Gamma-ray Search of Dark Matter

Nagisa Hiroshima
Univ. of Toyama, RIKEN iTHEMS
Contents:

1. Introduction
   advantage of the gamma-ray observations

2. To probe heavier WIMP
   facility, target, and the problems

3. Future prospects
   convolution of the instrumental response and models

4. Conclusion
Introduction

advantage of gamma-ray observations
DM Motivation & Candidate

DM = non-baryonic matter in the Universe of $\Omega_{DM} h^2 \sim 0.12$

- **motivation**
  - structure formation
  - rotation curves
  - bullet cluster
  - ...

- **candidate**
  - Weakly Interacting Massive Particle (WIMP)
  - Strongly (or self) Interacting Massive Particle (SIMP)
  - axion/axion-like particle (ALP)
  - primordial black hole (PBH)
  - ...
WIMP

- feel the gravity (massive)
- the mass $m_{\text{DM}} \sim \mathcal{O}(\text{GeV}) - \mathcal{O}(\text{TeV})$
- freeze-out scenario to achieve the relic abundance $\Omega_{\text{DM}} h^2 \sim 0.12$
- the annihilation cross-section $\langle \sigma v \rangle \sim \mathcal{O}(10^{-26} \text{cm}^3 \text{s}^{-1})$

We do not see the annihilation signature yet.
Three pillars of WIMP search

collider

DM

SM

DM

SM

direct detection

indirect detection
Indirect detections

\[ \text{DM} + \text{DM} \rightarrow \text{something in the SM} \]

- somewhere in the Universe
- on/around the Earth
  - \( \gamma, e^\pm, p, \bar{p}, \nu, \ldots \)

- \( \gamma \)-ray search
  - straight path from the source to the Earth
  - absorption is negligible at \( z \lesssim 0.1 \) for \( E_\gamma \lesssim 1 \text{TeV} \)
  - all the SM particle associates photons at the production
Current limits for WIMP

Fermi-LAT, 11y, 27 dwarf spheroidal galaxies (dSphs)

Hoof et al., 2020

$\sim 3 \times 10^{-26} \text{cm}^3/\text{s}$
To probe heavier WIMP

facility, target, and the problems
Current limits for WIMP

Fermi-LAT, 11y, 27 dwarf spheroidal galaxies (dSphs)

Hoof et al., 2020

Canonical

$\sim 3 \times 10^{-26} \text{cm}^3/\text{s}$
Probing the heavier
Cherenkov Telescope Array (CTA)

Imaging Atmospheric Cherenkov Telescope (IACT)

incoming $\gamma$-ray + atoms

$\rightarrow e^+ + e^- \rightarrow \gamma + \ldots$

$\rightarrow e^+ + e^- + \ldots$

optical telescope array on the ground

$\rightarrow$ high angular resolution!
Comparison

<table>
<thead>
<tr>
<th></th>
<th>Fermi</th>
<th>CTA</th>
</tr>
</thead>
<tbody>
<tr>
<td>type</td>
<td>satellite</td>
<td>IACT</td>
</tr>
<tr>
<td>observation</td>
<td>survey</td>
<td>pointing</td>
</tr>
<tr>
<td>energy coverage</td>
<td>20MeV-300GeV</td>
<td>30GeV-100TeV</td>
</tr>
<tr>
<td>energy resolution</td>
<td>&lt;8%</td>
<td>~10%</td>
</tr>
<tr>
<td>flux sensitivity</td>
<td>(10^{-12}) erg cm(^{-2}) s(^{-1}) (100GeV, 10year)</td>
<td>(10^{-13}) erg cm(^{-2}) s(^{-1}) (1TeV, 50h)</td>
</tr>
<tr>
<td>angular resolution</td>
<td>3.5-0.15deg</td>
<td>0.2-0.03deg</td>
</tr>
</tbody>
</table>

different properties & observing strategies
What we consider is…

We should be able to prove WIMP of $m_{DM} \gtrsim \mathcal{O}(1)$ TeV by observing dSphs with CTA!

• Observable

observable: $\gamma$-ray flux $\phi$

$$\phi = \frac{1}{2} \frac{1}{4\pi} \frac{\langle \sigma v \rangle}{m_{DM}^2} \int_{E_{th}}^{m_{DM}} dE \frac{dN}{dE} \cdot \int_{\Delta \Omega} d\Omega \int_{los} ds \rho_{DM}^2$$

particle physics

J-factor:

astrophysical part

$\phi \propto$ (integral of the squared DM density $\rho_{DM}^2 \sim J$)
dSphs: high $\rho_{DM}$ & inactive

- satellite of the Milky Way
- $\sim 40$ are confirmed

- $M \sim 10^{8-9} M_\odot$, $M/L \sim \mathcal{O}(10^3) M_\odot / L_\odot$

- do not show star formation activities

- dist $d \sim \mathcal{O}(100)$ kpc

- $\Delta \theta \lesssim \mathcal{O}(1 \text{deg})$

dSphs are resolved as extended sources with CTA!
density profile of dSphs

We should consider \( dJ/d\Omega \), rather than \( J \).

\[
J = \int_{\Delta \Omega} d\Omega \frac{dJ}{d\Omega} = \int_{\Delta \Omega} d\Omega \int_{l.o.s} ds \rho_{DM}^2(r)
\]

\( \rho_{DM}(r) \) ?

