Dark Matter γ-ray searches in Galaxy Clusters: status and prospects

SMASH
machine learning for science and humanities postdoctoral program

Co-funded by the European Union

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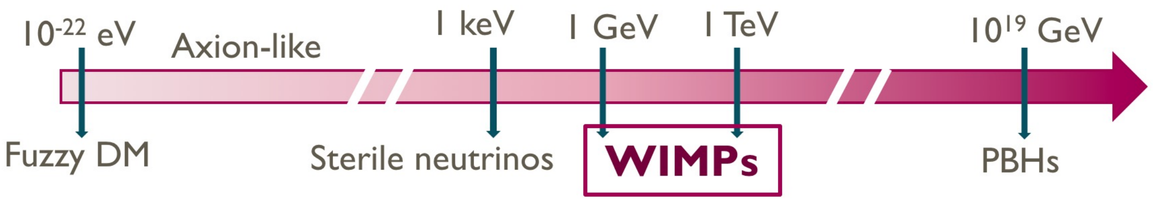
RICAP 2024 – Indirect DM Detection

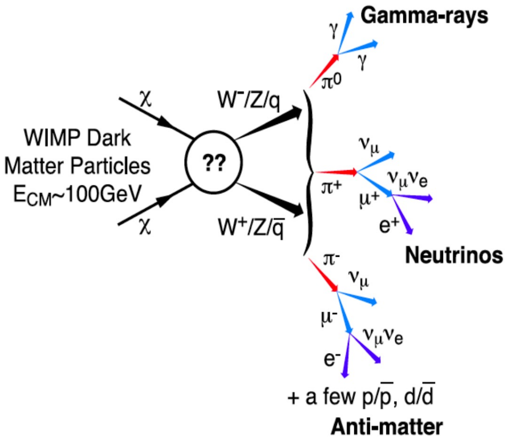
26/09/2024

AI generated image combining different algorithms interpreting:
“Gamma-rays from dark matter”

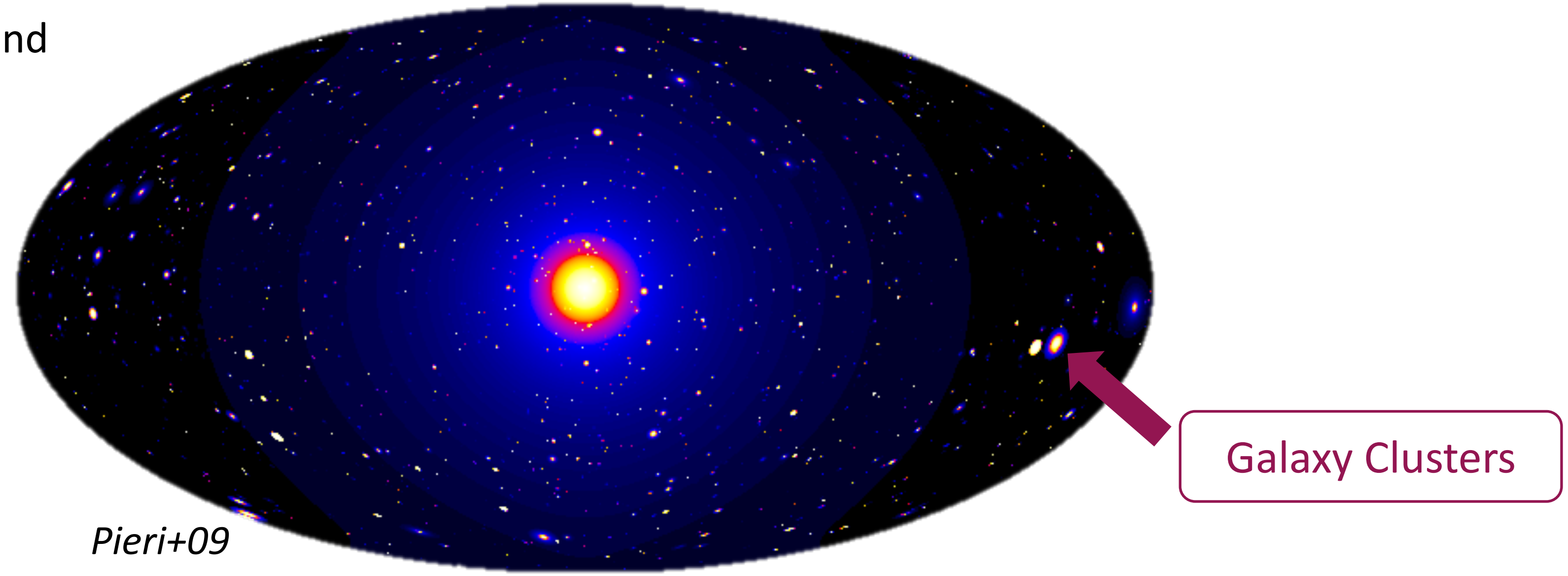
γ-RAY DM SEARCHES

- Several gravitational evidences for DM: ΛCDM Cosmology





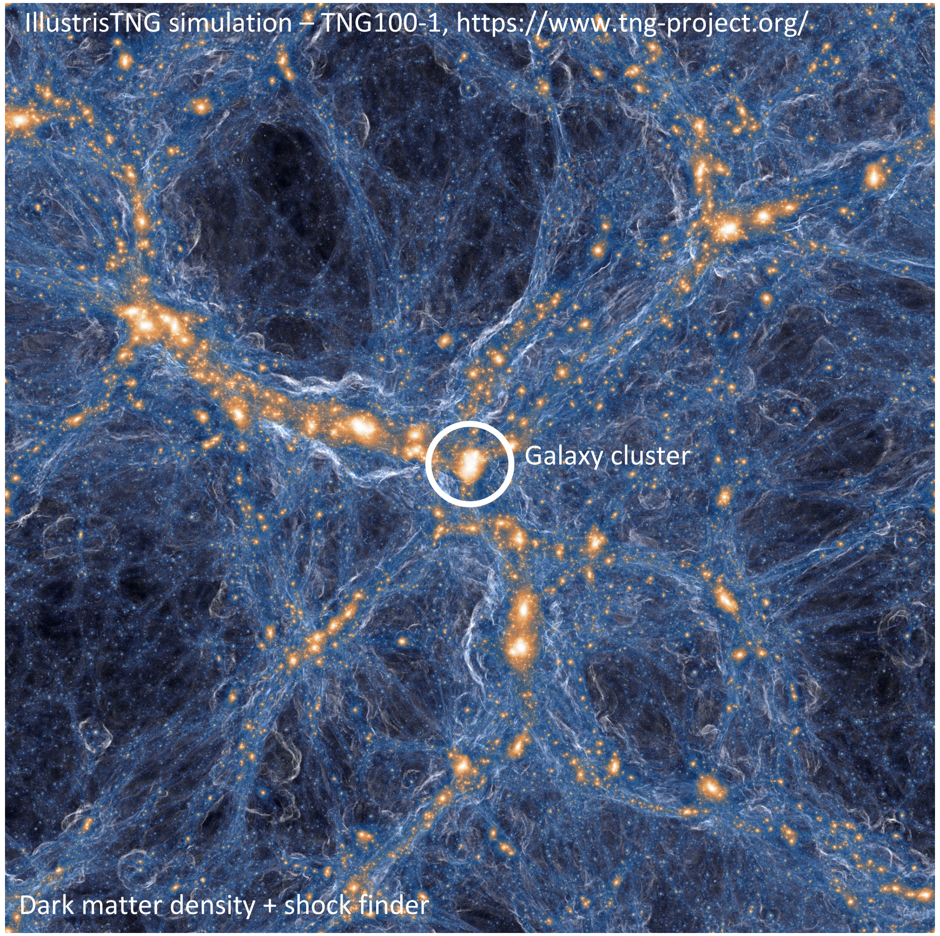
- Optimal conditions for indirect DM searches:
  - High DM density ($\phi_{\rm DM} \propto \rho_{\rm DM}{}^2$ for annihilation, $\phi_{\rm DM} \propto \rho_{\rm DM}$ for decay)
  - Massive nearby objects ($\phi_{\rm DM} \propto M/d_{Earth}{}^2$)
  - Low astrophysical background



Pieri+09

γ-RAY DM SEARCHES IN CLUSTERS

- Largest gravitationally bound structures formed by gravitational collapse
- Masses of order ~10^{14}-10^{15} $M_\odot$ ← Very massive objects ✓
- Components:
  - Baryonic Matter
  - Dark Matter (~80%) ← High DM density ✓
- Several in local Universe ← Closeby ✓



Decay • Best possible targets to consider → $\phi_{DM} \propto \rho_{DM}$

Annihilation • Competitive to other prime targets

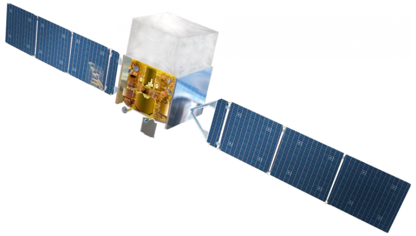
Caveat Expected γ-ray emission from astrophysical processes

γ-RAY DM SEARCHES IN CLUSTERS

How can we look for γ -ray DM-induced emission from galaxy clusters?

Present: *Fermi*-LAT

- Energy range: 400 MeV – 1 TeV
- Best sensitivity at ~200 GeV
- Angular resolution up to 0.1 deg
- 16 years of all-sky data



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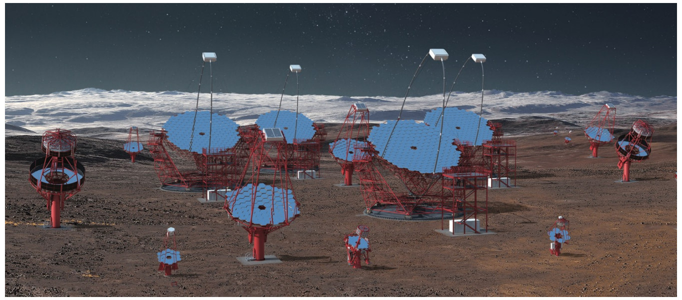
Present & Future: Cherenkov Telescope Array Observatory (CTAO)



- First telescope in operation since 2022
- Energy range: 20 GeV – 100 TeV
- Best sensitivity at ~1 TeV
- Angular resolution ~0.05 deg
- Deep dedicated surveys

Fermi Gamma-ray Space Telescope

Constraining the dark matter contribution of gamma-rays in cluster of galaxies using Fermi-LAT data
M. di Mauro, JPR, M. A. Sánchez-Conde, N. Fornengo
Phys. Rev. D 107, 083030, [arXiv:2303.16930]

CTAO

Prospects for gamma-ray observations of the Perseus galaxy cluster with the Cherenkov Telescope Array
The CTAO Consortium (corresponding authors - alphabetical: R. Adam, M. Hütten, JPR, M. A. Sánchez-Conde, S. Hernández Cadena)
Accepted for JCAP, [arXiv:2309.03712]

FERMI-LAT TARGET SELECTION

- *Fermi*-LAT does not have constraints on observation time → **Sample of best clusters for DM searches**
- Selection criteria:
  - Well-known M_{200} from X-rays measurements

    Masses from *Schellenberger&Reiprich17* (X-rays data from Chandra)
  - Local clusters

    $z < 0.1$
  - Mask of $|b| < 20$ deg to avoid Galactic diffuse emission
  - Separation of at least 2 deg to account for cluster extension

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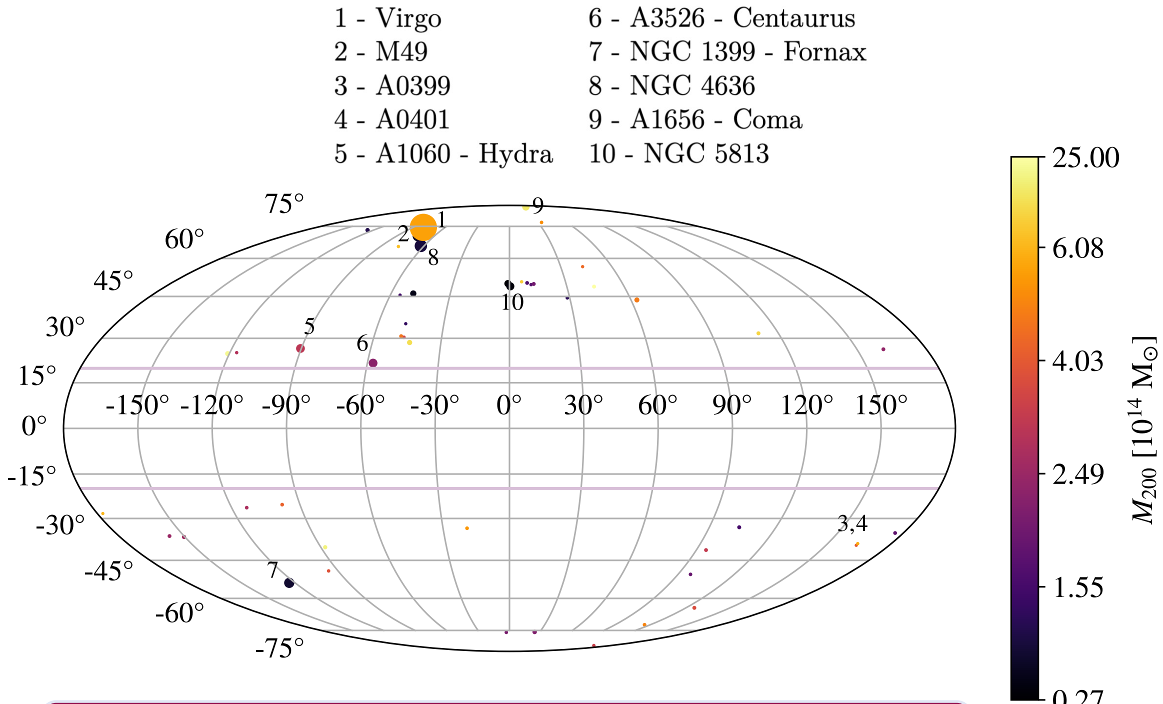
HIFLUGCS catalogue (*Reiprich&Böhringer02*)

- Clusters used in previous searches



Sample of 49 local galaxy clusters

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

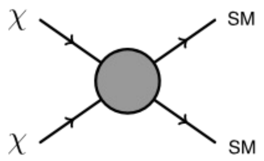
Cirelli+12 (EW corrections)

Charbonnier+12, Bonnivard+15, Hütten+18

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

Annihilation

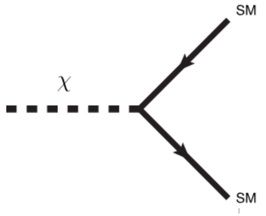
$$J(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega}\int_{l.o.s} \rho^2_{DM}(r)dr \rightarrow J \propto \frac{M_{200}c^3_{200}}{D^2_{\text{Earth}}}$$



DM density profile

Decay

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



3. Combined analysis with *Fermi*-LAT, [2303.16930]

CLUSTERS DM 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

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

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

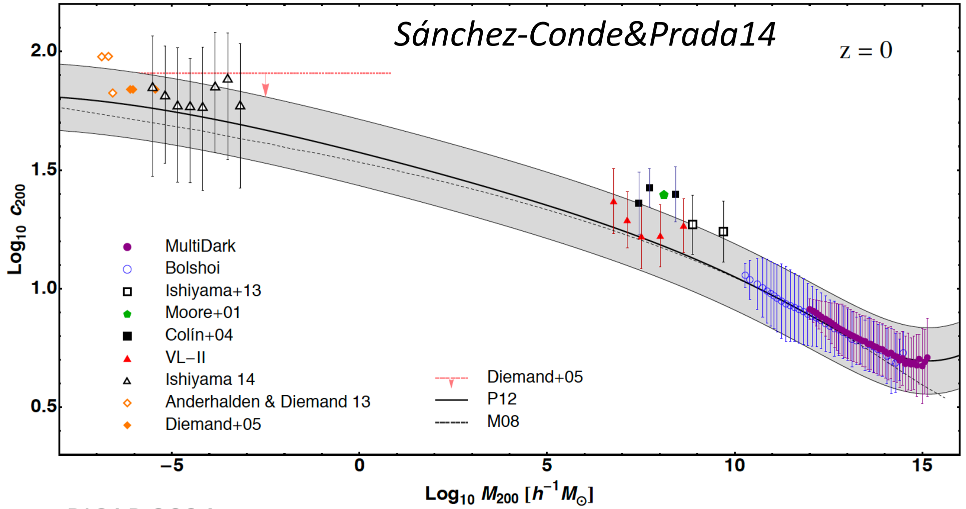
Assume density profile

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

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

  - "Cuspy"-like profile

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



3. Combined analysis with *Fermi*-LAT, [2303.16930]

CLUSTERS DM MODELLING (II): SUBSTRUCTURES

- 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

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

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

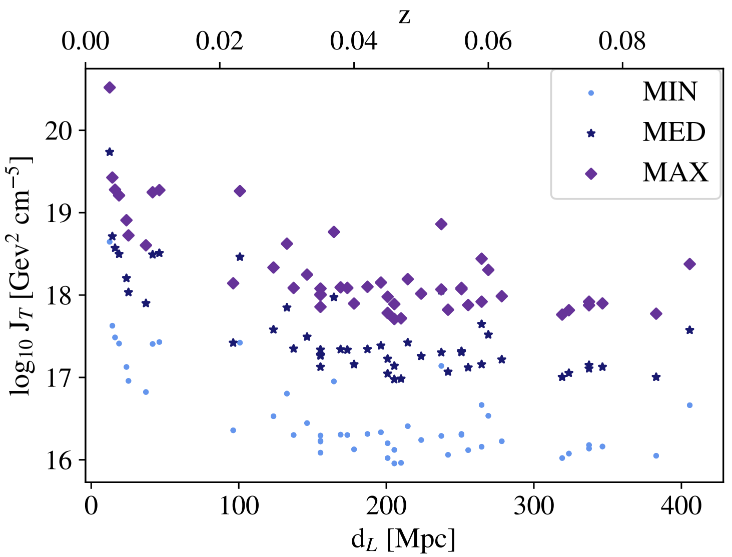
CLUMPY

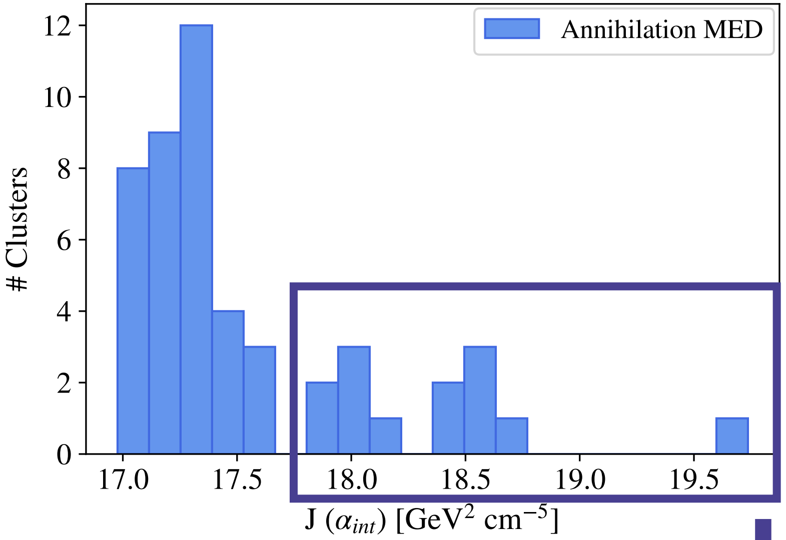
- We define benchmark models to encapsulate the uncertainty on the expected substructure population:
  - No substructure considered → MIN
  - Best guess → MED
  - Educated upper bound → MAX

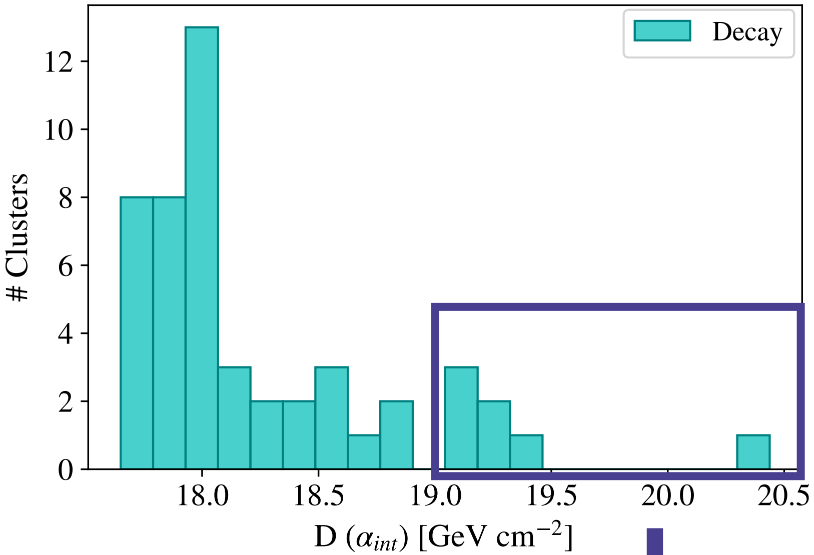
Model	SRD	α	$c(M)$	M_{min}	f_{sub}
MIN	-	-	-	-	-
MED	VL-II (*Diemand+08*)	1.9	*Moliné+17*	$10^{-6}\ M_\odot$	0.18
MAX	Aquarius (*Springer+08*)	2.0	*Moliné+17*	$10^{-9}\ M_\odot$	0.34

- Will reflect in different levels of contribution to the total J-factor

DM ANNIHILATION/DECAY FLUXES OF THE SAMPLE







Cluster	z	M_{200} [10^{14} M$_\odot$]	R_{200} [kpc]	θ_{200} [deg]	$\log_{10} J_{MIN}$ [GeV^{2}cm^{-5}]	$\log_{10} J_{MED}$ [GeV^{2}cm^{-5}]	$\log_{10} J_{MAX}$ [GeV^{2}cm^{-5}]	$\log_{10} D$ [GeV cm^{-2}]
Virgo	0.0036	5.60	1700	6.32	18.65	19.74	20.52	20.44
NGC 4636	0.004	0.53	777	2.61	17.63	18.71	19.43	19.33
M49	0.0044	0.46	741	2.26	17.49	18.57	19.28	19.18
A1060-Hydra	0.011	2.97	1376	1.70	17.43	18.51	19.27	19.19
A1656-Coma	0.023	13.16	2260	1.35	17.42	18.46	19.26	19.20
NGC 1399-Fornax	0.005	0.51	763	2.05	17.41	18.50	19.21	19.11
A3526-Centaurus	0.01	2.27	1258	1.70	17.41	18.49	19.25	19.16
A754	0.053	25.00	2800	0.75	17.14	18.05	18.86	18.82
NGC 5813	0.0064	0.27	620	1.31	16.96	18.03	18.72	18.62
A3571	0.037	10.90	2123	0.80	16.95	17.97	18.77	18.71

3. Combined analysis with *Fermi*-LAT, [2303.16930]

FERMI-LAT ANALYSIS SET-UP

Baseline set-up

Years of *Fermi* data	12
IRFs	P8R3_SOURCEVETO_V2
Energy range [GeV]	0.5 – 1000
Bins per decade	8
Region of Interest (ROI) [deg^2]	20 x 20
Pixel size [deg]	0.08
Catalogue	4FGL-DR2

- Standard template Fermi analysis
- Combined likelihood:

$$\log(\mathcal{L}_j(\mu_\chi, \nu_j | \mathcal{D}_j)) = \sum_i \log(\mathcal{L}_{i,j}(\mu_\chi, \nu_{i,j} | \mathcal{D}_{i,j}))$$

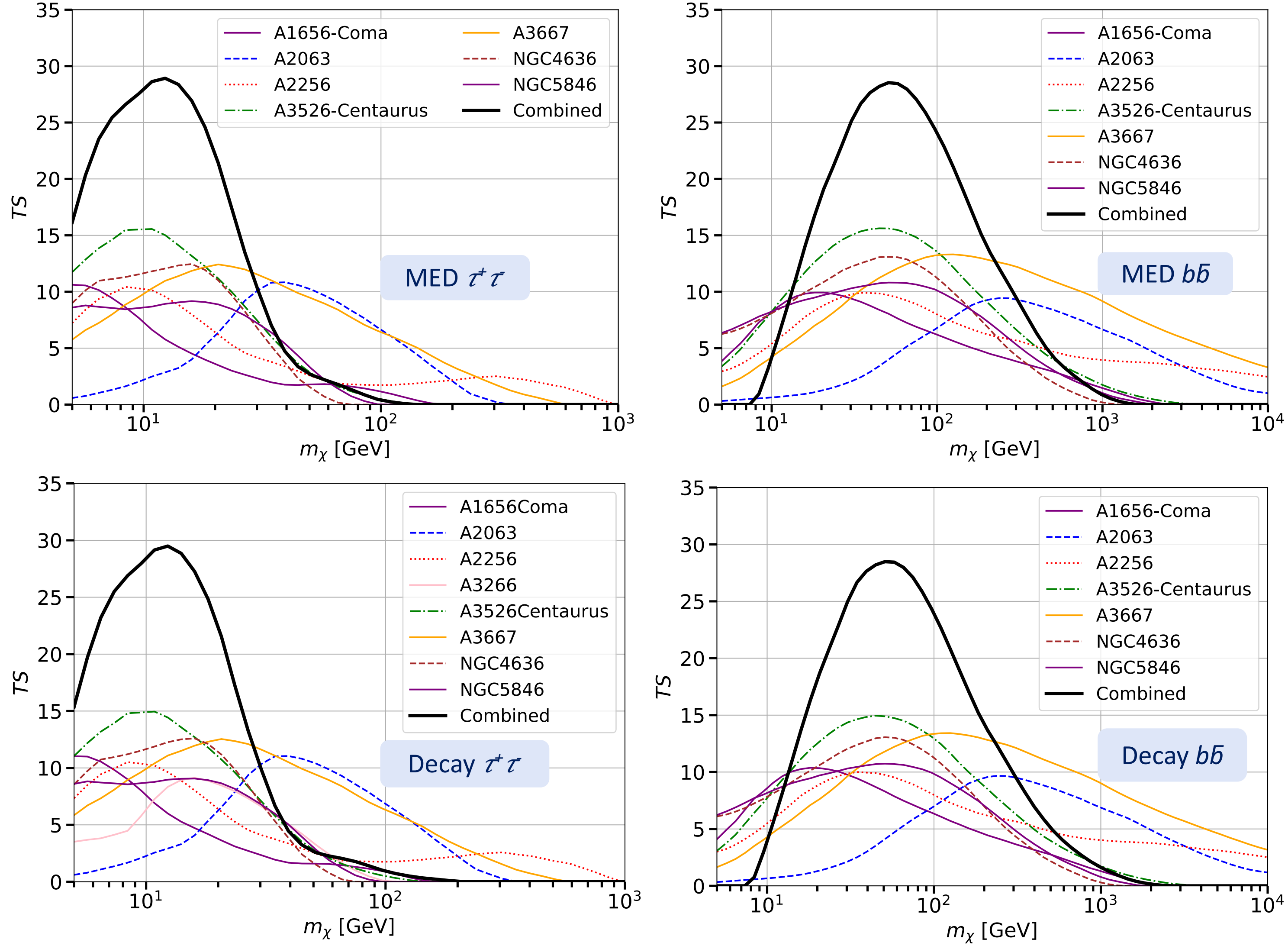
$$TS = 2 \ln \frac{\mathcal{L}(\mu, \hat{\hat{\nu}} | \mathcal{D})}{\mathcal{L}_{null}(\mu = 0, \hat{\nu} | \mathcal{D})}$$

- $TS < 25$ ➡ No signal

- Tested different set-ups for energy range, Region of Interest (RoI), IRFs and Background (BKG) models
- Background components:
  - Individual point-sources from LAT (4FGL-DR2) + search for new ones not included in catalogue
  - Fermi bubbles
  - Loop I + Sun + Moon
  - Isotropic emission
  - Galactic Interstellar Emission (IEM)

} Divided in: Bremsstrahlung + π^0 + Inverse Compton (CMB + starlight + Infrared)
Ackerman+17 [Fermi Collab.]

TS OF THE BENCHMARK MODELS



Individual *TS*

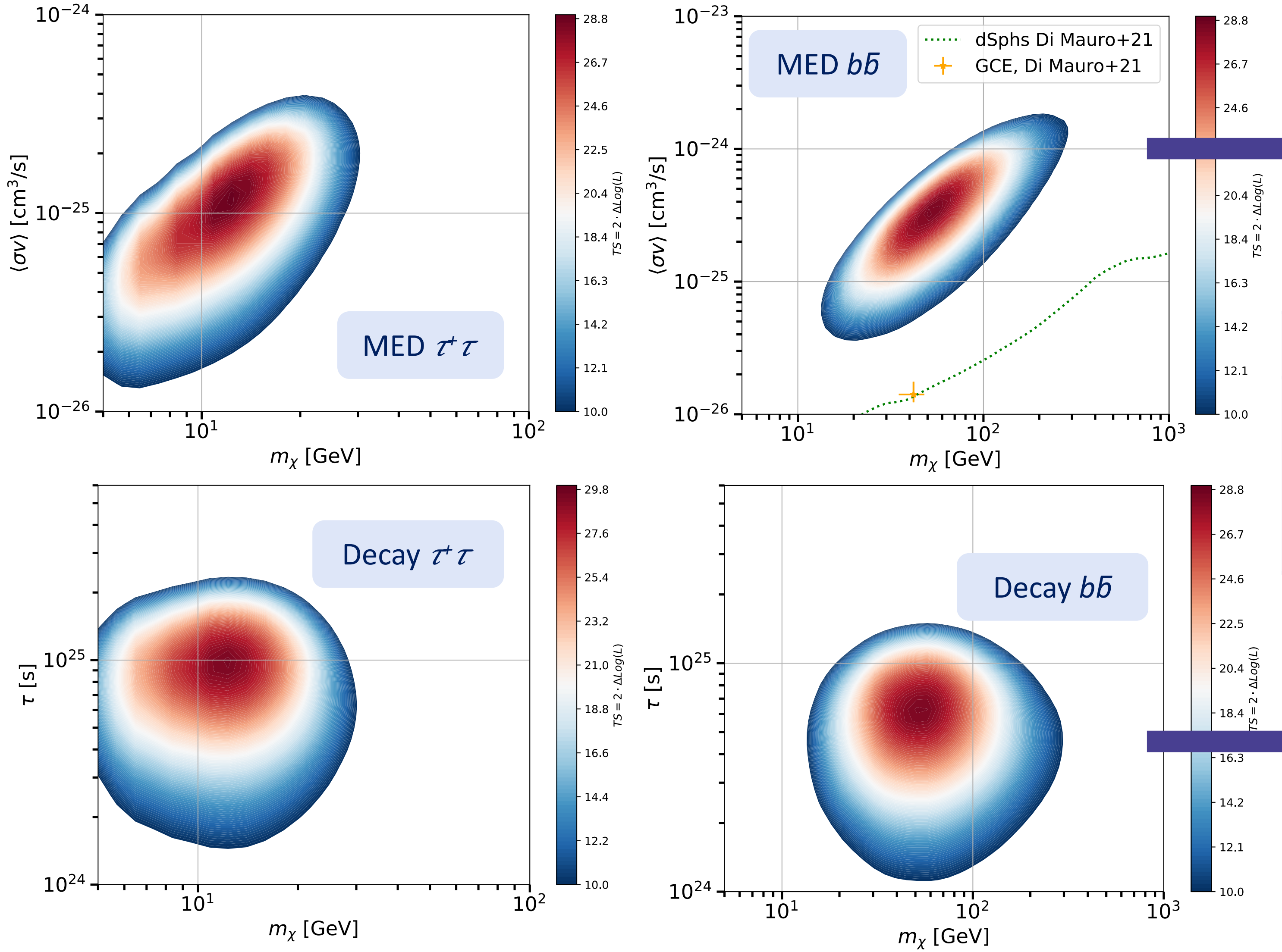
- Highest **A3526-Centaurus** – *TS* = 15
- A1656-Coma – *TS* ~10 (*Ackermann+17 [Fermi Collab.]*)

Combined *TS*

MIN	No sig.
MED	*TS* = 27
MAX	*TS* = 23
DECAY	*TS* = 28

3. Combined analysis with *Fermi*-LAT, [2303.16930]

TS VALUES INTERPRETED AS DM



- Not compatible with GC excess
- Ruled out by dSphs

	$b\bar{b}$ (40 - 60 GeV)	$\tau^+\tau^-$ (8-20 GeV)
MED	2-4 x 10^{-25} cm^{3}s^{-1}	8-20 x 10^{-26} cm^{3}s^{-1}
MAX	4-9 x 10^{-26} cm^{3}s^{-1}	1-3 x 10^{-26} cm^{3}s^{-1}
DECAY	5-8 x 10^{24} s	8-12 x 10^{24} s

- Ruled out by Isotropic γ–ray Background (IGRB) and GC

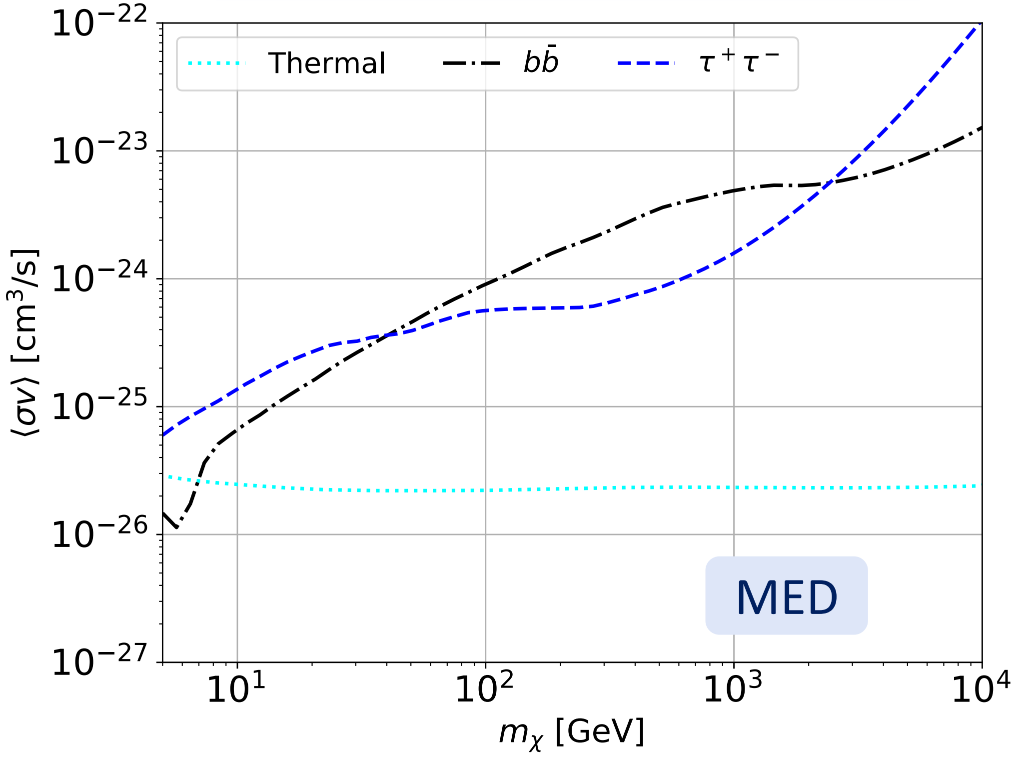
Blanco&Hooper18, Ando&Ishiwata15, Ackermann+12 [Fermi Collab.]

3. Combined analysis with *Fermi*-LAT, [2303.16930]

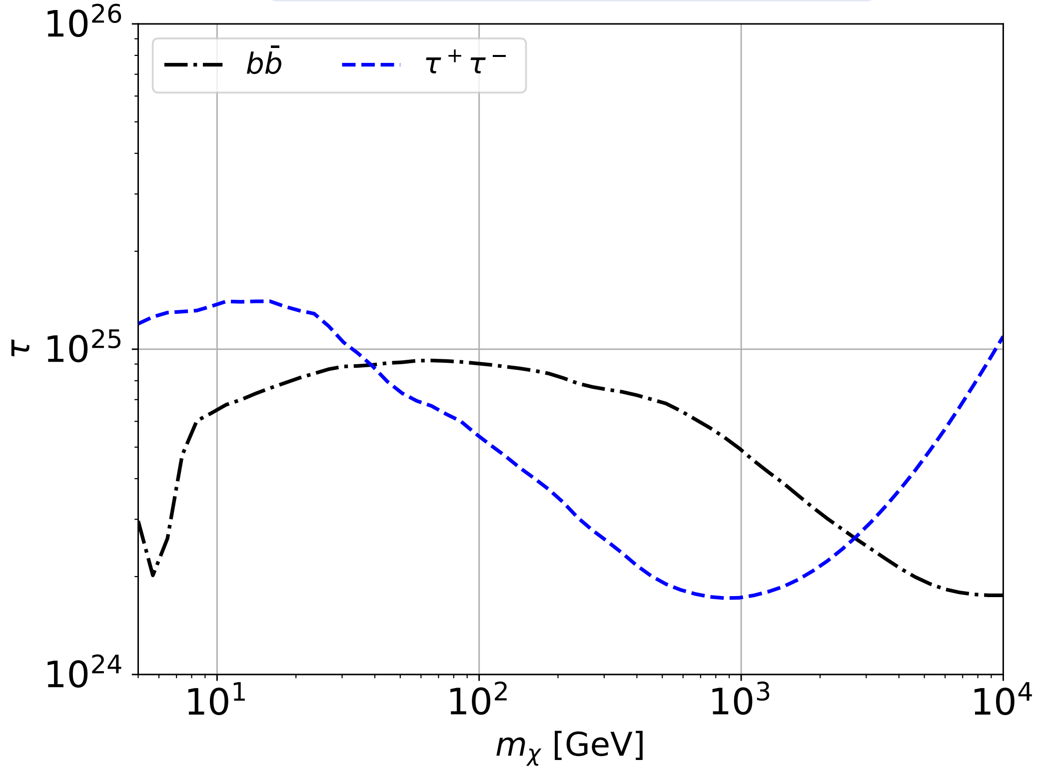
DM CONSTRAINTS FROM COMBINED CLUSTERS ANALYSIS

- We build the *TS* distribution for the null hypothesis using the same set-up: *TS* = 27 for MED ➡ *p* –value = 3.1 x 10^{-3} ➡ 2.7σ
- The signal is not significant and if interpreted as DM, is not compatible with existing limits

Annihilation 95% C.L. Upper Limits



Decay 95% C.L. Lower Limits



3. Combined analysis with *Fermi*-LAT, [2303.16930]

PERSEUS GALAXY CLUSTER WITH CTAO: A KEY SCIENCE PROJECT

CTAO's sensitivity improves more than *O*(1) magnitude that of current IACTs: superb capabilities to detect TeV DM

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

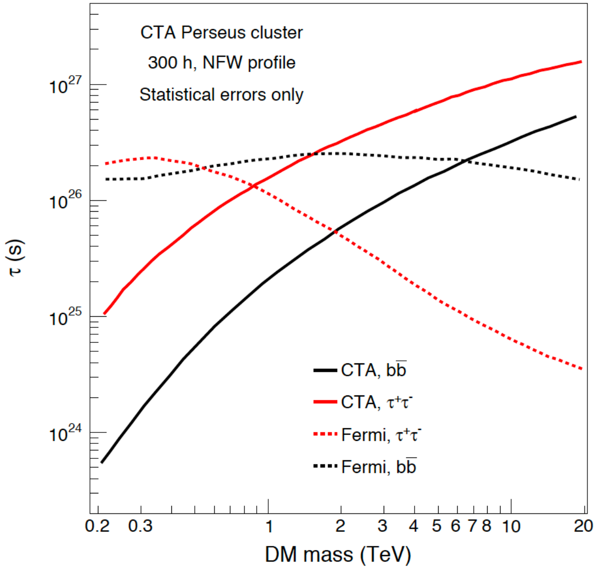
Object	l [deg]	b [deg]	d_L [Mpc]
Perseus	150.57	-13.26	75.01

- Hosts two Active Galactic Nuclei (AGN), both variable

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

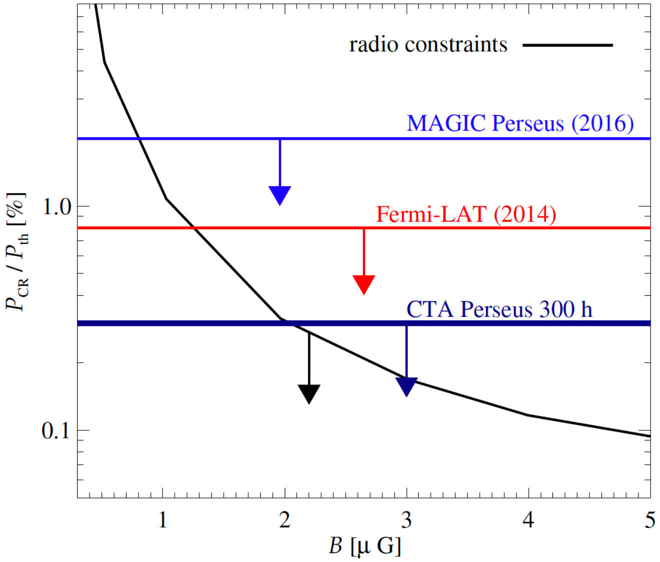
NGC 1275 aligned with X-rays centre

Optimal conditions for observation from the northern array



Prospects of constraints for DM decay

Acharya+17 [CTAO Cons.]



