GRAPPA
GRavitation AstroParticle Physics Amsterdam

News from the Dark 7
Montpellier
16 June 2022

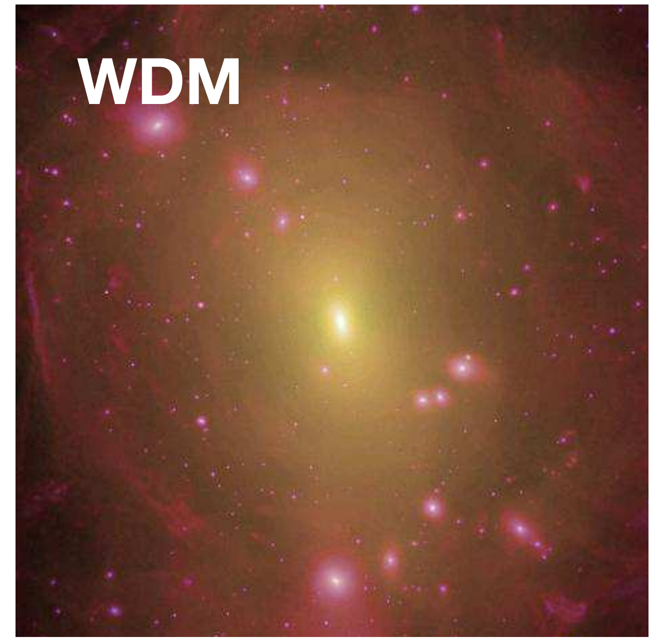
Formation and evolution of dark matter substructure: Semi-analytical approach

Shin'ichiro Ando
University of Amsterdam

Small-scale structure

WIMPs, axions, ALPs, PBHs

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

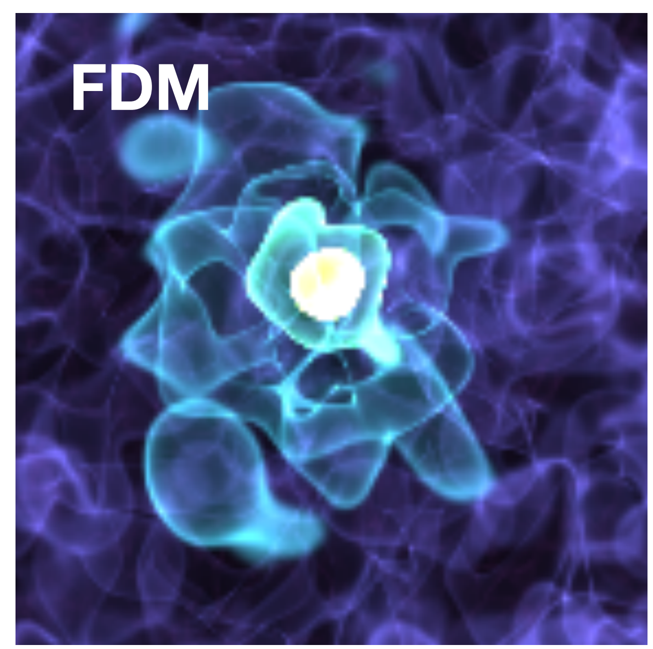


Sterile neutrinos

- Cutoff at sub-galaxy scale in the power spectrum

SIMPs, dark atoms

- Cores in density profiles induced by self scattering

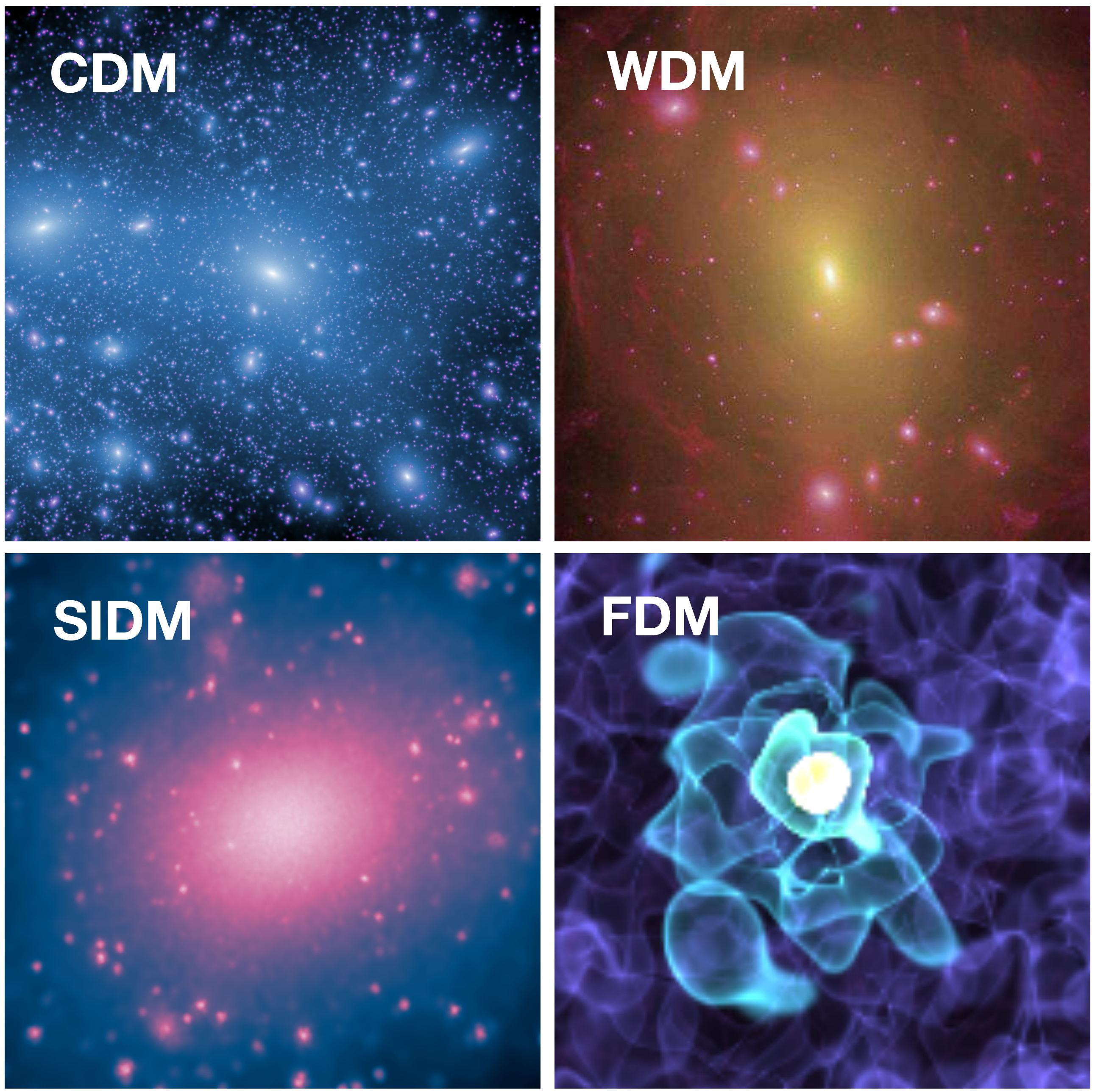


Ultralight bosons

- 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 **semi-analytic models**, calibrate with **numerical simulations**, and **establish reliable models** free from shot noise and numerical resolution

Personal motivation - where this started

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

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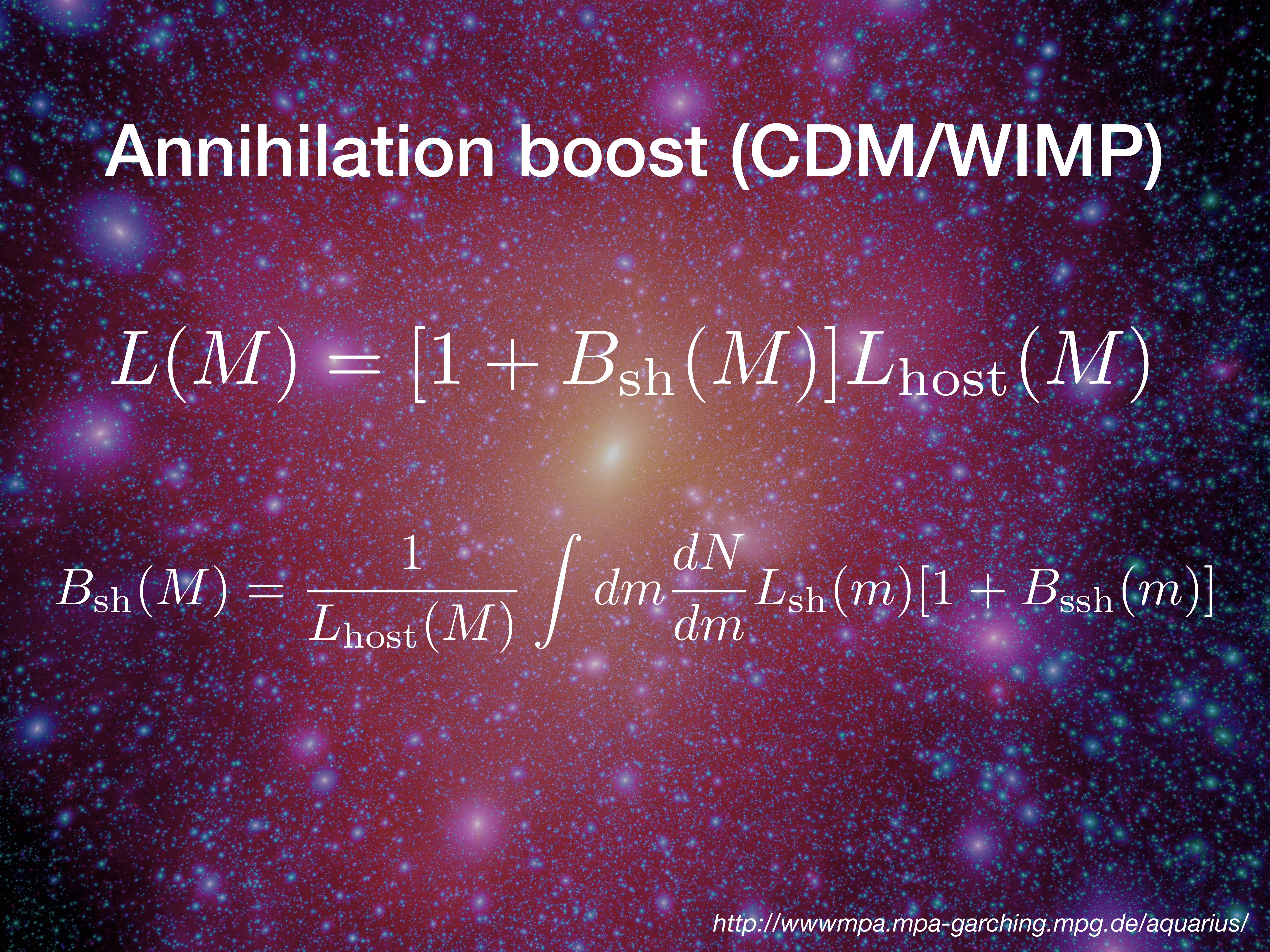
- **WIMP annihilation is sensitive to halos of all scales**

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



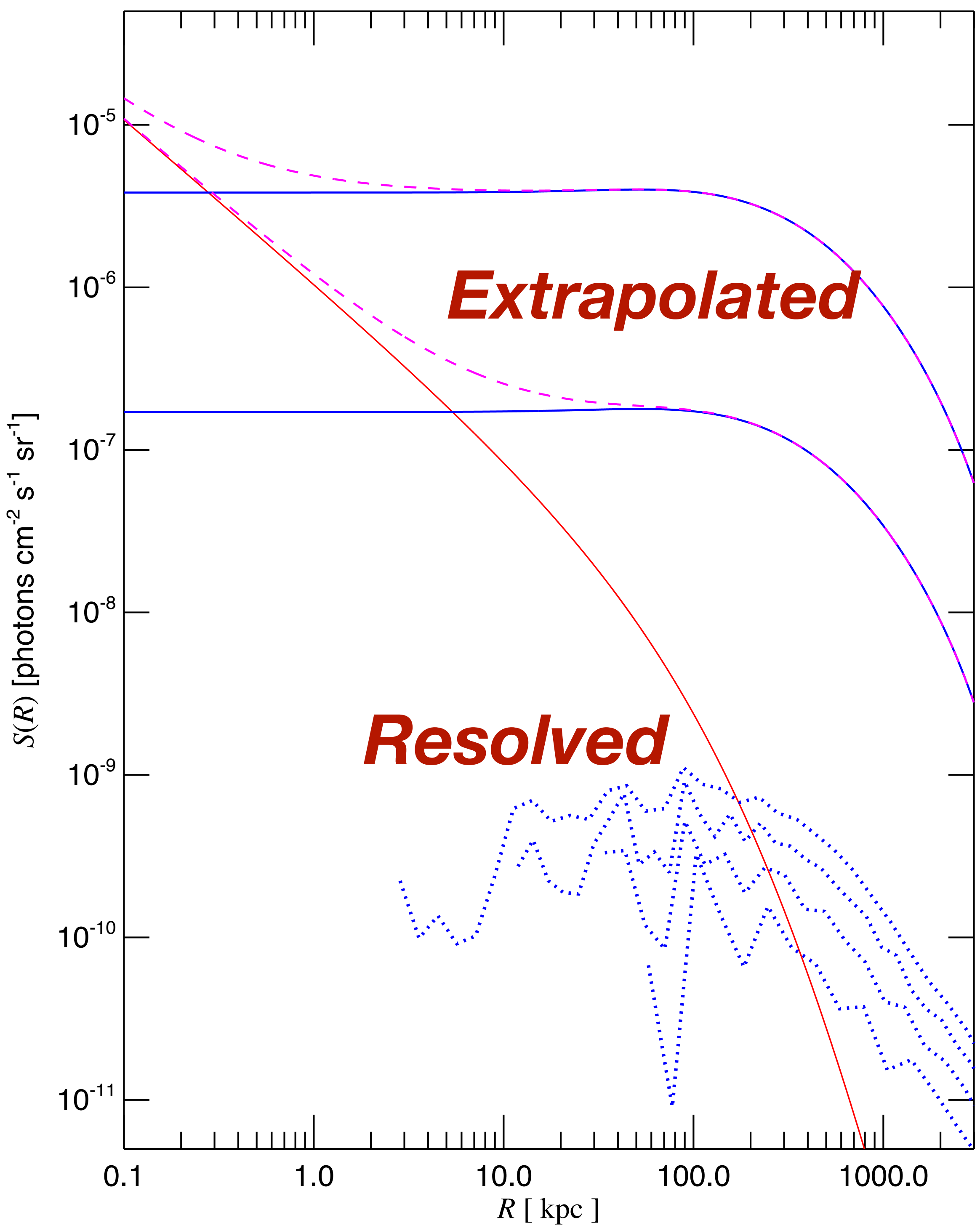
Annihilation boost (CDM/WIMP)

