Dark matter density profile estimation with cosmological models

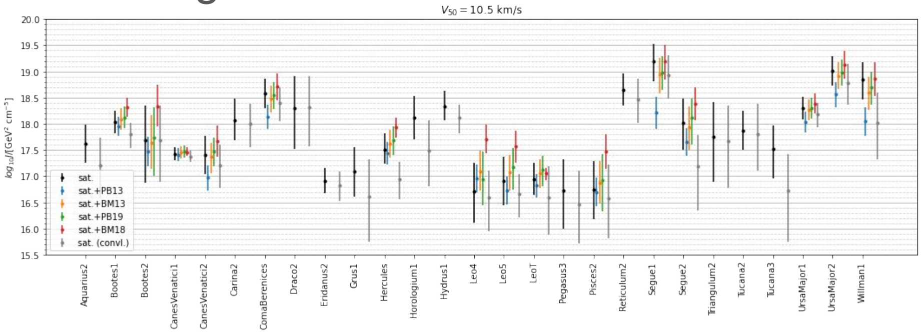
Shunichi Horigome (Kavli IPMU)

based on:
- [arXiv:2207.10378], collaboration with Kohei Hayashi and Shin'ichiro Ando
- [arXiv:in-prep], collaboration with Masato Shirasaki and Shin'ichiro Ando

Dark matter density profile estimation with cosmological models

Shunichi Horigome, Kavli IPMU

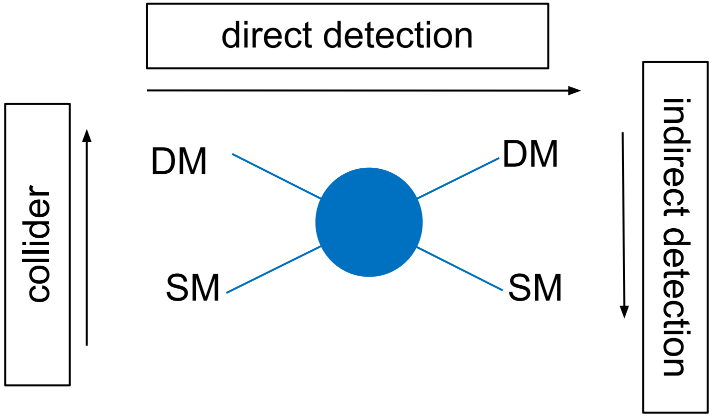
- Dark matter density profile of astronomical objects (dSph, MW) is important to study the nature of dark matter (mass, cross section, self-interaction)
- Cosmological models are useful to estimate these profiles by using stellar data
  - Satellire prior: prior on stuructural parameters of dSph dark matter profiles based on the extended Press-Schechter formalism
  - SHMR prior: empirical relation between stellar and dark matter mass
  - SIDM profile model: gravothermal fluid model calibrated by N-body simulation



Introduction

Introduction: Indirect detection

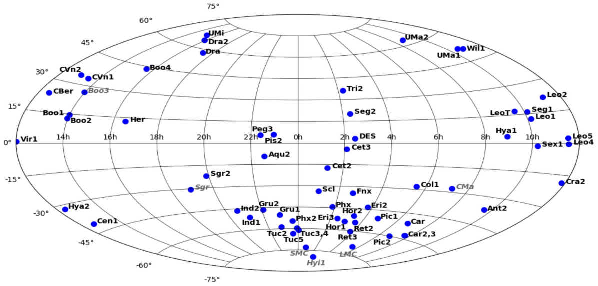
- Collider search
- Direct detection
- Indirect detection



Introduction: Indirect detection

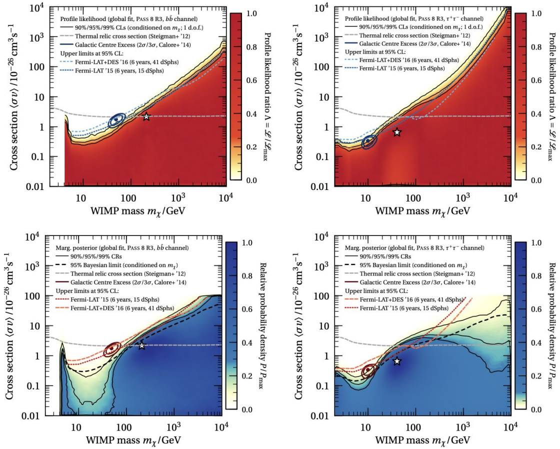
- e.g. Dwarf spheroidal galaxies (dSphs)
  - Containing large amount of DM
  - Good candidates for the indirect detection of the WIMP DM

e.g. Fornax dSph



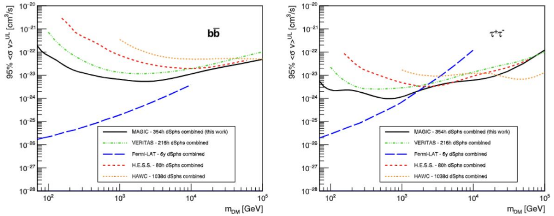
McConachie+(2020) [2007.05011]

Fermi-LAT



Hoof+(2020) [1812.06986]

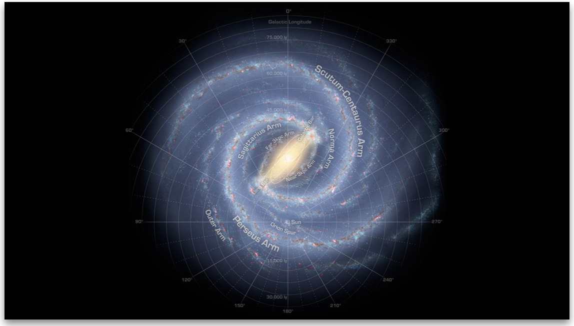
Combined (Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS)

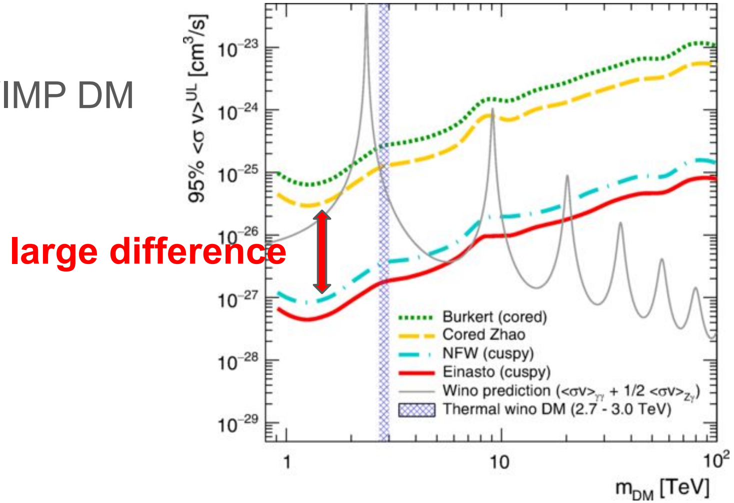


Armard+(2021) [2108.13646]

Introduction: Indirect detection

- e.g. Galactic center
  - Containing large amount of DM
  - Good candidates for the indirect detection of the WIMP DM





MAGIC colab. [2212.10527]

Problem: DM profile dependency

- The sensitivity of the indirect detection depends on the **DM profile** of targets
  - Indirect detection: DM annihilation into SM particles (gamma-ray etc.)
    - Signal flux:

$$\Phi(E, \Delta\Omega) = \underbrace{\left[\frac{C\langle\sigma v\rangle}{4\pi m_{\mathrm{DM}}^2} \sum_f b_f \left(\frac{dN_\gamma}{dE}\right)_f\right]}_{\text{Particle physics factor}} \times \underbrace{\left[\int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \mathrm{d}l\, \rho_{\mathrm{DM}}^2(l, \Omega)\right]}_{\text{Astronomical factor} = J(\Delta\Omega)}$$

Particle physics factor

Astronomical factor = $J(\Delta\Omega)$

Questions

- How is the DM density profile…
  - from **observational** viewpoints?
    - How can we precisely determine the density profile?
  - from **theoretical** viewpoints?
    - How should the profile be in specific DM scenarios?
      - e.g. CDM v.s. SIDM
        - CDM ← “cuspy”
        - SIDM ← “cored”

Questions

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  - from **observational** viewpoints?
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1.

2.

