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Halo as a key to indirect DM searches

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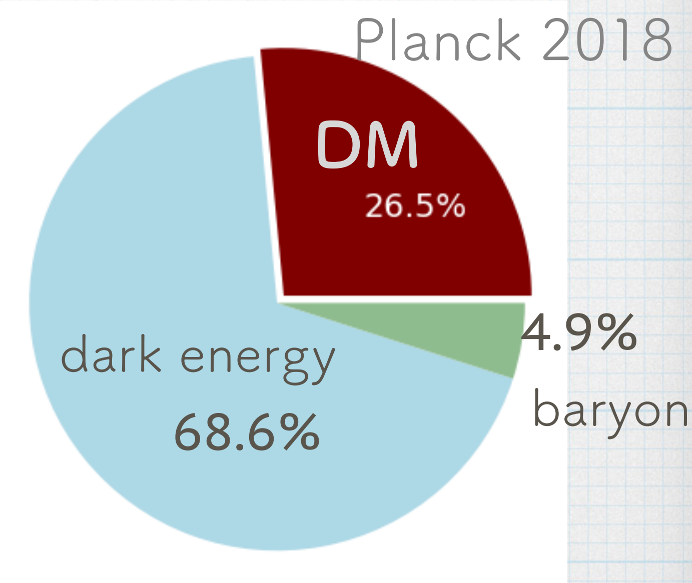
Contents:

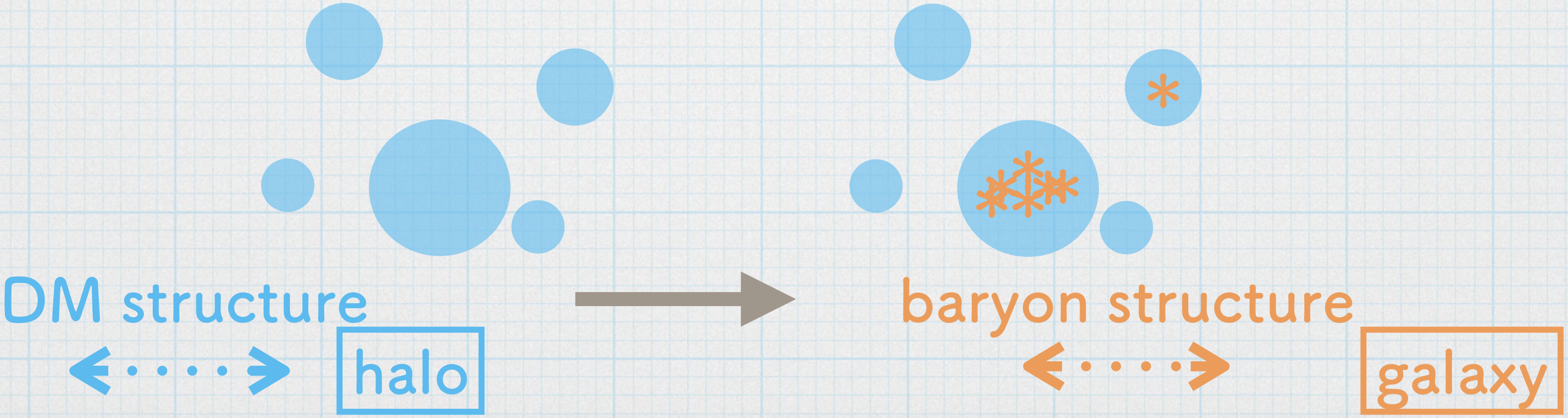
1. Hints of dark matter (DM)

Motivation for DM

DM=non-baryonic matter in the Universe of $\Omega_{\rm DM}h^2 \sim 0.12$

- **motivation**
  - galaxy cluster
  - rotation curves
  - bullet cluster
  - …
  - **structure formation (CMB)**





Property

- feel gravity
- cold (warm, hot)
- stable (or lifetime longer than cosmic age)
- (almost) neutral
- (almost) invisible

Property

- feel gravity

  because it should form halos and provide potential
- cold (warm, hot)

  in order not to erase small-scale fluctuations
- stable (or lifetime longer than cosmic age)

  because otherwise it should decay
- (almost) neutral

  in order to start structure formation before decoupling
- (almost) invisible

  since we have not seen electromagnetic signatures

Candidates

- Weakly Interacting Massive Particle (WIMP)
- Strongly/self- interacting massive particle (SIMP)
- sterile neutrinos
- axion and/or axion-like particle (ALP)
- primordial black hole (PBH)
- …

particle?

mass range?

$$(10^{-22}\ \mathrm{eV} \lesssim m \lesssim 10^{5} M_{\odot})$$

interaction type?

coupling strength?

