Supercomputer Simulations of Structure Formation in the Universe

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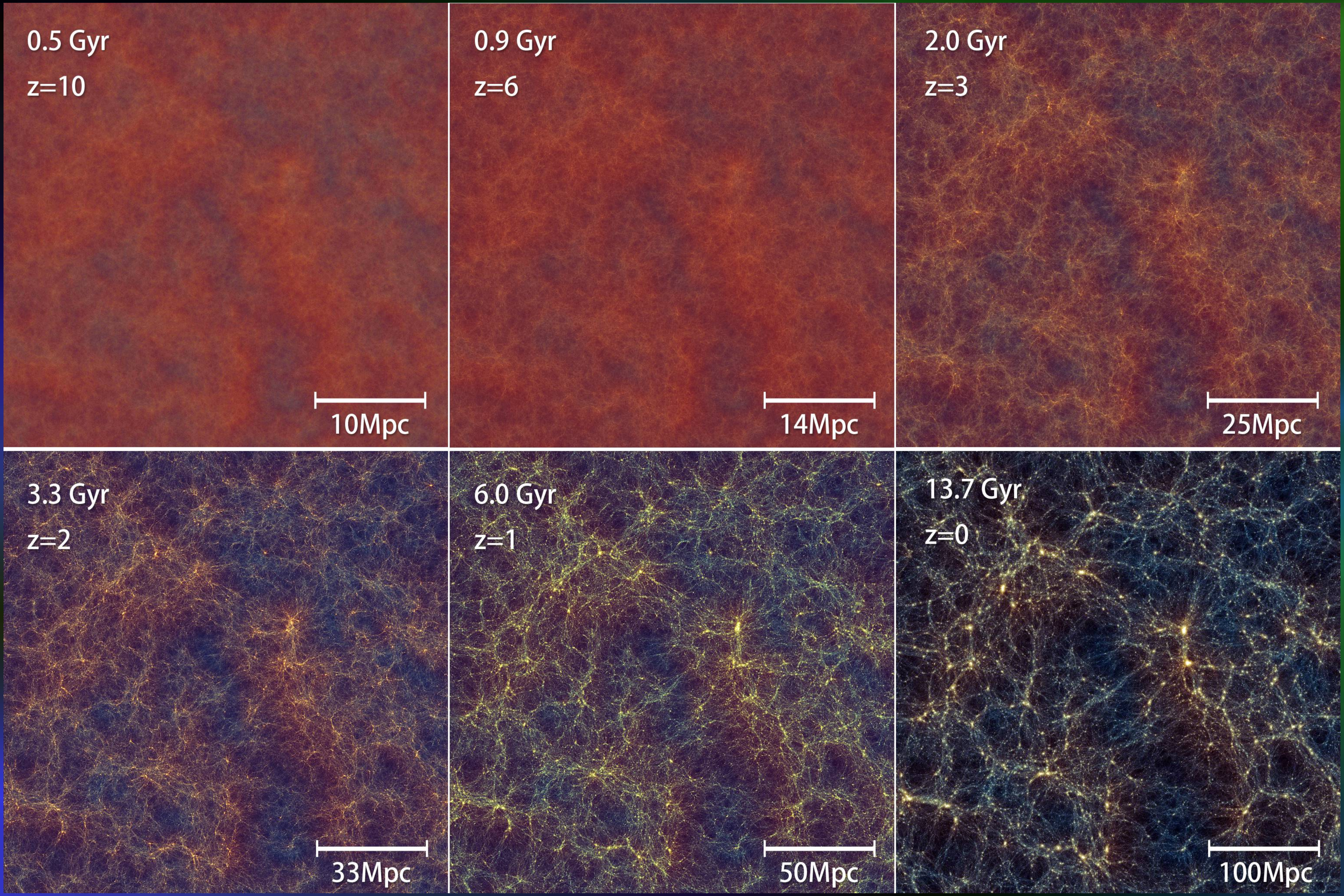
Cosmological simulation



Increase the number of particles

- **Enable to simulate larger volume**
  - Form rare objects
  - Improve statistics
- **Enable to increase mass resolution**
  - Observe finer structures , we have not ever reached

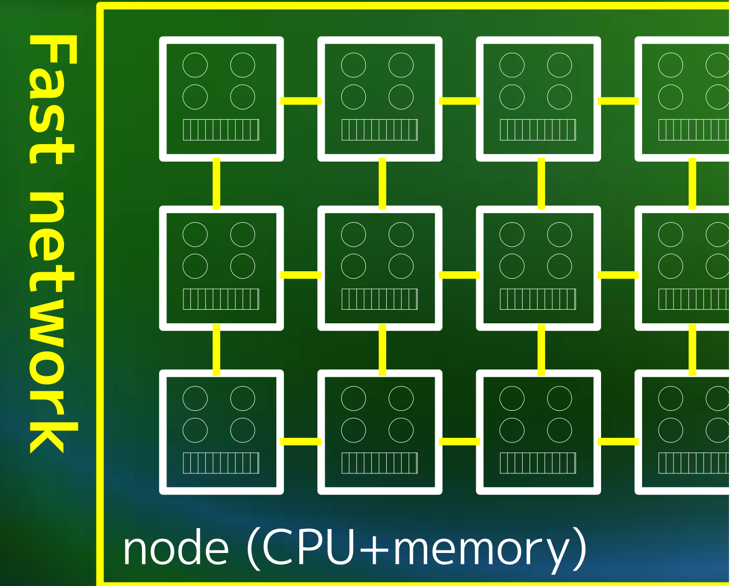
Both are crucial for understanding our universe

Supercomputers!

World’s fourth fastest supercomputer (Nov 2013)

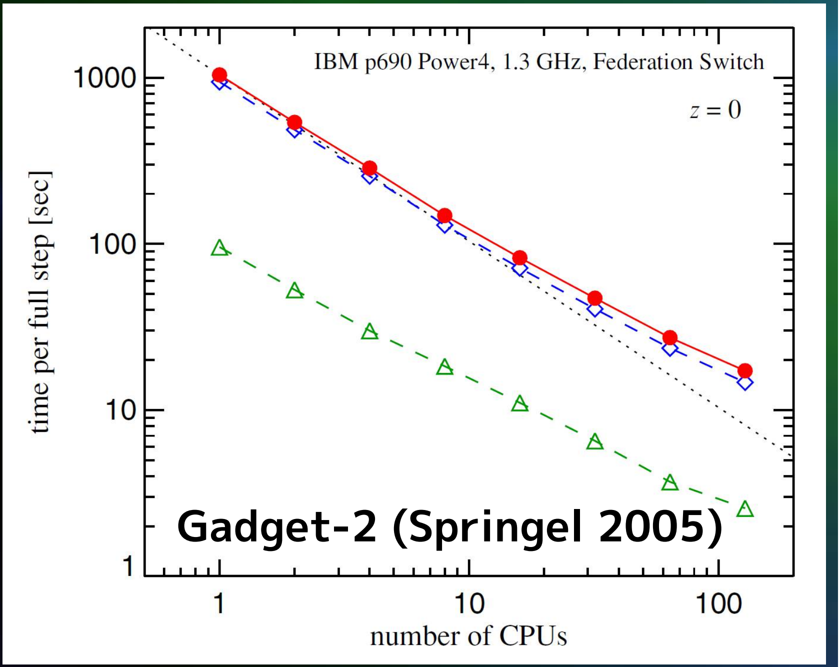
Scaling of parallel computing

- We hope that ***n*** times CPUs enable to
  - Increase the number of particles by a factor of ***n*** (**weak scaling**)
  - Accelerate simulations by a factor of ***n*** (**strong scaling**)



