arXiv:1608.01749
arXiv:1706.05481
arXiv:2002.04866

J-factor estimation of dwarf spheroidal galaxies with the member/foreground mixture model

Shunichi Horigome (Kavli IPMU)

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

Summary

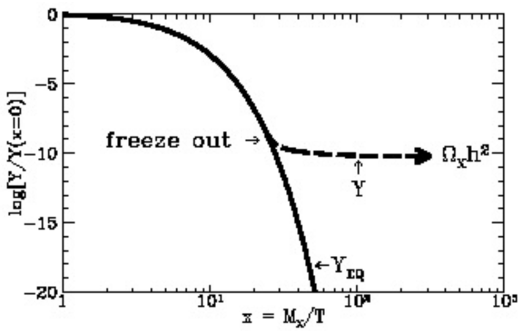
- **Dwarf spheroidal galaxies (dSphs)** are promising targets of **indirect detection** of dark matter (DM)
- The sensitivity of the detection depends on the DM distribution in dSphs (**J-factor**), but it suffers from some **astrophysical uncertainties**
- Some astrophysical uncertainties (**FG contamination** problem and Sampling bias) are solved by our method using new likelihood functions
- Our method can work well for mock dSph data sets (demonstration) and we calculated the J-factor values of some dSphs (application)
- Our J-factor values are consistent with conventional ones but slightly different because of the contamination effect
- Future work: UFD cases, other uncertainties (axisymmetry, anisotropy, …)

Contents

Indirect detection and “J-factor”

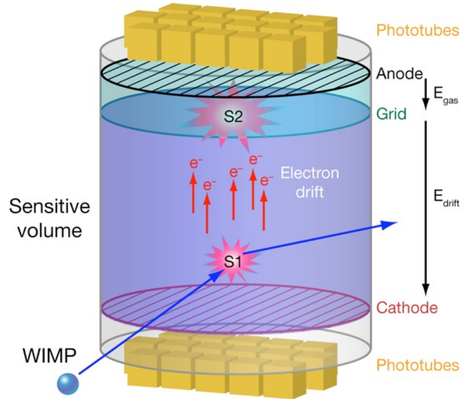
- Dark matter $\Omega_{\rm DM} = 0.258$ Planck (2015)
  - PBH?
  - Axion?
  - sterile neutrino?

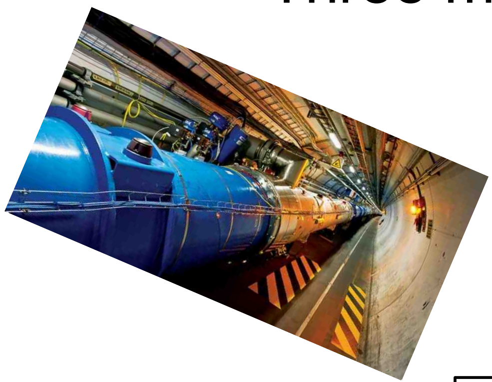
    …
  - WIMP?
    - (Weakly Interacting Massive Particle)
      - colorless, neutral
      - $M_{\rm WIMP} \simeq$ 10 GeV – 1 TeV

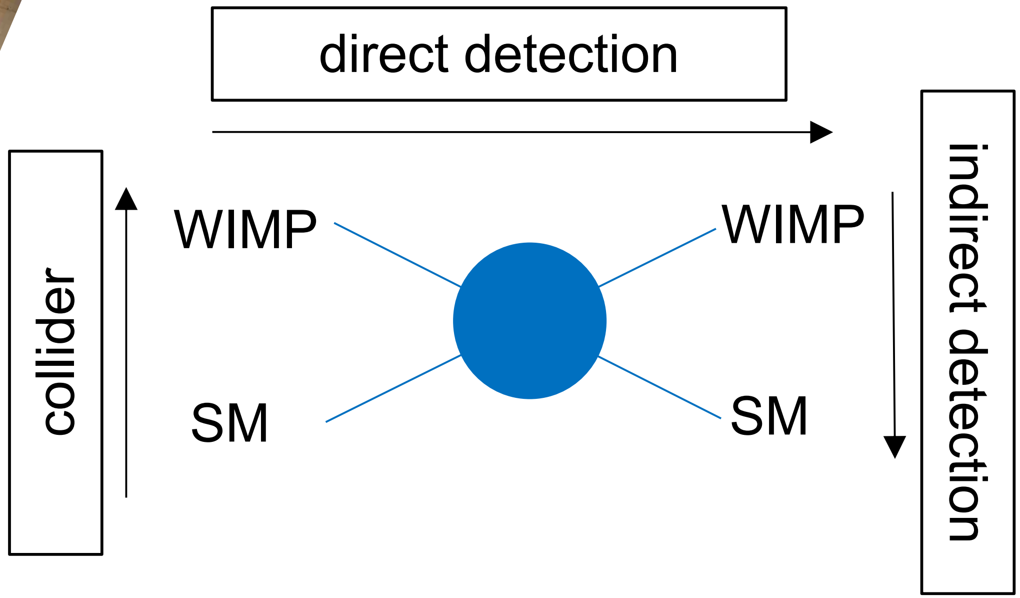


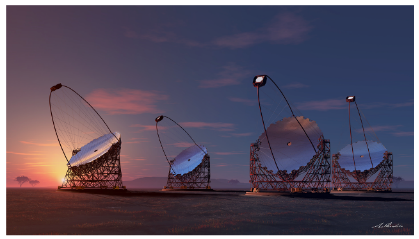
Indirect detection and “J-factor”

