Progress in Particle Physics 2026

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Impact of Dwarf Spheroidal Galaxy Non-Sphericity on CTAO Searches for Dark Matter Annihilation

Nagisa Hiroshima (Yokohama National U., iTHEMS RIKEN)

in collaboration with

K. Hayashi (NIT Sendai Col.) & T. Inada (Kyushu U.)

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keyword 2 Dwarf Spheroidal Galaxy

keyword 1 CTAO Searches

for Dark Matter Annihilation

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1. **indirect searches**

   speciality of γ-ray searches

2. **target selection**

   speciality of dwarf spheroidal galaxies (dSphs)

3. **analysis**

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1. indirect searches

our understanding

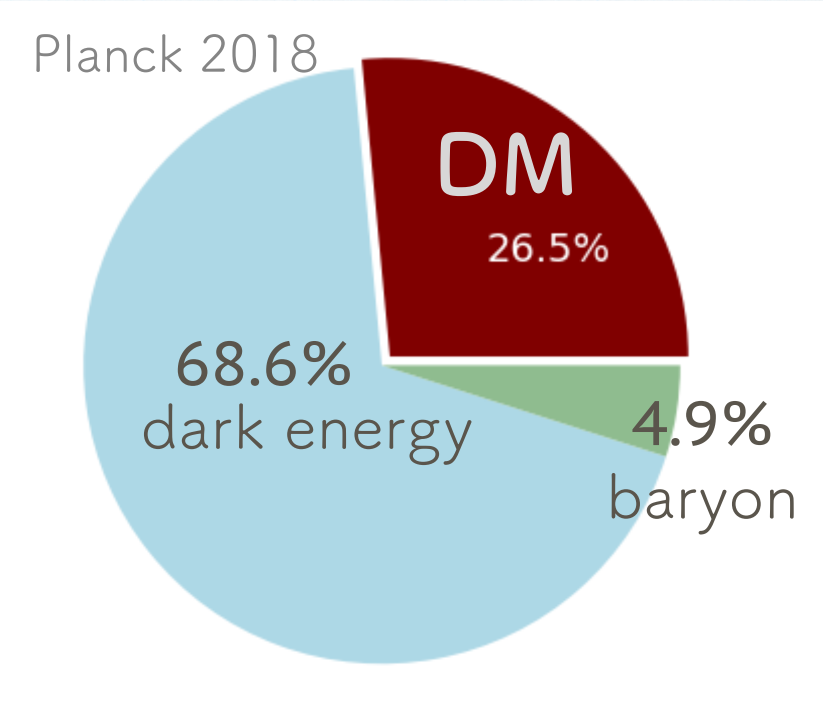
from cosmological/astrophysical observations …

- we need dark matter (DM)

which satisfies $\Omega_{\rm DM}h^2 \sim 0.12$

to realize our Universe.

- we know properties such as
  - feel gravity
  - non-relativistic, cold
  - form structures before baryons
  - almost invisible

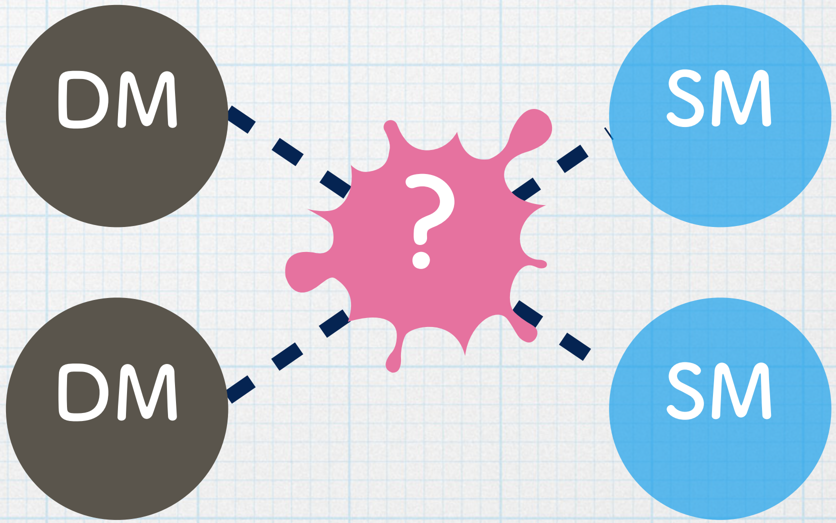


Common belief

DM can talk to the Standard Model sector through non-gravitational interactions.