We can rely on the facts that…

- Our galaxy cannot exist without gravitational potential of DM
- DM should feel gravity

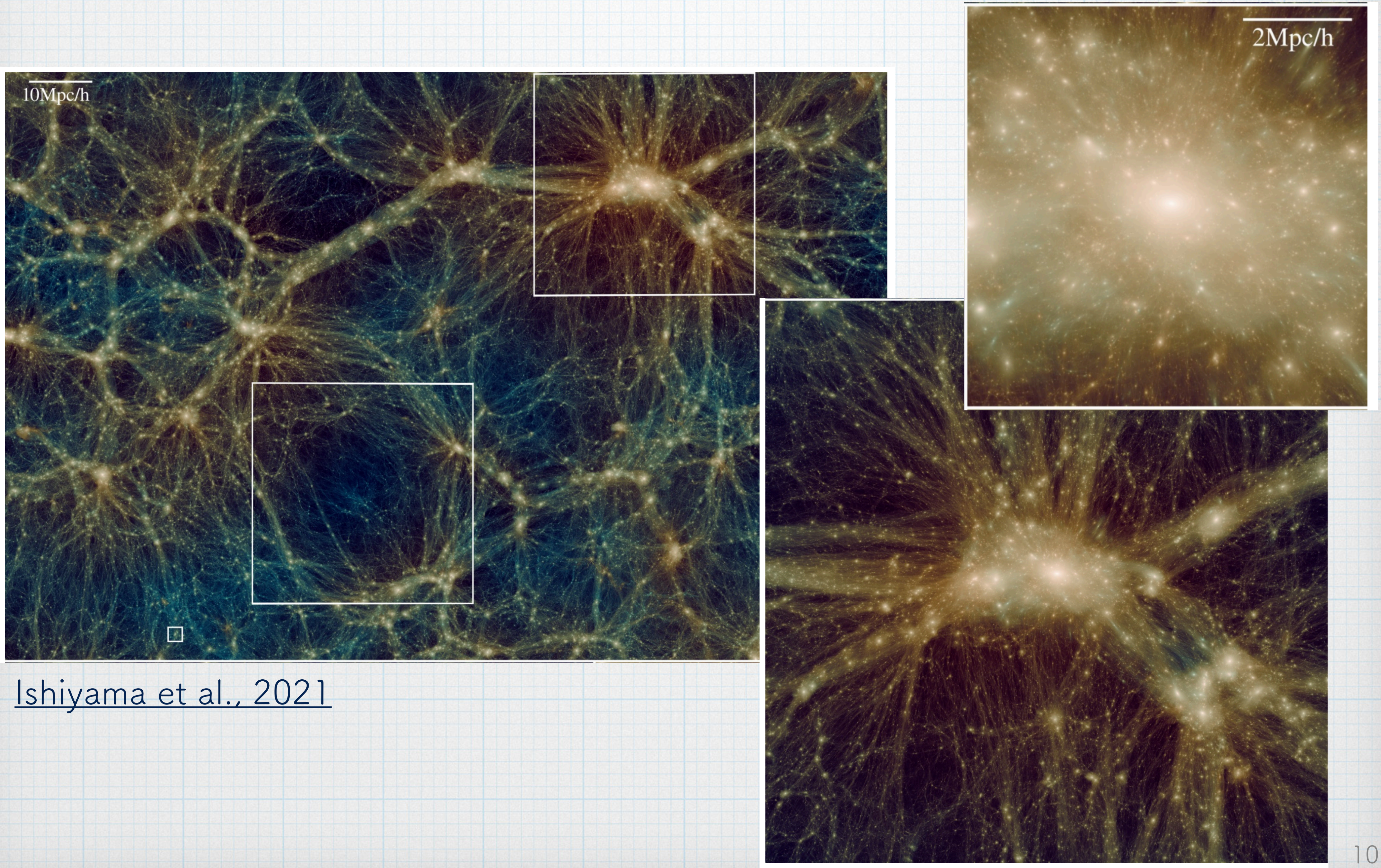
gravitational interaction → formation & evolution of halos

Investigation of halo physics can give us model-independent insights about the nature of DM.

(+ It should be indicative for various DM searches)

2. Physics of DM halo

cold DM halo structure



Ishiyama et al., 2021

characteristics of halos

- redshift range $z_{\rm eq}\ -\ 0$
- mass range: $\mathcal{O}(10^{-6})M_\odot?\ -\ \mathcal{O}(10^{16})M_\odot$

mass function $\dfrac{dN}{dm} = m^{-\alpha}\quad (\alpha \sim 2)$

- hierarchical structure formed through accretion, merger, and tidal interaction
- density profile (e.g. NFW $\rho(r) = \rho_s \left(\dfrac{r}{r_s}\right)^{-1} \left(1+\dfrac{r}{r_s}\right)^{-2}$)

DM halo for DM search

- density profile at Galactic Center (G.C.)
- density profile of dwarf spheroidal galaxies (dSphs)
- density profile near the solar position
- subhalo number count
- minimum mass of the halo
- …

