Varieties of DM density profile in Galactic dwarf spheroidal galaxies and the gamma-ray search of the annihilation signature

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Contents:

Introduction

Why is it important to determine the DM density profile?

WIMP:

- Weakly Interacting **Massive** Particle

  i.e., should feel the gravity

- achieve the relic abundance via the thermal freeze-out mechanism
- the mass $m_{\rm DM} \sim \mathcal{O}(\rm GeV) - \mathcal{O}(\rm TeV)$
- the annihilation cross-section

  $\langle \sigma v \rangle \sim \mathcal{O}(10^{-26} {\rm cm}^3 s^{-1})$

We do not see the annihilation signature yet.

Indirect search:

DM + DM → something in the SM

$\gamma, e^{\pm}, p, \bar{p}, \nu, \ldots$

https://www.nasa.gov/mission_pages/station/images/index.html

somewhere in the Universe

around the Earth

Input & Output

$$\phi = \frac{1}{2}\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\int dE\frac{dN}{dE}\int d\Omega\int_{los} ds\,\rho_{\rm DM}^2$$

observable

$$\equiv \int_{\Delta\Omega}\frac{dJ}{d\Omega}d\Omega = J_{\rm tot}$$

Input: flux ϕ of the (stable) standard model particle

knowns and/or assumptions

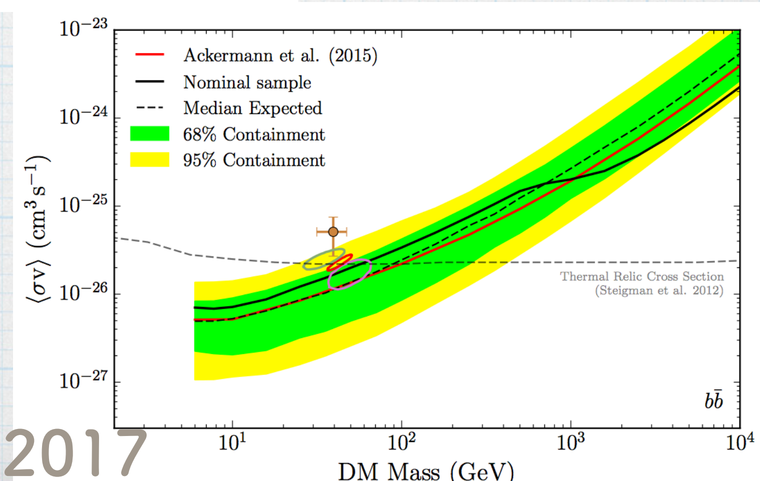
- target property

low background, high J-factor

- annihilation spectrum

Output: model parameter

$$m_{\rm DM} \;\&\; \langle\sigma v\rangle$$



Fermi-LAT&DES collaboration, 2017

target:

denser is better

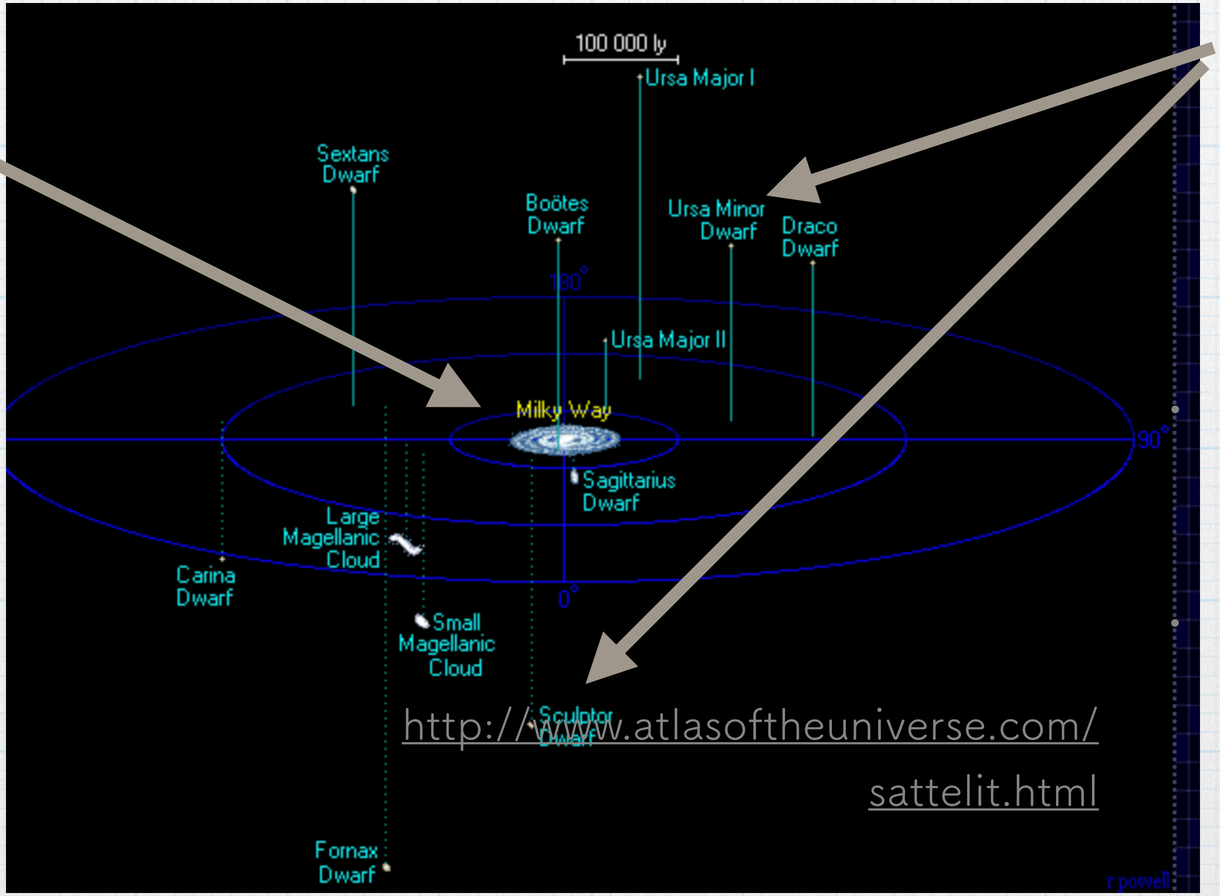
$$\phi = \frac{1}{2}\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\int dE\frac{dN}{dE}\boxed{\int d\Omega\int_{los} ds\ \rho_{\rm DM}^2}$$

The Galactic Center (G.C.)

