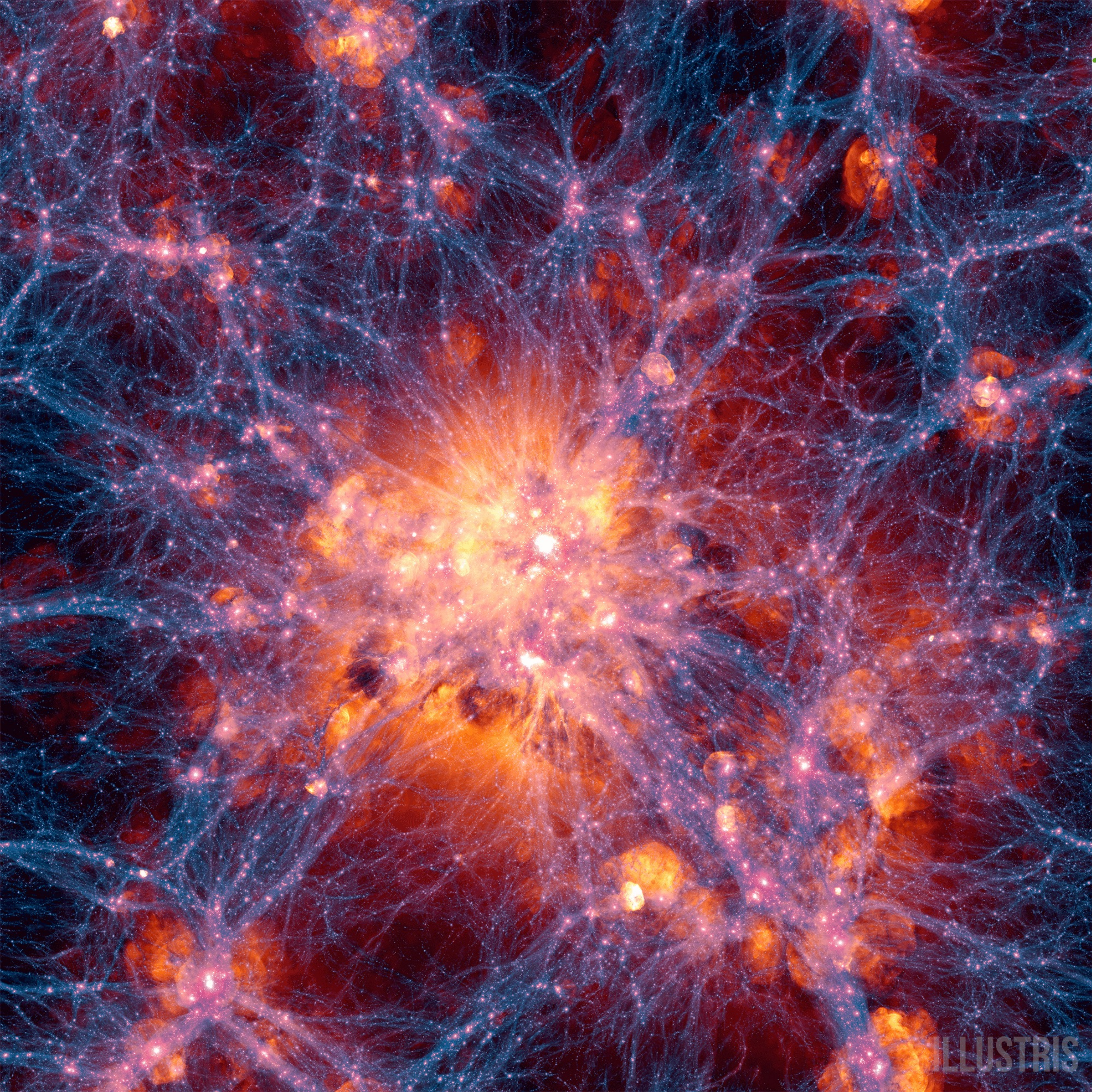


Search for cosmic-ray induced γ-ray emission from local galaxy clusters using *Fermi*-LAT data

Judit Pérez-Romero *(judit.perez@ung.si)*

R. Adam, M. Di Mauro, M. A. Sánchez-Conde, G. Zaharijas

SMASH machine learning for science and humanities postdoctoral program

Co-funded by the European Union

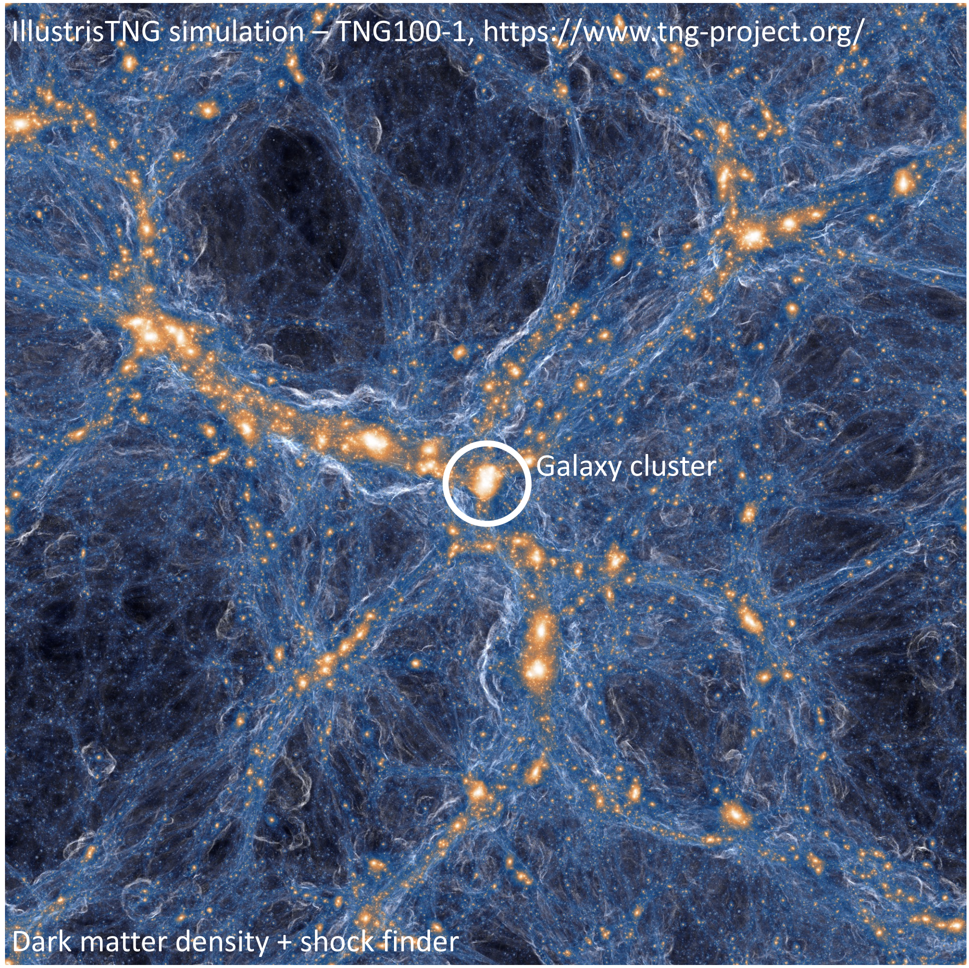
I FEEL SLOVENIA

TeV Particle Astrophysics TeVPA Valencia 2025

05/11/2025

γ-RAY DM SEARCHES IN CLUSTERS

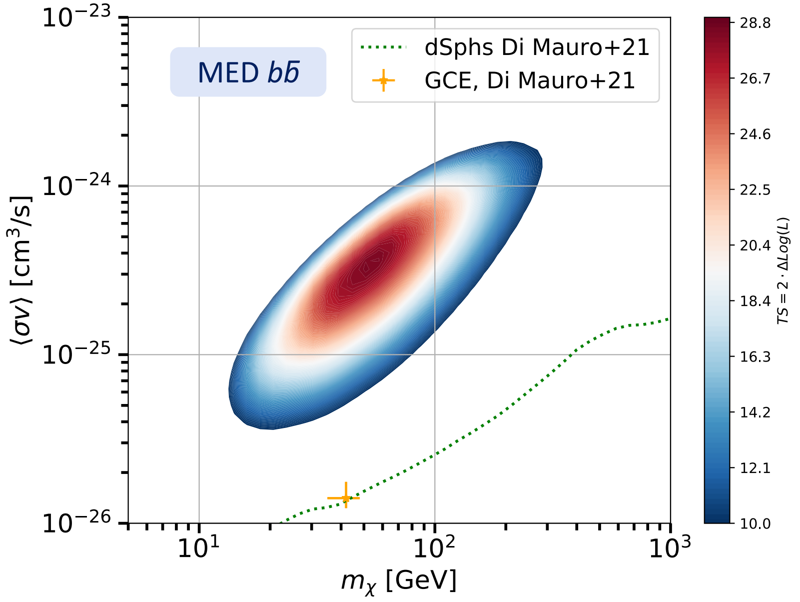
- Largest gravitationally bound structures formed by gravitational collapse
- Masses of order ~10^{14}-10^{15} $M_\odot$
- Components:
  - Baryonic Matter
    - Galaxies (~ 3% - 5%)
    - Intra Cluster Medium (~ 15% - 17%)
  - Dark Matter (~80%)
- Several in local Universe (z < 0.1)



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
Baghmanyan+22, **5.4σ**
HAWC Coll. 24– Virgo cluster
Mana&Desai 25 – Various clusters, ~8σ
LHAASO Coll. 25



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]

- Sample of 49 local clusters
- Seach for DM-induced emission
- Results of $TS_{combined}$ for the different benchmark models:

TS = 25 - 30 → 2.5-3.0σ

COSMIC-RAY INDUCED GAMMA-RAY EMISSION FROM LOCAL CLUSTERS

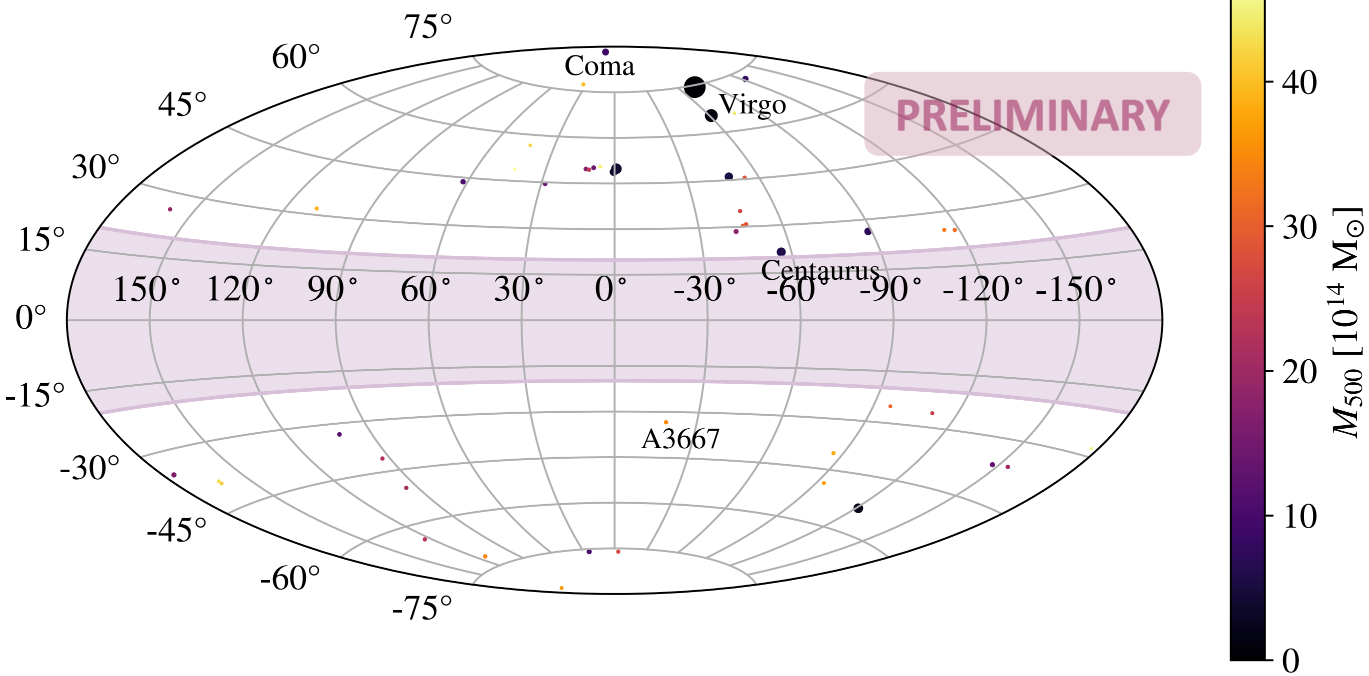
Search for cosmic-ray induced gamma-ray emission from local galaxy clusters using Fermi-LAT data
JPR, M. di Mauro, R. Adam, M. A. Sánchez-Conde, G. Zaharijas
In prep., [arXiv:25XX.XXXXX]

- Explore the possible **origin of the 2.5-3.0σ hint** found in our previous work:

    1. Develop models for the expected **CR-induced γ-ray** diffuse emission

    2. Combined analysis of the **same sample** of galaxy clusters:

        - HIFLUGCS catalogue (*Reiprich&Böhringer02*)
        - Clusters used in previous Fermi searches
        - Mask of $|b| < 20$ deg
        - $z < 0.1$
        - Separation of 2 deg to account for cluster extension



Sample of 48 local galaxy clusters

γ-RAY SEARCHES IN CLUSTERS

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

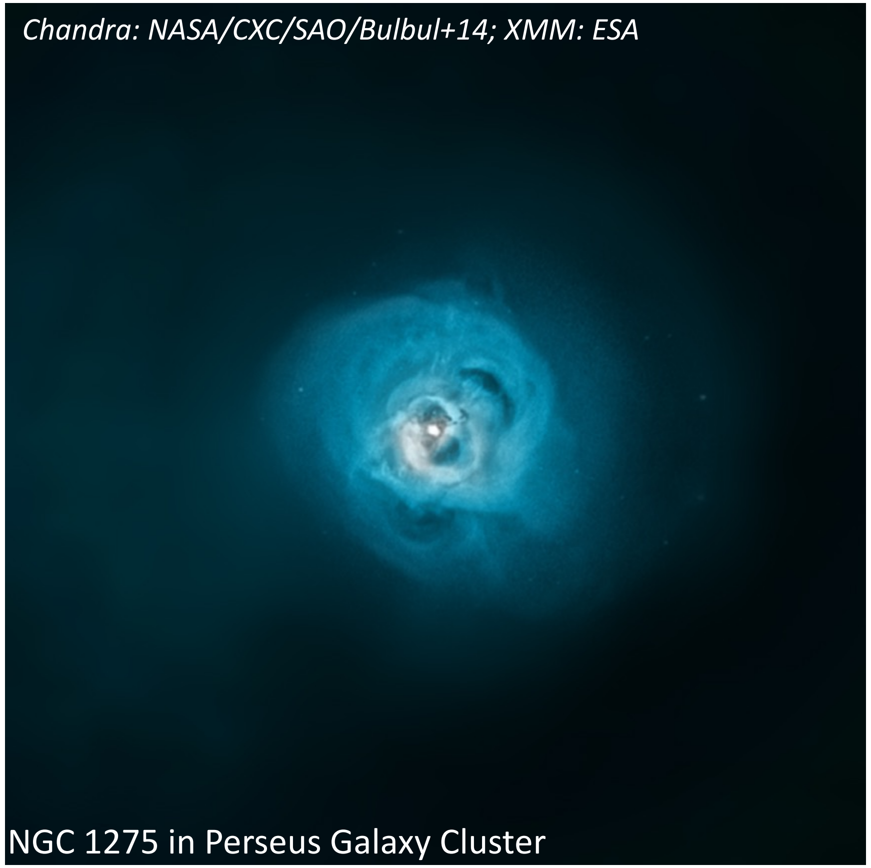
- Even supposedly virialized objects, a lot of activity
  - Merger events
  - Feedback from galaxies and AGNs
  - Magnetic fields
  - Turbulence

