Dark Matter Symposium
February 6, 2021

Group C02:
Cosmic structure formation

Shin'ichiro Ando
University of Amsterdam / University of Tokyo

GRAPPA
GRavitation AstroParticle Physics Amsterdam

KAVLI IPMU
INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Cold Dark Matter (CDM) is well established and has all the observational support

Cold Dark Matter (CDM) is well established and has all the observational support

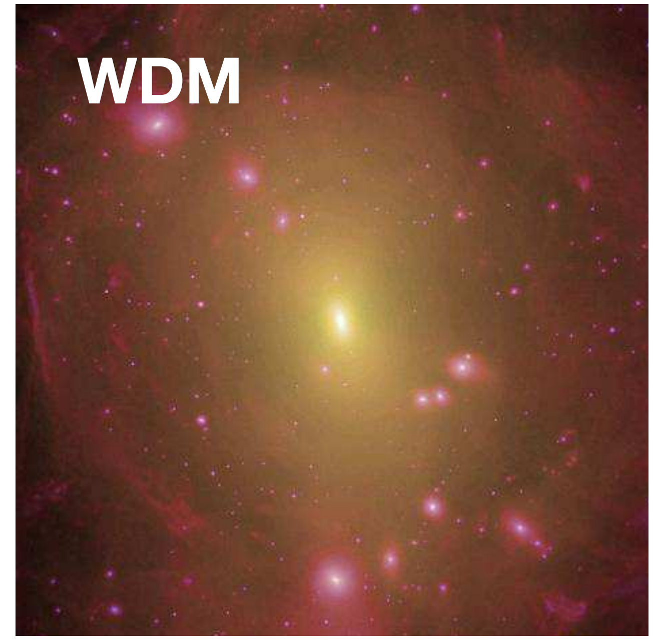
at large scales*

*** Scales larger than galaxies**

Small scale structure

WIMPs, axions, ALPs, PBHs

- Cusps in density profiles
- Very many small (sub)structures

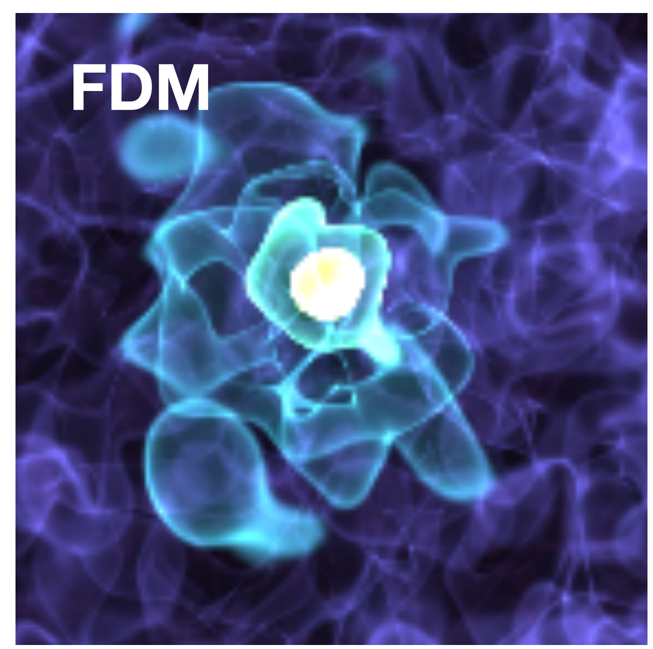


Sterile neutrinos

- Cutoff at sub-galaxy scale in the power spectrum

SIMPs, dark atoms

- Cores in density profiles induced by self scattering

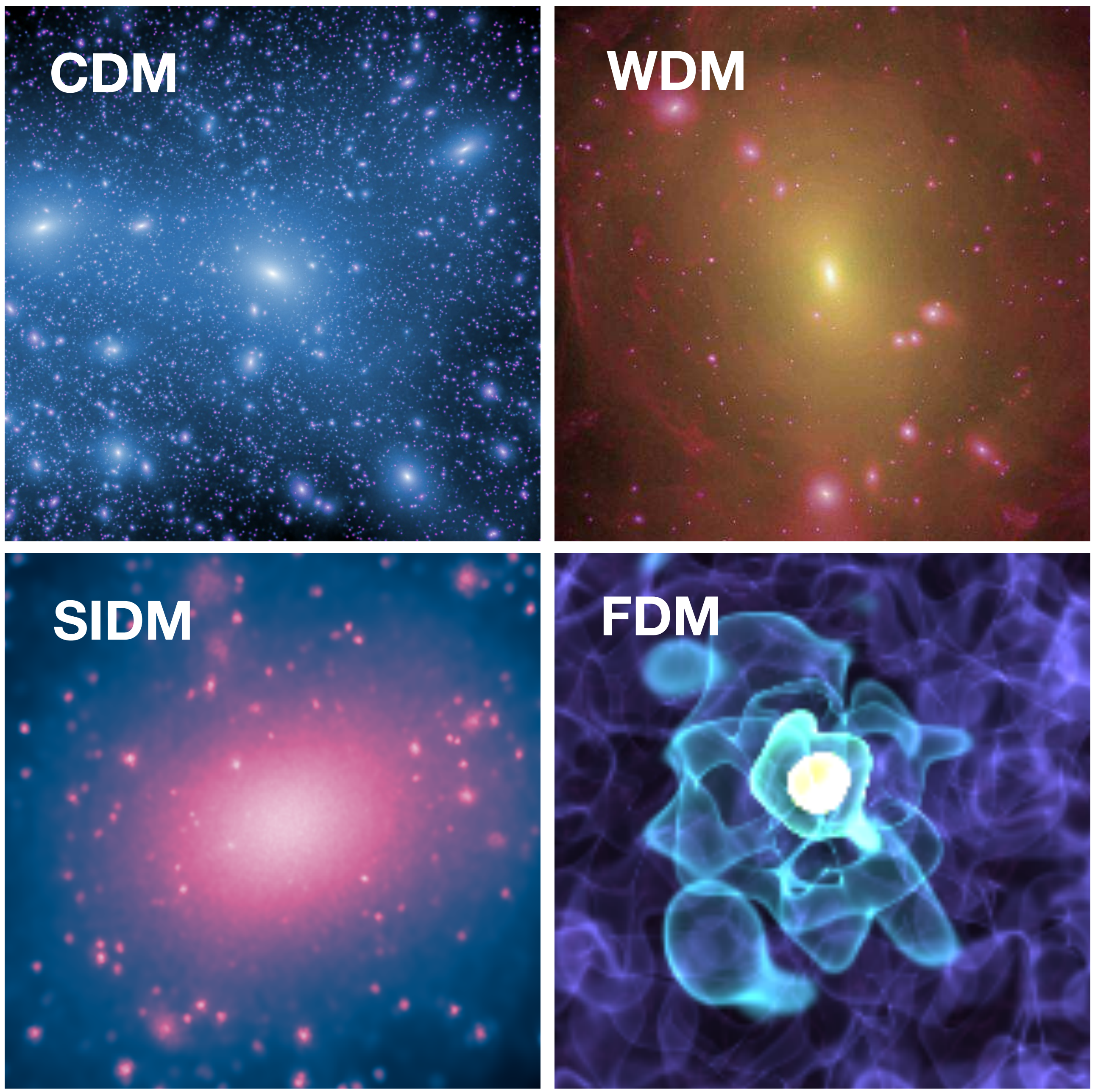


Ultralight bosons

- Pattern induced by de Broglie length at sub-galactic scales

Small scale structure

Scientific goals: develop models of small-scale structure formation, and apply them to various dark matter candidates



- What dark matter particles are determines small-scale distribution
  - Key to identifying particle nature
- Develop both **numerical simulations and semi-analytic models**, calibrate them, and **establish reliable models** free from shot noise and numerical resolution

My personal take - where this started

Bartels, Ando, *Phys. Rev. D* **92**, 123508 (2015)

My personal take - where this started

- WIMPs: Halo masses range **20 (!) orders of magnitude** from Earth to clusters of galaxies

Bartels, Ando, *Phys. Rev. D* **92**, 123508 (2015)

My personal take - where this started

- WIMPs: Halo masses range **20 (!) orders of magnitude** from Earth to clusters of galaxies

- Numerical simulations can resolve down to $\sim 10^5 M_\odot$ and observationally much larger

Bartels, Ando, *Phys. Rev. D* **92**, 123508 (2015)

My personal take - where this started

- WIMPs: Halo masses range **20 (!) orders of magnitude** from Earth to clusters of galaxies
- Numerical simulations can resolve down to $\sim 10^5 M_\odot$ and observationally much larger
- Lots of resources have been spent to understand baryonic effect rather than increasing this resolution over the last decade

Bartels, Ando, *Phys. Rev. D* **92**, 123508 (2015)

My personal take - where this started

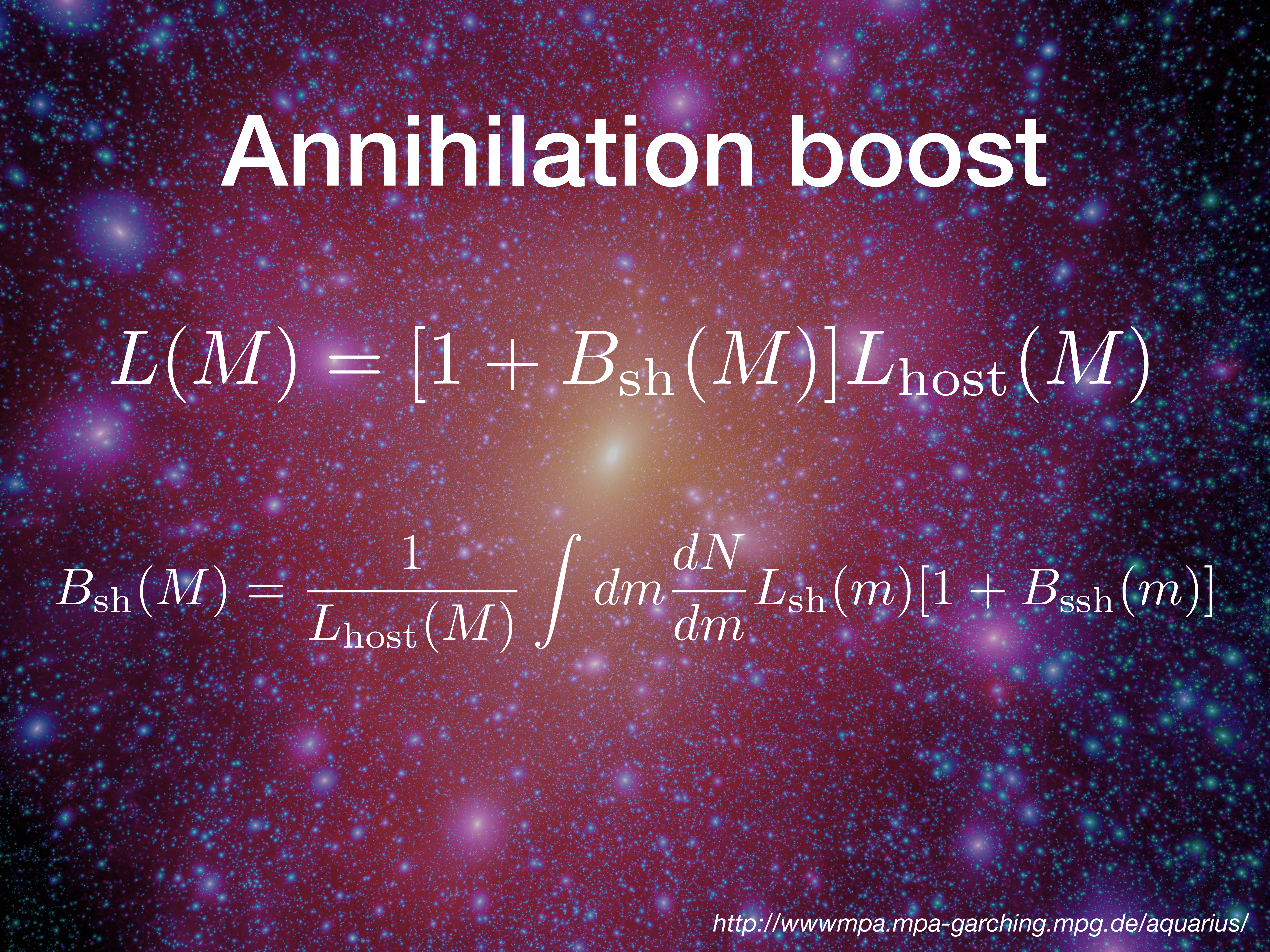
- WIMPs: Halo masses range **20 (!) orders of magnitude** from Earth to clusters of galaxies
- Numerical simulations can resolve down to $\sim 10^5 M_\odot$ and observationally much larger
- Lots of resources have been spent to understand baryonic effect rather than increasing this resolution over the last decade
- **WIMP annihilation is sensitive to halos of all scales**

