Structures of Dark Matter Halos and Their Impact on Detection Experiments

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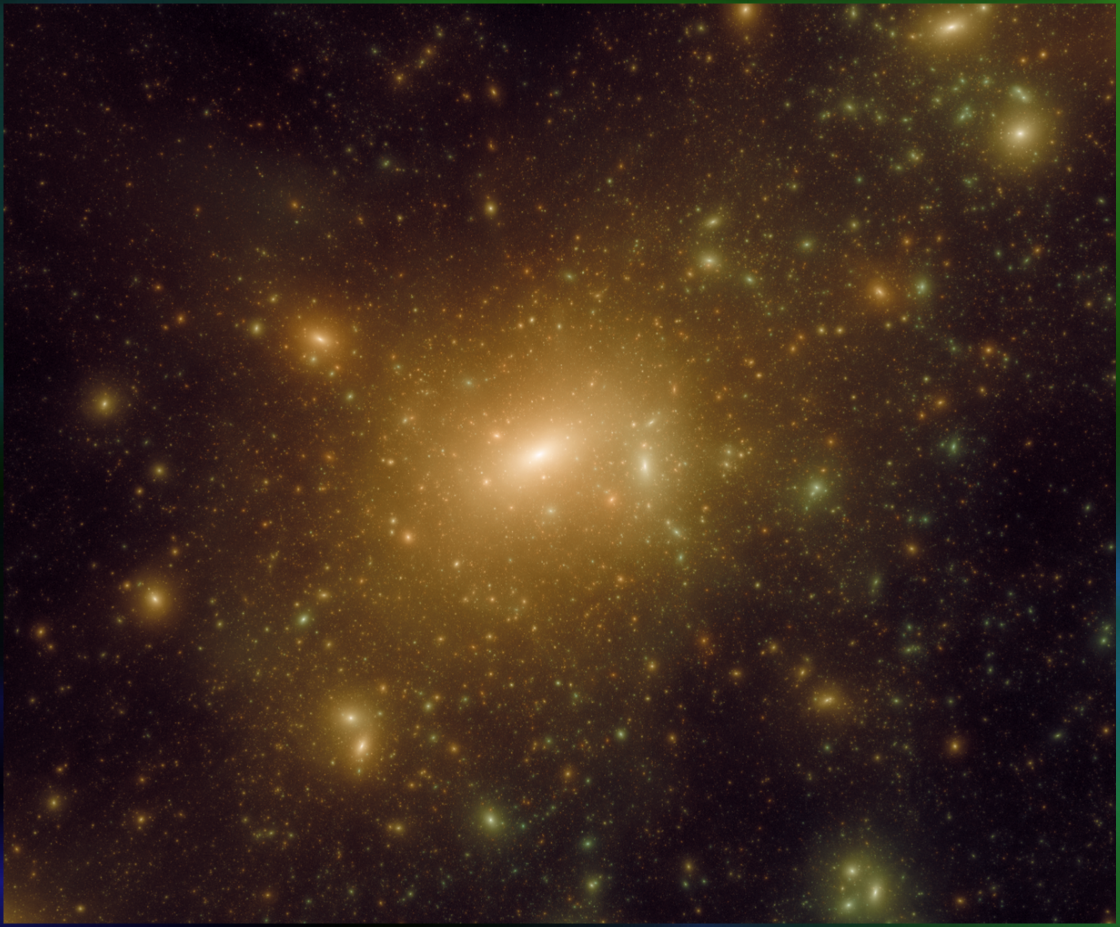
Structures of dark matter halos

