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Semi-analytic approaches for evolutions of DM halos

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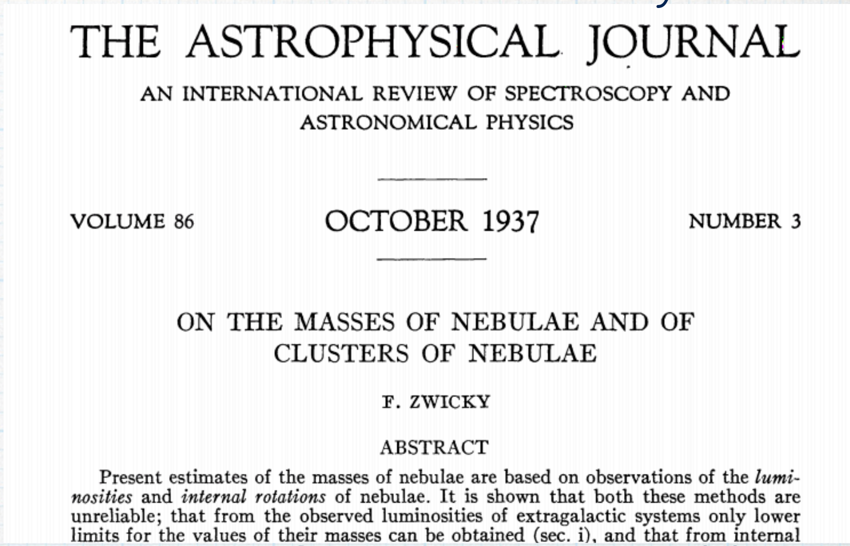
Contents:

1. Motivation for particle DM search

Evidence of invisible matter

- mass of galaxy cluster
- Rotation curves of galaxies
- bullet cluster observations
- large scale structures
- …

Zwicky, 1937



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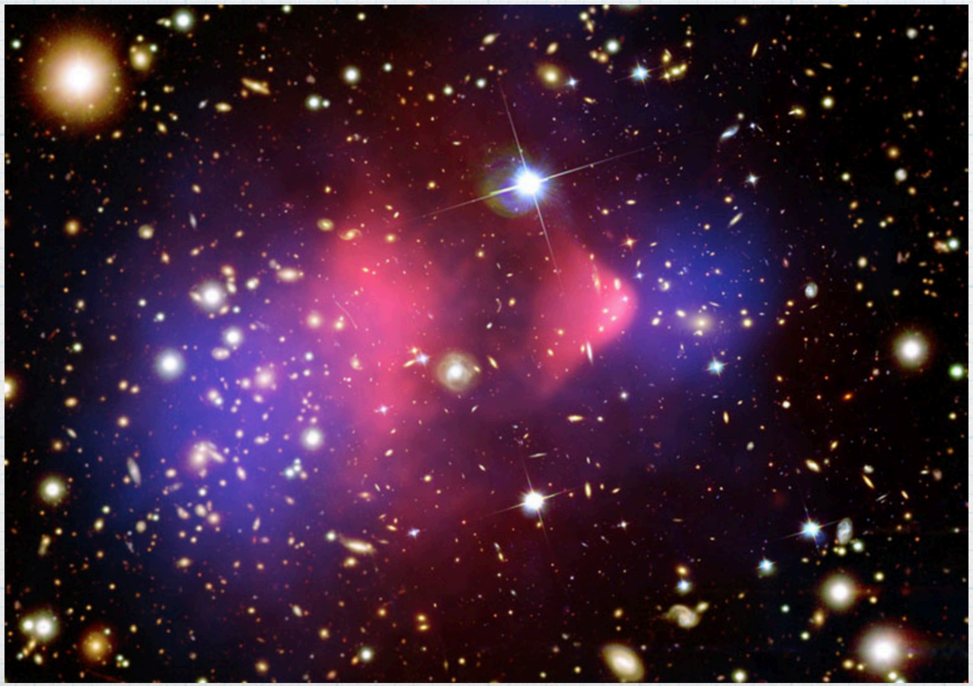
ON THE MASSES OF NEBULAE AND OF CLUSTERS OF NEBULAE

F. ZWICKY

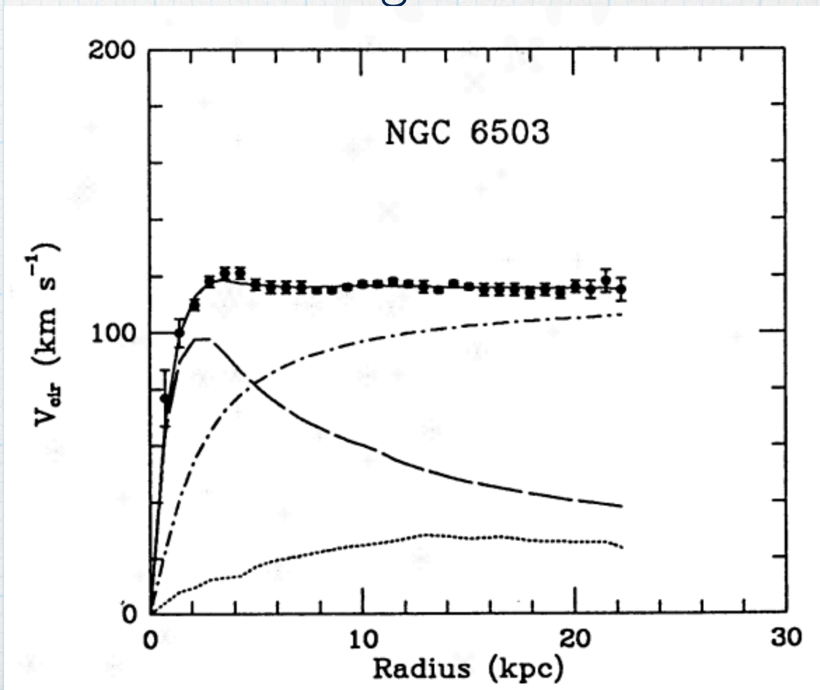
ABSTRACT

Present estimates of the masses of nebulae are based on observations of the *luminosities* and *internal rotations* of nebulae. It is shown that both these methods are unreliable; that from the observed luminosities of extragalactic systems only lower limits for the values of their masses can be obtained (sec. i), and that from internal

