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CTAO Cherenkov Telescope Array Observatory

Sensitivity of the CTAO to Dwarf Irregular Galaxies

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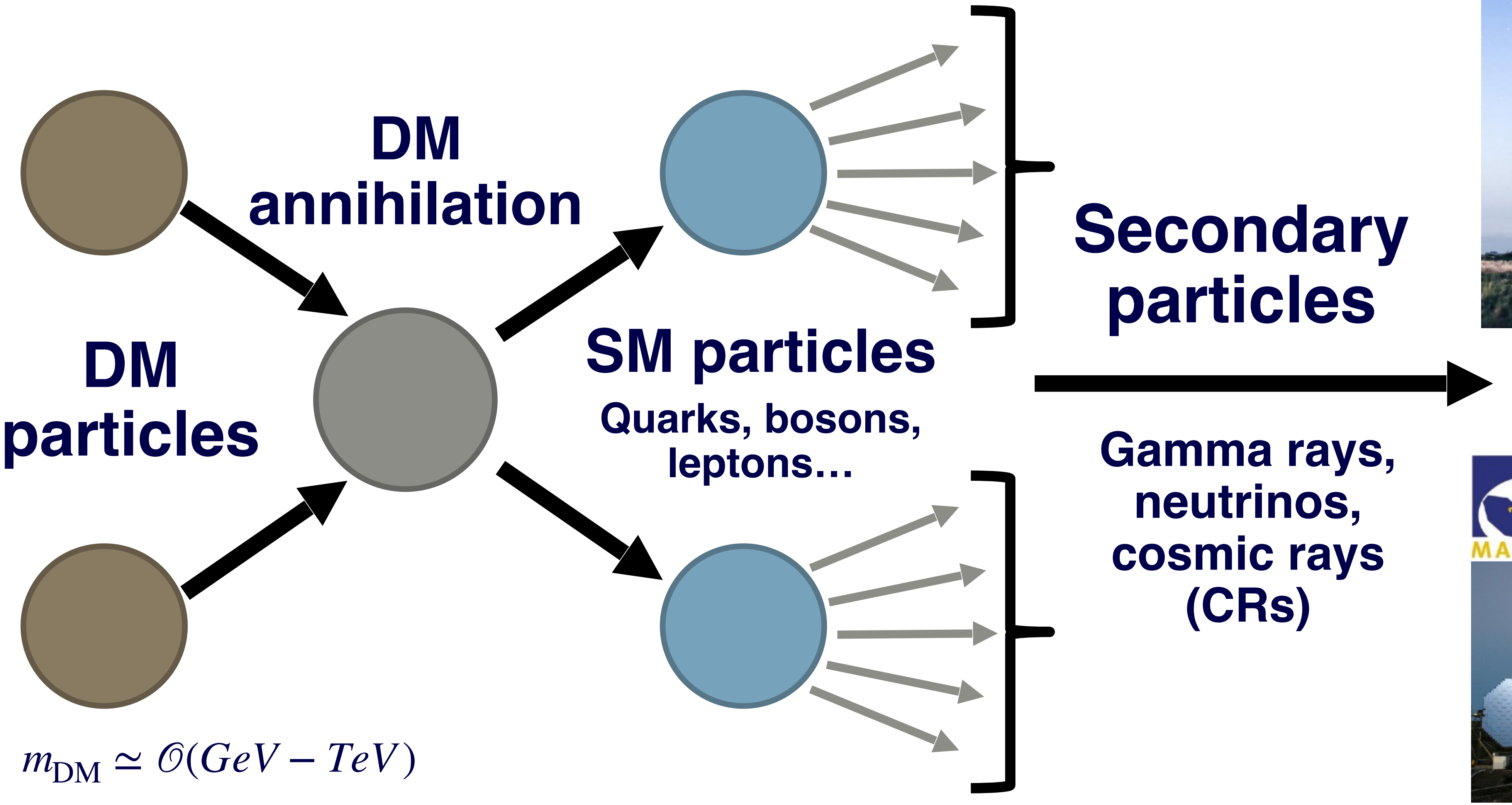
Context: Indirect Detection of WIMPs

Gamma Rays



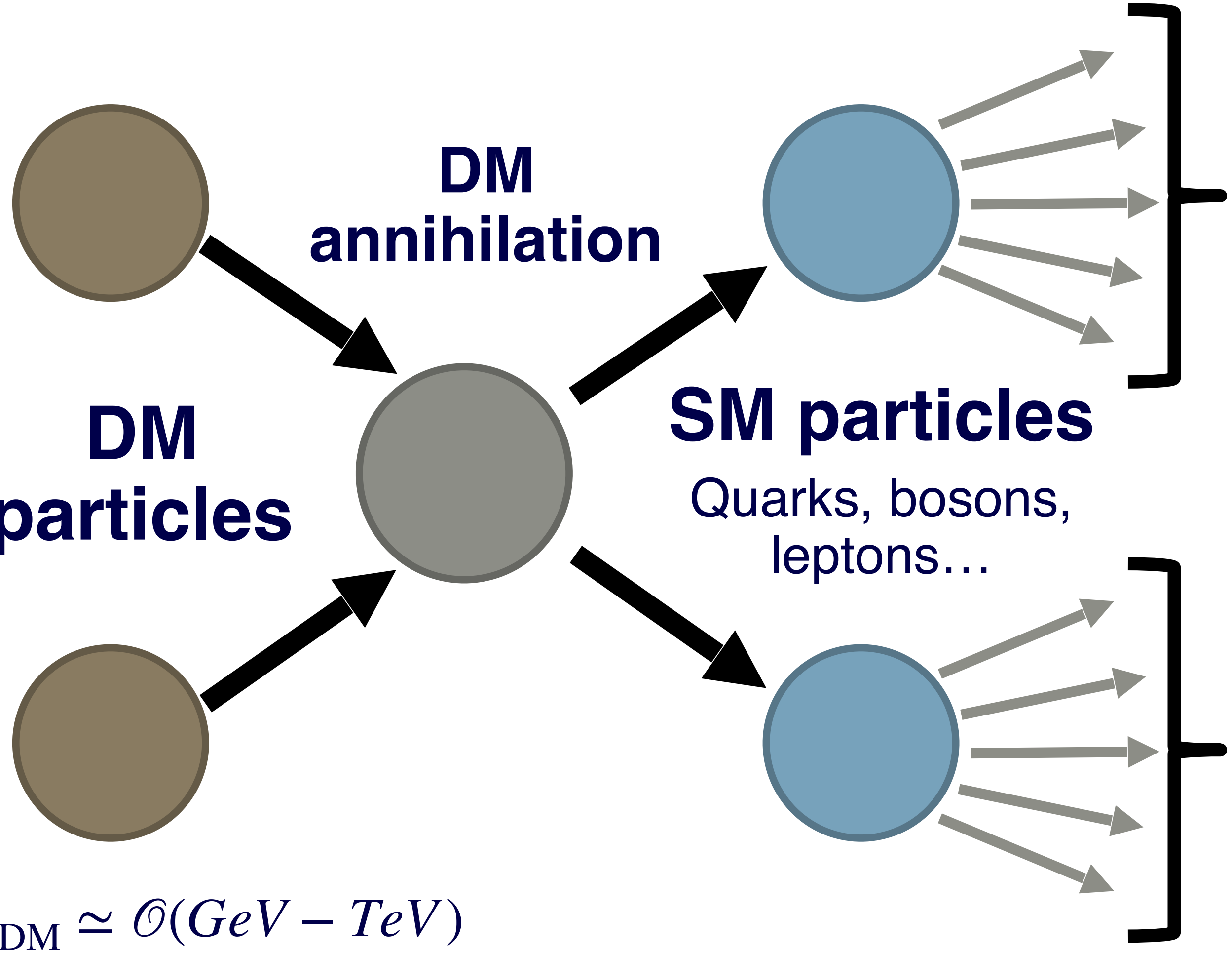
$m_{\rm DM} \simeq \mathcal{O}(GeV - TeV)$

CTAO - LST 1

MAGIC Telescopes

DM WIMPs Indirect Detection

Main Formula: Annihilation Flux



$m_{\mathrm{DM}} \simeq \mathcal{O}(GeV - TeV)$

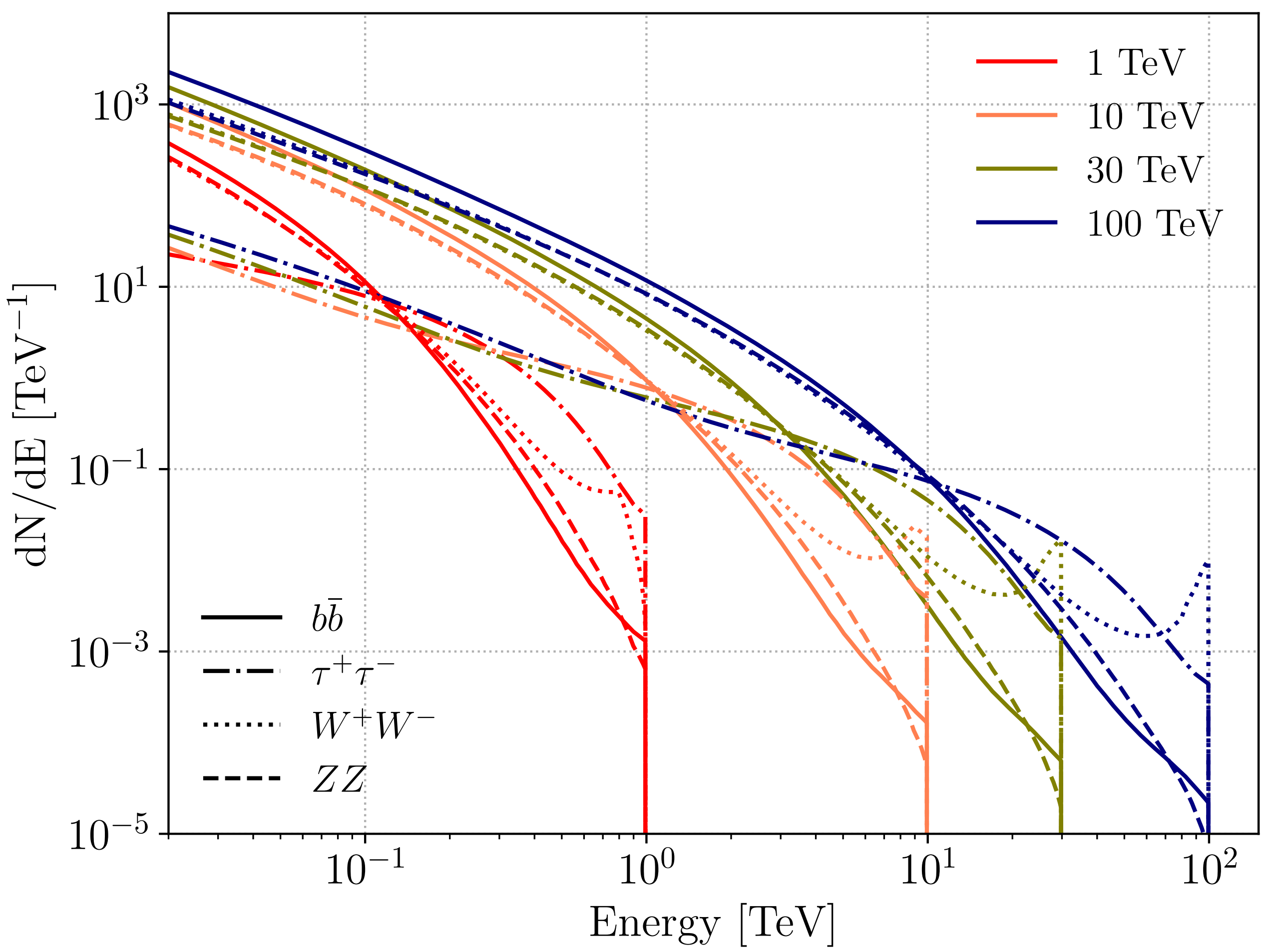
$$\frac{d\Phi_{\mathrm{DM}}}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_{\mathrm{DM}}^2} \sum_i^{\mathrm{channels}} \mathrm{BR}_i \frac{dN_i}{dE} J(\Delta\Omega)$$

- **Annihilation channels:** SM particles created from the annihilation
- $\boldsymbol{\langle \sigma v \rangle}$**:** velocity-averaged annihilation cross-section, to explain the measured thermal relic density $\Omega_{\mathrm{DM}} \simeq 0.27$

$$\langle \sigma v \rangle_{\mathrm{th}} \simeq 3 \times 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- $\boldsymbol{\frac{dN}{dE}}$: annihilation prompt emission of gamma rays
- $\boldsymbol{J(\Delta\Omega)}$ **J-factor:** information on the DM density distribution, astrophysical parameter

DM Annihilation Flux



JZP, V. Gammaldi & M. Sánchez-Conde, in preparation

$$\frac{d\Phi_{\rm DM}}{dE} = \frac{\langle \sigma v \rangle}{8\pi m_{\rm DM}^2} \sum_i^{\rm channels} {\rm BR}_i \frac{dN_i}{dE} J(\Delta\Omega)$$

- **Prompt production spectra** $\frac{dN}{dE}$ computed with **PPPC4DMID**

[M.Cirelli et al. 2011]

- **J-factor: DM density profile**

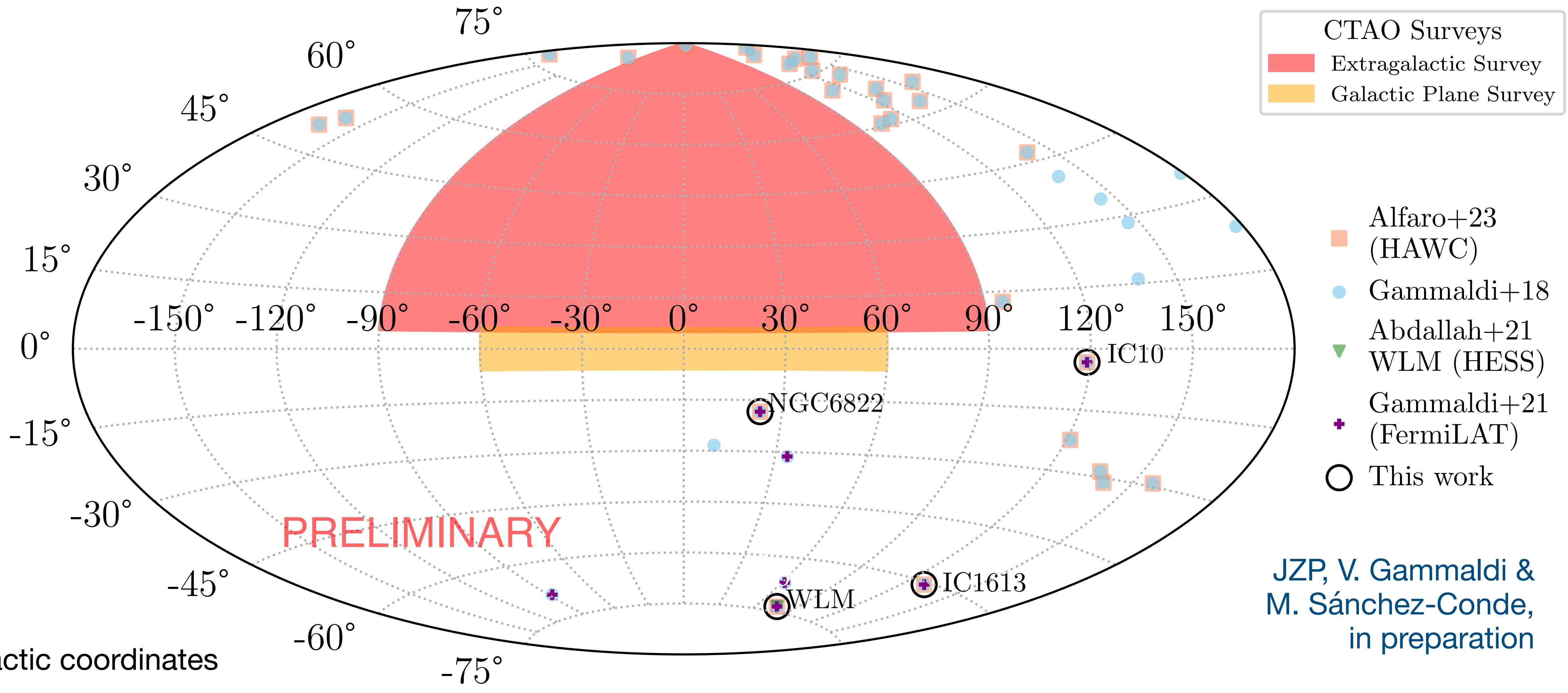
$$J(\Delta\Omega) = \int_{\Delta\Omega} {\rm d}\Omega \int_{l(\hat{\theta})_{\rm min}}^{l(\hat{\theta})_{\rm max}} \rho_{\rm DM}^2[r(l)]dl(\hat{\theta})$$

Comparison with other DM Targets

Type	Distance	DM mass	Astrophysical background	DM density profile
Galactic Center (100 pc)	~ 8.5 kpc	$\sim 10^{7}\ M_{\odot}$	Important, difficult to model (Sources + CRs)	Weak constraints
Dwarf Spheroidal Galaxies (dSph)	< 0.5 Mpc	$10^{7} - 10^{9}\ M_{\odot}$	Negligible	Pressure dominated
Galaxy Clusters	> 10 Mpc	$10^{14} - 10^{15}\ M_{\odot}$	Production from CRs	Smooth + subhalos population
dIrrs	> 0.5 Mpc	$10^{9} - 10^{10}\ M_{\odot}$	Negligible?	Rotation dominated