Acceleration mechanisms

Cosmic-rays (CRs)

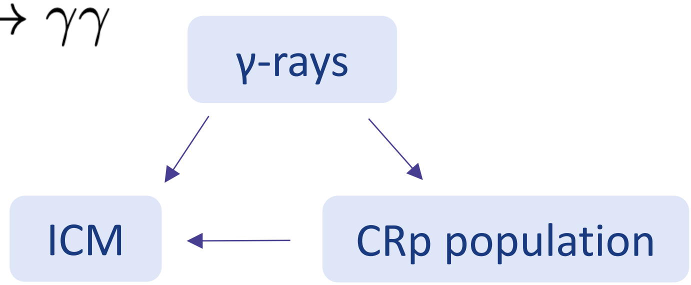
Leptons → Diffuse synchrotron emission

Hadrons → γ-rays



CLUSTERS CR MODELLING

- Main emission process for γ-rays at *Fermi* energies: $\mathrm{CR_p} + \mathrm{p_{ICM}} \rightarrow \pi^0 \rightarrow \gamma\gamma$
- Follow **MINOT** [*Adam+20*] software:
  - Hydrostatic equilibrium (+ second order corrections)
  - Spherically symmetrical
  - **Self-similar objects**



1. Proton number density $n_p(r) = \dfrac{\mu_e}{\mu_p} n_e(r)$

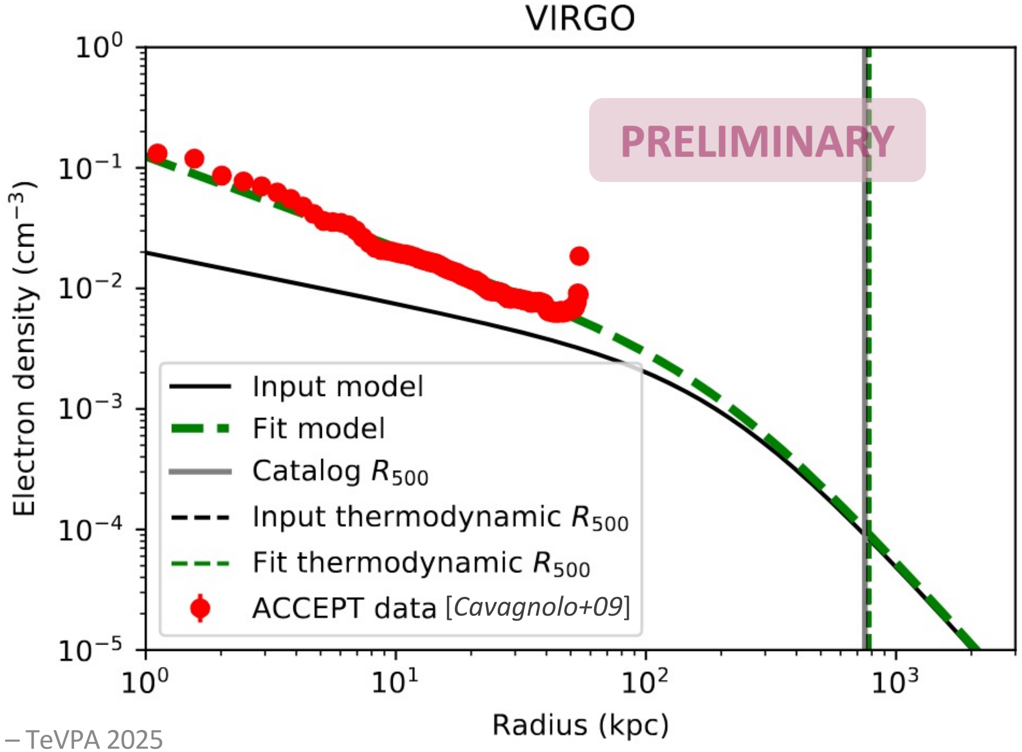
- From X-ray data for individual clusters
- General profile

Ghirardini+18 [1805.00042]

$$n_e^2(x) = n_0^2 \frac{(x/r_c)^{-\alpha}}{(1 + x^2/r_c^2)^{3\beta-\alpha/2}} \frac{1}{(1 + x^\gamma/r_s^\gamma)^{\epsilon/\gamma}}$$

$$x = R/R_{500} \text{ and } \gamma = 3$$

- Validated with ACCEPT data when available



CLUSTERS CR MODELLING

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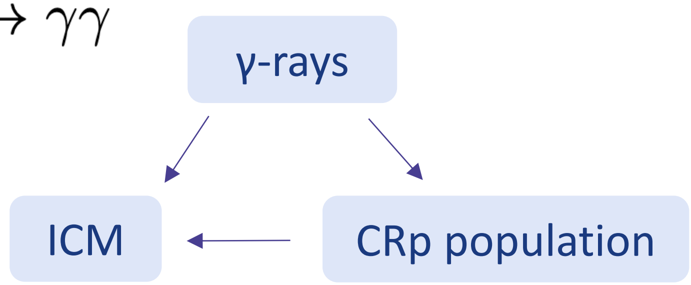
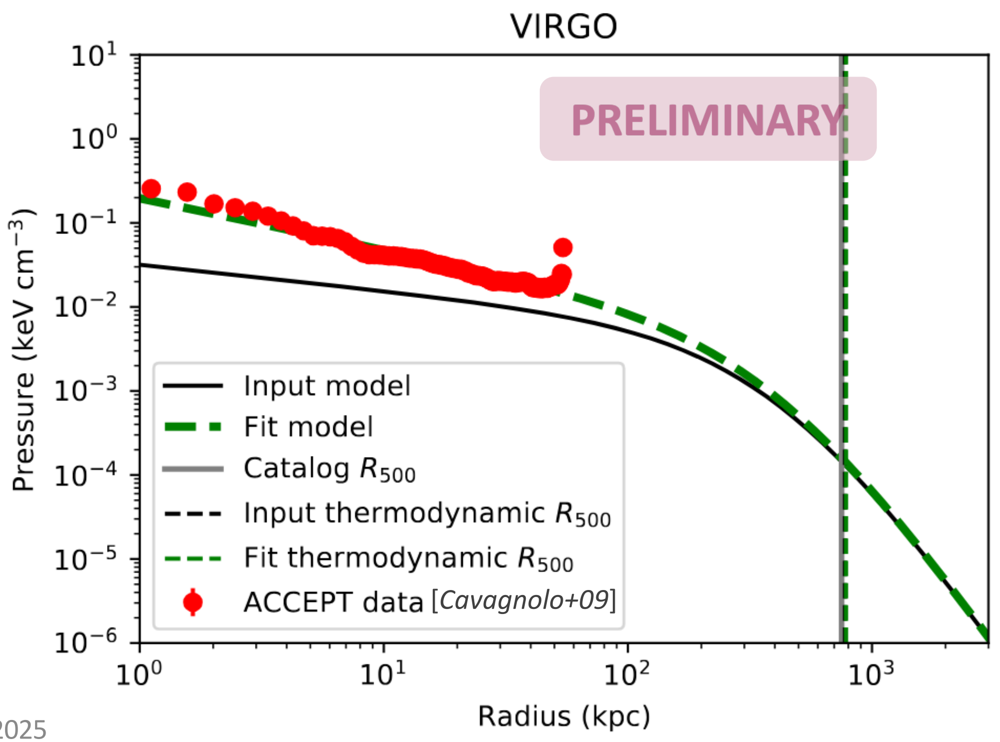


2. Thermal gas/electron pressure profile $P_{\rm gas}(r) = \frac{\mu_e}{\mu_{\rm gas}} P_e(r)$
   - Probed by tSZ effect for individual clusters
   - General profile

Arnaud+10 [0910.1234]

$$\frac{P(x)}{P_{500}} = \frac{P_0}{(c_{500}x)^\gamma[1+(c_{500}x)^\alpha]^{\frac{\beta-\gamma}{\alpha}}} \qquad x = R/R_{500}$$

   - Validated with ACCEPT data when available



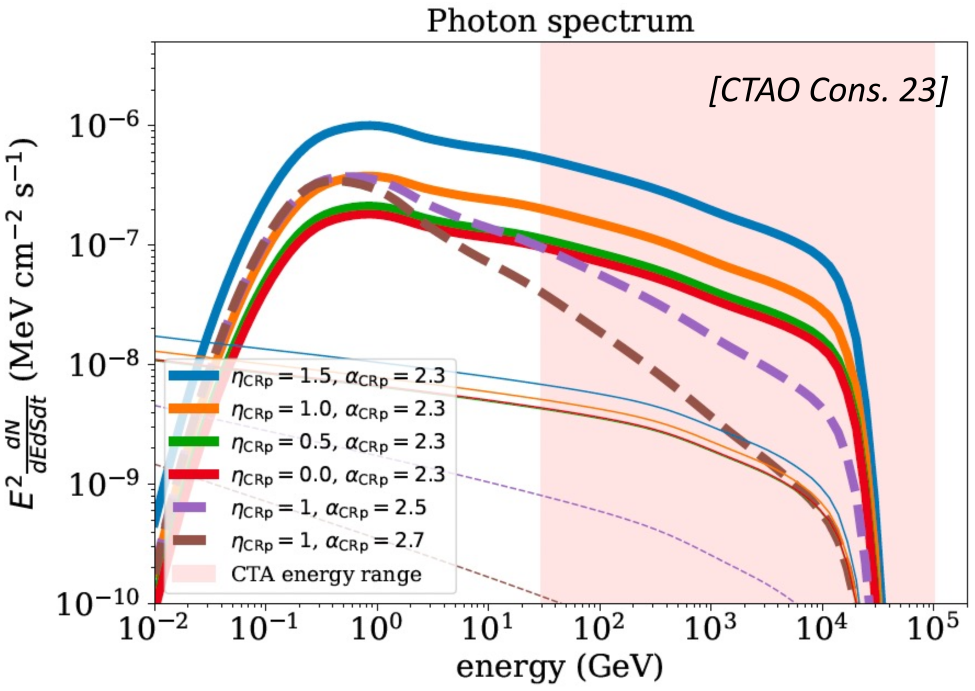
CLUSTERS CR MODELLING

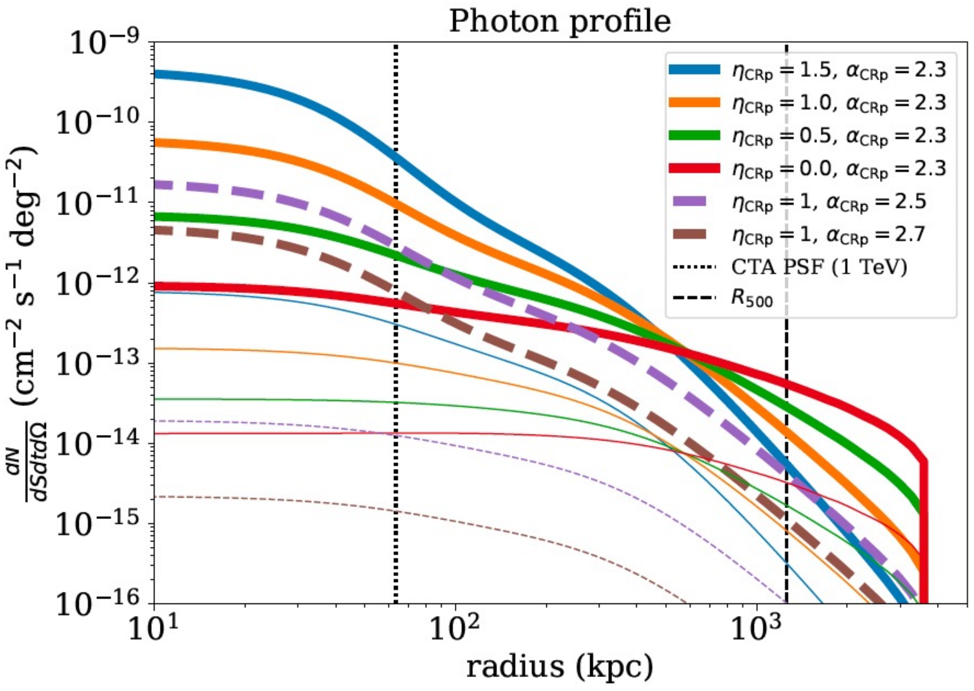
3. CRp distribution

$$\frac{dN_{\mathrm{CR_p}}}{dEdV}(E,r) = A_{\mathrm{CR_p}} \times E^{-\alpha_{\mathrm{CR_p}}} \times n_p^{\eta_{\mathrm{CR_p}}}$$

Normalized through

$$X_{500} = \frac{U_{\mathrm{CR_p}}(R_{500})}{U_{\mathrm{th}}(R_{500})}$$



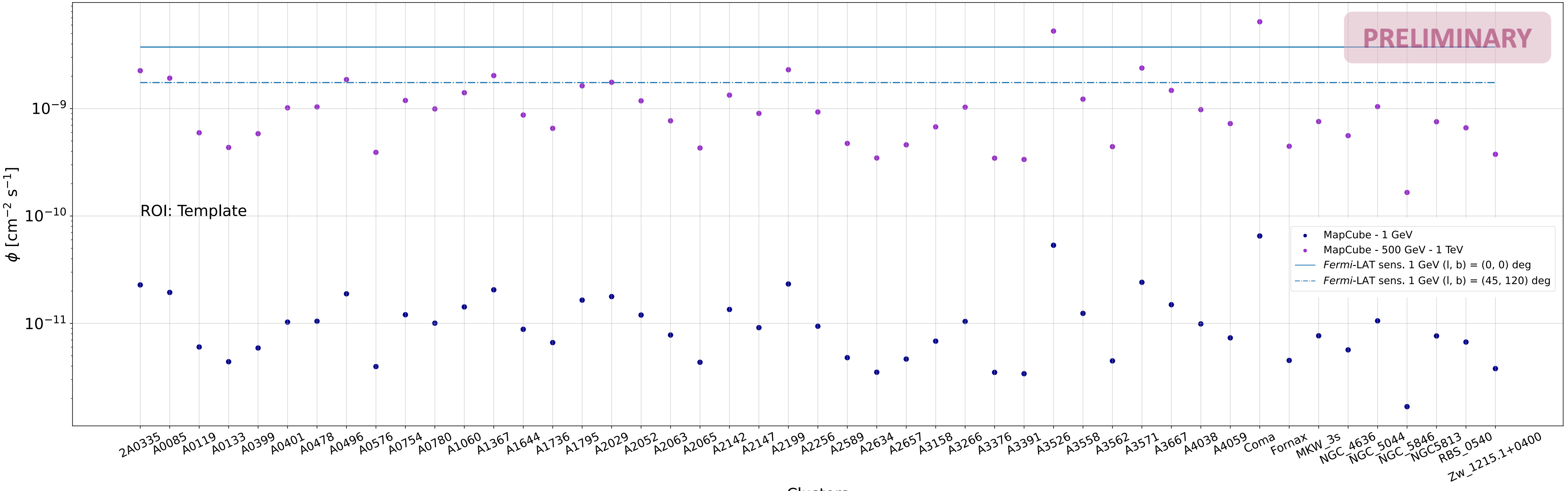


- Allowed parameter space:
  - $\eta_{\mathrm{CR_p}} \in [0, 1]$
  - $\alpha_{\mathrm{CR_p}} \in [2, 3]$
  - $X_{500} \sim 10^{-2}$

[Pinzke & Pfrommer 10]
[Enßlin+10]
[Bykov+19]

CLUSTERS CR MODELLING

- Baseline CR model $X_{500} = 0.01,\ \alpha_{\mathrm{CR_p}} = 2.3,\ \eta_{\mathrm{CR_p}} = 0.75$
- Benchmarks: $\alpha_{\mathrm{CR_p}} = 2.0, 2.3, 2.6, 2.9;\ \ \eta_{\mathrm{CR_p}} = 1.0$



FERMI-LAT ANALYSIS SET-UP

Baseline set-up

Years of Fermi data	16
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-DR4

- Standard template Fermi analysis
- Combined likelihood:

