Hierarchical Formation of Dark Matter Halos and the Free Streaming Scale

Tomoaki Ishiyama

University of Tsukuba (Kobe satellite)

Partially based on Ishiyama, 2014, ApJ, 788, 27 (arXiv:1404.1650)

筑波大学 University of Tsukuba

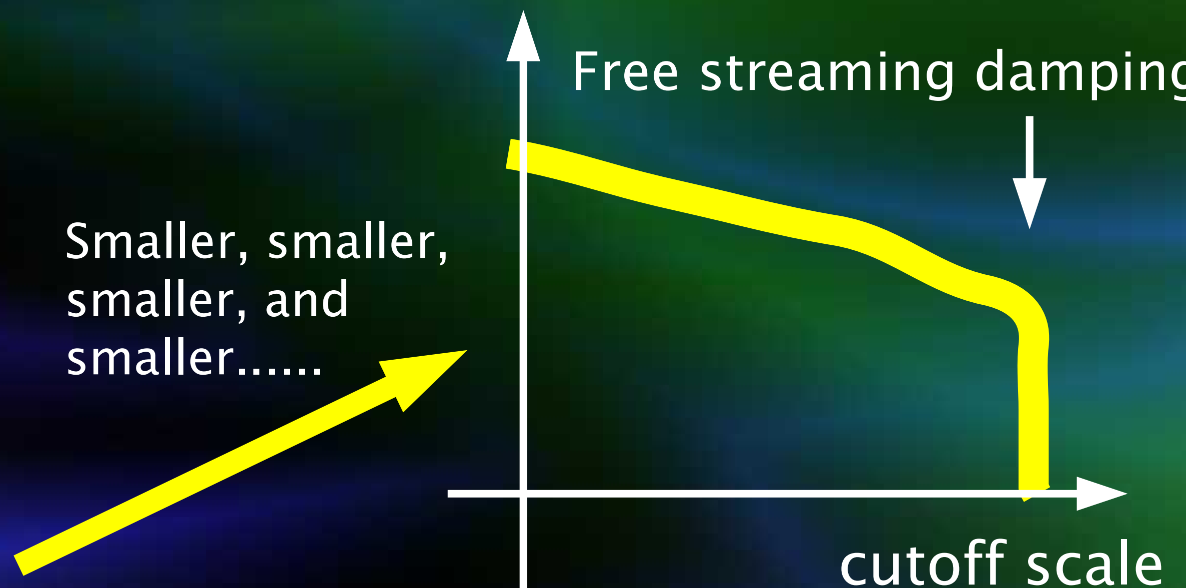
科研費 KAKENHI

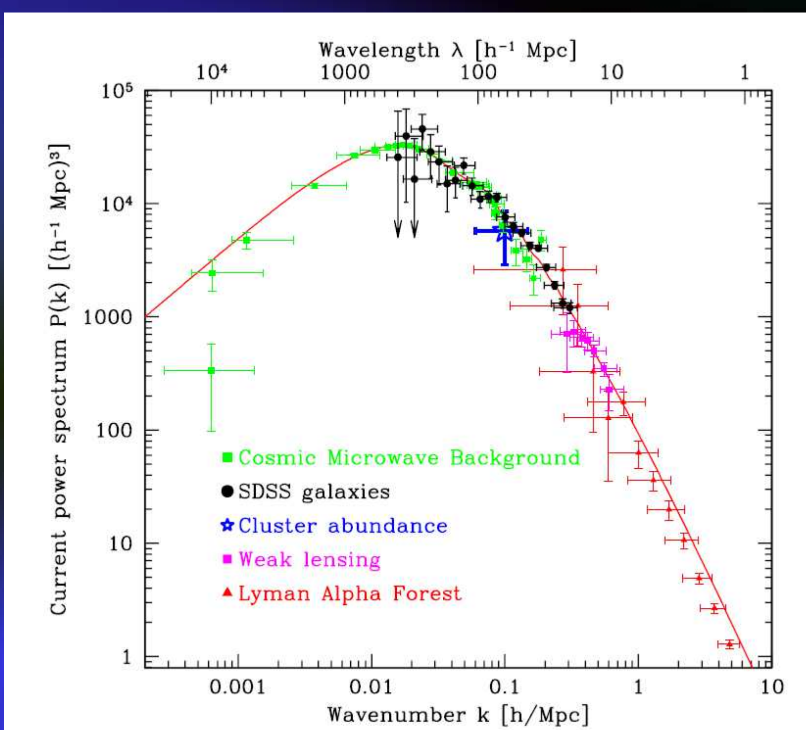
Outline

- **Motivation**
  - Free streaming damping
  - Fine structures of the Milky Way dark matter halo
- **Numerical Simulations**
- **Highlight results**
  - Structures of halos near the free streaming scale
  - Concentration at z=0
  - Evolution of density profiles
  - Annihilation boost factor by subhalos
- **Summary**

Free streaming damping

- Free streaming motions of dark matter particles wipe out the density fluctuation and impose a cutoff on P(k)
  - CDM: ~10^{-6} **Msun** (**microhalo**), if dark matter is the neutralino of 100GeV–1TeV (e.g. Zybin+1999, Hofmann+2001, Berezinsky+ 2003, , Green+2004)
  - WDM: 10^6~10^9 Msun

