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

cherenkov telescope array

Séminaries LLR (CNRS & École Polytechnique)
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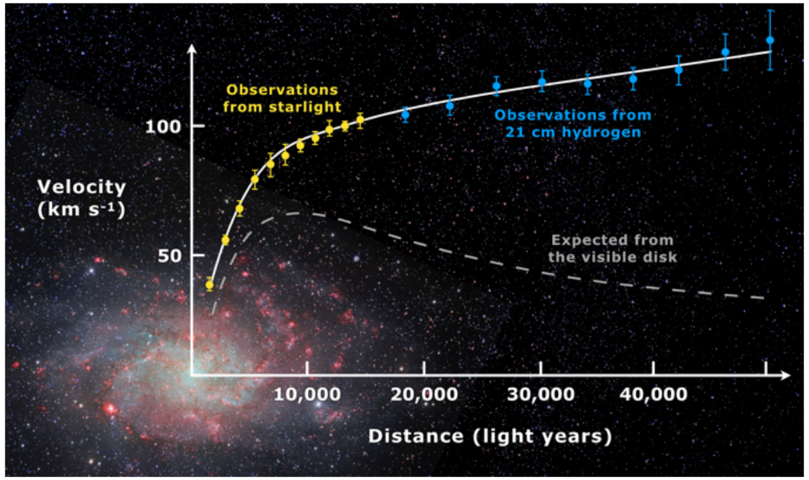
GOBIERNO DE ESPAÑA

MINISTERIO DE CIENCIA, INNOVACIÓN Y UNIVERSIDADES

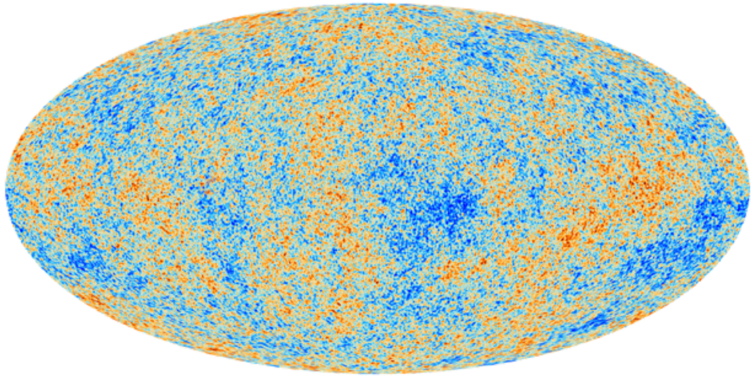
AGENCIA ESTATAL DE INVESTIGACIÓN

DARK MATTER EVIDENCE

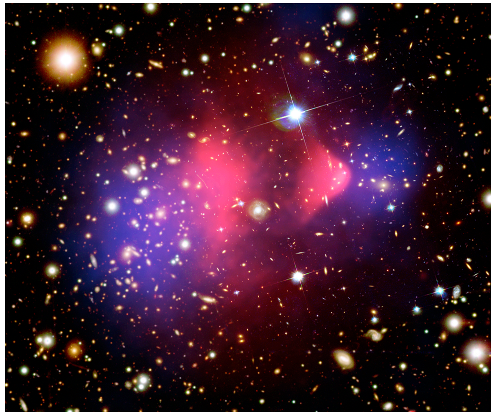
- Galactic rotational curves



- CMB anisotropies

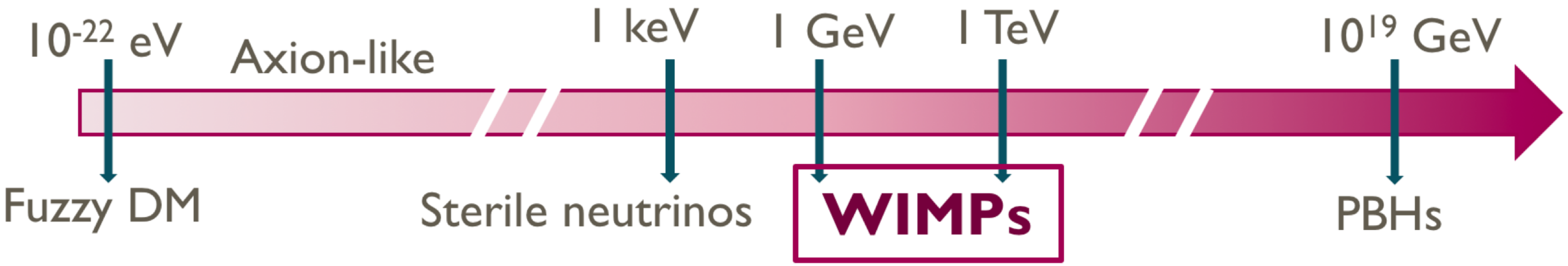


- Galaxy Clusters

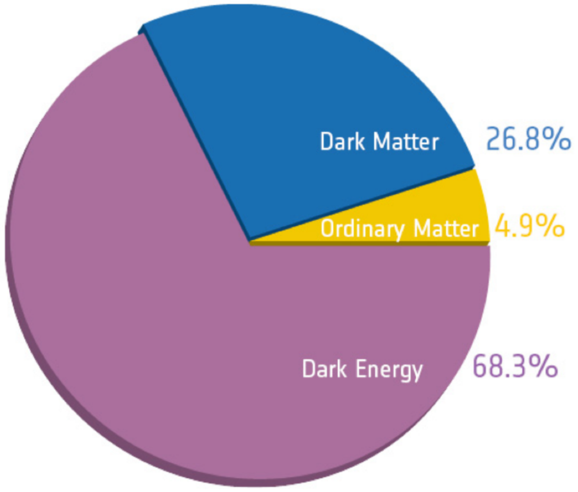


+ strong, weak lensing…

- Different DM candidates, wide range of masses:



DARK MATTER IN ΛCDM COSMOLOGY



Observational Dark Matter evidences

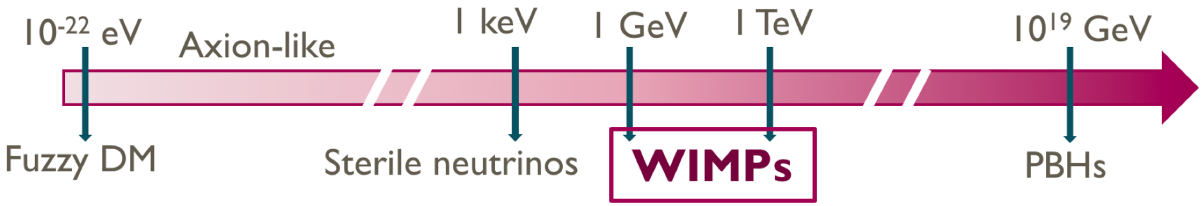
Component of

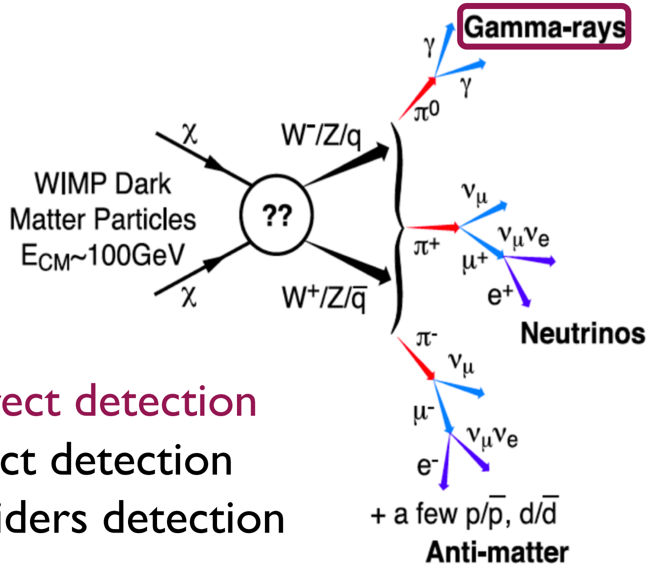
ΛCDM Cosmology

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

→ DM distribution in Halos and Subhalos

- Different DM candidates:



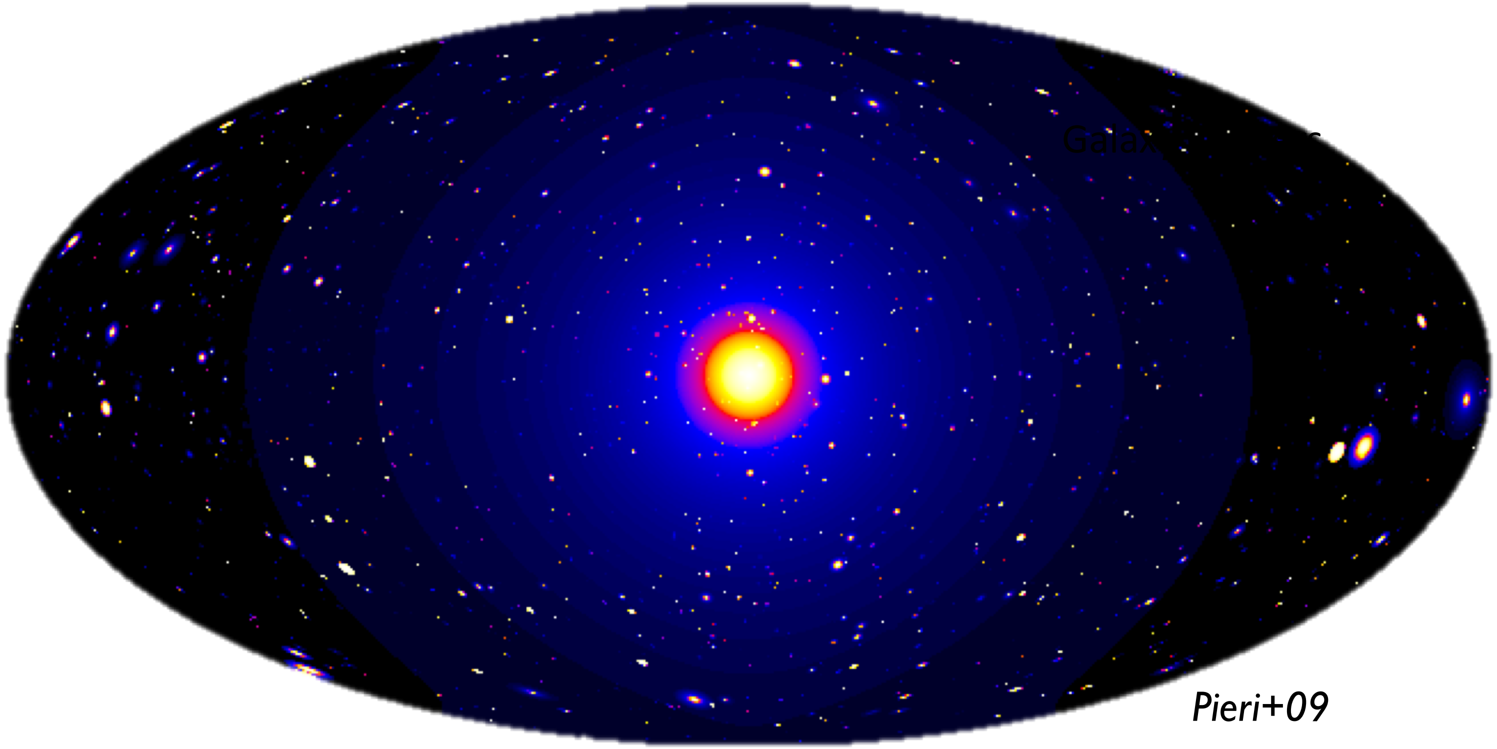


This γ-ray emission allows to perform Indirect DM Searches with current telescopes

- 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



Pieri+09

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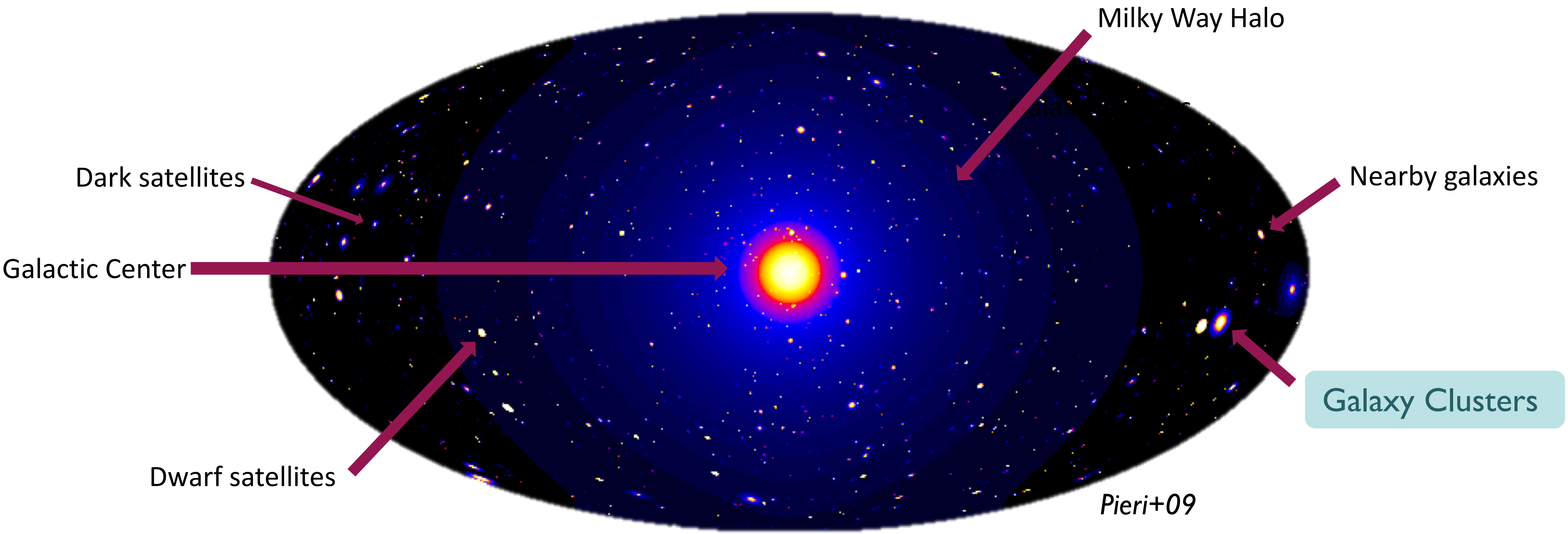


GAMMA-RAY EMISSION IN GALAXY CLUSTERS

- 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%)

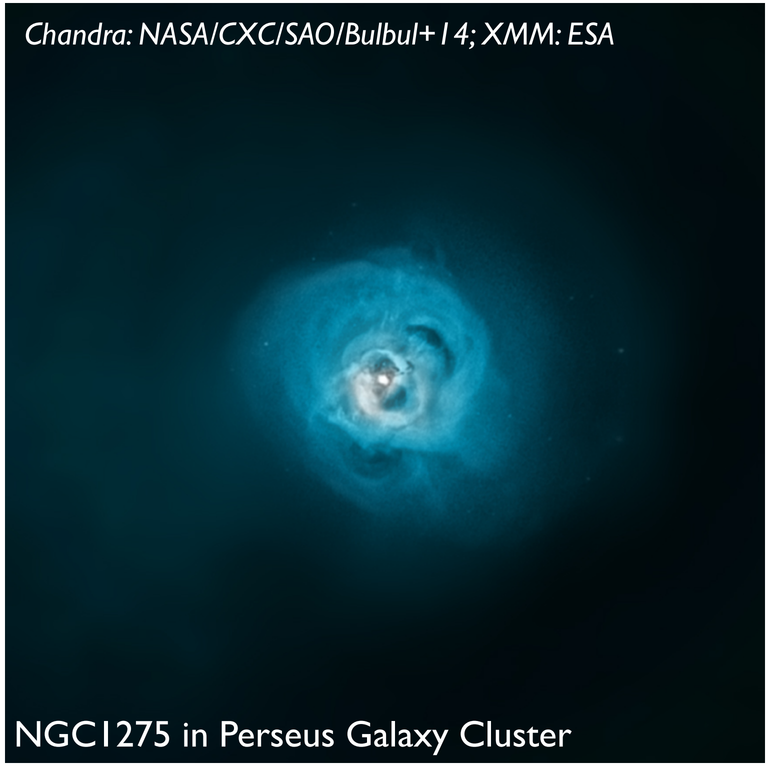
- Even supposedly virialized objects, a lot of activity → Merger events
  - Feedback from galaxies and AGNs
  - Magnetic fields
  - Turbulence

