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

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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)** … $\mathrm{DM\ DM} \to \gamma\gamma,\ E \gtrsim$ TeV !

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

- **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).

  Observables of stellar distribution:

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

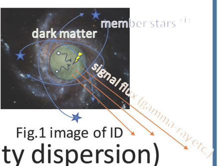

Fig.1 image of ID

- **Stellar kinematics … Jeans equation**:

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

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

  $M(r)$: 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.

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

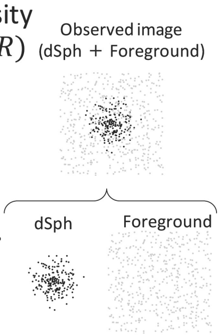

Fig. 2 Foreground contamination

→ 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:

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

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

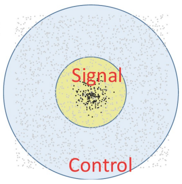

Fig. 3 Control / Signal regions

- **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:

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

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

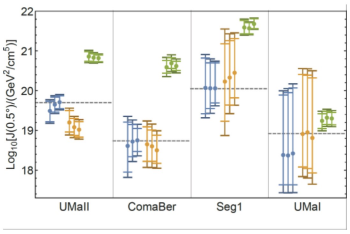

Fig. 4 Demonstration of J-factor estiamtion
(- - - : input)

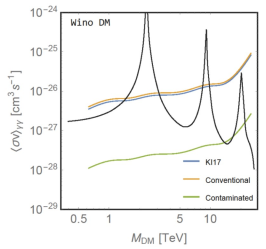

Fig. 5 Sensitivity lines of the Wino DM

ii. Sensitivity lines (Fig. 5)

- Considering Wino DM (typical mass $M_{\widetilde{w}} = 2.9\ \mathrm{TeV}$) 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

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