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GAMMA-RAY OBSERVATIONS OF GALAXY CLUSTERS – CONTINUING A MULTI-DECADE QUEST

The extreme Universe viewed in very-high-energy gamma rays, Feb 2 2026

OUTLINE

Why observing at gamma-rays? (focus: CR-interaction/calorimetry induced **conventional** science case!)

@ GeV energies: (since 2008:) Fermi-LAT

- accumulation of circumstantial evidence accumulation vs. more ambition

@ TeV energies: 3rd generation IACTs and HAWC/LHAASO

- recovering faint extended emission with IACTs
- recovering faint extended emission with HAWC/LHAASO

KSP for CTAO-N: Perseus

Why observing at Gamma-rays?

Think nonthermal, think CR!

Various scenarios appear to be able to energize the CRs
-> in merger or accretion shocks, turbulence, SN-driven winds, injection from radio- or active galaxies within a cluster

Principal processes to be considered:

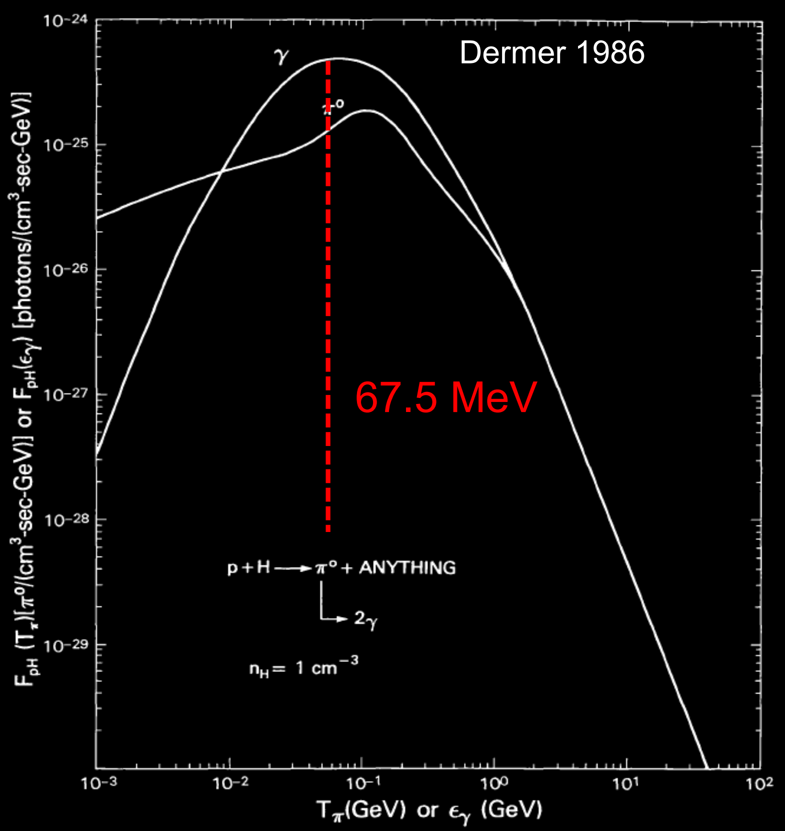
- pp-interactions -> π^0 decay -> HE γ's
- TeV electrons -> IC photon upscattering on CMB -> HE γ's
- UHECR p-acceleration -> CMB interaction /injection into ICM
  - -> photomeson production: $p\gamma \to \pi^0, \pi$'s, ...
  - -> Bethe-Heitler pair production: $p\gamma \to p, e^+, e^-$
- secondary pair production through $\gamma\gamma$-interactions of VHE gammas from AGN / IC CMB γ (UV/OPT: GeV, IR: TeV)

sole player in HEγ : Fermi LAT

Generalities:
Leptonic vs. hadronic dominated emission

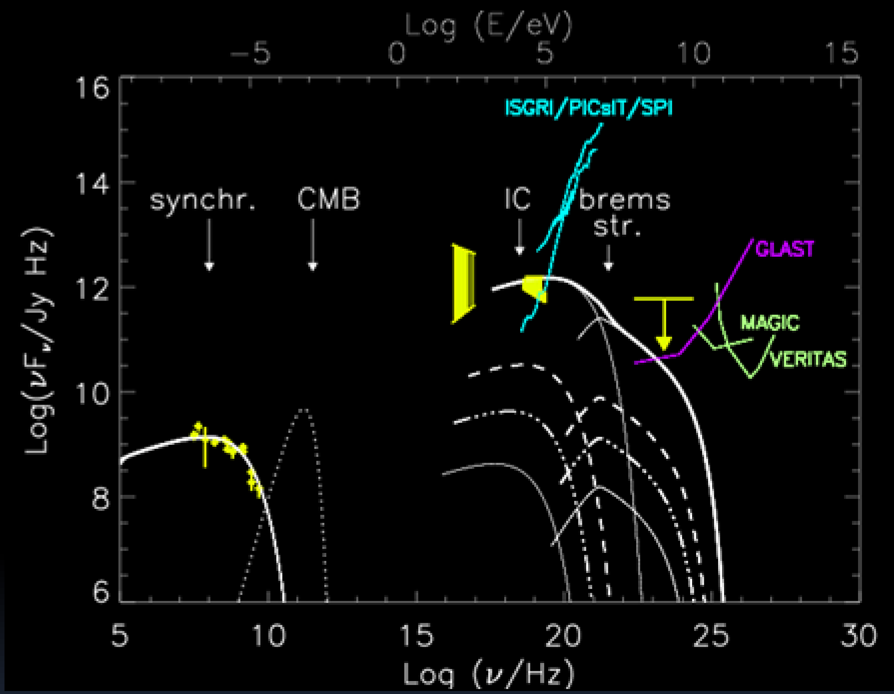
1) TeV-observations: shape of the high-energy IC component, cutoff in KN-regime (ambiguous, though)

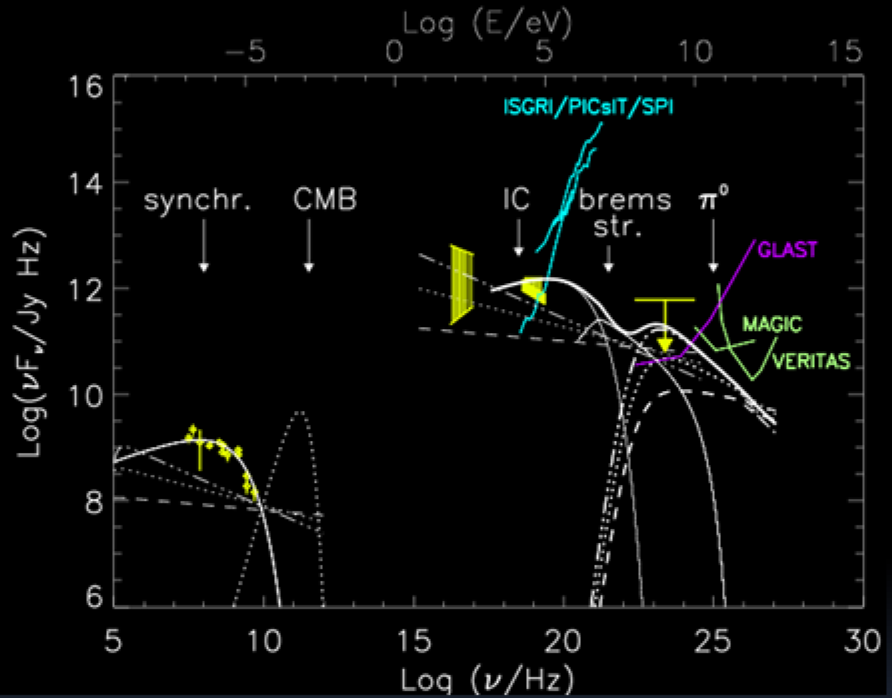
2) p + ISM $\rightarrow$ X + $\pi^0 \rightarrow$ **2** γ near production threshold (major constitutent of diffuse emission, some spectral resemblence with Bremsstrahlung)



Galaxy Cluster – γ by MWL priors

exemplary for the pre-Fermi era:
Coma SED modeling





Reimer ea (2004)

B= 0.1 μG

B= 0.7 μG

B= 1.9 μG

B= 6 μG

α = 2.1

α = 2.3

α = 2.5

Gamma-ray emission - CR calorimetry

Criteria based on non-DM induced astrophysical processes
[e.g. Jaffe ‘77, Dennison ‘80, Völk, Aharonian & Breitschwerdt ‘96, Colafrancesco & Blasi ‘99, Brunetti ea ’01+, Reimer ea ‘03, Berrington & Dermer ’03, Gabici & Blasi et al. ’03+, Pfrommer ’08+,…]

Preferred dark matter candidates similar; though expected flux **generally predicted to be weaker** than CR-induced signal

DM-annihilation related γ-ray flux unlikely to exceed non-DM-related one.

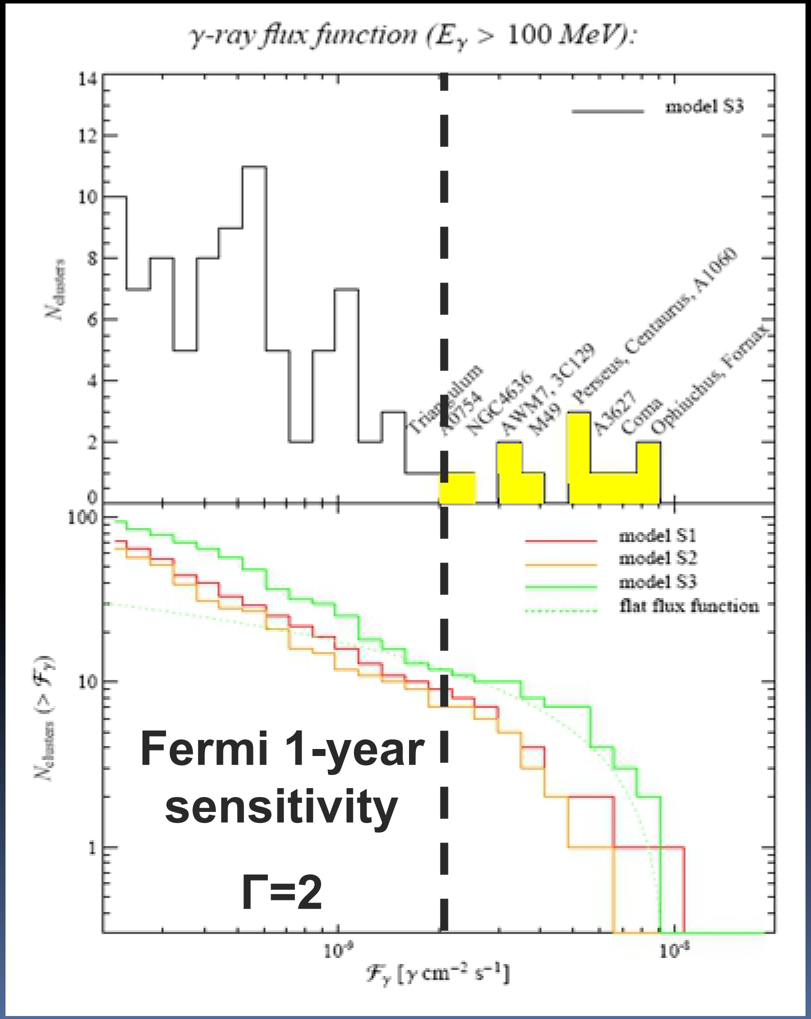
Several clusters were anticipated at LAT 1-year sensitivity:

Ophiuchus, Fornax, Coma, Perseus, Norma, Centaurus, …

(with gamma-ray detectability scaling largely governed ~ M/d^2)

Likewise, anticipation of AGN-related gamma-ray prominence in clusters

- ✓ fulfilled: NGC1275: Abdo ea (Fermi-LAT) 2009, M87: Abdo ea (Fermi-LAT) 2009…



Pfrommer 2008

Status Quo HEγ : 2026

Judit Perez Romero (Fermi LAT team) @TeVPA 2025:

- 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

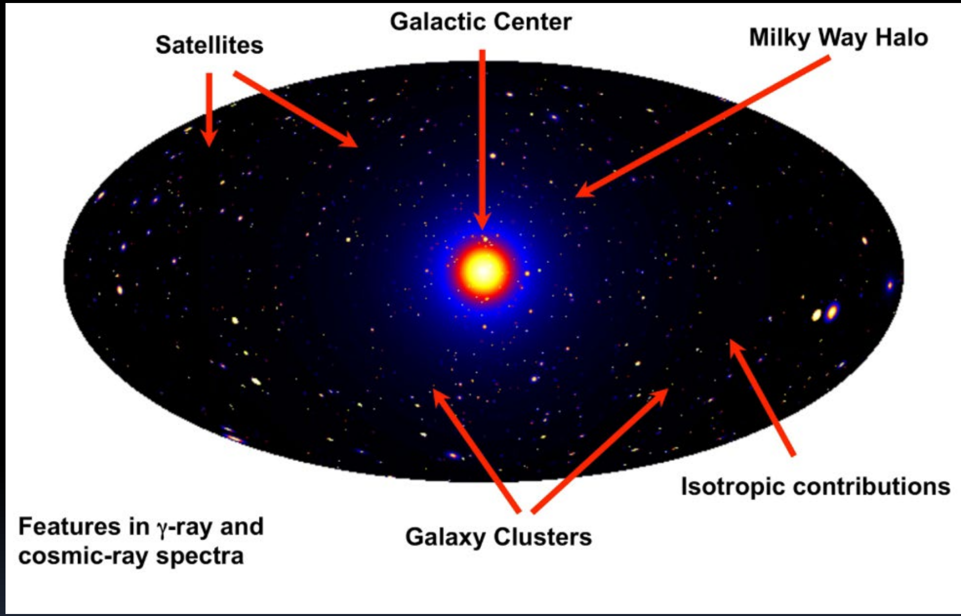
grey shaded: VHE/UHE

- ☞ ...could cut short talk at this point!
- ☞ …but some fineprint might be desirable, scrutinize on few cases from atop
- ☞ …we may want to digest some lessons for enforcing/revisiting our ©2013,2018,2024 CTA KSP Galaxy Cluster (Perseus)