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

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

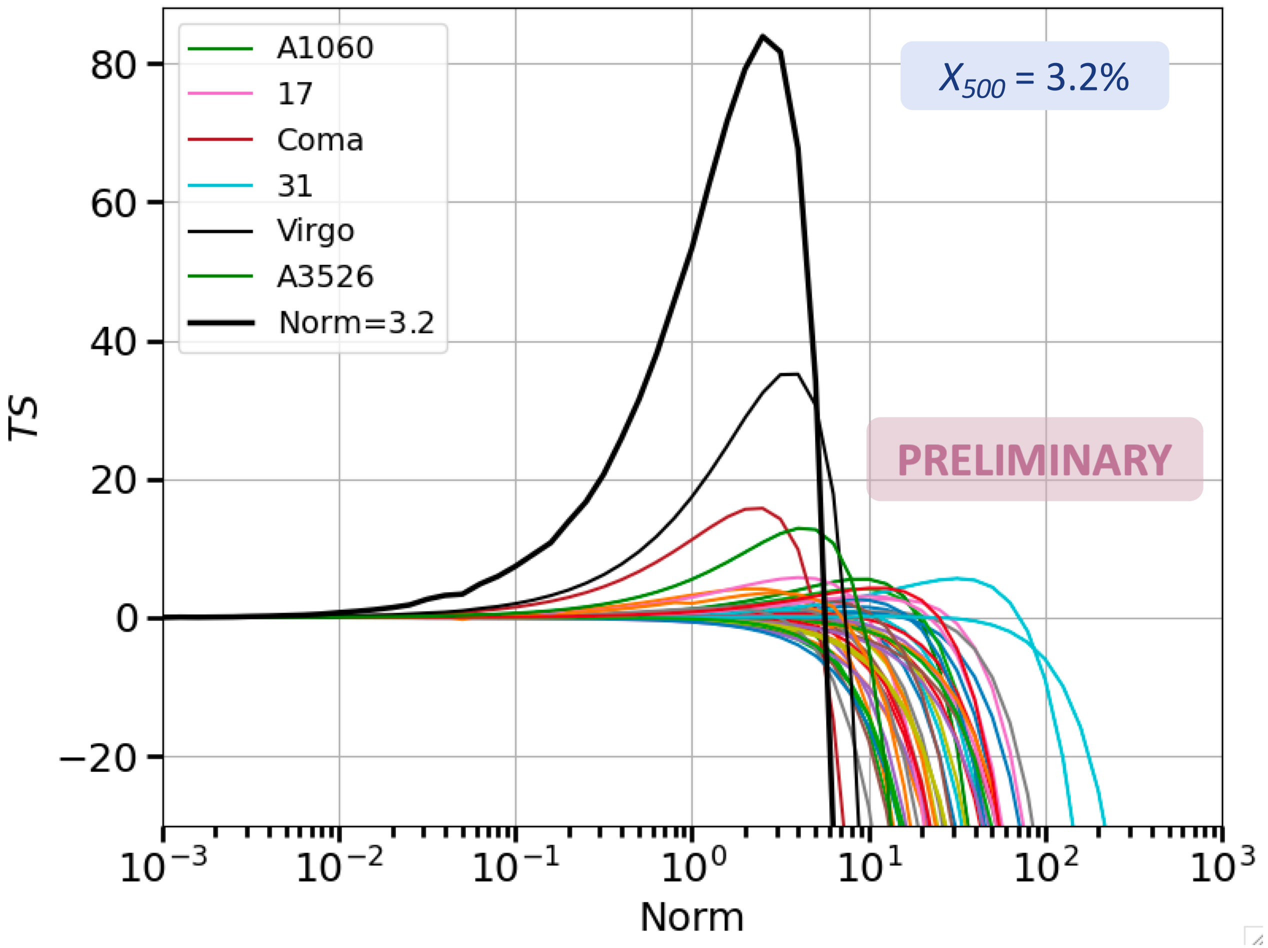
- *TS* < 25 ➡ No signal

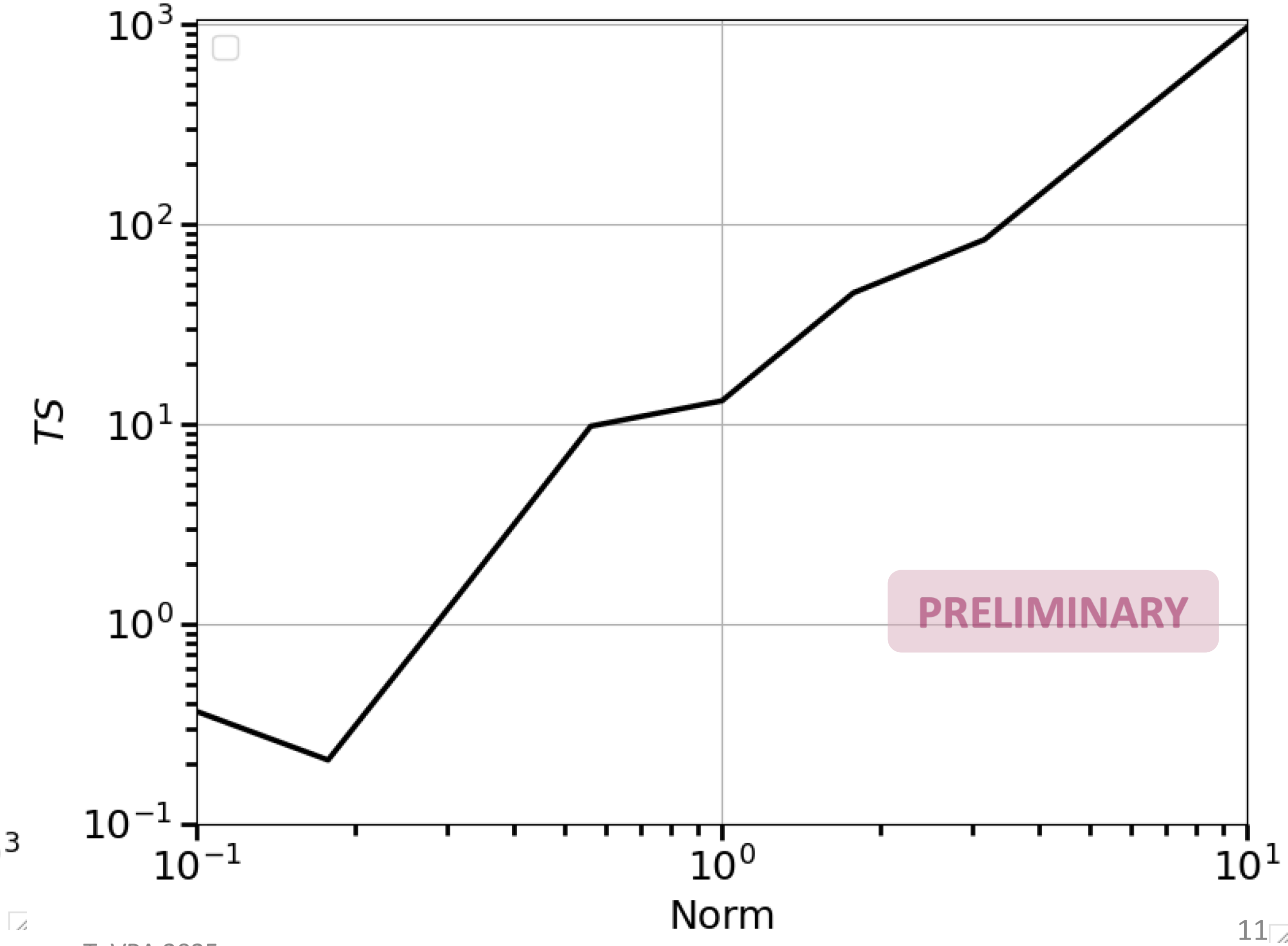
- Will test different set-ups for energy range, RoI, IRFs and Background (BKG) models
- Background components:
  - Individual point-sources from LAT (4FGL-DR4)
  - Fermi bubbles
  - Loop I + Sun + Moon
  - Isotropic emission
  - Galactic Interstellar Emission (IEM)

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

RECOVERY TESTS: DISCOVERY POTENTIAL

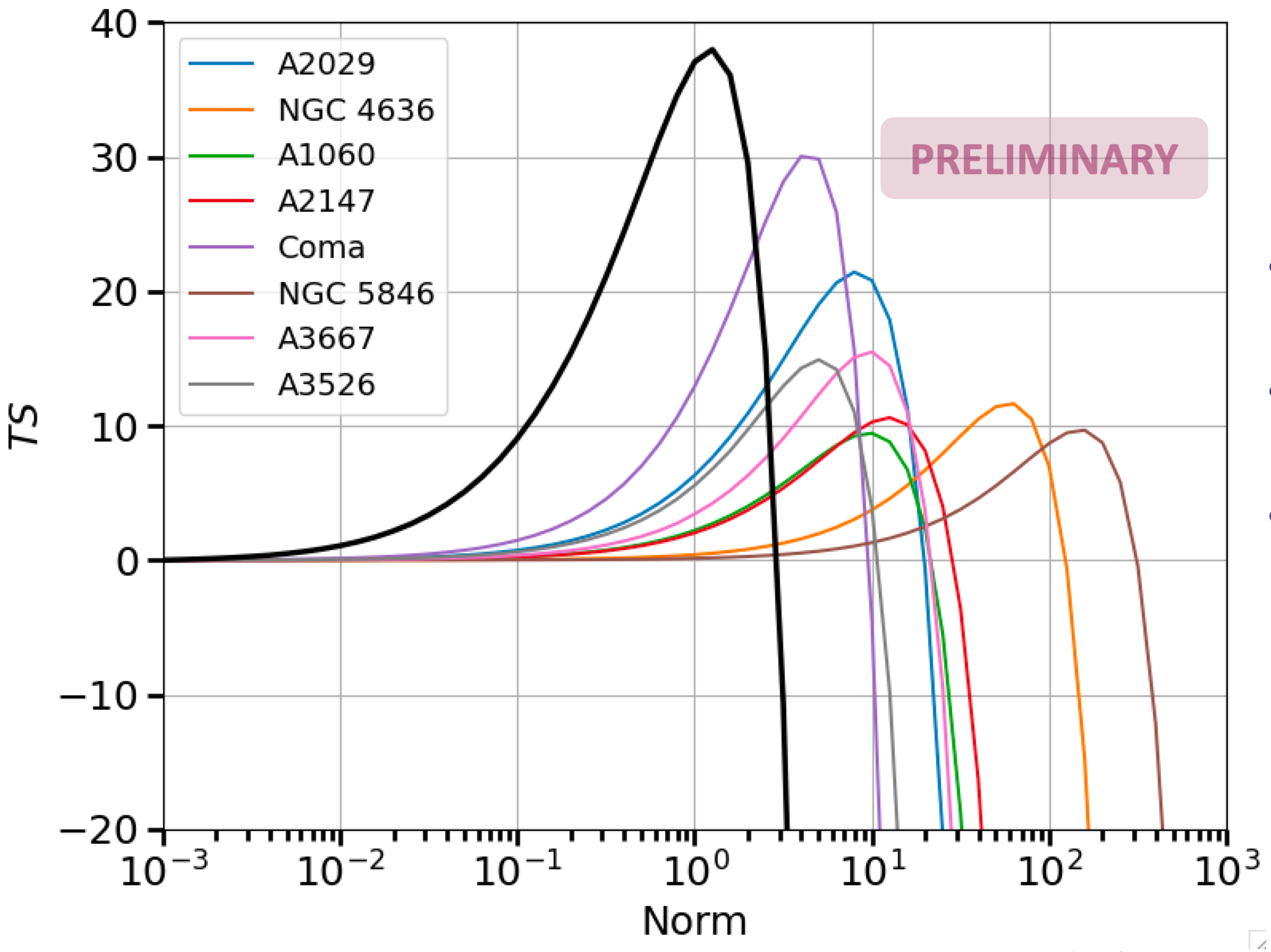
- Simulate *Fermi* data with injected signals and run analysis
- For signal of:
  - X_{500} = 0.5% - 1% → TS ~10
  - X_{500} = 5% → TS ~200





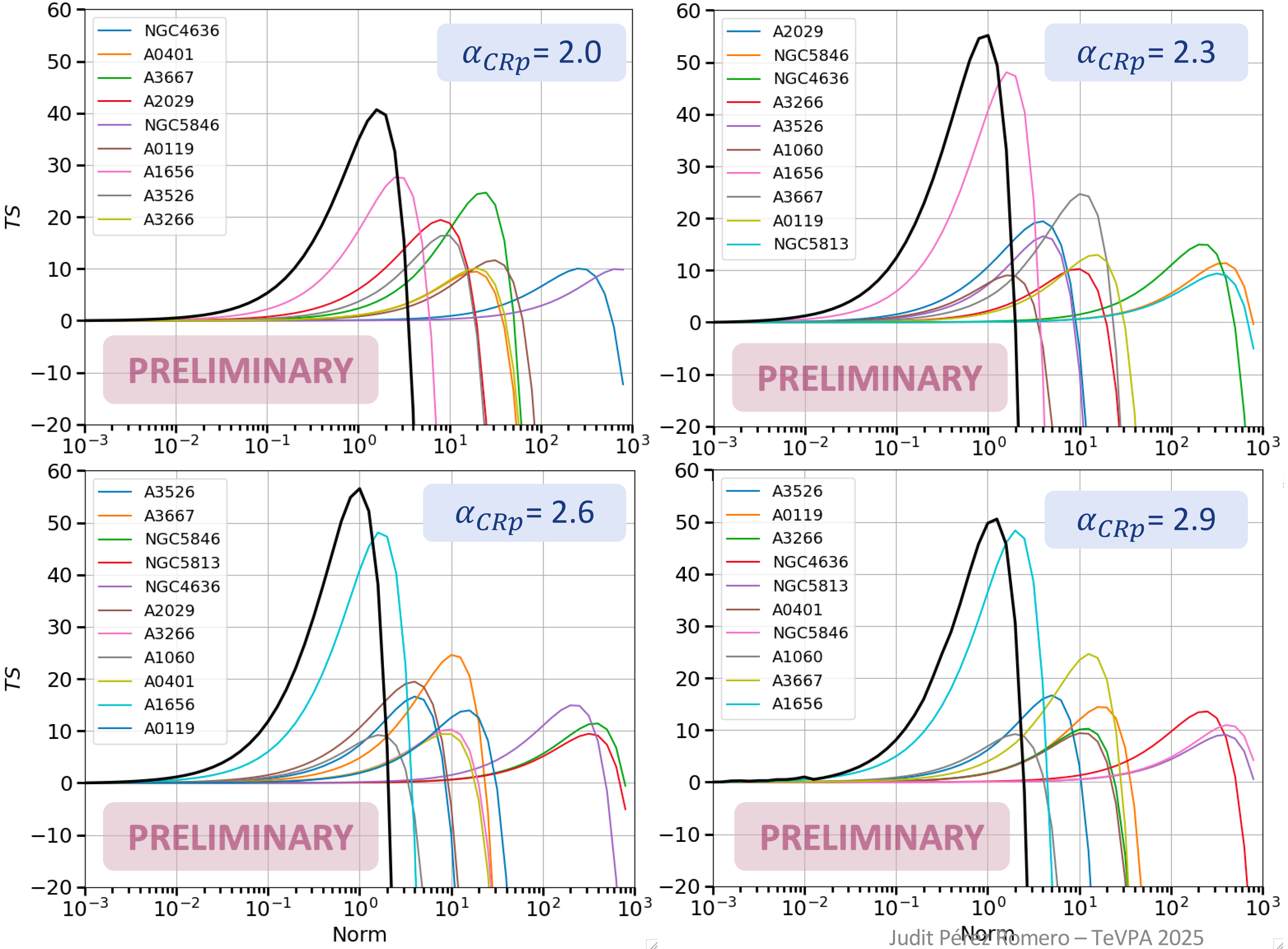
TS FOR THE BASELINE MODEL

- Baseline CR model $X_{500} = 0.01,\ \alpha_{\mathrm{CR_p}} = 2.3,\ \eta_{\mathrm{CR_p}} = 0.75$



