arXiv:1608.01749
arXiv:1706.05481
arXiv:20XX:XXXX

J-factor estimation of Draco, Sculptor, and Ursa Minor dwarf spheroidal galaxies with the member/foreground mixture model

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JSPS: 18J21186

Abstract & Contents

- **Abstract**
  - *To obtain precise sensitivity of dark matter (DM) indirect detection, we must know precise amounts of DM in target objects.*
  - *We have developed a new method to predict the DM amount with considering the **foreground contamination**, which remained ambiguous in conventional works.*
  - *Using this method, we estimate actual DM amounts (**J-factors**) of promising targets, namely, **Draco, Sculptor and Ursa Minor dSphs**.*
- **Contents**
  - Indirect detection of WIMP dark matter
  - J-factor estimation of dSphs
  - Uncertainty of J-factor: foreground contamination.

  - Member/Foreground mixture model
    - Flowchart
    - Likelihoods & Models
  - Results: J-factor of Draco, Sculptor, & Ursa Minor
  - Summary

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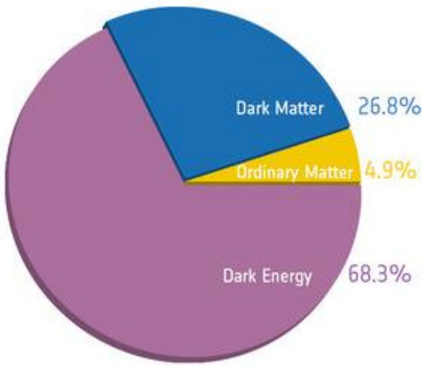
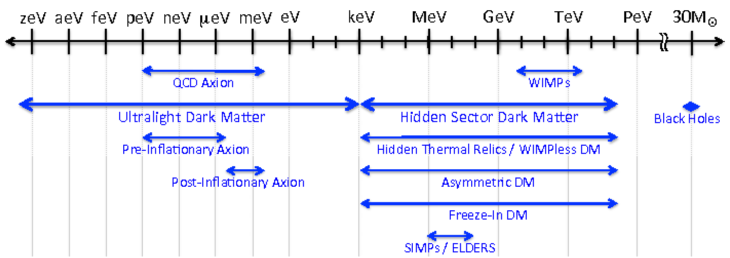
Indirect detection of WIMP dark matter

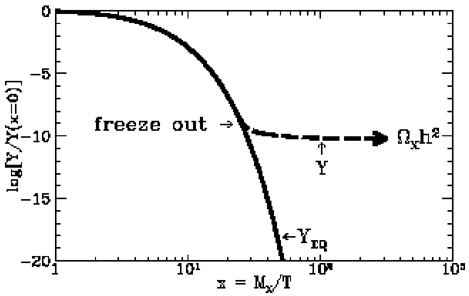


- Dark matter (DM)
  - $\Omega_{DM} = 0.258$ (Planck 2015)
- What is the DM?
  - PBH
  - Axion
  - Sterile neutrino

  …

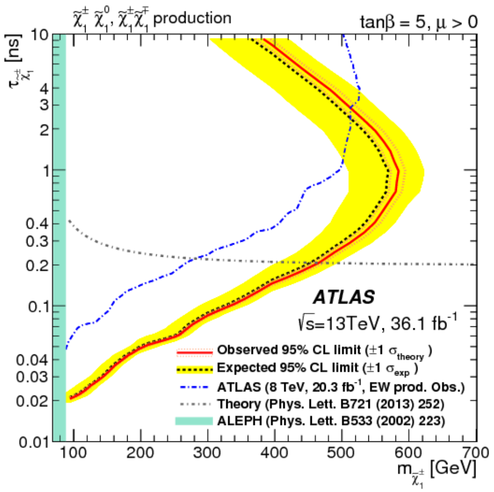


  - **WIMP (Weakly Interacting Massive Particle)**
    - colorless, neutral
    - Ω_{DM} naturally achieved by the *freeze out* mechanism
    - **Some BSM predict WIMP DM**
      - e.g. wino with its mass M_{wino} ~ TeV (SUSY)



Indirect detection of WIMP dark matter

- How to detect WIMP



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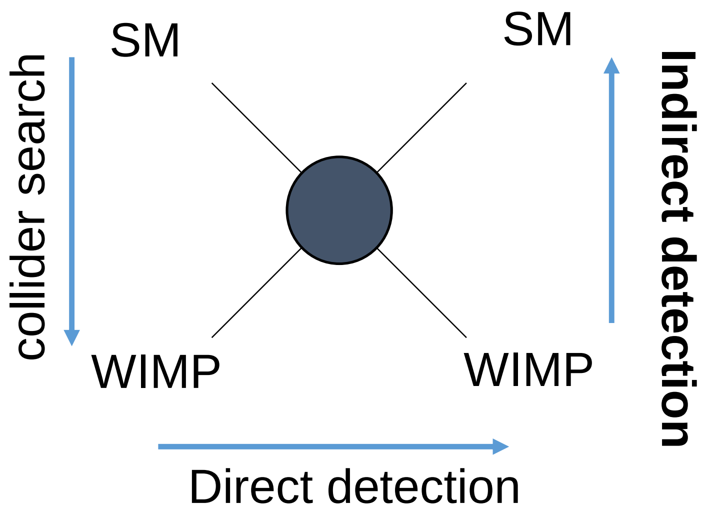
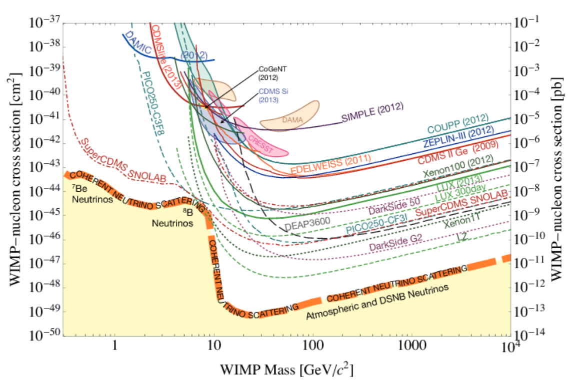
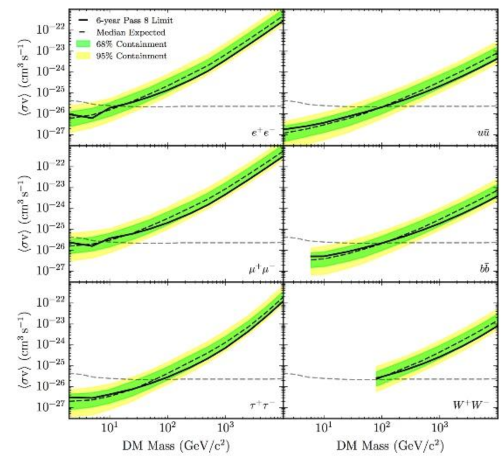




