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

Shin'ichiro Ando[1,2], Kohei Hayashi[3,4,5], Shunichi Horigome[2→4], Masahiro Ibe[5,2], Satoshi Shirai[2] [arXiv:2503.13650]

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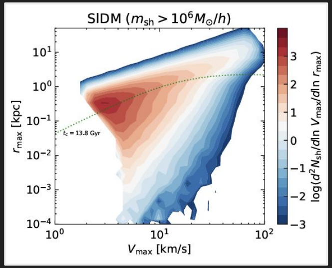
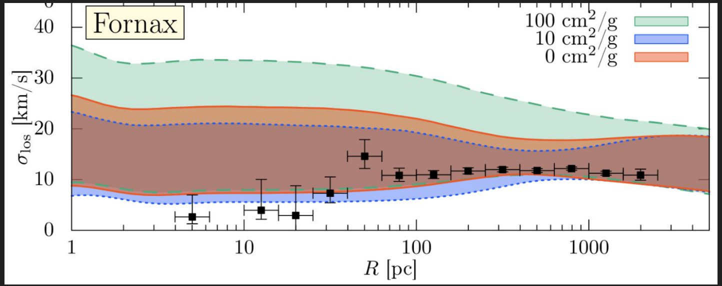
Kinematics of dSphs

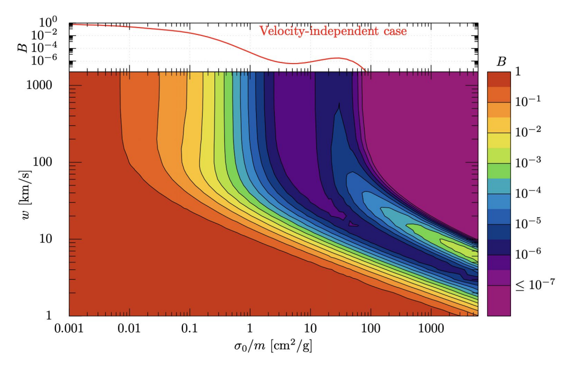
SIDM cosmology





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

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



Introduction

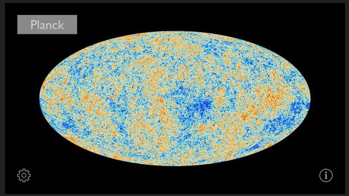
Dark matter in our universe

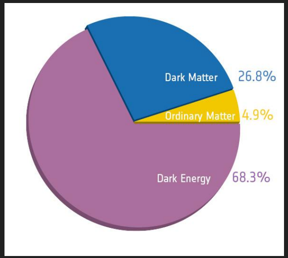
ΛCDM explains the **LSS** of the universe

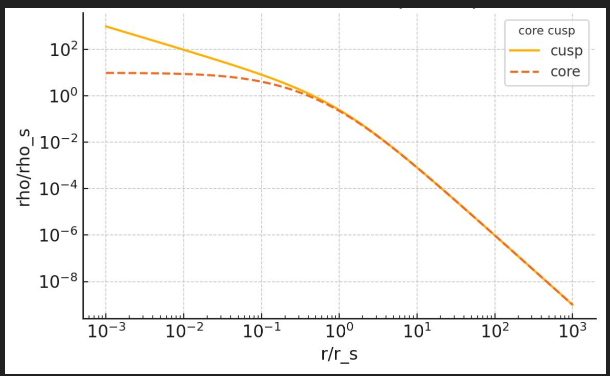
How about the **small** scale?

- Core vs. cusp
- Missing satellite
- Too-big-to-fail
- …

→ Any other solutions than CDM?







Self-Interacting Dark Matter (SIDM)

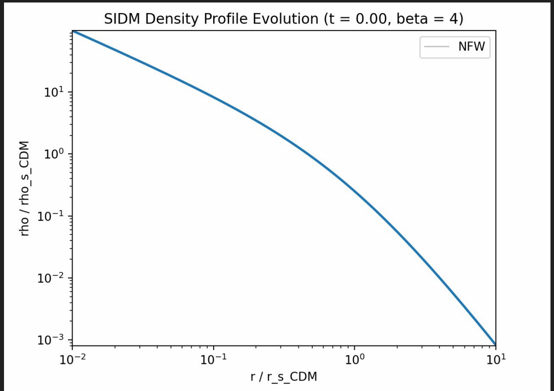
Large self-scattering cross section

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

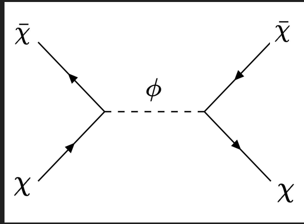
c.f. CDM (WIMP)

$$\sigma/m \lesssim 10^{-14}\ \mathrm{cm}^2/\mathrm{g}$$

→ Gravothermal evolution of halos



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

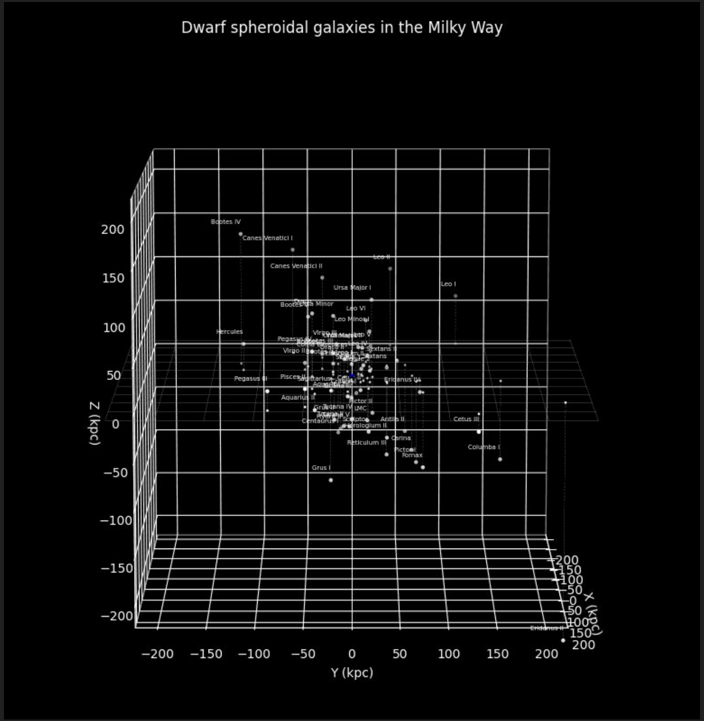


Dwarf spheroidal galaxies (dSphs)

Large M/L ratio: Υ=10-100
→ dark matter dominant objects

Important targets to investigate small scale issues of dark matter (core/cusp)

Q. Are SIDM predictions consistent with the observed dSph profiles?



Method

Bayesian analysis

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

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

- *L*: Likelihood from dSph observation
- *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

Jeans equation:

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

ν(r): Number density (Plummer model)
β(r): Anisotropy (general model by Baes & van Hese (2007))
σ(r): Velocity dispersion
ΔΦ(r) = 4πG ρ(r):

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

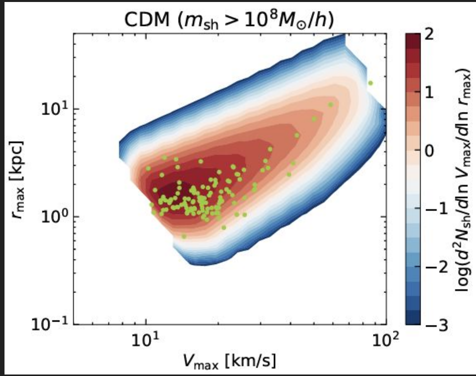
$r \gg r_c$: $\rightarrow \frac{\rho_s r_s^3}{r(r + r_s)^2}$ NFW

$r \ll r_c$: $\rightarrow \rho_s (r_s/r_c)^3$ 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}
  - …

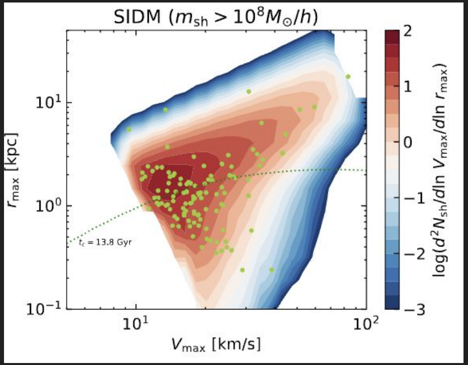


For **CDM**: [arXiv:2403.16633]

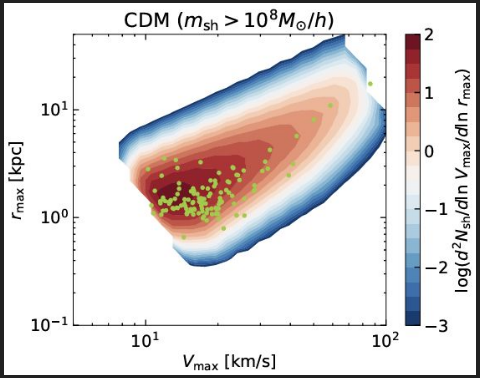
Prior: Cosmological constraint of SASHIMI-SIDM

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

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



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



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

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

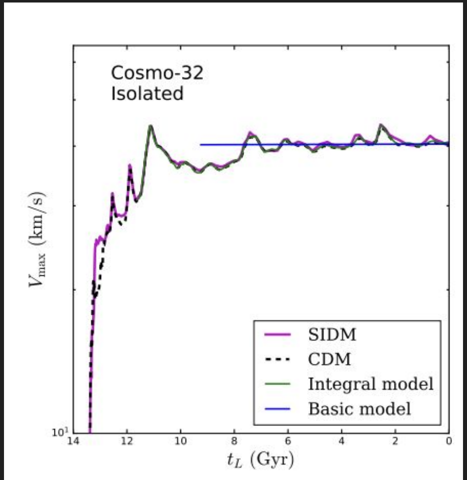
- Parametric model of SIDM halos [Yang+(2023)] to reinterpret CDM → SIDM
  - Empirical function of $\tau = t/t_c$
    - t_c: collapse time scale:

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

SIDM

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

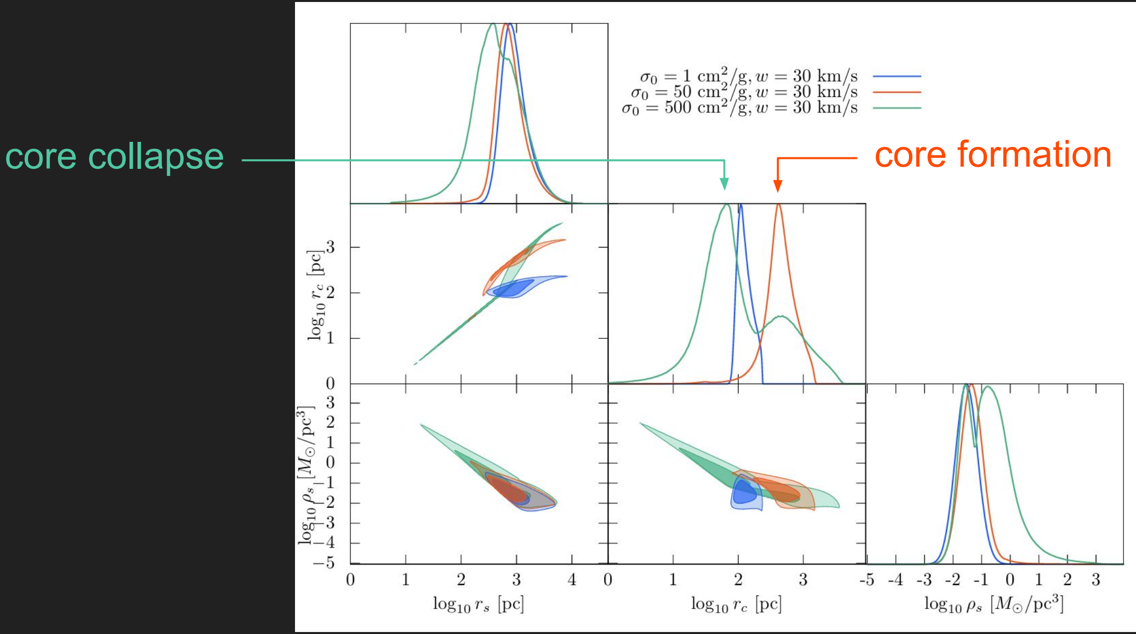
CDM



Yang+(2023)