[arXiv:2207.10378]

1. Cosmological prior for the J-factor estimation of dwarf spheroidal galaxies

Shunichi Horigome, Kohei Hayashi, Shinichiro Ando

[arXiv:2207.10378]

Cosmological prior for the J-factor estimation of dwarf spheroidal galaxies

Shunichi Horigome, Kohei Hayashi, Shinichiro Ando

We estimate DM density profile of dSphs by

- Satellite prior:
  cosmological model of CDM subhalo formation
  (semi-analytic model based on extended Press-Schechter formalizm)

- Stellar-to-halo mass relation (SHMR):
  Empirical relation between stellar and DM mass

- velocity dependent likelihood:
  probing velocity dispersion profile of dSph

Jeans analysis

- Jeans equation: kinematical equation of dSph systems
  - Assumption: sphericity

$$\frac{1}{\nu_*(r)}\frac{\partial(\nu_*(r)\sigma_r^2(r))}{\partial r}+\frac{2\beta(r)\sigma_r^2(r)}{r}=-\frac{GM_{\rm DM}(r)}{r^2}$$

(stellar distribution & velocity dispersion) ~ (inner dark matter mass)

- Observable: line-of-sight velocity dispersion (R-dependent)

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

- Models:
  - Stellar profile $\Sigma(R)$, $\nu(r)$: Plummer model
  - DM profile $\rho(r)$: truncated NFW model
  - Anisotropy profile $\beta(r)$: constant model

Likelihood

- Likelihood function

$$\mathscr{L}(\Theta) = \prod \mathscr{N}[v_i; v_{\rm dSph}, \sigma^2_{\rm los}(R_i) + \delta\sigma_i^2],$$

- Posterior probability

$$P(\Theta|D) = \frac{\mathscr{L}(\Theta)\pi(\Theta)}{\int {\rm d}\Theta\, \mathscr{L}(\Theta)\pi(\Theta)},$$

- $\pi(\Theta)$: **prior**

$$\pi = \begin{cases} \pi_{\rm photo.} & \text{(without any cosmological priors)} \\ \pi_{\rm photo.}\pi_{\rm sat.} & \text{(satellite prior only)} \\ \pi_{\rm photo.}\pi_{\rm sat.+SHMR} & \text{(satellite \& SHMR prior)} \end{cases}$$

Cosmological priors

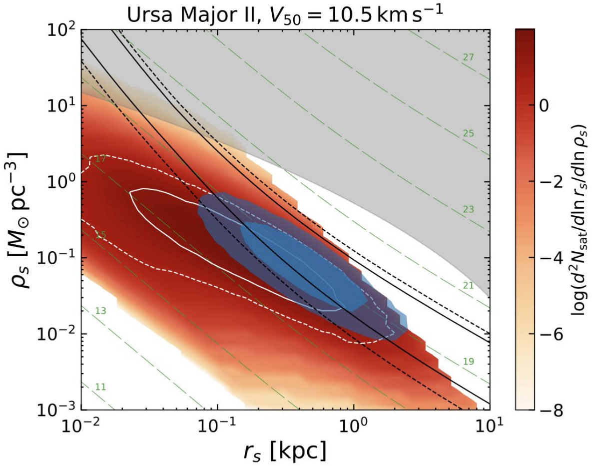
- Satellite prior [1803.07691, 2002.11956]
  - Accretion of subhalo: extended Press-Schechter (EPS) formalism
  - Tidal stripping effect: semi-analytical subhalo model calibrated by N-body simulation

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

$$P_{\rm sat}(r_s,\rho_s,r_t) \propto \frac{d^3N_{\rm sat}}{dr_s d\rho_s dr_t} = \frac{d^3N_{\rm sh}}{dr_s d\rho_s dr_t}P_{\rm form}(V_{\rm peak}).$$

$$P_{\rm form}(V_{\rm peak}) = \frac{1}{2}\left[1+{\rm erf}\left(\frac{V_{\rm peak}-V_{50}}{\sqrt{2}\sigma}\right)\right]$$

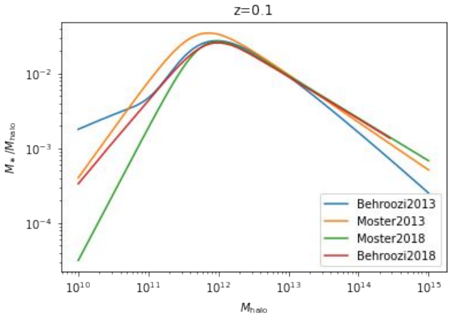
V_peak: maximum circular velocity
V_50 = 10.5 km/s or 18 km/s



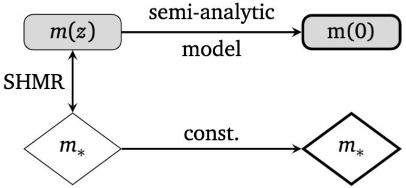
Ando+(2020) [2002.11956]

Cosmological priors

- The stellar-to-halo mass relation (SHMR)
  - empirical relation between the stellar and DM halo mass of galaxies: M_star = f(M_halo, z)
  - assumption: f(M_halo, z) is a monotonic function for M_halo
- Models:
  - Behroozi+(2013) [1207.6105]
    - calibrated by the Bolshoi simulation, complecate model
  - Moster+(2013) [1205.5807]
    - calibrated by the Millennium simulation, assuming simple double power law
  - Behroozi+(2019) [1806.07893]
    - Updated dataset and models, model selection based on Bayes factor
  - Moster+(2018) [1705.05373]
    - double-power law for efficiency evolution
- Prior:



$$\pi_{\rm SHMR}(\rho_s, r_s, r_t) = \frac{\mathcal{N}(M_{*,\rm obs}|M_*(M_{\rm halo}), \sigma^2)\pi_{\rm satellite}(\rho_s, r_s, r_t)}{\int dr_s\, d\rho_s\, dr_t\, \mathcal{N}(M_{*,\rm obs}|M_*(M_{\rm halo}), \sigma^2)\pi_{\rm satellite}(\rho_s, r_s, r_t)}$$



$$M_{\rm halo} \leftarrow (\rho_{s,0}, r_{s,0}, r_{t,0}) \longleftrightarrow (\rho_{s,a}, r_{s,a}, z) \xrightarrow{\rm SHMR} M_{*,a} = M_{*,0}$$

semi-analytic model in [2002.11956]

Target dSphs

- 8 classical + 26 ultrafaint dSph in [2002.11956]

Classical:

Carina
Draco
Fornax
Leo I
Leo II
Sculptor
Sextans
Ursa Minor

UFD:

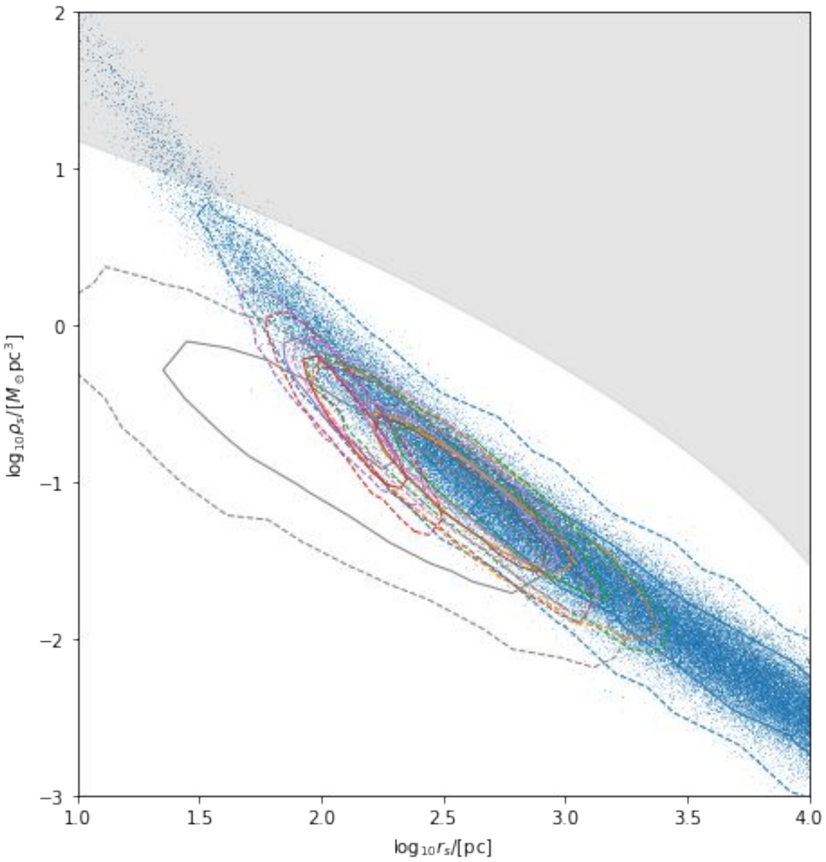
Aquarius 2
Bootes I
Bootes II
Canes Venatici I
Canes Venatici II
Carina II
Coma Berenices
Draco II
Eridanus II
Grus I
Hercules
Horologium I
Hyrdus 1
Leo IV
Leo T
Leo V
Pegasus III
Pisces II
Reticulum II
Segue 1
Segue 2
Triangulum II
Tucana II
Tucana III
Ursa Major I
Ursa Major II

