Cosmology-informed constraints on the fuzzy dark matter mass from dwarf-spheroidal stellar kinematics

Shunichi Horigome

Astronomical Institute, Tohoku University

with Elisa Ferreira (Kavli IPMU) and Shin'ichiro Ando (GRAPPA, Kavli IPMU) [in prep.]

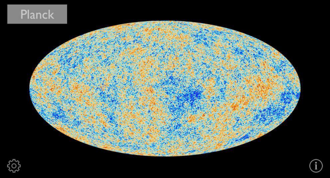
Cosmology-informed FDM constraints

- Goal: Constrain the FDM mass from dSph stellar kinematics
  - parameter degeneracy
- Method: Combine spherical Jeans analysis with <u>cosmology-informed</u> constraints using semi-analytical models (SASHIMI)
  - Motivation: The same kinematics + cosmology strategy yielded stringent SIDM constraints
- Main results — Segue 1
  - 95% CL: FDM mass > 9.1×10^{-22} eV
  - 68% CL: > $3.3 / 4.0 \times 10^{-21}$ eV (V_{50} = 10.5 / 18 km/s)

Introduction

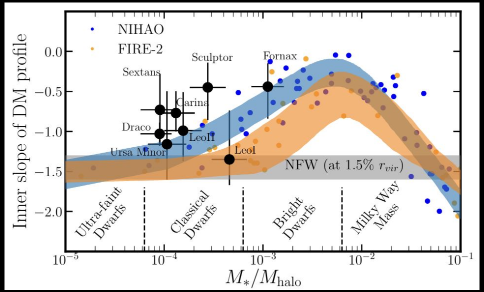
Dark matter in our universe

ΛCDM explains the large-scale structure of the universe very well



What happens on small scales?

- Satellite-count mismatch
  - Missing (or too many) satellites? Homma et al. (2023) [arXiv:2311.05439]
  - Too-big-to-fail?
- Structure of low-mass (sub)halos
  - <u>Core vs. cusp?</u>
    - Systematics in profile estimation?
    - Baryonic physics?
    - Dark matter (SIDM, FDM)?



Hayashi et al. (2020)

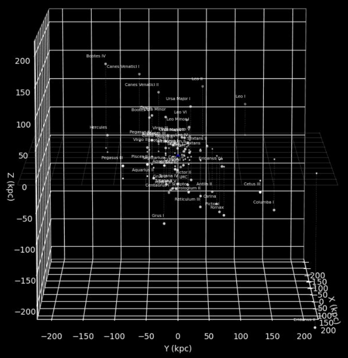
Dwarf spheroidal galaxies (dSphs)

Fornax dSph

Important targets for probing small-scale dark-matter structure

- Large mass-to-light ratio: Y=10-100 M/L
  → dark-matter-dominated systems
- Close to us

Dwarf spheroidal galaxies in the Milky Way



How to observe the dark matter density profile in dSphs?

Dynamical analysis

Jeans equation:

$$\frac{1}{\nu}\frac{d(\nu(r)\,\sigma_r^2(r))}{dr} + \frac{2\beta(r)\,\sigma_r^2(r)}{r} = -\frac{G\,M(r)}{r^2}$$

$$M(r) = \int dr 4\pi r^2 \rho_{\rm DM}(r)$$

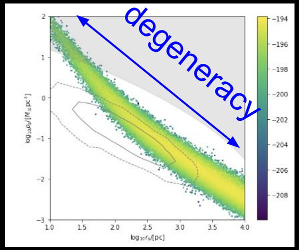
$\nu(r)$: Number density (e.g. Plummer model)

$\beta(r)$: Anisotropy (e.g. flat model, Baes & van Hese (2007) model)

$\sigma_r(r)$: Velocity dispersion

$\rho_{\rm DM}(r)$: DM density profile

plausible region from kinematical analysis



Horigome et al. (2022)

We have only limited data. Additional constraints to break degeneracy?

← Proper motions

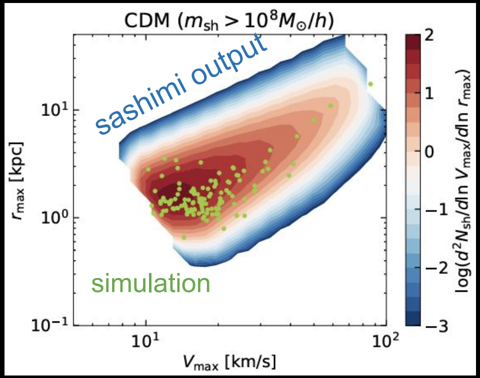
← Higher-order analysis

← **Cosmology**

Cosmology

SASHIMI (Semi-Analytical SubHalo Inference ModelIng) Ando et al. [arXiv:1803.07691], [arXiv:1903.11427]

- Efficiently calculates various subhalo properties using semi-analytical models
  - Before accretion: Extended Press-Schechter formalism
  - After accretion: empirical tidal stripping formula
- Output: catalog of subhalos
  - accretion redshift
  - mass
  - maximum circular velocity V_{max}, r_{max}
  - …

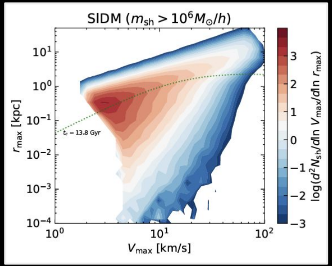


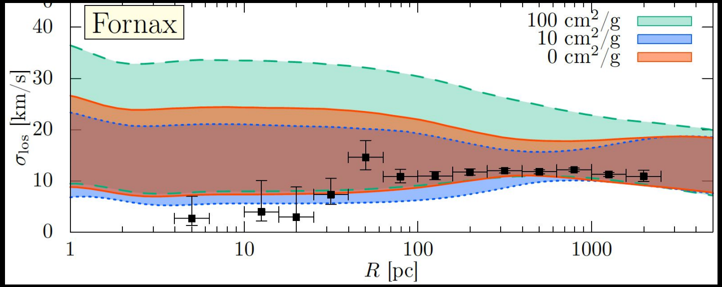
Stringent Constraints on Self-Interacting Dark Matter Using Milky Way Satellite-Galaxy Kinematics

Shin'ichiro Ando, Kohei Hayashi, Shunichi Horigome, Masahiro Ibe, Satoshi Shirai [arXiv:2503.13650]

Kinematics of dSphs

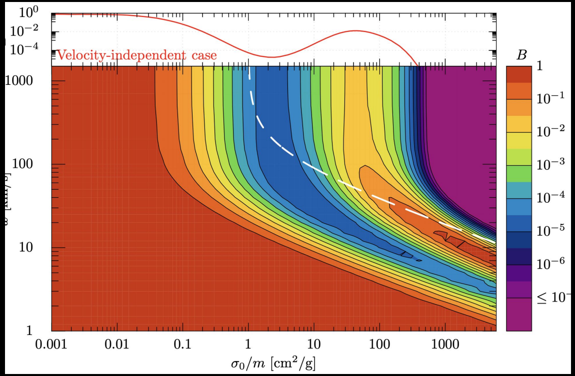
SIDM cosmology





- We test SIDM models by comparing
  - theory (SIDM cosmology)
  - observations (DM halos in dSphs)
- We obtain constraints on SIDM parameters
  - e.g. in the velocity-independent case:

$$\sigma/m \lesssim 0.2\ \mathrm{cm}^2/\mathrm{g}$$



FDM analysis

FDM profile

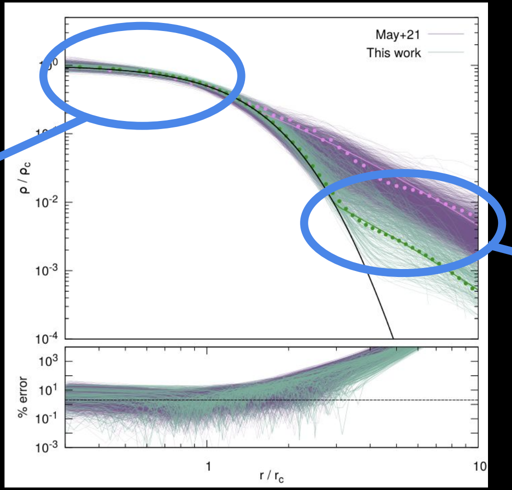
Shunichi Horigome, Elisa Ferreira, Shin'ichiro Ando [in prep.]

Schrödinger–Poisson equations

$$i\hbar\frac{\partial\psi}{\partial t} = -\frac{\hbar^2}{2ma^2}\nabla^2\psi + \frac{m\Phi}{a}\psi$$

Soliton core

$$\rho(r) = \rho_c\left[1 + 0.091\left(\frac{r}{r_c}\right)^2\right]^{-8}$$



Chan et al. (2021) [arXiv:2110.11882]

NFW-like

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

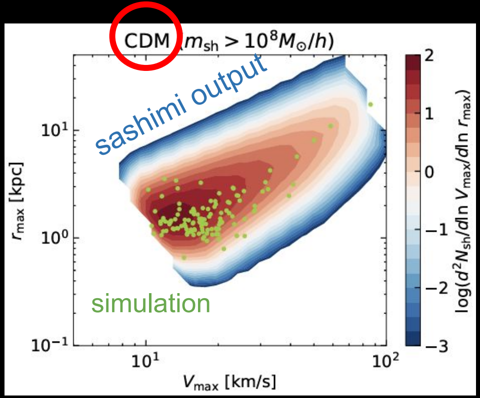
NOTE: We assume **smooth** density profile

FDM Cosmology?

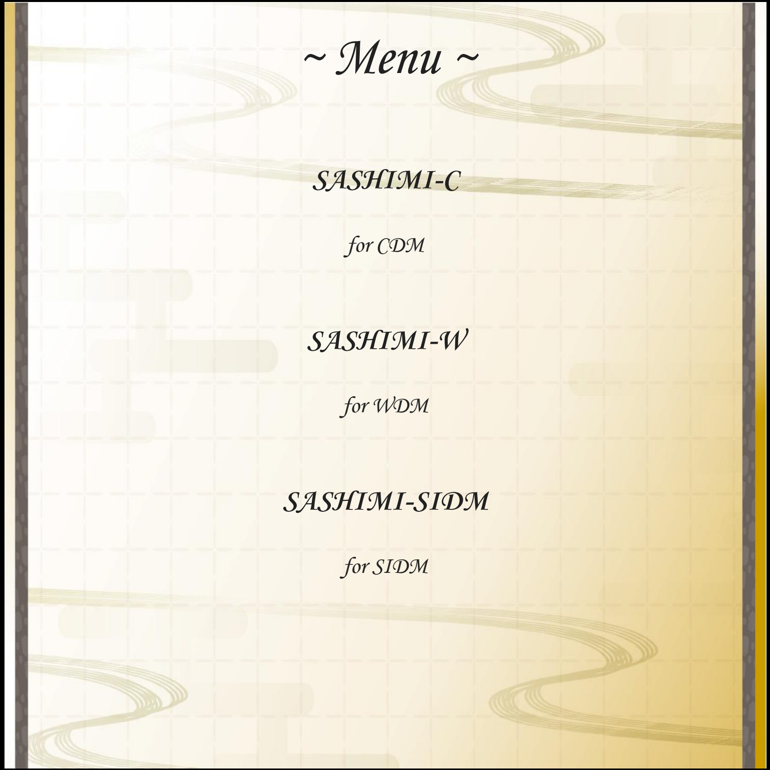
SASHIMI-C

SASHIMI (Semi-Analytical SubHalo Inference ModelIng) Ando et al. [arXiv:1803.07691], [arXiv:1903.11427]

- Efficiently calculates various subhalo properties using semi-analytical models
  - Before accretion: Extended Press-Schechter formalism
  - After accretion: empirical tidal stripping formula
- Output: catalog of subhalos
  - accretion redshift
  - mass
  - maximum circular velocity V_{max}, r_{max}
  - …



Various SASHIMI



cold

warm

self-interacting

- https://github.com/shinichiroando/sashimi-c
- https://github.com/shinichiroando/sashimi-w
- https://github.com/shinichiroando/sashimi-si

Various SASHIMI

~ *Menu* ~

SASHIMI-C

for CDM

SASHIMI-W

for WDM

SASHIMI-SIDM

for SIDM

Today's Special

SASHIMI-F

(or Aburi: axionlike bosons, ultralight, rarely interacting)

for FDM

cold

warm

self-interacting

fuzzy or aburi (炙り, *burned*)?