Prior: Cosmological constraint of SASHIMI-SIDM

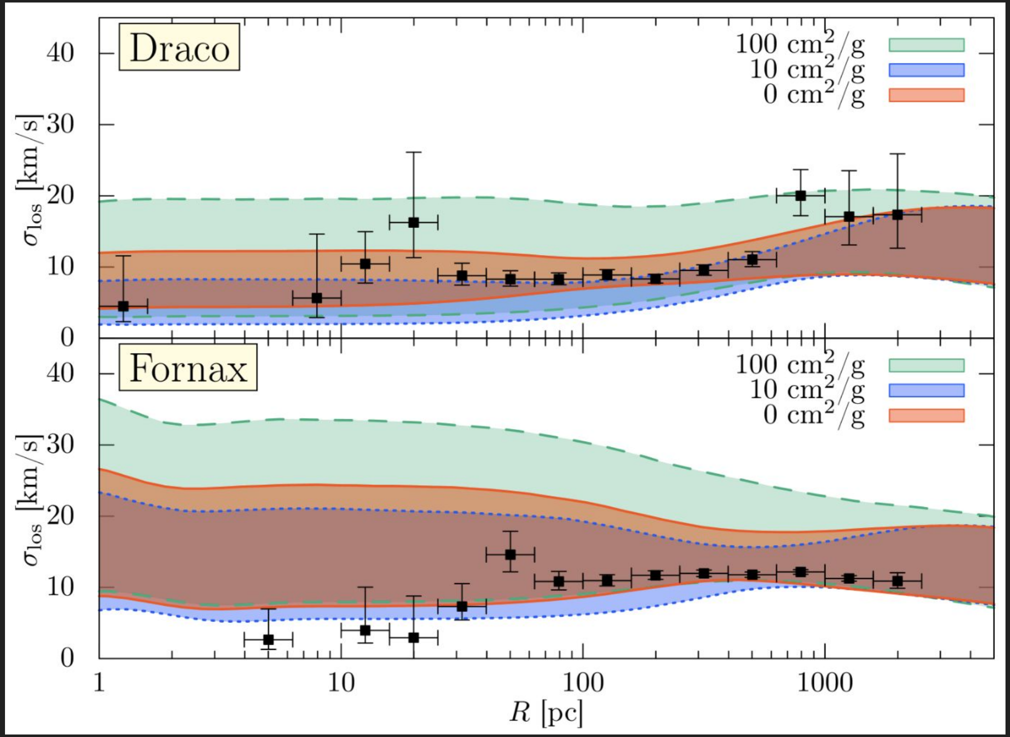
Example: Prior distributions for different SIDM parameters

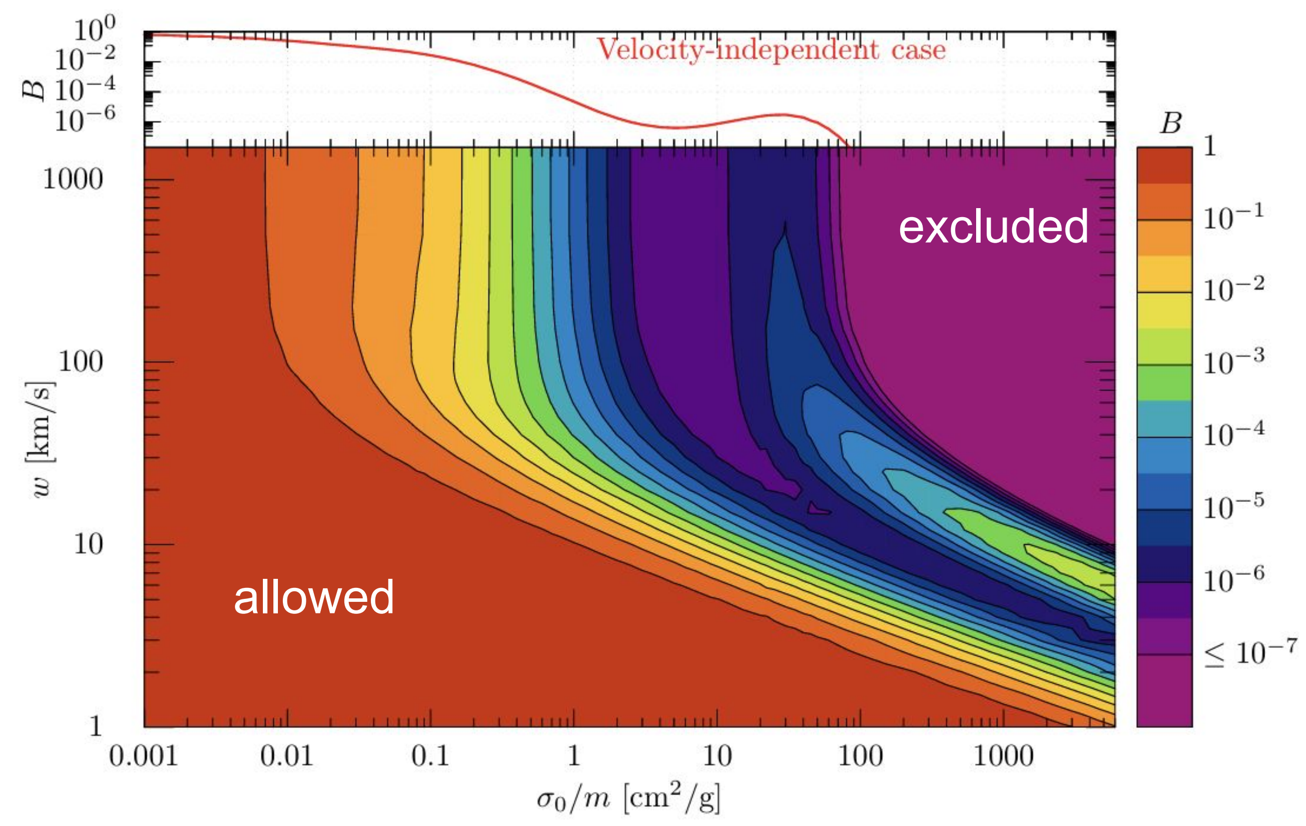


Results

Results

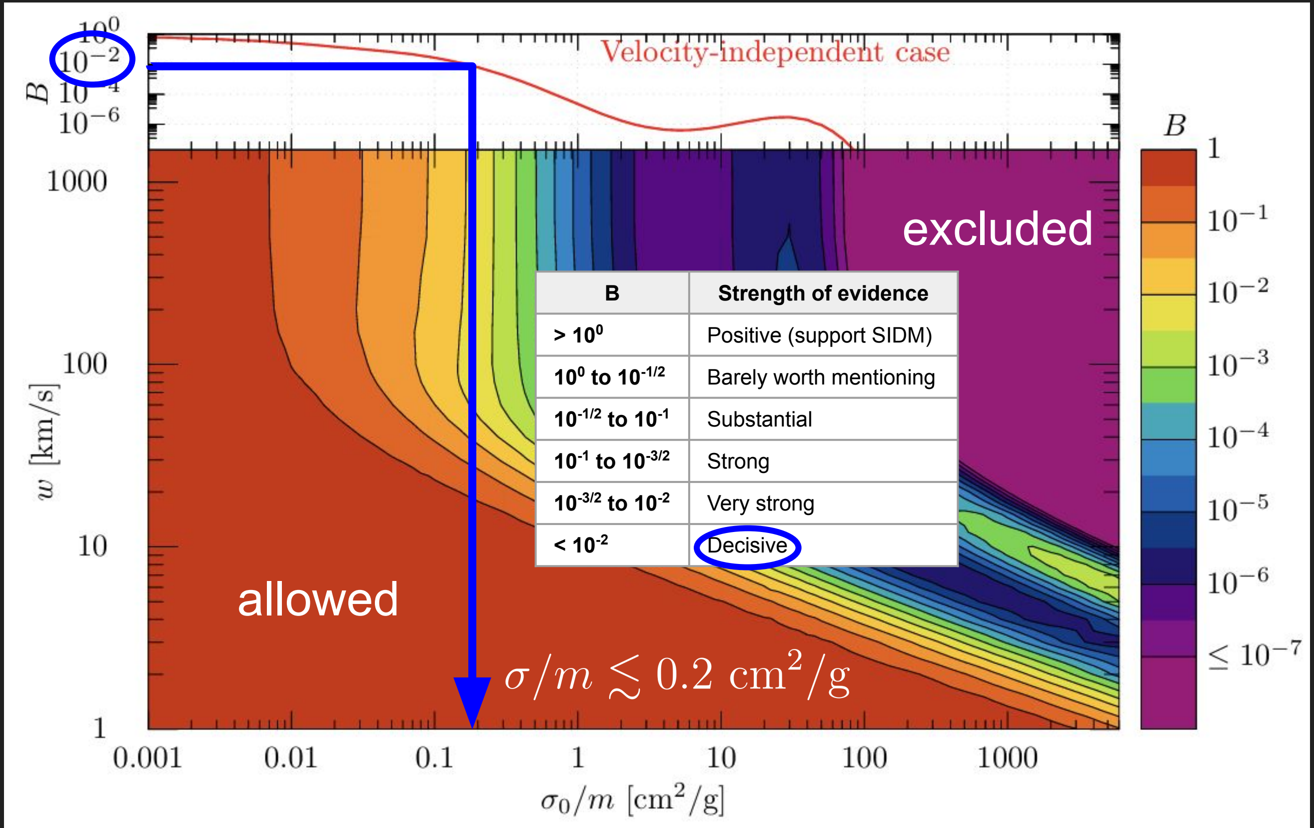
- Too large σ/m cannot fit observed velocity dispersion of stars
- To marginalize the diversity of dSphs, we compute total Bayes factor $B = \prod_i B_i$