Prospects of constraints for CR models

PERSEUS DM MODELLING

- Follow similar strategy: $\langle \rho_{\rm tot} \rangle(r) = \rho_{\rm sm}(r) + \langle \rho_{\rm subs} \rangle(r)$
  I. Model de main halo;

NFW

$\rho_{\rm sm} \rightarrow \rho(r) = \dfrac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$ + $(c_{200} - M_{200})$

Navarro+96, Navarro+97

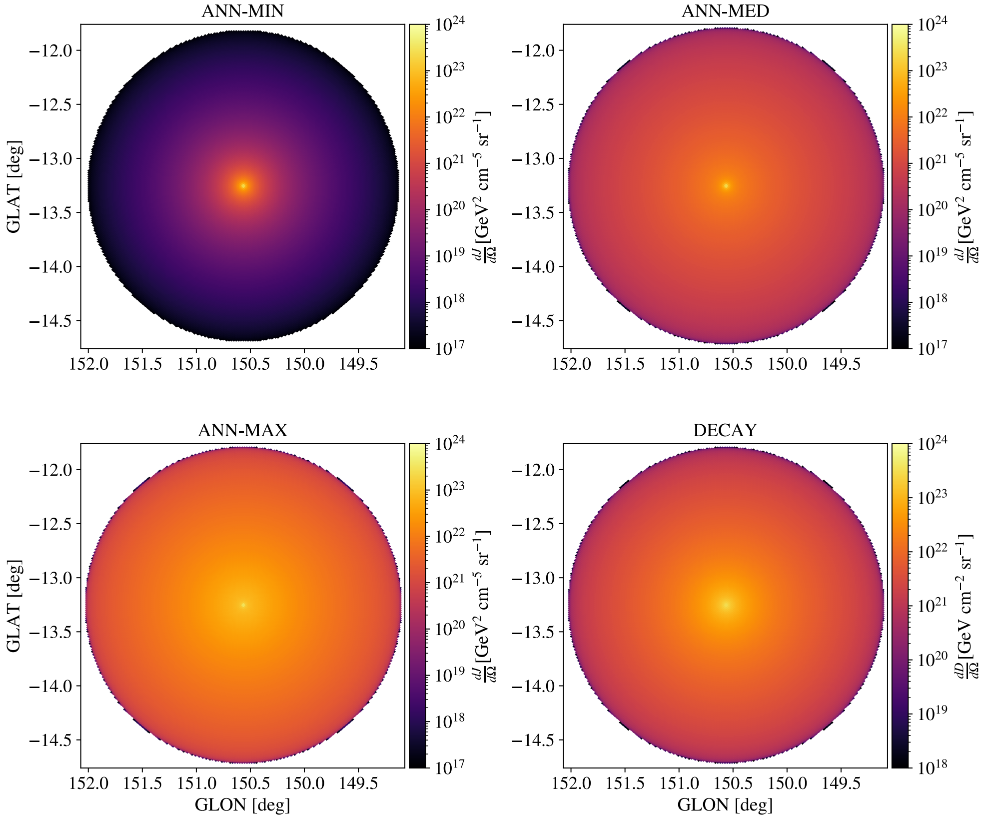
Sánchez-Conde &Prada14

  II. Model de substructure population defining benchmark models

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

Model	SRD	$(c-M)_{sub}$	α	f_{sub}	M_{min}
MIN	-	-	-	0	-
MED	*Antibiased* VL-II (*Diemand+08*)	*Moliné+17*	1.9	0.182	$10^{-6} M_\odot$
MAX	*Antibiased* VL-II (*Diemand+08*)	*Moliné+17*	2.0	0.319	$10^{-6} M_\odot$

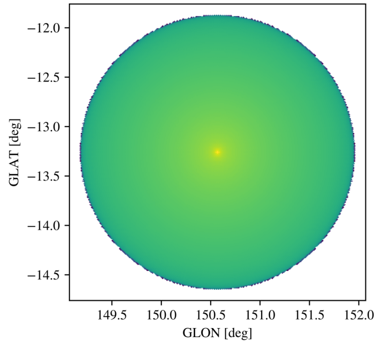
Annihilation	$\log_{10} J$ [GeV^{2}cm^{-5}]
MIN	17.42
MED	18.43
MAX	19.20
Decay	$\log_{10} D$ [GeV cm^{-2}]
	19.20



CTAO DM ANALYSIS ROADMAP

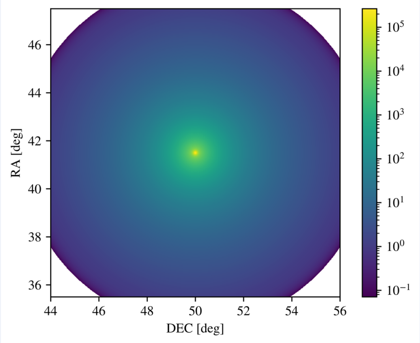
- Different γ-ray sources in Perseus region:

Total DM-induced $\boldsymbol{\gamma}$-rays



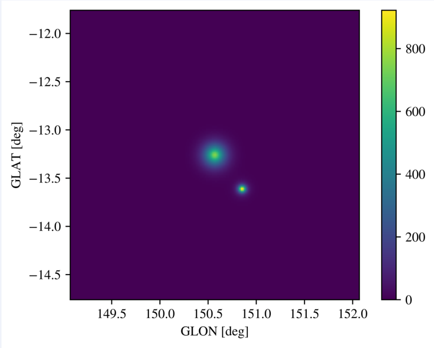
Our signal

Total CR-induced $\boldsymbol{\gamma}$-rays



Use as BKG

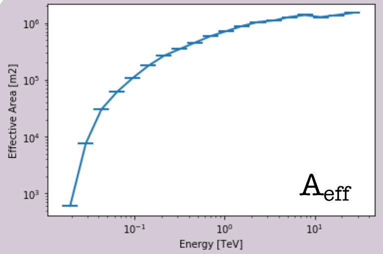
$\boldsymbol{\gamma}$-rays from AGNs

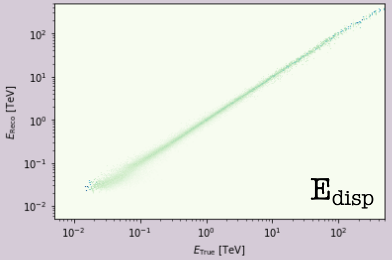


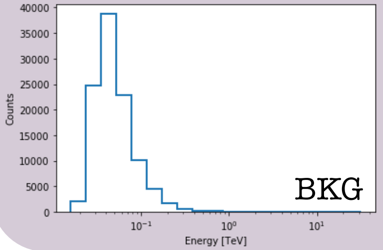
Use as BKG

- Fitting 8 parameters in total

$$\vec{\theta} \equiv \left(A_\chi, A_{\rm CR}, A_{\rm PS}^{(1,2)}, \alpha_{\rm PS}^{(1,2)}, A_{\rm bkg}, \alpha_{\rm bkg}\right)$$







CTAO IRFs

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

Observation Simulation

If no signal found

$$TS = 2\,\log\left[\frac{\mathcal{L}\left(A_\chi, \hat{\hat{\nu}}\right)}{\mathcal{L}_{\rm null}\left(A_\chi = 0, \hat{\hat{\nu}}\right)}\right]$$

Constraints on DM models

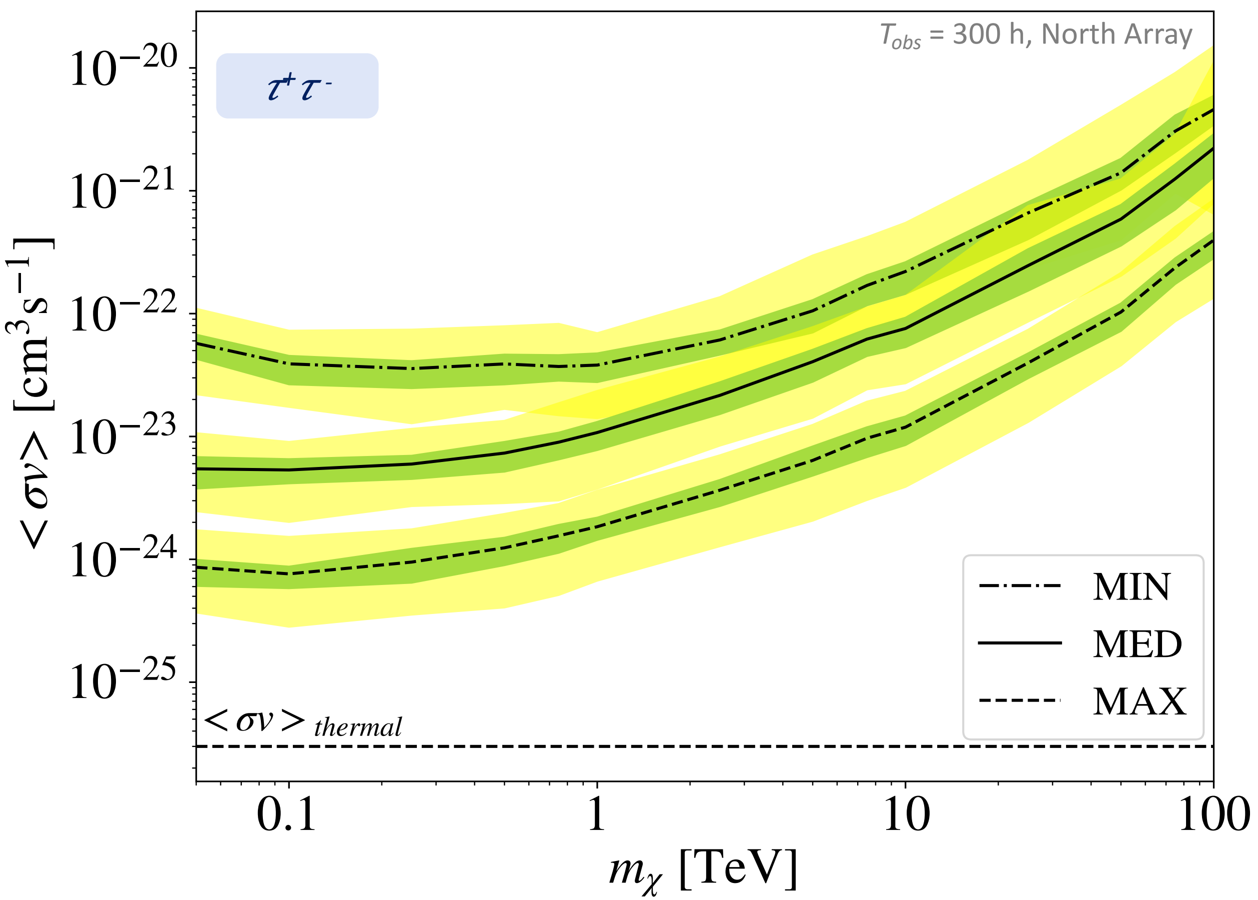
$$\frac{d\Phi_\chi^{Ann}}{dE} = \frac{<\sigma v>}{8\pi m_\chi^2}\frac{dN}{dE} \times J$$

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

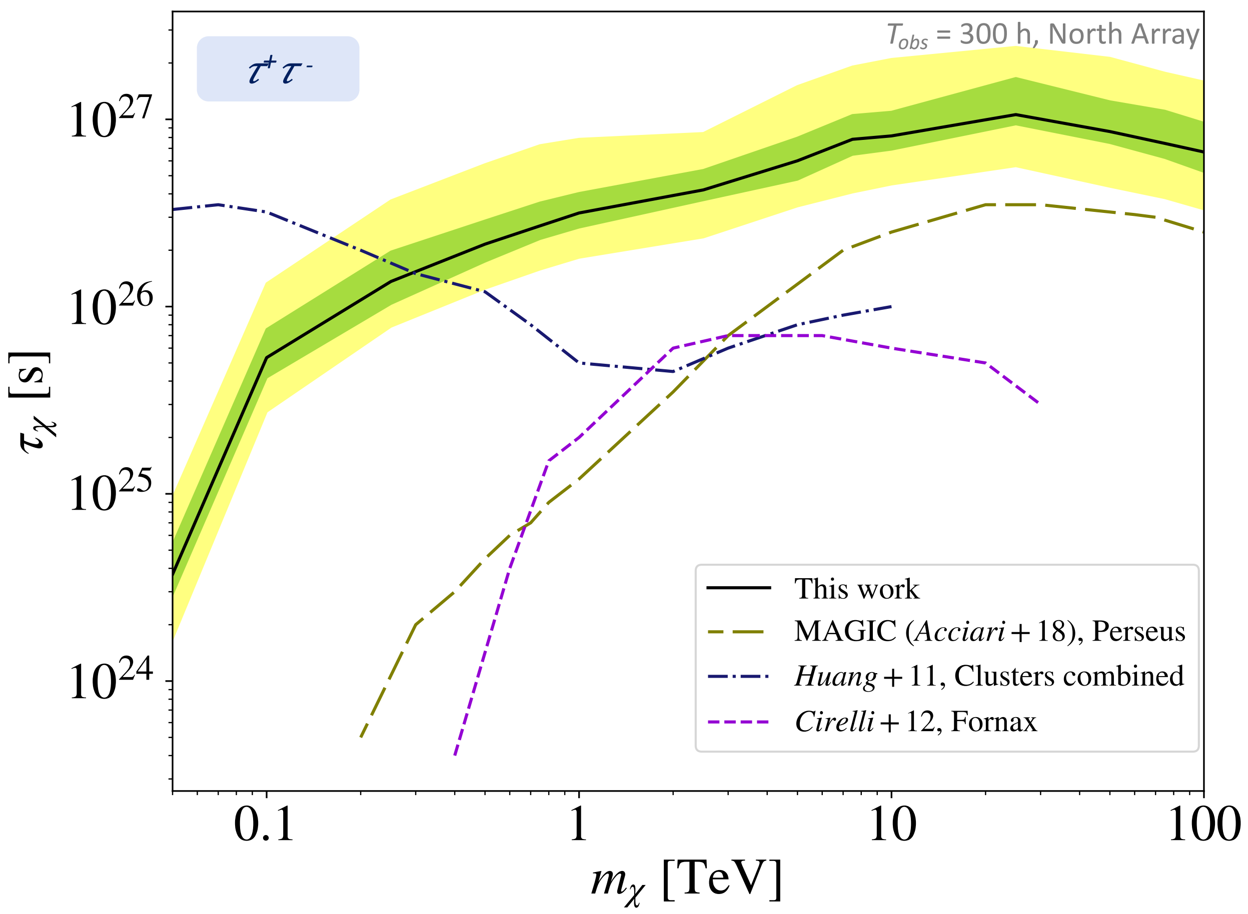
4. CTAO prospects from Perseus, [2309.03712]

CTAO ANALYSIS: DM PROSPECTS FOR CONSTRAINTS

Annihilation 95% C.L Upper Limits



Decay 95% C.L. Lower Limits



4. CTAO prospects from Perseus, [2309.03712]

SUMMARY AND CONCLUSIONS

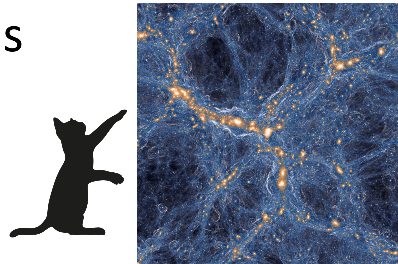
- We have focused on searching for WIMPs through the γ-ray channel
- Galaxy clusters are among the best targets to search for DM-induced γ-ray emission

Present: *Fermi*-LAT

- Construction of the **sample of best galaxy clusters** to search for DM in γ-rays with state-of-the-art modelling of subhalo population
- Template-fitting analysis using 12 years of LAT data with combined likelihood
- “Signal” from combined analysis at $m_\chi \sim O(10)$ GeV with $\langle \sigma v \rangle \sim 10^{-25}-10^{-26} \mathrm{cm^3 s^{-1}}$ or $\tau_\chi \sim 10^{24}$ s
- Significance **2.5 – 3σ** (pre-trials), uncertain origin

Present & Future: CTAO

- State-of-the-art DM modelling for Perseus: decay & annihilation + subhalo population through benchmark models
- Simulations of CTAO observations: CRs + NGC 1275 + IC 310 + BKG IRFs
- State of the art use of template fitting analysis in IACTs
- DM annihilation: most constraining results from cluster searches
- DM decay: **most constraining results** in the literature



Thanks for your attention

SMASH
machine learning for science and humanities postdoctoral program

Co-funded by the European Union

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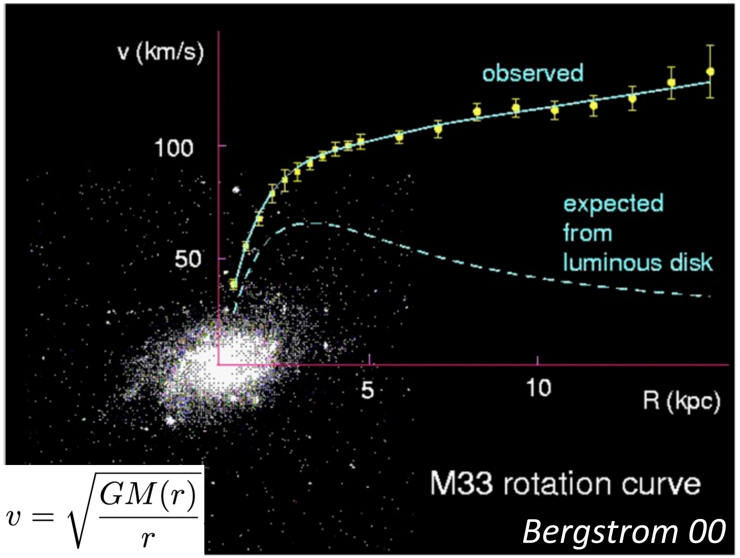
BACK UP MATERIAL

DARK MATTER (DM) EVIDENCE

Galactic scales

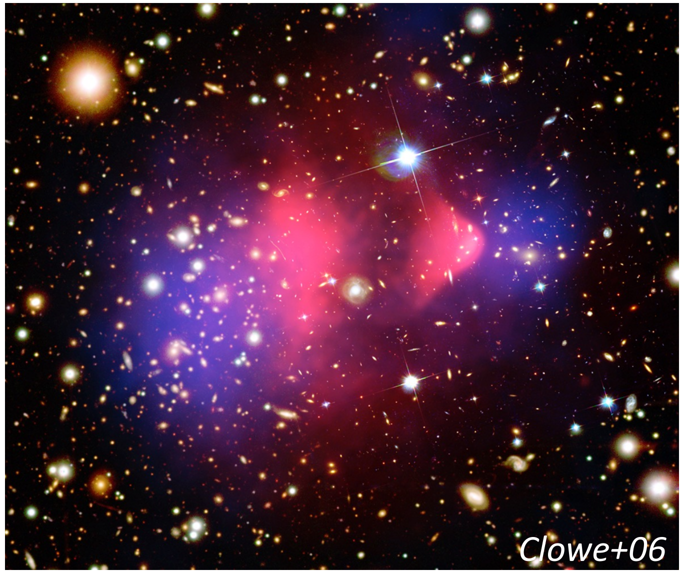


$$v = \sqrt{\frac{GM(r)}{r}}$$

Bergstrom 00

- Rotational curves
- Velocity dispersion

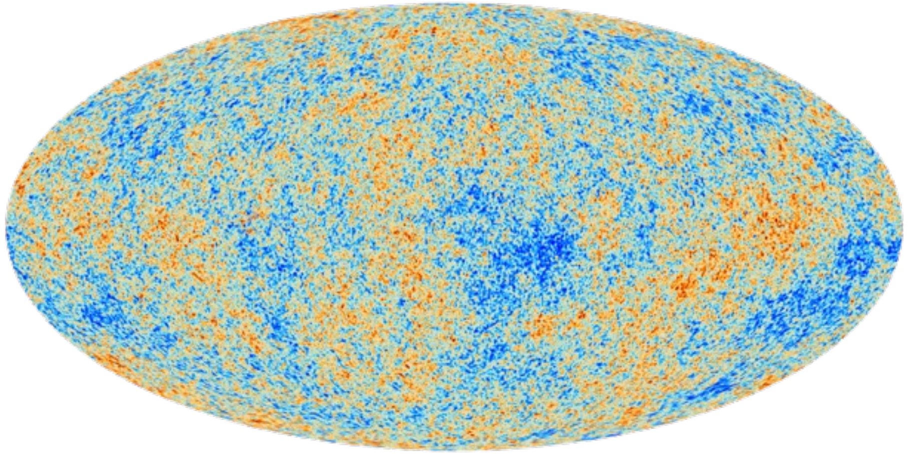
Galaxy cluster scales



Clowe+06

- Peculiar velocity flows
- Mass tracers (X-rays, Sunyaev–Zeldovich, strong&weak lensing)
- Dynamical systems

Cosmological scales

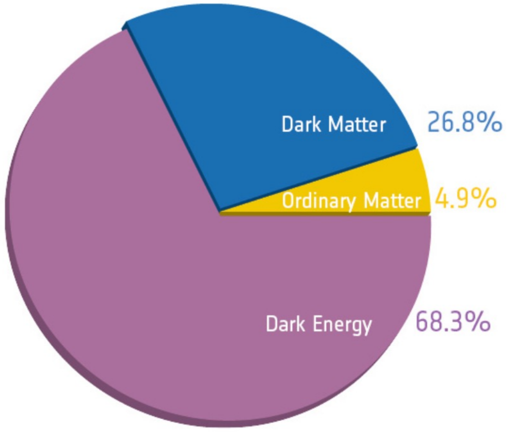


Planck Website

- Cosmic Microwave Background (CMB) anisotropies
- Large Scale Structure (LSS)

DM IN ΛCDM COSMOLOGY

- Observational DM evidences

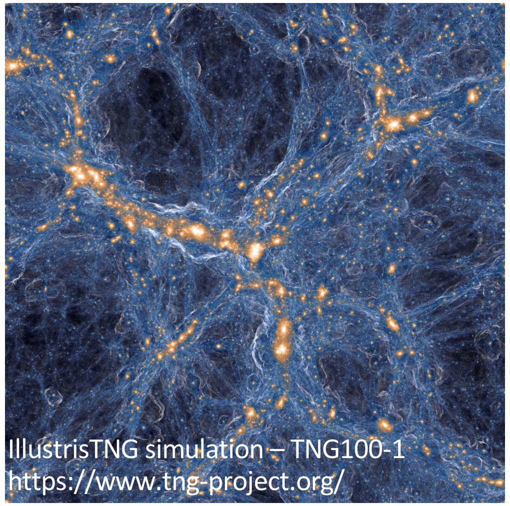


Component of

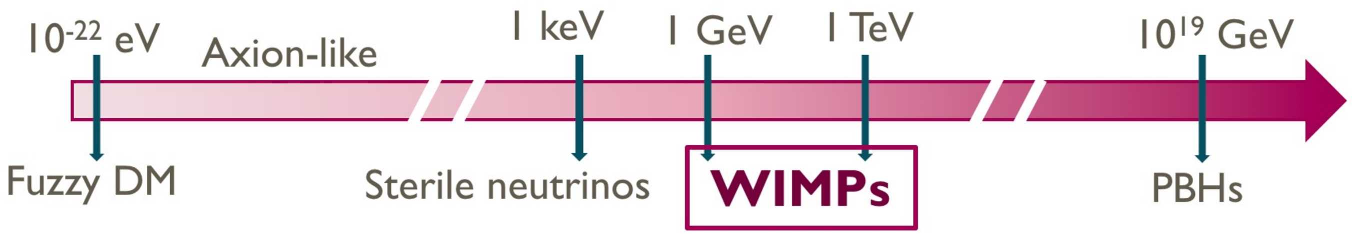
ΛCDM Cosmology

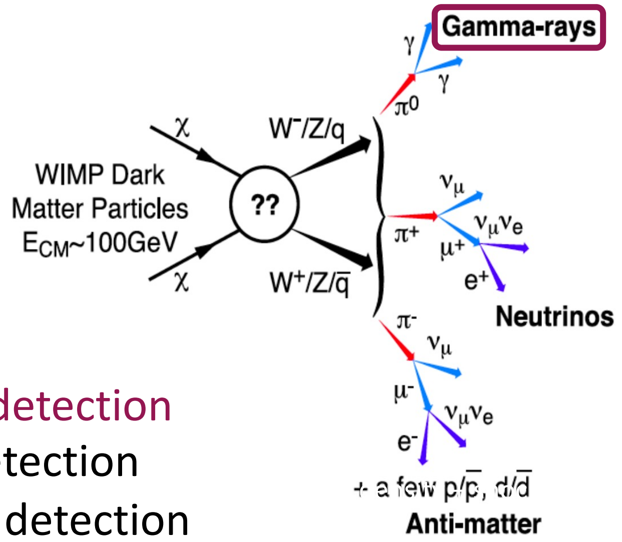
- Structure formation driven by DM
- Bottom-up scenario: smaller structures form first

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

STRUCTURE FORMATION IN ΛCDM

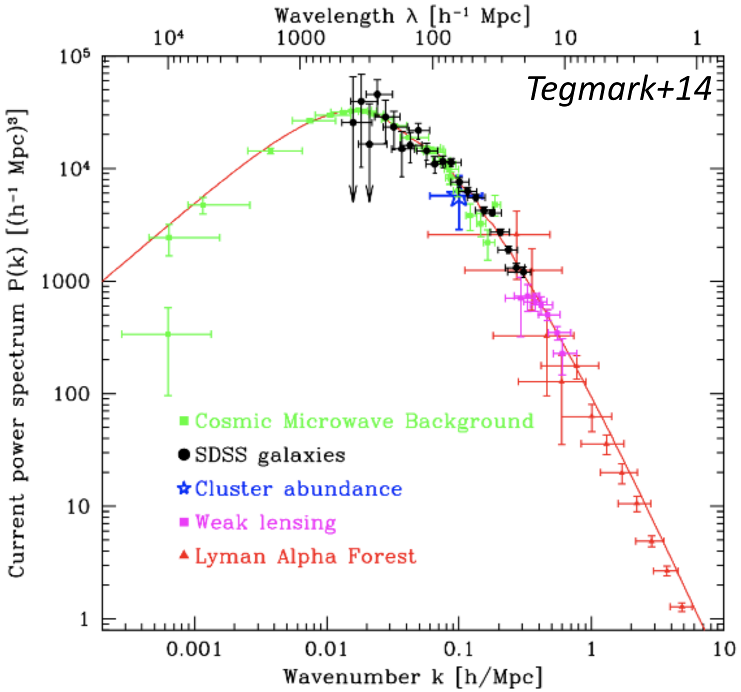
- **Cosmological principle**
  - Isotropy
  - Homogeneity
- **Components of the Universe**
- **Metric**

Friedman Equations

$$H^2(a) = H_0\left(\Omega_{r,0}(1+z)^4 + \Omega_{m,0}(1+z)^3 + \Omega_{k,0}(1+z)^2 + \Omega_{\Lambda,0}\right)$$

BUT

Need inhomogeneities to form structures



- **Inflation**
  - Seeds of perturbation in the field
  - Create curvature perturbation
  - Matter falls, creating **density perturbations**

$$\delta(\vec{x},t) = \frac{\rho(\vec{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)}$$

If δ<<1

Linear perturbation theory

Matter power spectrum

CDM

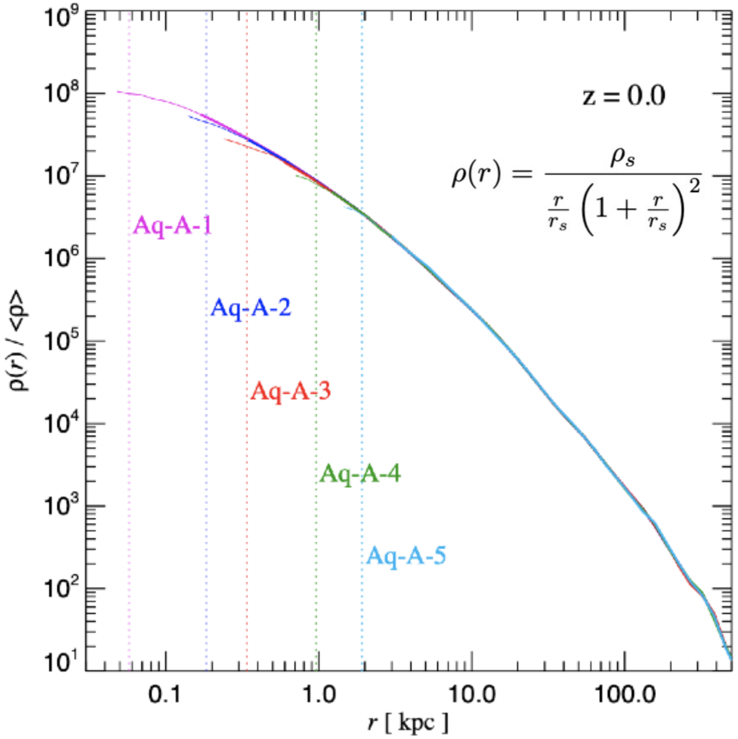
- dominant component is collisionless, non-relativistic dark matter
- gathers gravitationally on small scales
- seeds of larger structures by hierarchical clustering

Halos and subhalos

HALO AND SUBHALO PROPERTIES

Main halos

- Fundamental non-linear units of cosmic structures
- Inner density profile



- Mass distribution

$$\frac{dn}{dM} \propto M^{\alpha}$$

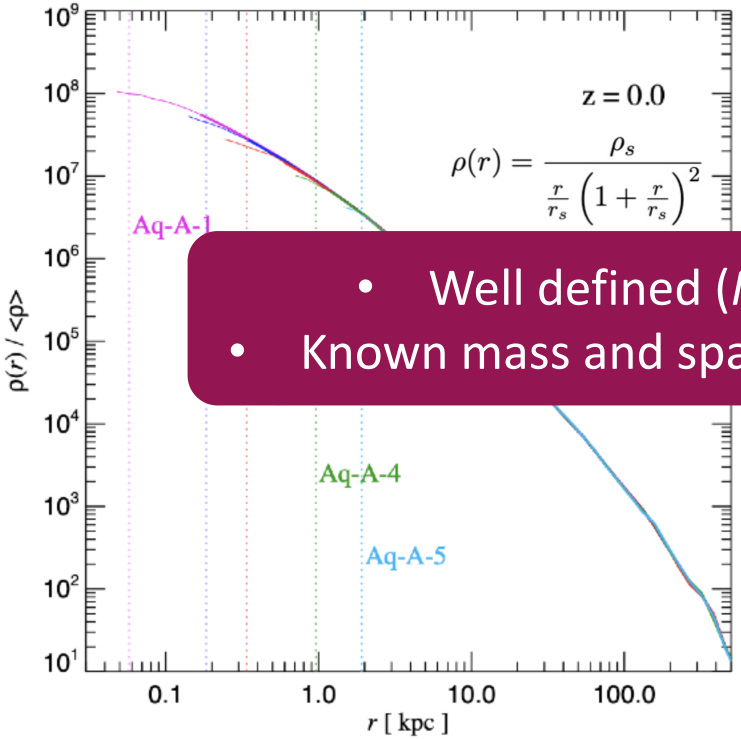
- Concentration

$$c(M)$$

HALO AND SUBHALO PROPERTIES

Main halos

- Fundamental non-linear units of cosmic structures
- Inner density profile



- Mass distribution

$$\frac{dn}{dM} \propto M^\alpha$$

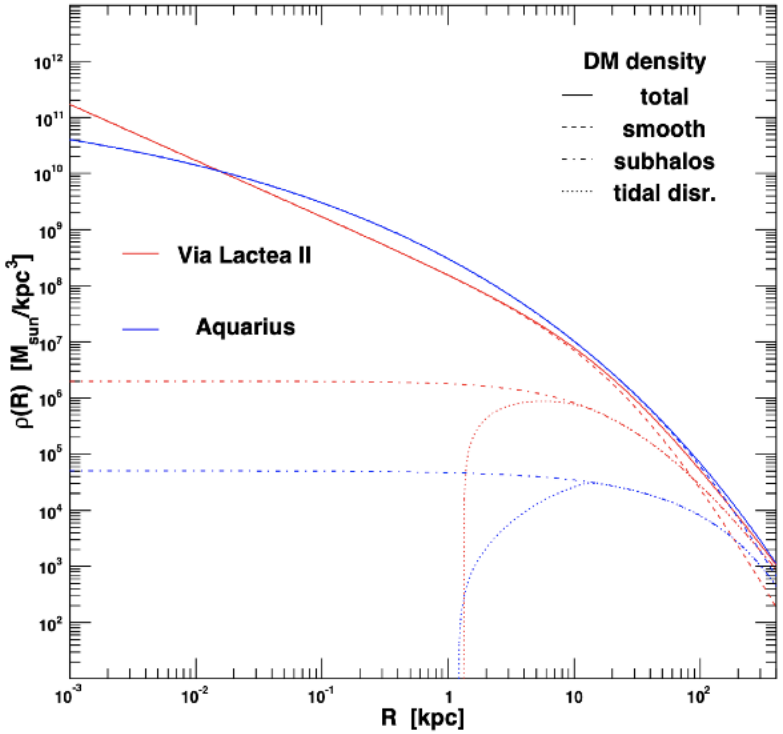
- Well defined (M_{200}, R_{200})
- Known mass and spatial distribution

- Concentration

$$c(M)$$

Subhalos

- The later halos that do not get to merge with the rest
- Fall in the potential wells of main halos



- Mass distribution

$$\frac{dn_{sub}}{dM_{sub}} \propto M_{sub}^\alpha$$

$\alpha \in [1.9, 2.0]$

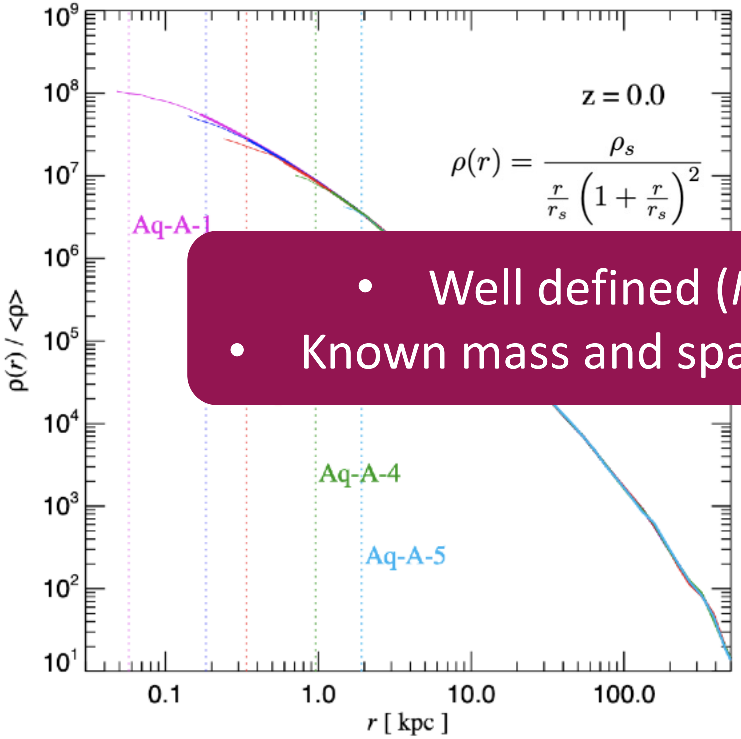
- Concentration

$$c_{sub}(M_{sub}, r_{sub})$$

HALO AND SUBHALO PROPERTIES

Main halos

- Fundamental non-linear units of cosmic structures
- Inner density profile



- Mass distribution

dn ... $\propto M^{\alpha}$

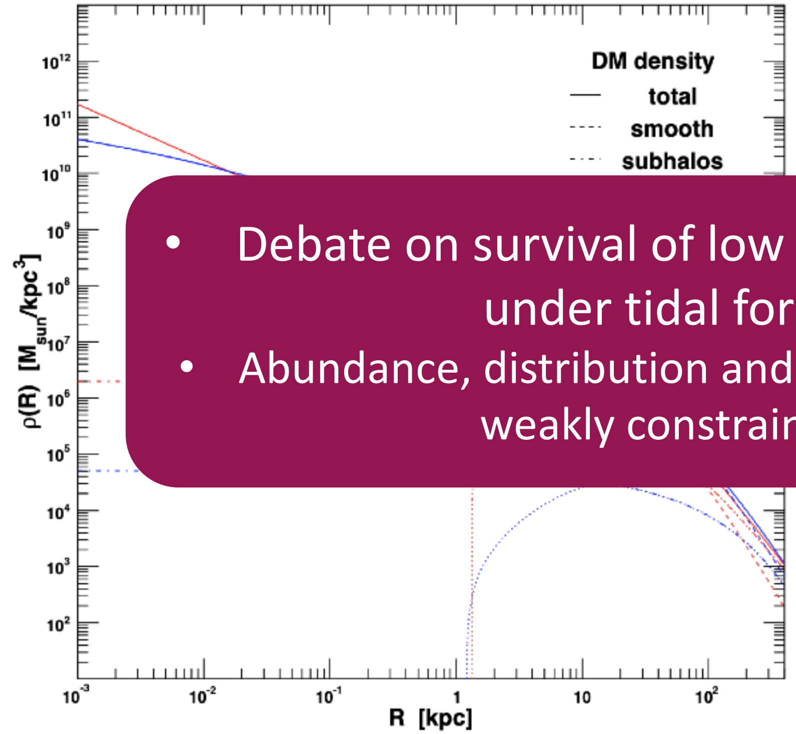
- Concentration

$c(M)$

- Well defined (M_{200}, R_{200})
- Known mass and spatial distribution

Subhalos

- The later halos that do not get to merge with the rest
- Fall in the potential wells of main halos



- Mass distribution

... M^{α}_{sub}

...]