Results

- Posterior density function

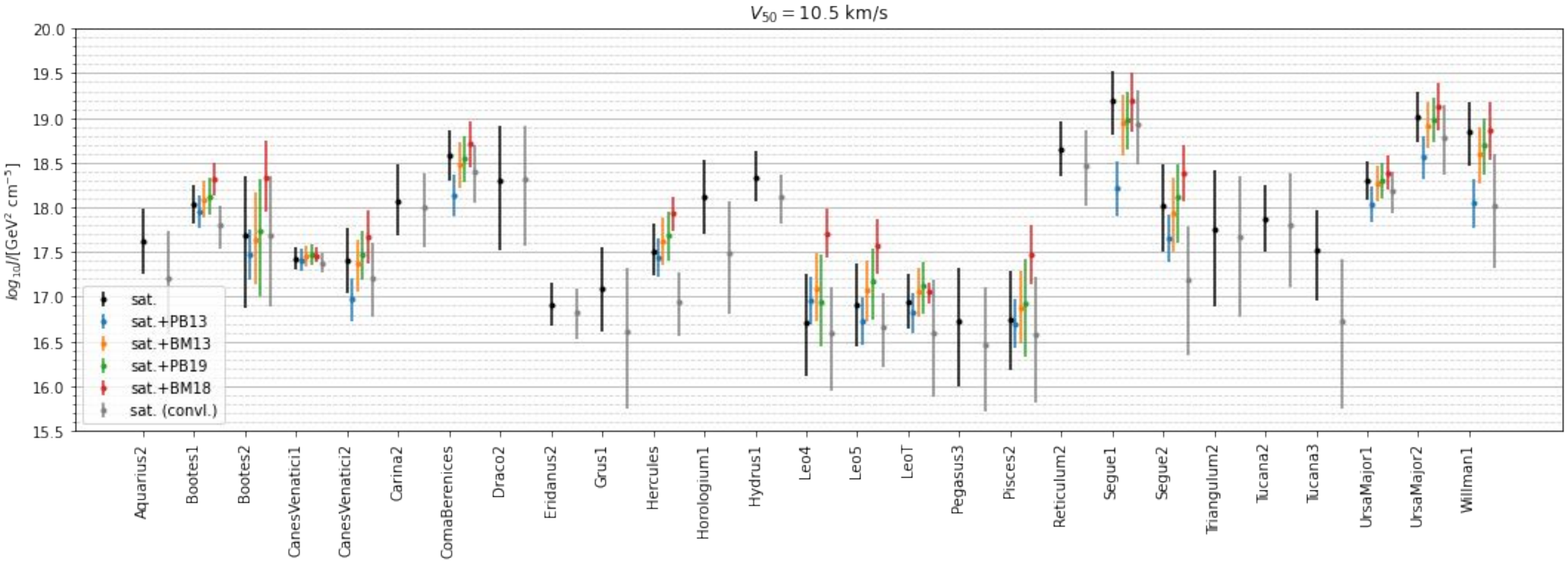
e.g. Coma Berenices

- satellite prior only
- likelihood only
- likelihood + satellite (V_50 = 10.5 km/s)
- likelihood + satellite (V_50 = 18 km/s)
- likelihood + satellite (V_50 = 10.5 km/s) + SHMR(Behroozi)
- likelihood + satellite (V_50 = 18 km/s) + SHMR(Behroozi)
- likelihood + satellite (V_50 = 10.5 km/s) + SHMR(Moster)
- likelihood + satellite (V_50 = 18 km/s) + SHMR(Moster)



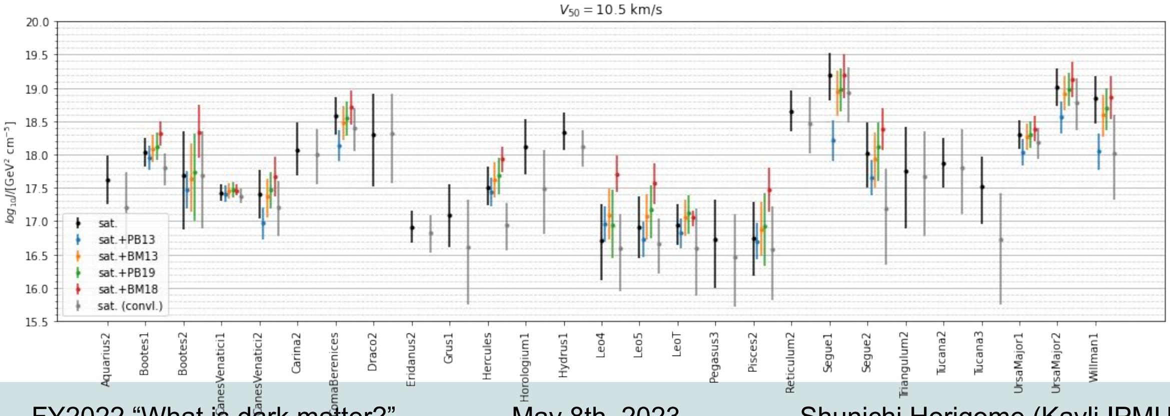
Results

- J-factor



Results

- J-factor
  - slightly larger than those of the velocity independent analysis
    - radial dependence of the likelihood excludes too compact or faint DM halo having small J-factor
      - Note: anisotropy profile dependence in the velocity dispersion
  - SHMR priors can decrease J-factor uncertainty (upto ~50%) but results are model dependent
    - Test of SHMR models by using dSphs?



Results

- J-factors vs. Bayes factors
  - Deviated results have less Bayes factor values
    → Results of the cosmological prior analysis is stable
    in terms of their Bayes factors

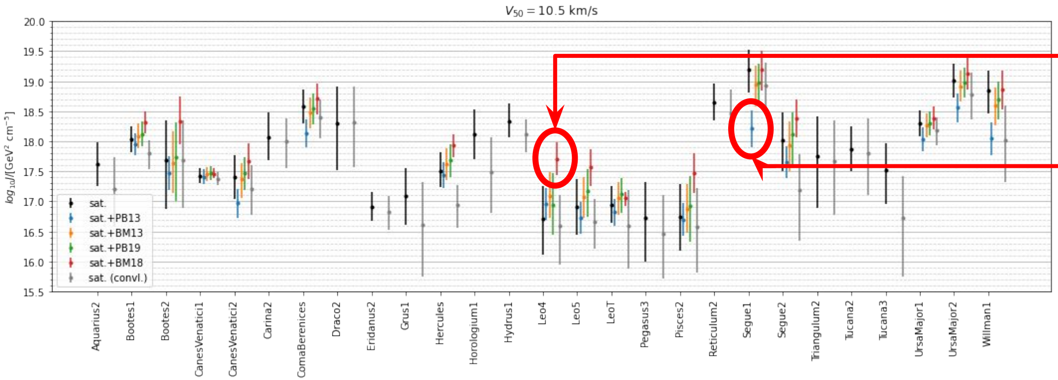


Table 6: The logarithm of Bayes factors of each model calculated according to Eq. (20). Column 1 shows the Bayes factor of sat_{18} to a reference model $sat_{10.5}$ for each dSphs. Columns 2-5 shows the Bayes factors of the satellite prior and SHMR analyses to the satellite prior only analysis $sat_{10.5}$ as a reference, so as Columns 6-9 not for $sat_{10.5}$ but sat_{18} cases. By definition, positive (negative) values mean that the corresponding model is more (less) credible than the reference model.

	$sat._{18}/sat._{10.5}$	$sat._{10.5}$				$sat._{18}$			
	w/o SHMR	PB13	BM13	PB19	BM18	PB13	BM13	PB19	BM18
Aquarius2	0.77	-	-	-	-	-	-	-	-
Bootes1	-0.01	0.34	0.20	0.17	0.09	0.12	0.10	0.21	0.11
Bootes2	-0.09	0.05	0.06	-0.05	-0.16	0.07	0.04	0.01	-0.01
CanesVenatici1	0.49	0.36	0.49	0.07	0.34	0.33	-0.01	-0.31	-0.03
CanesVenatici2	1.29	-0.70	0.64	0.92	2.08	-2.61	-0.70	0.15	0.71
Carina2	-0.14	-	-	-	-	-	-	-	-
ComaBerenices	1.06	-1.71	-0.09	0.35	1.75	-3.07	-0.52	0.07	0.64
Draco2	0.16	-	-	-	-	-	-	-	-
Eridanus2	0.79	-	-	-	-	-	-	-	-
Grus1	-0.30	-	-	-	-	-	-	-	-
Hercules	0.88	0.58	0.96	0.59	1.06	-0.04	-0.06	-0.07	0.15
Horologium1	1.12	-	-	-	-	-	-	-	-
Hydrus1	-0.17	-	-	-	-	-	-	-	-
Leo4	-0.16	0.34	0.02	[illegible]	-0.93	0.44	0.15	0.01	-0.72
Leo5	-0.03	0.34	0.51	0.04	0.24	-0.47	-0.15	0.31	0.45
LeoT	1.39	0.65	1.85	1.43	0.84	-0.01	0.47	0.08	-0.61
Pegasus3	1.28	-	-	-	-	-	-	-	-
Pisces2	0.27	0.49	0.26	-0.04	-0.07	0.29	-0.01	-0.11	-0.28
Reticulum2	0.96	-	-	-	-	-	-	-	-
Segue1	[illegible]	-2.63	-1.00	-0.27	1.36	-4.29	-1.01	-0.05	-0.41
Segue2	0.08	0.11	0.12	0.21	0.26	-0.17	-0.20	0.04	-0.10
Triangulum2	-0.65	-	-	-	-	-	-	-	-
Tucana2	-0.13	-	-	-	-	-	-	-	-
Tucana3	-2.75	-	-	-	-	-	-	-	-
UrsaMajor1	1.06	-5.26	-0.16	0.61	1.84	-5.30	-0.45	-0.08	0.80
UrsaMajor2	1.25	-4.98	-1.11	0.05	1.67	-5.93	-0.63	-0.21	0.37
Willman1	2.07	-3.05	-1.05	-0.62	1.71	-4.90	-1.26	-0.37	-0.29