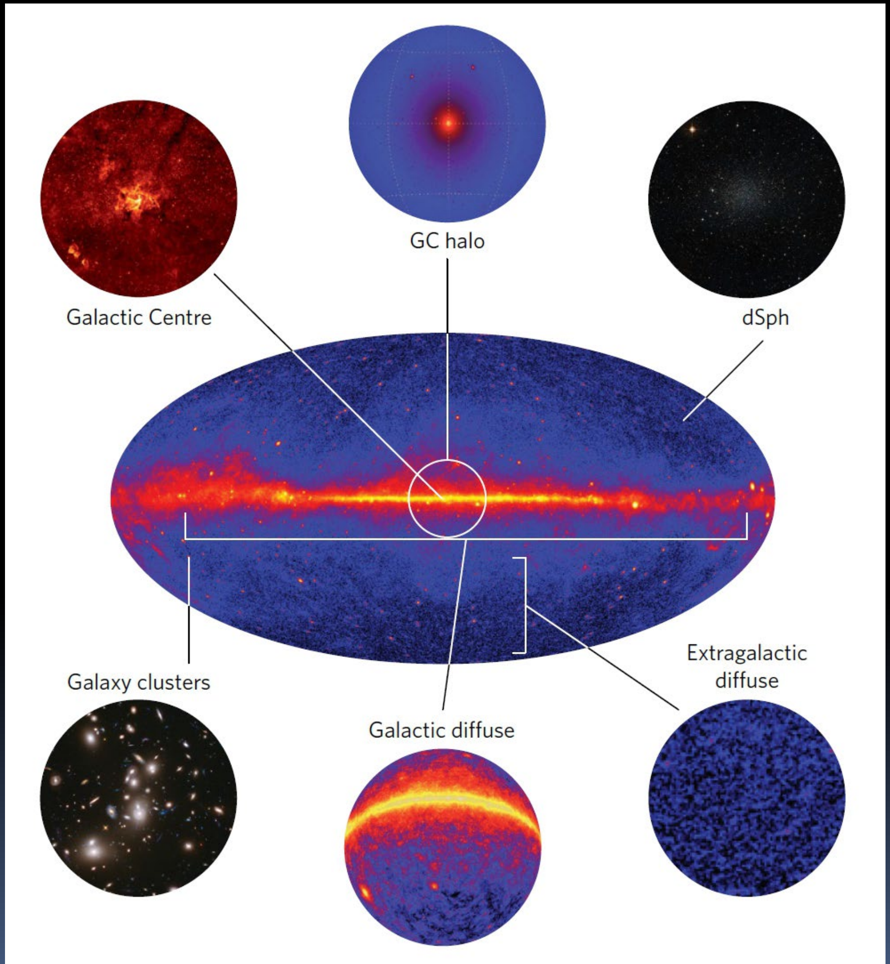
Fermi-LAT team work

☞ 1st Fermi-era word on galaxy clusters

2010 Constraints on dark matter annihilation in clusters of galaxies with the Fermi Large Area Telescope



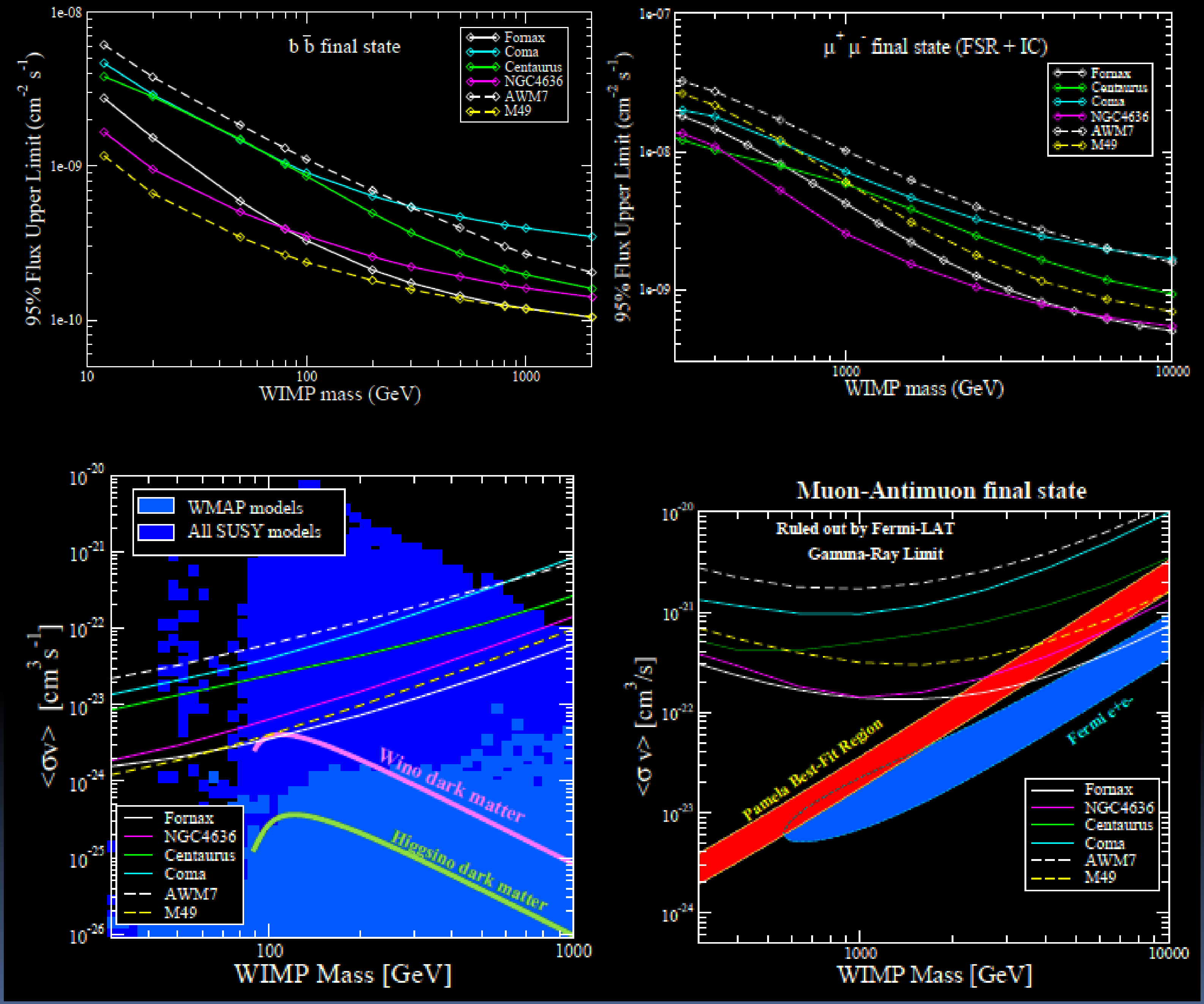
Pieri et al. MNRAS 2011
Large-scale Structure Formation Simulations (Via Lactea/Aquarius)



Conrad & Reimer Nature Physics 2017

u.l.’s

<σv>



b b̄ final state
Fornax
Coma
Centaurus
NGC4636
AWM7
M49
95% Flux Upper Limit (cm^-2 s^-1)
WIMP mass (GeV)
μ+ μ- final state (FSR + IC)
WIMP mass (GeV)
WMAP models
All SUSY models
Wino dark matter
Higgsino dark matter
<σv> [cm^3 s^-1]
WIMP Mass [GeV]
Muon-Antimuon final state
Ruled out by Fermi-LAT
Gamma-Ray Limit
Pamela Best-Fit Region
Fermi e+e-
<σ v> [cm^3/s]
WIMP Mass [GeV]

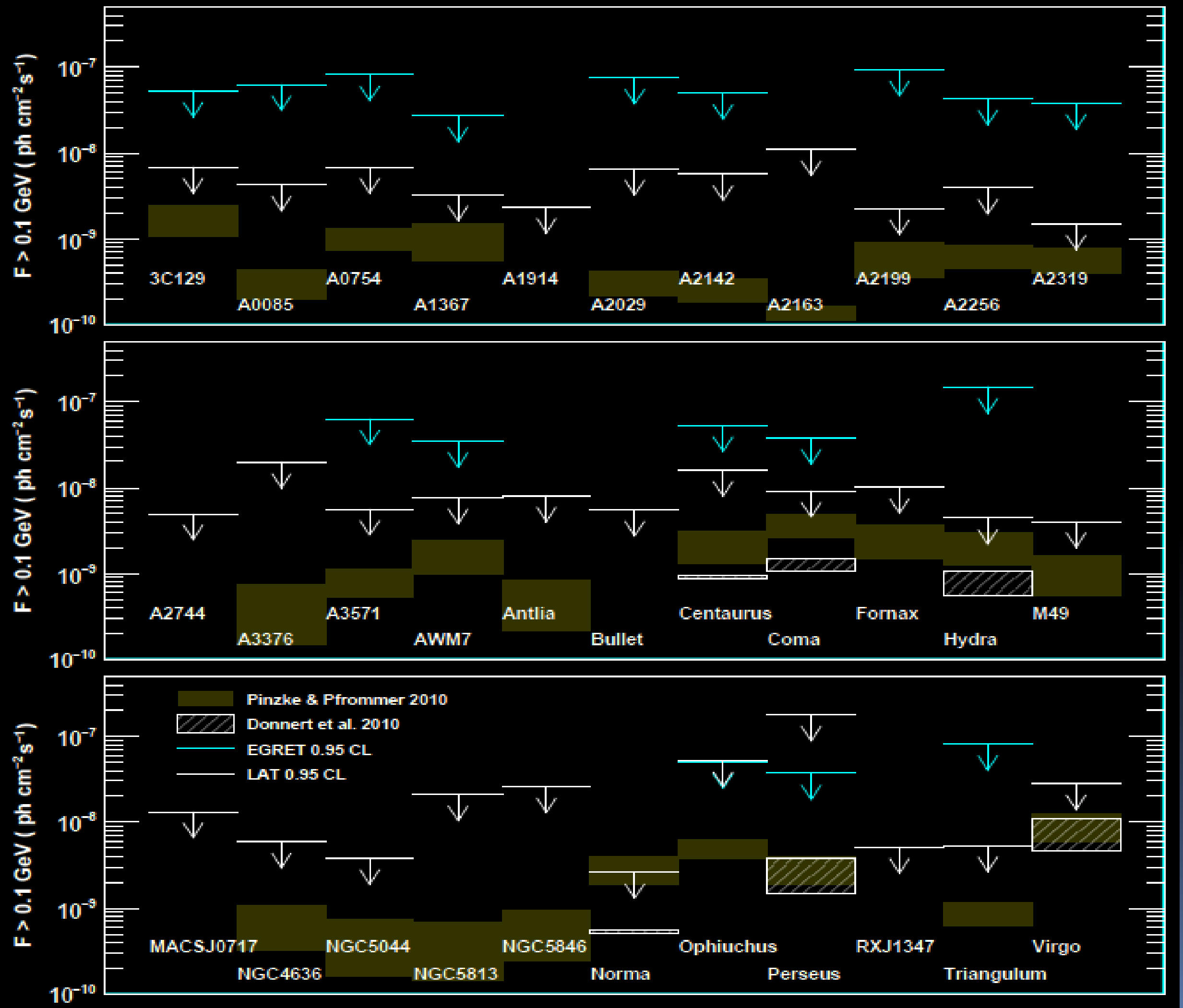
Fermi-LAT team work

2010 GeV Gamma-ray Flux Upper Limits from Clusters of Galaxies

1st Fermi-era word on CR-related science case galaxy clusters

- HIFLUGCS (X-ray brightest most nearby) refined to M / d^2
- NT priors (radio halo or relic)
- Exceptional individual not captured by the above defined criteria

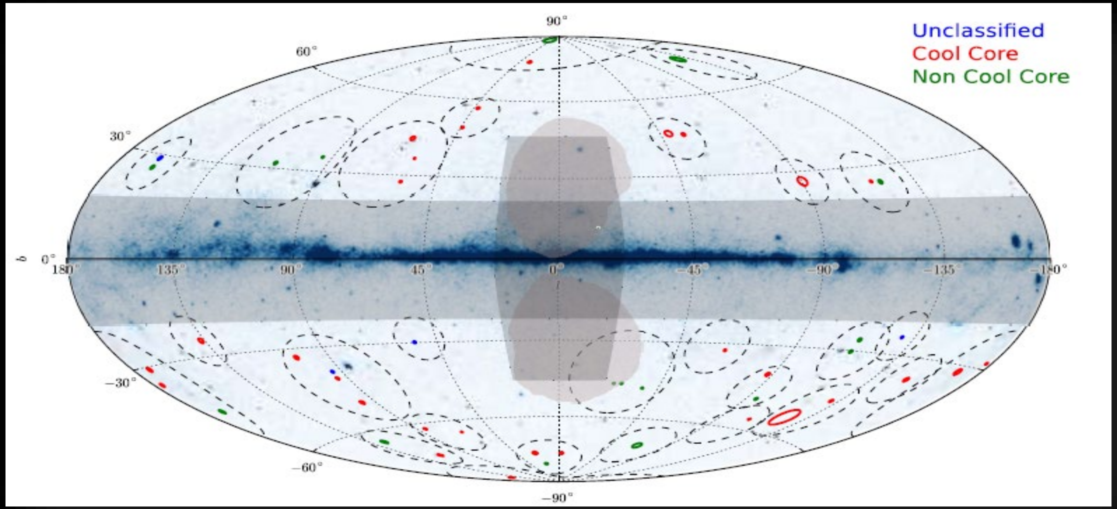
E > 200 MeV

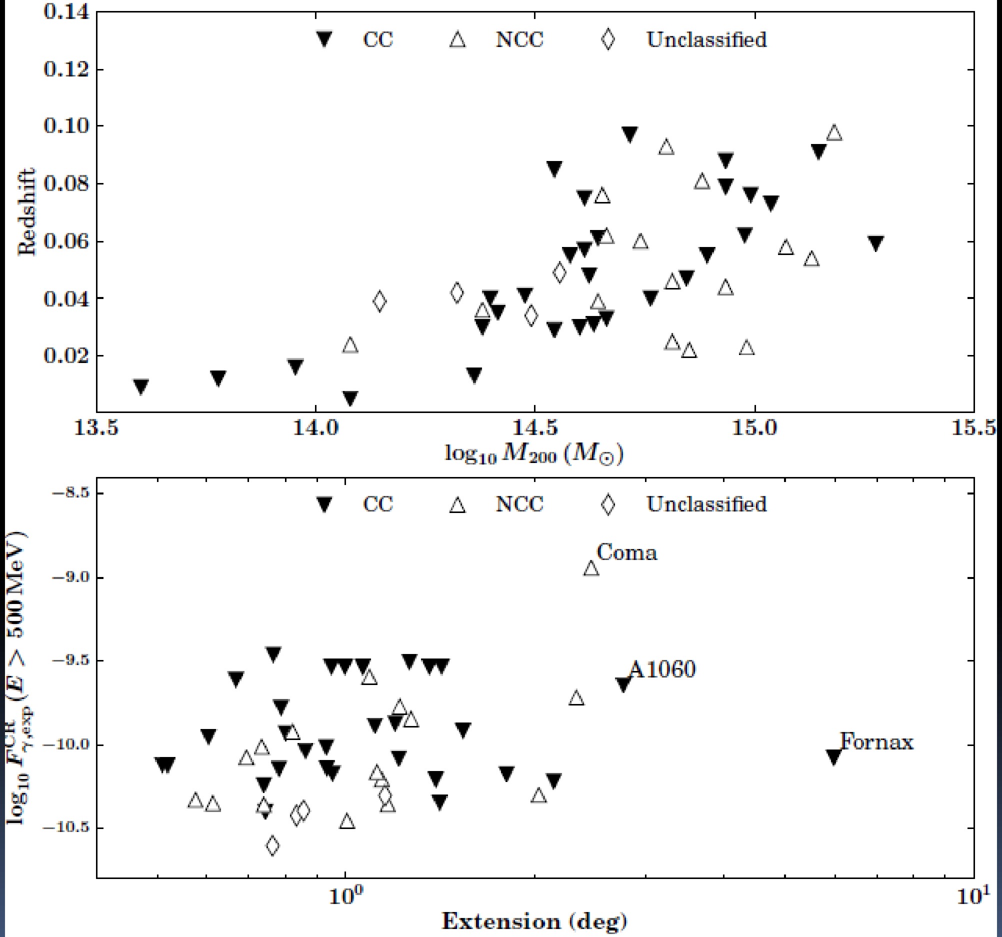


Fermi-LAT team work

2014 Search for cosmic-ray induced gamma-ray emission in galaxy clusters

☞ more exposure, refined selection criteria, improved response functions/diffuse modell