...n

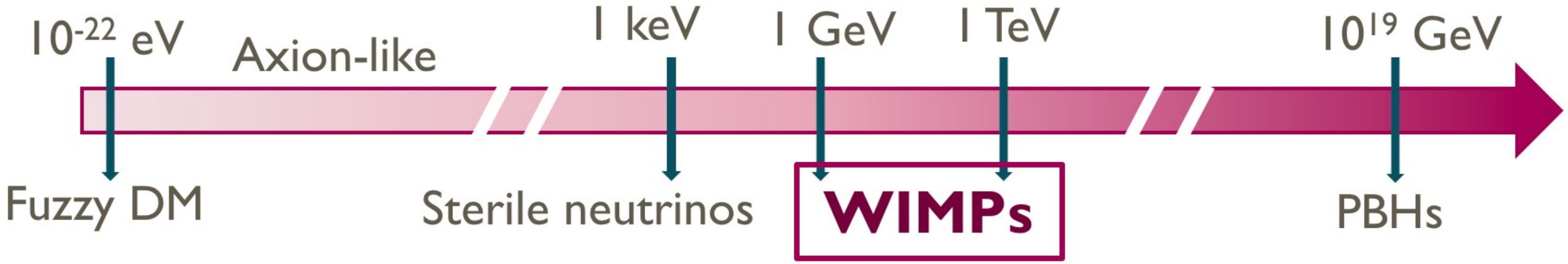
$c_{sub}(M_{sub}, r_{sub})$

- Debate on survival of low mass subhalos under tidal forces
- Abundance, distribution and inner structure weakly constrained

PARTICLE MODELS FOR DM: WIMPS

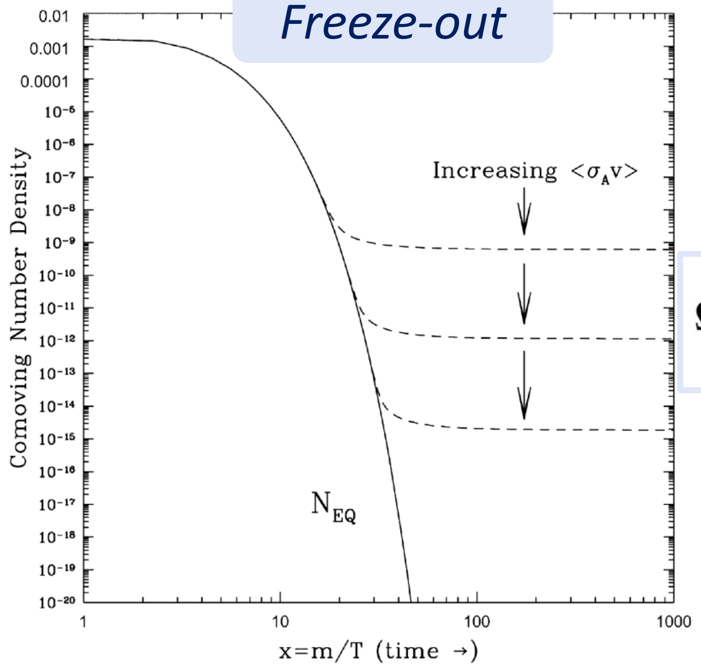
- Different DM candidates:
  - Non-baryonic
  - Electrically neutral
  - Non-relativistic & colissionless
  - Long-lived

Weakly Interacting Massive Particles



- Only interact via weak nuclear force with standard matter
- To be stable, usually assigned as lightest member of dark sector carrying conserved quantum number
- Produced as a thermal relic: their cosmological abundance is set by thermal production in the early Universe

Freeze-out

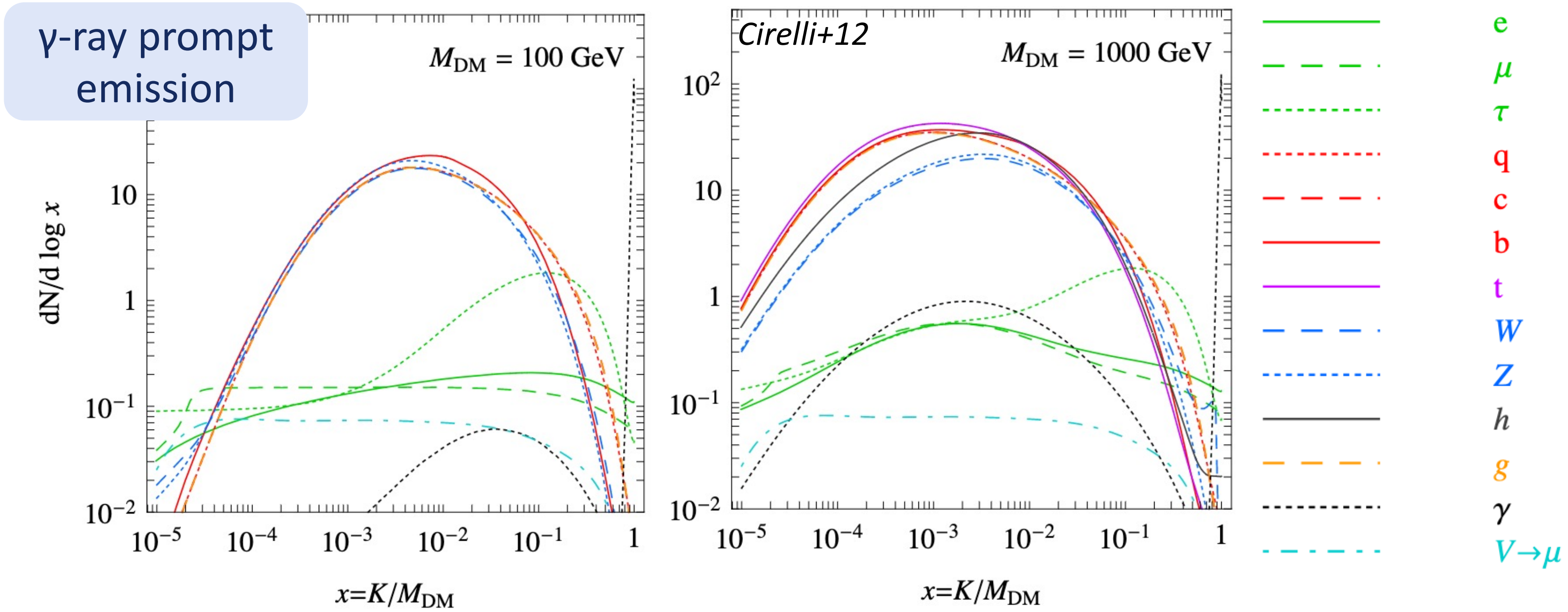


WIMP miracle

$$\Omega_\chi h^2 = \frac{10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{<\sigma v>}$$

PARTICLE MODELS FOR DM: WIMPS

- DM production at source: *Cirelli+12* (EW corrections)
  - includes electroweak radiation effects, specially important for the flux of γ and e± for energies around m_χ
  - s-wave non-relativistic DM-DM annihilation/decay
  - annihilation/decay into primary channel + photon radiation off quarks and leptons, as well as photon branching into quark or lepton pairs
  - γ-ray fluxes only include prompt emission and not the secondary radiation (e.g. Inverse Compton)



ASTROPHYSICAL γ-RAY EMISSION IN GALAXY CLUSTERS

- Components:
  - Dark Matter
  - Baryonic Matter →
    - Galaxies (~ 3% - 5%)
    - Intra Cluster Medium (~ 15% - 17%)

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

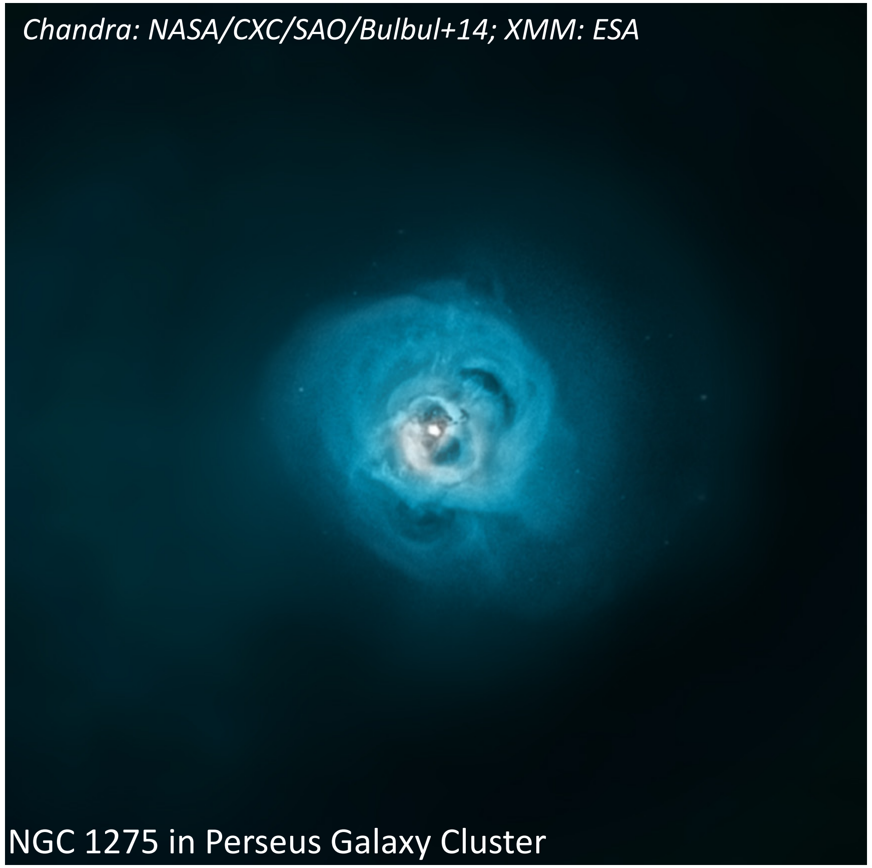
} Acceleration mechanisms

↓

Cosmic-rays (CRs)

Leptons → Diffuse synchrotron emission ✓

Hadrons → γ-rays



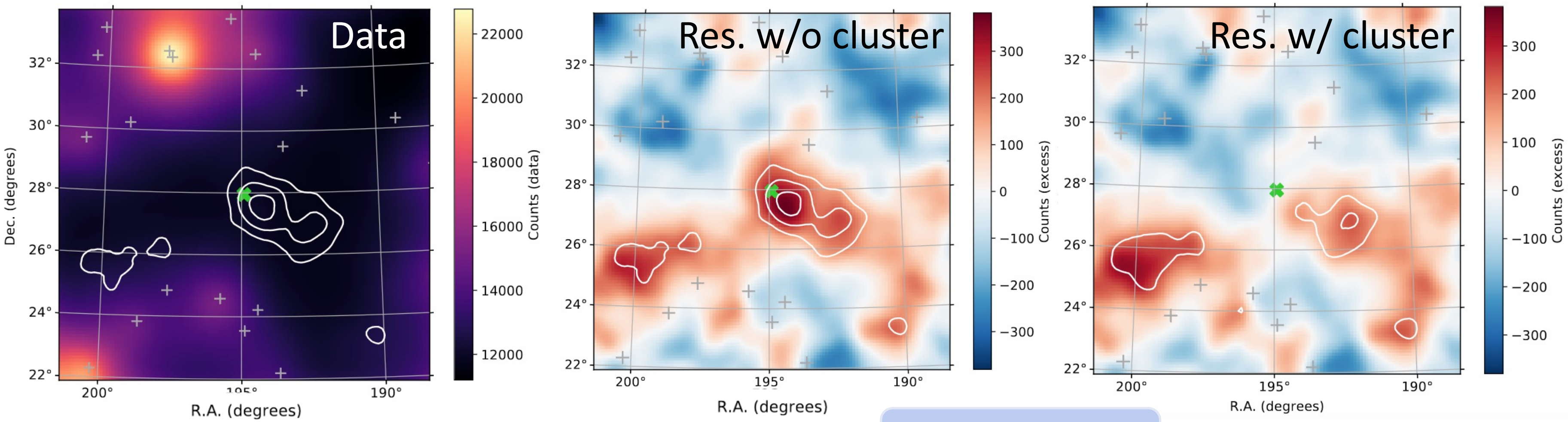
NGC 1275 in Perseus Galaxy Cluster

PREVIOUS γ-RAY DM SEARCHES IN GALAXY CLUSTERS

- Galaxy clusters should shine brightly in the γ-ray sky
- The search of diffuse γ -rays from clusters has been going on for over two decades (either originated from DM or/and CRs), but such signal has remained elusive

Reimer+03
Aharonian+08 [HESS Collab.]
Ackermann+10 [Fermi-LAT Collab.]
Aleksic+10 [MAGIC Collab.]
Dugger+10
Colafrancesco+10
Han+12 – Various clusters, ***hint***
Ando & Nagai 12
Huang+12
Aleksic+12 [MAGIC Collab.]
Arlen+12 [VERITAS Collab.]
Nezri+12
Abramowski+12 [HESS Collab.]
Cirelli+12
Hektor+12 – Various clusters, **3.6σ**
Huber+13
Prokhorov & Churazov 14 – Various clusters, **4-5σ**
***Ackermann+14 [Fermi-LAT Collab.]* – Various clusters, 2.4σ**
Griffin+14
Zandanel & Ando 14
Ackermann+15 [*Fermi-LAT Collab.*] – Virgo cluster, **hint**
Ahnen+16 [MAGIC Collab.]
Ackermann+16 [Fermi-LAT Collab.] – Coma cluster, **hint**
Xi+18 – Coma cluster, **hint**
Aleksic+18 [MAGIC Collab.]
Lisanti+18
Colavizenzo+19 – Various clusters, **3.5-3.8σ**
Tan & Colavicenzo 19
Adam+21 – Coma cluster, **4.9-5.8σ**
Thorpe-Morgan+21

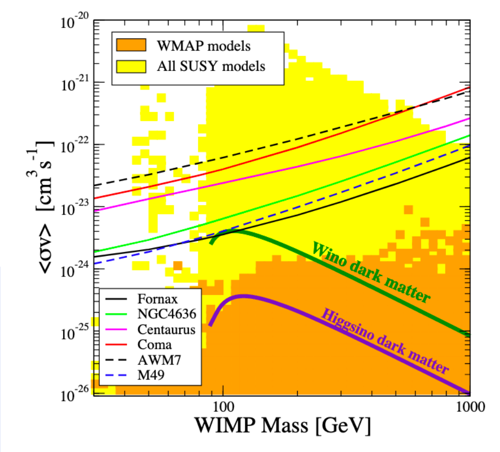
[Adam+21] – *Fermi*-LAT data of the Coma cluster



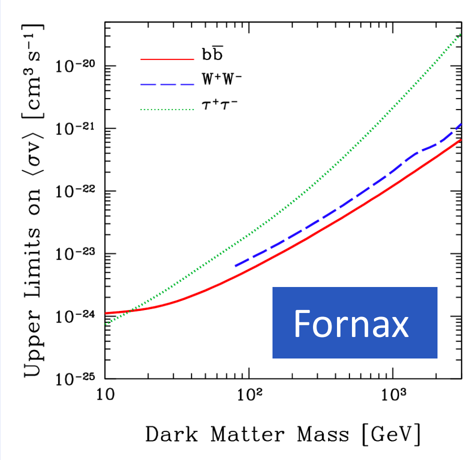
Hints of signal

PREVIOUS γ-RAY DM SEARCHES IN GALAXY CLUSTERS

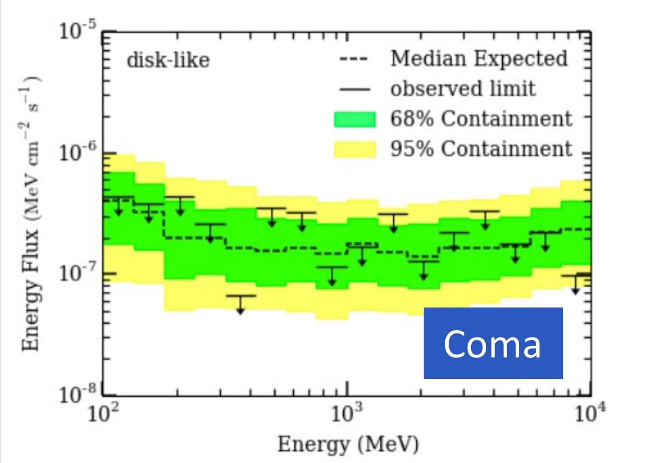
Fermi-LAT - Annihilation



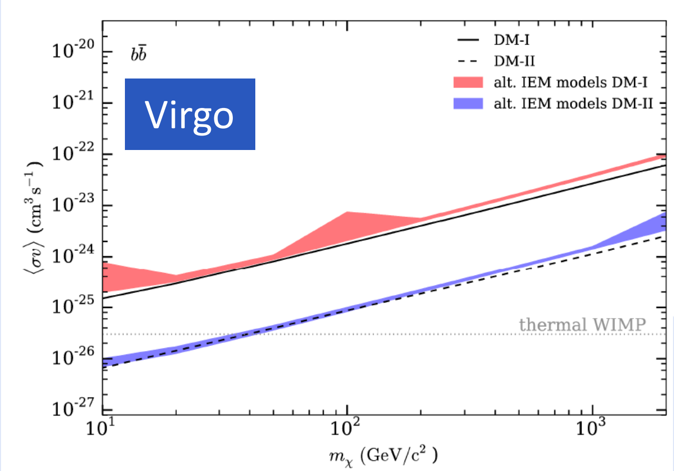
Ackermann+10 [Fermi-LAT Collab.]



Ando&Nagai12



Ackermann+16 [Fermi-LAT Collab.]

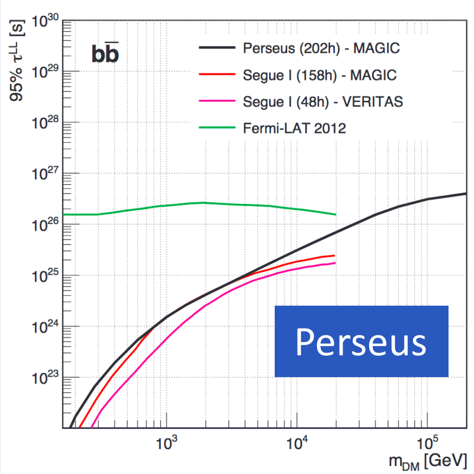


Ackermann+15 [Fermi-LAT Collab.]

- 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.]

PREVIOUS γ-RAY DM SEARCHES IN GALAXY CLUSTERS

- For annihilation of WIMPs:
  - $\phi_{DM} \propto \rho_{DM}^2$
  - $\phi_{DM} \propto 1/d^2$

DM distribution becomes extremely relevant

Credit: V. Springel
https://wwwmpa.mpa-garching.mpg.de/galform/data_vis/index.shtml

Galaxy cluster and its substructures from Millenium simulation

Large impact on the DM flux if we include:

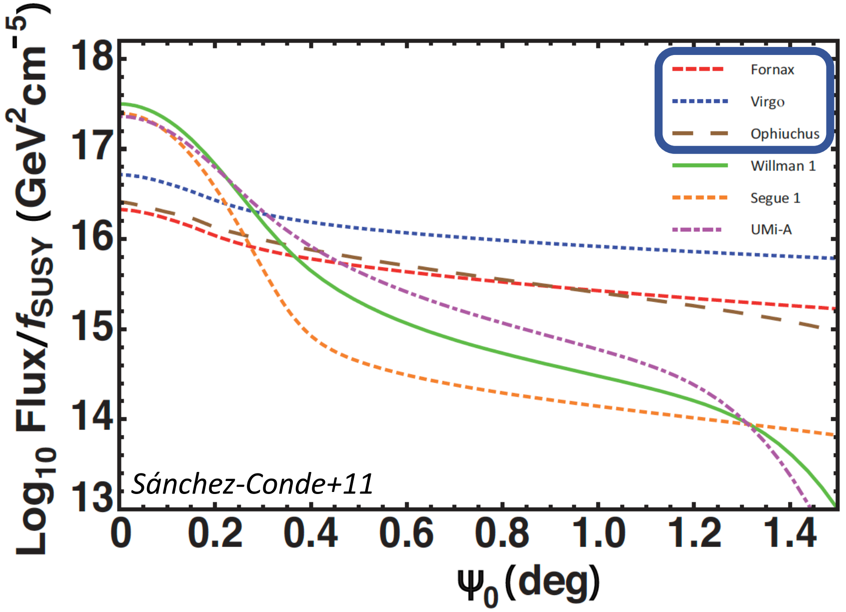
- Smooth component (historical approach)

+

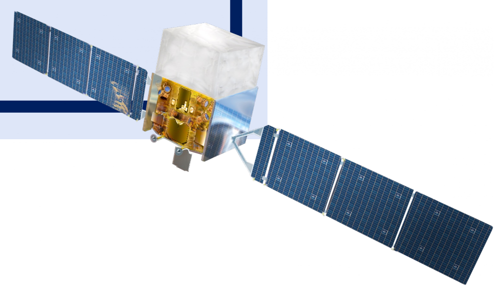
- **Substructure**

Sánchez-Conde+11

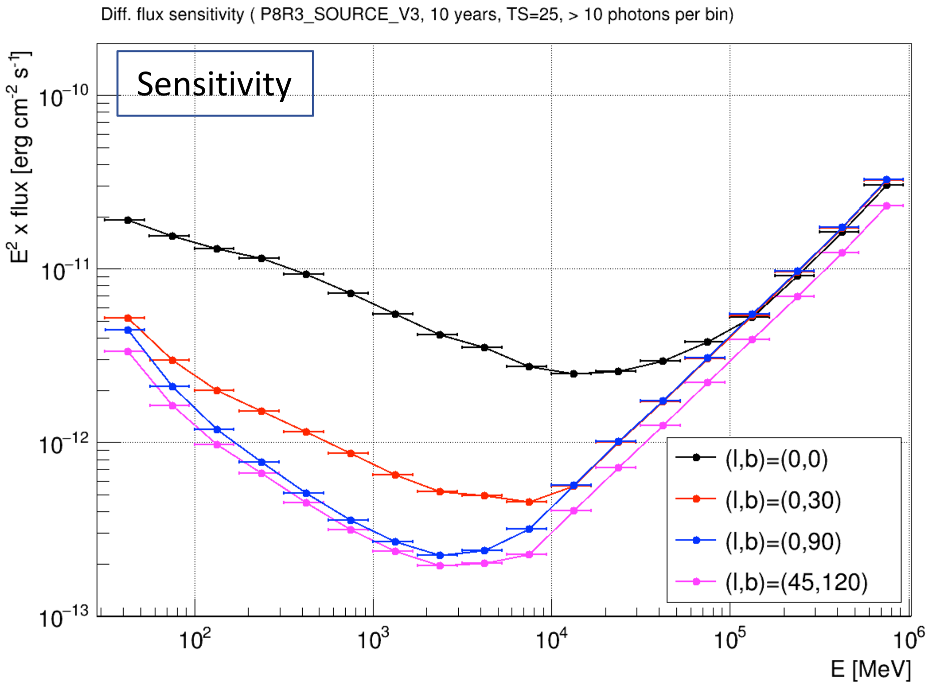
Object	Type	J_{tot} (GeV^2cm^{-5})
Fornax	Cluster	1.48×10^{18}
Willman 1	DSPH	8.51×10^{17}
Coma	Cluster	6.92×10^{17}
Perseus	Cluster	5.37×10^{17}
Segue 1	DSPH	5.13×10^{17}
Draco	DSPH	3.72×10^{17}



FERMI LARGE AREA TELESCOPE (LAT)

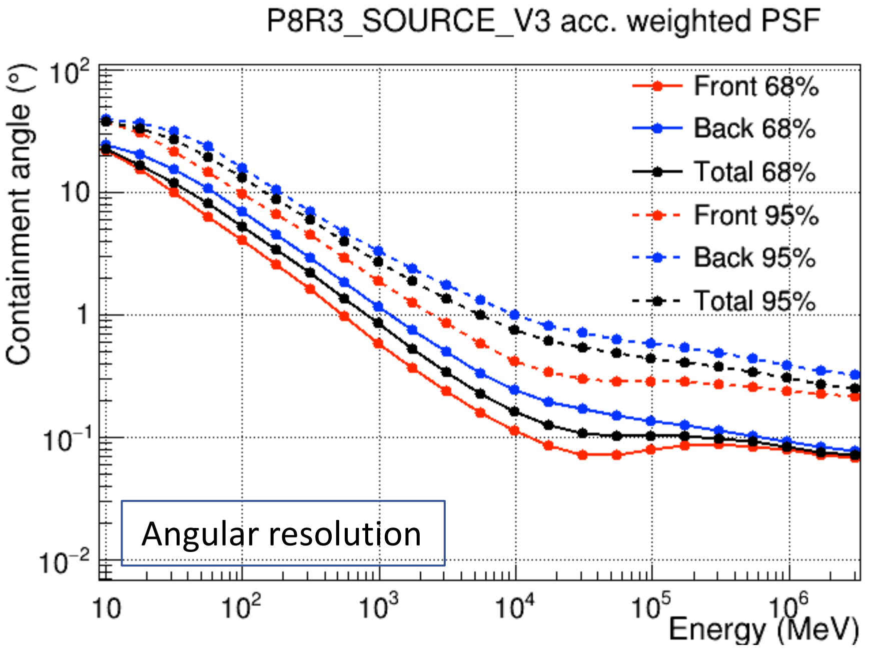


- Satellite-based telescope launched in June 2008 – 16 years of γ-ray data
- All sky survey mode, image of whole sky every 3 hours
- The γ–ray produces a pair of electron-positron, tracked and used to determine the energy of the primary γ-ray



10y Performance Capabilities

Instrument Response Functions (IRFs)



https://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

FERMI-LAT TARGET SELECTION

- *Fermi*-LAT does not have constraints on observation time → Sample of best clusters for DM searches
- Selection criteria:
  - Well-known M_{200} from X-rays measurements

    Masses from *Schellenberger&Reiprich17* (X-rays data from Chandra*)*
  - Local clusters

    $z < 0.1$
  - Mask of |*b*| < 20 deg to avoid Galactic diffuse emission
  - Separation of at least 2 deg to account for cluster extension

HIFLUGCS catalogue (*Reiprich&Böhringer02*)

- 50 local clusters
- $f_X \geq 1.7 \cdot 10^{-11}$ erg s^{-1} cm^{-2}
- biased towards cool-cored clusters (*Käfer+19*)

+

- Clusters used in previous searches:

  Ackermann+10 [Fermi-LAT Coll.]

  Sánchez-Conde+11

  Ackermann+14 [Fermi-LAT Coll.]

Sample of 49 local galaxy clusters

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 $\Delta_{200} = \frac{3M_{200}}{4\pi R_{200}^3 \rho_{crit}}$

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

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

CLUSTERS DM MODELLING: SUBSTRUCTURES

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

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

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

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

$$\rho_{\rm sub}^{Aq}(r) = \rho_s \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^{\alpha} - 1\right]\right)$$

Aquarius
Biased relation
Springel+08

Subhalo Mass Function (SHMF)

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

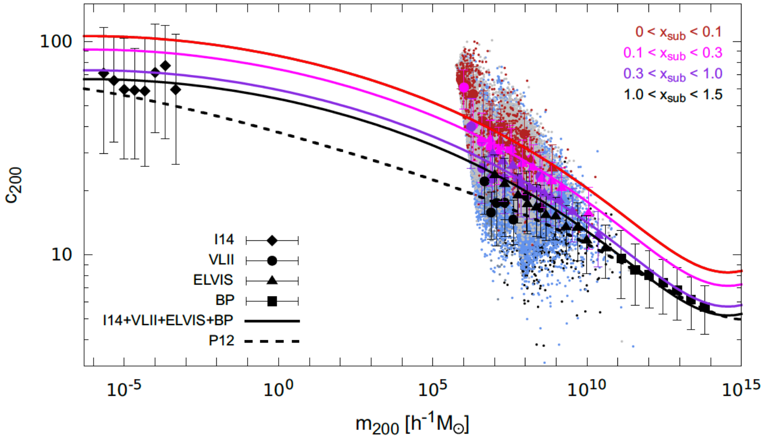
$\alpha = 1.9$

Springel+08

$\alpha = 2.0$

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

MAIN UNCERTAINTY: DM DENSITY PROFILES

- To model the DM density profile in the objects, we split the contributions:

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

→ Subhalo population (if any)

ρ_{sm} ↓ Main halo

- Cuspy-like, from N-body simulations
- Cored-like, phenomenologically motivated

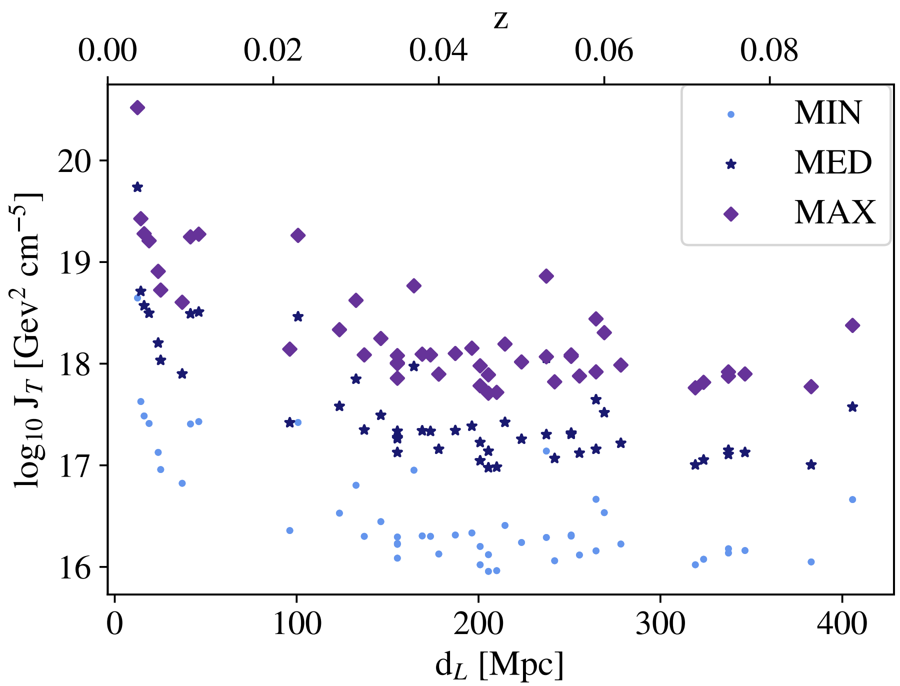
$$\rho_{NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$$

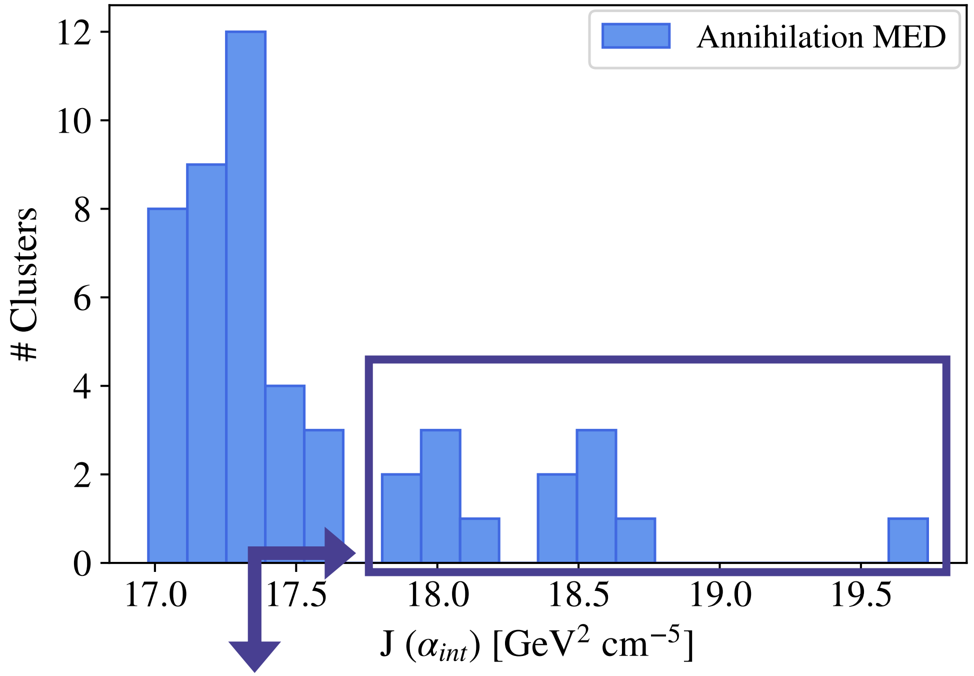
$$\rho_{Ein}(r) = \rho_s \exp\left(-\frac{2}{\alpha}\left[\left(\frac{r}{r_s}\right)^\alpha - 1\right]\right)$$

$$\rho_{Bur}(r) = \frac{\rho_c r_c^3}{(r+r_c)(r^2+r_c^2)}$$

- Fit the profiles either:
  - Rotational curves (spiral galaxies, dwarf irregular galaxies)
  - Velocity dispersion measurements (dSphs)
  - Normalize to the measured mass (galaxy clusters) → $M_\Delta = \int_0^{R_\Delta} \rho(r) r^2 dr d\Omega$

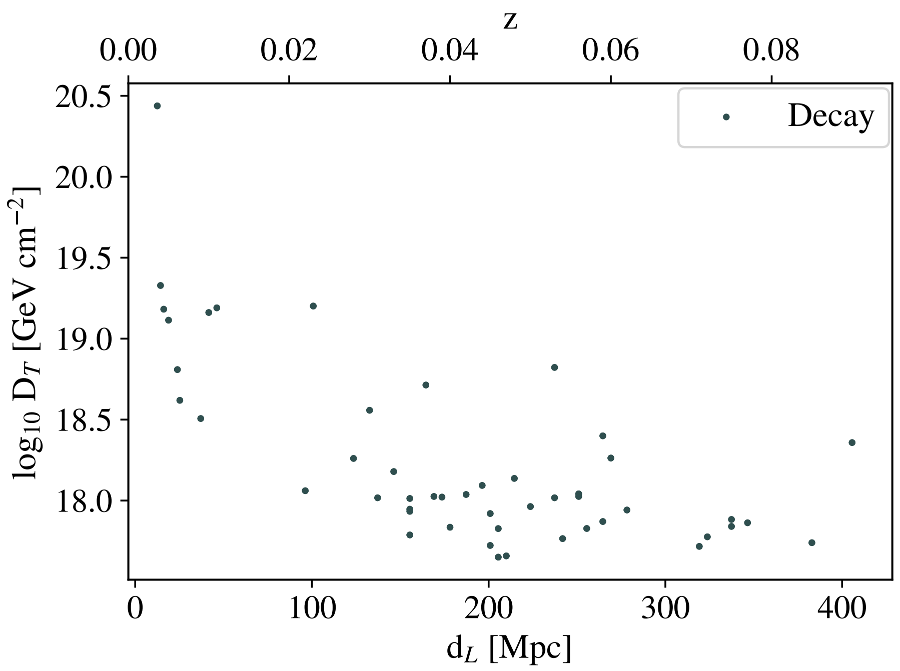
DM ANNIHILATION FLUXES OF THE SAMPLE

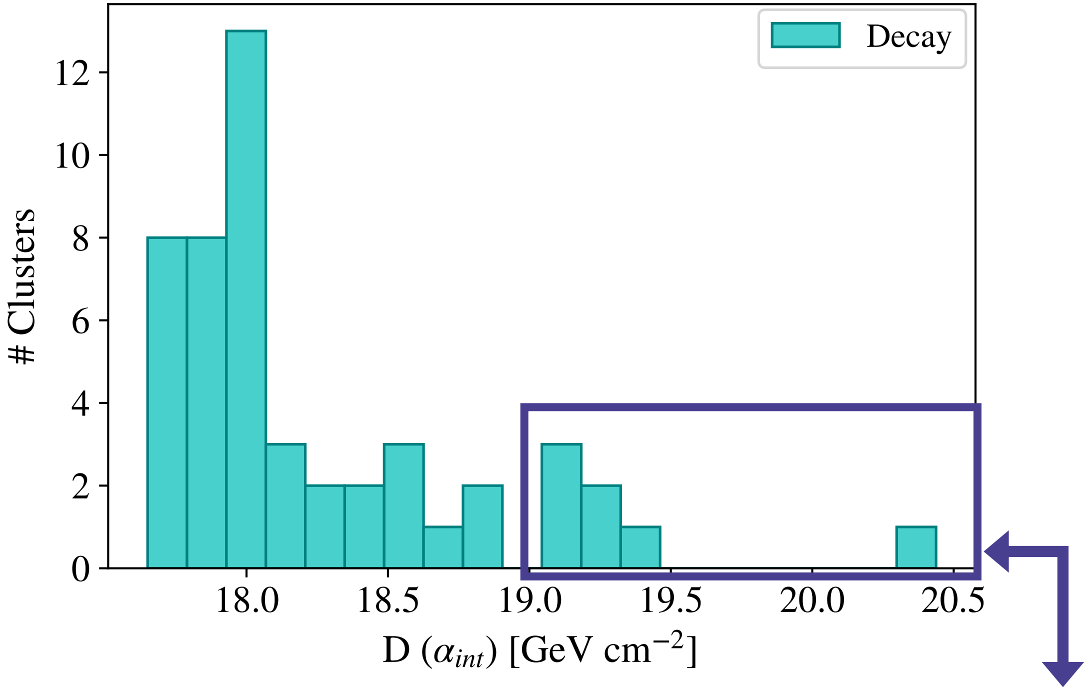




Cluster	z	M_{200} [10^{14} M$_\odot$]	R_{200} [kpc]	θ_{200} [deg]	$\log_{10} J_{MIN}$ [GeV^{2}cm^{-5}]	$\log_{10} J_{MED}$ [GeV^{2}cm^{-5}]	$\log_{10} J_{MAX}$ [GeV^{2}cm^{-5}]	$\log_{10} D$ [GeV cm^{-2}]
Virgo	0.0036	5.60	1700	6.32	18.65	19.74	20.52	20.44
NGC 4636	0.004	0.53	777	2.61	17.63	18.71	19.43	19.33
M49	0.0044	0.46	741	2.26	17.49	18.57	19.28	19.18
A1060-Hydra	0.011	2.97	1376	1.70	17.43	18.51	19.27	19.19
A1656-Coma	0.023	13.16	2260	1.35	17.42	18.46	19.26	19.20
NGC 1399-Fornax	0.005	0.51	763	2.05	17.41	18.50	19.21	19.11
A3526-Centaurus	0.01	2.27	1258	1.70	17.41	18.49	19.25	19.16
A754	0.053	25.00	2800	0.75	17.14	18.05	18.86	18.82
NGC 5813	0.0064	0.27	620	1.31	16.96	18.03	18.72	18.62
A3571	0.037	10.90	2123	0.80	16.95	17.97	18.77	18.71

