

The v^2 GC Simulations: Quantifying the Dark Side of the Universe in the Planck Cosmology



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Partially based on Ishiyama, Enoki, Kobayashi, Makiya,
Nagashima, Oogi, PASJ, 67, 61 (arXiv: 1412.2860)

Gpc scale mock galaxy/AGN catalogs

- Ongoing wide/deep surveys (e.g., Hyper-Suprime-Cam on Subaru telescope) 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
→ $\sim 10^{-6} \text{ Mpc}^{-3}$

Gpc scale mock catalogs !!



Power of semi analytic galaxy/AGN formation model

- Cosmological hydrodynamical simulations (e.g., Illustris, Eagle, MassiveBlack-II)
 - ~ 100 Mpc boxes with high mass resolution ($\sim 10^6$ Msun)
 - Large volume ($>$ a few hundreds Mpc) simulations with sufficient resolution require huge computational cost \Rightarrow **currently impossible**
 - Difficult to perform many runs with varying many physical processes

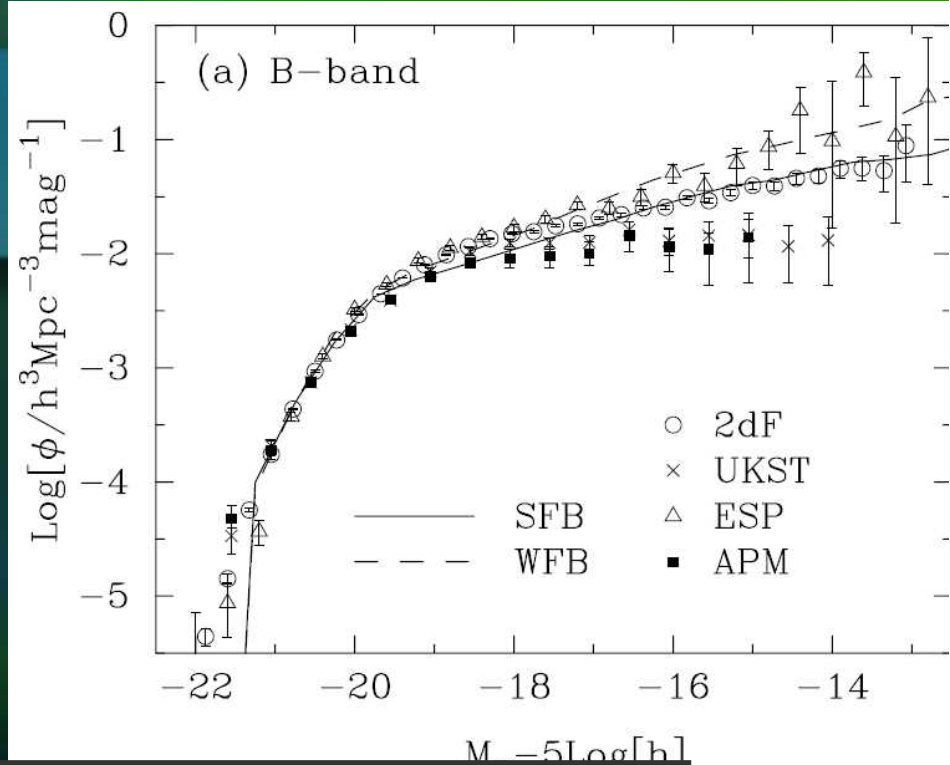
↓↑ *complementary*

- **Semi analytic galaxy/AGN formation model** (e.g., Galacticus, Morgana, vGC ...)
 - Depending on the quality of dm only cosmological simulations
 - Relatively easy to perform compared to hydrodynamical simulations
 - Low computational cost
 - Easily change many physical processes and test them