Questions

- How is the DM density profile…
  - from **observational** viewpoints?
    - How can we precisely determine the density profile?
  - from **theoretical** viewpoints?
    - How should the profile be in specific DM scenarios?
      - e.g. CDM v.s. SIDM
        - CDM ← “cuspy”
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1.

2.

[arXiv: in prep]

2. Comparison of MW-sized halo profiles in cosmological SIDM simulations and gravothermal fluid models

Masahiro Shirasaki, Shunichi Horigome, Shinichiro Ando

[arXiv:2207.10378]

2. Comparison of MW-sized halo profiles in cosmological SIDM simulations and gravothermal fluid models

Masahiro Shirasaki, Shunichi Horigome, Shinichiro Ando

What is the physics underlying the formation of core-like profiles?

…we assume the SIDM halo can be described by the

“gravothermal fluid model”

and test it by a cosmological N-body simulation

Gravothermal fluid model

"What is dark matter?"

← … a "gravitationally bound and thermally conducting fluid" [Balberg+(2002)]

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

mass conservation

$$\frac{\partial(\rho\sigma_v^2)}{\partial r} = -G\frac{M\rho}{r}$$

Hydrostatic equilibrium

$$\frac{L}{4\pi r^2} = -\kappa\frac{\partial T}{\partial r} = -\kappa\rho\frac{\partial}{\partial r}\left(\frac{3\sigma_v^2}{2}\right)$$

Heat conduction

$$\frac{\partial L}{\partial r} = -4\pi r^2 \rho\left[\left(\frac{\partial}{\partial t}\right)_M \frac{3\sigma_v^2}{2} + p\left(\frac{\partial}{\partial t}\right)_M \frac{1}{\rho}\right] = -4\pi r^2 \rho v^2 \left(\frac{\partial}{\partial t}\right)_M \log\left(\frac{\sigma_v^3}{\rho}\right)$$

1st law of thermodynamics

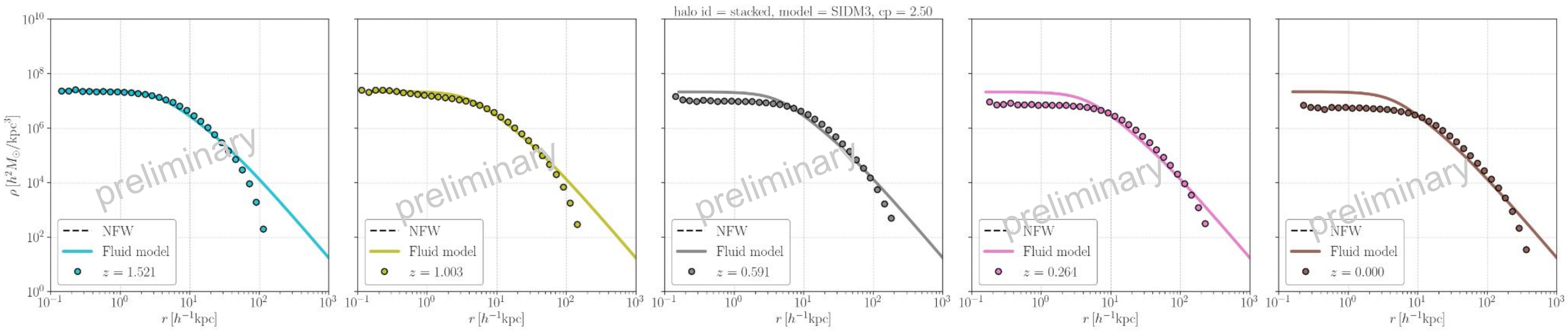
Model parameter: thermal conductivity κ ← caribrated by **isolated** N-body simulation [Koda+(2011)]

Application to cosmological N-body simulation

- How about **cosmological** N-body simulation?
  → Simulation data: [Ebisu, Ishiyama, Hayashi(2022)]
  - 1024^3 particles in the comoving volume of (8 Mpc/h)^3
  - particle mass: $4.1 \times 10^4 h^{-1} M_\odot$
  - CDM and two different SIDM runs ($\sigma/m = 1, 3\,\mathrm{cm}^2\mathrm{g}^{-1}$) are available
  - Select 9 Milky-Way-sized halos and measure the density and velocity dispersion profiles
  - Mass accretion history (MAH) of each halo is also available

Result

- Roughly fit higher z halo
- discrepancy in lower z halo
    - mass accretion?



Summary

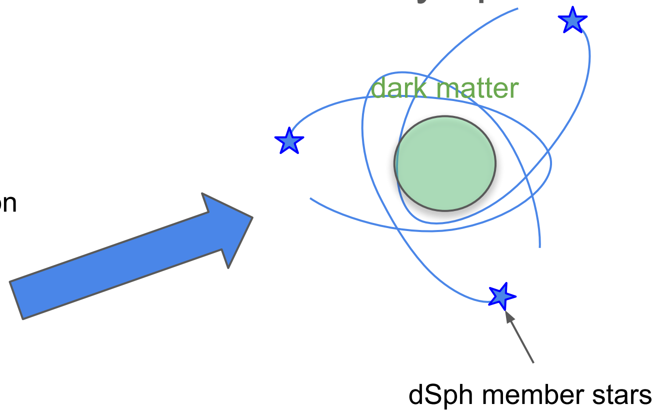
- Dark matter density profile of (sub-)halos plays an important the indirect detection method, but they are not well understood yet
- From observational viewpoint, we decreased the uncertainty of dark matter density profile of dSphs by introducing
  - Satellite prior: DM subhalo formation model based on extended Press-Schechter formalizm
  - Stellar-to-halo mass relation (SHMR): Empirical relation between stellar and DM mass
  - velocity dependent likelihood: probing velocity dispersion profile of dSph
- From theoretical viewpoint, we study density profile of SIDM halos by gravothermal fluid model
  - potentially useful to cosmological N-body simulation (in progress)

Backup slides

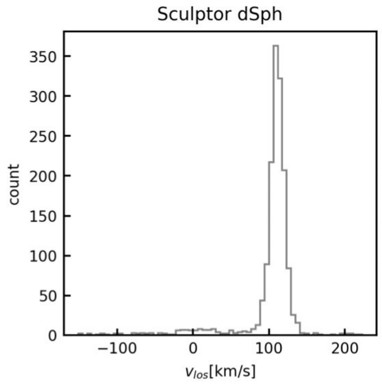
How to estimate DM density profile

- dSph member stars move in the gravitational potential yielded by DM mass density
- Velocity of member stars is observed by spectroscopic telescope

spectroscopic observation

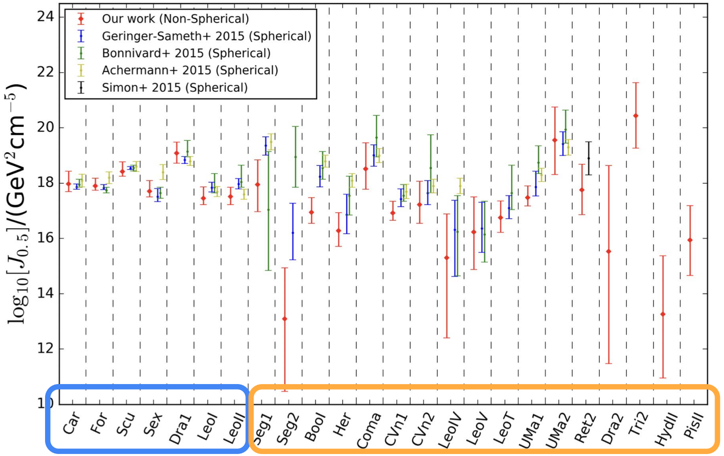


e.g. Stellar velocity distibution of the Sculptoir dSph



J-factor uncertainty

- J-factor has large uncertainty
  - Limited number of dataset
    - Classical: O(100)
    - Ultrafaint: O(10)