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

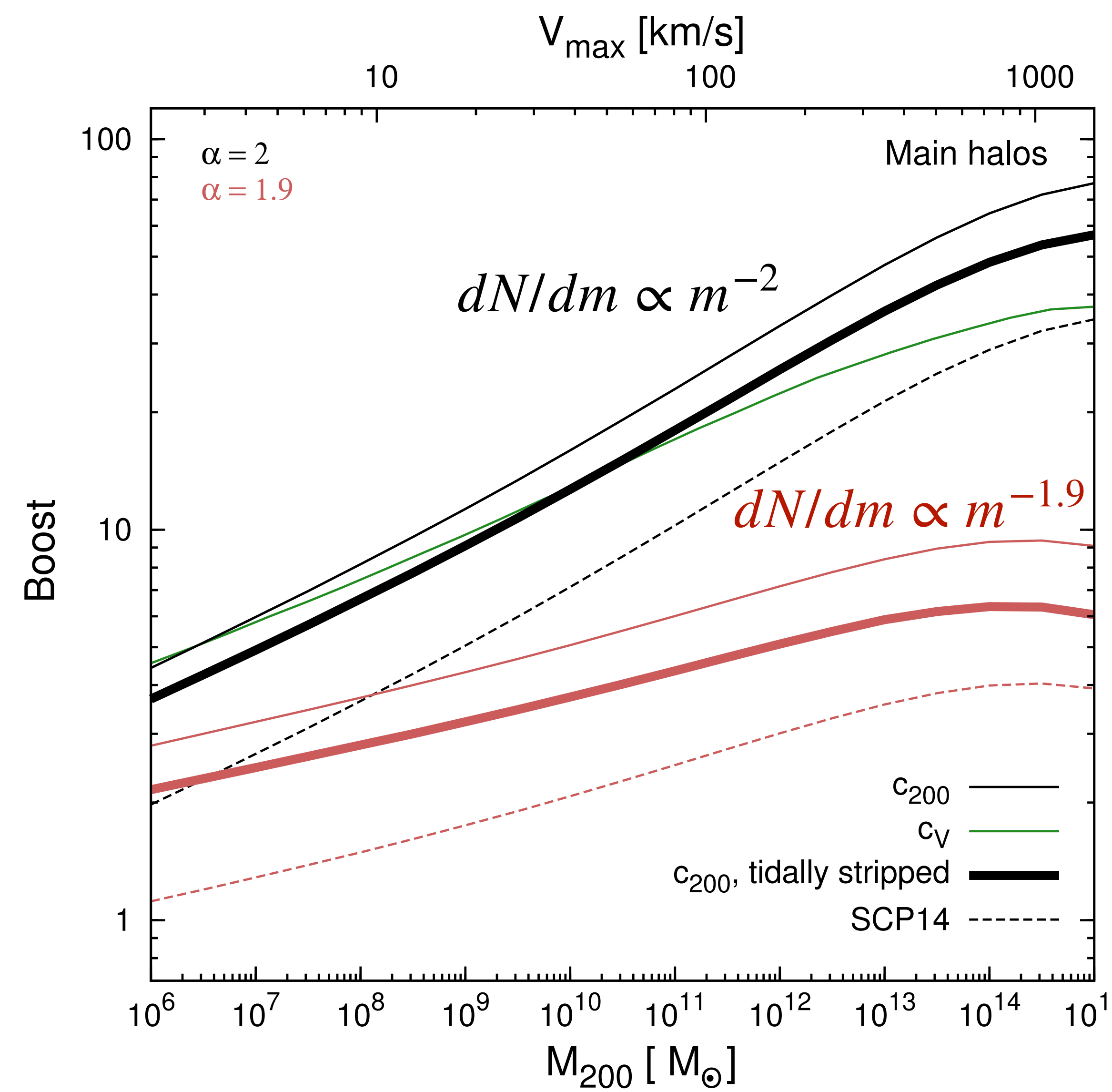
$$B_{\rm sh}(M) = \frac{1}{L_{\rm host}(M)}\int dm \frac{dN}{dm} L_{\rm sh}(m)[1 + B_{\rm ssh}(m)]$$

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

How uncertain is 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-analytical 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-analytical modeling

Structures start to form

↓

Smaller halos merge and accrete to form larger ones

↓

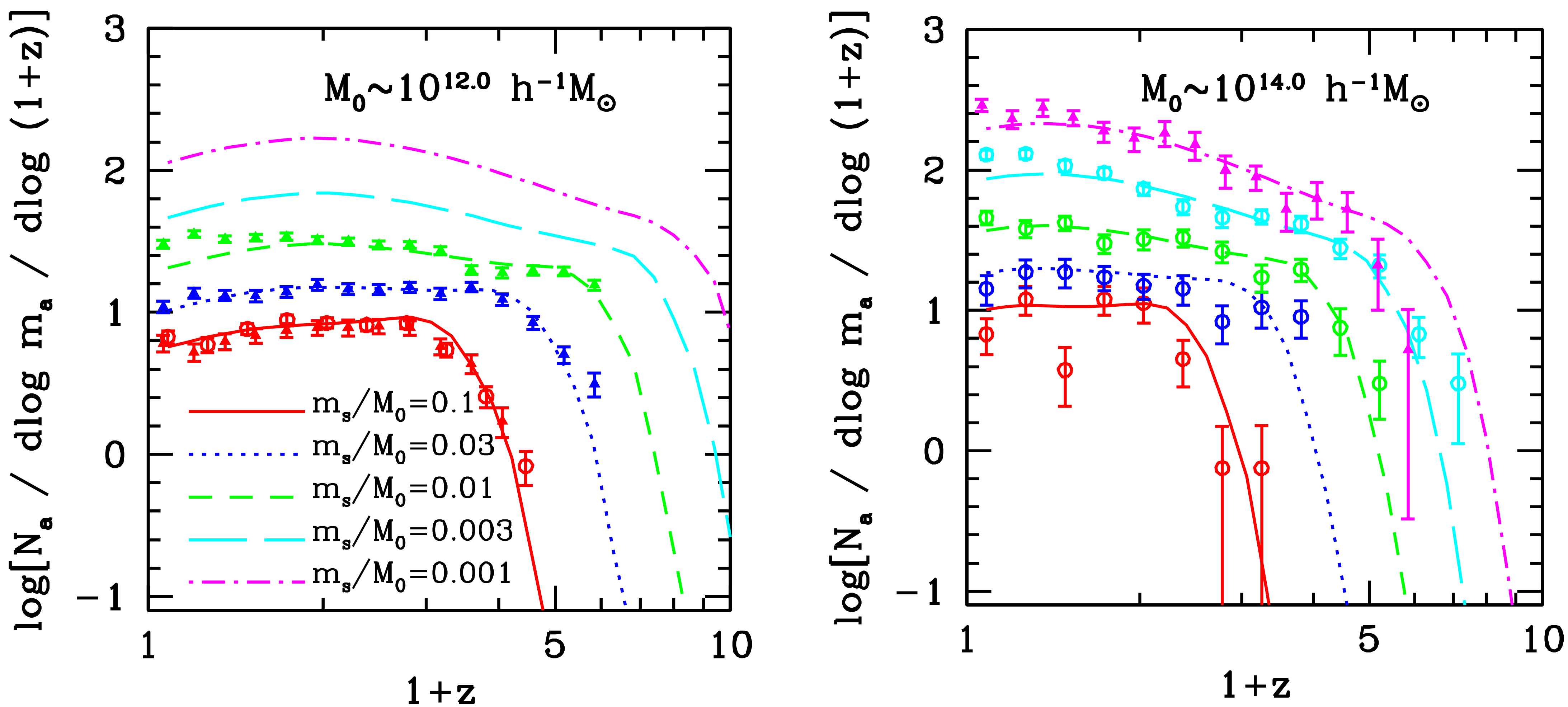
Subhalos experience mass loss

Initial condition: Primordial power spectrum

Extended Press-Schechter formalism

Modeling for tidal stripping and mass-loss rate

Subhalo accretion



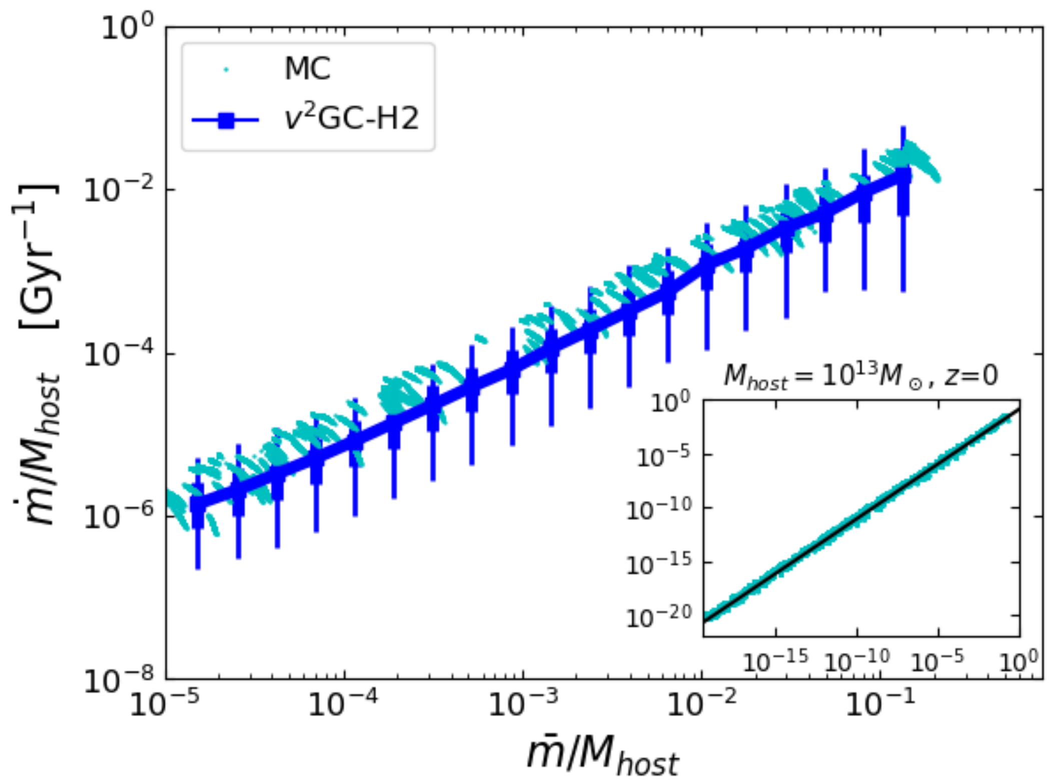
Yang et al., *Astrophys. J.* **741**, 13, (2011)