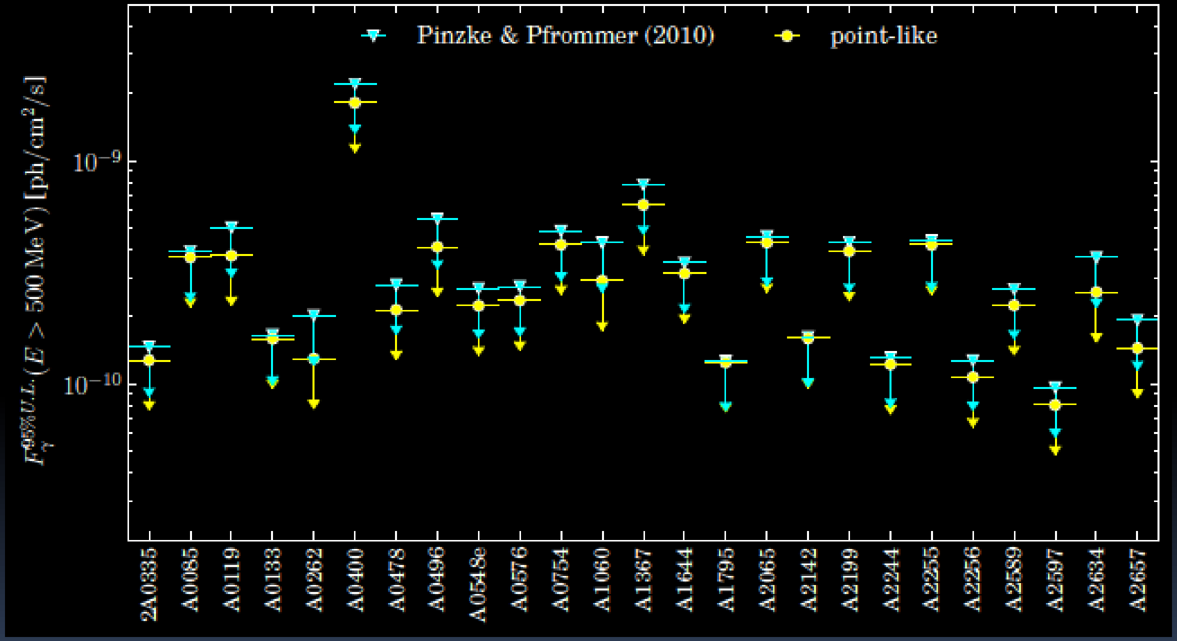


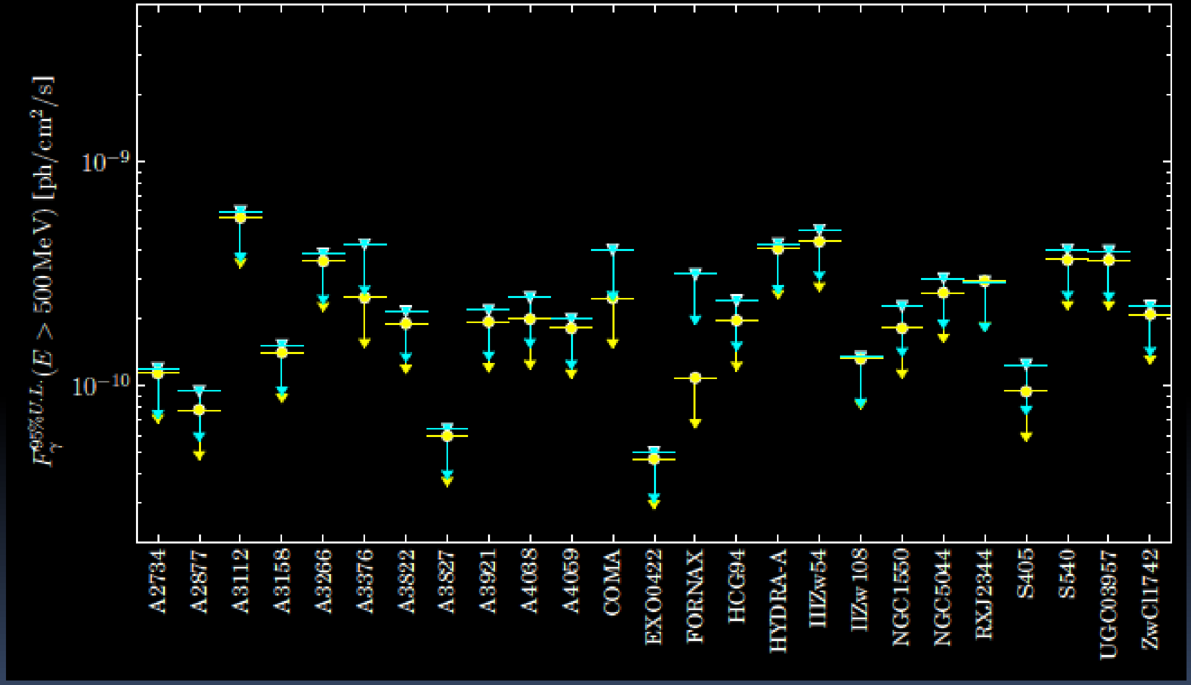
- 4 years of Fermi data
- individual cluster
- sample investigation
- CC vs. NCC split in sample

Fermi-LAT team work

2014 Search for cosmic-ray induced gamma-ray emission in galaxy clusters

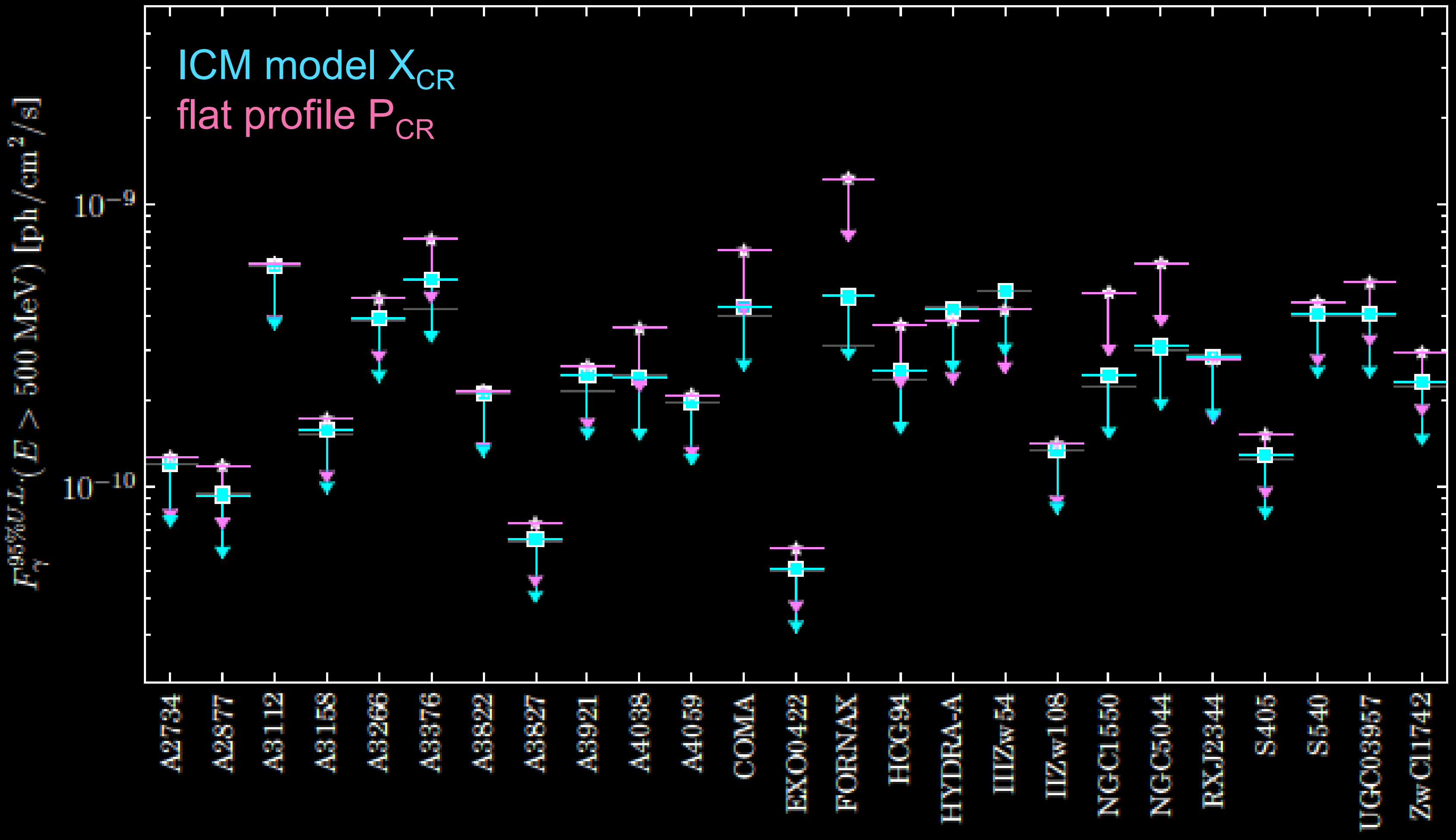
1st) Individual gamma-ray flux limits (50 cluster)





2nd) For constant spatial profile X_{CR} and P_{CR} (50 cluster)

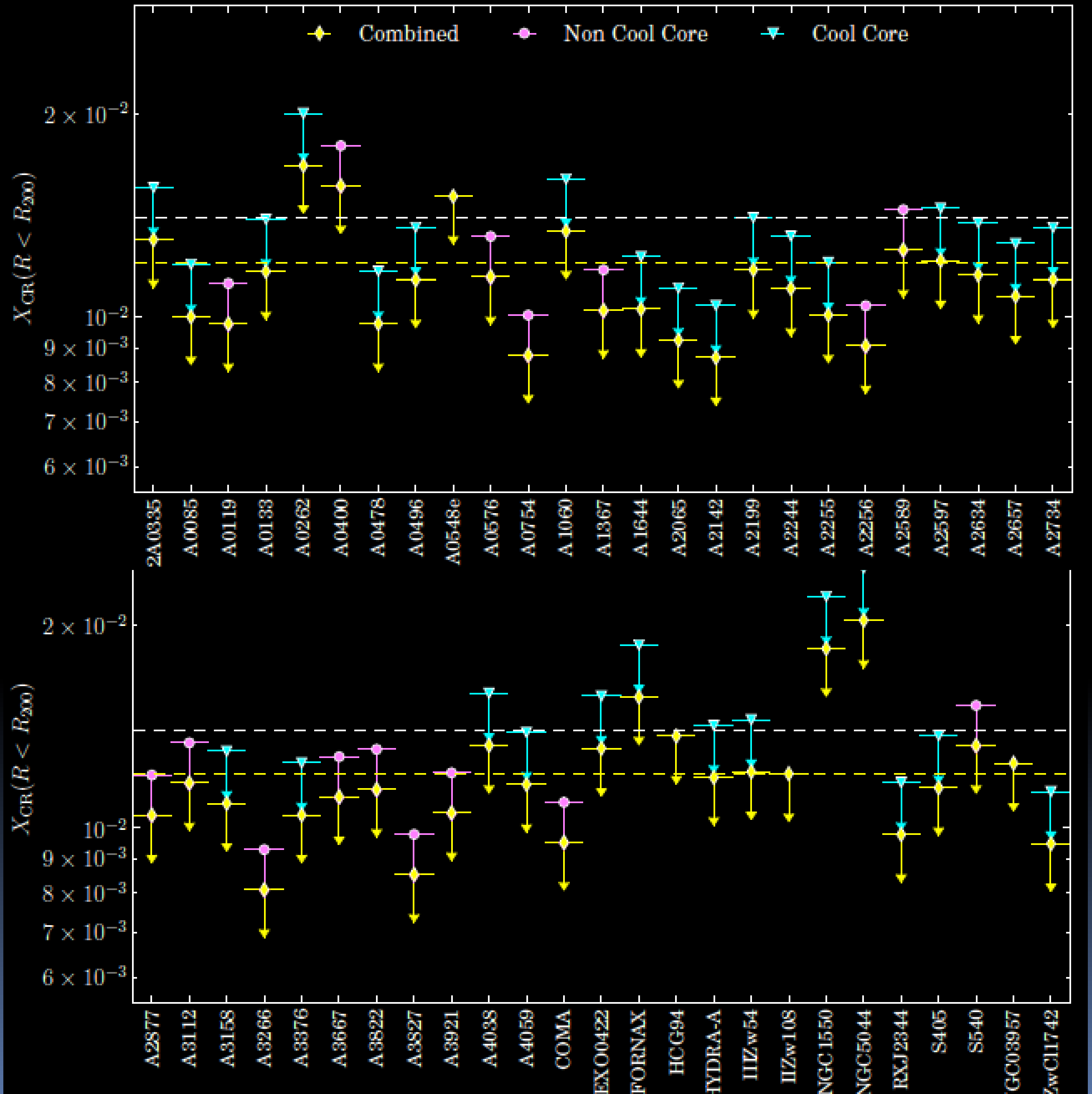
$$\langle X_{\rm CR}\rangle = \langle P_{\rm CR}\rangle_V / \langle P_{\rm th}\rangle_V$$



3rd) Individual X_{CR} (universality assumption, 50 cluster)