$J \sim \mathcal{O}(10^{21-22})$

$[\mathrm{GeV}^2\mathrm{cm}^{-5}]$

high star formation activities



http://www.atlasoftheuniverse.com/sattelit.html

dwarf spheroidal galaxies (dSphs)

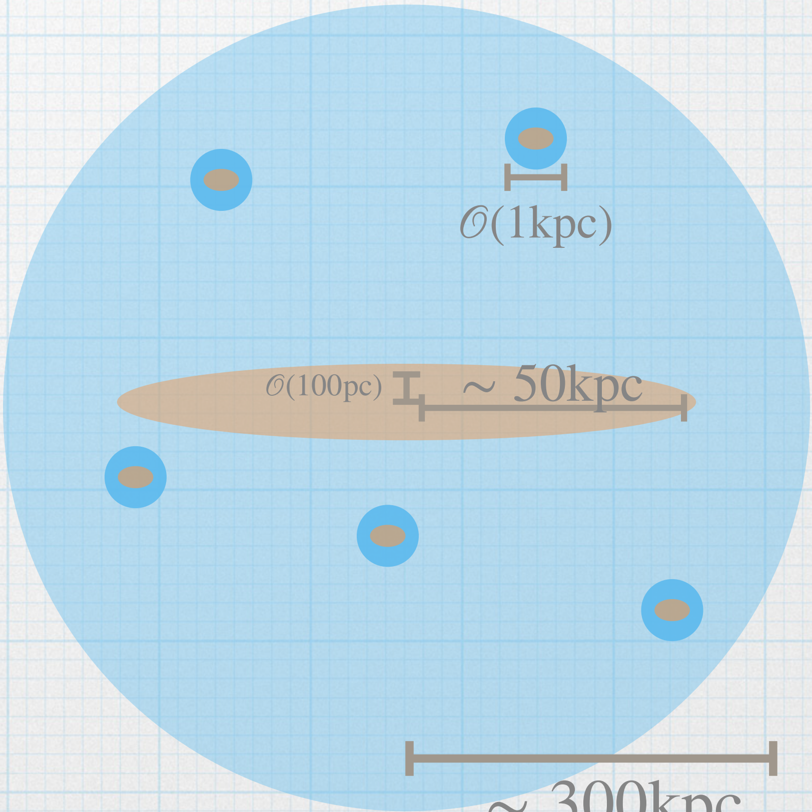
$J \sim \mathcal{O}(10^{16-20})$

$[\mathrm{GeV}^2\mathrm{cm}^{-5}]$

inactive star formations

dSph:

- satellite of the Milky Way
- ~40 are confirmed
- do not show star formation activities
- $M/L \lesssim 10^3 M_\odot / L_\odot$
- $M \sim 10^{8-9} M_\odot$
- $\Delta\theta \lesssim \mathcal{O}(1\mathrm{deg})$
- dist $(d) \sim \mathcal{O}(100)$ kpc



Procedure:

model 1 model 2

$$\phi = \frac{1}{2}\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\int dE\frac{dN}{dE}\int d\Omega\int_{los} ds\, \rho_{\rm DM}^2$$

observable

1. determine & observe the target
2. determine the model
   2-1. models of (observed) spectrum
   It only depends on the particle physics.
   (We neglect the propagation effect.)
   2-2. models of DM distribution responsible for the observation
   We need other astrophysical observations.
3. perform likelihood analysis

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model 1 model 2

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How can we know the profile $\rho_{\rm DM}$ of the invisible?

Method

What should we do to determine the DM density profile?

Tracer: stars

- (kinetic energy)
  $\sim$ (potential energy)
- Mass is dominated by DM

kinetic energy $\sim \sigma_V^2 = 3\sigma_r^2$

potential energy $\sim \frac{GM(r)}{r} = \frac{G\int^r 4\pi r^2 \rho_{\rm DM}(r)dr}{r}$

Jean's eq. $\frac{d\nu_*\sigma_r^2}{dr} + \frac{2\beta(r)}{r}\nu_*\sigma_r^2 + \frac{\nu_* GM(r)}{r^2} = 0$