- **Central Cusp**
  - Einasto profile
  - NFW profile

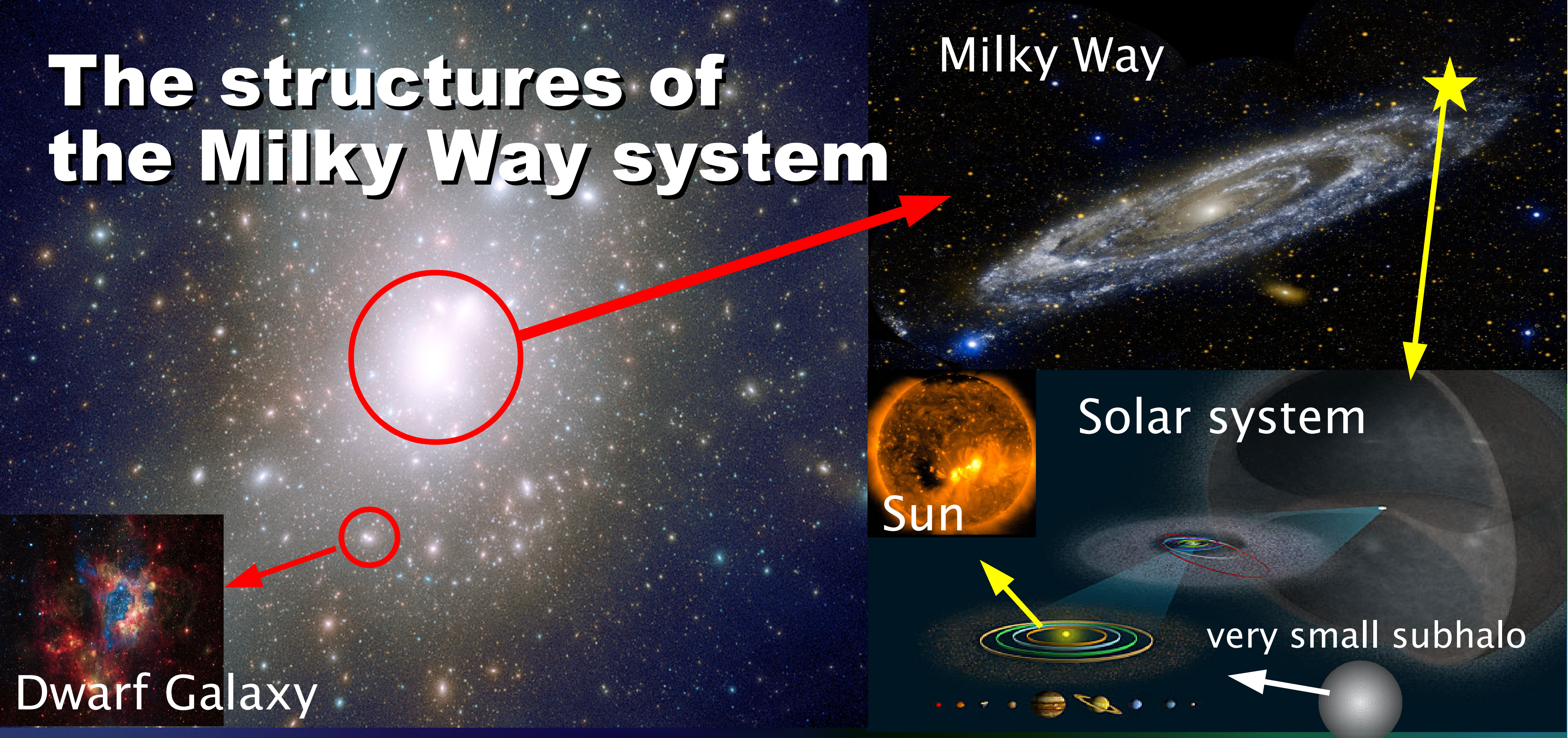
$$\rho(r) = \frac{\rho_s}{(r/r_s)[1+(r/r_s)]^2}$$

- **Myriad subhalo**
  - $dn/dm \sim m^{-(1.8-2)}$
- **Triaxial**
- **Non Universality**
  - Weak dependence on the halo mass
  - halo to halo variation
    - halo formation epoch



