Progress in Particle Physics 2020

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Gamma-ray Search of Dark Matter

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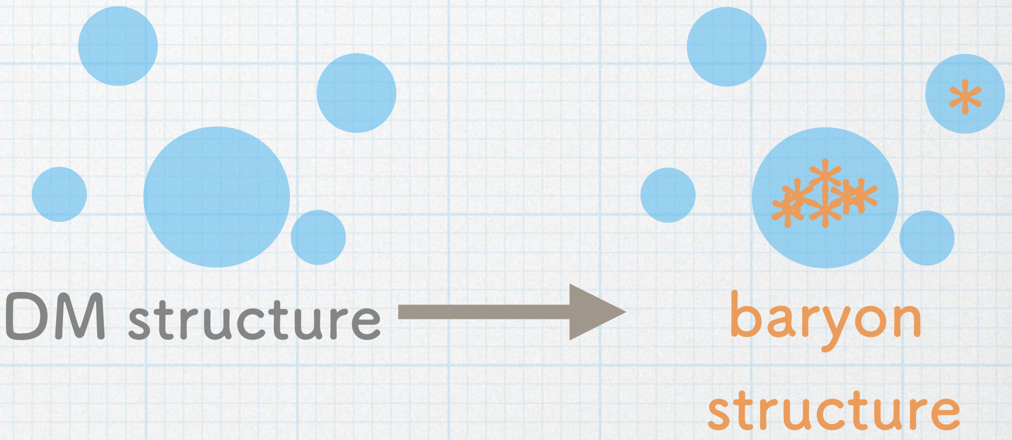
Introduction

advantage of gamma-ray observations

DM Motivation & Candidate

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

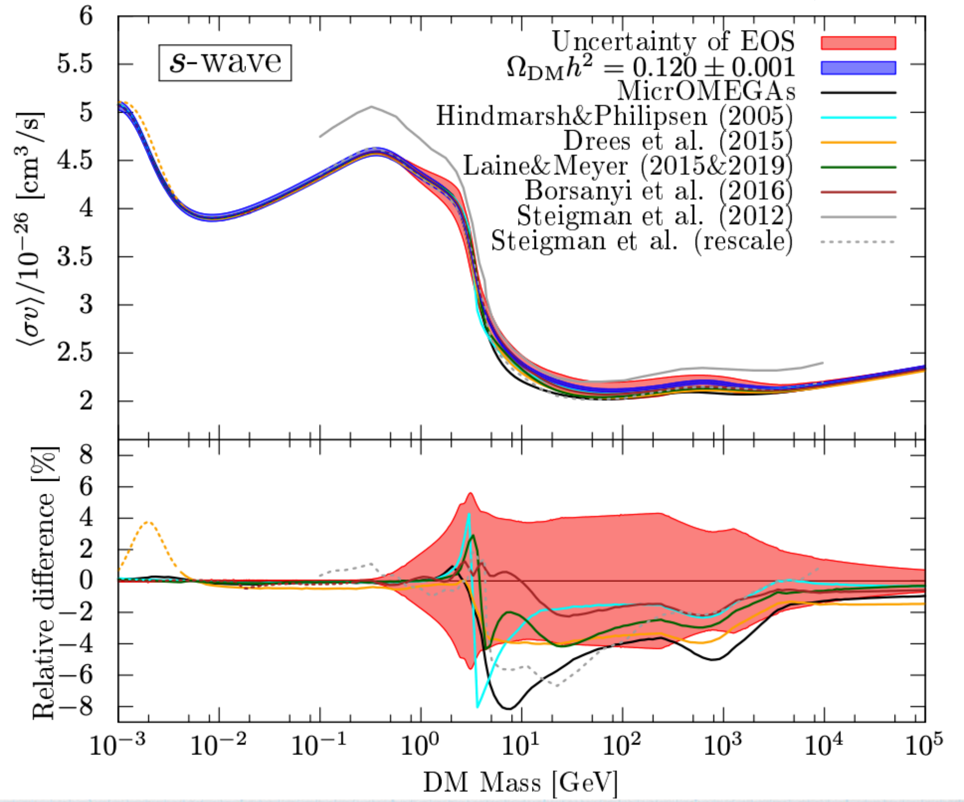
- motivation
  - structure formation
  - rotation curves
  - bullet cluster
  - …



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

WIMP

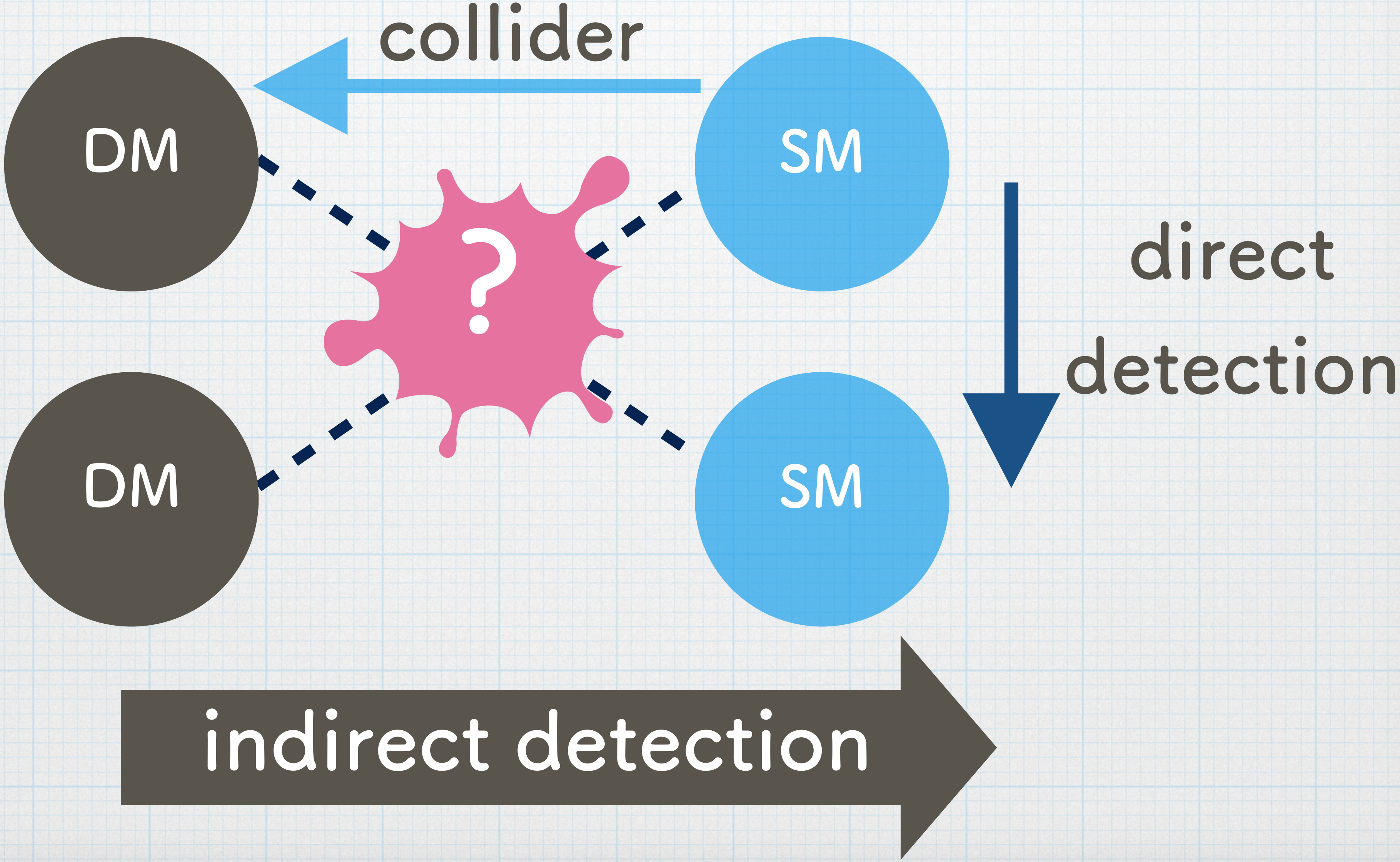
- feel the gravity (massive)
- the mass $m_{\rm DM} \sim \mathcal{O}(\rm GeV) - \mathcal{O}(\rm TeV)$
- freeze-out scenario to achieve the relic abundance $\Omega_{\rm DM}h^2 \sim 0.12$
- the annihilation cross-section $\langle \sigma v \rangle \sim \mathcal{O}(10^{-26}{\rm cm}^3 s^{-1})$



Saikawa & Shirai, 2020

We do not see the annihilation signature yet.