$B = \Pi_i B_i$

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



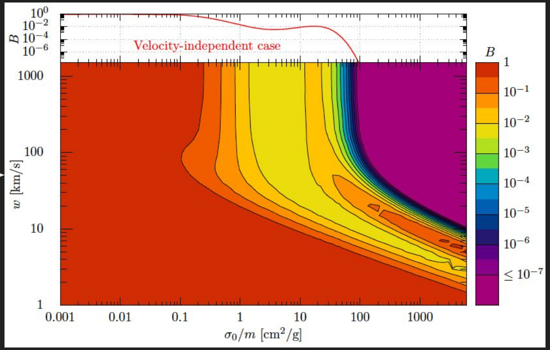
B	Strength of evidence
$> 10^{0}$	Positive (support SIDM)
10^{0} to $10^{-1/2}$	Barely worth mentioning
$10^{-1/2}$ to 10^{-1}	Substantial
10^{-1} to $10^{-3/2}$	Strong
$10^{-3/2}$ to 10^{-2}	Very strong
$< 10^{-2}$	Decisive

$B = \Pi_i B_i$

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

Discussion & Future direction

- 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



Summary

- DSphs are promising targets to verify the small scale issues of DM
- We investigate if SIDM can explain DM profiles of dSphs by considering
  - **Kinematics of dSph**: (spherical) Jeans equation
  - **Cosmology**: SASHIMI-SIDM (semianalytical SIDM cosmology)
    - including **gravothermal core-collapse effect**
- We found that
  - SIDM with large self-interaction cannot explain the observed dSph profiles
    - Velocity independent case: $\sigma/m \lesssim 0.2\ \mathrm{g/cm^2}$
- Future works
  - Better understanding of subhalo & satellite galaxy

Backup

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:

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

Projection:

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

Likelihood: Jeans analysis

Models

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

- SIDM profile:

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

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

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

Various SASHIMI

~ Menu ~

SASHIMI-C

for CDM

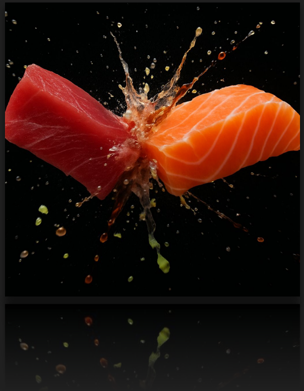
SASHIMI-W

for WDM

Today's Special

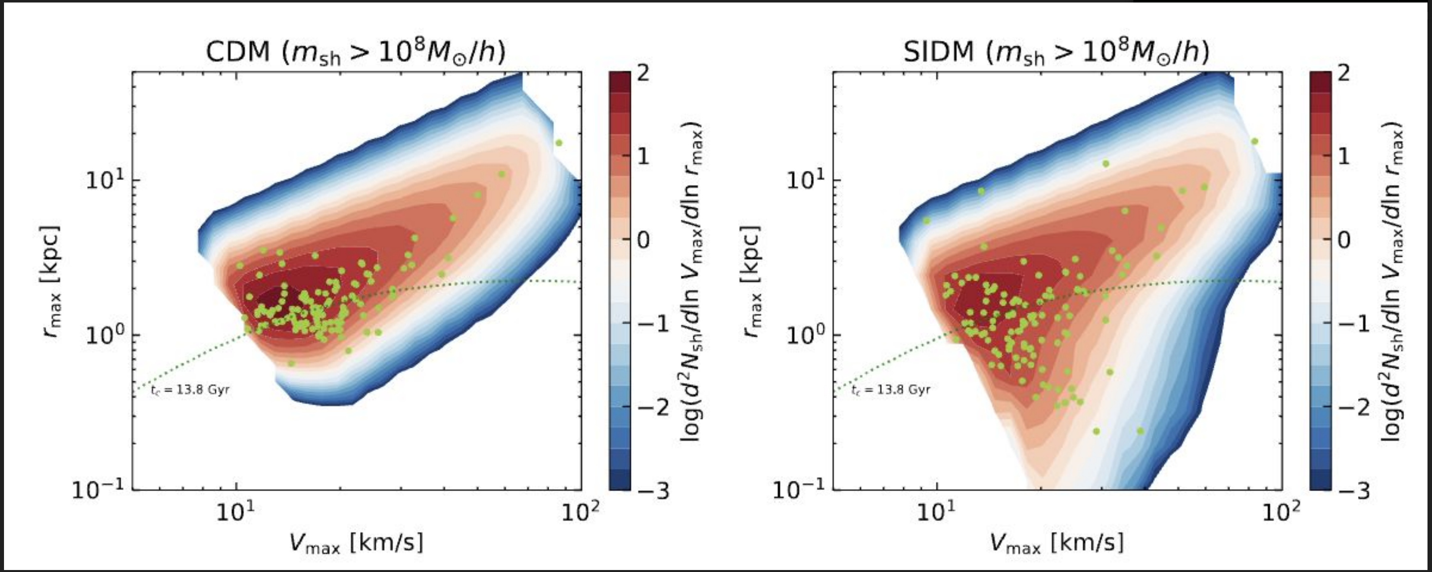
SASHIMI-SIDM

for SIDM

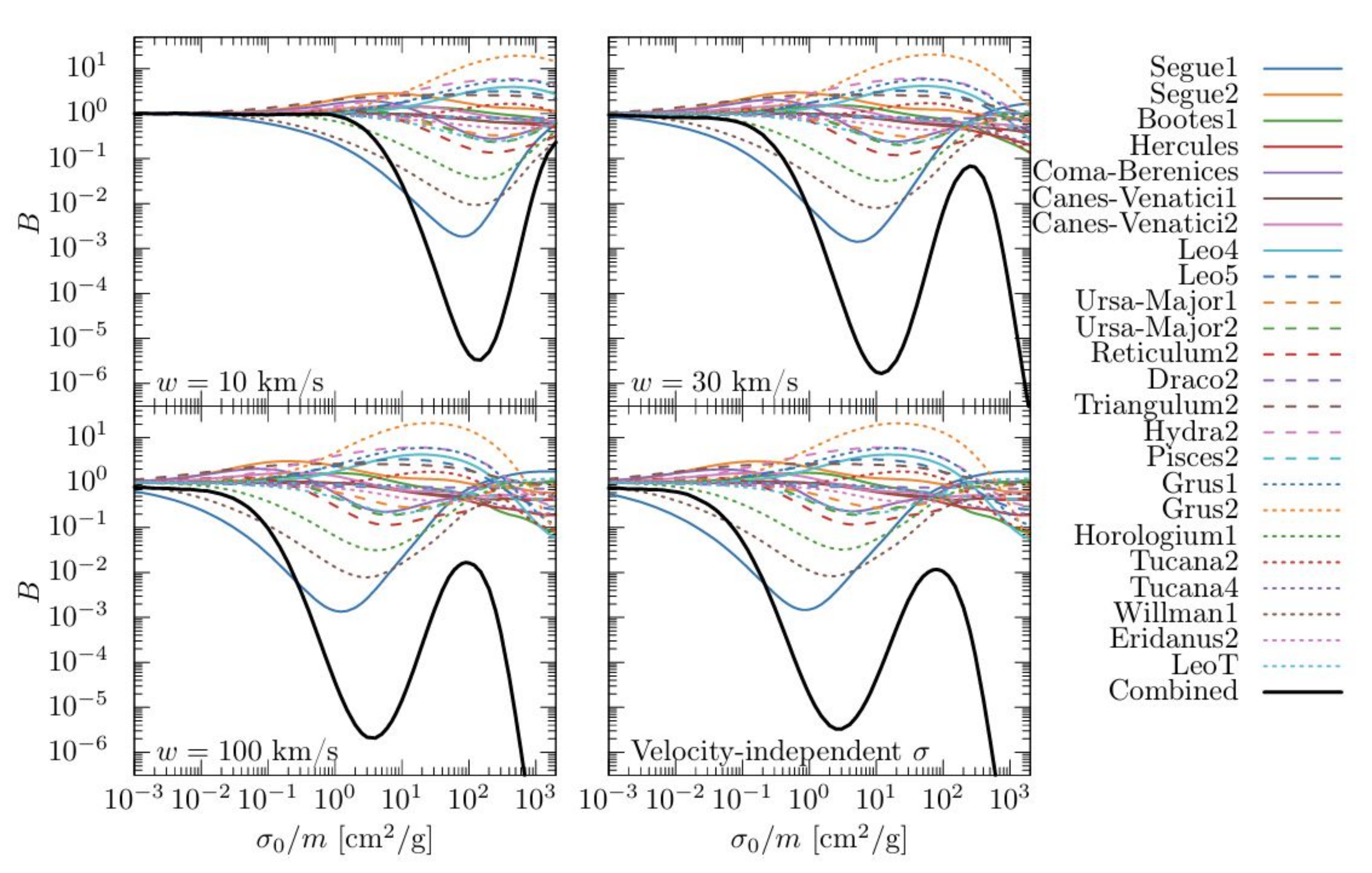


Testing and Tasting SASHIMI-SIDM

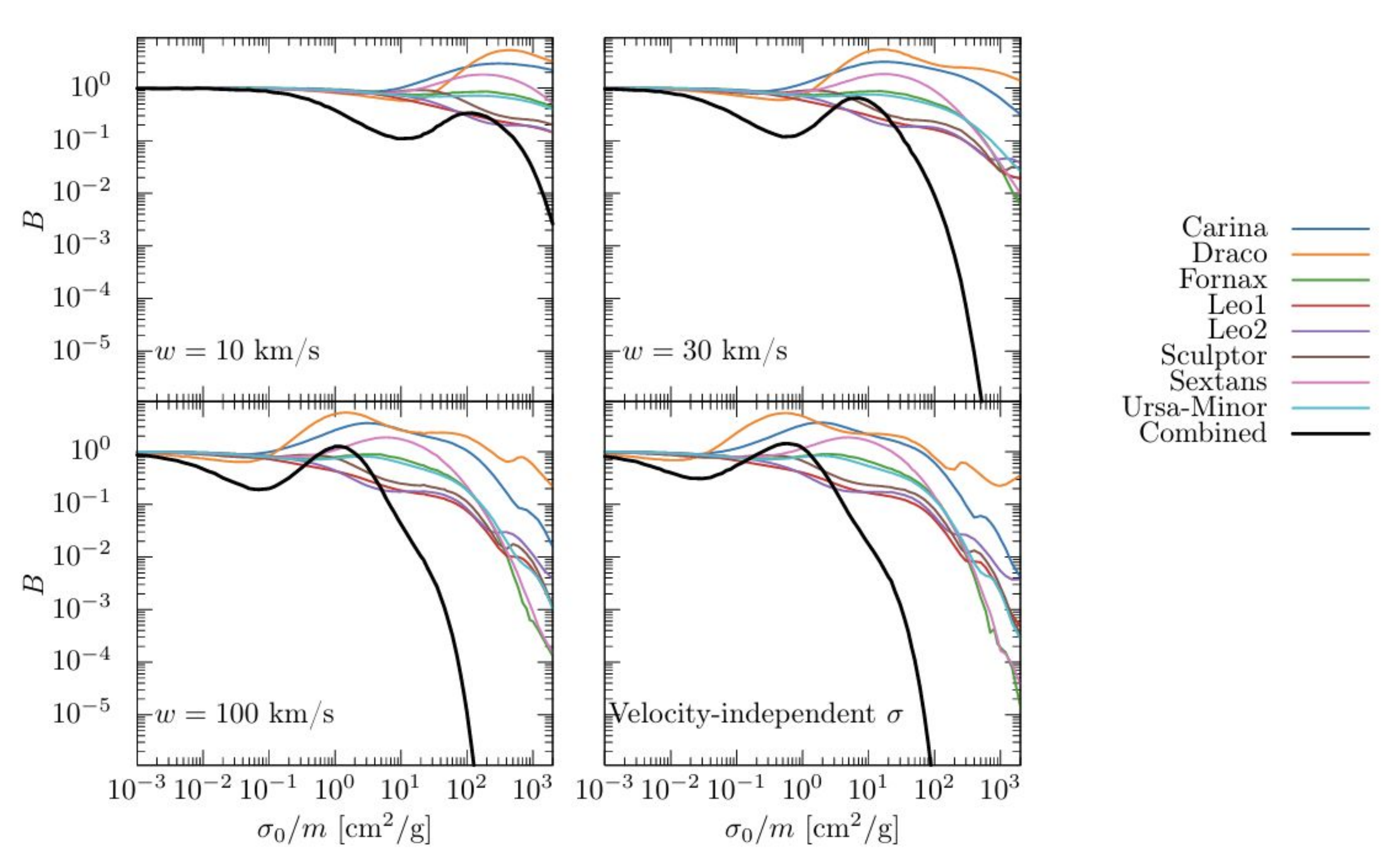
SASHIMI-SIDM can reproduce N-body results