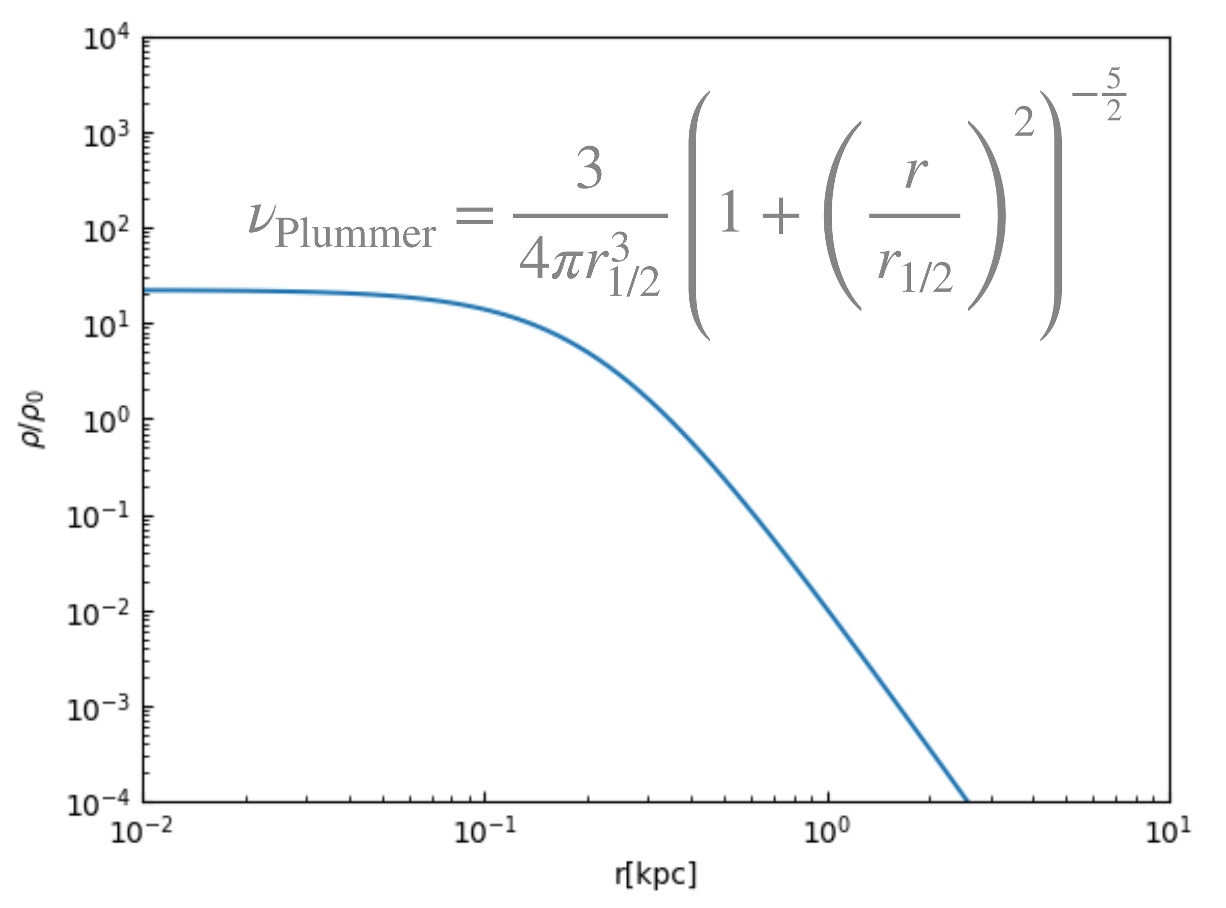
Stellar distribution ν_*:

- 3D Distribution:

  ν_* & $\rho_{\rm DM}$

- observable: σ_{los}

  2D projection



$$\left(\int_{los} \nu_*(r)ds\right)\sigma_{los}(R) = 2\int_R^\infty dr\left[1-\beta(r)\frac{R^2}{r^2}\right]\frac{r\nu_*\sigma_r^2(r)}{\sqrt{r^2-R^2}}$$

DM distribution:

- (generalized) NFW

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

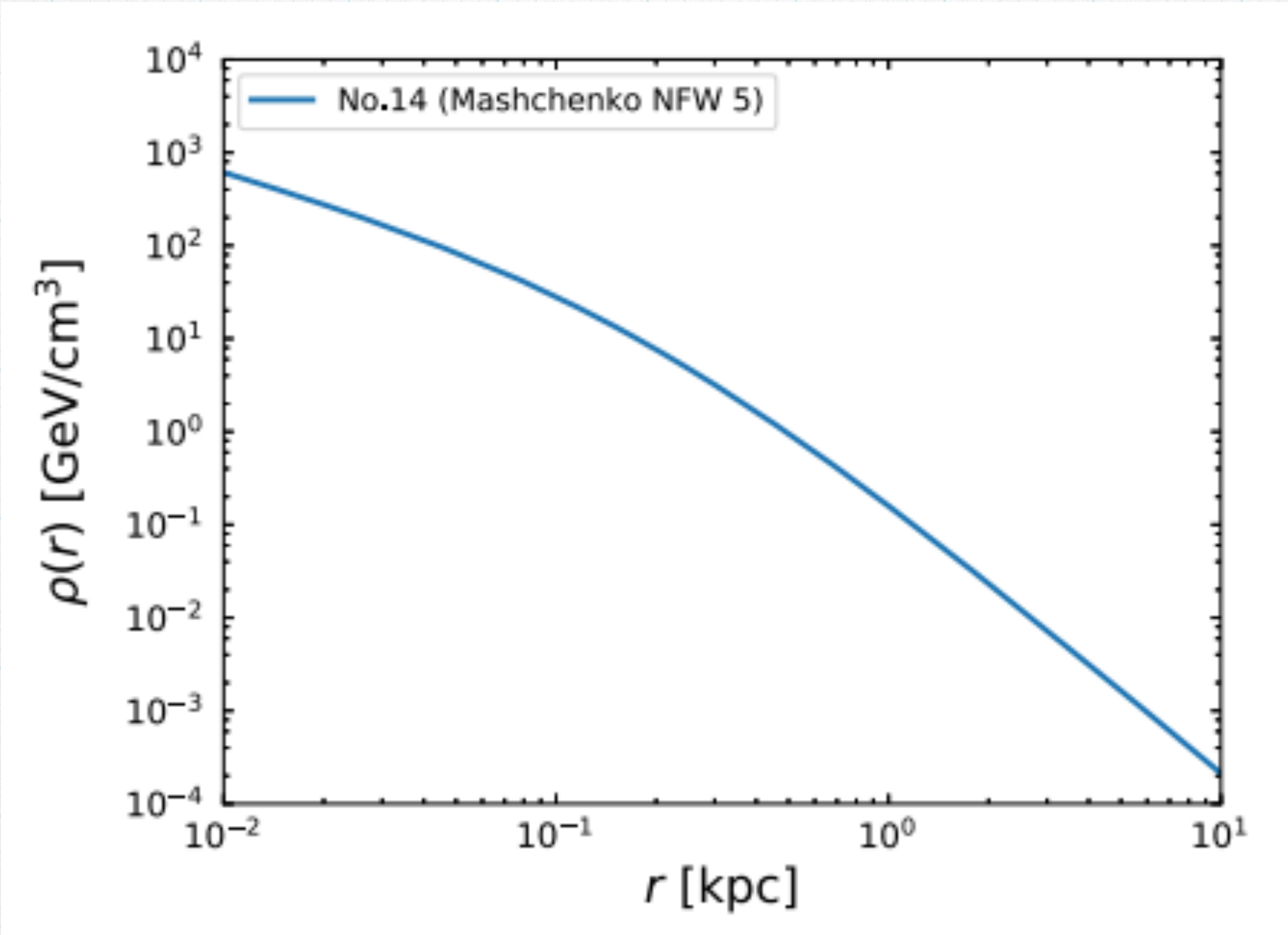
- Burkert

$$\rho(r) = \rho_s \left(1 + \frac{r}{r_s}\right)^{-1} \left[1 + \left(\frac{r}{r_s}\right)^{2}\right]^{-1}$$

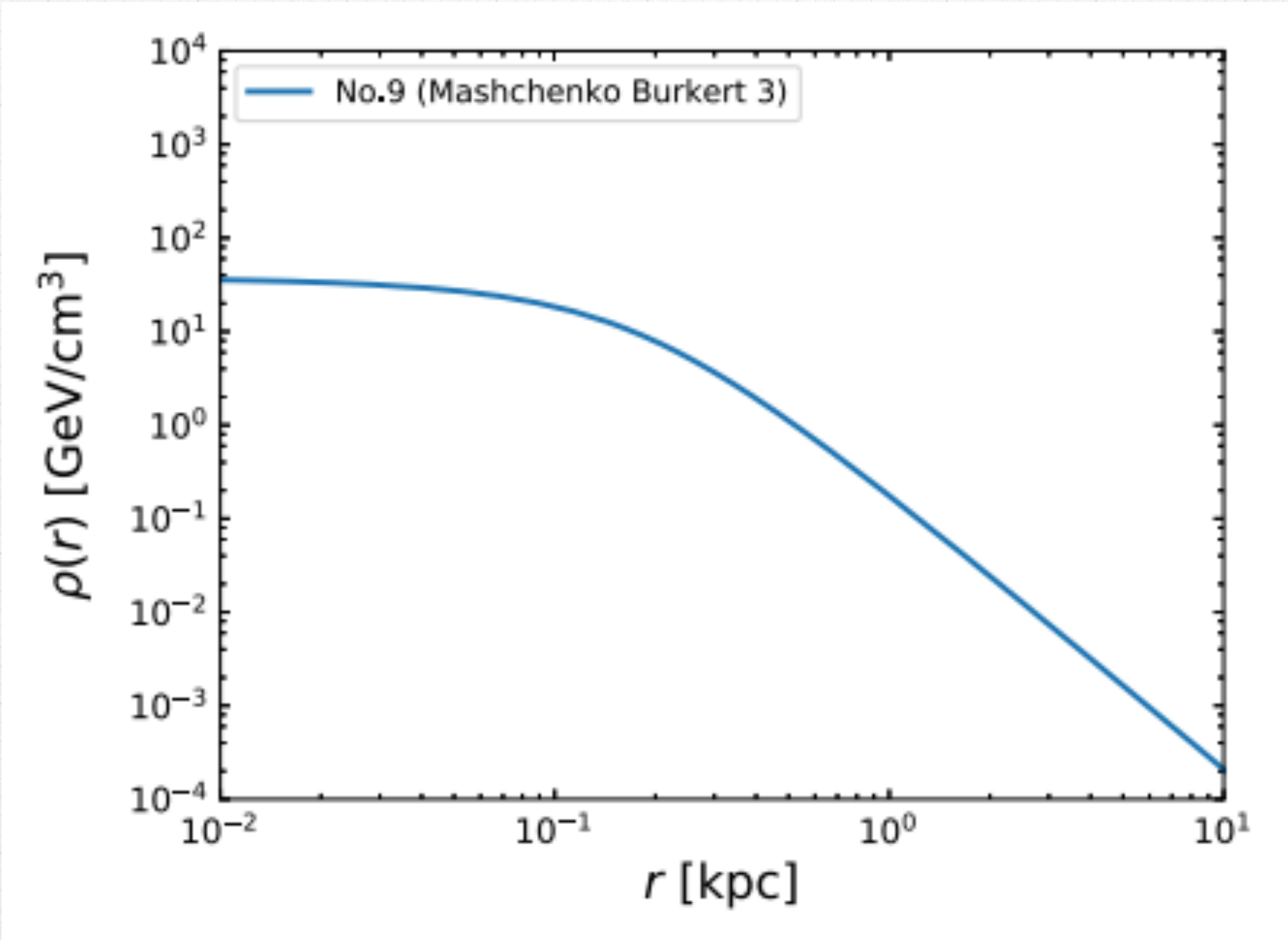
- Power Law (PL) + exp.cutoff

$$\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \exp\left[-\frac{r}{r_s}\right]$$