Three pillars of WIMP search



collider

DM

DM

?

SM

SM

direct detection

indirect detection

Indirect detections

DM + DM → **something in the SM**

somewhere in the Universe

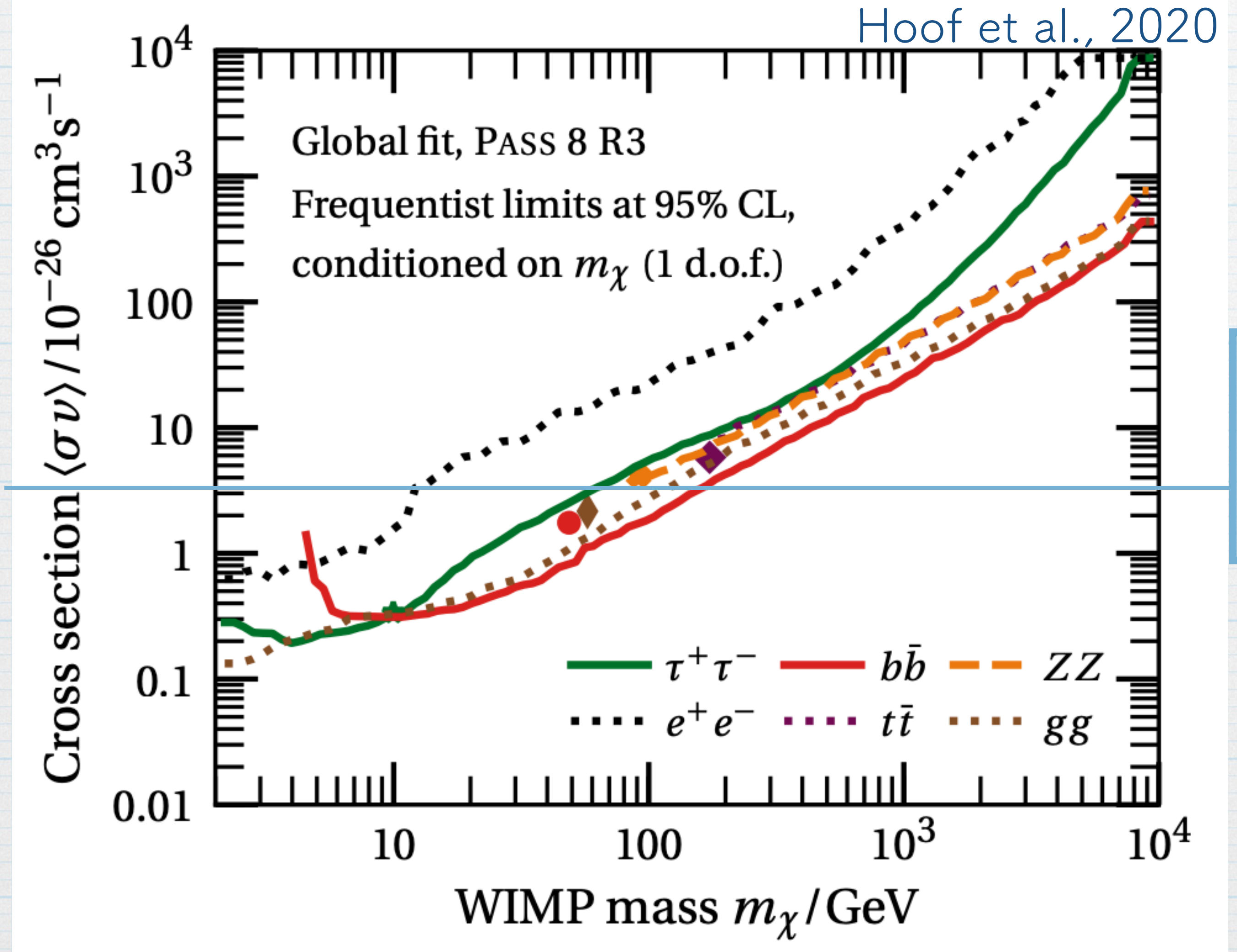
on/around the Earth

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

- γ-ray search
  - straight path from the source to the Earth
  - absorption is negligible at $z \lesssim 0.1$ for $E_\gamma \lesssim$ 1TeV
  - 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