candidates:

- Weakly Interacting Massive Particle (WIMP)
- Strongly/self- interacting massive particle (SIMP)
- sterile neutrino
- axion and/or axion-like particle (ALP)
- primordial black hole (PBH)…

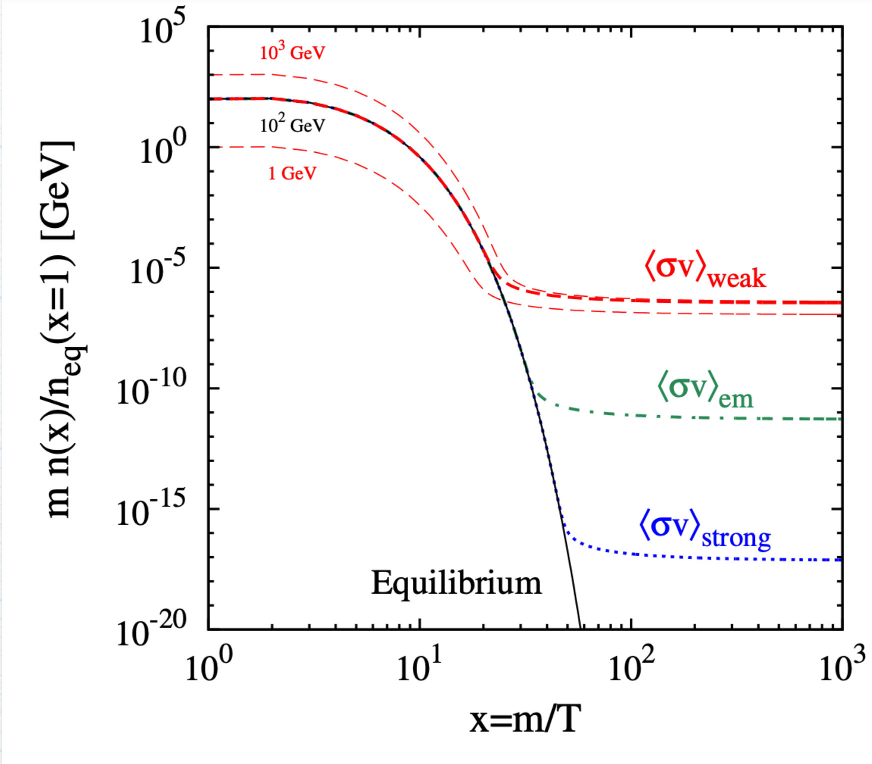


WIMP as a good example

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

DM + DM → SM + SM

Steigman et al.,2012,



cold DM property & DM annihilation channel exists

Indirect search

DM + DM $\longrightarrow$ something in the SM

somewhere in the Universe

on/around the Earth

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

Pros & Cons

- ◉ DM should be abundant in our Universe
- ◉ accessibility to heavy DM ($m_{\rm DM} \gtrsim \mathcal{O}(10)$ TeV)
- ◉ varieties of probe particles
- ✳ astrophysical emissions
- ✳ limited knowledge of propagation effects
- ✳ **limited knowledge of spatial distribution of DM**

