SENSITIVITY OF CTA TO GAMMA-RAY EMISSION FROM THE PERSEUS GALAXY CLUSTER

cta cherenkov telescope array

ICRC 2021
THE ASTROPARTICLE PHYSICS CONFERENCE

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AGENCIA ESTATAL DE INVESTIGACIÓN

GAMMA-RAY EMISSION IN GALAXY CLUSTERS

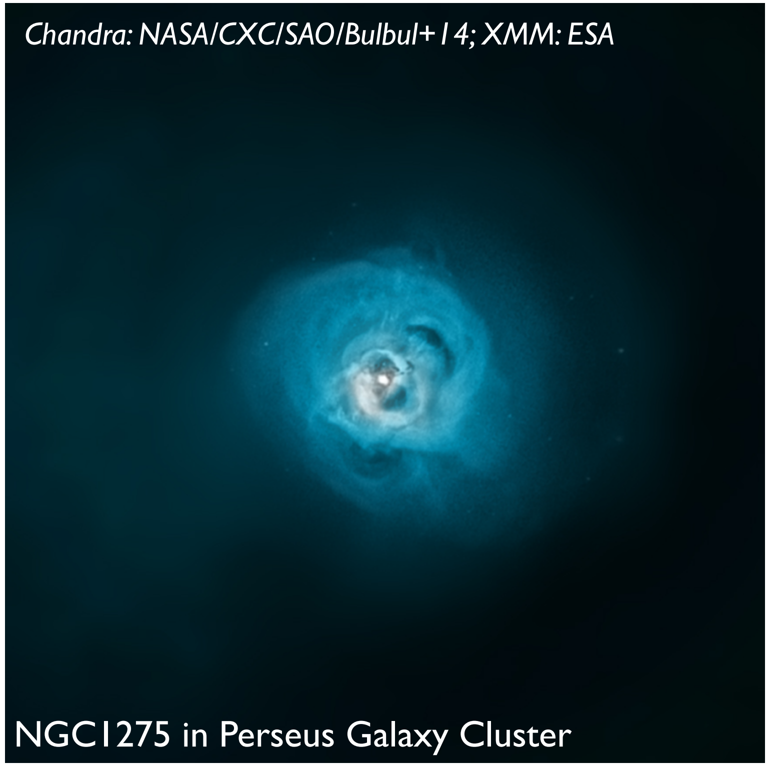
- Largest gravitationally bound structures formed by gravitational collapse
- Masses of order ~10^{14}-10^{15} $M_\odot$
- Components:
  - Baryonic Matter
    - Galaxies (~ 3% - 5%)
    - ICM (~ 15% - 17%)
  - Dark Matter (~80%)

- 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 ✗

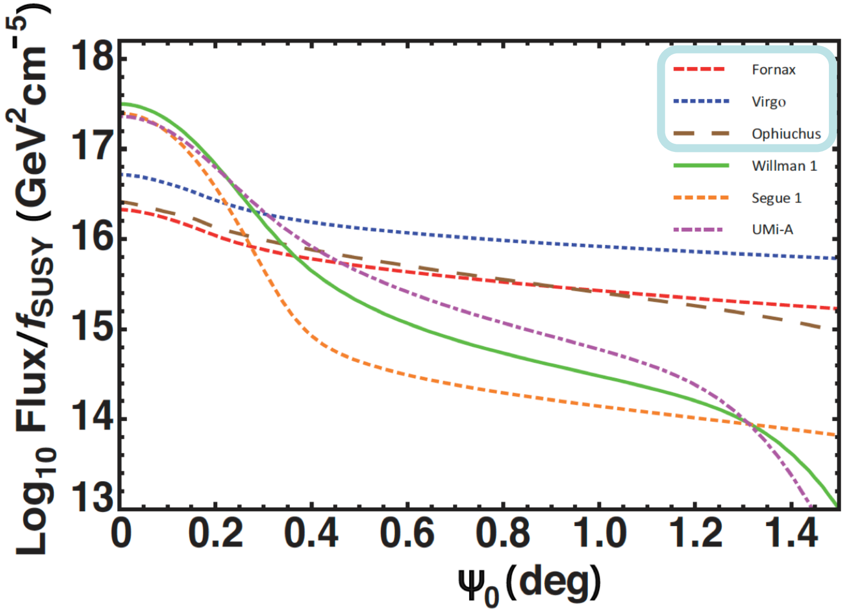


NGC1275 in Perseus Galaxy Cluster

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} (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

