The foreground effect on the J-factor estimation of dwarf spheroidal galaxies

[arXiv:1608.01749], [arXiv:1706.05481]

Shunichi Horigome (Kavli IPMU, The University of Tokyo)
(Collaborate with Koji Ichikawa, Miho N. Ishigaki, Shigeki Matsumoto, Masahiro Ibe, Hajime Sugai, Kohey Hayashi)

Abstract:

- **Indirect detection** is one of the detection methods of dark matter (DM), where we observe signal flax of the DM annihilation from astronomical objects. In particular, dwarf spheroidal galaxies (dSphs) are ideal target of detection, whose DM mass distribution is estimated by stellar kinematics. However various **systematical uncertainties** remain.
- We focused on **foreground contamination error** and constructed a new method which reduces the effect of contamination by **data-driven way**. We validated our method with using the mock observational data of the **Prime Focus Spectrograph (PFS).** Using this method, we calculate **sensitivity without foreground contamination effect** for the future observations by the **Cherenkov Telescope Array (CTA)**.

1. Introduction of dark matter (DM) indirect detection:

- target: **Weakly Interacted Massive Particles (WIMPs)**
  - Attracting candidate, weakly interact with SM particles
- Detection methods:
  - Collider/Direct Detections … Energy range $E \lesssim$ TeV …
  - **Indirect detection (ID)** … DM DM → $\gamma\gamma$, $E \gtrsim$ TeV !

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

- **Large *J*-factor? … dwarf spheroidal galaxies (dSphs)**
  - Near, DM-dominant, and noise-free!

2. The uncertainty of the J-factor:

- **How to estiamte the *J*-factor of dSphs**

We can know $\rho_{\rm DM}(r)$ by the observation of stellar motion, becausethe member stars of dSphs go around DM mass $\rho_{\rm DM}(r)$ (dSphs are DM dominant, Fig. 1).

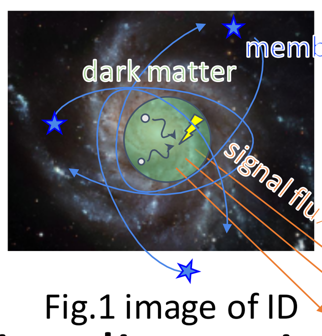


Fig.1 image of ID

Observables of stellar distribution:

$\Sigma_*(R)$, $\sigma_{l.o.s}^2(R)$ (2D density, velocity dispersion)

- **Stellar kinematics … Jeans equation**:

$$\frac{1}{\nu_*(r)}\frac{\partial(\nu_*(r)\sigma_r^2(r))}{\partial r} + \frac{2\beta_{\rm ani}\sigma_r^2(r)}{r} = -\frac{GM(r)}{r^2}$$

$$\rightarrow \sigma_r^2(r) = \frac{1}{\nu_*(r)}\int_r^\infty \nu_*(r')\left(\frac{r'}{r}\right)\frac{GM(r')}{r'^2}dr'$$

$M(r)$: enclosed mass, $\nu_*(r)$: 3D density
$\sigma_r^2(r)$: intrinsic dispersion $\xrightarrow[proj.]{} \sigma_{l.o.s}^2(R)$

- **Systematic errors in the estimation of $\Sigma_*(R)$, $\sigma_{l.o.s}^2(R)$**

Seeds of systematical error:
- Non-sphericity, radial anisotropy, **foreground (FG) contamination** etc.

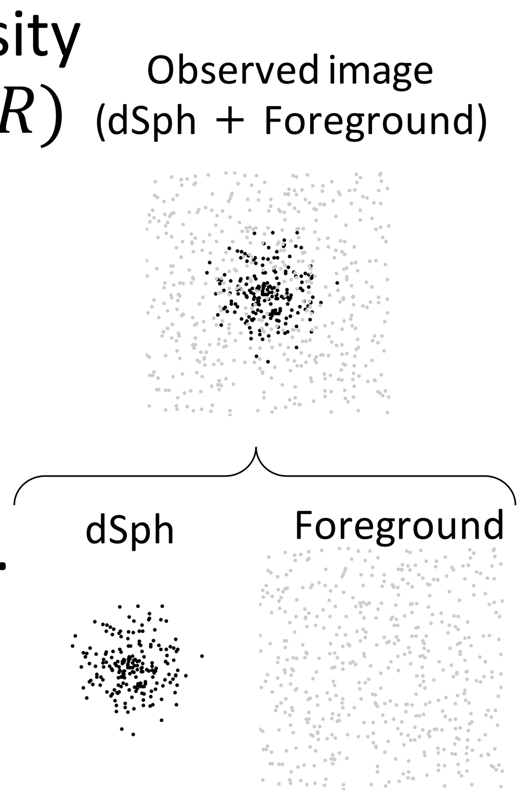


Fig. 2 Foreground contamination

← The Milky way stars overlap target dSphs so that the observed image is contaminated (Fig. 2).

→ Careful treatment of FG contamination is required to obtain accurate DM distribution and the conservative sensitivity of ID. If we over-estimate the DM mass accidentally, it leads too severe exclusion of parameter space of DM models.

(i) MW picture only for the illustration (our actual targets are dSph but too faint to look)

3. Our Analysis Method and Demonstration:

- **Naïve cut:** color-magnitude, velocity, surface gravity
- **Likelihood analysis:** includes both of member and FG

$$\mathcal{L} = \prod_i (sf_{\rm Mem}(v_i,R_i) + (1-s)f_{\rm FG}(v_i,R_i))$$

s: total contamination rate

$f_{\rm Mem/FG}$: phase-space distribution function of the dSph/FG stars, defined by Gaussian:

$$f_{\rm Mem}(v,R) = 2\pi R\Sigma_*(R)C_{\rm Mem}\mathcal{G}[v; v_{\rm Mem}, \sigma_{l.o.s}],$$
$$f_{\rm FG}(v,R) = 2\pi R C_{\rm FG}\mathcal{G}[v; v_{\rm FG}, \sigma_{\rm FG}]$$

$v_{\rm FG}, \sigma_{\rm FG}$: determined by the observation of the control region (Fig. 3).