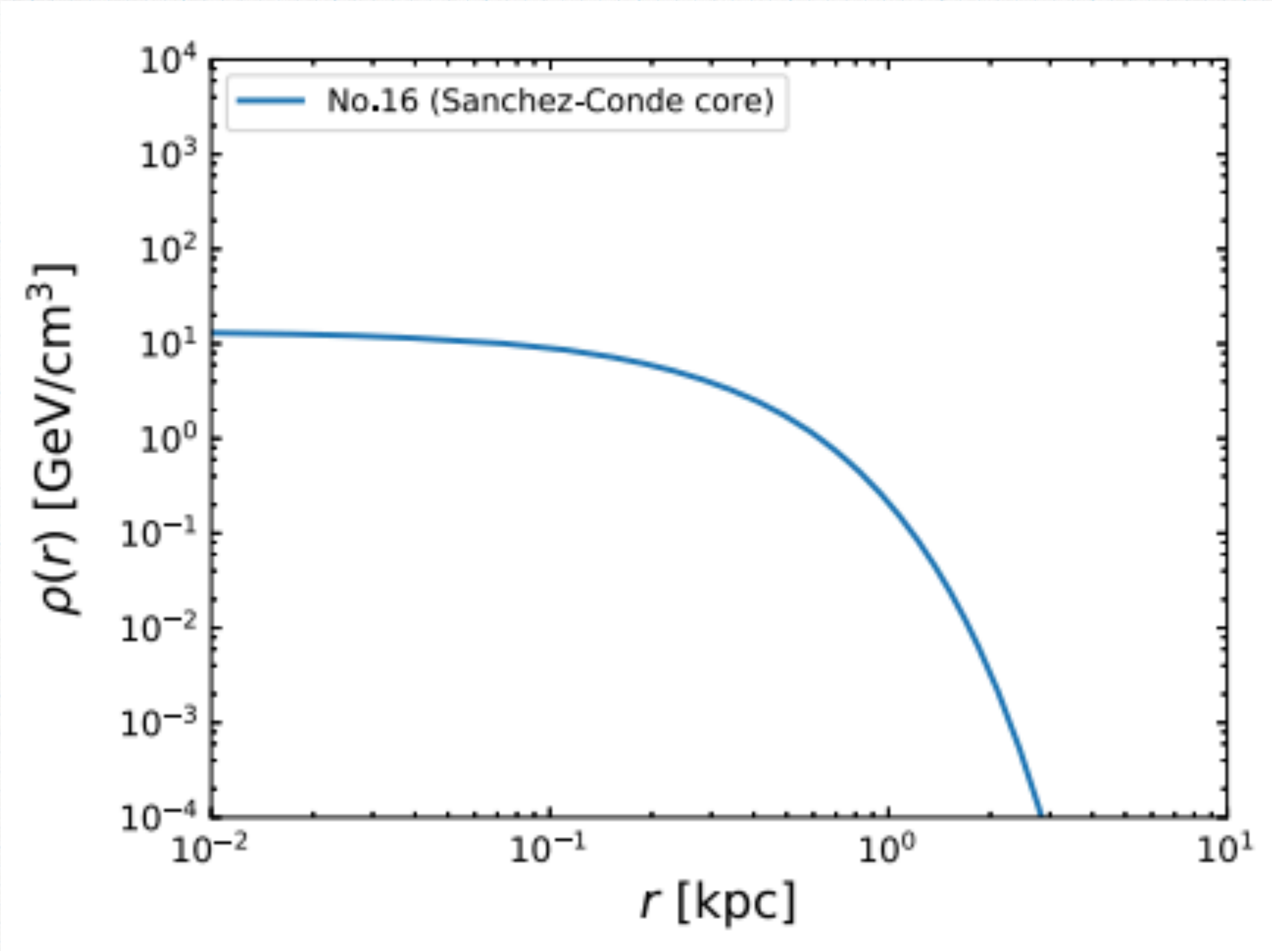
NFW: $\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-1} \left(1 + \left(\frac{r}{r_s}\right)^{\alpha}\right)^{-2}$



Burkert: $\rho(r) = \rho_s \left(1 + \frac{r}{r_s}\right)^{-1} \left[1 + \left(\frac{r}{r_s}\right)^2\right]^{-1}$



PL+exp.cutoff: $\rho(r) = \rho_s \left(\frac{r}{r_s}\right)^{-\gamma} \exp\left[-\frac{r}{r_s}\right]$



Difficulties:

- **dSphs are dark (but visible) in optical wavelength.**

  e.g. DES collaboration, 2015

- **We need precise spectroscopic observations.**

  If not, we have to rely on the scaling relation.