Target Selection

Targets chosen following best candidates from previous works



Galactic coordinates

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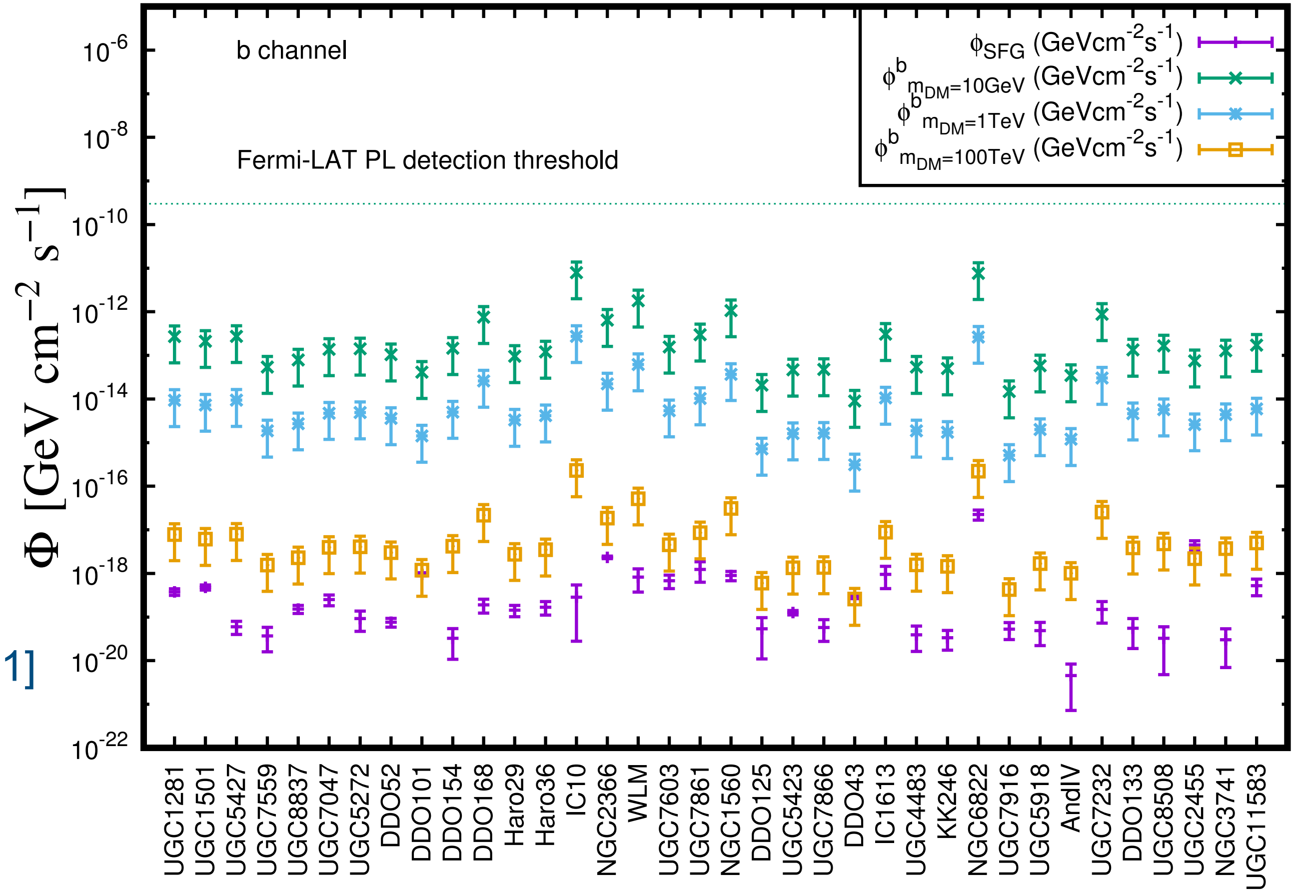
CTAO South: WLM, NGC6822, IC1613 **CTAO North:** IC10, IC1613

DIrrs Theoretical Predictions

Intrinsic Astrophysical Emission

Gammaldi et al., 2018

- **36 candidates** analysed
- **Negligible astrophysical background (MeV-GeV)** compared to the DM annihilation flux, **similar to dSphs**
- **Upper limits** already computed with **Fermi-LAT**, $\sim \mathcal{O}(10)$ worse constraints than dSphs [Gammaldi et al., 2021]
- **What about the GeV-TeV energy range?**



Star-Forming Region (SFR) emission

Gamma-ray Intrinsic Astrophysical Emission

- **For** $m_{\rm DM} \lesssim 10\,\text{TeV}$, the integrated **DM flux is greater than the SFR emission** by $\mathcal{O}(10)$
- **At** $m_{\rm DM} \gtrsim 60\,\text{TeV}$, the flux is of **the same order**
- **Similar behavior for the 4 dlrrs**
- **Power-law** with spectral index $\gamma = 2.5$
- **High uncertainty** in the normalization (~ 2 orders of magnitude)

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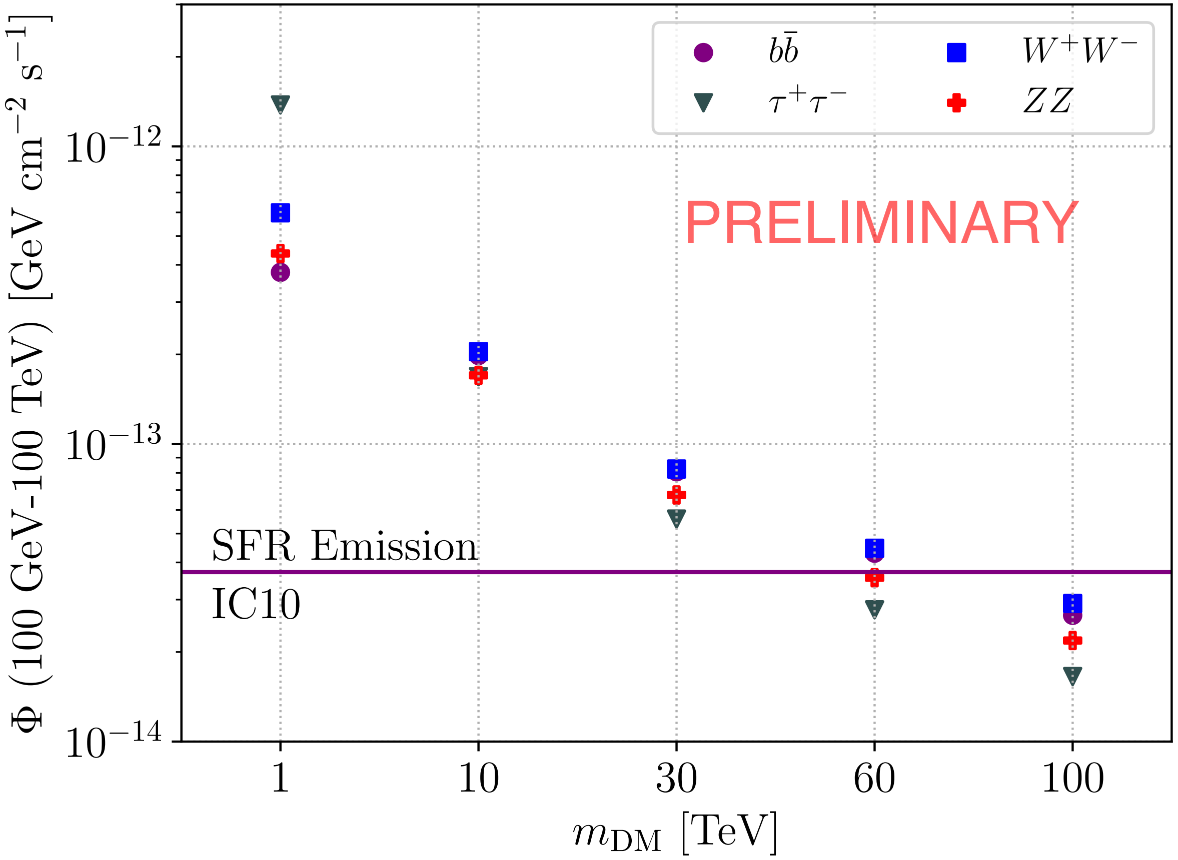


SFR gamma-ray luminosity: P. Martin 2014

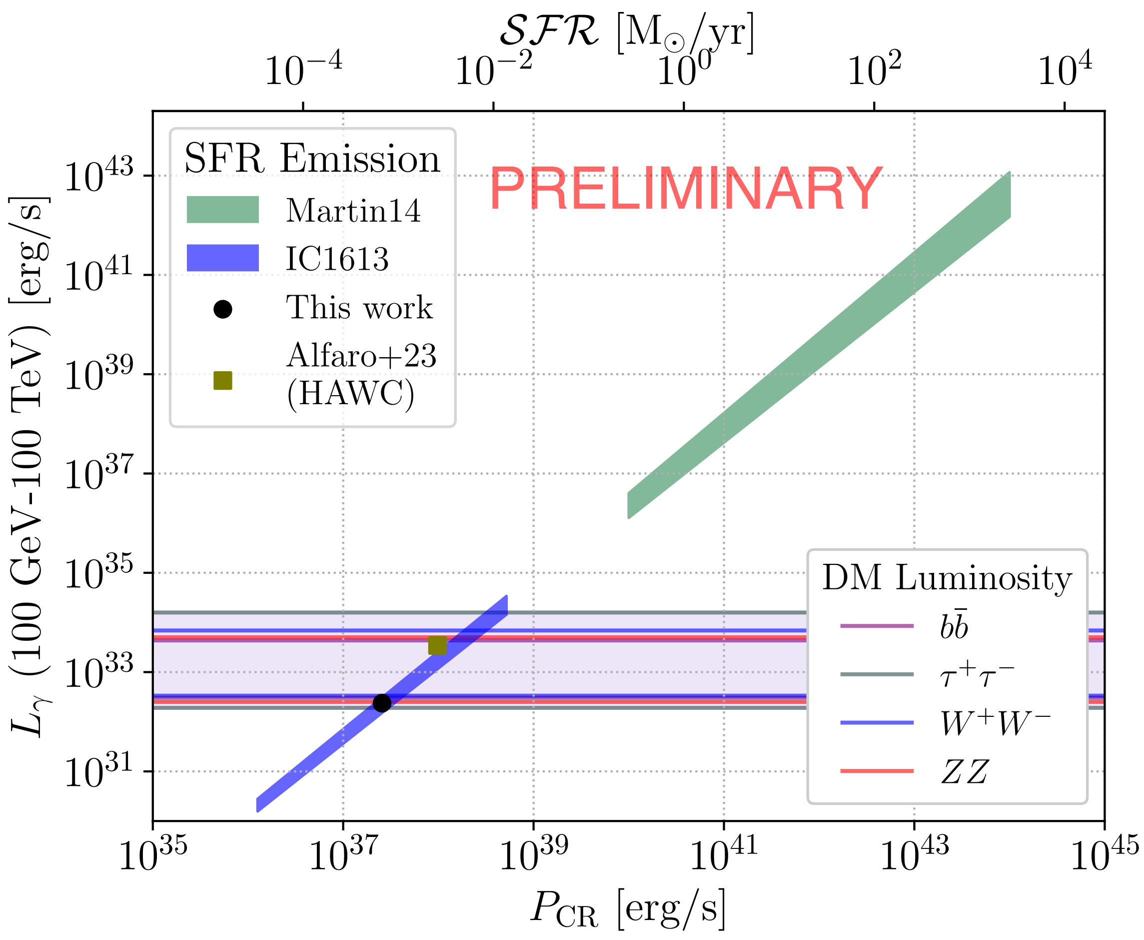
SFR estimation: S. McGaugh, J. Schombert & F.Elli 2017

SFR emission

Gamma-ray Intrinsic Astrophysical Emission

- The **main parameter** is the **star formation rate**
- **Big uncertainties:** we choose the middle point, but an **in-depth study is performed discussing the SFR emission detection**
- **Spatial extension:** the **optical size** of the galaxy ($\theta_{opt} \in (0.04° - 0.13°)$)

Star Formation Rate [$M_\odot$/yr]



Spectral modeling following R.Alfaro et al. 2023 (HAWC)

SFR gamma-ray luminosity: P. Martin 2014

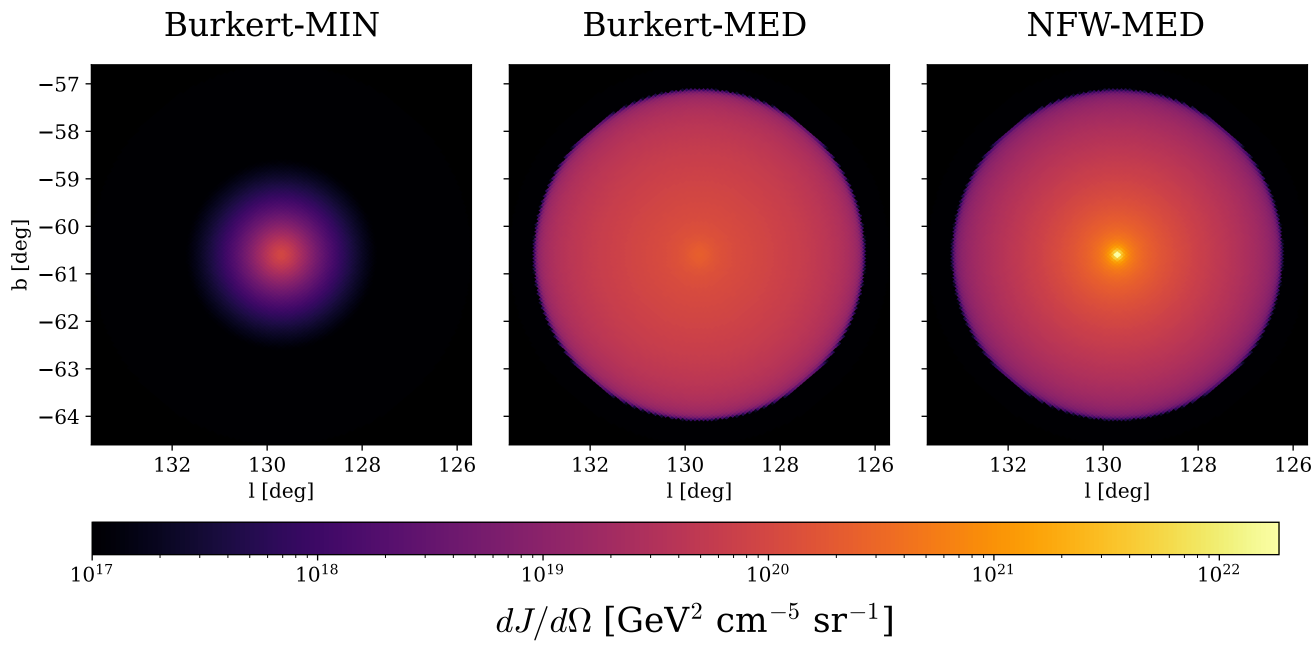
SFR estimation: S. McGaugh, J. Schombert & F.Elli 2017

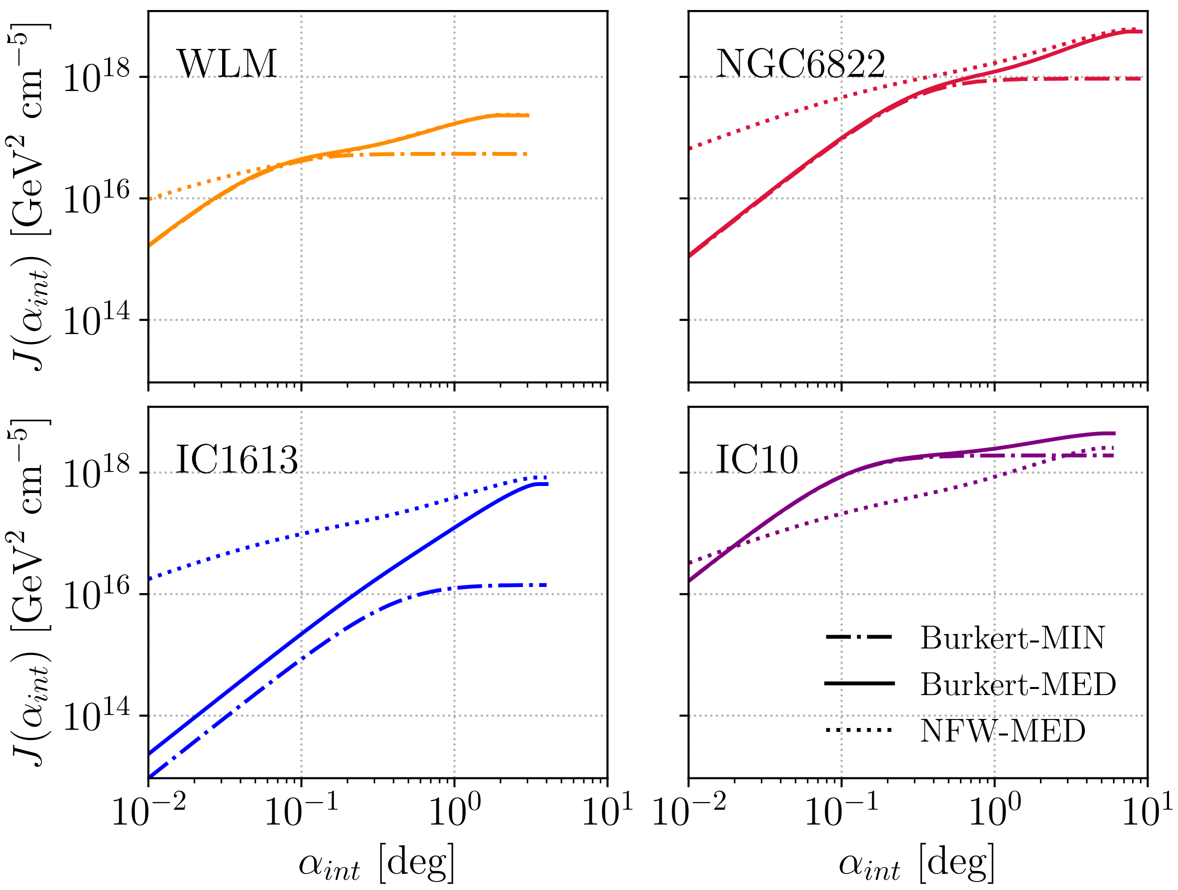
Spatial Distribution: J-Factors

- **Cored profile:** $$\rho_{\rm Bur}(r) = \frac{\rho_s}{(1+\frac{r}{r_s})(1+(\frac{r}{r_s})^2)}$$
- **Cuspy profile:** $$\rho_{\rm NFW}(r) = \frac{\rho_s}{(\frac{r}{r_s})(1+\frac{r}{r_s})^2}$$

$$J(\alpha_{\rm int}) = \int_{\Delta\Omega(\alpha_{\rm int})} d\Omega \int_{l(\hat\theta)_{\rm min}}^{l(\hat\theta)_{\rm max}} \rho^2_{\rm DM}[r(l)]dl(\hat\theta)$$

