

# 2025 CAU-IBS Beyond the Standard Model Workshop

## Indirect dark matter searches with the CTAO telescope

Lucca Radicce Justino  
Chung Ang University Phd Student

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Chung-Ang University, Department of Physics  
Theoretical High Energy Physics Group

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cherekov  
telescope  
array

arXiv:1709.07997v2 [astro-ph.IM] 22 Jan 2018

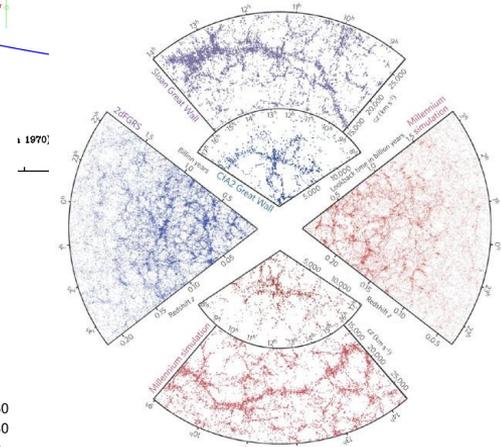
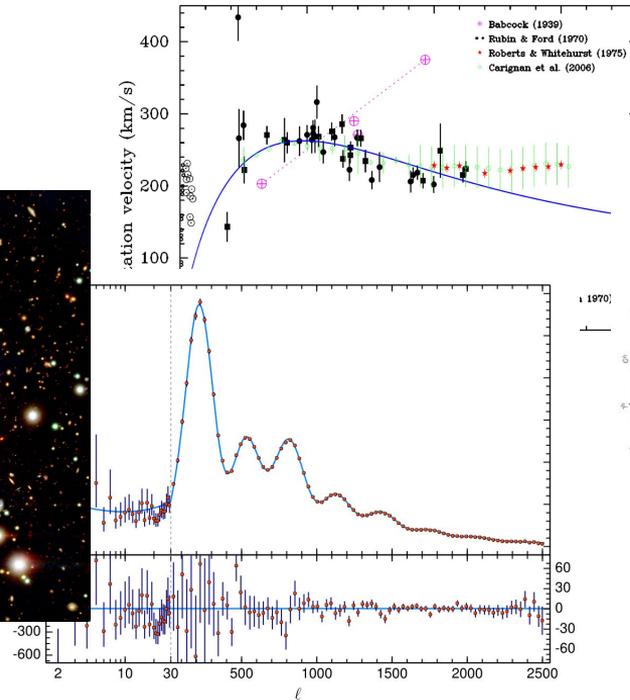
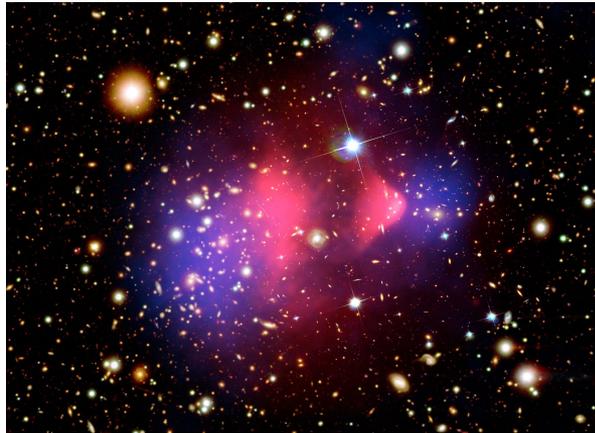
# Science with the Cherenkov Telescope Array



# INTRODUCTION

# Introduction: evidences for dark matter

A lot of evidences point out to the “missing mass problem” in the Universe...

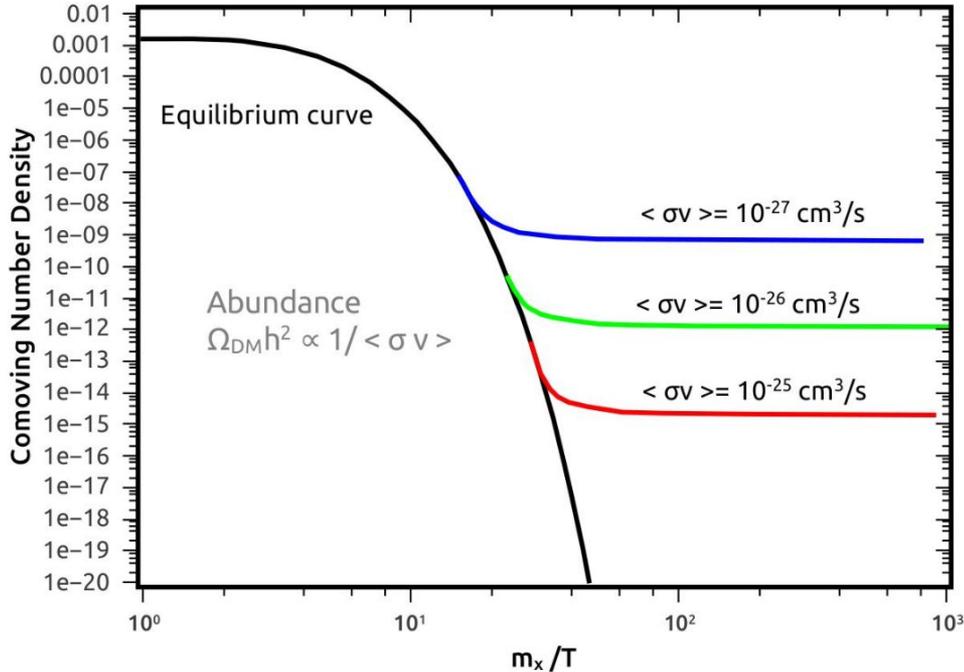


# Dark matter candidates



Diagram of models of dark matter grouped in clusters of theories. Source: Bertone & Tait.

# Freeze-out and the WIMP miracle



Solution of the Boltzmann equation for different annihilation cross sections.  
Source: Arcadi et al.

- **FREEZE-OUT**  $\Gamma_{eq} \approx H$ :

$$Y(x) \approx \begin{cases} Y_{eq}(x) & x \ll x_f \\ Y_{eq}(x_f) & x \gg x_f \end{cases}$$

- With some assumptions, the **cold relic abundance** is

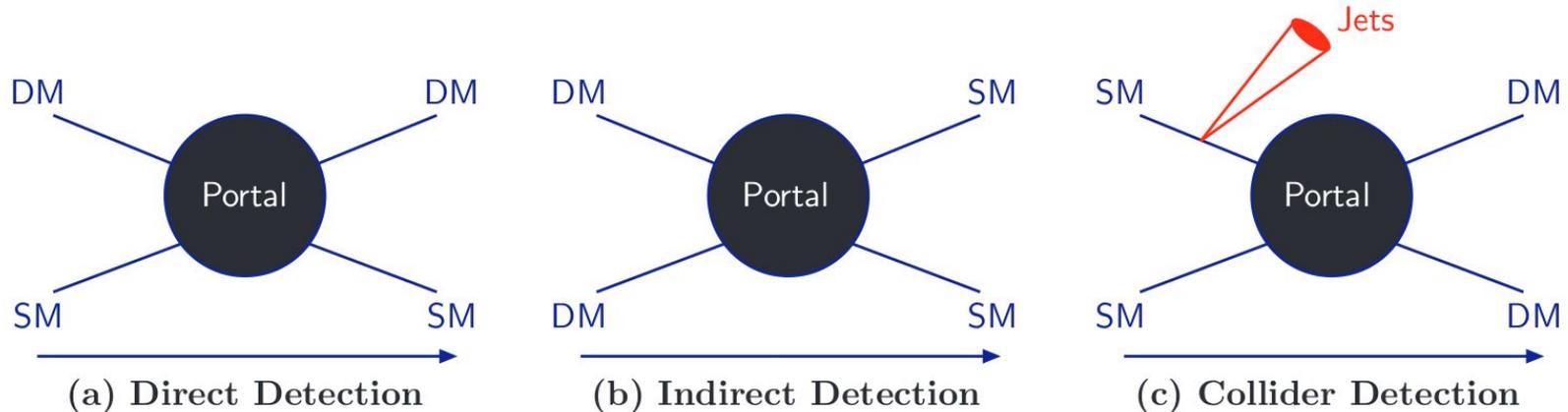
$$Y_\infty = \frac{3.79 (n+1) x_f}{\left(g_{*S}/g_*^{1/2}\right) m_{PL} m \langle \sigma v \rangle}$$

where  $\langle \sigma v \rangle \sim x^{-n}$ .

# Dark matter detection methods

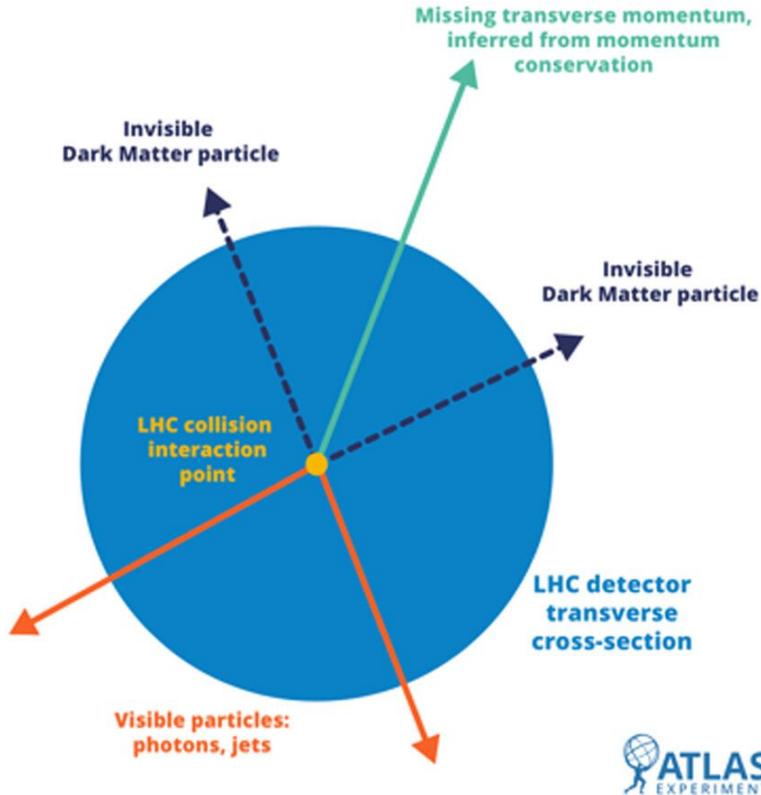
**WIMP dark matter  $\Rightarrow$  coupling with SM.**

The  $\chi\chi \leftrightarrow SM SM$  diagram allows three kinds of WIMP searches:



Three main kinds of WIMP detection methods. Source: ARCADI et al.