canonical

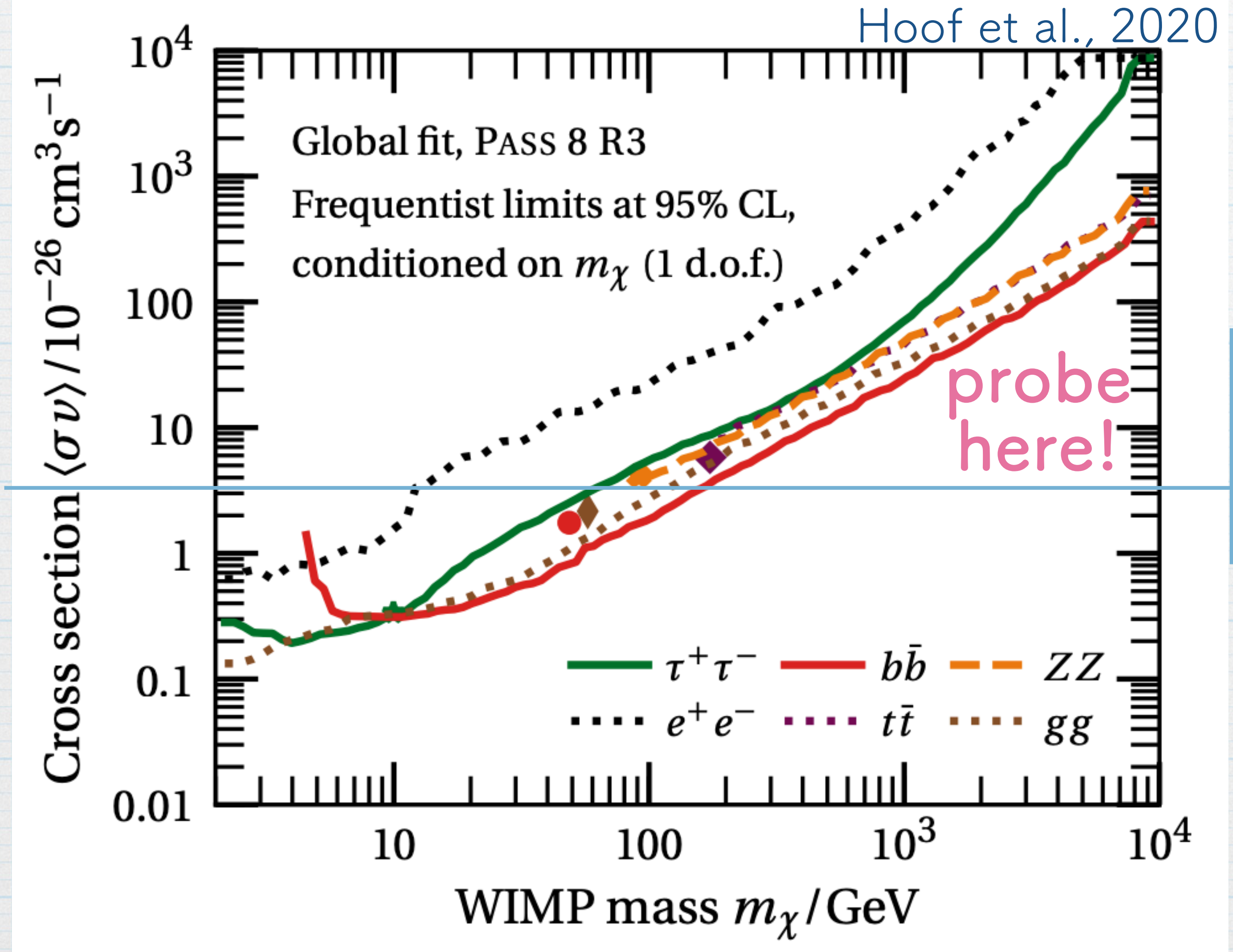
$\sim 3\times10^{-26}\mathrm{cm}^3/s$

To probe heavier WIMP

facility, target, and the problems

Current limits for WIMP

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



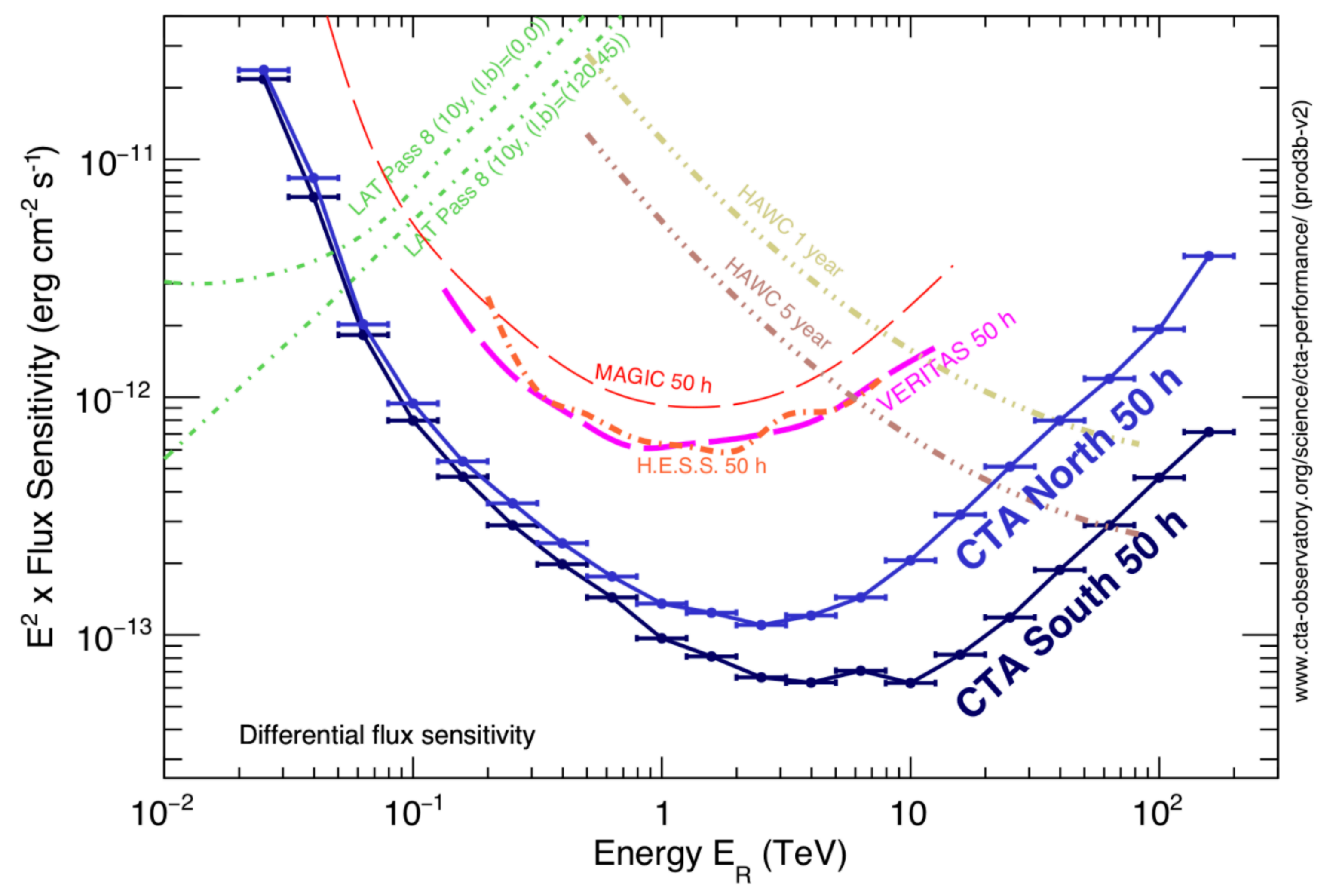
Hoof et al., 2020

probe here!

canonical

$\sim 3\times10^{-26}\mathrm{cm}^3/s$

Probing the heavier



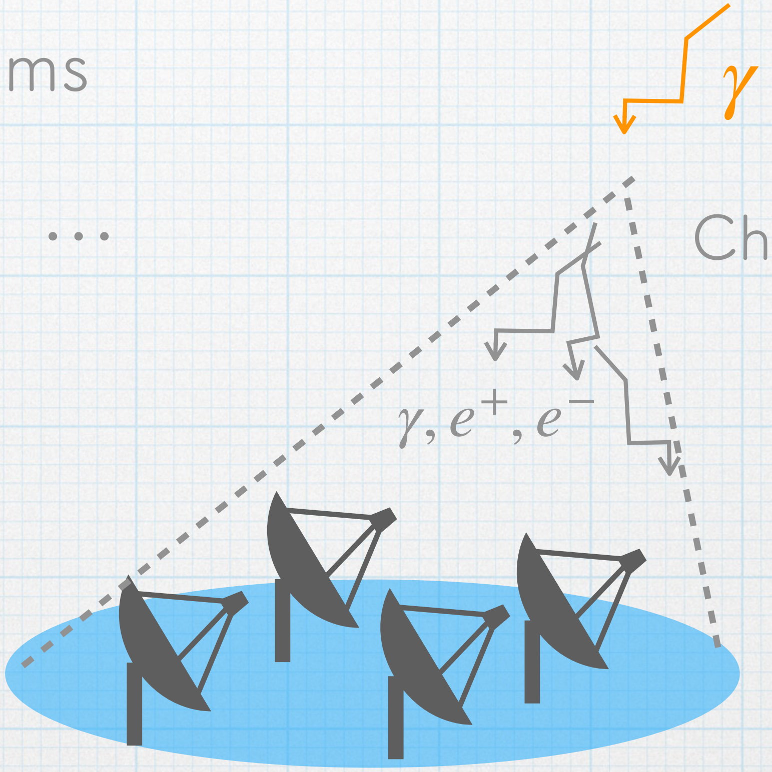
Cherenkov Telescope Array (CTA)

Imaging Atmospheric Cherenkov Telescope (IACT)

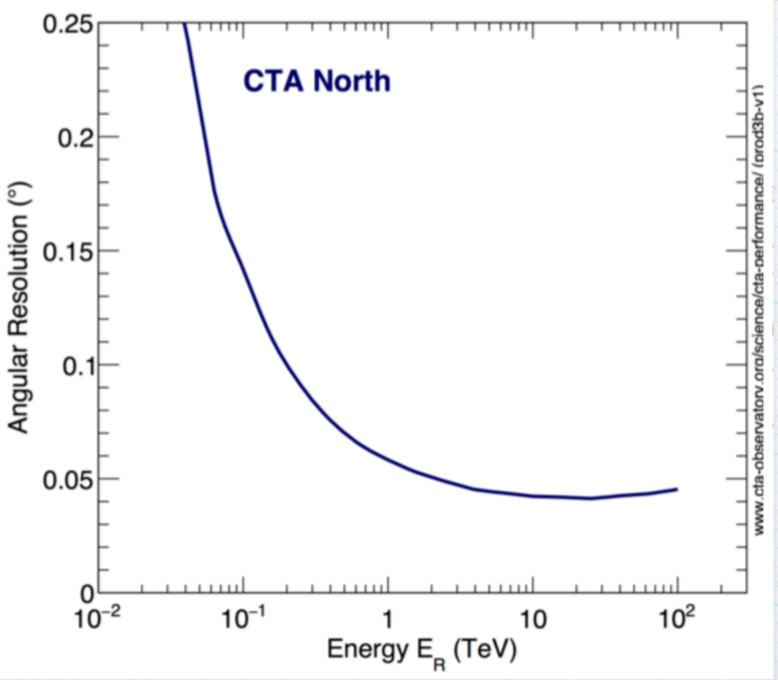
incoming γ-ray + atoms

$$\rightarrow e^{+} \; + \; e^{-} \rightarrow \gamma \; + \; \ldots$$

$$\rightarrow e^{+} \; + e^{-} \; + \ldots$$



Cherenkov light



optical telescope array on the ground

→high angular resolution!

Comparison

	Fermi	CTA
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

different properties & observing strategies

What we consider is···

We should be able to prove WIMP of $m_{\rm DM} \gtrsim \mathcal{O}(1)$ TeV

by observing dSphs with CTA!