Bartels, Ando, *Phys. Rev. D* **92**, 123508 (2015)

Annihilation boost

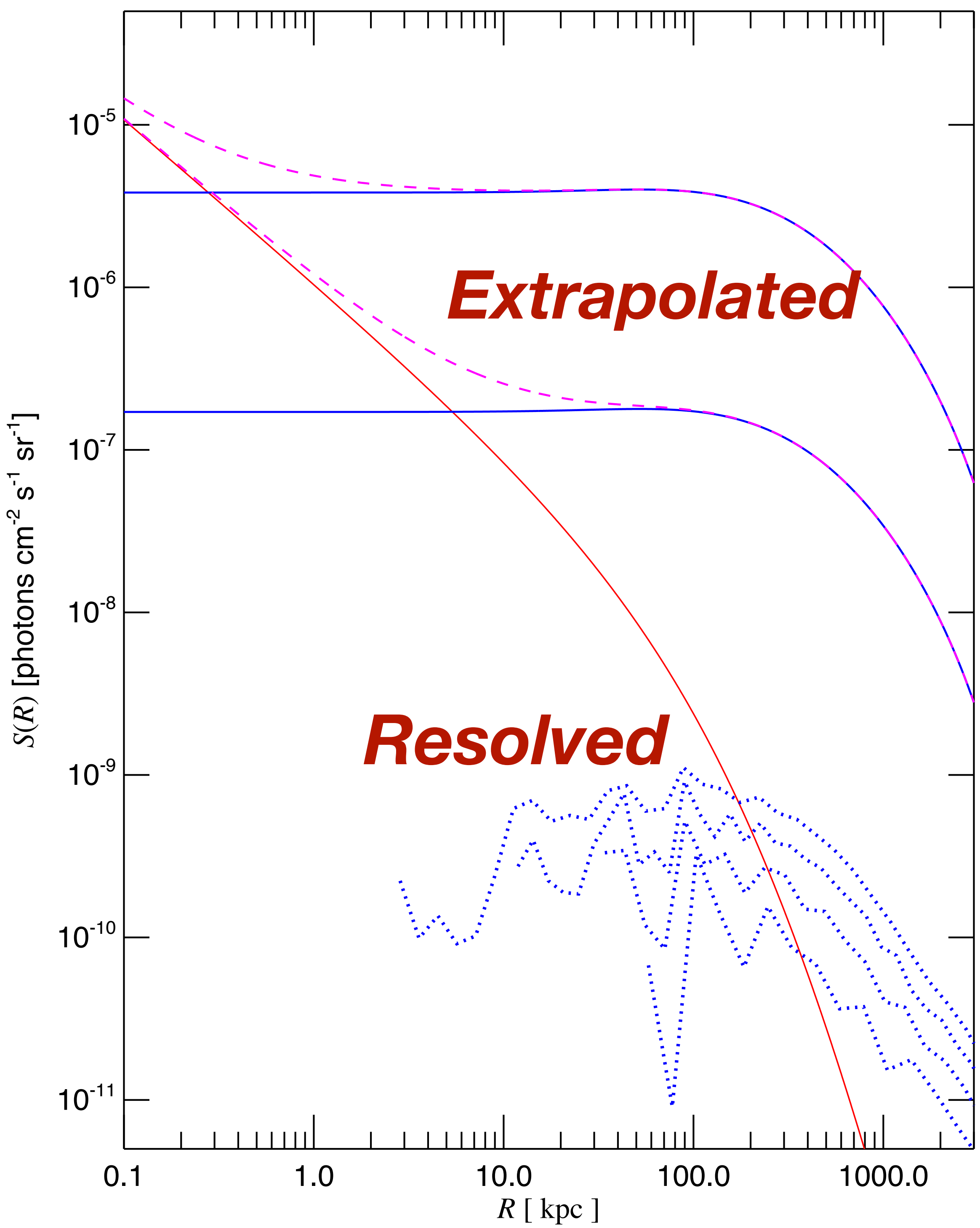
$$L(M) = [1 + B_{\rm sh}(M)] L_{\rm host}(M)$$

$$B_{\rm sh}(M) = \frac{1}{L_{\rm host}(M)} \int dm \frac{dN}{dm} L_{\rm sh}(m) [1 + B_{\rm ssh}(m)]$$

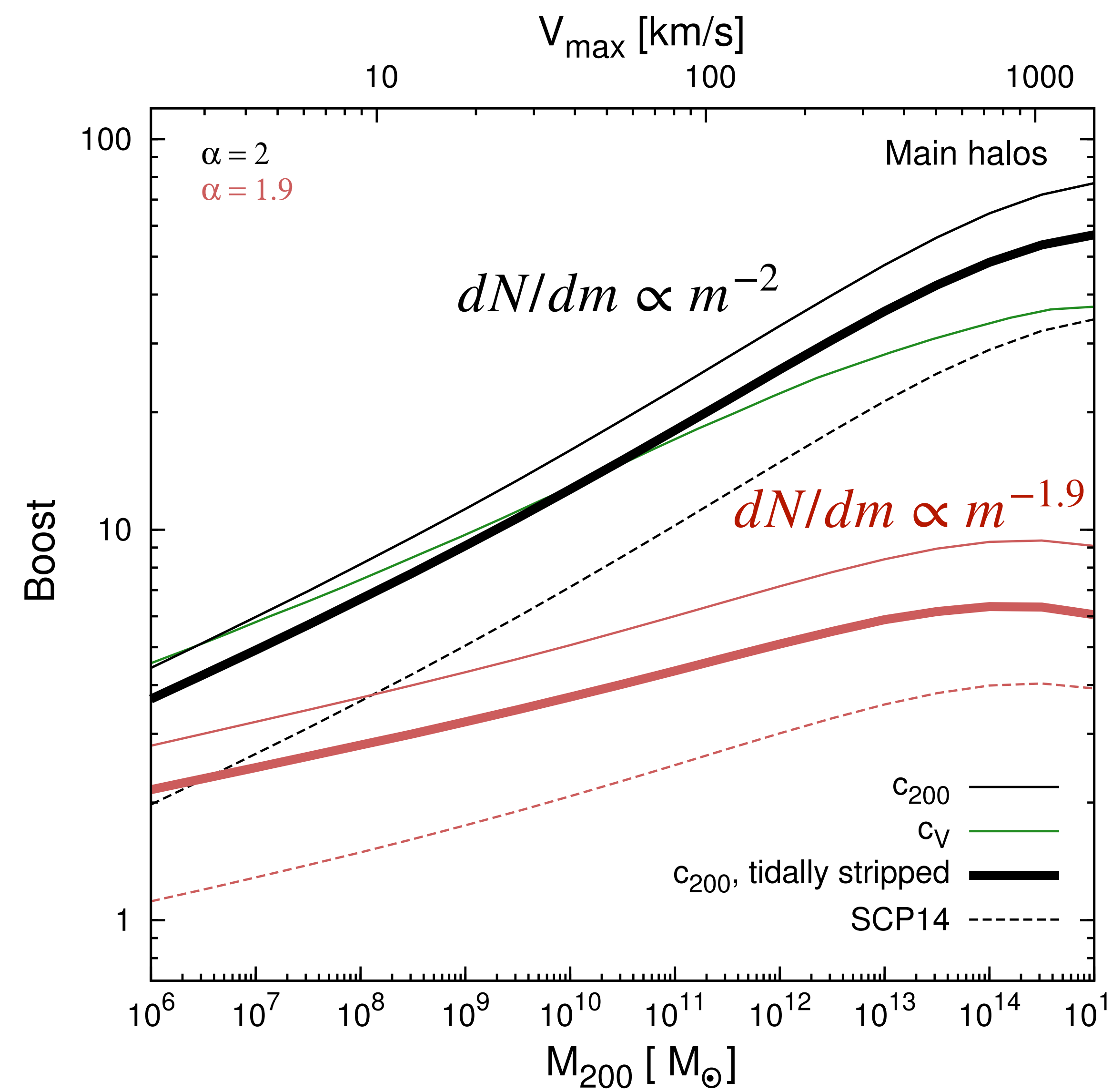


http://wwwmpa.mpa-garching.mpg.de/aquarius/

Annihilation boost



Gao et al., *Mon. Not. R. Astron. Soc.* **419**, 1721 (2012)



Moliné et al., *Mon. Not. R. Astron. Soc.* **466**, 4974 (2017)

- Very uncertain, of which we don’t even have good sense
- **No way that it can be solved with numerical simulations**

Semi-analytic models of subhalos

- Complementary to numerical simulations
- Light, flexible, and versatile
- Can cover large range for halo masses (**micro-halos to clusters**) and redshifts (***z*** **~ 10 to 0**) based on physics modeling
- **Accuracy:** Reliable if it is **calibrated with simulations** at resolved scales

