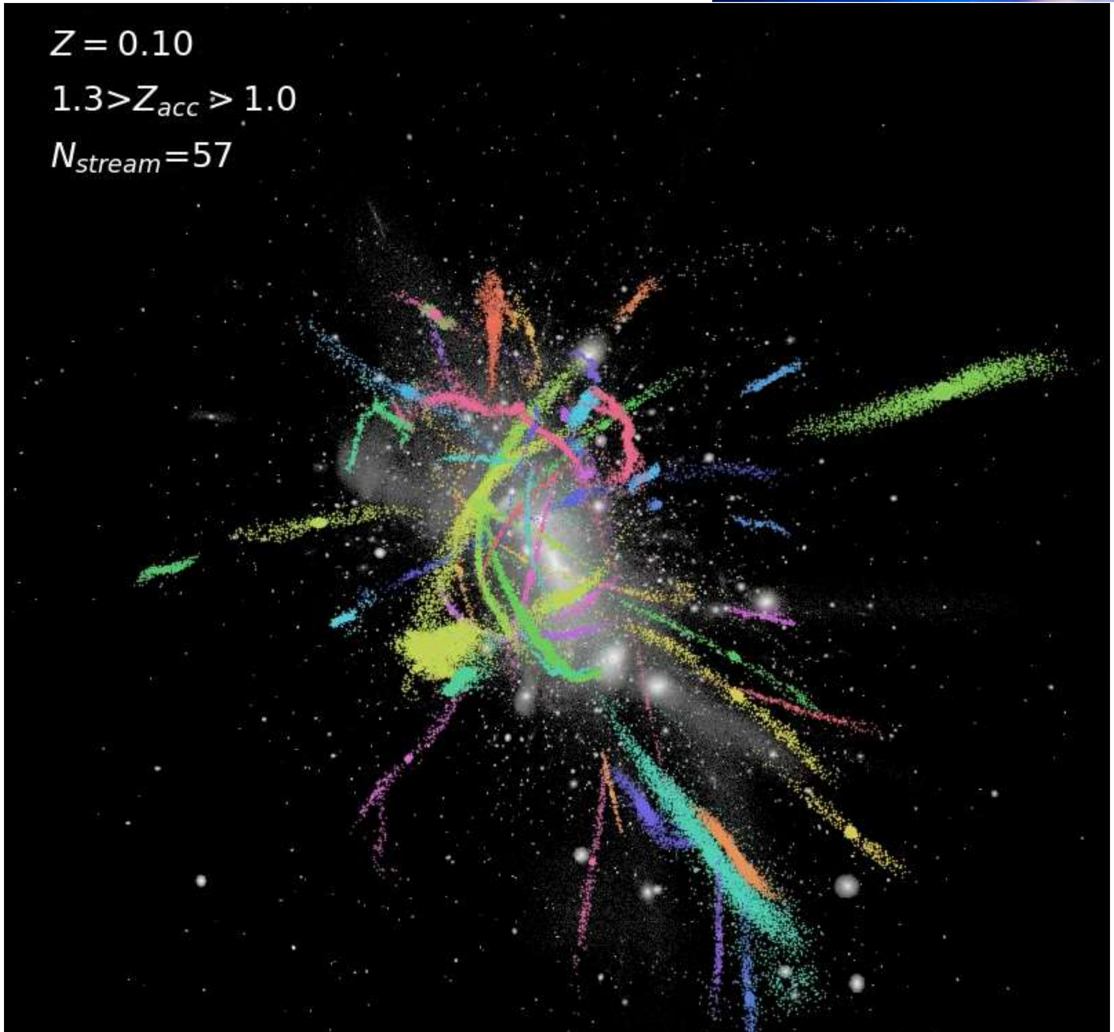
- Many group make their simulations publicly available because of its computational expensiveness
- http://hpc.imit.chiba-u.jp/~ishiymtm/db.html
  At least 30 papers are published/submitted from 2015