- **Observable**

observable: γ-ray flux ϕ

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

particle physics

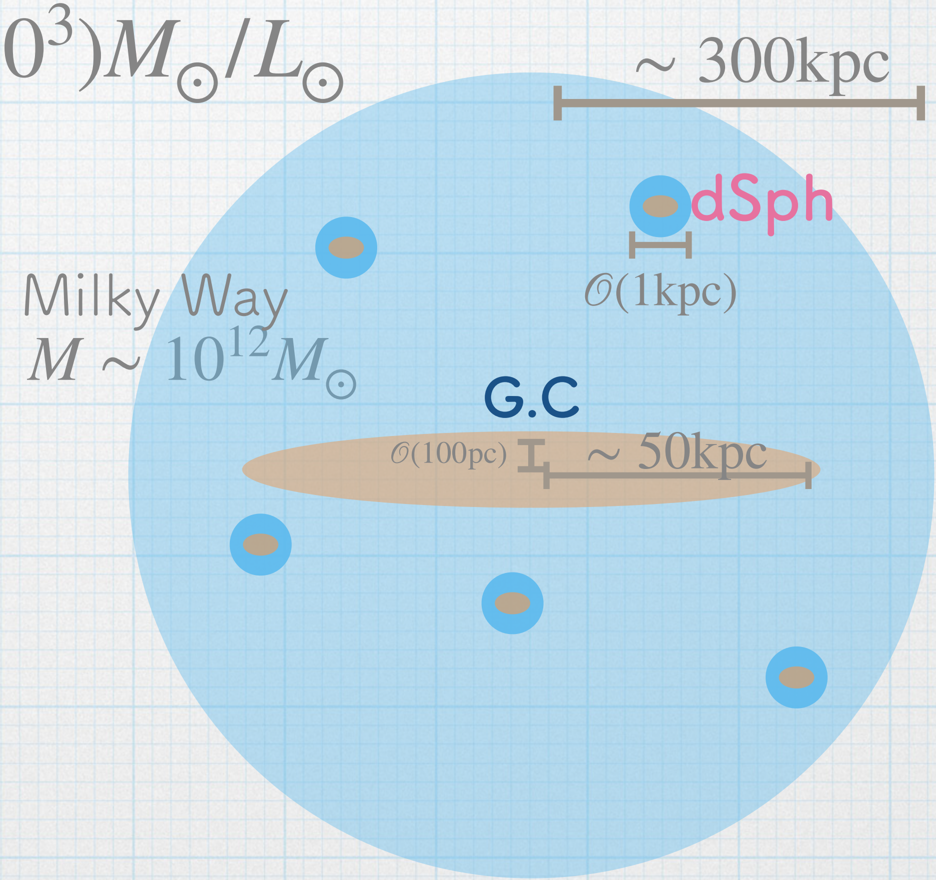
J-factor:

astrophysical part

$\phi \propto$ (integral of the squared DM density $\rho_{\rm DM}^2 \sim$ J

dSphs: high $\rho_{\rm DM}$ & inactive

- satellite of the Milky Way
- ~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.

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

- $\rho_{\mathrm{DM}}(r)$?

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

…but dSphs are dark, i.e., limited numbers of stars are available for reconstructing $\rho_{\mathrm{DM}}(r)$