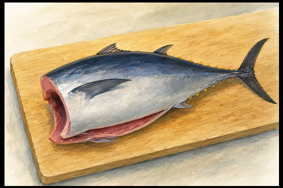
How to prepare SASHIMI-F/ABURI

Choose/define cosmology

Ω_m, Ω_b, h

EPS

Subhalo mass function



Tidal stripping

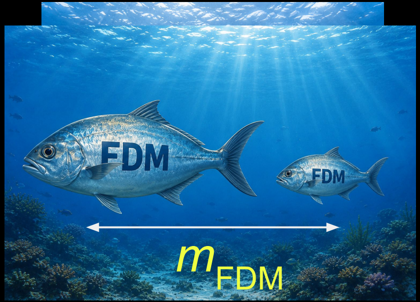
$$\dot{m}(z) = -A \frac{m(z)}{\tau_{\rm dyn}(z)} \left[\frac{m(z)}{M(z)}\right]^{\zeta},$$

Subhalo Catalog

$r_s, \quad \rho_s, \quad r_{\rm trunc}$

How to prepare SASHIMI-F/ABURI

Choose/define cosmology



&

Ω_m, Ω_b, h

EPS

Subhalo mass function

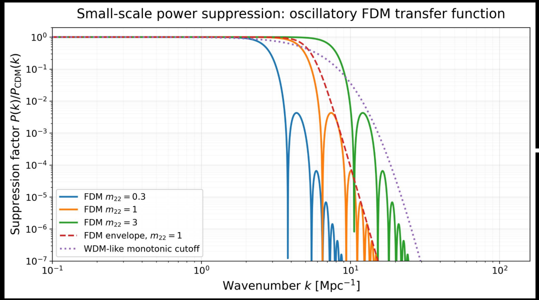
Tidal stripping

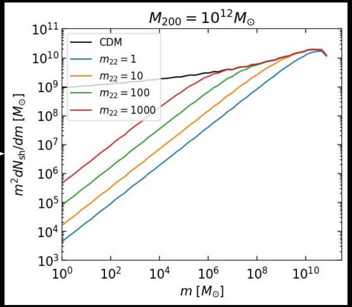
Subhalo Catalog'

$r_s, \quad \rho_s, \quad r_{\rm trunc}$

Power spectrum suppression [Hu et al. (2000)]

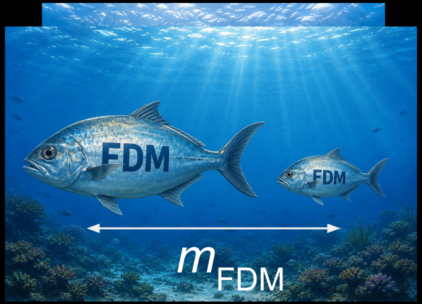
$$P_{\rm FDM}(k) = |T(k)|^2 P_{\rm CDM}(k)$$





How to prepare SASHIMI-F/ABURI

Choose/define cosmology



&

Ω_m, Ω_b, h

EPS

Subhalo mass function

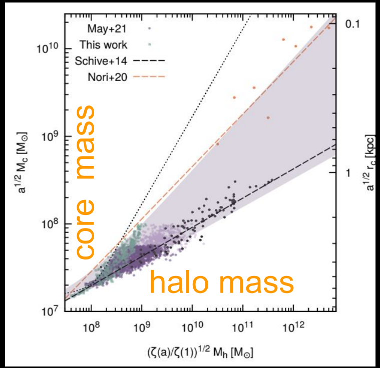
Tidal stripping

Subhalo Catalog'

$r_s, \quad \rho_s, \quad r_{\mathrm{trunc}}$ & r_{core}

Core mass–halo mass relation [Chan et al. (2021)]

$$\mu_c(M_h) = \log_{10}\left[\beta\left(\frac{m}{m_{\mathrm{ref}}}\right)^{-3/2} + \left(\frac{M_h}{\gamma}\right)^{\alpha}\left(\frac{m}{m_{\mathrm{ref}}}\right)^{\frac{3(\alpha-1)}{2}}\right]$$



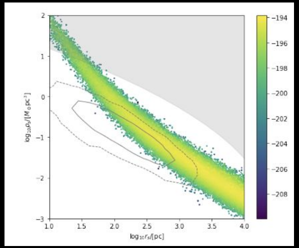
FDM cosmology

Shunichi Horigome, Elisa Ferreira, Shin'ichiro Ando [in prep.]

- SASHIMI-F(Aburi)

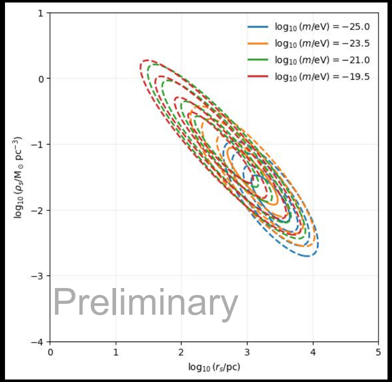
Contours: SASHIMI output (r_s, ρ_s)
for specific FDM masses

Jeans



Horigome et al. (2022)

×



$$\pi_{\rm sat}(\Theta_{\rm sat}\,|\,m) = \mathcal{N}(\theta_{\rm sat};\boldsymbol{\mu}(m),\,\boldsymbol{\Sigma}(m))$$

$$\chi^2_{\rm sat}(\Theta_{\rm sat}) \equiv -2\ln\pi_{\rm sat}(\Theta_{\rm sat})$$

FDM analysis

Shunichi Horigome, Elisa Ferreira, Shin'ichiro Ando [in prep.]

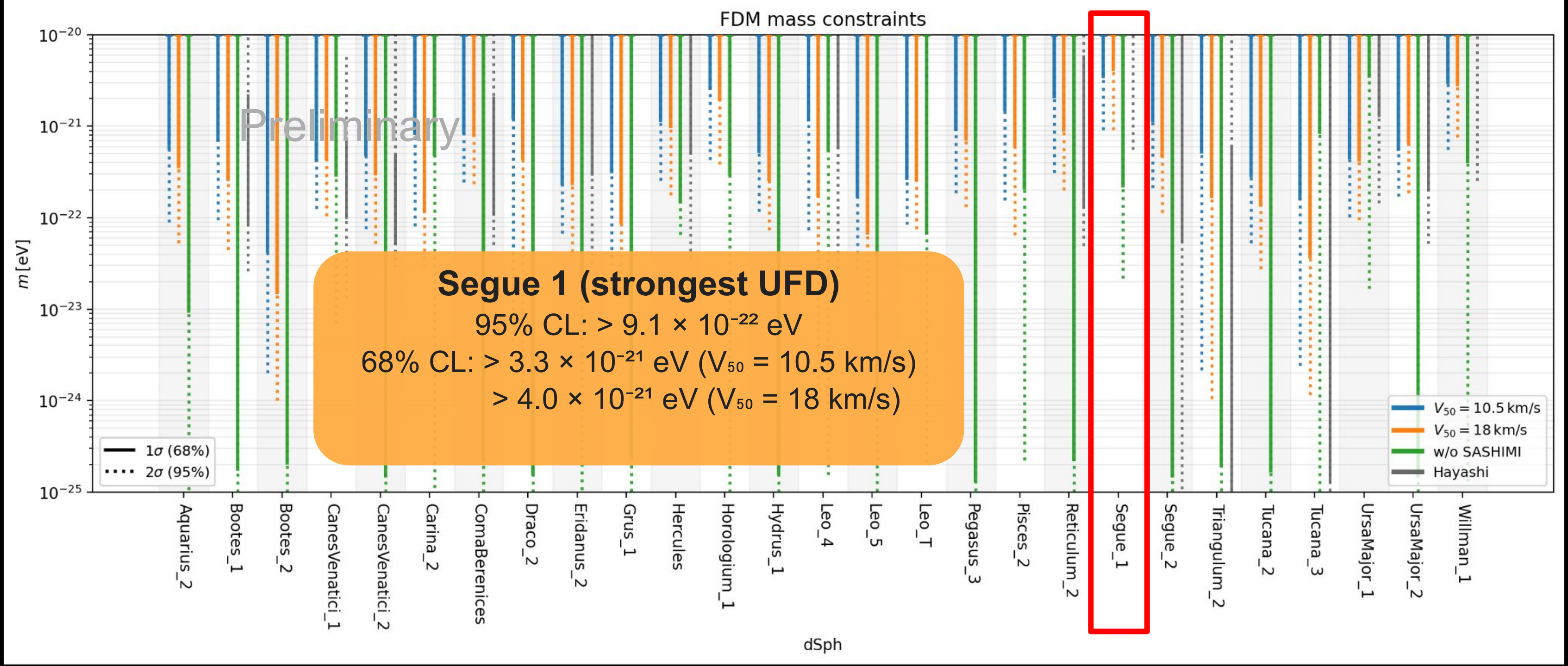
- Profile likelihood: Chi-square

$$\chi^2_{\mathrm{tot}}(\Theta) = \sum_{k \in \{\mathrm{kin},\, M, \mathrm{photo},\, \mathrm{sat},\, \mathrm{flat}\}} \chi^2_k(\Theta_k)$$

- χ^2_{flat} : hard bounds on the parameters
- χ^2_{kin} : kinematical likelihood based on the Jeans analysis
- χ^2_M : deviation from the core-halo mass relation
- χ^2_{photo} : prior on the photometric parameters
- χ^2_{sat} : prior on the satellite parameters

FDM results — Segue 1

Shunichi Horigome, Elisa Ferreira, Shin'ichiro Ando [in prep.]



Segue 1 (strongest UFD)

95% CL: > 9.1×10^{-22} eV

68% CL: > 3.3×10^{-21} eV (V_{50} = 10.5 km/s)

> 4.0×10^{-21} eV (V_{50} = 18 km/s)

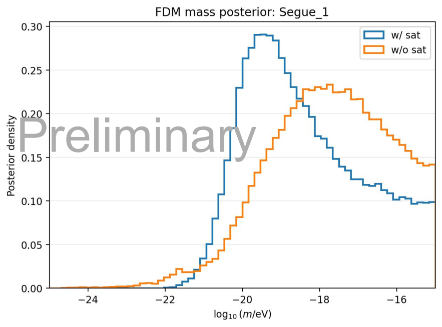
Discussion

- **What drives the constraint**
  - Joint use of dSph kinematics and SASHIMI cosmology
- **Main caveat**
  - The lower bound changes with the statistical treatment and the cosmological prior
- **Current interpretation**
  - The bound is weaker than aggressive previous Jeans limits, but cosmologically more explicit

Segue 1

FDM mass > 9.1 × 10^{-22} eV

95% CL (both V50 choices)



Summary

- **Cosmology-informed FDM constraints from dSphs**
- Method
  - **Spherical Jeans kinematics**
  - **Cosmology-informed SASHIMI constraints**
    - for FDM subhalo structure
- Strongest UFD limit - Segue 1
  - 95% CL: FDM mass > 9.1×10^{-22} eV
  - 68% CL: > 3.3 / 4.0×10^{-21} eV (V_{50} = 10.5 / 18 km/s)
- Interpretation and next steps
  - The bound depends on cosmological and statistical assumptions (Bayes / Freq.)
  - FDM-specific subhalo modeling and higher-order dynamics

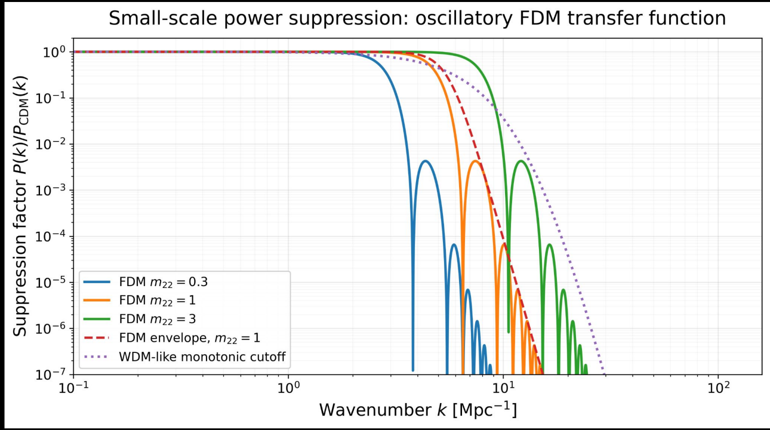
Backup

FDM cosmology

Shunichi Horigome, Elisa Ferreira, Shin'ichiro Ando [in prep.]

- Power-spectrum suppression [Hu et al. (2000)]

$$P_{\mathrm{FDM}}(k) = |T(k)|^2 P_{\mathrm{CDM}}(k)$$

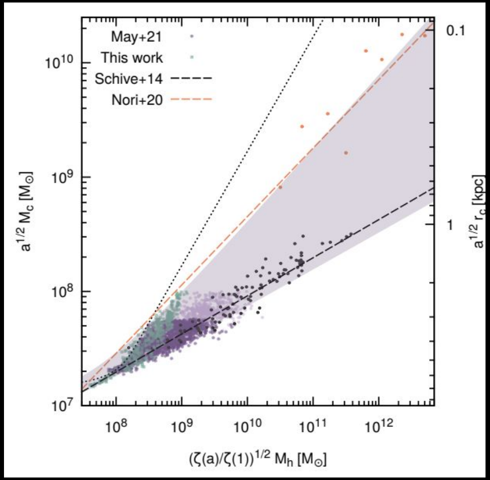


$$T_{\mathrm{FDM}}(k) = \frac{\cos(x^3)}{1+x^8},$$
$$\frac{P_{\mathrm{FDM}}(k)}{P_{\mathrm{CDM}}(k)} = T^2_{\mathrm{FDM}}(k),$$
$$x = 1.61\, m_{22}^{1/18}\, \frac{k}{k_J},$$
$$k_J = 9\, m_{22}^{1/2}\, \mathrm{Mpc}^{-1},$$
$$m_{22} = \frac{m}{10^{-22}\,\mathrm{eV}}.$$

FDM cosmology

Shunichi Horigome, Elisa Ferreira, Shin'ichiro Ando [in prep.]