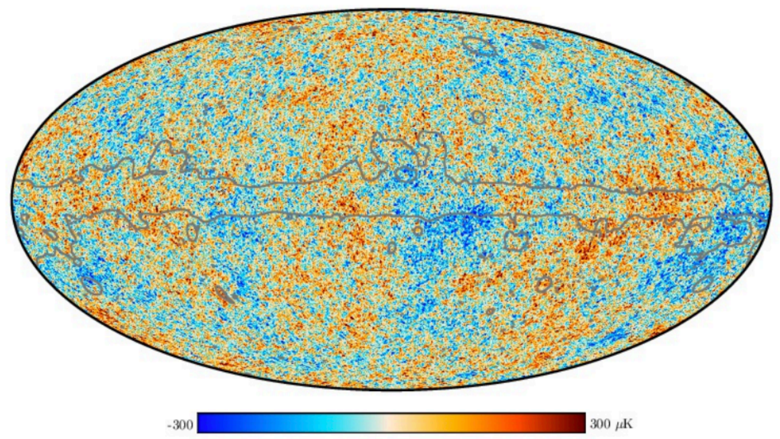
Markevitch et al., 2004

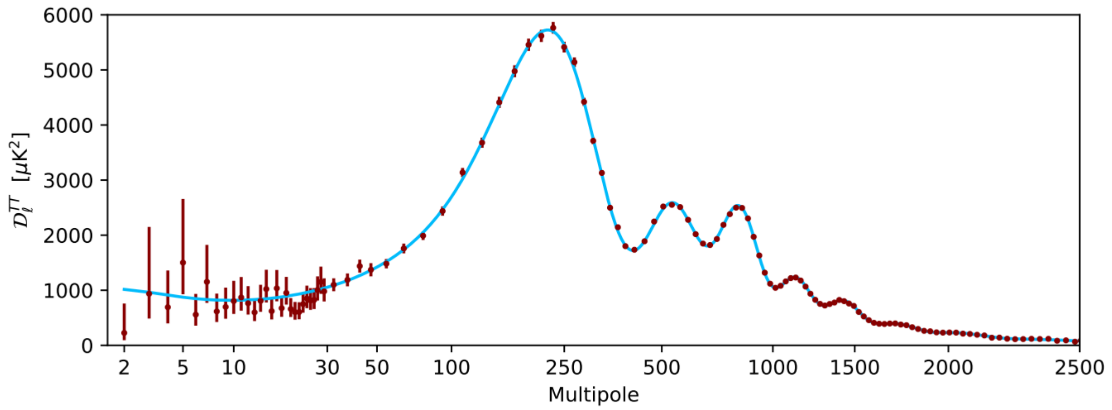


Begeman et al., 1991



Cosmological Requirement





Parameter	*Planck* alone	*Planck* + BAO
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{MC}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42
Ω_Λ	0.6847 ± 0.0073	0.6889 ± 0.0056
Ω_m	0.3153 ± 0.0073	0.3111 ± 0.0056
$\Omega_m h^2$	0.1430 ± 0.0011	0.14240 ± 0.00087
$\Omega_m h^3$	0.09633 ± 0.00030	0.09635 ± 0.00030
σ_8	0.8111 ± 0.0060	0.8102 ± 0.0060
$\sigma_8(\Omega_m/0.3)^{0.5}$ . . .	0.832 ± 0.013	0.825 ± 0.011
z_{re}	7.67 ± 0.73	7.82 ± 0.71
Age[Gyr]	13.797 ± 0.023	13.787 ± 0.020
r_*[Mpc]	144.43 ± 0.26	144.57 ± 0.22
$100\theta_*$	1.04110 ± 0.00031	1.04119 ± 0.00029
r_{drag}[Mpc]	147.09 ± 0.26	147.57 ± 0.22
z_{eq}	3402 ± 26	3387 ± 21
k_{eq}[Mpc^{-1}]	0.010384 ± 0.000081	0.010339 ± 0.000063
Ω_K	-0.0096 ± 0.0061	0.0007 ± 0.0019
Σm_ν [eV]	< 0.241	< 0.120
N_{eff}	$2.89^{+0.36}_{-0.38}$	$2.99^{+0.34}_{-0.33}$
$r_{0.002}$	< 0.101	< 0.106

Planck 2018

Brief cosmological history

Inflation

↓

radiation dominated era

↓

matter dominated era $T \sim \mathcal{O}(10^4)$ K (z=3500)

DM structure formation starts

CMB $T \sim \mathcal{O}(10^3)$ K (z=1100)

baryon structure formation starts

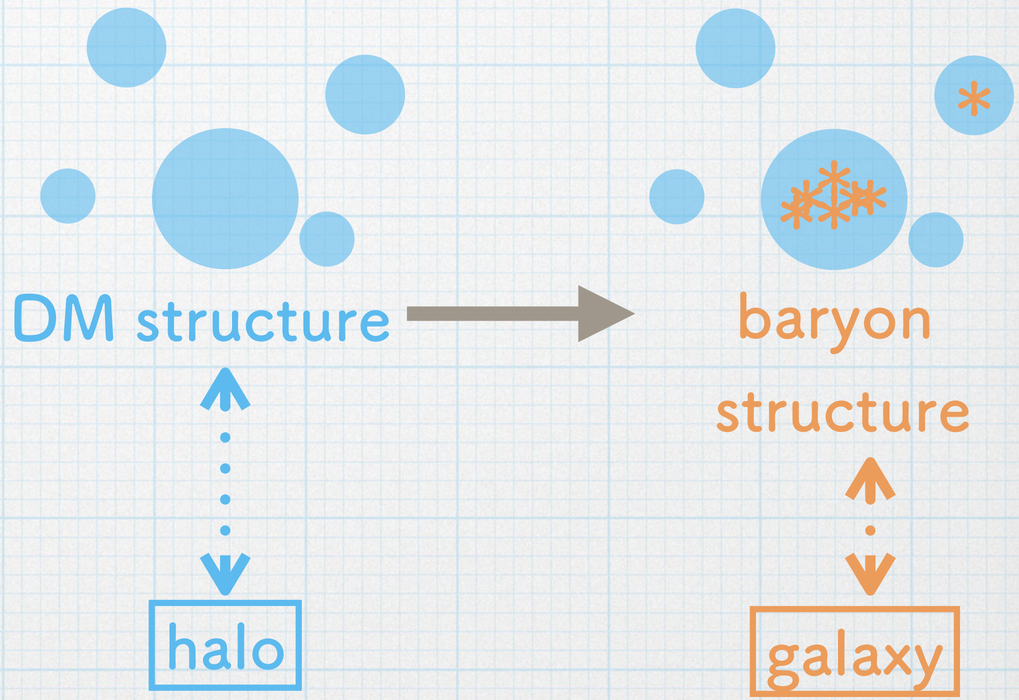
↓

current Universe $T \sim 2.7\mathrm{K}$ (z=0)

Our understanding

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

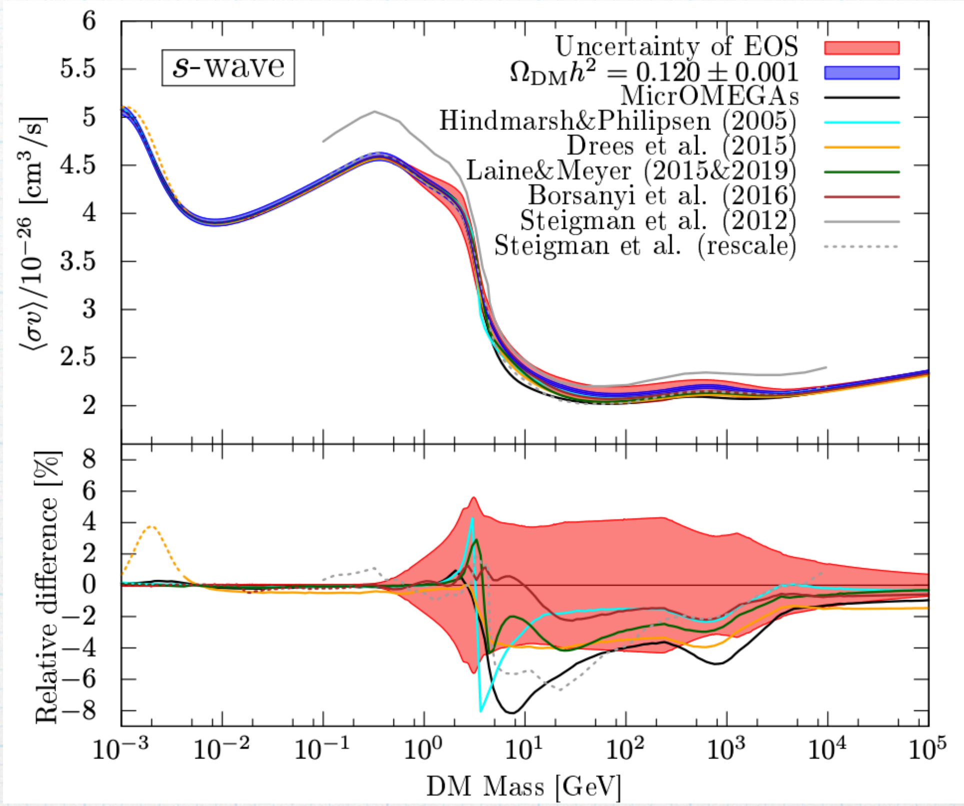
- **motivation**
  - structure formation
  - rotation curves
  - bullet cluster
  - …
- **properties**
  - non-relativistic
  - cold (warm, hot)
  - almost invisible
  - feel gravity