  } Acceleration mechanisms ↓

Cosmic-rays

Leptons → Diffuse synchrotron emission ✓

Hadrons → Gamma-rays



NGC1275 in Perseus Galaxy Cluster

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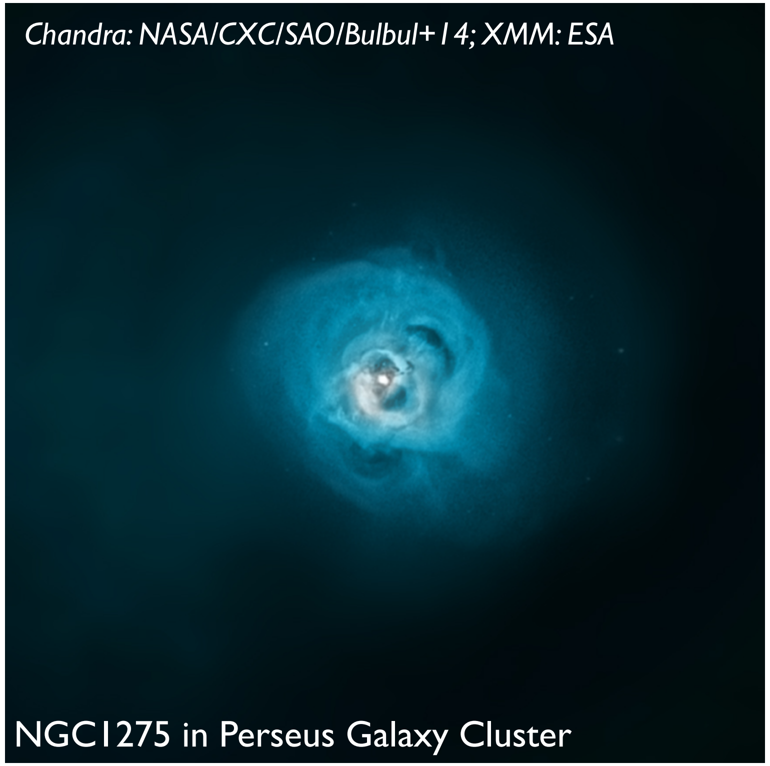
  } Acceleration mechanisms → Cosmic-rays

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



GAMMA-RAY DM SEARCHES IN CLUSTERS?

- Optimal conditions for indirect Dark Matter (DM) searches:
  - High DM density
  - Massive nearby objects
  - Low astrophysical background (Cosmic Rays - CR)

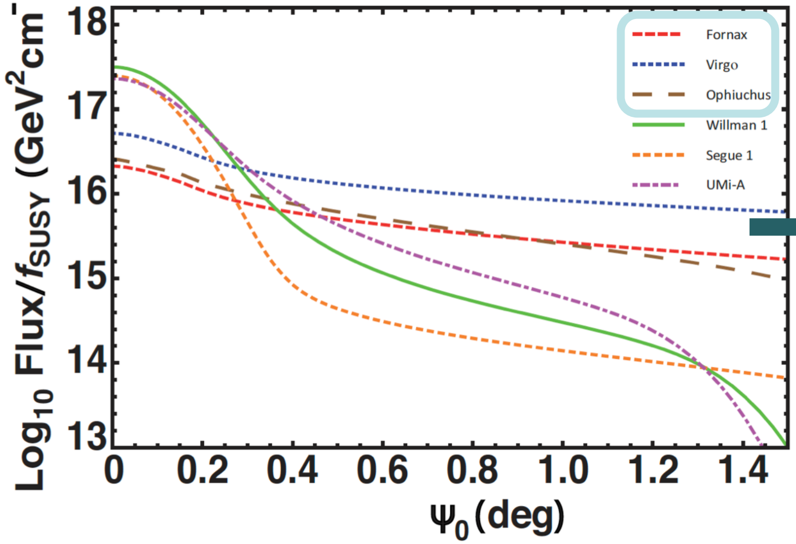
Decay

- Most massive known objects
- Located in the local Univers
- 80% of its mass is DM

Best possible targets to consider

Annihilation

Sánchez-Conde+11



Competitive compared to other prime targets (e.g. dSphs) considering:

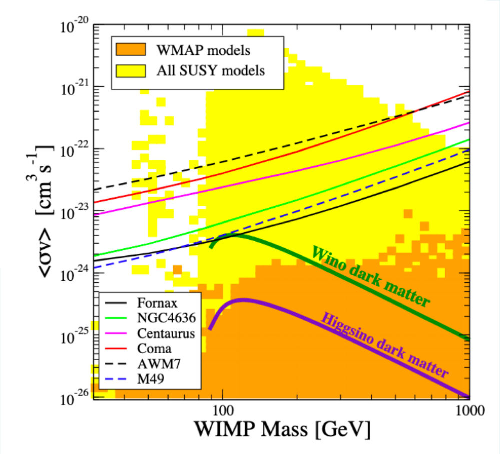
- Smooth DM halo component

+

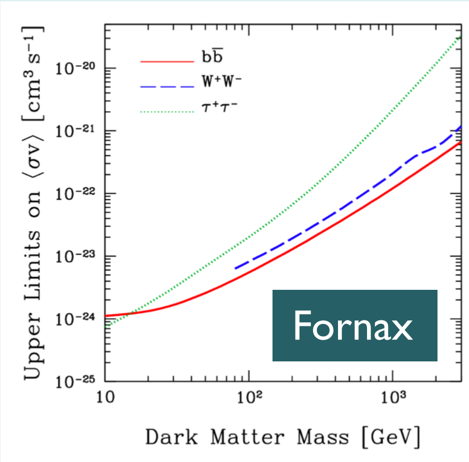
- Halo substructure

PREVIOUS GAMMA-RAY DM SEARCHES IN GALAXY CLUSTERS

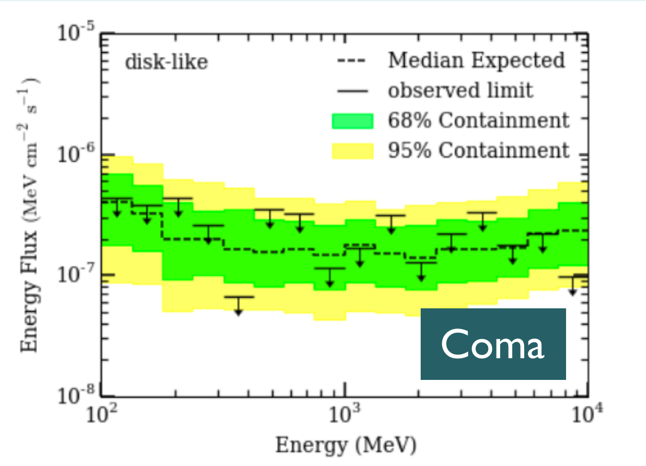
Fermi-*LAT* - Annihilation



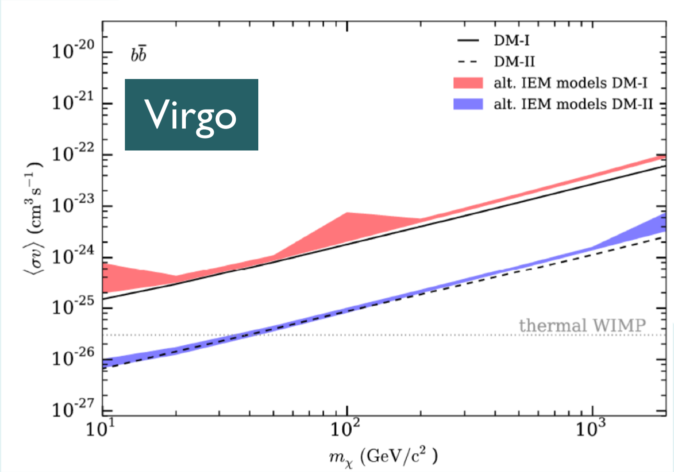
Ackermann+10 [Fermi-LAT Collab.]



Ando&Nagai12



Ackermann+16 [Fermi-LAT Collab.]

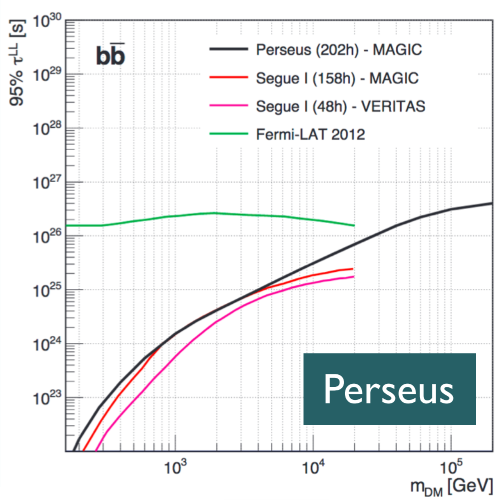


Ackermann+15 [Fermi-LAT Collab.]

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

MAGIC - Decay

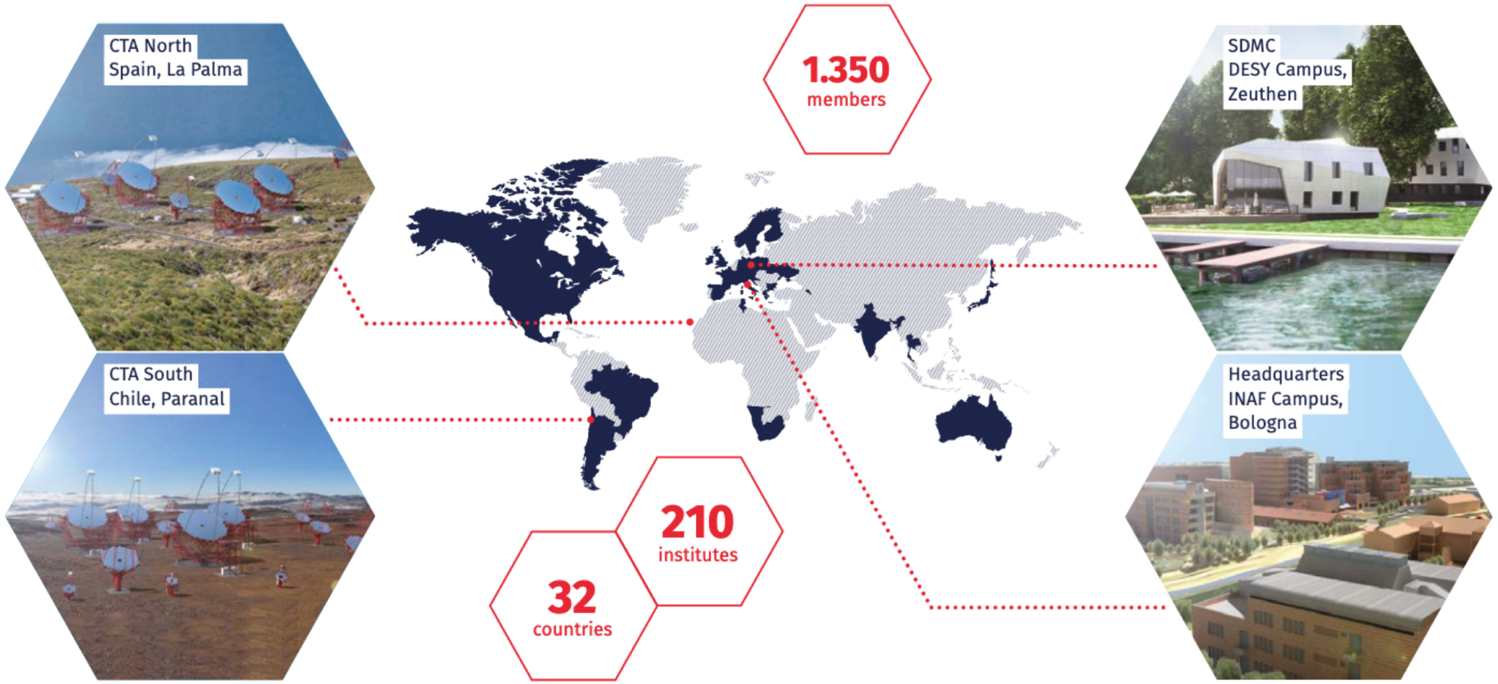
Best constraints so far!



Acciari+18 [MAGIC Collab.]

THE CHERENKOV TELESCOPE ARRAY (CTA)

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



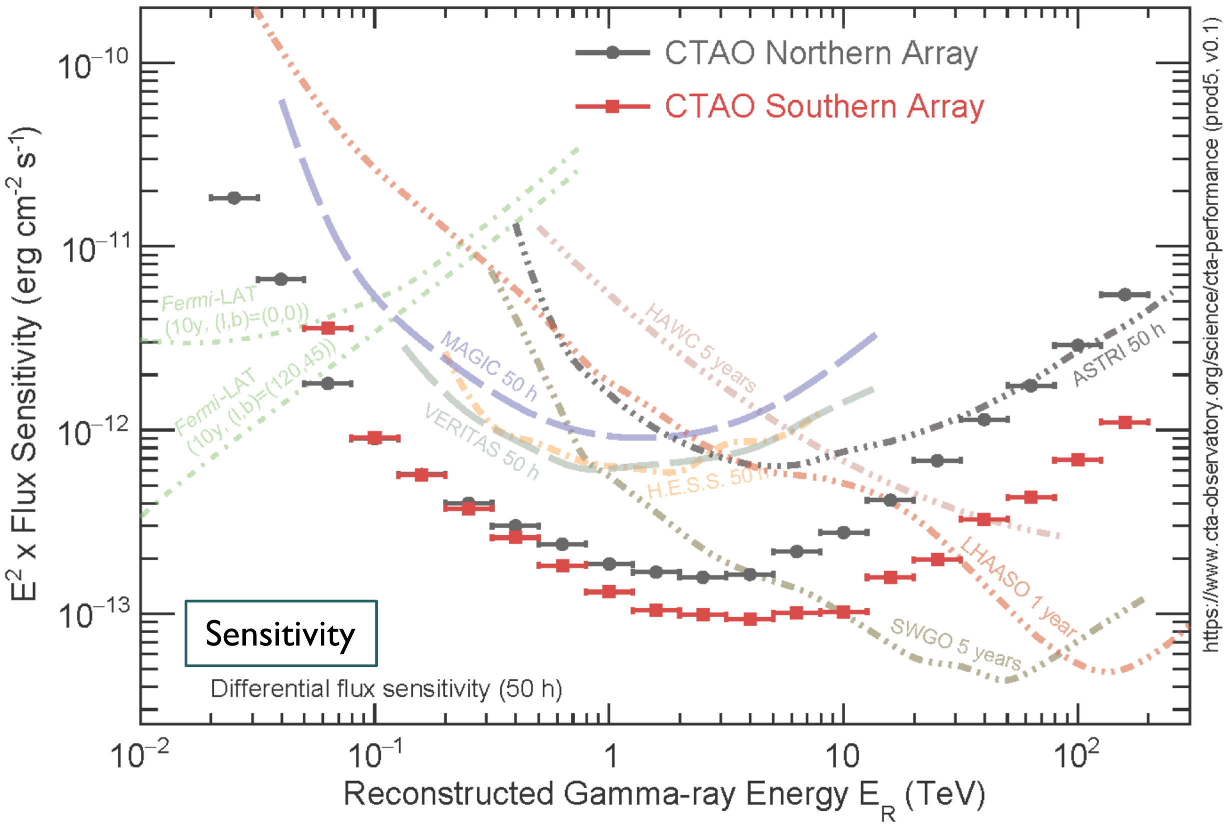
SST	MST	LST
1-300 TeV	100 GeV–10 TeV	20-200 GeV

