

Robust estimate of dark halo in the Galactic dwarf spheroidal galaxies

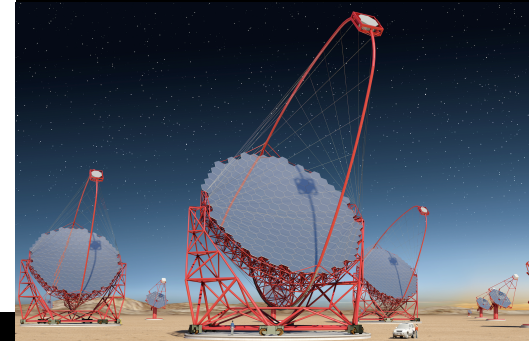
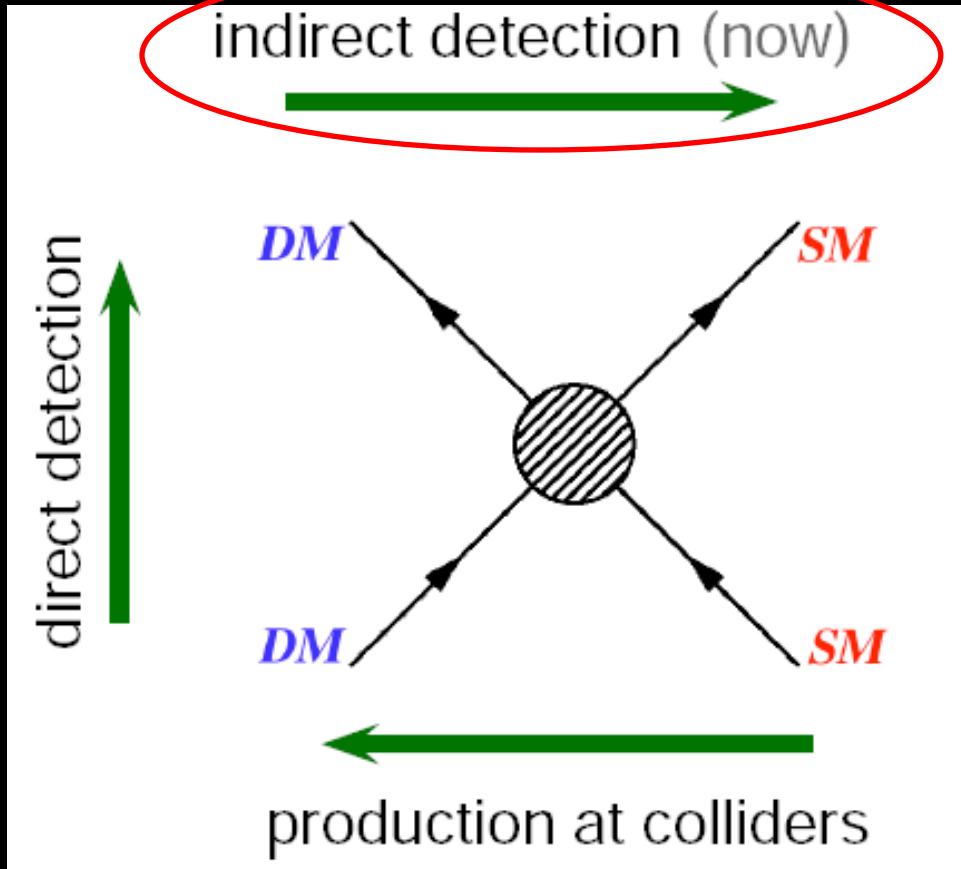
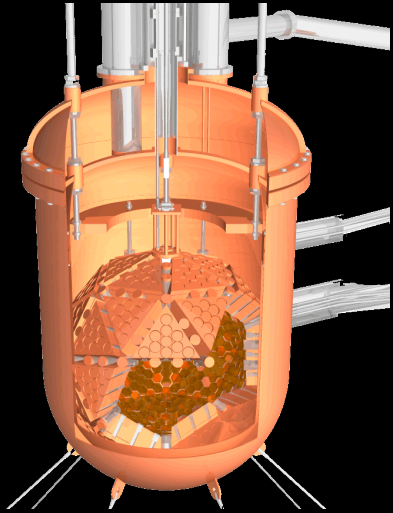
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3. Institute for Cosmic Ray Research (ICRR)

Dark Matter Search

$$m_{\text{DM}} \sim 50\text{-}2000\text{GeV}$$



Indirect search for dark matter

Galactic dSphs are ideal sites for detecting a dark matter Signal!!