WIMP: a famous example

- the mass $m_{\rm DM} \sim \mathcal{O}(\mathrm{GeV}) - \mathcal{O}(\mathrm{TeV})$
- freeze-out scenario to achieve the relic abundance $\Omega_{\rm DM}h^2 \sim 0.12$
- the annihilation cross-section $\langle \sigma v \rangle \sim \mathcal{O}(10^{-26}\mathrm{cm}^3 s^{-1})$

Saikawa & Shirai, 2020

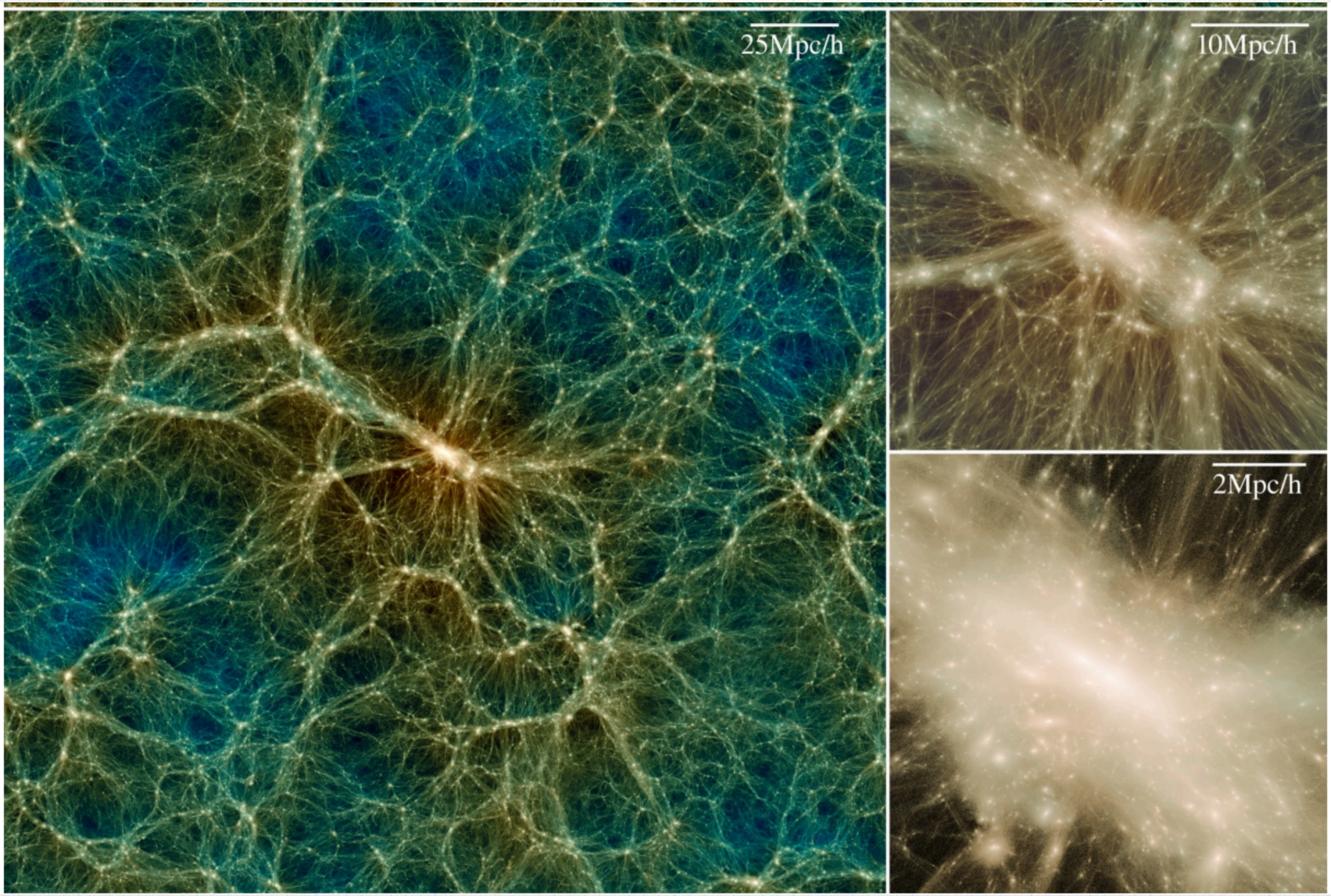


DM + DM → SM + SM : signal search @z~0

Behave as cold dark matter (CDM)

CDM structure

Ishiyama et al., 2021



DM halo for DM search

DM halo for DM search

- density profile of at Galactic Center (G.C.)
- dwarf spheroidal galaxies (dSphs)

→ indirect search

DM + DM → SM + SM

- density profile near the solar position

→ direct search

DM + SM → DM + SM

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

→ particle nature

$\mathscr{L}_{\rm DM} = \cdots$

- …

mass range : $\mathcal{O}(10^{-6})\ M_\odot$ (?) - $\mathcal{O}(10^{16})\ M_\odot$

2. Semi-analytic subhalo mass function

Key quantities

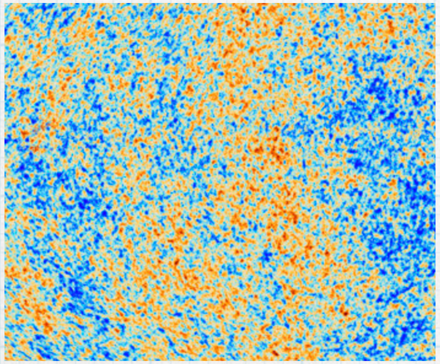
- halo mass function
- halo density profiles

Obstacles

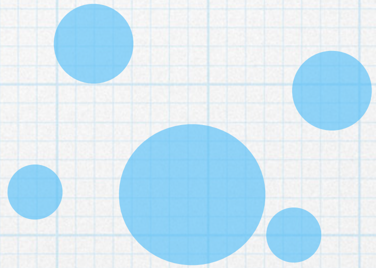
- wide halo mass range ($\sim 10^{-6}M_{\odot} - 10^{16}M_{\odot}$)
- wide redshift range
- different evolution histories of individual halos
- halo statistics

Story of DM halo

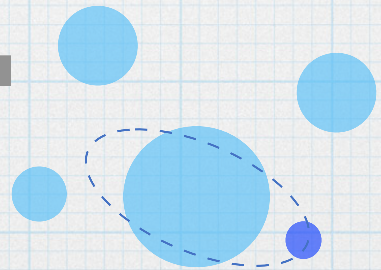
1, initial density fluctuation



2, gravitational collapse
(halo formation)