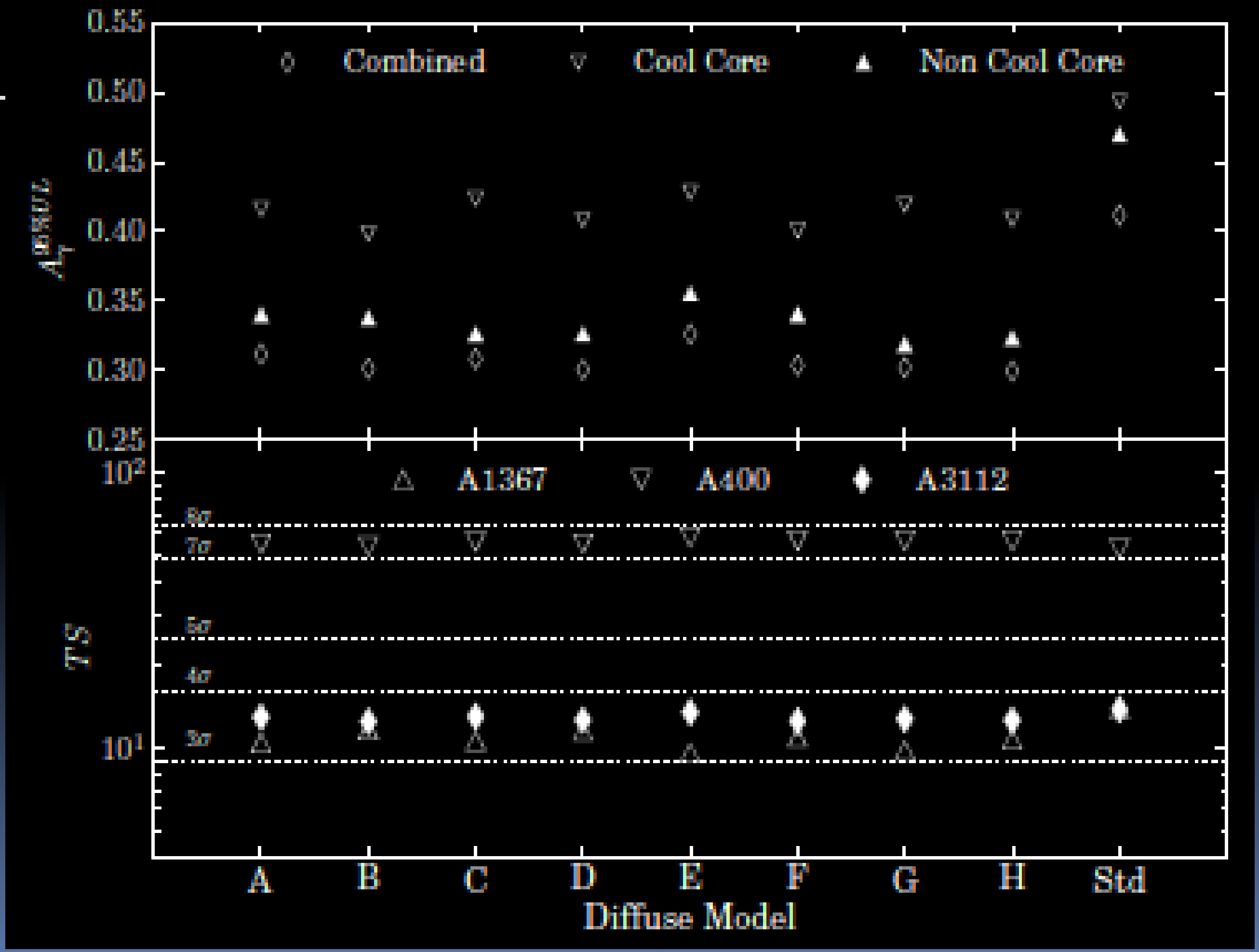
AVERAGE NCC, CC

TOTAL AVERAGE



4^{th}) Systematics, e.g. different galactic diffuse models

Label	CR Source Distribution	Halo Size (kpc)	Spin Temperature (K)
A	Lorimer	10	10^5
B	Lorimer	10	150
C	Lorimer	4	10^5
D	Lorimer	4	150
E	SNR	10	10^5
F	SNR	10	150
G	SNR		
H	SNR		



Conclusions

$$F^{\rm CR}_{\gamma,\exp}(>E) = A_\gamma\, \lambda_{\pi^0\to\gamma}(>E) \int_V dV\, \kappa_{\pi^0\to\gamma}(R),$$

where the integral extends over the cluster volume V, $\lambda_{\pi^0\to\gamma}(>E)$ is the spectral γ-ray distribution, and $\kappa_{\pi^0\to\gamma}(R)$ is the spatial distribution

- no significant detection
- three hints of excess emission
- bounds on the common scale-factor Aγ
- use jointly derived Aγ bound to calculate volume-averaged CR-to thermal pressure $<X_{CR}>$
- compute median upper limits within R_{200}

☞ **most stringent one being $<X_{CR}> < 0.012$ for the combined sample**

☞ **for the CC and NCC subsamples $<X_{CR}> <0.013$ and $<X_{CR}> <0.014$**

Fermi-LAT team work

Of course, the Fermi-LAT catalogs: … → 4FGL-DR3 (2022) … 4FGL-DR4 (now)

- Galaxy Clusters catalogs not queued via the LAT team source association pipeline.
- Nevertheless, interesting sources are found in the catalogs!

…. in Coma-cluster field:

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

* analysis flag 001:
Source with TS > 35 which went to TS < 25 when changing the diffuse model. Note that sources with TS < 35 are not flagged with this bit because normal statistical fluctuations can push them to TS < 25.

Yang, Hare & Kargaltsev 2024
A Multiwavelength Machine-learning Approach to Classifying X-Ray Sources in the Fields of Unidentified 4FGL-DR4 Sources

Classifications and Multiwavelength Properties of Potential X-Ray Counterparts for UnIDed 4FGL Sources

4FGL Name[a]	2CXO Name[b]	Class[c]	Class Prob[d]	CT	F_γ (10^{-13} cgs)	F_X (10^{-13} cgs)	$HR^{e}_{h(ms)}$	P_{intra}	Gmag (mag)	Jmag (mag)	W1mag (mag)	F_R (mJy)	f_X/f_O
J1256.9+2736	J125705.5+273252	AGN	97 ± 5	13	18	0.2	0.1	0.89	⋯	⋯	17.8	⋯	⋯
J1256.9+2736	J125724.3+273606	AGN	98 ± 4	16	18	0.1	0.0	0.83	⋯	⋯	17.9	⋯	⋯
J1256.9+2736	J125724.4+272952	AGN (AGN [8])	⋯	⋯	18	0.2	−0.7	0.92	20.7	12.8	10.6	133	0.3
J1256.9+2736	J125730.0+272612	AGN	92 ± 8	6.7	18	0.4	−0.4	0.88	20.8	⋯	16.5	⋯	0.5
J1256.9+2736	J125734.0+272730	AGN	99 ± 1	48	18	0.3	0.2	0.73	⋯	⋯	16.0	⋯	⋯
J1256.9+2736	J125740.2+273118	AGN (AGN [5,9])	99 ± 1	50	18	0.7	−0.1	0.96	19.5	⋯	15.8	⋯	0.3
J1256.9+2736	J125745.0+273210	AGN (AGN [5,9])	98 ± 2	22	18	0.2	−0.1	0.31	19.3	⋯	16.0	⋯	0.1
J1256.9+2736	J125746.6+273137	AGN	99 ± 2	32	18	0.2	0.2	0.94	⋯	⋯	16.4	⋯	⋯
J1256.9+2736	J125751.0+273231	AGN (AGN [5,9])	96 ± 3	14	18	0.3	−0.1	0.01	19.7	⋯	16.9	⋯	0.1

Fermi-LAT team work

Judit Pérez-Romero, M. Di Mauro, M. A. Sánchez-Conde, G. Zaharijas, R. Adam   Proc. 39th ICRC, 2025

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

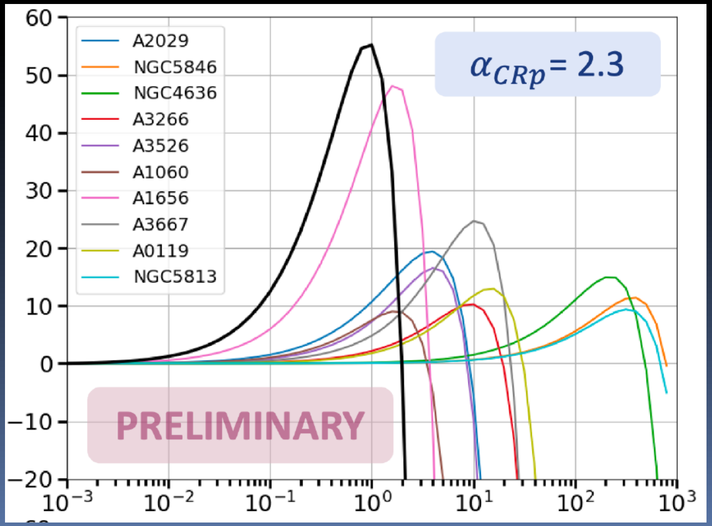
CRp distribution is modeled according to a radial profile and a canonical power-law:

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

$$X_{500} = 1\%, \alpha_{\mathrm{CR_p}} = 2.0, 2.3, 2.6, 2.9; \quad \eta_{\mathrm{CR_p}} = 1.0.$$

$$X_{500} = 1\%, \ \alpha_{\mathrm{CR_p}} = 2.3, \ \eta_{\mathrm{CR_p}} = 0.75.$$

top 10 brightest clusters according to benchmark models (descending order):
A1656 (Coma), A3526 (Centaurus), A3571, A2199, 2A0335, A1367, A0085, A0496, A2029, A1795



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Coma-cluster cont.

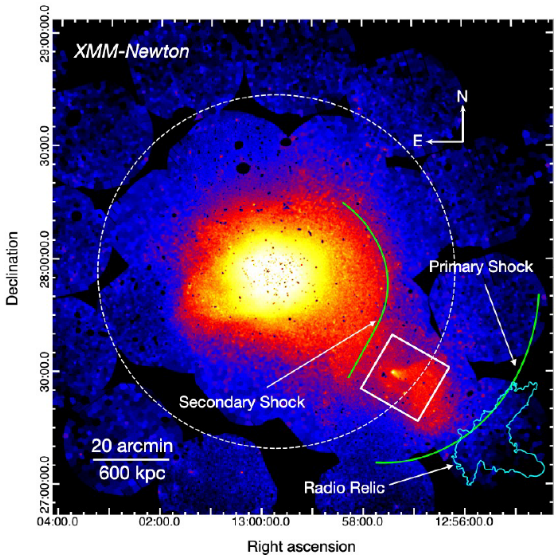
z	D_L [Mpc]	(l, b) [deg]	M_{500} [M_{sun}]	R_{500} [kpc]	α_{500} [deg]	α_{200} [deg]
0.0231	100.7	(57.23, 87.99)	4.28e14	1138	0.65	0.99

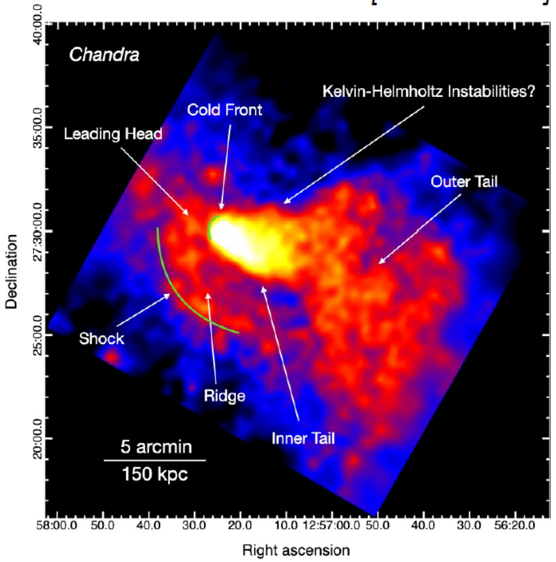
[MCXC Catalogue]

- 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]





Fermi-LAT team work

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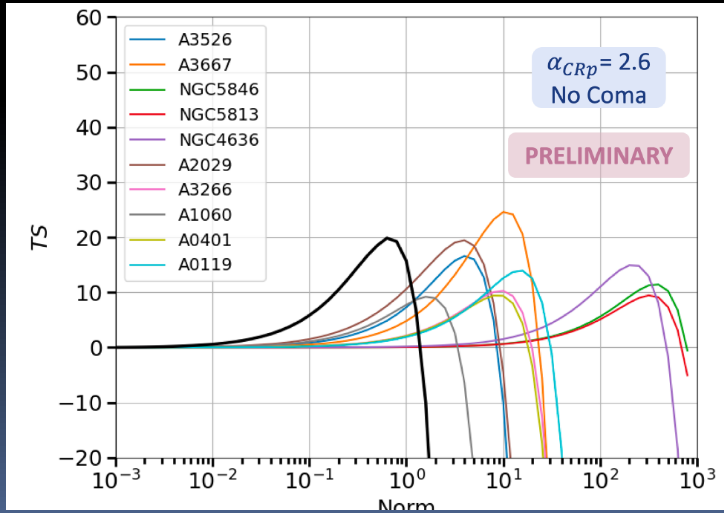
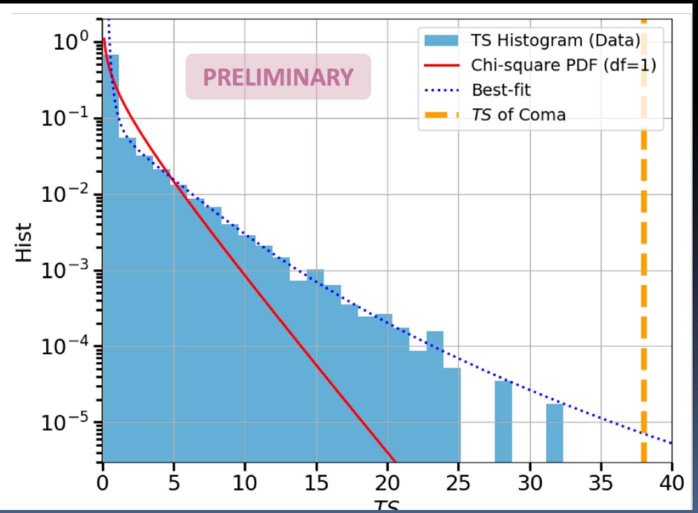
Coma-cluster cont.