- Core mass–halo mass relation



Chan et al. (2021)

$$\mu_c(M_h) = \log_{10}\left[\beta\left(\frac{m}{m_{\rm ref}}\right)^{-3/2} + \left(\frac{M_h}{\gamma}\right)^{\alpha}\left(\frac{m}{m_{\rm ref}}\right)^{\frac{3(\alpha-1)}{2}}\right]$$

$$\chi^2_M(\Theta_M) = \frac{\left(\mu_c - \mu_{c,\rm best}(M_h)\right)^2}{\sigma^2_{\mu_c}(M_h)}$$

$$\sigma_{\mu_c}(M_h) = \max_{a\in\{\rm lower,upper\}}\left|\mu_{c,a}(M_h) - \mu_{c,\rm best}(M_h)\right|,$$

FDM cosmology

Shunichi Horigome, Elisa Ferreira, Shin'ichiro Ando [in prep.]

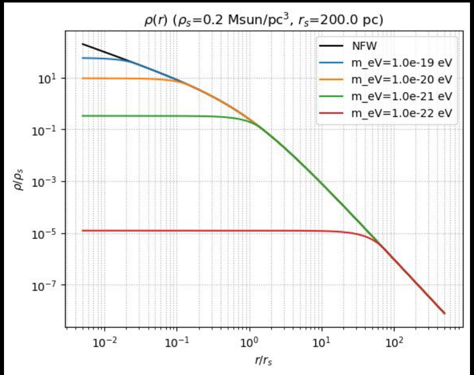
SASHIMI (Semi-Analytical SubHalo Inference ModelIng) [arXiv:1803.07691], [arXiv:1903.11427]

- Efficiently calculates various subhalo properties using semi-analytical models

- Power spectrum suppression

$$P_{\rm FDM}(k) = |T(k)|^2 P_{\rm CDM}(k)$$

- $M_c - M_h$ relation



DM density profile with different FDM mass

What is V_{50}?

- **Definition**
  - V_{50} is the V_peak where 50% of subhalos are assumed to host a visible galaxy.
- **Occupation model**
  - $f\_galaxy(>V\_peak) = \frac{1}{2}[1 + \mathrm{erf}((V\_peak - V_{50})/(\sqrt{2}\,\sigma))]$
- **Choices used here**
  - 18 km/s: conventional reionization-quenching scale.
    10.5 km/s: lower-threshold model motivated by Milky Way satellite counts.

Galaxy occupation

$f\_galaxy(V_{50}) = 0.5$

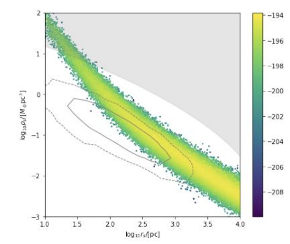
$V_{50} = 10.5 / 18$ km s^{-1}

FDM cosmology

Shunichi Horigome, Elisa Ferreira, Shin'ichiro Ando [in prep.]

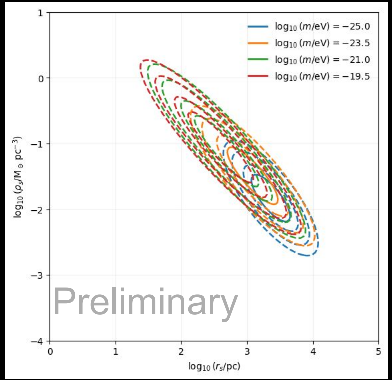
- SASHIMI-F(Aburi)

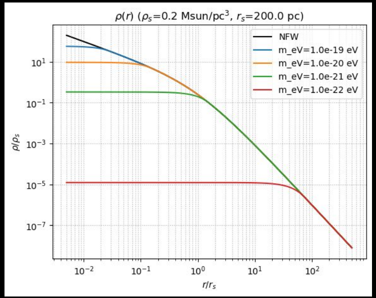
Contours: 3D satellite prior projected onto the (r_s, ρ_s) plane



Horigome et al. (2022)

×





$$\pi_{\rm sat}(\Theta_{\rm sat}\,|\,m) = \mathcal{N}(\theta_{\rm sat}; \boldsymbol{\mu}(m),\, \boldsymbol{\Sigma}(m))$$

$$\chi^2_{\rm sat}(\Theta_{\rm sat}) \equiv -2\ln \pi_{\rm sat}(\Theta_{\rm sat})$$

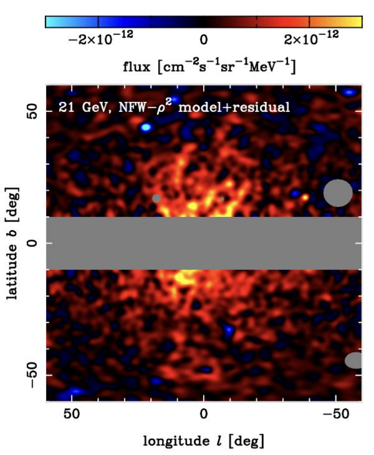
Dynamical heating: stronger constraints, more assumptions

- **Existing heating limit**
  - FDM wave interference heats stellar orbits; Segue 1/2 give m_FDM > 3 × 10^{-19} eV (99% CL) — a much higher lower bound than ours, though with different assumptions and CL.
- **Why is it so strong?**
  - It is a cumulative Gyr-scale effect: very compact, dynamically cold UFDs leave little room for repeated potential fluctuations.
- **Important ingredients / caveats**
  - Inference depends on stellar age/initial phase-space structure; halo/soliton structure and fluctuations; heating regime (diffusive vs coherent/tidal); tides/environment; and UFD kinematic systematics. Full Schrödinger–Poisson simulations support strong heating, but mapping it to m_FDM is more history-dependent than an equilibrium Jeans fit.

Dalal & Kravtsov, PRD 106, 063517 (2022) [arXiv:2203.05750]; May, Dalal & Kravtsov (2025) [arXiv:2509.02781]; Liu & Li (2026) [arXiv:2604.26393]

Has dark matter finally been detected?

- Halo gamma-ray excess [Totani (2025)]
  - Tension with dSph searches….




YOL 讀賣新聞 オンライン

朝刊記事 紙面ビューアー 社説 English

すべて | トップ 速報 社会 政治 経済 スポーツ 国際 地域 科学･IT エンタメ･文化 ライフ 受験･就活

注目ワード #サッカーW杯 #イスラエル・中東情勢 #株・為替 #ウクライナ情勢 #大谷翔平 #ウィンブルドン

トップ > 科学・ＩＴ

宇宙のダークマターの痕跡、見つけたかも…東京大・戸谷友則教授が論文発表

2025/12/01 21:45

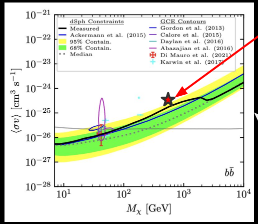
保存して後で読む　シェアする

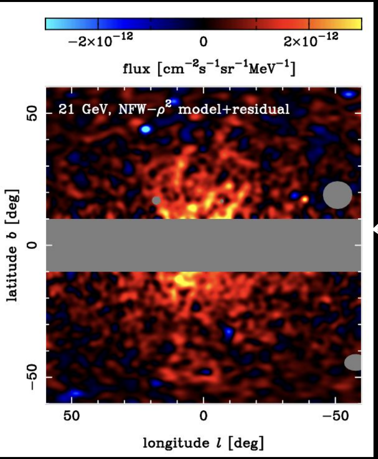
っていない「暗黒物質（ダークマター）」
東京大の戸谷友則教授（宇宙物理学）が
ば天文学・物理学で最大の謎の一つが解

質は、重力を持ちながらも既知の物質
る謎の存在で、宇宙全体の質量やエネ
うち２７％を占めると考えられてい
重力で光が曲げられる現象が観測され

Has dark matter finally been detected?

- Halo gamma-ray excess [Totani (2025)]
  - Tension with dSph searches….





Resonant Annihilation of WIMP Dark Matter for Halo Gamma Ray Signal
Hitoshi Murayama[1,2,3]

Modified annihilation scenario

Electroweak Doublet Dark Matter for a Galactic Halo Gamma-Ray Excess
Yasunori Nomura[1,2,3,4] and Tomonori Totani[5,6]

Particle-physics model for cross-section enhancement

Legacy analysis of Milky Way dwarf spheroidal satellite galaxies: an update
Antonio Circiello,[1] Mattia Di Mauro,[2] Marco Ajello,[1] Christopher Karwin,[1] Alex Drlica-Wagner,[3,4,5] and Miguel Á. Sánchez-Conde[6,7]

Weak signal from a reanalysis of dSph indirect searches

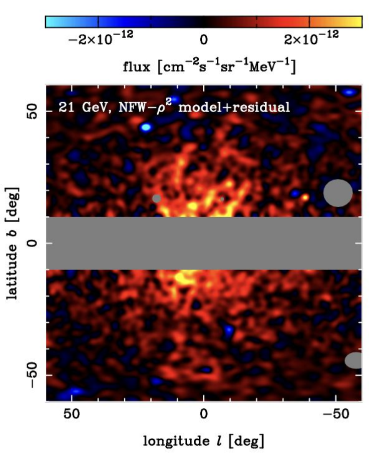
Constraining the dark matter origin of the halo-like 20 GeV γ-ray excess with the AMS-02 antiproton data
Xiao Wang, Kai-Kai Duan

Tension with AMS-02 antiproton observations

Intriguing, but far from a confirmed discovery.

Has dark matter finally been detected?

- Halo gamma-ray excess [Totani (2025)]
  - Tension with dSph searches….



Resonant Annihilation of WIMP Dark Matter for Halo Gamma Ray Signal
Hitoshi Murayama[1,2,3]

Modified annihilation scenario

Electroweak Doublet Dark Matter for a Galactic Halo Gamma-Ray Excess
Yasunori Nomura[1,2,3,4] and Tomonori Totani[5,6]

Particle-physics model for cross-section enhancement

Legacy analysis of Milky Way dwarf spheroidal satellite galaxies: an update
Antonio Circiello,[1] Mattia Di Mauro,[2] Marco Ajello,[1] Christopher Karwin,[1] Alex Drlica-Wagner,[3,4,5] and Miguel Á. Sánchez-Conde[6,7]

Weak signal from a reanalysis of dSph indirect searches

Constraining the dark matter origin of the halo-like 20 GeV γ-ray excess with the AMS-02 antiproton data
Xiao Wang, Kai-Kai Duan

Tension with AMS-02 antiproton observations

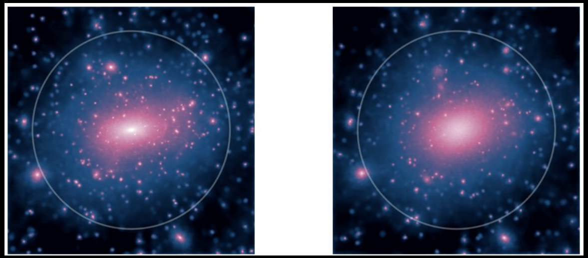
Intriguing, but far from a confirmed discovery.

Alternative DM models for small-scale challenges

SIDM (Self-Interacting Dark Matter)

- Dark-matter self-interactions can prevent the formation of cuspy profiles

$$\rho(r_{\rm core})\frac{\langle\sigma v\rangle t_{\rm age}}{m_{\rm SIDM}} \simeq 1$$

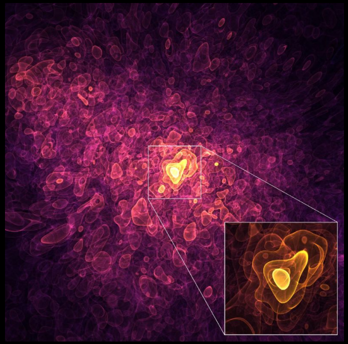


Brinckmann et al. (2017) [arXiv:1705.00623]

FDM (Fuzzy Dark Matter)

- Cored profile due to the wave nature of an ultralight particle
  - Soliton core
  - Interference

$$r_c \simeq 1.6\ {\rm kpc}\ m_{22}^{-1}\left(\frac{M_h}{10^9\ M_\odot}\right)^{-1/3} a^{1/2}$$



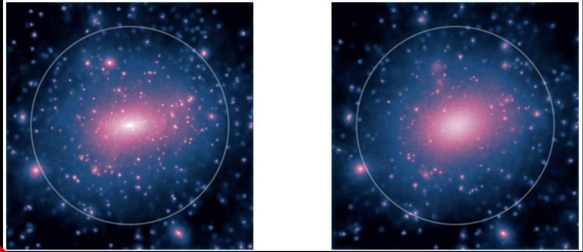
Schive (2025) [arXiv:2509.23231]

Alternative DM models for small-scale challenges

SIDM (Self-interacting Dark Matter)

- Dark-matter self-interactions can prevent the formation of cuspy profiles

$$\rho(r_{\rm core})\frac{\langle\sigma v\rangle t_{\rm age}}{m_{\rm SIDM}} \simeq 1$$

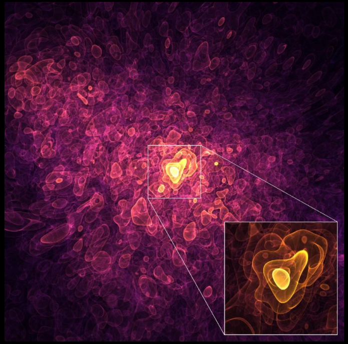


Brinckmann et al. (2017) [arXiv:1705.00623]

FDM (Fuzzy Dark Matter)