- **Just dream**. Since there is communication.
  - Gravity is the long-range force
  - We can not imagine that Gadget-2 shows good scaling on > 1000 parallel

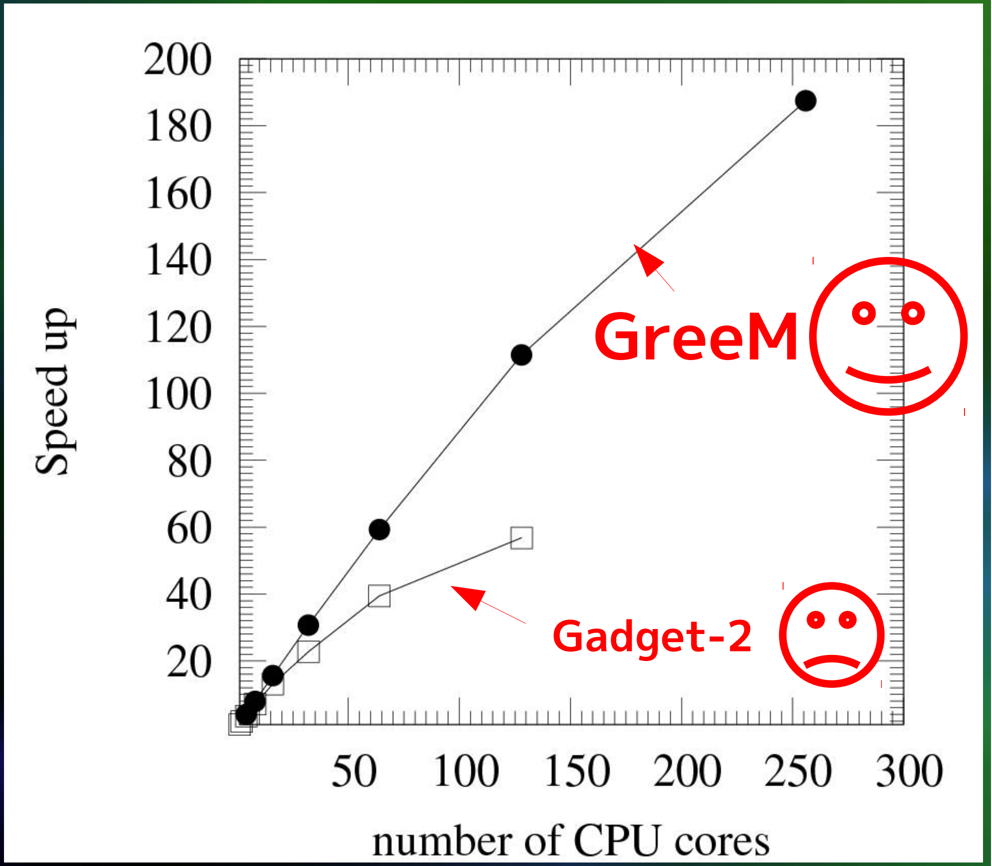
- But we want to increase the number of particles and calculate faster



Massively Parallel N-body code: GreeM

- **GRAPE TreePM**
- Dynamic domain decomposition
- Sophisticated load balancer
- Novel communication algorithm for all-to-all communication
- Highly optimized gravity kernel with handy SIMD
  - Utilize Phantom-GRAPE (Nitadori+2006, Tanikawa+2012, 2013)
- Flat MPI or MPI+OpenMP
- 2-10 times faster than Gadget-2

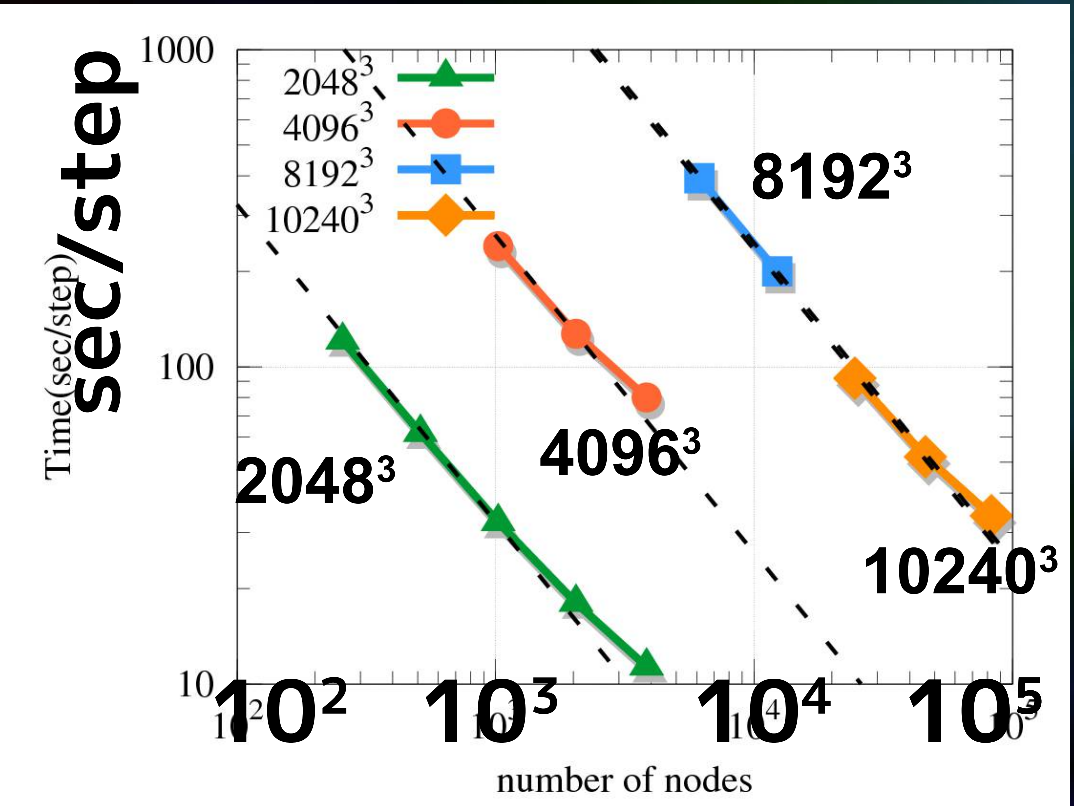
Ishiyama+ 2009, 2012



Based on TreePM code
(Yoshikawa and Fukushige, 2005)
for small (~10 nodes) GRAPE clusters