Hayashi et al. [1603.08046]

- We use "cosmological prior" to improve the accuracy

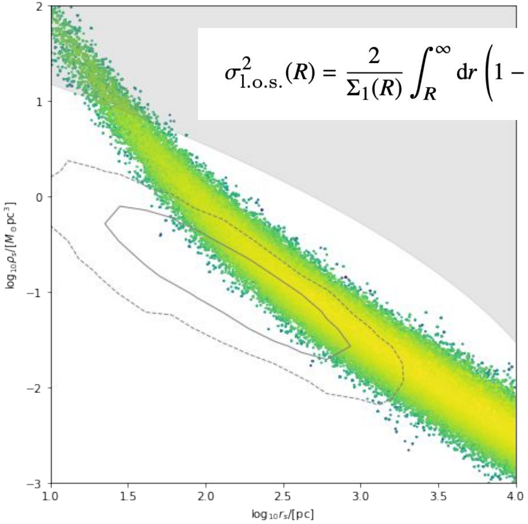
Priors

- Photometry prior: for stellar distribution
  - half-light radius determined by phtometric observation

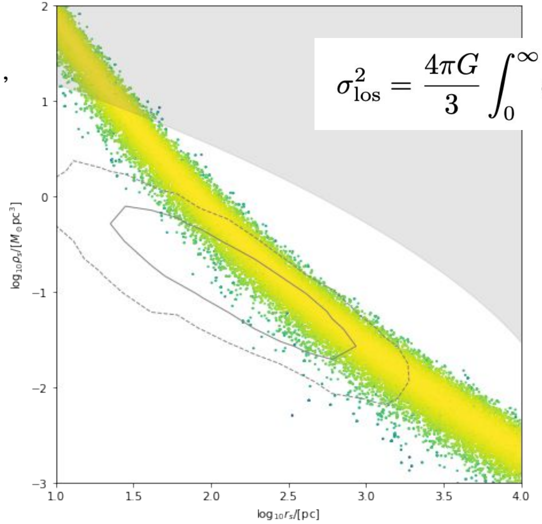
Name	$\log_{10} r_e/[\mathrm{pc}]$
Aquarius 2	2.094 ± 0.078
Boötes 1	2.204 ± 0.015
Boötes 2	1.523 ± 0.068
CanesVenatici 1	2.529 ± 0.017
CanesVenatici 2	1.732 ± 0.086
Carina	2.392 ± 0.005
Carina 2	1.870 ± 0.045
ComaBerenices	1.757 ± 0.029
Draco	2.256 ± 0.005
Draco 2	1.121 ± 0.182
Eridanus 2	2.196 ± 0.046
Fornax	2.849 ± 0.003
Grus 1	1.267 ± 0.459
Hercules	2.080 ± 0.042
Horologium 1	1.488 ± 0.097
Hydrus 1	1.727 ± 0.030
Leo 1	2.353 ± 0.004
Leo 2	2.217 ± 0.005
Leo 4	2.013 ± 0.053
Leo T	2.125 ± 0.051
Leo 5	1.571 ± 0.181
Pegasus 3	1.616 ± 0.158
Pisces 2	1.678 ± 0.072
Reticulum 2	1.495 ± 0.018
Sagittarius	3.191 ± 0.020
Sculptor	2.359 ± 0.004
Segue 1	1.295 ± 0.062
Segue 2	1.528 ± 0.038
Sextans 1	2.538 ± 0.004
Triangulum 2	1.096 ± 0.134
Tucana 2	2.212 ± 0.073
Tucana 3	1.640 ± 0.058
UrsaMajor 1	2.176 ± 0.024
UrsaMajor 2	1.930 ± 0.022
UrsaMinor	2.434 ± 0.006
Willman 1	1.304 ± 0.045

Results

- vs. radial independent analysis [2002.11956]
  - radial dependence of the likelihood break the degeneracy of the parameter



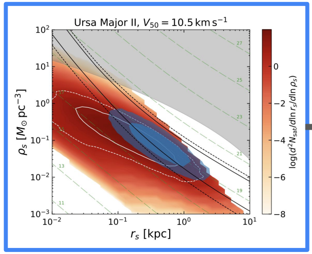
$$\sigma^2_{\mathrm{l.o.s.}}(R) = \frac{2}{\Sigma_1(R)} \int_R^\infty \mathrm{d}r \left(1 - \beta_{\mathrm{ani}} \frac{R^2}{r^2}\right) \frac{\nu_1(r)\sigma_r^2(r)}{\sqrt{1 - R^2/r^2}} \, ,$$

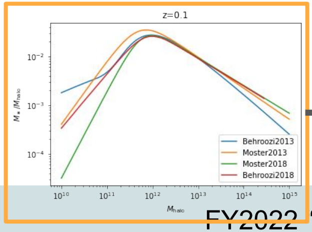


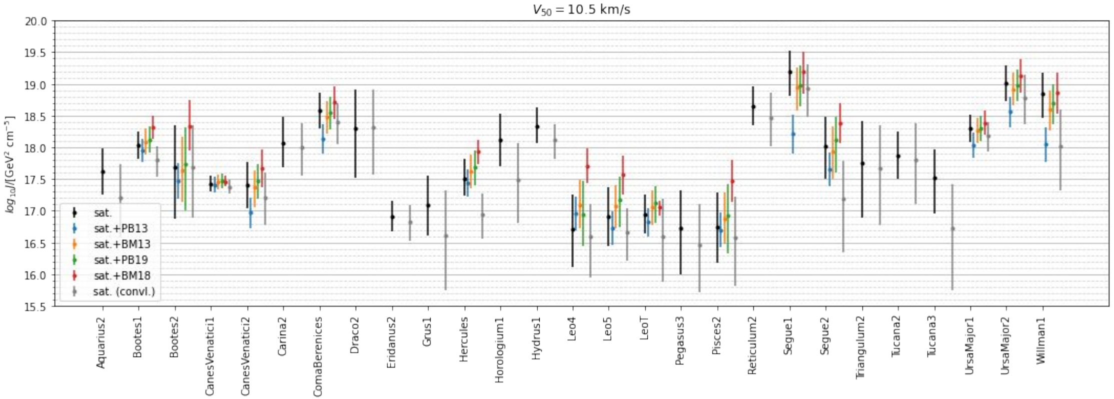
$$\sigma^2_{\mathrm{los}} = \frac{4\pi G}{3} \int_0^\infty dr \; r\nu_\star(r) M(r),$$

Cosmological prior for the J-factor estimation of dwarf spheroidal galaxies

- Dwarf spheroidal galaxies (dSph) play important roles for dark matter detection but their dark matter halo profiles have large uncertainties
- For the halo profile estimation of dSphs, we apply two **cosmological priors**:
  - Satellite prior: constraint distribution of halo parameter based on a structure formation model
  - Stellar-to-halo mass relation prior: empirical relation between stellar mass and halo mass
- The cosmological priors are useful to decrease the uncertainty in the estimation and give a better understanding of dSphs

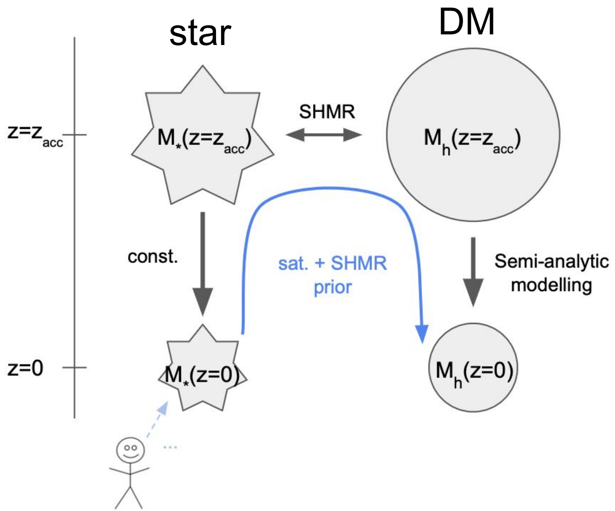






SHMR

- The stellar-to-halo mass relation (SHMR)
  - empirical relation between the stellar and DM halo mass of galaxies: M_star = f(M_halo, z)
  - assumption: f(M_halo, z) is a monotonic function for M_halo



MCMC Analysis

- Jeans analysis
  - 6 Parameters
  - Prior choices
    - photometry only
    - photometry + satellite
    - photometry + satellite + SHMR
  - Bayesian analysis to calculate posterior probability
    - MCMC tool: `emcee 3.0.2`