- Cored profile due to the wave nature of an ultralight particle
  - Soliton core
  - Interference

$$r_c \simeq 1.6\ {\rm kpc}\ m_{22}^{-1}\left(\frac{M_h}{10^9\ M_\odot}\right)^{-1/3} a^{1/2}$$



Schive (2025) [arXiv:2509.23231]

Self-Interacting Dark Matter (SIDM)

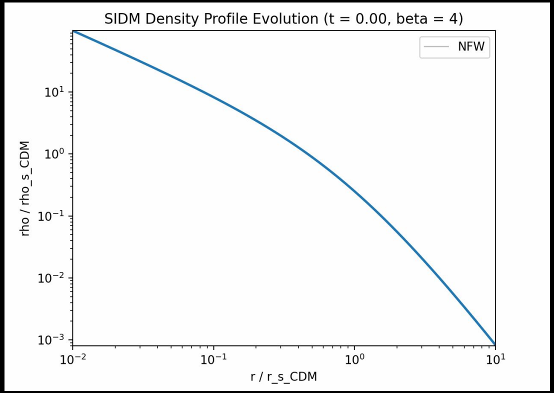
Large self-scattering cross section

$$\sigma/m \simeq 1\ \mathrm{cm}^2/\mathrm{g}$$

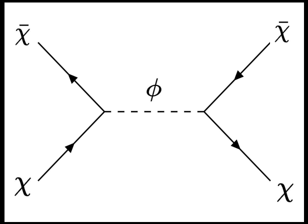
cf. CDM (wino DM)

$$\sigma/m \approx G_F^2 m \approx 10^{-12} \left(\frac{m_\chi}{100\,\mathrm{GeV}} \right) \mathrm{cm}^2/\mathrm{g}$$

→ Gravothermal evolution of halos



$$\frac{d\sigma}{d\cos\theta} = \frac{\sigma_0}{2\left[1 + (v/w)^2 \sin^2(\theta/2)\right]^2}$$

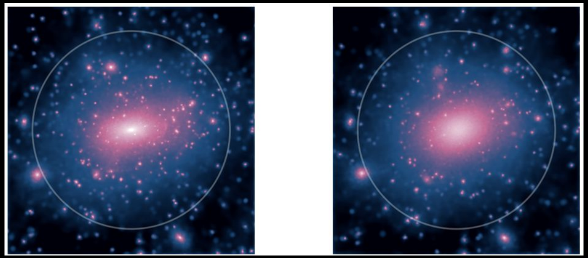


Alternative DM models for small-scale challenges

SIDM (Self-Interacting Dark Matter)

- Dark-matter self-interactions can prevent the formation of cuspy profiles

$$\rho(r_{\rm core})\frac{\langle\sigma v\rangle t_{\rm age}}{m_{\rm SIDM}} \simeq 1$$

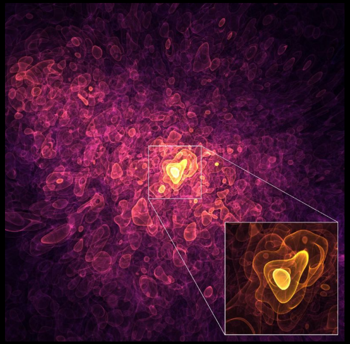


Brinckmann et al. (2017) [arXiv:1705.00623]

FDM (Fuzzy Dark Matter)

- Cored profile due to the wave nature of an ultralight particle
  - Soliton core
  - Interference

$$r_c \simeq 1.6~{\rm kpc}~m_{22}^{-1}\left(\frac{M_h}{10^9~M_\odot}\right)^{-1/3} a^{1/2}$$



Schive (2025) [arXiv:2509.23231]

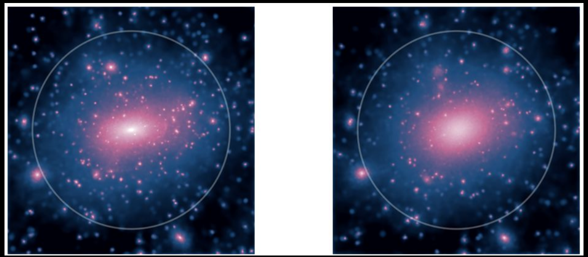
Alternative DM models for small-scale challenges

(in prep….)

SIDM (Self-Interacting Dark Matter)

- Dark-matter self-interactions can prevent the formation of cuspy profiles

$$\rho(r_{\rm core})\frac{\langle\sigma v\rangle t_{\rm age}}{m_{\rm SIDM}} \simeq 1$$

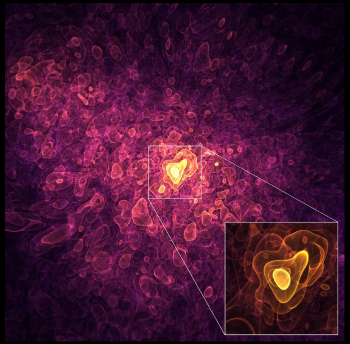


Brinckmann et al. (2017) [arXiv:1705.00623]

FDM (Fuzzy Dark Matter)

- Cored profile due to the wave nature of an ultralight particle
  - Soliton core
  - Interference

$$r_c \simeq 1.6~{\rm kpc}~m_{22}^{-1}\left(\frac{M_h}{10^9~M_\odot}\right)^{-1/3} a^{1/2}$$



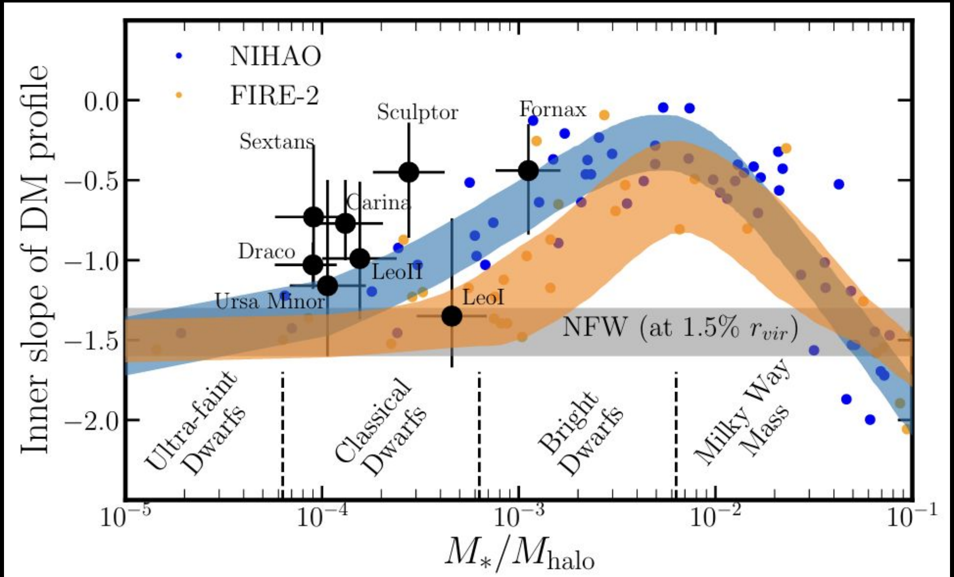
Schive (2025) [arXiv:2509.23231]

Core v.s. cusp?

- Neither fully cored, nor fully cuspy
  → Diversity

Origin of the diversity?

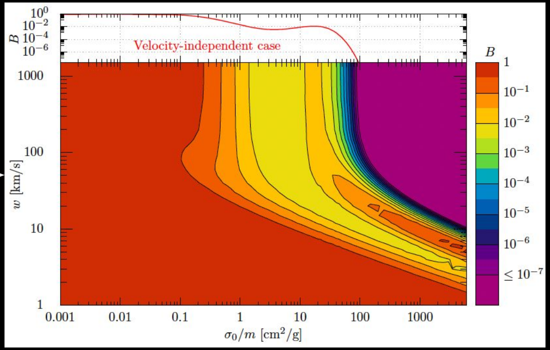
- Baryonic effect?
- Dark matter?



Hayashi+(2020)[arxiv:2007.13780]

Discussion & Future direction

Shin'ichiro Ando, Kohei Hayashi, Shunichi Horigome, Masahiro Ibe, Satoshi Shirai [arXiv:2503.13650]



- Baryonic feedback
  - Classical dSphs might be affected
- Galaxy formation model
  - Uncertainty: DM halo → Galaxy (e.g. V_{50}= 18 km/s)
- Spatial SASHIMI
  - Simulate precise mass-loss history of dSphs by tracing their orbital information
- Axisymmetric SASHIMI
  - Considering axisymmetricity & tidal disruption

Method: Jeans analysis

Jeans equation:

$$\frac{1}{\nu}\frac{d(\nu(r)\,\sigma_r^2(r))}{dr} + \frac{2\beta(r)\,\sigma_r^2(r)}{r} = -\frac{G\,M(r)}{r^2} \qquad M(r) = \int dr 4\pi r^2 \rho_{\rm DM}(r)$$

$\nu(r)$: Number density (e.g. Plummer model)
$\beta(r)$: Anisotropy (e.g. flat model, Baes & van Hese (2007) model)
$\sigma_r(r)$: Velocity dispersion
$\rho_{\rm DM}(r)$: DM density profile

SIDM: $$\rho(r) = \frac{\rho_s r_s^3}{(r^4 + r_c^4)^{1/4}(r + r_s)^2}$$

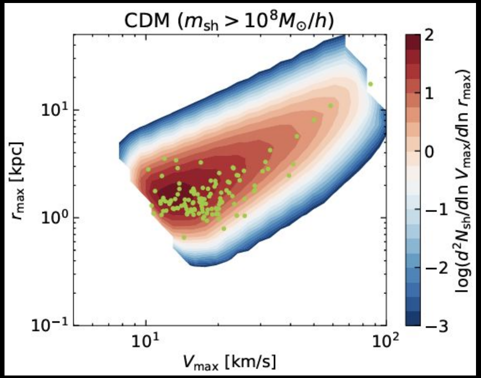
$r \gg r_c$: $\dfrac{\rho_s r_s^3}{r(r + r_s)^2}$ NFW

$r \ll r_c$: $\rho_s (r_s/r_c)^3$ const. (cored)

Prior: Cosmological constraint of SASHIMI-SIDM

SASHIMI (Semi-Analytical SubHalo Inference ModelIng) [arXiv:1803.07691], [arXiv:1903.11427]

- calculate various subhalo properties efficiently using semi-analytical models
  - Extended Press-Schechter formalism
  - Tidal stripping effect
- Outputs: catalogue of subhalos
  - accretion redshift
  - mass
  - V_{max}, r_{max}
  - …

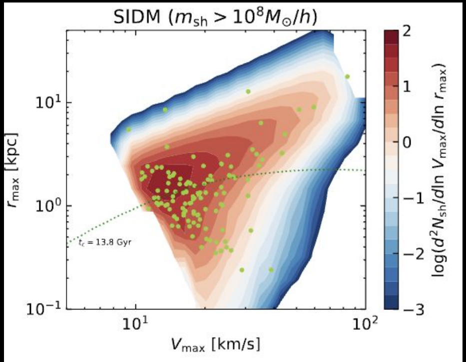


For **CDM**: [arXiv:2403.16633]

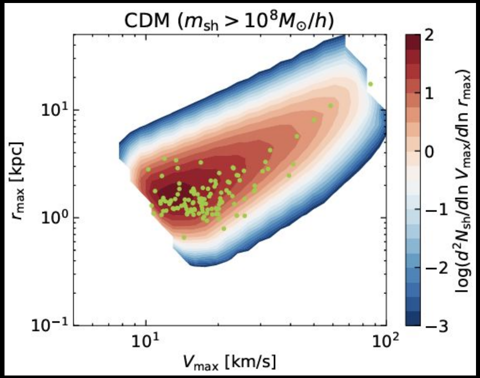
Prior: Cosmological constraint of SASHIMI-SIDM

SASHIMI (Semi-Analytical SubHalo Inference ModelIng) for **SIDM** [arXiv:2403.16633]

- Parametric model of SIDM halos [Yang+(2023)] to reinterpret CDM → SIDM



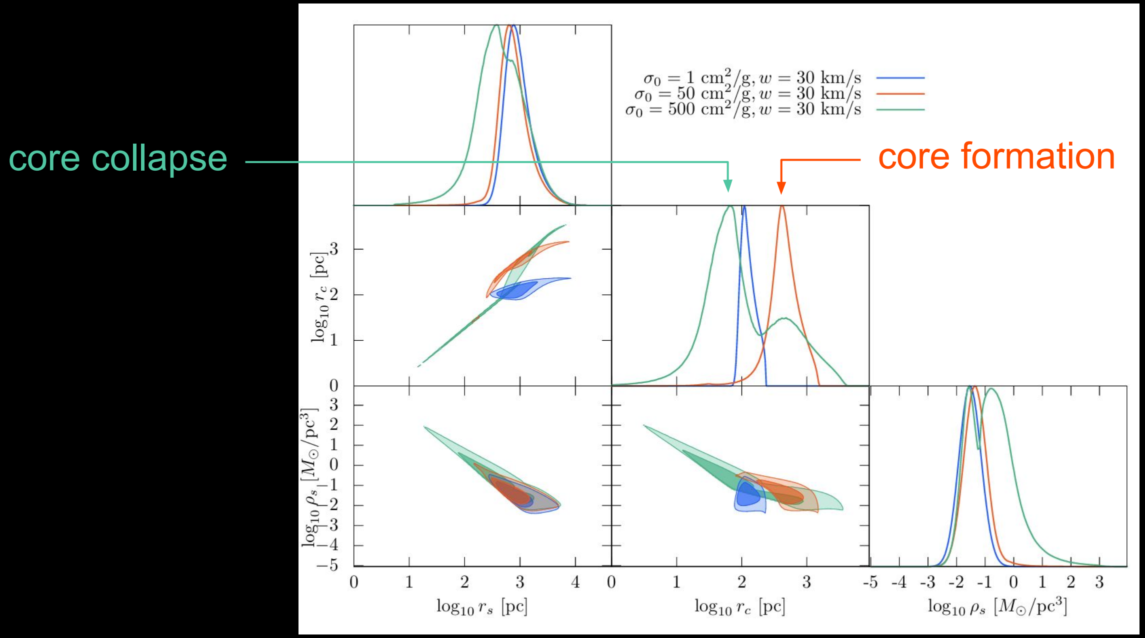
For **SIDM**: [arXiv:2403.16633]



