Title: Formation and evolution of dark matter substructure: Semi-analytic approach

Speakers: Shin'ichiro Ando

Series: Cosmology & Gravitation

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Abstract:

Although cold dark matter (CDM) has been established, this is only the case for measurements at large scales, which are larger than galaxy-sized structures. Even though we need to understand the important role of baryonic components, matter distribution at small scales can be the key to distinguishing different particle dark matter candidates. In fact, warm dark matter, self-interacting dark matter, and fuzzy dark matter have been proposed, yielding different matter distributions at sub-galactic scales. These small-scale distributions have been studied with numerical simulations. Whereas very reliable, numerical simulations suffer certain issues. They are limited by both numerical resolution and shot noise. They tend to take a lot of computational time. These might be a bottleneck for surveying through multi-dimensional parameter space of various dark matter models. I present semi-analytic models of small-scale structure, especially dark matter subhalos, which are based on structure formation theory and the tidal evolution of subhalos. Our models for CDM have been well tested against the results of various numerical simulations. The semi-analytic models are free from all the problems of the numerical simulations mentioned above. Therefore, they might be essential ingredients for identifying the particle nature of dark matter through gravitational (lensing, pulsar timing), astrophysical (satellite counts, stellar streams), and astroparticle probes (gamma rays).

GRAPPA
GRavitation AstroParticle Physics Amsterdam

Cosmology Seminar
Perimeter Institute
September 14, 2021

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

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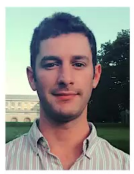

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(Former bachelor students in Amsterdam)

Ad

Dark Matter Consortium in Japan

- **What is dark matter? - Comprehensive study of the huge discovery space in dark matter**
- Program from 11/2020 to 3/2025
- JPY1.3B = €10M research budget; two postdocs in my team

科研費
KAKENHI

PI	H. Murayama (Berkeley / Tokyo)	
A01	F. Takahashi (Tohoku)	Light DM
A02	K. Murase (PSU / Kyoto)	Heavy DM
A03	C. Yoo (Nagoya)	PBH
B01	Y. Michimura (Tokyo)	KAGRA
B02	M. Takada (Tokyo)	Subaru PFS
B03	S. Miyazaki (NAOJ)	Subaru HSC
B04	N. Yamasaki (JAXA)	XRISM
B05	S. Nishida (KEK)	Belle II
B06	E. Komatsu (MPA / Tokyo)	CMB
C01	M. Yamazaki (Tokyo)	Quantum gravity
C02	S. Ando (Amsterdam / Tokyo)	Cosmic structure

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

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

Small scale structure

WIMPs, axions, ALPs, PBHs

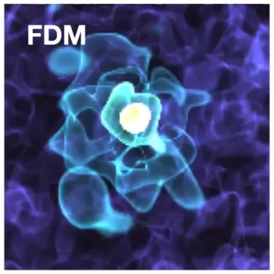
- Cusps in density profiles
- Very many small (sub)structures

Sterile neutrinos

- Cutoff at sub-galaxy scale in the power spectrum

SIMPs, dark atoms

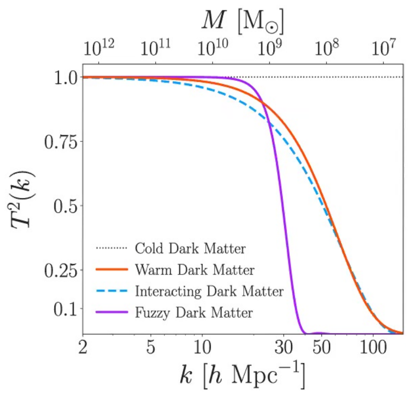
- Cores in density profiles induced by self scattering