arXiv:[1410.4960]



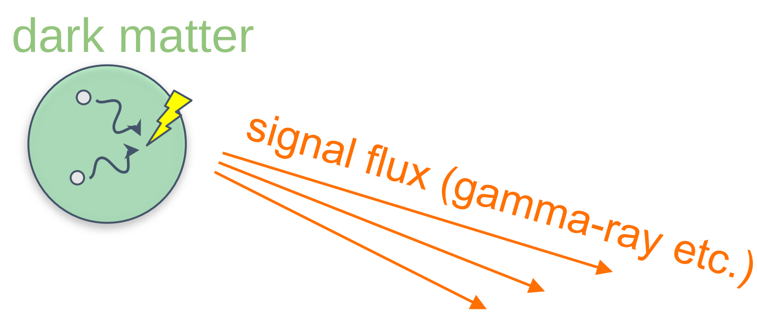
arXiv:[1310.0828]
Sensitivity line of Fermi-LAT

J-factor estimation of dSphs

- Indirect detection
  - Observing DM rich targets to find DM annihilation signal
  - To calculate the sensitivity, we must estimate the amount of signal flux
  - Annihilation signal flux $\Phi(E, \Delta\Omega)$ is proportional to a "***J*-factor**":

$$\Phi(E, \Delta\Omega) = \underbrace{\left[\frac{\langle \sigma v \rangle}{8\pi m_{\mathrm{DM}}^2} \sum_f b_f \left(\frac{dN_\gamma}{dE} \right)_f \right]}_{\text{particle physics factor}} \times \underbrace{\left[\int_{\Delta\Omega} d\Omega \int_{l.o.s} dl \rho^2(l, \Omega) \right]}_{\text{astrophysical factor}(\equiv J)}$$

- Targets:
  - Galactic center
  - Center of galaxies
  - Dwarf spheroidal galaxies
  - DM halo



…Which astrophysical object has a large *J*-factor?

J-factor estimation of dSphs

- **Dwarf Spheroidal galaxy (dSph)**:
  - close to the earth
  - DM rich
  - without gamma-ray noise

