arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

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

Shunichi Horigome, Kavli IPMU

(Collaboration with Koji Ichikawa, Miho Ishigaki, Shigeki Matsumoto, Masahiro Ibe, Hajime Sugai and Kohei Hayashi)

JSPS: 18J21186

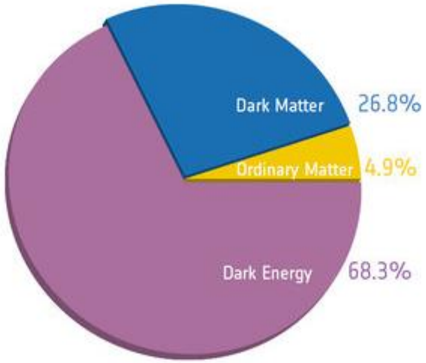
Contents

- Indirect detection of WIMP dark matter
- J-factor estimation of dSphs
- Uncertainty of J-factor: foreground effect

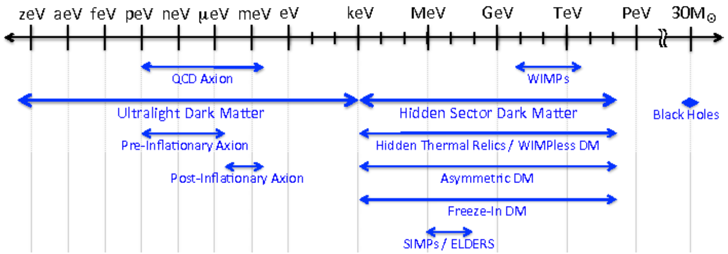
- Member/Foreground mixture model
  - Flowchart
  - Likelihoods & Models
  - Results: J-factor of Draco, Sculptor, and Ursa Minor dSphs
- Summary

Indirect detection of WIMP dark matter

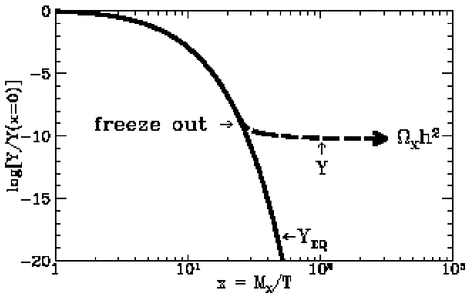
- Dark matter (DM)
  - $\Omega_{DM} = 0.258$ (Planck 2015)



- What is the DM?
  - PBH
  - Axion
  - Sterile neutrino

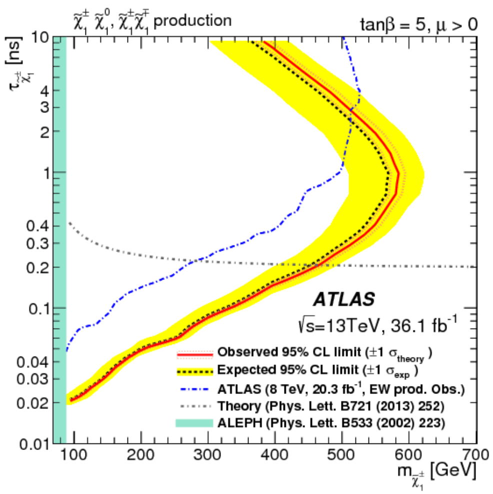


  - **WIMP (Weakly Interacting Massive Particle)**
    - colorless, neutral
    - Ω_{DM} naturally achieved by the *freeze out* mechanism
    - **Some BSM predict WIMP DM**
      - e.g. wino with its mass M_{wino} ~ TeV (SUSY)