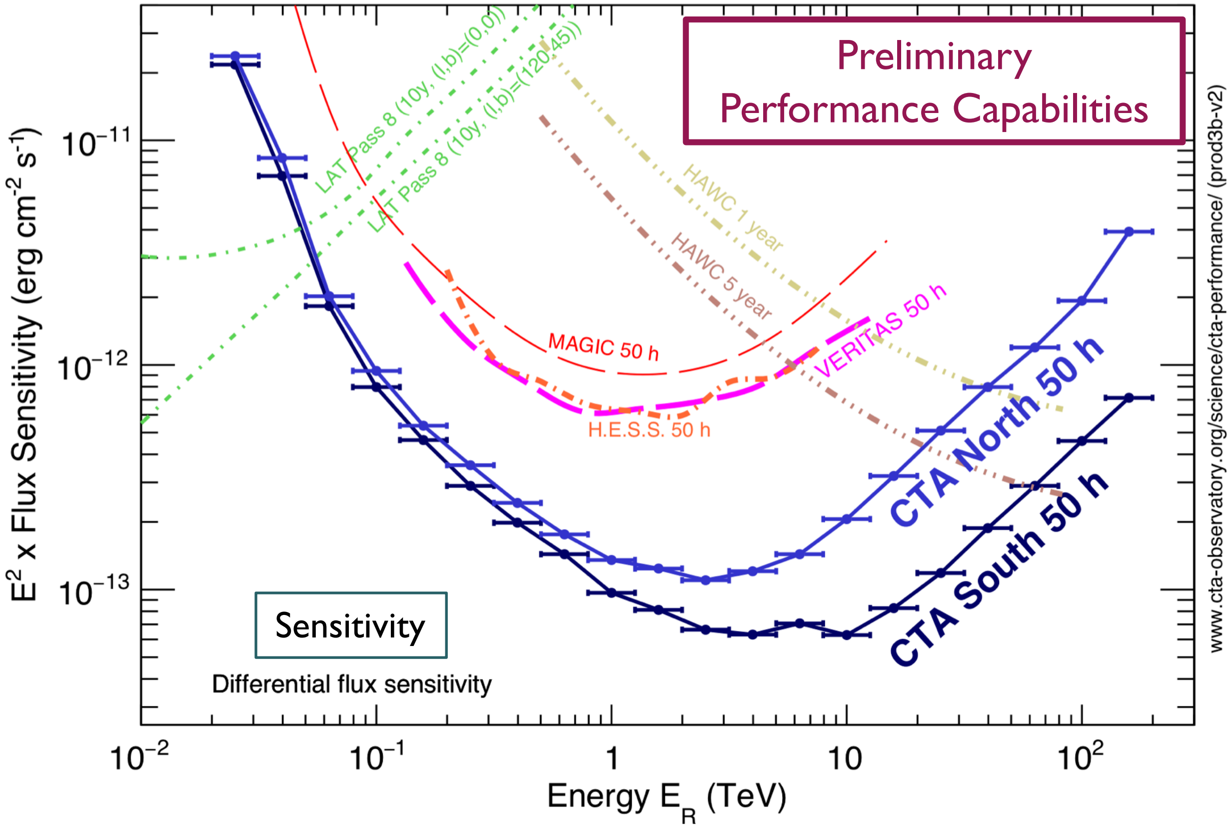
Considering:
- Smooth component

+

- Substructure

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

PERSEUS GALAXY CLUSTER WITH CTA

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

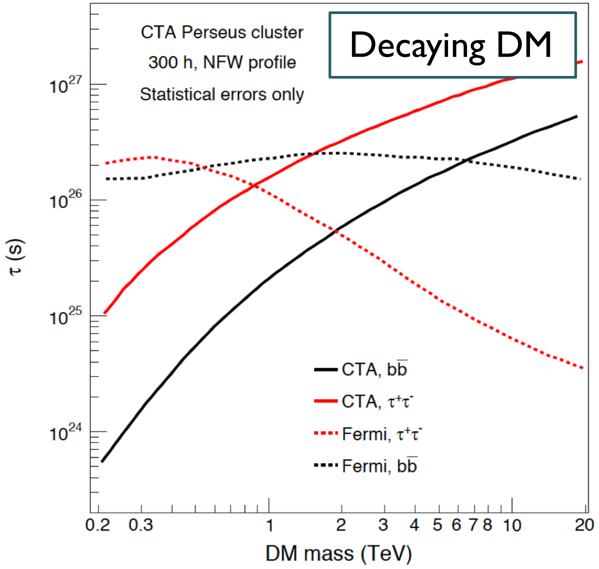
Object	l [deg]	b [deg]	d_L [Mpc]
Perseus	150.57	-13.26	75.01

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

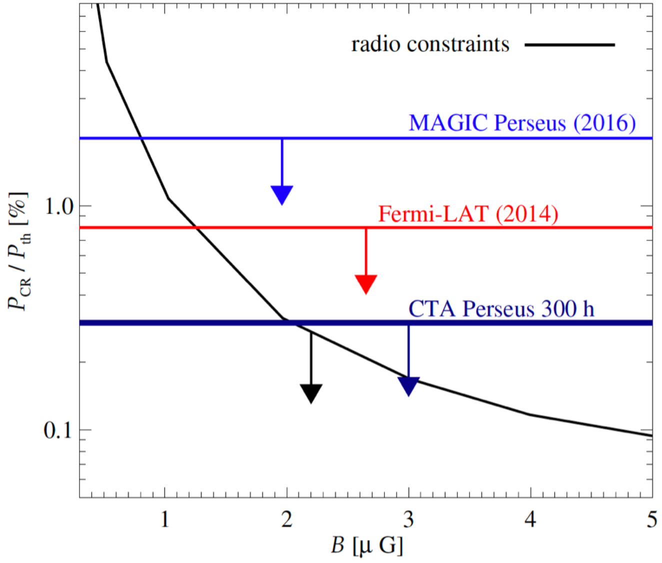
Object	l [deg]	b [deg]
NGC1275	150.58	-13.26
IC310	150.18	-13.74

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 IRFs to perform the analysis

DARK MATTER MODELLING: MAIN HALO

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

DM-induced γ-ray flux from an astrophysical object

Particle Physics Model

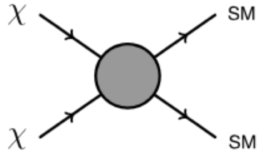
Cirelli+12 (EW corrections)

Hütten+18, Bonnivard+15, Charbonnier+12

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

Annihilation

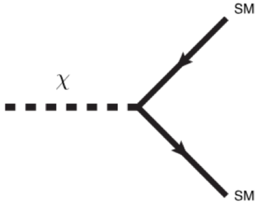
$$J(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega}\int_{l.o.s} \rho^2_{DM}(r)dr \rightarrow J \propto \frac{M_{200}c^3_{200}}{D^2_{\text{Earth}}}$$



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: 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

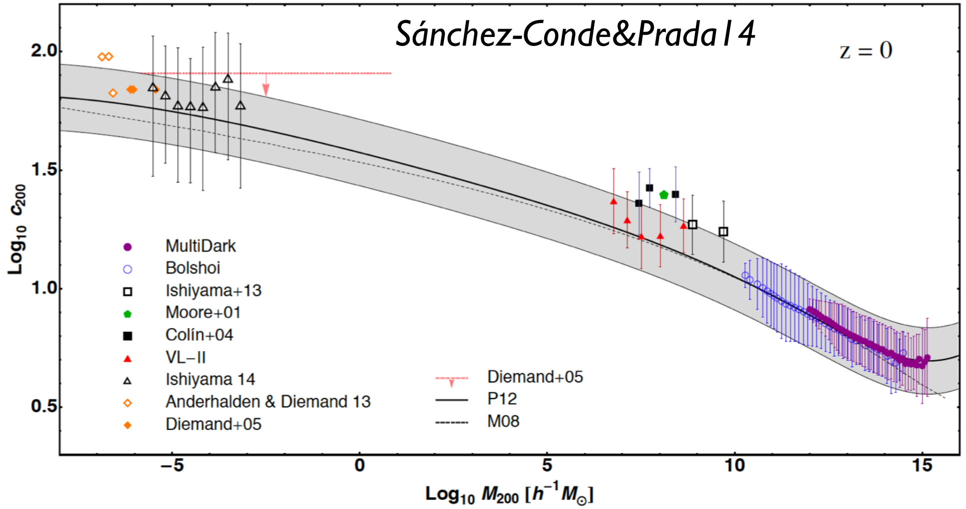
- State-of-the-art parametrization of the DM in galaxy clusters:

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

Assume a profile → NFW

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

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



DARK MATTER MODELLING: 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

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

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

DM subhalo profile: NFW

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

Subhalo Radial Distribution (SRD)

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

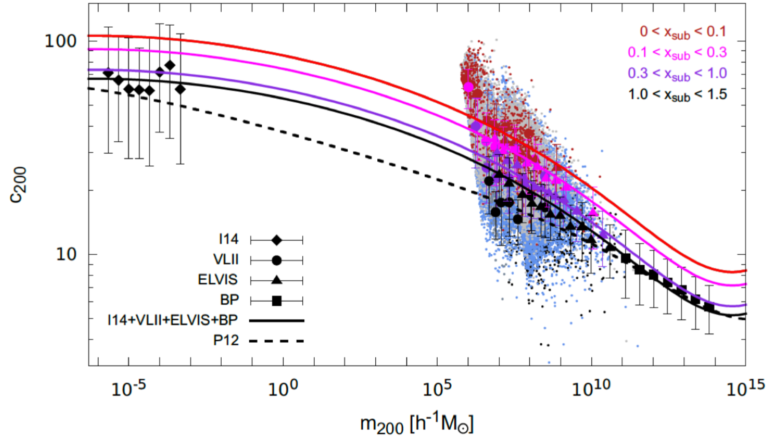
Via Lactea - II
Anti-biased relation
Diemand+08

Subhalo Mass Function (SHMF)

