FY2023

"What is dark matter? - Comprehensive study of the huge discovery space in dark matter"

2024. 3. 8

Semi-analytic description of halo structures and its application

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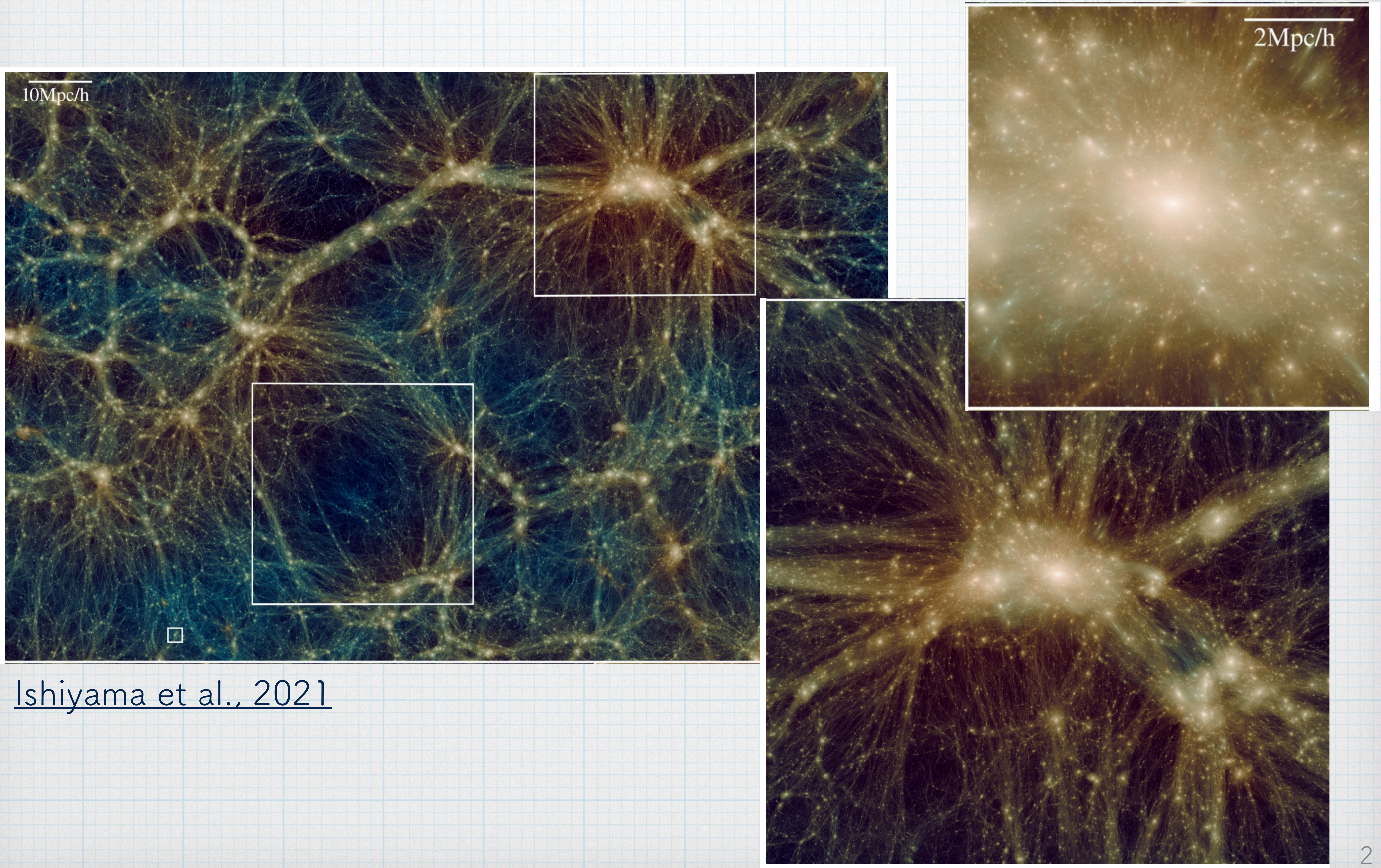
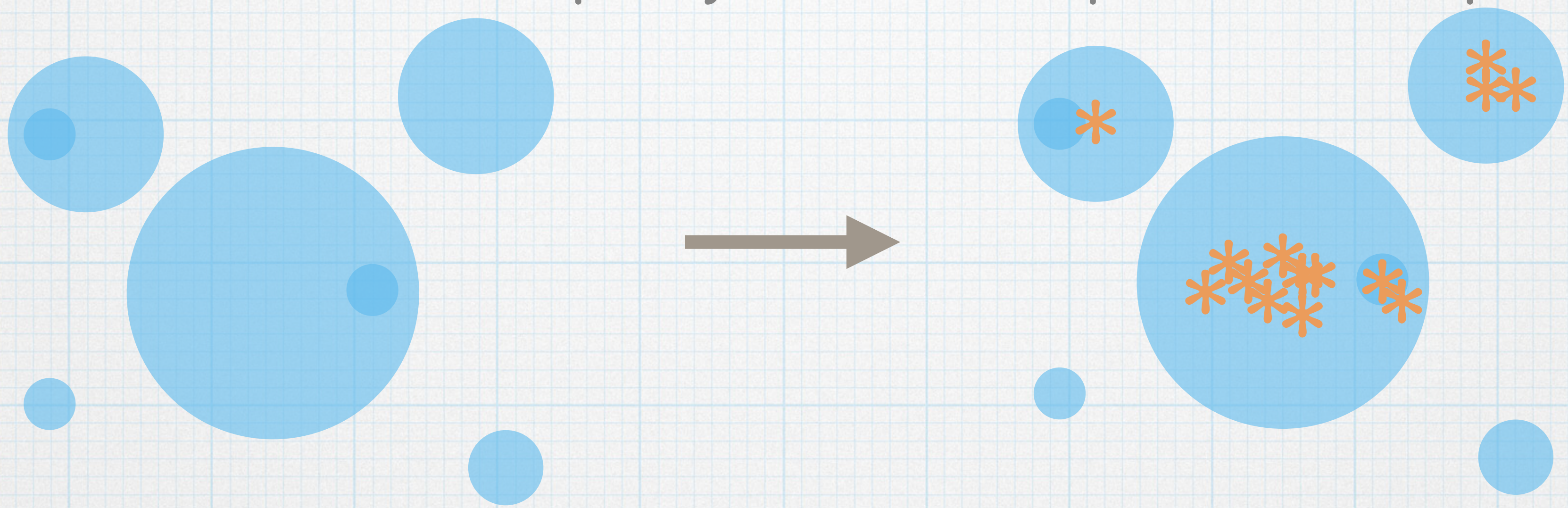
Structure of the Universe