Semi-analytic modeling

Structures start to form

Initial condition: Primordial power spectrum

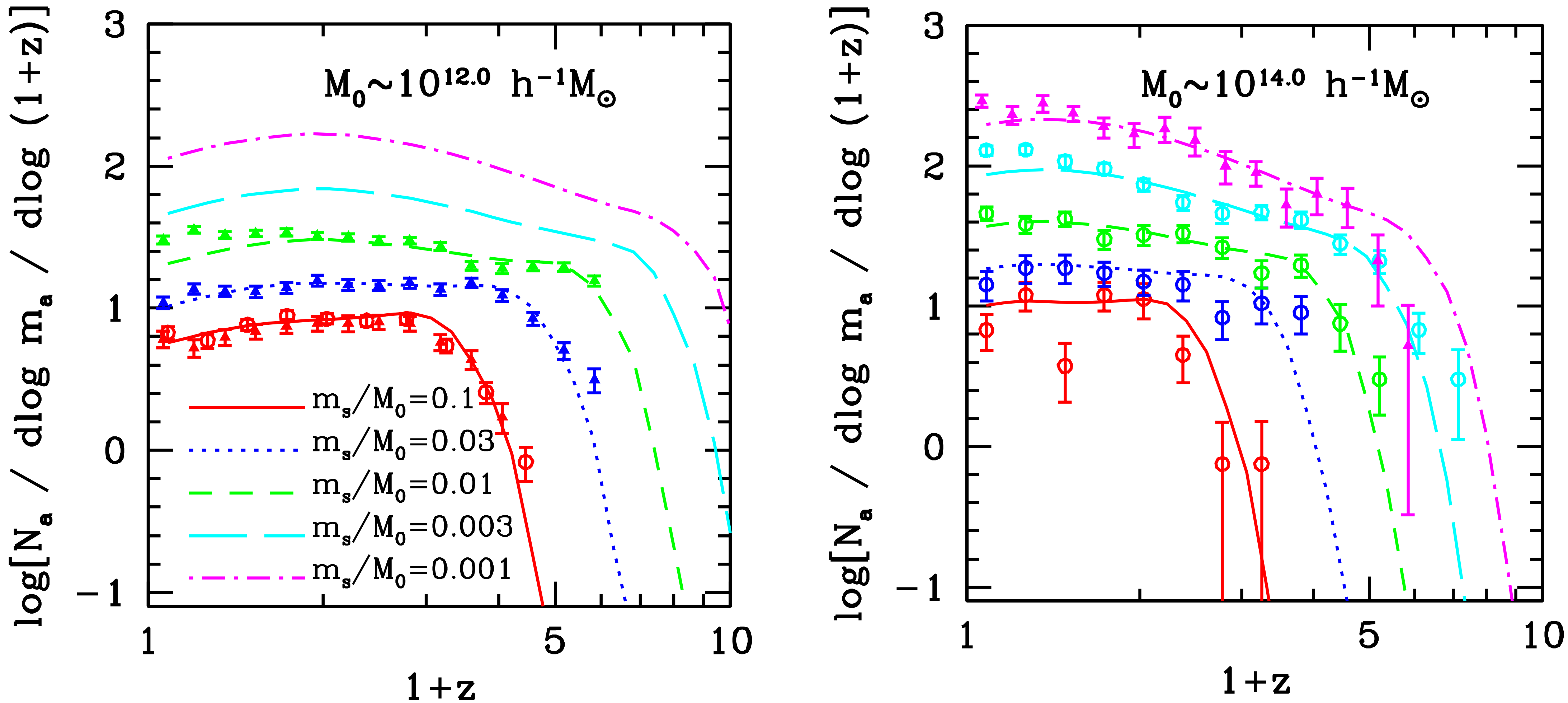
Smaller halos merge and accrete to form larger ones

Extended Press-Schechter formalism

Subhalos experience mass loss

Modeling for tidal stripping and mass-loss rate

Subhalo accretion



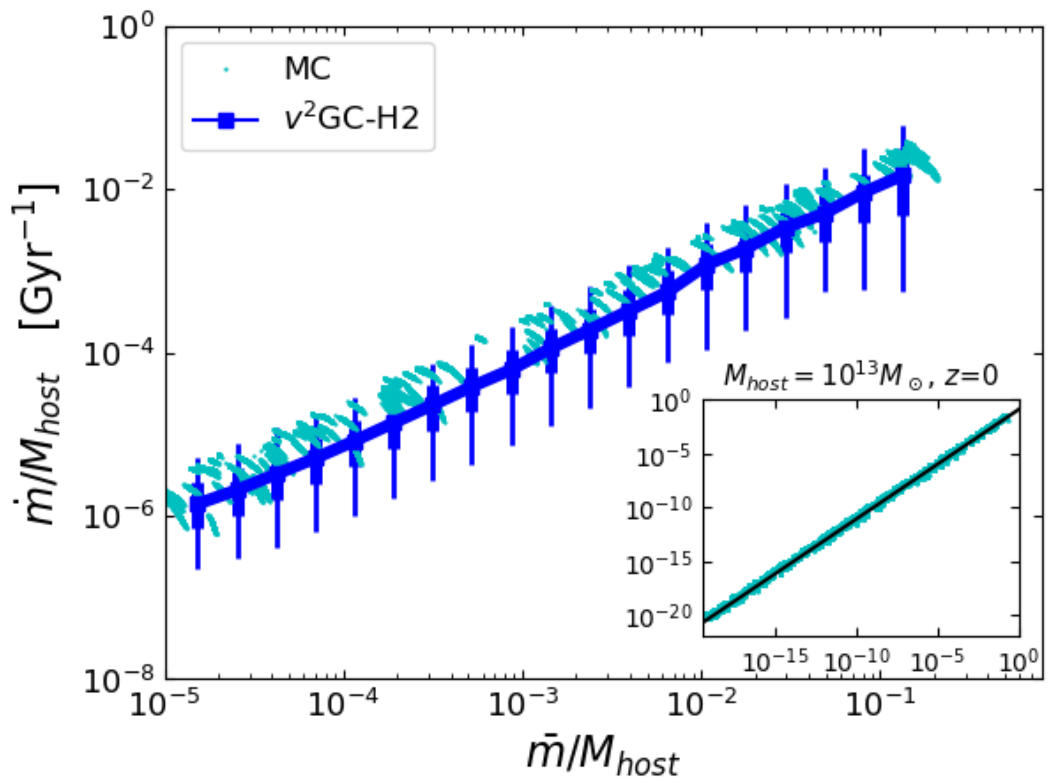
Yang et al., *Astrophys. J.* **741**, 13, (2011)

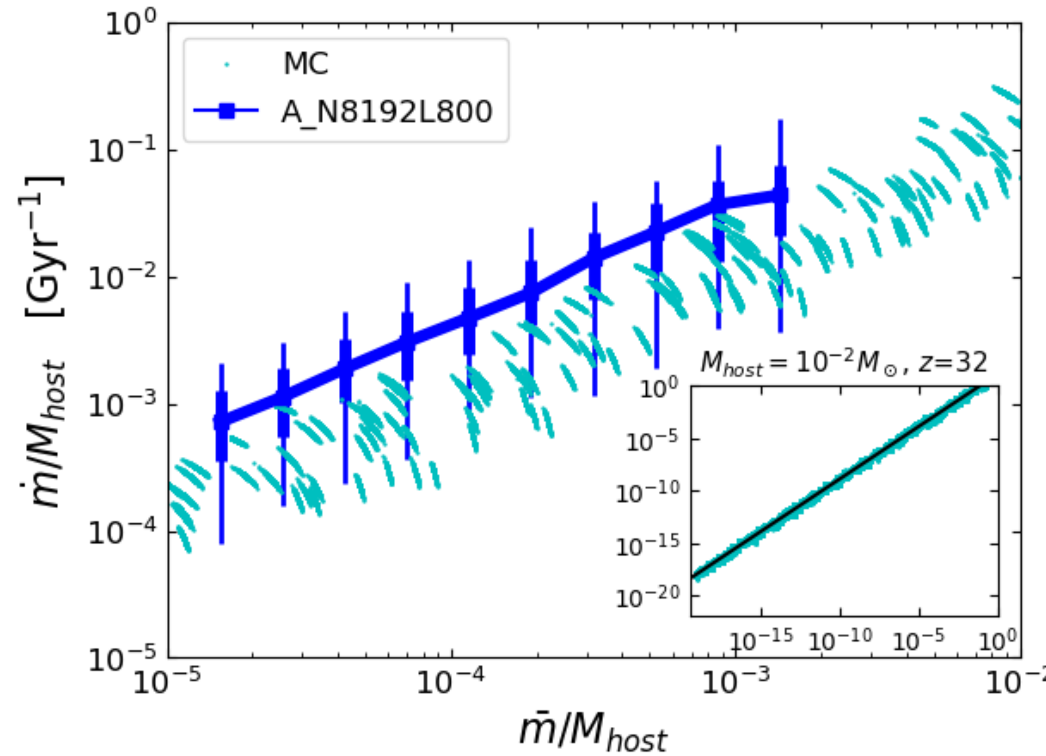
Infall distribution of subhalos:
Extended Press-Schechter formalism

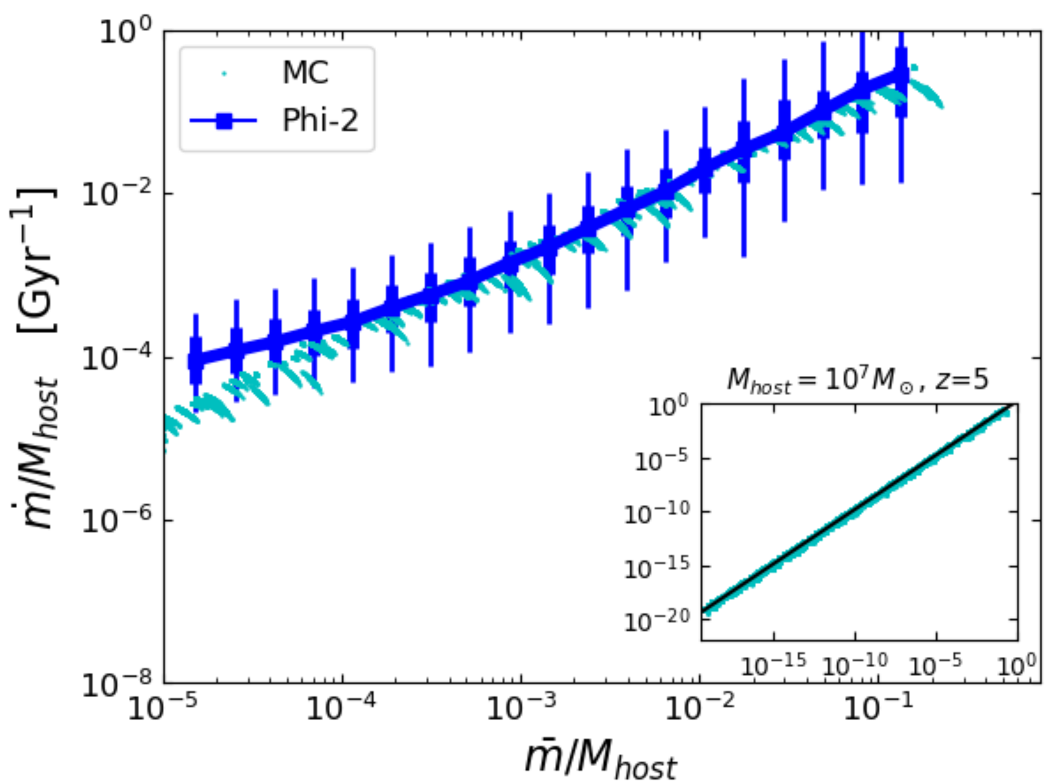
$$\frac{d^2N_{\rm sh}}{dm_{\rm acc}dz_{\rm acc}} \propto \frac{1}{\sqrt{2\pi}}\frac{\delta(z_{\rm acc})-\delta_M}{(\sigma^2(m_{\rm acc})-\sigma_M^2)^{3/2}}\exp\left[-\frac{(\delta(z_{\rm acc})-\delta_M)^2}{2(\sigma^2(m_{\rm acc})-\sigma_M^2)}\right]$$

Subhalo evolution

Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)







- Monte Carlo approach
  - Determine orbital energy and angular momentum
  - Assume the subhalo loses all the masses outside of its tidal radius instantaneously at its peri-center passage
- Internal structure changes follow Penarrubia et al. (2010)