Impact on the galaxy formation, Dark matter detection experiment

The structures of the Milky Way system

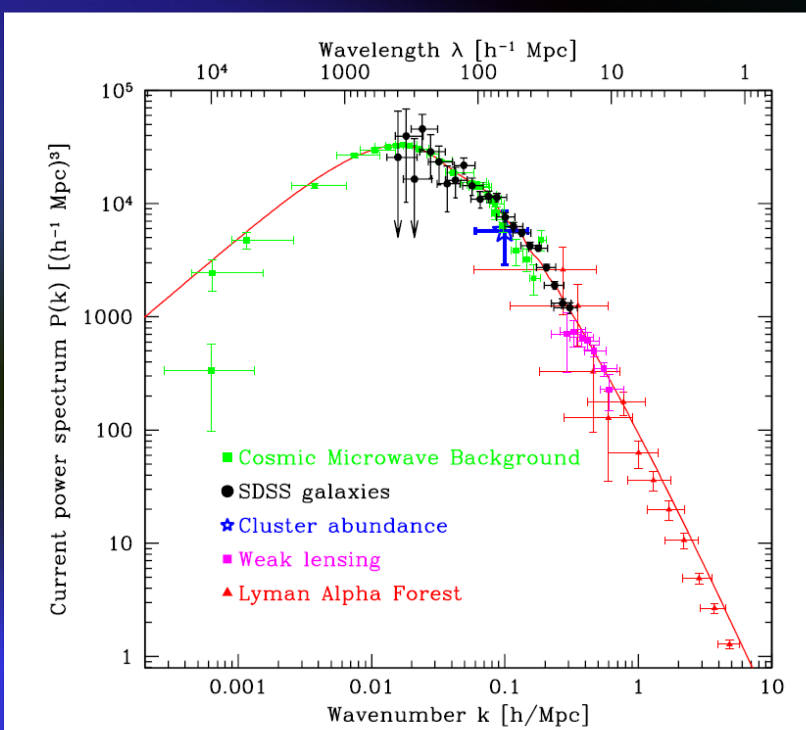


- Numerous subhalos ($10^{-6} \sim 10^{10}$ solar mass)
  - $dn/dm \propto m^{-2 \sim -1.8}$
- Where can we observe gamma-ray flux due to dark matter annihilation ?
  - The center of the Milky Way halo ?
  - Dwarf Galaxy ?
  - Microhalos near Sun ?