Highlight results

Performance results on K computer



- **Scalability (2048^3 - 10240^3)**
  - Excellent strong scaling
  - 10240^3 simulation is well scaled from 24576 to 82944 (full) nodes of K computer
- **Performance (12600^3)**
  - The average performance on full system is ~**5.8Pflops**,

~**55**% of the peak speed

Ishiyama et al. 2012 (arXiv: 1211:4406), SC12 Gordon Bell Prize Winner

Comparison with Gadget-2

- 1024^3, 320Mpc/h, 512CPU cores
  - **GreeM 20763 sec**, **Gadget-2 44752 sec**
- 512^3, 1Gpc/h, 256CPU cores
  - **GreeM 1678 sec**, **Gadget-2 3577 sec**
- 512^3, 21Mpc/h, 256CPU cores
  - **GreeM 10756 sec**, **Gadget-2 62005 sec**

Aterui(XC30)

Our code can perform cosmological simulations 2-10 times faster than Gadget-2

Application 1 :

Structures of Dark Matter Microhalos

Based on
Ishiyama, Makino, Ebisuzaki, 2010, ApJL
Ishiyama, 2014 submitted to ApJ

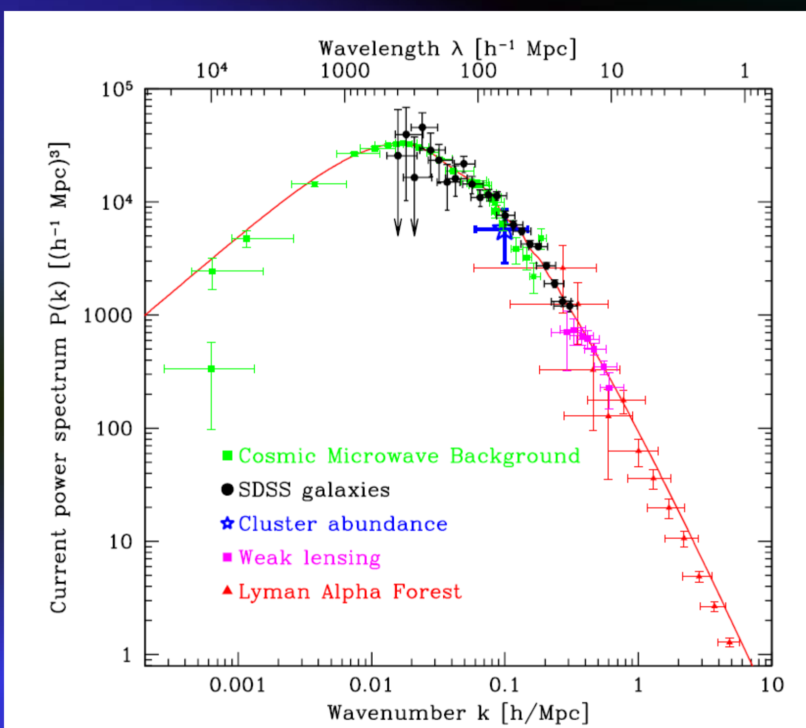
Smallest Halo (Microhalo)

- Smallest halo : ~10^{-6} Msun (earth mass),

  if dark matter is the neutralino of 100GeV–1TeV

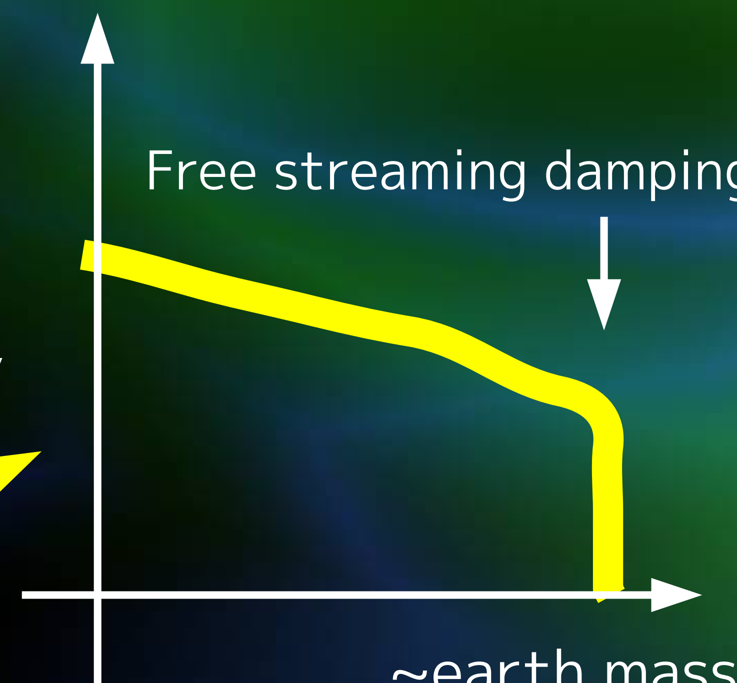
  (Zybin+1999, Hofmann+2001, Green+2004, Loeb & Zaldarriaga 2005, Berezinsky+ 2003, 2008)