Reproducing stellar stream in cosmological context

- Progenitors of streams are accreted at z=0.5-2.5

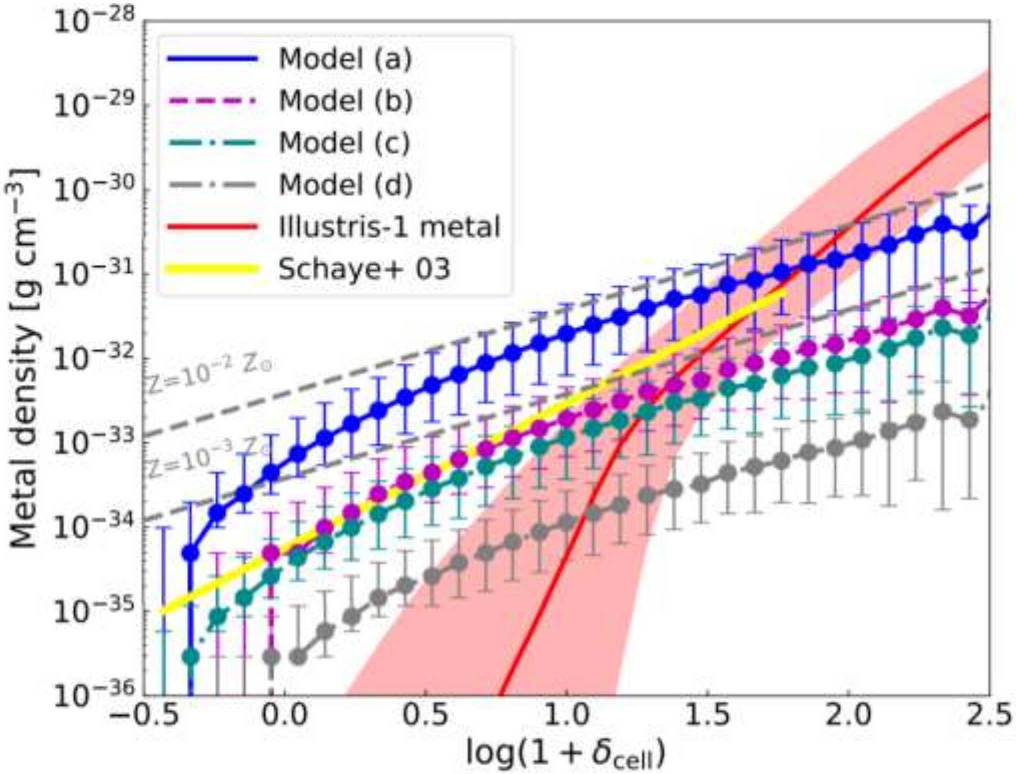


Andromeda stream by HSC (Komiyama+ 2018)