For **CDM**: [arXiv:2403.16633]

Prior: Cosmological constraint of SASHIMI-SIDM

Example: Prior distributions for different SIDM parameters

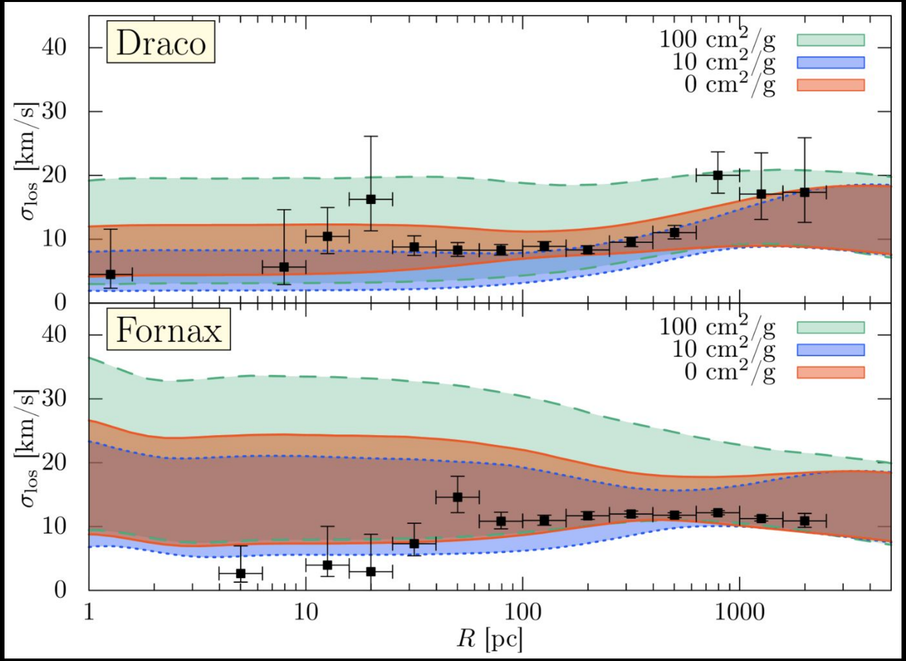


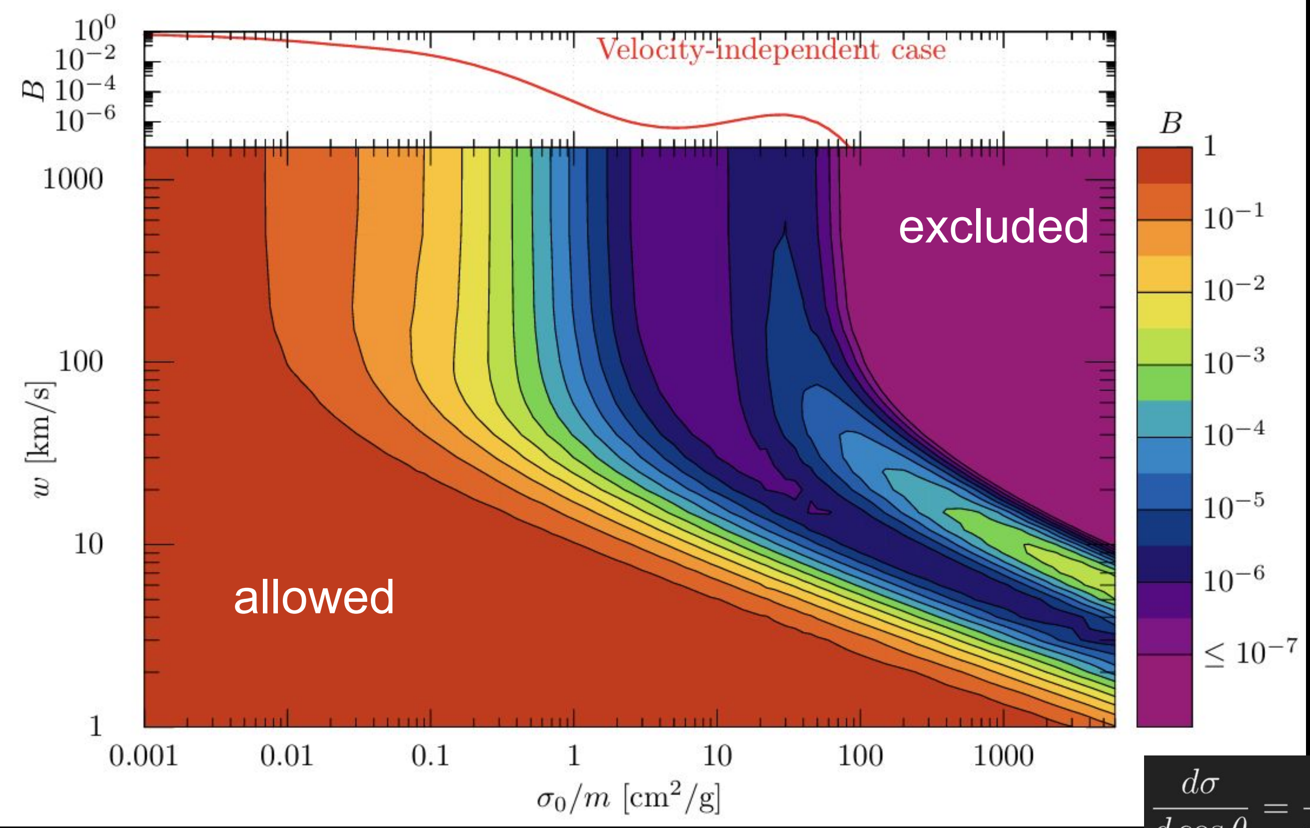
Results (SIDM)

Results

Shin'ichiro Ando, Kohei Hayashi, Shunichi Horigome, Masahiro Ibe, Satoshi Shirai [arXiv:2503.13650]

- Too large σ/m cannot fit observed velocity dispersion of stars
- To marginalize the diversity of dSphs, we compute total Bayes factor $B = \prod_i B_i$

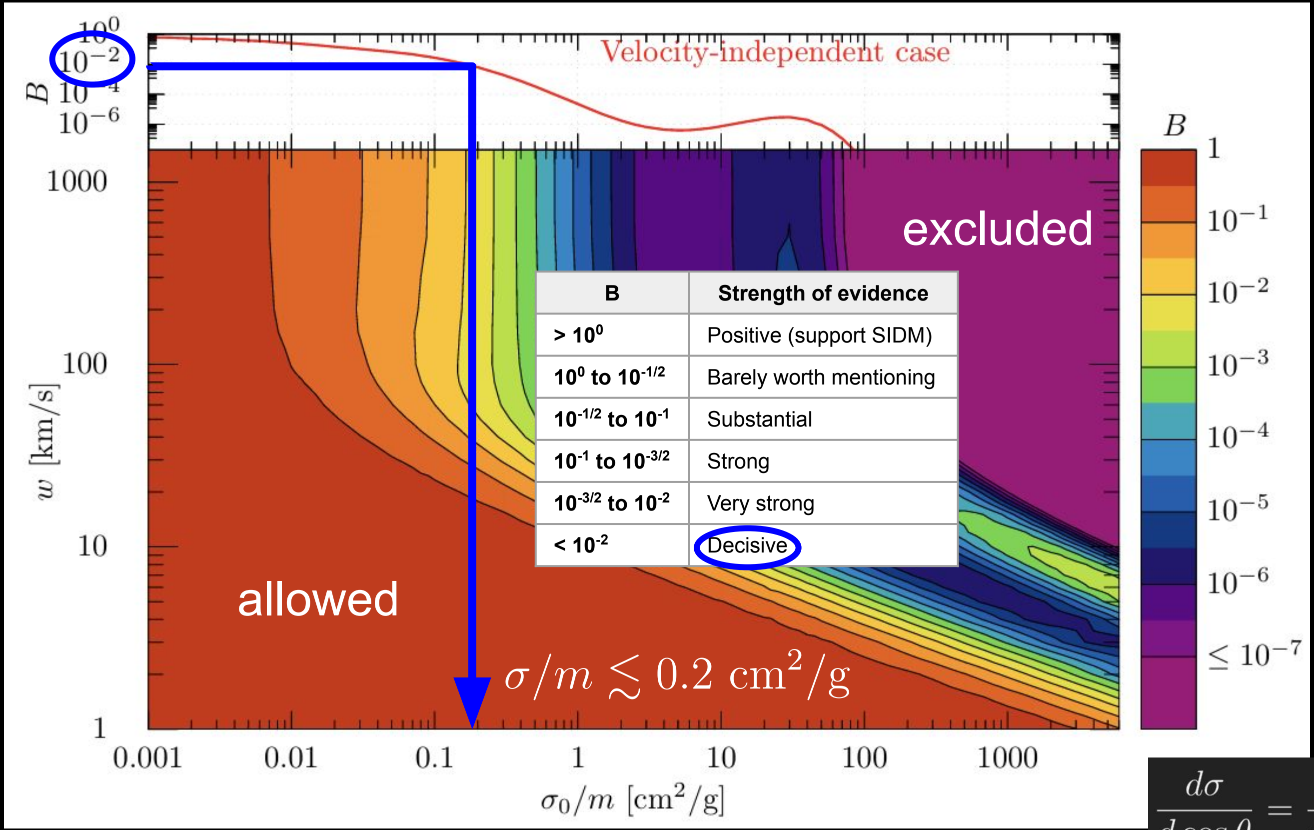




$B = \Pi_i B_i$

$B_i = Z_{SIDM,i}/Z_{CDM,i}$

$$\frac{d\sigma}{d\cos\theta} = \frac{\sigma_0}{2\left[1 + (v/w)^2 \sin^2(\theta/2)\right]^2}$$

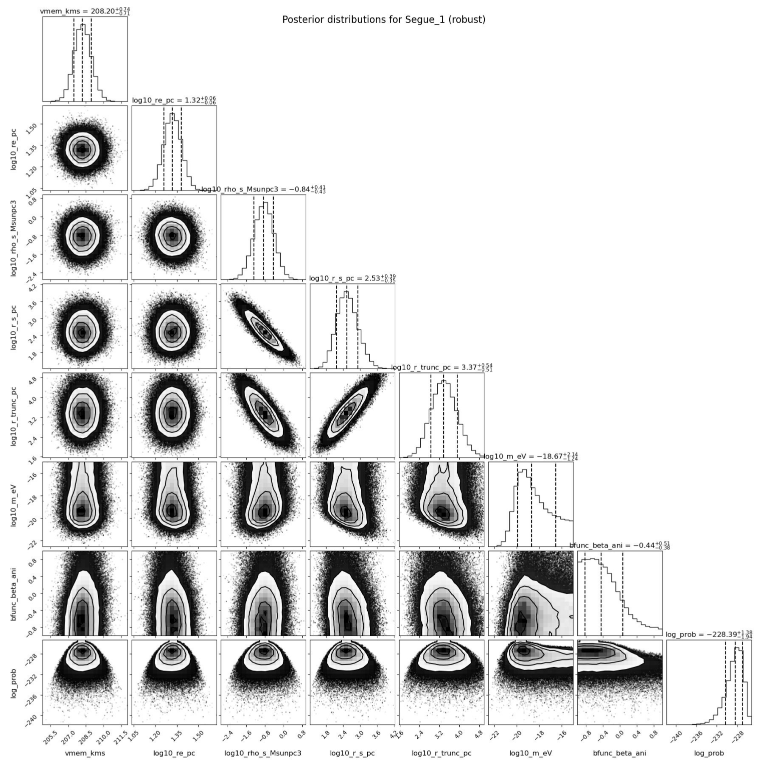


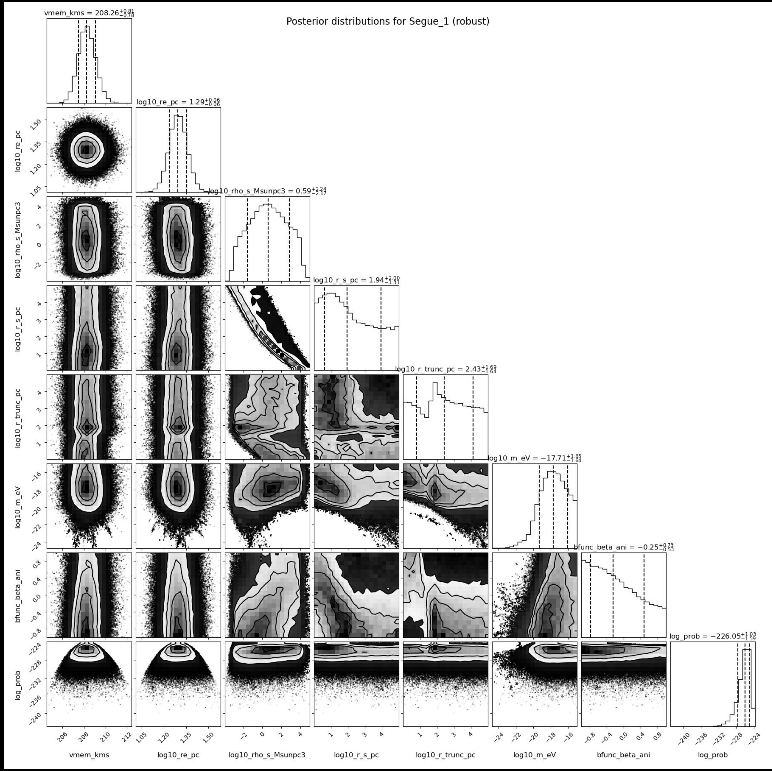
B	Strength of evidence
$> 10^0$	Positive (support SIDM)
10^0 to $10^{-1/2}$	Barely worth mentioning
$10^{-1/2}$ to 10^{-1}	Substantial
10^{-1} to $10^{-3/2}$	Strong
$10^{-3/2}$ to 10^{-2}	Very strong
$< 10^{-2}$	Decisive