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**

Preference for extended + PS combined emission





Summary GeV

- presently studied: 16 years of Fermi-LAT data in the direction of 49 galaxy clusters searching for CR-induced γ-ray emission
- results of excess diffuse γ-ray emission consistent for Coma cluster field

Still at mild significance, mind systematics from LAT analysis model, assumptions for theoretical baseline model, existence of cluster member galaxies (resolved/unresolved)

- Baseline model: $TS_{Combined} = 38$ for $R_{X500} = 1\%$ for joint sample analysis
- … highest $TS_{Combined} = 20$ (for $\alpha = 2.6$, most optimistic scenario) once Coma removed from sample

Galaxy Clusters as *source class* at GeV energies not yet convincingly established

VHE low GeV to ~100 TeV – Imaging atmospheric Cherenkov telescopes

UHE: TeV-scale EAS arrays with γ-hadron separation capability

Status Quo VHEγ : 2026 (actually ~2018)

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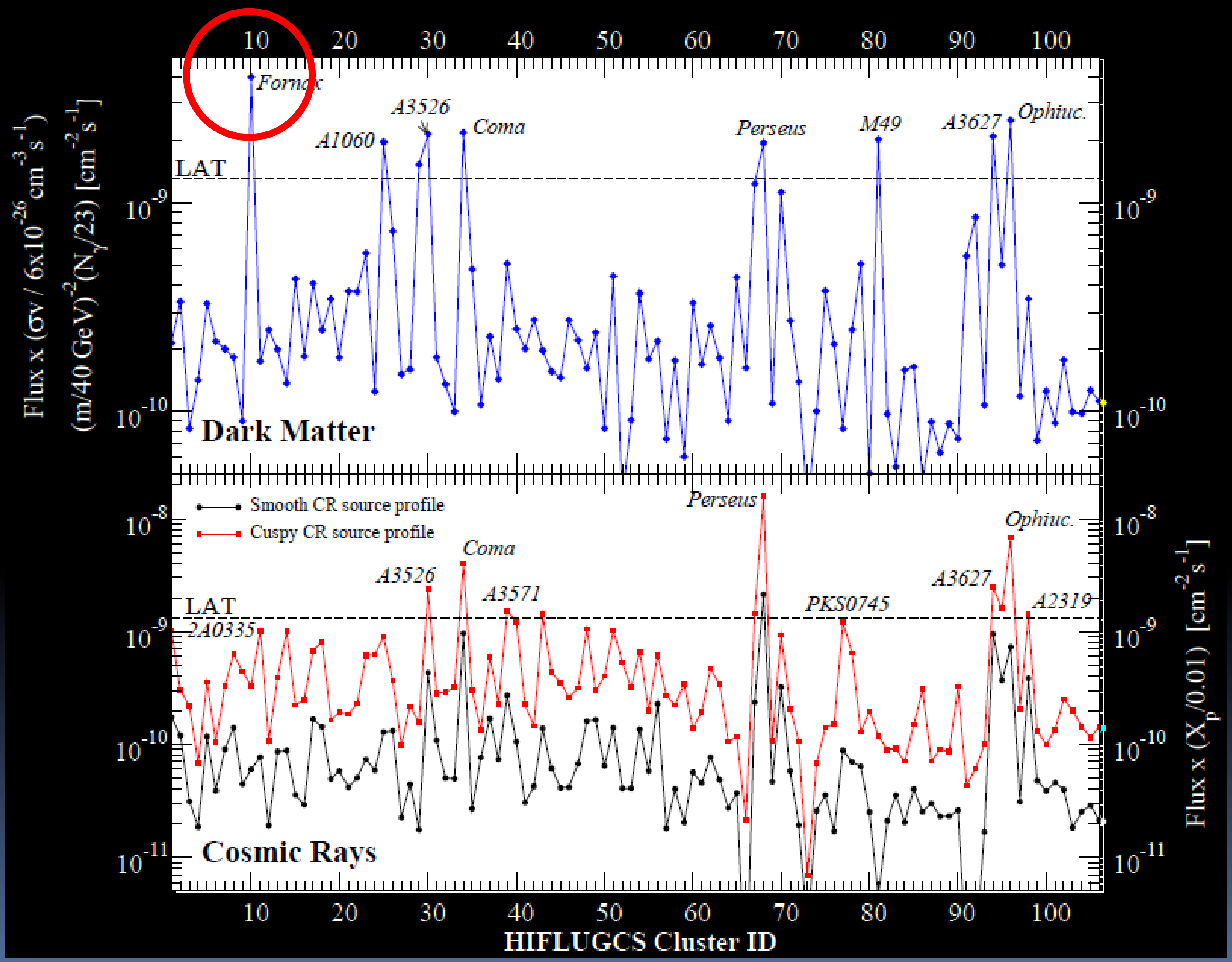
☞ recap status-quo before we…

…. may want to digest some lessons for enforcing/revisiting our ©2013,2018,2024 CTA KSP Galaxy Cluster (Perseus)

VHE observations of galaxy clusters

Fornax (Abramowski ea [H.E.S.S.] 2012)



Jeltema, Kehaiyas & Profumo 2009

VHE observations of galaxy clusters

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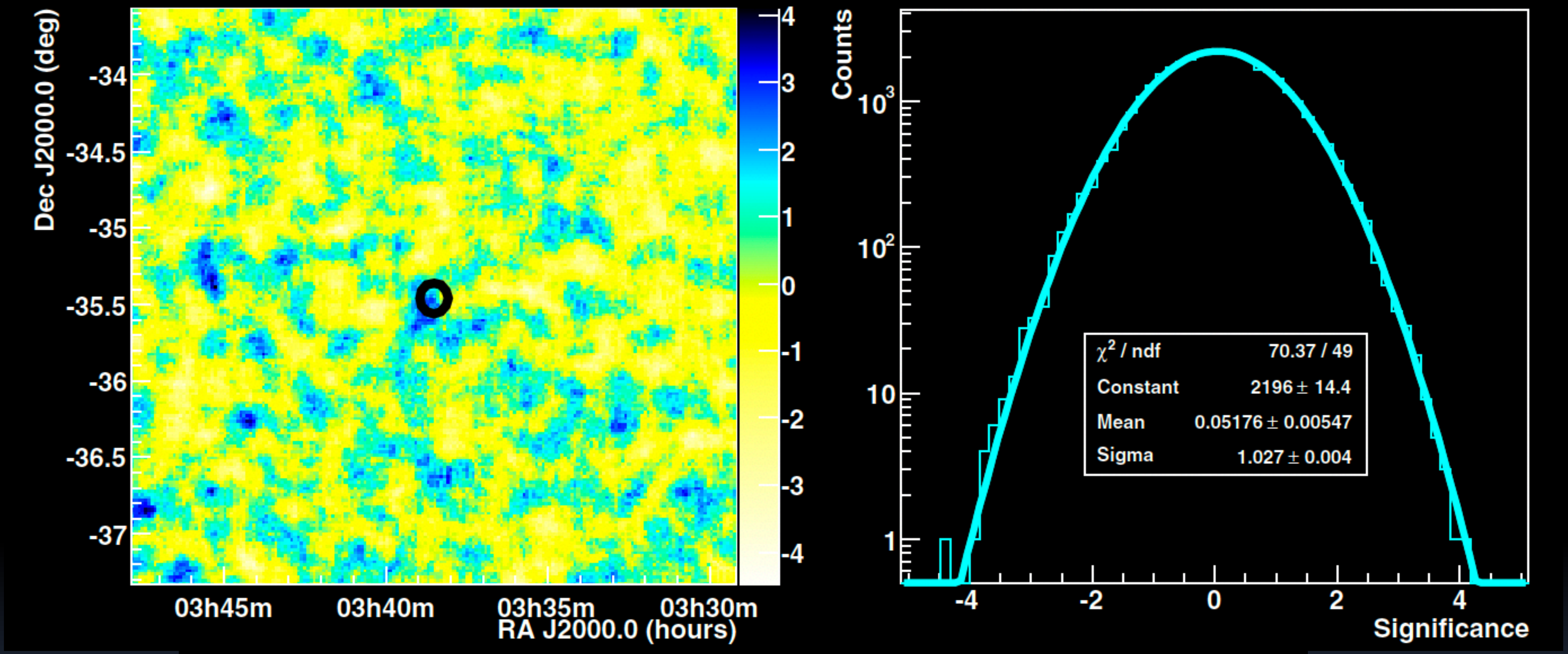
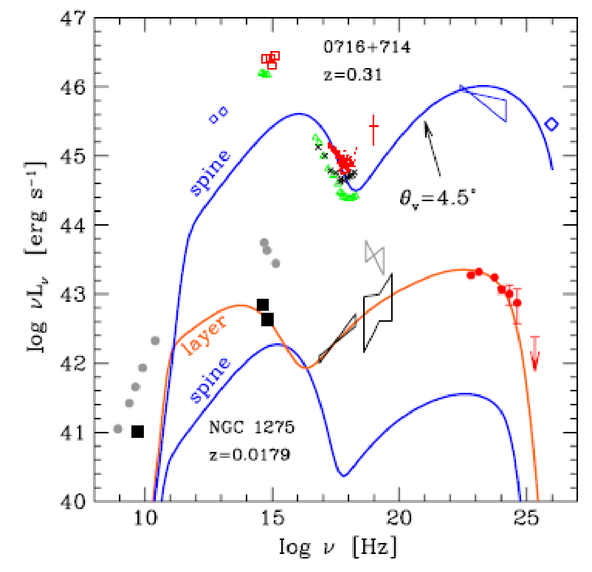


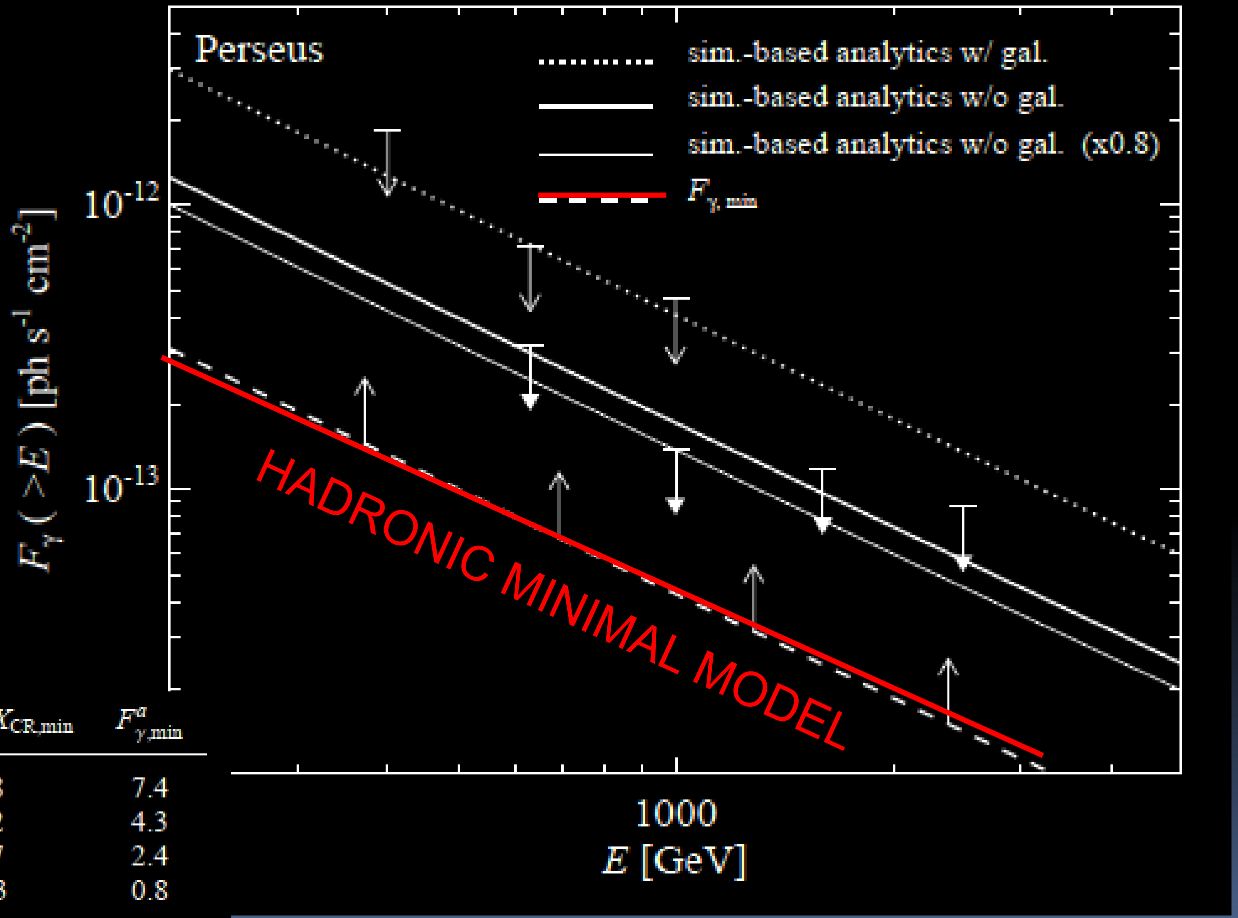
$\theta_{\max}$	$N_\gamma^{95\%\,\mathrm{C.L.}}(E_\gamma > E_{\min})$	$\Phi_\gamma^{95\%\,\mathrm{C.L.}}(E_\gamma > E_{\min})(10^{-12}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1})$ $\Gamma = 1.5$	$\Gamma = 2.5$
0.1°	41.3	0.8	1.0
0.5°	135.1	2.3	3.3
1.0°	403.5	6.8	10.0

VHE observations of galaxy clusters

Perseus (Aleksic ea [MAGIC] 2012) E_{CRp} ~ **1-2% depending on CR model and assumptions**

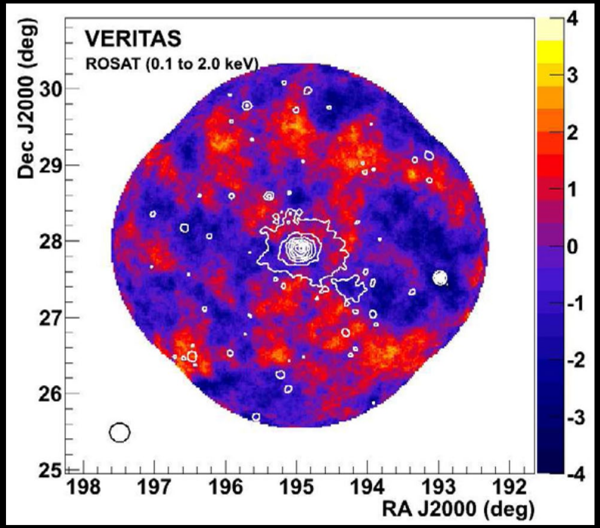


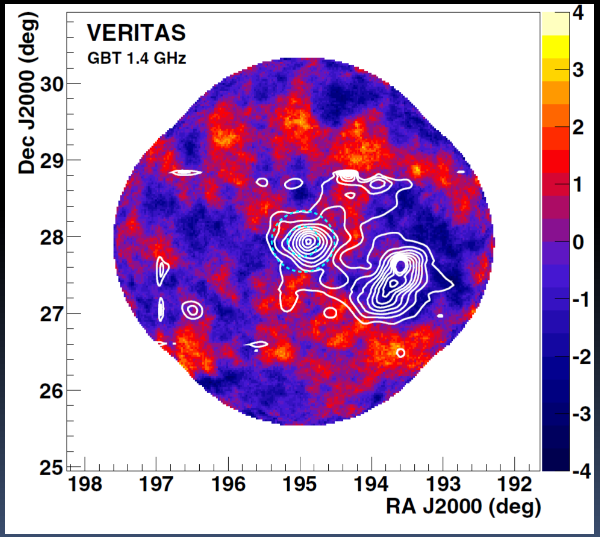
- NGC1275 : as prominent at TeV as at GeV energies !
- IC310 !