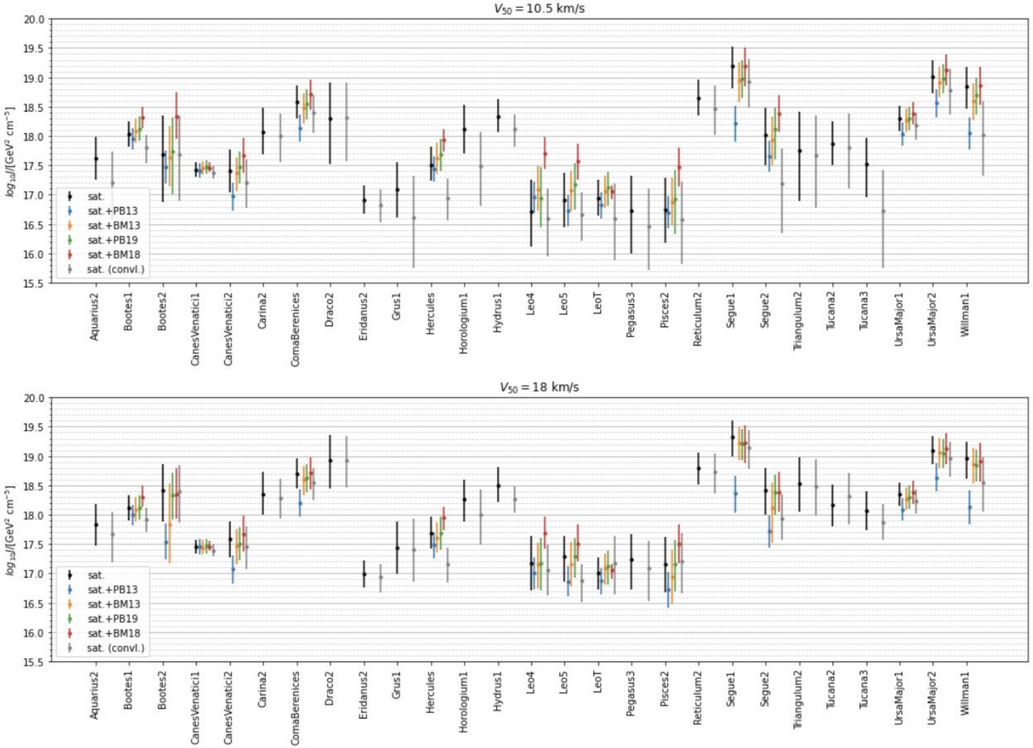
parameter	min.	max.
$\log_{10} R_e/[\mathrm{pc}]$	1.0	3.5
$\log_{10} r_s/[\mathrm{pc}]$	0.0	5.0
$\log_{10} \rho_s/[M_\odot \mathrm{pc}^{-3}]$	-4.0	4.0
$\log_{10} r_t/[\mathrm{pc}]$	0.0	5.0
$-\log_{10}(1-\beta_{\mathrm{ani}})$	-1.0	1.0
$v_{\mathrm{dSph}}/[\mathrm{km\,s^{-1}}]$	-1000	1000

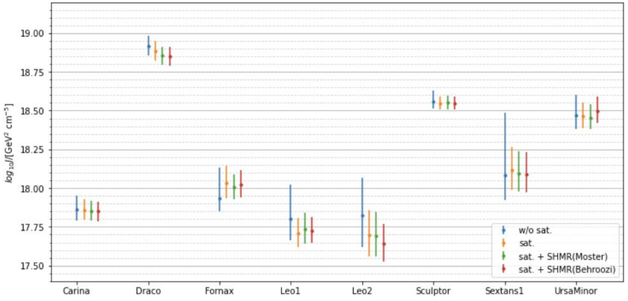
J-factors (table)

	w/o SHMR			PB13		BM13		PB19		BM18	
	flat	$sat._{10.5}$	$sat._{18}$	$sat._{10.5}$	$sat._{18}$	$sat._{10.5}$	$sat._{18}$	$sat._{10.5}$	$sat._{18}$	$sat._{10.5}$	$sat._{18}$
Aquarius2	$18.2^{+0.6}_{-0.6}$	$17.6^{+0.4}_{-0.4}$	$17.8^{+0.3}_{-0.4}$	-	-	-	-	-	-	-	-
Bootes1	$18.2^{+0.3}_{-0.3}$	$18.0^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$17.9^{+0.2}_{-0.2}$	$18.0^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$
Bootes2	$16.6^{+2.8}_{-4.9}$	$17.7^{+0.7}_{-0.8}$	$18.4^{+0.5}_{-0.5}$	$17.5^{+0.3}_{-0.3}$	$17.5^{+0.3}_{-0.3}$	$17.6^{+0.5}_{-0.5}$	$17.8^{+0.7}_{-0.7}$	$17.7^{+0.6}_{-0.7}$	$18.3^{+0.4}_{-0.4}$	$18.3^{+0.4}_{-0.4}$	$18.4^{+0.4}_{-0.4}$
CanesVenatici1	$17.6^{+0.3}_{-0.2}$	$17.4^{+0.1}_{-0.1}$	$17.5^{+0.1}_{-0.1}$	$17.4^{+0.1}_{-0.1}$	$17.4^{+0.1}_{-0.1}$	$17.5^{+0.1}_{-0.1}$	$17.4^{+0.1}_{-0.1}$	$17.5^{+0.1}_{-0.1}$	$17.5^{+0.1}_{-0.1}$	$17.5^{+0.1}_{-0.1}$	$17.5^{+0.1}_{-0.1}$
CanesVenatici2	$17.9^{+0.5}_{-0.5}$	$17.4^{+0.4}_{-0.4}$	$17.6^{+0.3}_{-0.3}$	$17.0^{+0.2}_{-0.2}$	$17.1^{+0.2}_{-0.2}$	$17.4^{+0.3}_{-0.3}$	$17.5^{+0.3}_{-0.3}$	$17.5^{+0.3}_{-0.3}$	$17.5^{+0.3}_{-0.3}$	$17.7^{+0.3}_{-0.3}$	$17.7^{+0.3}_{-0.3}$
Carina2	$18.4^{+0.6}_{-0.5}$	$18.1^{+0.4}_{-0.4}$	$18.4^{+0.4}_{-0.4}$	-	-	-	-	-	-	-	-
ComaBerenices	$19.0^{+0.3}_{-0.4}$	$18.6^{+0.3}_{-0.3}$	$18.7^{+0.3}_{-0.3}$	$18.1^{+0.2}_{-0.2}$	$18.2^{+0.2}_{-0.2}$	$18.5^{+0.2}_{-0.3}$	$18.6^{+0.2}_{-0.3}$	$18.5^{+0.3}_{-0.3}$	$18.6^{+0.2}_{-0.2}$	$18.7^{+0.3}_{-0.3}$	$18.7^{+0.3}_{-0.3}$
Draco2	$16.8^{+2.5}_{-4.8}$	$18.3^{+0.6}_{-0.8}$	$18.9^{+0.4}_{-0.5}$	-	-	-	-	-	-	-	-
Eridanus2	$17.3^{+0.4}_{-0.4}$	$16.9^{+0.3}_{-0.2}$	$17.0^{+0.2}_{-0.2}$	-	-	-	-	-	-	-	-
Grus1	$17.4^{+0.9}_{-0.9}$	$17.1^{+0.5}_{-0.5}$	$17.4^{+0.4}_{-0.4}$	-	-	-	-	-	-	-	-
Hercules	$17.9^{+0.4}_{-0.4}$	$17.5^{+0.3}_{-0.3}$	$17.7^{+0.3}_{-0.3}$	$17.4^{+0.2}_{-0.2}$	$17.5^{+0.2}_{-0.2}$	$17.6^{+0.3}_{-0.3}$	$17.6^{+0.3}_{-0.3}$	$17.7^{+0.3}_{-0.3}$	$17.7^{+0.3}_{-0.3}$	$17.9^{+0.2}_{-0.2}$	$18.0^{+0.2}_{-0.2}$
Horologium1	$19.1^{+0.7}_{-0.6}$	$18.1^{+0.4}_{-0.4}$	$18.3^{+0.3}_{-0.4}$	-	-	-	-	-	-	-	-
Hydrus1	$18.5^{+0.4}_{-0.3}$	$18.3^{+0.3}_{-0.3}$	$18.5^{+0.3}_{-0.3}$	-	-	-	-	-	-	-	-
Leo4	$15.6^{+1.9}_{-5.1}$	$16.7^{+0.5}_{-0.6}$	$17.2^{+0.5}_{-0.5}$	$17.0^{+0.3}_{-0.3}$	$17.0^{+0.3}_{-0.3}$	$17.1^{+0.4}_{-0.4}$	$17.1^{+0.4}_{-0.4}$	$16.9^{+0.5}_{-0.5}$	$17.2^{+0.4}_{-0.5}$	$17.7^{+0.3}_{-0.3}$	$17.7^{+0.3}_{-0.3}$
Leo5	$17.2^{+0.8}_{-0.8}$	$16.9^{+0.4}_{-0.5}$	$17.3^{+0.4}_{-0.4}$	$16.7^{+0.3}_{-0.3}$	$16.9^{+0.3}_{-0.3}$	$17.1^{+0.3}_{-0.3}$	$17.2^{+0.4}_{-0.4}$	$17.2^{+0.4}_{-0.4}$	$17.3^{+0.3}_{-0.4}$	$17.6^{+0.3}_{-0.3}$	$17.5^{+0.3}_{-0.3}$
LeoT	$17.6^{+0.4}_{-0.4}$	$16.9^{+0.3}_{-0.3}$	$17.0^{+0.3}_{-0.3}$	$16.8^{+0.2}_{-0.2}$	$16.9^{+0.2}_{-0.2}$	$17.1^{+0.3}_{-0.3}$	$17.1^{+0.2}_{-0.3}$	$17.1^{+0.3}_{-0.3}$	$17.1^{+0.3}_{-0.3}$	$17.1^{+0.1}_{-0.1}$	$17.1^{+0.1}_{-0.1}$
Pegasus3	$17.8^{+1.0}_{-2.1}$	$16.7^{+0.6}_{-0.7}$	$17.2^{+0.4}_{-0.5}$	-	-	-	-	-	-	-	-
Pisces2	$17.2^{+0.9}_{-1.2}$	$16.7^{+0.6}_{-0.6}$	$17.2^{+0.5}_{-0.5}$	$16.7^{+0.3}_{-0.3}$	$16.7^{+0.3}_{-0.3}$	$16.9^{+0.4}_{-0.4}$	$16.9^{+0.5}_{-0.5}$	$16.9^{+0.5}_{-0.6}$	$17.2^{+0.4}_{-0.5}$	$17.5^{+0.3}_{-0.3}$	$17.5^{+0.3}_{-0.3}$
Reticulum2	$19.0^{+0.4}_{-0.4}$	$18.7^{+0.3}_{-0.3}$	$18.8^{+0.3}_{-0.3}$	-	-	-	-	-	-	-	-
Segue1	$19.7^{+0.4}_{-0.4}$	$19.2^{+0.3}_{-0.4}$	$19.3^{+0.3}_{-0.3}$	$18.2^{+0.3}_{-0.3}$	$18.4^{+0.3}_{-0.3}$	$18.9^{+0.3}_{-0.4}$	$19.2^{+0.3}_{-0.3}$	$19.0^{+0.3}_{-0.3}$	$19.2^{+0.3}_{-0.3}$	$19.2^{+0.3}_{-0.4}$	$19.2^{+0.3}_{-0.4}$
Segue2	$18.0^{+0.7}_{-2.1}$	$18.0^{+0.5}_{-0.5}$	$18.4^{+0.4}_{-0.4}$	$17.7^{+0.3}_{-0.3}$	$17.7^{+0.3}_{-0.3}$	$17.9^{+0.4}_{-0.4}$	$18.1^{+0.4}_{-0.6}$	$18.1^{+0.4}_{-0.5}$	$18.4^{+0.3}_{-0.4}$	$18.4^{+0.3}_{-0.3}$	$18.4^{+0.3}_{-0.3}$
Triangulum2	$14.4^{+2.9}_{-3.9}$	$17.7^{+0.7}_{-0.9}$	$18.5^{+0.4}_{-0.5}$	-	-	-	-	-	-	-	-
Tucana2	$18.1^{+0.6}_{-0.5}$	$17.9^{+0.4}_{-0.4}$	$18.2^{+0.4}_{-0.4}$	-	-	-	-	-	-	-	-
Tucana3	$15.7^{+1.8}_{-4.3}$	$17.5^{+0.5}_{-0.6}$	$18.1^{+0.3}_{-0.3}$	-	-	-	-	-	-	-	-
UrsaMajor1	$18.7^{+0.3}_{-0.3}$	$18.3^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$	$18.0^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$	$18.4^{+0.2}_{-0.2}$	$18.4^{+0.2}_{-0.2}$
UrsaMajor2	$19.5^{+0.4}_{-0.4}$	$19.0^{+0.3}_{-0.3}$	$19.1^{+0.2}_{-0.2}$	$18.6^{+0.2}_{-0.2}$	$18.6^{+0.2}_{-0.2}$	$18.9^{+0.3}_{-0.3}$	$19.1^{+0.3}_{-0.3}$	$19.0^{+0.2}_{-0.2}$	$19.0^{+0.3}_{-0.2}$	$19.1^{+0.3}_{-0.3}$	$19.1^{+0.3}_{-0.3}$
Willman1	$19.5^{+0.4}_{-0.4}$	$18.8^{+0.3}_{-0.4}$	$19.0^{+0.3}_{-0.3}$	$18.0^{+0.3}_{-0.3}$	$18.1^{+0.3}_{-0.3}$	$18.6^{+0.3}_{-0.3}$	$18.9^{+0.3}_{-0.3}$	$18.7^{+0.3}_{-0.3}$	$18.8^{+0.3}_{-0.3}$	$18.9^{+0.3}_{-0.3}$	$18.9^{+0.3}_{-0.3}$