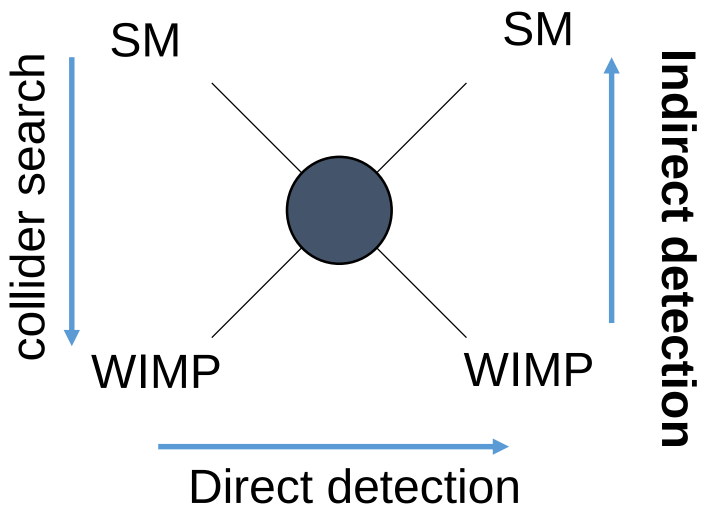


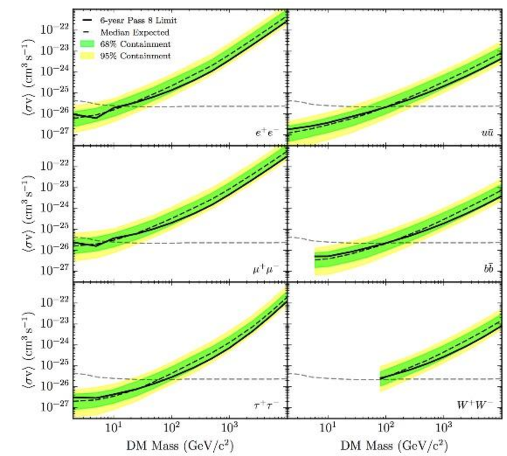
Indirect detection of WIMP dark matter

- How to detect WIMP

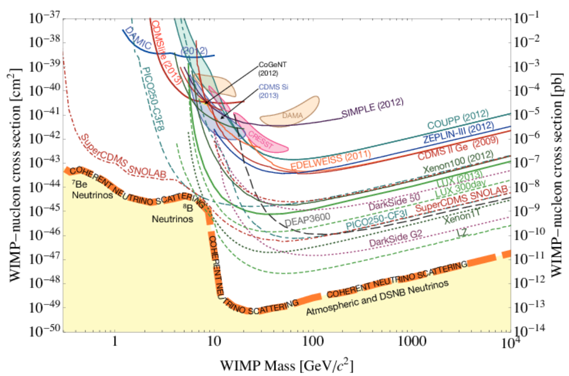


arXiv:[1712.02118]





arXiv:[1310.0828]
Sensitivity line of Fermi-LAT



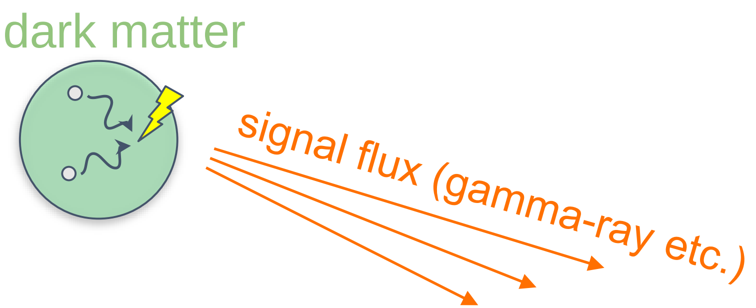
arXiv:[1410.4960]

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**":

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

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

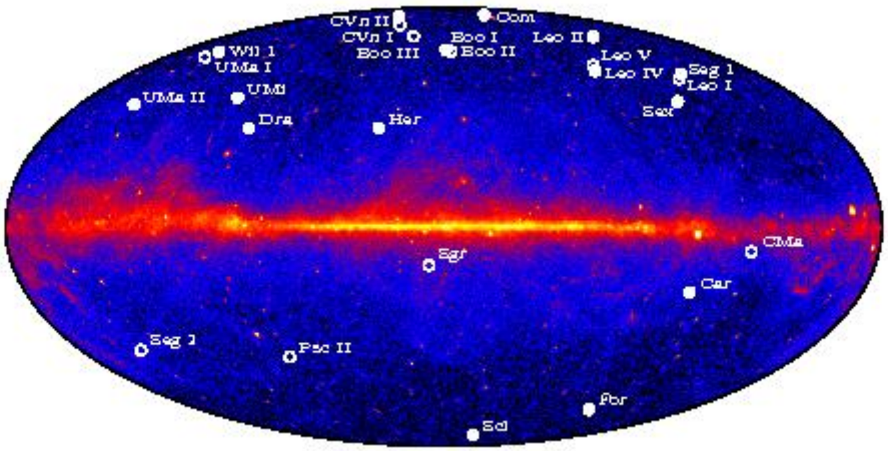


…Which astrophysical object has a large *J*-factor?

J-factor estimation of dSphs

arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

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



Two class of dSph:

- Classical dSph
  - Discovered before 2005
  - Bright
- Ultrafaint dSph
  - Discovered after 2005
  - Faint

Many dSphs (about 20 or 30) have been observed.

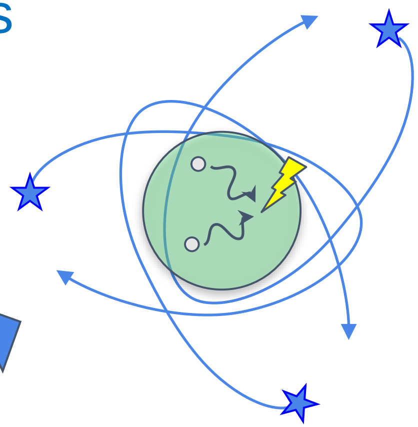
Some of them are reported to have large J-factors.

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

arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

J-factor estimation of dSphs

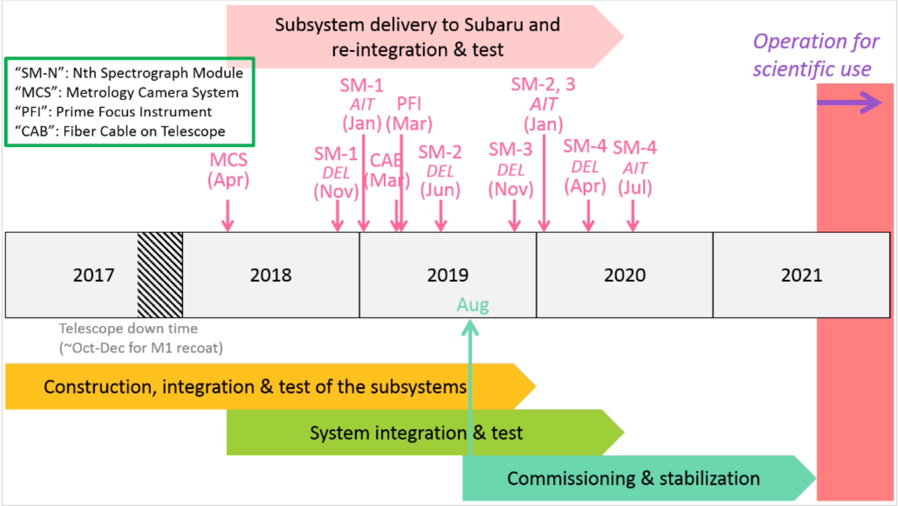
- The J-factor of a dSph is estimated by observing the velocity dispersion curve of dSph member stars by spectroscopic telescopes.



