SENSITIVITY OF THE CHERENKOV TELESCOPE ARRAY TO DARK MATTER INDUCED EMISSION FROM PERSEUS GALAXY CLUSTER

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For the CTA Consortium

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Cosmology from Home 2022

4 July – 15 July

cta cherenkov telescope array

ift

UAM Universidad Autónoma de Madrid

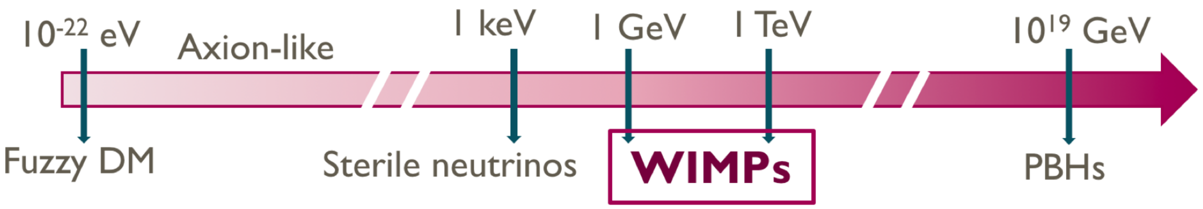
GOBIERNO DE ESPAÑA

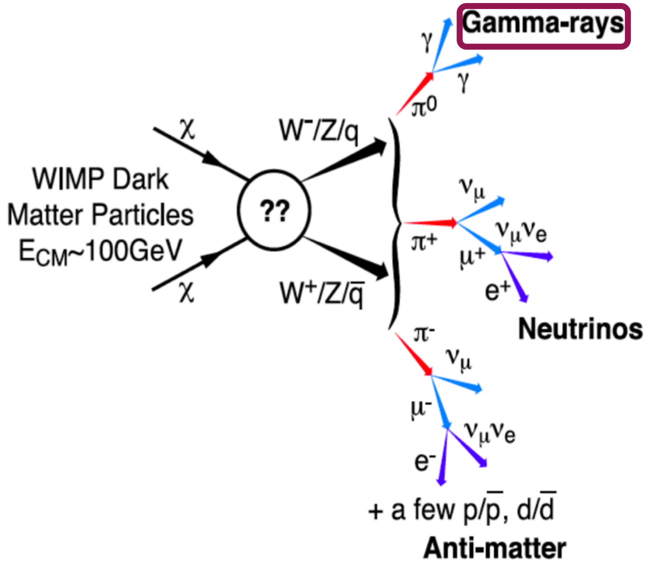
MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

AGENCIA ESTATAL DE INVESTIGACIÓN

DARK MATTER PARADIGM

- Different DM candidates:

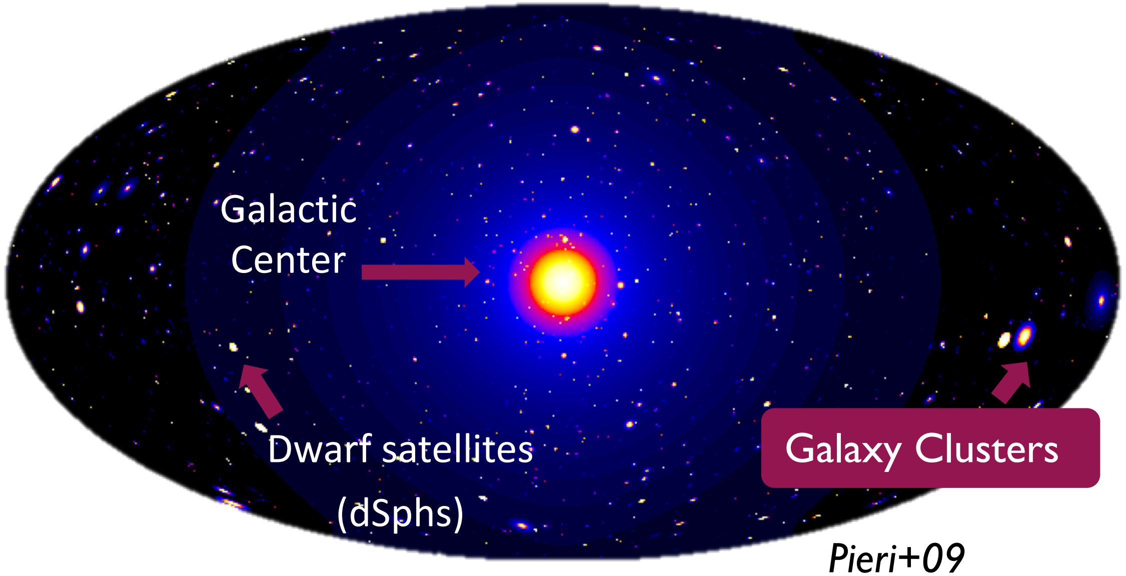




This γ-ray emission allows to perform Indirect DM Searches with current telescopes

- DM distribution in the Universe

ΛCDM Cosmology

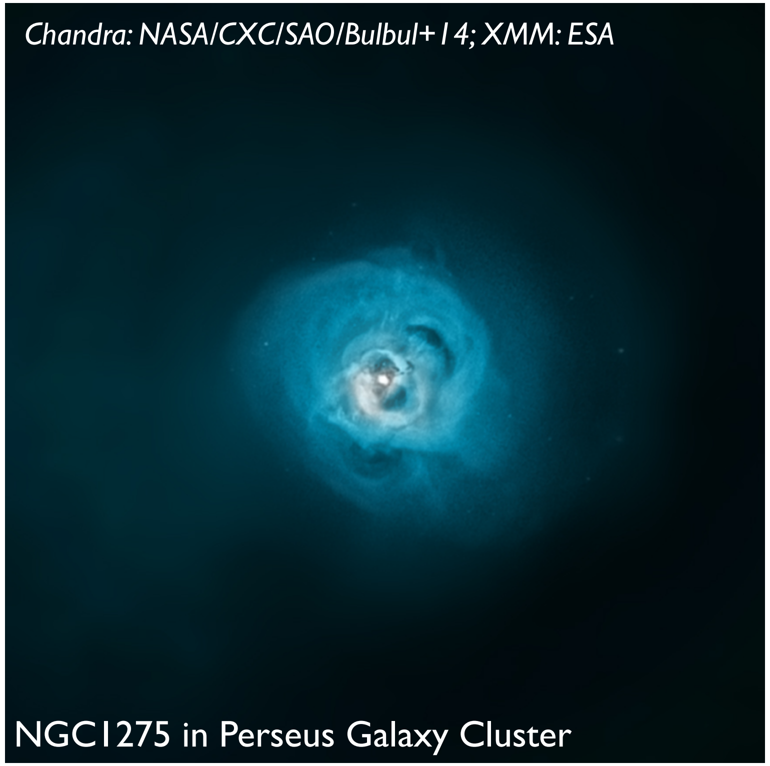


Pieri+09

- Which are the optimal targets?
  - High DM density ($\phi_{DM} \propto \rho_{DM}^2$ for annihilation, $\phi_{DM} \propto \rho_{DM}$ for decay)
  - Massive nearby objects ($\phi_{DM} \propto M/d_{Earth}^2$)
  - Low astrophysical background

GAMMA-RAY DM SEARCHES IN CLUSTERS

- Largest gravitationally bound structures formed by gravitational collapse
- Masses of order ~10^{14}-10^{15} $M_\odot$
- Components:
  - Baryonic Matter
    - Galaxies (~ 3% - 5%)
    - Intra Cluster Medium (~ 15% - 17%)
  - Dark Matter (~80%)



- In terms of DM searches:

Decay

Best possible targets to consider

Annihilation

Competitive compared to other prime targets, considering substructure

[Sánchez-Conde+11]

Caveat

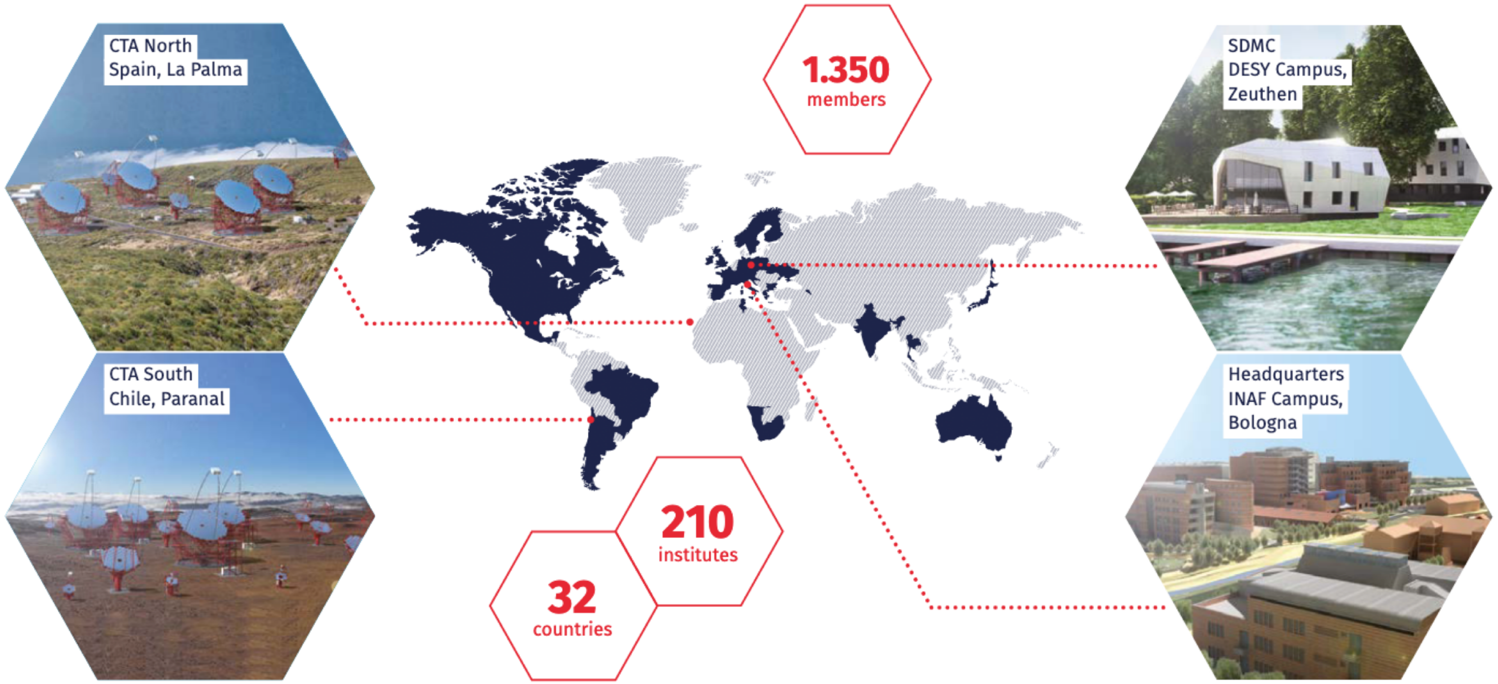
Expected gamma-ray emission from hadronic processes

- No clear detection but some hints claimed

Ackermann+15 [Fermi-LAT Collab.], Xi+18, Adam+21

THE CHERENKOV TELESCOPE ARRAY (CTA)

- Future of Imaging Atmospheric Cherenkov Telescopes for VHE gamma-ray energies.
- 2 arrays: Northern Array (La Palma, Spain) and Southern Array (Paranal, Chile)



https://www.cta-observatory.org/

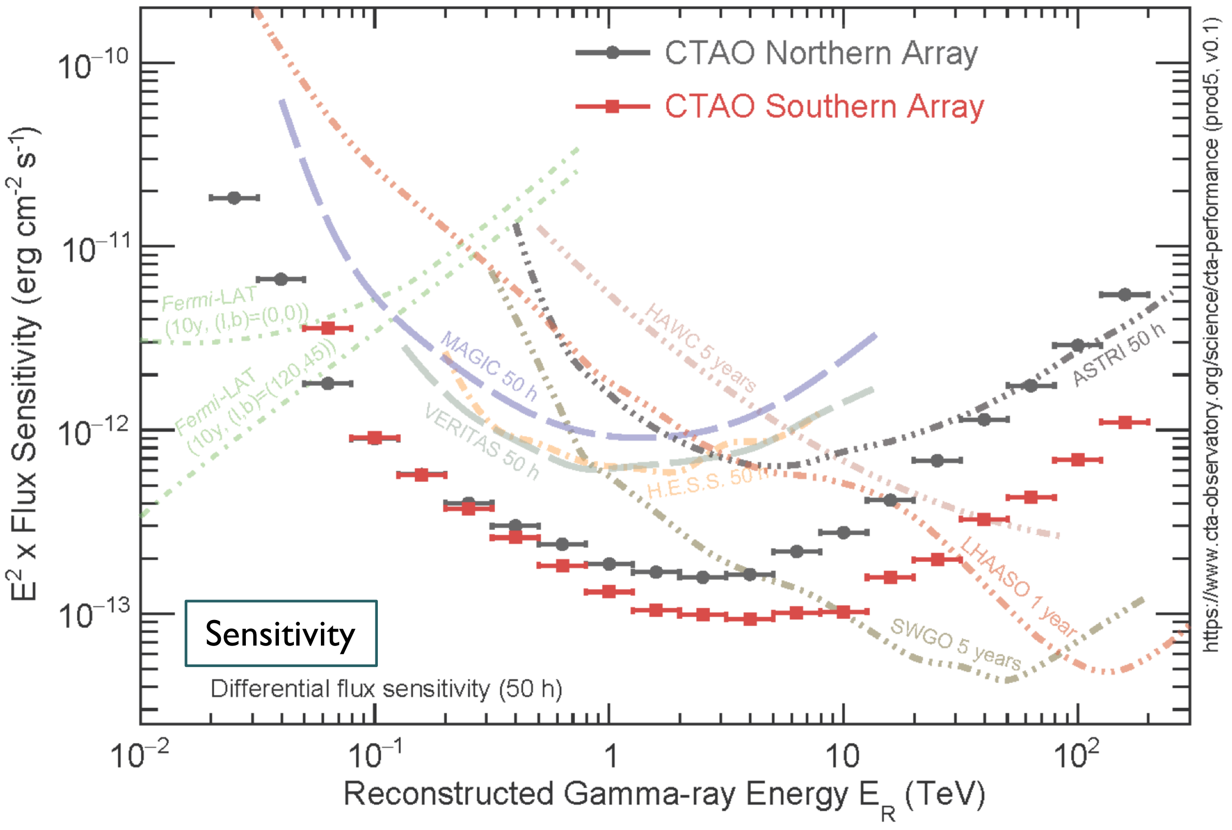
Energy range 20 GeV - 300 TeV

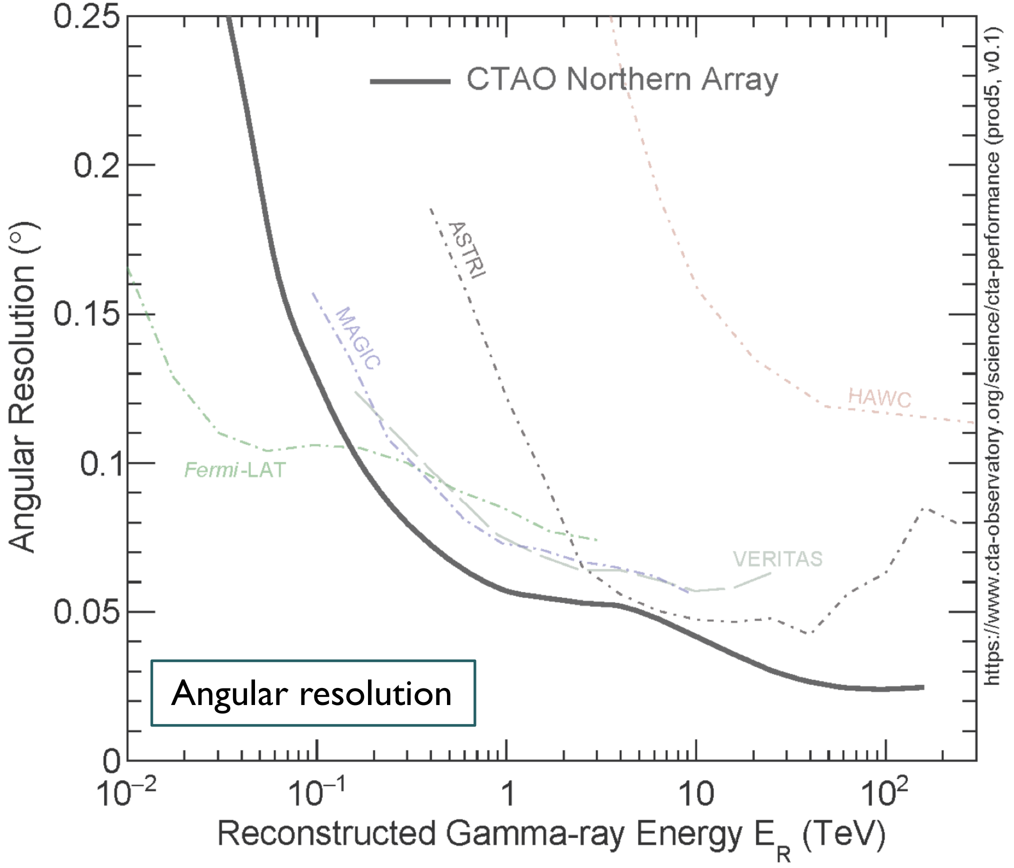
SST	MST	LST
1- 300 TeV	150 GeV - 5 TeV	20 - 150 GeV
$D_{\varnothing}$ = 4m	$D_{\varnothing}$ = 12m	$D_{\varnothing}$ = 23m

CTA PERFORMANCE

Preliminary Performance Capabilities

https://www.cta-observatory.org/





CTA has superb capabilities for DM gamma-ray searches

KEY SCIENCE PROJECT: PERSEUS GALAXY CLUSTER WITH CTA

- Among local clusters, Perseus is the brightest in X-ray sky.
- Cool-cored, relaxed cluster

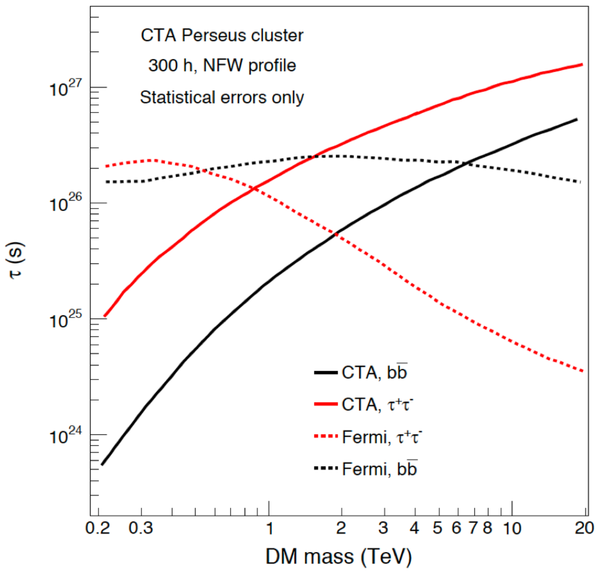
Object	l [deg]	b [deg]	d_L [Mpc]
Perseus	150.57	-13.26	75.01

- Host two Active Galactic Nucleai, both variable

Object	l [deg]	b [deg]
NGC1275	150.58	-13.26
IC310	150.18	-13.74

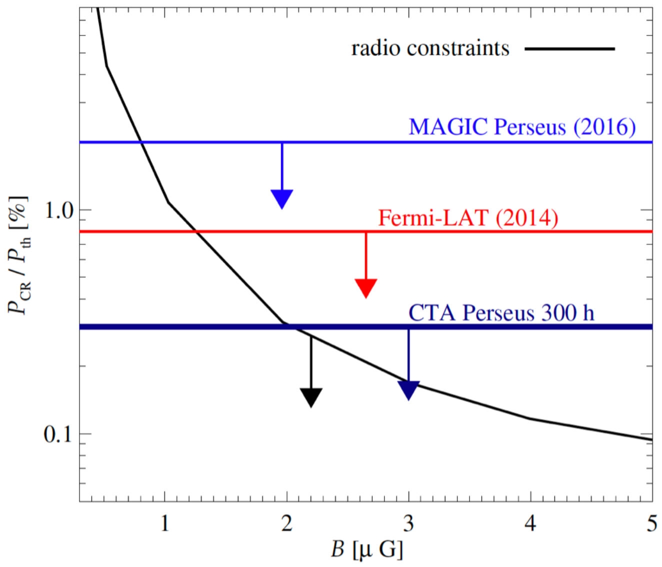
NGC1275 aligned with X-rays center

Optimal conditions for observation from the northern array



Prospects of constraints for DM decay

Acharya+17 [CTA Cons.]



Prospects of constraints for CR models

We use the lastest version of the CTA science tools with the latest Instrument Response Functions (IRFs) to perform the analysis

DARK MATTER MODELLING

$$\frac{d\Phi_{DM}}{dE}(E, l.o.s, \Delta\Omega, z) = \frac{d\phi}{dE}(E, z) \times \text{Astrophysical factor}$$

DM-induced γ-ray flux from an astrophysical object

WIMPs spectra

Cirelli+12 (EW corrections)

Annihilation

$$J(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega}\int_{l.o.s} \rho^2_{DM}(r)dr$$

DM density profile

$$D(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega}\int_{l.o.s} \rho_{DM}(r)dr$$

Decay

CLUMPY

[Charbonnier+12, Bonnivard+15, Hütten+18]

- State-of-the-art parametrization of the DM in Perseus: main halo + substructures $\langle\rho_{tot}\rangle(r) = \rho_{sm}(r) + \langle\rho_{subs}\rangle(r)$

ρ_{sm}

$$\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})[1+\frac{r}{r_s}]^2}$$

Navarro – Frenk – White (NFW)
Navarro+96, Navarro+97

- "Cuspy"-like profile, most of the material in the centre

$\langle\rho_{subs}\rangle$

$$\frac{d^3N}{dVdMdc} = N_{tot}\frac{d\mathcal{P}_V}{dV}(r)\cdot\frac{d\mathcal{P}_M}{dM}(M)\cdot\frac{d\mathcal{P}_c}{dc}(M,c)$$

- Bracketing their contribution with benchmark models:

MIN → No substructure considered

MED → Best guess according to most recent results

MAX → Educated upper bound

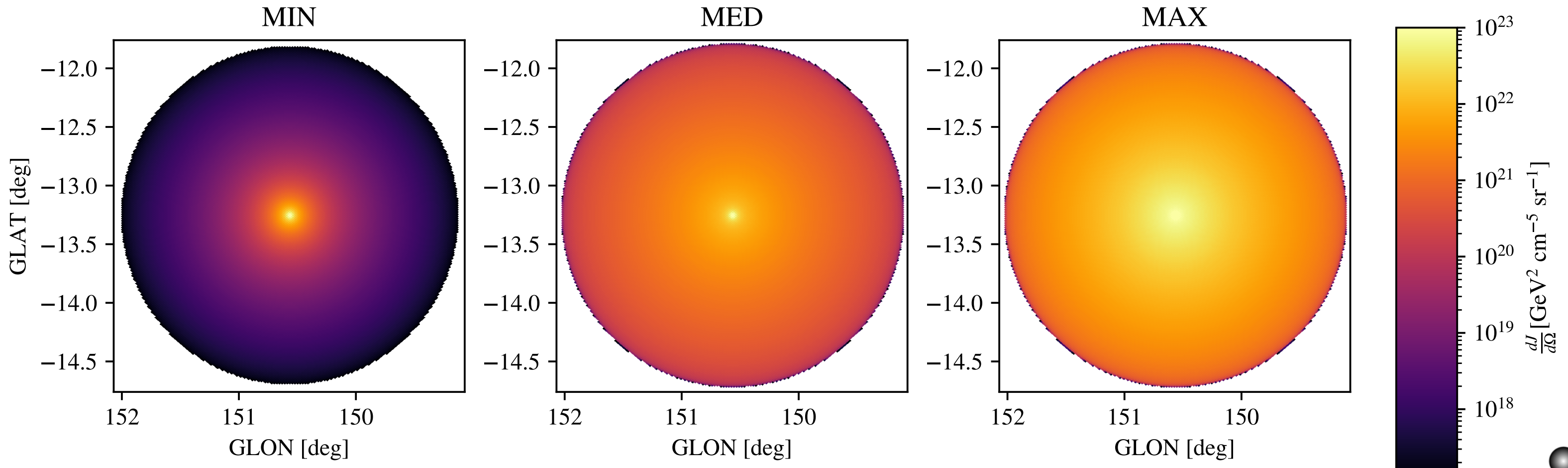
DM INDUCED EXPECTED SIGNAL

- Applying modelling formalism we obtain:

Annihilation	$\log_{10} J$ [GeV^{2}cm^{-5}]
MIN	17.42
MED	18.43
MAX	19.20
Decay	$\log_{10} D$ [GeV cm^{-2}]
	19.20