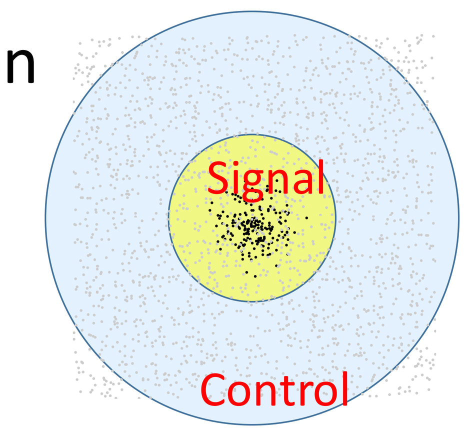


Fig. 3 Control / Signal regions

- **Demonstration:** we create mock data of the future observation by **the Prime Focus Spectrograph (PFS).**
  - Mock distribution has similar properties to the original dSphs, based on the inversion formula of the distribution:

$$\nu(r), \Phi(r) \xrightarrow{\text{inversion}} f_{\rm Mem}(\mathbf{x},\mathbf{v}) \rightarrow (\text{mock data})$$

4. Results of demonstration and Summary:

i. J-factor estimation of ultra-faint dSphs (UFDs) (Fig. 4):

- 100 % contaminated (green), 5 % (orange) and ours (blue)
- Even 5% contamination affected the J-factor to deviated from the input (see UMaII) but our method reproduce the true J-factor value for all of four dSphs

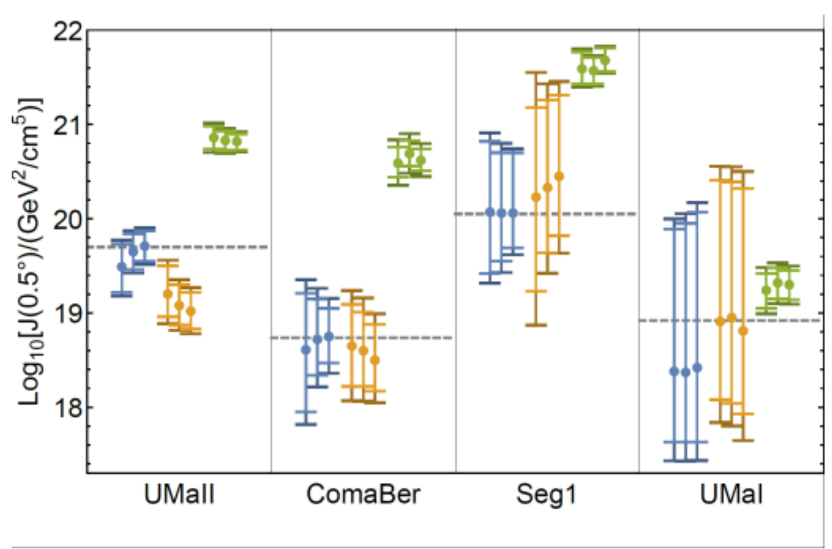


Fig. 4 Demonstration of J-factor estiamtion
(- - - : input)

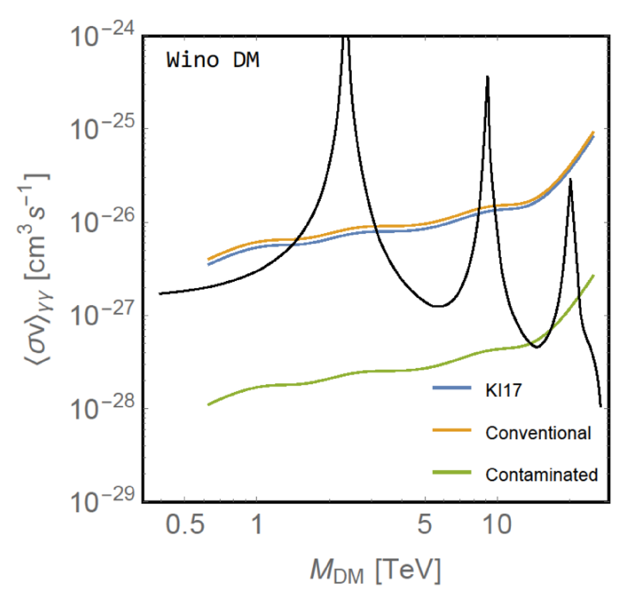


Fig. 5 Sensitivity lines of the Wino DM

ii. Sensitivity lines (Fig. 5)

- Considering Wino DM (typical mass $M_{\tilde{w}} = 2.9$ TeV) and 50 h observation of the four UFDs, utilizing the **Cherenkov Telescope Array (CTA)**
- Over-exclusion in the contaminated case (green)
- Our result (blue) is guaranteed to lead more accurate result **(without systematical error of FG contamination)**

Future work: other errors (anisotropy, non-sphericity…), update J-factor values by the present observation

(JSPS KAKENHI Grant Number No. 18J21186)

Precise Estimation of Dark Matter Distribution for Indirect Detection of Dark Matter

[arXiv:1608.01749], [arXiv:1706.05481]

Shunichi Horigome (Kavli IPMU, The University of Tokyo)
(Collaborate with Koji Ichikawa, Miho N. Ishigaki, Shigeki Matsumoto, Masahiro Ibe, Hajime Sugai, Kohey Hayashi)

Abstract:

- **Indirect detection** is one of the detection methods of dark matter (DM), whose sensitivity reaches to TeV DM. The amount of signal flax of the detection depends on the DM distribution of the target astronomical object. This distribution is estimated by stellar kinematics, but various **systematic uncertainties** are not taken into account.
- For precise estimation, we focused on **the contamination of the foreground stars** and constructed the method which reduces the effect of contamination by **data-driven way**. We validated our method, using the **mock observational data** of the **Prime Focus Spectrograph (PFS).** Using this method, we calculate **sensitivity without foreground contamination effect** for the future observations by the **Cherenkov Telescope Array (CTA**).

1. Introduction of dark matter (DM) indirect detection:

- target: **Weakly Interacted Massive Particles (WIMPs)**
  - Attracting candidate, weakly interact with SM particles
- Detection methods:
  - Collider/Direct Detections … Energy range $E \lesssim$ TeV …
  - **Indirect detection (ID)** … DM DM $\rightarrow \gamma\gamma$, $E \gtrsim$ TeV !

[illegible]

- **Large J-factor? … dwarf spheroidal galaxies (dSphs)**
  - Near, DM-dominant, and noise-free!