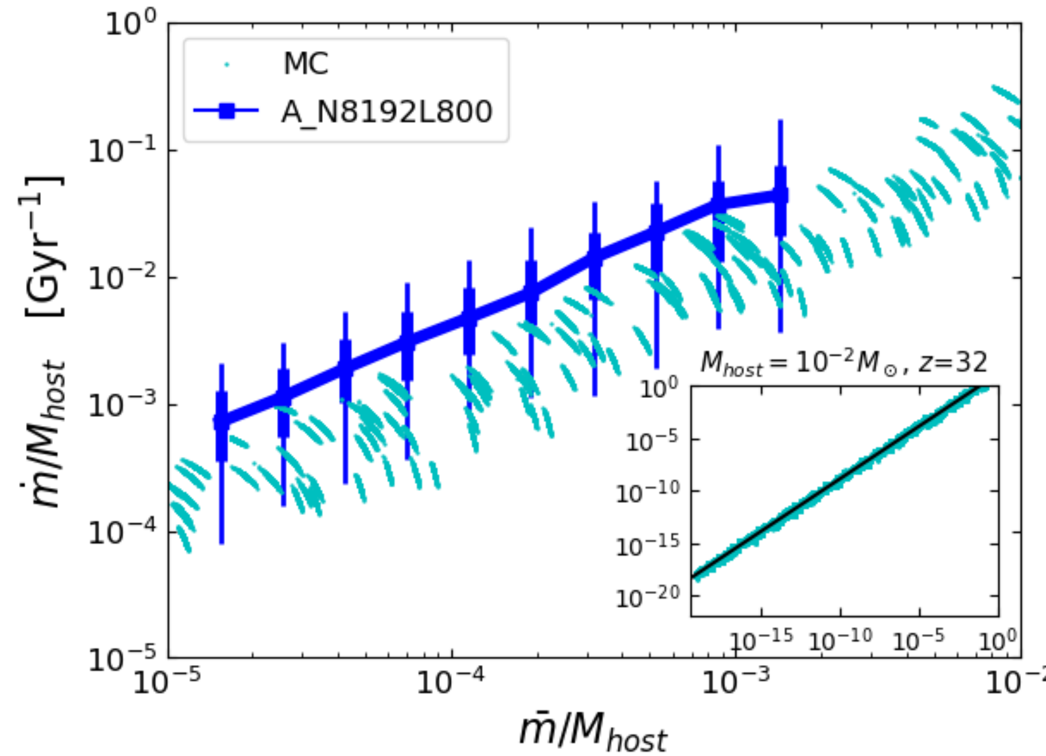
Infall distribution of subhalos:
Extended Press-Schechter formalism

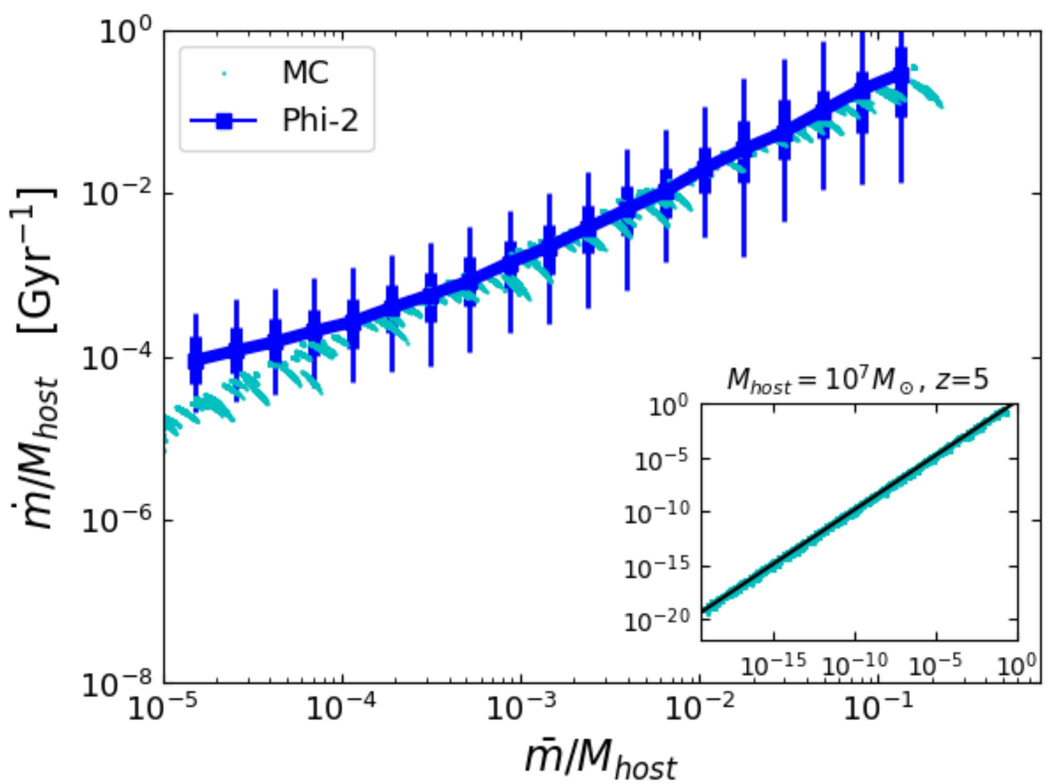
$$\frac{d^2 N_{\rm sh}}{dm_{\rm acc}dz_{\rm acc}} \propto \frac{1}{\sqrt{2\pi}} \frac{\delta(z_{\rm acc}) - \delta_M}{(\sigma^2(m_{\rm acc}) - \sigma_M^2)^{3/2}} \exp\left[-\frac{(\delta(z_{\rm acc}) - \delta_M)^2}{2(\sigma^2(m_{\rm acc}) - \sigma_M^2)}\right]$$

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-analytical modeling

Structures start to form

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Smaller halos merge and accrete to form larger ones

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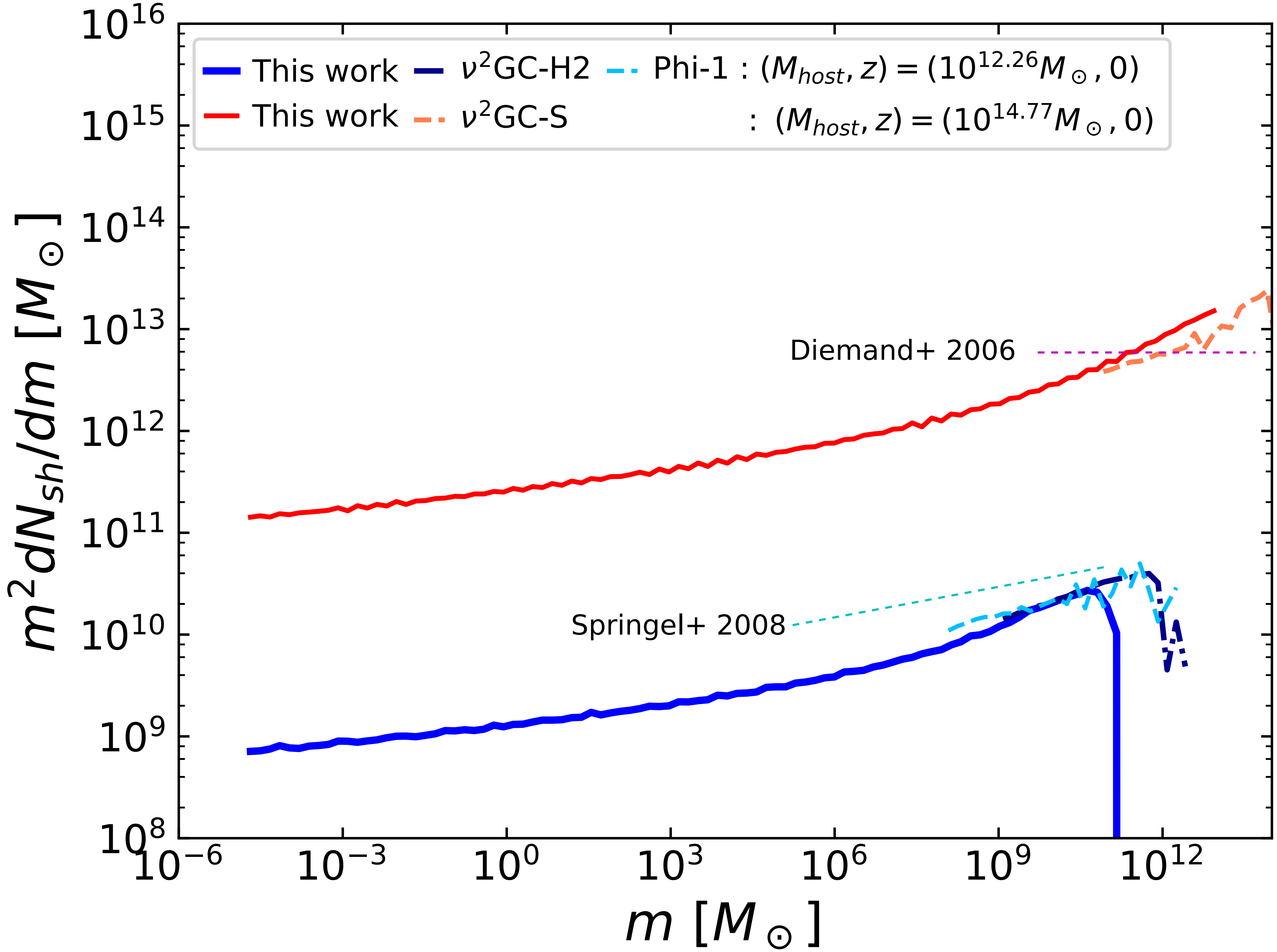
Subhalos experience mass loss

✓ **Initial condition: Primordial power spectrum**

✓ **Extended Press-Schechter formalism**

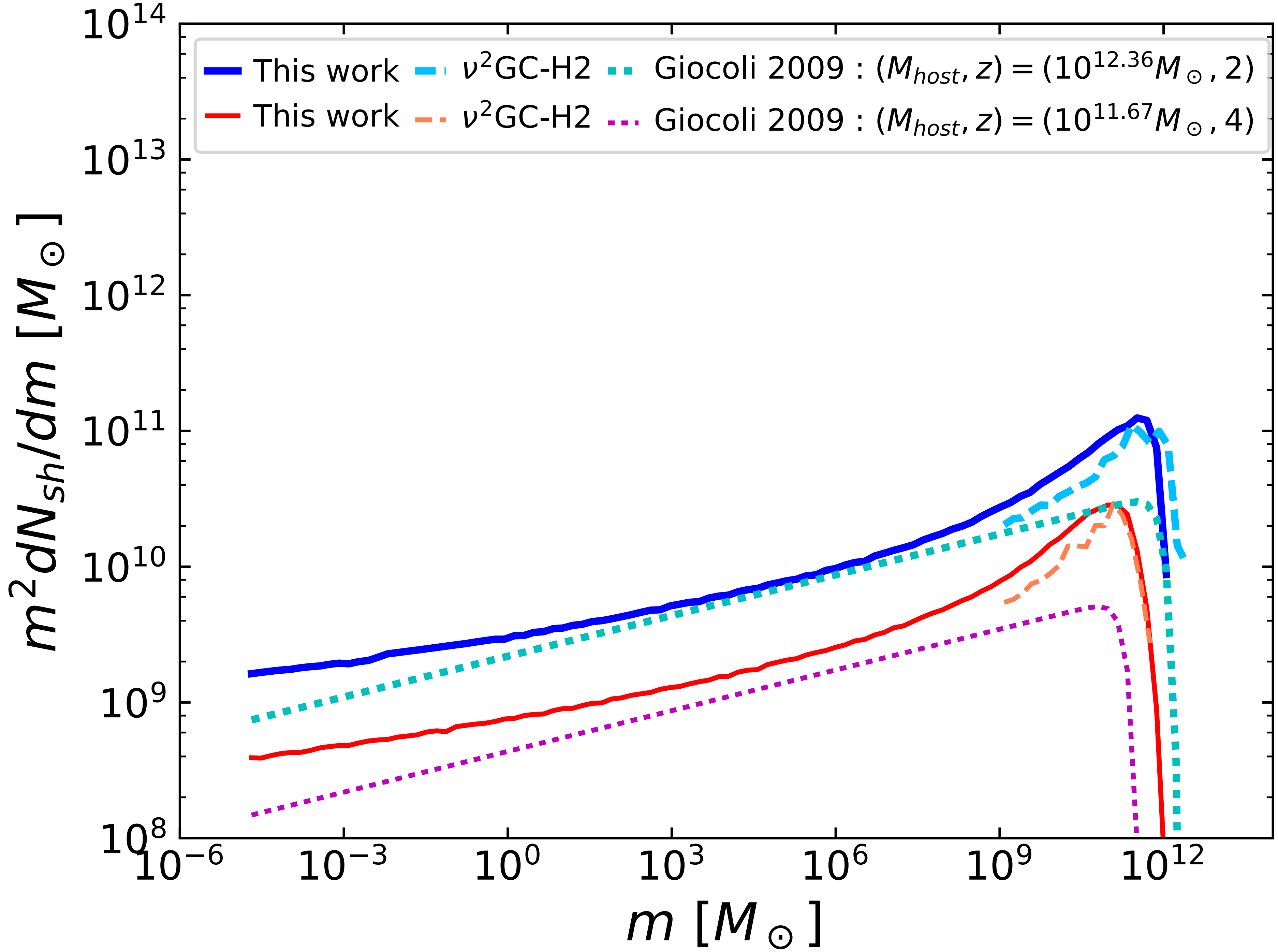
✓ **Modeling for tidal stripping and mass-loss rate**