- Highest combined *TS* = 38 for X_{500} ~ 1%
- Highest individual *TS* = 30 for **Coma** at X_{500} ~ 3%
- Other individual clusters peak at *TS* < 25 (not significant)

TS FOR THE BENCHMARK MODELS



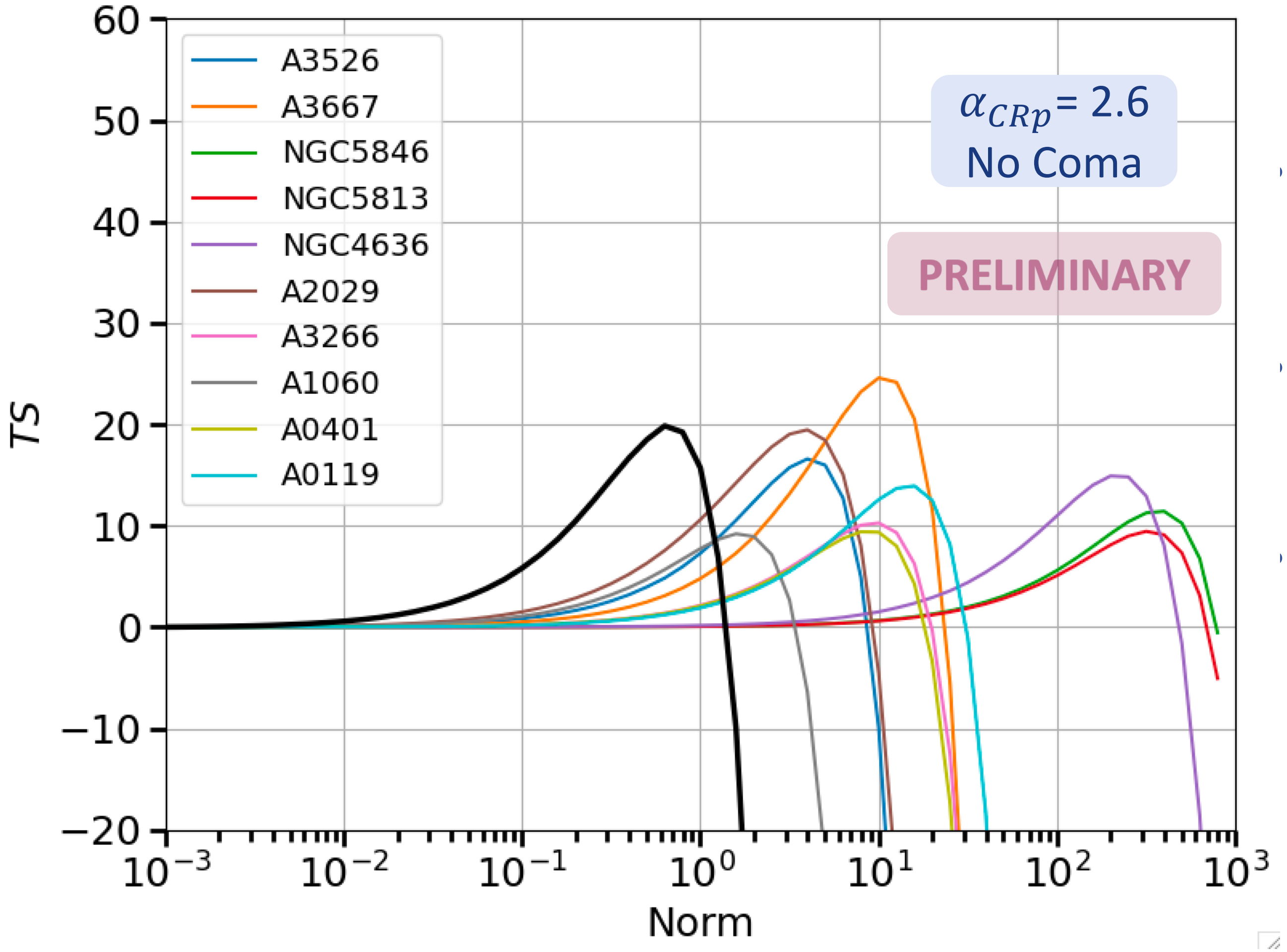
$$\alpha_{\mathrm{CR_p}} = 2.0, 2.3, 2.6, 2.9; \quad \eta_{\mathrm{CR_p}} = 1.0$$

α_{CRp}= 2.0	*TS* = 41
α_{CRp}= 2.3	*TS* = 54
α_{CRp}= 2.6	*TS* = 56
α_{CRp}= 2.9	*TS* = 51

- In all cases, $TS_{combined}$ are dominated by Coma (A1656):
  - *TS* = 47 for α_{CRp} = 2.6 and X_{500} ~ 2%
- Next in contribution is A3667, but always below *TS* = 25

TS FOR THE BENCHMARK MODELS

- If Coma is removed from the sample and the analysis:



- Combined *TS* no longer significant, even for the best α_{CRp}
- Individual clusters are also not significantly detected
- We will translate these results in the parameter space of X_{500} - α_{CRp} to set constraints

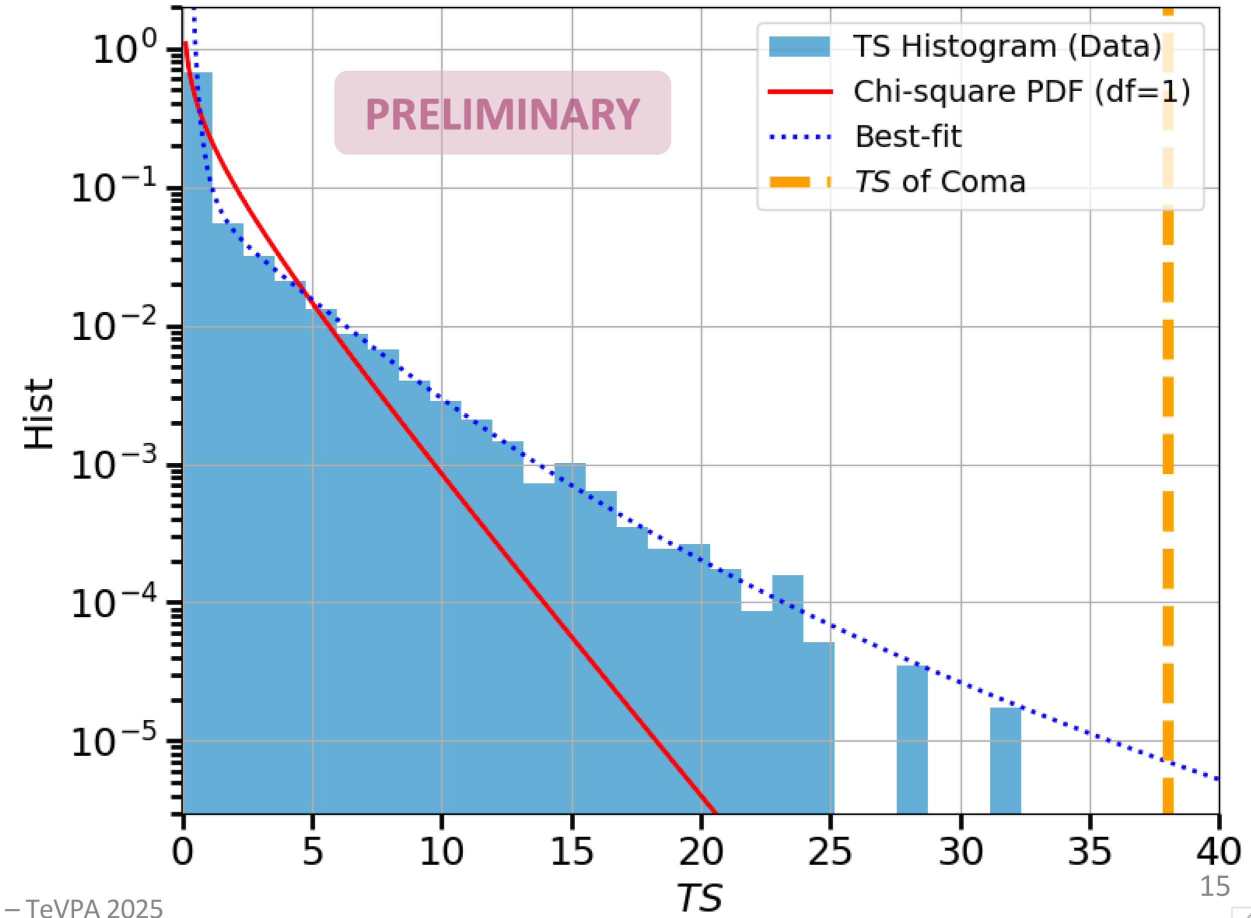
NULL HYPOTHESIS FOR *TS* DISTRIBUTION

- Ideal knowledge of BKGs → *TS* distribution described as $\chi^2/2$ *Chernoff 54* BUT → Analysis of real data at low energies for extended sources

- Build *TS* distribution with 50000 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 baseline model:

TS = 38 for Coma → p –value = 7e-6 (local) → **4.3σ**



THE CASE OF COMA CLUSTER

z	D_L [Mpc]	(l, b) [deg]	M_{500} [M_{sun}]	R_{500} [kpc]	α_{500} [deg]	α_{200} [deg]
0.0231	100.7	(57.23, 87.99)	4.28e14	1138	0.65	0.99

[MCXC Catalogue]

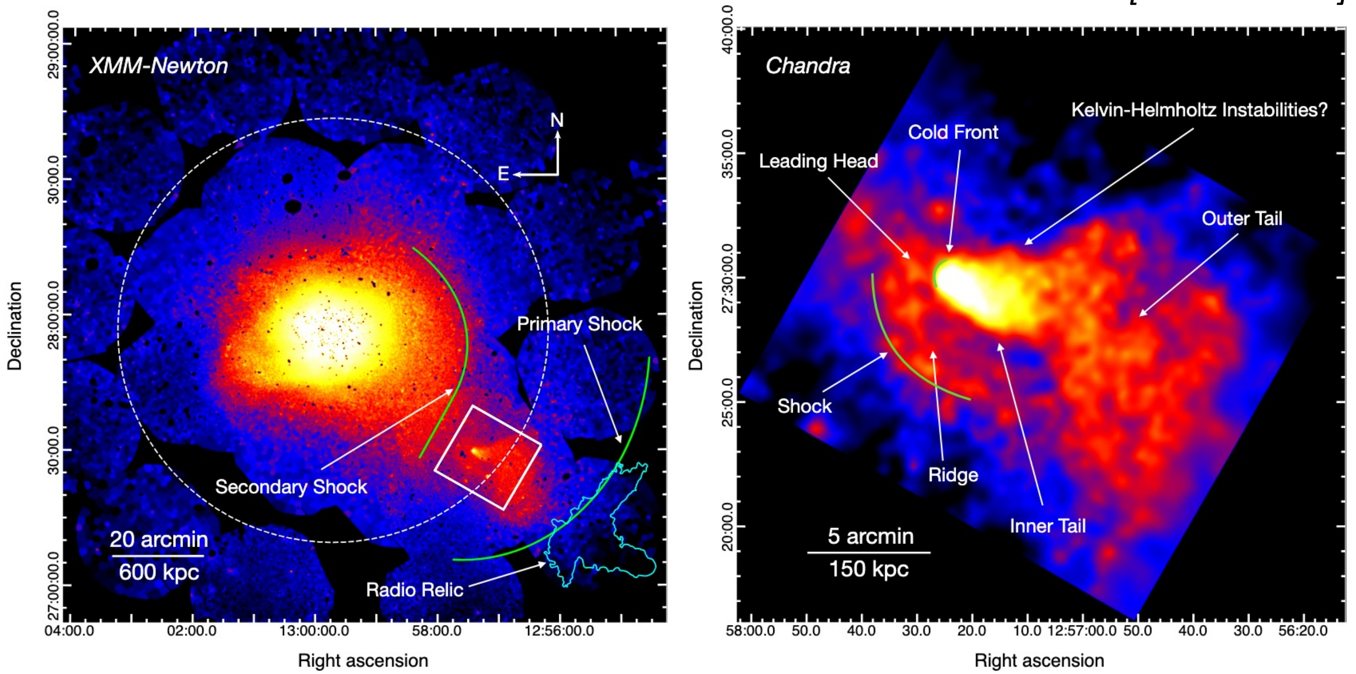
- Coma in the radio band:
  - extended, non-thermal, radio halo for the cluster core
  - diffuse radio relic at the virial radius

- Coma in the X-rays shows a complex morphology:
  - sub-group connected to NGC 4839
  - sub-structure between the center NGC 4839

- Several claims of a detection in the last years:

Xi+18	9 yrs	TS_{best} = 22
Adam+21	12 yrs	TS_{best} = 34
Baghmanyan+22	12.3 yrs	TS_{best} = 52

[Mirakhor+23]



THE CASE OF COMA CLUSTER

- In the 4FGL-DR4 catalogue:

	(RA, DEC) [deg]	Offset [deg]	Detection significance
4FGL J1256.9+2736	(194.24, 27.61)	0.71	5.56

- Could the emission be from the point source?

Model	TS_{Coma}	TS_{AGN}	TS_{Ext}	Extension [deg]	Position [deg]
Single PS	41.8	--	--	--	--
PS + 4FGL	29.4	17.3	--	--	--
Best benchmark	56.0	--	--	--	--
Best bench. + 4FGL	39.5	8.3	--	--	
Best bench. + NGC 4839	41.8	5.7	--	--	--
Gaussian relocated	59.3	--	12.6	0.79 ± 0.17	**0.59**
Gauss. rel. + NGC 4839	37.7	10.2	5.0	0.32 ± 0.12	**0.05**

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Preference for extended + PS combined emission

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Even the lowest *TS* is significant for Coma

Preference for extended + PS combined emission

SUMMARY AND FUTURE WORK

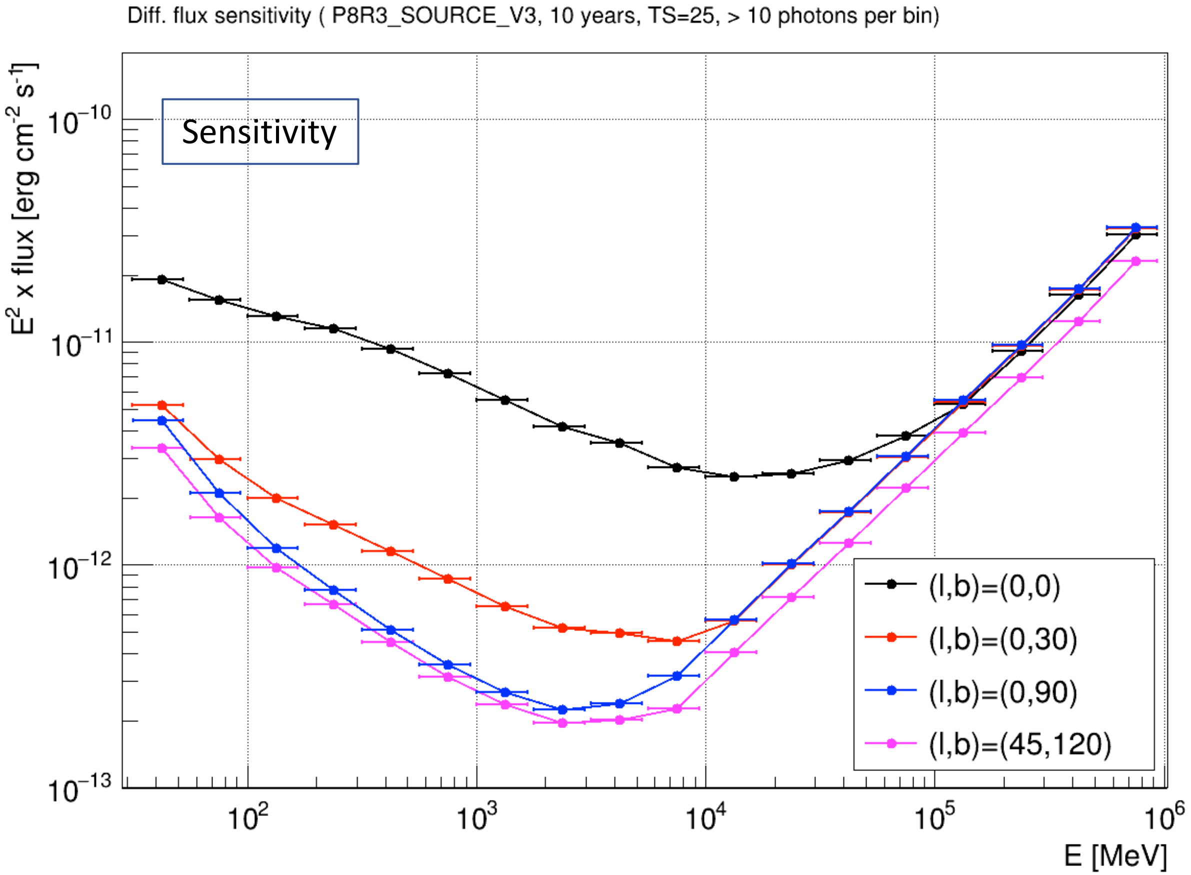
- The **detection of diffuse γ-ray emission** from galaxy clusters is a long awaited milestone
- Several studies in the most recent years hint towards mild detections
- Analyzed **16 years of *Fermi*-LAT data** in the direction of 49 galaxy clusters searching for CR-induced γ-ray emission
- Build models for the induced CR emission for the selected sample on the basis of cluster self-similarity, defining benchmark models to encapsulate the uncertainty in the CR population composition and spectra
- For baseline model: $TS_{combined}$ = 38 for X_{500} = 1%, but highest $TS_{combined}$ is reached for α_{CRp}= 2.6
- The **analysis is dominated by Coma**, if removed, $TS_{combined}$ = 20 for the best scenario
- Computing the significance with the null TS distribution, **Coma is still ~4σ**
- The analysis including 4FGL source yields TS_{Coma} = 29.5 – 59.3, with a **preference for a diffuse + ps model**