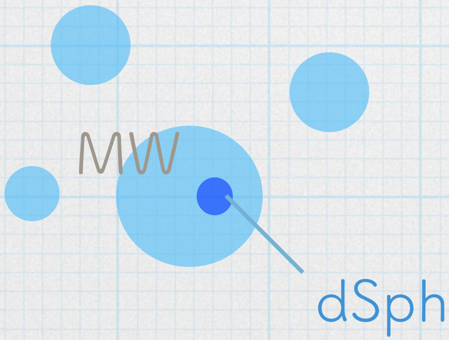


3, halo evolution



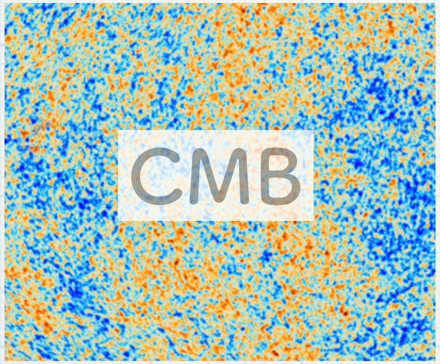
- merger
- accretion
- stripping

4, hierarchal halo structures



Story of DM halo

1, initial density fluctuation



2, gravitational collapse

(halo formation)

EPS formalism

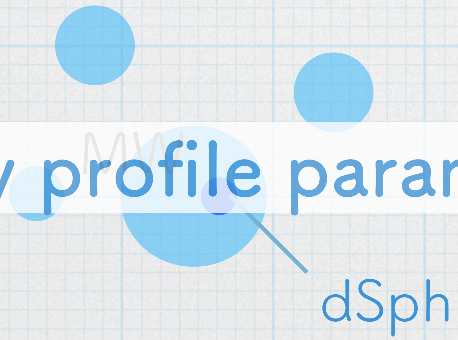
(analytic)

3, halo evolution

- merger
- accretion
- stripping

analytical modeling

4, hierarchal halo structures



density profile parameters

Extended Press-Shechter

- overdensity collapse to form halo

- two parameters:
  collapse redshift ($\delta(z)$) & mass scale ($\sigma(M)$)
- initial condition: power spectrum