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

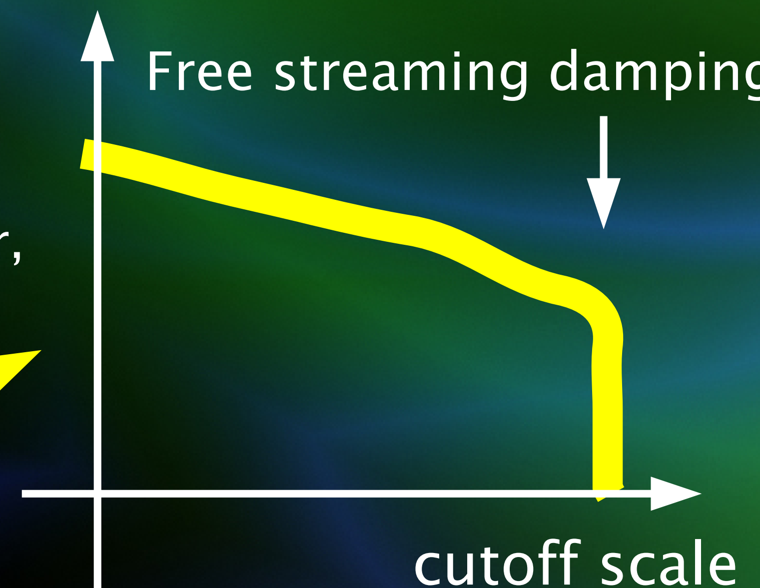
Free streaming damping

- 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

Smaller, smaller, smaller, and smaller……



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

Aim

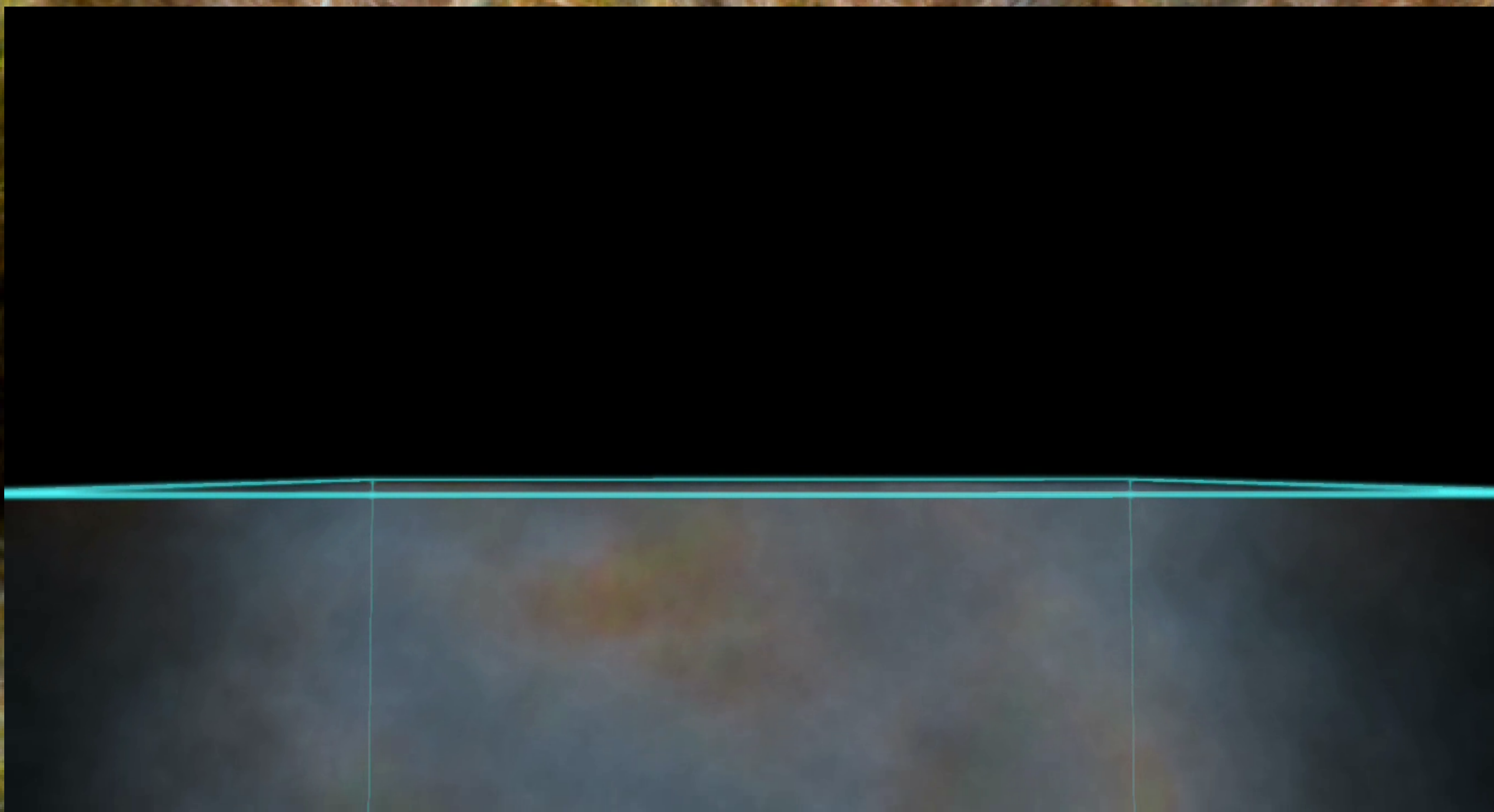
- Clarify the structure of **halos near the free streaming scale** by large cosmological N-body simulations
  - Typically, NFW or Einasto is assumed
  - Previous works focused on only the smallest microhalos and simulated only a few microhalos
    (Diemand+ 2005, Ishiyama+2010, Anderhalden & Diemand 2013)
    - Steeper cusps (-1.4~-1.5) are observed (Ishiyama+ 2010)

- **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 detection experiments

Ishiyama, 2014, ApJ, 788, 27

Cosmological N-body simulations



- z=400 to 32

Movie:
Takaaki Takeda
(4D2U, NAOJ
VASA)