IC1613



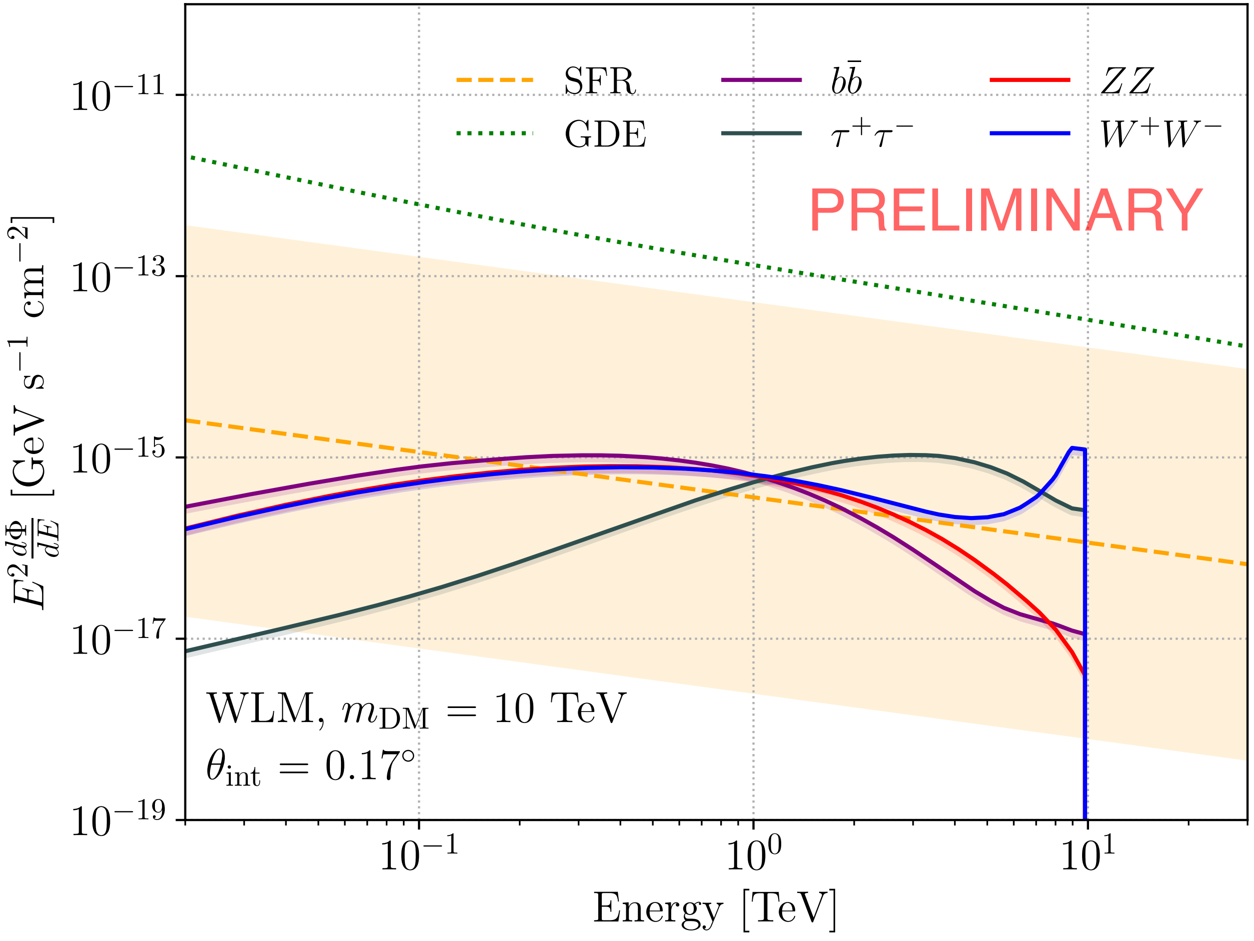


Spectral Component: Adding all up

- **SFR emission:** depending on the uncertainty, can be of the some order than DM flux
- **DM flux:** $b\bar{b}, \tau^+\tau^-, ZZ, W^+W^-$ channels [M.Cirelli et al. 2011]
- **Galactic diffuse emission (GDE):** greater than the rest of the fluxes

γ-optimized Max model:
P. de la Torre Luque et al., 2023

Integrated up to scale radius r_s



The Cherenkov Telescope Array Observatory (CTAO)

- **Array of 64 telescopes:** unprecedented flux and angular sensitivity (**Alpha configuration**)
- **With 2 locations:** full sky coverage
- **South sky:** Cerro Paranal, Chile
    - 37 Medium-Sized Telescopes (MSTs)
    - 14 Small-Sized Telescopes (SSTs)
- **North sky:** La Palma, Spain
    - 4 Large-Sized Telescopes (LSTs)
    - 9 MSTs
- Currently under construction phase
- With the **Alpha configuration**, we simulate **50h of observation per target**

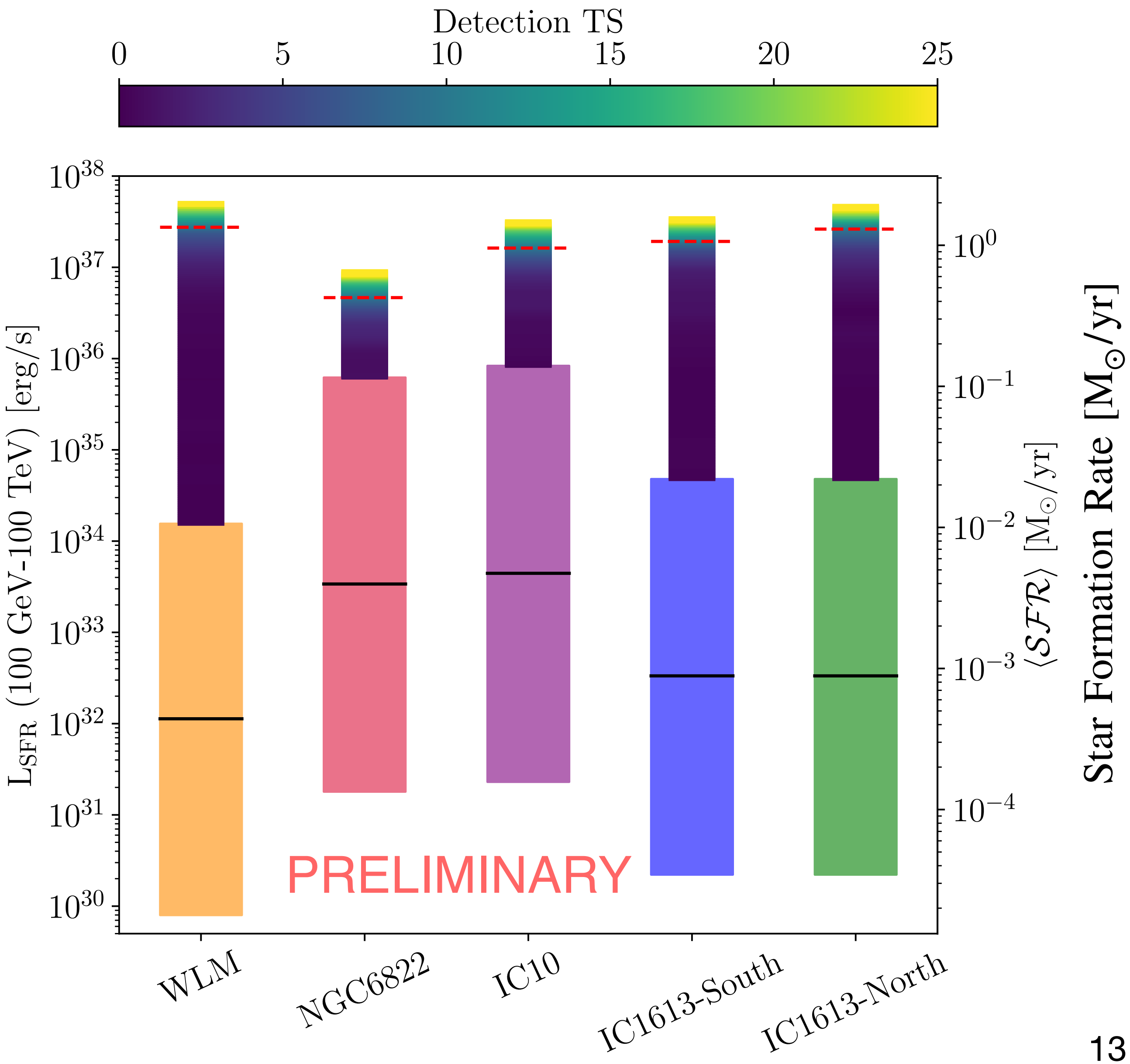
CTAO LST-1

SFR Emission Detection?

No DM signal simulated

- **Required flux** for a 3σ hint or 5σ **detection**
- **The flux needed is about 1 to 3 orders of magnitude** above the highest flux allowed by the uncertainty of our modeling
- **DIrrs are not expected to be detected** by CTAO as astrophysical sources

$$TS = -2\log \frac{\mathscr{L}_{null}(\theta_{SFR}=0, \theta_{bkg}\,|\,n)}{\mathscr{L}_{best-fit}(\hat{\theta}_{SFR}, \hat{\theta}_{bkg}\,|\,n)} \simeq \sigma^2$$

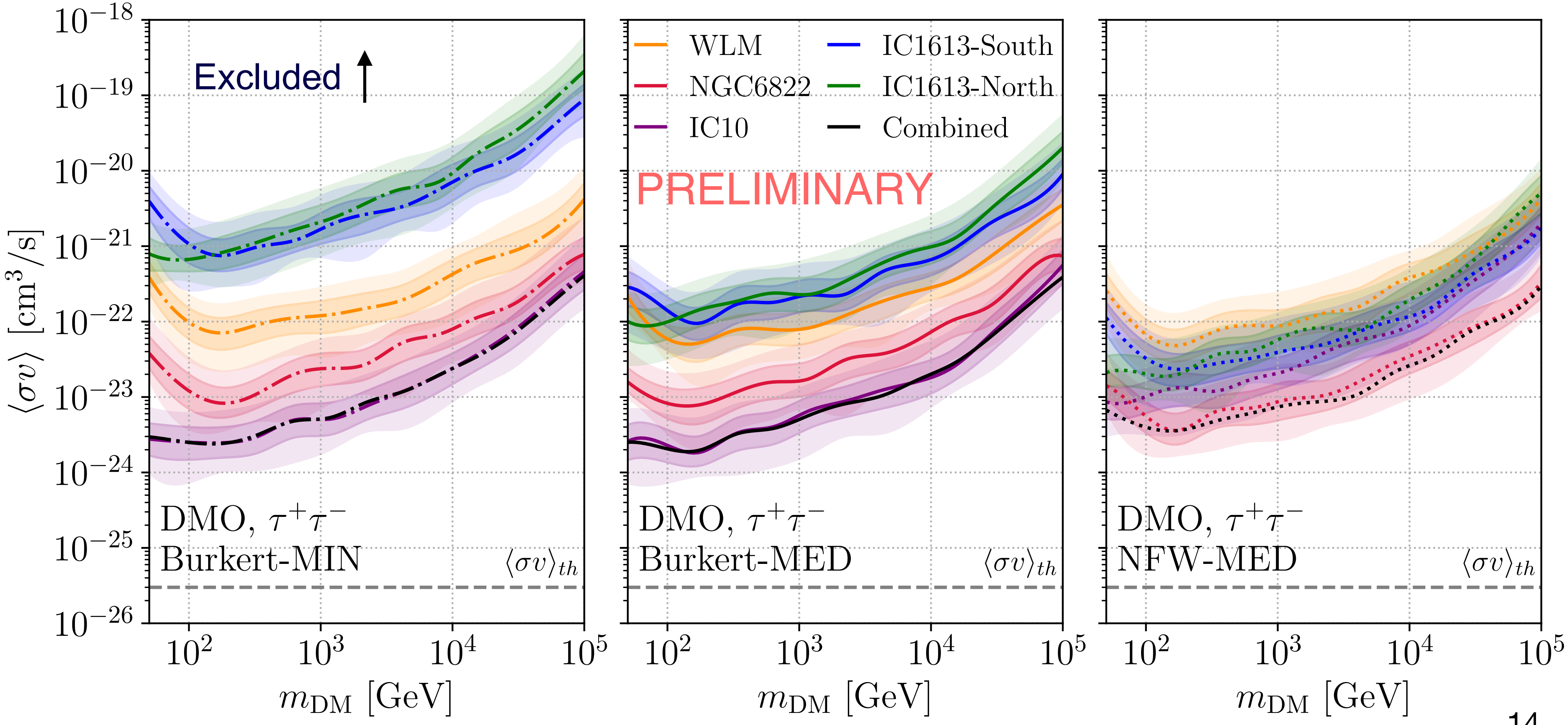


DM constraints: spatially extended DM-only analysis

$$TS = -2\log\frac{\mathscr{L}_{95\%}(\langle\sigma v\rangle_{95\%},\theta_{95\%}\,|\,\mathrm{n})}{\mathscr{L}_{\text{best-fit}}(\langle\hat{\sigma v}\rangle,\hat{\theta}\,|\,\mathrm{n})} = 2.71$$

In the absence of detection, we set constraints

- 1σ & 2σ uncertainties from poissonian noise
- We average over 100 simulations



Full DM analysis: extended DM & Astrophysical Emission

$$\mathrm{TS} = -2\log\frac{\mathscr{L}_{95\%}(\langle\sigma v\rangle_{95\%}, \theta_{95\%}\,|\,\mathrm{n})}{\mathscr{L}_{\text{best-fit}}(\langle\hat{\sigma v}\rangle, \hat{\theta}\,|\,\mathrm{n})} = 2.71$$

In the absence of detection, we set constraints

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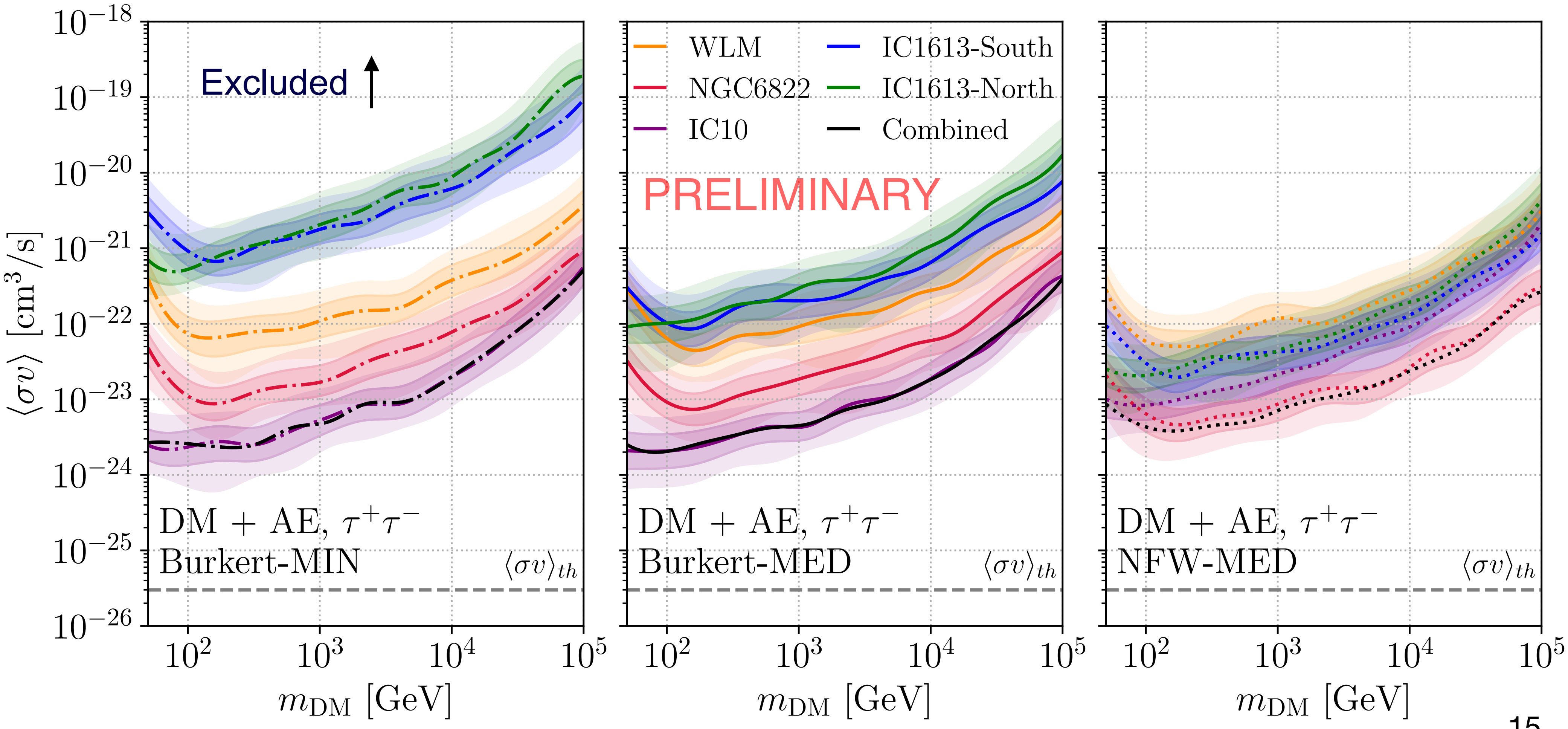
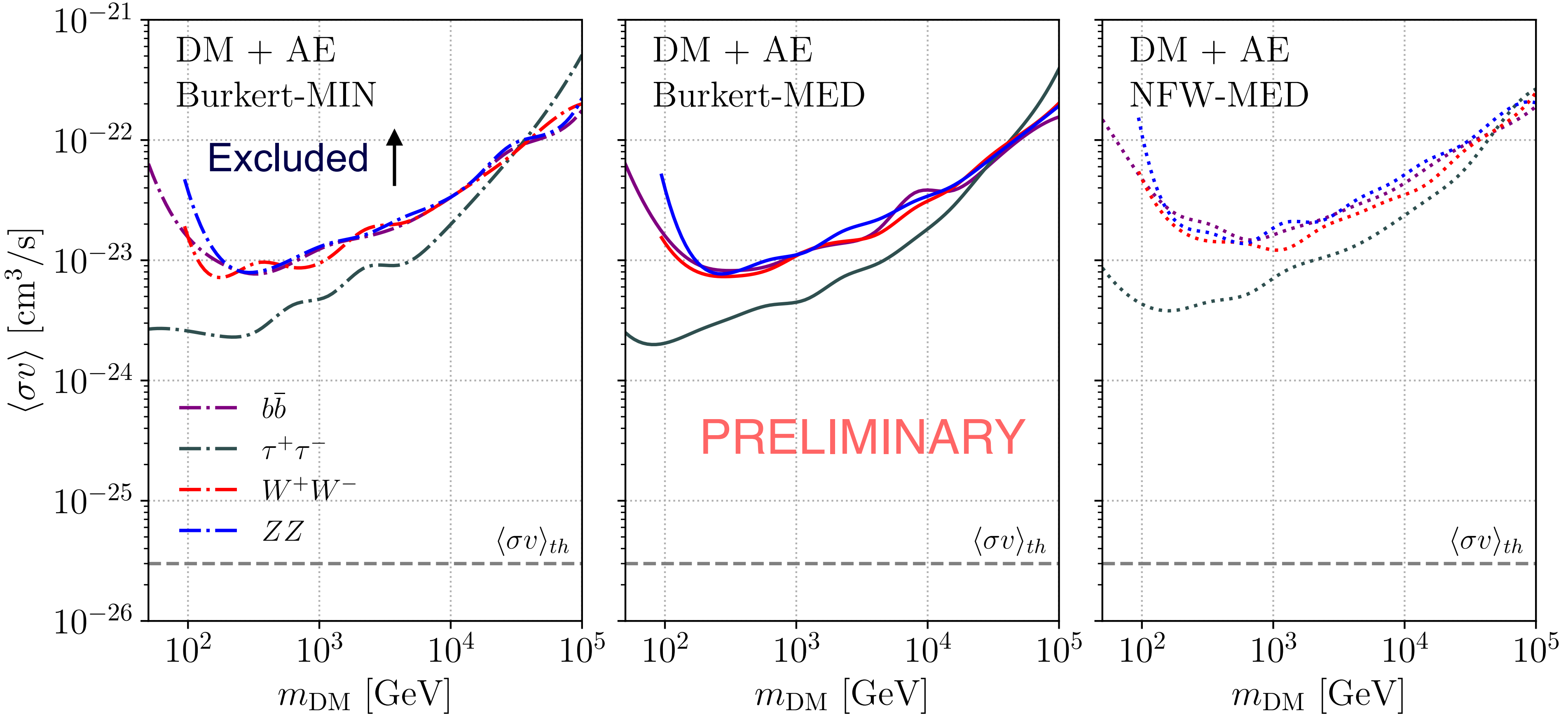


