[in prep.]

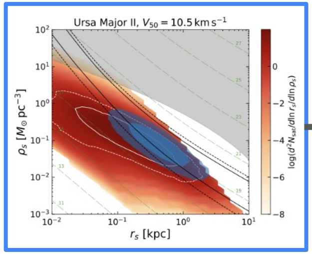
Cosmological prior for the J-factor estimation of dwarf spheroidal galaxies

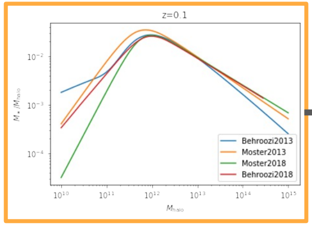
Shinichiro Ando, Kohei Hayashi, Shunichi Horigome

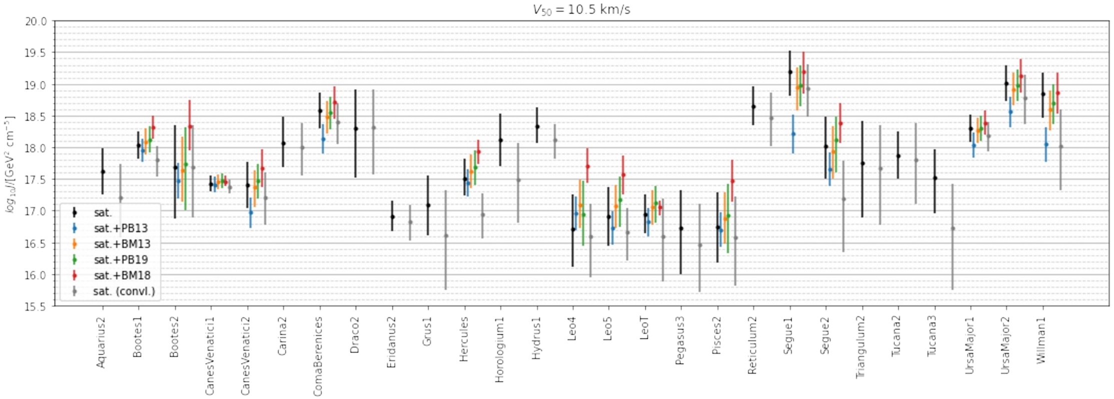
Dark matter symposium 29 March 2022

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





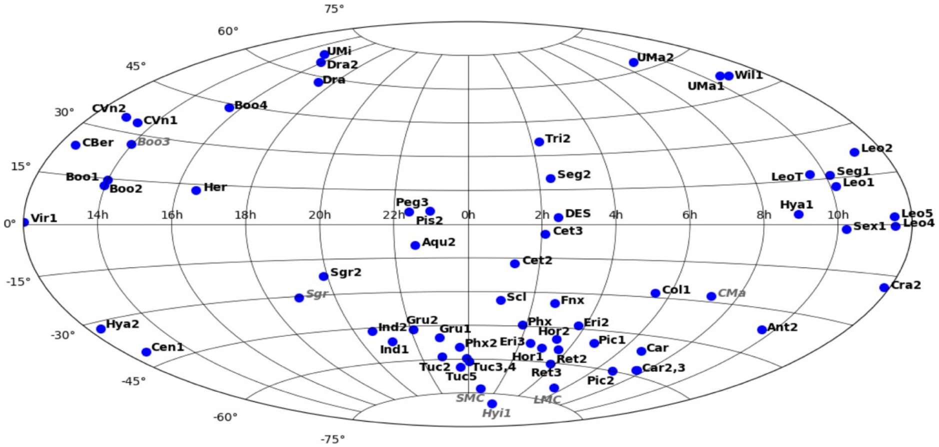


Introduction

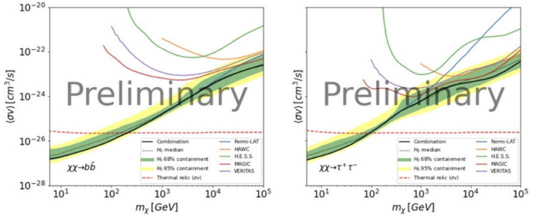
dSphs and DM detection

- Dwarf spheroidal galaxies (dSphs)
    - Large amount of DM
    - good candidates for the indirect detection of the WIMP DM

e.g. Fornax dSph



McConachie et al. [2007.05011]