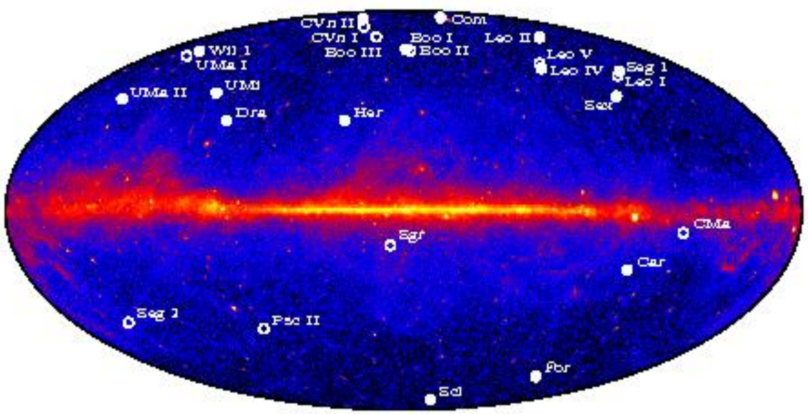


Table 1
Basic Information

(1) Galaxy	(2) Other Names	(3)	(4)	(5) R.A. J2000	(6) Decl. J2000	(7) Original Publication
The MW sub-group (in order of distance from the MW)						
The Galaxy	The MW	G	S(B)bc	$17^h45^m40^s.0$	$-29^d00^m28^s$	...
Canis Major		G	????	$07^h12^m35^s.0$	$-27^d40^m00^s$	Martin et al. (2004a)
Sagittarius dSph		G	dSph	$18^h55^m19^s.5$	$-30^d32^m43^s$	Ibata et al. (1994)
Segue (I)		G	dSph	$10^h07^m04^s.0$	$+16^d04^m55^s$	Belokurov et al. (2007)
Ursa Major II		G	dSph	$08^h51^m30^s.0$	$+63^d07^m48^s$	Zucker et al. (2006a)
Bootes II		G	dSph	$13^h58^m00^s.0$	$+12^d51^m00^s$	Walsh et al. (2007)
Segue II		G	dSph	$02^h19^m16^s.0$	$+20^d10^m31^s$	Belokurov et al. (2009)
Willman 1	SDSS J1049+5103	G	dSph	$10^h49^m21^s.0$	$+51^d03^m00^s$	Willman et al. (2005a)
Coma Berenices		G	dSph	$12^h26^m59^s.0$	$+23^d54^m15^s$	Belokurov et al. (2007)
Bootes III		G	dSph?	$13^h57^m12^s.0$	$+26^d48^m00^s$	Grillmair (2009)
LMC	Nubecula Major	G	Irr	$05^h23^m34^s.5$	$-69^d45^m22^s$	...
SMC	Nubecula Minor NGC 292	G	dIrr	$00^h52^m44^s.8$	$-72^d49^m43^s$	...
Bootes (I)		G	dSph	$14^h00^m06^s.0$	$+14^d30^m00^s$	Belokurov et al. (2006)
Draco	UGC 10822 DDO 208	G	dSph	$17^h20^m12^s.4$	$+57^d54^m55^s$	Wilson (1955)
Ursa Minor	UGC 9749 DDO 199	G	dSph	$15^h09^m08^s.5$	$+67^d13^m21^s$	Wilson (1955)
Sculptor		G	dSph	$01^h00^m09^s.4$	$-33^d42^m33^s$	Shapley (1938a)
Sextans (I)		G	dSph	$10^h13^m03^s.0$	$-01^d36^m53^s$	Irwin et al. (1990)
Ursa Major (I)		G	dSph	$10^h34^m52^s.8$	$+51^d55^m12^s$	Willman et al. (2005b)
Carina		G	dSph	$06^h41^m36^s.7$	$-50^d57^m58^s$	Cannon et al. (1977)
Hercules		G	dSph	$16^h31^m02^s.0$	$+12^d47^m30^s$	Belokurov et al. (2007)
Fornax		G	dSph	$02^h39^m59^s.3$	$-34^d26^m57^s$	Shapley (1938b)
Leo IV		G	dSph	$11^h32^m57^s.0$	$-00^d32^m00^s$	Belokurov et al. (2007)
Canes Venatici II	SDSS J1257+3419	G	dSph	$12^h57^m10^s.0$	$+34^d19^m15^s$	Sakamoto & Hasegawa (2006) Belokurov et al. (2007)
Leo V		G	dSph	$11^h31^m09^s.6$	$+02^d13^m12^s$	Belokurov et al. (2008)
Pisces II		G	dSph	$22^h58^m31^s.0$	$+05^d57^m09^s$	Belokurov et al. (2010)
Canes Venatici (I)		G	dSph	$13^h28^m03^s.5$	$+33^d33^m21^s$	Zucker et al. (2006b)
Leo II	Leo B UGC 6253 DDO 93	G	dSph	$11^h13^m28^s.8$	$+22^d09^m06^s$	Harrington & Wilson (1950)
Leo I	UGC 5470 DDO 74 Regulus Dwarf	G/L	dSph	$10^h08^m28^s.1$	$+12^d18^m23^s$	Harrington & Wilson (1950)

Many dSphs have been observed.

Some of them are reported to have large *J*-factors.

… How can we know their J-factors or DM distributions?

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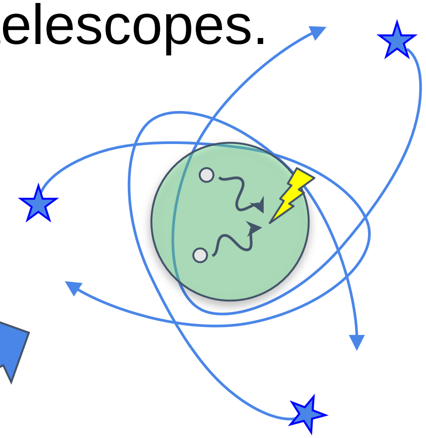
J-factor estimation of dSphs

- The J-factor of a dSph is estimated by observing the velocity of dSph member stars by spectroscopic telescopes.

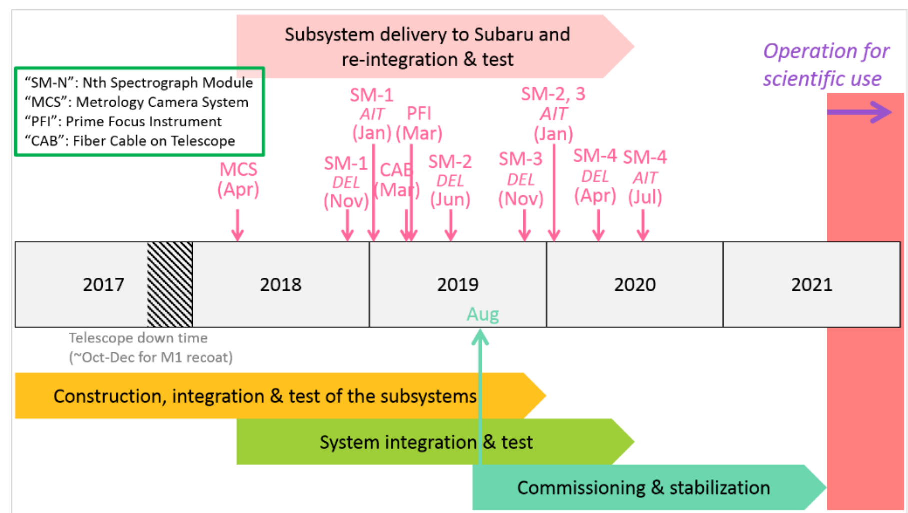


- e.g. Prime Focus Spectrograph (PFS):
  - Large FoV! (~1.3 deg)
  - 2400 fibers!

  → We will observe all the dSph stars simultaneously.

★ 's velocity is ...