Semi-analytic modeling

Structures start to form

✓ **Initial condition: Primordial power spectrum**

↓

Smaller halos merge and accrete to form larger ones

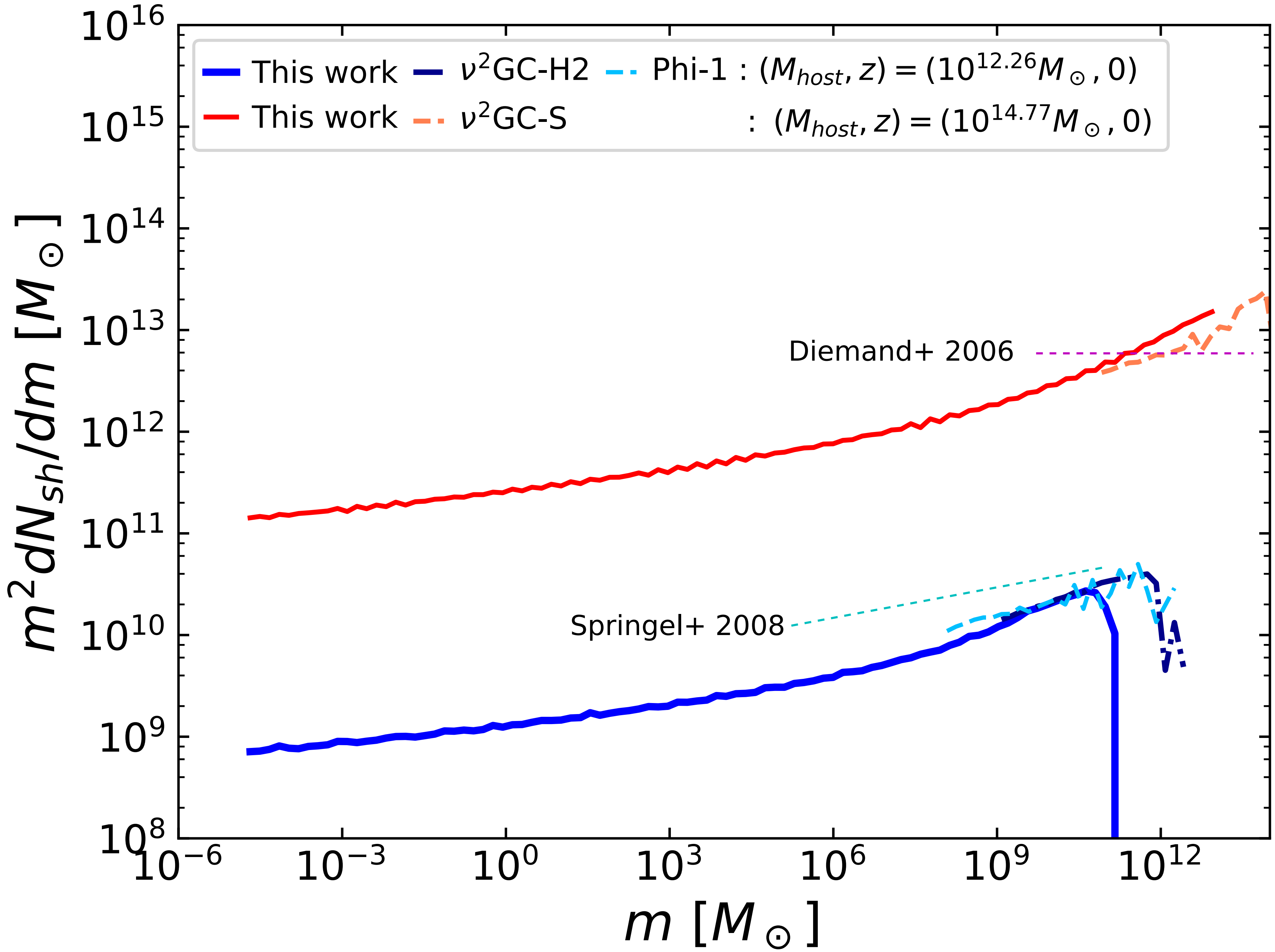
✓ **Extended Press-Schechter formalism**

↓

Subhalos experience mass loss

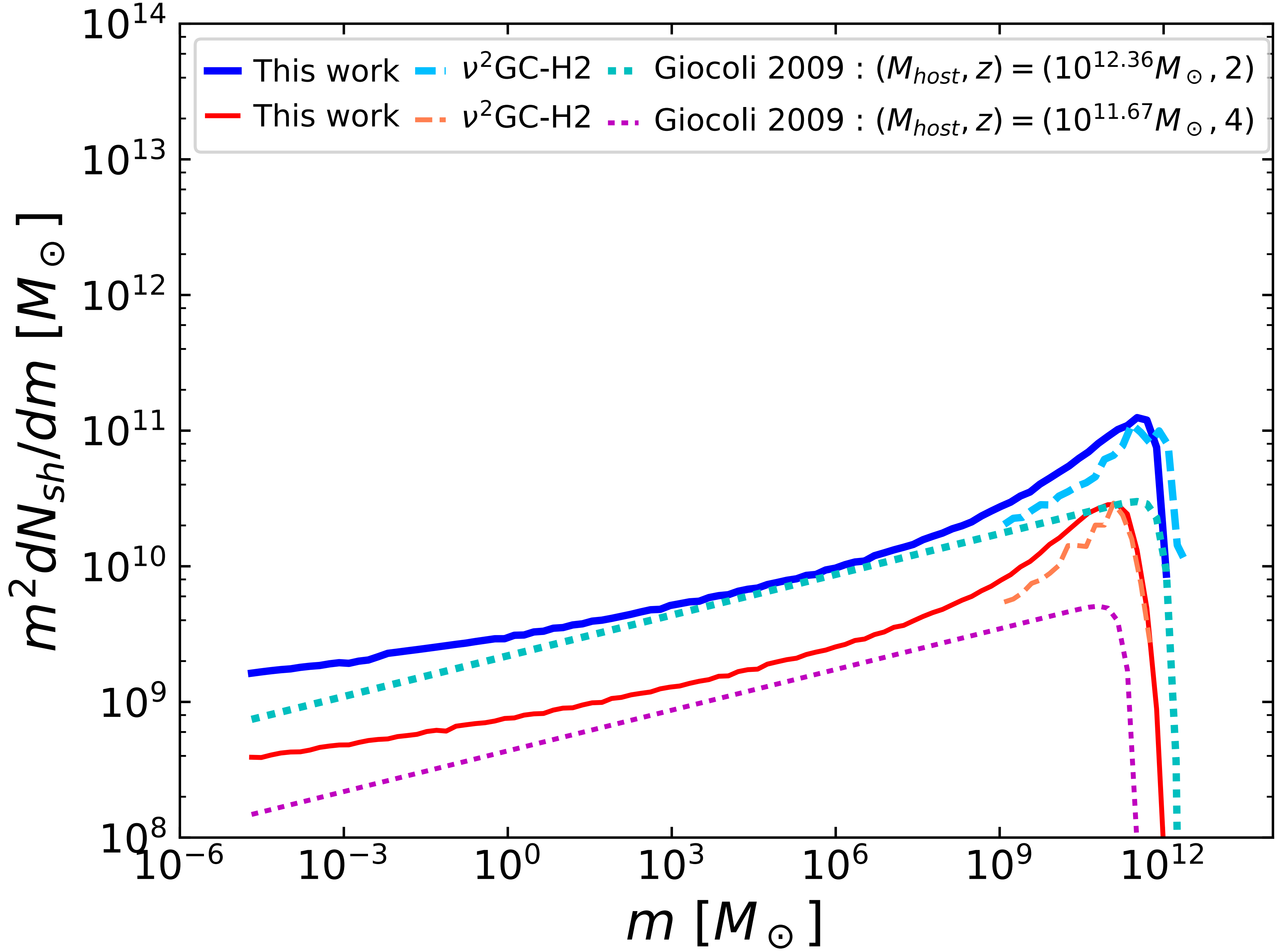
✓ **Modeling for tidal stripping and mass-loss rate**

Subhalo mass function: Clusters and galaxies



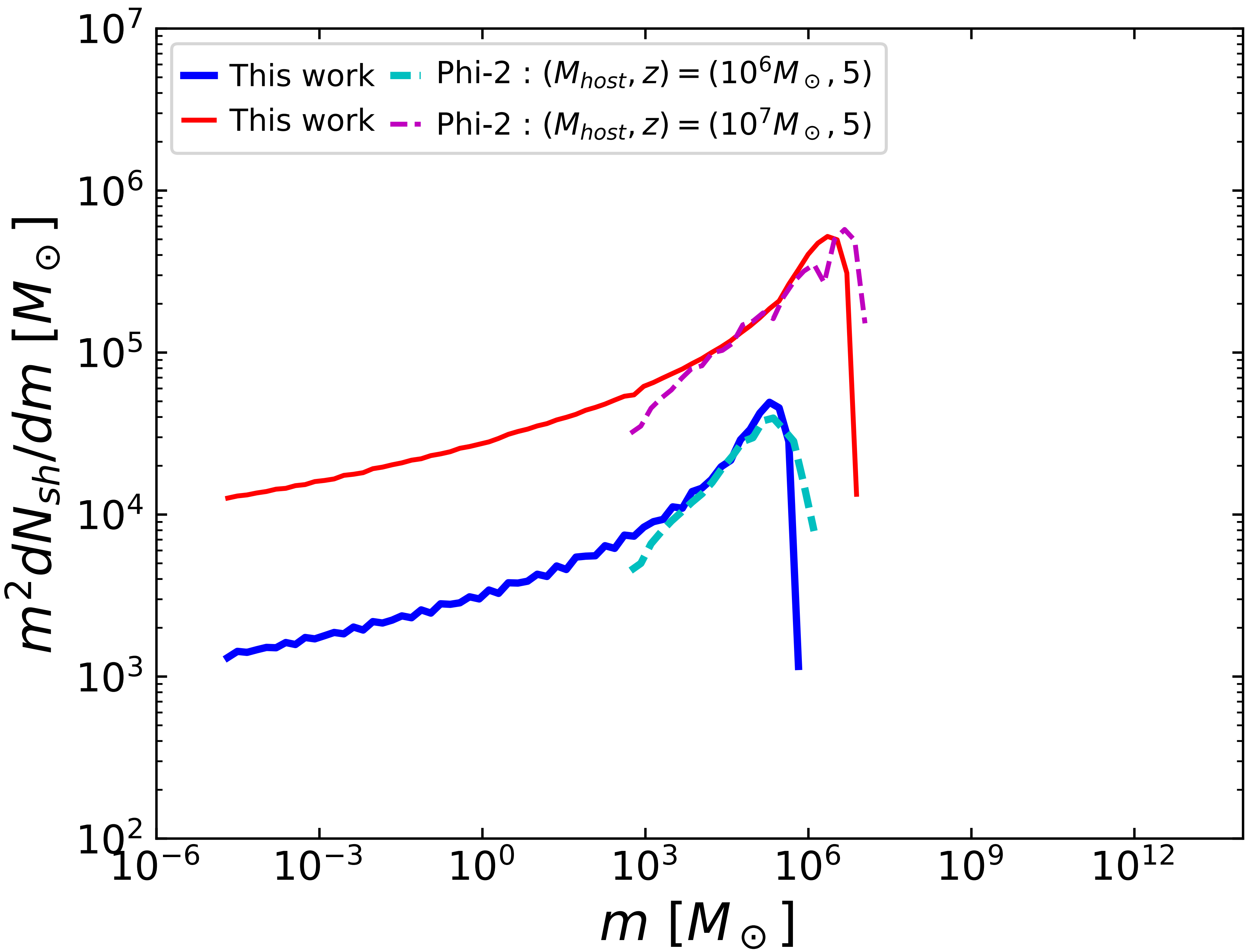
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function: Galaxies at z=2,4



Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function: Dwarfs at z=5

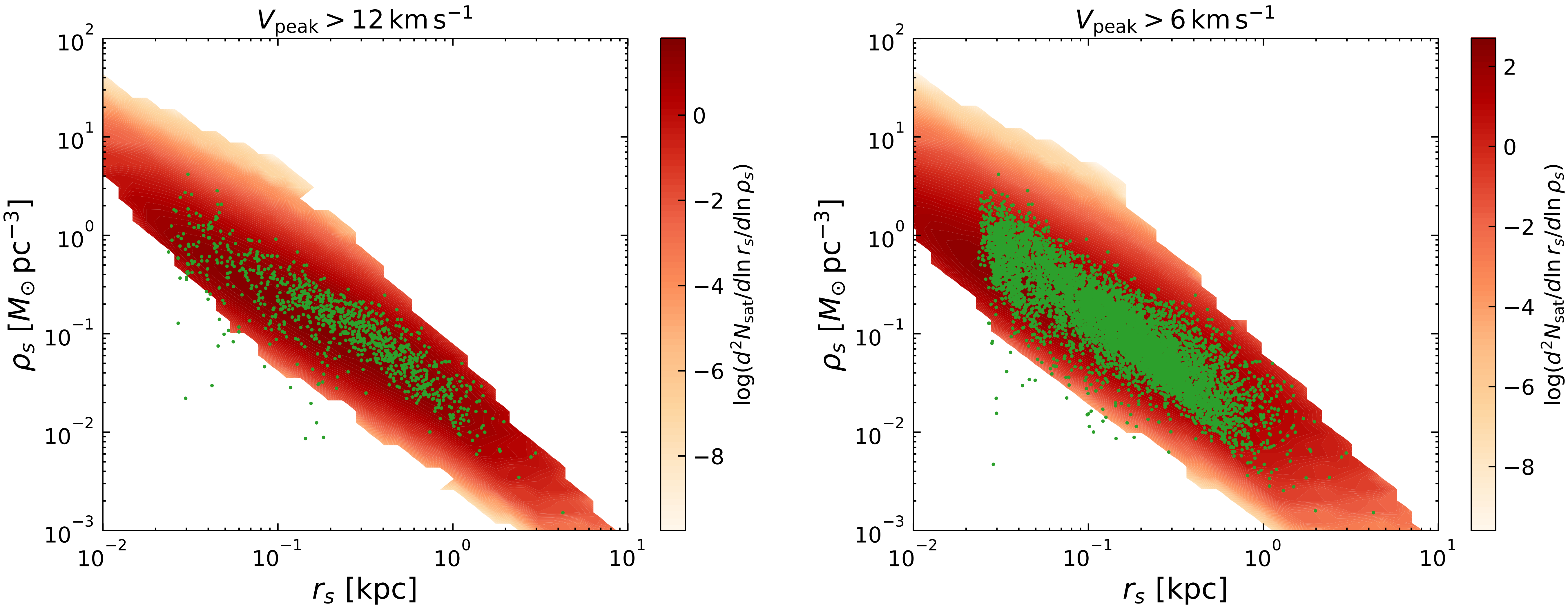


Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Distribution of r_s and ρ_s

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

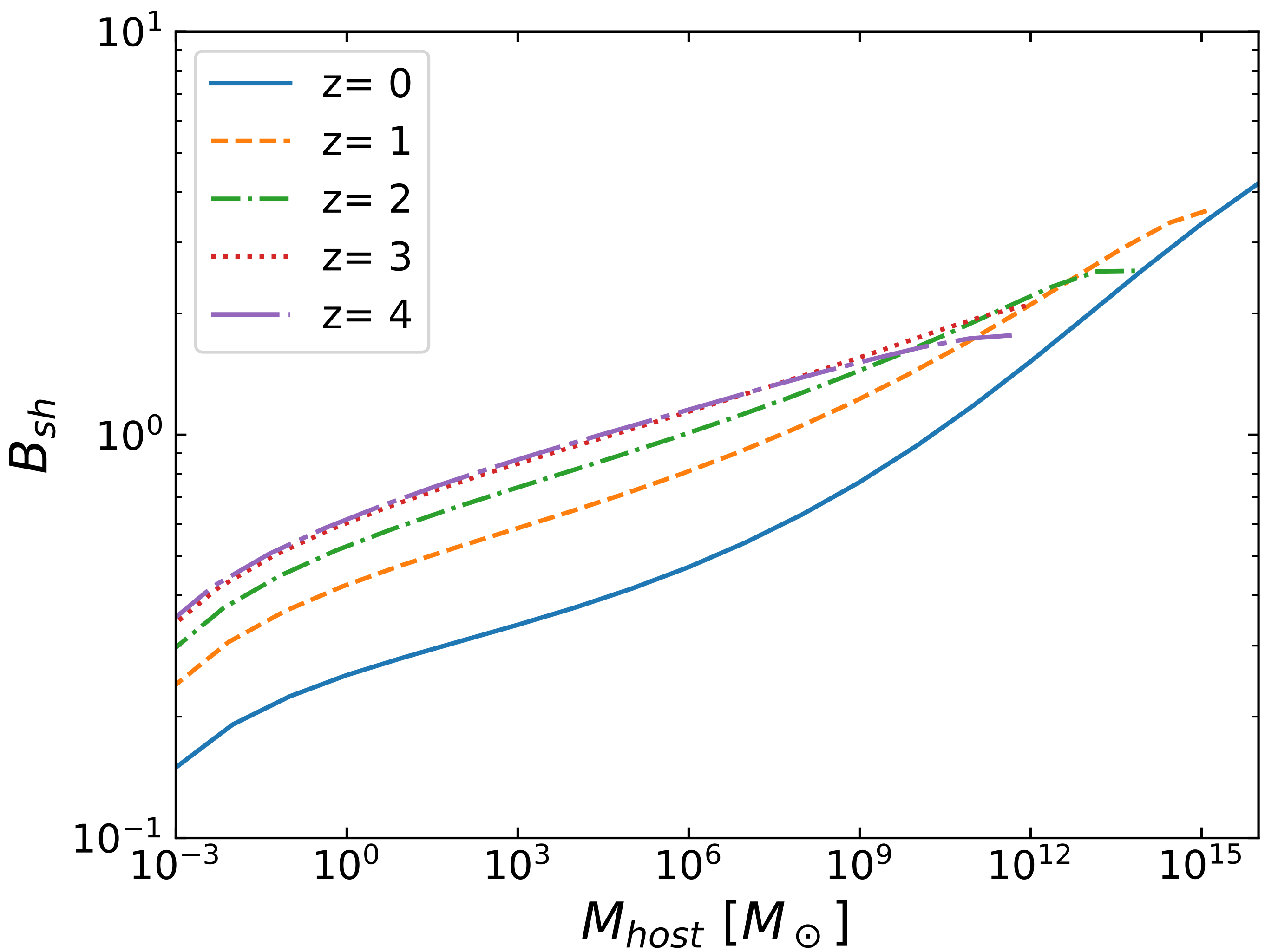
Ando et al., *Phys. Rev. D* **102**, 061302 (2020)



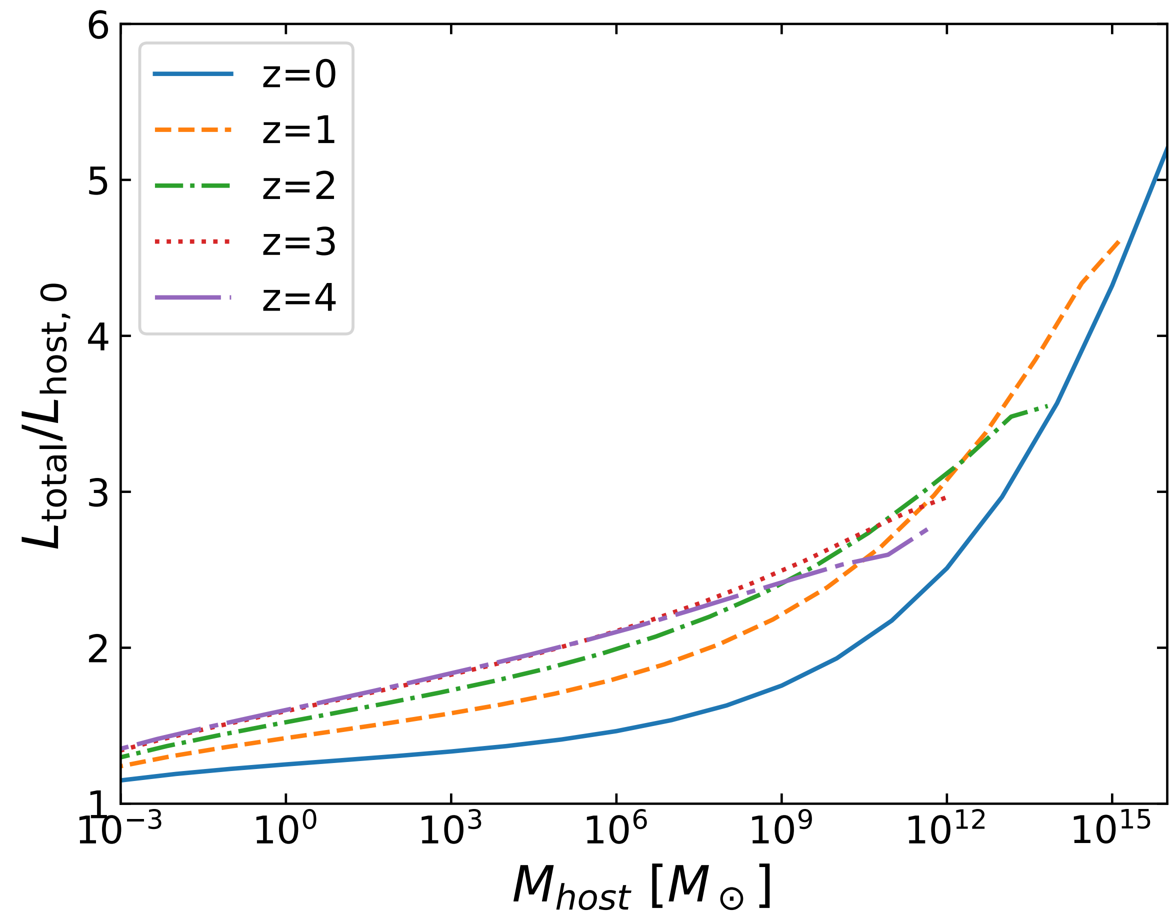
Good agreement with simulation results (Vea Lactea II)

Annihilation boost

Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)
Ando, Ishiyama, Hiroshima, *Galaxies* **7**, 68 (2019)