DM halo for DM search

- density profile at Galactic Center (G.C.)
- **density profile of dSphs**

→ indirect search

- density profile near the solar position

→ direct search

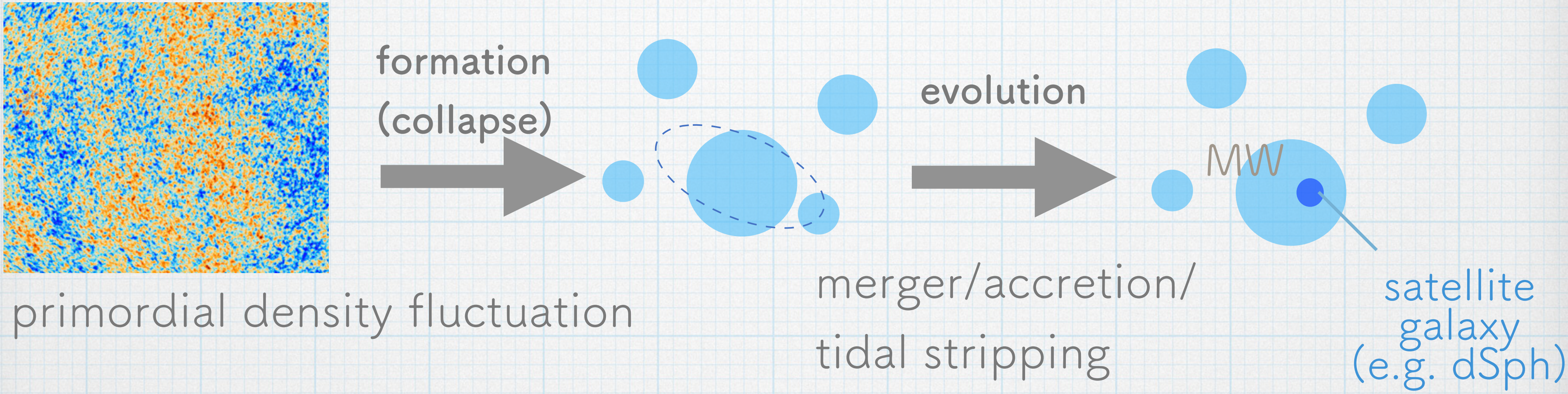
- subhalo number count
- minimum mass of the halo in galaxy

→ particle nature

- …

halo connects particle nature of DM to observables

Story of DM halo



formation
(collapse)

evolution

MW

merger/accretion/
tidal stripping

satellite
galaxy
(e.g. dSph)

primordial density fluctuation

- **process driven by gravitational interaction:**

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

- **halo evolution history remains in current galaxy structures**

semi-analytical scheme works in covering wide scales

halo formation & accretion

Extended Press-Schechter theory

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

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

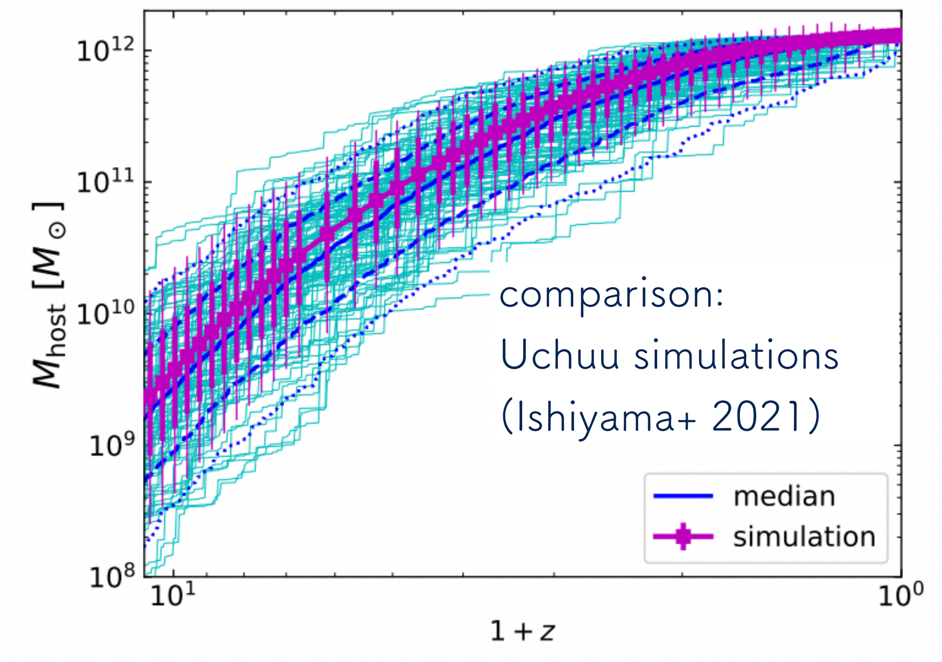
- halo formation
  = collapse of overdensity
- two parameters:
  - collapse redshift $\delta(z)$
  - mass scale $\sigma(M)$

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

⇒ **unique progenitor**

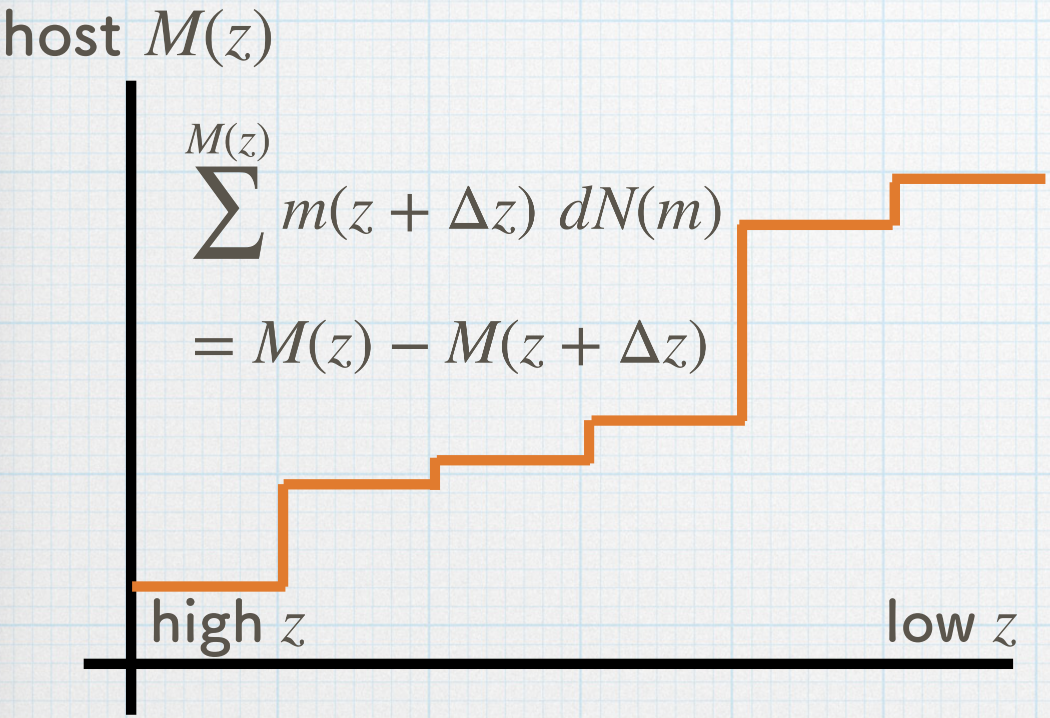
(remaining = subhalo accretion → tidal evolution)