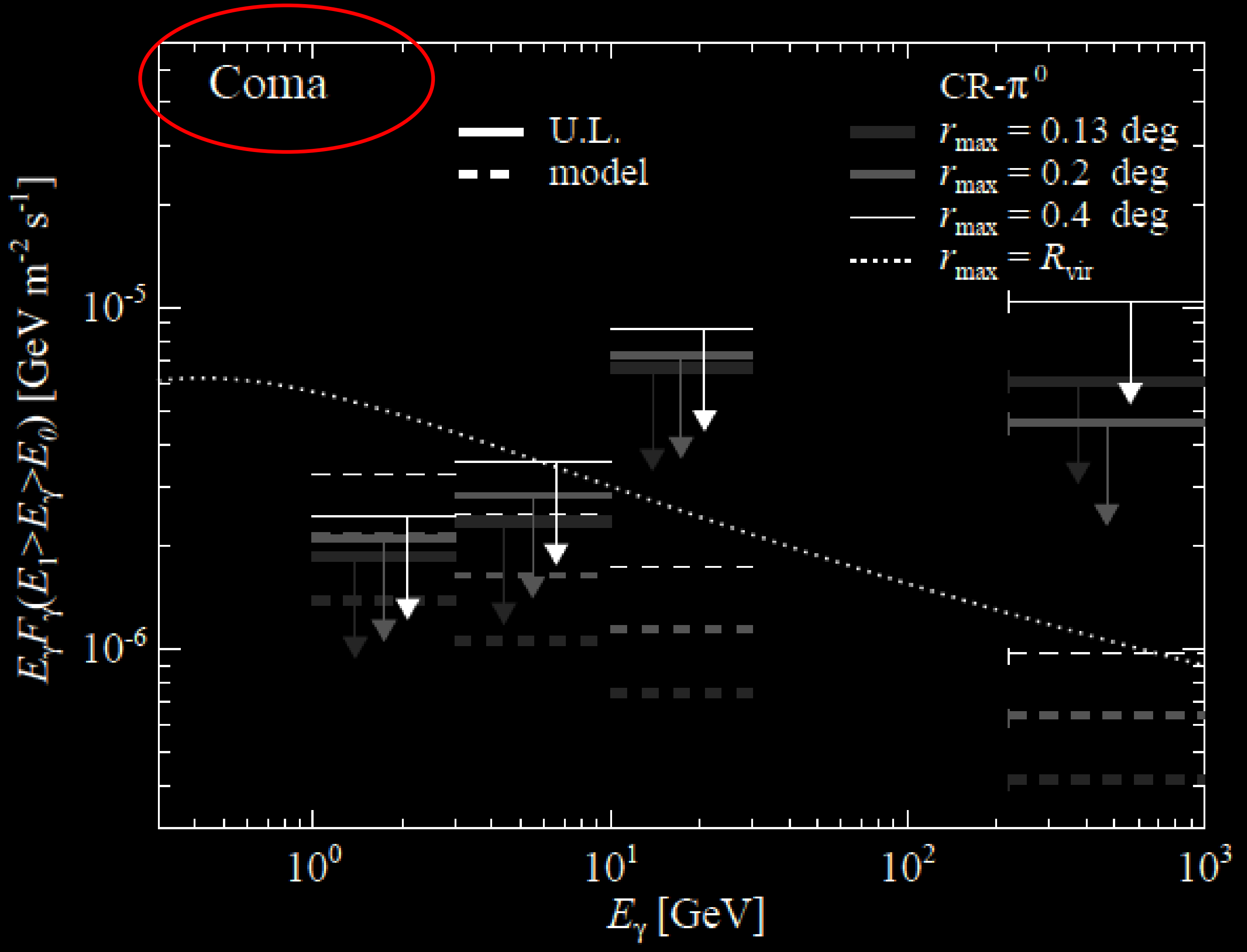
α	$X_{CR,max}$ [%]	$X_{CR,min}$ [%]	$X_{CR,max}/X_{CR,min}$	$F^a_{\gamma,min}$
2.1	0.77	0.42	1.8	7.4
2.2	1.12	0.35	3.2	4.3
2.3	2.17	0.38	5.7	2.4
2.5	11.6	0.67	17.3	0.8

VHE observations of galaxy clusters



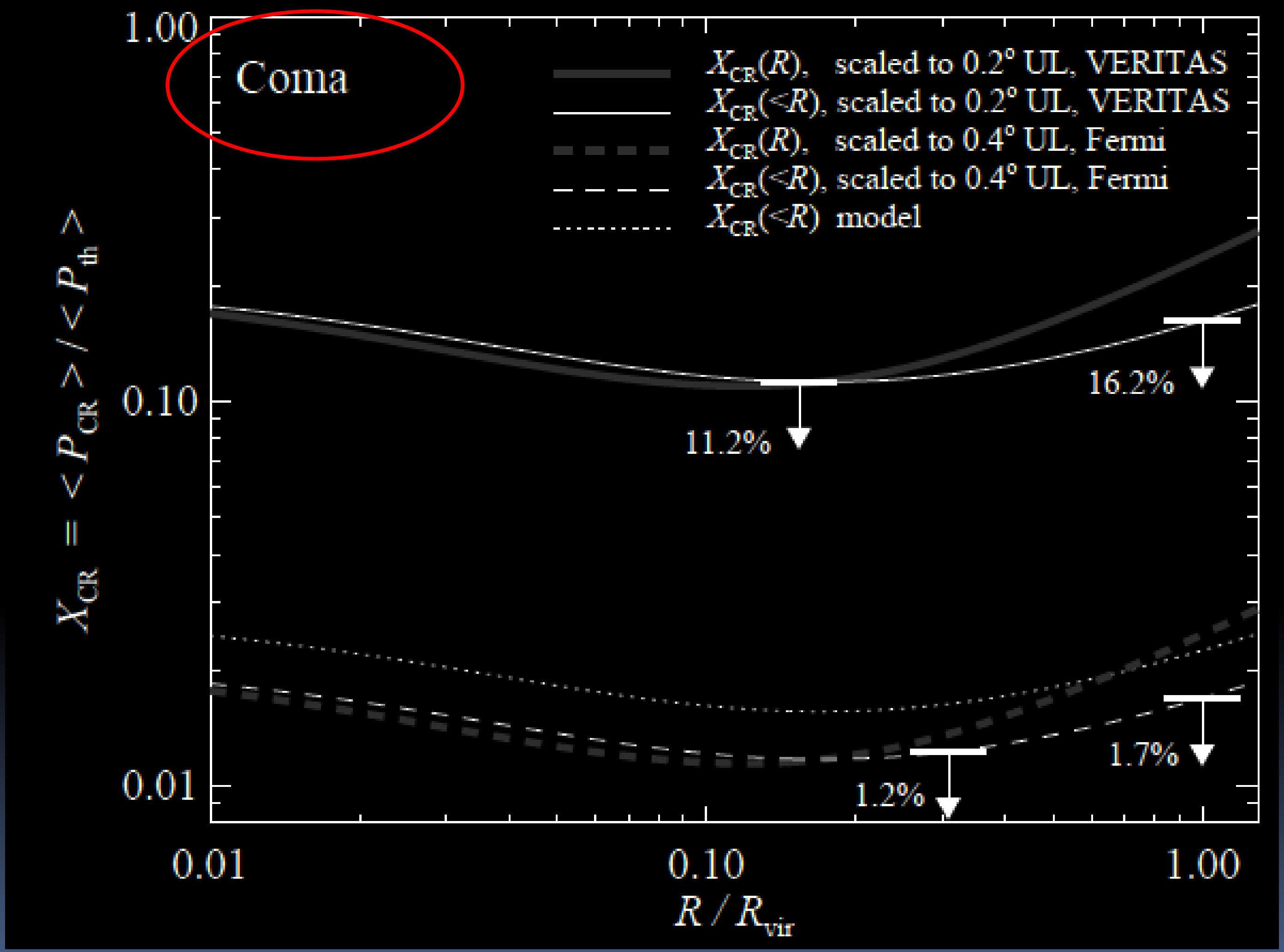


Arlen ea (VERITAS) 2012



VHE observations of galaxy clusters

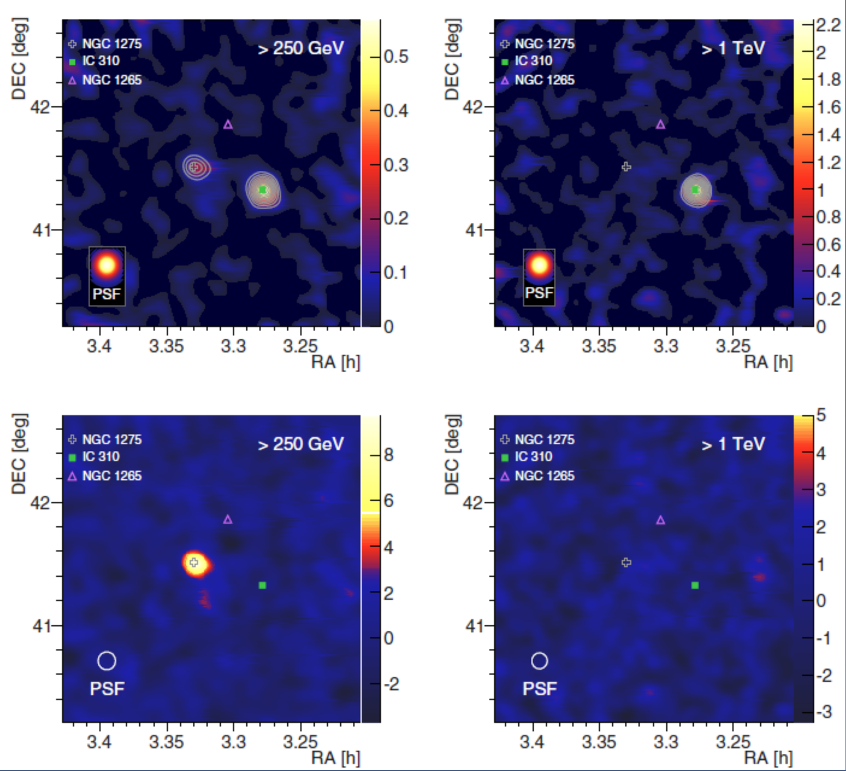
Arlen ea (VERITAS) 2012



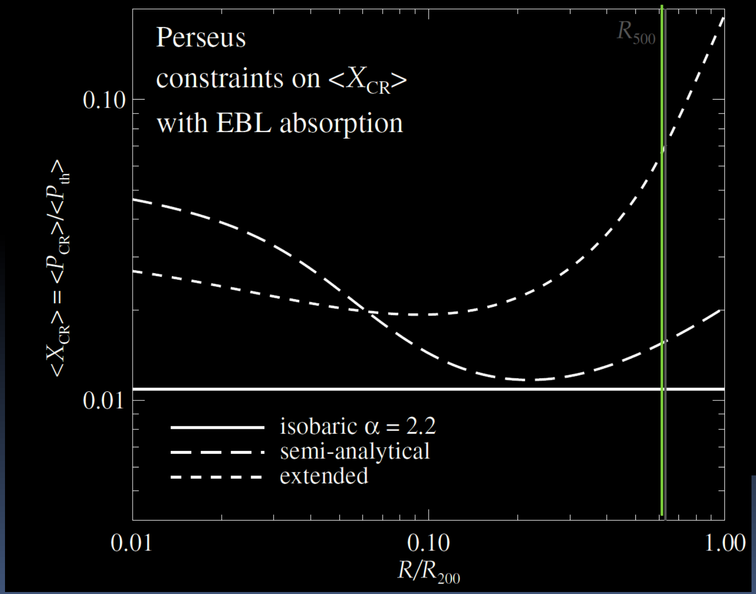
VHE observations of galaxy clusters

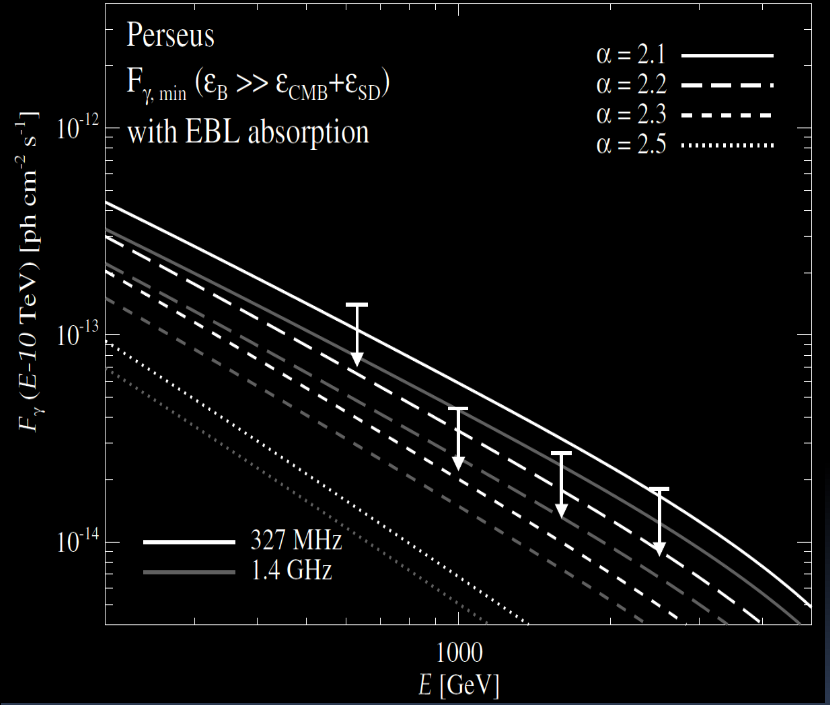
Perseus (Ahnen ea [MAGIC] 2016) **Deep observation of the NGC1275 region with MAGIC: Search of diffuse γ-ray emission from cosmic rays in the Perseus cluster**

253h (!) between 2009…2014



Model	α	$\langle X_{\rm CR,max}^{\rm no-EBL}\rangle$ [%]	$\langle X_{\rm CR,max}\rangle$ [%]
Isobaric	2.1	0.5	0.7
	2.2	0.8	1.1
	2.3	1.7	2.3
	2.5	11.4	15.2
Semi-analytical	2.2	1.5	2.0
Extended	2.2	14.2	19.2





Large FoV UHEγ arrays: HAWC

VIRGO (Albert ea [HAWC] 2024)

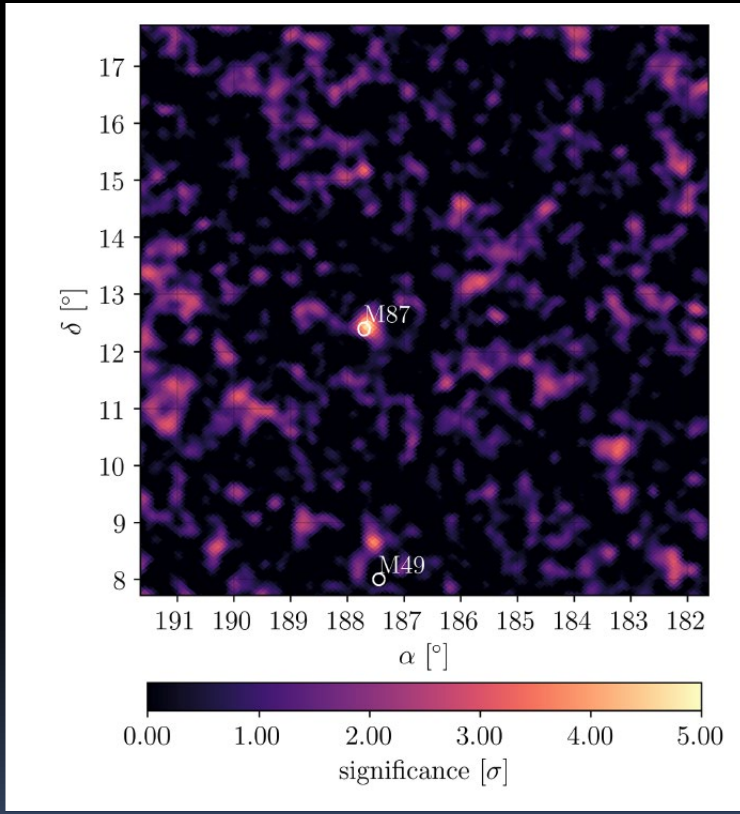


TABLE I. The best-fit spectral normalization and index for the fit to Eq. (1) for M87, with E_0 fixed at 1 TeV. The reported uncertainties are statistical.