- 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

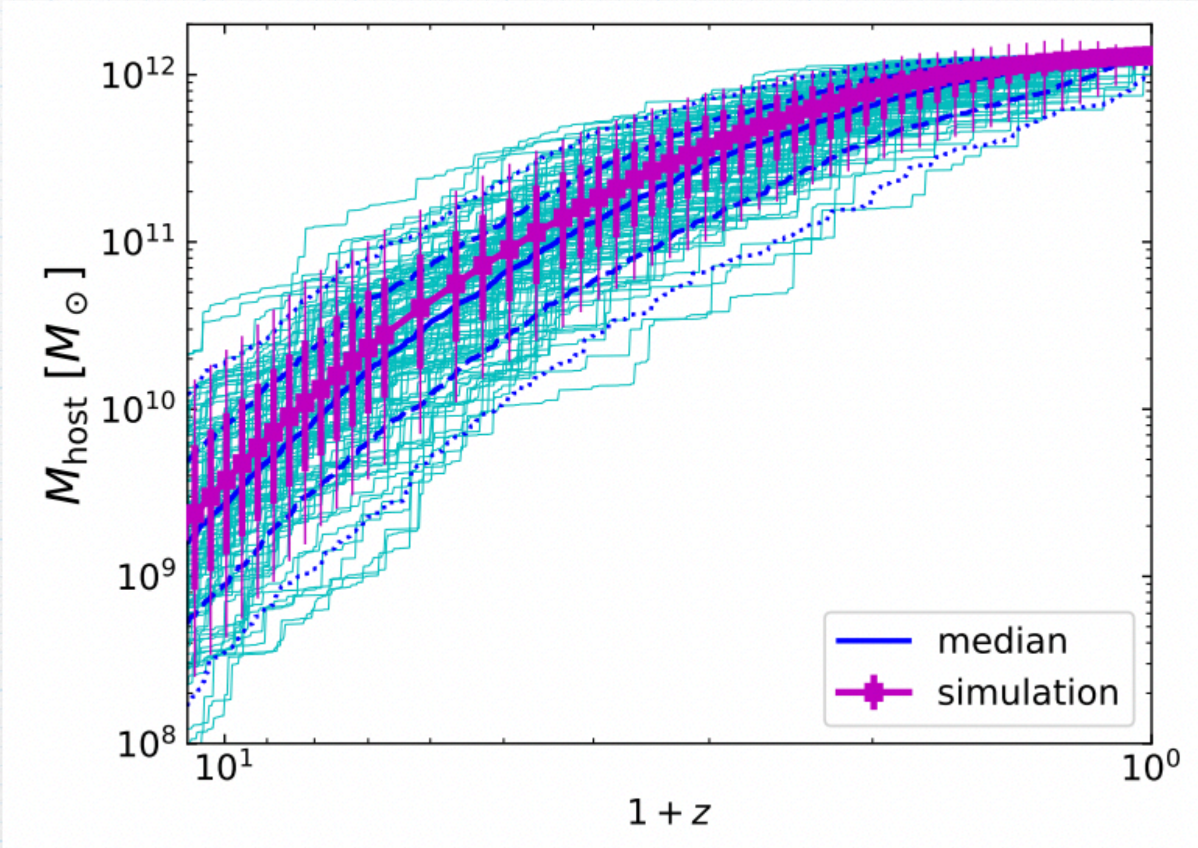
evolution history of $M(z)$

- distribution function

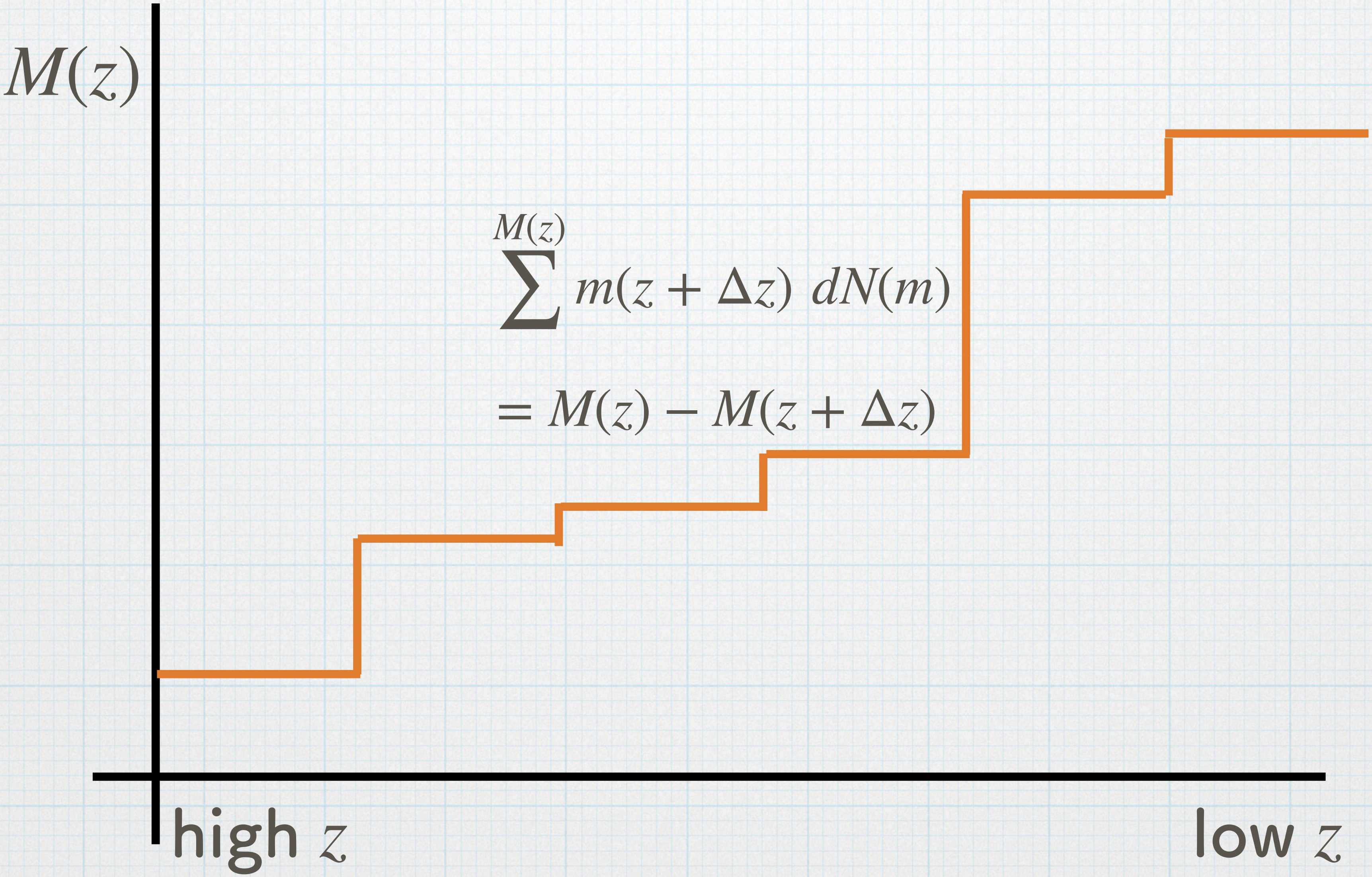
$$f(\sigma^2(m), \delta(z+\Delta z)\,|\,\sigma^2(M), \delta(z)) = \frac{1}{\sqrt{2\pi}} \frac{\delta(z+\Delta z) - \delta(z)}{[\sigma^2(m) - \sigma^2(M)]^{3/2}} \exp\left[-\frac{(\delta(z+\Delta z) - \delta(z))^2}{2(\sigma^2(m) - \sigma^2(M))}\right]$$

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

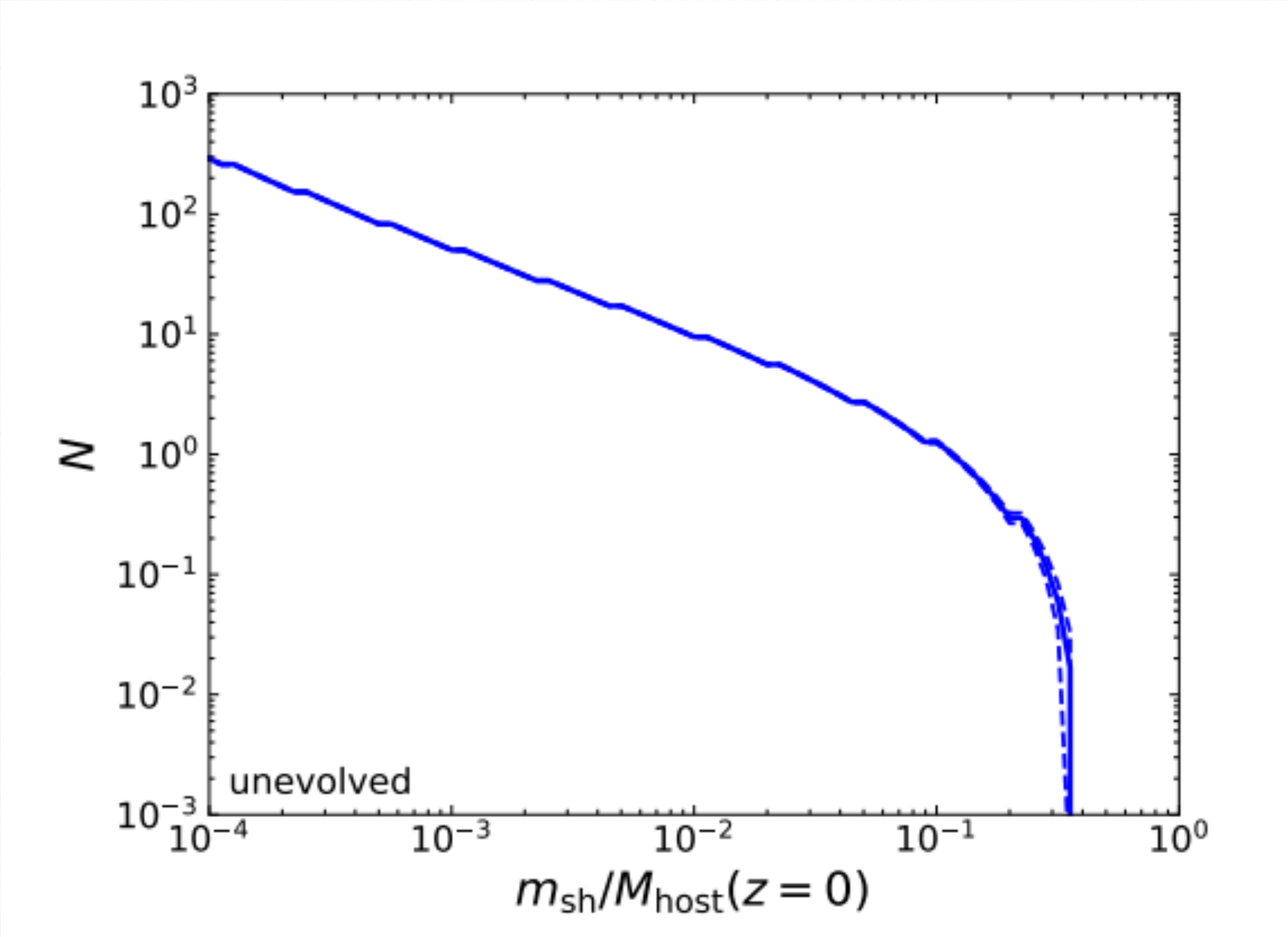
$\Rightarrow$ **unique progenitor**



unevolved mass function



unevolved mass function



tidal evolution: assumption

- The DM density distribution of the host and accreting subhalo follow the NFW profiles

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

- Tidal stripping rate is determined at the pericenter of the accreting orbit

- The DM distribution of subhalos after the tidal stripping are NFW profile with truncation