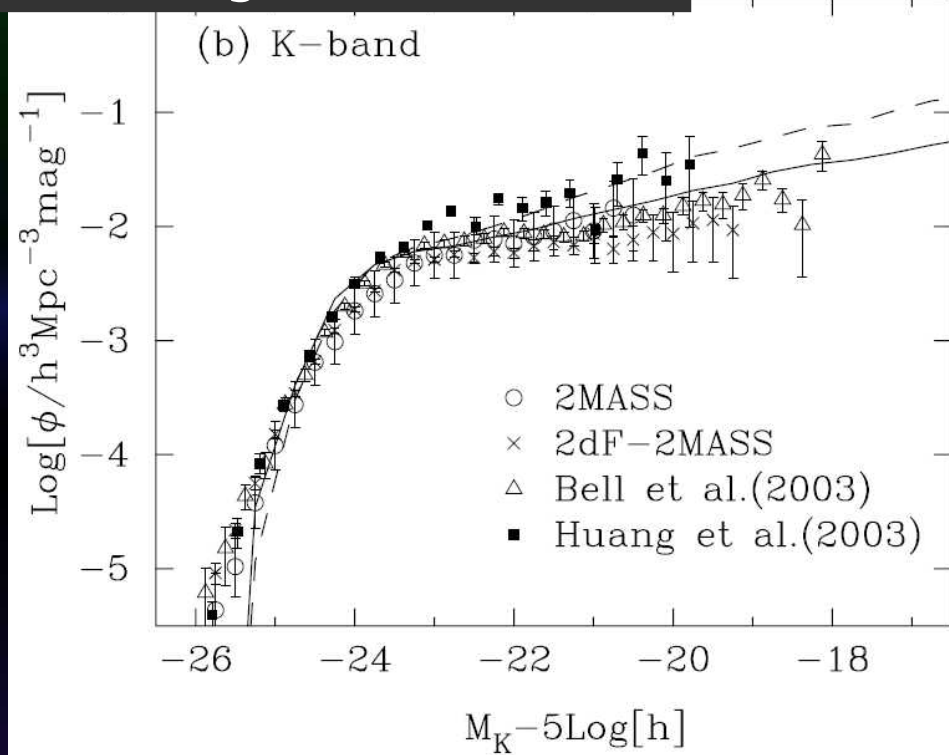
v²GC: New Numerical Galaxy Catalog

- Successor of Numerical Galaxy Catalog (vGC: Nagashima+ 2005)
 - All basic physics are included
 - MCMC parameter fitting
- Combining with ultralarge simulations
 - **The mass resolution is the highest among simulations of >1Gpc boxes**
→ 8192³ particles in 1.12Gpc/h box

Collaboration with
 M. Enoki (Tokyo Keizai)
 M.A.R. Kobayashi (Ehime)
 R. Makiya (Tokyo)
 M. Nagashima (Bunkyo)
 T. Okamoto (Hokkaido)
 K. Okoshi (TUS)
 T. Oogi (Bunkyo)
 H. Shirakata (Hokkaido)



vGC (Nagashima+ 2005)



Our goal

- Generating huge mock galaxies/AGNs catalogs that we can use to compare with ongoing/forthcoming wide/deep surveys
 - Makiya et al. in prep
- Release halo/subhalo and mock catalogs for many purposes
 - Part of catalogs are already released
- Provide fitting functions to describe halo properties for analytical works
 - Mass function
 - Mass accretion rate
 - Formation redshift
 - Merger rate

ν^2 GC simulation suite

- Compared with Millennium simulation (Springel+05)
 - **11x** larger volume, **4x** better mass resolution
- Planck Cosmology
- Many runs → **Covering low- and high-z galaxies and AGNs**
- Dark Sky Simulation (Skillman+ 2014, 10240^3 particles) is larger than ν^2 GC-L . But boxsize is too large (8 Gpc/h), mass resolution is not good for galaxy/AGN (3.9×10^{10} Msun/h)

Name	N	$L(h^{-1}\text{Mpc})$	$m(h^{-1}M_{\odot})$	$\varepsilon(h^{-1}\text{kpc})$	$M_{\min}(h^{-1}M_{\odot})$
ν^2 GC-L	$8192^3 = 549,755,813,888$	1120.0	2.20×10^8	4.27	8.79×10^9
ν^2 GC-M	$4096^3 = 68,719,476,736$	560.0	2.20×10^8	4.27	8.79×10^9
ν^2 GC-S	$2048^3 = 8,589,934,592$	280.0	2.20×10^8	4.27	8.79×10^9
ν^2 GC-H1	$2048^3 = 8,589,934,592$	140.0	2.75×10^7	2.14	1.10×10^9
ν^2 GC-H2	$2048^3 = 8,589,934,592$	70.0	3.44×10^6	1.07	1.37×10^8
ν^2 GC-H3	$4096^3 = 68,719,476,736$	140.0	3.44×10^6	1.07	1.37×10^8

Facilities

- Massively parallel TreePM poisson solver, **GreeM** (Ishiyama+ 2009, 2012)
 - High performance and scalability upto a million CPU cores at least
 - **SC12 Gordon Bell Prize Winner**
 - 2–10 times faster than "Gadget-2" (Springel 2005)
 - ~5 times faster than HACC (Habib+ 2012)
- K Computer at RIKEN, Japan
 - World's fourth fastest supercomputer (10.6 Pflops)
 - Total 0.66 million cores
- Aterui supercomputer at CfCA, NAOJ
 - ~ 1 Pflops
 - Astro only



4-dimensional movie is available !!!