Armard et al. [2108.13646]

dSphs and DM detection

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

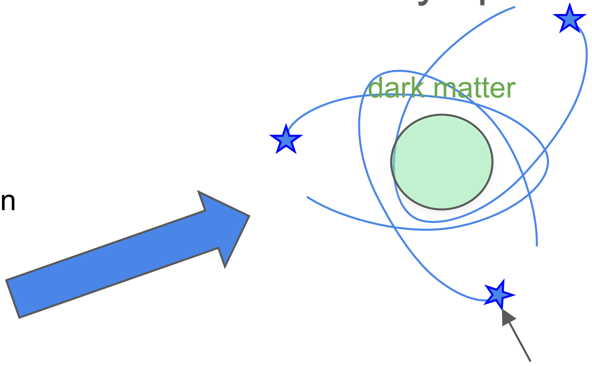
$$\Phi(E, \Delta\Omega) = \left[\frac{C\langle\sigma v\rangle}{4\pi m_{\mathrm{DM}}^2} \sum_f b_f \left(\frac{dN_\gamma}{dE} \right)_f \right] \times J(\Delta\Omega)$$

$$J(\Delta\Omega) = \left[\int_{\Delta\Omega} \mathrm{d}\Omega \int_{\mathrm{l.o.s.}} \mathrm{d}l\, \rho_{\mathrm{DM}}^2(l,\, \Omega) \right]$$

How to estimate DM density profile

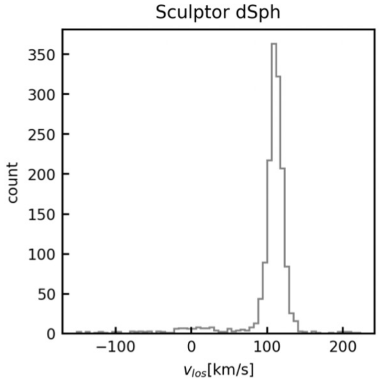
- dSph member stars move in the gravitational potential yielded by DM mass density
- Velocity of member stars is observed by spectroscopic telescope

spectroscopic observation



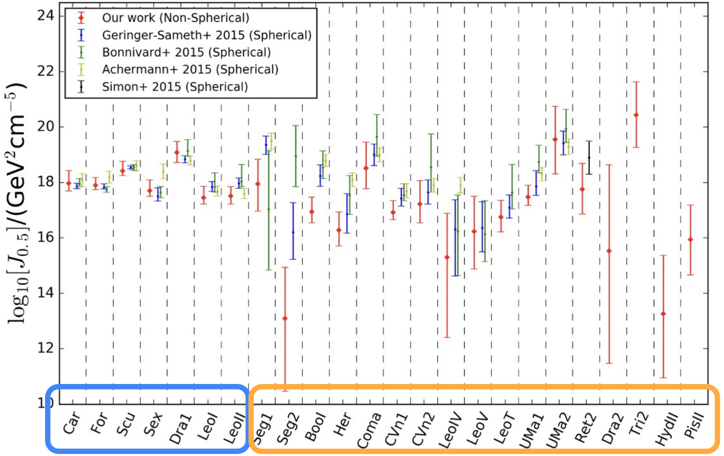
dSph member stars

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

Our analysis:
Estimation with cosmological prior

Jeans analysis

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

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

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

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

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

- Models:
  - Stellar profile: Plummer model
  - DM profile: truncated NFW model
  - Anisotropy profile: constant model

Likelihood

- Likelihood function

$$\mathcal{L}(\Theta) = \prod \mathcal{N}[v_i; v_{\mathrm{dSph}}, \sigma_{\mathrm{los}}^2(R_i) + \delta\sigma_i^2],$$

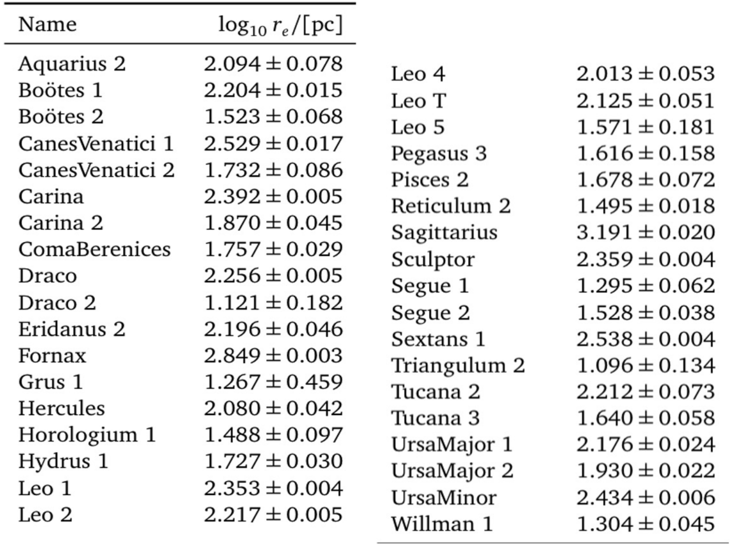
- Posterior probability

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

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

Priors (1/3)