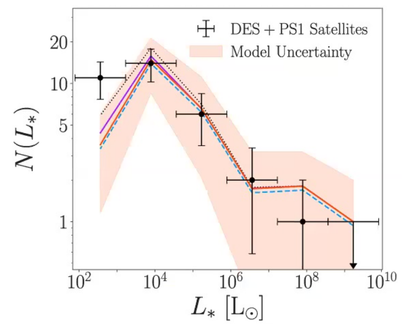
Ultralight bosons

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

Recent development (1)
Satellite counts



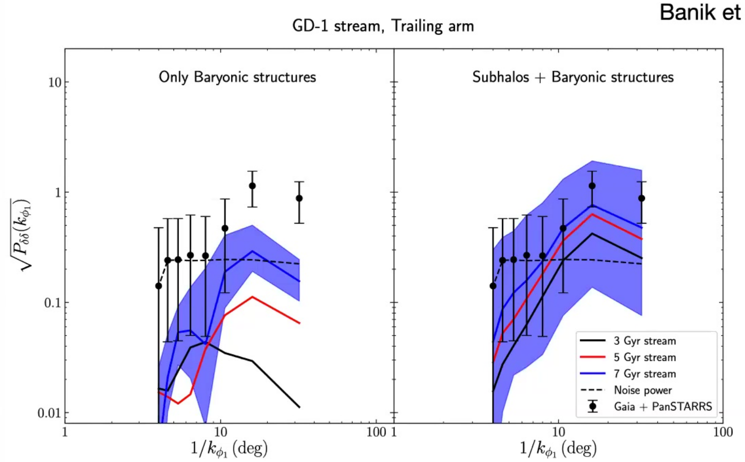
Nadler et al., *Phys. Rev. Lett.* **126**, 091101 (2021)

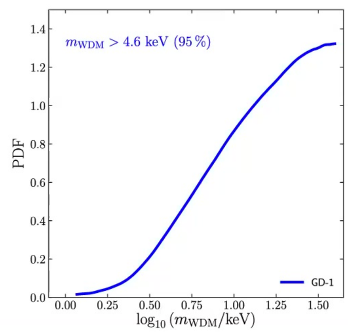


$$m_{\mathrm{WDM}} > 6.5 \text{ keV}$$
$$m_{\mathrm{FDM}} > 2.9 \times 10^{-21} \text{ eV}$$

Recent development (2)
Stellar streams

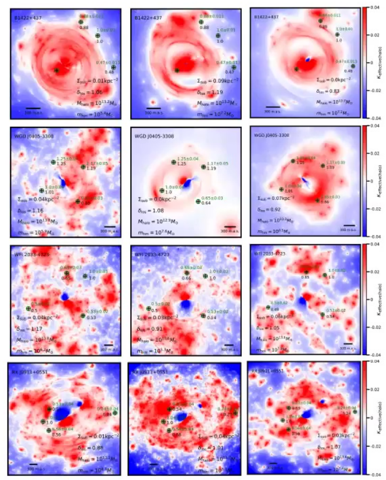
Banik et al., arXiv:1911.02663 [astro-ph.GA]

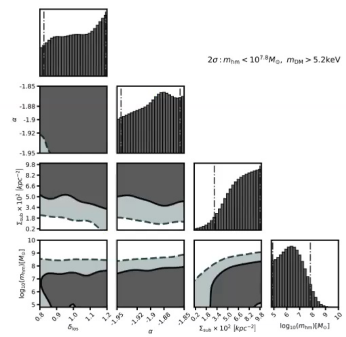




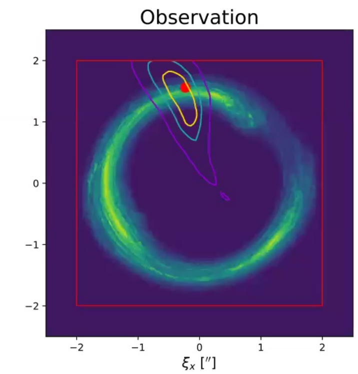
Caveat: *These results are based on fitting functions of the simulation results, which are extrapolated below resolution*

Recent development (3) Gravitational lensing





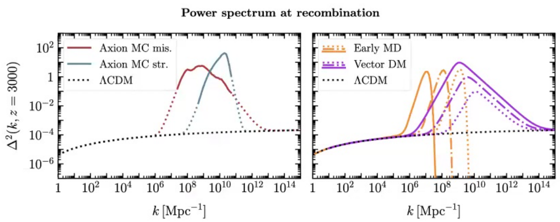
Coogan et al., arXiv:2010.07032 [astro-ph.CO]



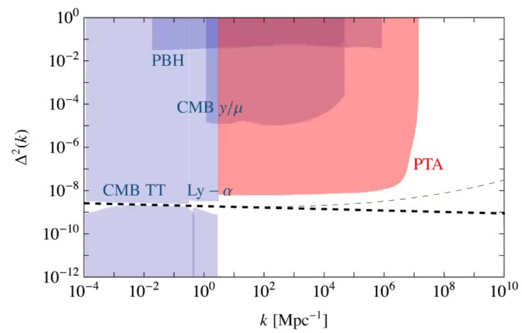
Gilman et al., *Mon. Not. R. Astron. Soc.* **491**, 6077 (2020)