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



10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
B
$w = 10$ 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

Future works

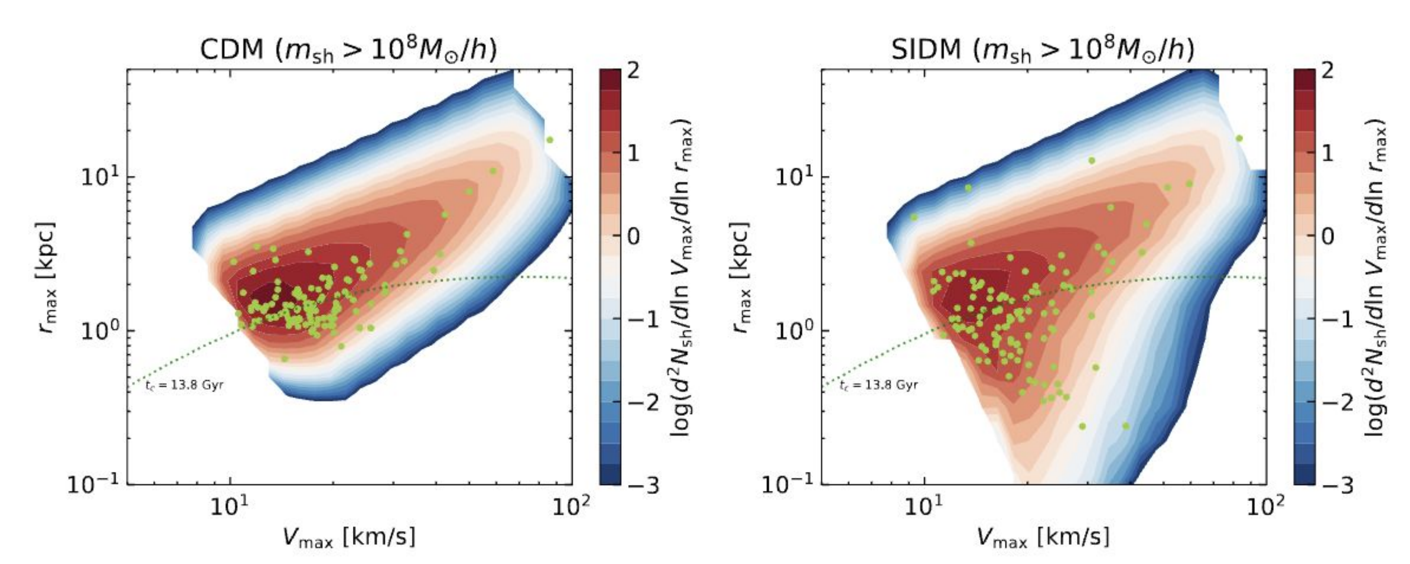
- Baryonic feedback
  - Classical dSphs might be affected
- Formation history
  -
- Spatial SASHIMI
  - Simulate precise mass-loss history of dSphs by tracing their orbital information
- Axisymmetric SASHIMI
  -

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

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

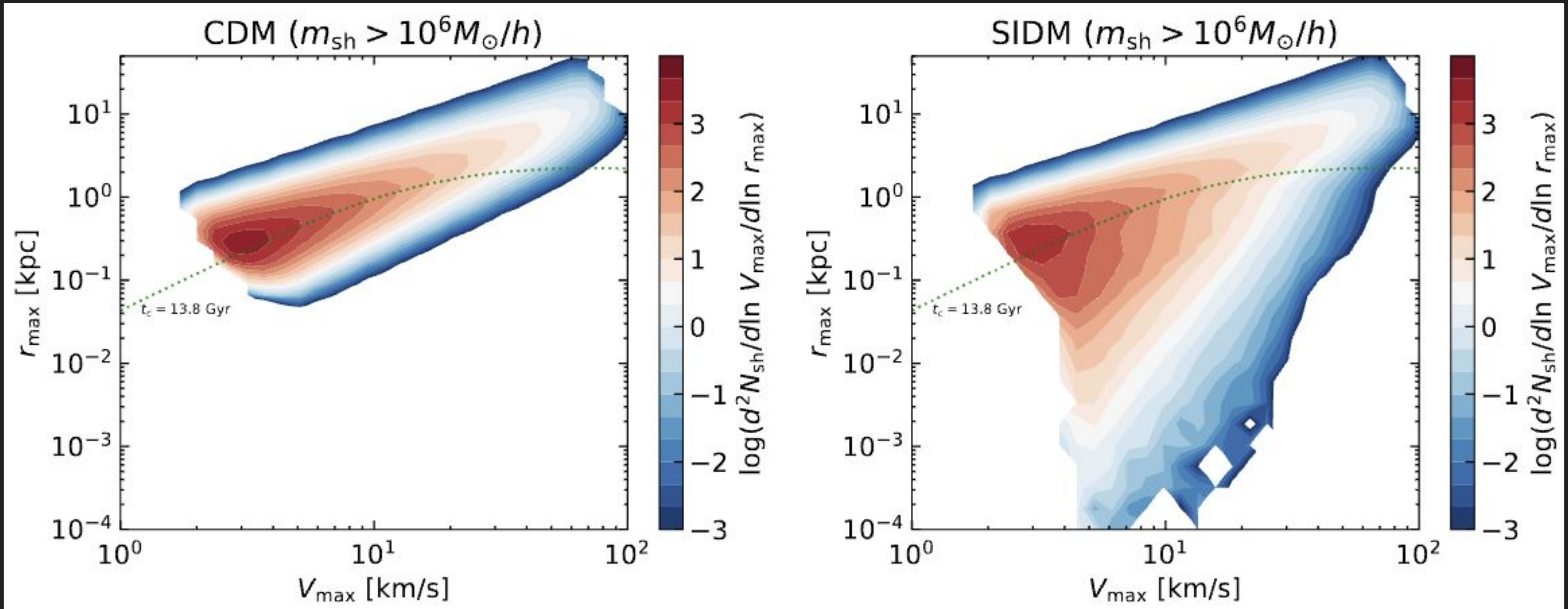
SASHIMI-SIDM: Semi-analytical approach to simulate SIDM models