- 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

Priors (2/3)

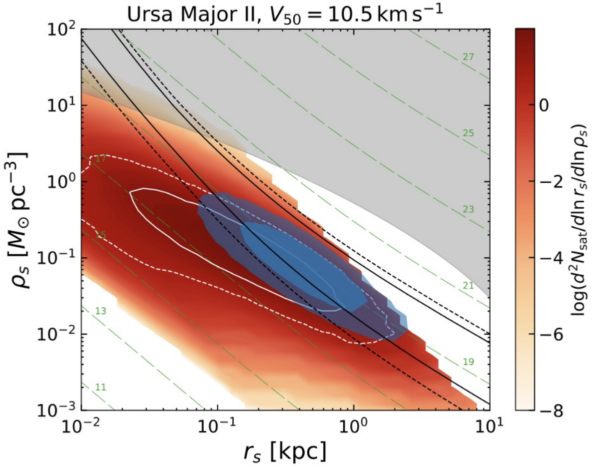
- Satellite prior [1803.07691, 2002.11956]
  - Accretion of subhalo: extended Press-Schechter (EPS) formalism
  - Tidal stripping effect: semi-analytical subhalo model calibrated by N-body simulation

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

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

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

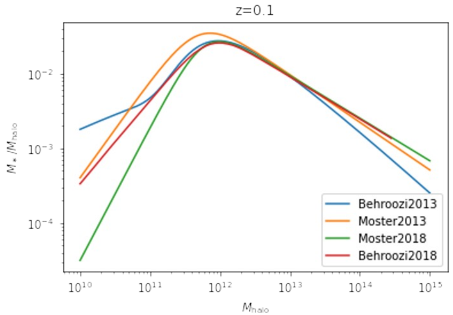
V_peak: maximum circular velocity
V_50 = 10.5 km/s or 18 km/s



Ando+(2020) [2002.11956]

Priors (3/3)

- 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
- We use:
  - 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:

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

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

↑

semi-analytic model in [2002.11956]

Target dSphs

- 8 classical + 26 ultrafaint dSph in [2002.11956]

Classical:

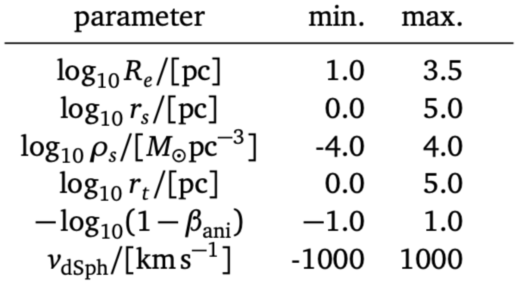
Carina
Draco
Fornax
Leo I
Leo II
Sculptor
Sextans
Ursa Minor

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

MCMC Analysis

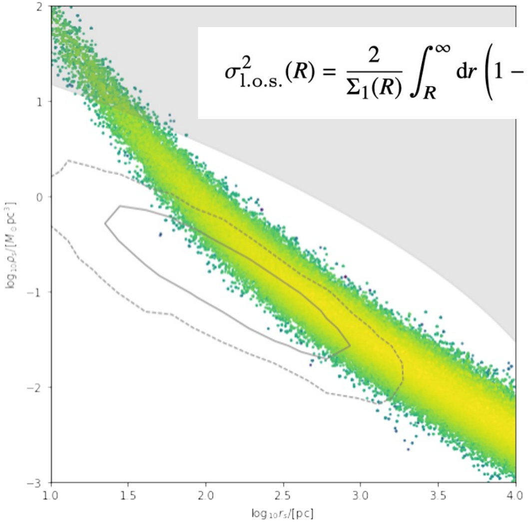
- Jeans analysis
  - 6 Parameters
  - Prior choices
    - photometry only
    - photometry + satellite
    - photometry + satellite + SHMR
  - Bayesian analysis to calculate posterior probability
    - MCMC tool: `emcee 3.0.2`