2. The uncertainty of the J-factor:

- **How to estiamte the J-factor of dSphs**
  - Two observables of dSph member star: (v, R)
  - (v,R) distribution: described by stellar number density $\nu_*(r)$ and velocity dispersion $\sigma_{l.o.s}^2(r)$.

  They are related by the gravitational potential $\Phi(r)$:

$$\nu_*(r), \sigma_{l.o.s}^2(r) \xleftrightarrow[\text{kinematics}]{} \Phi(r) \longrightarrow \rho_{\rm DM}(r) \;\rightarrow J!$$

- **Stellar kinematics … Jeans equation**:

$$\frac{1}{\nu_*(r)}\frac{\partial(\nu_*(r)\sigma_r^2(r))}{\partial r} + \frac{2\beta_{\rm ani}\sigma_r^2(r)}{r} = -\frac{GM(r)}{r^2}$$

$$\rightarrow \sigma_r^2(r) = \frac{1}{\nu_*(r)}\int_r^\infty \nu_*(r')\left(\frac{r'}{r}\right)\frac{GM(r')}{r'^2}dr'$$

$M(r)$: enclosed mass of the DM halo

$\sigma_r^2(r)$: intrinsic dispersion $\xrightarrow[\text{proj.}]{} \sigma_{l.o.s}^2(R)$

- **Parametrization of the distributions**
  - $\nu_*(r)$ … Plummer model (naïve model)
  - $\rho_{\rm DM}(r)$… NFW model (general model)
- **Observation of $\nu_*(r), \sigma_{l.o.s}^2(r)$**
  - obtained from photometric and spectroscopic observations
  - Systematic errors: Non-sphericity, radial anisotropy, **foreground contamination** (dominant) etc.

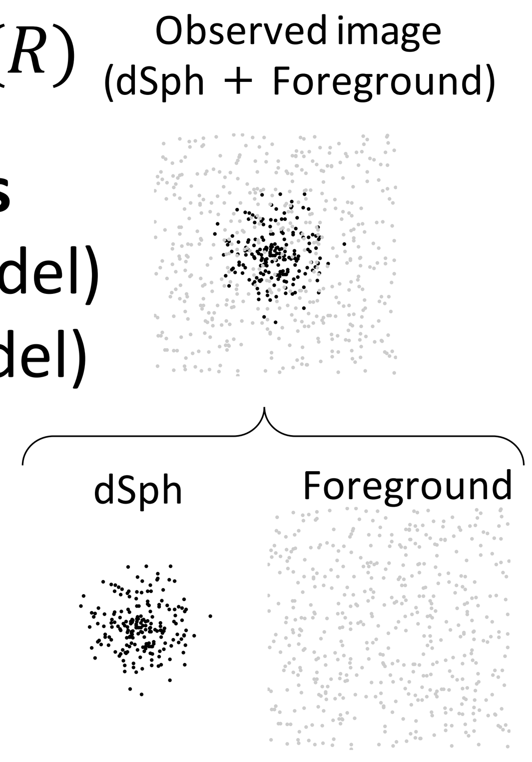


Fig. 1 Foreground contamination

← The Milky way halo stars overlap a target dSph so that the observed image is contaminated (Fig. 1).

→ Careful treatment is required to obtain accurate DM distribution and the conservative sensitivity of the ID.

3. Analysis Method:

- **Naïve cut:** color-magnitude, velocity, surface gravity
- **Likelihood analysis:** with foreground contamination

$$\mathcal{L} = \prod_i (sf_{\rm Mem}(v_i, R_i) + (1-s)f_{\rm FG}(v_i, R_i))$$

where the parameter s is total contamination rate, $f_{\rm Mem/FG}$ denotes the phase-space distribution function of the dSph/foreground stars, defined by Gaussian:

$$f_{\rm Mem}(v, R) = 2\pi R\Sigma_*(R)C_{\rm Mem}\mathcal{G}[v; v_{\rm Mem}, \sigma_{l.o.s}],$$
$$f_{\rm FG}(v, R) = 2\pi RC_{\rm FG}\mathcal{G}[v; v_{\rm FG}, \sigma_{\rm FG}]$$

$v_{\rm FG}, \sigma_{\rm FG}$: determined by the observation of the control region (Fig. 2).

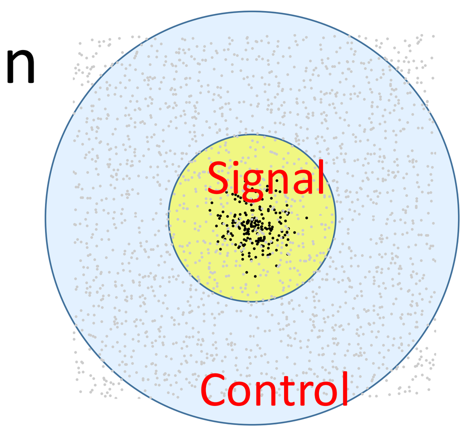


Fig. 2 Control / Signal regions

- **Mock construction**: for demonstration
  - Considering the future observation of **the Prime Focus Spectrograph (PFS)**
  - Create mock data having similar properties to the original dSphs, based on the inversion formula of the distribution:

$$\nu(r), \Phi(r) \xrightarrow{\text{inversion}} f_{\rm Mem}(\mathbf{x}, \mathbf{v}) \rightarrow (\text{mock data})$$

4. Results and Summary:

i. J-factor estimation of ultra-faint dSphs (UFDs) (Fig. 3):

- 100 % contaminated (green), 5 % (orange) and ours (blue)
- Even 5% contamination affected the result to deviated from the input but our method successfully reproduce it