  - Free streaming damping



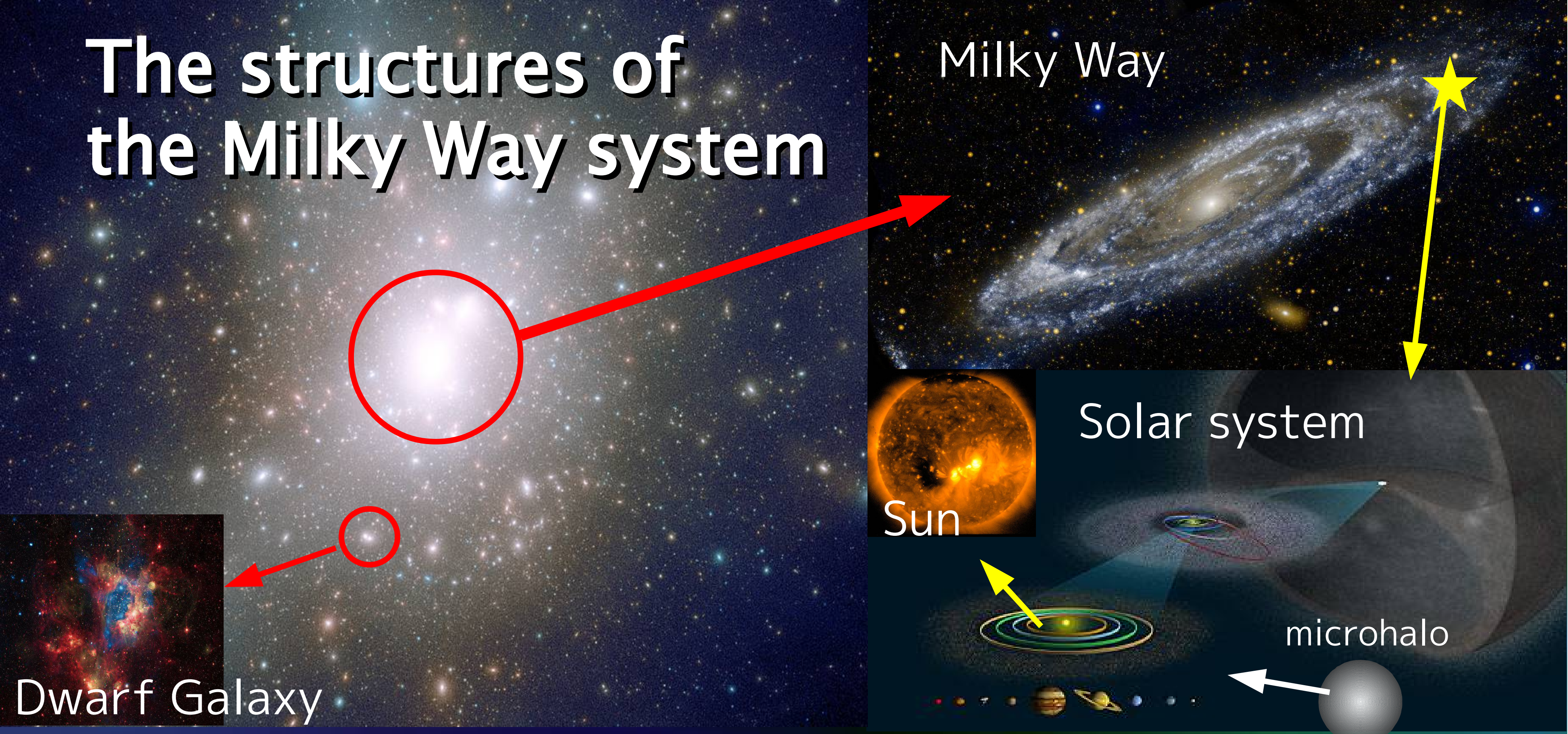
Tegmark et al. 2004

Smaller, smaller, smaller, and smaller……



The difference of spectrum shape may change the structures of halo

The structures of the Milky Way system

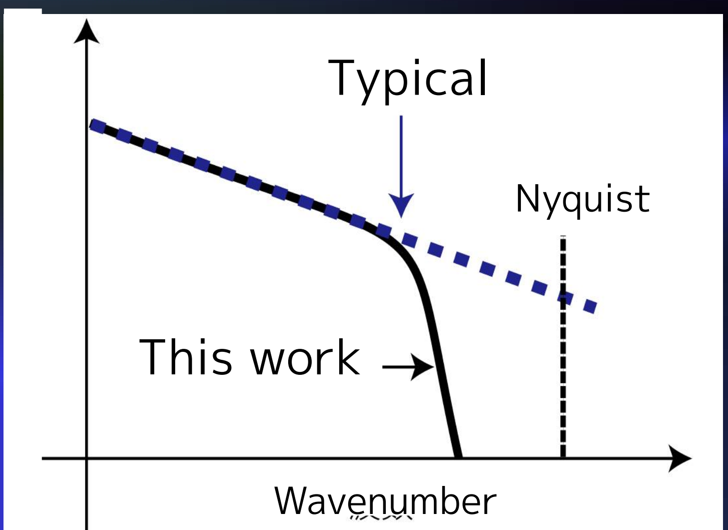


- Myriad subhalos (10^{-6} ~ 10^{10} solar mass)
  - $dn/dm \propto m^{-2 \sim -1.8}$
- Where can we observe gamma-ray flux due to dark matter annihilation ?
  - The center of the Milky Way halo ?
  - Dwarf Galaxy ?
  - Microhalos near Sun ?

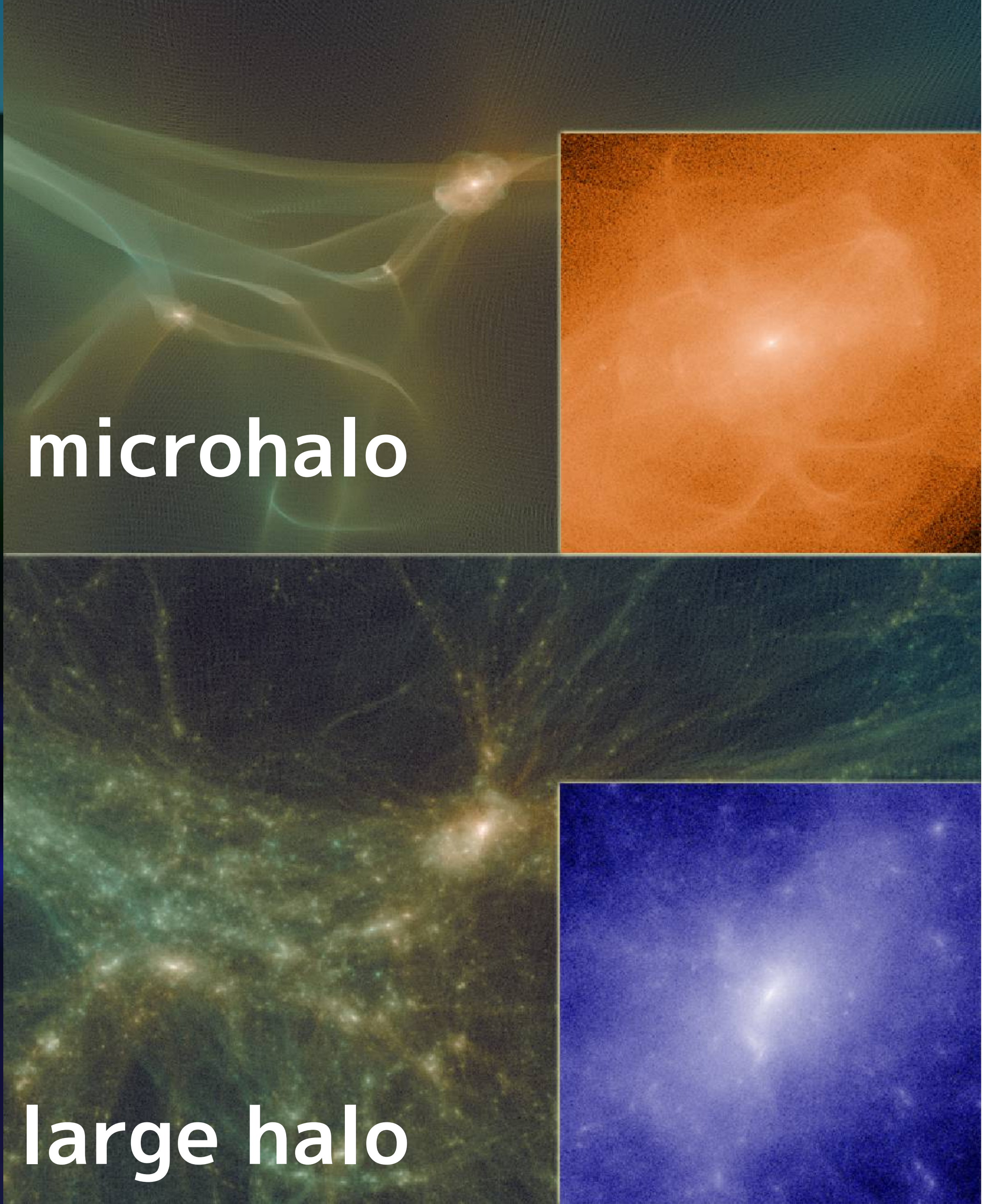
$Flux \propto \rho^2$ →
Density structures of the halo & subhalos and spatial distribution of subhalos are very important