DM DECAY FLUXES OF THE SAMPLE





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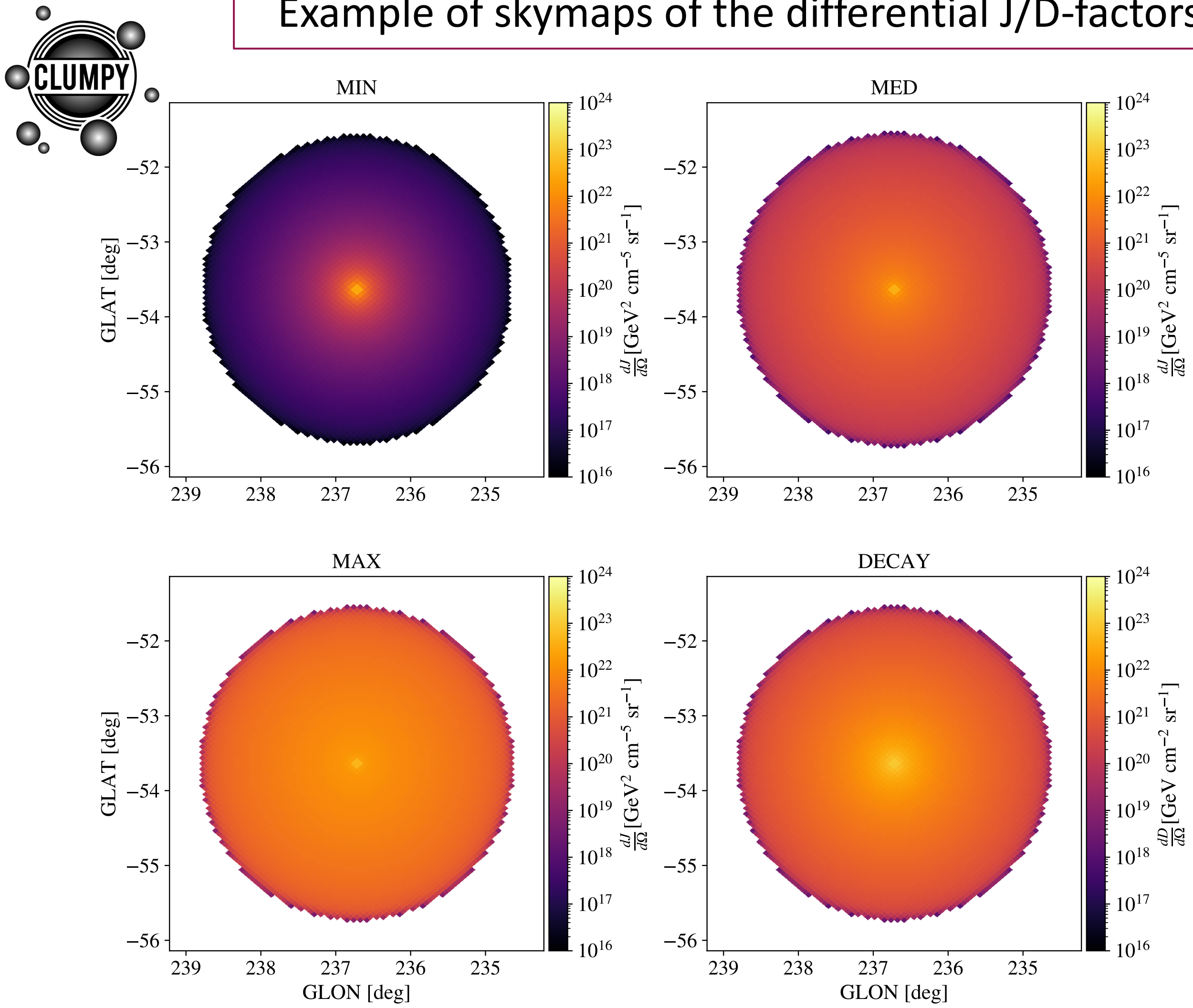
A3571	0.037	10.90	2123	0.80	16.95	17.97	18.77	18.71

DM FLUXES OF THE SAMPLE

Example of skymaps of the differential J/D-factors for NGC 1399-Fornax



- Effects of substructure:
  - Most relevant in outskirts
  - Boost factor:

$$B = J^X / J^{\mathrm{MIN}} - 1$$

B_{MED} = 11 (B~9 – *Moliné+17*)

B_{MAX} = 60 (B~65 – *Moliné+17*)

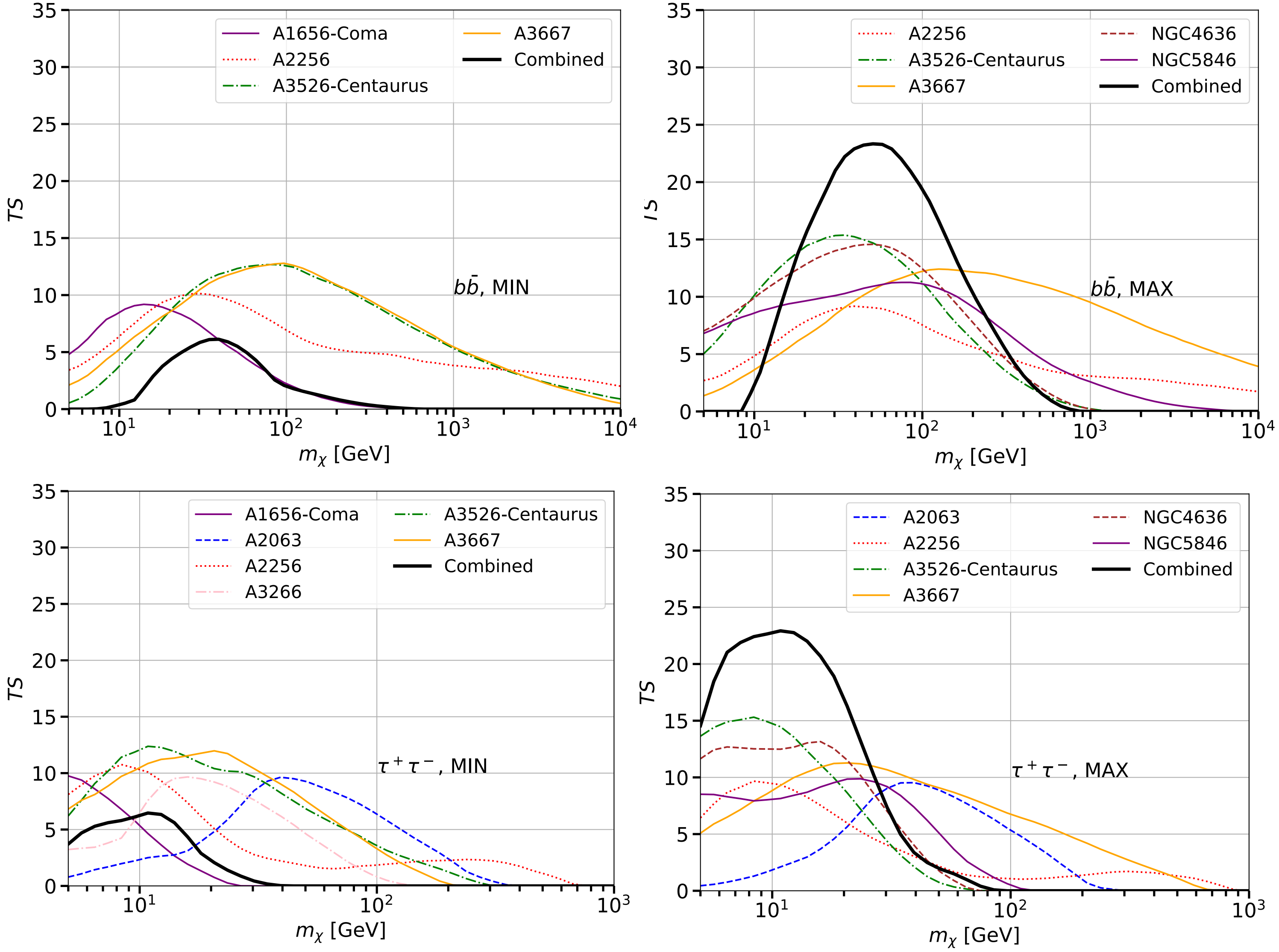
CLUSTERS SAMPLE

Cluster	d_L	M_{200}	c_{200}	ρ_s	r_s	R_{200}	θ_{200}	$\log_{10} J_{MIN}$	$\log_{10} J_{MED}$	B_{MED}	$\log_{10} J_{MAX}$	B_{MAX}	$\log_{10} D$	TS
	[Mpc]	[10^{14} $M_\odot$]		[$M_\odot$/kpc^3]	[kpc]	[kpc]	[deg]	[GeV^{2}cm^{-5}]	[GeV^{2}cm^{-5}]		[GeV^{2}cm^{-5}]		[GeV cm^{-2}]	
A478	387.29	6.08	5.06	303795	345.37	1747.71	0.30	16.05	17.00	9.03	17.77	52.90	17.74	0.00
A399	320.39	4.03	5.14	314222	296.58	1523.16	0.31	16.02	17.00	9.54	17.76	54.90	17.72	5.69
A2065	325.13	4.73	5.10	309802	314.87	1607.11	0.33	16.08	17.05	9.46	17.82	55.00	17.78	4.94
A1736	203.92	1.45	5.40	352863	200.77	1084.70	0.33	15.96	16.98	10.50	17.71	56.70	17.65	4.89
A1644	208.50	1.55	5.38	349910	205.81	1107.83	0.33	15.96	16.98	10.50	17.72	56.70	17.66	1.90
A401	339.38	5.92	5.06	304380	342.03	1732.25	0.34	16.14	17.11	9.34	17.88	54.90	17.84	8.07
A2029	348.92	6.59	5.05	302105	355.64	1795.26	0.34	16.16	17.13	9.21	17.90	54.40	17.86	0.26
Hydra-A	240.76	2.60	5.24	328469	251.56	1317.25	0.35	16.06	17.07	10.20	17.82	57.70	17.76	3.74
ZwCl1215	339.38	6.54	5.05	302272	354.58	1790.34	0.35	16.18	17.15	9.32	17.92	55.00	17.88	0.00
MKW3S	199.34	1.66	5.36	346794	211.39	1133.45	0.36	16.02	17.05	10.60	17.78	57.60	17.72	0.00
A133	254.68	3.35	5.18	319842	276.74	1432.35	0.36	16.12	17.12	10.10	17.88	57.70	17.83	2.46
A3158	263.99	3.97	5.14	314620	295.06	1516.19	0.37	16.16	17.16	9.99	17.92	57.70	17.87	5.39
A4059	203.92	2.19	5.28	334997	235.56	1244.13	0.38	16.12	17.14	10.50	17.89	58.90	17.83	0.06
A1795	278.01	5.17	5.09	307558	325.36	1655.37	0.38	16.23	17.22	9.81	17.99	57.50	17.94	0.42
A2657	176.55	1.69	5.36	345942	212.97	1140.70	0.40	16.13	17.16	10.80	17.90	58.90	17.84	4.53
A2147	153.91	1.17	5.47	363492	184.45	1009.48	0.40	16.09	17.13	11.00	17.86	58.70	17.79	5.72
A3376	199.34	2.58	5.24	328779	250.74	1313.53	0.41	16.20	17.23	10.60	17.98	59.90	17.92	0.84
A3562	222.29	3.53	5.16	318132	282.44	1458.40	0.41	16.24	17.26	10.40	18.02	59.70	17.96	0.03
A85	250.04	5.09	5.09	307918	323.62	1647.33	0.42	16.30	17.31	10.10	18.07	59.00	18.03	0.31
A3391	236.13	4.51	5.11	311034	309.49	1582.37	0.43	16.29	17.30	10.30	18.07	59.90	18.02	0.11
A3667	250.04	5.30	5.08	306940	328.42	1669.45	0.43	16.31	17.32	10.10	18.09	59.50	18.04	13.31
A2052	153.91	1.63	5.37	347614	209.89	1126.58	0.45	16.22	17.26	11.00	18.00	60.10	17.93	0.03
2A0335	153.91	1.66	5.36	346659	211.64	1134.59	0.45	16.23	17.27	11.00	18.01	60.20	17.95	5.44
A2589	185.64	2.99	5.20	323540	265.28	1379.98	0.46	16.31	17.34	10.70	18.10	61.20	18.04	0.13
EXO0422	172.01	2.49	5.25	330093	247.36	1298.09	0.47	16.30	17.33	10.80	18.09	61.30	18.02	0.18

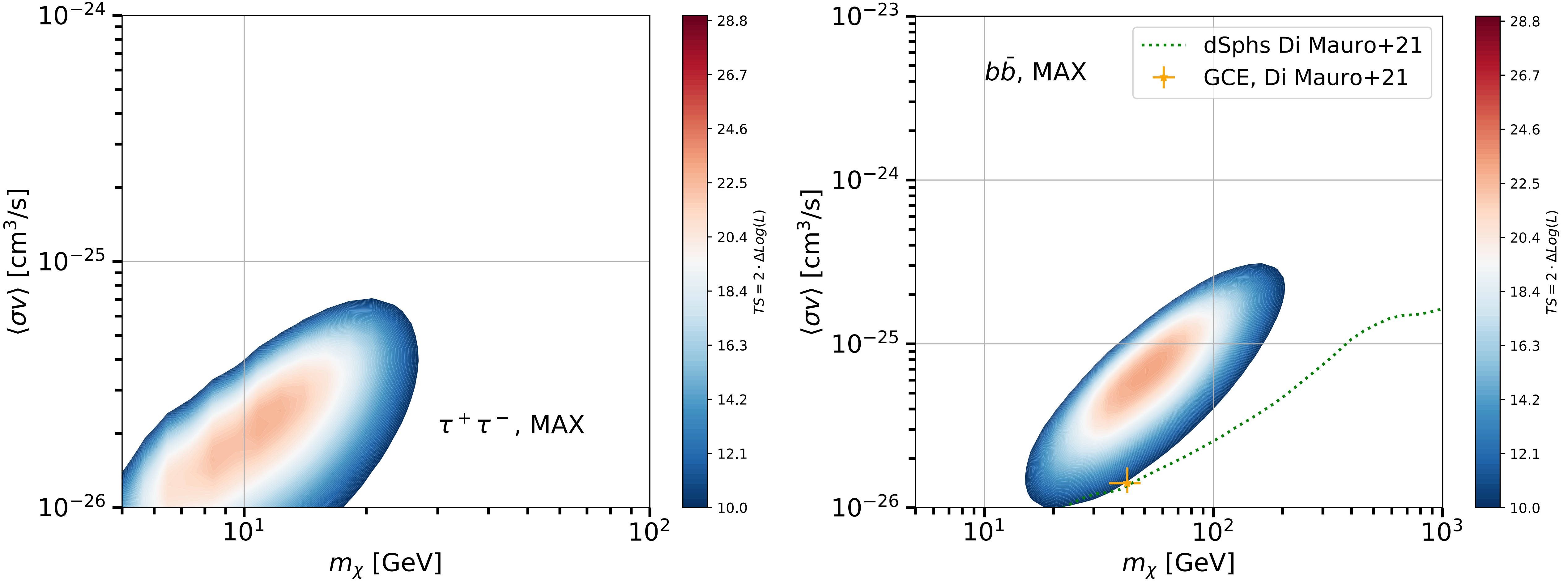
CLUSTERS SAMPLE

Cluster	d_L	M_{200}	c_{200}	ρ_s	r_s	R_{200}	θ_{200}	$\log_{10} J_{MIN}$	$\log_{10} J_{MED}$	B_{MED}	$\log_{10} J_{MAX}$	B_{MAX}	$\log_{10} D$	TS
	[Mpc]	[10^{14} $M_\odot$]		[$M_\odot$/kpc^3]	[kpc]	[kpc]	[deg]	[GeV^{2}cm^{-5}]	[GeV^{2}cm^{-5}]		[GeV^{2}cm^{-5}]		[GeV cm^{-2}]	
A576	167.47	2.37	5.26	331959	242.73	1276.91	0.47	16.31	17.34	10.90	18.09	61.30	18.03	0.99
A2063	153.91	1.97	5.31	339288	226.15	1201.08	0.48	16.29	17.34	11.00	18.08	61.00	18.01	9.44
A3558	213.09	4.89	5.10	308961	318.70	1624.70	0.48	16.41	17.42	10.30	18.19	60.90	18.14	0.35
A2142	411.48	28.03	4.97	291172	585.57	2908.46	0.48	16.66	17.57	8.15	18.38	51.70	18.36	0.00
A119	194.77	3.96	5.14	314731	294.64	1514.28	0.49	16.33	17.39	11.20	18.15	65.60	18.09	8.49
A2634	135.92	1.55	5.38	349762	206.07	1109.02	0.50	16.30	17.35	11.20	18.09	60.90	18.02	4.31
A2256	268.66	10.17	4.99	294929	415.33	2074.55	0.50	16.53	17.52	9.65	18.31	59.10	18.26	9.91
A496	144.90	2.56	5.24	329080	249.96	1309.96	0.55	16.45	17.49	11.10	18.25	63.50	18.18	0.00
A3266	263.99	13.44	4.97	292052	457.72	2276.43	0.55	16.67	17.65	9.57	18.44	59.60	18.40	8.19
A1367	95.81	0.88	5.57	379136	164.49	916.83	0.57	16.36	17.42	11.50	18.14	60.80	18.06	0.99
A4038	122.49	2.23	5.28	334336	237.08	1251.09	0.62	16.53	17.58	11.30	18.33	64.00	18.26	0.71
A754	236.13	25.00	4.96	290649	564.09	2799.56	0.75	17.14	18.05	8.23	18.86	52.70	18.82	0.28
A2199	131.44	5.07	5.09	308030	323.08	1644.84	0.76	16.80	17.85	11.10	18.62	66.00	18.56	1.86
A3571	162.95	10.90	4.99	294084	425.60	2123.16	0.80	16.95	17.97	10.50	18.77	65.20	18.71	0.00
NGC 5044	38.81	0.41	5.88	428317	121.16	711.87	1.07	16.82	17.90	11.90	18.60	60.50	18.51	0.00
NGC 5813	27.55	0.27	6.06	460583	102.21	619.60	1.31	16.96	18.03	11.80	18.72	58.30	18.62	4.10
A1656-Coma	100.24	13.16	4.97	292223	454.37	2260.40	1.35	17.42	18.46	11.00	19.26	69.60	19.20	9.93
NGC 5846	26.25	0.38	5.91	434293	117.22	692.90	1.53	17.13	18.20	11.90	18.91	60.40	18.81	10.81
A1060-Hydra	47.51	2.97	5.20	323860	264.34	1375.66	1.70	17.43	18.51	12.00	19.27	70.00	19.19	5.41
A3526-Centaurus	43.16	2.27	5.27	333726	238.51	1257.60	1.70	17.41	18.49	12.10	19.25	69.20	19.16	15.62
NGC 1399-Fornax	21.50	0.51	5.79	413641	131.82	762.97	2.05	17.41	18.50	12.20	19.21	62.60	19.11	4.01
M49	18.91	0.46	5.82	419644	127.27	741.24	2.26	17.49	18.57	12.10	19.28	62.00	19.18	0.00
NGC 4636	17.18	0.53	5.77	409991	134.72	776.79	2.61	17.63	18.71	12.20	19.43	63.00	19.33	13.09
VIRGO	15.46	5.60	5.07	305646	335.10	1700.27	6.32	18.65	19.74	12.30	20.52	74.80	20.44	1.05

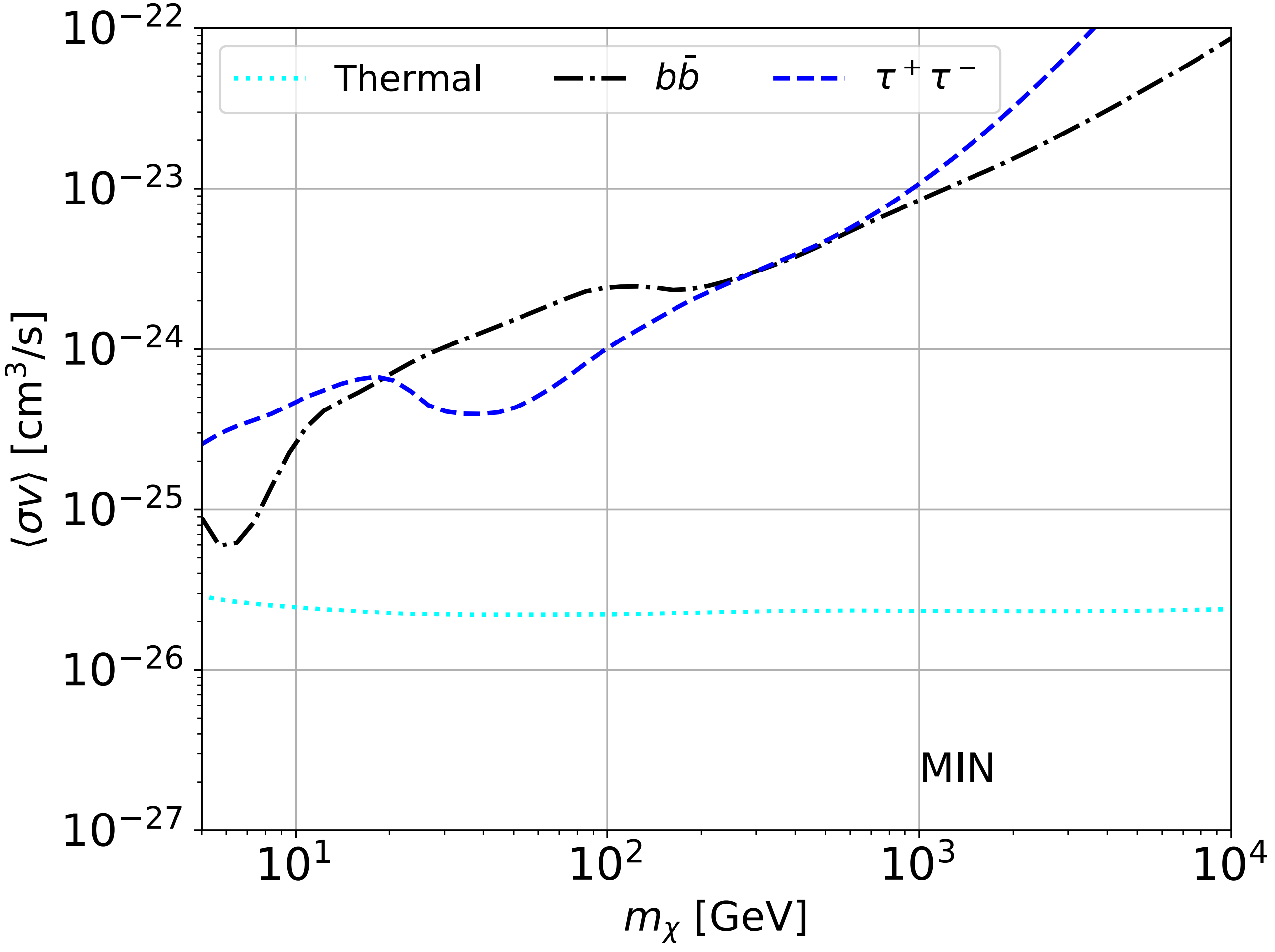
INSIGHT RESULTS: OTHER CHANNELS & MODELS

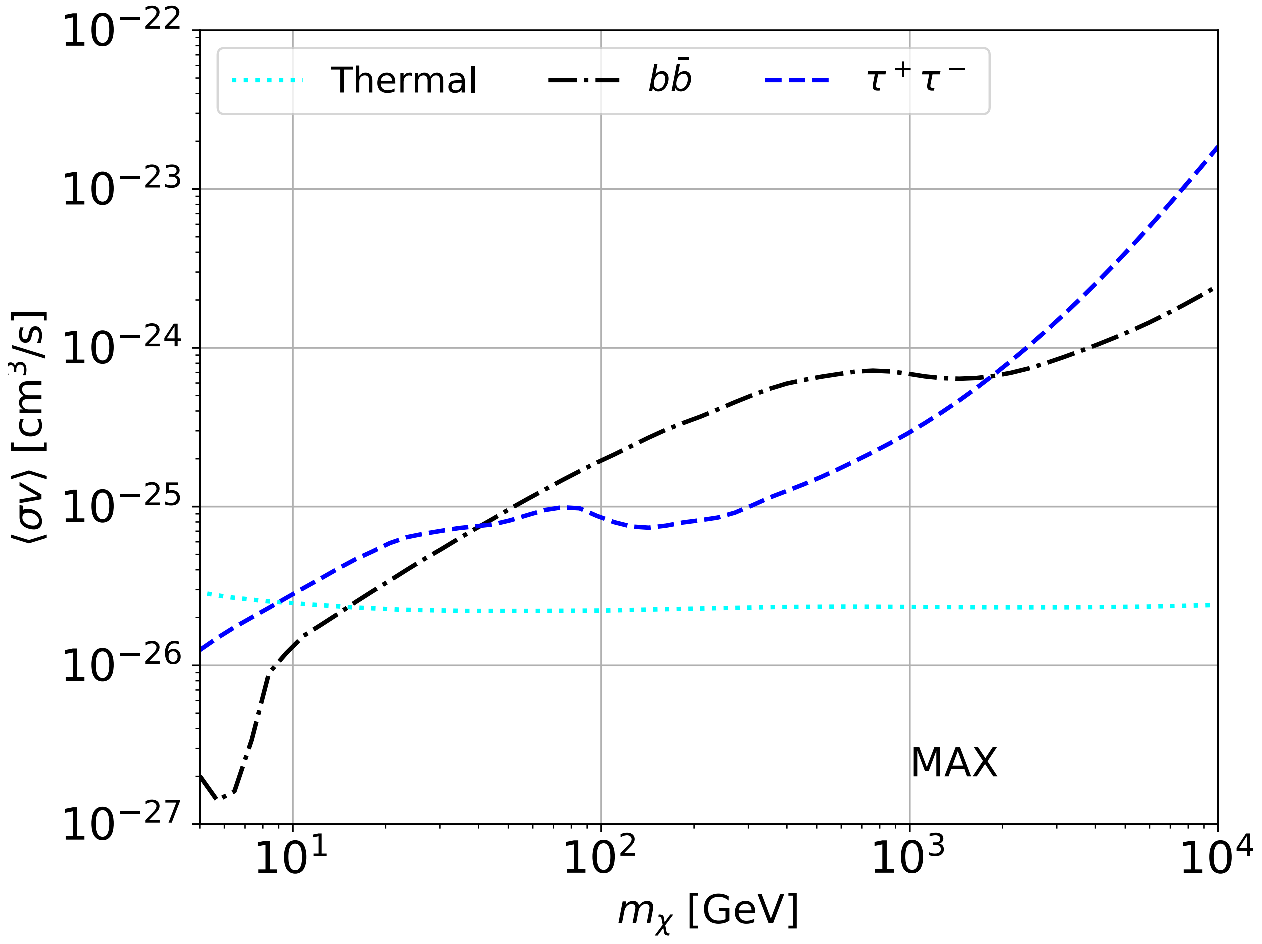


INSIGHT RESULTS: OTHER CHANNELS & MODELS

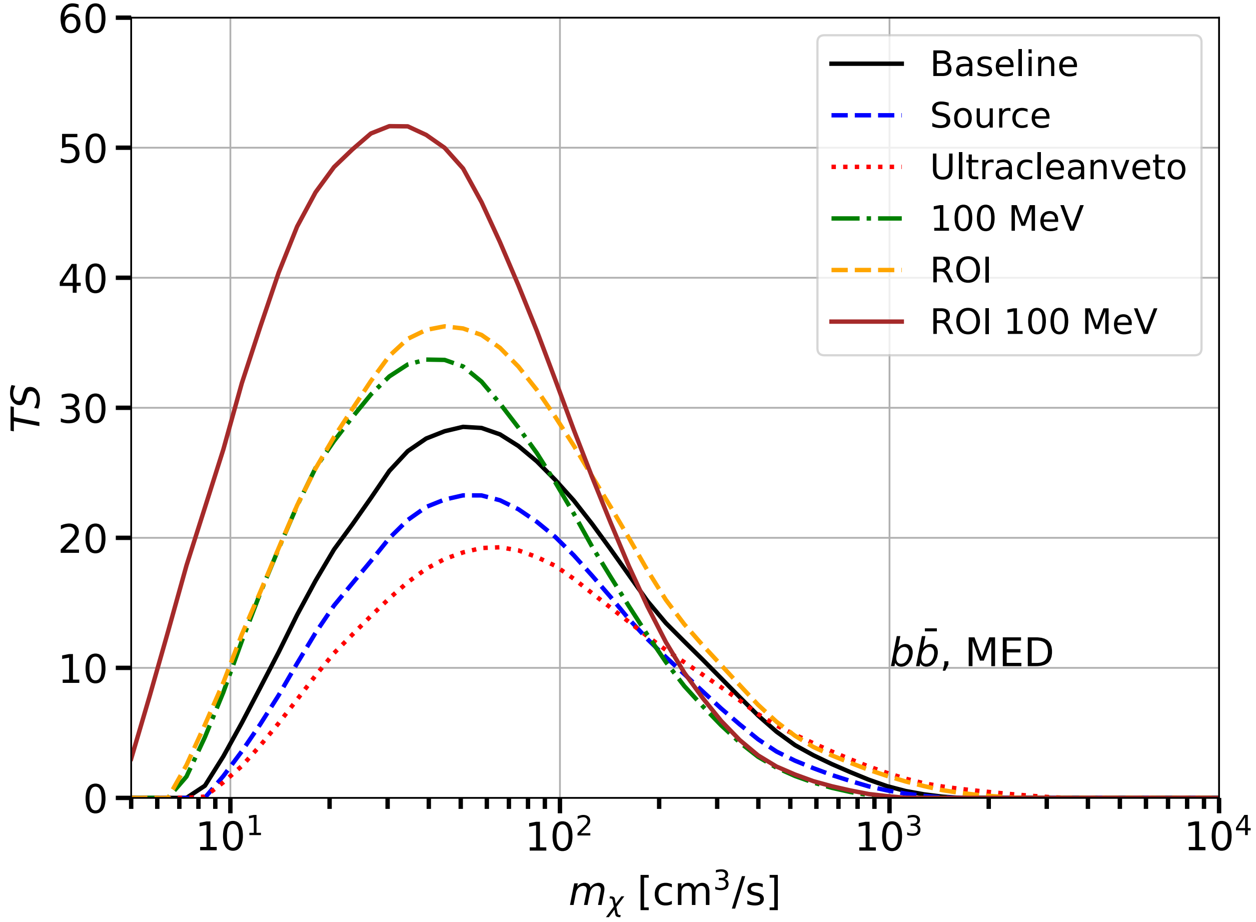


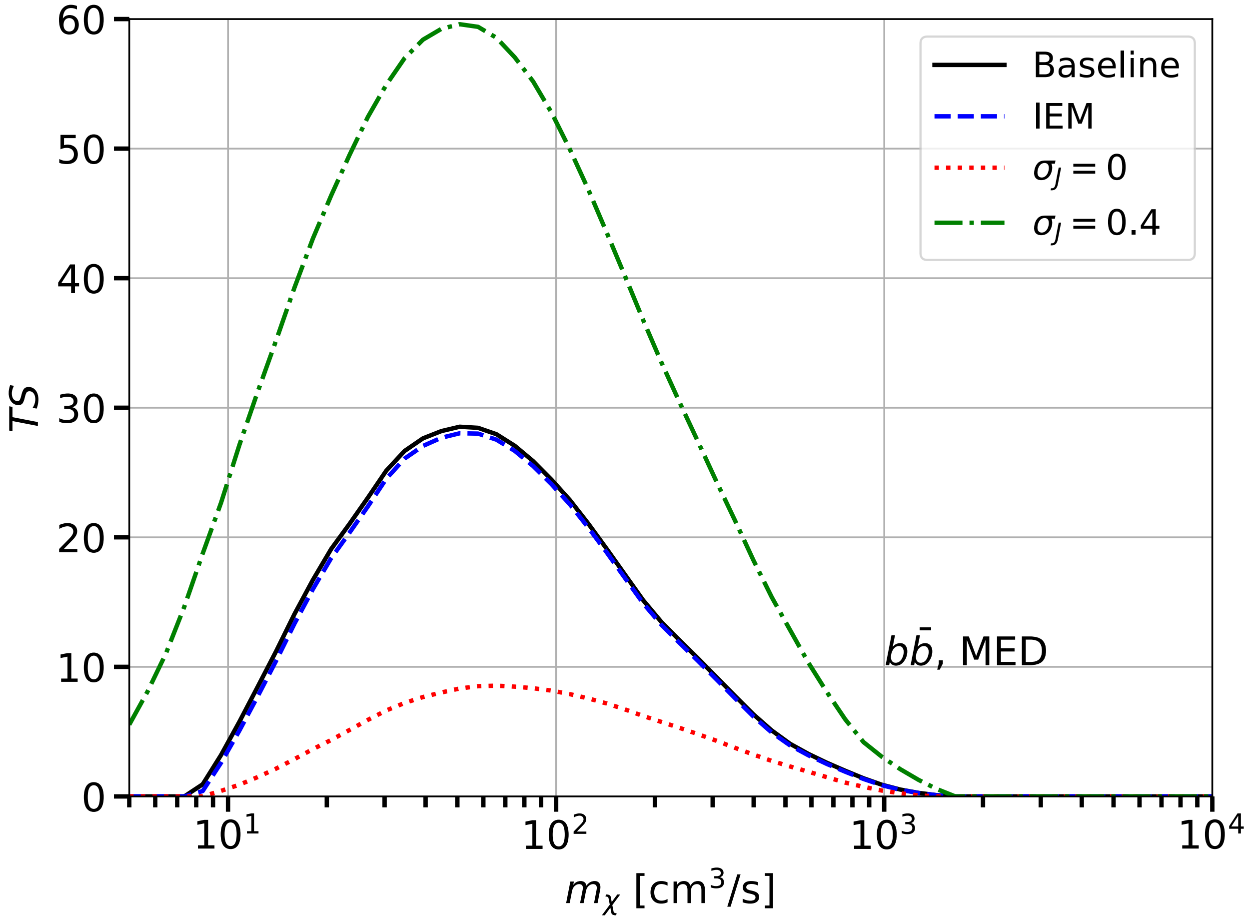
INSIGHT RESULTS: OTHER CHANNELS & MODELS





INSIGHT RESULTS: OTHER ANALYSIS SET-UPS





NULL HYPOTHESIS FOR *TS* DISTRIBUTION

- Ideal knowledge of BKGs → *TS* distribution described as $\chi^2_2/2$ BUT → Analysis of real data at low energies for extended sources

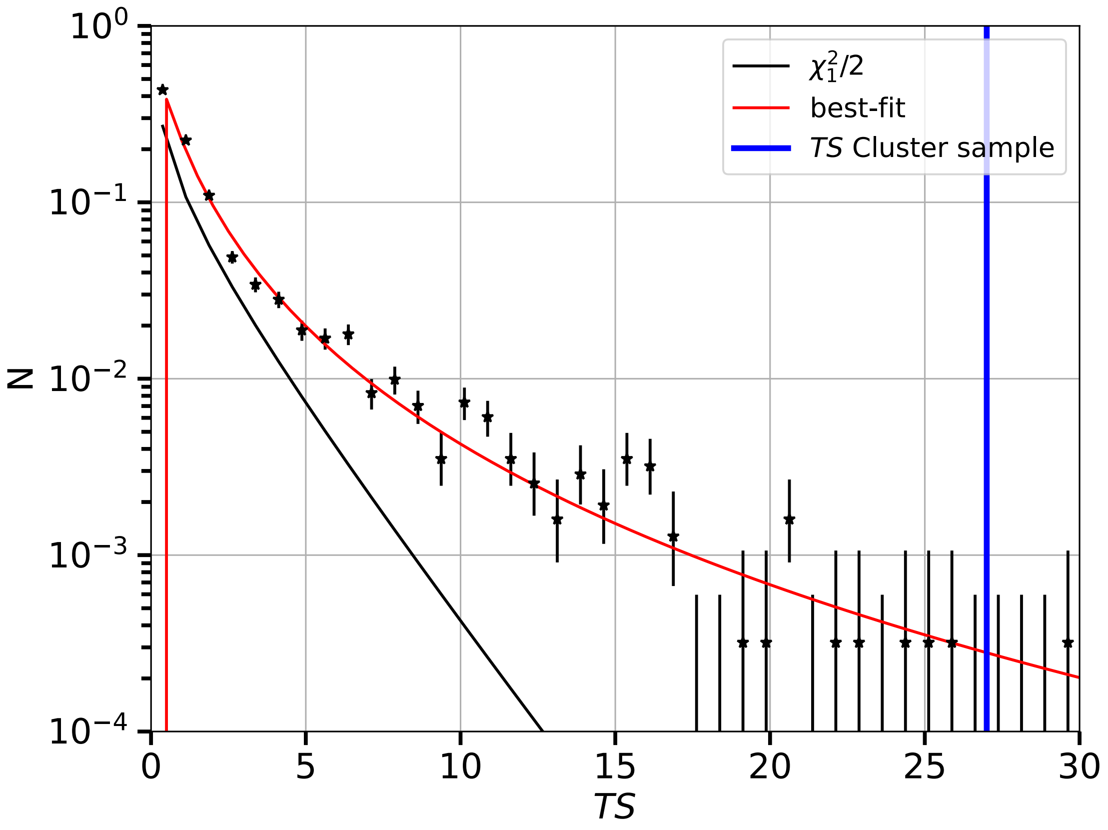
Chernoff 54

- Build *TS* distribution using 3100 random blank sky directions
  - Remove directions with $|b|$<20 deg
  - Farther than 2 deg from known sources
  - Limited to extension of sources and ROI