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

α = 1.9 *Springel+08*
α = 2.0 *Diemand+08*

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



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

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

Moliné+17

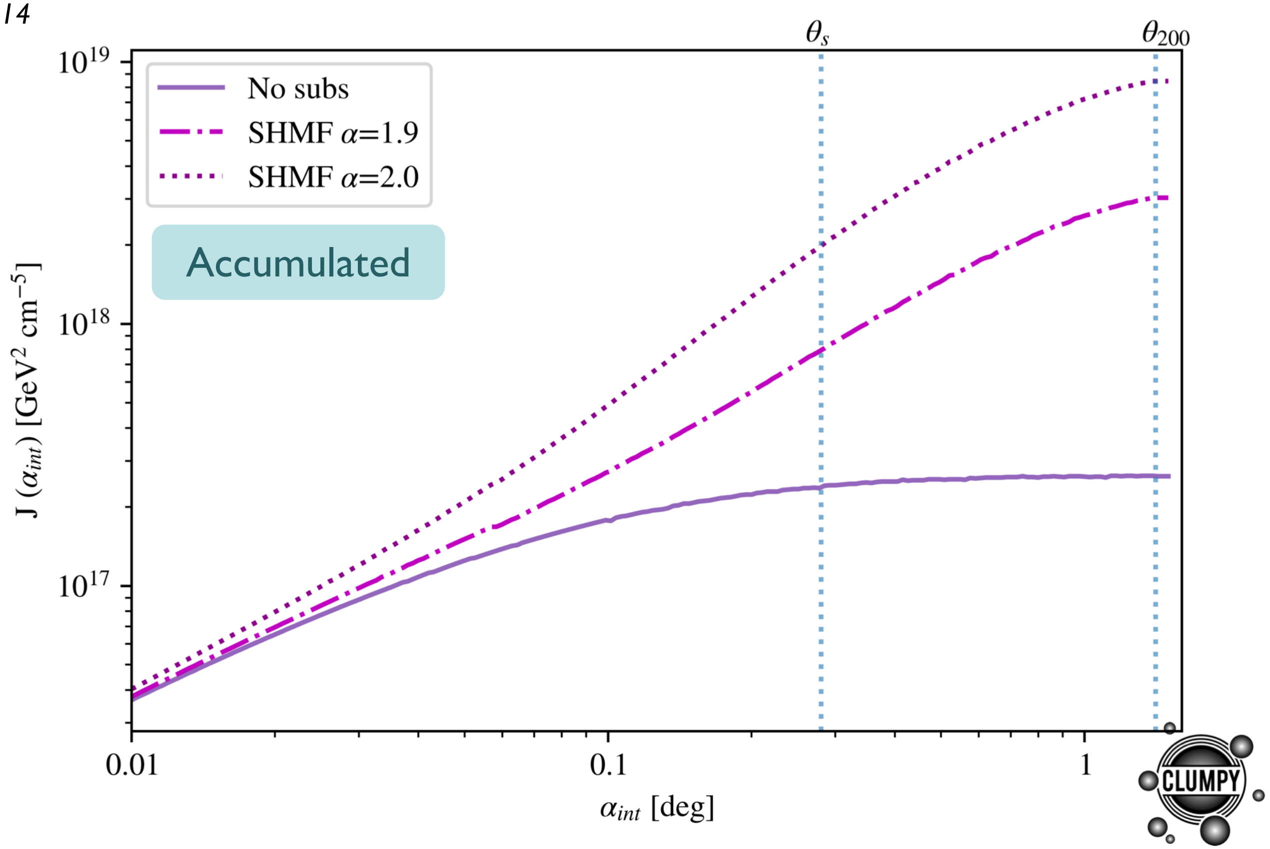
SUMMARY OF DM MODELLING FOR PERSEUS

Agreed parameters for DM and CR models

Reference					Reference
Hitomi Coll.18	z	0.017284	l, b	150.58 deg, -13.26 deg	NED
Urban+14	M_{200}	7.52×10^{14} $M_\odot$	R_{200}	1865.0 kpc	Urban+14
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 $M_\odot/\mathrm{kpc}^3$	

Annihilation	$\log_{10} J$ [GeV^{2}cm^{-5}]
J_T	17.42
$J_T^{1.9}$	18.48
$J_T^{2.0}$	18.93
Decay	$\log_{10} D$ [GeV cm^{-2}]
D_T	19.20