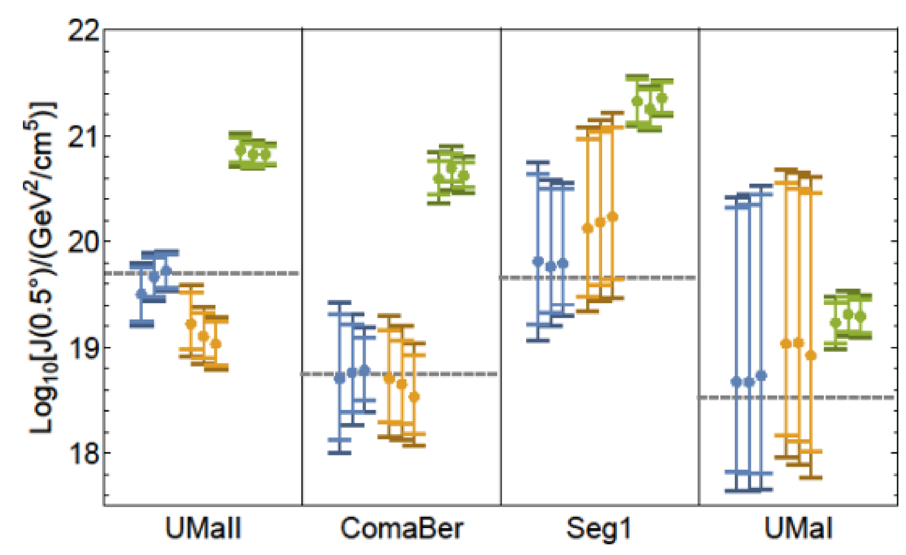


Fig. 3 Estimated J-factor values

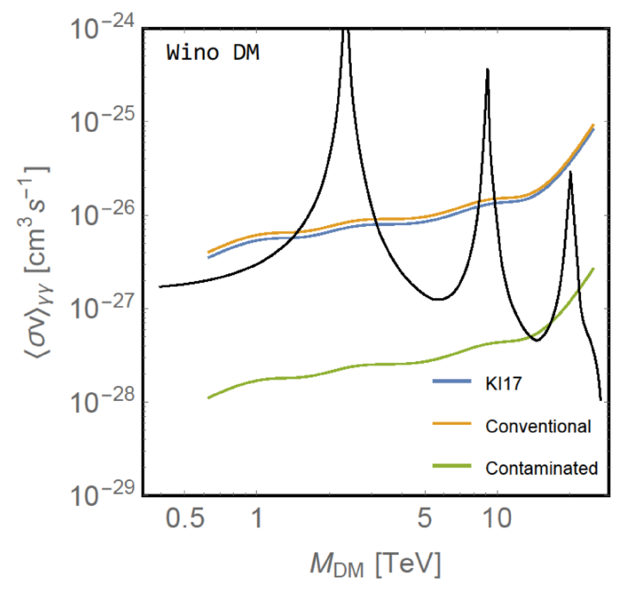


Fig. 4 Sensitivity lines of the Wino DM

ii. Sensitivity lines (Fig. 4)

- Assuming Wino DM (typical mass $M_{\tilde{w}} = 2.9$ TeV)
- 50 hours observation of the four UFDs, utilizing the **Cherenkov Telescope Array (CTA)**
- Over-exclusion in the contaminated case (green)
- Conventional way lead consistent sensitivity to ours, but
- Our result is guaranteed to lead **accurate sensitivity line** (blue)

The ID will be a more reliable method for >TeV DM search.

Future tasks: other errors (anisotropy, non-sphericity…)

(JSPS KAKENHI Grant Number No. 18J21186)

Precise Estimation of an Astrophysical Factor in Dark Matter Indirect Detection

[arXiv:1608.01749], [arXiv:1706.05481]

Shunichi Horigome (Kavli IPMU, The University of Tokyo)
(Collaborate with Koji Ichikawa, Miho N. Ishigaki, Shigeki Matsumoto, Masahiro Ibe, Hajime Sugai, Kohey Hayashi)

Abstract:
- **Indirect detection** is a promising method because of its sensitivity for TeV-range dark matter (e.g. **WIMP**).
- Unfortunately, predicted amount of the signal flux has error because of **uncertainties of DM distribution**.
- For precise estimation, we considered **the contamination of the foreground stars**, **driven by data** in control region.
- Our analysis successfully reproduce the dark matter profile of generated mock stellar data based on the **PFS**.
- Utilizing the results, we reported **the most conservative sensitivity** of future telescopes, such as **CTA**.

1. Introduction – gamma-ray flux from dSph
- Dark Matter (DM)
  - Weakly Interacted Massive Particle (WIMP)
    - attracting candidate, $M_{\mathrm{WIMP}} \sim O(1)$

Detection methods:
- Collider/Direct Detections - <TeV.
- Indirect detection (ID) - utilizing DMDM $\to \gamma\gamma$

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

- Promising target … dwarf spheroidal galaxies (dSphs)
  - DM-dominant, and noise-free

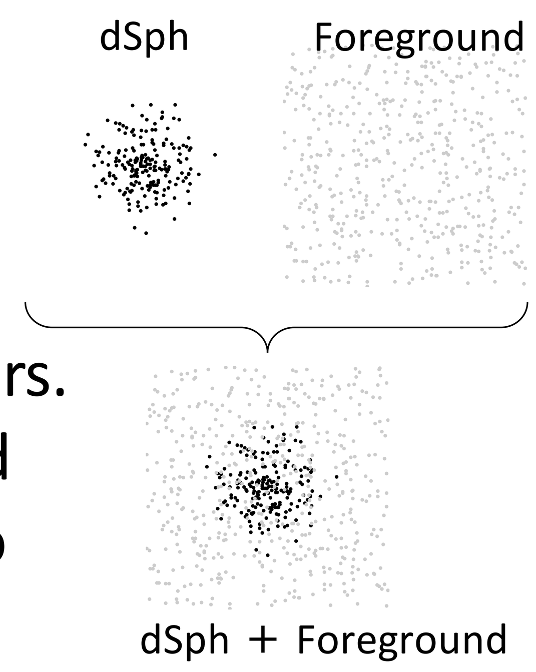
-> DM distribution ρ_{DM} in dSph?

2. The uncertainty of DM distribution
Stellar kinematics … Jeans equation:

$$\frac{1}{\nu_*(r)}\frac{\partial(\nu_*(r)\sigma_r^2(r))}{\partial r} + \frac{2\beta_{\mathrm{ani}}\sigma_r^2(r)}{r} = -\frac{GM(r)}{r^2}$$

$$\to \sigma_r^2(r) = \frac{1}{\nu_*(r)}\int_r^\infty \nu_*(r')\left(\frac{r'}{r}\right)\frac{GM(r')}{r'^2}dr'$$

$\nu_*(r)$ … Plummer model
$M(r) = \int_0^r dr\, 4\pi r^2 \rho_{DM}(r)$ … NFW model (general model)



σ_r^2 is projected to the velocity dispersion along with the line-of-site $\sigma_{l.o.s}^2$, obtained by the spectroscopic observation.
However there are some seeds of its errors. The most dominant one is the foreground contamination, where the Milky way halo stars overlap a target dSph so that the observed image is contaminated by halo stars.