PFS



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Uncertainty of J-factor: foreground effect

- (Spherical) Jeans equation: Kinematics of dSph

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

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

This Jeans analysis has some biases:

- Anisotropy modelling (Some works assume $\beta(r)=\mathrm{const.}$ for simplicity)
- Non-sphericity (dwarf *spheroidal* galaxy) ← Hayashi+*(2016)*
- Prior bias (few stars to determine DM distribution sufficiently)
- **Foreground (FG) contamination** ← Walker+(2009), Bonnivard+(2015) and our works: Ichikawa+(2017, 2018), Shunichi+(in prep.)

We should take care of these assumptions or uncertainty.

In particular, **FG contamination** is important even for future observations yielding a large amount of stellar velocity data.

So, what is the **FG contamination**?

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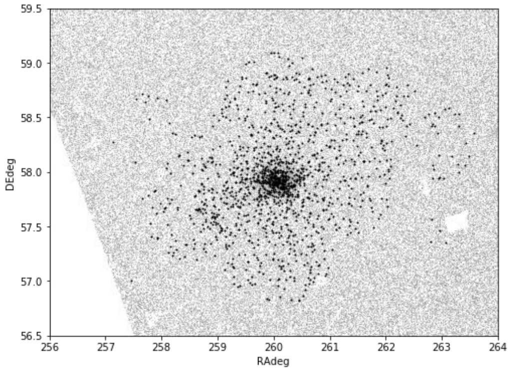
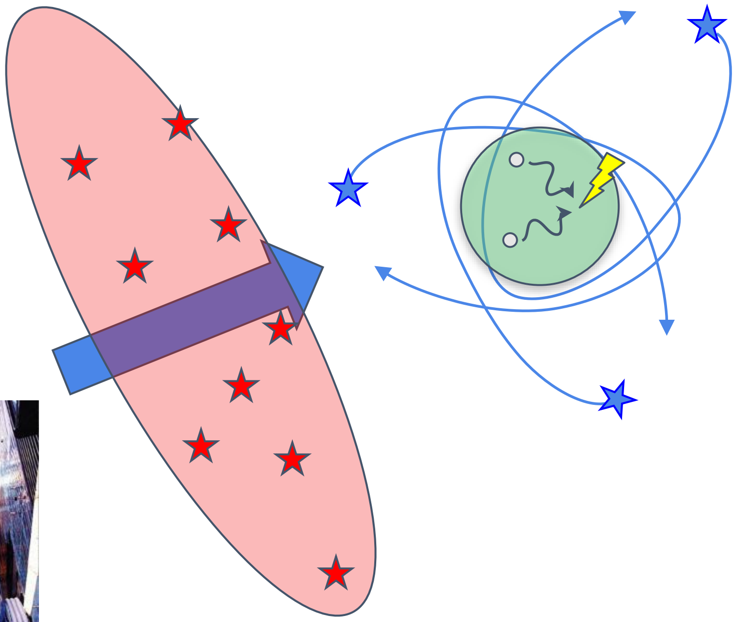
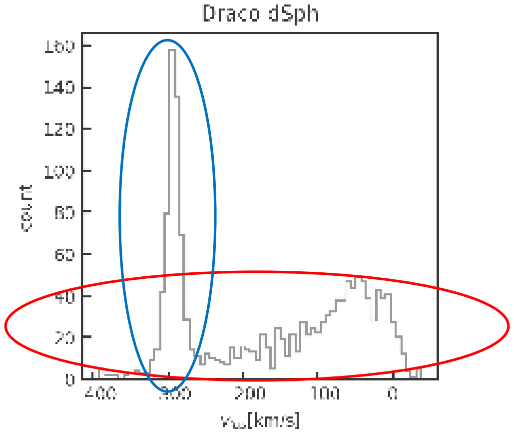
Uncertainty of J-factor: foreground effect

- **Foreground contamination**
  - Observed data are contaminated by Milky Way stars
  - We cannot distinguish member stars from FG stars





★ or ★ ???



- FG stars distort the velocity dispersion curve → biased *J*-factors

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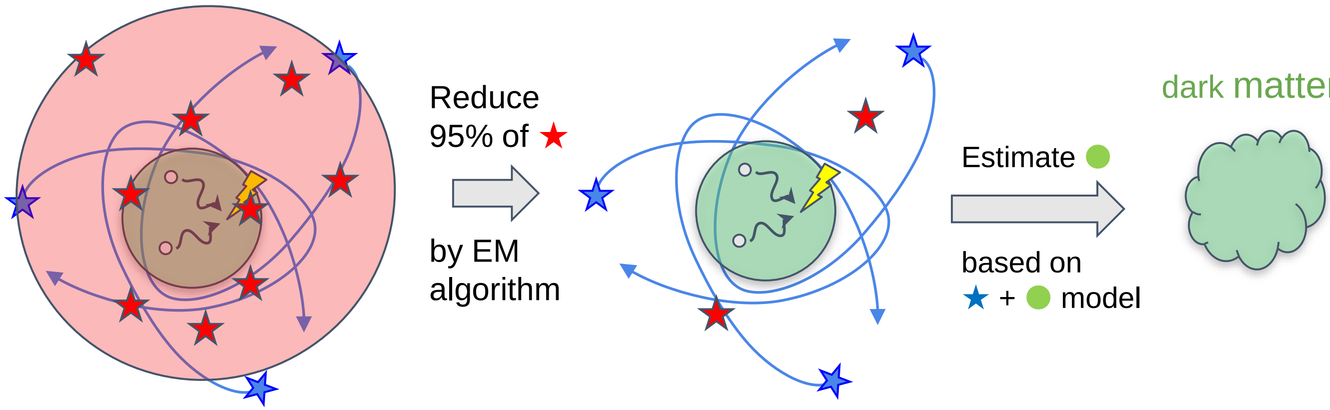
Uncertainty of J-factor: foreground effect