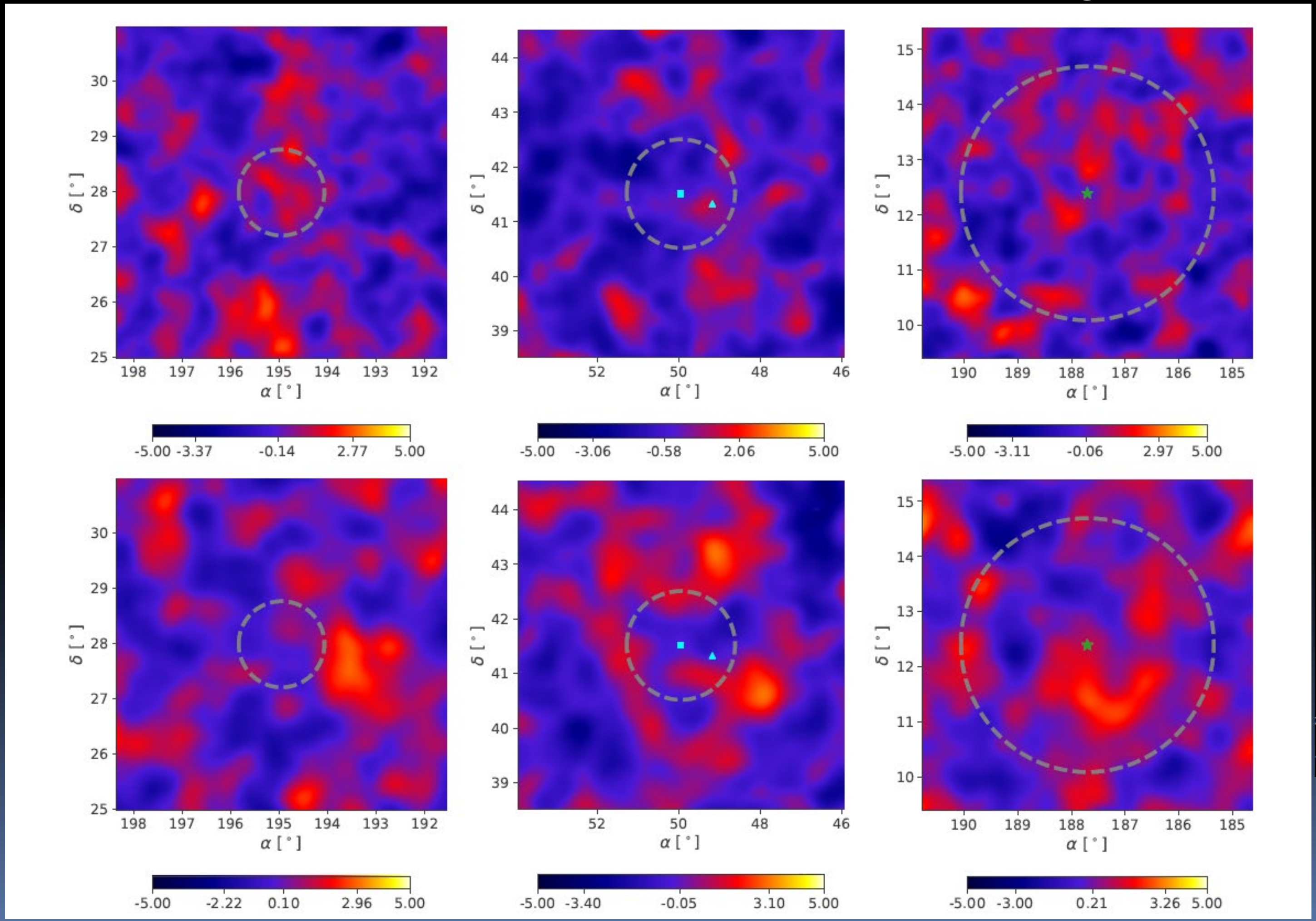
$A \times 10^{-13}$ (TeV^{-1} cm^{-2} s^{-1})	γ
3.8 ± 1.8	2.2 ± 0.2

3HWC: The Third HAWC Catalog of Very-high-energy Gamma-Ray Sources (Albert et al 2020) : $\varnothing$

Large FoV UHEγ arrays: LHAASO

Constraining the Cosmic-ray Energy Based on Observations of Nearby Galaxy Clusters by LHAASO (Cao ea 2025)

Coma Perseus Virgo



WCDA
1…25 TeV

		Spatial model	TS	TS_{disk}[a]	Flux U.L[b].
Coma	WCDA	disk-2.3	6.25	6.25	61.4
		disk-2.7	7.33	7.33	69.0
		disk-2.3+1pt	13.3	1.51	49.4
		disk-2.7+1pt	14.5	2.75	57.1
	KM2A	disk-3.0	3.51	3.51	1.34
Perseus	WCDA	disk-2.3+2pt	19.3	0.00	13.7
		disk-2.7+2pt	16.5	0.00	13.7
	KM2A	disk-3.0	1.08	1.08	1.14
Virgo	WCDA	disk-2.3+1pt	31.72	0.43	54.0
		disk-2.7+1pt	31.47	0.19	44.9
	KM2A	disk-3.0	0.53	0.53	0.40

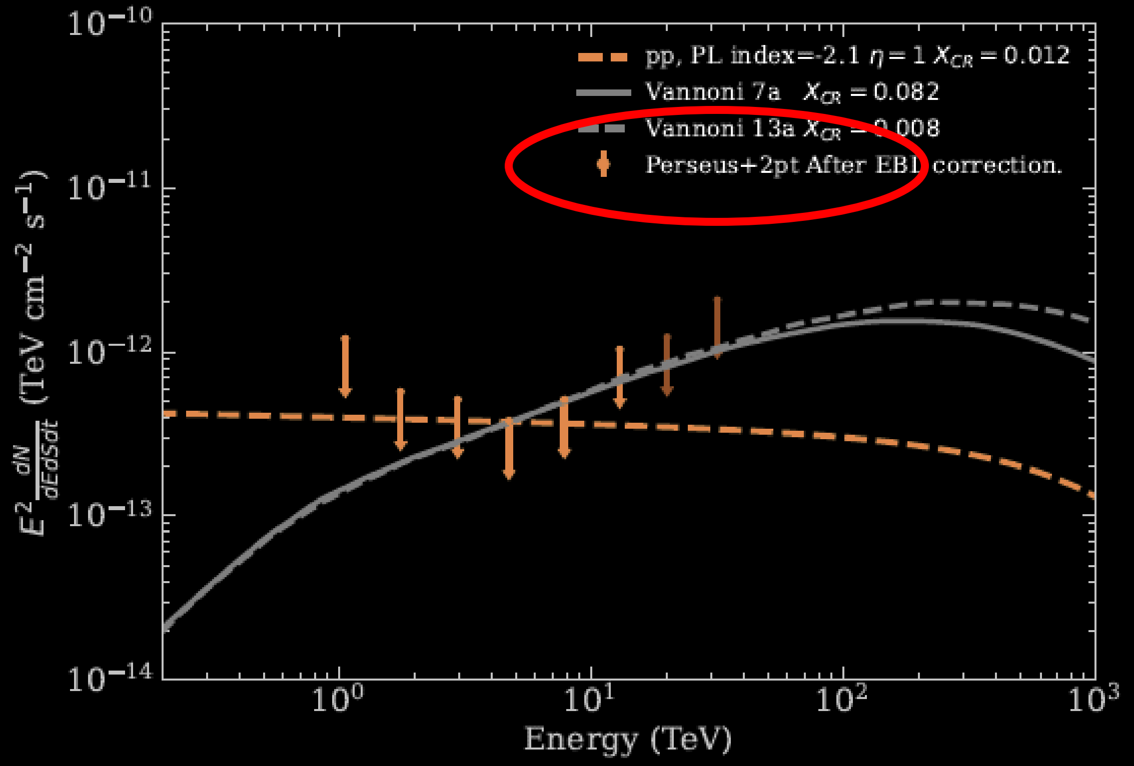
?

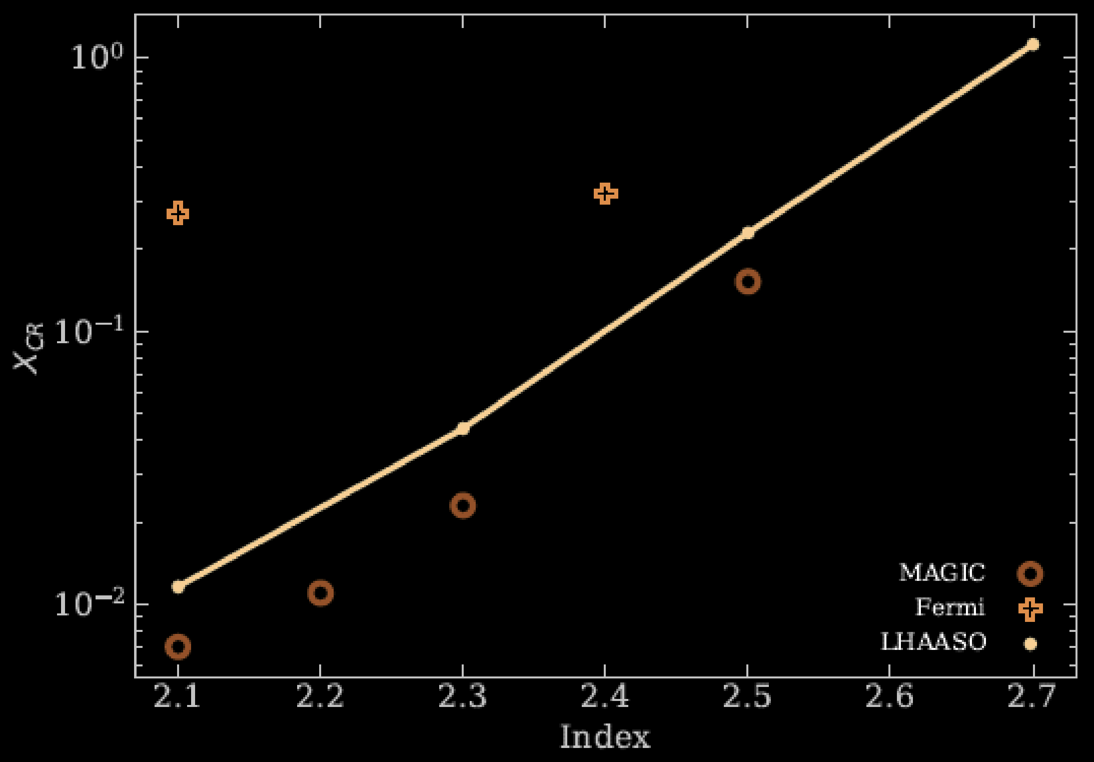
[a] The increase in the TS value resulting from the inclusion of the disk model under the assumption of the existence of other sources in the Spatial model.

KM2A
>25 TeV

Large FoV UHEγ arrays: LHAASO

Constraining the Cosmic-ray Energy Based on Observations of Nearby Galaxy Clusters by LHAASO (Cao ea 2025)





Towards our CTAO KSP then…

Theme 1: Cosmic Particle Acceleration

- ☞ How and where are particles accelerated?
- ☞ How do they propagate?
- ☞ What is their impact on the environment?

Theme 2: Probing Extreme Environments

- ☞ Processes close to neutron stars and black holes
- ☞ Processes in relativistic jets, winds and explosions
- ☞ Exploring cosmic voids

Theme 3: Physics Frontiers – beyond the SM

- ☞ What is the nature of Dark Matter? How is it distributed?
- ☞ Is the speed of light a constant for high energy photons?
- ☞ Do axion-like particles exist?

Towards our CTAO KSP then…

Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

RECEIVED: September 8, 2023
ACCEPTED: September 6, 2024
PUBLISHED: October 1, 2024

Prospects for γ-ray observations of the Perseus galaxy cluster with the Cherenkov Telescope Array

cta cherenkov telescope array

The CTA consortium

103 pp !!

Perseus cluster (Abell 426) is the brightest cluster in the X-ray sky

is one of the most massive nearby clusters and presents the typical properties of a relaxed cool-core cluster with a dense core. (two main cold fronts have been identified and interpreted as the result from the sloshing due to minor mergers)

hosts a radio mini-halo and X-ray cavities associated with the radio lobes of the central AGN, NGC 1275 (3C84), IC310, NGC 1265, NGC 1272, CR 15,…

Once again, I look here only at the CR-related science case

$$\frac{dN_{\mathrm{CRp}}}{dpdV}(E,r) = A_{\mathrm{CRp}}\; p^{-\alpha_{\mathrm{CRp}}}\; n_e(r)^{\eta_{\mathrm{CRp}}}$$

Towards our CTAO KSP then...