Simulation: T.I

Visualization: Hirotaka Nakayama (4D2U, NAOJ)

360 degree panoramic video for head mounted displays is available on
<http://4d2u.nao.ac.jp/english/>

The image shows a large-scale visualization of the cosmic web, a network of dark matter filaments and galaxy clusters. The background is a dense, interconnected web of thin, golden-brown filaments against a dark blue background. Two large, white-outlined rectangular regions are highlighted, showing zoomed-in views of the structure. The top-left zoom shows a complex network of filaments and small galaxy groups. The bottom-right zoom shows a more dense, galaxy-rich region with a prominent central cluster.

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

$L = 1.12 \text{ Gpc}/h$
 $m = 2.2 \times 10^8 \text{ Msun}/h$

Planck Cosmology

11x larger volume,
4x better mass res,
compared to
Millennium Run
(Springel+ 2005)

- $N = 2160^3$
- $L = 0.5 \text{ Gpc}/h$
- $m = 8.6 \times 10^8 \text{ Msun}/h$
- WMAP1 ($\sigma_8=0.9$)

Data size : ~1 PB

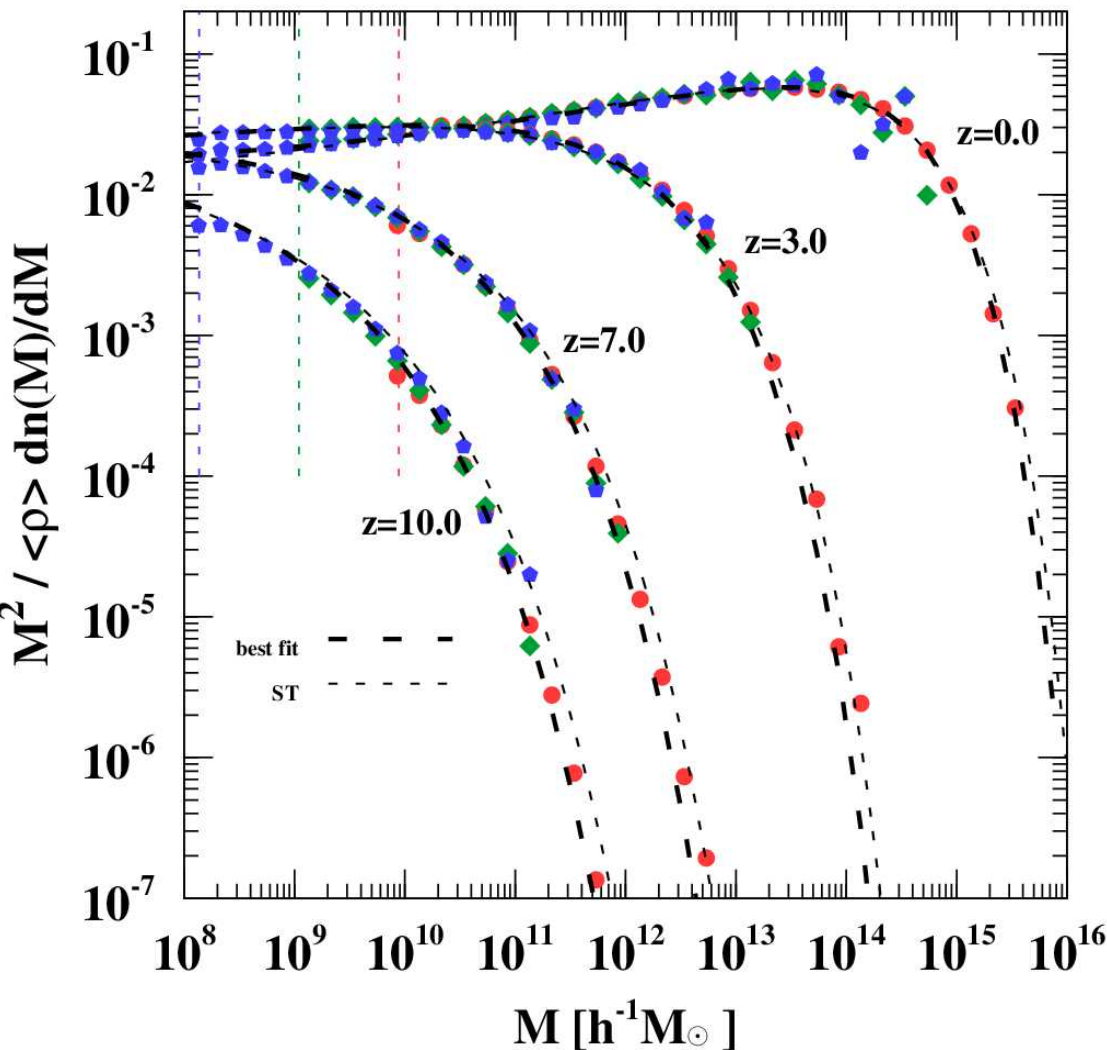
$z=0$

Mass functions

$$\frac{dn}{dM} = \frac{\rho_0}{M} \frac{d \ln \sigma^{-1}}{dM} f(\sigma)$$

$$f(\sigma) = A \left[\left(\frac{B}{\sigma} \right)^C + 1 \right] \exp \left(\frac{-D}{\sigma^2} \right)$$