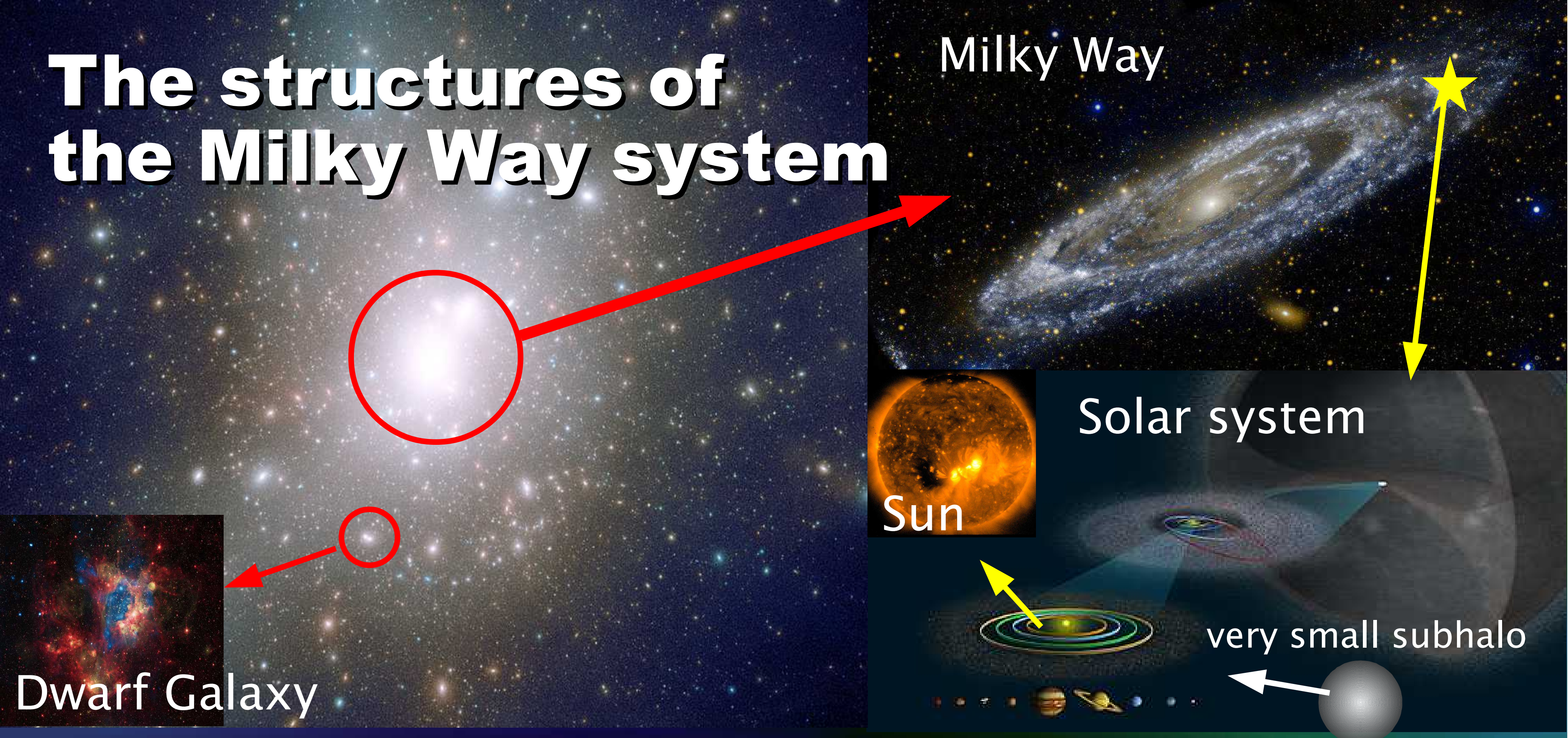




Tegmark et al. 2004

The difference of spectrum shape may change the structures of halo
(Because they do not form hierarchically)

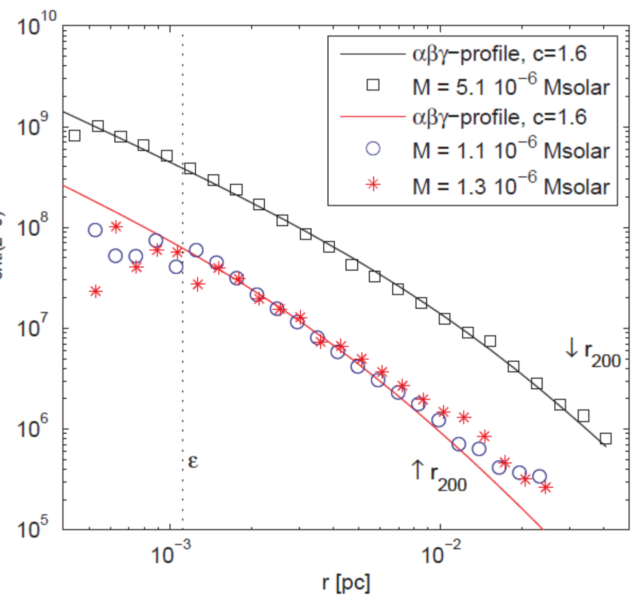
The structures of the Milky Way system



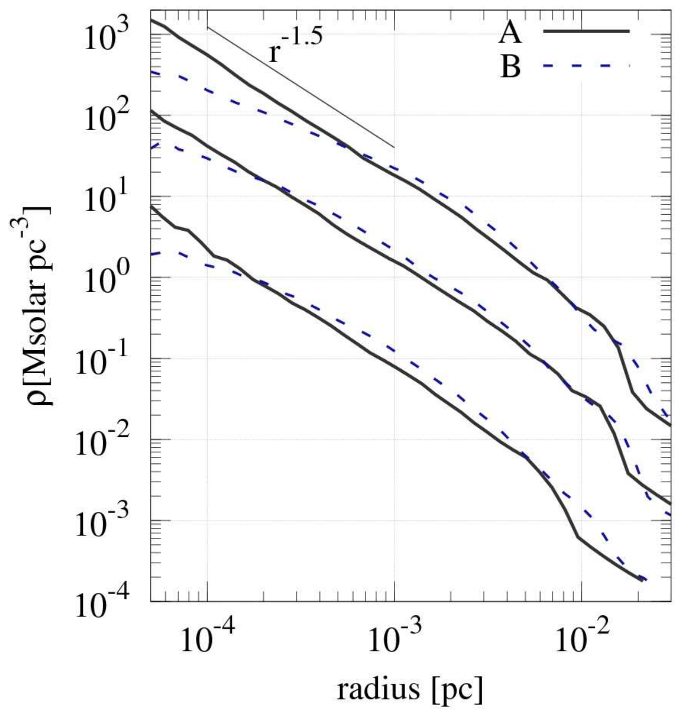
- Numerous subhalos ($10^{-6} \sim 10^{10}$ solar mass)
  - $dn/dm \propto m^{-2 \sim -1.8}$
- Where can we observe gamma-ray flux due to dark matter annihilation ?
  - The center of the Milky Way halo ?
  - Dwarf Galaxy ?
  - Microhalos near Sun ?