- Quick calculation of SIDM halo properties and subhalo mass functions



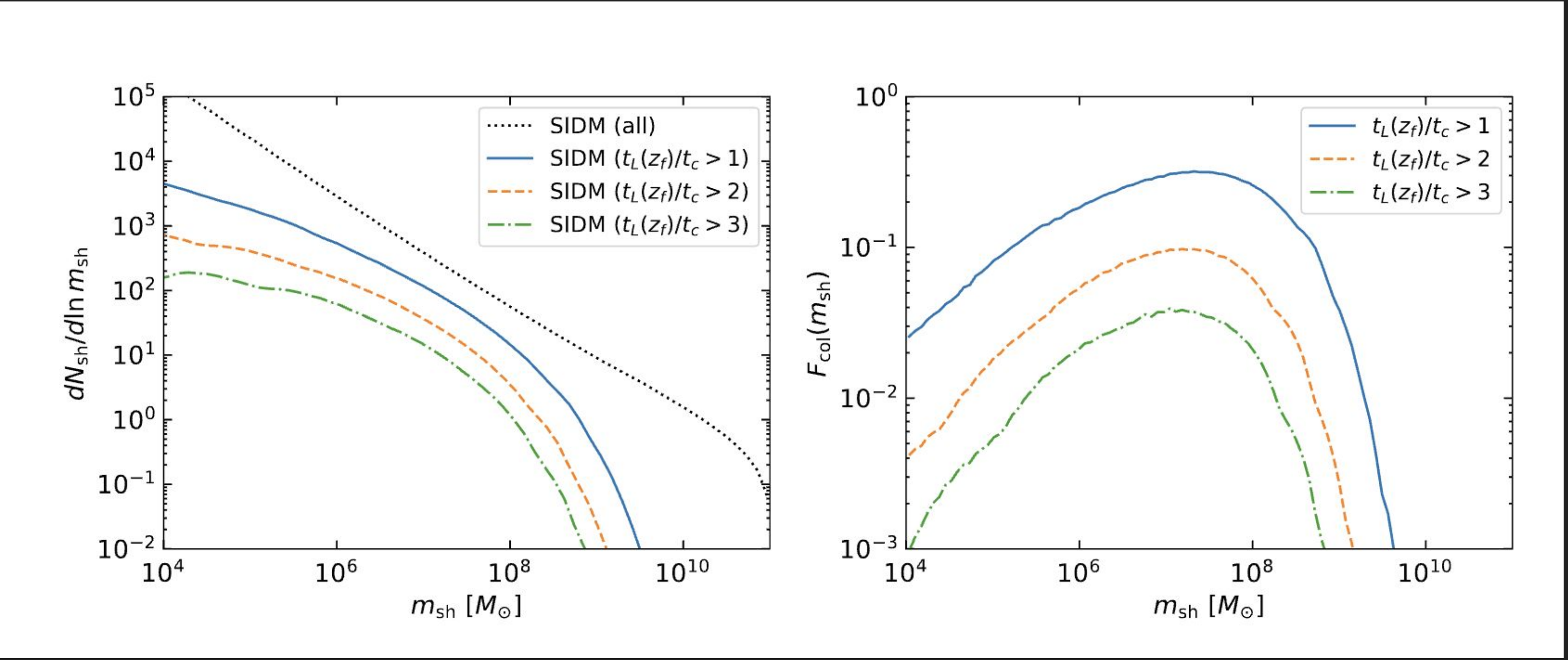
SASHIMI-SIDM

Use Case: Property for lighter subhalos



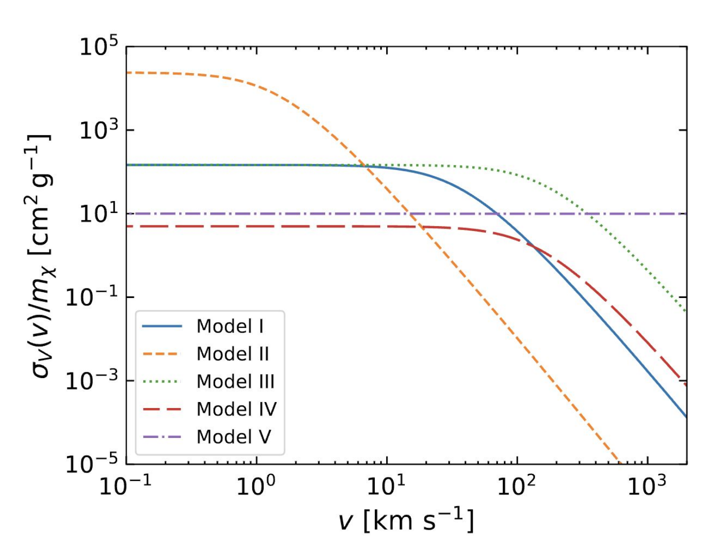
SASHIMI-SIDM

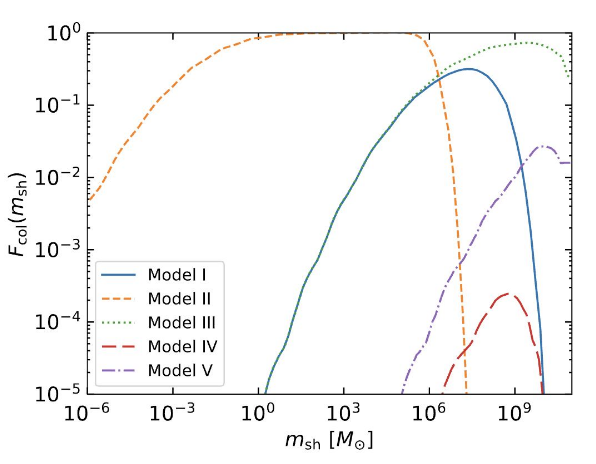
Use case: Subhalo mass function



SASHIMI-SIDM

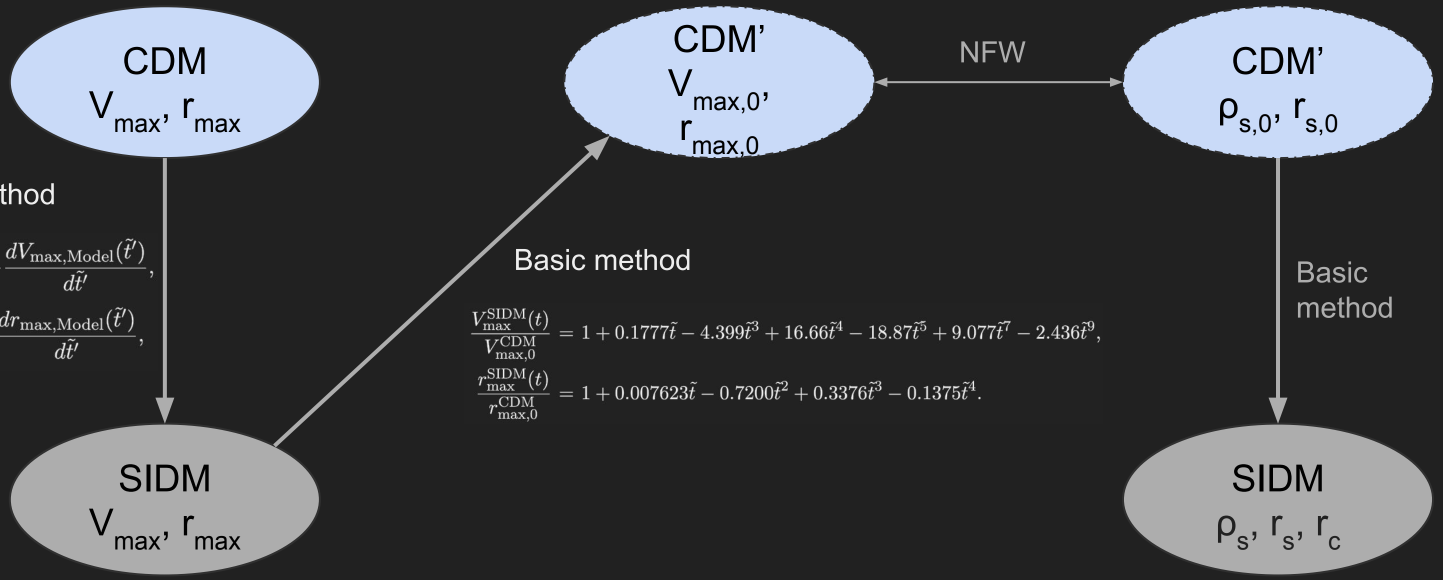
Subhalo mass function for various SIDM models





It works for lighter subhalo masses

Parametric Model



$$V_{\rm max}^{\rm SIDM}(t) = V_{\rm max}^{\rm CDM}(t) + \int_{t_f}^{t} \frac{dt'}{t_c(t')} \frac{dV_{\rm max,Model}(\tilde{t}')}{d\tilde{t}'},$$

$$r_{\rm max}^{\rm SIDM}(t) = r_{\rm max}^{\rm CDM}(t) + \int_{t_f}^{t} \frac{dt'}{t_c(t')} \frac{dr_{\rm max,Model}(\tilde{t}')}{d\tilde{t}'},$$