# Colliders



- Process: **WIMP production**

$$SM SM \rightarrow DM DM$$

- Observable: **missing transverse momentum.**
- Advantage: **controlled environment.**
- Disadvantage: limits are usually model-dependent.

# Direct detection

- Process: **WIMP-nucleus scattering**

$$SM DM \rightarrow SM DM$$

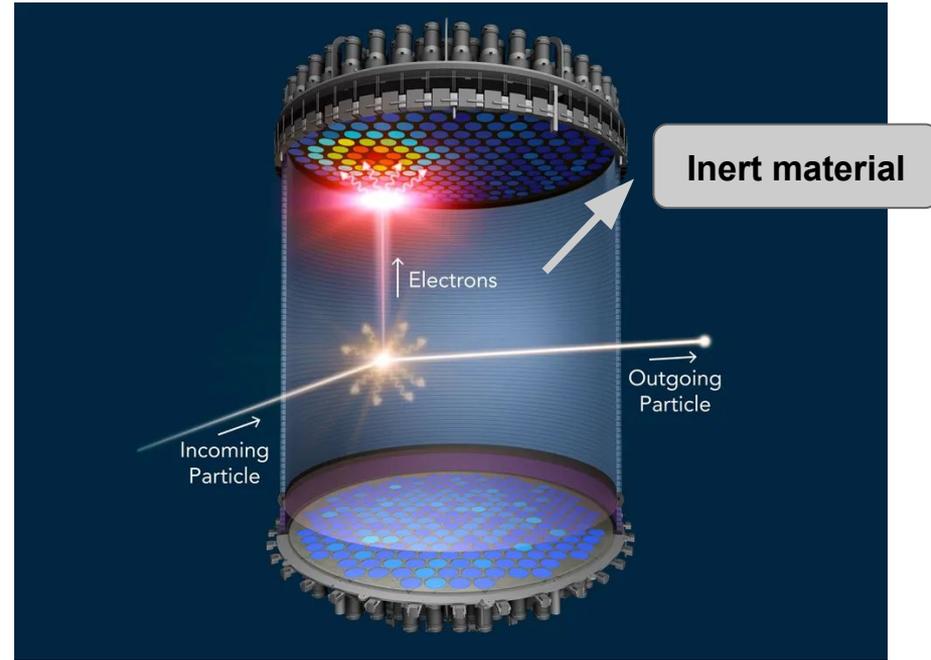
- Observable: **recoil energy** of the nucleus:

$$E_R = \frac{q^2}{2m_N} = \frac{\mu^2 v^2}{m_N} (1 - \cos \theta)$$

Rate of events: 
$$\frac{dR}{dE_R} = \frac{N_t \rho_{DM}}{m_{DM}} \left\langle \frac{d\sigma_{DM-N}}{dE_R} v \right\rangle$$

- Splitting into **spin-dependent** and a **spin-independent** components:

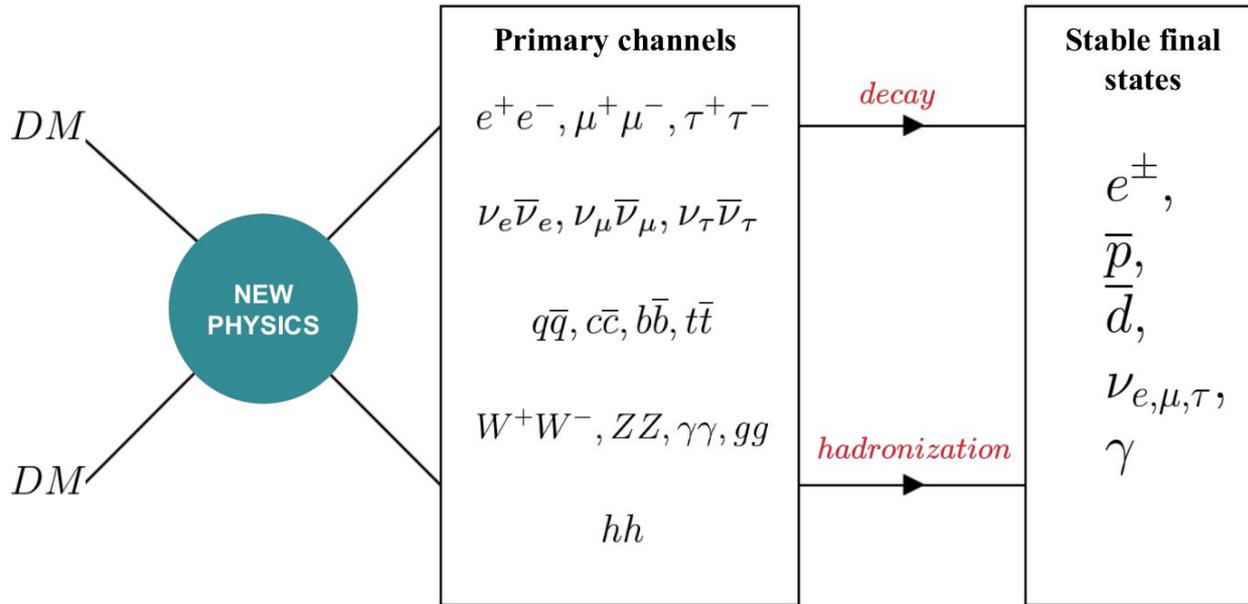
$$\frac{d\sigma_{DM-N}}{dE_R} = \left( \frac{d\sigma_{DM-N}}{dE_R} \right)_{SI} + \left( \frac{d\sigma_{DM-N}}{dE_R} \right)_{SD}$$



Representation of the LUX-ZEPLIN (LZ) experiment of dark matter direct detection. Source: SLAC National Accelerator Laboratory.

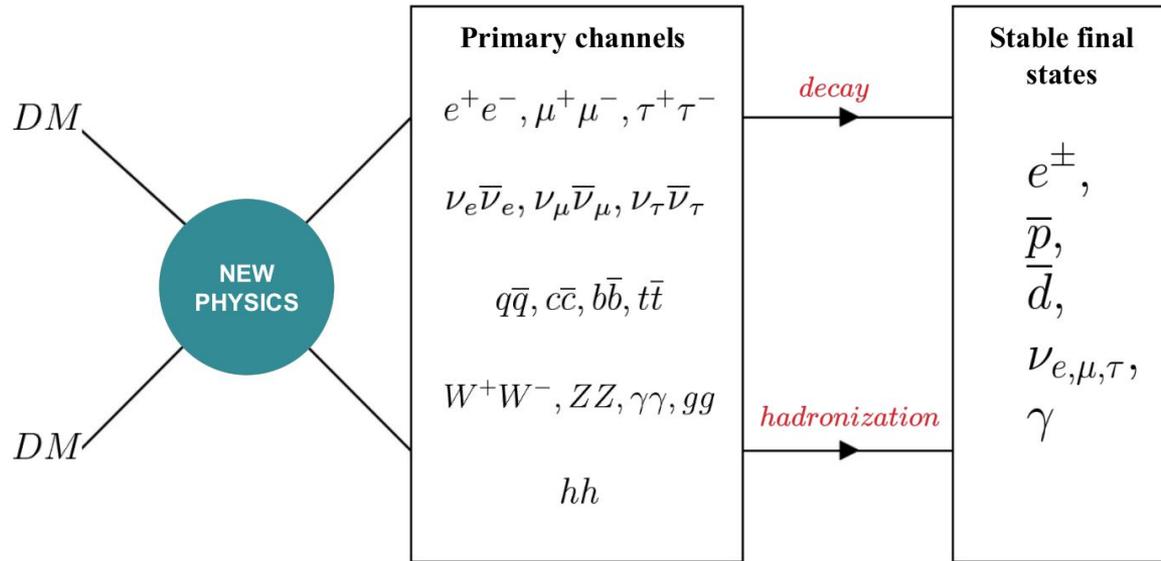
# Indirect detection

- Process: **WIMP self-annihilation in astrophysical objects**  $DM DM \rightarrow SM SM$
- Discovery: excess of cosmic messengers