$$A = 0.193, B = 2.184, C = 1.550, D = -1.186$$

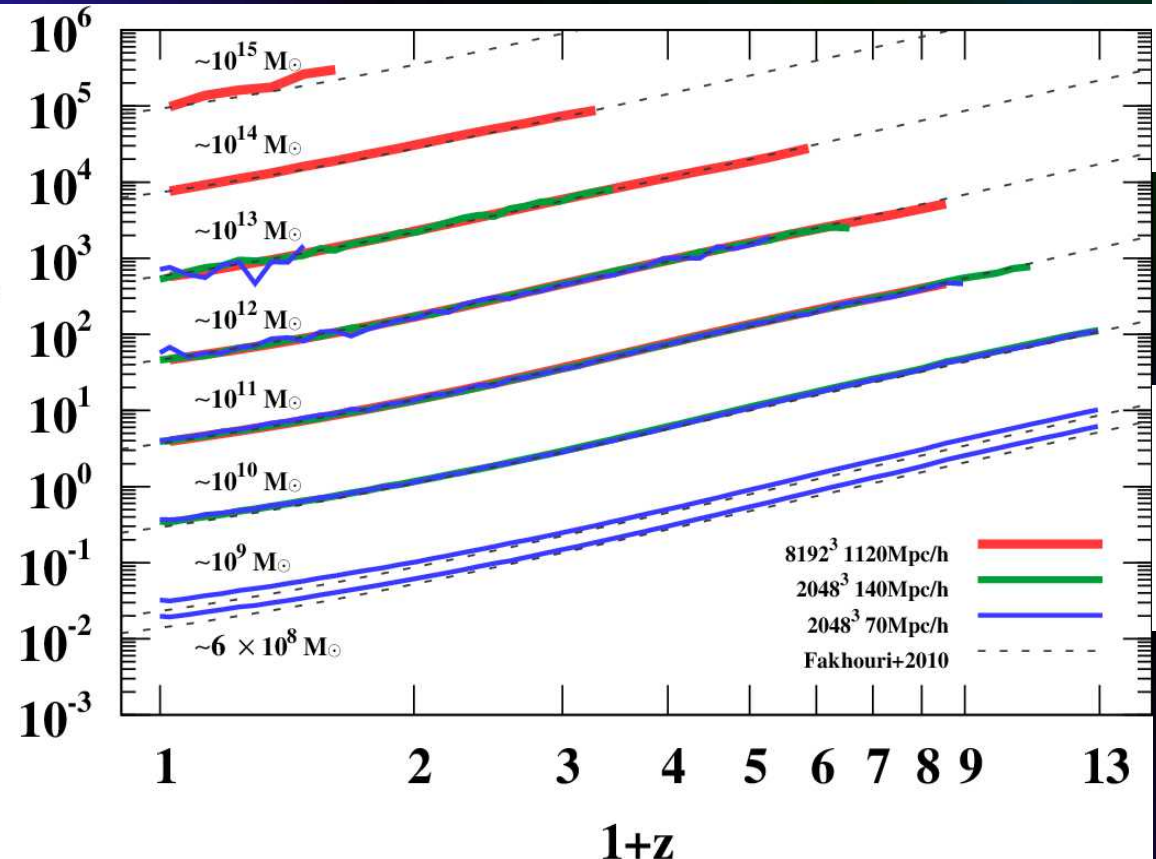
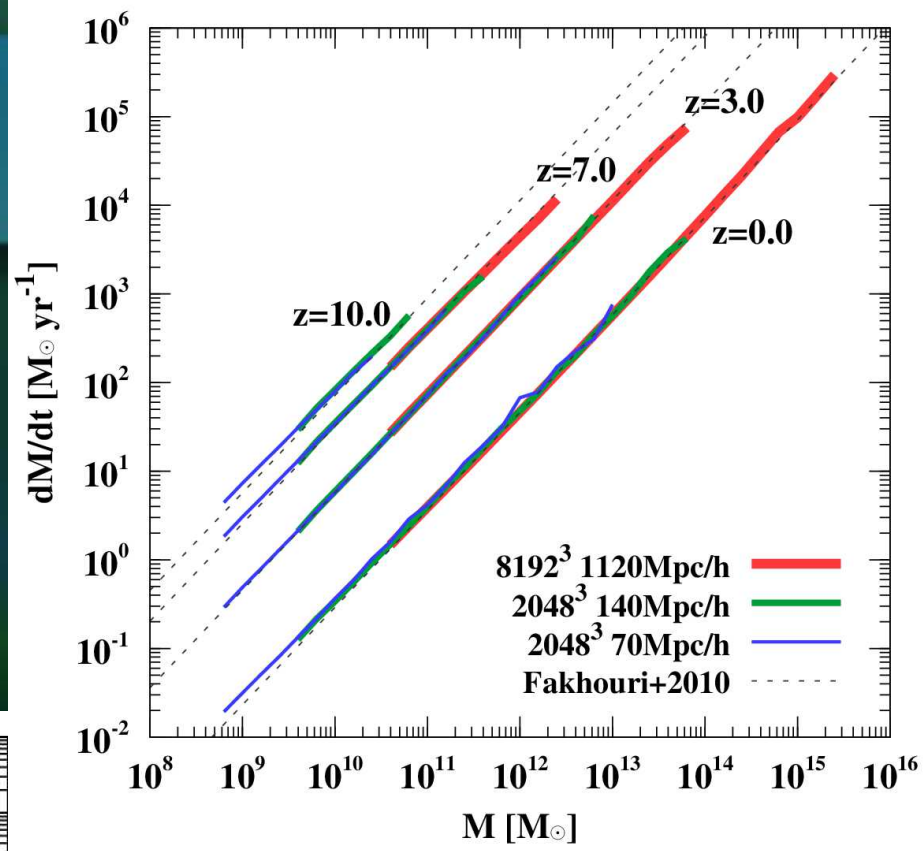


All mass functions are well converged regardless of redshifts !!!

Simple single fitting formula describes mass functions of various redshifts pretty much!