Comparison between channels

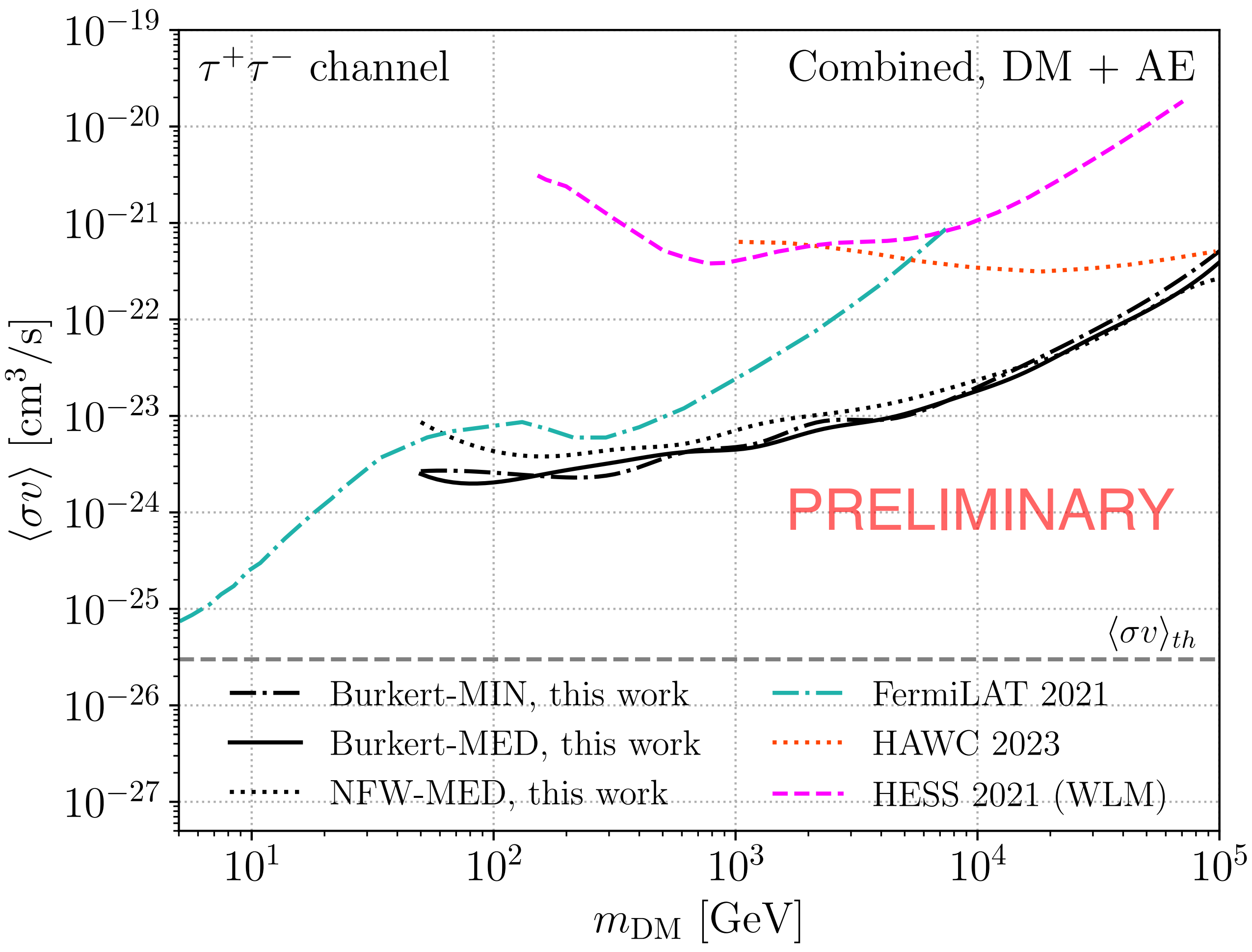
$$\mathrm{TS} = -2\log\frac{\mathcal{L}_{95\%}(\langle\sigma v\rangle_{95\%},\theta_{95\%}\,|\,\mathrm{n})}{\mathcal{L}_{\mathrm{best-fit}}(\langle\hat{\sigma v}\rangle,\hat{\theta}\,|\,\mathrm{n})} = 2.71$$

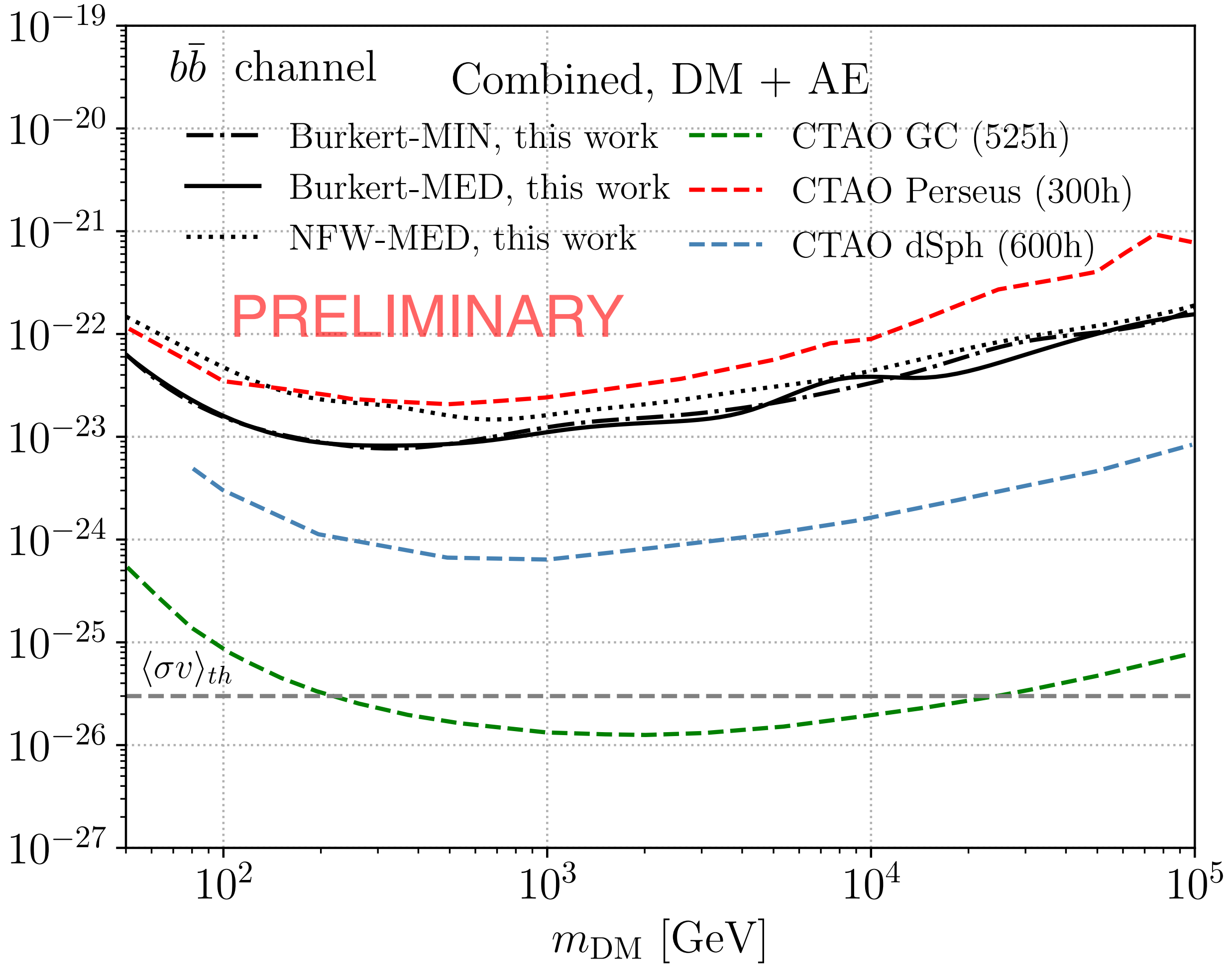
- **Best results** for $\tau^+\tau^-$ channel and Burkert-MED
- **Burkert profile:** dominates IC10
- **NFW profile:** dominates NGC6822



Comparison with other constraints

50h of observation per target





JZP, V. Gammaldi & M. Sánchez-Conde,
in preparation

Conclusions

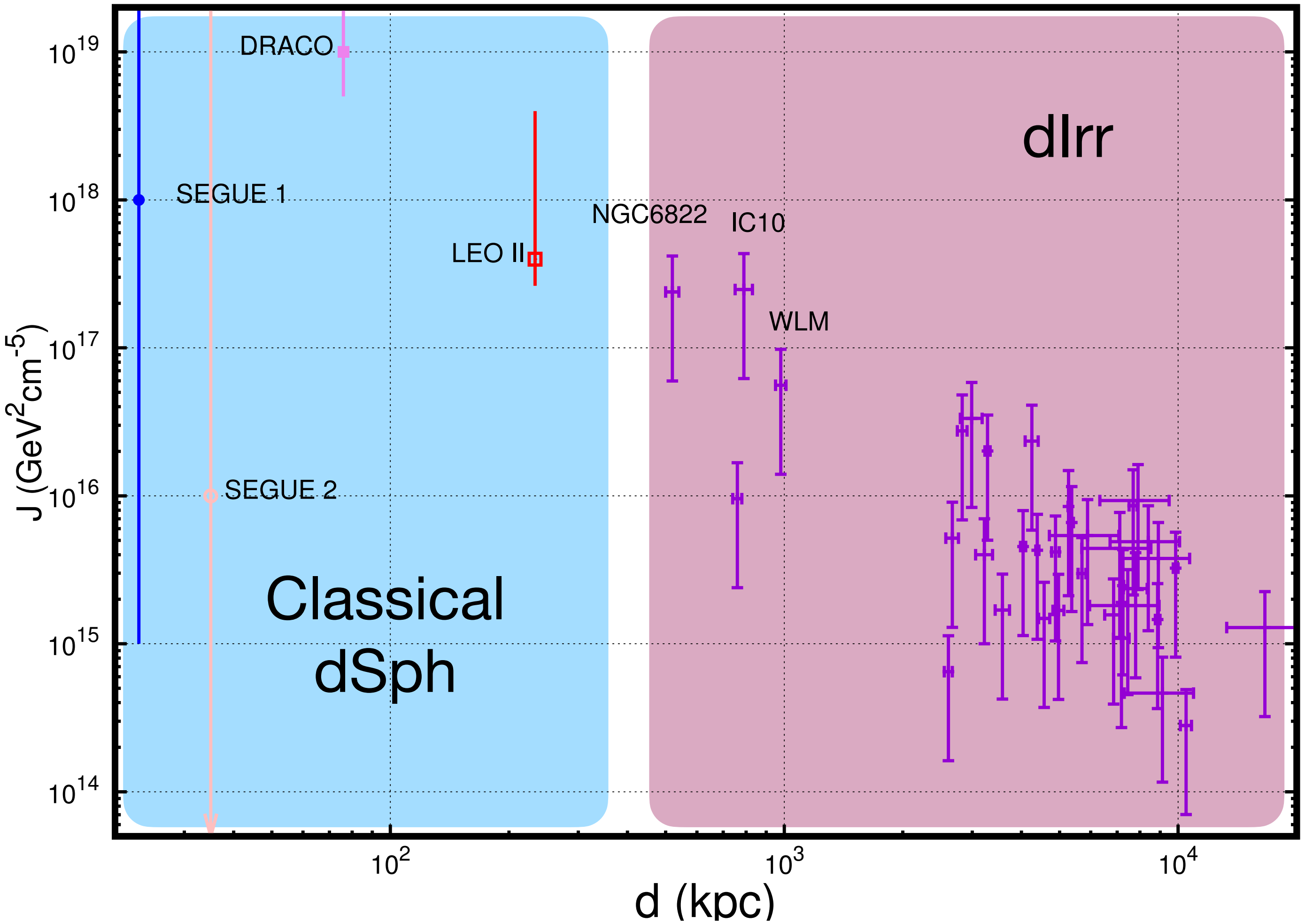
- **We do not expect to detect dIrrs as astrophysical sources** (SFR emission) in gamma rays **with CTAO**, Star Formation Rate needed $\sim 1\ \mathrm{M_{\odot}/yr}$
- 2 galaxies dominate the DM constraints: **IC10** and **NGC6822**
- **Very similar results with the inclusion/exclusion of the AE**, like dSphs
- **Complementary and competitive results** compared to e.g. **CTAO's constraints** from **Perseus Galaxy Cluster**

Thank you for your time!

CTAO

Comparison with DSphs

J-Factor comparison



J-Factor computed for $\theta = 0.5°$

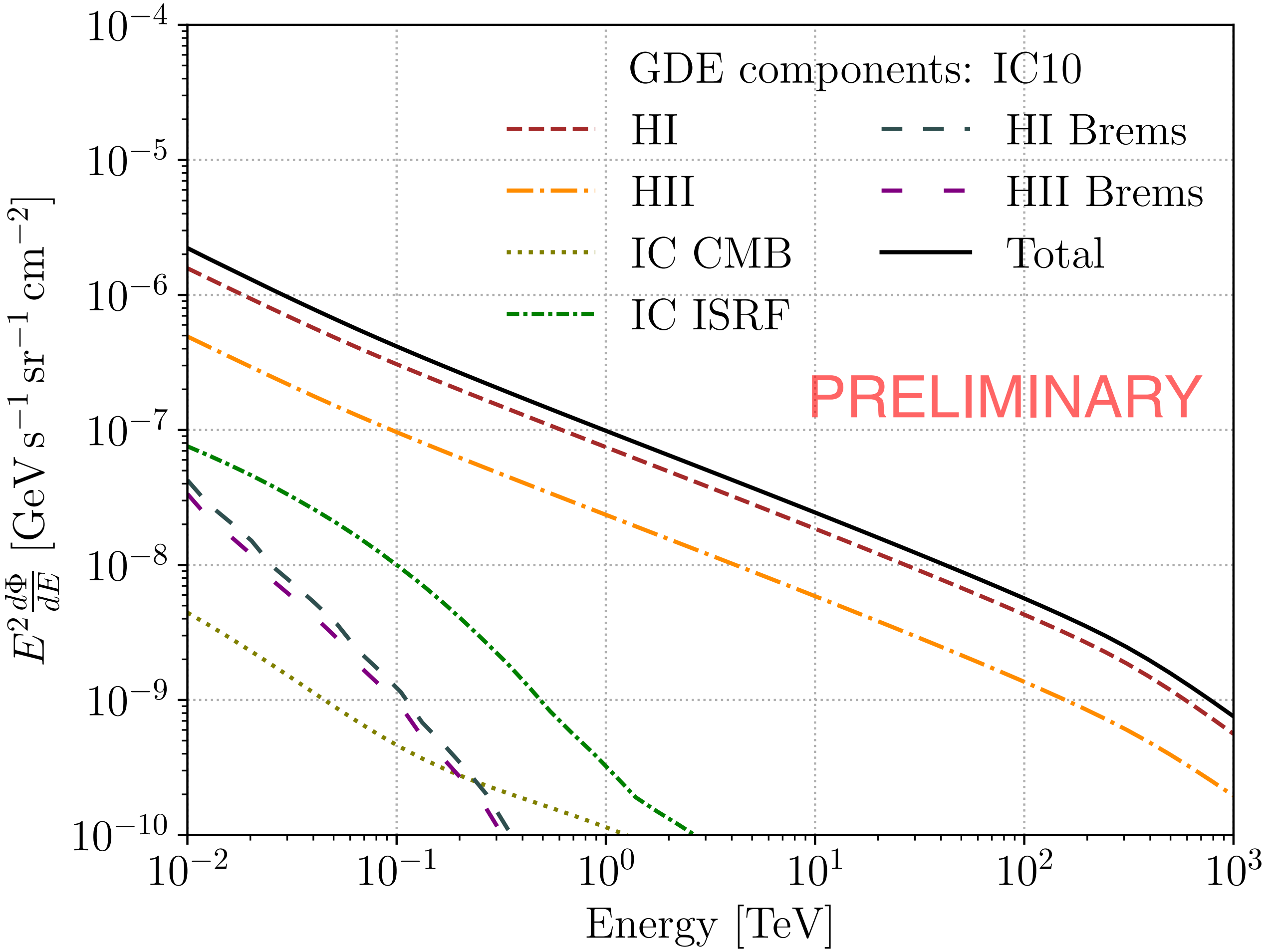
- **Competitive J-Factor** values
- Low uncertainties
- **Subhalos:** an extra boost factor ~ 5

Gammaldi et al., 2018

Spectral Component: Galactic Diffuse Emission

Galactic Diffuse Emission (GDE): Milky Way Contribution

- Spectra for the Milky Way Diffusion Emission when pointing to the galaxies chosen
- GDE computed with DRAGON: γ-optimized Max model
- This model features a spatial dependent diffusion coefficient

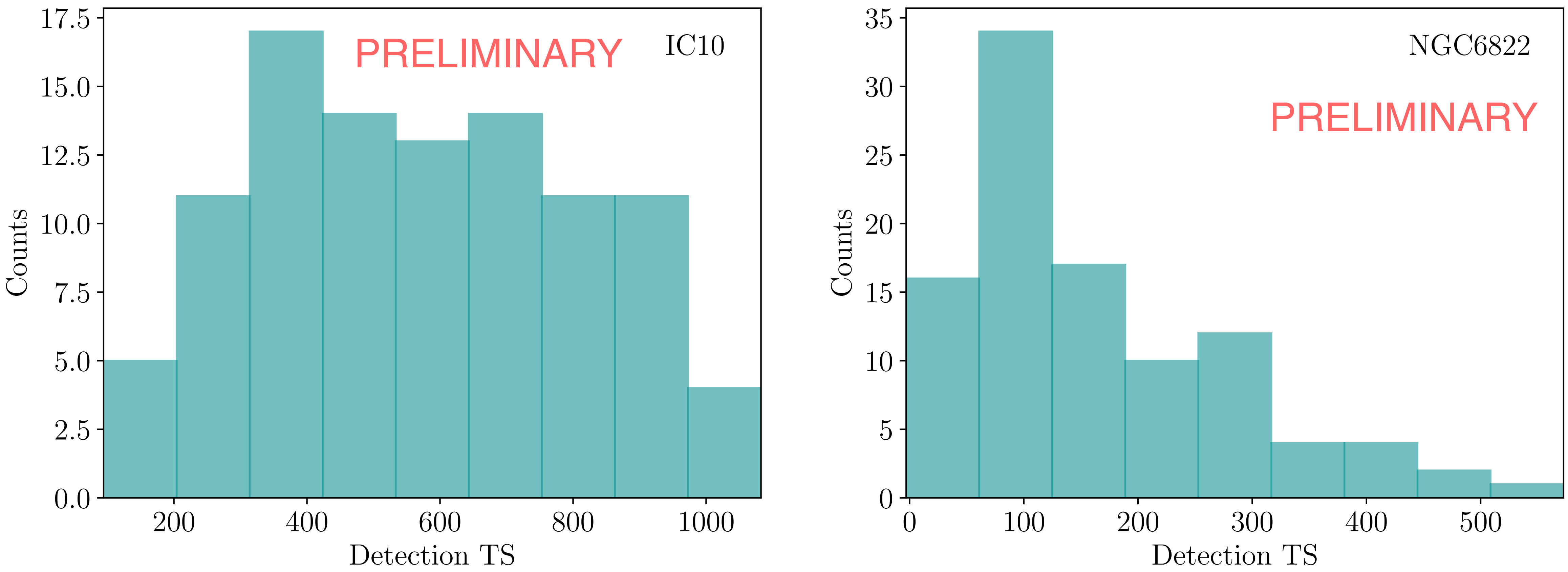


γ-optimized Max model:
P.D.I.T. Luque et al. 2023

GDE detection?