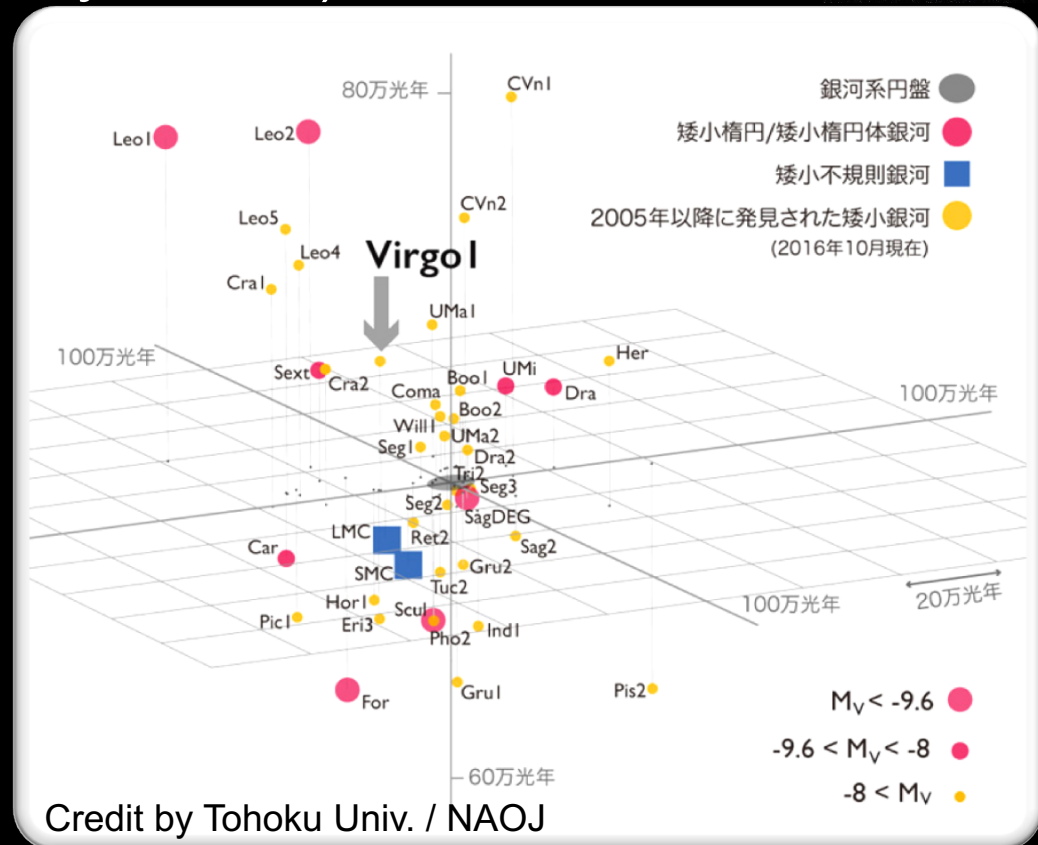
Galactic dSphs:

- ✓ DM rich ($M/Ls \sim 10$ to 1000)
- ✓ Proximity ($D \sim 20 - 100$ kpc)
- ✓ Clean (no astrophysical γ -ray source)



Type of dSph galaxy

	Classical	Ultra-faint
# of dSphs	8	> 30
M/Ls	10-100	100-1000
# of stars	500-2500	10-100