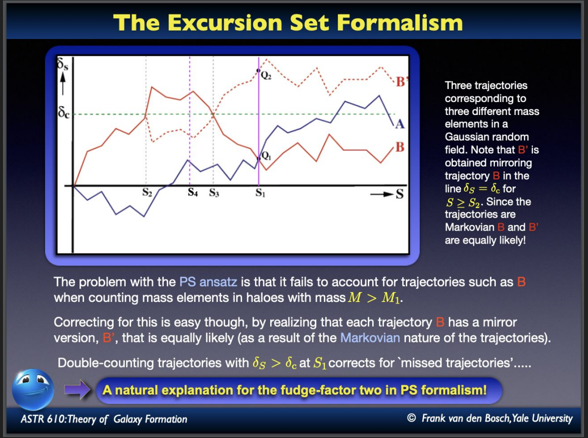
$$\frac{V_{\rm max}^{\rm SIDM}(t)}{V_{\rm max,0}^{\rm CDM}} = 1 + 0.1777\tilde{t} - 4.399\tilde{t}^3 + 16.66\tilde{t}^4 - 18.87\tilde{t}^5 + 9.077\tilde{t}^7 - 2.436\tilde{t}^9,$$

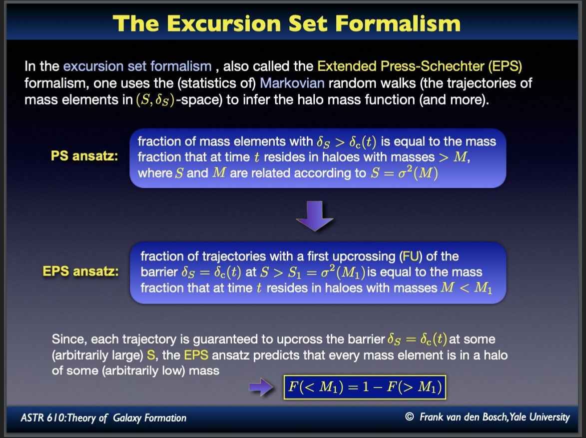
$$\frac{r_{\rm max}^{\rm SIDM}(t)}{r_{\rm max,0}^{\rm CDM}} = 1 + 0.007623\tilde{t} - 0.7200\tilde{t}^2 + 0.3376\tilde{t}^3 - 0.1375\tilde{t}^4.$$

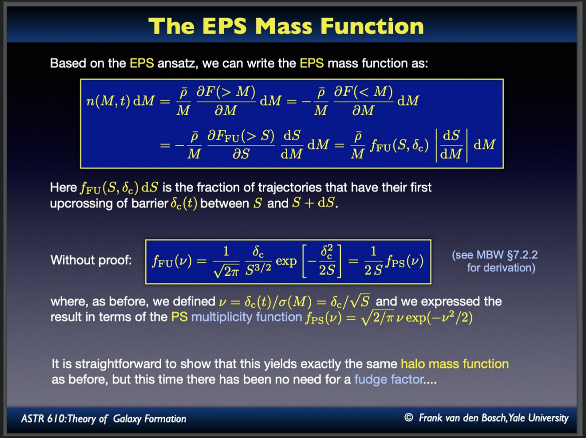
EPS formalism

[Press & Schechter(1974)]

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





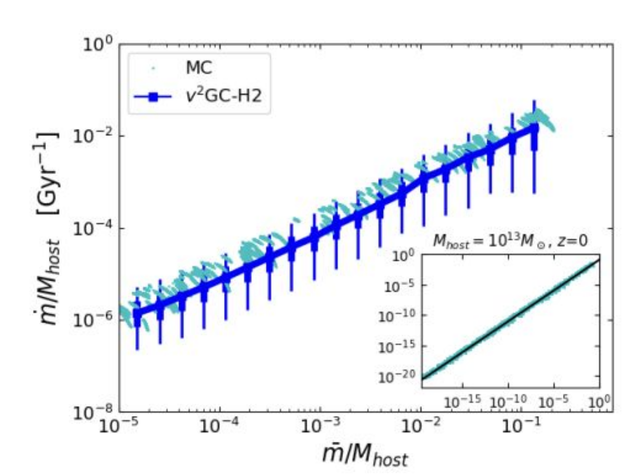


SASHIMI

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"