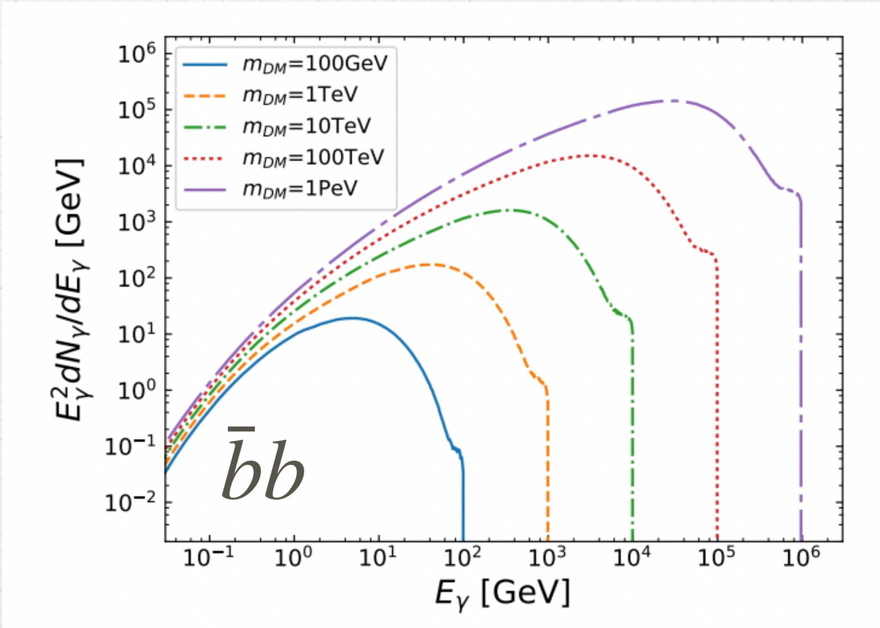
γ-ray search

DM + DM → something in the SM

somewhere in the Universe

$l^+l^-, \gamma \to W^\pm + \ldots \to \ldots$
$W^+W^- \to q\bar{q} + \ldots \to \ldots$
$b\bar{b} \to \pi^0 + \ldots \to 2\gamma + \ldots$

- all the SM particle associates photon productions
- straight path from the source to the Earth
- absorption is negligible at $z \lesssim 0.1$ for $E_\gamma \lesssim$ 10TeV