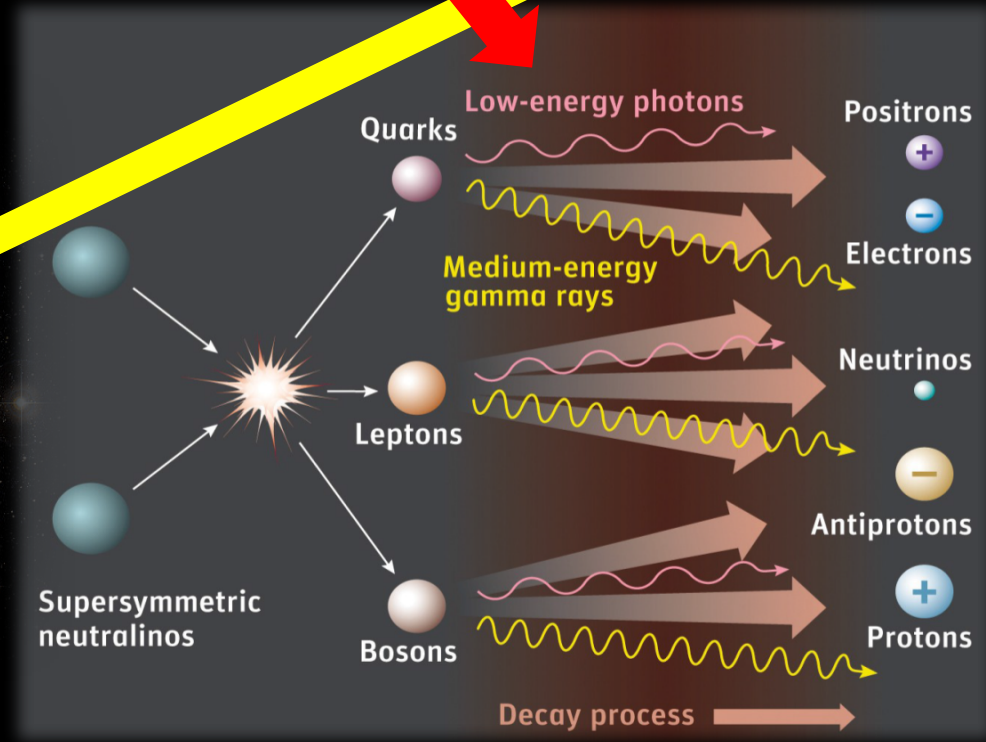


Indirect search for dark matter

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

Observable Particle physics Astrophysics (J-factor)

dSph galaxy



γ-ray detector



To robust estimate J-factor value,
revealing **the dark halo structure of the dSphs** is of importance!

Deriving DM profiles from dynamical analysis

ex. Spherical mass model

Jeans equation

$$\sigma_p^2(R) = \frac{2}{I(R)} \int_R^\infty \left(1 - \beta_a \frac{R^2}{r^2}\right) \frac{\nu(r) \overline{v_r^2} r}{\sqrt{r^2 - R^2}} dr$$

$$\frac{1}{\nu(r)} \frac{d}{dr} [\nu(r) \overline{v_r^2}(r)] + 2 \frac{\beta_a(r) \overline{v_r^2}(r)}{r} = - \frac{GM(r)}{r^2}$$

observed

$$\text{Stellar profile: } I(R) = \frac{L}{\pi R_{\text{half}}^2} \frac{1}{(1 + R^2/R_{\text{half}}^2)^2}$$