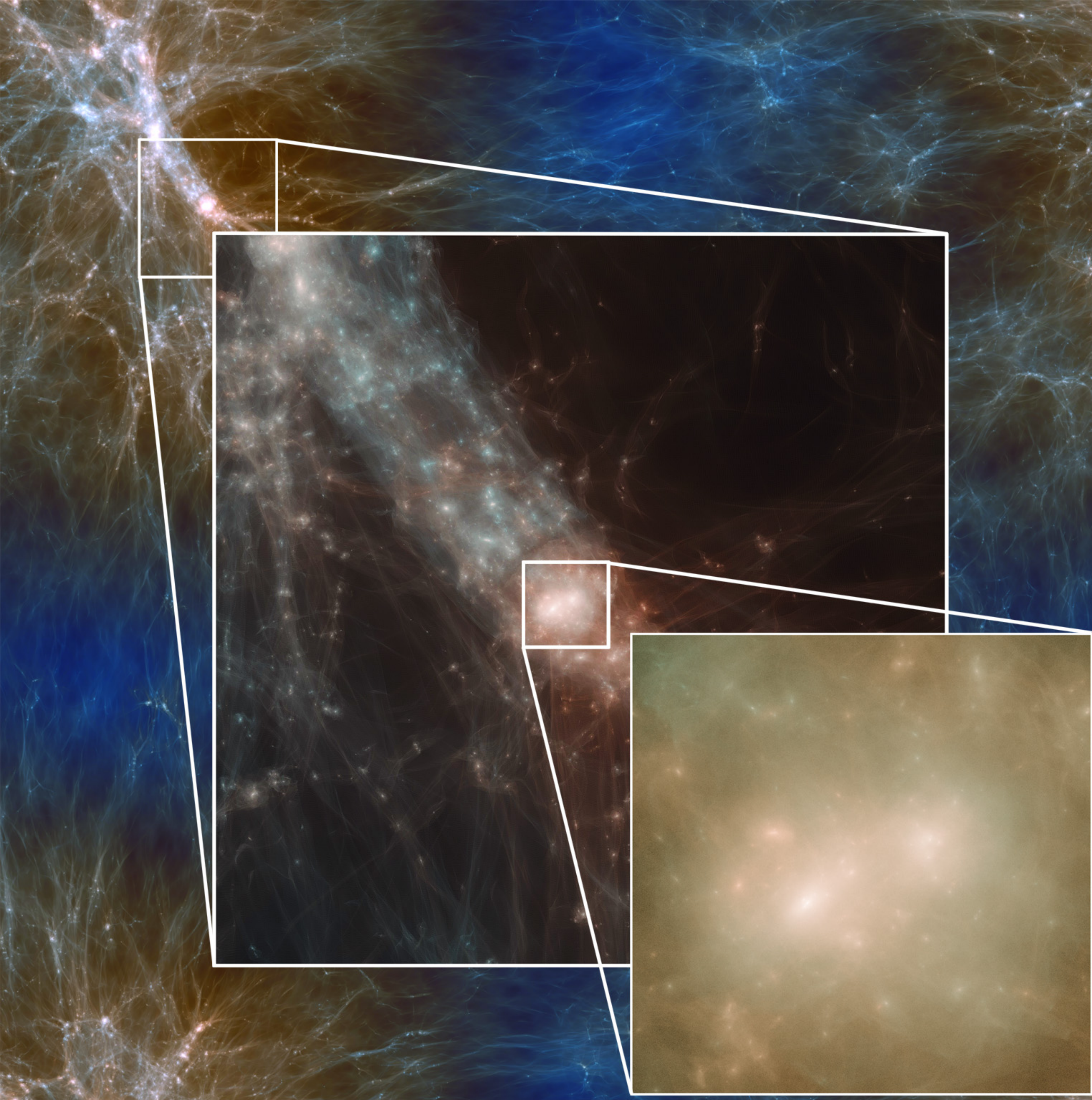
Name	N	L(pc)	ε(pc)	$m(M_\odot)$	$m_{\rm DM}$ (GeV)
A_N4096L400	4096^3	400.0	2.0×10^{-4}	3.4×10^{-11}	100
A_N4096L200	4096^3	200.0	1.0×10^{-4}	4.3×10^{-12}	100
B_N2048L200	2048^3	200.0	2.0×10^{-4}	3.4×10^{-11}	w/o cutoff

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
  - ~ 1Pflops
  - Astro only