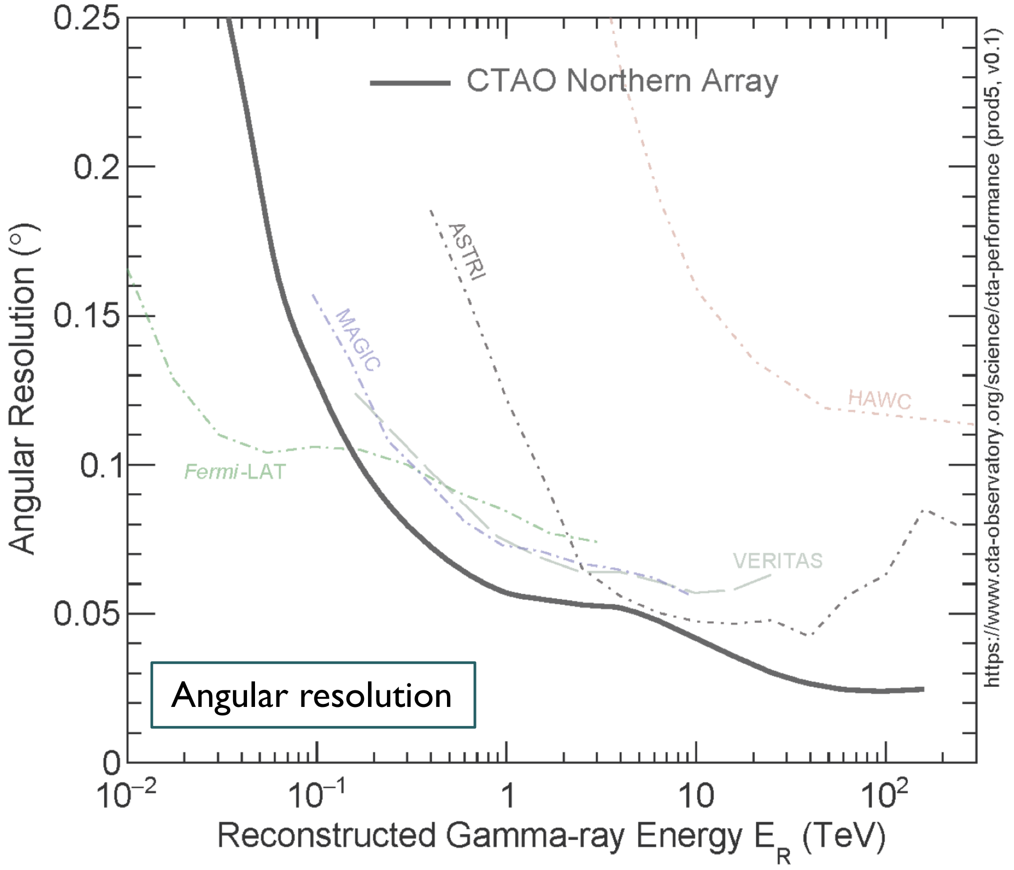
https://www.cta-observatory.org/

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

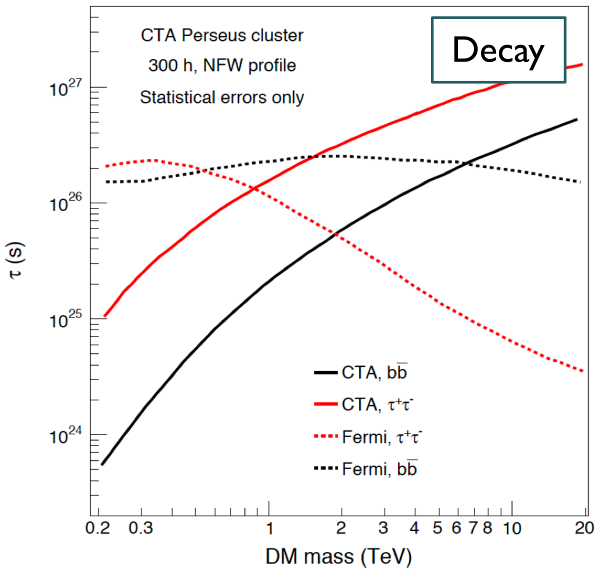
Object	l [deg]	b [deg]	d_L [Mpc]
Perseus	150.57	-13.26	75.01

- Host two AGNs, the BCG NGC1275 and IC310, both variable

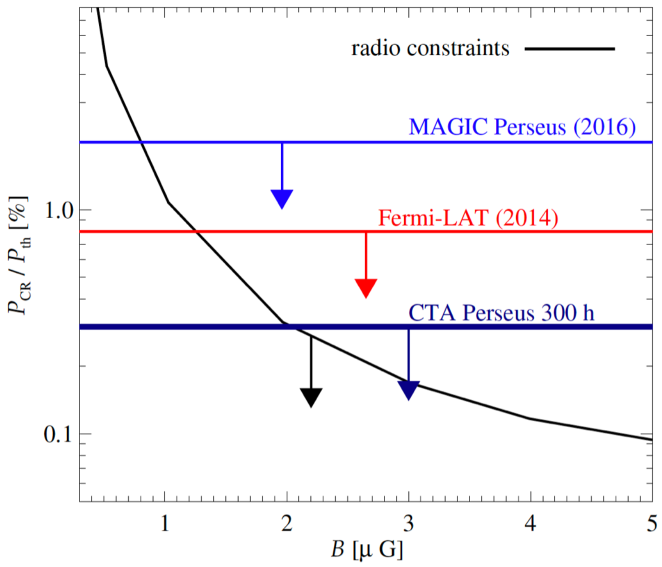
Object	l [deg]	b [deg]
NGC1275	150.58	-13.26
IC310	150.18	-13.74

BCG aligned with X-rays center

Optimal conditions for observation from the northern array



Acharya+17 [CTA Cons.]



Our goal: State-of-the-art study of the sensitivity of CTA to Dark Matter and Cosmic-Ray signals in Perseus cluster

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

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Object
Perseus

- Host tw
and IC31

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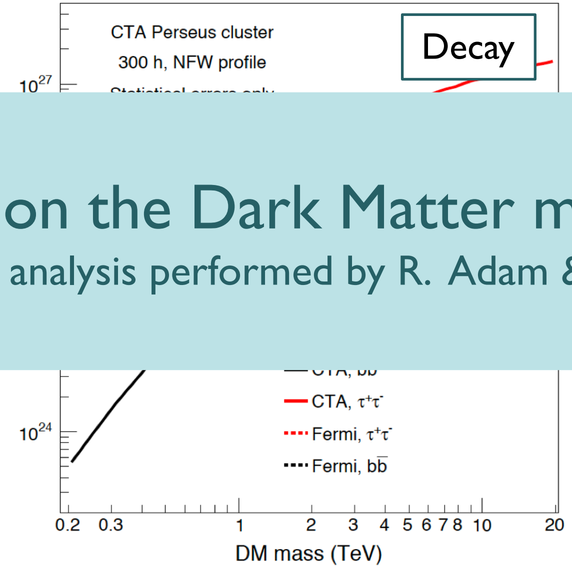
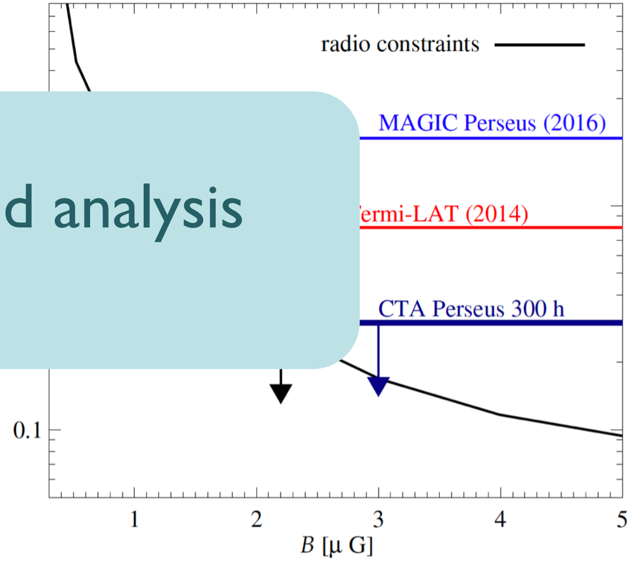




Our goal today: Focus on the Dark Matter modelling and analysis
(CR modelling and analysis performed by R. Adam & collaborators)

Our goal: State-of-the-art study of the sensitivity of CTA to Dark Matter and Cosmic-Ray signals in Perseus cluster

Use lastest version of CTA science tools with 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

Particle Physics Model

Cirelli+12 (EW corrections)

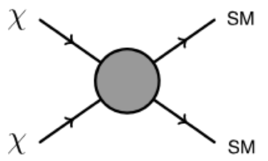
CLUMPY

Charbonnier+12, Bonnivard+15, Hütten+18

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

Annihilation

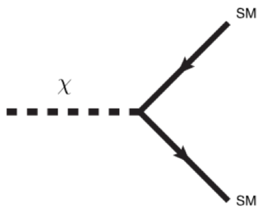
$$J(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega} \int_{l.o.s} \rho^2_{DM}(r)dr \rightarrow J \propto \frac{M_{200} c^3_{200}}{D^2_{\text{Earth}}}$$



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

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

DM density profile

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

Decay

MIN → Main halo without substructure

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

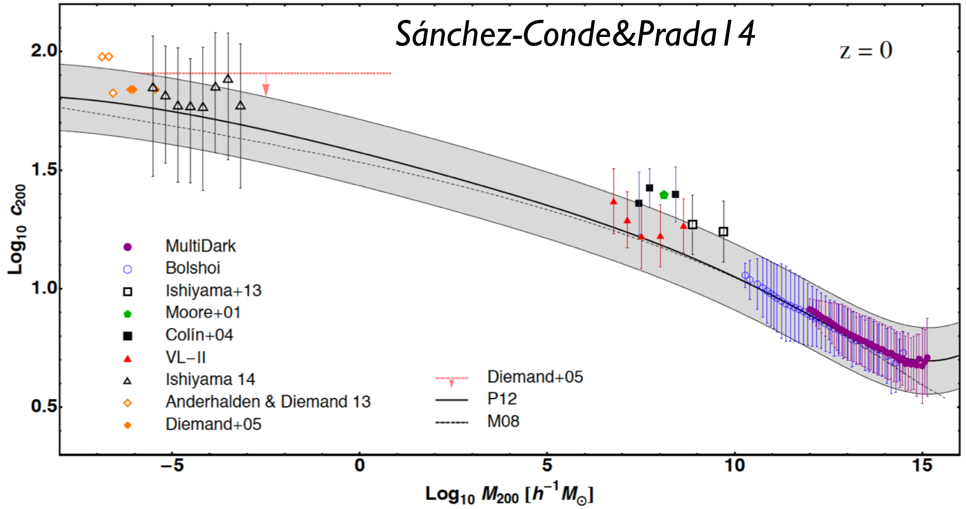
$$\langle\rho_{\rm tot}\rangle(r) = \rho_{\rm sm}(r) + \langle\rho_{\rm subs}\rangle(r)$$

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 $\rho_{\rm DM}$ using state-of-the-art subhalo models

$$\langle\rho_{\rm tot}\rangle(r) = \rho_{\rm sm}(r) + \langle\rho_{\rm subs}\rangle(r) \longrightarrow \frac{d^3N}{dV dM dc} = N_{\rm tot}\frac{d\mathcal{P}_V}{dV}(r)\cdot\frac{d\mathcal{P}_M}{dM}(M)\cdot\frac{d\mathcal{P}_c}{dc}(M,c)$$

DM subhalo profile: NFW

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

Subhalo Radial Distribution (SRD)

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

Via Lactea - II
Anti-biased relation
Diemand+08

Subhalo Mass Function (SHMF)