Structures of the smallest microhalos

- Cosmological N-body simulations only for microhalos (z=31)
  - #particles 1024^3
- Nature of microhalos
  - mass $\sim 10^{-6}$ Msun
  - size $\sim 10^{-2}$ pc
  - velocity dispersion ~1m/s



Ishiyama+, 2010, ApJL, 723, L195



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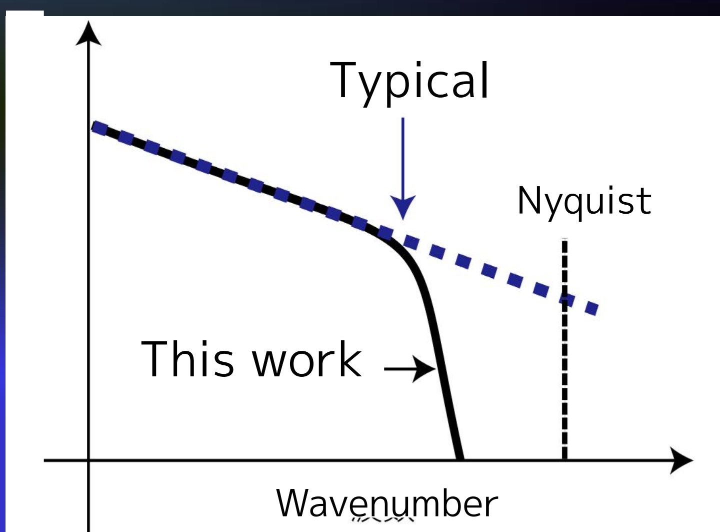

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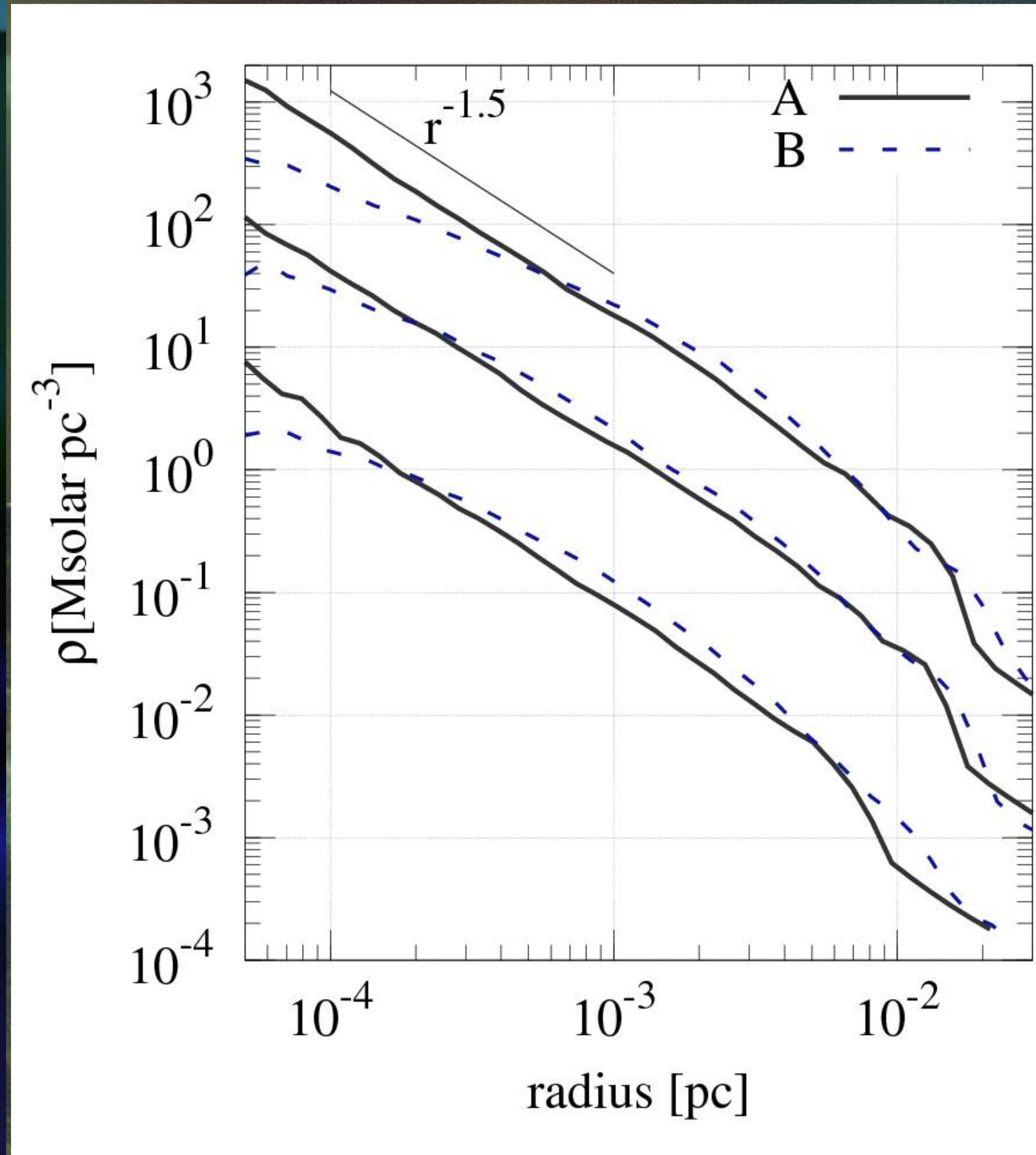
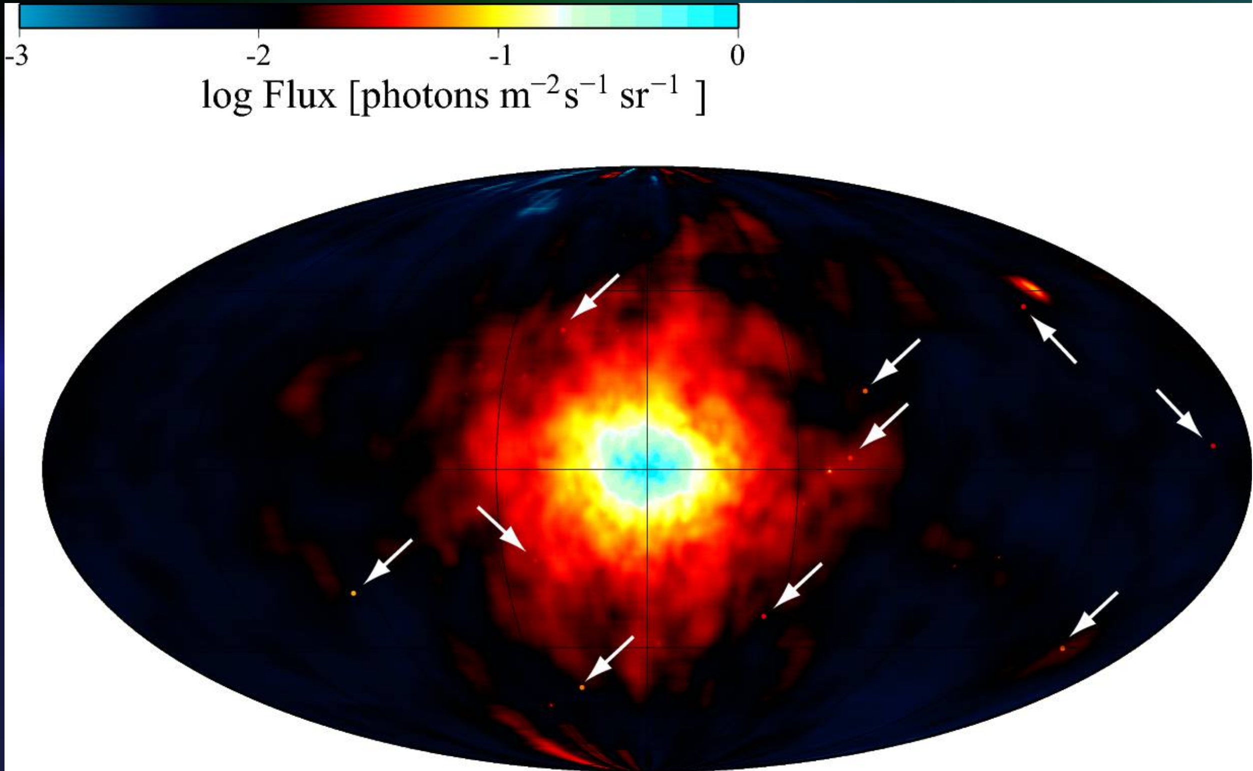