$$-2\log\frac{\mathscr{L}_{\rm null}(\langle\sigma v\rangle = 0,\theta\,|\,{\rm n})}{\mathscr{L}_{\rm best-fit}(\langle\hat{\sigma v}\rangle,\hat{\theta}\,|\,{\rm n})} \simeq \sigma^2$$

GDE can be detected for the galaxies **close to the Galactic Plane:** IC10 and NGC6822



Spectral Modelling: SFR Emission

Gamma-ray Intrinsic Astrophysical Emission

- The modeling is based computing the Star Forming Rate of each galaxy with its stellar mass (M_*)

Star formation rate estimation: S. McGaugh, J. Schombert & F.Elli 2017

$$\log(\text{Star Formation Rate}\,[\text{M}_\odot/\text{yr}]) = -10.75 \pm 0.53 + 1.04 \pm 0.06 \log(M_*/\text{M}_\odot) \pm 0.34$$

- With the star formation rate estimated, the gamma-ray flux is given by:

$$P_{\text{CR}} \propto \text{Star Forming Rate}$$

Normalization $$\log(L_\gamma[\text{erg/s}]) = \beta \log(P_{\text{CR}}) + \delta$$

SFR gamma-ray luminosity: P. Martin 2014

Differential Flux $$\frac{d\Phi}{dE} \propto E^{-2.5}$$

Spectral Modelling: SFR Emission

Gamma-ray Intrinsic Astrophysical Emission

Galaxy	$M_* \, [\mathrm{M_\odot}]$	Star formation rate $[\times 10^{-3} \, \mathrm{M_\odot/yr}]$	L_γ [erg/s]	$\theta_{\rm opt}$ [deg]	i [deg]	e
IC10	1.18×10^8	$(0.20, 4.42, 99.88)$	4.44×10^{33}	0.04	$-$	0.59
IC1613	1.94×10^7	$(0.03, 0.68, 13.70)$	2.37×10^{32}	0.11	-40	0.46
WLM	1.23×10^7	$(0.02, 0.42, 8.30)$	1.13×10^{32}	0.13	-86	0.89
NGC6822	1.00×10^8	$(0.17, 3.72, 83.18)$	3.39×10^{33}	0.04	240	0.65

Spatial Morphology: DM Density Profiles

DM profiles from FermiLAT 2021 [Gammaldi et al. 2021]

	WLM		IC10		IC1613		NGC6822	
DM Profile	NFW	Burkert	NFW	Burkert	NFW	Burkert	NFW	Burkert
ρ_s [$M_\odot$/kpc^3]	1.00e7	6.31e7	6.31e6	1.58e8	7.94e6	2.00e6	7.94e6	3.16e7
r_s [kpc]	2.8	1.3	6.8	2.0	4.0	7.0	5.9	3.3
R_{VIR} [kpc]	33.6	33.3	70.3	71.3	45.7	45.7	62.6	62.9
θ_{VIR}	1.98°	1.97°	5.09°	5.16°	3.44°	3.44°	7.43°	7.47°
D [kpc]	970		790		760		480	

$$\rho_{NFW}(r) = \frac{\rho_s}{(\frac{r}{r_s})(1+\frac{r}{r_s})^2} \qquad \rho_{Bur}(r) = \frac{\rho_s}{(1+\frac{r}{r_s})(1+(\frac{r}{r_s})^2)}$$

Subhalo Population Parameters

$$\frac{d^3N}{dVdMdc} = N_{\text{tot}} \frac{dP_V}{dV}(R) \frac{dP_M}{dM}(M) \frac{dP_c}{dc}(M,c)$$

- **Subhalo Radial Distribution** $\frac{dP_V}{dV}$:
  follow main halo (with scale radius $10 \times r_s$)
- **Subhalo Mass Function** $\frac{dP_M}{dM} \propto M^{-\alpha}$
- **Concentration-mass relation** $c - M$:
  kMOLINE17_200 [A. Moliné et al. 2017]
- **Subhalo Concentration Distribution** $\frac{dP_c}{dc}$:
  no scatter considered

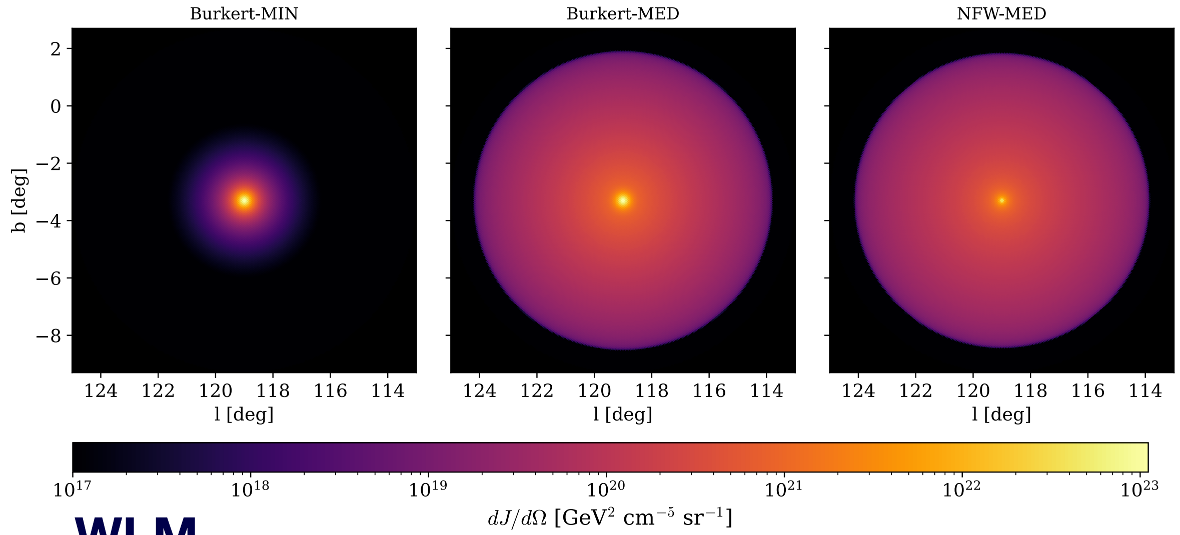
Model	Burkert-MIN	Burkert-MED	NFW-MED
Main Halo	Burkert	Burkert	NFW
# of sublevels	0	2	2
Subhalo	-	NFW	NFW
SRD	-	Burkert	NFW
SHMF	-	$\alpha = 1.9$	$\alpha = 1.9$

Following FermiLAT 2021 and CTAO Perseus Paper

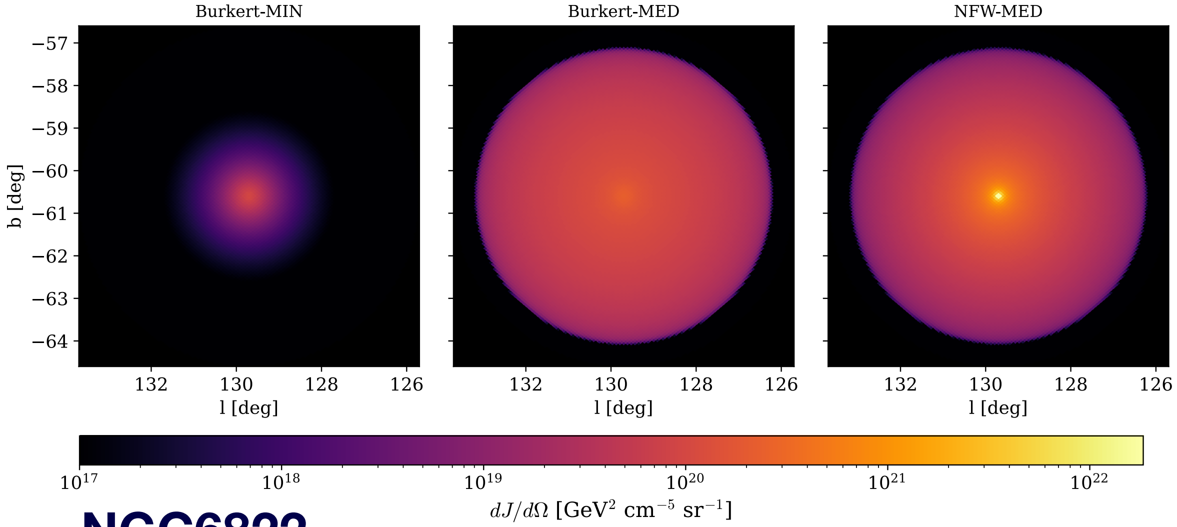
[V. Gammaldi et al. 2021] [R. Adam et al., CTAO collaboration, 2023]

Spatial Distribution: J-Factors

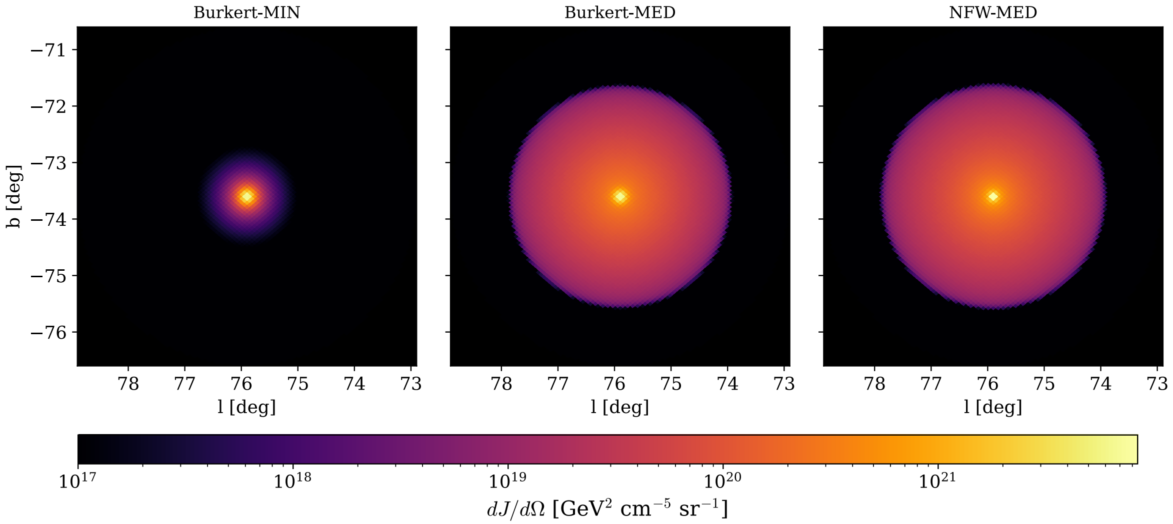
IC10



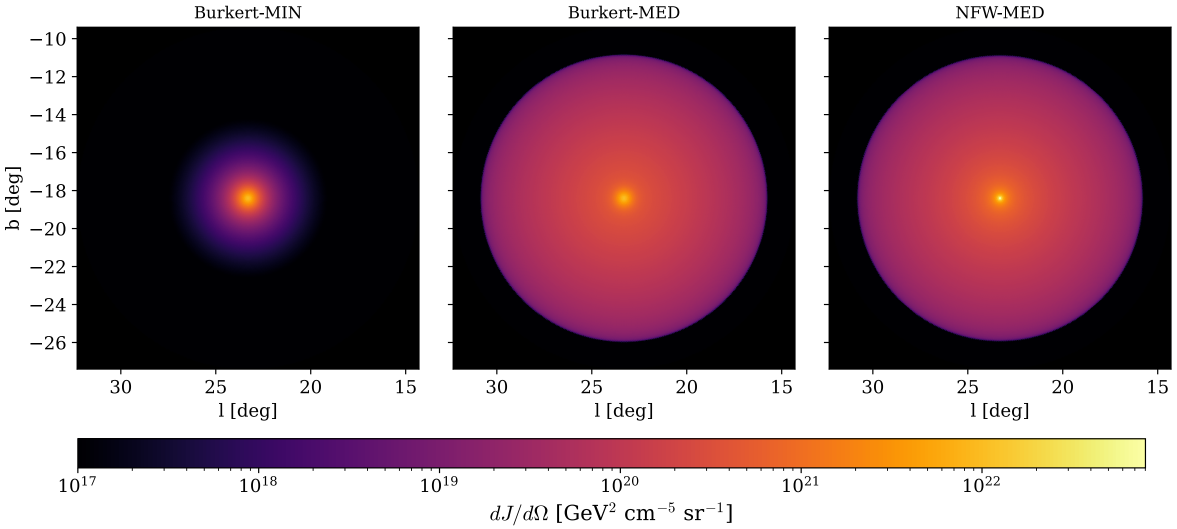
IC1613



WLM



NGC6822



Main Objectives

Template Analysis, 50h observation per target

1. **Astrophysical emission:** detectability prospects of dIrrs as astrophysical sources

2. **WIMP DM: detectability prospects** and benchmark $\langle \sigma v \rangle$ **upper limits**

   2.1. **Spatially extended DM-only analysis:**

   only modeling of the DM annihilation emission, as in previous works

   2.2. **Full analysis: extended DM & Astrophysical Emission:**

   DM annihilation + SFR emission + GDE

$$\mathscr{L}(\mu \,|\, n) = \prod_{i,j} e^{-\mu_{i,j}} \frac{\mu_{i,j}^{n_{i,j}}}{n_{i,j}!}$$

Methodology

Pipeline based on gammapy v1.2

- **CTAO's Instrument Response Functions** (IRFs): prod5 v0.1
- **Instrumental CR Background**
- **Spectral and Spatial templates**

Simulation of the counts (n)

Observed counts map

Template analysis:

expected counts (μ) from the models to test

$$\mathscr{L}(\mu \,|\, n) = \prod_{i,j} e^{-\mu_{i,j}} \frac{\mu_{i,j}^{n_{i,j}}}{n_{i,j}!}$$

Sensitivity prospects

Detection of the signal

$$-2 \log \frac{\mathscr{L}_{\rm null}(\langle \sigma v \rangle = 0, \theta \,|\, \mathrm{n})}{\mathscr{L}_{\rm best-fit}(\hat{\langle \sigma v \rangle}, \hat{\theta} \,|\, \mathrm{n})} \simeq \sigma^2$$

Upper limits

$$-2 \log \frac{\mathscr{L}_{95\%}(\langle \sigma v \rangle_{95\%}, \theta_{95\%} \,|\, \mathrm{n})}{\mathscr{L}_{\rm best-fit}(\hat{\langle \sigma v \rangle}, \hat{\theta} \,|\, \mathrm{n})} = 2.71$$

Note:

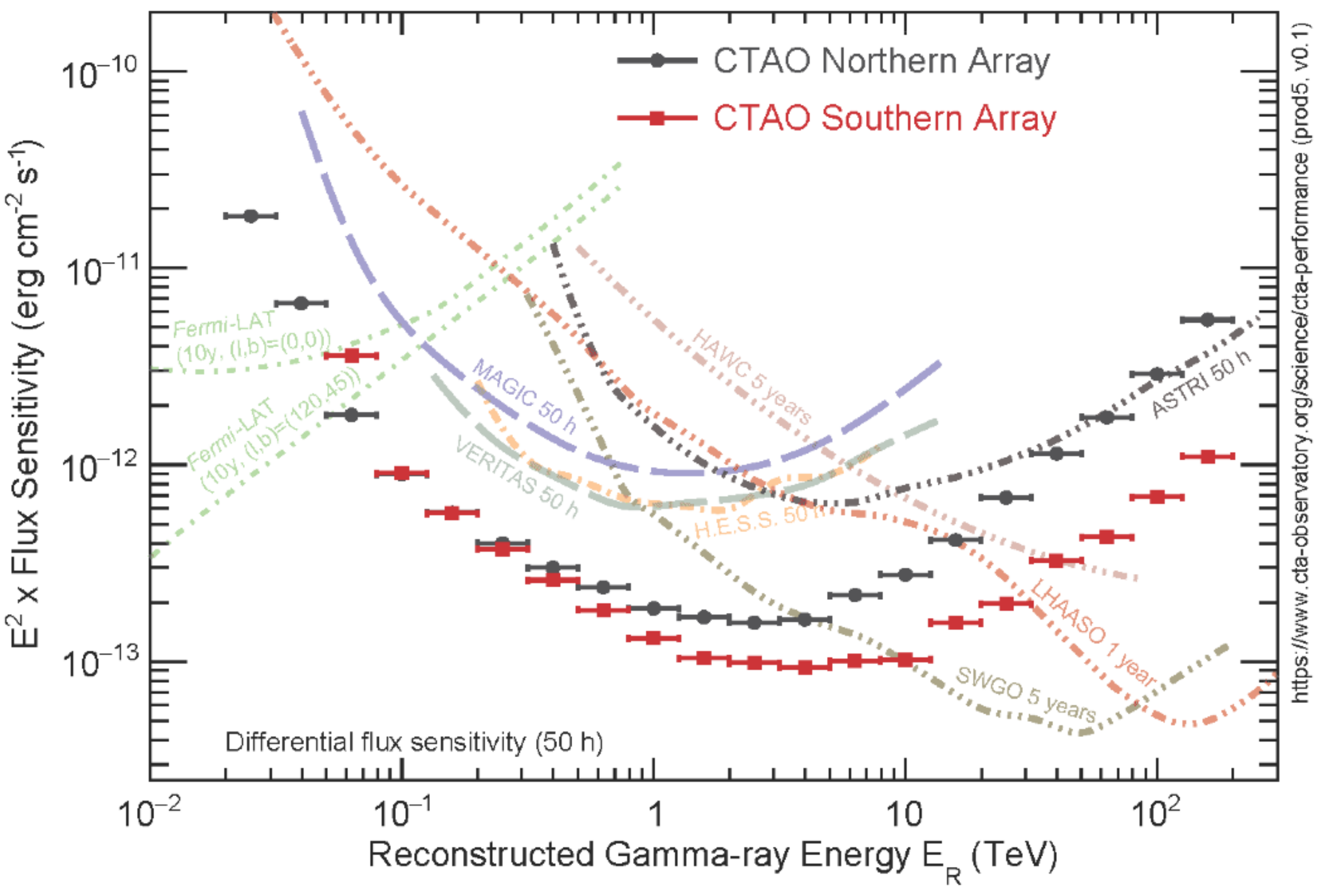
Given the Poissonian statistics of the counts simulation, for each modeling 100 simulations are performed