- How to detect WIMP
  - Three methods:



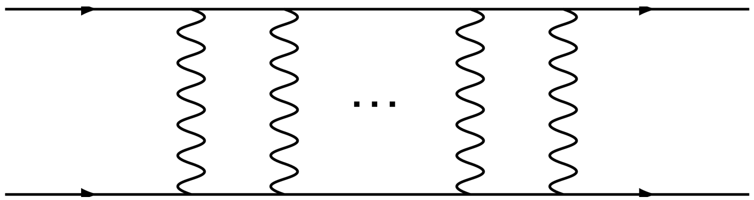


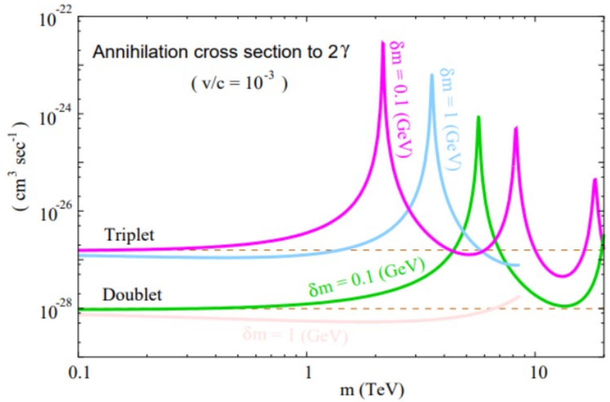




Indirect detection and "J-factor"

- Motivation of the indirect detection
  - EWIMP (Electoweakly Interacting Massive partivle)
    - Suggested by new physics models (SUSY, MDM, …)
    - Large annihilation cross section thanks to non-perturbative quantum effect of non-relativistic scattering (Sommerfeld effect)
    - The large cross section is useful for the indirect detection