Estimated Gamma-ray map

- Emissions from microhalos only
- Galactic center is the brightest source
- Individual microhalos nearby can be observed as point sources
  - **0.2 deg/year proper motion**

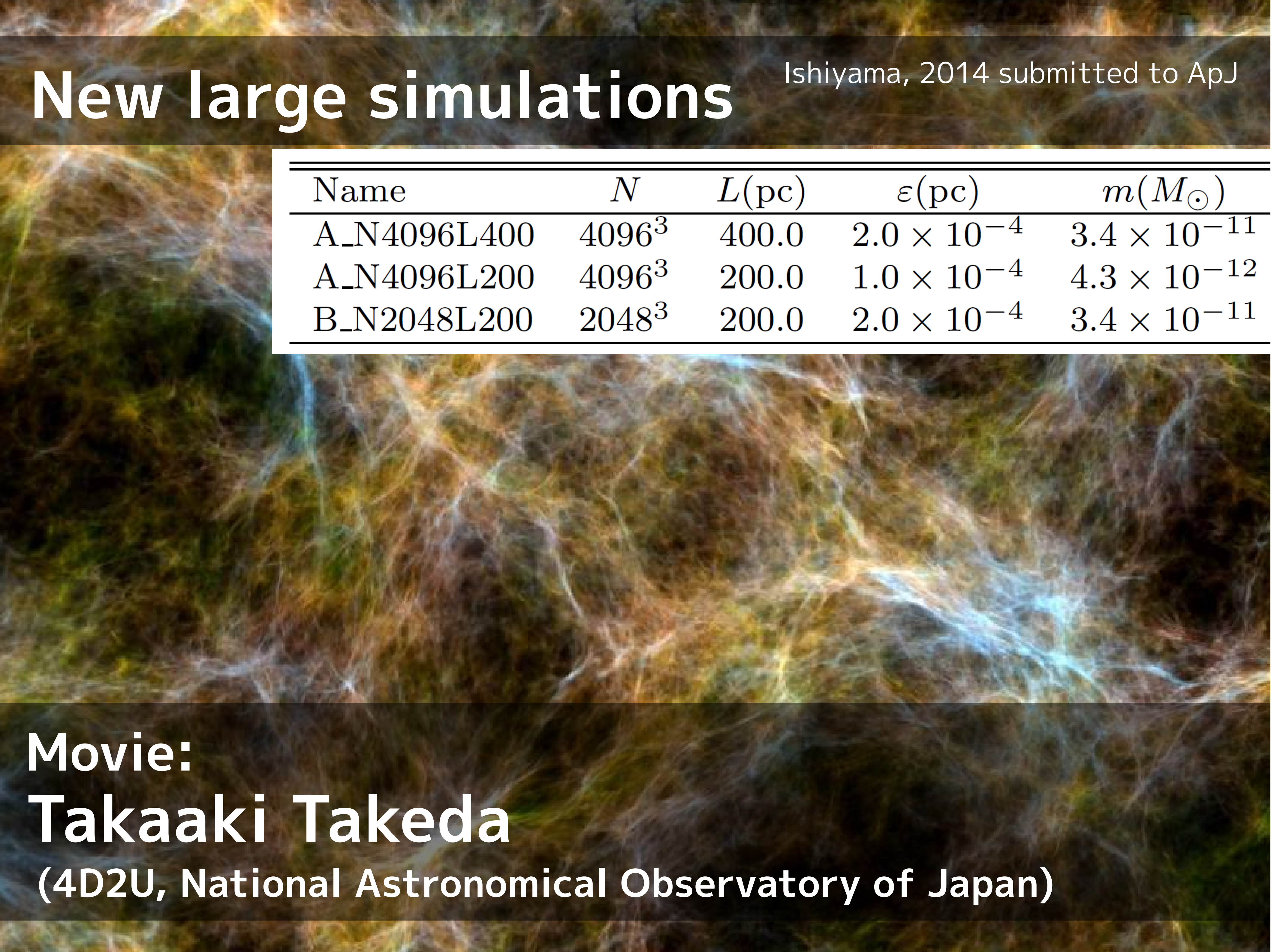
- They might be too dim to be observed by Fermi



New large simulations

Ishiyama, 2014 submitted to ApJ

Name	N	L(pc)	ε(pc)	$m(M_\odot)$
A_N4096L400	4096^3	400.0	2.0×10^{-4}	3.4×10^{-11}
A_N4096L200	4096^3	200.0	1.0×10^{-4}	4.3×10^{-12}
B_N2048L200	2048^3	200.0	2.0×10^{-4}	3.4×10^{-11}