$B = \Pi_i B_i$

$B_i = Z_{SIDM,i}/Z_{CDM,i}$

$$\frac{d\sigma}{d\cos\theta} = \frac{\sigma_0}{2\left[1 + (v/w)^2 \sin^2(\theta/2)\right]^2}$$


Posterior distributions for Segue_1 (robust)
vmem_kms
log10_re_pc
log10_rho_s_Msunpc3
log10_r_s_pc
log10_r_trunc_pc
log10_m_eV
bfunc_beta_ani
log_prob


Posterior distributions for Segue_1 (robust)
vmem_kms
log10_re_pc
log10_rho_s_Msunpc3
log10_r_s_pc
log10_r_trunc_pc
log10_m_eV
bfunc_beta_ani
log_prob

$$
\begin{aligned}
-1000 &\leq v_{\mathrm{mem}}/(\mathrm{km\,s^{-1}}) \leq 1000, \\
0 &\leq \log_{10}(R_e/\mathrm{pc}) \leq 5, \\
-5 &\leq \log_{10}(\rho_s/(M_\odot\,\mathrm{pc}^{-3})) \leq 5, \\
0 &\leq \log_{10}(r_s/\mathrm{pc}) \leq 5, \\
0 &\leq \log_{10}(r_{\mathrm{trunc}}/\mathrm{pc}) \leq 5, \\
-25 &\leq \log_{10}(m/\mathrm{eV}) \leq -15, \\
-1 &\leq b \equiv \log_{10}(1-\beta_{\mathrm{ani}}) \leq 1.
\end{aligned}
$$

Prior: Cosmological constraint of SASHIMI-SIDM

SASHIMI (Semi-Analytical SubHalo Inference ModelIng) **for SIDM** [arXiv:2403.16633]

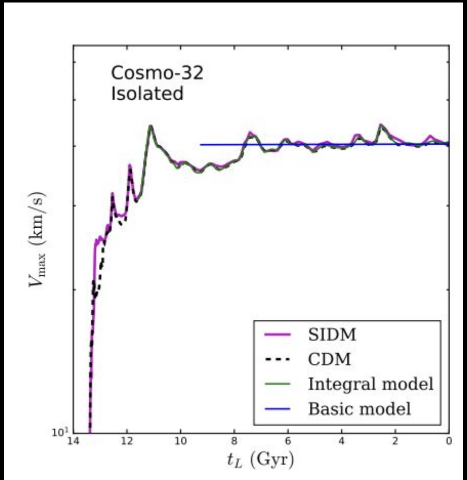
- Parametric model of SIDM halos [Yang+(2023)] to reinterpret CDM → SIDM
  - Empirical function of $\tau = t/t_c$
    - t_c: collapse time scale:

$$t_c = \frac{150}{C} \frac{1}{(\sigma_{\rm eff}/m)\rho_{\rm eff} r_{\rm eff}} \frac{1}{\sqrt{4\pi G \rho_{\rm eff}}},$$

SIDM

$$\frac{V_{\rm max}}{V_{\rm max,0}} = 1 + 0.1777\tau - 4.399\tau^3 + 16.66\tau^4 - 18.87\tau^5 + 9.077\tau^7 - 2.436\tau^9$$

CDM



Yang+(2023)

Bayesian analysis

DM halo parameters — nuisance parameters

$$\mathcal{L}_{\rm eff}(\overbrace{r_s, \rho_s, r_c}^{\text{DM halo parameters}}) = \int d[\overbrace{r_\beta, \eta, \beta_{0,\infty}, r_{1/2}}^{\text{nuisance parameters}}]\mathcal{L}$$

$$\underbrace{Z(\sigma_0/m, w)}_{\text{SIDM paramters}} = \int d\rho_s dr_s dr_c \mathcal{L}_{\rm eff}(r_s, \rho_s, r_c) P(\rho_s, r_s, r_c | \sigma_0/m, w)$$

SIDM paramters

- *L*: Likelihood of dSph kinematics (Jeans analysis)
- *P*: Prior from SIDM Cosmology
- *Z(σ/m,w)*: marginal likelihood (model *evidence*)
- *B(σ/m,w) = Z(σ/m,w)/Z(0,0)*: Bayes factor

Likelihood: Jeans analysis

$$-2\log(\mathcal{L}) = \sum_i \left[\frac{(v_i - V)^2}{\sigma_i^2} + \log\left(2\pi\sigma_i^2\right)\right]$$

v(r): number desnity
σ(r): velocity dispersion
β(r): anisotropy

Jeans equation:

$$\frac{\partial \nu(r)\sigma_r^2(r)}{\partial r} + \frac{2\beta_{\mathrm{ani}}(r)\sigma_r^2(r)}{r} = -\nu(r)\frac{\partial \Phi}{\partial r}$$

Projection:

$$\sigma_{\mathrm{los}}^2(R) = \frac{2}{\Sigma(R)}\int_R^\infty dr\left(1 - \beta_{\mathrm{ani}}(r)\frac{R^2}{r^2}\right)\frac{\nu(r)\sigma_r^2(r)}{\sqrt{1 - R^2/r^2}}$$

Likelihood: Jeans analysis

Models

- v(r): Plummer profile
- β(r): Baes & van Hese (2007)

- SIDM profile:

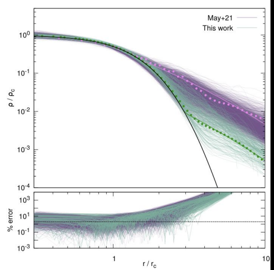
$$\rho(r) = \frac{\rho_s r_s^3}{(r^4 + r_c^4)^{1/4}(r + r_s)^2}$$

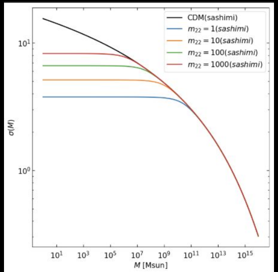
$r \gg r_c$: $\dfrac{\rho_s r_s^3}{r(r + r_s)^2}$ NFW

$r \ll r_c$: $\rho_s (r_s / r_c)^3$ const. (cored)

Difference from Dafa

- Smooth transition
- Cosmological prior
- Higher order momemnt
- Core mass–halo mass relation