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

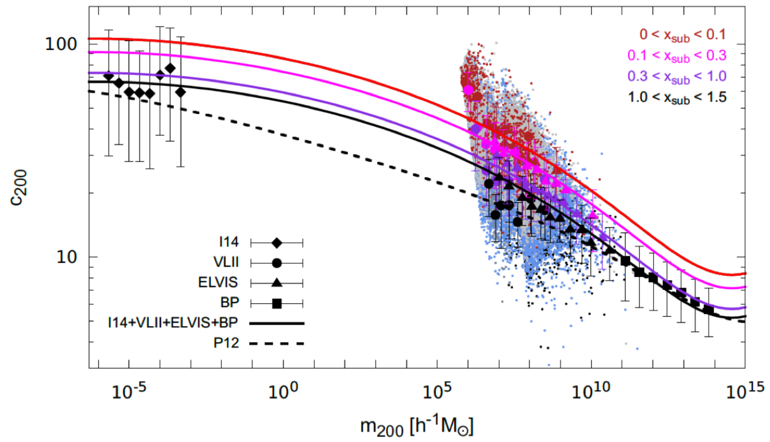
α = 1.9 ⟶ MED

Springel+08

α = 2.0 ⟶ MAX

Diemand+08

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



Dependence on the subhalo position

$$c_{200}(m_{200}, x_{\rm sub})$$
$$x_{\rm sub} \equiv R_{\rm sub}/R_{\Delta}$$

Moliné+17

EXPECTED DM SIGNAL

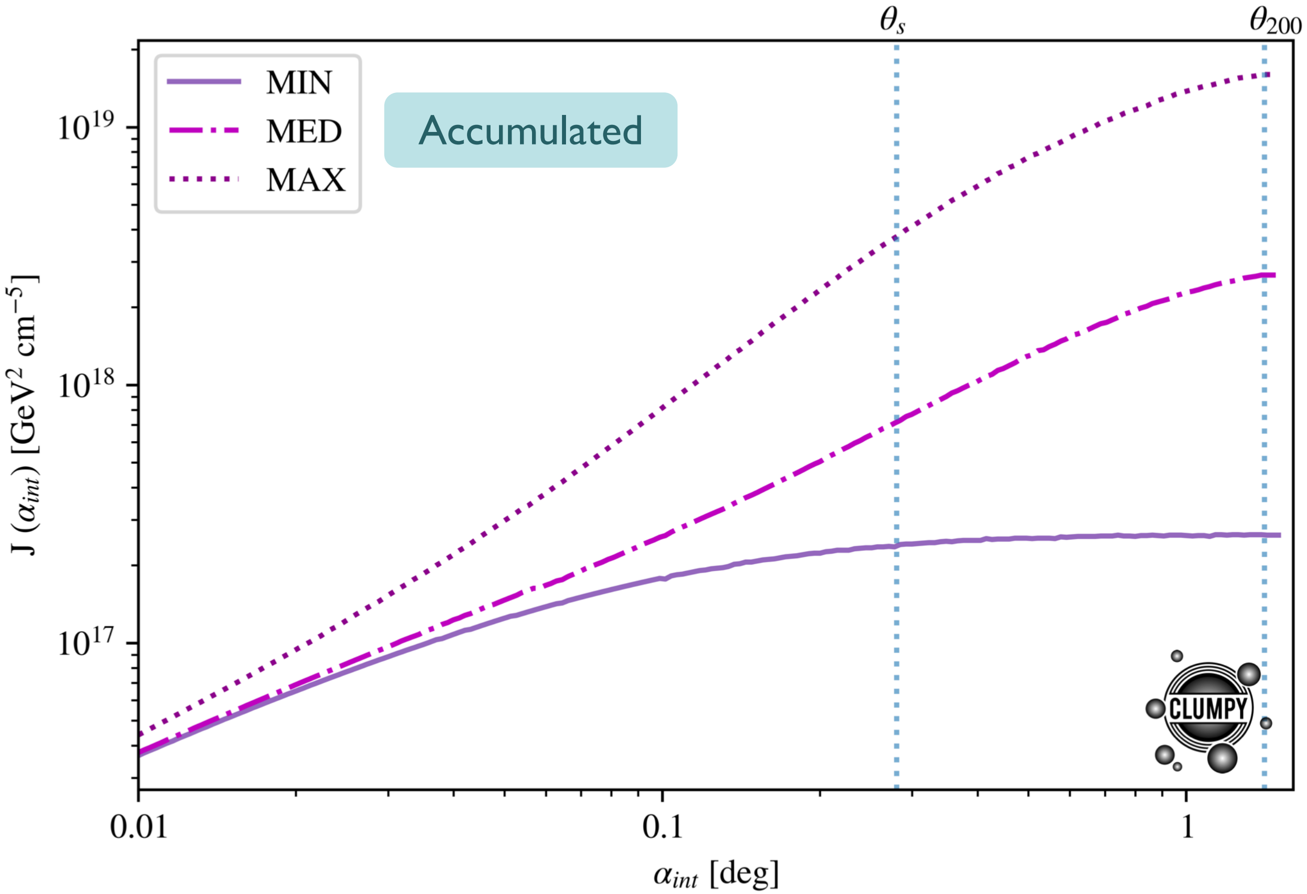
General parameters

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

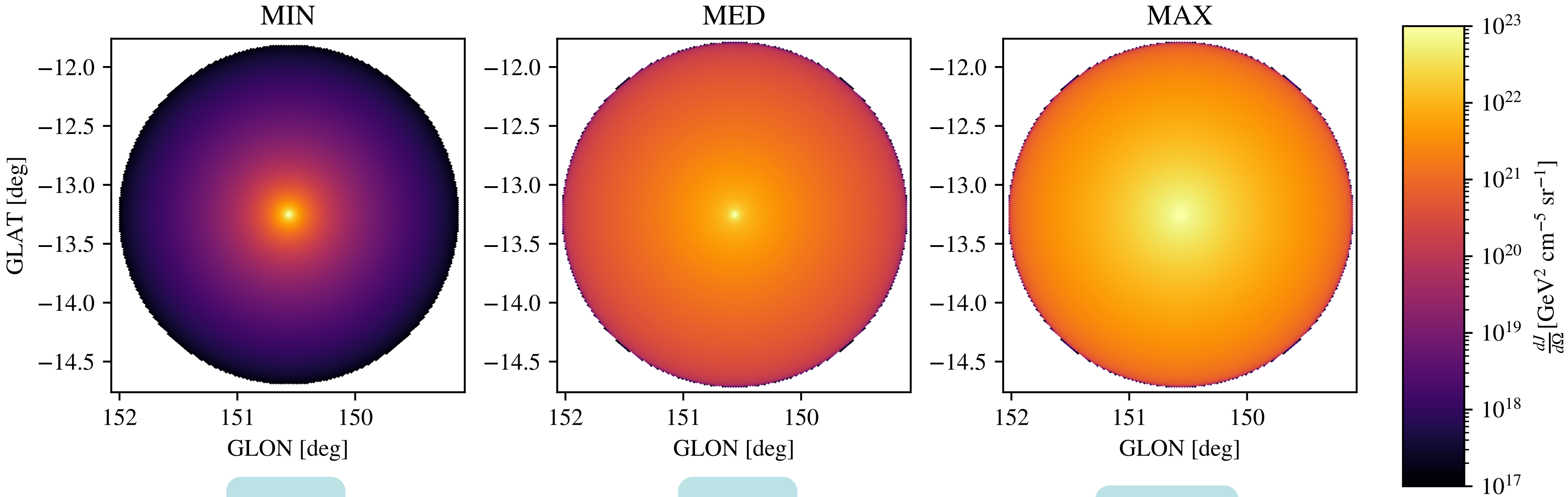
Annihilation flux profile



MORPHOLOGY OF DM SIGNAL

Skymaps of the differential J-factor

Annihilation



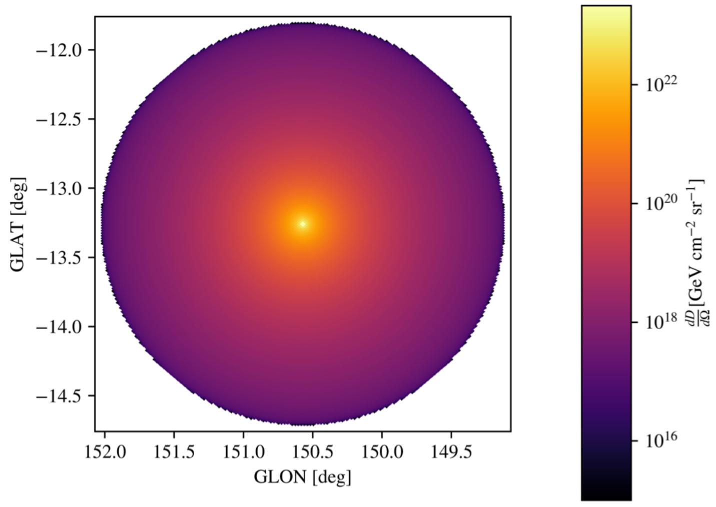
MIN

MED

MAX

Skymap of the differential D-factor

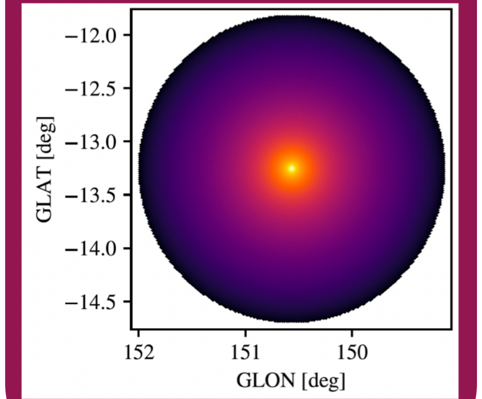
Decay



CTA DM ANALYSIS ROADMAP

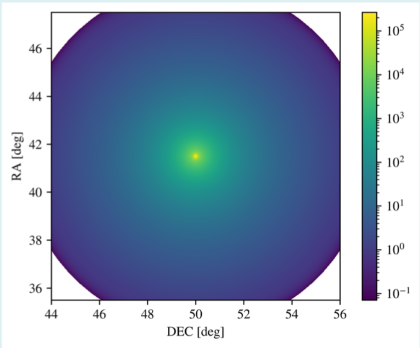
- Different gamma-ray sources in Perseus region:

Total DM-induced γ-rays



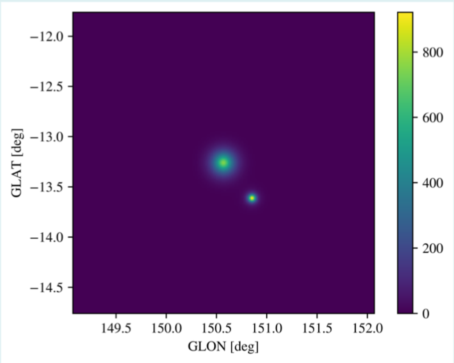
Our signal

Total CR-induced γ-rays



Use as BKG

Total AGNs γ-rays

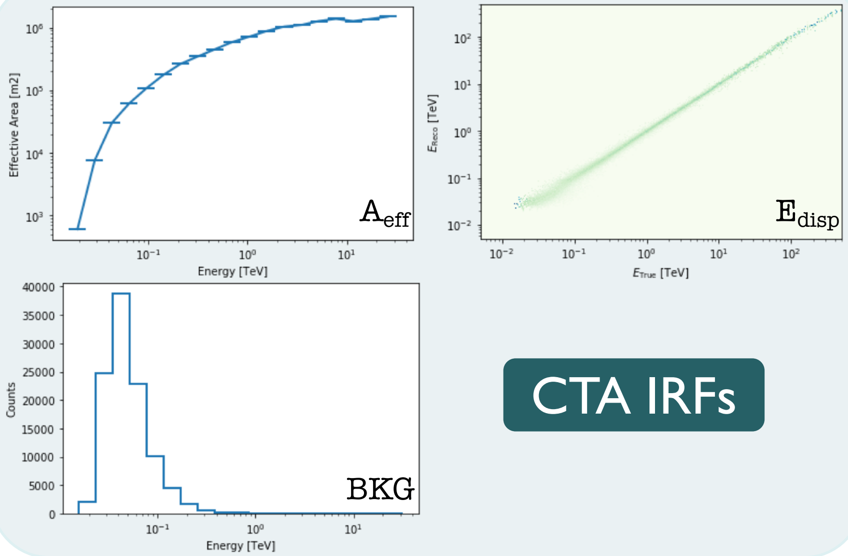


Use as BKG

Using both

$\gamma\pi$

ctools
cherenkov telescope array



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

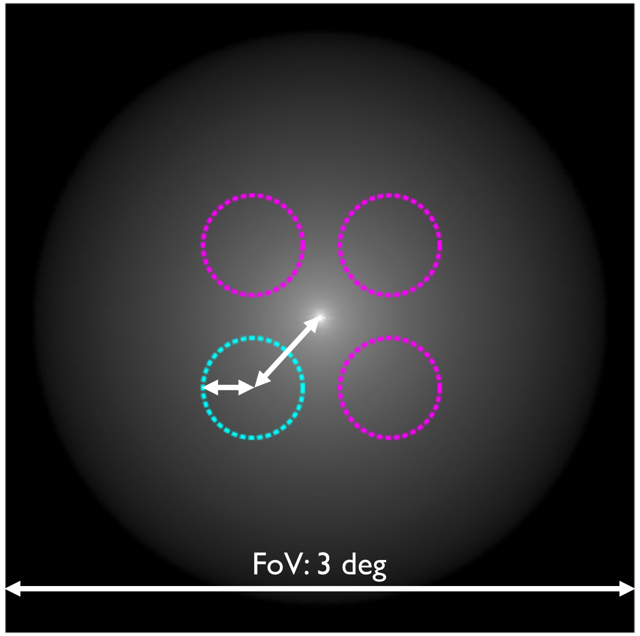
  → Lowest level of complexity, more constraining results

  - Historically used in Imaging Air Cherenkov Telescopes (IACTs) as MAGIC → Direct comparisons

- 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]	0.5

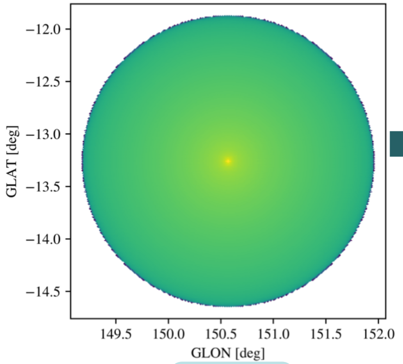
N_{obs}	50
T_{obs} [h]	300
IRFs	`North_z20_50h, prod3b-v2`
Energy range [TeV]	0.03 - 100



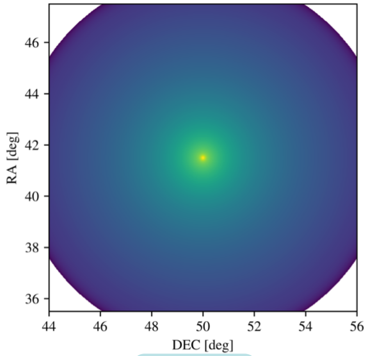
CTA ANALYSIS CONFIGURATION (II): TEMPLATE FITTING

On-going (in collab. with R. Adam)

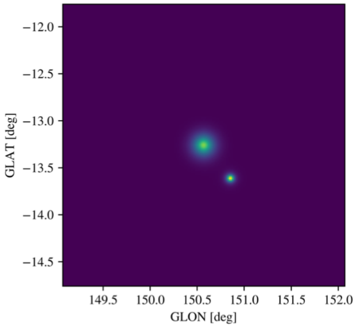
- Final analysis goal:
  - Includes all possible gamma-ray sources: DM + CRs + AGNs + BKG IFRs