NH, Ando, Ishiyama, 2022



comparison:
Uchuu simulations
(Ishiyama+ 2021)

unevolved mass function



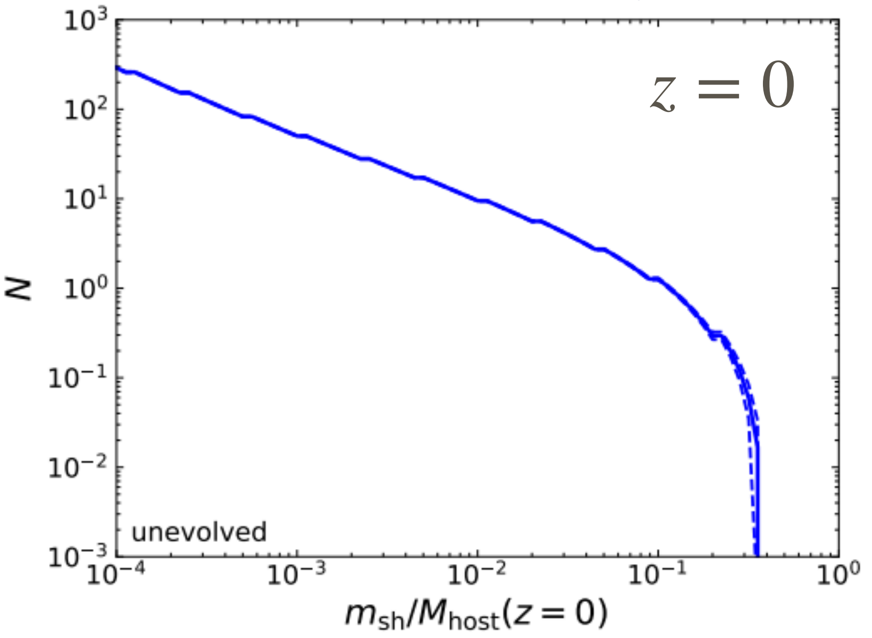
$$\sum^{M(z)} m(z+\Delta z)\ dN(m)$$

$$= M(z) - M(z+\Delta z)$$

normalization condition

from host evolution

NH, Ando, Ishiyama, 2022

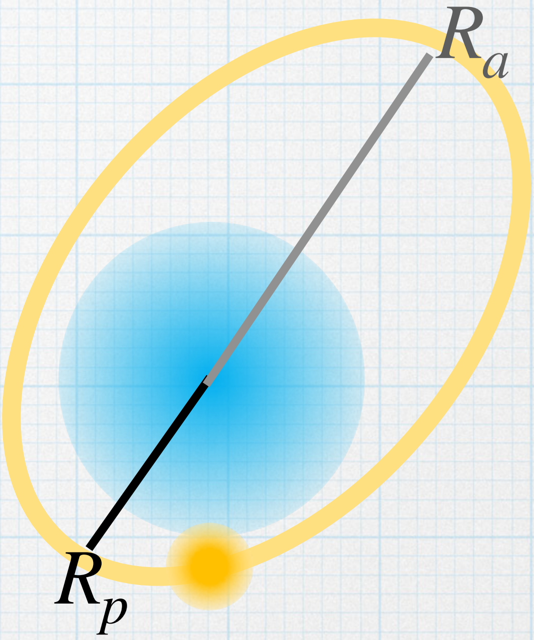


unevolved mass function

as the sum of ones at each z

mass increment of the host = sum of accreted halo mass

after accretion: tidal evolution



1. mass-loss rate: $\dot{m} = \left[m - m(<r_t)\right] T^{-1}$
2. host potential

$$\Phi(R) = -V_{\rm vir}^2 \frac{\ln\left[1 + c_{\rm vir}^{\rm host} R/R_{\rm vir}\right]}{f(c_{\rm vir}^{\rm host}) R/R_{\rm vir}}, \; c_{\rm vir} = r_{\rm vir}/r_s$$

3. pericenter(R_p) & apocenter(R_a)

$$R^{-2} + 2\left[\Phi(R) - E\right] L^{-2} = 0$$

4. orbital period:$T = 2\int_{R_p}^{R_a} \frac{dR}{\sqrt{2(E - \Phi(R)) - L^2/R^2}}$
5. truncation radius

$$r_t = R_p \left[\frac{m(<r_t)\,.\,M(<R_p)}{2 + L^2(R_p G M(<R_p))^{-1} - d\ln M/d\ln R\,|_{R_p}}\right]^{1/3}$$