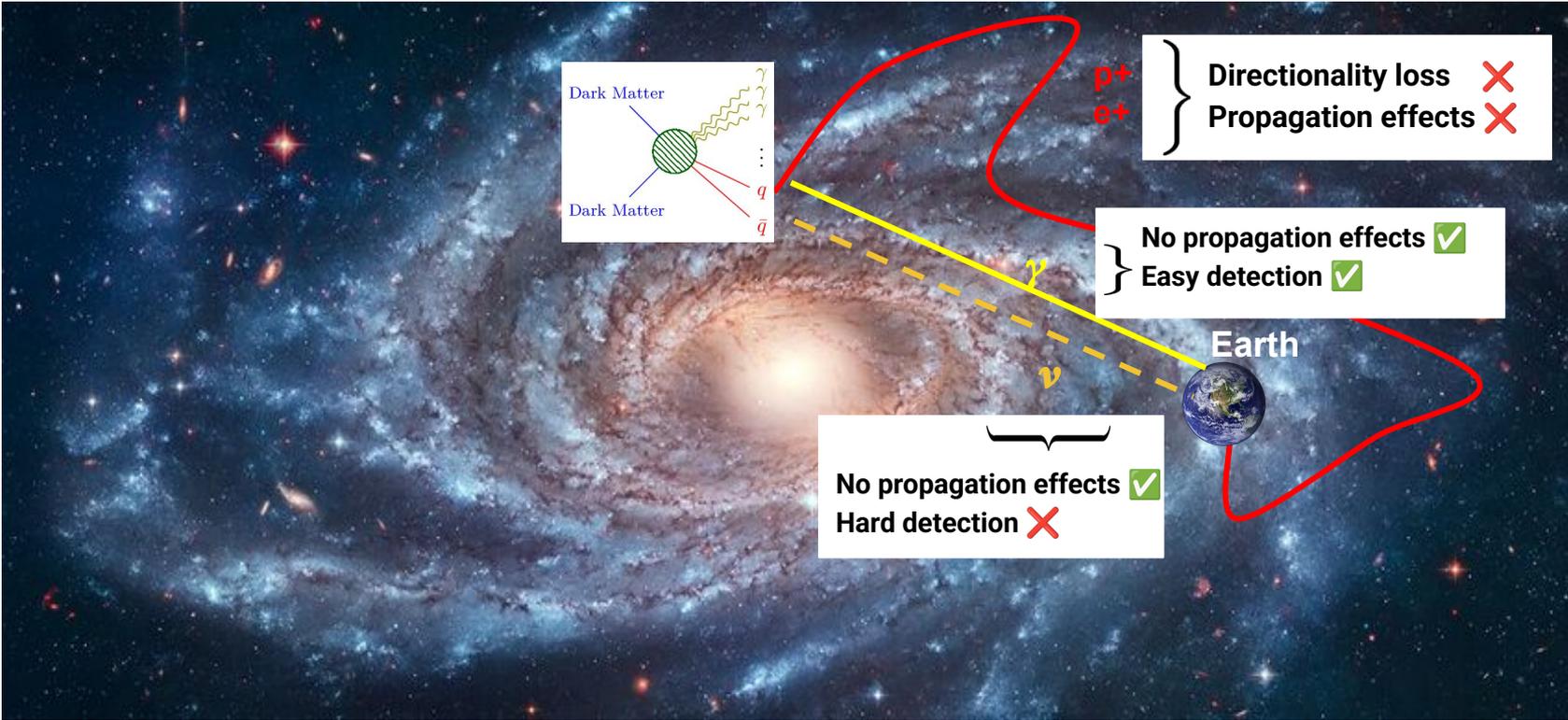
# Indirect detection

- **Pros:** can reach energies above current colliders, probe the the thermal relic annihilation cross-section.
- **Cons:** astrophysical uncertainties and background, low precision in energy and direction.



# **INDIRECT DETECTION APPROACH**

# Indirect detection: cosmic messengers



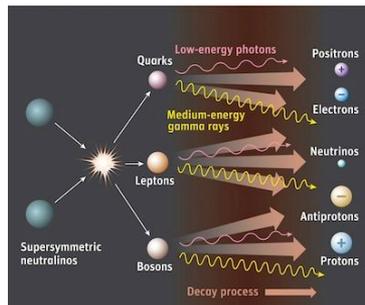
# The gamma-ray flux from dark matter annihilation

$$\frac{d\Phi_{\text{ann}}}{dE}(E, \Delta\Omega) = \frac{\langle\sigma v\rangle}{8\pi m_{DM}^2} \frac{dN}{dE} \int_{\Delta\Omega} d\Omega \int_{\text{l.o.s.}} ds \rho_{DM}^2$$

Gamma-ray Flux



Particle Physics

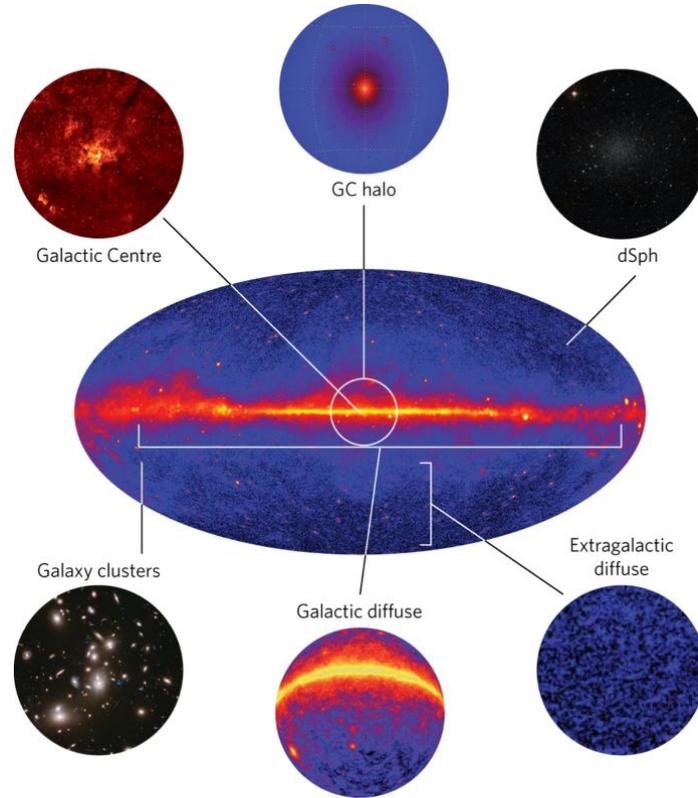


DM Distribution  
(astrophysics)



# Indirect detection: astrophysical targets

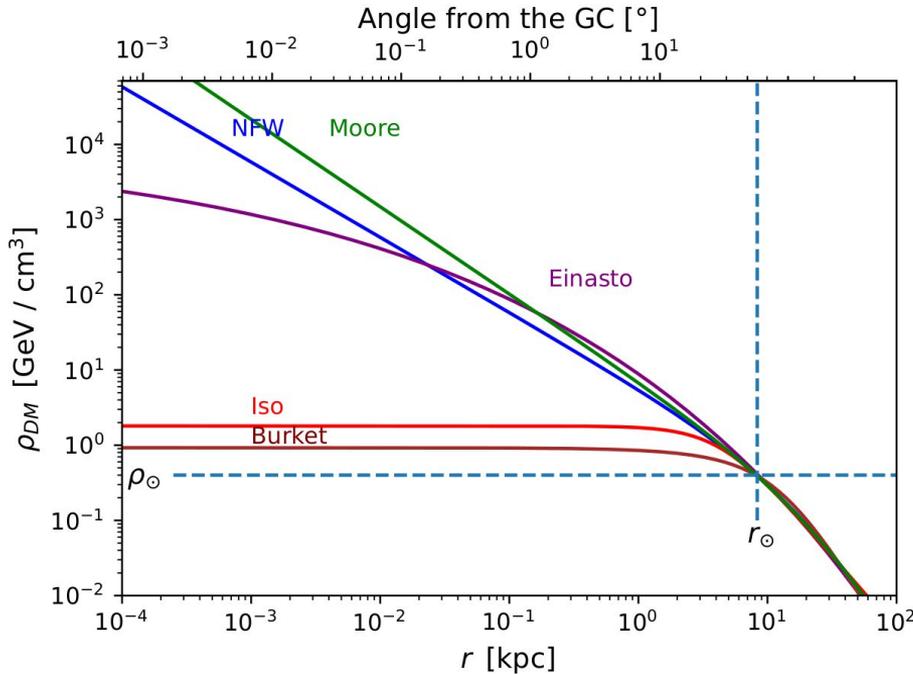
- Galactic center:
  - Strongest signal
  - High background
  - Uncertainty on dark matter density
- Galaxy clusters:
  - Strong signal
  - Background may be important
  - Sub-halos can increase dark matter amount



- Dwarf Galaxies:
  - Lower signal
  - Clean background
  - Well-known dark matter distribution

Targets for dark matter indirect detection searches. Source: Conrad & Reimer. DOI: 10.1038/NPHYS4049

# Dark matter halo models



Dark matter density versus distance from the **Galactic Center** for the **Milky Way** halo according to the profile models. Source: adapted from Cirelli et al.

Two classes of halo profile models:

## Cuspy profiles:

- Power-law  $\rho \sim 1/r^\gamma, \gamma > 0$
- Supported by N-body simulations.
- Ex: **NFW, Moore, Einasto.**

## Cored profiles: **Burket, Isothermal.**

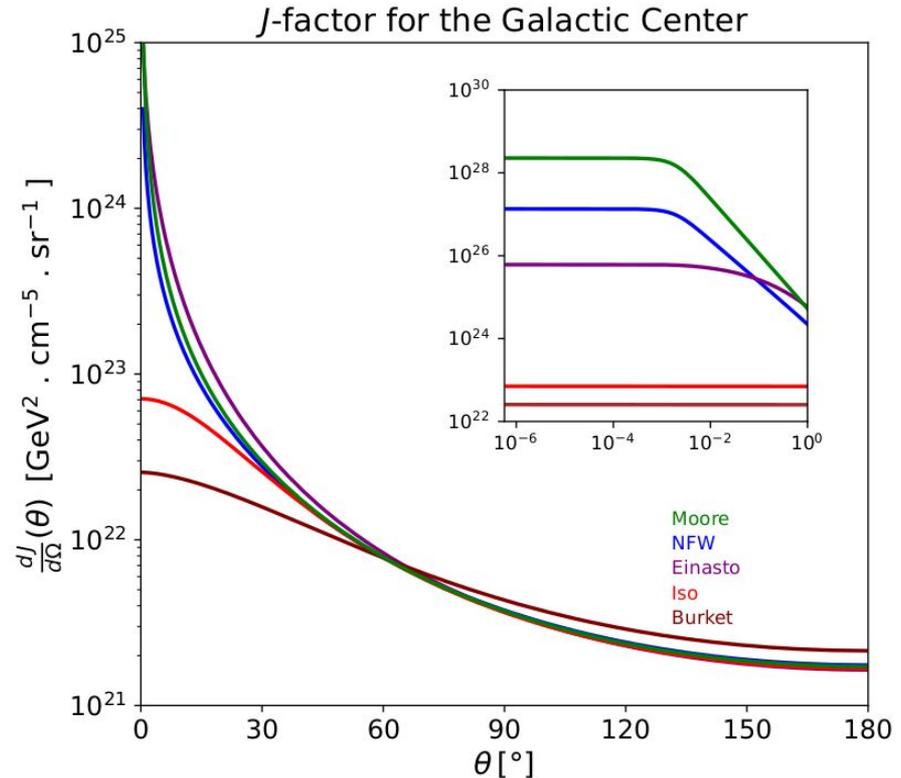
- Flat near the center.
- Supported by galactic rotation data of some dwarf galaxies.
- Ex: **Isothermal, Burket.**