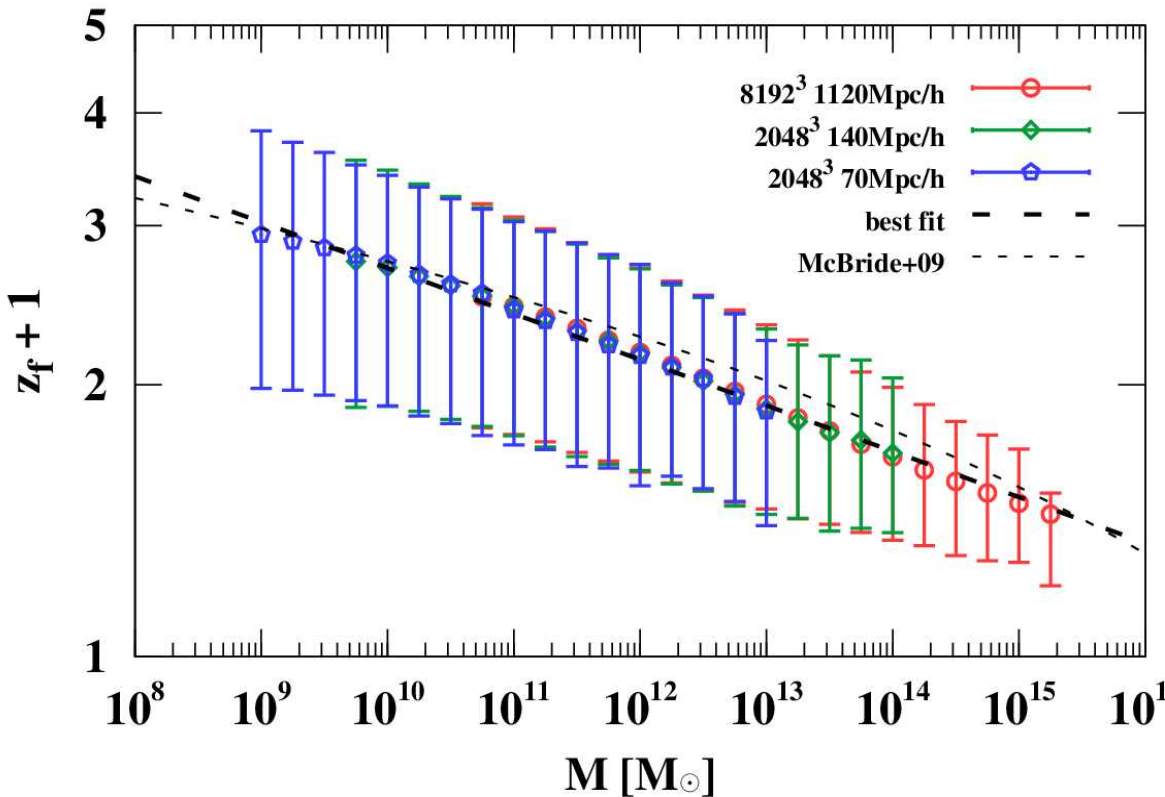
Mass accretion rate

- Mass and redshift dependence is consistent with Millennium (e.g. Fakhouri+ 2010)