- For each ROI, fit MED DM template and $b\bar{b}$ annihilation for m_χ=50 GeV

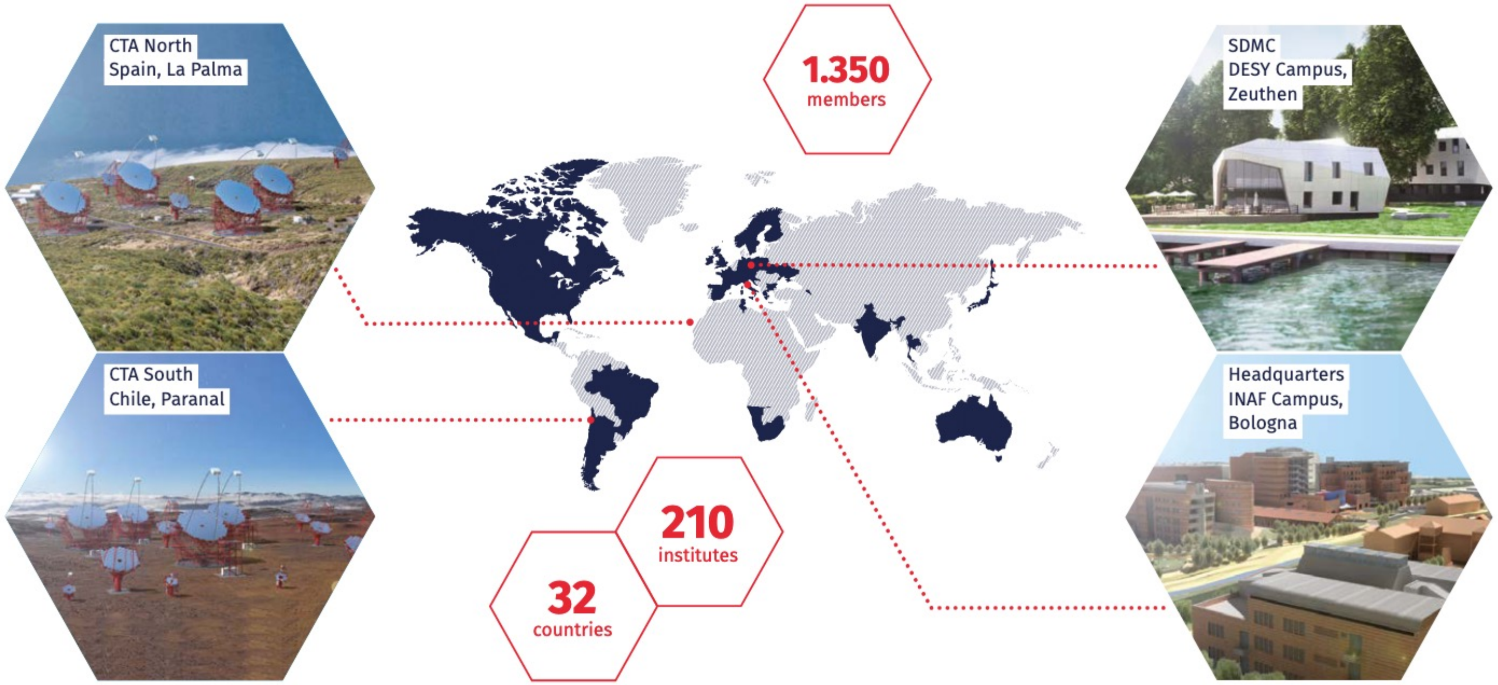
$$N_{\rm norm}(TS) = 0.22 \times (TS)^{-1.29-0.31\log(TS/2.55)}$$

TS = 27 for MED → *p* –value = 3.1 x 10^{-3} (local) → 2.7σ



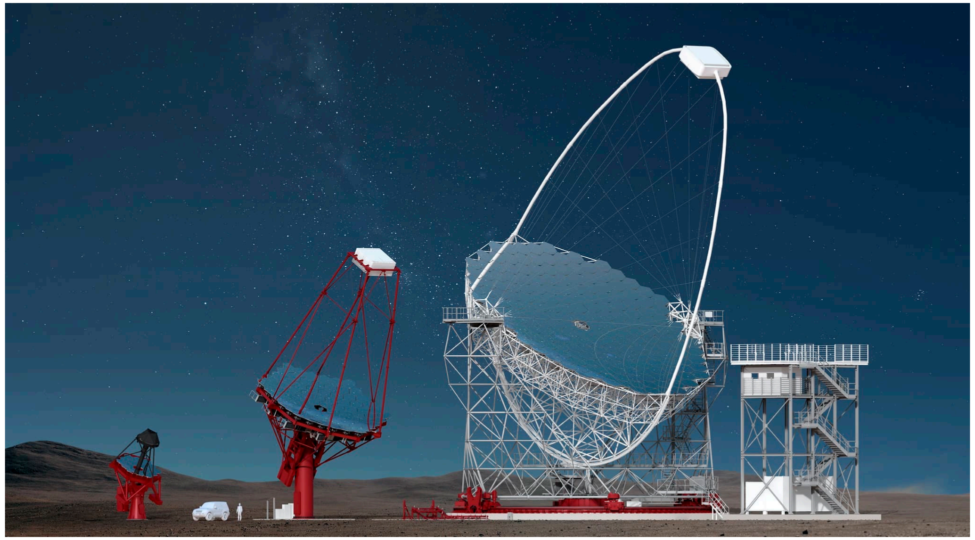
THE CHERENKOV TELESCOPE ARRAY OBSERVATORY (CTAO)

- Future of Imaging Atmospheric Cherenkov Telescopes for very-high-energy (VHE) γ-ray astronomy
- 2 arrays: Northern Array (La Palma, Spain) and Southern Array (Paranal, Chile)
- First telescope already operating



https://www.ctao.org/

Energy range 20 GeV - 300 TeV



SST	MST	LST
5 - 300 TeV	150 GeV - 5 TeV	20 - 150 GeV
$D_{\varnothing}$ = 4.3m	$D_{\varnothing}$ = 11.5m	$D_{\varnothing}$ = 23m

THE CHERENKOV TELESCOPE ARRAY OBSERVATORY (CTAO)

- Future of Imaging Atmospheric Cherenkov Telescopes for very-high-energy (VHE) γ-ray astronomy
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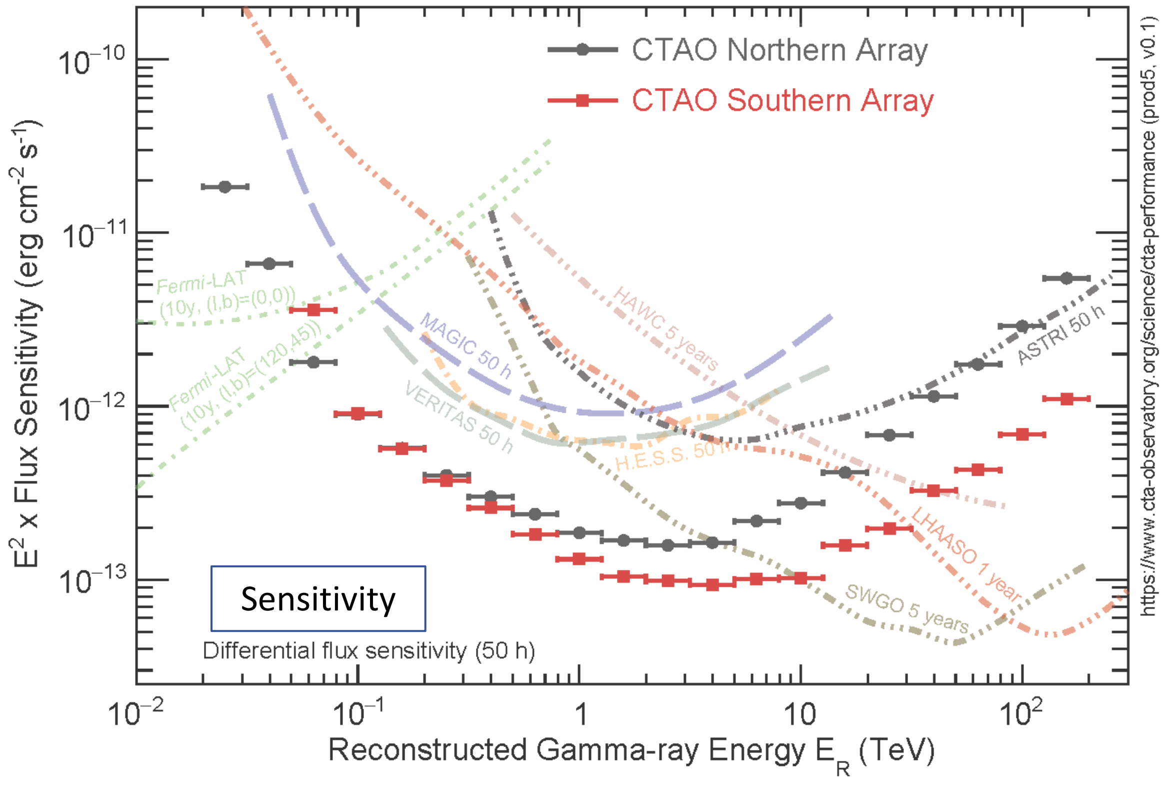
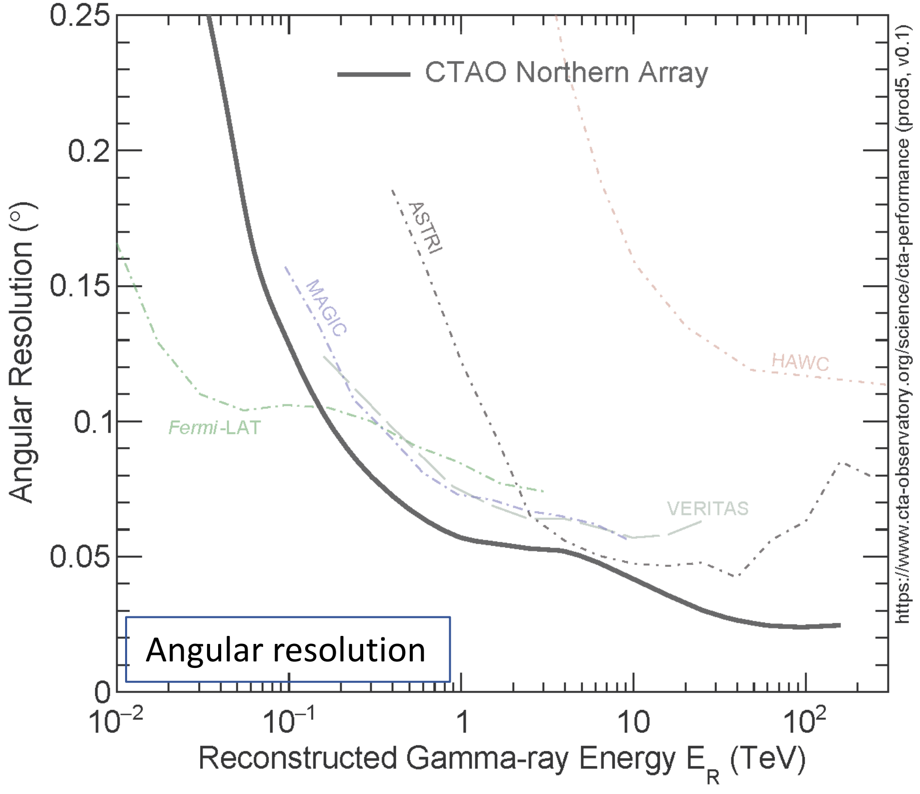


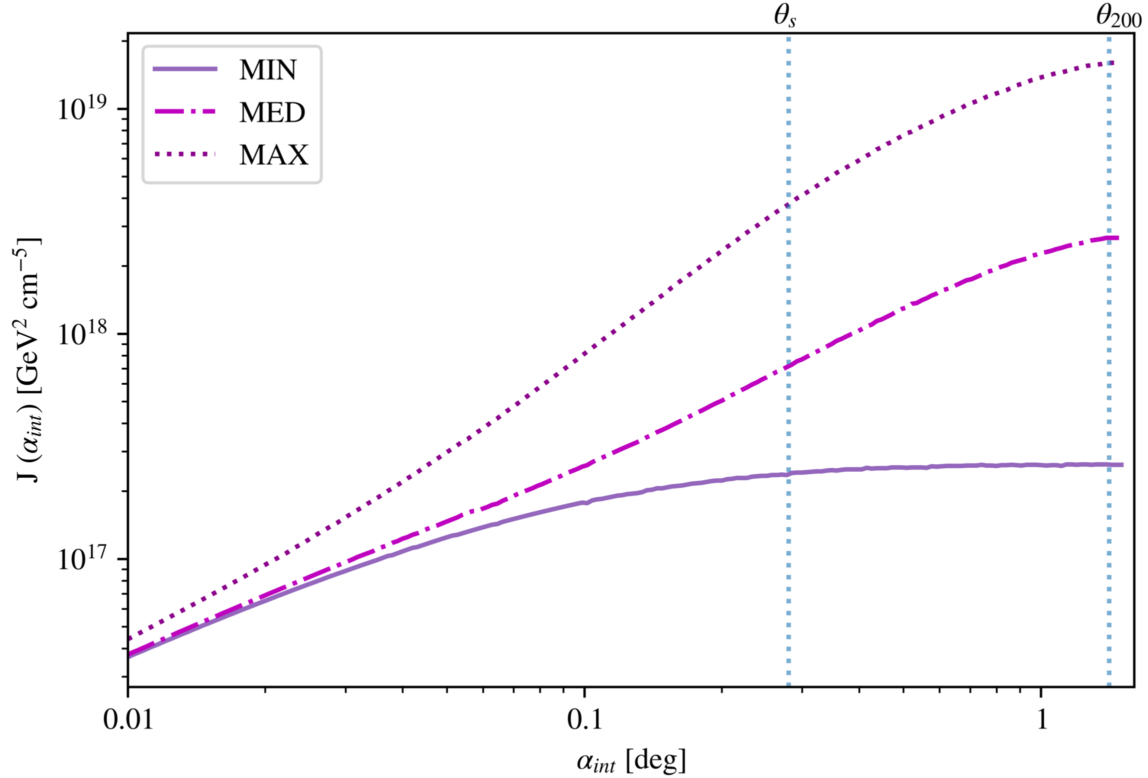
https://www.ctao.org/



EXPECTED PERSEUS DM SIGNAL

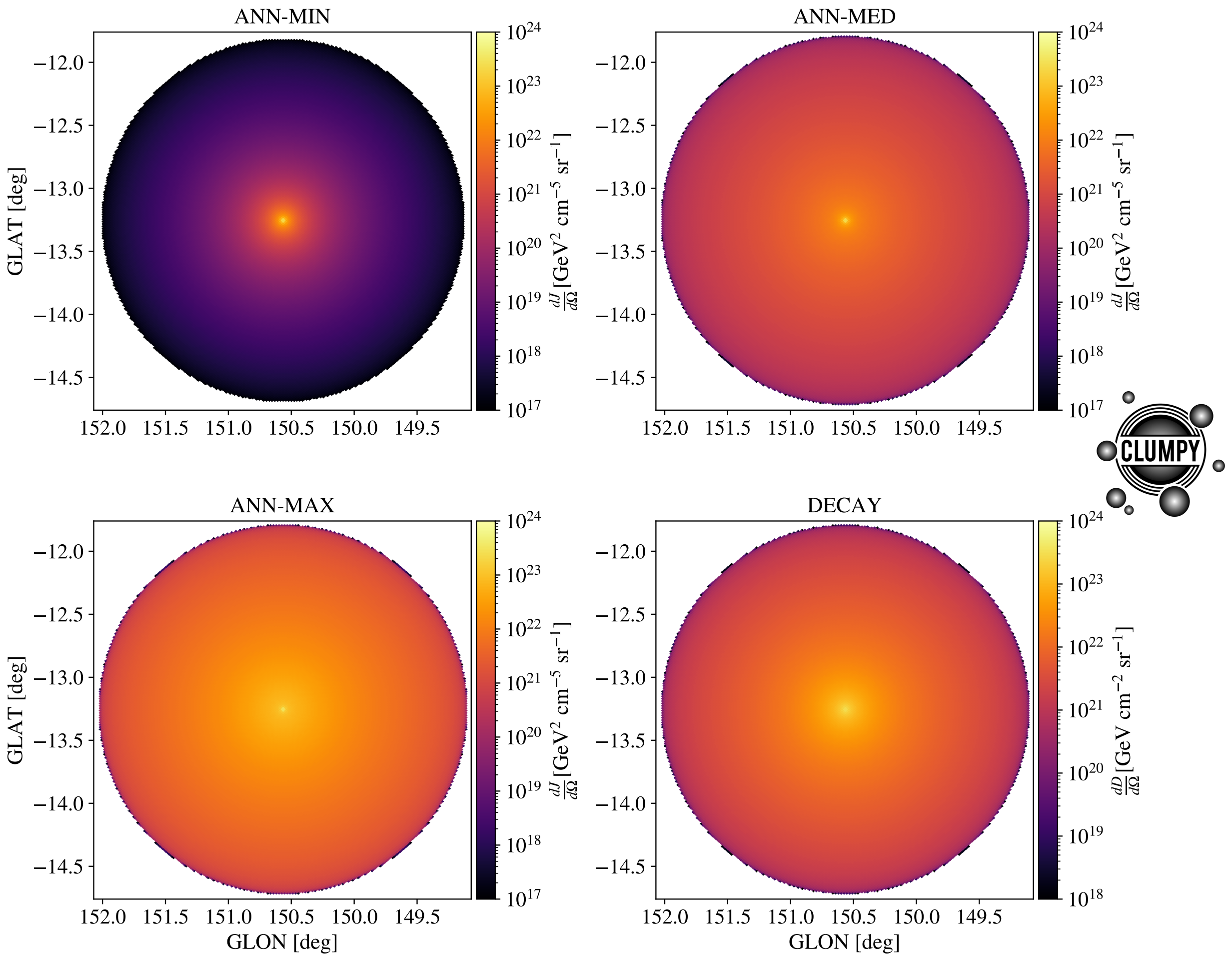
- Accumulated annihilation flux profile

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

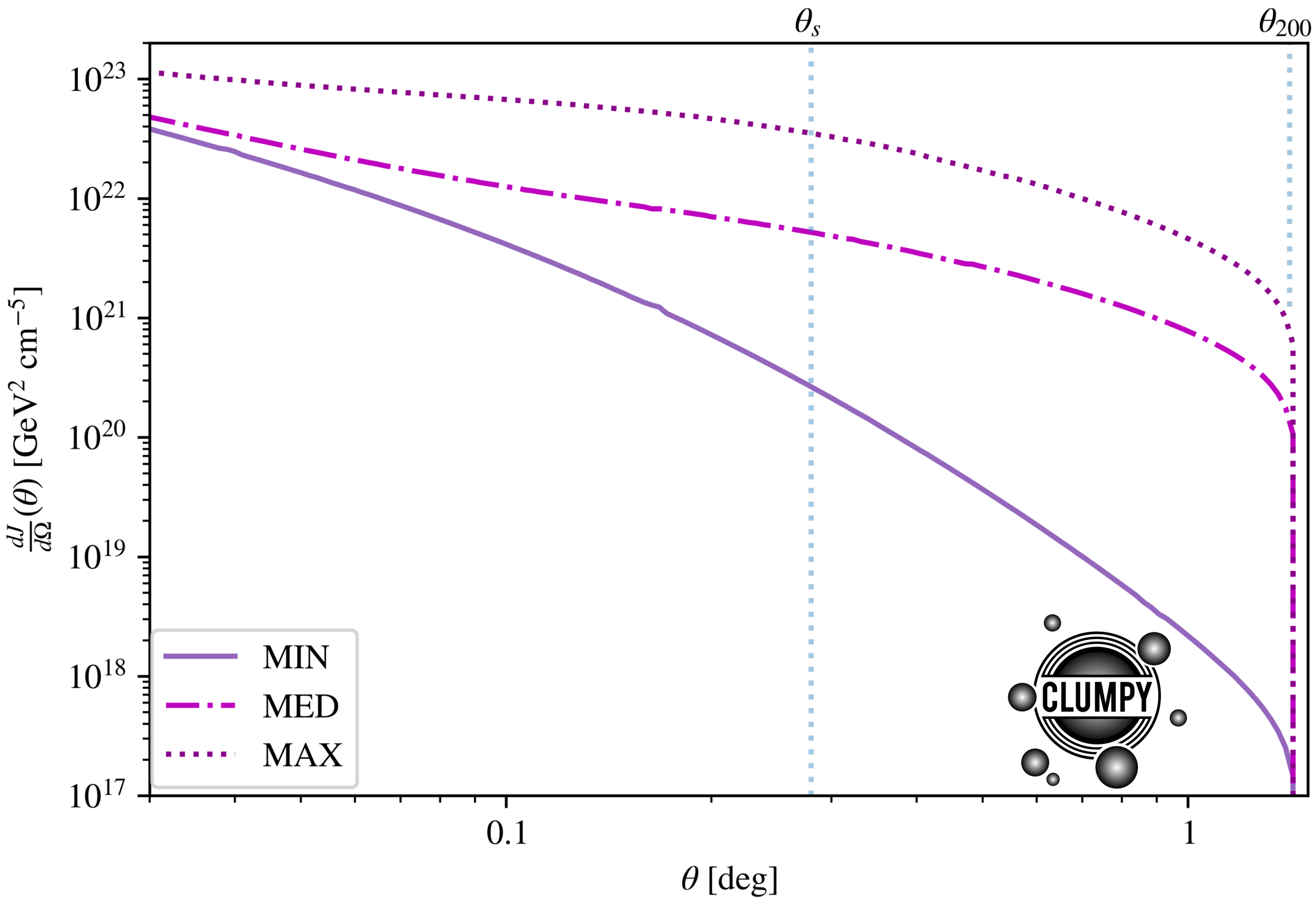


- Skymaps of the differential J/D-factors

B_{MED} = 9 (B~9 – *Moliné+17*)
B_{MAX} = 59 (B~72 – *Moliné+17*)



PERSEUS DIFFERENTIAL ANNIHILATION FLUX PROFILE



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 $M_\odot$/kpc^3

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

UNCERTAINTIES FOR CLUSTER'S DM MODELS

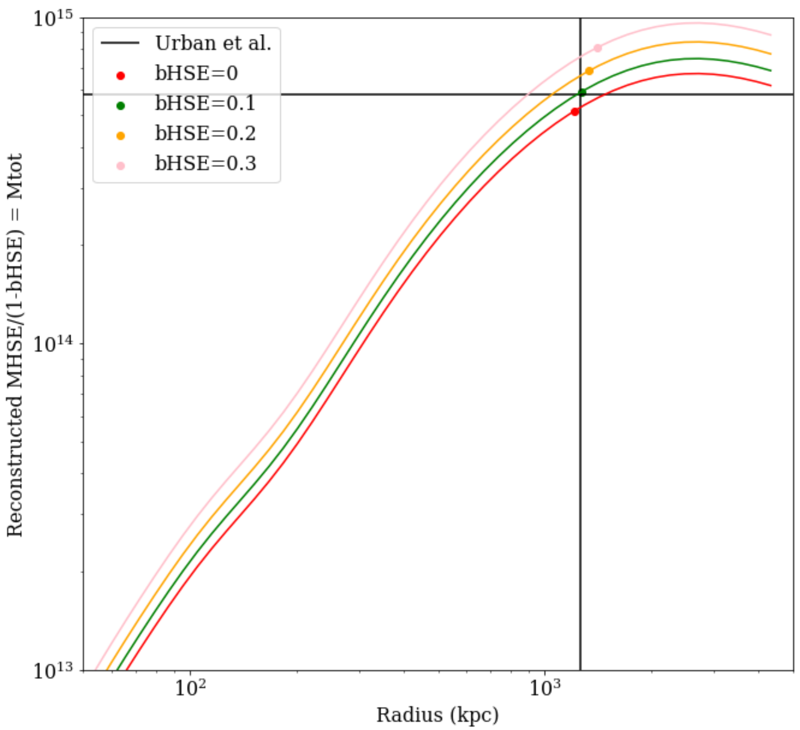
- Uncertainties in the J/D-factor enter through:

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

- Masses from other methods
- Other X-rays measurements

- ~ O(0.14) 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



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

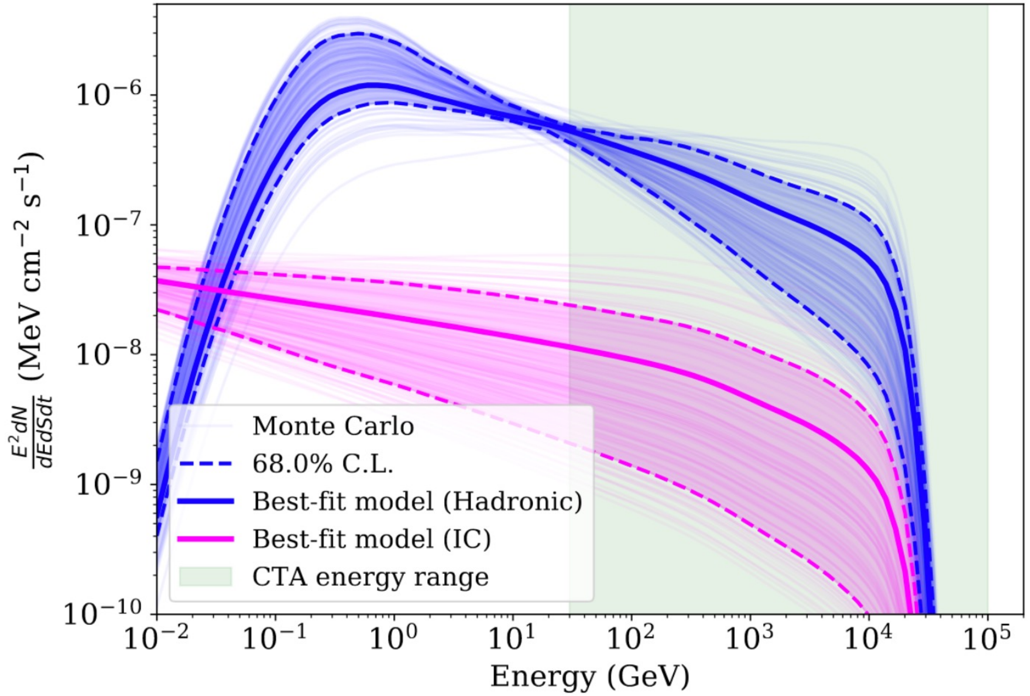
Gaussian prior in J-factor uncertainty

CHARACTERISTICS OF THE SIMULATIONS

- Background models: CR baseline model + NGC1275 & IC310 + CTAO IRFs instrumental

- From simulations by *Pinzke&Pfrommer 2010:* π^0 decay + Inverse Compton

Model	X_{500} (%)	$\alpha_{\rm CRp}$	$\eta_{\rm CRp}$	$F^{\rm (had)}_{500,E_\gamma>150\ \rm GeV}$	$F^{\rm (IC)}_{500,E_\gamma>150\ \rm GeV}$ [10^{-14} cm^{-2} s^{-1}]
	reference value, [min, max]				
Baseline	1.0, [0.0, 20.0]	2.30, [2.0, 3.0]	1.0, [0.0, 1.5]	70.2, [0, 11373.8]	2.1, [0, 625.4]



- Quiescent states

  - NGC 1275 (*Ahnen+16*)

$$\frac{dN}{dEdSdt} = 2.1 \times 10^{-11} \left(\frac{E}{200\ \mathrm{GeV}}\right)^{-3.6}\ \mathrm{cm^{-2}s^{-1}TeV^{-1}}$$

  - IC 310 (*Alecksic+14*)

$$\frac{dN}{dEdSdt} = 0.741 \times 10^{-12} \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-1.81}\ \mathrm{cm^{-2}s^{-1}TeV^{-1}}$$

CHARACTERISTICS OF THE SIMULATIONS

- Input models:

DM Annihilation (thermal cross-section)
DM Decay (τ_χ = 10^{27}s)
m_χ = 10 TeV
$b\bar{b}$

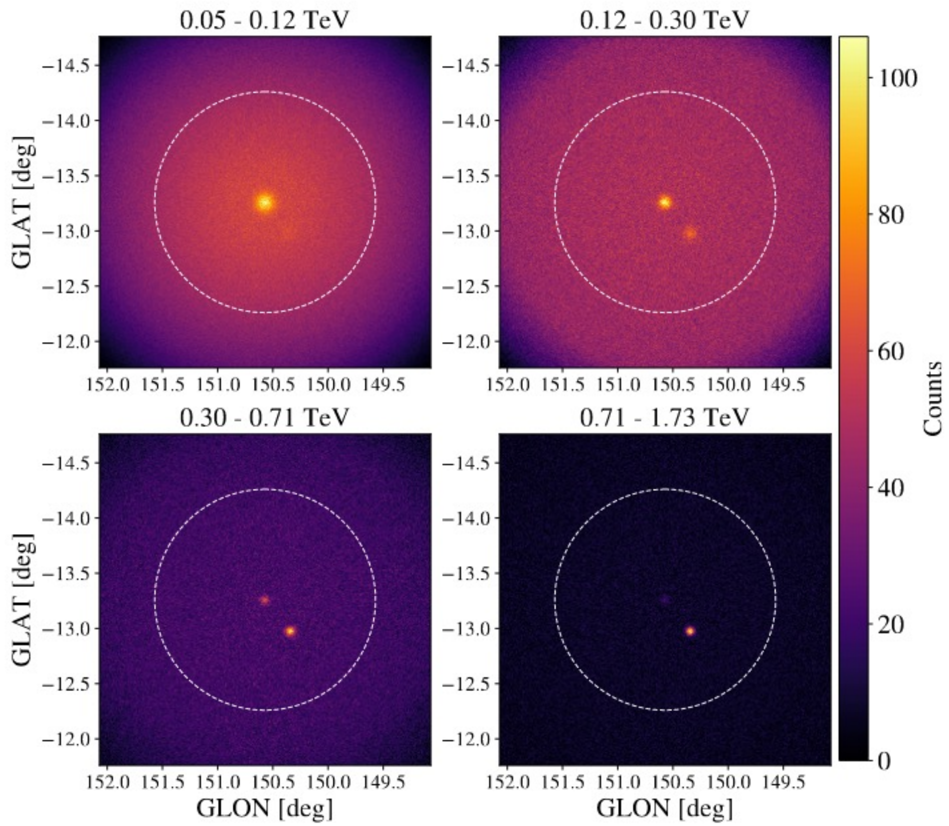
+

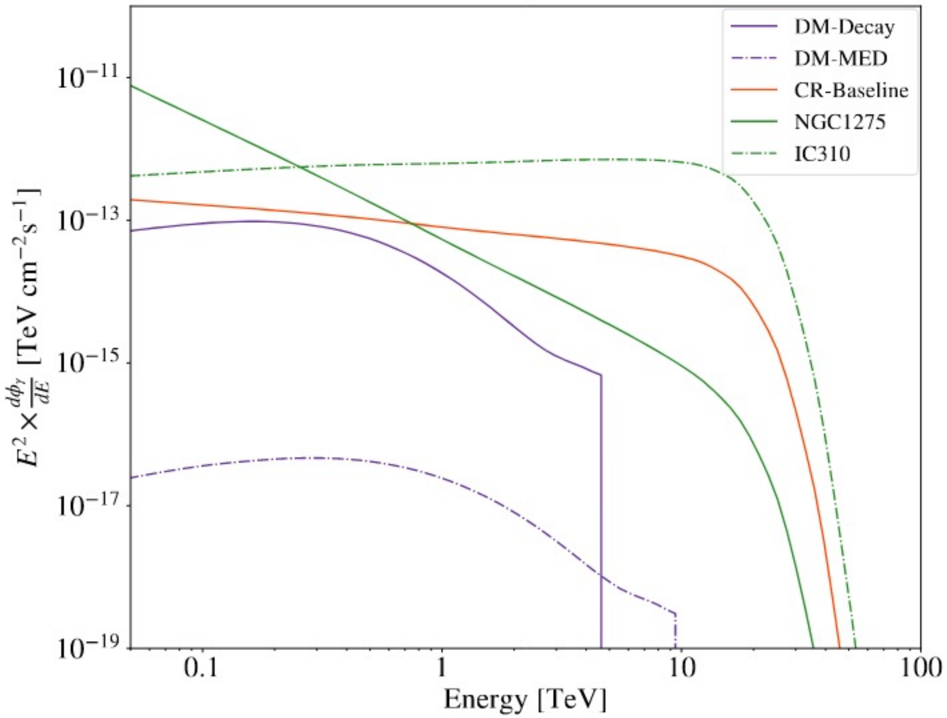
CR baseline model

NGC1275
&
IC310

+

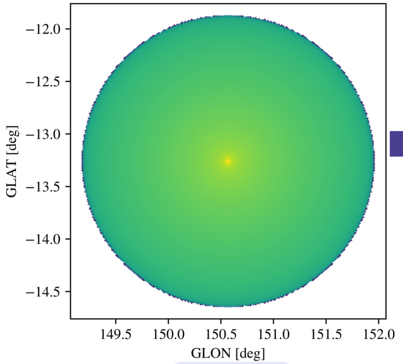
EBL
Domínguez+11



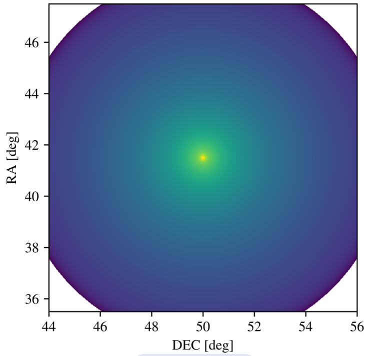


CTAO ANALYSIS CONFIGURATION: TEMPLATE FITTING

- Includes all expected γ-ray sources: DM + CRs + AGNs + BKG IRFs

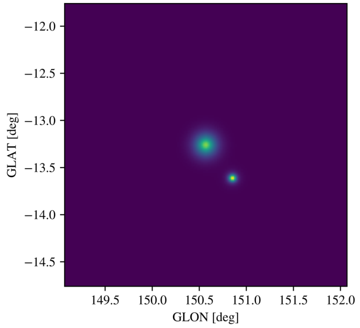


DM



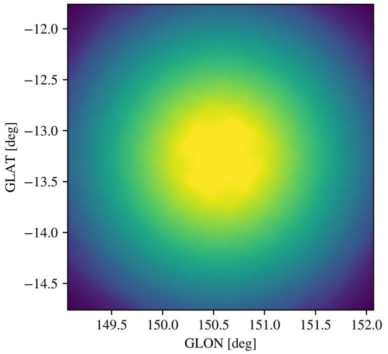
CR

[baseline]



AGNs

[*CTA Cons. 21* – γ-ray propagation]



BKG

[from IRFs]

Most realistic physical scenario

- Fitting 8 parameters in total

$$\vec{\theta} \equiv \left(A_\chi, A_{\rm CR}, A_{\rm PS}^{(1,2)}, \alpha_{\rm PS}^{(1,2)}, A_{\rm bkg}, \alpha_{\rm bkg} \right)$$

- Use likelihood ratio test to fit the models to the simulated data:

$$\ln\mathcal{L}(\vec{\theta}|D) = \sum_i \tilde{M}_i(\vec{\theta}) - d_i \ln(\tilde{M}_i(\vec{\theta}))$$

Poissonian likelihood for each parameter

$$TS = 2\,\log\left[\frac{\mathcal{L}\left(A_\chi, \hat{\hat{\nu}}\right)}{\mathcal{L}_{\rm null}\left(A_\chi = 0, \hat{\nu}\right)}\right]$$

Donath+23
https://gammapy.org/

N_{obs}	100
T_{obs} [h]	300
IRFs	`North_z20_50h, prod5`
Energy range [TeV]	0.03 - 100

CTAO ANALYSIS ELEMENTS

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

- Likelihood ratio test:

$$TS = 2\log\left[\frac{\mathcal{L}\left(A_\chi, \hat{\hat{\nu}}\right)}{\mathcal{L}_{\rm null}\left(A_\chi = 0, \hat{\nu}\right)}\right]$$

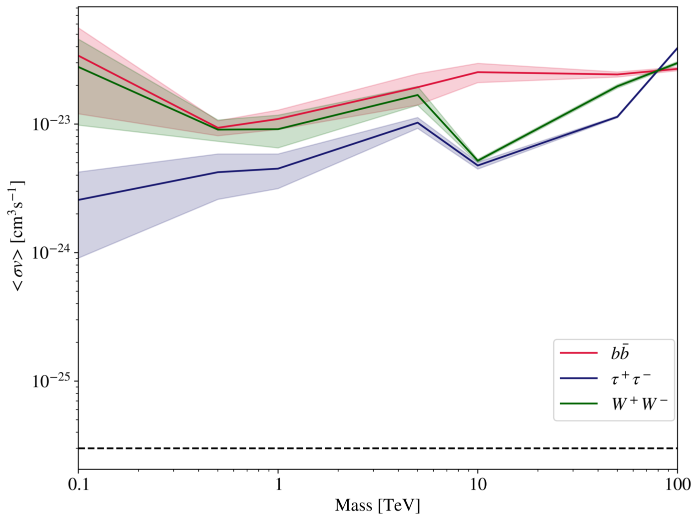
  - *TS* < 25 ⟶ No signal

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

$$\ln\mathcal{L}(\vec{\theta}|D) = \sum_i \tilde{M}_i(\vec{\theta}) - d_i \ln(\tilde{M}_i(\vec{\theta})) \qquad \vec{\theta} \equiv \left(A_\chi, A_{\rm CR}, A_{\rm PS}^{(1,2)}, \alpha_{\rm PS}^{(1,2)}, A_{\rm bkg}, \alpha_{\rm bkg}\right)$$

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

$$\mathcal{L}(A_\chi|D) = \prod_{ij} \frac{(N_{ij}^S + \kappa_{ij} N_{ij}^B)^{N_{ij}^{ON}}}{N_{ij}^{ON}!} e^{-(N_{ij}^S + \kappa_{ij} N_{ij}^B)} \times \frac{(N_{ij}^B)^{N_{ij}^{OFF}}}{N_{ij}^{OFF}!} e^{-N_{ij}^B}$$

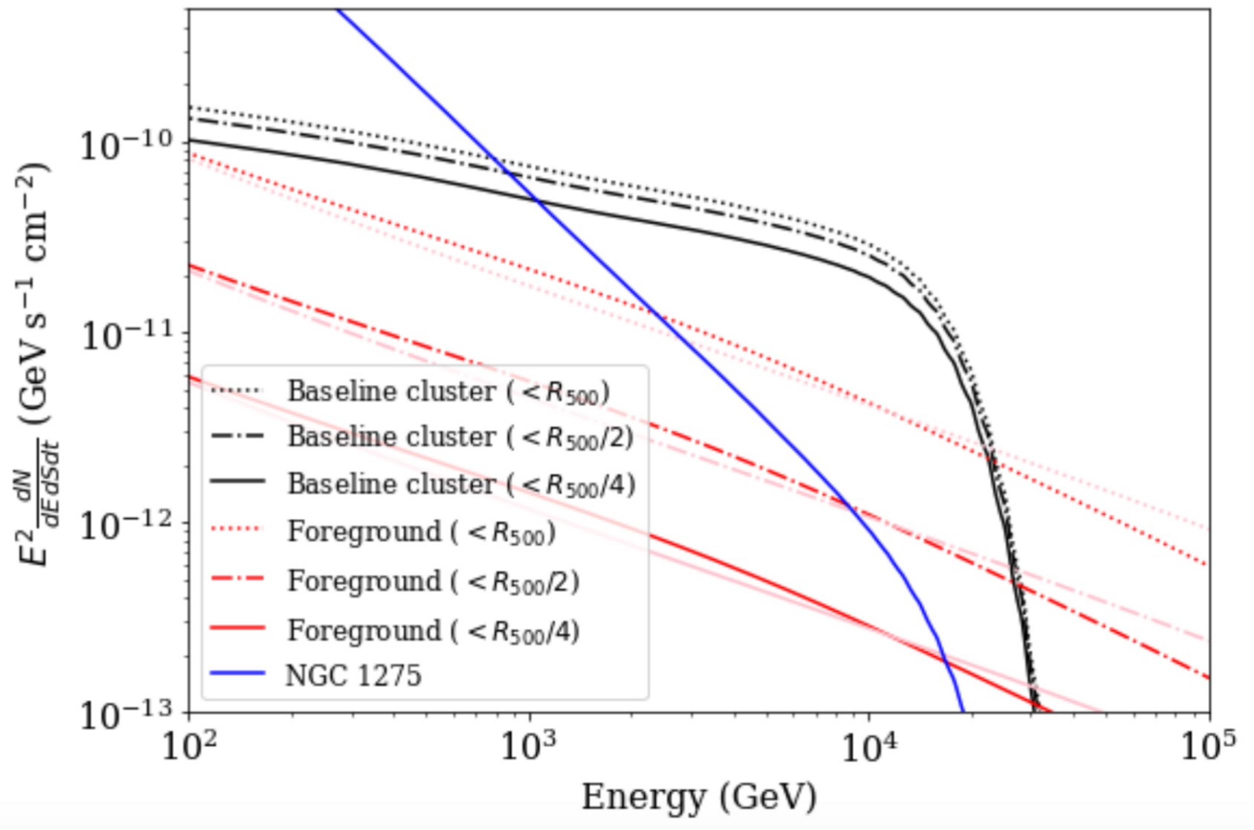


Caveat

- 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.