Skymaps of the differential J-factor

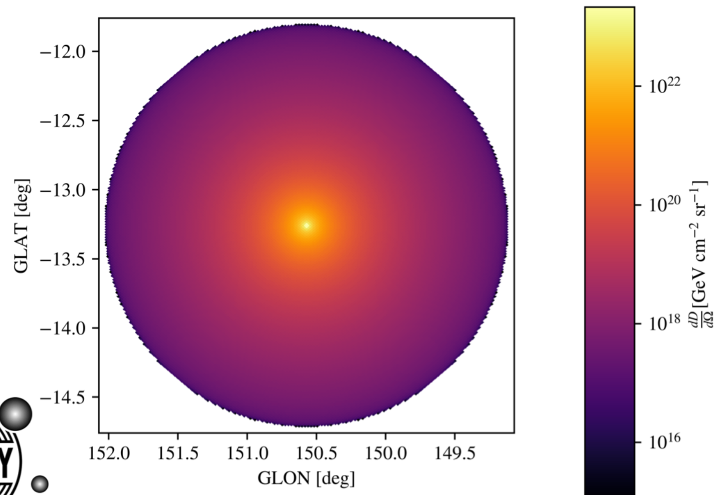
Annihilation



MIN MED MAX

Skymap of the differential D-factor

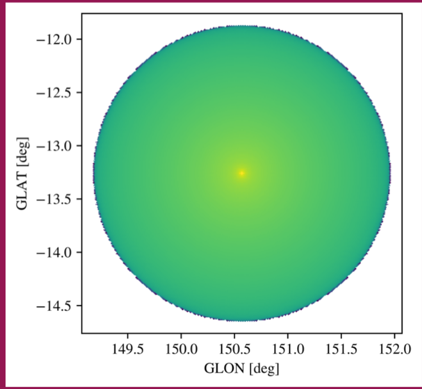
Decay



CTA DM ANALYSIS ROADMAP

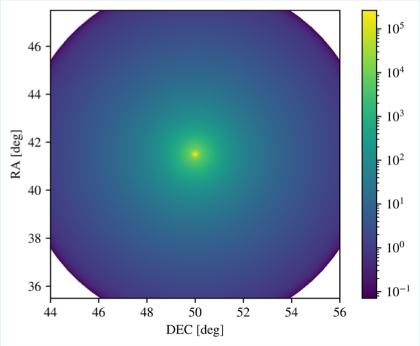
- Different gamma-ray sources in Perseus region:

Total DM-induced γ-rays



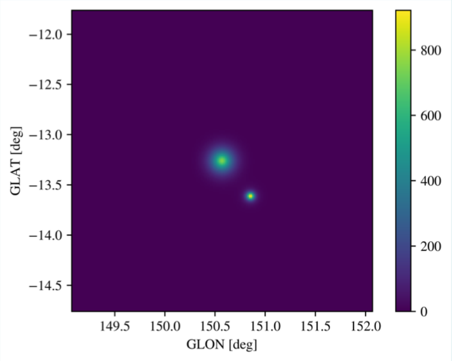
Our signal

Total CR-induced γ-rays



Use as BKG

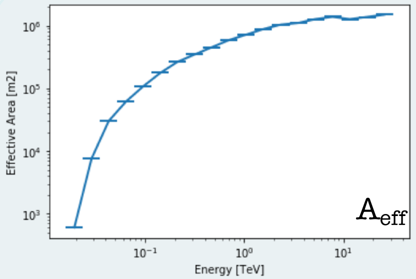
Total AGNs γ-rays

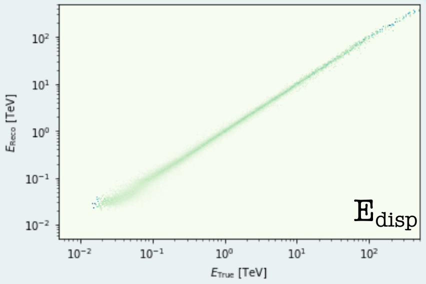


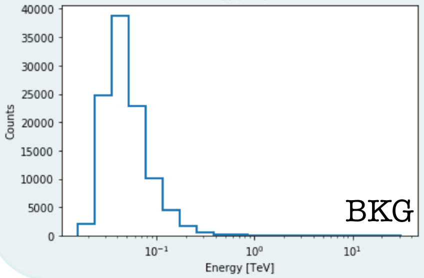
Use as BKG

Available tools

ctools







CTA IRFs

Observation Simulation

If no signal found

Constraints on DM models

$$\frac{d\Phi_{DM}^{Annihil}}{dE} = \frac{<\sigma v>}{8\pi m_{DM}^2}\frac{dN}{dE} \times J$$

$$\frac{d\Phi_{DM}^{Decay}}{dE} = \frac{1}{4\pi m_{DM}\tau_{DM}}\frac{dN}{dE} \times D$$

CTA ANALYSIS CONFIGURATION (I): ON/OFF ANALYSIS

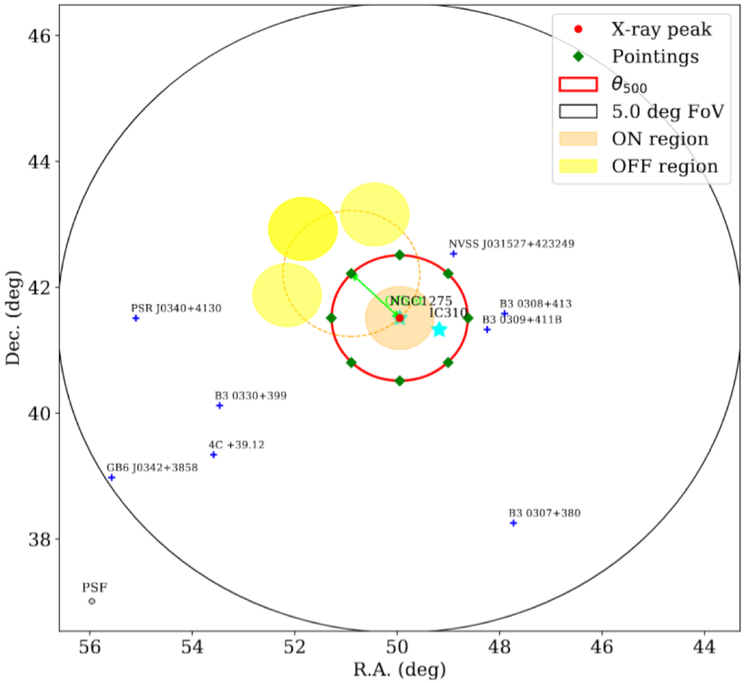
- First analysis approach
  - Only includes gamma-ray emission from DM and background from IRFs
  - Assumes Perseus as a point-like source
  - Historically used in Imaging Air Cherenkov Telescopes (IACTs) as MAGIC → Direct comparisons

Lowest level of complexity, more constraining results

- Different set-ups tested, best results for:

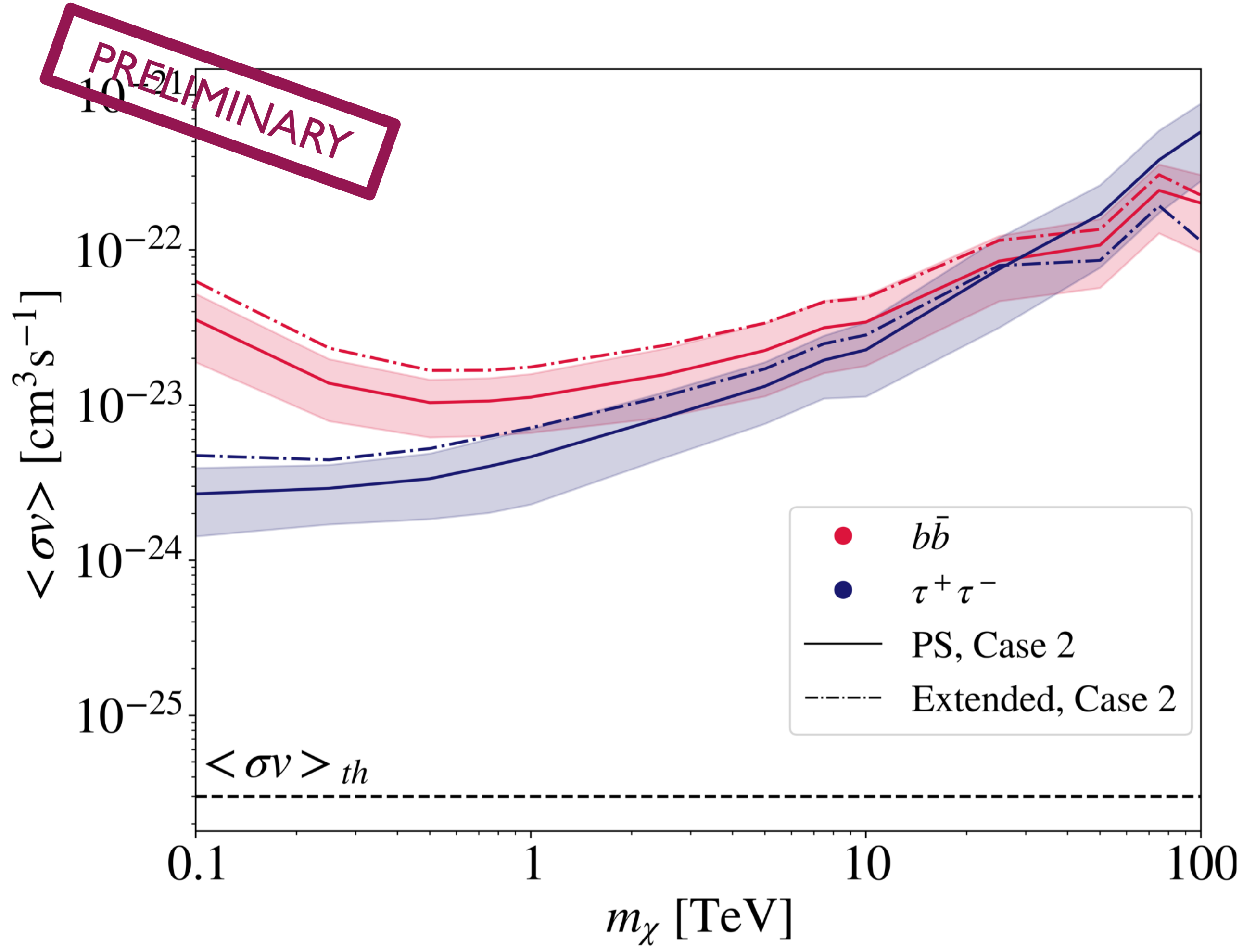
Regions	1 On/3 Off
Regions radius [deg]	0.5
Pointing (l, b) [deg]	(150.57, -13.26)
Offset [deg]	1

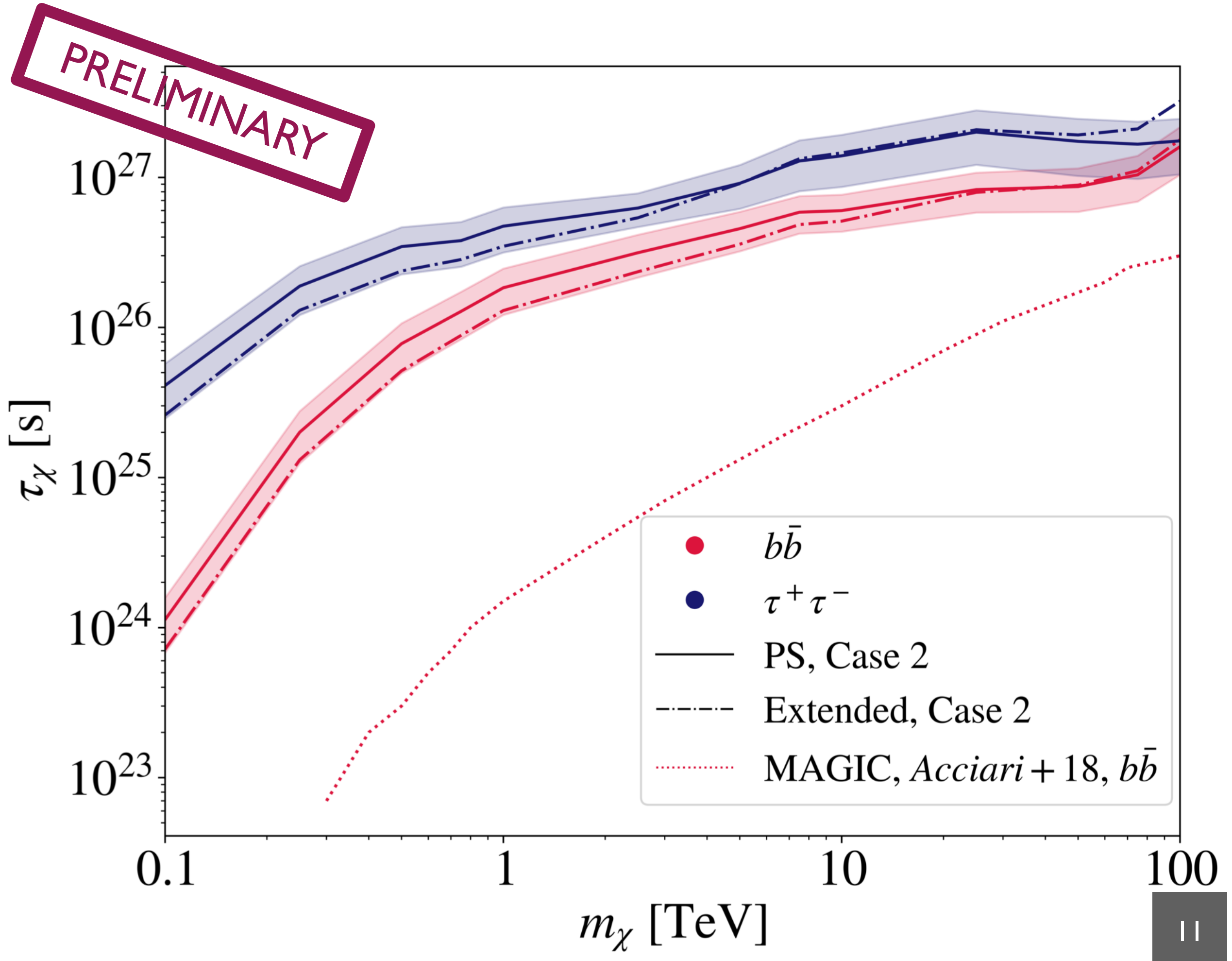
N_{obs}	50
T_{obs} [h]	300
IRFs	`North_z20_50h, prod3b-v2`
Energy range [TeV]	0.03 - 100



ON/OFF RESULTS: DM CONSTRAINTS

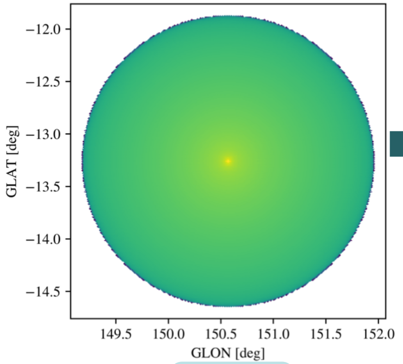
Limits for Perseus for MED annihilation model for On/Off configuration:
Point-like morphology vs. DM template



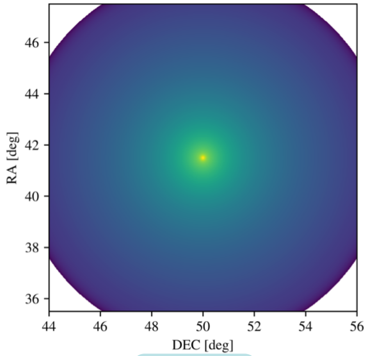


CTA ANALYSIS CONFIGURATION (II): TEMPLATE FITTING

- Final analysis goal:
  - Includes all possible gamma-ray sources: DM + CRs + AGNs + BKG IFRs

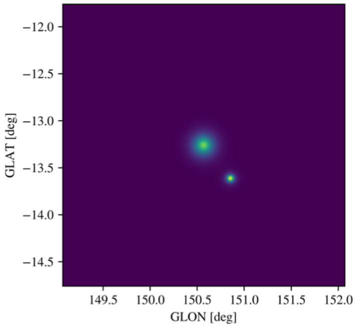


DM



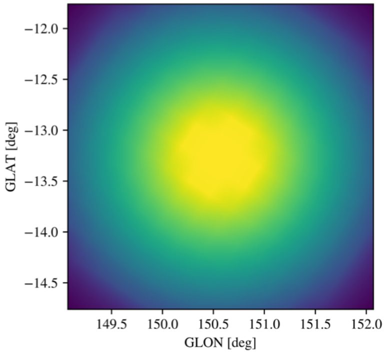
CR

[baseline]



AGNs

[*CTA Cons. 21* – gamma-ray propagation]



BKG

[from IRFs]

More realistic physical scenario

  - Considers the different morphologies of each emission
  - Allows to check correlations between components
  - Historically used in Fermi-*LAT* analysis and in a recent CTA analysis (*Acharyya+20 [CTA Cons.]*)

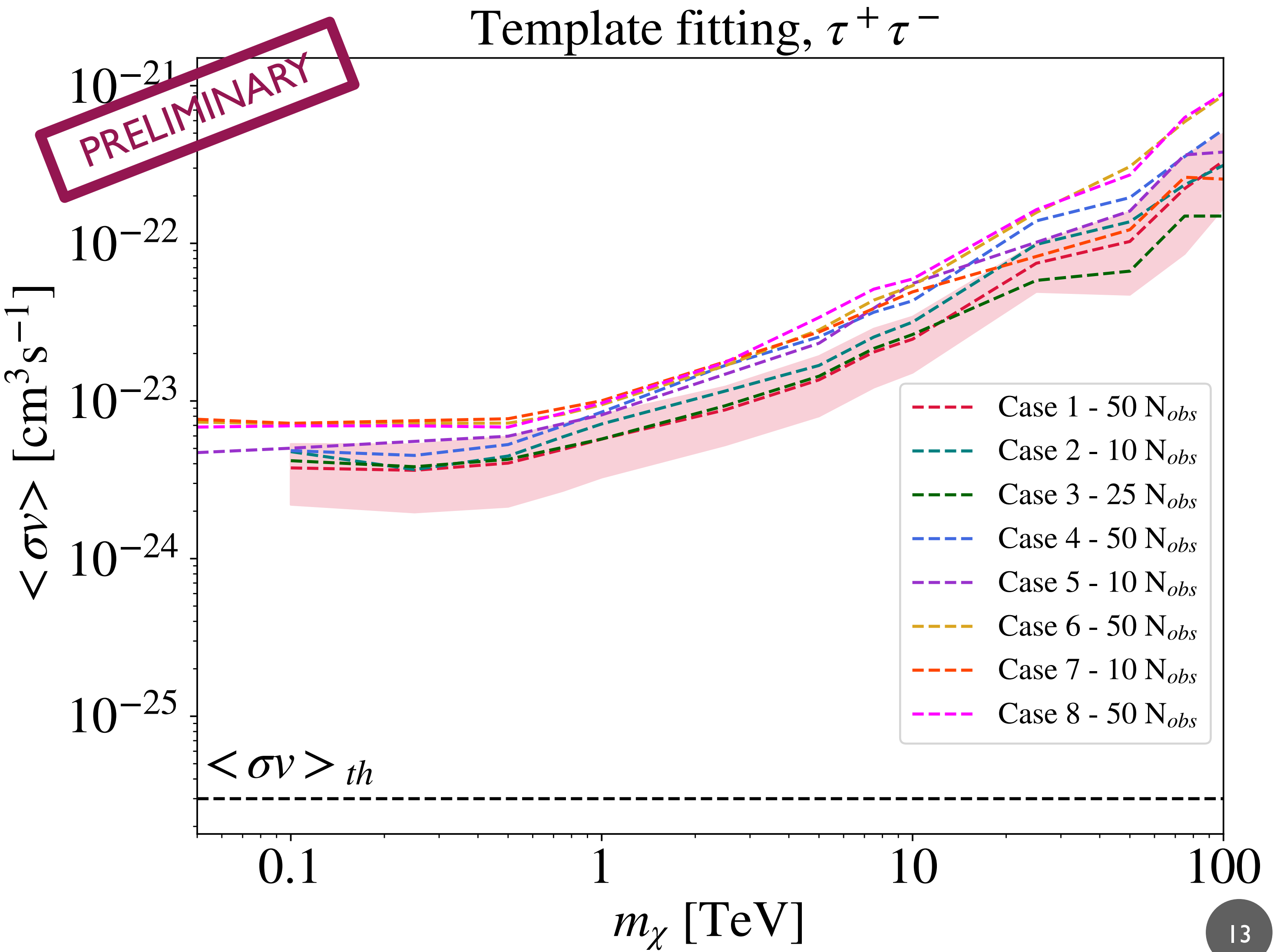
State-of-the-art analysis pipeline

TEMPLATE FITTING RESULTS: DM CONSTRAINTS

- Steps of the analysis: **8 parameters in total**

Name	DM		BKG IRFs		CR	NCG1275		IC310	
	Norm	Sys	Norm	Tilt	Norm	Norm	Tilt	Norm	Tilt
Case 1	X	–	–	–	–	–	–	–	–
Case 2	X	–	X	–	–	–	–	–	–
Case 3	X	–	X	X	–	–	–	–	–
Case 4	X	–	X	X	X	–	–	–	–
Case 5	X	–	X	X	X	X	–	–	–
Case 6	X	–	X	X	X	X	X	–	–
Case 7	X	–	X	X	X	X	X	X	–
Case 8	X	–	X	X	X	X	X	X	X

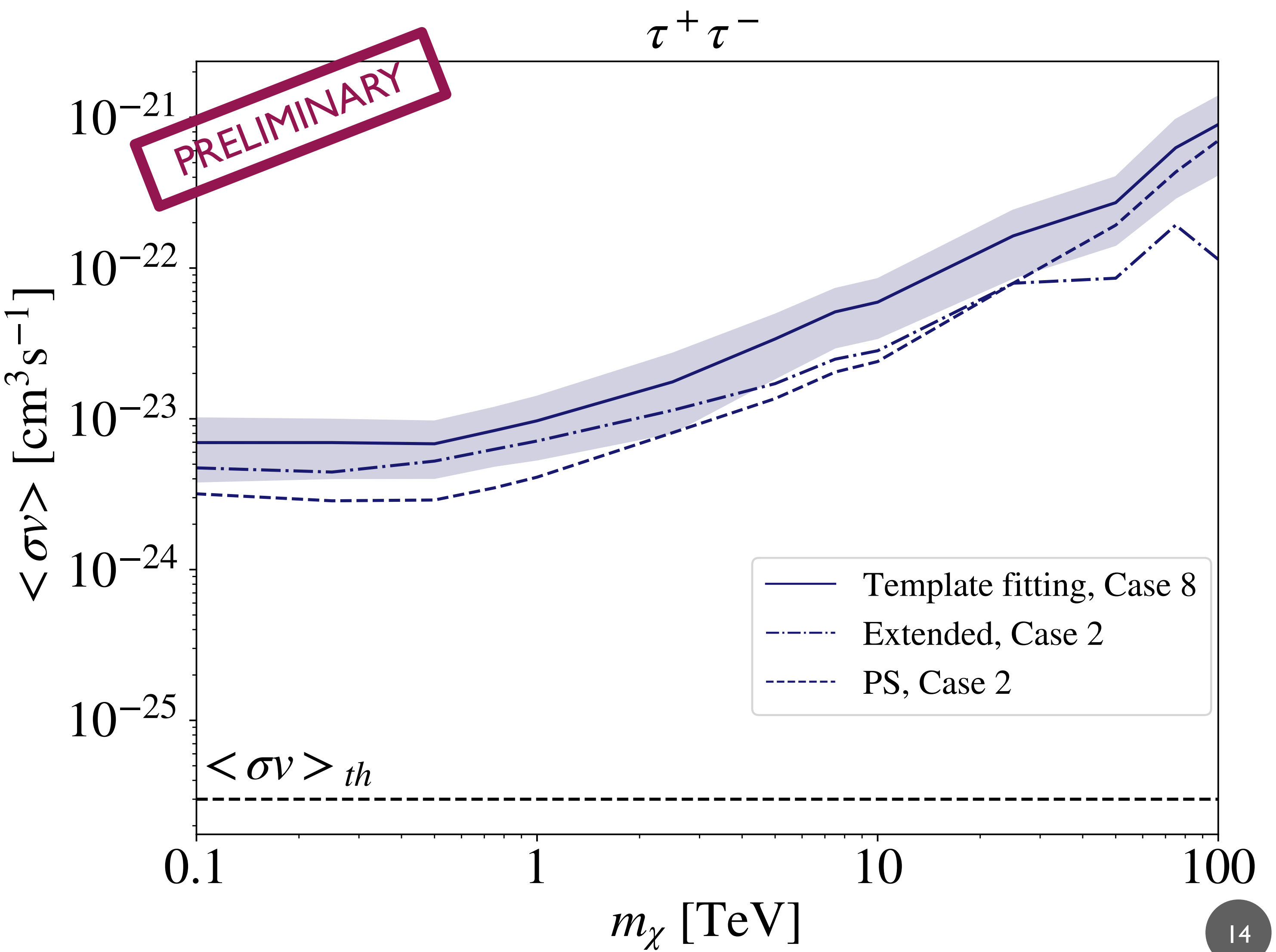
- Tested if posible dependency in best fit values depending on channel or DM mass
- Values of best fit & errors for BKG & CR params compatible with input



TEMPLATE FITTING RESULTS: DM CONSTRAINTS

- Steps of the analysis: **8 parameters in total**

Name	DM		BKG IRFs		CR	NCG1275		IC310	
	Norm	Sys	Norm	Tilt	Norm	Norm	Tilt	Norm	Tilt
Case 1	X	–	–	–	–	–	–	–	–
Case 2	X	–	X	–	–	–	–	–	–
Case 3	X	–	X	X	–	–	–	–	–
Case 4	X	–	X	X	X	–	–	–	–
Case 5	X	–	X	X	X	X	–	–	–
Case 6	X	–	X	X	X	X	X	–	–
Case 7	X	–	X	X	X	X	X	X	–
Case 8	X	–	X	X	X	X	X	X	X



SUMMARY

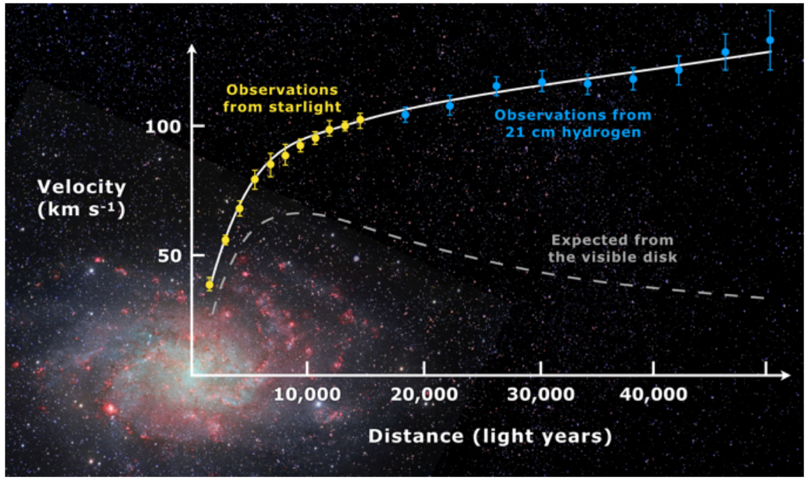
- State-of-the-art DM modelling for Perseus including halo substructure: MIN, MED & MAX
- On/Off analysis for annihilation and decay point-like: Most optimistic
  - Annihilation upper limits of ~O(10^{-23}) $cm^3\ s^{-1}$
  - Nearly and order of magnitude difference between MIN-MED-MAX
  - Decay upper limits of ~O(10^{26}) s : will be the best limits
- On/Off analysis for annihilation and decay with DM template: Simple but more realistic
  - Limits less constraining only a factor ~1.5 respect point-like, still ~O(1-2) better than MAGIC for decay
- Template fitting analysis: Most realistic
  - Annihilation limits less constraining only a factor ~2-3 respect point-like

Thanks a lot for your attention!