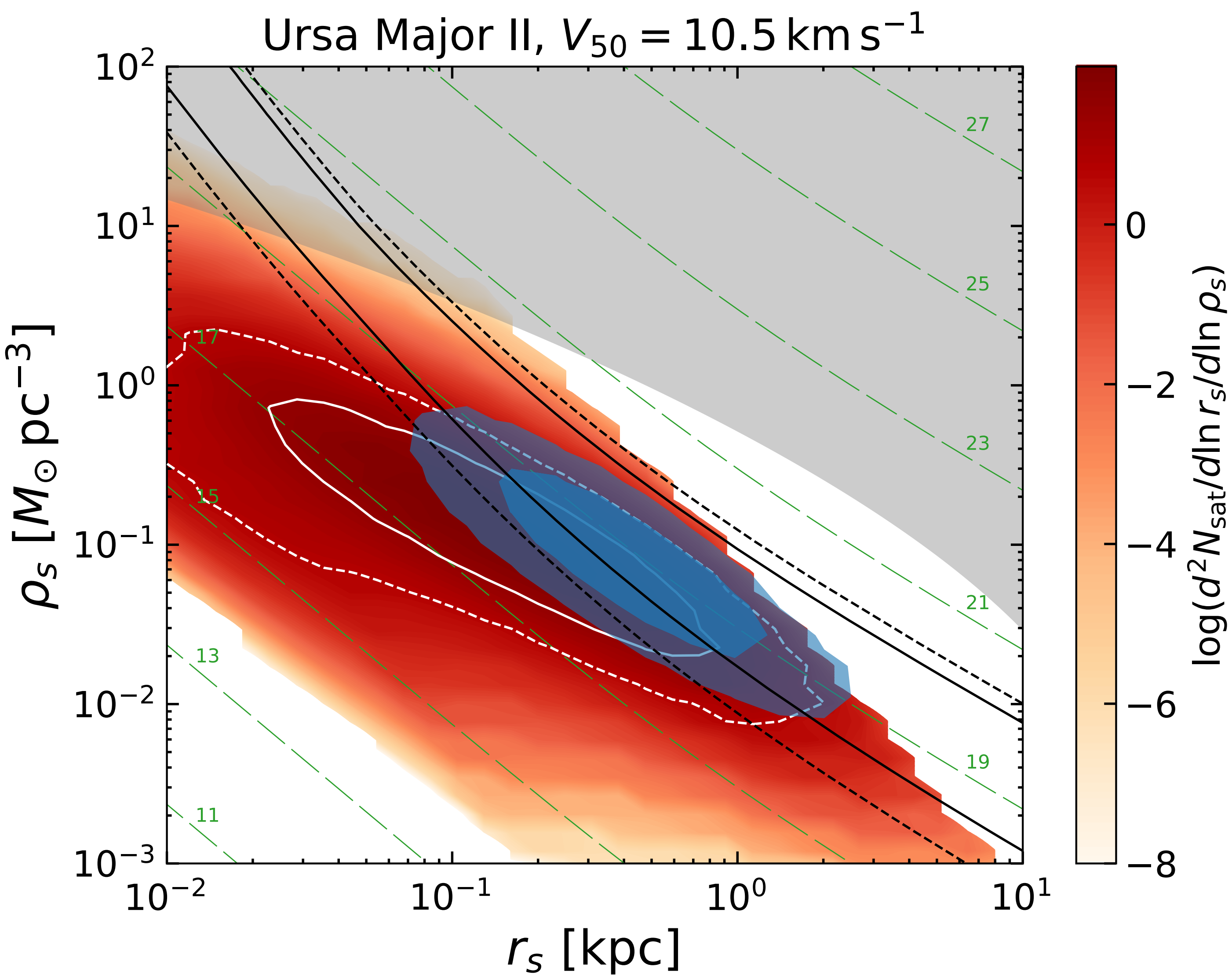
w/ up to sub³-subhalos



- Boost can be as large as ~1 (3) for galaxies (clusters)
- Boost factors are higher at larger redshifts, but saturates after z = 1
- For one combination of host mass and redshifts (*M*, *z*), the code takes **only ~*O*(1) min to calculate the boost** on a laptop computer

Estimates of dwarf density profiles

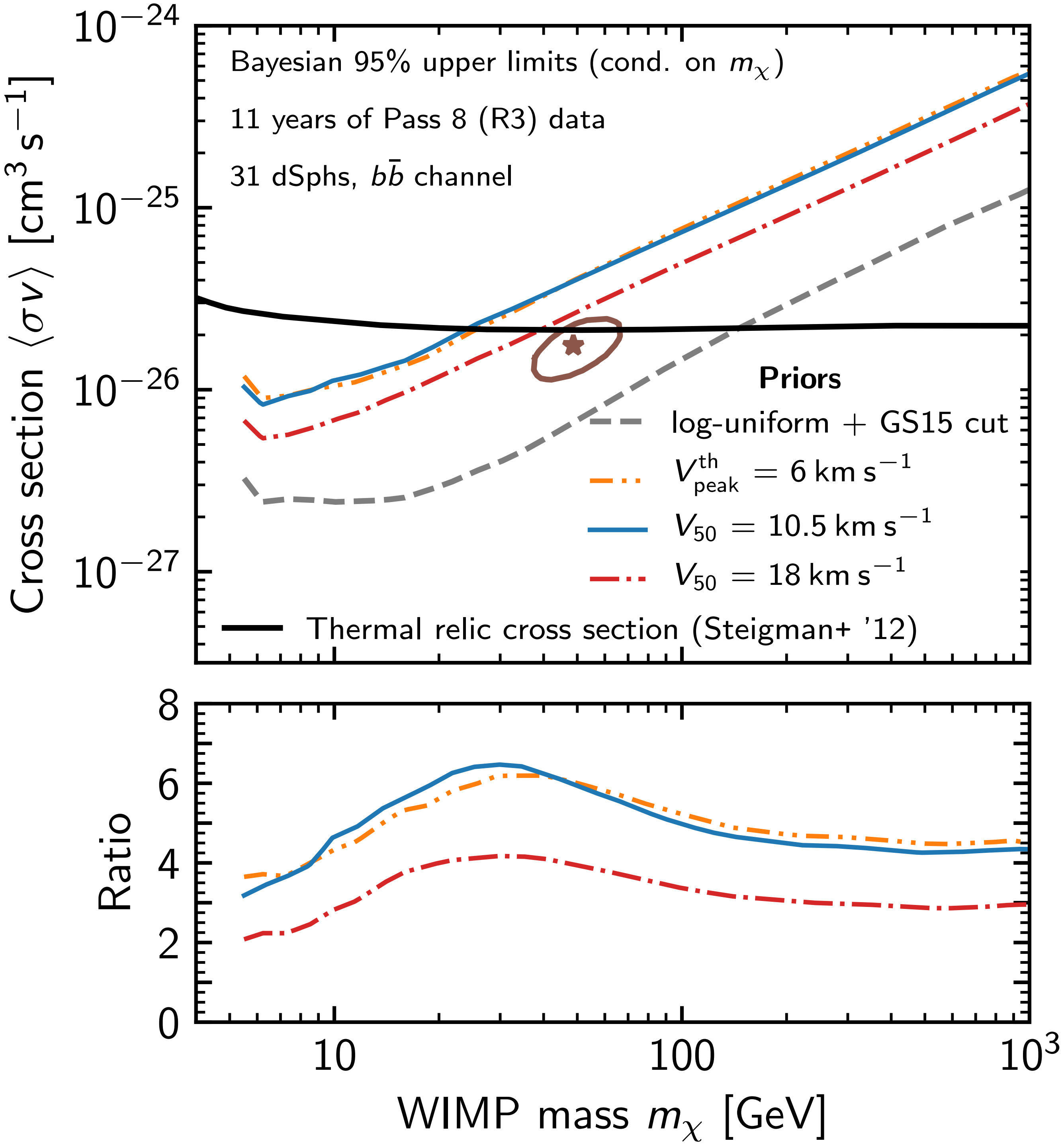
Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker,
Phys. Rev. D **102**, 061302 (2020)



- **Black: Likelihood contours**
- **Green: log [*J*/(GeV²/cm⁵)]**
- **Red: Prior density**
- **Blue: Posterior density**

- Having small data only does not break the degeneracy between r_s and ρ_s
- Cosmological arguments have been adopted to chop off upper regions of the parameter space (e.g., Geringer-Sameth et al. 2015)
- Satellite prior does this job naturally as well as breaks the degeneracy
- This is hard to achieve with simulations as they are limited by statistics of finding dwarf candidates

Cross section constraints



- Adopting satellite priors **weaken** the cross section constraints by **a factor of 2-7**
- The effect is relatively insensitive to condition of satellite formation: **robust prediction**
- Thermal cross section can be excluded only up to 20-50 GeV
- Also very relevant for wino dark matter targeted by CTA

Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker, *Phys. Rev. D* **102**, 061302 (2020)

Summary: Semi-analytic modeling

- Benchmark models for CDM / WIMP

Summary: Semi-analytic modeling

- Benchmark models for CDM / WIMP
    - Free from resolution (useful for small mass ranges)

Summary: Semi-analytic modeling

- Benchmark models for CDM / WIMP
  - Free from resolution (useful for small mass ranges)
  - Free from shot noise (useful for large mass ranges)

Summary: Semi-analytic modeling

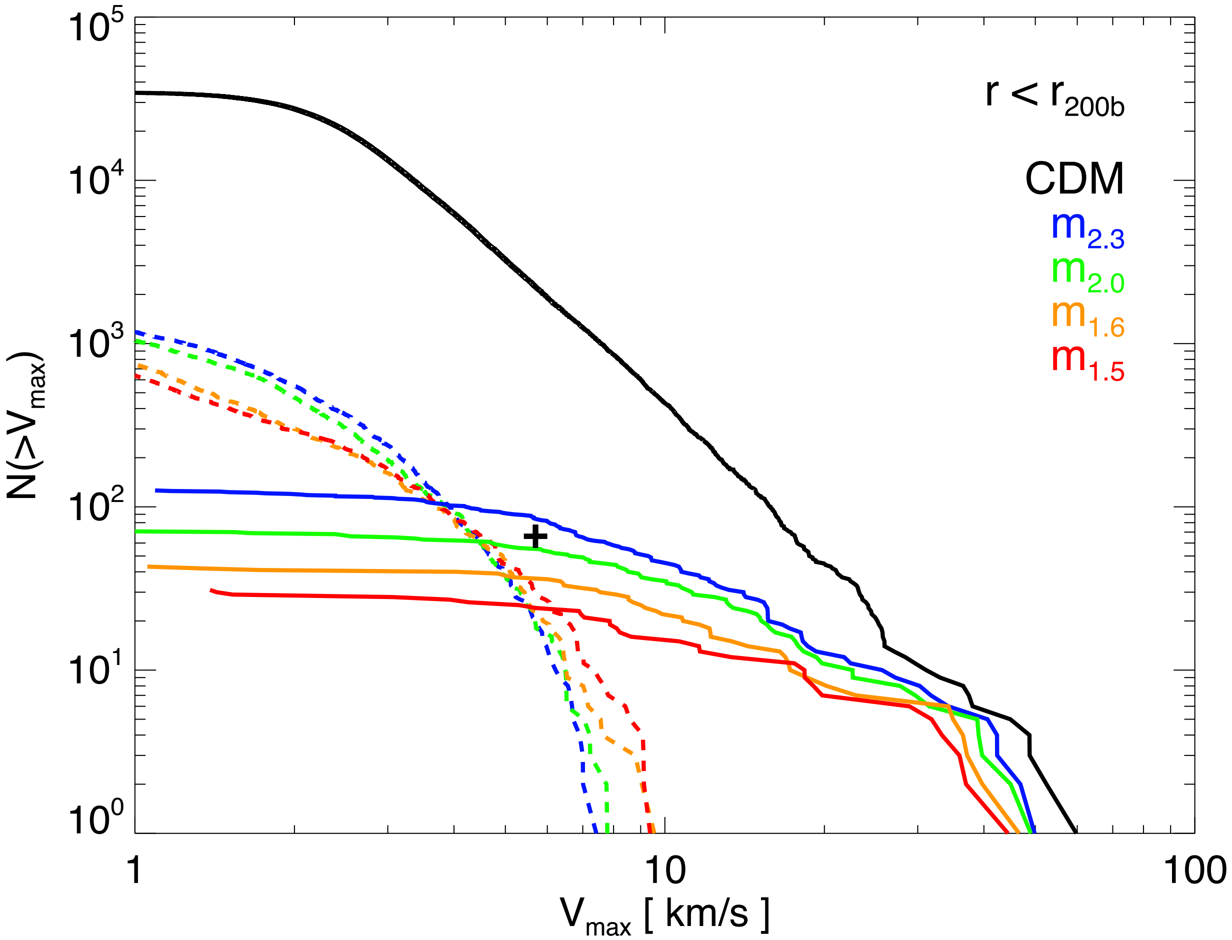
- Benchmark models for CDM / WIMP
  - Free from resolution (useful for small mass ranges)
  - Free from shot noise (useful for large mass ranges)
  - Well tested against numerical simulations of halos with various masses at various redshifts