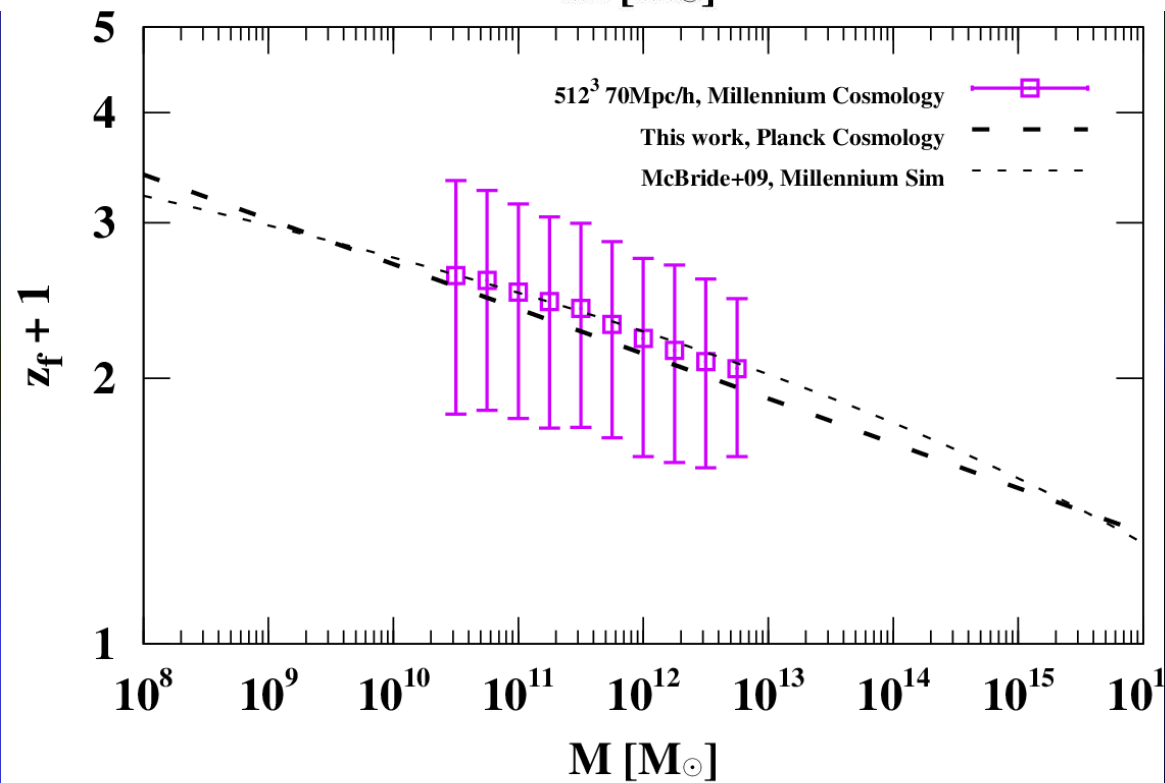


$$\left\langle \frac{dM}{dt} \right\rangle = 46.1 M_{\odot} \text{ yr}^{-1} \left(\frac{M}{10^{12} M_{\odot}} \right)^{1.1} \times \frac{1}{(1 + 1.11z) \sqrt{\Omega_0 (1+z)^3 + \lambda_0}}$$