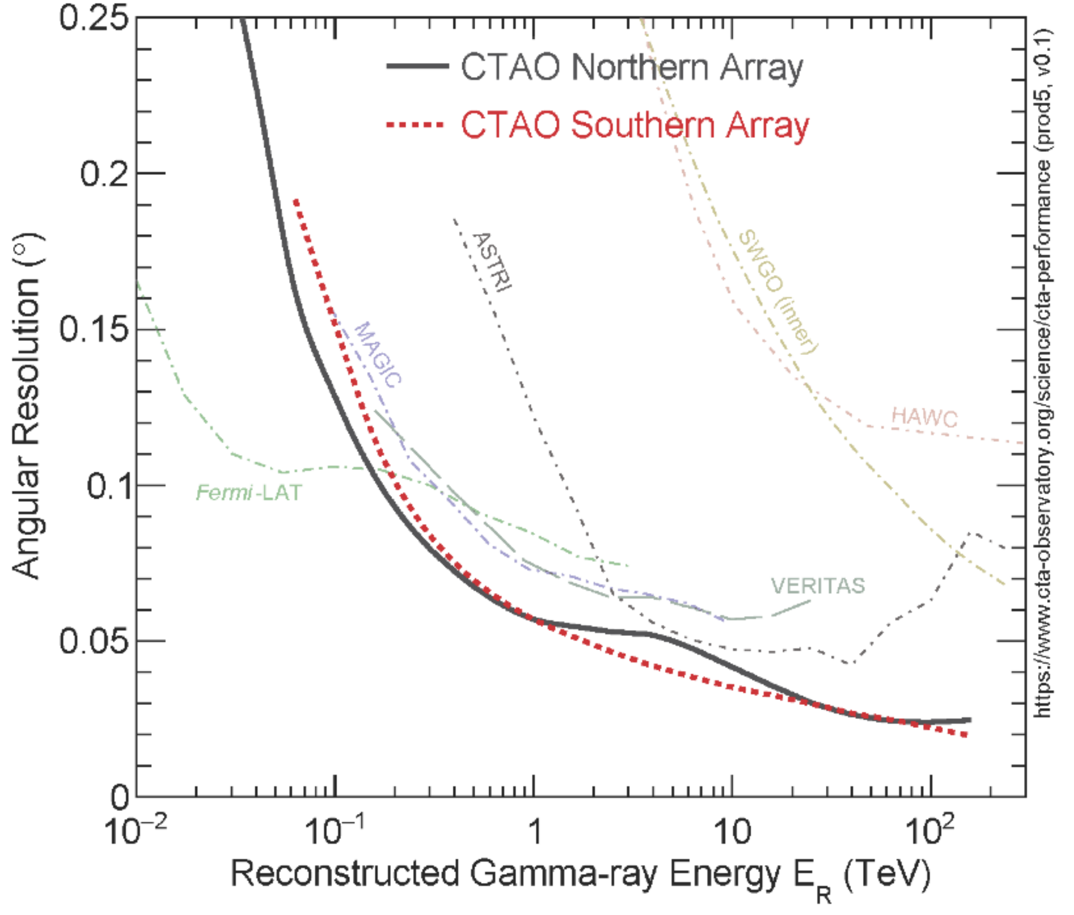
Simulation Setup

- **Sky simulation, observation simulation and statistical analysis:** pipeline based on **Gammapy** (v1.2)
- **Angular binning:** sky map with grid 0.02°
- **Energy binning:** 10 bins logarithmically spaced between 20 GeV and 150 TeV
- **Observations:** 50h of observation time per target
- **IRFs:**
  - North site: Prod5-North-20deg-AverageAz-4LSTs09MSTs.180000s-v0.1
  - South site: Prod5-South-20deg-AverageAz-14MSTs37SSTs.180000s-v0.1
- **Statistical consistency:** 100 realizations per observation (similar to the KSP Perseus Paper)
- **Template analysis:**

$$\mathscr{L}(\mu \,|\, n) = \prod_{i,j} e^{-\mu_{i,j}} \frac{\mu_{i,j}^{n_{i,j}}}{n_{i,j}!}$$

CTAO Sensitivity

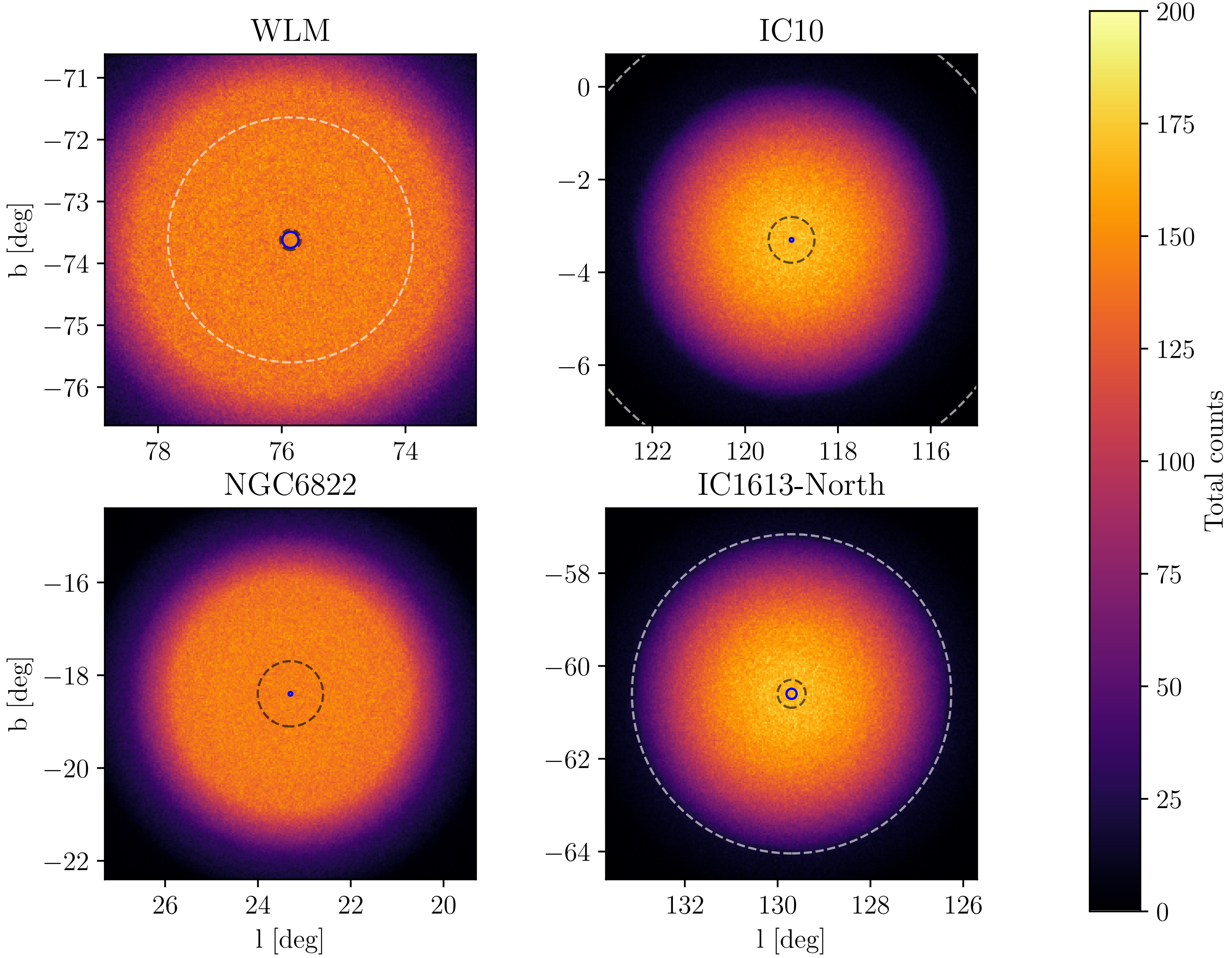




https://www.ctao.org/es/for-scientists/performance/

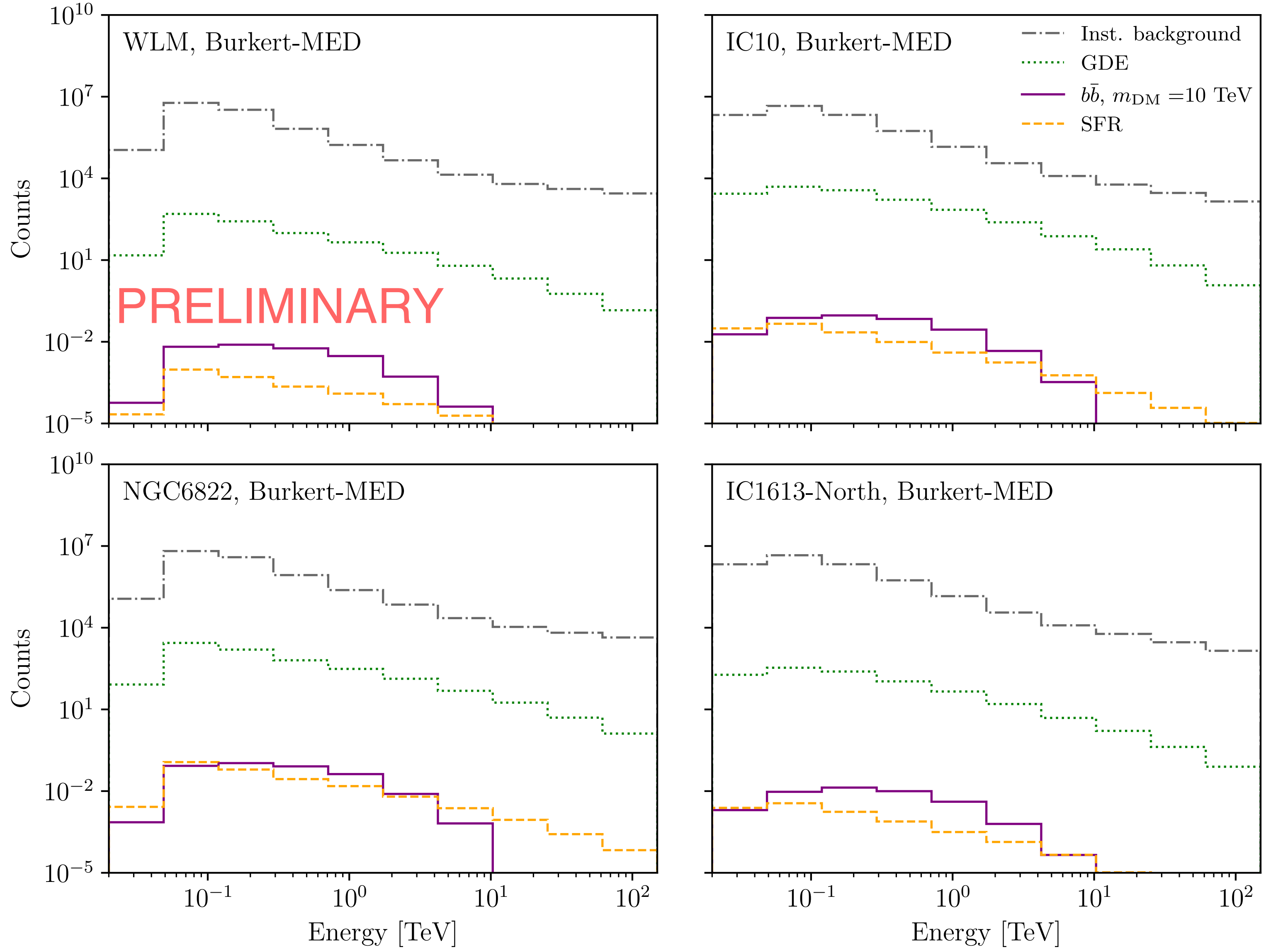
Gamma-ray Simulation: Spatial maps

- Burkert-MED
- Instrumental CR background dominates the counts



Gamma-ray Simulation: Spectral Counts

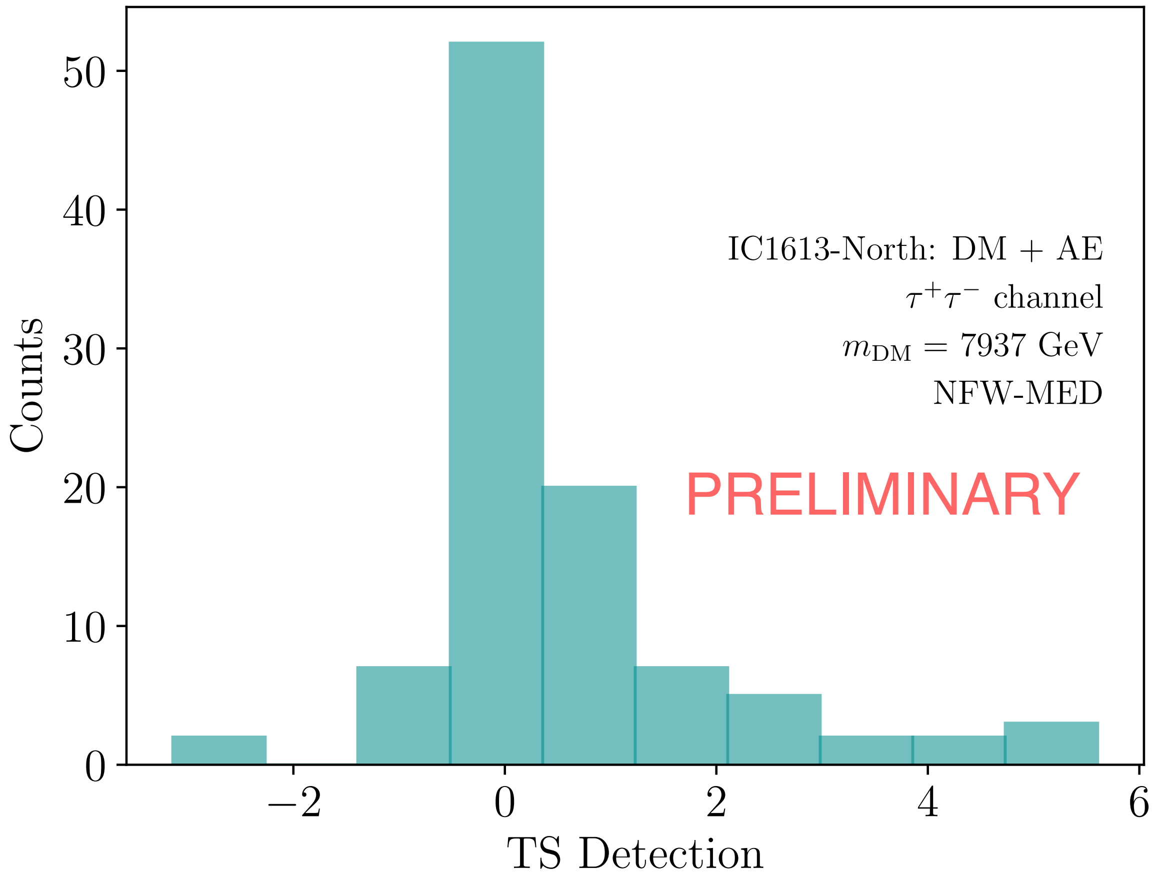
- Burkert-MED
- Instrumental CR background dominates the counts

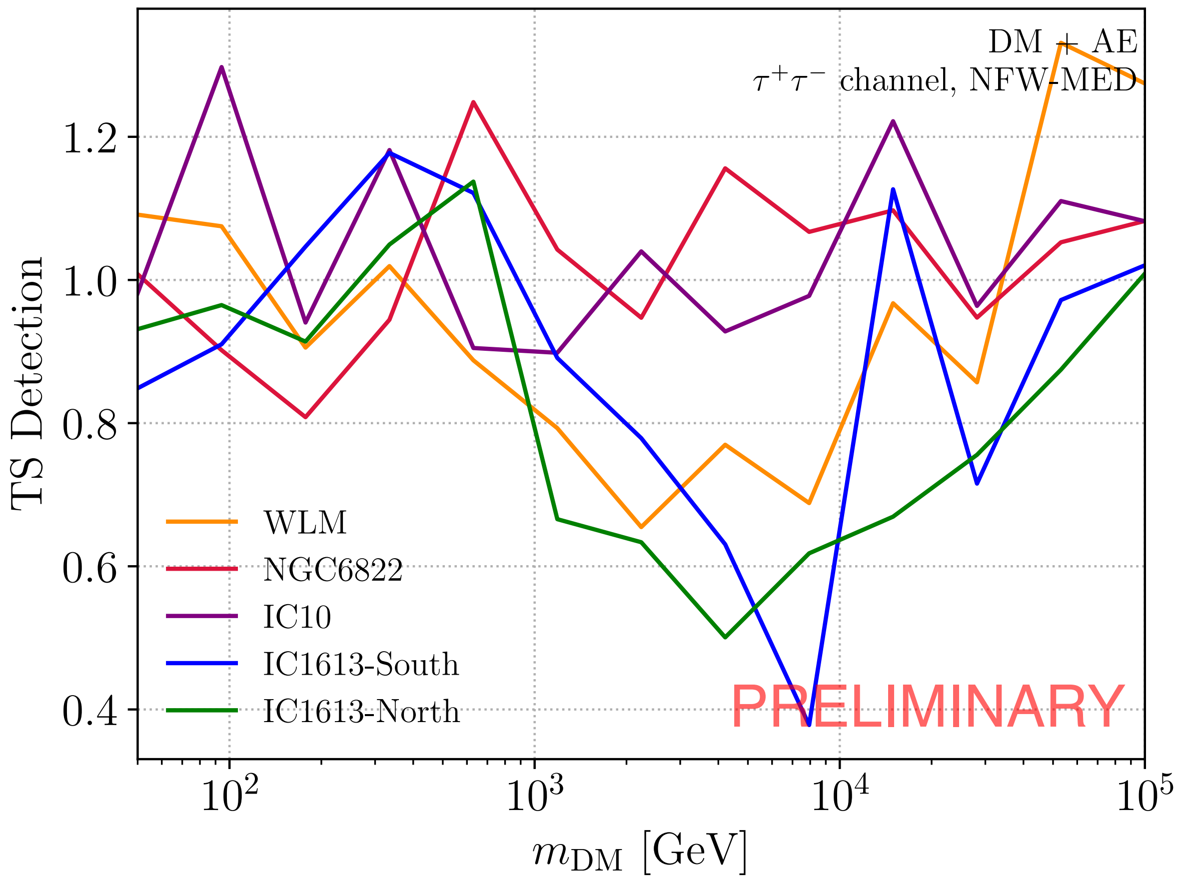


DM Detection prospects

No significant detection in any of the cases

$$-2\log\frac{\mathscr{L}_{\rm null}(\langle\sigma v\rangle = 0,\theta\,|\,{\rm n})}{\mathscr{L}_{\rm best-fit}(\langle\hat{\sigma v}\rangle,\hat{\theta}\,|\,{\rm n})} \simeq \sigma^2$$