Subhalo mass function: Clusters and galaxies



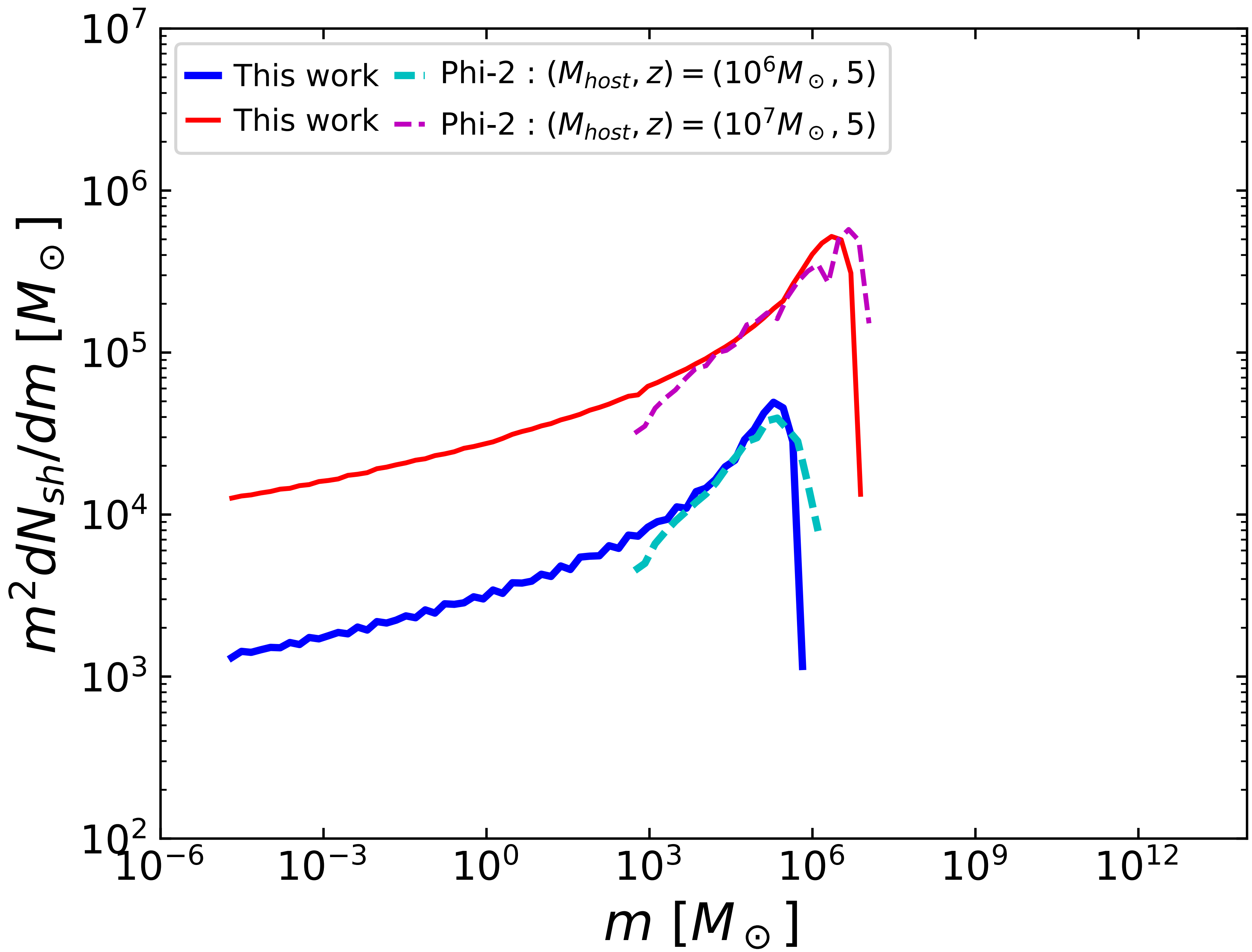
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function: Galaxies at z=2,4



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

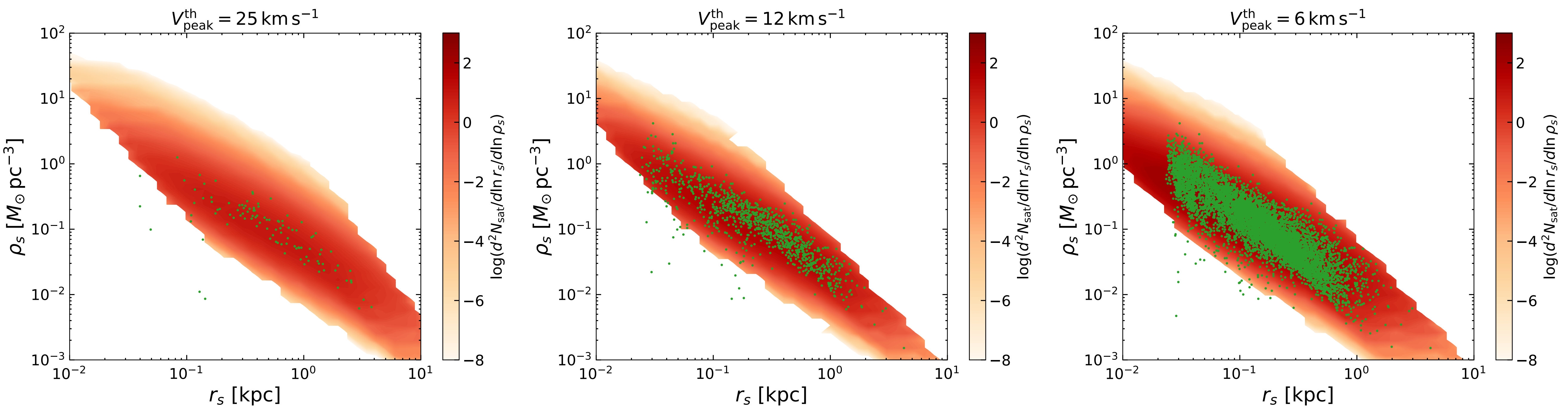
Subhalo mass function: Dwarfs at z=5



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

Good agreement with simulation results (Vea Lactea II)

Summary: Semi-analytical modeling

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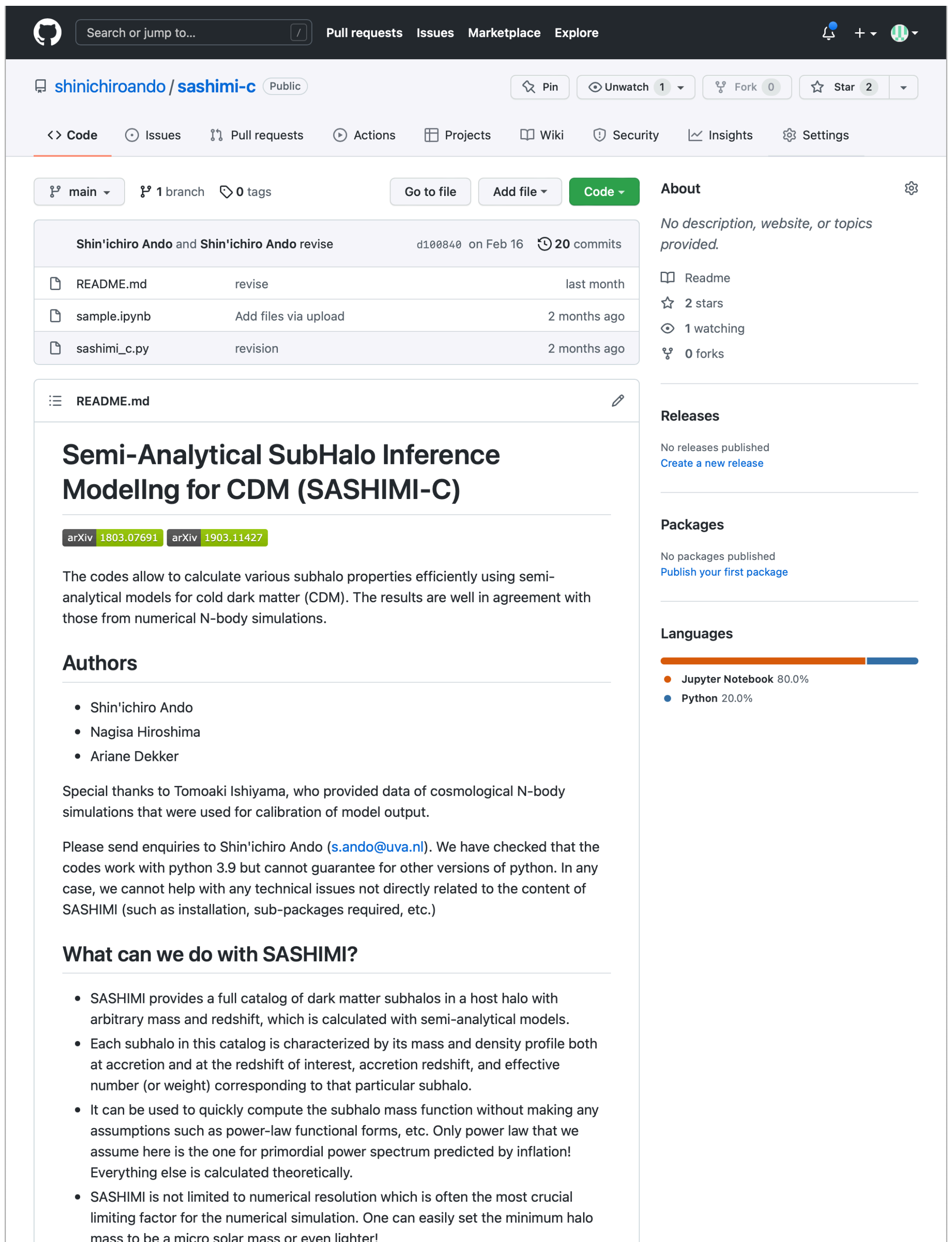
  - Well tested against numerical simulations of halos with various masses at various redshifts

Summary: Semi-analytical 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

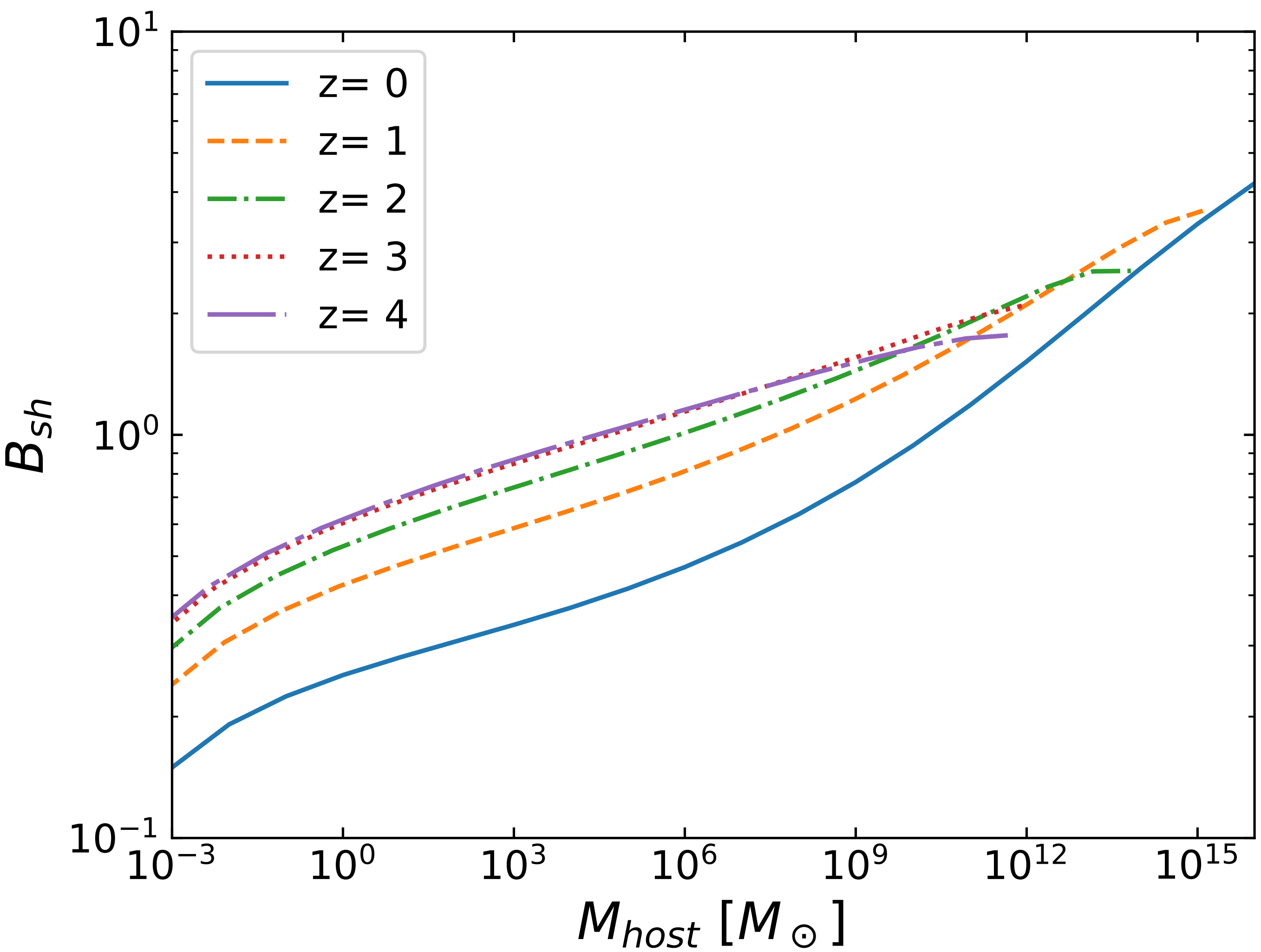
Release of public codes for semi-analytical subhalo models (CDM)