Half mass formation redshift

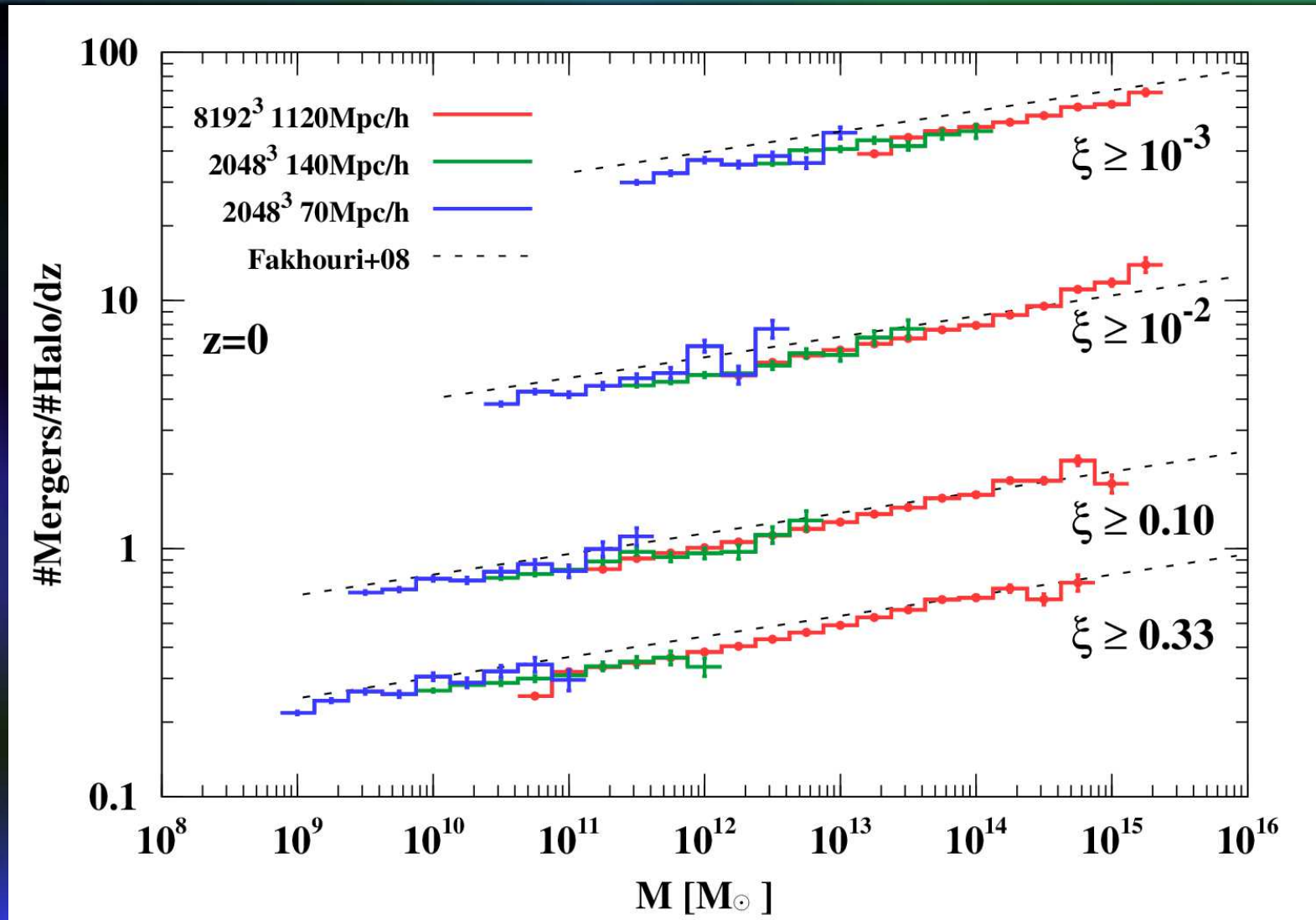


- Average values slightly shift lower redshifts than those of Millennium
- Due to the difference of cosmological parameters



$$1 + z_f = 2.69 \left(\frac{M}{10^{10} M_\odot} \right)^{-0.0508}$$

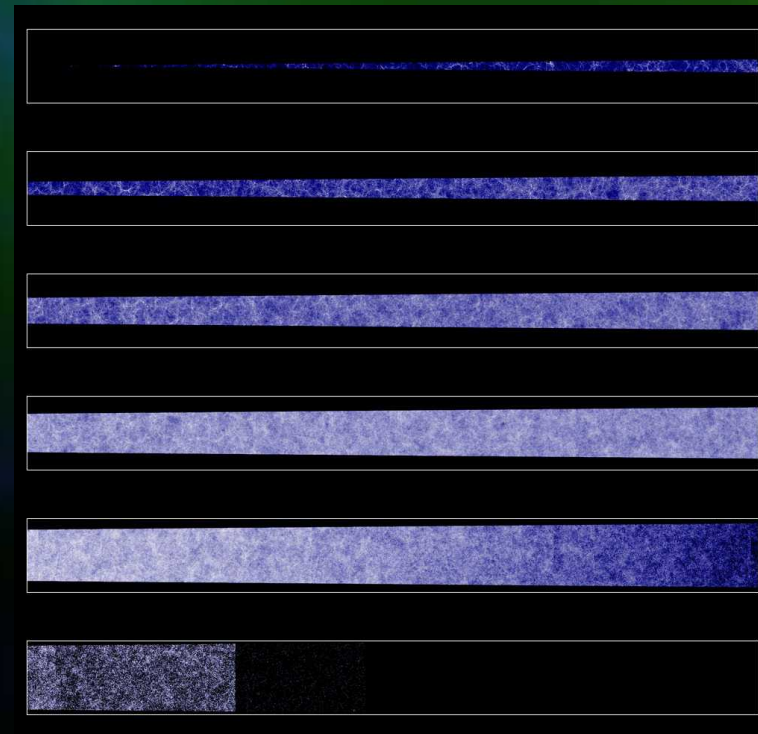
Mean merger rate



- Weak dependence on the halo mass
- Fitting formulae (based on Millennium (Fakhouri+08)) slightly overestimate the number of mergers

Public data

- Friends-of-friends (Davis+ 1985) and Rockstar (Behroozi+ 2013) halo/subhalo catalogs are available on <http://www.imit.chiba-u.jp/faculty/nngc/>
 - v^2GC-M , v^2GC-S , v^2GC-H1 , v^2GC-H2
 - $z=0, 1, 3, 7$
- Catalogs on other redshifts and FoF merger trees can be available upon request
(→ ishiyama AT chiba-u.jp)
- Mock galaxy/AGN catalogs (Makiya+ in prep) and Rockstar merger trees are available soon



Summary

Ishiyama, Enoki, Kobayashi, Makiya,
Nagashima, Oogi, PASJ, 67, 61 (arXiv: 1412.2860)

- Details of ultralarge cosmological simulations, **the v²GC suite** are presented, for next-generation mock galaxy and AGN catalogs based on our new semi analytic model
 - Gpc³ scale volume
 - Can resolve dwarf galaxy scale
 - Better than Millennium catalogs
- Some halo/subhalo catalogs are available on <http://www.imit.chiba-u.jp/faculty/nngc/>
- Mock galaxy/AGN catalogs will be available near future (Makiya et al. in prep)
- 360 degree panoramic video for head mounted displays is available on <http://4d2u.nao.ac.jp/english/>