evolved mass function

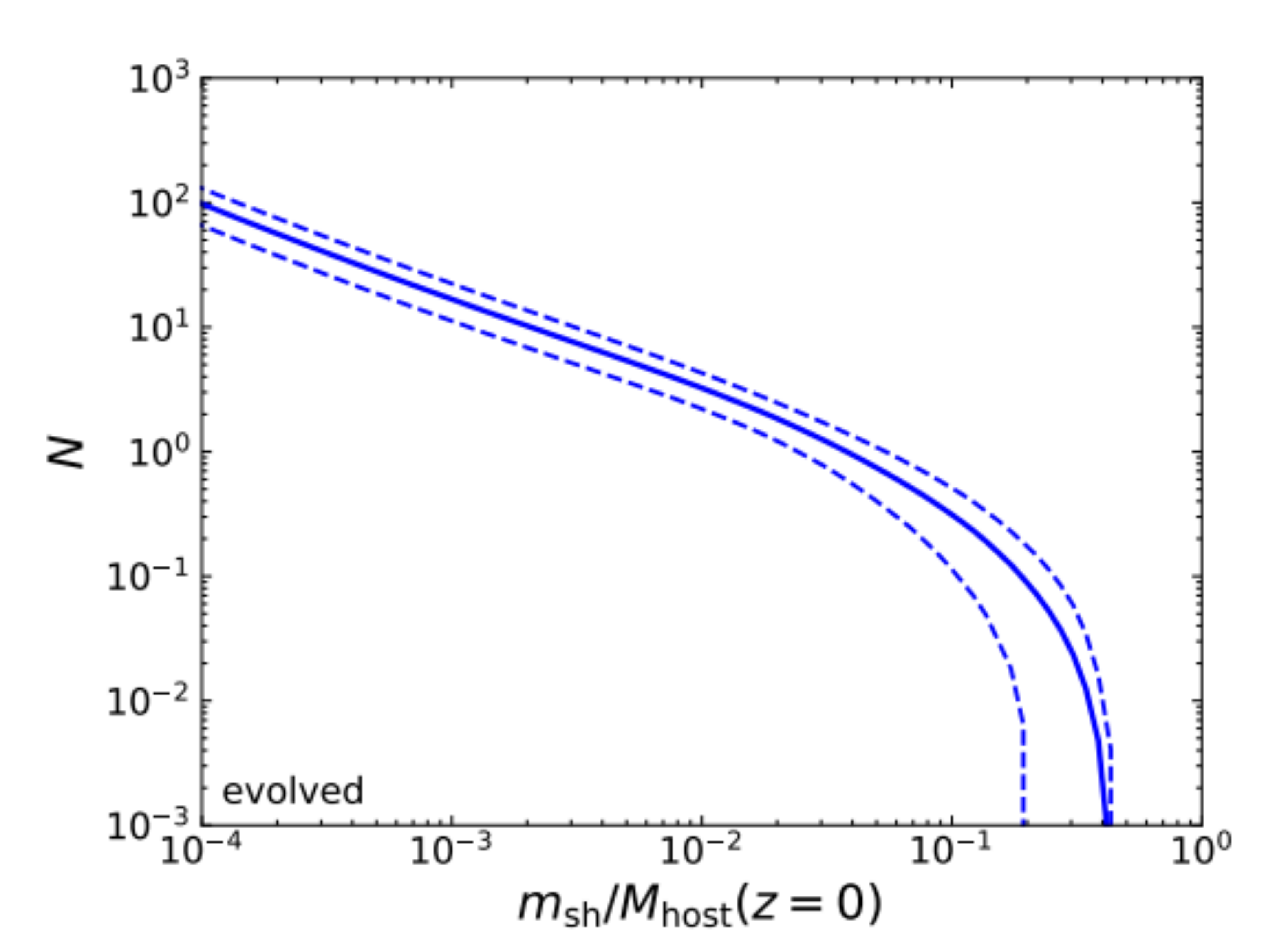
- # distribution at accretion: given (unevolved mass function)

- 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

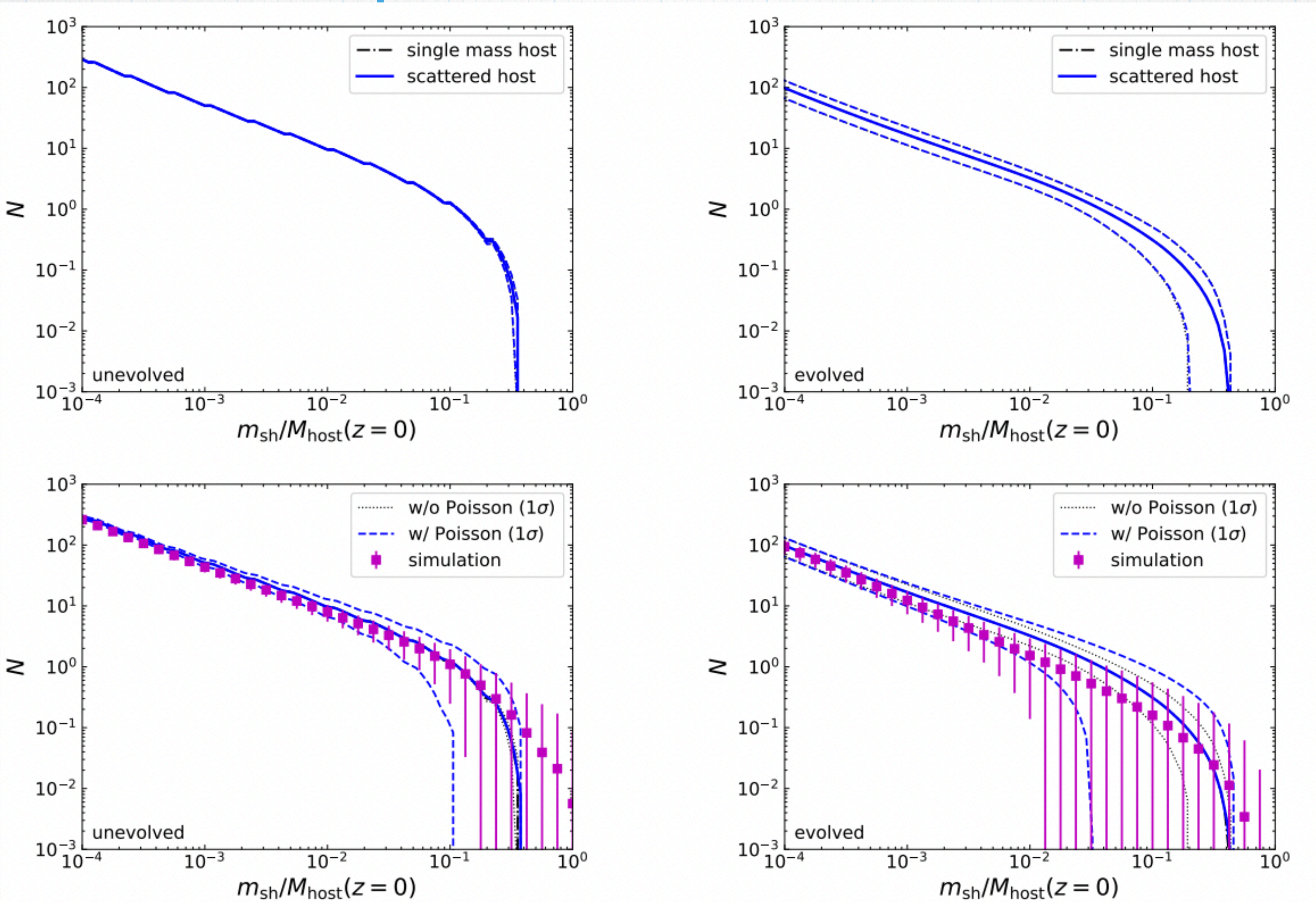


3. Applications

(a) observable vs intrinsic

- observed/simulated:
  - host mass uncertainty (obs.)
    or finite mass range of the sample host (sim.)
  - always with Poisson fluctuation (obs. & sim.)
- intrinsic
  - definite host mass at $z = 0$,
    1)calc. for different host masses
    2)incl. of the error in the host mass estimate
  - no Poisson fluctuation in the # count
    Poisson distribution of expectation value N
    -> recalculate mass function