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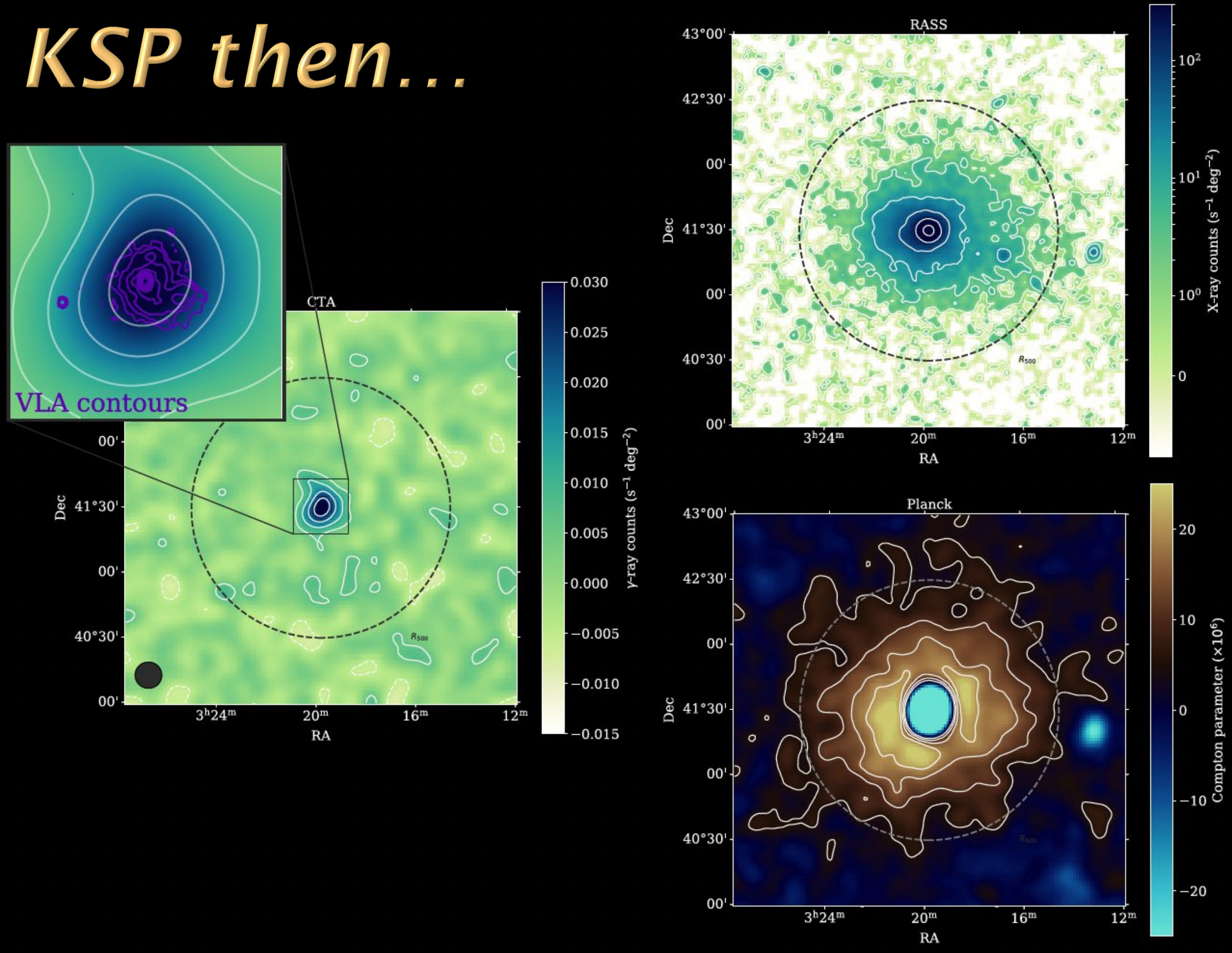
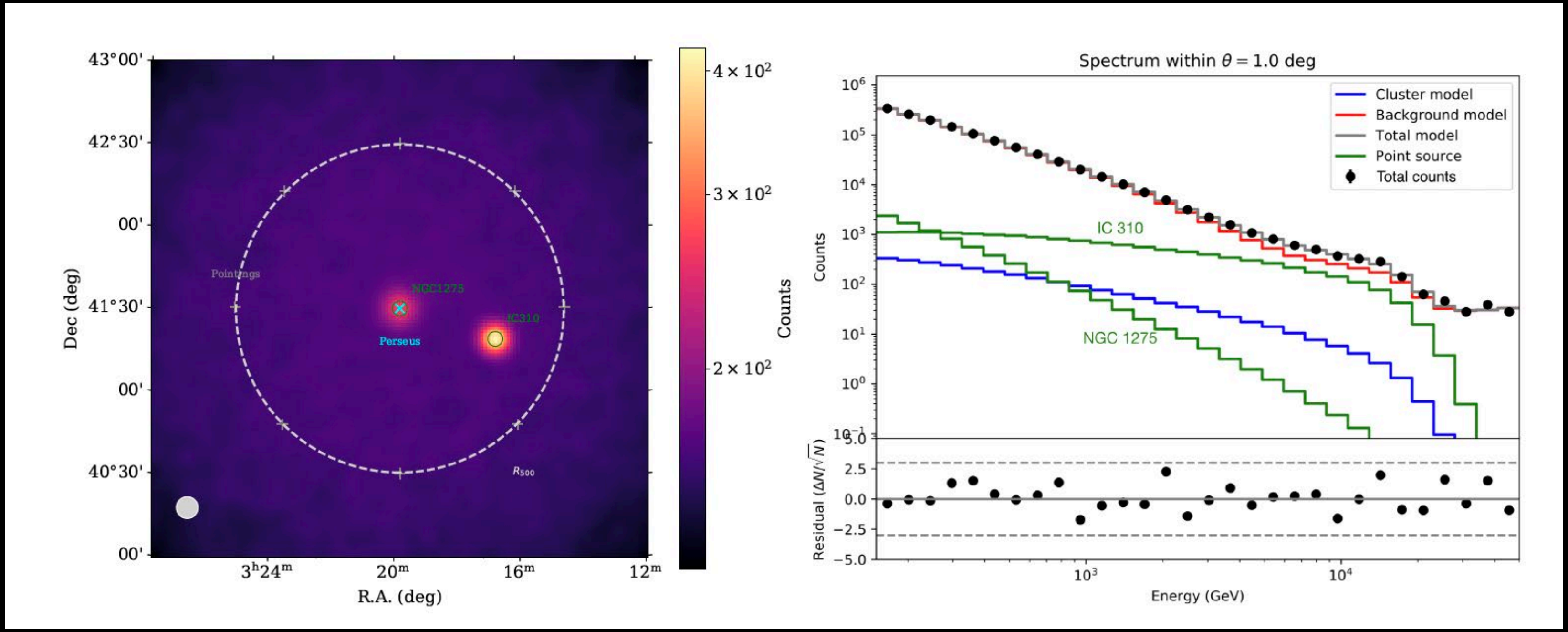
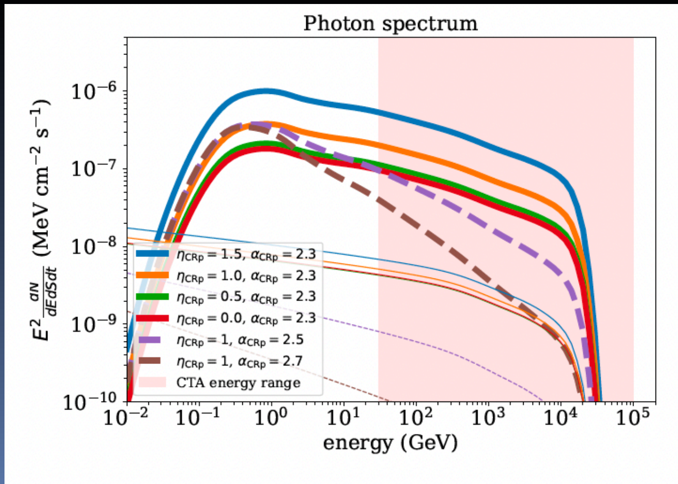
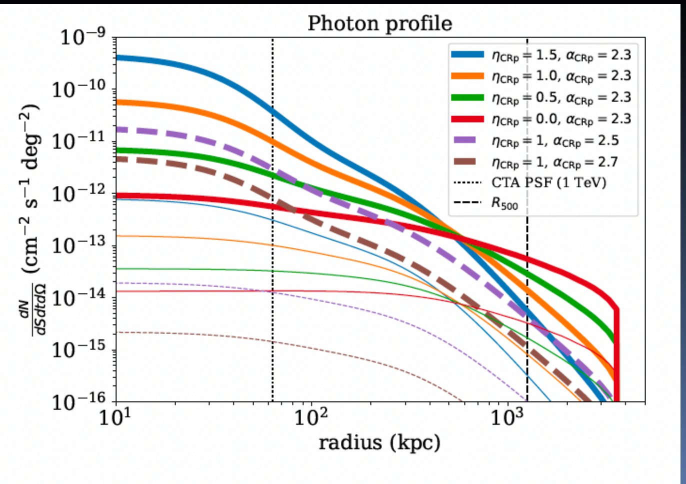


Towards our CTAO KSP then…

150 GeV – 50 TeV

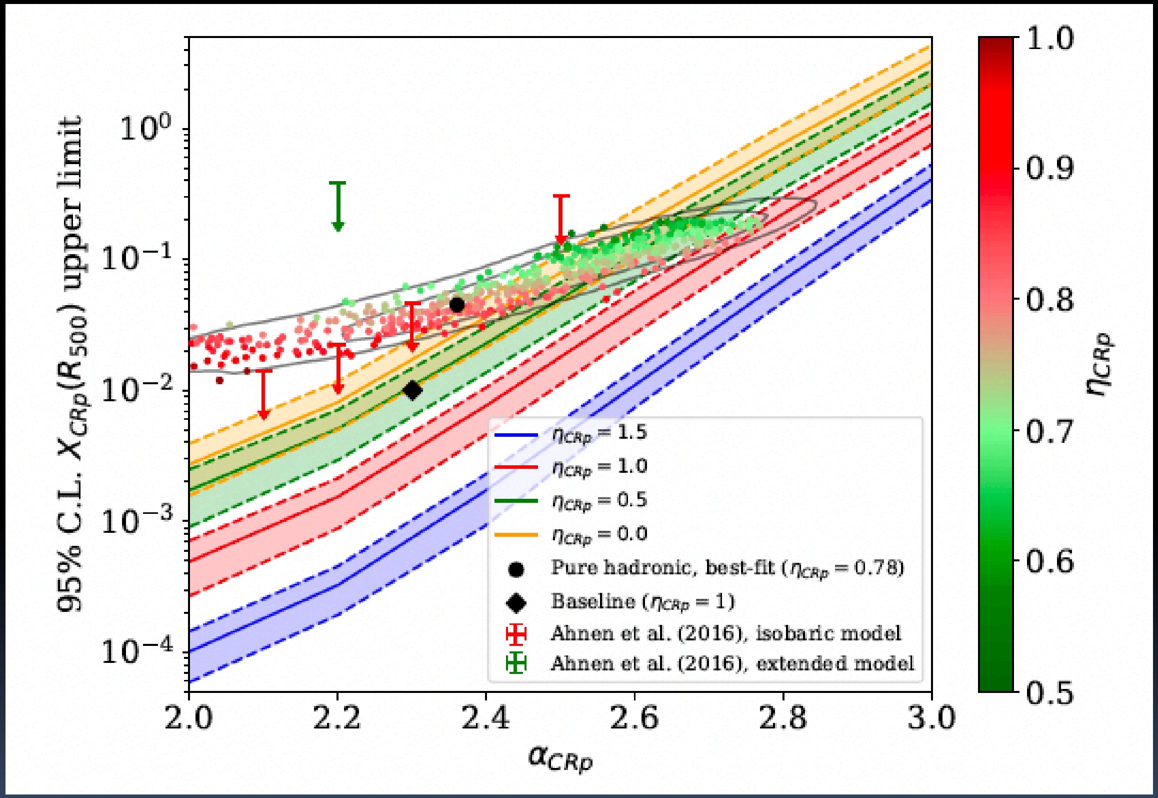


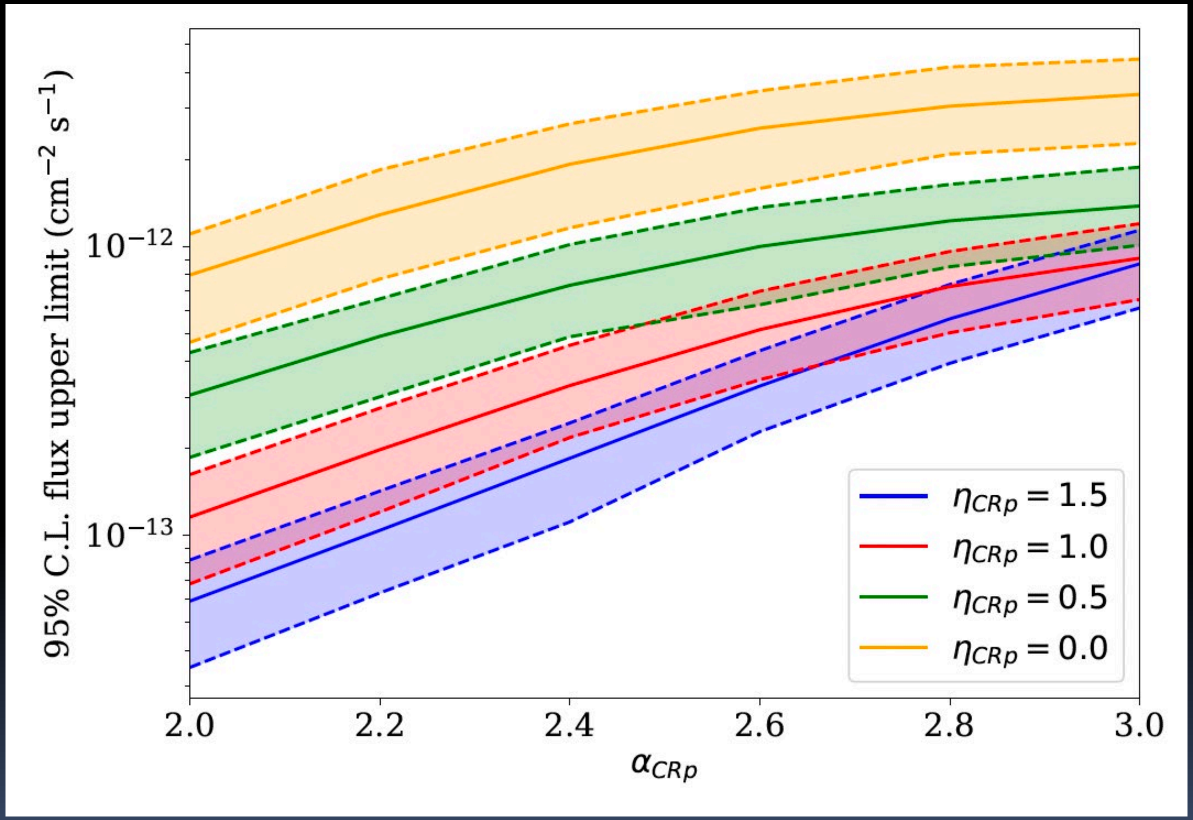




4FGL name	Alt. name	$z^{\dagger}$	Offset (deg)	Type	Spectrum model	PL index	PL extrapolation at 100 GeV (cm^{-2} TeV^{-1} s^{-1})
J0319.8+4130	NGC 1275*	0.01756	0.0	RDG	LP	—	—
J0316.8+4120	IC 310*	0.01894	0.6	RDG	PL	1.85	4.5×10^{-11}
J0315.5+4231	NVSS J031527+423249	N/A	1.3	BCU	PL	1.95	1.3×10^{-11}
J0312.9+4119	B3 0309+411B	0.134	1.3	RDG	PL	2.69	1.5×10^{-12}
J0311.6+4134	B3 0308+413	N/A	1.5	BCU	PL	1.95	1.2×10^{-11}
J0333.8+4007	B3 0330+399	N/A	3.0	BCU	PL	2.17	1.3×10^{-11}
J0334.3+3920	4C +39.12	0.02059	3.5	RDG	PL	1.81	4.0×10^{-11}
J0310.9+3815	B3 0307+380	0.816	3.7	FSRQ	PL	2.40	8.3×10^{-12}
J0340.3+4130	PSR J0340+4130	0	3.9	PSR	PLSEC	—	—
J0342.2+3858	GB6 J0342+3858	0.945	5.0	FSRQ	PL	2.26	1.2×10^{-11}

Towards our CTAO KSP then…





Conclusions

- science case CR still ambiguous owing to *complex analyses & interpretations* at deep nonthermal energies

- likely *not decisively settled in the GeVs* over the Fermi-LAT era

- *tough* for IACTs, although progress on *characterization of cluster member galaxies*

- *even more tough* for HAWC/LHAASO, owing to analysis model extrapolation in weakly constrained parameter space
  (direct combination UHE/VHE @LHAASO/LACT might overcome this handicap)