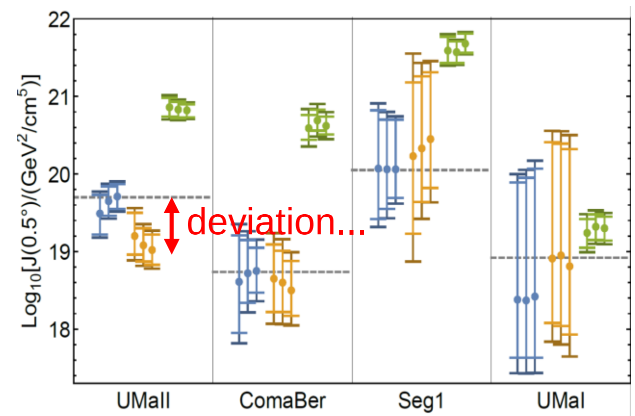
- conventional method to remove FG stars

Conventional method
Walker et al. (2009)



- In a conventional analysis, foreground stars are removed based on *membership probabilities* P_M, calculated by the expectation-maximization (EM) algorithm.
  - e.g. selecting the stars with $P_M > 0.95$ (95% member-like stars)
- However, even if we try to remove FG-like stars, some FG stars remain.
  → biased *J*-factors (e.g. UMa II)

Mock dSph demonstration



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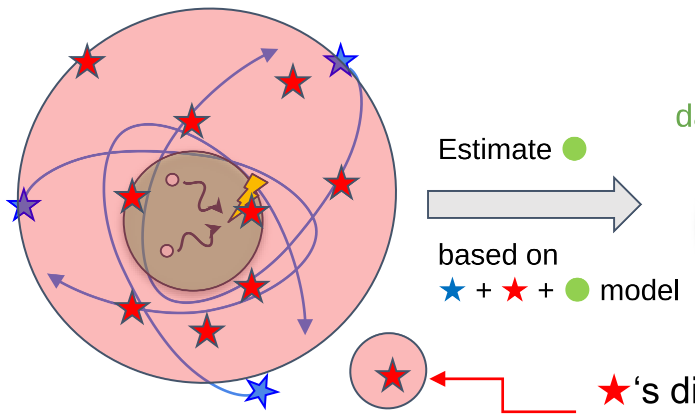
Uncertainty of J-factor: foreground effect

• conventional method to remove FG stars

KI17 (Mem/FG)
Ichikawa et. al. (2017)

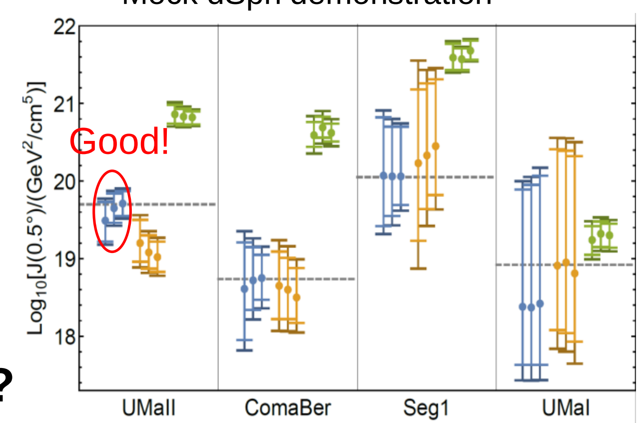


★'s distribution is estimated by control region in advance.

- We developed a mixture model, which includes a foreground model as well as a member model.
- Foreground stars are not removed. Their distribution is also fitted by the model.
- This model can reproduce input parameter of mock dSphs (even for UMaII).

→ **Mem/FG analysis for actual observation data?**

Mock dSph demonstration



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Our Analysis: Member/Foreground model

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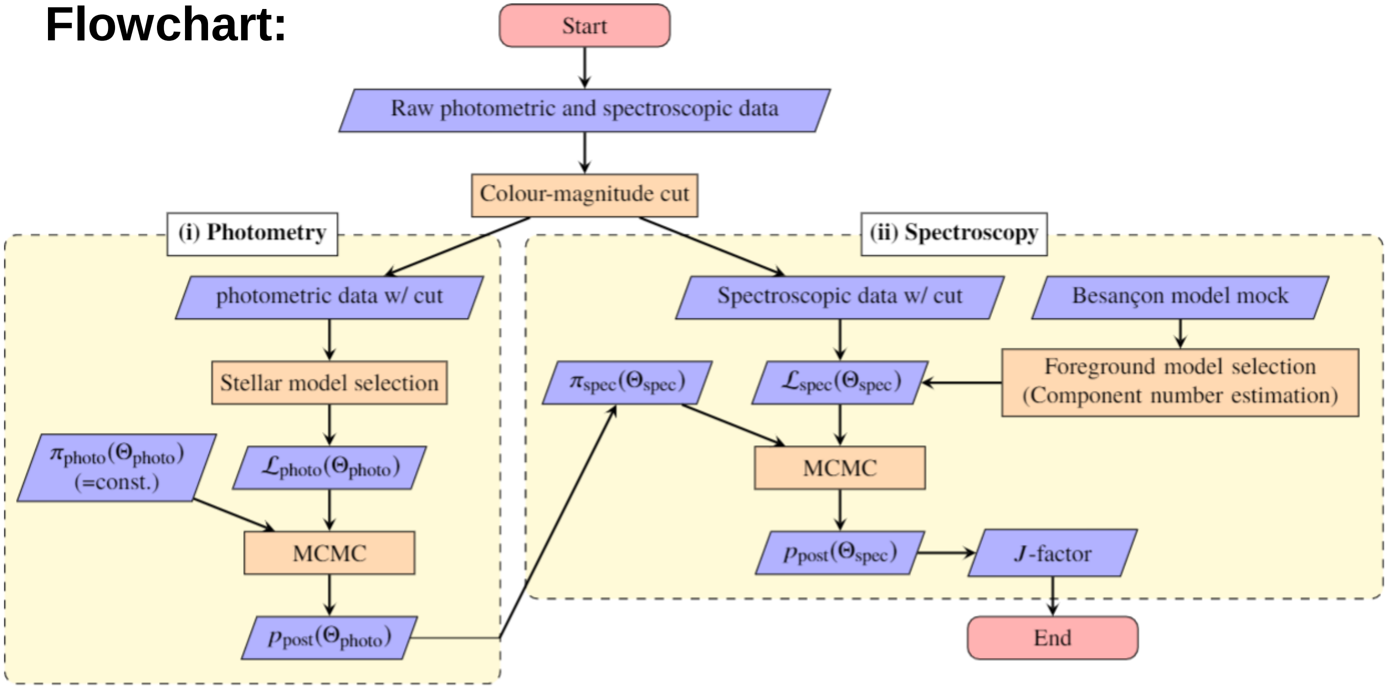
Our Analysis: Member/Foreground model