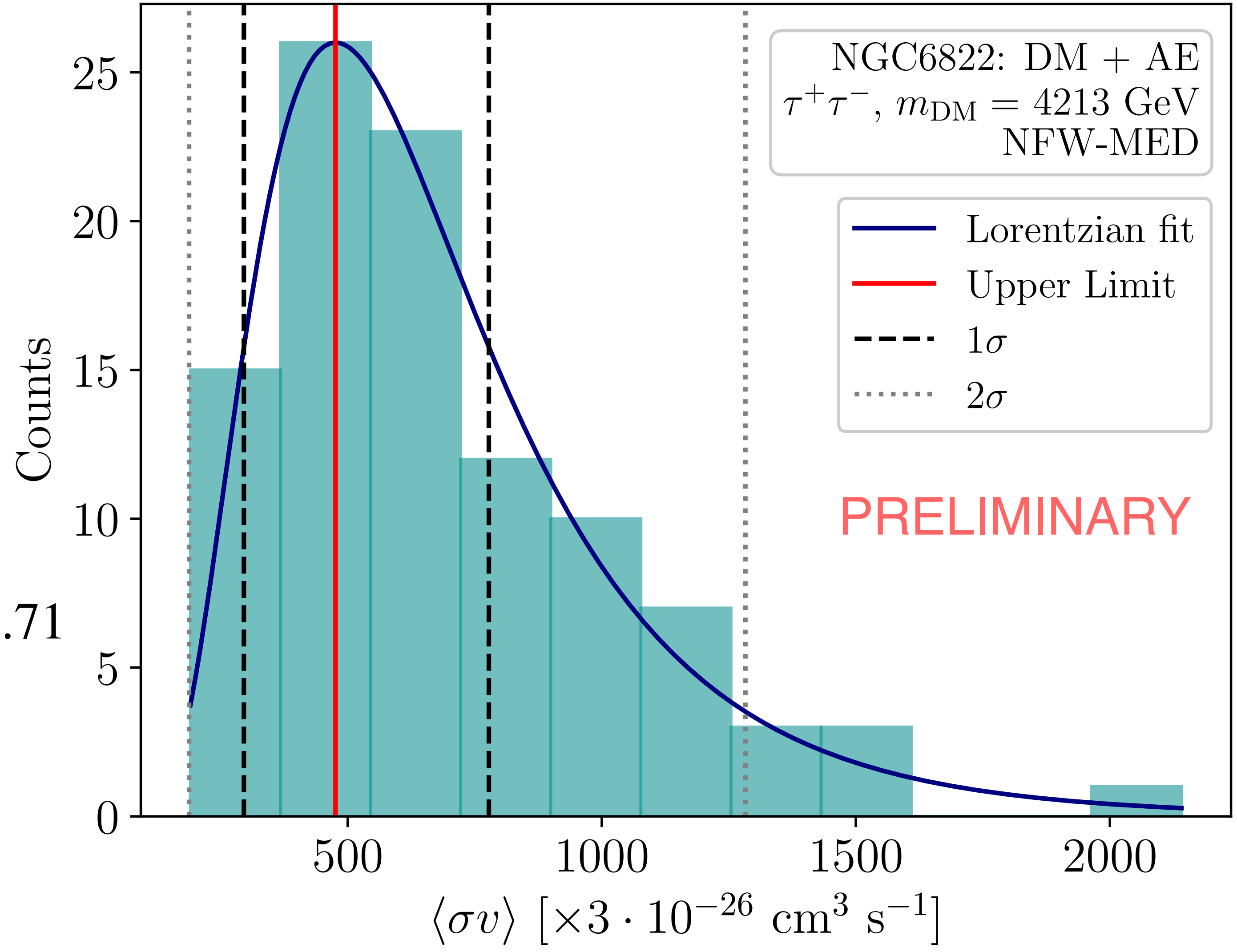


Assuming thermal relic $\langle\sigma v\rangle_{\rm th}$

Individual Constraints: Poissonian Uncertainties

We make 100 simulations in order to get the statistical behavior of the “real” observation (lorentzian probability distribution function)

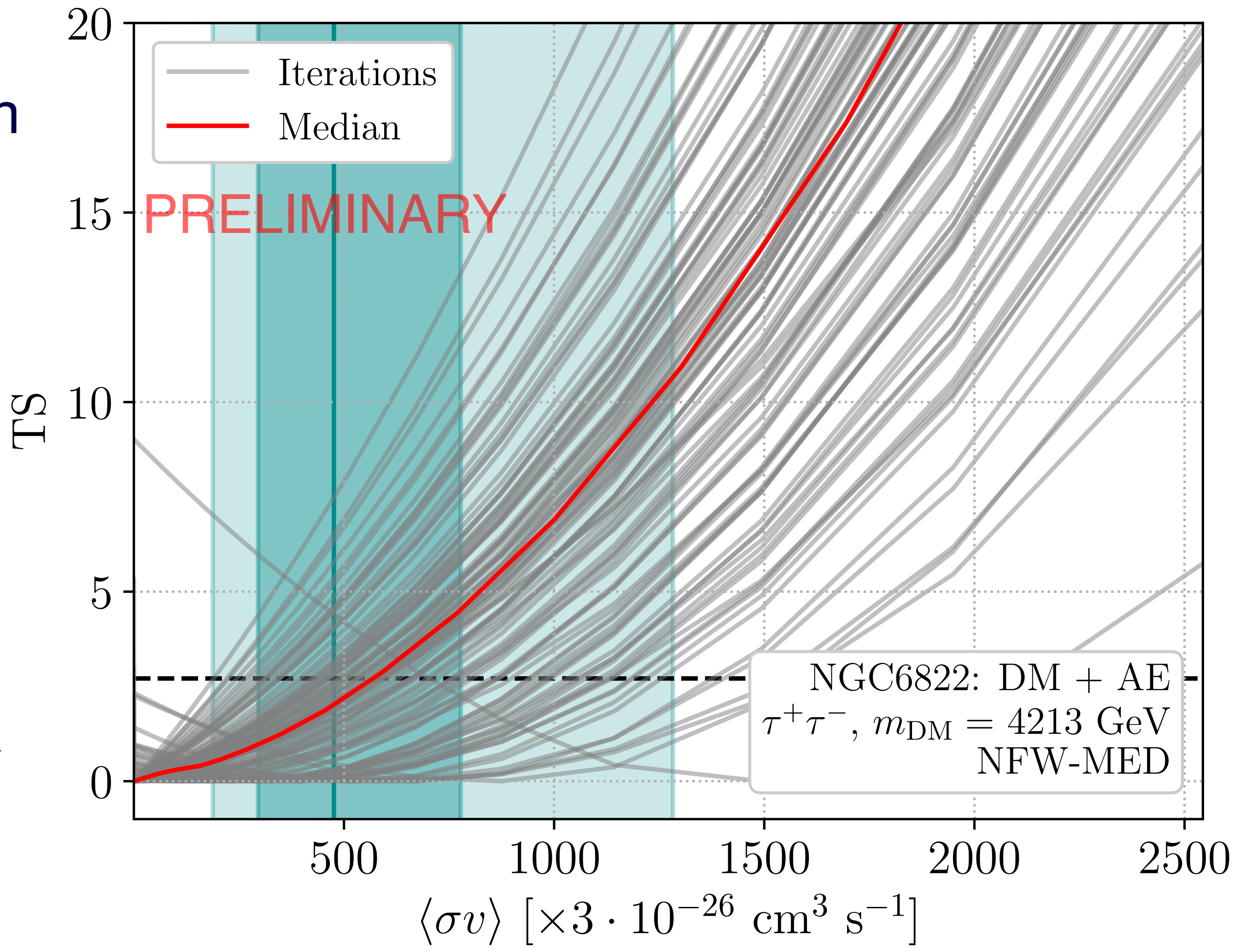
$$\mathrm{TS} = -2\log\frac{\mathscr{L}_{95\%}(\langle\sigma v\rangle_{95\%}, \theta_{95\%}\,|\,\mathrm{n})}{\mathscr{L}_{\text{best-fit}}(\langle\hat{\sigma v}\rangle, \hat{\theta}\,|\,\mathrm{n})} = 2.71$$



From Individual to Combined

- **Representative TS profile:** from the 100 realizations, we compute the median
- Good agreement between the median and the estimated Upper limits

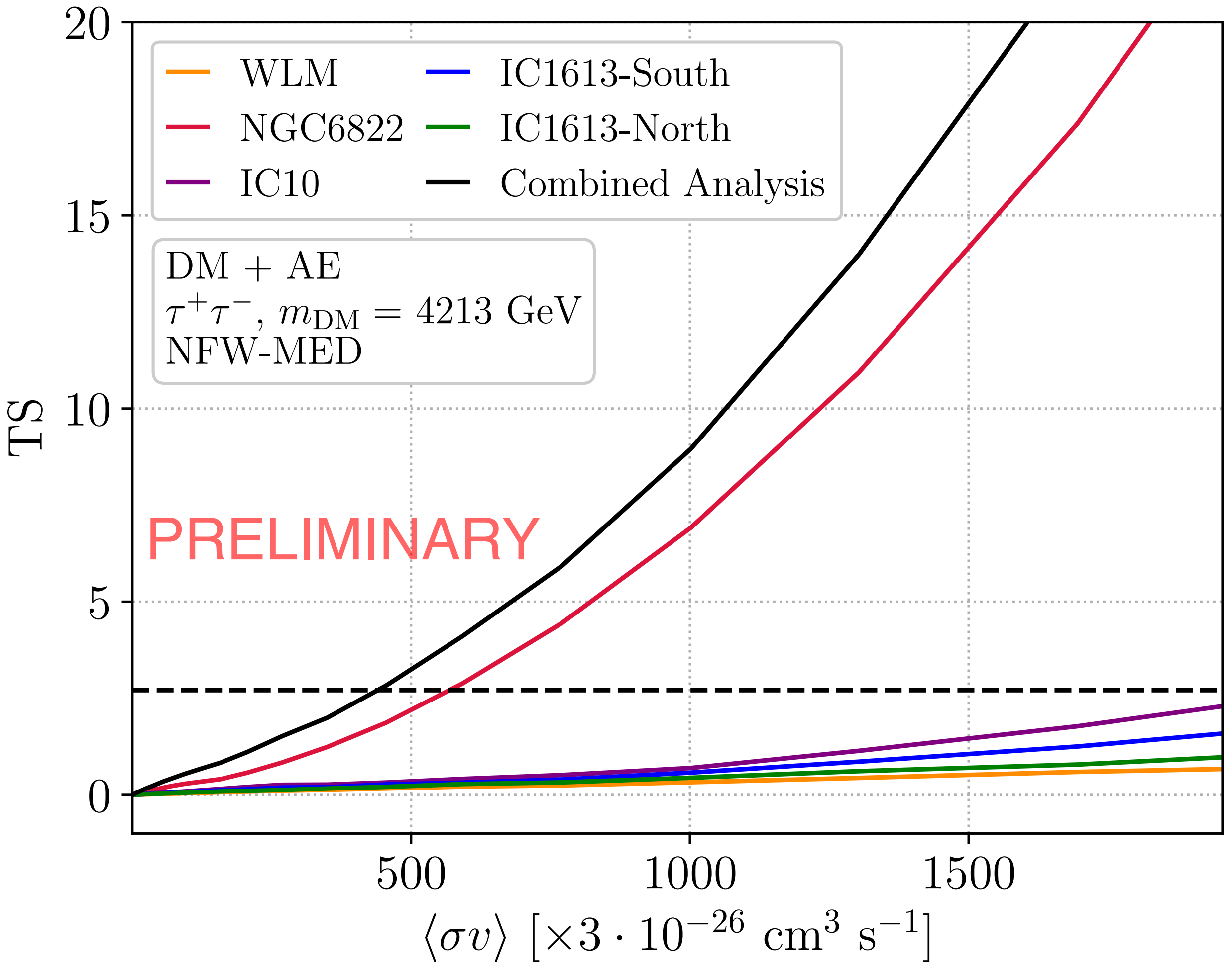
$$\mathrm{TS} = -2\log\frac{\mathscr{L}_{95\%}(\langle\sigma v\rangle_{95\%}, \theta_{95\%}\,|\,\mathrm{n})}{\mathscr{L}_{\mathrm{best-fit}}(\langle\hat{\sigma v}\rangle, \hat{\theta}\,|\,\mathrm{n})} = 2.71$$



From Individual to Combined

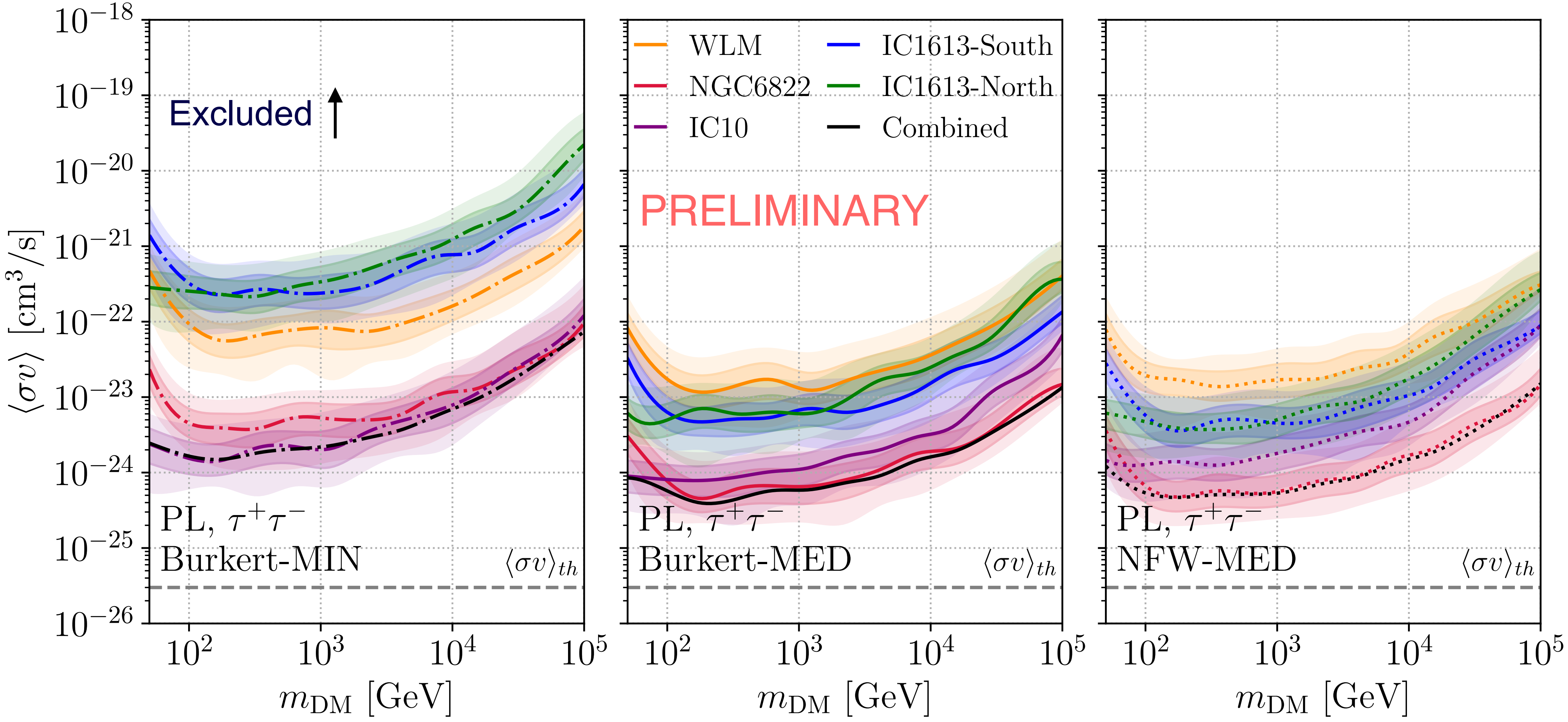
- **Representative TS profile:** from the 100 realizations, we compute the median
- From each individual TS profile, we can compute the **combined profile**

$$\mathrm{TS} = -2\log\frac{\mathscr{L}_{95\%}(\langle\sigma v\rangle_{95\%}, \theta_{95\%}\,|\,\mathrm{n})}{\mathscr{L}_{\mathrm{best-fit}}(\langle\hat{\sigma v}\rangle, \hat{\theta}\,|\,\mathrm{n})} = 2.71$$



Constraints: Point-Like DM-Only

$$\mathrm{TS} = -2\log\frac{\mathcal{L}_{95\%}(\langle\sigma v\rangle_{95\%},\theta_{95\%}\,|\,\mathrm{n})}{\mathcal{L}_{\text{best-fit}}(\langle\hat{\sigma v}\rangle,\hat{\theta}\,|\,\mathrm{n})} = 2.71$$

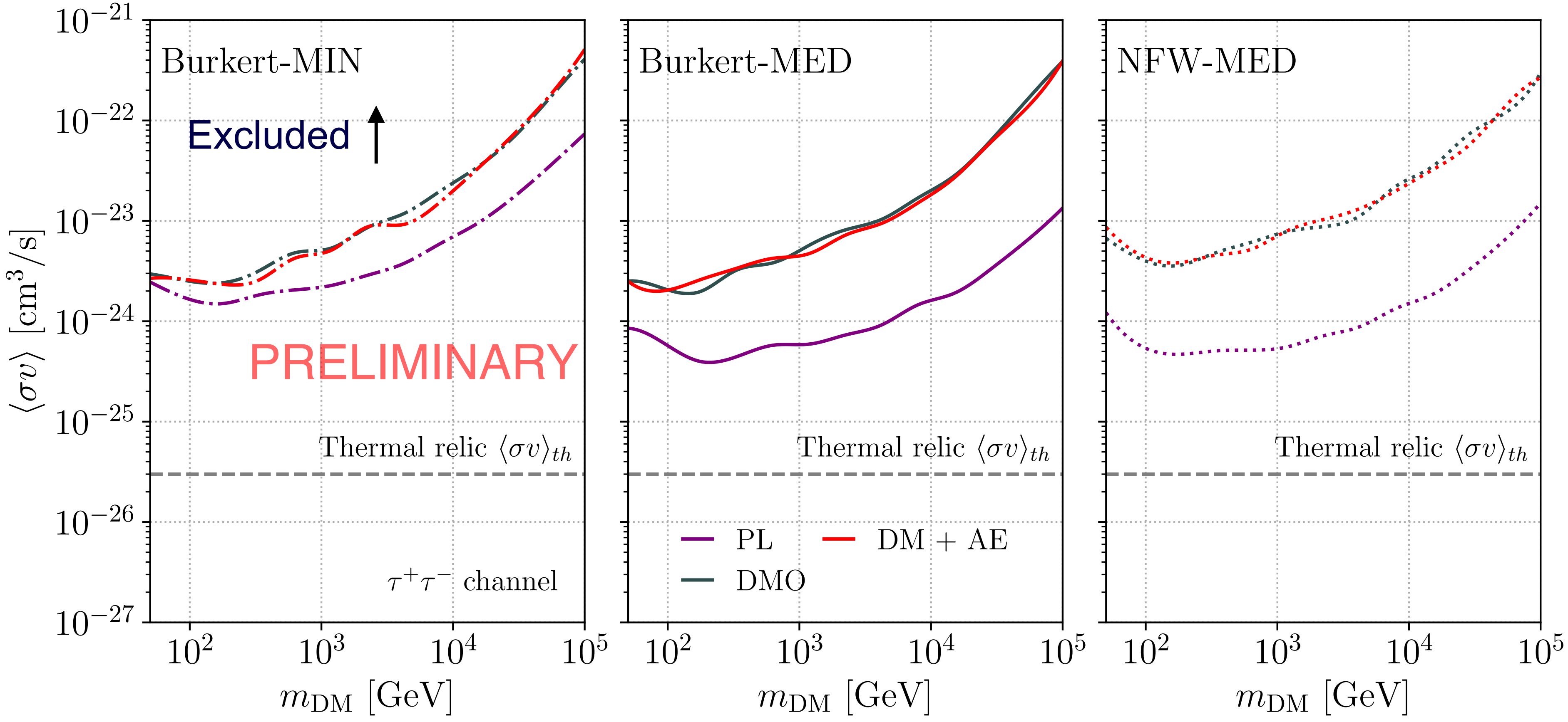


JZP, V. Gammaldi & M. Sánchez-Conde, in preparation

Comparison between the approaches

$$\mathrm{TS} = -2\log\frac{\mathscr{L}_{95\%}(\langle\sigma v\rangle_{95\%}, \theta_{95\%}\,|\,\mathrm{n})}{\mathscr{L}_{\text{best-fit}}(\langle\hat{\sigma v}\rangle, \hat{\theta}\,|\,\mathrm{n})} = 2.71$$