Morinaga and Ishiyama et al., 2019

Discrimination of heavy elements originating from Pop III stars in z=3 IGM

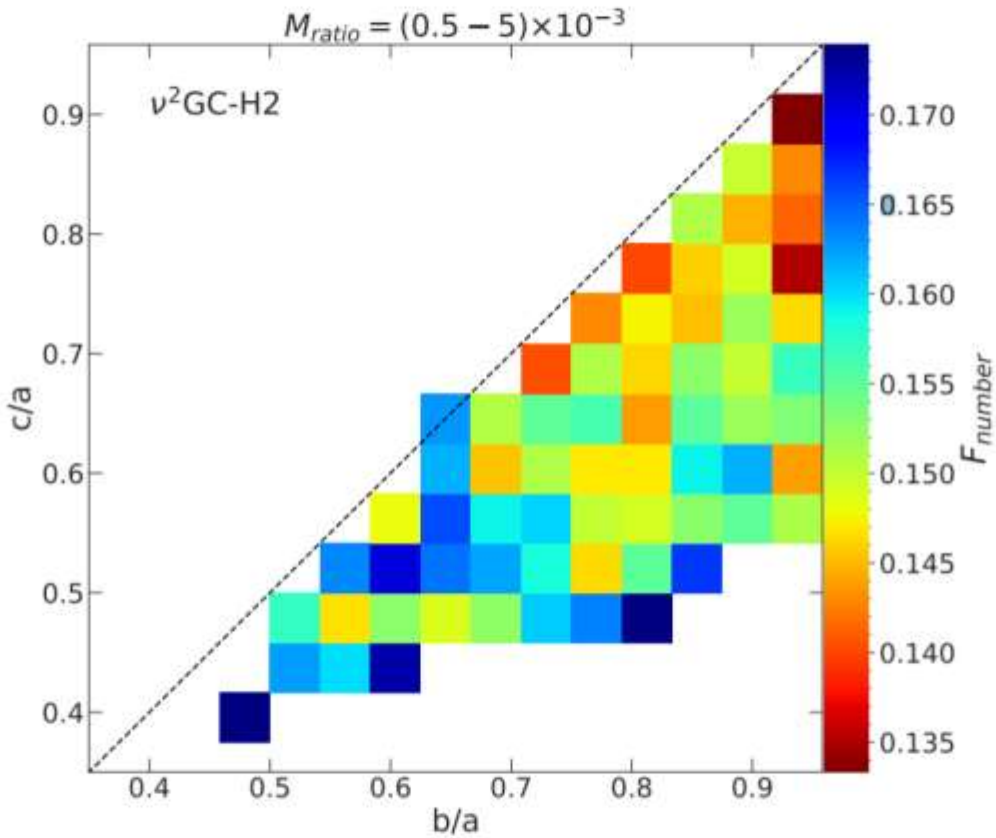


Kirihara, Hasegawa, Umemura, Mori, TI, 2020

You can find poster presentation somewhere in this room

- cosmological simulation
  +
  Pop III formation model
  +
  metal enrichment model
- heavy elements provided by Pop III often dominate in low density regions
- Spectroscopic observations with the next generation telescopes are expected to detect the metals imprinted on quasar spectra

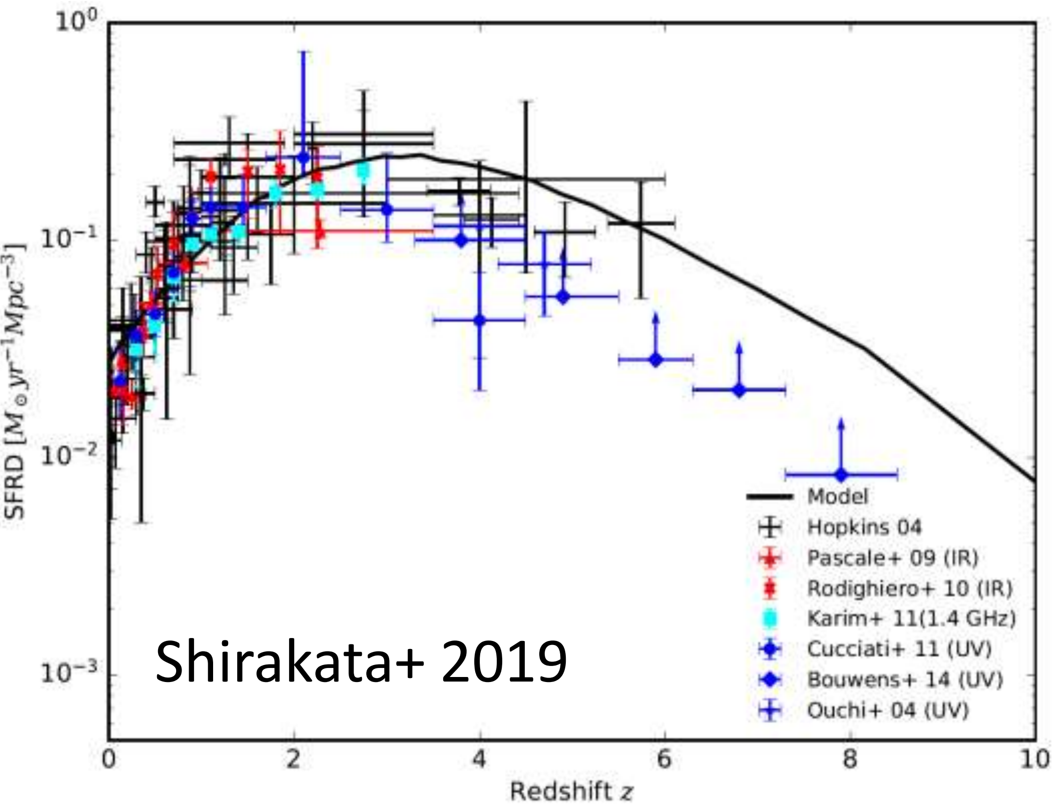
The impact of filamentary accretion of subhaloes on the shape and orientation of haloes



Morinaga and Ishiyama, arXiv:1912.11647

- Haloes with highly anisotropic accretion become more spherical or oblate, while haloes with isotropic accretion become more prolate or triaxial