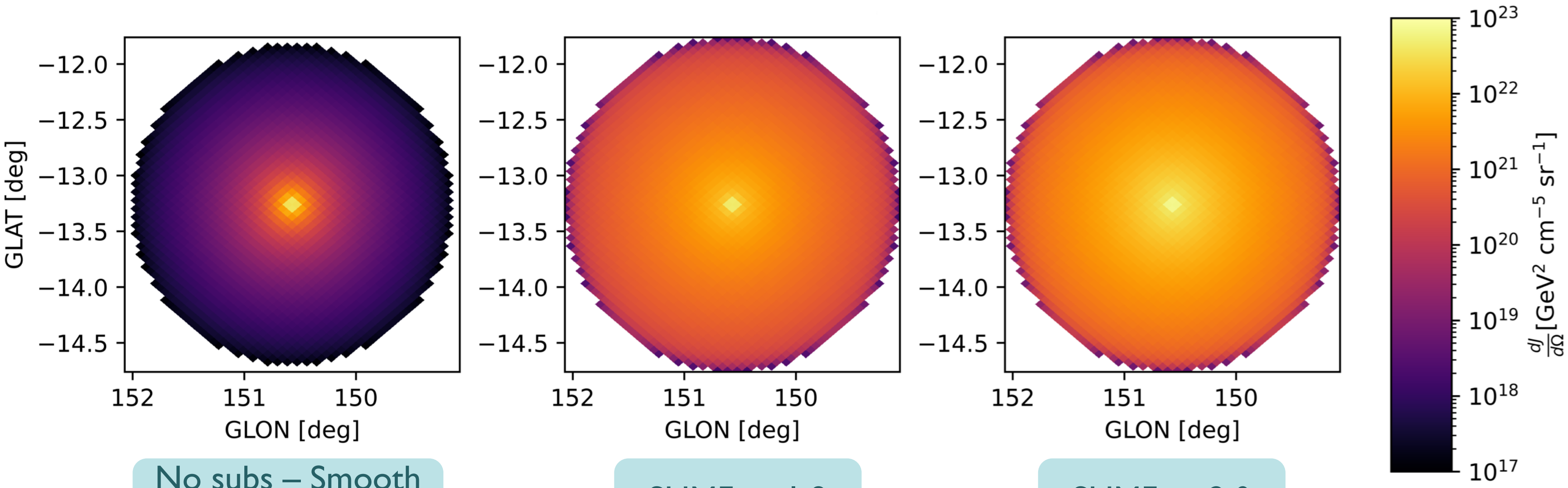
Annihilation flux profile



MORPHOLOGY OF DM SIGNAL

Skymaps of the differential J-factor

Annihilation



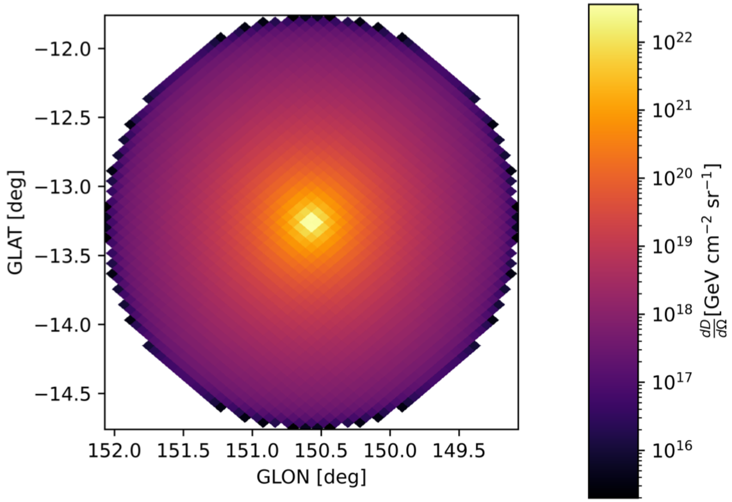
No subs – Smooth component

SHMF α=1.9

SHMF α=2.0

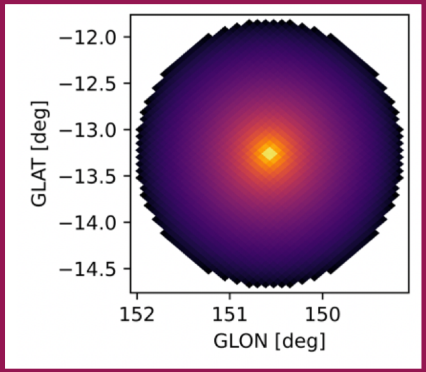
Skymap of the differential D-factor

Decay



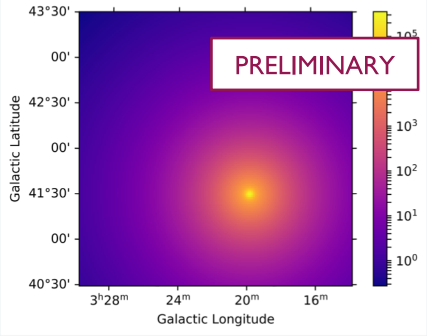
CTA DM ANALYSIS ROADMAP

Total DM-induced γ-rays



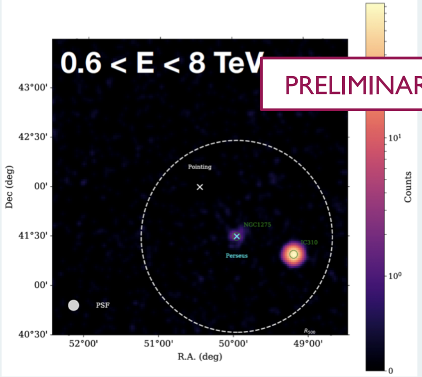
Our signal

Total CR-induced γ-rays

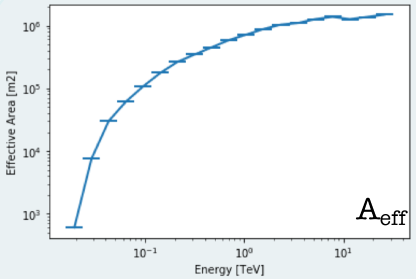


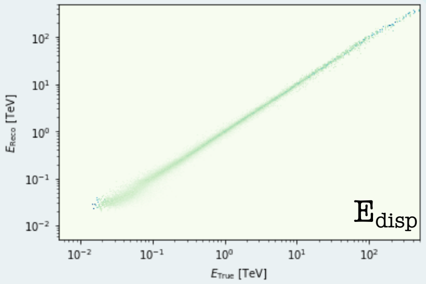
Use as BKG

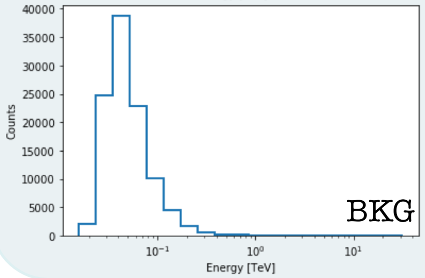
Total AGNs γ-rays



Use as BKG







CTA IRFs

Observation Simulation

If no signal found

Constraints on DM models

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

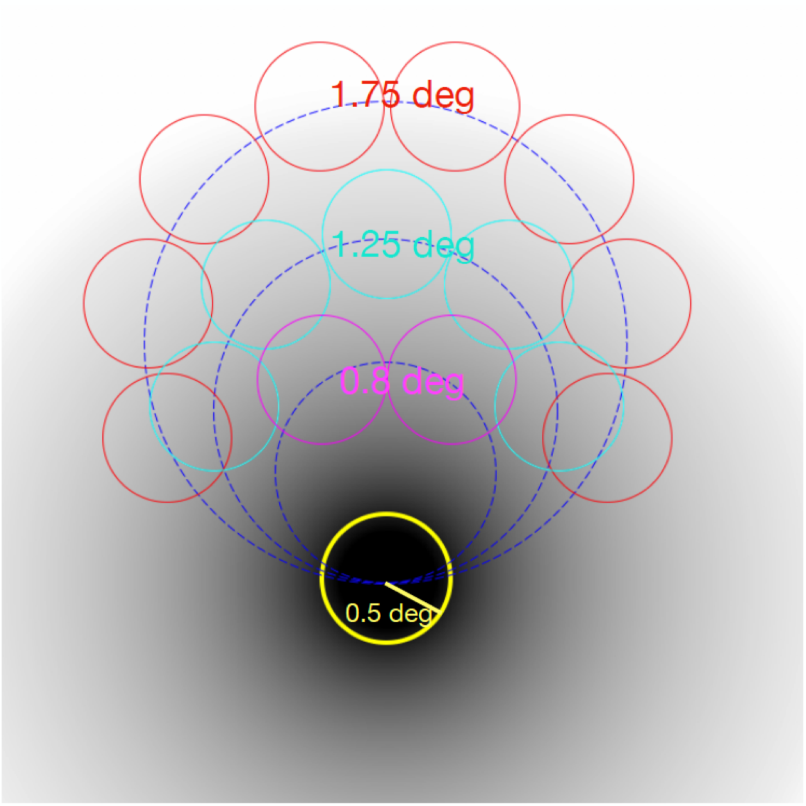
$$\frac{d\Phi^{Decay}_{DM}}{dE} = \frac{1}{4\pi m_{DM}\tau_{DM}} \frac{dN}{dE} \times D$$