Caveat: *These results are based on fitting functions of the simulation results, which are extrapolated below resolution*

Recent development (4)
Pulsar timing array



Lee et al., arXiv:2012.09857 [astro-ph.CO]

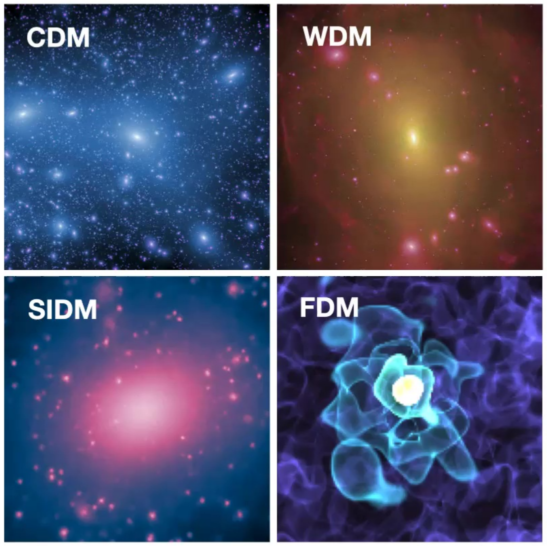


Primordial power spectrum might be probed with pulsar timing measurements

Caveat: *Simple analytic prescription was adopted for predicting small subhalo distributions*

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

My personal take - where this started

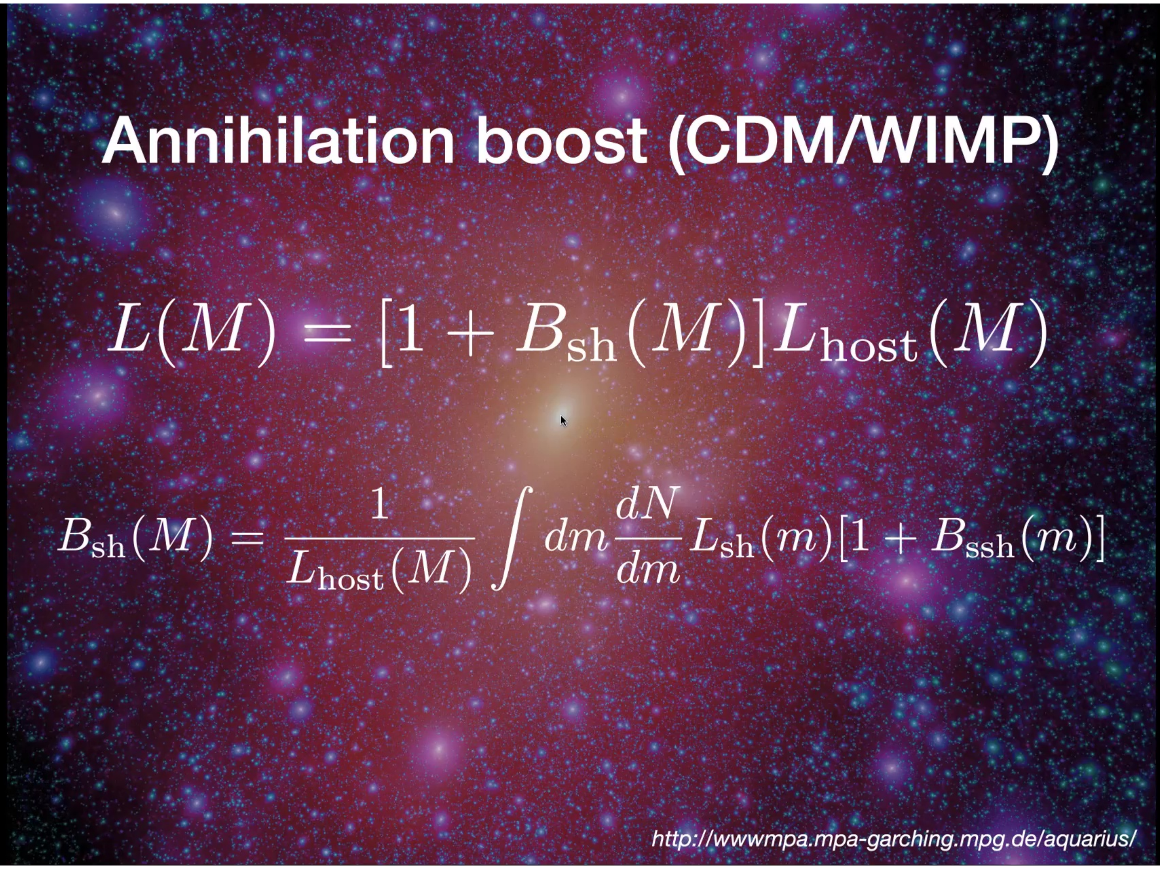
- WIMPs: Halo masses range **20 (!) orders of magnitude** from Earth to clusters of galaxies
- Numerical simulations can resolve down to $\sim 10^5 M_{\odot}$ and observationally much larger
- Lots of resources have been spent to understand baryonic effect rather than increasing this resolution over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