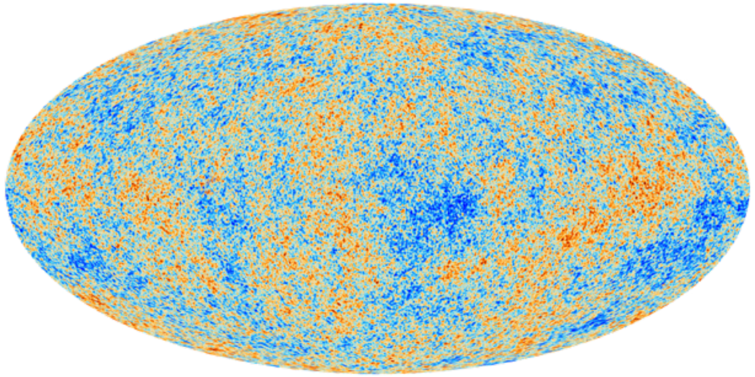
Back-up material

DARK MATTER EVIDENCE

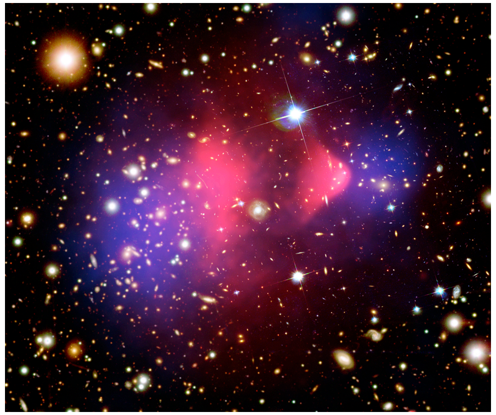
- Galactic rotational curves



- CMB anisotropies

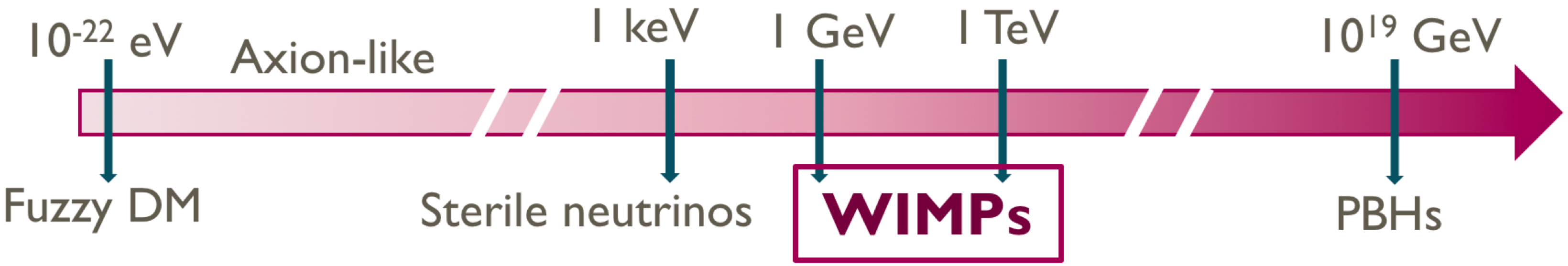


- Galaxy Clusters

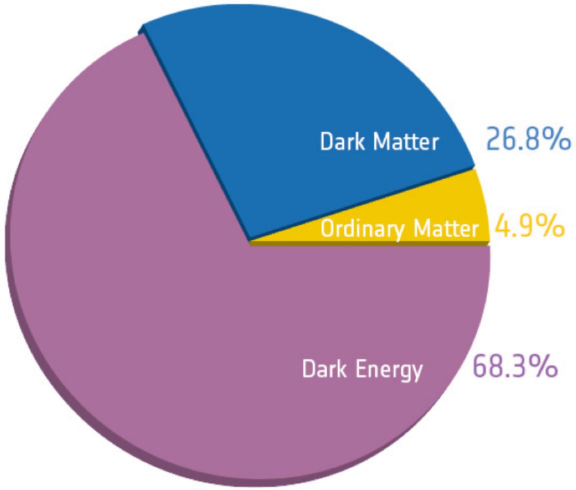


+ strong, weak lensing…

- Different DM candidates, wide range of masses:



DARK MATTER IN ΛCDM COSMOLOGY



Observational Dark Matter (DM) evidences

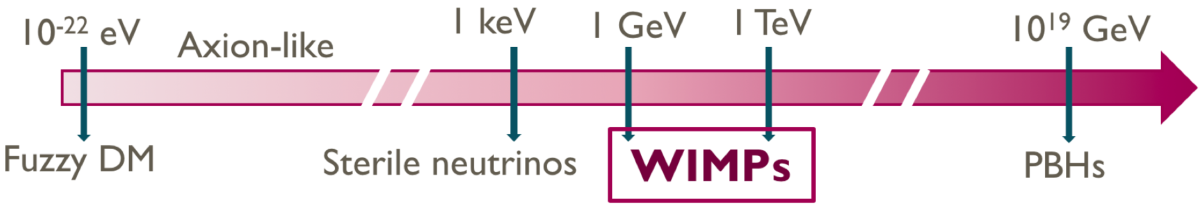
Component of

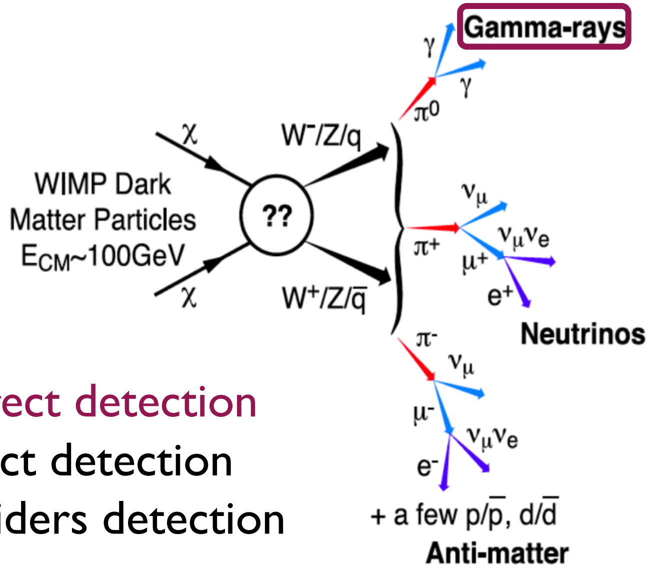
ΛCDM Cosmology

- Structure formation driven by DM
- Bottom-up scenario: smaller structures form first

→ DM distribution in Halos and Subhalos

- Different DM candidates:



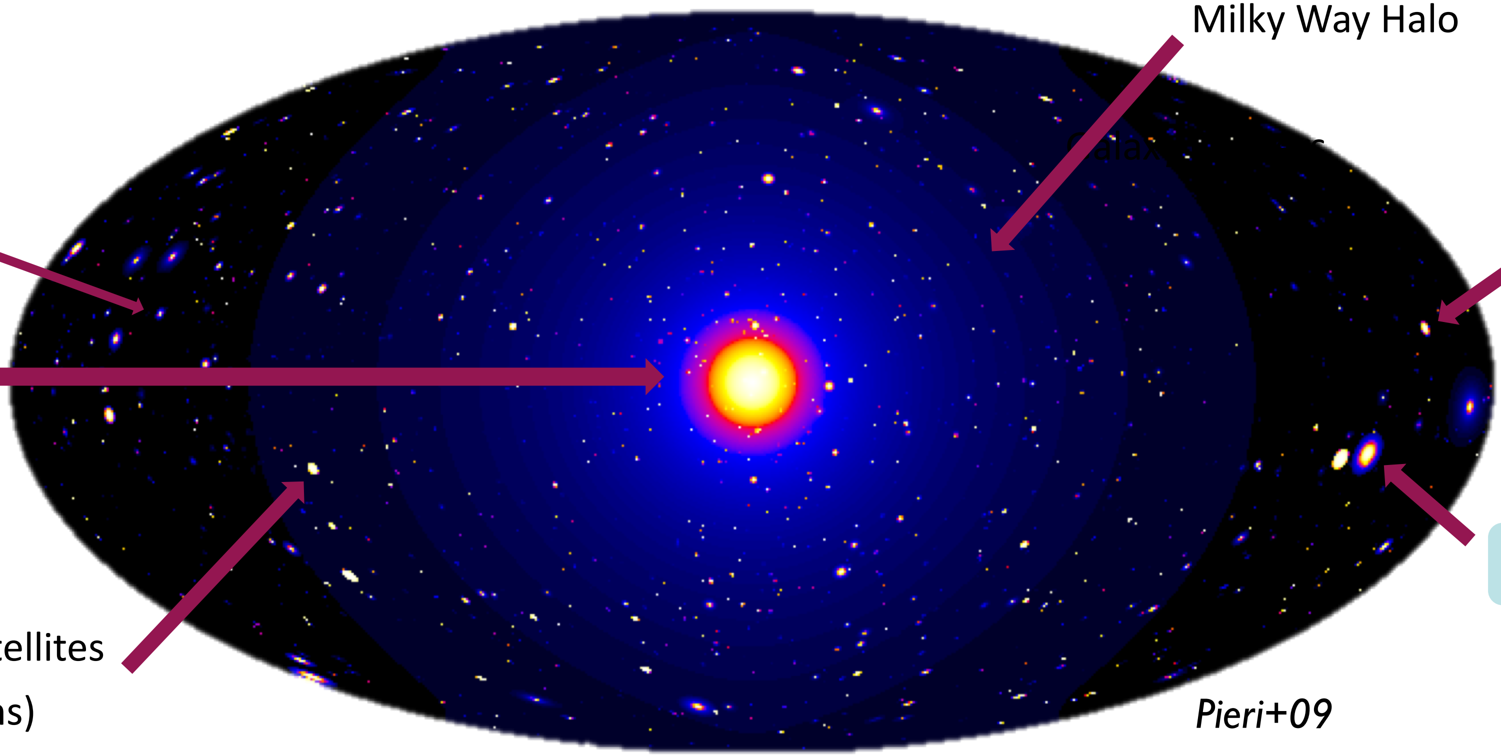


This γ-ray emission allows to perform Indirect DM Searches with current telescopes

- The search for the WIMP
  - Annihilation/Decay → Indirect detection
  - Collision → Direct detection
  - Production → Colliders detection

GAMMA-RAY DM SEARCHES

- Optimal conditions for indirect DM searches:
  - High DM density ($\phi_{DM} \propto \rho_{DM}^2$ for annihilation, $\phi_{DM} \propto \rho_{DM}$ for decay)
  - Massive nearby objects ($\phi_{DM} \propto M/d_{Earth}^2$)
  - Low astrophysical background



GAMMA-RAY EMISSION IN GALAXY CLUSTERS

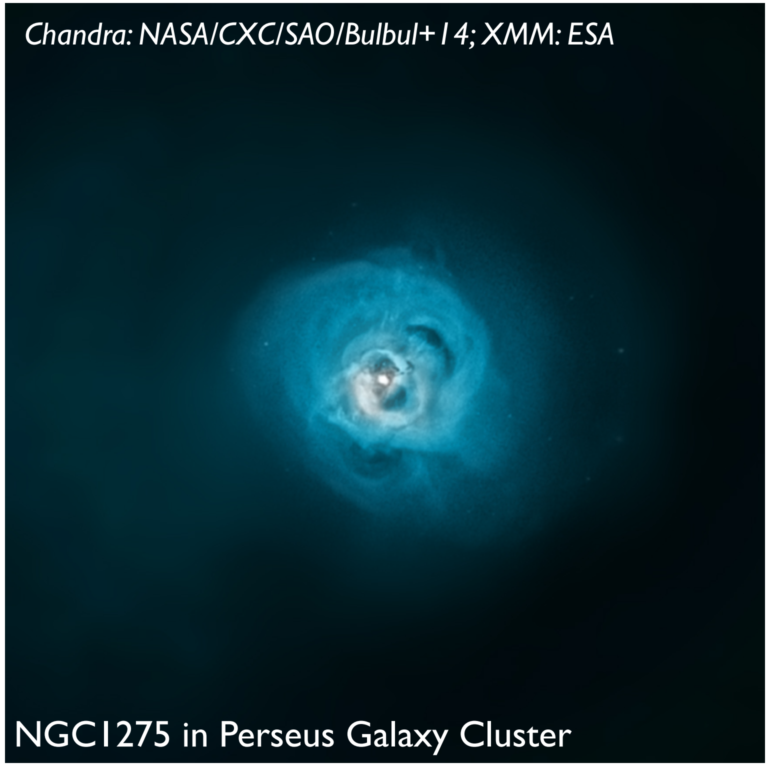
- Largest gravitationally bound structures formed by gravitational collapse
- Masses of order ~10^{14}-10^{15} $M_{\odot}$
- Components:
  - Baryonic Matter → Galaxies (~ 3% - 5%); ICM (~ 15% - 17%)
  - Dark Matter (~80%)
- Even supposedly virialized objects, a lot of activity → Merger events
  - Feedback from galaxies and AGNs
  - Magnetic fields
  - Turbulence

} Acceleration mechanisms → Cosmic-rays

Cosmic-rays — Leptons → Diffuse synchrotron emission ✓

Cosmic-rays — Hadrons → Gamma-rays: No clear detection but some hints claimed…

Ackermann+15 [Fermi-LAT Collab.], Xi+18, Adam+21

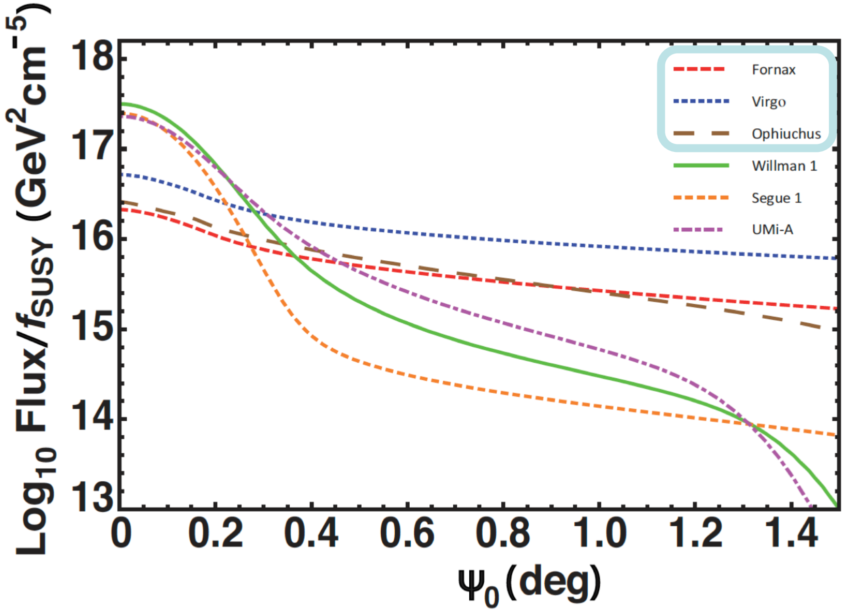


NGC1275 in Perseus Galaxy Cluster

GAMMA-RAY DM SEARCHES IN CLUSTERS?

- Optimal conditions for indirect Dark Matter (DM) searches:
  - ✓ High DM density ($\phi_{DM} \propto \rho_{DM}^2$, for annihilating DM)
  - ✓ Very massive nearby objects ($\phi_{DM} \propto 1/d^2$)
  - ? Relatively low astrophysical background (Cosmic Rays - CR)

- Competitive compared to other prime DM targets (e.g. dSphs)



Object	Type	J_{tot} $(\mathrm{GeV^2 cm^{-5}})$
Fornax	Cluster	1.48×10^{18}
Willman 1	DSPH	8.51×10^{17}
Coma	Cluster	6.92×10^{17}
Perseus	Cluster	5.37×10^{17}
Segue 1	DSPH	5.13×10^{17}
Draco	DSPH	3.72×10^{17}

Sánchez-Conde+11

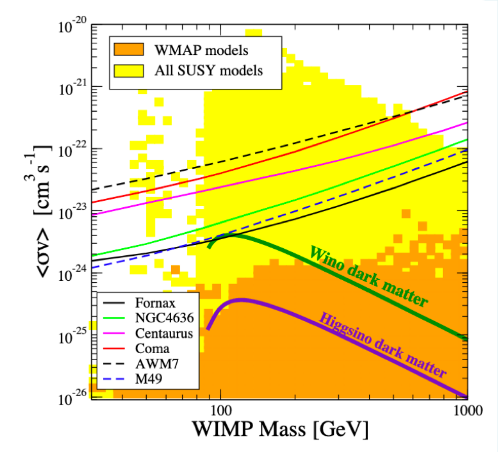
Considering:
- Smooth component

+

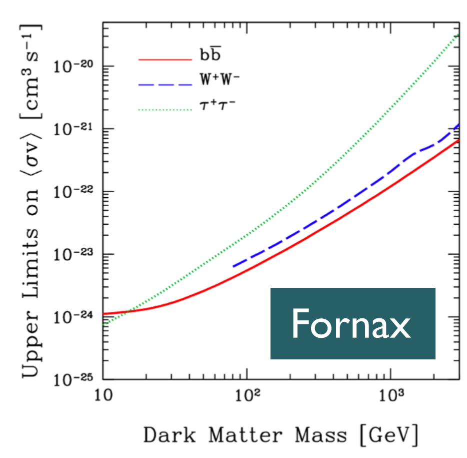
- Substructure

PREVIOUS GAMMA-RAY DM SEARCHES IN GALAXY CLUSTERS

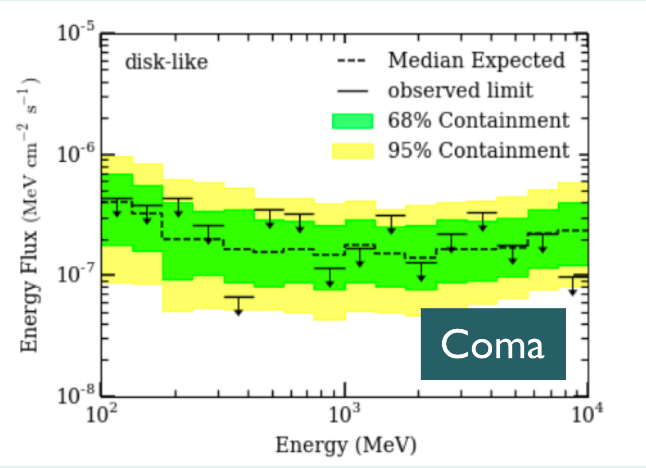
Fermi-*LAT* - Annihilation



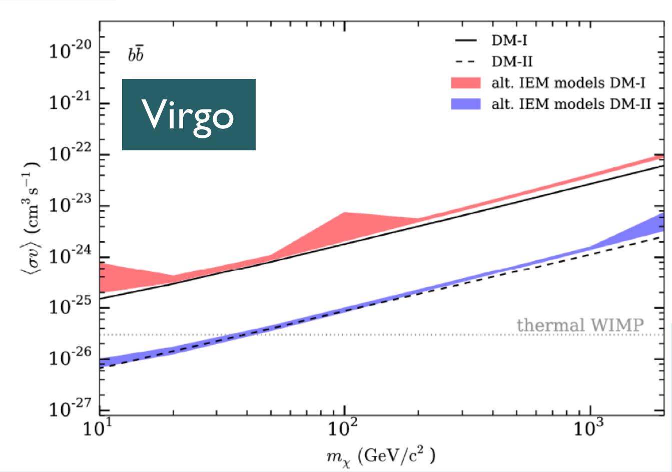
Ackermann+10 [Fermi-LAT Collab.]



Ando&Nagai12



Ackermann+16 [Fermi-LAT Collab.]

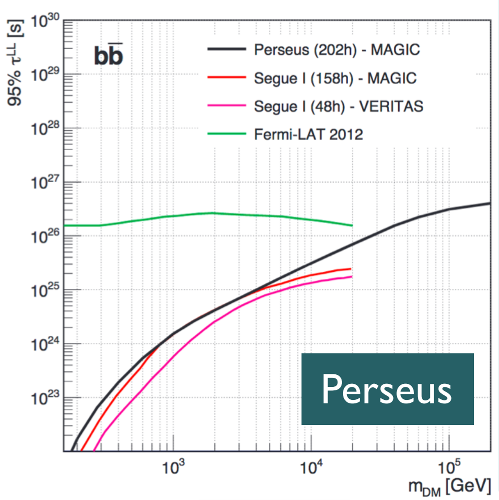


Ackermann+15 [Fermi-LAT Collab.]

- Last word about gamma-ray searches in a big sample of galaxy clusters: CR focused (*Ackermann+14 [Fermi-LAT Collab.]*)

MAGIC - Decay

Best constraints so far!



Acciari+18 [MAGIC Collab.]