CTA ANALYSIS SET-UP

- We use both γπ and ctools cherenkov telescope array

Analysis parameters

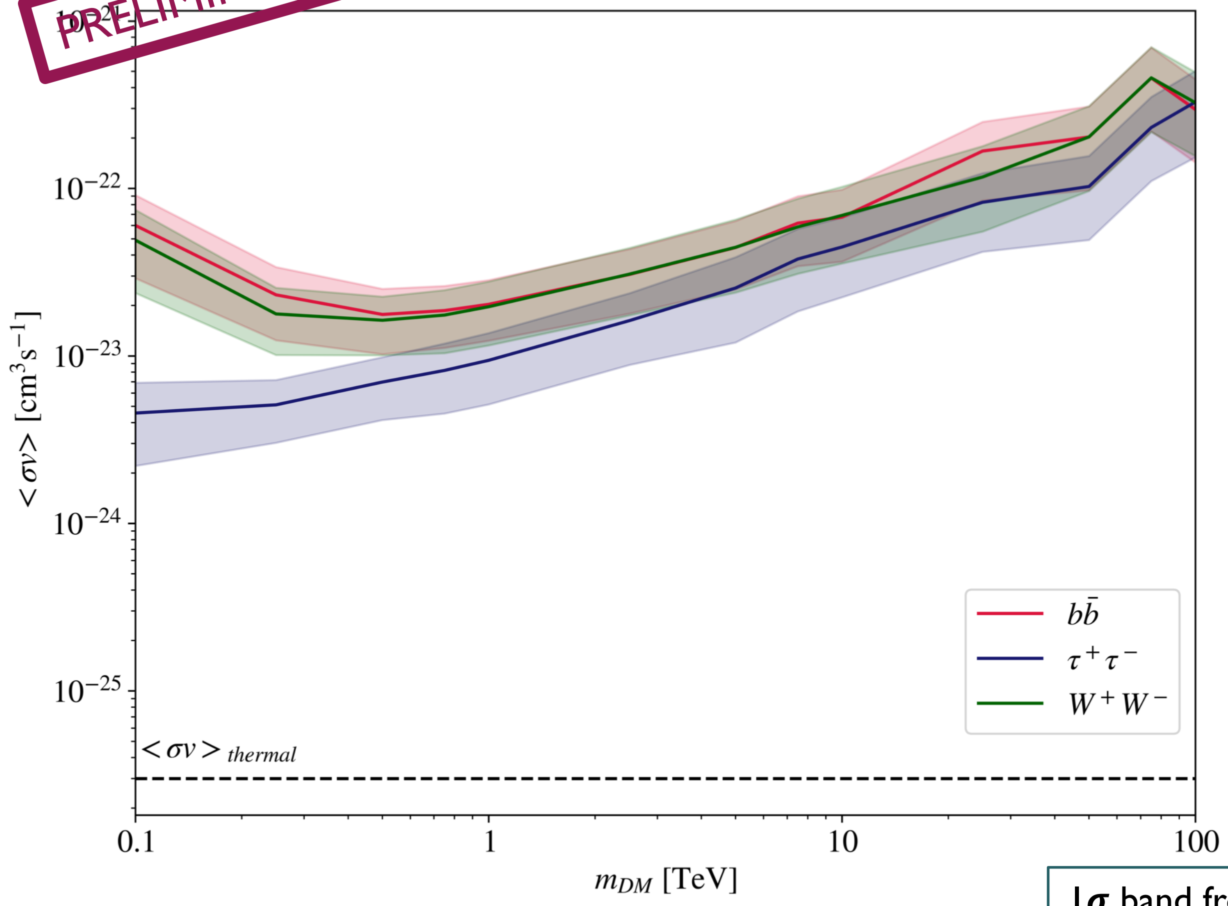
N_{obs}	50
T_{obs} [h]	300
IRFs	North_z20_50h, prod3b-v2
Obs. strategy	1 ON/ 3 OFF
Pointing $(l,\ b)$ [deg]	(150.57, -13.26)
Offset [deg]	1.0
On Region [deg]	1.0
Energy range [TeV]	0.03 - 100



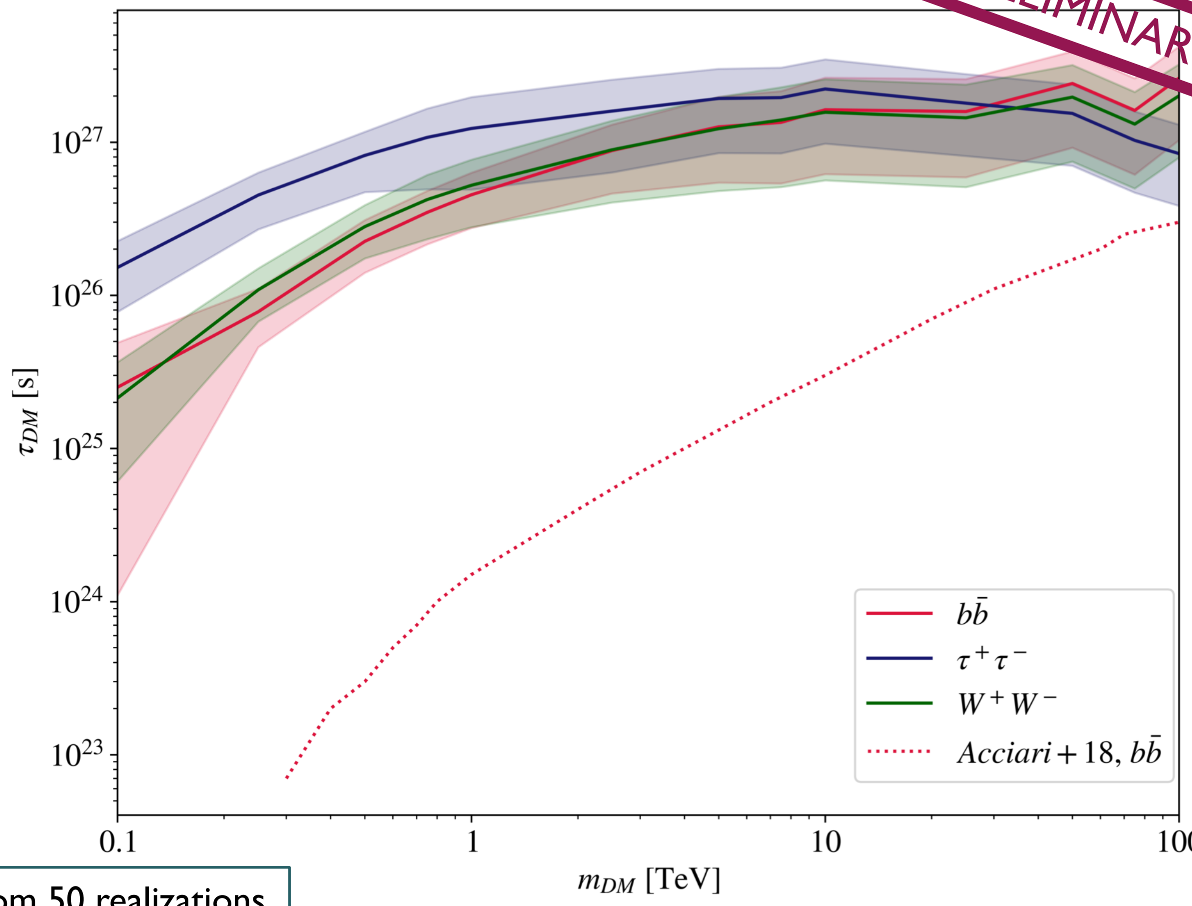
DM CONSTRAINTS

Limits for Perseus with α=1.9, assuming point-like morphology and no J/D-factor or systematic uncertainties

Annihilation



Decay



1σ band from 50 realizations

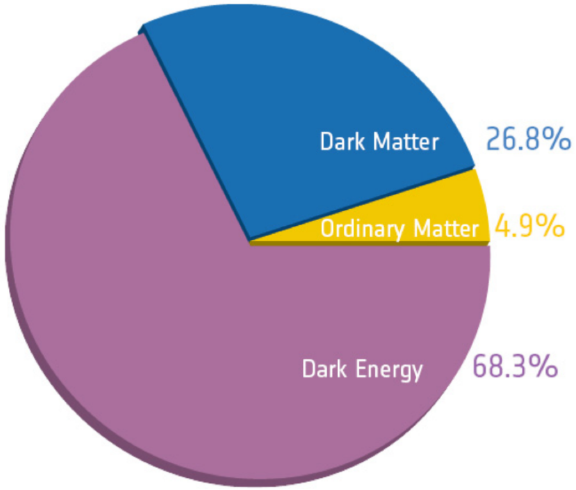
FINAL REMARKS

- CTA is the future project for VHE gamma-ray astronomy, with superb capabilities for WIMP searches.
- Perseus Galaxy Cluster has optimal conditions for observation with CTA-North
- Complete and comprehensive study of the different expected emissions ongoing: DM+CR+AGNs
- State-of-the-art DM modelling for Perseus in place including substructure
- Point-like analysis completed for annihilation and decay:
  - Annihilation upper limits of ~O(10^{-23}) cm^3 s^{-1}
  - Decay upper limits of ~O(10^{26}) s
- Ongoing extended analysis and inclusion of systematic uncertainties

Thanks for your attention!