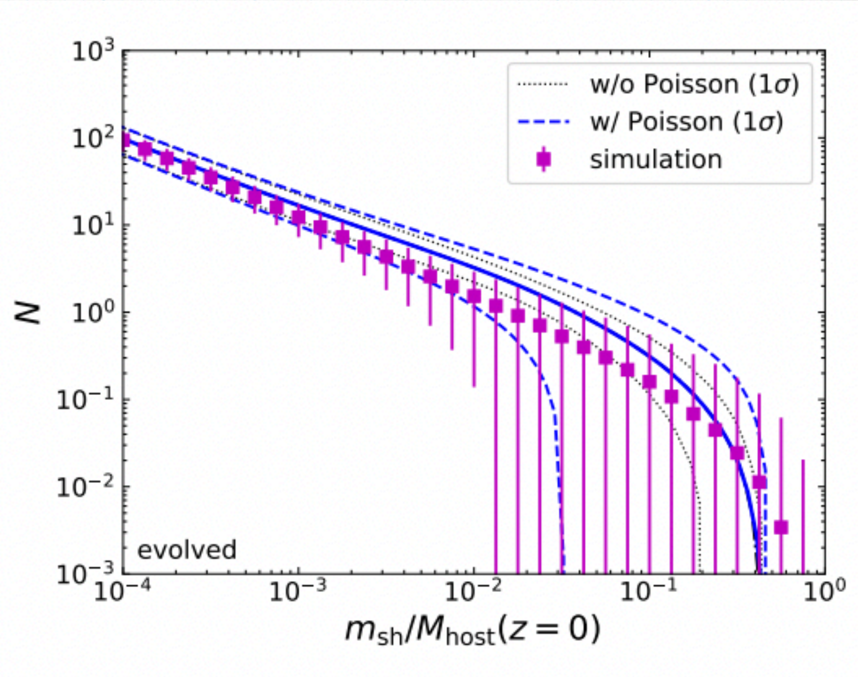
evolved mass function

NH, Ando, Ishiyama, 2018

- NFW profiles for host & subhalos

- tidal stripping rate evaluated at the pericenter

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

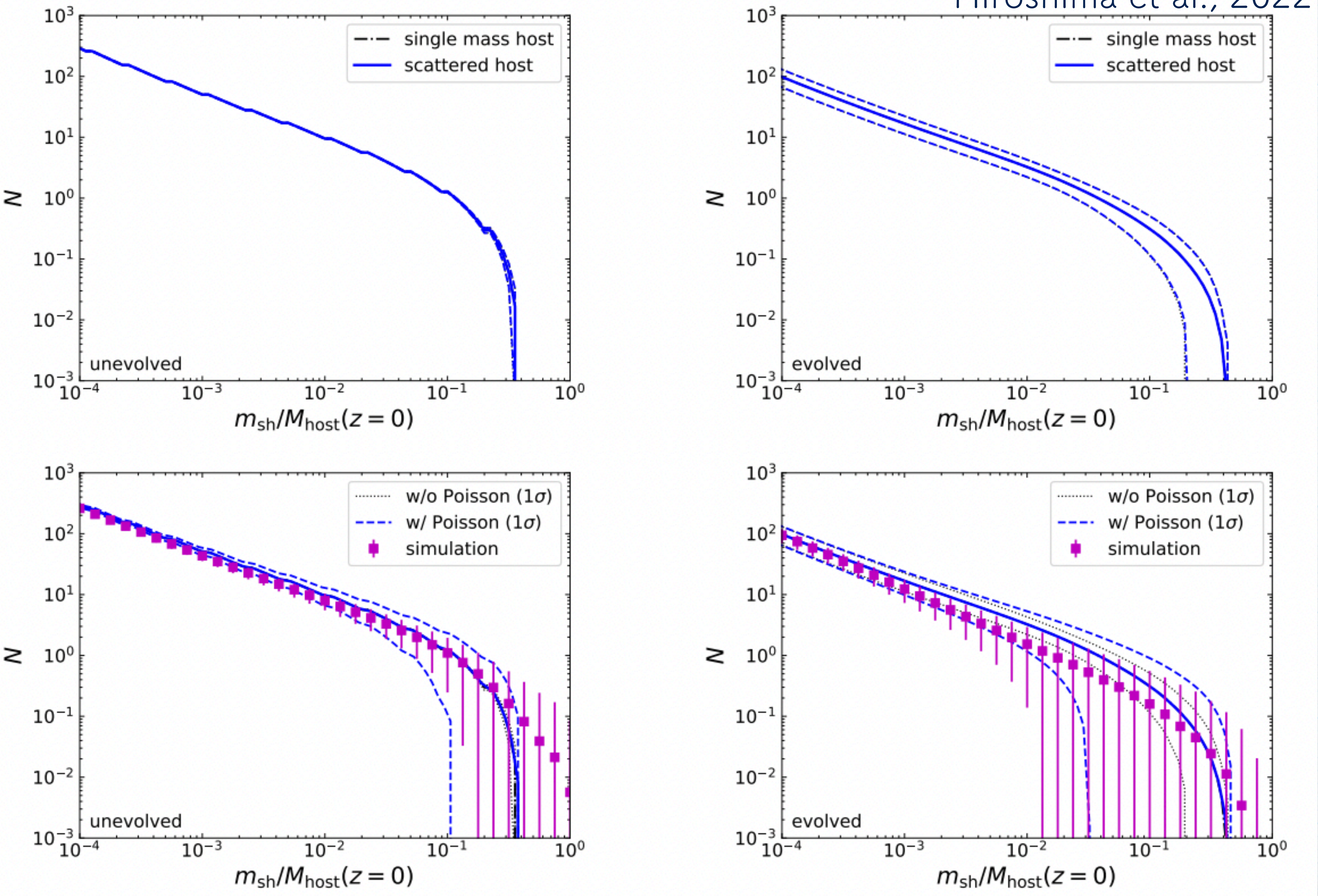


- Evolution of the density profile parameters can be a function of lost-mass
  → estimate of the current subhalo structures