CTAO 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



CTAO ANALYSIS APPROACHES: DMTOOLS

- Most DM projects within CTAO with same needs in terms of analysis tools and statistical treatment

Common set of tools

- Unified definitions, methodology
- Avoids repetition of same coding
- Allows easy comparison of results.
- Everyone can potentially contribute

- Creation & coordination of *DMTools Task Force* within CTAO
- Gammapy beta-testing and software development

Since v-0.8 to v-1.0
(15 versions)

- Gammapy embedded functions:
  - DarkMatterAnnihilationSpectralModel
- GitHub repository:
  - Gammapy-DMTools
  https://github.com/peroju/dmtools_gammapy
- Gammapy coding sprints

CTAO ANALYSIS APPROACHES: DMTOOLS

ON-OFF/Wobble Analysis

Standard for IACTs

Point-like

- Lowest complexity
- Most constraining results

Extended

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

Template fitting

State-of-the-art pipeline

Minuit

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

MCMC

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

CTAO ANALYSIS APPROACHES: DMTOOLS

Basic functioning of the pipelines

Input DM model
- Spectral (based on *Cirelli+12*)
- Spatial (point-like, analytical, FITS files)

\+

Combine with observation set-up
- IRFs
- Observation time
- Backgrounds

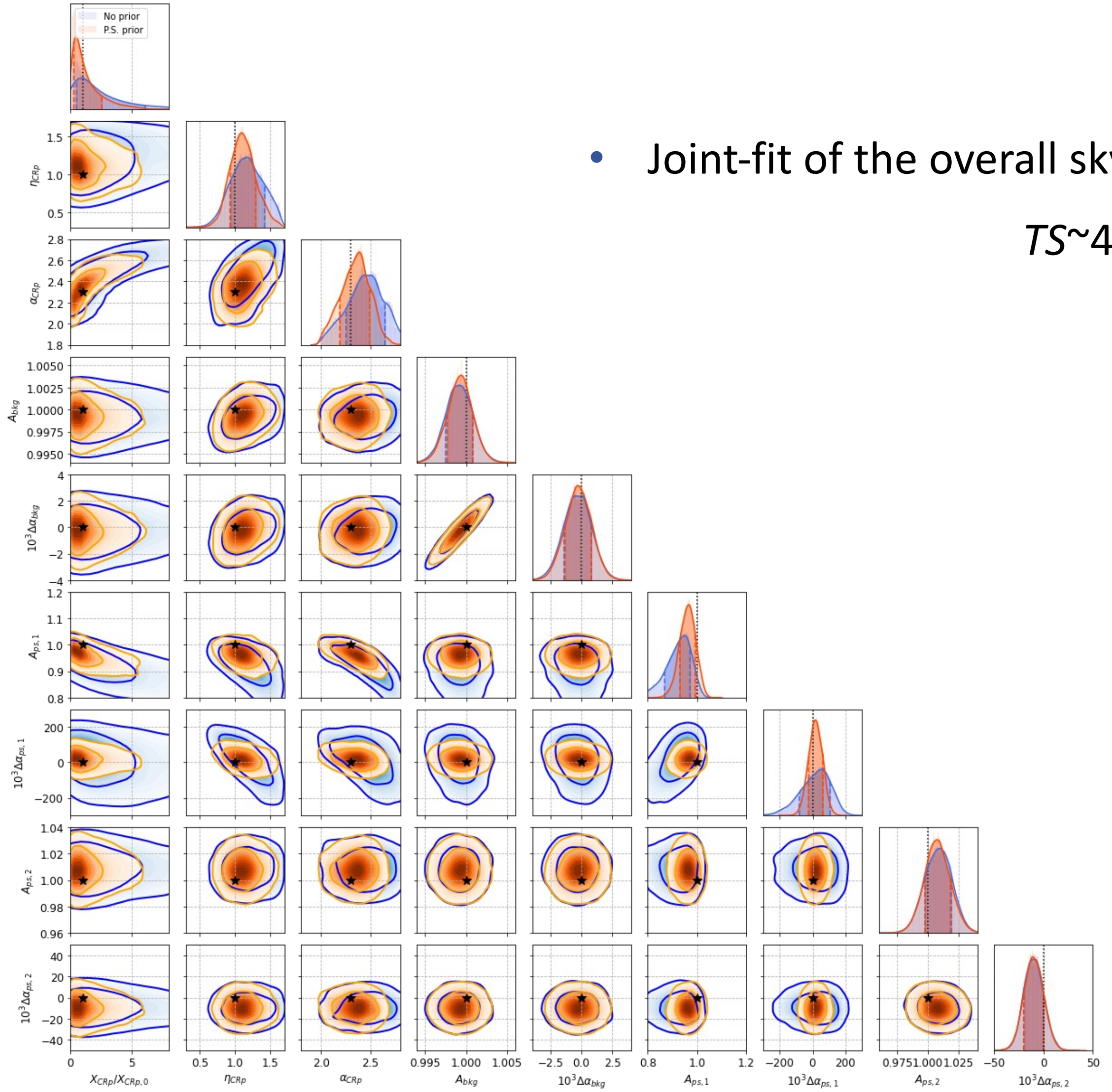
→

- Simulated Observation (Poisson realization)
- Observation

Enter the DM fit loop

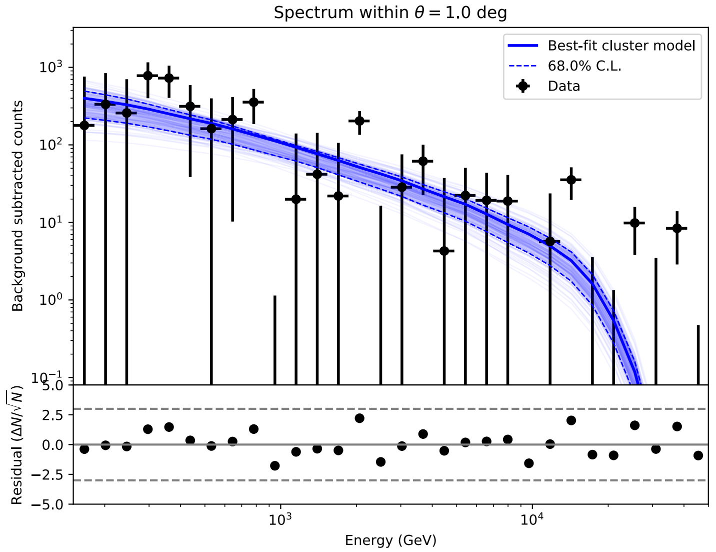
1. For each realization, consider a list of channels and for each, a list of DM masses
2. Perform a likelihood fit to this specific model
3. Check $TS(H_{null}) \geq 25$
4. Compute $<\sigma v>$ upper limits with $TS(\mathrm{H}_{\text{best-fit}}) = 2.71$

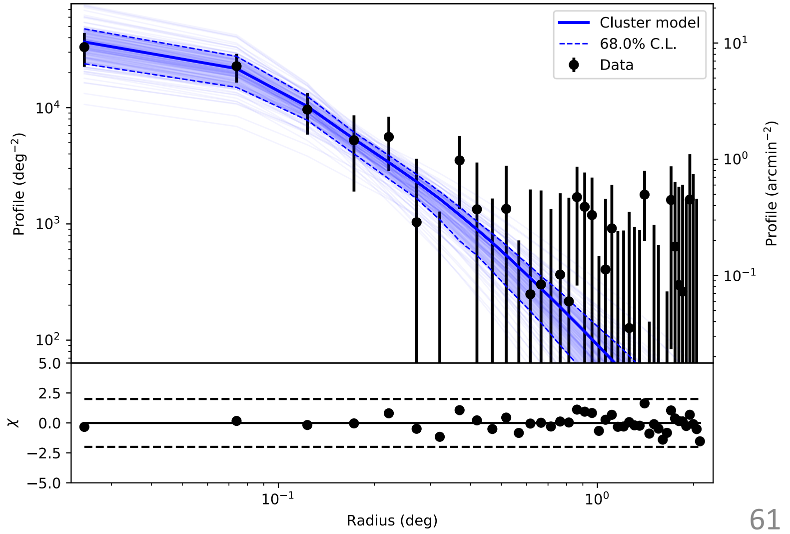
INSIGHT RESULTS: CR ANALYSIS SUMMARY



- Joint-fit of the overall sky model simultaneously

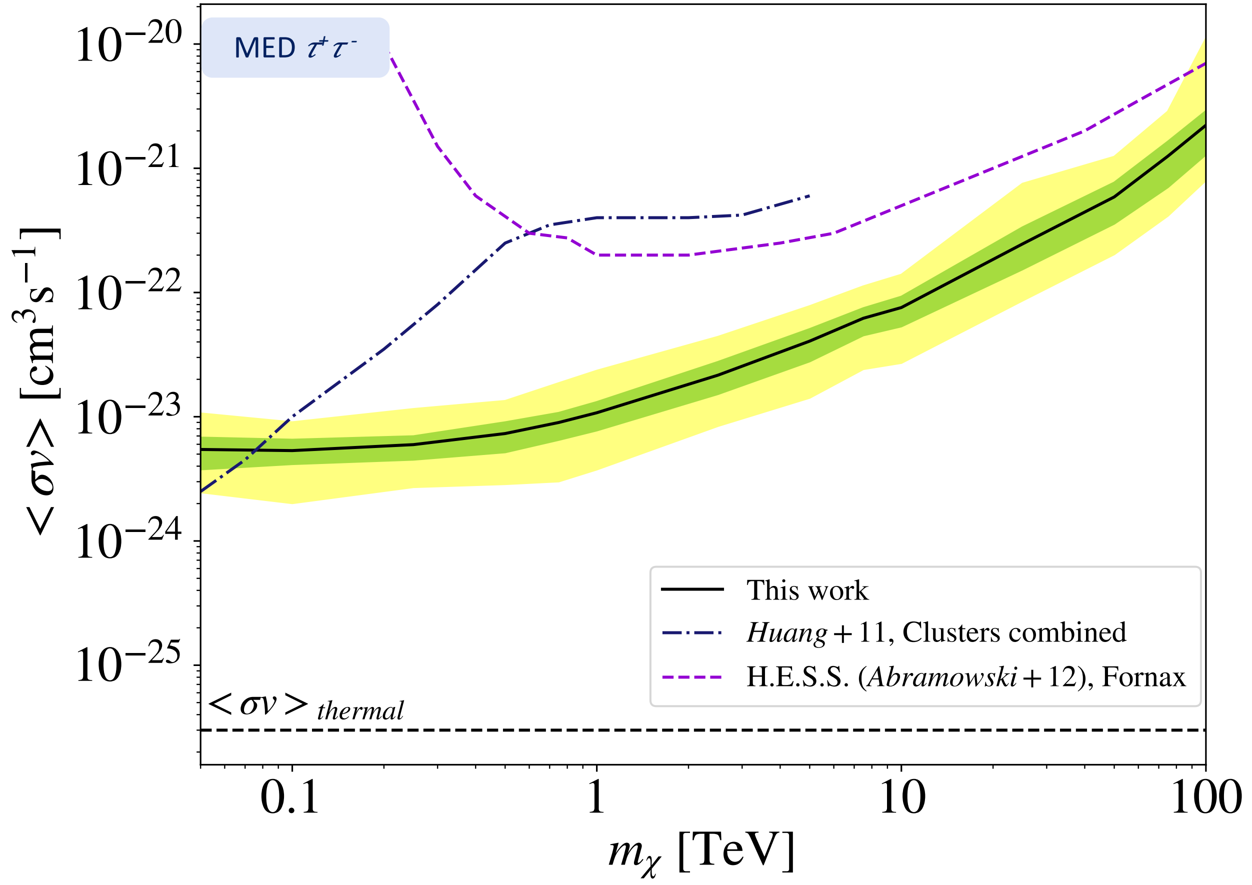
TS~42

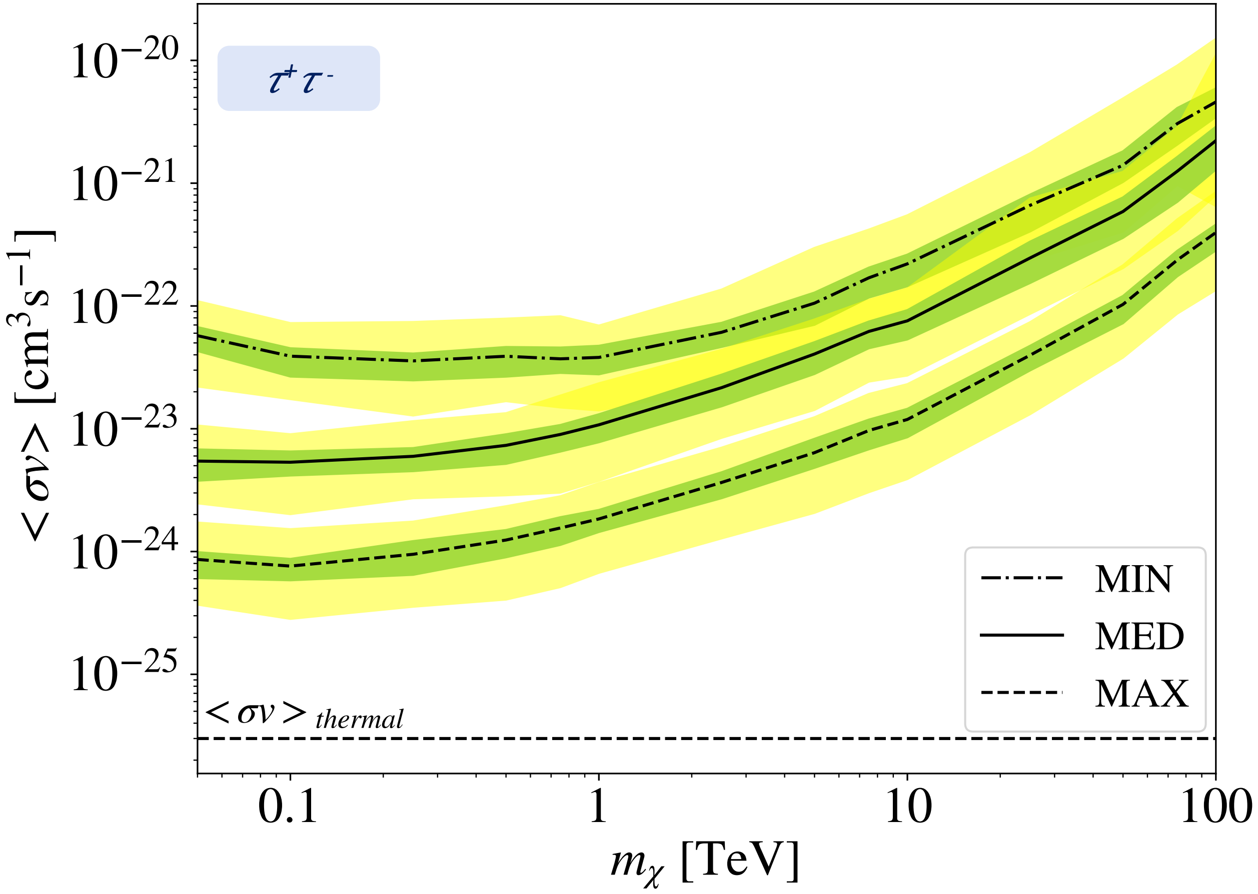




CTAO ANALYSIS: DM PROSPECTS FOR CONSTRAINTS

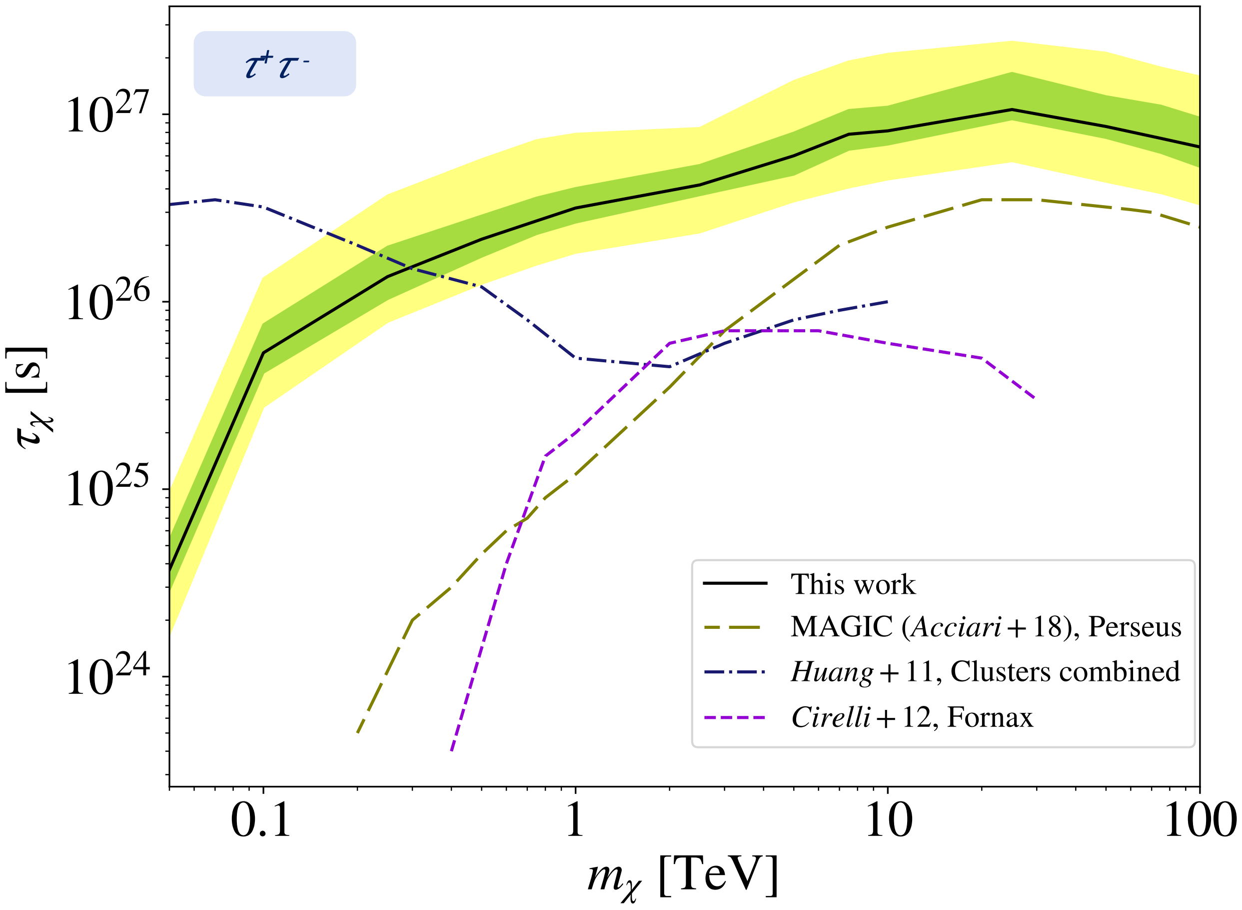
Annihilation 95% C.L Upper Limits

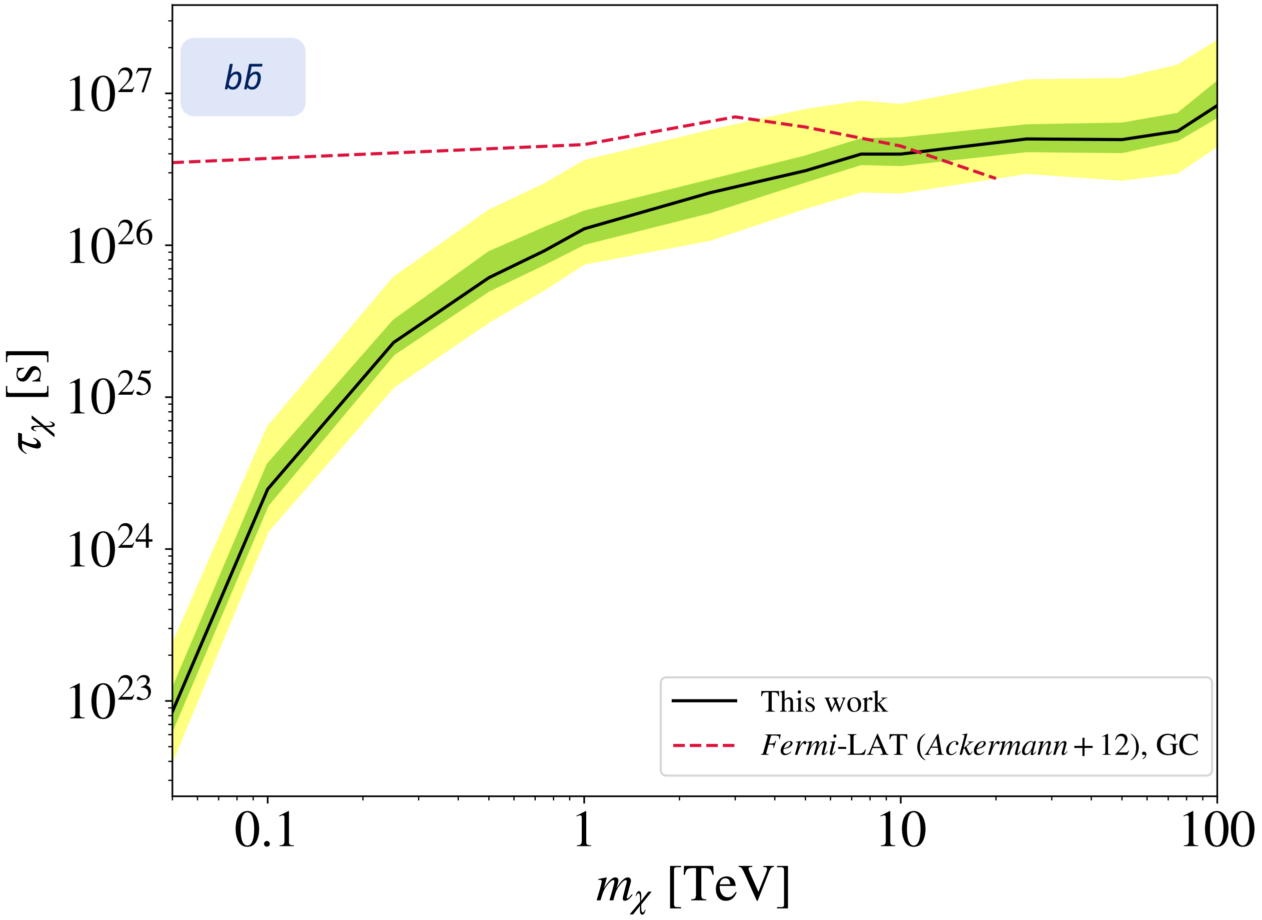




CTAO ANALYSIS: DM PROSPECTS FOR CONSTRAINTS

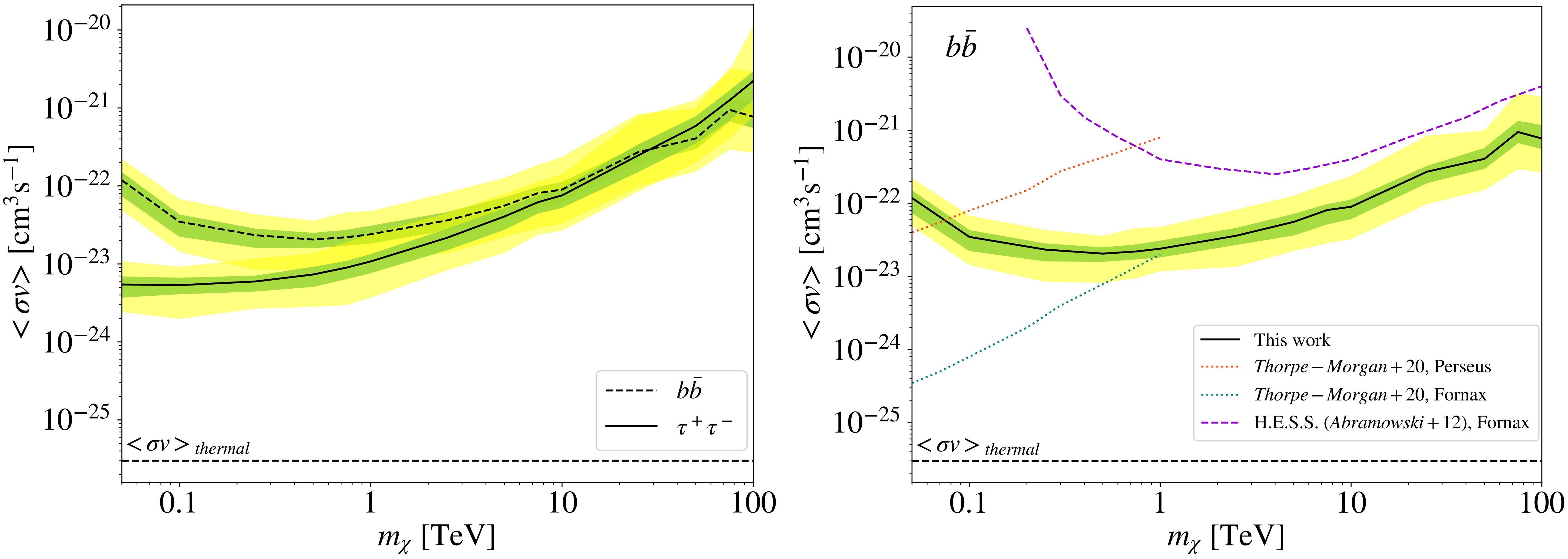
Decay 95% C.L. Lower Limits





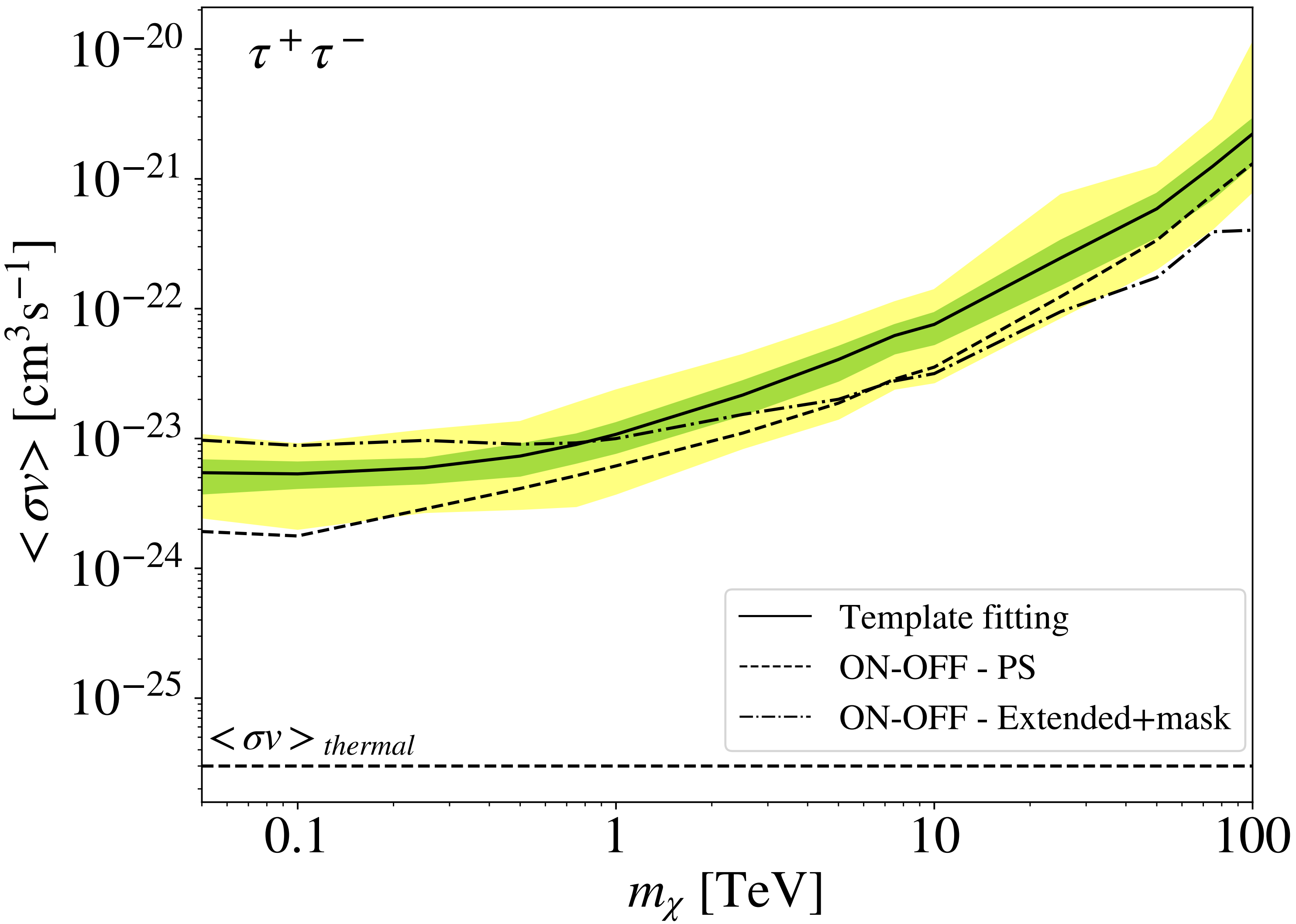
INSIGHT RESULTS: DM CONSTRAINTS

Annihilation (MED)



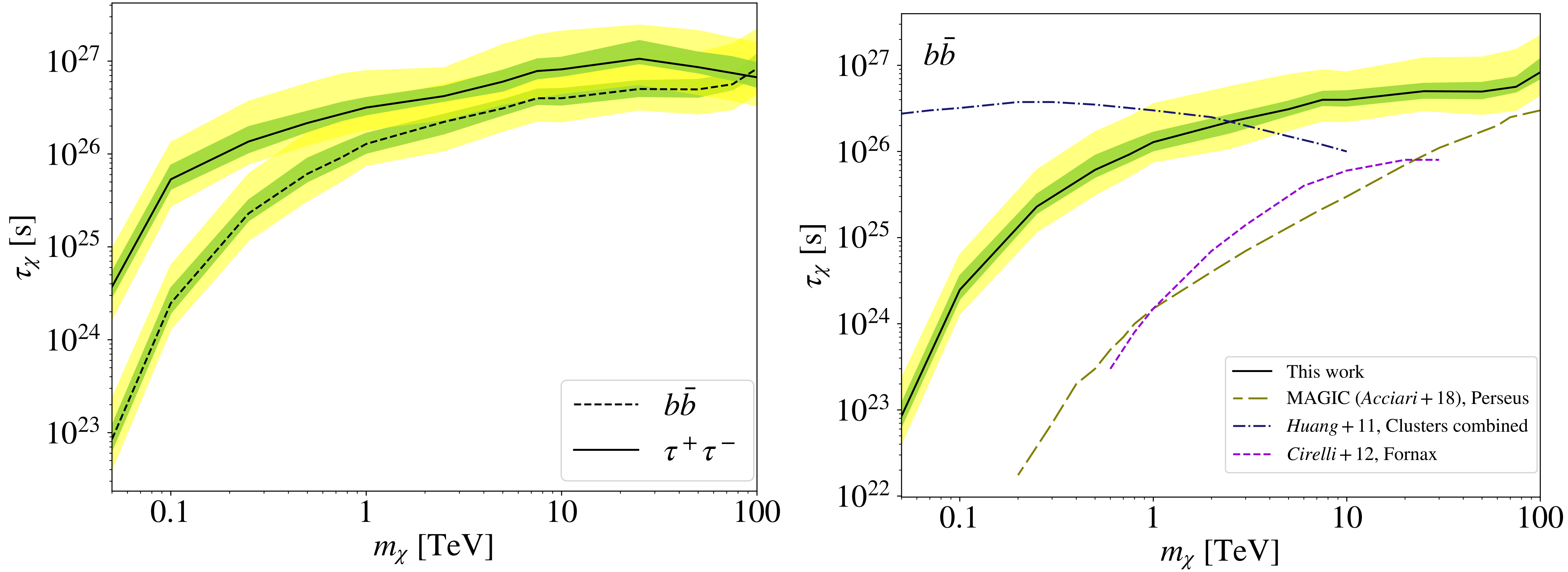
INSIGHT RESULTS: DM CONSTRAINTS

Annihilation (MED)