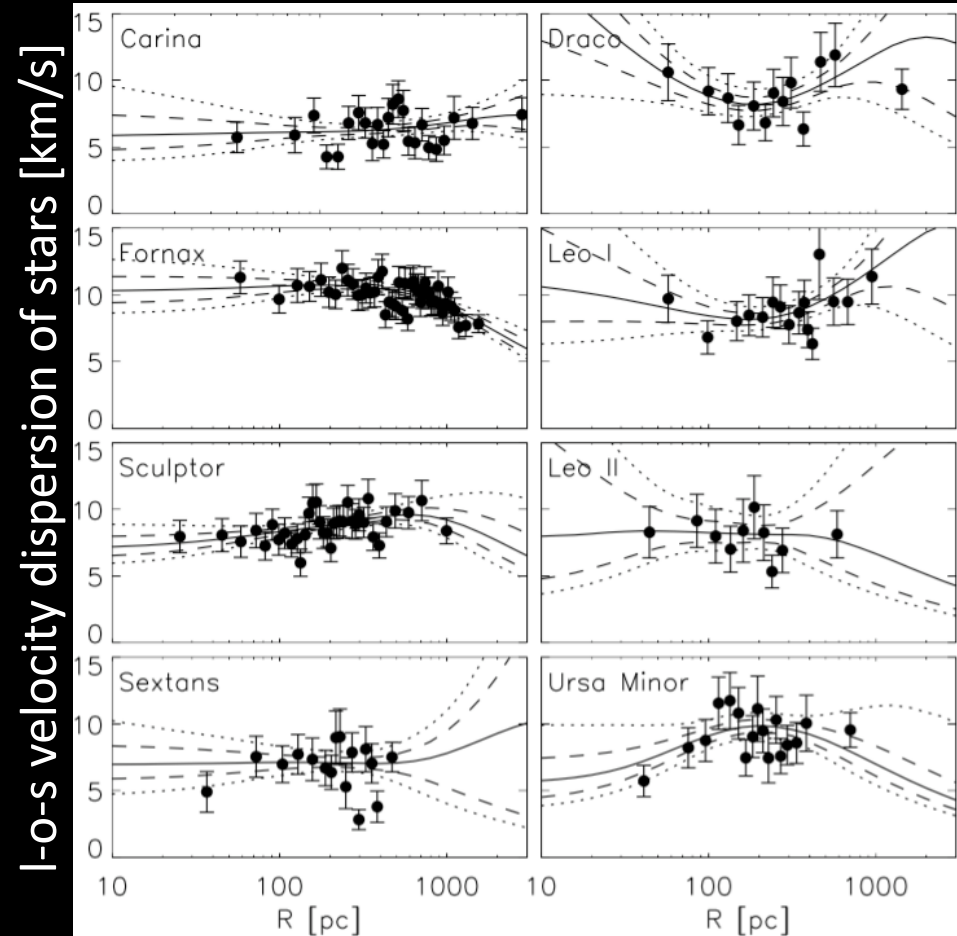
not observed

Velocity anisotropy:

$$\beta_a(r) = 1 - \frac{\sigma_\phi^2 + \sigma_\theta^2}{2\sigma_r^2}$$

DM halo profile:

$$\rho(r) = \frac{\rho_s}{(r/r_s)^\gamma [1 + (r/r_s)^\alpha]^{(\beta-\gamma)/\alpha}}$$



Major systematic uncertainties on J

- **Non-spherical dark halo**

Most previous works estimated J values by assuming spherical mass models, even though observational stellar distribution of dSph on the sky are actually not spherical, and Λ CDM model has predicted non-spherical virialized dark halos on all mass scales. (Hayashi et al. 2016)

- **Foreground contaminations**

These have largely impact on determining dark halo profiles, especially ultra faint dwarfs (Ichikawa (incl. KH) et al.).

- **Velocity anisotropy**

Velocity anisotropy as commonly parameter is strongly degenerated with mass profile of dark halo. Therefore, studies of dark matter in dSphs have been hampered by this degeneracy.

Axisymmetric fit

Assumptions

- Dynamical equilibrium
- DM dominated and collisionless system
- Axisymmetry in both stellar and DM components.
- Velocity anisotropy, β_z , is constant.

Parameters

- Halo density ρ_0
- Halo radius b_{halo}
- Inner slope α
- **Axial ratio** Q
- Inclination i
- Velocity anisotropy β_z

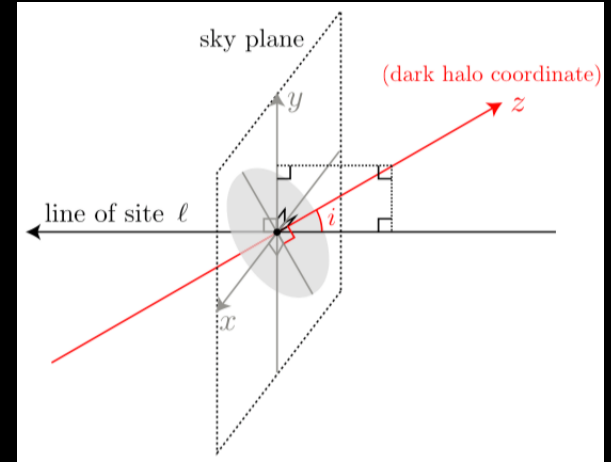
- DM halo profile

$$\rho(R, z) = \rho_0 \left(\frac{m}{b_{\text{halo}}} \right)^\alpha \left[1 + \left(\frac{m}{b_{\text{halo}}} \right)^2 \right]^{-(\alpha+3)/2}$$

$$m^2 = R^2 + z^2/Q^2$$

- Velocity anisotropy

$$\beta_z = 1 - \overline{v_z^2} / \overline{v_R^2}$$

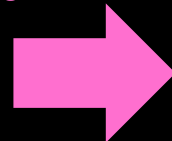


Axisymmetric Jeans eqs.

$$\overline{v_z^2} = \frac{1}{\nu(R, z)} \int_z^\infty \nu \frac{\partial \Phi}{\partial z} dz$$

$$\overline{v_\phi^2} = \frac{1}{1 - \beta_z} \left[\overline{v_z^2} + \frac{R}{\nu} \frac{\partial(\nu \overline{v_z^2})}{\partial R} \right] + R \frac{\partial \Phi}{\partial R}$$