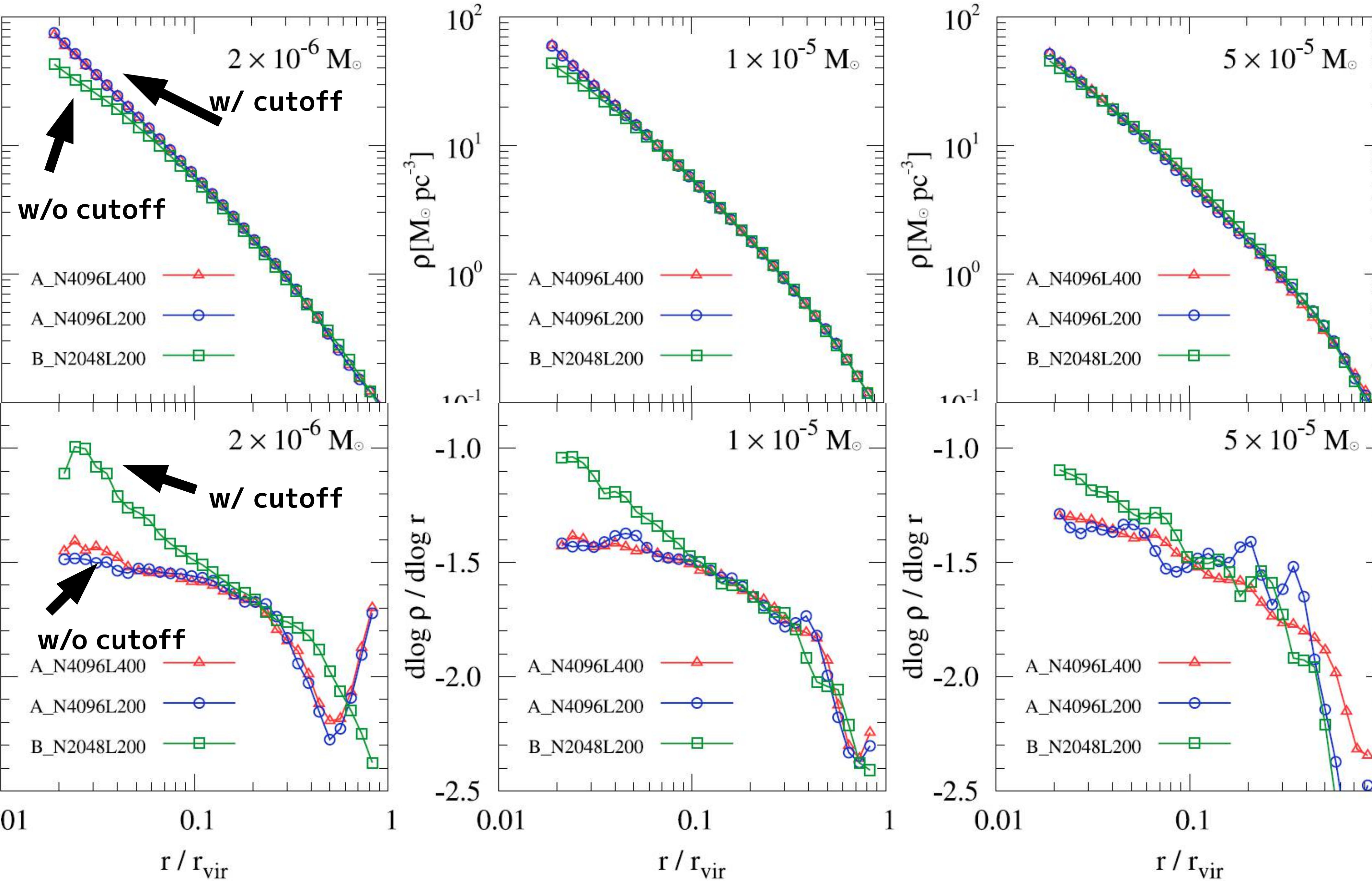


Movie:

Takaaki Takeda

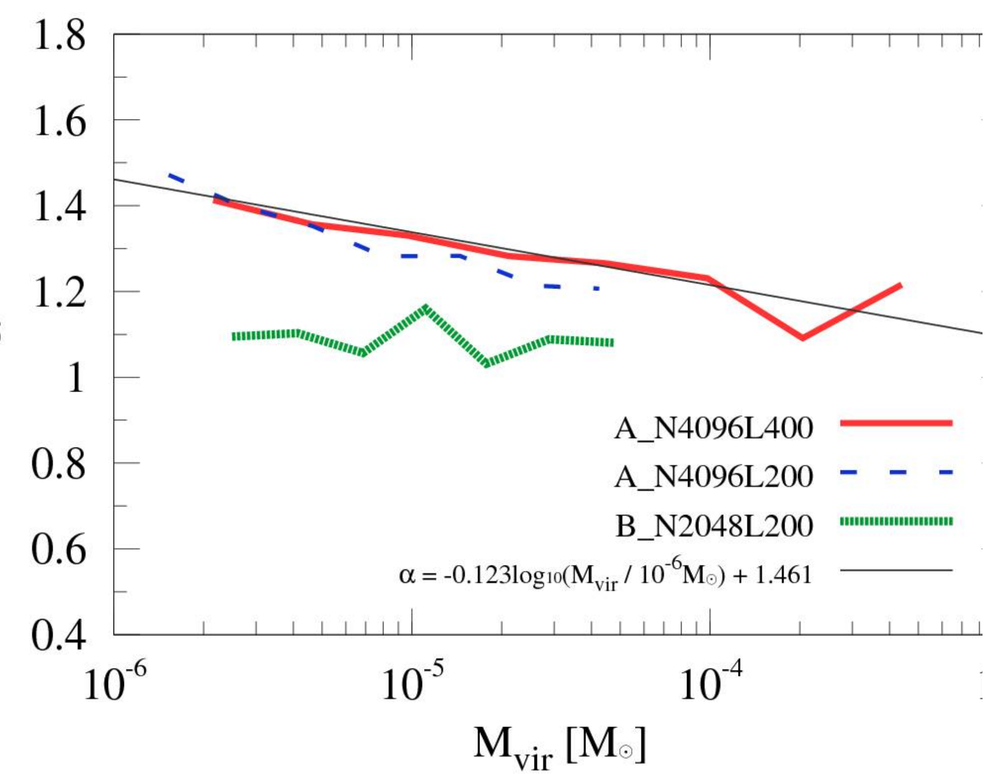
(4D2U, National Astronomical Observatory of Japan)