ν²GC: New Numerical Galaxy Catalog



Makiya+ 2016
Oogi+ 2016, 2017, 2019
Shirakata+ 2015, 2016, 2019 など

- Phenomenological modelling luminous objects on dark halo merger trees
- Successor of Numerical Galaxy Catalog (νGC: Nagashima+ 2005)
  - All basic physics are included
  - MCMC parameter fitting
- Luminosity functions of AGNs at z<6.0 are also reproduced

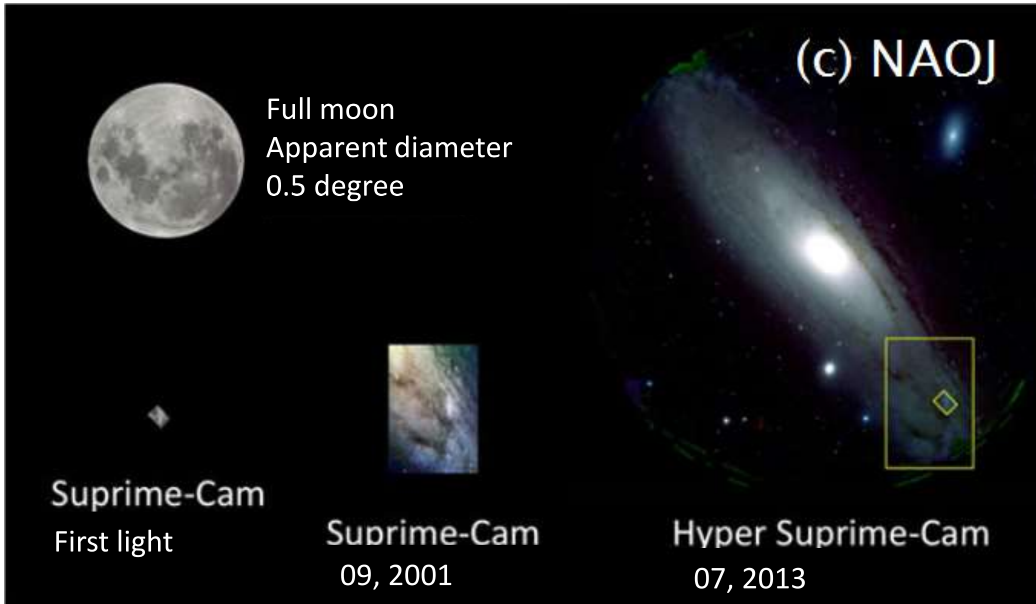
Next generation mock galaxy/AGN catalogs

- Ongoing wide/deep surveys (e.g., Hyper-Suprime-Cam on Subaru telescope, Euclid) give extremely large dataset of galaxies/AGNs

→ Large numerical catalogs are needed to compare with each other
  - Cosmological Hydrodynamical simulation
  - Semi analytic galaxy/AGN formation model