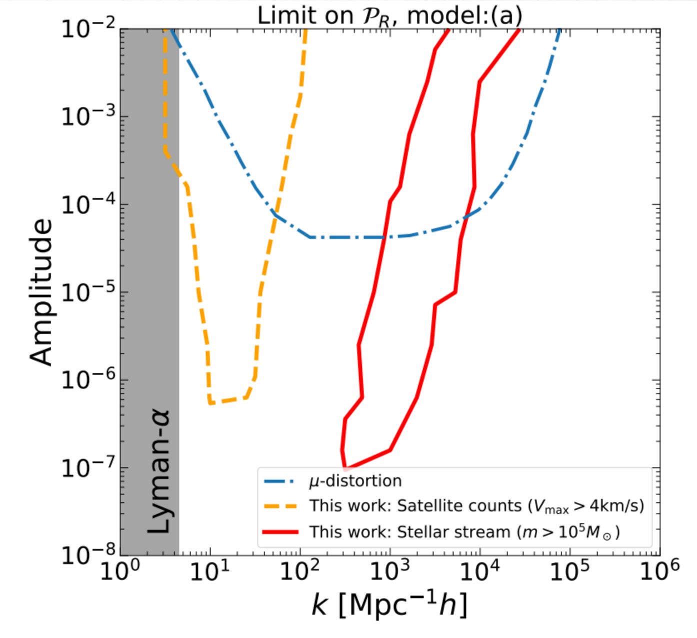
3. Indications

observable vs intrinsic

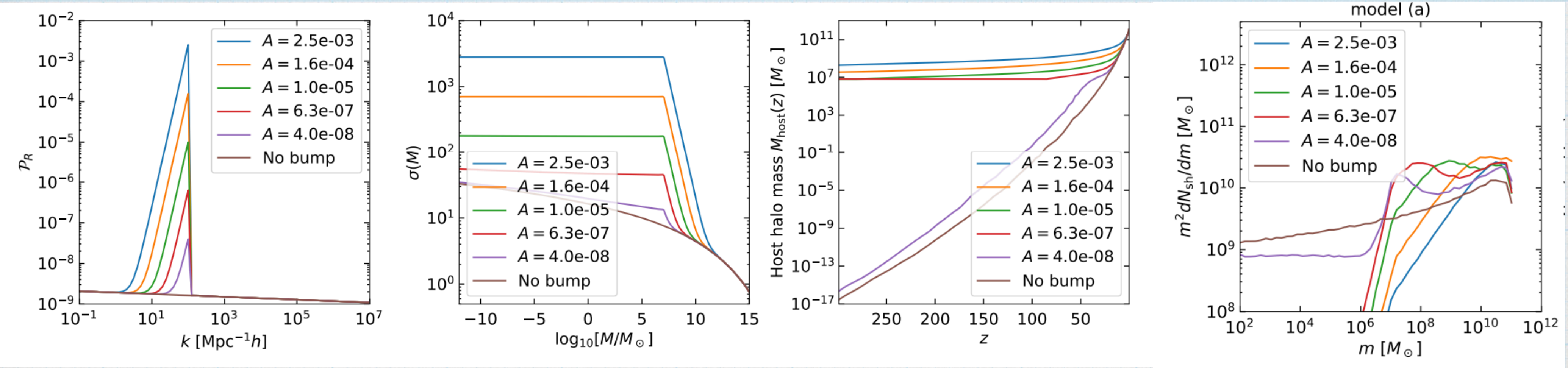
Hiroshima et al., 2022



testing cosmologies



- halo profile ↔ fuzzy DM test
  (e.g. Hayashi et al., 2021)
- halo statistics ↔ warm DM test
  (e.g. Dekker et al., 2022)
- halo statistics ↔ cosmological model
  (e.g. Ando, NH, Ishiwata, 2022)



Ando, NH, Ishiwata, 2022

Improved J-factor estimates

DM annihilation flux

$$\phi_\gamma = = \frac{1}{8\pi}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\boxed{\int_{E_{\rm th}}^{m_{\rm DM}} dE_\gamma \frac{dN_\gamma}{dE_\gamma}}\cdot\boxed{\int_{\Delta\Omega} d\Omega \int_{l.o.s} ds\rho_{\rm DM}^2}$$

particle model J-factor (astrophysics)

To obtain $J = \int d\Omega \int_{los} ds\rho_{\rm DM}^2$:

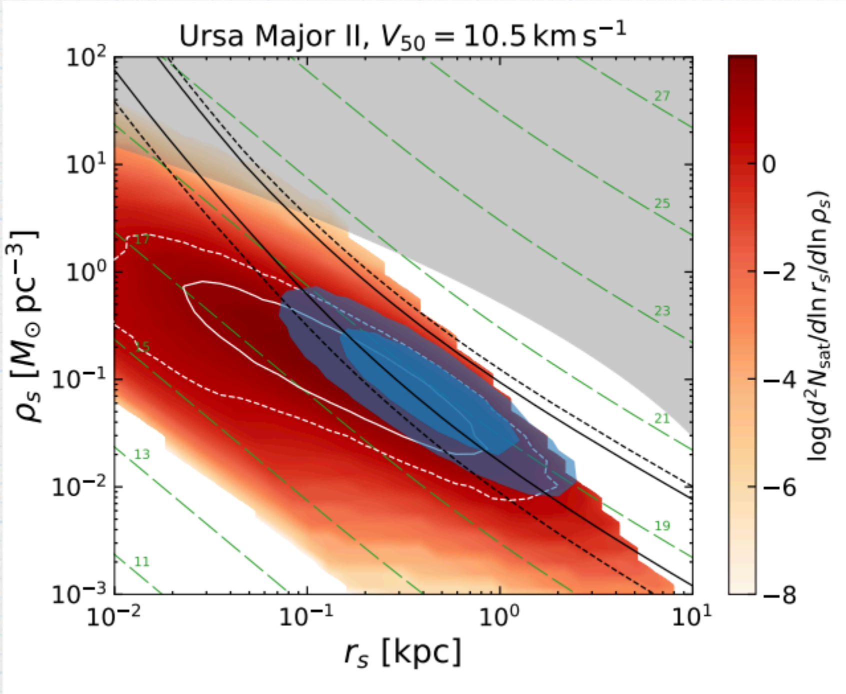
1. observe stellar motions
2. reconstruct gravitational potential (e.g. analyzing O(10)-O(1000) stars to determine ~ 5 parameters

dominant source of uncertainties in $\langle\sigma v\rangle$ limits

Improved J-factor estimates

dSphs reside in subhalos of the Milky Way halo

- # of subhalos at accretion : predicted with extended Press-Schechter theory
- tidal evolution after accretion: analytical estimate
- density profile evolution: numerical fitting formula



red: # of the satellite with EPS theory =physical prior(white)