# J-factor

## DM Distribution $\Rightarrow$ J-factor

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

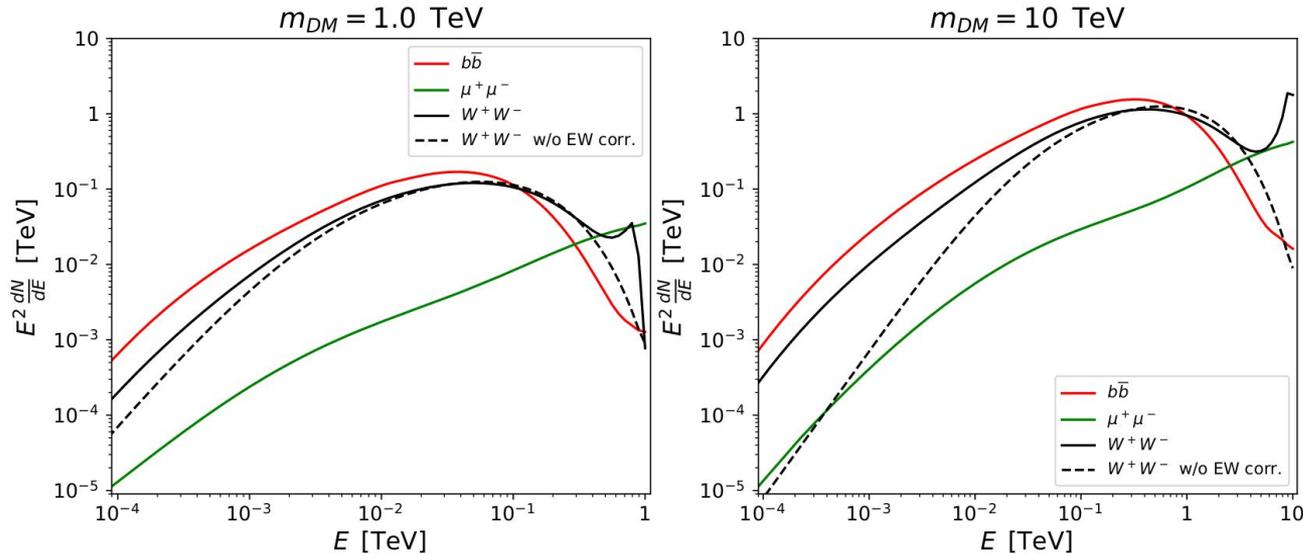
- Cuspy vs Cored profiles on GC  $\Rightarrow$   
high difference between models  $\Rightarrow$   
**high uncertainty on J-factor.**
- Solution: consider extreme cases.



Differential astrophysical factor in Milky Way in function of the opening angle  $\theta$  from the Galactic Center. Source: adapted from Cirelli et al.

# Gamma-ray spectra from dark matter annihilation

Gamma-ray annihilation spectrum can be divided into the **primary channels**:  $\frac{dN}{dE} = \sum_i B_i \frac{dN_i}{dE}$

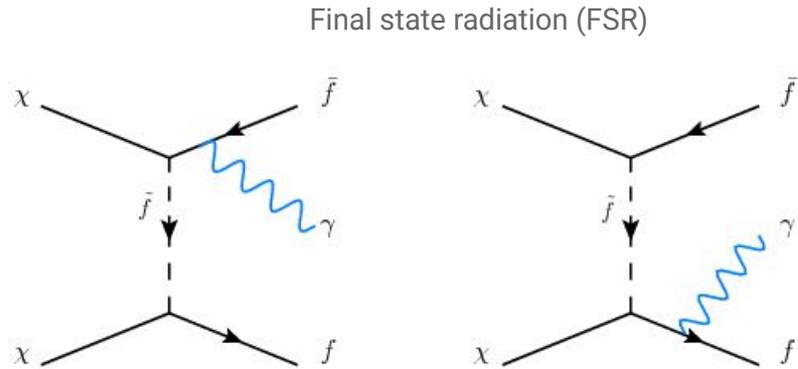
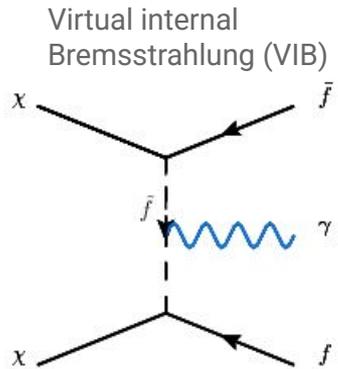


## DM spectral features

- 1) **Variable slope.**
- 2) **Cutoff at the dark matter particle mass  $m_{DM}$ .**

Dark matter annihilation gamma-ray spectra for the channels  $b\bar{b}$  (red line),  $\mu^+\mu^-$  (green line) and  $W^+W^-$  with (dashed black line) and without (solid black line) EW corrections. Source: Adapted from CIRELLI et al.

# Gamma-ray spectra from dark matter annihilation



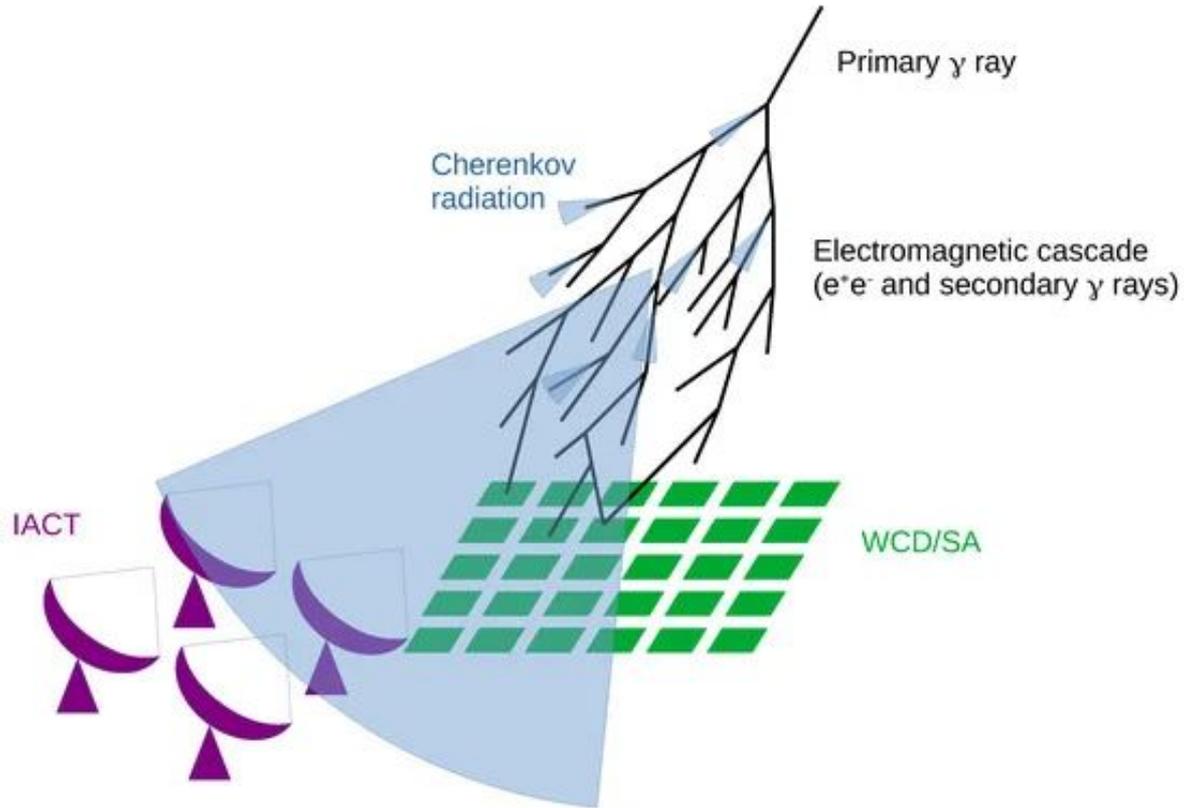
[arXiv:1306.3646](https://arxiv.org/abs/1306.3646)

## DM spectral features

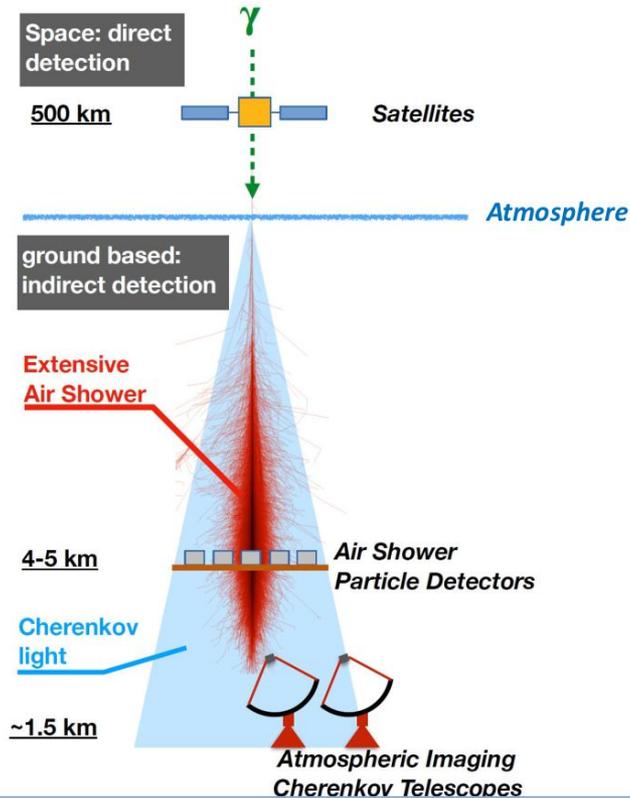
- 3) **Gamma-lines** from ElectroWeak for the  $W+W-$  channel.