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

Annihilation boost (CDM/WIMP)

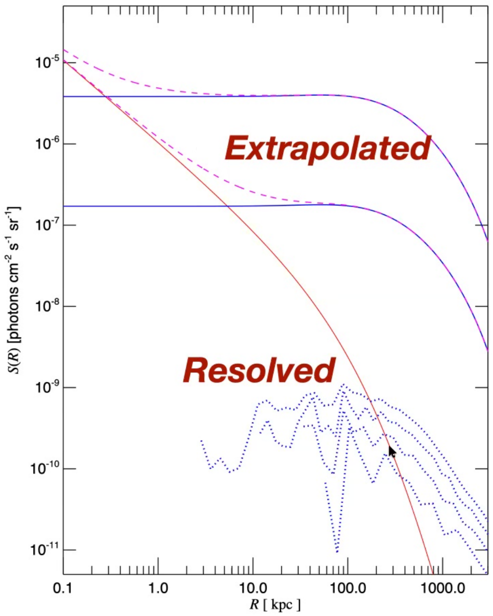
$$L(M) = [1 + B_{\rm sh}(M)]L_{\rm host}(M)$$

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

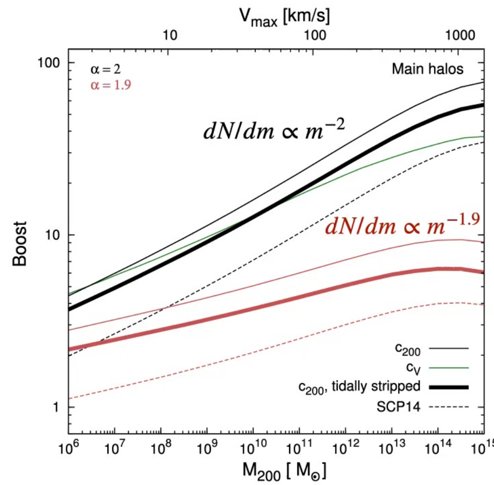


http://wwwmpa.mpa-garching.mpg.de/aquarius/

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-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

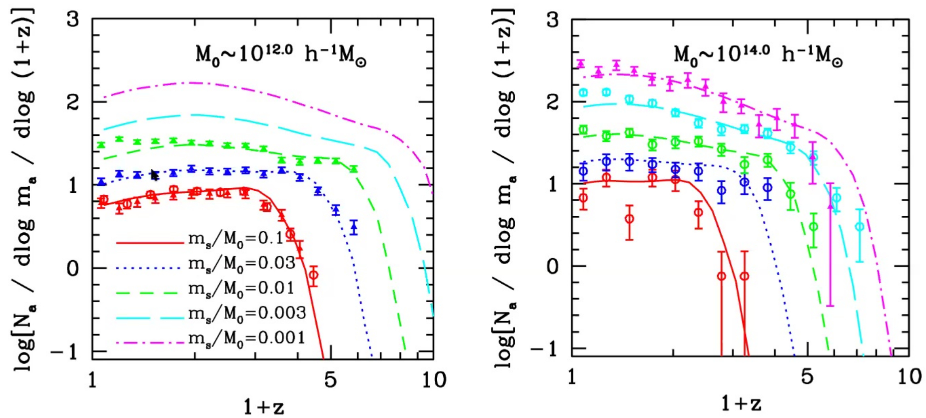
Extended Press-Schechter formalism

↓

Subhalos experience mass loss

Modeling for tidal stripping and mass-loss rate

Subhalo accretion



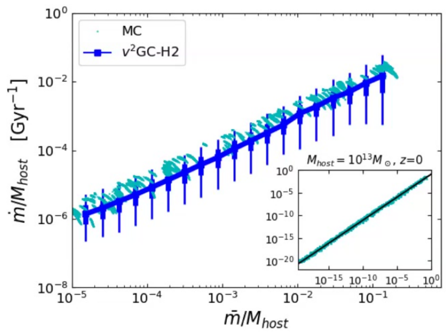
Yang et al., *Astrophys. J.* **741**, 13, (2011)