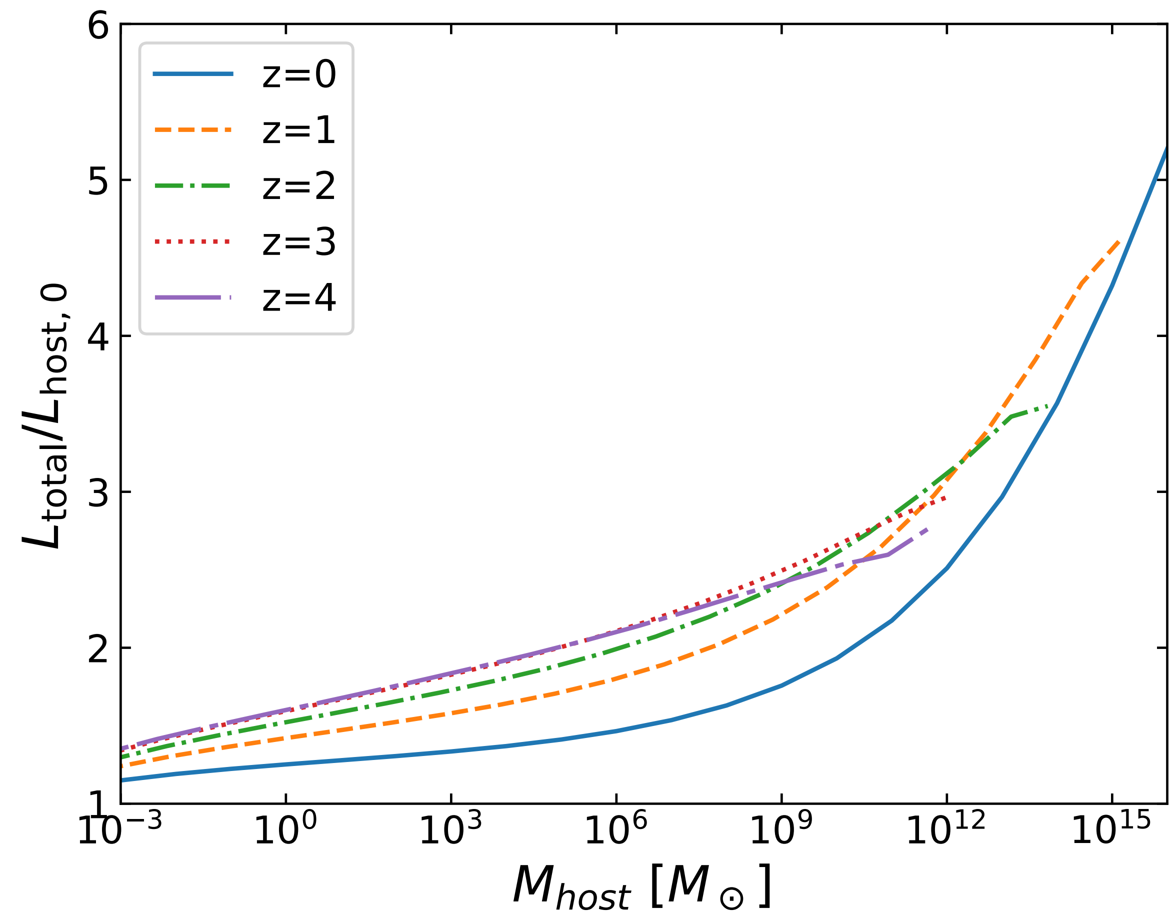
- **S**emi-**A**nalytical **S**ub**H**alo **I**nference **M**odel**I**ng
- "Cold" SASHIMI: *github.com/shinichiroando/sashimi-c*
- Only 760 lines of simple python codes, which enable to calculate (nearly) everything we did in Hiroshima et al. (2018)
    - Subhalo mass function, substructure boost of dark matter annihilation, etc.
- Well documented and useful sample codes provided

Application I: 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

Application II: Dwarf *J* factors

$$J = \int d\Omega \int d\ell \, \rho^2(r(\ell, \Omega))$$

- Estimates of density profiles and hence *J* factors of dwarf galaxies are based on stellar kinematics data
- *J* factors of promising dwarfs are ~10^{19} GeV^2/cm^5 or larger
- But *ultrafaint* dwarfs do not host many stars

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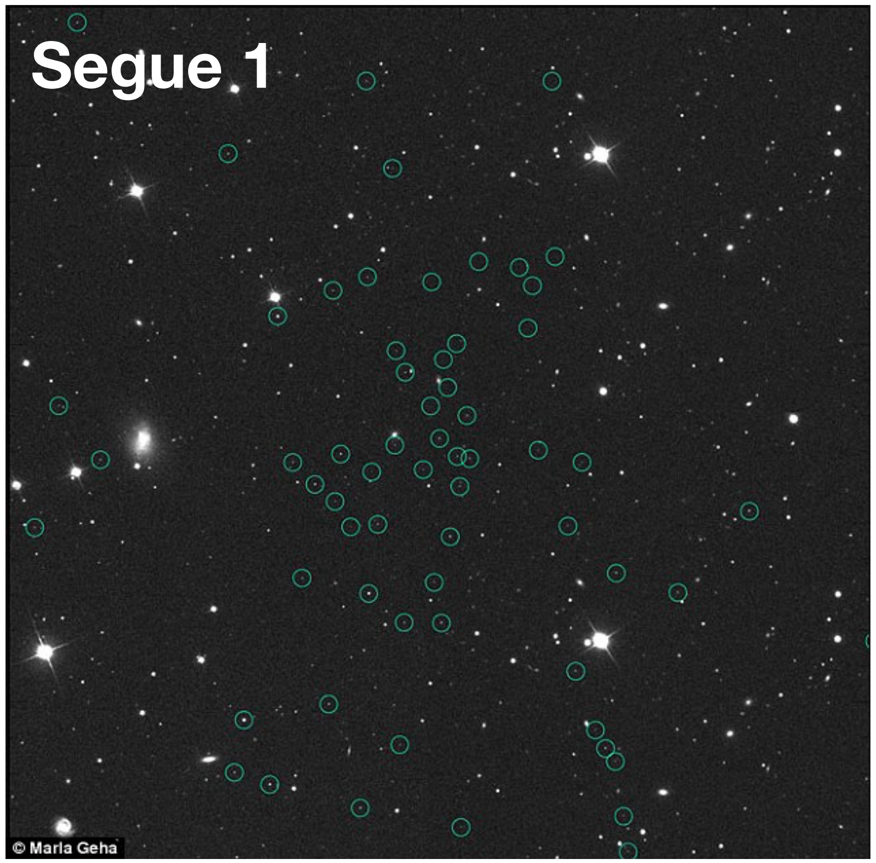

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Estimates of density profiles

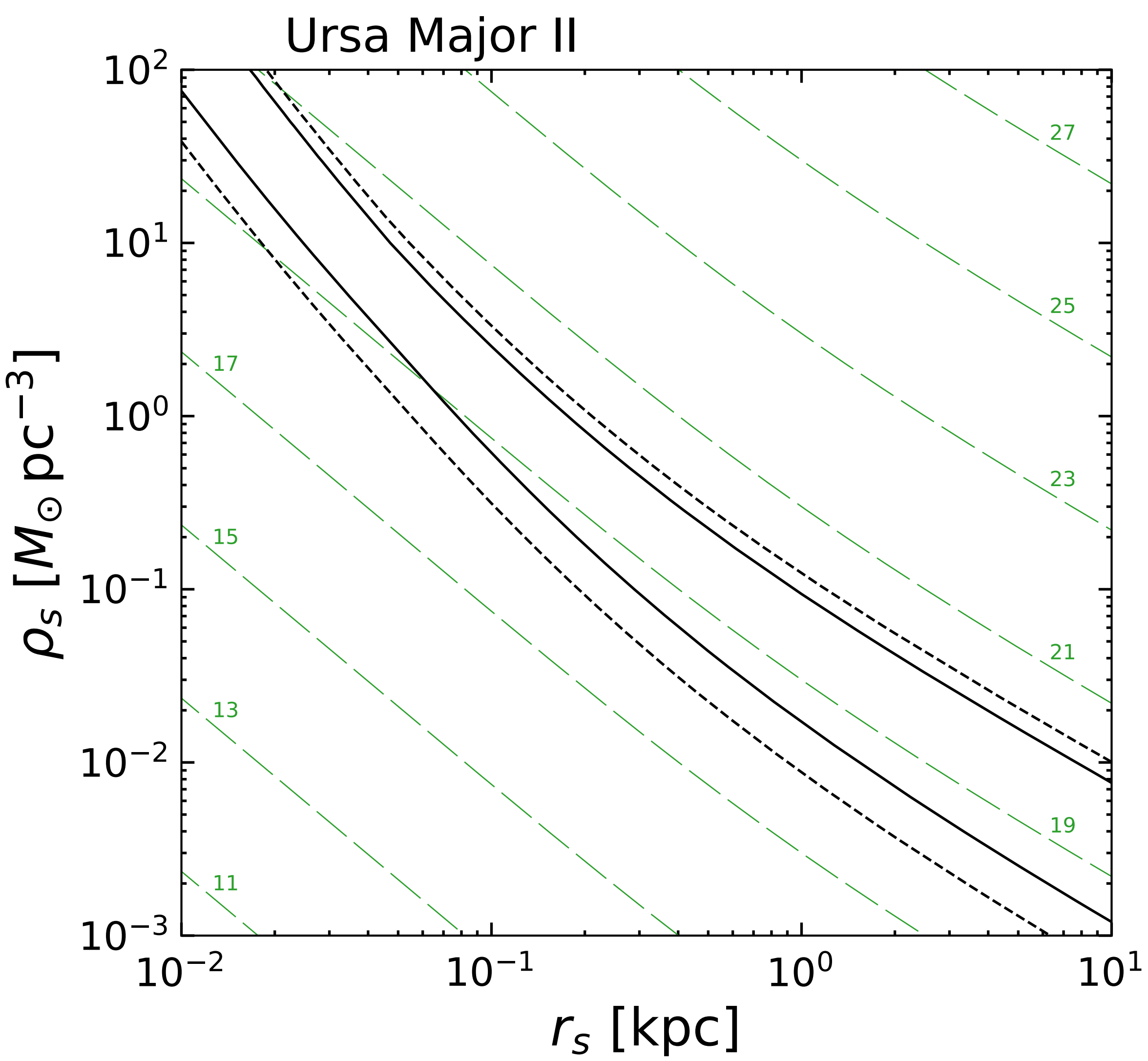
- Estimates of r_s and ρ_s usually rely on Bayesian statistics:

$$P(r_s, \rho_s \,|\, \mathbf{d}) \propto P(r_s, \rho_s)\mathscr{L}(\mathbf{d} \,|\, r_s, \rho_s)$$

- If data are not constraining, **the posterior depends on prior choices**
- Usually **log-uniform priors** are chosen for both r_s and ρ_s
- Doing frequentist way is very challenging, which is done only for *classical* dwarfs (Chiappo et al. 2016, 2018)

Impact of *satellite prior*

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



- **Black: Likelihood contours**
- **Green: log [*J*/(GeV^2/cm^5)]**

- Having small data only does not break the degeneracy between r_s and ρ_s

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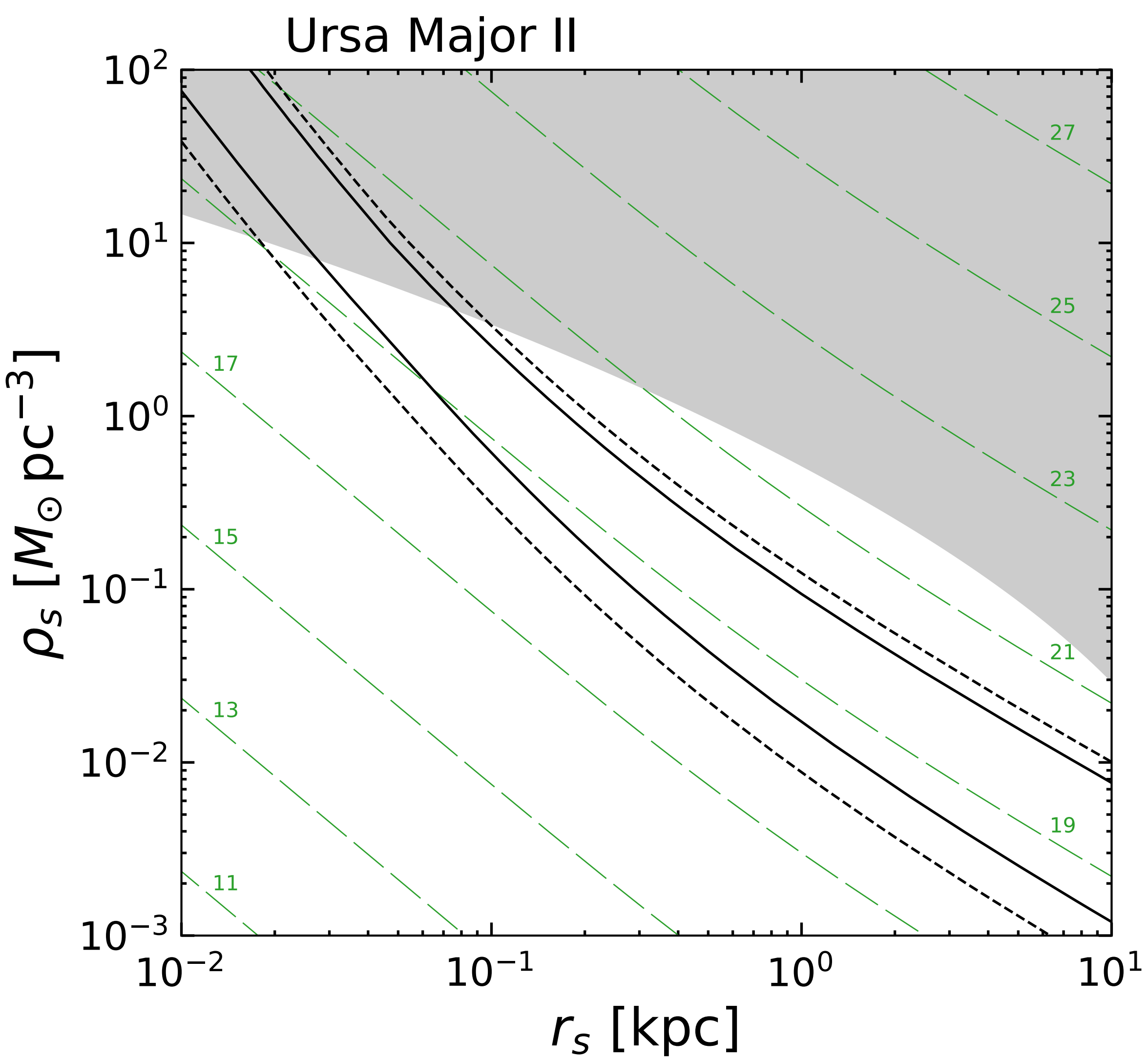