Back-up material

DARK MATTER PARADIGM



Some observational Dark Matter (DM) evidences:

- Galactic rotational curves
- Strong and weak lensing
- CMB anisotropies

Encoded in

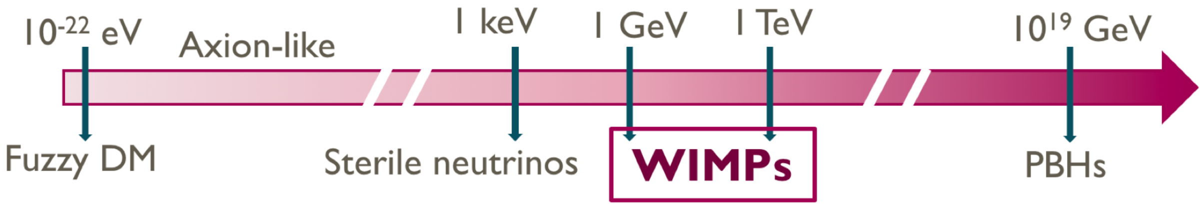
ΛCDM Cosmology

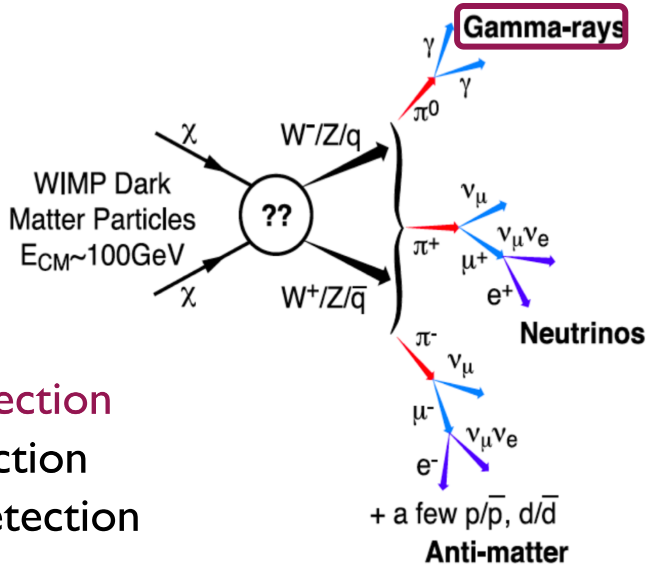
- Structure formation driven by DM
- Bottom-up scenario: smaller structures form first

↓

Parametrize the DM distribution in **Haloes and Sub-halos**

- Different DM candidates:



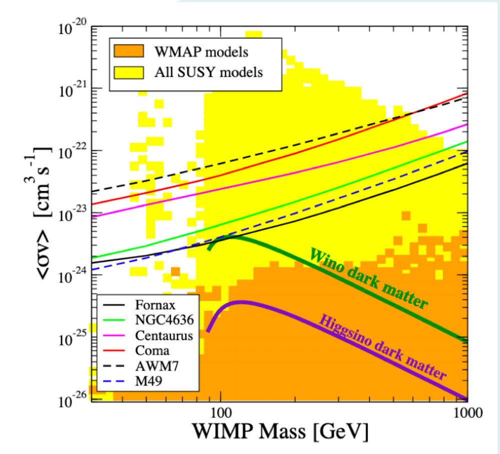


This γ-ray emission allows to perform Indirect DM Searches in Galaxy Clusters

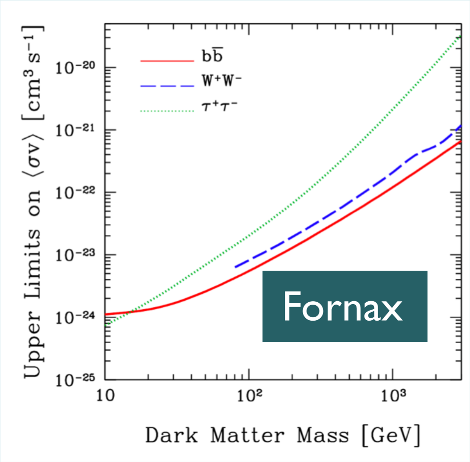
- The search for the WIMP
  - Annihilation ⟶ Indirect detection
  - Collision ⟶ Direct detection
  - Production ⟶ Colliders detection

GAMMA-RAY SEARCHES IN GALAXY CLUSTERS

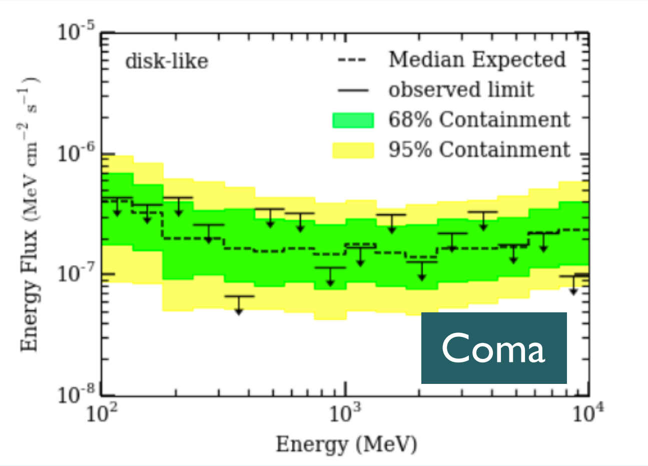
Fermi-*LAT*



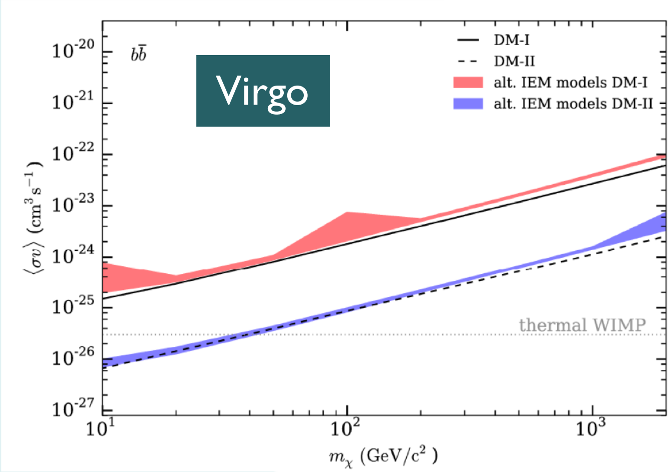
Ackermann+10 [Fermi-LAT Collab.]