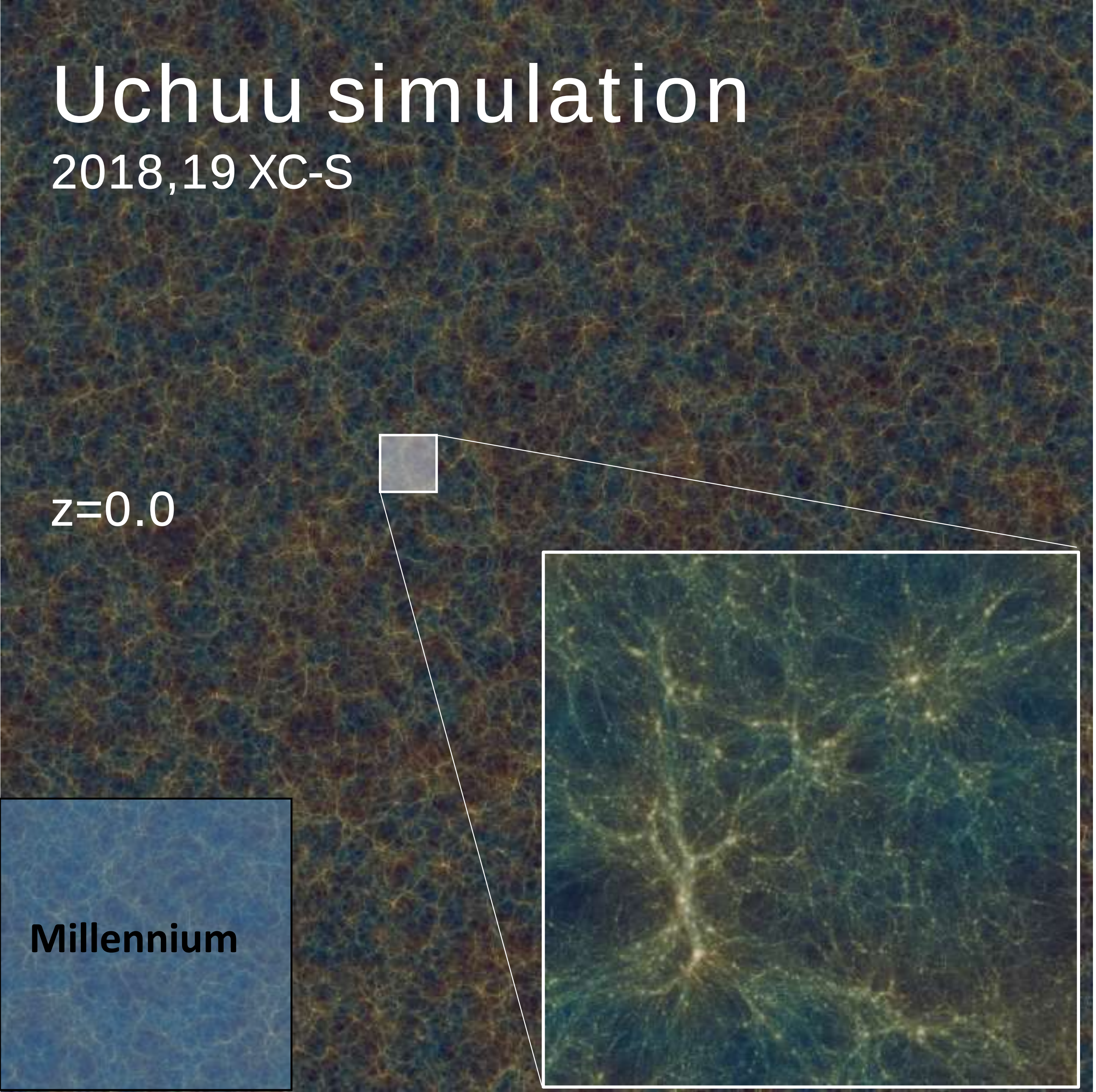
- Survey areas are over 1Gpc
- Number density of bright AGNs at high redshift → ～10^{-6} Mpc^{-3}