Aterui
© CfCA, NAOJ

K Computer
(c) RIKEN,



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

L = 400 pc
M = 3.4×10^{-11} Msun

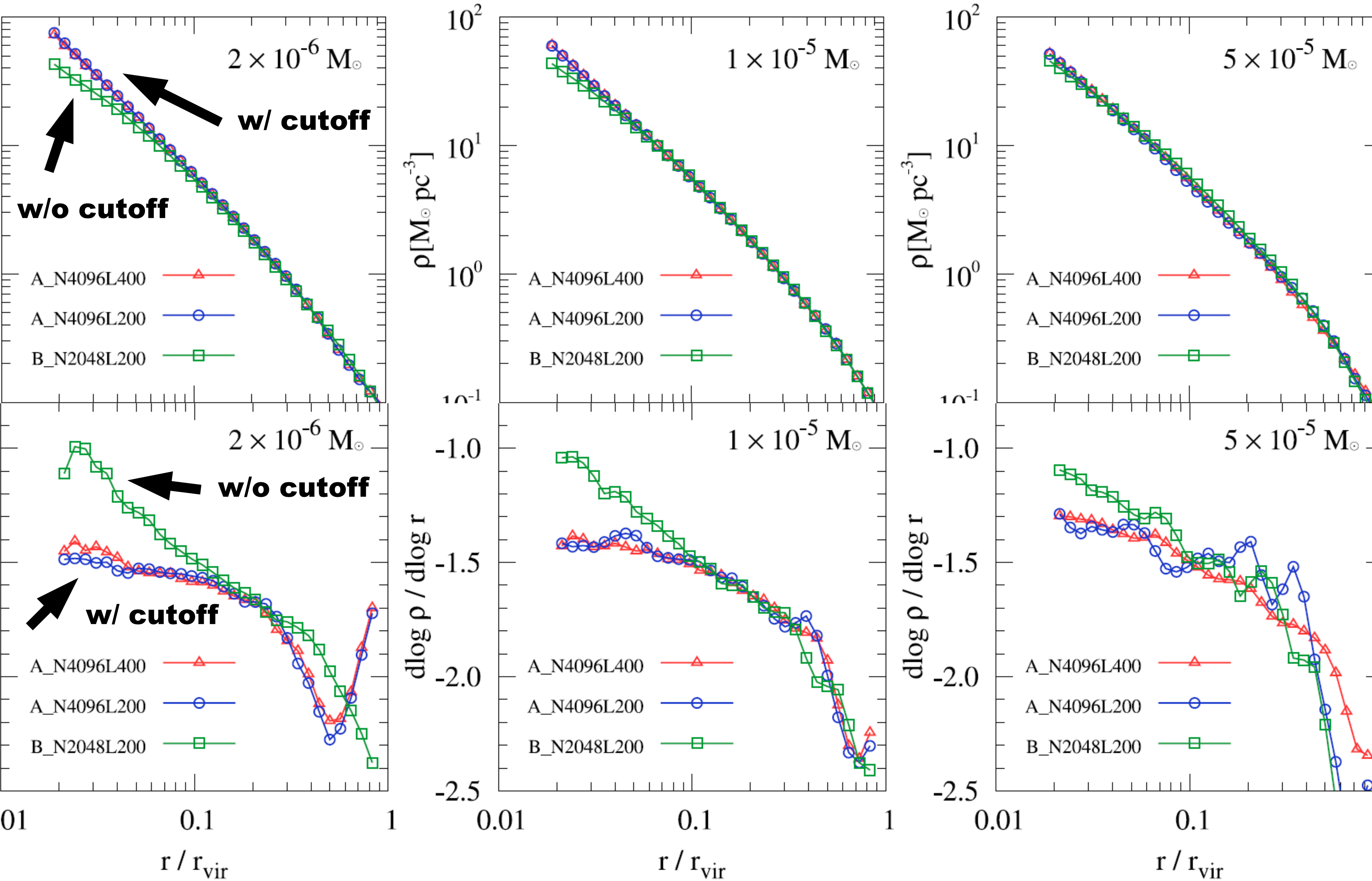
Analyze
$10^{-6} \sim 10^{-4}$ Msun halos

#halos > 5000
Good statistics !!!