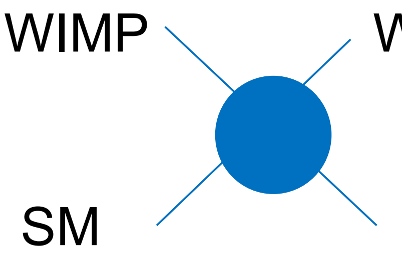


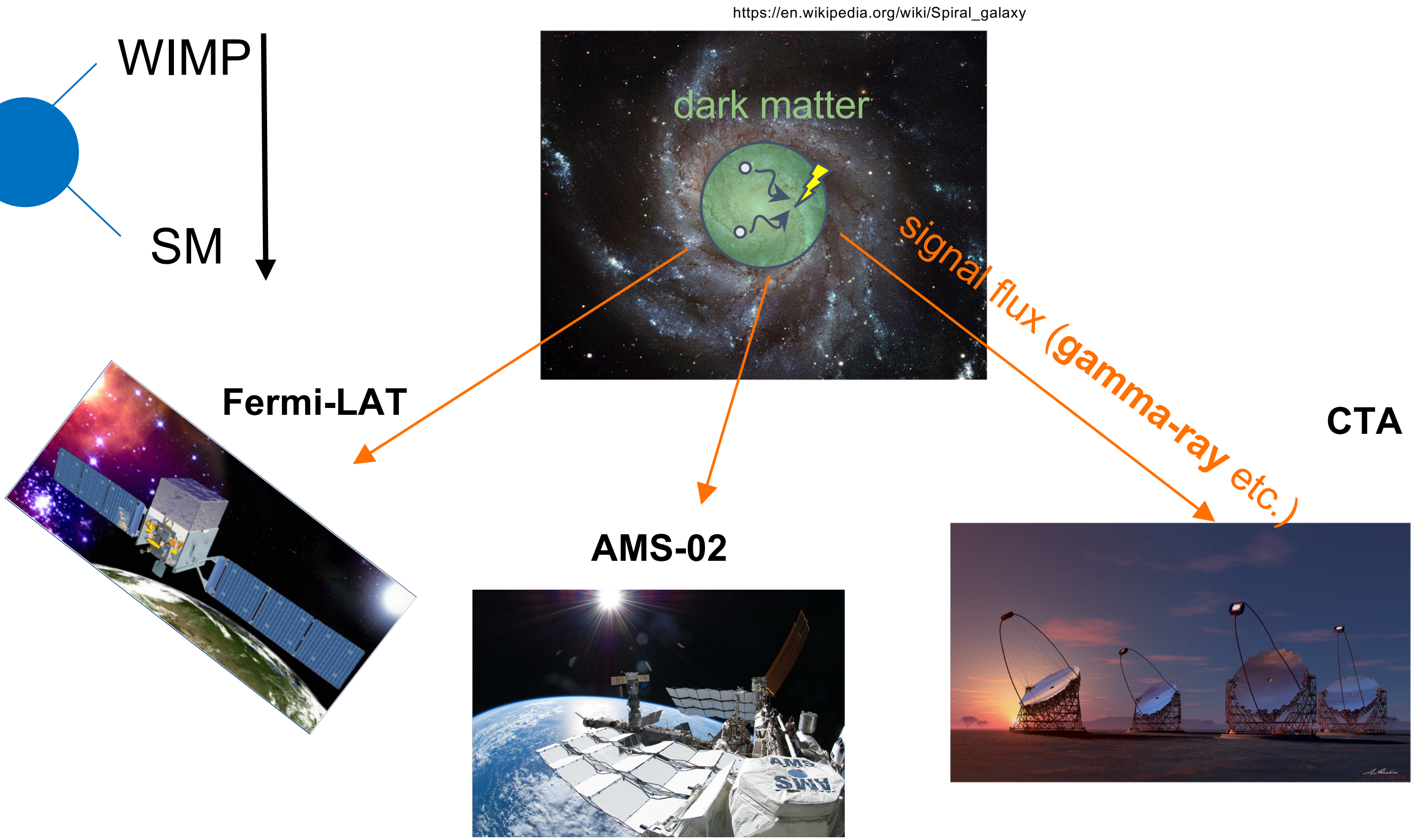


Hisano et.al. (2003)

Indirect detection and “J-factor”

- Indirect detection





Indirect detection and "J-factor"

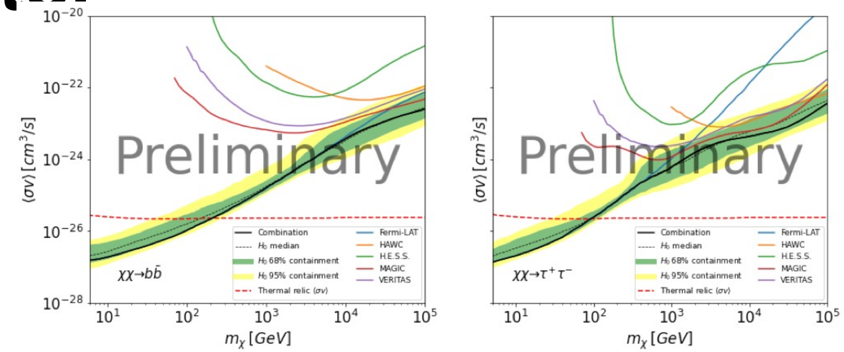
- Targets
  - Cluster of Galaxies (CG)
    - D ~ O(10) Mpc,
    - $M_{\rm cl} \sim 10^{14}\ {\rm M}_\odot$
  - Galactic Center (GC)
    - D ~ O(10) kpc
    - $M_{\rm gal} \sim 10^{12}\ {\rm M}_\odot$
  - Dwarf Spheroidal galaxy (dSph)
    - D ~ O(10) kpc
    - $M_{\rm dSph} \sim 10^{7}\ {\rm M}_\odot$
  - …

GC

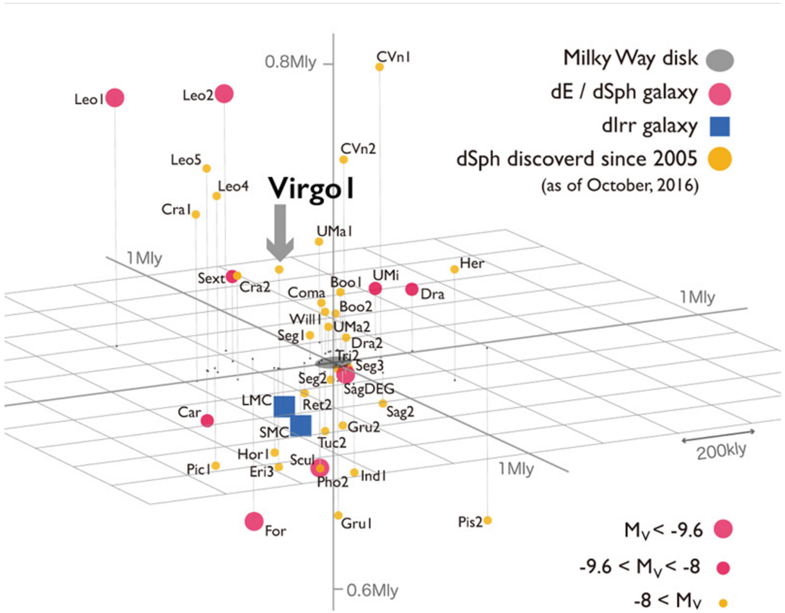
CG

Indirect detection and “J-factor”

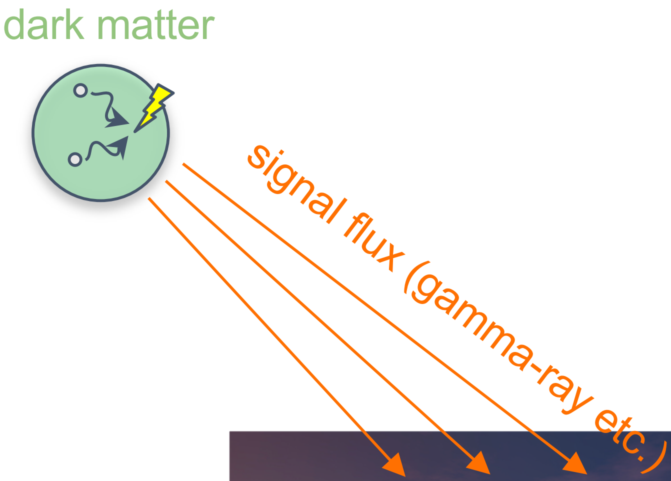
- Dwarf Spheroidal galaxy (dSph)
  - Close to the earth
  - DM dominant
  - no other gamma-ray source