Integration along



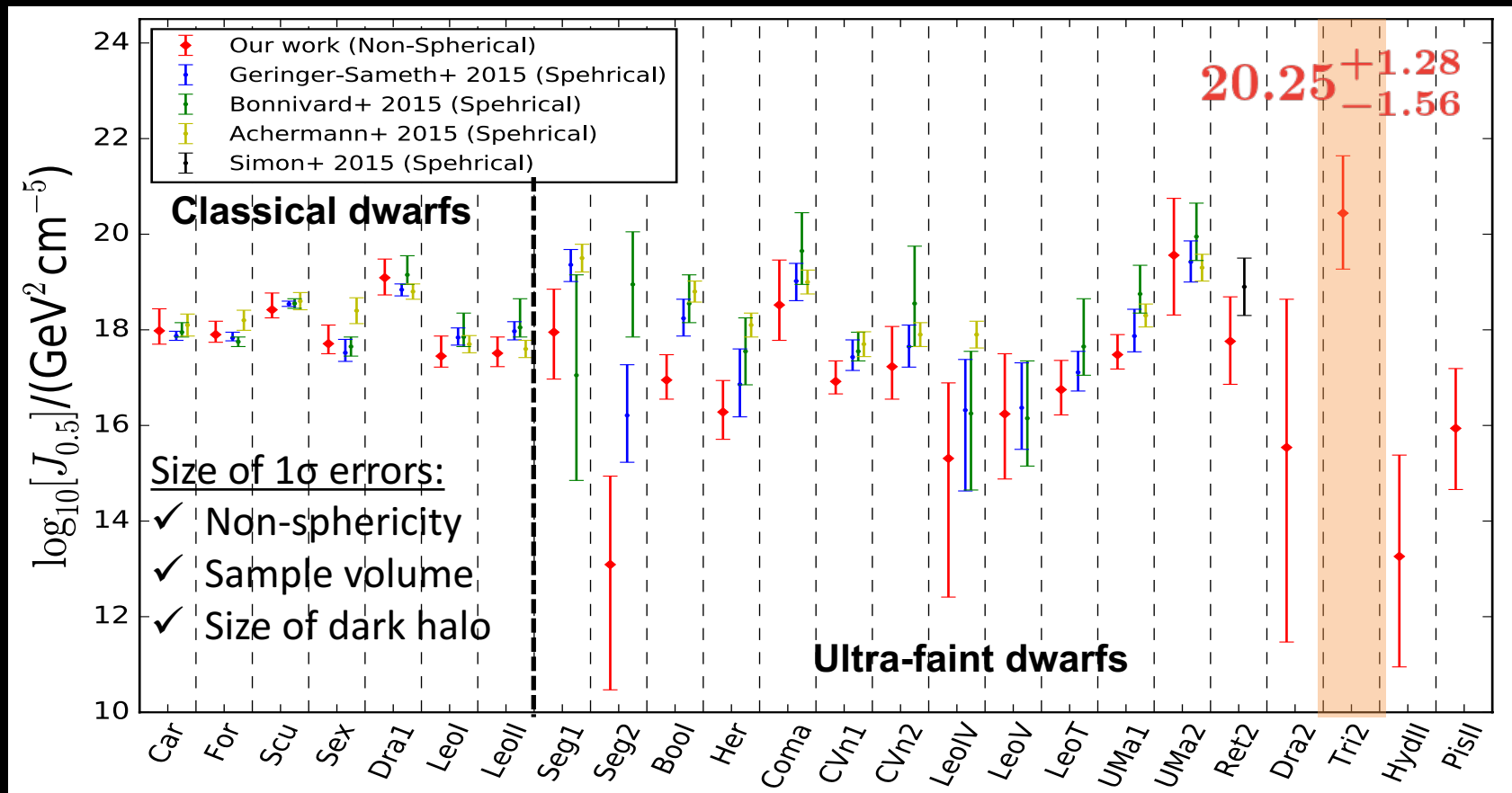
line-of-sight

$$\overline{v_{\text{l.o.s}}^2}(x, y)$$

J-factor values for axisymmetric mass models

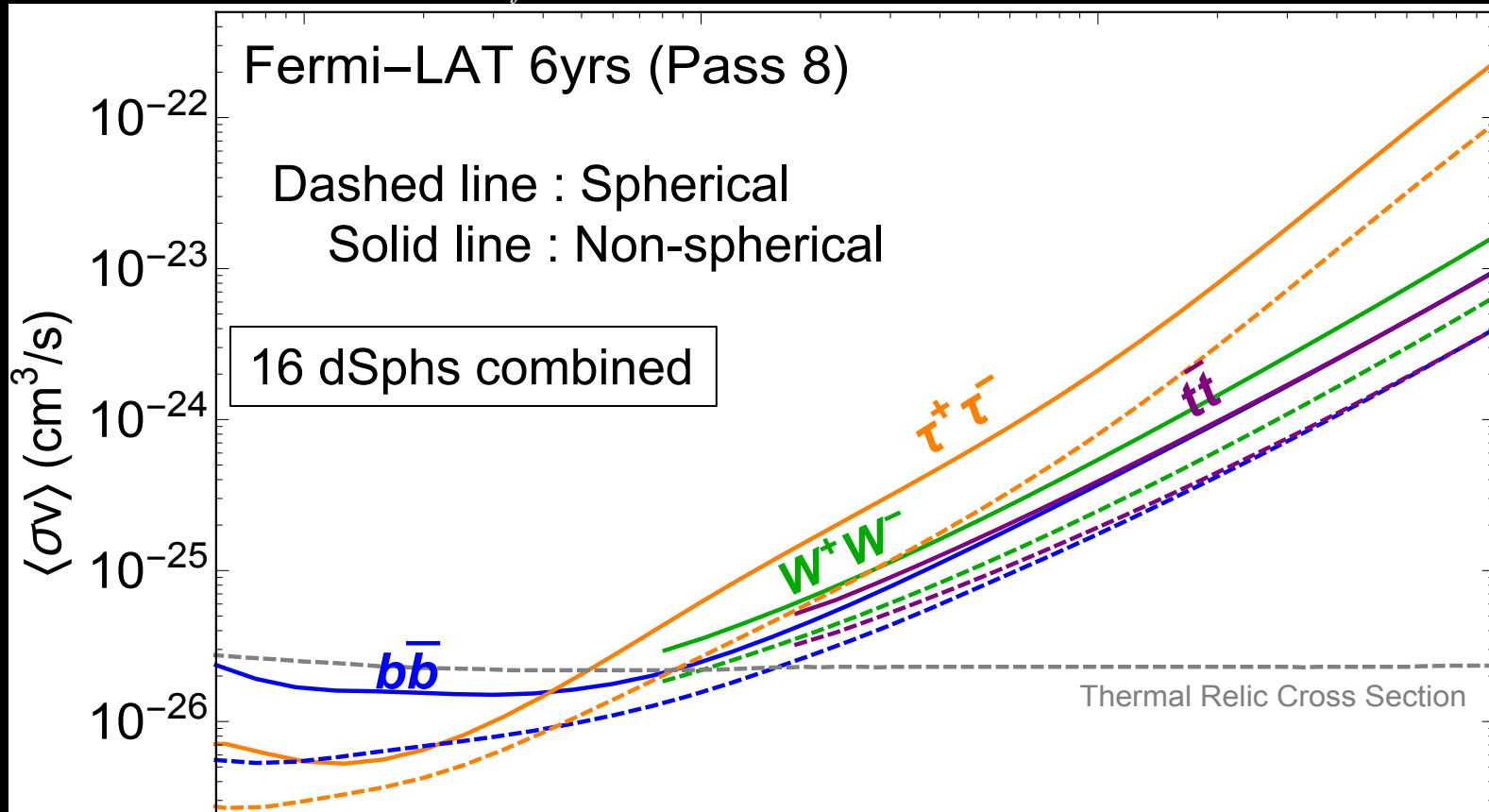
$$J \equiv \int_{\Delta\Omega} d\Omega \int_{\text{l.o.s}} d\ell \rho^2(\ell, \Omega)$$

- ❖ It is found that there are differences between the values of J-factors estimated from spherical and non-spherical models, especially for UFDs.
- ❖ Our estimation is included non-sphericity as well as sample volume, size of dark halo, thus J-factor values from axisymmetric are more conservative than these from spherical mass models.
- ❖ Triangulum 2 is the most promising target for dark matter annihilation.



Sensitivity line on the $\langle\sigma v\rangle$ - m_{DM} map

$$\Phi(E, \Delta\Omega) = \left[\frac{\langle\sigma v\rangle}{8\pi m_{\text{DM}}^2} \sum_f \text{Br}(\text{DM DM} \rightarrow f) \left(\frac{dN_\gamma}{dE} \right) \right] \left[\int_{\Delta\Omega} d\Omega \int_{\text{l.o.s}} d\ell \rho^2(\ell, \Omega) \right]$$



Our analysis clearly makes each sensitivity line more conservative than spherical one, because the estimated J-factor values in our analysis include surely systematic uncertainties of non-sphericity.

m_{DM} (GeV)