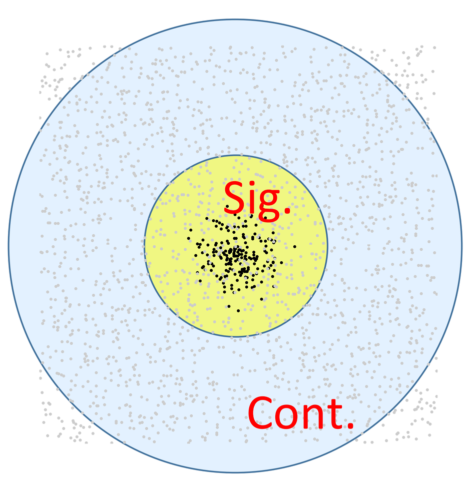
Methods:
We constructed a likelihood function to adopt the foreground contamination:

$$\mathcal{L} = \prod_i (s f_{\mathrm{Mem}}(v_i,R_i) + (1-s) f_{\mathrm{FG}}(v_i,R_i))$$

where s is a total contamination rate and $f_{\mathrm{Mem/FG}}$ denotes the phase-space distribution function of the dSph/foreground stars, defined by

$$f_{\mathrm{Mem}}(v,R) = 2\pi R \Sigma_*(R) C_{\mathrm{Mem}} \mathcal{G}[v; v_{\mathrm{Mem}}, \sigma_{l.o.s}],$$
$$f_{\mathrm{FG}}(v,R) = 2\pi R C_{\mathrm{FG}} \mathcal{G}[v; v_{\mathrm{FG}}, \sigma_{\mathrm{FG}}]$$

Before the likelihood analysis, we imposed naïve cuts (color-magnitude, velocity and surface gravity).
The foreground distribution is estimated by the control region around the signal region.



In order to demonstrate our analysis, we create mock data having similar properties to the original dSph, considering the future observation of the Prime Focus Spectrograph (PFS).

Result: J-factor and sensitivities
Fig. 1 shows the estimated J-factor values.
In the contaminated analysis estimated J-factor values were overestimated.
In contrast our analysis successfully reproduced the source J-factor values.

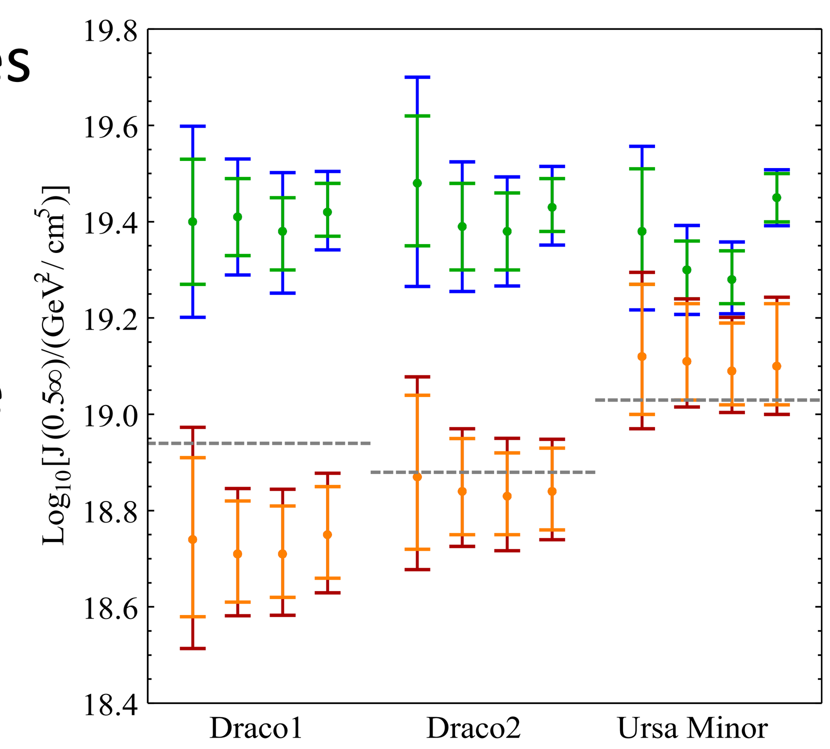
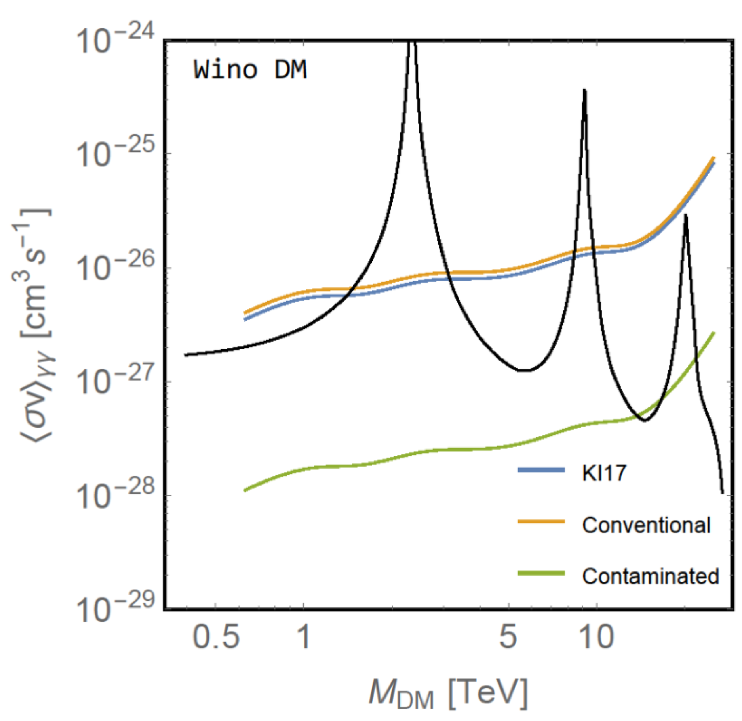


Fig.2 shows the estimated sensitivity lines of future telescopes, CTA. Our result leads more conservative sensitivity than conventional ways. It is important because it avoid too drastic exclusion of the parameter space.