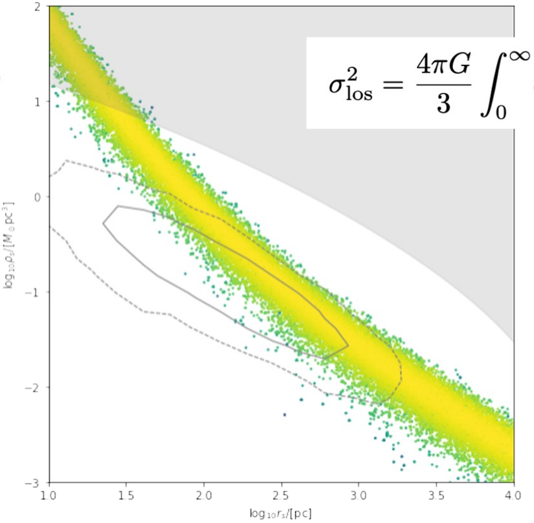
parameter	min.	max.
$\log_{10} R_e/[\mathrm{pc}]$	1.0	3.5
$\log_{10} r_s/[\mathrm{pc}]$	0.0	5.0
$\log_{10} \rho_s/[M_\odot \mathrm{pc}^{-3}]$	-4.0	4.0
$\log_{10} r_t/[\mathrm{pc}]$	0.0	5.0
$-\log_{10}(1-\beta_{\mathrm{ani}})$	-1.0	1.0
$v_{\mathrm{dSph}}/[\mathrm{km\,s^{-1}}]$	-1000	1000

Results

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



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

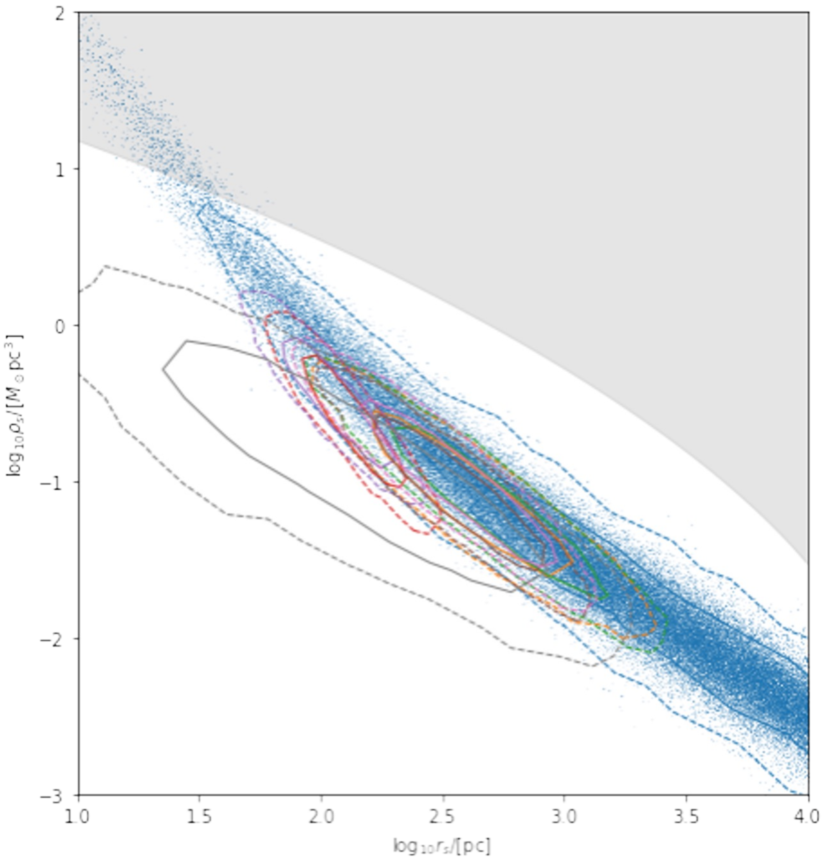


$$\sigma^2_{\mathrm{los}} = \frac{4\pi G}{3}\int_0^\infty dr\; r\nu_\star(r)M(r),$$