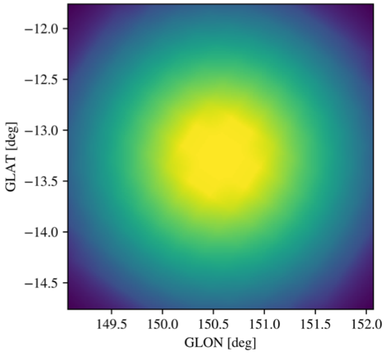
DM



CR



AGNs



BKG

  - Considers the different morphologies of each emission

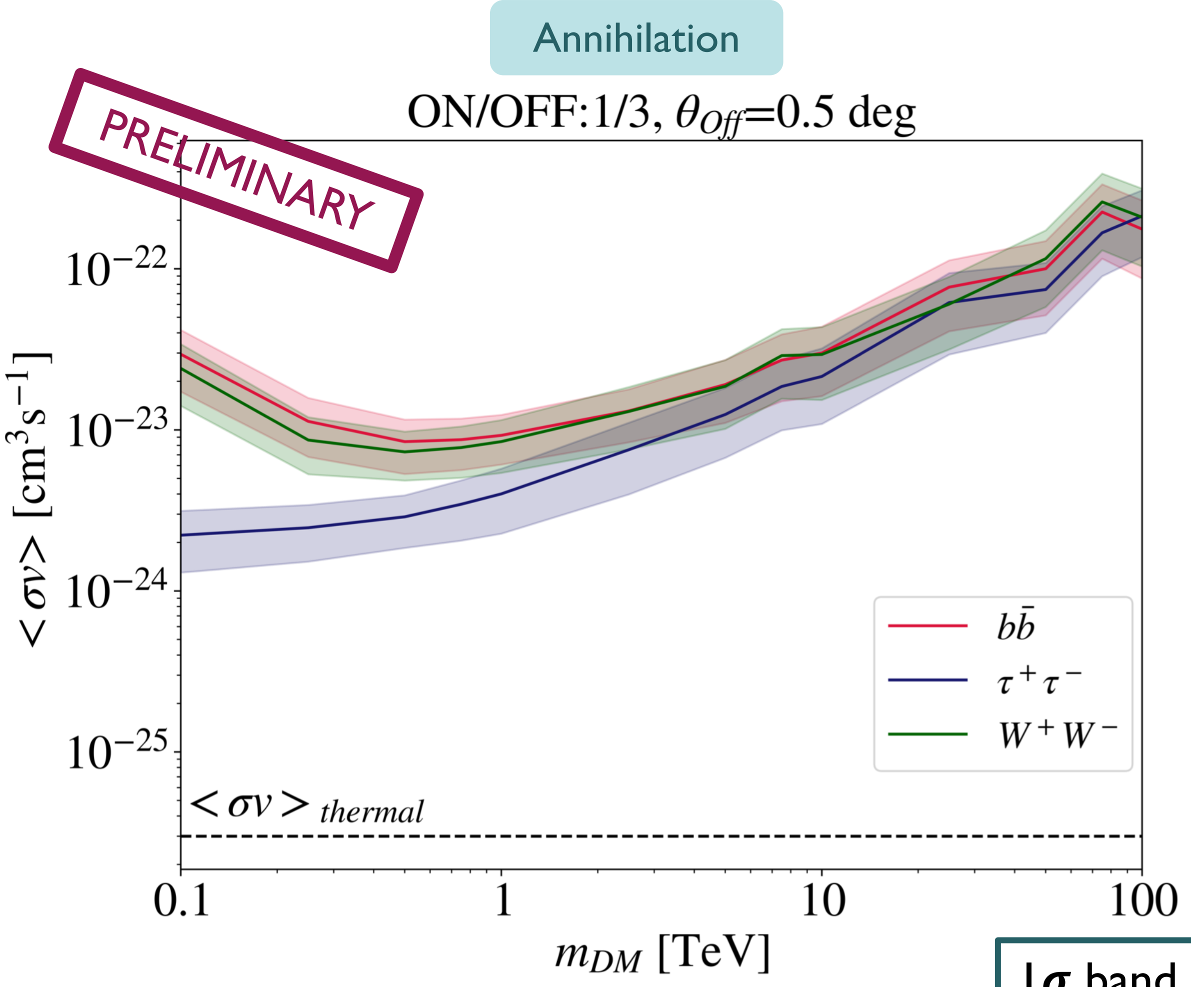
More realistic physical scenario

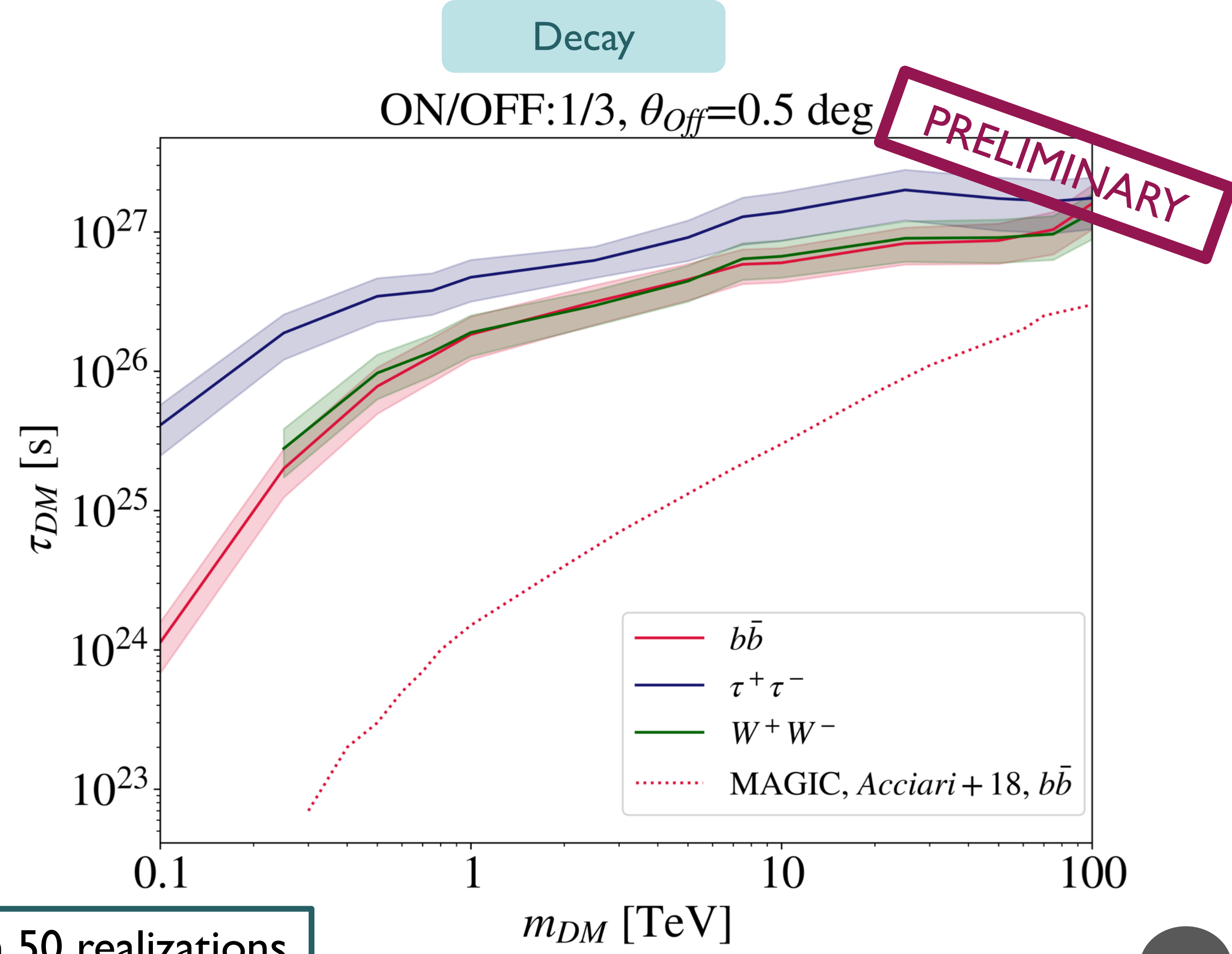
  - Allows to check correlations between components
  - Historically used in Fermi-*LAT* analysis and in a recent CTA analysis (*Acharyya+20* [*CTA Cons.*])

State-of-the-art analysis pipeline

ON/OFF RESULTS: DM CONSTRAINTS

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



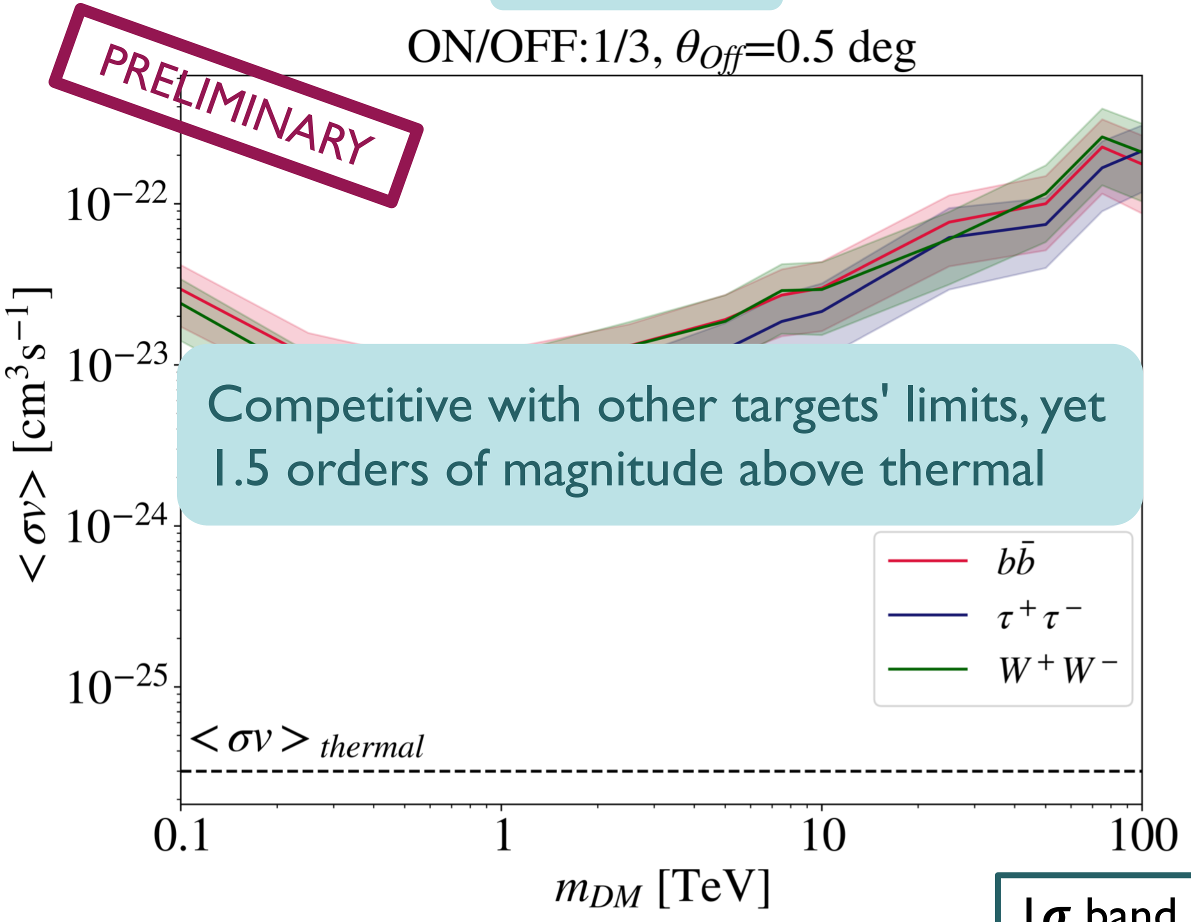


1σ band from 50 realizations

ON/OFF RESULTS: DM CONSTRAINTS

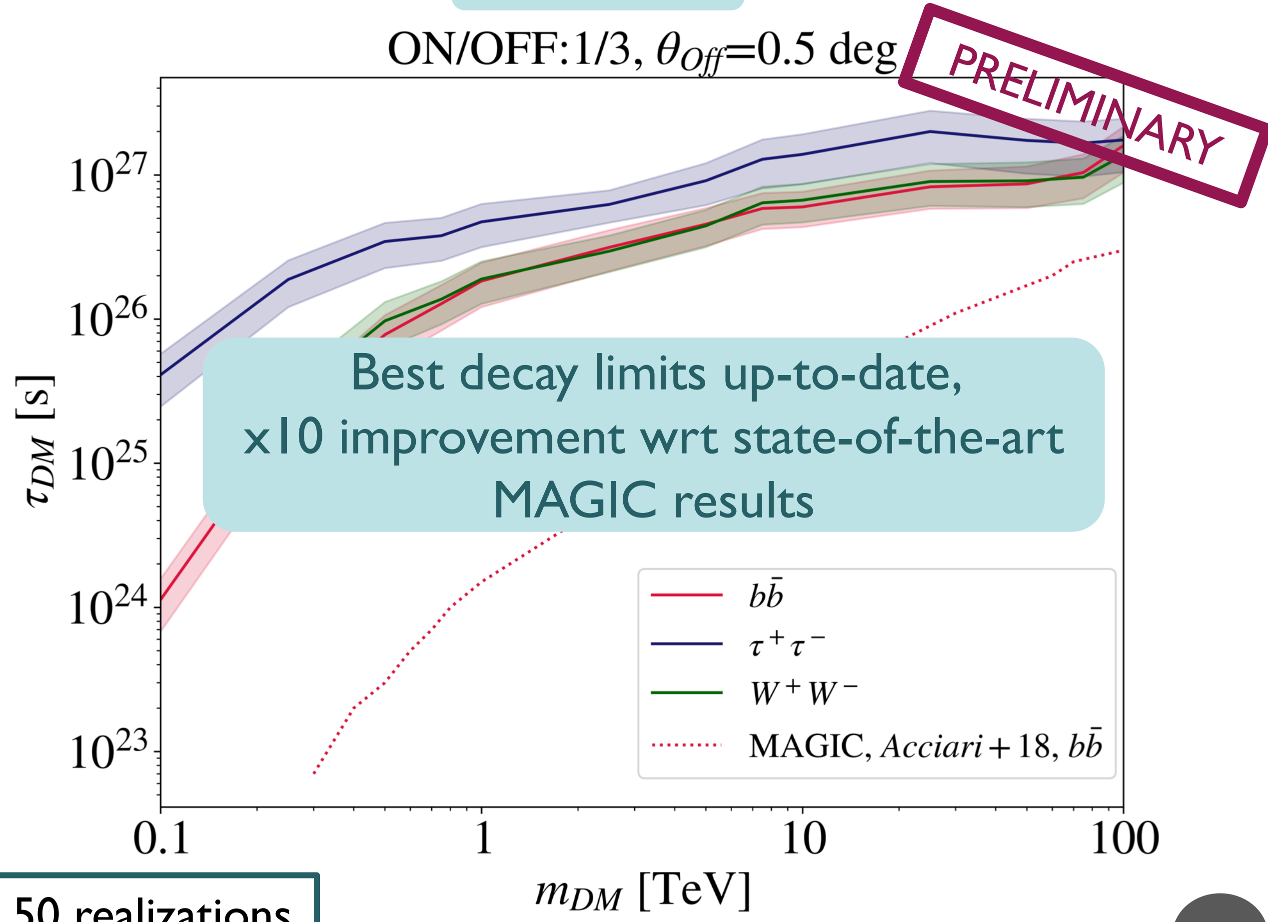
Limits for Perseus for MED annihilation model and decay
(point-like morphology & no J/D-factor uncertainties)

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

SUMMARY

- Galaxy clusters are excellent target for indirect DM searches (massive, closeby)
- Still no clear gamma-ray signal from clusters detected
- CTA is the future for VHE gamma-ray astronomy, with superb capabilities for WIMP searches
- Perseus Galaxy Cluster has optimal conditions for observation with CTA-North
- State-of-the-art DM modelling for Perseus including halo substructure
- Complete and comprehensive study of the different expected emissions: DM+CR+AGNs
- ON/OFF analysis for annihilation and decay main results:
  - Annihilation upper limits of ~O(10^{-23}) cm^3 s^{-1}
  - Decay upper limits of ~O(10^{26}) s : will be the best limits
  - Most optimistic limits
- On-going template fitting analysis and inclusion of J/D-factor uncertainties for more realistic predictions

Thanks for your attention!

Back-up material

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

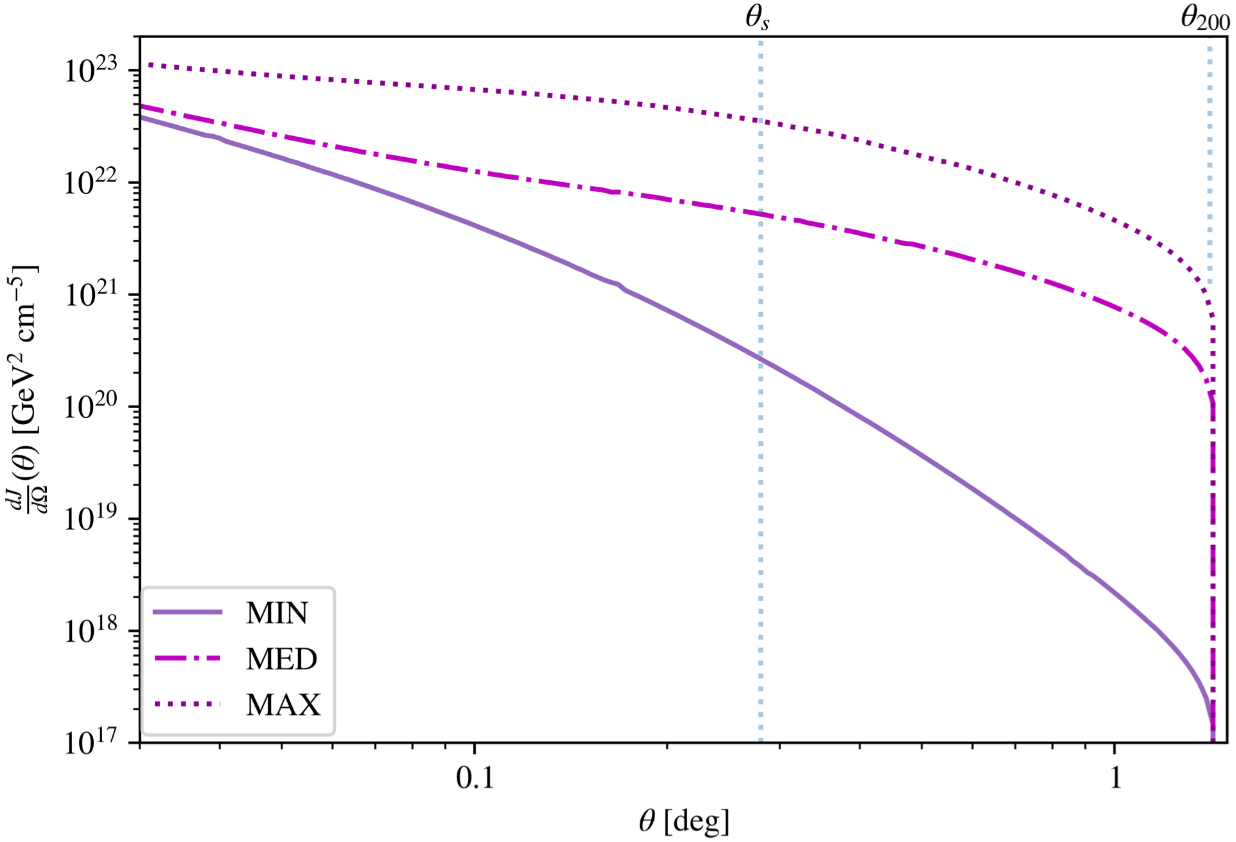
$$c_{200} = \frac{R_{200}}{r_s}$$

Angular extension

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

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 $M_\odot$/kpc^3

CTA ANALYSIS ELEMENTS

- 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

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

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

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

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

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

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

Mass modelling and extrapolations:
- Masses from other methods
- Other X-rays measurements