Precise Estimation of an Astrophysical Factor in Dark Matter Indirect Detection

[arXiv:1608.01749], [arXiv:1706.05481]

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Abstract:

- **Indirect detection** is a promising method because of its sensitivity for TeV-range dark matter (e.g. **WIMP**).
- Unfortunately, predicted amount of the signal flux has error because of the **large uncertainty of DM distribution**.
- For precise estimation, we considered **the contamination of the foreground stars**, **driven by data** in control region.
- Our analysis successfully reproduce the dark matter profile of generated mock stellar data based on the PFS.
- Utilizing the results, we reported **the most conservative sensitivity** of future telescopes, such as **CTA**.

1. Introduction – Signal flux

The identification of dark matter (DM) is a important task in particle physics and cosmology. Weakly Interacted Massive Particle (WIMP) is one of the most attracting candidates, who has TeV-scale mass. Unfortunately, present collider experiments and direct detections are hard to reach >TeV. Indirect detection (ID) is another detection method, utilizing the DM annihilation into gamma-ray. The amount of flux is given by

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

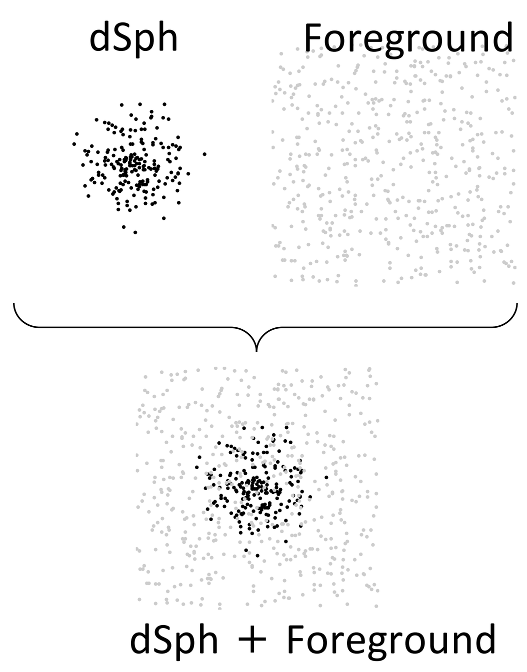
The most promising targets of the ID are dwarf spheroidal galaxies (dSphs), considered to be DM-rich and noise-free objects. Thus we need the information of their DM distribution.

2. The uncertainty of DM distribution

The DM distribution or the gravitational potential of the dSphs can be obtained by inversion of their stellar dynamics, which is ordered by the spherical Jeans equation:

$$\frac{1}{\nu_*(r)}\frac{\partial(\nu_*(r)\sigma_r^2(r))}{\partial r} + \frac{2\beta_{\rm ani}\sigma_r^2(r)}{r} = -\frac{GM(r)}{r^2}$$

where ν_* and $M(r)$ is parameterized by the Plummer model and the NFW model. The velocity dispersion σ_r^2 is obtained by the spectroscopic observation, PFS for example. However there are some seeds of its errors. The most dominant one is the foreground contamination, where the Milky way halo stars overlap a target dSph so that the observed image is contaminated by halo stars.



Methods:

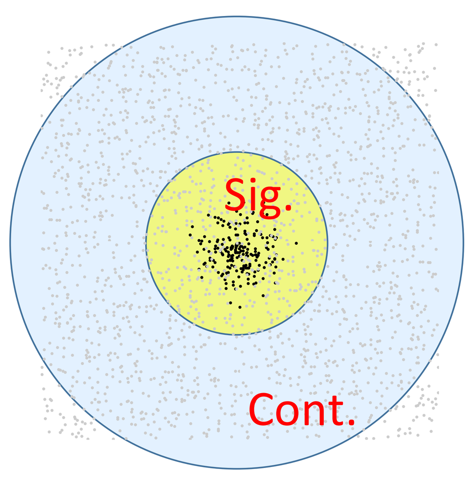
We constructed a likelihood function to adopt the foreground contamination:

$$\mathcal{L} = \prod_i (s f_{\rm Mem}(v_i,R_i) + (1-s) f_{\rm FG}(v_i,R_i))$$

where s is a total contamination rate and $f_{\rm Mem/FG}$ denotes the phase-space distribution function of the dSph/foreground stars, defined by

$$f_{\rm Mem}(v,R) = 2\pi R \Sigma_*(R) C_{\rm Mem} \mathcal{G}[v; v_{\rm Mem}, \sigma_{l.o.s}],$$
$$f_{\rm FG}(v,R) = 2\pi R C_{\rm FG} \mathcal{G}[v; v_{\rm FG}, \sigma_{\rm FG}]$$

Before the likelihood analysis, we imposed naïve cuts (color-magnitude, velocity and surface gravity). The foreground distribution is estimated by the control region around the signal region.



In order to demonstrate our analysis, we create mock data having similar properties to the original dSph.

Result:

J-factor estimation (Fig. 1)

- Contamination leaded the over estimation (green)
- Our analysis successfully reproduced the input (orange)