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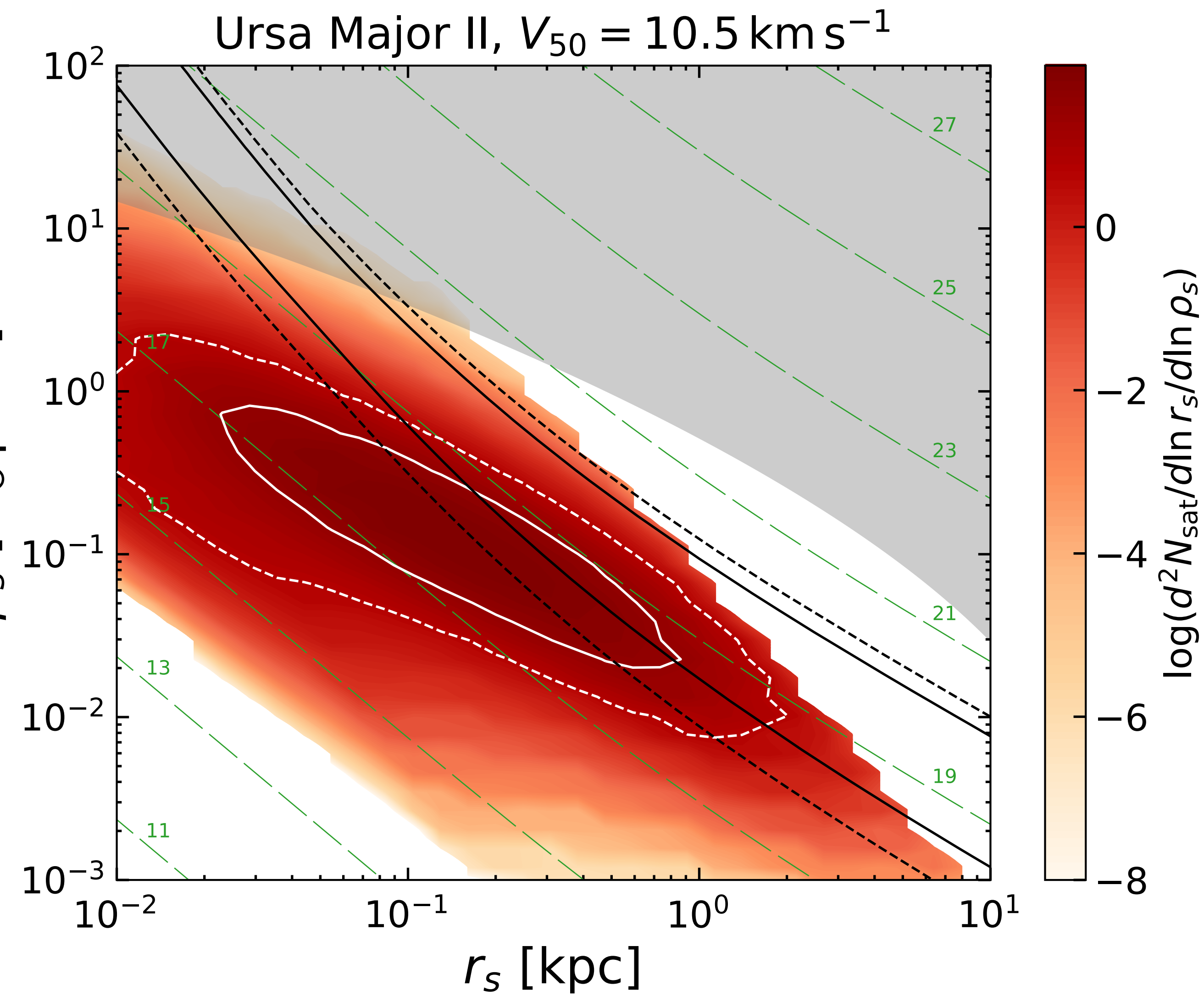

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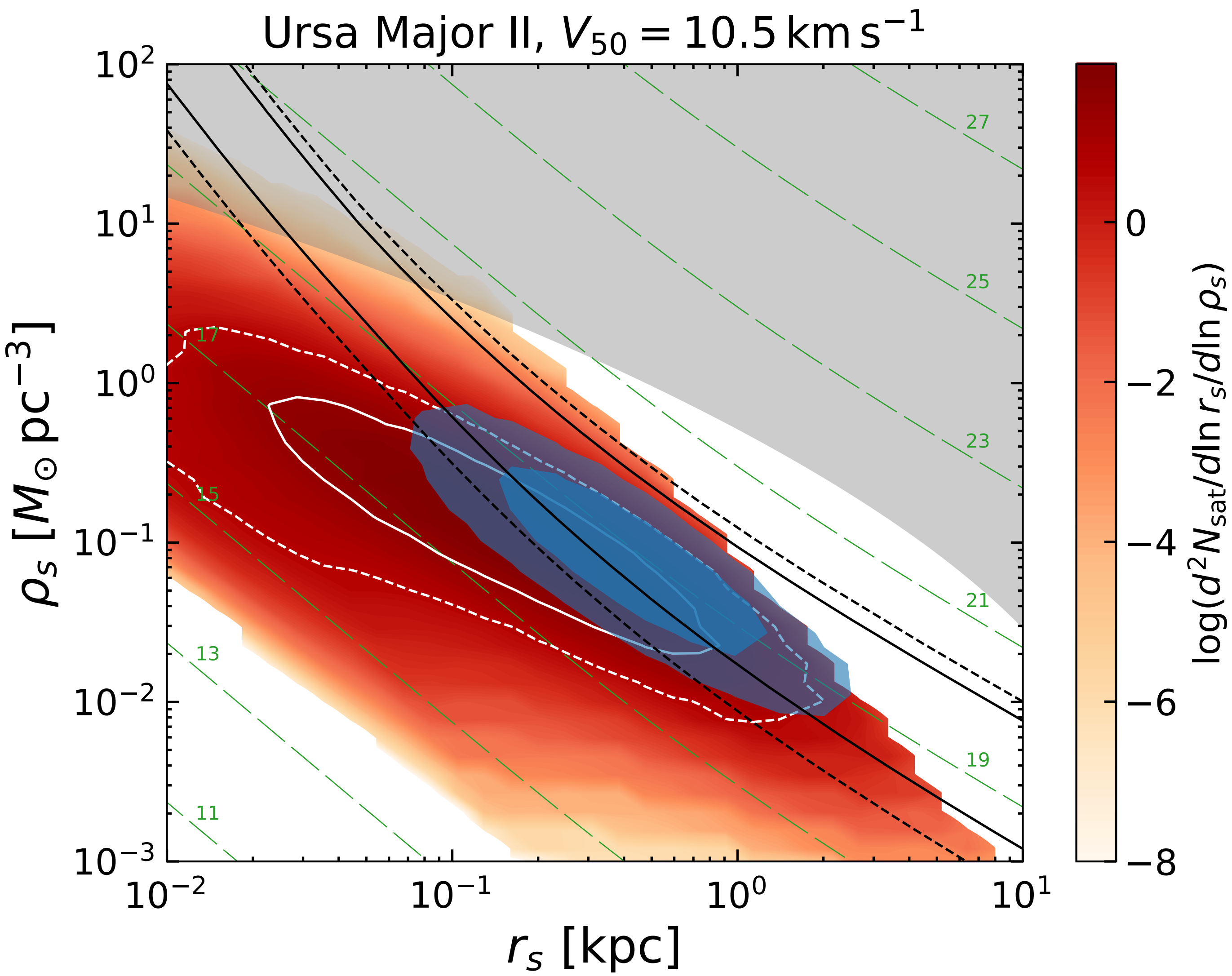

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- **Blue: Posterior density**

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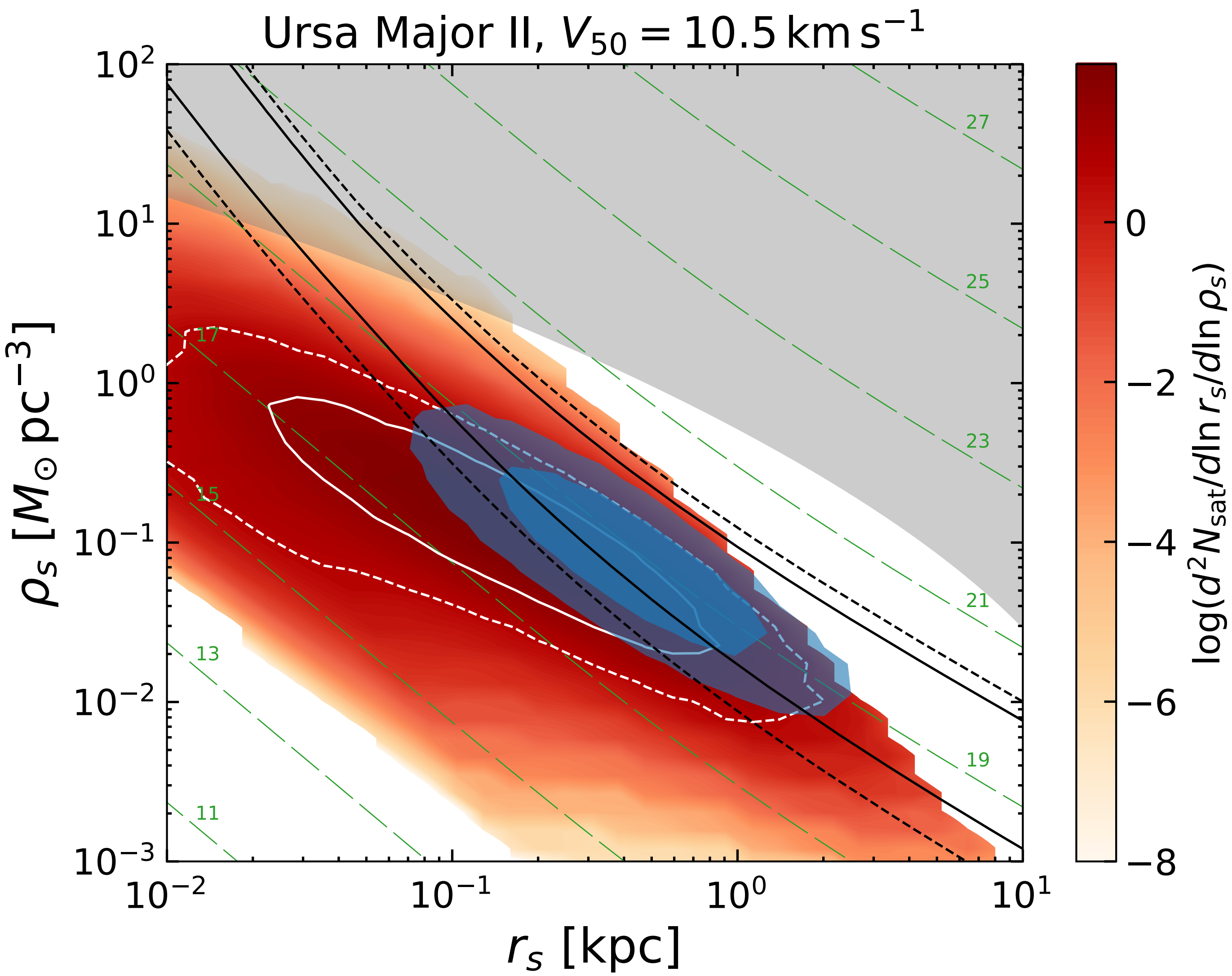