c(M) – M scatter:
- ~ O(0.3) dex for *Sánchez-Conde & Prada 14*

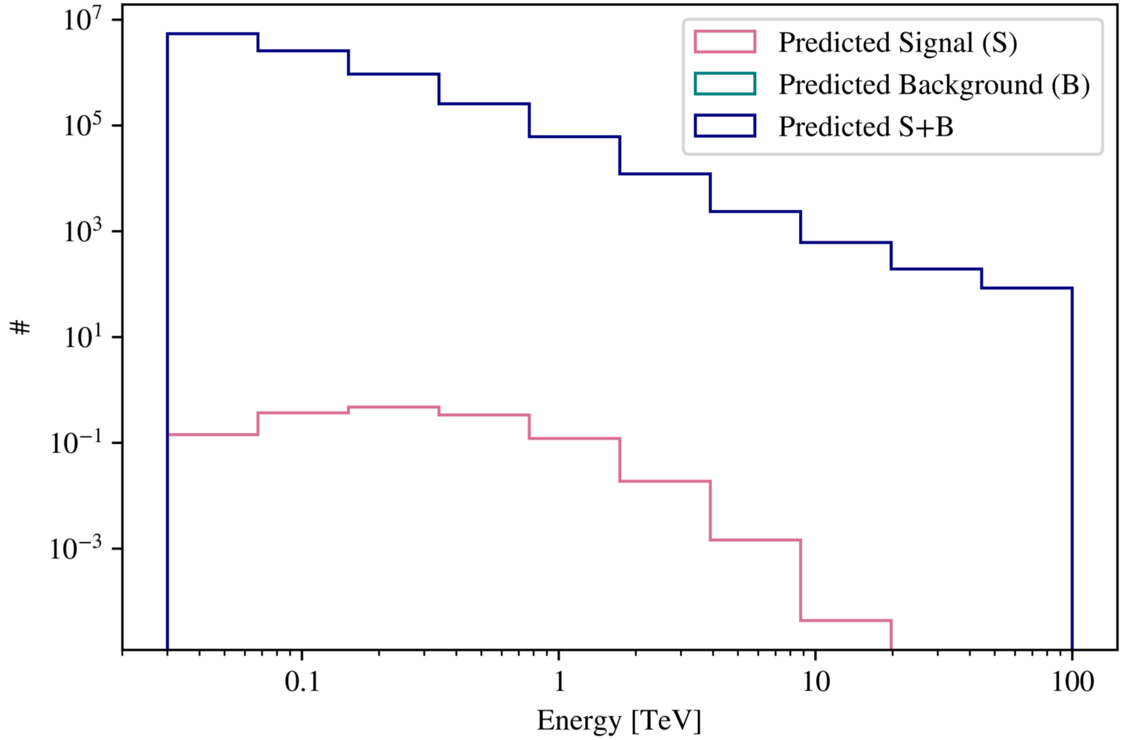
$$\mathcal{J}(J\,|\,J_{\rm obs},\sigma_J) = \frac{1}{\ln(10)J_{\rm obs}\sqrt{2\pi}\sigma_J}\times e^{-\left(\log_{10}(J)-\log_{10}(J_{\rm obs})\right)^2/2\sigma_J^2}$$