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

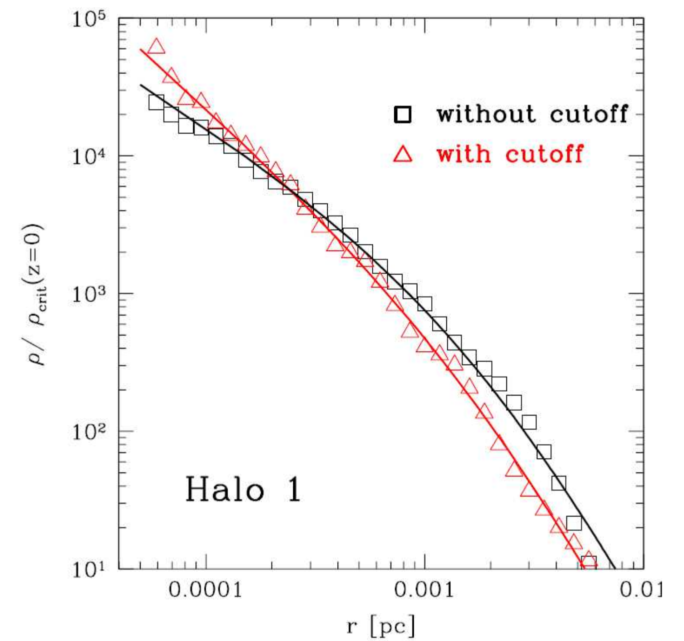
Resolution is very important !



Diemand+ 2005:
~10,000 particle /halo
Insufficient resolution to
resolve central regions



Ishiyama+2010:
~5M particles /halo
Steep central cusp!



Anderhalden and Diemand 2013
~10M particles /halo
Steep central cusp!

- To resolve central regions are very important ! -> **large number of particles**
- High resolution reduces the effect of artificial fragmentation as seen in WDM (e.g. Wang and White 2007, Schneider+ 2013, Angulo+ 2013)

Our studies

- Clarify the structure of **halos near the free streaming scale** by large cosmological N-body simulations
  - Typically, NFW or Einasto is assumed, thought, it is likely different from them
  - Previous works focused on only the smallest microhalos and simulated only a few microhalos (Diemand+ 2005, Ishiyama+2010, Anderhalden & Diemand 2013)

- **4096^3 particles** were used for the largest simulation
  - Impose the cutoff in the matter power spectrum
  - Focus on CDM, but should be applied for WDM etc

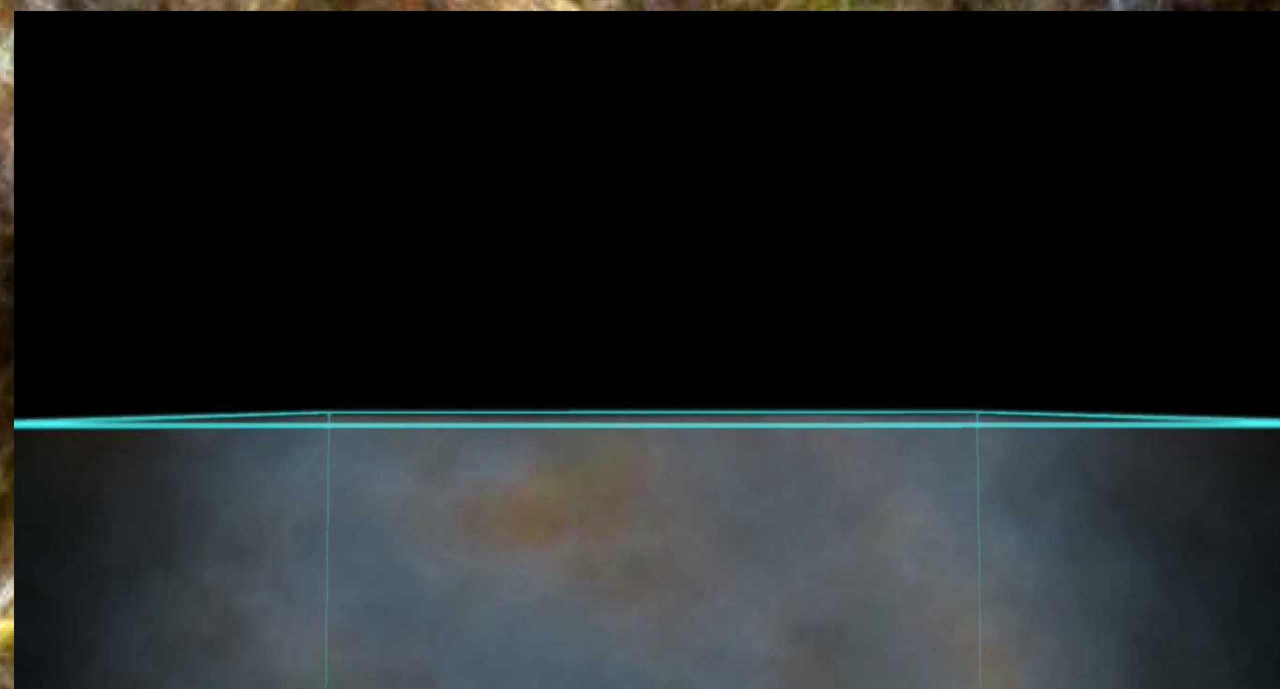
- Quantify shapes, concentrations and their distribution
- Evaluate the contribution to the annihilation gamma-ray