# **GAMMA-RAY TELESCOPES AND THE CTAO**

# Imaging Air Cherenkov Telescopes



# Gamma-ray telescopes



Representation of the detection methods of gamma-ray astronomy. Source: Viana.

## Satellites

- **Energy range:**  $\sim$ MeV -  $\sim$ TeV
- **Area:**  $\sim$ m<sup>2</sup>
- **Ex:** Fermi-LAT, EGRET

## Air Shower Particle Detectors

- **Energy range:**  $\sim$ 100 GeV -  $\sim$ PeV
- **Area:**  $\sim$  km<sup>2</sup>
- **Ex:** SWGO, HAWC, LHAASO.

## Atmospheric Imaging Cherenkov Telescopes (IACTs)

- **Energy range:**  $\sim$ 100 GeV -  $\sim$ 100 TeV
- **Area:**  $\sim$ 0.1 -  $\sim$ 1 km<sup>2</sup>
- **Ex:** VERITAS, HESS, MAGIC, CTAO

# Instrument Response Functions (IRFs)

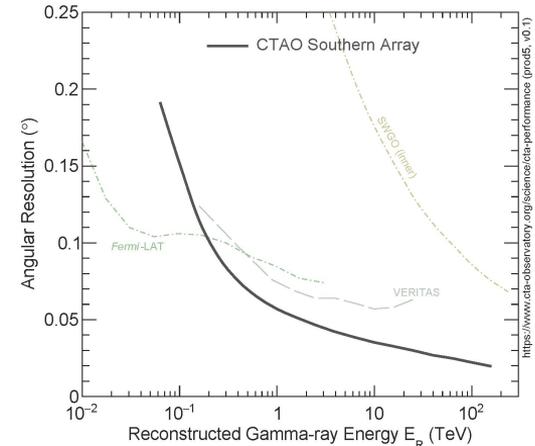
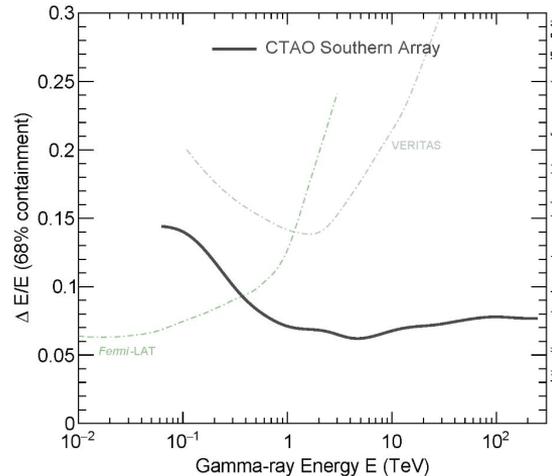
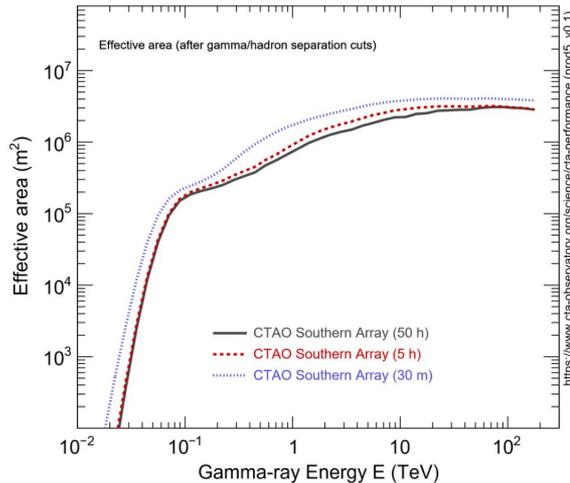
The observed count of gamma events is related with the differential flux by

Observation time

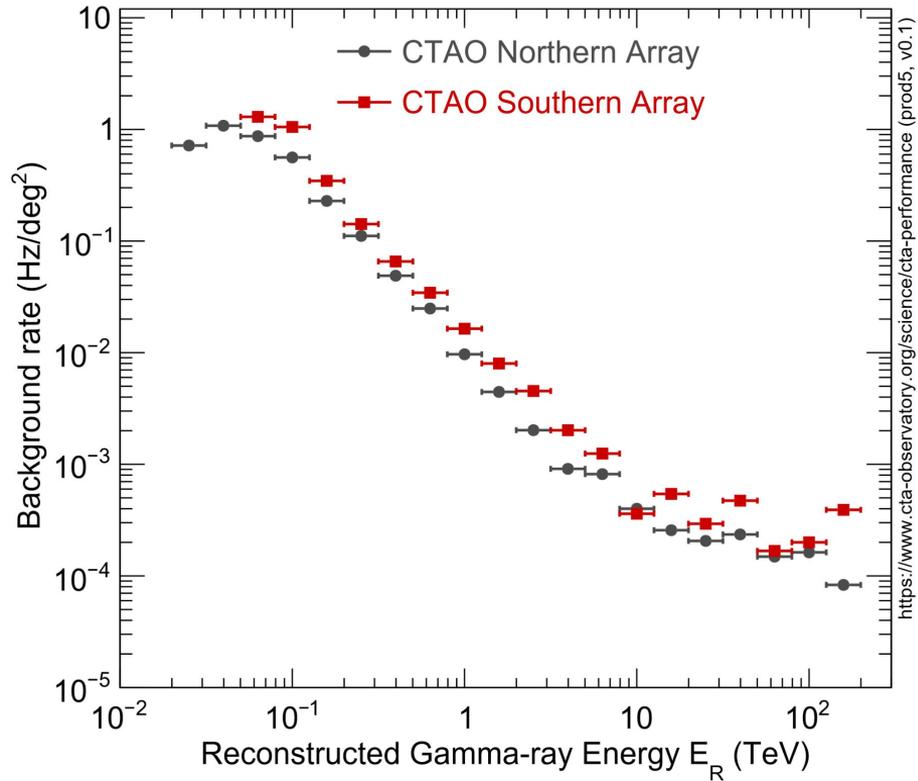
$$N = T_{\text{obs}} \int_{\Delta E'} dE' \int_0^\infty dE \frac{d\Phi}{dE} A_{\text{eff}}(E, \Delta\Omega) R(E, E')$$