Results

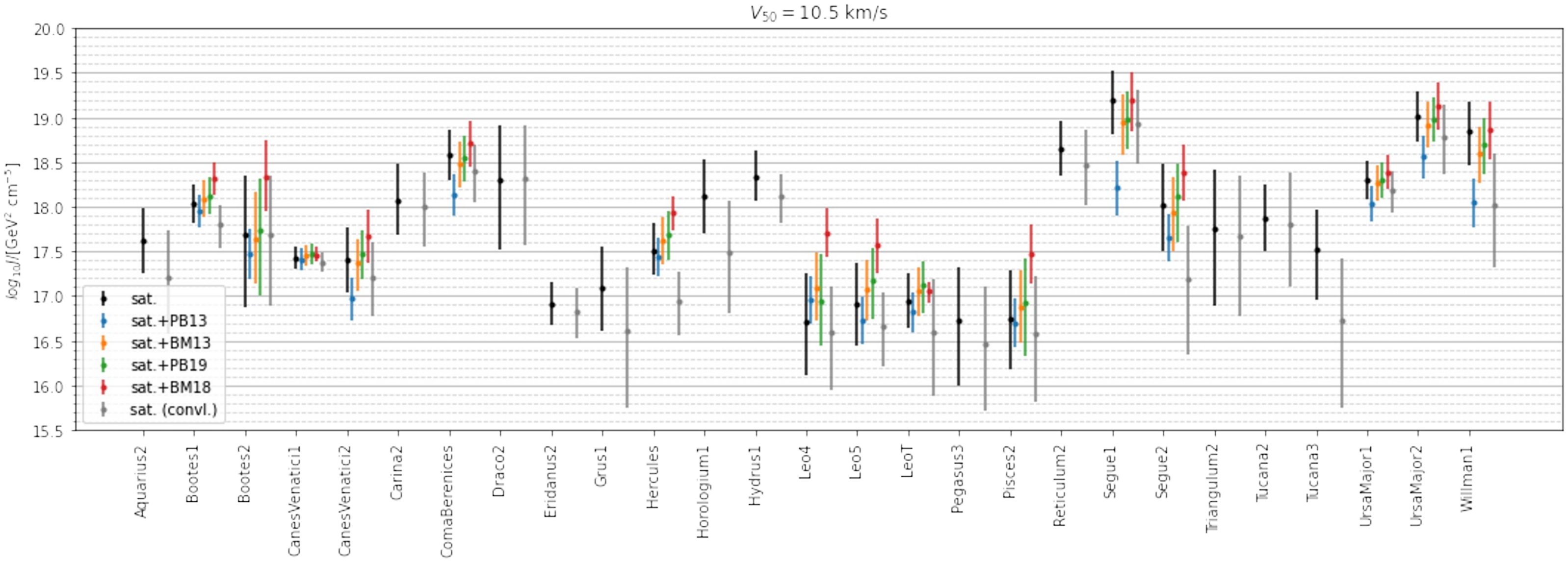
- Posterior density function

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)



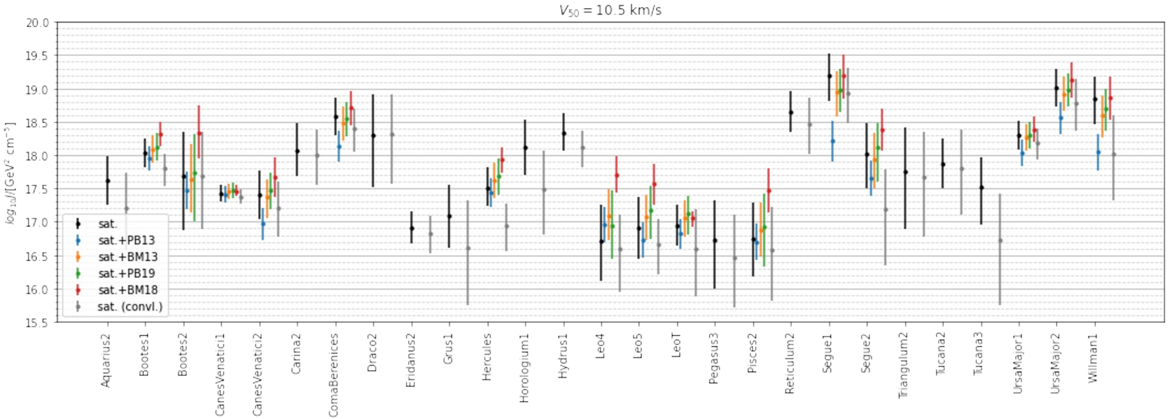
Results

- 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 model dependent
        - Test of SHMR models by using dSphs?