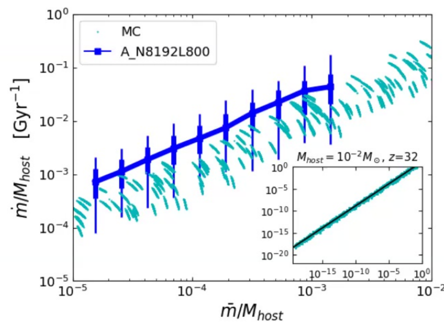
Infall distribution of subhalos:
Extended Press-Schechter formalism

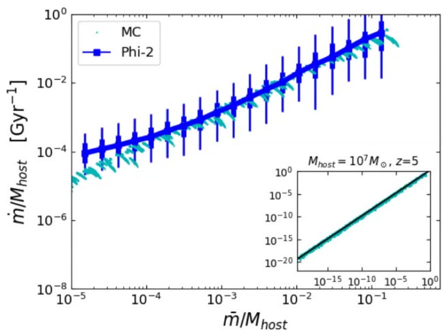
$$\frac{d^2N_{\rm sh}}{dm_{\rm acc}dz_{\rm acc}} \propto \frac{1}{\sqrt{2\pi}} \frac{\delta(z_{\rm acc})-\delta_M}{(\sigma^2(m_{\rm acc})-\sigma_M^2)^{3/2}} \exp\left[-\frac{(\delta(z_{\rm acc})-\delta_M)^2}{2(\sigma^2(m_{\rm acc})-\sigma_M^2)}\right]$$

Subhalo evolution

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

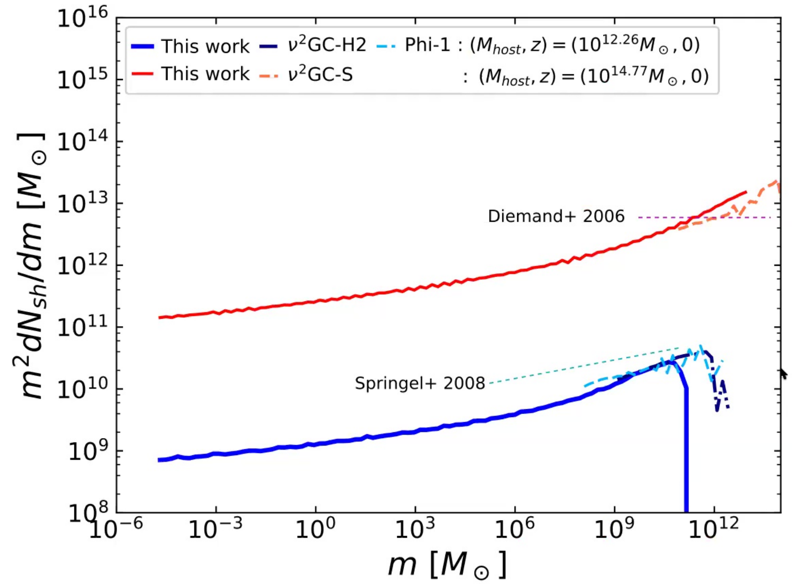






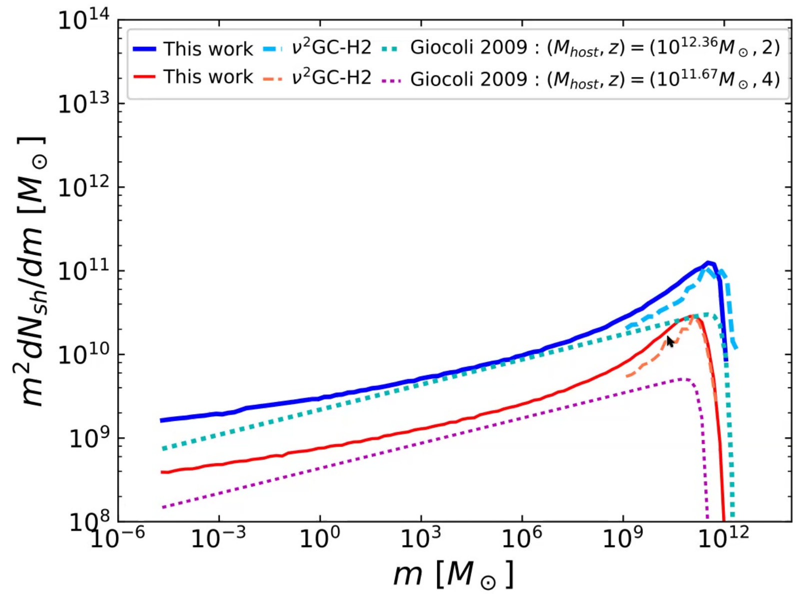
- Monte Carlo approach
  - Determine orbital energy and angular momentum
  - Assume the subhalo loses all the masses outside of its tidal radius instantaneously at its peri-center passage
- Internal structure changes follow Penarrubia et al. (2010)