1. observe proper motion of stars distribution
2. derive the gravitational potential
3. reconstruct the density profile \( \rho_{DM}(r) \)

\( \cdots \) but dSphs are dark, i.e., limited numbers of stars are available for reconstructing \( \rho_{DM}(r) \)
Varieties of profiles

-(generalized) NFW

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

NFW: \((\alpha, \beta, \gamma) = (1,3,1)\)

-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

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

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

\[ \ln r \ \text{vs} \ \ln \rho_{DM}(r) \]
Example: Burkert

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

\( \ln r \) vs \( \ln \rho_{\text{DM}}(r) \)
Example: PL + exp.cutoff

\[ \rho(r) = \rho_s \left( \frac{r}{r_s} \right)^{-0} \exp \left[ -\frac{r}{r_s} \right] \]

\[ \ln r \text{ vs } \ln \rho_{DM}(r) \]

\[ \log_{10} J \text{ [GeV}^2{\text{/cm}^5}] \]
Intermediate summary

- $\gamma$-ray observation of dSphs is a powerful tool to probe the nature of WIMP.
- In near future, we can go heavier with CTA, with which we should see dSphs as extended sources.
- Then we have to be careful about the DM distribution in target dSphs.
- However, it is difficult to model and still under debate.

We quantify the systematic errors in our sensitivity to DM annihilation cross-section with CTA coming from the DM distribution in dSphs
Future prospect
convolution of the instrumental response and models
## Ingredients

How does the density profile of the target dSph affect our sensitivity to the DM annihilation cross-section with CTA?

<table>
<thead>
<tr>
<th>Observable</th>
<th>Density Profiles of the Target</th>
<th>DM Annihilation Spectrum</th>
<th>γ-ray Flux (Observable)</th>
</tr>
</thead>
<tbody>
<tr>
<td>observer</td>
<td>Draco dSph, $J \sim \mathcal{O}(10^{19}\text{GeV}^2/\text{cm}^5)$</td>
<td>$\bar{b}b, W^+W^-, \tau^+\tau^-$</td>
<td>Simulation</td>
</tr>
</tbody>
</table>

16 patterns

hadronization

model
$\rho_{DM}$ models of Draco dSph

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

Draco is one of the best-studied dSphs
- 10 generalized NFW, 3 Burkert, 3 PL+cutoff profiles
- $\log_{10} J$ varies from 18.70 to 19.56 in our collection
2. DM annihilation spectra

- $\bar{b}b$ (quark)
- $W^+W^-$ (weak boson)
- $\tau^+\tau^-$ (lepton)

pythia8 for hadronization
(http://home.thep.lu.se/Pythia/)
3. $\gamma$-ray flux

c-tools: simulation and analysis software for VHE $\gamma$-ray observations (http://cta.irap.omp.eu/c-tools/)

- CTA-North, full array

IRF prod3b North, z20, average, 50h

- $4 \times 4$deg around Draco dSph

- position center

(RA, DEC) = (260.052, 57.915)

- 500 hour

- $E = 0.03 - 180$TeV photon

(example: 92188344 $\gamma$-ray like events w/o source)
Combine: likelihood ratio test

1. simulate 500 hours of observation @ Draco dSph
2. select data & bin the data
   0.03-180 TeV, 5 energy bin / decade
3. likelihood analysis assuming
   16 profiles * 3 annihilation channels = 48 models

Which is more likely,
… “DM signal of the model exists” or
“the data is consistent with the background”?
Our accessibility: $\bar{b}b$ case

Hiroshima et al., 2019

$J = 10^{18.56}$

$J = 10^{18.69}$

$J = 10^{19.15}$

$J = 10^{19.15}$

95% C.L
Our accessibility: $W^+W^-$ case

Hiroshima et al., 2019

95% C.L
Our accessibility: $\tau^+\tau^-$ case

Hiroshima et al., 2019

95% C.L
Conclusion
Conclusion:

- WIMP search at $E_\gamma \lesssim \mathcal{O}(1)$ TeV is already successful.
- dSphs are good targets to search the WIMP signature since they are rich in DM but poor in astrophysical $\gamma$.
- We can access heavier WIMP in the near future.
- With CTA, we can resolve dSphs as extended sources, hence their inner DM distribution becomes important.
- $\rho_{DM}$ of dSphs is still under debate.
- Convolved with the CTA’s instrumental response, it is sure that we can access new parameter spaces, however, our sensitivity could differ by a factor of $\sim 10$. 