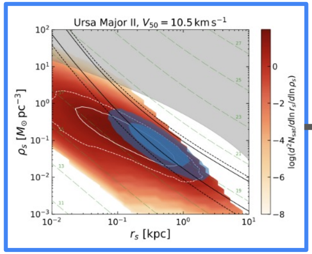


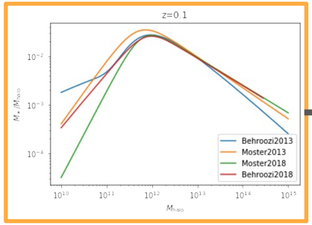
Summary

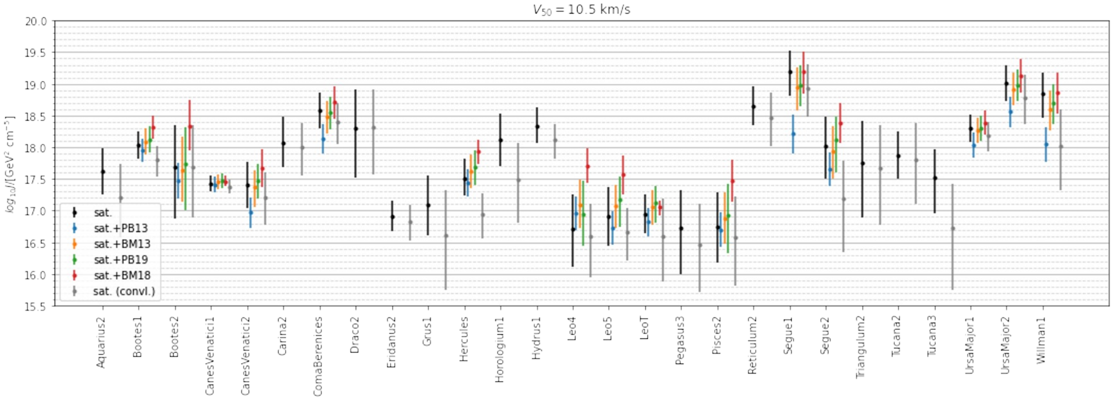
- dSphs play an important role of detecting dark matter by the indirect detection method, but their dark matter density are still ambiguous
- We estimate the DM density profile using velocity dependent likelihood with
  - satellite prior
  - stellar-to-halo mass relation (SHMR)
- The radial dependence of the velocity dispersion breaks the parameter degeneracy and gives more reasonable results
- SHMR priors decrease J-factor uncertainties but results have SHMR model dependence