Ishiyama, 2014, ApJ, 788, 27

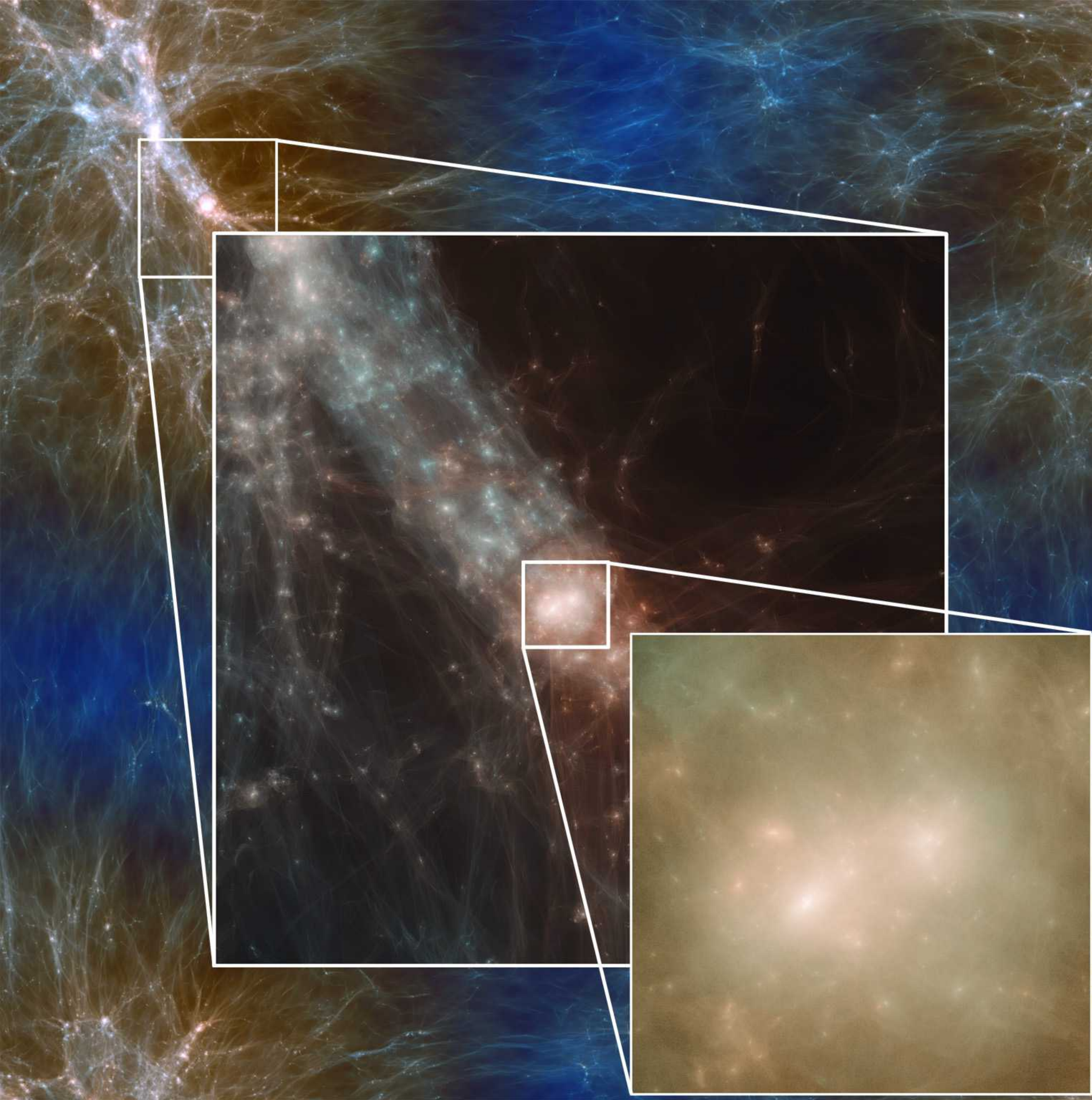
Cosmological N-body simulations

Name	N	L(pc)	ε(pc)	$m(M_\odot)$	$m_{\rm DM}$ (GeV)
A_N4096L400	4096^3	400.0	2.0×10^{-4}	3.4×10^{-11}	100
A_N4096L200	4096^3	200.0	1.0×10^{-4}	4.3×10^{-12}	100
B_N2048L200	2048^3	200.0	2.0×10^{-4}	3.4×10^{-11}	w/o cutoff

- z=400 to z=32
- GreeM parallel TreePM code (Ishiyama+ 2009, 2012)
  - ~10 times faster than Gadget-2



Movie:
Takaaki Takeda
(4D2U, National Astronomical Observatory of Japan)



$N = 4096^3 =$
68,719,476,736

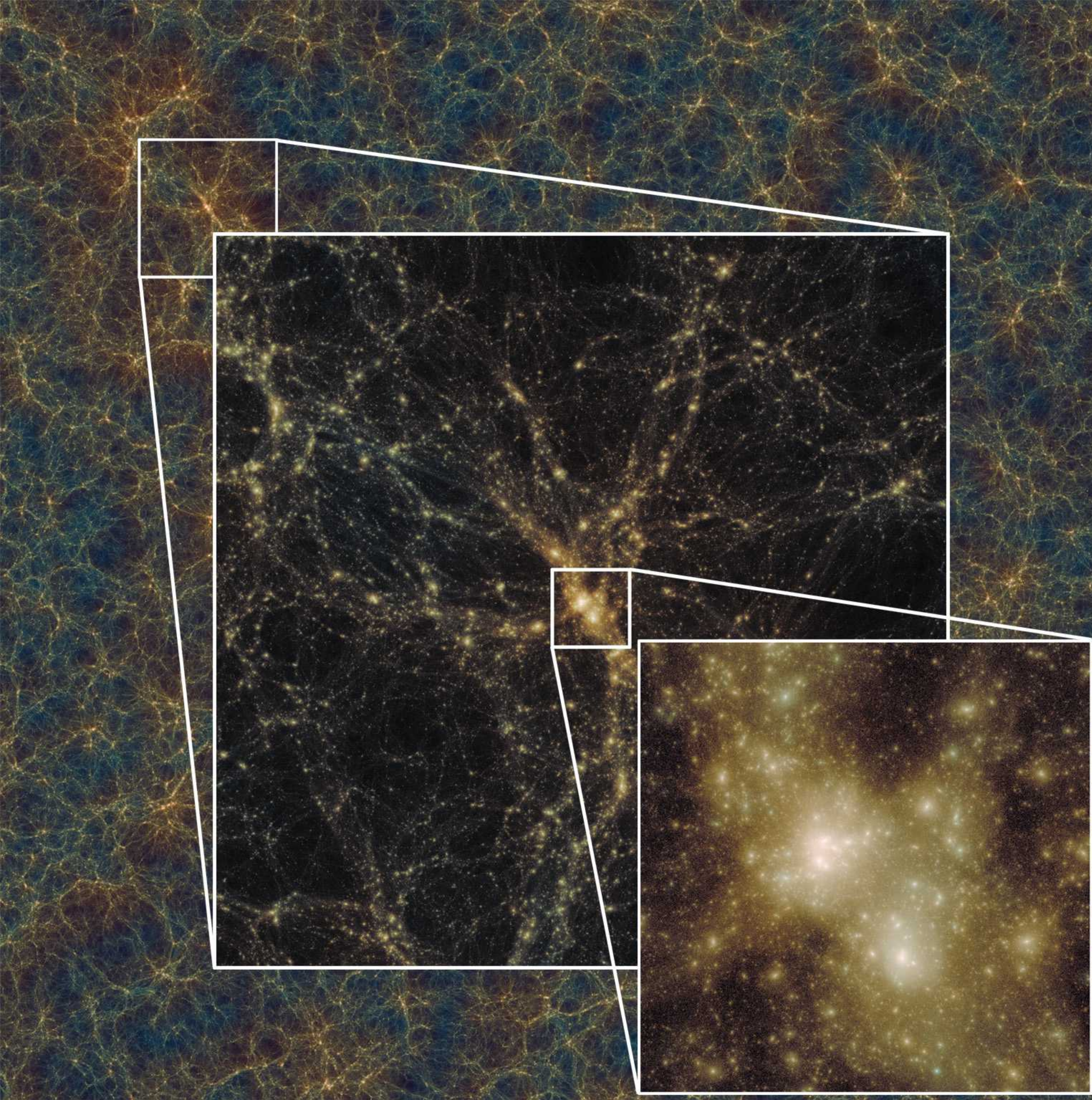
L = 400 pc
$M = 3.4 \times 10^{-11}$ Msun