Ref. “Combined dark matter searches towards dwarf spheroidal galaxies with Fermi-LAT, HAWC, H.E.S.S., MAGIC, and VERITAS ” [arXiv:2108.13646]



http://earthsky.org/space/dwarf-galaxy-virgo1-nov-2016



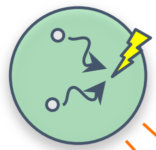
Fermi-LAT, AMS-02, CTA, etc.

https://www.cta-observatory.org/project/technology/lst/

Indirect detection and "J-factor"

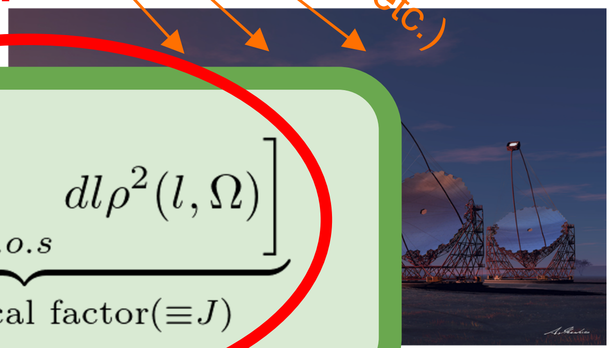
- Signal flux from dSphs

dark matter



signal flux (gamma-ray etc.)

Fermi-LAT, AMS-02, CTA, etc.



/lst/

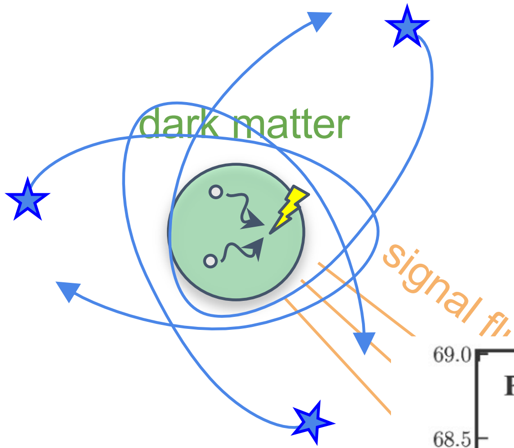
Flux from dSph:

***J*-factor**

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

J-factor estimation of dSph

- How to determine J-factor



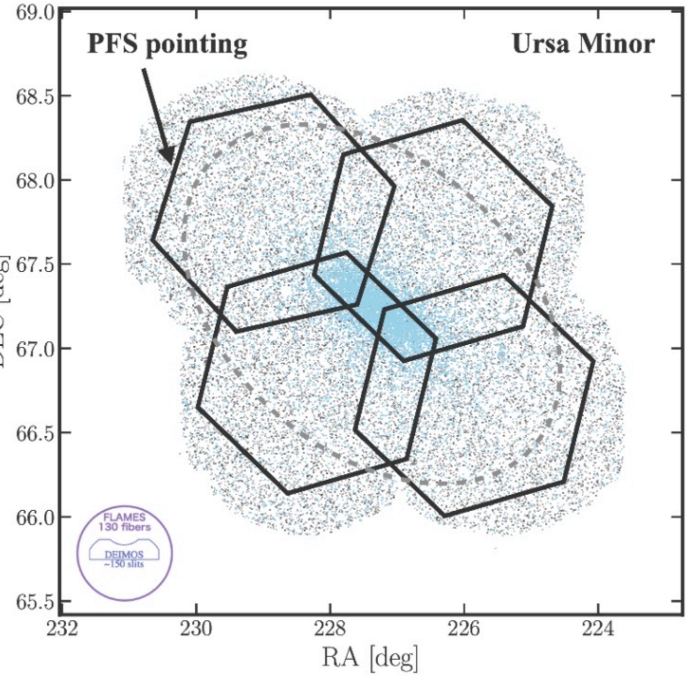
Spectrograph

☆ 's velocity is ...

http://pfs.ipmu.jp/ja/instrumentation.html

Prime Focus Spectrograph (PFS)
- **Large FoV**
- **Many fibers (~2400)**

→ large dataset



htt

J-factor estimation of dSph

- Kinematics of dSph:
  - Collisionless system:
    (relaxation time scale) > (dynamical time scale)
  - Collisionless Boltzmann equation

$$\frac{df}{dt} = \frac{\partial f}{\partial t} + \{f, H\} = 0$$

$f(\boldsymbol{x}, \boldsymbol{v})$: distribution function $\left(\int \mathrm{d}^3x\, \mathrm{d}^3v\, f(\boldsymbol{x}, \boldsymbol{v}) = 1\right)$

  - Observables: photometric & spectroscopic telescopes
    - Position: (α, δ) (right ascension, declination) → $\boldsymbol{x}_\perp$
    - Velocity: v_{los} (line-of-sight velocity) → $v_\parallel$