Ando&Nagai12



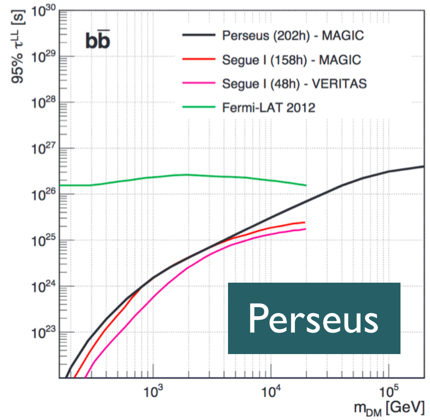
Ackermann+16 [Fermi-LAT Collab.]



Ackermann+15 [Fermi-LAT Collab.]

MAGIC

Acciari+18 [MAGIC Collab.]



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

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

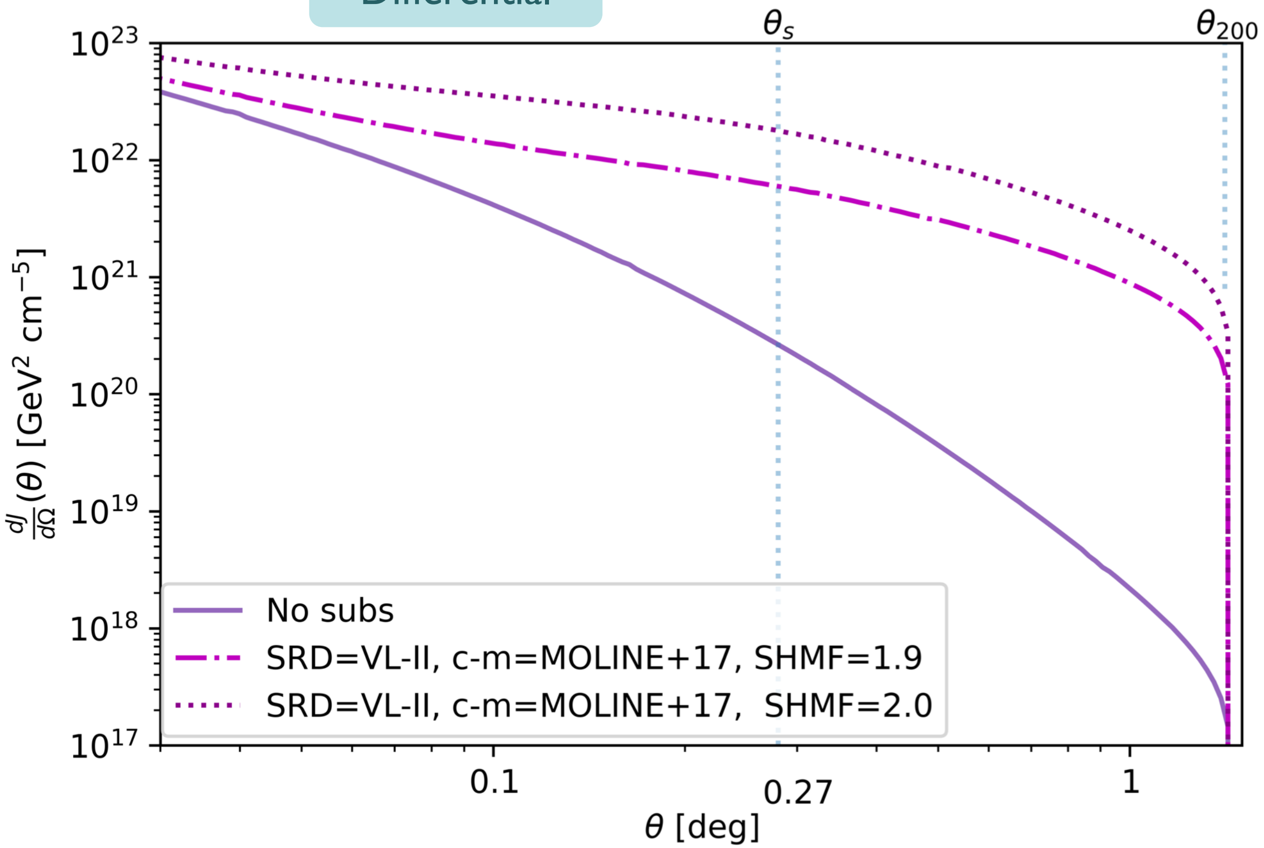
$$c_{200} = \frac{R_{200}}{r_s}$$

Angular extension

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

DIFFERENTIAL ANNIHILATION FLUX PROFILE

Differential



Agreed parameters for DM and CR models

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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

UNCERTAINTIES AND BACKGROUNDS

- Uncertainties in the J-factor enter through:

X-rays measurements

Mass modelling and extrapolations

Urban+14

Masses from other methods:

- Dynamic masses – galaxy velocity dispersion
- SZ measurements
- Other X-rays measurements

- Gamma-ray Cosmic Ray Emission:

We will produce two templates

- DM-induced gamma-ray emission

CLUMPY

- CR-induced gamma-ray emission

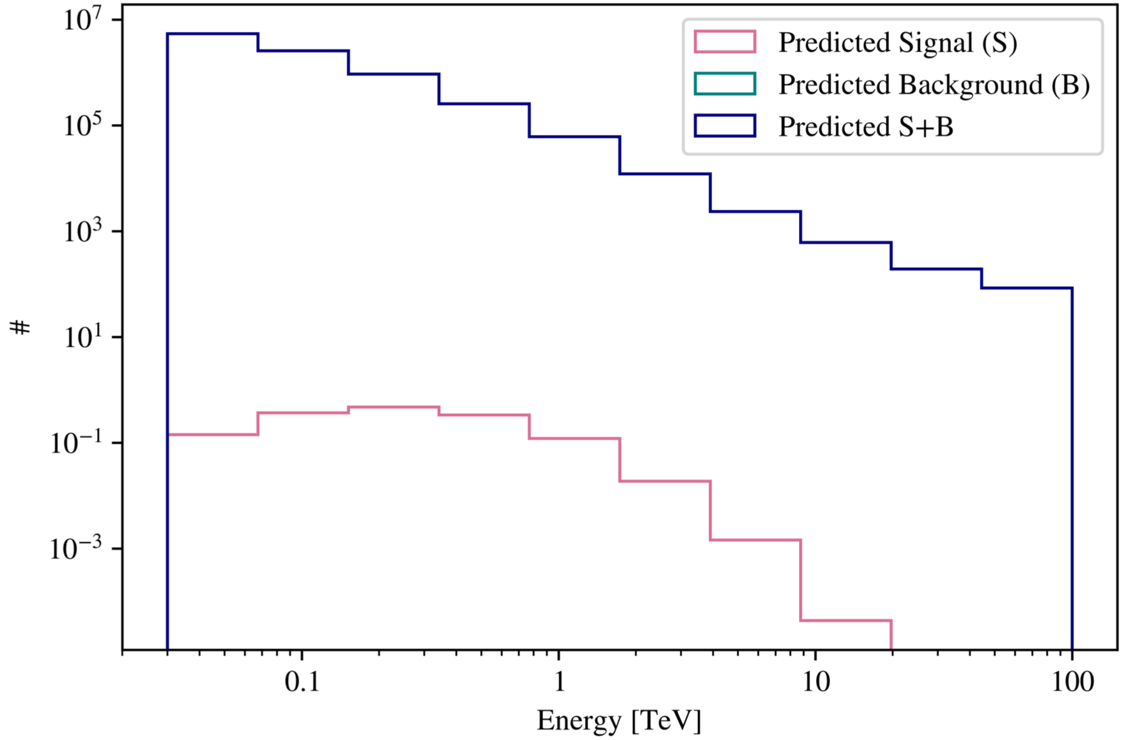
MINOT

Adam+20

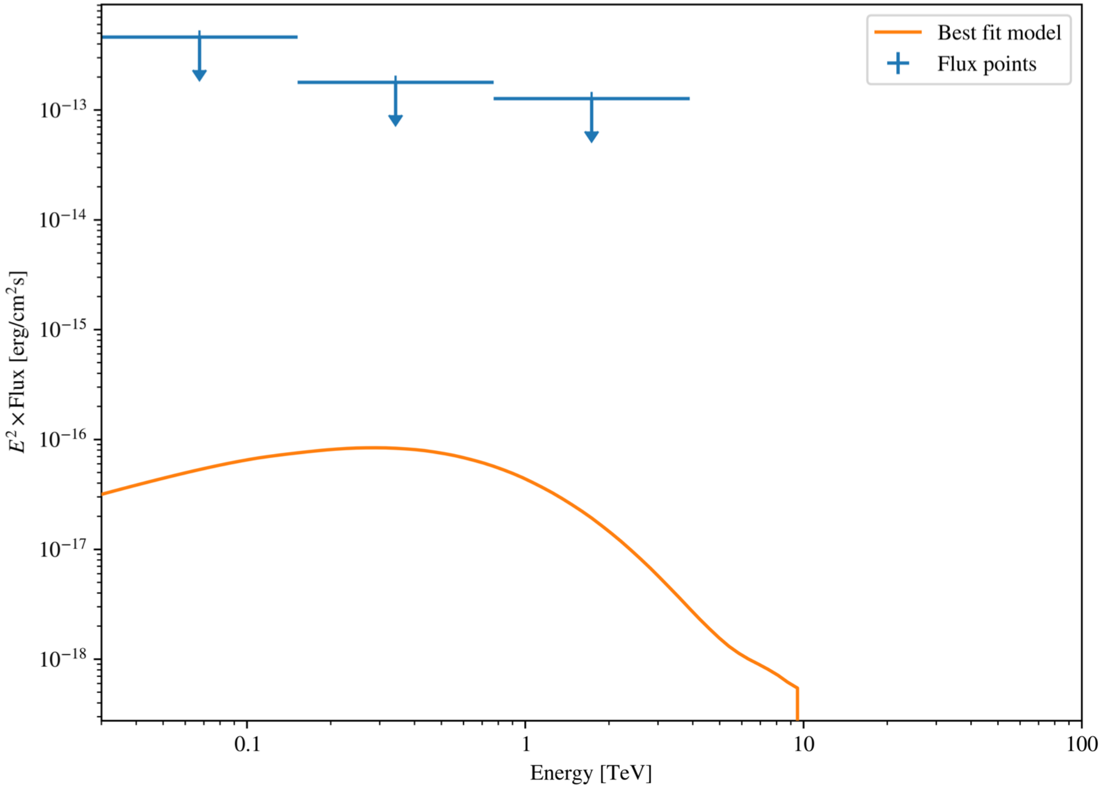
CHARACTERISTICS OF THE SIMULATIONS

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

Counts

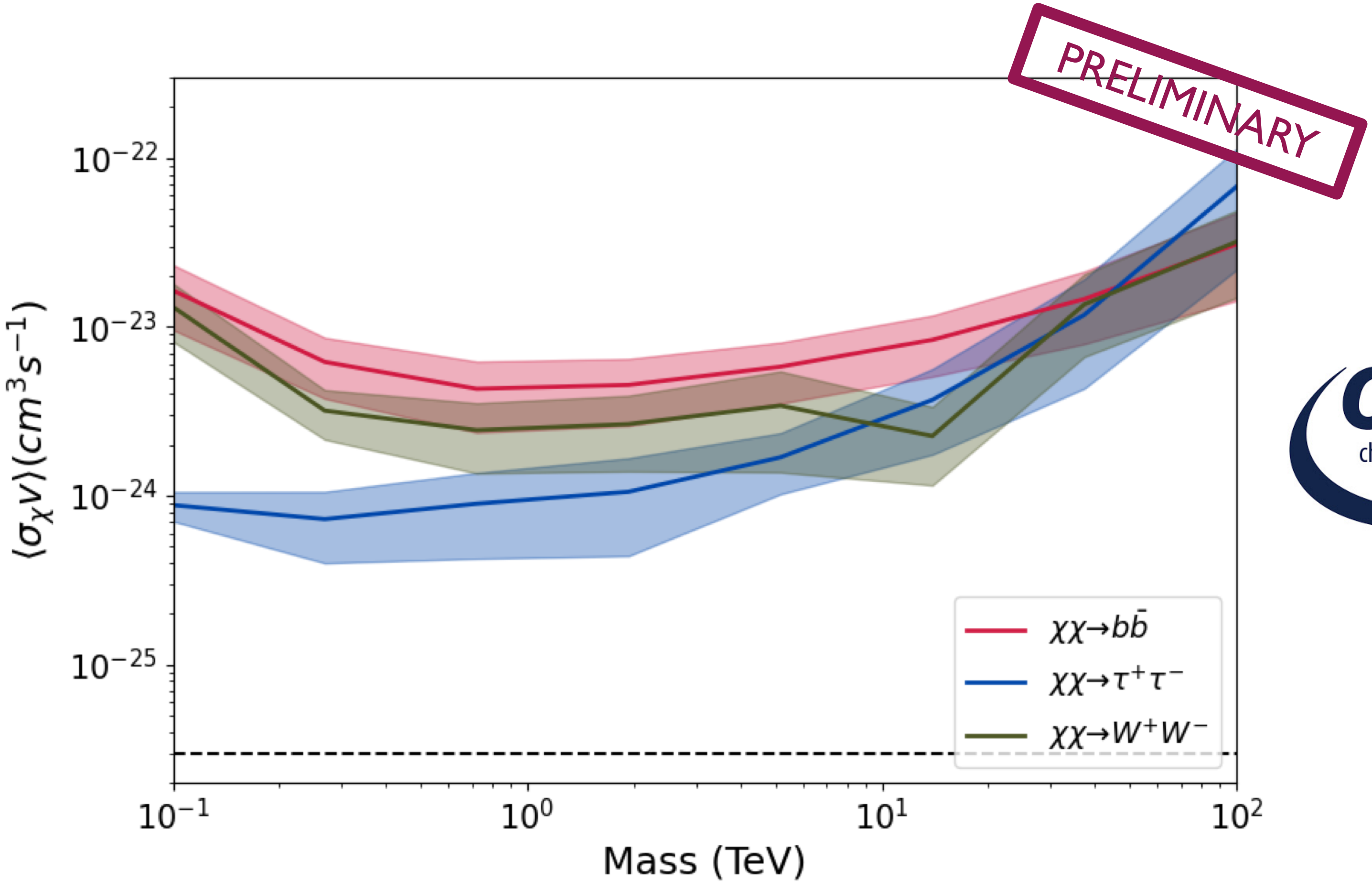


SED + ULs



DM CONSTRAINTS: CTOOLS

Limits for Perseus with substructure, assuming point-like morphology and no J-factor uncertainties



Only **On**! Will update results to On/Off observations