	w/o SHMR		$SHMR_{Moster}$	$SHMR_{Behroozi}$
	flat	sat.	sat.	sat.
Carina	$17.9^{+0.1}_{-0.1}$	$17.9^{+0.1}_{-0.1}$	$17.9^{+0.1}_{-0.1}$	$17.9^{+0.1}_{-0.1}$
Draco	$18.9^{+0.1}_{-0.1}$	$18.9^{+0.1}_{-0.1}$	$18.9^{+0.1}_{-0.1}$	$18.8^{+0.1}_{-0.1}$
Fornax	$17.9^{+0.2}_{-0.1}$	$18.0^{+0.1}_{-0.1}$	$18.0^{+0.1}_{-0.1}$	$18.0^{+0.1}_{-0.1}$
Leo1	$17.8^{+0.2}_{-0.1}$	$17.7^{+0.1}_{-0.1}$	$17.7^{+0.1}_{-0.1}$	$17.7^{+0.1}_{-0.1}$
Leo2	$17.8^{+0.2}_{-0.2}$	$17.7^{+0.2}_{-0.1}$	$17.7^{+0.2}_{-0.1}$	$17.6^{+0.1}_{-0.1}$
Sculptor	$18.6^{+0.1}_{-0.0}$	$18.5^{+0.0}_{-0.0}$	$18.6^{+0.0}_{-0.0}$	$18.5^{+0.0}_{-0.0}$
Sextans1	$18.1^{+0.4}_{-0.2}$	$18.1^{+0.1}_{-0.1}$	$18.1^{+0.1}_{-0.1}$	$18.1^{+0.1}_{-0.1}$
UrsaMinor	$18.5^{+0.1}_{-0.1}$	$18.5^{+0.1}_{-0.1}$	$18.5^{+0.1}_{-0.1}$	$18.5^{+0.1}_{-0.1}$

J-factors


$V_{50} = 10.5$ km/s
$V_{50} = 18$ km/s
$log_{10}J/[GeV^2 cm^{-5}]$
sat.
sat.+PB13
sat.+BM13
sat.+PB19
sat.+BM18
sat. (convl.)
Aquarius2
Bootes1
Bootes2
CanesVenatici1
CanesVenatici2
Carina2
ComaBerenices
Draco2
Eridanus2
Grus1
Hercules
Horologium1
Hydrus1
Leo4
Leo5
LeoT
Pegasus3
Pisces2
Reticulum2
Segue1
Segue2
Triangulum2
Tucana2
Tucana3
UrsaMajor1
UrsaMajor2
Willman1


$log_{10}J/[GeV^2 cm^{-5}]$
w/o sat.
sat.
sat. + SHMR(Moster)
sat. + SHMR(Behroozi)
Carina
Draco
Fornax
Leo1
Leo2
Sculptor
Sextans1
UrsaMinor

Difference of Jeans analyses

- [2002.11956]: velocity dispersion averaged over total system

$$\sigma_{\rm los}^2 = \frac{4\pi G}{3}\int_0^\infty dr\, r\nu_\star(r)M(r),$$

- This work: radial dependent velocity dispersion calculated by the spherical Jeans equation

$$\sigma_{\rm l.o.s.}^2(R) = \frac{2}{\Sigma_1(R)}\int_R^\infty {\rm d}r \left(1-\beta_{\rm ani}\frac{R^2}{r^2}\right)\frac{\nu_1(r)\sigma_r^2(r)}{\sqrt{1-R^2/r^2}}\,,$$