J-factor estimation of dSph

- Kinematics of dSph:
  - Equation of momemts (Jeans equation)
    - $\int d^3\boldsymbol{v}\, v_i^2 (\text{Boltsmann eq.}) \equiv (\text{Jeans eq.})$
  - Jeans equation of spherical systems

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

$\nu_*(r)$: (3D) number density

$$\beta_{\rm ani}(r) \equiv 1 - \frac{\sigma_\theta^2 + \sigma_\phi^2}{2\sigma_r^2}$$

$\sigma_a^2(r)$: velocity dispersion

Uncertainty of J-factor: foreground effect

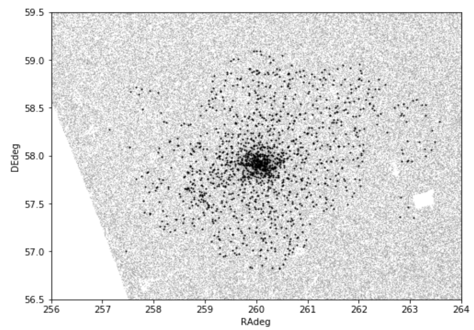
- Kinematics ←→ gravitational Potential (= DM)
  - (Spherical) Jeans equation

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

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

  - Observables:
    - Photometry: surface number density

$$\Sigma_*(R)=2\int_R^\infty\frac{r\,\mathrm{d}r}{\sqrt{r^2-R^2}}\nu_*(r)$$



    - Spectroscopy: line-of-sight velocity dispersion

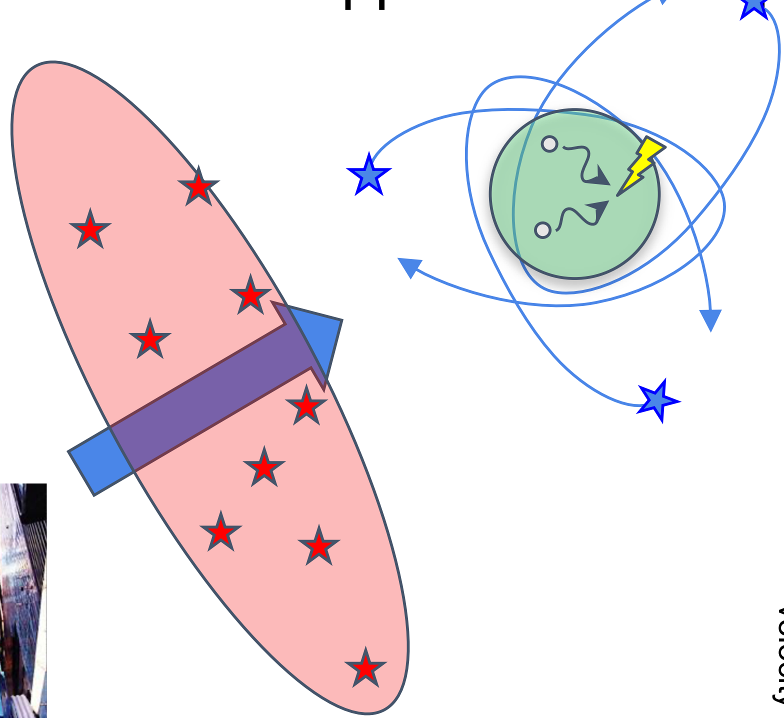
$$\sigma_{l.o.s.}^2(R)=\frac{2}{\Sigma_*(R)}\int_R^\infty\frac{\mathrm{d}r}{\sqrt{1-R^2/r^2}}\left(1-\beta_{\rm ani}\frac{R^2}{r^2}\right)\nu_*(r)\sigma_r^2(r)$$

Uncertainty of J-factor: foreground effect

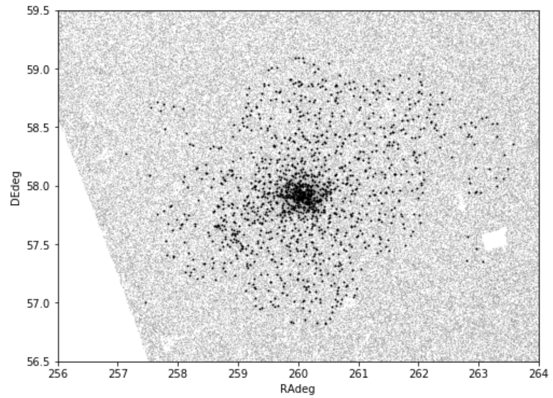
- DM density estimation has some biases (uncertanity):
  - Uncertainty from dSph modelling
    - Stellar profile modelling
    - Anisotropy modelling ($\beta(r) = \beta\ (const)$, …)
    - Symmetry (Spherical, Axisymmetric, triaxial,…)
  - Uncertainty not from dSph modelling
    - **Foreground contamination**
    - Sampling bias
- They affect the sensitivity of Indirect detection….
  - DM distribution itself is also interesting
    - e.g. Cored vs Cuspy problem

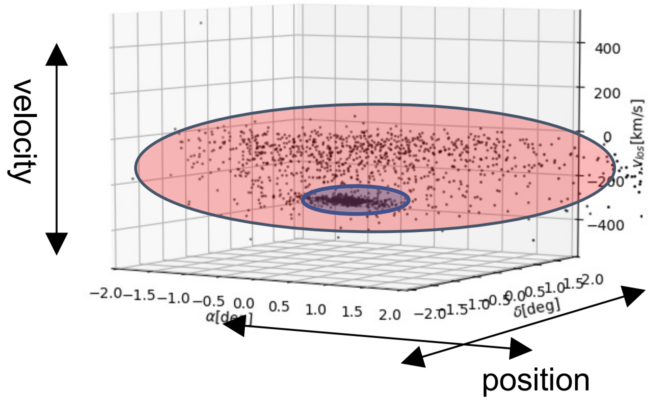
Uncertainty of J-factor: foreground effect

- Foreground contamination
  - MW stars are overlapped on the dSph distribution…



★ or ★ ???