(a) comparison

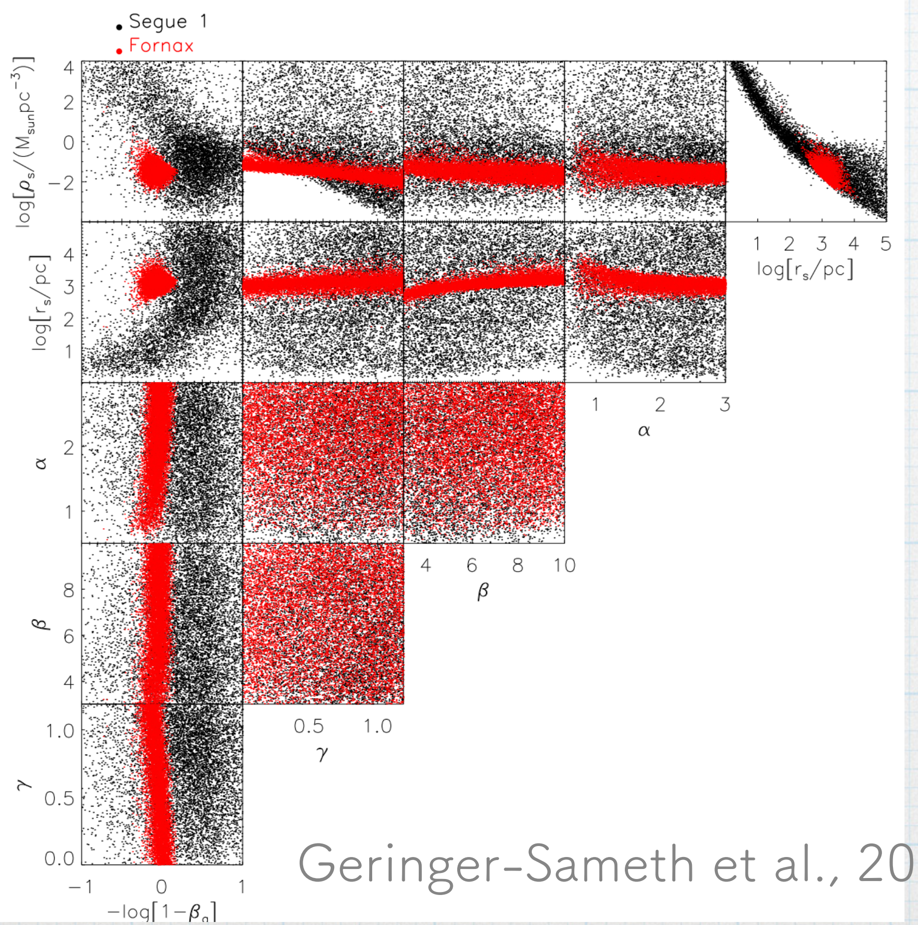


(b) individual history

density profiles of MW satellites

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

J-factor

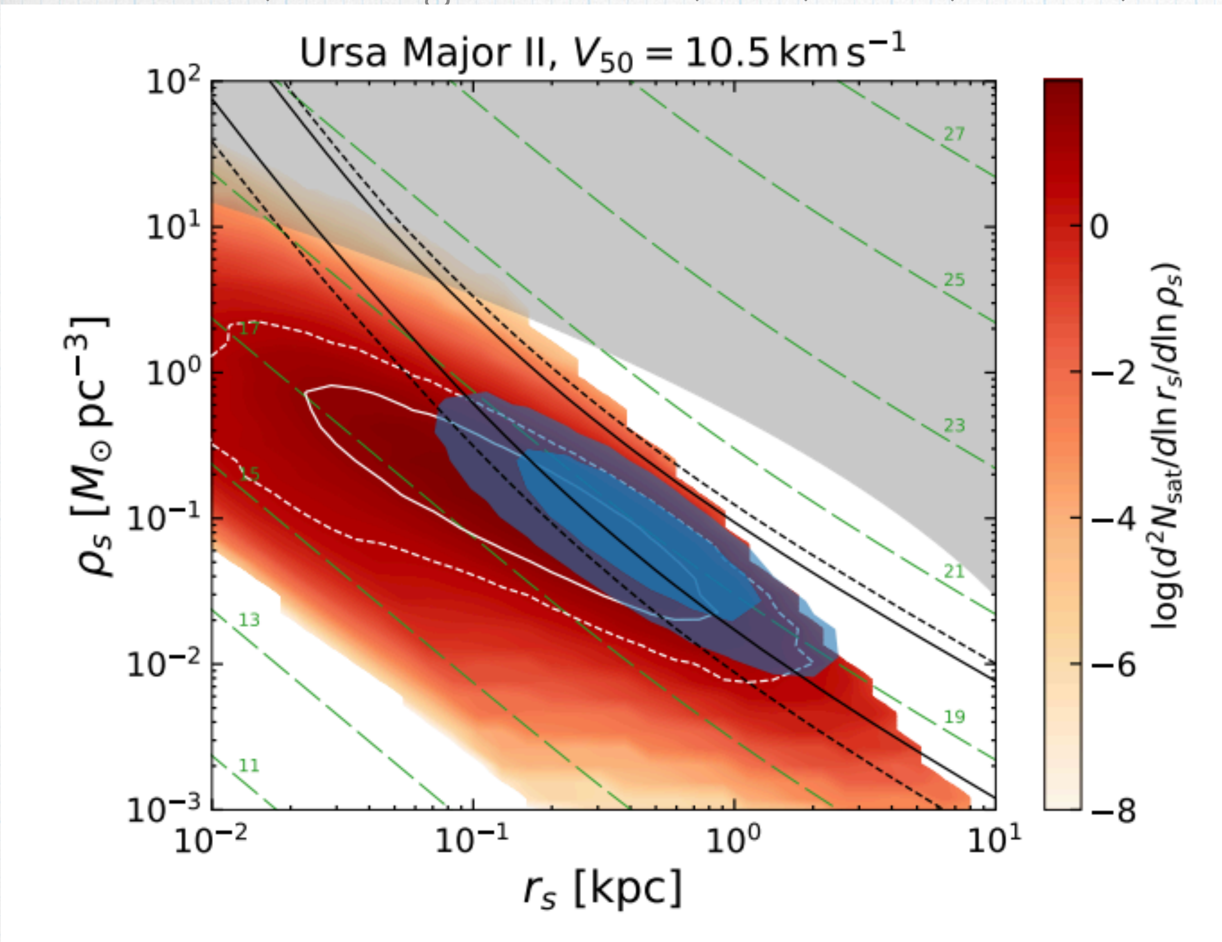


Geringer-Sameth et al., 2015

uncertainties in dSph's J-factor
↔ uncertainties in annihilation cross-section constraints