  - 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



arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

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 $\beta(r)=\text{const.}$ 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.

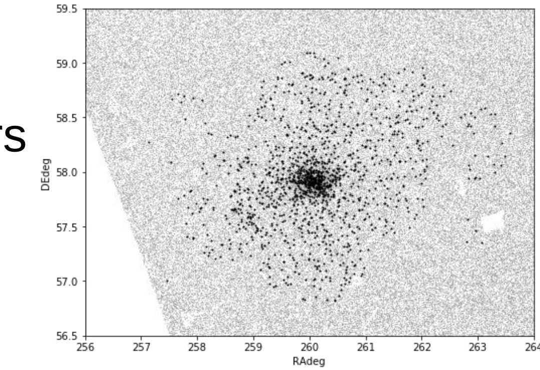
In particular, **FG contamination** is important even for future observations yielding a large amount of stellar velocity data.

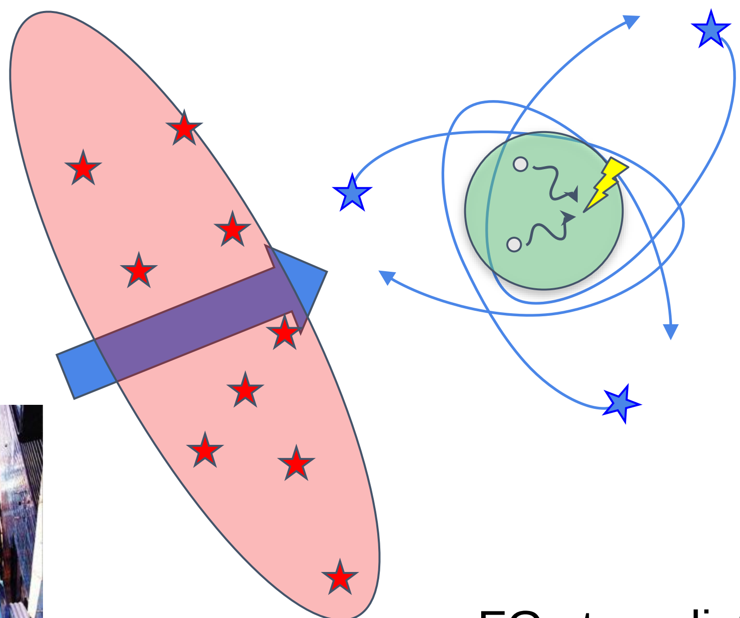
So, what is the **FG contamination**?

arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

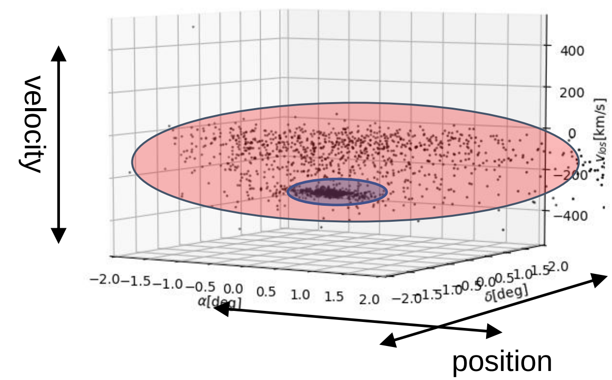
Uncertainty of J-factor: foreground effect

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





★ or ★ ???



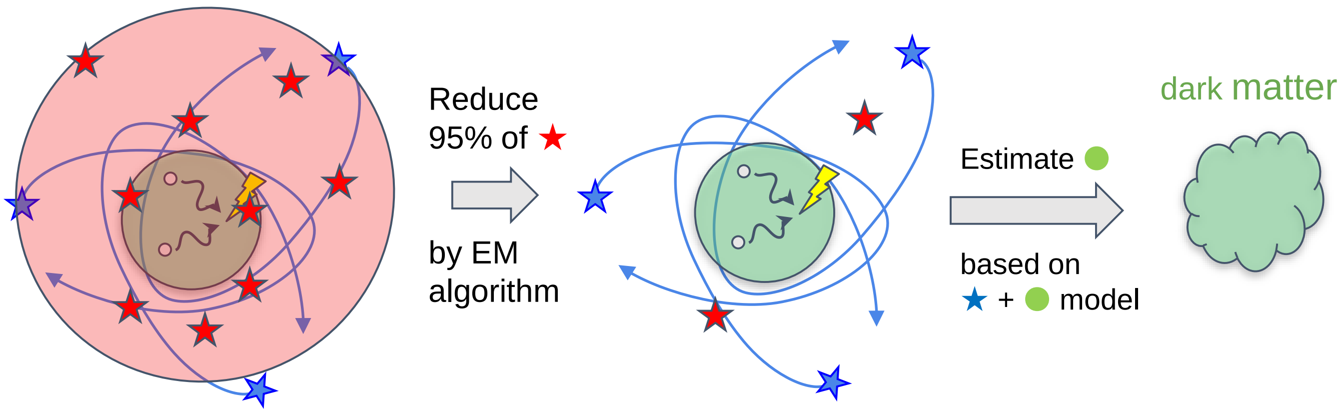
- FG stars distort the velocity dispersion curve → biased *J*-factors

arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

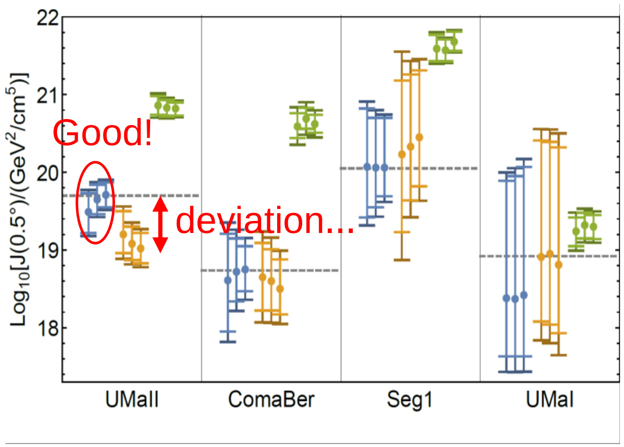
Uncertainty of J-factor: foreground effect

- 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
- However, our mixture model works well!!



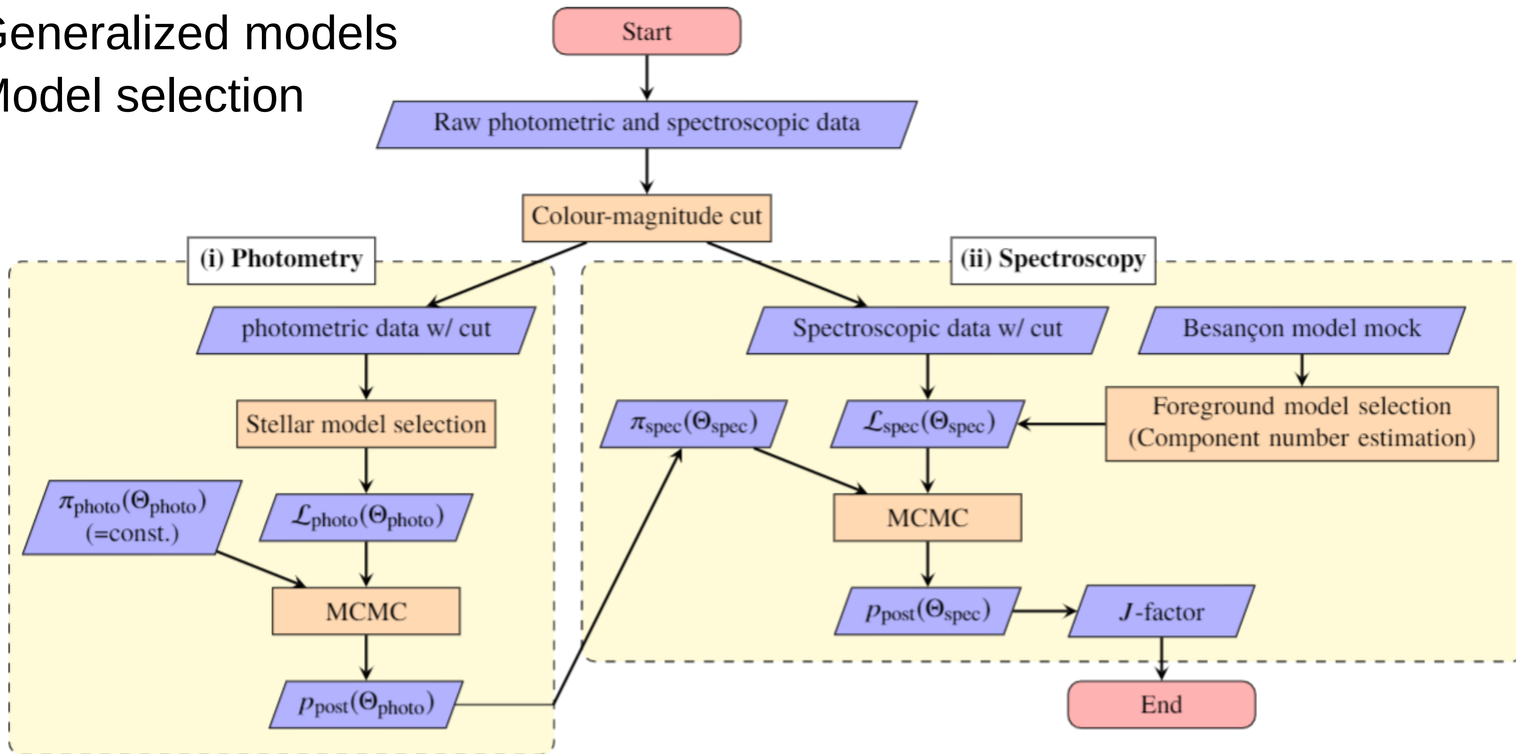
arXiv: [1709.05481]

Our Analysis:
Member/Foreground model

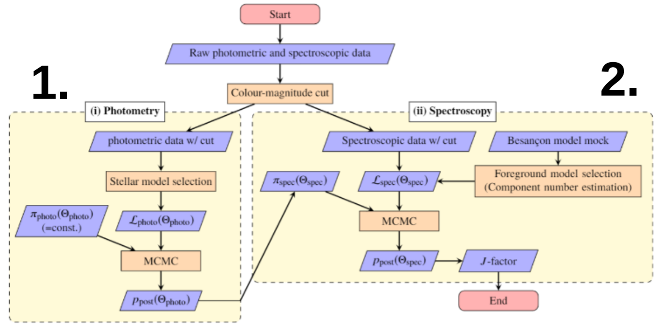
arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