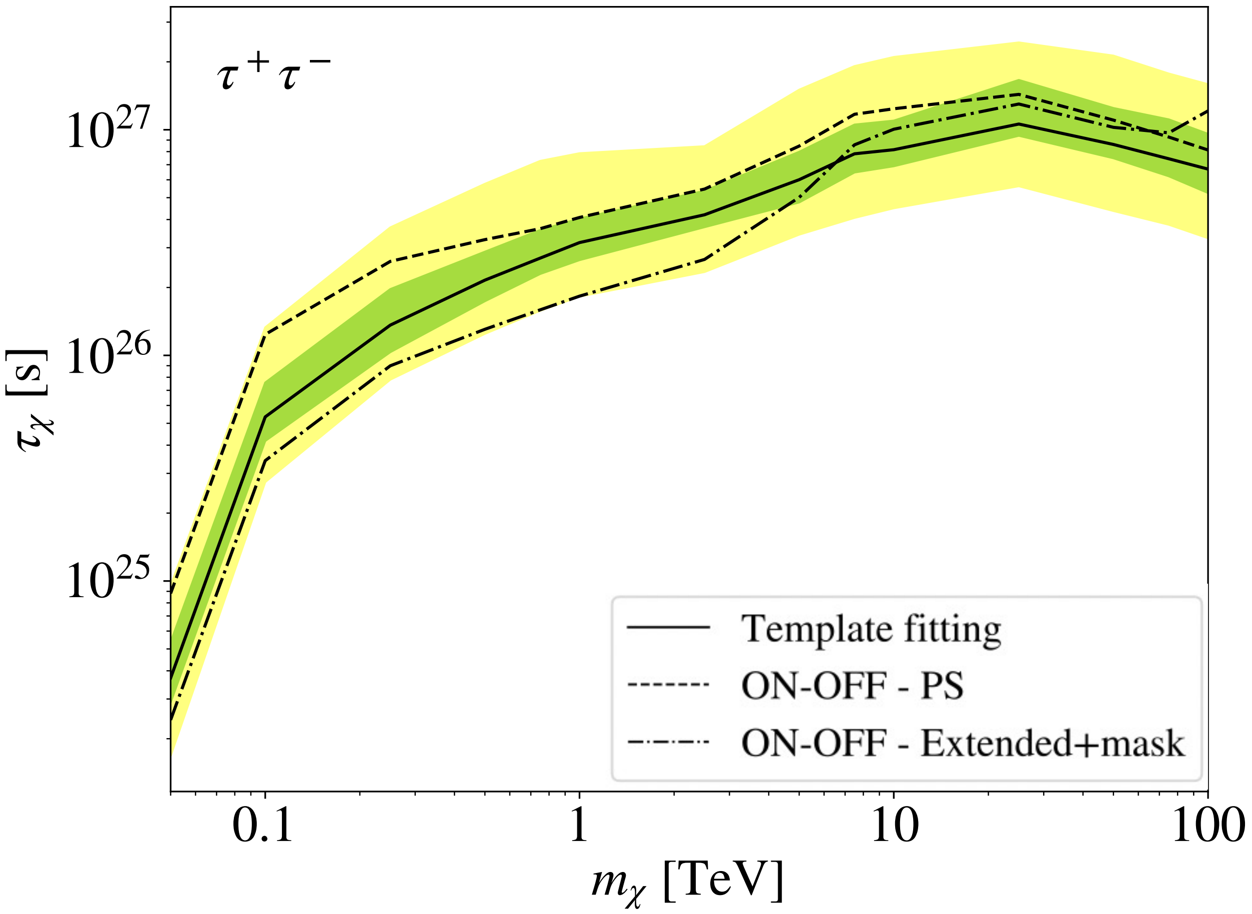
INSIGHT RESULTS: DM CONSTRAINTS

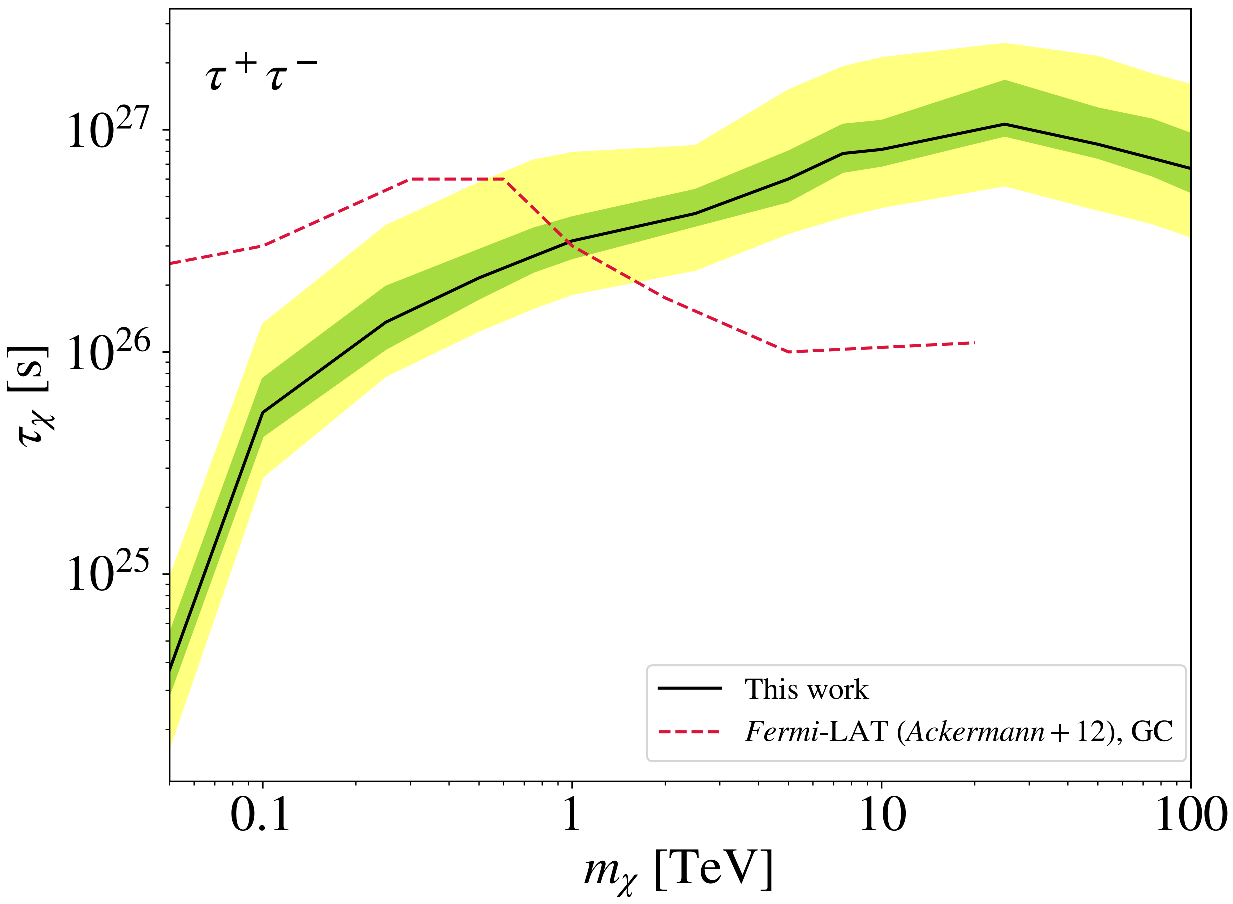
Decay



INSIGHT RESULTS: DM CONSTRAINTS

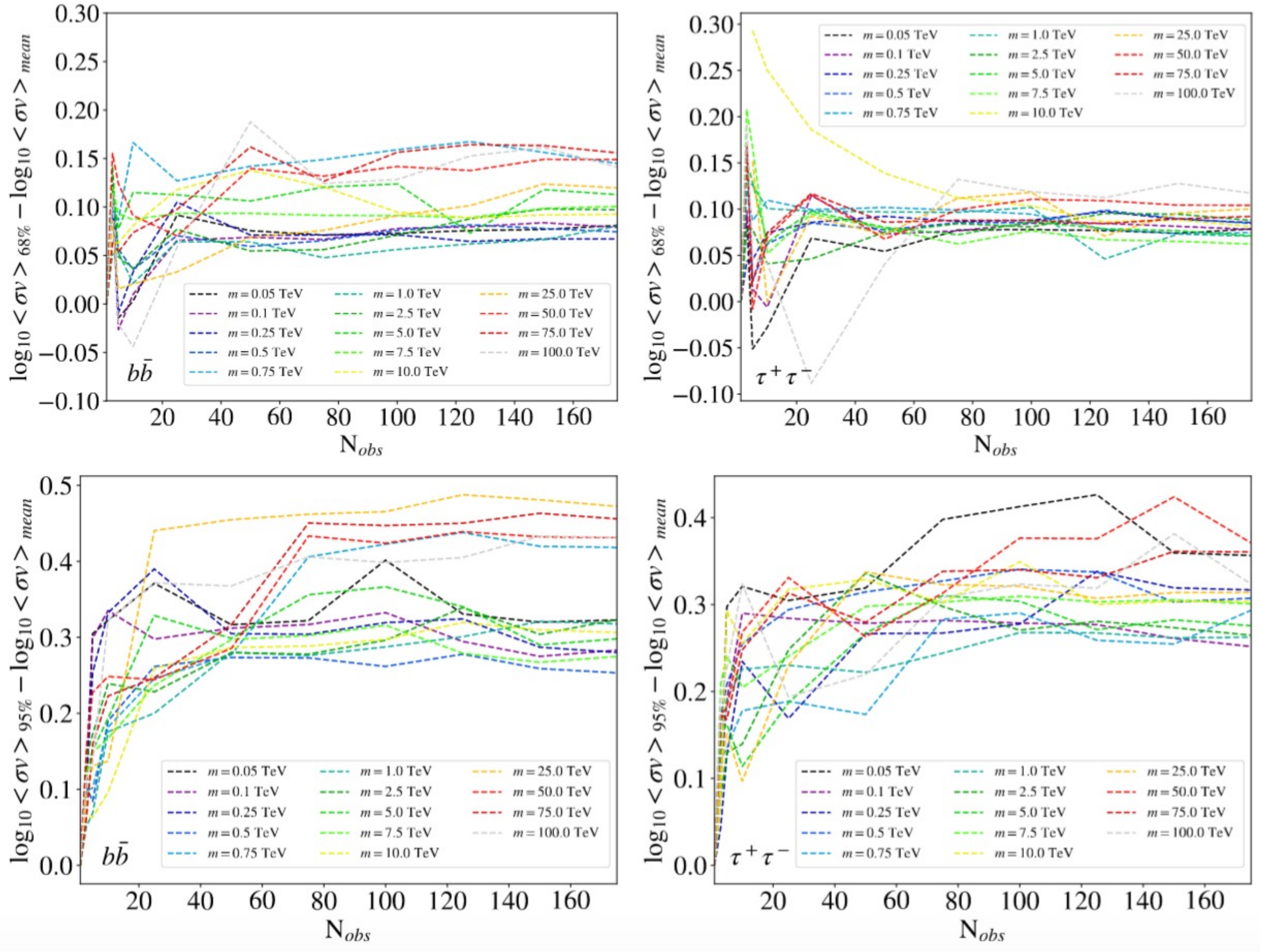
Decay





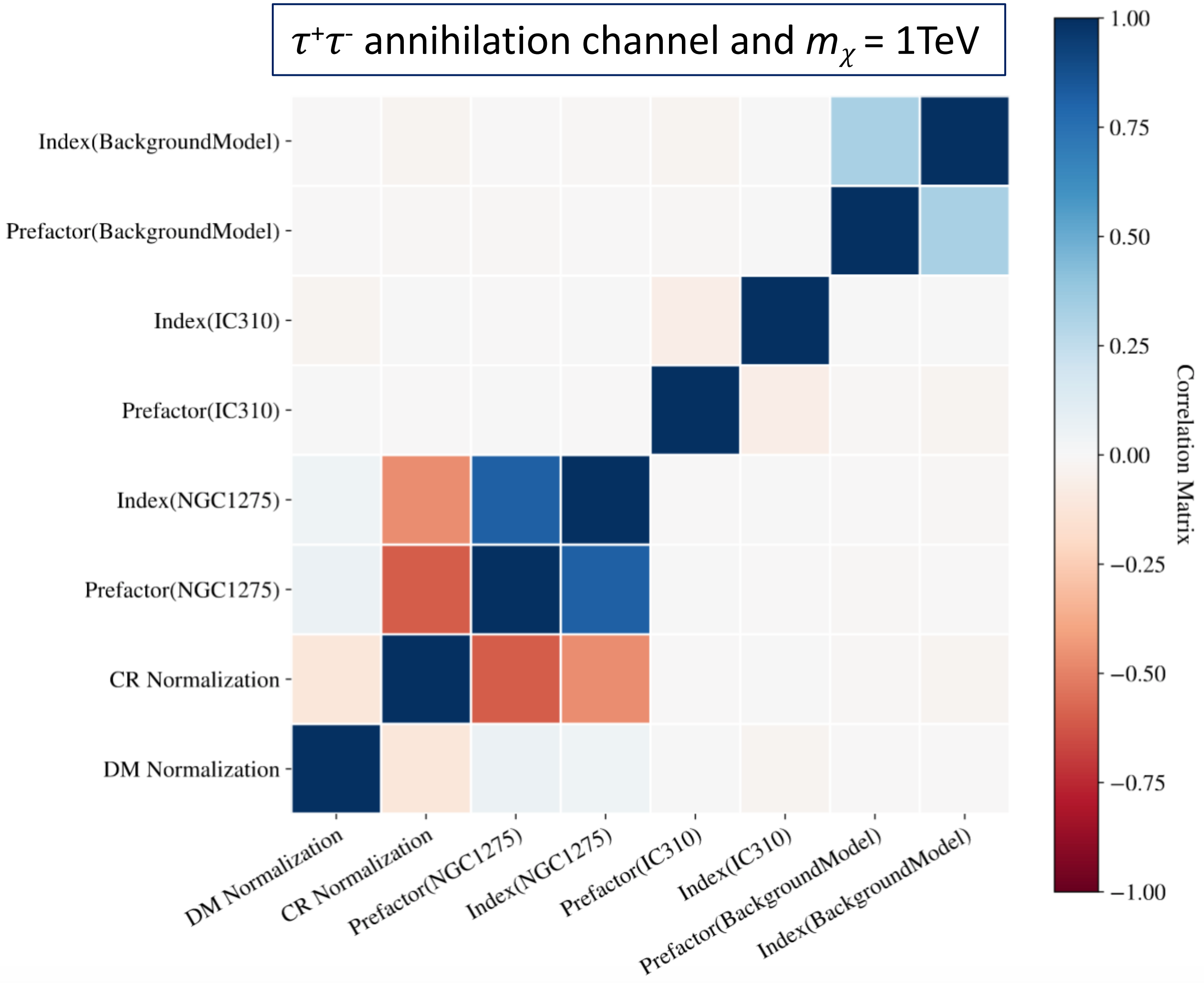
DM CONSTRAINTS: SCATTER BANDS

One-sided 1σ & 2 σ scatter bands evolution with the number of realizations
(annihilation MED model, template fitting)



CTAO ANALYSIS: INTERPLAY BETWEEN COMPONENTS

$\tau^+\tau^-$ annihilation channel and m_χ = 1TeV



- Recovered mean values for CRs, NGC 1275, IC 310 and IRF-BKG within 1σ, independently of the channel or m_χ
- May be dependent on the considered DM scenario (annihilation/decay), channel or m_χ
- DM flux should not be neglected, as it seems to affect the correlations of CR normalization and NGC 1275

CTA ANALYSIS CONFIGURATION (II): ON-OFF ANALYSIS

- First analysis approach
  - Only includes γ-ray emission from DM and background from IRFs
  - Assumes the DM emission template
  - Circular mask of 0.1 deg in the centre
  - Historically used in Imaging Air Cherenkov Telescopes (IACTs) as MAGIC

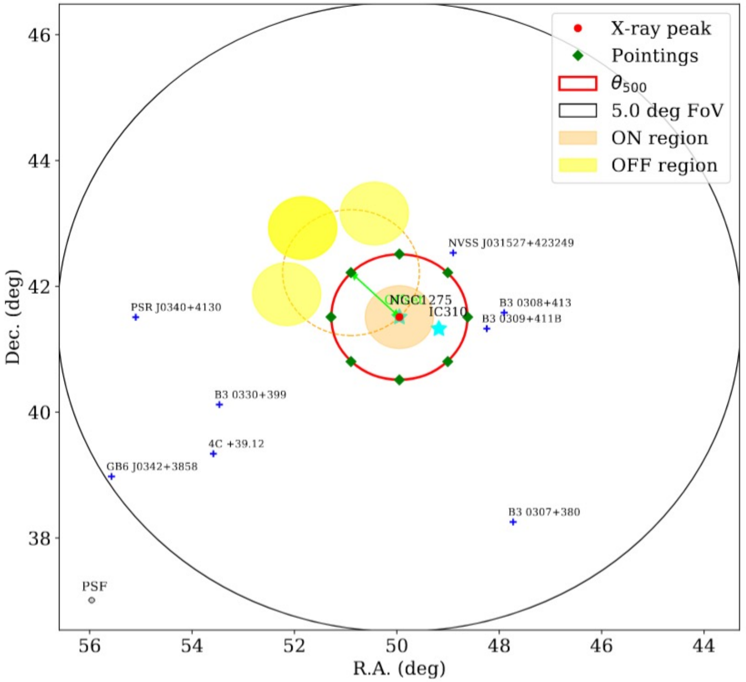
Lowest level of complexity, more constraining results

→ 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]	1

N_{obs}	100
T_{obs} [h]	300
IRFs	North_z20_50h, prod5
Energy range [TeV]	0.03 - 100

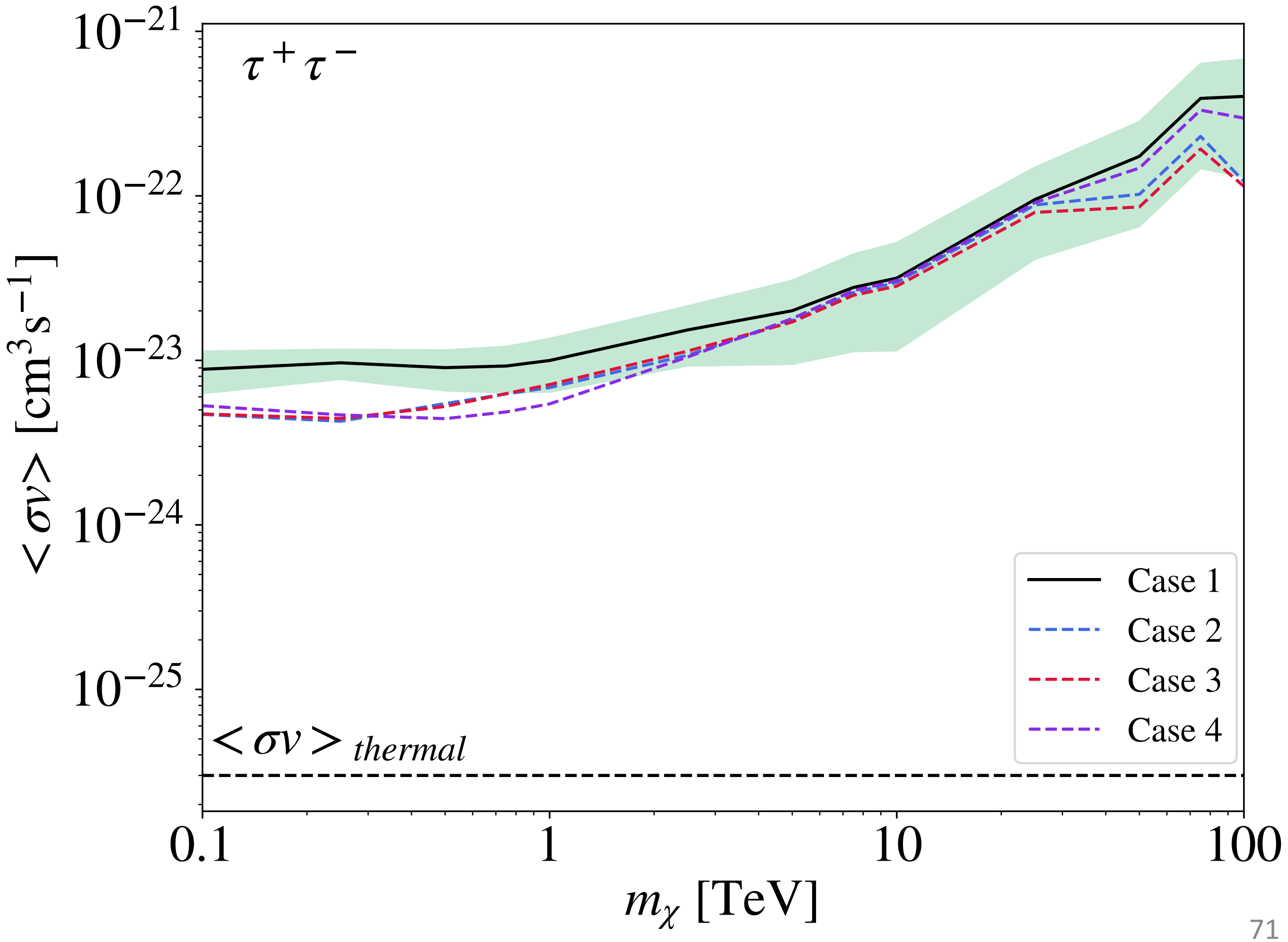


DM CONSTRAINTS: ON-OFF SET-UPS

Different configurations tested with the ON-OFF set-up

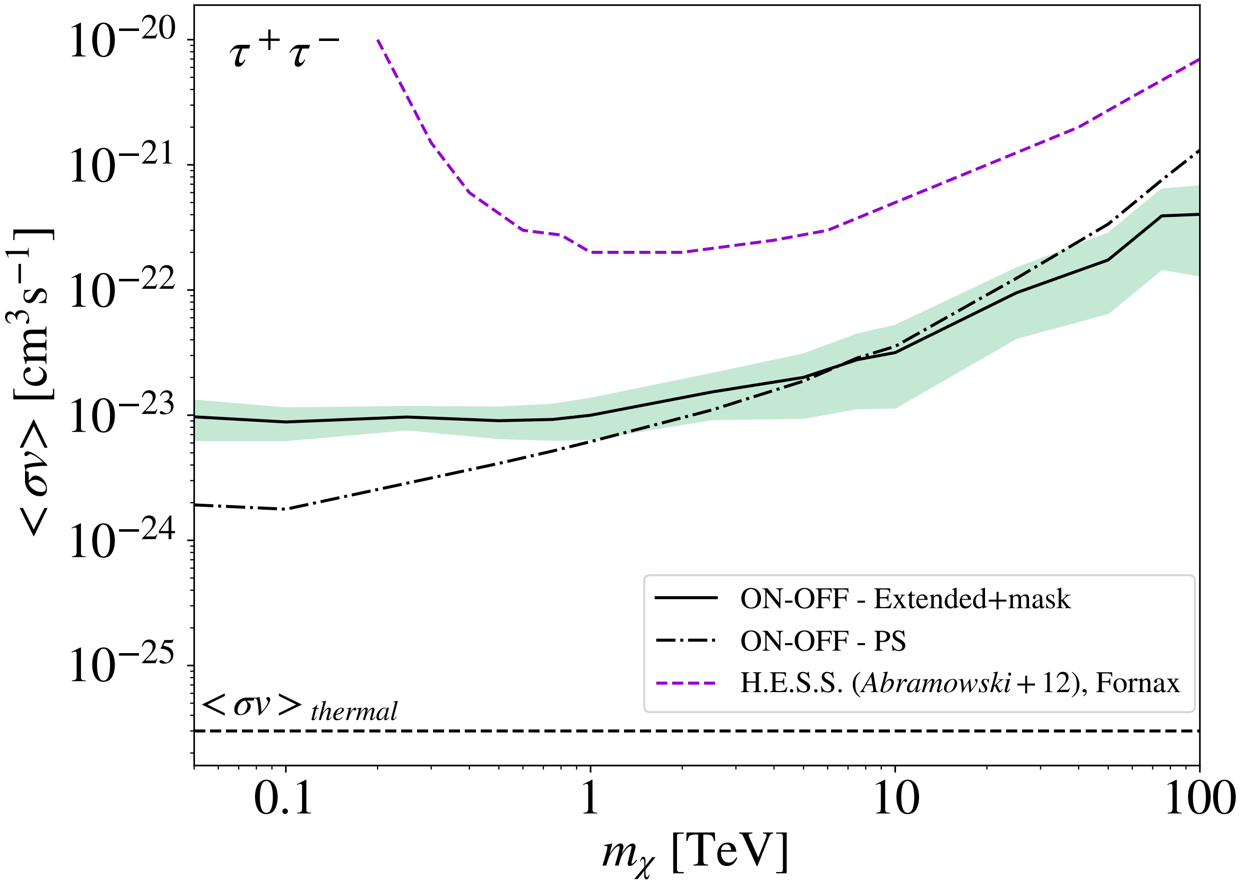
Case	$\theta_{pointing}$ [deg]	θ_{ON} [deg]	N_{OFF}	κ
1	**1**	**0.5**	**3**	**3**
2	0	1	3	3
3	0.5	0.5	3	3
4	1	0.5	5	5

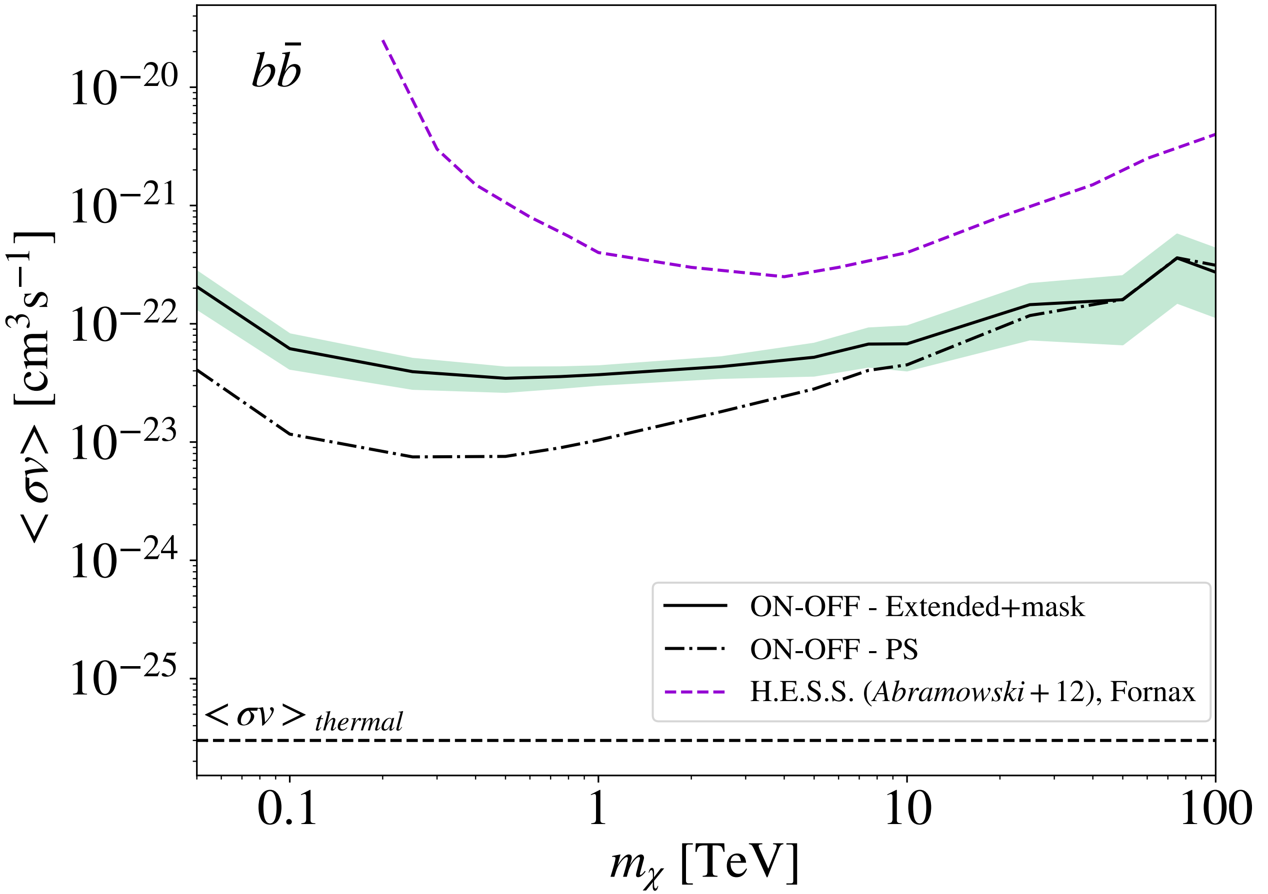
Limits for Perseus for MED annihilation model
(DM template + mask)



ON-OFF RESULTS: DM CONSTRAINTS

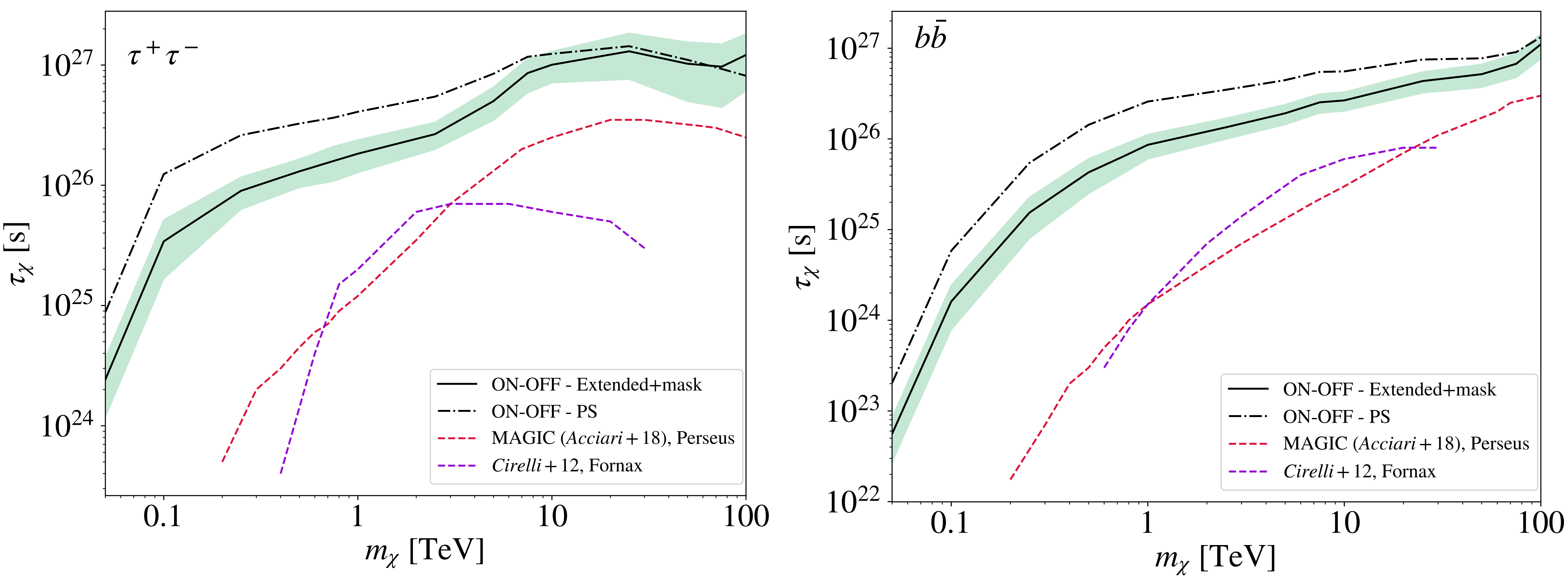
Annihilation (MED)





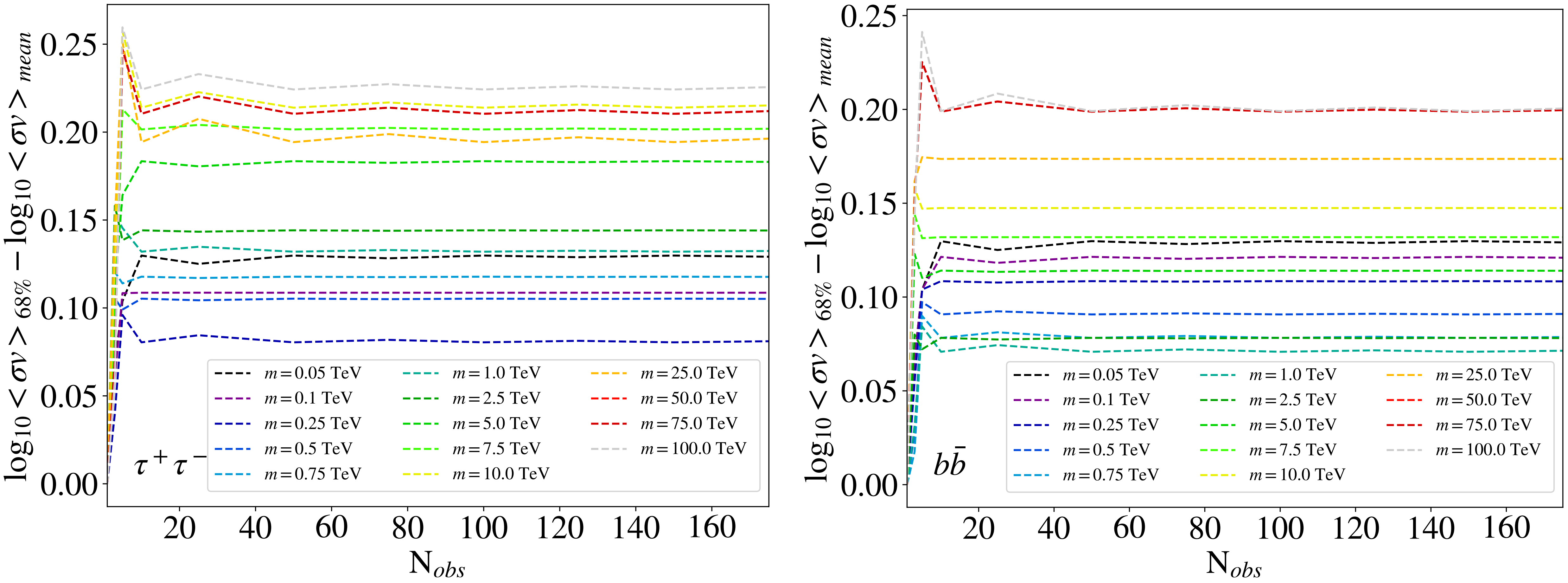
ON-OFF RESULTS: DM CONSTRAINTS

Decay

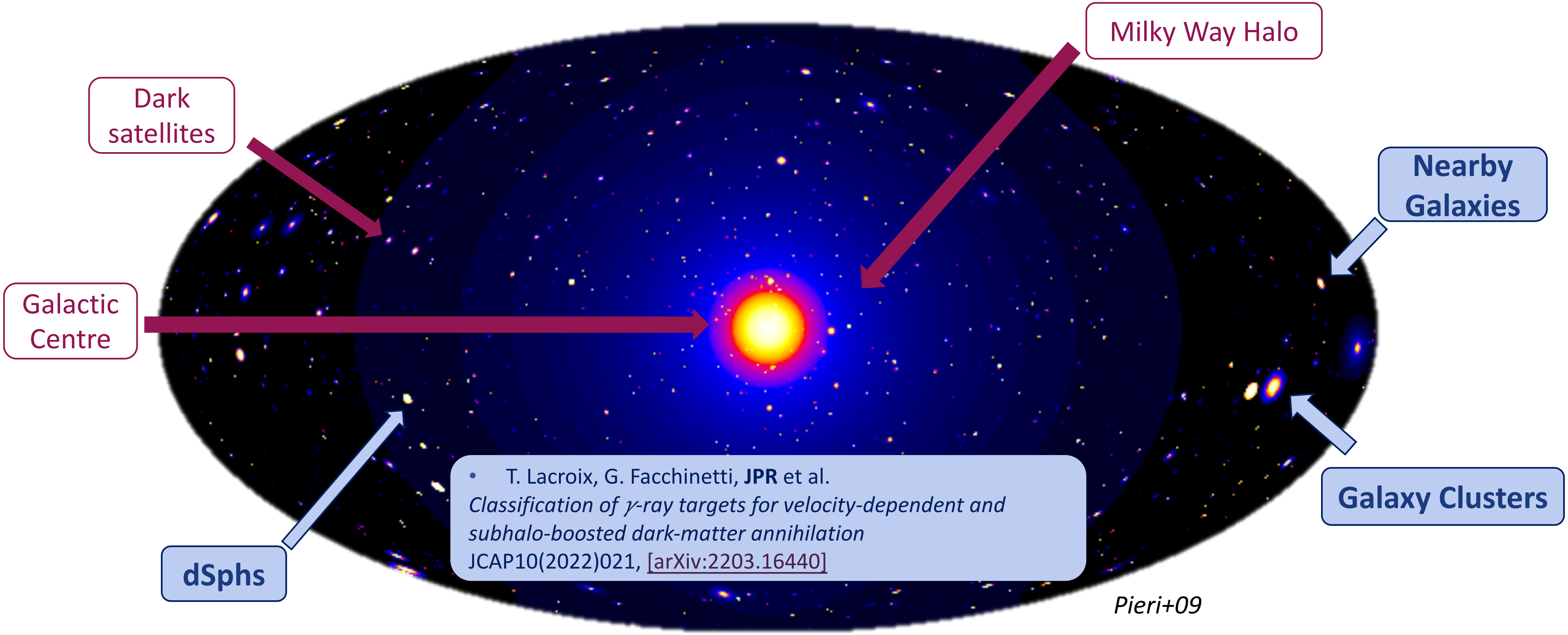


ON-OFF RESULTS : SCATTER BAND

One-sided 1σ band evolution with the number of realizations
(annihilation MED model, ON-OFF - Extended+mask)



γ-RAY DM SEARCHES IN DIFFERENT ASTROPHYSICAL OBJECTS



- T. Lacroix, G. Facchinetti, **JPR** et al.
Classification of γ-ray targets for velocity-dependent and subhalo-boosted dark-matter annihilation
JCAP10(2022)021, [arXiv:2203.16440]

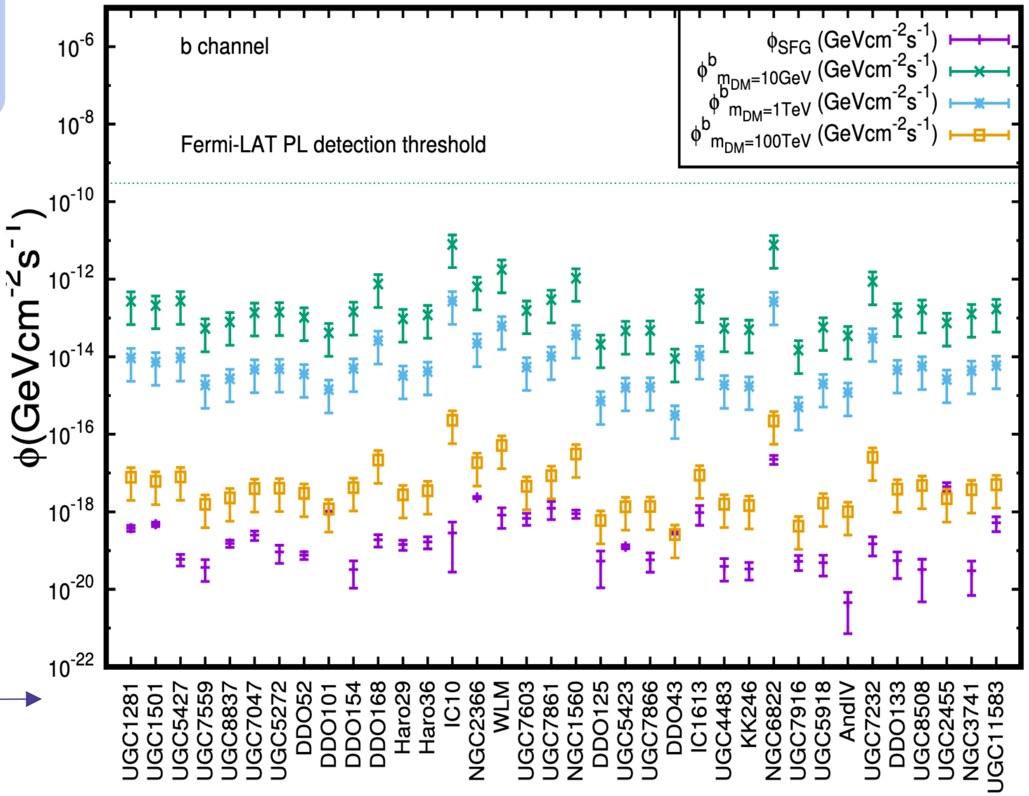
DM modelling for a classification of targets [2203.16440]

DIRRS AS TARGETS FOR γ–RAYS DM SEARCHES

- Dwarf Irregular Galaxies (dIrrs)
  - Rotationally supported objects
    - High DM density → DM density from their rotation curves (RCs)
  - Located in our Local Volume:

    $0.5\ \text{Mpc} < d_L < 10\ \text{Mpc}$ ← Closeby
  - Have masses between $10^8 - 10^{10}\ M_\odot$

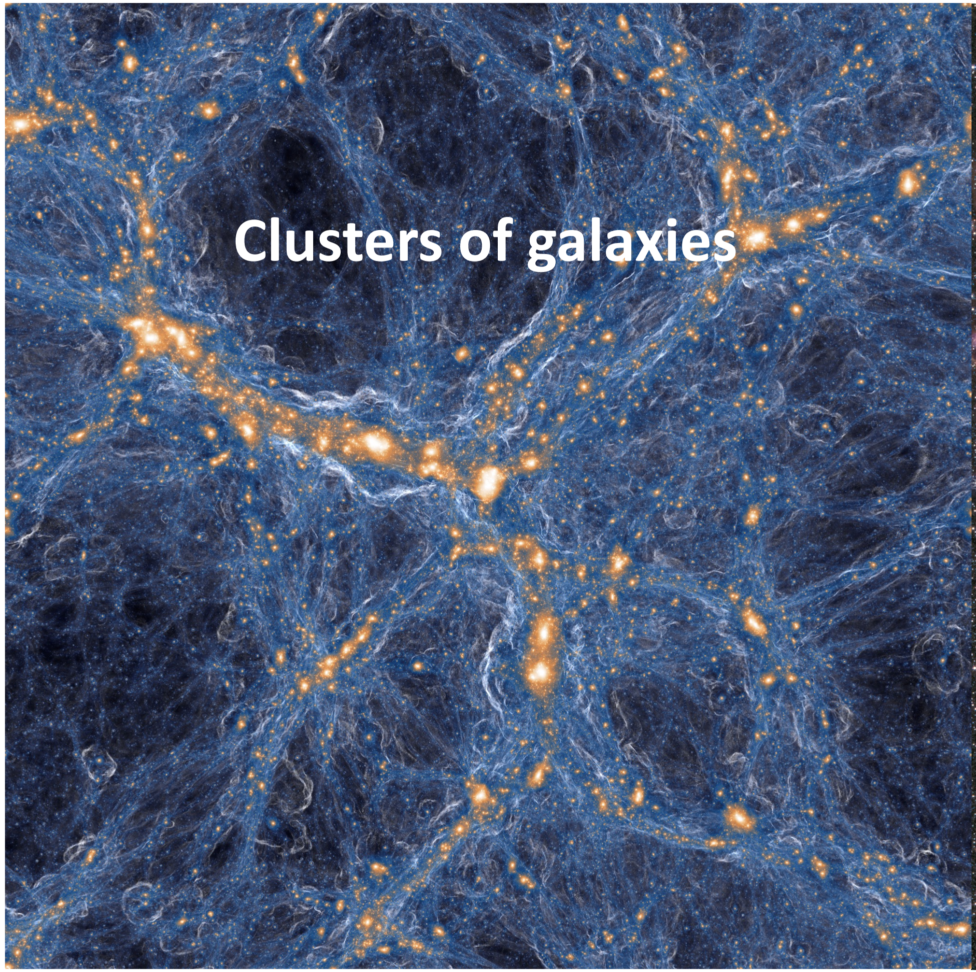
    ↓ Massive objects → Population of substructures expected
  - Star-forming galaxies → Negligible γ–ray background → *Gammaldi+17*

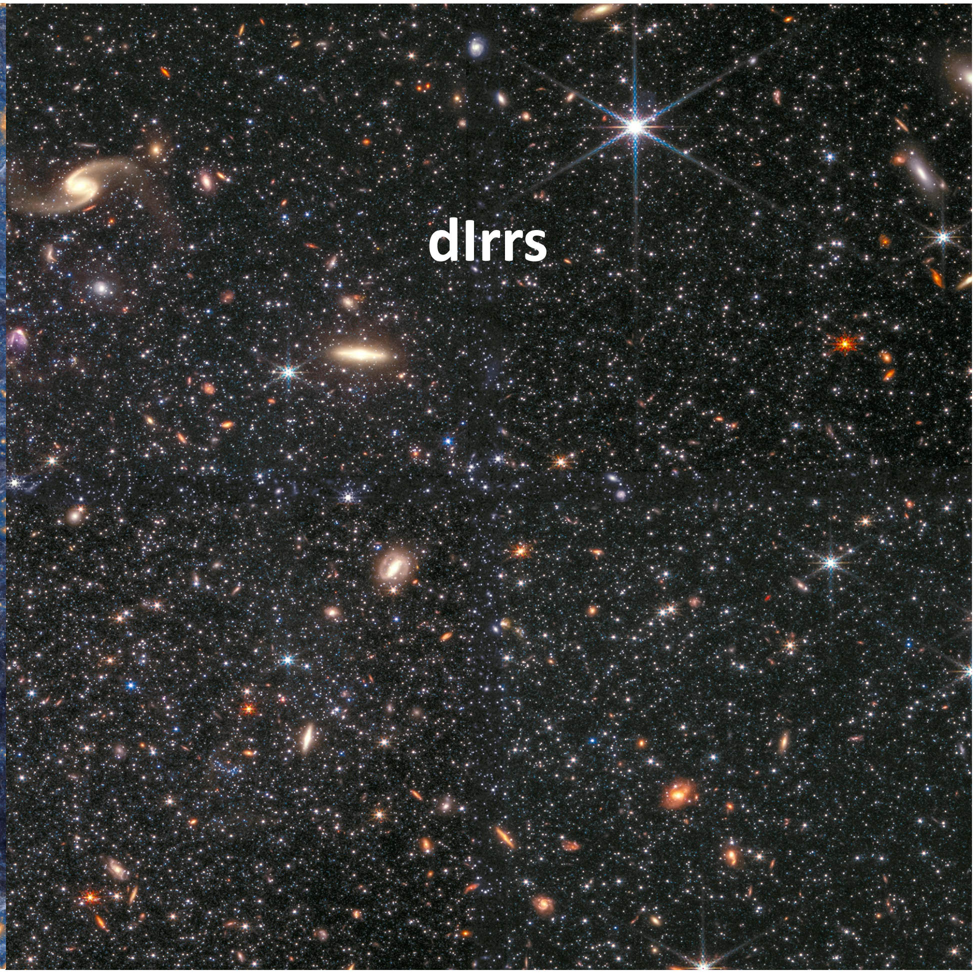


DM modelling for a classification of targets [2203.16440]

CAN WE CLASSIFY THE STUDIED TARGETS?