- **Feature:**
  - Separated into two parts
    - Photometric part
    - Spectroscopic part
  - Generalized models & Model selection

Flowchart:



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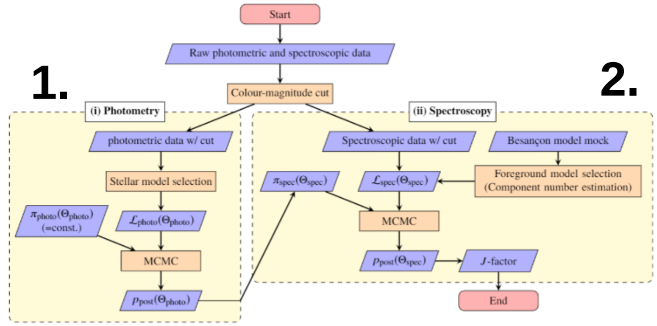
Our Analysis: Member/Foreground model



- **Likelihoods** :
  (parameters) $\Theta_{\rm tot} = \Theta_{\rm photo} + \Theta_{\rm spec}$

1. Photometric part

$$\mathcal{L}_{\rm photo}(\Theta_{\rm photo}|D_{\rm photo}) = s\,\Sigma_{\rm Mem}(R) + (1-s)\Sigma_{\rm FG}$$

- Σ : stellar number density
- s: total contamination rate
- $\Theta_{\rm photo}$: parameters (local contamination rate & half-light-radius)

→ determine the contamination rate in advance (obtain a prior $\pi(\Theta_{\rm photo})$)

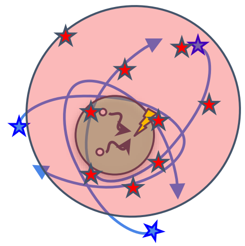
2. Spectroscopic part

$$\mathcal{L}_{\rm spec}(\Theta_{\rm tot}|D_{\rm spec}) = \prod_i \left(s\,\mathcal{G}_{\rm mem}(v_i; v_{\rm mem}, \sigma_{\rm l.o.s.}(R_i)) + (1-s)\prod_c \mathcal{G}_{\rm FG}(v_i; v_c, \sigma_c) \right) \times \pi(\Theta_{\rm photo})$$

- $\mathcal{G}$: Gaussian function:

- Estimate the posterior probability of all parameters by using a MCMC sampler (*emcee*)
  → posterior of J-factor!

Our Analysis: Member/Foreground model



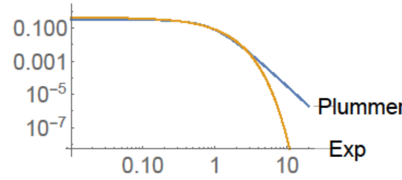
- **Models:**
  - **DM profile**: Generalized NFW (Zhao) profile

$$\rho_{\rm DM}(r) = \rho_s (r/r_s)^{-\gamma}\left(1+(r/r_s)^{\frac{-\beta+\gamma}{\alpha}}\right)^{\alpha}$$

    - γ : power of inner region (core ($\gamma=0$) vs. cusp ($\gamma>0$))

  - **Stellar profile**: Plummer or exponential profile & Jeans analysis

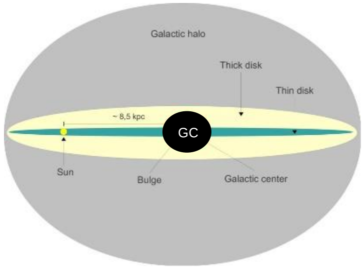
$$\Sigma_1(R) = \begin{cases} \frac{1}{\pi R_{1/2}^2}\left[1+(R/R_{1/2})^2\right]^{-2} & \text{(Plummer profile)} \\ \frac{1}{2\pi R_e^2}\exp(-R/R_e) & \text{(Exponential profile)} \end{cases}$$



  - **Foreground profile**: up to 3-components (thin disk, thick disk, halo)
    - Gaussian mixture model (GMM)

$$p_{\rm FG}(v|R) = \sum_{i\in{\rm thin,thick \atop halo}} s_i \mathcal{G}[v, \bar{v}_{\rm FG,i}, \sigma_{\rm FG,i}]$$

We select suitable models based on their Bayes factor.