Our Analysis: Member/Foreground model

- **Feature:**
  - Using photometric and spectroscopic data
  - Separated into two parts
  - Generalized models
  - Model selection



Our Analysis: Member/Foreground model



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

1. Photometric part

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

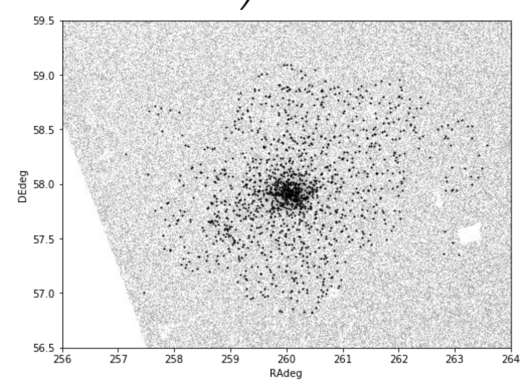
- Σ : stellar number density
- s: total contamination rate
- Θ_{photo}: parameters (local contamination rate & half-light-radius)

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

2. Spectroscopic part

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

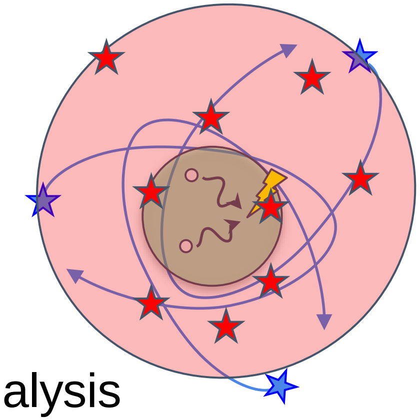
- $\mathcal{G}$: Gaussian function:



- 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 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 ($\gamma > 0$))

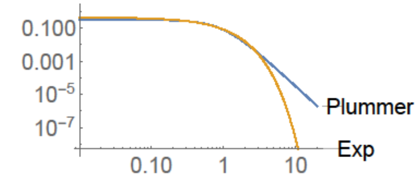
  - **Stellar profile**: Plummer or exponential profile & Jeans analysis

Jeans analysis and line-of-sight projection,

$$\sigma_r^2(r) = \frac{1}{\nu_*(r)}\int_r^\infty {\rm d}r'\,\nu_*(r')\left(\frac{r'}{r}\right)^{2\beta_{\rm ani}}\frac{GM(r')}{r'^2}$$

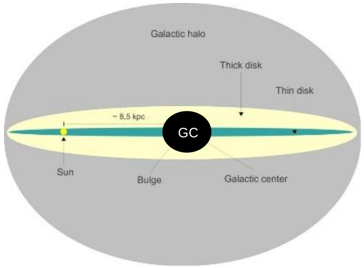
$$\sigma_{l.o.s}^2(R) = \frac{2}{\Sigma_*(R)}\int_R^\infty \frac{{\rm d}r}{\sqrt{1-R^2/r^2}}\left(1-\beta_{\rm ani}\frac{R^2}{r^2}\right)\nu_*(r)\sigma_r^2(r)$$

$\nu_*(r)$, $\Sigma_*(R)$: number density (3D, 2D)



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

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



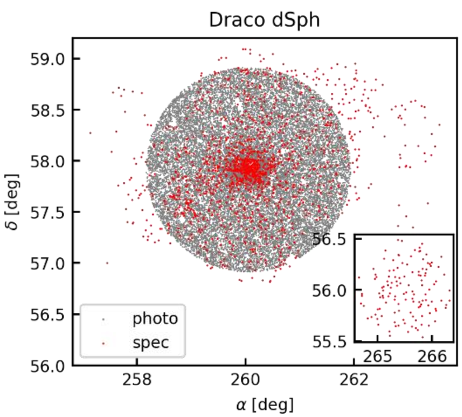
We select suitable models based on their Bayes factor.

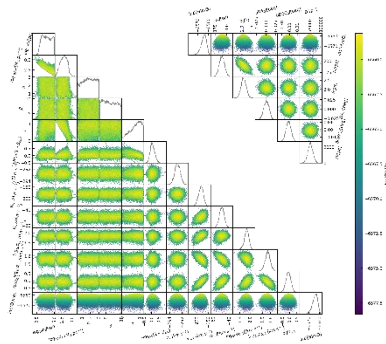
arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

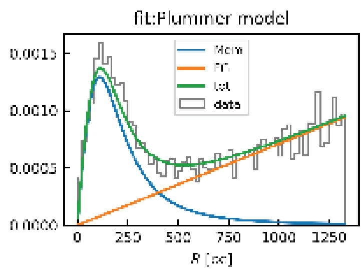
Our Analysis: Member/Foreground model

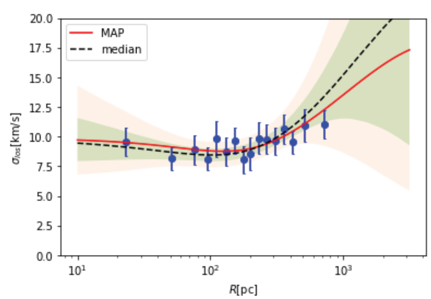
- **Results: J-factor of Draco, Sculptor, and Ursa Minor dSphs (preliminary,** arXiv:1911:XXXX…)
  - Estimate the J-factors of hopeful dSphs: Draco, Sculptor, Ursa Minor
  - Data set: photometry & spectroscopy
    - Draco: SDSS & MMT/Hectochelle
    - Sculptor: DES & MMFS
    - Ursa Minor: Pan-STARRS & MMT/Hectochelle