Gpc scale mock catalogs！！



Uchuu simulation

2018,19 XC-S



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

L = 2.0 Gpc/h
$m = 3.27 \times 10^8$ Msun/h

Planck Cosmology

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

One of the largest
cosmological
N-body simulation
in the world

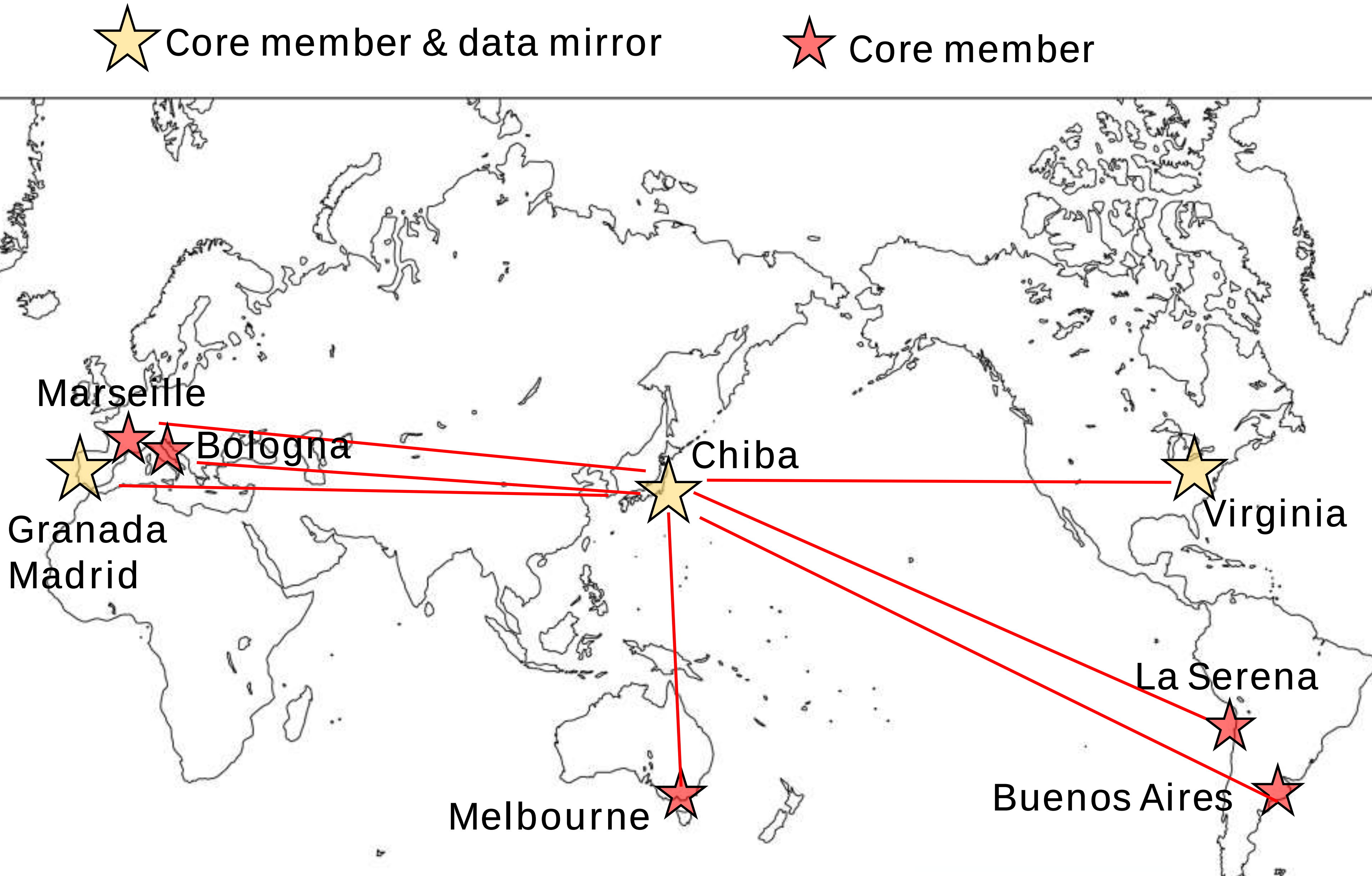
64 x larger volume,
3 x better mass res,
compared to
Millennium Run
(WMAP1 cosmology)

IO error？

- 数十万ファイルに1つくらいの確率で、
  途中までしか書きこまれていないように見える
- システムログにも何も出ない
- 異なる複数のコードで発生する

- ファイルサイズ (バイト) が 2097152 の倍数である

Big international collaboration based on simulations conducted on Aterui-II



Project overview (Uchuu project)

- International collaboration across the world
- Perform huge cosmological N-body simulations
- Provide halo/subhalo catalogs and mock galaxy/AGN catalogs that can be suitable to compare with next-generation wide/deep surveys
    - HSC
    - Euclid
    - PFS
    - WFIRST
    - TMT
- Use several models to construct mock catalogs
    - ν^2GC, SAGE, and SAG

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 (Tokyo)
- Francisco Prada (Granada) **
- Manodeep Sinha (Melbourne)
- Sylvain De la Torre (Marseille)
- Cristian Vega (La Serena)
- and many other collaborators