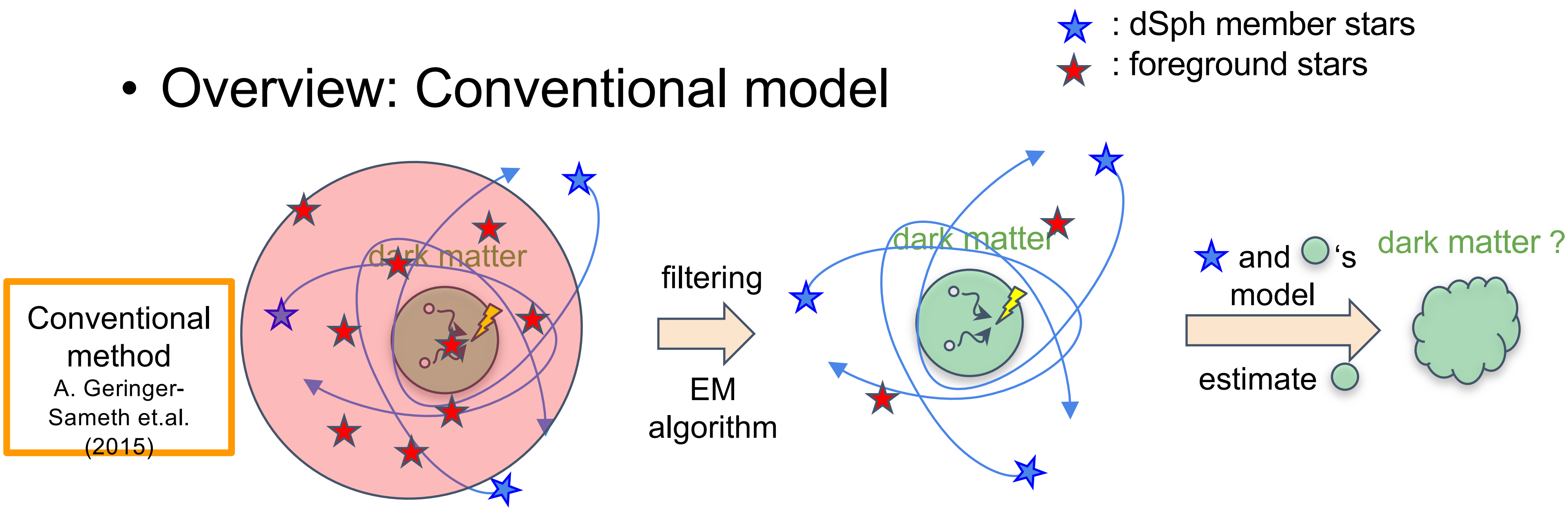




arXiv:1608.01749
arXiv:1706.05481

Member/Foreground mixture model

- Overview: Conventional model



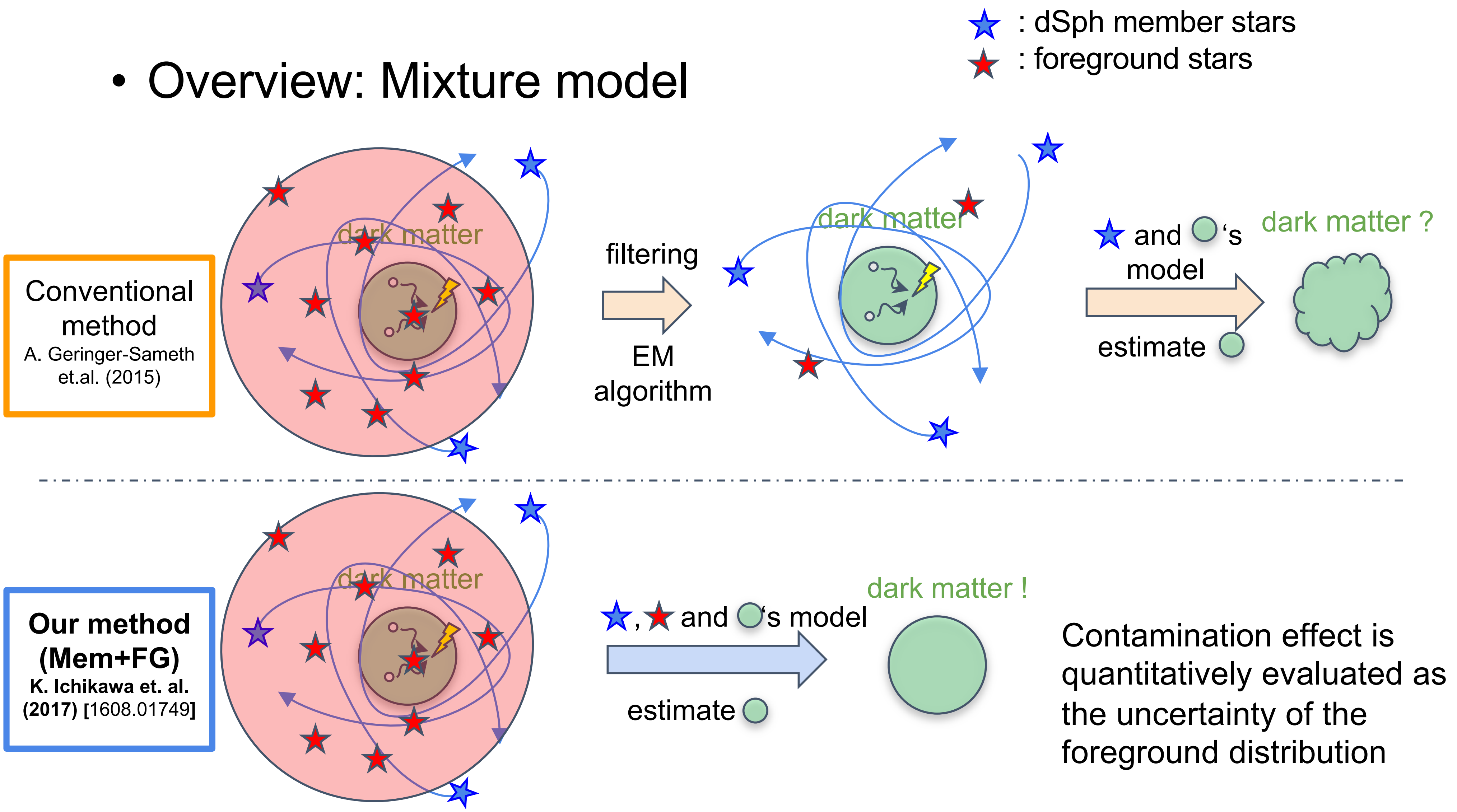
Problems:

- Remained foreground stars (★) affect the estimation
- Contamination effect cannot be evaluated quantitatively (all stars after the filtering are regarded as "member" stars)

arXiv:1608.01749
arXiv:1706.05481

Member/Foreground mixture model

- Overview: Mixture model



Contamination effect is quantitatively evaluated as the uncertainty of the foreground distribution

Member/Foreground mixture model

- Likelihood function(s):

1. (Control region fit)