Analyze
$10^{-6} \sim 10^{-4}$ Msun halos

#halos > 5000
Good statistics !!!

Sharp cosmic web is observed, compared to large scale structures

z=32



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

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

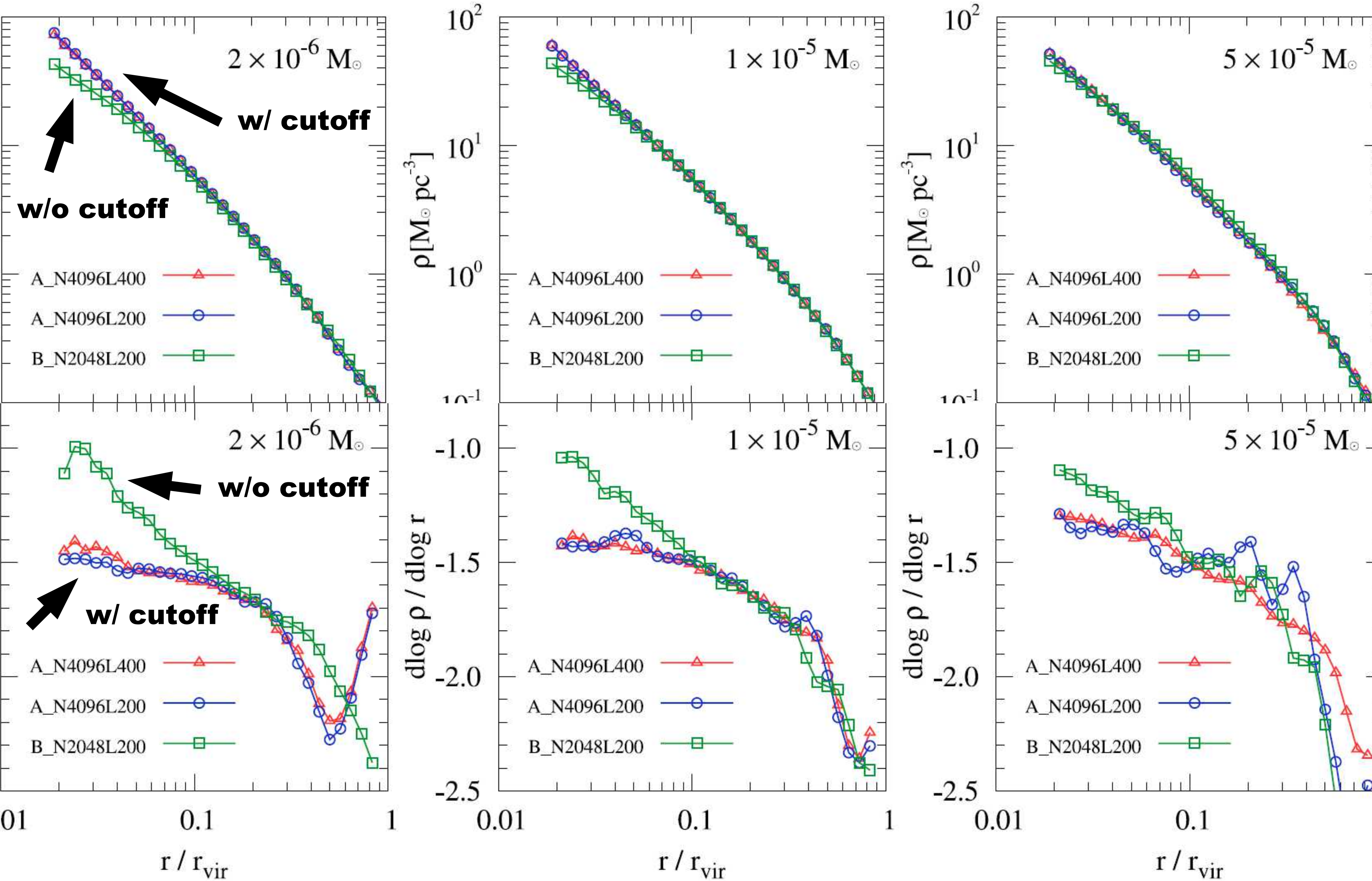
Planck Cosmology

11x larger volume,
4x better mass res,
compared to
Millennium simulation

$z=0$

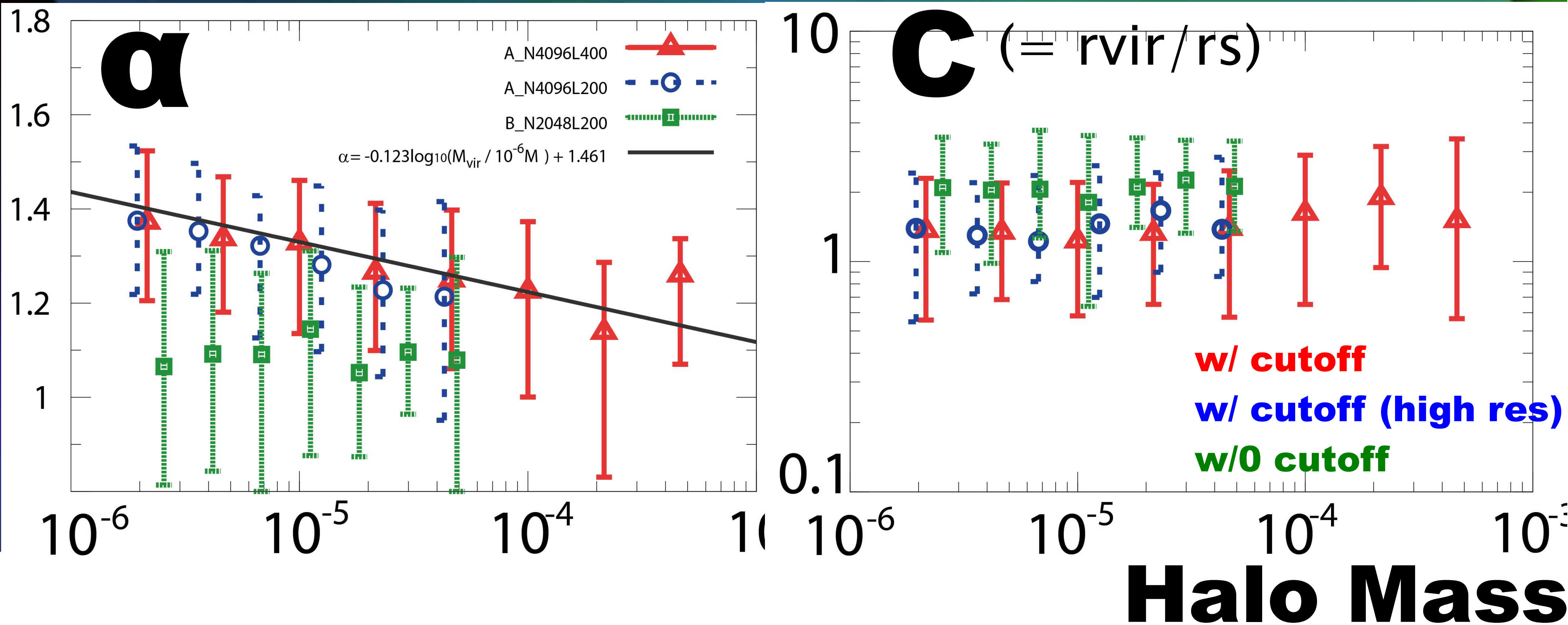
Ishiyama, 2014, ApJ, 788, 27