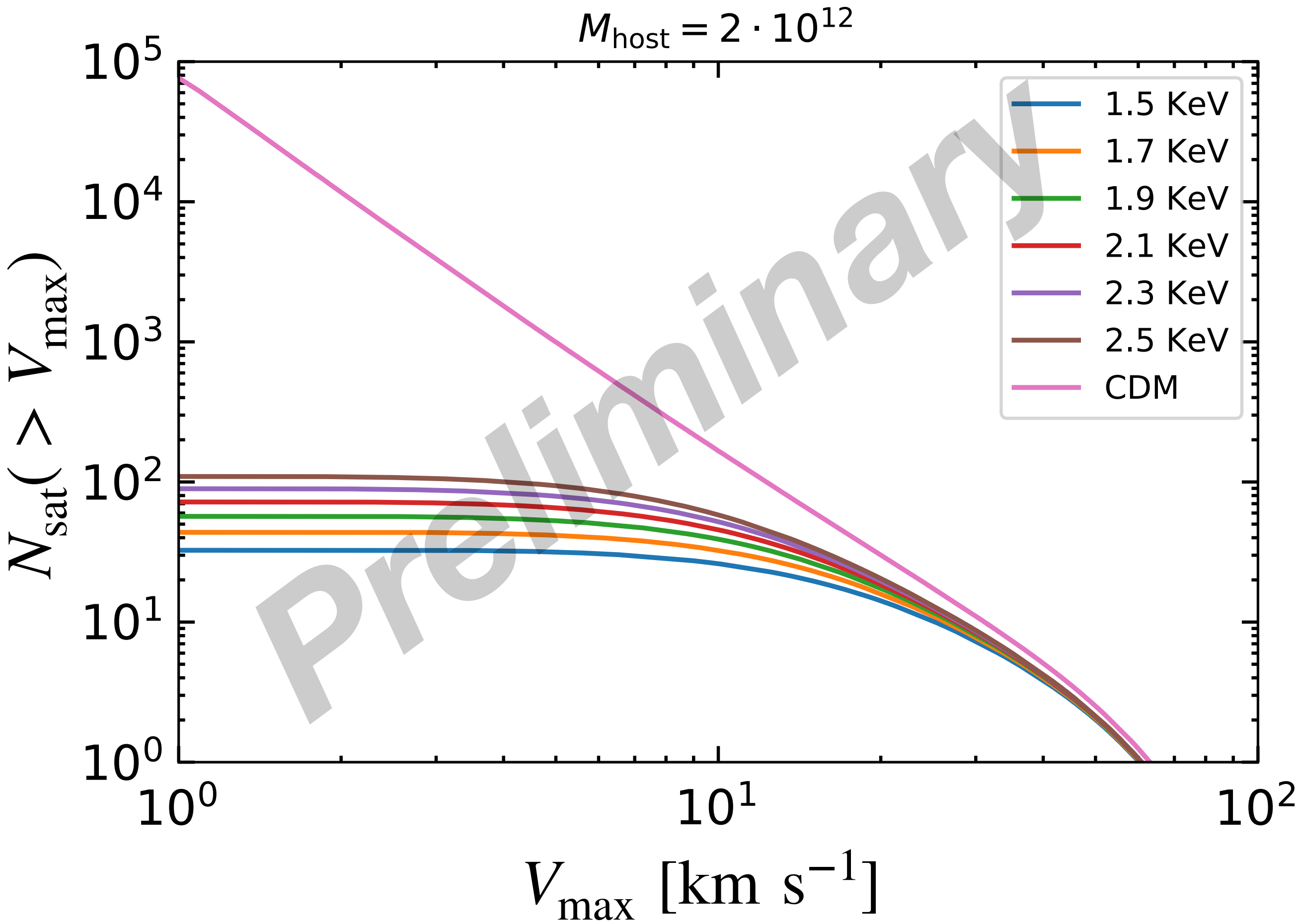
Summary: Semi-analytic modeling

- Benchmark models for CDM / WIMP
  - Free from resolution (useful for small mass ranges)
  - Free from shot noise (useful for large mass ranges)
  - Well tested against numerical simulations of halos with various masses at various redshifts
  - Quick implementation, which is crucial to survey through parameter spaces for different dark matter models

Application to WDM

Lovell et al. *Mon. Not. R. Astron. Soc.* **439**, 300 (2014)