GALAXY CLUSTERS KSP IN CTA: PERSEUS GALAXY CLUSTER

Galaxy Clusters Task Force

Perform a state-of-the-art study of the sensitivity of CTA for Dark Matter (DM) and Cosmic-Ray (CR) signals in Perseus cluster

https://portal.cta-observatory.org/WG/PHYS/SitePages/Consortium%20Publication%20Galaxy%20Clusters.aspx

- State-of-the-art modeling of its DM distribution and CR densitiy
- Use the lastest version of the CTA science tools with the latest IRFs to perform the analysis
- Coordinators:
  - Dark Matter: M. Hütten, JPR, M. Á. Sánchez-Conde
  - Cosmic Rays: R. Adam, G. Brunetti

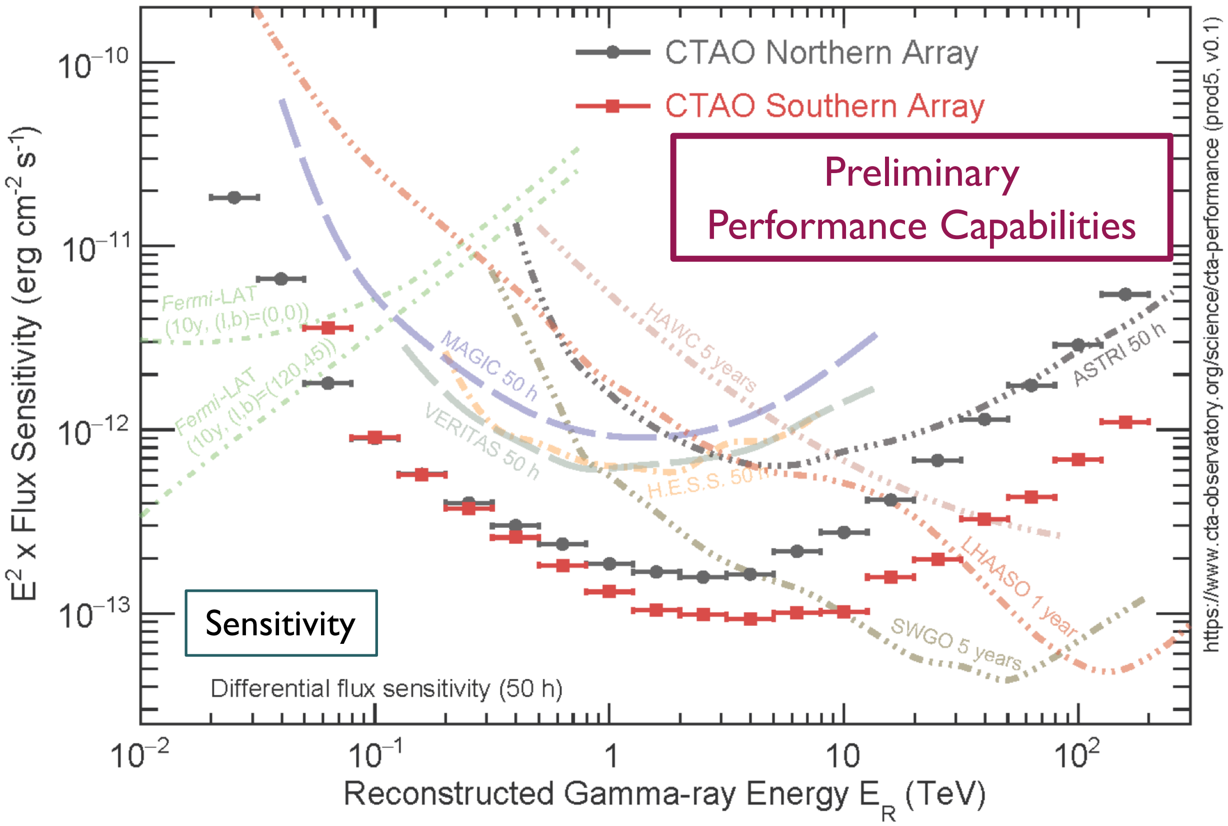
} **Joint Key Science Project** → DM + CR

(Achaya+17 [CTA Cons.])

- Monthly meetings, welcome to join! cta-wg-phys-clusters@cta-observatory.org

DM SEARCH WITH THE CHERENKOV TELESCOPE ARRAY (CTA)

- Future of ground-based VHE gamma-ray astronomy, 2 arrays: Northern Array (La Palma, Spain) and Southern Array (Paranal, Chile)



https://www.cta-observatory.org/

CTA has superb capabilities for DM gamma-ray searches

DARK MATTER MODELLING

$$\frac{d\Phi_{DM}}{dE}(E, l.o.s, \Delta\Omega, z) = \frac{d\phi}{dE}(E, z) \times \text{Astrophysical factor}$$

DM-induced γ-ray flux from an astrophysical object

Particle Physics Model

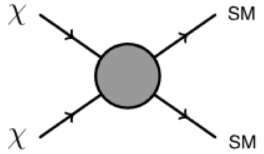
Cirelli+12 (EW corrections)

Charbonnier+12, Bonnivard+15, Hütten+18

https://clumpy.gitlab.io/CLUMPY/

Annihilation

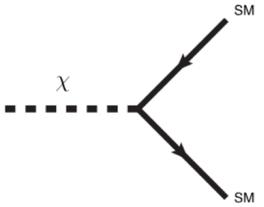
$$J(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega} \int_{l.o.s} \rho^2_{DM}(r)dr \rightarrow J \propto \frac{M_{200} c^3_{200}}{D^2_{\text{Earth}}}$$



DM density profile

Decay

$$D(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega} \int_{l.o.s} \rho_{DM}(r)dr \rightarrow D \propto \frac{M_{200}}{D^2_{\text{Earth}}}$$



DARK MATTER MODELLING (I): MAIN HALO

Annihilation

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

DM density profile

$$D(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega}\int_{l.o.s} \rho_{DM}(r)dr$$

Decay

MIN → Main halo without substructure

- State-of-the-art parametrization of the DM in galaxy clusters:

$$\langle\rho_{\rm tot}\rangle(r) = \rho_{\rm sm}(r) + \langle\rho_{\rm subs}\rangle(r)$$

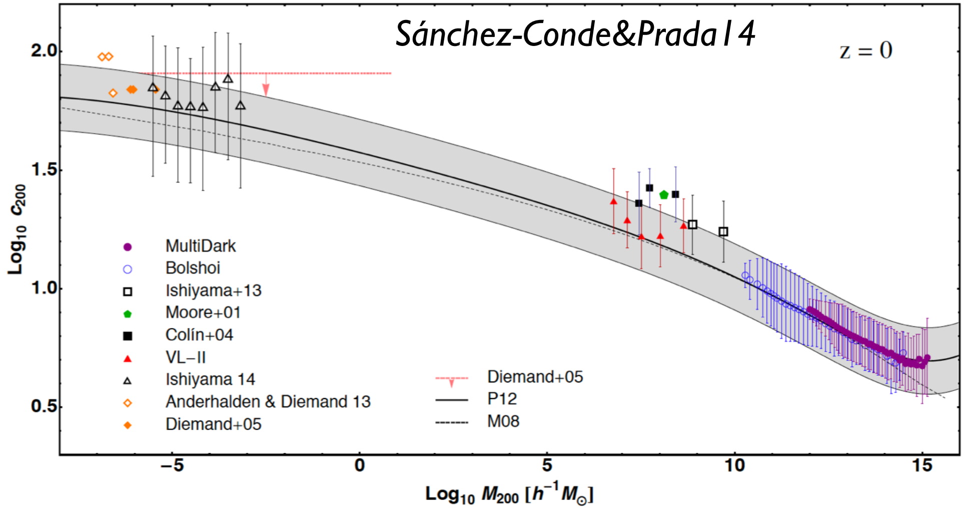
Assume density profile →

$$\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})[1+\frac{r}{r_s}]^2}$$

Navarro – Frenk – White (NFW)

Navarro+96, Navarro+97

- To build the DM profile, we assume a concentration-mass relation ($c_{200} - M_{200}$):



DARK MATTER MODELLING (II): SUBSTRUCTURE

- Galaxy clusters are the most massive objects today, large amount of substructure expected
- Inclusion through ρ_{DM} using state-of-the-art subhalo models

$$\langle \rho_{\mathrm{tot}} \rangle (r) = \rho_{\mathrm{sm}}(r) + \langle \rho_{\mathrm{subs}} \rangle (r)$$

$$\frac{d^3 N}{dV dM dc} = N_{\mathrm{tot}} \frac{d\mathcal{P}_V}{dV}(r) \cdot \frac{d\mathcal{P}_M}{dM}(M) \cdot \frac{d\mathcal{P}_c}{dc}(M, c)$$

CLUMPY

DM subhalo profile: NFW

$$\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})[1+\frac{r}{r_s}]^2}$$

Subhalo Radial Distribution (SRD)

$$\rho_{\mathrm{sub}}^{VLII}(R) = \frac{\rho_{\mathrm{tot}}^{VLII}(R)\,(R/R_a)}{\left(1+\frac{R}{R_a}\right)}$$

Via Lactea - II

Anti-biased relation

Diemand+08

Subhalo Mass Function (SHMF)

$$dN/dm = A/M(m/M)^{-\alpha}$$

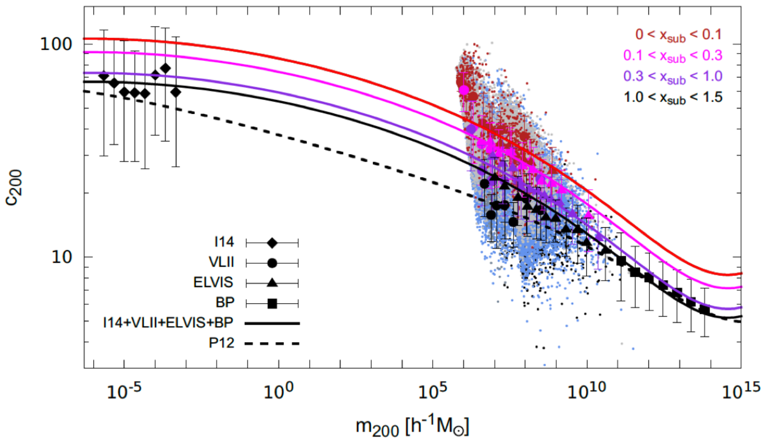
α = 1.9 → MED

Springel+08

α = 2.0 → MAX

Diemand+08

Subhalo Concentration-Mass relation (c_{200}-M_{200})



Dependence on the subhalo position

$$c_{200}(m_{200}, x_{\mathrm{sub}})$$

$$x_{\mathrm{sub}} \equiv R_{\mathrm{sub}}/R_{\Delta}$$

Moliné+17

OBTENTION OF DM MODEL PARAMETERS

- State-of-the-art parametrization of the DM in galaxy clusters: $\langle\rho_{\rm tot}\rangle(r) = \rho_{\rm sm}(r) + \langle\rho_{\rm subs}\rangle(r)$

1 Assume a DM profile $\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})[1+\frac{r}{r_s}]^2}$ NFW

2 Assume a concentration-mass relation ($c_{200} - M_{200}$): *Sánchez-Conde&Prada14* $c_{200}(M_{200}, z=0) = \sum_{i=0}^{5} c_i \times \left[\ln\left(\frac{M_{200}}{h^{-1}M_\odot}\right)\right]^i$

3 Assume spherical collapse from an overdensity Δ = 200 over the critical density $\Delta_{200} = \frac{3M_{200}}{4\pi R_{200}\rho_{crit}}$

4 Compute remaining parameters

Scale density

$$\rho_0 = \frac{2\Delta_{200}\rho_{crit}c_{200}}{3F(c_{200})}$$

with

$$F(c_{200}) = \frac{2}{c_{200}^2}\left(\ln(1+c_{200}) - \frac{c_{200}}{1+c_{200}}\right)$$

Scale radius

$$c_{200} = \frac{R_{200}}{r_s}$$

Angular extension

$$\theta_{200} = \tan\left(\frac{R_{200}}{d_L}\right)$$

EXPECTED DM SIGNAL

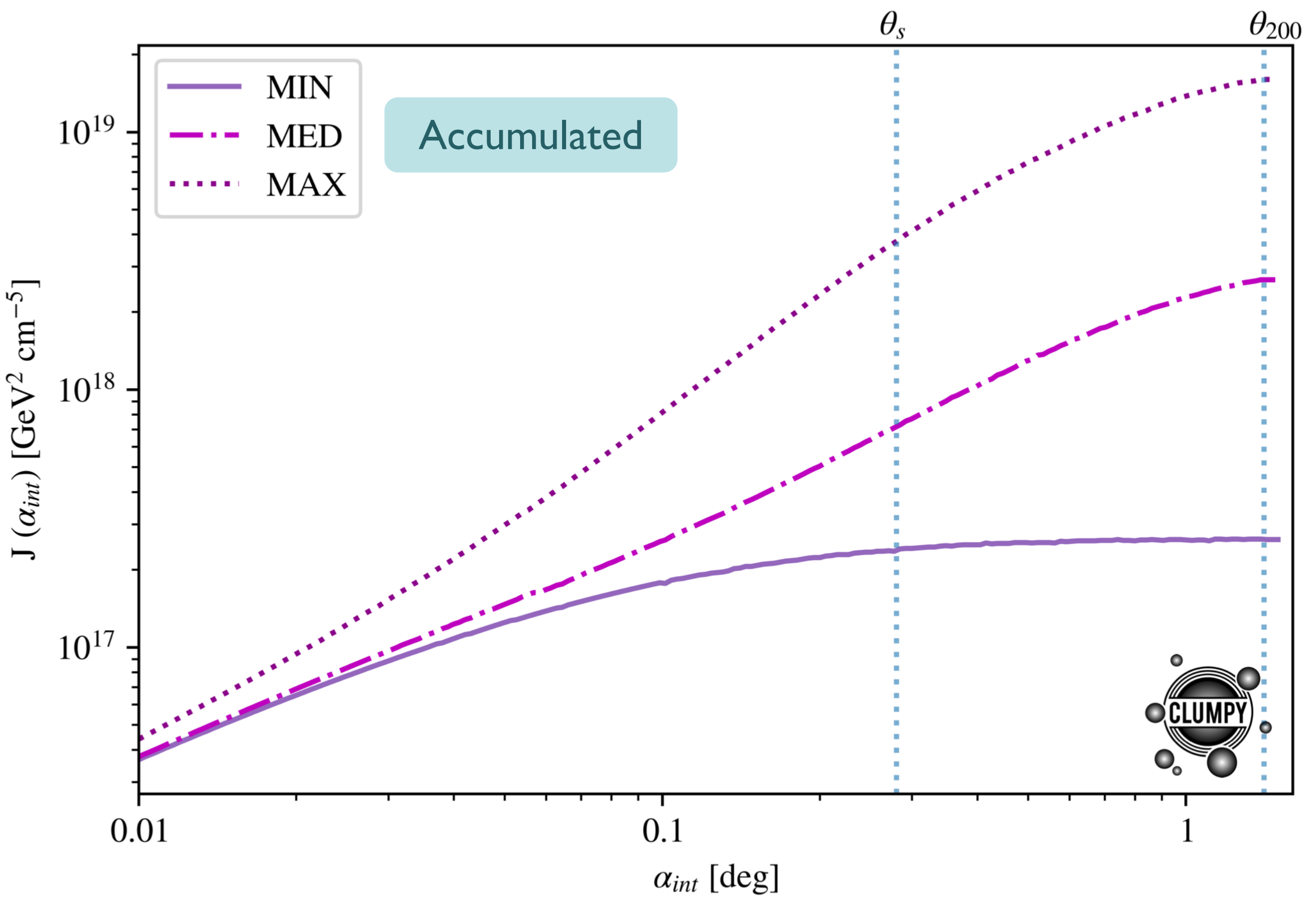
General parameters

Hitomi Coll.18	z	0.017284	l, b	150.58 deg, -13.26 deg
Urban+14	M_{200}	7.52×10^{14} $M_\odot$	R_{200}	1865.0 kpc
Sánchez-Conde & Prada 14	c_{200}	5.03	θ_{200}	1.42 deg
	r_s	370.82 kpc	θ_s	0.28 deg
Flat ΛCDM	d_L	75.01 Mpc	ρ_s	299581 $M_\odot/\mathrm{kpc}^3$

Apply modelling formalism

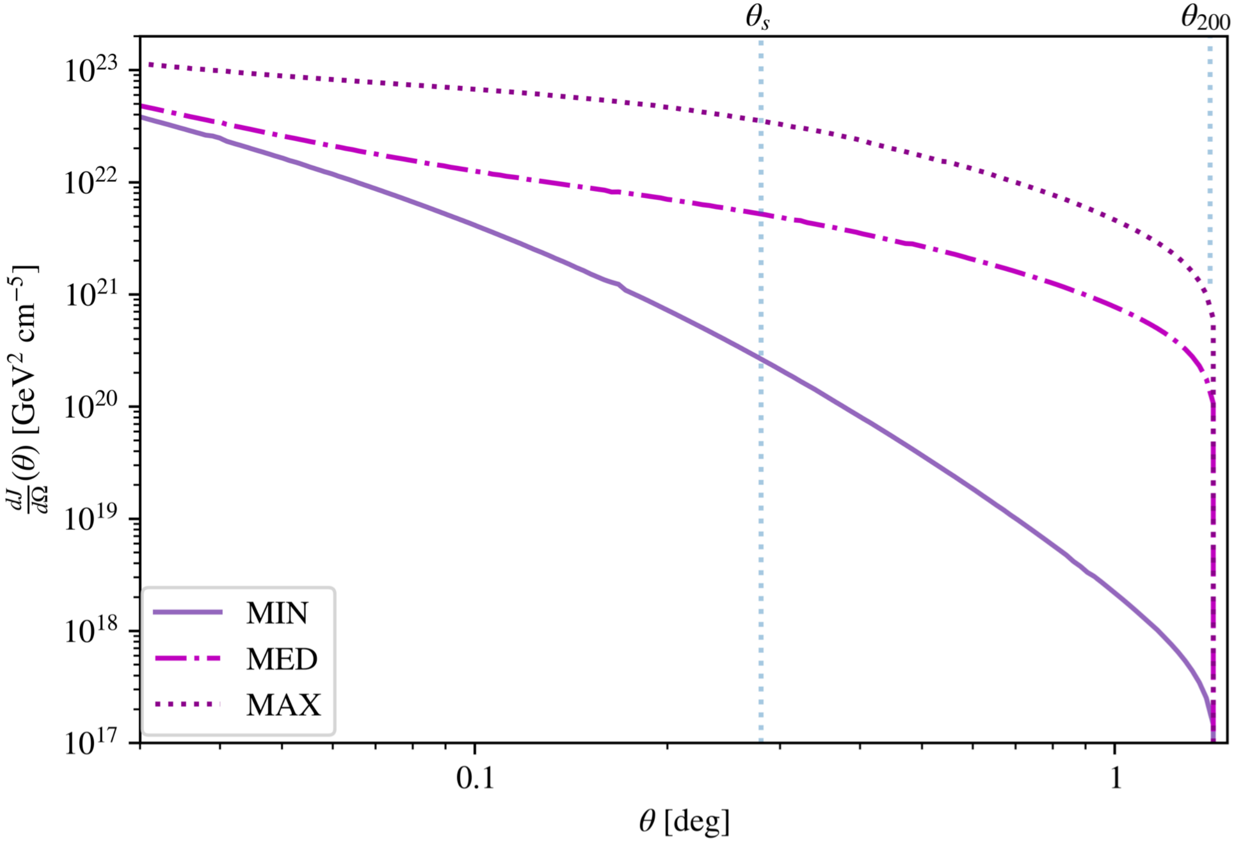
Annihilation	$\log_{10} J$ [$\mathrm{GeV}^2\mathrm{cm}^{-5}$]
MIN	17.42
MED	18.43
MAX	19.20
Decay	$\log_{10} D$ [GeV cm^{-2}]
	19.20

Annihilation flux profile



DIFFERENTIAL ANNIHILATION FLUX PROFILE

Differential



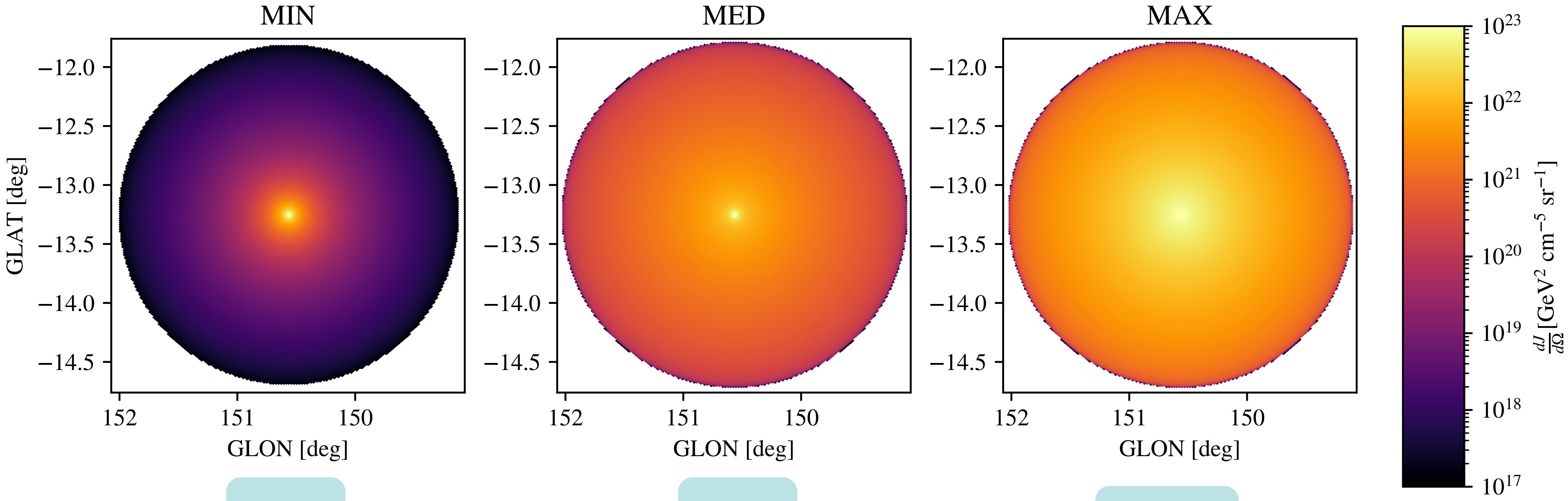
General parameters

z	0.017284	l, b	150.58 deg, -13.26 deg
M_{200}	7.52×10^{14} $M_\odot$	R_{200}	1865.0 kpc
c_{200}	5.03	θ_{200}	1.42 deg
r_s	370.82 kpc	θ_s	0.28 deg
d_L	75.01 Mpc	ρ_s	299581 $M_\odot/\mathrm{kpc}^3$

MORPHOLOGY OF DM SIGNAL

Skymaps of the differential J-factor

Annihilation



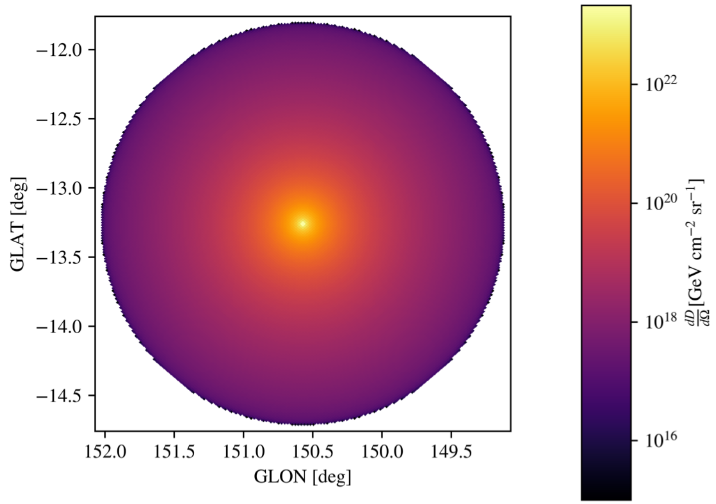
MIN

MED

MAX

Skymap of the differential D-factor

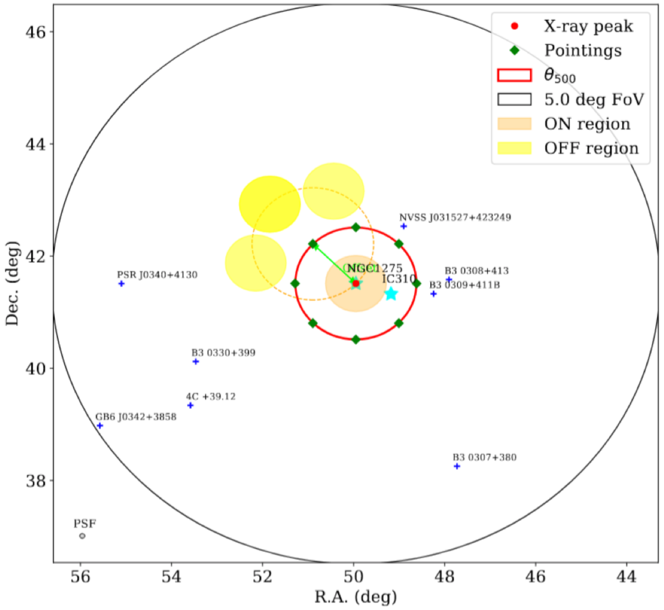
Decay



DMTOOLS MOTIVATION

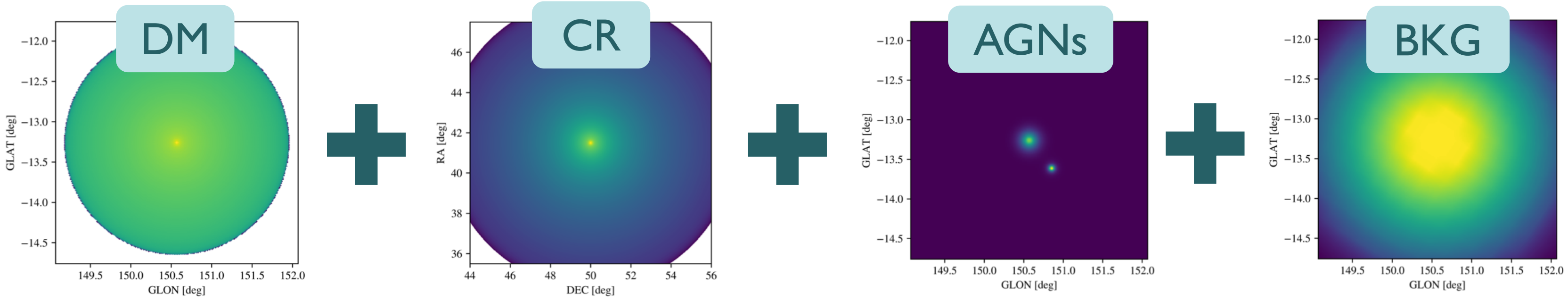
- Most DM projects within the WG with same needs in terms of analysis tools and statistical treatment.
- A common set of DM tools would be very beneficial:
  - Unifies definitions, nomenclature, methodology within DMEP.
  - Everyone follows the 'DM conventions doc' 'naturally'.
  - Avoids repetition of same tasks/coding along the years.
  - Saves time to young students and postdocs.
  - Allows for easy comparison of results.
  - Allows for quick cross-checks of results and debugging.
  - Everyone can potentially contribute to further developments without having to start from scratch.
- All together, a set of common tools would make the whole DMEP WG more efficient and our works more robust and sound.