- **We should remove the foreground contamination.**

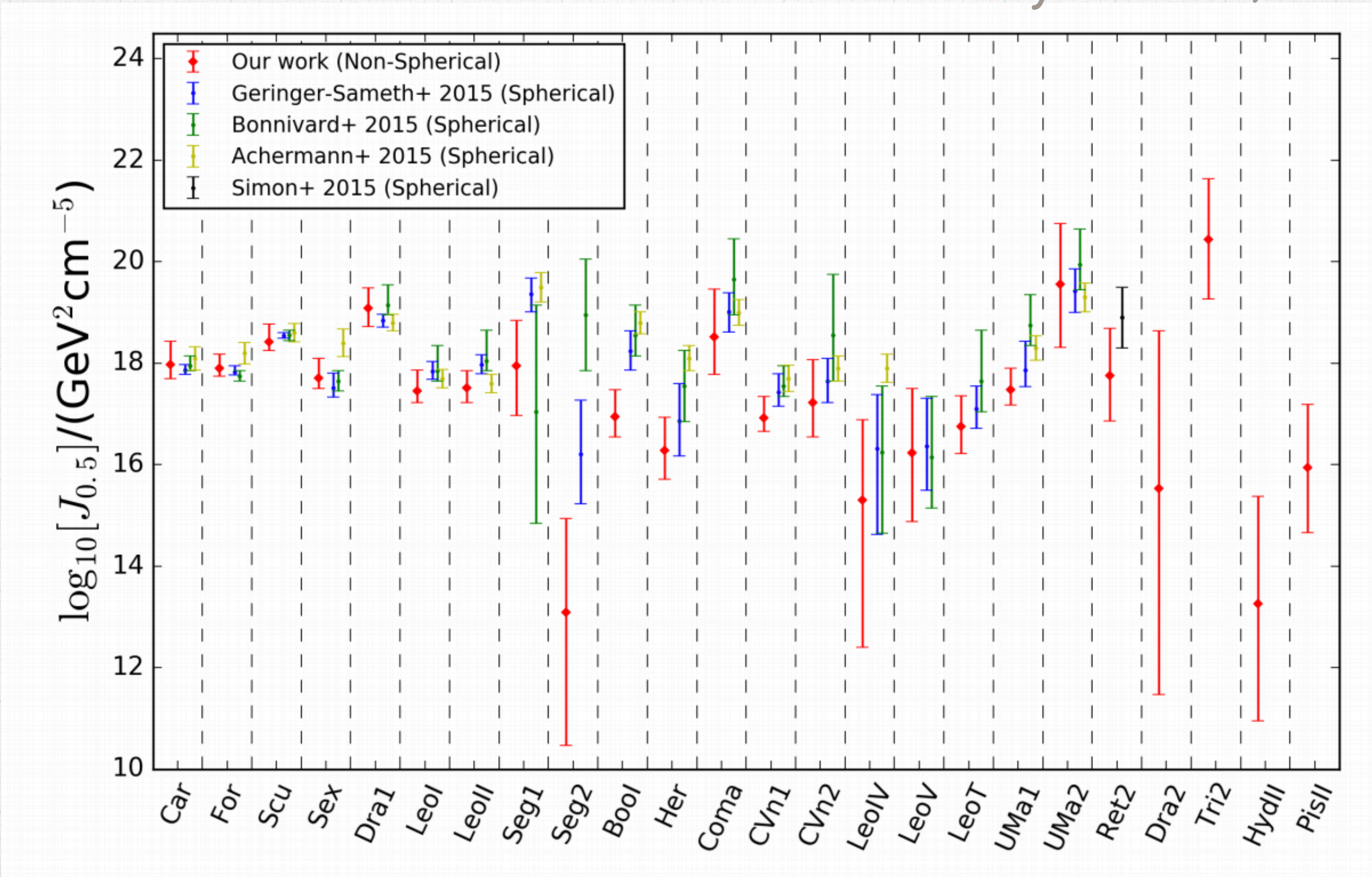
  e.g. Ichikawa et al., 2017

- **Many models for both of the stellar and DM density distributions**

  For DM, we have NFW, Burkert, …

Current understanding:

Hayashi et al., 2016



Outcomes

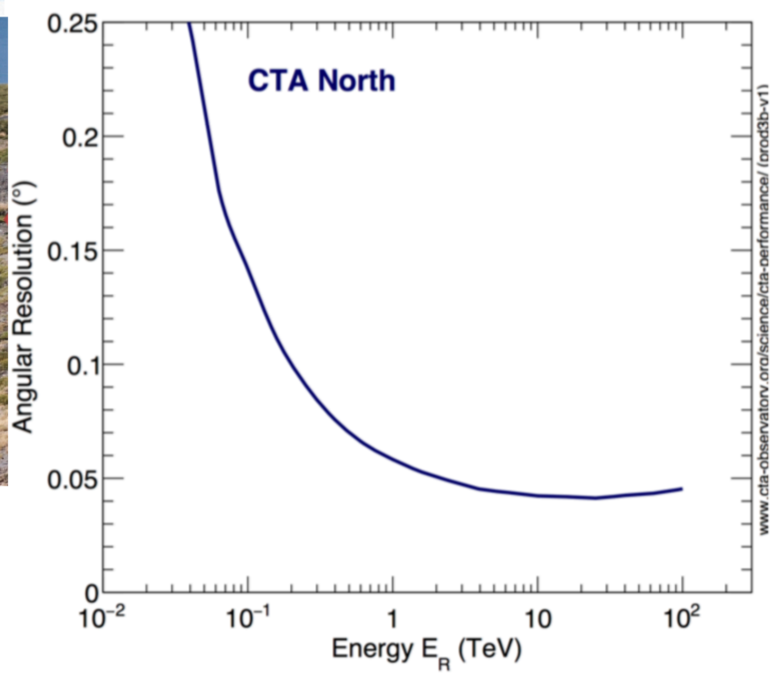
How does it affect the gamma-ray search of WIMP?