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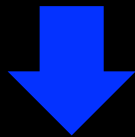
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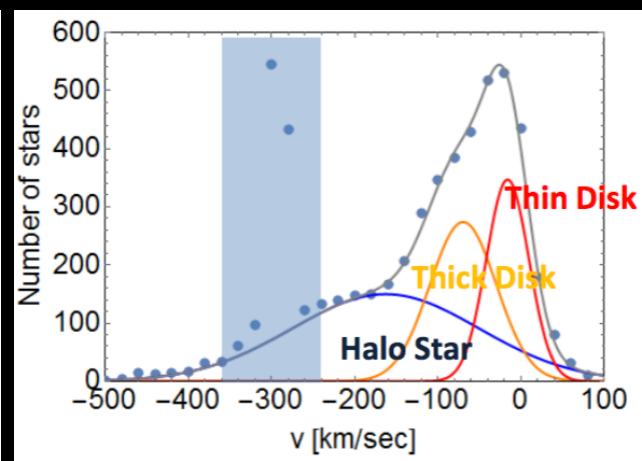
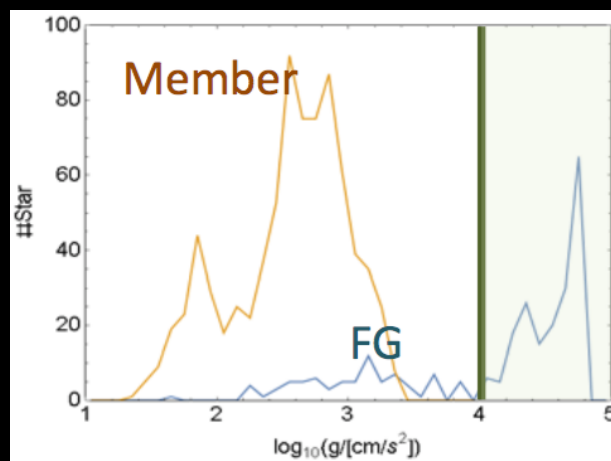
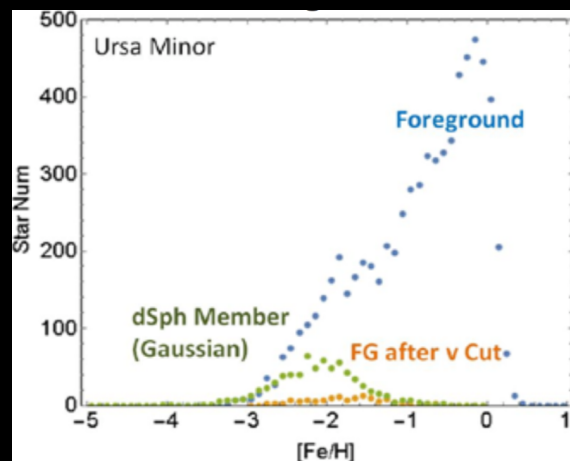
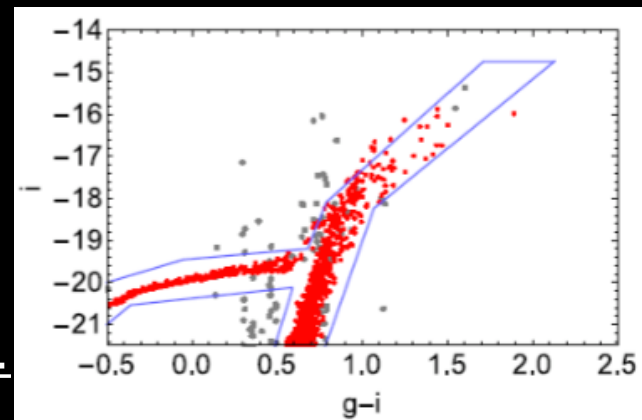
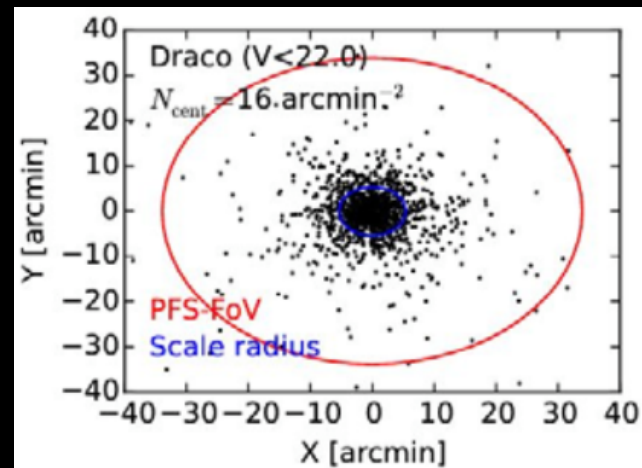
Foreground contaminations

Big efforts to reduce contaminations...