Ishiyama et al., 2021

Halo as a building block

after the matter-radiation equality → after photon decoupling



DM structure ↕ **halo**

baryon structure ↕ **galaxy**

subhalo

satellite galaxy

from $m \sim \mathcal{O}(10^{-6}? - 10^{16})M_{\odot}$, $z \sim (z_{eq}, 0)$

Hint for DM from halos

- How the density profile looks like?
- How many subhalos does the Milky Way have?
- How massive the minimum halo is?
- How about the connection to the cosmological model?
- How dense subhalos can be at $z = 0$?

  And can we expect sufficient flux from DM annihilations (or decays)?
- What about the structure around the solar system?
- …

from $m \sim \mathcal{O}(10^{-6}? - 10^{16}) M_{\odot}$, $z \sim (z_{\rm eq}, 0)$

Semi-analytic modeling

Merit

- cost-effective
- multi-scale coverage ($m \sim \mathcal{O}(10^{-6}? - 10^{16}) M_\odot$)
- multi-redshift coverage ($z = 0 \sim z_{\rm eq}$)

Applicability

- prediction of subhalo number count
- quantification of the source of the scatter
- equipping halo probes for cosmological studies
- reduction of J-factor uncertainty

Extended Press-Schechter

- overdensity collapse to form halo
- two parameters:
  collapse redshift ($\delta(z)$) & mass scale ($\sigma(M)$)
- distribution function

$$f(\sigma^2(m), \delta(z+\Delta z) \,|\, \sigma^2(M), \delta(z)) = \frac{1}{\sqrt{2\pi}} \frac{\delta(z+\Delta z) - \delta(z)}{[\sigma^2(m) - \sigma^2(M)]^{3/2}} \exp\left[-\frac{(\delta(z+\Delta z) - \delta(z))^2}{2(\sigma^2(m) - \sigma^2(M))} \right]$$

fraction of halo of which mass was m at $z + \Delta z$ in M at z

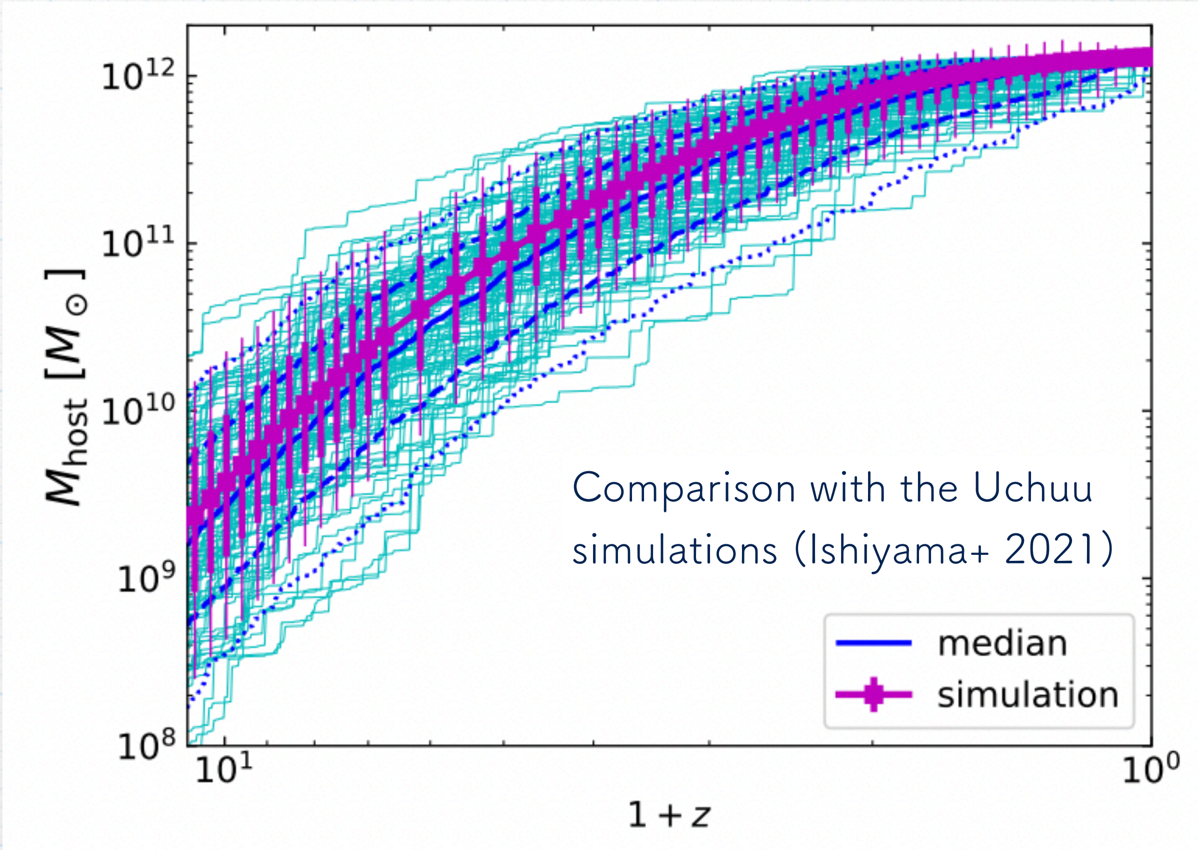
evolution history of $M(z)$

- distribution function

$$f(\sigma^2(m), \delta(z+\Delta z) \,|\, \sigma^2(M), \delta(z)) = \frac{1}{\sqrt{2\pi}} \frac{\delta(z+\Delta z) - \delta(z)}{[\sigma^2(m) - \sigma^2(M)]^{3/2}} \exp\left[-\frac{(\delta(z+\Delta z) - \delta(z))^2}{2(\sigma^2(m) - \sigma^2(M))}\right]$$