Sharp cosmic web is observed, compared to large scale structures

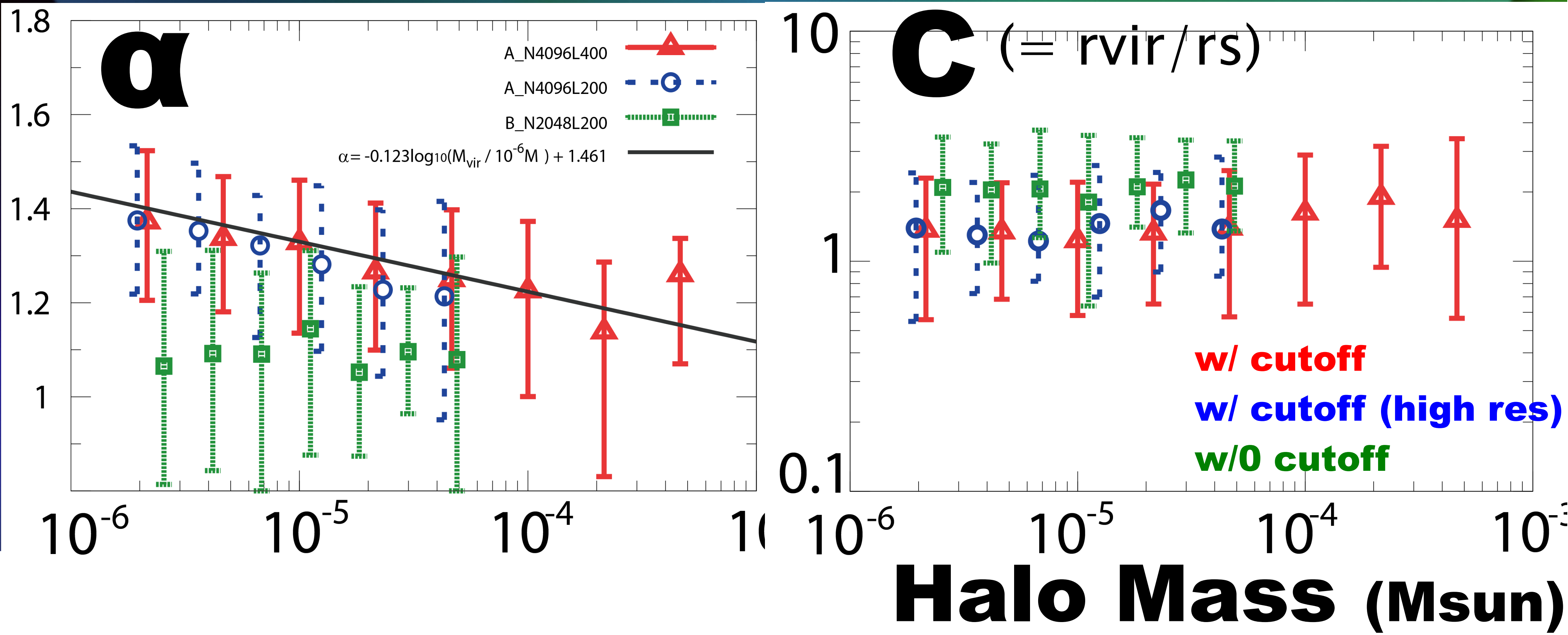
$z=32$

Stacked density profiles (z=32)



Shape, concentration (z=32)