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

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

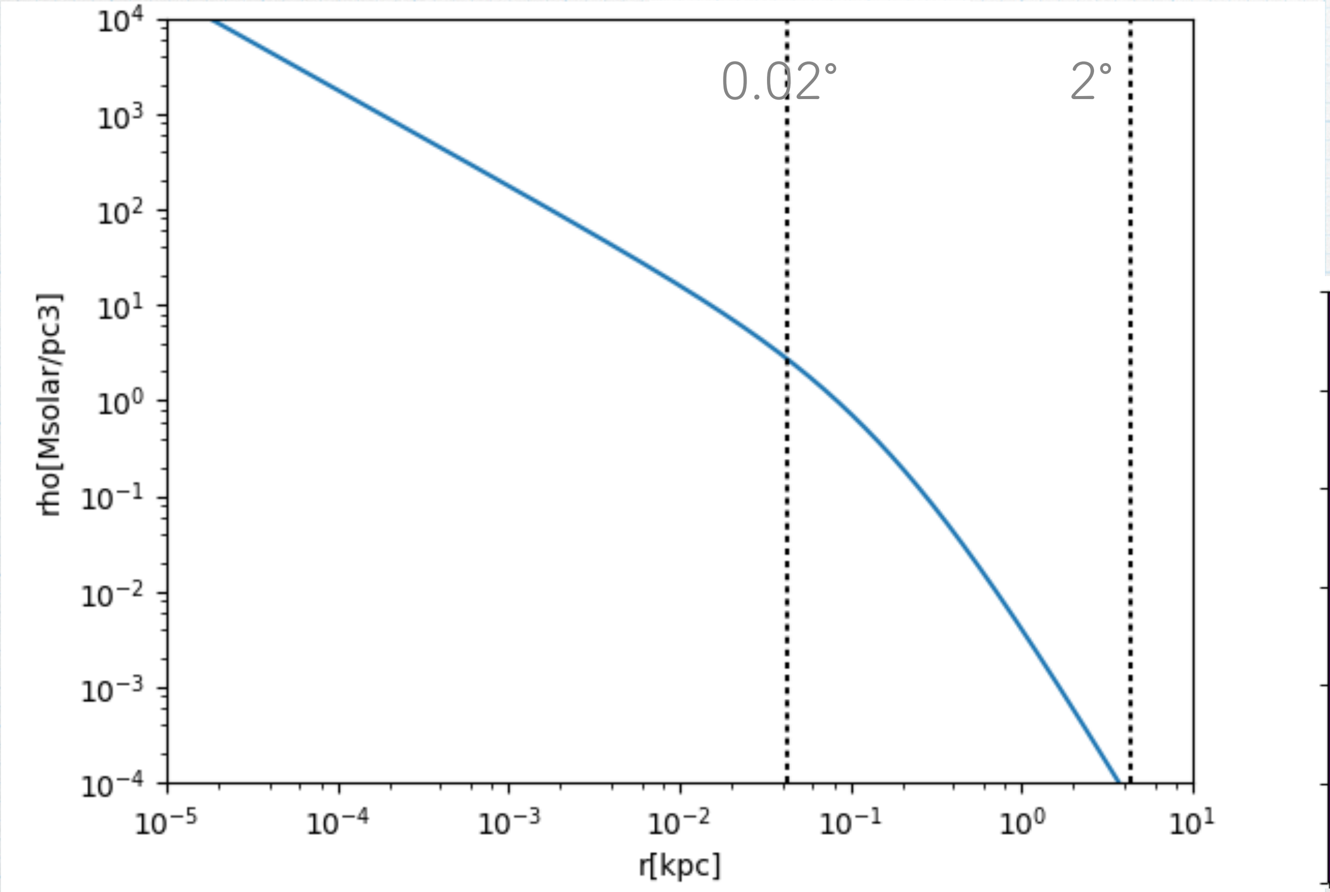
-Power Law (PL) + exp.cutoff

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

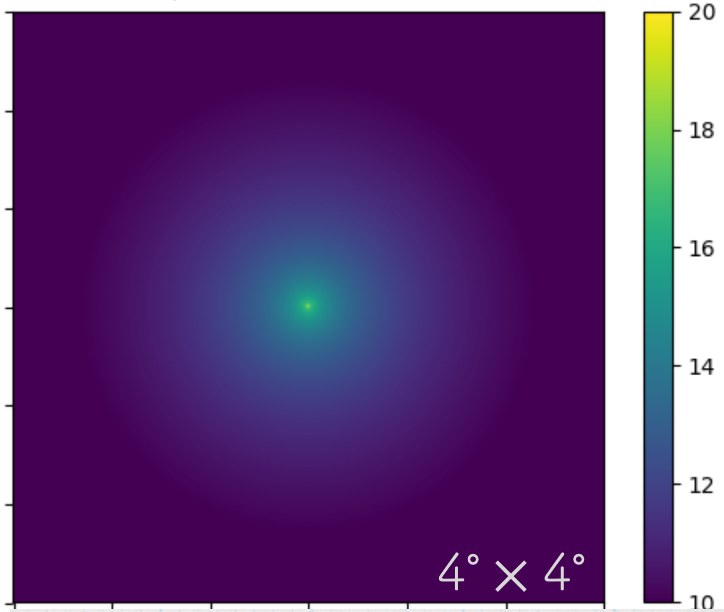
Example: NFW

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

$\ln r$ vs $\ln \rho_{\mathrm{DM}}(r)$



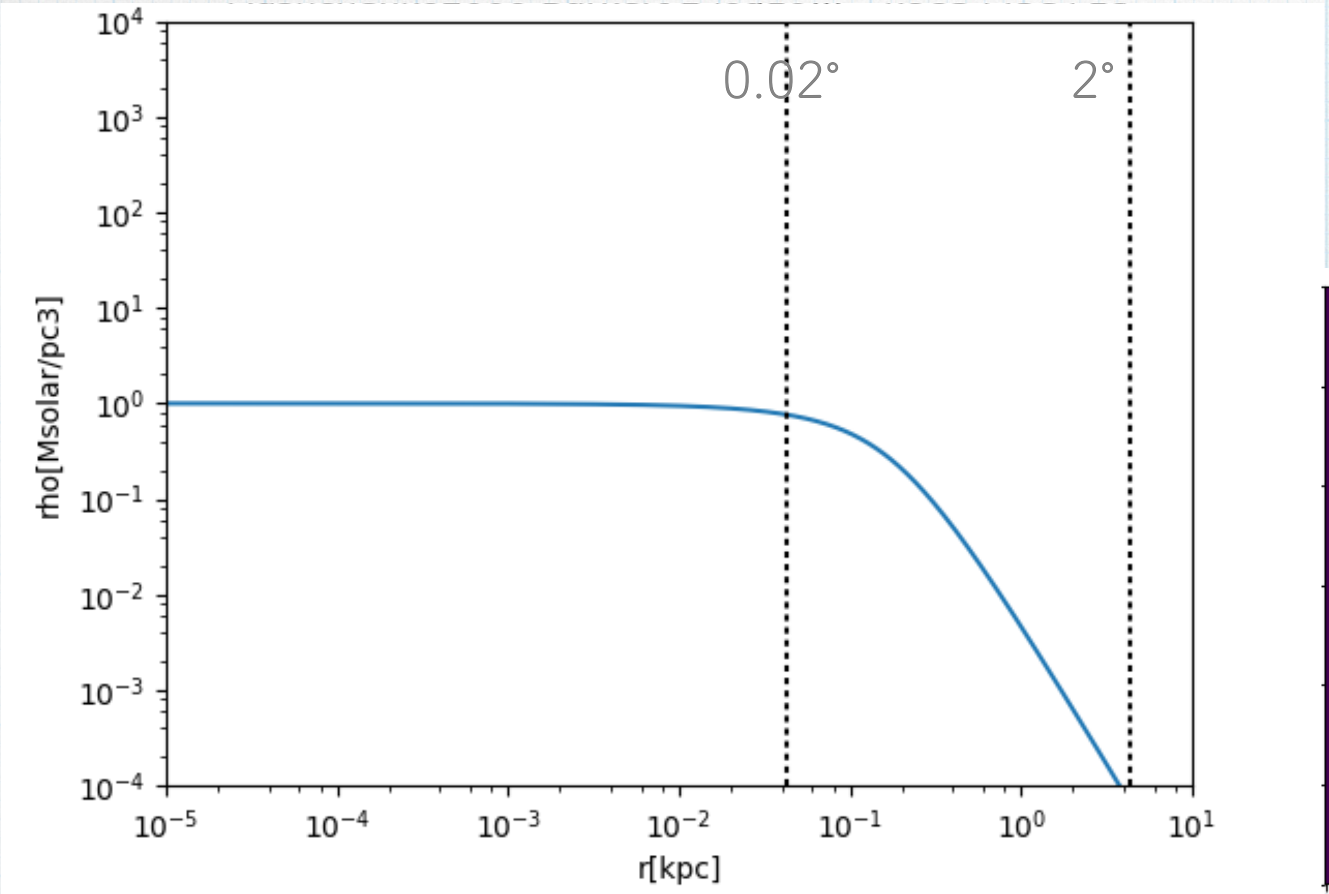
$\log_{10} J$ [GeV^2/cm^5]



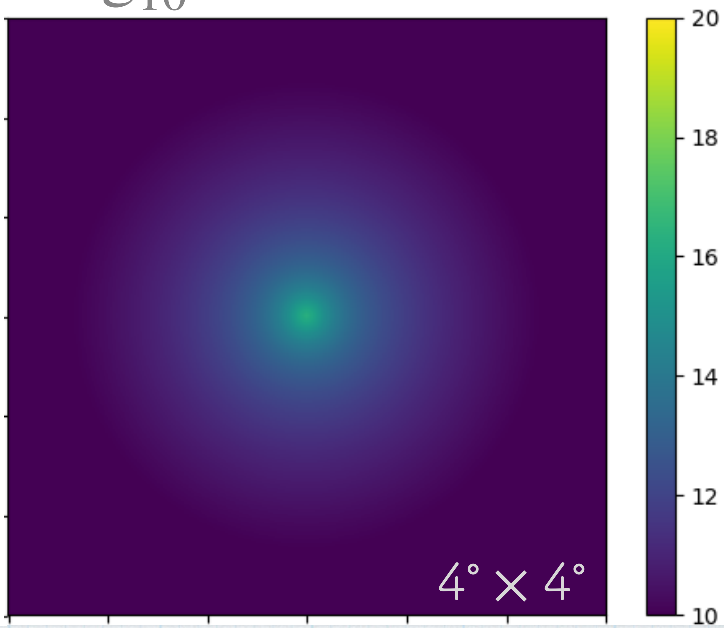
Example: Burkert

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

$\ln r$ vs $\ln \rho_{\mathrm{DM}}(r)$



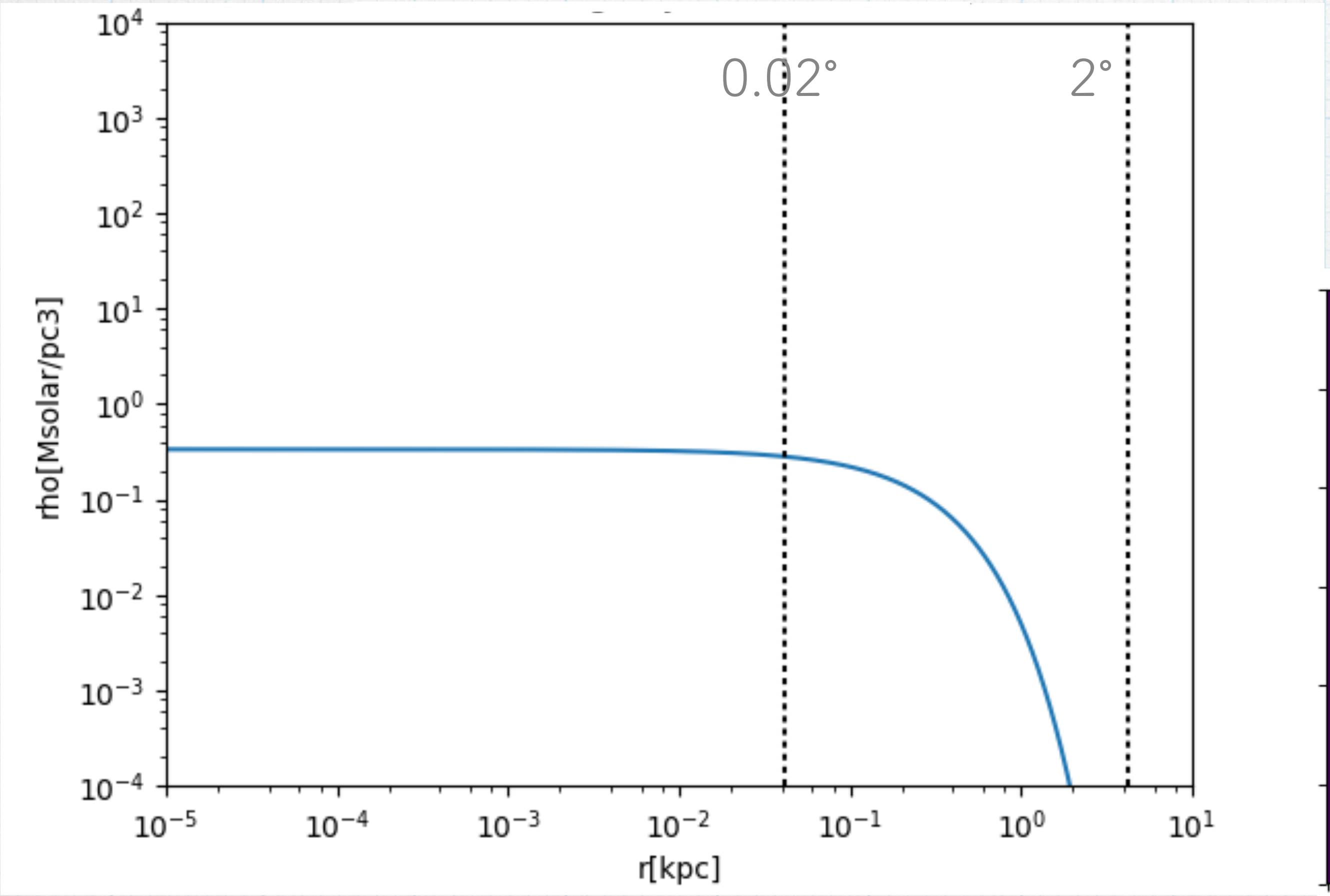
$\log_{10} J$ [GeV^2/cm^5]