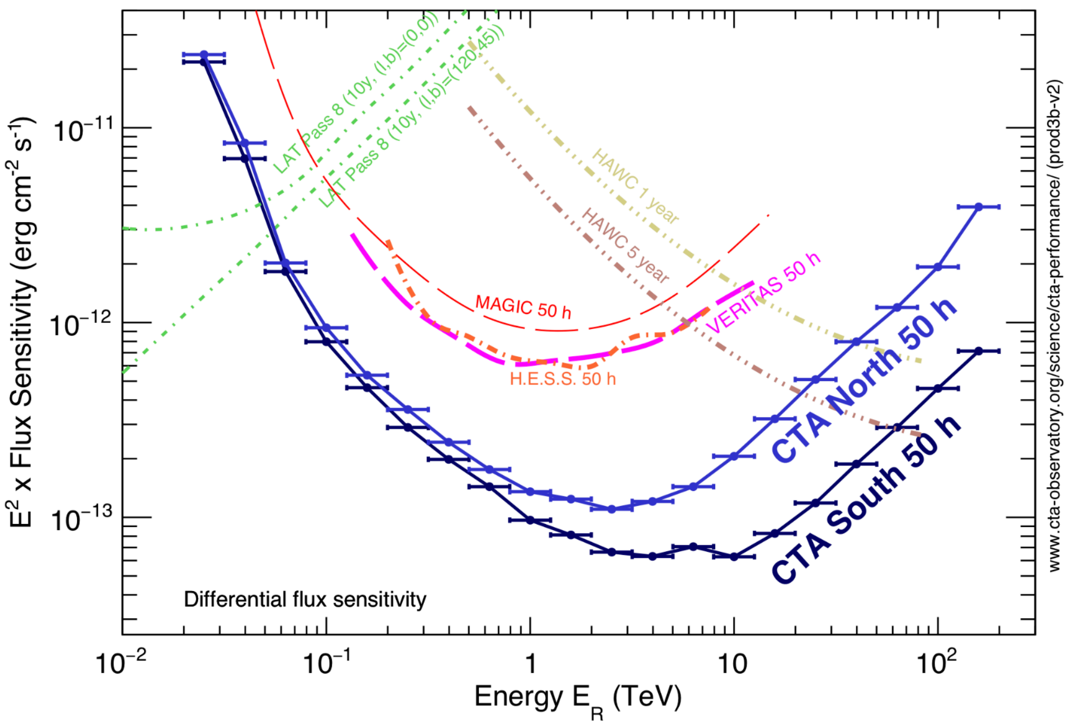
We now have…

- varieties of models for DM distribution in dSphs
- infinite number of models of DM annihilation spectrum from particle theories
- accessibility to the GeV-TeV γ-ray photons from DM annihilations with on-going (e.g. Fermi-LAT, MAGIC, HESS, …) and future experiments

WIMP search with γ-ray in 2020s:

Northern Hemisphere Site Rendering; credit: Gabriel Pérez Diaz, IAC





We can probe TeV WIMP with high angular-resolution facilities!

WIMP search in dSphs with CTA

- Our accessibility enhances by orders at $\mathcal{O}(1)$ TeV.
- dSphs are good targets of low-background and moderately high J-factor.
- **The typical angular size of the dSphs are much larger than the angular resolution of the CTA facilities.**

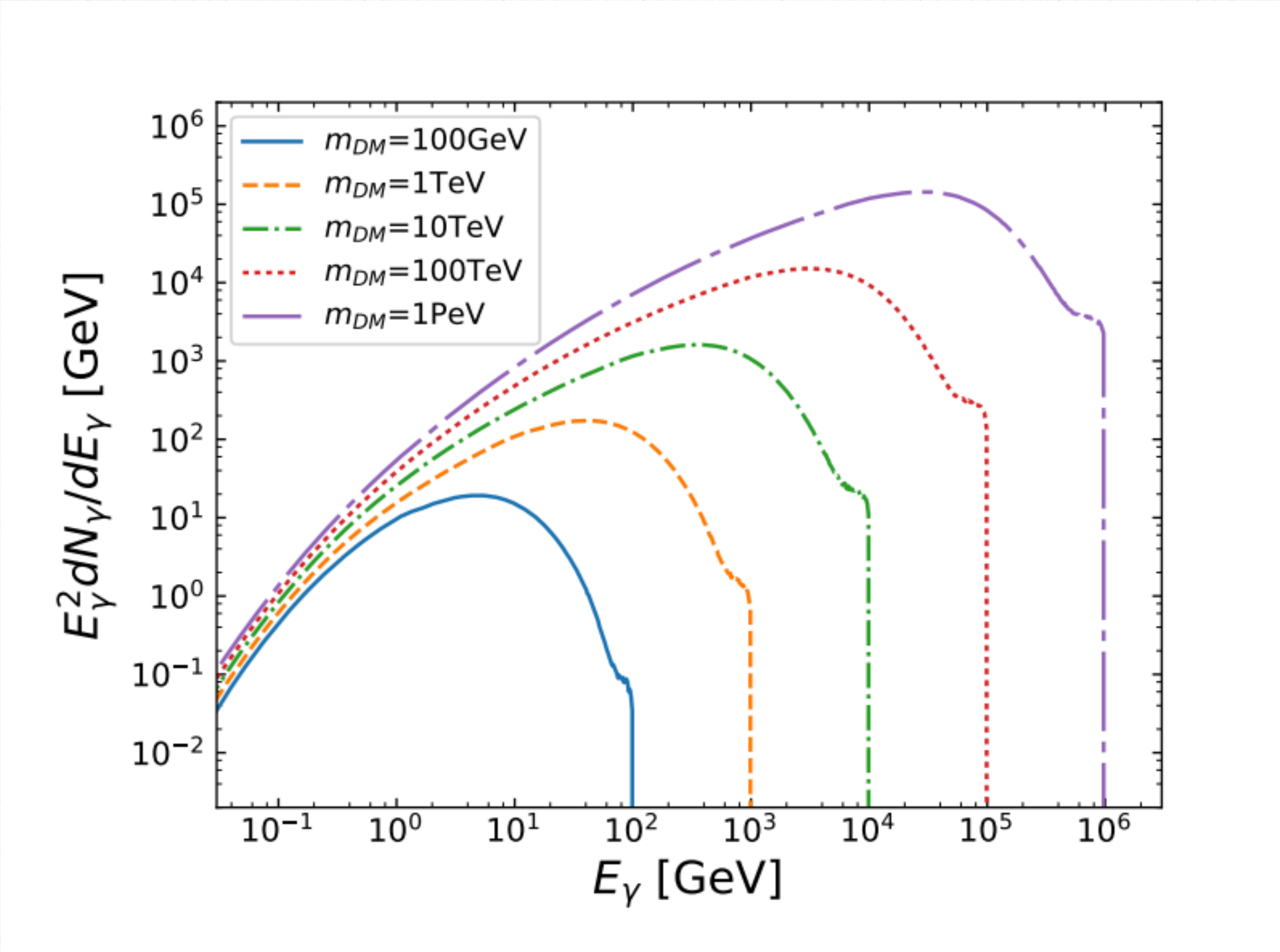
We should go beyond the $J_{\rm tot} = \int_{\Delta\Omega} d\Omega \frac{dJ}{d\Omega}$