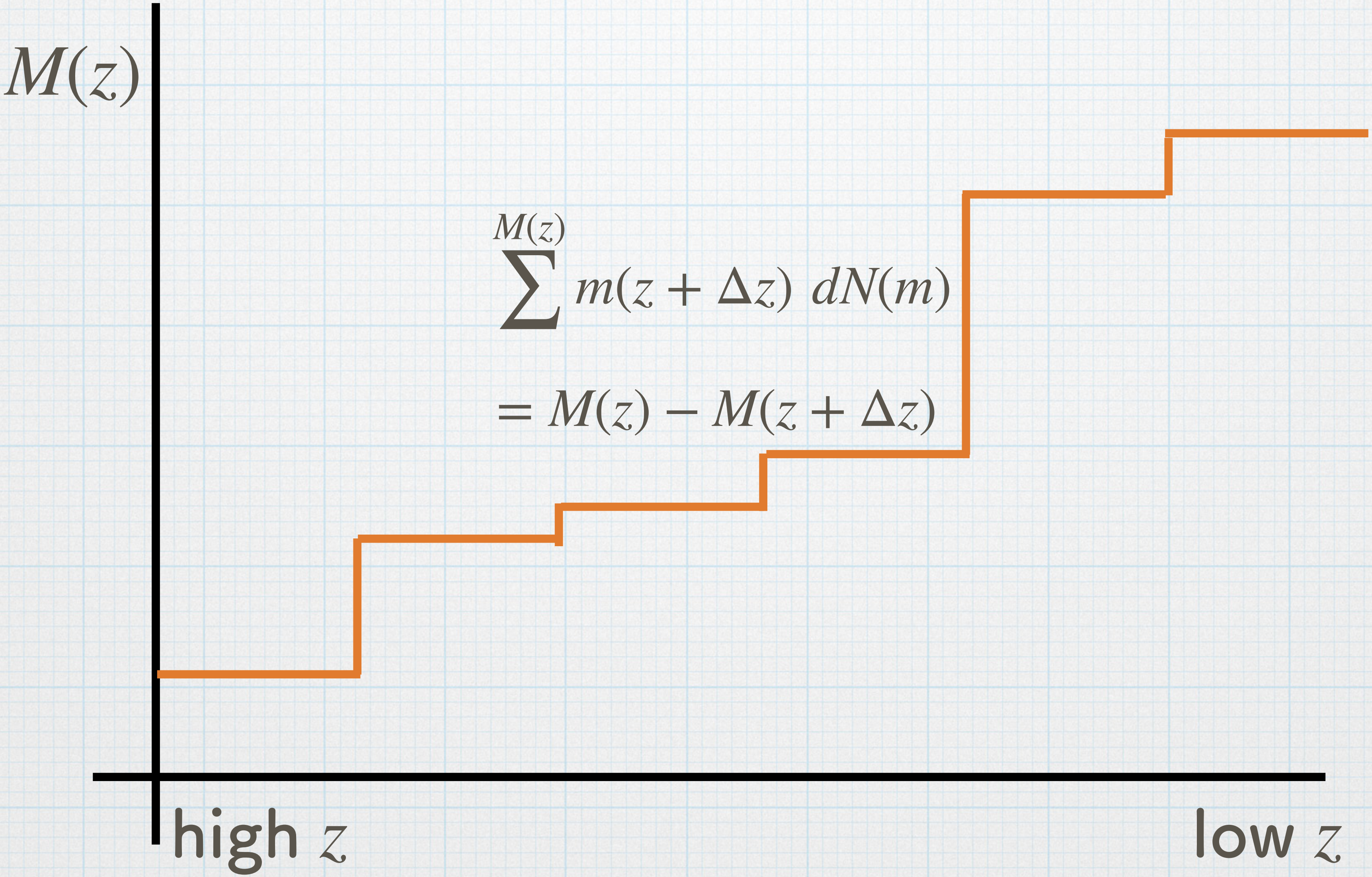
$^{\exists} m(z+\Delta z) > M(z)/2$

⇒ **unique progenitor**



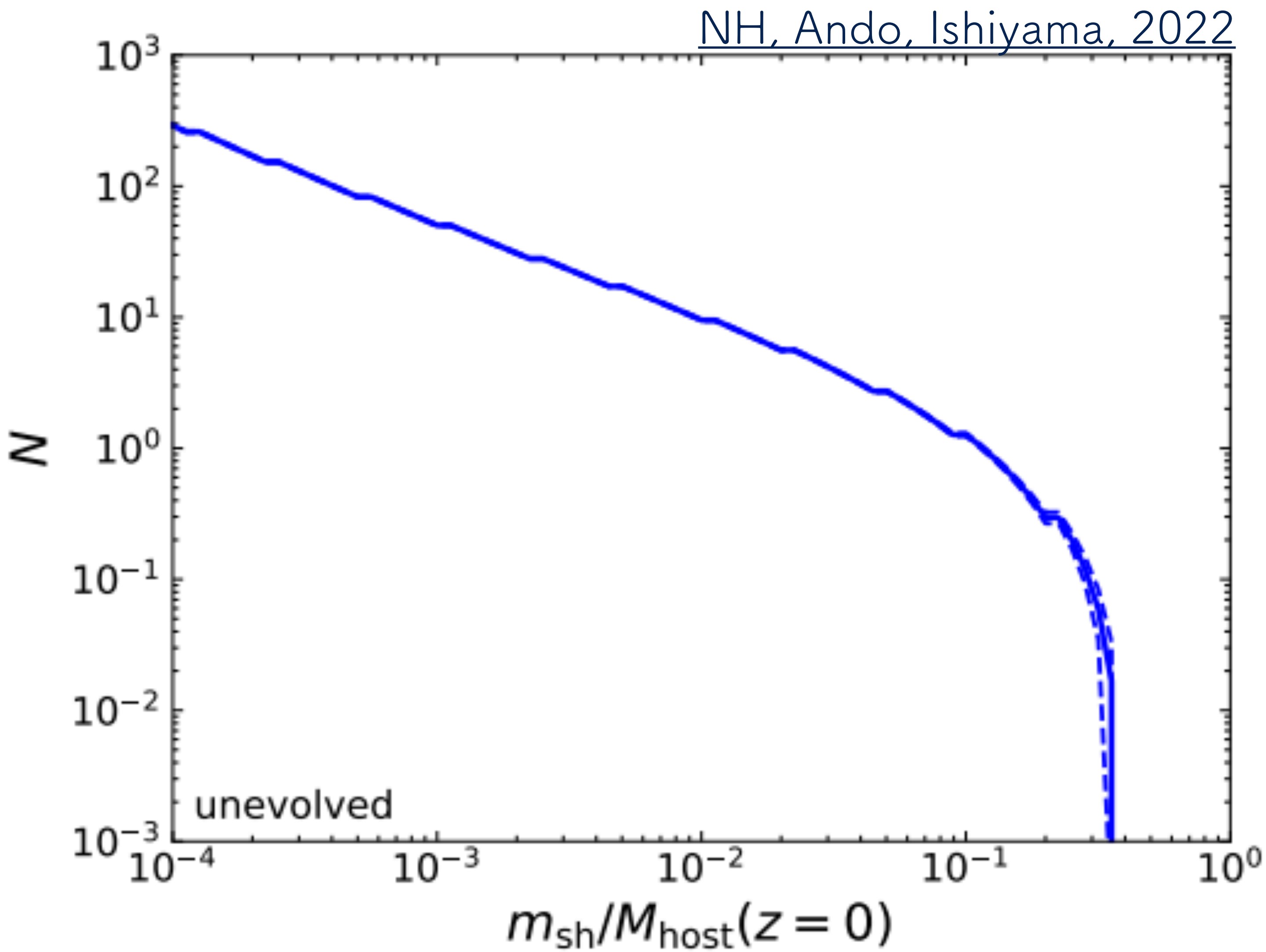
NH, Ando, Ishiyama, 2022

unevolved mass function



integrate in z for obtaining the mass function at $z=0$

unevolved mass function