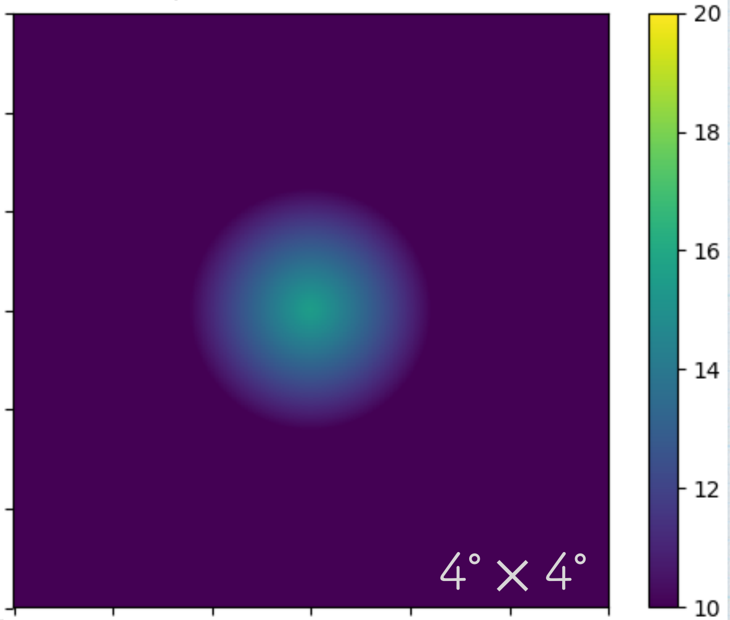
Example: PL + exp.cutoff

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

$\ln r$ vs $\ln \rho_{\rm DM}(r)$



$\log_{10} J$ [GeV^2/cm^5]



Intermediate summary

- γ-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?

$$\text{observable}\quad \underset{3}{\boxed{\phi}} = \frac{1}{2}\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{m_{\rm DM}^2}\underbrace{\int dE\frac{dN}{dE}}_{2}\int d\Omega\int_{los}\underbrace{ds\ \rho_{\rm DM}^2}_{1}\quad \text{model}$$

1. density profile**s** of the target:

   Draco dSph, $J \sim \mathcal{O}(10^{19}\text{GeV}^2/\text{cm}^5)$

   16 patterns

2. DM annihilation spectrum:

   $\bar{b}b, W^+W^-, \tau^+\tau^-$

   hadronization

3. γ-ray flux (observable)

   simulation

1. $\rho_{\rm DM}$ models of Draco dSph

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

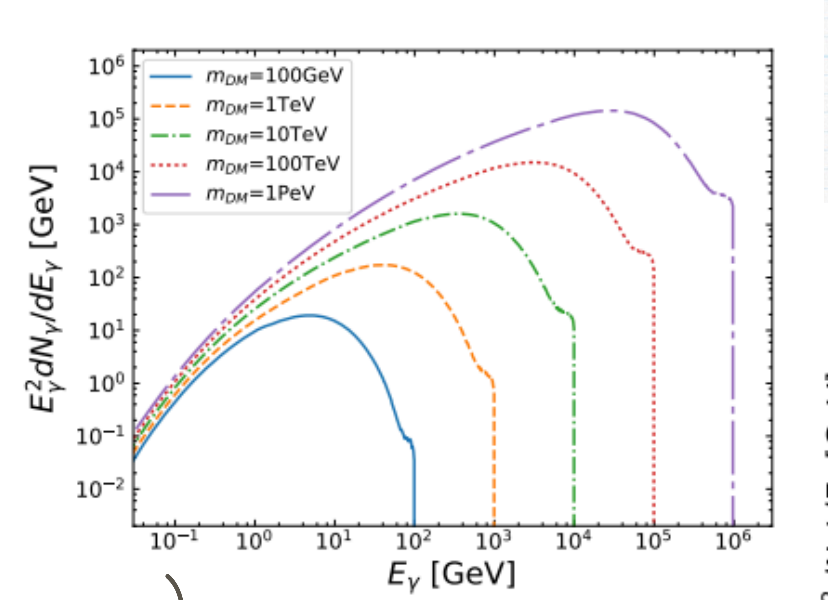
Draco is one of the best-studied dSphs

- 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

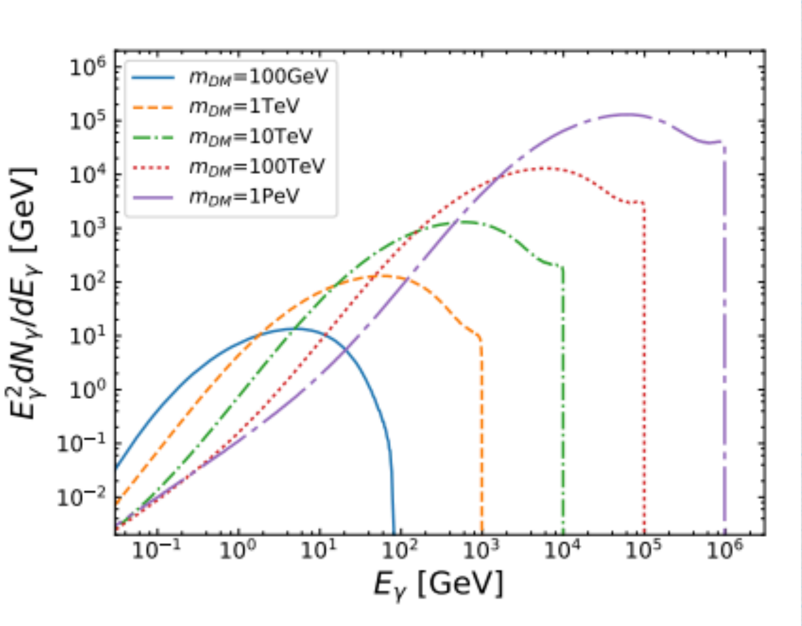
- $\bar{b}b$

  (quark)



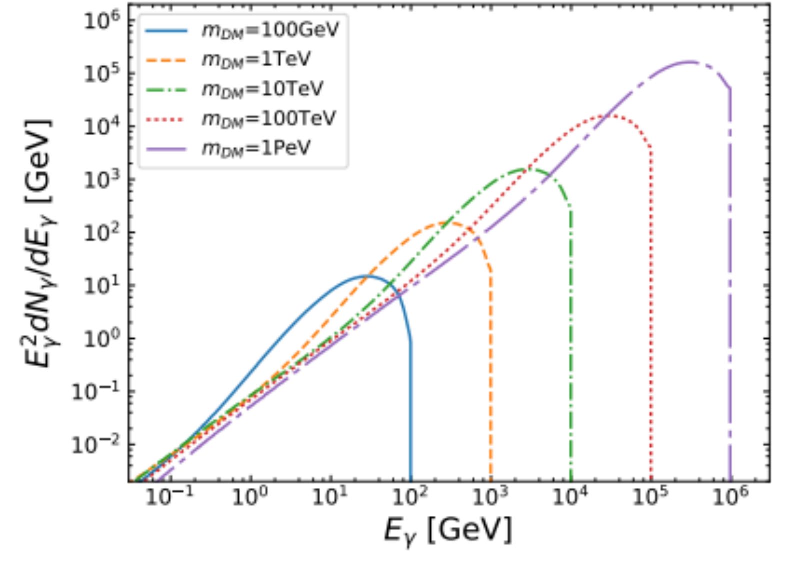
- W^+W^-

  (weak boson)