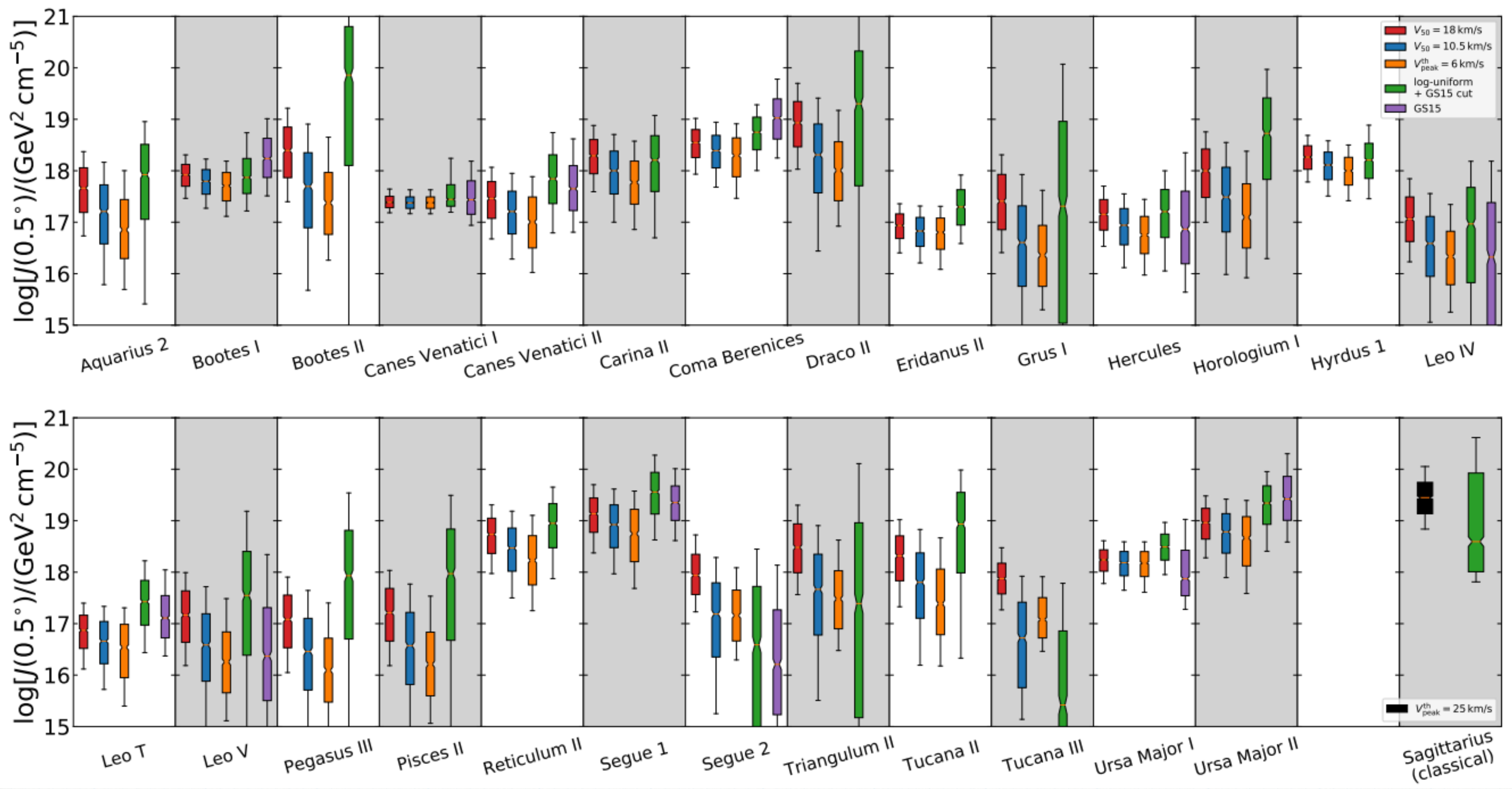
black: likelihood

blue: posterior

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

J-factor estimate

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

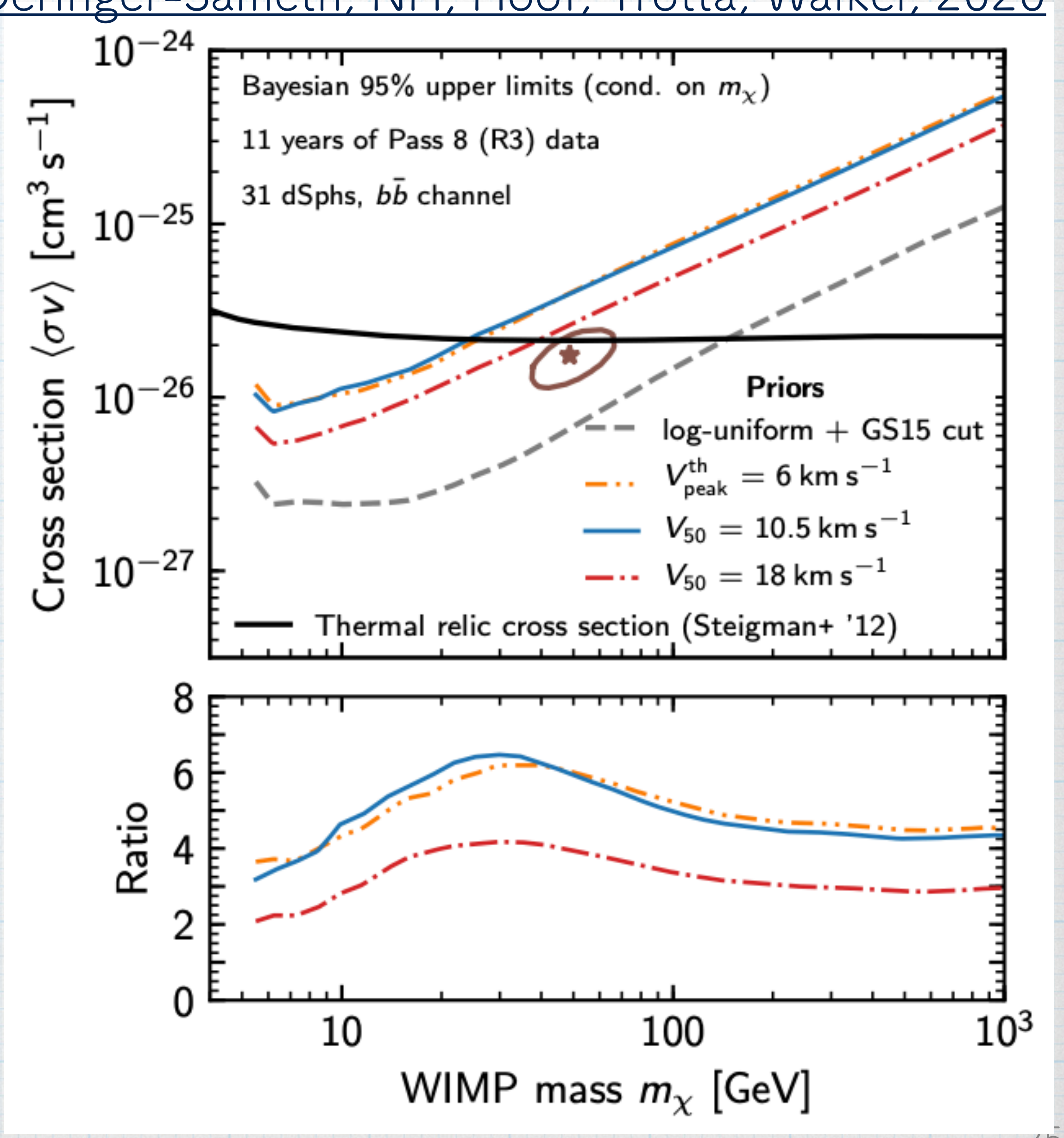


WIMP $\langle\sigma v\rangle$ constraints

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

$$\boxed{\phi_\gamma = \frac{1}{8\pi}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\left(\int\frac{dN}{dE}dE\right)\cdot J}$$

- Bayesian analysis is conducted combining 31 dSph's data
- The constraints gets milder by a factor of 2-6 due to the shifts in the J-factors.



4. Summary

Summary:

- Structure formation of the Universe requires matter components which are different from baryons.
- There is a huge model space for DM.
- Gravitational interaction can exist as a nature of DM and it should result in halo formations.
- Study of halos is connected to many aspects of DM.

  Semi-analytic scheme is capable of covering a wide range of halo physics.
- Quick calculation of halos with semi-analytic scheme can be a new way to probe DM nature and cosmologies.