Effective area

Energy reconstruction

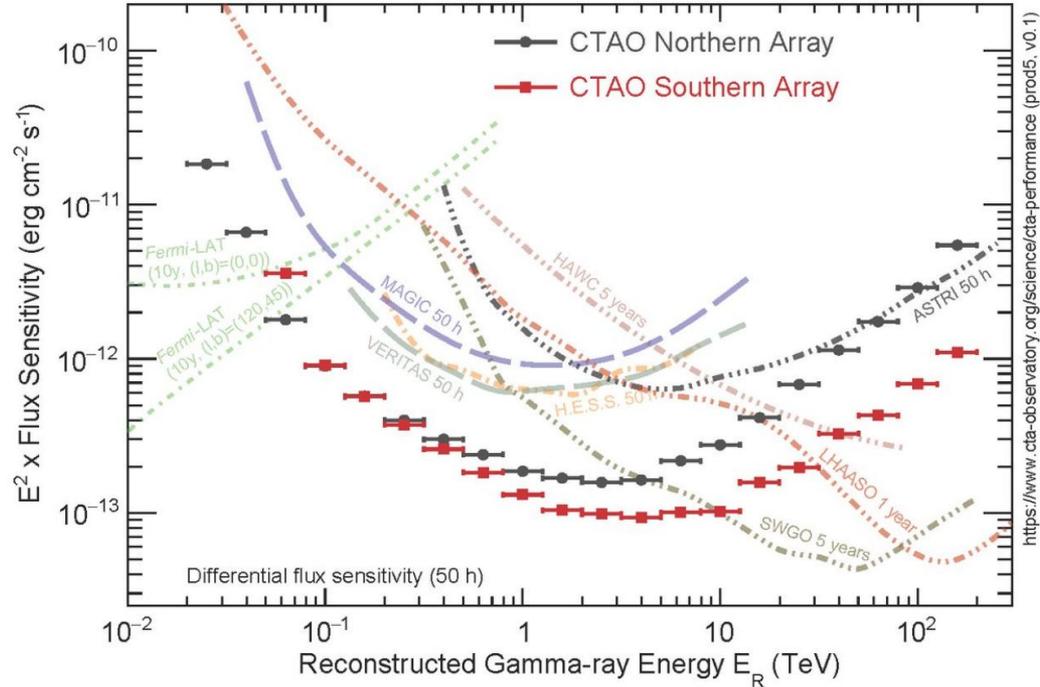


# Instrument Response Functions (IRFs)



# Sensitivity flux

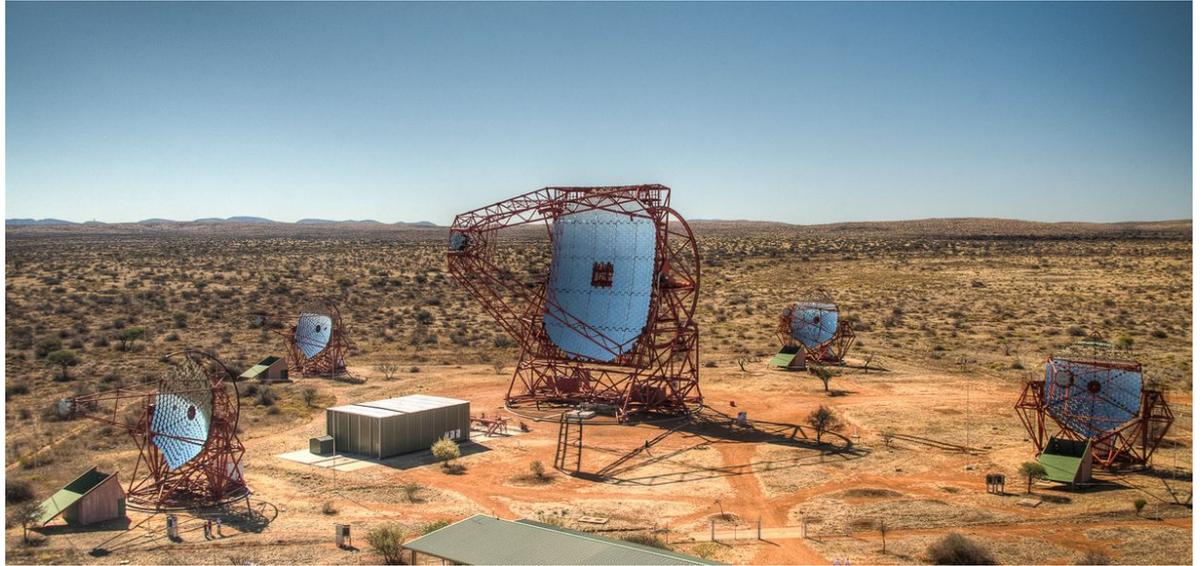
The minimum gamma-ray flux to claim a discovery ( $5\sigma$ ) of a point-like source:



Differential sensitivity on function of the reconstructed energy for different gamma-ray instruments, in both hemispheres.

# The High Energy Stereoscopic System (HESS)

- **Location:** Namibian desert (**Southern Hemisphere**).
- **Telescopes:** 4 small telescopes (Phase I) + 1 single large telescope (Phase II).
- **Energy resolution:** ~10% above 100 GeV

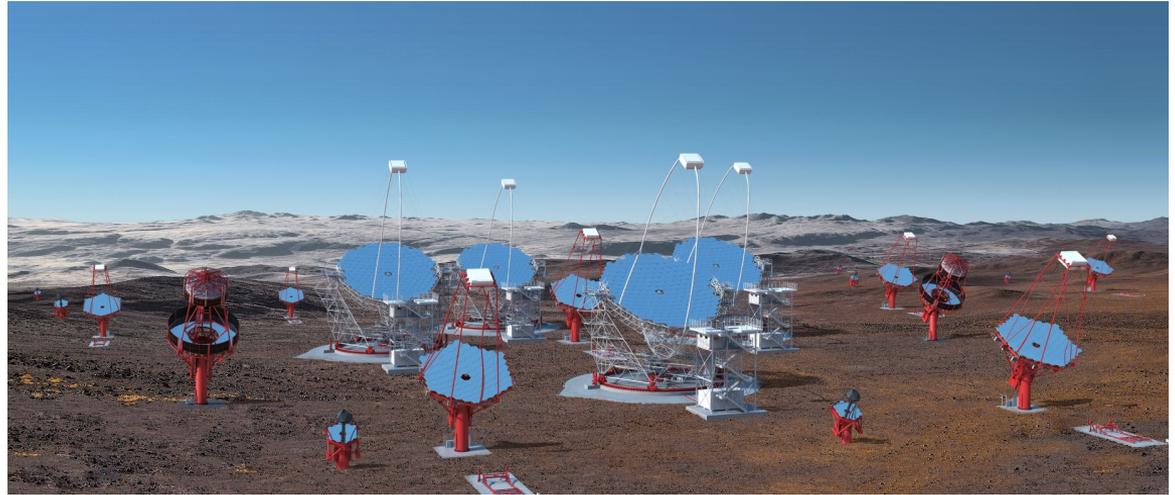


Picture of the 28 and the four 12-meter telescopes of HESS, in the Namibian desert. Image credit: HESS Collaboration.

# The Cherenkov Telescope Array Observatory (CTAO)

- **Location:**
  - **North site:** Canary Islands (Spain)
  - **South site:** Paranal (Chile)
- **Telescopes:** SSTs, MSTs and LSTs
- **Energy resolution:** ~10% above 100 GeV
- **Aims:** increase **sensitivity, effective area and energy resolution**

## Future IACT (under construction)



Artistic illustration of the CTA array. Image credit: Gabriel Pérez Diaz, IAC/Marc- André Besel, CTAO. Source: CTA CONSORTIUM.

# Statistical analysis

Gamma-ray counts: **Poisson distributions.**

- Expected count  $\lambda$  (parameter)
- Observed count  $N$  (dataset)

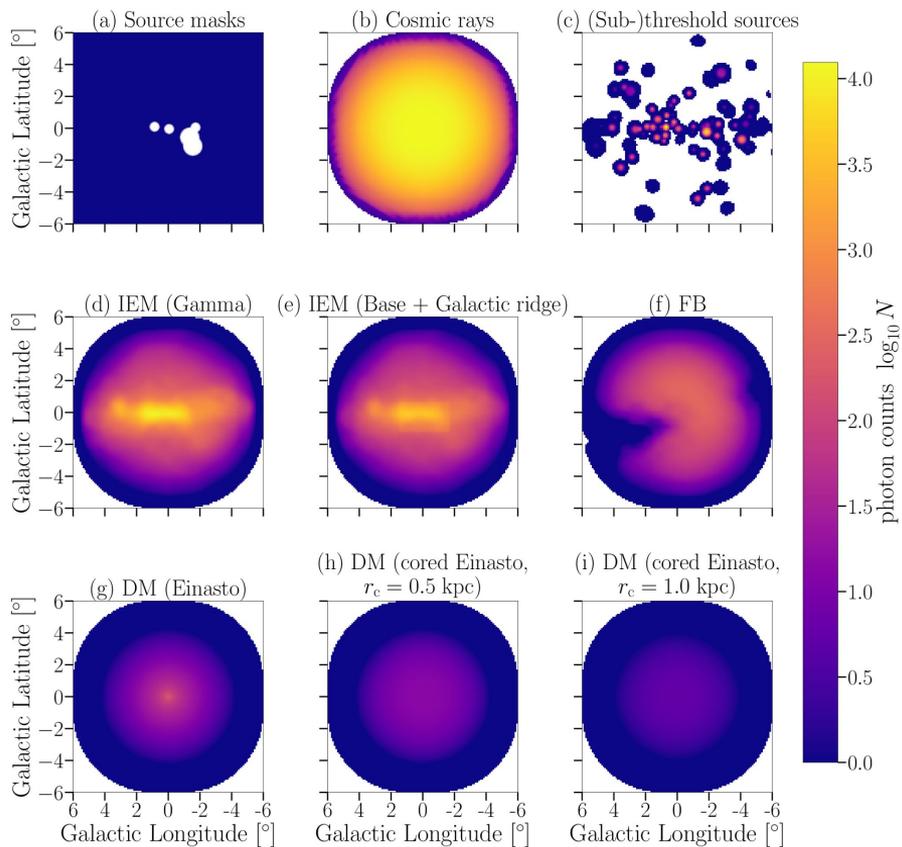
$$Pr(N|\lambda) = \frac{\lambda^N}{N!} e^{-\lambda}$$

The best-fitting parameter is determined by the maximization of the **likelihood function** given by

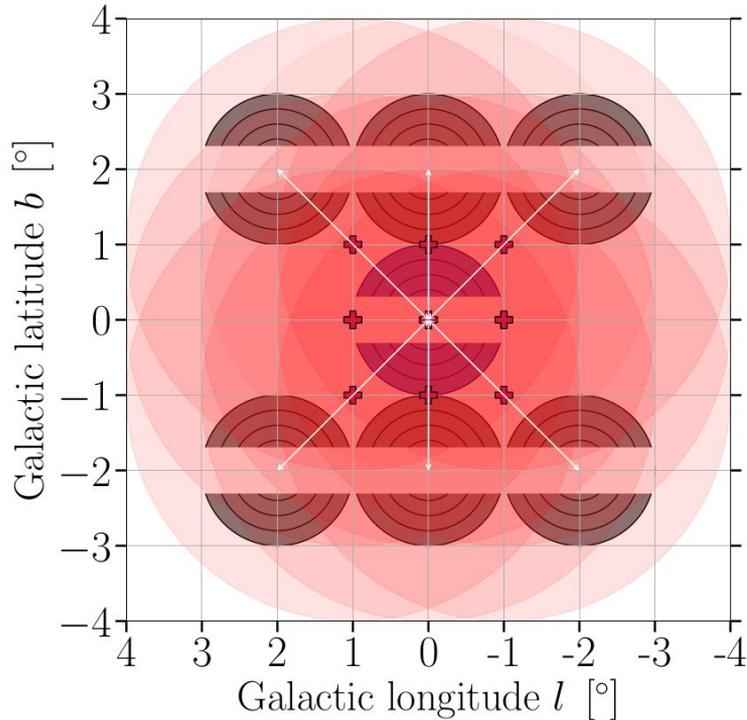
$$\mathcal{L}(N|\lambda) = \frac{\lambda^N}{N!} e^{-\lambda}$$

Multiple measurements (dataset):  $\mathcal{L}(N|\lambda) = \prod_i \mathcal{L}(N_i|\lambda)$

# Strategy: background modeling method



# Strategy: ON/OFF method



Scheme of the spatial binning of the GC region as it will be implemented in the CTA's GC survey.

For the GC region: **2D-binning (energy and space)** with **exclusion band** ( $|b| < 0.3^\circ$ ).