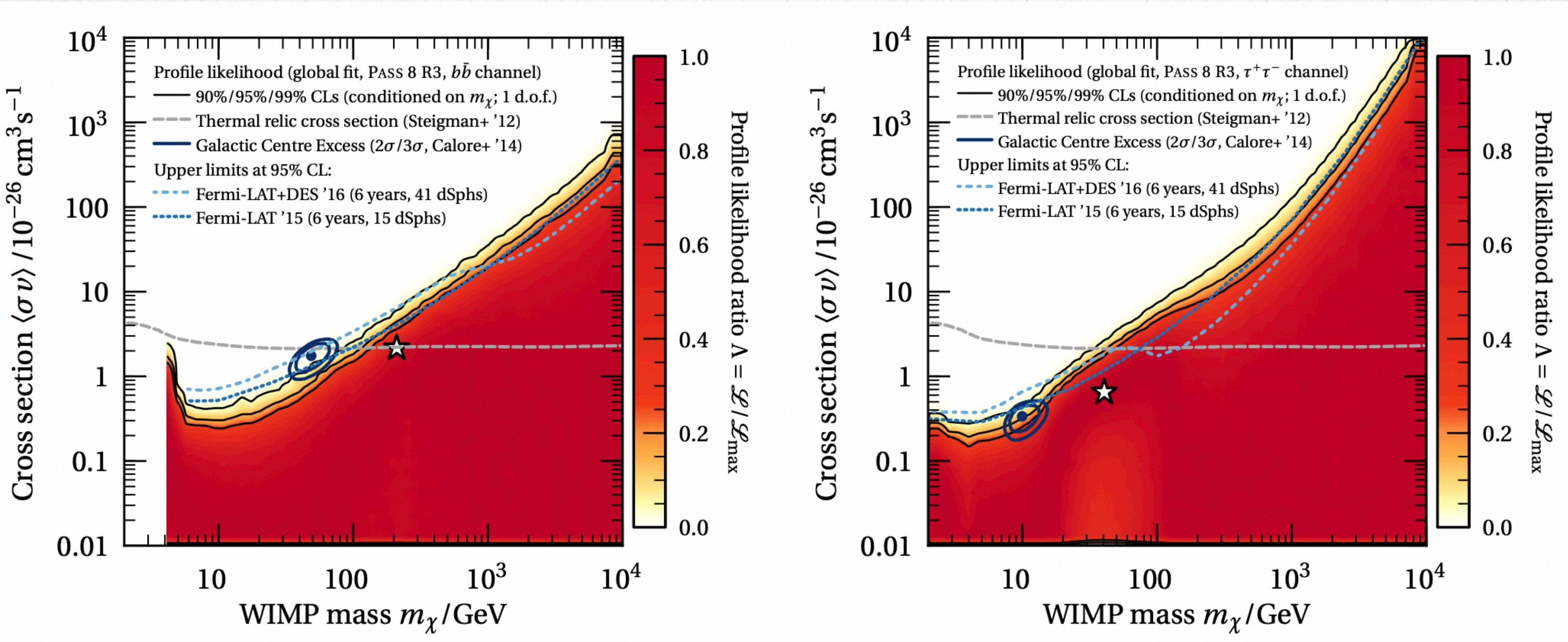


Hiroshima et al., 2019

e.g.) constraints using Fermi-LAT data

Fermi-LAT, Pass 8, 27 dSphs

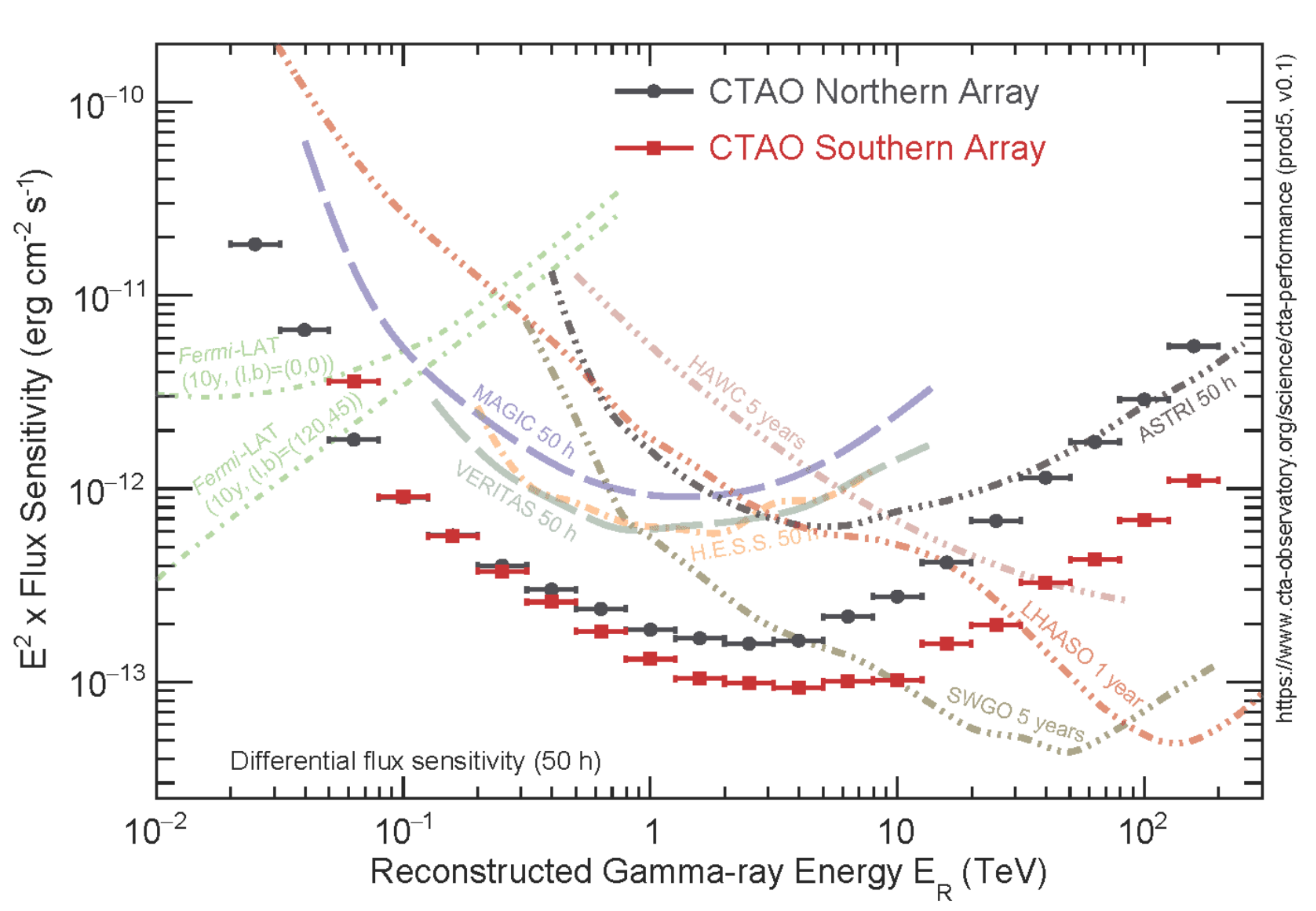
Hoof et al.,2020



$\bar{b}b$ $\qquad\qquad$ $\tau^+\tau^-$

keyword 1: CTAO

Cherenkov Telescope Array Observatory

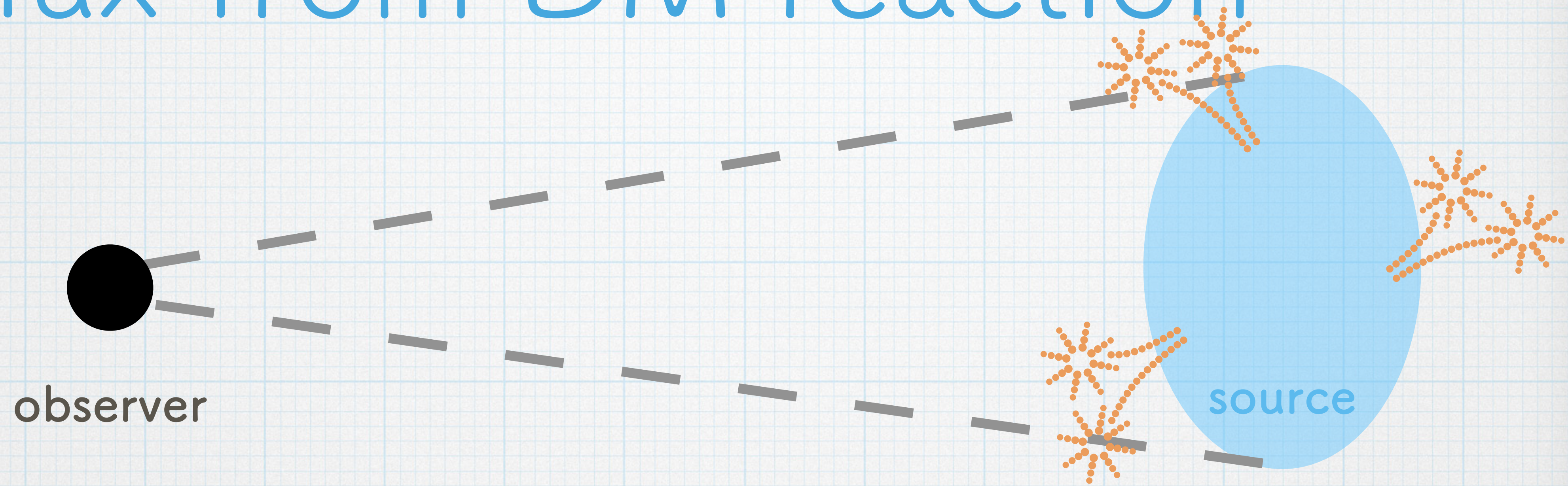


cf. comparison

	Fermi	CTAO
type	satellite	IACT
observation	survey	pointing
energy coverage	20MeV-300GeV	**30GeV-100TeV**
energy resolution	<8%	~10%
flux sensitivity	10^{-12} erg cm^{-2} s^{-1} (100GeV, 10year)	10^{-13} erg cm^{-2} s^{-1} (1TeV, 50h)
angular resolution	3.5-0.15deg	**0.2-0.03deg**

2. target selection

flux from DM reaction



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

$$\phi_{\rm decay} = \frac{1}{4\pi}\boxed{\frac{\Gamma}{m_{\rm DM}}\int_{E_{\rm th}}^{m_{\rm DM}} dE\frac{dN}{dE}}\cdot\boxed{\int_{\Delta\Omega} d\Omega \int_{los} ds\ \rho_{\rm DM}}$$

particle physics part

astrophysical part

J-factor/D-factor

where to observe?