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

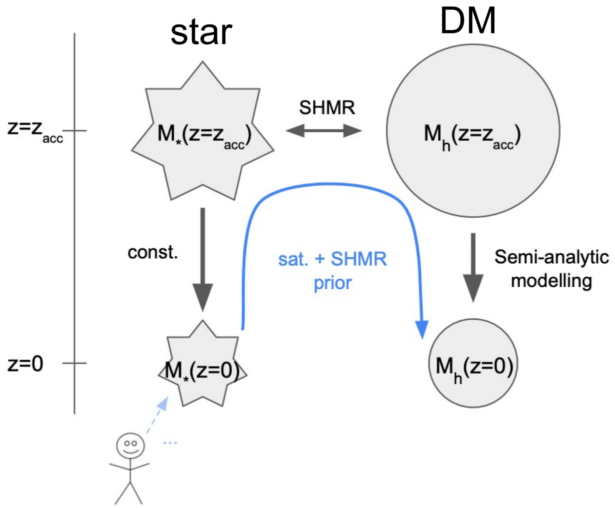




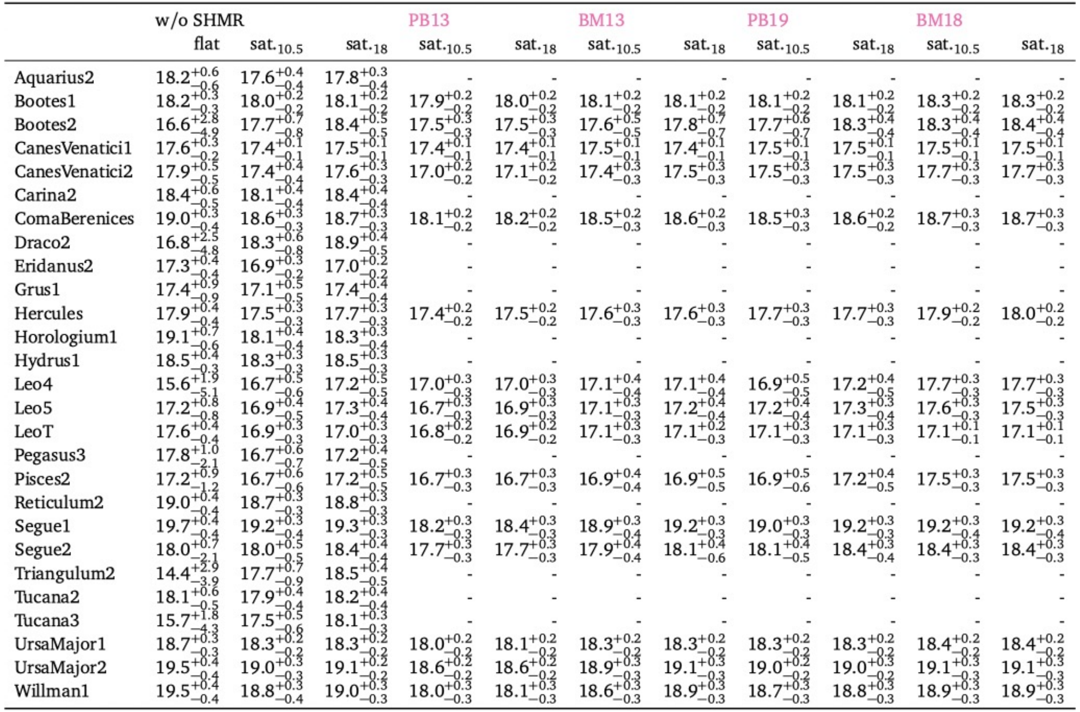


SHMR

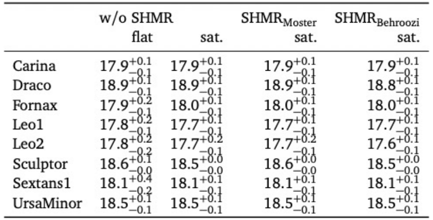
- The stellar-to-halo mass relation (SHMR)
  - empirical relation between the stellar and DM halo mass of galaxies: M_star = f(M_halo, z)
  - assumption: f(M_halo, z) is a monotonic function for M_halo



J-factors (table)