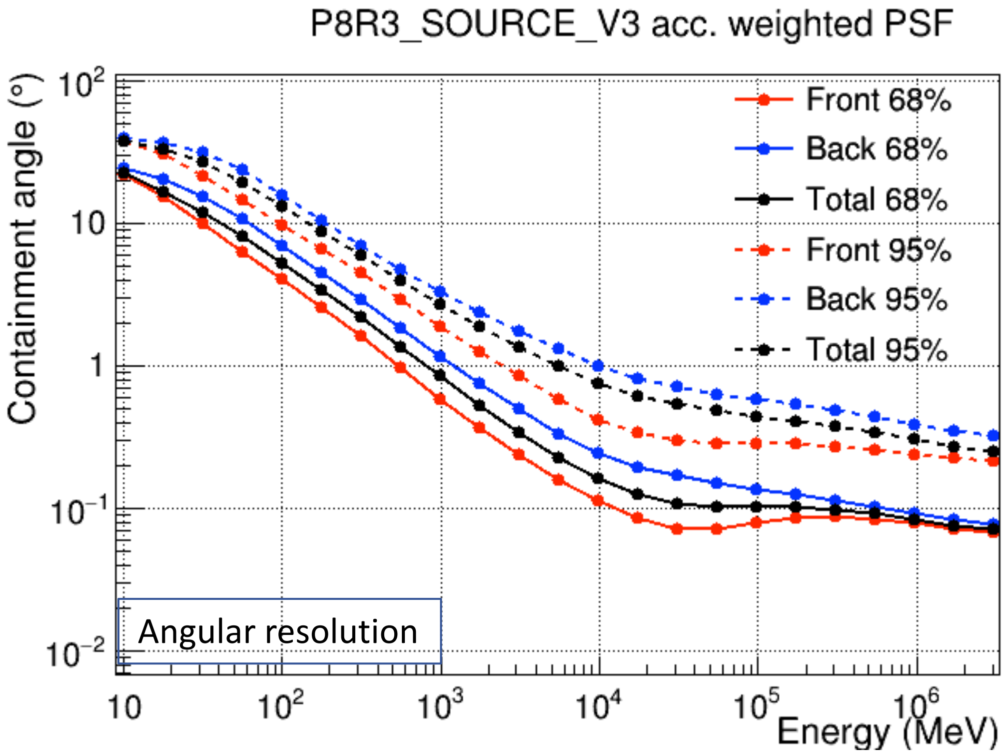
THANKS FOR YOUR ATTENTION

FERMI-LAT PERFORMANCE

10y Performance Capabilities

Instrument Response Functions (IRFs)





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

γ-RAY DM SEARCHES IN CLUSTERS

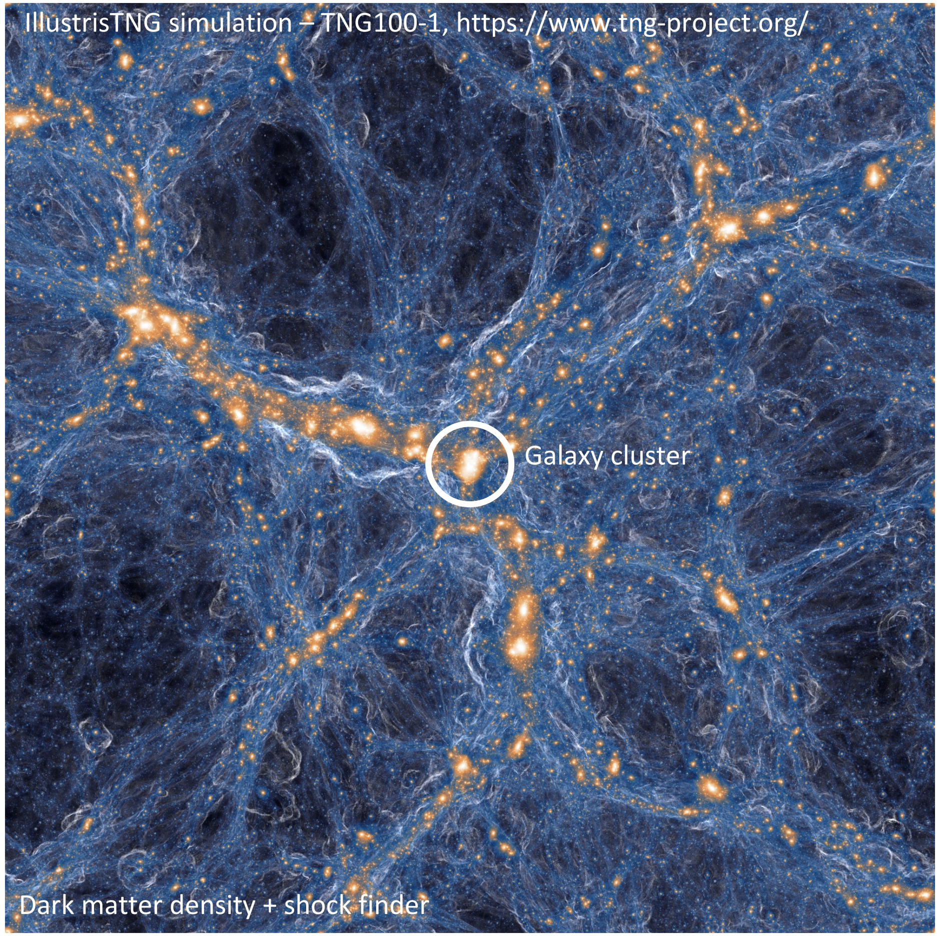
- Components:
  - Dark Matter
  - Baryonic Matter

Very massive objects | High DM density | Closeby objects

Decay **Annihilation**

- Best possible targets to consider $\longrightarrow \phi_{\mathrm{DM}} \propto \rho_{\mathrm{DM}}$
- Competitive to other prime targets

Caveat Expected γ-ray emission from astrophysical processes



CLUSTERS SAMPLE – *FERMI*-LAT (DM VALUES)

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 – *FERMI*-LAT (DM VALUES)

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} $M_\odot$]		[$M_\odot/\mathrm{kpc}^3$]	[kpc]	[kpc]	[deg]	[$\mathrm{GeV}^2\mathrm{cm}^{-5}$]	[$\mathrm{GeV}^2\mathrm{cm}^{-5}$]		[$\mathrm{GeV}^2\mathrm{cm}^{-5}$]		[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

CR MODELLING: MINOT APPROACH

To compute the CR-induced γ-ray flux:

$$\frac{dN_X}{dE_X dV dt} = \int_{E_X}^{+\infty} \frac{dN_{\rm col}}{dE_{\rm CRp} dV dt} F_X\left(E_X, E_{\rm CRp}\right) dE_{\rm CRp}.$$

Where X are γ-rays

$F_X\left(E_X, E_{\rm CRp}\right)$ number of secondary particles produced in a collision pert energy of the produced particle as a function of the initial energy of the CRp (fit to collider data)

$$\frac{dN_{\rm col}}{dE_{\rm CRp} dV dt} = \sigma_{\rm pp} \times v_{\rm CRp} \times \overset{1}{n_{\rm p}} \times \overset{2}{J_{\rm CRp}},$$

proton-proton interaction cross section

c (relativistic)

1

$$n_p(r) = \frac{\mu_e}{\mu_p} n_e(r).$$

Assume n_e follows the gas distribution, *Ghirardini+18* [1805.00042] useed deprojection models to extract n_e from X-COP X-ray surface brightness data from various clusters, and fitted to a universal density profile model from *Vilkhinin+06*

$$n_e^2(x) = n_0^2 \frac{(x/r_c)^{-\alpha}}{(1 + x^2/r_c^2)^{3\beta-\alpha/2}} \frac{1}{(1 + x^\gamma/r_s^\gamma)^{\epsilon/\gamma}}$$

where
$x = R/R_{500}$ and $\gamma = 3$

For the rest of parameters, they provide a general fit, a fit for CC and NCC

CR MODELLING: MINOT APPROACH

To compute the CR-induced γ-ray flux:

$$\frac{dN_X}{dE_X dV dt} = \int_{E_X}^{+\infty} \frac{dN_{\rm col}}{dE_{\rm CRp} dV dt} F_X\left(E_X, E_{\rm CRp}\right) dE_{\rm CRp}.$$

Where X are γ-rays

$F_X\left(E_X, E_{\rm CRp}\right)$ number of secondary particles produced in a collision pert energy of the produced particle as a function of the initial energy of the CRp (fit to collider data)

1 2

$$\frac{dN_{\rm col}}{dE_{\rm CRp} dV dt} = \sigma_{\rm pp} \times v_{\rm CRp} \times n_{\rm p} \times J_{\rm CRp},$$

proton-proton interaction cross section

c (relativistic)

2 $J_{\rm CR}(r, E) = A_{\rm CR} f_1(E) f_2(r),$

$$\frac{dN_{\rm CR_p}}{dEdV}(E, r) = A_{\rm CR_p} \times E^{-\alpha_{\rm CR_p}} \times n_p^{\eta_{\rm CR_p}}$$

where $\eta_{\rm CR_p} \in [0, 1]$ Flat/ follows exactly gas density profile

$\alpha_{\rm CR_p} \in [2, 3]$

$$X_{\rm CR}(R) = \frac{U_{\rm CR}(R)}{U_{\rm th}(R)},$$

$$U_{\rm CR}(R) = 4\pi \int_0^R u_{\rm CR} r^2 dr.$$

$$u_{\rm CR}(r) = 3P_{\rm CR}(r) = \int_{E_1}^{E_2} E_{\rm CR} J_{\rm CR}(E_{\rm CR}) dE_{\rm CR},$$

Normalize A_{CRp} with a value of $X_{500} \sim 10^{-2}$

$$U_{\rm th}(R) = 4\pi \int_0^R u_{\rm th} r^2 dr$$

$$u_{\rm th} = \frac{3}{2} n_{\rm gas} k_{\rm B} T = \frac{3}{2} P_{\rm gas}$$

$$P_{\rm gas}(r) = \frac{\mu_e}{\mu_{\rm gas}} P_e(r),$$

Generalized profile *Arnaud+10*

CR MODELLING: MINOT APPROACH

To compute the CR-induced γ-ray flux:

$$\frac{dN_X}{dE_X dV dt} = \int_{E_X}^{+\infty} \frac{dN_{\rm col}}{dE_{\rm CRp} dV dt} F_X\left(E_X, E_{\rm CRp}\right) dE_{\rm CRp}.$$

Where X are γ -rays

$F_X\left(E_X, E_{\rm CRp}\right)$ number of secondary particles produced in a collision pert energy of the produced particle as a function of the initial energy of the CRp (fit to collider data)

$$\frac{dN_{\rm col}}{dE_{\rm CRp} dV dt} = \sigma_{\rm pp} \times v_{\rm CRp} \times \overset{1}{n_{\rm p}} \times \overset{2}{J_{\rm CRp}},$$