Model selection

- We select suitable models (Plummer or exp., up to three FG components) based on their **Bayes Factor:**

$$\mathrm{BF} = \frac{\mathcal{E}_1}{\mathcal{E}_0} \qquad \text{Evidence: } \mathcal{E} = \int \mathrm{d}\Theta\, \mathcal{L}(\Theta)\pi(\Theta)$$

- BIC ~ - ln($\mathcal{E}$)

$$\text{BIC} = -\ln \mathcal{L}\left(\widehat{\Theta}\right) + \frac{d}{2}\ln(\#\mathrm{sample})$$

$\widehat{\Theta}$: Maximum likelihood

- **WBIC** ~ - ln($\mathcal{E}$)

$$\text{WBIC} = \frac{\int d\Theta \ln(\mathcal{L}(\Theta))\, \mathcal{L}(\Theta)^{\beta}\pi(\Theta)}{\int d\Theta\, \mathcal{L}(\Theta)^{\beta}\pi(\Theta)}$$

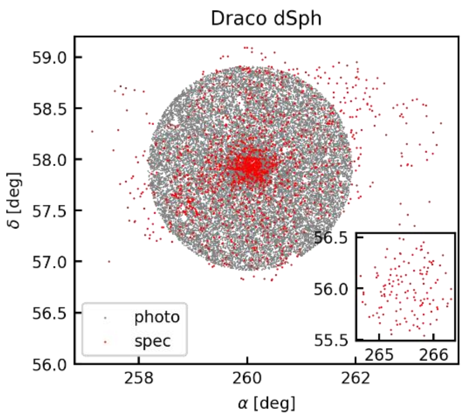
$$\beta = 1/\log(\#\mathrm{sample})$$

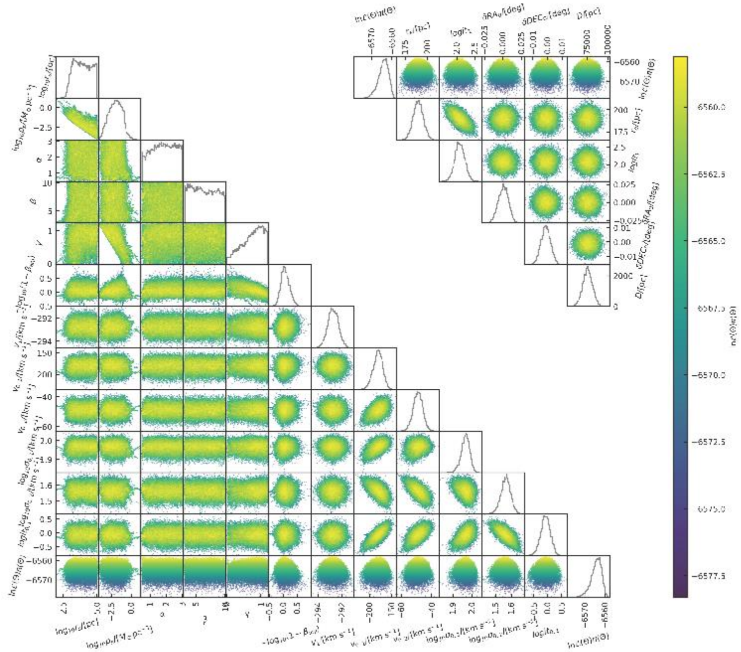
  - WBIC can be easily evaluated by a MCMC sampling
  - Even for the case of multimodal likelihoods (cf. GMM), WBIC gives a good approximation of the evidence

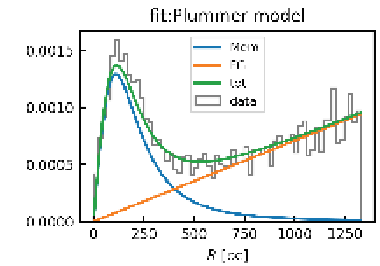
Our Analysis: Member/Foreground model

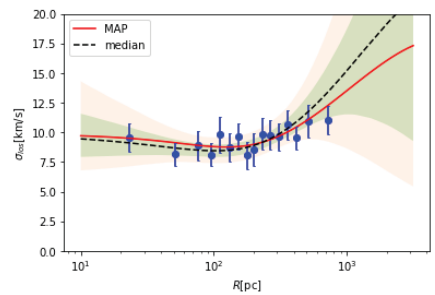
- **Results: J-factor of Draco, Sculptor, and Ursa Minor dSphs (preliminary,** arXiv:20XX:XXXX…)
  - Estimate the J-factors of hopeful dSphs: Draco, Sculptor, Ursa Minor
  - Data set: photometry & spectroscopy
    - Draco: SDSS & MMT/Hectochelle
    - Sculptor: DES & MMFS
    - Ursa Minor: Pan-STARRS & MMT/Hectochelle