$$\phi \propto J = \int_{\Delta\Omega} d\Omega \int_{l.o.s} ds \rho_{\mathrm{DM}}^2 \quad J \leftrightarrow$$ **signal expectation**

- isotropic emissions
- Galactic Center ($J \sim \mathcal{O}(10^{22})\mathrm{GeV}^2/\mathrm{cm}^5$)
- **dwarf spheroidal galaxies** ($J \lesssim \mathcal{O}(10^{19})\mathrm{GeV}^2/\mathrm{cm}^5$)
- galaxy clusters

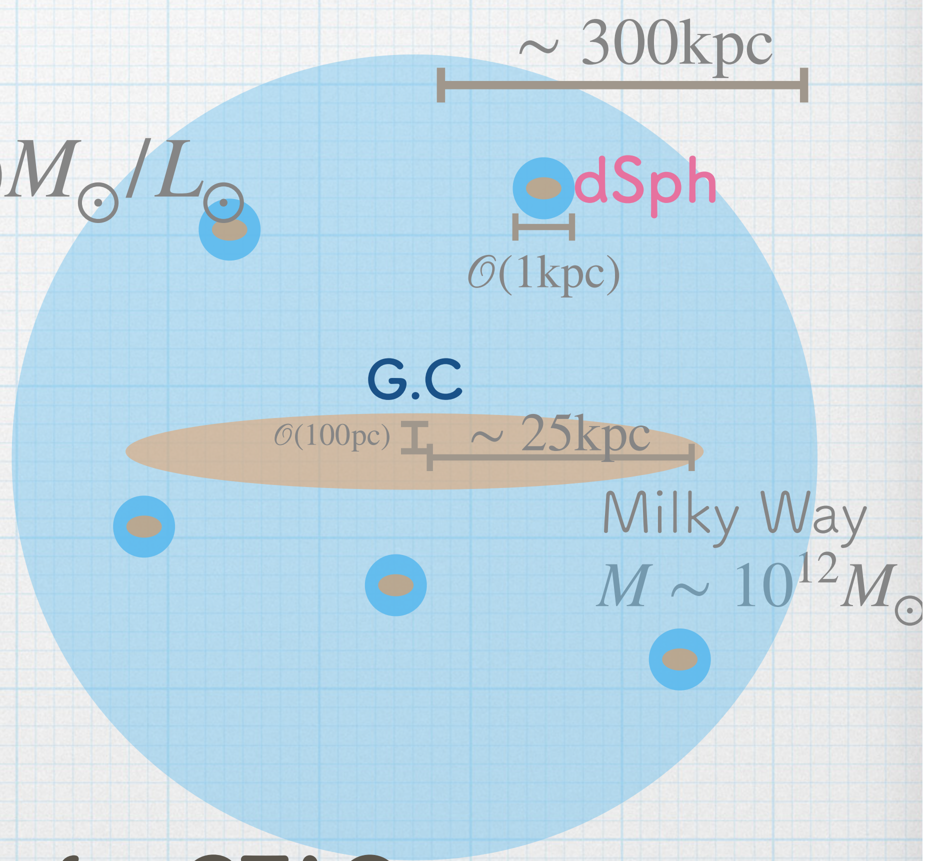
target selection = J-factor value +

- astrophysical contamination
- accuracy of J-factor estimate
- properties of facilities
- analysis cost
- ...