Subhalo mass function: Clusters and galaxies



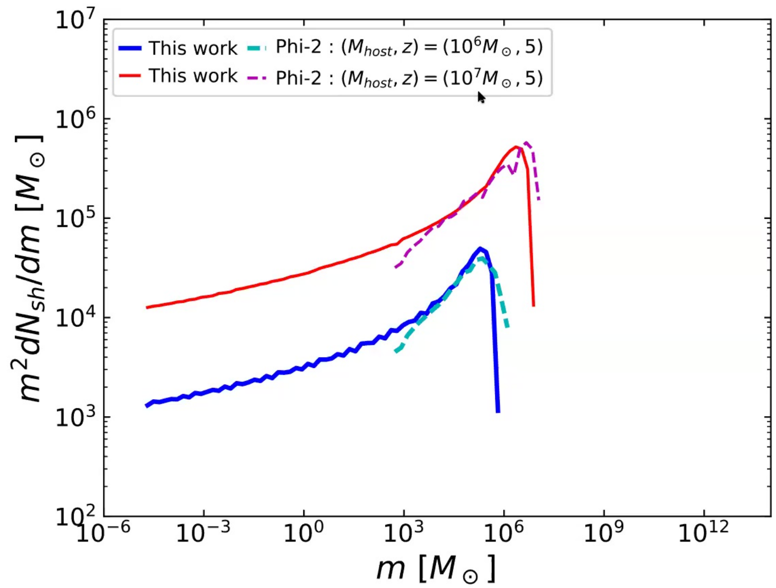
Hiroshima, Ando, Ishiyama, *Phys. Rev. D* **97**, 123002 (2018)

Subhalo mass function: Galaxies at z=2,4



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

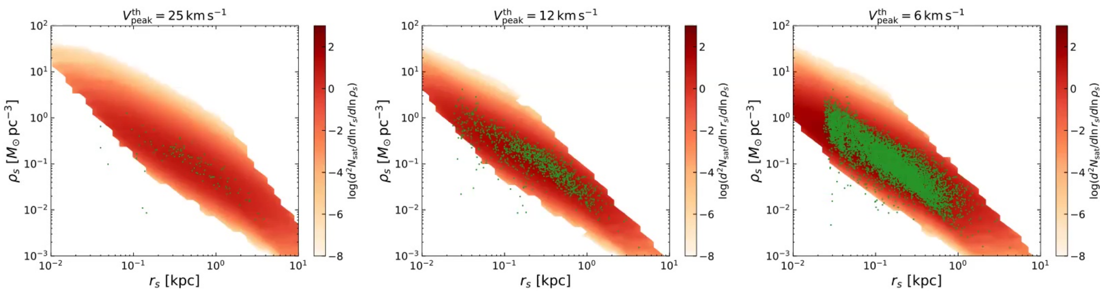
Subhalo mass function:
Dwarfs at z=5



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)

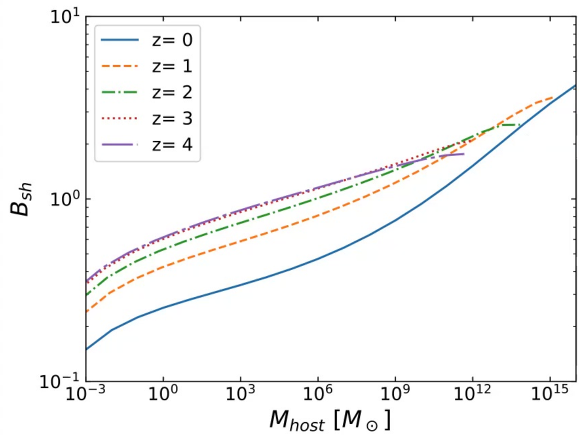
Good agreement with simulation results (Vea Lactea II)