e.g. the Draco dSph





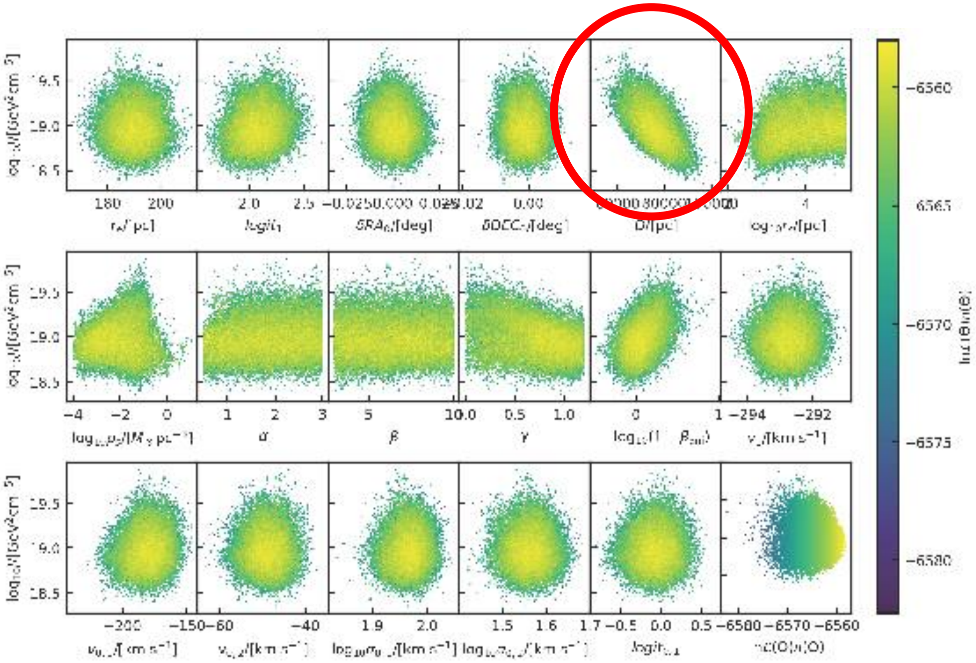




Our Analysis: Member/Foreground model

- **Results: J-factor of Draco, Sculptor, and Ursa Minor dSphs (preliminary,** arXiv:20XX:XXXX…)
  - We found that distance to dSphs (=*D*) has a correlation with J-factor ($J \propto D^{-3}$)
    - $\frac{\Delta D}{D} \approx 0.1$
    - Further studies of distance determination are required to achieve more precise results

e.g. the Draco dSph



Estimated J-factor:

dSph	$\log_{10}(J(0.5°)/[\mathrm{GeV^2 cm^{-5}}])$
Draco	$18.96^{+0.21}_{-0.17}$
Sculptor	$18.53^{+0.12}_{-0.11}$
Ursa Minor	$18.75^{+0.17}_{-0.13}$

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Summary

- dSphs are good targets of the indirect detection of DM.
- The sensitivity of the indirect detection has an uncertainty due to the foreground contamination of the J-factor estimation.
- We present the Member/Foreground mixture model to calculate accurate J-factors. Our method can work even for the case of highly-contaminated dSphs.
- Using the Member/Foreground mixture model, we obtain the J-factors of the Draco, Sculptor, and Ursa Minor dSphs.
- Reducing distance error improves the uncertainty of J-factors.

    - Future work:
        - J-factors of other dSphs, the J-factor table of all dSphs
        - other systematic uncertainties (e.g. non-sphericity, anisotropy, etc.)

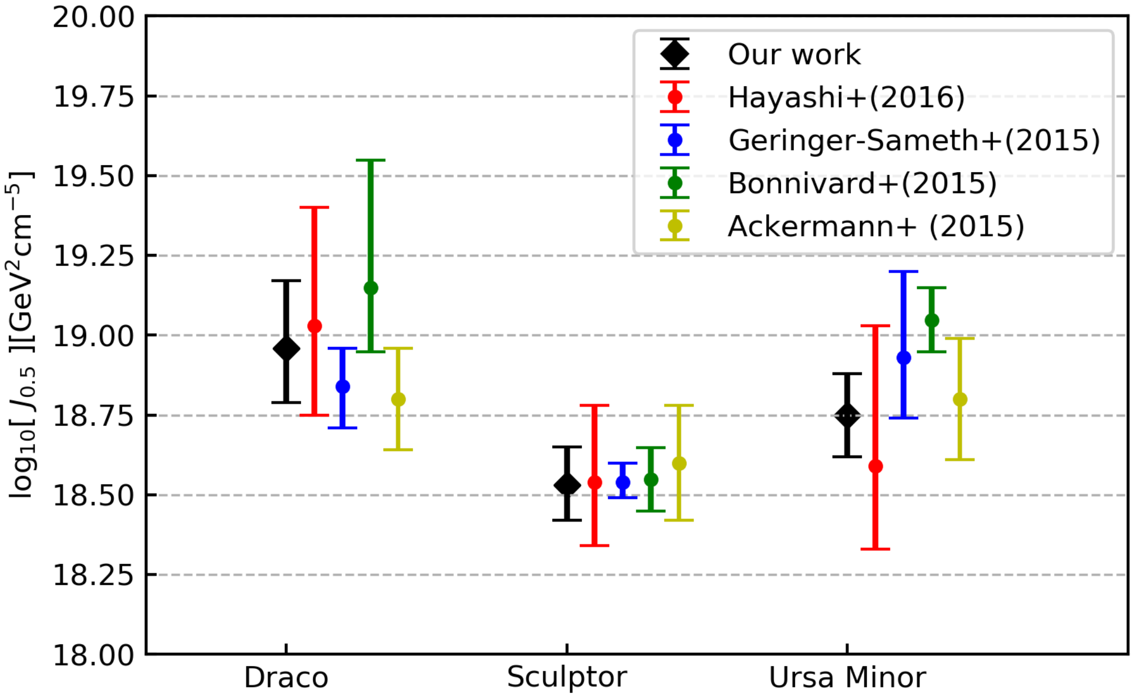
JSPS: 18J21186

Back Up

JSPS: 18J21186

Comparison to other works

- The fluctuation of the J-factors by several works
  - In particular, Draco and Ursa Minor
    - We found that the contamination rates of these two dSphs are relatively higher than that of the Sculptor dSph
      → It suggests the importance of Member/FG model



dSph Modelling toolkit

- dSph Modelling toolkits (provisional) can:
  - Implement major dSph models
    - Anisotropy profile
    - Foreground effect
    - Stellar & DM profile
  - compare models based on Bayes factors
  - define user custom model
  - Switch a sampling algorithm among MCMC samplers (emcee, Multinest, …)