Gaussian prior

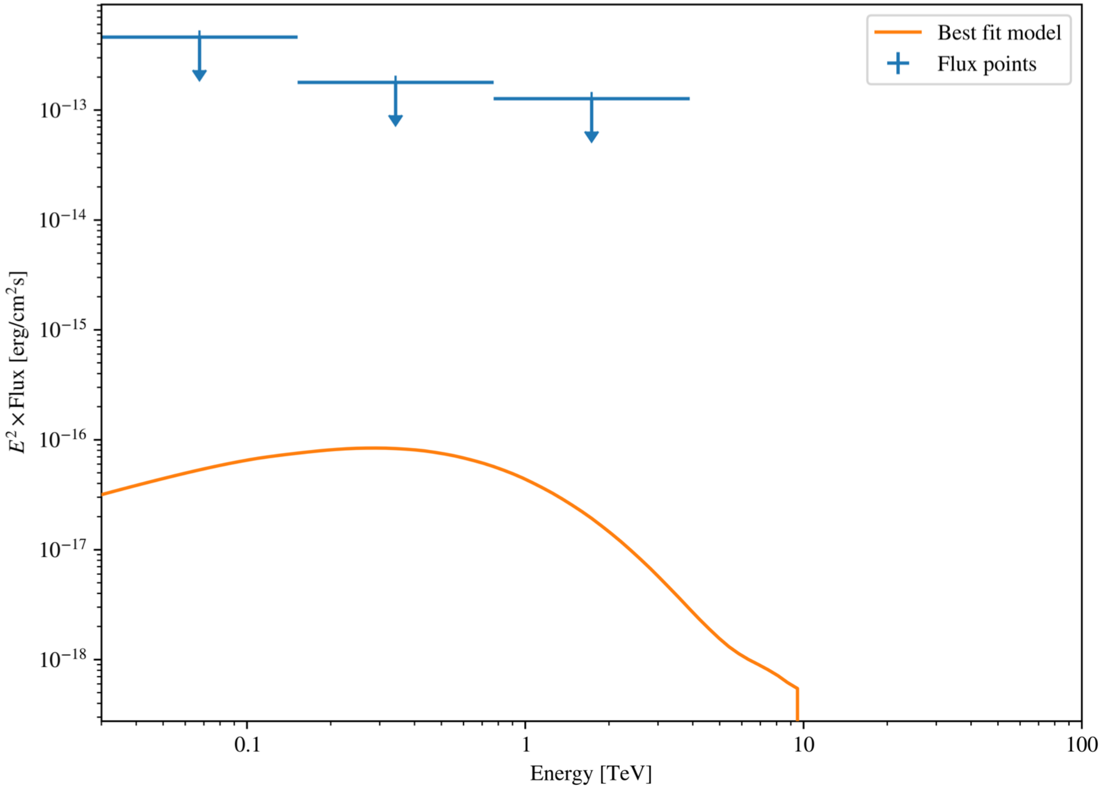
CHARACTERISTICS OF THE SIMULATIONS

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

Counts

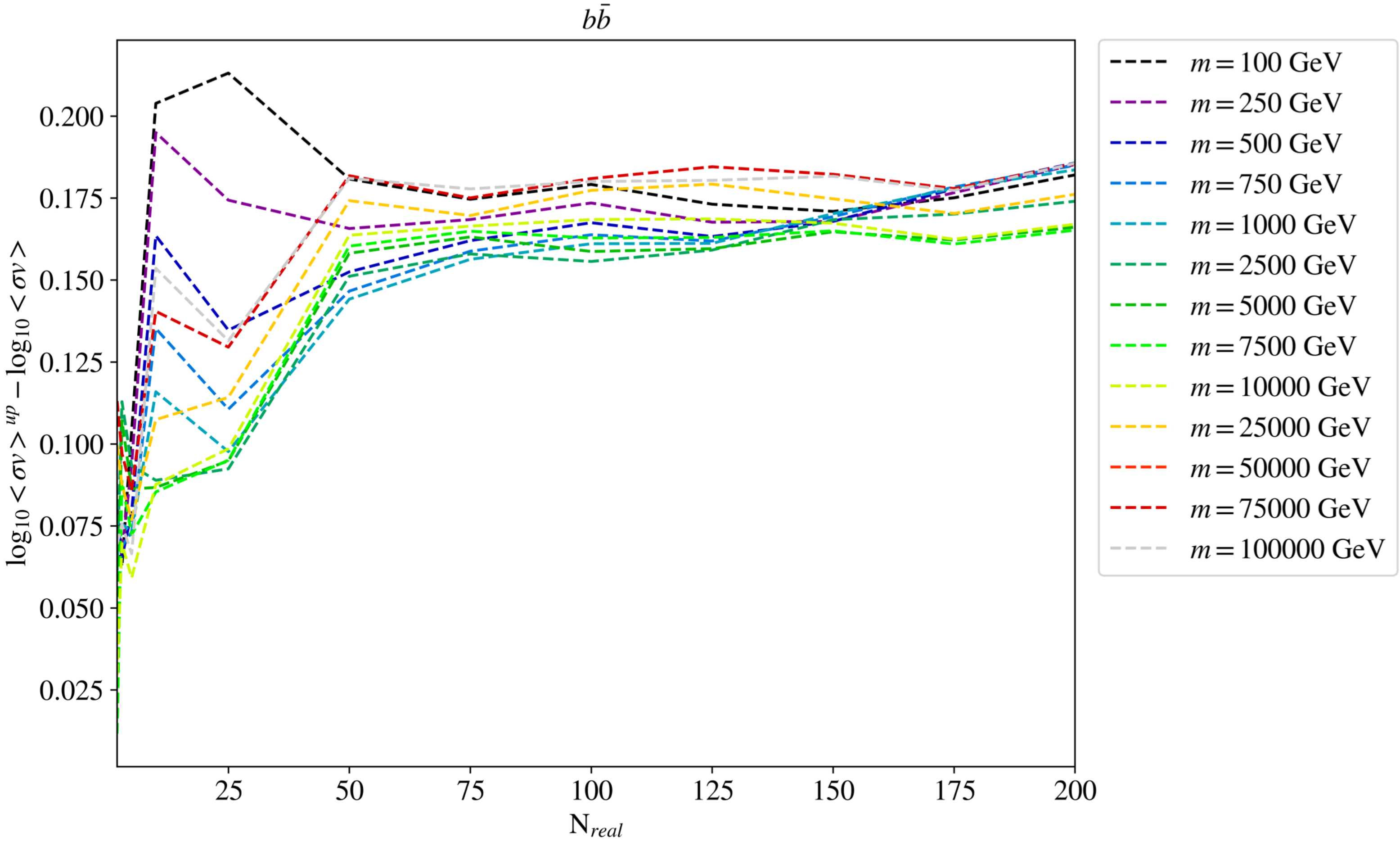


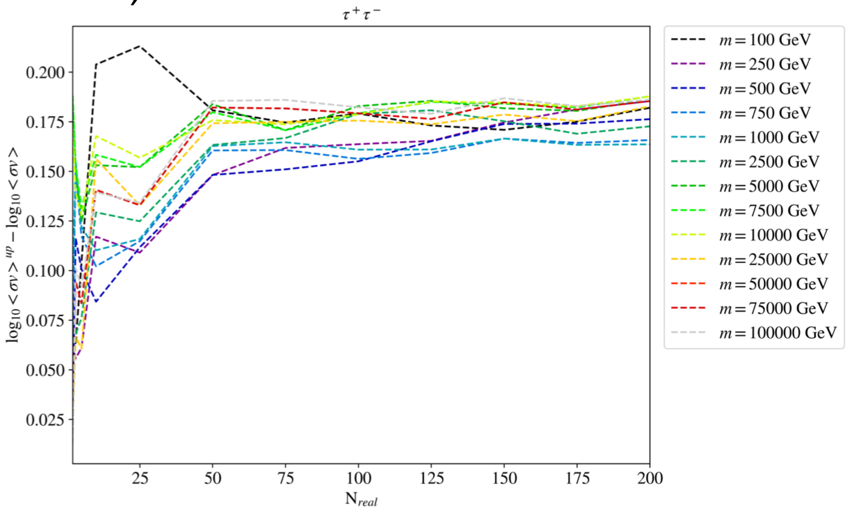
SED + ULs

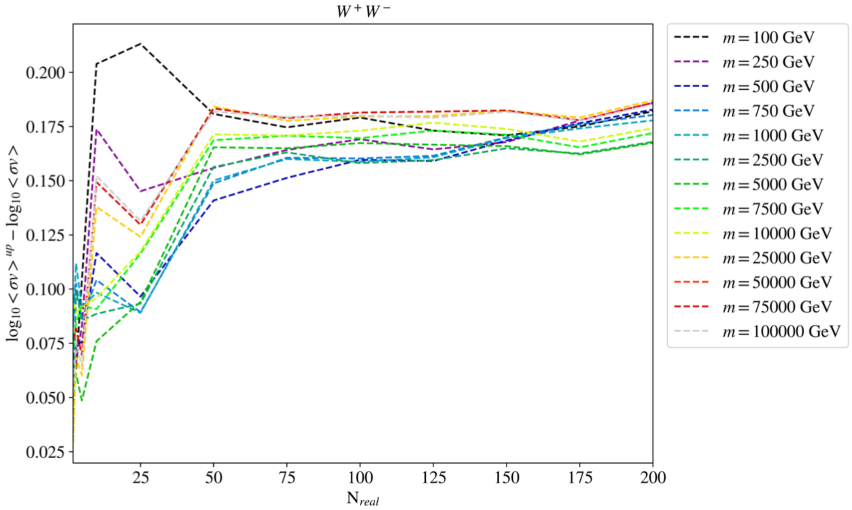


DM CONSTRAINTS: 1σ BAND

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

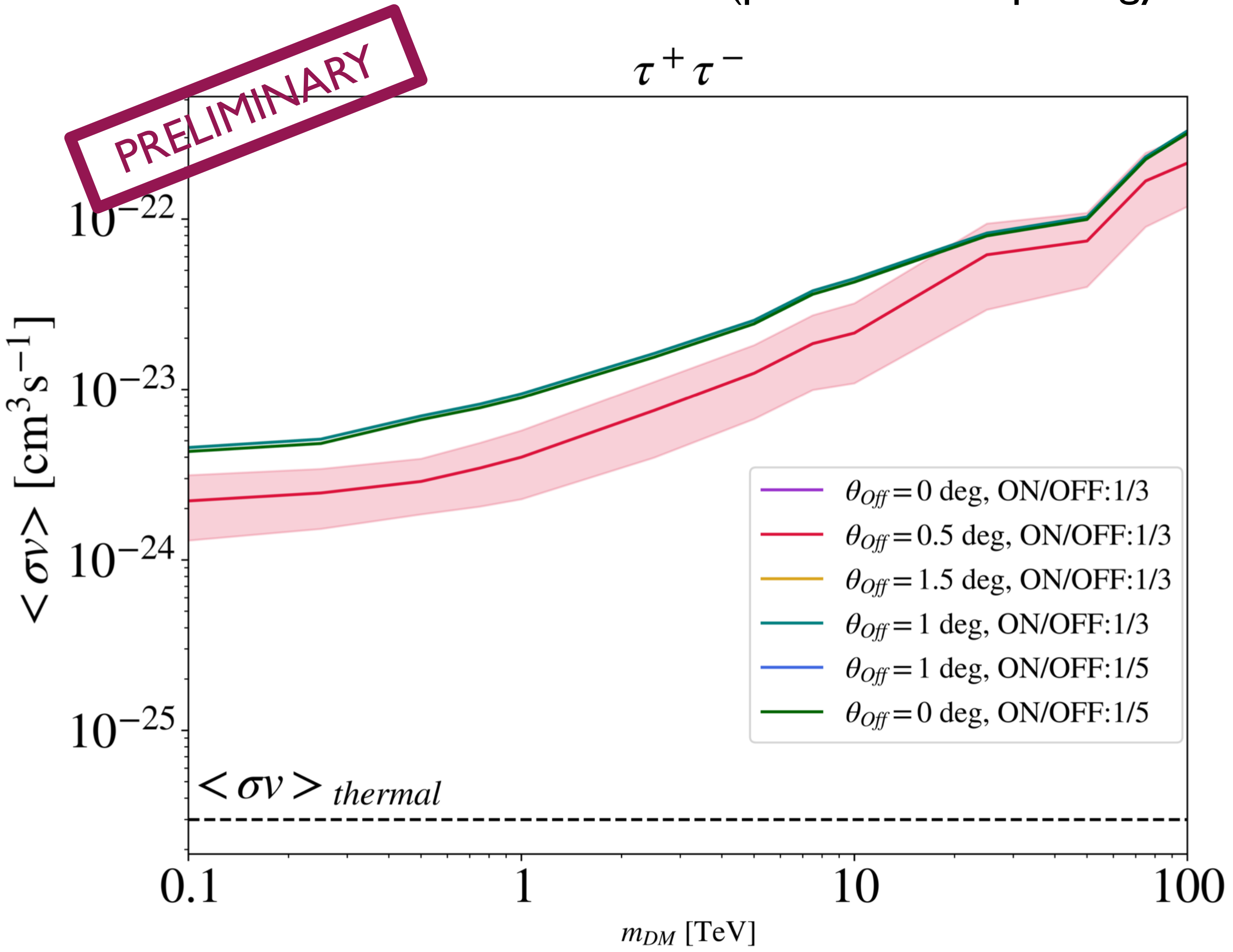


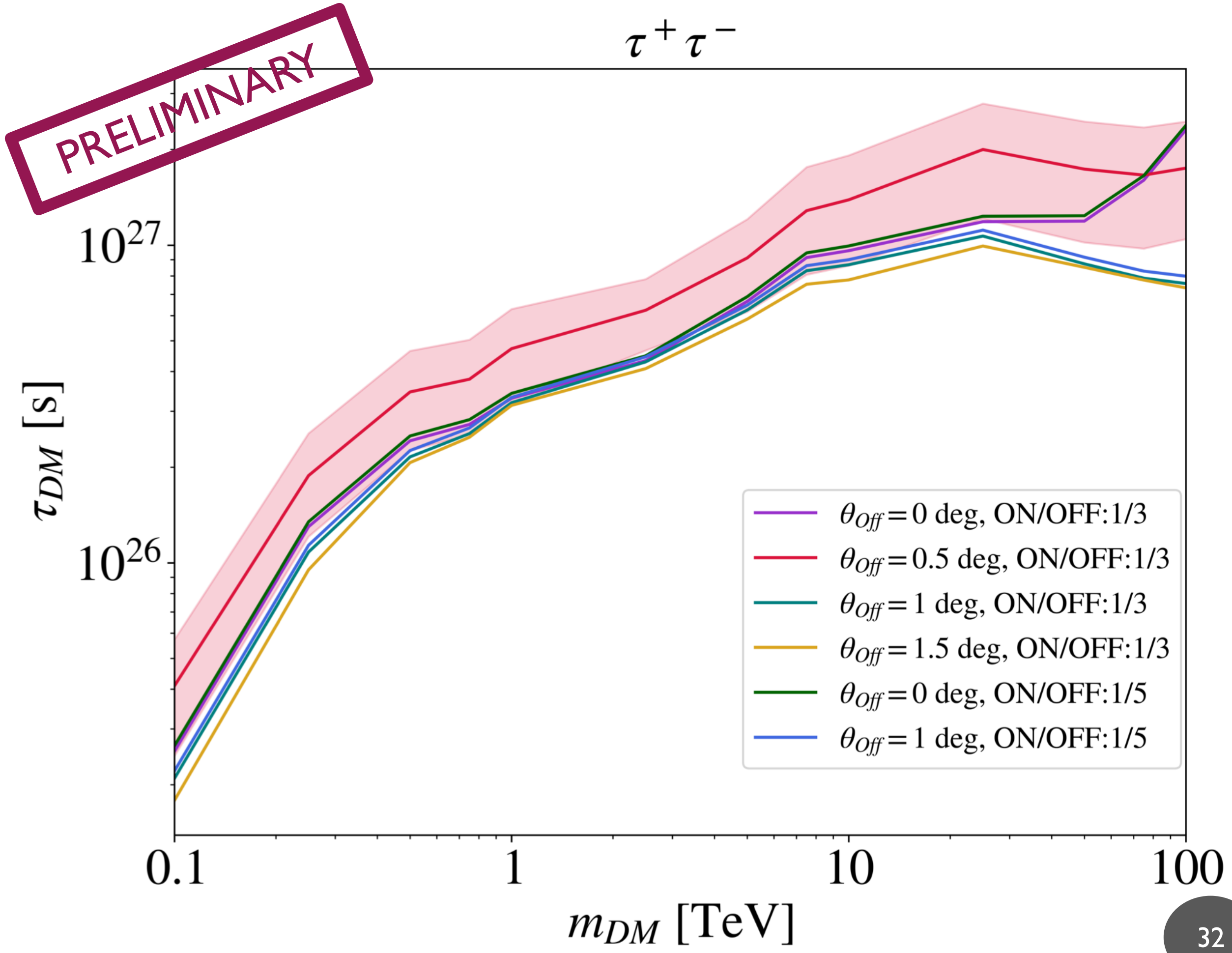




DM CONSTRAINTS: ON/OFF SET-UPS

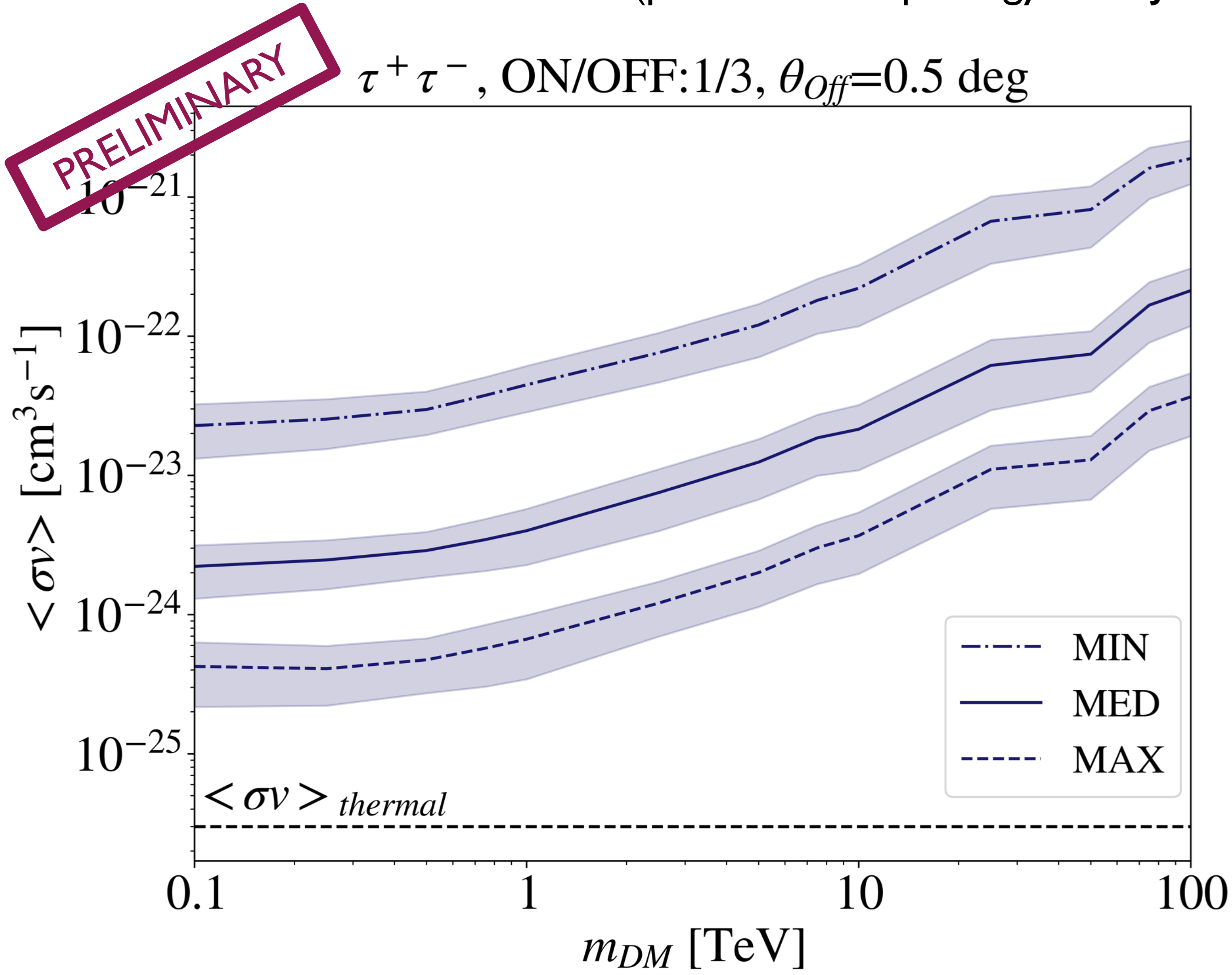
Limits for Perseus for $\tau^+\tau^-$ annihilation and decay models
(point-like morphology & no J/-D-factor uncertainties)





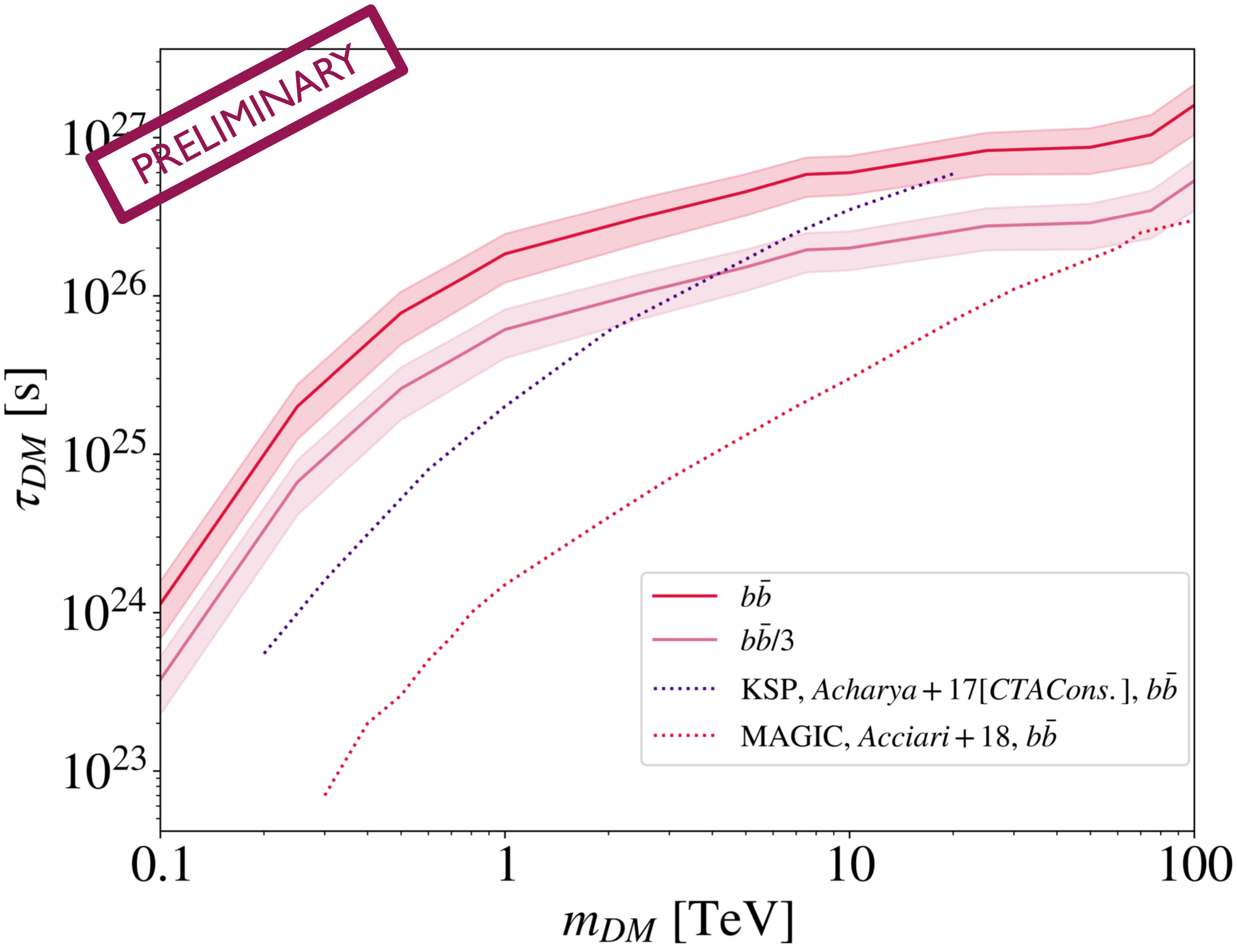
DM CONSTRAINTS: MIN-MED-MAX

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



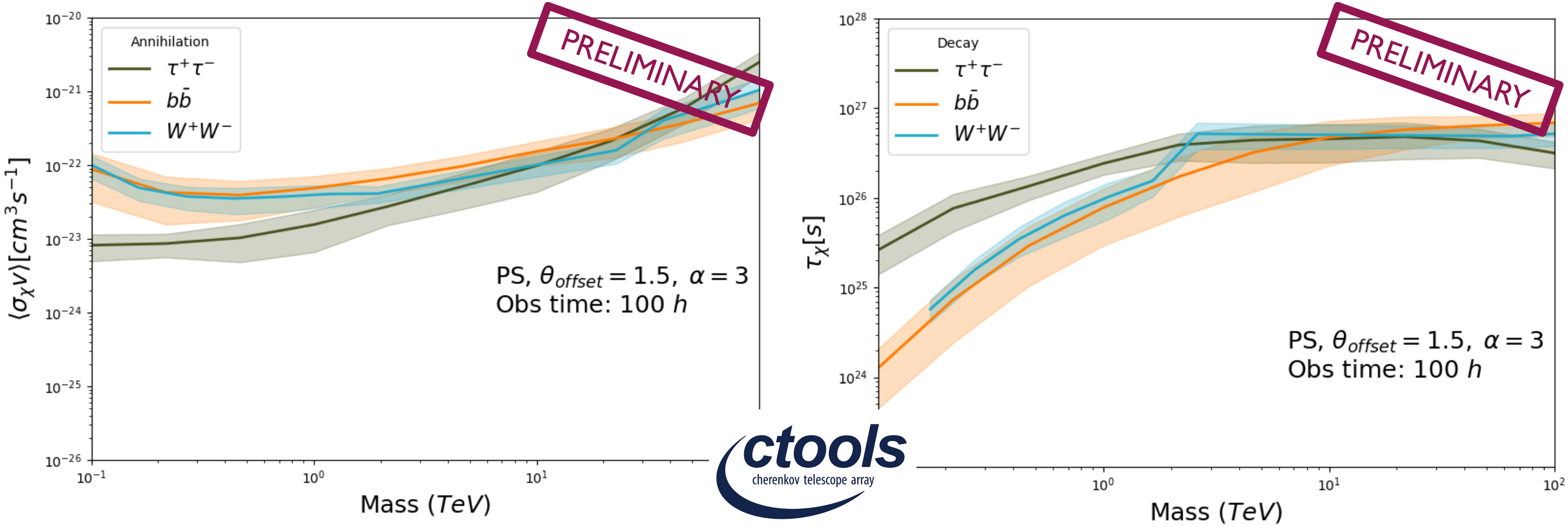
DM CONSTRAINTS: DECAY INSIGHT

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



DM CONSTRAINTS: CTOOLS

Limits for Perseus for MED annihilation model and decay, assuming point-like morphology and no J/D-factor uncertainties