$$\mathcal{L}_{\rm cont}(\Theta_{\rm FG}|\{v_i\}_{\rm cont}) = \prod_{i\in{\rm cont}} \int {\rm d}R_i\, f_{\rm FG}(v_i, R_i)$$

→ Obtain Prior

2. Signal region fit

$$\mathcal{L}(\Theta_{\rm tot}|\{v_i, R_i\}_{\rm sig}) = \prod_{i\in{\rm sig}} f_{\rm sig}(v_i, R_i)$$

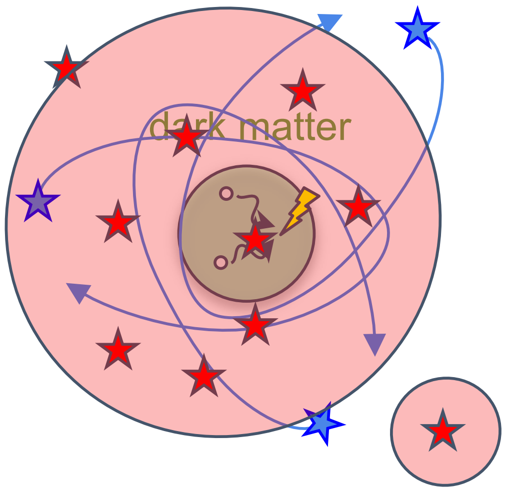
$$= \prod_{i\in{\rm sig}} (s f_{\rm mem}(v_i, R_i) + (1-s) f_{\rm FG}(v_i, R_i)) \times \pi(\Theta_{\rm FG})$$

- phase space distribution functions :

$$f_{\rm mem}(v, R) = 2\pi R \Sigma_{\rm mem}(R) \mathcal{G}[v, \bar{v}_{\rm mem}, \sigma_{los}(R)]$$

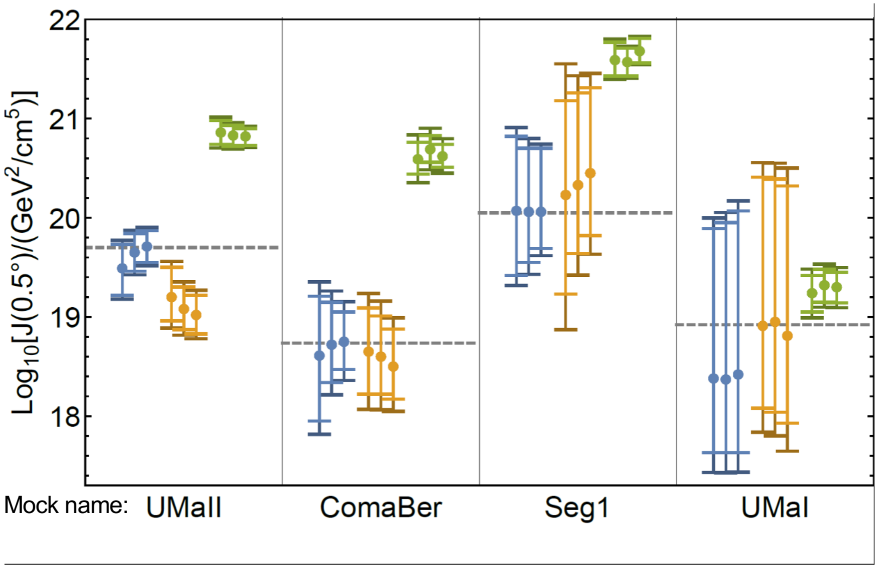
$$f_{\rm FG}(v, R) = 2\pi R \Sigma_{\rm FG} \sum_i s_i \mathcal{G}[v, \bar{v}_{\rm FG,i}, \sigma_{\rm FG,i}]$$