Stacked density profiles (z=32)



Shape, concentration (z=32)

$$\rho(r) = \frac{\rho_0}{(r/r_s)^{\alpha}(1+r/r_s)^{(3-\alpha)}}$$

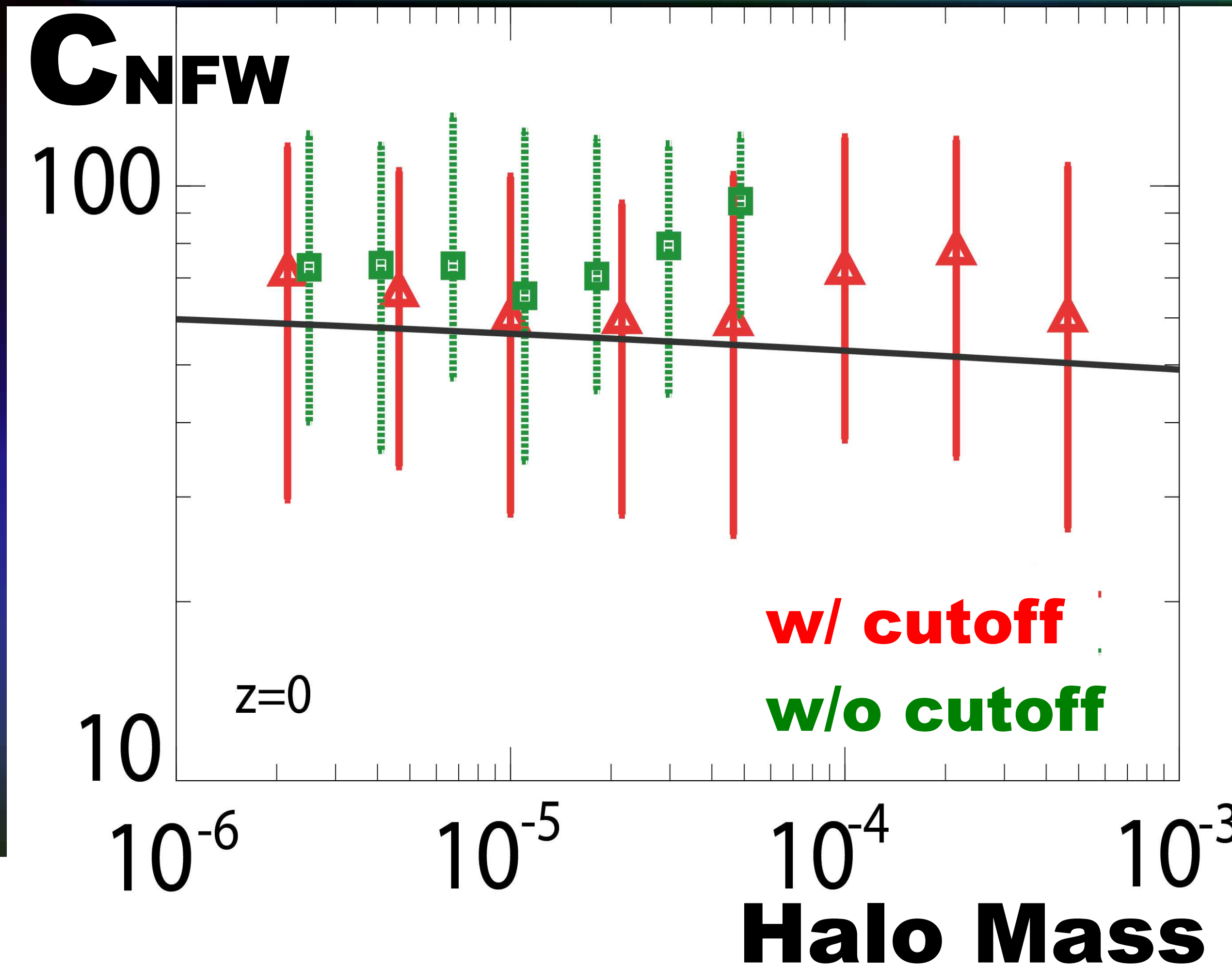


- Larger halo -> shallower cusp

$$\alpha = -0.123 \log(M_{\mathrm{vir}}/10^{-6}\, M_{\odot}) + 1.461$$

  - Reach NFW like profile at 10^{-3}~10^{-2} Msun !
- Concentration shows little dependence on the halo mass (c=1.2~1.7)
  - Because the formation epoch shows little dependence on the mass