evolved mass function

- # distribution at accretion: given (unevolved mass function)

- tidal effect: determined by the host mass & redshift

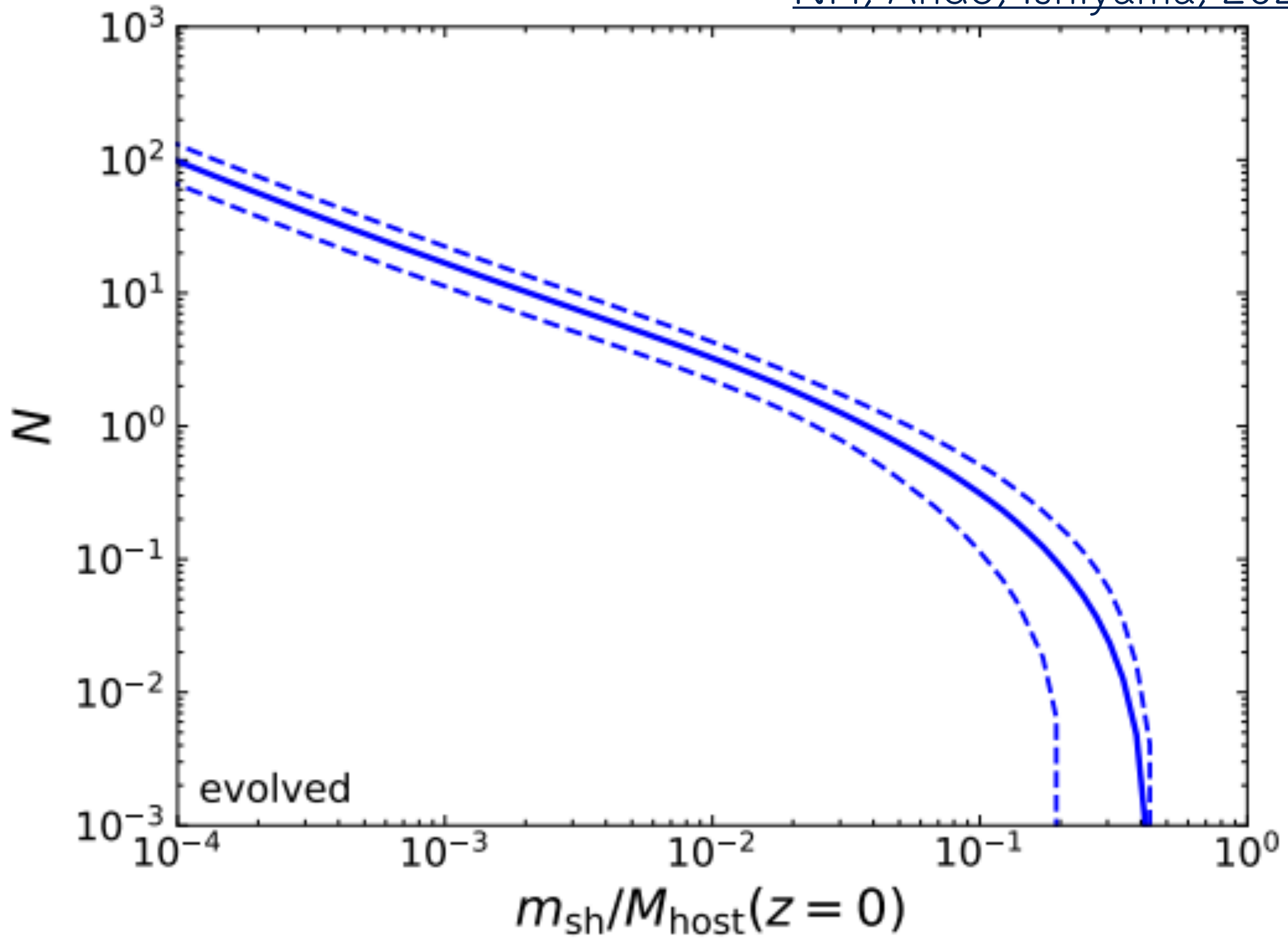
$$\dot{m}(z) = -A(M,z)\frac{m}{\tau_{\rm dyn}}\left(\frac{m}{M}\right)^{\zeta(M,z)}$$