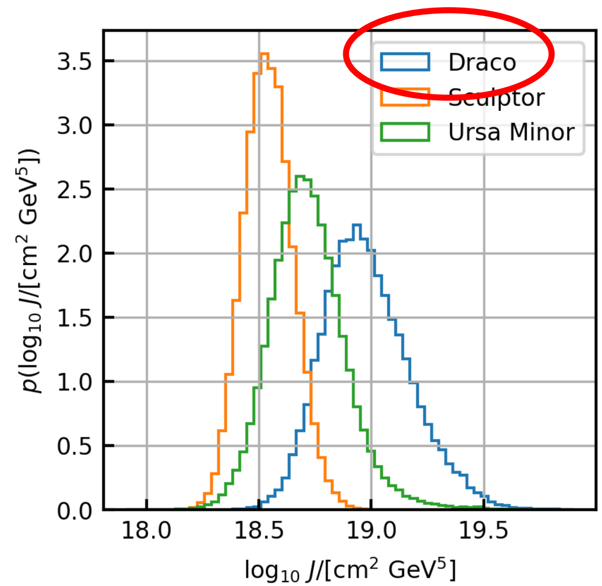
e.g. the Draco dSph











arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

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.

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

감사 합나다 !

JSPS: 18J21186

Back Up

JSPS: 18J21186

Model selection

- We select suitable models (Plummer or exp., how many 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($\mathcal{E}$)

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

$\widehat{\Theta}$: Maximum likelihood

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

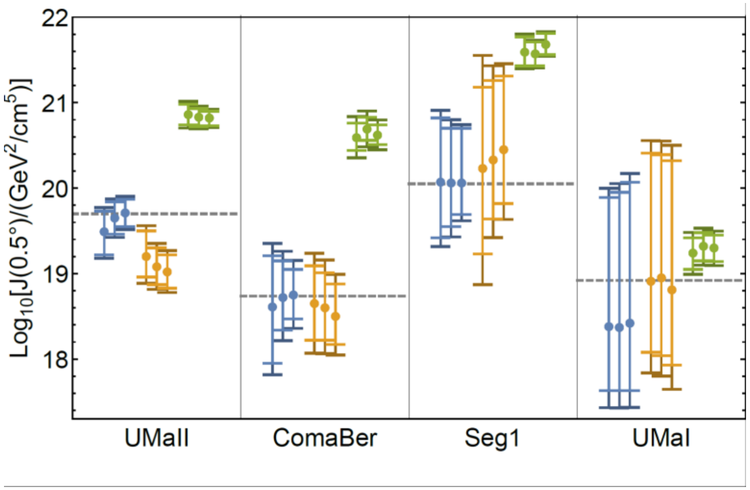
$$\mathrm{WBIC} = \frac{\int d\Theta \ln(\mathcal{L}(\Theta))\, \mathcal{L}(\Theta)^{\beta}\pi(\Theta)}{\int d\Theta\, \mathcal{L}(\Theta)^{\beta}\pi(\Theta)}$$

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

  - 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 statistical evidence

Our Analysis: Member/Foreground model

- **Demonstration**
  - We create mock observational data of the Prime Focus Spectrograph and verify that our analysis works well (arXiv: [1608.01749] & [1709.05481])



i-band magnitude = 21.0, 21.5, 22.0

Blue: ours (Member/FG model)
Orange: 95% filtering (5% contaminated)
Green: no filtering (100% contaminated)
▪ : median I : 68% quantile
- - - - : *True* value (input of mock)

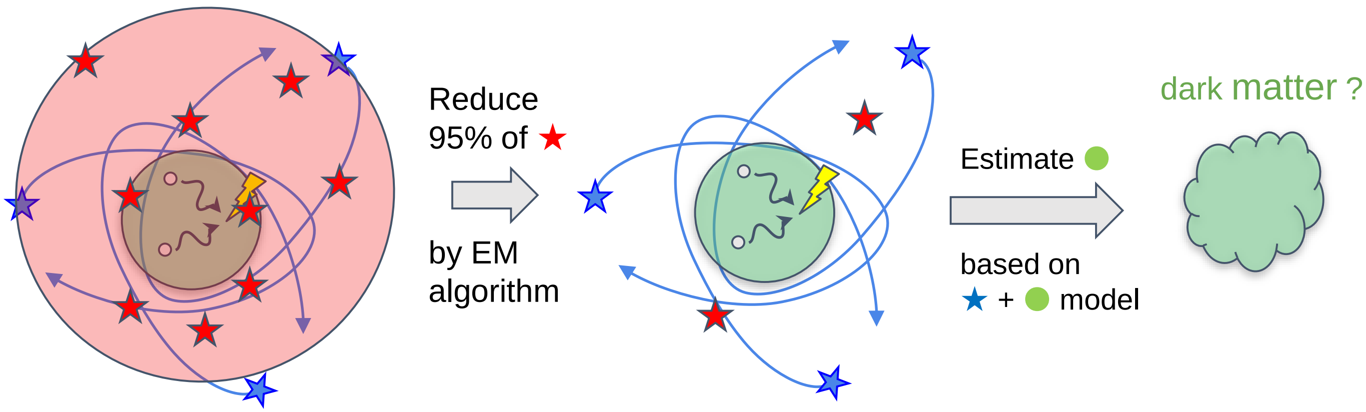
- Filtering procedure (5% contaminated):
  - UMaII-like dSph: estimated J-factor deviates from the true value (~1σ)
  - Median of Estimated J-factor does not converged into the true value even for the larger (deeper) spectroscopic data set
- Our analysis: works well **for all dSphs**

arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

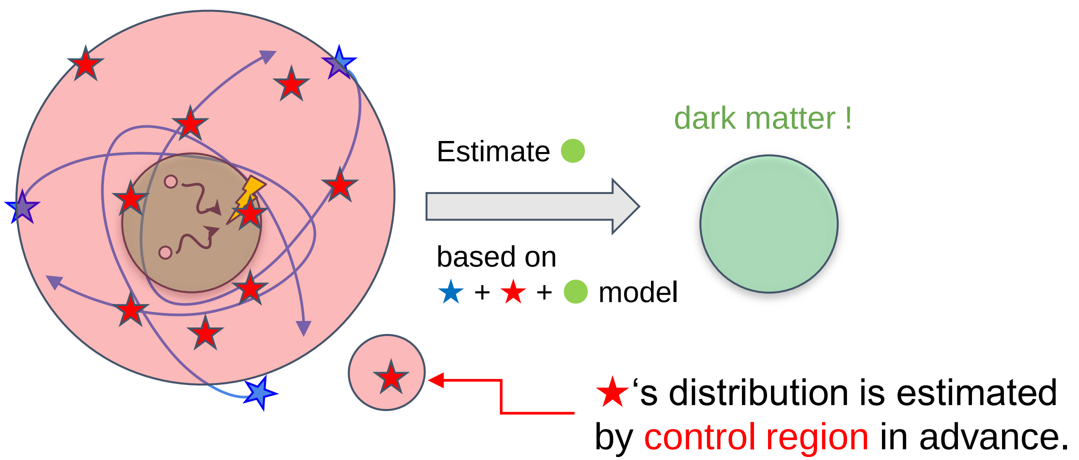
Our Analysis: Member/Foreground model

- **Overview:** Conventional vs. Ours

Conventional method
Walker et al. (2009)



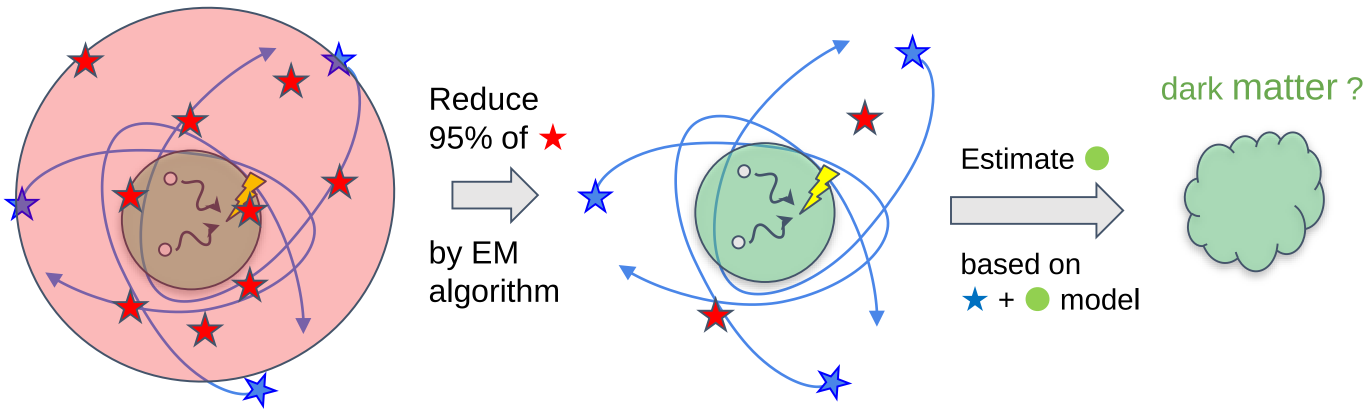
Kl17 (Mem/FG)
Ichikawa et. al. (2017)



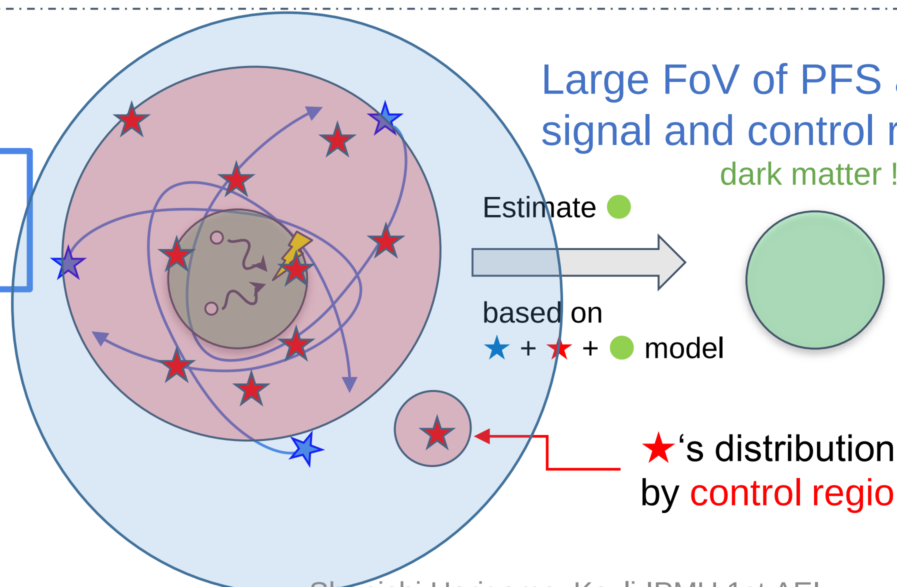
Our Analysis: Member/Foreground model

- **Overview:** Conventional vs. Ours

Conventional method
Walker et al. (2009)