Various SASHIMI

~ Menu ~

SASHIMI-C

for CDM

SASHIMI-W

for WDM

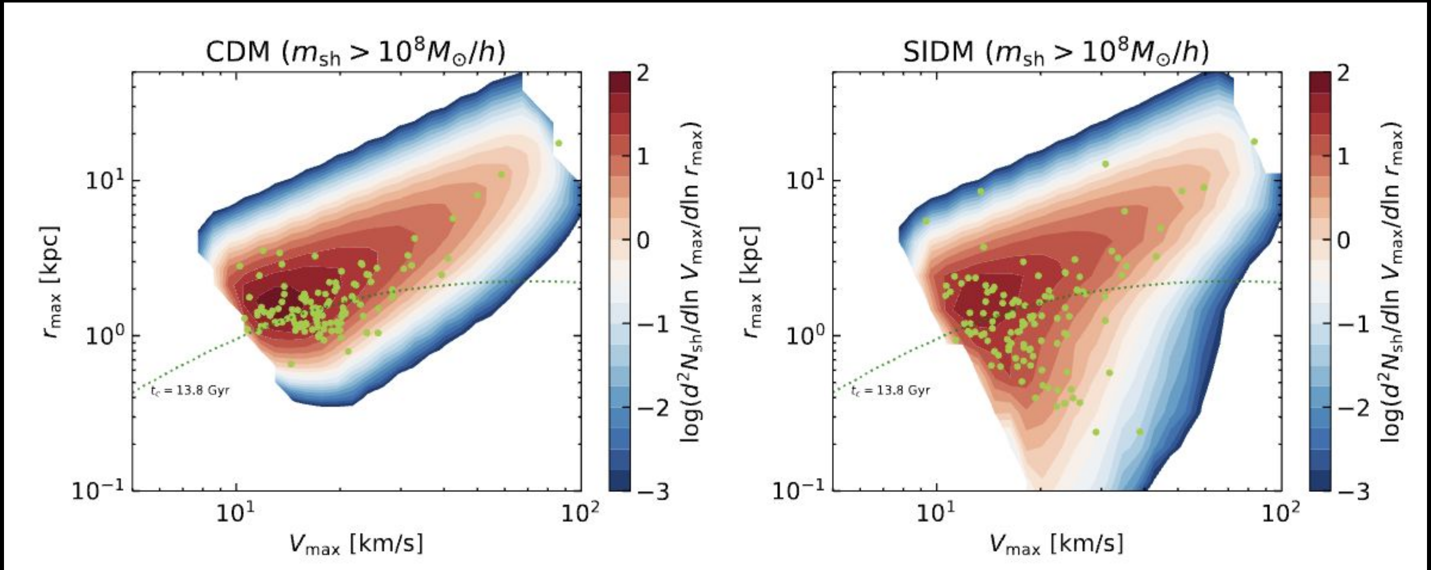
Today's Special

SASHIMI-SIDM

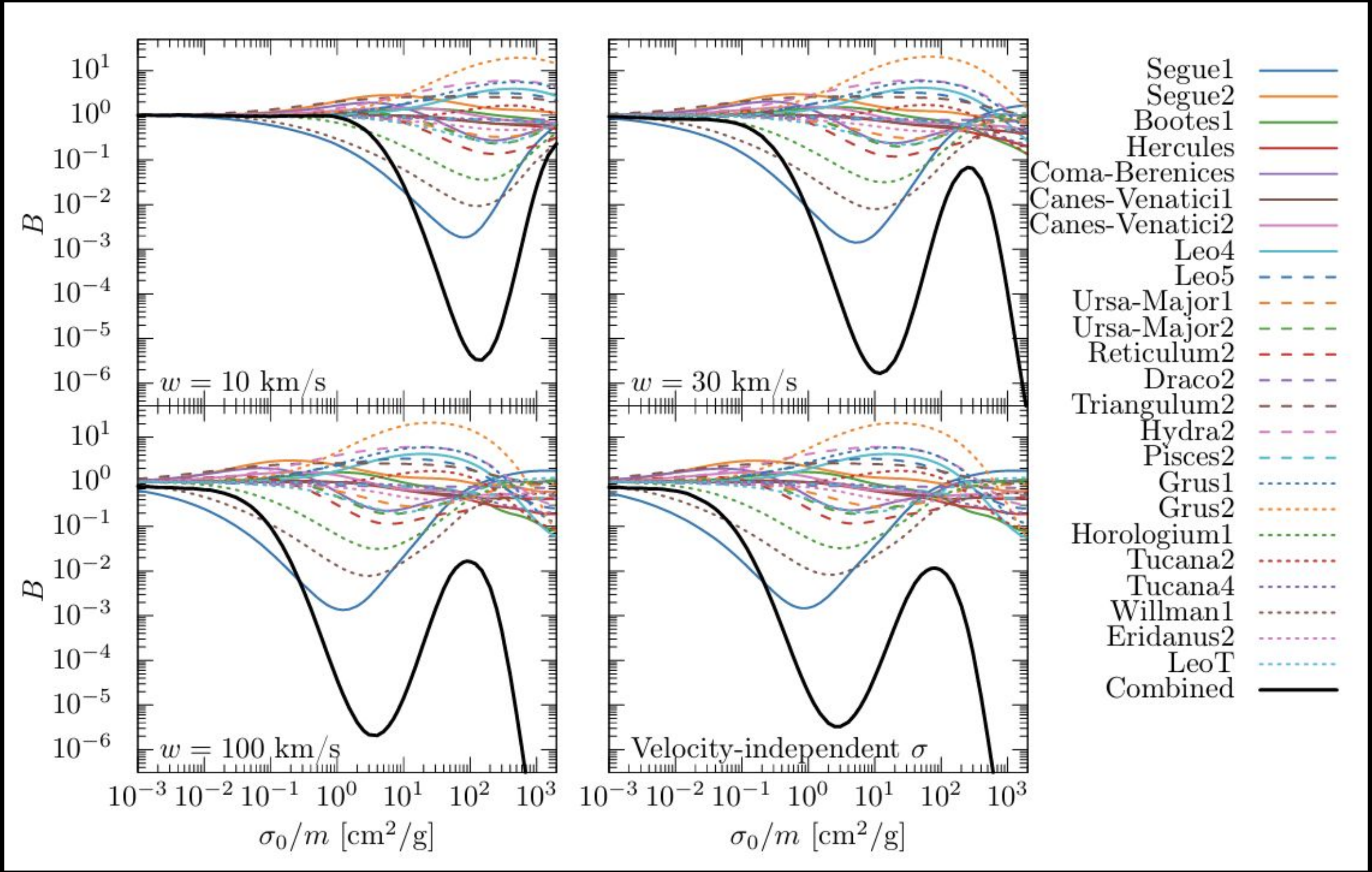
for SIDM

Testing and Tasting SASHIMI-SIDM

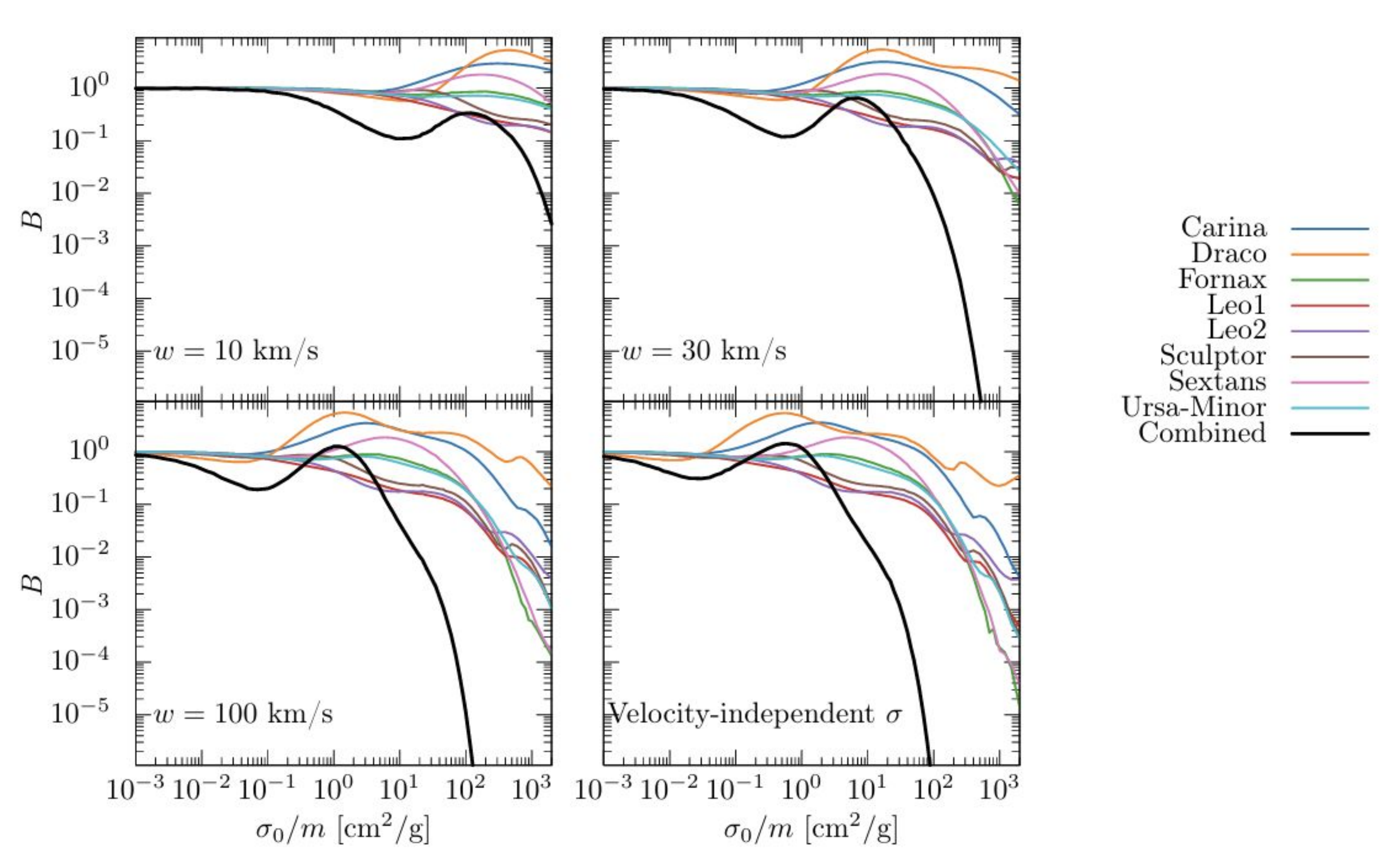
SASHIMI-SIDM can reproduce N-body results



SASHIMI-SIDM allows us to play with SIDM cosmology easily in a few minutes



B
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
$w = 10$ km/s
$w = 30$ km/s
$w = 100$ km/s
Velocity-independent σ
10^{-3} 10^{-2} 10^{-1} 10^{0} 10^{1} 10^{2} 10^{3}
σ_0/m [cm^2/g]
Segue1
Segue2
Bootes1
Hercules
Coma-Berenices
Canes-Venatici1
Canes-Venatici2
Leo4
Leo5
Ursa-Major1
Ursa-Major2
Reticulum2
Draco2
Triangulum2
Hydra2
Pisces2
Grus1
Grus2
Horologium1
Tucana2
Tucana4
Willman1
Eridanus2
LeoT
Combined


B
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$w = 10$ km/s
$w = 30$ km/s
$w = 100$ km/s
Velocity-independent σ
10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3
σ_0/m [cm^2/g]
Carina
Draco
Fornax
Leo1
Leo2
Sculptor
Sextans
Ursa-Minor
Combined

Interpretation and next steps

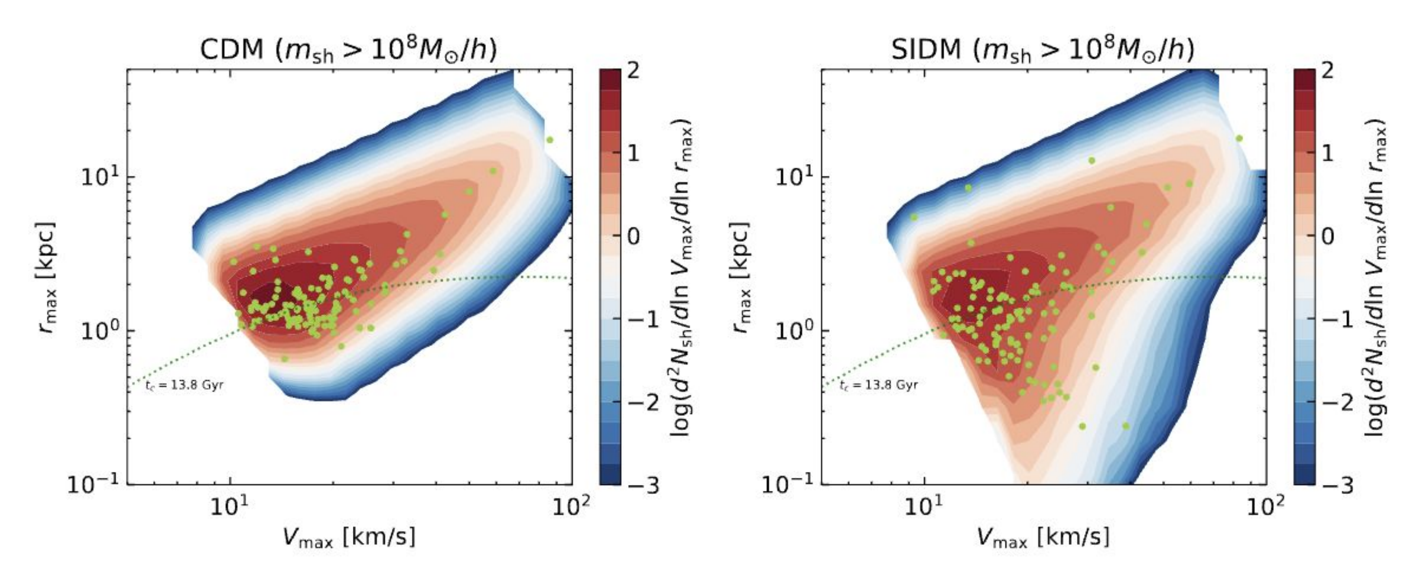
- Baryonic feedback
  - Classical dSphs might be affected
- Formation history
  -
- Spatial SASHIMI
  - Simulate precise mass-loss history of dSphs by tracing their orbital information
- Axisymmetric SASHIMI
  -

SIDM halo structure and evolution: Semi-analytical and effective models

S. Ando, S. Horigome, E. O. Nadler, D. Yang, H.-B. Yu [in prep.]

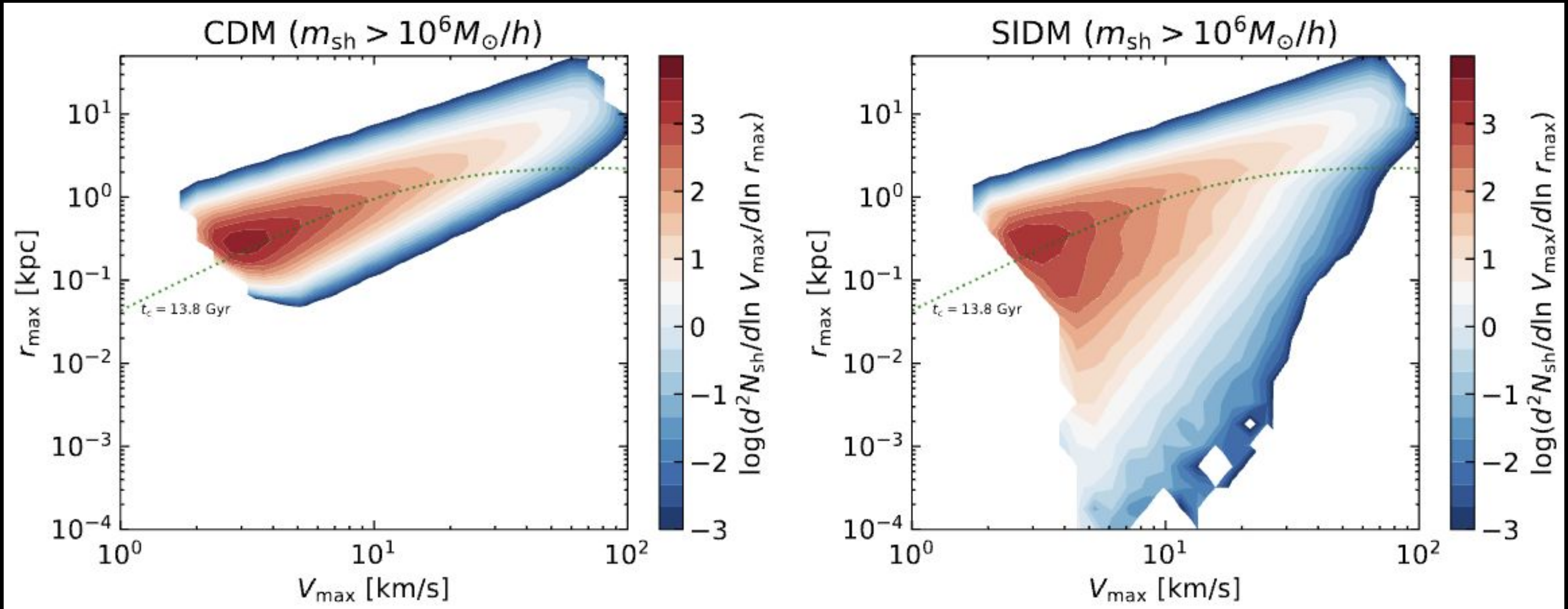
SASHIMI-SIDM: Semi-analytical approach to simulate SIDM models