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



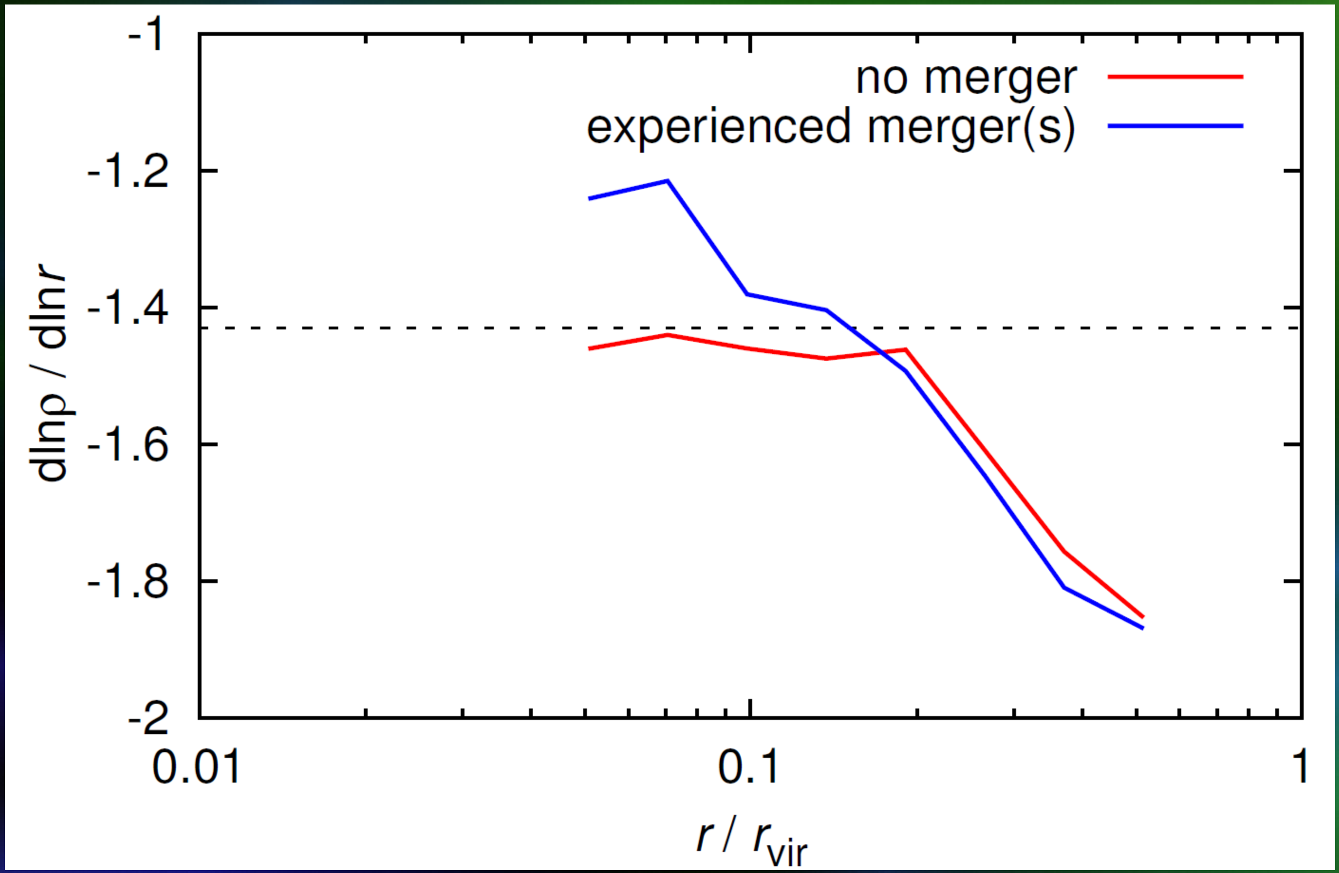
- Larger halo -> shallower cusp

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

  - 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

Why cusp becomes shallower?

- Cusps are shallowing as the halos grow
- Major mergers of primordial halos are responsible for shallowing cusps
- Density profile is more susceptible to a merging process compared to that of galactic halos
- Controlled (not cosmological) merger simulations reproduce these resutls



Ogiya, Nagai, Ishiyama, arXiv: 1604.02866

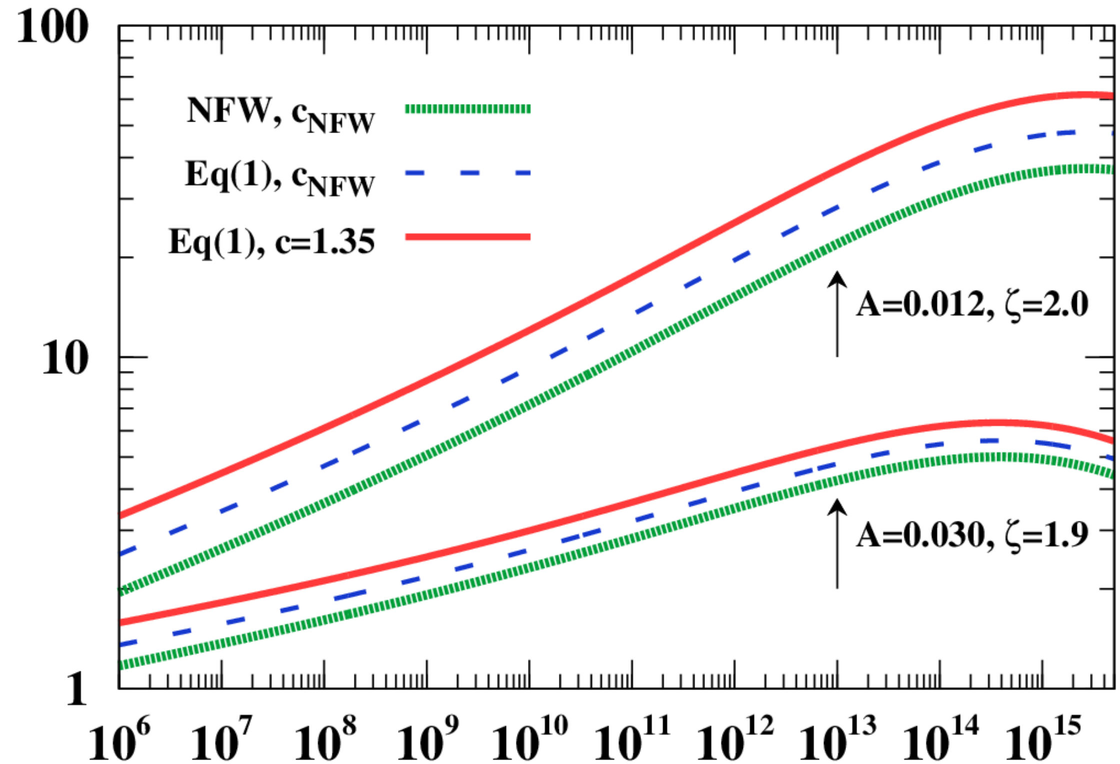
Annihilation boost factor by subhalos

- 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

Boost factor



Halo Mass (Msun)

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

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

Structure of halos near the free streaming scale

- 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 does not fit well, 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
  - Exclude single power law mass-concentration relation

- Early merger phase play a important role to make the cusp shallower as the halo mass increases
- Steeper cusps enhance the annihilation luminosity of MW between 12~67%
- New simulations could make more robust predictions for direct/indirect detection experiments