Summary: Semi-analytic modeling

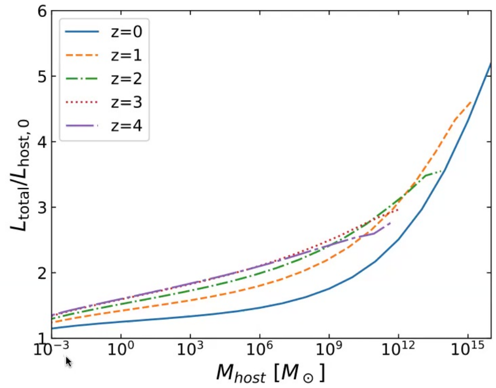
- Benchmark models for CDM / WIMP
  - Free from resolution (useful for small mass ranges)
  - Free from shot noise (useful for large mass ranges)
  - Well tested against numerical simulations of halos with various masses at various redshifts
  - Quick implementation, which is crucial to survey through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

Application 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} $\mathrm{GeV^2/cm^5}$ or larger
- But *ultrafaint* dwarfs do not host many stars

Estimates of density profiles

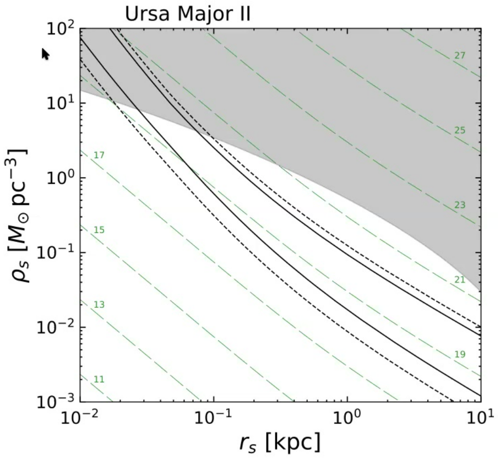
- Estimates of r_s and ρ_s usually rely on Bayesian statistics:

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

- 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)

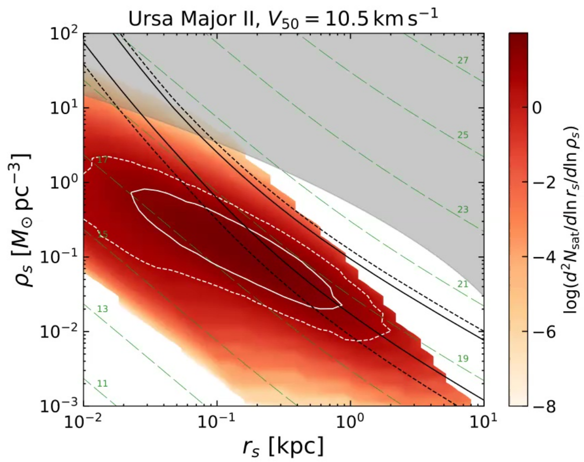


- **Black: Likelihood contours**
- **Green: log [*J*/(GeV²/cm⁵)]**

- 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)

Impact of *satellite prior*

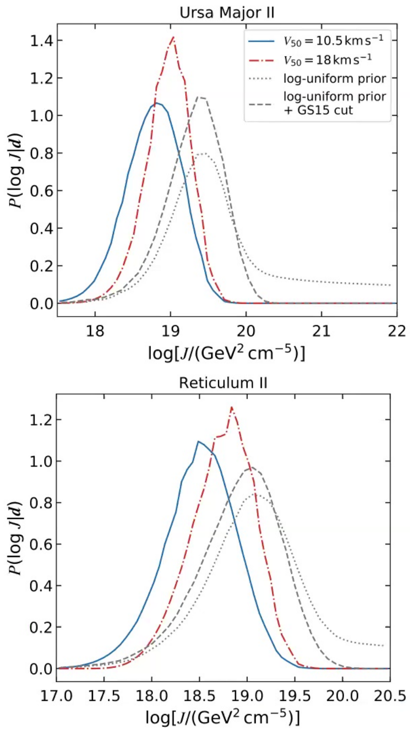
Ando, Geringer-Sameth, Hiroshima, Hoof, Trotta, Walker,
Phys. Rev. D **102**, 061302 (2020)