- $\tau^+\tau^-$

  (lepton)

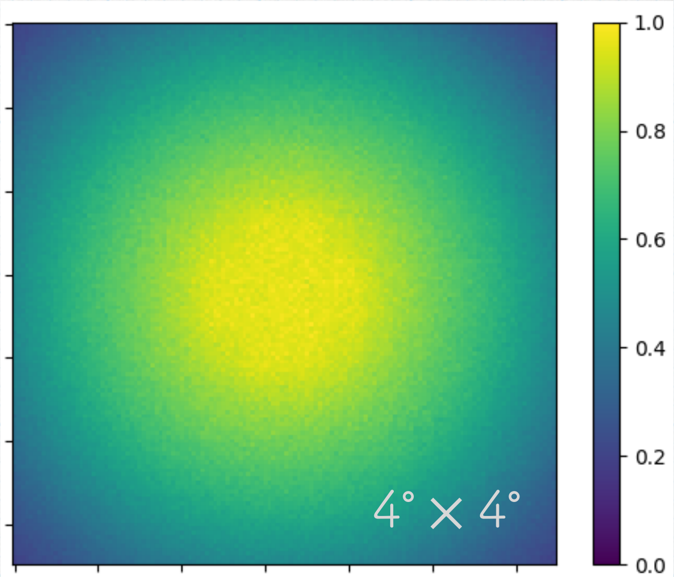


pythia8 for hadronization (http://home.thep.lu.se/Pythia/)

3.γ-ray flux

ctools: simulation and analysis software
for VHE γ-ray observations (http://cta.irap.omp.eu/ctools/)

- CTA-North, full array
  IRF prod3b North, z20, average, 50h
- 4 × 4deg around Draco dSph
- position center
  (RA, DEC)=(260.052, 57.915)
- 500 hour
- E=0.03-180TeV photon



example:
92188344 γ-ray like events w/o source

Combine: likelihood ratio test

1. simulate 500hours of observation @Draco dSph
2. select data & bin the data

   0.03-180 TeV, 5 energy bin / decade
3. likelihood analysis assuming

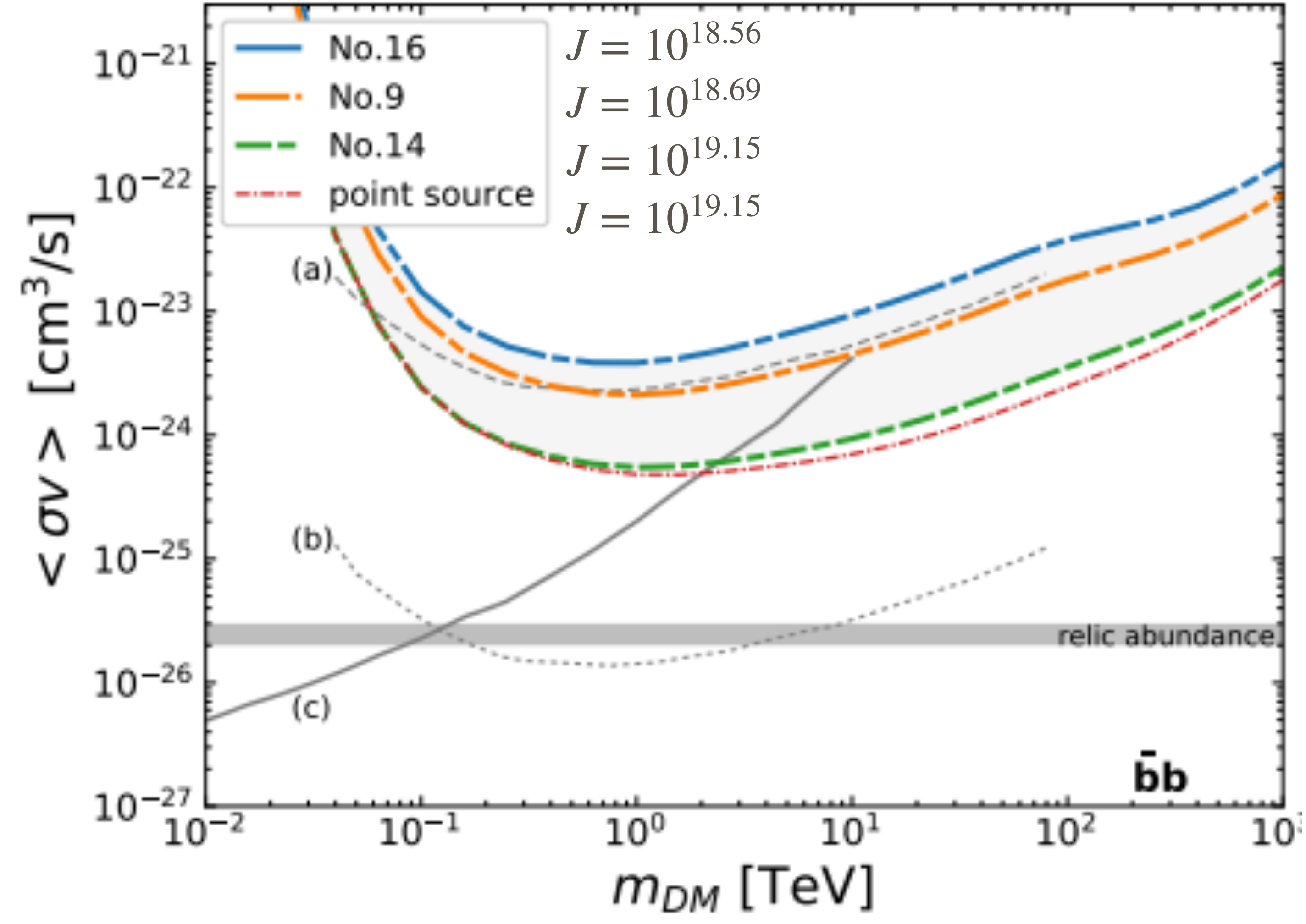
   16 profiles * 3 annihilation channels = 48 models

Which is more likely,

… "DM signal of the model exists" or

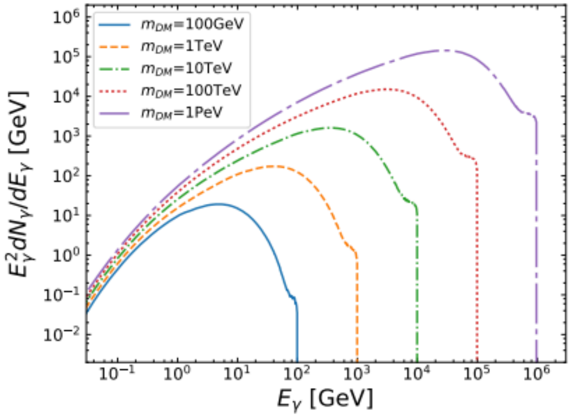
"the data is consistent with the background" ?