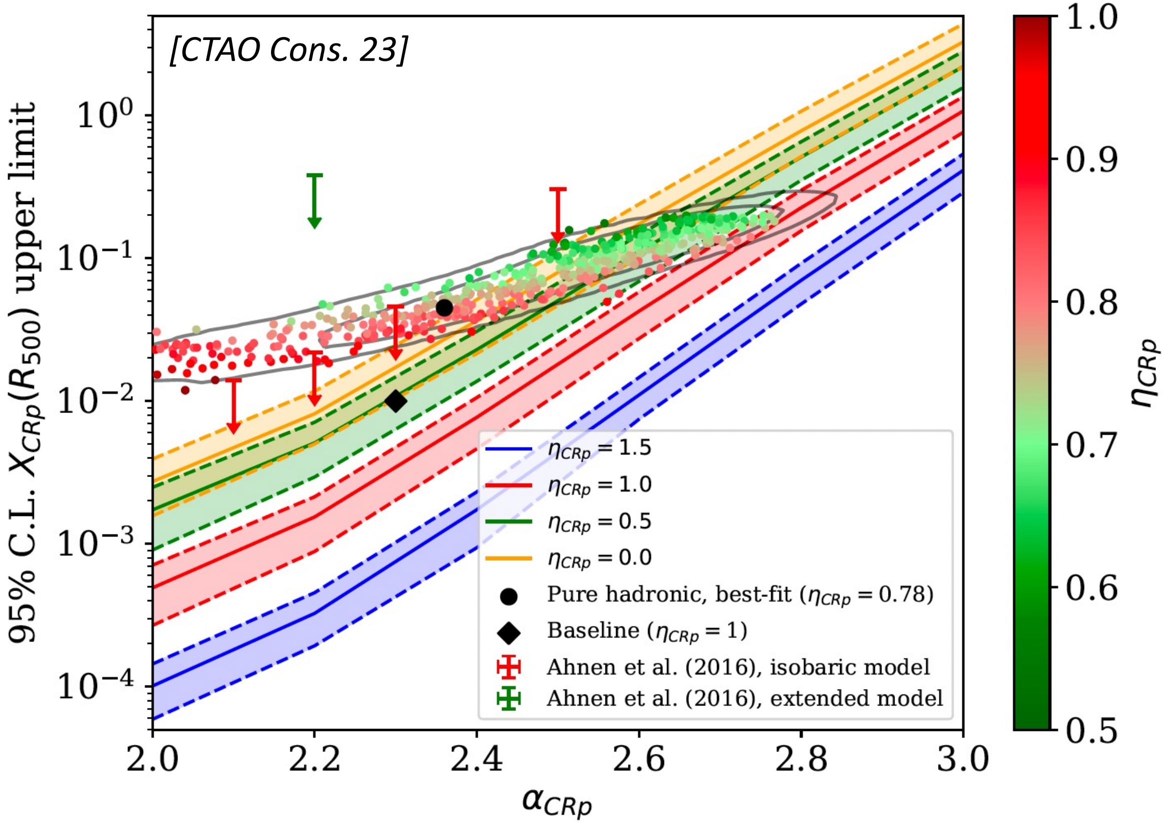
proton-proton interaction cross section

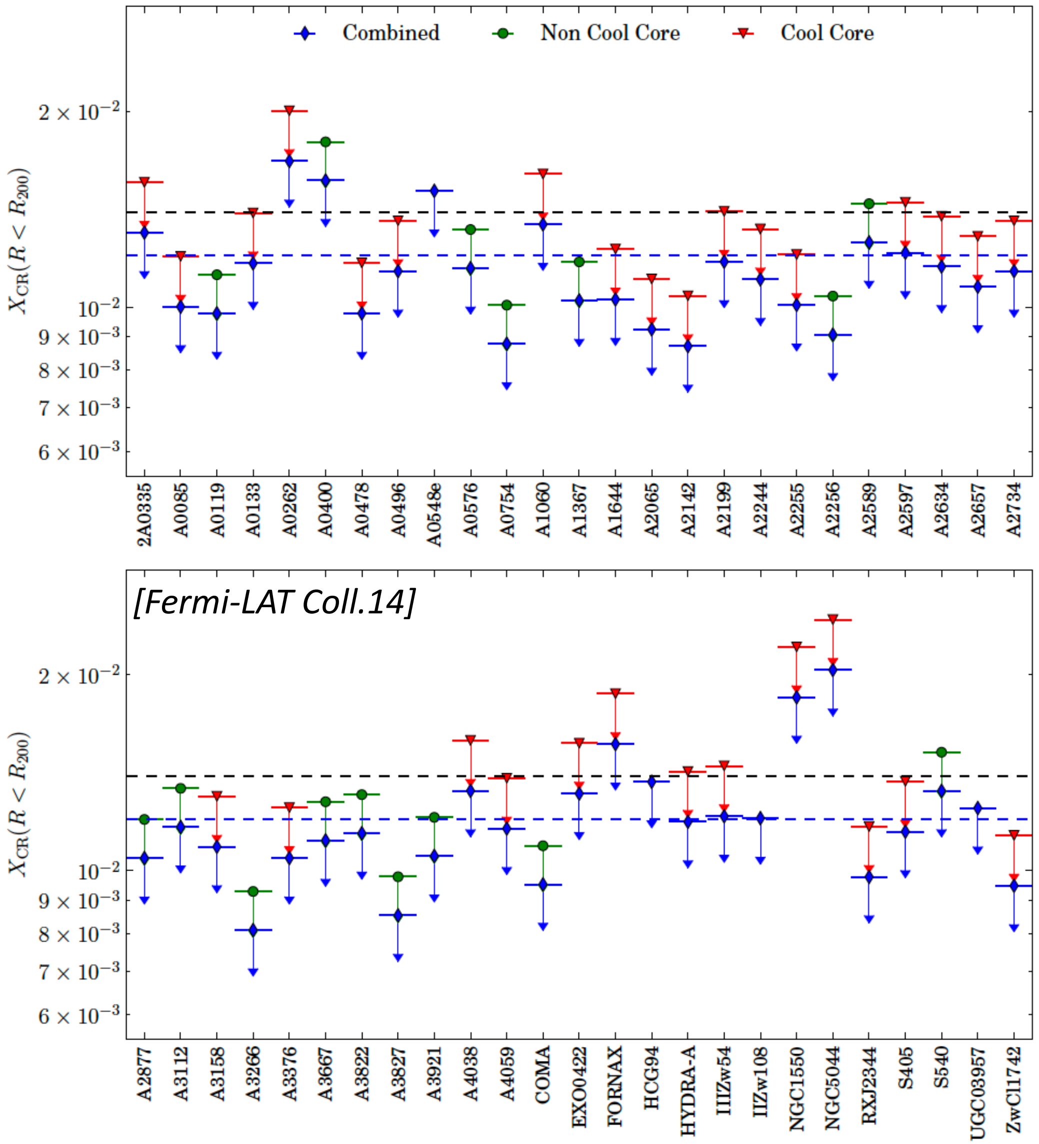
c (relativistic)

To model the CR-induced γ-ray flux from a cluster we need:

- P_e & n_e / P_e & T_g / T_e & n_e $\longrightarrow$ $k_{\rm B}\, T_e(r) = P_e(r)/n_e(r) \equiv k_{\rm B}\, T_{\rm gas}(r).$
- Assume a value for X_{500}, α_{CRp} and η_{CRp} $\longrightarrow$ $X_{500} \sim 10^{-2}$ $\eta_{\rm CR_p} \in [0, 1]$ $\alpha_{\rm CR_p} \in [2, 3]$
- Self-similarity between clusters: CR populations have been accumulating in the cluster since beginning of formation (CR are generated from propagation schocks from the mergers and turbulence), also we take the assumption of hydrostatic equilibrium to have a mass proxy, even though we consider corrections for CC vs. NCC

CR MODELLING: PARAMETER SPACE





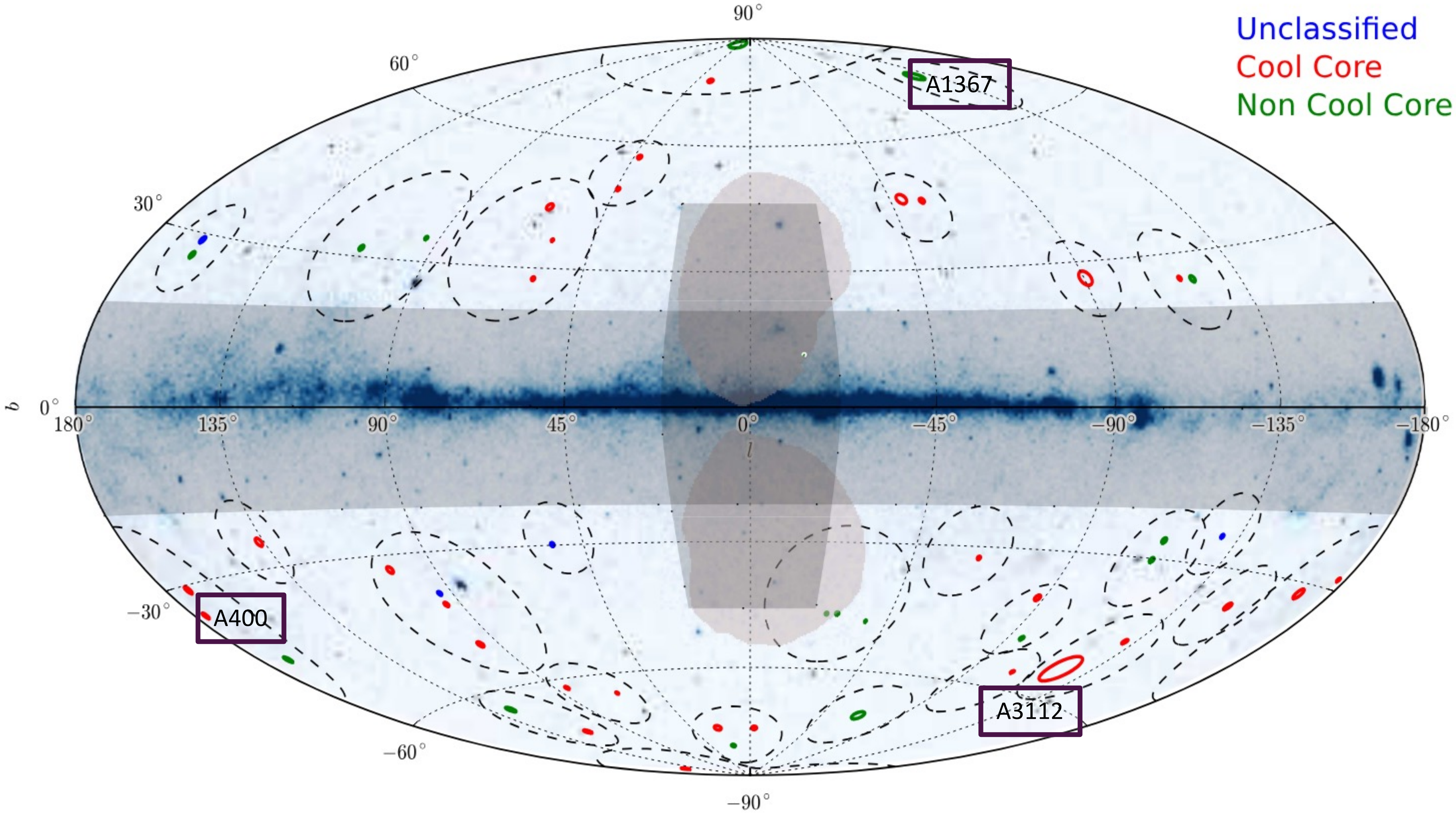
- Expected values from simulations:

  [Pinzke & Pfrommer 10]
  [Enßlin+10]
  [Bykov+19]

- Allowed values from constraints:

  [MAGIC Coll. 16]
  [Fermi-LAT Coll.14]

SEARCH OF DIFFUSE CR-EMISSION WITH FERMI: LAST RESULTS FROM FERMI



- *Fermi-LAT Coll.* [1308.5654] $F\gamma$ are from [*Pinzke & Pfrommer 2010]*

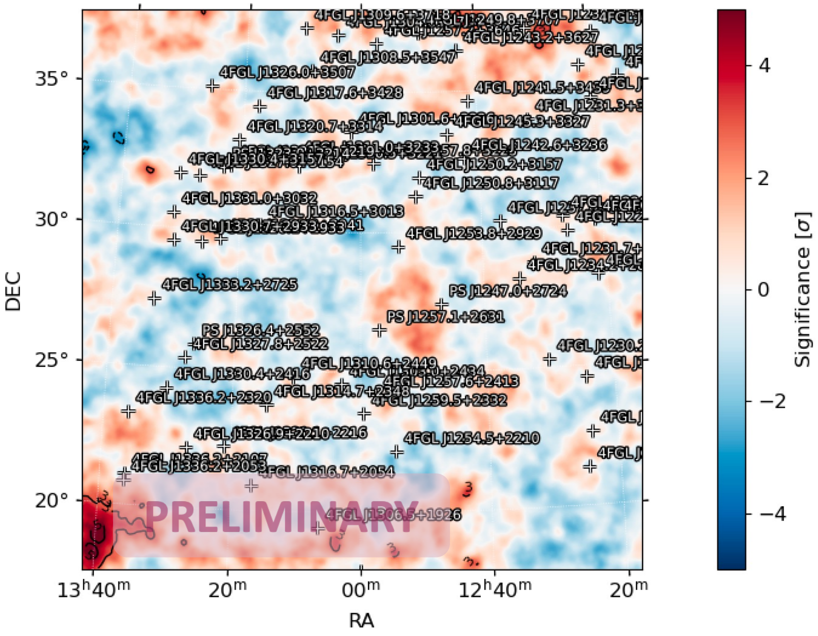
- Their results (26 RoIs):
  - global *TS*=7.3 (2.7σ) of the scale factor for their full sample (50 clusters)
  - largest contributors are A400, and less A1367 and A3112

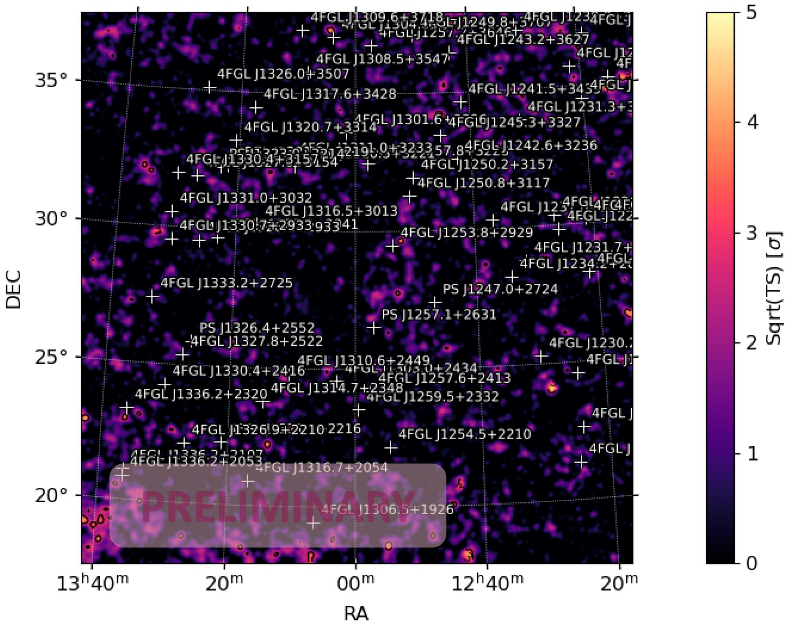
	Xi+18	Adam+21	Baghmanyan+22	This work
Years of LAT data	9 yrs	12 yrs	12.3 yrs	16 yrs
Energy range	200 MeV – 300 GeV (100, 300, 500, 800 MeV)	200 MeV – 300 GeV	100 MeV – 1 TeV	500 (100) MeV – 1 TeV
ROI	12x12 deg^2	12x12 deg^2	12x12 deg^2	20x20 deg^2
PS catalogue	3FGL	4FGL-DR2	4FGL-DR2	4FGL-DR4
Type of analysis	Binned, norms + indeces free (centers fix)	Binned, indeces fixed (PS - 4FGL, coma - α_{CRp} 2.8, centers fix)	Binned, norms + indeces + centers free	Binned, norms + indeces free (centers fix)
TS cluster ext only	15 – 22 (α_{CRp} 2.70–2.88)	11 - 34	50-52 (α_{CRp} 2.23)	27 – 49 (depending on α_{CRp})
TS PS only	25.3 (index 2.67)	25.61	29.8 (index 2.77)	---
TS cluster only as PS	14.3 (α_{CRp} 3.39)	17.54	---	---
TS cluster ext + PS	28 – 31 (idxs 2.80-5.14/2.21-2.41)	26-36 (1-18/7-23)	---	(35-43/6-11)
Correlation	--	Norm-norm: ~ -0.45	---	Norm-norm: -(0.035 – 0.043) Norm-index: -(0.015 – 0.018) Index-norm: -(0.013 – 0.037) Index-index: -(0.019 – 0.022)
TS cluster as PS + PS	28.9 (idxs 3.57/2.56)	32.24	---	---

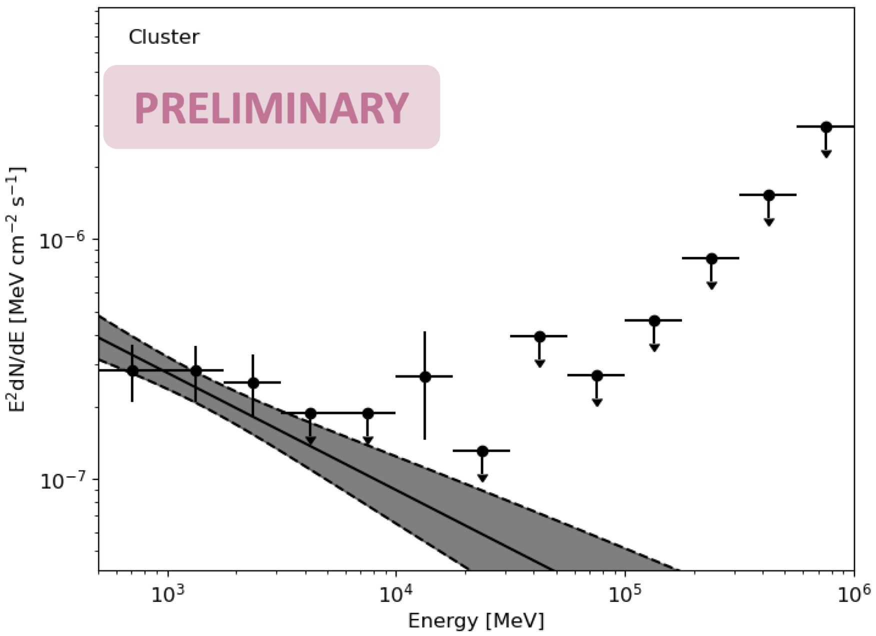
THE CASE OF COMA CLUSTER

- Frist approach analysis: test the extension of the source using a disk or gaussian

Model	TS	$TS_{extension}$	Best extension [deg]	Extension U.L. [deg]
Disk	48.68	6.75	0.41 ± 0.16	0.68
Gaussian	47.69	6.31	0.30 ± 0.06	0.47