keyword 2: dSph

dwarf spheroidal galaxies

- satellite of the Milky Way
- more than 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
- $\Delta\theta \lesssim \mathcal{O}(1\mathrm{deg})$



extended sources for CTAO

3. analysis

$\rho_{\rm DM}$ determination

1. measure the line-of-sight velocities of stars in dSphs
2. derive the gravitational potential
3. reconstruct the density profile $\rho_{\rm DM}(r)$

previous analysis: **spherical** assumption vs real morphology: **spheroidal**

Ursa Minor

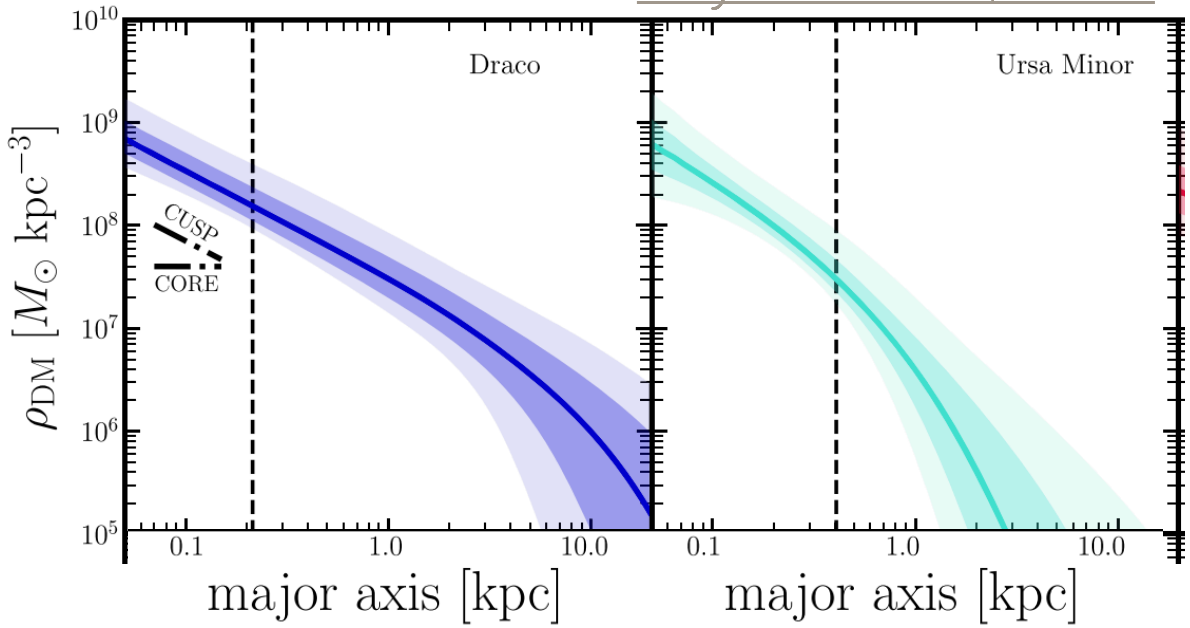
axisymmetric Jeans analysis

- stellar profile $\rho_*(r_*) = \dfrac{3L}{4\pi r_p^3}\left[1 + (r_*^2/r_p^2)\right]^{-5/2}$, $r_*^2 = R^2 + z^2/q^2$

- DM profile $\rho_{\rm DM}(r) = \dfrac{\rho_s}{(r/r_s)^\gamma\left[1+(r/r_s)^\alpha\right]^{(\beta-\gamma)/\alpha}}$, $r^2 = R^2 + z^2/Q^2$