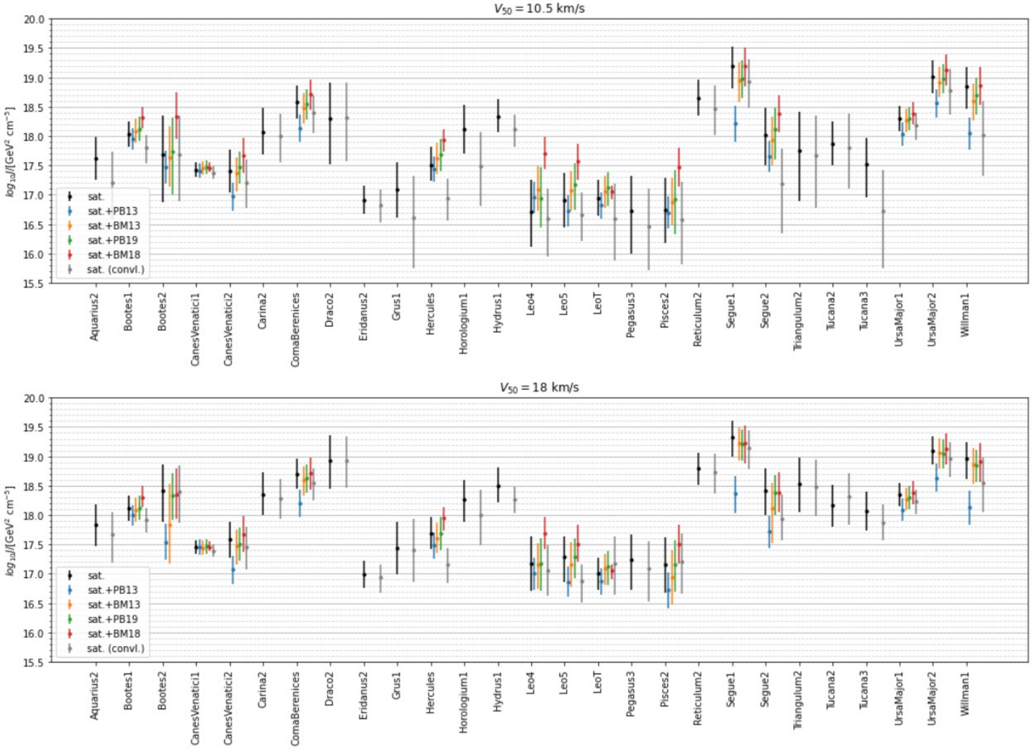


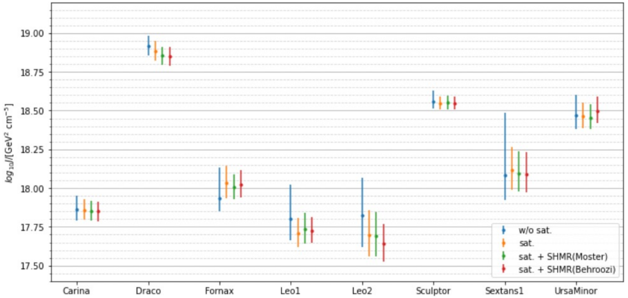
	w/o SHMR			PB13		BM13		PB19		BM18	
	flat	$\text{sat.}_{10.5}$	sat._{18}	$\text{sat.}_{10.5}$	sat._{18}	$\text{sat.}_{10.5}$	sat._{18}	$\text{sat.}_{10.5}$	sat._{18}	$\text{sat.}_{10.5}$	sat._{18}
Aquarius2	$18.2^{+0.6}_{-0.6}$	$17.6^{+0.4}_{-0.4}$	$17.8^{+0.3}_{-0.4}$	-	-	-	-	-	-	-	-
Bootes1	$18.2^{+0.3}_{-0.3}$	$18.0^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$17.9^{+0.2}_{-0.2}$	$18.0^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.1^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$	$18.3^{+0.2}_{-0.2}$
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		$\text{SHMR}_{\text{Moster}}$	$\text{SHMR}_{\text{Behroozi}}$
	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
$log_{10}J/[\mathrm{GeV}^2\ \mathrm{cm}^{-5}]$
20.0
19.5
19.0
18.5
18.0
17.5
17.0
16.5
16.0
15.5
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


$log_{10}J/[\mathrm{GeV}^2\ \mathrm{cm}^{-5}]$
19.00
18.75
18.50
18.25
18.00
17.75
17.50
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

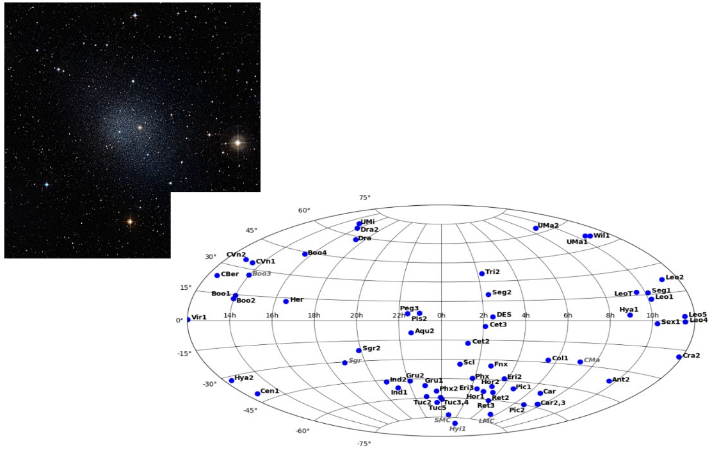
$$\rho(r) = \begin{cases} \rho_s\left(\frac{r}{r_s}\right)^{-1}\left(1+\frac{r}{r_s}\right)^{-2} & (0 \le r \le r_t) \\ 0 & (r_t < r) \end{cases},$$

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

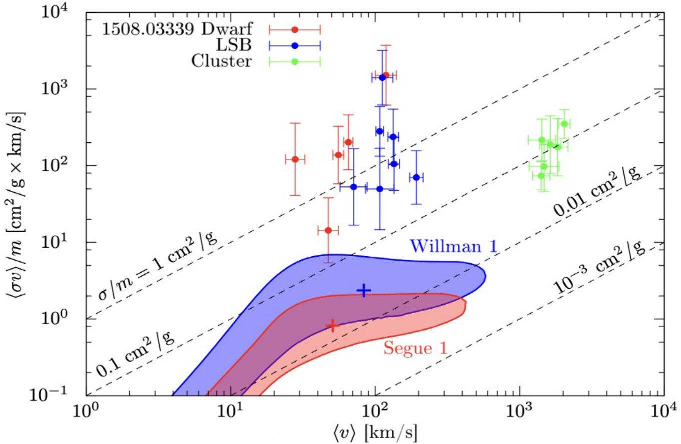
dSphs and DM detection

- 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