- Quick calculation of SIDM halo properties and subhalo mass functions



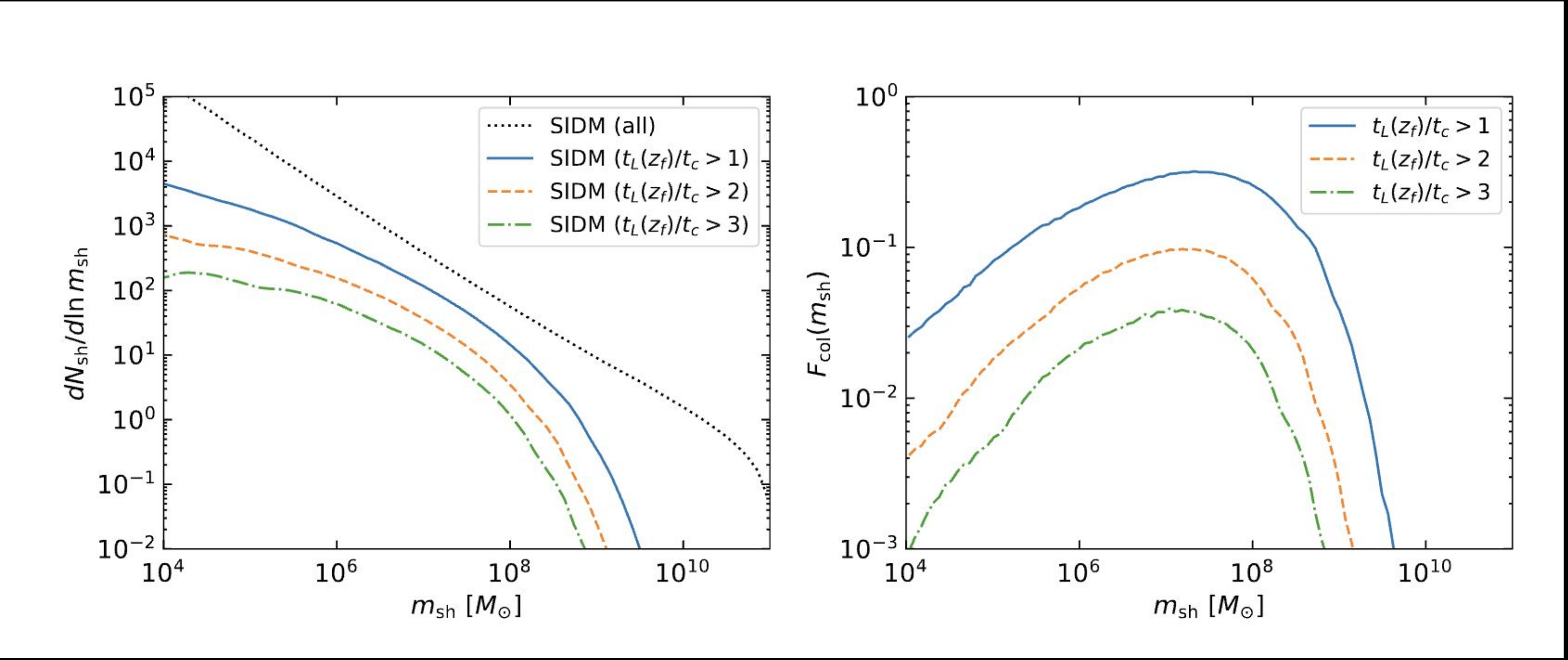
SASHIMI-SIDM

Use Case: Property for lighter subhalos



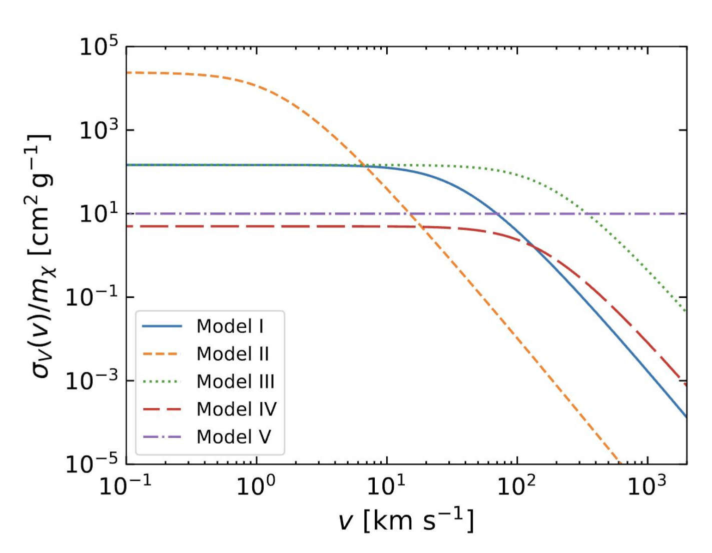
SASHIMI-SIDM

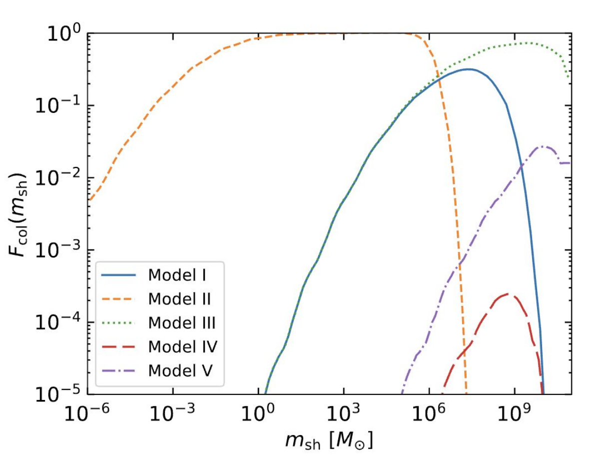
Use case: Subhalo mass function



SASHIMI-SIDM

Subhalo mass function for various SIDM models





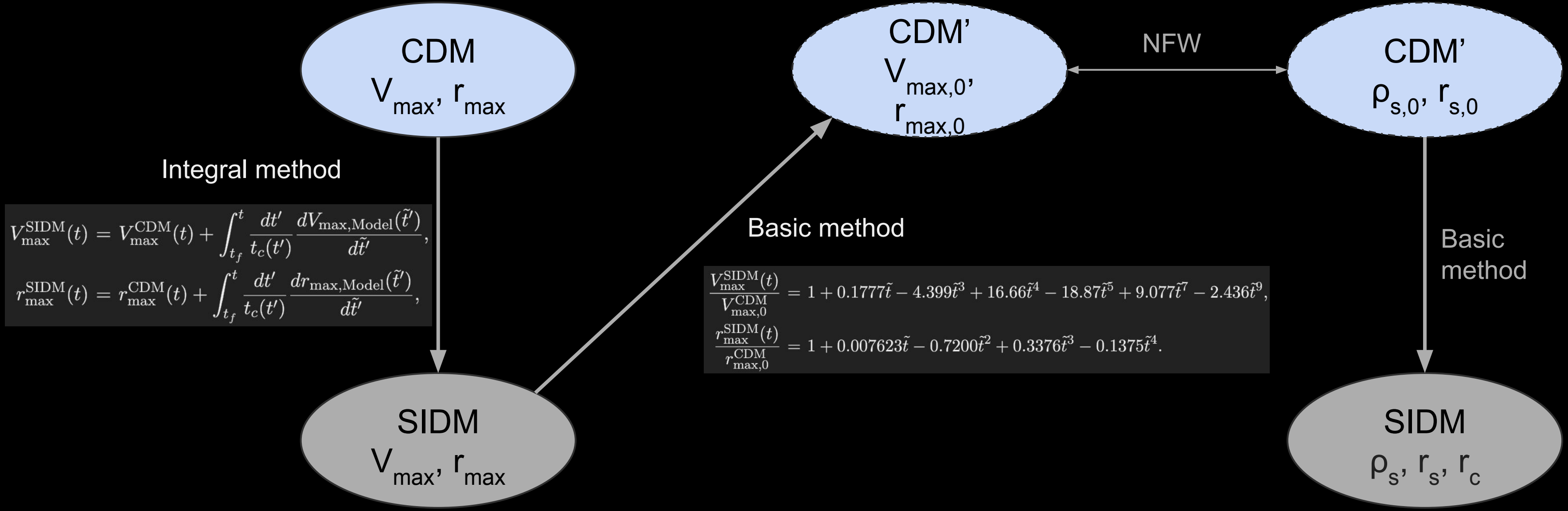
It works for lighter subhalo masses

Simulation setup behind the SIDM model

- **What simulations?**
  - DM-only N-body simulations (not hydrodynamical; no baryonic disk/feedback).
  - GADGET-2 + SIDM scattering module.
- **Calibration: isolated BM2 halo**
  - Initial NFW: $\rho_s = 2.74 \times 10^8\ M_\odot\ \mathrm{kpc}^{-3}$; $r_s = 0.141$ kpc.
  - 4 million DM particles; full gravothermal evolution from core formation to collapse.
  - Rutherford-like velocity/angular-dependent scattering + constant-cross-section tests.
  - $\sigma_{eff}/m = 7.1\ \mathrm{cm}^2\ \mathrm{g}^{-1}$..
- **Validation: cosmological MW zoom-in**
  - Matched CDM/SIDM zoom-in of an MW-like host + LMC analog.
  - $m_p = 4 \times 10^4\ M_\odot\ h^{-1}$; $\varepsilon = 80$ pc h^{-1}.
  - High-res region ≈3 Mpc (≈10 R_{vir}).
  - SIDM benchmark: $\sigma_0/m = 147.1\ \mathrm{cm}^2\ \mathrm{g}^{-1}$; $w = 24.33\ \mathrm{km\ s}^{-1}$.
  - Test cut: $M_{vir} > 10^8\ M_\odot\ h^{-1}$; >3500 particles.

Refs: [Yang+2024] [arXiv:2305.16176] — parametric SIDM / isolated N-body calibration
[Yang+2023] [arXiv:2211.13768] — DMO cosmological MW zoom-in
[Ando+2024] [arXiv:2403.16633] — SASHIMI-SIDM implementation

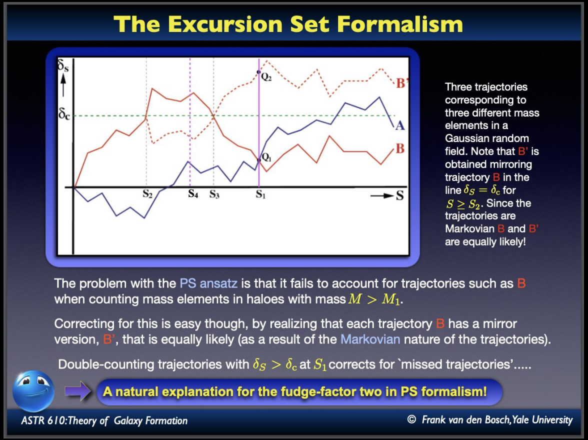
Parametric Model

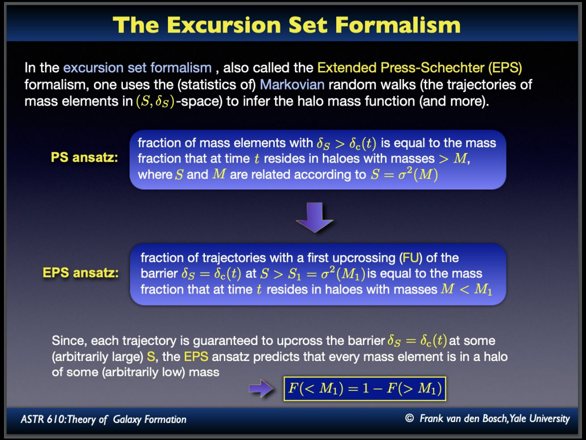


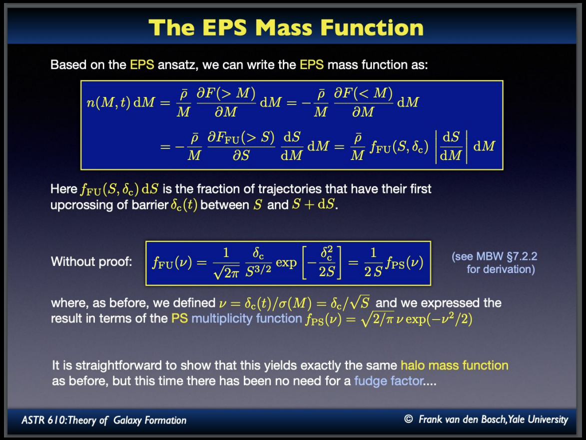
EPS formalism

[Press & Schechter(1974)]

Ref: http://www.astro.yale.edu/vdbosch/astro610_lecture9.pdf





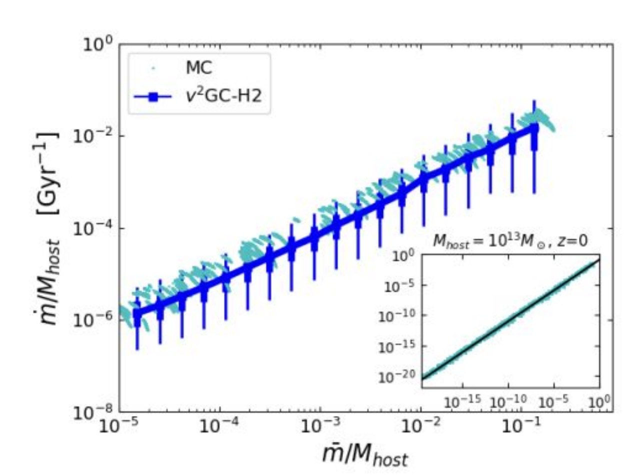


SASHIMI

Tidal stripping: [Hiroshima+(2018)]

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

$$\begin{aligned}\log A &= \left[-0.0003\log\left(\frac{M_{\rm host}}{M_\odot}\right)+0.02\right]z \\ &\quad +0.011\log\left(\frac{M_{\rm host}}{M_\odot}\right)-0.354, \\ \zeta &= \left[0.00012\log\left(\frac{M_{\rm host}}{M_\odot}\right)-0.0033\right]z \\ &\quad -0.0011\log\left(\frac{M_{\rm host}}{M_\odot}\right)+0.026.\end{aligned}$$



SIDM review

Sean Tulin, Hai-Bo Yu, "Dark Matter Self-interactions and Small Scale Structure"