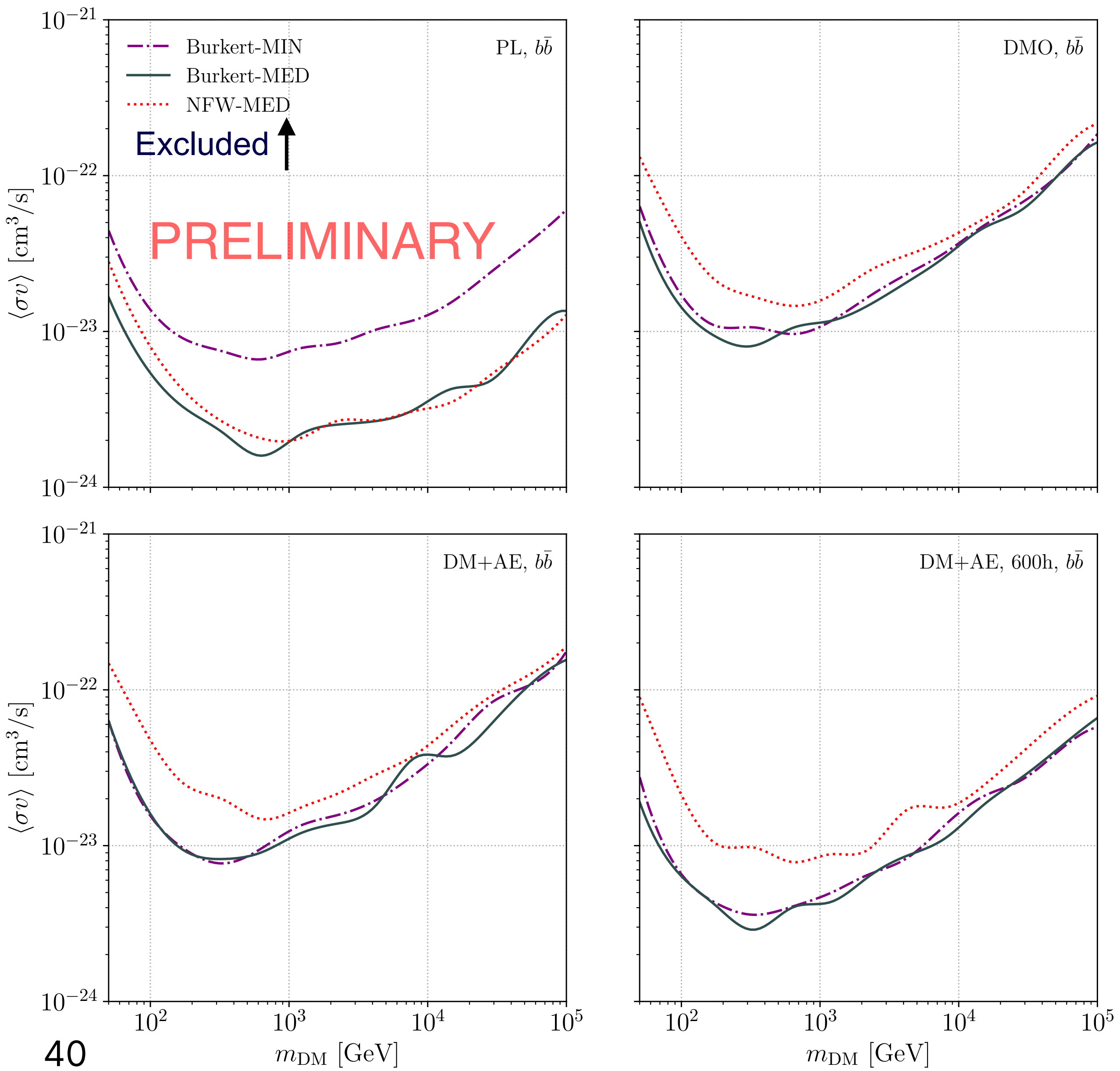
- **Very similar results** with and without **astrophysical emission,** like the case of dSphs



Comparison between the profiles

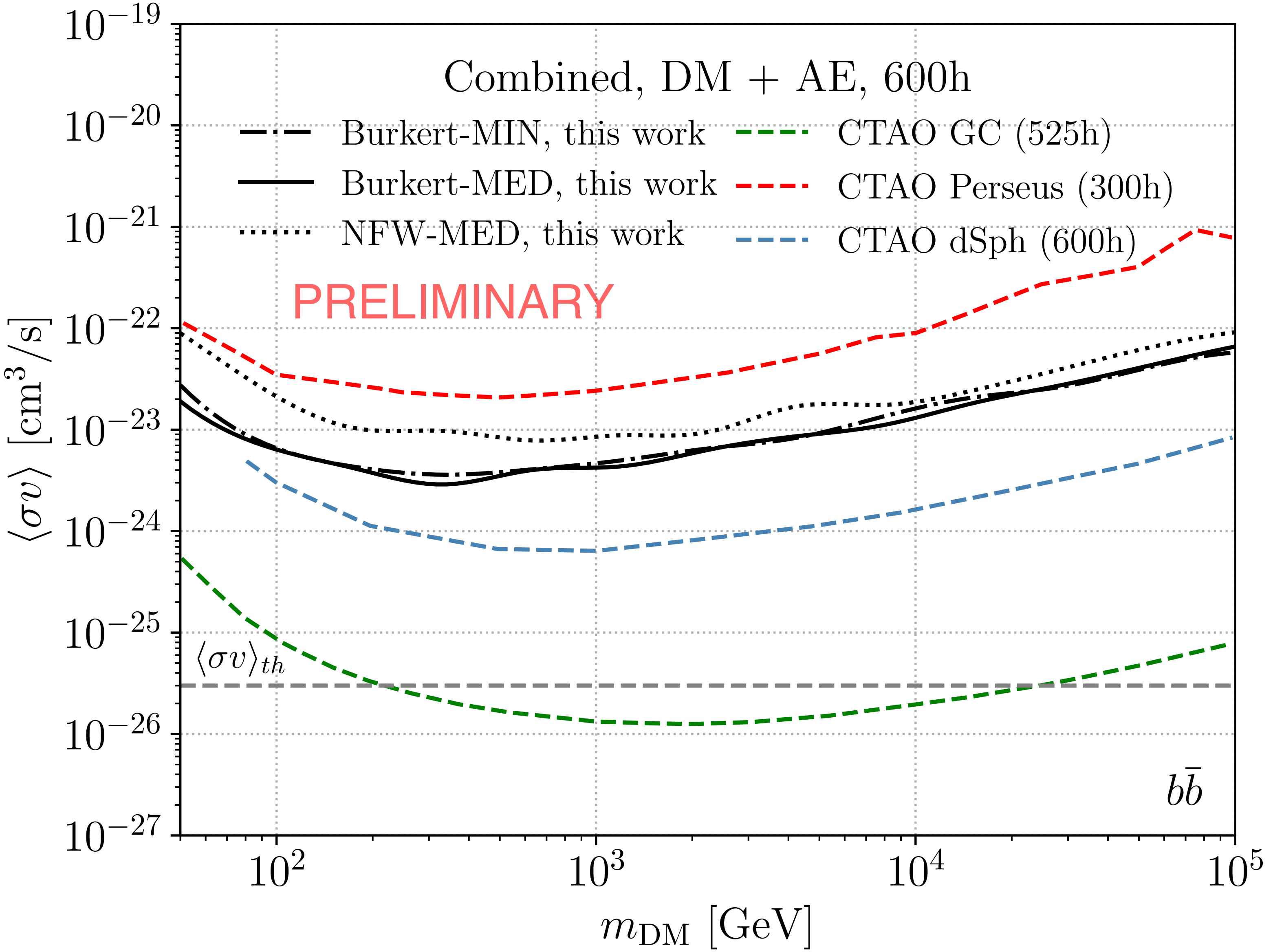
Combined results

- **Best results** with the Burkert profile (MIN & MED)
  - With Burkert dominates IC10, but in that galaxy the sub-halos are not important
- **Extending up to 600h** (only IC10 and NGC6822) **improves all constraints** a factor of $\sim (300/50)^{-1/2} = 6^{-1/2}$
- Very similar results between DM-Only and DM+AE



Constraints: comparing with CTAO dSphs

- **Choosing our 2 best targets:** NGC6822 and IC10
- 600h of observation time between them (like dSph KSP)
- Factor of a few above dSphs limits



DM Annihilation Rates

- In general, **the DM annihilation cross-section can be expanded** as a function of **the relative velocity** between the DM particles ($v_{\rm rel}$):

$$\sigma_{\rm an}(v_{\rm rel})v_{\rm rel} = \sigma_{\rm s-wave}(v_{\rm rel})c + \sigma_{\rm p-wave}(v_{\rm rel})c(v_{\rm rel}/c)^2 + \mathcal{O}((v_{\rm rel}/c)^4)$$

- The annihilation rate is given by (Majorana DM) in a given point $\vec{r}$:

$$\frac{dN_{\rm ann}}{dVdt} = \Gamma(\vec{r}) = \int f\left(\vec{r},\vec{v}_1\right) f\left(\vec{r},\vec{v}_2\right) \frac{\sigma_{\rm an}(v_{\rm rel})v_{\rm rel}}{2} d^3\vec{v}_1 d^3\vec{v}_2$$

- **In the typical WIMP scenario** (first order approximation):
  - Annihilation through an **effective velocity-independent interaction (s-wave)**
  - Therefore $\sigma_{\rm an}v_{\rm rel}$ is independent of $v_{\rm rel}$: the integral of $f(\vec{v}_i)$ is the DM density profile

$$\Gamma(\vec{r}) = \int f\left(\vec{r},\vec{v}_1\right) f\left(\vec{r},\vec{v}_2\right) \frac{\sigma_{\rm s-wave}c}{2} d^3\vec{v}_1 d^3\vec{v}_2 = \frac{\langle\sigma_{\rm s-wave}v_{\rm rel}\rangle}{2}\int f(\vec{r},\vec{v}_1) f(\vec{r},\vec{v}_2) d^3\vec{v}_1 d^3\vec{v}_2 = \frac{\langle\sigma_{\rm s-wave}v_{\rm rel}\rangle}{2}\frac{\rho^2_{\rm DM}(\vec{r})}{m^2_{\rm DM}}$$

Constraints: Sommerfeld enhancement

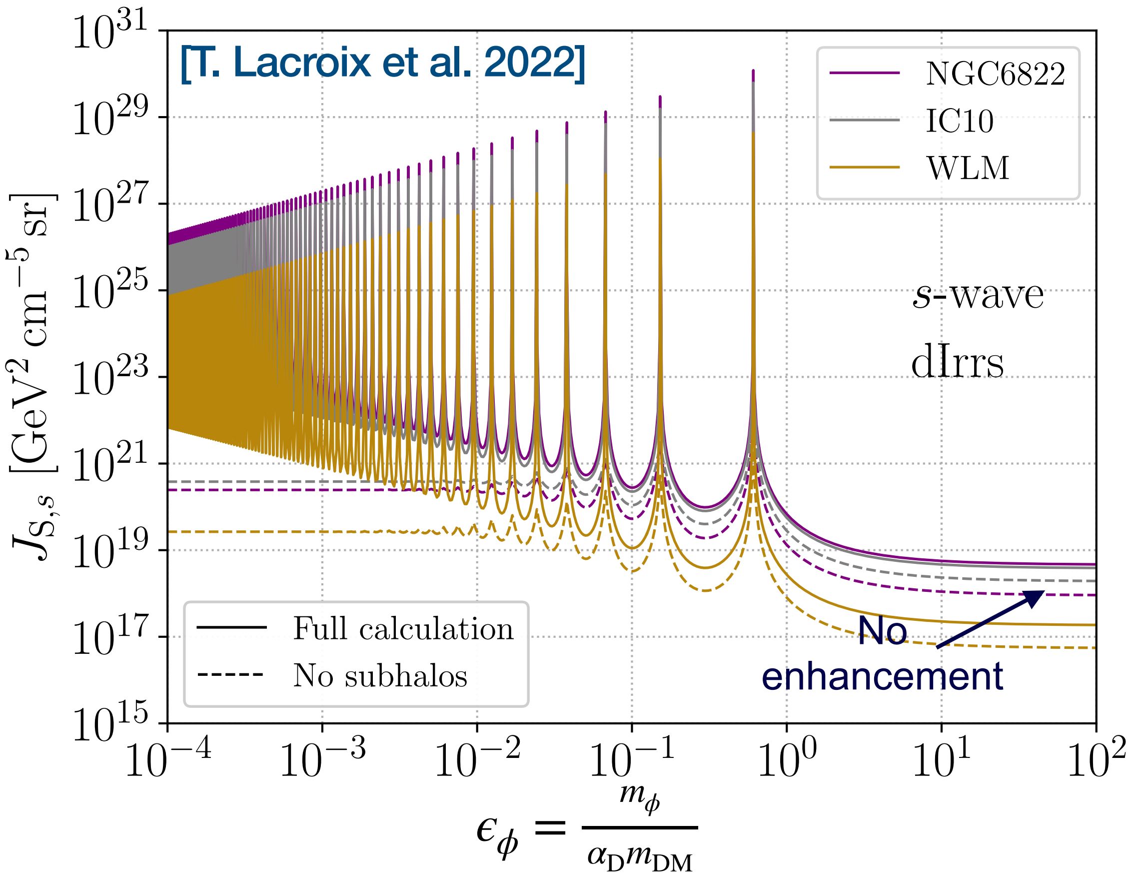
- When $\sigma_{an}(\vec{v}_{rel})$ depends on $\vec{v}_{rel}$, we can define a generalized J-factor

$$J_S(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{l.o.s.} ds \int d^3\vec{v}_1 \int d^3\vec{v}_2 f\left(r(s,\Omega),\vec{v}_1\right) f\left(r(s,\Omega),\vec{v}_2\right) \mathcal{S}\left(\frac{v_{rel}}{2}\right)$$

Where $\mathcal{S}\left(\frac{v_{rel}}{2}\right)$ has the dependencies of $\sigma_{an}(v_{rel})$

- We focus on the **s-wave case** (p-wave have less restrictive constraints)
- **Sommerfeld enhancement:** light scalar ϕ mediator between DM and Standard Model particles
- A light mediator mass (m_ϕ) leads to a long-range interaction
- It can distort the wave function of the two-body system in a non-perturbative way
- Coupling α_D to the DM and Standard Model particles

$$\alpha_D = 0.01$$



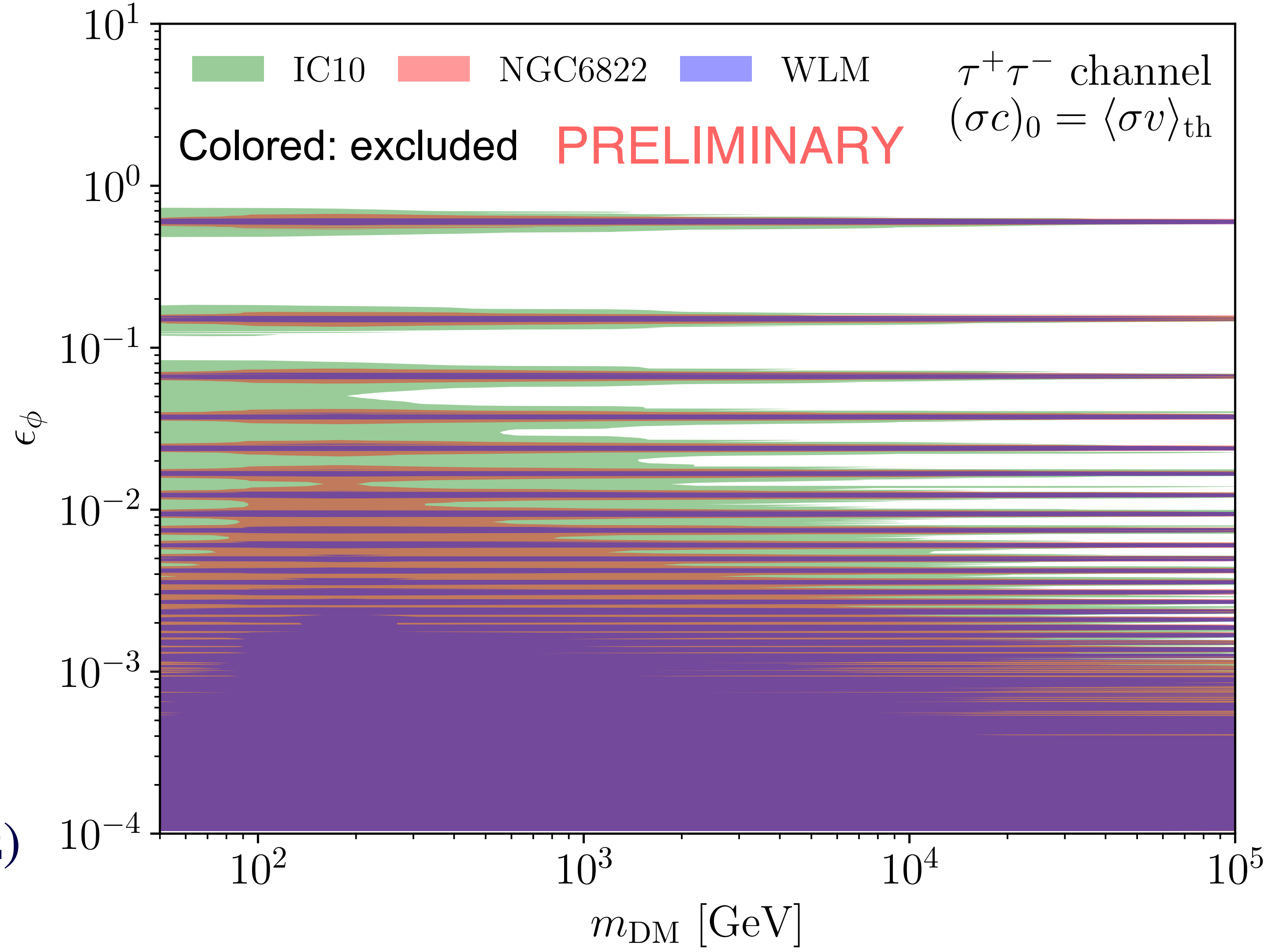
Huge enhancement of the J-factor up to $\mathcal{O}(10^8)$

Constraints: Sommerfeld enhancement

- **Ruled out parameter space** assuming $\langle \sigma v \rangle_{\text{th}}$
- **s-wave results** (p-wave are less restrictive constraints)
- **Rescaled** results for the Burkert-MED case

$$\epsilon_\phi = \frac{m_\phi}{\alpha_D m_{DM}} \qquad \alpha_D = 0.01$$

$$\frac{d\Phi_{DM}}{dE} = \frac{(\sigma c)_0}{8\pi m_{DM}^2} \sum_i^{\text{channels}} BR_i \frac{dN_i}{dE} J_S(\Delta\Omega)$$



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