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

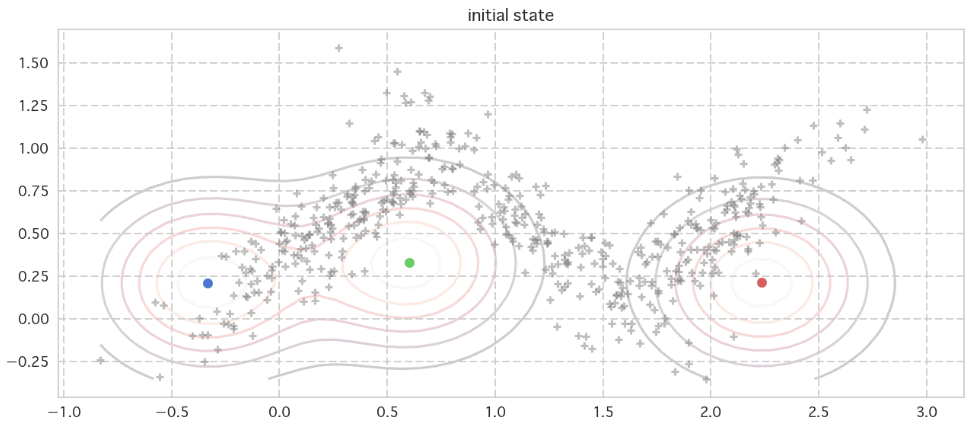


Large FoV of PFS allows us to observe the signal and control regions simultaneously

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

Expectation-Maximization algorithm

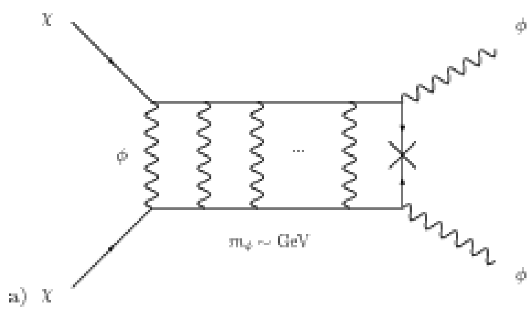
- One of the methods to find maximum of likelihood function with unknown latent observables; membership
- Assumption: “Each observed star belongs to either member or FG.”
- EM algorithm can find the maximum of likelihood and probability density functions of the latent observables (membership probability) at the same time.

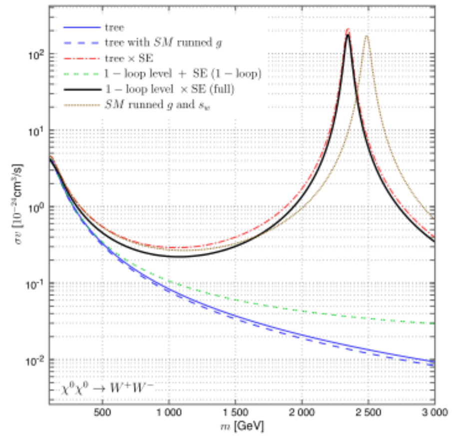


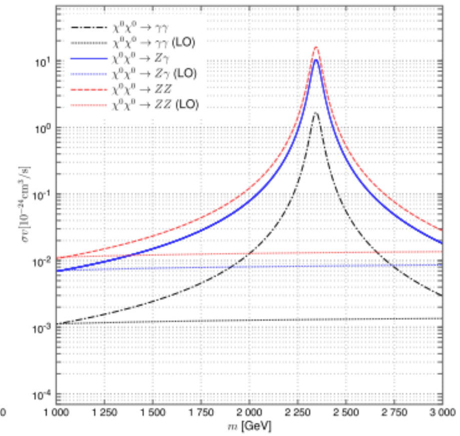
e.g. Fitting of 2D three Gaussian distribution

Sommerfeld effect

- Thermally averaged cross section $\langle\sigma v\rangle$ can be enhanced thanks to the **Sommerfeld effect:**
  - non-perturbative effect of nonrelativistic scattering of heavy particles
  - Light particles behave like a long-range force







$\sigma_{los}(R)$ from $M(r)$

- Solve Jeans equation:

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

$$\rightarrow \nu_*(r)\sigma_r^2(r)=\int_r^\infty {\rm d}r'\,\nu_*(r')\left(\frac{r'}{r}\right)^{2\beta_{\rm ani}}\frac{GM(r')}{r'^2}$$

- Line-of-sight projection:

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

$$\beta_{\rm ani}=1-\frac{\sigma_\theta^2+\sigma_\phi^2}{2\sigma_r^2}$$

arXiv:1608.01749
arXiv:1706.05481
arXiv:1911:XXXX

Detectors

- Gamma-ray telescopes:
  - Fermi-LAT
  - HESS
  - VERITAS
  - MAGIC
  - …
- Cosmic ray observatory:
    - AMS-02
    - PAMERA
    - …

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