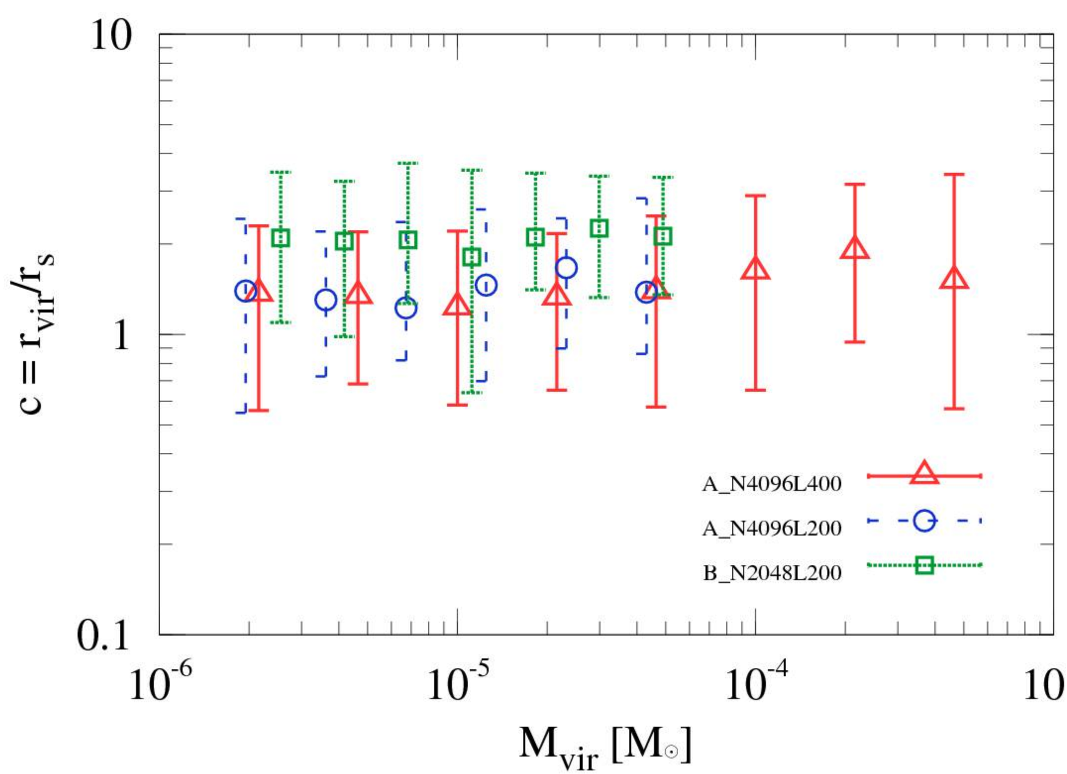
Stacked density profiles (z=32)



Shape, concentration (z=32)

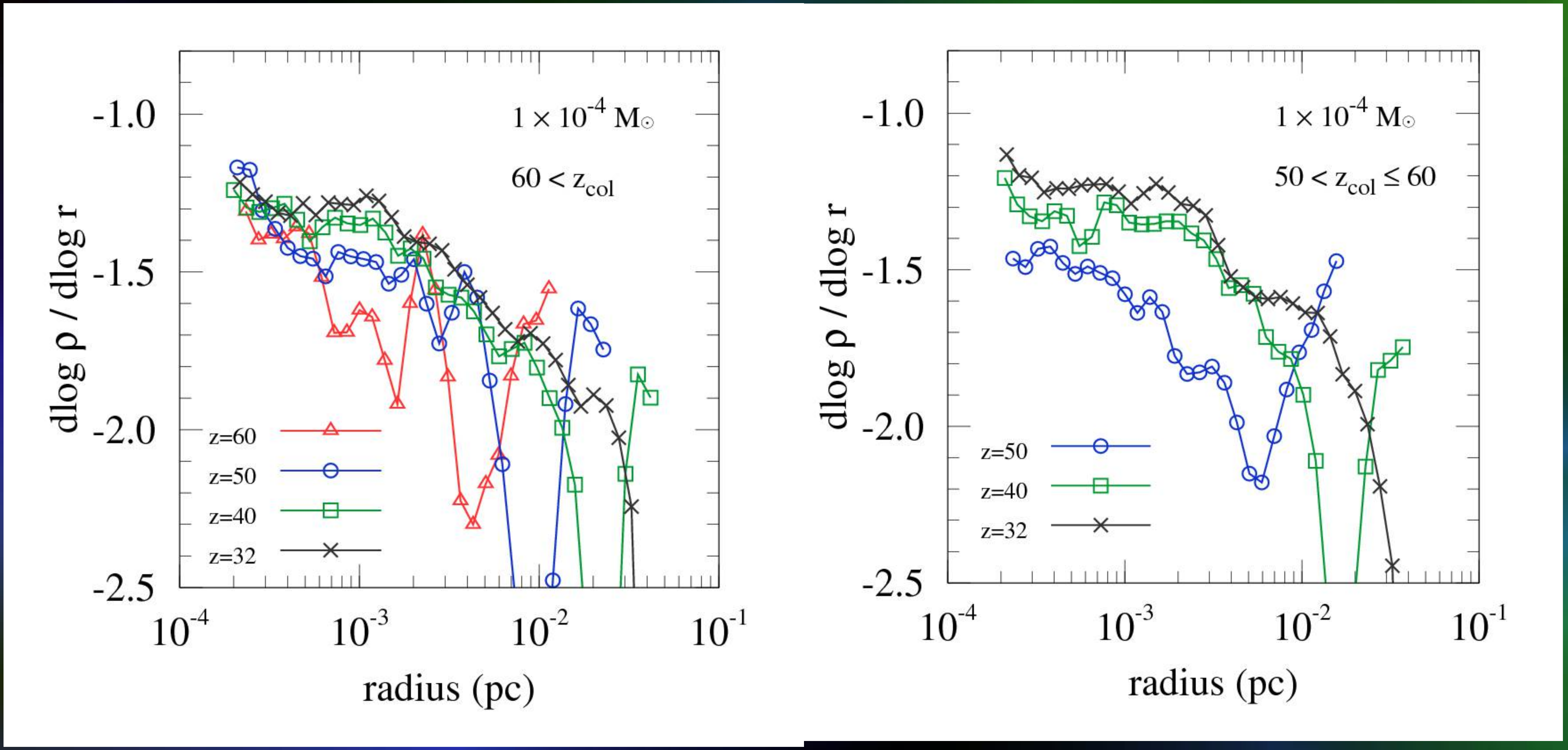
$$\rho(r) = \frac{\rho_0}{(r/r_s)^{\alpha}(1 + r/r_s)^{(3-\alpha)}}$$





- Larger halo -> shallower cusp
- Concentration does not depend on the halo mass
  - Reflect the fact that the formation epoch does not depend on the mass
  - Rule out single power law fitting functions

Evolution of density profiles



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

Summary

- We developed massively parallel N-body code
  - ~**5.8Pflops** is achieved on K computer, which correspond to ~**55**% of the peak speed
  - We could perform simulations, 2-10 times faster than public codes like Gadget-2
- $N>10^{10}$ simulations can first reveal the structures of dark matter halos near the free streaming scale
  - Different structures from larger halos like galatic halos
  - Impact on the dark matter detection experiments
- Next-generation mock galaxy and AGN catalogs
  - Better than Millennium catalogs