Our accessibility: $\bar{b}b$ case



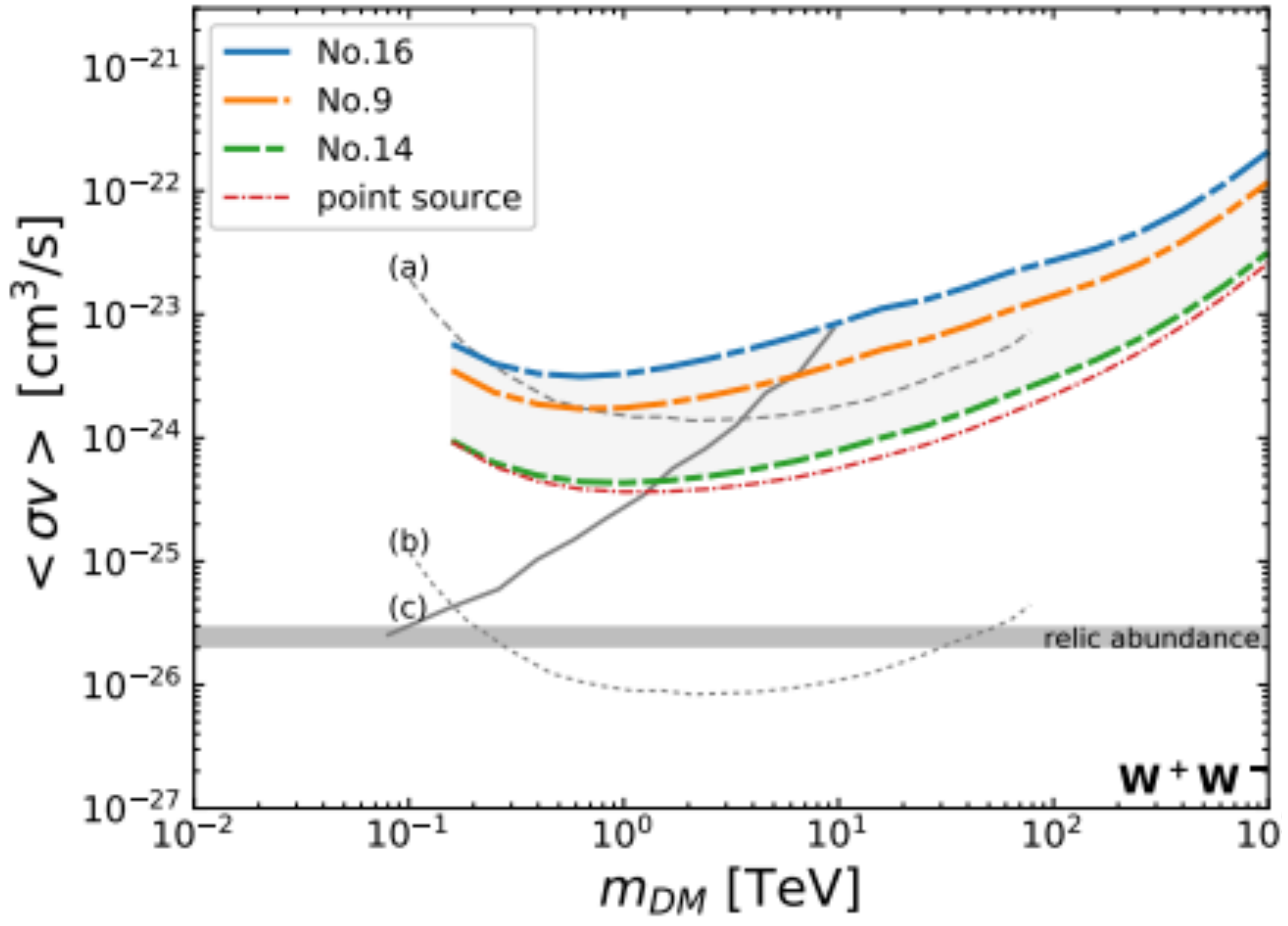
Hiroshima et al., 2019

95% C.L

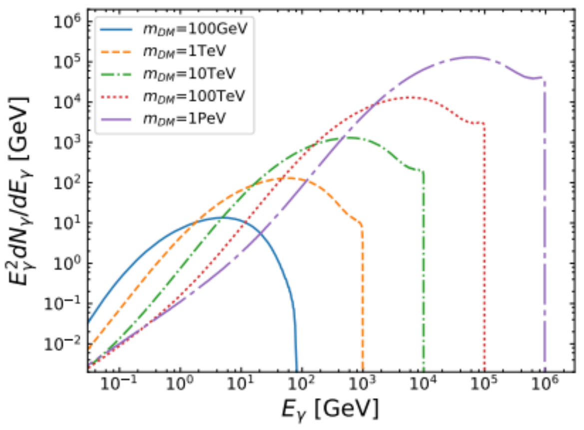


Our accessibility: W^+W^- case

Hiroshima et al., 2019

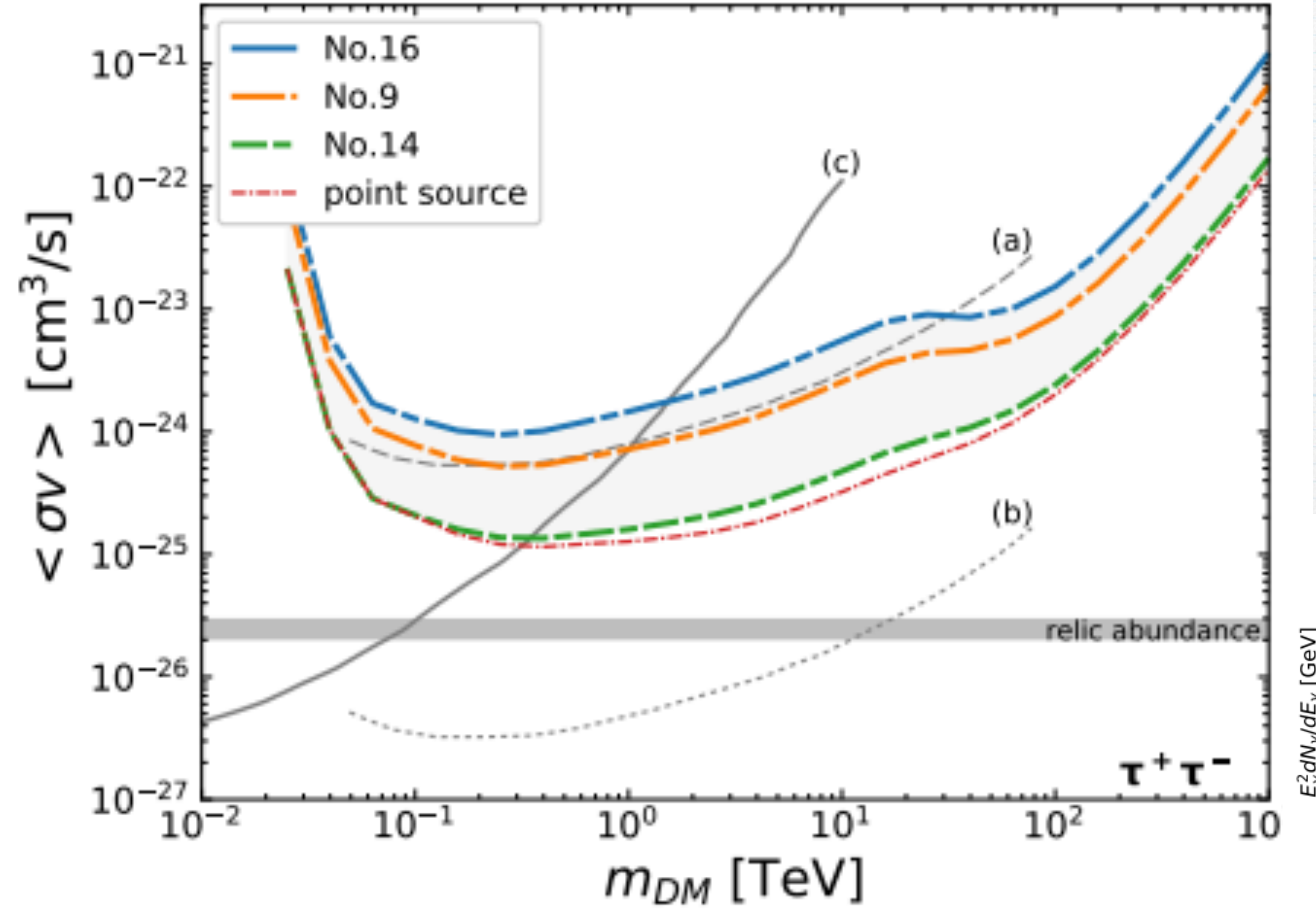


95% C.L

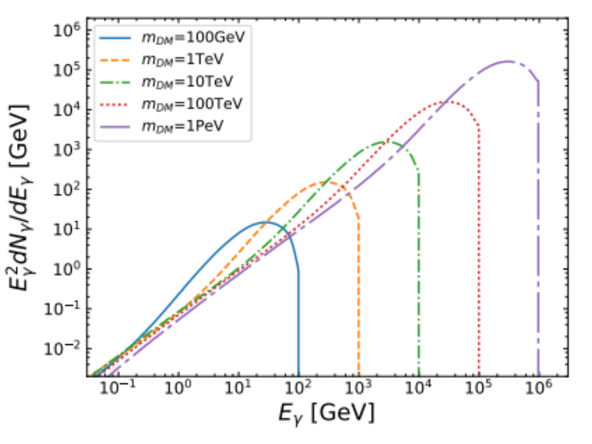


Our accessibility: $\tau^+\tau^-$ case

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 γ.

- 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.
- $\rho_{\rm DM}$ 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 ~ 10