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

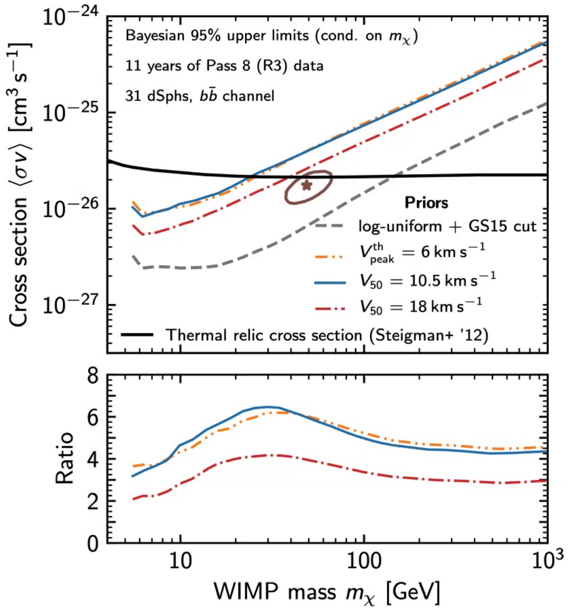
Impact of *satellite prior*



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

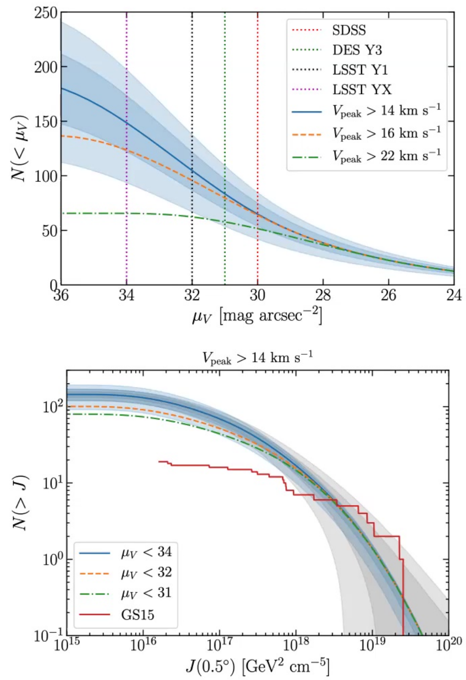
Cross section constraints



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

Prospects for LSST

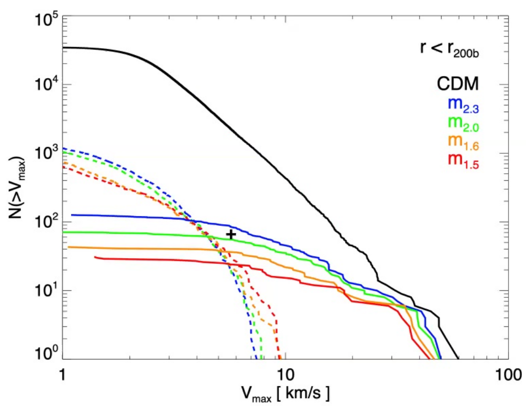


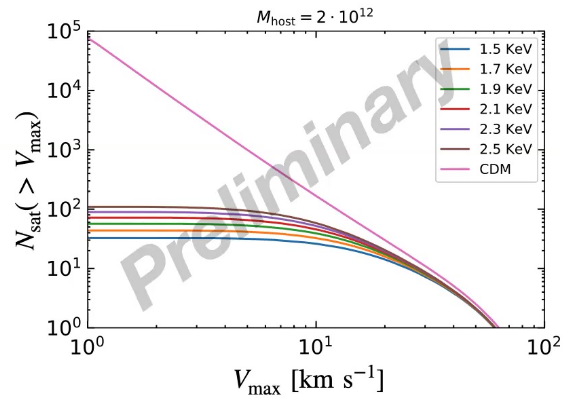
Ando et al., *JCAP* **10**, 040 (2019)

- LSST will cover nearly half the sky and expected to discover many dwarf galaxies
- Our subhalo models with simple phenomenological prescription of forming satellites predict several tens to hundred dwarfs to be discovered with LSST
- **High-*J* tail is dominated by Poisson uncertainty**, making other uncertainties (e.g., MW mass measurements) less of an issue
- **LSST wouldn't dramatically increase the number of dwarfs with very high *J* factors**

Application IV: 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

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
- Various applications: annihilation, dwarf density profile, etc.
- Extension to different dark matter candidates (e.g., WDM, SIDM, FDM) and inflation models (e.g., PBH)