CTA ANALYSIS CONFIGURATIONS



1. First approach - **On/Off Analysis**
   - Lowest level of complexity (only DM + BKG emission, point-like/DM template)
   - More constraining results
   - Allow direct comparisons (historically used in Imaging Air Cherenkov Telescopes (IACTs) as MAGIC)

2. Final analysis goal - **Template fitting**
   - More realistic physical scenario (different sources, spatial morphologies)

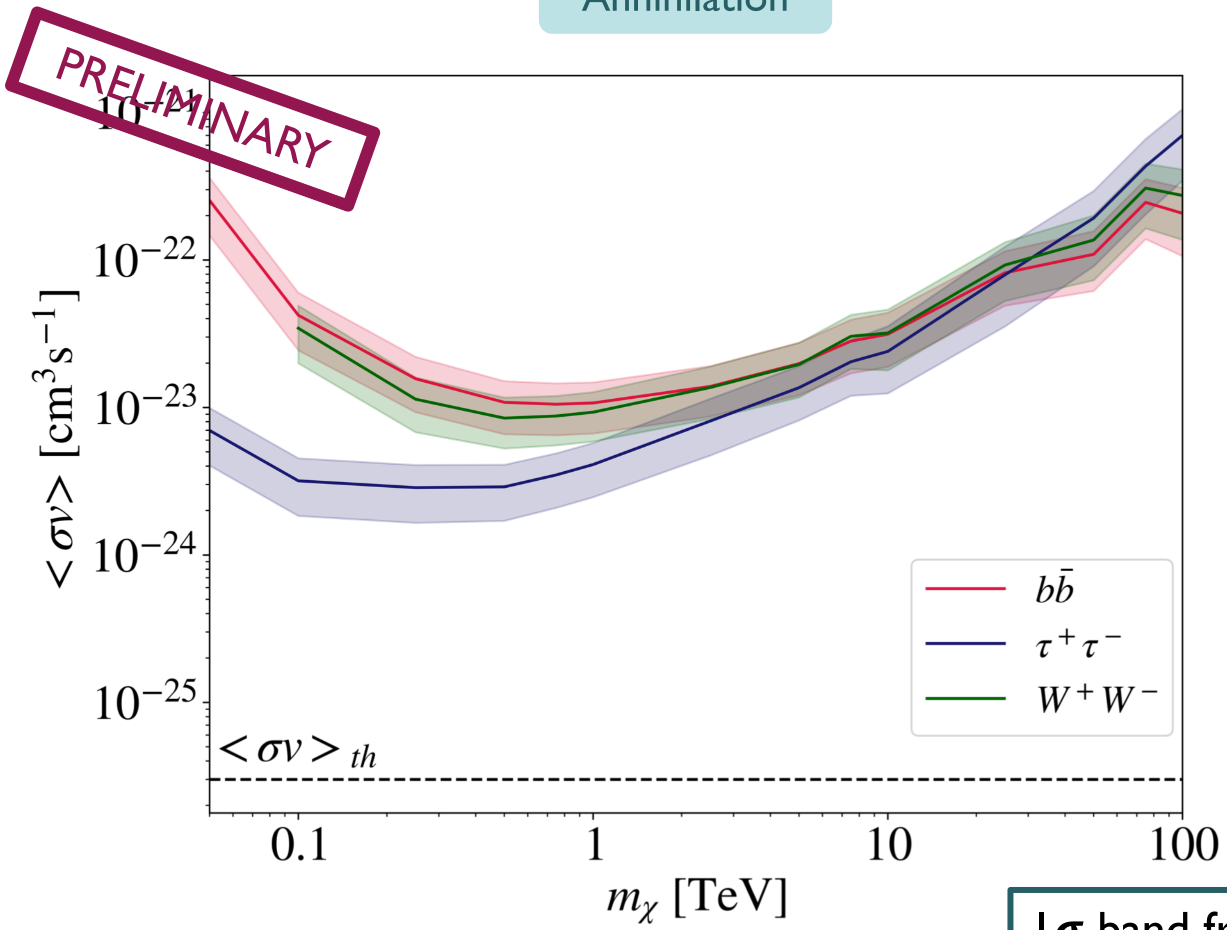


- Allows to check correlations between components
- Historically used in Fermi-*LAT* analysis and in state-of-the-art for IACTs (*Acharyya+20* [*CTA Cons.*])

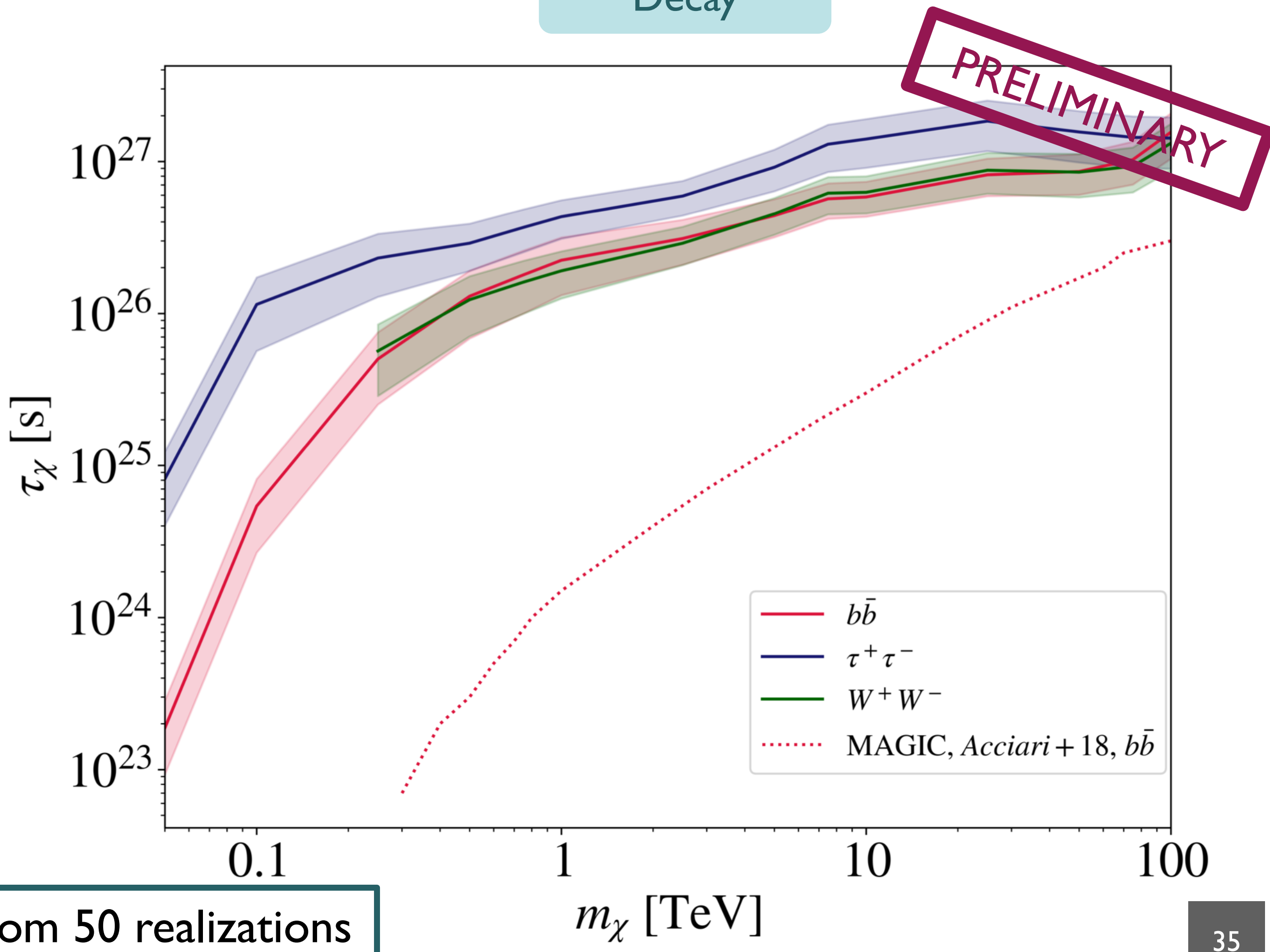
ON/OFF RESULTS: DM CONSTRAINTS

Limits for Perseus for MED annihilation model and decay
(point-like morphology & no J/D-factor uncertainties)

Annihilation



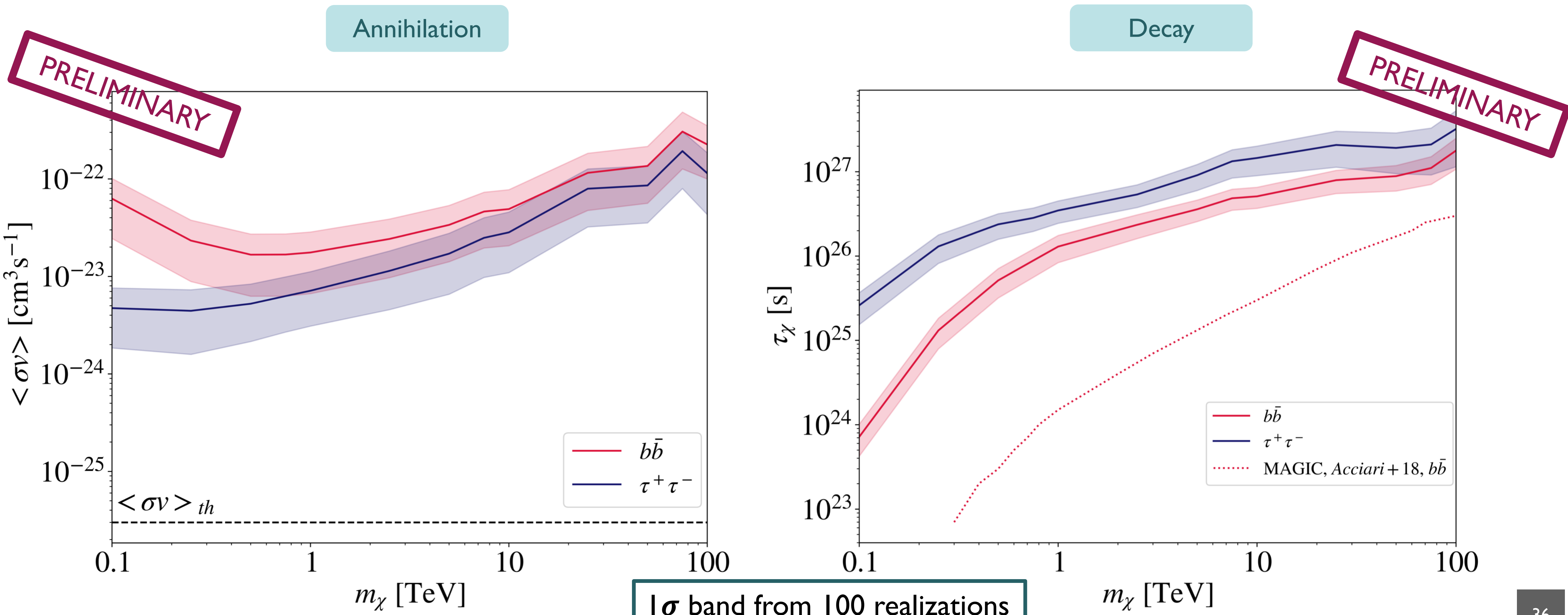
Decay



1σ band from 50 realizations

ON/OFF RESULTS: DM CONSTRAINTS

Limits for Perseus for MED annihilation model and decay
(DM template & no J/D-factor uncertainties)



1σ band from 100 realizations

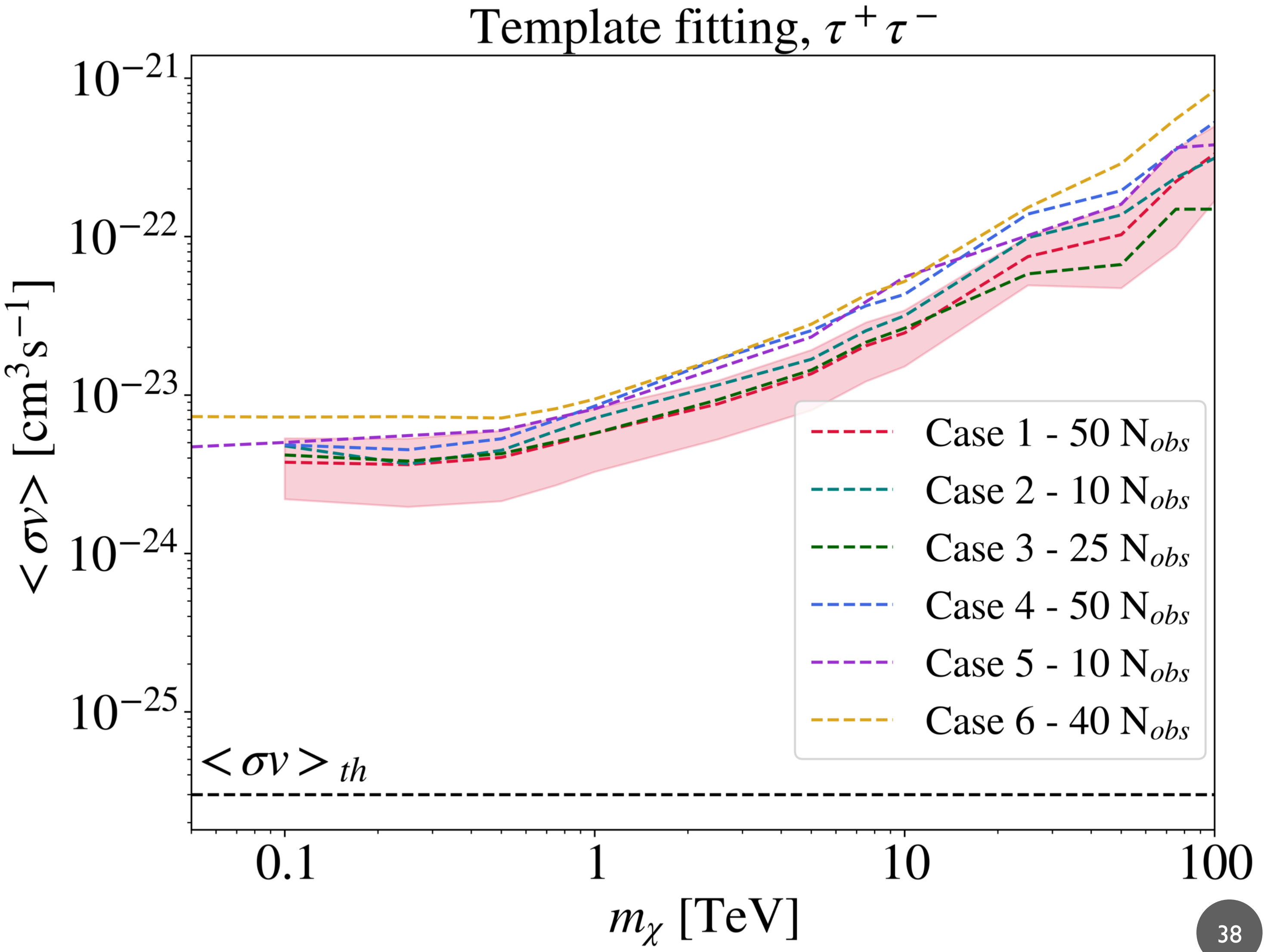
CTA ANALYSIS CONFIGURATION (II): TEMPLATE FITTING

- Template fitting for DM pipeline including the Perseus gamma-ray sources
- Steps of the analysis **8 parameters in total**
  1. Fit DM model (observation DM+IRF BKG)
  2. Fit DM model + IRF BKG
     1. Normalization IRF BKG
     2. Tilt IRF BKG
  3. Fit DM model + IRF BKG + CR normalization
  4. Fit DM model + IRF BKG + CR normalization + PS
     1. NGC1275 Norm & tilt
     2. IC310 Norm & tilt

Name	DM		BKG IRFs		CR	NCG1275		IC310	
	Norm	Sys	Norm	Tilt	Norm	Norm	Tilt	Norm	Tilt
Case 1	X	–	–	–	–	–	–	–	–
Case 2	X	–	X	–	–	–	–	–	–
Case 3	X	–	X	X	–	–	–	–	–
Case 4	X	–	X	X	X	–	–	–	–
Case 5	X	–	X	X	X	X	–	–	–
Case 6	X	–	X	X	X	X	X	–	–
Case 7	X	–	X	X	X	X	X	X	–
Case 8	X	–	X	X	X	X	X	X	X

TEMPLATE FITTING RESULTS: DM CONSTRAINTS

- Steps of the analysis
  1. Fit DM model (observation DM+IRF BKG)
  2. Fit DM model + IRF BKG
     1. Normalization IRF BKG
     2. Tilt IRF BKG
  3. Fit DM model + IRF BKG + CR normalization
  4. Fit DM model + IRF BKG + CR normalization + PS
     1. NGC1275 Norm & tilt
     2. IC310 Norm & tilt
- Tested if posible dependency in best fit values depending on channel or DM mass
- Values of best fit & errors for BKG & CR params compatible with input and MCMC



CTA ANALYSIS CONFIGURATION (III): SUMMARY

ON/OFF Analysis

Standard for IACTs

Point-like

- Lowest complexity
- Most constraining results

Done

Extended

- More complex and realistic than point-like approach
- Benefits from CTA large FoV and angular resolution

On-going

Template fitting

State-of-the-art pipeline

Minuit

- Already embedded in Gammapy
- Historically used fitter and very well documented (stability)

On-going

MCMC

- Flexible definition of likelihood and priors
- Easy analysis of correlations

On-going

CTA ANALYSIS ELEMENTS

- https://docs.gammapy.org/0.19/stats/fit_statistics.html
- Likelihood ratio test:

$$TS = -2\ln\frac{\mathcal{L}(\alpha;\hat{\hat{\nu}}|\mathcal{D})}{\mathcal{L}(\hat{\alpha};\hat{\nu}|\mathcal{D})}$$

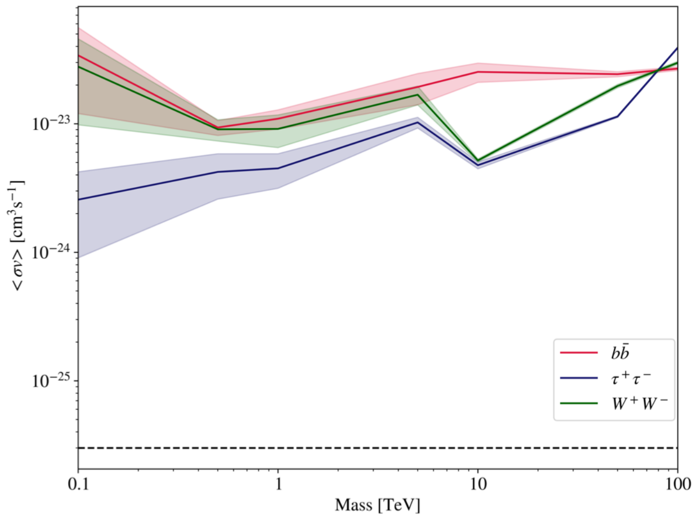
  - *TS* < 25 → No signal

Template fitting: Poisson likelihood for each component, *Cash* statistics (*Cash 79*)

$$C = 2(\mu - n\ln\mu)$$

ON/OFF analysis: Poisson likelihood for signal and background, *Wstat* statistics (*XSpec manual*)

$$W = 2(\mu_{sig}+(1+r)\mu_{bkg}-n_{ON}-n_{OFF}-n_{ON}(\ln(\mu_{sig}+r\mu_{bkg})-\ln n_{ON})-n_{OFF}(\ln\mu_{bkg}-\ln n_{OFF}))$$



Caveat

- Since WStat takes into account background estimation uncertainties and makes no assumption such as a background model, it usually gives larger statistical uncertainties on the fitted parameters. If a background model exists, to properly compare with parameters estimated using the Cash statistics, one should include some systematic uncertainty on the background model.
- Note also that at very low counts, WStat is known to result in biased estimates. This can be an issue when studying the high energy behaviour of faint sources. When performing spectral fits with WStat, it is recommended to randomize observations and check whether the resulting fitted parameters distributions are consistent with the input values.