- Several astrophysical objects studied, with pros and cons





DM modelling for a classification of targets [2203.16440]

CAN WE CLASSIFY THE STUDIED TARGETS?

- Several astrophysical objects studied, with pros and cons

Clusters of galaxies

- Most massive - 10^{14}-10^{15} $M_{\odot}$
- Further – $z < 0.1$
- Higher substructure boost – B~9
- Best targets for decay
- Astrophysical γ–ray emission
- Up to $\log_{10} J_{MED}$ ~18.40

dIrrs

- Less massive - $10^{8} – 10^{10}$ $M_{\odot}$
- Closer – $d_L < 1$ Mpc
- Lower substructure boost – B~4
- Not studied for decay
- Negligible astrophysical γ–ray emission
- Several at $\log_{10} J_{MED}$ ~ 18.50

➕ **dSphs**

- Classical
- Ultra-faint

DM modelling for a classification of targets [2203.16440]

CAN WE CLASSIFY THE STUDIED TARGETS?

- Build intra- and inter-family ranking of targets for γ-ray DM searches
- The absence of firm detection of vanilla-WIMP DM

Let us broaden the theoretical particle framework…

Velocity dependence of <*σv*>	Canonical *s*-wave partial wave may be naturally suppressed	Mediator is a scalar
Modification of the short-range <*σv*>	Exchange of light mediator induces a long-range interaction between DM particles	Complex dark sectors
Contribution of DM subhalos	Dependent on host halo mass and their structural properties	ΛCDM structure formation paradigm

→ *p*-wave dominates $\sigma v_{\mathrm{rel}} \propto v_{\mathrm{rel}}^2$

→ Sommerfeld enhacement

→ Boost computation for velocity-dependent annihilations

DM modelling for a classification of targets [2203.16440]

CLASSIFY THE STUDIED TARGETS

- Build intra- and inter-family ranking of targets for γ-ray DM searches
- The absence of firm detection of vanilla-WIMP DM

Let us broaden the theoretical particle framework…

Jointly included and systematically studied for the three families of targets

Our work: provide DM models for dIrrs and clusters

Velocity dependence of <σv>	suppressed	Mediator is a scalar	…ates $\sigma v_{\rm rel} \propto v_{\rm rel}^2$
Modification of the short-range <σv>	range interaction between DM particles	Complex dark sectors	Sommerfeld enhacement
Contribution of DM subhalos	Dependent on host halo mass and their structural properties	ΛCDM structure formation paradigm	Boost computation for velocity-dependent annihilations

DM modelling for a classification of targets [2203.16440]

DM MODELS FOR SELECTED DIRRS

- Use the DM models that just developed → V. Gammaldi, **JPR** *et al., Dark Matter search in dwarf irregular galaxies with the Fermi Large Area Telescope,* Phys. Rev. D 105, 083006, [arXiv:2204.00267]
- Select the most promising targets of the studied according to:
  - Highest J-factors
  - More available kinematic data
- Use core&cusp profiles to account for model uncertainties:

$$\rho_{\rm Bur}(r) = \frac{\rho_c\, r_c^3}{(r + r_c)\,(r^2 + r_c^2)}$$

$$\rho_{\rm NFW}(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

dIrr	(l, b) [deg]	D [kpc]	M_{200} [10^{10} $M_\odot$]	Profile	ρ [10^7 $M_\odot$ kpc^{-3}]	r [kpc]	R_{200} [kpc]
NGC6822	(25.34, -18.40)	480	3.16	Burkert*	3.16	3.3	62.9
				NFW	0.79	5.9	62.6
IC10	(118.96, -3.33)	790	3.98	Burkert*	15.85	2.0	71.3
				NFW	0.63	6.8	70.3
WLM	(75.87, -73.86)	970	0.40	Burkert*	6.31	1.3	33.3
				NFW	1.00	2.8	33.6

DM modelling for a classification of targets [2203.16440]

DM MODELS FOR SELECTED CLUSTERS

- Start from a smaller sample: *Sánchez-Conde+11*

Coma Fornax Virgo Perseus Ophiuchus → Too close to Galactic Centre

Virgo ↓ Highest J-factor ↓ BUT ↓ On going merger event

DM MODELS FOR SELECTED CLUSTERS

- Start from a smaller sample: *Sánchez-Conde+11*

Coma, Fornax → *Schellenberger&Reiprich17*

Perseus → *Reiprich&Böhringer02*

- Build NFW profiles from M_{200}: *Schellenberger&Reiprich17* *Reiprich&Böhringer02*

- Model uncertainties from:

M_{200} X-ray measurements

- $M_{200} < 5 \times 10^{14} h^{-1} \mathrm{M}_\odot$ → $M_{\rm hydro}/M_{SZ} = 0.86 \pm 0.01$ → Understimated 20%
- $M_{200} > 5 \times 10^{14} h^{-1} \mathrm{M}_\odot$ → $M_{\rm hydro}/M_{SZ} = 1.46 \pm 0.08$ → Overestimated 50%

\+

(c-M) scatter

σ_c = 0.14 dex

$$c_{200}(M_{200}^{(\rm max)}) \times 10^{+\sigma_c}$$

$$c_{200}(M_{200}^{(\rm min)}) \times 10^{-\sigma_c}$$

DM modelling for a classification of targets [2203.16440]

DM MODELS FOR SELECTED CLUSTERS

- Start from a smaller sample: *Sánchez-Conde+11*

Coma Fornax Perseus

- Build NFW profiles from M_{200}: *Schellenberger&Reiprich17* (Coma, Fornax) *Reiprich&Böhringer02* (Perseus)

Cluster	$(l,\ b)$ [deg]	D [Mpc]	Mass estimate	M_{200} [10^{14} $M_\odot$]	R_{200} [10^2 kpc]	ρ_0 [10^6 $M_\odot$ kpc^{-3}]	r_s [10^2 kpc]
Coma	(58.09, 87.96)	102.18	Hydrostatic	13.16	23.19	2.29	3.38
			Lower*	8.77	20.26	5.37	5.58
Fornax	(236.72, -53.64)	20.35	Hydrostatic*	0.51	7.83	7.42	1.86
			Upper	0.61	8.32	3.20	1.05
Perseus	(150.57, -13.26)	80.69	Hydrostatic	7.71	19.41	2.35	2.80
			Lower*	5.14	16.96	5.57	4.59

BARYONIC CONTENT OF CLUSTERS

- From the X-rays surface brightness $S(r) = S_0\left(1 + (r/r_c)^2\right)^{-3\beta+1/2}$ **Beta-model**

See *Schellenberger&Reiprich 17*

$$\rho_{\rm gas}(r) = \rho_{\rm gas}(0)\left(1+\frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta}$$

$$\rho_{gas}(0) = m_e n_e(0) + m_p n_p(0) + m_{He} n_{He}(0)$$

$$n_{\rm e}(r) = n_{\rm e}(0)\left(1+\frac{r^2}{r_c^2}\right)^{-\frac{3}{2}\beta} + n_X(r) = \frac{\mu_Y}{\mu_X} n_Y(r)$$

Main responsible of X-rays emission → **Thermal electron density** — From the beta-model

Thermal X density — Thermal ICM

Where μ are the mean molecular weights

$$\mu_e = \frac{1}{(1-\frac{1}{2}Y-\frac{1}{2}Z)} \simeq 1.15$$

$$\mu_p = \frac{1}{1-Y-Z} \simeq 1.35$$

$$\mu_{\rm He} = \frac{4}{Y} \simeq 14.6,$$

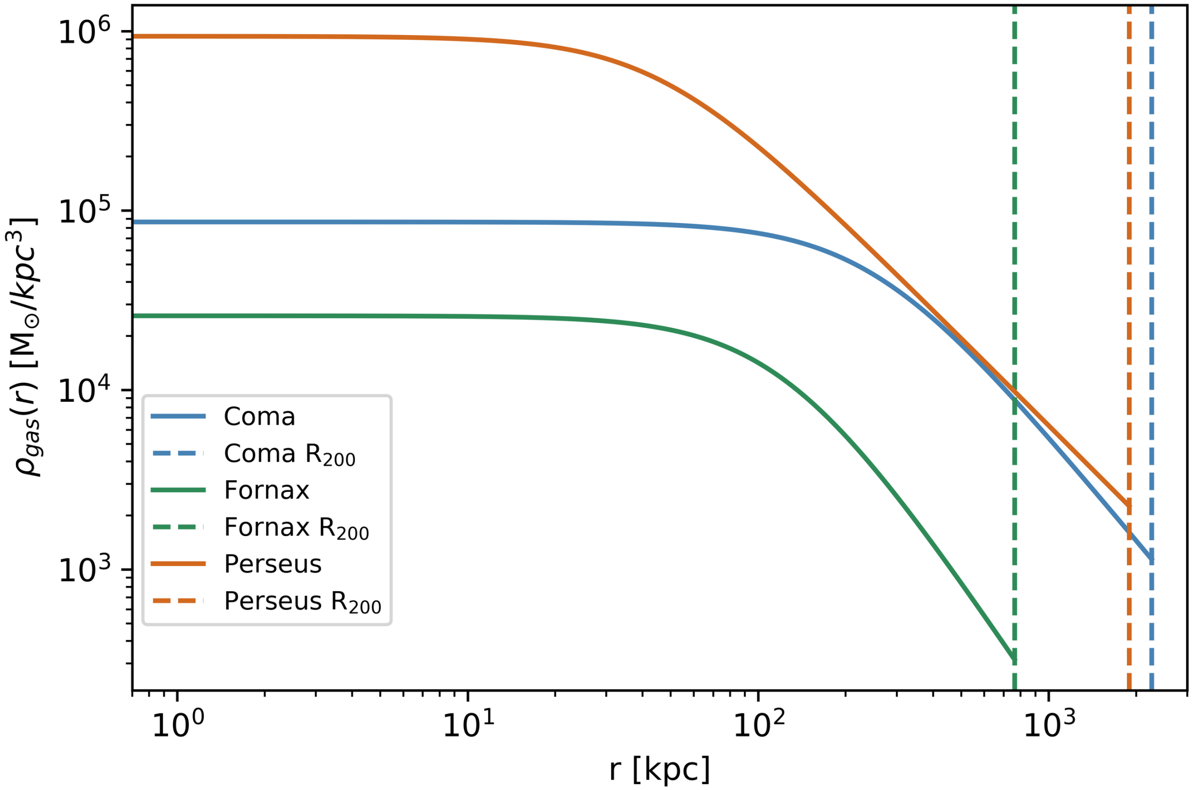
Adam+20

BARYONIC CONTENT OF CLUSTERS

- *Chen+09* performed a state-of-the-art X-ray analysis for nearby clusters and found the following parameters

Name	β	r_c [kpc]	n_{center} [10^{-2}cm^{-3}]	$\rho_{gas}(0)$ [M$_\odot$kpc^3]
Perseus	0.540	63	3.25	86402
Fornax	0.804	173	0.09	25921
Coma	0.654	343	0.30	936017

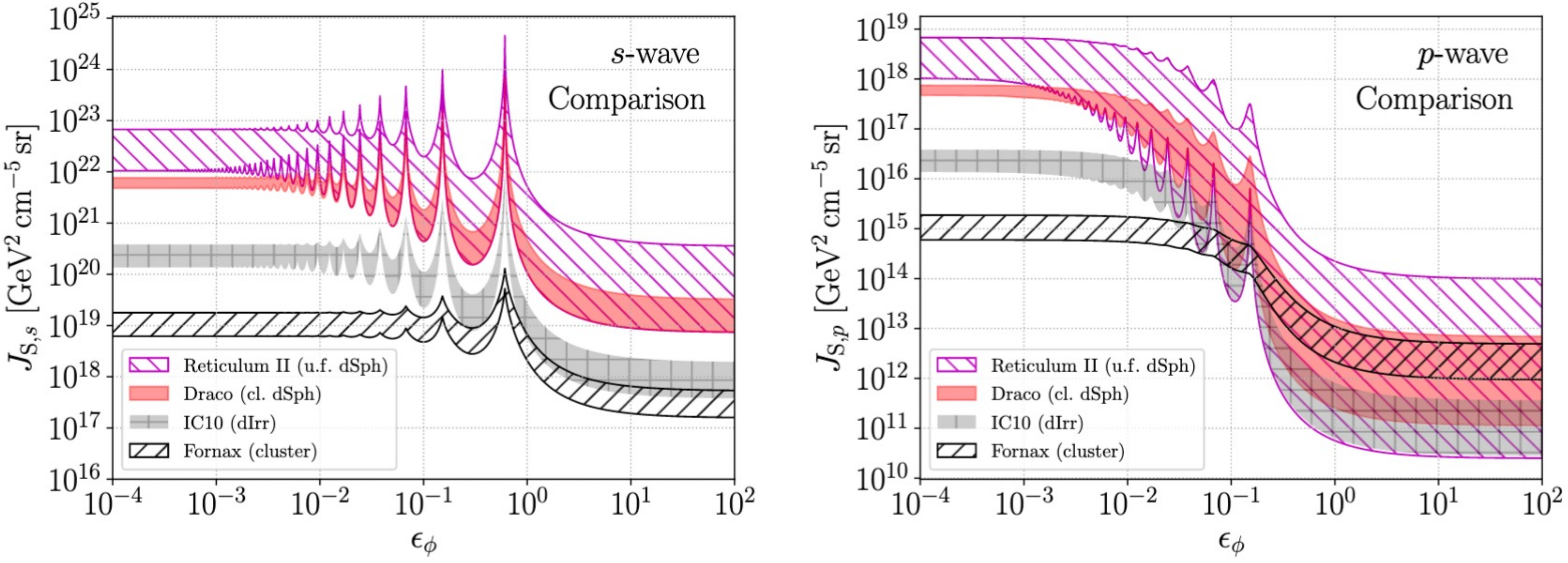
MINOT software (*Adam+20*)



RESULTS ON CLASSIFICATION OF TARGETS

Main halos

$\epsilon_\phi \equiv \frac{m_\phi}{\alpha_D m_\chi}$

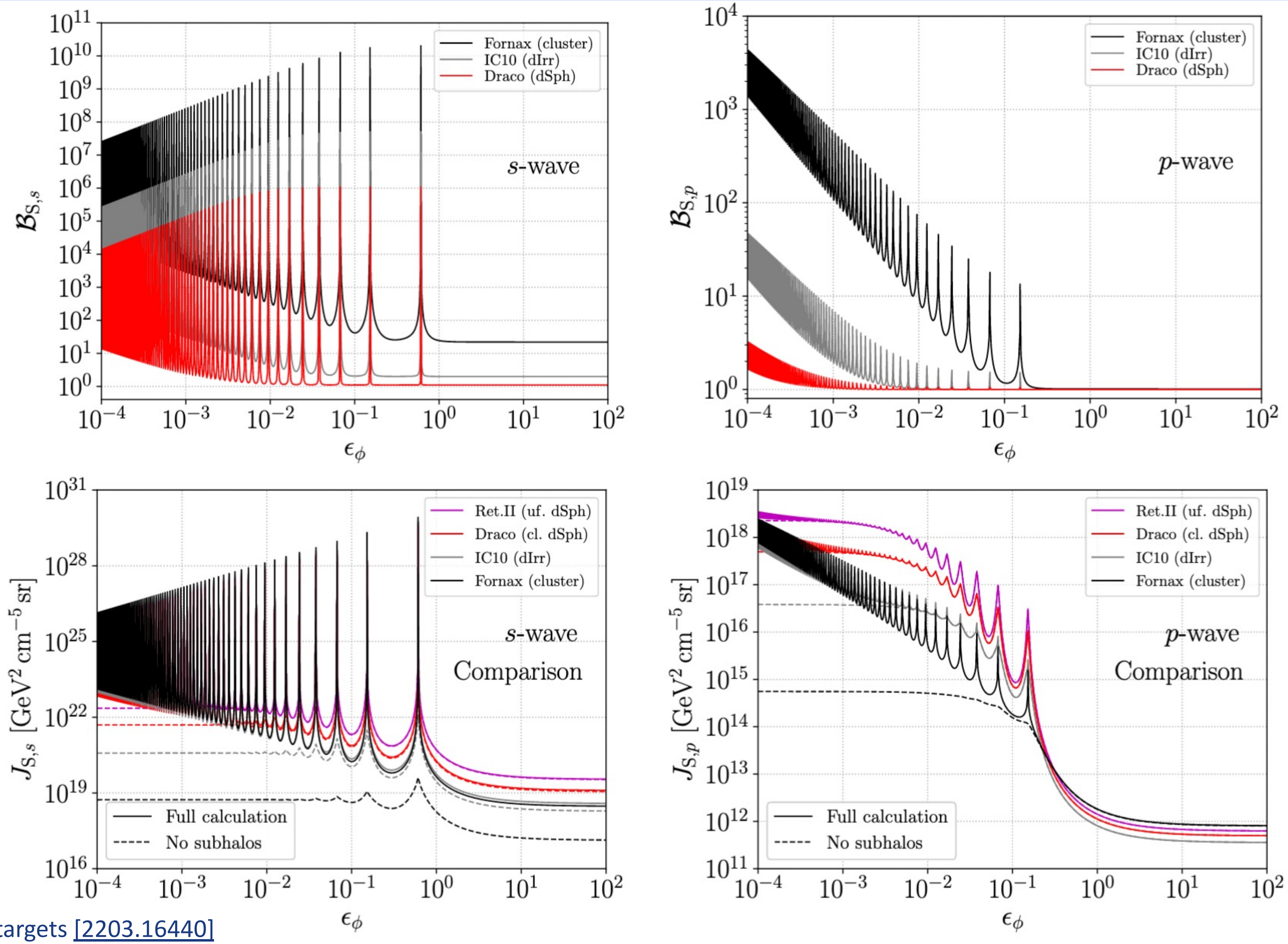


DM modelling for a classification of targets [2203.16440]

RESULTS ON CLASSIFICATION OF TARGETS

Main halos
+
substructures

$$\mathcal{B}_S = \frac{J_{S,tot}}{J_{S,host}}$$



DM modelling for a classification of targets [2203.16440]

CLASSIFICATION OF TARGETS: SUMMARY

- Diversification of targets allows to distinguish and understand the impact of the systematics that each target suffers
- If DM detection is present in any of them, we should see it in others, as DM properties are universal
- After studying several targets, important to build intra- and inter-family ranking of targets under same theoretical framework
- These DM models take into account the specific uncertainties of each kind of object

DM modelling for a classification of targets [2203.16440]

CLASSIFICATION OF TARGETS: SUMMARY

- Diversification of targets allows to di ... of the systematics tha
- If DM ... is present in any of them, we shoul ... properties are universal
- After s ... build intra- and inter-family ranking of targets ... framework
- These DM models take into account the specific uncertainties of each kind of object

Starting point to compute generalized J-factors, including *p*-wave annihilation, Sommerfeld enhancement and boost from subhalo population

Ranking (where typically dSphs rank first) can be drastically modified: most striking case is *s*-wave on resonances and *p*-wave in the no-Sommerfeld enhancement regime, where galaxy clusters can outshine all others

DM modelling for a classification of targets [2203.16440]

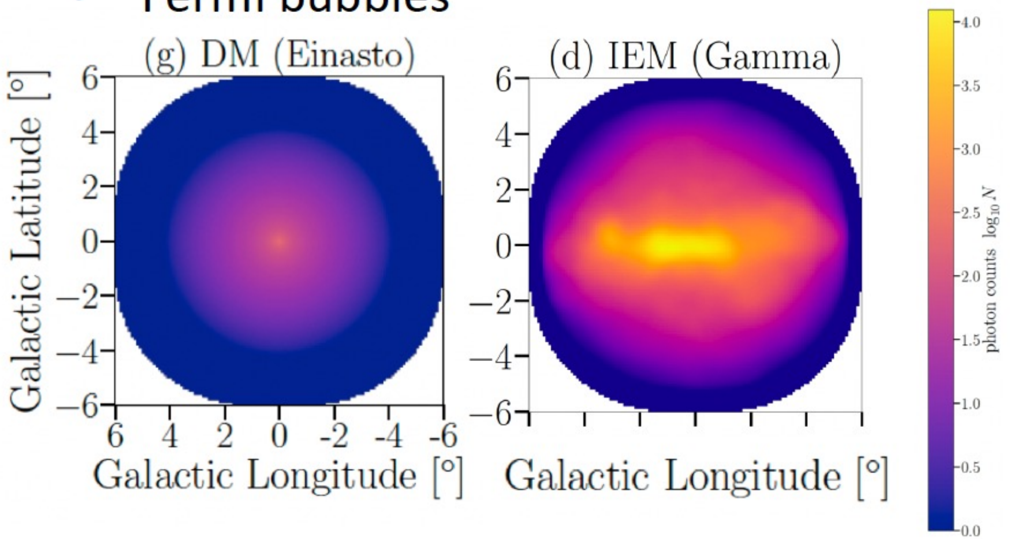
CTAO DM SEARCHES

Properties of the Galactic Center

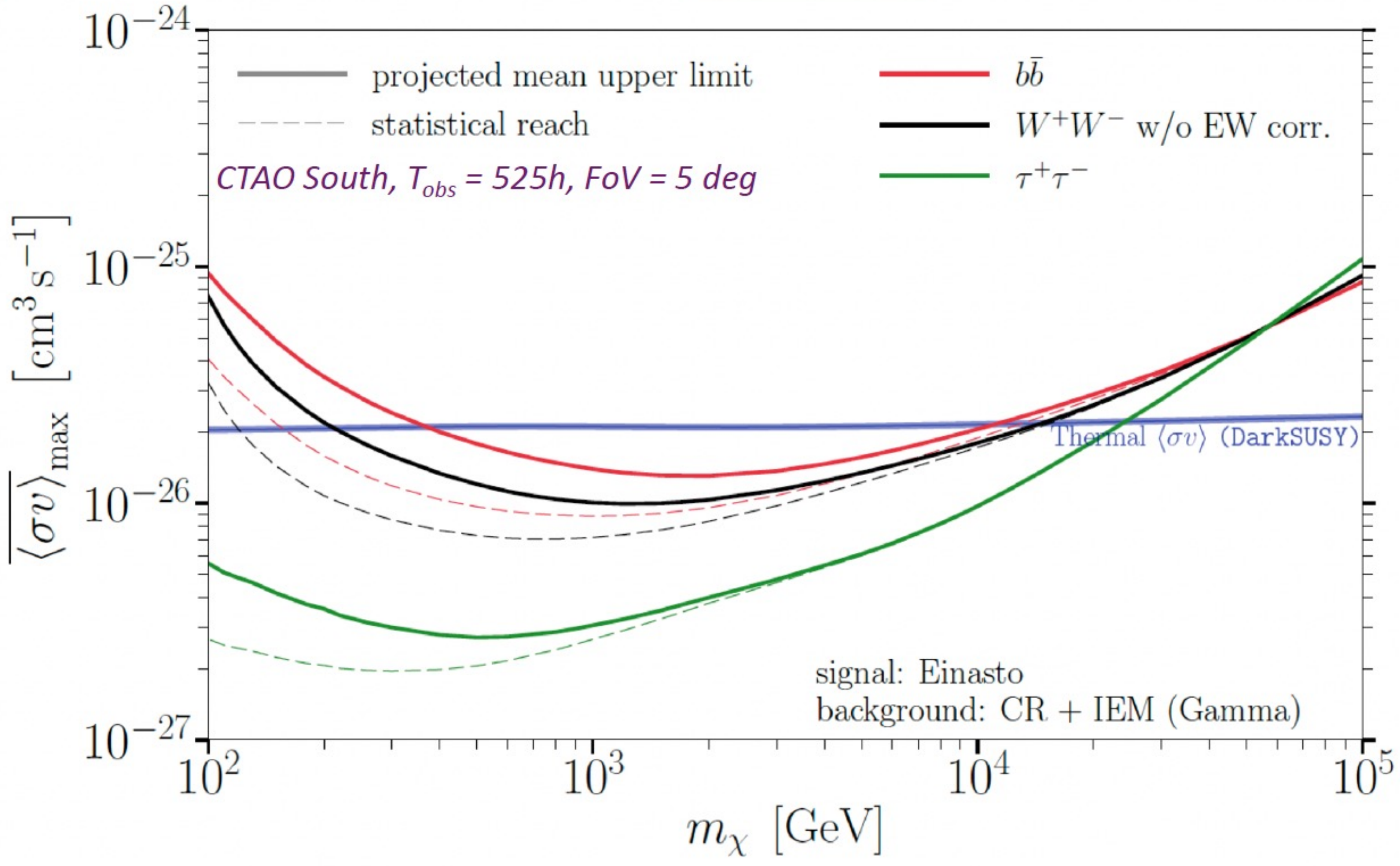
- Very close (d_L = 8.5 kcp), highly DM dominated object

$\log_{10} J_{Ein} = 22.85$

- Astrophysical γ–ray emission expected from:
  - Point-like sources
  - Inter-stellar emission (IEM)
  - Fermi bubbles



CTA Cons. 21



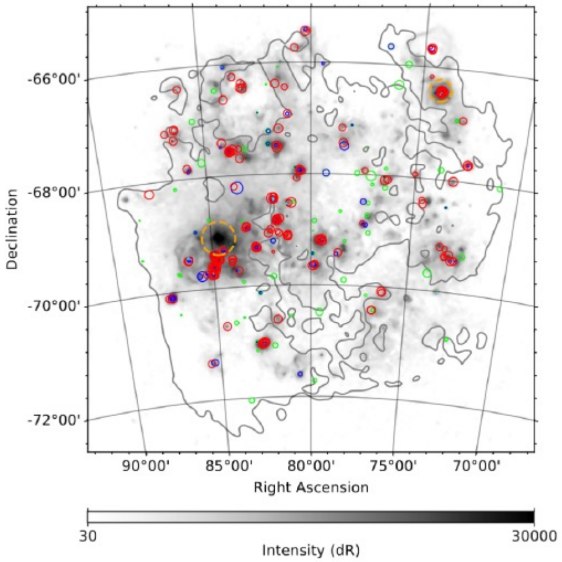
CTAO DM SEARCHES

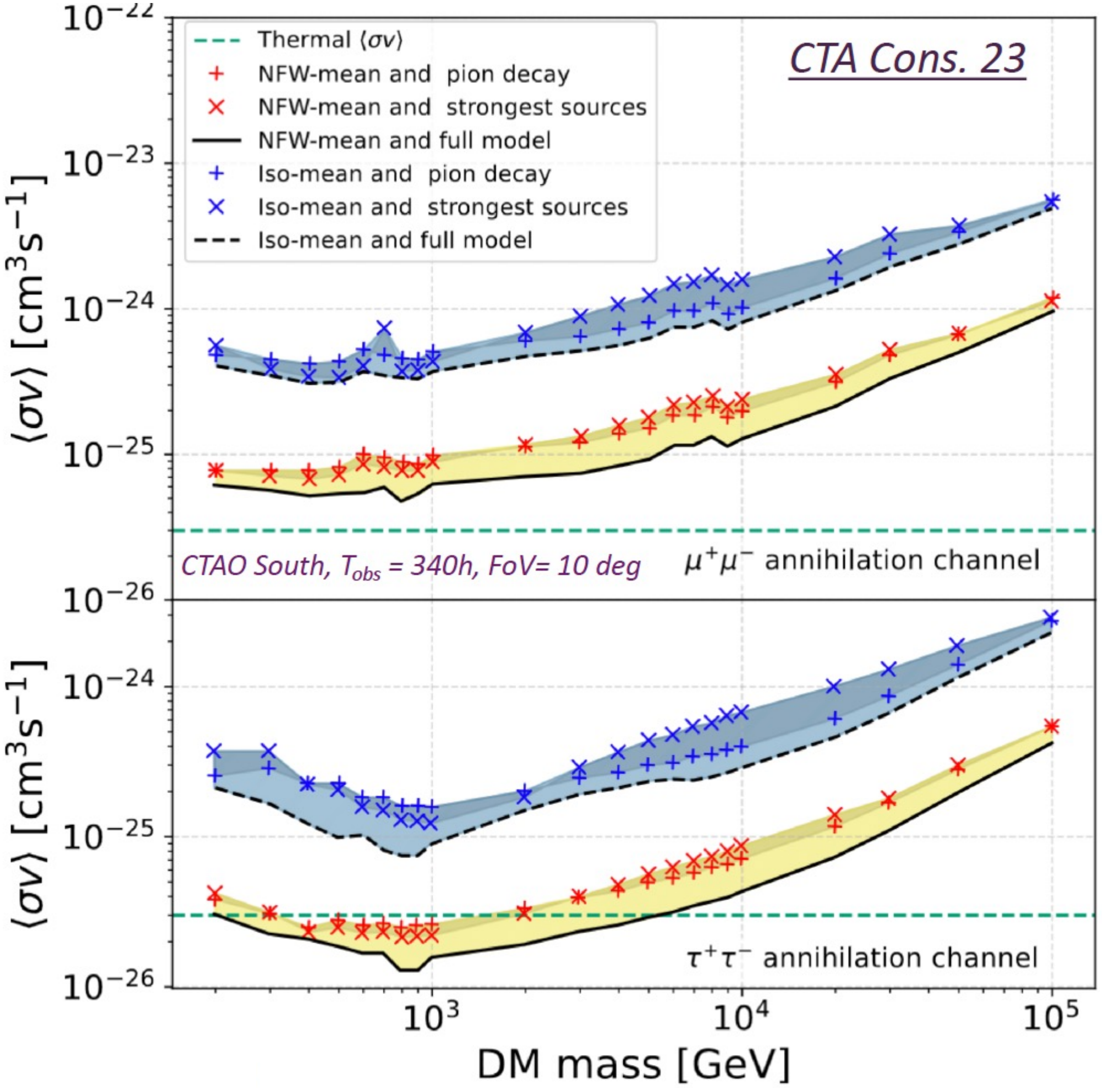
Properties of the LMC

d_L	50.1 kpc	M ($\leq$10 deg)	1.2×10^8 $M_\odot$
l	279.65 deg	b	-33.34 deg

- MW satellite
- High star-forming region
- Astrophysical γ–ray emission expected from:
  - 4 known very high energy sources
  - SNRs, PWNs and pulsar halos
  - IEM

$\log_{10} J_{\text{NFW-MEAN}} = 21.14$



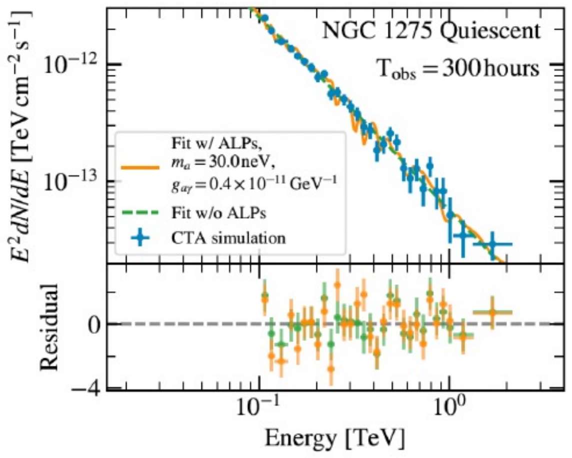


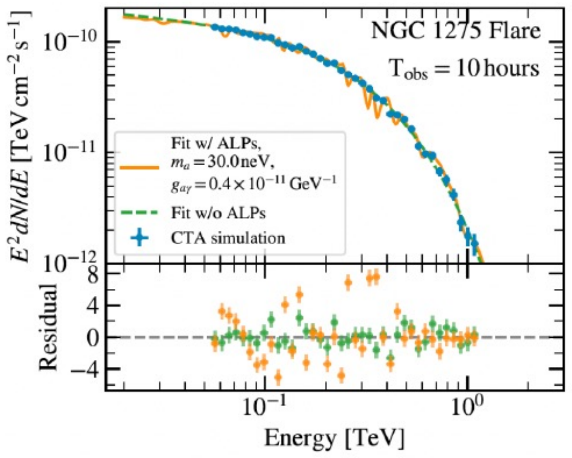
CTAO DM SEARCHES

- Target: NGC1275 – Birghtest AGN of Perseus cluster
- At energies around:

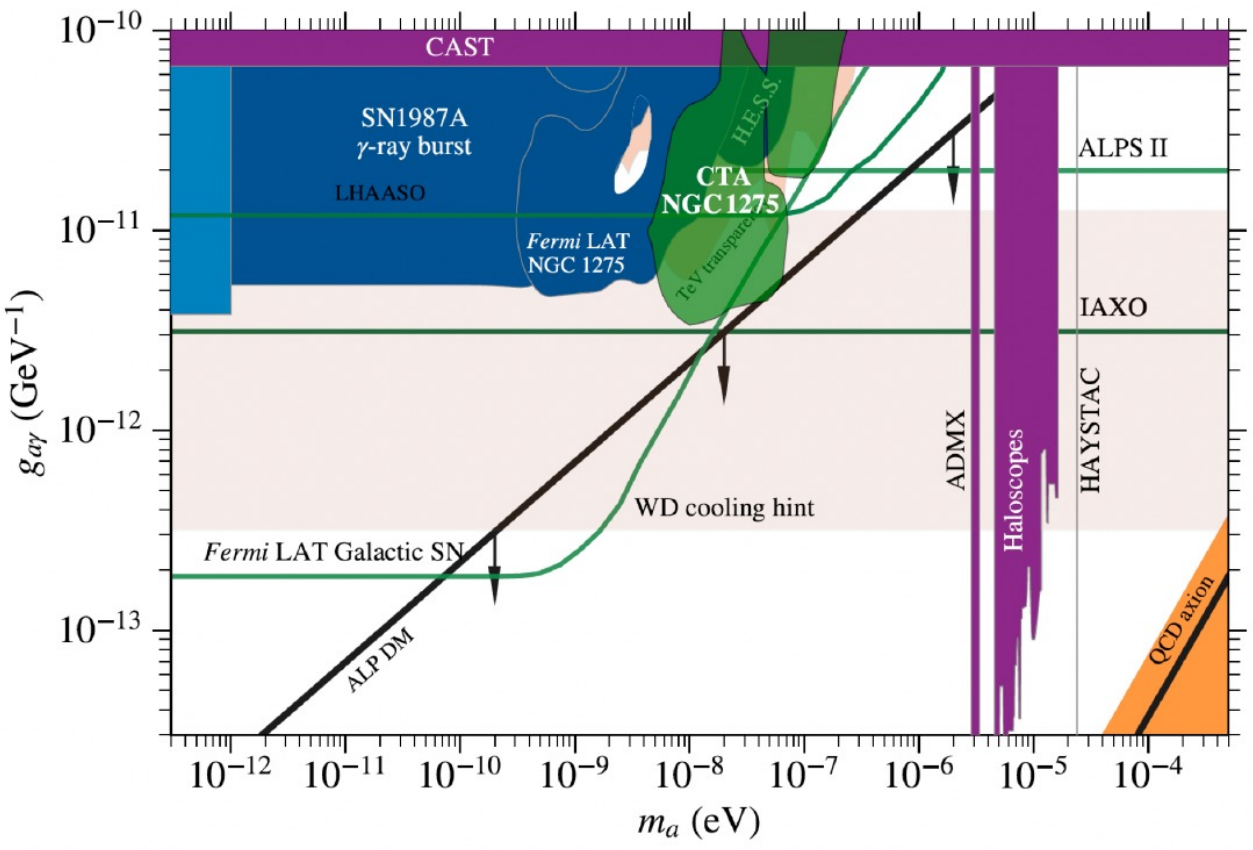
$$E_{\rm crit} \sim 2.5\,{\rm GeV} \left(\frac{|m_a - \omega_{\rm pl}|}{1\,{\rm neV}}\right)^2 \left(\frac{B}{1\,\mu{\rm G}}\right)^{-1} \left(\frac{g_{a\gamma}}{10^{-11}\,{\rm GeV}^{-1}}\right)^{-1}$$

oscillatory patterns are expected in the AGN spectra





CTA Cons. 21



About SMASH program

SMASH
machine learning for science and humanities postdoctoral program

- SMASH is intersectoral, career-development training program for **postdoctoral researchers**, centered on developing cutting-edge machine learning applications for science and humanities, cofunded by **Marie Sklodowska Curie COFUND Action**.
- Duration: 2023 – 2028 - 3 calls for applicants will be launched in the period 2023 – 2028
- Coordinator: University of Nova Gorica, Dr. Gabrijela Zaharijas
- SMASH offers 2-year fellowships to 50 talented postdoc individuals to harness the potential of VEGA, one of Europe's newest petascale High-Performance Computers
- 5 host organisations in SLOVENIA: University of Nova Gorica, University of Ljubljana, Jožef Stefan Institute, Institute of Information Science and Slovenian Environment Agency
- 5 key research areas (and 17 sub-areas): https://smash.ung.si/research-areas/
- Website: https://smash.ung.si/

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REPUBLIC OF SLOVENIA
MINISTRY OF THE ENVIRONMENT, CLIMATE AND ENERGY
SLOVENIAN ENVIRONMENT AGENCY

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