- Spatial binning:
  - **ON: signal+background.**
  - **OFF: background**
- Joint-Likelihood:

$$\mathcal{L} = \prod_{ij} \mathcal{L}_{ij}$$

- Likelihood of region of interest (ROI)  $ij$  :

$$\mathcal{L}_{ij} (N_{ON}, N_{OFF} | S, B) = \frac{(S + B)^{N_{ON}} e^{-(S+B)}}{N_{ON}} \frac{(B/\alpha)^{N_{OFF}} e^{-B/\alpha}}{N_{OFF}}$$

# Statistical analysis: upper limits for dark matter

- Signal from **dark matter annihilation in the GC**:

$$S_{ij}(\langle\sigma v\rangle) = \langle\sigma v\rangle \frac{T_{\text{obs}} J(\Delta\Omega_j)}{8\pi m_{DM}^2} \int_{\Delta E'_i} \int_0^\infty \frac{dN}{dE} A_{\text{eff}}(E) R(E, E')$$

- **TS for exclusion limits**:

$$TS_{\text{upper}}(\langle\sigma v\rangle) = \begin{cases} -2 \ln \frac{\lambda(\langle\sigma v\rangle)}{\lambda(0)}, & \widehat{\langle\sigma v\rangle} < 0 \\ -2 \ln \lambda(\langle\sigma v\rangle), & 0 \leq \widehat{\langle\sigma v\rangle} \leq \langle\sigma v\rangle, \\ 0, & \widehat{\langle\sigma v\rangle} > \langle\sigma v\rangle \end{cases}$$

where

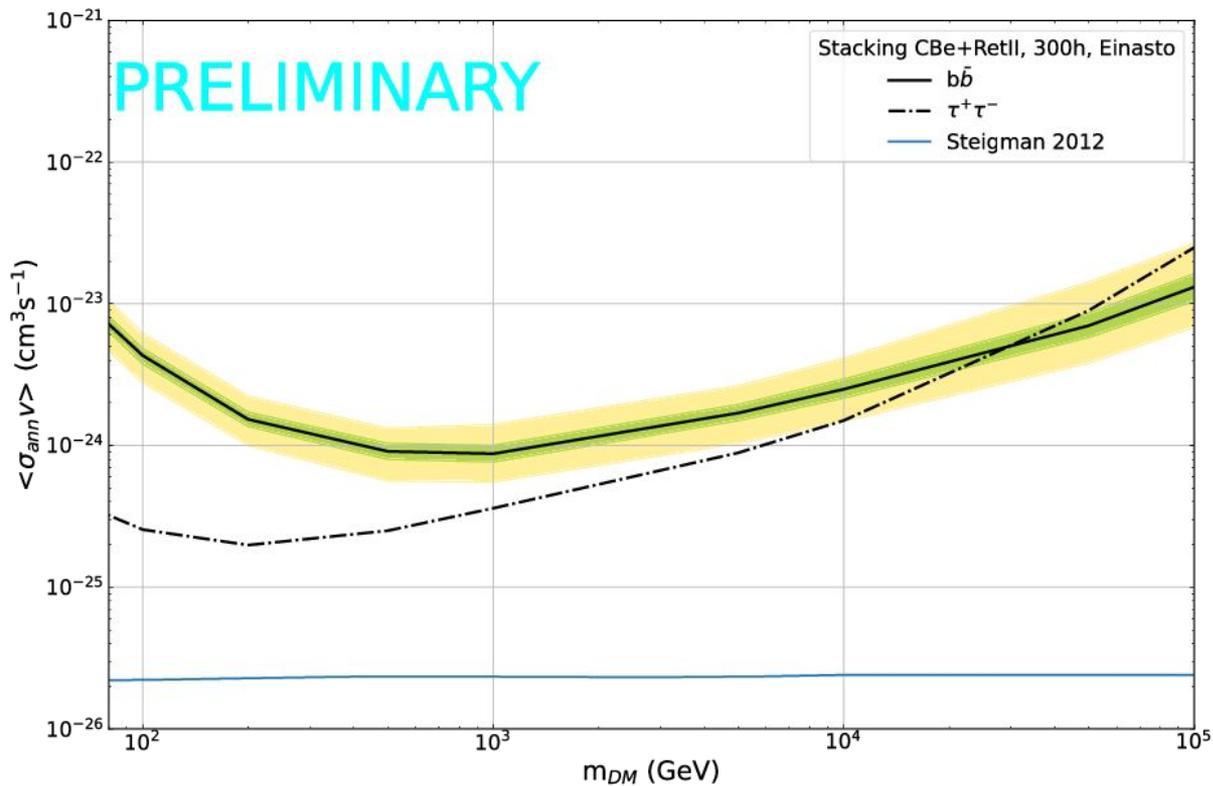
(From [Cowan et al.](#))

$$\lambda(\langle\sigma v\rangle) = \frac{\mathcal{L}(\langle\sigma v\rangle, \hat{B})}{\mathcal{L}(\widehat{\langle\sigma v\rangle}, \hat{B})}$$

- **Upper limits at 95% C.L.**:  $\langle\sigma v\rangle^{95\%CL} = TS_{\text{upper}}^{-1}(2.71)$  .

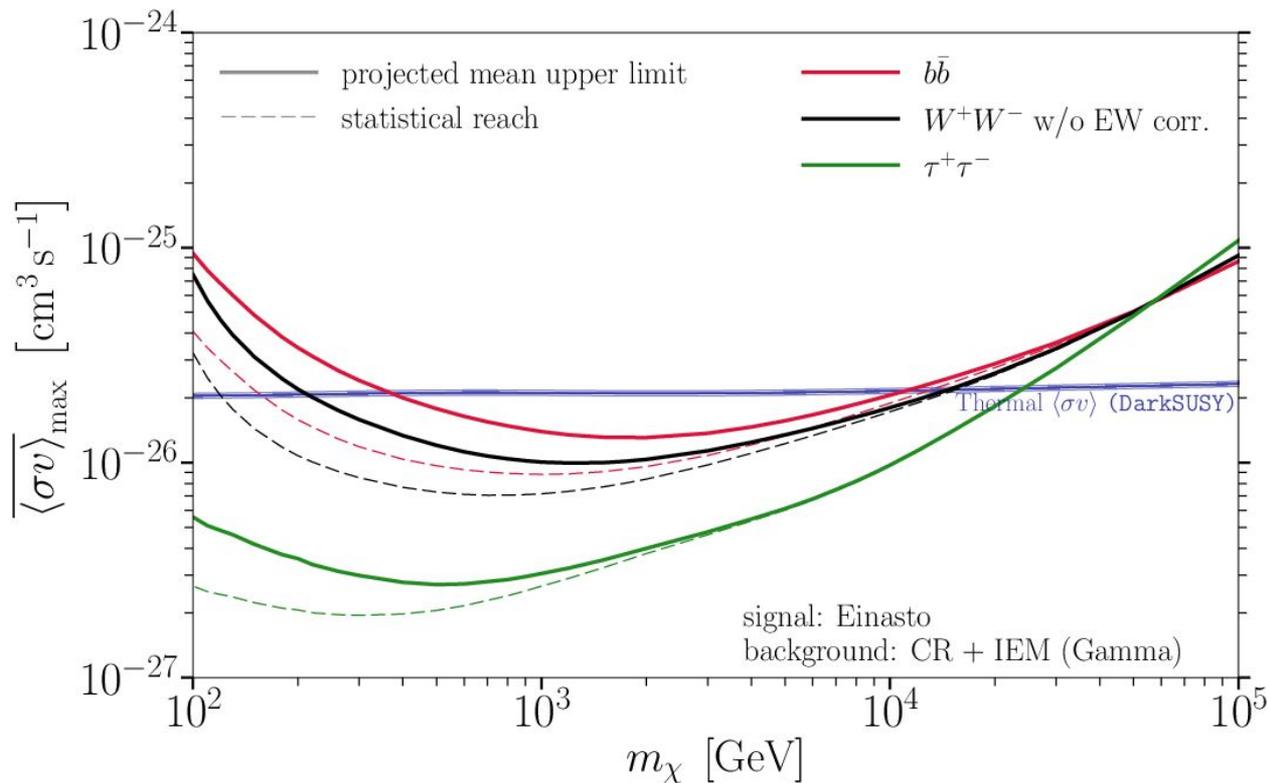
# PROJECTED LIMITS

# Limits for Dwarf Galaxies



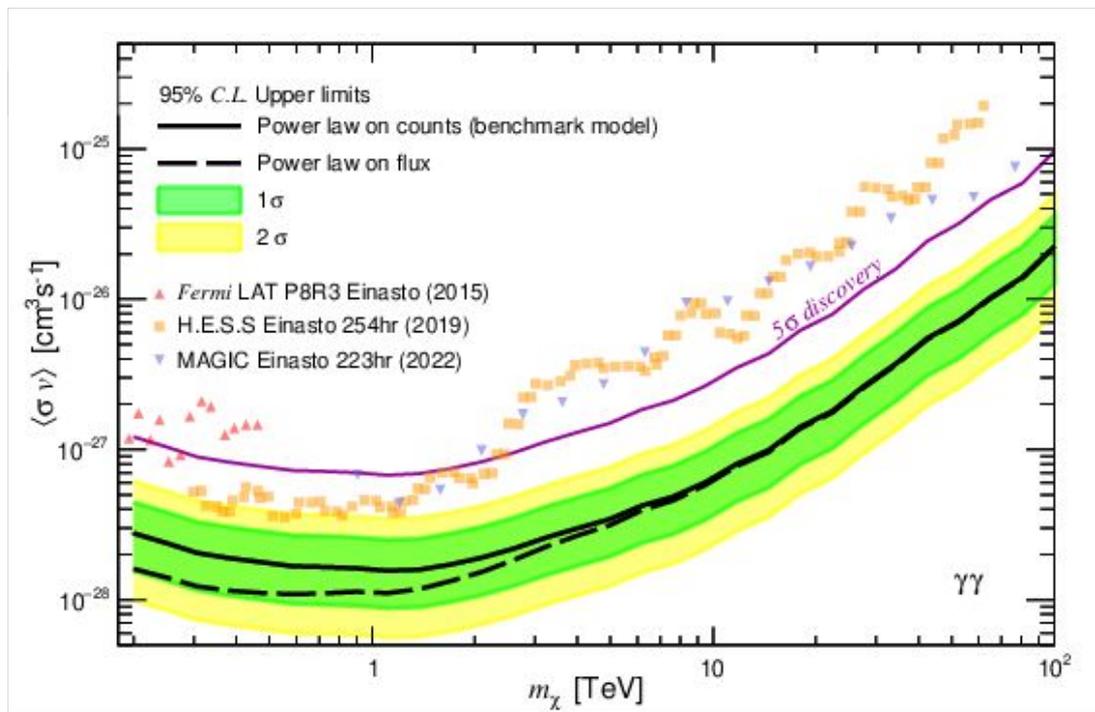
[arXiv:2309.09607v1](https://arxiv.org/abs/2309.09607v1)