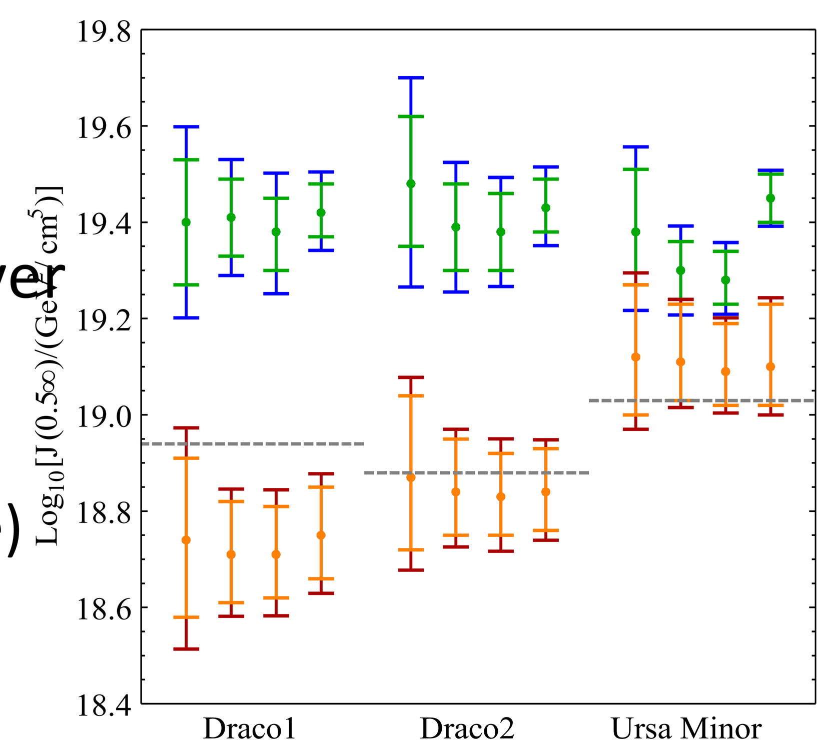


Fig.1 Estimated J-factor values

Sensitivity (Fig. 2)

- Wino DM case
- 50 hours observation of four ultra-faint dSphs utilizing Cherenkov Telescope Array (CTA)
- Too aggressive sensitivity (green)
- Our result leaded the most conservative sensitivity (blue)

-> avoid over exclusion

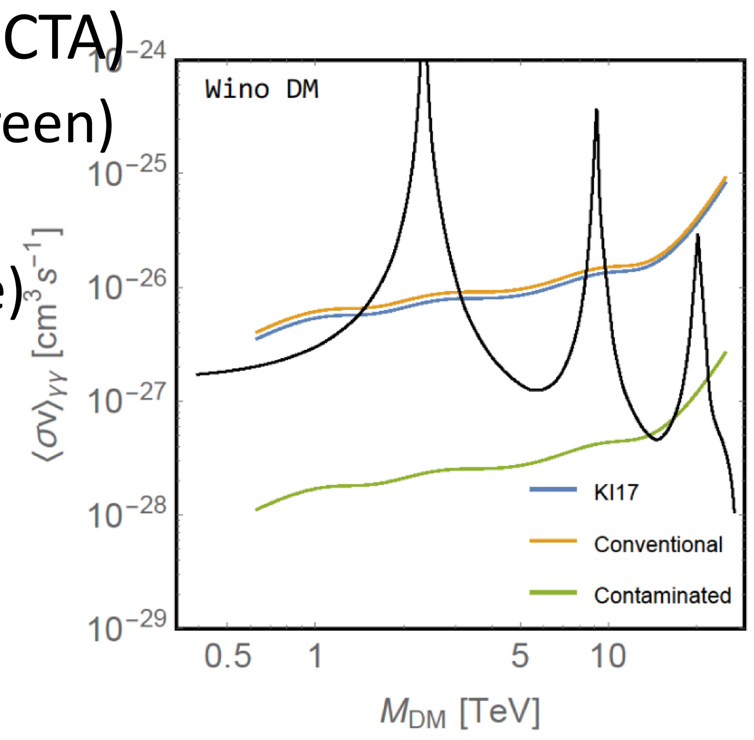


Fig.2 Sensitivity lines of the Wino DM

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Abstruct:

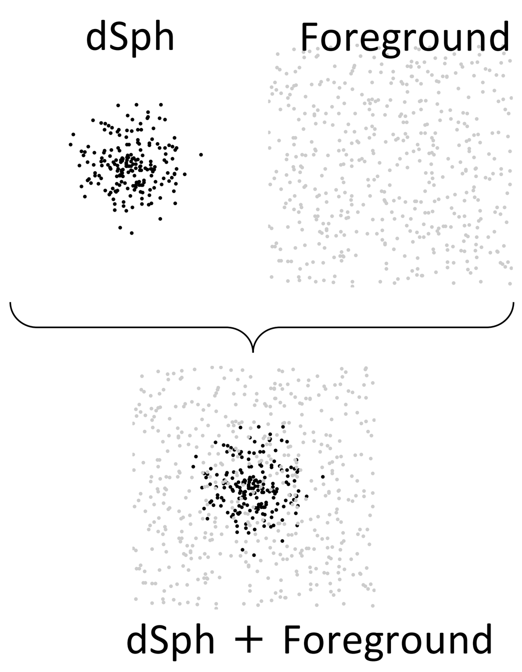
- Indirect detection is one of the useful methods to find dark matter (DM), where we detect gamma-ray flux coming from an astrophysical object.
- However, predicted amount of the flux has significant error because of the large uncertainty of DM distribution.
- For precise estimation, we considered contamination of the foreground stars.
- Our analysis successfully reproduce the dark matter profile of generated mock stellar data based on the PFS.
- We also estimate the detection sensitivity utilizing future telescopes, such as CTA.

J-factor estimation

We could determine the J-factor by inversely solving the kinematics of dSph member stars. The kinematics is ordered by the Jeans equation:

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

whose velocity distribution can be observed by the spectroscopic observation, utilizing PFS for example. However there are some seeds of its errors. The most dominant one is the foreground contamination, where the Milky way halo overlap a target dSph so that the observed image is contaminated by halo stars.



Methods:

We constructed a stellar distribution model to adopt this effect:

$$\mathcal{L}=\prod_i (s f_{\rm Mem}(v_i,R_i)+(1-s)f_{\rm FG}(v_i,R_i))$$

where f_men/FG denotes the phase-space distribution function of the dSph/foreground stars and parameter S is the fraction of total member star.

In order to demonstrate our analysis, we create mock data having similar properties to the original dSph.