General agreement with gammapy results accounting for statistical errors and different configurations

BEYOND KSP: SAMPLE OF GALAXY CLUSTERS

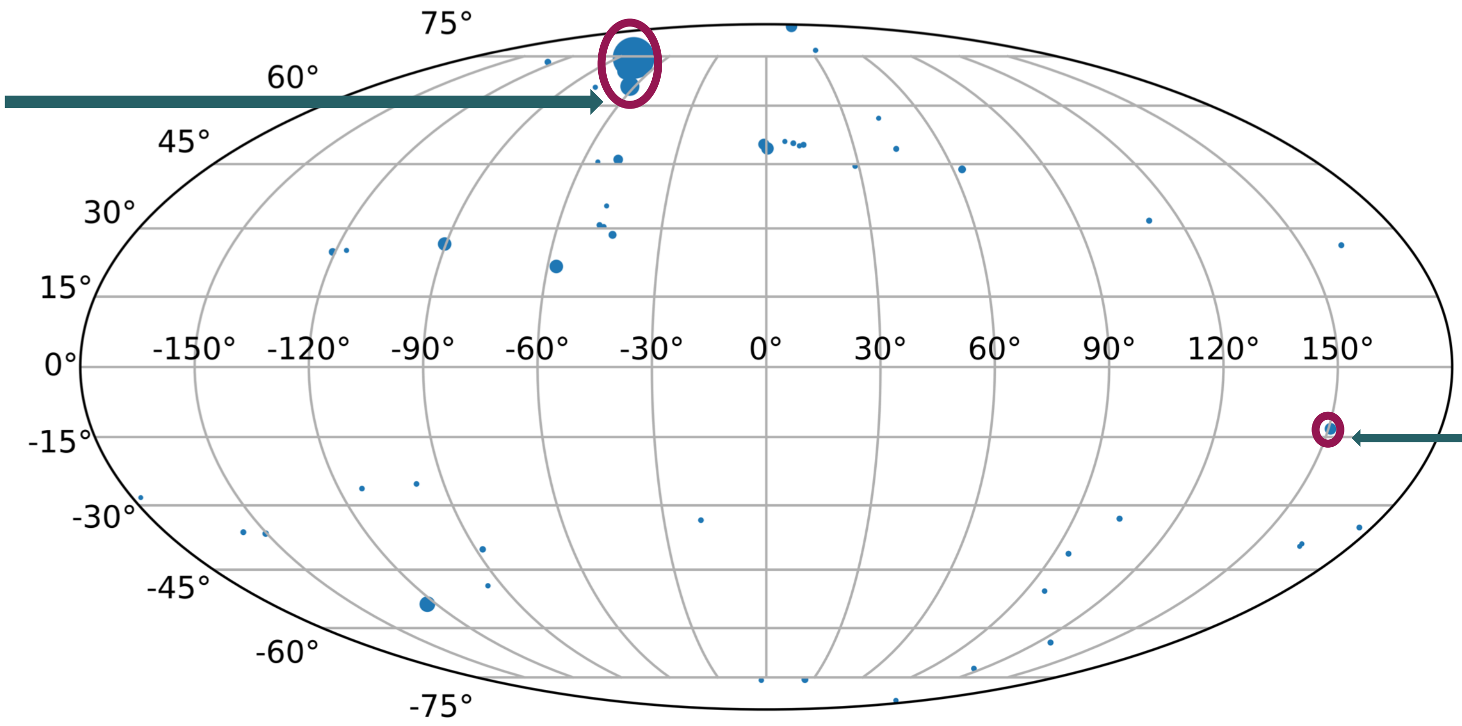
- Search in catalogues for other interesting galaxy clusters to study in a DM context
- Natural extension of the KSP: why just focus on Perseus for DM searches?
- Built up of "gold" cluster sample for DM studies
- Will follow similar procedure than KSP, just applied to few other galaxy clusters and DM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

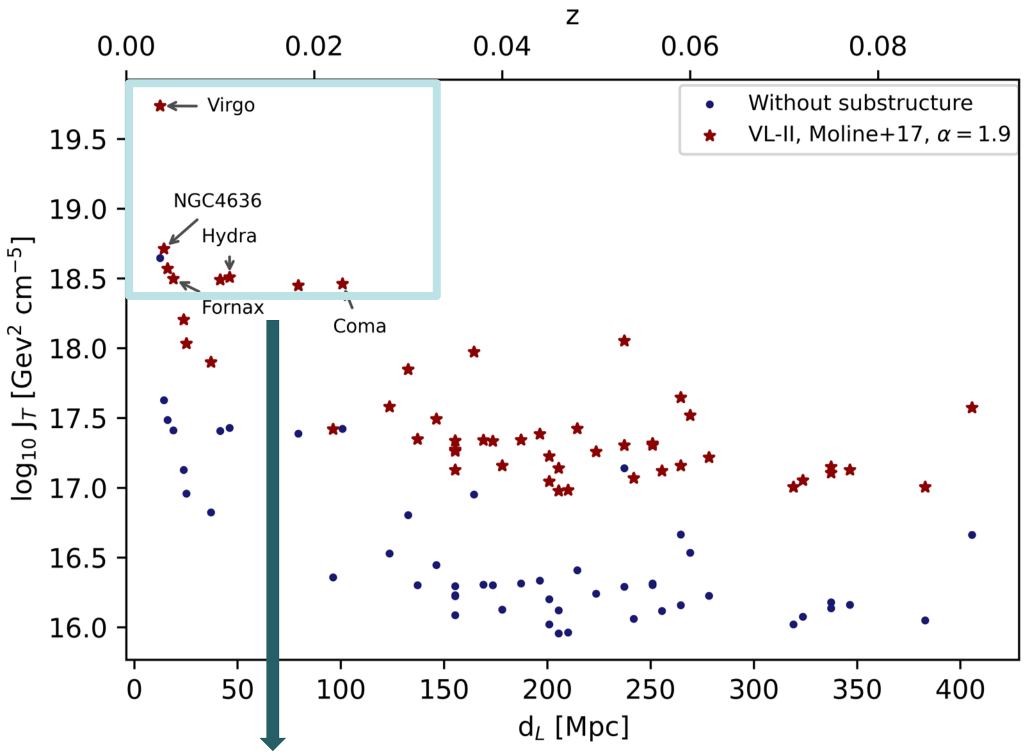
Separation of at least 2deg to account for cluster extension, except for M49 + Virgo

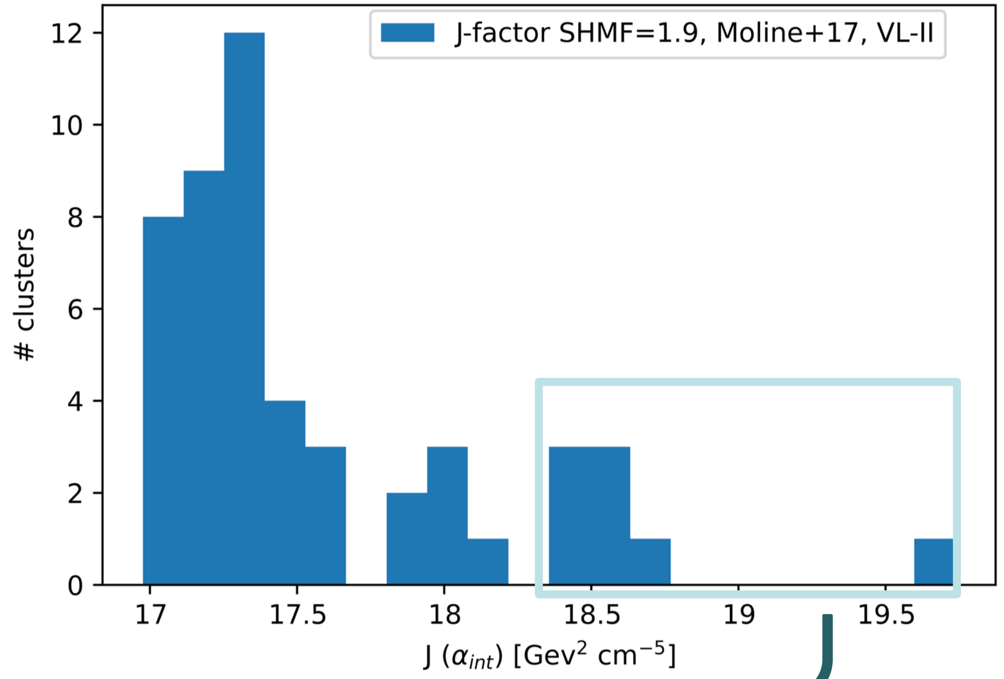


Mask |*b*| < 20deg, except Perseus, to avoid GDE

- 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





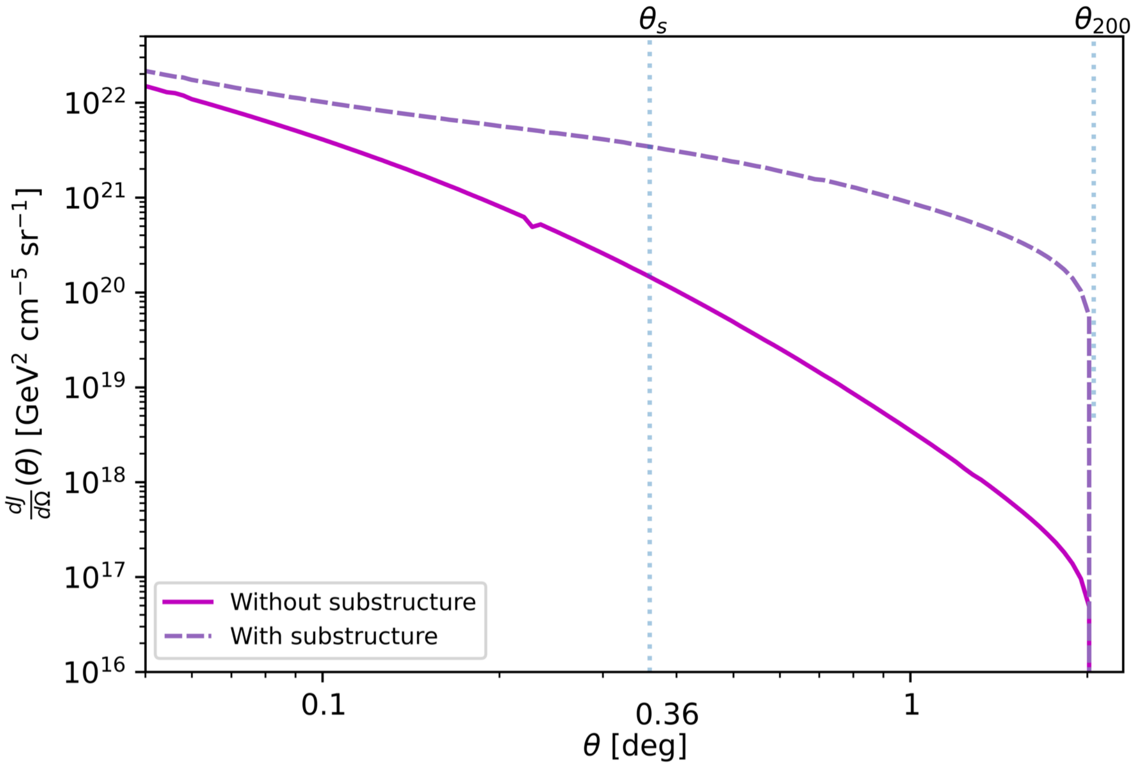
Object	z	M_{200} [10^{14} $M_\odot$]	R_{200} [kpc]	θ_{200} [deg]	$J_{no-subs}$ [10^{17}GeV^{2}cm^{-5}]	J_{subs} [10^{18}GeV^{2}cm^{-5}]
Virgo	0.0036	5.600	1700	6.32	44.3	54.5
NGC3646	0.0040	0.534	777	2.60	4.24	5.15
M49	0.0044	0.464	741	2.26	3.06	3.72
A1060/Hydra	0.0110	2.966	1376	1.70	2.69	3.23
NGC1399/Fornax	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*)

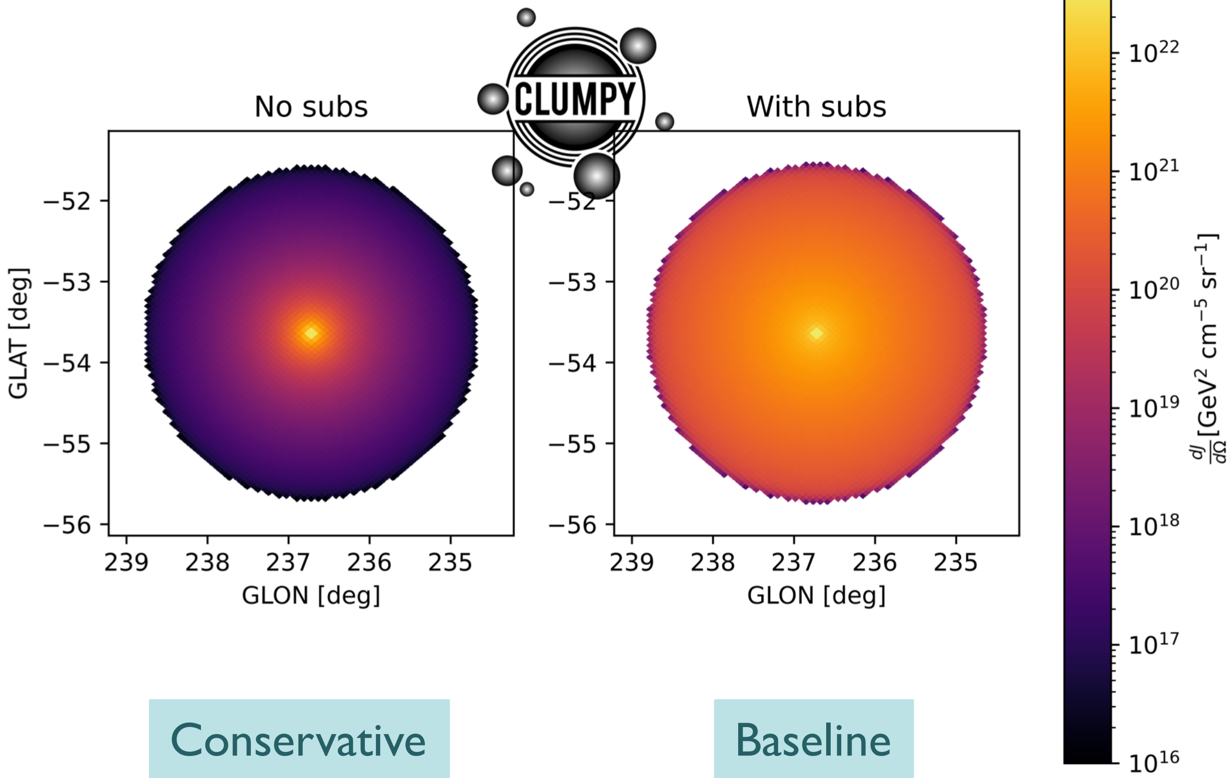
DARK MATTER MODELLING: FORNAX

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