** Co-PI, * core board

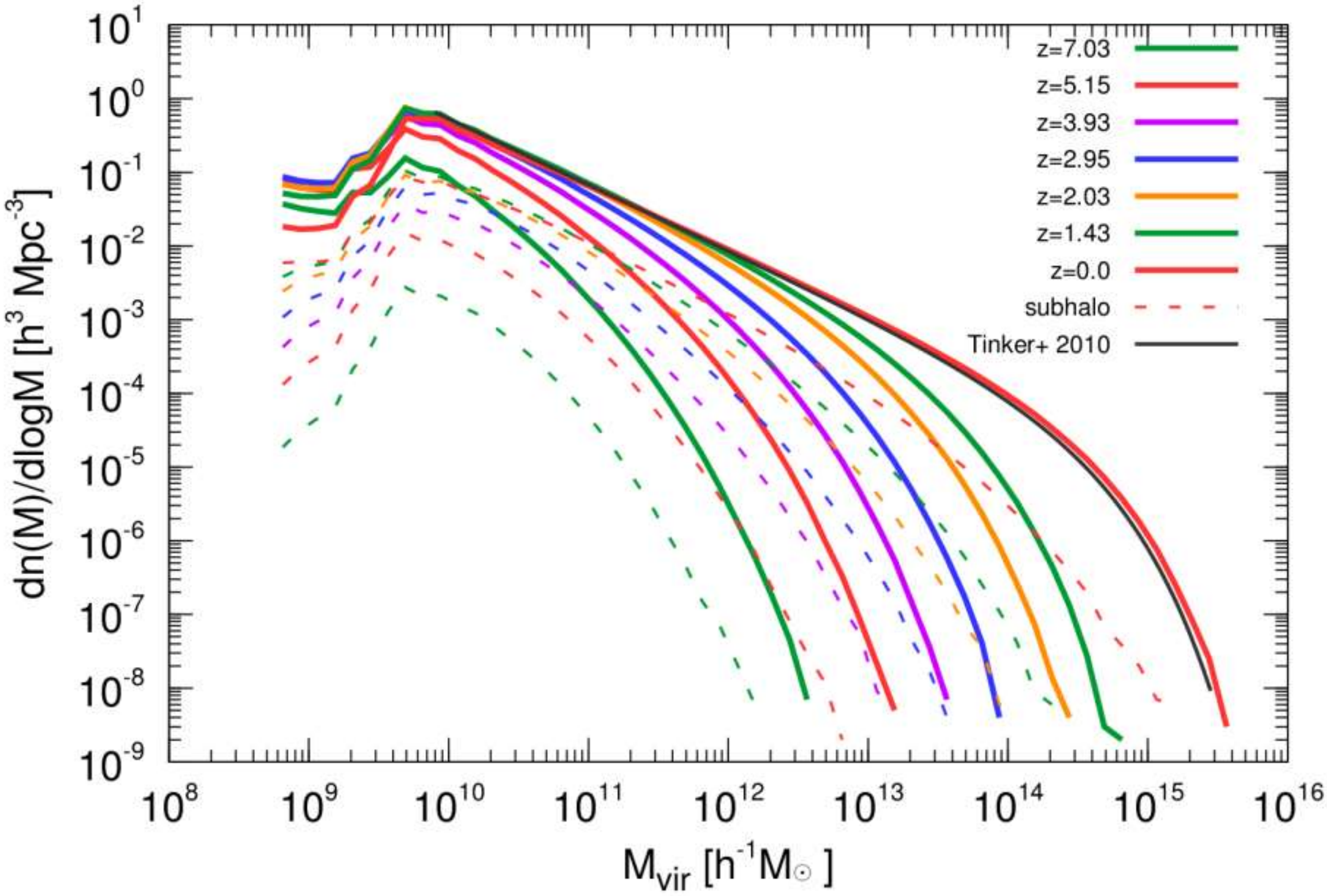
Scientific targets

- Thanks to large volume, we can study the formation and evolution of a number of objects at high-z probed by HSC and PFS

- Origin of AGNs/QSOs and co-evolution with galaxies
- Emission line galaxies and large scale structures
- Statistics of galaxy clusters and proto-clusters
- Cosmological probes including weak lensing and galaxy surveys
- and many other