- Estimate the posterior probability of all parameters by using MCMC (MH algorithm, or emcee)
→ posterior of J-factor!



Demonstration

- We proposed a new method to solve contamination problem
- Proof of principle: demonstration of our method by using mock observational data of the Prime Focus Spectrograph for:
  - Classical dSph [1608.01749]
  - Ultrafaint dSph (UFD) [1706.05481]



e.g. For UFD:

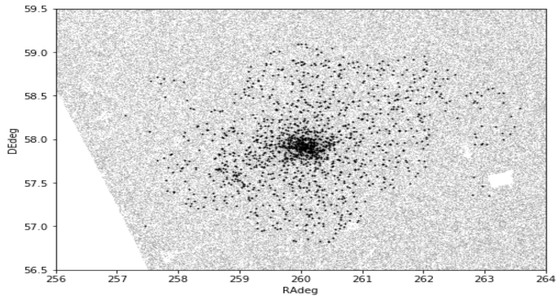
i-band magnitude (brightness) = 21.0, 21.5, 22.0

Blue: ours (Member/FG model)
Orange: 95% filtering (Conventional)
Green: contaminated (no filtering)
Dotted line: *True* value (input of mock)

- → Improvement of estimation accuracy

Application to actual J-factor estimation

- Actual datasets have sampling bias:
  - (observed surface density) ≠ (actual surface density)



  - Modification of likelihood function

$$\mathcal{L} \equiv \prod_i f(\mathbf{v}_i, \mathbf{x}_i)$$

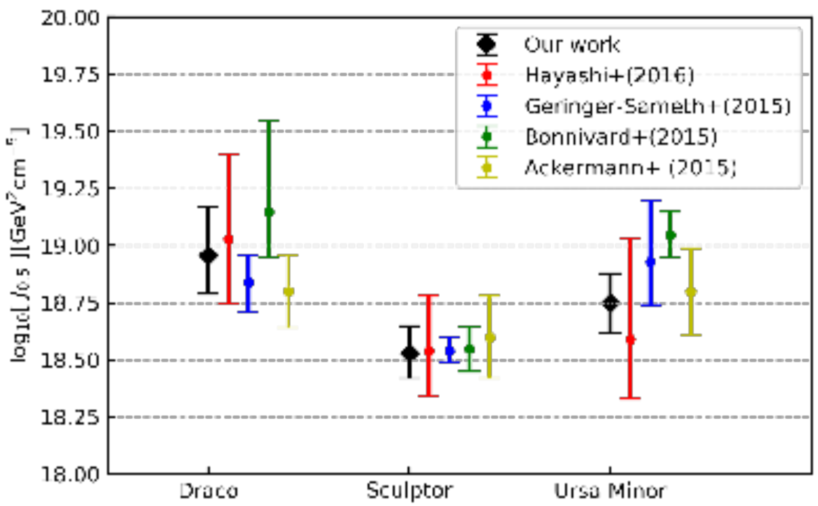
f: distribution function

$$\rightarrow \mathcal{L}' \equiv \prod_i f(\mathbf{v}_i | \mathbf{x}_i), \quad f(\mathbf{v}_i|\mathbf{x}_i) \equiv \frac{f(\mathbf{v}_i, \mathbf{x}_i)}{\int \mathrm{d}\mathbf{v}_i \, f(\mathbf{v}_i, \mathbf{x}_i)}$$

- Including photometric samples: estimation of $\nu_*(r)$

Application to actual J-factor estimation

- We applied our method to actual datasets of Draco, Sculptor, and Ursa Minor (large J-factor)



- Consistent with other results even when considering the contamination effect, but slightly different
  - NOTE: The contamination effect can be more significant in UFD cases (fewer stars, highly contaminated)

Summary

- **Dwarf spheroidal galaxies (dSphs)** are promising targets of **indirect detection** of dark matter (DM)
- The sensitivity of the detection depends on the DM distribution in dSphs (**J-factor**), but it suffers from some **astrophysical uncertainties**
- Some astrophysical uncertainties (**FG contamination** problem and Sampling bias) are solved by our method using new likelihood functions
- Our method can work well for mock dSph data sets (demonstration) and we calculated the J-factor values of some dSphs (application)
- Our J-factor values are consistent with conventional ones but slightly different because of the contamination effect
- Future work: UFD cases, other uncertainties (axisymmetry, anisotropy, …)