# Limits for the Galactic Center



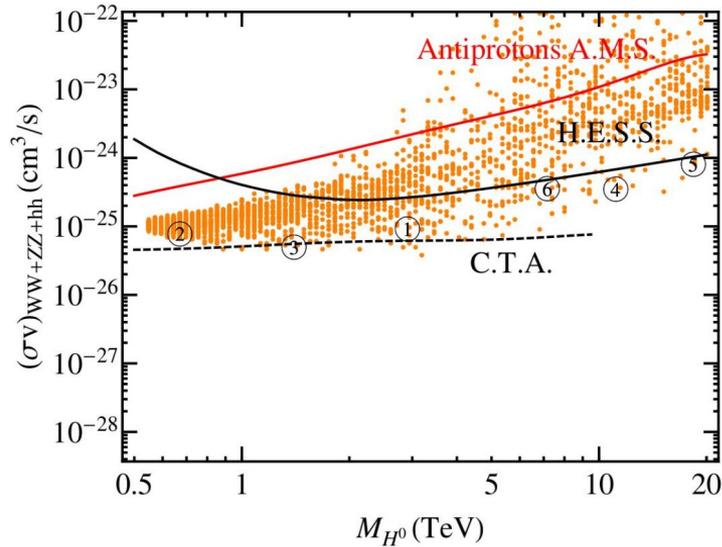
arXiv:2007.16129

# Limits for gamma-ray lines

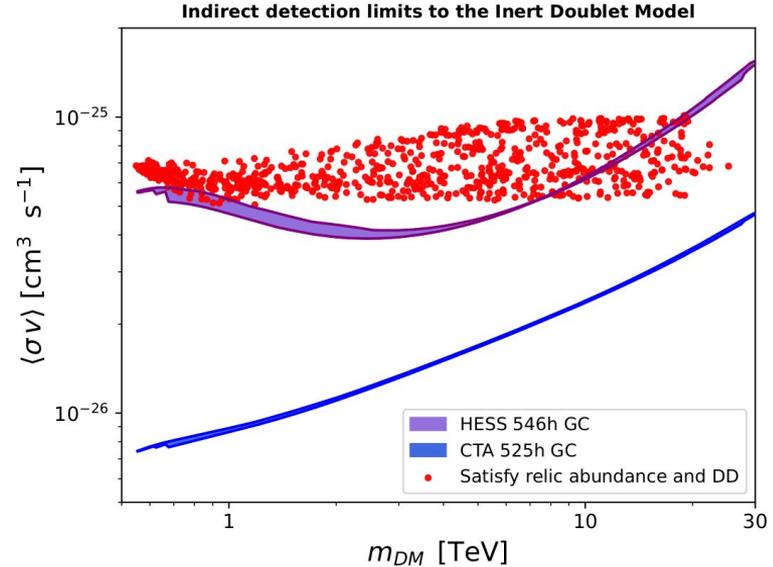


[arXiv:2007.16129v2](https://arxiv.org/abs/2007.16129v2)

# Model-dependent limits



HESS, CTAO and antiprotons AMS (Sommerfeld enhancement).  
[arXiv:1512.02801v3](https://arxiv.org/abs/1512.02801v3) Garcia-Clay & Ibarra.



HESS and CTAO [arXiv:2411.05909v1](https://arxiv.org/abs/2411.05909v1)

1) CTA's IRFs. 2) HESS 546h limits at the GC region. 3) LUX-ZEPLIN results.

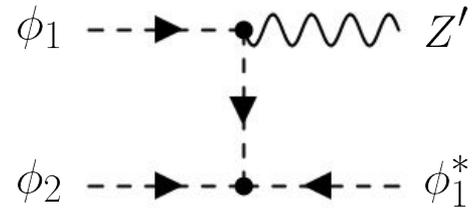
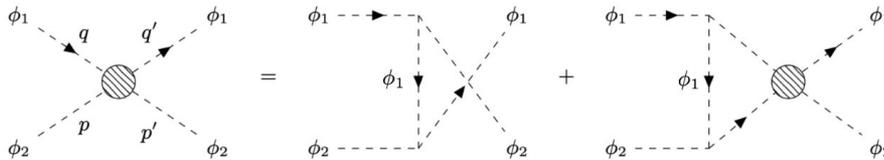
# Summary

- Indirect Detection provide an important window for probing dark matter annihilation, **covering many orders of mass magnitude**.
- Nevertheless, ID faces **several astrophysical and instrumental uncertainties**. This means that an unanimous claim for DM detection should come from **multi-messenger searches** and **with collider and direct detection signals**.
- The **CTAO** will be a fundamental experiment to probe thermal DM in the mass scale of 0.1- 10 TeV and a key test for the WIMP paradigm.

# Current project: Self-resonant dark matter

- **Self-interacting DM** can explain **small scale problems**.
- **Multi-component DM** can enhance both **DM self-scattering** and **annihilation** (without a light mediator).
- Former results (arXiv:2202.13717v3, SeongSik) found that the **u-channel** can lead to **Sommerfeld Enhancement** in semi-annihilation processes.
- Current project: extend the analysis from the Z3 to the Z4 symmetry and analyze ID and DD (boosted DM) for semi-annihilation

$$\mathcal{L} = |\partial_\mu \phi_1|^2 - m_1^2 |\phi_1|^2 + \frac{1}{2} (\partial_\mu \phi_2)^2 - \frac{1}{2} m_2^2 \phi_2^2 - 2gm_1 \phi_2 |\phi_1|^2$$



BACKUP

# Statistical analysis: log-likelihood method

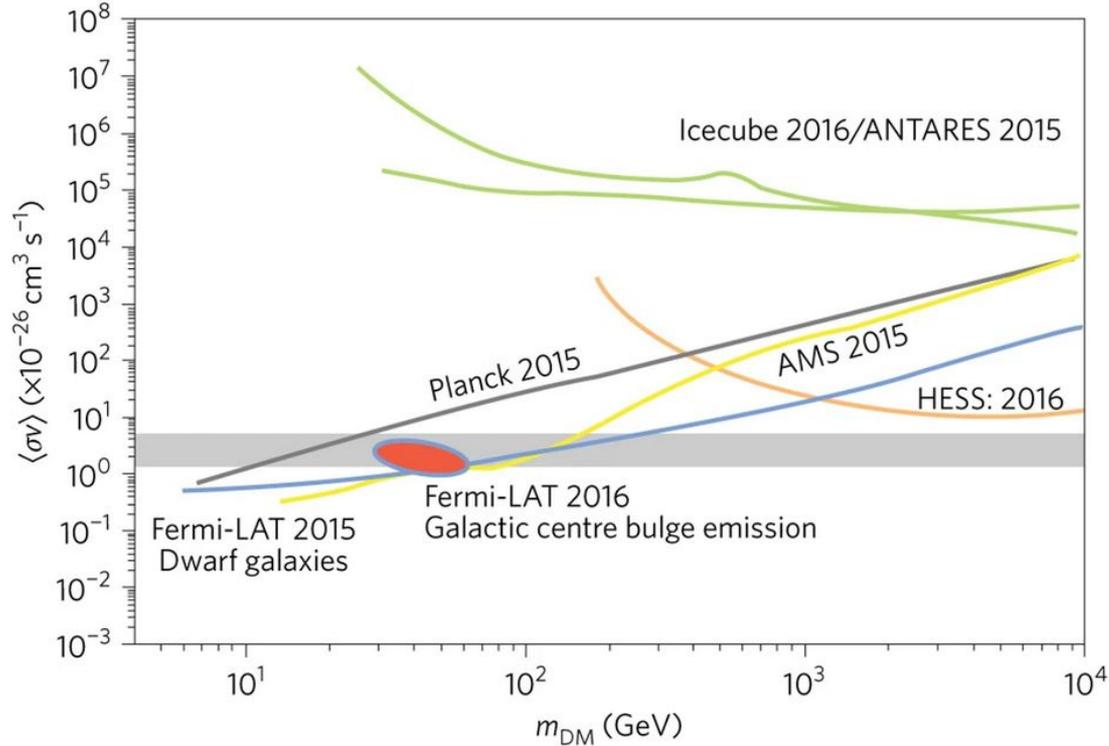
A source on gamma-ray astronomy or a hypothesis in high-energy physics can be tested only statistically. We rely on Wilks' theorem which gives a **test statistic** for comparing two hypothesis (new vs null):

$$TS \equiv -2 \ln \left[ \frac{\mathcal{L}(\mathbf{x} | \lambda_o, \hat{\mu}_o)}{\mathcal{L}(\mathbf{x} | \hat{\lambda}, \hat{\mu})} \right],$$

where  $\mathcal{L}$  is the maximum likelihood associated to each hypothesis. The conditional maximum at the null hypothesis is  $(\lambda_o, \hat{\mu}_o)$  while the global maximization is obtained at  $(\hat{\lambda}, \hat{\mu})$ .

Wilks' theorem shows that, for a large dataset,  $TS \sim \chi^2(r)$ , which enables us to define **confidence levels** (CL).

# Indirect detection limits



Compilation of limits on the dark matter annihilation cross-section according to dark matter particle mass from different channels of annihilation. Source: Conrad et al.