CTA ANALYSIS ELEMENTS

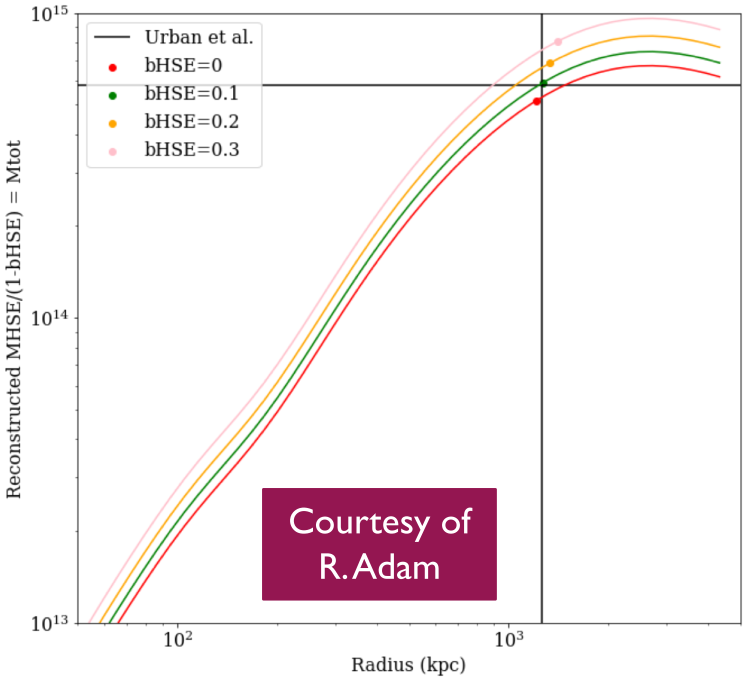
- Uncertainties in the J/D-factor enter through:

X-rays measurements → Mass modelling and extrapolations (*Urban+14*) → *c(M) – M* scatter →

- Masses from other methods
- Other X-rays measurements

- ~ O(0.3) dex for *Sánchez-Conde & Prada 14*

	σ_J	σ_D
$M_{min} + c_{200,min}$	0.2	0.003
M_{min}	0.002	0.0
M_{max}	0.005	0.0
$M_{max} + c_{200,max}$	0.2	0.0

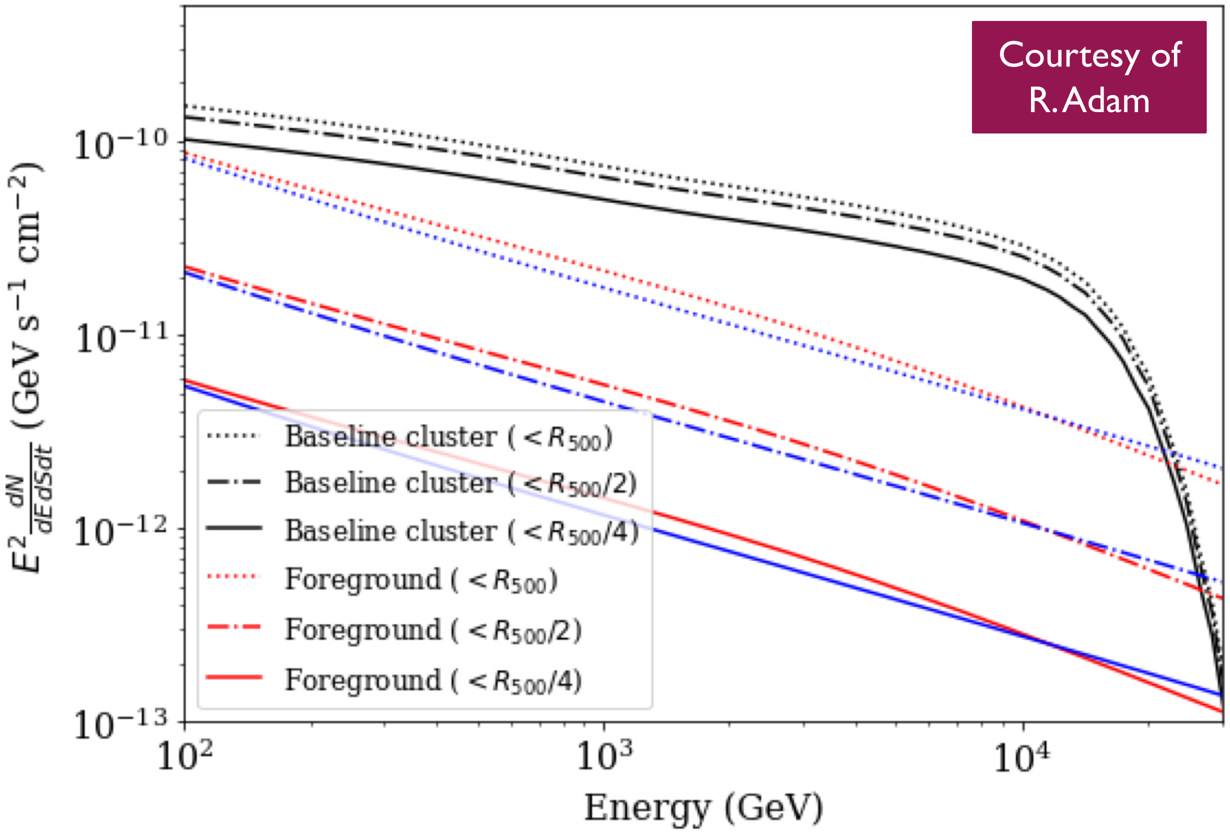


$$\mathcal{J}(J \,|\, J_{\rm obs}, \sigma_J) = \frac{1}{\ln(10) J_{\rm obs} \sqrt{2\pi}\sigma_J} \times e^{-\left(\log_{10}(J) - \log_{10}(J_{\rm obs})\right)^2 / 2\sigma_J^2}$$

Gaussian prior in MCMC template fitting

CTA ANALYSIS ELEMENTS

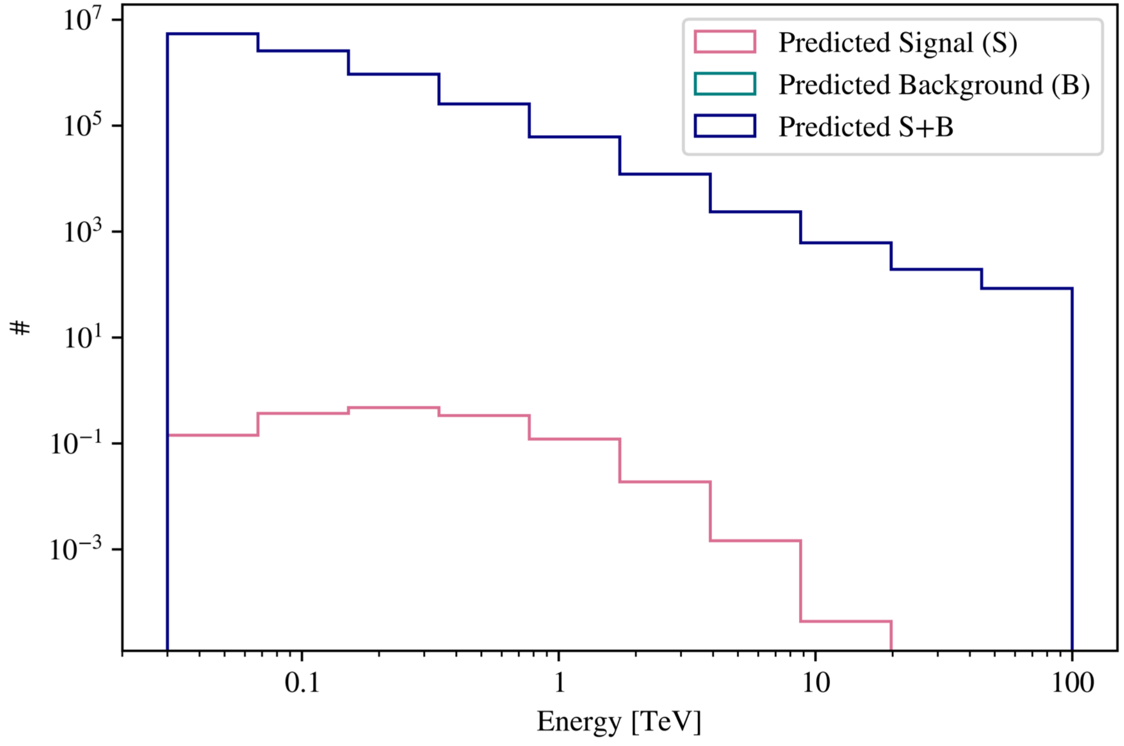
- Role of the Galactic diffuse emission:
  - Perseus is located "close" to the galactic plane (150.57, -13.26) deg
  - Baseline model for the galactic diffuse emission provided by D. Gaggero & P. de la Torre Luque
  - Integrated up to different radius and compared to CR baseline model
  - Worst case scenario, still factor ~few 10 below the expected CR emission



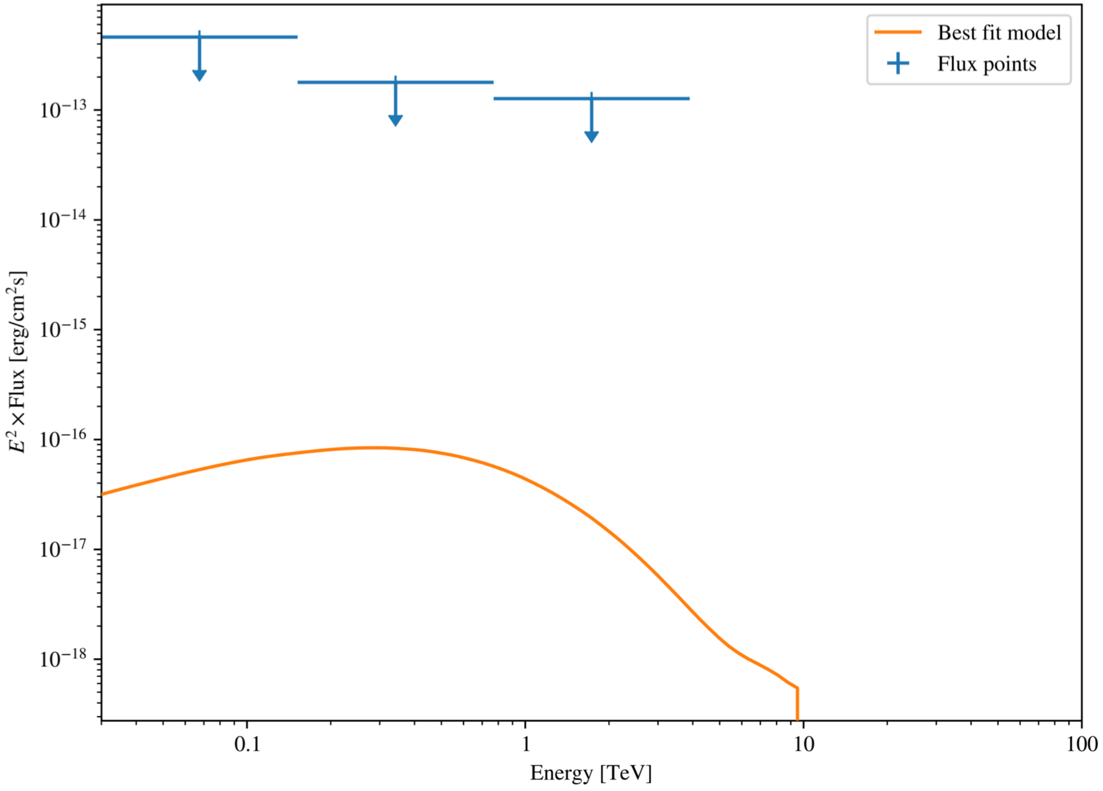
CHARACTERISTICS OF THE SIMULATIONS

- One example simulation:
  - Annihilation
  - 10 TeV
  - *b* channel

Counts

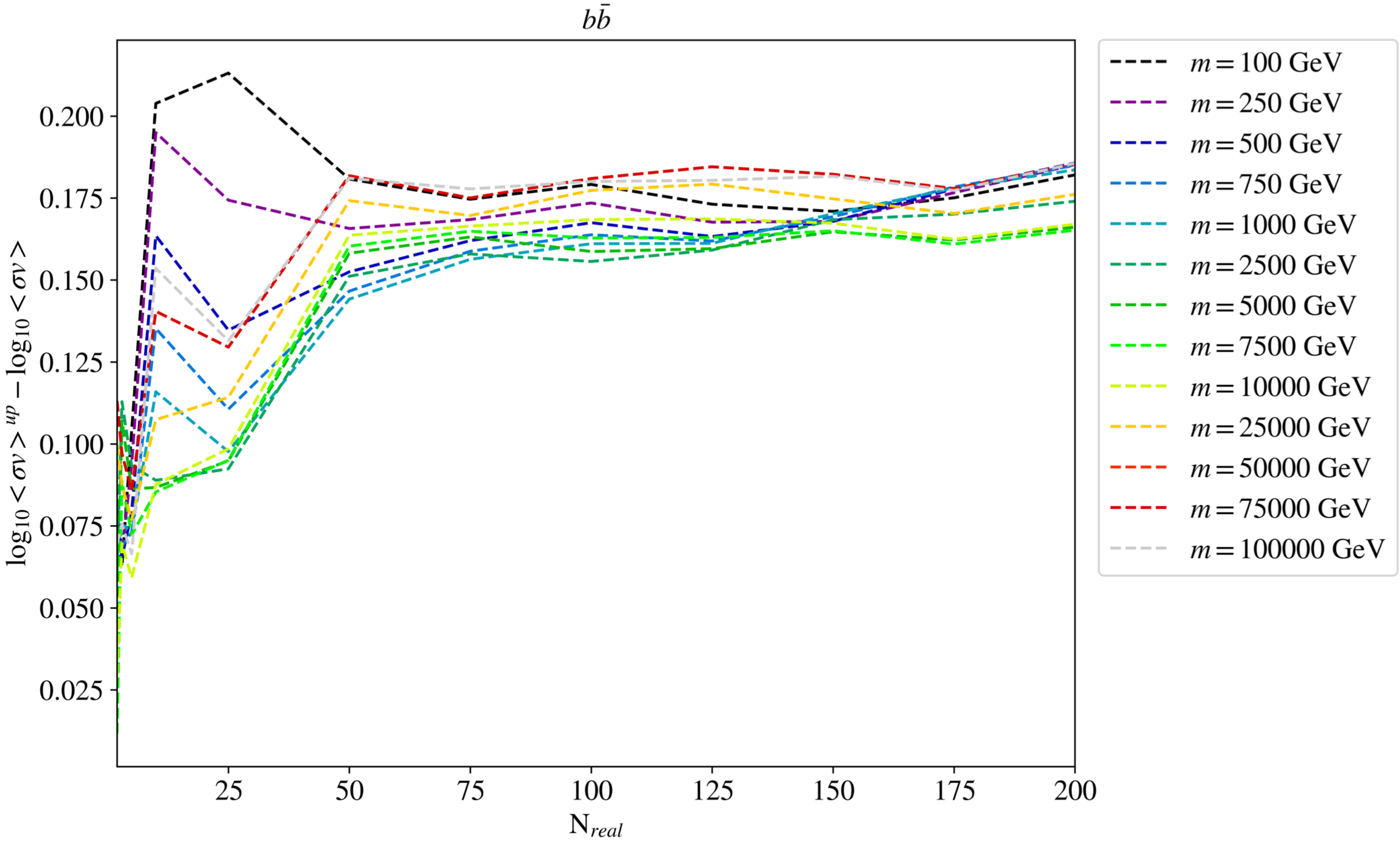


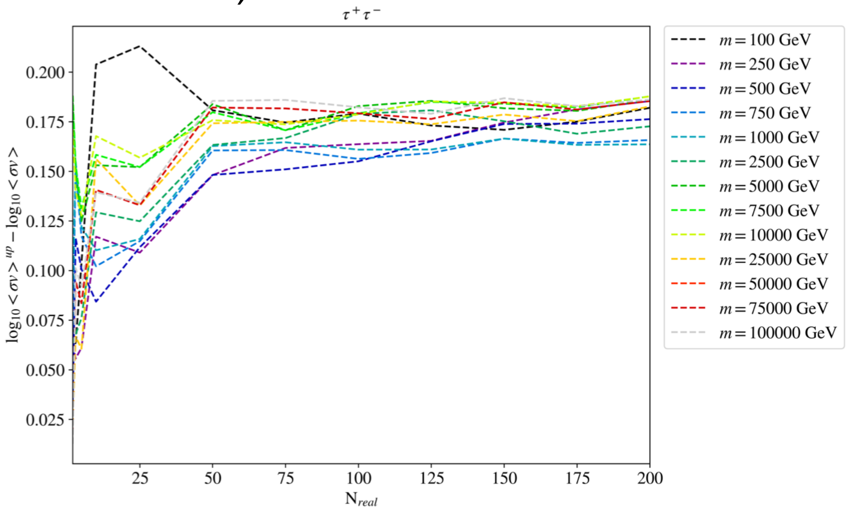
SED + ULs

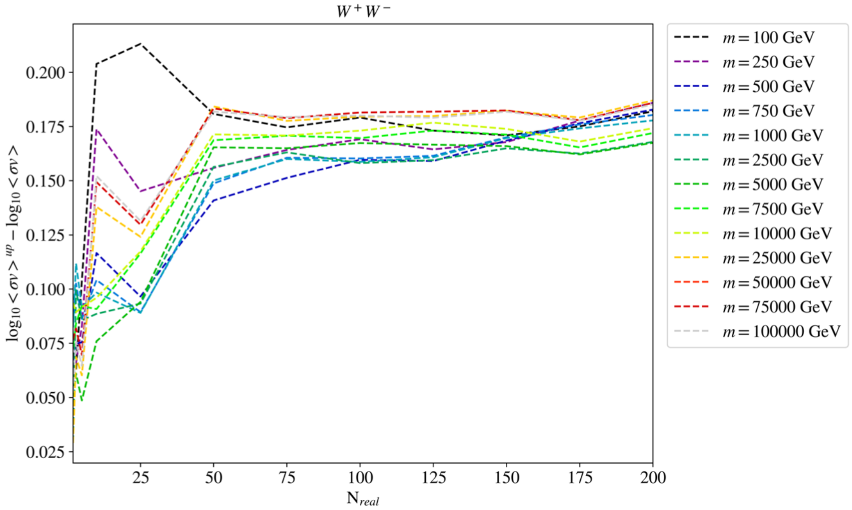


DM CONSTRAINTS: 1σ BAND

One-side 1σ band evolution with the number of realizations (using annihilation MED model, draft config., point-like morphology & no J-factor uncertainties)

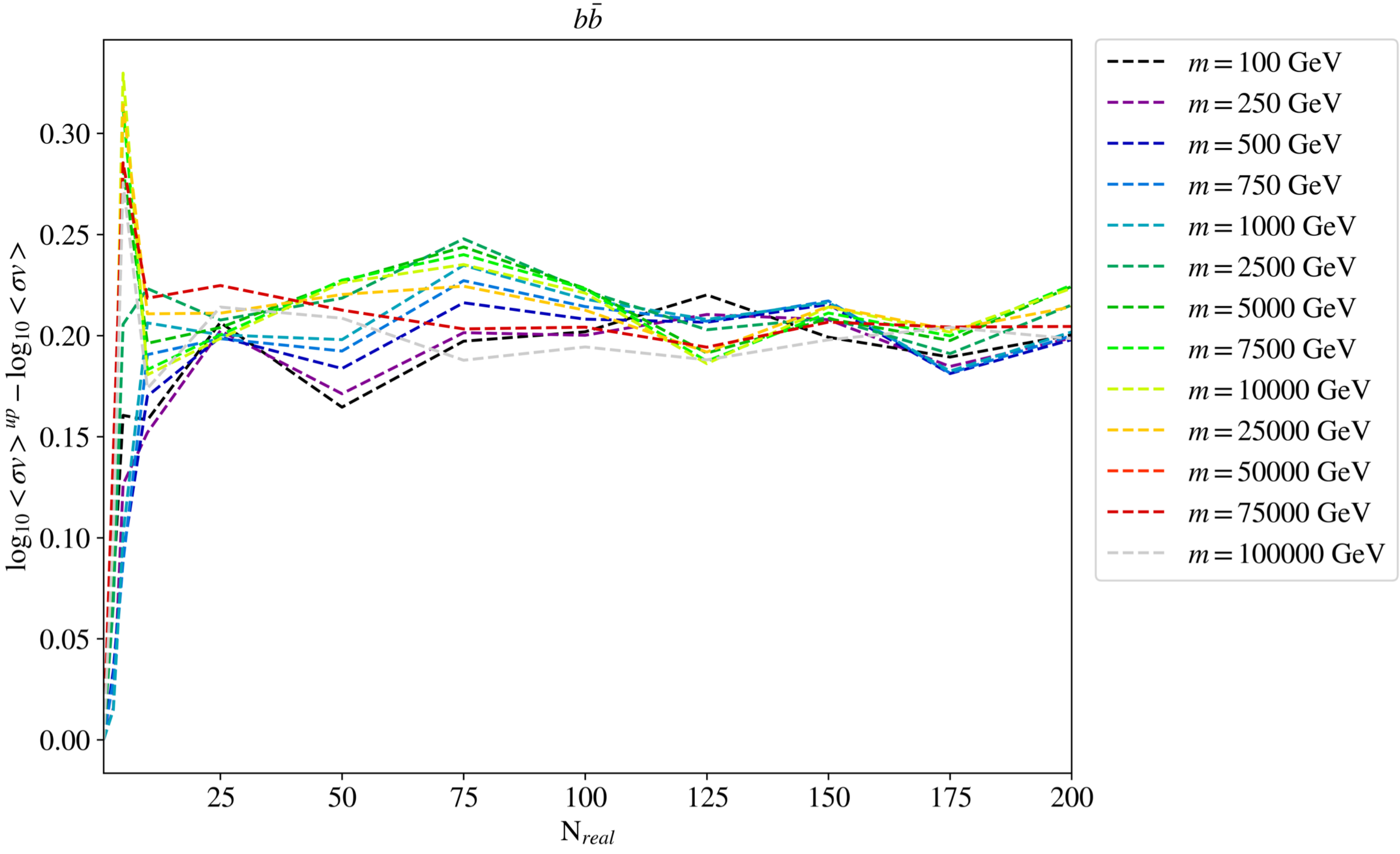


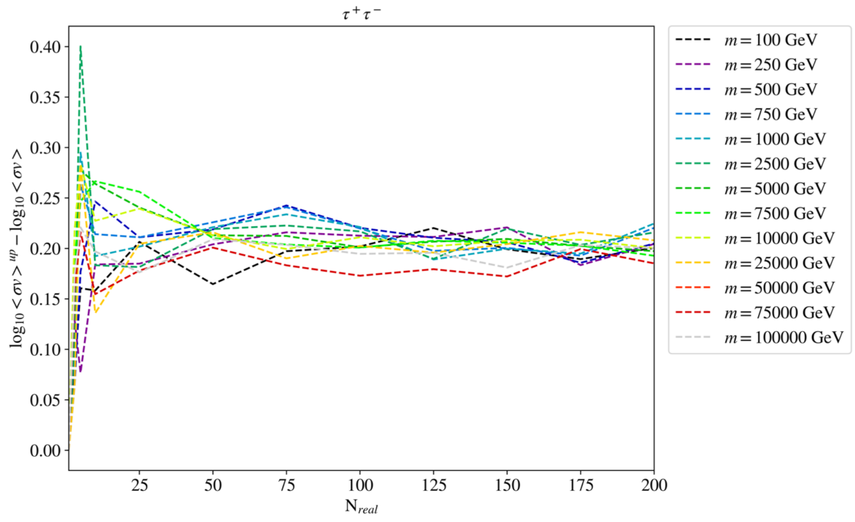


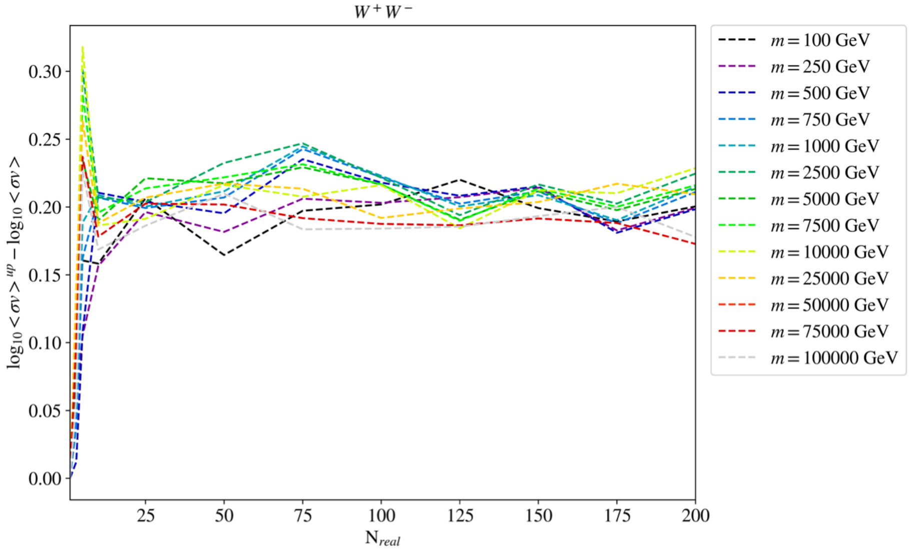


DM CONSTRAINTS: 1σ BAND

One-side 1σ band evolution with the number of realizations (using annihilation MED model, draft config., DM template & no J-factor uncertainties)







DM CONSTRAINTS: ON/OFF SET-UPS

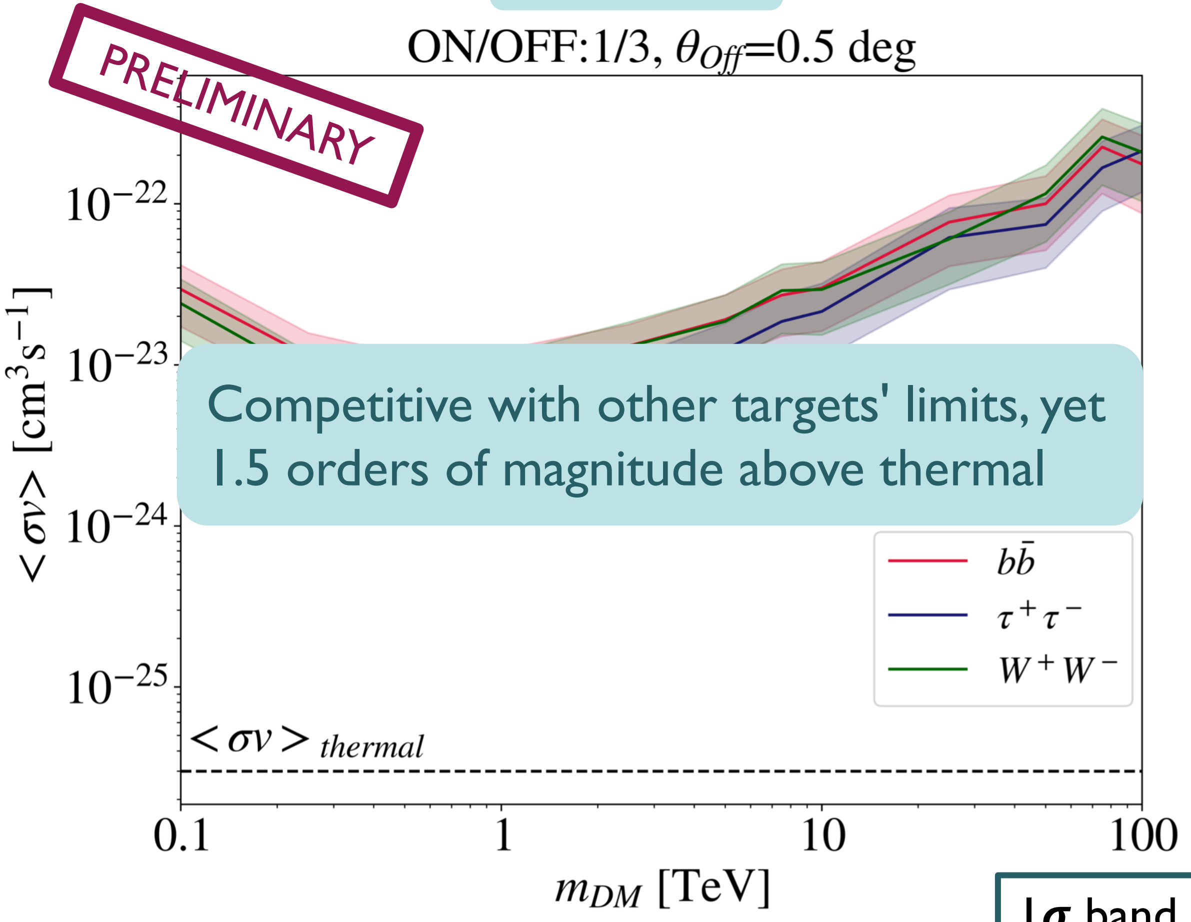
Different configurations tested in the On/Off set-up