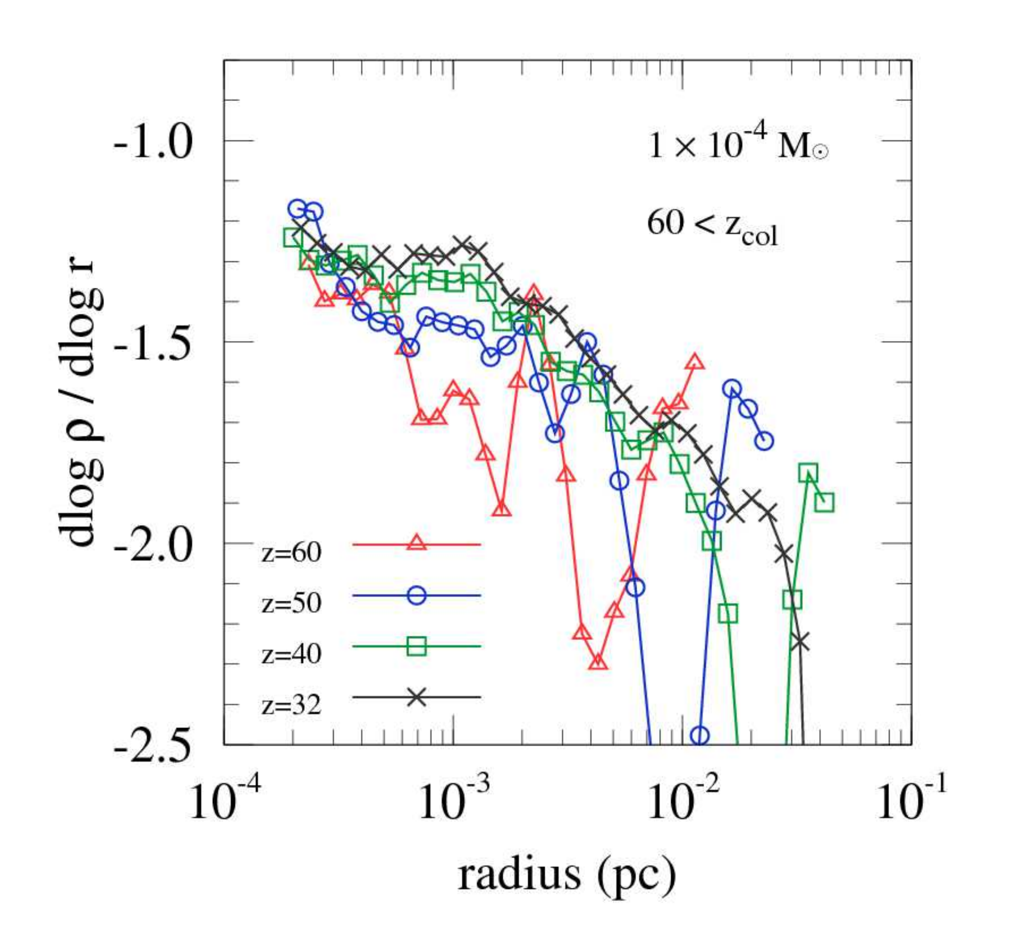
Converted NFW concentration at z=0

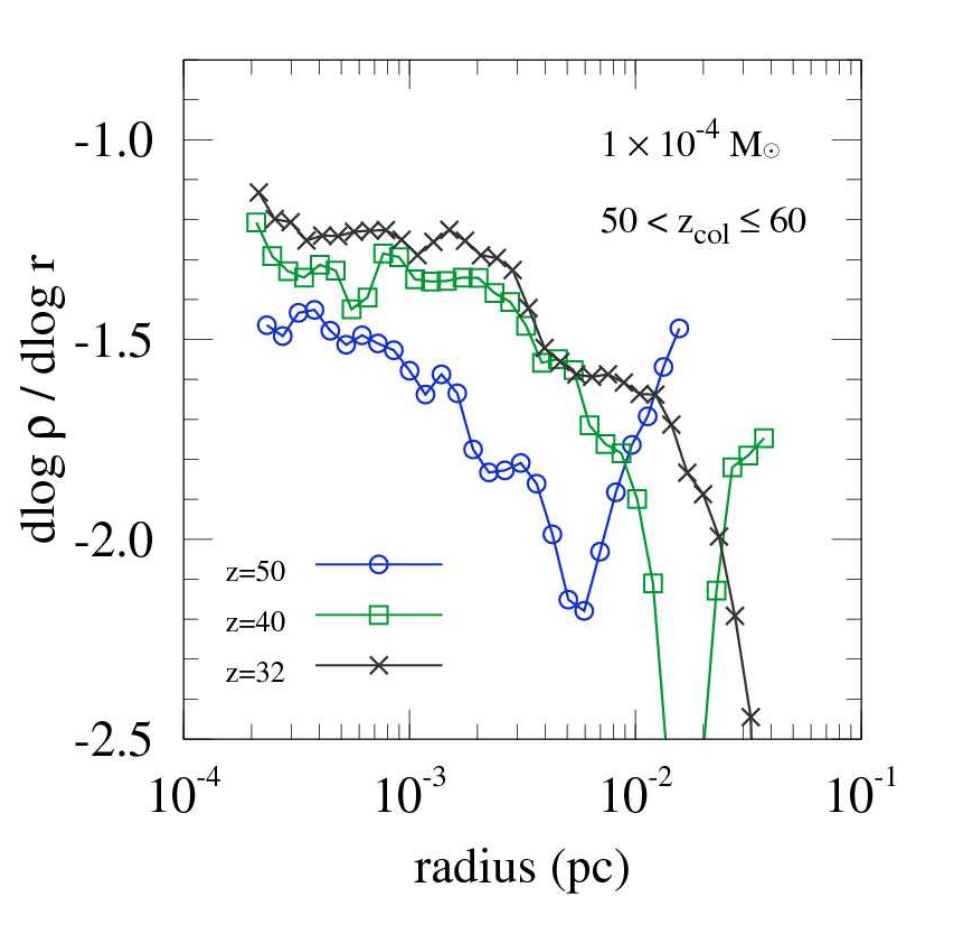


- The median is 60~70
- Consistent with the fitting proposed by Sanchez-Conde and Prada (2014, black curve)
- Exclude single power law fitting function
- Exclude very large concentrations (~1000) for microhalos