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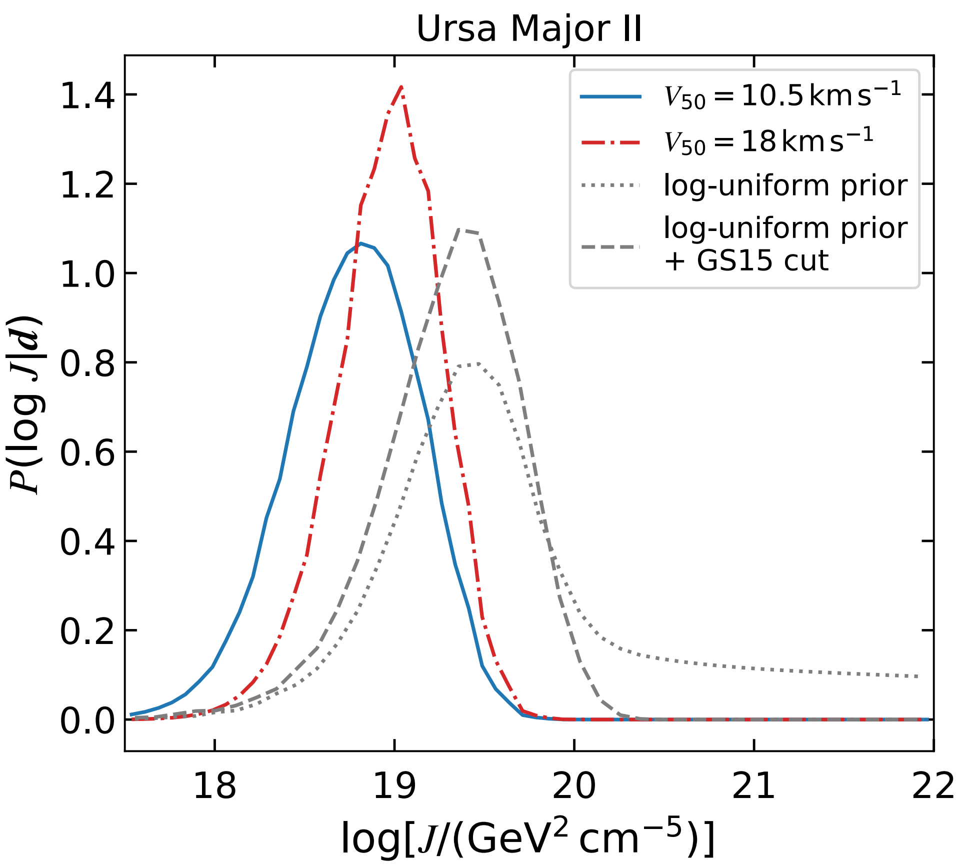
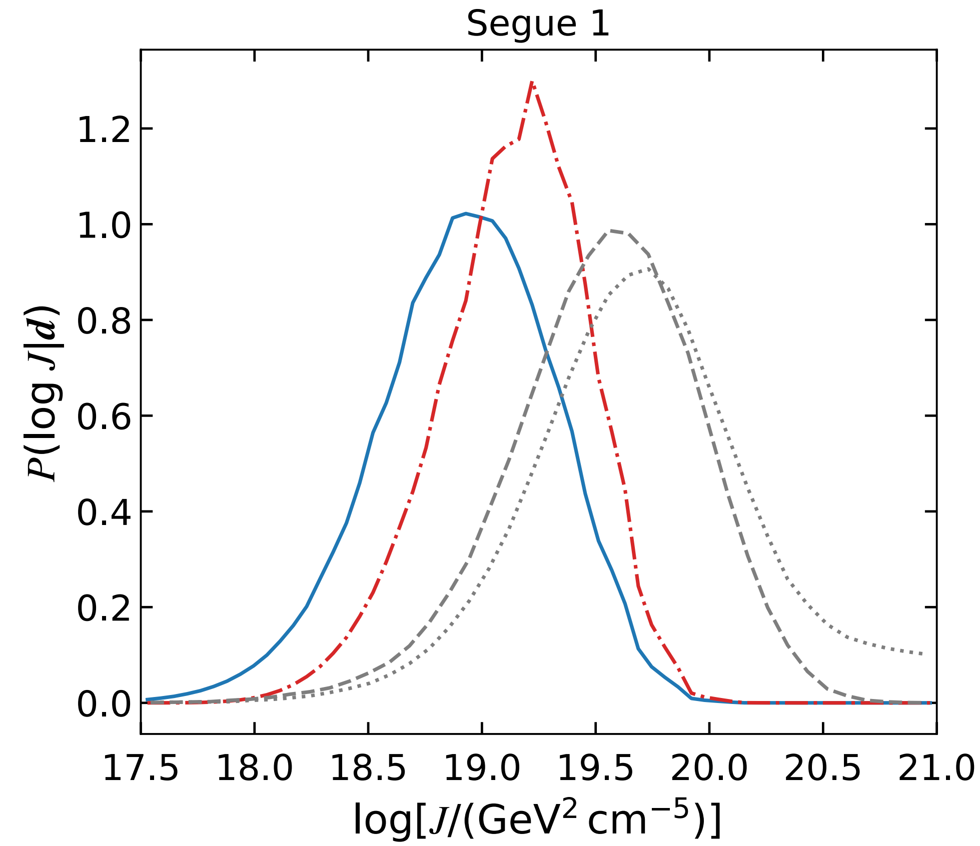
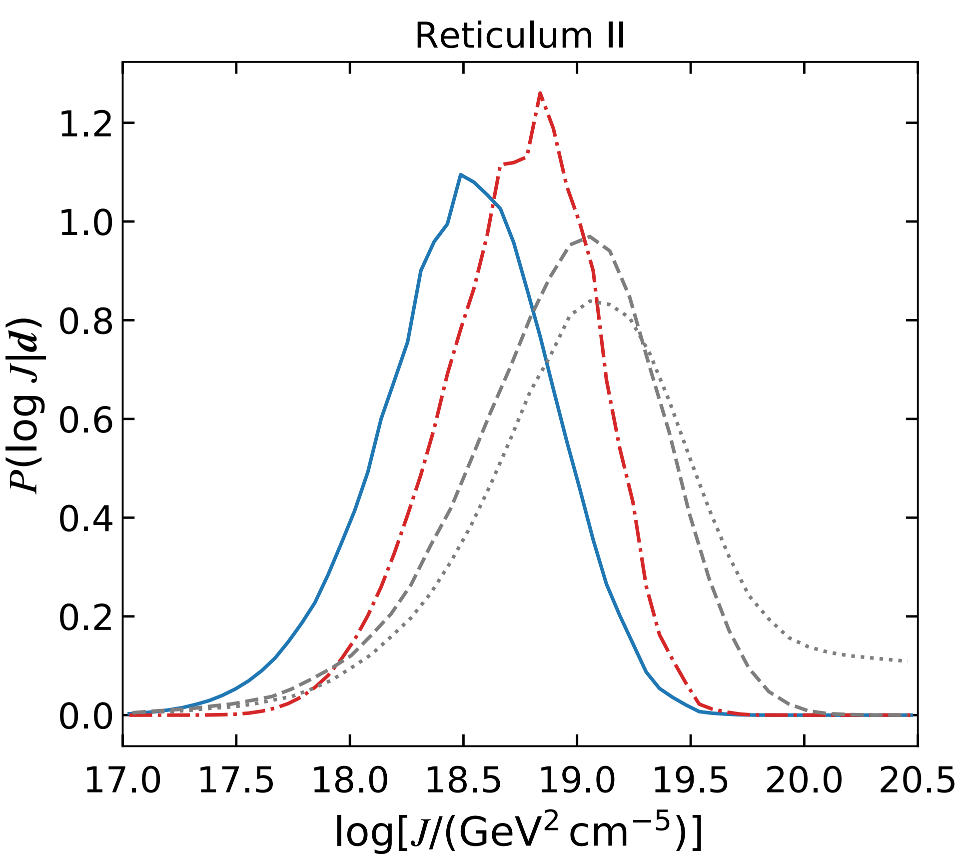
- Satellite prior does this job naturally as well as breaks the degeneracy
- This is hard to achieve with simulations as they are limited by statistics of finding dwarf candidates

Impact of *satellite prior*



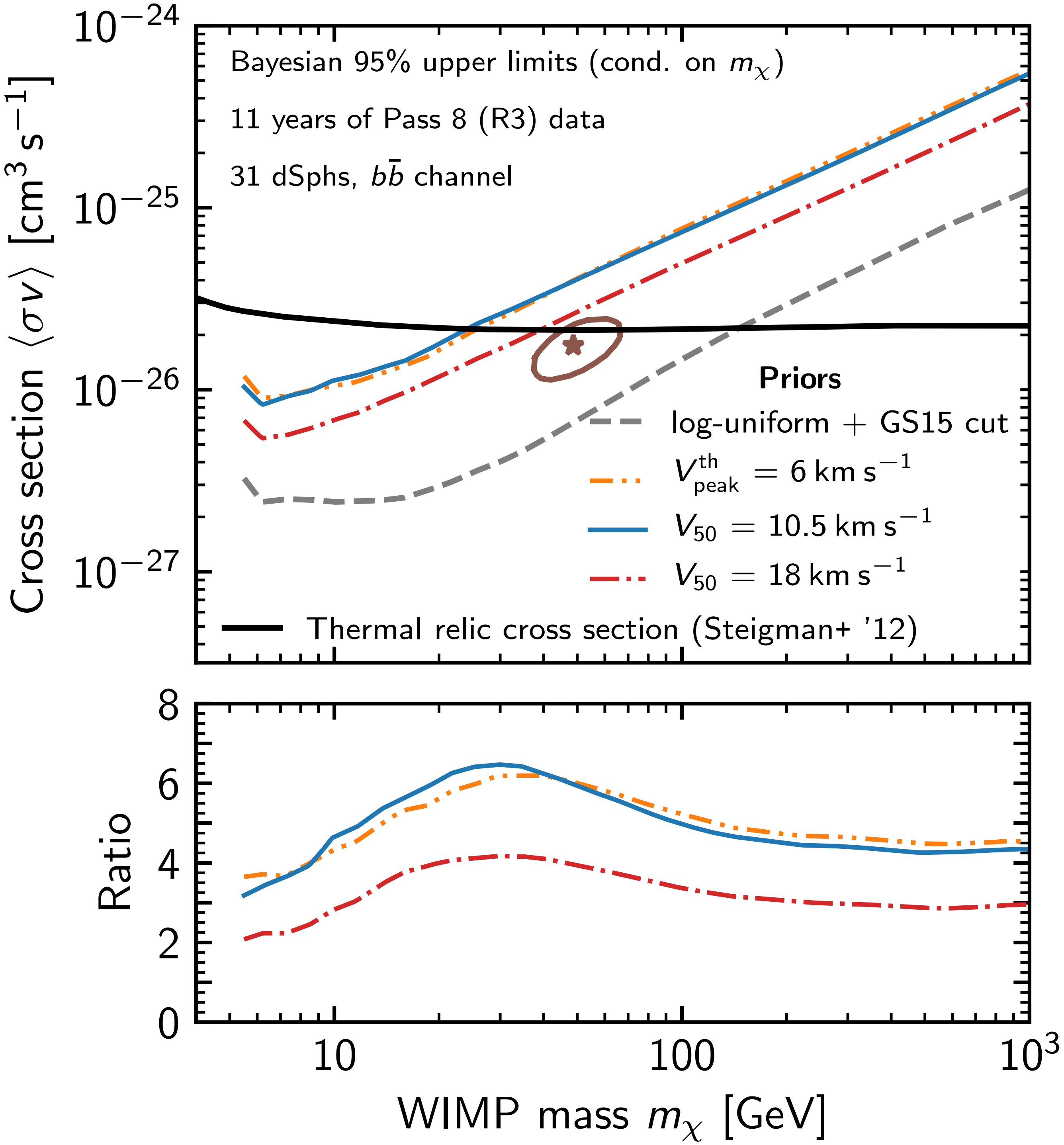




Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker, *Phys. Rev. D* **102**, 061302 (2020)

- Using satellite priors will systematically shift the *J* distribution toward lower values
- But this depends on satellite formation models