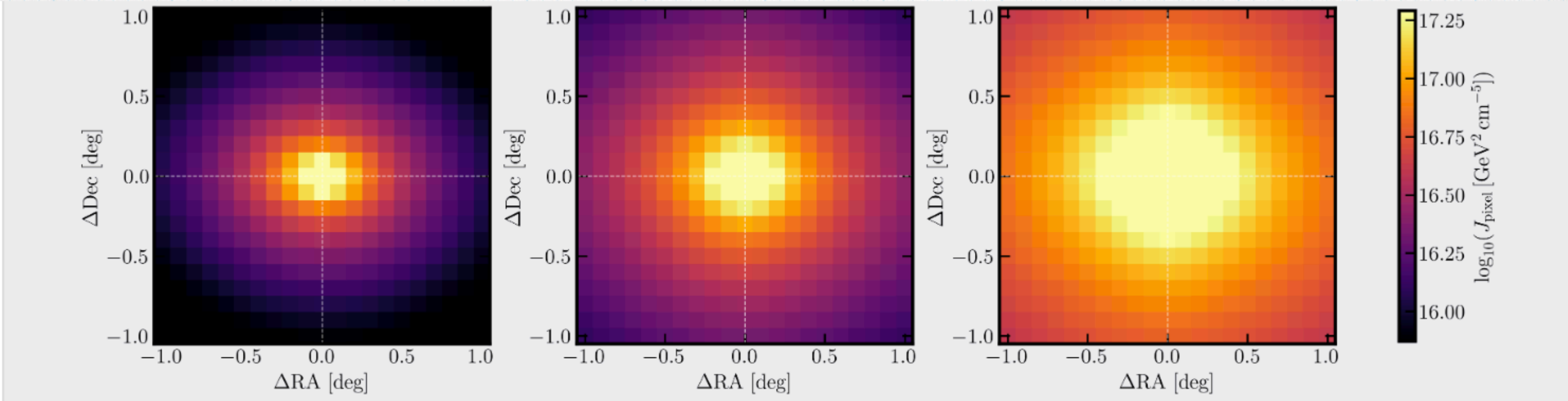
axisymmetric
Jeans analysis

Hayashi et al., 2020

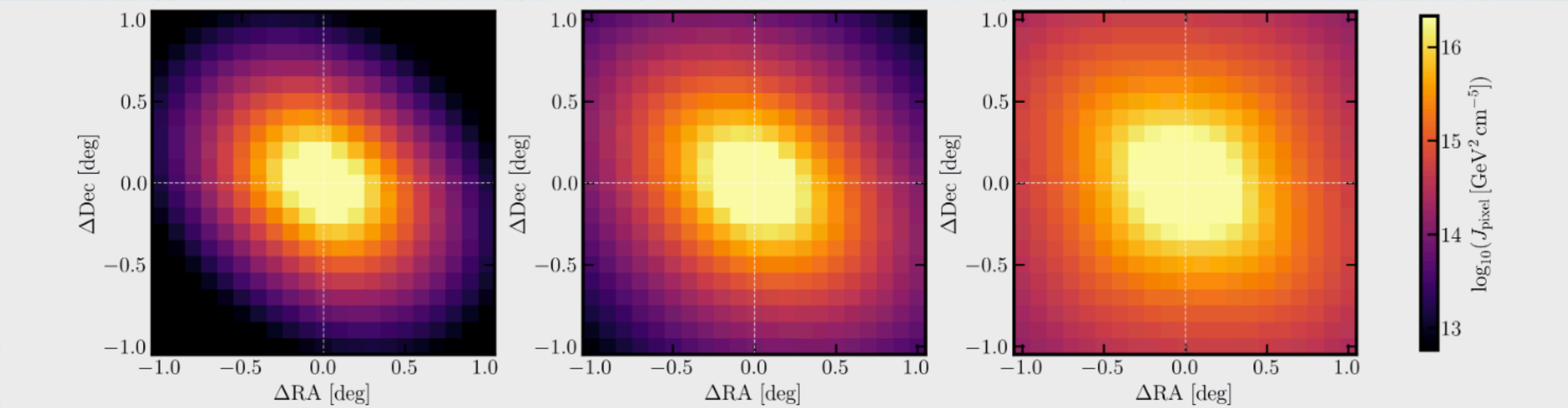


profile map

Draco



Ursa Minor



γ-ray data analysis

- 100h for each dSph (classical dSph, 8 objects)
- 60 seed, bkg only, $2^\circ \times 2^\circ$ for each dSph
- template model: axisymmetric
- spectrum model: $b\bar{b}$, W^+W^-, $\tau^+\tau^-$, 2γ
- observation at zenith angle $20^\circ - 60^\circ$
- $E_\gamma = [0.02, 150]$ TeV

likelihood analysis with Gammapy-ver2.1,
CTAO IRF Prod5-ver.0.1

4. summary

Summary

- Plenty of theoretical/observational supports exist for accelerate indirect searches of DM.
- Among various targets, dSphs are good to see in γ-rays with little astrophysical emissions.
- CTAO should powerfully probe candidates in regimes of $E \gtrsim \mathcal{O}(1)$TeV with high angular resolution.
- With the angular resolution of the CTAO facilities, non-sphericity of target dSphs have non-negligible impacts on sensitivity.