- How to convert:
  - fixed Rvmax (Ricotti 2003)
  - Rvir and Rs are scalable to z=0 by multiplying 1+z (Bullock+ 2001)

Evolution of density profiles





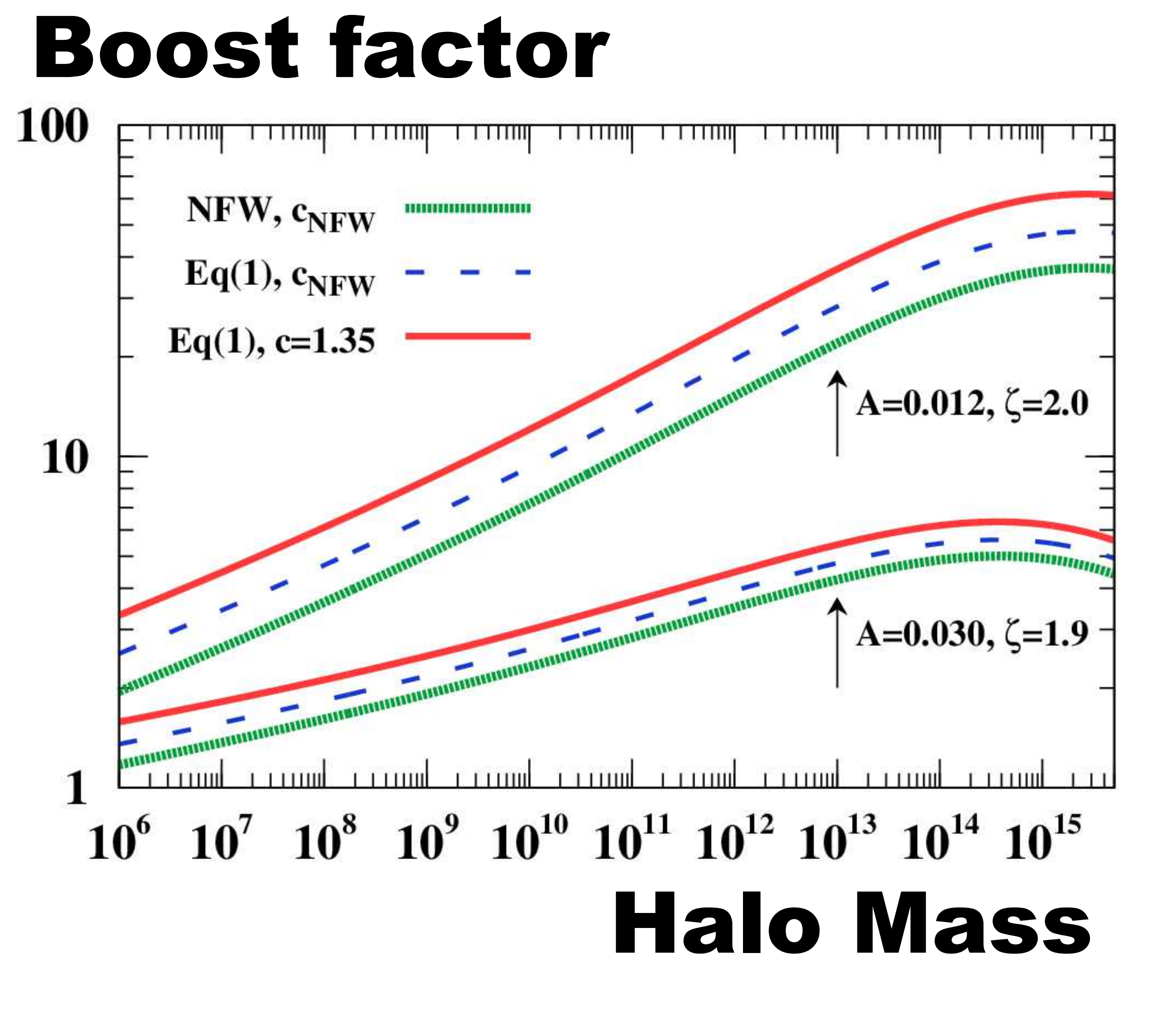
- Not depending on the collapse epoch, profiles of progenitors soon after the collapse are similar to those of the smallest halos.
- Cusps are shallowing as the halos grow.

Annihilation boost factor by subhalos

- Gamma-ray luminosity of a halo by neutralino self-annihilation seen from a distant observer

- **NFW case (green)**
- **Based on this work**
  (Red and blue)

- The steeper inner cusps of halos near the free streaming scale enhance the annihilation luminosity of a Milky Way sized halo between 12 to 67%.
  - Strongly depending on the subhalo mass function



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

$$dn/dm = A/M(m/M)^{-\zeta}$$

Summary

Ishiyama, 2014, ApJ, 788, 27

- The central cusps of halos near the free streaming scale are much steeper than that of the NFW profile
  - Becomes gradually shallower as the halo mass increases.
  - NFW shows bad fitting, additional shape parameter is needed

$$\alpha = -0.123 \log(M_{\rm vir}/10^{-6}\, M_{\odot}) + 1.461$$

- Concentration shows little dependence on the halo mass
  - The median with the cutoff is 1.2~1.7 at z=32
  - Corresponding to conventional concentrations (based on the NFW profile) of 60~70 at z=0
  - Exclude single power law mass-concentration relation

- Steeper cusps enhance the annihilation luminosity of MW between 12~67%

- Analyzing web structures are key to know the physical origin of cusps ???