Models

- Plummer model

$$\nu(r) = \frac{3}{4\pi R_e^3}\left(1+\left(\frac{r}{R_e}\right)^2\right)^{-5/2},$$

$$\Sigma(R) = \frac{1}{\pi}\left(1+\frac{R^2}{R_e^2}\right)^{-2},$$

- Truncated NFW model
  - Outermost halo is striped by tidal force

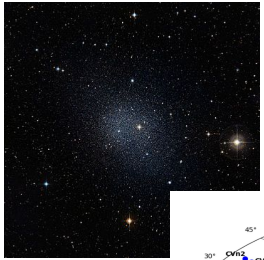
$$\rho(r) = \begin{cases} \rho_s\left(\frac{r}{r_s}\right)^{-1}\left(1+\frac{r}{r_s}\right)^{-2} & (0 \le r \le r_t) \\ 0 & (r_t < r) \end{cases},$$

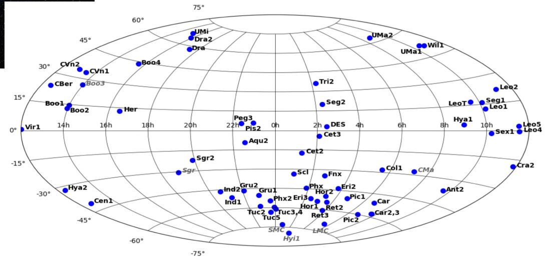
$$M(r) = \begin{cases} 4\pi\rho_s r_s^3\left(\log\left(1+\frac{r}{r_s}\right)-\frac{r}{r+r_s}\right) & (0 \le r \le r_t) \\ 4\pi\rho_s r_s^3\left(\log\left(1+\frac{r_t}{r_s}\right)-\frac{r_t}{r_t+r_s}\right) & (r_t < r), \end{cases}$$

dSphs and DM detection

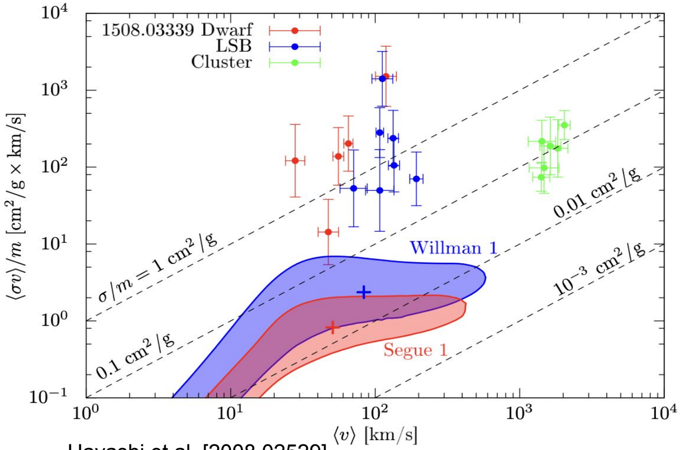
- Dwarf spheroidal galaxies (dSphs)
  - inner DM halo profile gives constraints on DM self-interaction

e.g. Fornax dSph





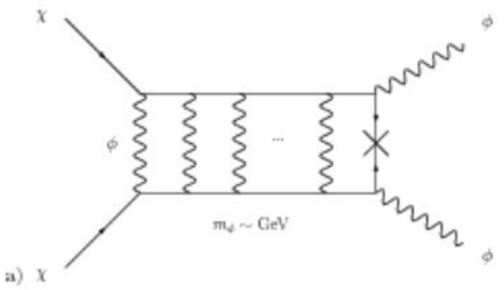
McConachie et al. [2007.05011]

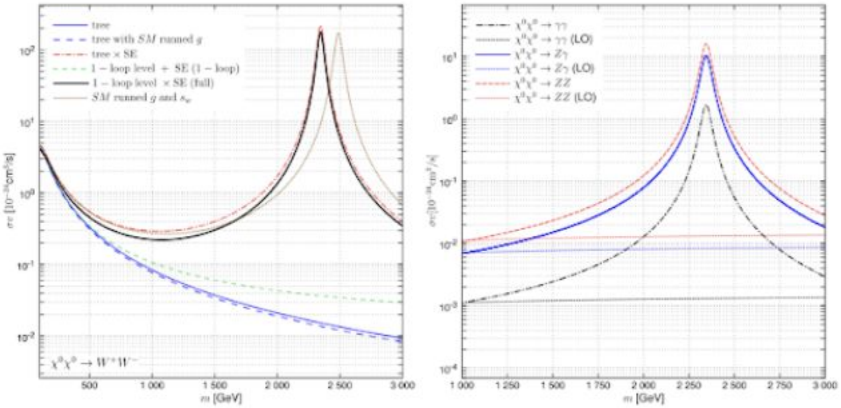


Hayashi et al. [2008.02529]

Sommerfeld effect

- Sommerfeld effect:
  - nonrelativistic effect of scattering





Difference of SHMRs

-

For low-mass haloes ($M_h < 10^{11}$ $M_\odot$), the best-fitting model has a weaker upturn in the SMHM ratio than found by Behroozi et al. (2013e); this is because Behroozi et al. (2013e) assumed a strong surface-brightness incompleteness correction for faint galaxies that is no longer observationally supported (Williams et al. 2016). This will make it easier to reconcile observed galaxy counts with the HI mass function and observed HI gas fractions in faint galaxies (Popping et al. 2015).

The SMHM relation for star-forming vs. quiescent galaxies depends on the correlation between galaxy and halo assembly (§4.2) and the evolution of the SMHM relation (see also Moster et al. 2018). As shown in Fig. 38, there remain significant differences across studies (see also Wechsler & Tinker 2018). Our model is flexible in terms of both the SMHM relation evolution and the galaxy–halo assembly correlation, and suggests that the stellar mass–halo mass relation at fixed halo mass is similar for star-forming and quiescent central galaxies, matching the conclusion in Zu & Mandelbaum (2016). The results of Moster et al. (2018) and Rodríguez-Puebla et al. (2015) give opposite conclusions of higher and lower (respectively) median stellar masses for quiescent compared to star-forming galaxies, despite using the same underlying data (correlation functions in the SDSS) to constrain their models. In part, these divergent conclusions arise because correlation functions and weak lensing measurements are both very sensitive to satellite clustering; hence, small changes to the satellite halo occupation can lead to large changes in the inferred occupation for central galaxies. Applying a cut to first remove satellites before measuring clustering, environment, or lensing (as in both this study and Zu & Mandelbaum 2016) is hence necessary to robustly determine SMHM differences for star-forming and quiescent central galaxies. As noted in Zu & Mandelbaum (2016) and Moster et al. (2018), having an equivalent median stellar mass at fixed halo mass does *not* imply that the median halo mass at fixed stellar mass will be equal for star-forming and quiescent galaxies. Because the ratio of star-forming to quiescent galaxies drops rapidly with increasing halo mass, it is much more likely in this case that a given massive star-forming galaxy will be hosted by a lower-mass halo than a massive quiescent galaxy.

Behroozi+(2019) [1806.07893]

Gravothermal fluid model

"**What** ... thermally conducting fluid" [Balberg+(2002)]

$\leftarrow$

$$\kappa = b_* \sigma_v \left[\left(\frac{1}{\lambda} \right) + \left(\frac{b_* \sigma_v t_r}{C_* H_g} \right) \right]^{-1}$$

$$\frac{\partial M}{\partial r} = 4\pi r^2 \rho$$

where $H_g \equiv \sqrt{\sigma_v^2/(4\pi G\rho)}$ is the gravitational scale height of the system, $\lambda = (\rho\sigma/m)^{-1}$ is the collisional scale for the mean free path, $t_r \equiv \lambda/(a\sigma_v)$ is the relaxation time with a coefficient of order of unity being a, and we adopt $a = \sqrt{16/\pi}$ for hard-sphere scattering of particles with a Maxwell-Boltzmann velocity distribution (Reif 1965).

In the limit of $\lambda \ll H_g$, the thermal conductivity is given by $\kappa \simeq (3/2)(k_B/m)b_*\rho\lambda^2/(at_r)$ and b_* can be regarded as an effective impact parameter among particle collisions. In the limit of $\lambda \gg H_g$, one finds $\kappa \simeq (3/2)(k_B/m)C_*\rho H_g^2/t_r$, reproducing an empirical formula of gravothermal collapse of globular clusters (Lynden-Bell & Eggleton 1980).

$$\frac{L}{4\pi r^2} = -\kappa \frac{\partial T}{\partial r} = -\kappa\rho \frac{\partial}{\partial r}\left(\frac{3\sigma_v^2}{2}\right)$$

Heat conduction

$$4\pi r^2 \rho \left[\left(\frac{\partial}{\partial t}\right)_M \frac{3\sigma_v^2}{2} + p \left(\frac{\partial}{\partial t}\right)_M \frac{1}{\rho} \right] = -4\pi r^2 \rho v^2 \left(\frac{\partial}{\partial t}\right)_M \log\left(\frac{\sigma_v^3}{\rho}\right)$$

1st law of thermodynamics

$\kappa \leftarrow$ caribrated by **isolated** N-body simulation