Cross section constraints

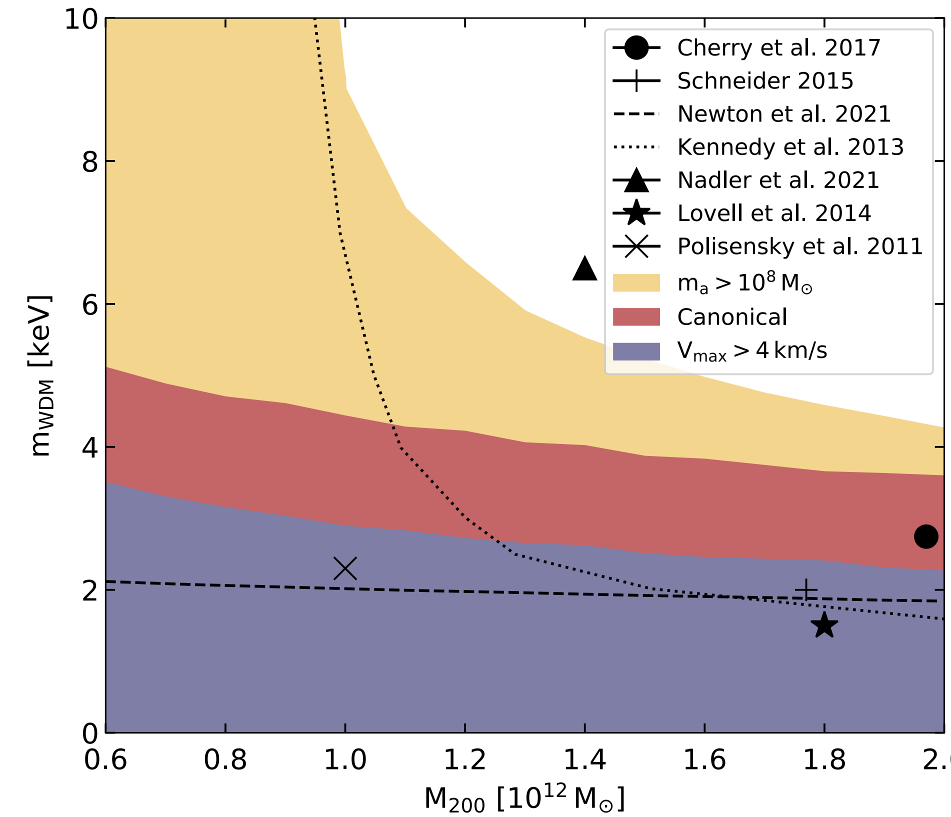


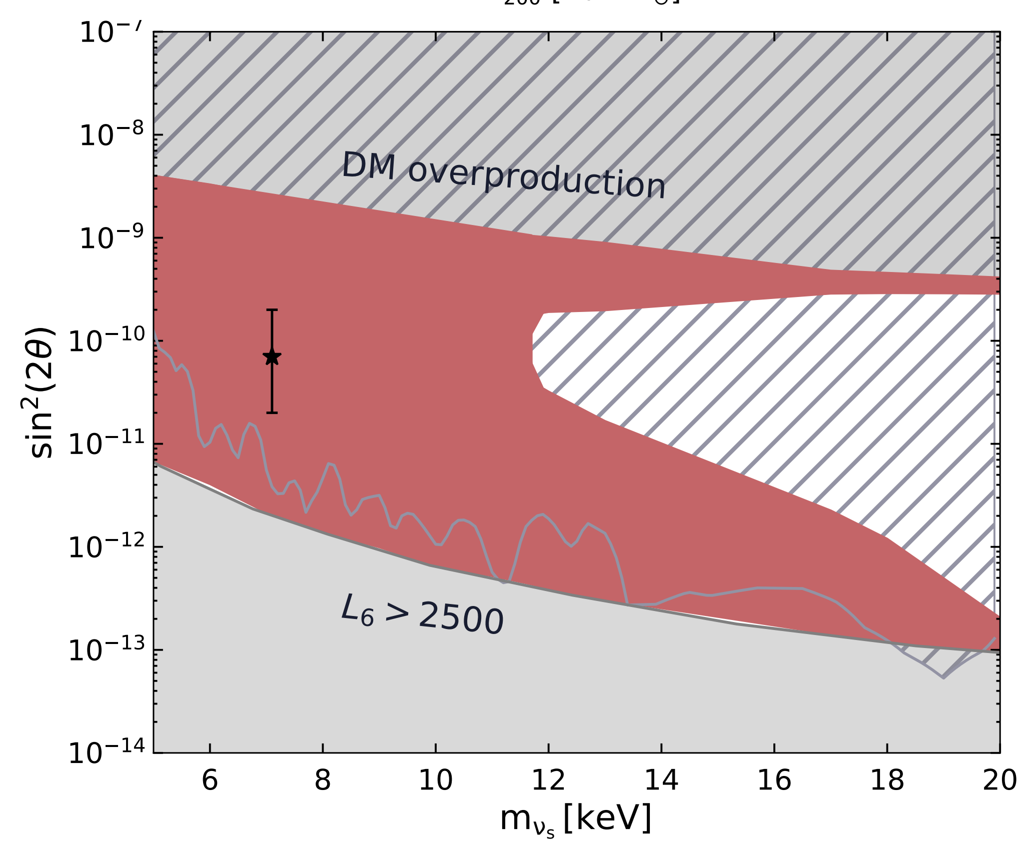
- Adopting satellite priors **weaken** the cross section constraints by **a factor of 2-7**
- The effect is relatively insensitive to condition of satellite formation: **robust prediction**
- Thermal cross section can be excluded only up to 20-50 GeV
- Also very relevant for wino dark matter targeted by CTA (*Ando, Ishiwata 2021*)

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

Application III: WDM

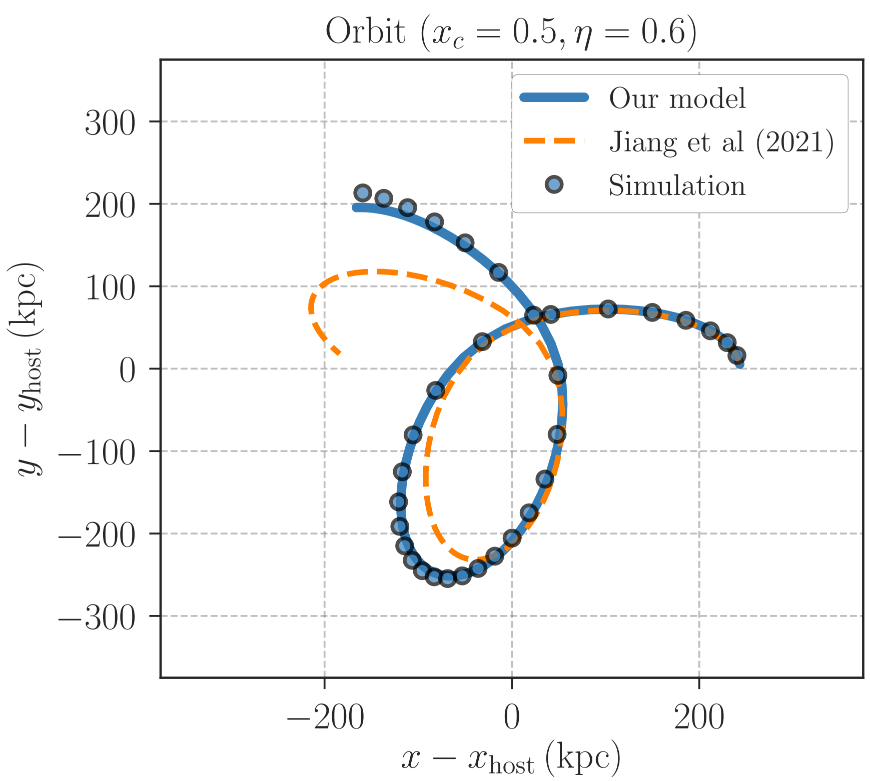
- "Warm" SASHIMI (*github.com/shinichiroando/sashimi-w*)
    - Applied SASHIMI codes to the case of WDM by modifying power spectrum, etc.
- Compare with satellite number counts (DES+PanSTARRS1)
    - Excluding WDM mass of < 3.6-5.1 keV (without baryon physics uncertainties)
    - Excluding sterile neutrino dark matter (combined with X rays)

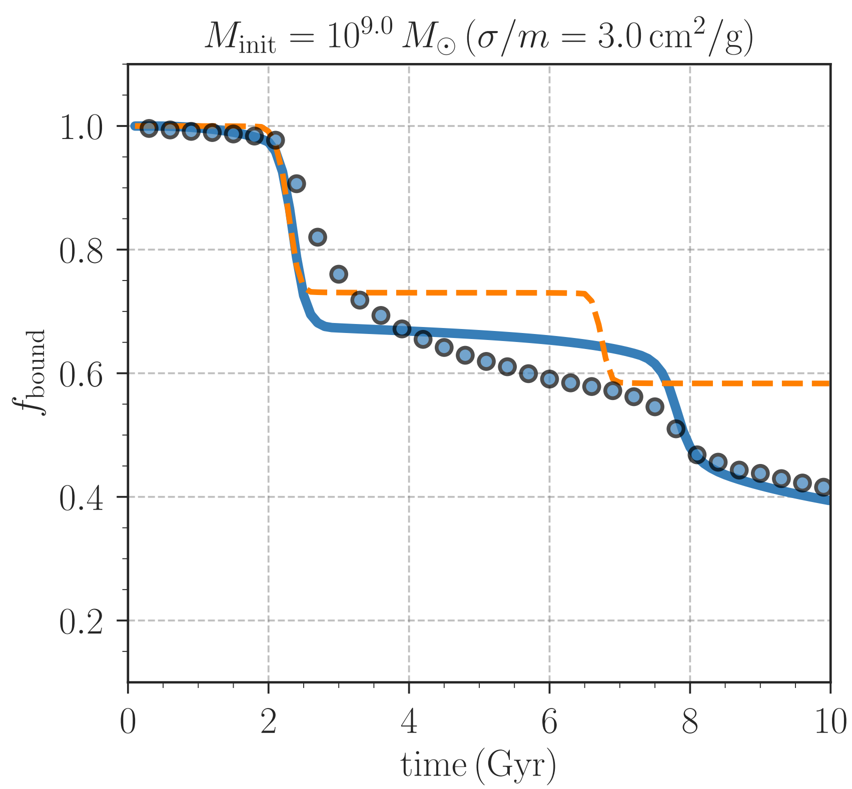


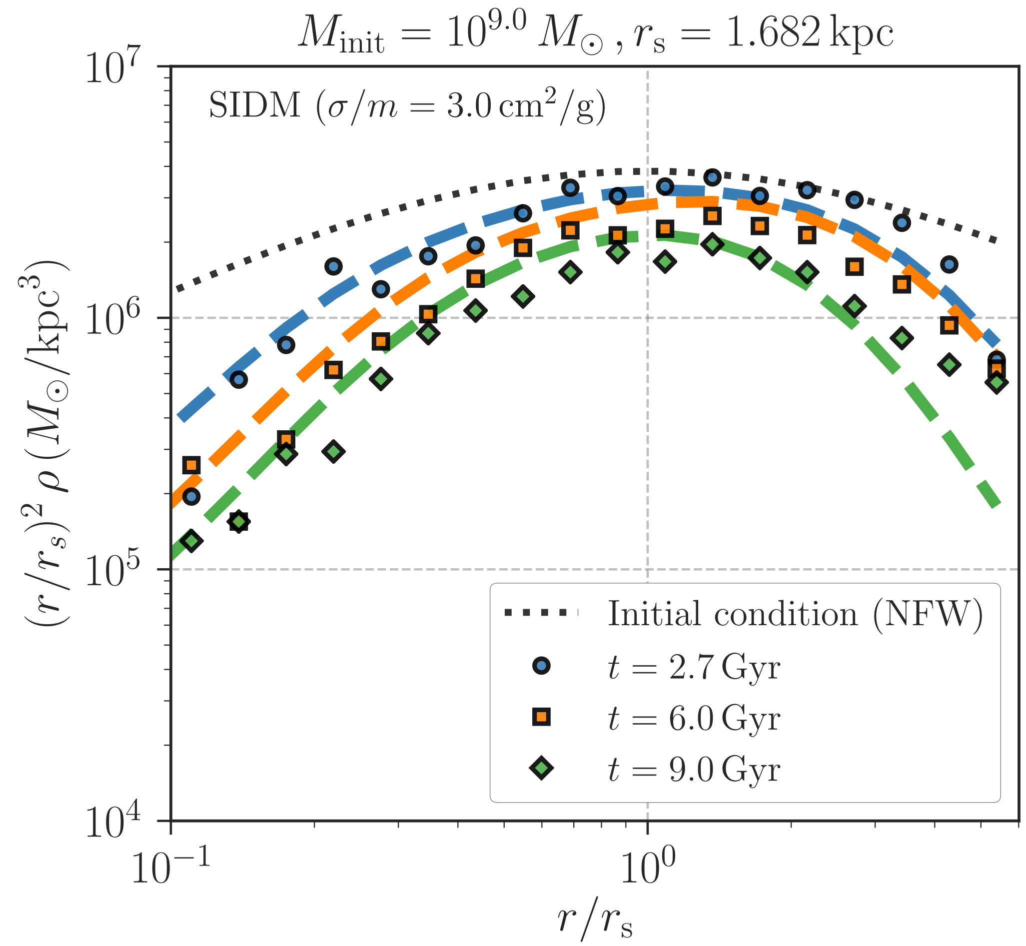


Dekker, Ando, Correa, Ng, arXiv:2111.13137 [astro-ph.CO]

Application IV: SIDM







Shirasaki, Okamoto, Ando, arXiv:2205.09920 [astro-ph.CO]

- Building semi-analytical models for SIDM in calibration with N-body simulations

Conclusions and prospects

- **Small-scale distribution** of dark matter is essential in discriminating different particle dark matter candidates

- We base our theoretical studies on **benchmark subhalo models for CDM/WIMP**; there still are many tasks to make the models more accurate (e.g., the impact of halo assembly history; *Hiroshima, Ando, Ishiyama 2022*)

- Various applications: annihilation, dwarf density profile, etc.

- Extension to different dark matter candidates such as **WDM** and **SIDM**, and **inflation models** (primordial power spectrum)