Name	ON in center?	θ_{offset} [deg]	ON [deg]	N_{OFF}	OFF [deg]	α
Case 1	Y	0	1	3	1	1/3
Case 2	Y	0.5	0.5	3	0.5	1/3
Case 3	Y	1	1	3	1	1/3
Case 4	Y	1.5	1	3	1	1/3
Case 5	Y	0	1	5	1	1/5
Case 6	Y	1	1	5	1	1/5
Draft	Y	1	0.5	5	0.5	1/5
Draft plus	Y	1	1	5	0.5	1/1.25
Final	**Y**	**1**	**0.5**	**3**	**0.5**	**1/3**

ON/OFF RESULTS: DM CONSTRAINTS

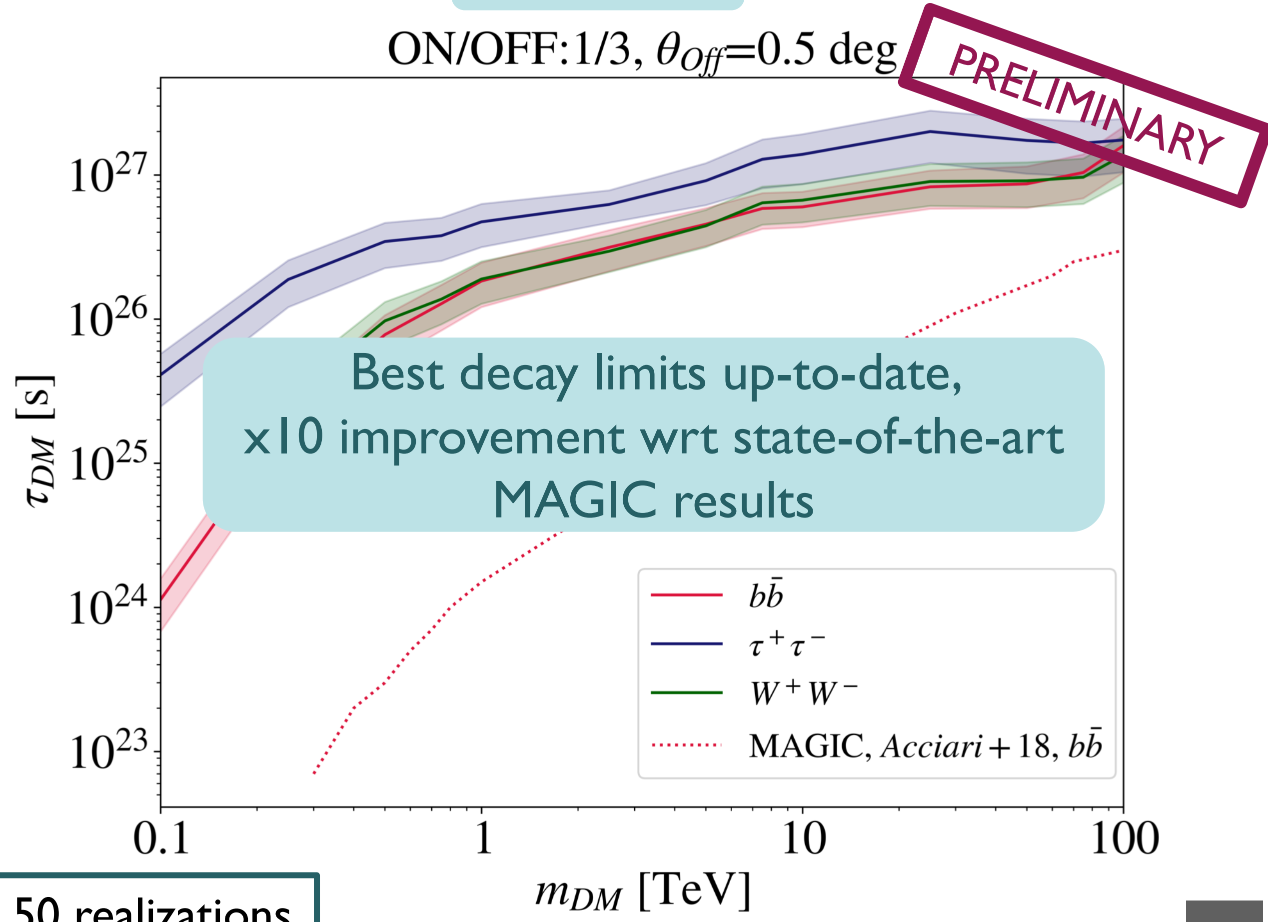
Limits for Perseus for MED annihilation model and decay
(point-like morphology & no J/D-factor uncertainties)

Annihilation



Competitive with other targets' limits, yet 1.5 orders of magnitude above thermal

Decay

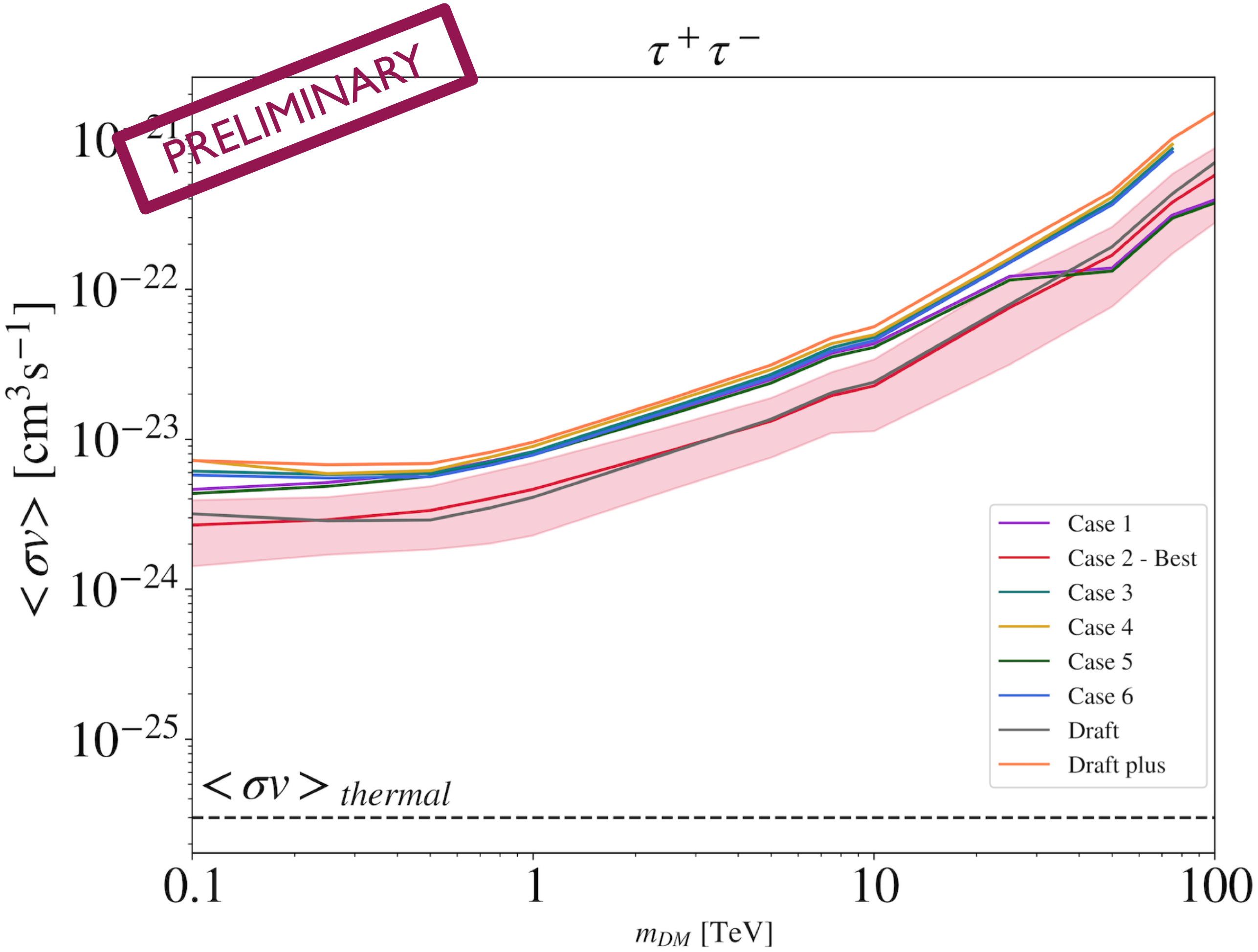


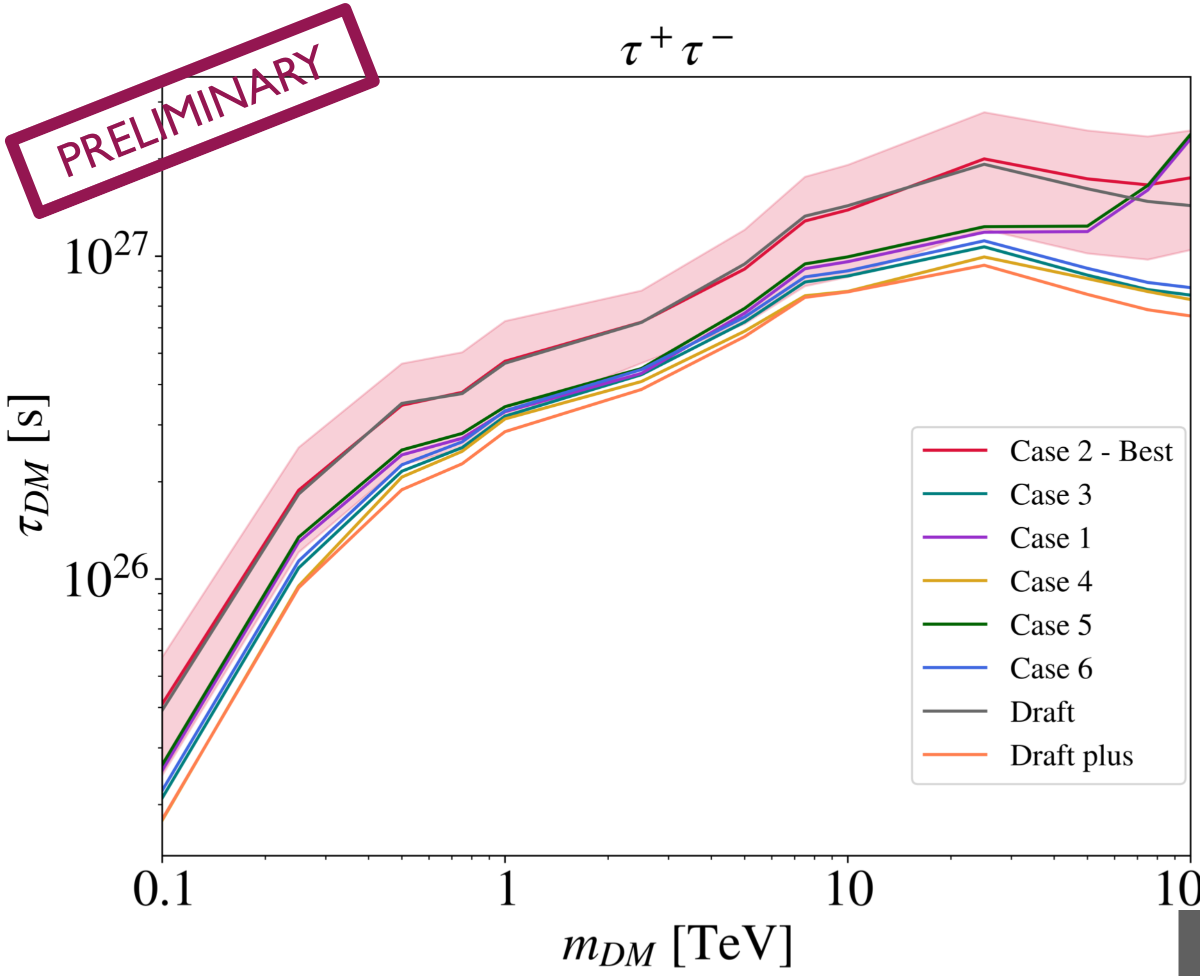
Best decay limits up-to-date,
x10 improvement wrt state-of-the-art MAGIC results

1σ band from 50 realizations

DM CONSTRAINTS: ON/OFF SET-UPS

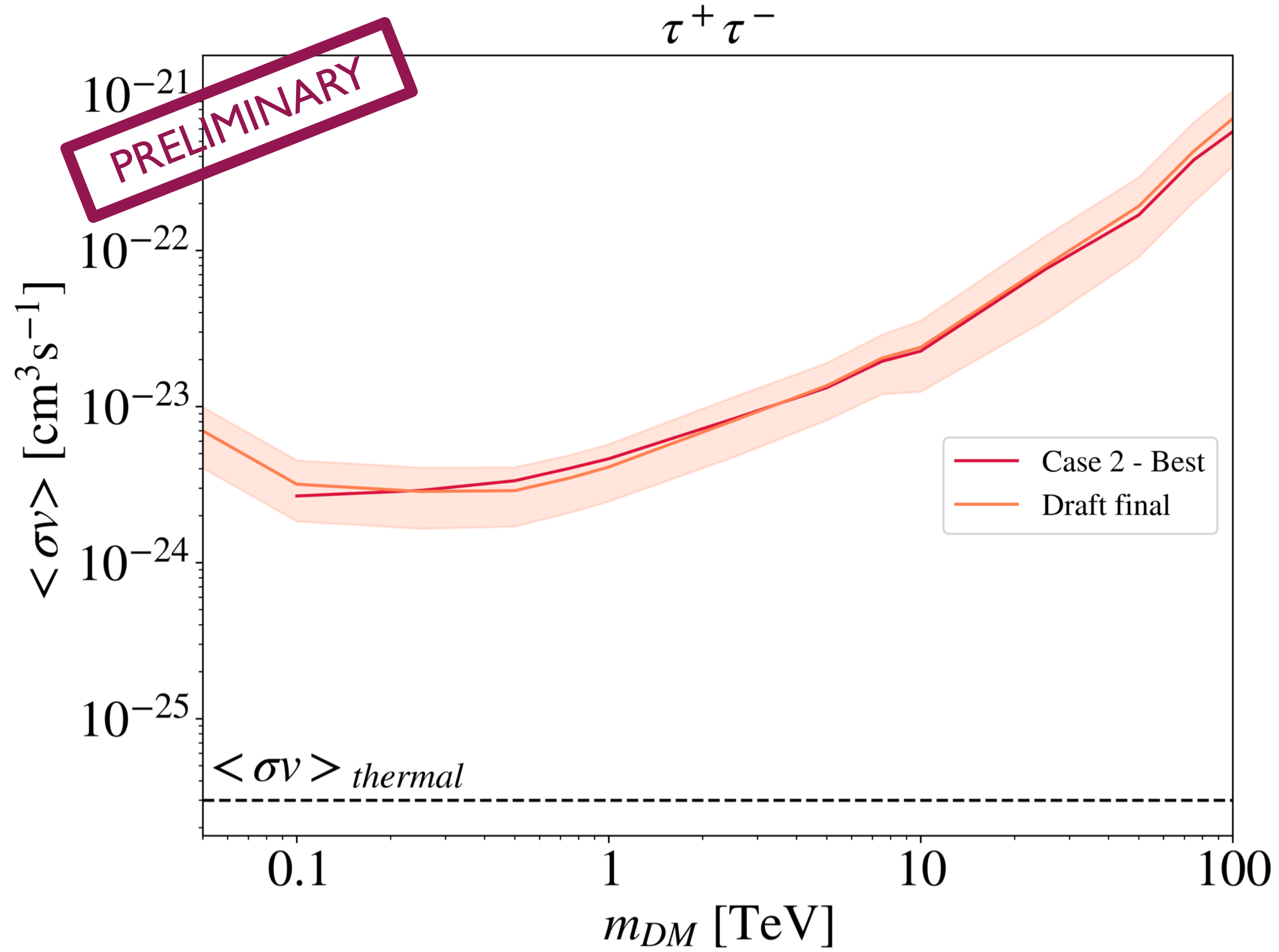
Limits for Perseus for $\tau^{+}\tau^{-}$ annihilation and decay models
(point-like morphology & no J/-D-factor uncertainties)





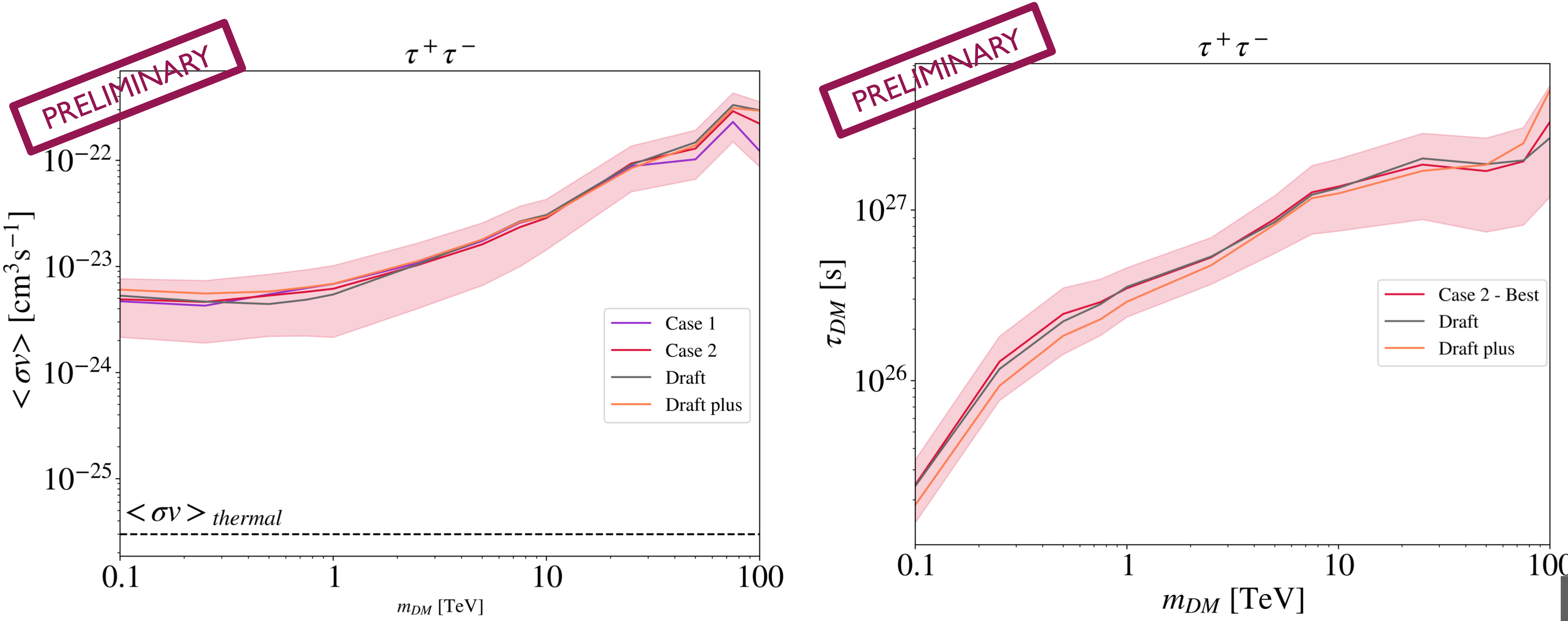
DM CONSTRAINTS: ON/OFF SET-UPS

Limits for Perseus for $\tau^+\tau^-$ annihilation and decay models
(point-like morphology & no J-factor uncertainties)



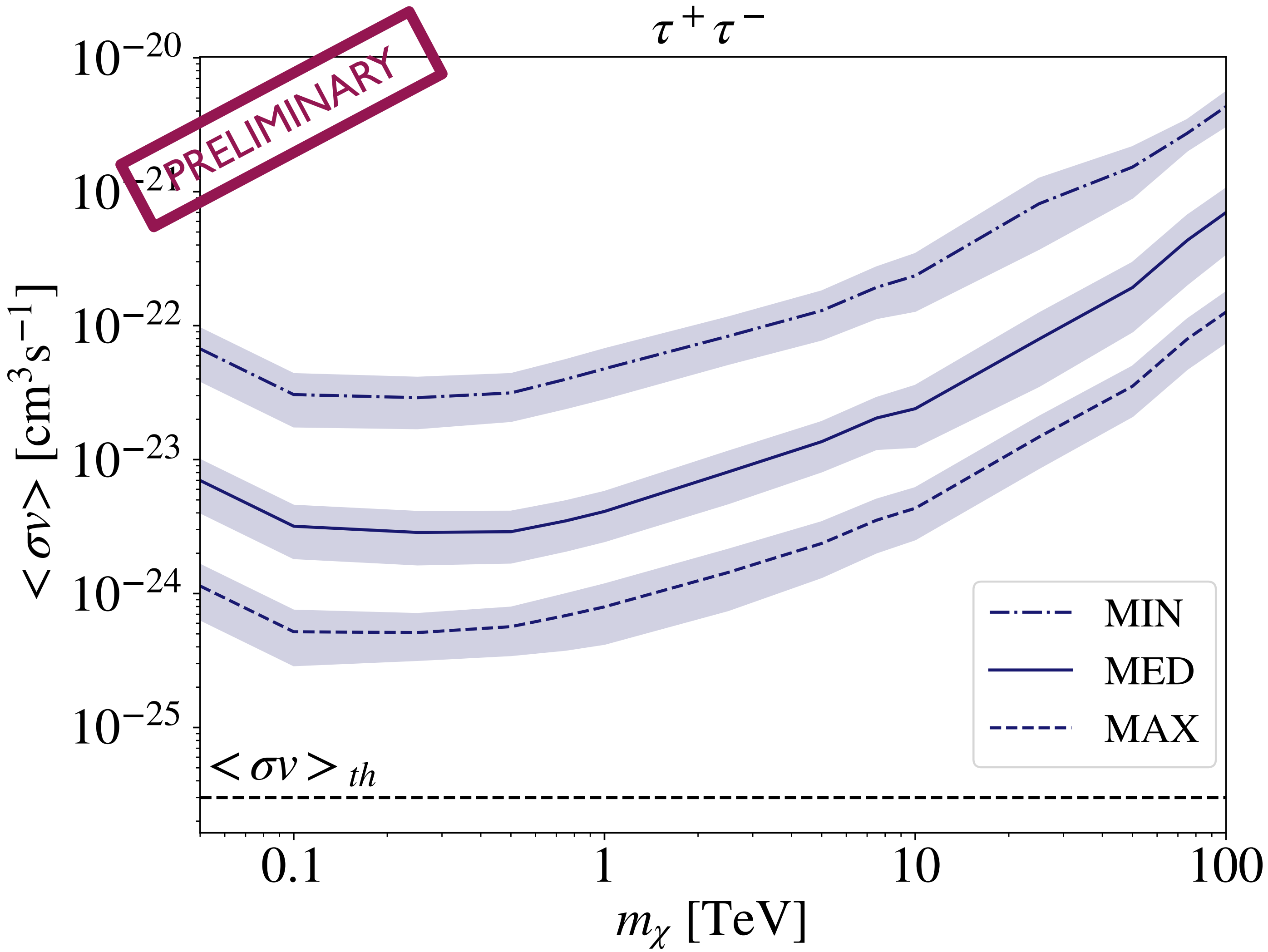
DM CONSTRAINTS: ON/OFF SET-UPS

Limits for Perseus for $\tau^+\tau^-$ annihilation and decay models
(DM template & no J/D-factor uncertainties)