different host evolution ↔ different tidal evolution

evolved mass function

intrinsic scatter only

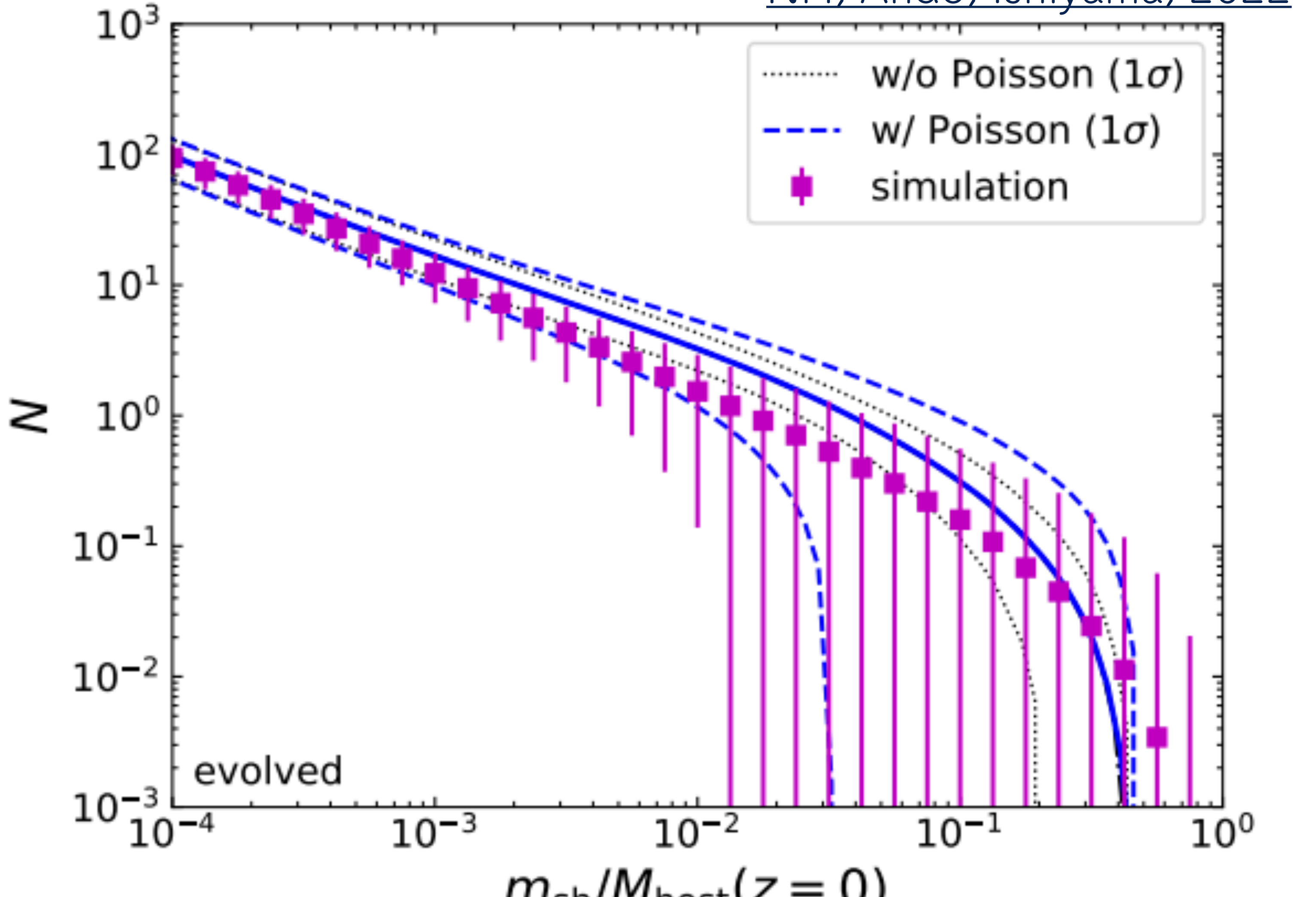
NH, Ando, Ishiyama, 2022



evolved mass function

Poisson effect included

NH, Ando, Ishiyama, 2022



Examples of applications

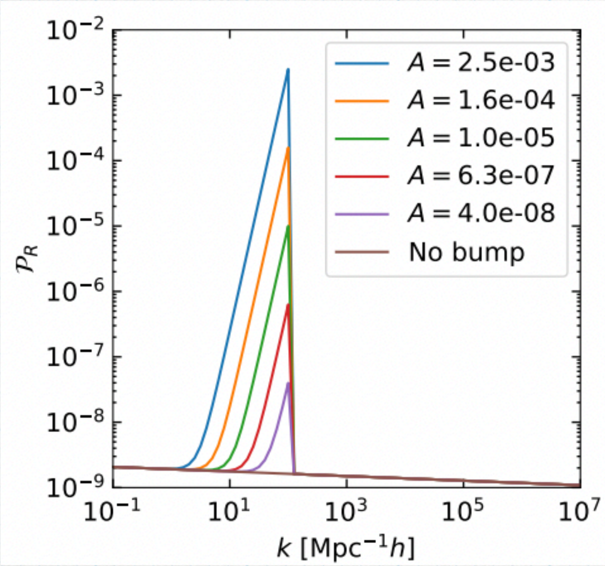
Assumptions & Approximations

- NFW profile for both the host and subhalos
  - $\rho(r) = \rho_s \left(r/r_s\right)^{-1} \left(1 + r/r_s\right)^{-2}$
  - $(\rho_s, r_s) \leftrightarrow (V_{\max}, r_{\max})$
- tidal mass-loss at the pericenter dominates
- concentration-mass relation
- scaling of the profile parameter $(V_{\max}, r_{\max})$ to the mass ratio before and after the tidal evolution
- galaxy formation condition determined by $V_{\max}$