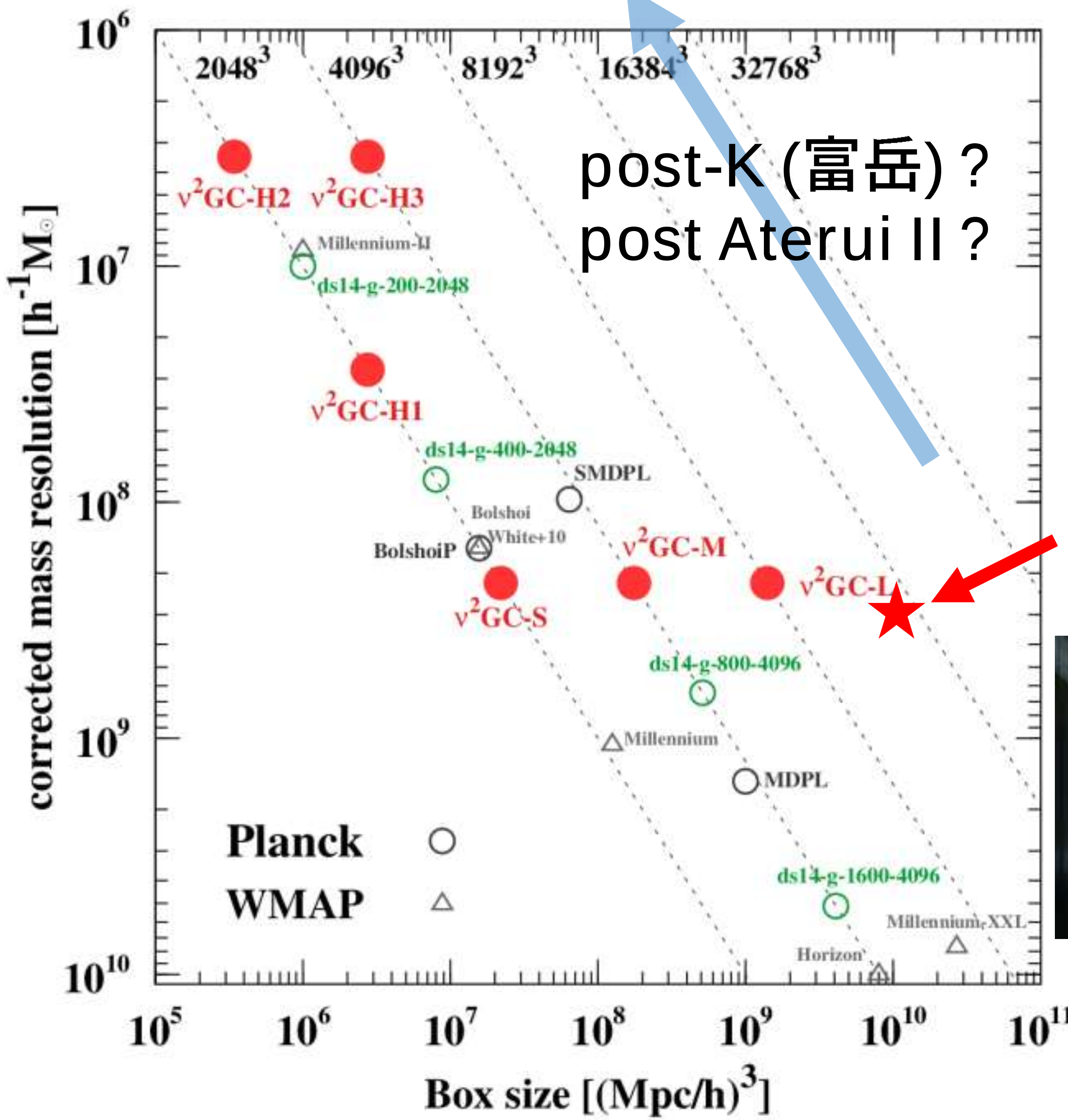
First results

halo mass function



Data products and release schedule

- Date for DR1: April 1st, 2020
- Data products for DR1 (* partially available upon request)
  - Rockstar halo/subhalo catalogs (including Vpeak, Vacc, Mpeak)
  - Merger trees
  - Random sample of particles (0.5%)
  - Lensing products: maps, etc
  - Codes for analysis
- Data for DR2: in 2020
  - Mock galaxy/AGN catalogs constructed by ν^2GC, SAGE, and SAG
- Data are going to be available at
  - http://skiesanduniverses.org
  - http://hpc.imit.chiba-u.jp/~ishiymtm/db.html



post-K (富岳) ?
post Aterui II ?

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

Big numerical challenge !!

Grand challenge in the next era

- Solar mass resolution for MW halo
  - Precise modelling of halo/subhalo structures for dark matter detection experiments
- Impact of first stars on the evolution of Universe
  - Both resolving minihalos and large scale structures
- Mock catalogs for next generation observations

Summary

- 次世代の大規模天体サーベイ観測と比較可能なスケールの、銀河/活動銀河核の模擬カタログ構築、公開のための国際プロジェクト進めている
  - 一辺 2Gpc/h の空間サイズ
  - 複数の準解析的モデルによるカタログ

- DR1: April 1st, 2020
  - 既に一部データは利用可
- collaborator 募集中。興味ある人は石山まで