(b) prior construction

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

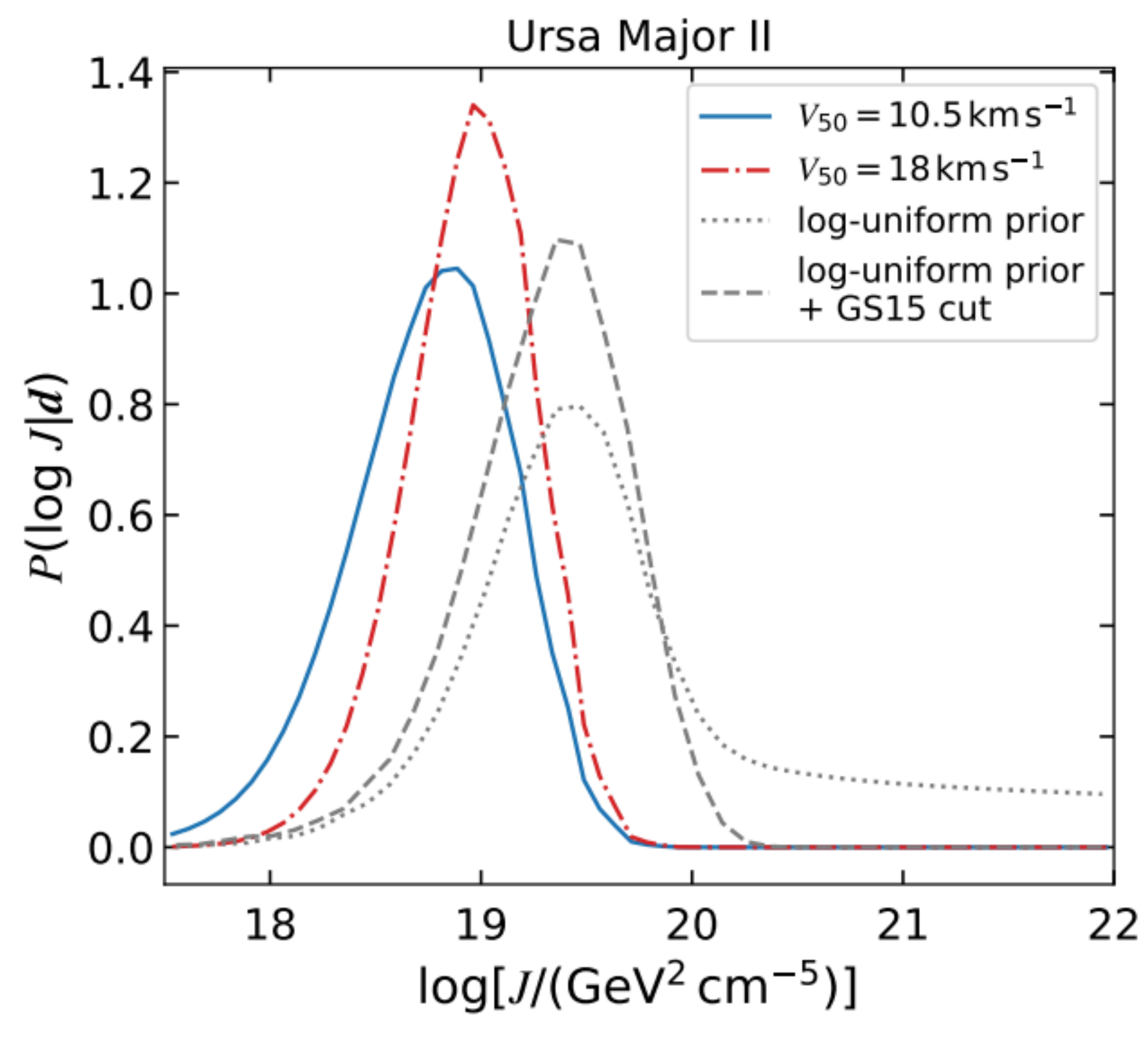


- red: number of the satellite in Via Lactae II simulation
- **white: "informative" prior distribution**
- black: likelihood
- blue: posterior distribution

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

(b) J-factor estimate

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



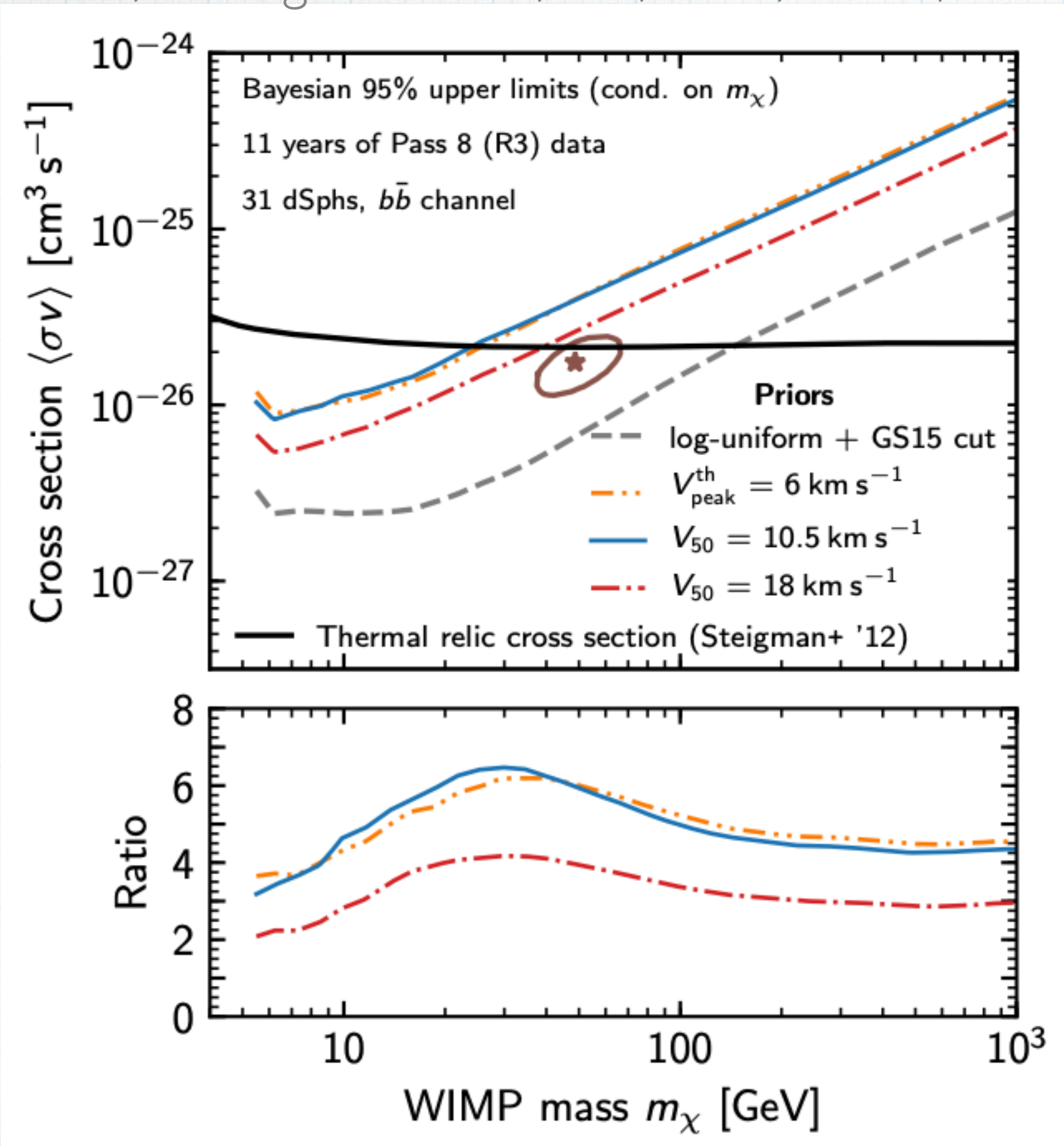
$$\phi_\gamma = \frac{1}{8\pi}\frac{\langle \sigma v\rangle}{m_{\rm DM}^2}\left(\int \frac{dN}{dE}dE\right)\cdot J$$

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

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

Constraints on the $< \sigma v >$

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



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

- 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:

- Halo is a key to access the nature of DM
- Evolution of CDM subhalo can be well-described in semi-analytical ways.
- Quick calculation of halo evolution enables us to probe physics beyond the Standard scenarios using observational data around our Galaxy.
- Further applications are now being considered.