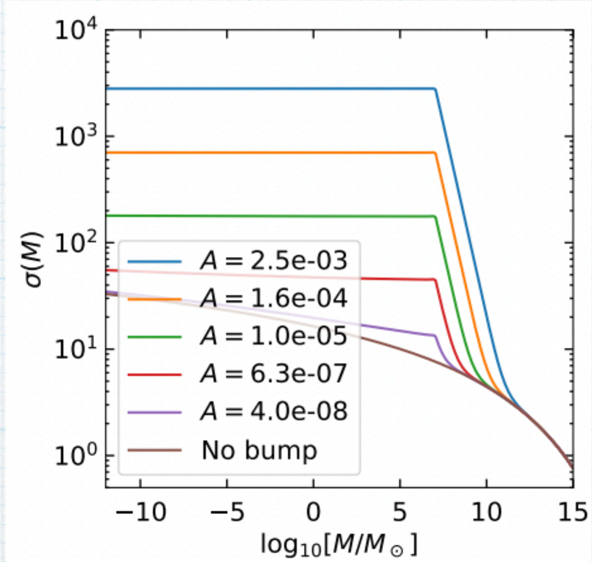
Ando, NH, Ishiwata, 2022

1. Test for cosmology

curvature perturbation $\mathscr{P}_R(k) = \mathscr{P}_R^{(0)} + \mathscr{P}_R^{\mathrm{bump}}$

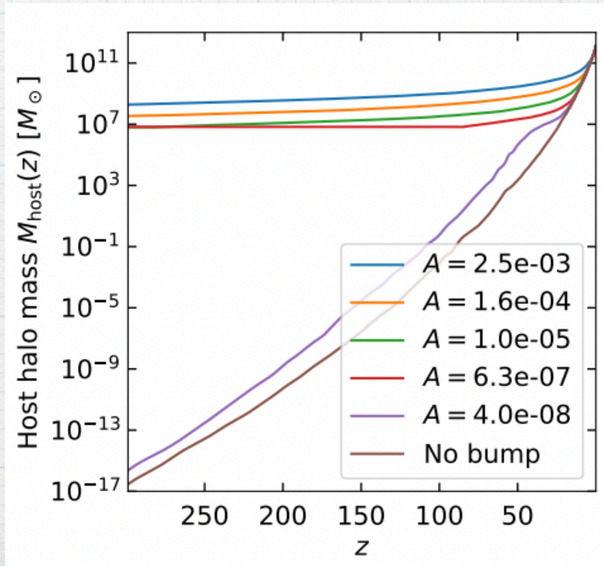


different $P(k)$



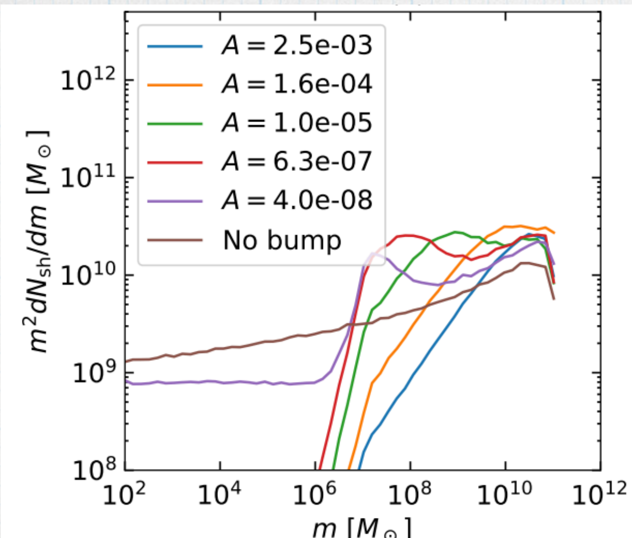
different $\sigma(M)$

different host evolution



different subhalo mass function

& satellite galaxy count



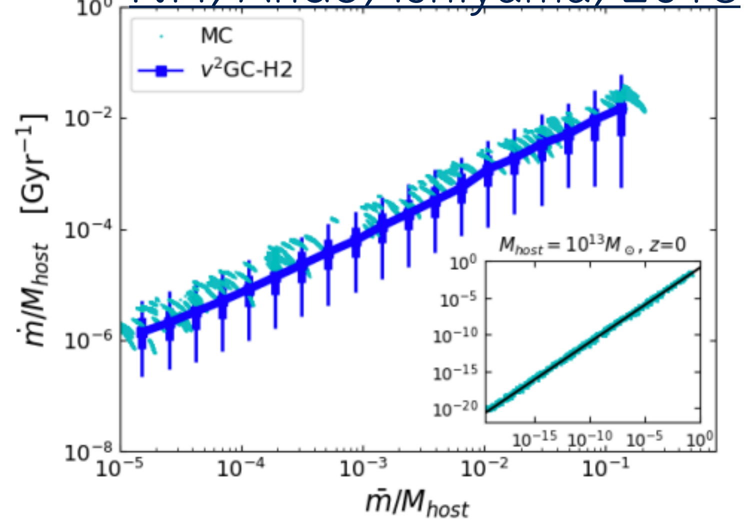
Process

input: $\delta(z)$ & $\sigma(M)$ (or $\mathscr{P}(k)$)

1. host halo evolution: using EPS formula
   $^\exists m(z+\Delta z) > M(z)/2 \Rightarrow$ unique progenitor
2. subhalo mass function at accretion:
   normalization at each redshift→integration to $z=0$
3. tidal evolution of subhalos:

$$\dot{m}(z) = -g\frac{m}{\tau_{\rm dyn}}\left(\frac{m}{M(z)}\right)^{\zeta}$$

NH, Ando, Ishiyama, 2018



4. subhalo-satellite galaxy connection

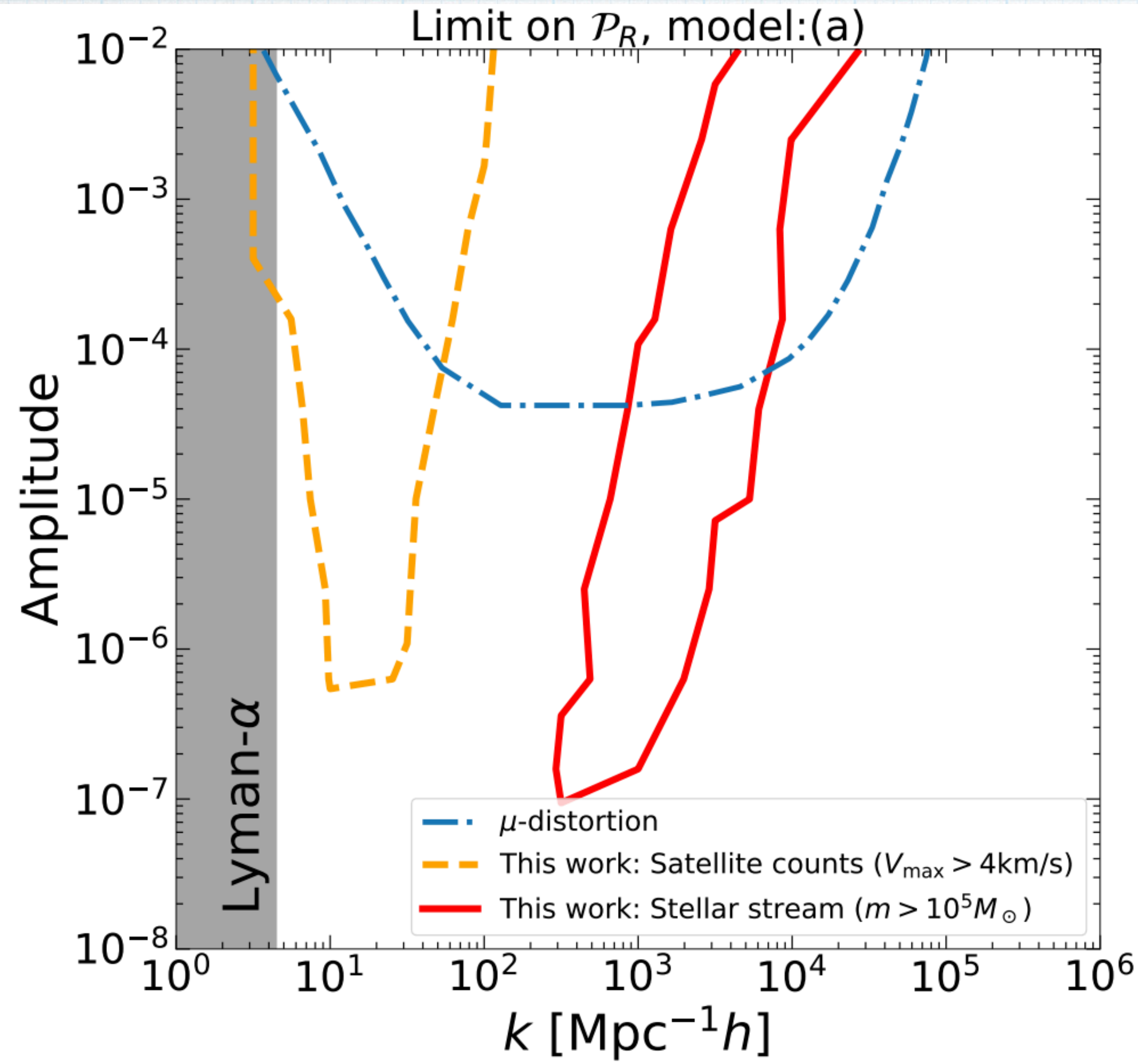
input: $\delta(z)$ & $\sigma^2(M) = \int d\ln k \frac{k^3}{2\pi^2}P(k)W^2(kR)$

Ando, Hiroshima, Ishiwata, 2022

Exclusion of Bump

$$\mathcal{P}_R(k) = \mathcal{P}_R^{(0)} + \mathcal{P}_R^{\rm bump}, \quad \mathcal{P}_R^{\rm bump} = \begin{cases} (A - \mathcal{P}_R^{(0)}(k_b))\left(\frac{k}{k_b}\right)^{n_b} & (k \le k_b) \\ 0 & (k > k_b) \end{cases}$$

$(n_b = 4)$



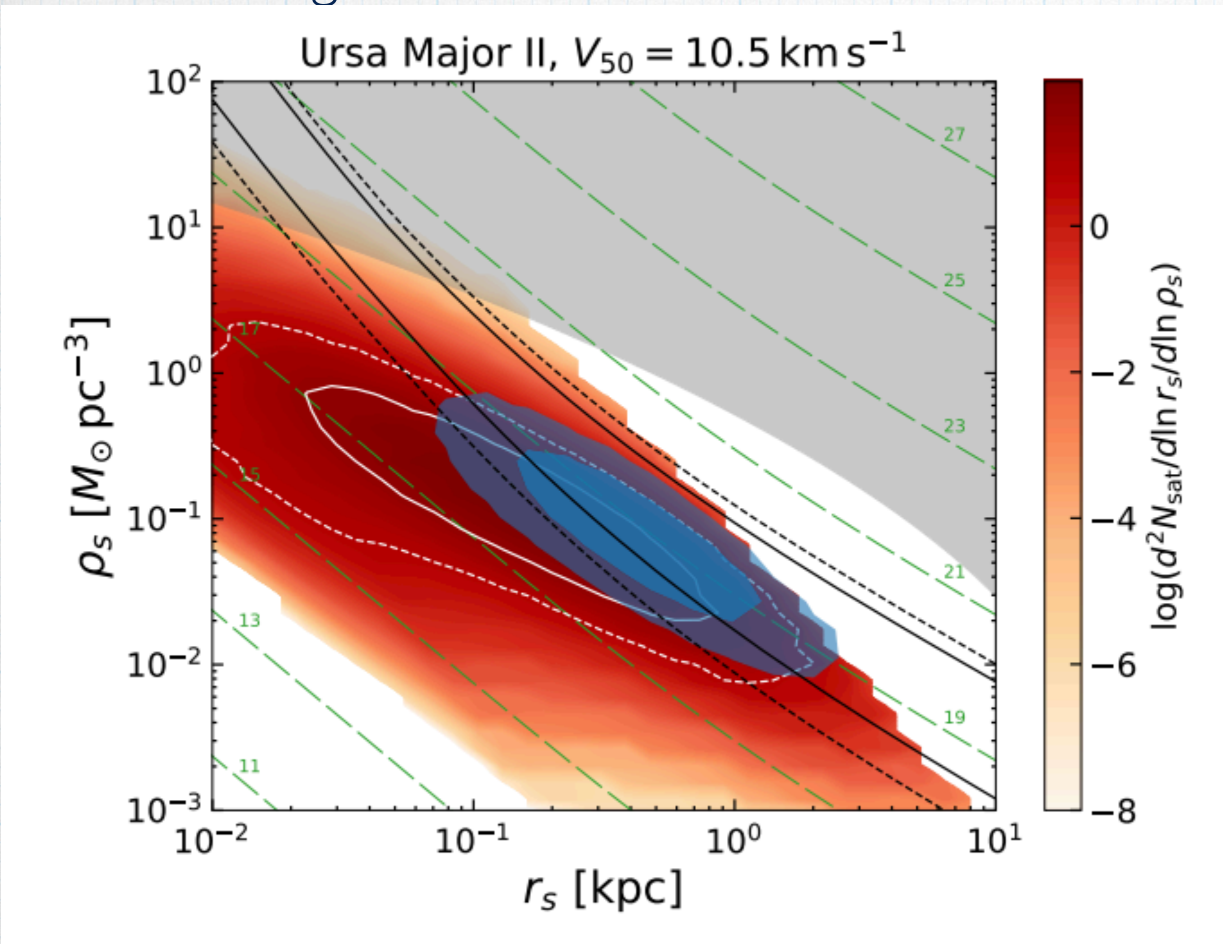
- condition from subhalo number counts:

  $N(V_{\rm max} > 4{\rm km/s}) > 94$

- requirement to satisfy GD-1 stream observation

subhalo profile estimate

Ando, Geringer-Sameth, NH, Hoof, Trotta, Walker, 2020

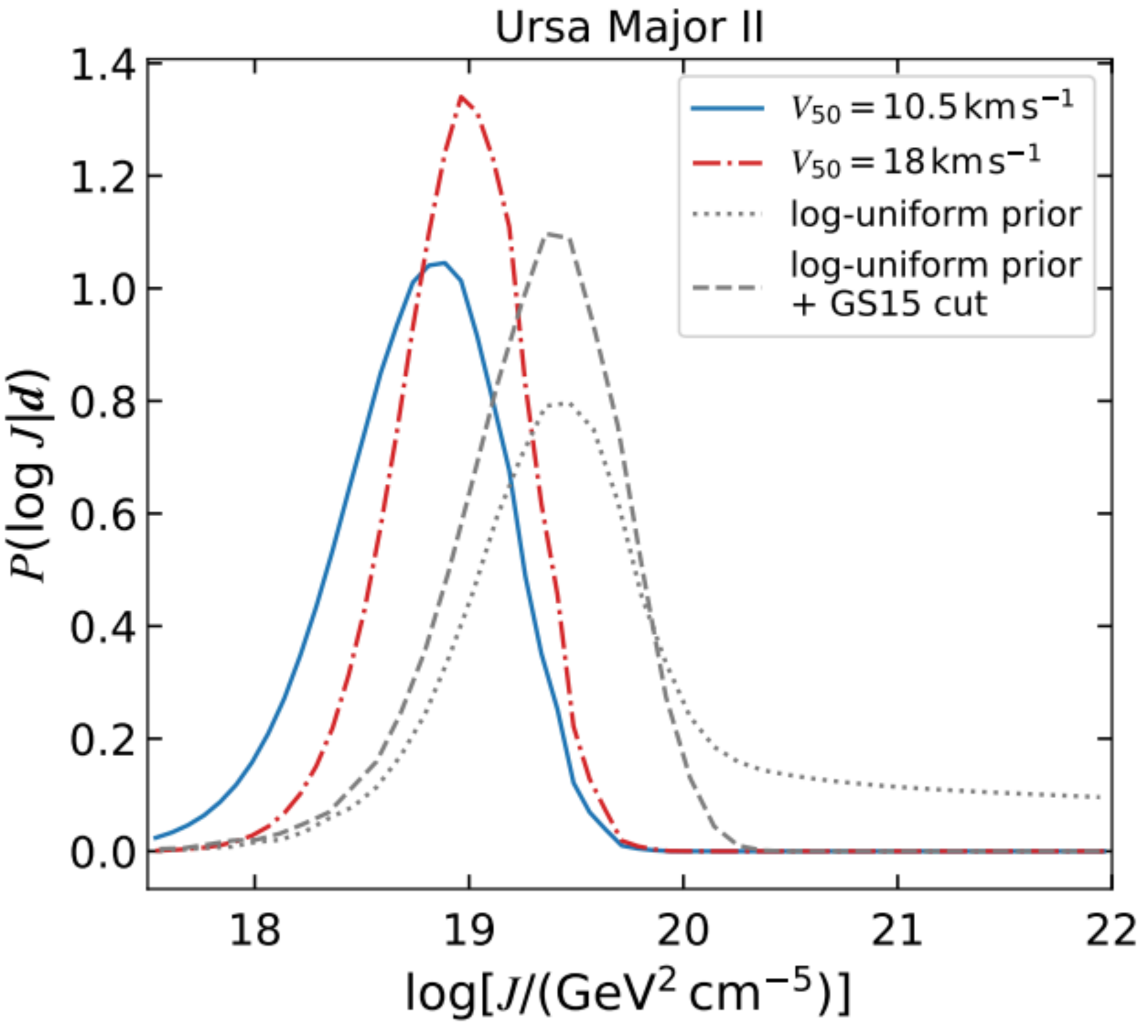


- red: prediction of satellite counts
- **white: "informative" prior distribution**
- black: likelihood
- blue: posterior distribution

making use of the evolution history of DM halos to obtain good priors for the Milky Way's satellites

Reduction of uncertainty

Ando, Geringer-Sameth, NH, Hoof, Trotta, Walker, 2020



$$J = \int_{\Delta\Omega=0.5^\circ} d\Omega \int_{l.o.s} \rho_{\mathrm{DM}}^2(r)ds$$

- The J-factor shifts to a lower value.
- The probability distribution of the J-factor gets sharper.

Summary

Summary

- Properties of DM halo provide us with hints about the nature of DM.
- We can study halos and its implications in a scale-free way by adopting semi-analytic scheme.
- Our scheme enables us to directly connect subhalo evolution to the evolution history of the host.
- Cost-effective calculations of subhalos helps us to investigate issues around, such as cosmology and J-factor uncertainties.
- Further extensions are now on-going.