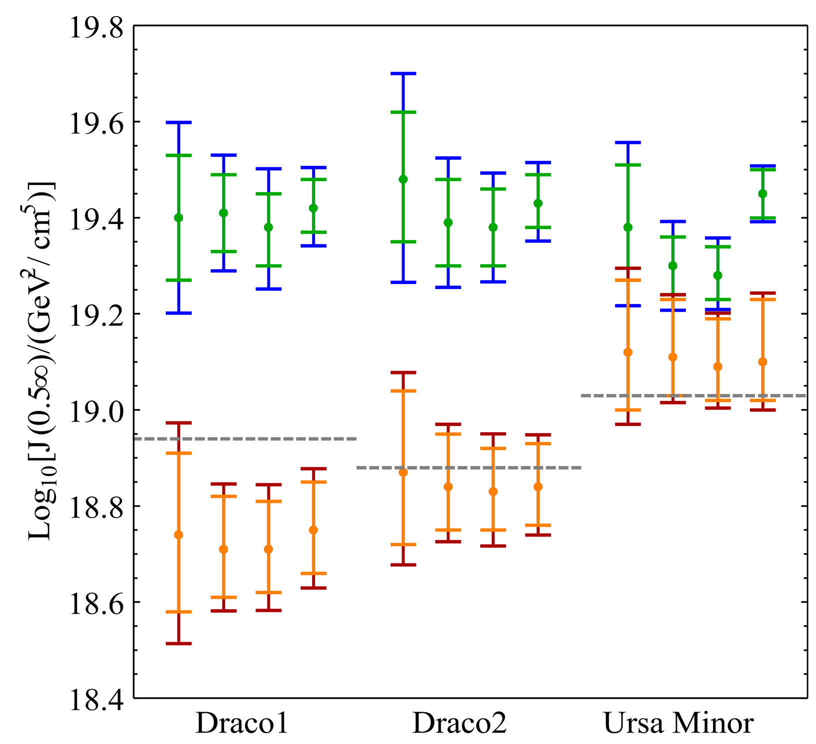
1. Introduction

DM search is one of the most important topics to research the BSM. Unfortunately, collider experiments and direct detections have not reported the significant DM signal. Indirect detection is another DM detection method, where we aim to detect the gamma-ray signal yielded by the annihilation of the DM. The amount of the flux is calculated by:

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

Dwarf spheroidal galaxies (dSphs), which considered to be DM rich objects, are promising targets.

Result (restriction)



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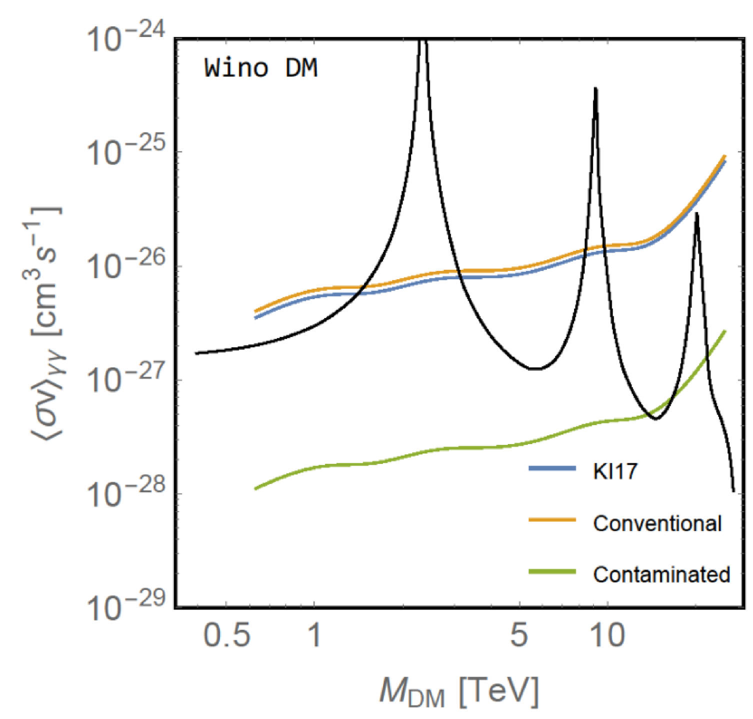

Conclusion

Precise Estimation of Dark Matter Distribution in dwarf spheroidal galaxies for Indirect Detection

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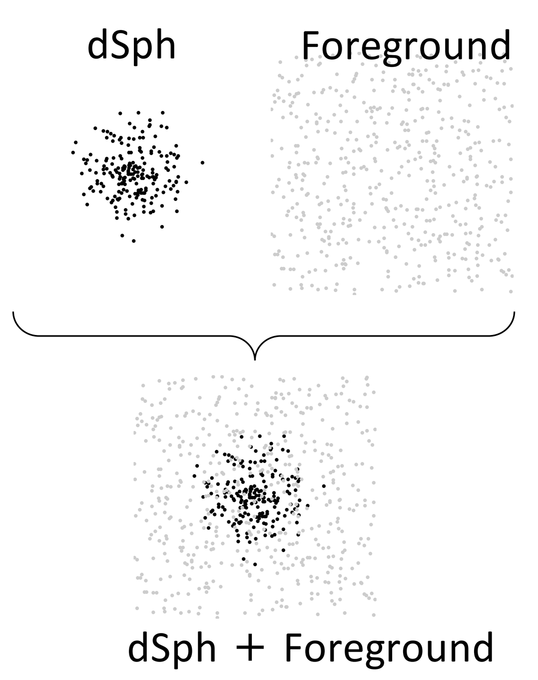
Abstruct:
Indirect detection is one of the useful methods to find dark matter (DM), where we detect gamma-ray flux coming from an astrophysical object. However, predicted amount of the flux has significant error because of the large uncertainty of DM distribution. For precise estimation, we took into account contamination of the foreground stars. Our analysis successfully reproduce the dark matter profile of generated mock stellar data based on the PFS. We also estimate the detection sensitivity utilizing future telescopes, such as CTA.

J-factor estimation
We could determine the J-factor by inversely solving the kinematics of dSph member stars, whose velocity distribution can be observed by the spectroscopic observation, utilizing PFS for example. However there are some seeds of its errors. The most dominant one is the foreground contamination, where the Milky way halo overlap a target dSph so that the observed image is contaminated by halo stars.



1. Introduction
DM search is one of the most important topics to research the BSM. Unfortunately, collider experiments and direct detections have not reported the significant DM signal. Indirect detection is another DM detection method, where we aim to detect the gamma-ray signal yielded by the annihilation of the DM. The amount of the flux is calculated by:

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

Dwarf spheroidal galaxies (dSphs), which considered to be DM rich objects, are promising targets.

$$\mathcal{L} = \prod_i \left(s f_{\rm Mem}(v_i,R_i) + (1-s) f_{\rm FG}(v_i,R_i)\right)$$

Statistical
We constructed a stellar distribution model to adopt this effect:

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Result (restriction)

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Conclusion