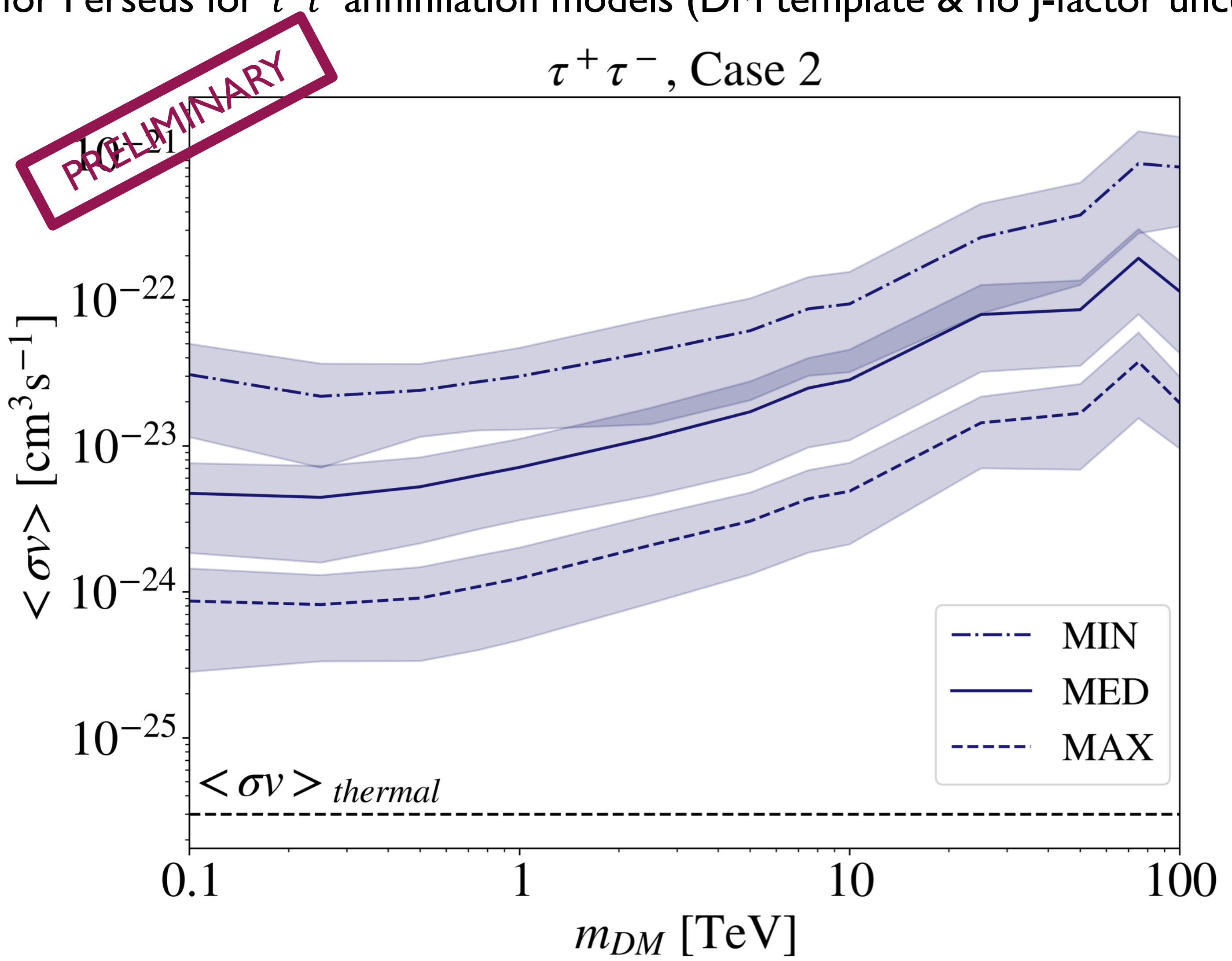
DM CONSTRAINTS: MIN-MED-MAX

Limits for Perseus for $\tau^+\tau^-$ annihilation model (point-like morphology & no J-factor uncertainties)



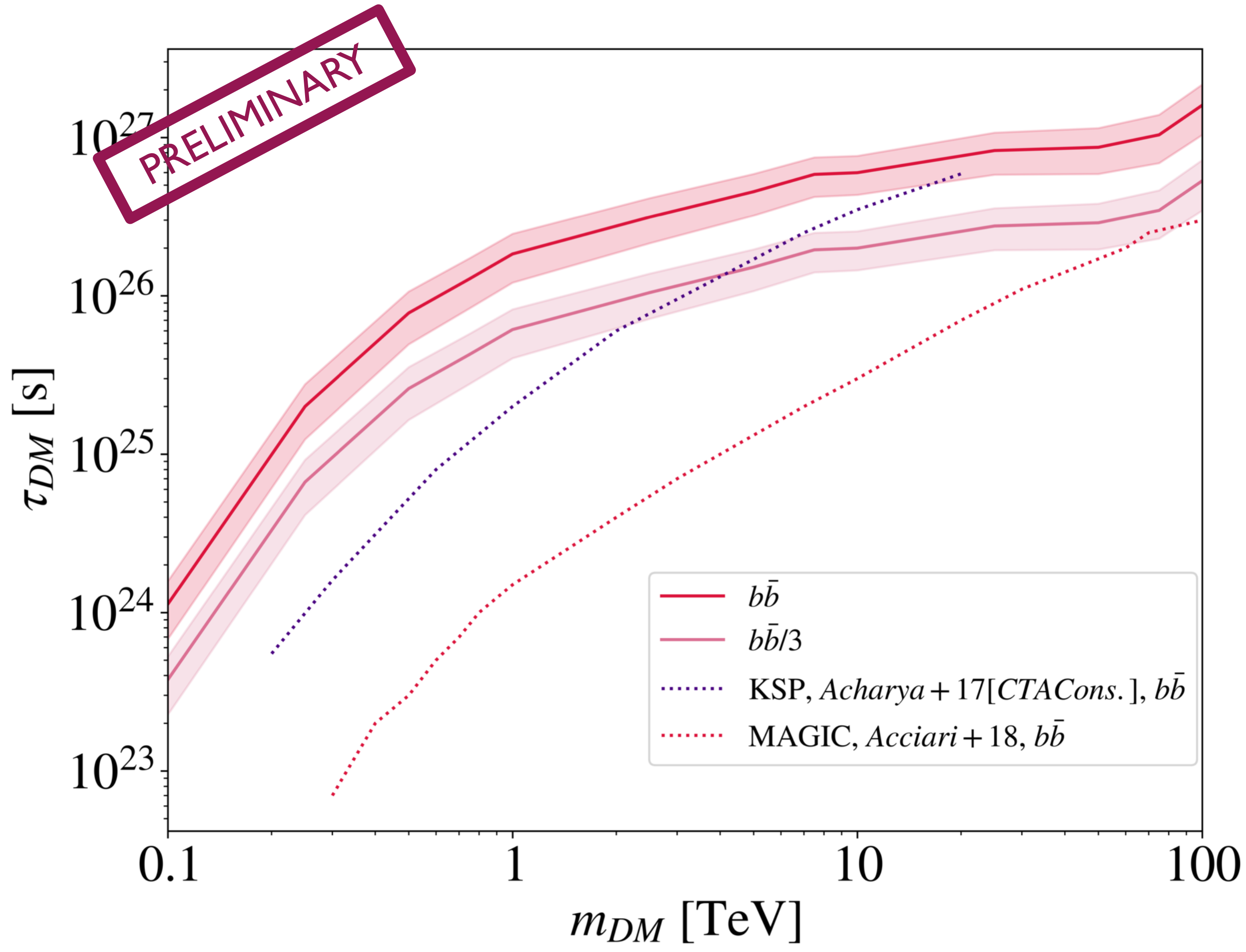
DM CONSTRAINTS: MIN-MED-MAX

Limits for Perseus for $\tau^+\tau^-$ annihilation models (DM template & no J-factor uncertainties)



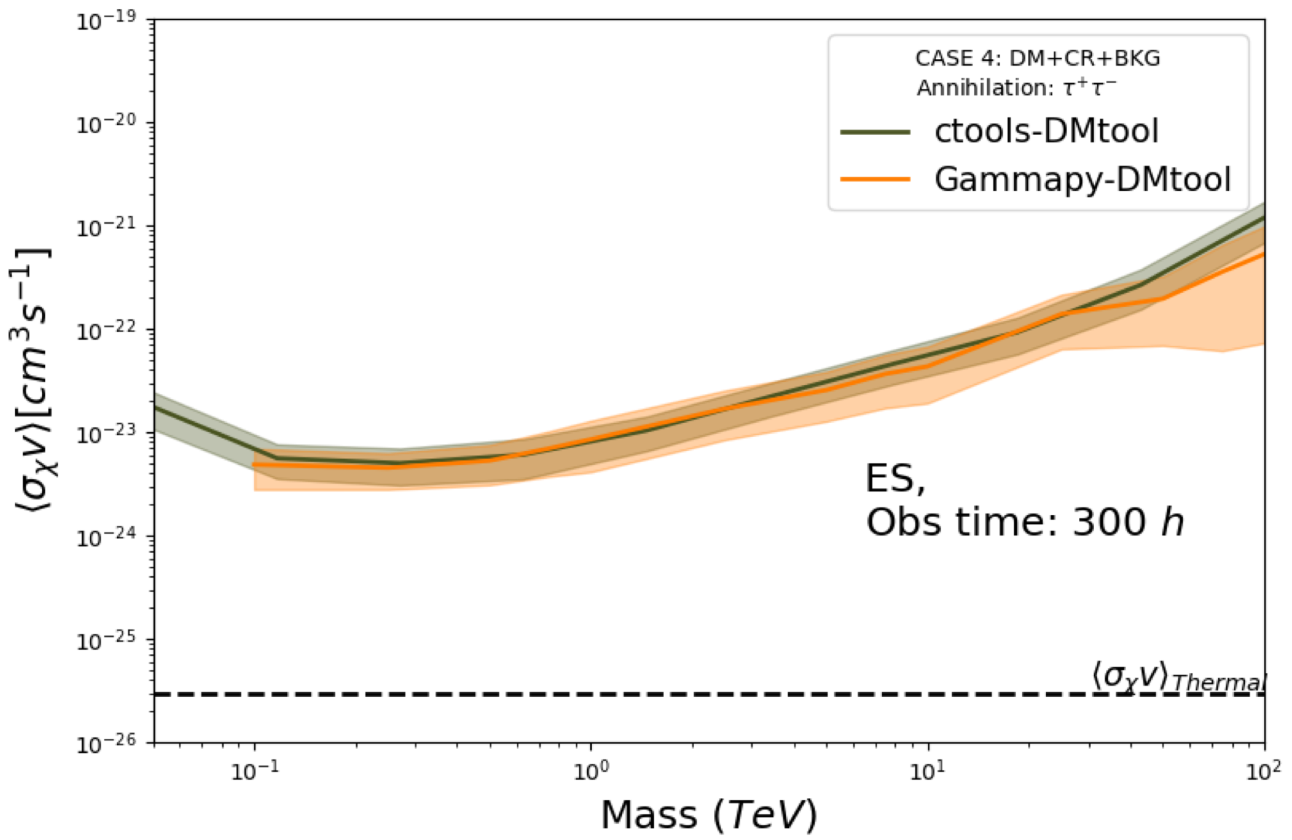
DM CONSTRAINTS: DECAY INSIGHT

Limits for Perseus for decay ON/OFF analysis (point-like morphology & no D-factor uncertainties)



EXCLUSION LIMITS IN PERSEUS: CORRELATION MATRIX

1. Both limits are consistent within uncertainties.
2. Difference at high masses due to the relatively small number of repetitions in gammapy.
3. More work in progress



BEYOND KSP: SAMPLE OF GALAXY CLUSTERS

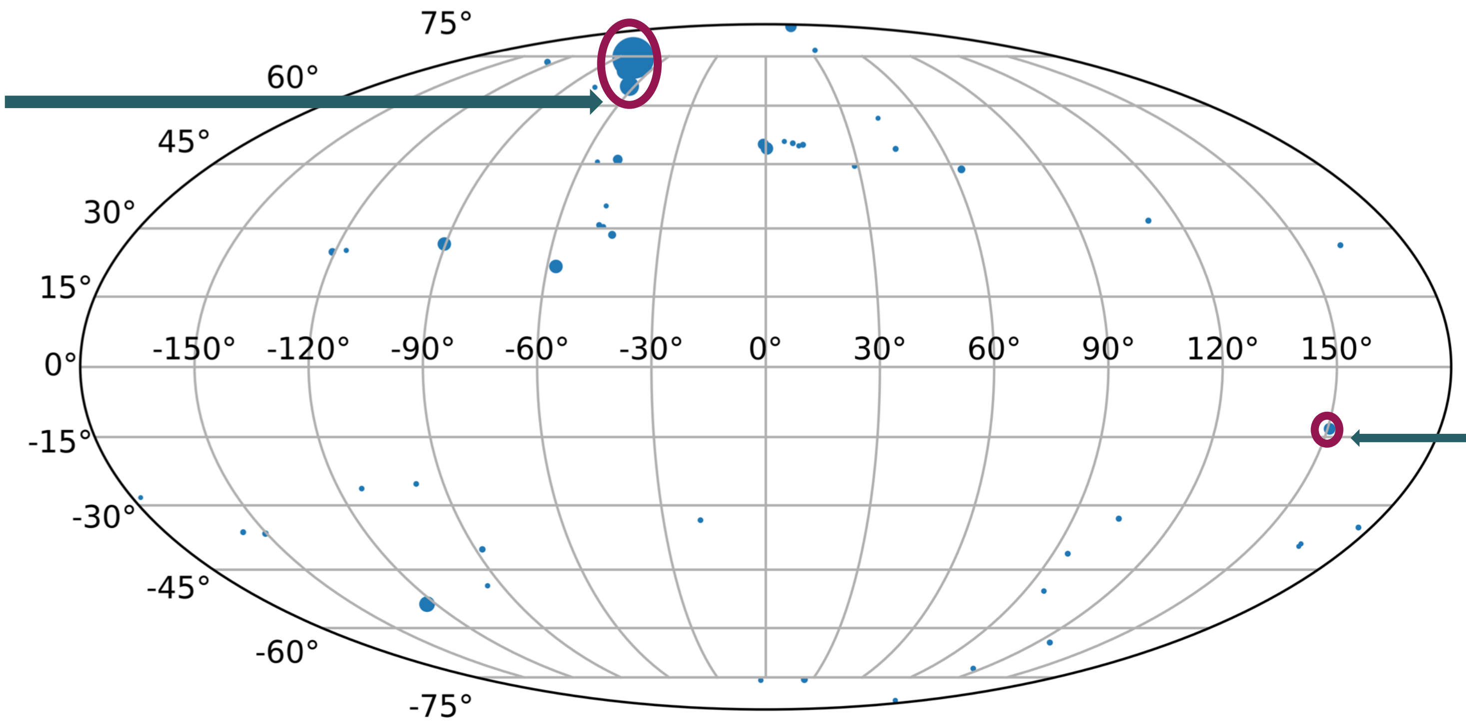
- Search in catalogues for other interesting galaxy clusters to study in a DM context
- Natural extension of the KSP: why just focus on Perseus for DM searches?
- Built up of "gold" cluster sample for DM studies
- Will follow similar procedure than KSP, just applied to few other galaxy clusters and DM focused:

- Well-known M_{200} : from observations in X-rays using *Schellenberger&Reiprich17*
- State-of-the-art parametrization of $\rho_{\rm DM}$ CLUMPY
- Local clusters: z < 0.1 *(Ando&Nagai12)* → $J \propto \frac{1}{d^2}$

BEYOND KSP: TARGET SELECTION

Identification of best targets

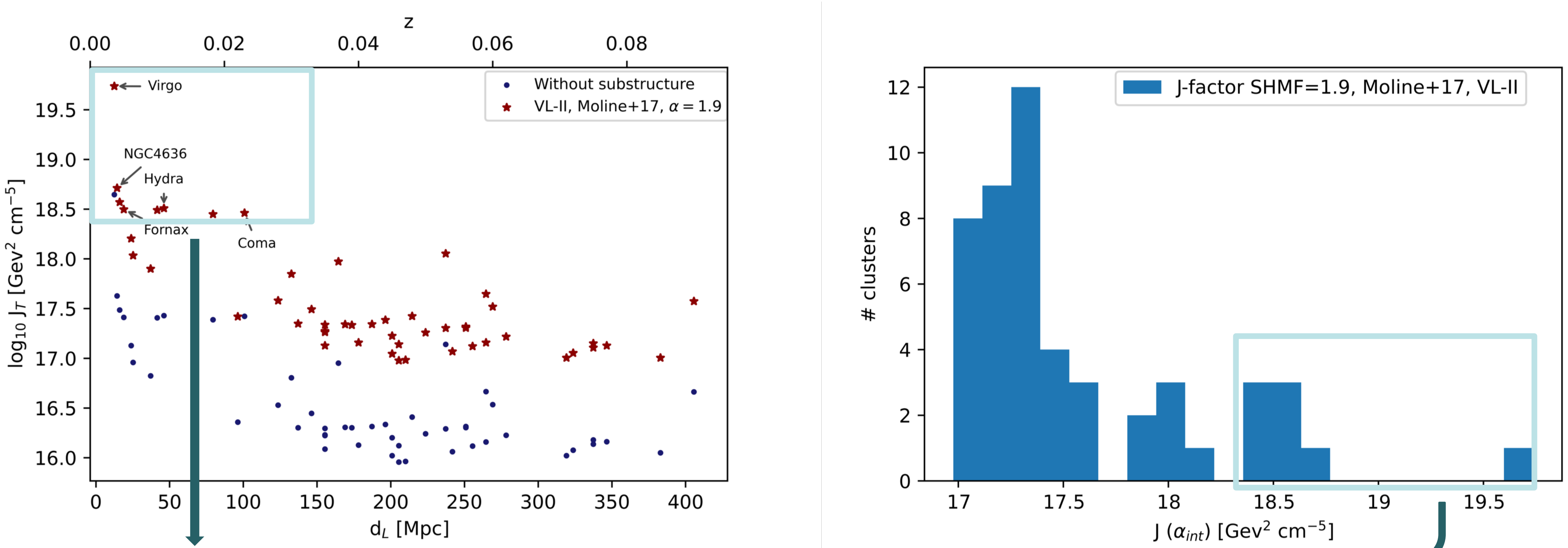
Separation of at least 2deg to account for cluster extension, except for M49 + Virgo



Mask |*b*| < 20deg, except Perseus, to avoid GDE

- Sample based on extended HIFLUGCS catalogue *(Reiprich&Borhinger02), Ackermann+10 [Fermi-LAT Coll.] and Ackermann+14 [Fermi-LAT Coll.]*.
- 50 local clusters, $f_x \geq 1.7 \cdot 10^{-11}$ erg s^{-1} cm^{-2}

BEYOND KSP: DM MODELLING

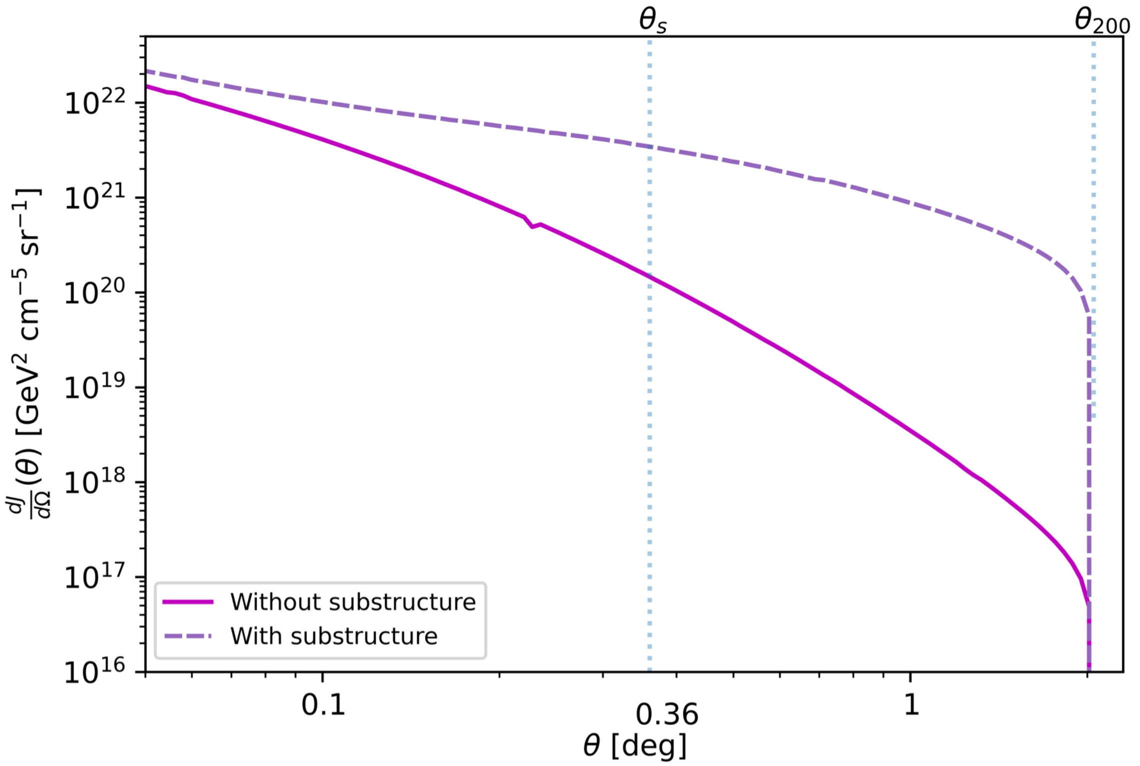


Object	z	M_{200} [10^{14} $M_\odot$]	R_{200} [kpc]	θ_{200} [deg]	$J_{no-subs}$ [10^{17}GeV^{2}cm^{-5}]	J_{subs} [10^{18}GeV^{2}cm^{-5}]
Virgo	0.0036	5.600	1700	6.32	44.3	54.5
NGC3646	0.0040	0.534	777	2.60	4.24	5.15
M49	0.0044	0.464	741	2.26	3.06	3.72
A1060/Hydra	0.0110	2.966	1376	1.70	2.69	3.23
NGC1399/Fornax	0.0050	0.506	763	2.05	2.58	3.14
A3526/Centaurus	0.0100	2.266	1258	1.70	2.55	3.10
A1656/Coma	0.0230	13.158	2260	1.35	2.64	2.90
A0426/Perseus	0.0183	7.714	1892	1.41	2.44	2.81

- Two models:
  - Conservative: No substructure
  - Baseline: Conservative inclusion of substructure
- Substructure boosts O(10) for typical cluster masses (*Sánchez-Conde+11, Sánchez-Conde+14, Moliné+17*)

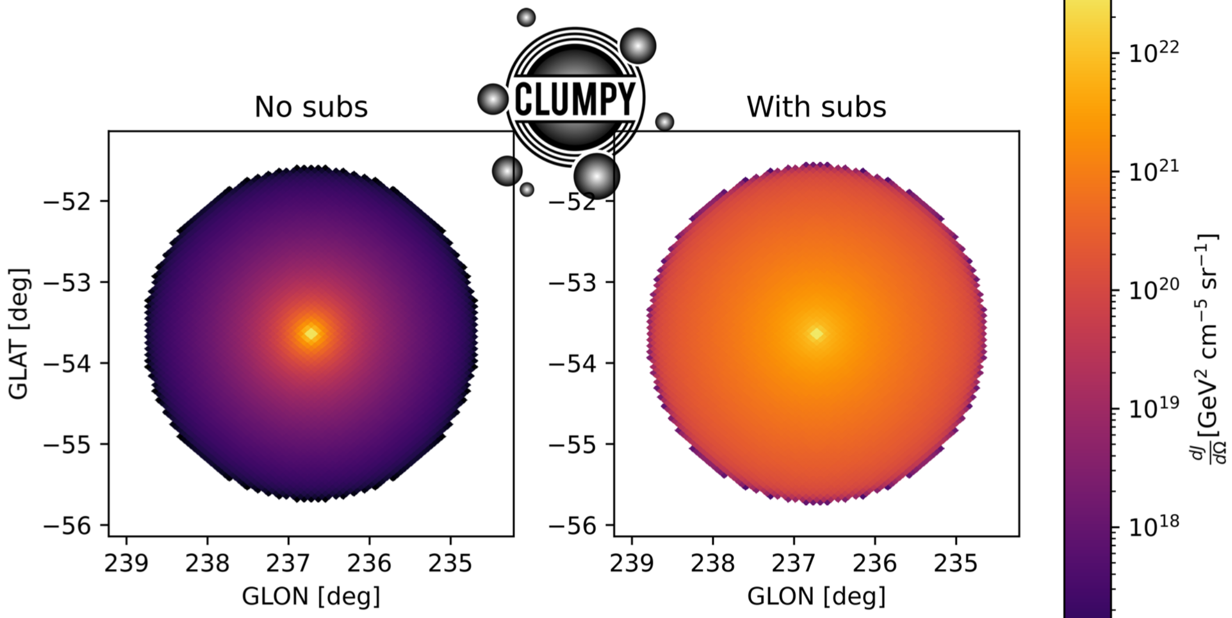
DARK MATTER MODELLING: FORNAX

Object	M_{200} [10^{14} $M_\odot$]	c_{200}	R_{200} [kpc]	θ_{200} [deg]	r_s [kpc]	θ_s [deg]
Fornax/NGC1399	0.506	5.79	763	2.05	132	0.36



Integration angle	$J_{no-subs}$ [10^{17}GeV^{2}cm^{-5}]	J_{subs} [10^{17}GeV^{2}cm^{-5}]
θ_{200}	2.58	31.40

Skymaps of the differential J-factor for Fornax



Conservative

Baseline

- Effects of substructure:
  - Annihilation Boost = 11.2
  - Important in outskirts
- Adopt baseline DM model (substructure scenario) α=1.9 for the slope of the sub-halo mass function