1. Region of interest cut
2. Color-Magnitude cut
3. Velocity cut
4. Surface gravity cut
5. Effective temperature cut
6. Metallicity cut



Indistinguishable contaminations still remain...



New fitting function including FG contaminations

Ichikawa (incl. KH) et al. (arXiv:1608.01749)

Ichikawa (incl. KH) et al. (in prep.)

$$-2 \ln \mathcal{L} = -2 \sum_i \ln(s f_{\text{Mem}}(v_i, R_i) + (1 - s) f_{\text{FG}}(v_i, R_i))$$

- Membership fraction parameter

Green: Contaminated (regard FG as member star)

Orange: Our fit

To treat foreground contaminations more accurately, we require a number of stellar spectra of FG stars as well as member stars in outer region.

- Distribution functions

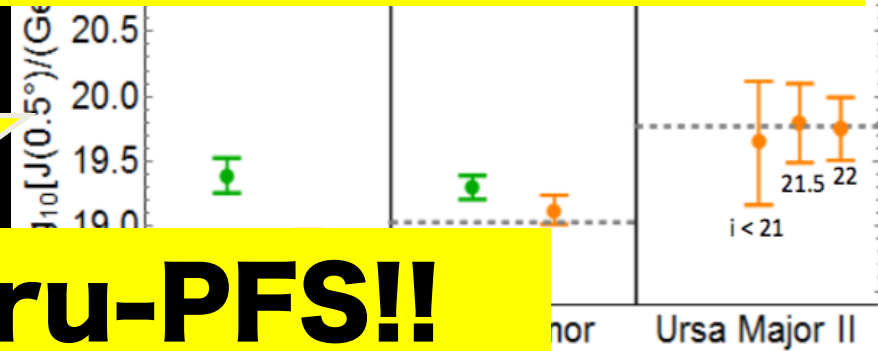
$$f_{\text{FG}}(v, R) = 2\pi R N_{\text{FG}} \exp\left[-\frac{(v - v_{\text{FG}})^2}{2\sigma_{\text{FG}}^2}\right]$$

$$f_{\text{Mem}}(v, R) =$$

Yes, Subaru-PFS!!

From dark halo parameters (& Jeans equation)

Our new likelihood successfully reproduces the input J values.



Future Prospects

Major systematic uncertainties on J

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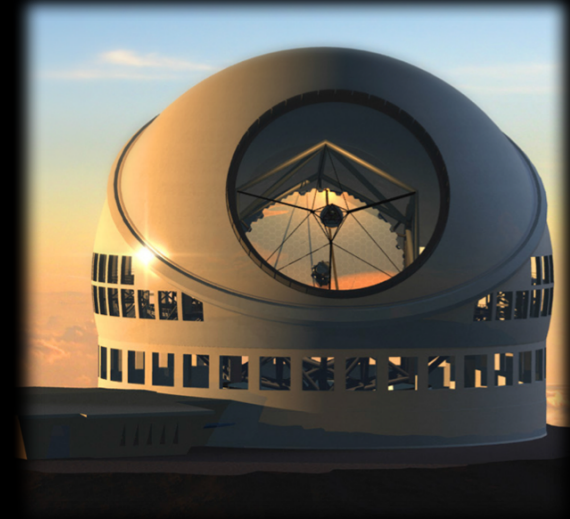
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$$\beta_a(r) = 1 - \frac{\sigma_\phi^2 + \sigma_\theta^2}{2\sigma_r^2}$$

Subaru-PFS + TMT = 3D velocity information



Line-of-sight velocities



Proper motions

**The only one way to break the degeneracy is
to measure 3D velocities of stars in the dSphs**

Q. How many 3D velocity data do we need to improve the constraint on the dark matter distribution and thus the J-factor of dSphs?

To be continued...

Summary

1. The MW dSphs are ideal targets in the indirect dark matter searches.
2. However, **many hidden systematic uncertainties are still remain.**
3. We obtain more conservative results by our axisymmetric models.
4. Among analyzed dSphs, **Triangulum 2 ultra faint dwarf galaxy is the most promising target** in spite of large uncertainties.
5. Reduction of foreground stars can be achieved by our cut and new likelihood.
6. Investigation of stellar spectra via PFS will play a crucial role.
7. The synergy between PFS & TMT will have the remarkable capability to break the embarrassing but crucial degeneracy.

Thank you!