Change $\delta_c(z)$ and $\sigma(M)$ with those for WDM; others unchanged

w/ Ariane Dekker, Camila Correa, Kenny Ng

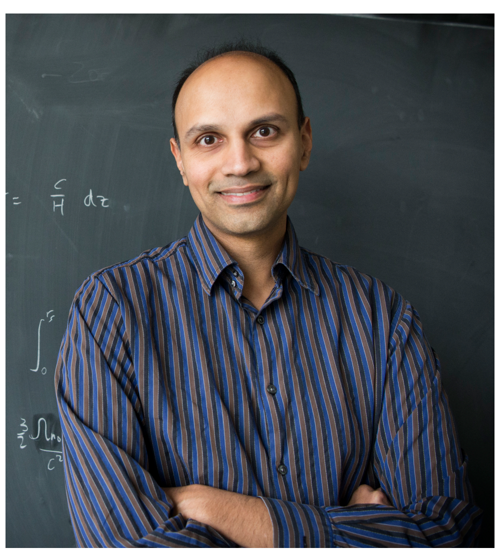
C02: Team members

Shin'ichiro Ando

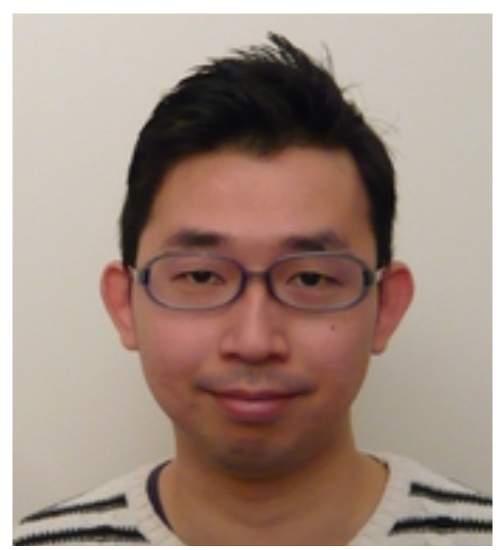
Masato Shirasaki

Atsushi Taruya

Theory



Neal Dalal



Takahiro Nishimichi

Takashi Okamoto

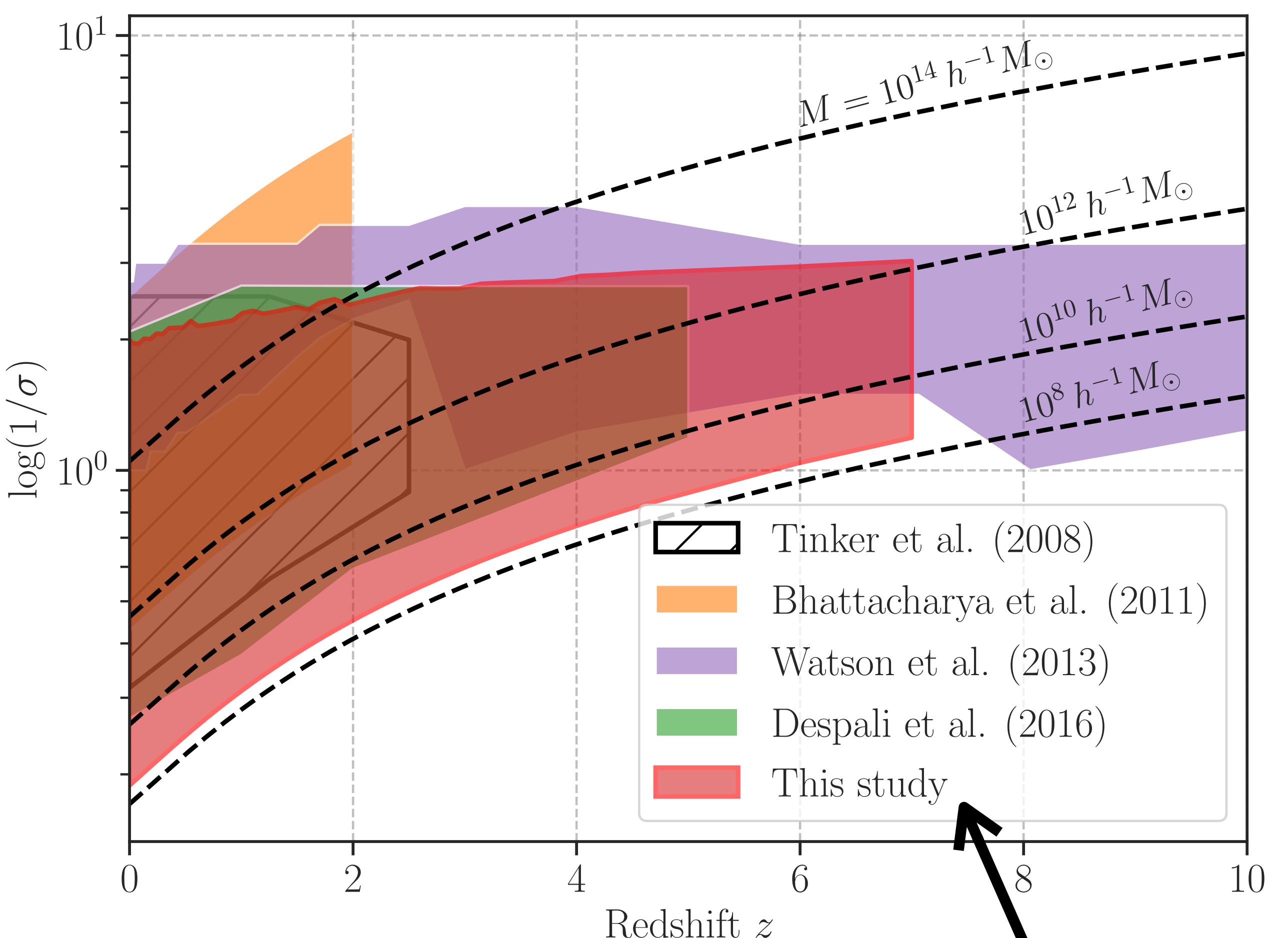
Simulations

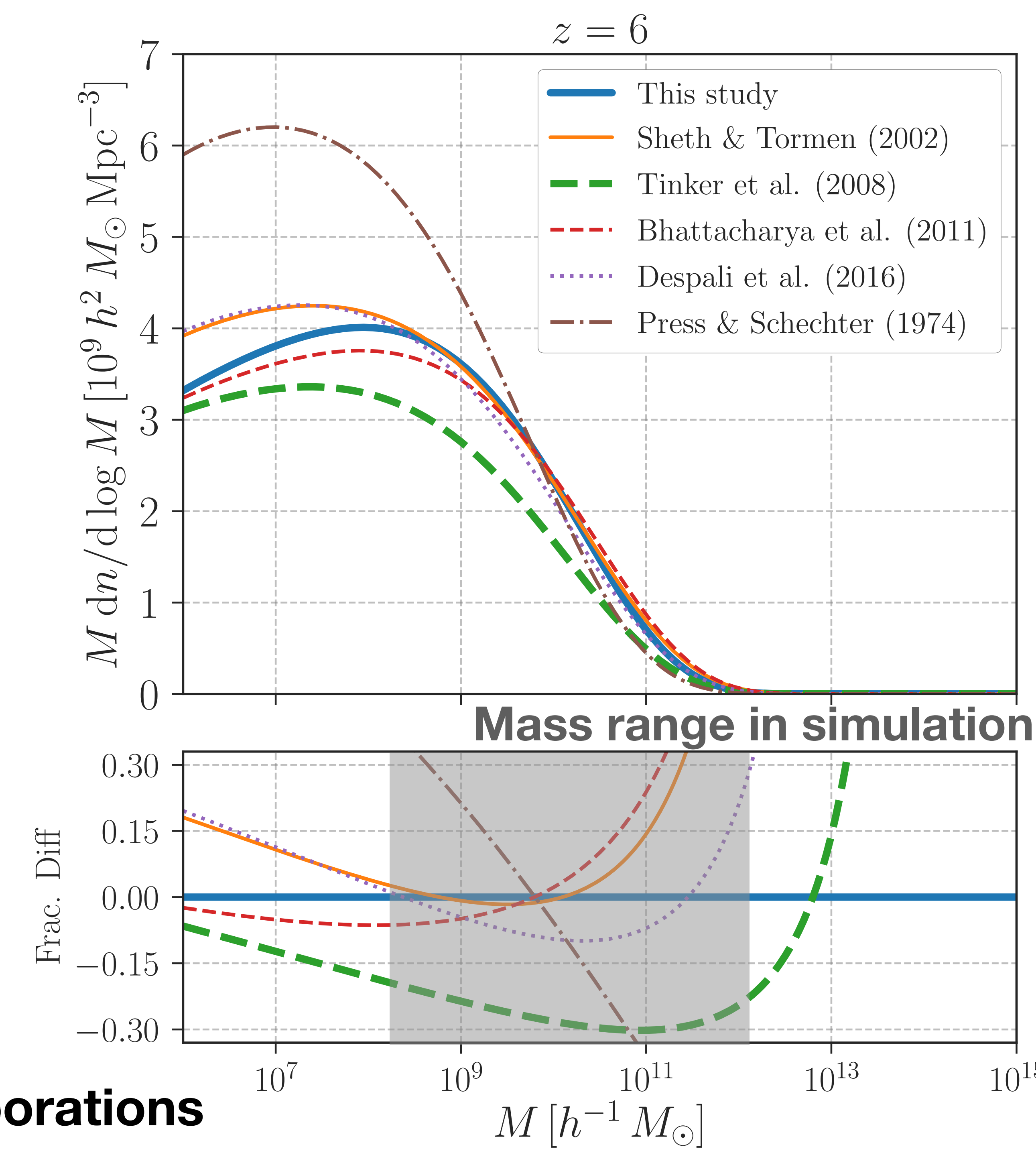
+ 2 postdoctoral researchers

Calibration of halo mass functions

Shirasaki, Ishiyama, Ando, in preparation

For set out a better (CDM) baseline for constraining other dark matter models





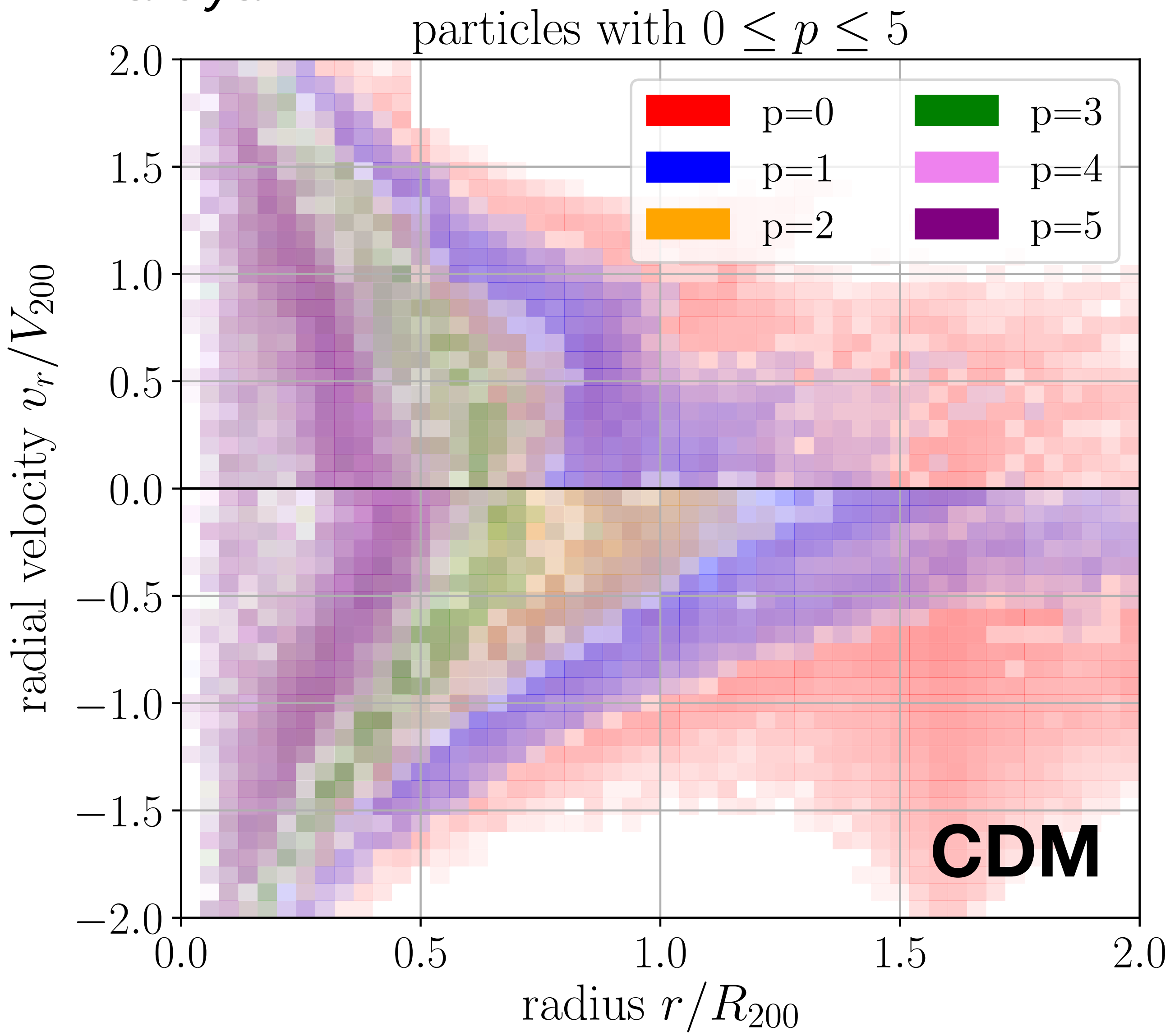
117 high-res simulations from nu2gc collaborations

(https://hpc.imit.chiba-u.jp/~nngc/index.html)

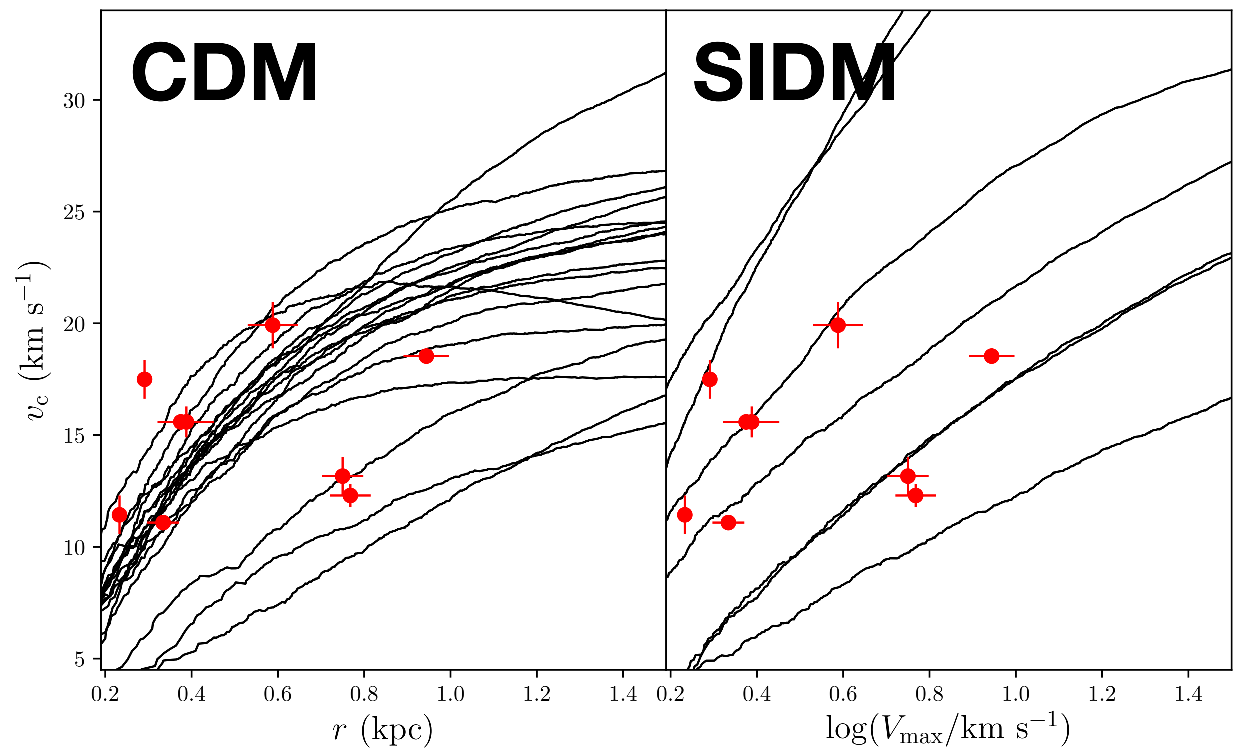
+ lensing constraints on, e.g., WDM (Dalal)

Phase-space distribution

Taruya+



Okamoto+



Understanding the phase-space structure of subhalos and dependence on dark matter models using simulations + machine learning (Nishimichi)

Prospects

- Small scale distribution of dark matter is essential in discriminating different particle dark matter candidates
- C02 will also provide important information for researches carried out by the other groups
- We base our theoretical studies on benchmark models for CDM/WIMP; there still are many tasks to make the models more accurate
- Simulations will incorporate various dark matter candidates as well as baryonic physics
- We are looking forward to hearing many unique ideas on structure formation through open-solicited programs