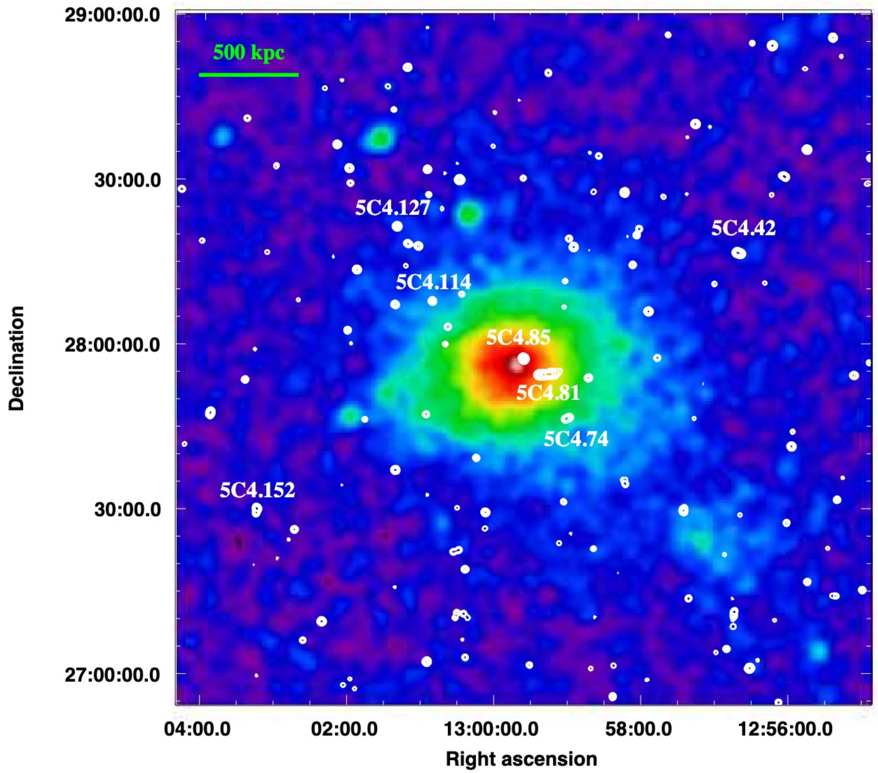


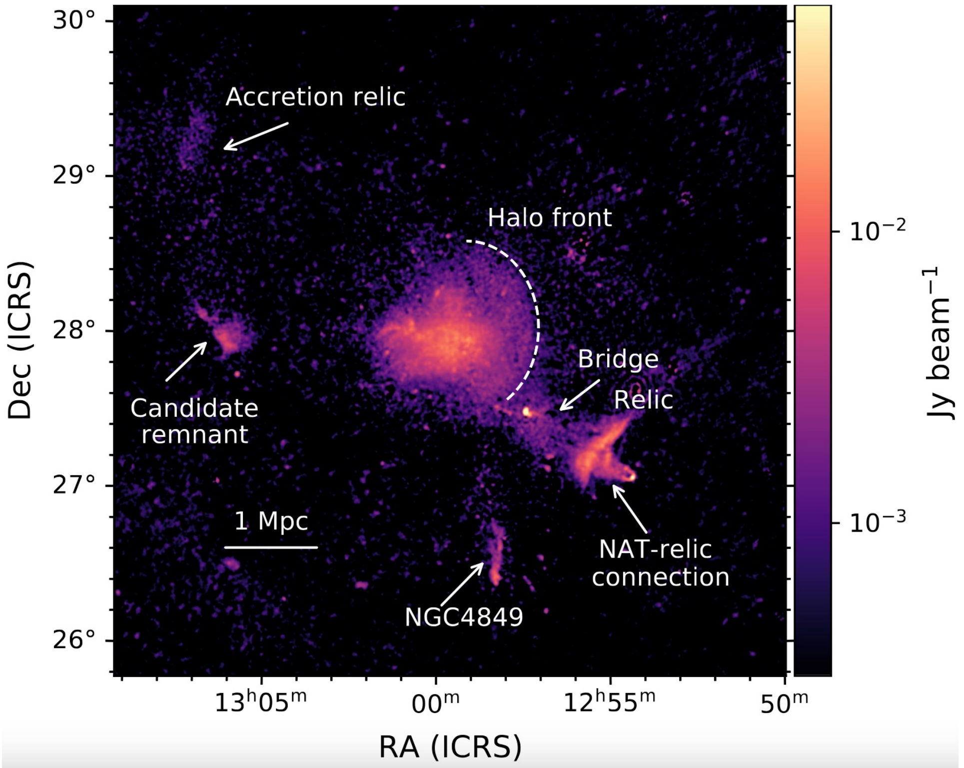
SEARCH OF DIFFUSE CR-EMISSION WITH FERMI: COMA DETECTION

- Tests for different cases:
  1. Coma cluster as point source without 4FGL source
  2. Coma cluster as point source with 4FGL source
  3. Coma cluster with CRs template without 4FGL source
  4. Coma cluster with CRs template with 4FGL source
  5. Coma cluster with CRs template with 4FGL source placed at the NED position of the AGN
  6. Gaussian function for extension of Coma cluster and refitting localization and extension (no 4FGL source)
  7. Gaussian function for extension of Coma cluster and refitting extension (no 4FGL source)
  8. Gaussian function for extension of Coma cluster and refitting localization and extension (WITH 4FGL source)
  9. Gaussian function for extension of Coma cluster and refitting extension (WITH 4FGL source)
  10. 10,11,12,13 as 6,7,8,9 but for a disk shape

COMA RADIO SOURCES

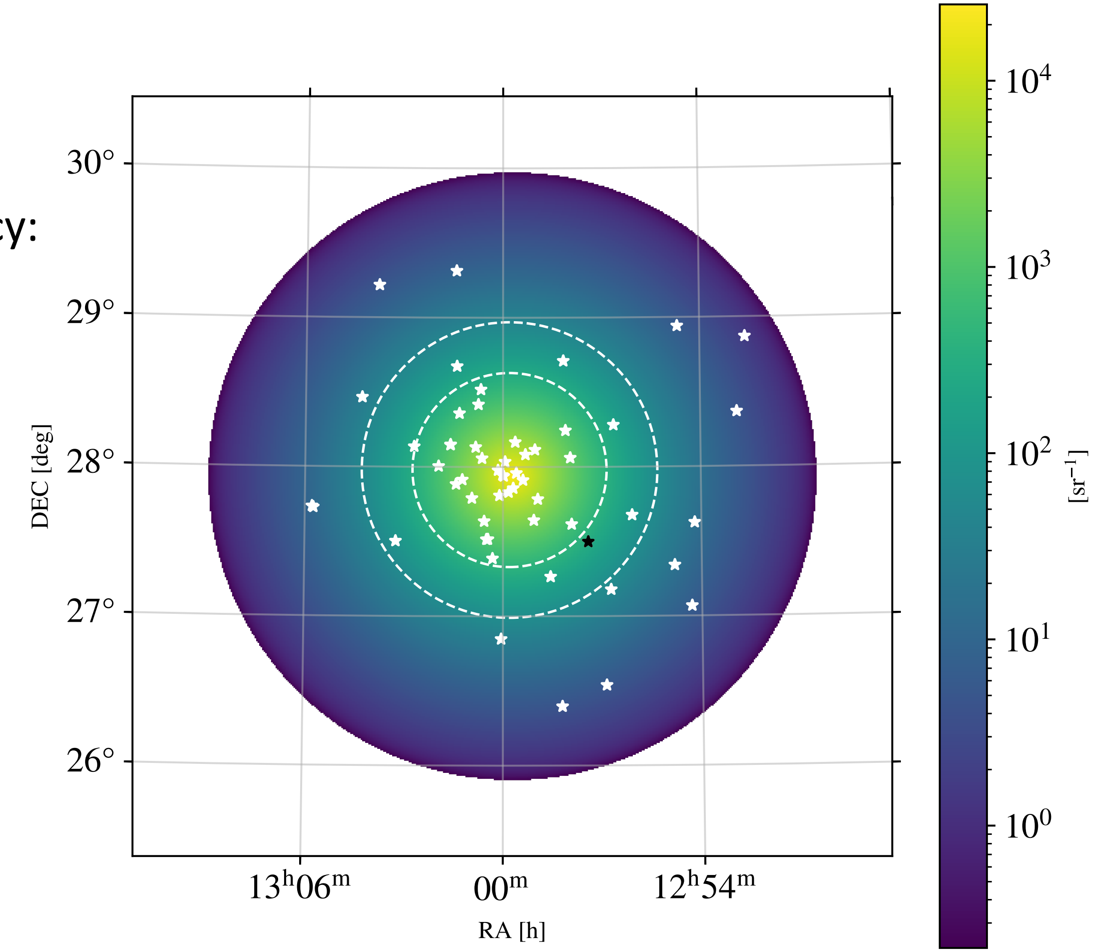
- Due to the inconclusiveness of results, check if emission may come from Coma's radio sources
- Sources in the Coma field:
  - https://arxiv.org/pdf/1002.0594
  - https://arxiv.org/pdf/2203.01958
  - https://articles.adsabs.harvard.edu/pdf/1975ApJ...199...10T
  - https://articles.adsabs.harvard.edu/pdf/1977ApJ...217..944T
  - https://arxiv.org/pdf/1208.0676





COMA RADIO SOURCES

- 55 putative radio sources identified among the literature
- 14 of them have not been associated to any radio emission yet
- 41 rest do have at least one measurement in one radio frequency:
  - 6 liner AGNs (NGC 4874 - BCG)
  - 3 QSOs
  - 7 galaxies (towards cluster)
  - 3 radio sources
  - 5 radio galaxies (NGC 4869, **NGC 4839**)
  - 1 BL Lac (Coma A)
  - 1 Seyfert galaxy
  - 9 emission-line galaxies
  - 2 (-5?) starburst galaxies
  - 3 AGNs
  - 1 galaxy



- 4 of them have measurements at 5 GHz core (mentioned above, & at 151 MHz)
- 26 have measurements at 151 MHz, 21 at 1.4 GHz, 15 at ~5 GHz

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

DARK MATTER MODELLING

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

DM-induced γ-ray flux from an astrophysical object

Particle Physics Model

Cirelli+12 (EW corrections)

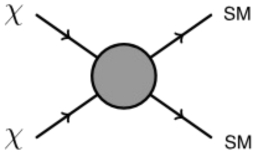
CLUMPY

Charbonnier+12, Bonnivard+15, Hütten+18

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

Annihilation

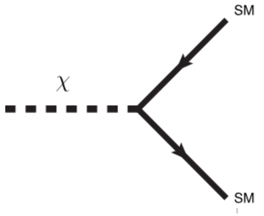
$$J(l.o.s, \Delta\Omega, z) = \int_{\Delta\Omega} \int_{l.o.s} \rho^2_{DM}(r)dr \quad \longrightarrow \quad J \propto \frac{M_{200} c^3_{200}}{D^2_{\text{Earth}}}$$



DM density profile

Decay

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



CLUSTERS DM MODELLING (I): MAIN HALO

Annihilation

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

DM density profile

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

Decay

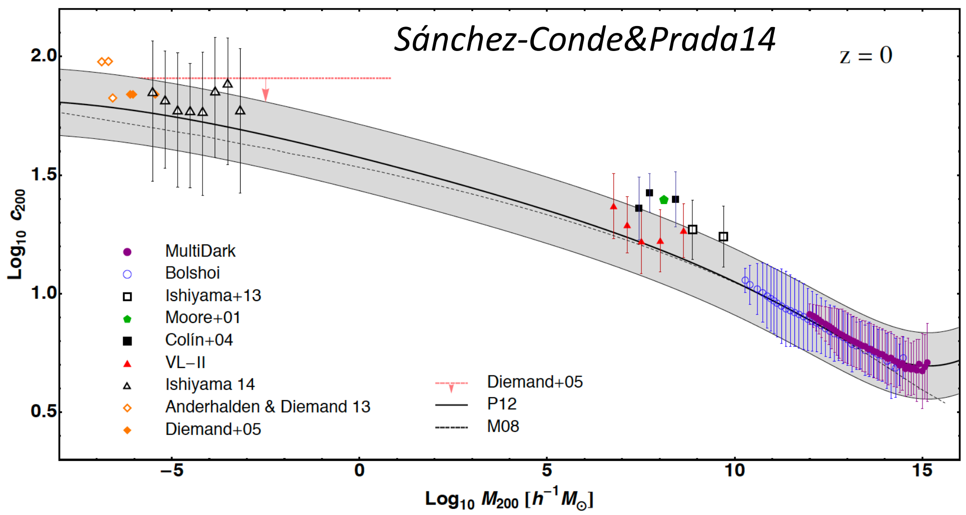
- State-of-the-art parametrization of the DM in galaxy clusters:

$$\langle\rho_{\rm tot}\rangle(r) = \boxed{\rho_{\rm sm}(r)} + \langle\rho_{\rm subs}\rangle(r) \xrightarrow{\text{Assume density profile}} \boxed{\rho(r) = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}}$$

  - "Cuspy"-like profile

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

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



CLUSTERS DM MODELLING (II): 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

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

CLUMPY

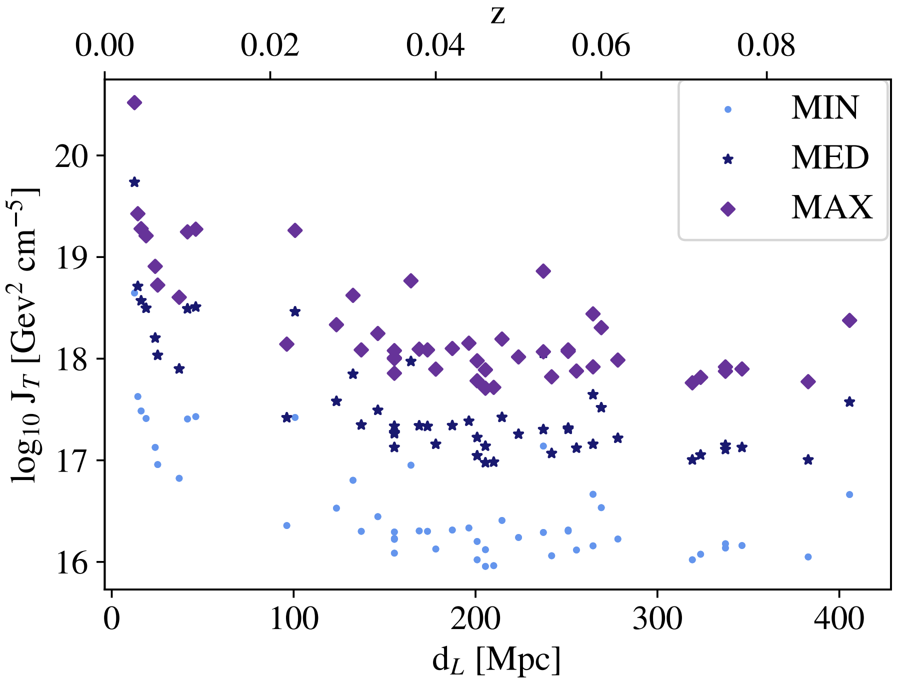
- We define benchmark models to encapsulate the uncertainty on the expected substructure population:

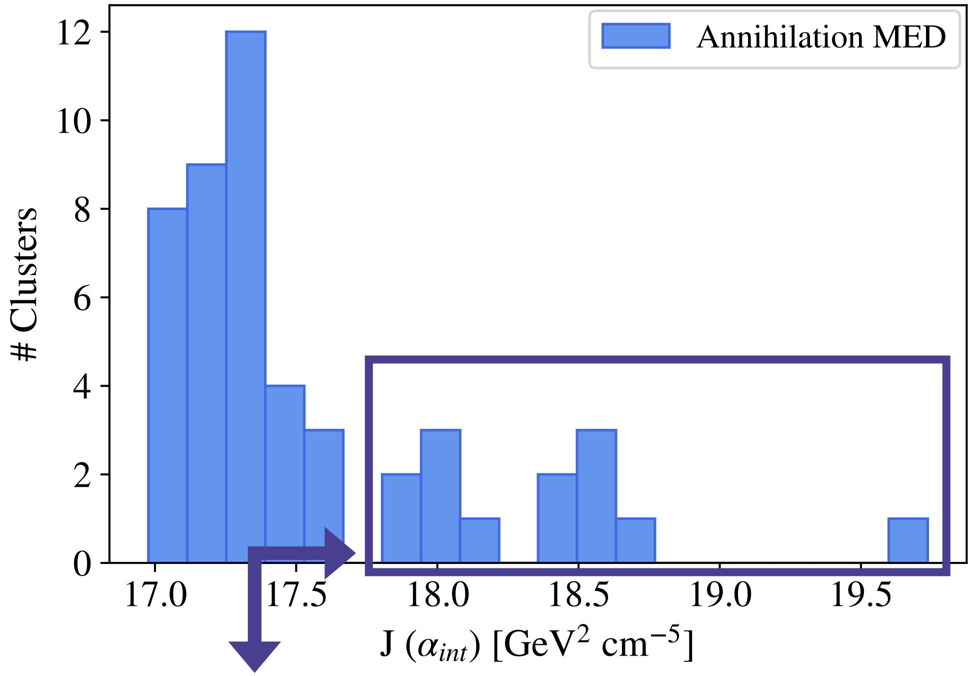
- No substructure considered → MIN
- Best guess → MED
- Educated upper bound → MAX

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

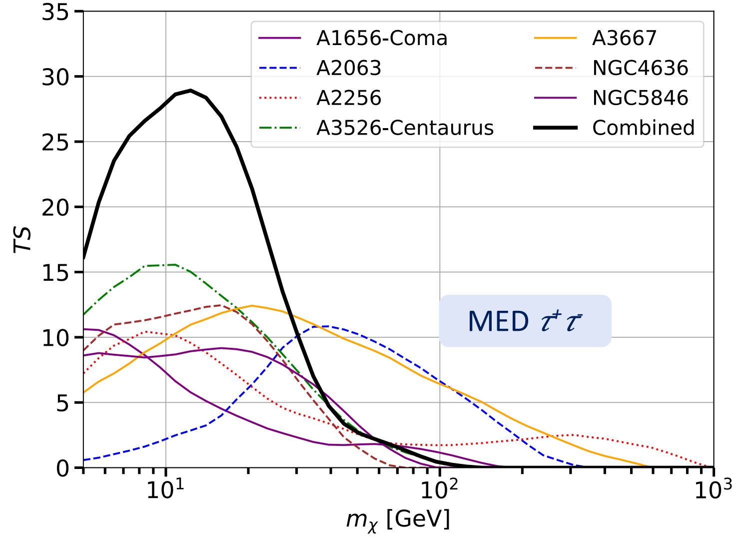
DM ANNIHILATION FLUXES OF THE SAMPLE

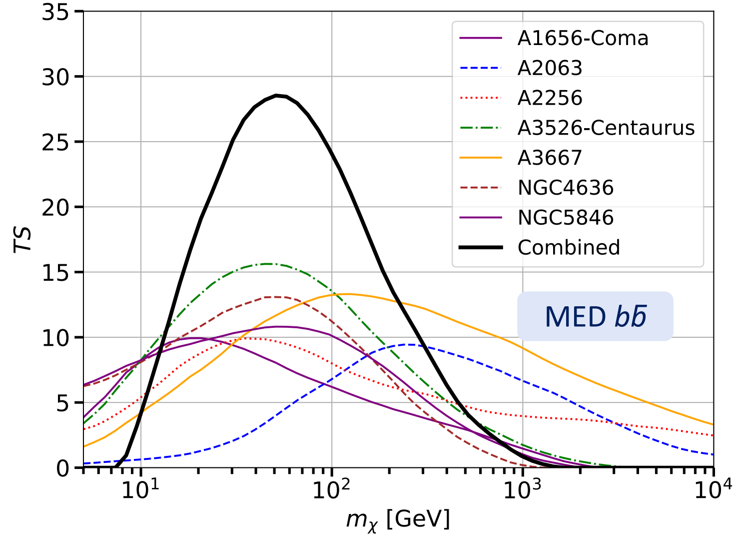


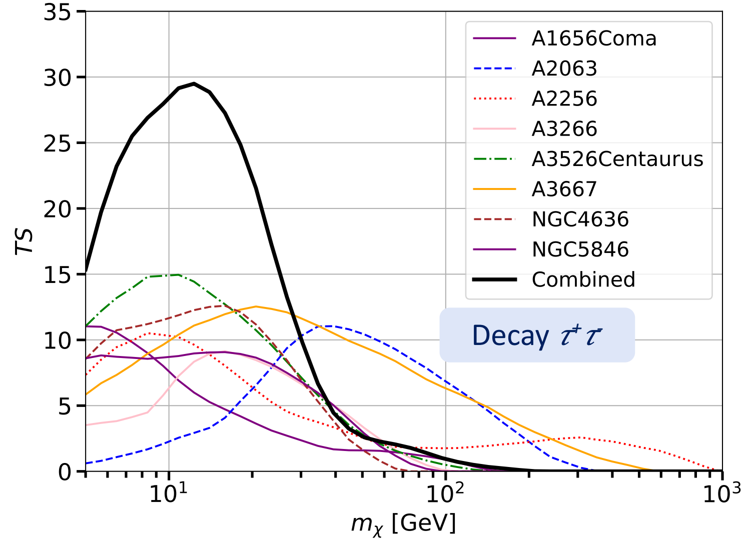


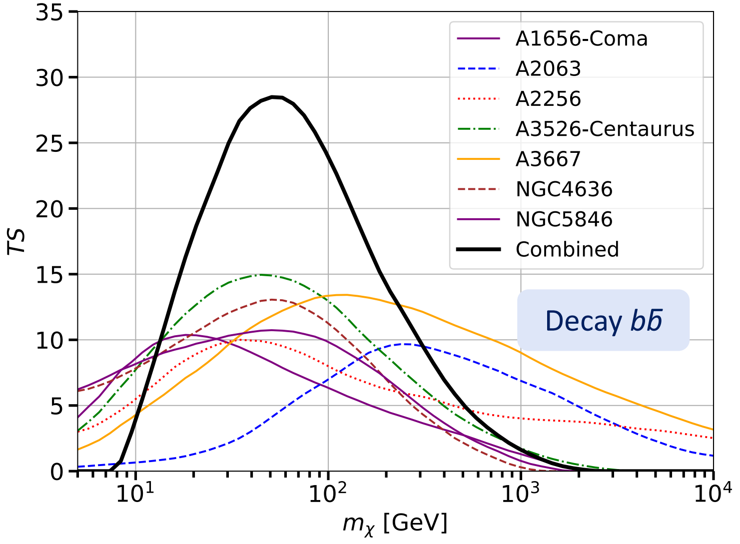
Cluster	z	M_{200} [10^{14} M$_\odot$]	R_{200} [kpc]	θ_{200} [deg]	$\log_{10} J_{MIN}$ [GeV^{2}cm^{-5}]	$\log_{10} J_{MED}$ [GeV^{2}cm^{-5}]	$\log_{10} J_{MAX}$ [GeV^{2}cm^{-5}]	$\log_{10} D$ [GeV cm^{-2}]
Virgo	0.0036	5.60	1700	6.32	18.65	19.74	20.52	20.44
NGC 4636	0.004	0.53	777	2.61	17.63	18.71	19.43	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

TS OF THE BENCHMARK MODELS









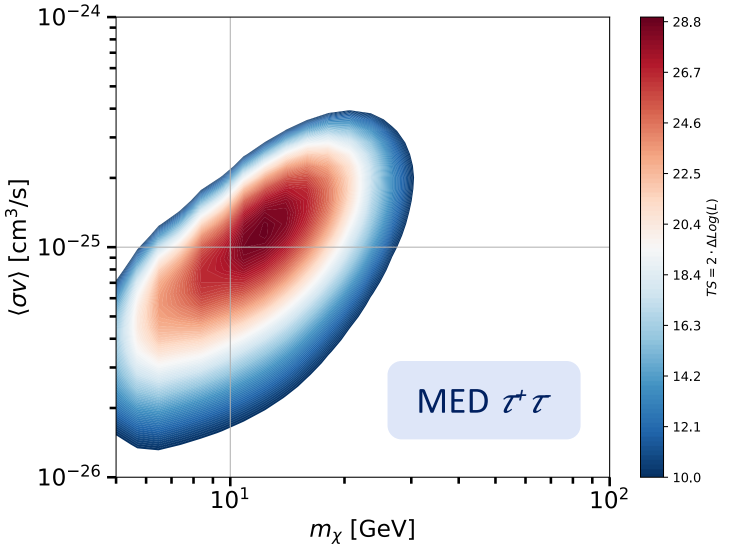
Individual *TS*

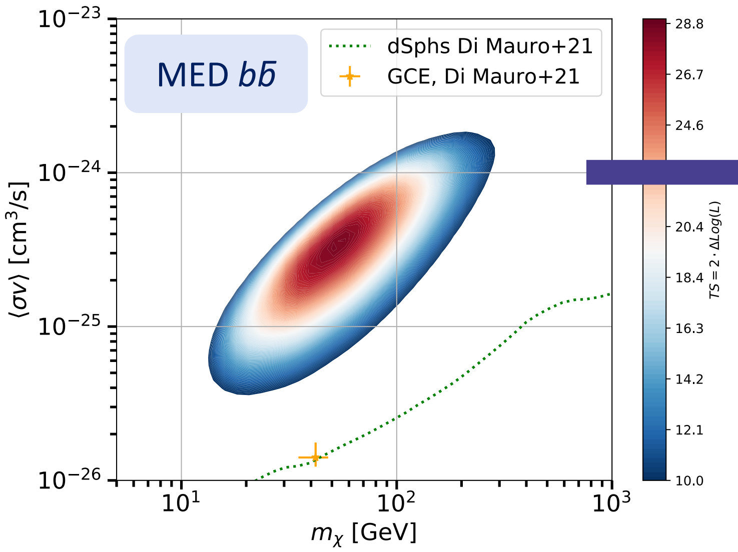
- Highest **A3526-Centaurus** – *TS* = 15
- A1656-Coma – *TS* ~10 (*Ackermann+17 [Fermi Collab.]*)

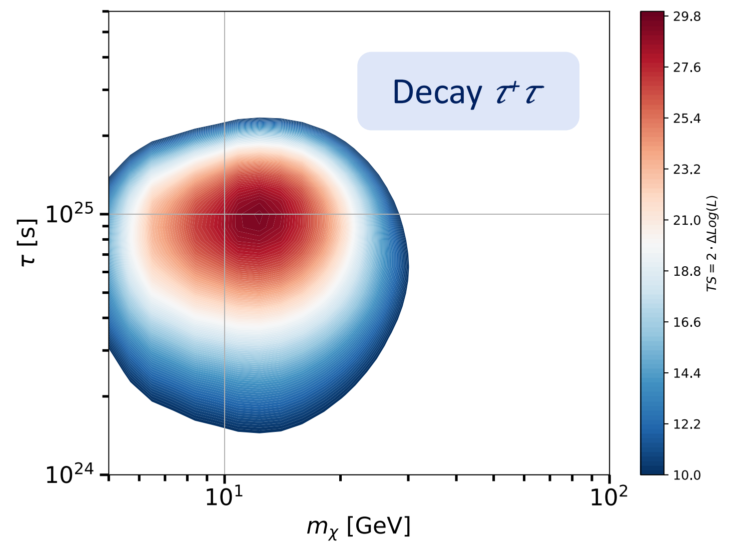
Combined *TS*

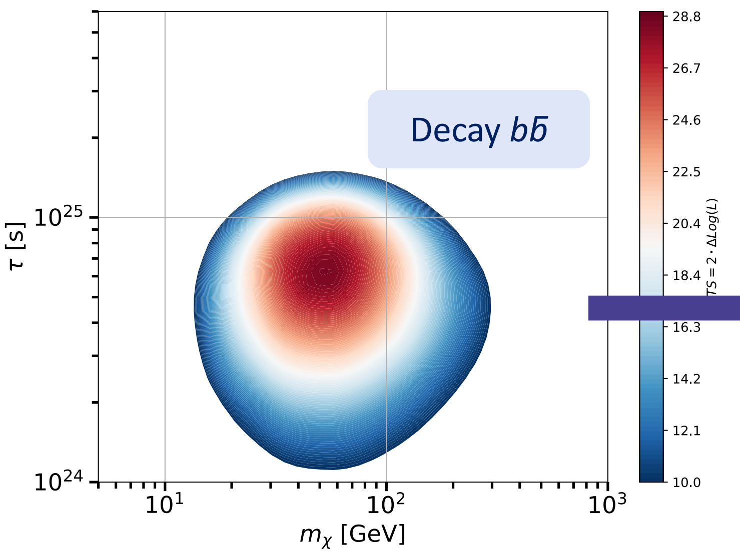
MIN	No sig.
MED	*TS* = 27
MAX	*TS* = 23
DECAY	*TS* = 28

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.]

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

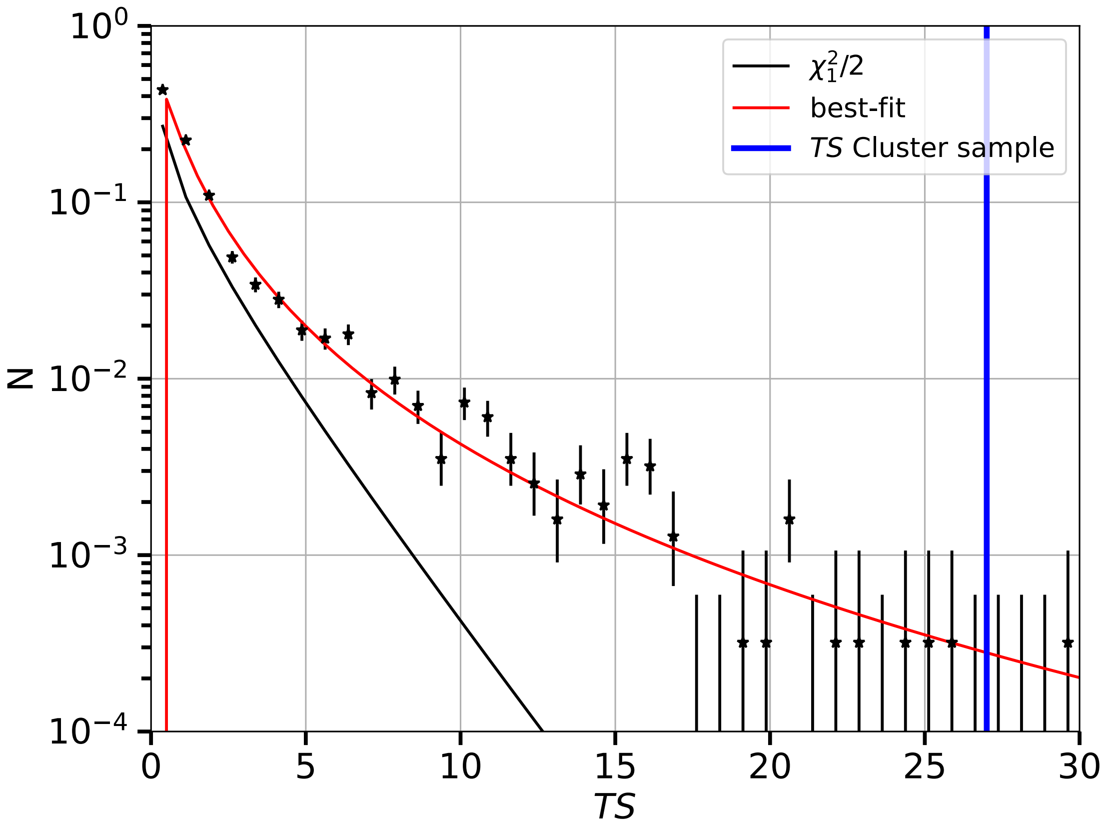
  Chernoff 54

- 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



DM CONSTRAINTS FROM COMBINED CLUSTERS ANALYSIS

- 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