Test case: Draco dSph

- (RA, DEC) = (260.052,57.915)
- $d \sim 80$ kpc
- # of stars ~ 1000
- radius of the outermost star $\theta_{\rm max} \sim 1.3$ deg
- $\mathrm{J} \sim \mathcal{O}(10^{19})\ \mathrm{GeV^2 cm^{-5}}$

We collect 16 spherical models of $\rho_{\rm DM}$ for this dSph.

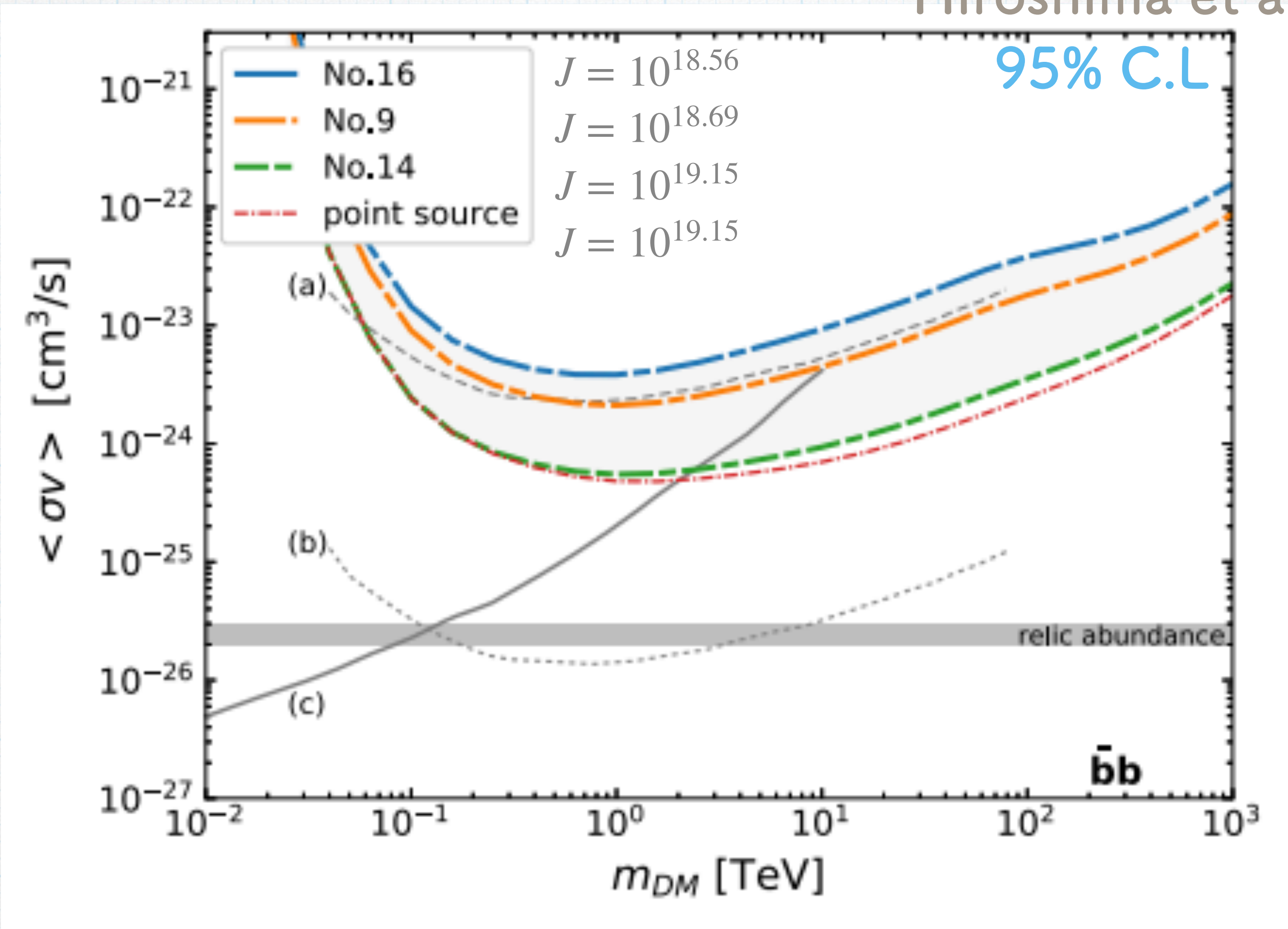
Spectrum:



e.g.) $\mathrm{DM} + \mathrm{DM} \to \bar{b}b$

Our accessibility:

Hiroshima et al., 2019



Conclusion

Conclusion:

- We can access TeV WIMP by taking indirect strategies.
- dSphs are good regions to see for gamma-ray experiments with high J-factor and low bkg.
- The J-factor is derived using stellar kinematics data.
- The J-factor of some dSphs are determined in the accuracy of the factor, while only in the order for the others (especially for the newer dSphs).
- The spatial distribution as well as the its integral of the J-factor is important for future facilities.